Physics at a future e+e– collider

Jenny List (DESY)
Particle Physics Seminar
U Bonn
16 November 2023

HELMHOLTZ
CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

Outline

Today's menu

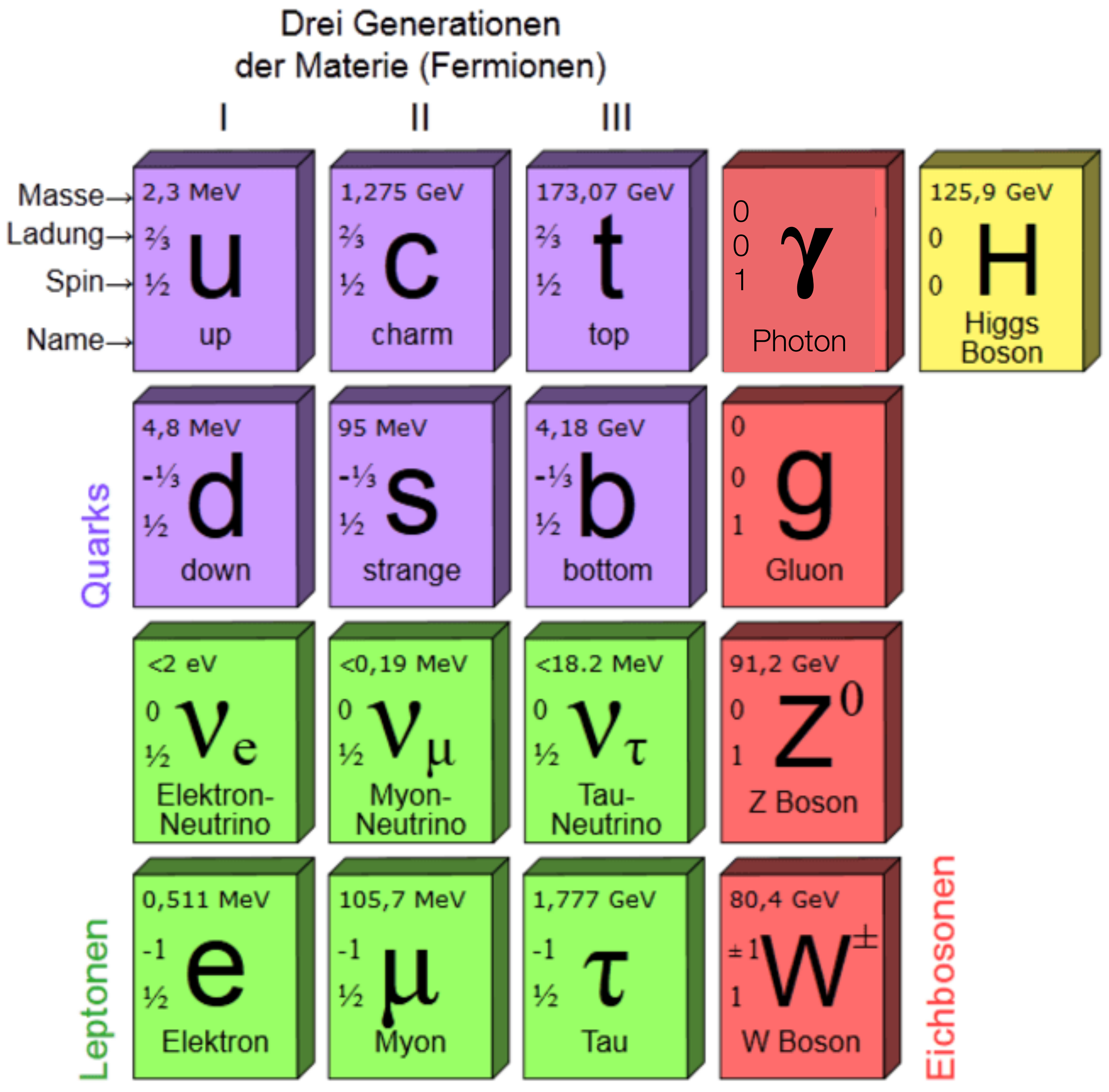
- Introduction: The Higgs Physics and Higgs Factories
- The basic Higgs Factory program
- Beyond the minimal Higgs program
- Higgs Factories Detector Concepts, Performance & Physics Analysis Challenges
- Conclusions

Many thanks to all who contributed material!
(with and without being asked ;)

Introduction:
Higgs Physics &
Higgs Factories

The Higgs Boson and the Standard Model of Particle Physics

A discovery which is only the beginning …



The Standard Model of Particle Physics

- describes (nearly) all measurements down to the level of quantum fluctuations
- based on only a few fundamental ideas:
  - special relativity
  - quantum mechanics
  - invariance under local gauge transformations: $SU(3) x SU(2)_L x U(1)_Y$

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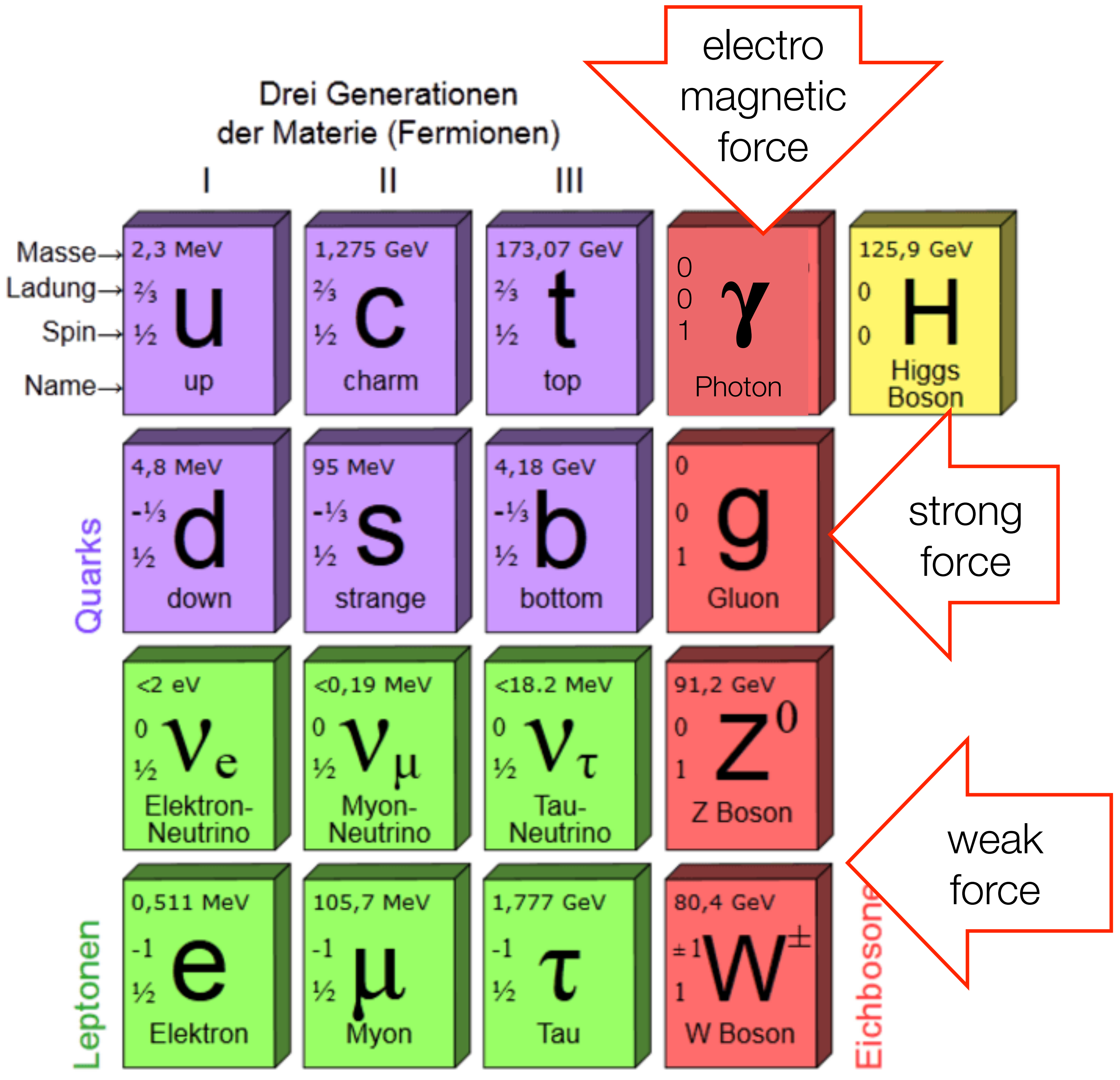

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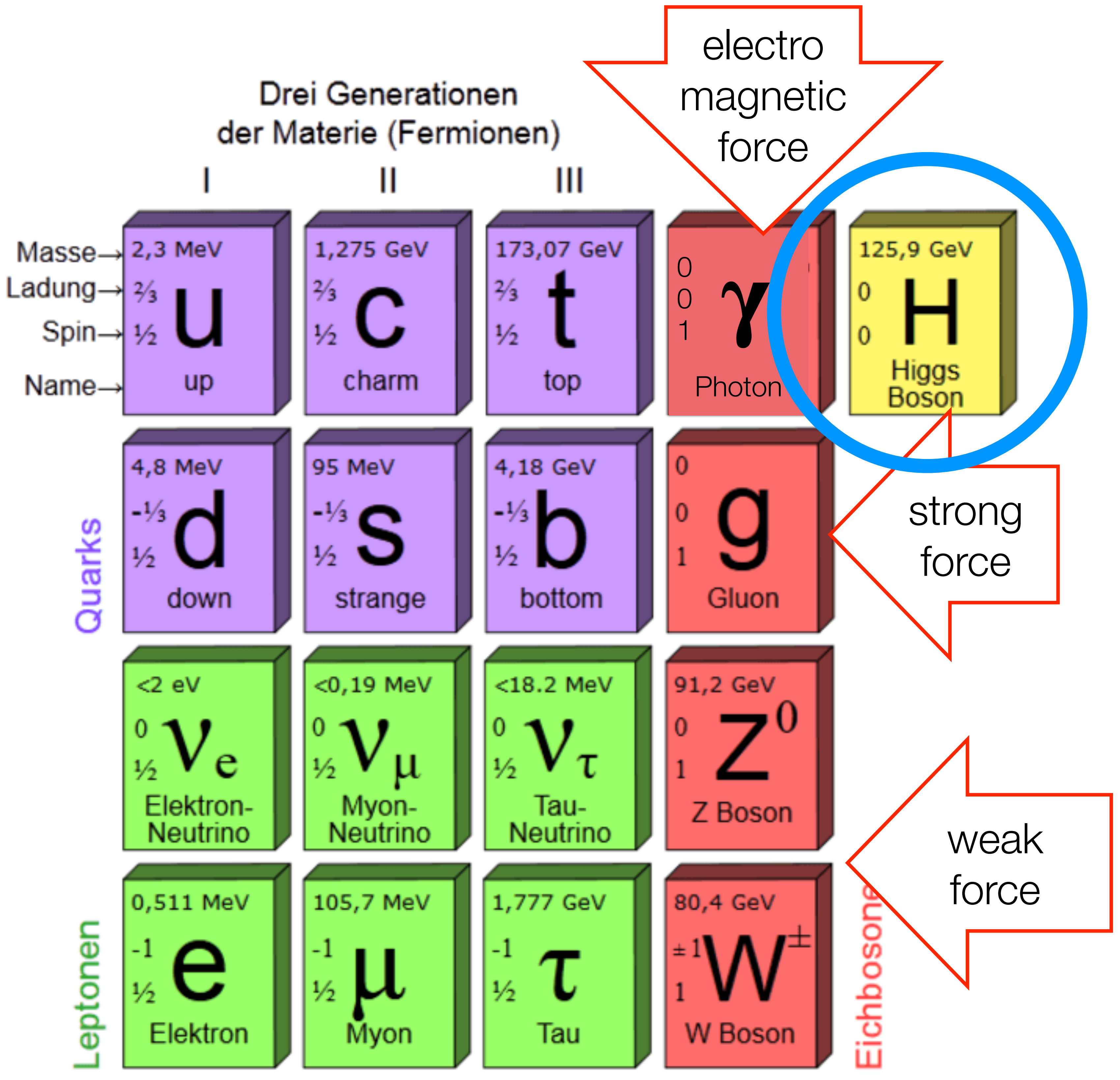

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2012: Discovery of a Higgs bosons at the LHC!

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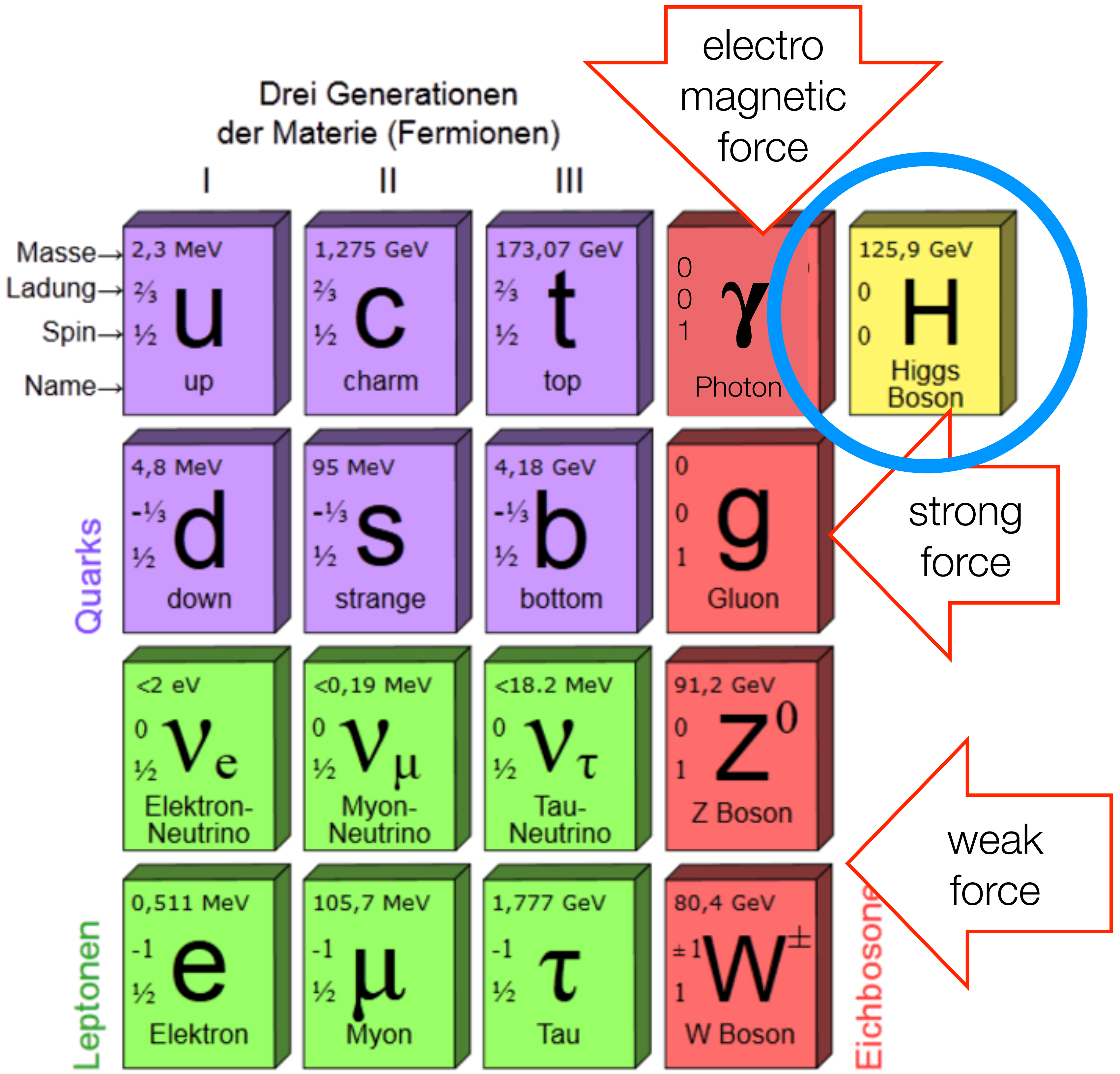

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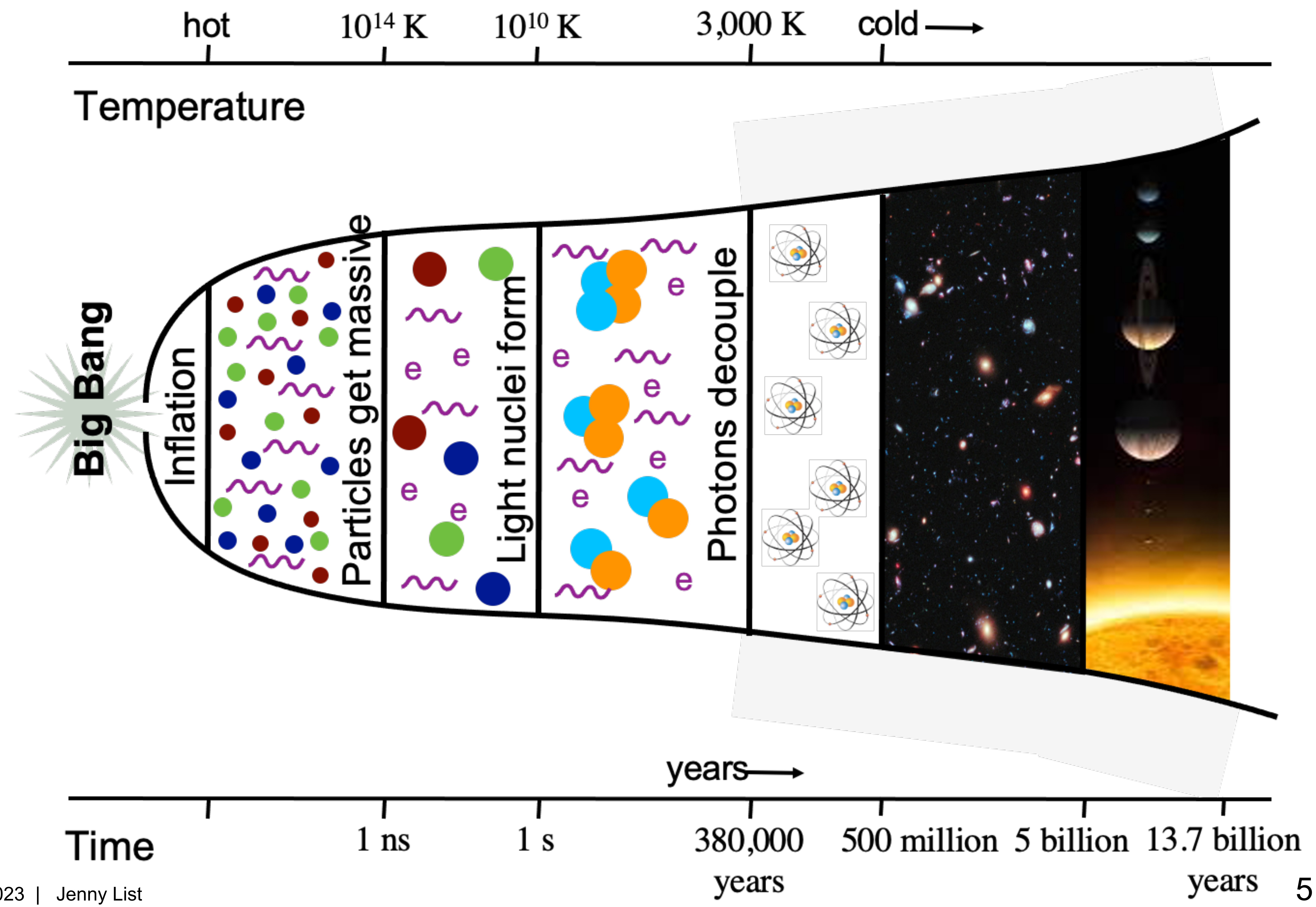
Are we done? — No! — The Higgs Boson is

1. **a mystery in itself: how can an elementary spin-0 particle exist and be so light?**
2. **intimately connected to cosmology => precision studies of the Higgs are a *new* messenger from the early universe!**

A new messenger from the early universe

The Higgs Boson



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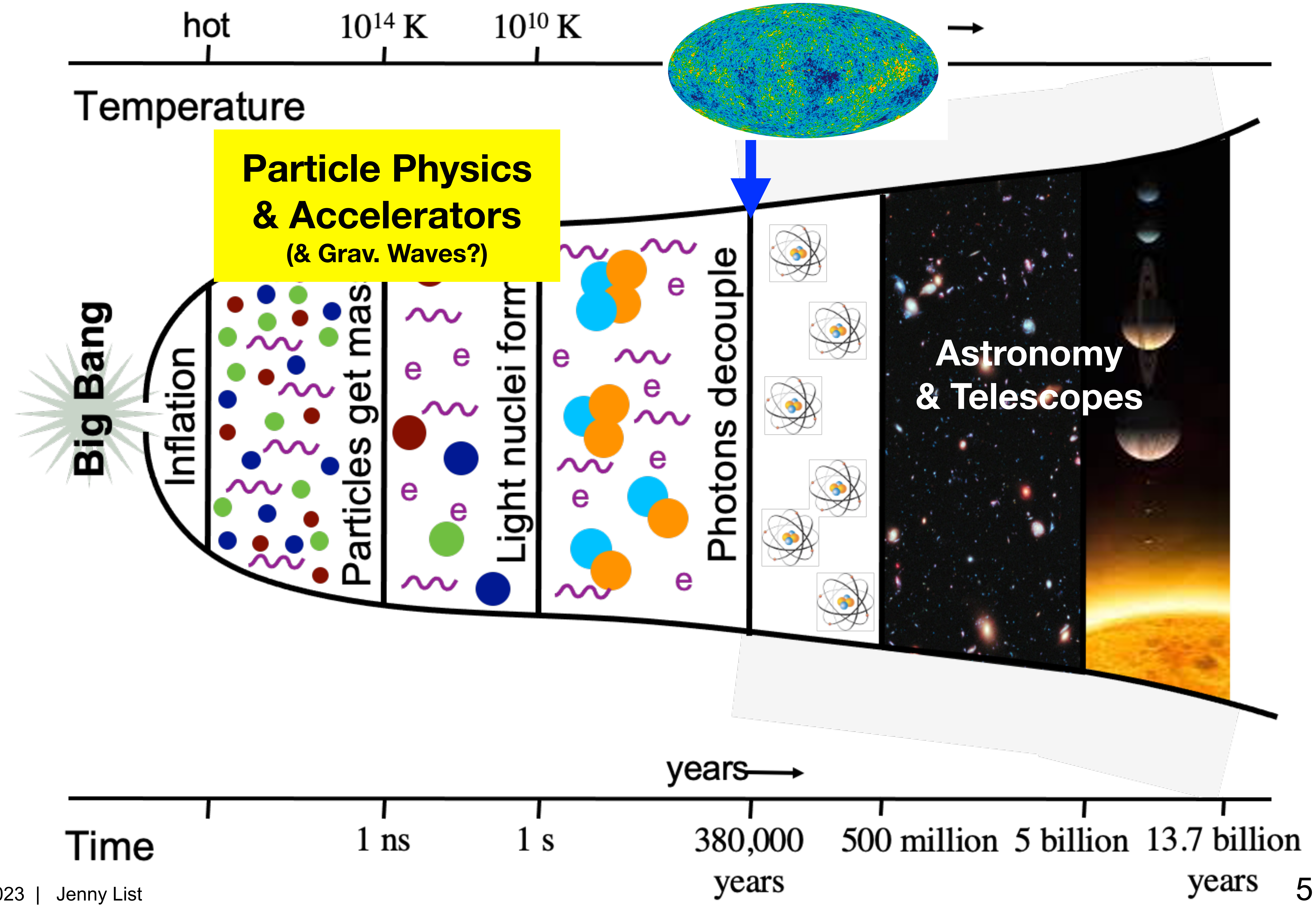

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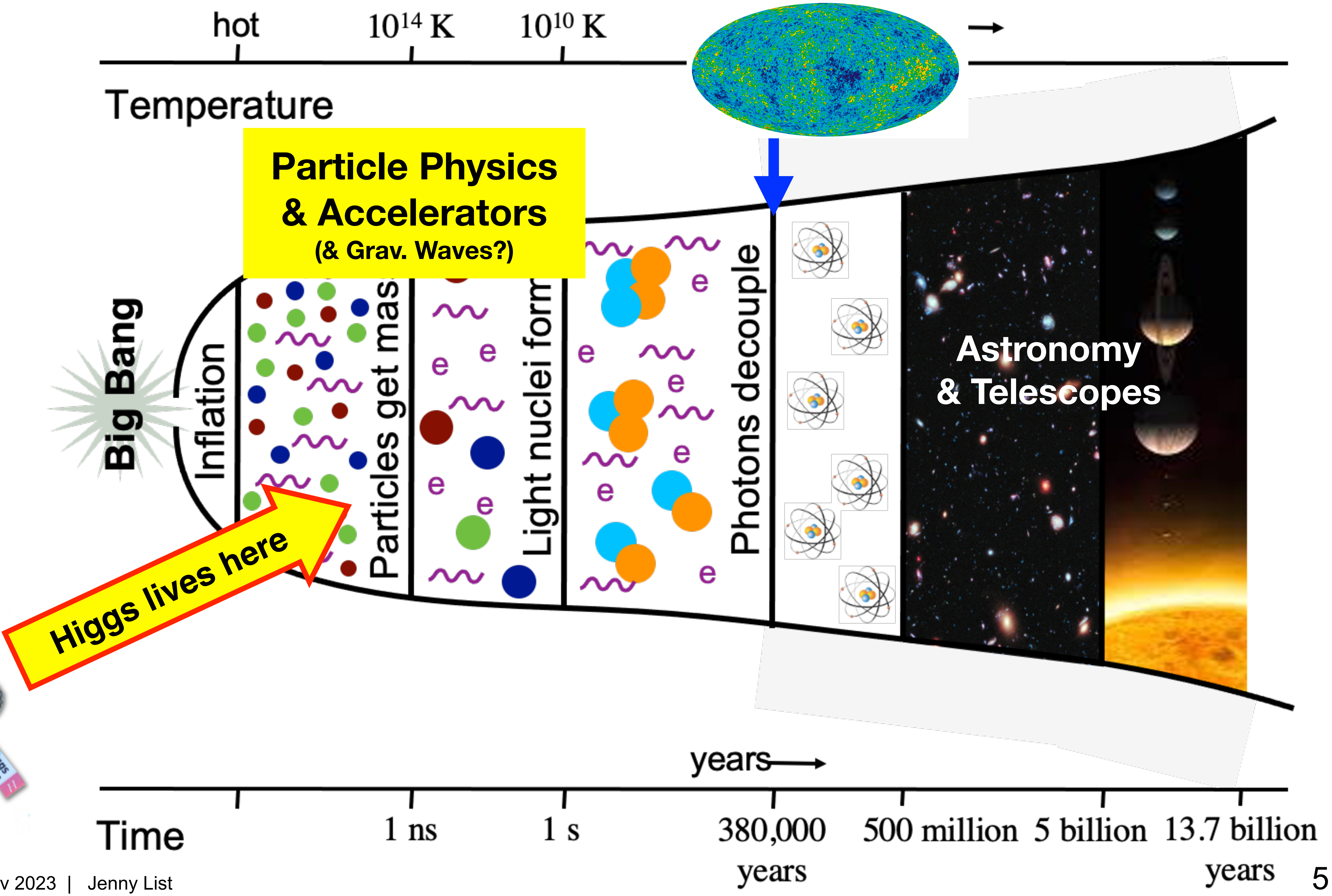

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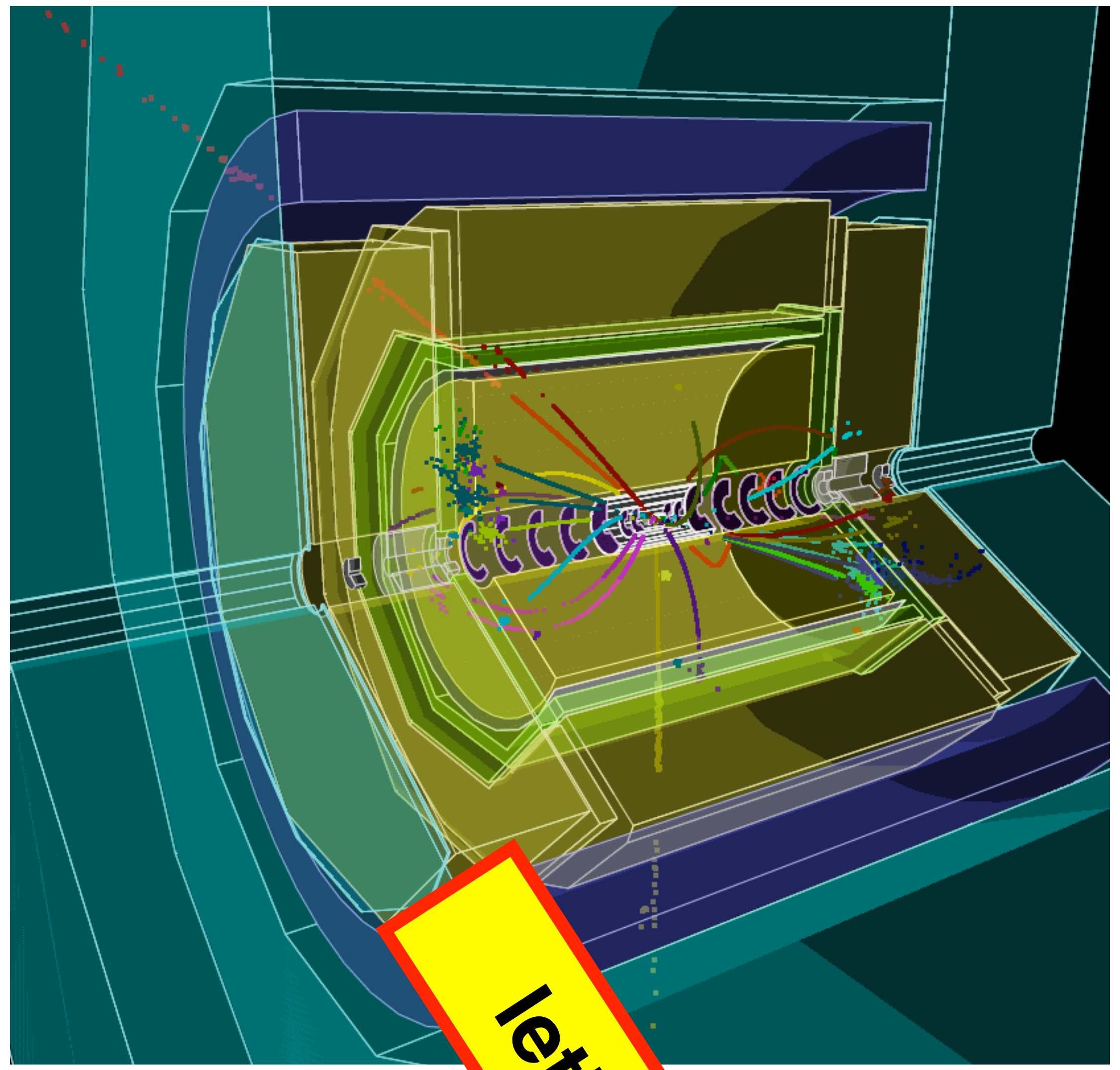
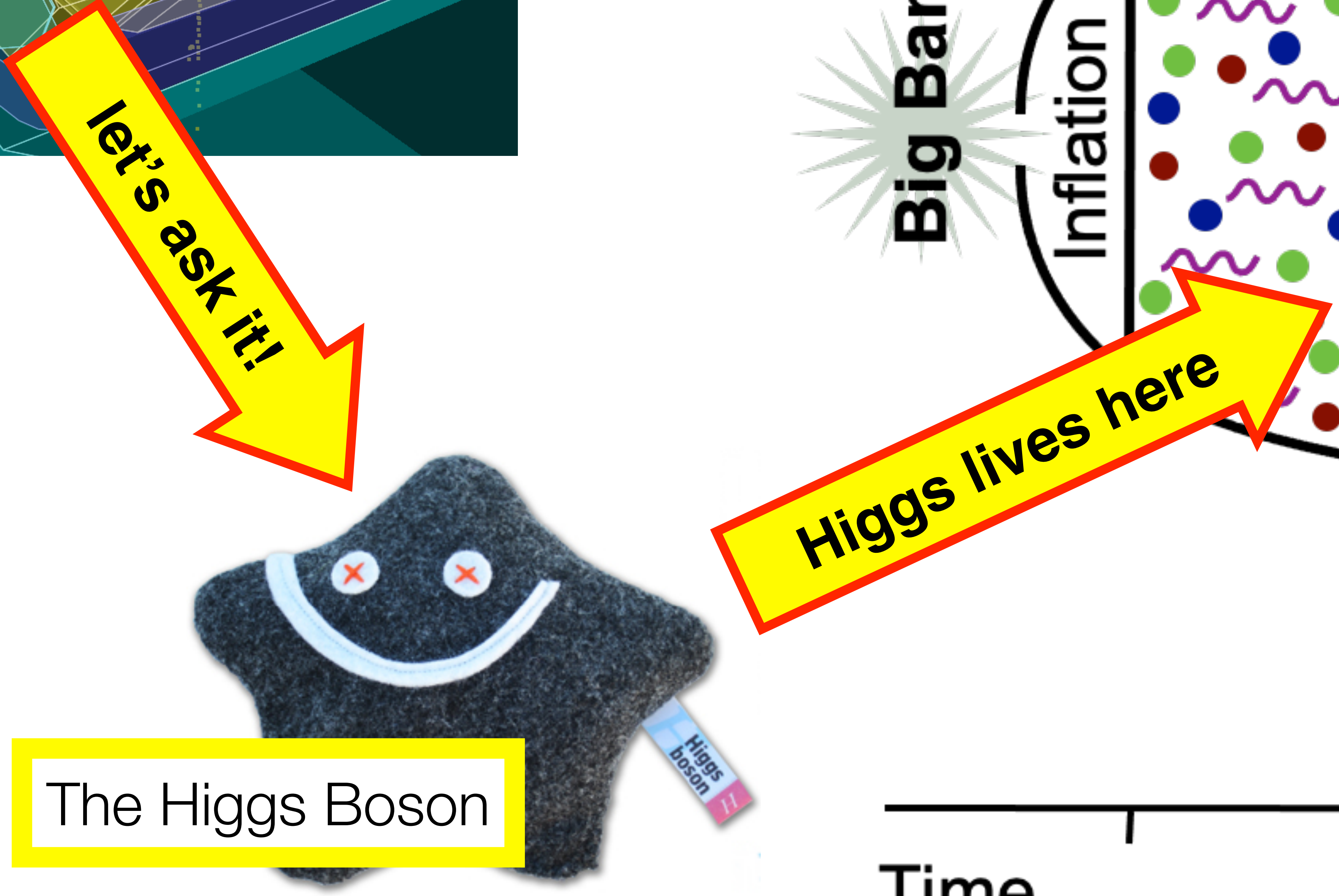
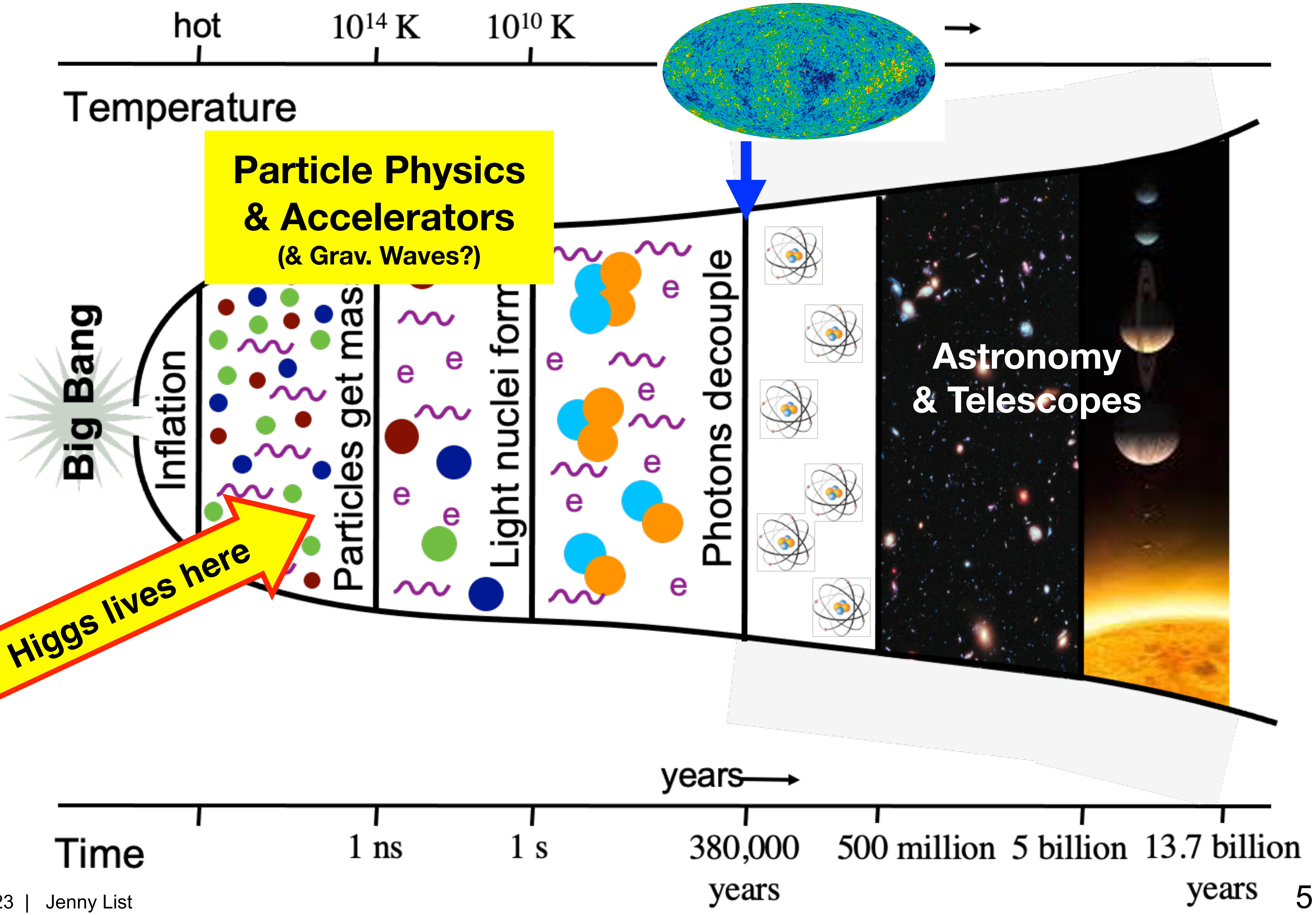
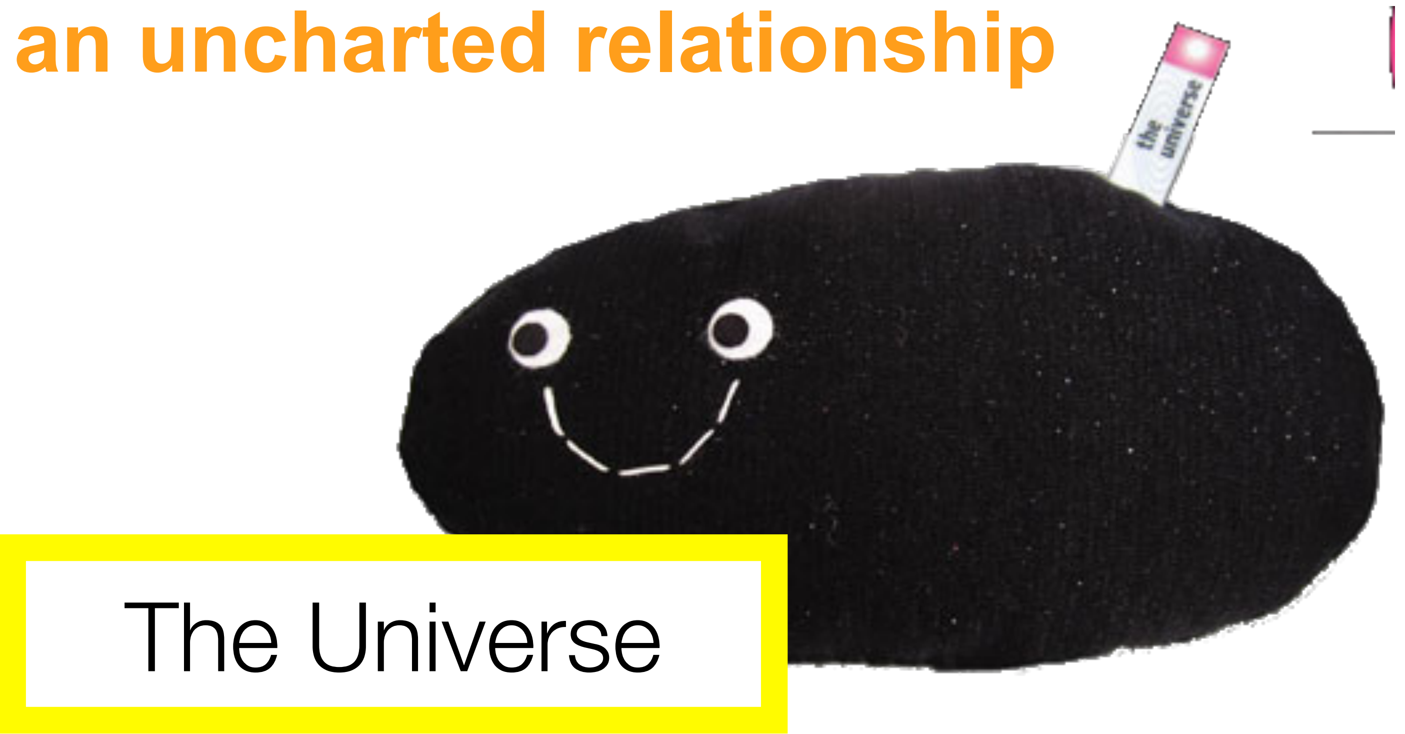






The Higgs Boson and the Universe

Exploration of an uncharted relationship



What we'd really like to know

- What is Dark Matter made out of?
- What drove cosmic inflation?
- What generates the mass pattern in quark and lepton sectors?
- What created the matter-antimatter asymmetry?
- What drove electroweak phase transition?
  - **and could it play a role in baryogenesis?**
- …

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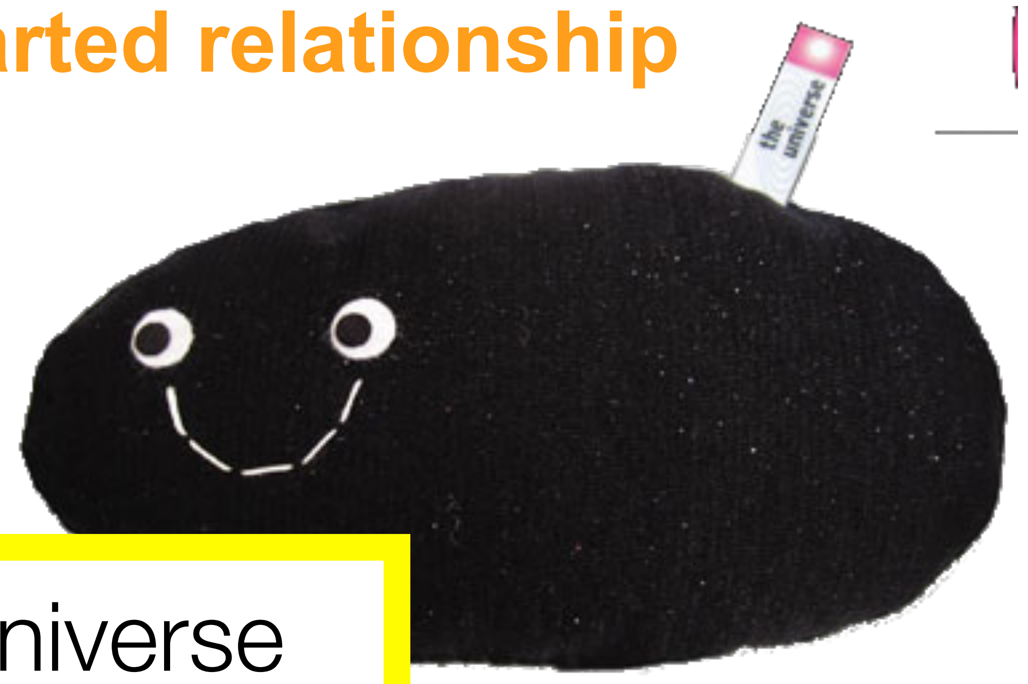

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Is the Higgs the portal to the Dark Sector?

- does the Higgs decays "invisibly", i.e. to dark sector particles?
- does the Higgs have siblings in the dark (or the visible) sector?

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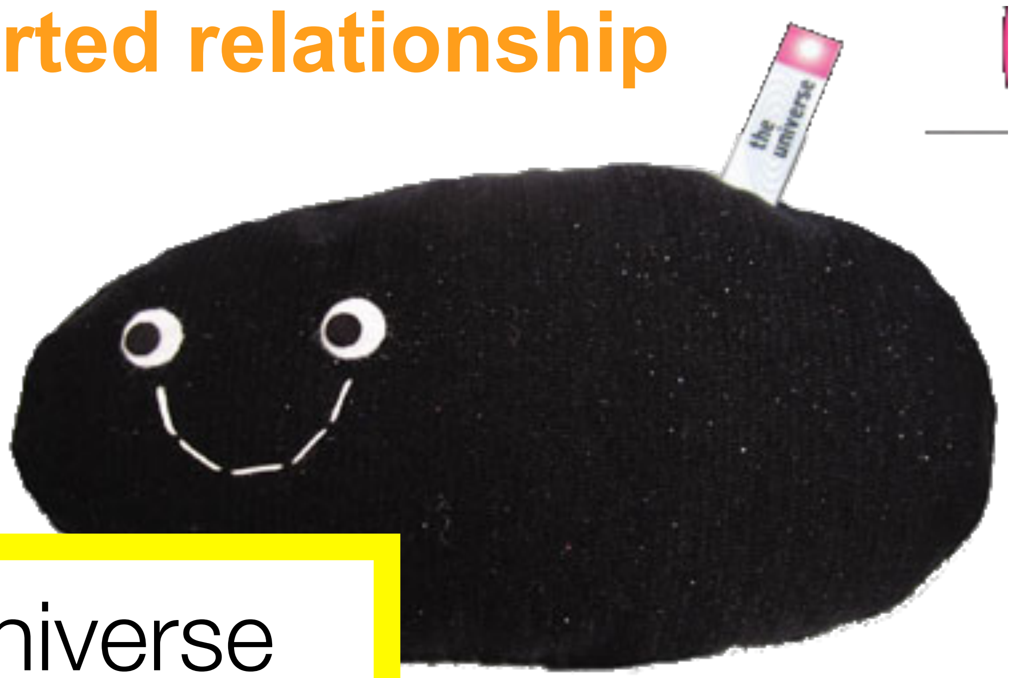

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Is the Higgs the portal to the Dark Sector?

- **The Higgs could be first "elementary" scalar we know -**
  - is it really elementary?
  - is it the inflaton?
  - even if not - it is the best "prototype" of a elementary scalar we have

=> study the Higgs properties precisely and look for siblings

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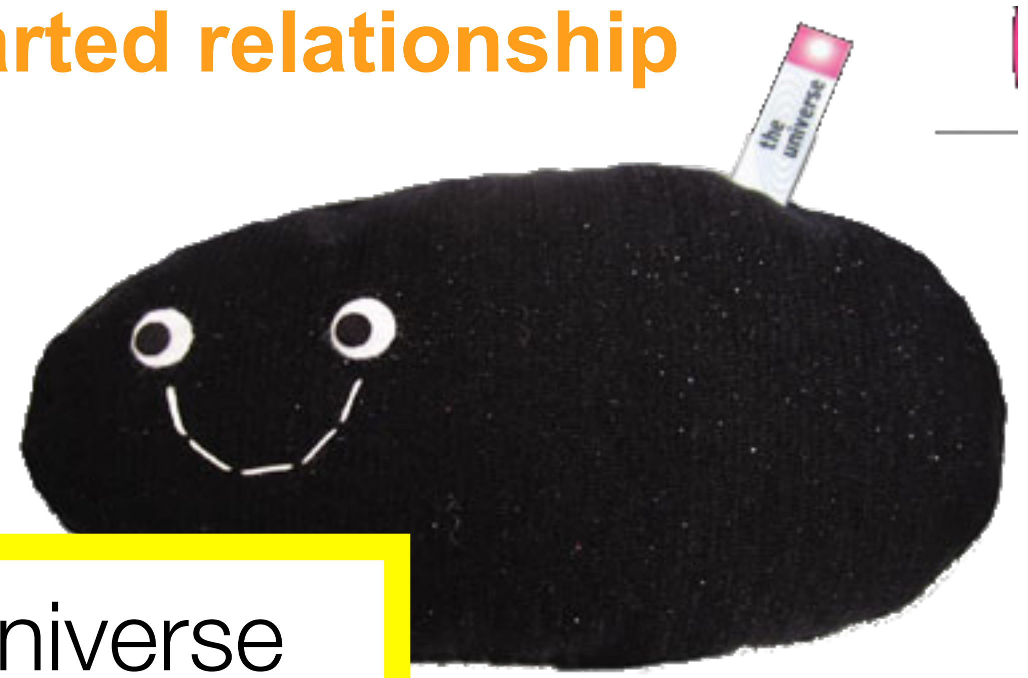

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Why is the Higgs-fermion interaction so different between the species?

- does the Higgs generate all the masses of all fermions?
- are the other Higgses involved - or other mass generation mechanisms?
- what is the Higgs' special relation to the top quark, making it so heavy?
- is there a connection to neutrino mass generation?

=> study Higgs and top - and search for possible siblings!

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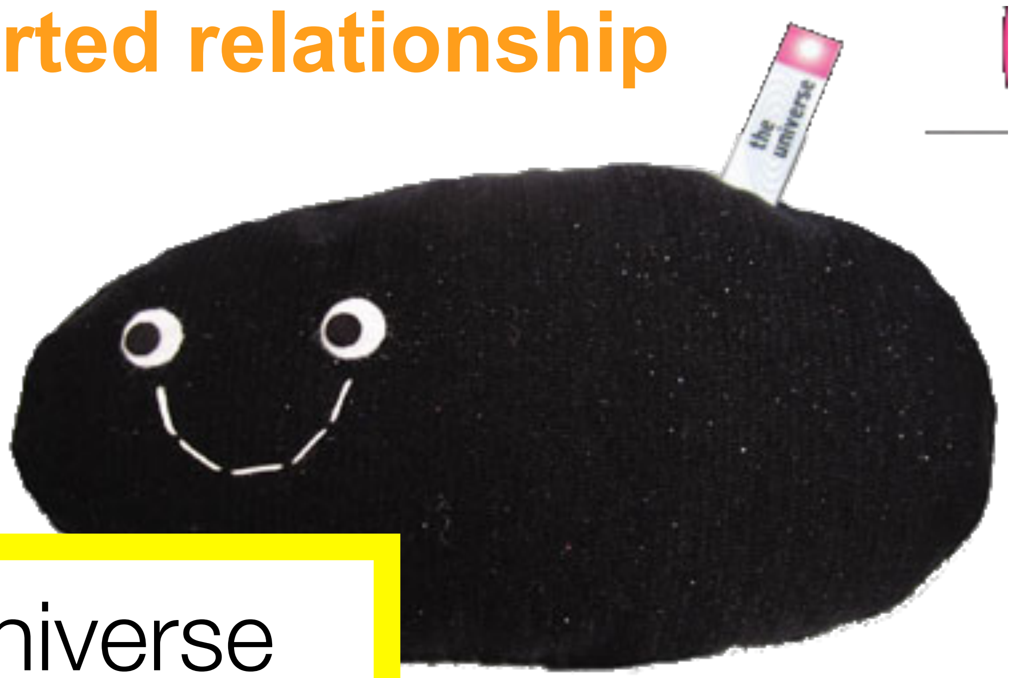

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Does the Higgs sector contain additional CP violation?

- in particular in couplings to fermions?
- or do its siblings have non-trivial CP properties?

=> small contributions -> need precise measurements!

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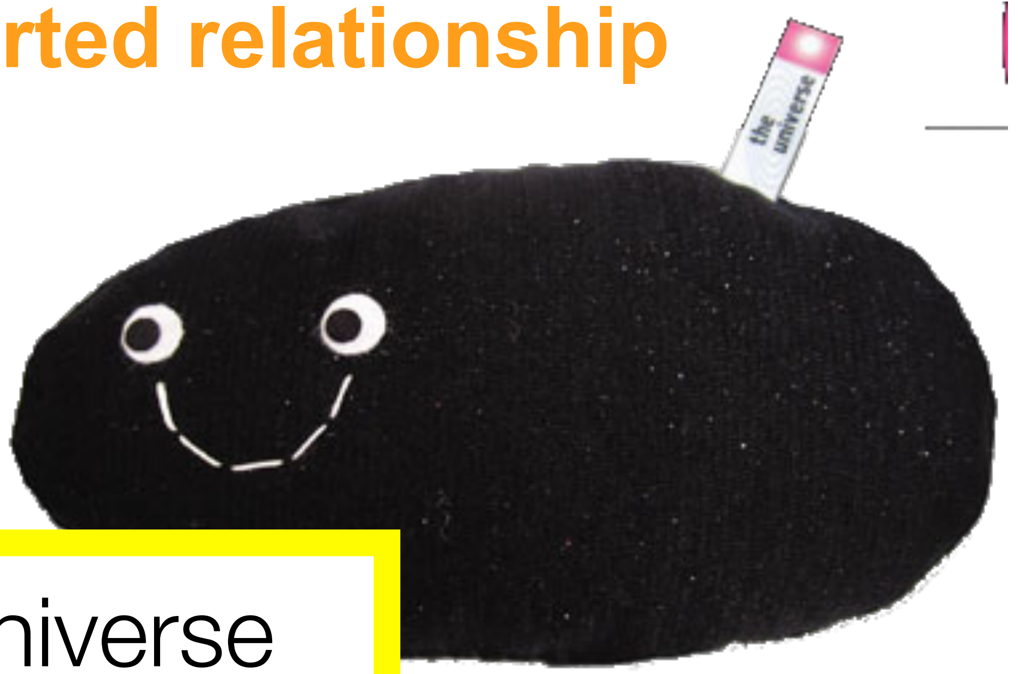

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What is the shape of the Higgs potential, and its evolution?

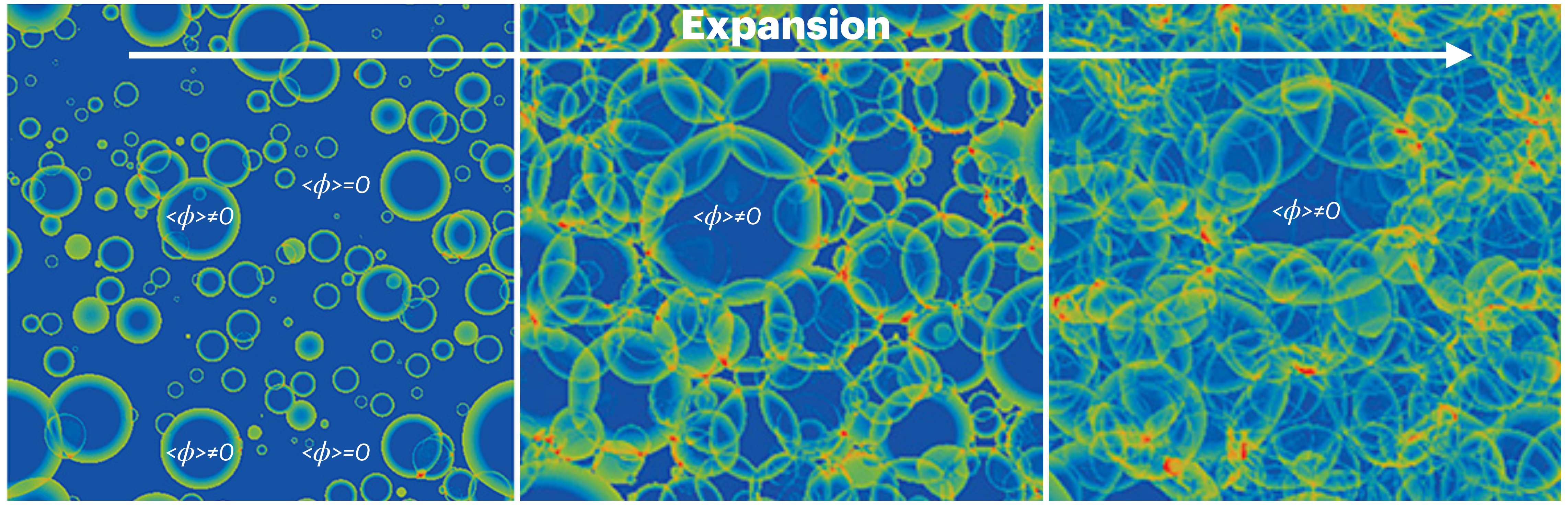
- do Higgs bosons self-interact?
- at which strength? => 1st or 2nd order phase transition?

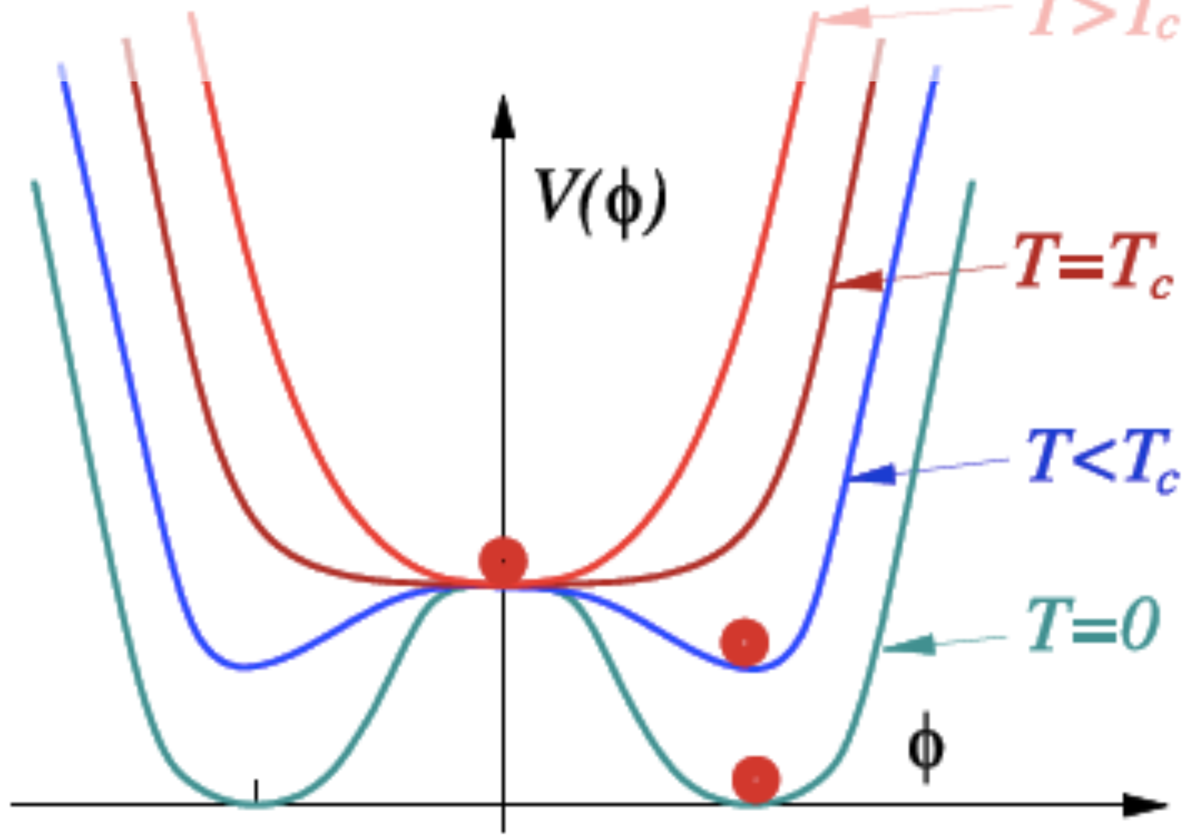
=> discover and study di-Higgs production

The Higgs potential, the Higgs self-coupling and Baryogenesis

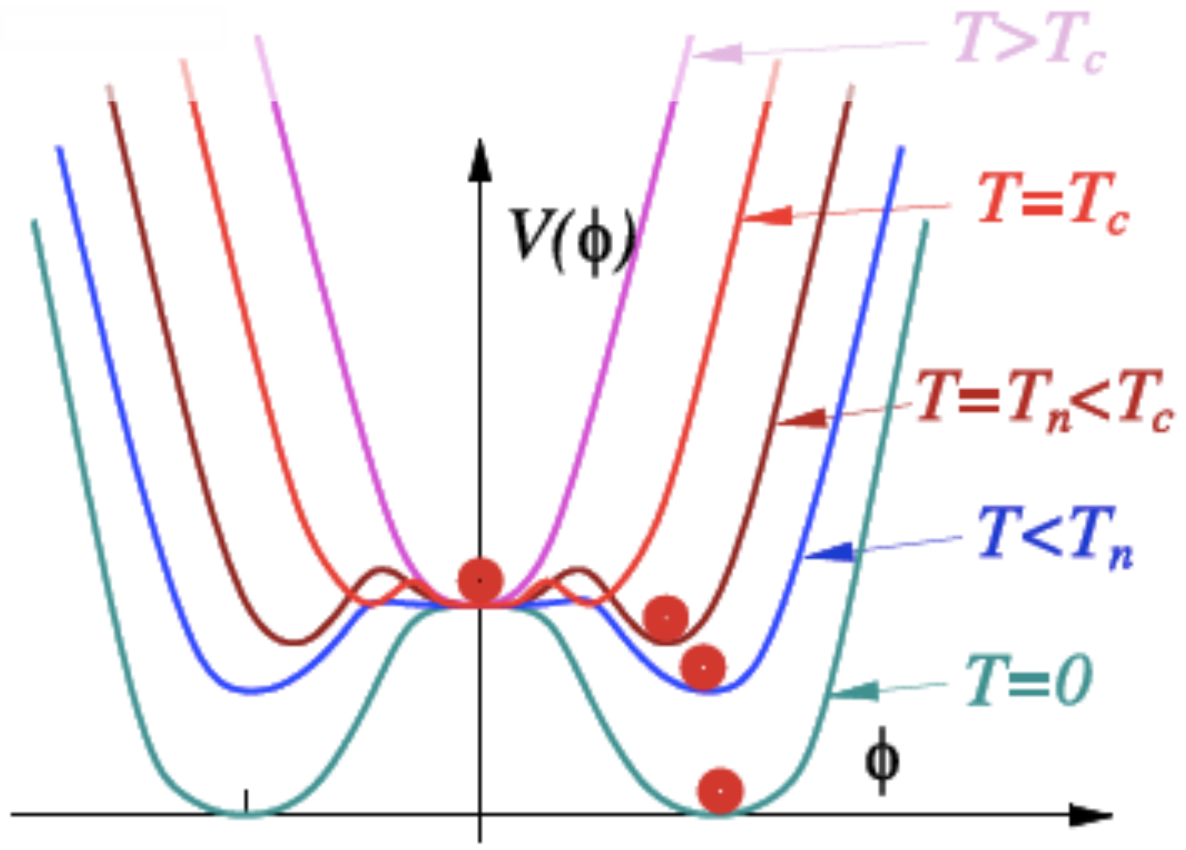
1st vs 2nd order phase transition

- origin of matter-antimatter asymmetry: universe must have been out of thermal equilibrium => 1.order phase transition
- **Electroweak phase transition?**





2nd order



1st order, requirement for EW baryogenesis

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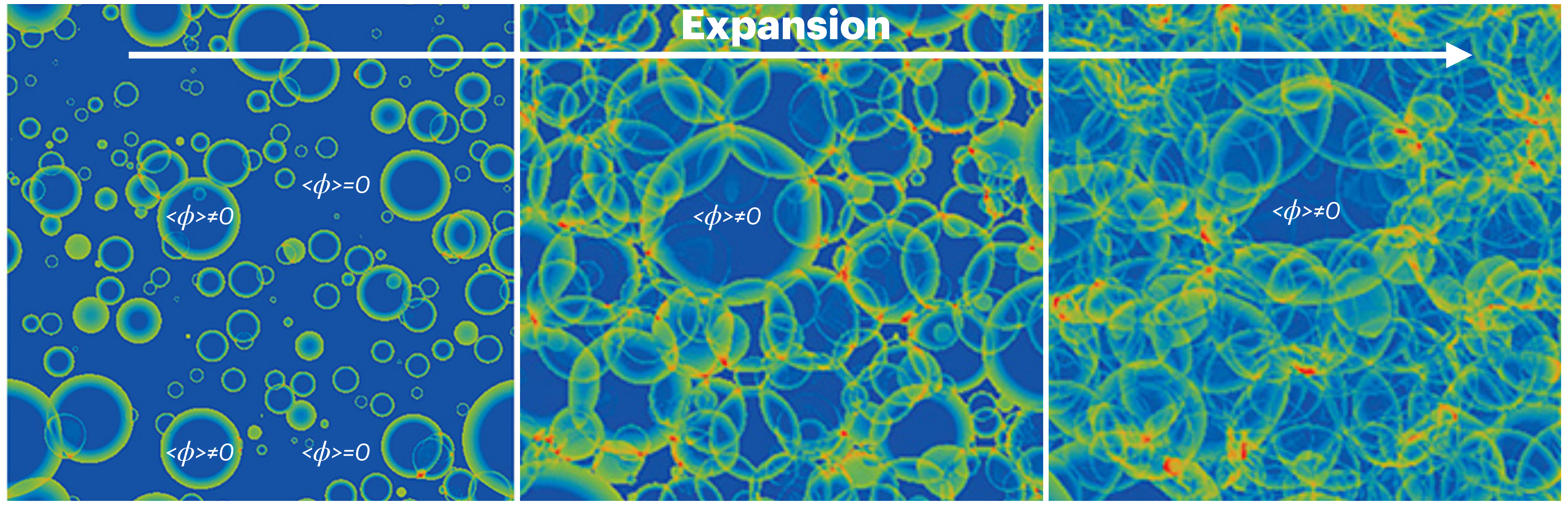

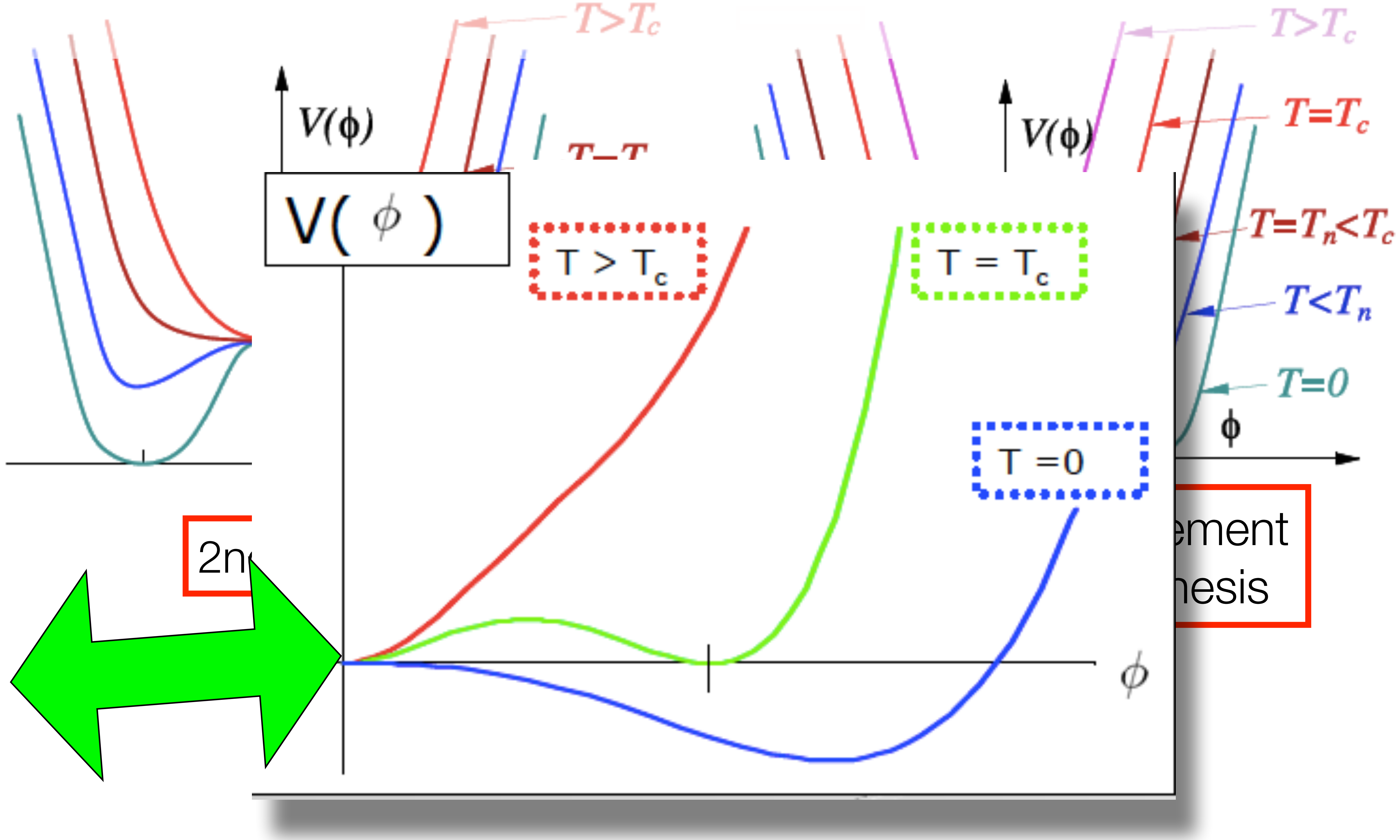

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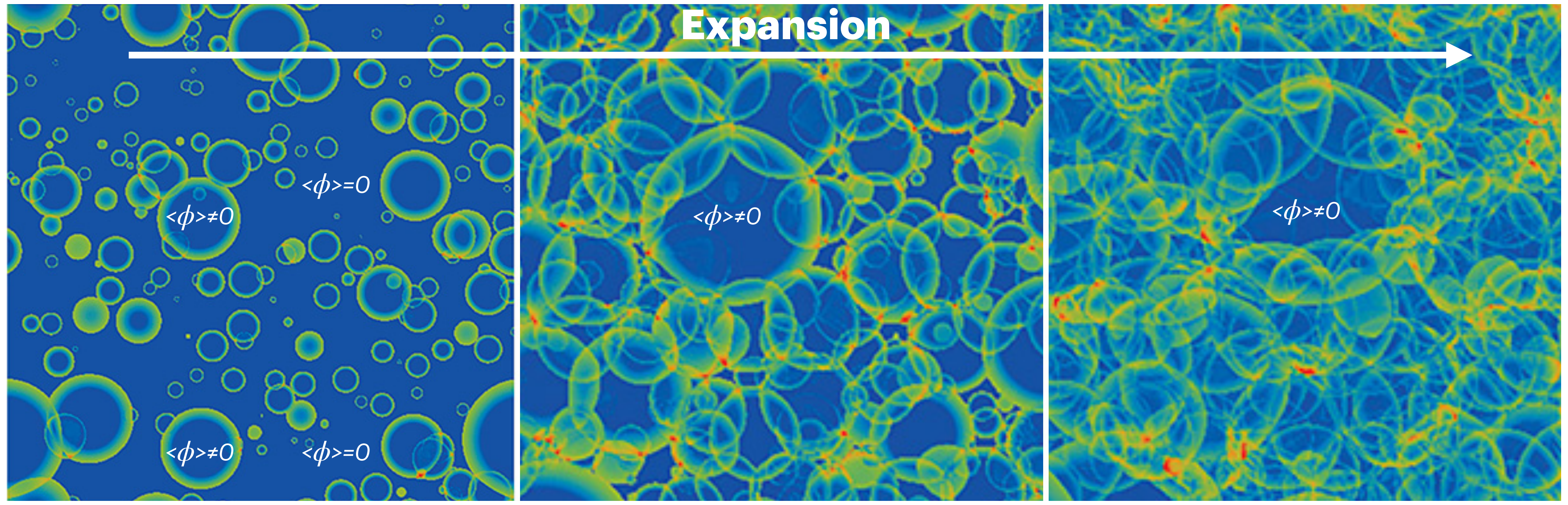

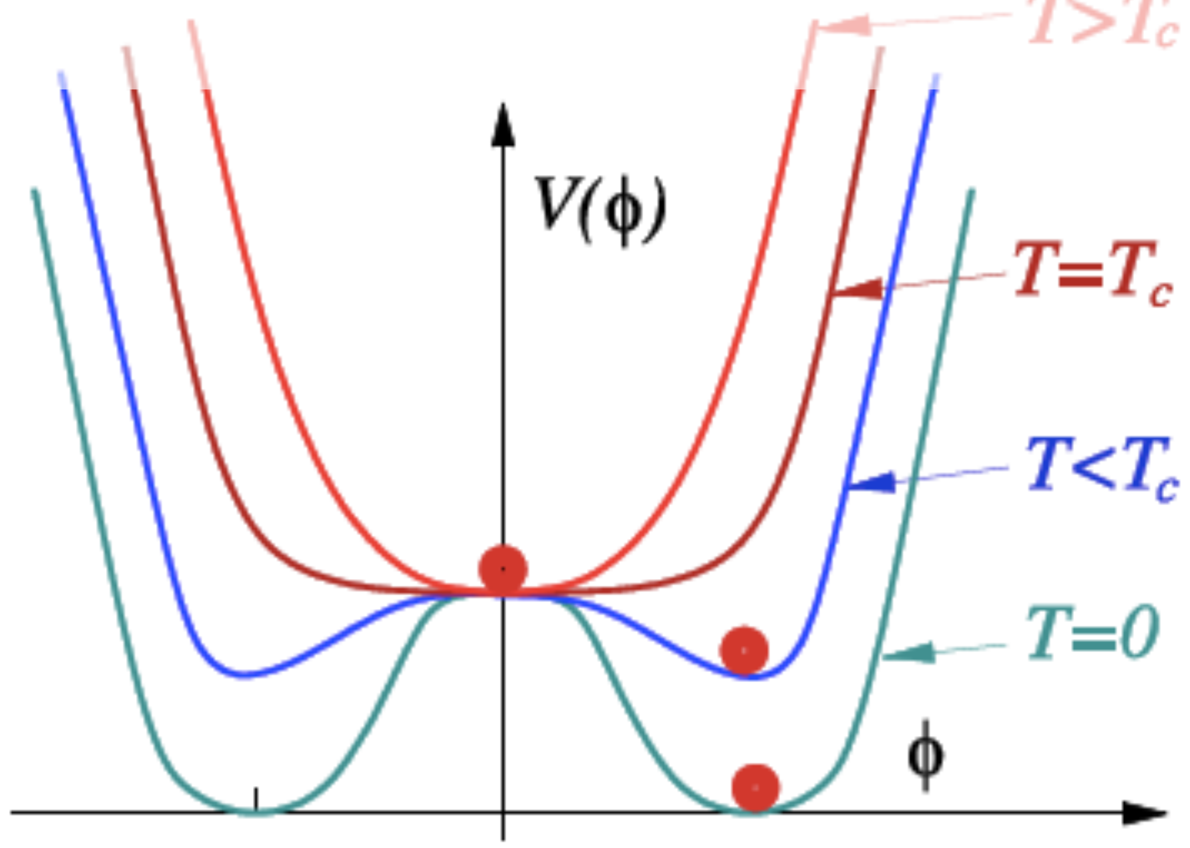

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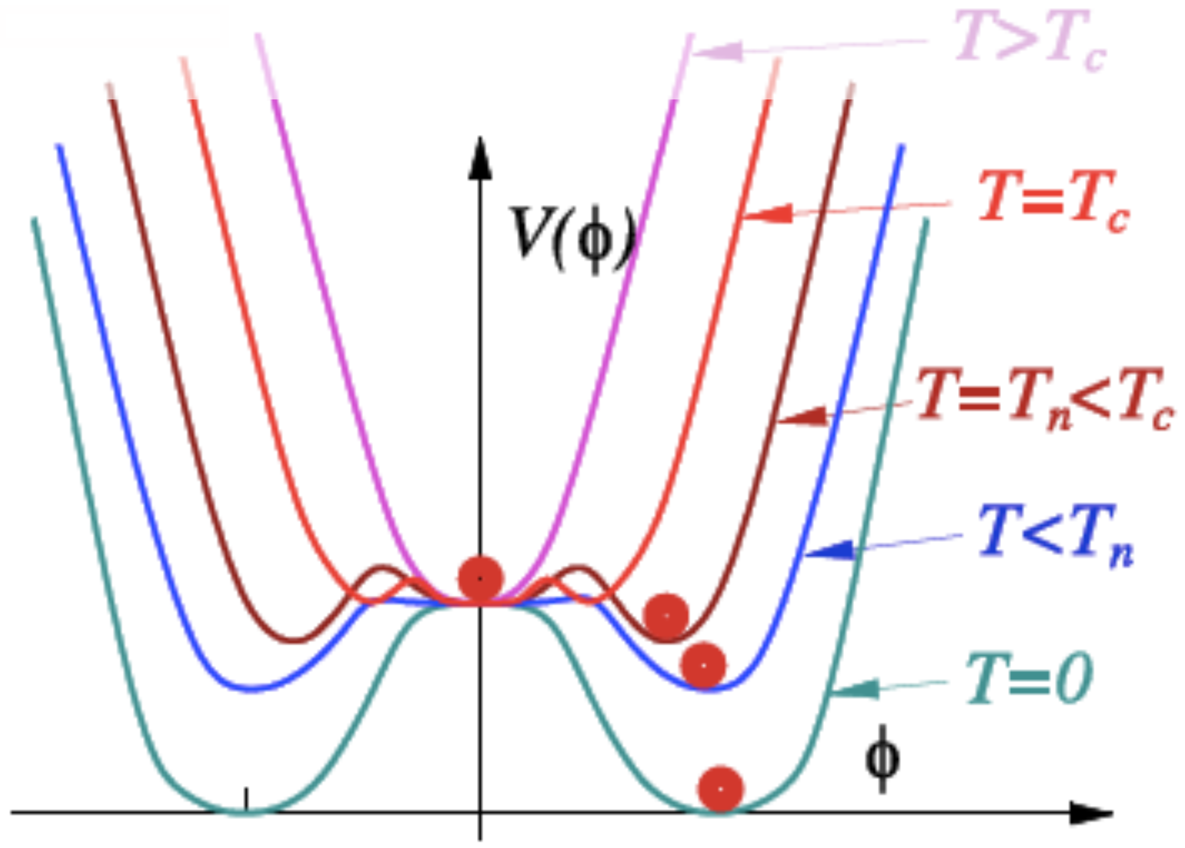

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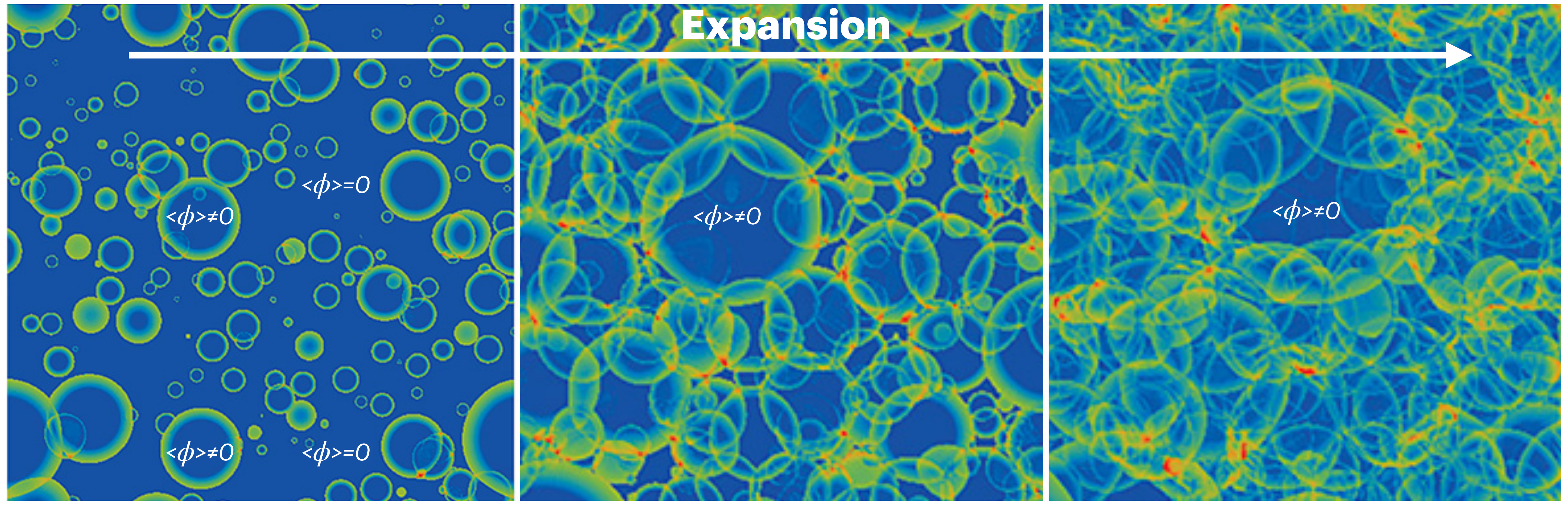

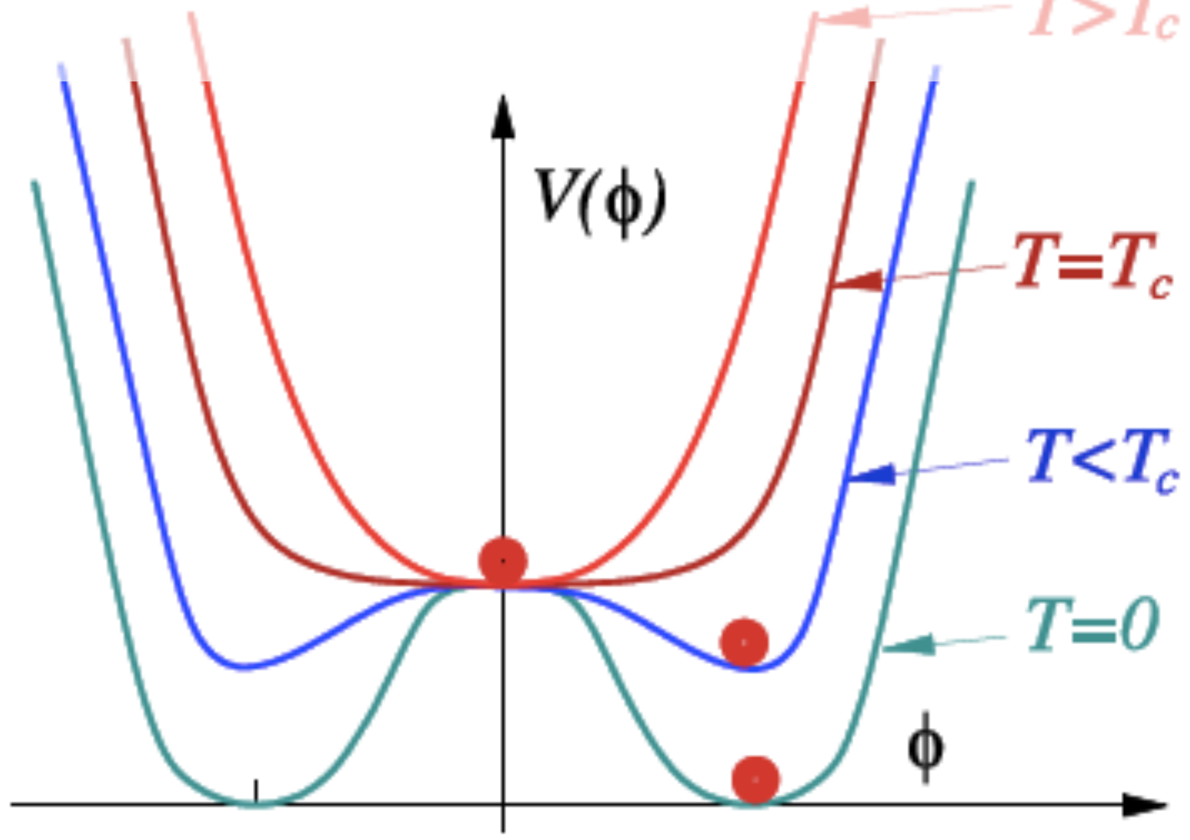

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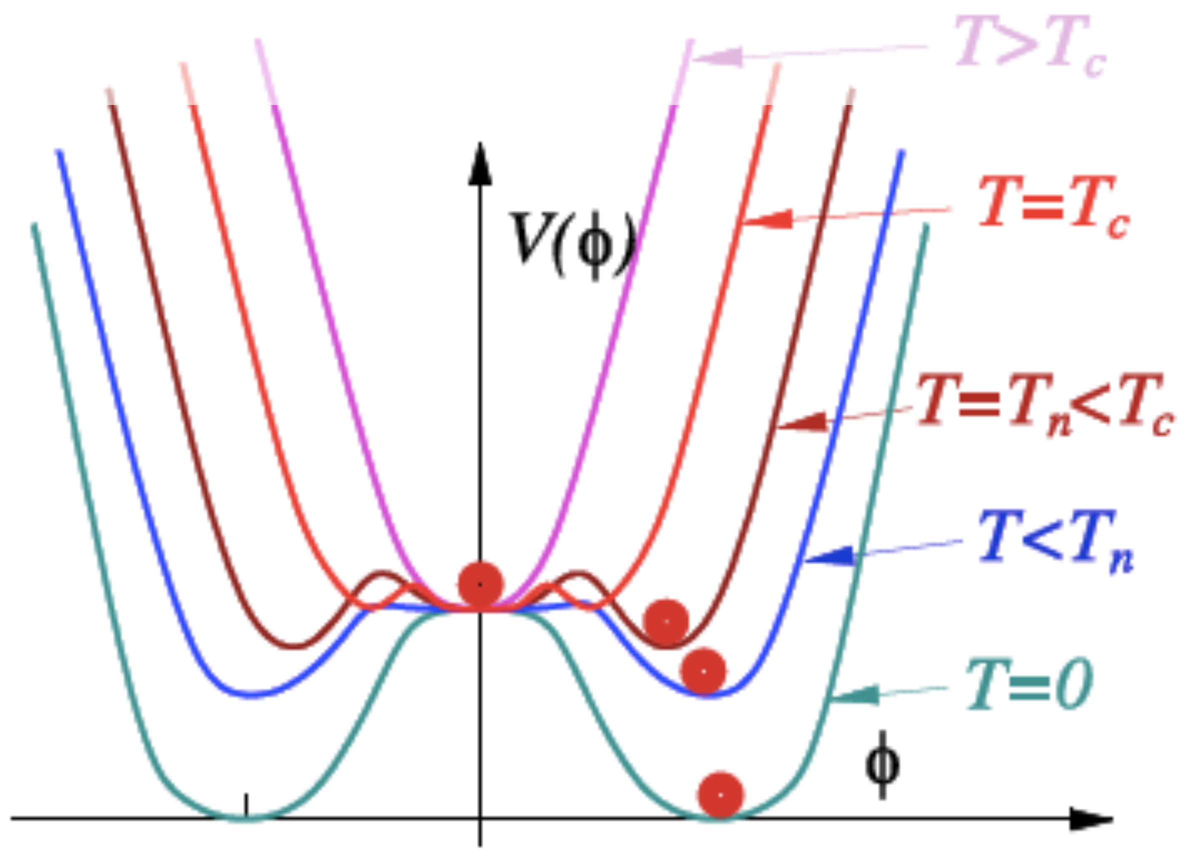

1st order, requirement for EW baryogenesis

- SM with M_H = 125 GeV: 2nd order :(
- value of self-coupling λ determines shape of Higgs potential
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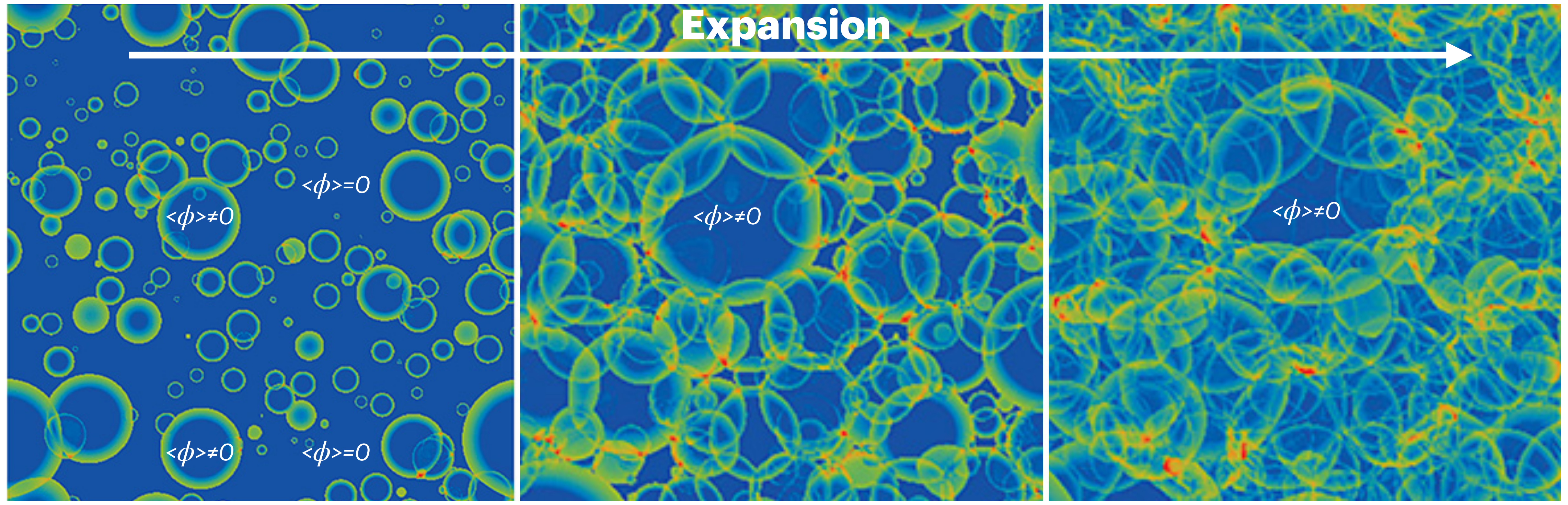

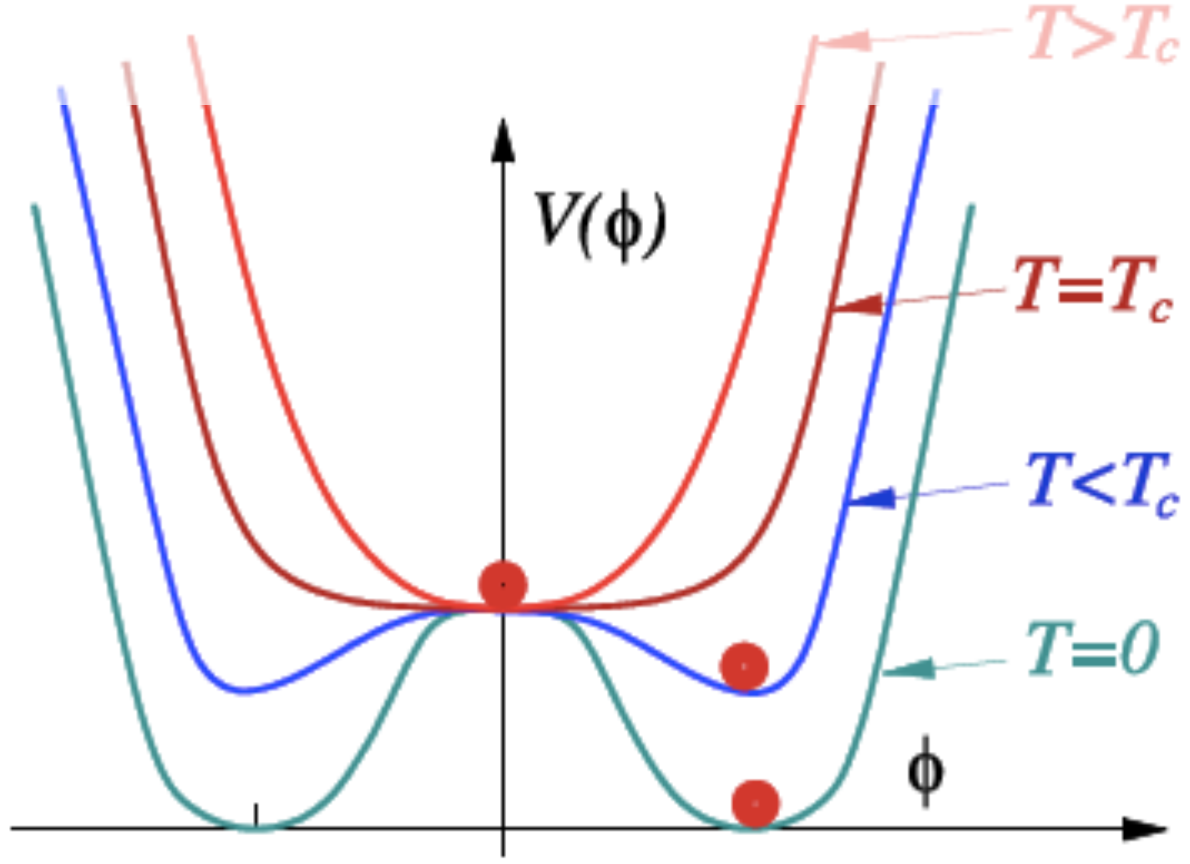

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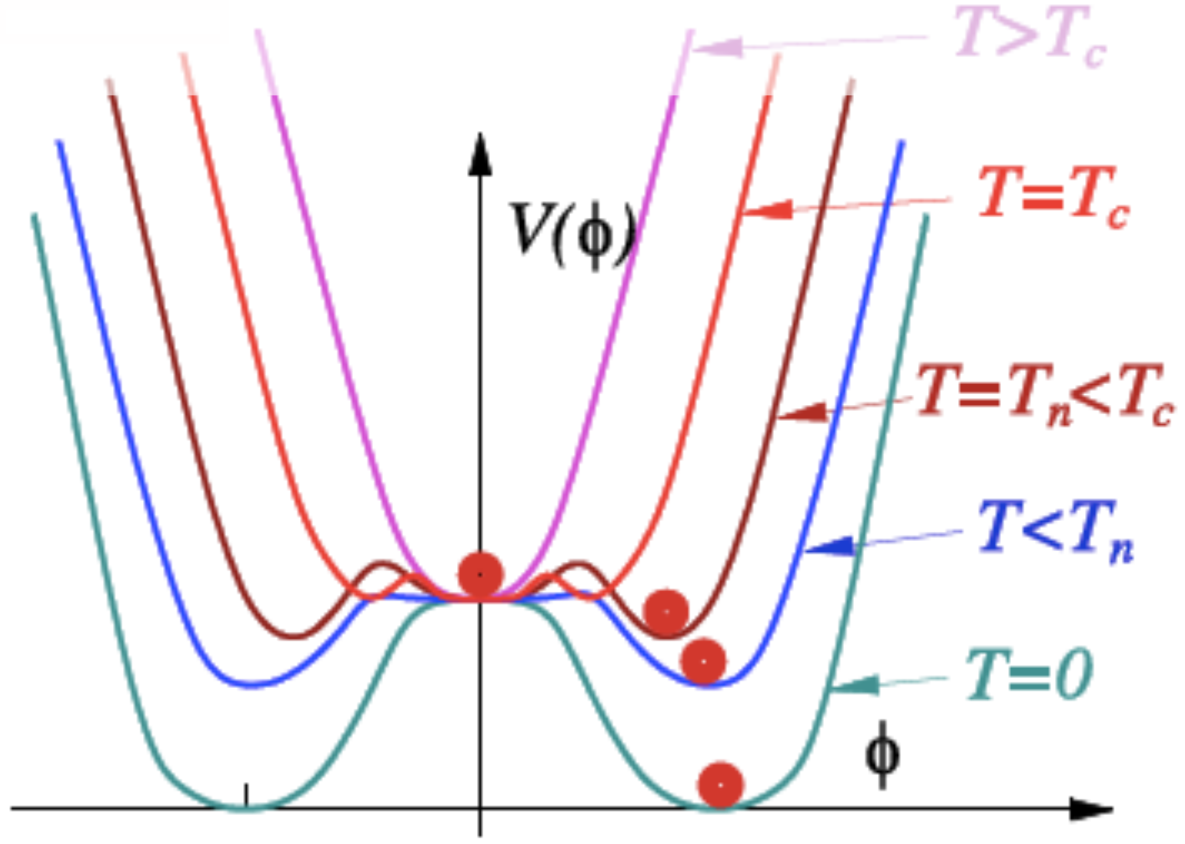

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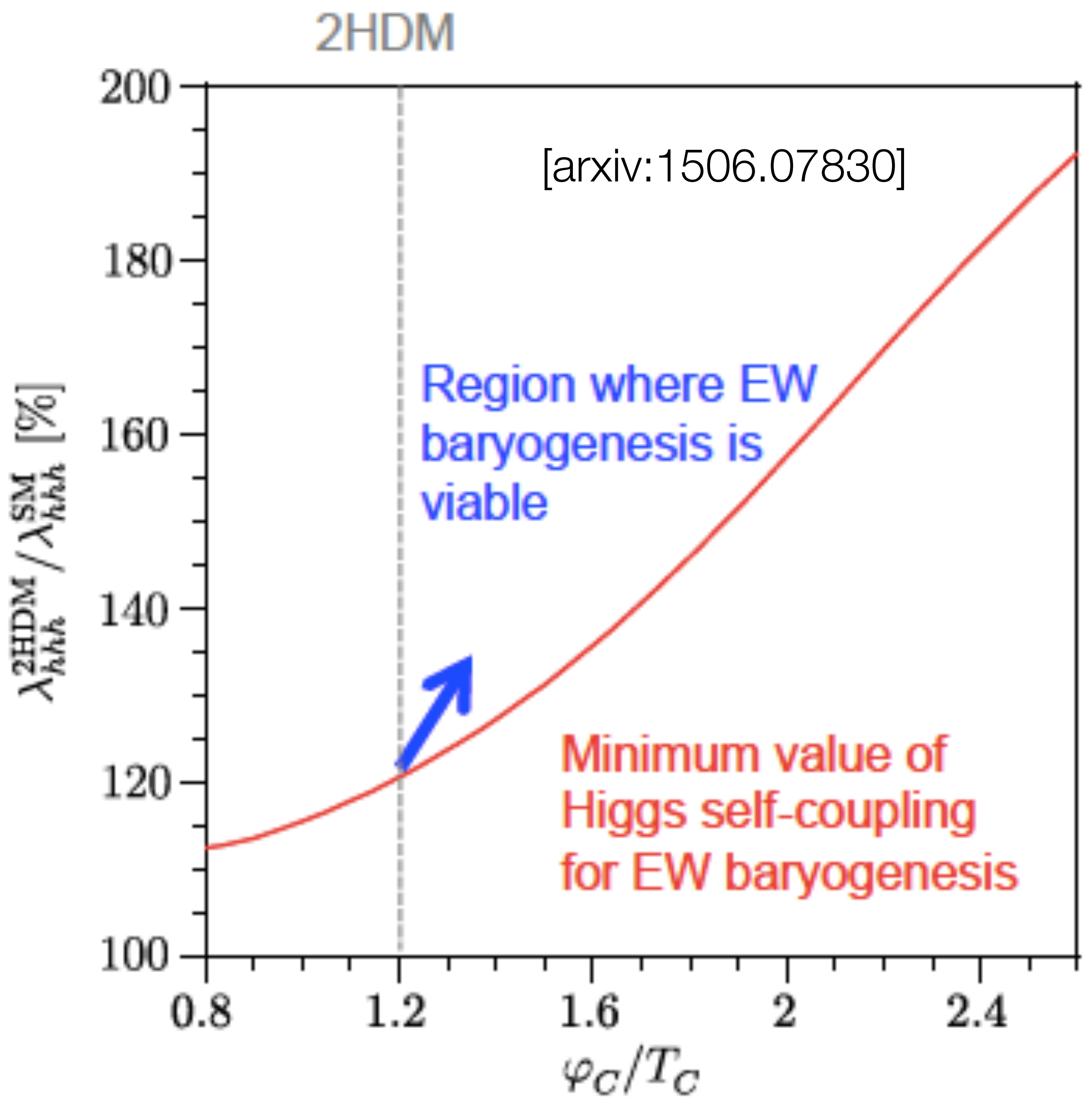

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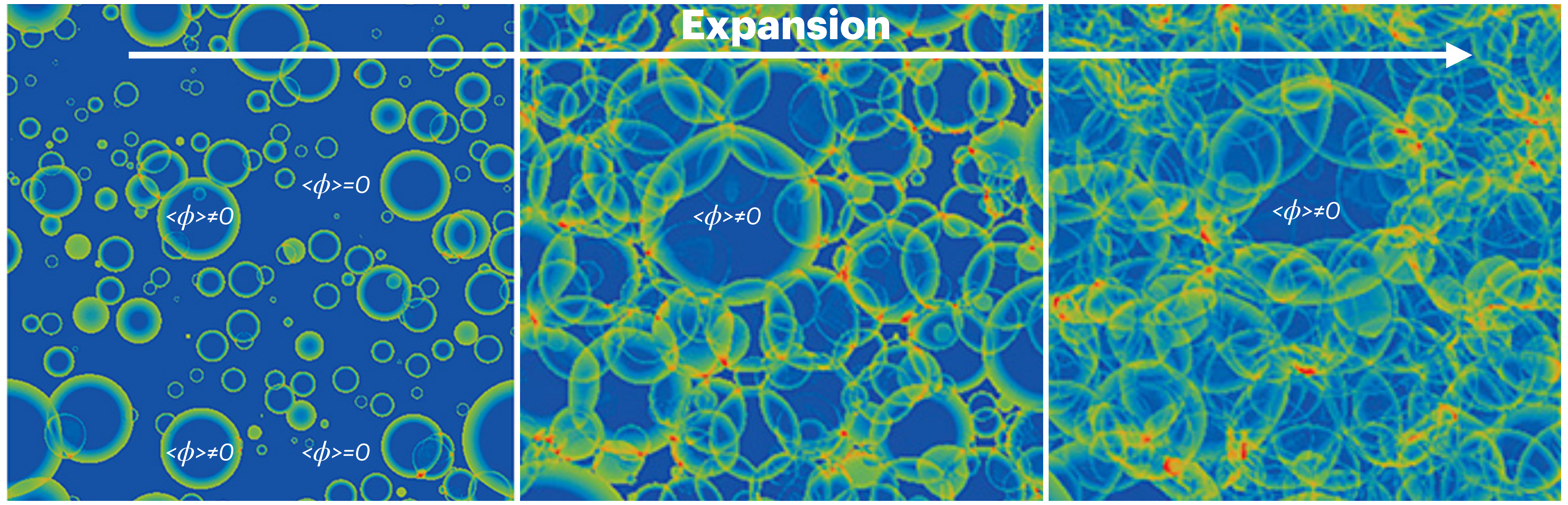

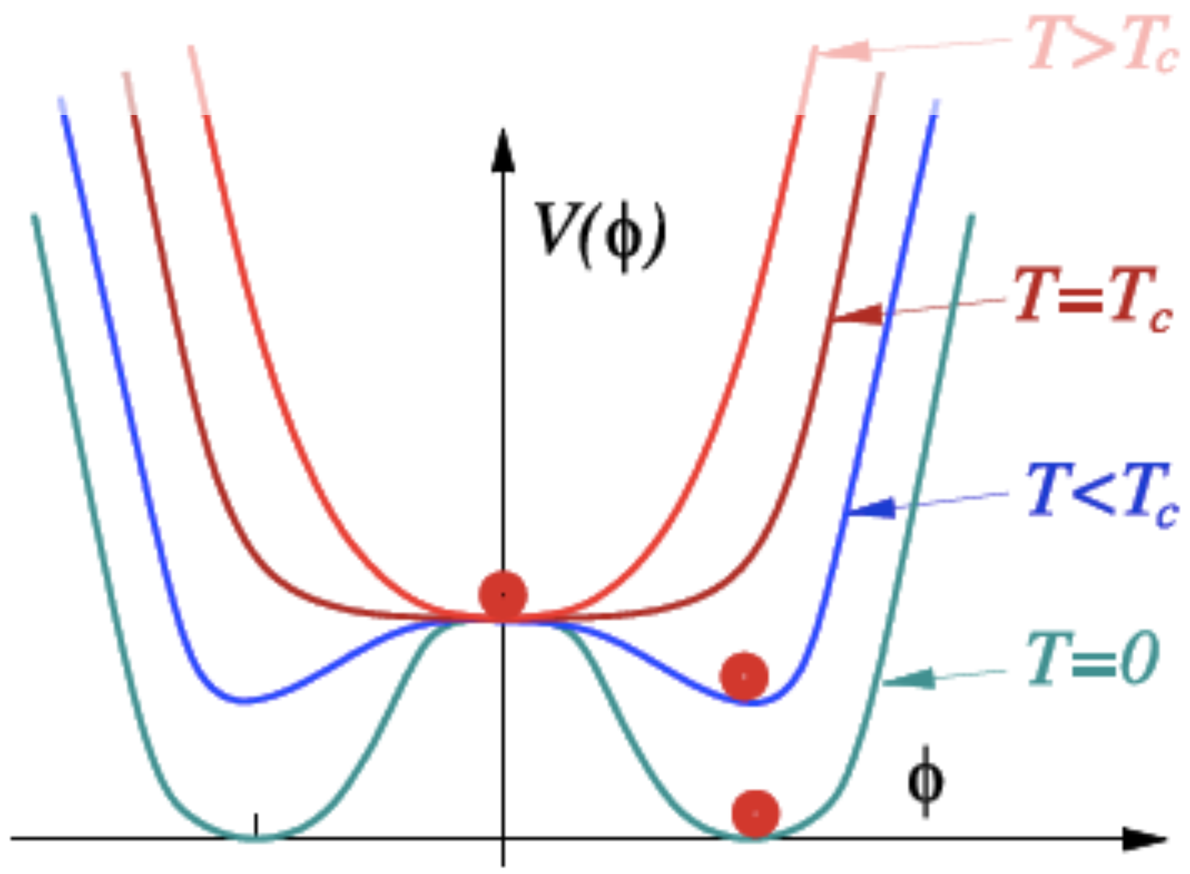

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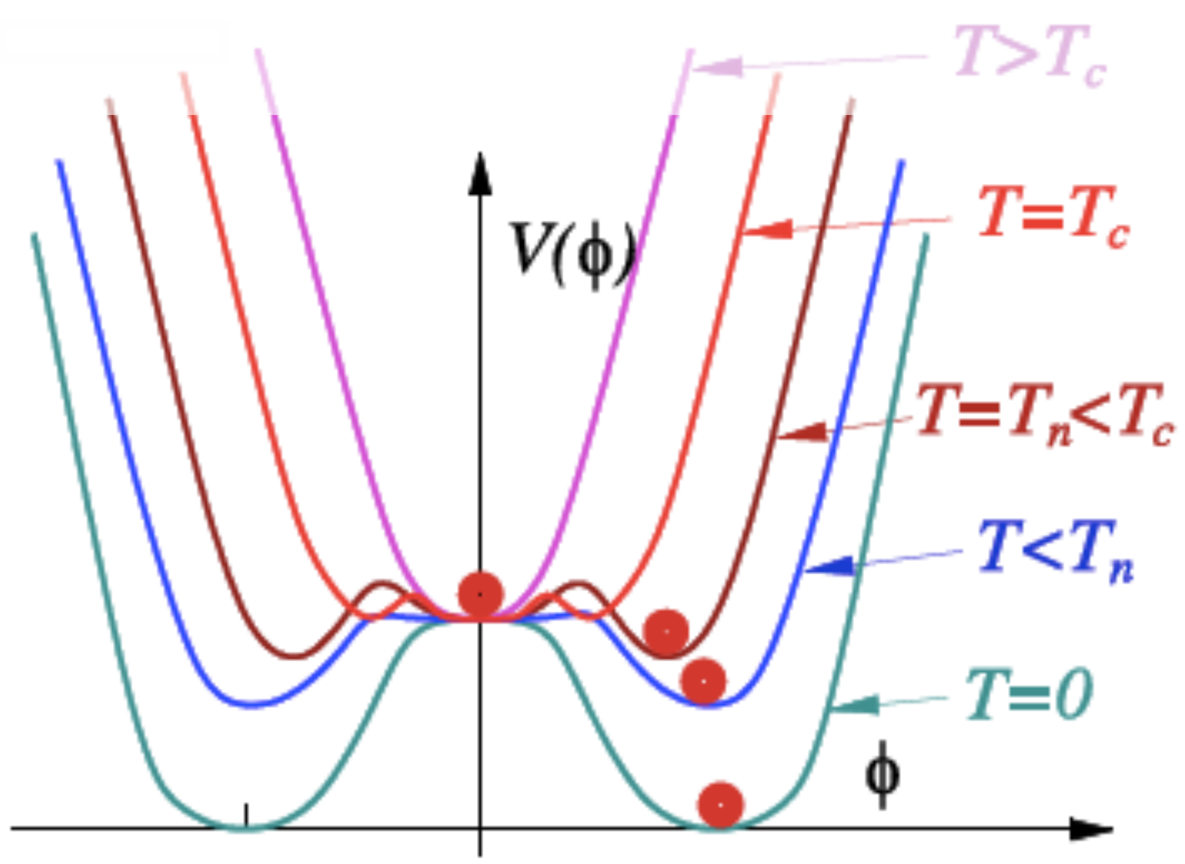

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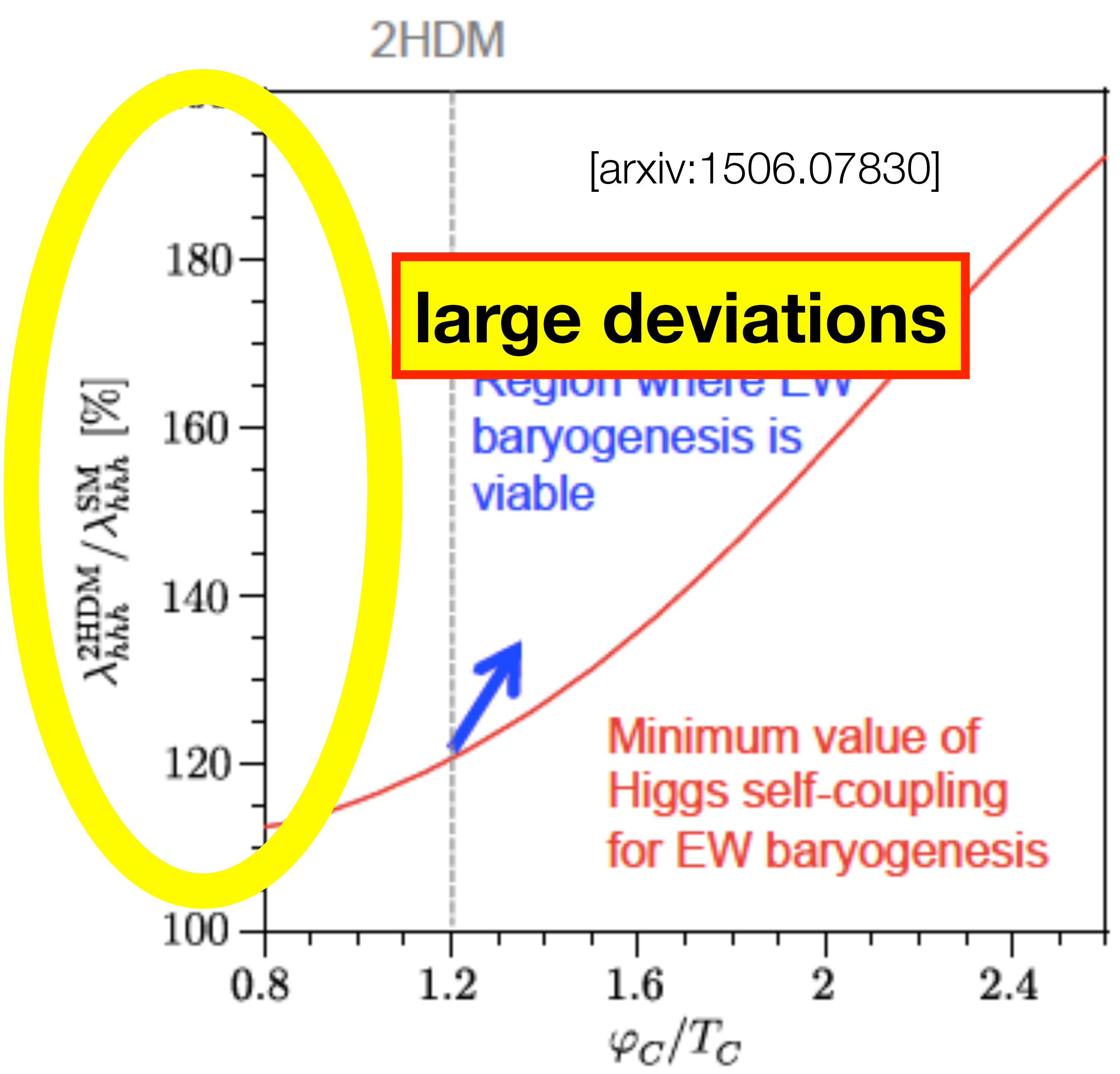

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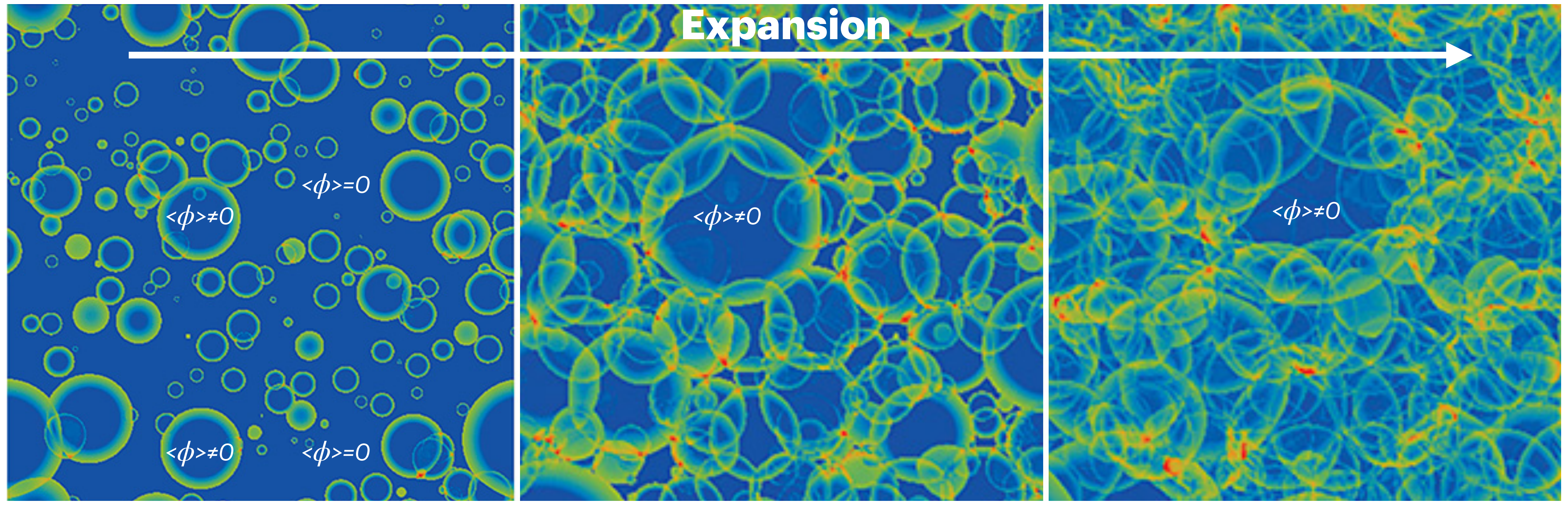

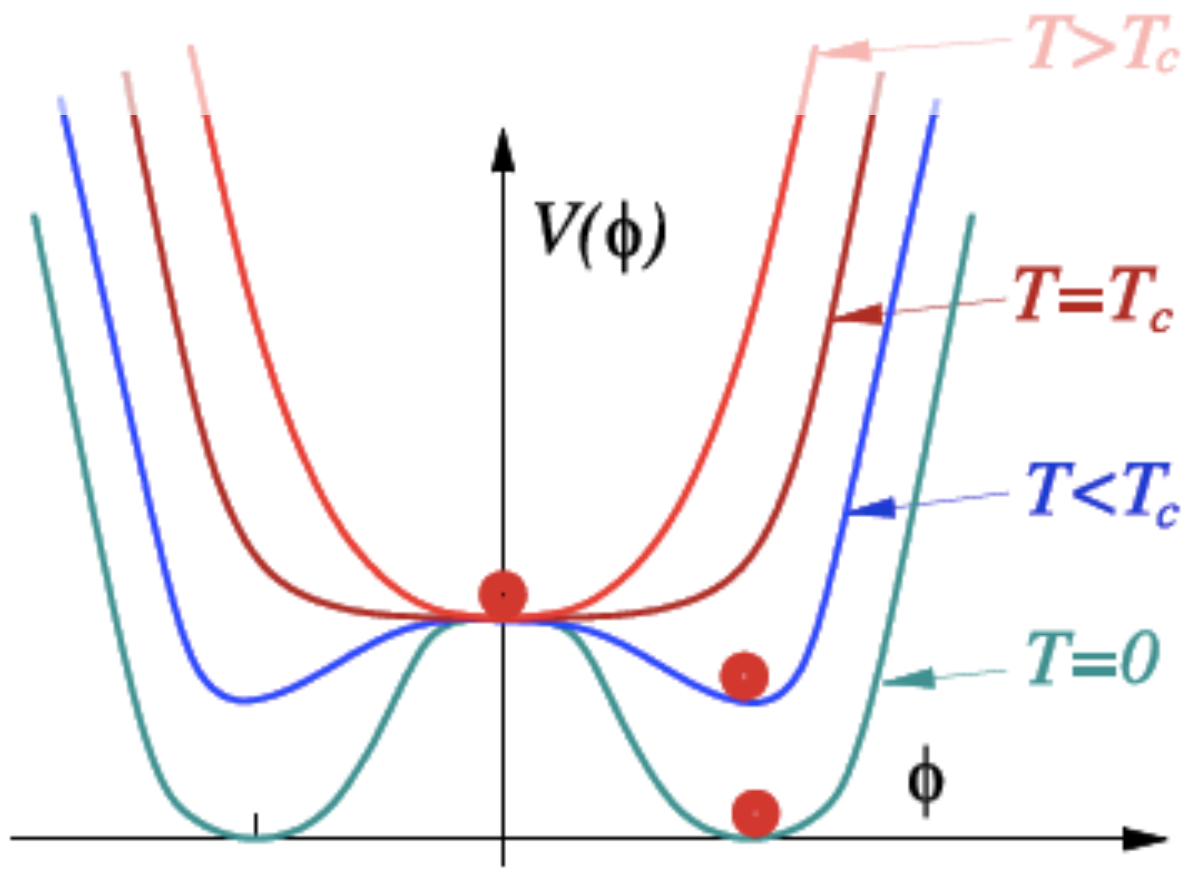

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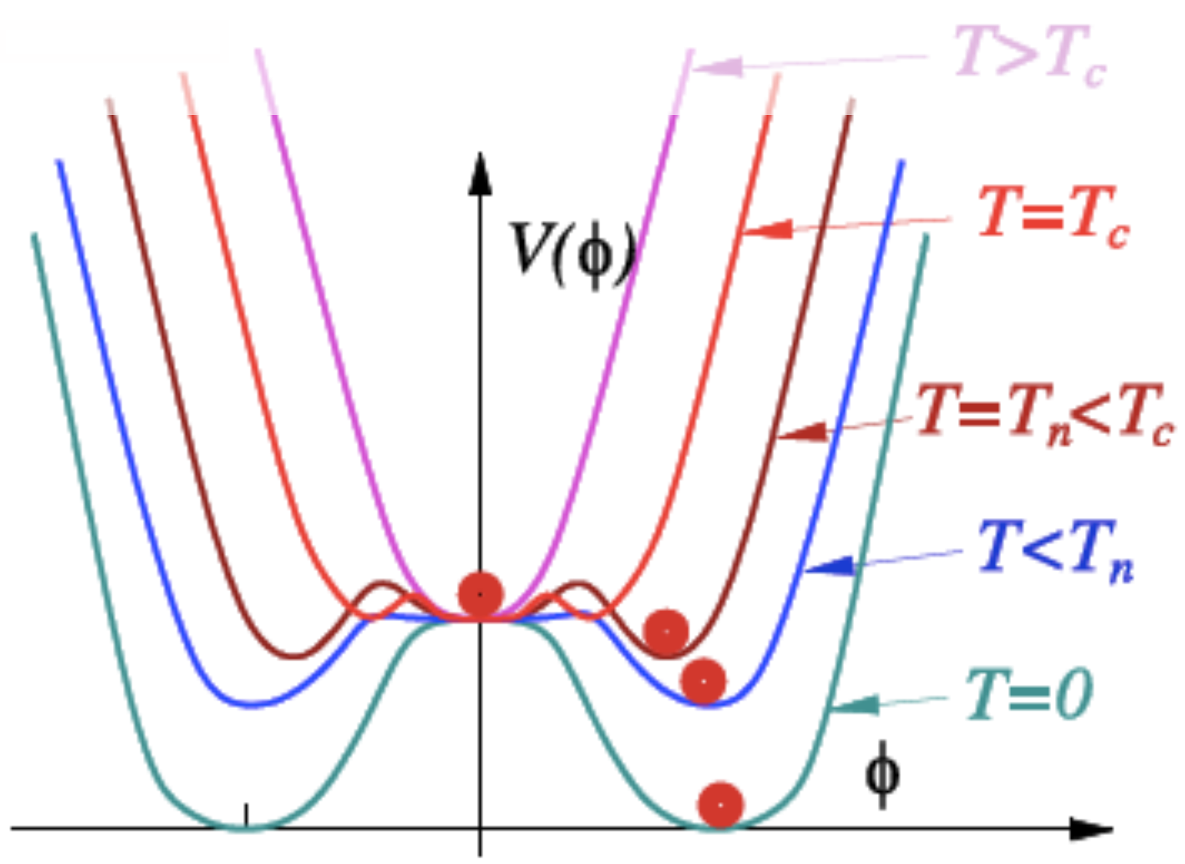

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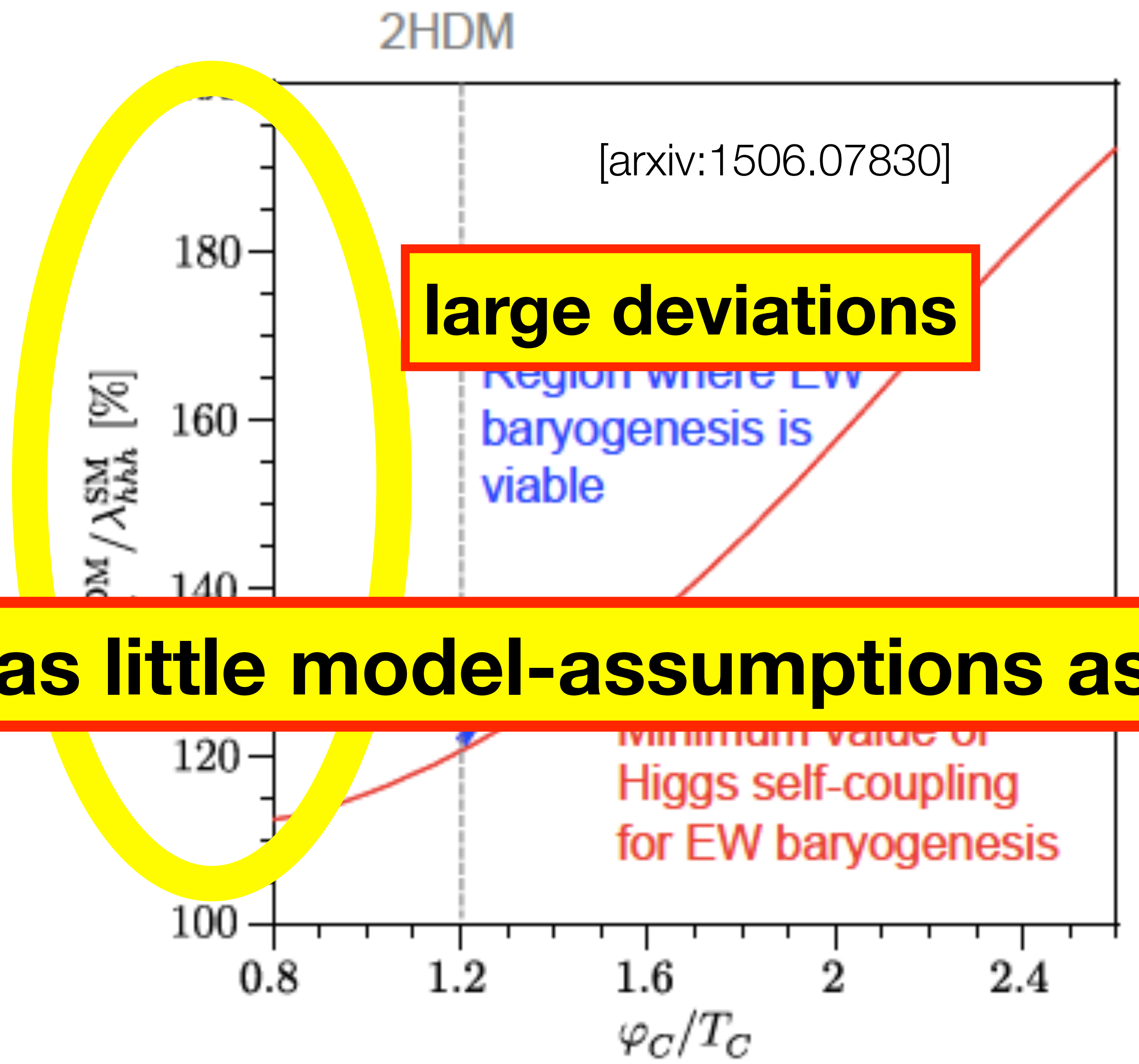

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=> measure λ, with as little model-assumptions as possible!

The Higgs Boson Mission

Why we need a Higgs Factory

- **Find out as much as we can about the 125-GeV Higgs**
  - Basic properties:
    - **total production rate**, total width
    - decay rates to known particles
    - **invisible decays**
    - search for “exotic decays”
  - CP properties of couplings to gauge bosons and fermions
  - **self-coupling**
  - Is it the only one of its kind, or are there **other Higgs (or scalar) bosons**?
- **To interprete these Higgs measurements, also need**
  - top quark: mass, Yukawa & electroweak couplings, their CP properties…
  - Z / W bosons: masses, couplings to fermions, triple gauge couplings, incl CP…
- **Search for direct production of new particles - and determine their properties**
  - Dark Matter? **Dark Sector?**
  - Heavy neutrinos?
  - SUSY? **Higgsinos?**
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=> e+e- Higgs factory identified as the highest priority next collider by
- European Strategy for Particle Physics (2020)
- The Snowmass process in the US (2022)

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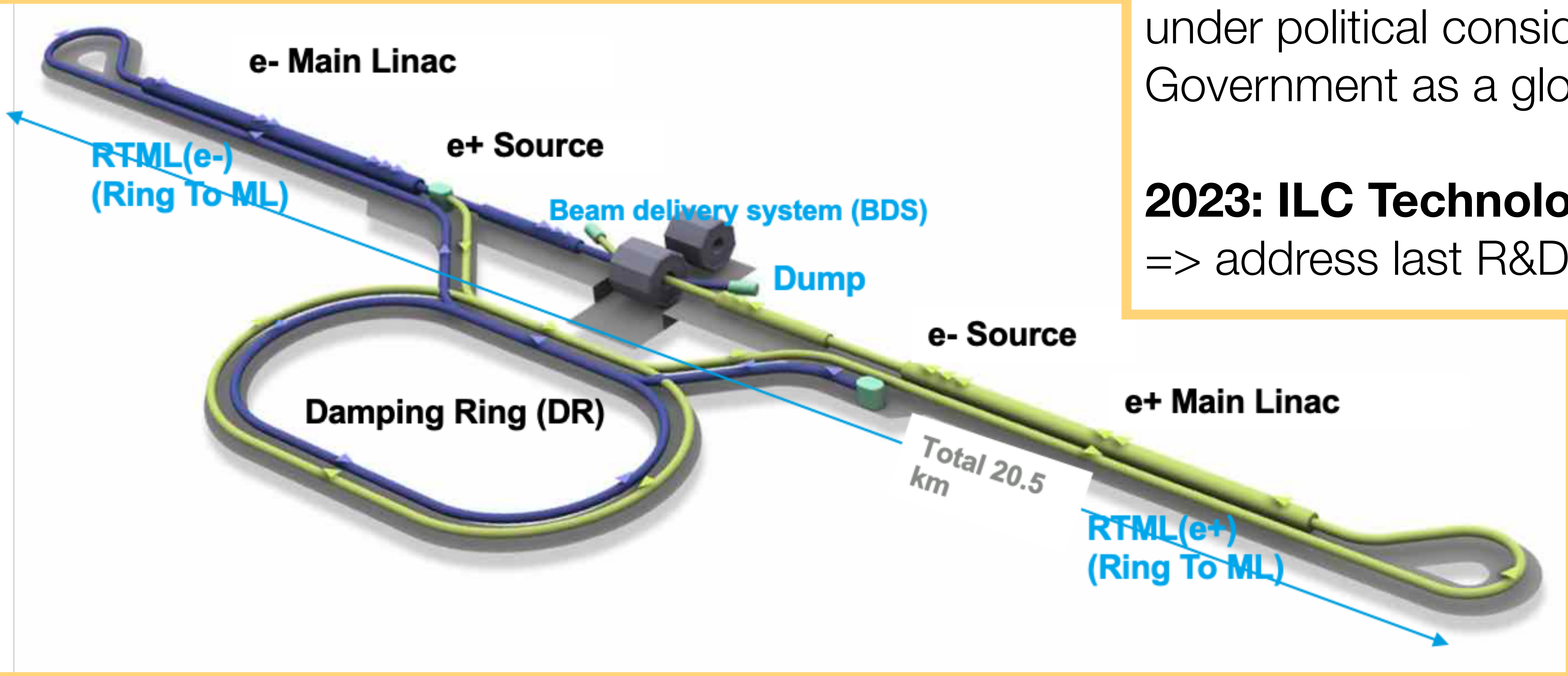
The key contenders

Status overview



ILC: e^+e^- @ 90, 160**, 250,** 350**, 500 GeV, 1TeV**
TDR in **2012; 2017:** staged start at **250 GeV**
Superconducting RF

under political consideration by Japanese Government as a global project

2023: ILC Technology Network
=> address last R&D questions on accelerator

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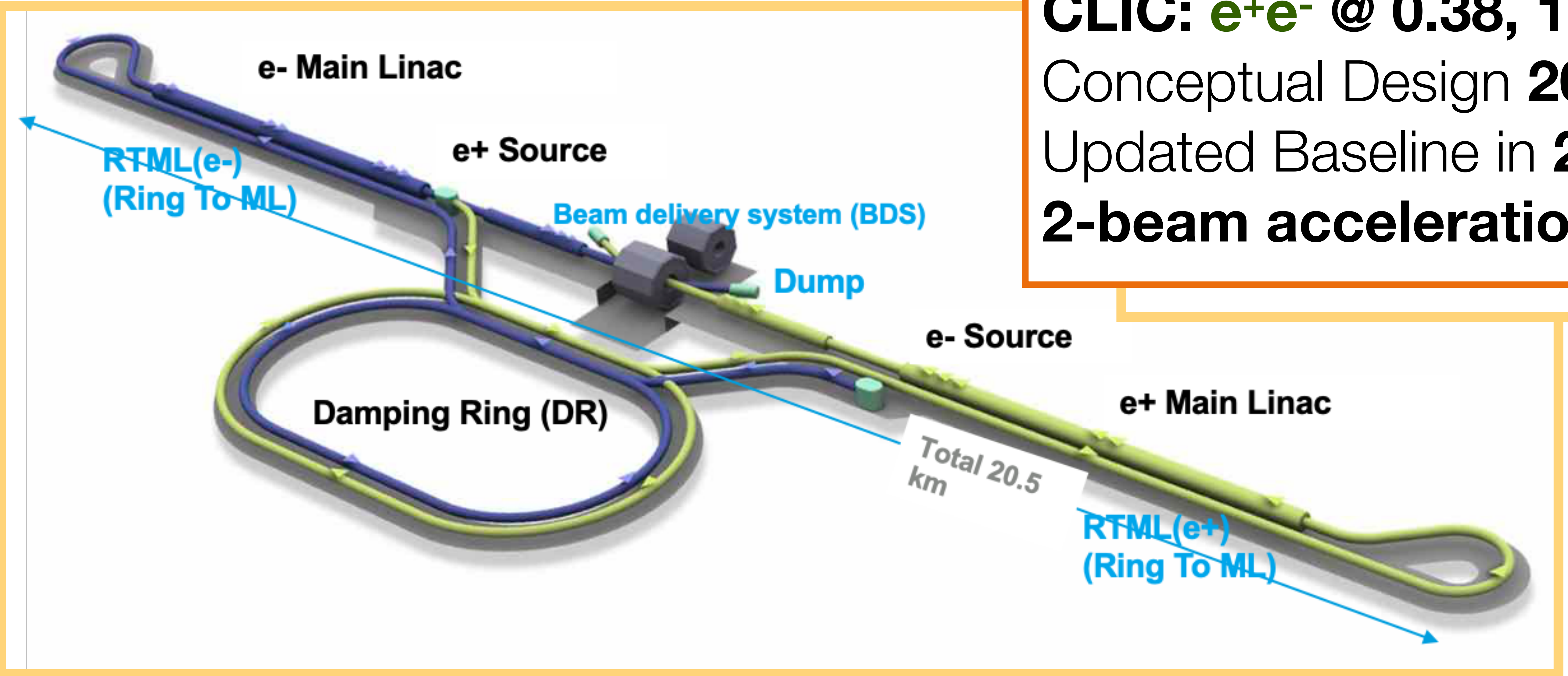
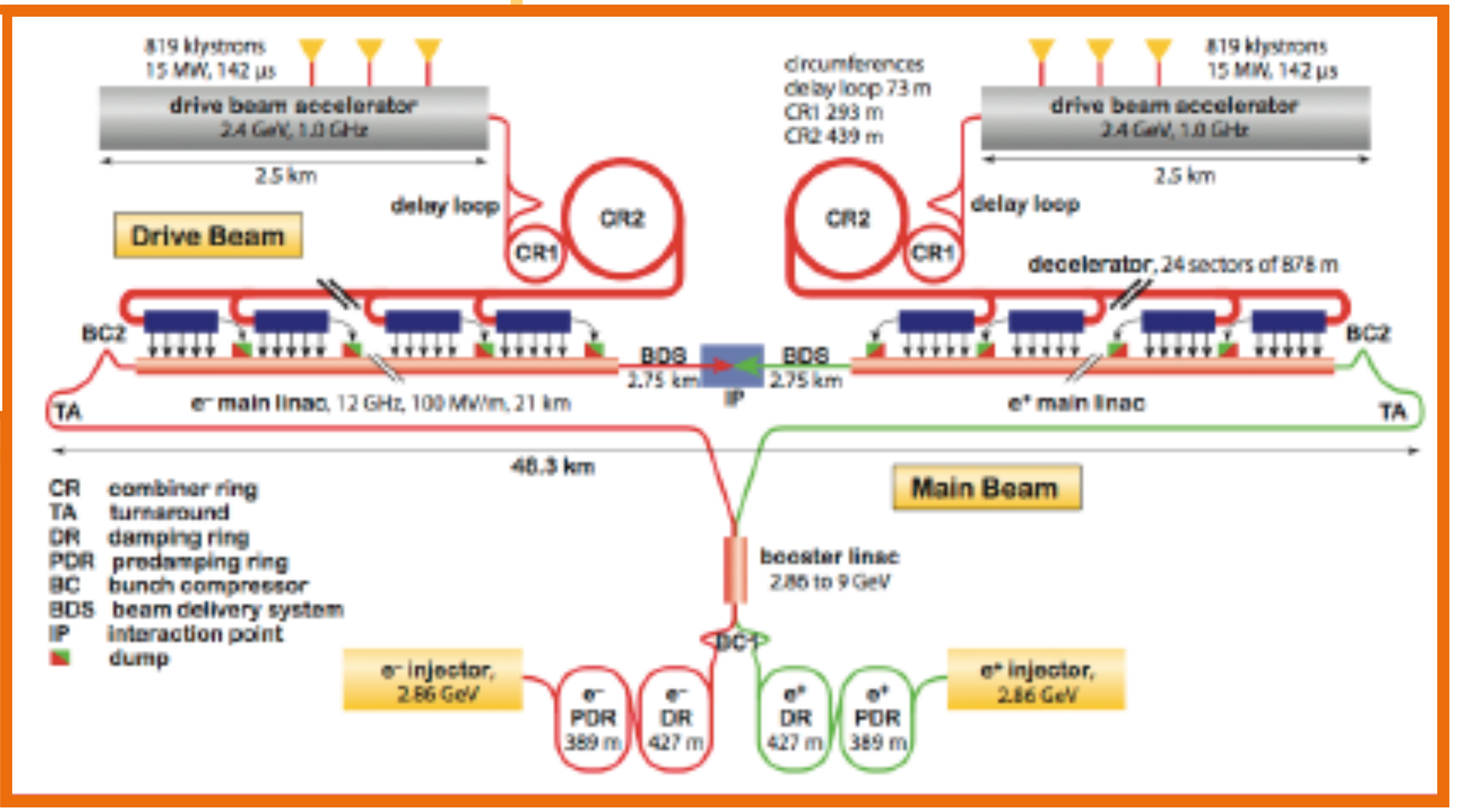


CLIC: e+e- @ 0.38, 1.4, 3 TeV
Conceptual Design **2013**
Updated Baseline in **2017**
2-beam acceleration



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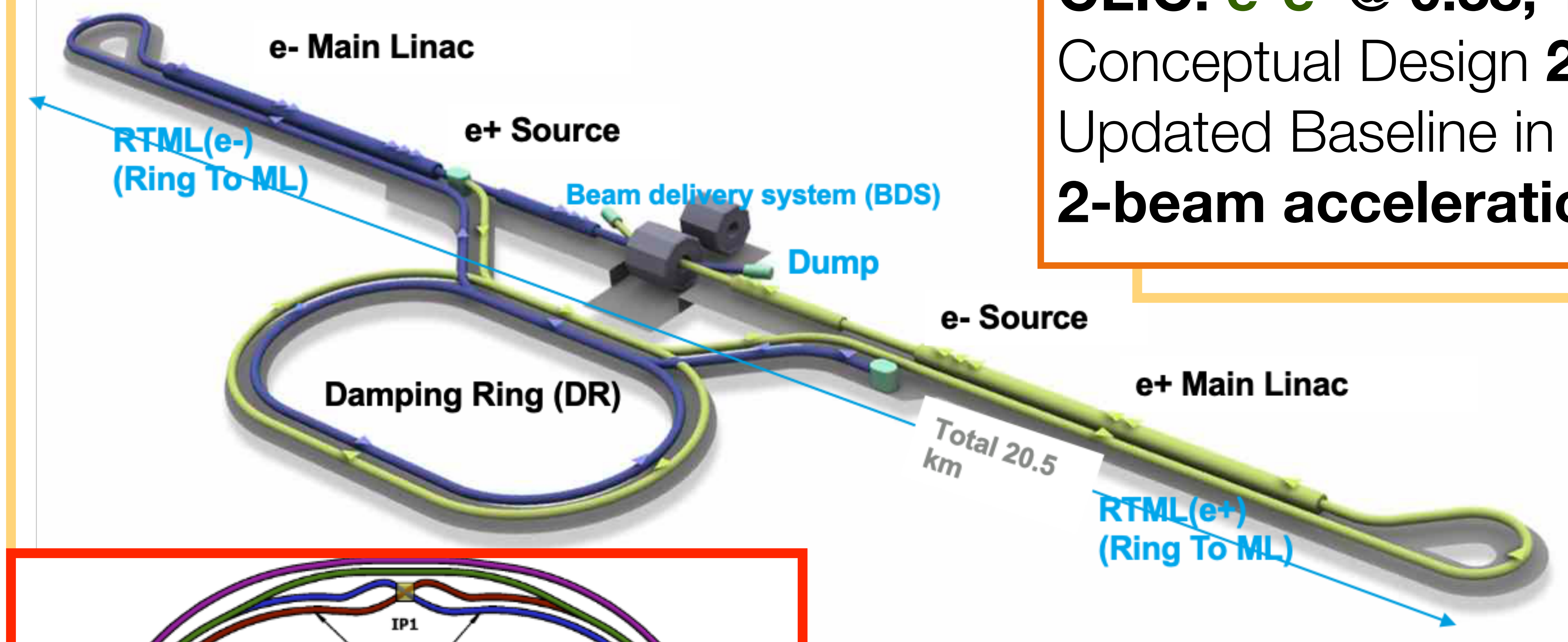

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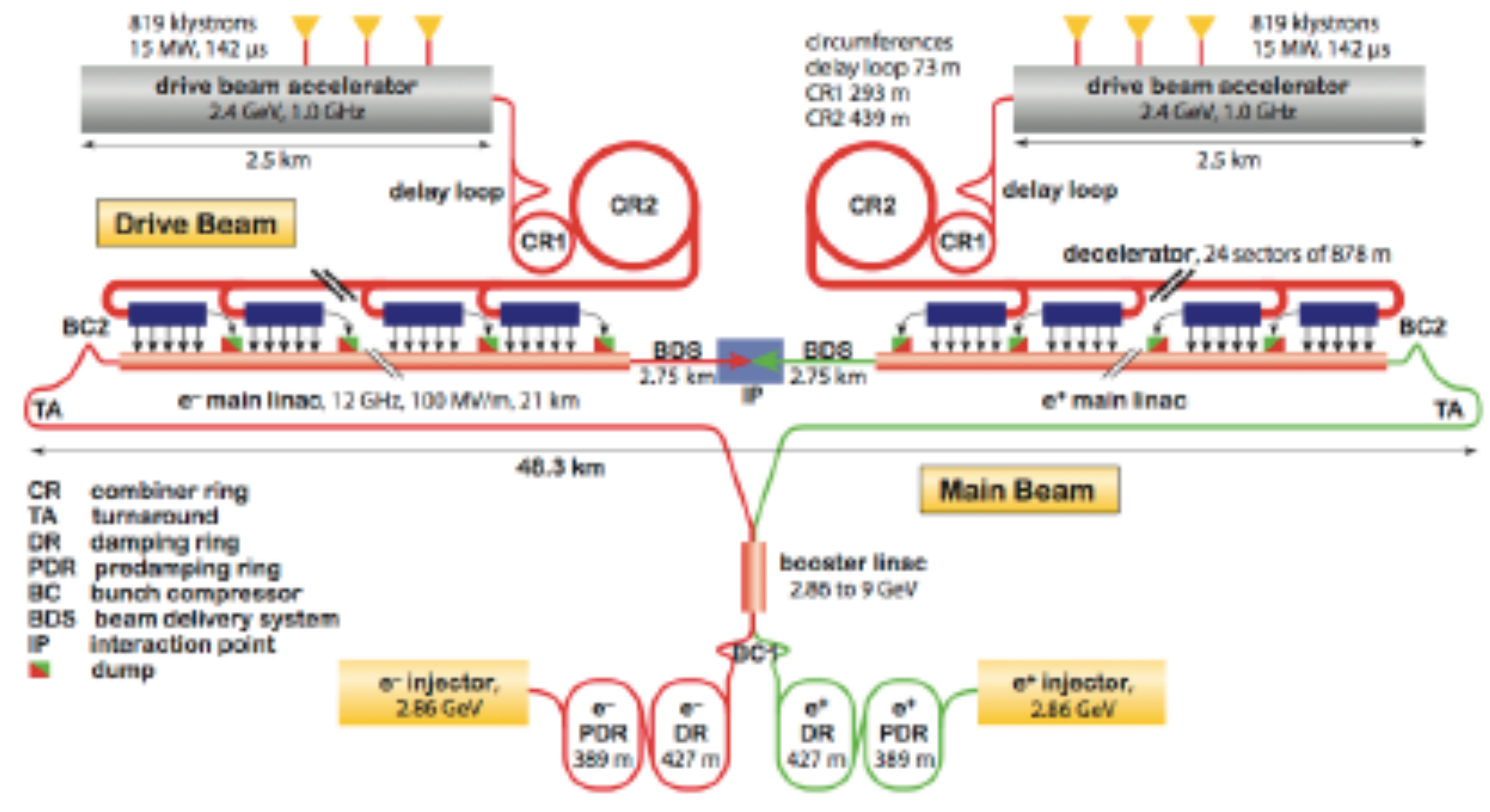
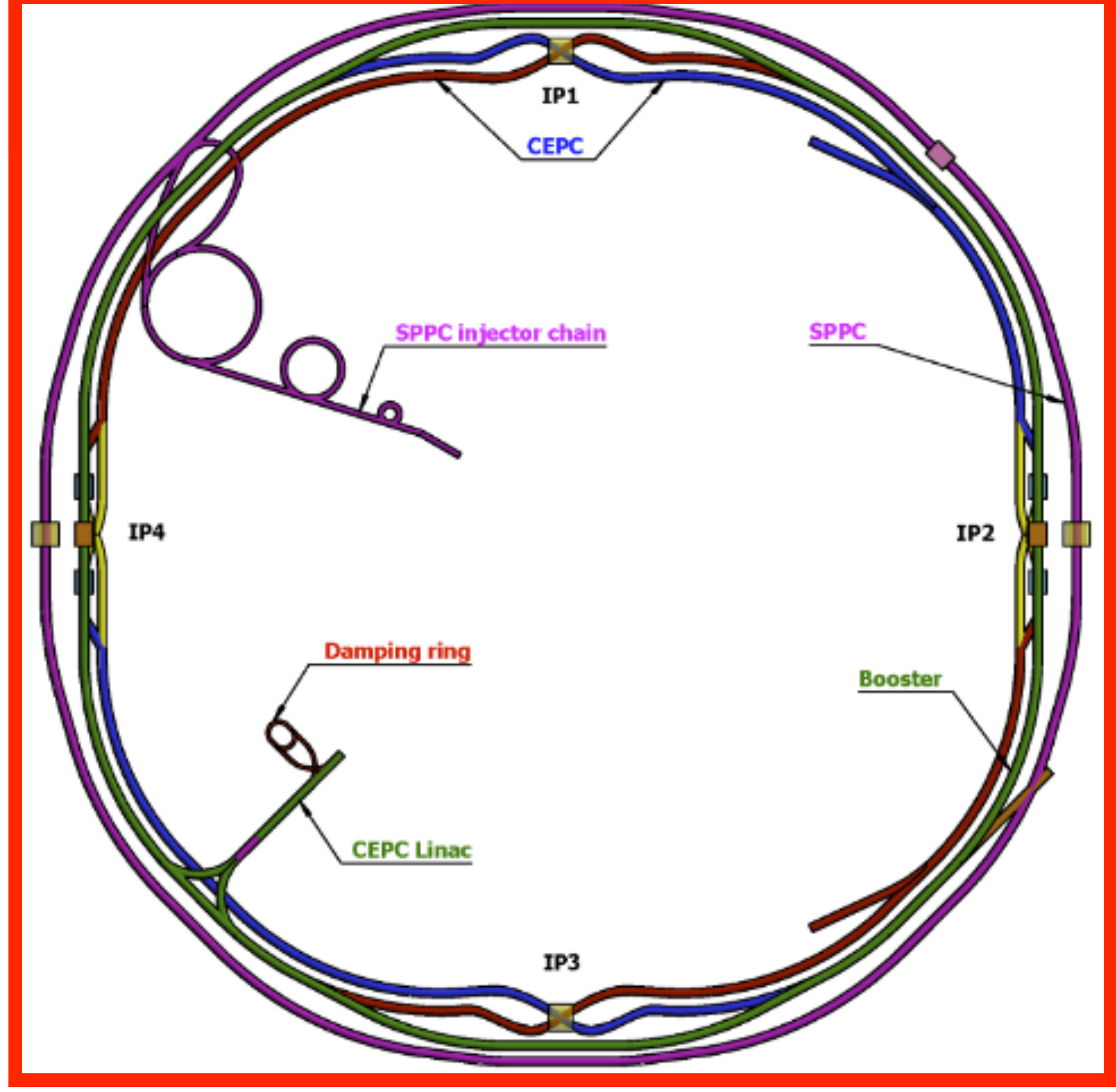
2-beam acceleration





CEPC: e+e- @ **90-365 GeV**

<u>CDR published 2018</u>
TDR in preparation, incl. cost review (Sep)
aiming for approval in next 5-year-plan (2025)
ranked 1st in HEP preselection

The key contenders

Status overview

ILC: e^+e^- @ 90, 160, **250,** 350, **500 GeV, 1TeV**
TDR in **2012; 2017:** staged start at **250 GeV**
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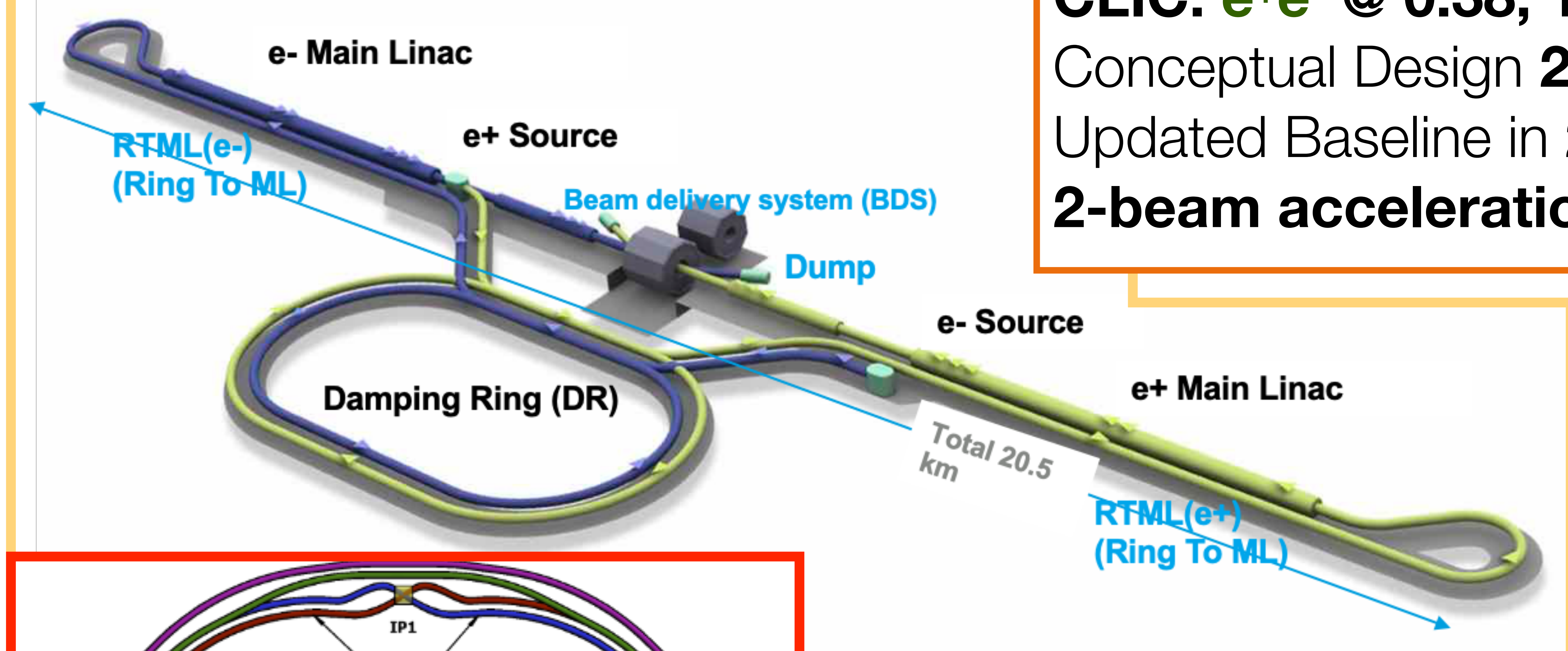

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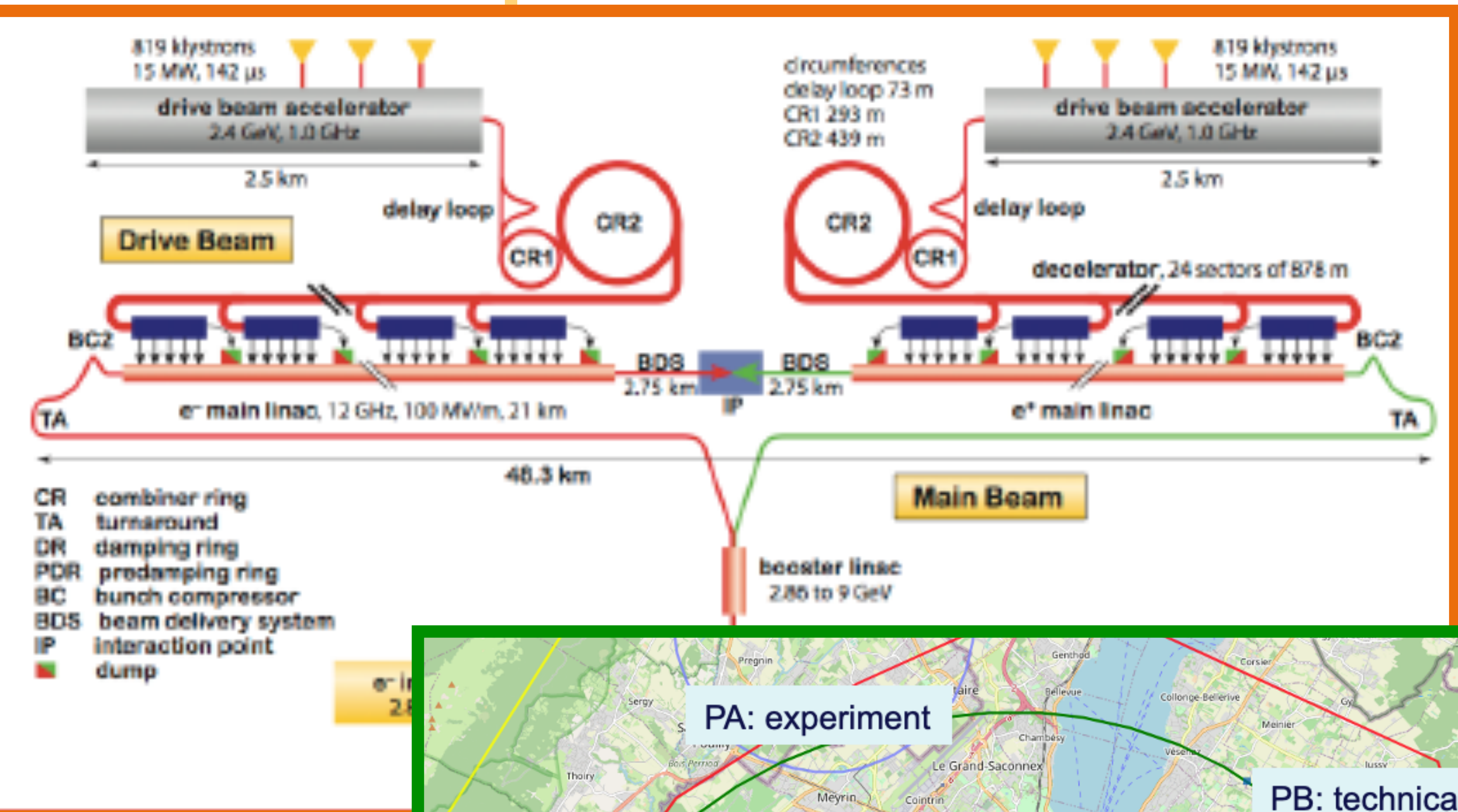

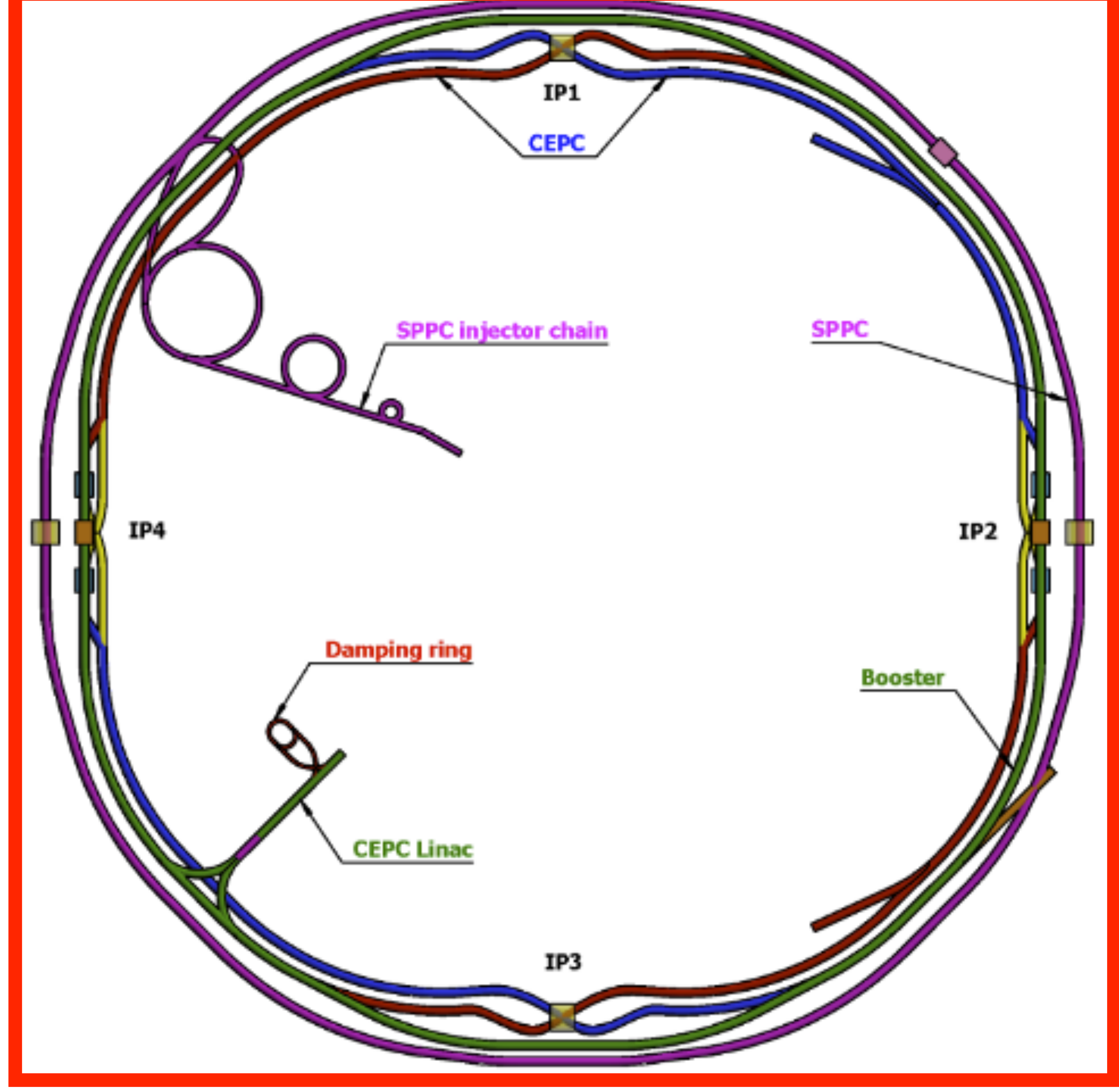

CEPC

CDR p
TDR i
aimin
ranke

FCC-ee e^+e^- @ 90-365 GeV
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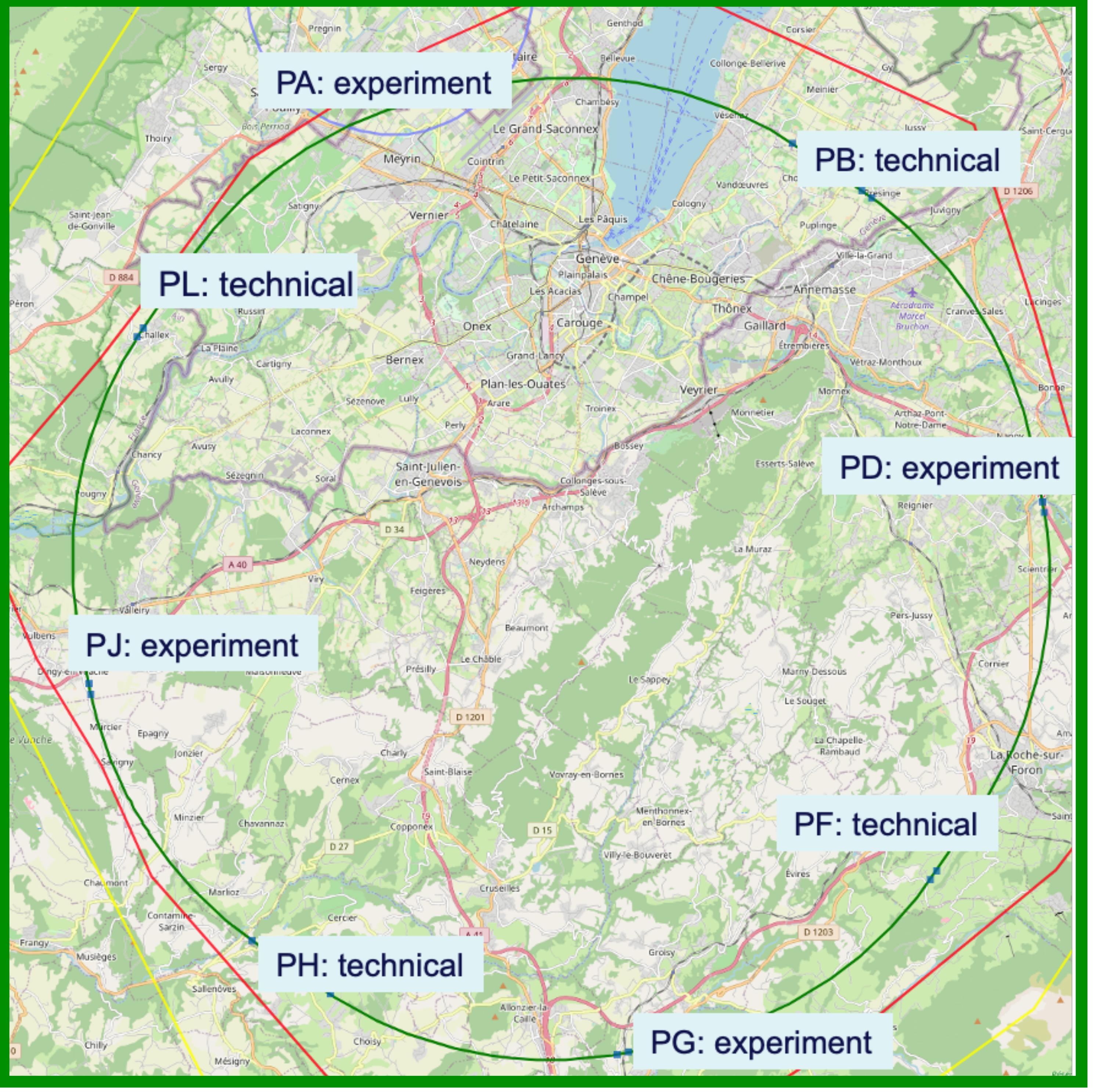
Since 2021: FCC Feasibility Study
(implementation scenario, environmental analysis, high-field magnets, ..)
=> demonstrate feasibility of FCC-ee by 2025

Special Council Session in Feb 2024



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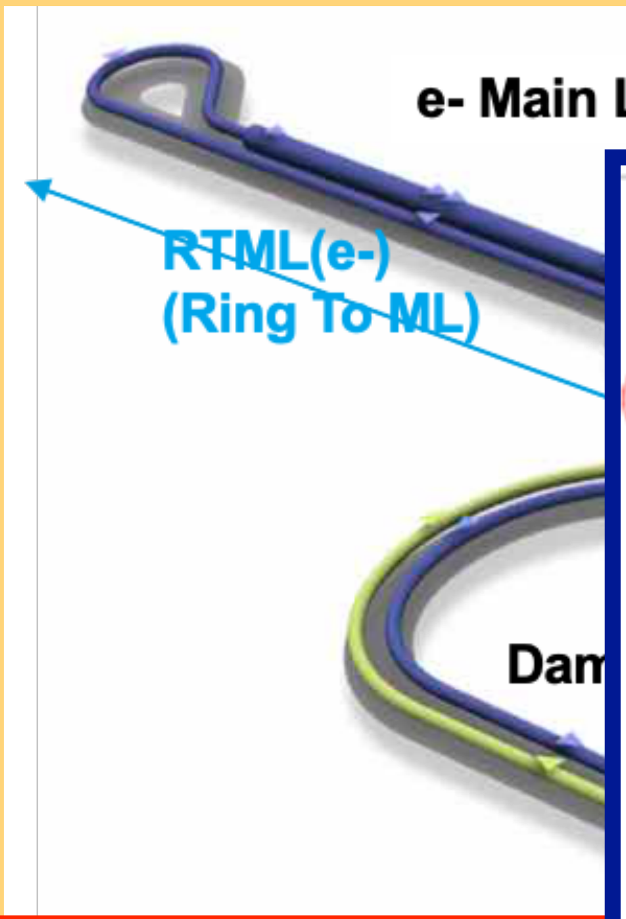

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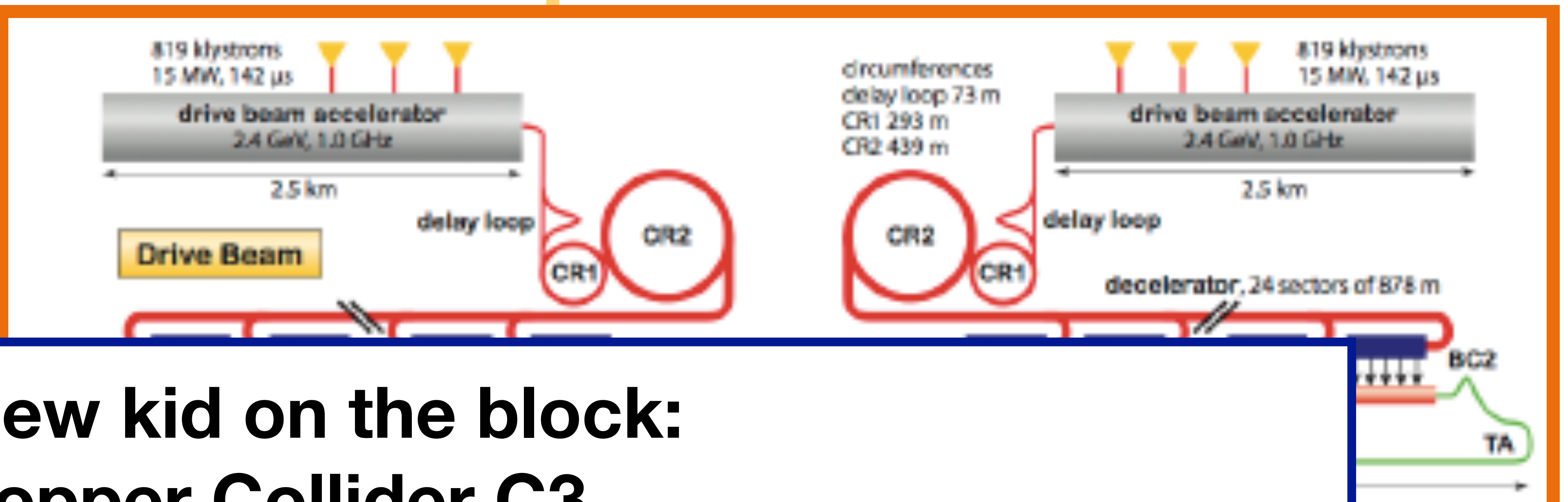
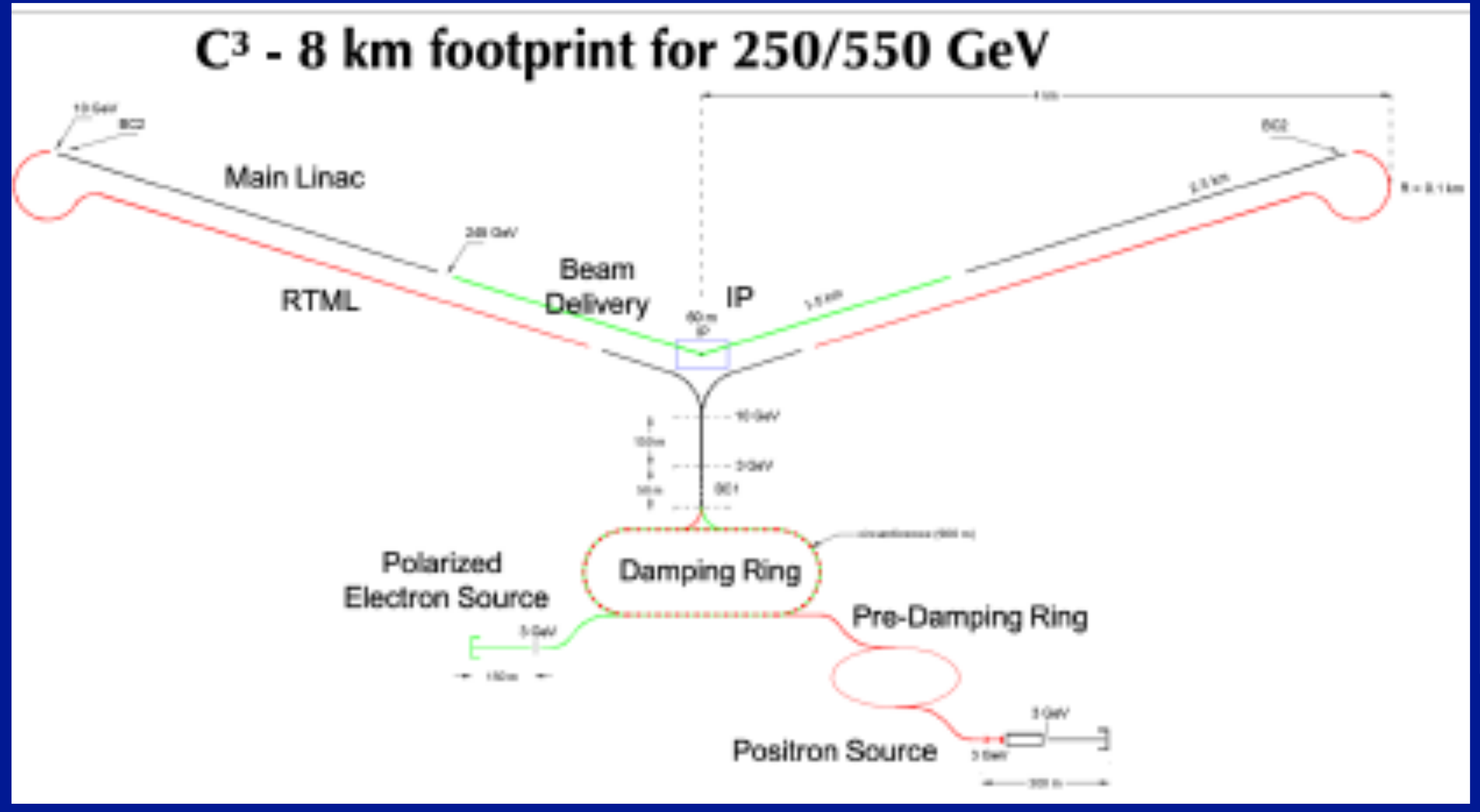
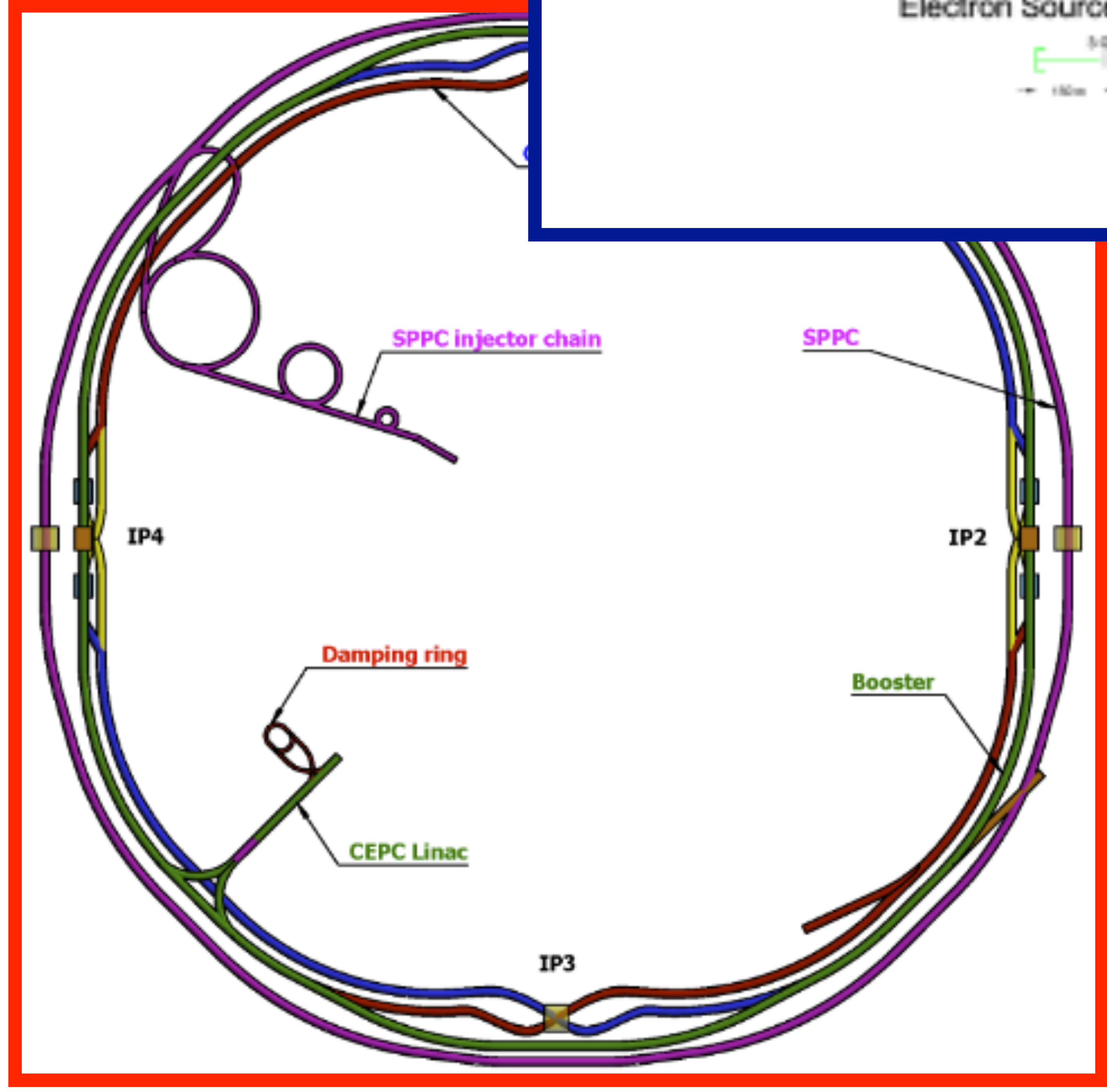




...and the new kid on the block:
the Cool Copper Collider C3,
first proposed 2018, arXiv:1807.10195

4km, time structure compatible with ILC detectors
hoping for support by P5 for 5-year R&D program



CEPC
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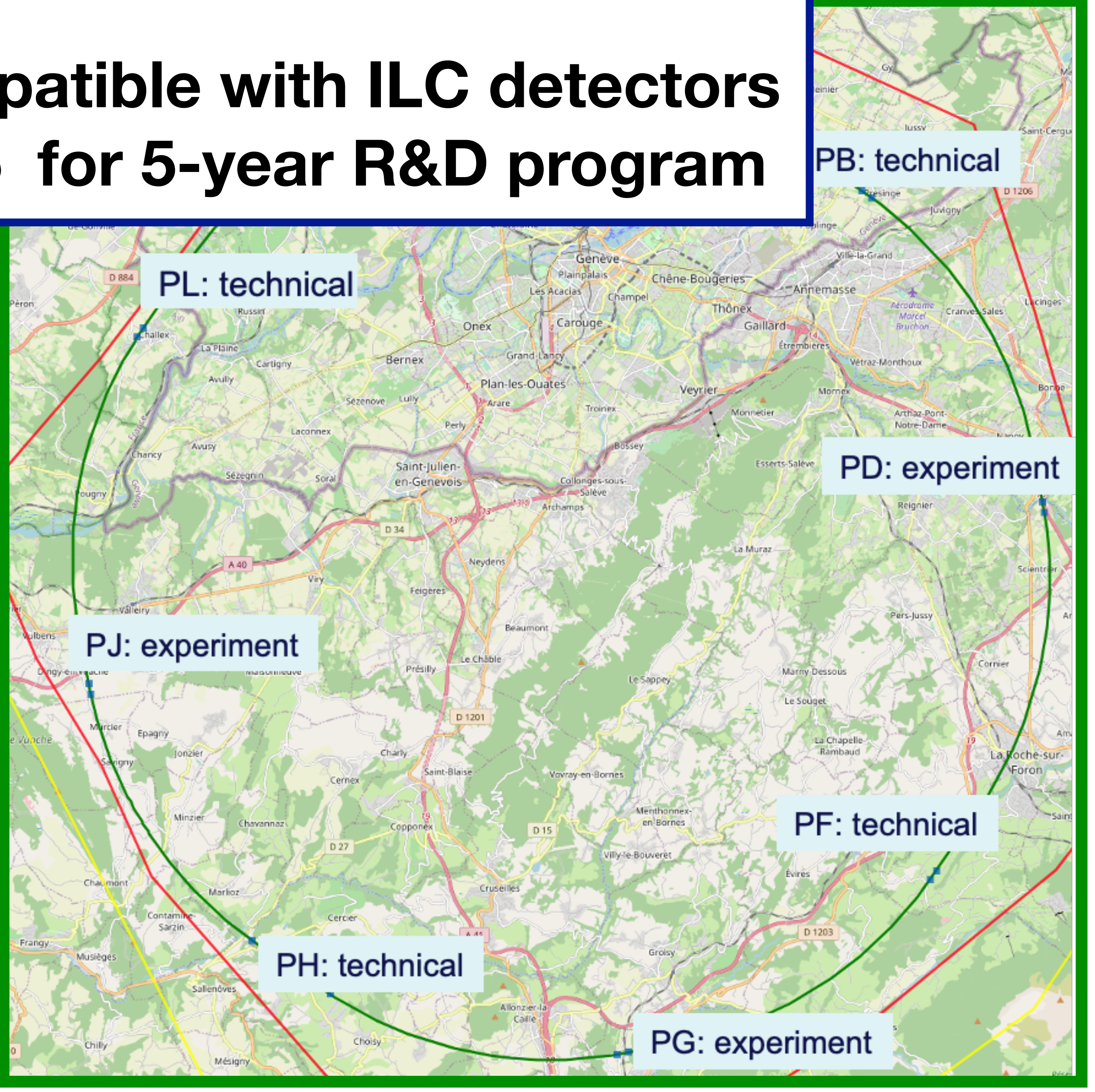

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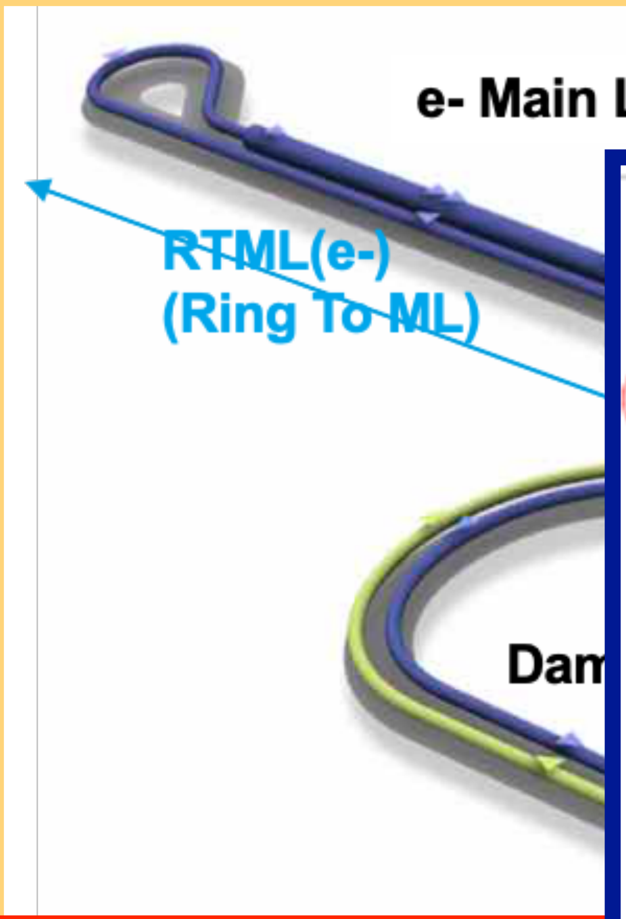

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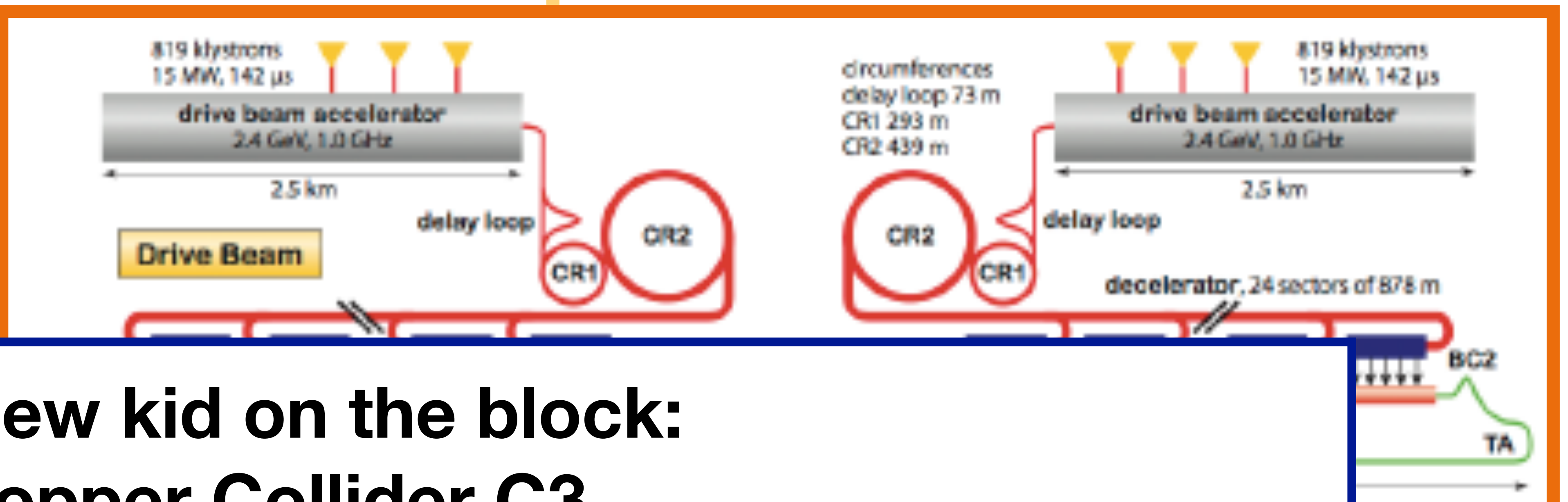

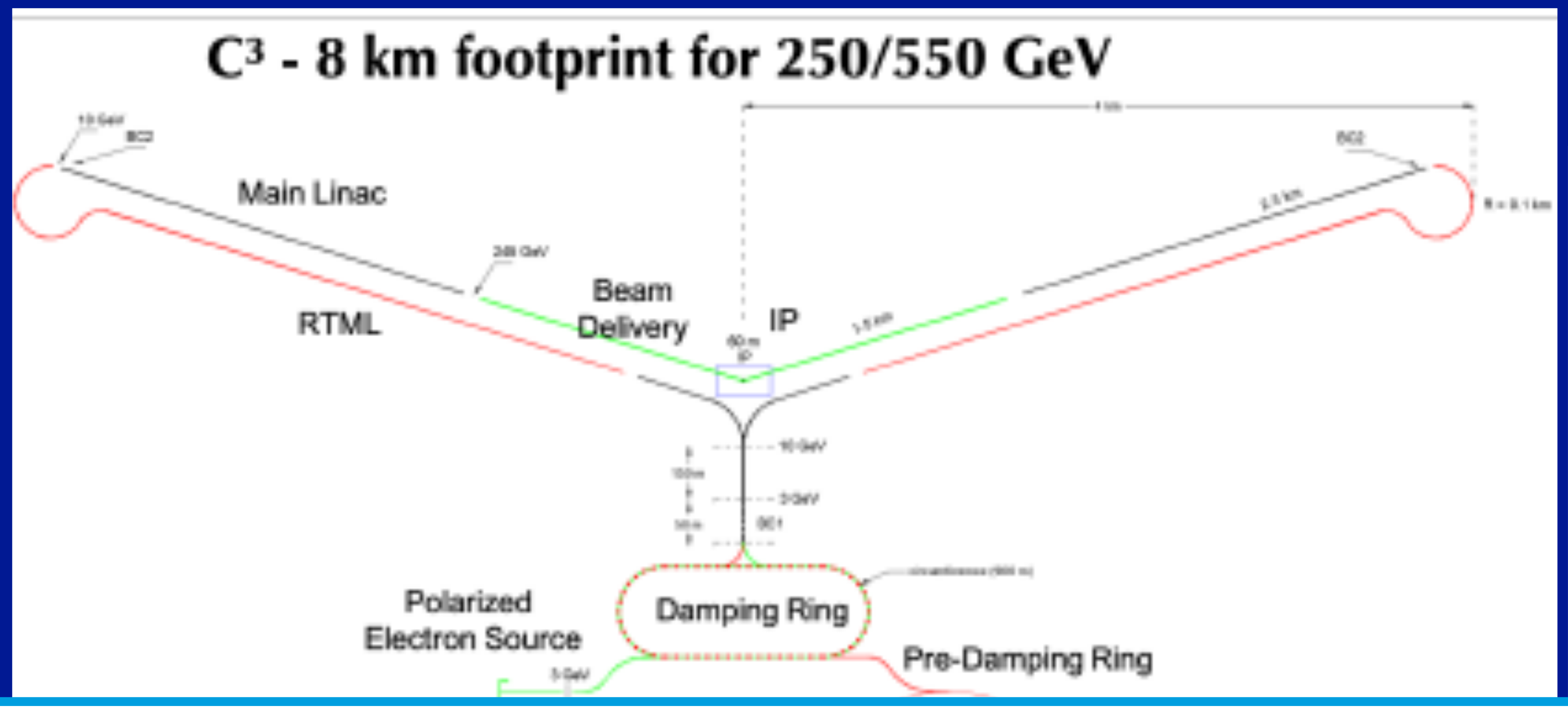

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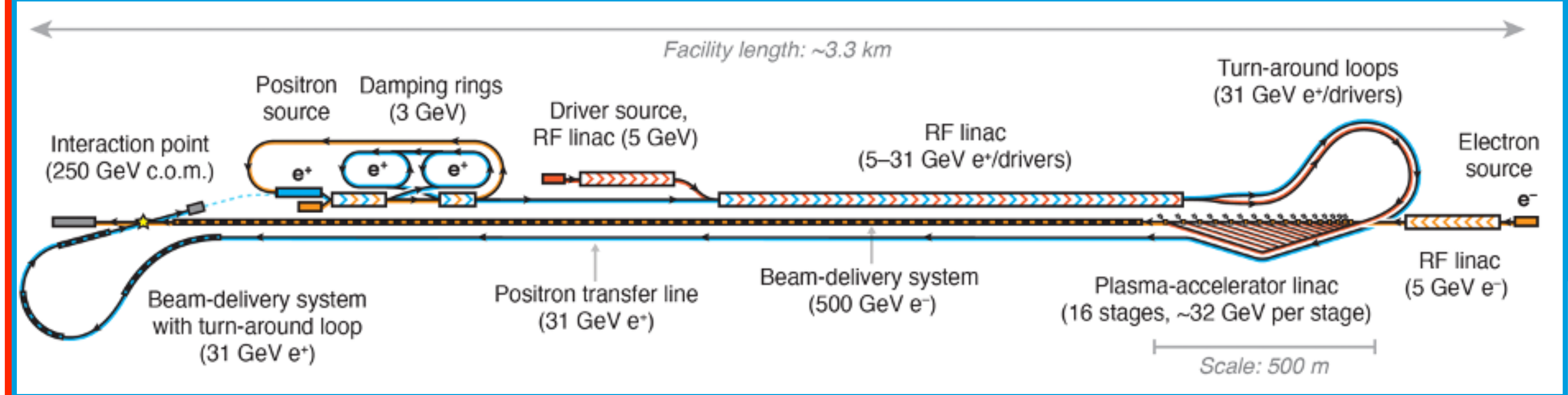
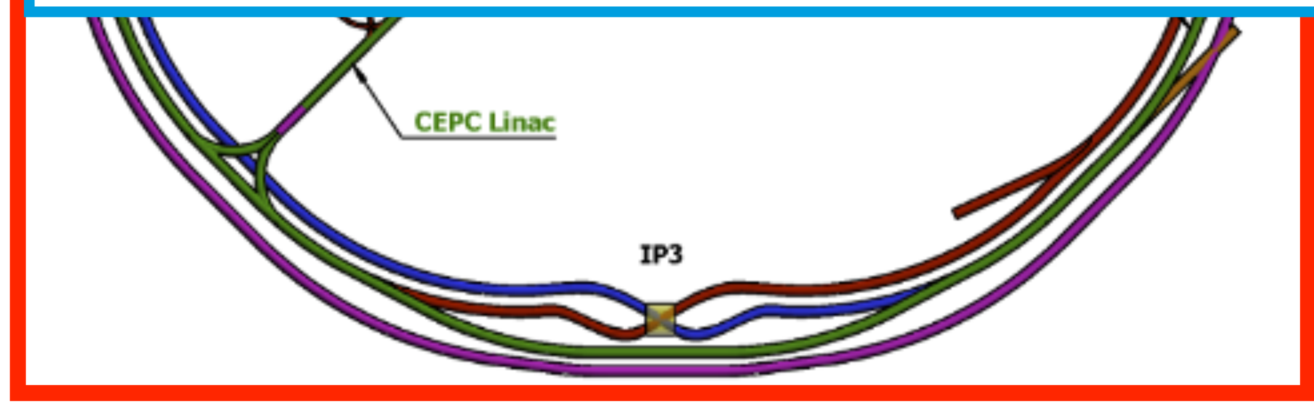
some first studies on detector / physics
estimated ~10 years of R&D for PWFA part





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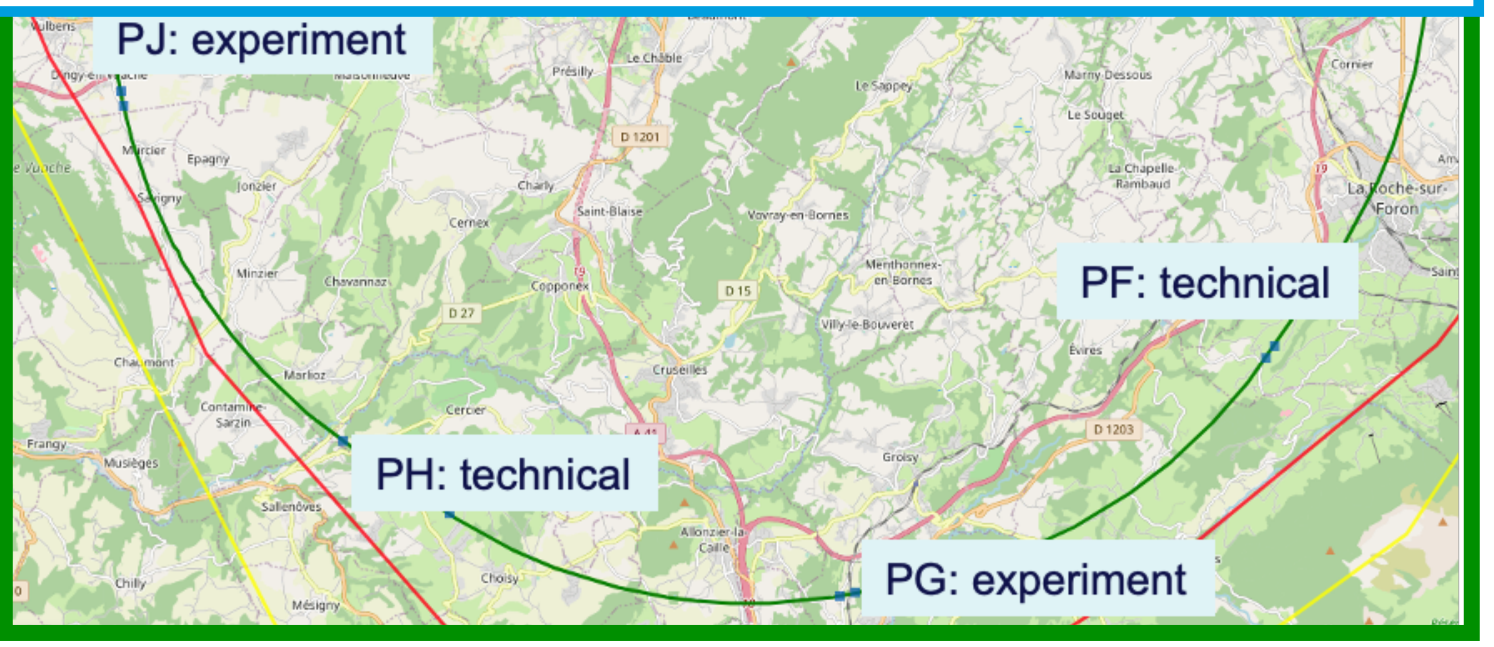

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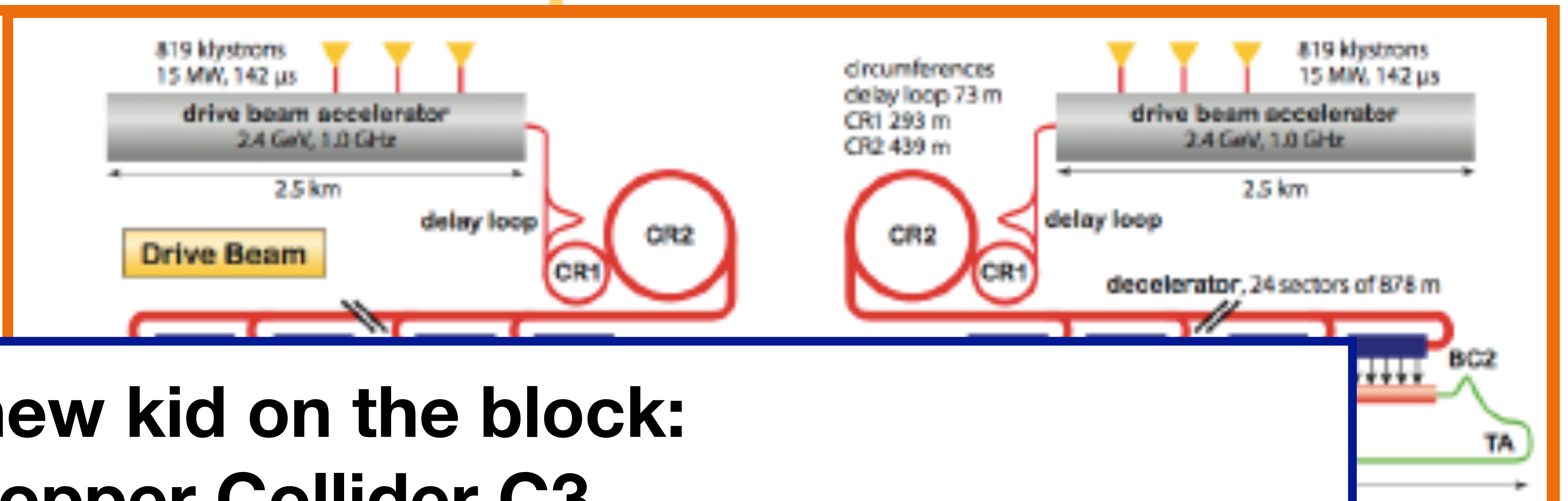

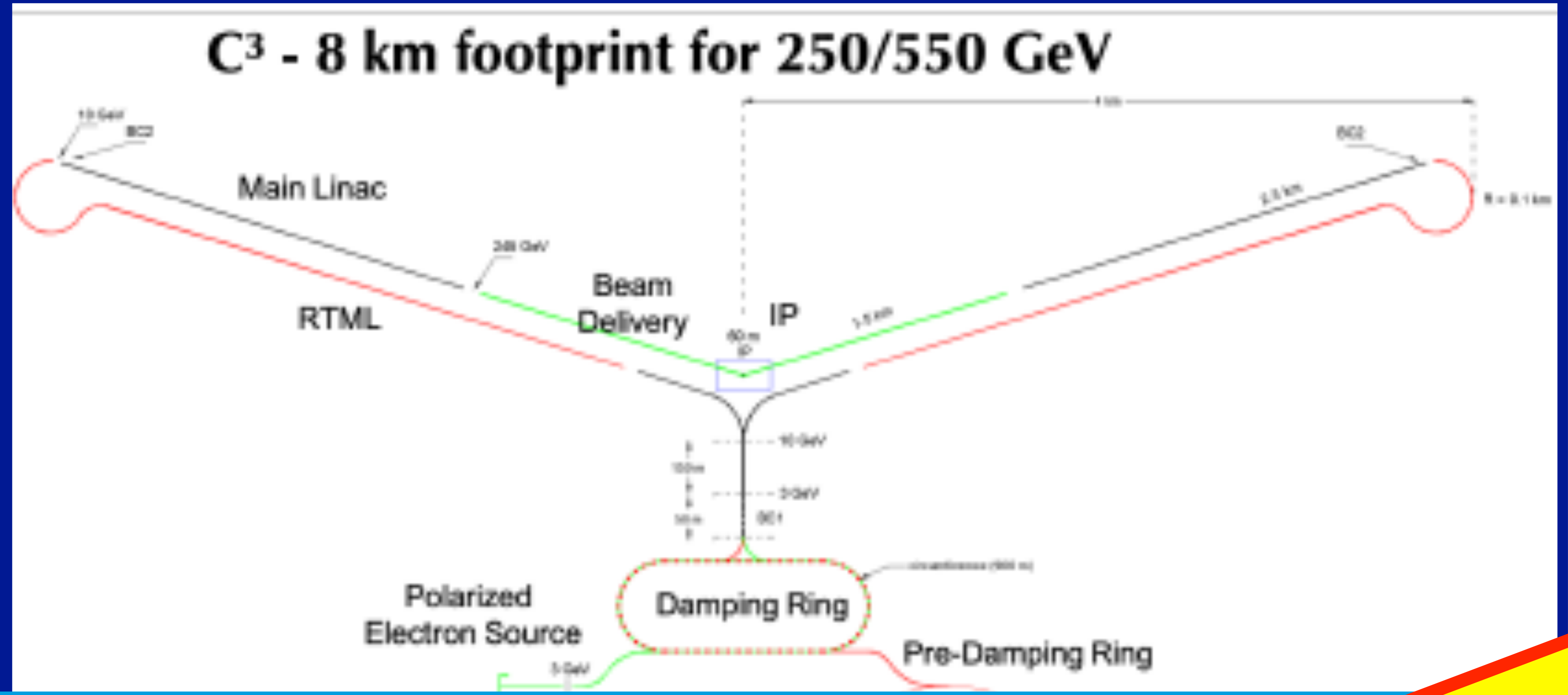

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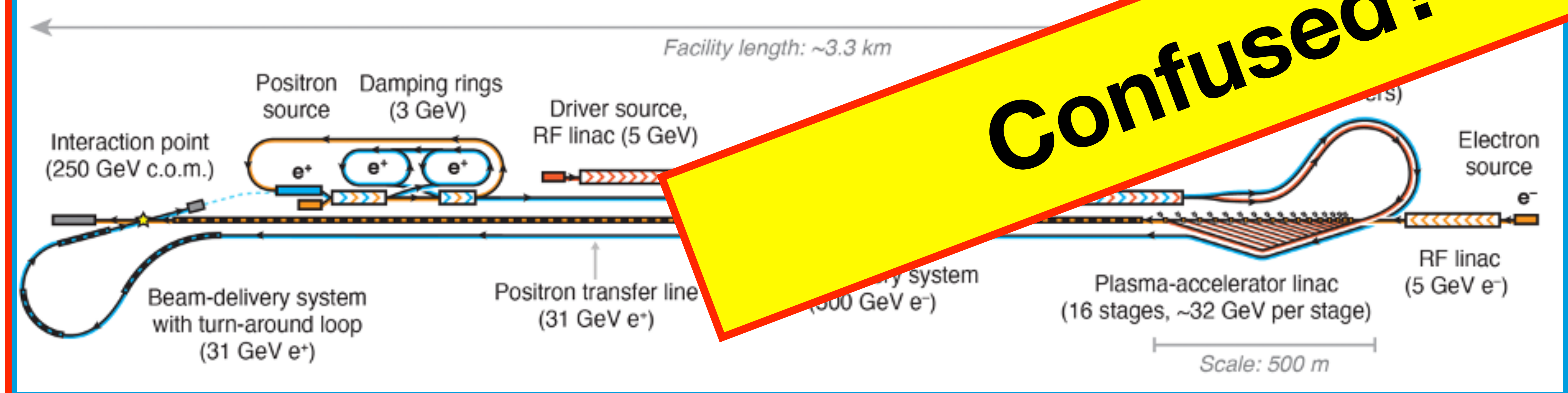

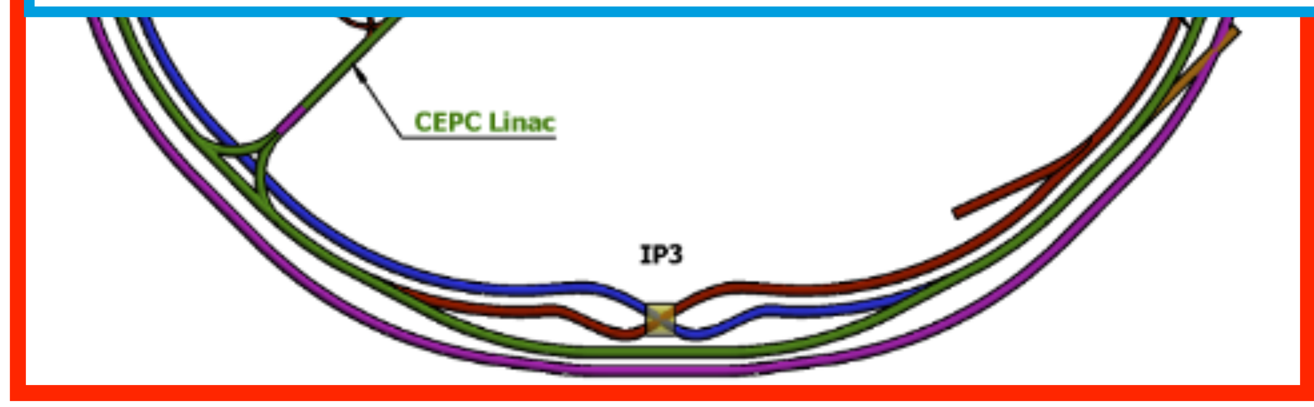

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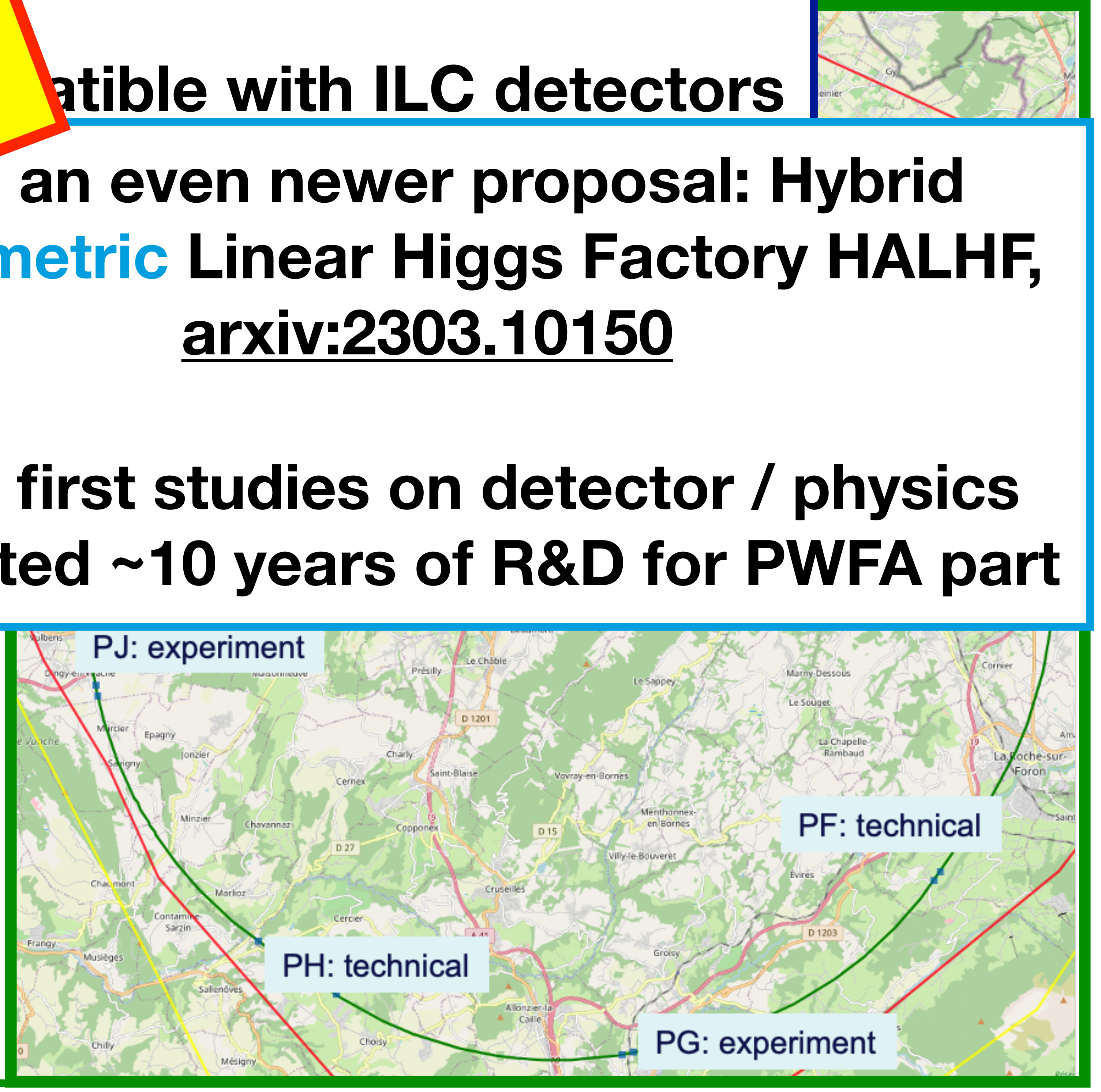
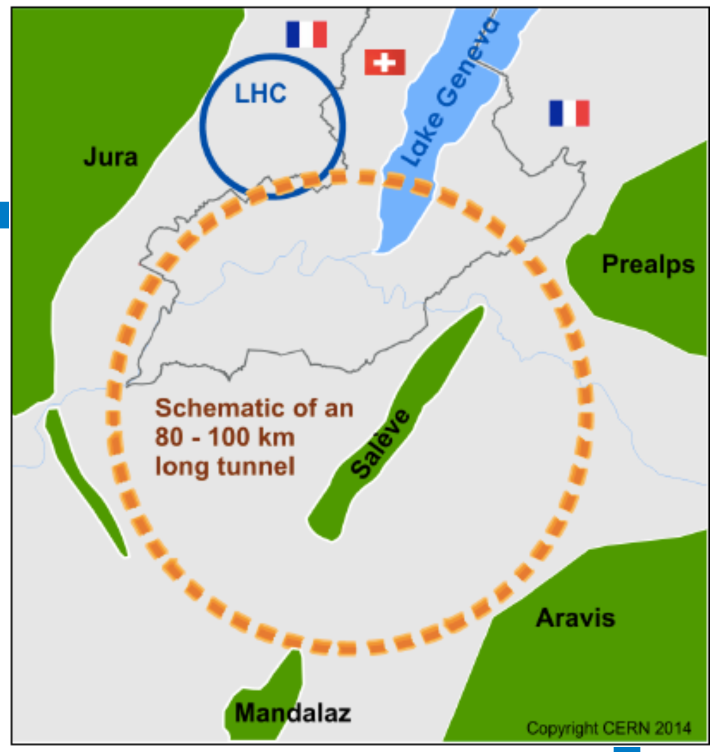


Confused?

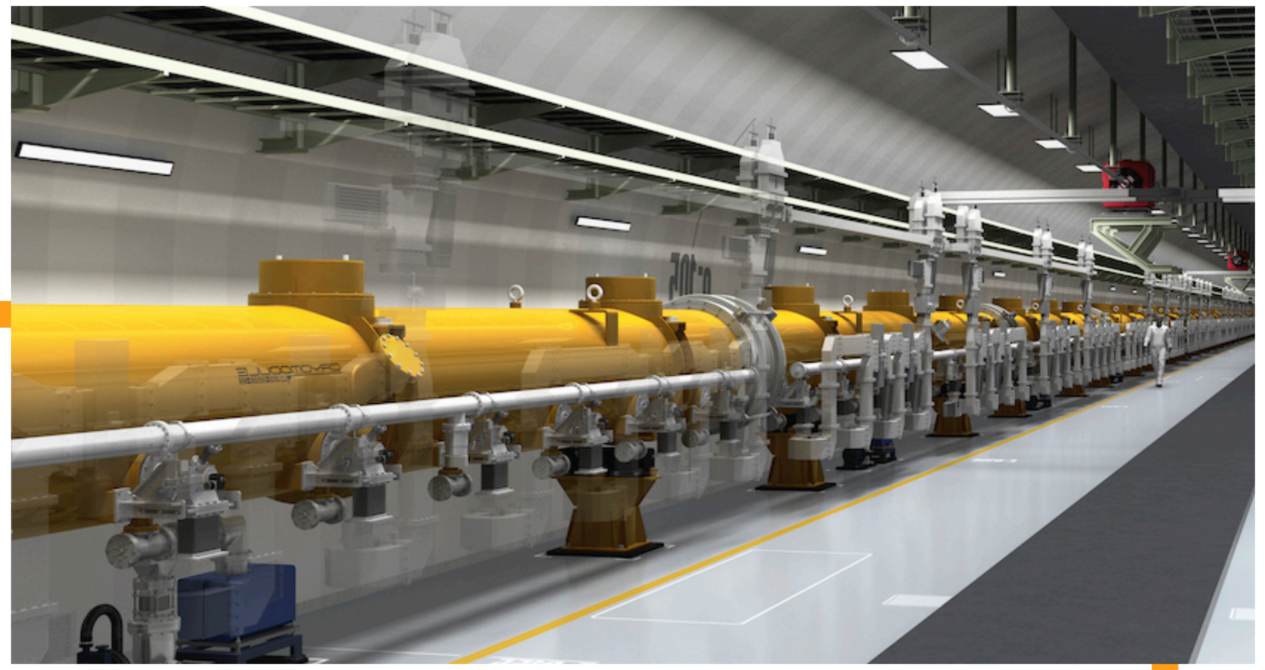
They fall into two classes

Each have their advantages



Circular e+e- Colliders

- FCCee, CEPC
- length 250 GeV: 90…100km
- high luminosity & power efficiency at **low energies**
- **multiple interaction regions**
- very clean: little beamstrahlung etc



Linear Colliders

- ILC, CLIC, C^3, …
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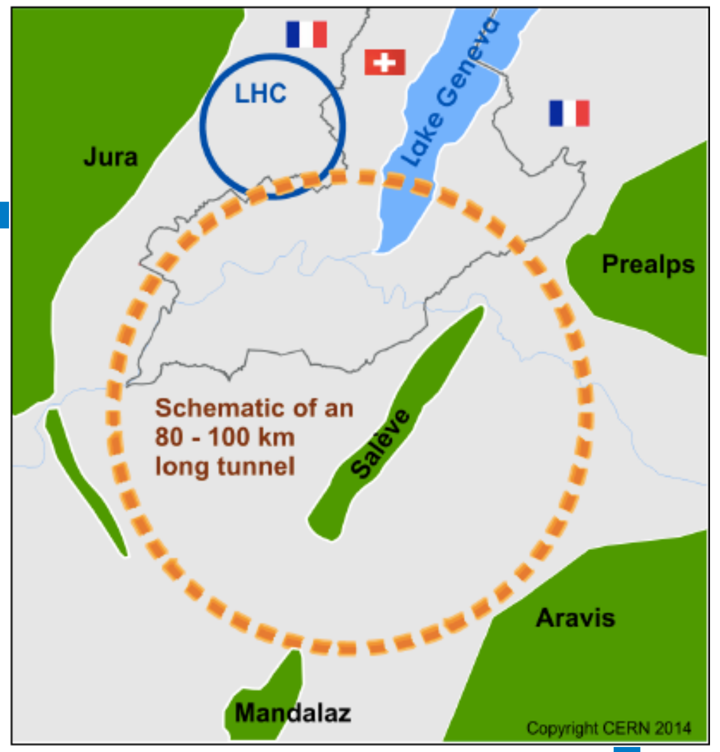

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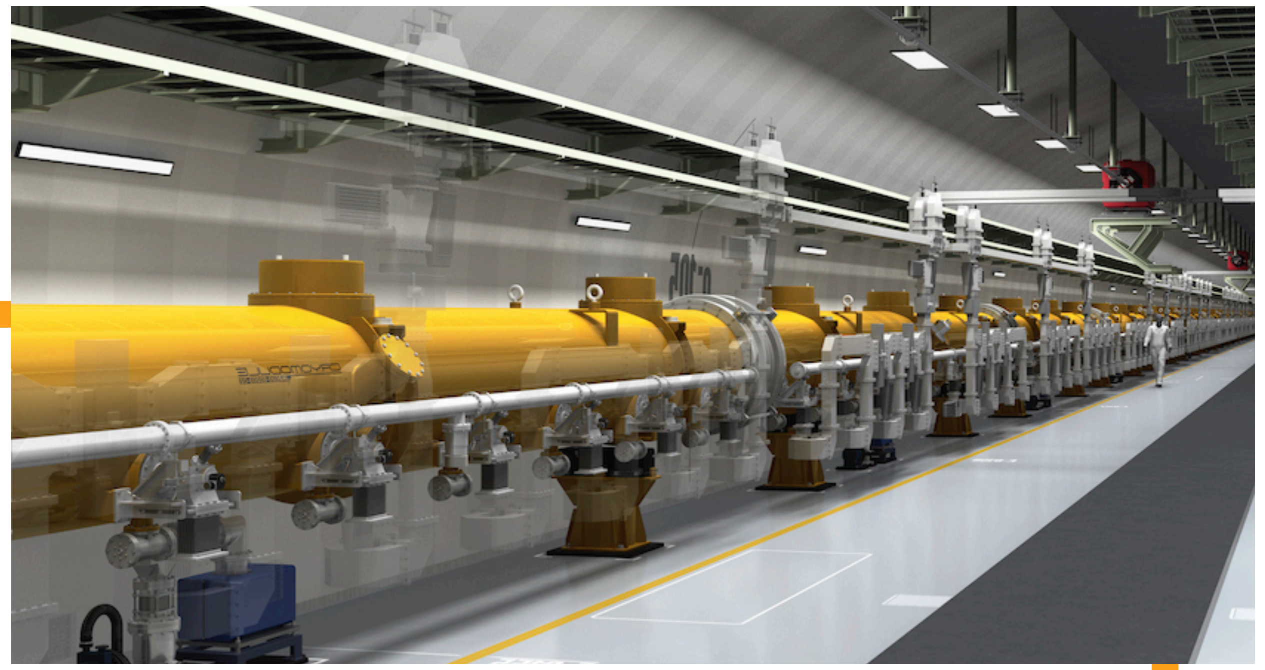
Long-term vision: re-use of tunnel for pp collider

- technical and financial feasibility of required magnets still a challenge



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Long-term upgrades: energy extendability

- same technology: by increasing length
- **or by replacing accelerating structures with advanced technologies**
  - RF cavities with high gradient
  - plasma acceleration ?

Luminosity vs Energy - a long debate…

Reminder: accelerated charges radiate

- **Synchrotron radiation ~ operation cost:**
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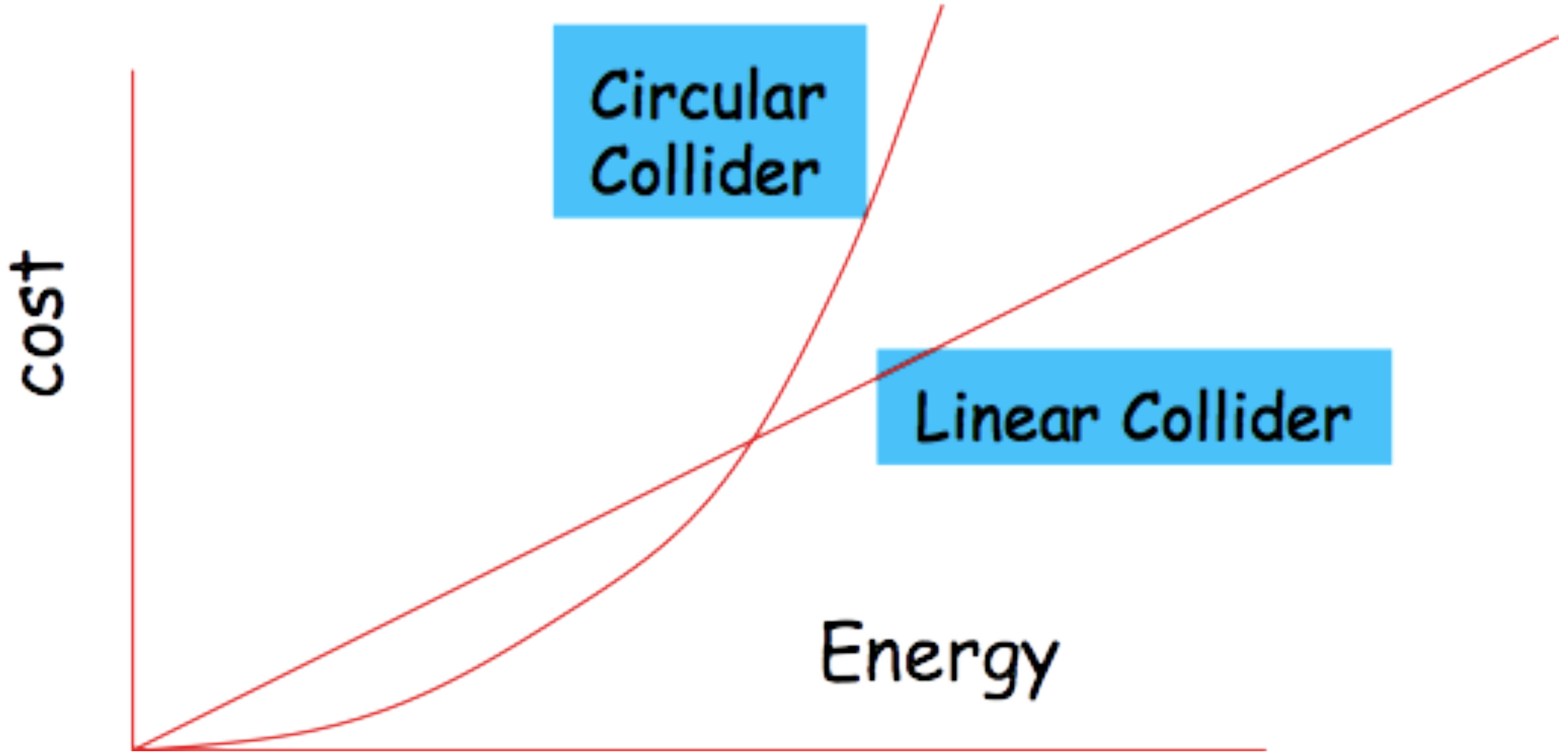

1978[1)]

LIMITATIONS ON PERFORMANCE OF e^+e^- STORAGE RINGS AND

LINEAR COLLIDING BEAM SYSTEMS AT HIGH ENERGY

J.-E. Augustin*, N. Dikanski†, Ya. Derbenev†, J. Rees‡, B. Richter‡, A. Skrinski†, M. Tigner**, and H. Wiedemann‡

Introduction

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1) very first paper on this topic: M.Tigner 1965

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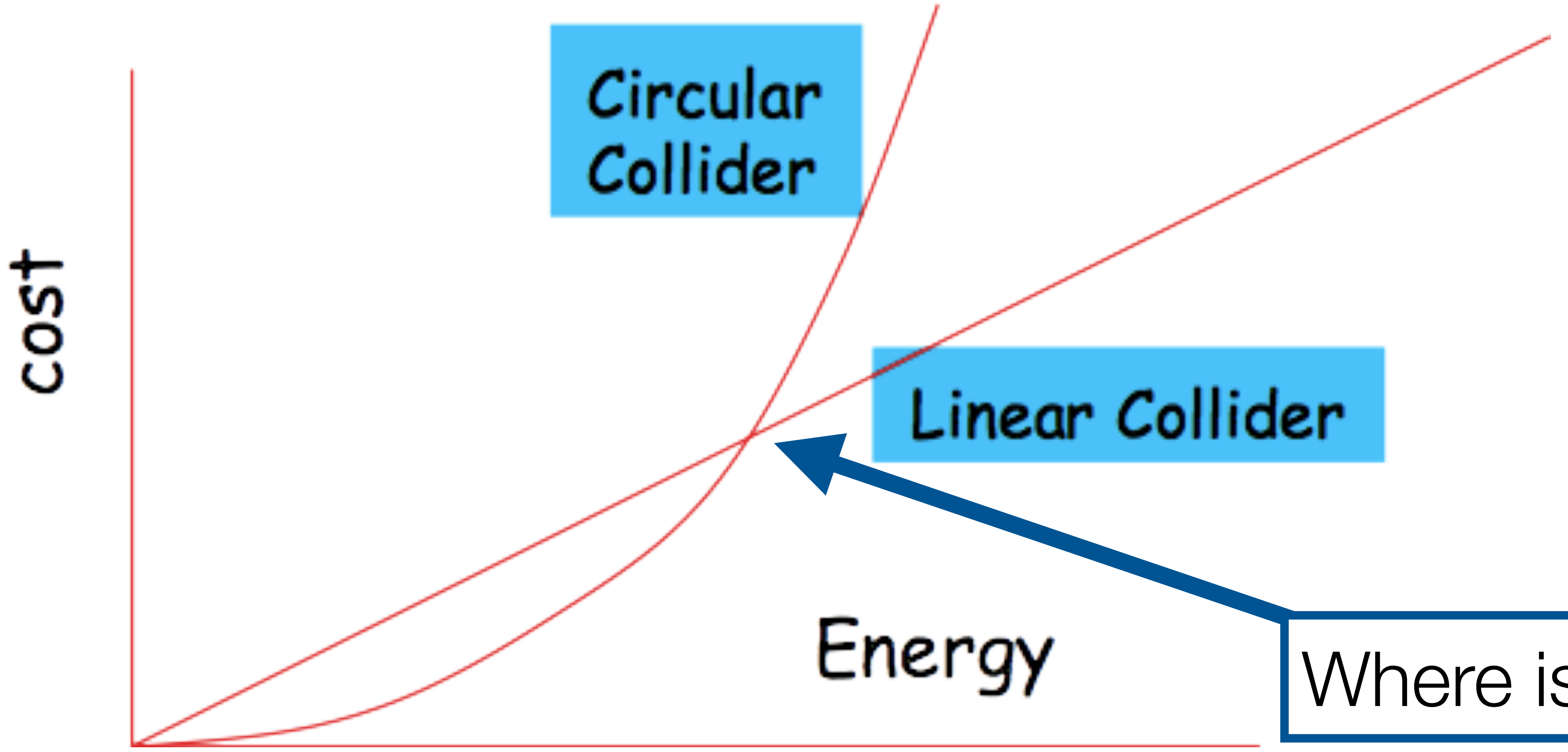

Where is the crossing point?

1978[1)]

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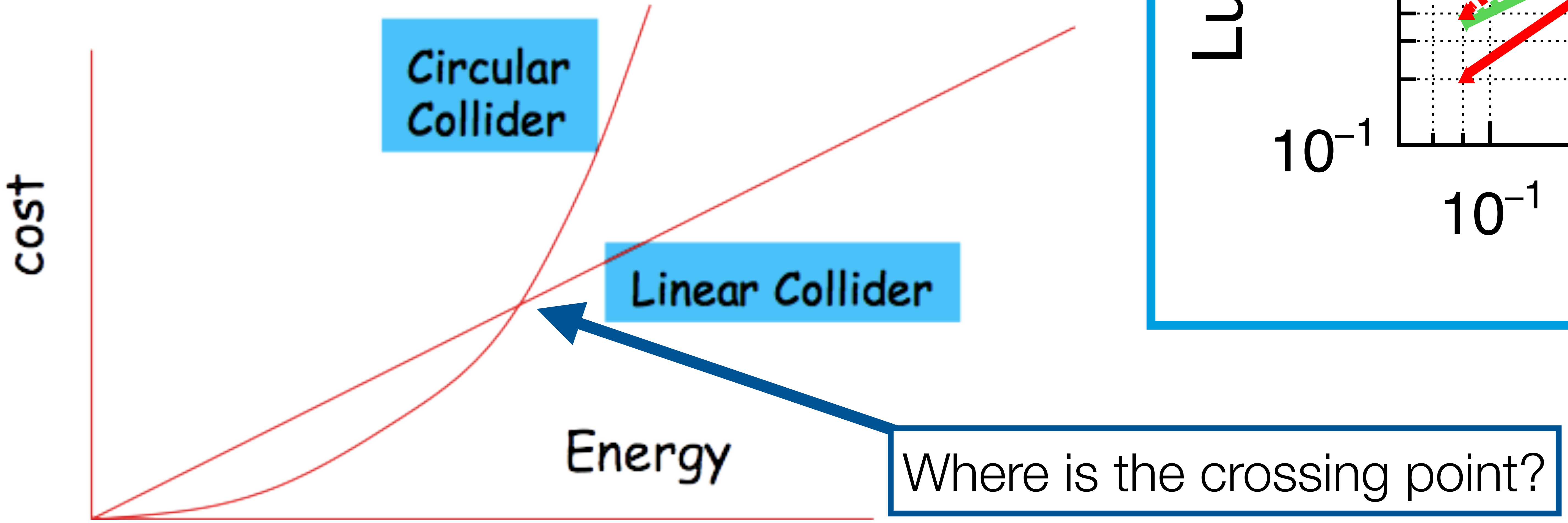

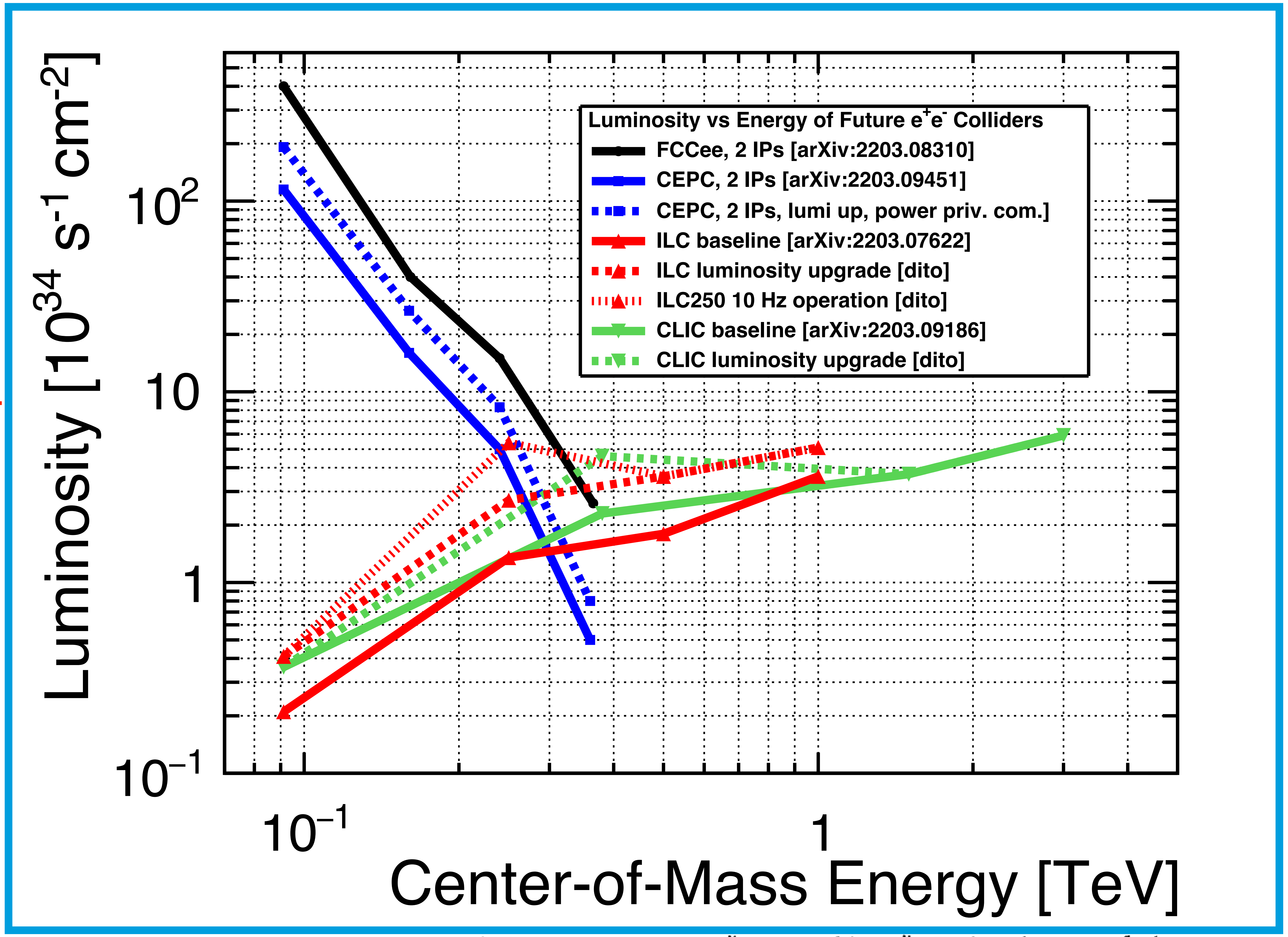

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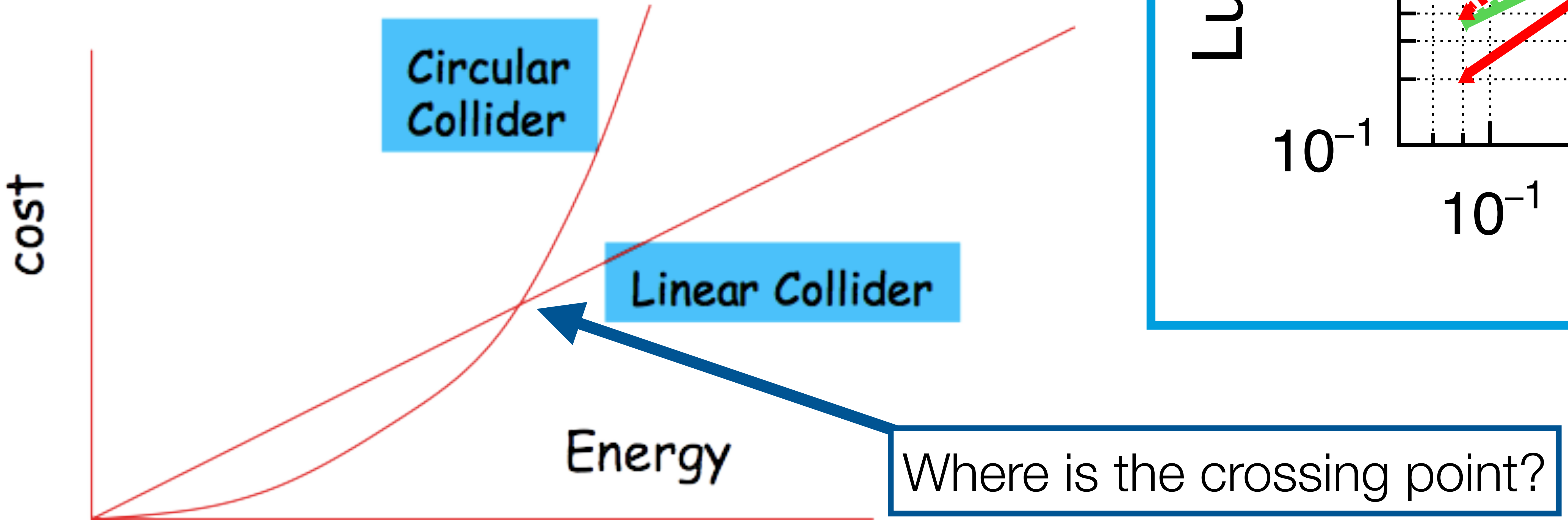

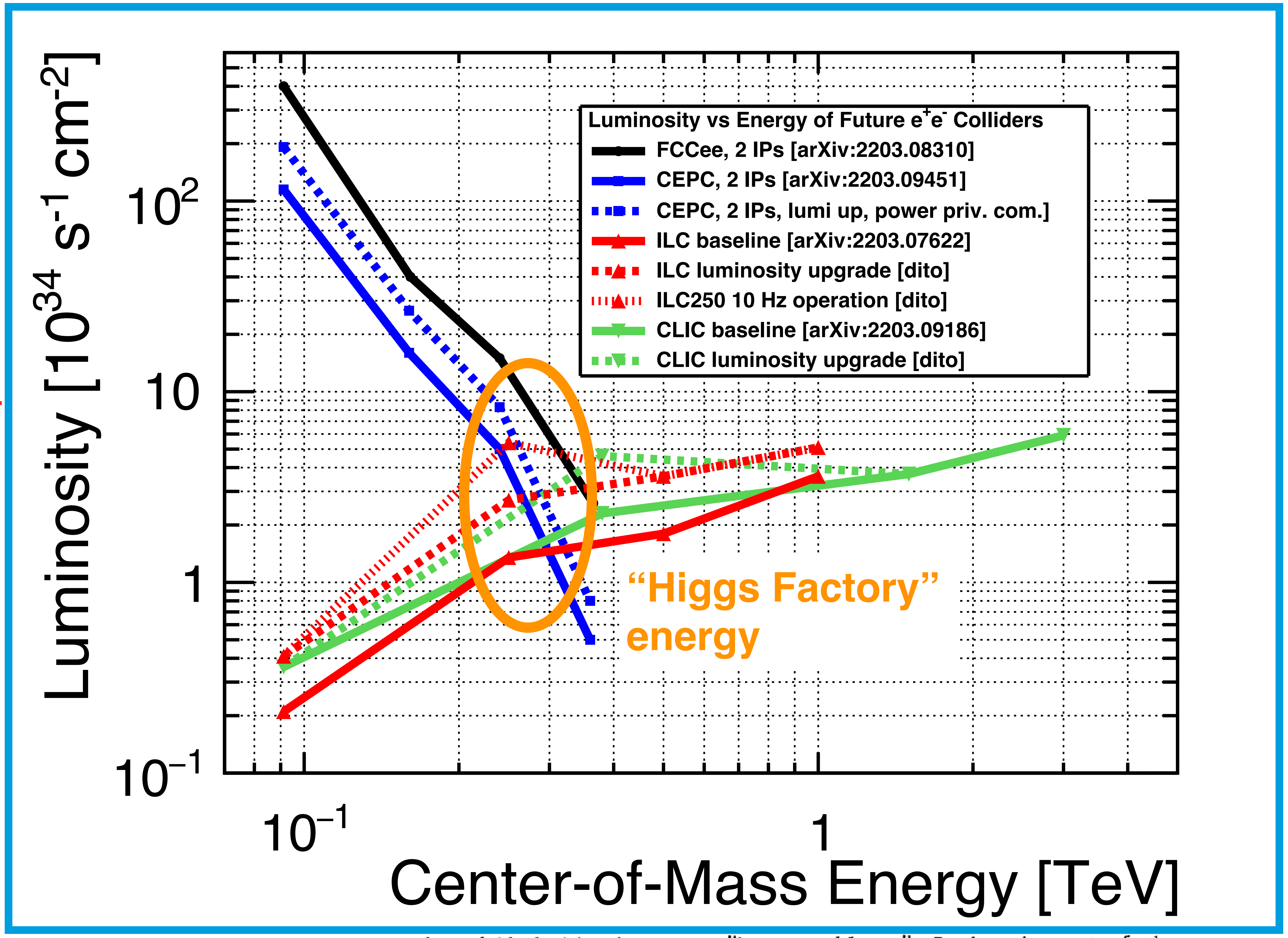

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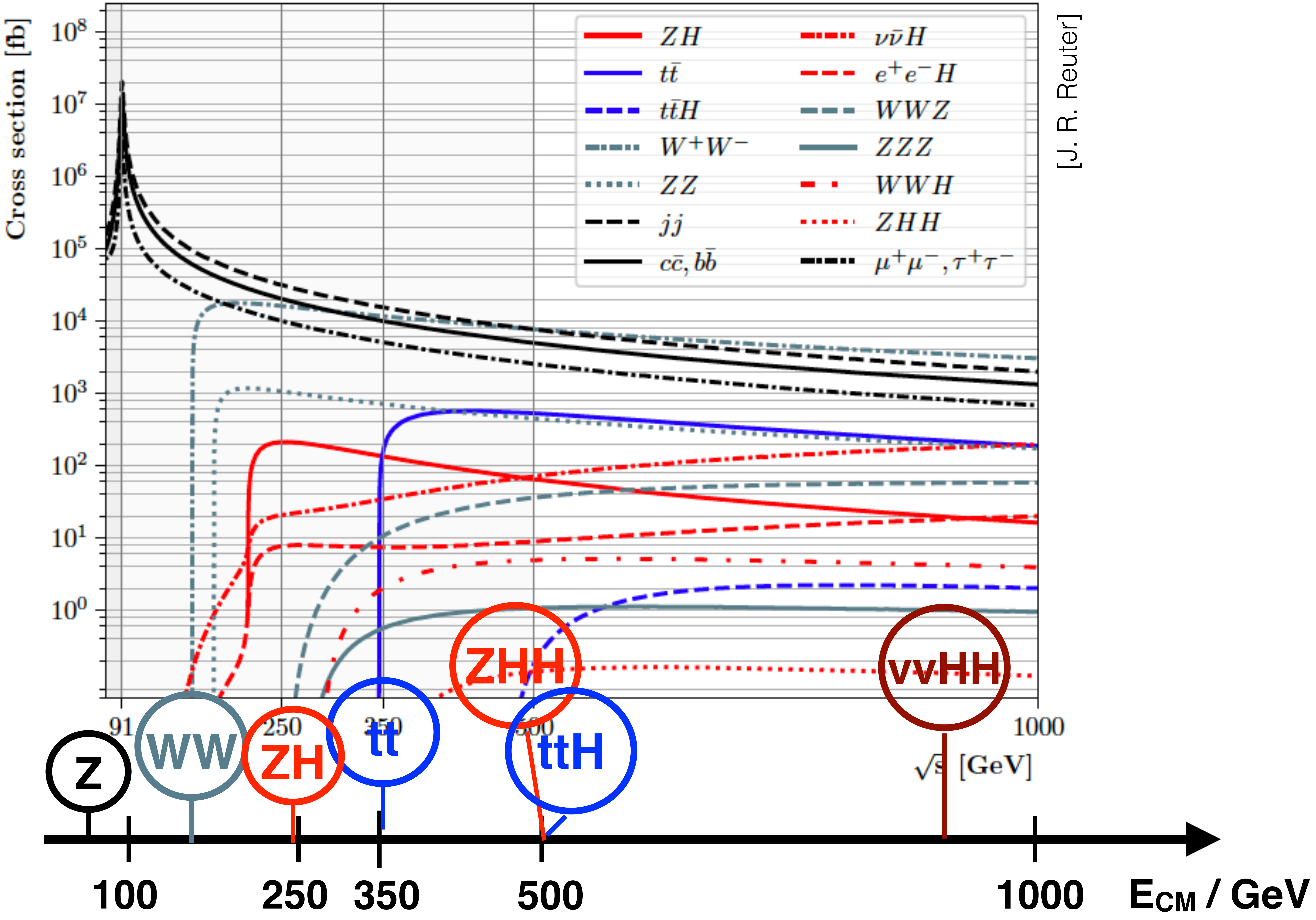
The basic
Higgs Factory program

The key physics at a Higgs Factory

Production rates vs collision energy



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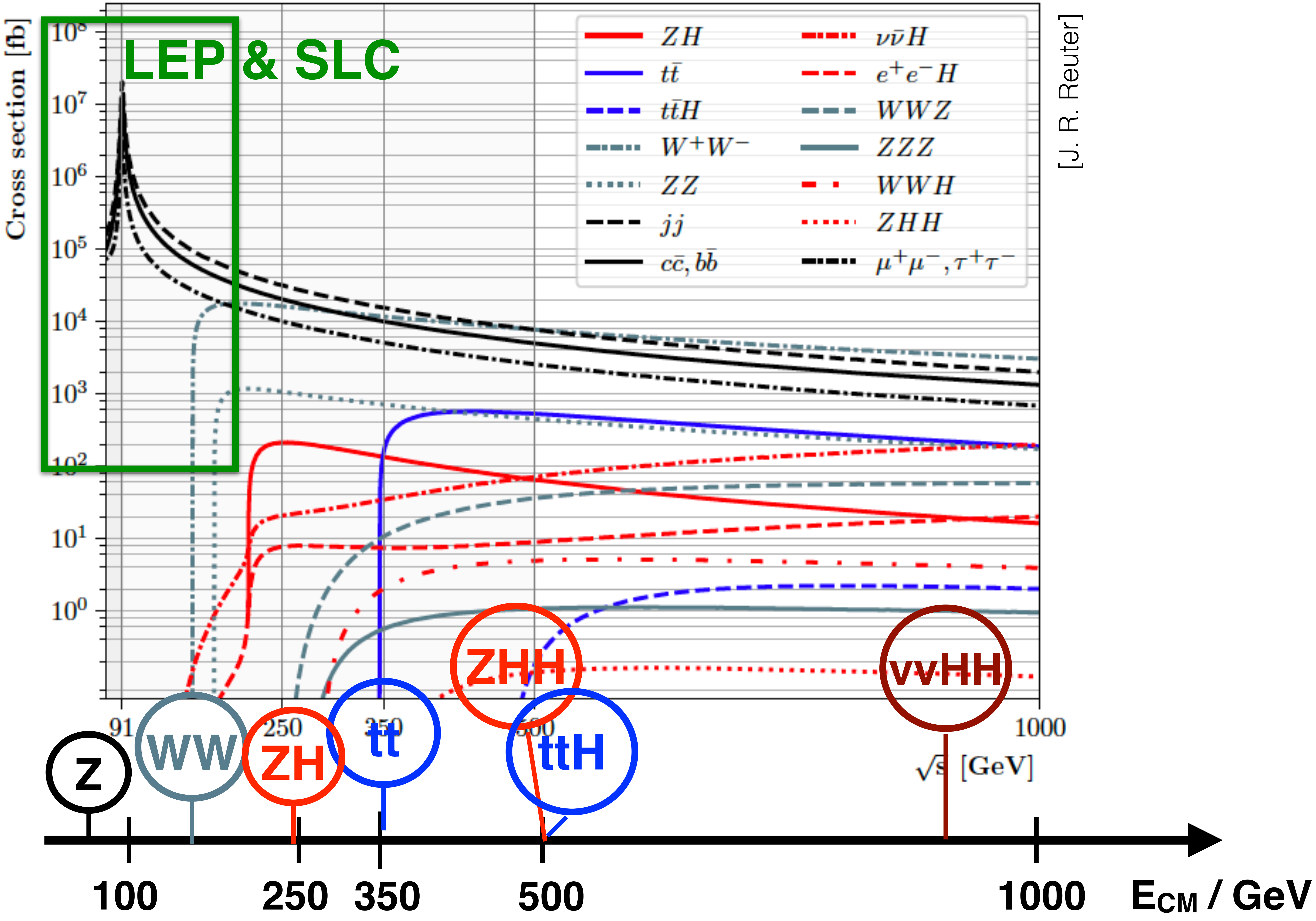

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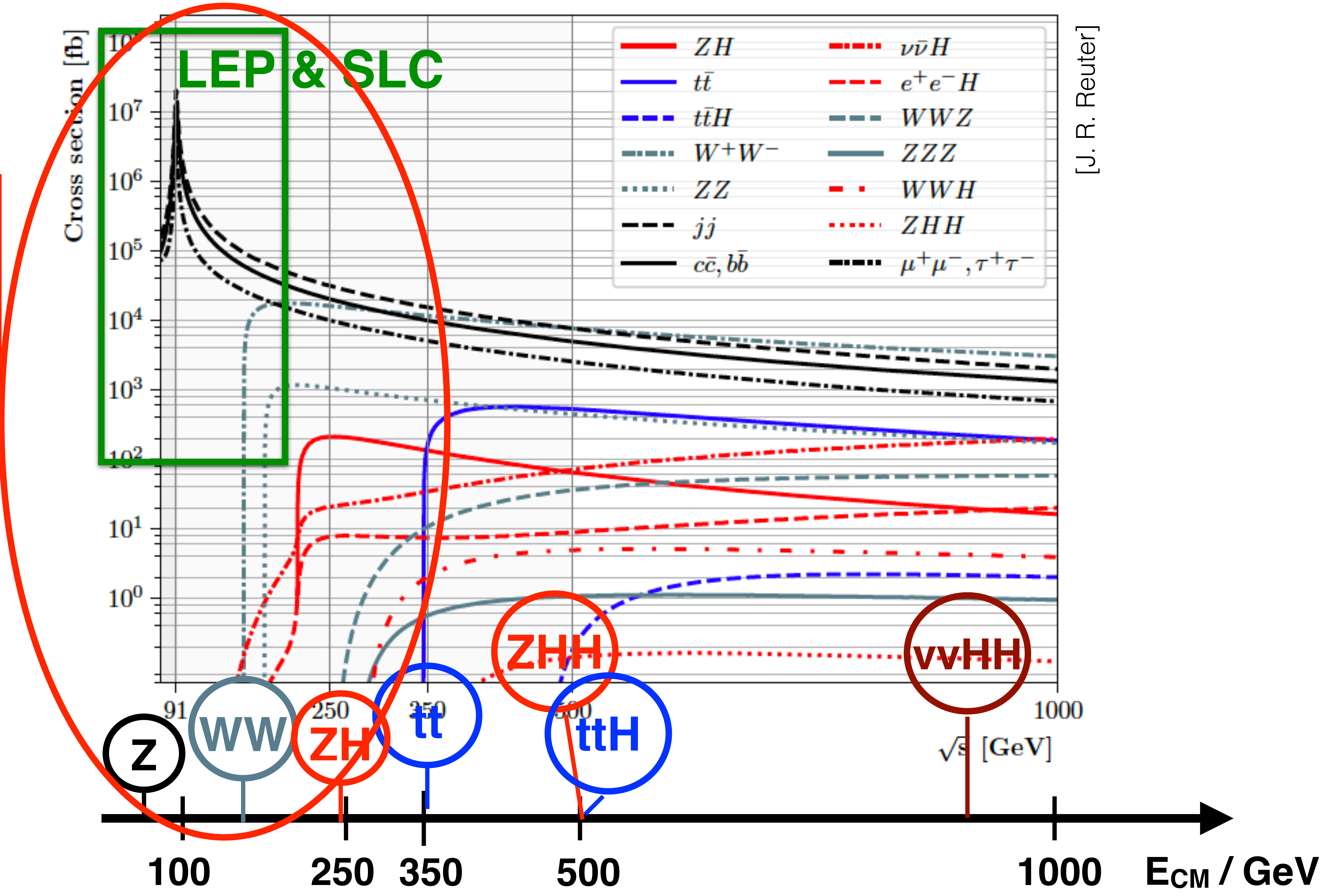
Production rates vs collision energy

considered by all proposed e+e- projects



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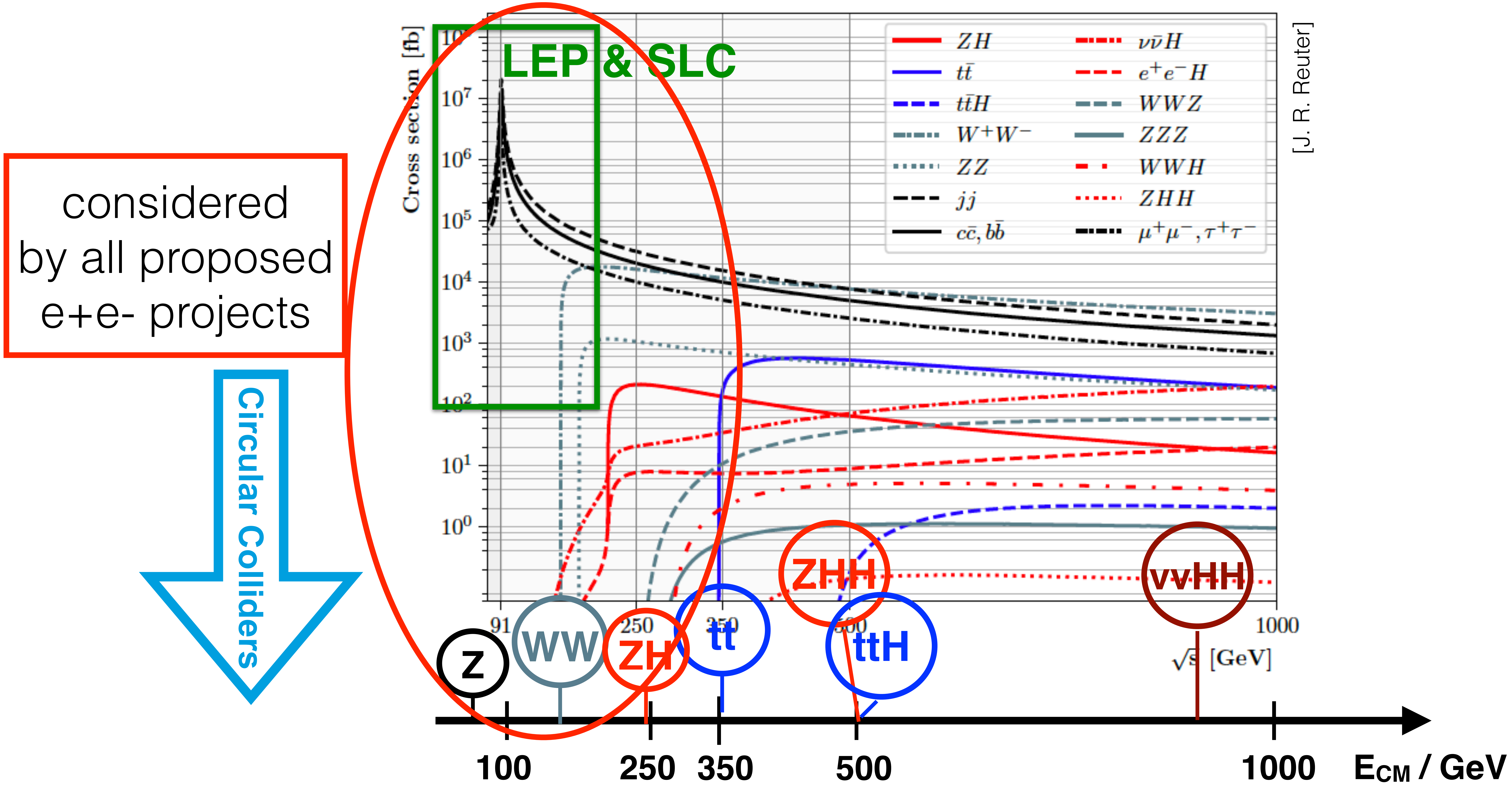

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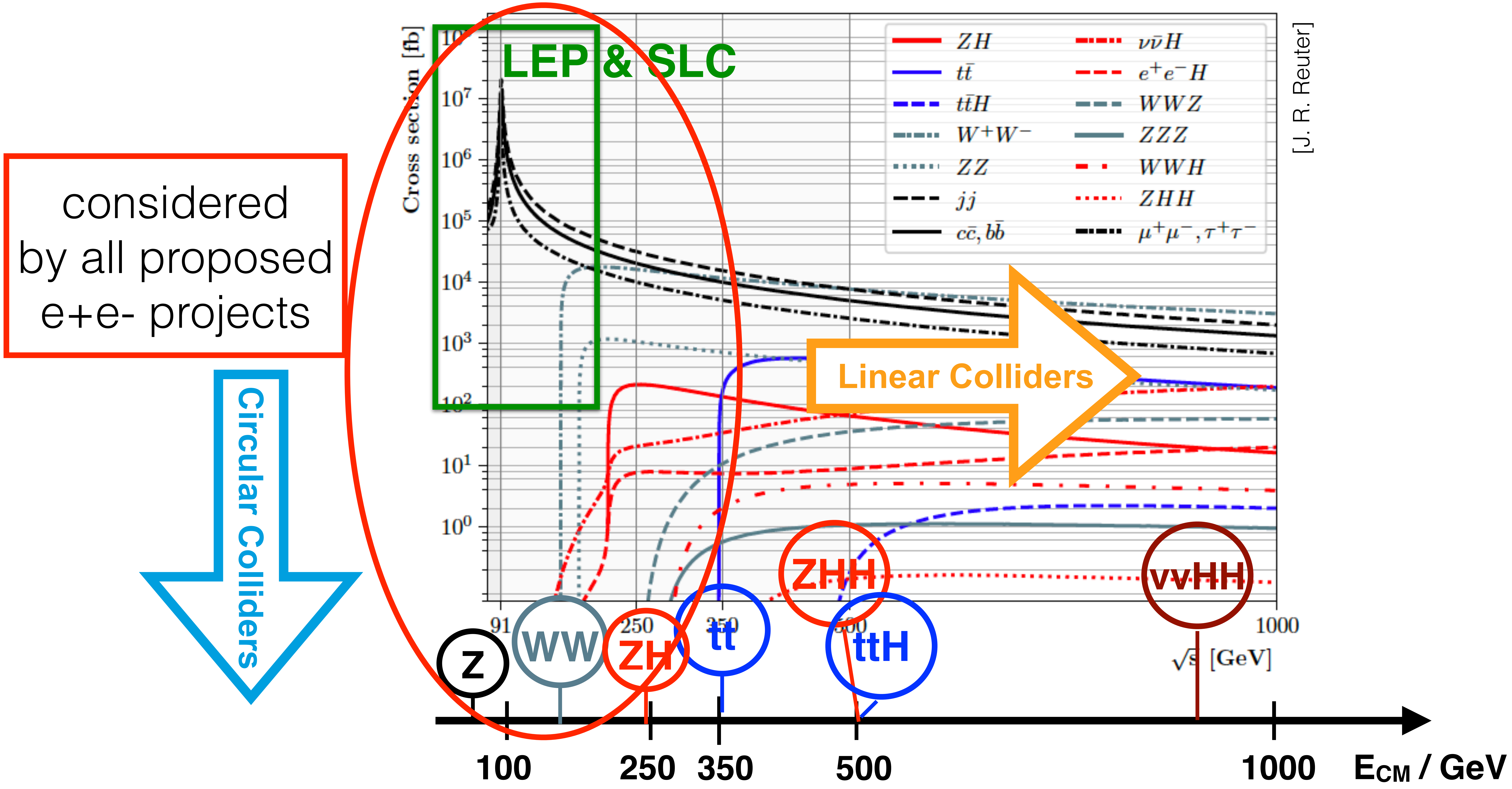

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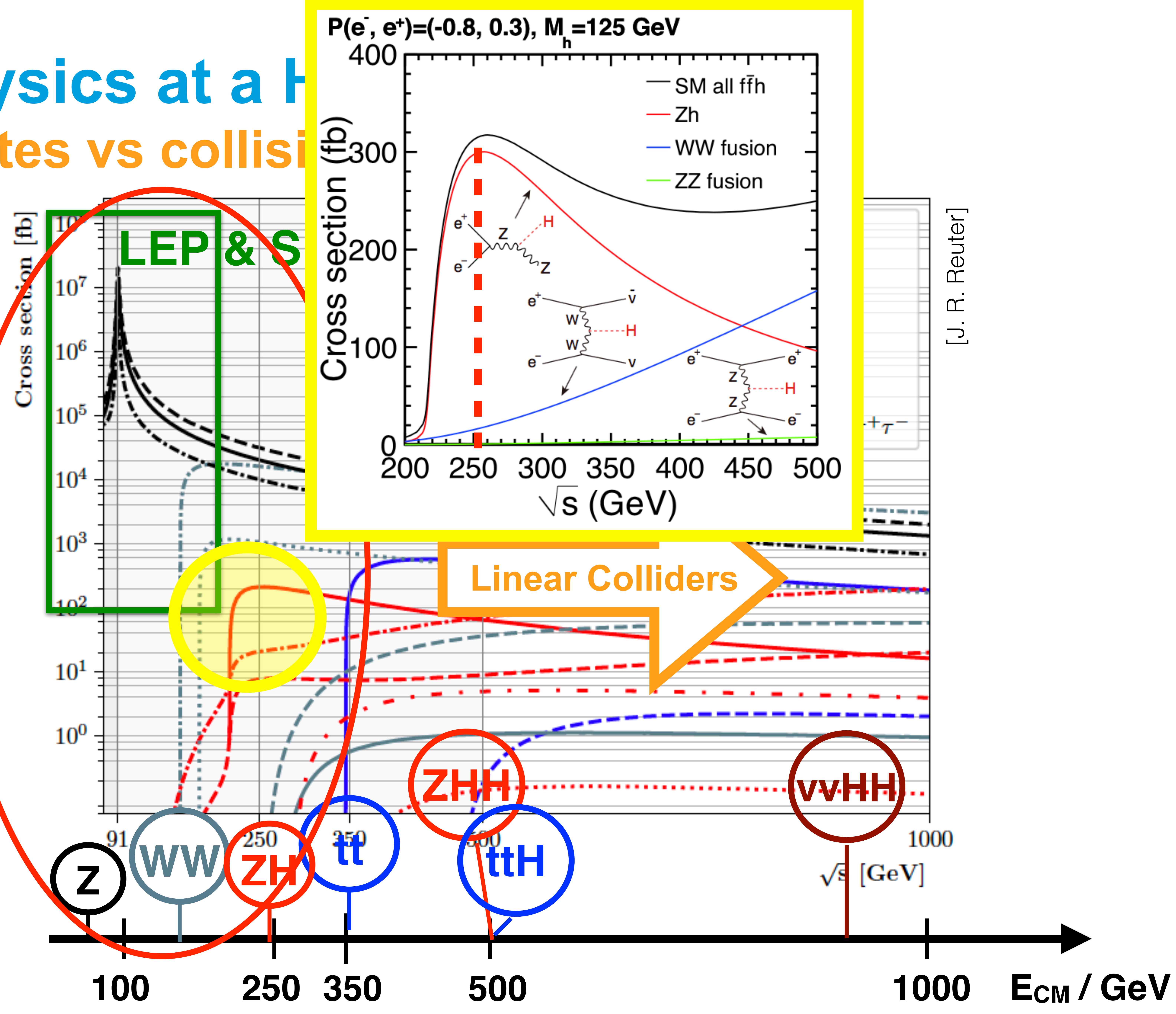

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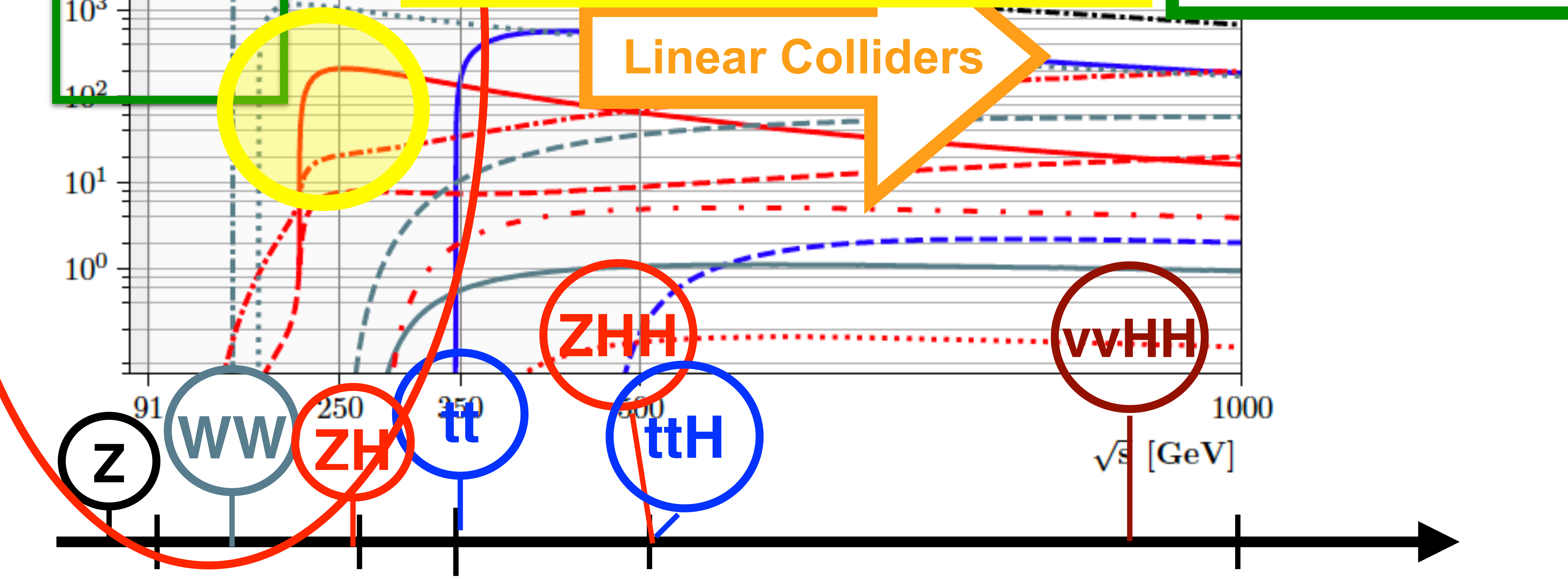

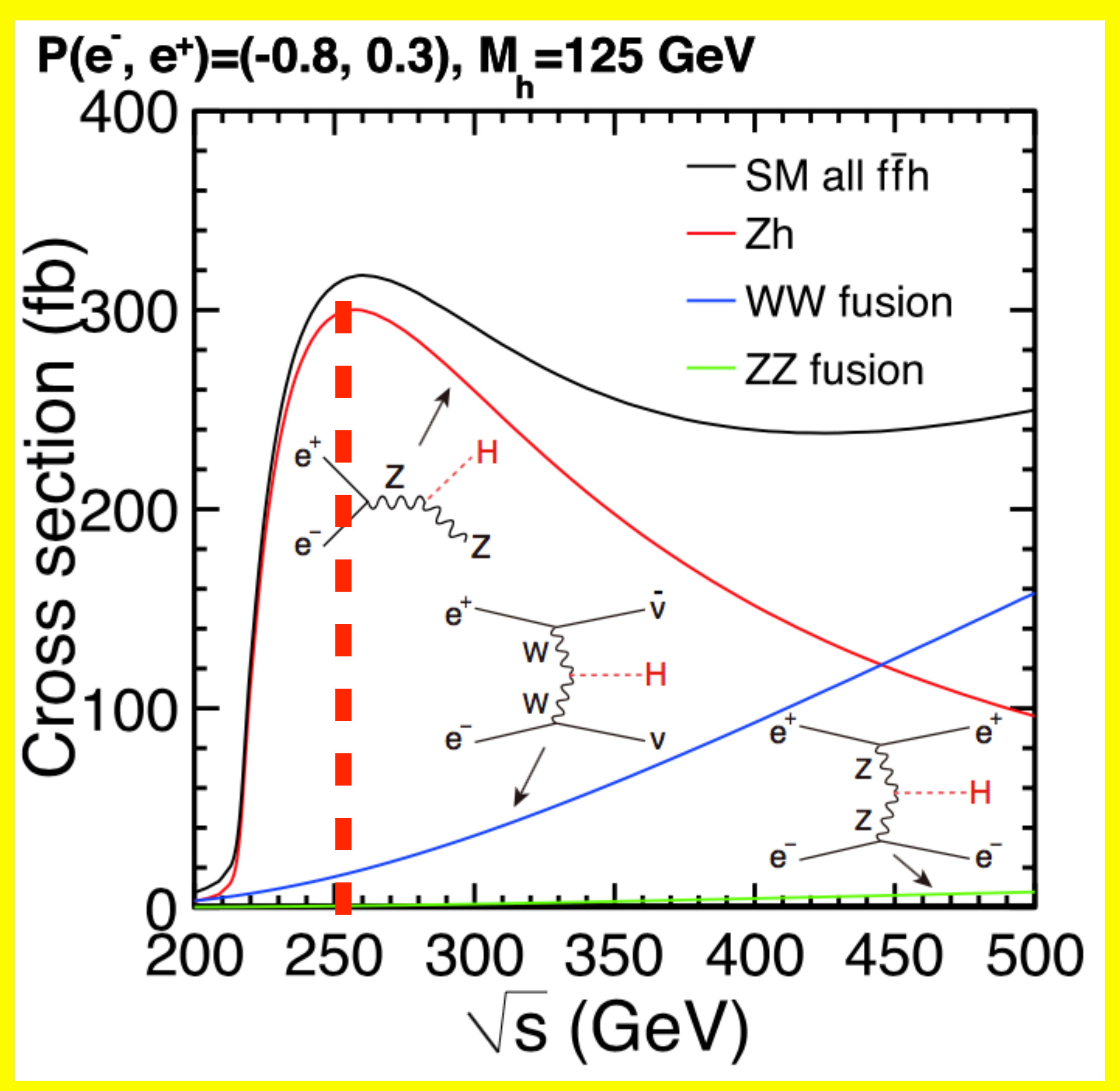

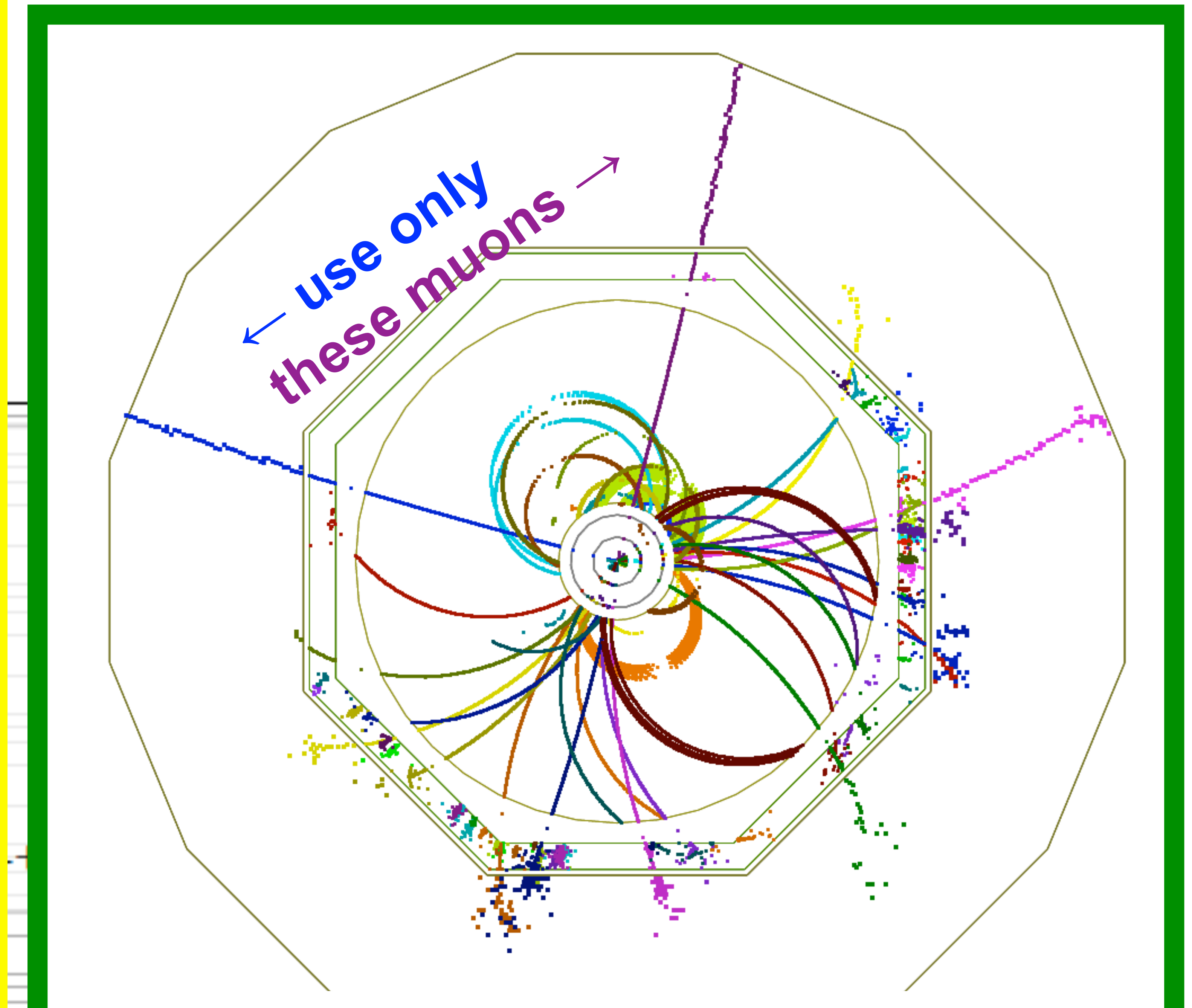

$e^+e^- \rightarrow \mu^+\mu^-H \rightarrow \mu^+\mu^-$ bb in ILD

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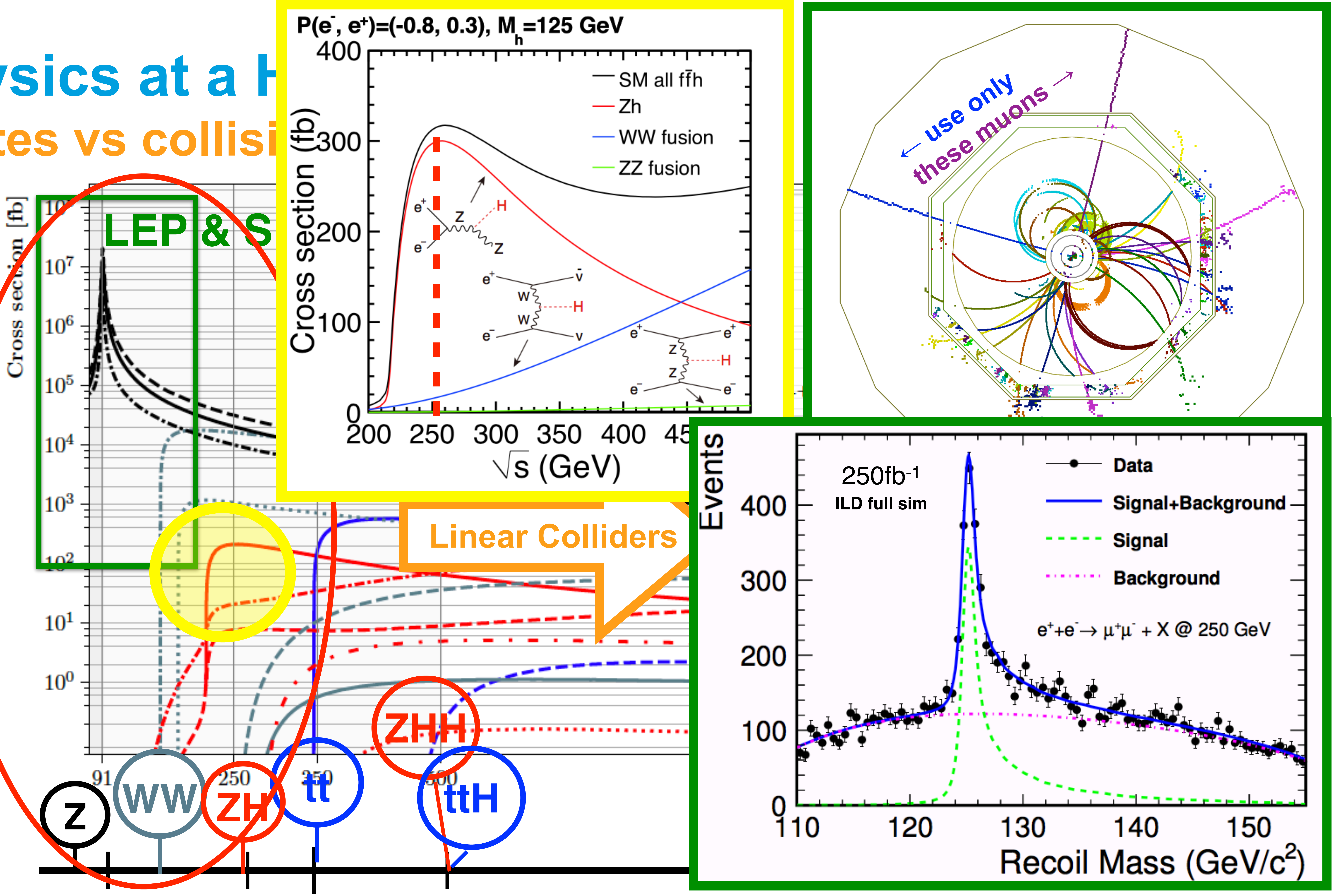

100 250 350 500 1000 E_{CM} / GeV

The key physics at a H…

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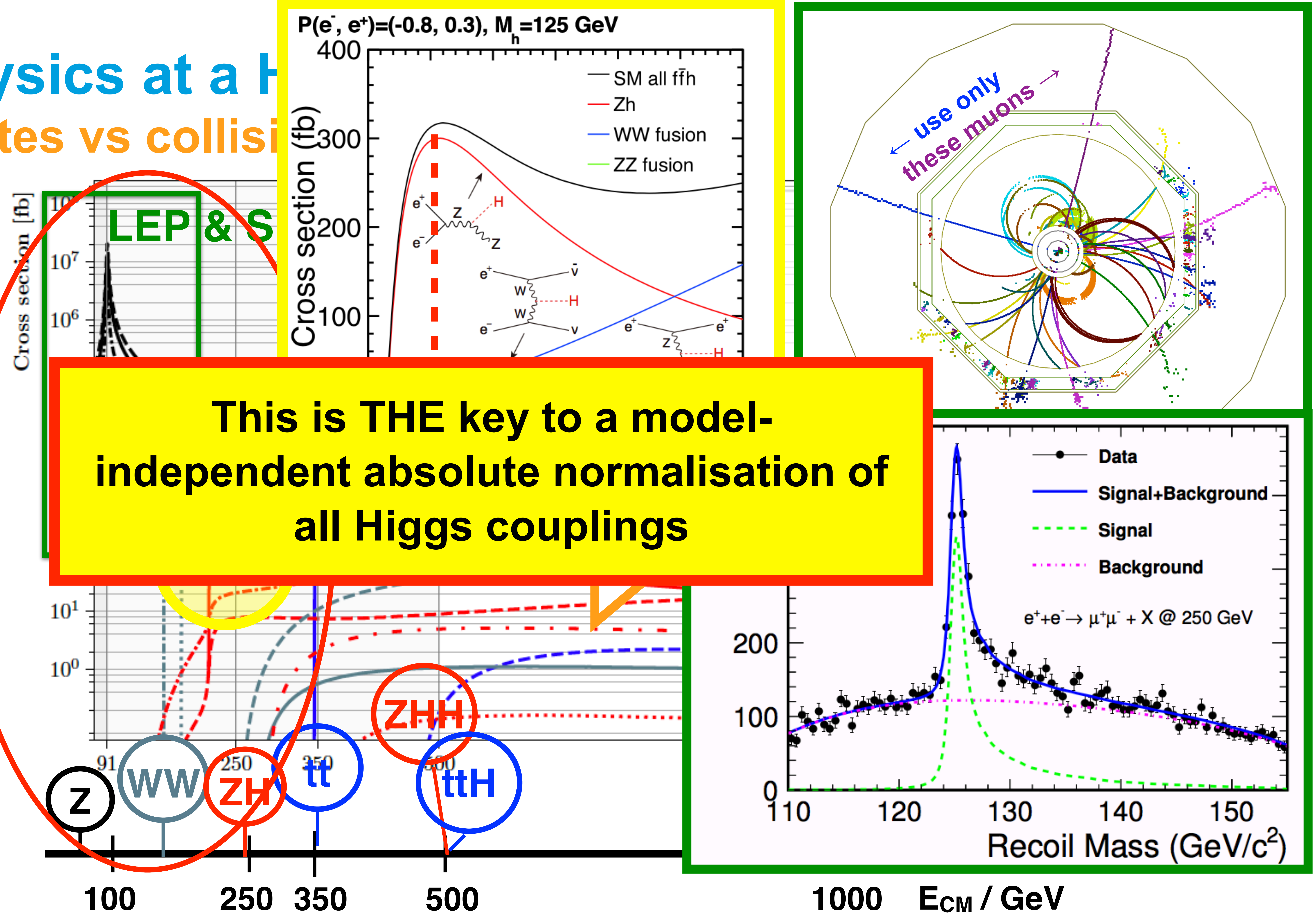
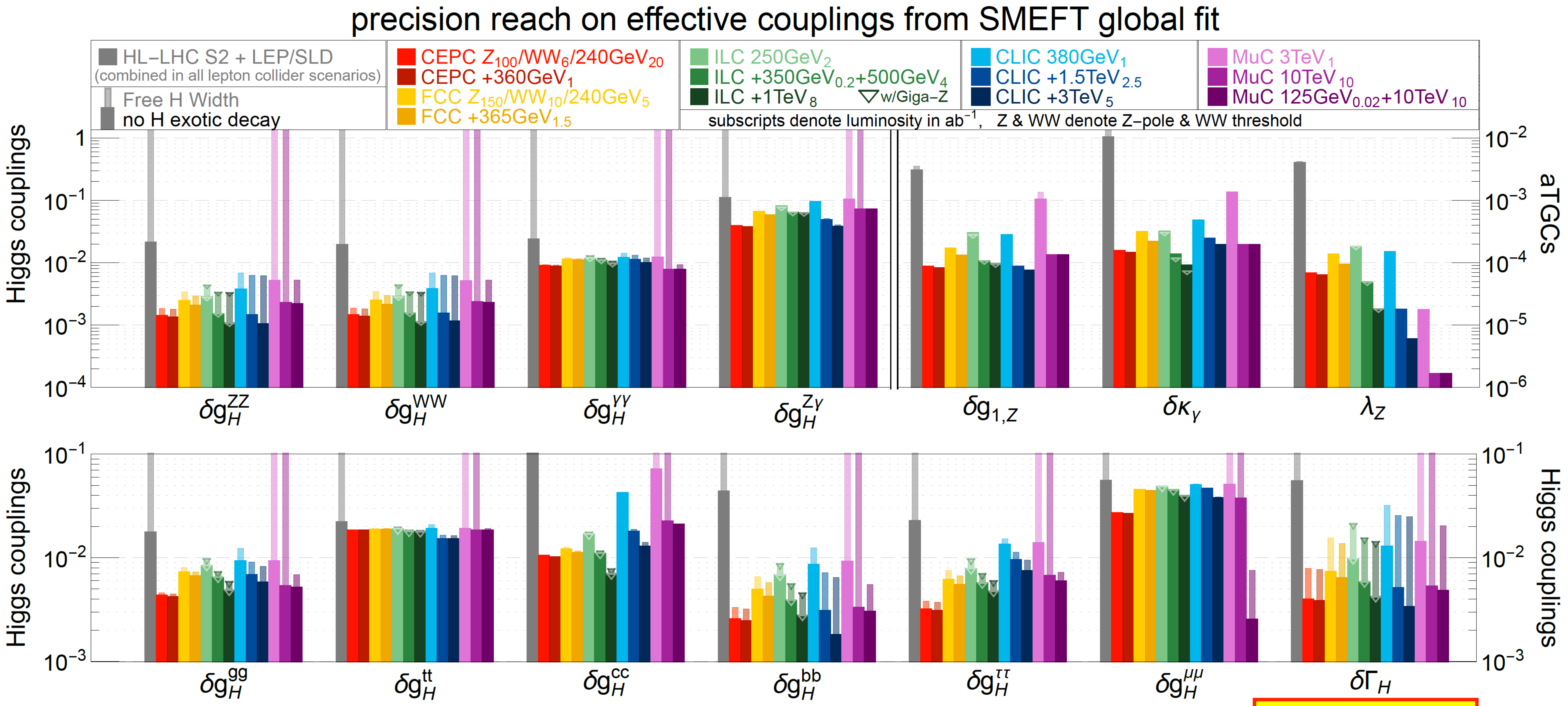


This is THE key to a model-independent absolute normalisation of all Higgs couplings

Higgs Couplings: The Snowmass SMEFT fit

Rainbow-Manhattans



arXiv:2206.08326

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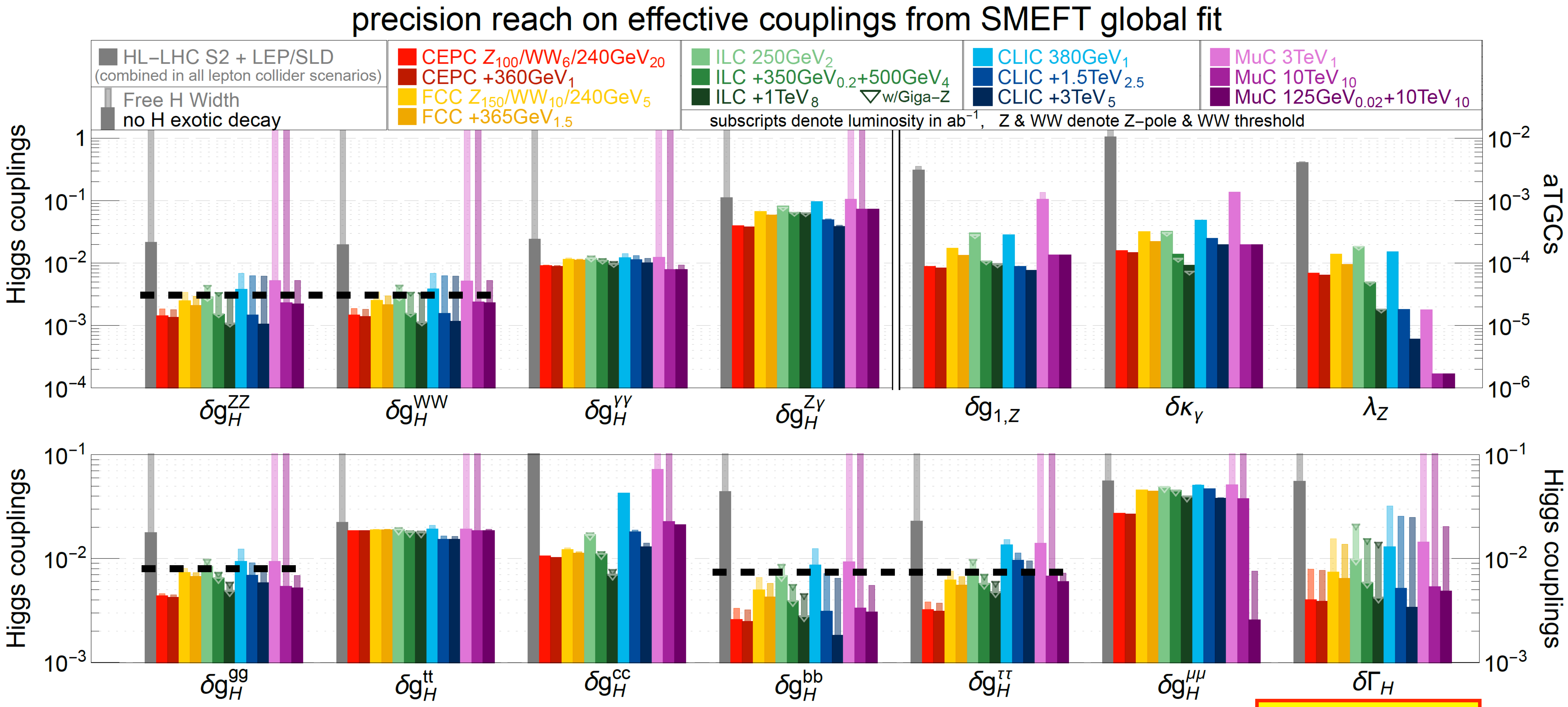

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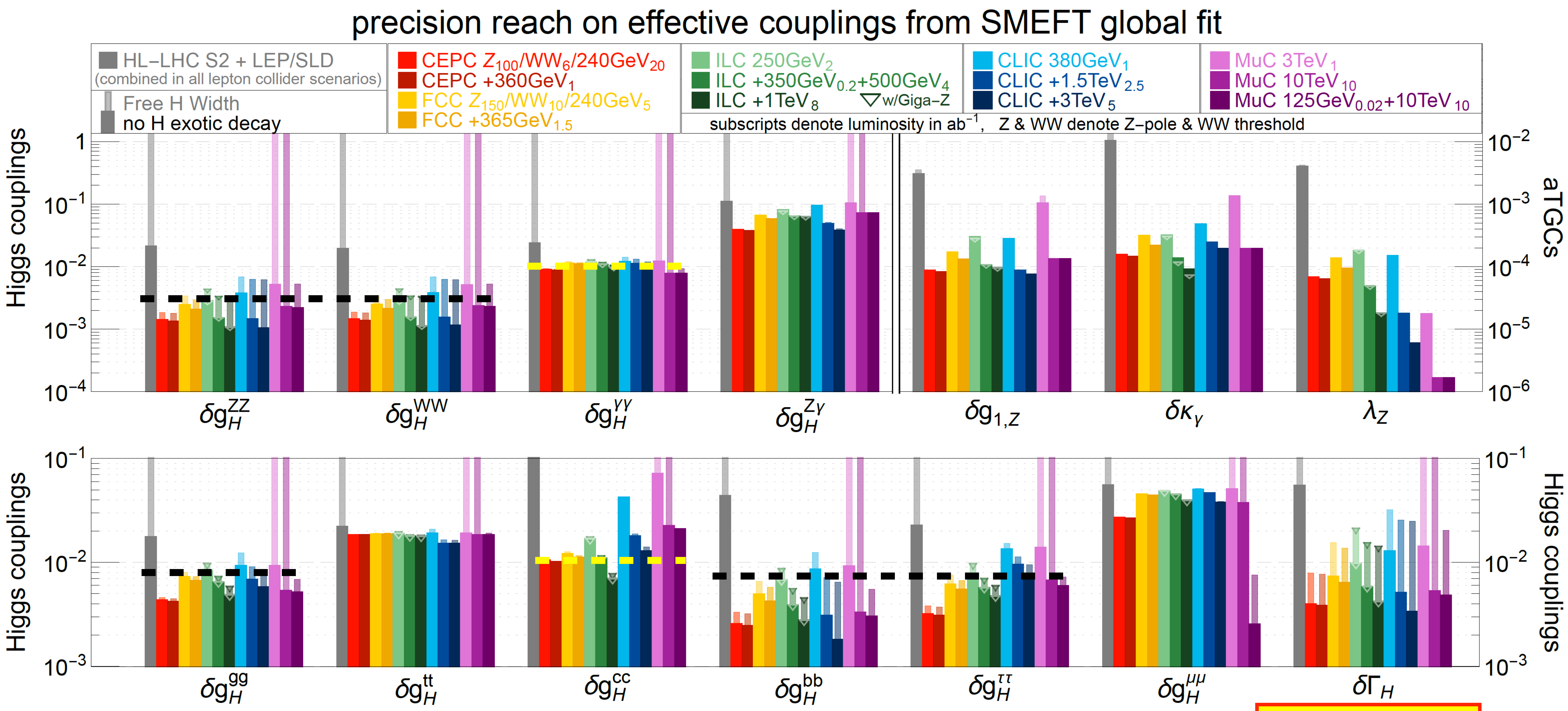

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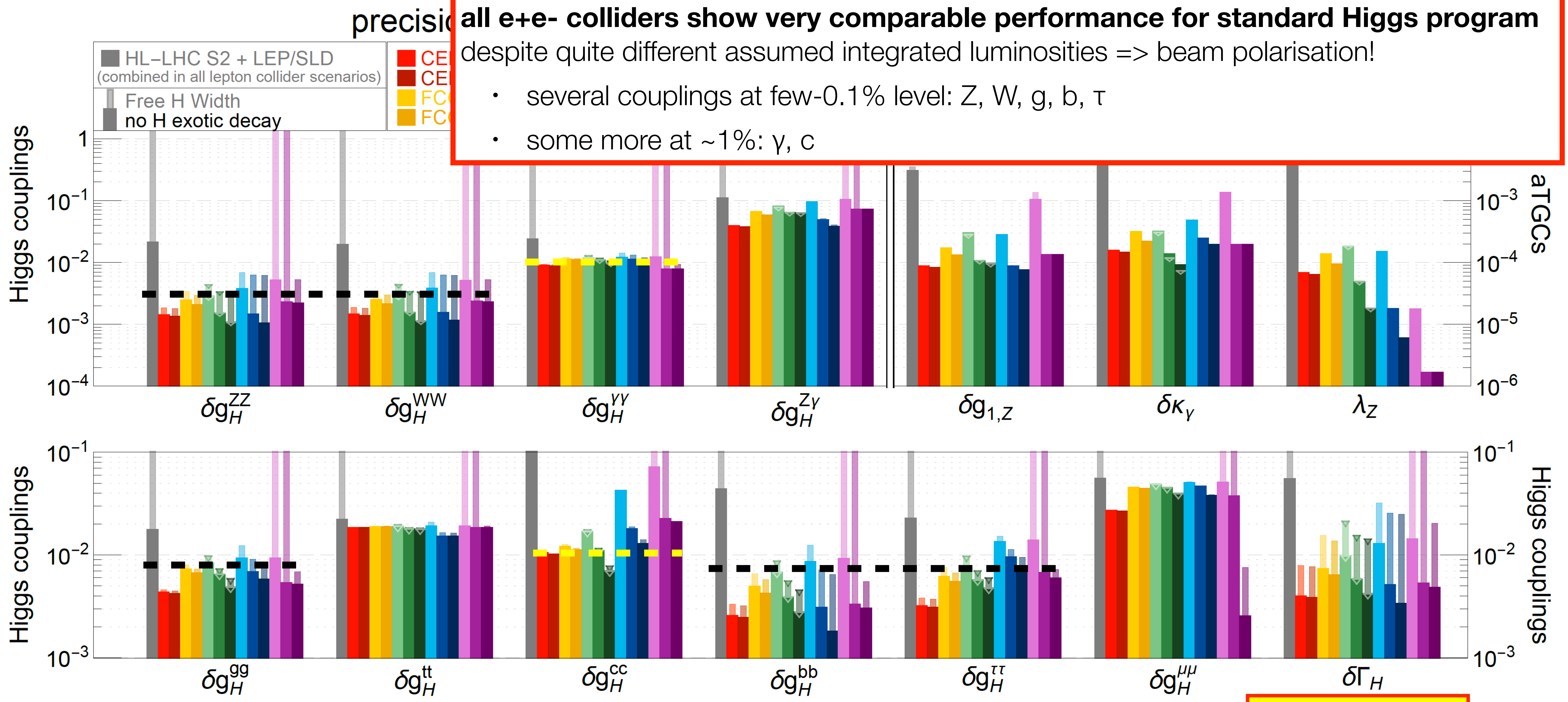

all e+e- colliders show very comparable performance for standard Higgs program
despite quite different assumed integrated luminosities => beam polarisation!

- several couplings at few-0.1% level: Z, W, g, b, τ
- some more at ~1%: γ, c

arXiv:2206.08326

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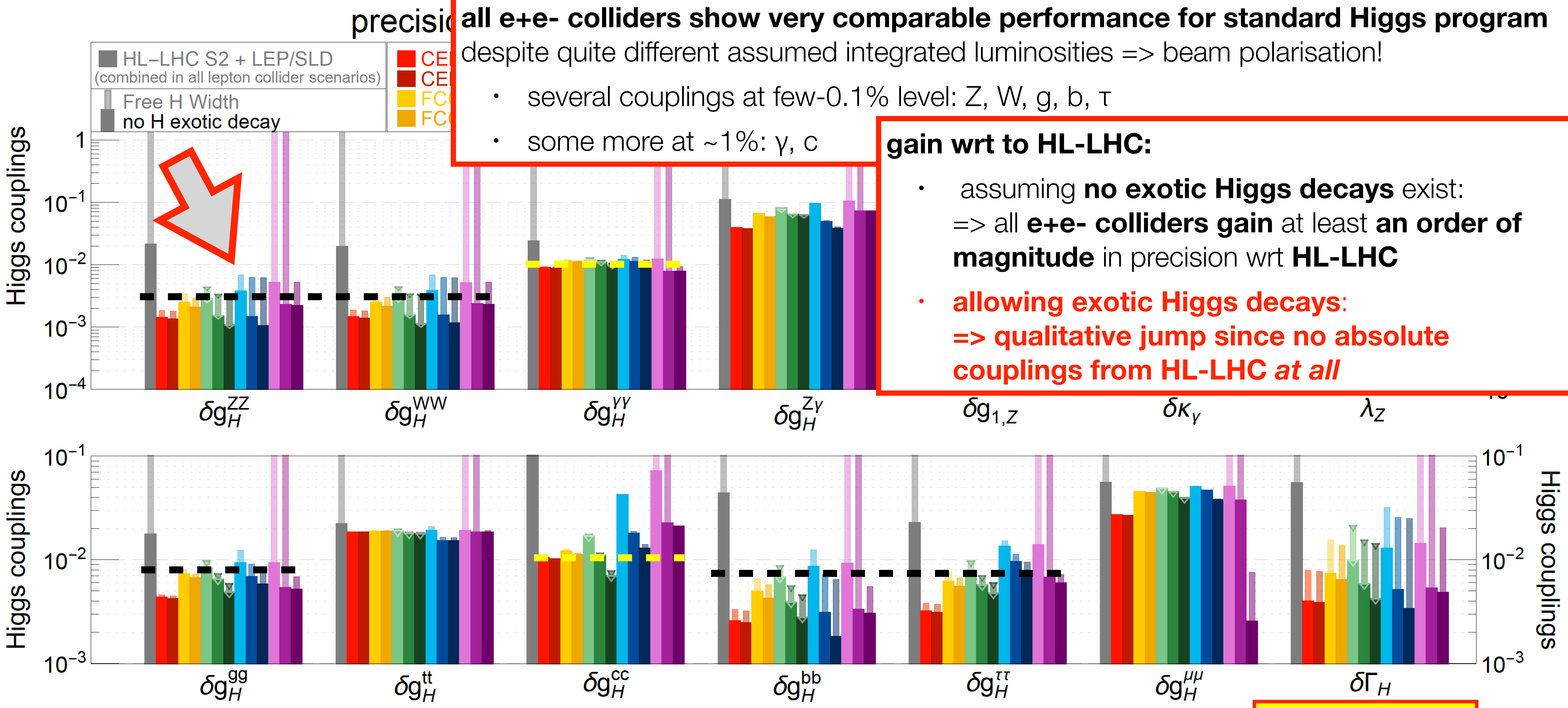

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gain wrt to HL-LHC:

- assuming **no exotic Higgs decays** exist: => all **e+e- colliders gain** at least **an order of magnitude** in precision wrt **HL-LHC**
- **allowing exotic Higgs decays**: **=> qualitative jump since no absolute couplings from HL-LHC *at all***

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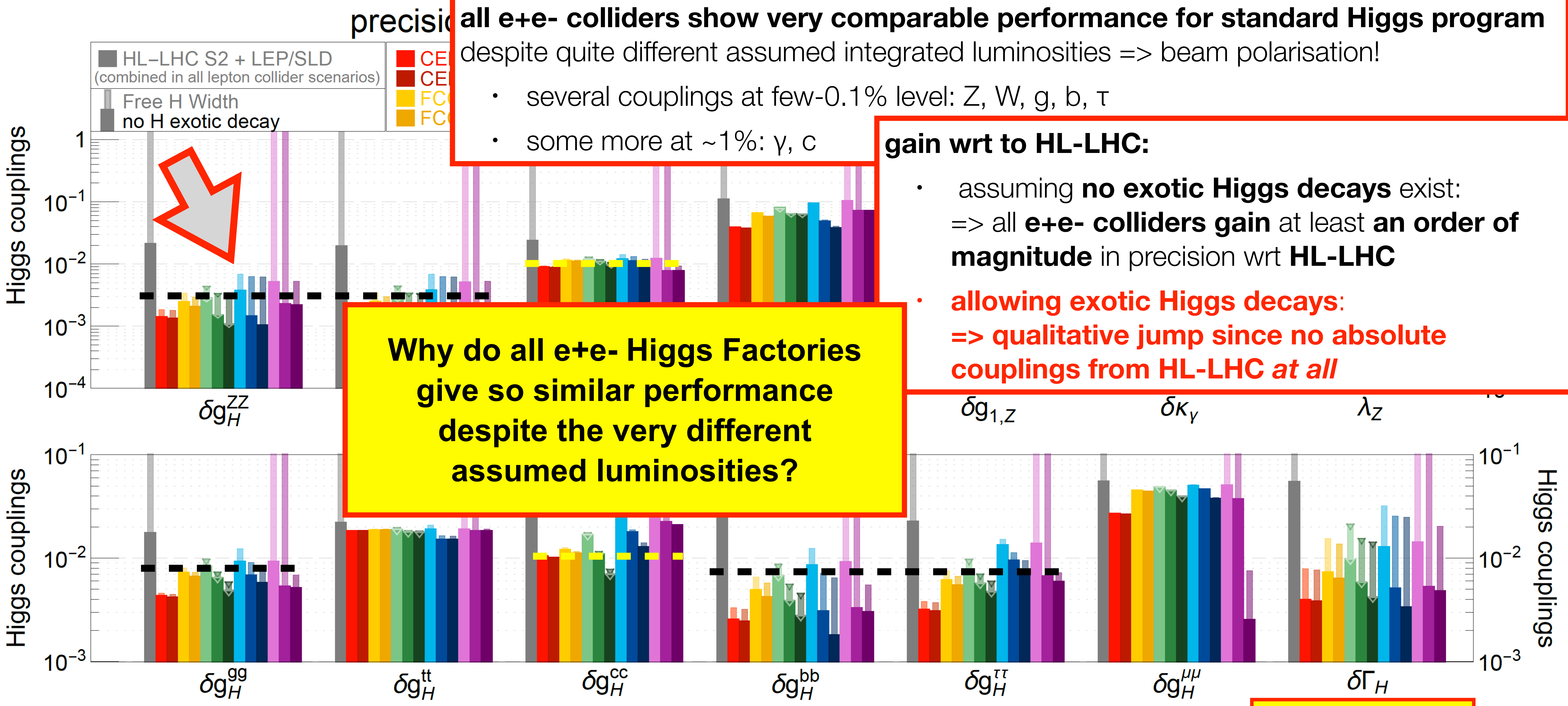

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Why do all e+e- Higgs Factories give so similar performance despite the very different assumed luminosities?

arXiv:2206.08326

Interlude: Chirality in Particle Physics

Just a quick reminder…

- Gauge group of weak x electromagnetic interaction: $SU(2)_L$ x U(1)
- L: left-handed, spin anti-|| momentum*
  R: right-handed, spin || momentum*
- **left-handed particles are fundamentally different from right-handed ones:**
  - only left-handed fermions (e^-) and right-handed anti-fermions (e^+) take part in the charged weak interaction, i.e. couple to the W bosons
  - there are (in the SM) no right-handed neutrinos
  - right-handed quarks and charged leptons are singlets under $SU(2)_L$
  - also couplings to the Z boson are different for left- and right-handed fermions
- **checking whether the differences between L and R are as predicted in the SM is a very sensitive test for new phenomena!**

$$P = \frac{N_R - N_L}{N_R + N_L}$$

* for massive particles, there is of course a difference between chirality and helicity, no time for this today, ask at the end in case of doubt!

Physics benefits of polarised beams

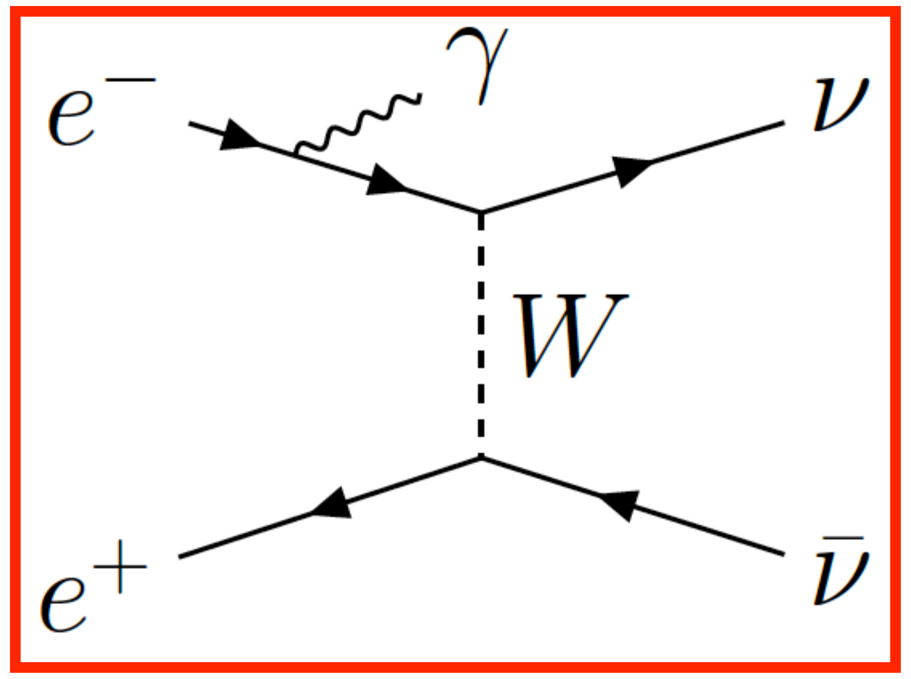
Much more than statistics!

General references on polarised e+e- physics:

- **arXiv:1801.02840**
- **Phys. Rept. 460 (2008) 131-243**

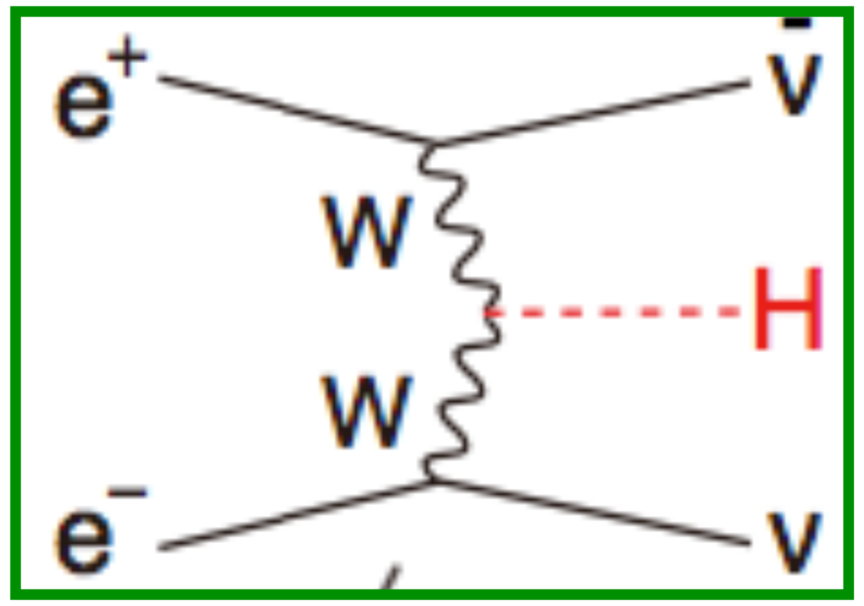
background suppression:

- $e^+e^- \to WW$ / $\nu_e\nu_e$ strongly P-dependent since t-channel only for $e^-_L e^+_R$



signal enhancement:

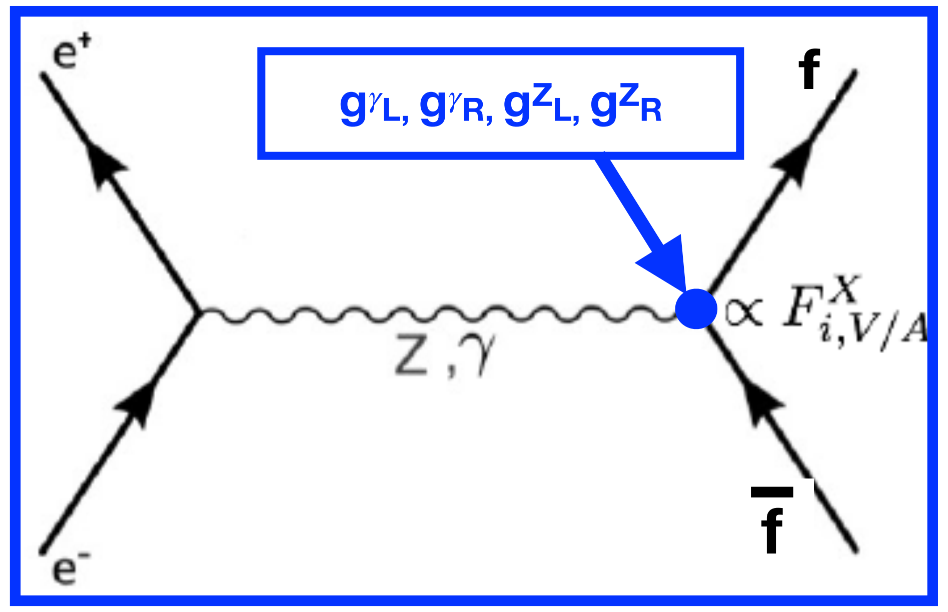
- Higgs production in WW fusion
- many BSM processes



have strong polarisation dependence => higher S/B

chiral analysis:

- SM: Z and γ differ in couplings to left- and right-handed fermions



- BSM:
chiral structure unknown, needs to be determined!

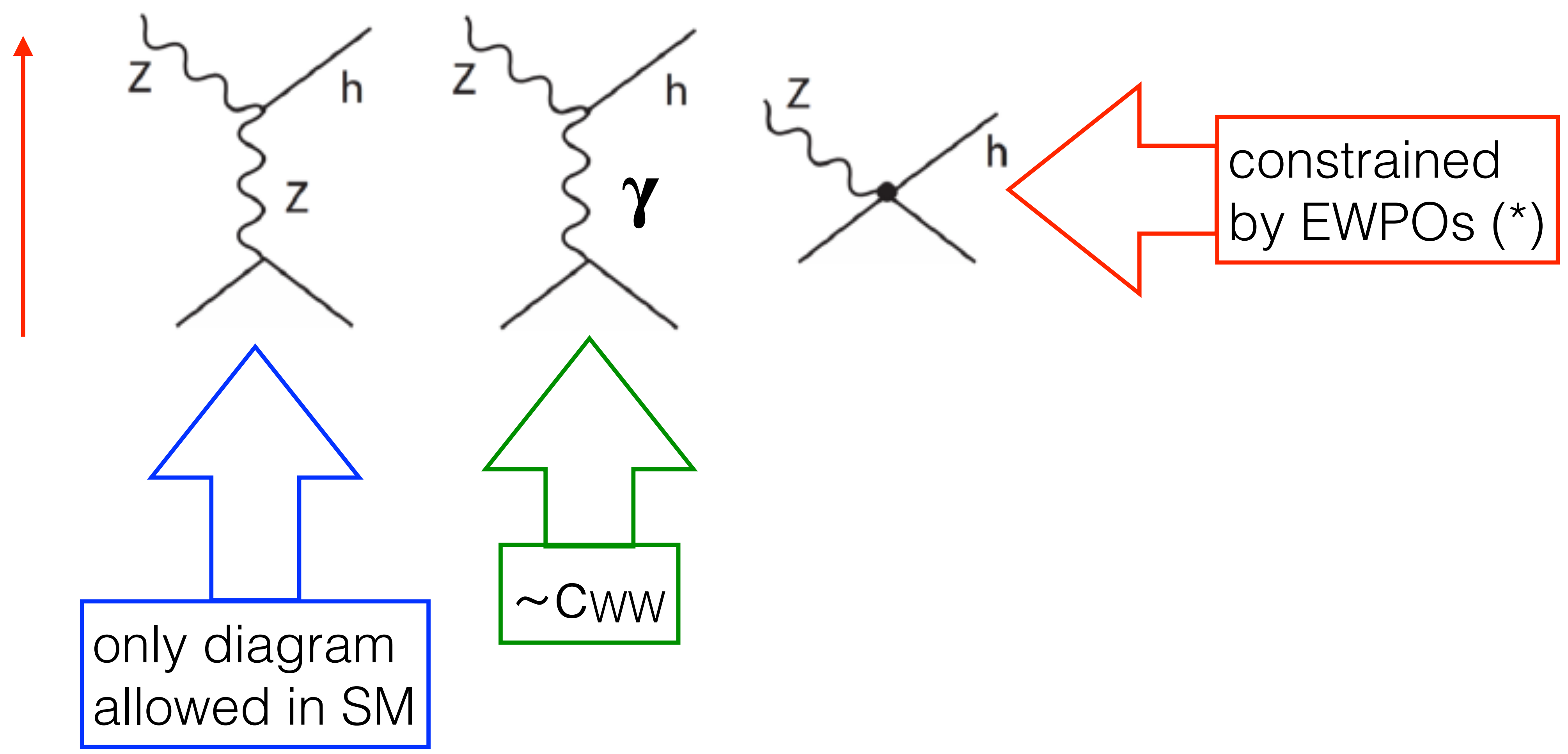
redundancy & control of systematics:

- “wrong” polarisation yields “signal-free” control sample
- flipping *positron* polarisation controls nuisance effects on observables relying on *electron* polarisation
- essential: fast helicity reversal for *both* beams!

Polarisation & Higgs Couplings

A relationship only appreciated a few years ago…

- **THE key process** at a Higgs factory: **Higgsstrahlung $e^+e^- \to Zh$**
- **A_{LR}** of Higgsstrahlung: very important to **disentangle** different **SMEFT operators!**



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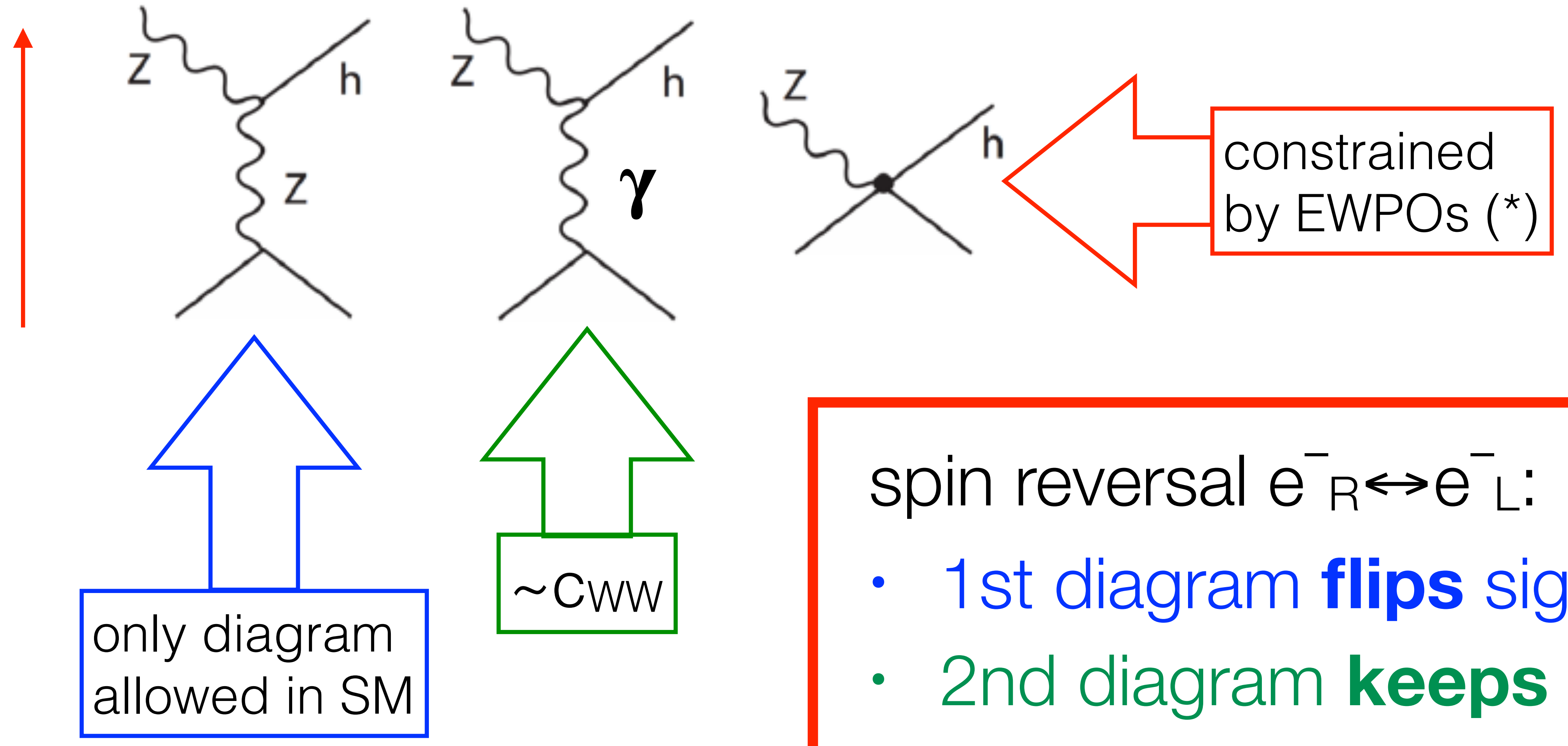

spin reversal $e^-_R \leftrightarrow e^-_L$:

- 1st diagram **flips** sign
- 2nd diagram **keeps** sign

⇒ A_{LR} lifts degeneracy between operators!

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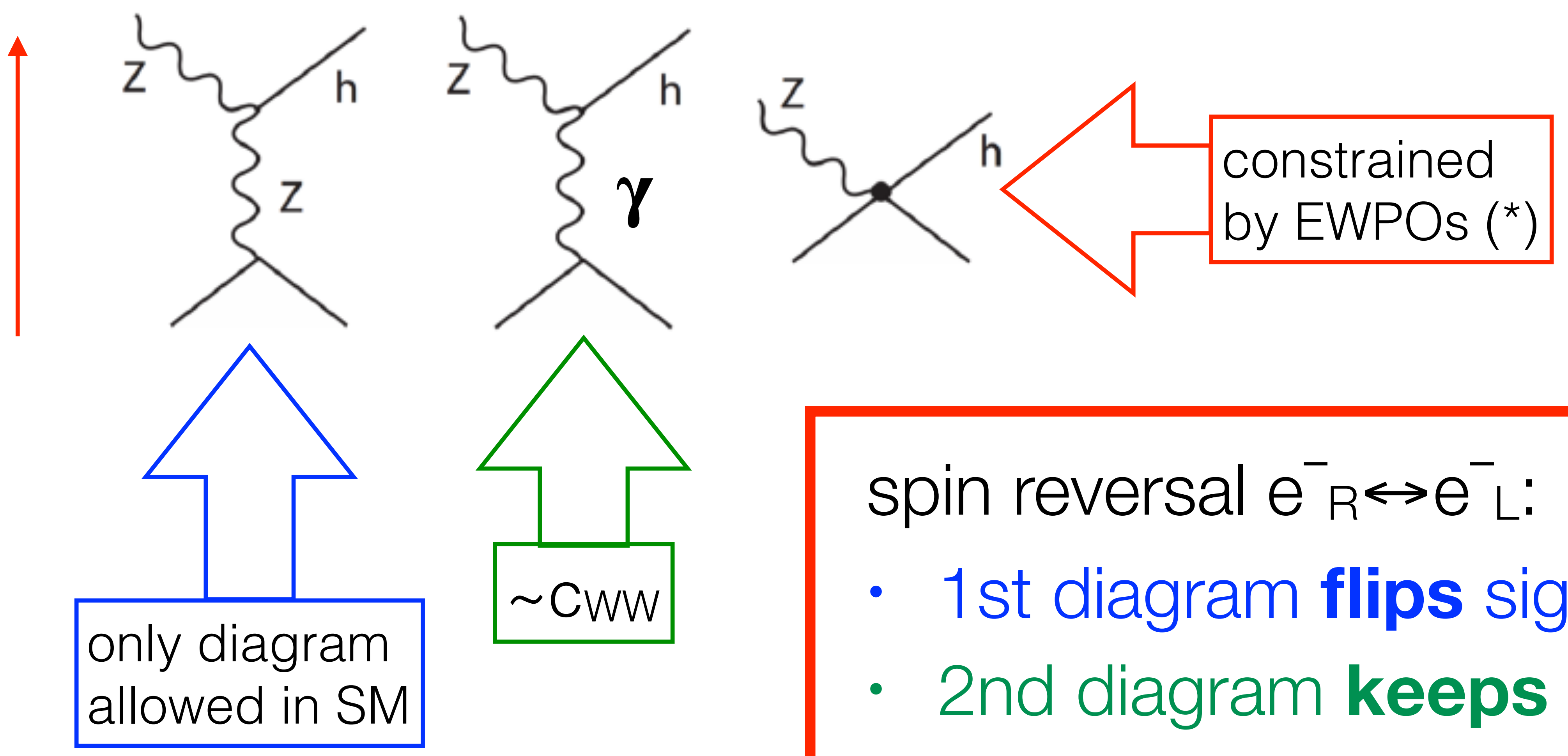

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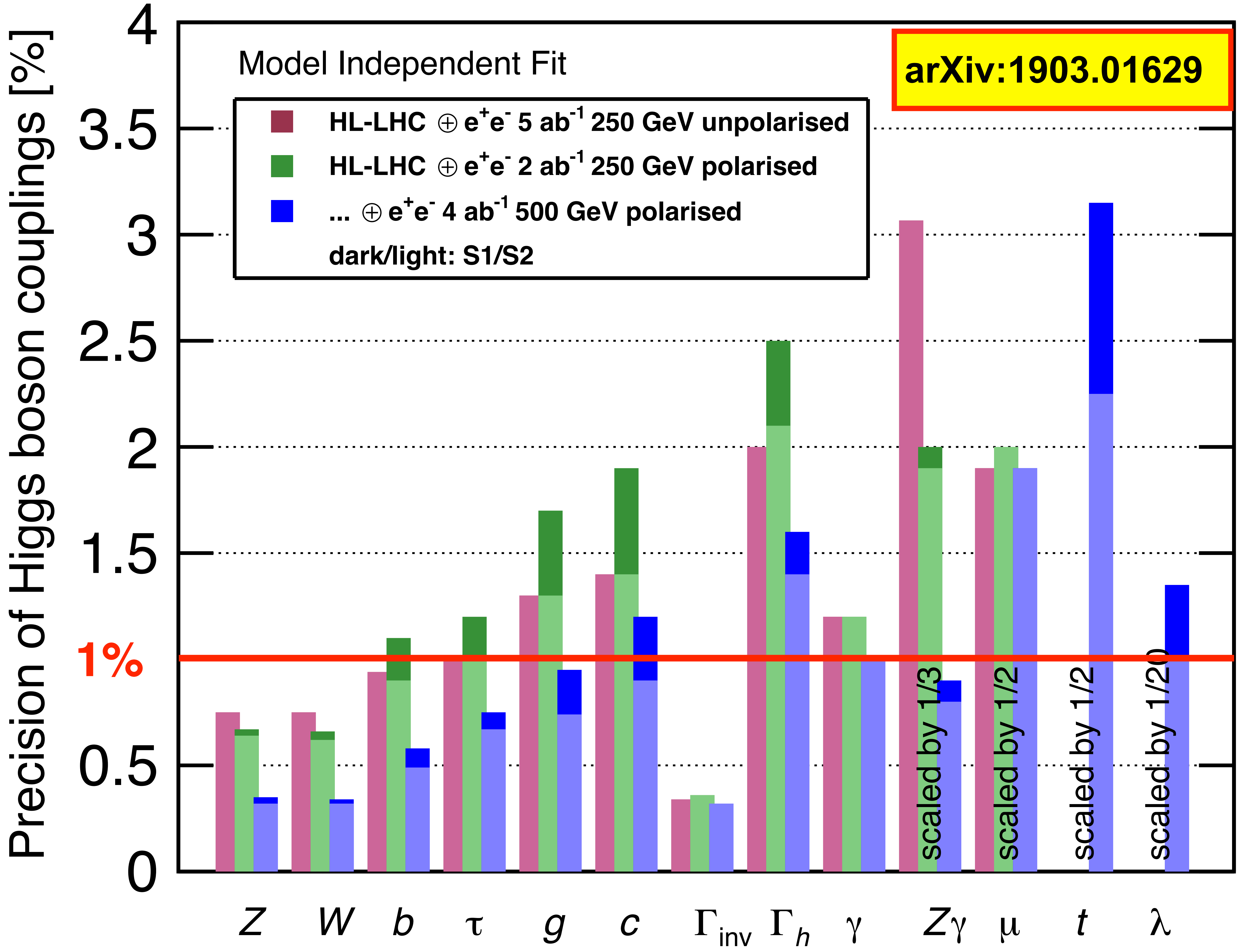

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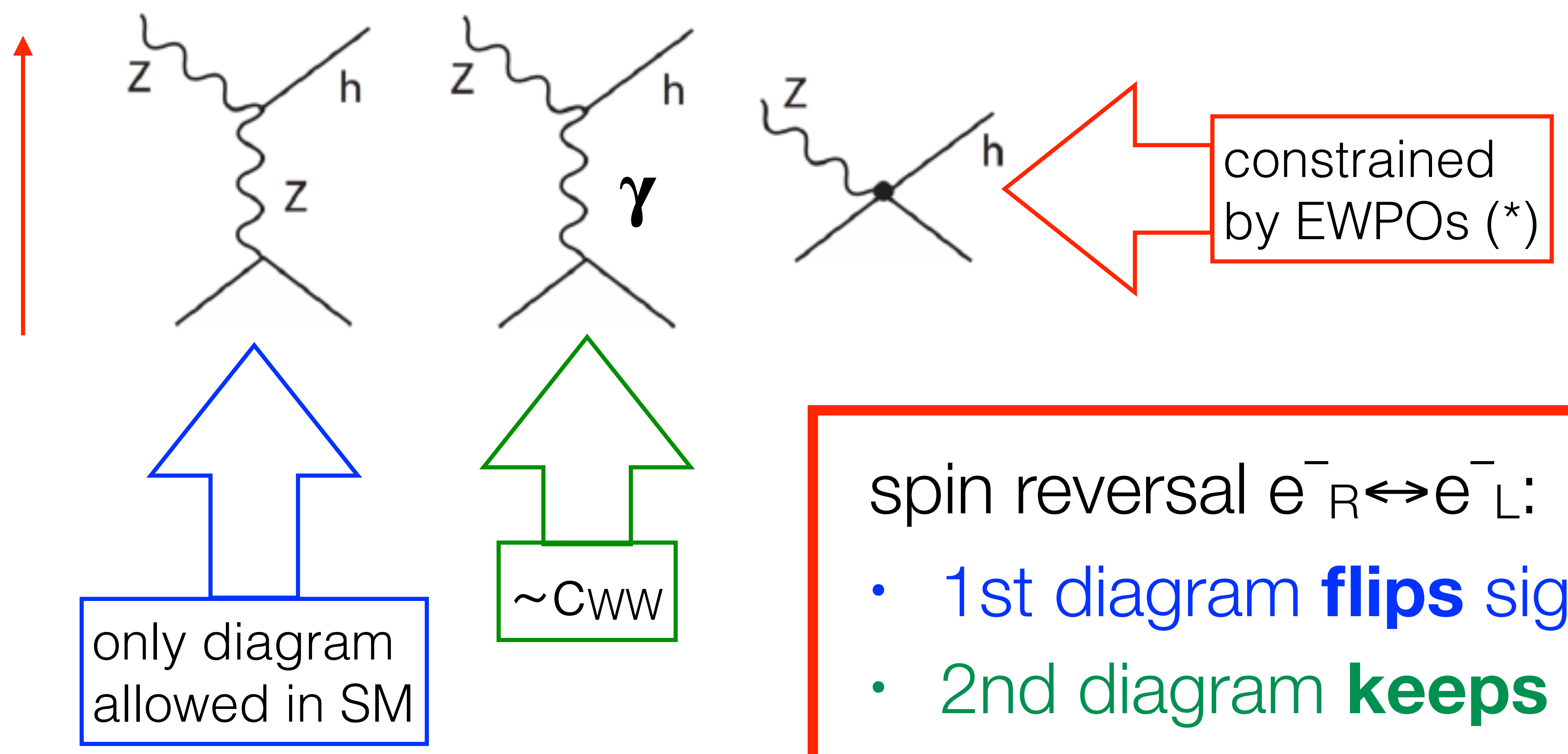

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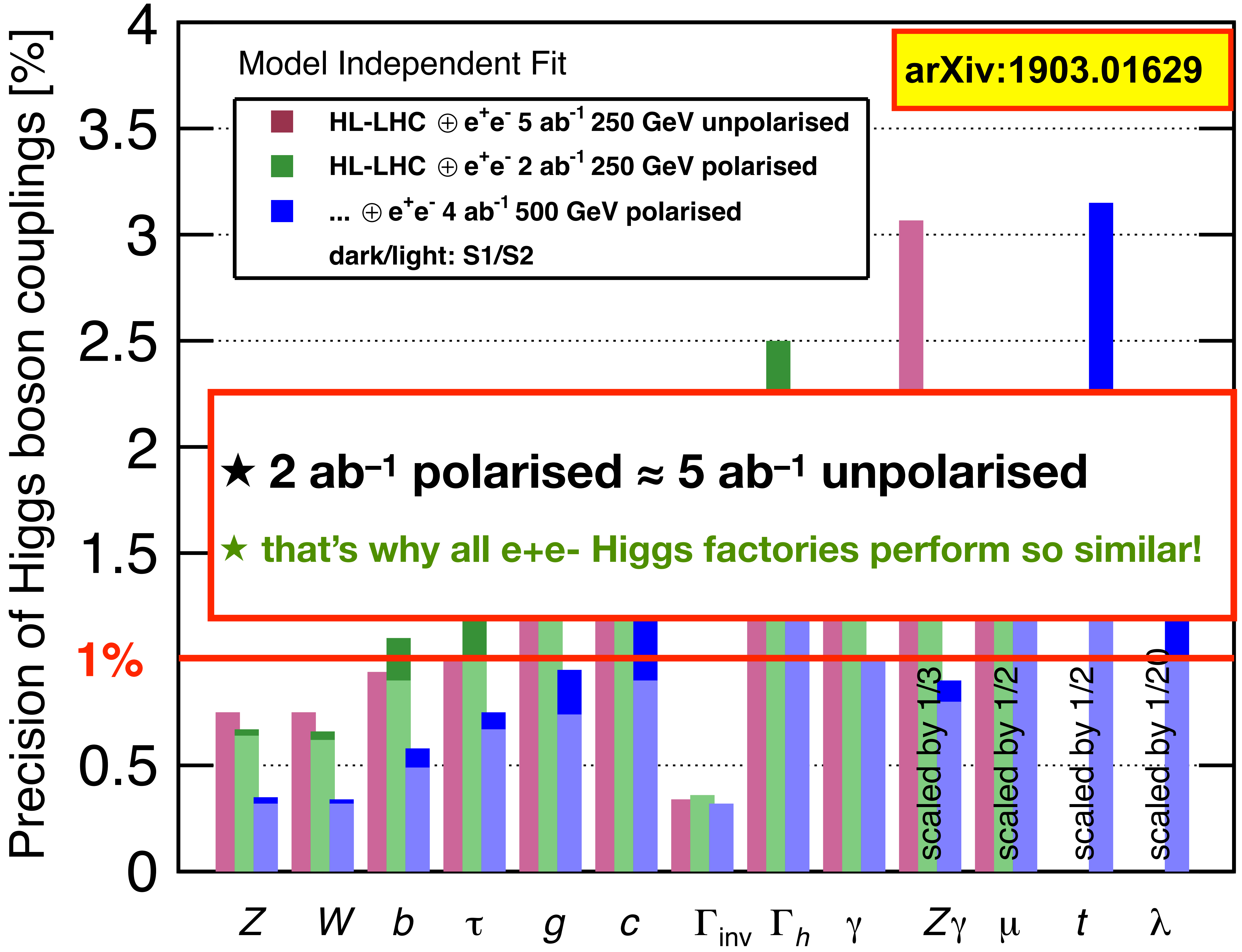
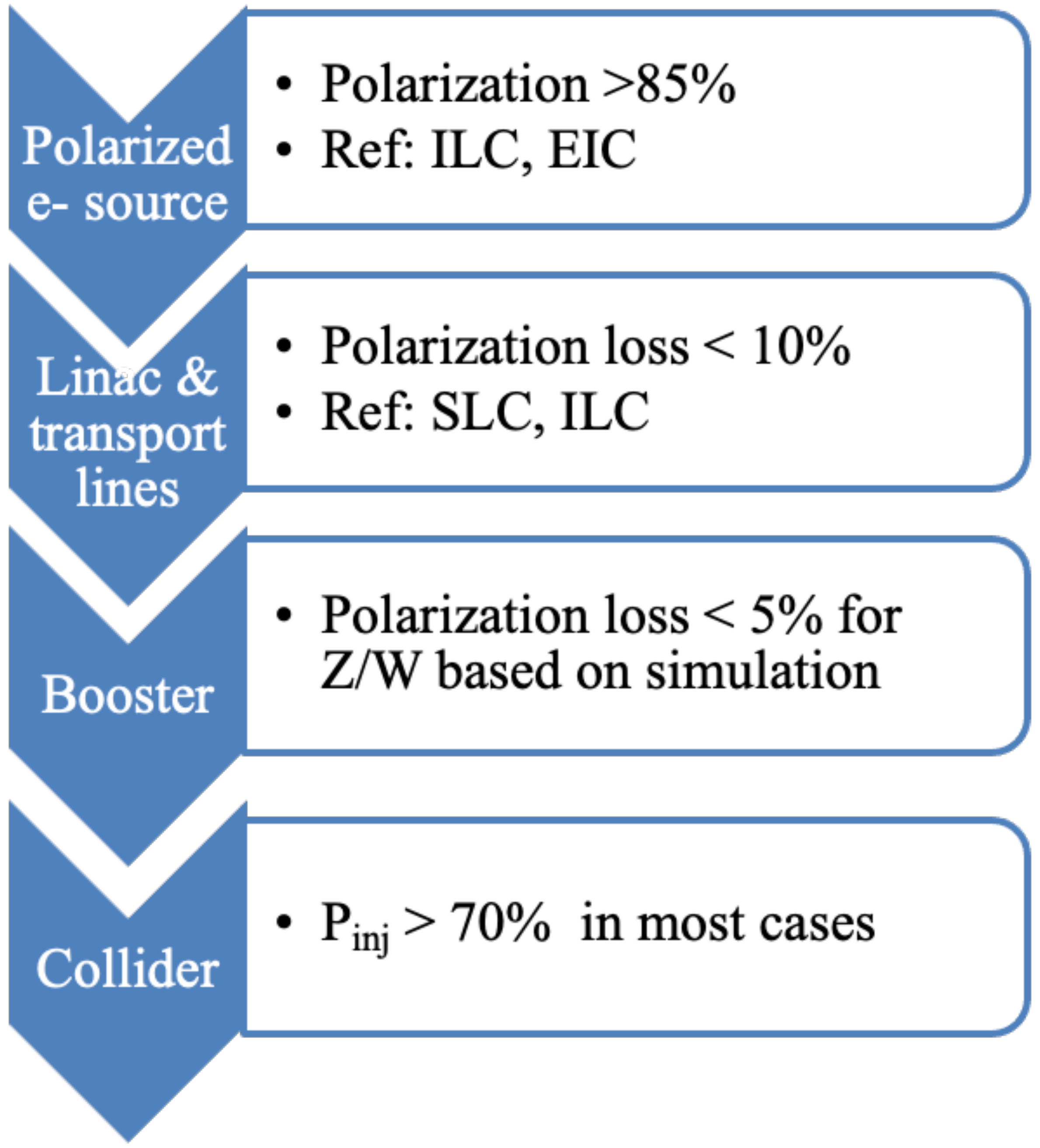
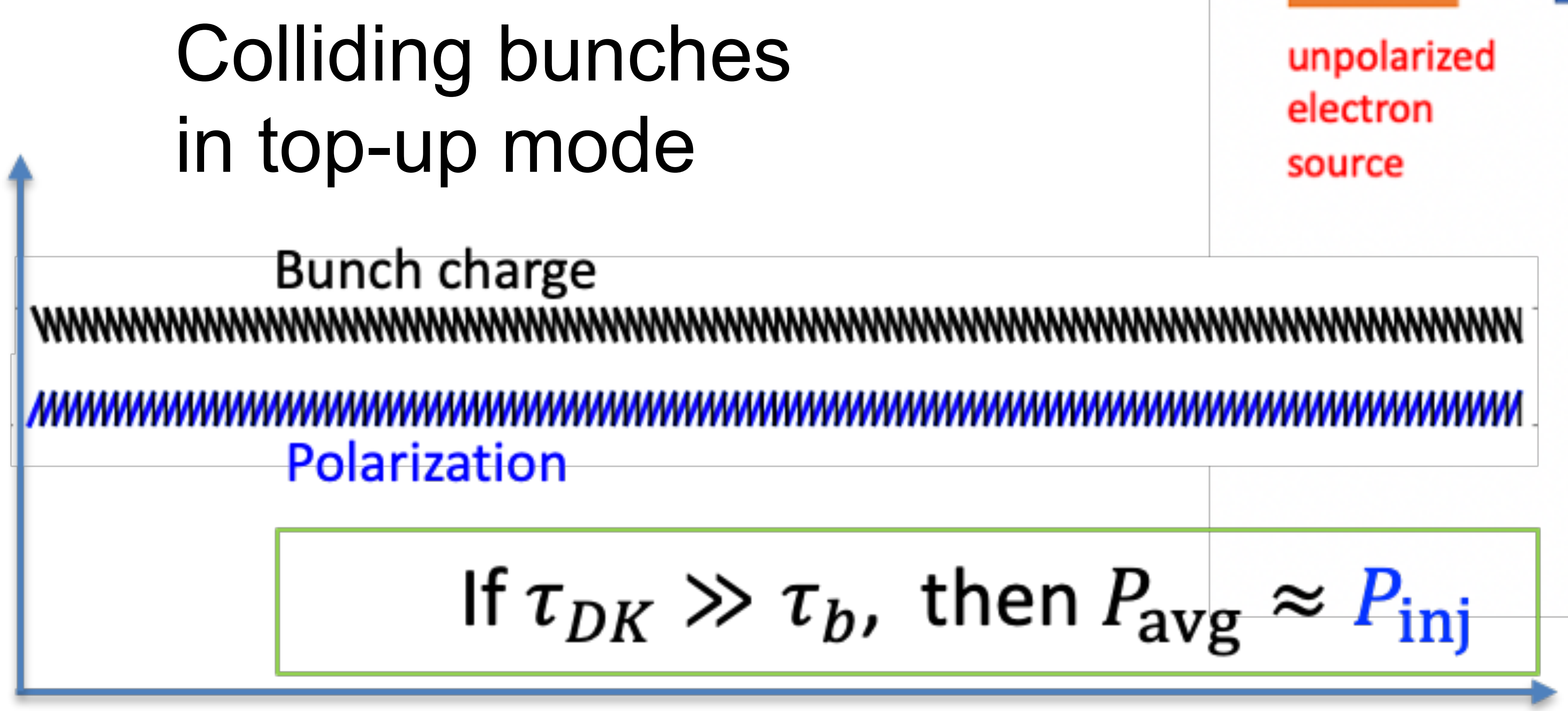


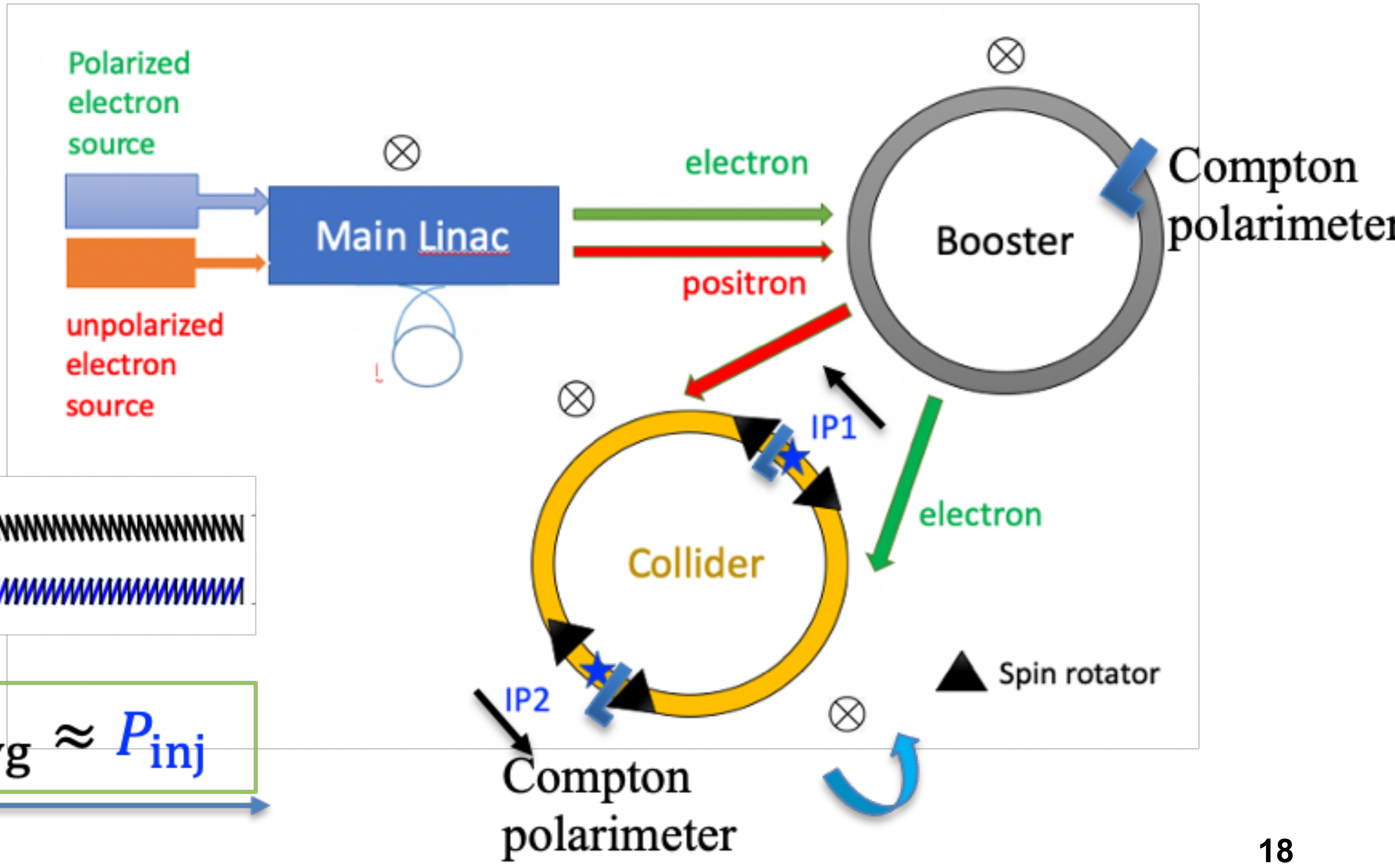
Polarisation for CEPC

Longitudinal polarization for physics?

- so far CCs considered transverse polarisation of non-colliding pilot bunches for energy calibration
- **CEPC: simulations support average polarization > 50% for colliding bunches in Z and W runs**
- currently only e- , could use same scheme for e+ once a polarized e+ source meets specs
- next: integration of spin rotators and polarimeters into lattice







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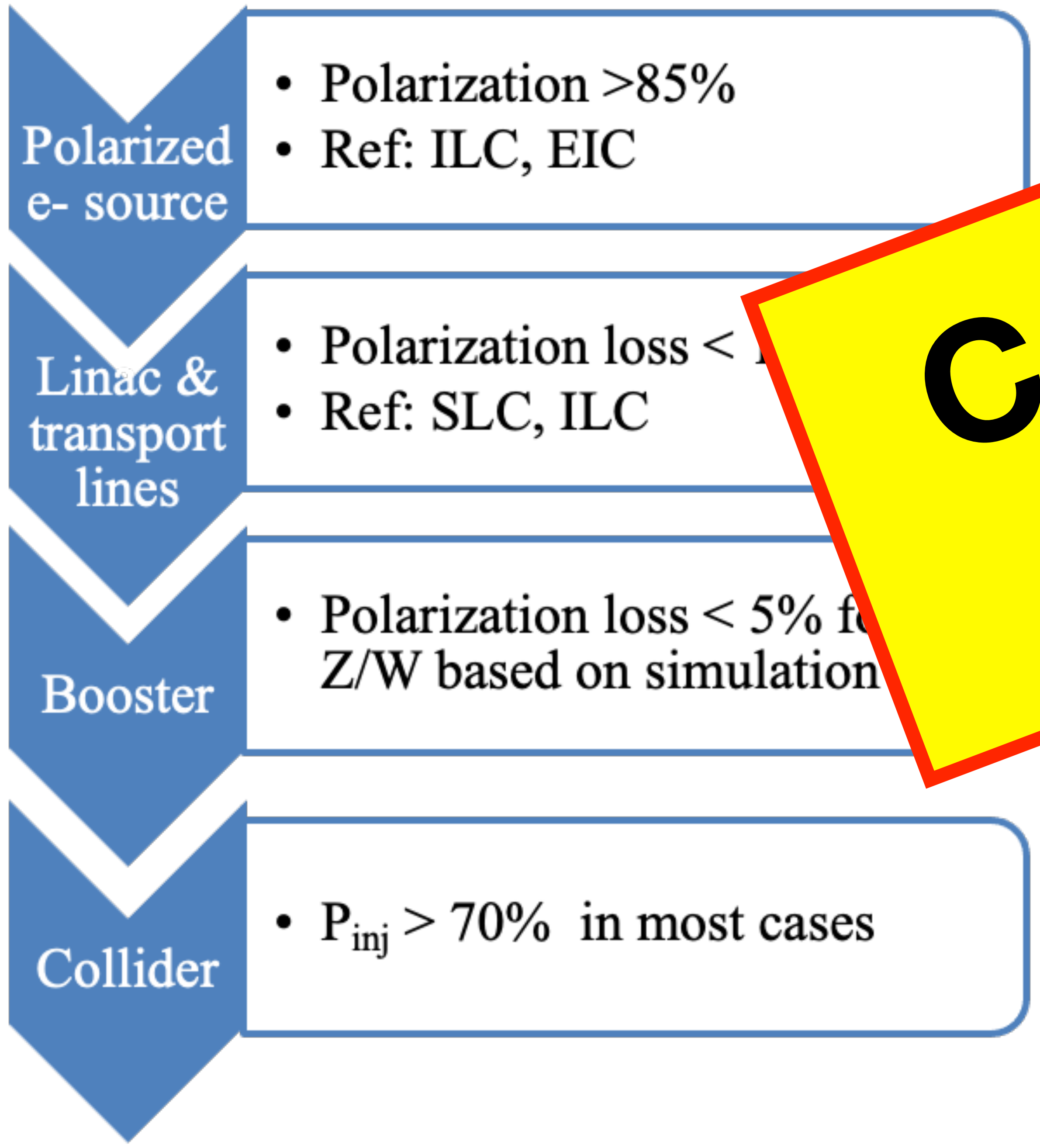
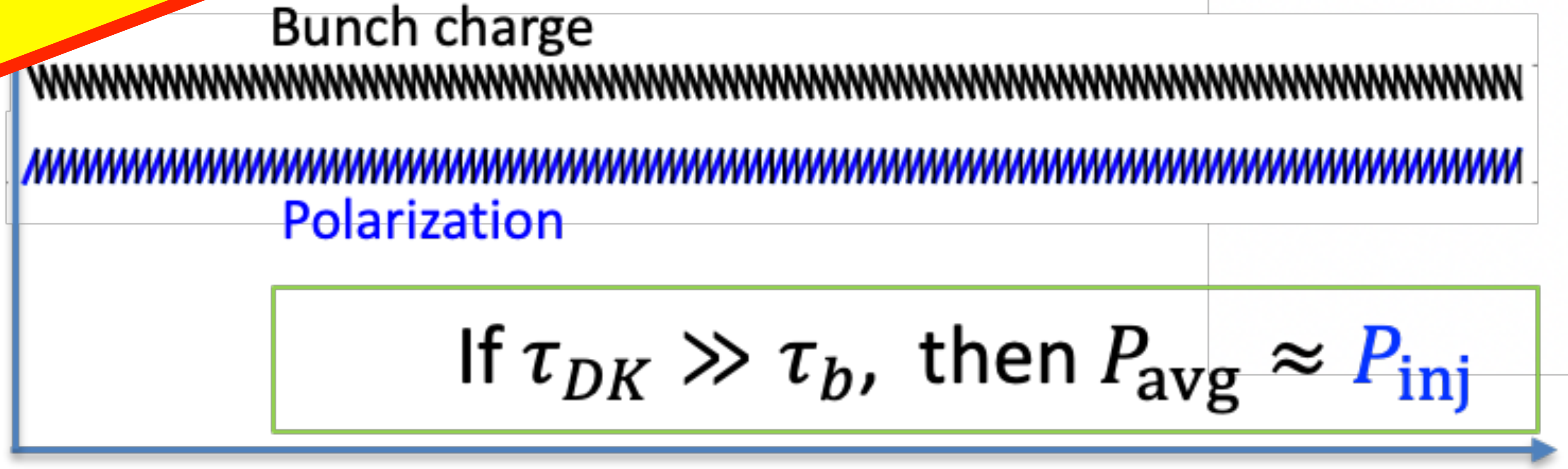
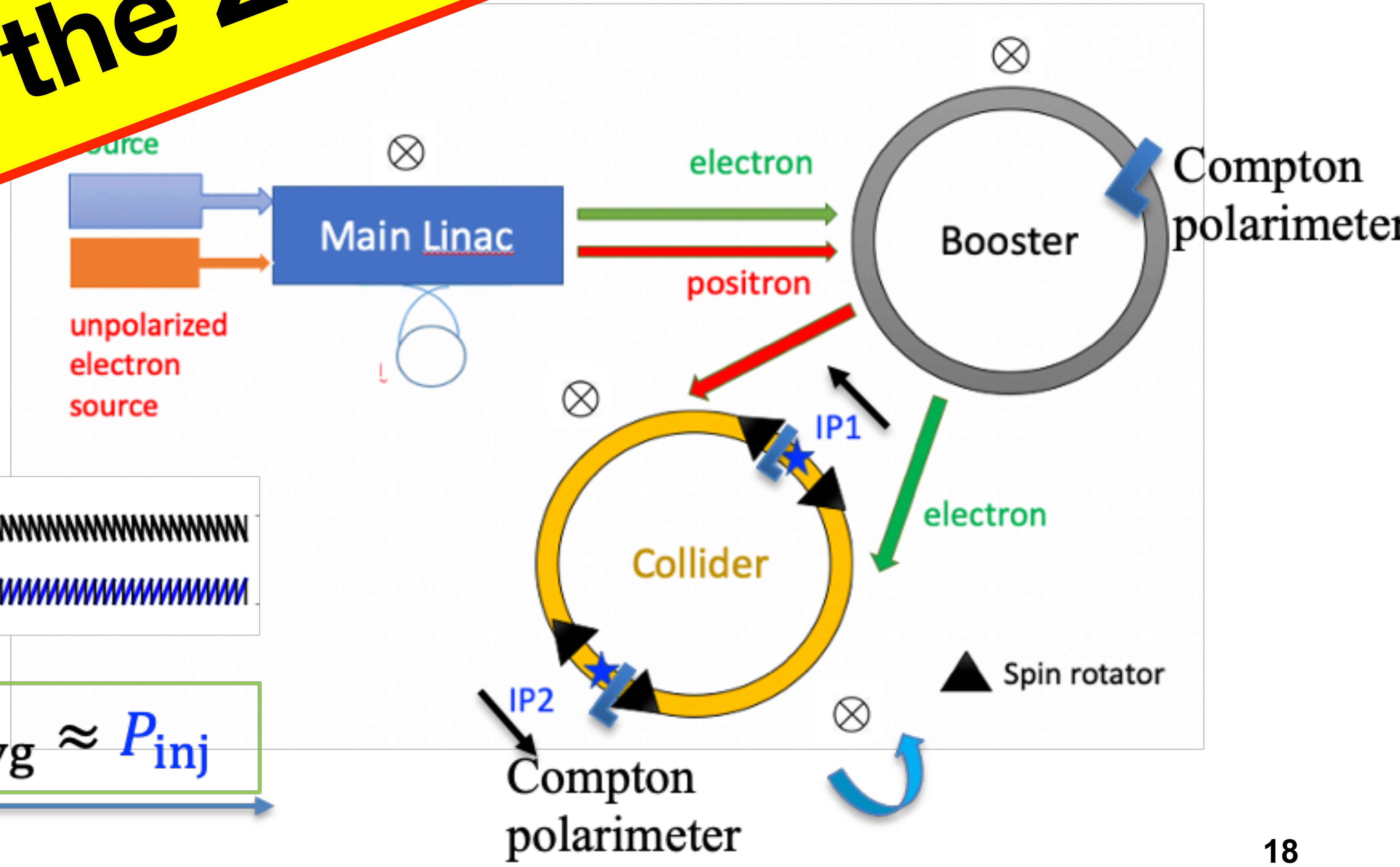
Could this work also at FCC-ee ?
And what about the ZH run?

...nes
...p mode







Why do we need to know the couplings of the Higgs boson?

Discovering new phenomena

- Any deviation from the SM prediction is a discovery of a new phenomenon
- Higgs couplings allow finger-printing new phenomena via their different *patterns* of deviations
- *size* of deviations depends on energy scale of new particles:
  the more precise the measurement, the larger the discovery potential
- need at least 1%-level of precision for Higgs couplings
- **all proposed Higgs factories can deliver this program - (HL-)LHC cannot do this**

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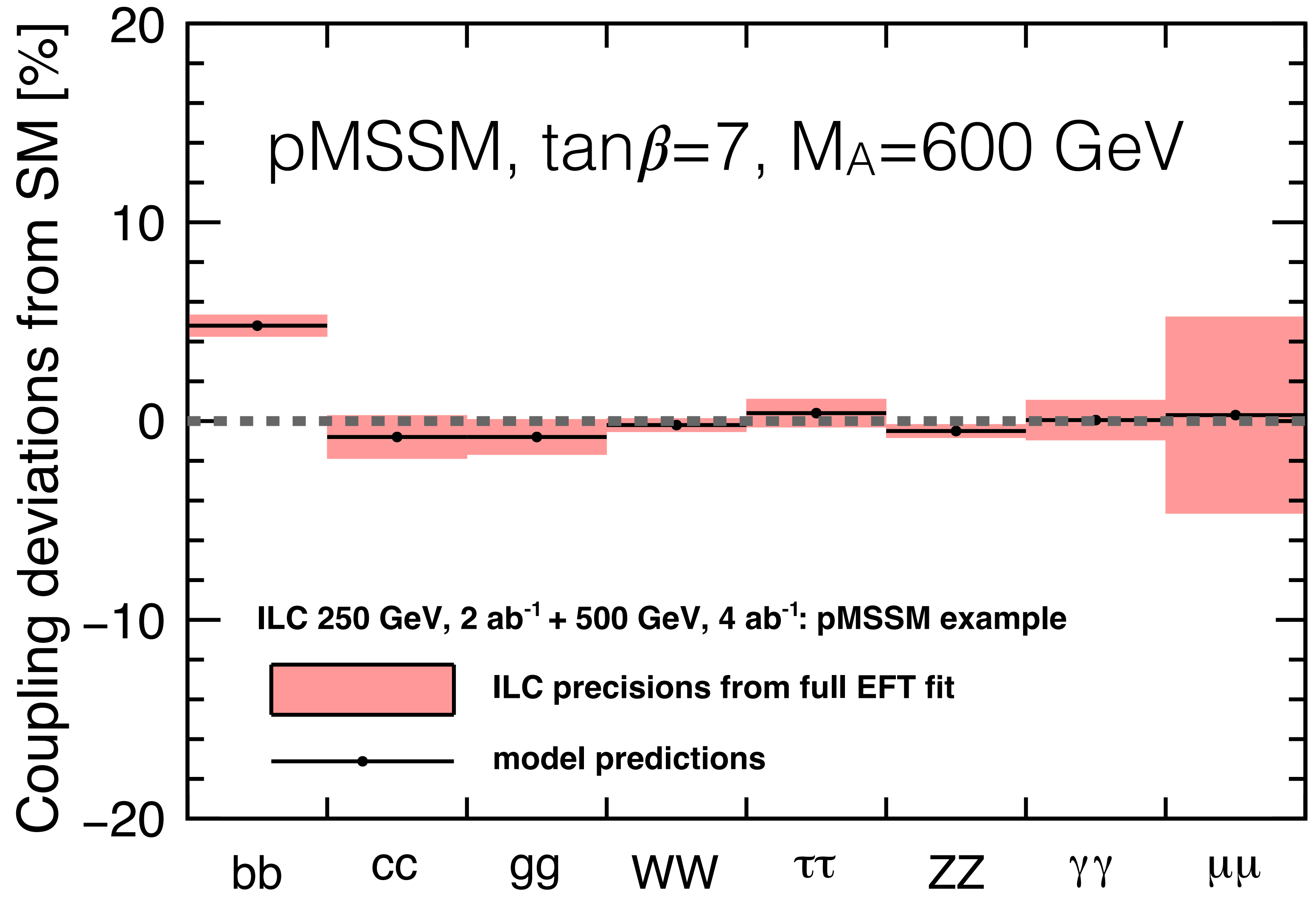

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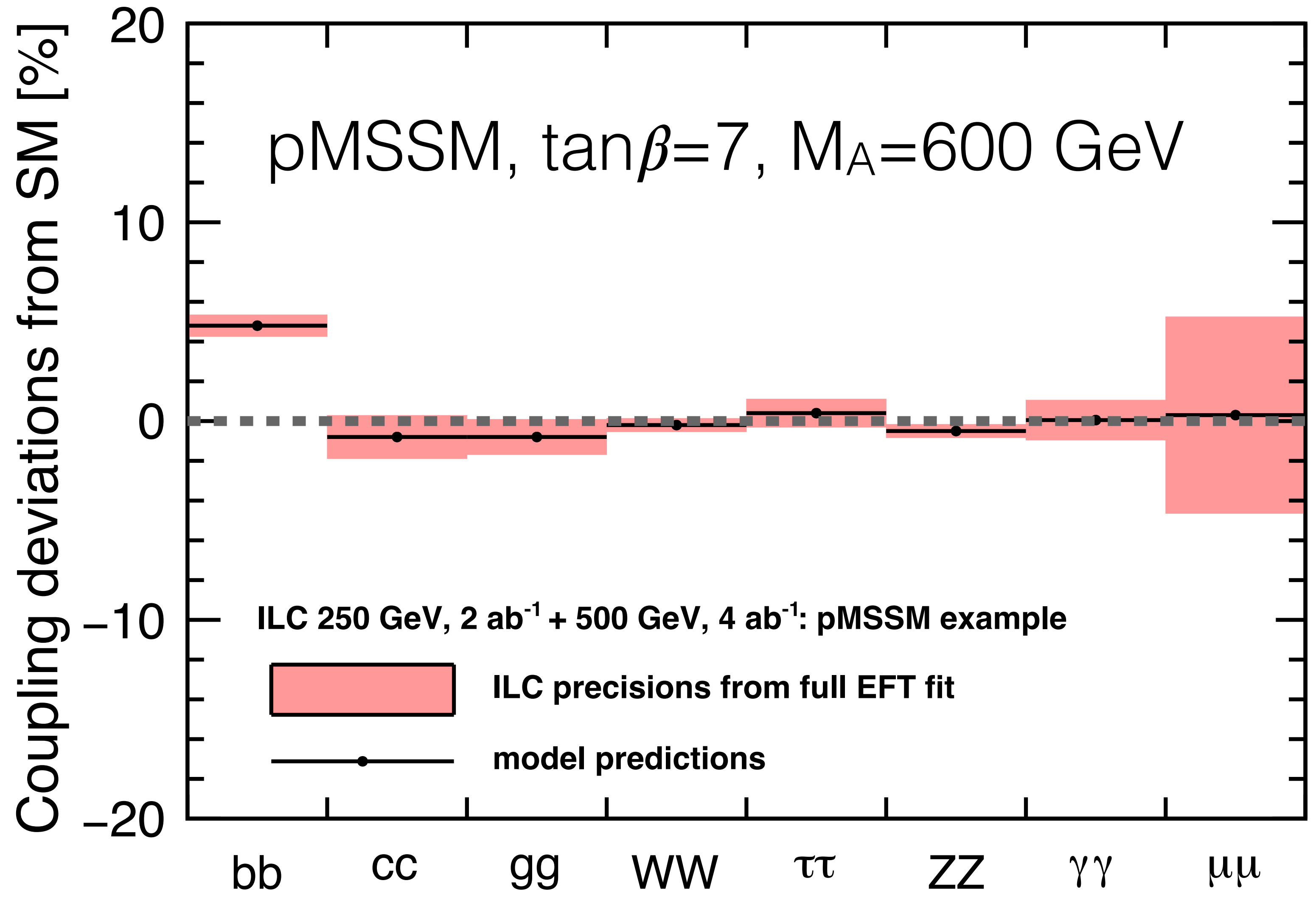

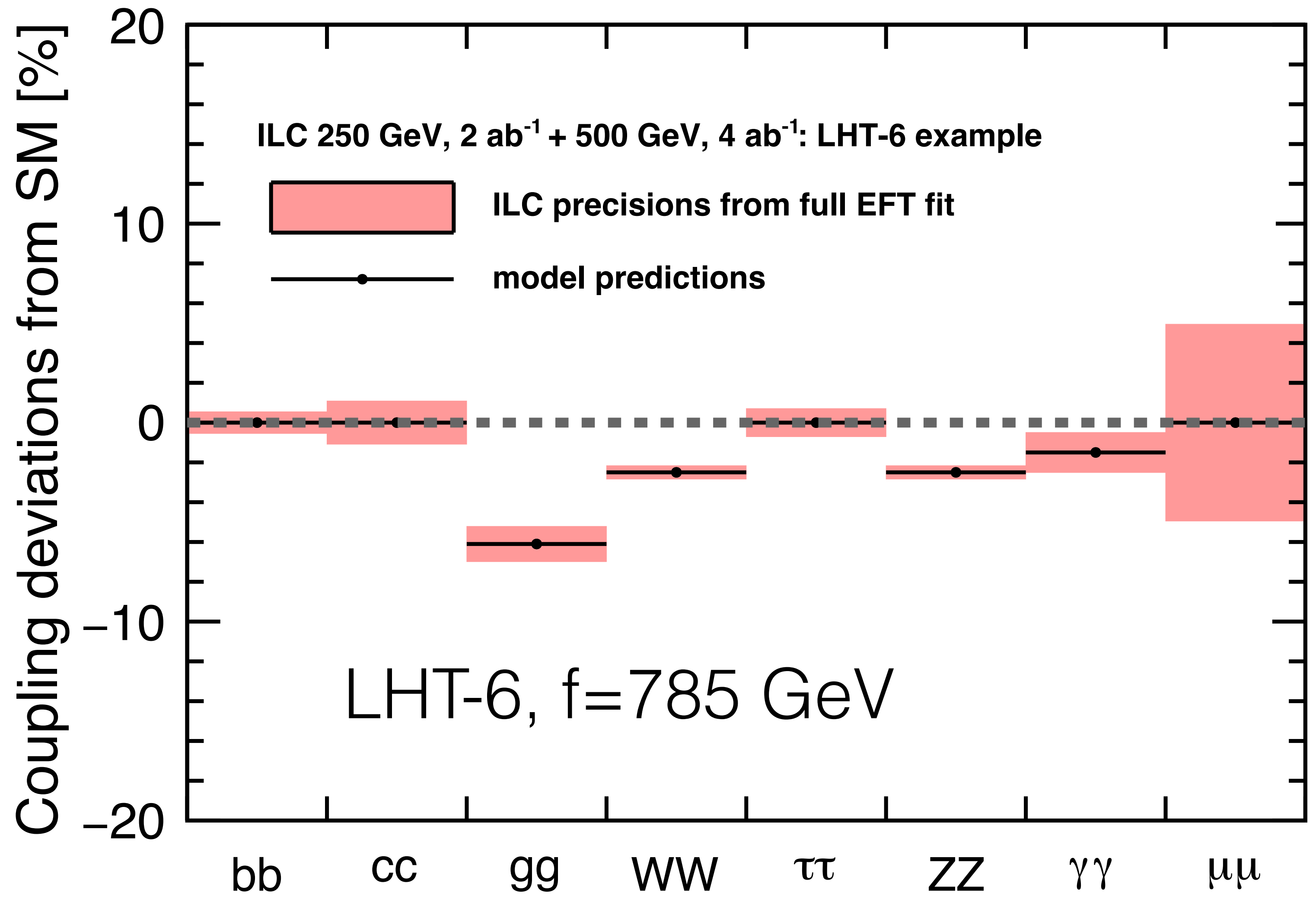

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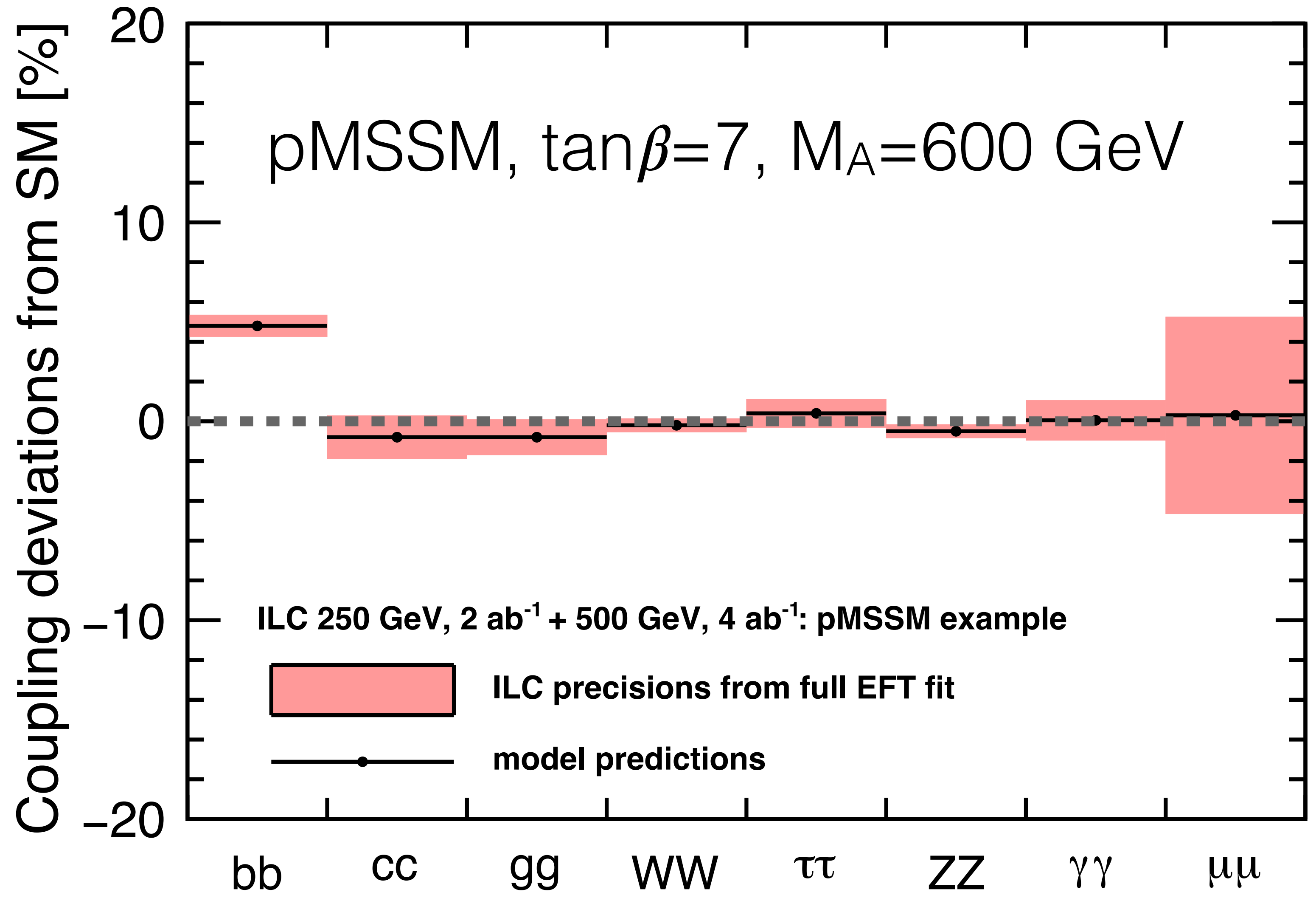

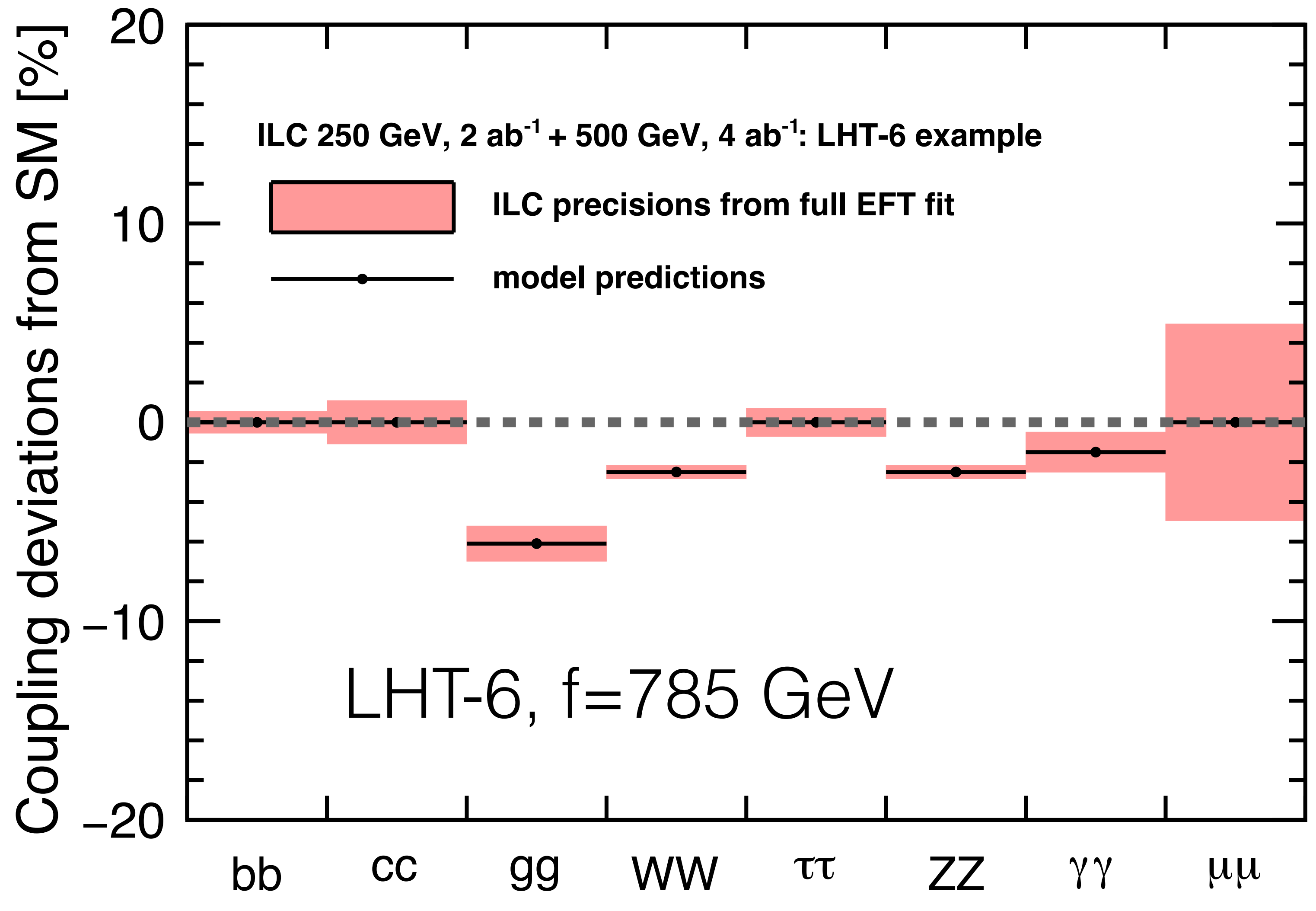

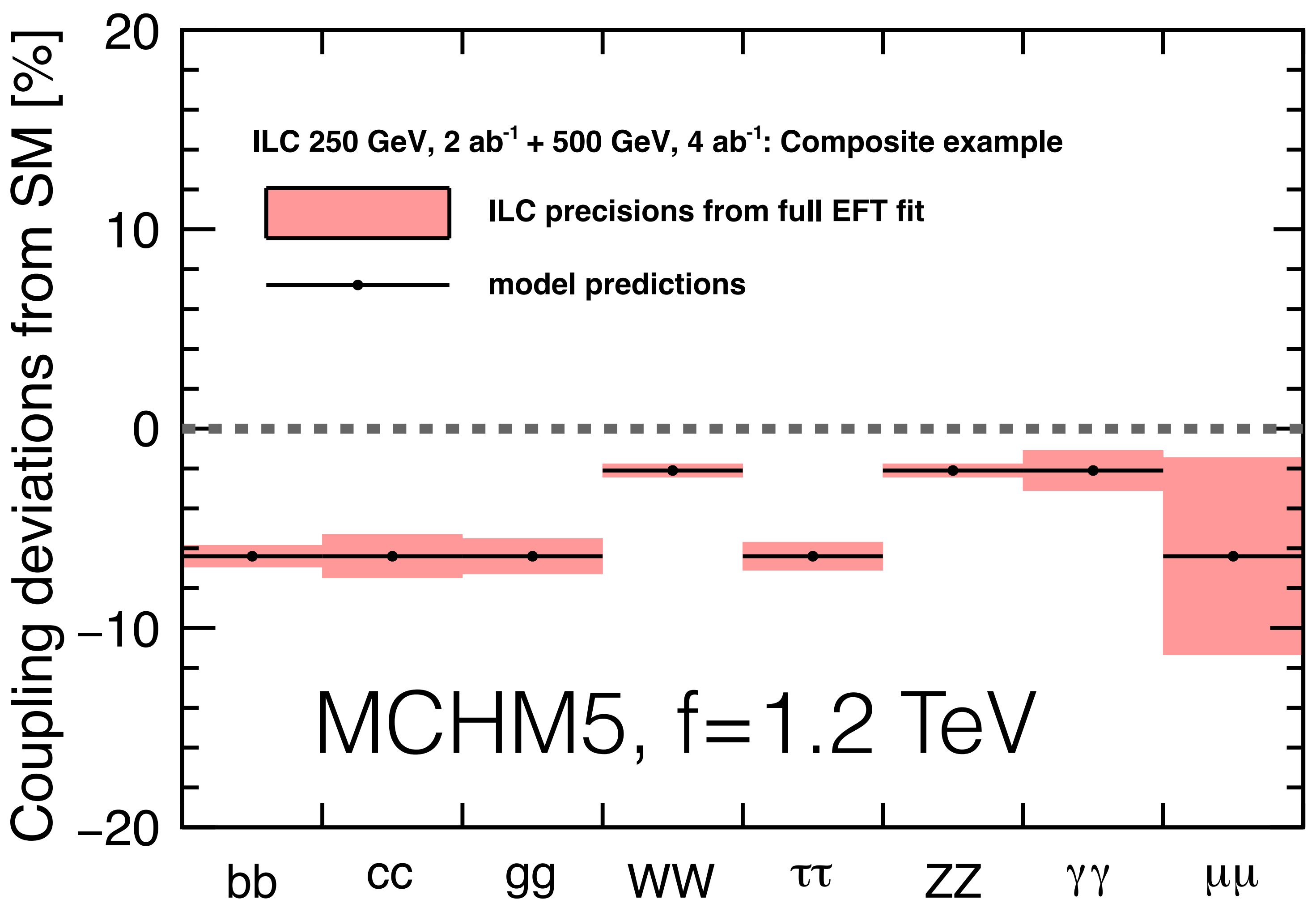

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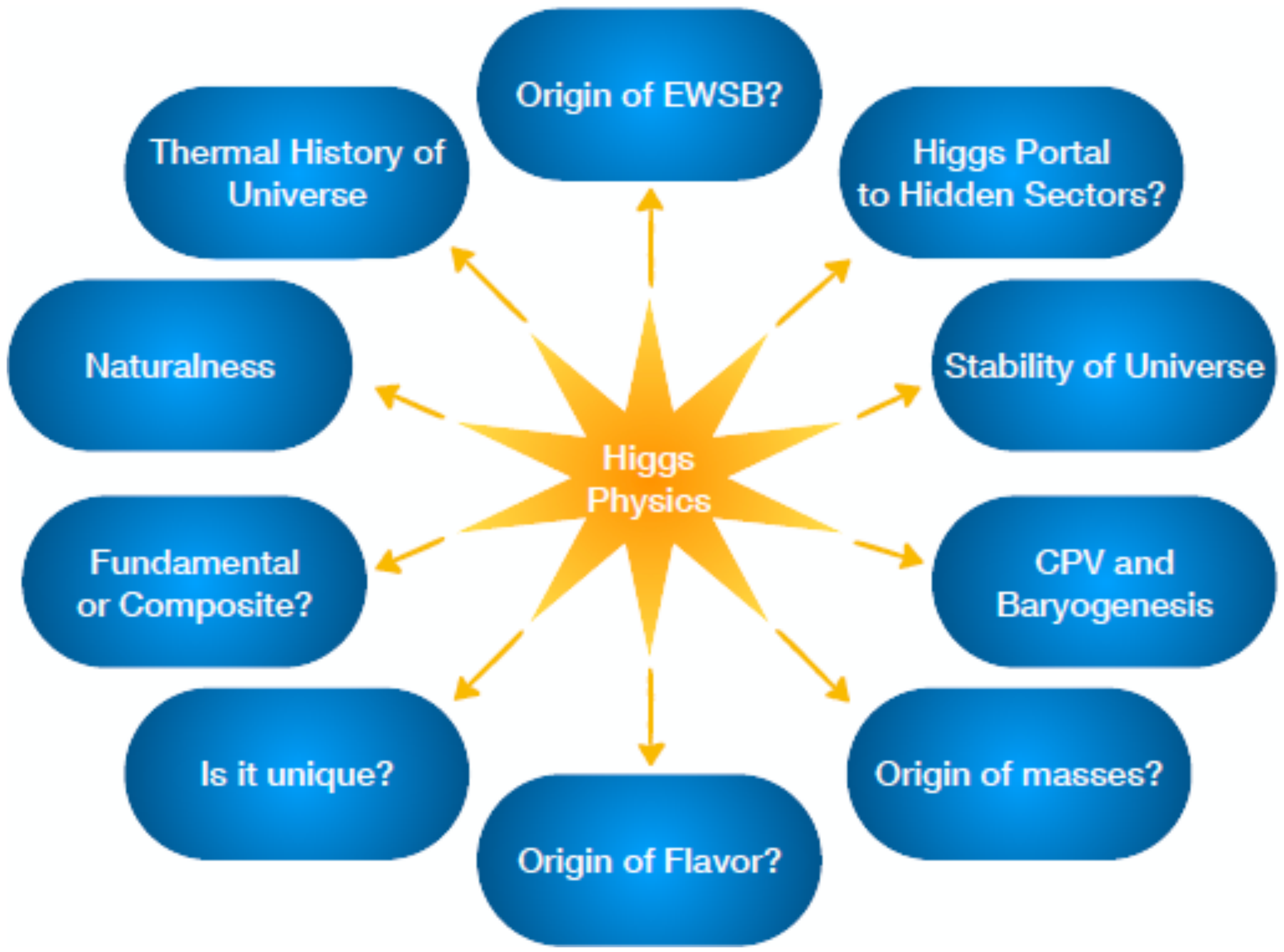
Why do we care about the length of these colored bars?!

The Higgs is connected to our fundamental questions about the universe



Snowmass EF Higgs Topical Report
S. Dawson, PM, I. Ojalvo, C. Vernieri et al
2209.07510

- **We need to understand this more quantitatively**
  - the interplay of precision measurements and direct searches
  - relation SMEFT <-> UV complete models
  - “inverse problem”, i.e. how do we figure out the underlying theory
- **requires much more than the Higgs**
  - precision Z, W & top masses
    => essential for SM and BSM tests
  - precision W, Z and top couplings
    => essential for Higgs interpretation
  - direct BSM discovery potential complementary to LHC

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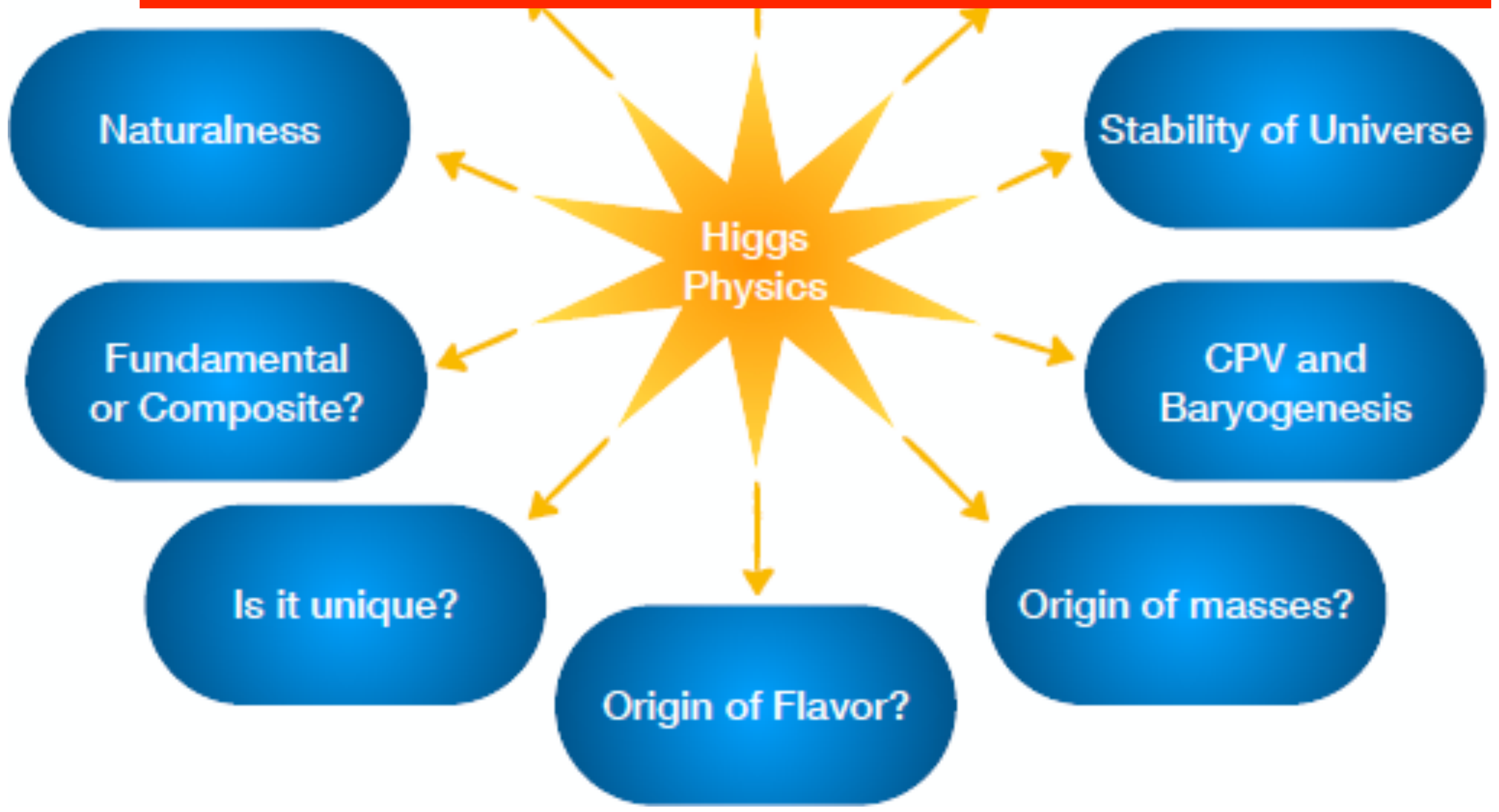
We need a much better way to explain this to policy makers and colleagues from other fields!



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Beyond the minimal Higgs program

FCCee (and CEPC) physics programme

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And also outstanding challenges

Overview on Z lineshape parameter precisions….

Observables	Present value	FCC-ee stat.	FCC-ee current syst.	FCC-ee ultimate syst.	Theory input (not exhaustive)
m_Z (keV)	91187500 ± 2100	4	100	10 ?	Lineshape QED unfolding Relation to measured quantities
Γ_Z (keV)	2495500 ± 2300 [*]	4	25	5 ?	Lineshape QED unfolding Relation to measured quantities
σ^0_{had} (pb)	41480.2 ± 32.5 [*]	0.04	4	0.8	Bhabha cross section to 0.01% $e^+e^- \to \gamma\gamma$ cross section to 0.002%
N_ν ($\times 10^3$) from σ_{had}	2996.3 ± 7.4	0.007	1	0.2	Lineshape QED unfolding $(\Gamma_{\nu\nu}/\Gamma_{\ell\ell})_{SM}$
R_ℓ ($\times 10^3$)	20766.6 ± 24.7	0.04	1	0.2 ?	Lepton angular distribution (QED ISR/FSR/IFI, EW corrections)
$\alpha_s(m_Z)$ ($\times 10^4$) from R_ℓ	1196 ± 30	0.1	1.5	0.4 ?	Higher order QCD corrections for Γ_{had}
R_b ($\times 10^6$)	216290 ± 660	0.3	?	< 60 ?	QCD (gluon radiation, gluon splitting, fragmentation, decays, …)

From: P.Janot talk at FCC theory workshop in June 2022

… similar for asymmetries

but note again effect of polarised beams

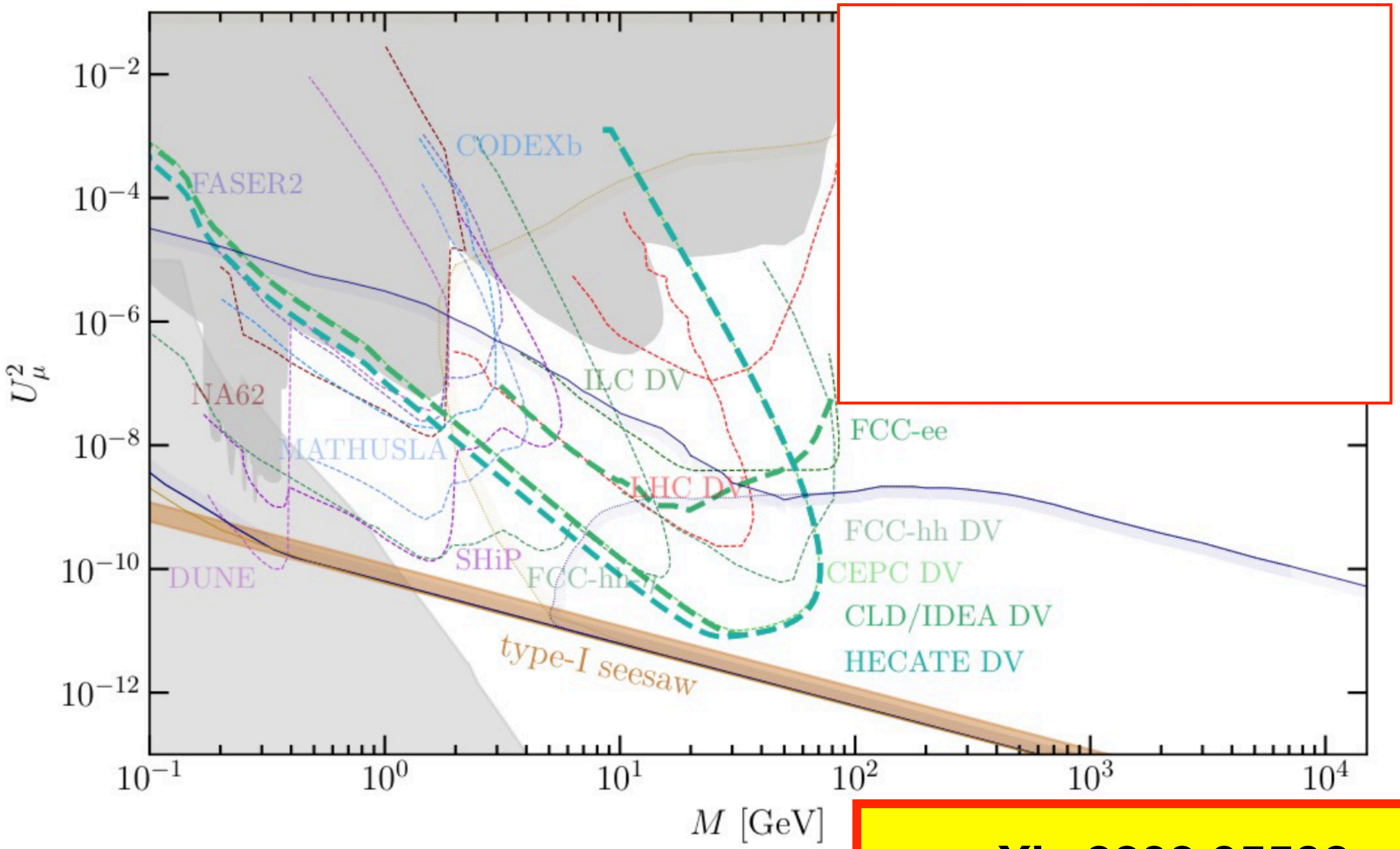
Observables	Present value ($\times 10^4$)	TeraZ / GigaZ stat.	TeraZ / GigaZ current syst.	Theory input (not exhaustive)
A_e from P_τ (FCC-ee)	1514 ± 19	0.07	0.20	SM relation to measured quantities
A_e from A_{LR} (ILC)		0.15	0.80	
A_μ from A_{FB} (FCC-ee)	1456 ± 91	0.23	0.22	Accurate QED (ISR, IFI, FSR)
A_μ from A_{FB}^{pol} (ILC)		0.30	0.80	
A_τ from P_τ (FCC-ee)	1449 ± 40	0.05	2.00	Prediction for non-τ backgrounds
A_τ from A_{FB} (FCC-ee)		0.23	1.30	
A_τ from A_{FB}^{pol} (ILC)		0.30	0.80	
A_b from A_{FB} (FCC-ee)	8990 ± 130	0.24	2.10	QCD calculations
A_b from A_{FB}^{pol} (ILC)		0.90	5.00	
A_c from A_{FB} (FCC-ee)	65400 ± 210	2.00	1.50	
A_c from A_{FB}^{pol} (ILC)		2.00	3.70	

From: P.Janot talk at FCC theory workshop in June 2022

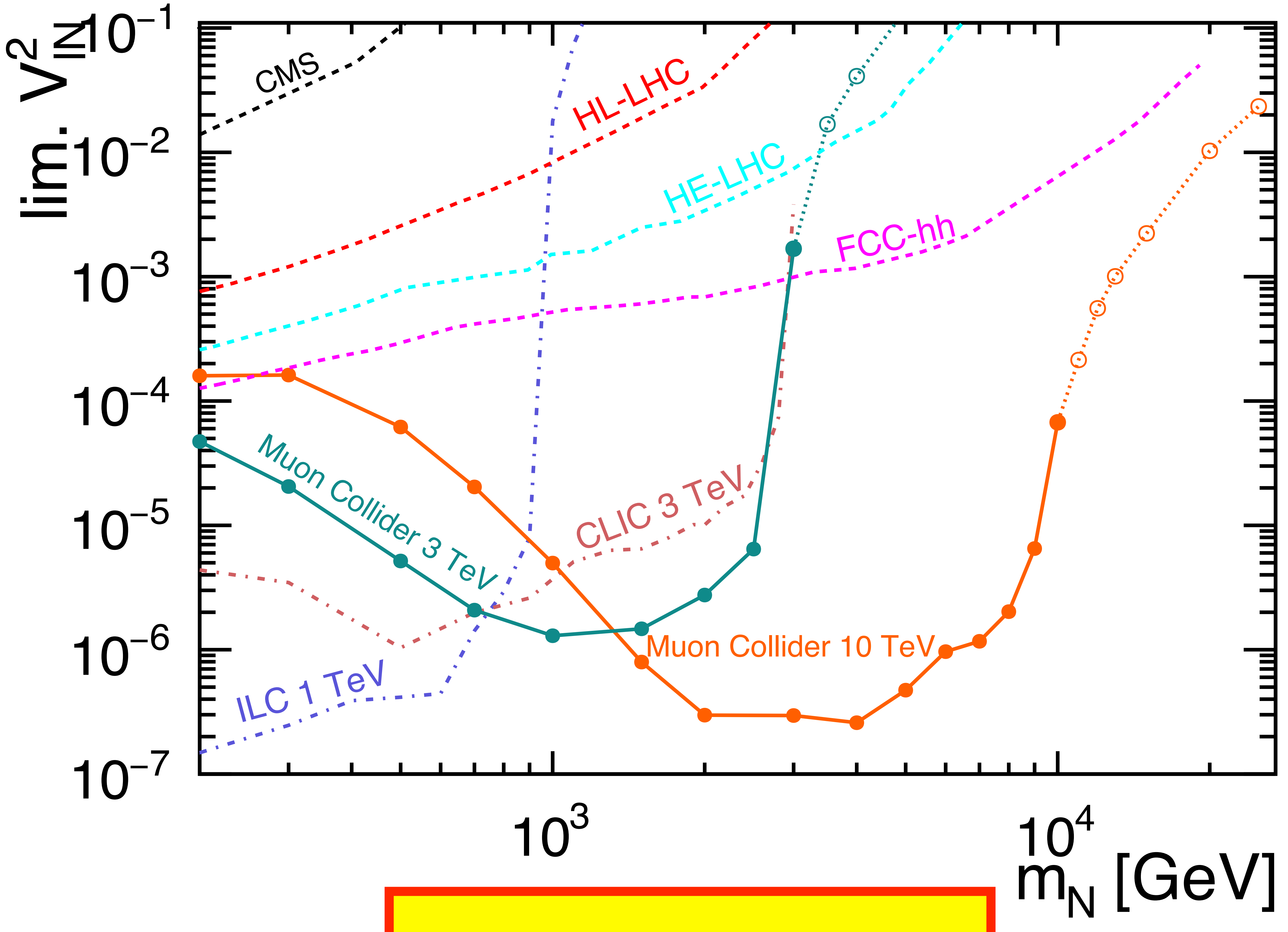
Heavy Neutral Leptons

Discovery reach for lepton colliders - complementary to FCC-hh

in Z decays with displaced vertices… …and at high masses in prompt decays



arXiv:2203.05502

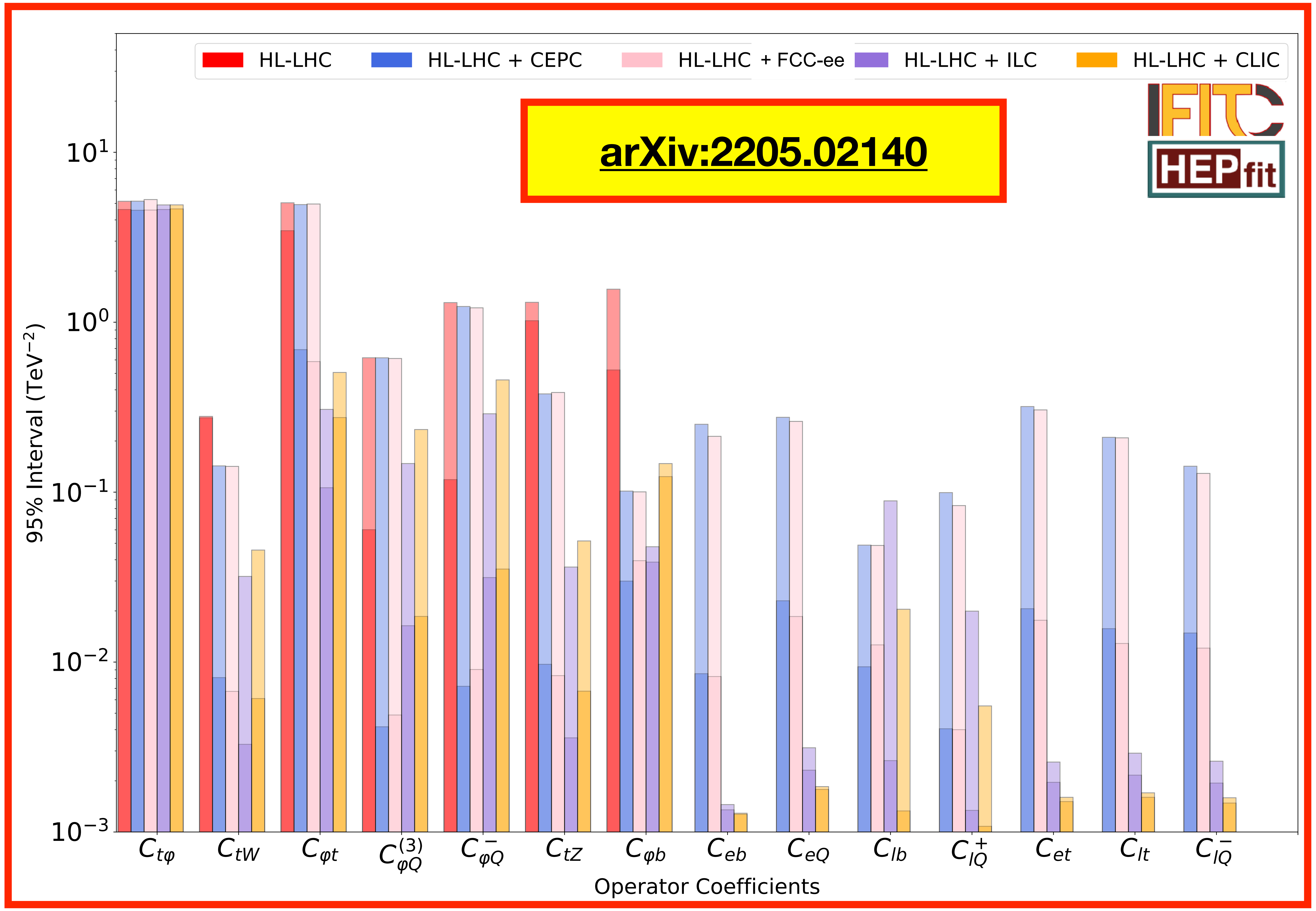


arXiv:2301.02602

Full SMEFT analysis of top quark sector

Essential to understand special relation of top quark and Higgs boson

- expected precision on Wilson coefficients for HL-LHC alone and combined with various e+e- proposals
- e+e- at high center-of-mass energy and with polarised beams lifts degeneracies between operators



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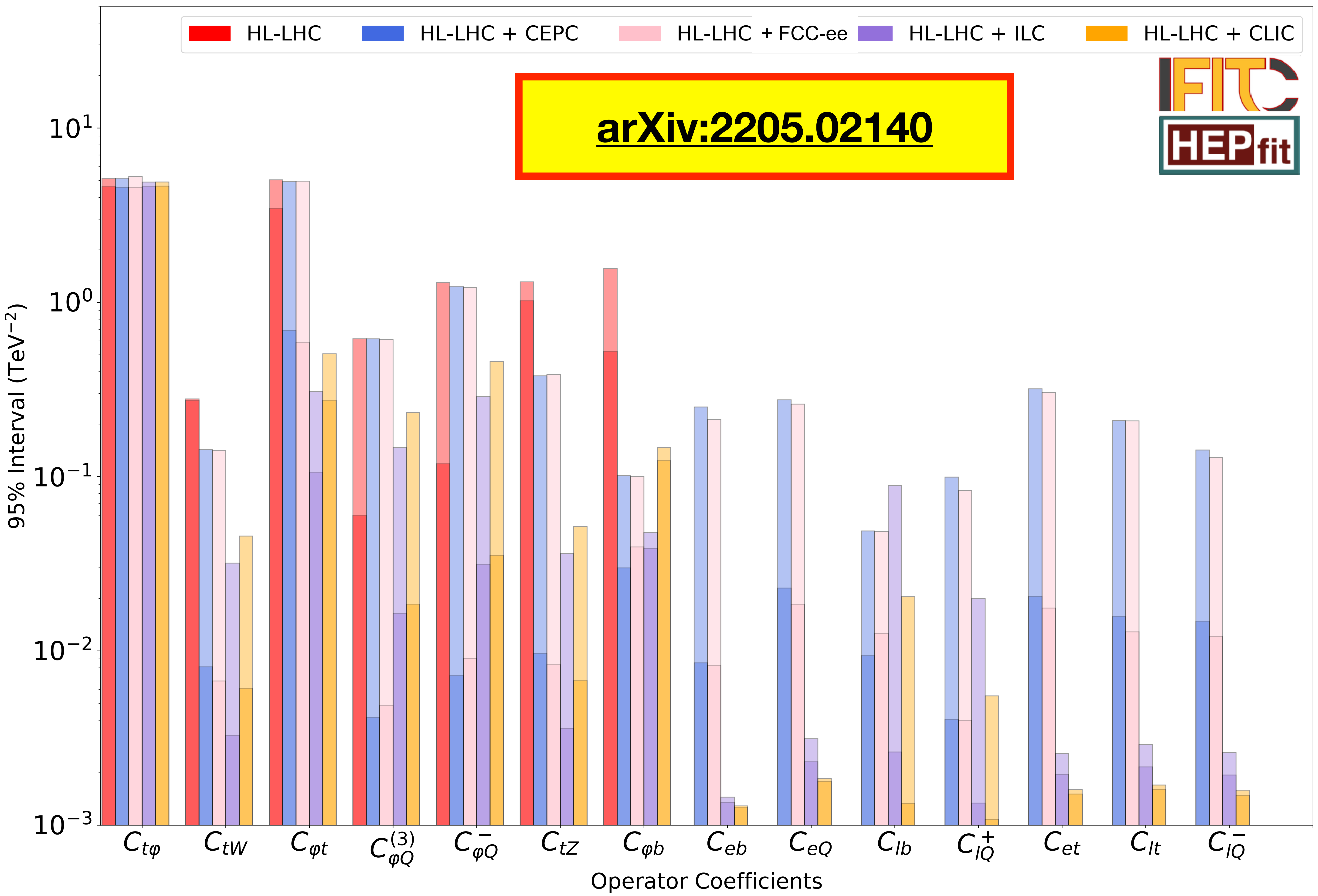
top-quark physics does not end at the ttbar threshold…



BSM reach of ee → cc / bb

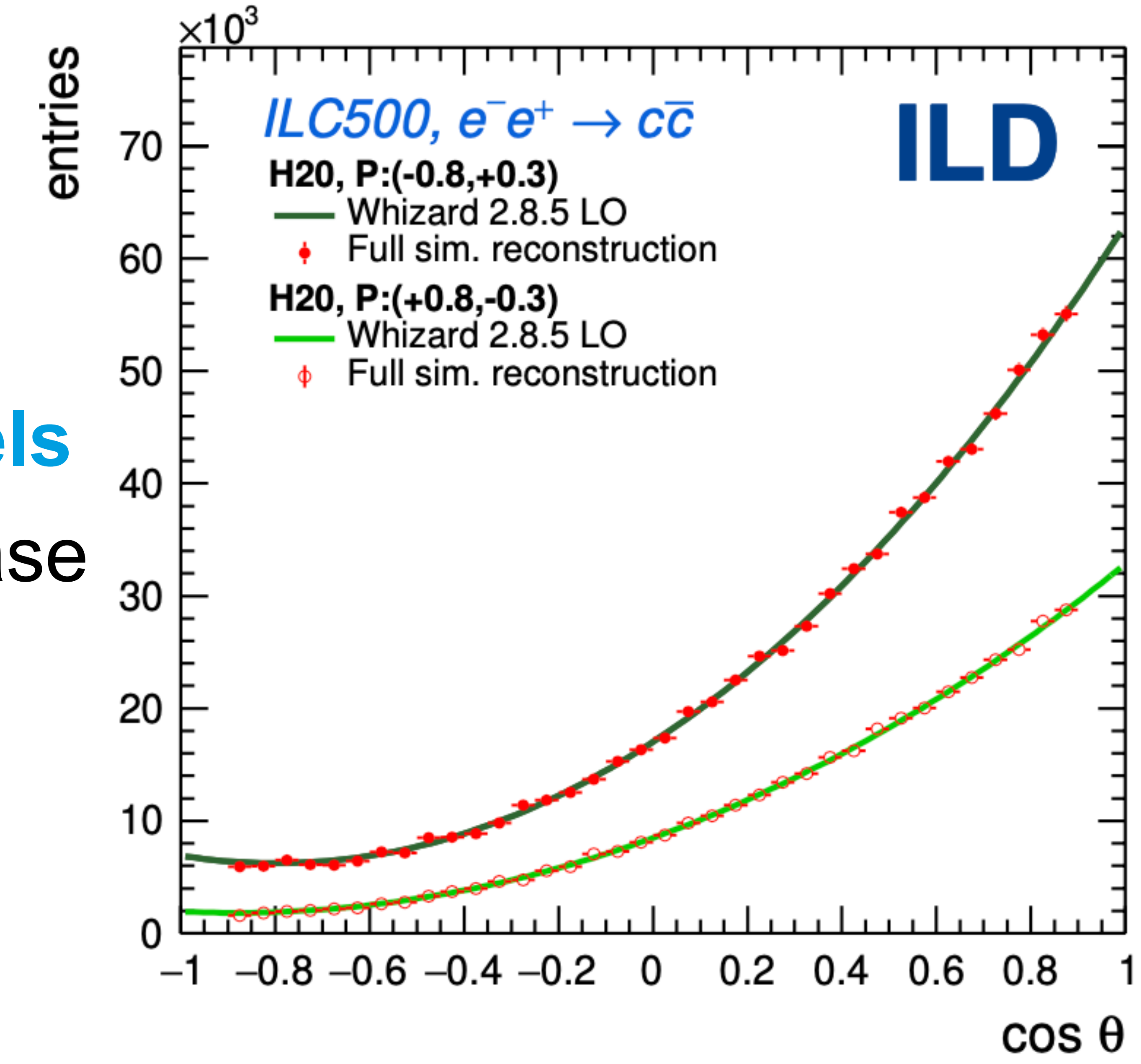
Forward-backward and left-right asymmetries above the Z pole

Study of ee → cc / bb

- full Geant4-based simulation of ILD [A.Irles et al, pub. in prep.]

BSM example: Gauge-Higgs Unification models

- Higgs field = fluctuation of Aharonov-Bohm phase in warped extra dimension
- Z' as Kaluza-Klein excitations of γ, Z, Z_R
- various model point with $M_{Z'}$ = 7…20 TeV



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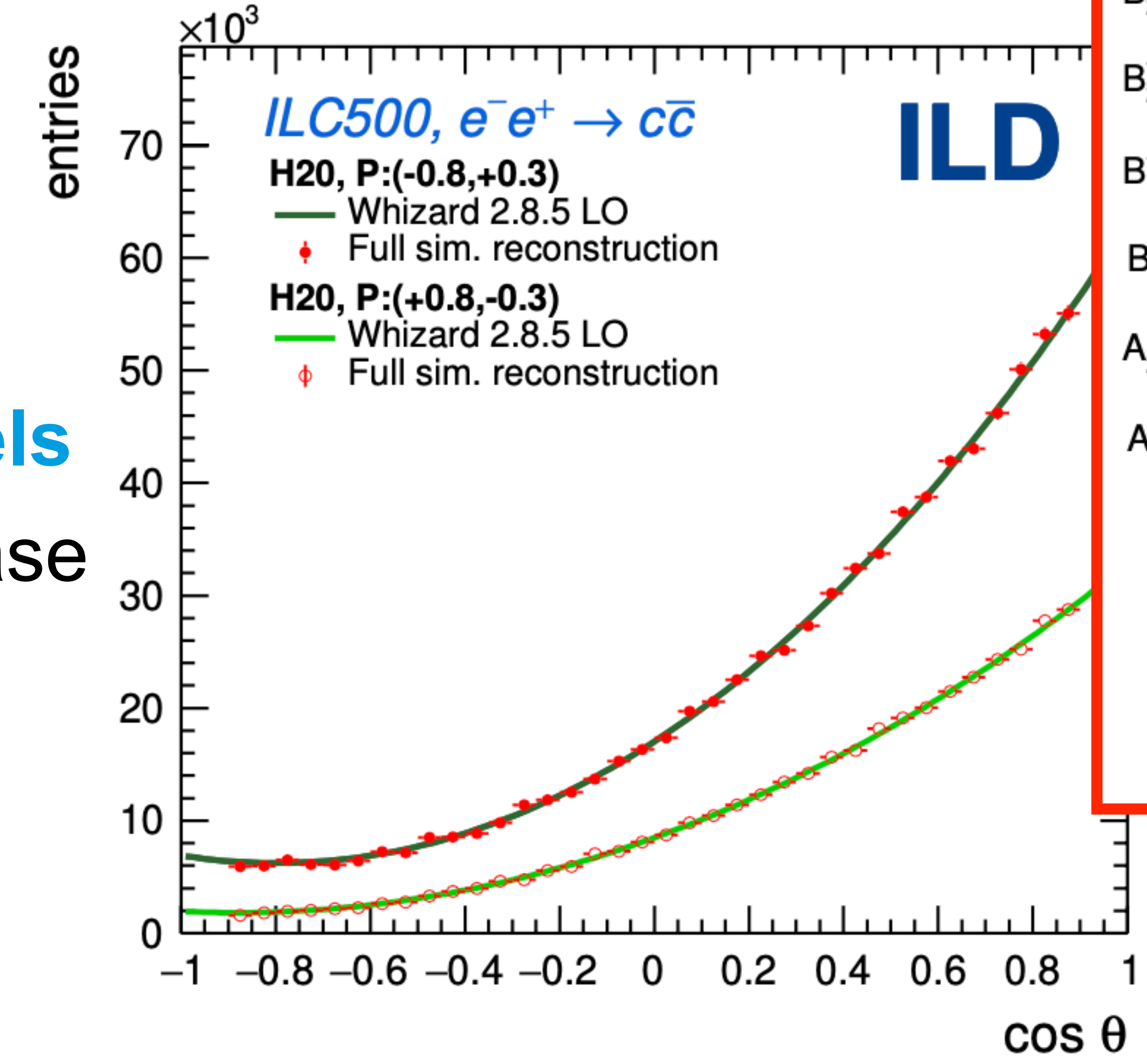

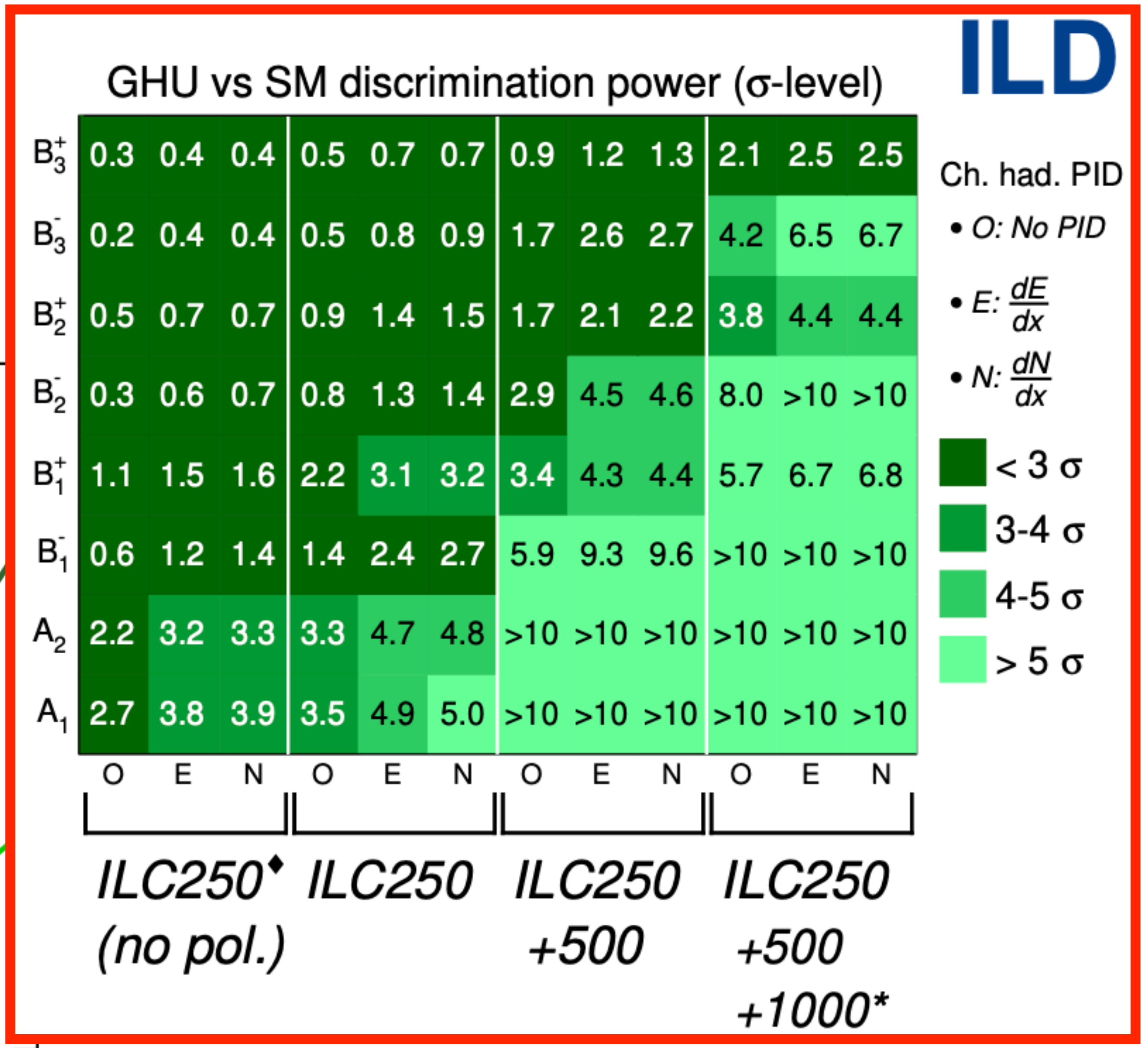

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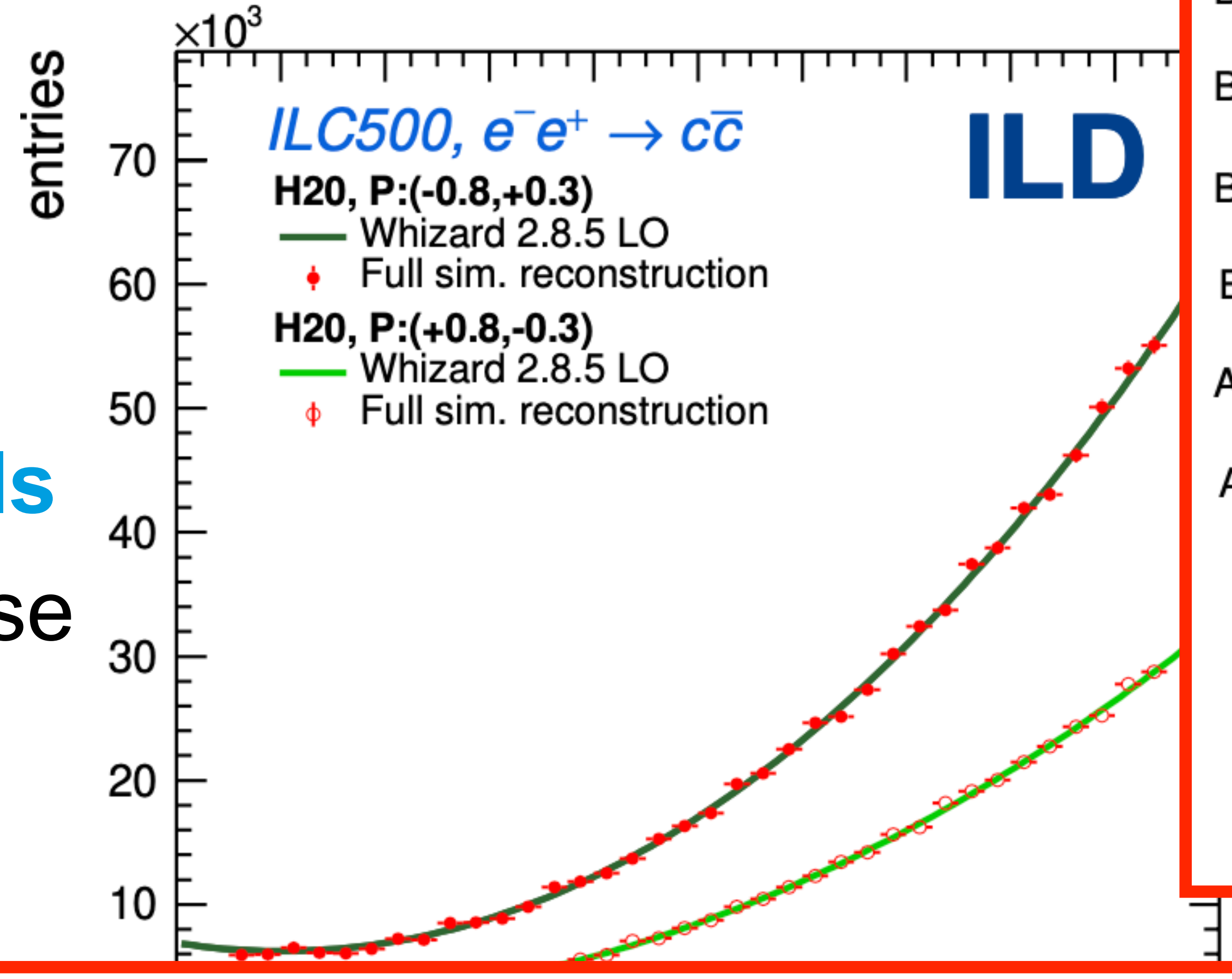


ILD

GHU vs SM discrimination power (σ-level)

	ILC250♦ (no pol.) O	E	N	ILC250 O	E	N	ILC250 +500 O	E	N	ILC250 +500 +1000* O	E	N
B_3^+	0.3	0.4	0.4	0.5	0.7	0.7	0.9	1.2	1.3	2.1	2.5	2.5
B_3^-	0.2	0.4	0.4	0.5	0.8	0.9	1.7	2.6	2.7	4.2	6.5	6.7
B_2^+	0.5	0.7	0.7	0.9	1.4	1.5	1.7	2.1	2.2	3.8	4.4	4.4
B_2^-	0.3	0.6	0.7	0.8	1.3	1.4	2.9	4.5	4.6	8.0	>10	>10
B_1^+	1.1	1.5	1.6	2.2	3.1	3.2	3.4	4.3	4.4	5.7	6.7	6.8
B_1^-	0.6	1.2	1.4	1.4	2.4	2.7	5.9	9.3	9.6	>10	>10	>10
A_2	2.2	3.2	3.3	3.3	4.7	4.8	>10	>10	>10	>10	>10	>10
A_1	2.7	3.8	3.9	3.5	4.9	5.0	>10	>10	>10	>10	>10	>10

Ch. had. PID
- *O: No PID*
- *E: $\frac{dE}{dx}$*
- *N: $\frac{dN}{dx}$*

< 3 σ; 3-4 σ; 4-5 σ; > 5 σ

Between-model discrimination power (σ-level) — ILD — *ILC250♦ (no pol.)* (2000 fb⁻¹)

	A_1	A_2	B_1^-	B_1^+	B_2^-	B_2^+	B_3^-	B_3^+
B_3^+	3.9	3.2	1.5	1.3	0.9	0.4	0.5	
B_3^-	4.1	3.4	1.1	1.4	0.4	0.7		
B_2^+	3.6	2.9	1.6	1.0	1.0			
B_2^-	4.1	3.5	0.7	1.6				
B_1^+	2.7	2.0	1.9					
B_1^-	4.2	3.7						
A_2	0.8							
A_1								

Between-model discrimination power (σ-level) — ILD — *ILC250* (2000 fb⁻¹)

	A_1	A_2	B_1^-	B_1^+	B_2^-	B_2^+	B_3^-	B_3^+
B_3^+	5.0	4.7	2.5	2.8	1.4	0.9	0.9	
B_3^-	5.4	5.1	2.1	3.1	0.7	1.4		
B_2^+	4.3	4.1	2.5	2.1	1.7			
B_2^-	5.4	5.1	1.6	3.1				
B_1^+	2.7	2.4	3.4					
B_1^-	5.3	5.1						
A_2	0.5							
A_1								

Between-model discrimination power (σ-level) — ILD — *ILC250+500* (2000 fb⁻¹ + 4000 fb⁻¹)

	A_1	A_2	B_1^-	B_1^+	B_2^-	B_2^+	B_3^-	B_3^+
B_3^+	>10	>10	>10	3.9	4.9	1.3	2.9	
B_3^-	>10	>10	7.6	5.1	2.4	3.4		
B_2^+	>10	>10	>10	3.0	5.2			
B_2^-	>10	>10	5.4	6.4				
B_1^+	>10	>10	>10					
B_1^-	>10	>10						
A_2	2.9							
A_1								

Between-model discrimination power (σ-level) — ILD — *ILC250+500+1000** (2000 fb⁻¹ + 4000 fb⁻¹ + 8000 fb⁻¹)

	A_1	A_2	B_1^-	B_1^+	B_2^-	B_2^+	B_3^-	B_3^+
B_3^+	>10	>10	>10	5.4	>10	2.7	7.6	
B_3^-	>10	>10	>10	>10	6.7	8.6		
B_2^+	>10	>10	>10	4.1	>10			
B_2^-	>10	>10	>10	>10				
B_1^+	>10	>10	>10					
B_1^-	>10	>10						
A_2	>10							
A_1								

< 3 σ; 3-4 σ; 4-5 σ; > 5 σ

BSM reach of ee → cc / bb

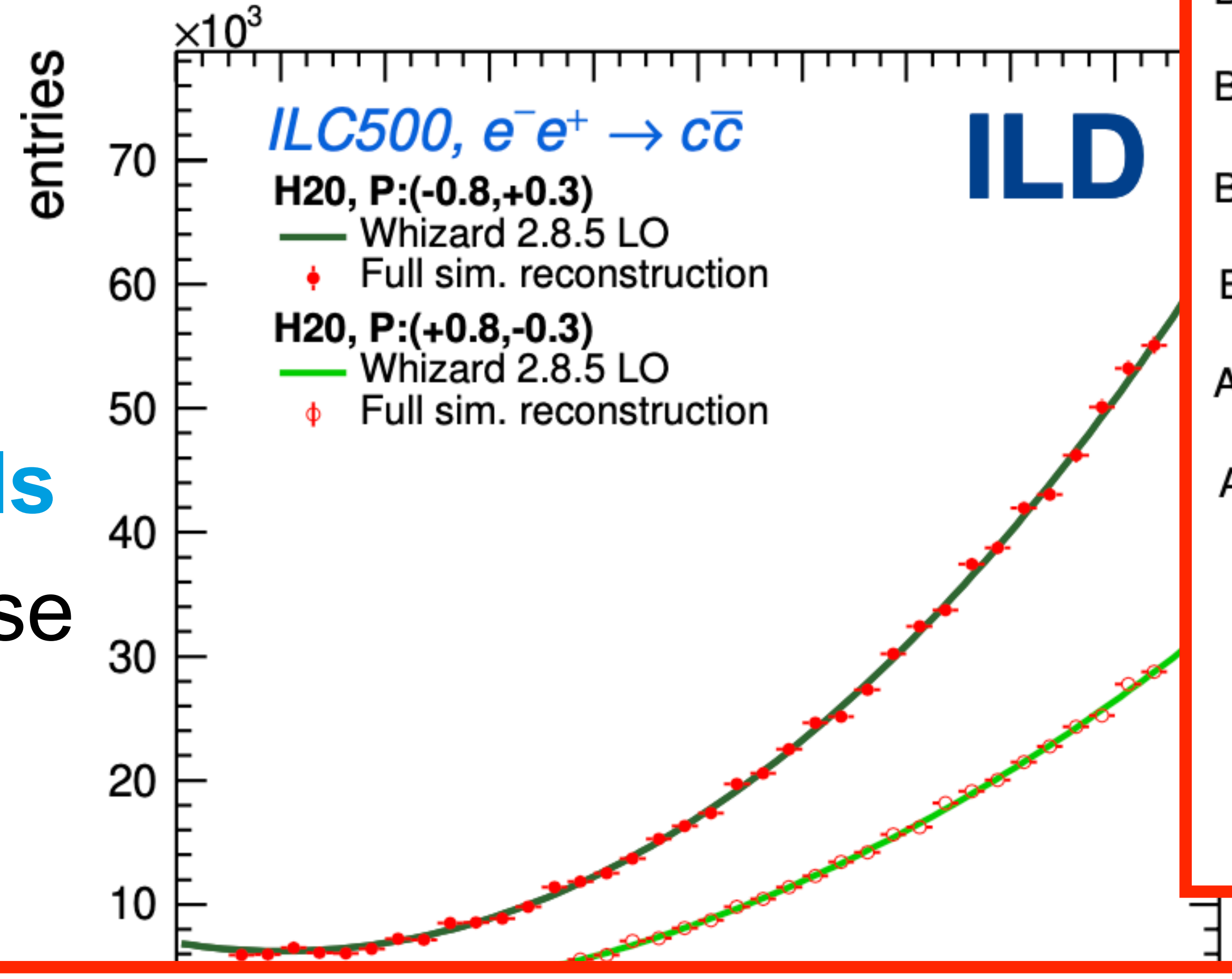
Forward-backward and left-right asymmetries above the Z pole

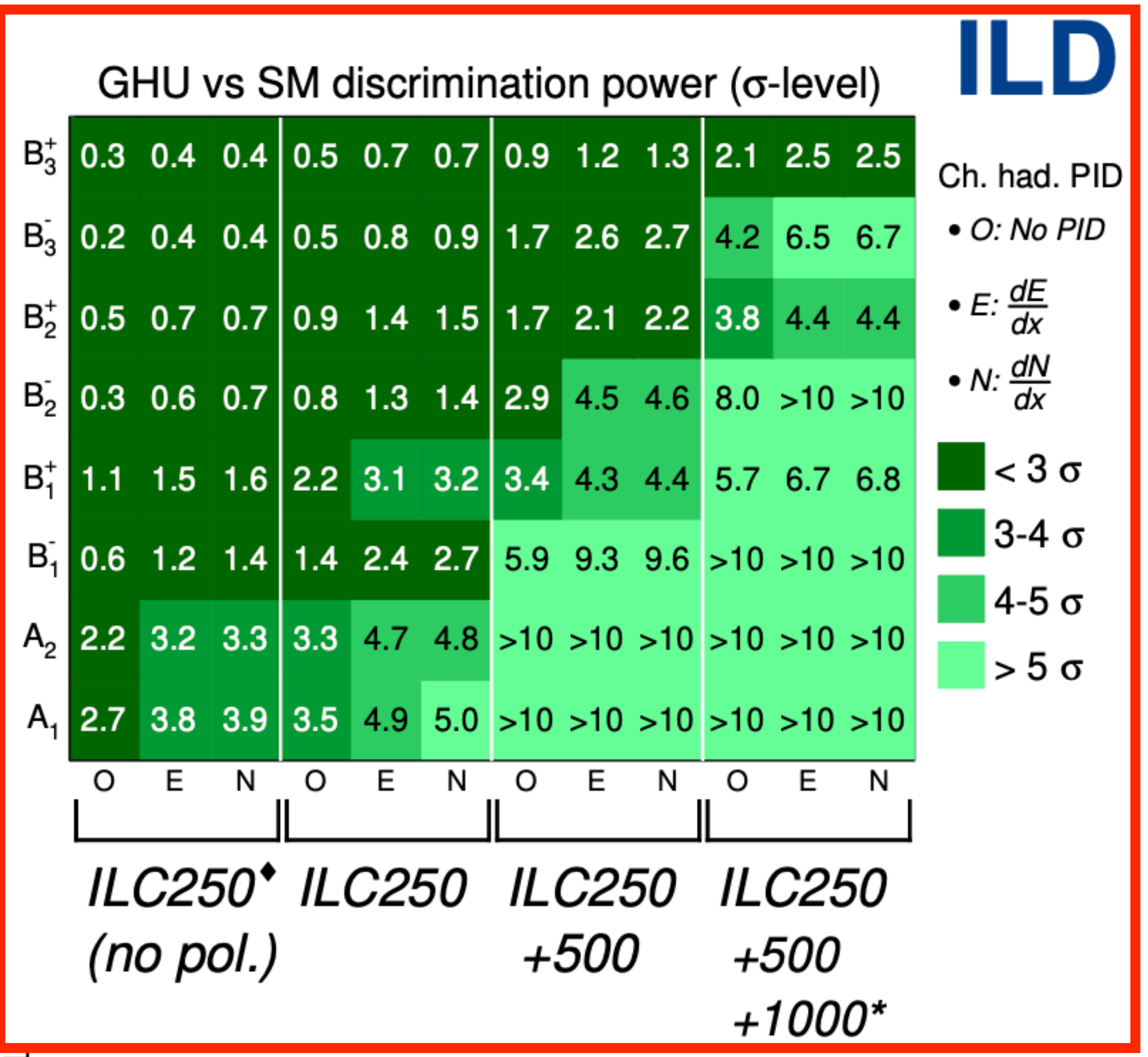
Study of ee → cc / bb

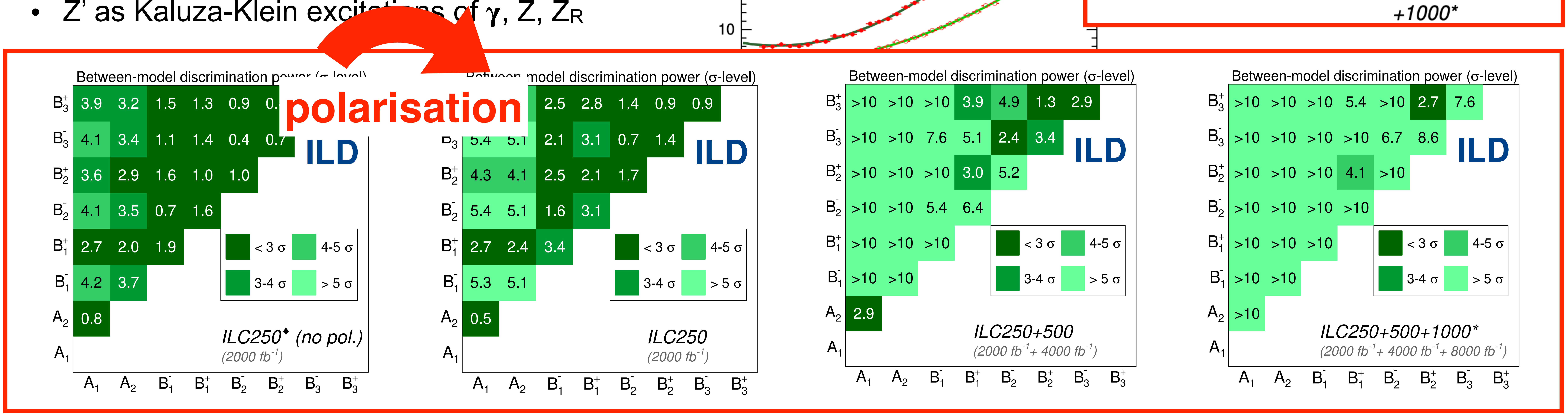
- full Geant4-based simulation of ILD [A.Irles et al, pub. in prep.]

BSM example: Gauge-Higgs Unification models

- Higgs field = fluctuation of Aharonov-Bohm phase in warped extra dimension
- Z' as Kaluza-Klein excitations of γ, Z, Z_R







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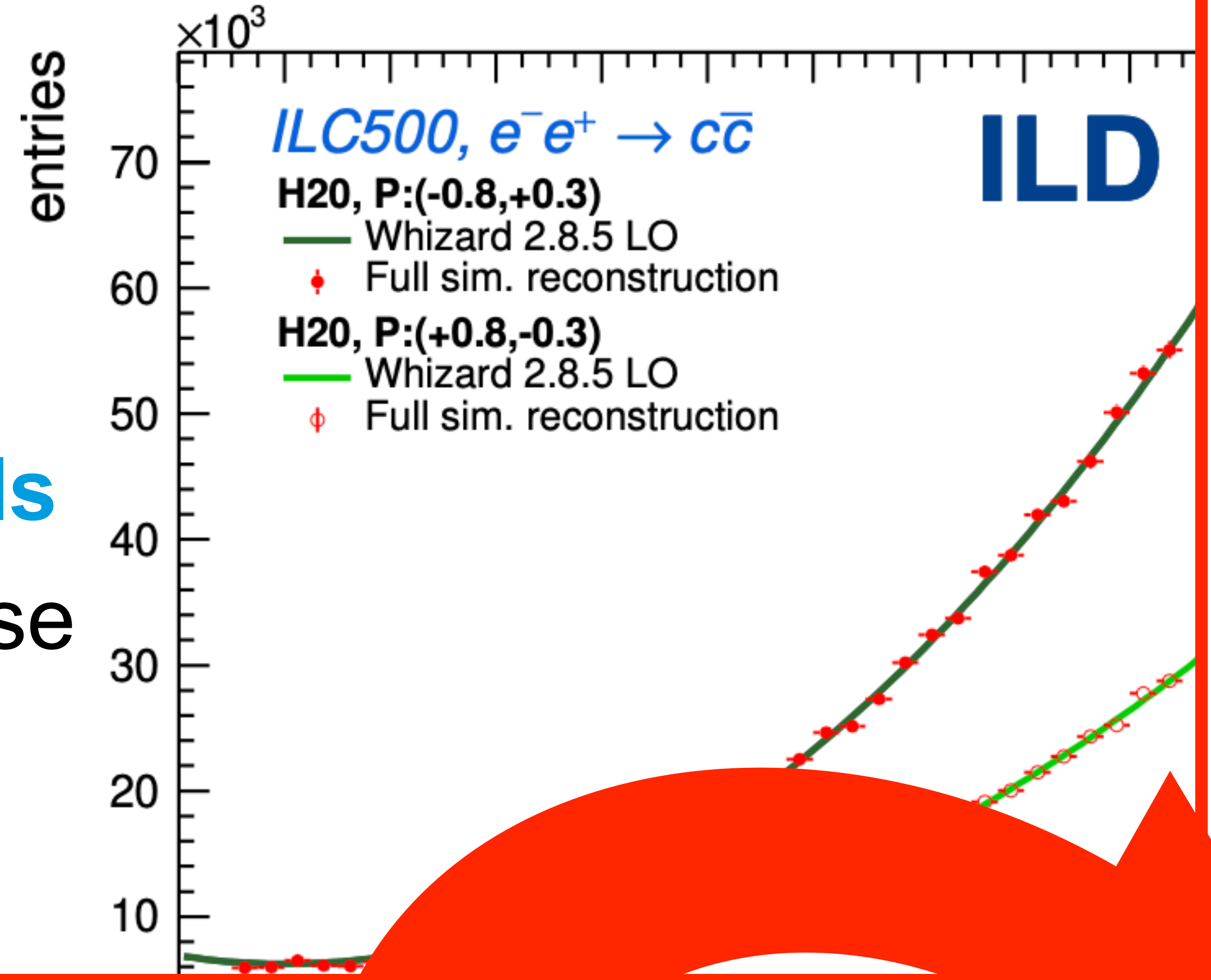
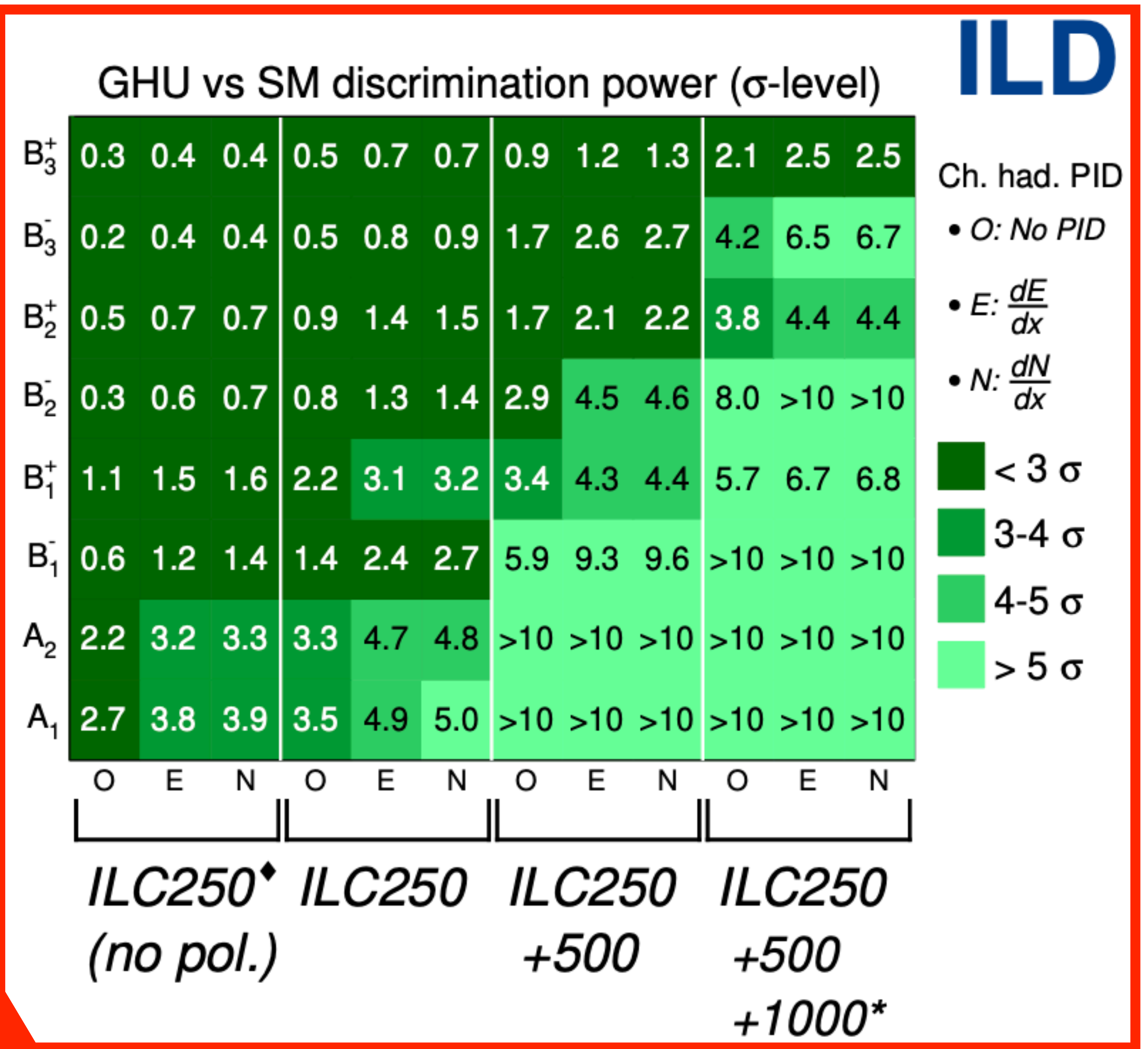
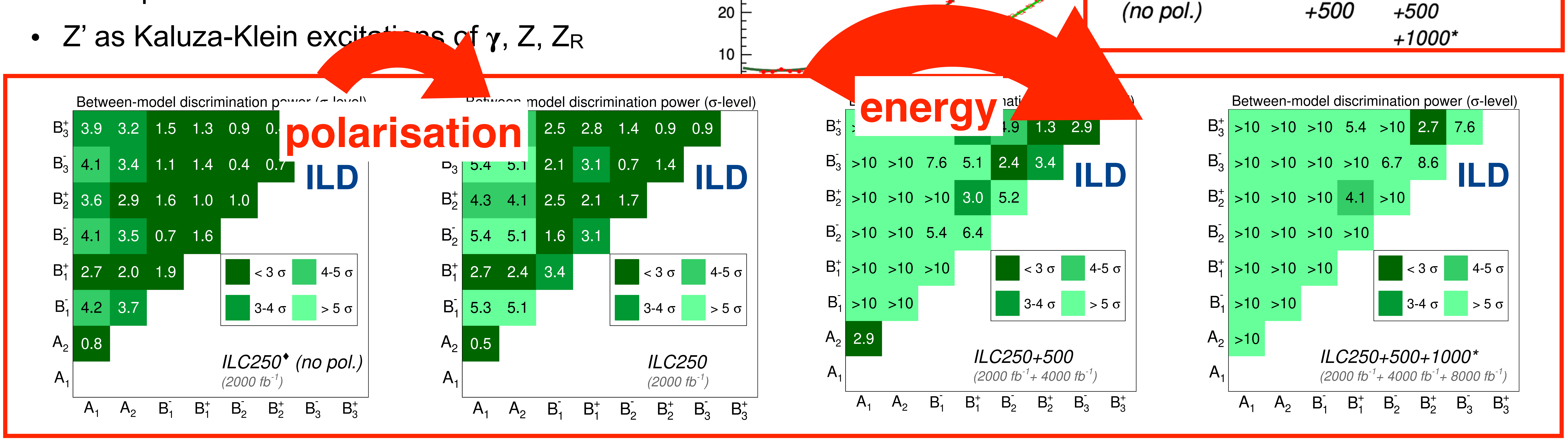


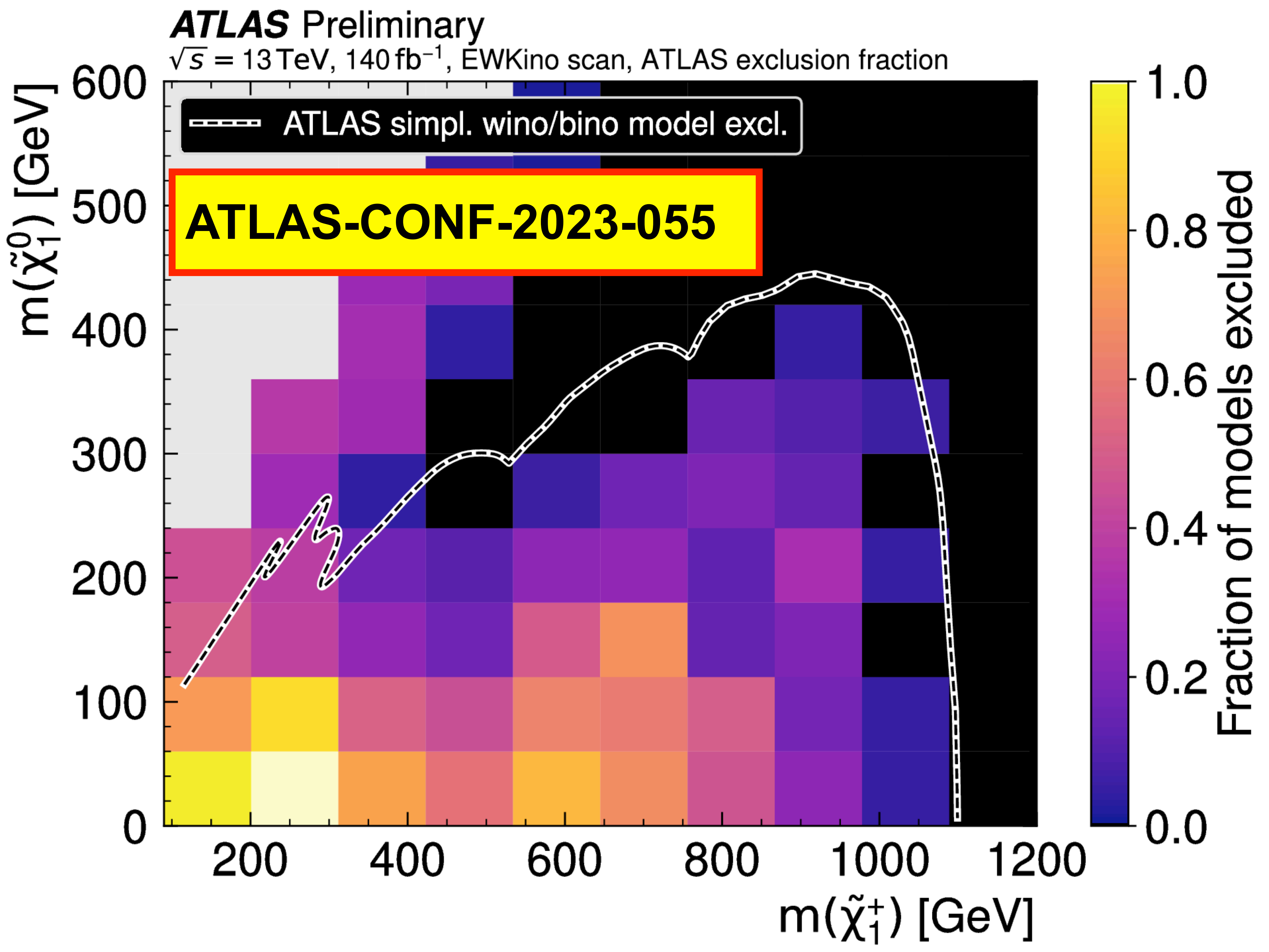




Light Higgsinos

Or: beware what LHC limits really mean!

- LHC does very well on probing some BSM phase space
- but beware that exclusion regions are extremely model-dependent, especially for electroweak new particles (eg charginos, staus, …)
- ILD study of full detector simulation for two benchmark points ☆☆ - motivated by leptogenesis & gravitino DM - and extrapolation to full plane
- conclusions:
  - loop-hole free discovery / exclusion potential up to ~ half E_{CM}
  - even in most challenging cases few % precision on masses, cross-sections etc
  - SUSY parameter determination, cross-check with cosmology



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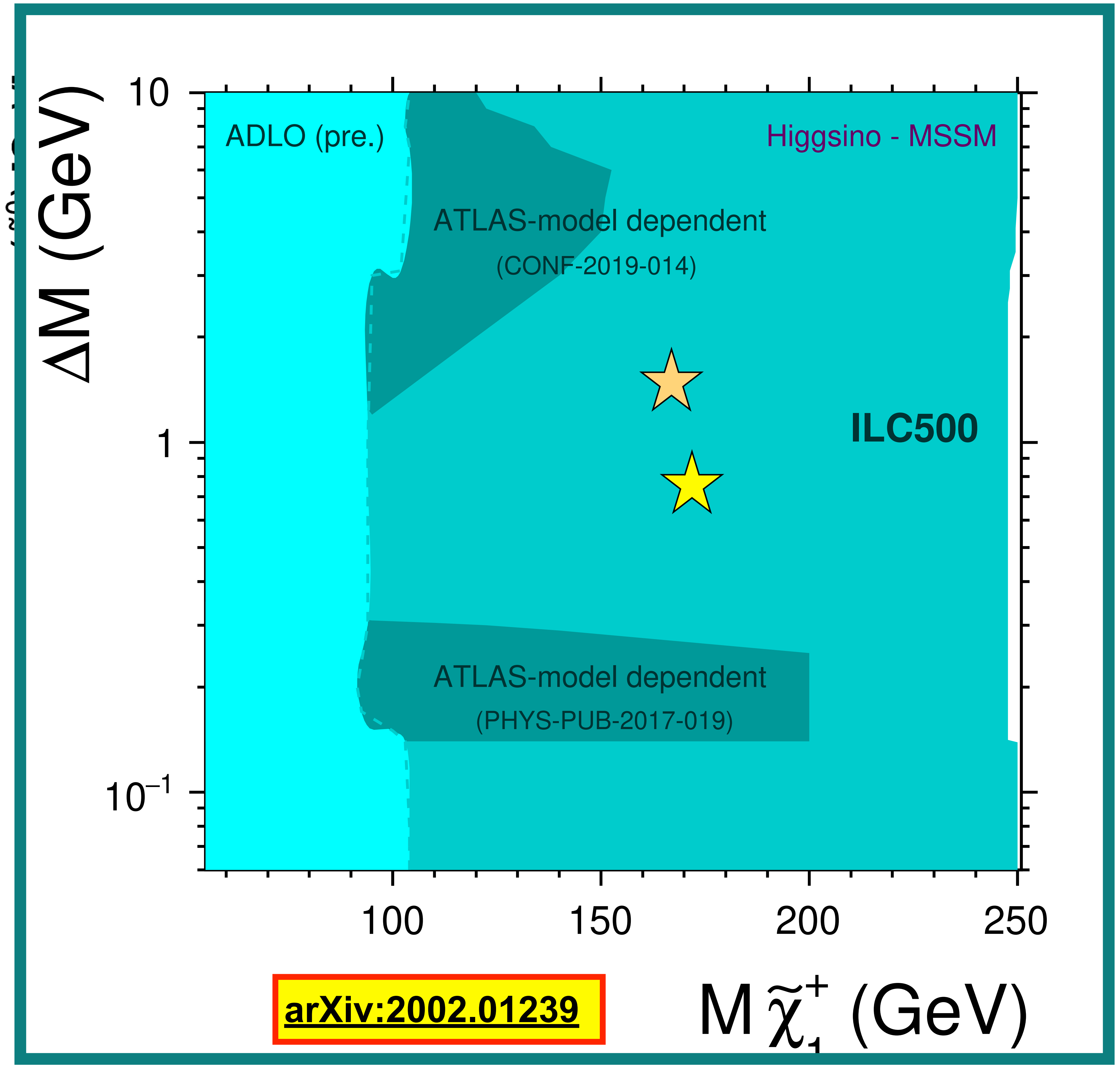

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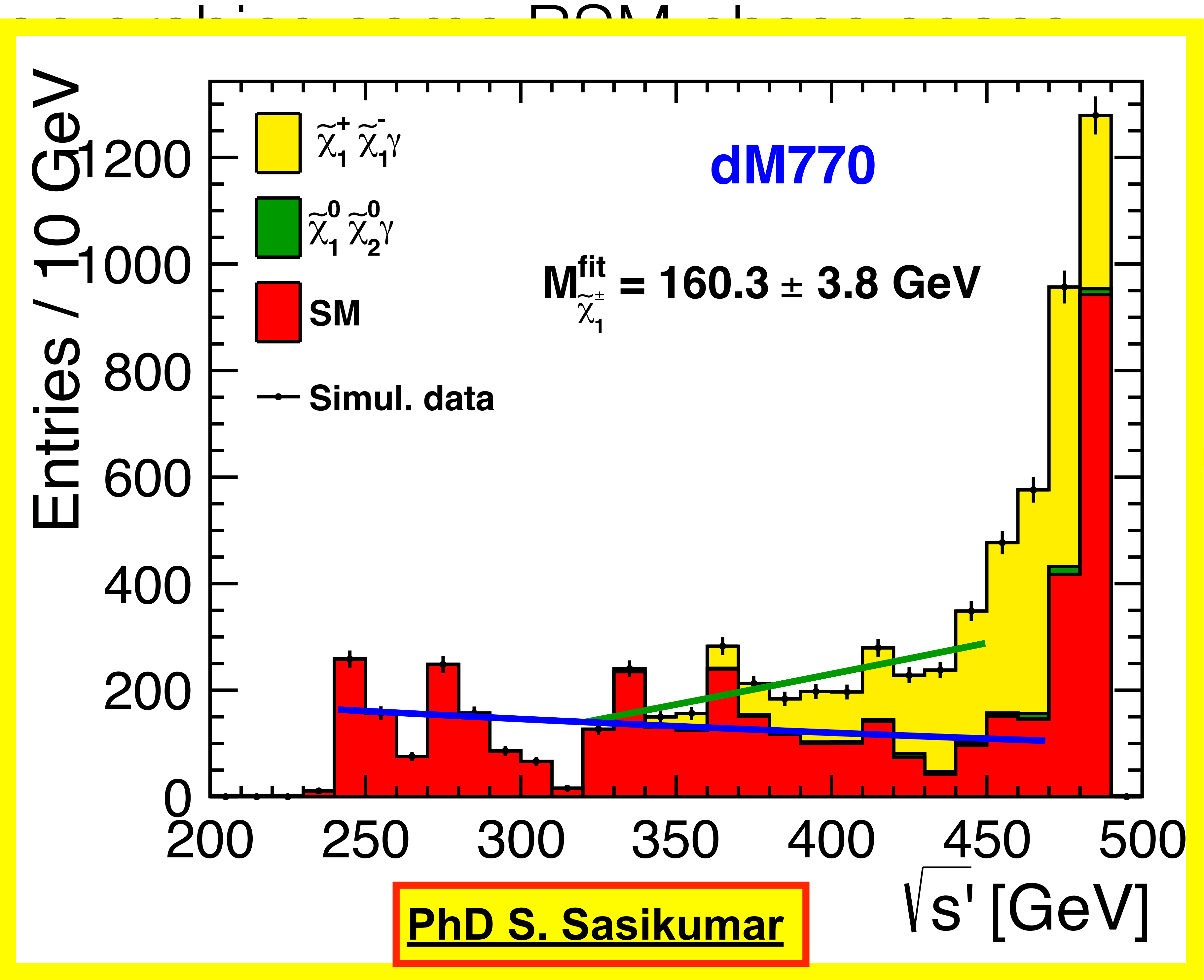

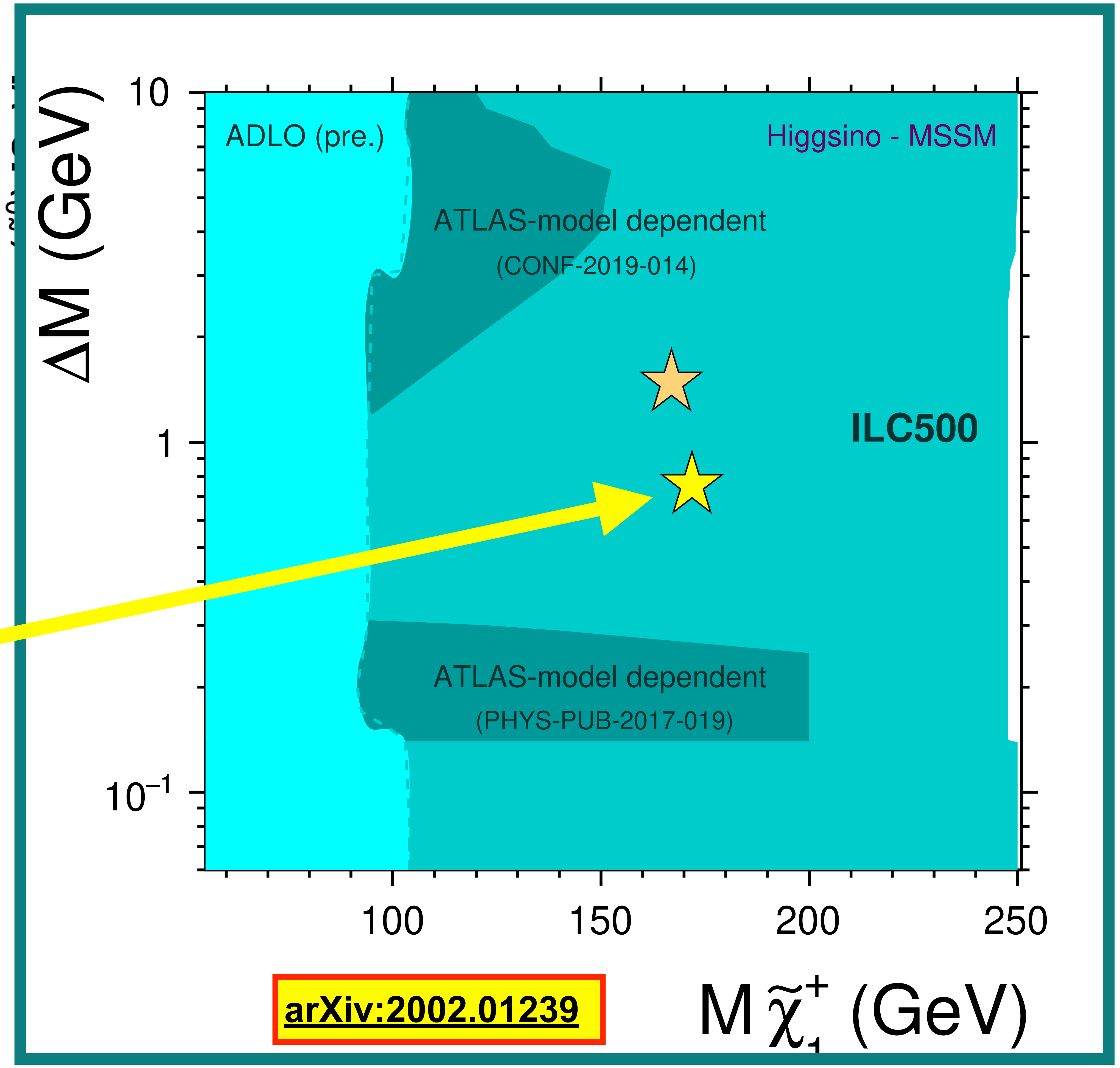

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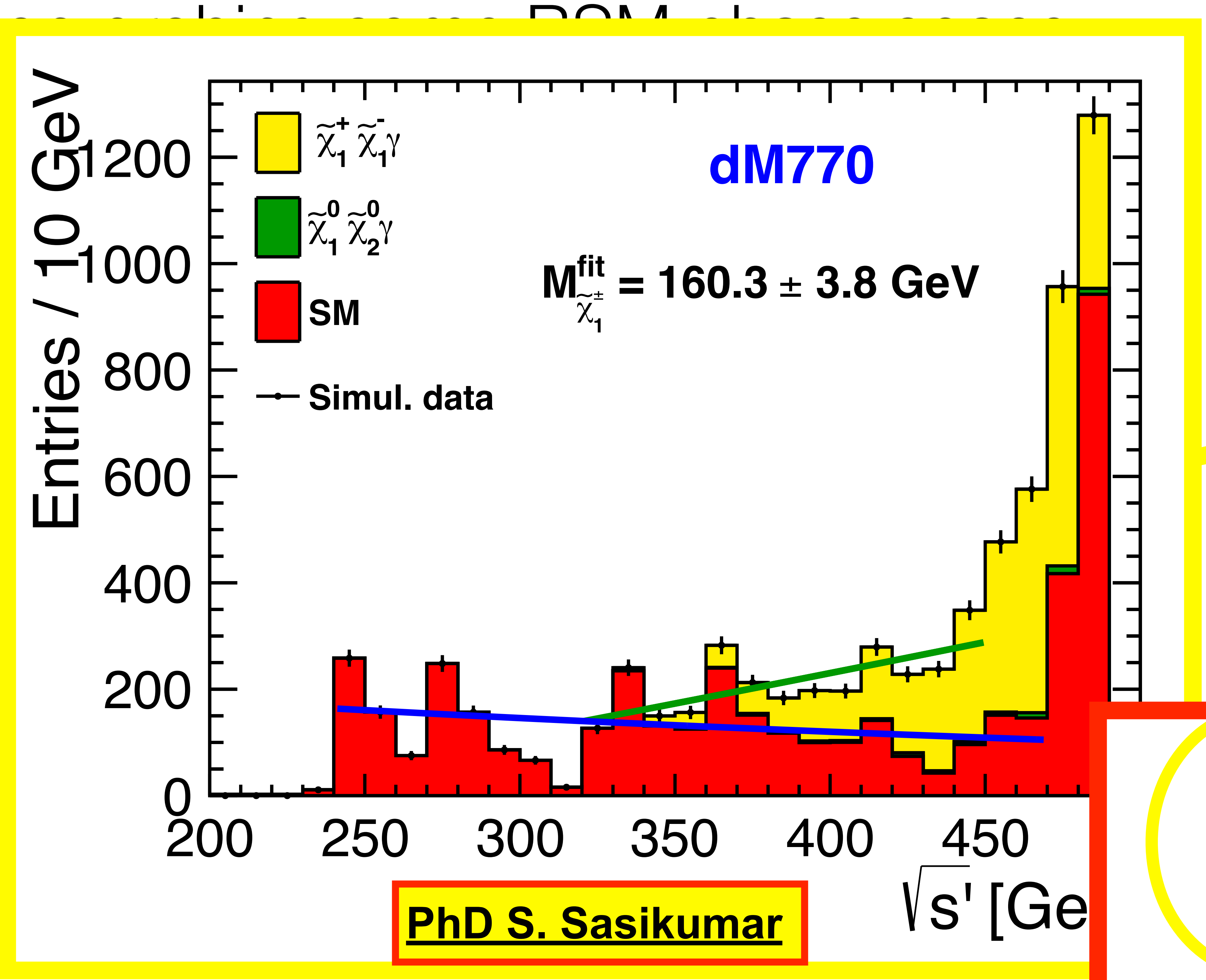

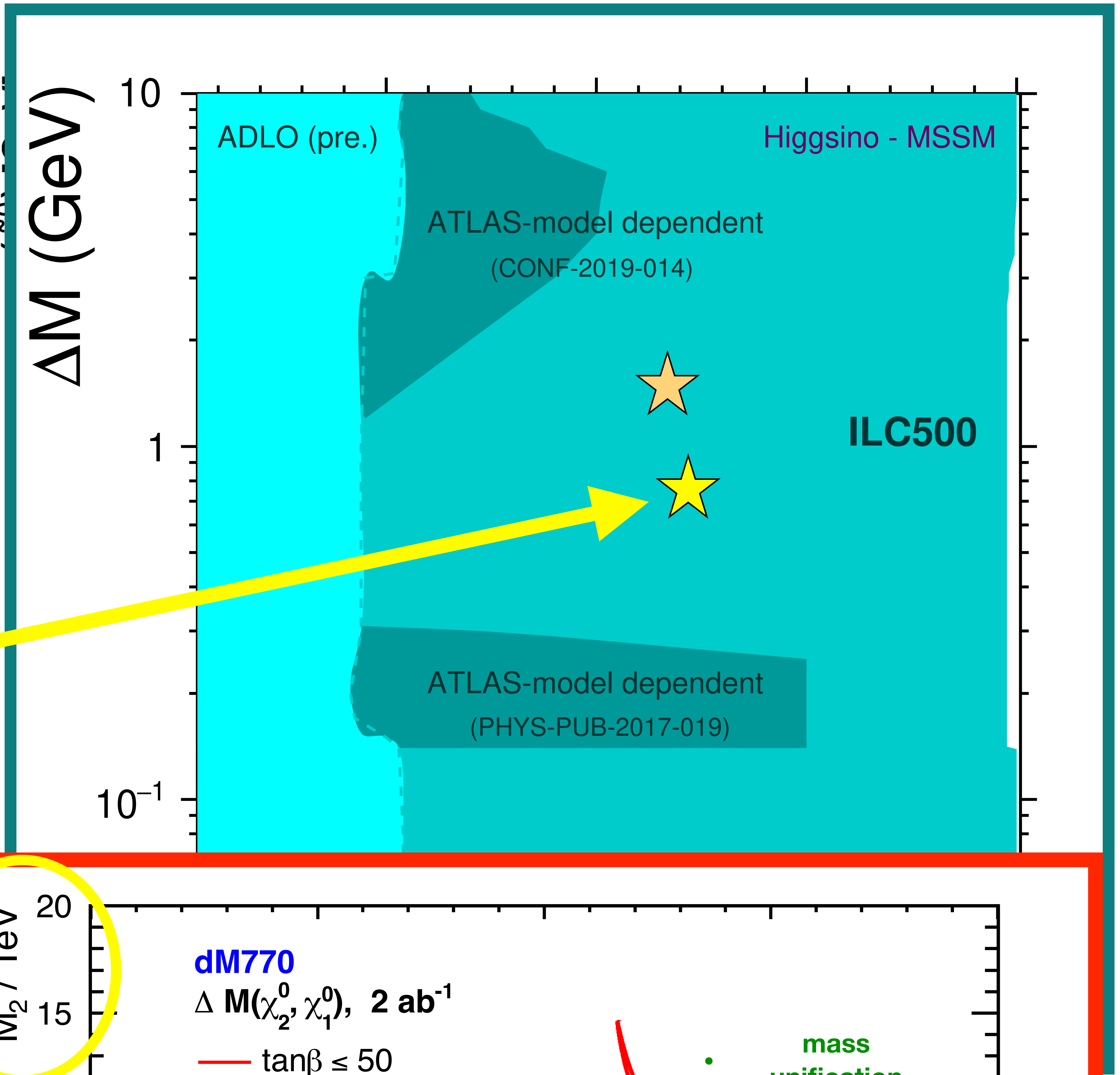

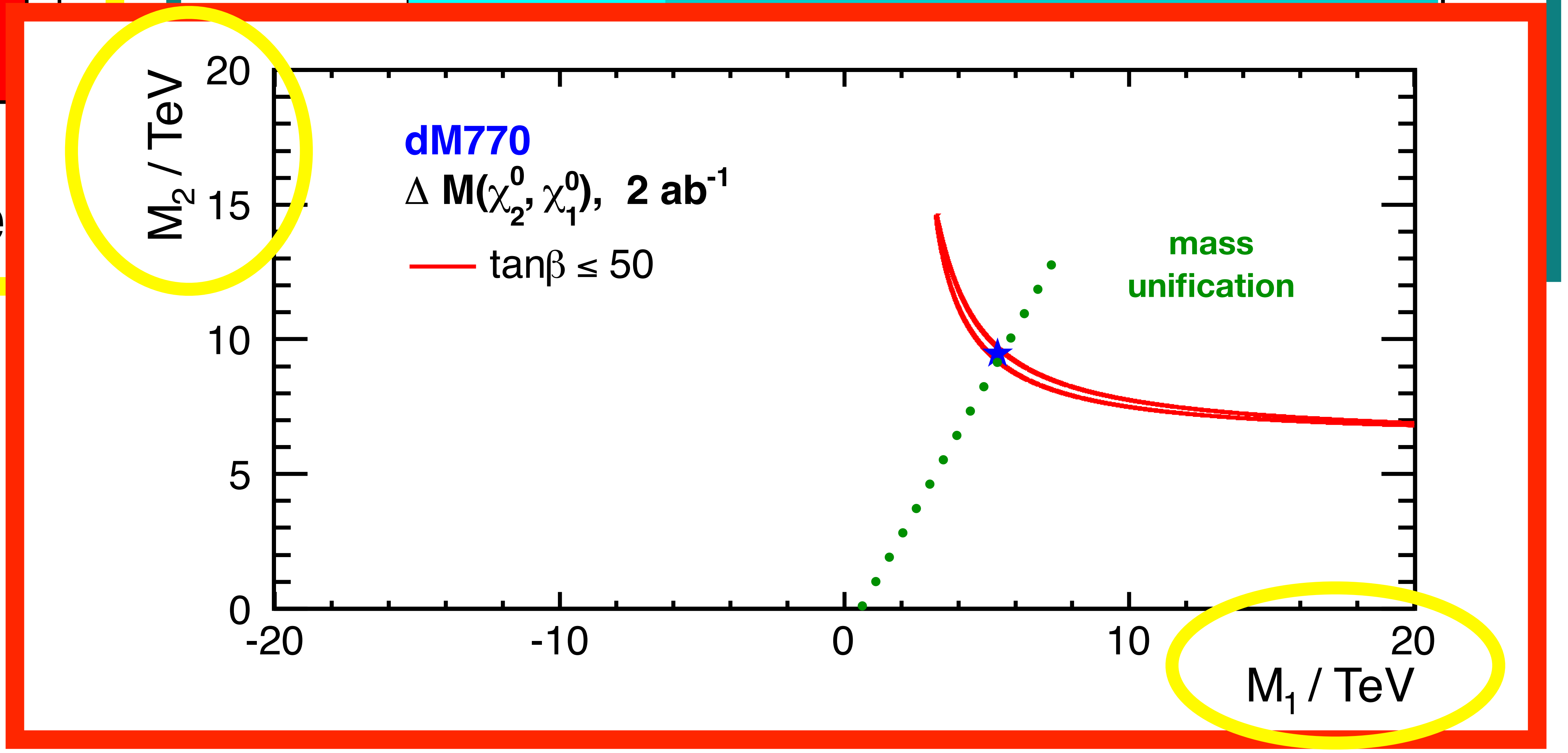

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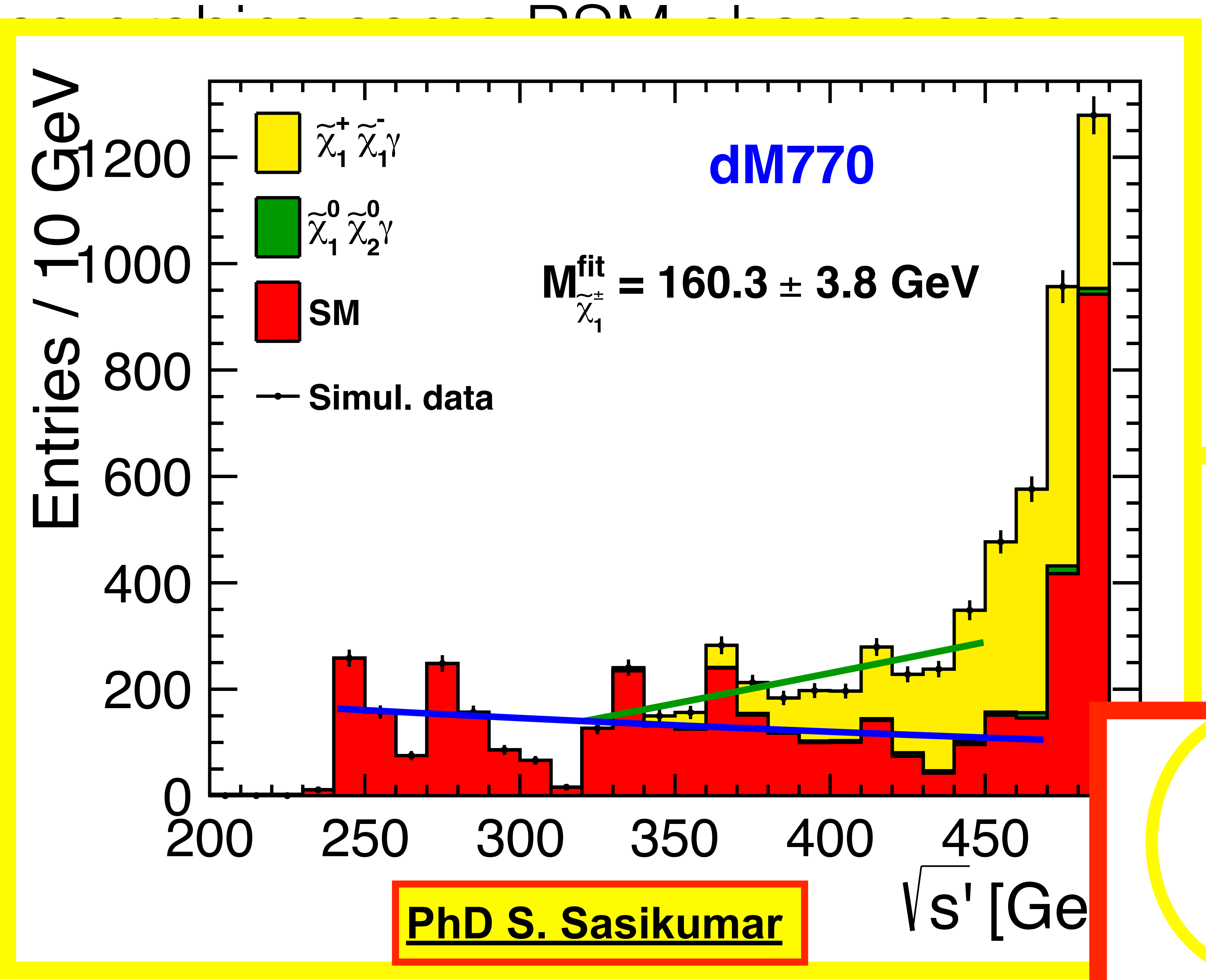
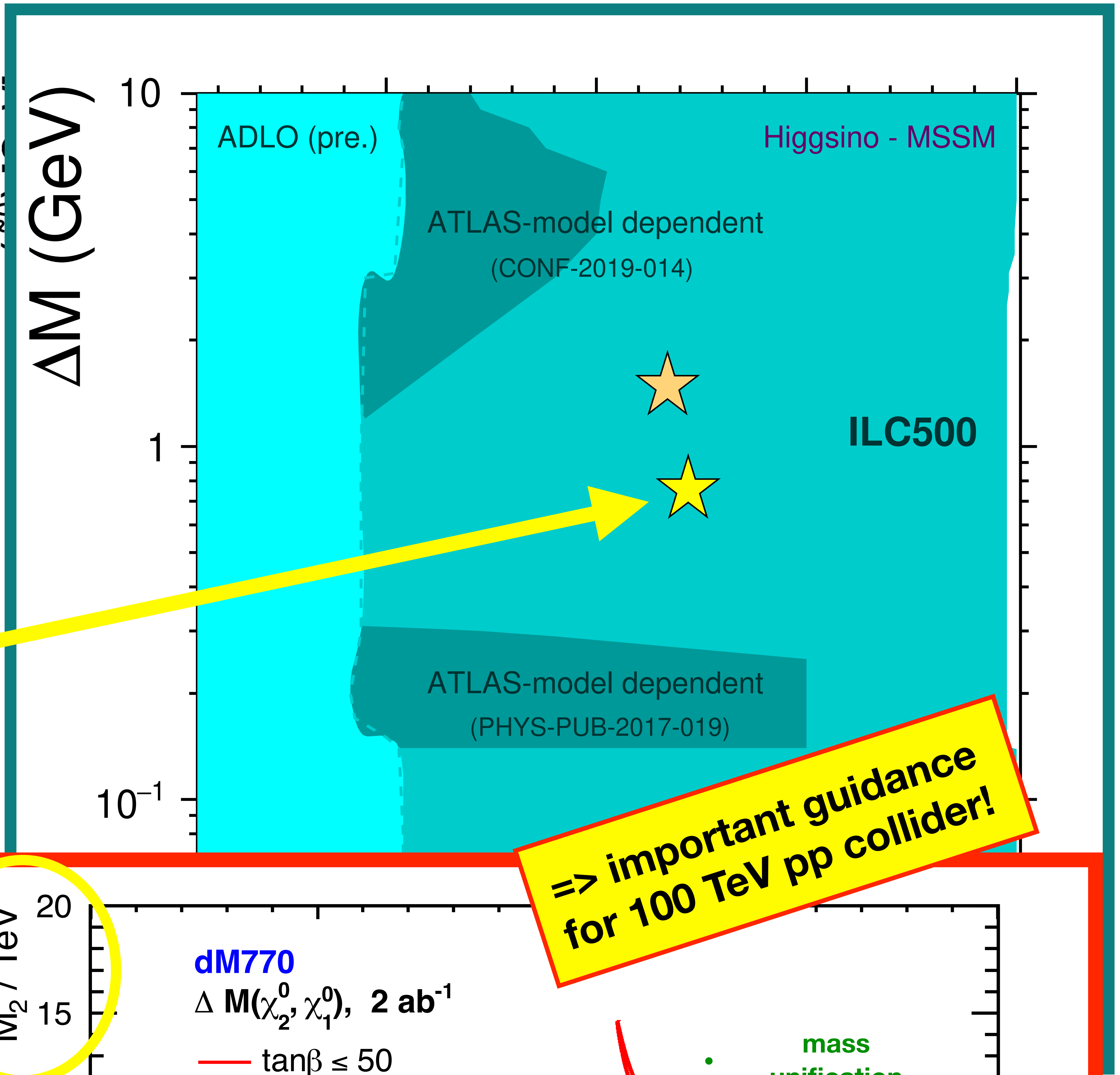
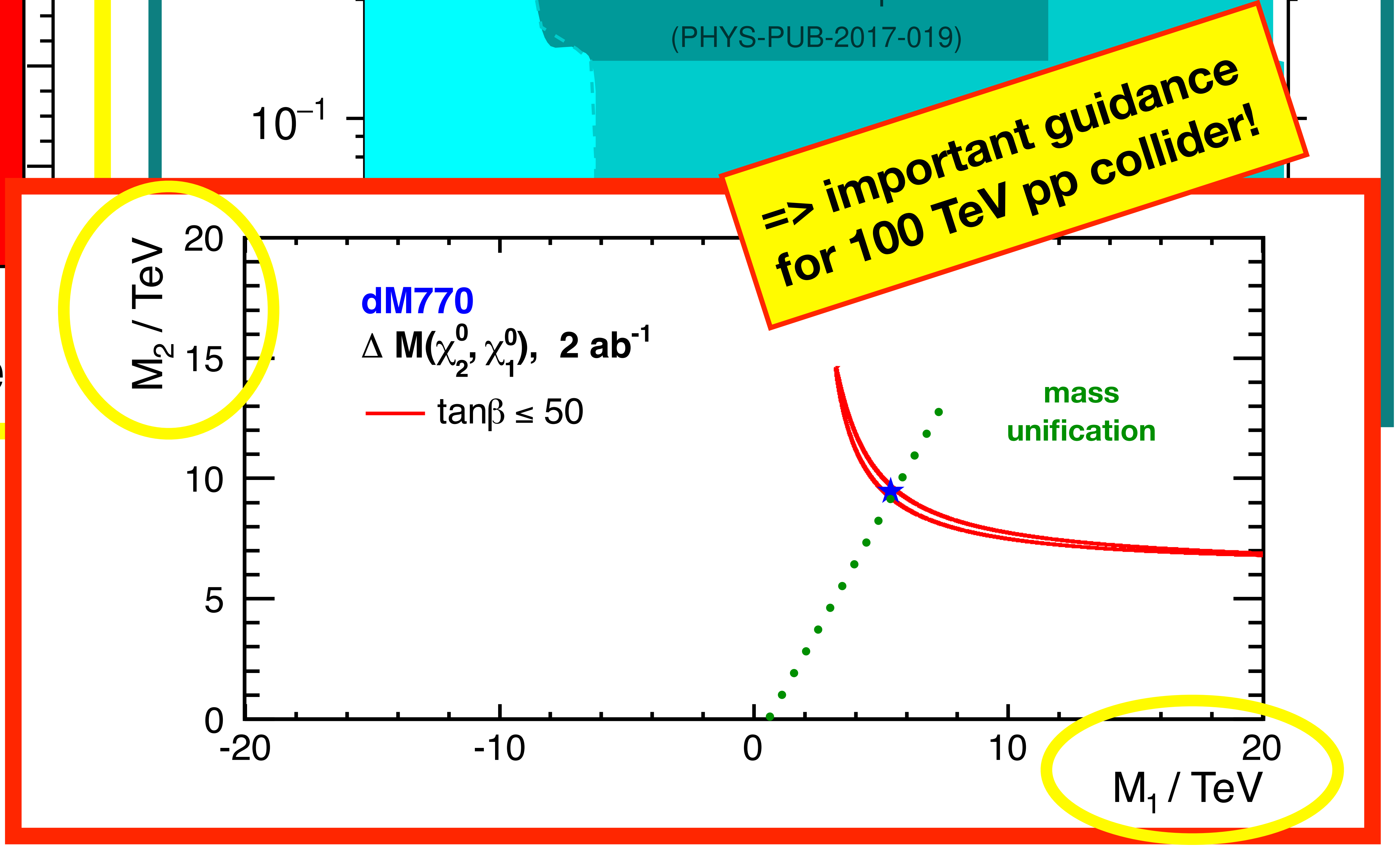


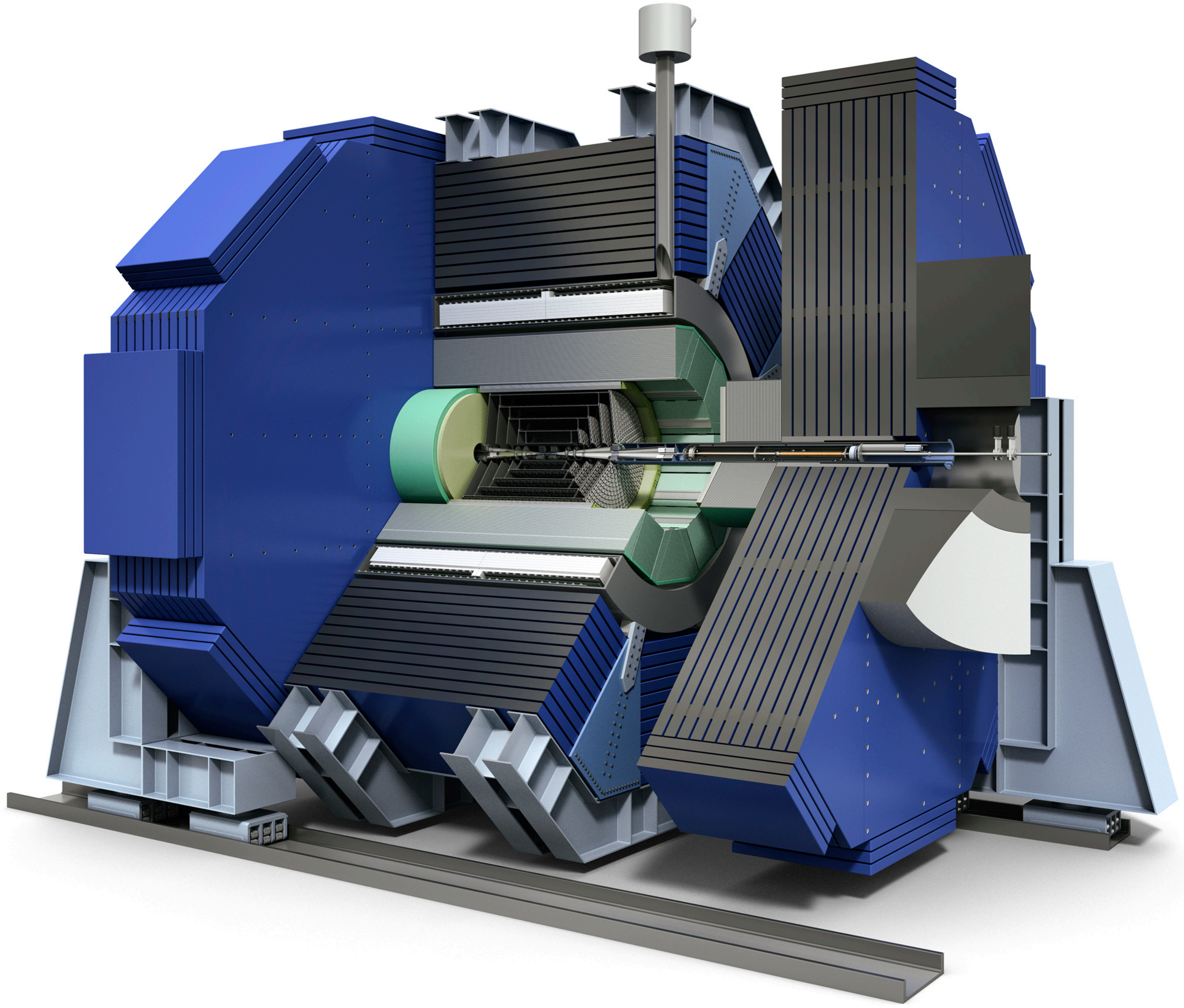


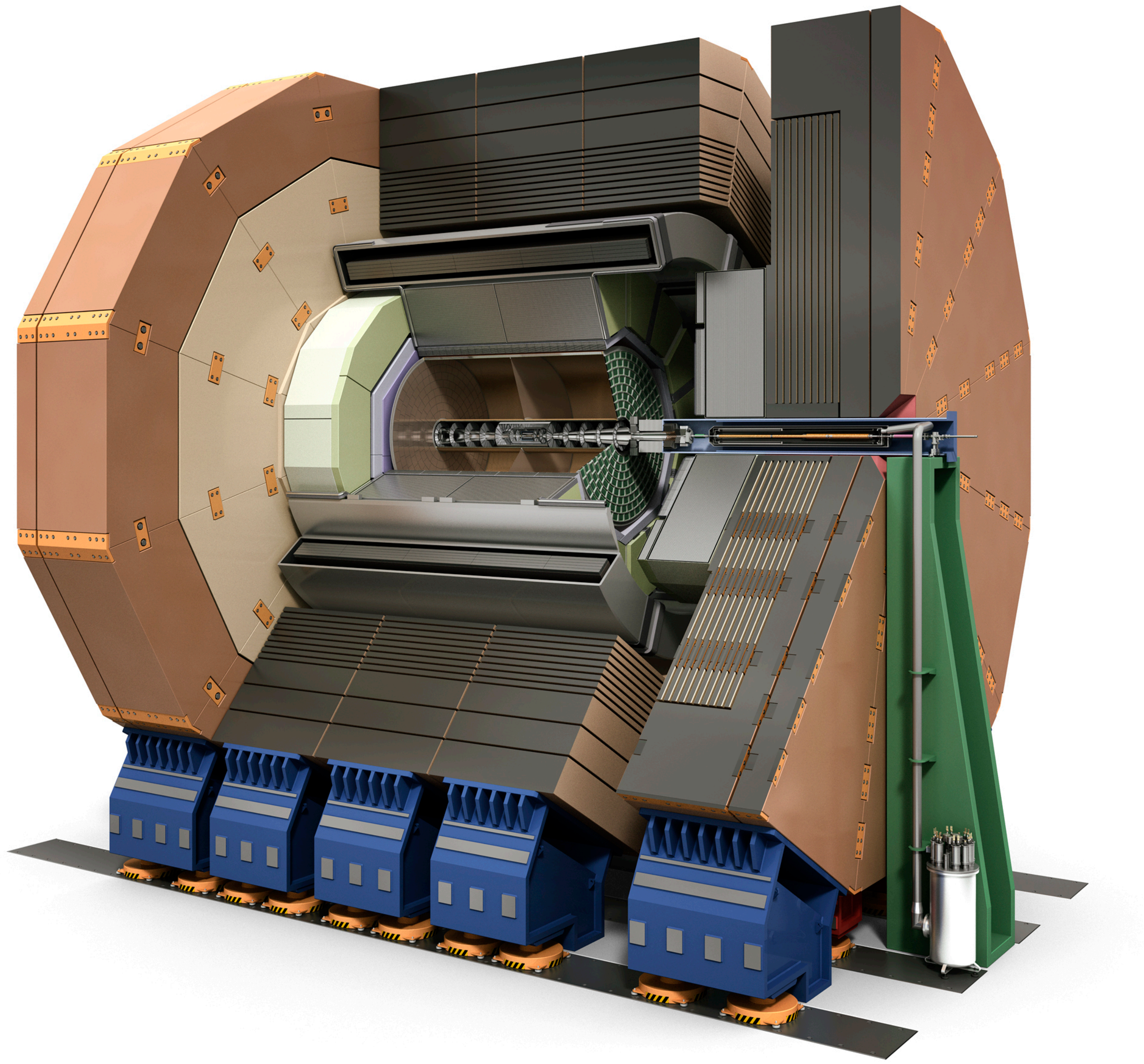


Higgs Factory Detector Concepts, Performance & Physics Analysis Challenges

Higgs Factory Detector Concepts

for linear & circular





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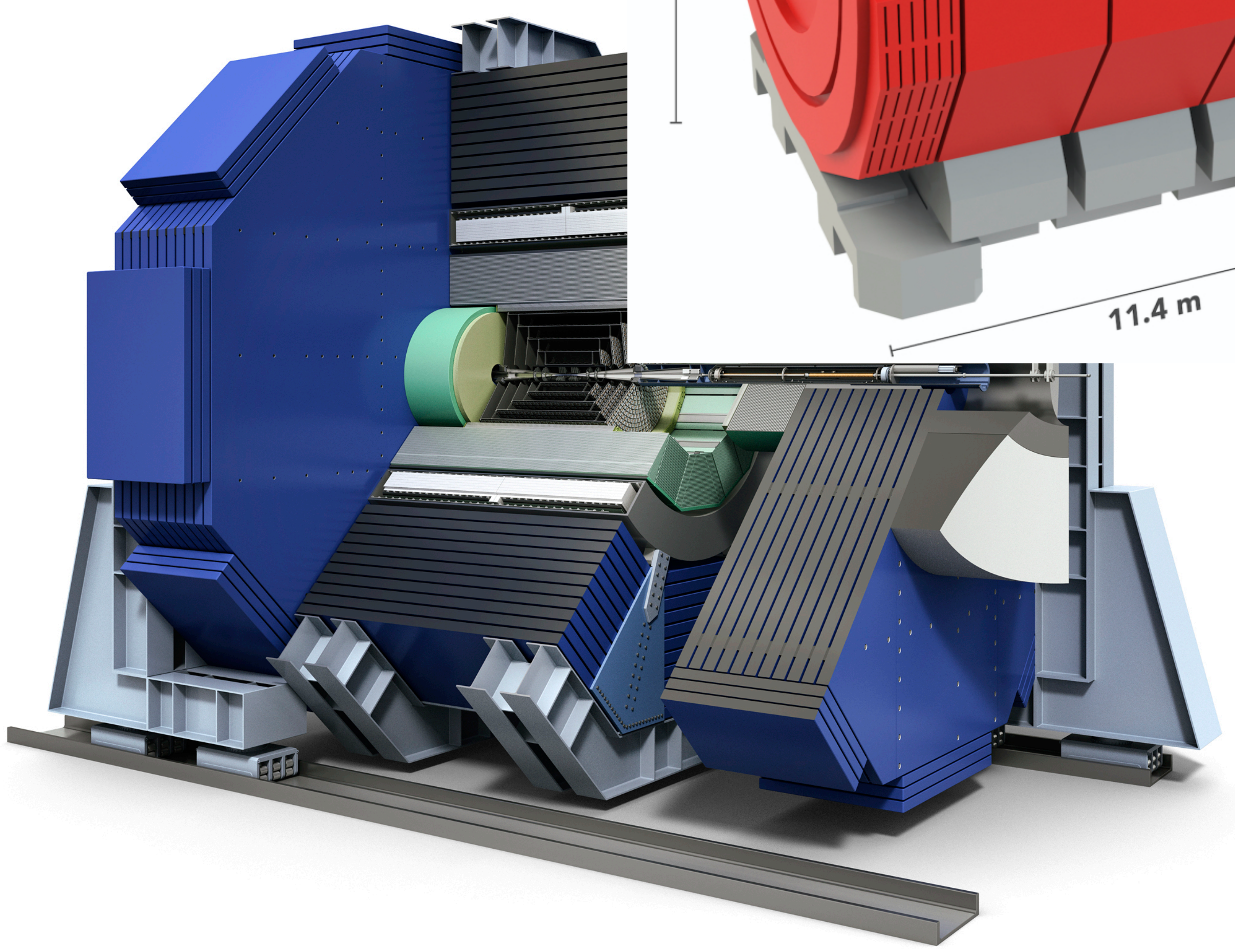

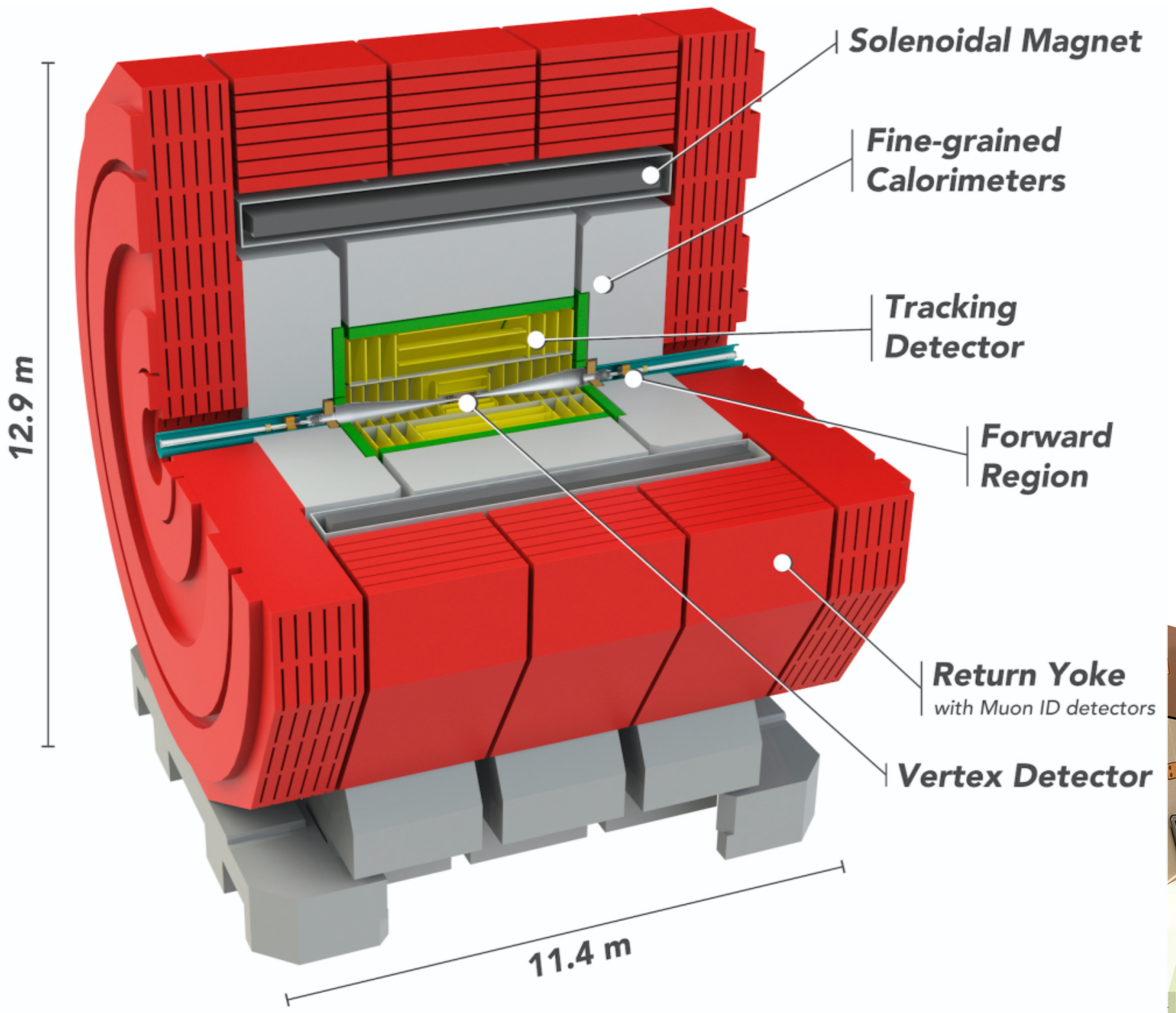

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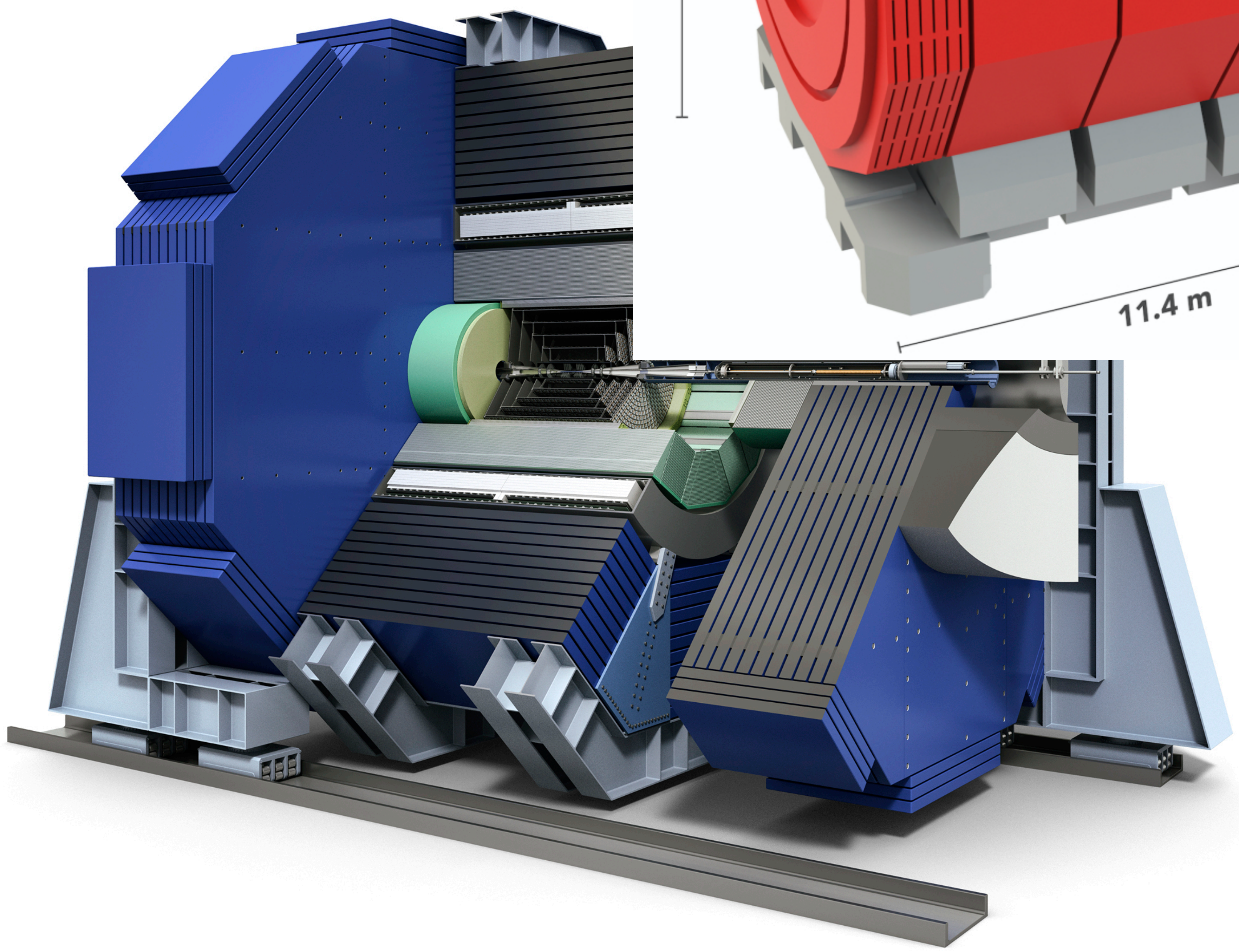

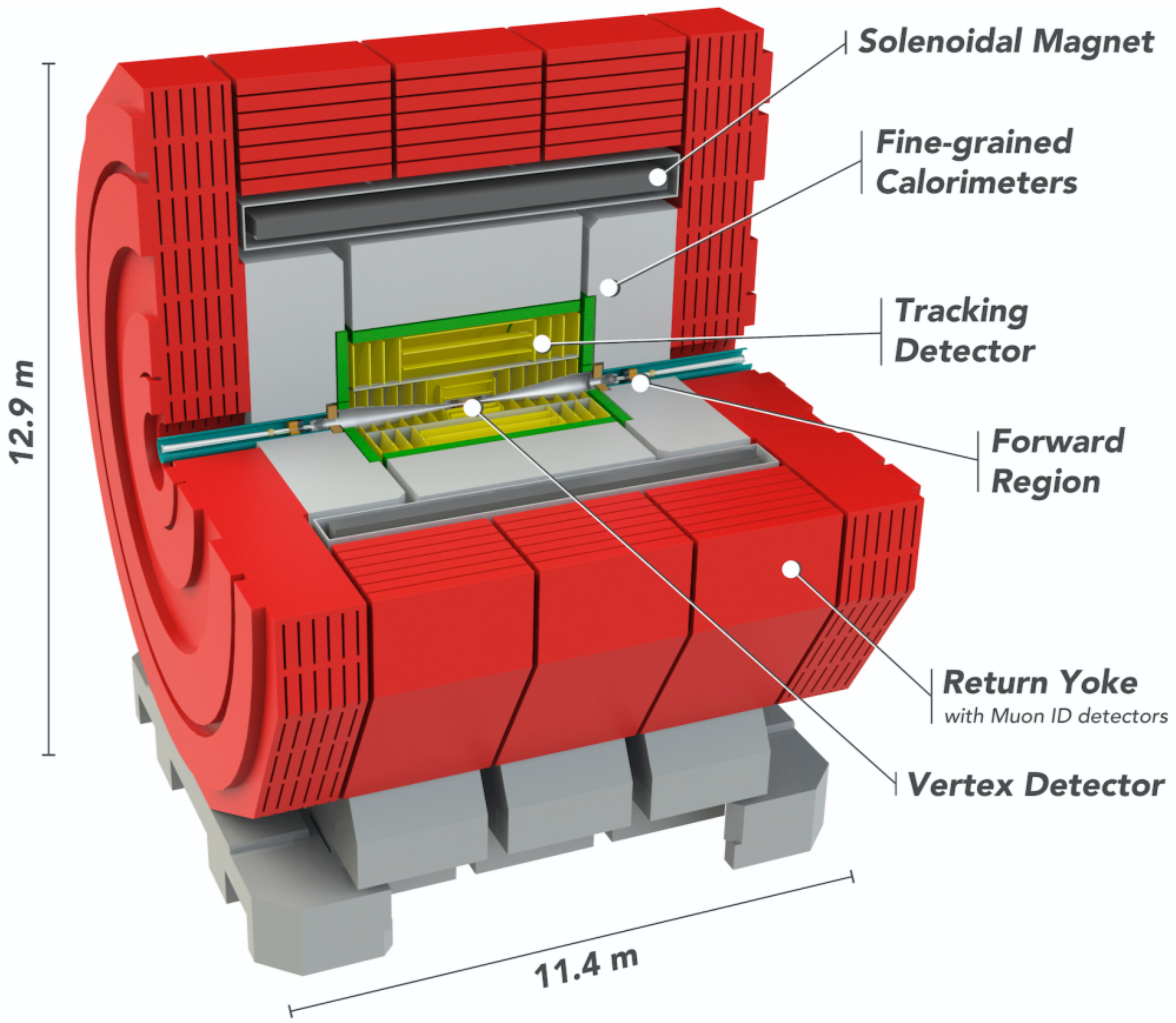

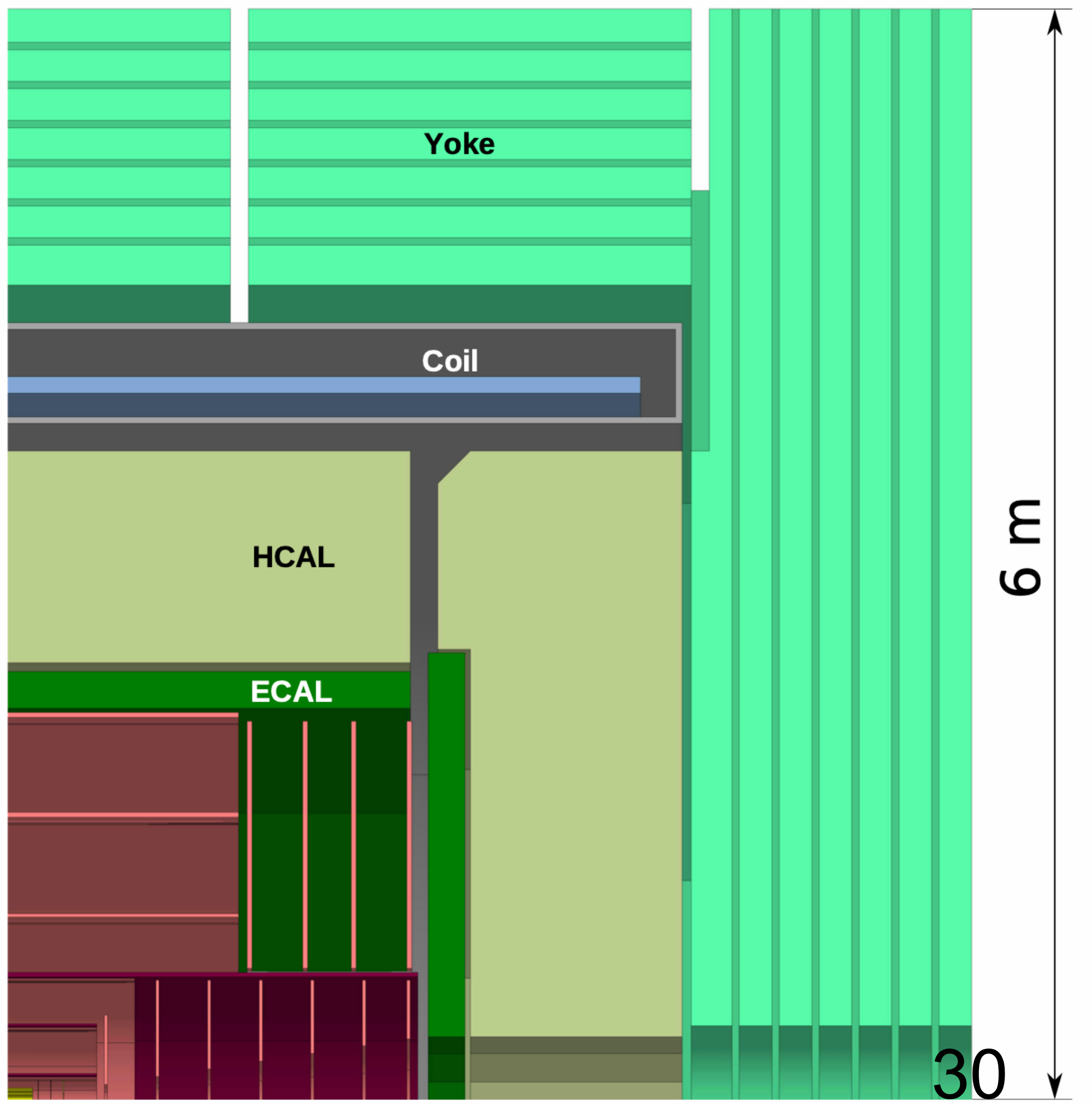

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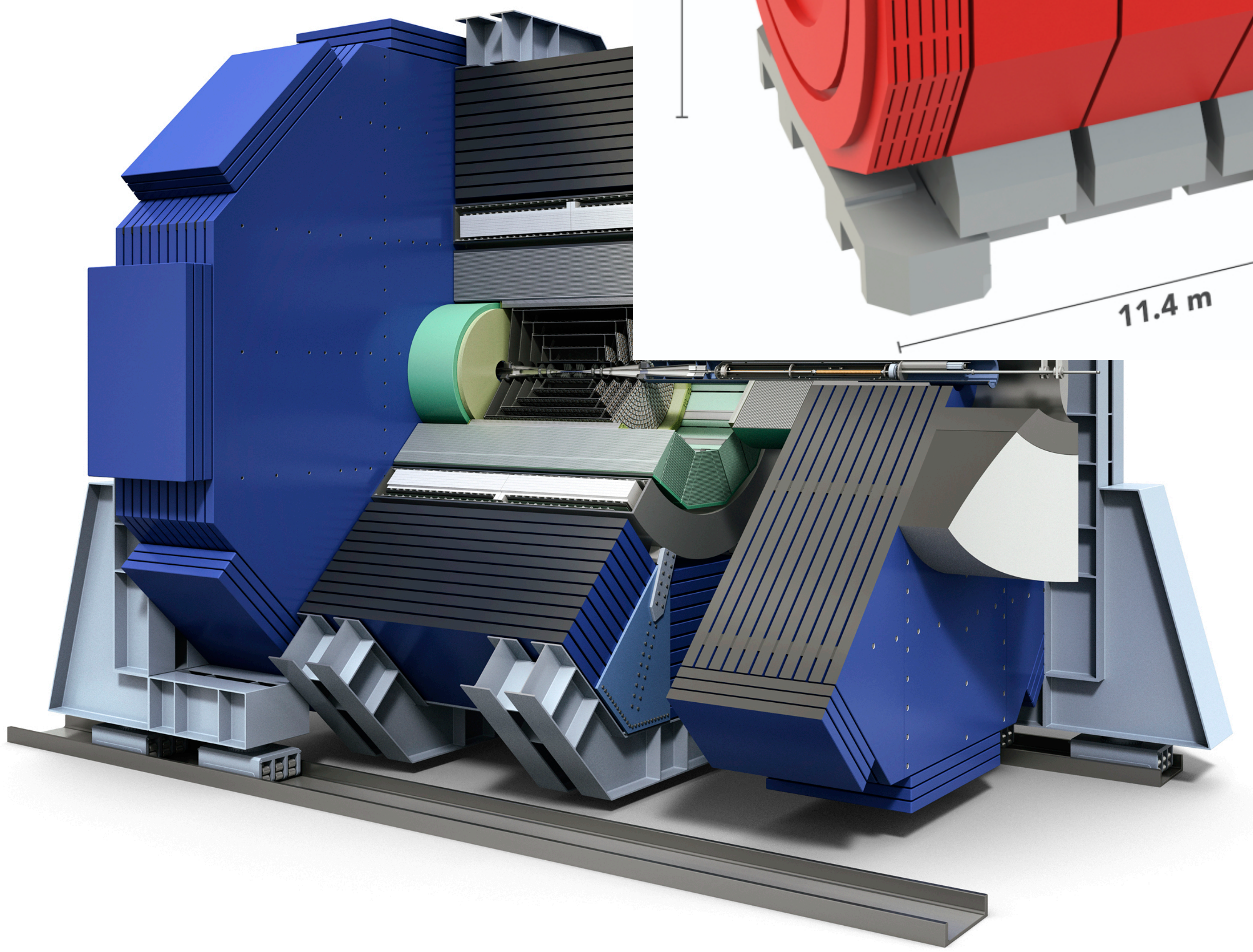

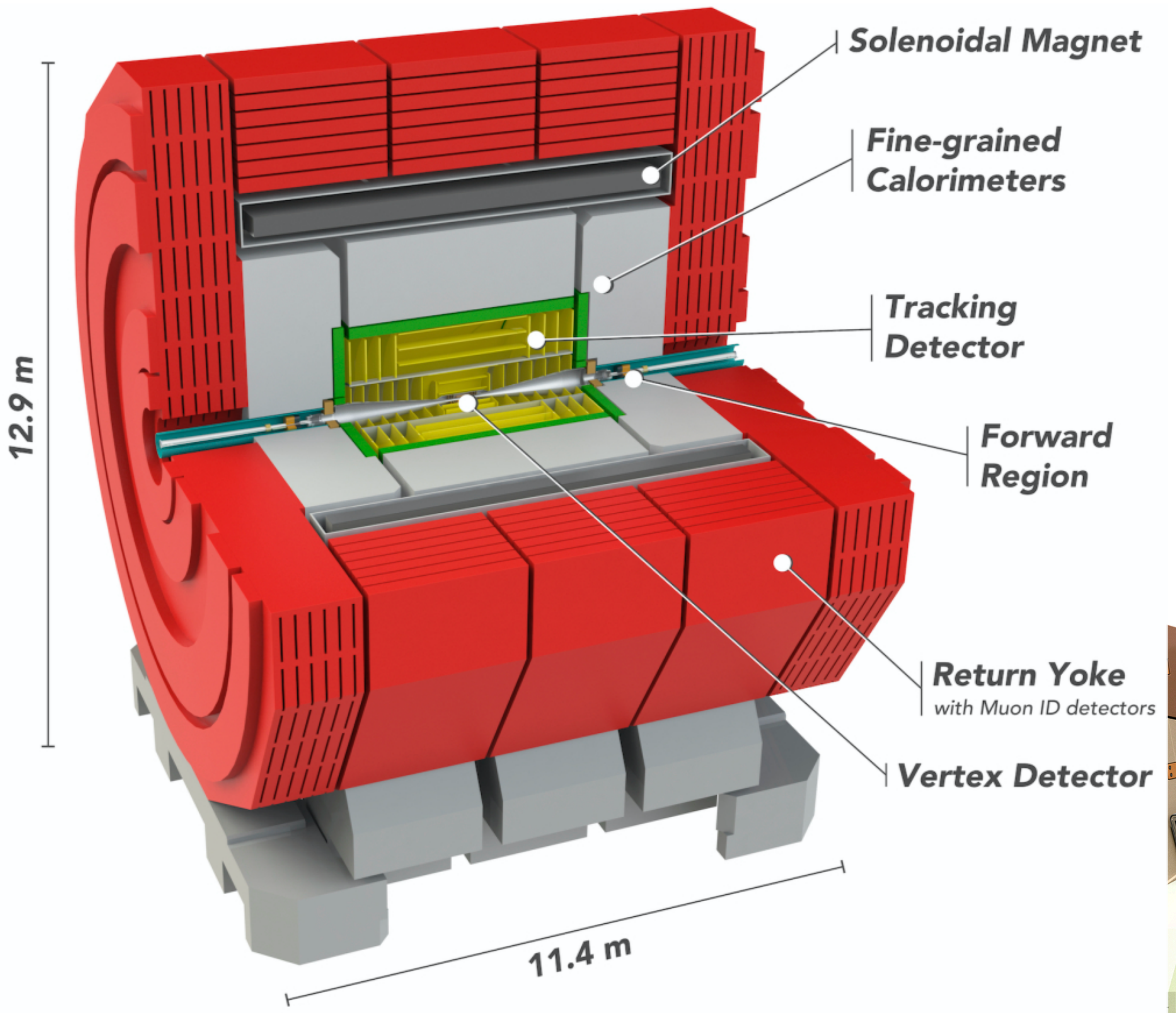

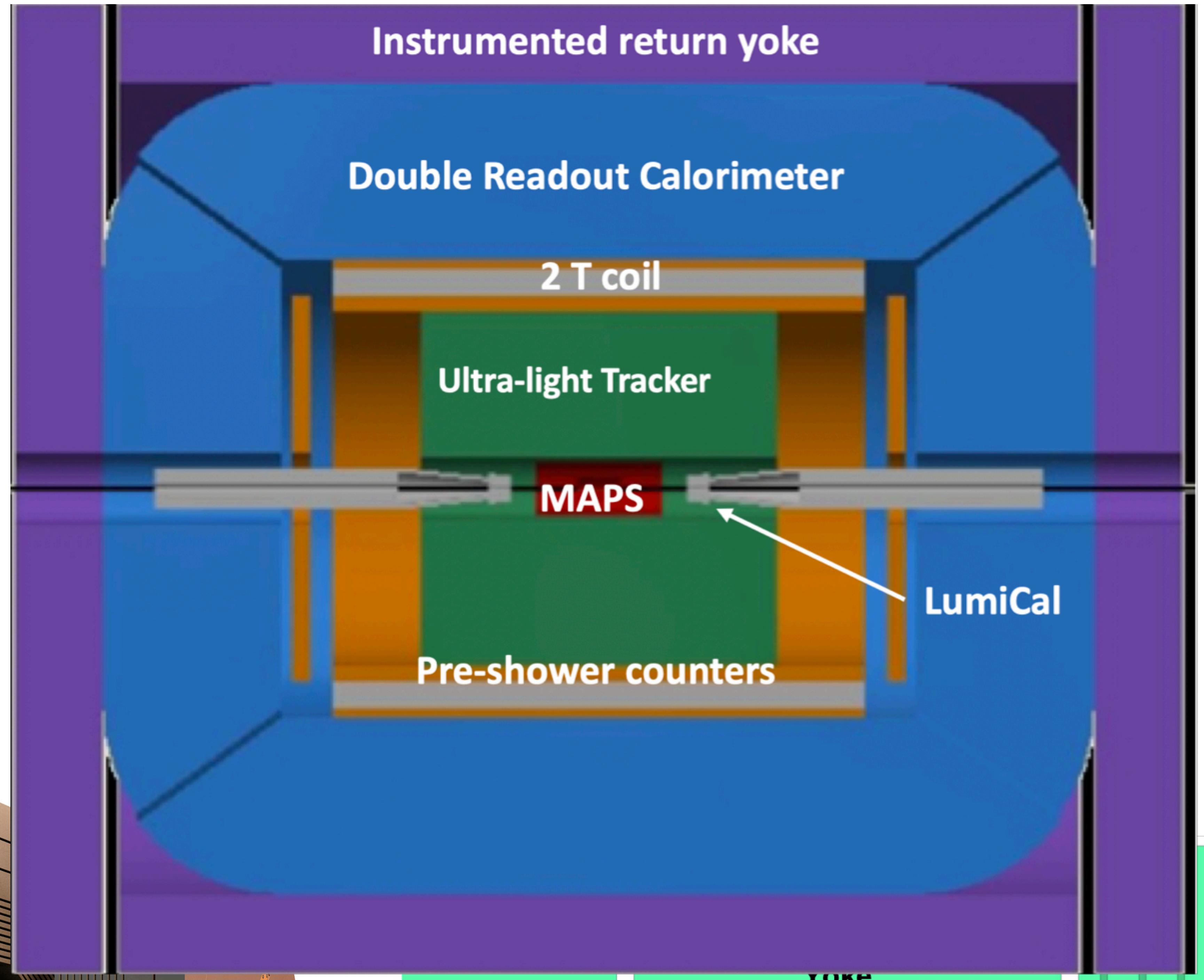

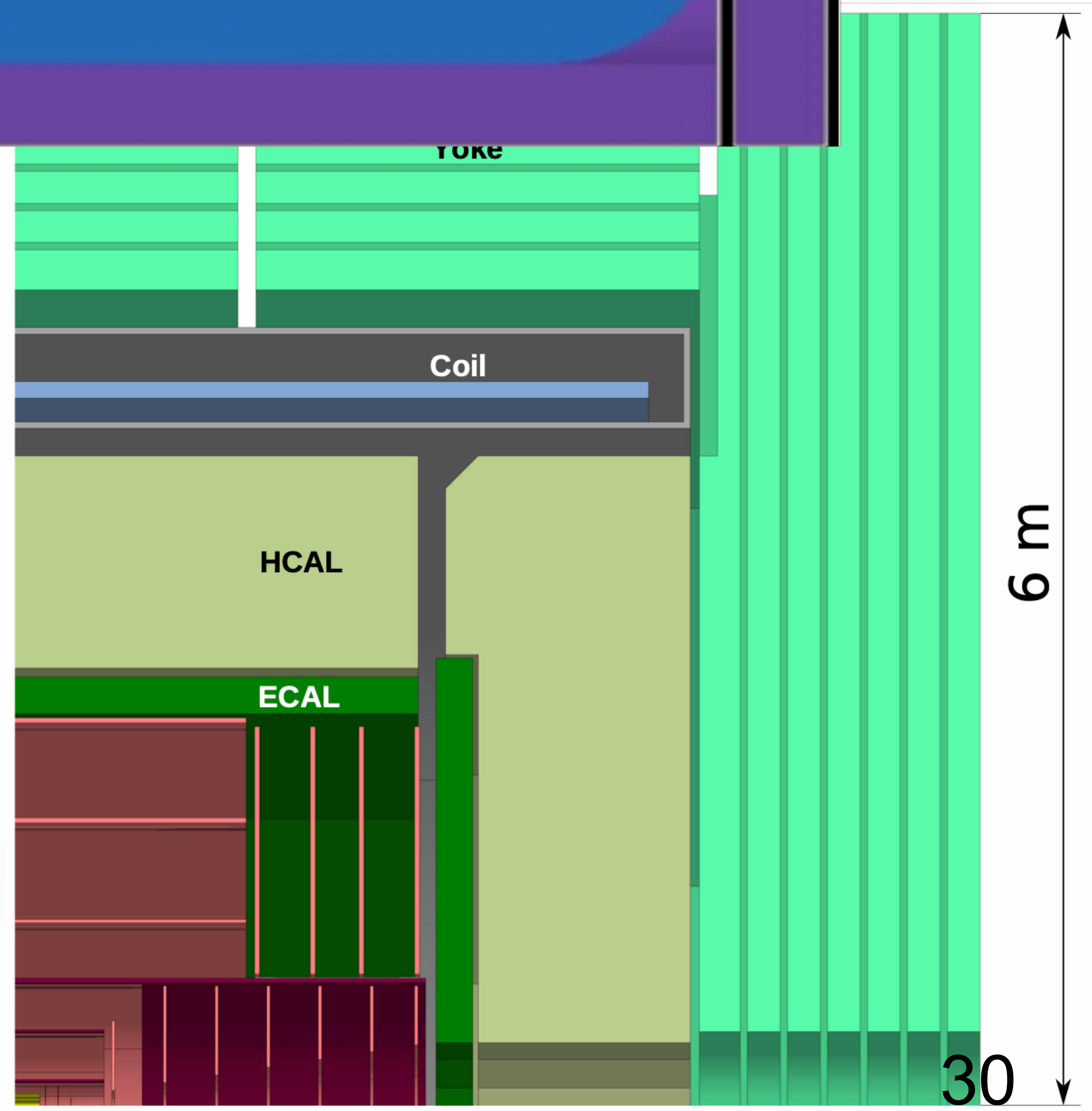

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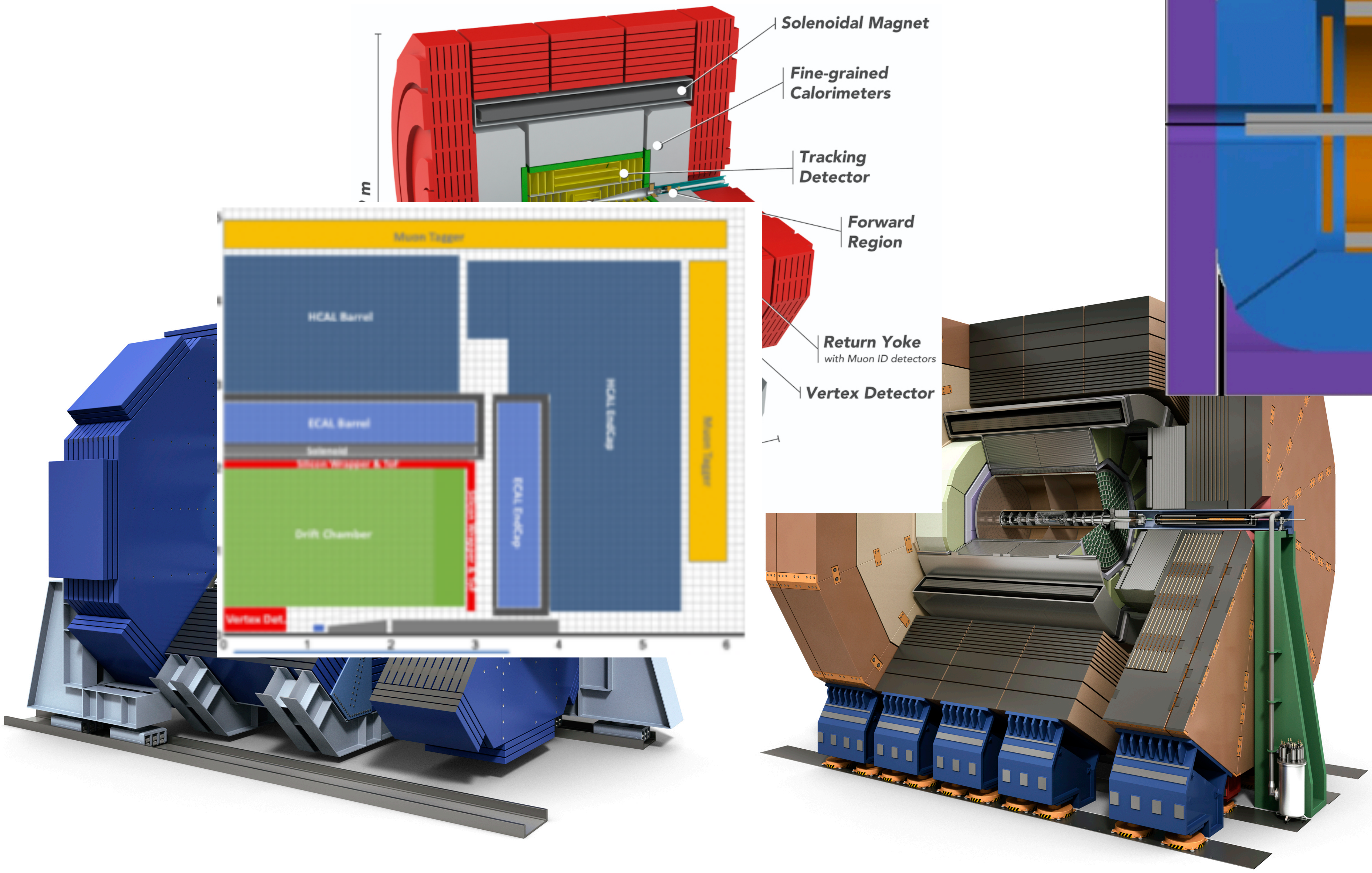

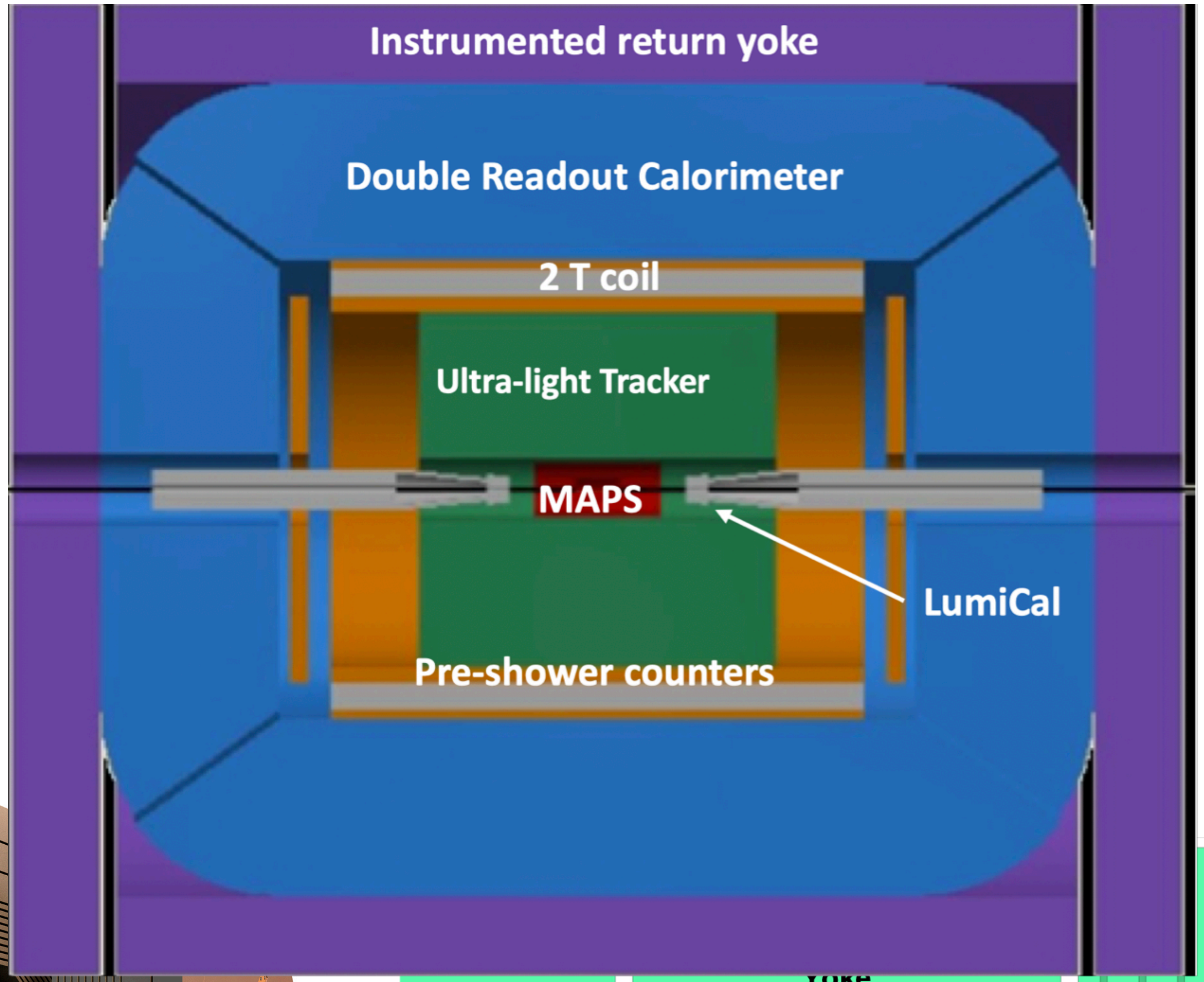

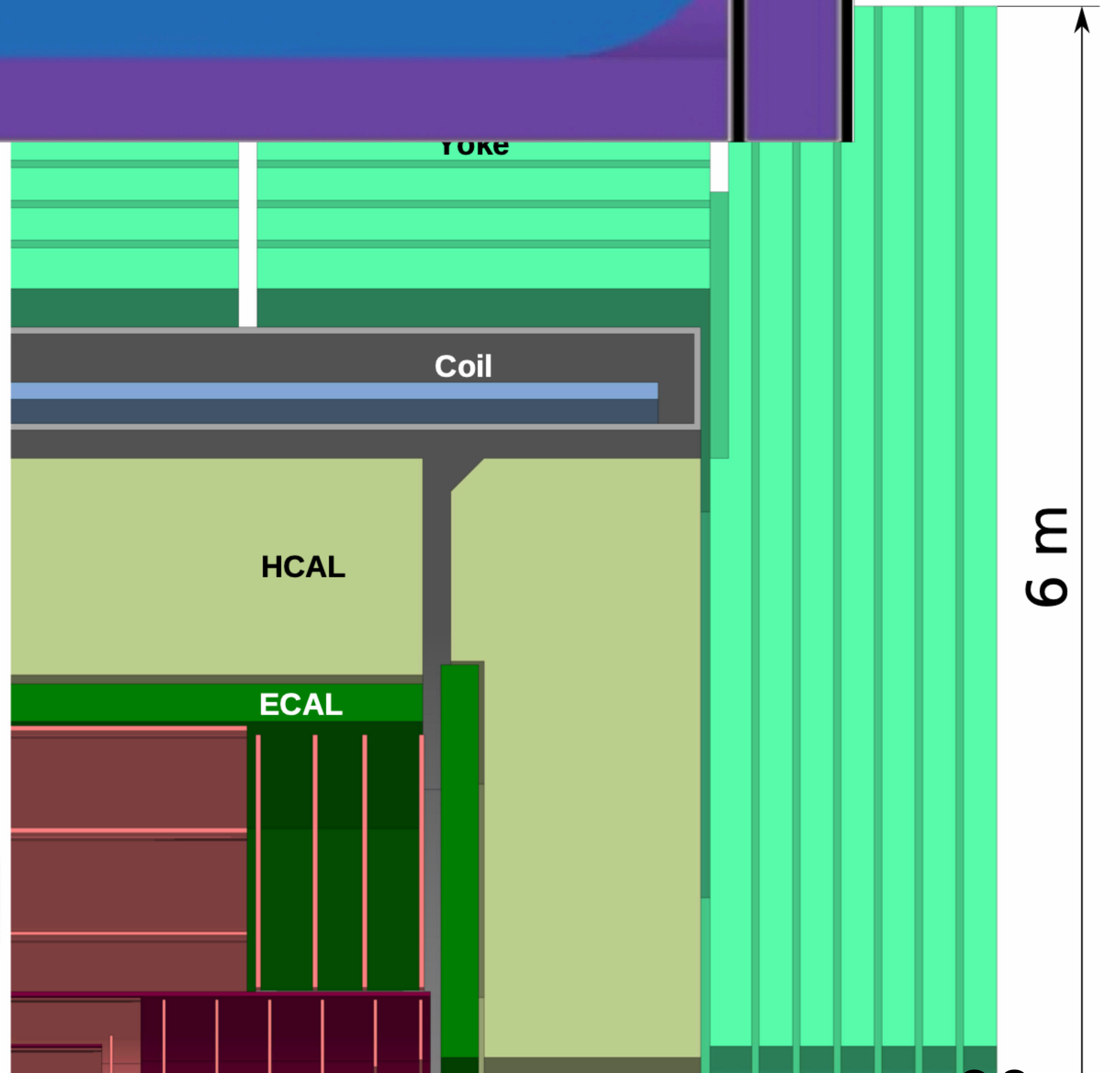

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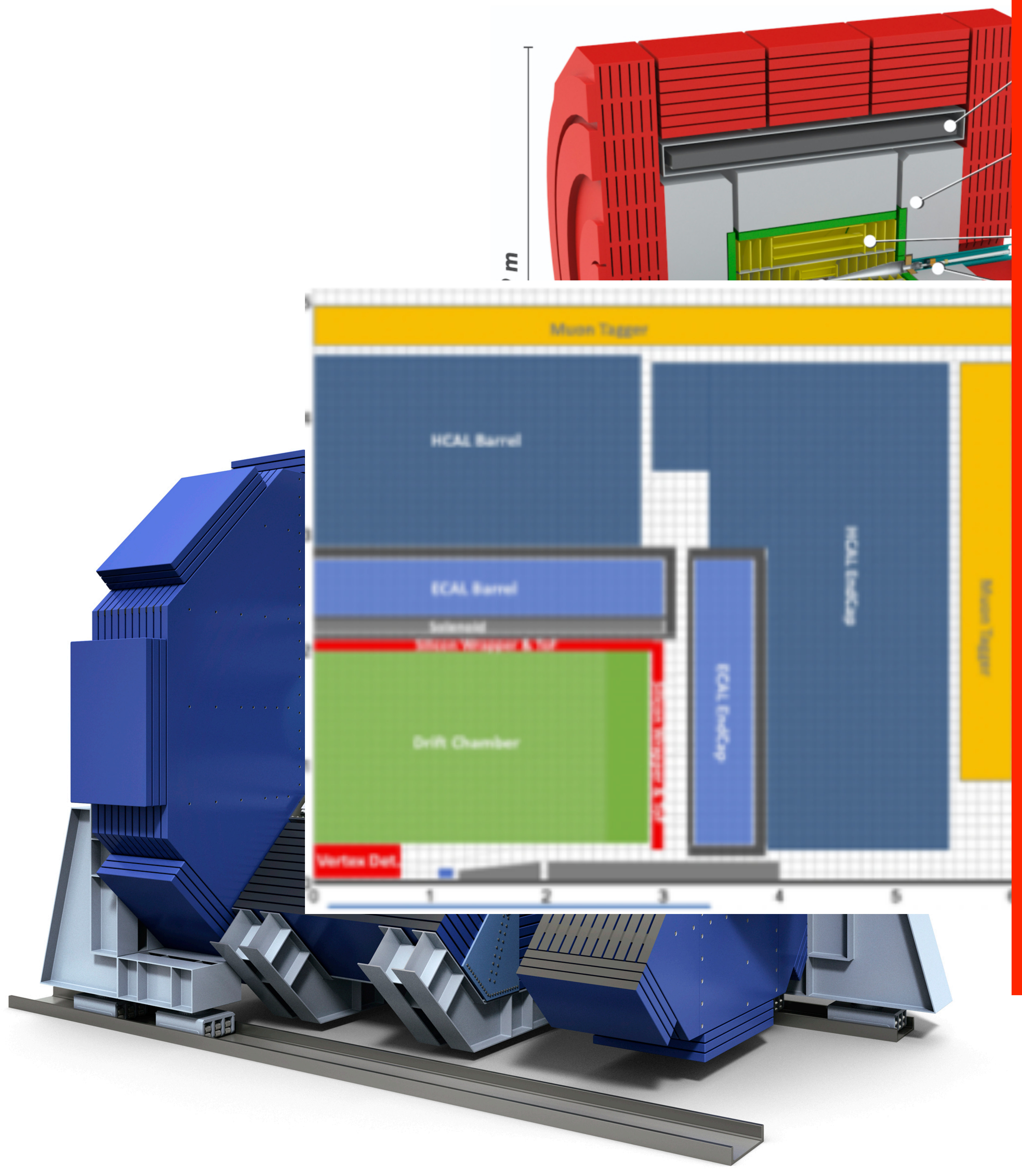

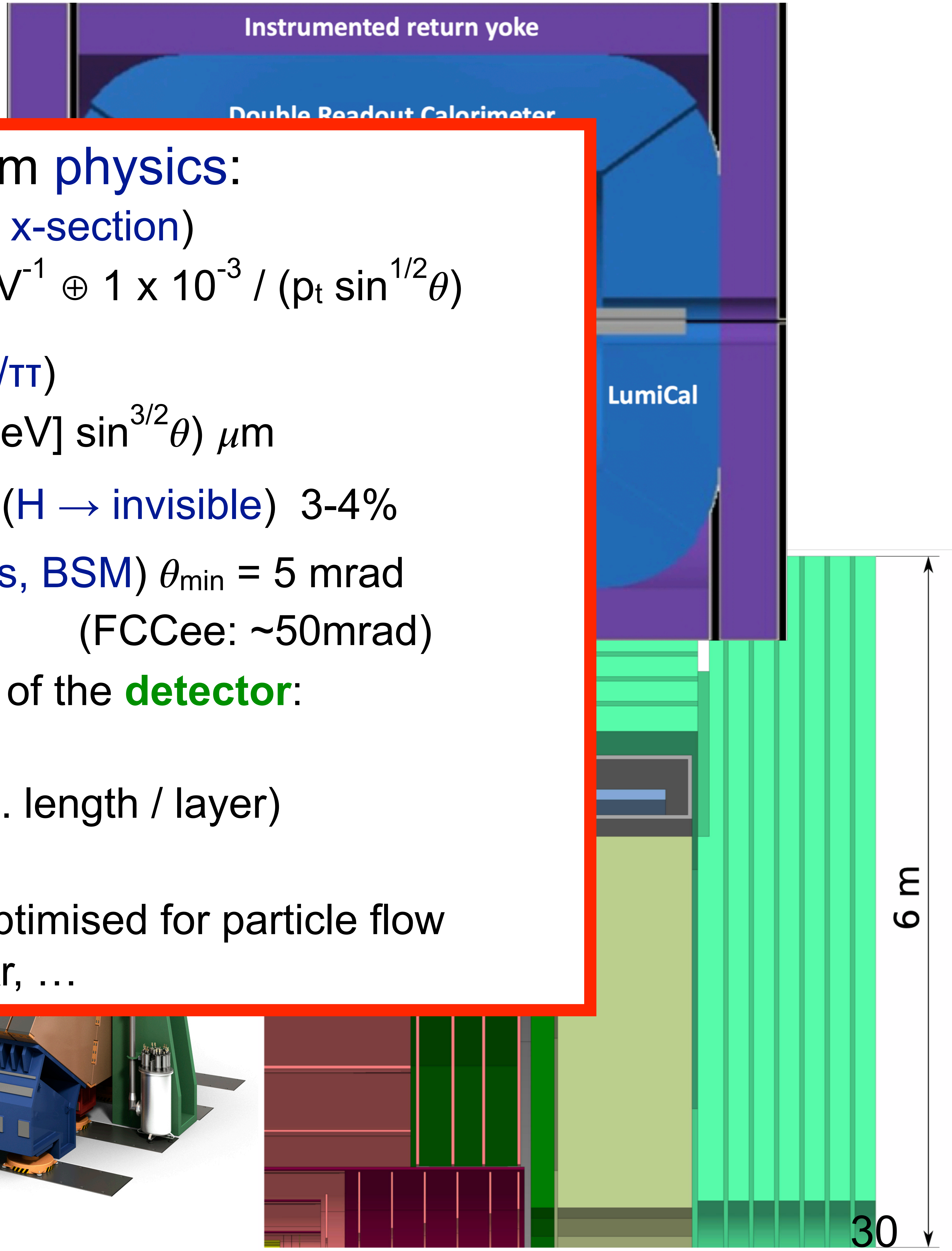

Key requirements from physics:

- **p_t resolution** (total ZH x-section)
  $\sigma(1/p_t) = 2 \times 10^{-5}\ \mathrm{GeV}^{-1} \oplus 1 \times 10^{-3} / (p_t \sin^{1/2}\theta)$
- **vertexing** ($H \rightarrow bb/cc/\tau\tau$)
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- **jet energy resolution** ($H \rightarrow$ invisible) 3-4%
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  (FCCee: ~50mrad)

Determine to key features of the detector:

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  - **highly granular,** optimised for particle flow
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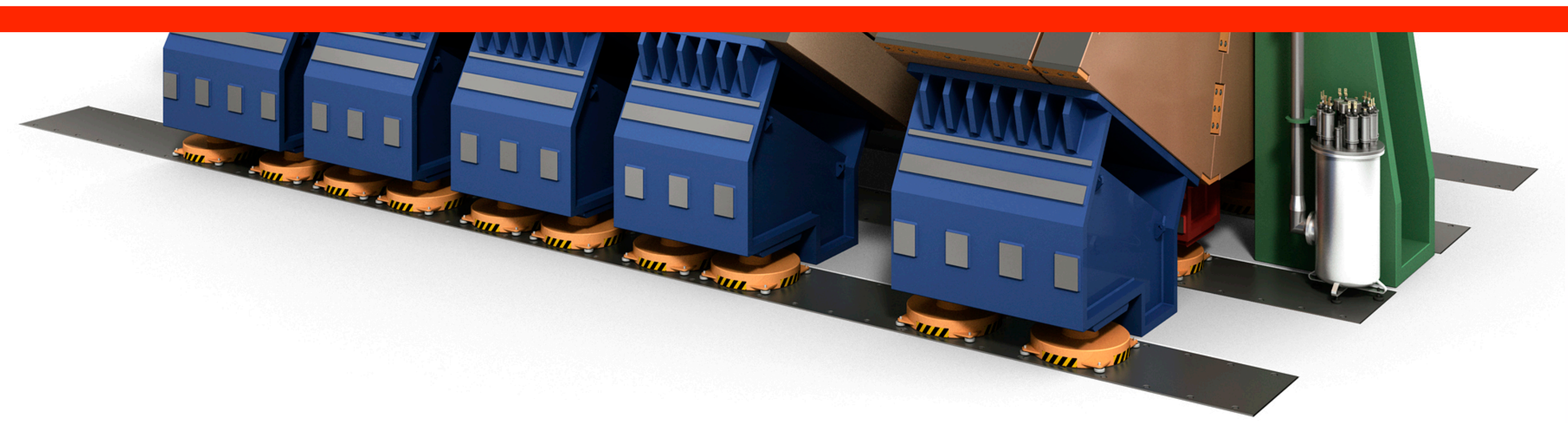

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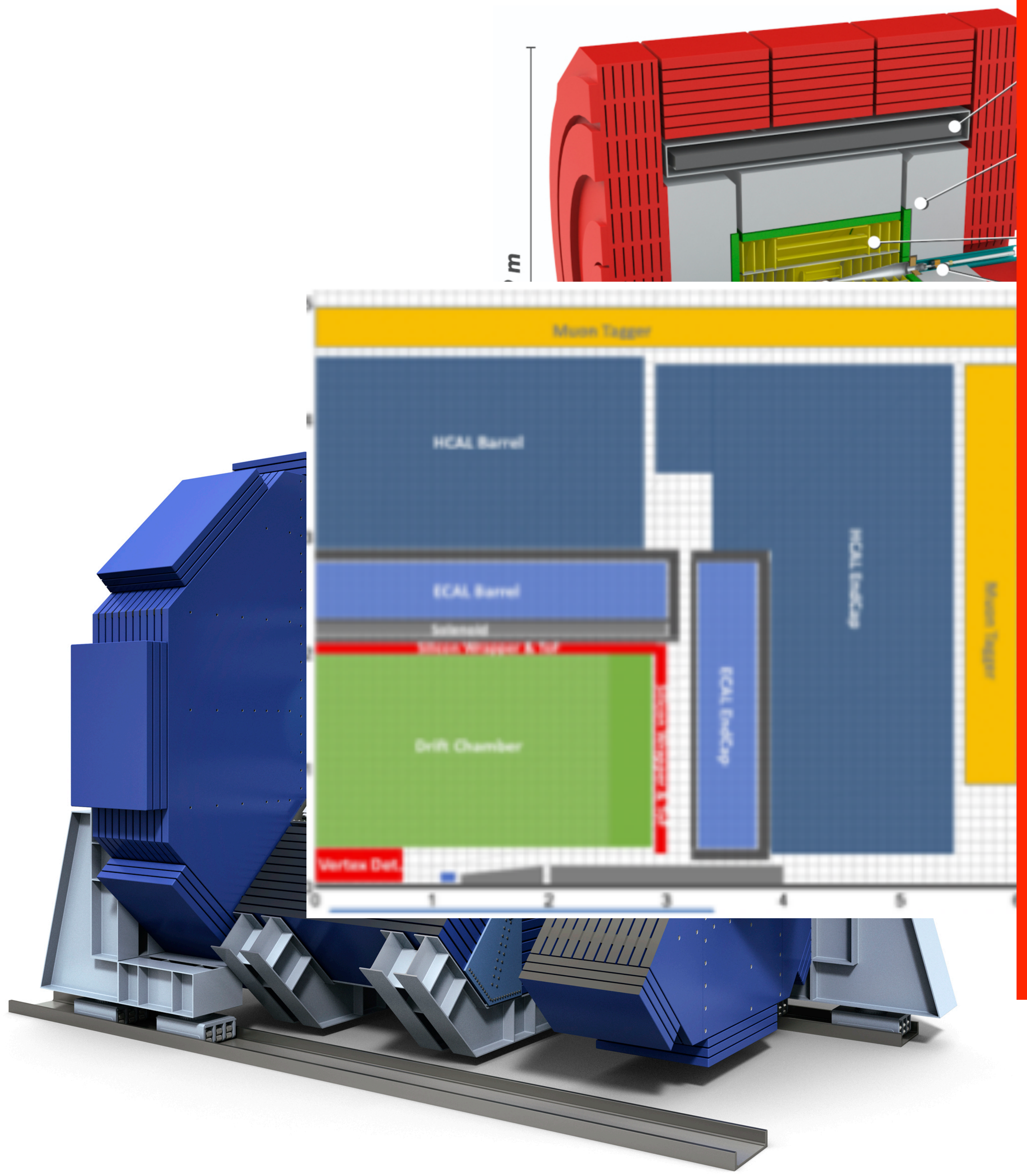

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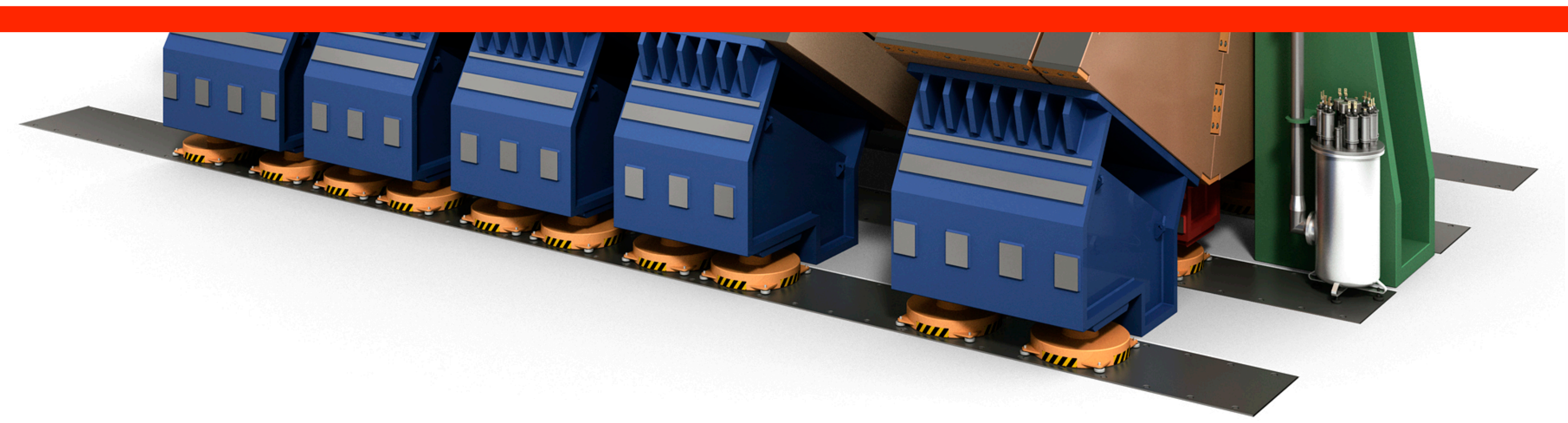

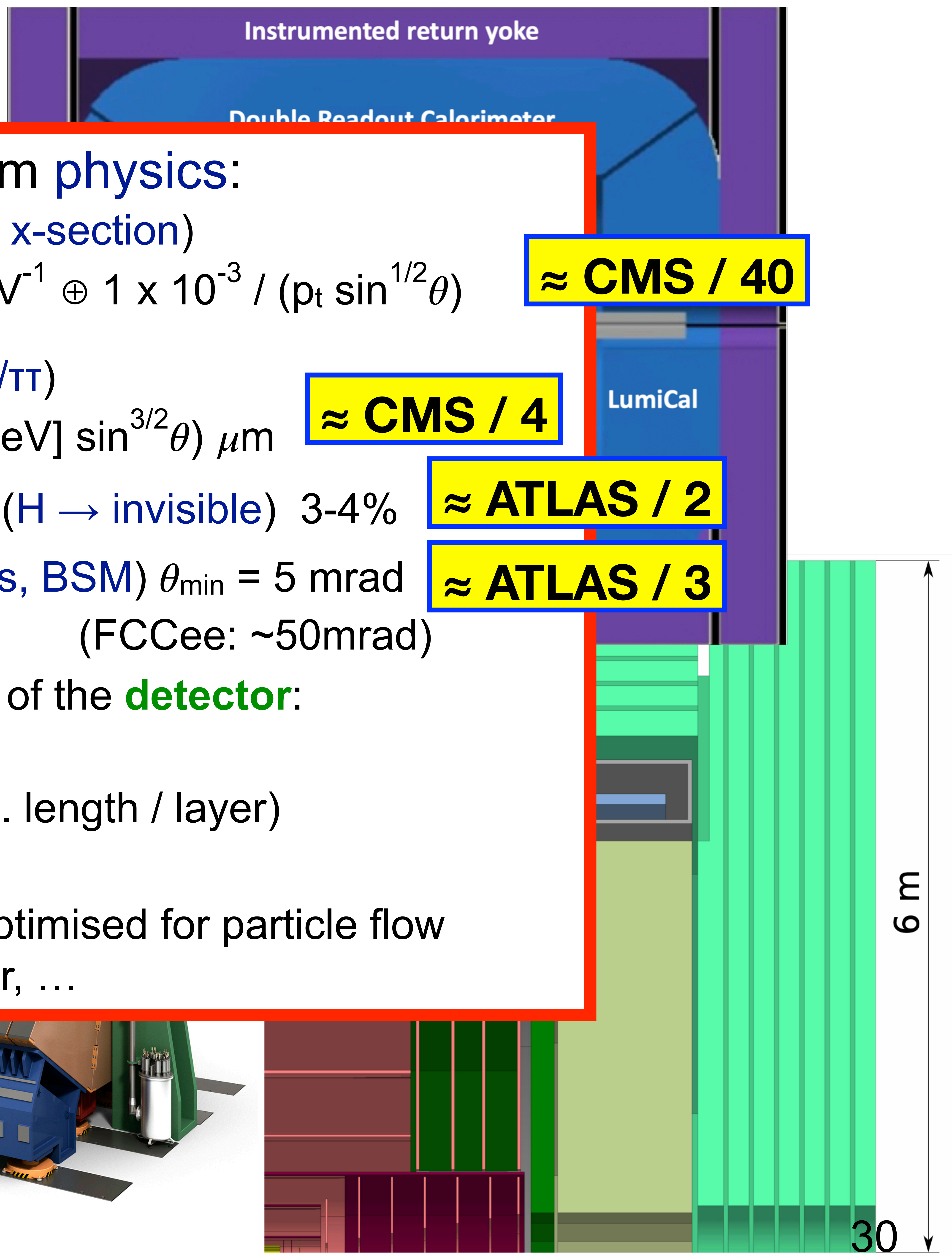

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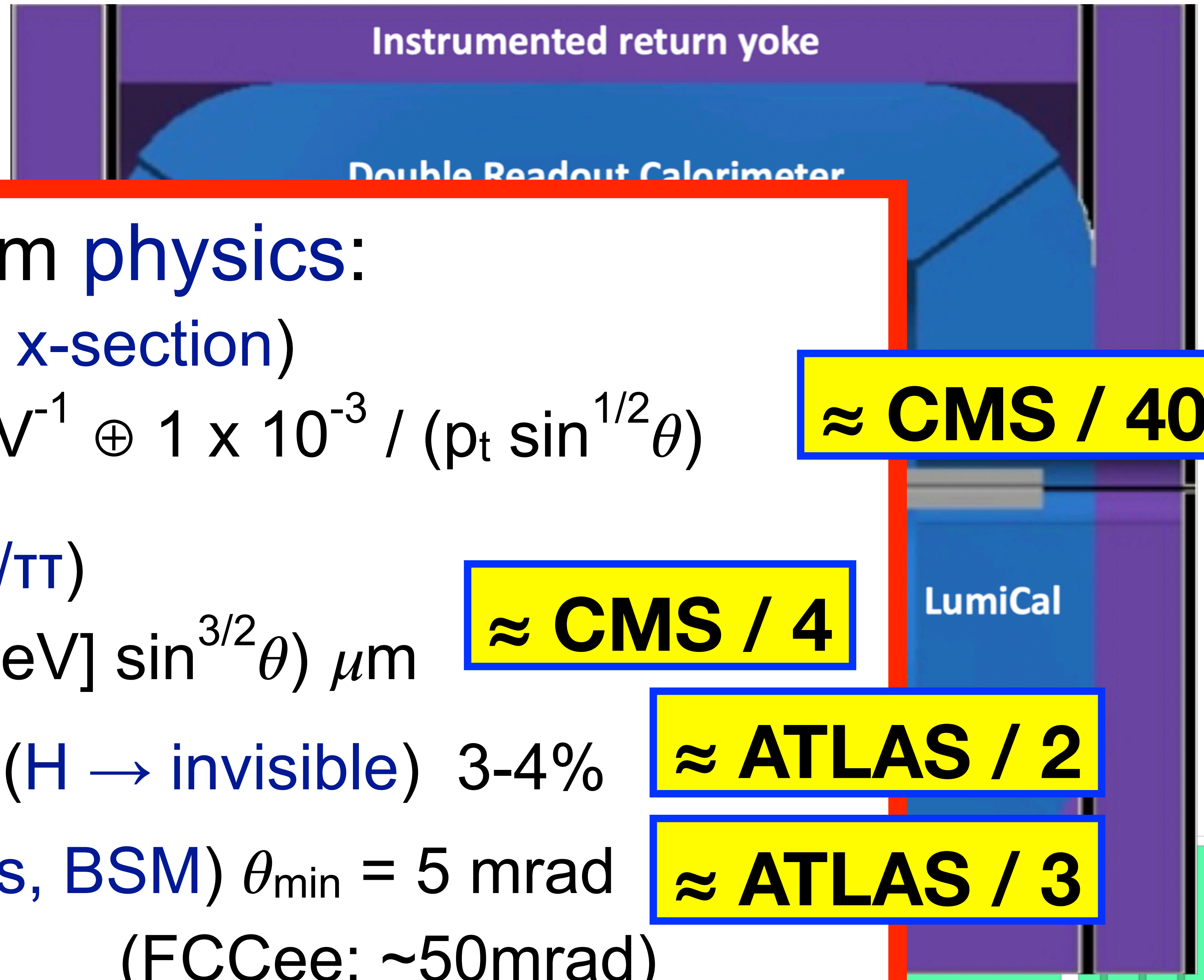

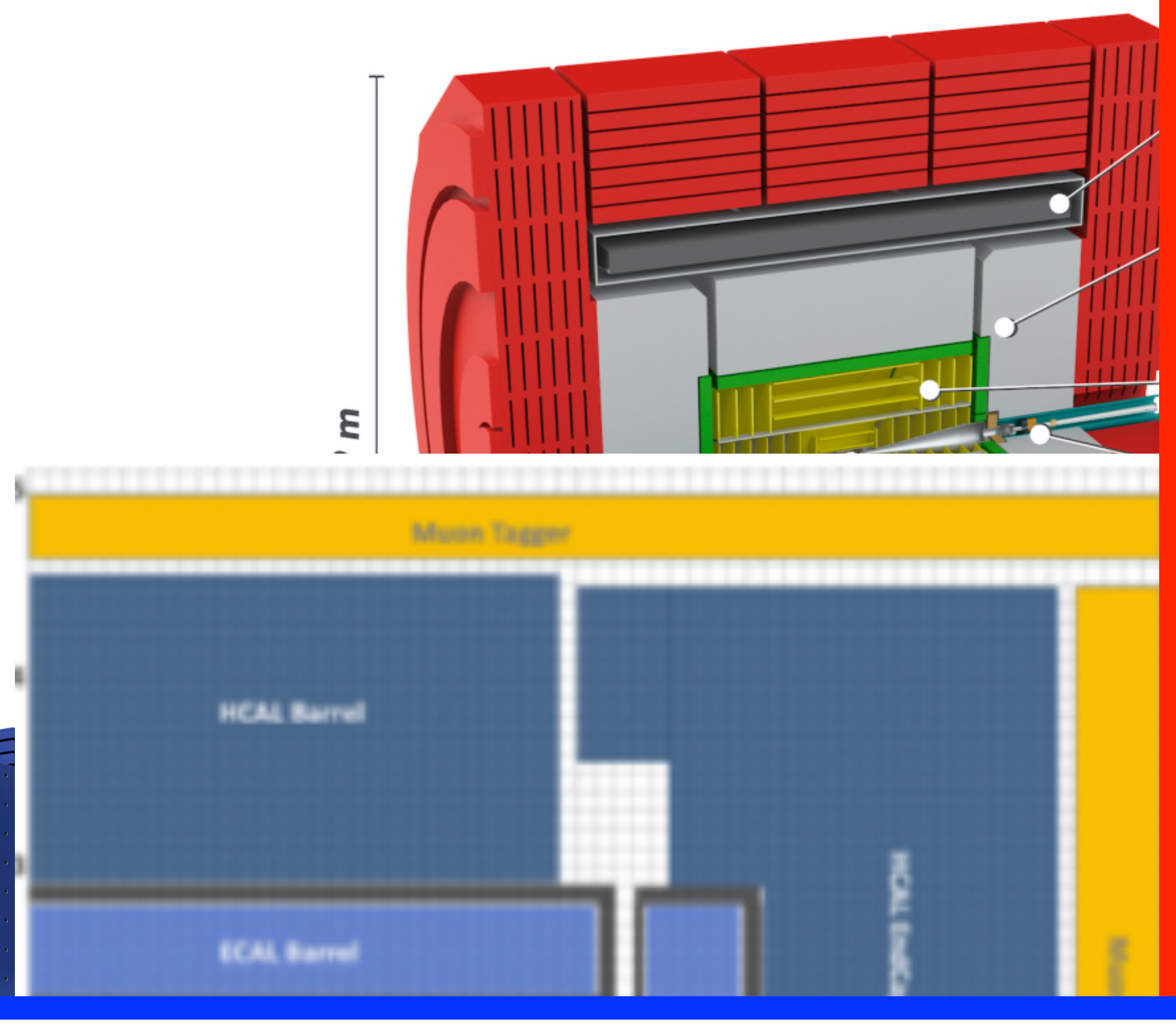

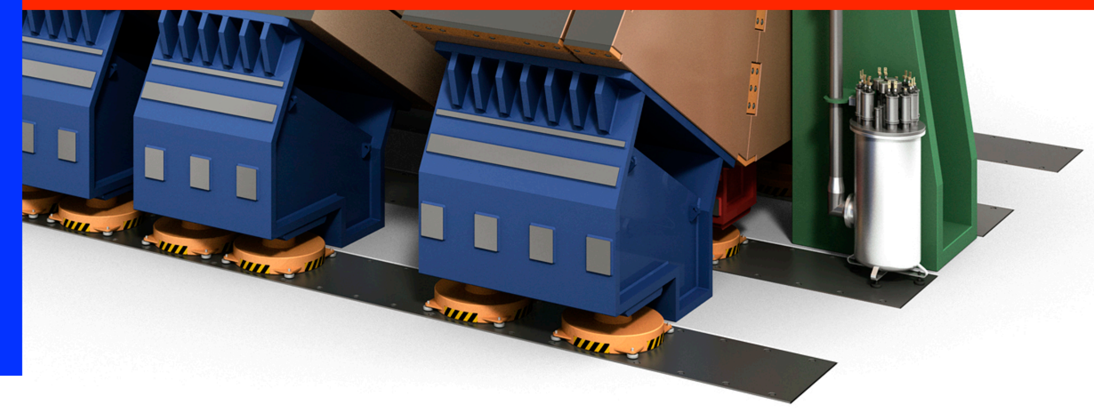

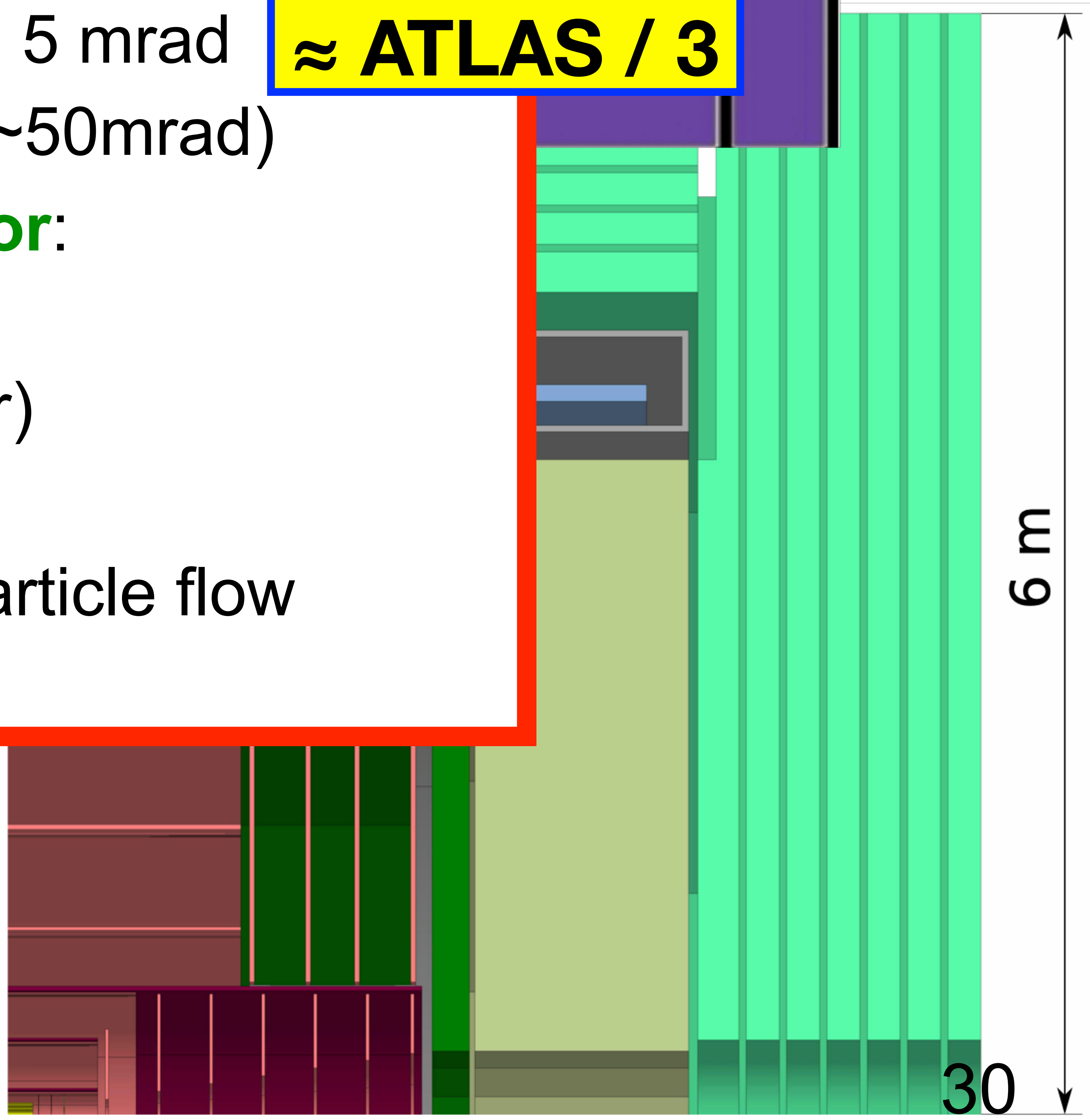

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Possible since experimental environment in e+e- very different from LHC:

- much lower backgrounds
- much less radiation

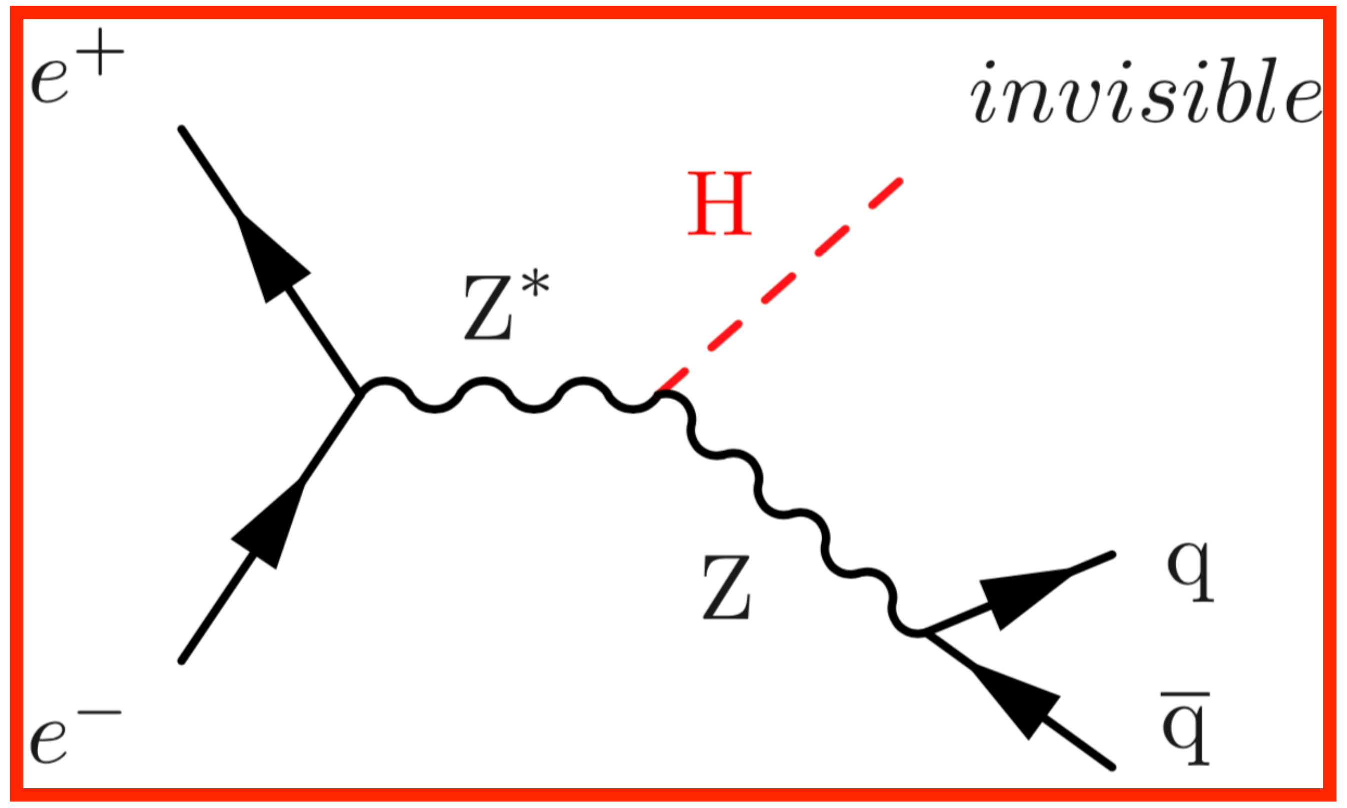
only Linear Colliders: lower collision rate enables

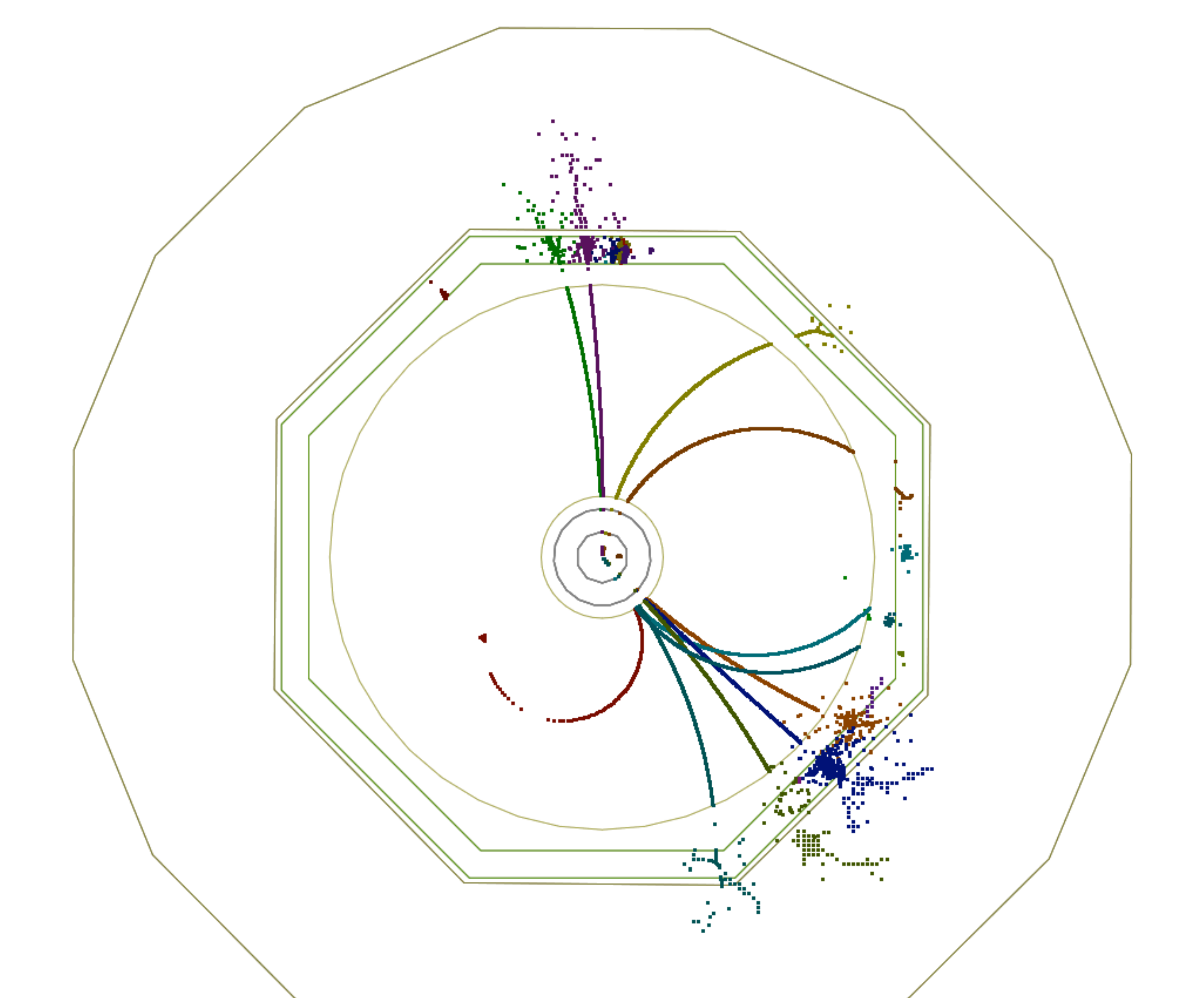
- passive cooling only => low material budget
- triggerless operation

Example: Higgs decay to "invisible"

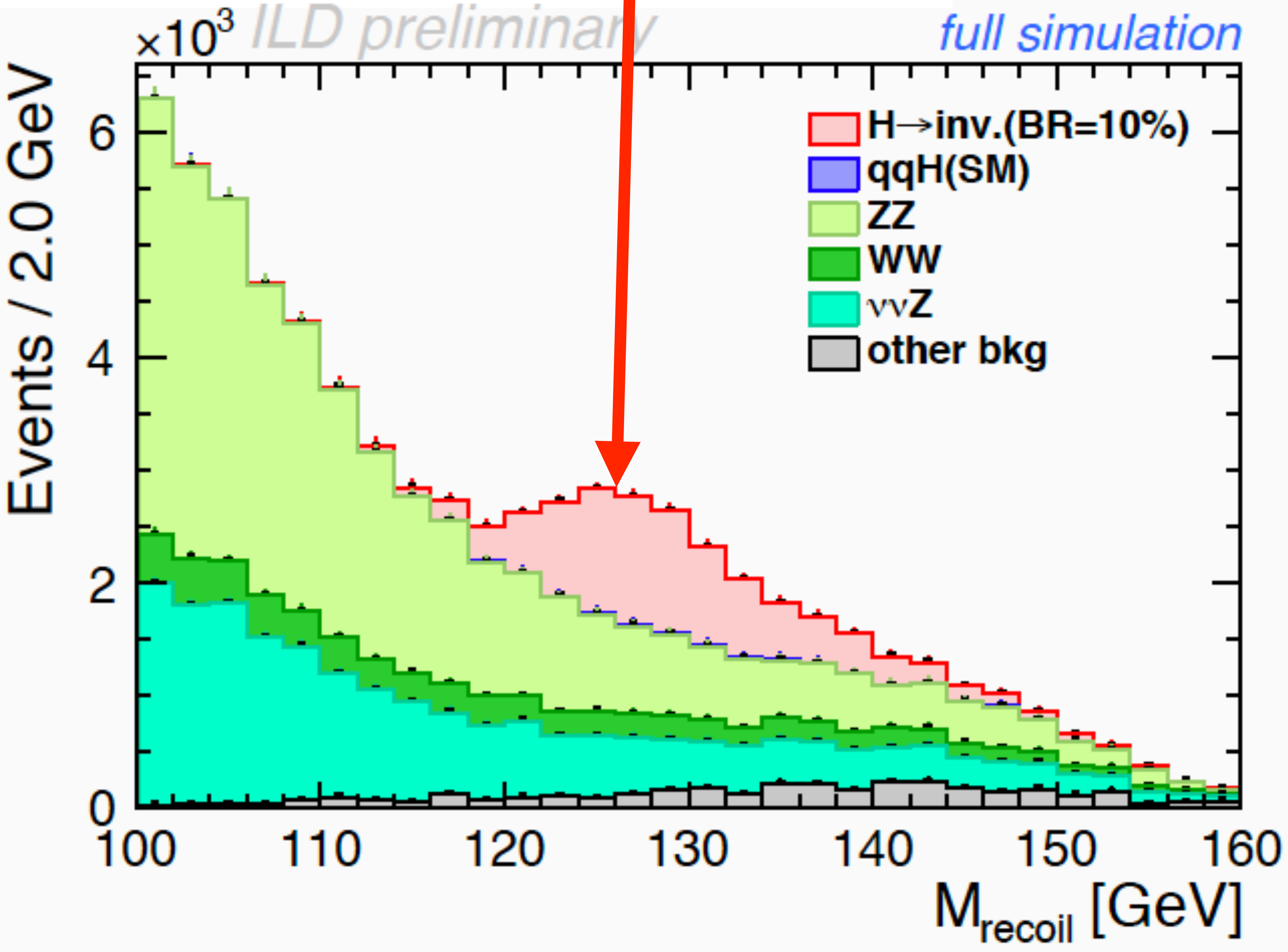
Dark Sector Portal?

- use $e^+e^- \to Z\, h$ process
- select a **visible final state (qq, ee, μμ) compatible with a Z decay**
- **recoiling against "nothing"**
- **if signal observed: discovery! Of Dark Matter?**
- **if no signal observed e.g. at ILC250: exclude BF > 0.16% at 95% CL (HL-LHC expectation: 2.5%, SM prediction: 0.12%)**





e⁺e⁻ → qq̄H → qq inv in ILD detector



arXiv:2203.08330 (SiD) &
***PoS* EPS-HEP2019 (2020) 358 (ILD)**

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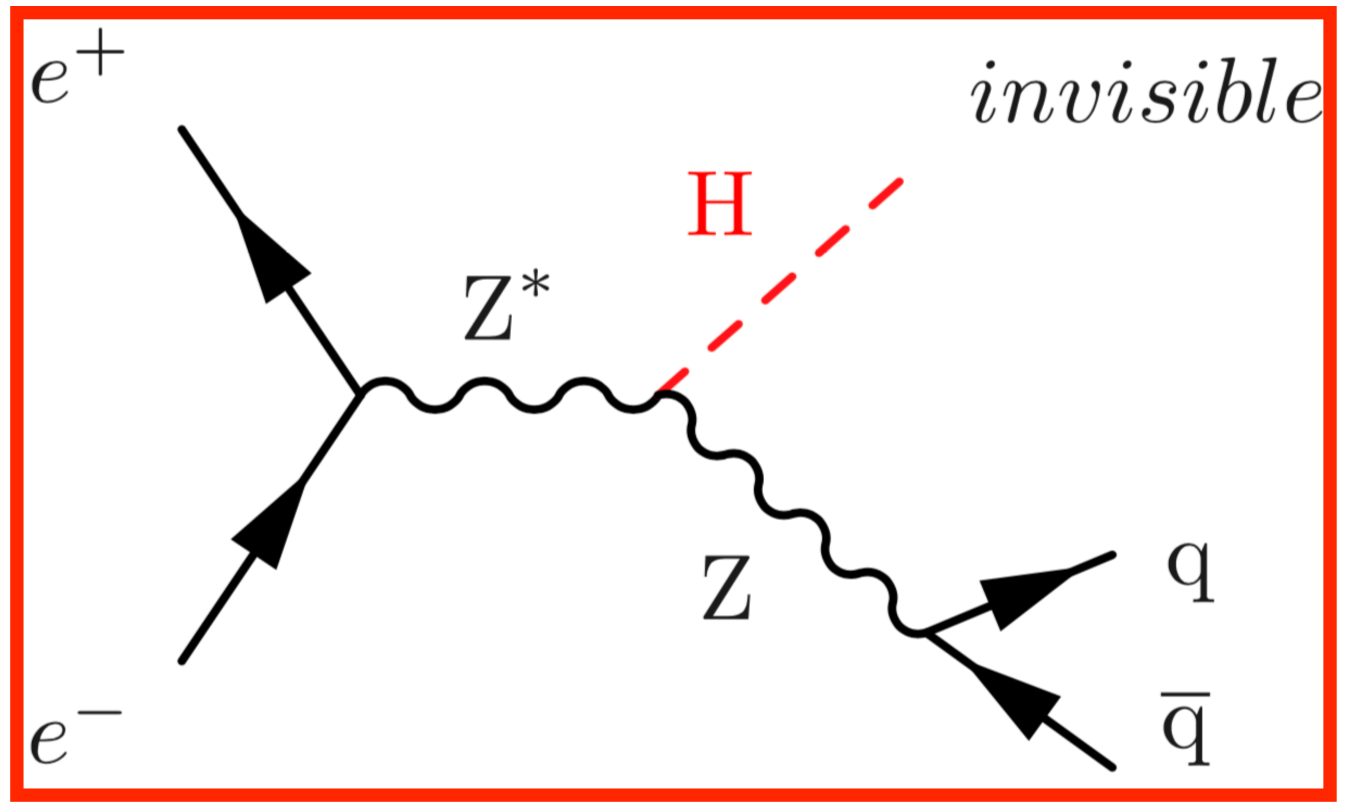
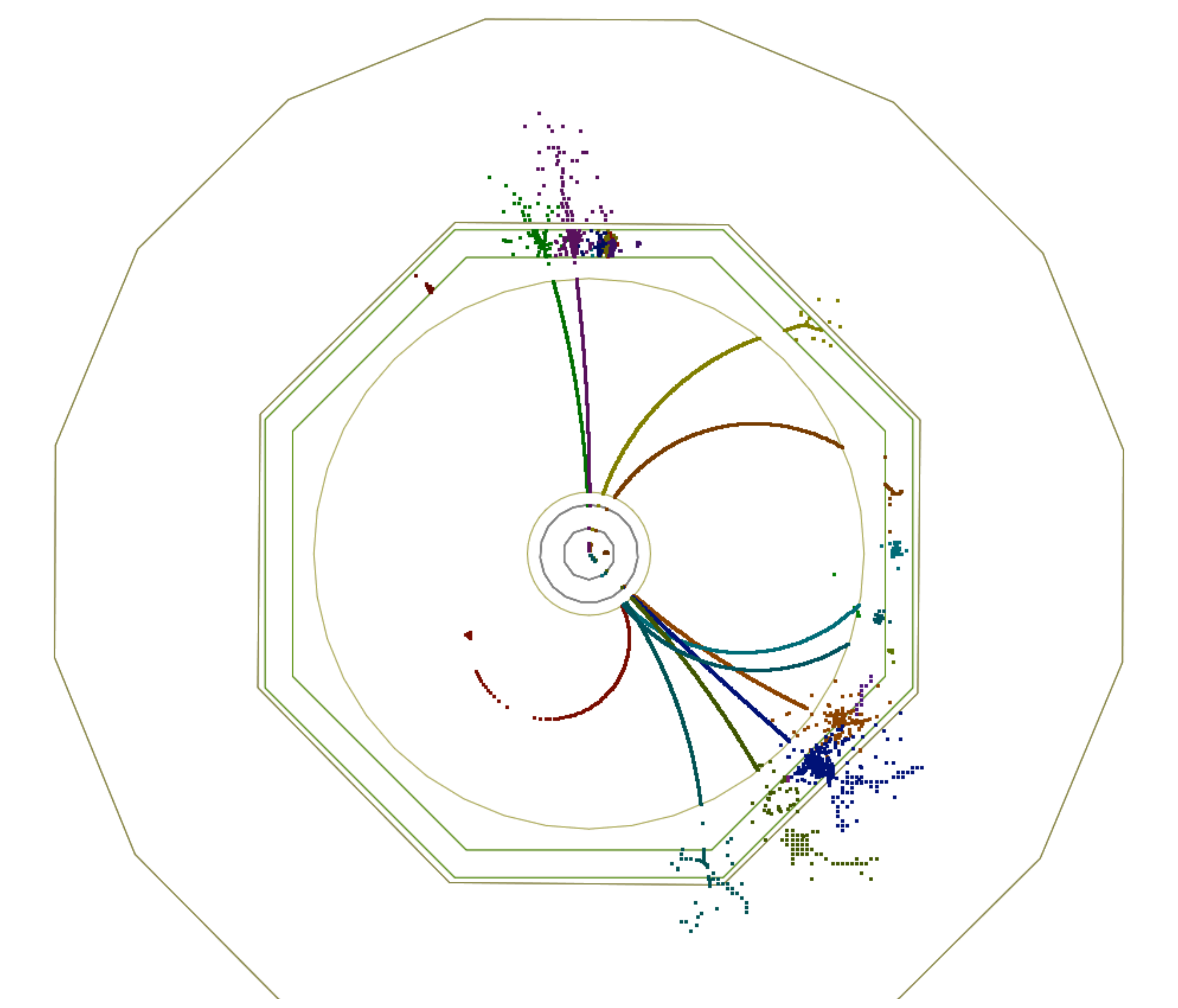
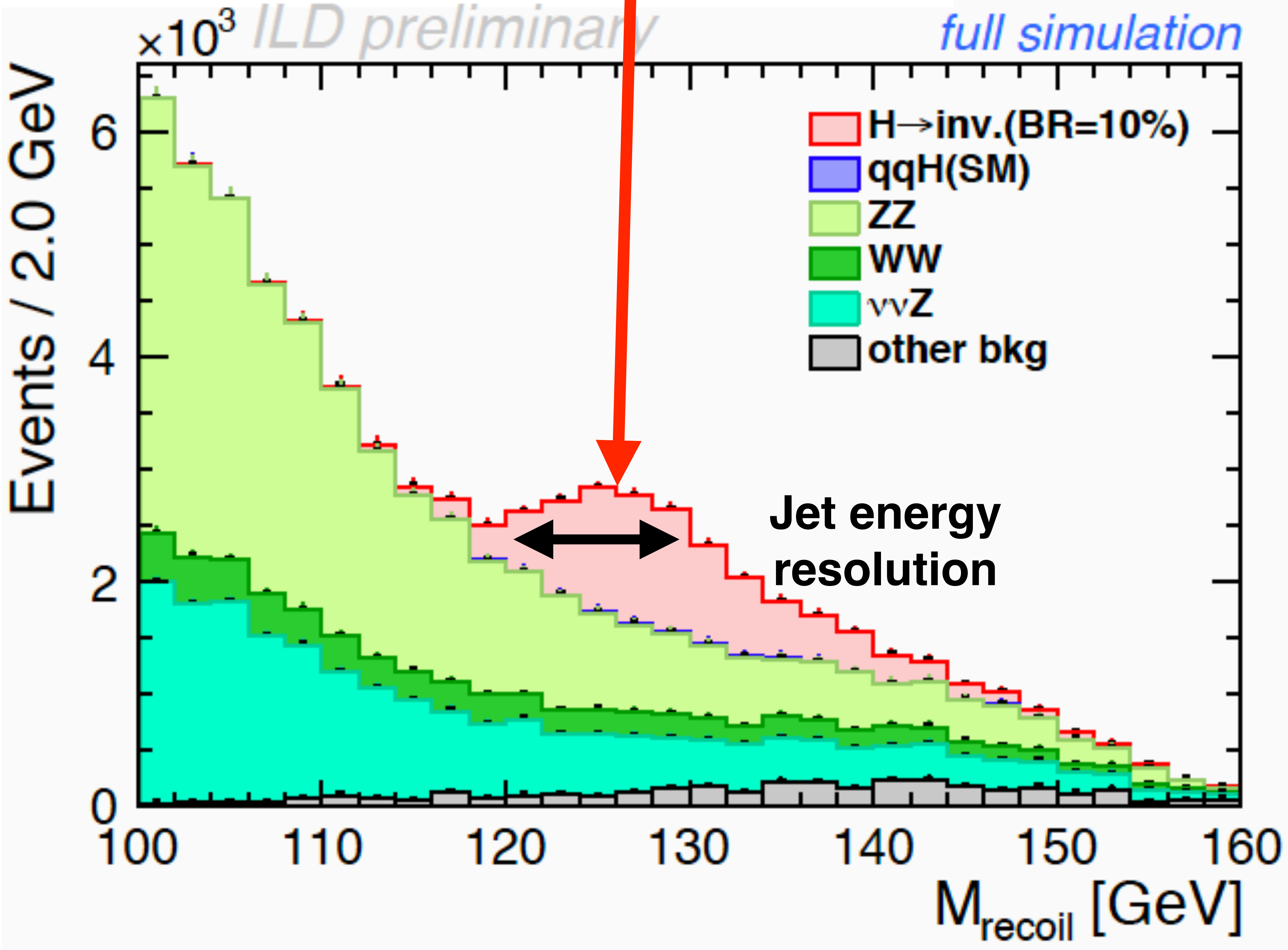




$e^+e^- \rightarrow q\bar{q}H \rightarrow qq$ inv in ILD detector



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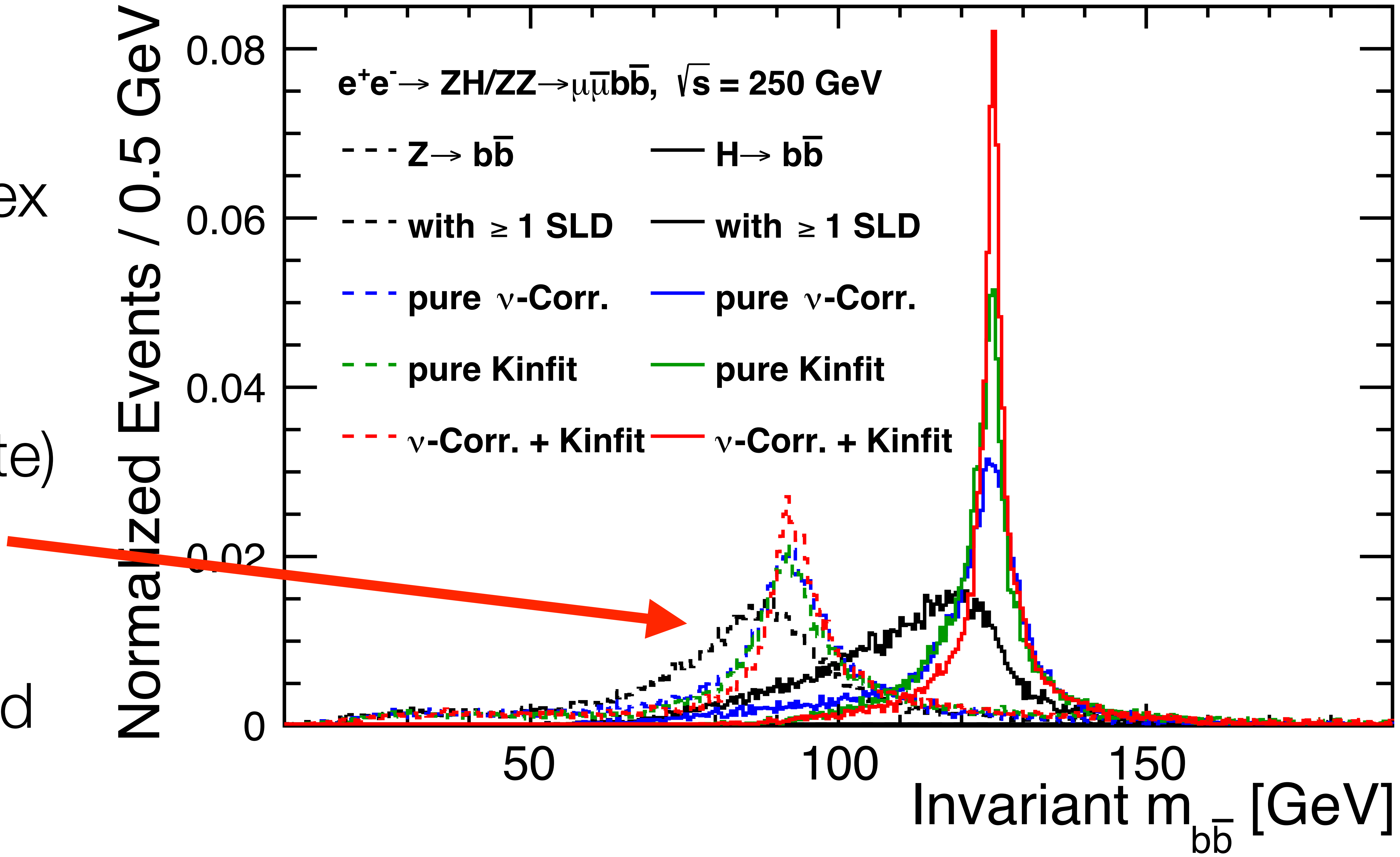
Recent developments

Improvements in reconstructing Z/H -> hadrons (Y. Radkhorrami, L. Reichenbach)

- correct semi-leptonic b/c decays
  - identify leptons in c- / b-jets
  - associate them to secondary / tertiary vertex
  - reconstruct neutrino kinematics (2-fold ambiguity)
- ErrorFlow (jet-by-jet covariance matrix estimate)
- feed both into kinematic fit
- (very) significant improvement in H->bb/cc and Z->bb/cc reconstruction
- ready to be applied to many analyses…



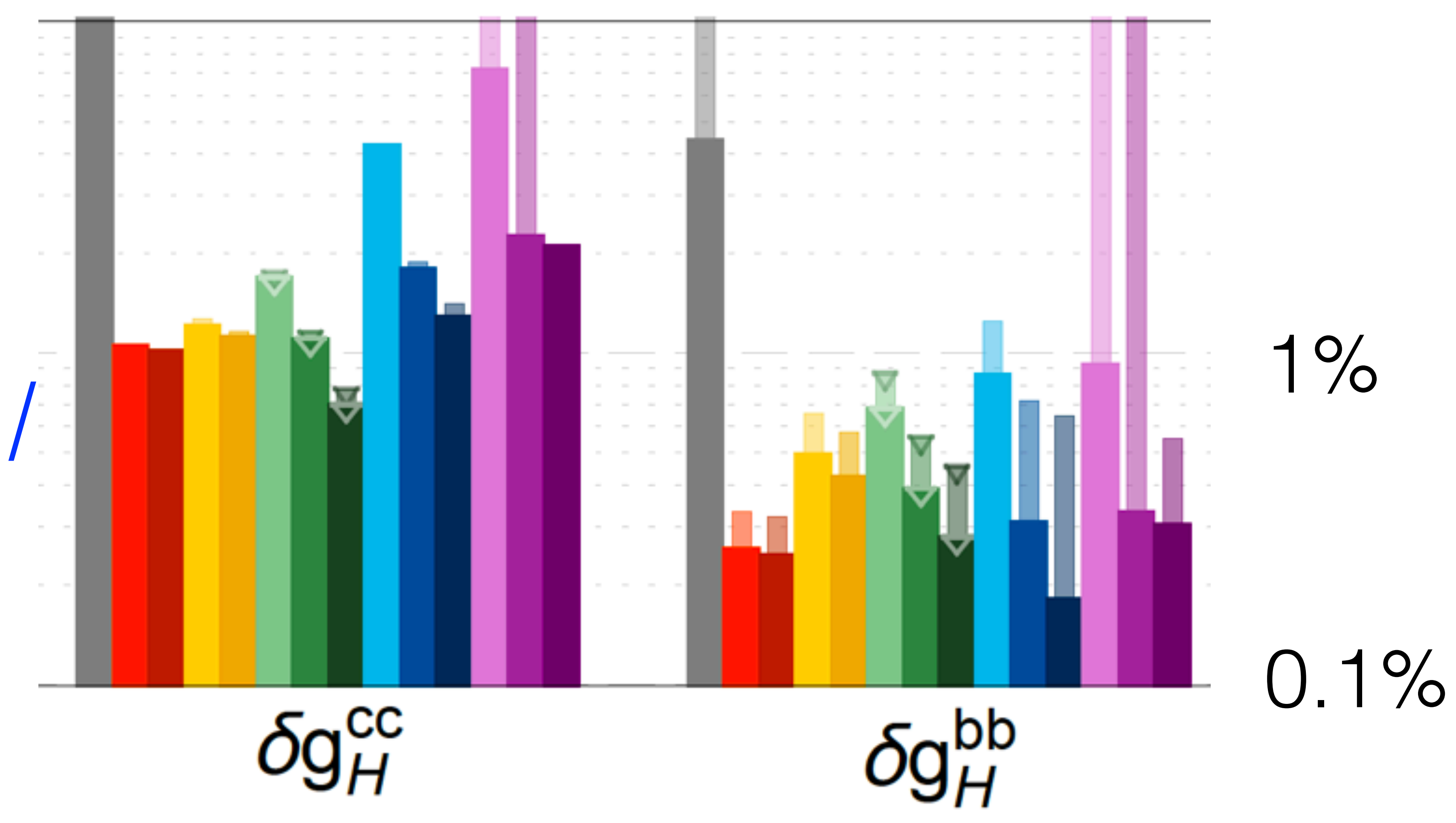
arXiv:2111.14775

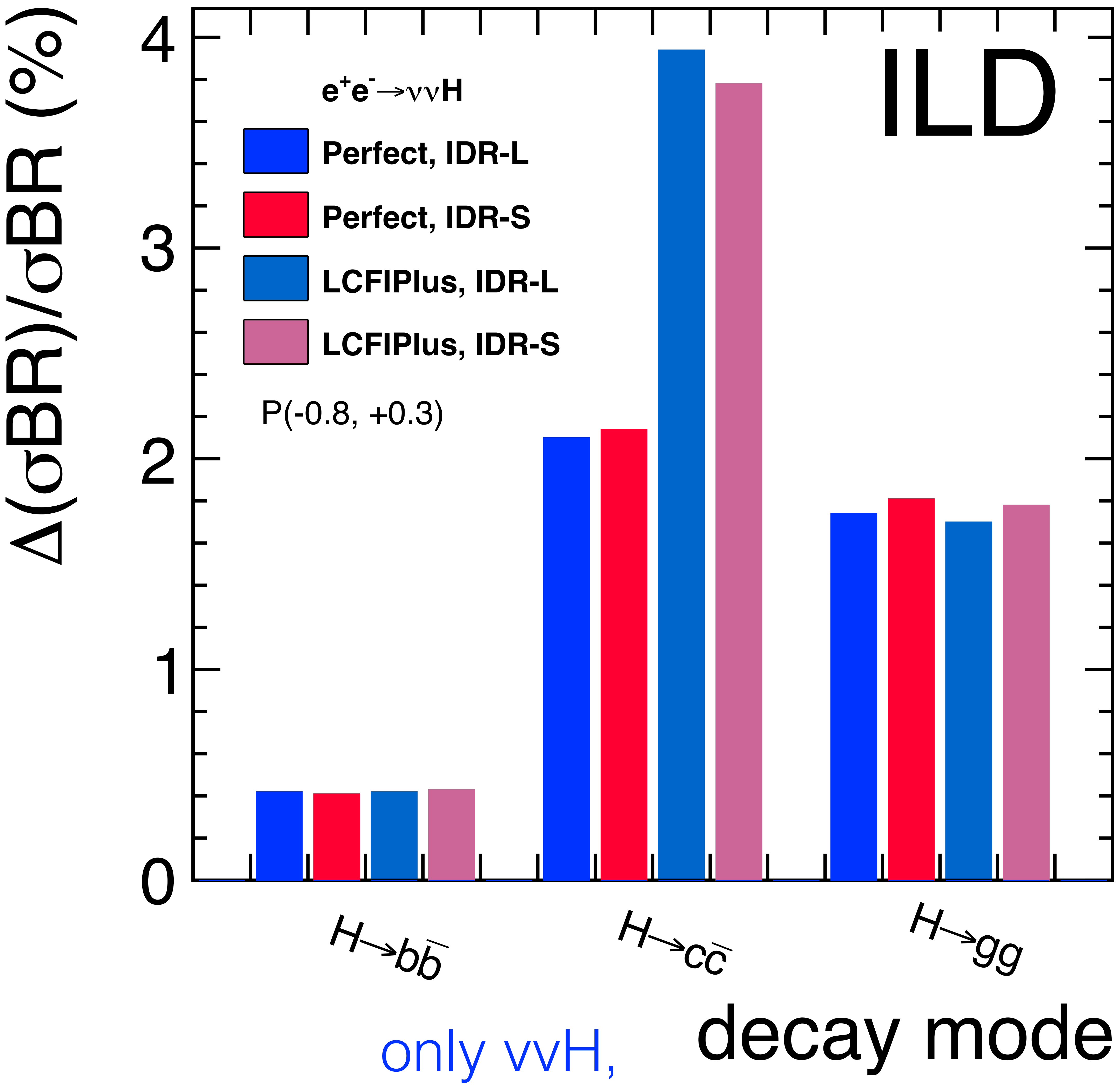
Higgs decay to bb/cc/gg

…the experimental situation

- use all visible decay modes of Z and ννH
- H->jets and Z->jets play important role!
- Example from ILD IDR:
  - **σxBR(bb) to ~0.4%** from one channel & data set alone
  - σxBR(cc) shows a lot (!) of room for improvement by smarter flavour tag algorithm

all channels / data sets





only ννH, 1.6ab-1 P(-0.8,+0.3) @ 500 GeV

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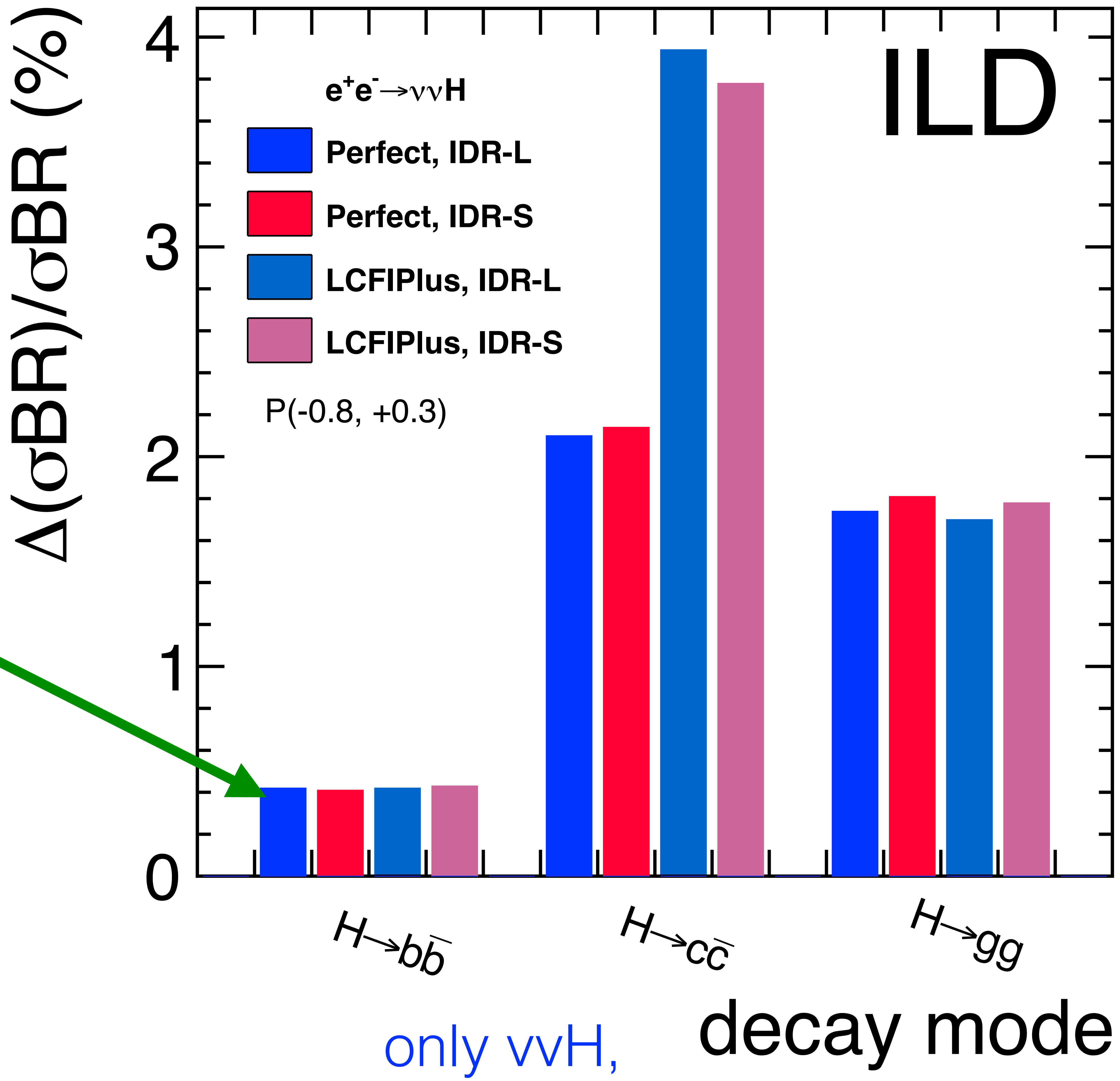

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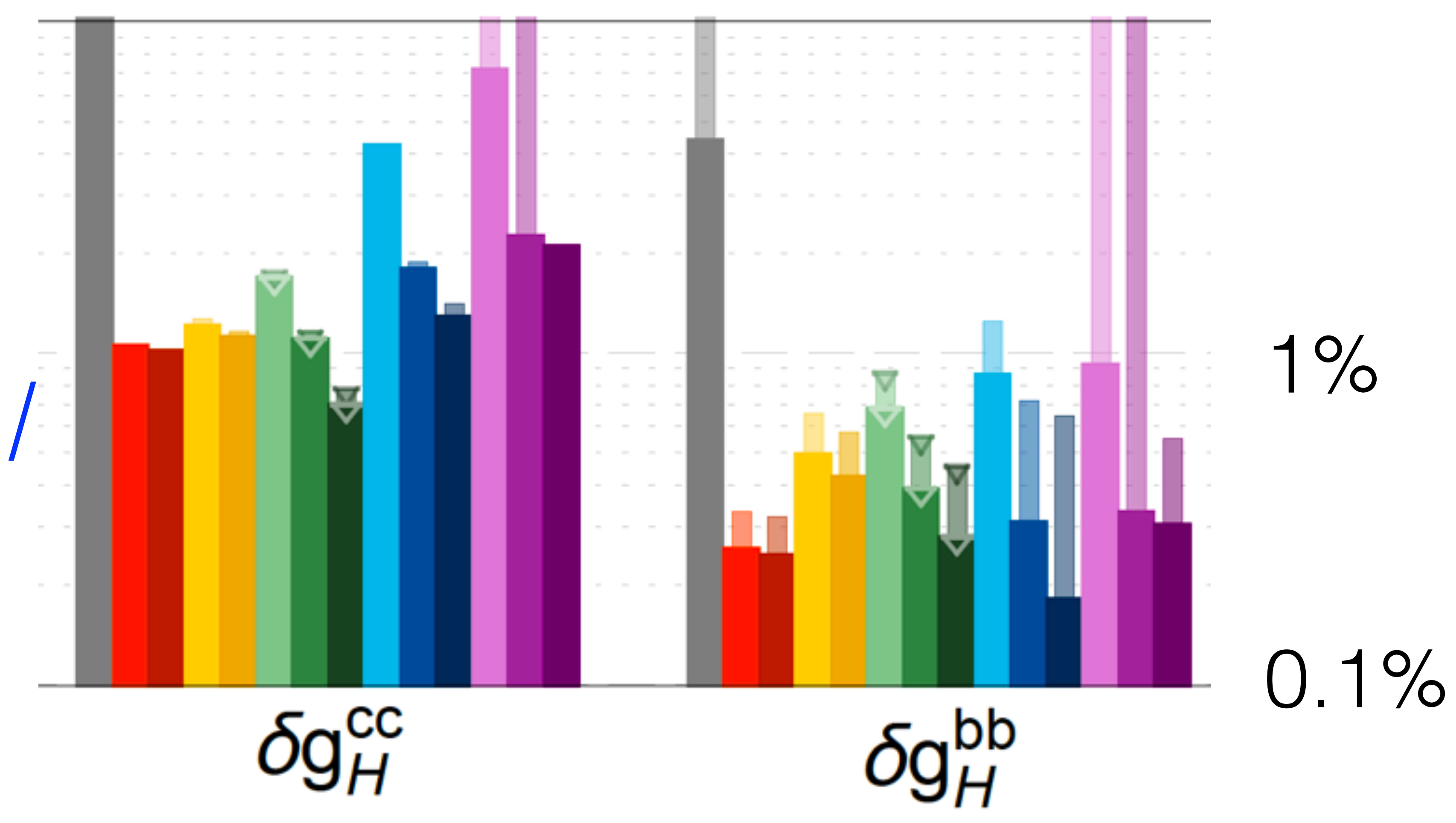

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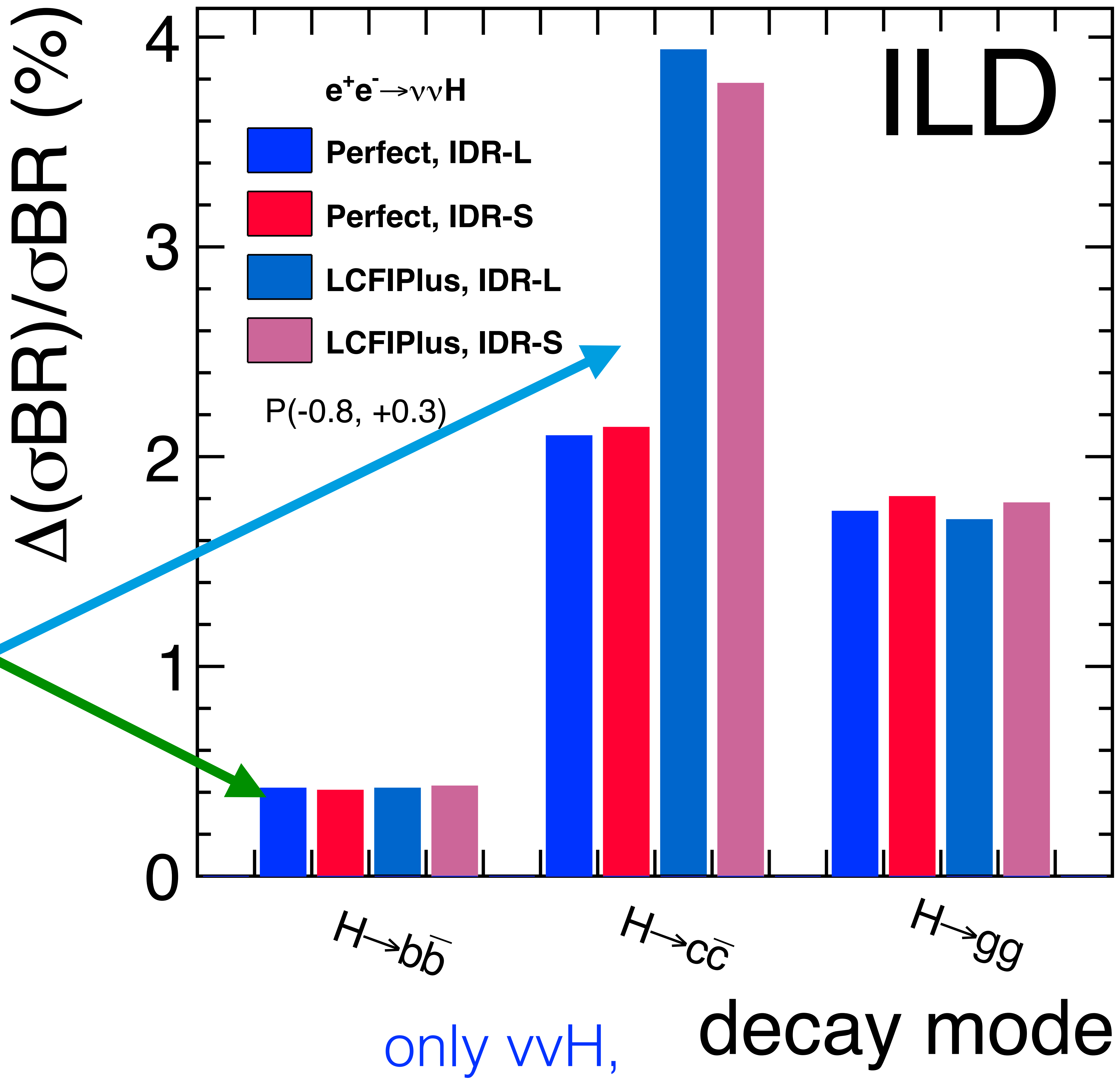

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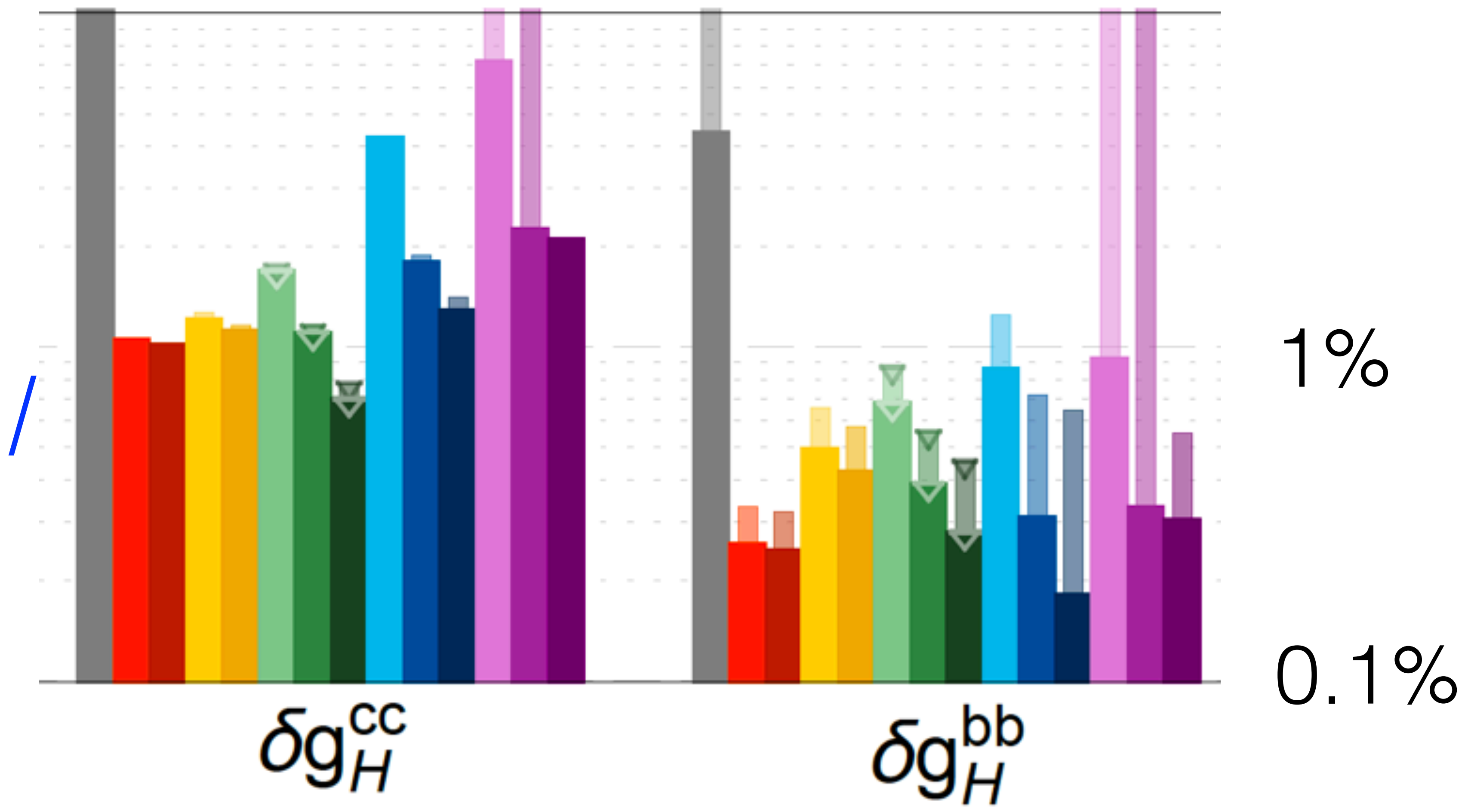

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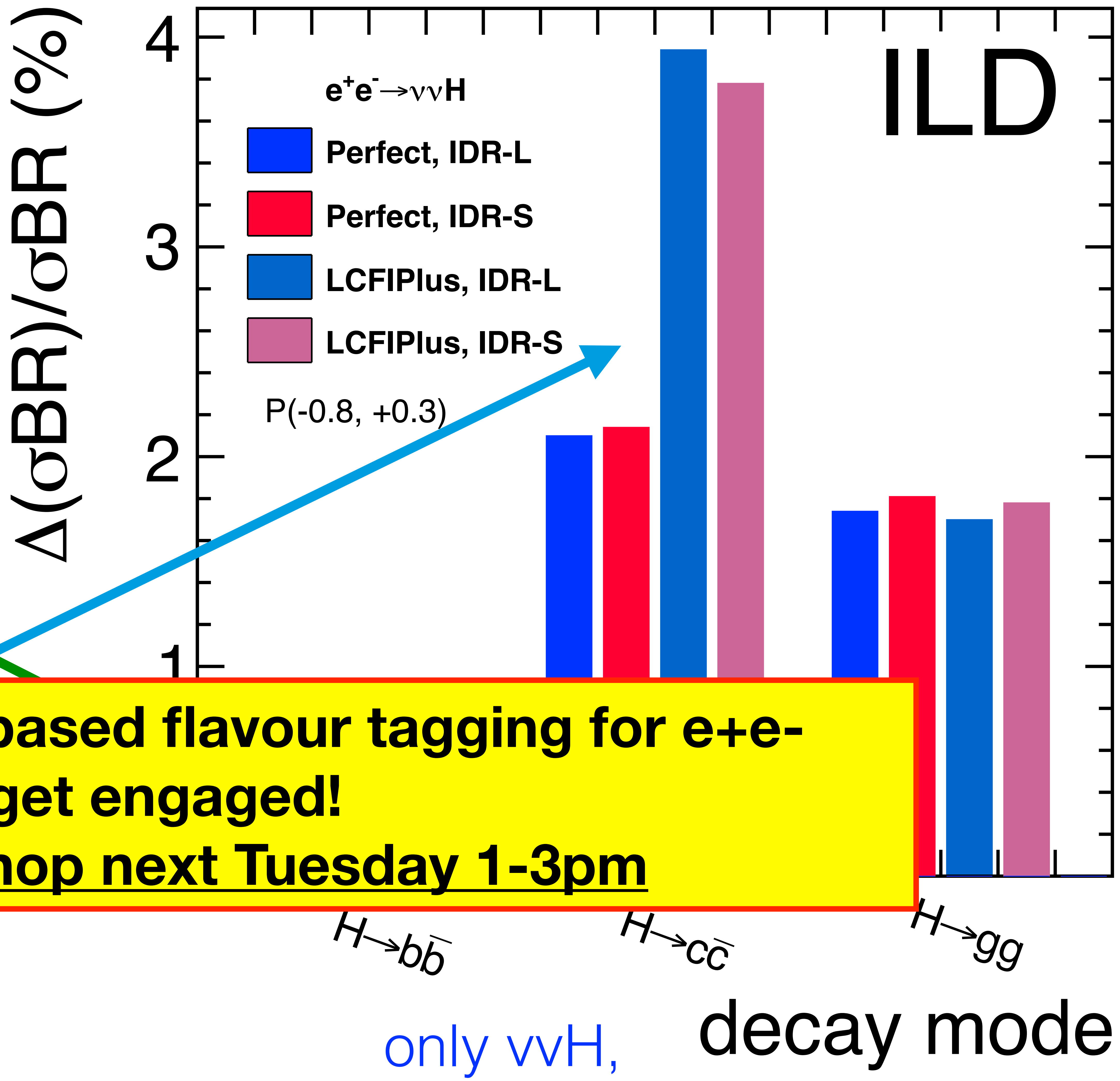
Just starting: development of ML-based flavour tagging for e+e-
=> ideal place to get engaged!
=> dedicated 2h-mini-workshop next Tuesday 1-3pm



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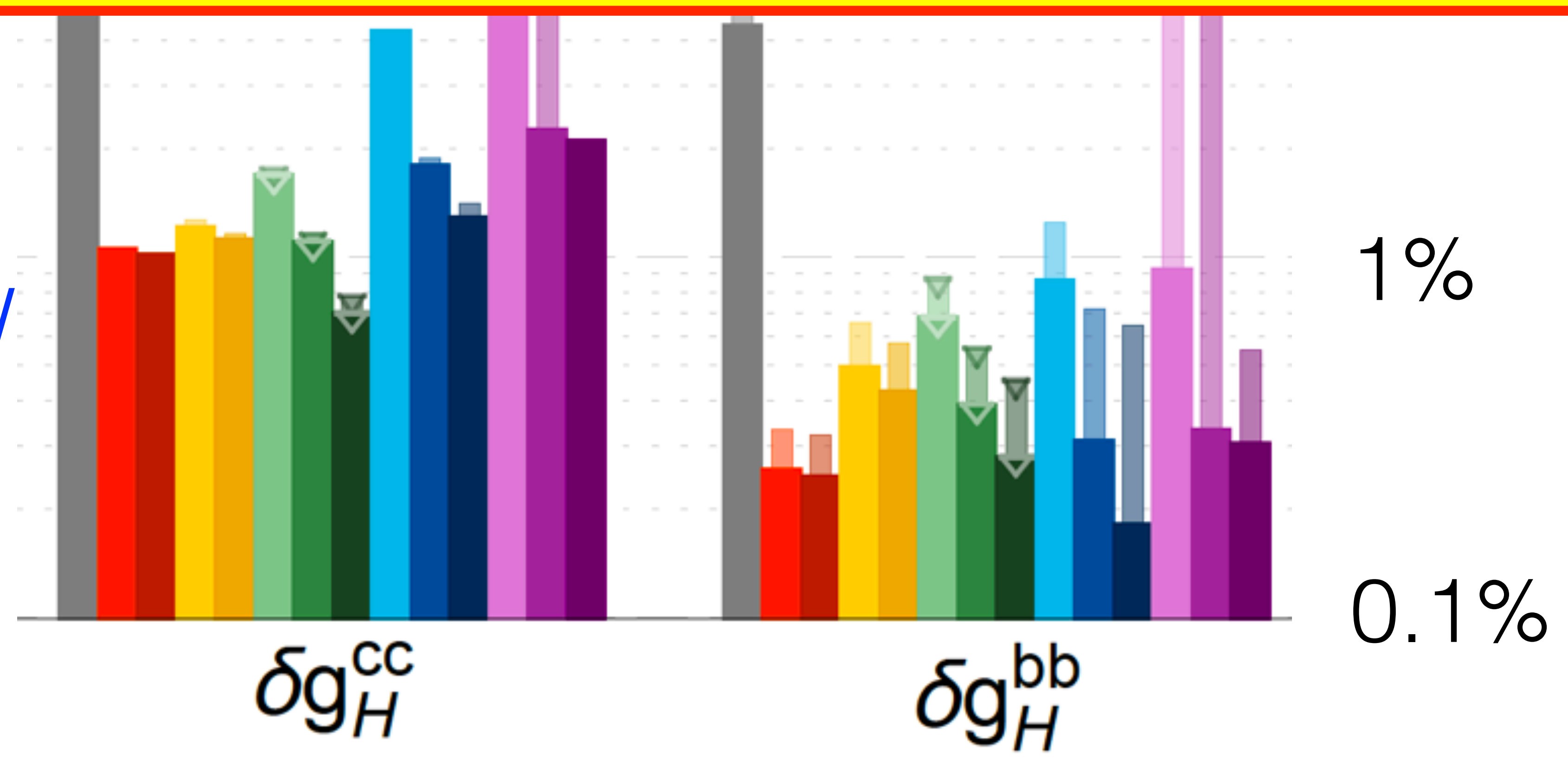
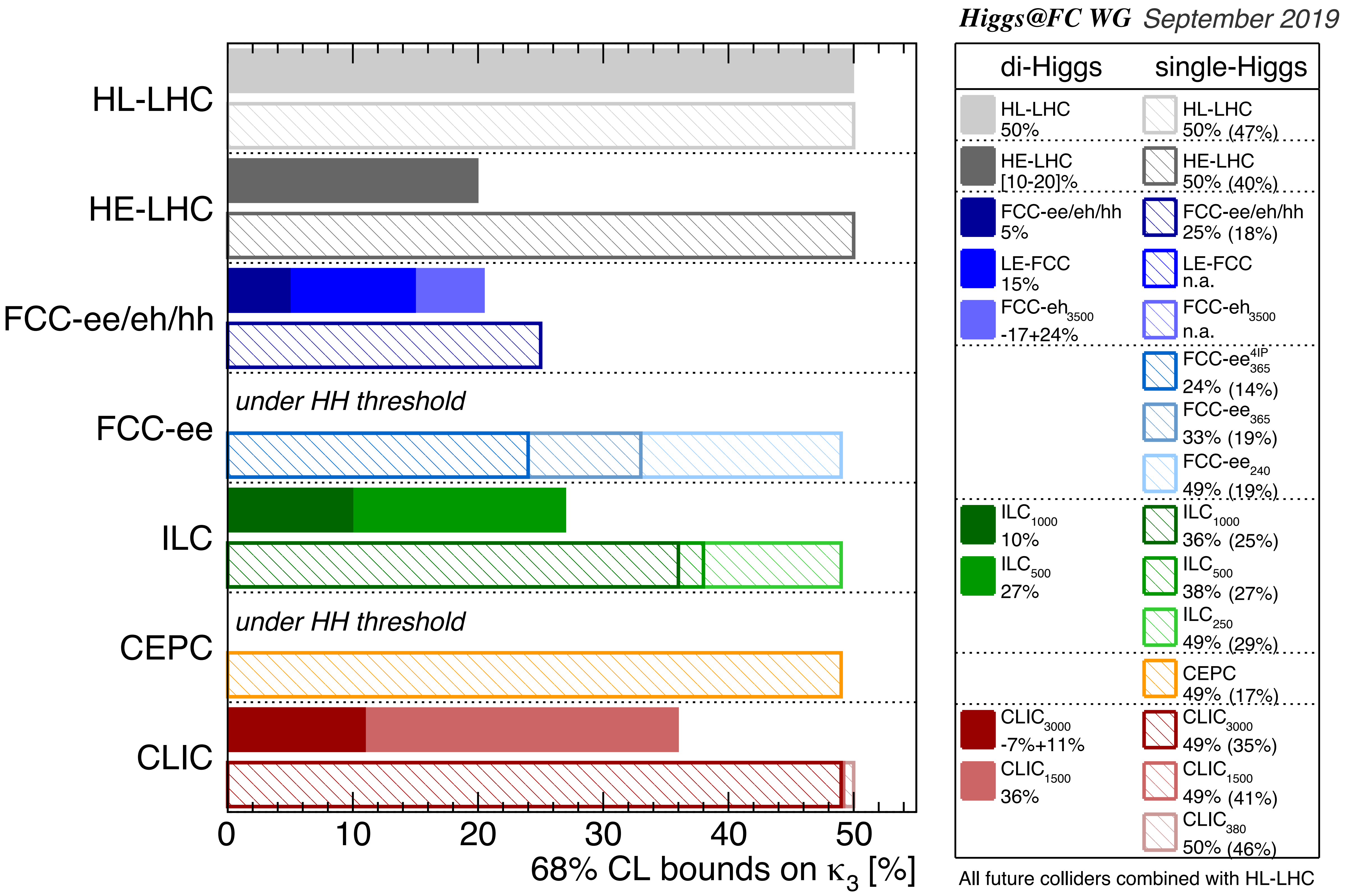


Higgs self-coupling

Electroweak Baryogenesis?



most detailed ILC ref: PhD Thesis C.Dürig
Uni Hamburg, **DESY-THESIS-2016-027**
UPDATE ONGOING!

Higgs self-coupling

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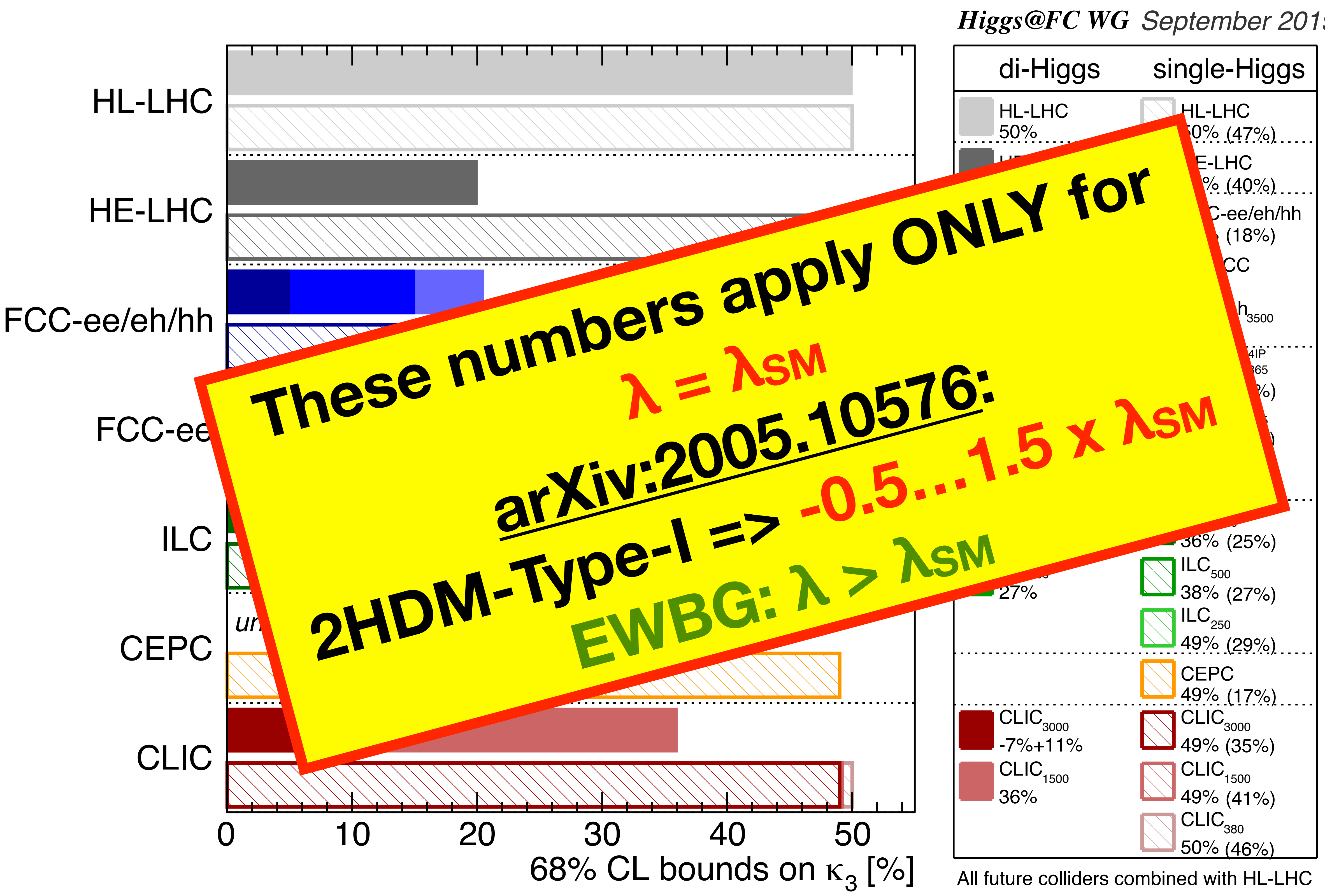

These numbers apply ONLY for $\lambda = \lambda_{SM}$

arXiv:2005.10576:

2HDM-Type-I => $-0.5\ldots1.5 \times \lambda_{SM}$

EWBG: $\lambda > \lambda_{SM}$

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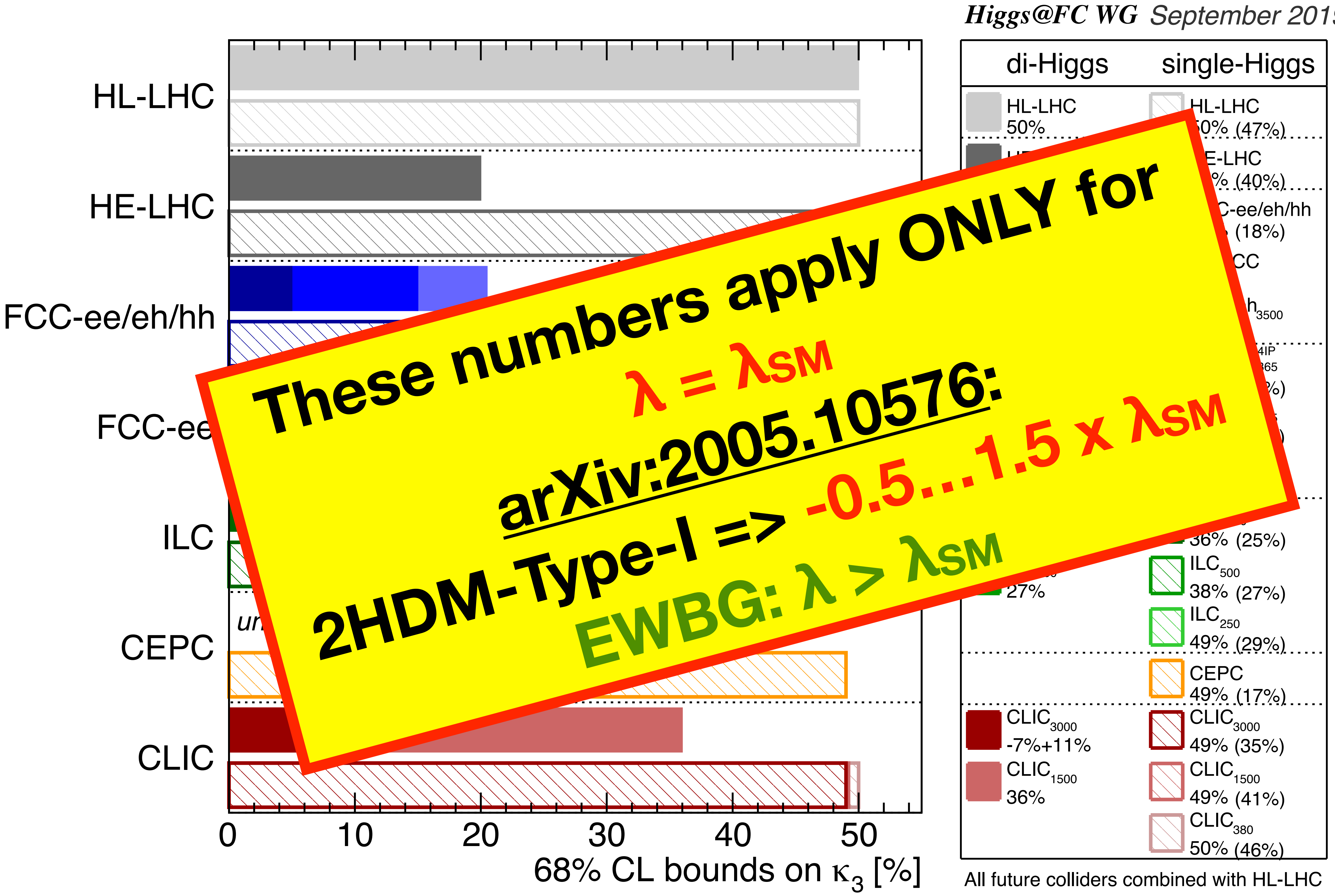

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- **pp cross section drops**
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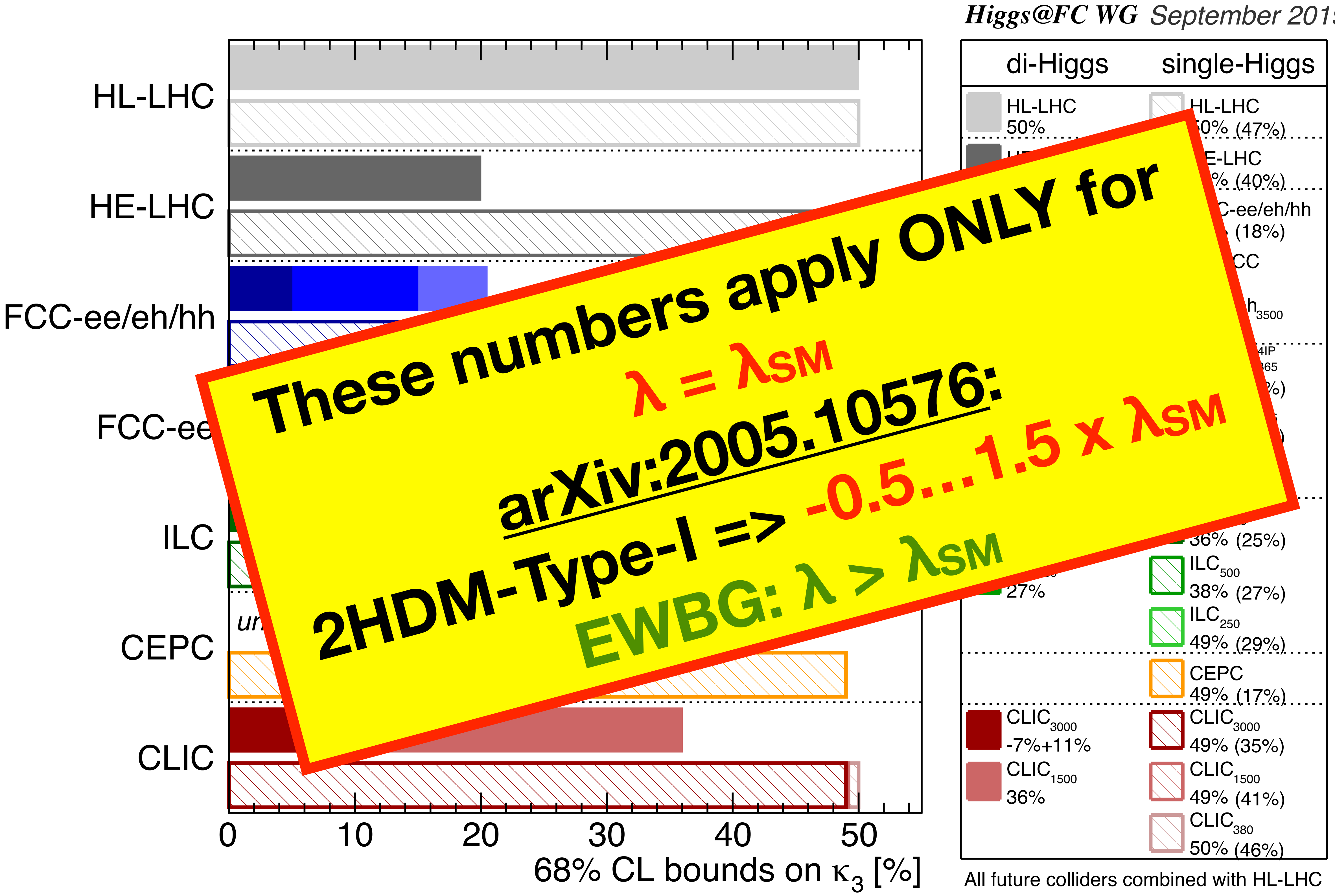

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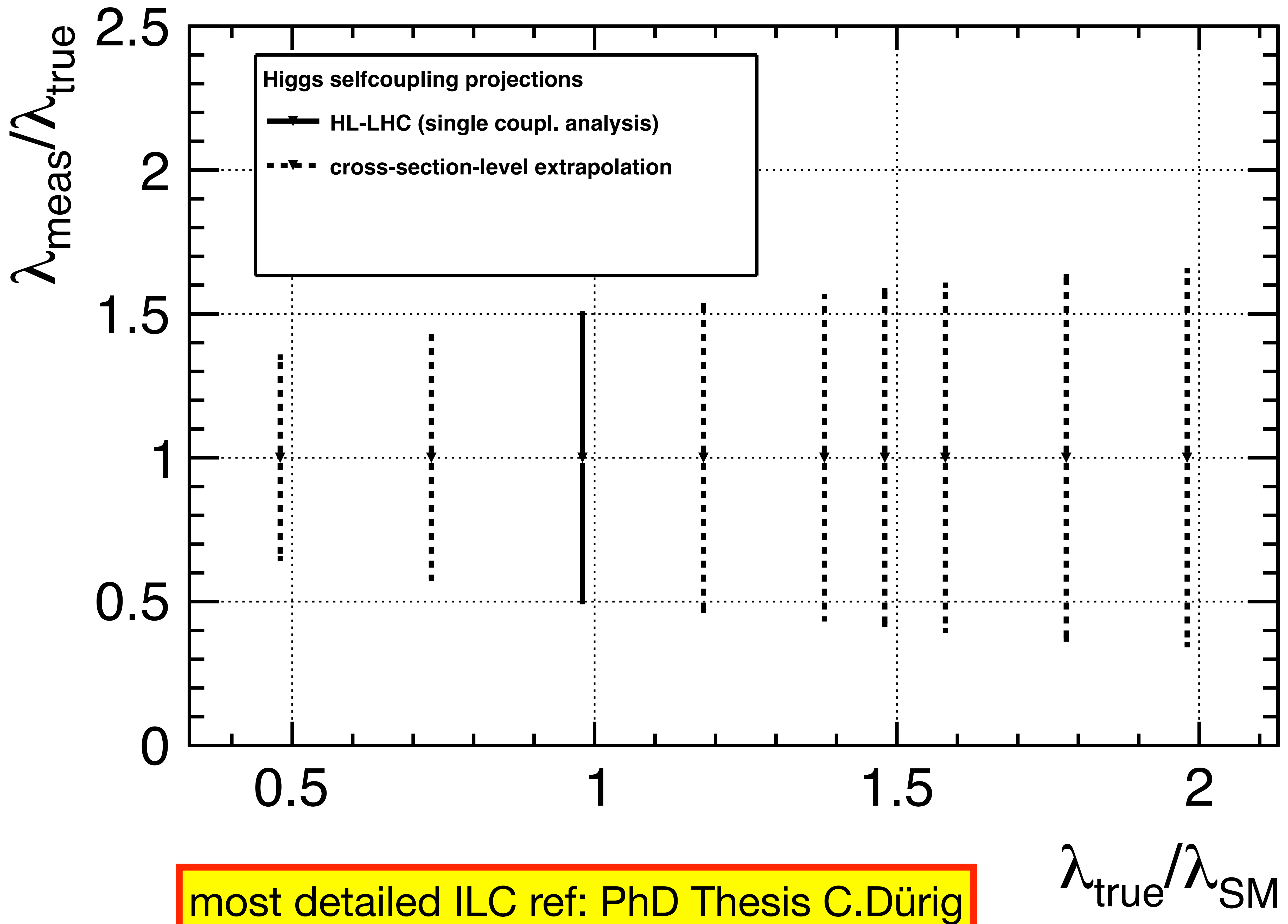

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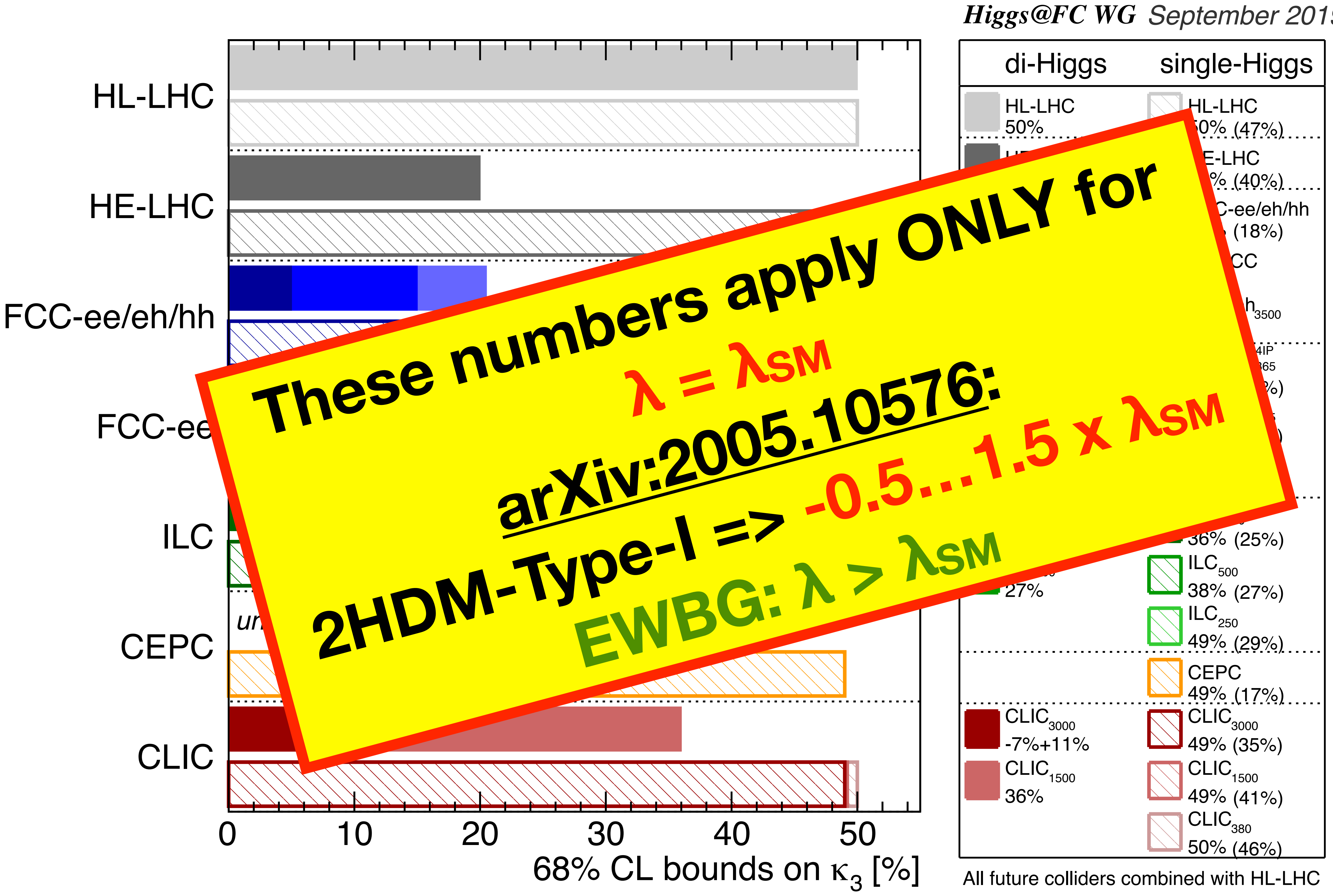

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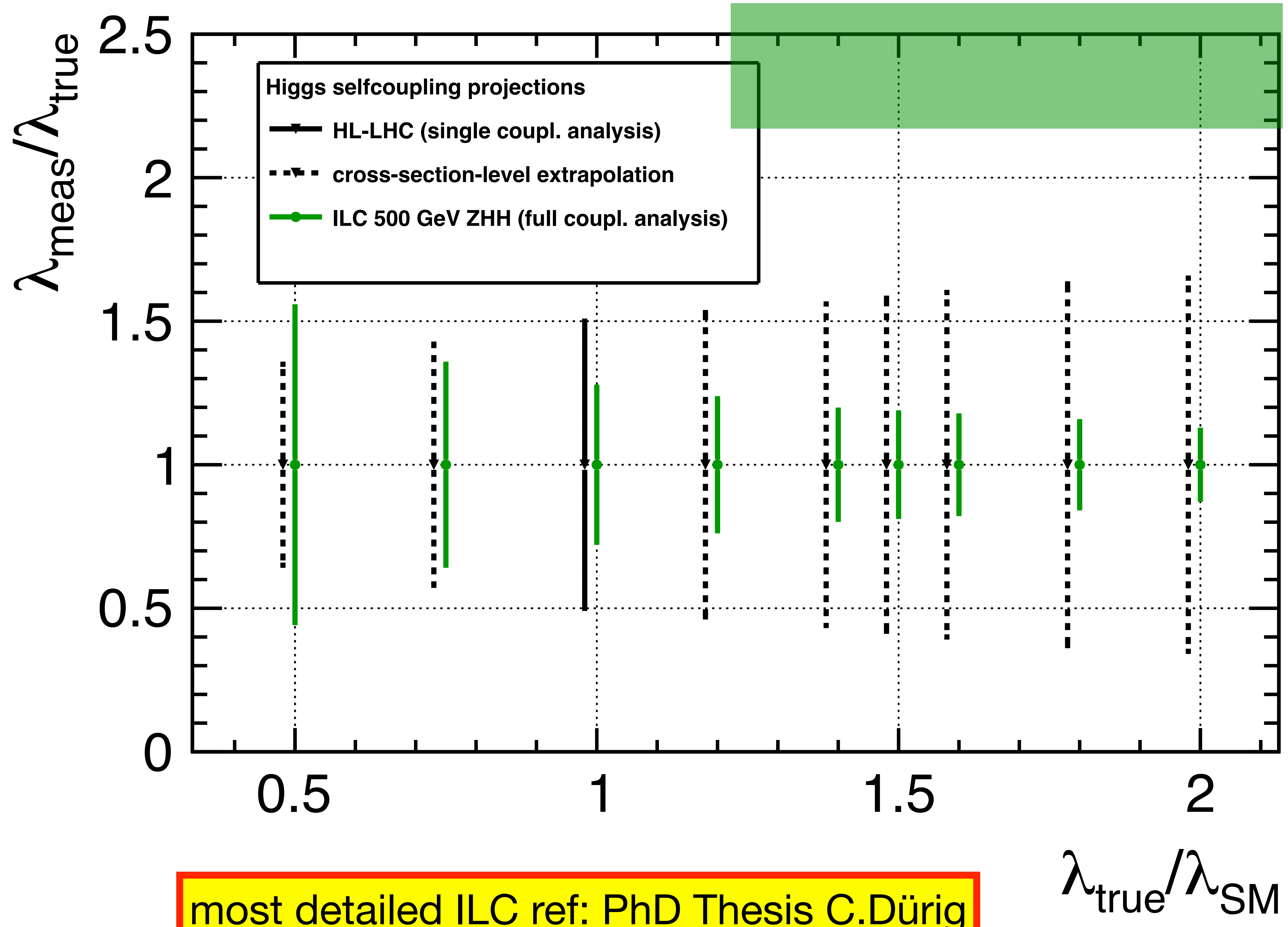
Region of interest for electroweak baryogenesis



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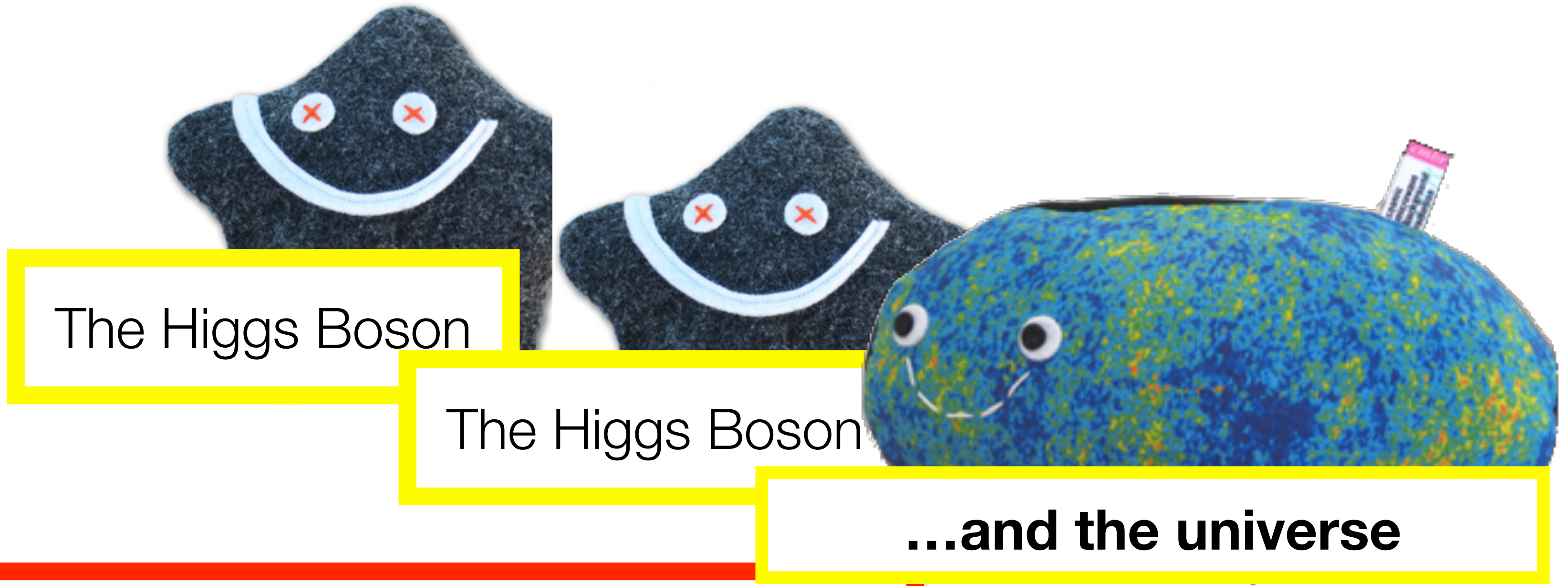
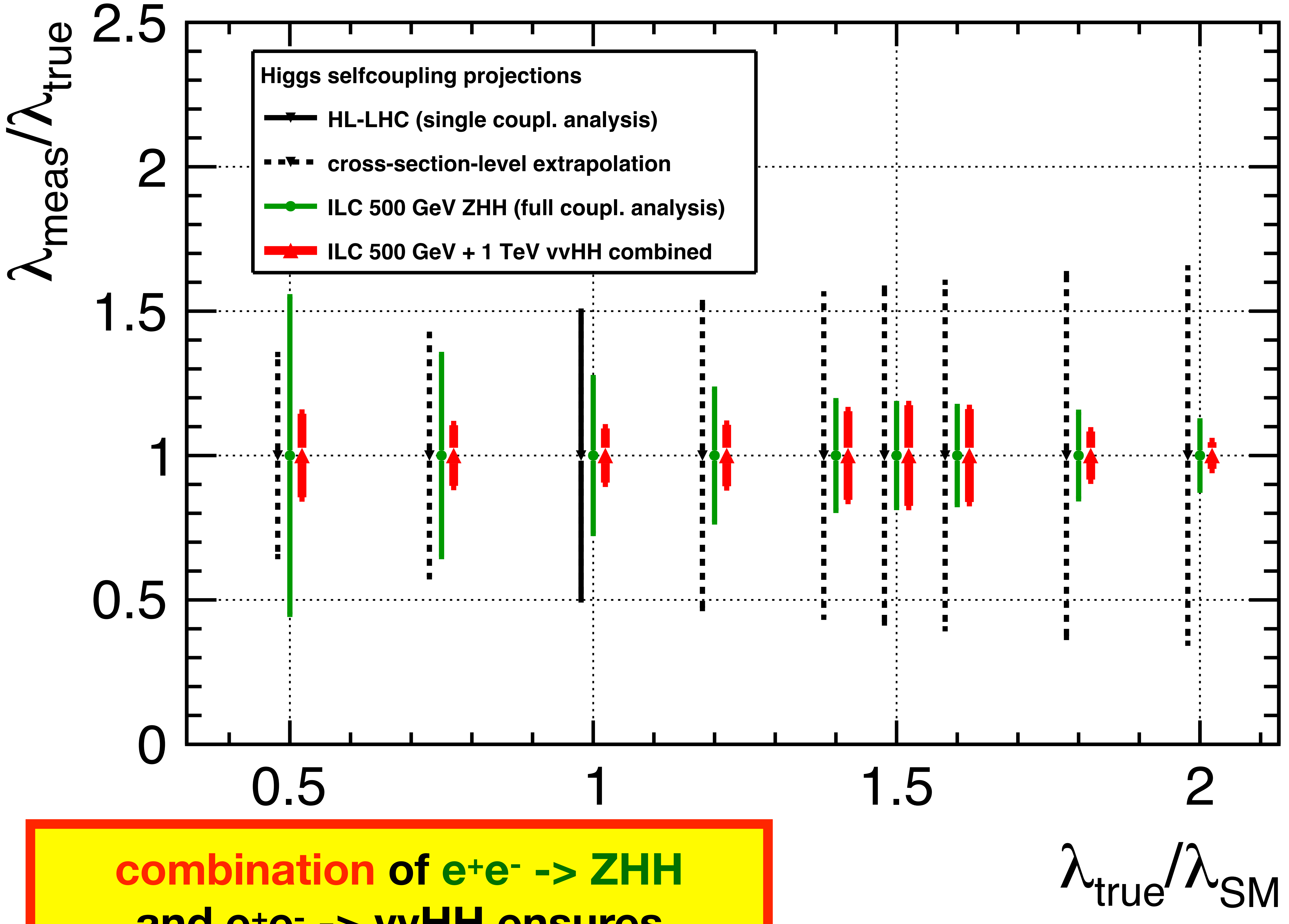
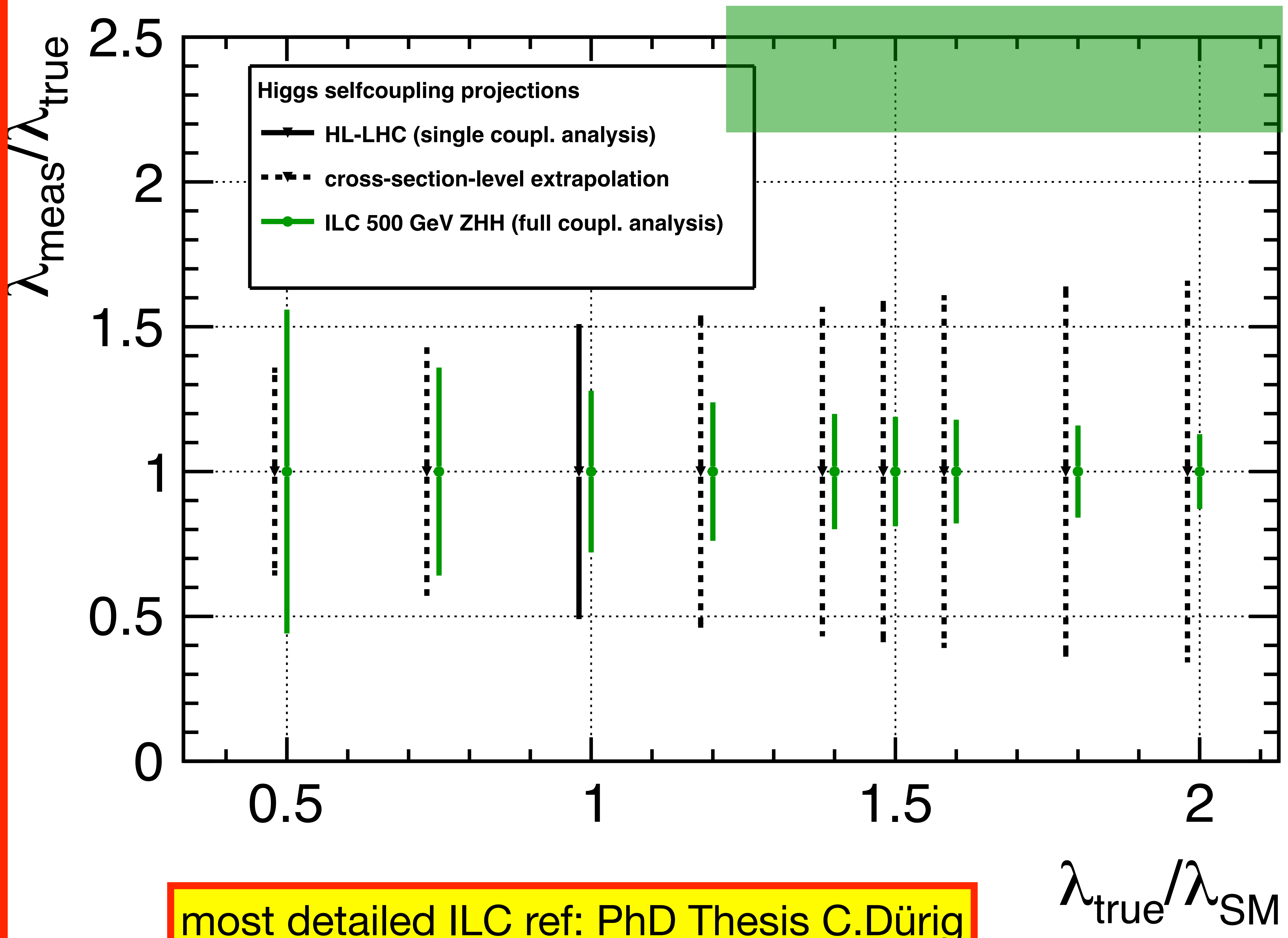




combination of e^+e^- -> ZHH and e^+e^- -> ννHH ensures at least 10-15% precision for all λ

Region of interest for electroweak baryogenesis



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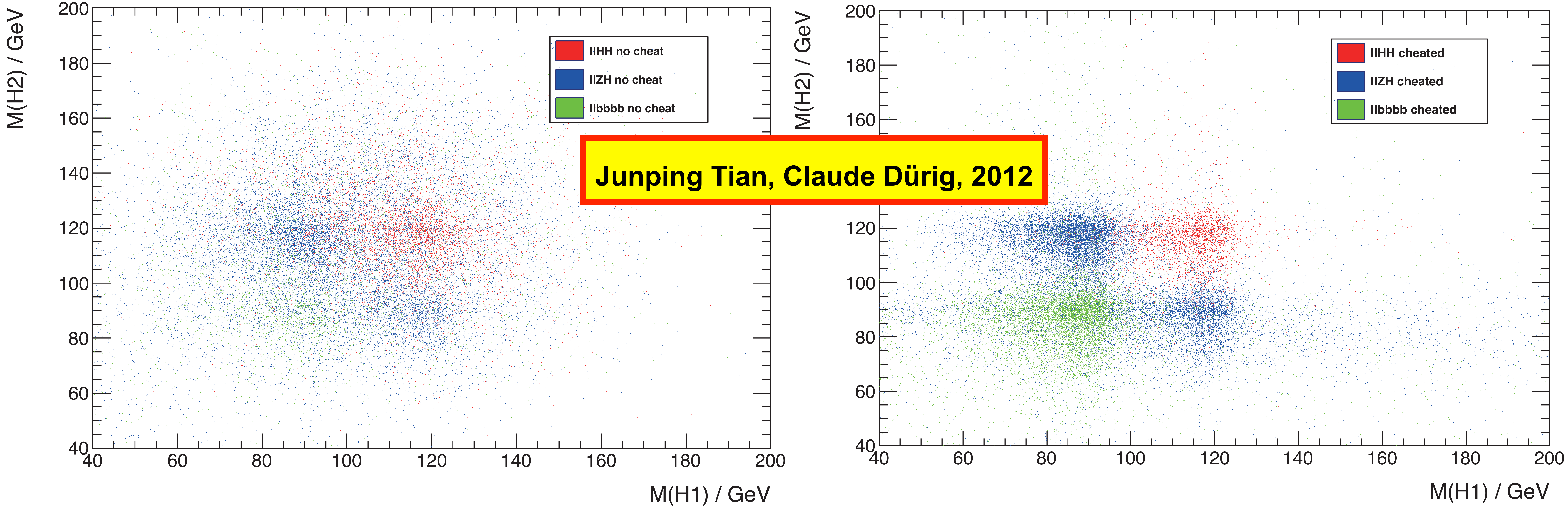
UPDATE ONGOING!

Urgently wanted: modern jet clustering

… bottle-neck for Higgs self-coupling precision



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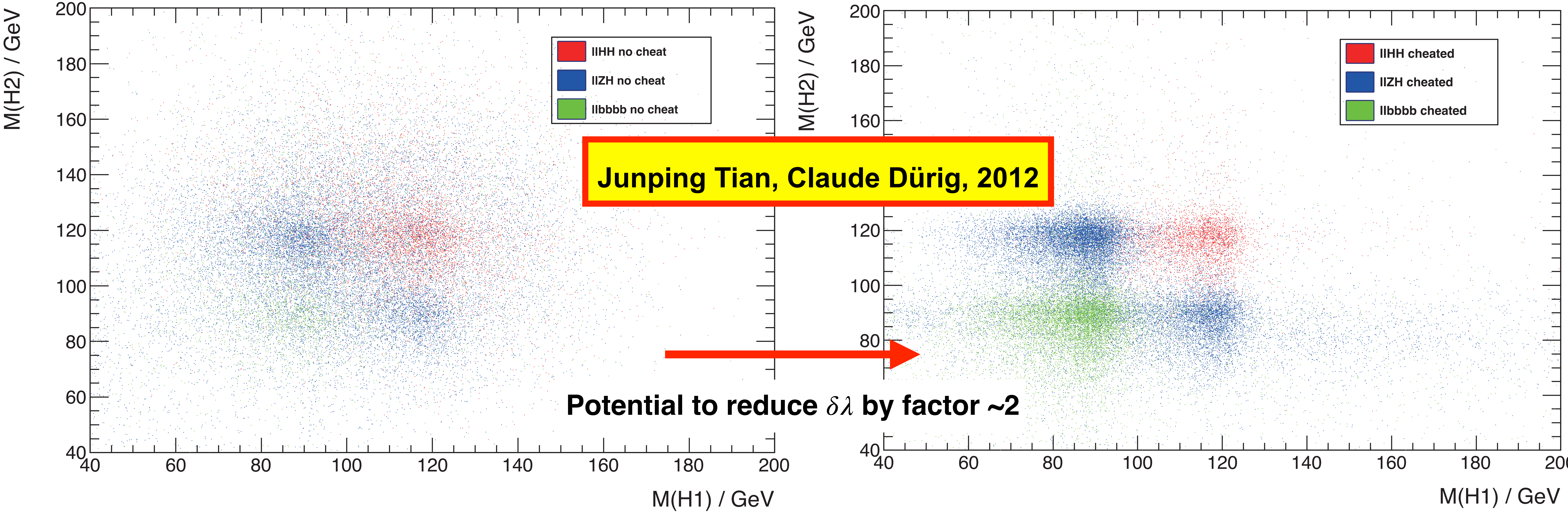

Junping Tian, Claude Dürig, 2012

Potential to reduce $\delta\lambda$ by factor ~2

Urgently wanted: modern jet clustering

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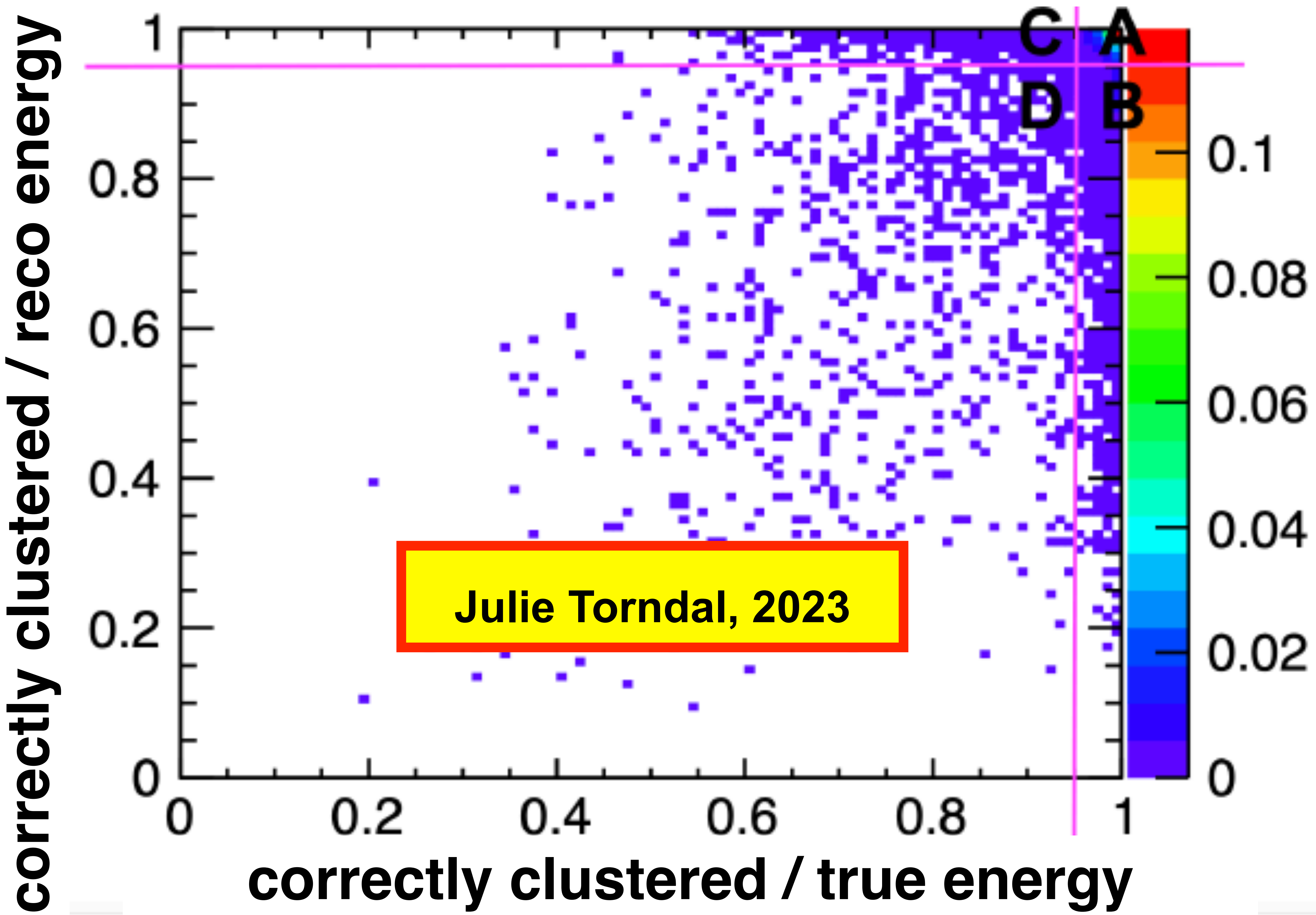

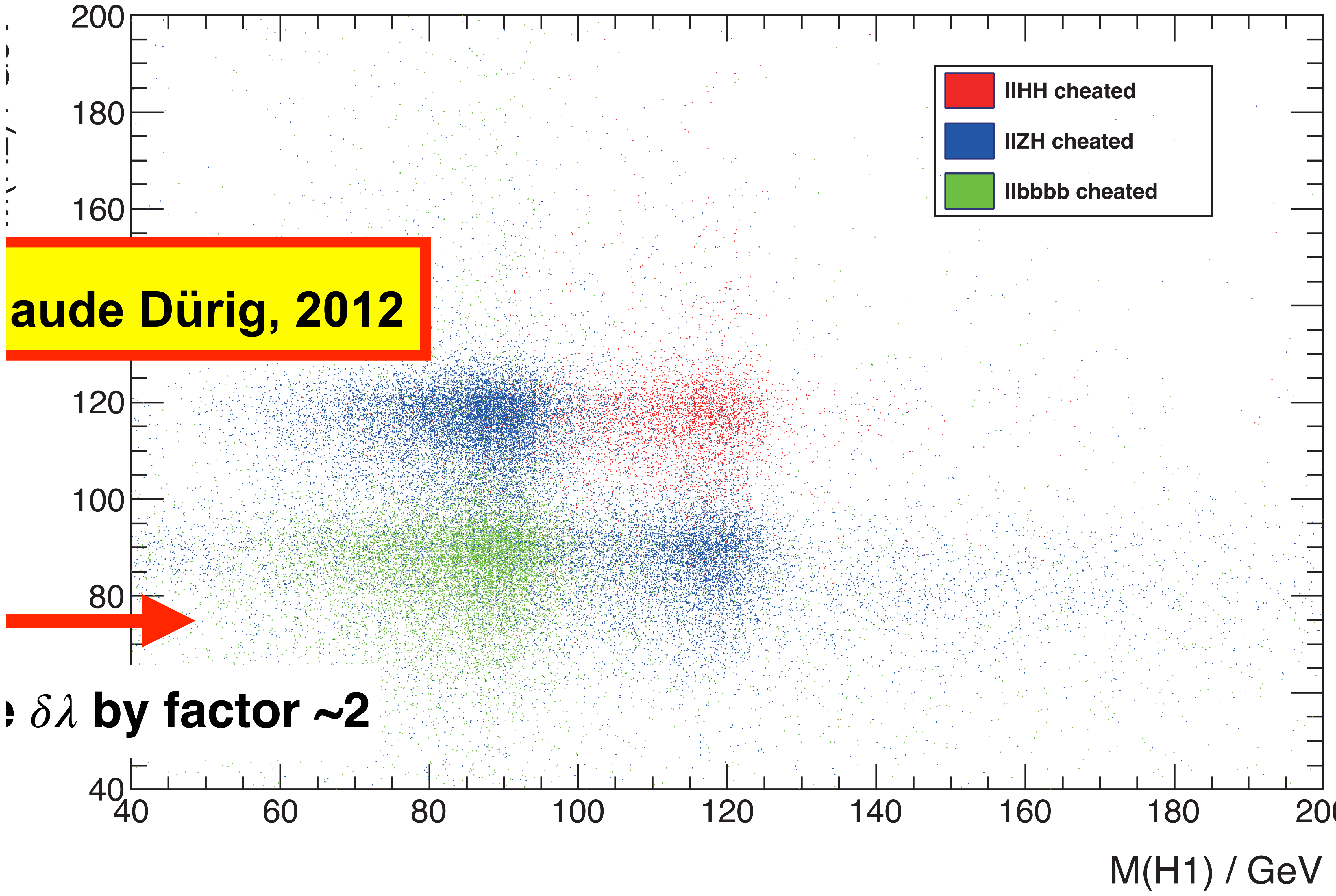

$\delta\lambda$ **by factor ~2**

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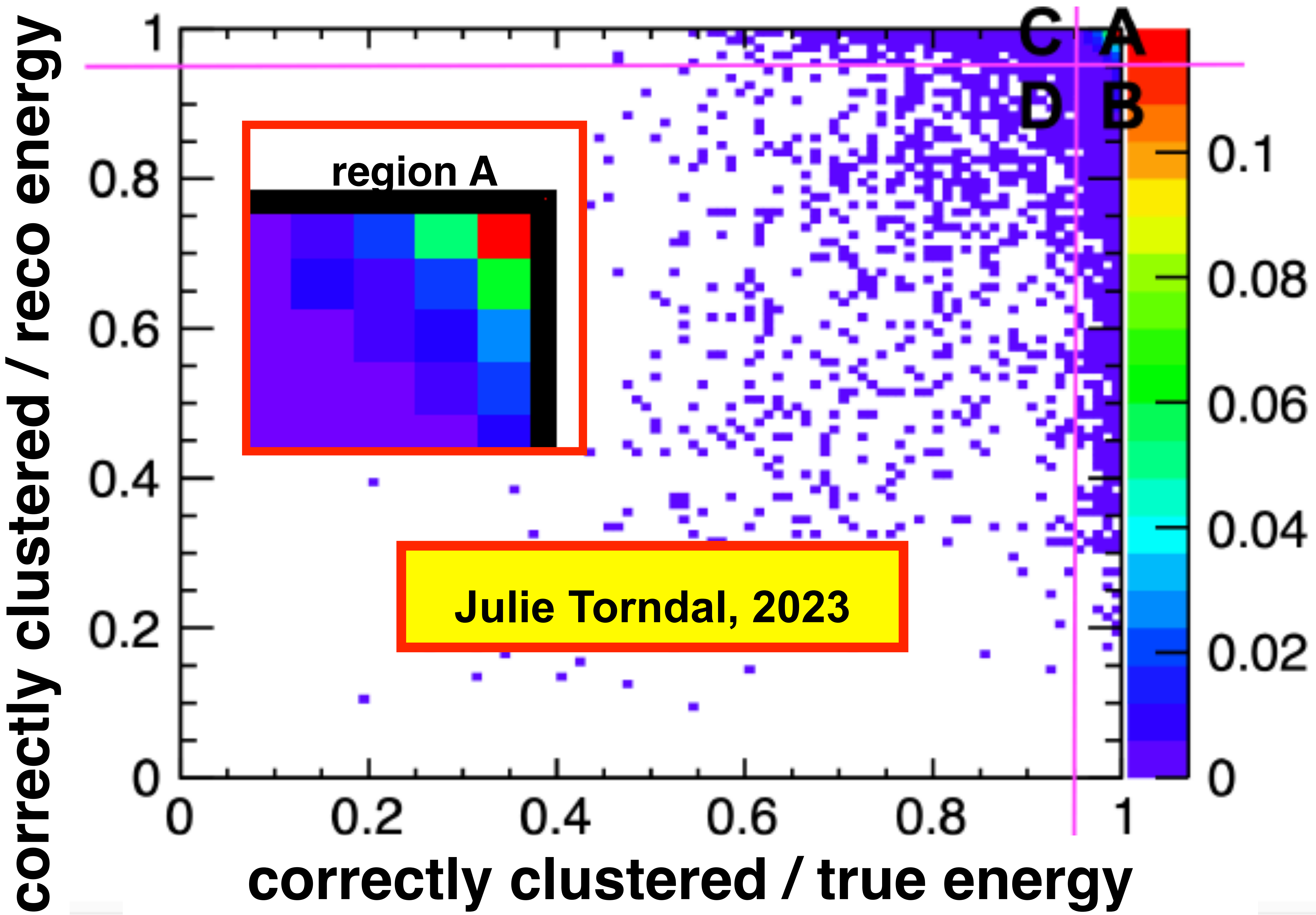

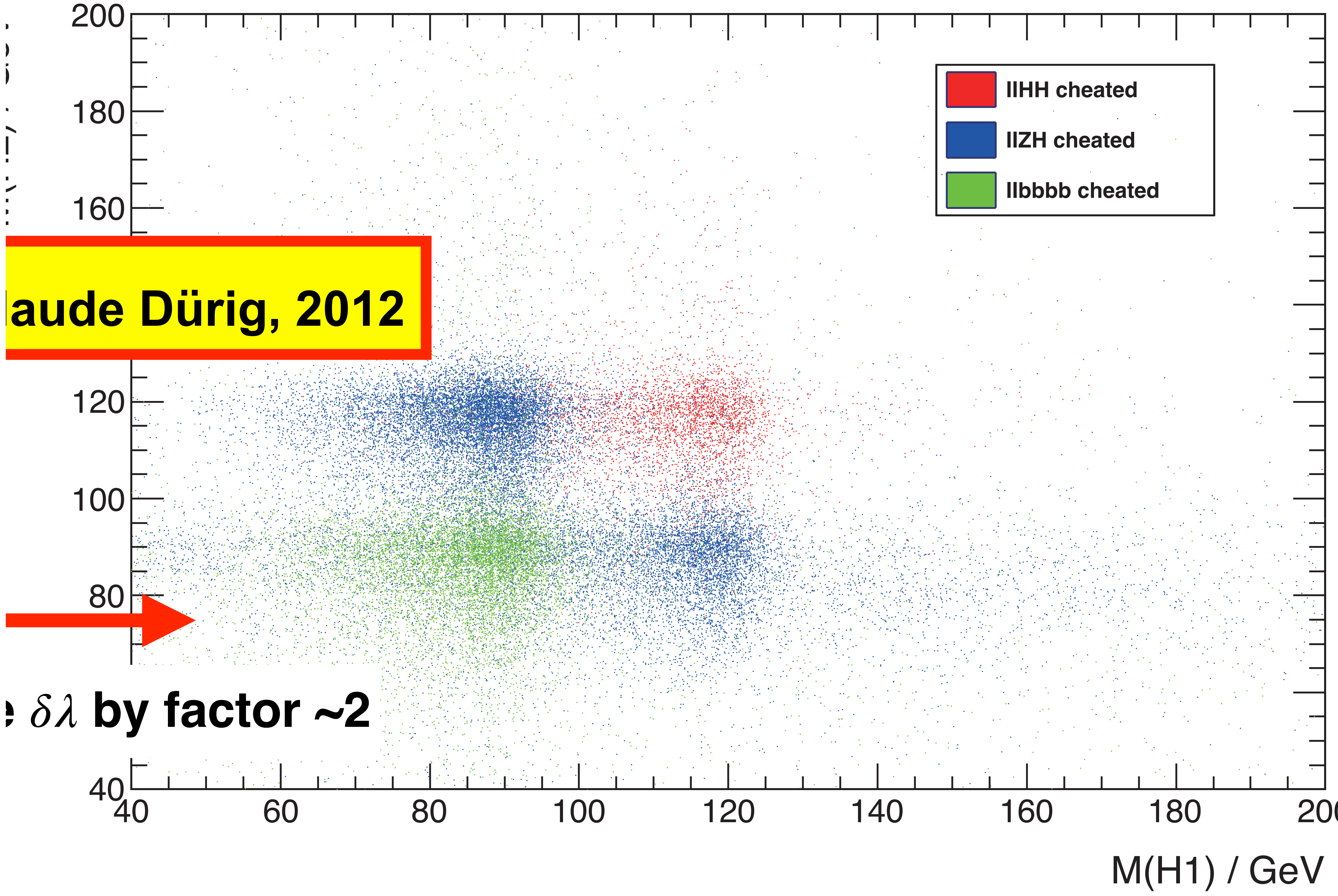

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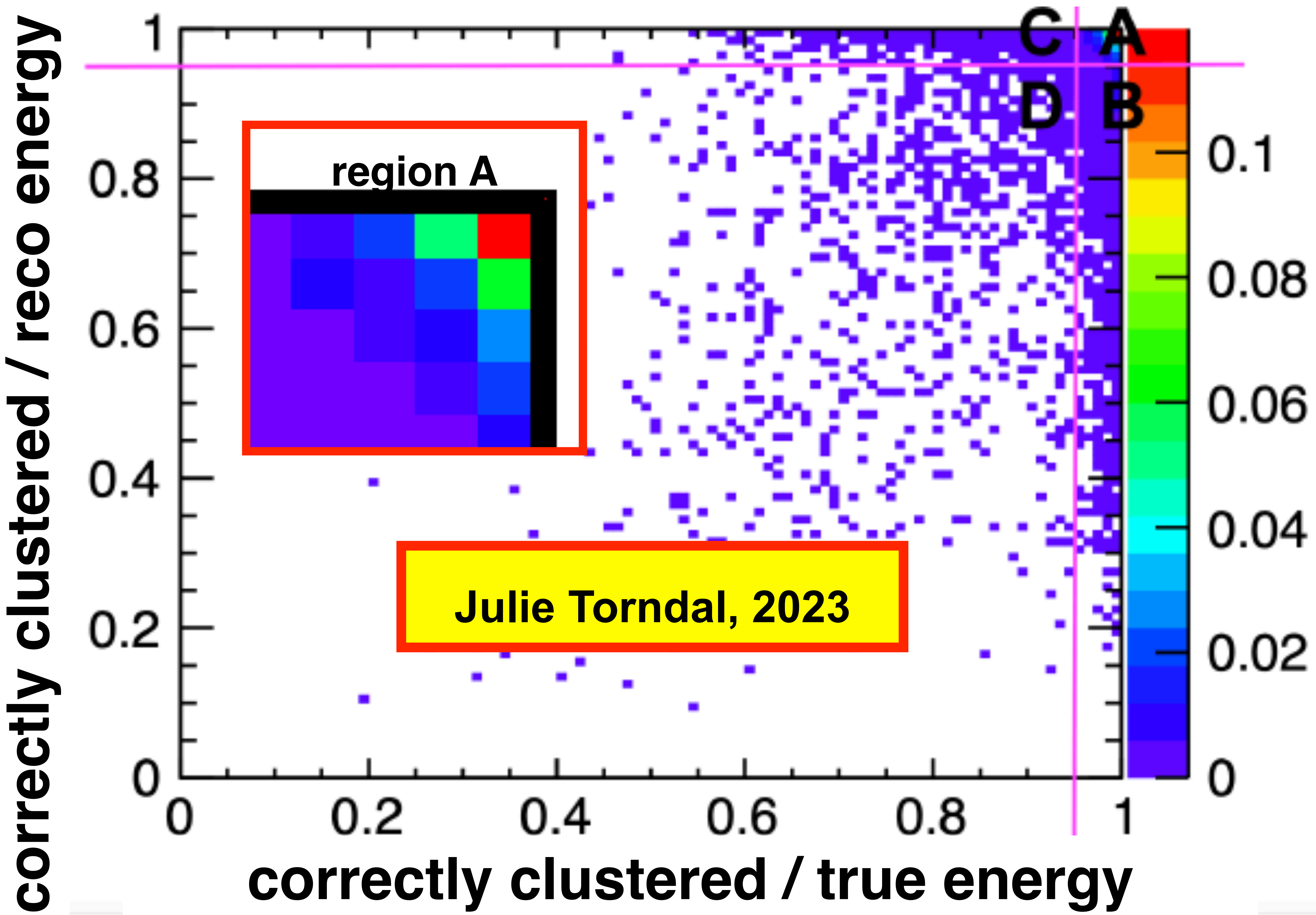

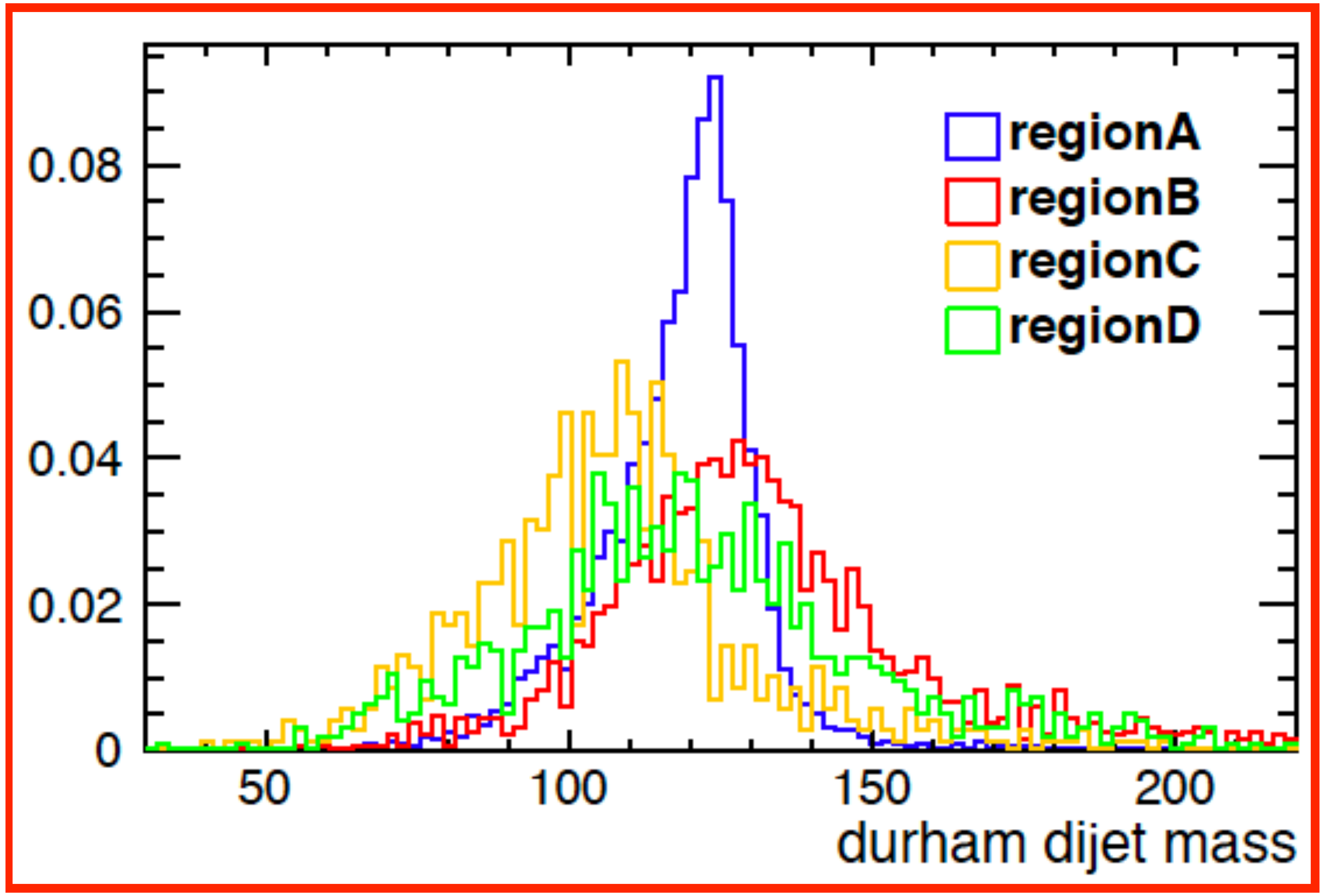

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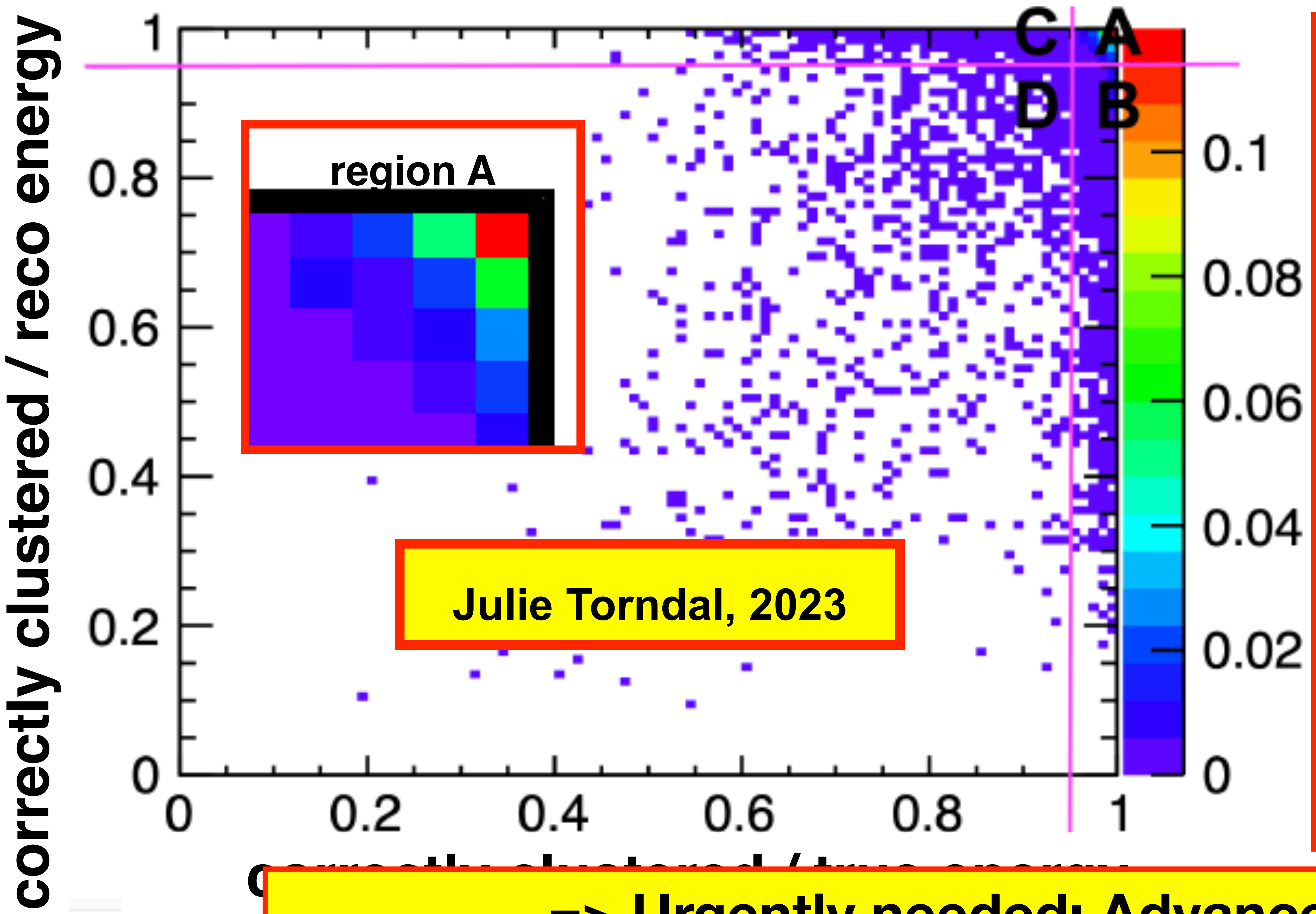
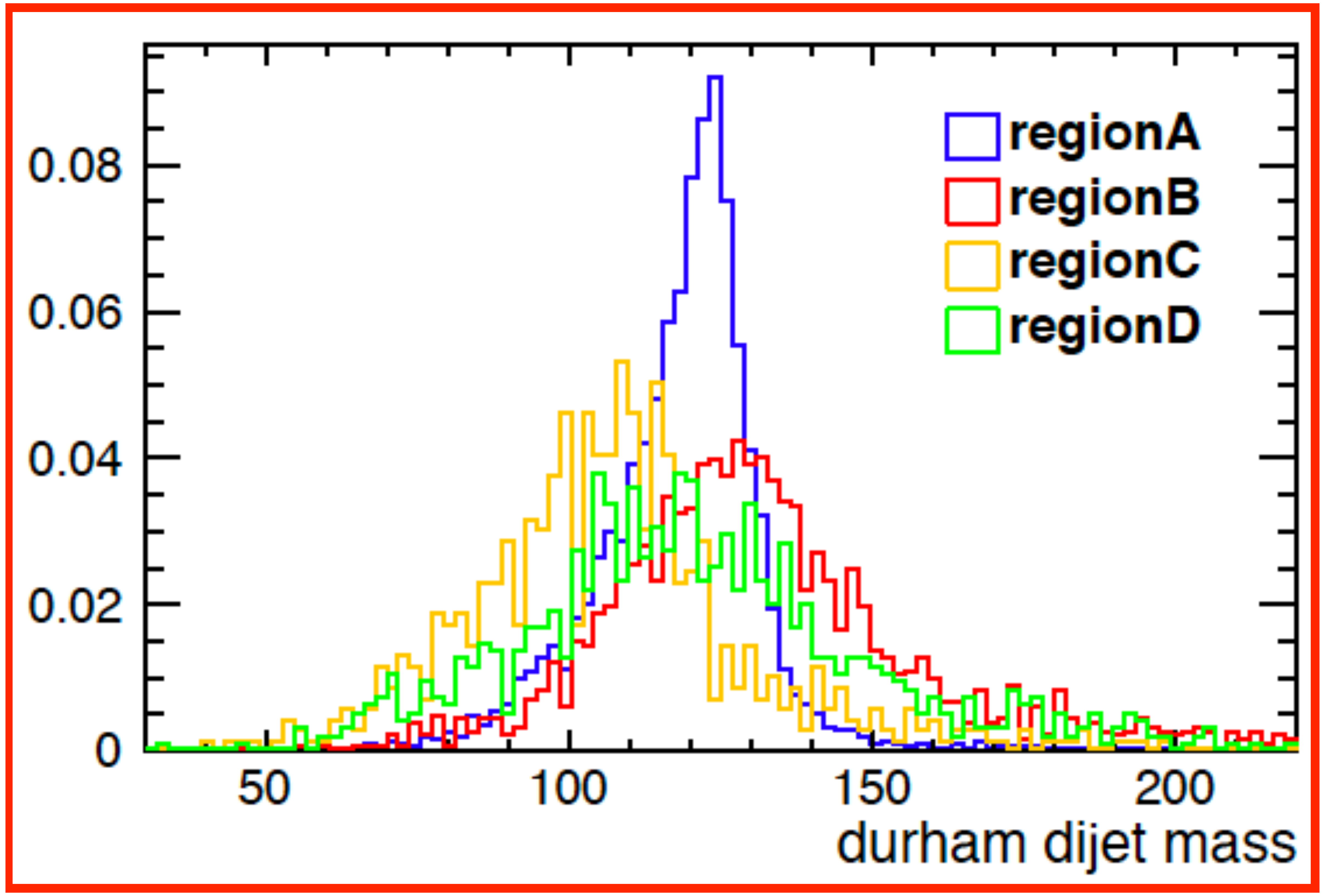




=> Urgently needed: Advanced Jet Clustering, ML, …

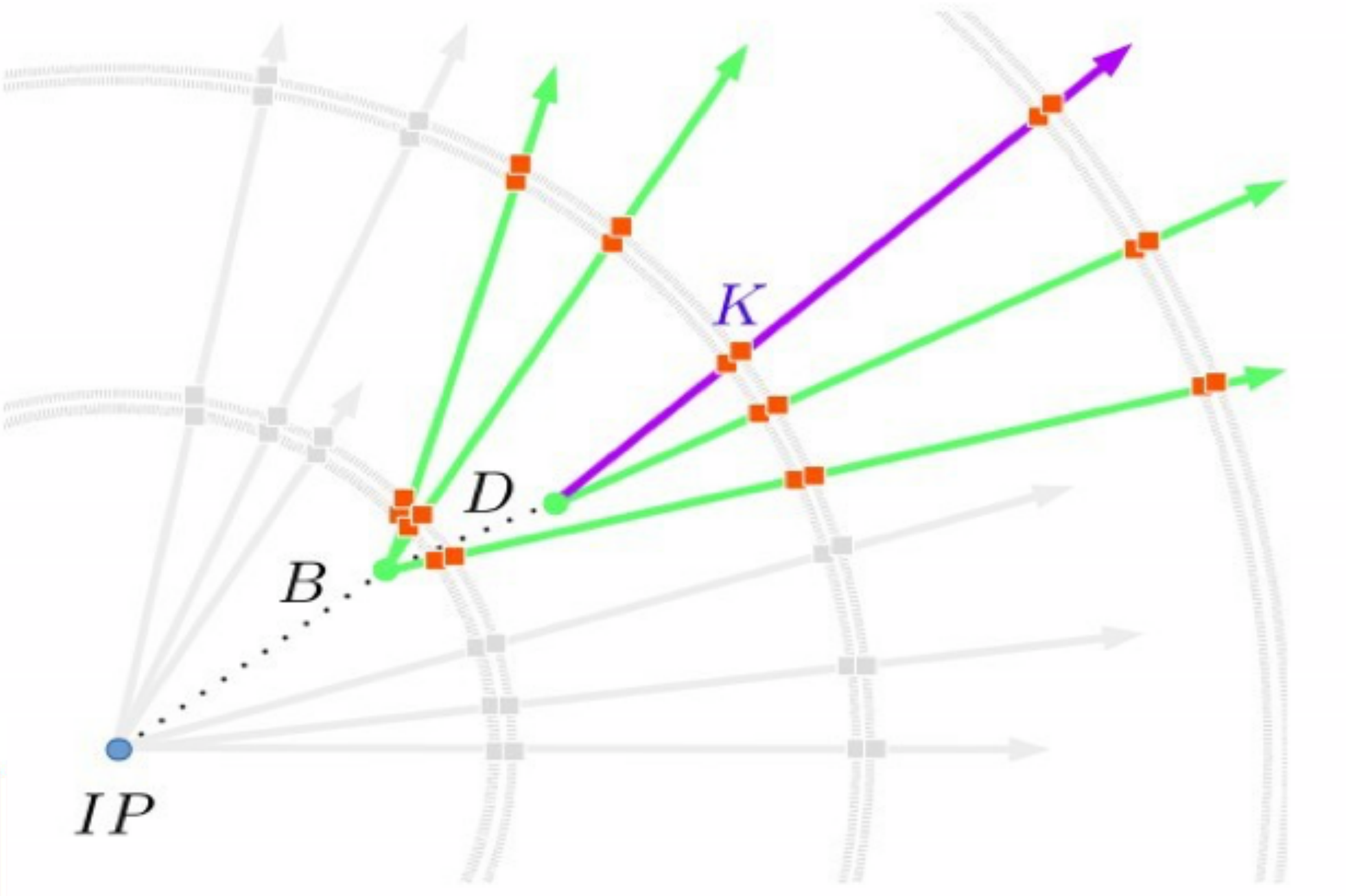
can we get rid of B, C, D ???

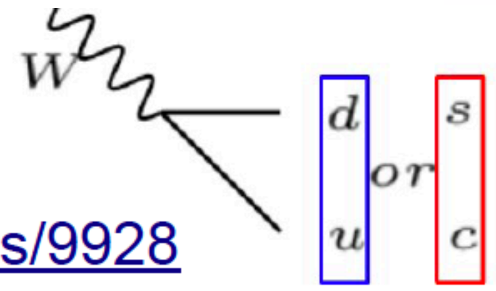
which additional detector information would help?

The new kid on the block: Particle ID

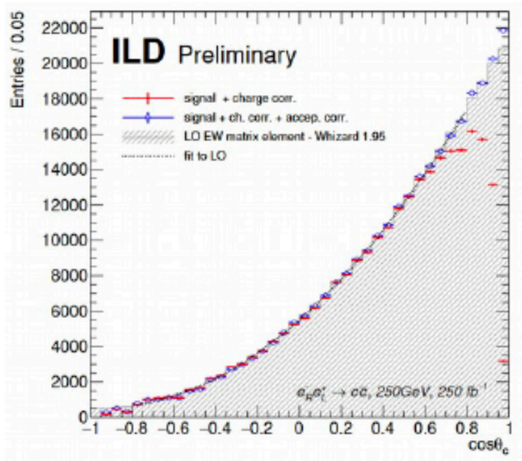
… only starting to be explored

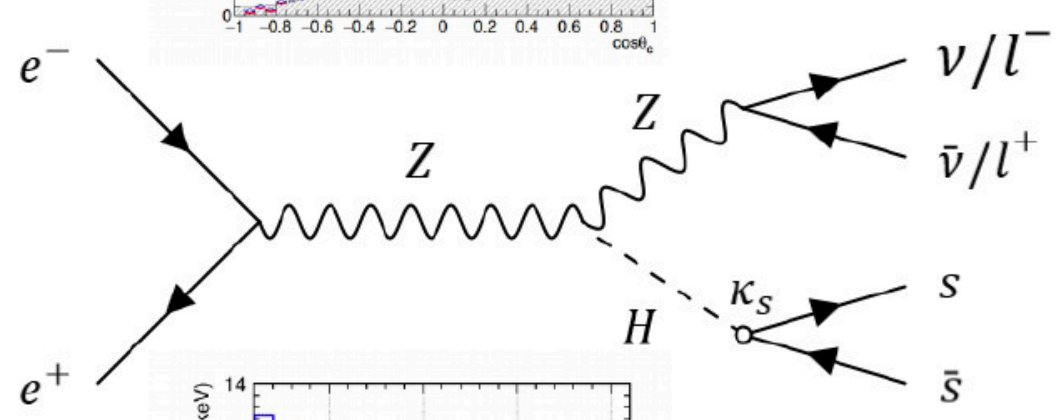
A boost of analyses using in particular Kaon ID - many of them intrisically not possible without!

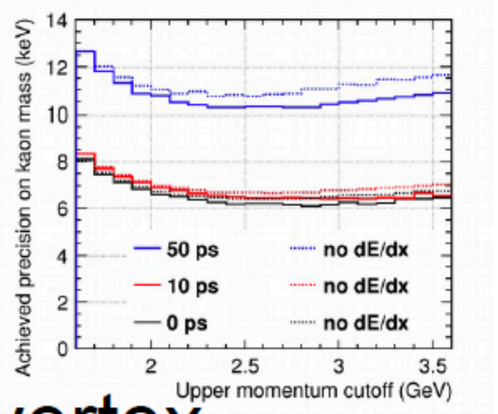


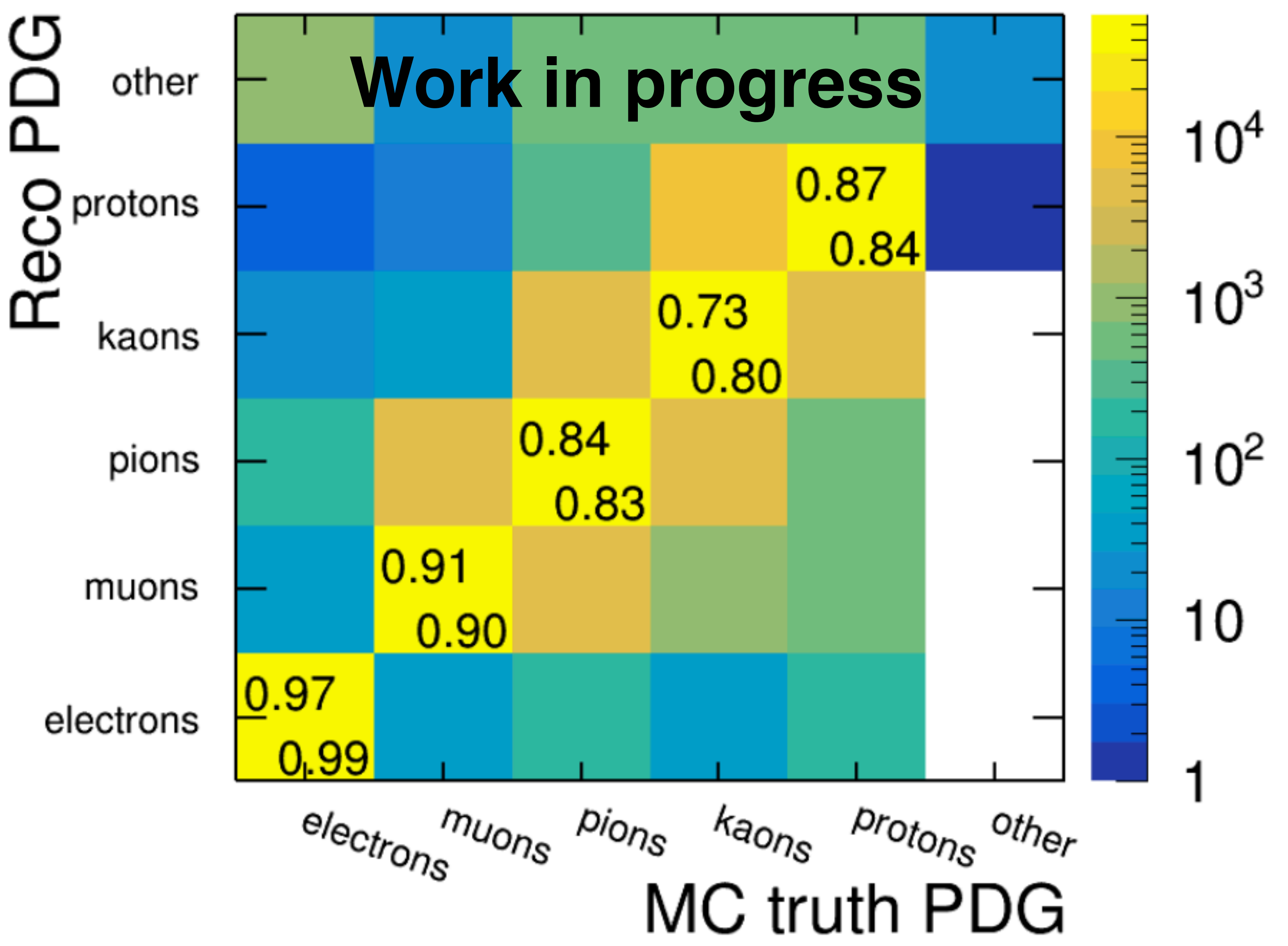


- Z and W hadronic decay branching fractions via flavour tagging
  → make connection between quark flavour and jet composition
  https://ediss.sub.uni-hamburg.de/handle/ediss/9634 , https://ediss.sub.uni-hamburg.de/handle/ediss/9928
- Forward-backward asymmetry in e+e- → $q\bar{q}$
  → study asymmetry in each flavour channel exclusively
  overview: https://tel.archives-ouvertes.fr/tel-01826535
  e^+e^- → tt, bb: https://agenda.linearcollider.org/event/8147
  e^+e^- → bb/cc: https://arxiv.org/abs/2002.05805 ,
  https://agenda.linearcollider.org/event/9211/contributions/49358/
  e^+e^- → bb/cc, ss: https://agenda.linearcollider.org/event/9440 ,
  https://agenda.linearcollider.org/event/9285
- H → $s\bar{s}$ with s-tagging
  → identify high-momentum kaons to tag $s\bar{s}$ events
  https://arxiv.org/abs/2203.07535
- Kaon mass with TOF
  https://pos.sissa.it/380/115/
- Track refit with correct particle mass for better momentum and vertex
  https://agenda.linearcollider.org/event/8498/







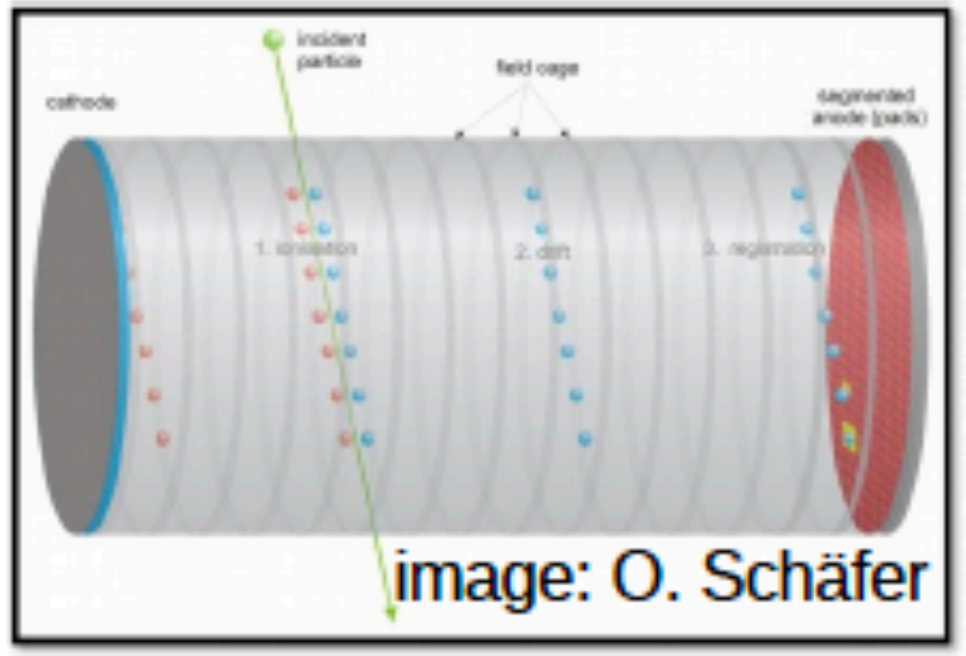


U.Einhaus

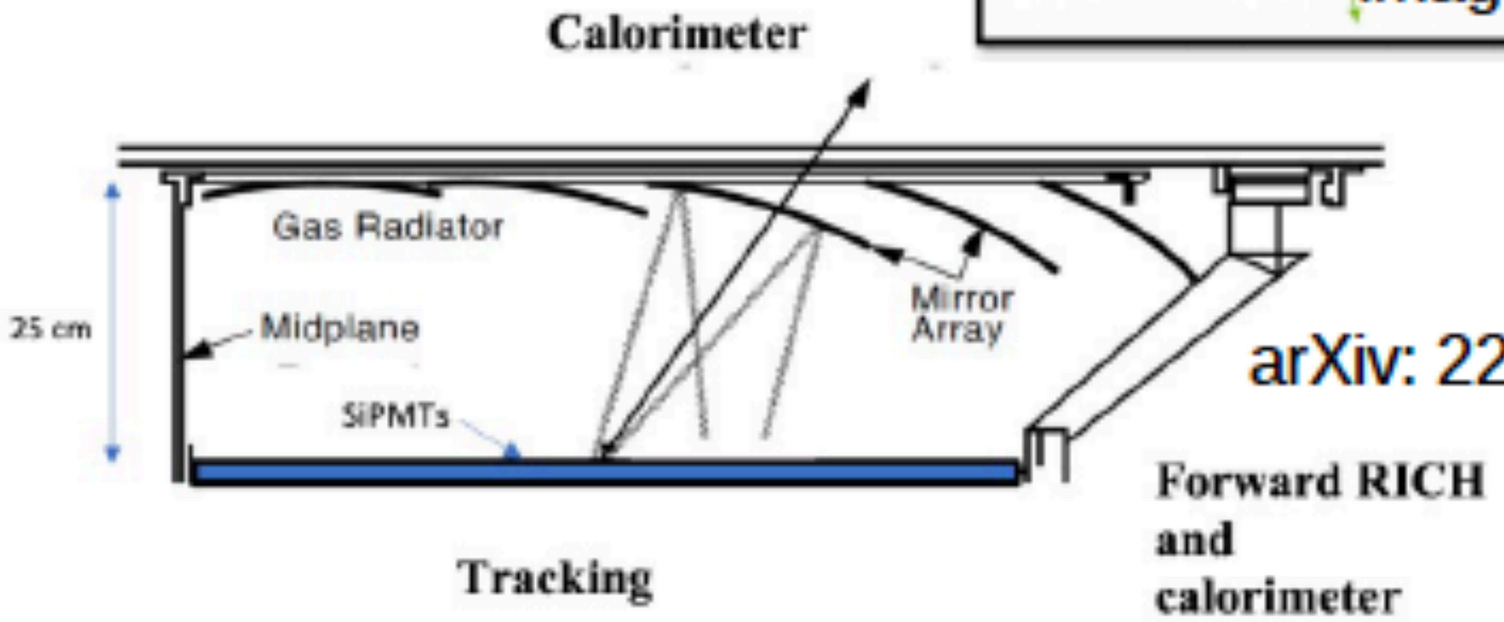
Particle ID - How to ?!

… many open questions

- Gaseous trackers (Time Projection Chamber, Drift Chamber): specific energy loss dE/dx, via gas ionisation, up to 20 GeV

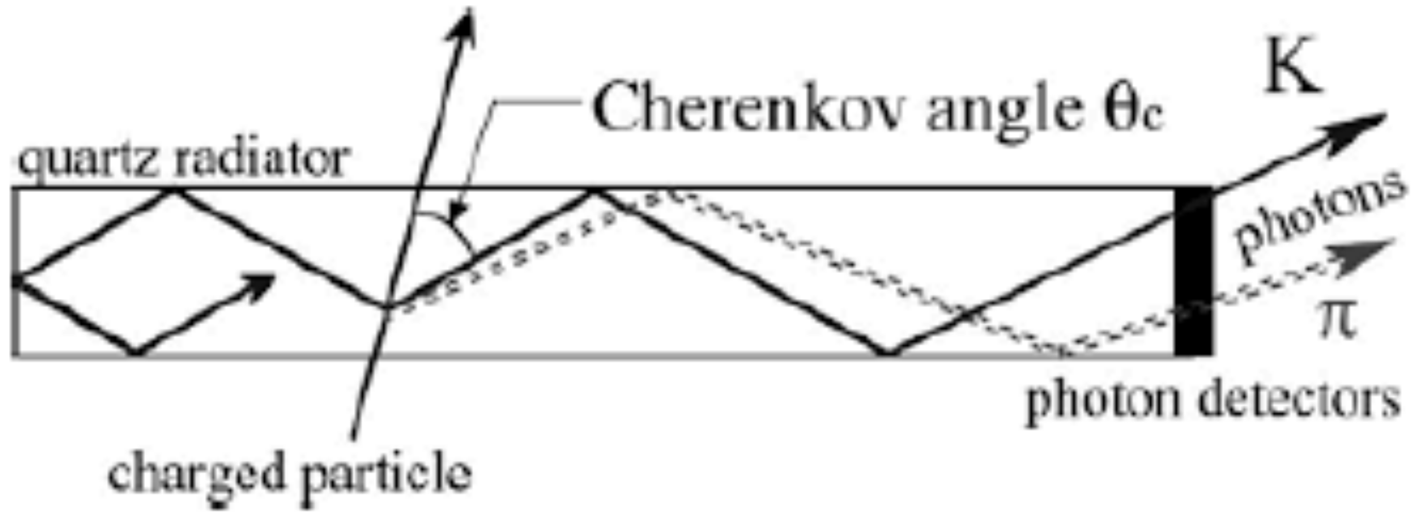


- Ring Imaging Cherenkov Detectors: Cherenkov angle, via imaging, 10 to 50 GeV



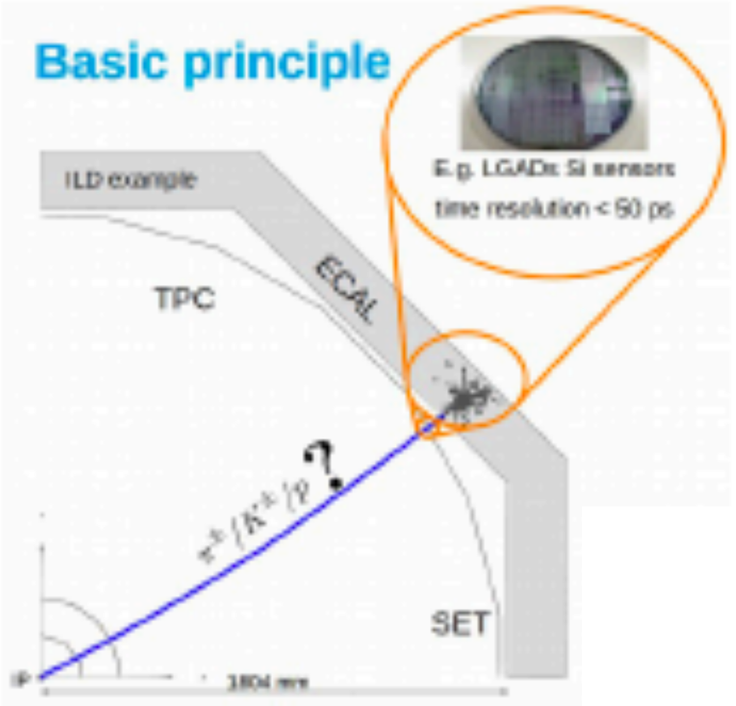
arXiv: 2203:07535

- Time of Propagation Counter: Cherenkov angle, via timing, up to 10 GeV



https://doi.org/10.1016/j.nima.2017.02.045

- Time of Flight: time, via Silicon timing, up to 5 GeV



U.Einhaus

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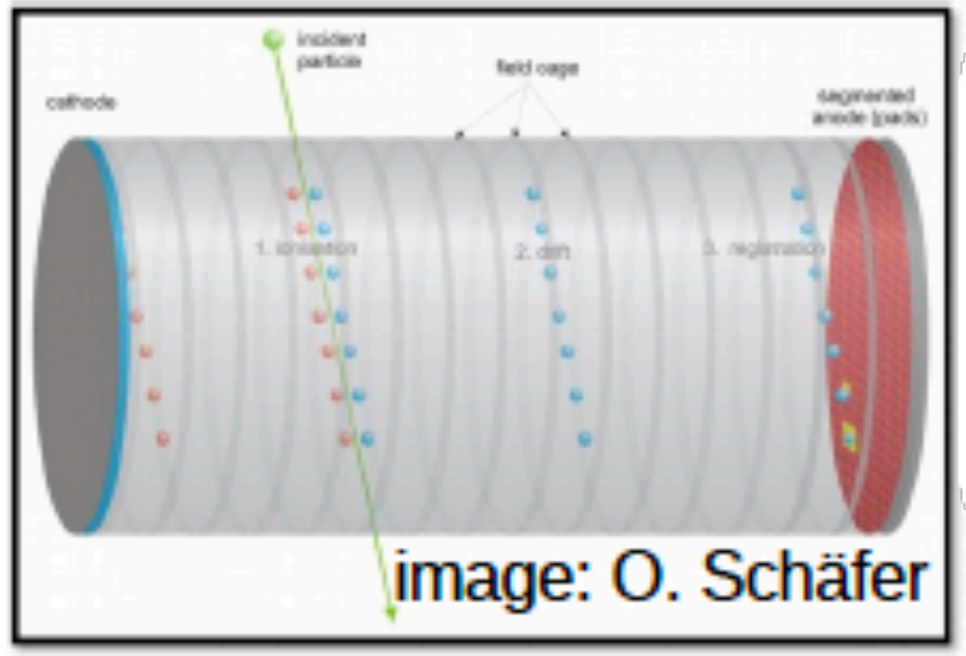
image: O. Schäfer

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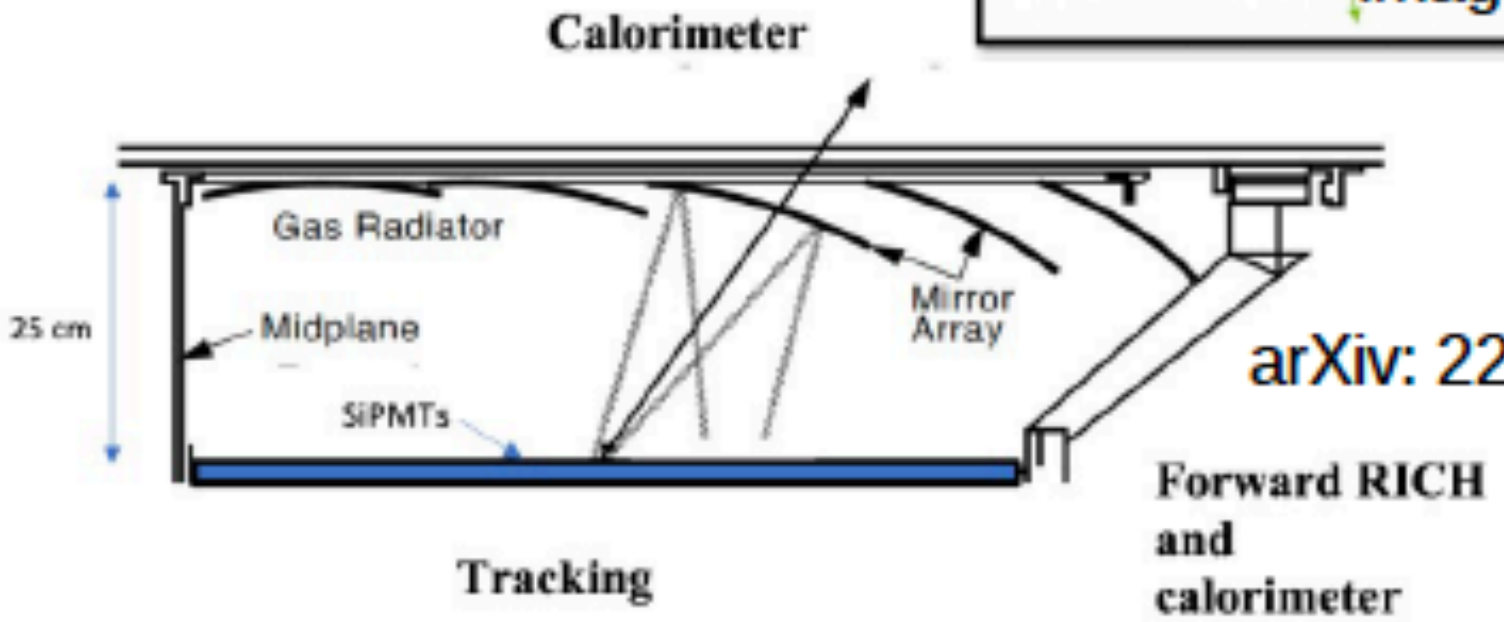

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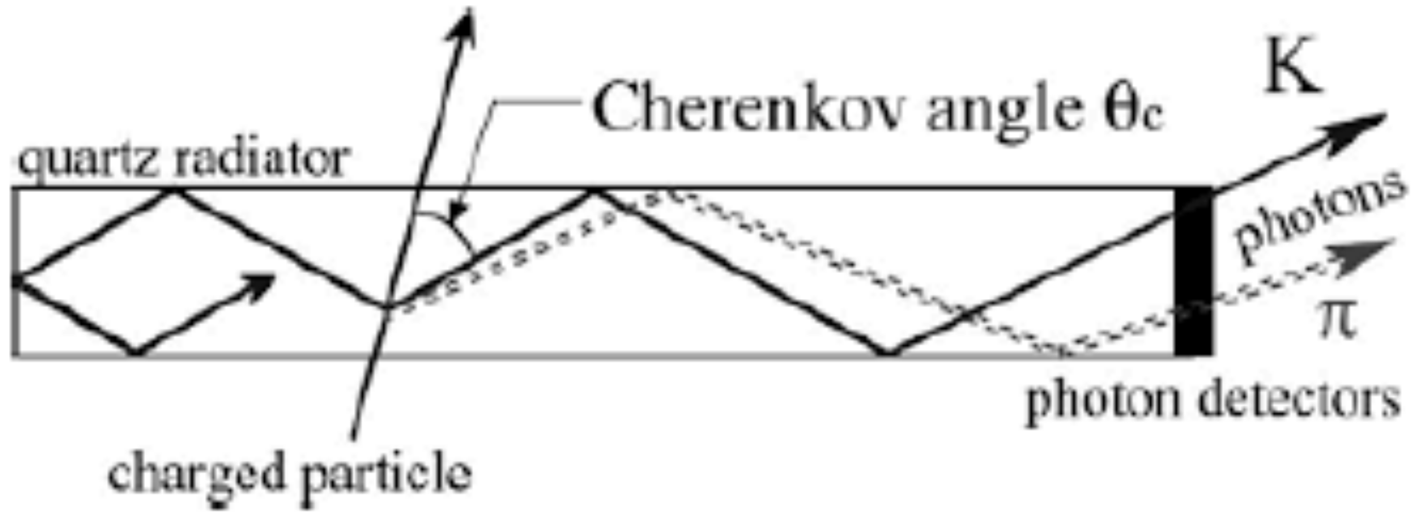

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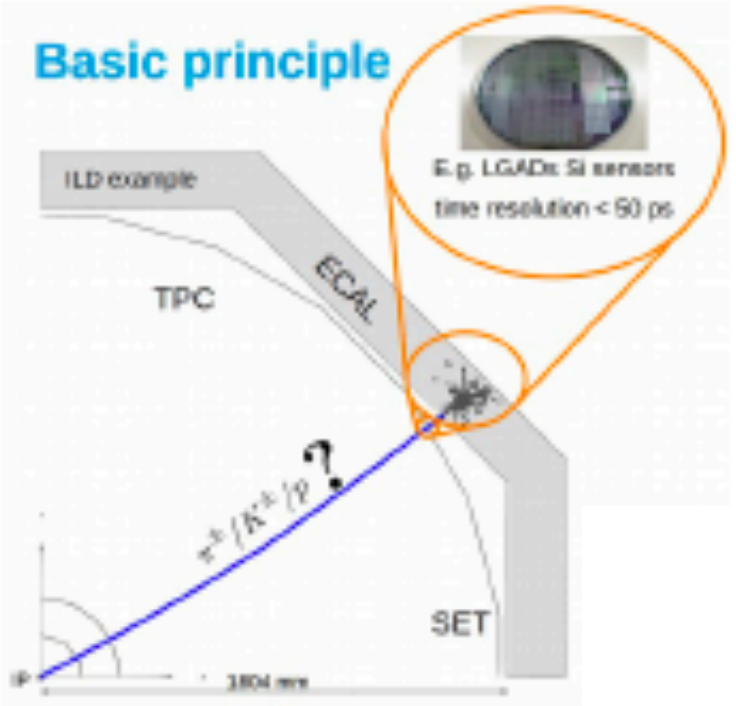

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U.Einhaus

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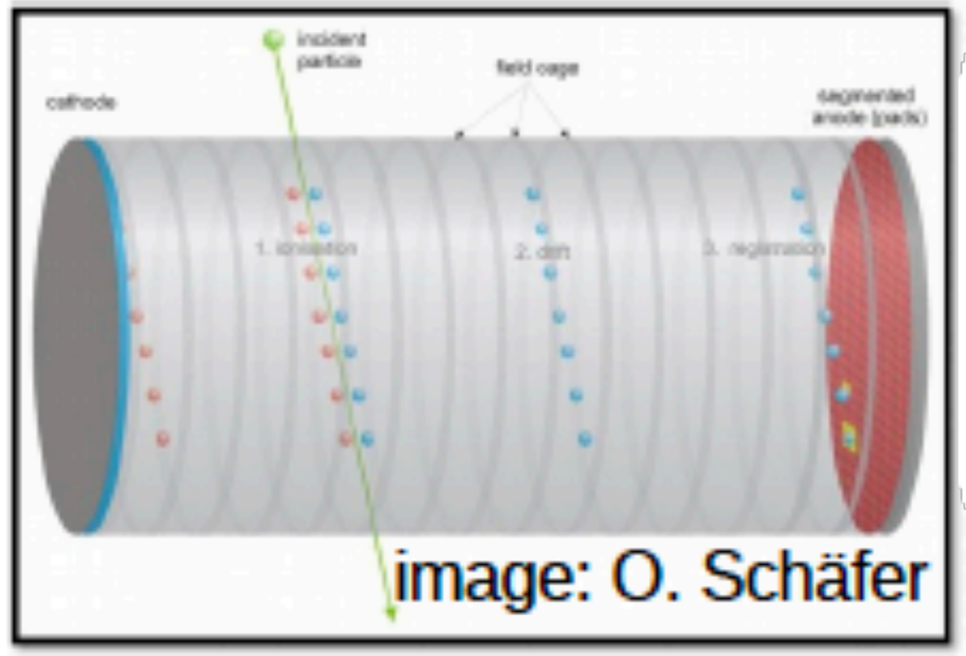

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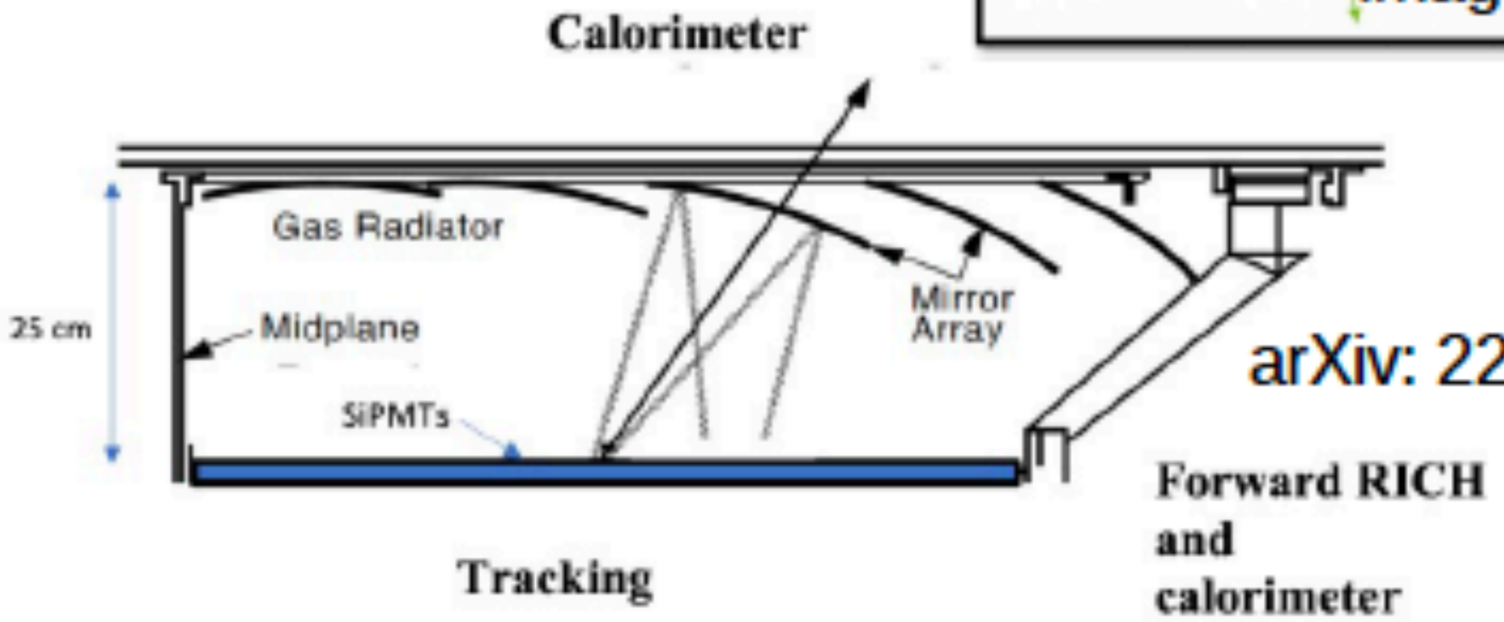

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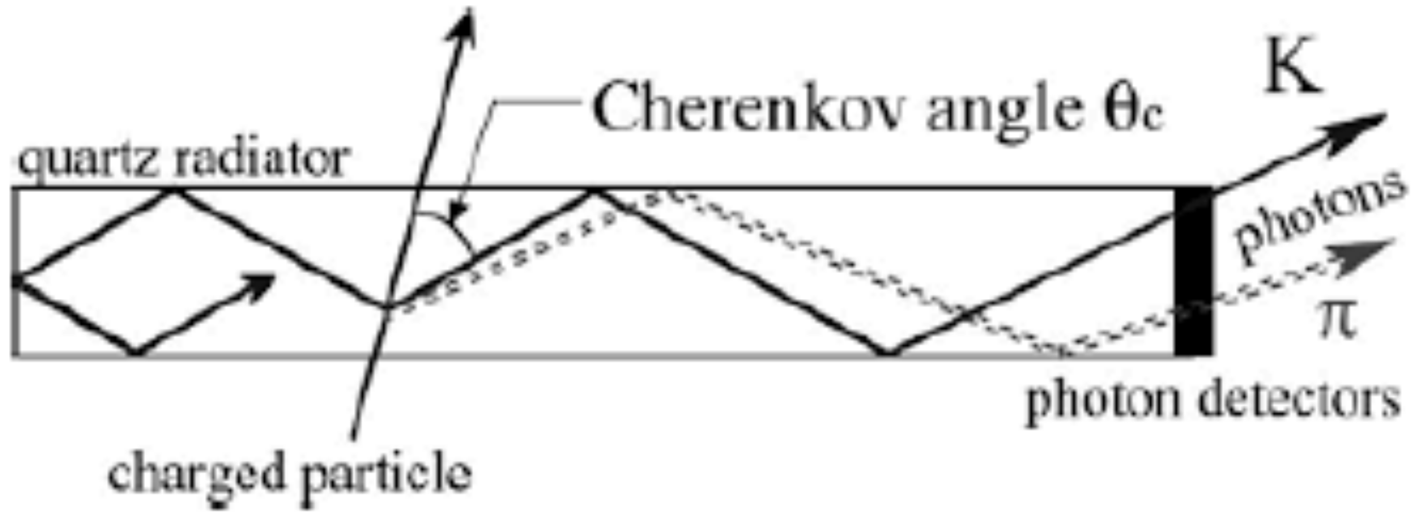

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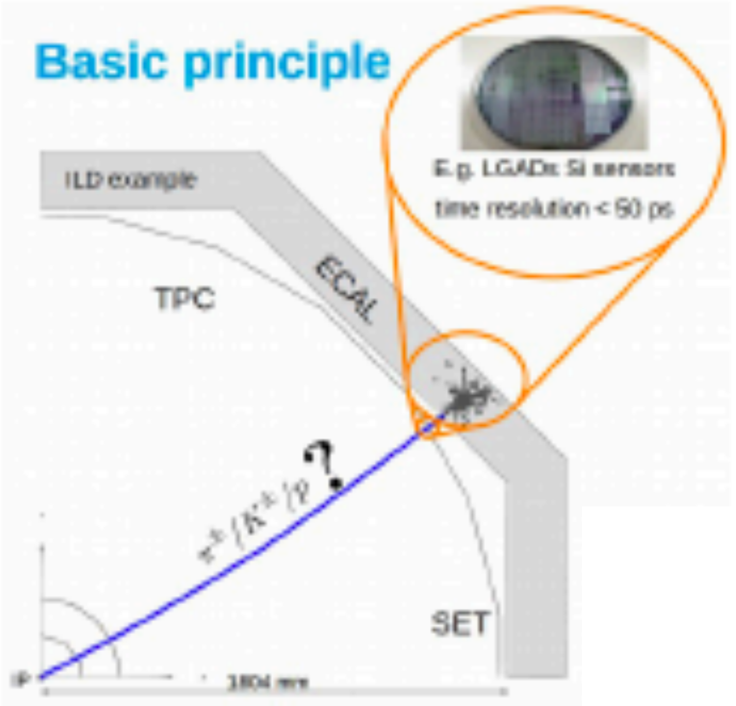

U.Einhaus

Interesting momentum range
=> impact on ParticleFlow / Jet Energy Resolution?!

Particle ID - How to ?!

… many open questions

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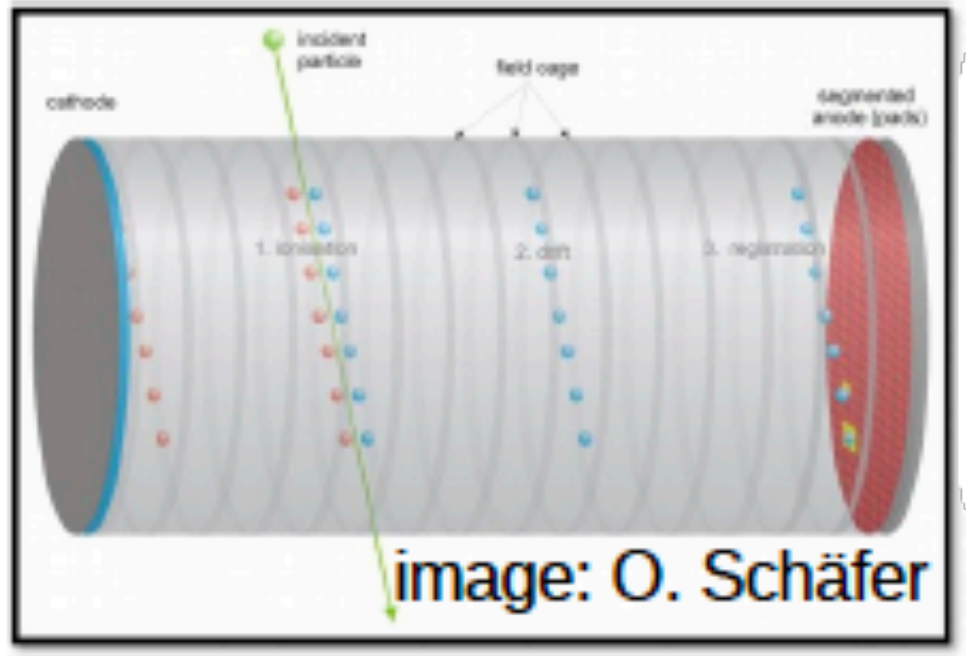
- Time of Flight: time, via Silicon timing, up to 5 GeV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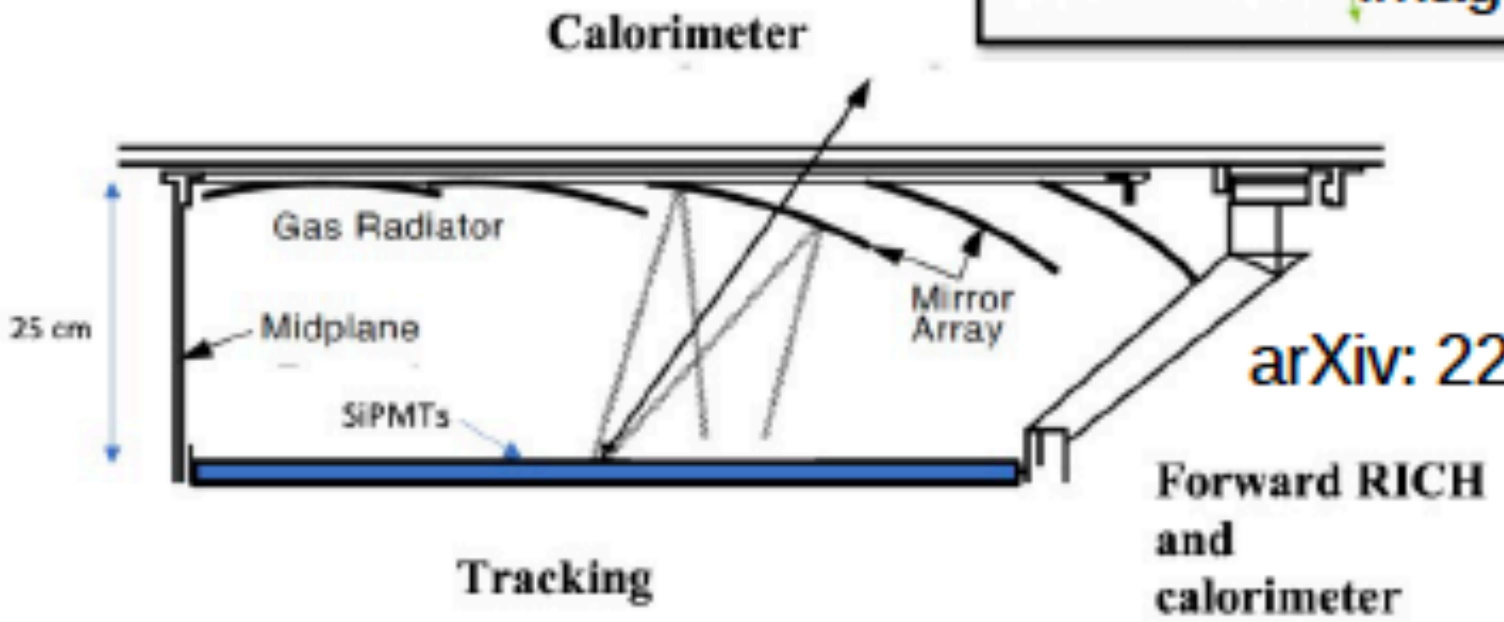

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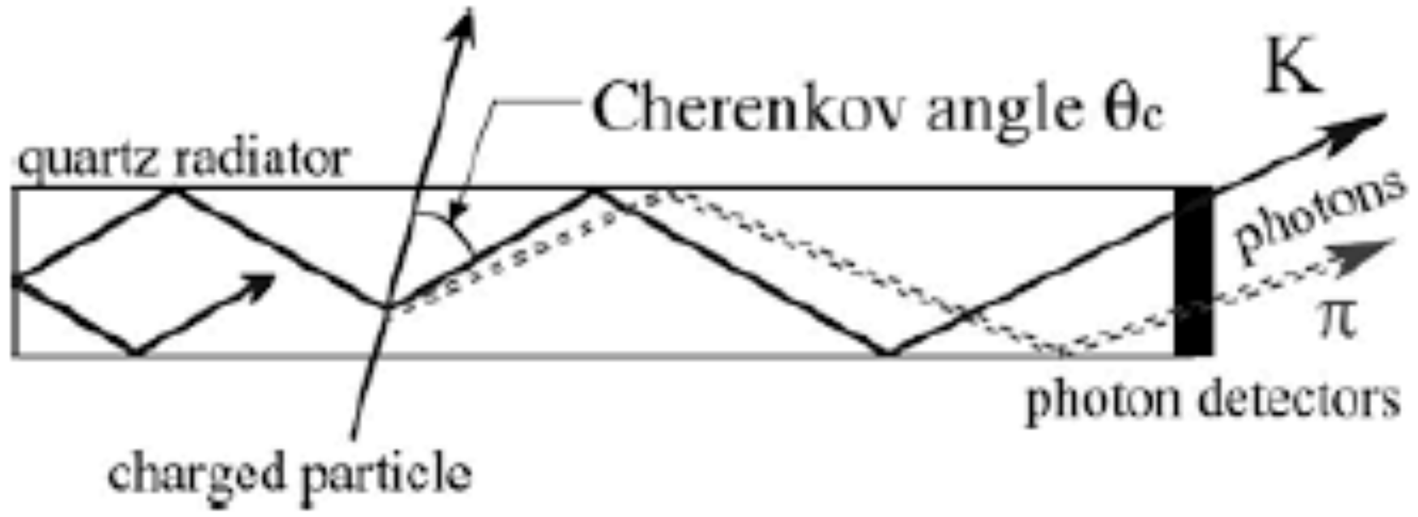

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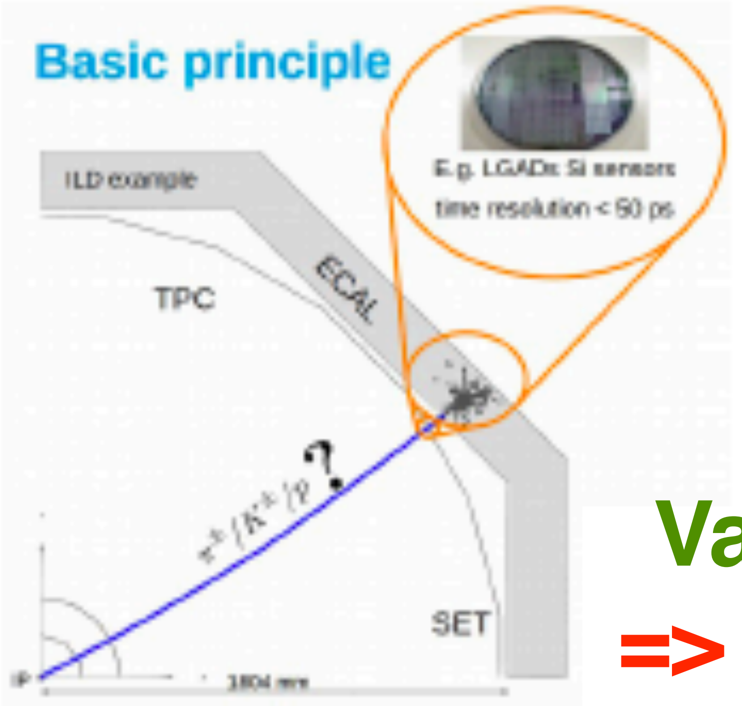


U.Einhaus

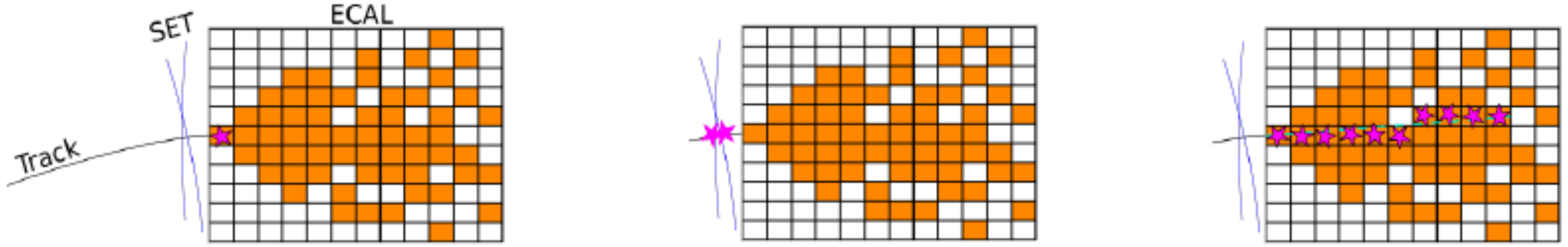
Interesting momentum range => impact on ParticleFlow / Jet Energy Resolution?!

Various implementation options in Si tracking or ECal
=> use-case for low-momentum PID not yet understood

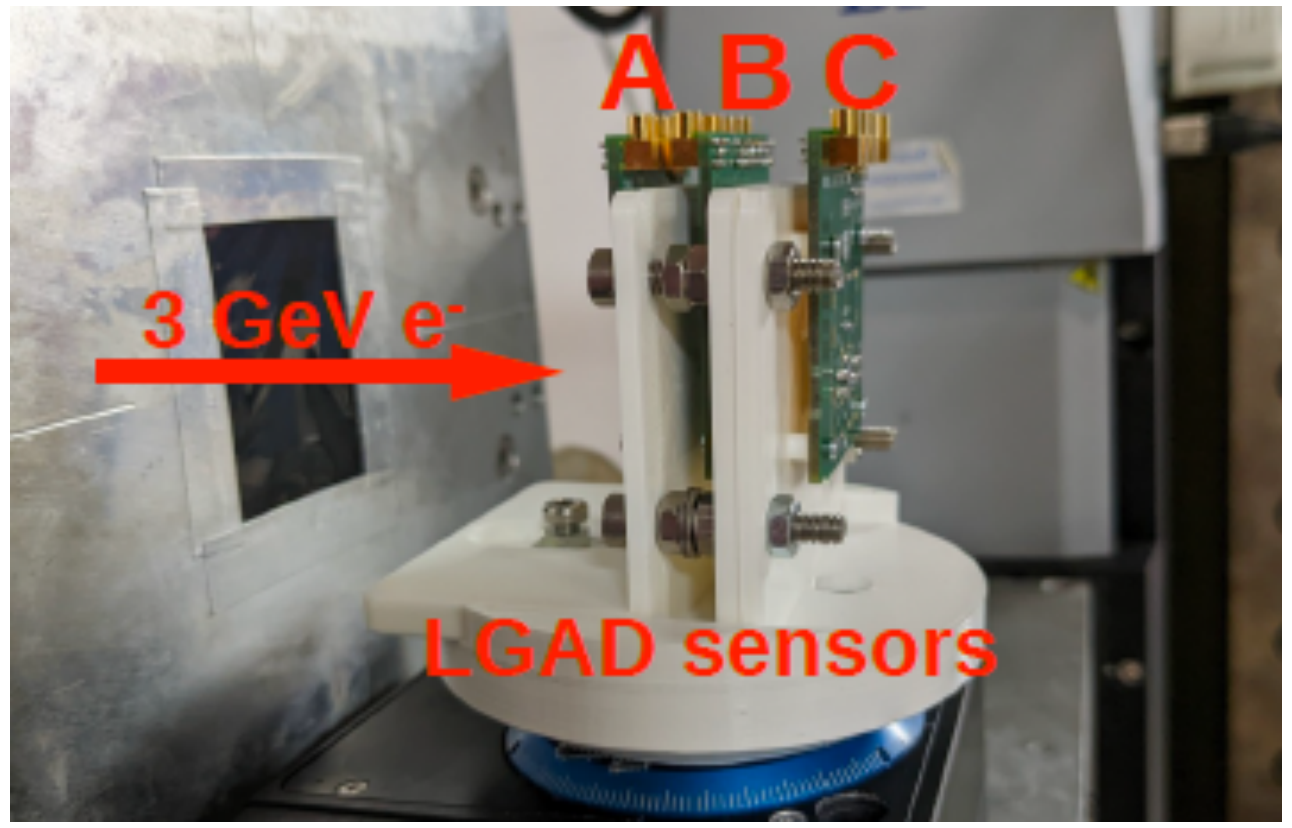
Fast Timing

not only PID!

Timing implementation in the ILD



Placement:	Dedicated ECAL timing layer (LGADs)	Two Si strips of external tracker (LGADs?)	10 ECAL layers (not LGADs)
Hit time resolution:	~ 30 ps	~ 50 ps	~ 100 ps
TOF resolution:	~ 30 ps	~ ? ps	~ ? ps

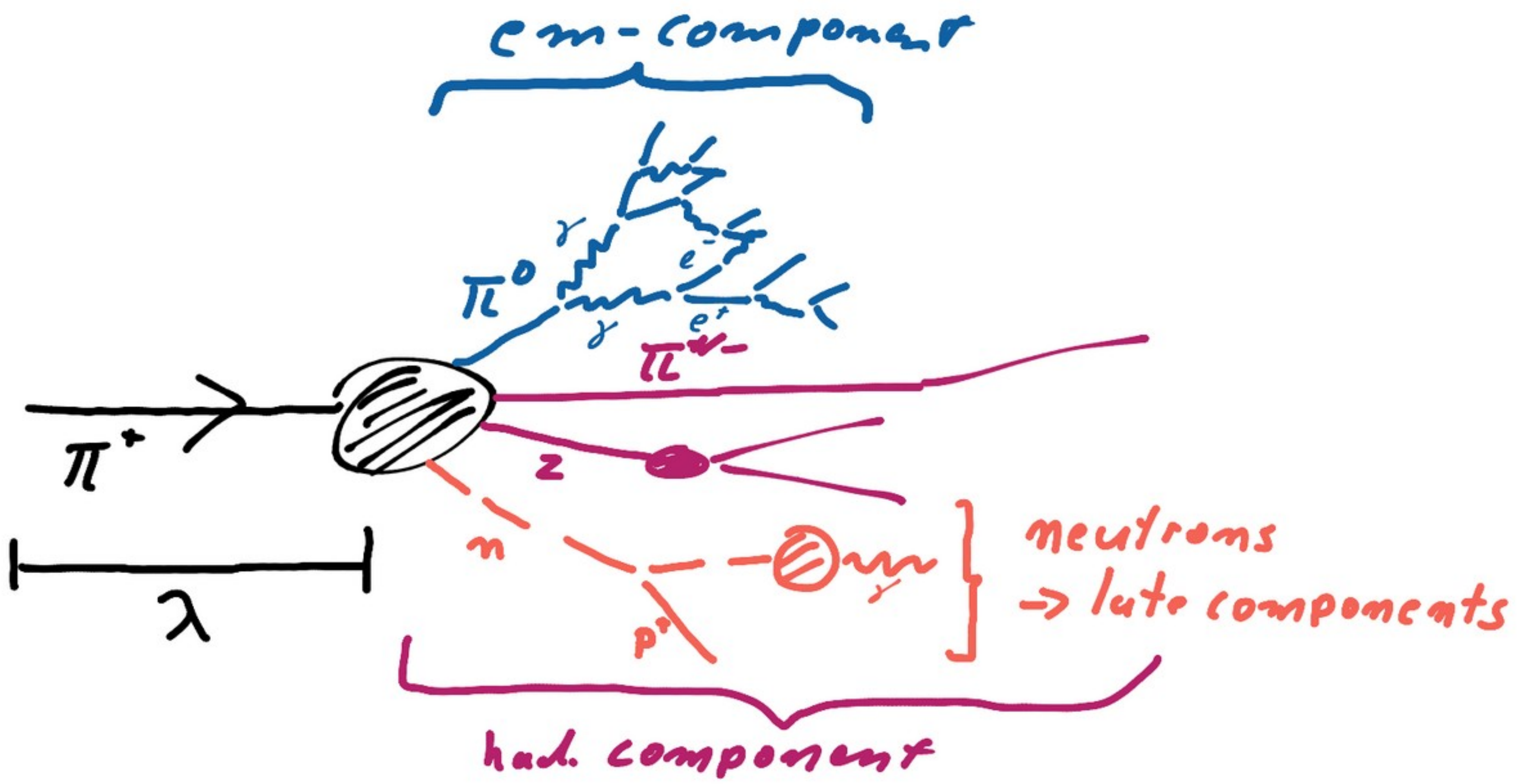


LGADs in the detector:
→ high power consumption
→ active cooling
→ space& material budget
→ not good

B.Dudar

Timing measurements for shower developments

- Neutral and slow components
  - Require ~ns precision
  - Reachable today with "standard" silicon, scintillators calorimeters
- ~0.1 ns scale: near the corner
- An even lower with GRPC (20ps)



A. Irles

Ready to take on one of these challenges?

How to contribute

- **Get involved**
  - **ECFA set up a workshop series on Physics, Experiments and Detectors at a Higgs, Top and Electroweak factory cf https://indico.cern.ch/event/1044297/**
    - address topics in common between all e^+e^- colliders, i.e. theory prediction, assessment of systematic uncertainties, software tools
    - trigger joint work across e+e- collider projects **=> starting now: 15 Focus Topics**
    - will give important input to next update of European Strategy

  you don't won't to commit to a specific collider project ?
  => this is your way to contribute => get in touch!

- **All Higgs factories are using the same software framework (Key4HEP):**
  - share algorthmic developments
  - share / exchange data sets for comparable analyses etc

  => anybody who'd like to shape the experiments of the next collider would be wise to build up expertise on Key4HEP *now*

Conclusions

And invitation

- **strong scientific consensus that an e+e- Higgs Factory is the highest-priority next collider**
  - a lot is going on in accelerator and detector R&D as well as physics studies
  - better communication needed: other scientists, politics, general public
  - …and also inside our field, in particular to the next generation!
- **open scientific question: how to best complement the minimal Higgs Factory in e+e-?**
  - very strong Z pole program but limited in energy reach?
  - upgrades to higher energies but more modest Z program?
- **next big project needs**
  - a compelling science case
  - ready for fastest possible construction
  - technologically and scientifically exciting upgrade options
  - well justified usage of ressources - money; CO_2, electrical power, rare earths, …

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Most importantly:
A Future Collider can only happen based on broad support within HEP community
=> get more people engaged and make it happen!

Bonus

Sustainability

Gro Harlem Brundlandt at WEF 1989

Cover of the “Brundtland Report” 1987

Development that meets the needs of current generations without compromising the ability of future generations to meet their needs and aspirations. (WCED, 1987)

WCED (World Commission for Environment and Development) (1987) *Our Common Future*, Oxford University Press, Oxford.

Sustainability

2016 …..

Additional Design Considerations

- **power consumption:**
  - public acceptance for large scale projects significantly challenged if (substantial fractions of) extra power plant required!
  - **ILC design driven by *self-imposed* limits on total site power:**
    - **200 MW for 500 GeV**
    - **300 MW for 1 TeV**

- **cost awareness:**
  - from RDR to TDR critical review of design in order to reduce costs
  - value engineering
  - power reduction in favour of stronger focussing

- **at the end of the day: luminosity ~ power ~ money**

Sustainability

2016 …..

Additional Design Considerations

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- **at the end of the day: luminosity ~ power ~ money**

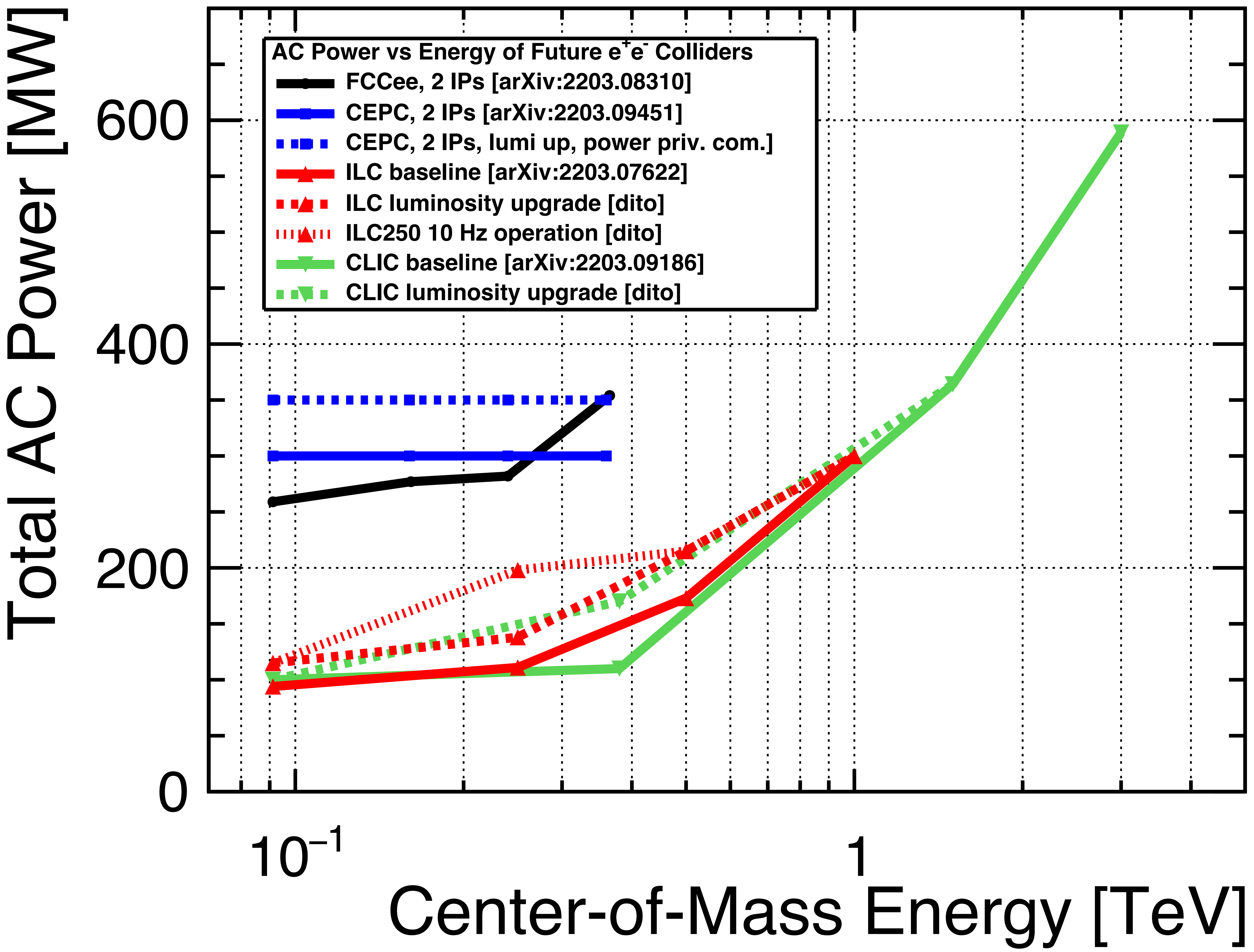
- **minimal usage of resources was always design criterion for serious projects**
- **but only a reduction of the energy consumption is not sufficient anymore**
- **change of paradigm:**
  => the next collider project must be sustainable in every aspect

… and tomorrow: Sustainability of new Accelerators

Much more than CO2 equivalents…

minimal use of resources to reach physics goals

- Operation -> **total electrical site power**:
  - **minimize**:
    - even if - or especially if - all power will come from regenerative sources, the competition with other human needs will be high
    - optimizing all components for minimal energy consumption
  - **be flexible**:
    - must be able to handle large variations in availability of regenerative power
    - could cooling capacities be used as buffer for energy, also for society in general?
- Construction, concrete etc
  - **tunnel as short as possible**
  - use concrete with low(er) CO2 emission => extra costs ?!
  - avoid usage of rare earths and other problematic substances



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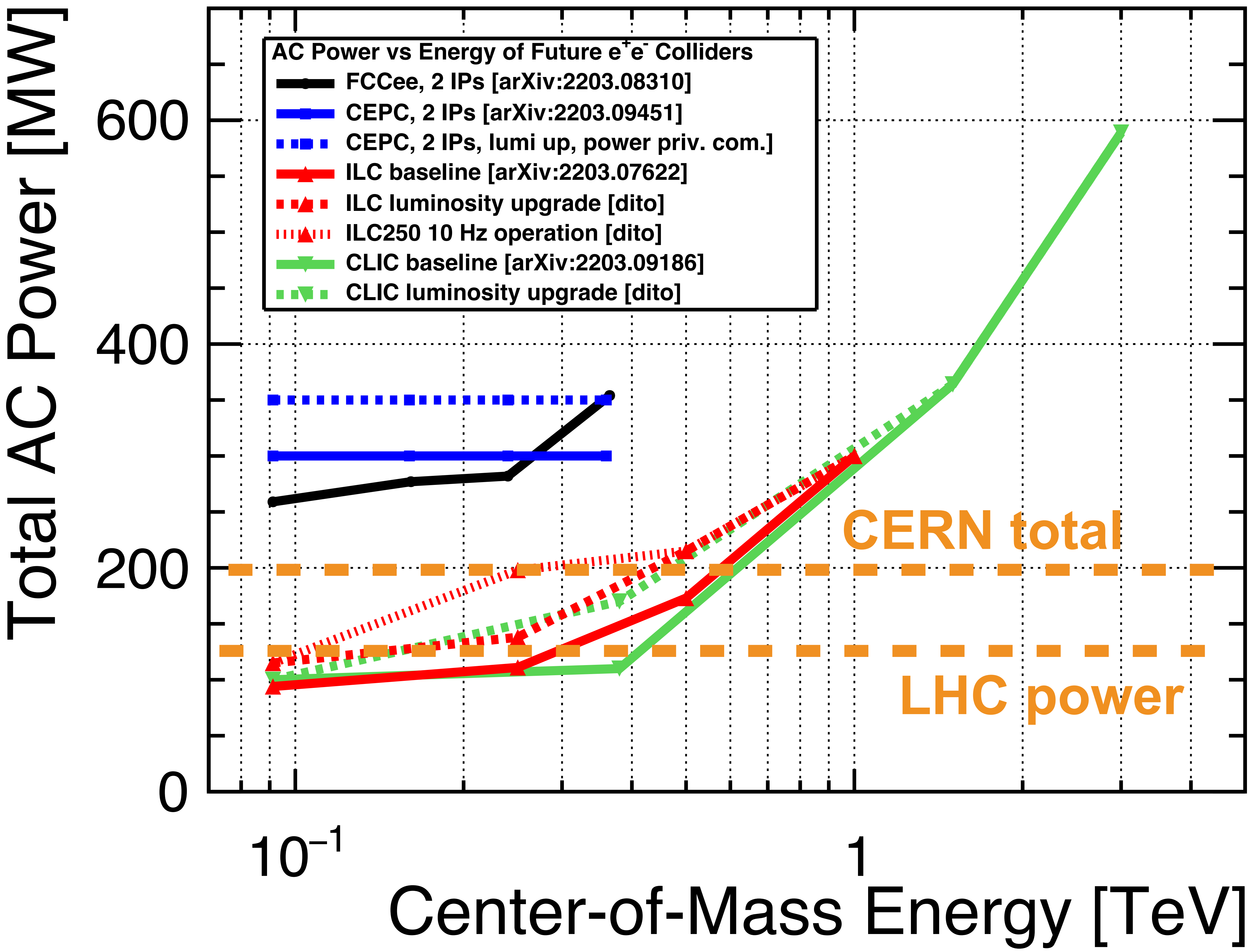
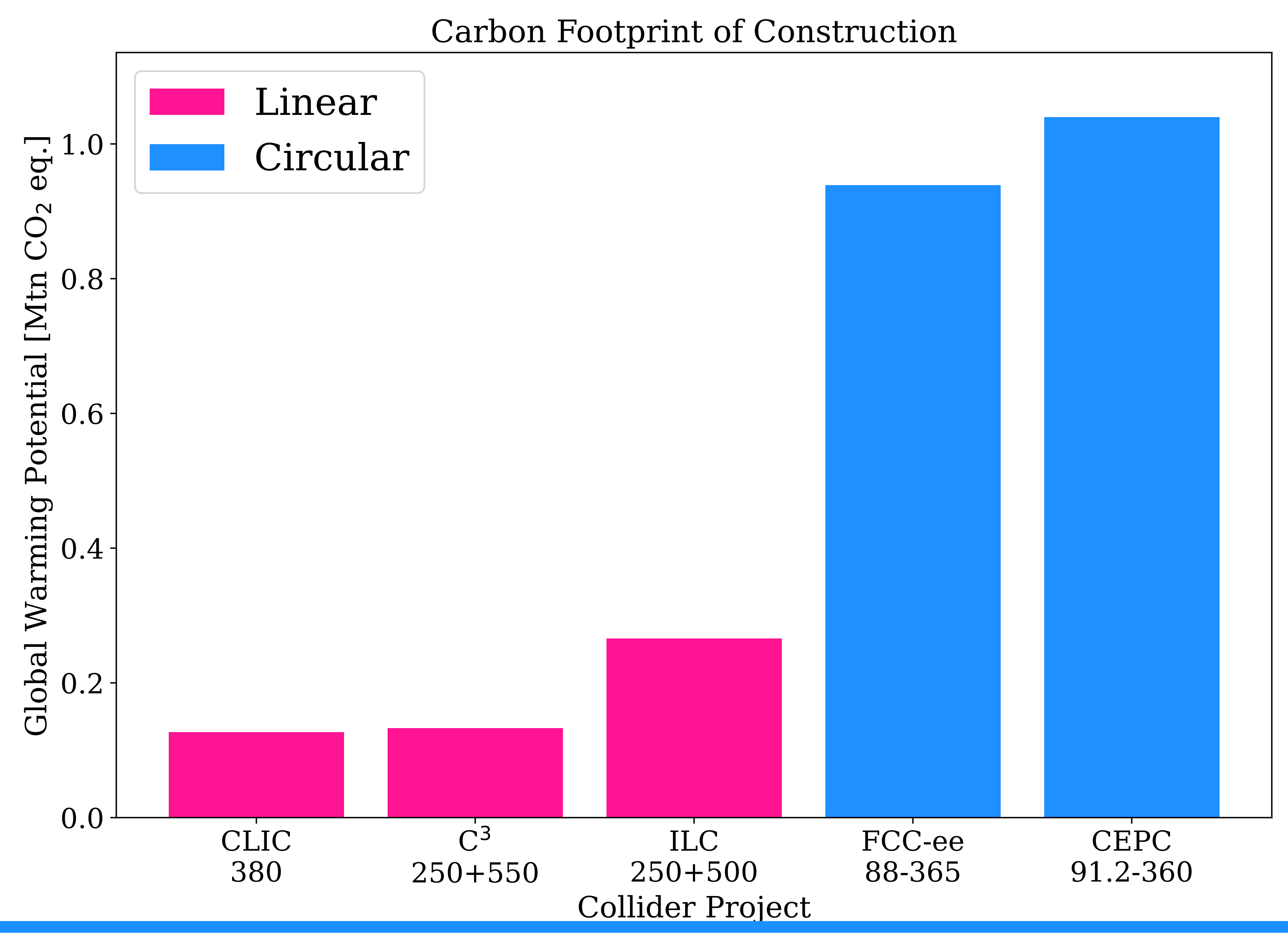


Global Warming Potential

Study by C3

GWP of construction dominated by CO2 emission from the required concrete & steel => tunnel length (diameter, tunneling technique)



arXiv:2307.04084

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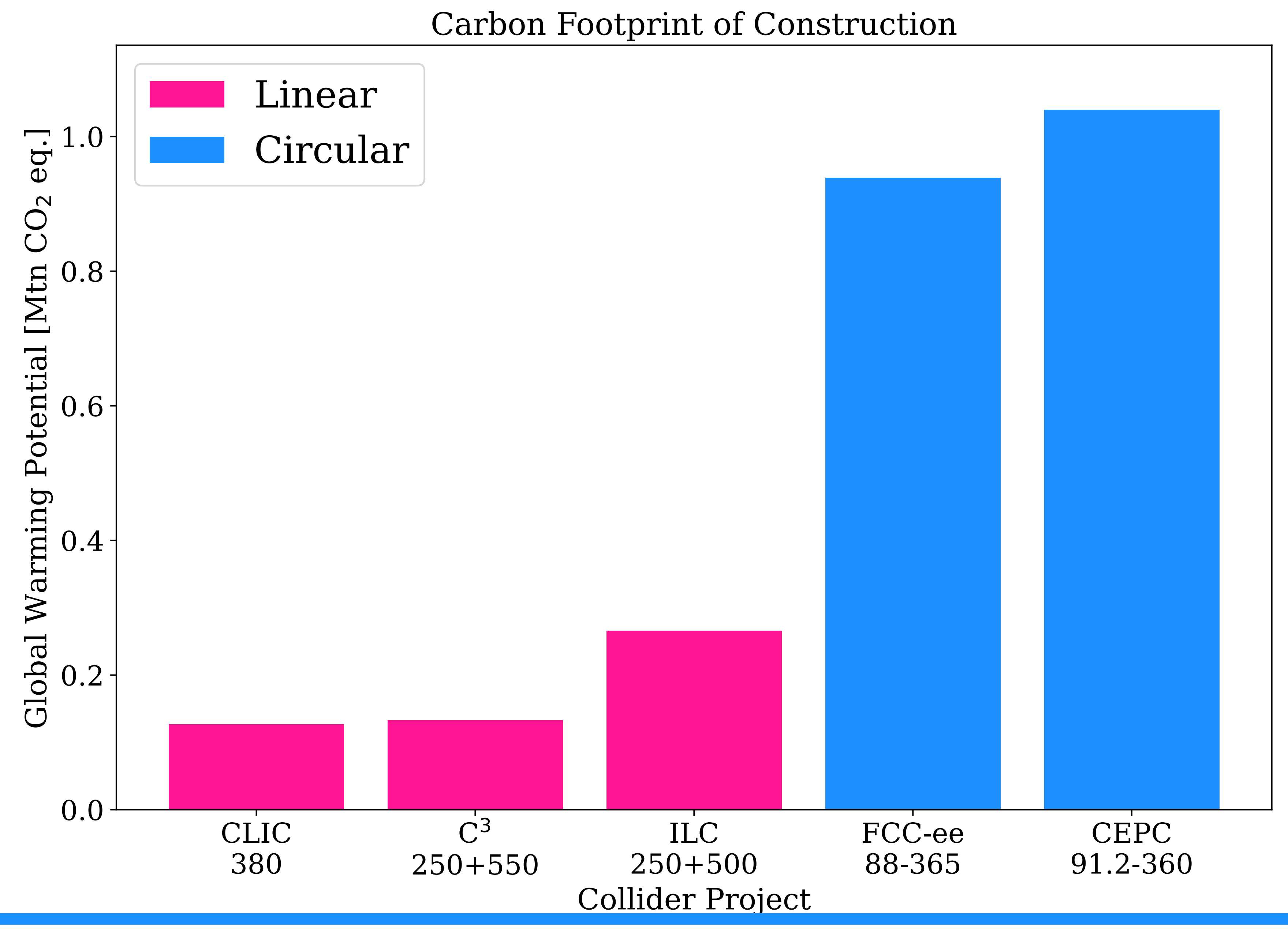
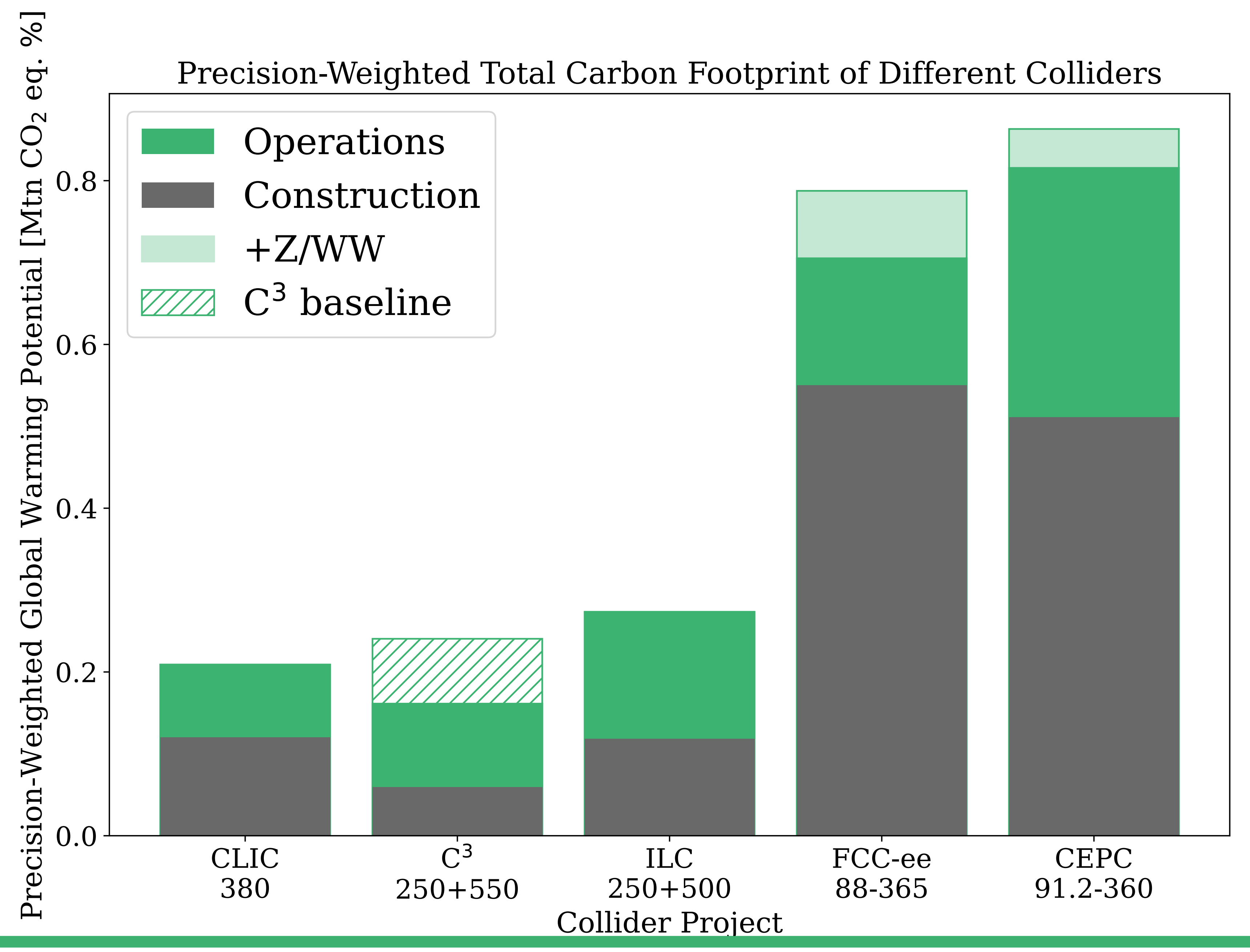




Adding operation GWP

(here weighted by improvement of Higgs couplings over HL-LHC, and with power mix predictions for CERN, US, Japan, China):

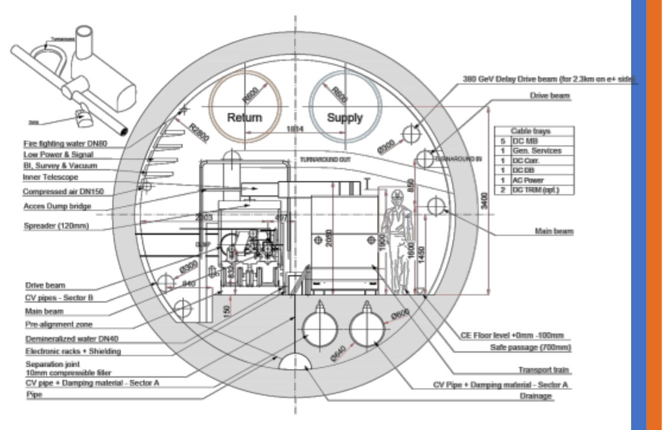
- **Operation dominates for LCs**
- **Construction dominates for CCs**

arXiv:2307.04084

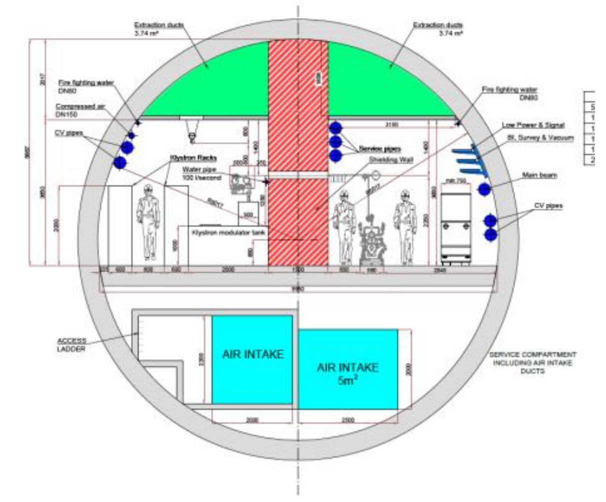
GWP of tunnel construction

Study by CLIC and ILC

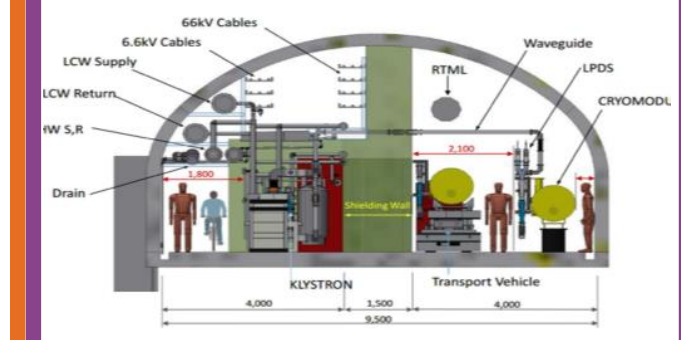
- **full life-cycle assessment according to ISO standards by consultancy company (ARUP)**
- **green house gas emission plus 13 more impact categorie**
- roughly confirms C3 estimates (prev. slide)



CLIC Drive beam, 5.6m dia.



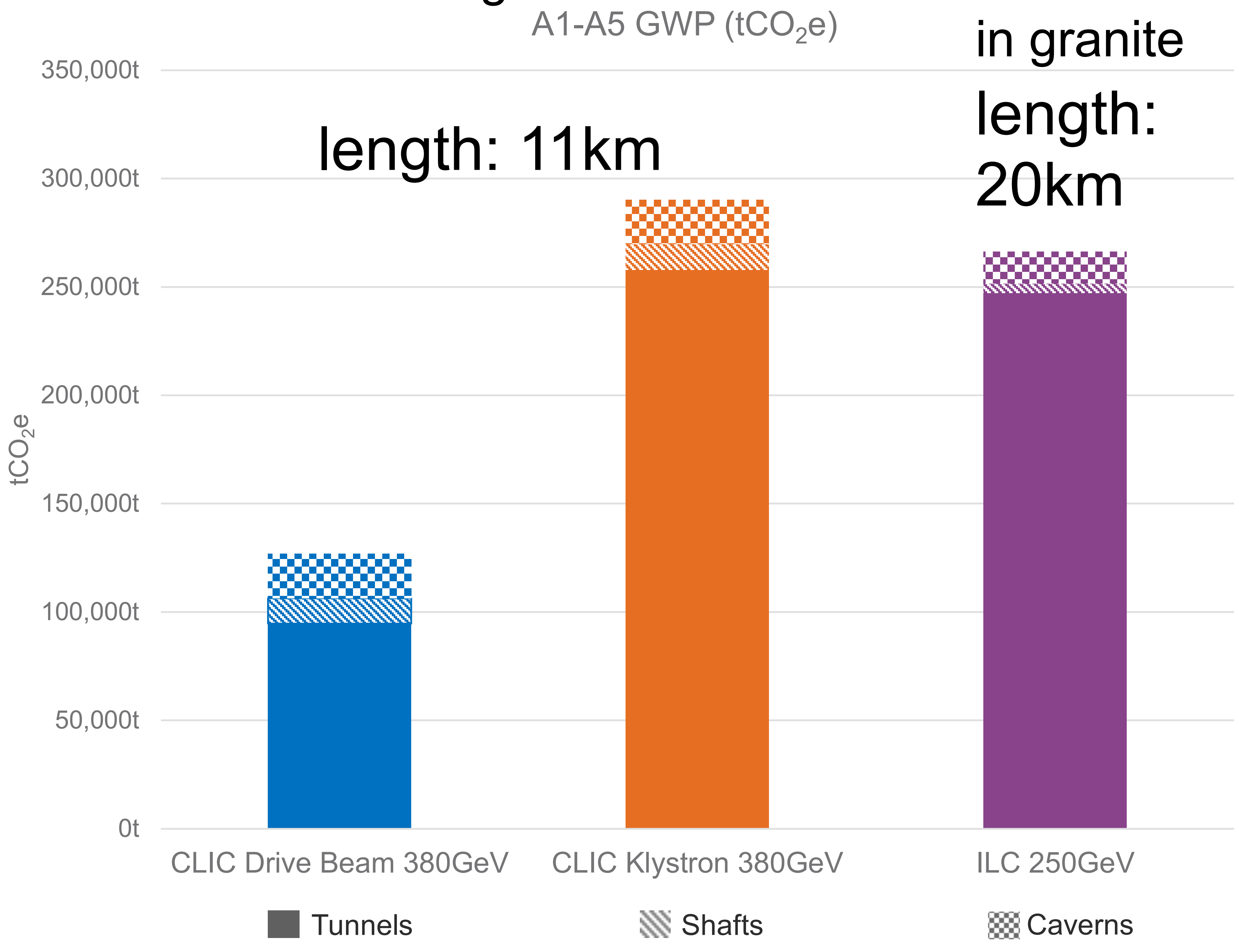
CLIC Klystron, 10m dia.



ILC, 9.5m span

tunnel boring in molasse

drill&blast in granite



https://edms.cern.ch/document/2917948/1

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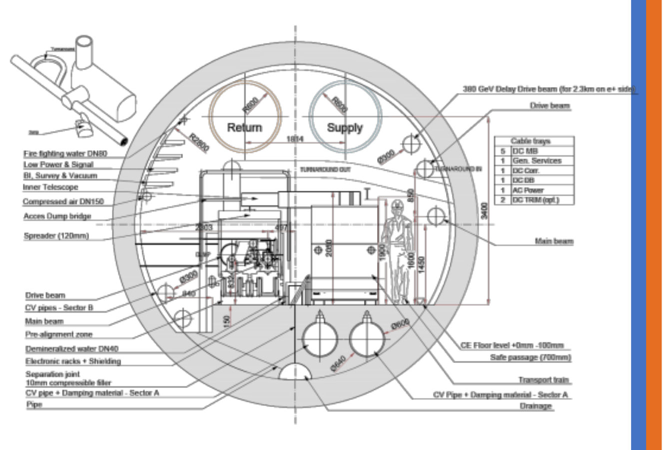

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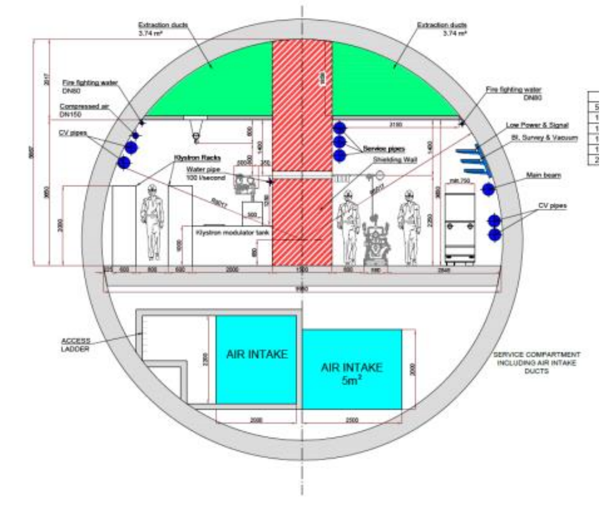

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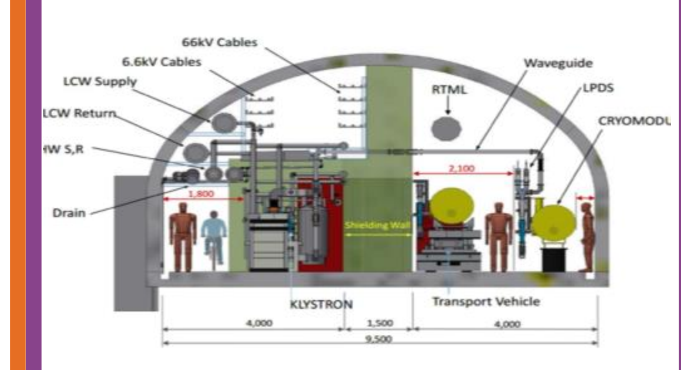

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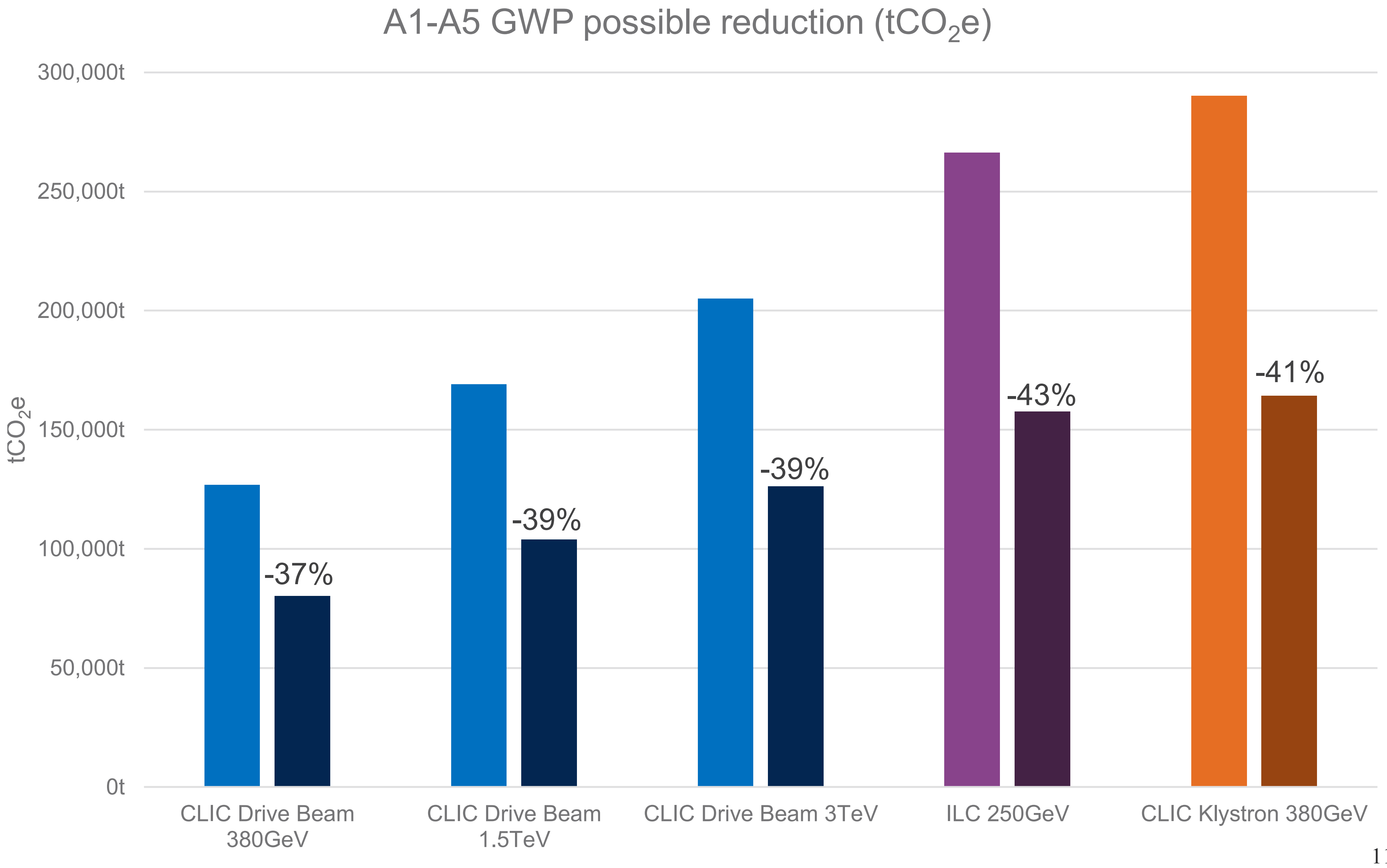

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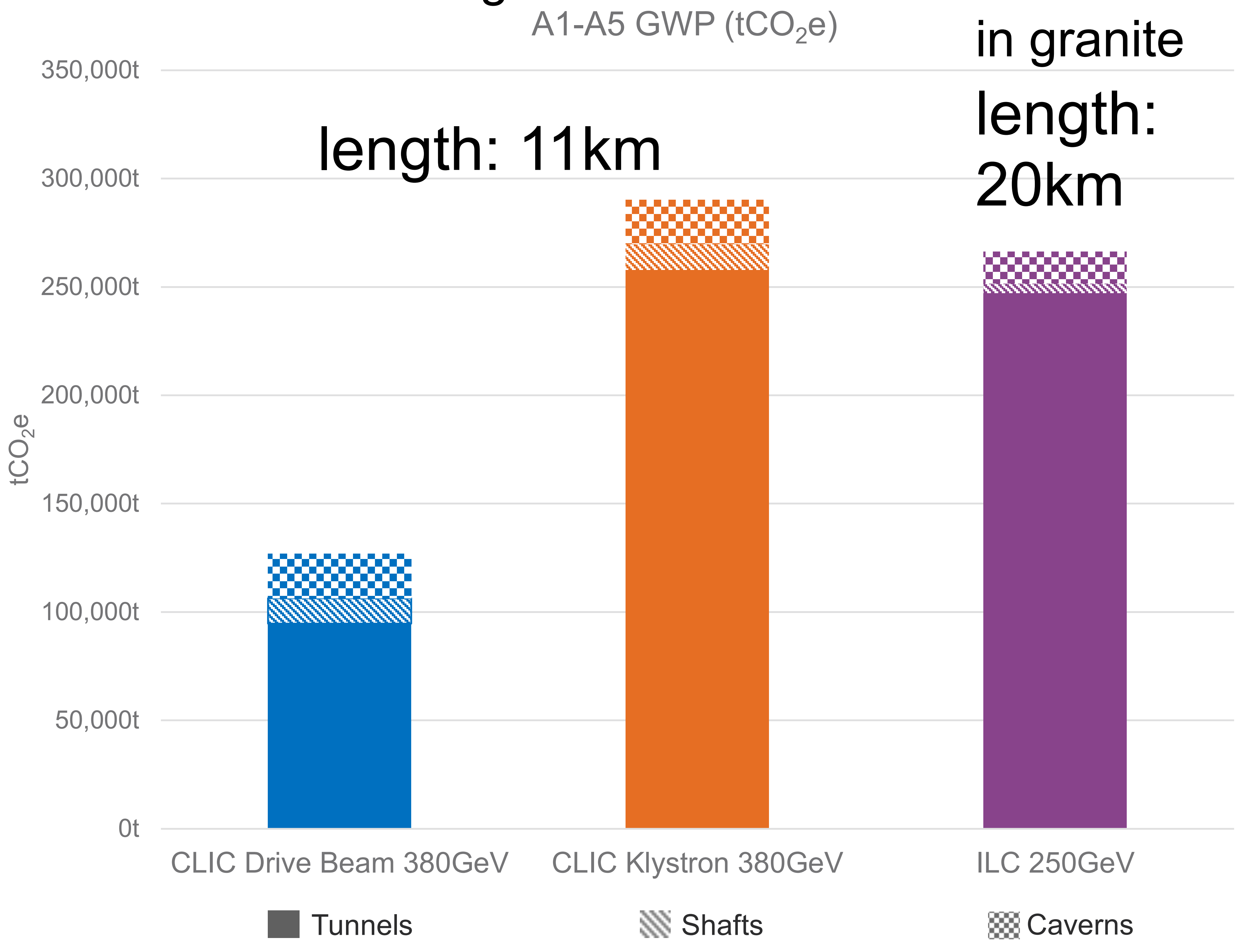

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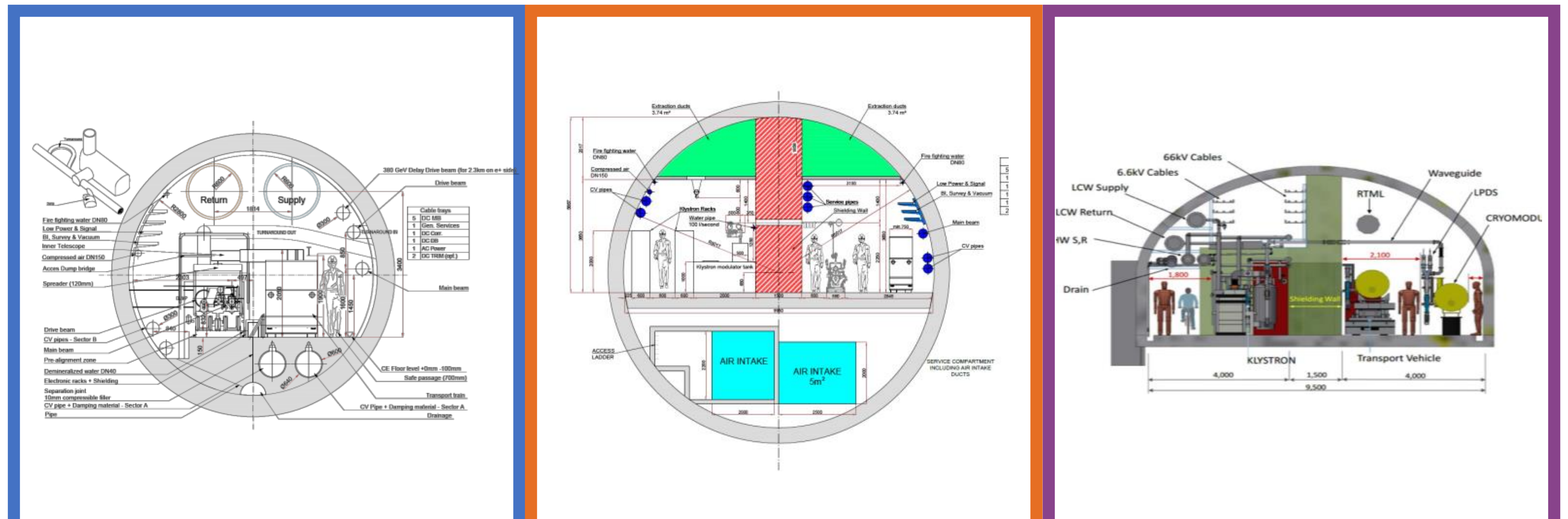

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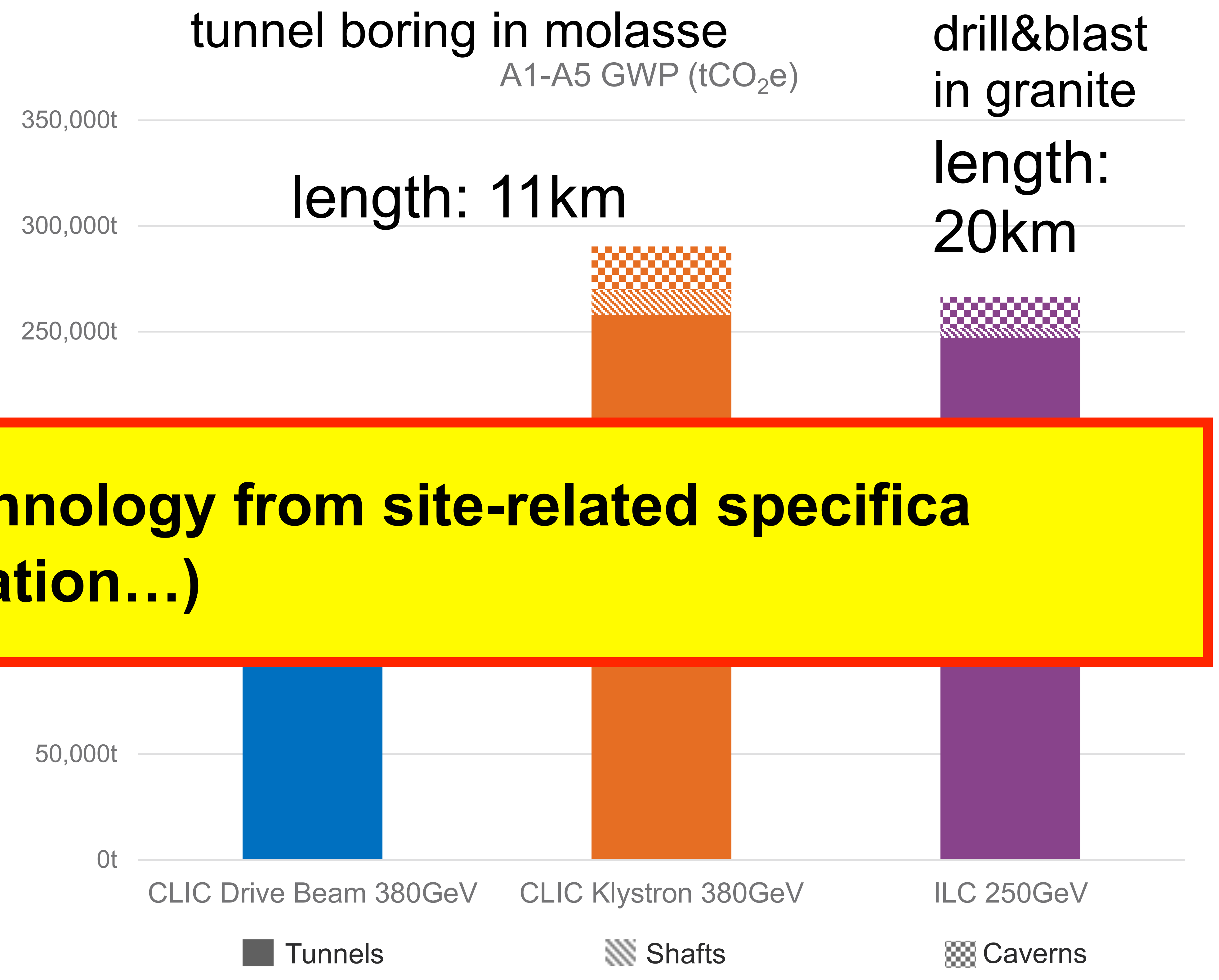
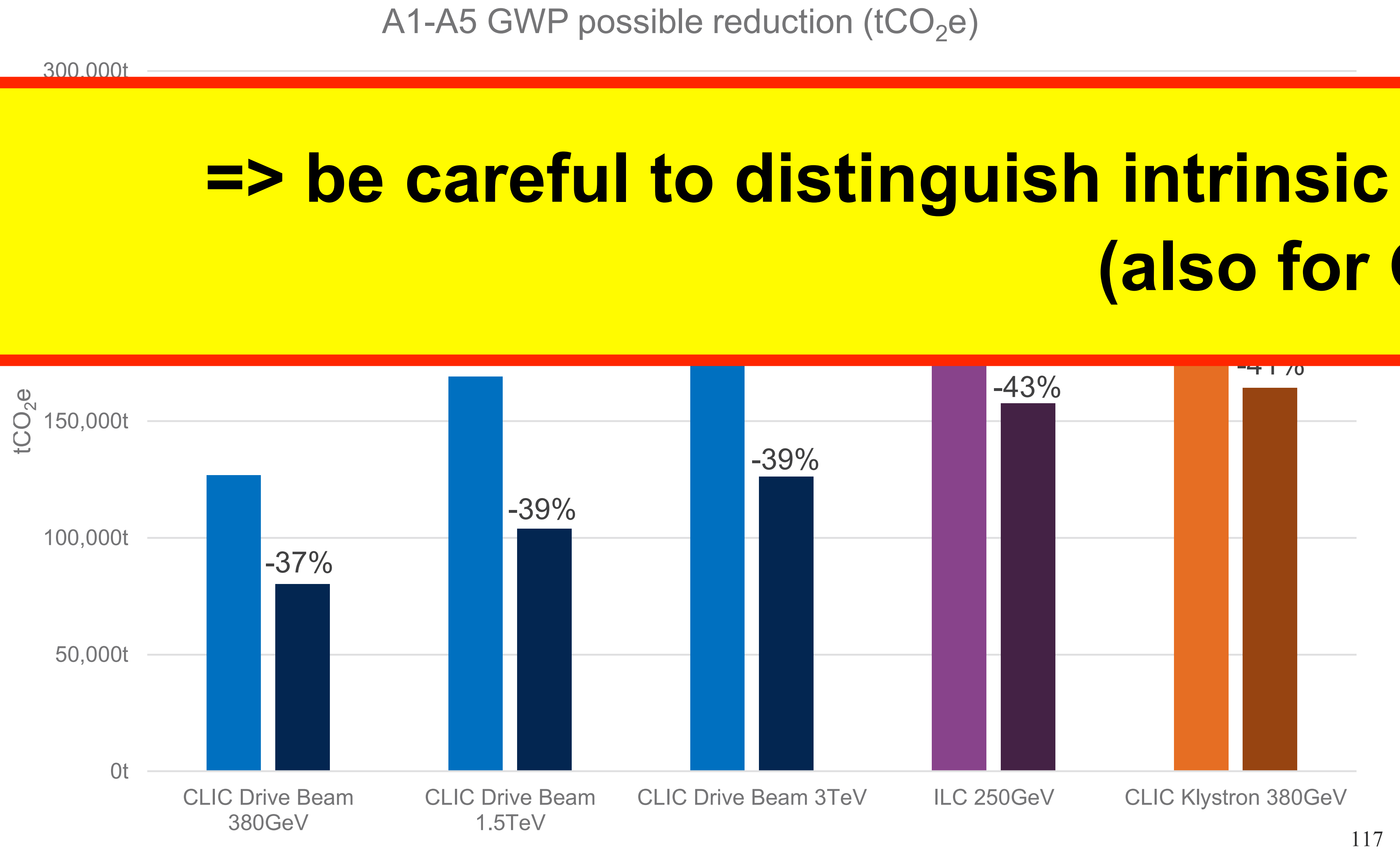




=> be careful to distinguish intrinsic needs of technology from site-related specifica (also for GWP of operation…)

117

https://edms.cern.ch/document/2917948/1

Sustainability: Objective Assessment of New Infrastructures

New Working Group of the European Lab Directors Group

- **goal:**
  - define to all new infrastructure proposals what they should quantify and report upon so that fair comparisons can be made between these proposals
  - e.g. key performance indicators, methodology, assumptions, …
- **membership:** designated experts from each of the foreseen collider projects (FCC, ILC, CLIC, Muon Collider, …??), ~10 or less
- **timeline:**
  - preliminary report to LDG by Spring 2024
  - final report by Summer 2024
    => enable new projects to carry out their sustainability assessments in a timescale compatible with the next European Strategy Update for PP (likely in 26/27).

c.f. presentation at Open Meeting of European Lab Directors Group, Frascati, 11th July 2023 https://agenda.infn.it/event/35700/contributions/205193/

Backup

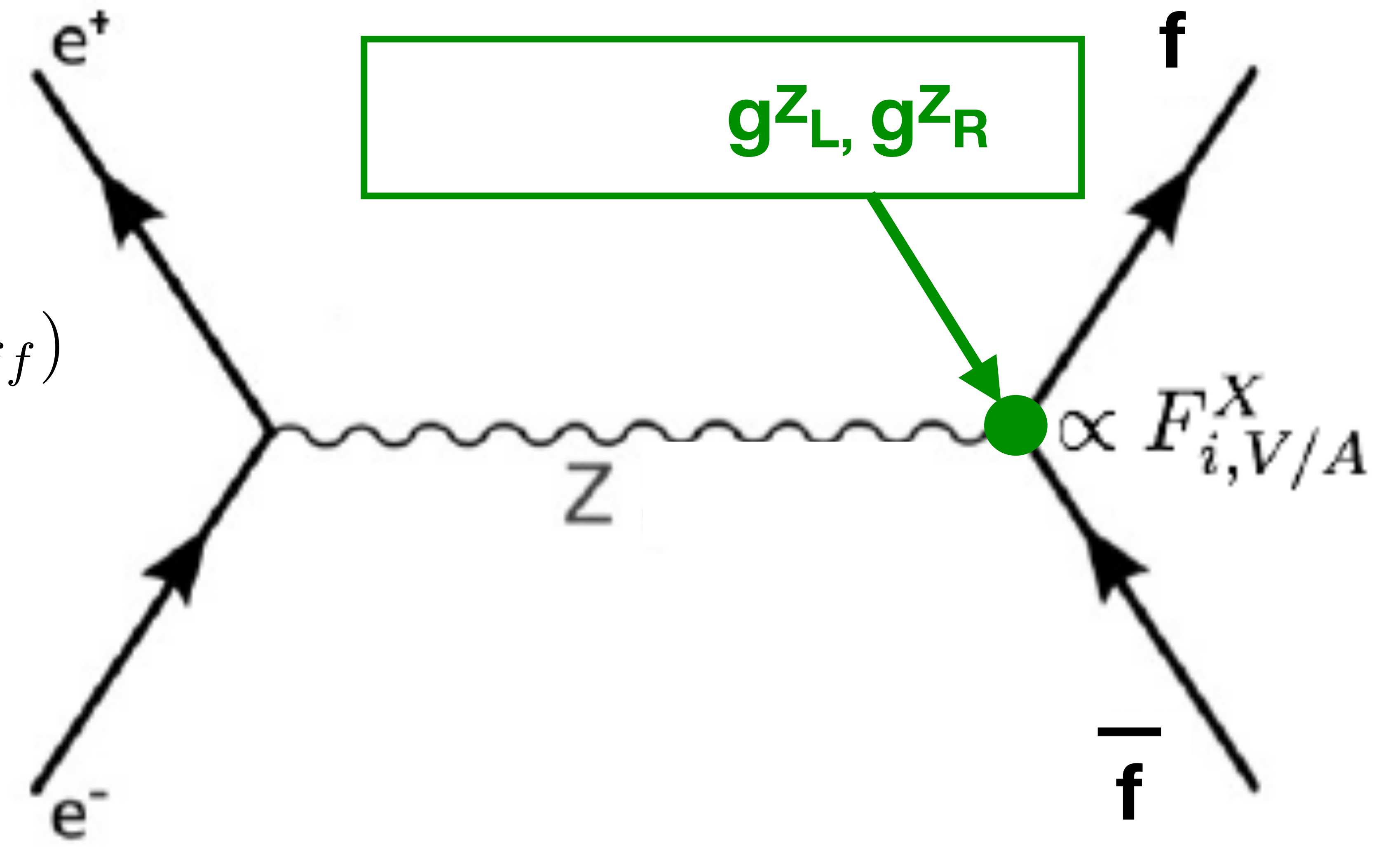
Polarisation & Electroweak Physics

let's first recall at the Z pole situation

g_{Lf}, g_{Rf} : helicity-dependent couplings of Z to fermions - at the Z pole:

=> $$A_f = \frac{g_{Lf}^2 - g_{Rf}^2}{g_{Lf}^2 + g_{Rf}^2}$$

specifically for the electron: $A_e = \frac{(\frac{1}{2} - \sin^2\theta_{eff})^2 - (\sin^2\theta_{eff})^2}{(\frac{1}{2} - \sin^2\theta_{eff})^2 + (\sin^2\theta_{eff})^2} \approx 8(\frac{1}{4} - \sin^2\theta_{eff})$



at an *un*polarised collider:

$$A^f_{FB} \equiv \frac{(\sigma_F - \sigma_B)}{(\sigma_F + \sigma_B)} = \frac{3}{4} A_e A_f$$

=> no direct access to A_e, only via tau polarisation

While at a ***polarised*** collider:

$$A_e = A_{LR} \equiv \frac{\sigma_L - \sigma_R}{(\sigma_L + \sigma_R)}$$

and

$$A^f_{FB,LR} \equiv \frac{(\sigma_F - \sigma_B)_L - (\sigma_F - \sigma_B)_R}{(\sigma_F + \sigma_B)_L + (\sigma_F + \sigma_B)_R} = \frac{3}{4} A_f$$

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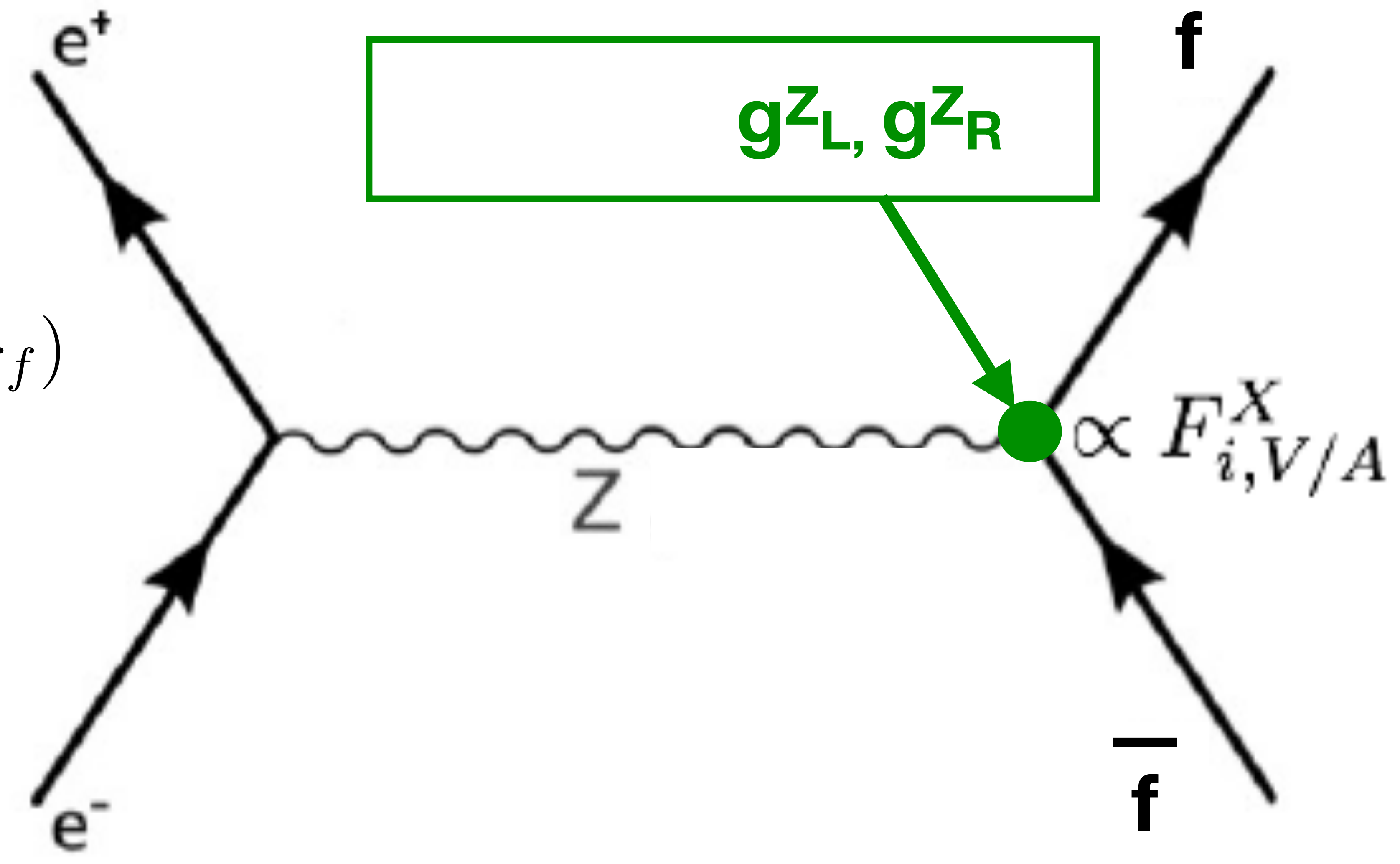

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trading theory uncertainty:

the **polarised** $A_{FB,LR}^f$ receives 7 x smaller radiative corrections than the **unpolarised** A_{FB}^f !

Polarisation & Electroweak Physics

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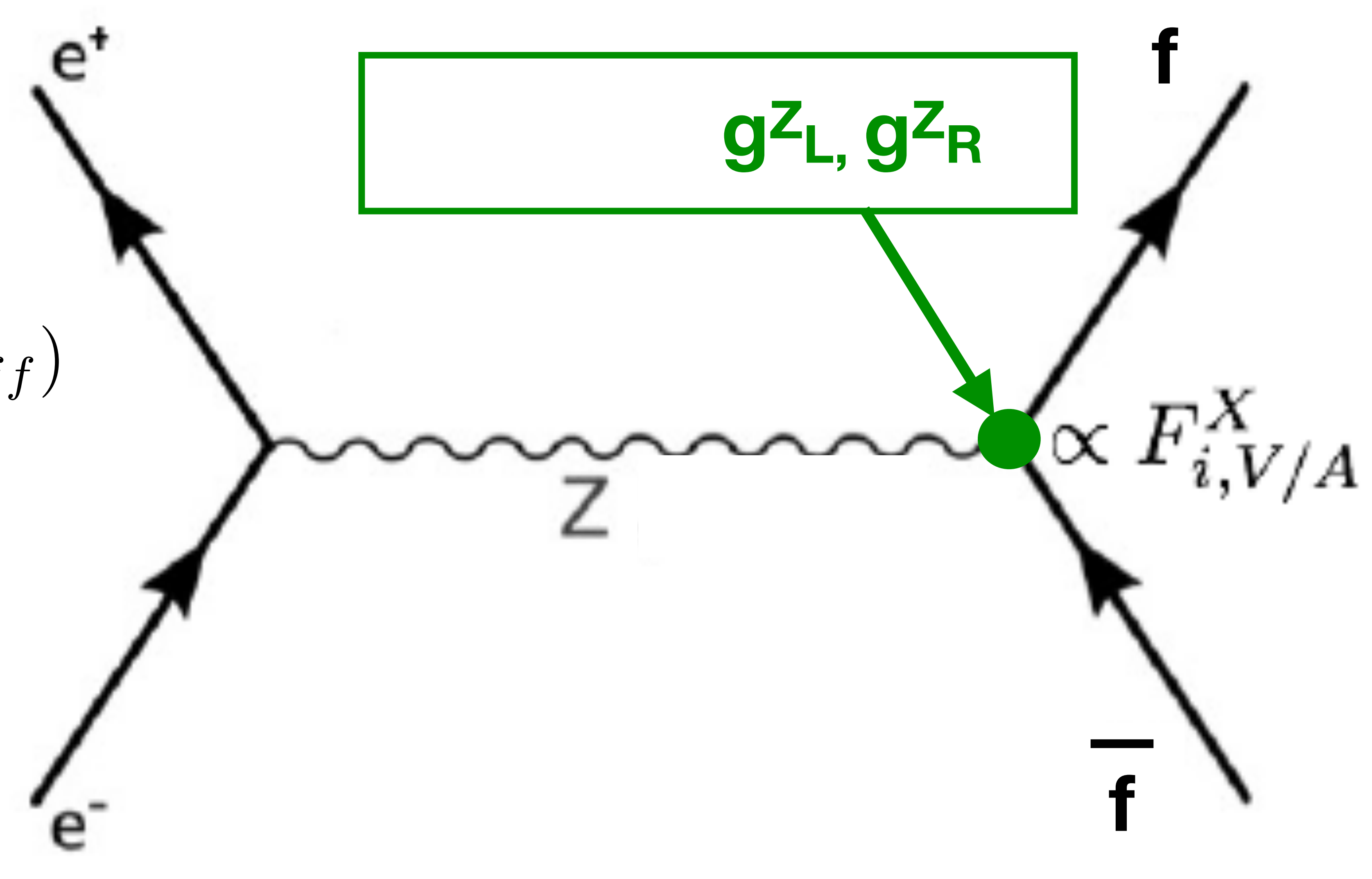

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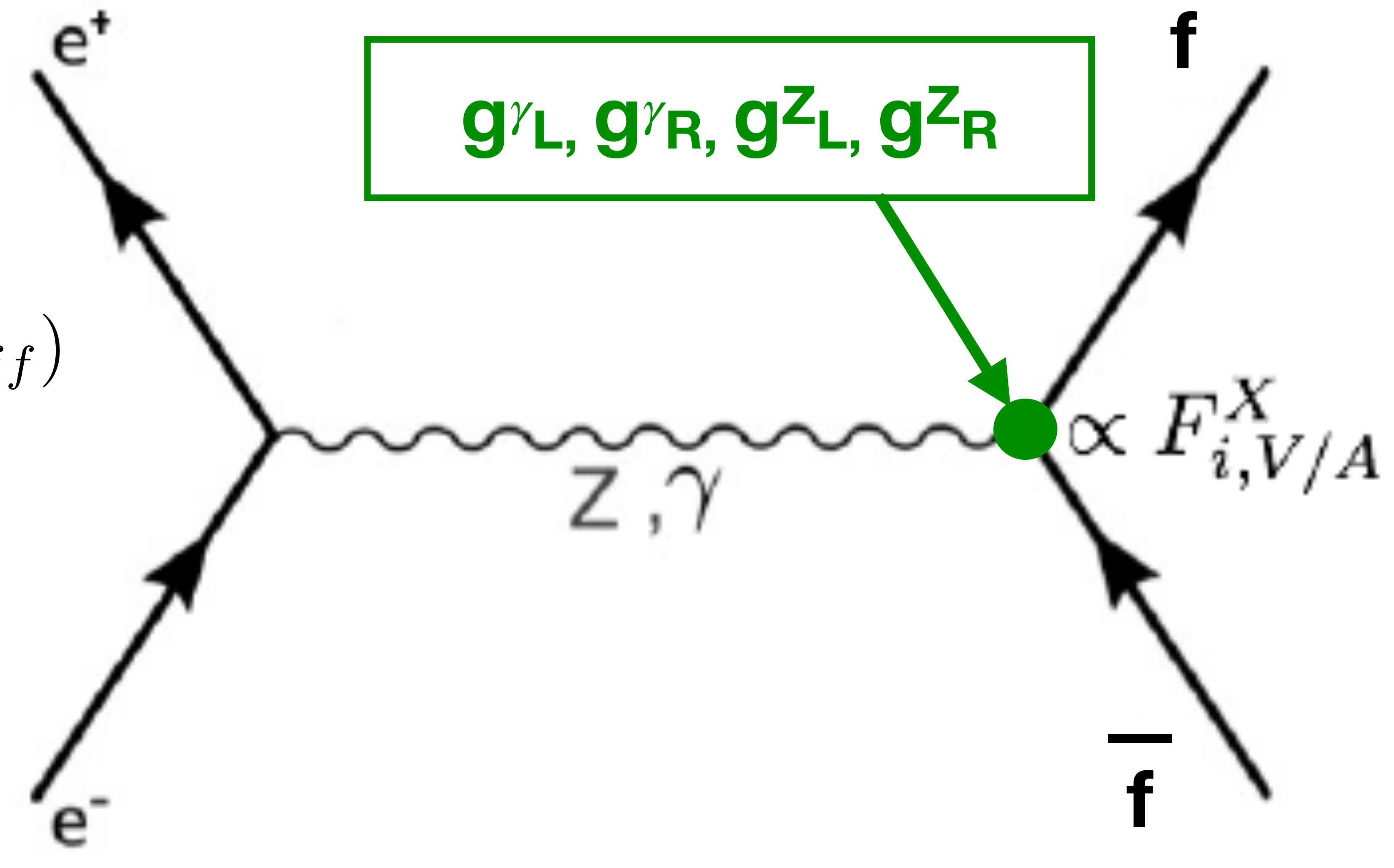

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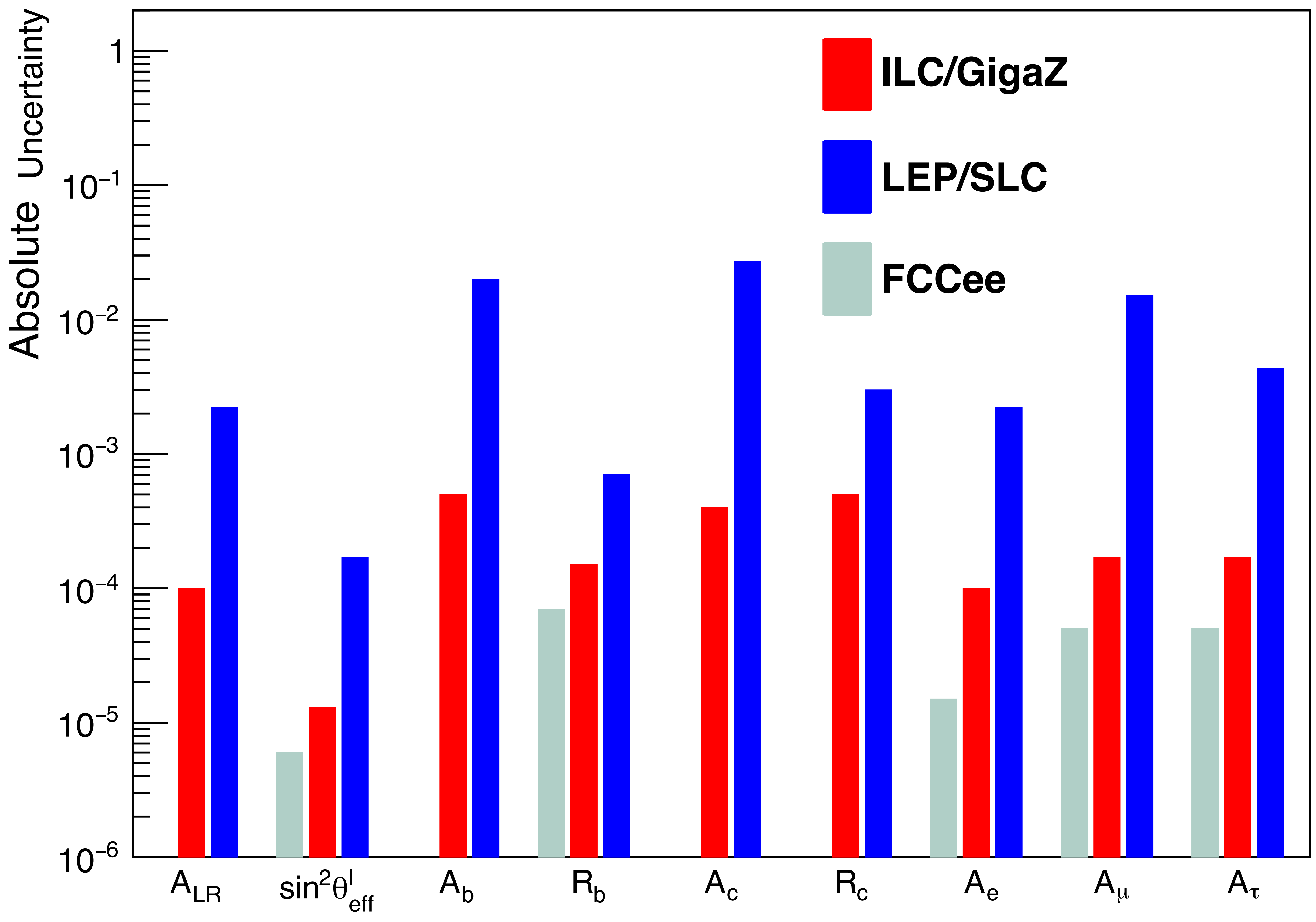
Polarisation & Electroweak Physics at the Z pole

LEP, ILC, FCCee

recent detailed studies by ILD@ILC:

- at least factor 10, often ~50 improvement over LEP/SLC
- note in particular:
  - **A_c nearly 100 x better** thanks to excellent charm / anti-charm tagging:
    - excellent vertex detector
    - tiny beam spot
    - Kaon-ID via dE/dx in ILD's TPC

polarised "GigaZ" typically only factor 2-3 less precise than FCCee's unpolarised *TeraZ*
=> polarisation buys
a factor of ~100 in luminosity



Note: not true for pure decay quantities!

arXiv:1908.11299

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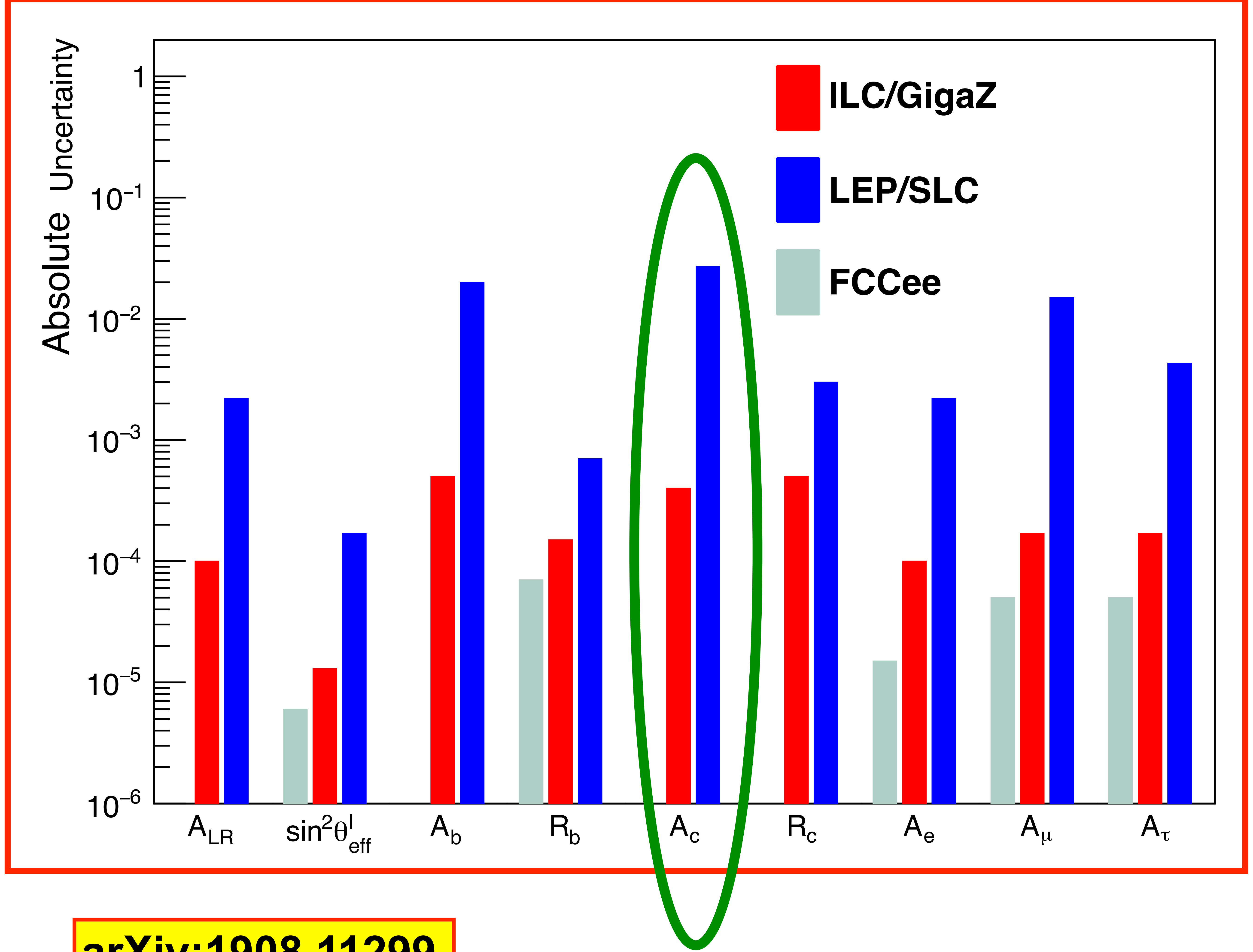

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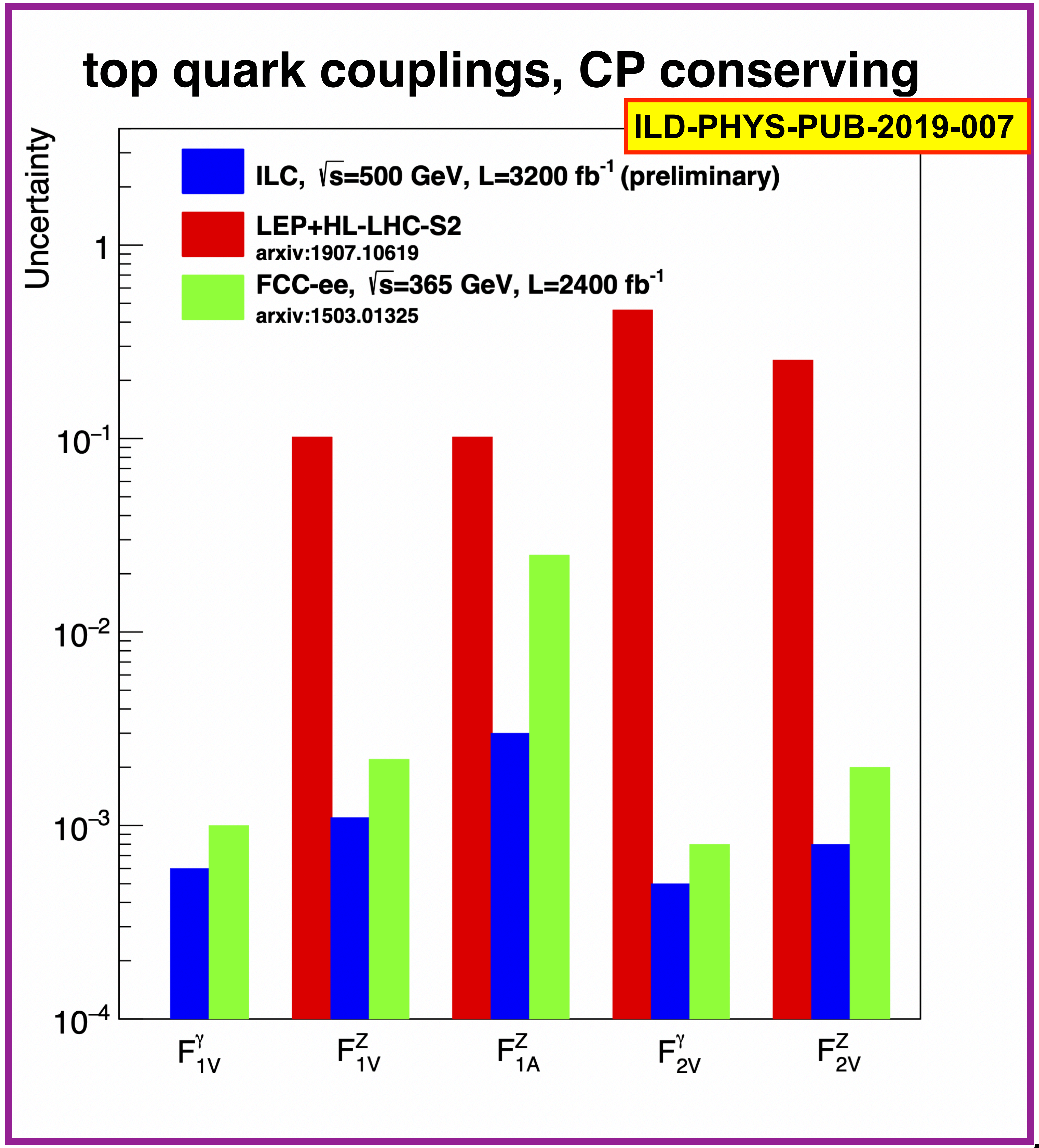
Polarisation & Electroweak Physics at high energies

e+e- at 500 GeV and 1 TeV

- ex1: top quark pair production - disentangle Z / γ:
  - unpolarised case: from final-state analysis only
  - polarised case: direct access
    - final state analysis can be done in addition
    => redundancy, control of systematics
- ex2: oblique parameters for 4-fermion operators
  - beam polarisation essential to disentangle Y vs W
  - ILC 250 outperforms HL-LHC
  - ILC 500 outperforms unpolarised e^+e^- machines



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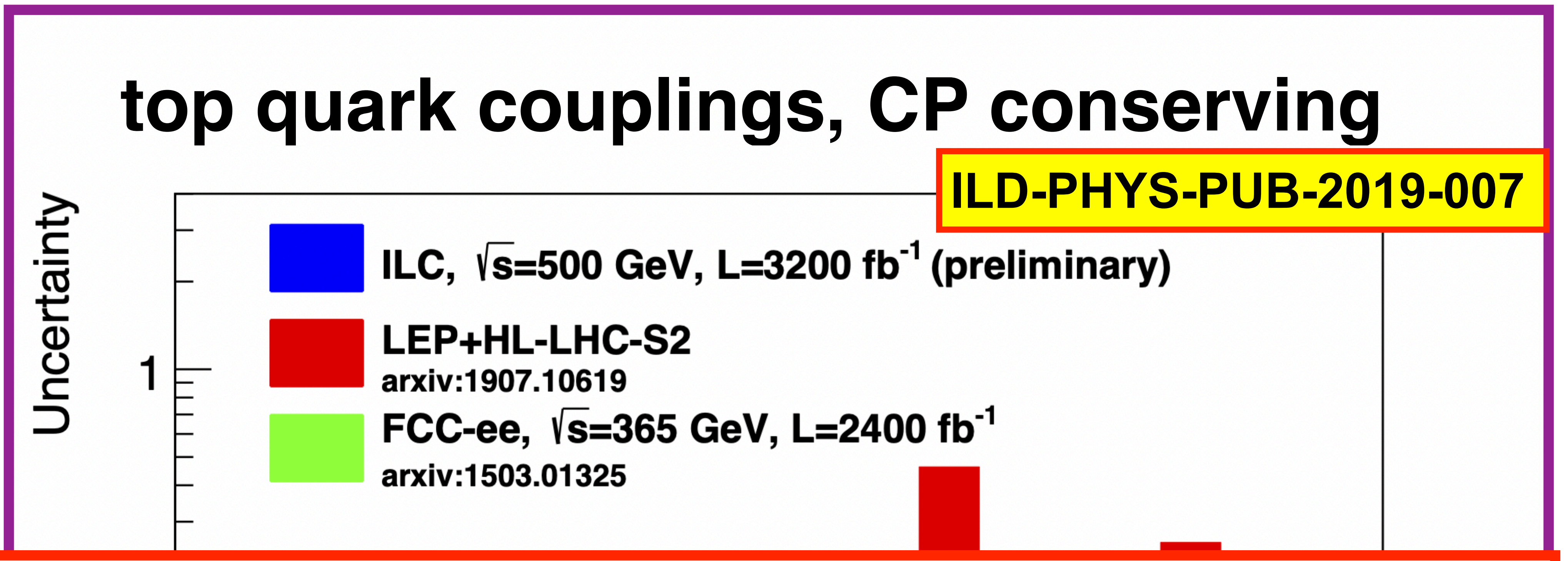
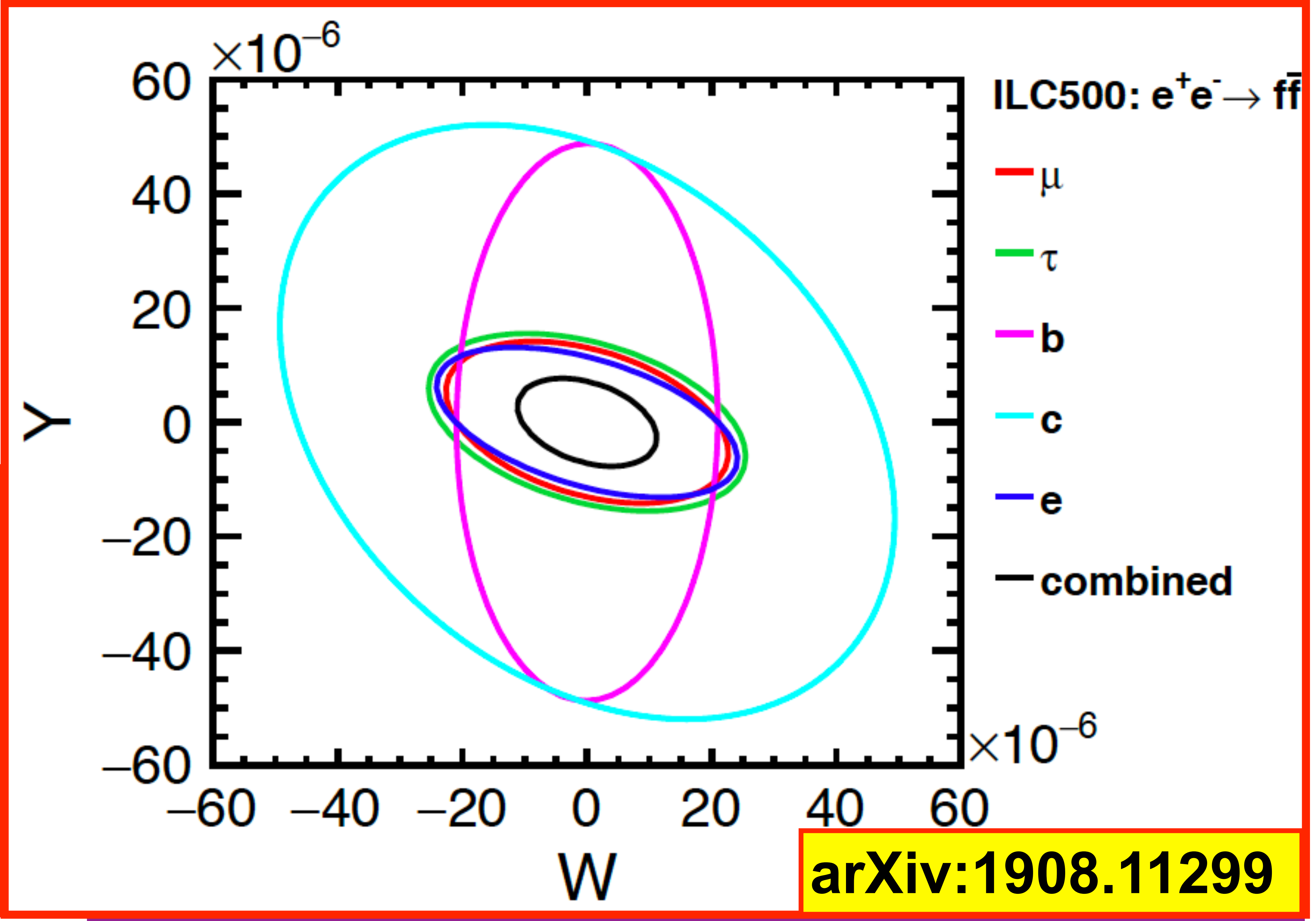
$\sqrt{s}$	ΔW	ΔY	ρ
HL-LHC	15×10^{-5}	20×10^{-5}	-0.97
ILC250	3.4×10^{-5}	2.4×10^{-5}	-0.34
ILC500	1.1×10^{-5}	0.78×10^{-5}	-0.35
ILC1000	0.39×10^{-5}	0.27×10^{-5}	-0.38
500 GeV, no beam pol.	2.0×10^{-5}	1.2×10^{-5}	-0.78

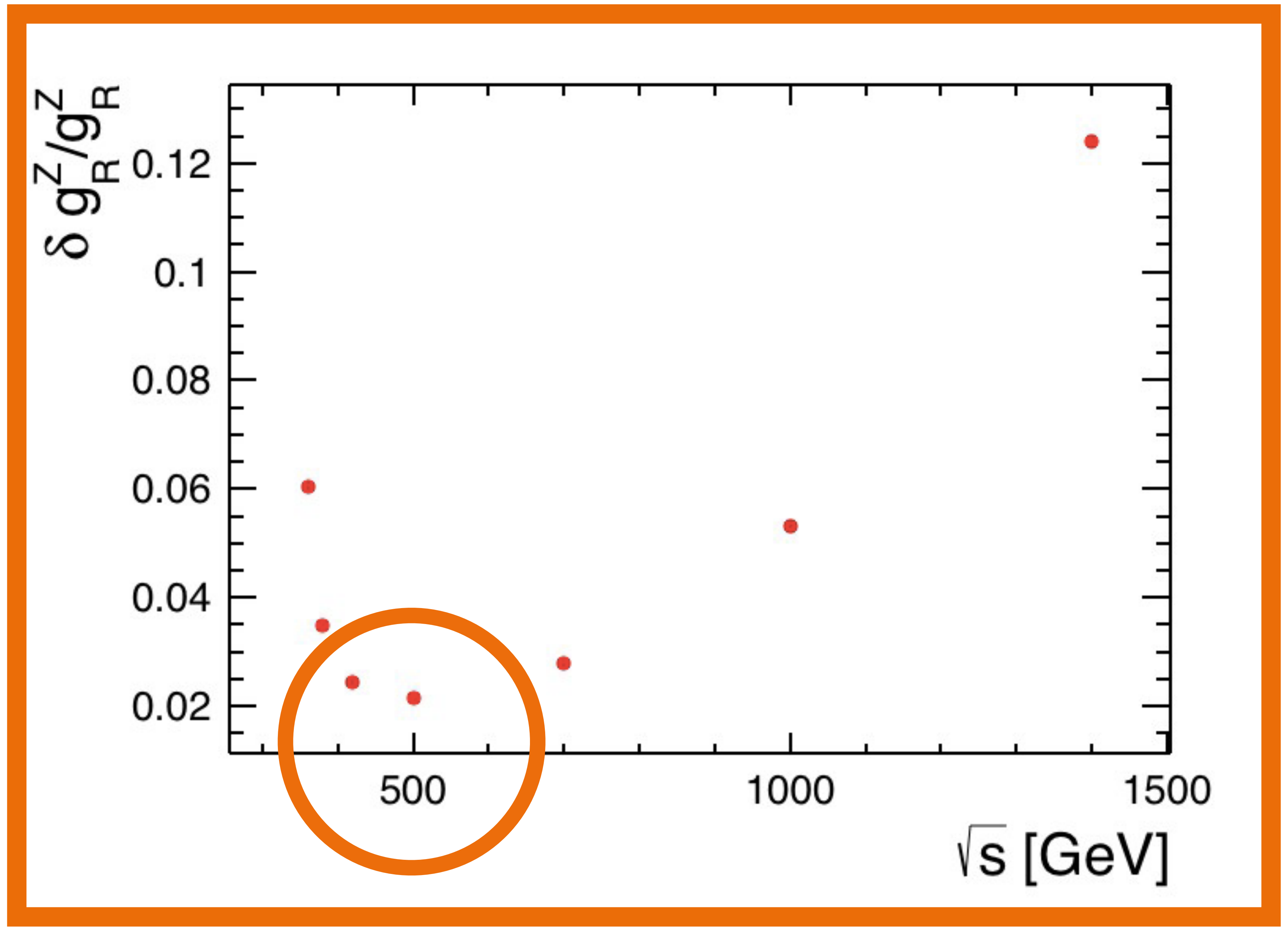




"2nd stage" energy for LCs

500…550…600 GeV?

- ECM ≈ 500 GeV is a sweet-spot for top couplings
- known ever since the Higgs discovery with mH ≈ 125 GeV: ECM=500 GeV "borderline" for ttH production
- **C3 decided for 550 GeV as baseline**
- ILC:
    - no official discussion, focus on getting 250 GeV approved
    - scientifically, it seems obvious that the 500 GeV choice needs to be re-assessed
- CLIC: completely different choice with 380 GeV and 1.4 TeV



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- ECM ≈ 500 GeV is a sweet-spot for top couplings
- known ever since the Higgs discovery with mH ≈ 125 GeV: ECM=500 GeV “borderline” for ttH production
- **C3 decided for 550 GeV as baseline**
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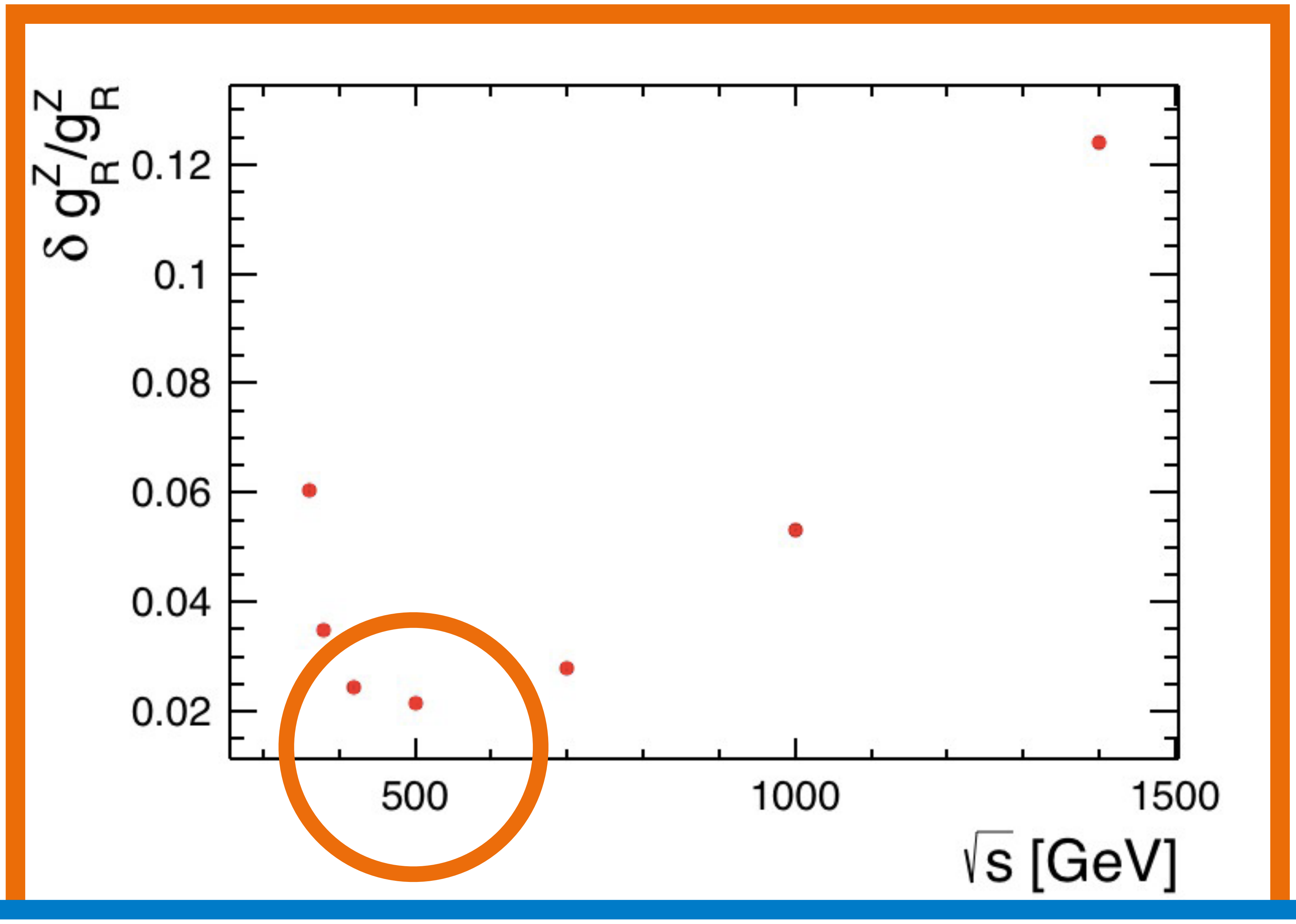
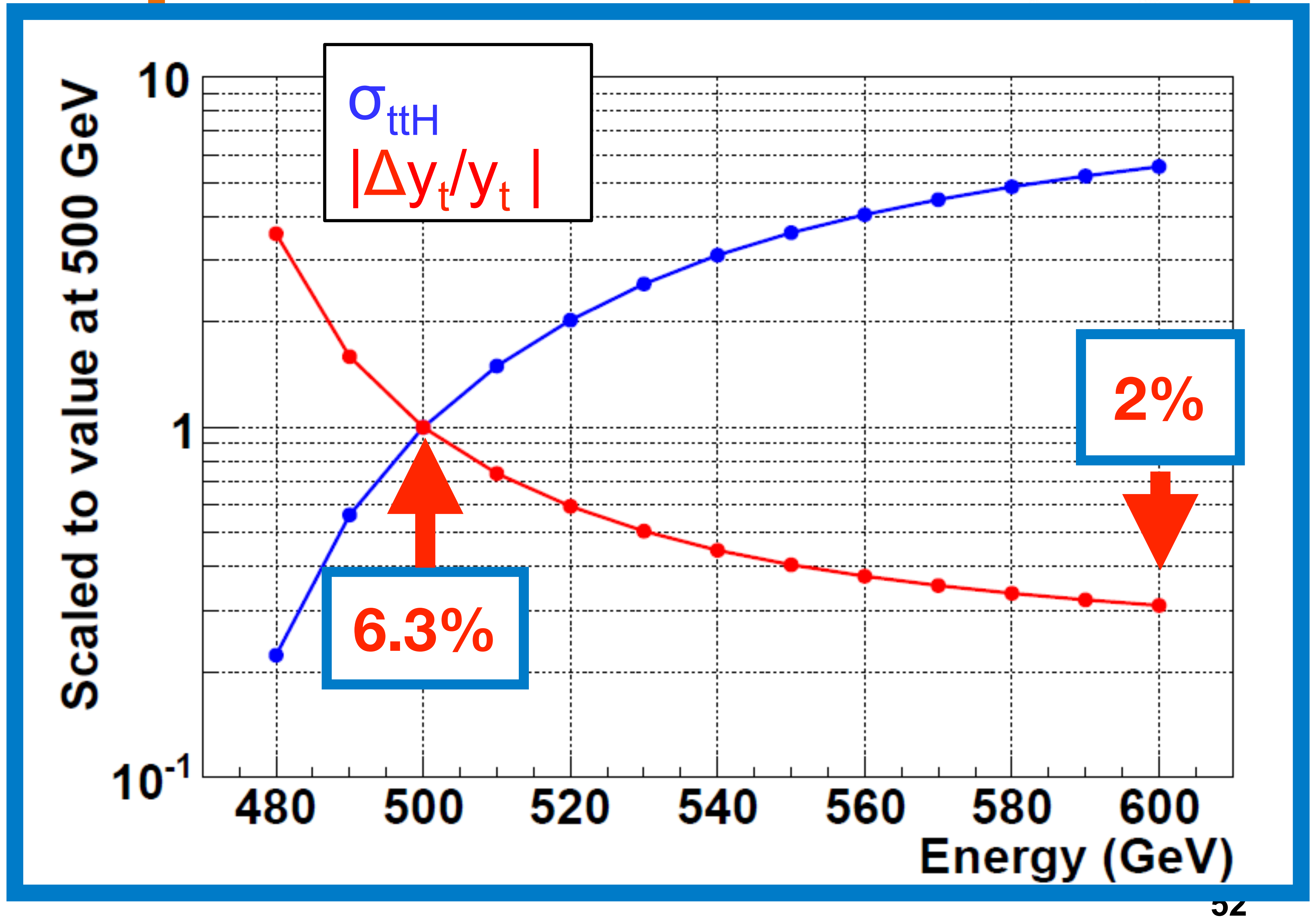
- CLIC: completely different choice with 380 GeV and 1.4 TeV





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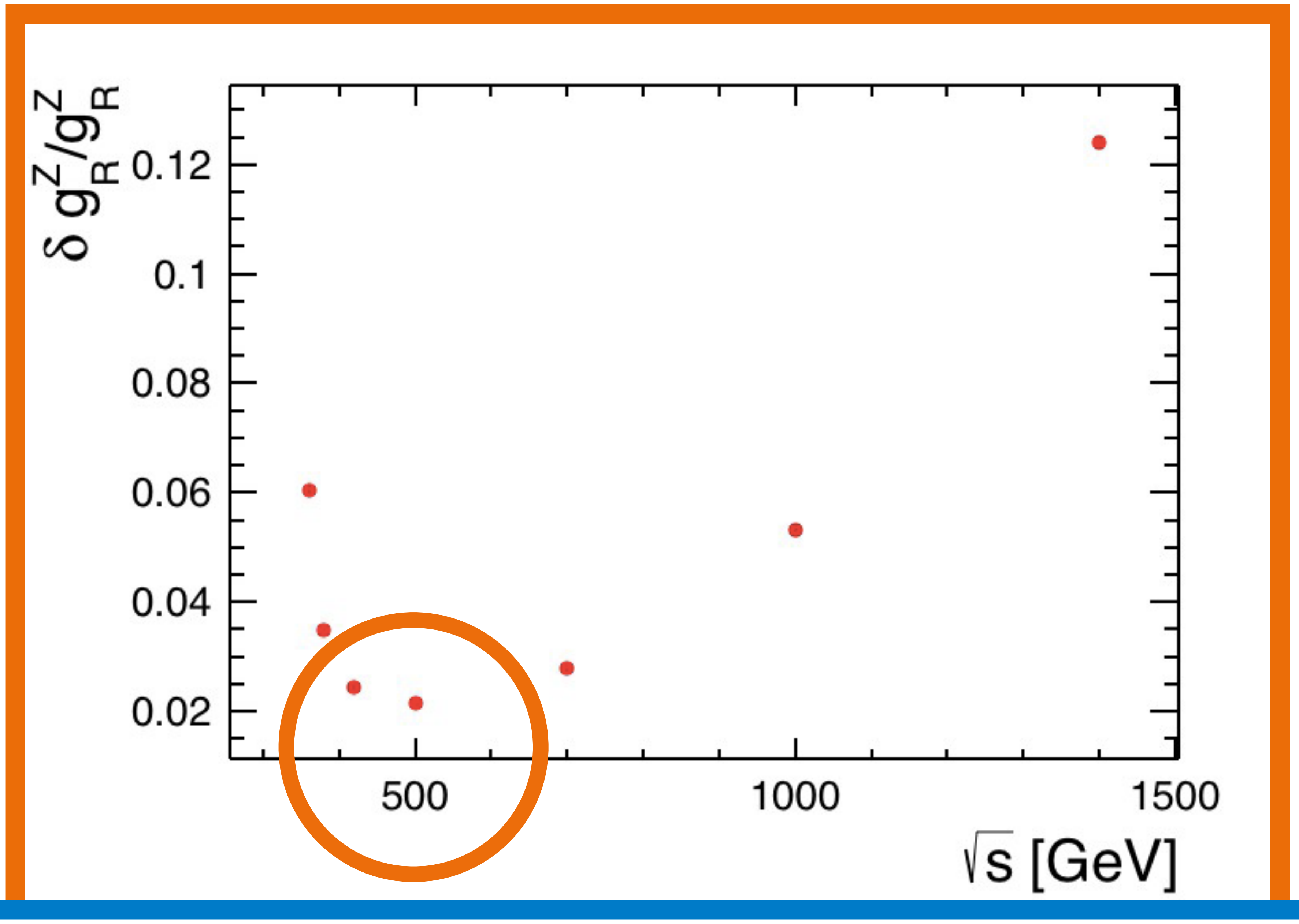

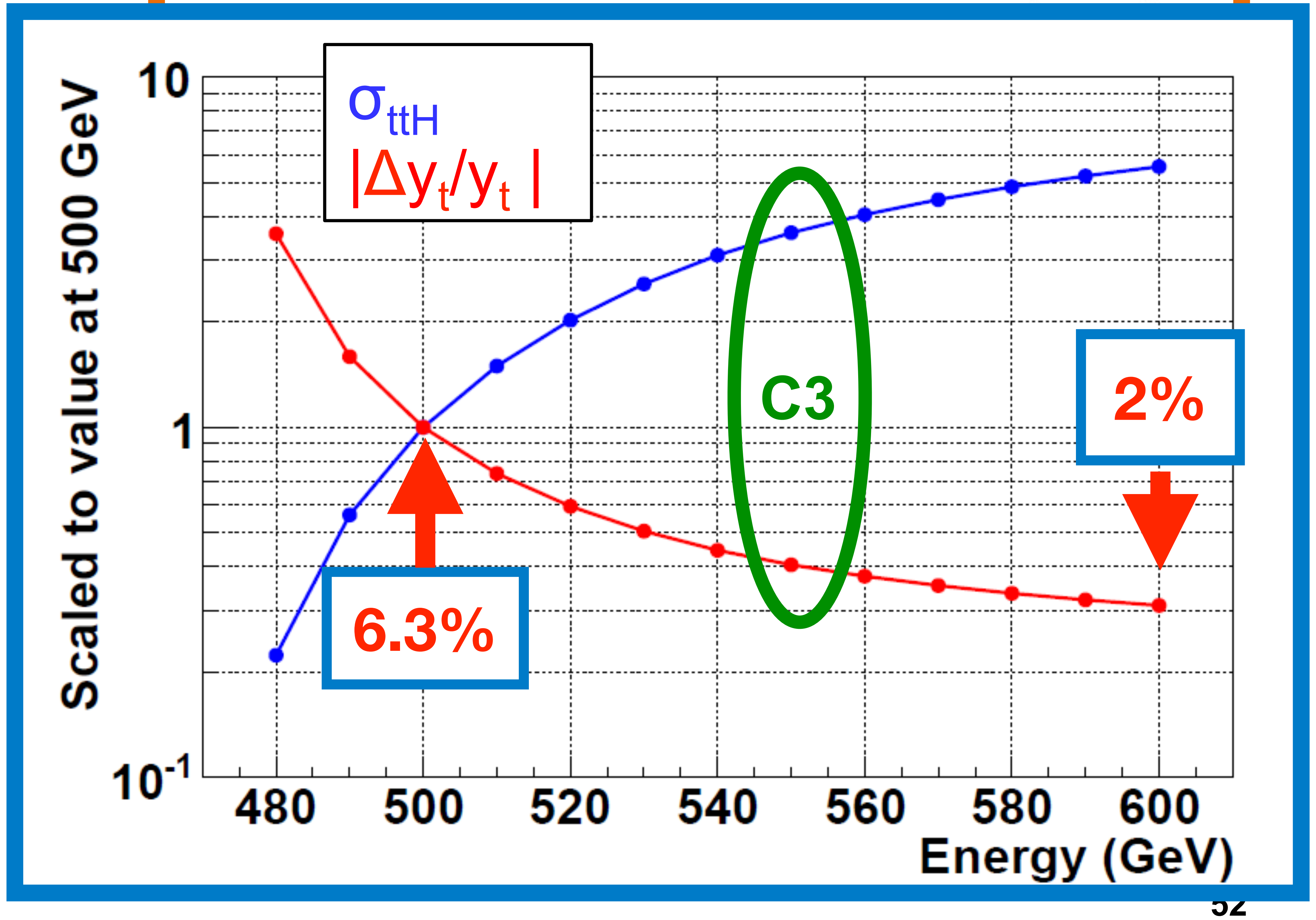

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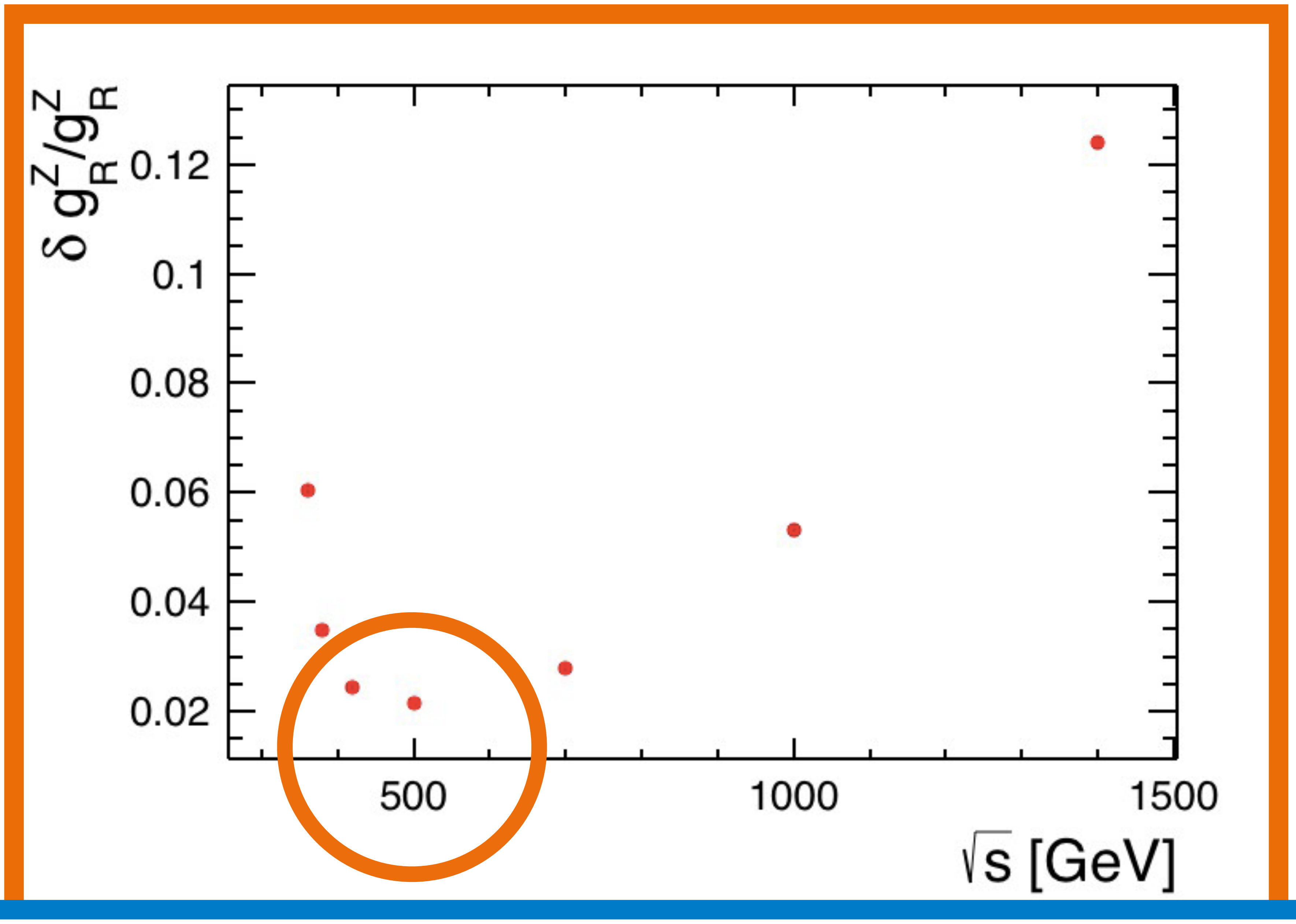
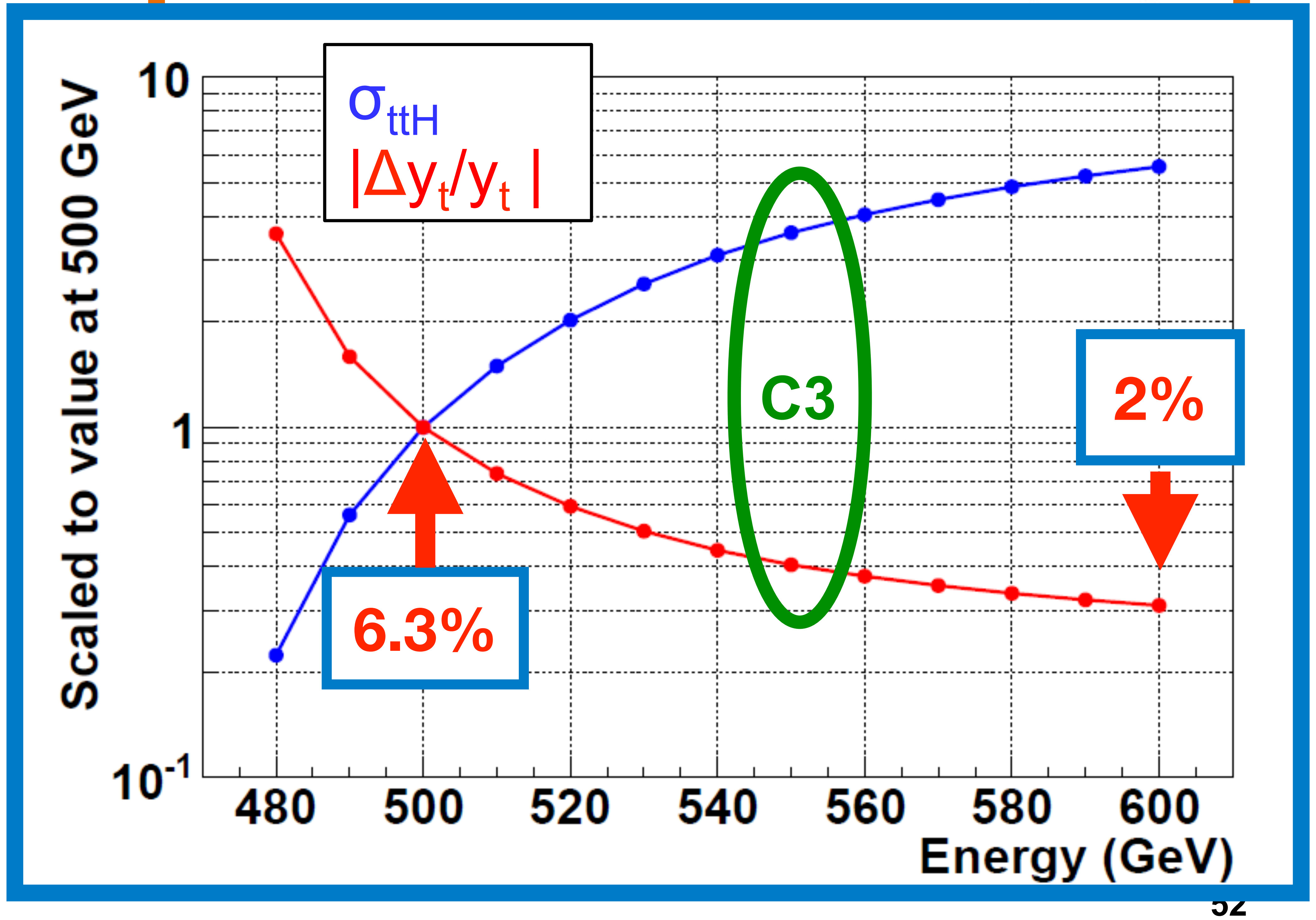
=> Is there a need to re-discuss the physics-optimized energy choices for LCs de-coupled from technology ?



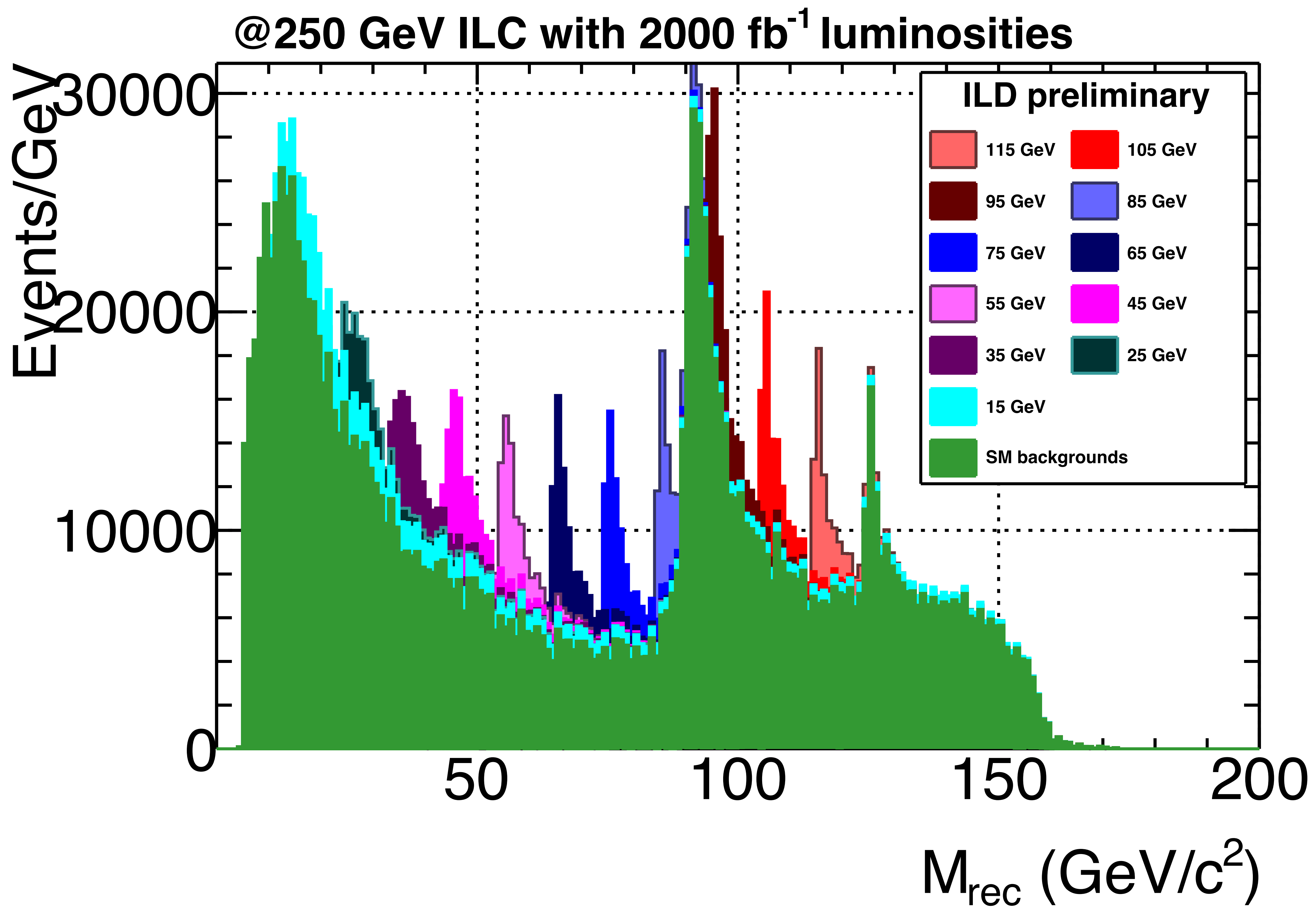


Extra Higgs Bosons ?

Siblings of the Higgs

- must "share" coupling to the Z with the 125-GeV guy:
  - $g_{HZZ}^2 + g_{hZZ}^2 \leq 1$
  - 250 GeV Higgs measurements:
    $g_{hZZ}^2 < 2.5\%\ g_{SM}^2$ excluded at 95% CL
- probe smaller couplings by ***recoil* of h against Z**

=> decay mode independent!



ILD full detector simulation @ ILC 250 GeV & 500 GeV, arxiv:2005.06265

- **fully complementary to measurement of ZH cross section**
- **other possibility: ee -> bbh (via Yukawa coupling)**

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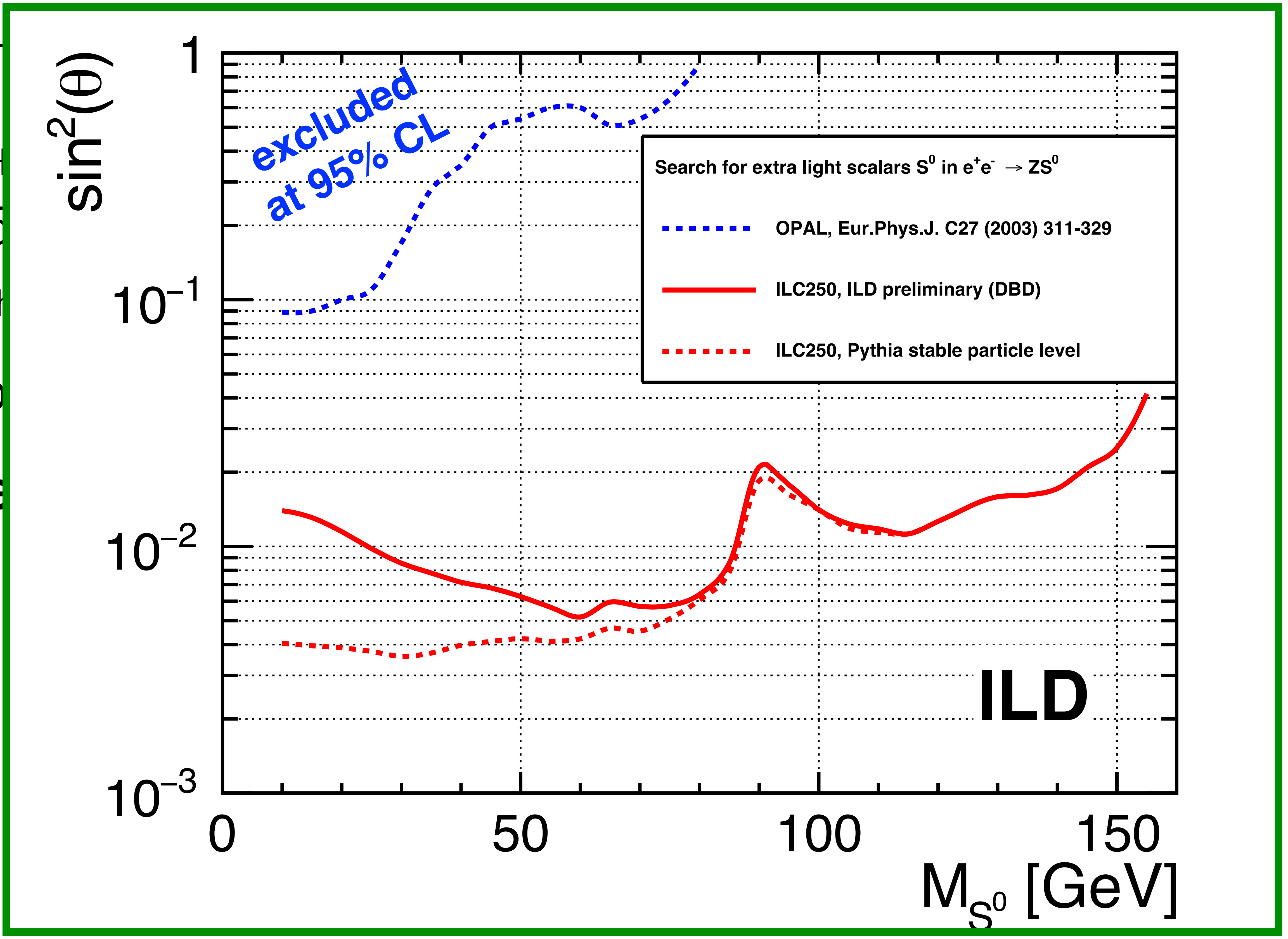
Siblings of the Higgs

- must
  - g_H
  - 25
    g
- prob

=> de



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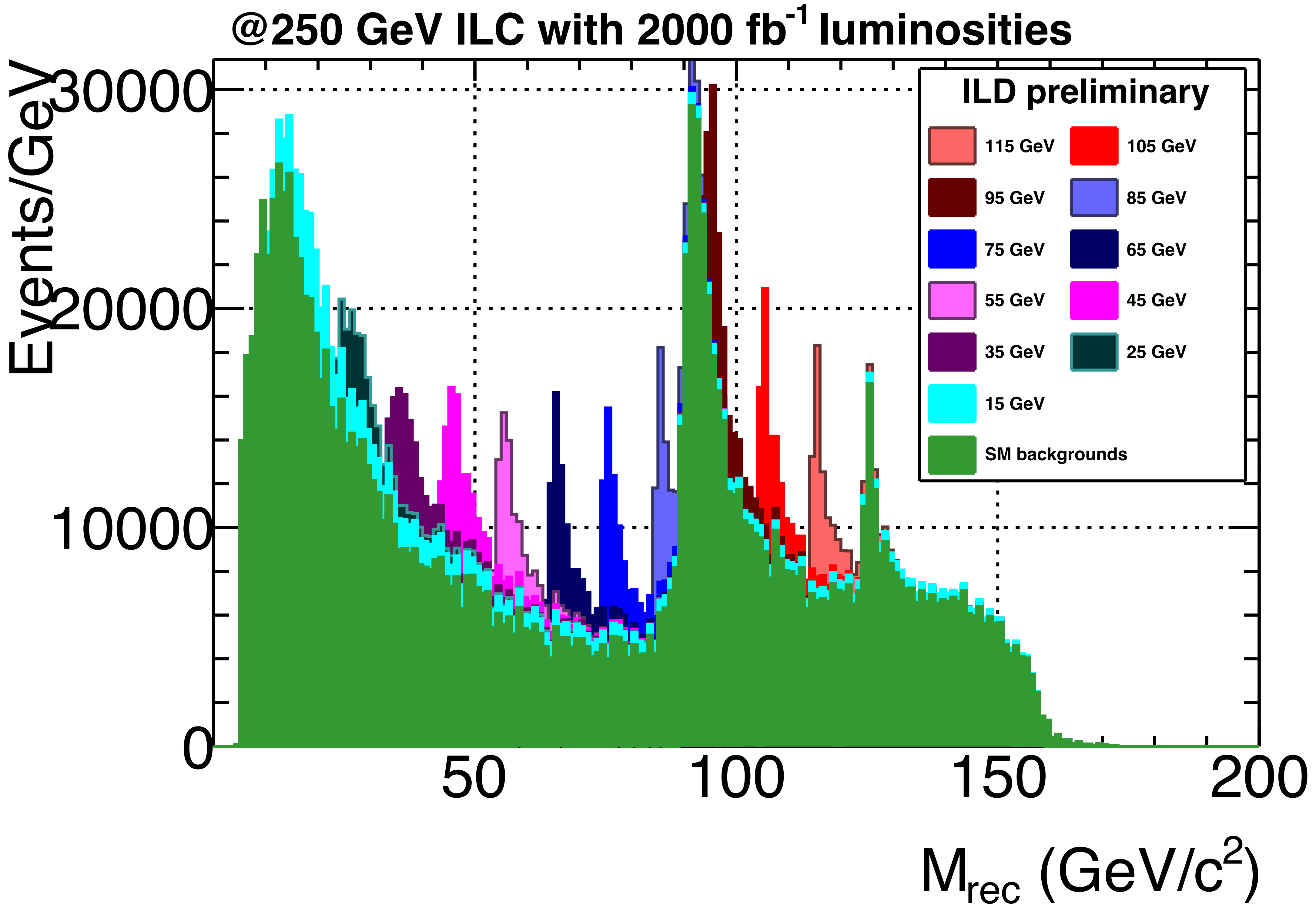

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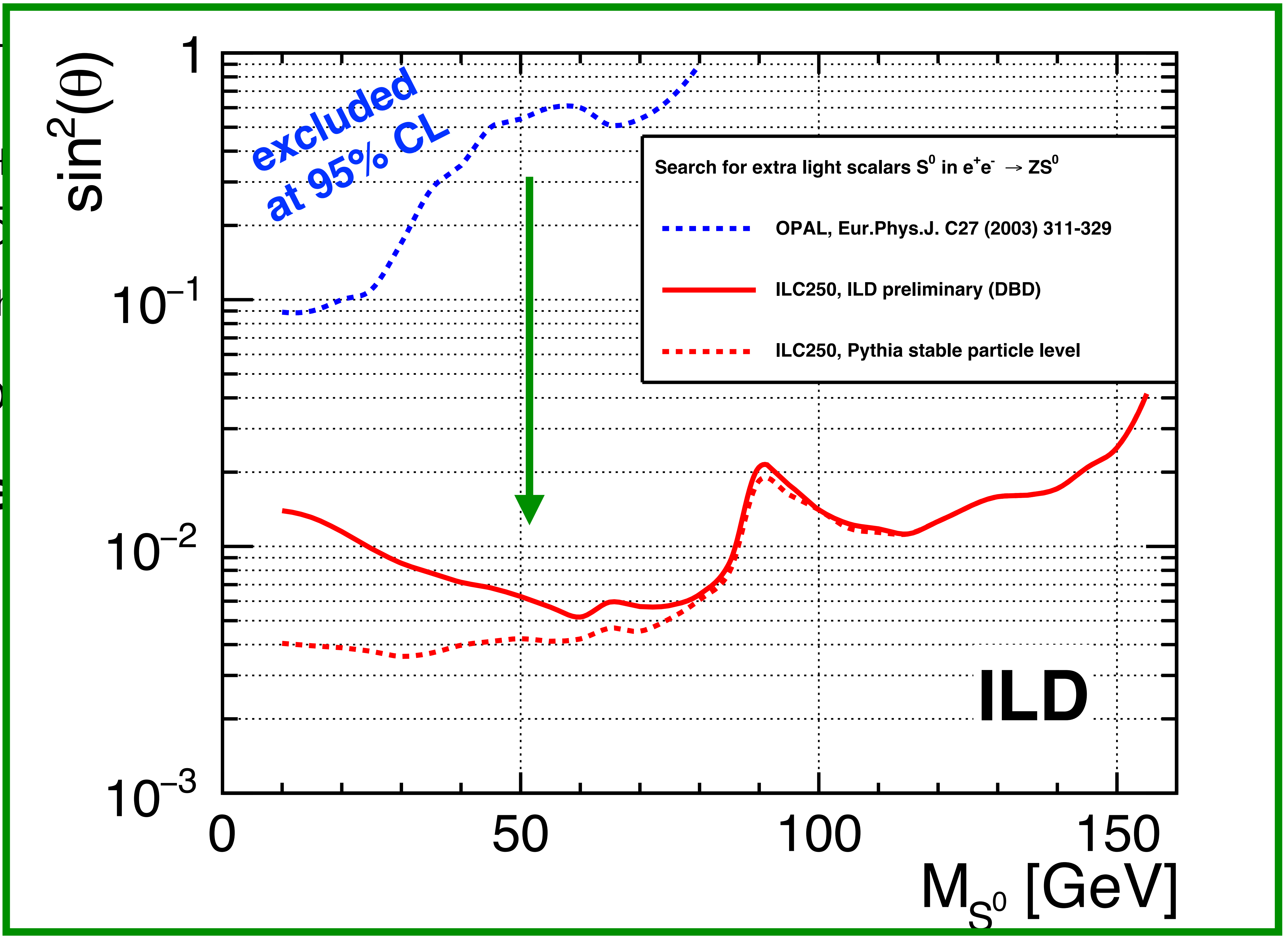

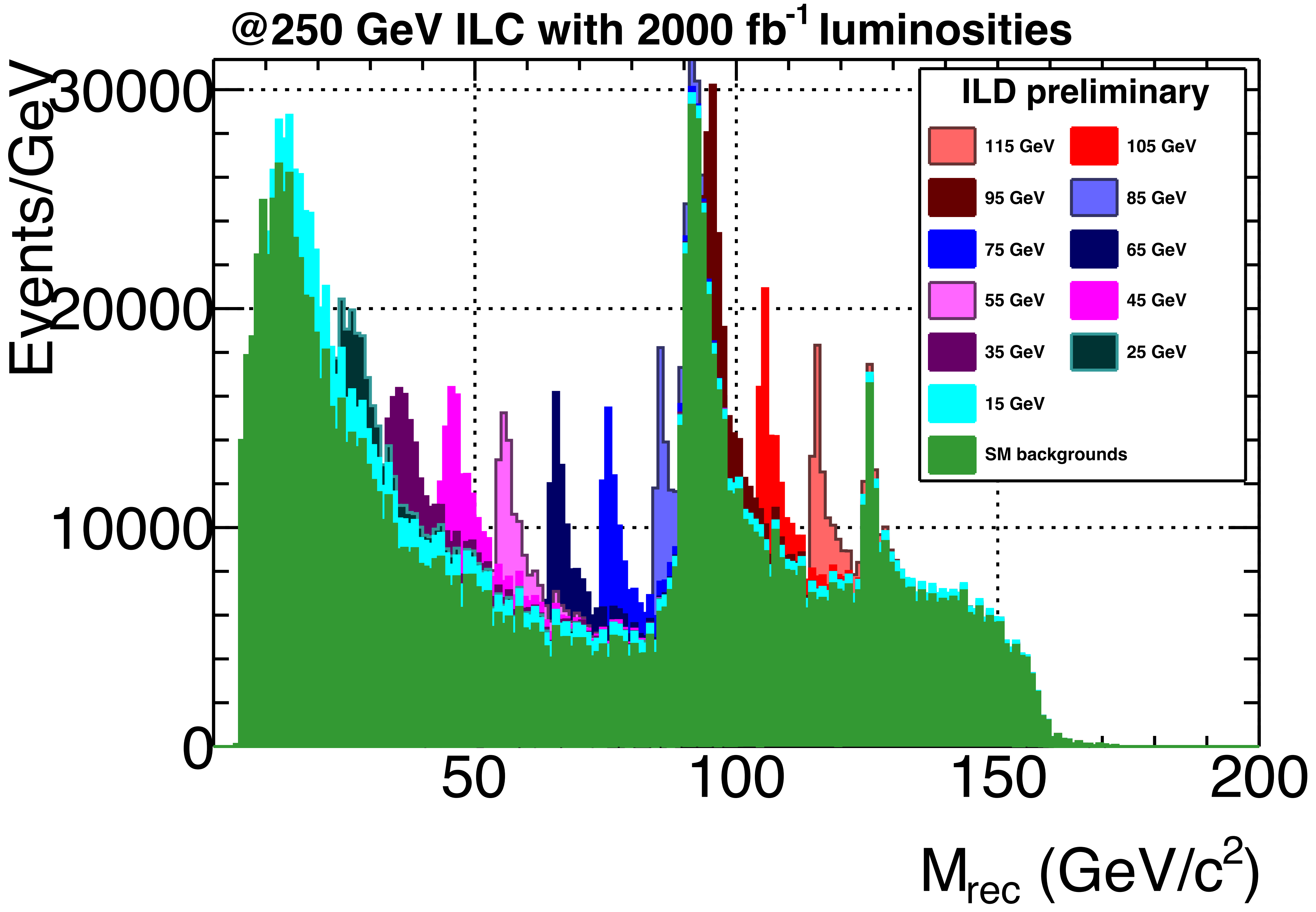

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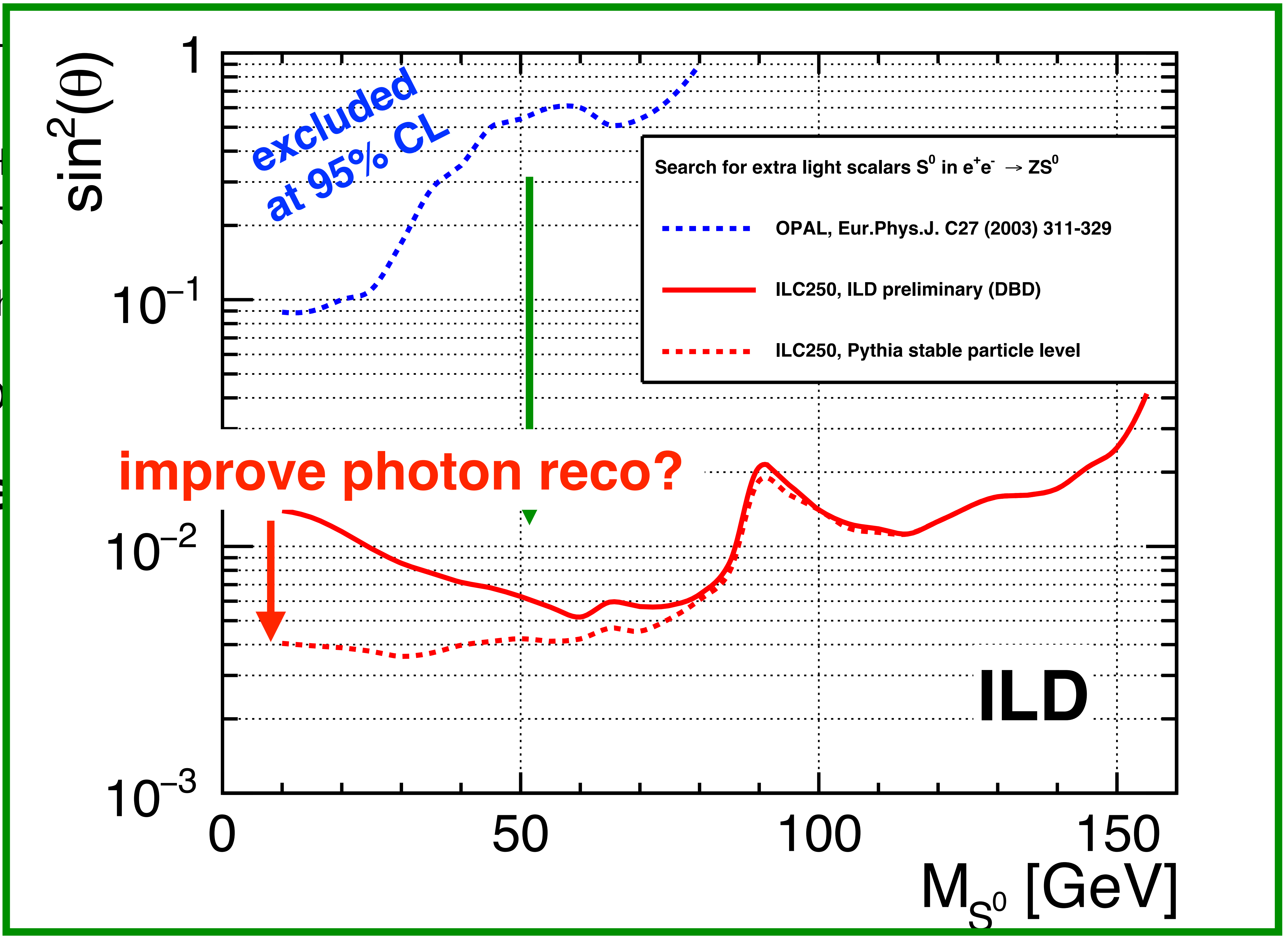

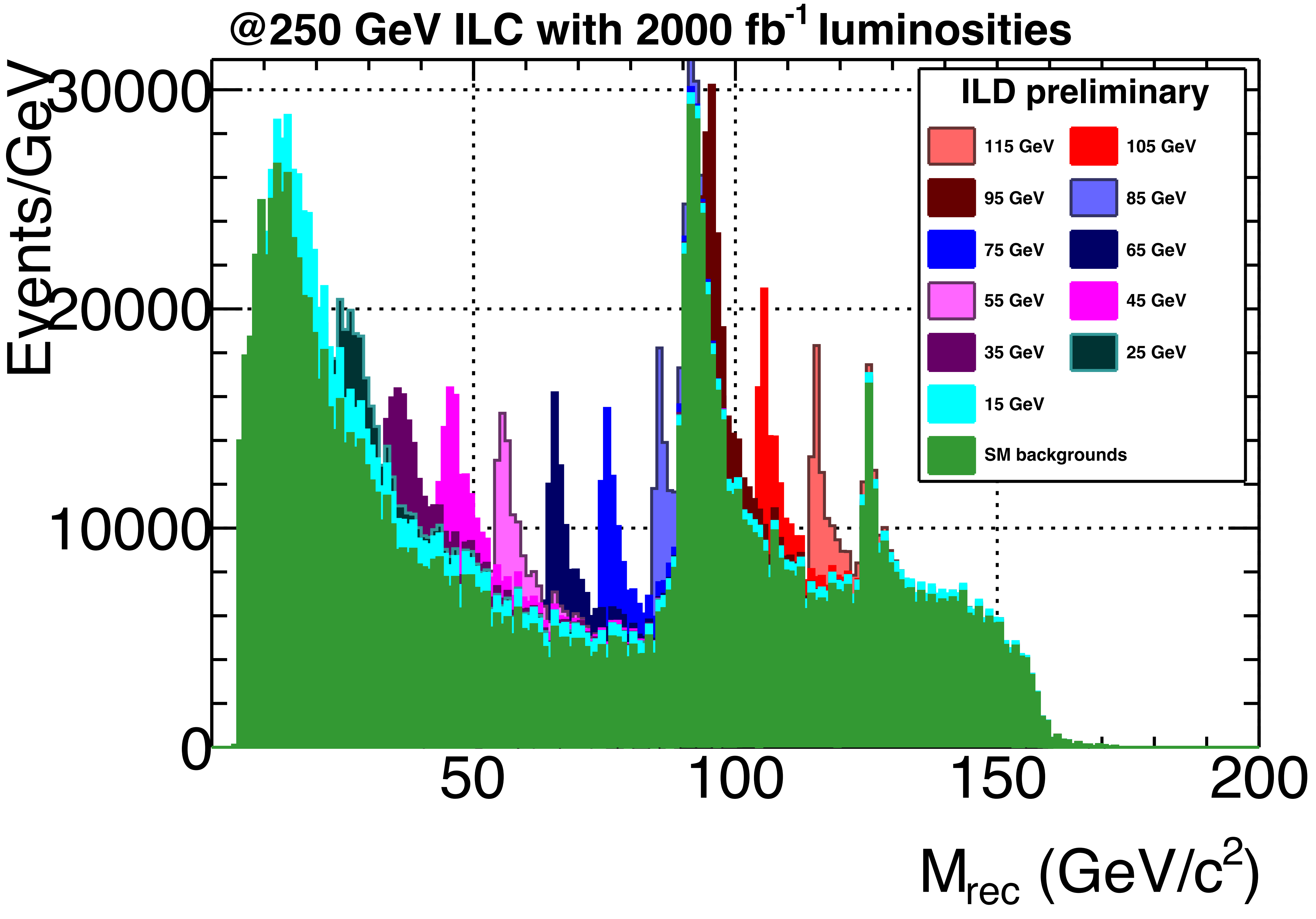

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… and how to tackle them at colliders

electron-positron & proton-proton

Our tools:

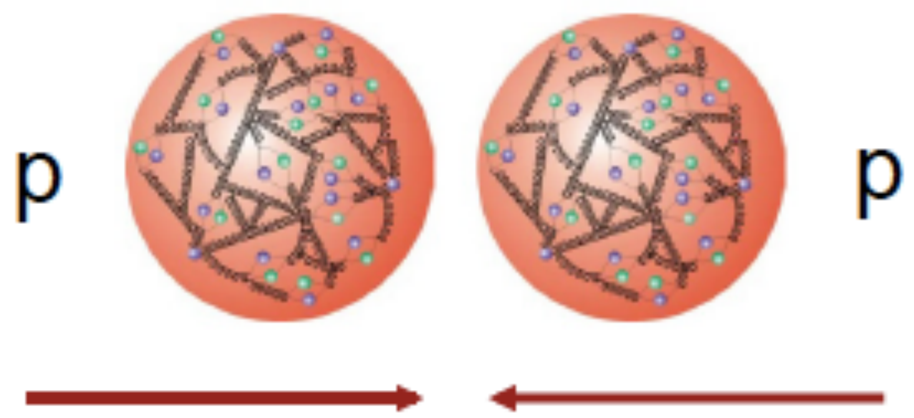
The Top and Bottom Quark

Z & W Bosons

The Higgs Boson

Discoveries of new particles ?

- elementary particles
- different E_{CM} via accelerator operation
- E_{CM} known on event-by-event level



- proton structure
- E_{CM} of “hard” interactions cover all energies < pp E_{CM}
- not known on event-by-event level

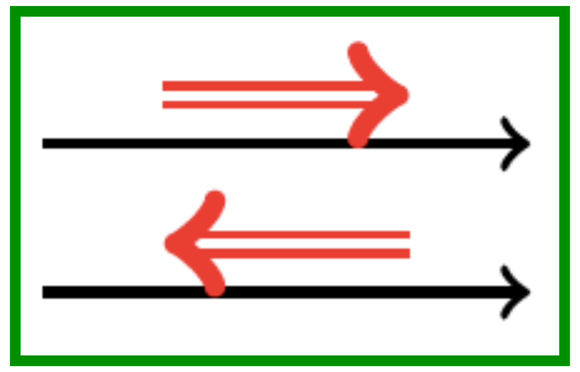
Other important parameters in e^+e^- collisions

Luminosity

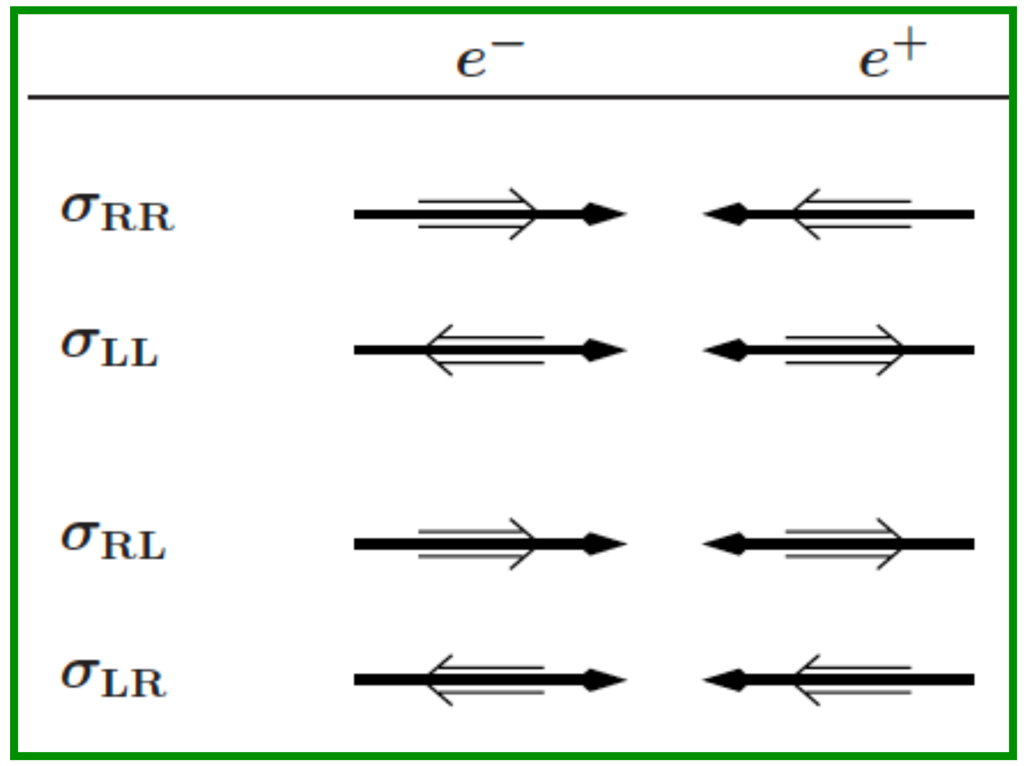
- Defines event rate => size of data set
- Future e^+e^- colliders aim for $10^3..10^6$ larger data sets than LEP
- Depends strongly on invest costs and power consumption => be careful to compare apples to apples!
- Are there fundamental boundaries *beyond* statistics?
  (e.g. theory & parametric uncertainties, detector resolution, …)

Beam polarisation:

$$P := \frac{N_R - N_L}{N_R + N_L}$$



- Electroweak interactions highly sensitive to chirality of fermions: $SU(2)_L \times U(1)$
- both beams polarised => “four colliders in one”:



New Physics Interpretation of Higgs & EW

Illustrating the principle - based on older fit!

Test various example BSM points - all chosen such that no hint for new physics at HL-LHC

	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [36]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [35]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [35]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
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5	Composite Higgs [37]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [38]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
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8	Higgs-Radion [40]	-1.5	- 1.5	+10.	-1.5	-1.5	-1.5	-1.0	-1.5
9	Higgs Singlet [41]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

Table 3: Percent deviations from SM for Higgs boson couplings to SM states in various new physics models. These model points are unlikely to be discoverable at 14 TeV LHC through new particle searches even after the high luminosity era ($3\,\mathrm{ab}^{-1}$ of integrated luminosity). From [15].

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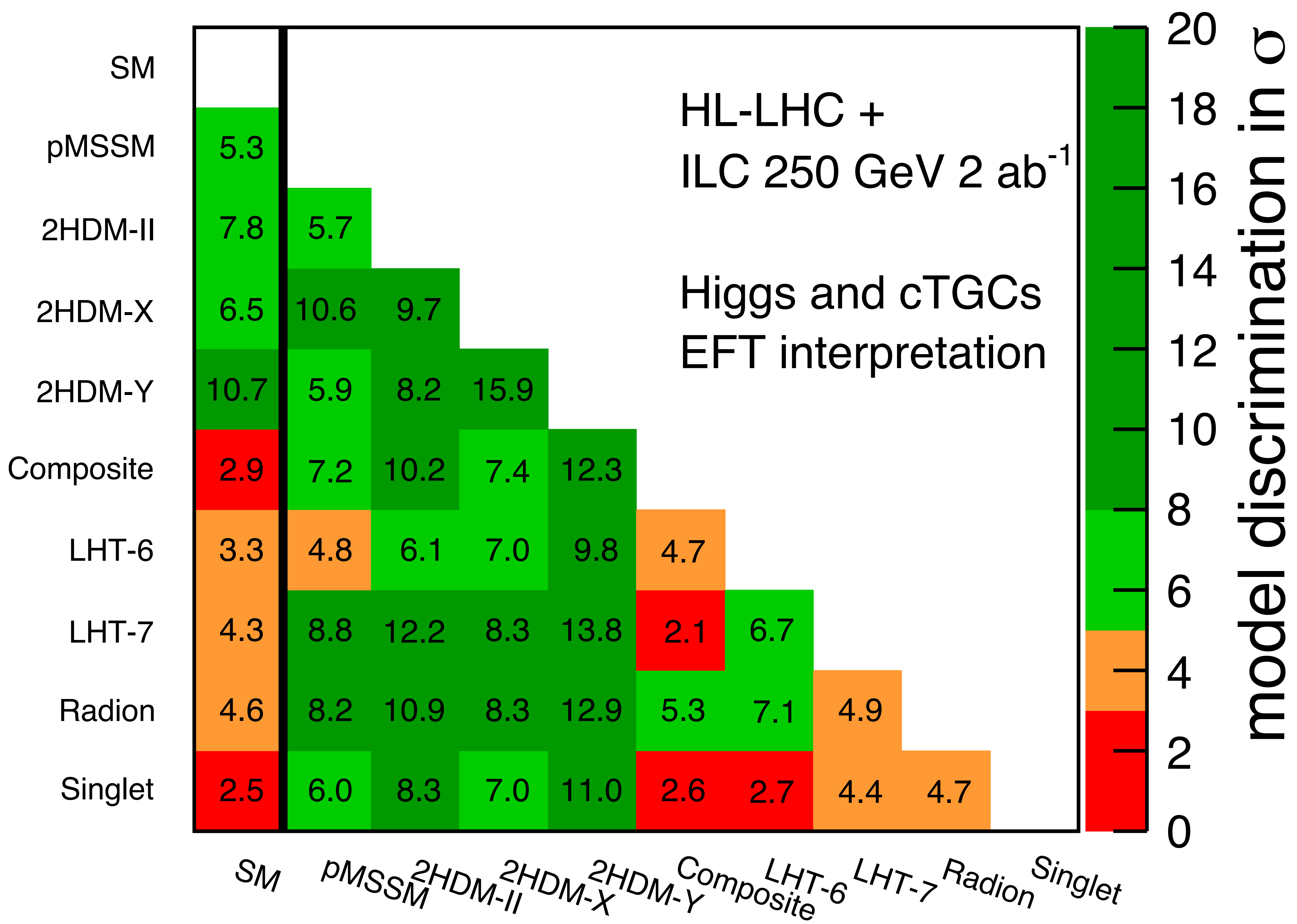

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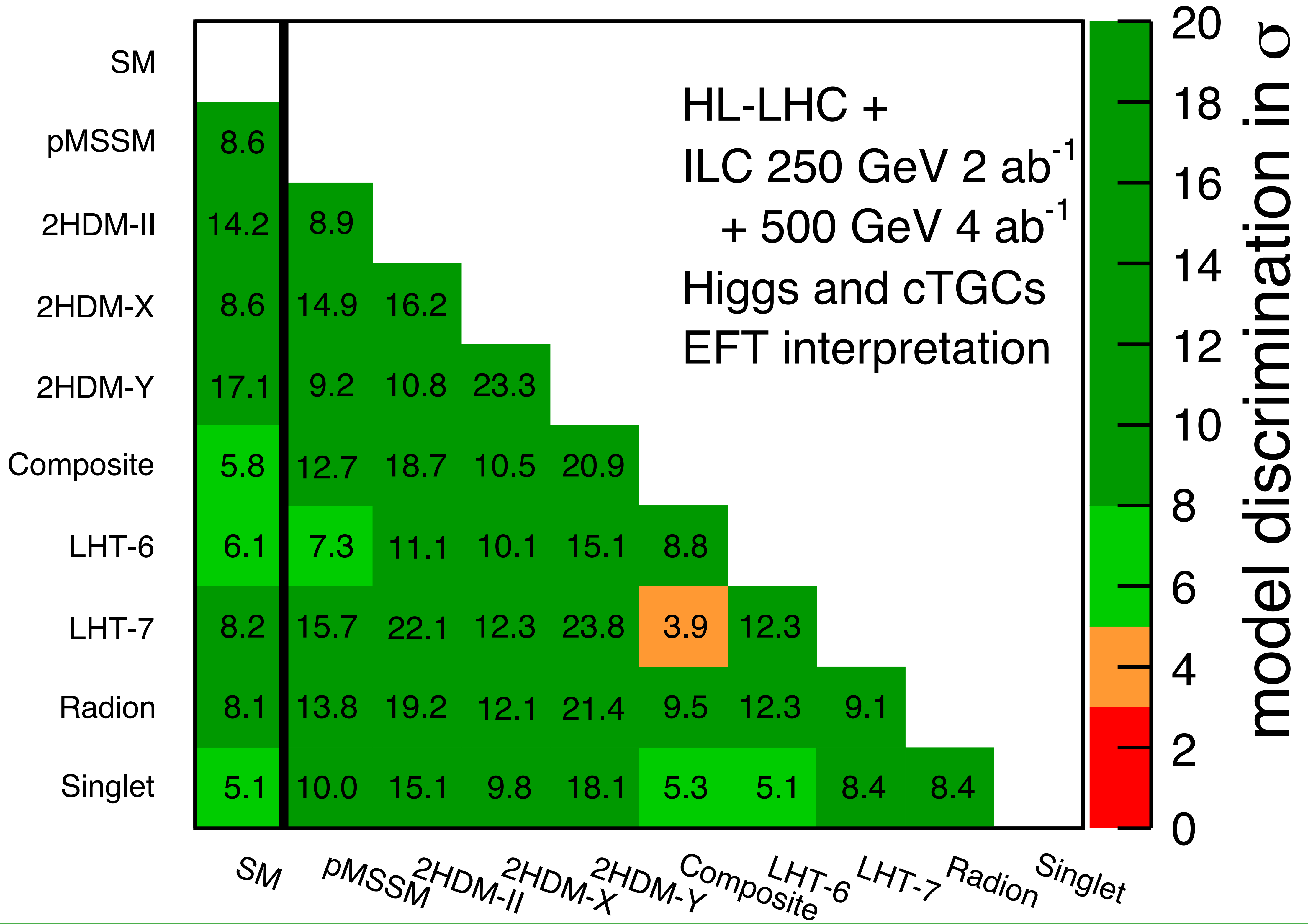

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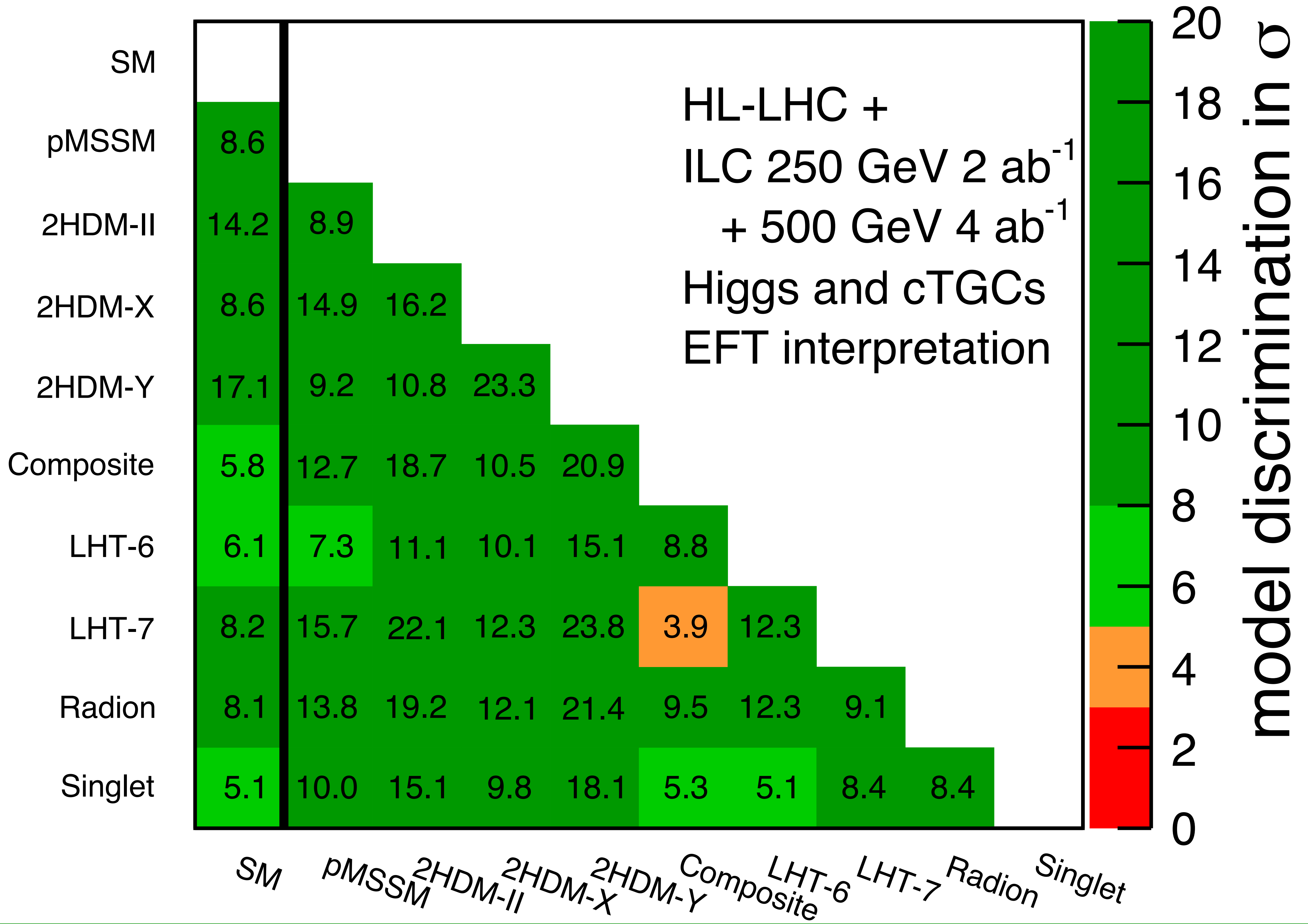
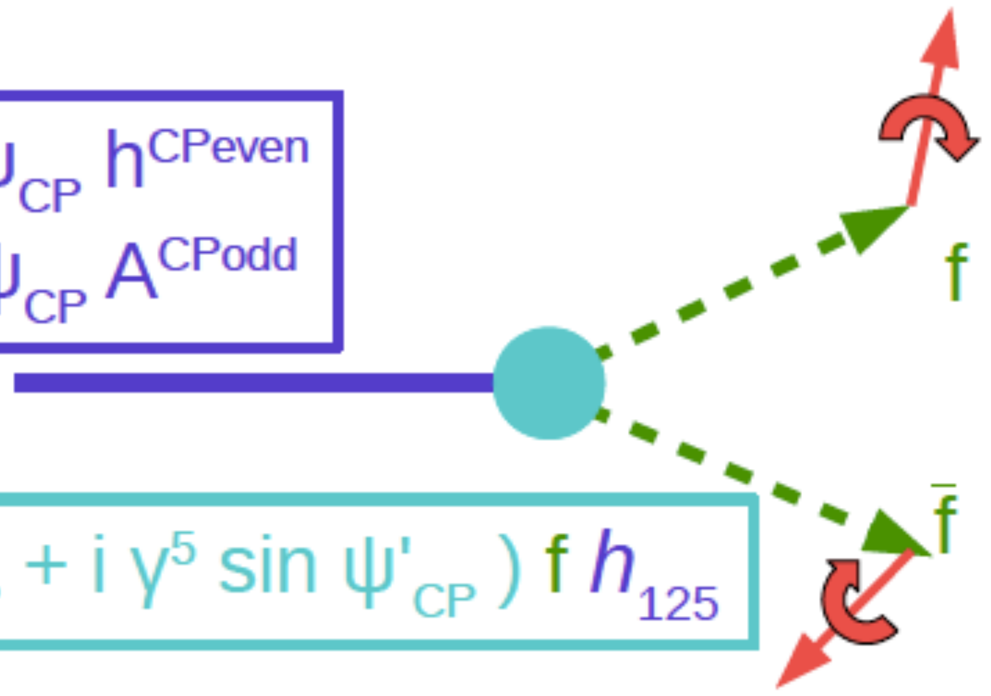


illustrates the ILC's discovery and identification potential - complementary to (HL-)LHC!

CP properties in h->$\tau\tau$

ZH production ideal

$$h_{125} = \cos\psi_{CP}\, h^{CPeven} + \sin\psi_{CP}\, A^{CPodd}$$



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h is a spin 0 state:

$$|f\,\bar{f}\rangle = |\uparrow\downarrow\rangle + e^{2i\psi}\, |\downarrow\uparrow\rangle$$

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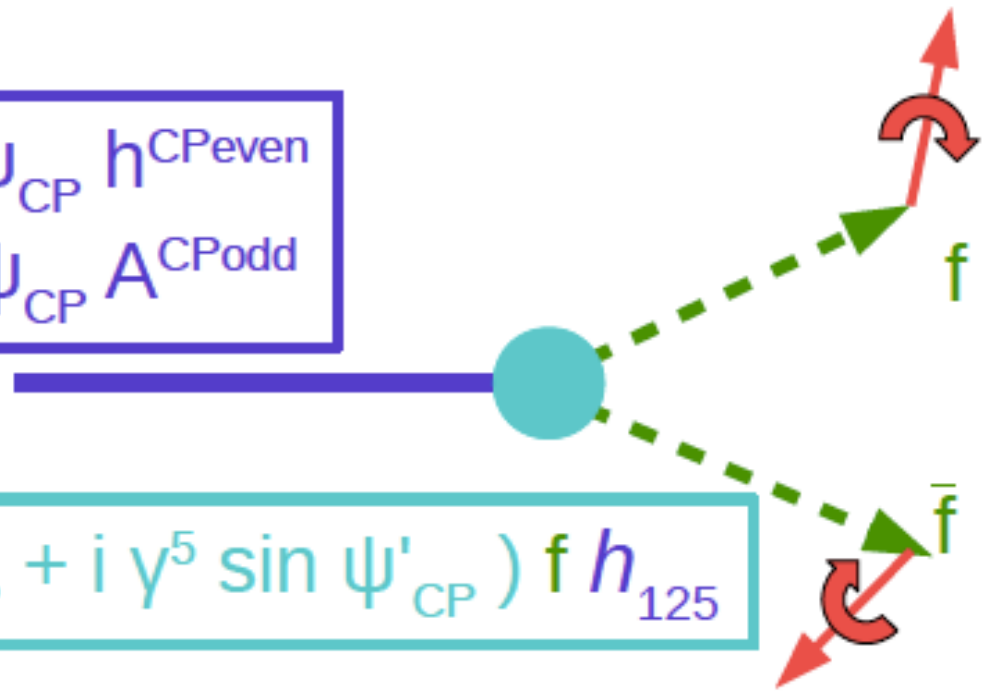

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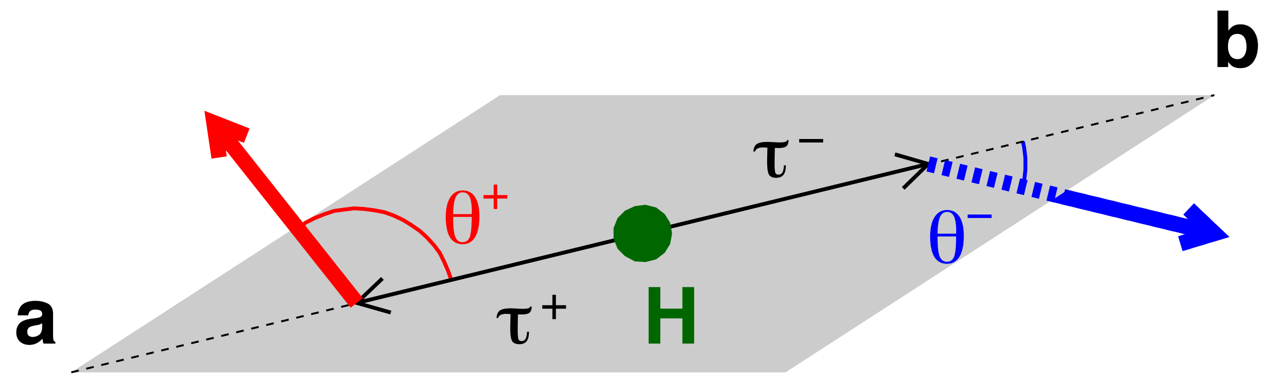

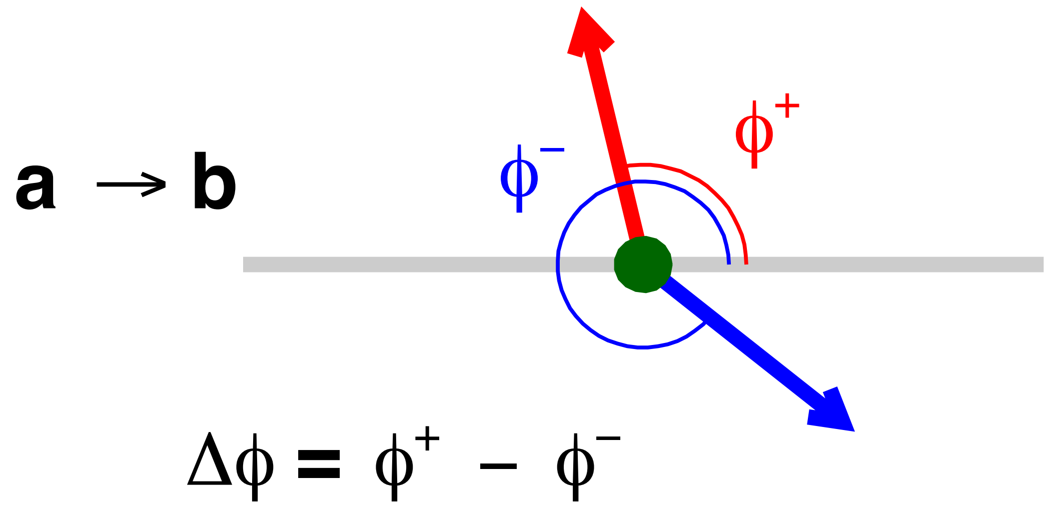

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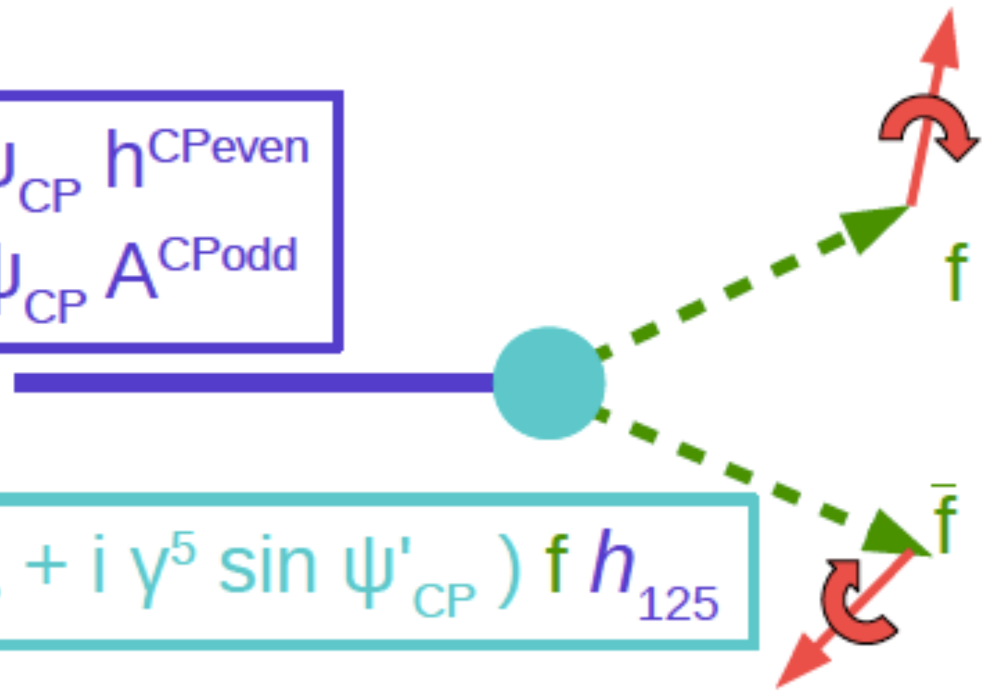

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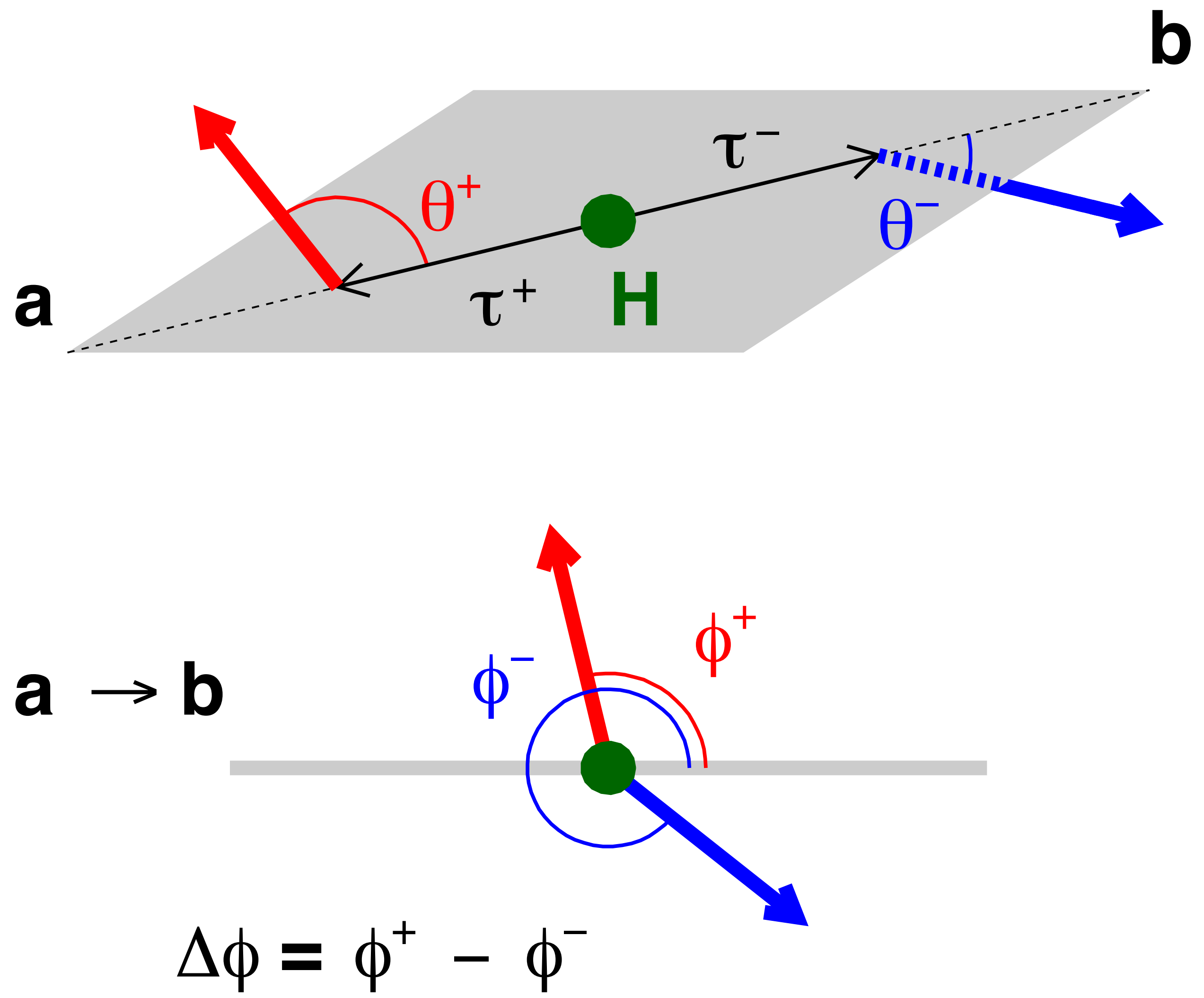

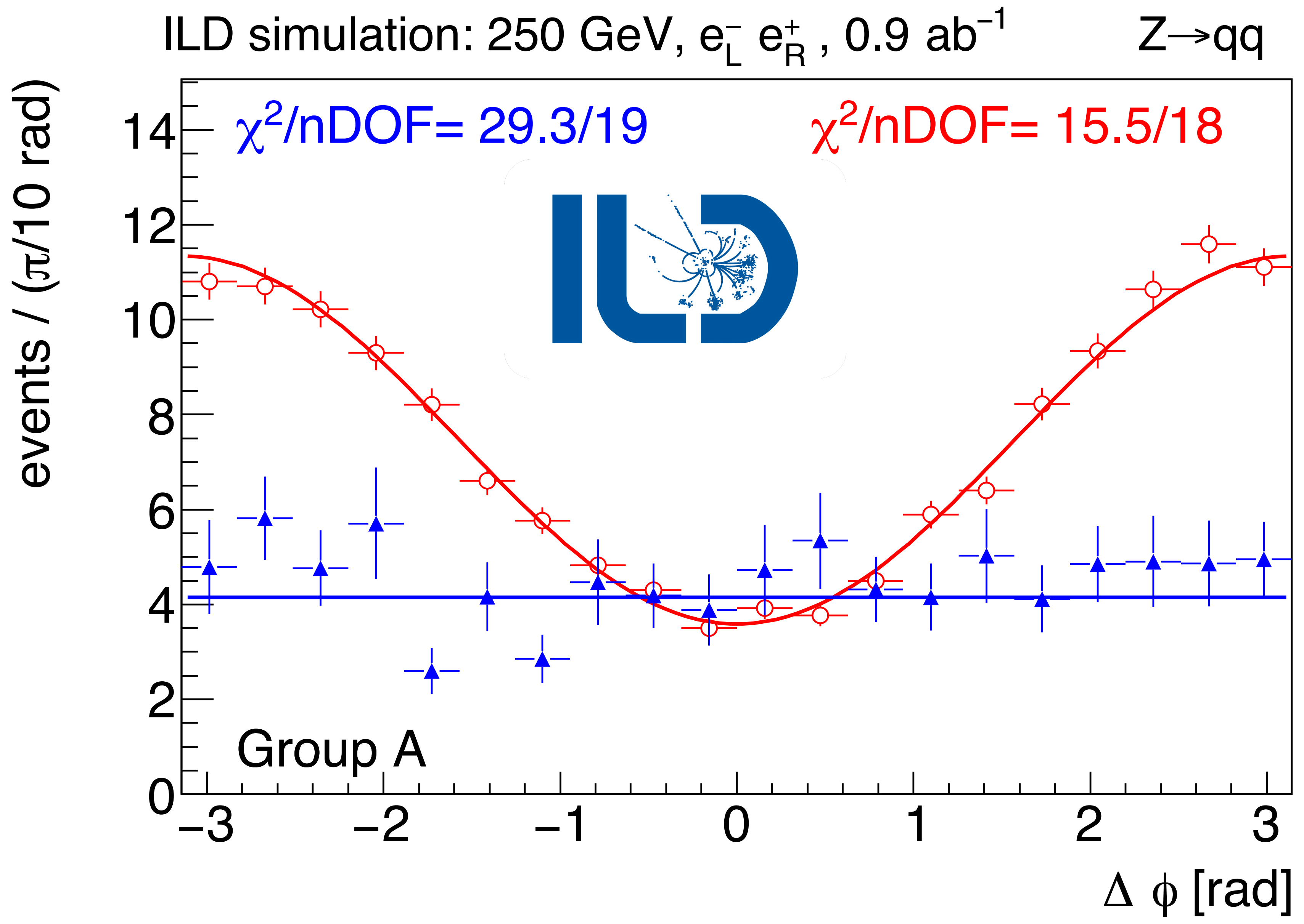

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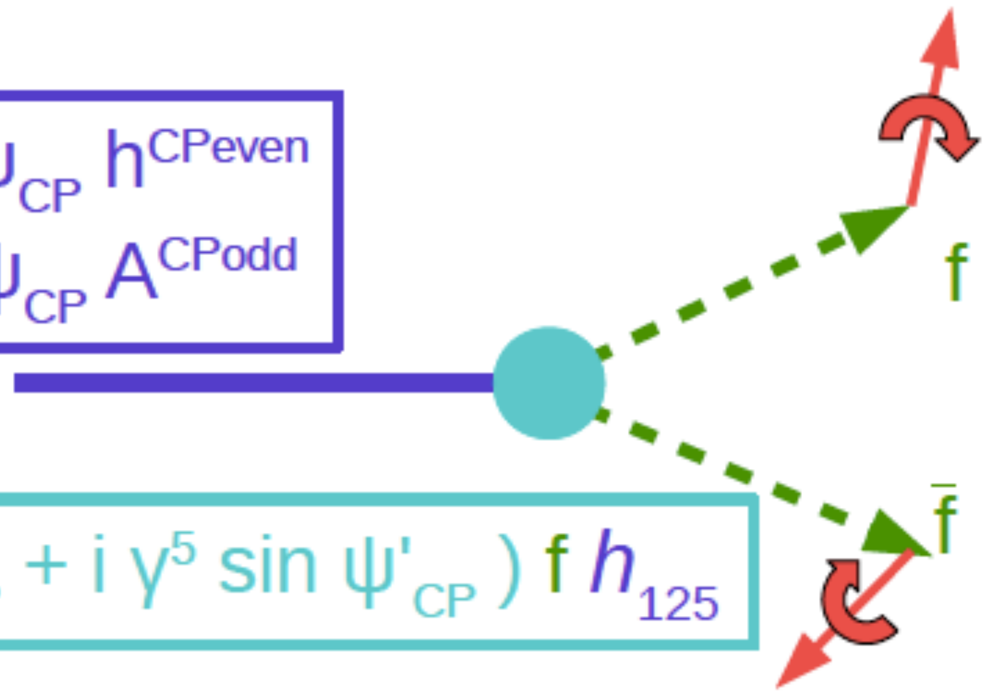

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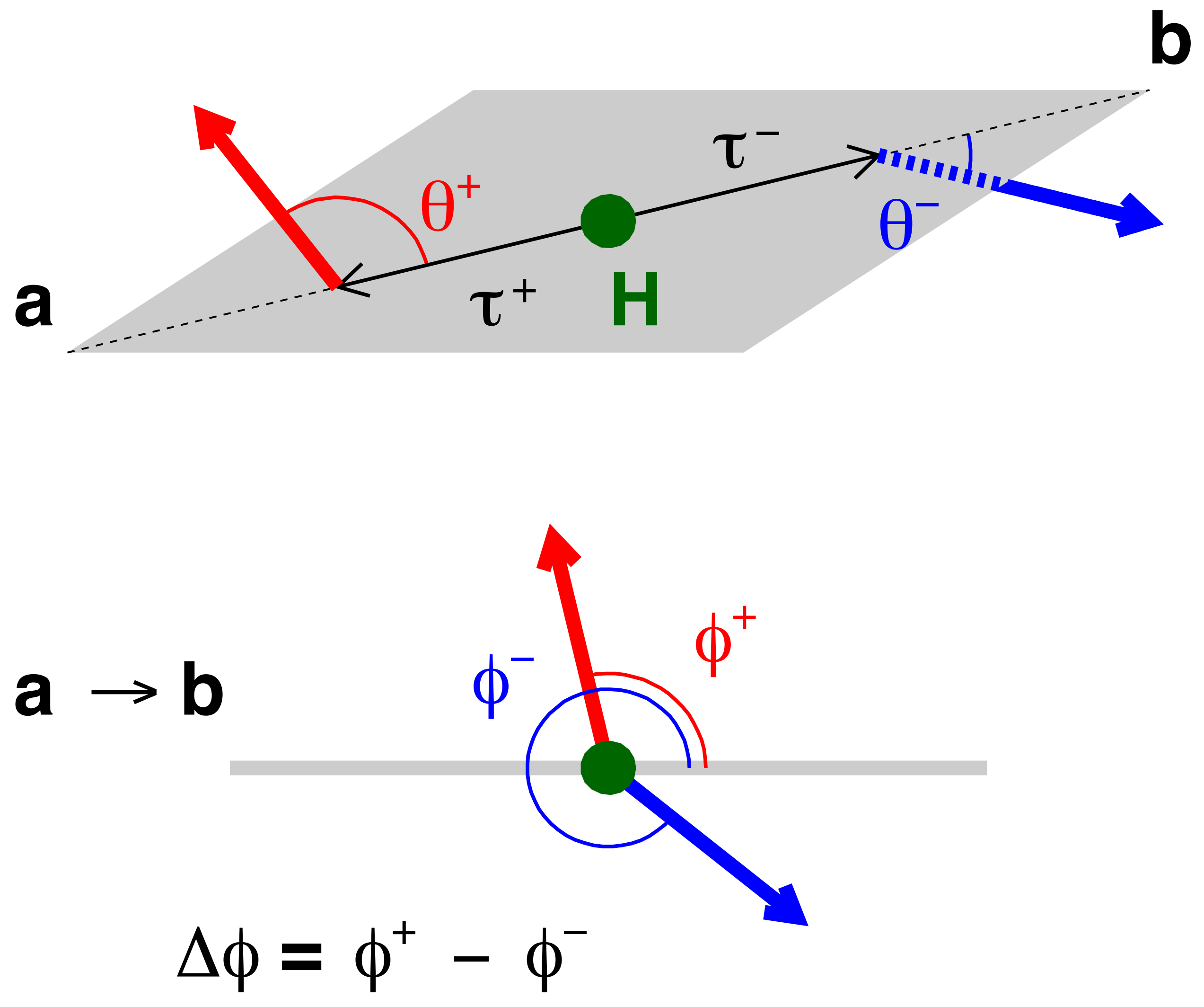

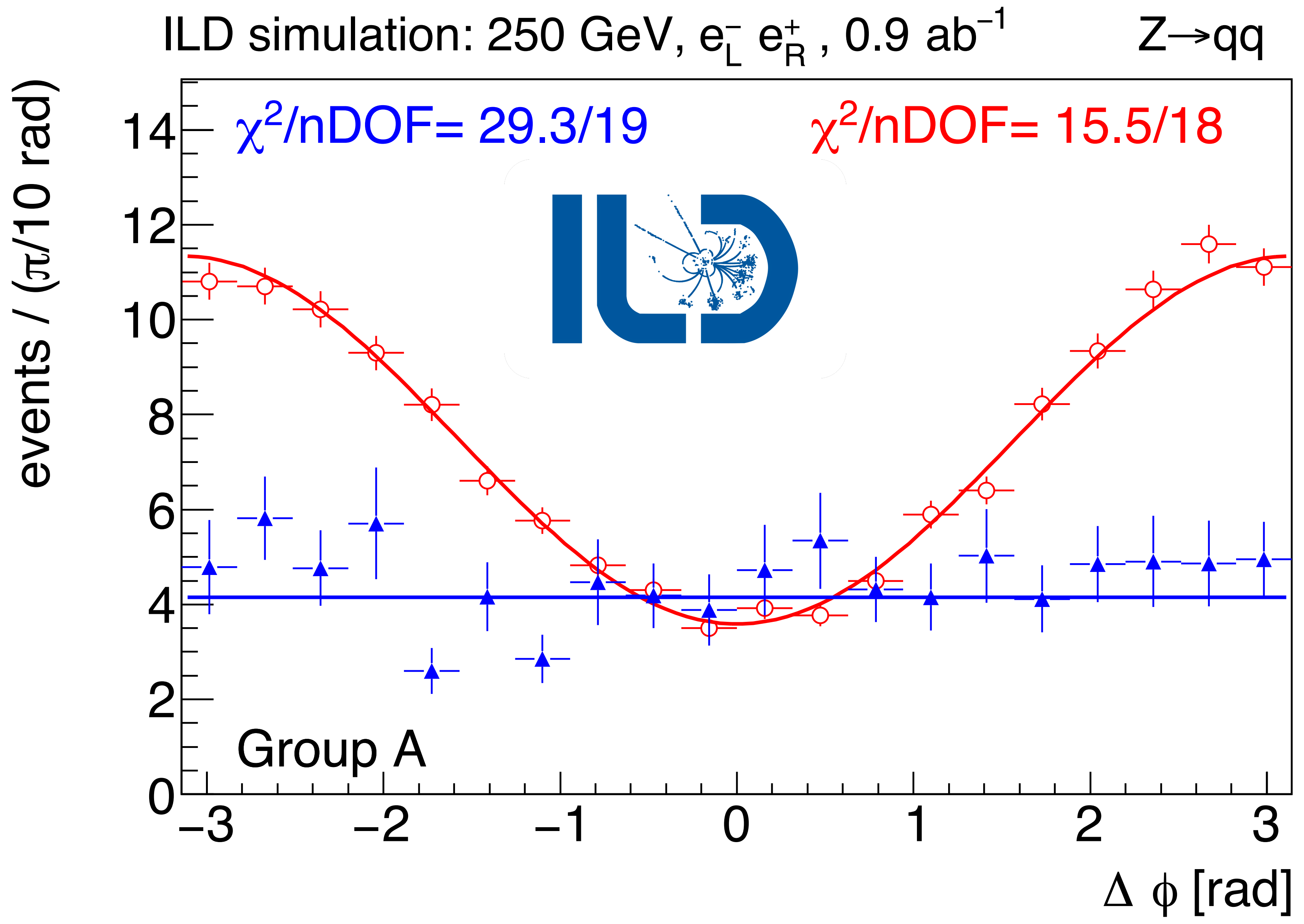

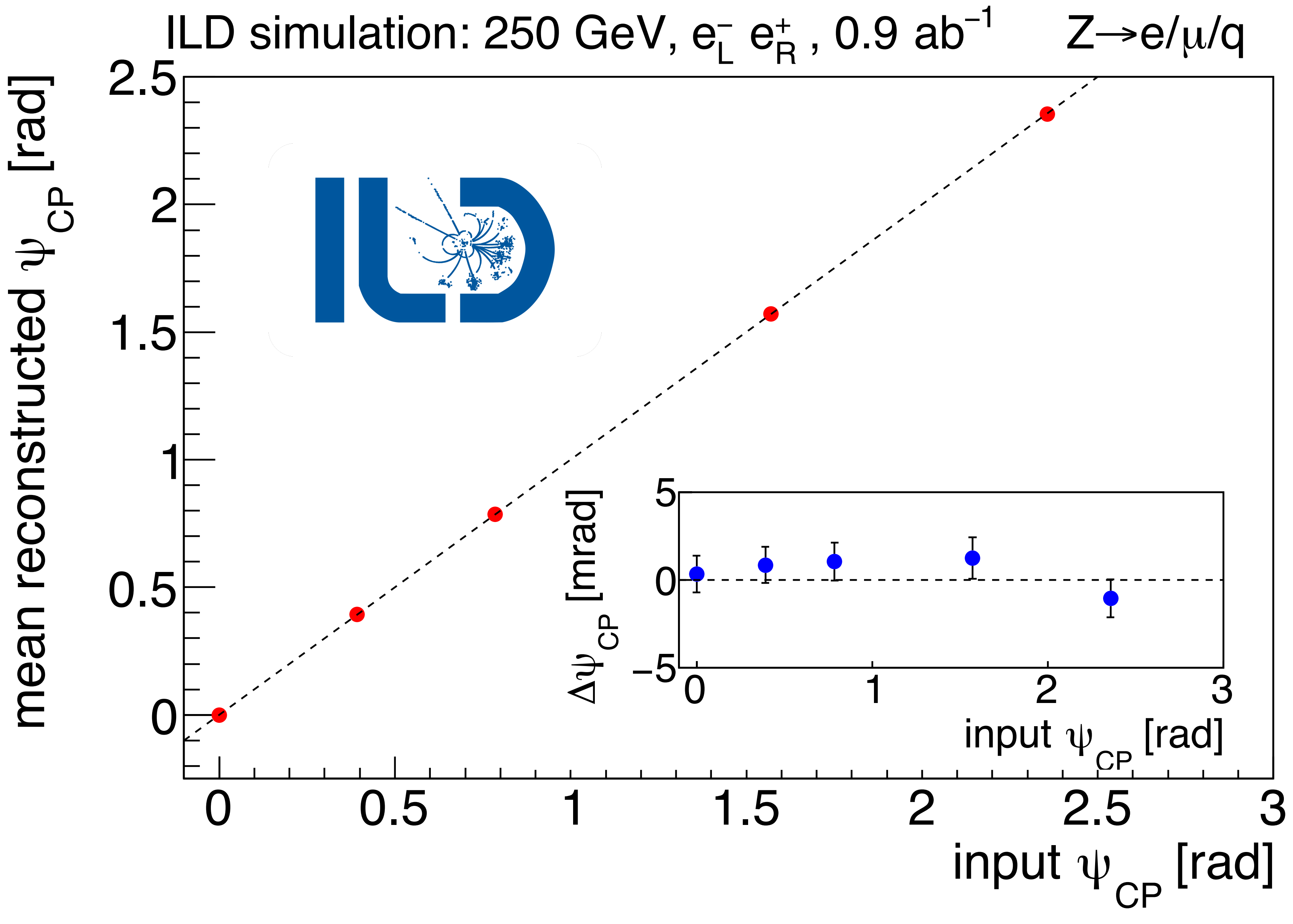

arxiv:1804.01241

based on NIM A810 (2016) 51-58

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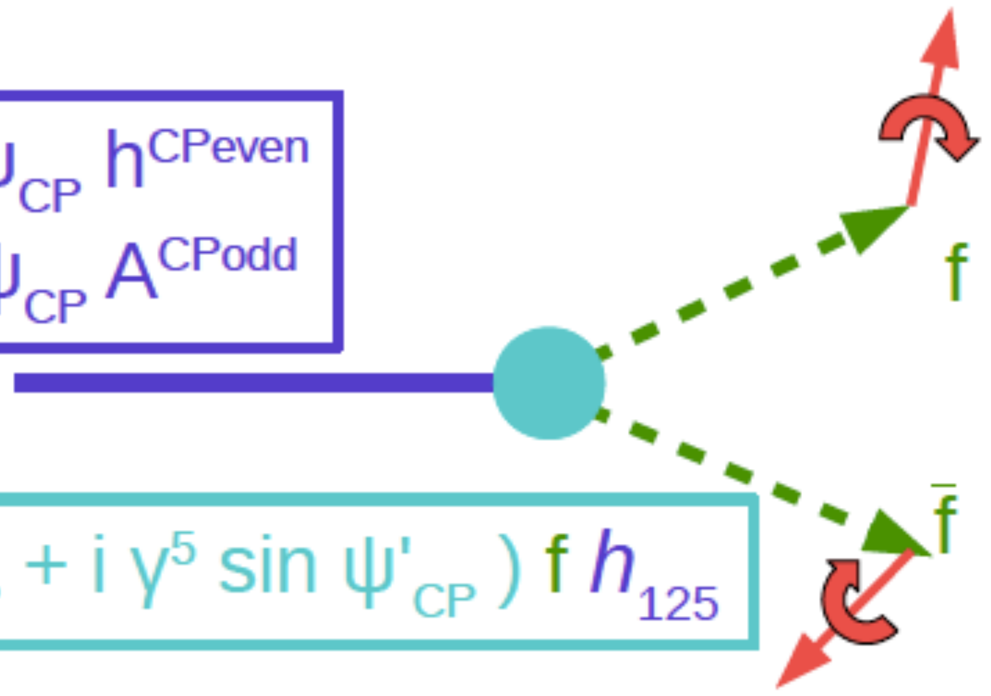

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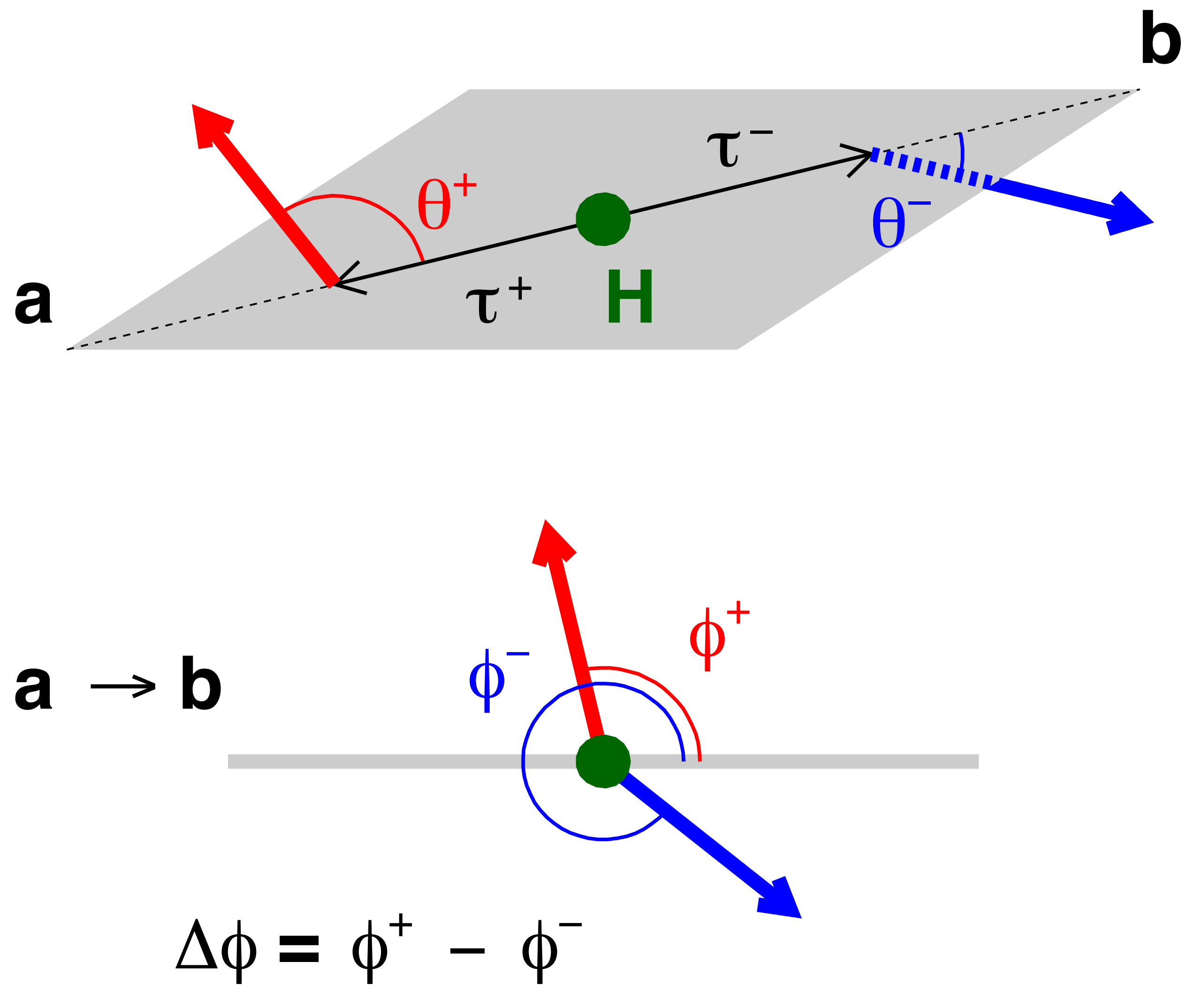
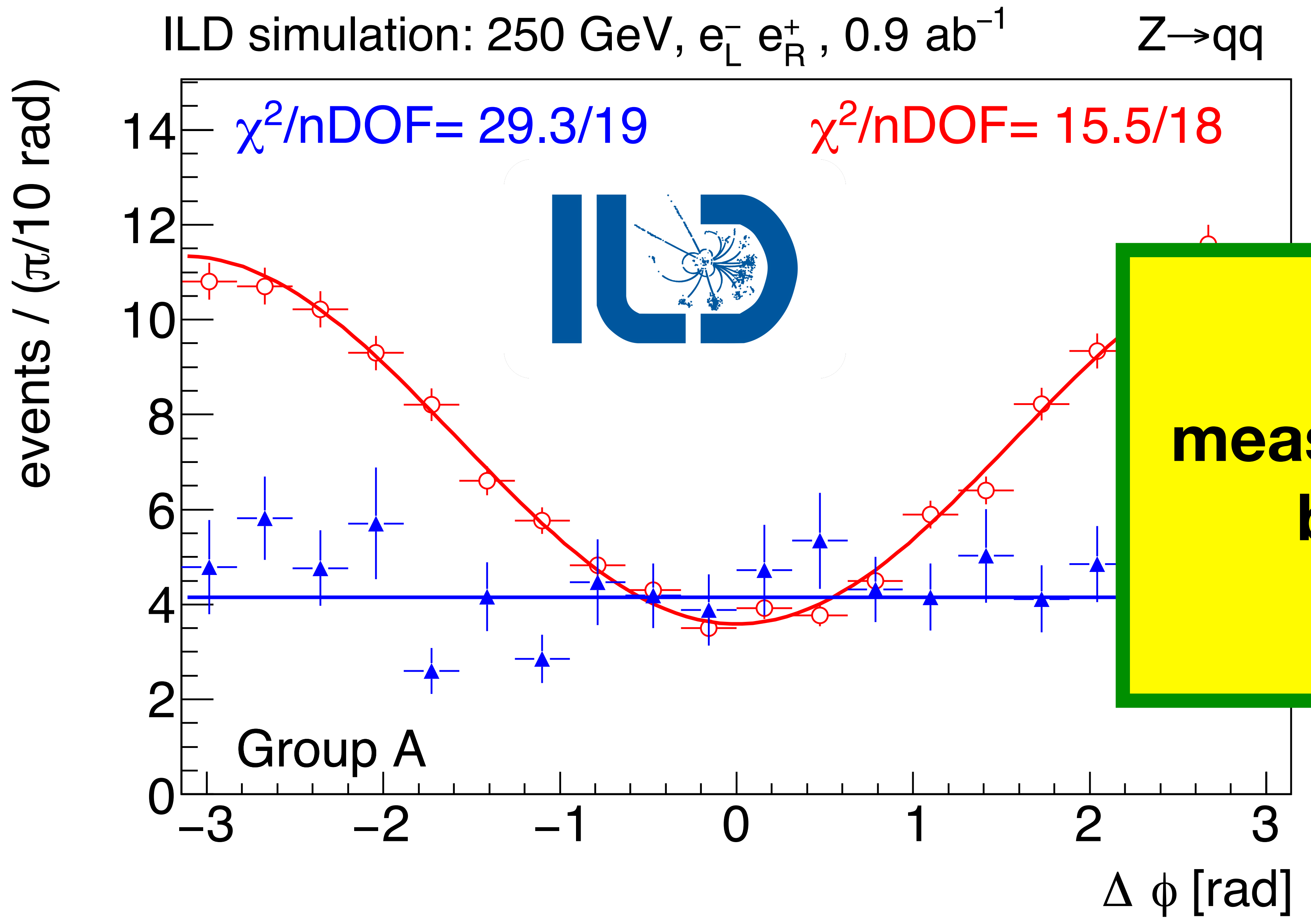
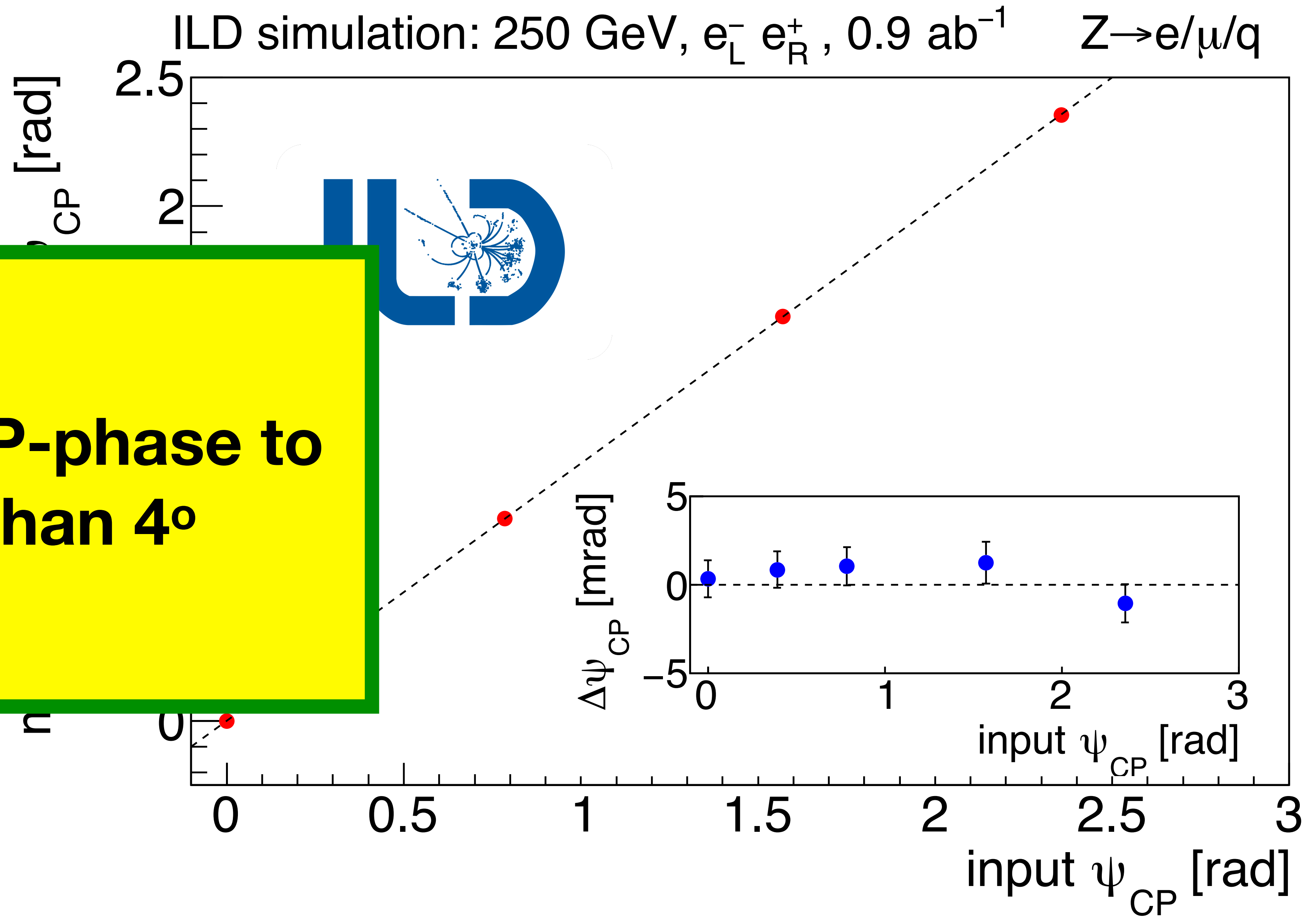




measure CP-phase to better than 4°



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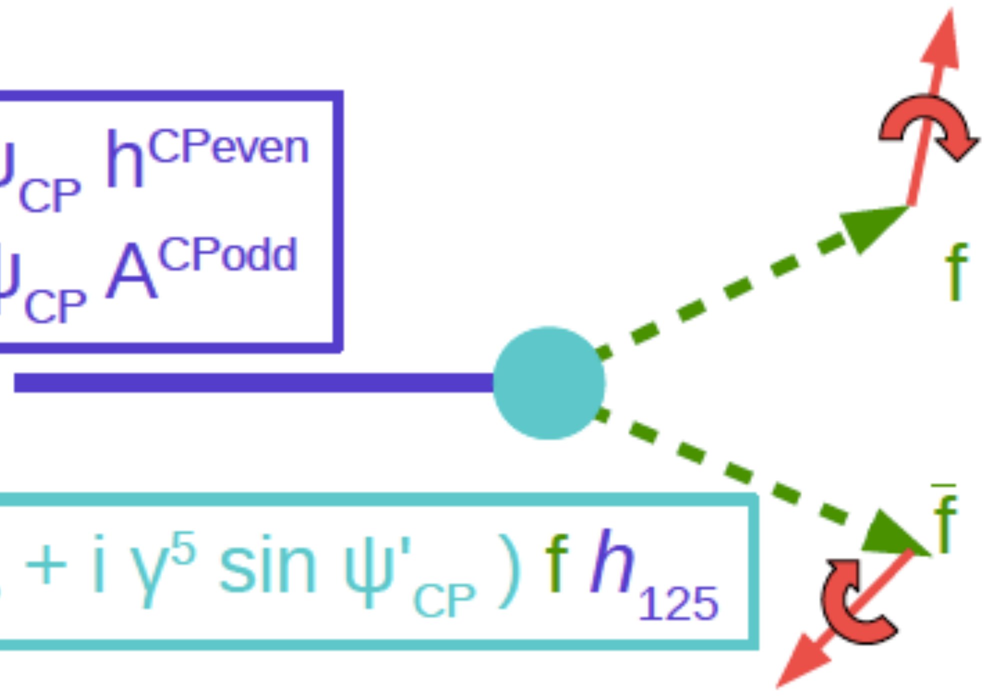
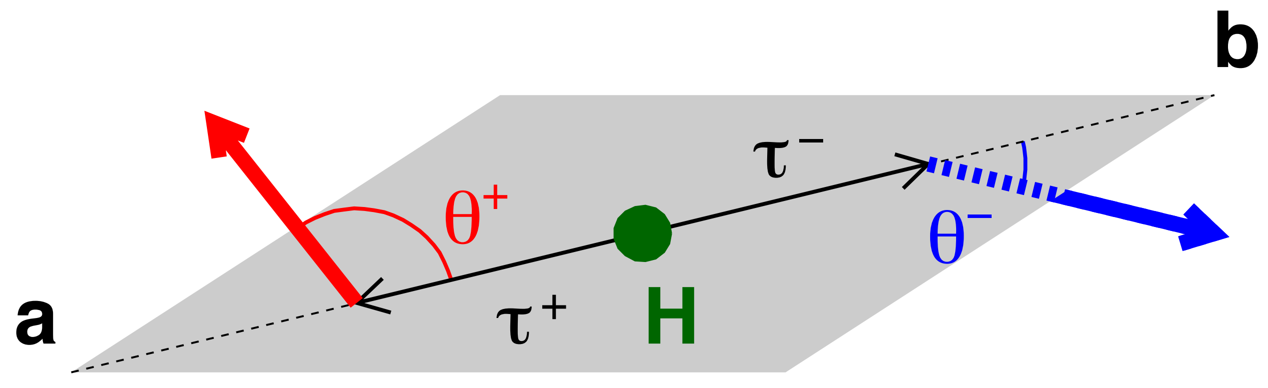


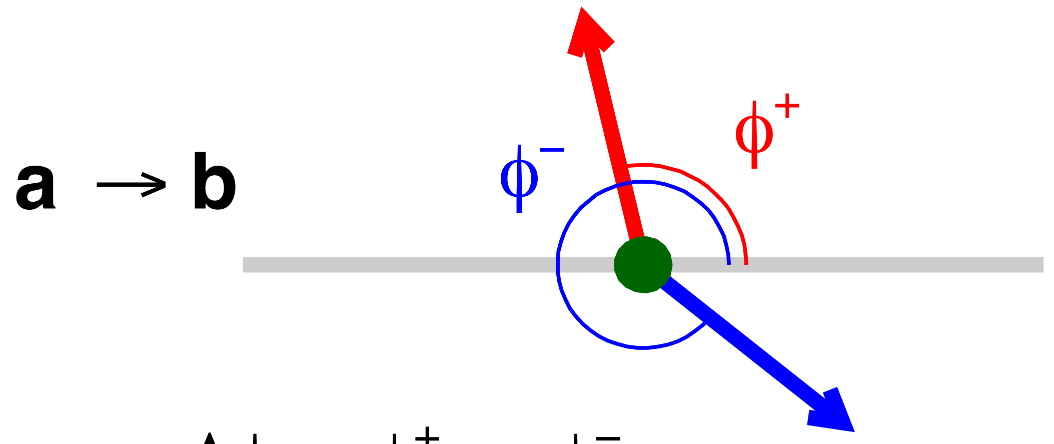
$g\, \bar{f}\, (\cos\psi'_{CP} + i\, \gamma^5 \sin\psi'_{CP})\, f\, h_{125}$

h is a spin 0 state:

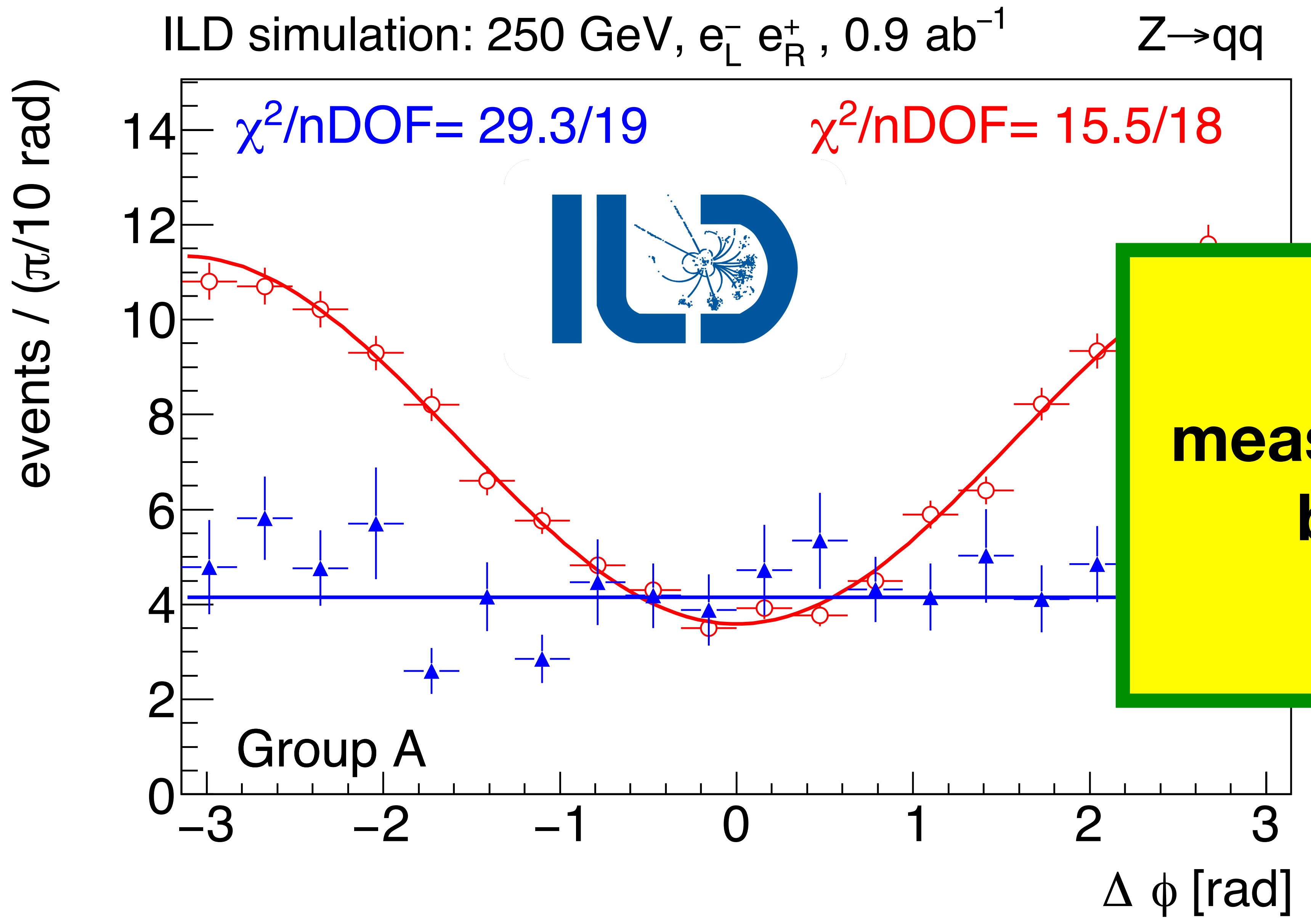
$| f\ \bar{f} > = |\uparrow\downarrow> + e^{2i\psi} |\downarrow\uparrow>$

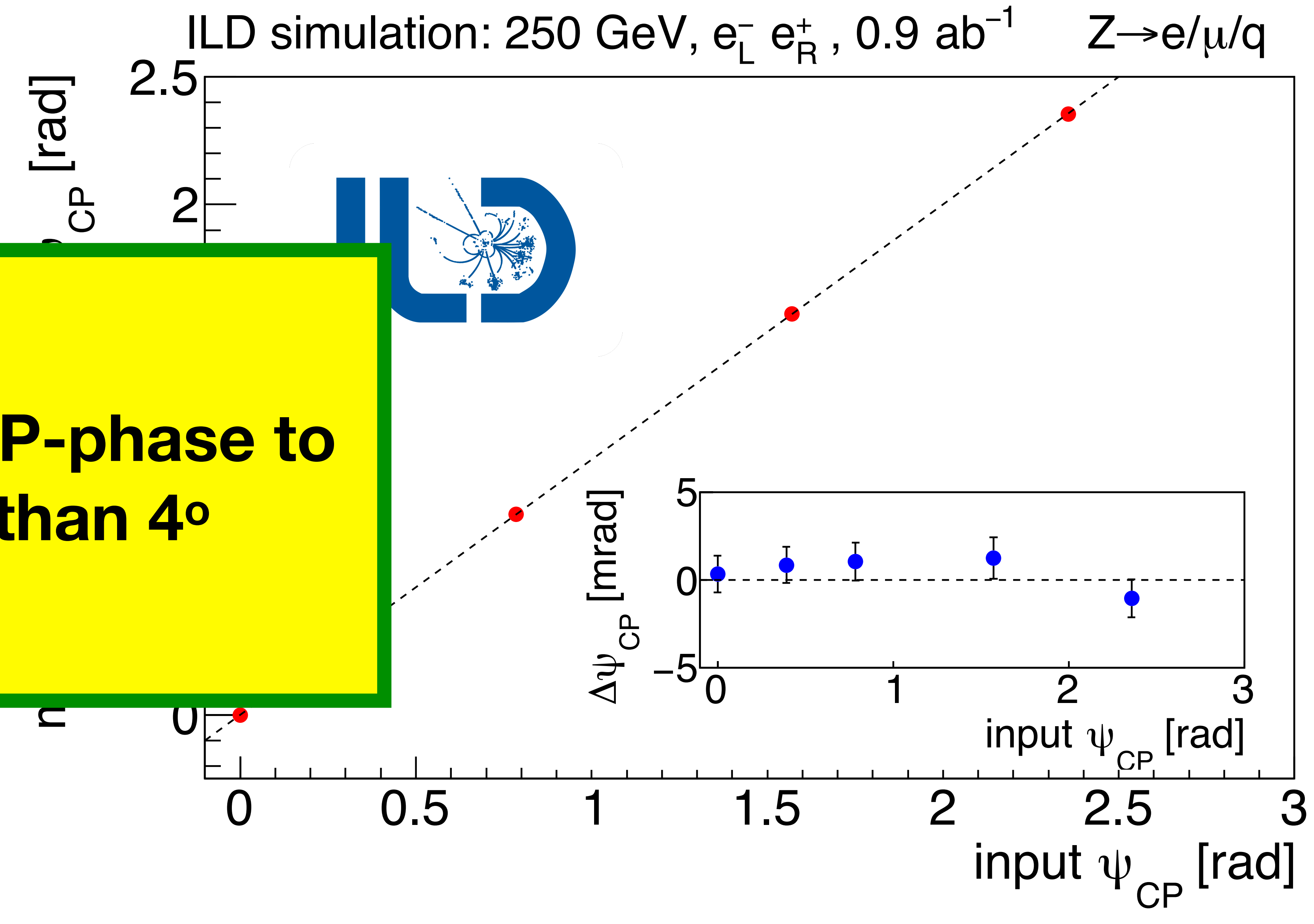
[ψ = 0 CP even, $\pi/2$ CP odd]





$\Delta\phi = \phi^+ - \phi^-$





measure CP-phase to better than 4°

..and CPV in Zh coupling:

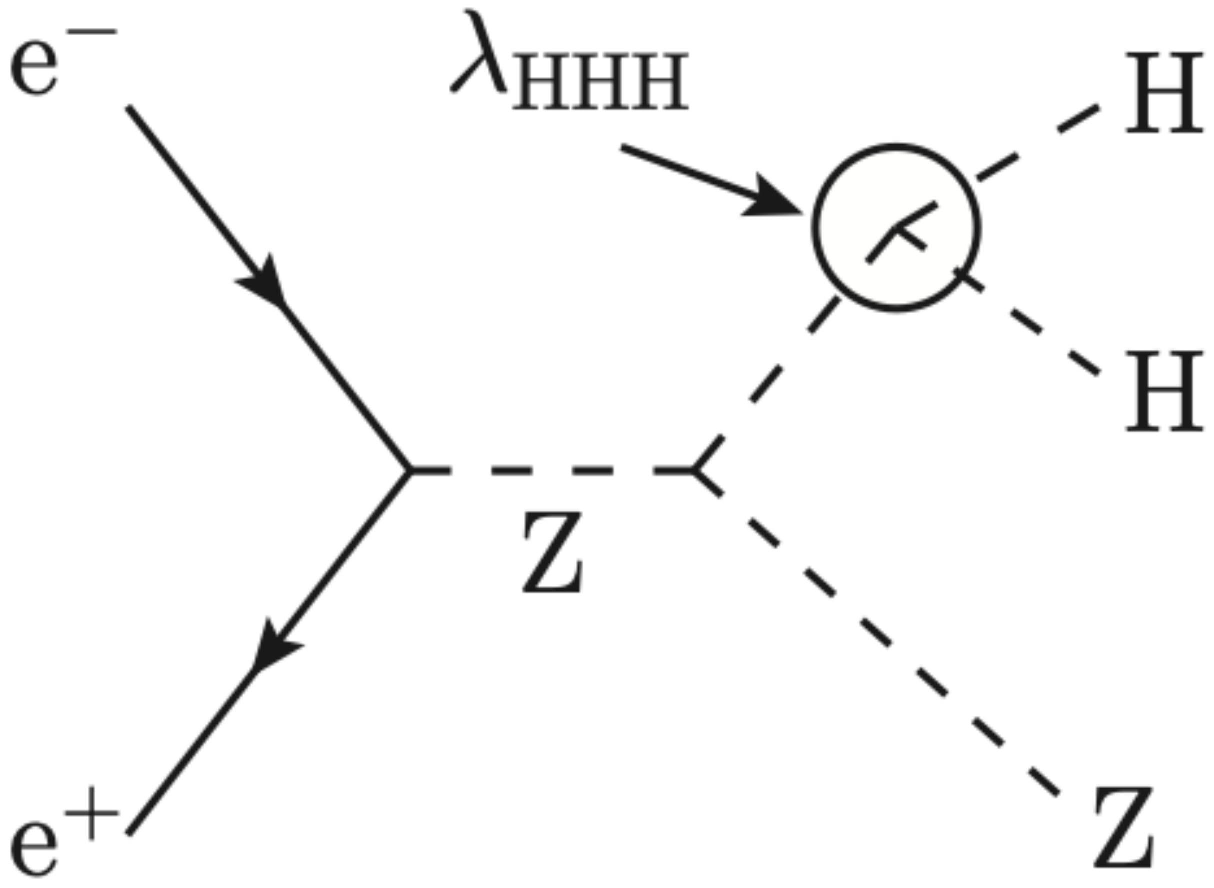
$$\Delta\mathcal{L}_{hZZ} = \frac{1}{2}\frac{\tilde{b}}{v} h Z_{\mu\nu}\tilde{Z}^{\mu\nu}$$

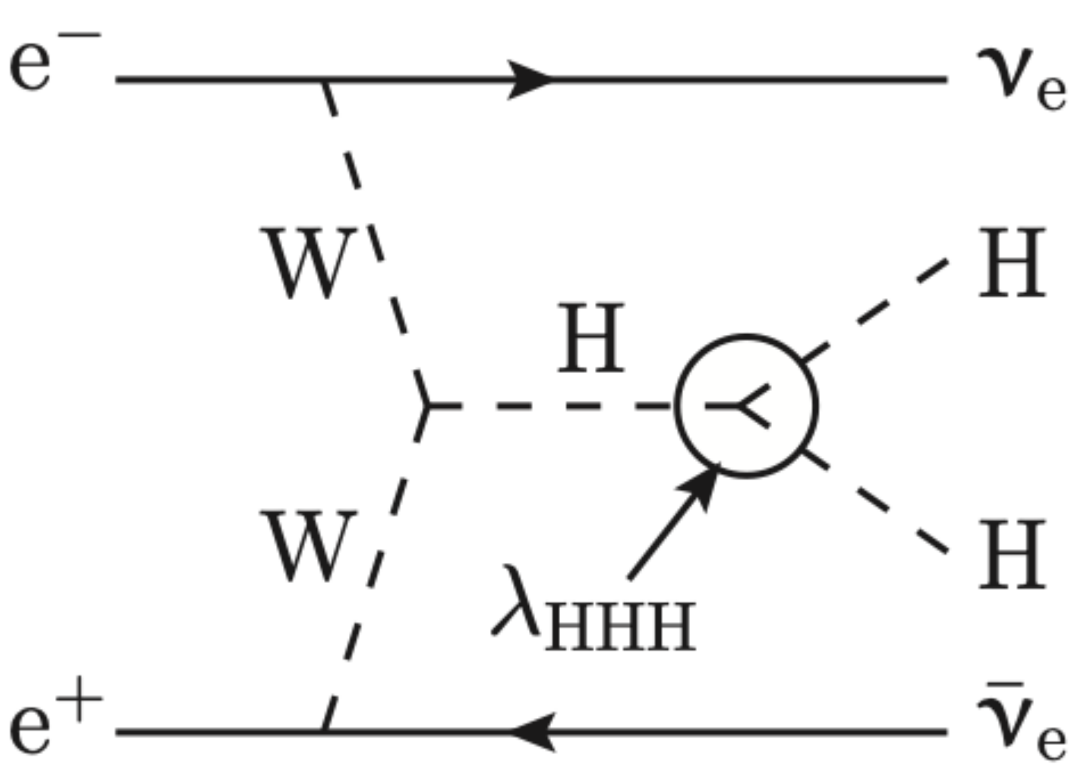
=> $\tilde{b}$ **to ±0.005**

arxiv:1804.01241

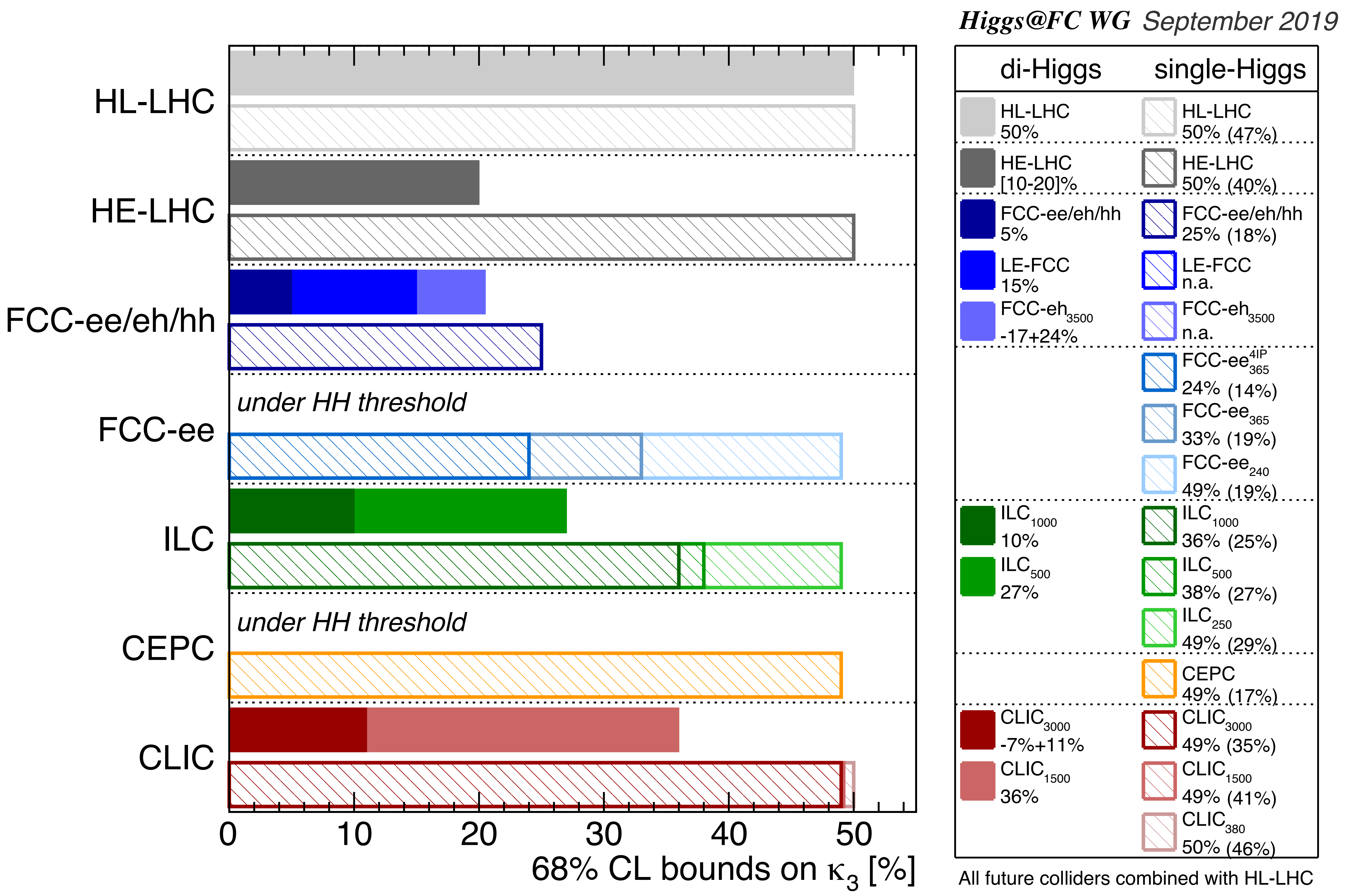
based on NIM A810 (2016) 51-58

Higgs measurements only possible at 500 GeV and above: di-Higgs and ttH production





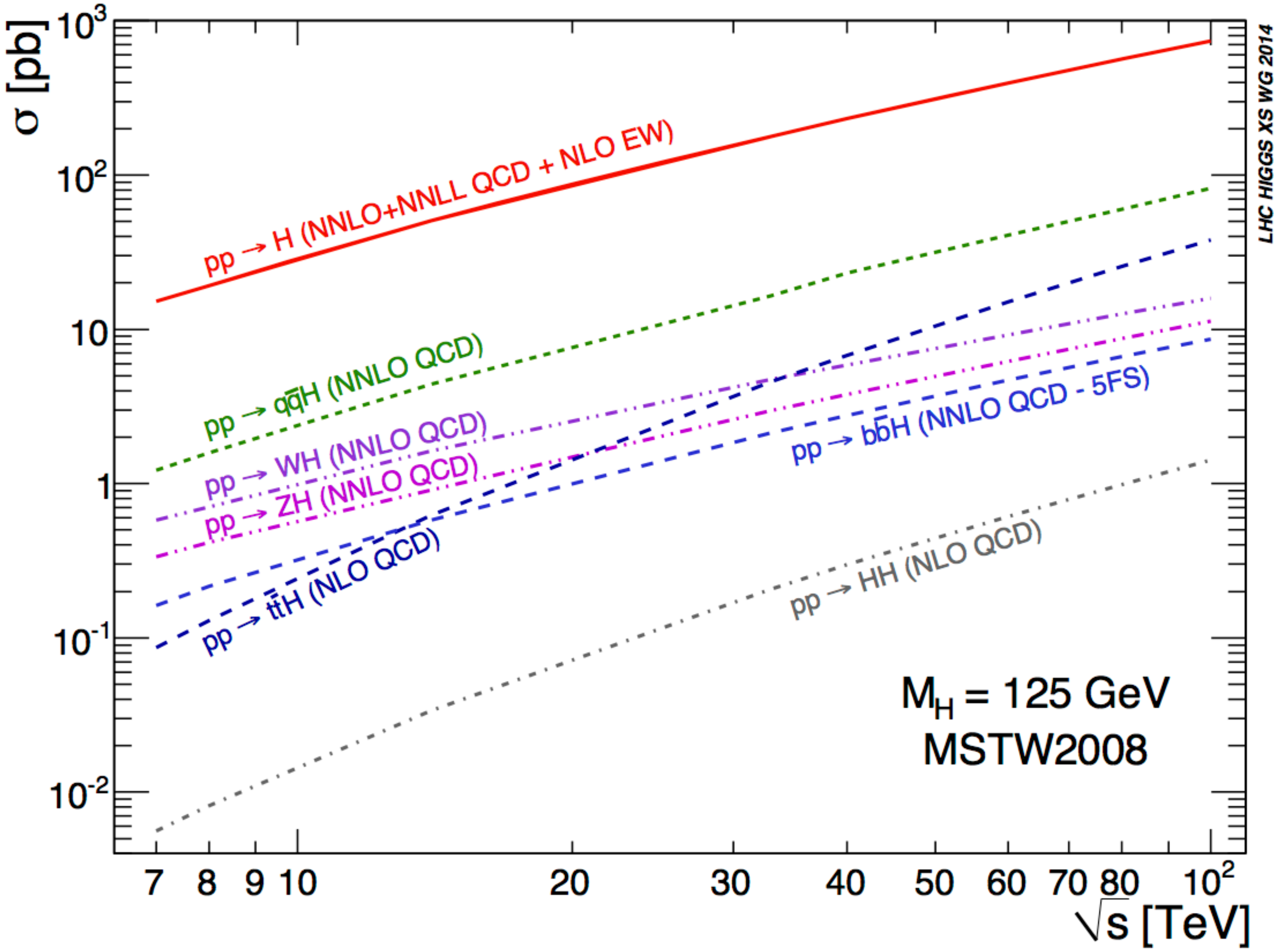
The ECFA Higgs@Future Report



At lepton colliders, double Higgs-strahlung, $e+e- \rightarrow$ *ZHH*, gives stronger constraints on positive deviations ($\varkappa 3 > 1$), while VBF is better in constraining negative deviations, ($\varkappa 3 < 1$). While at HL-LHC, values of $\varkappa 3 > 1$, as expected in models of strong first order phase transition, result in a smaller double-Higgs production cross section due to the destructive interference, at lepton colliders for the *ZHH* process they actually result in a larger cross section, and hence into an increased precision. For instance at ILC_{500}, the sensitivity around the SM value is 27% but it would reach 18% around $\varkappa_3 = 1.5$.

This figure applies ONLY for $\lambda = \lambda_{SM}$
no studies of BSM case apart from ILC

Di-Higgs Production Cross sections - pp



dependence on ECM:
14 TeV -> 100 TeV : ~40 x larger cross section
14 TeV -> 38 TeV: ~8 x larger cross section

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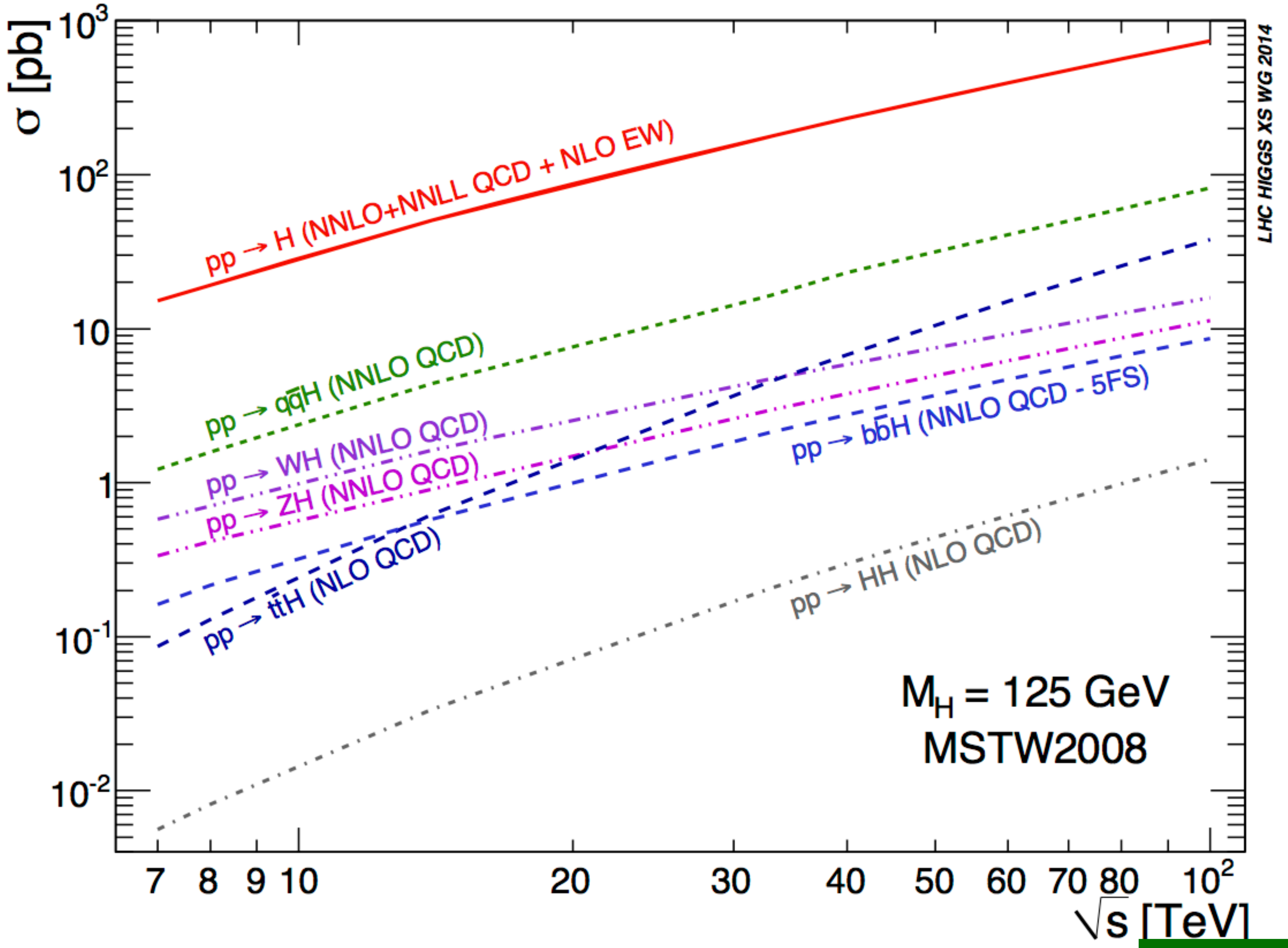

differential distributions!

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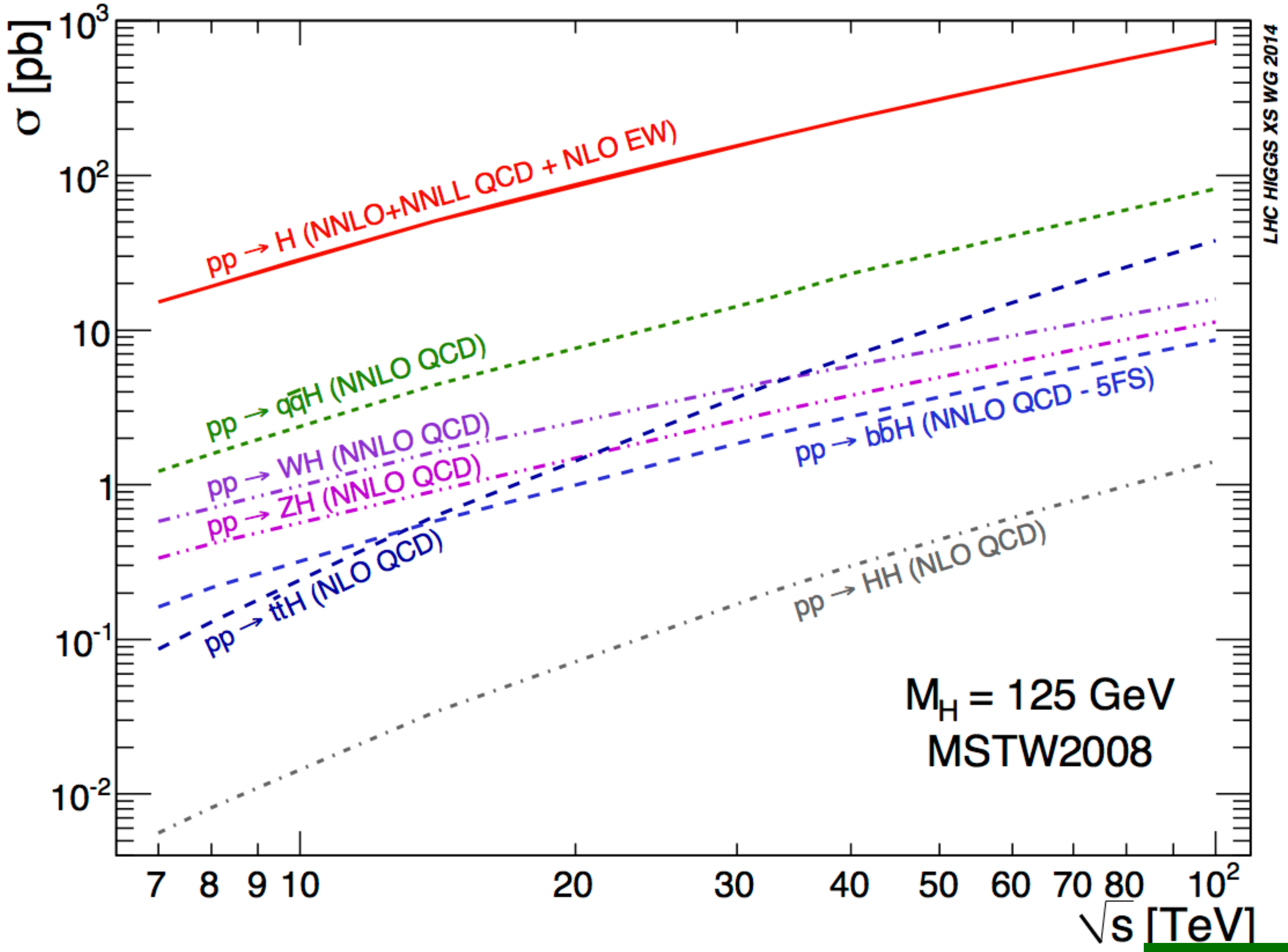

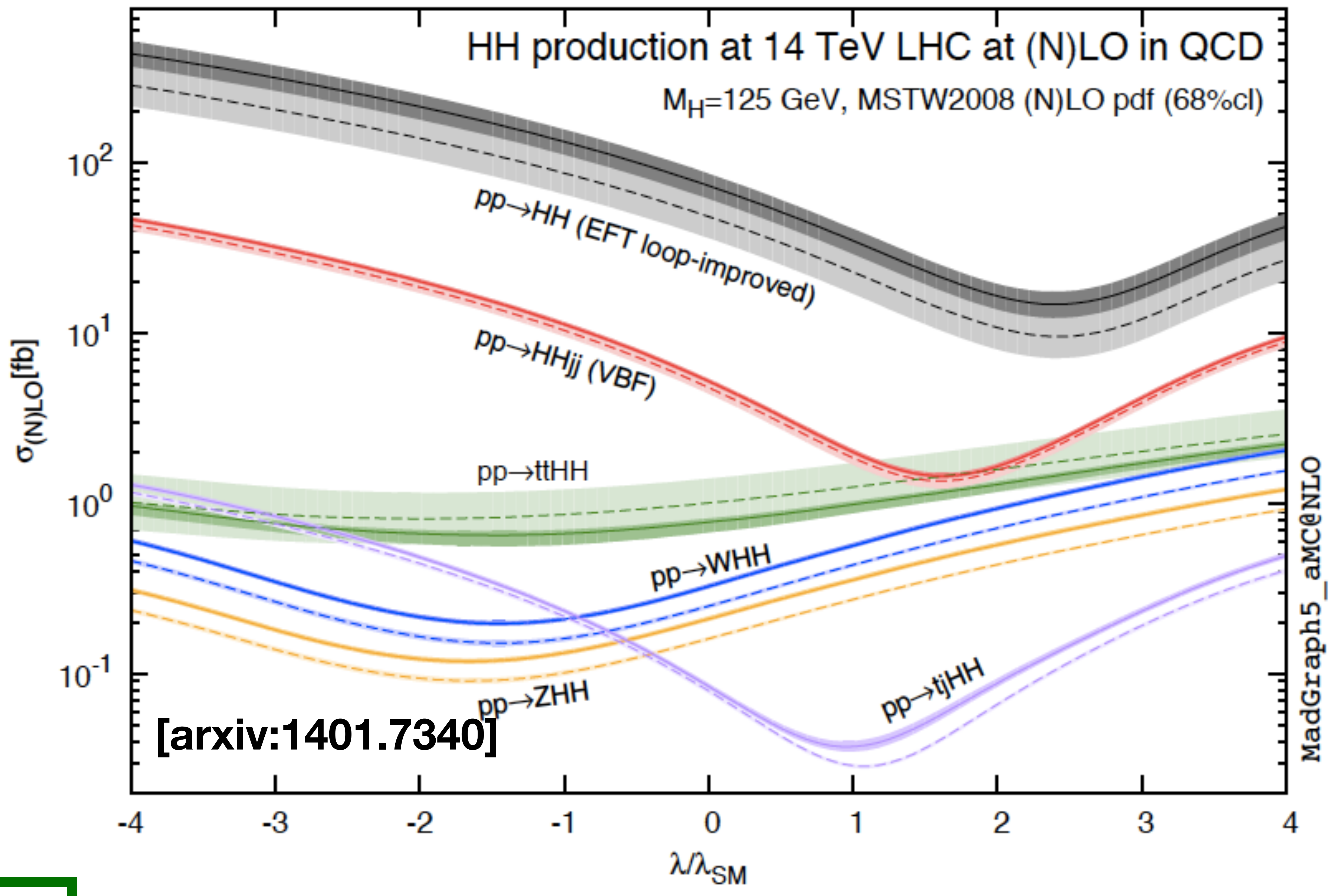

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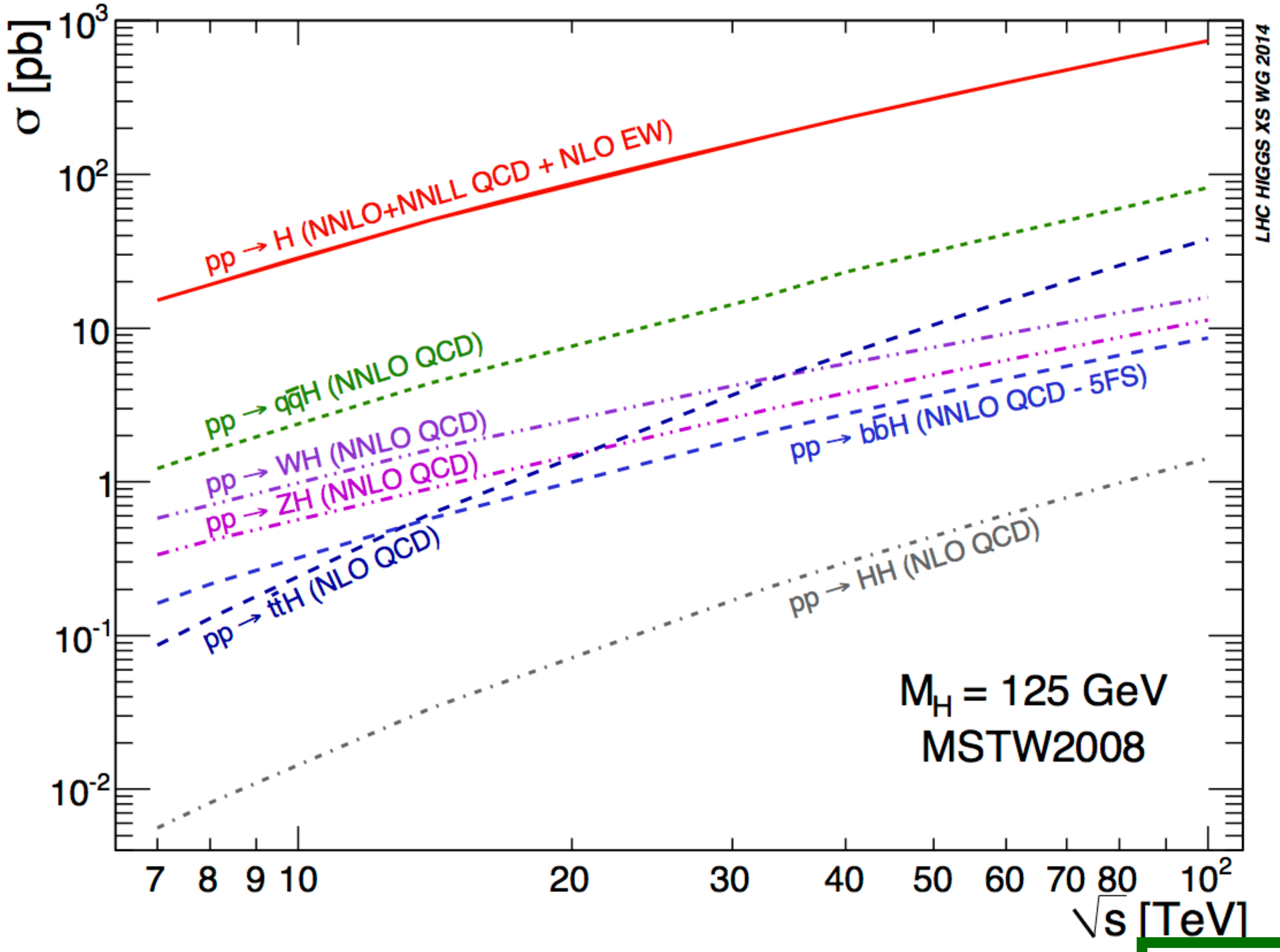

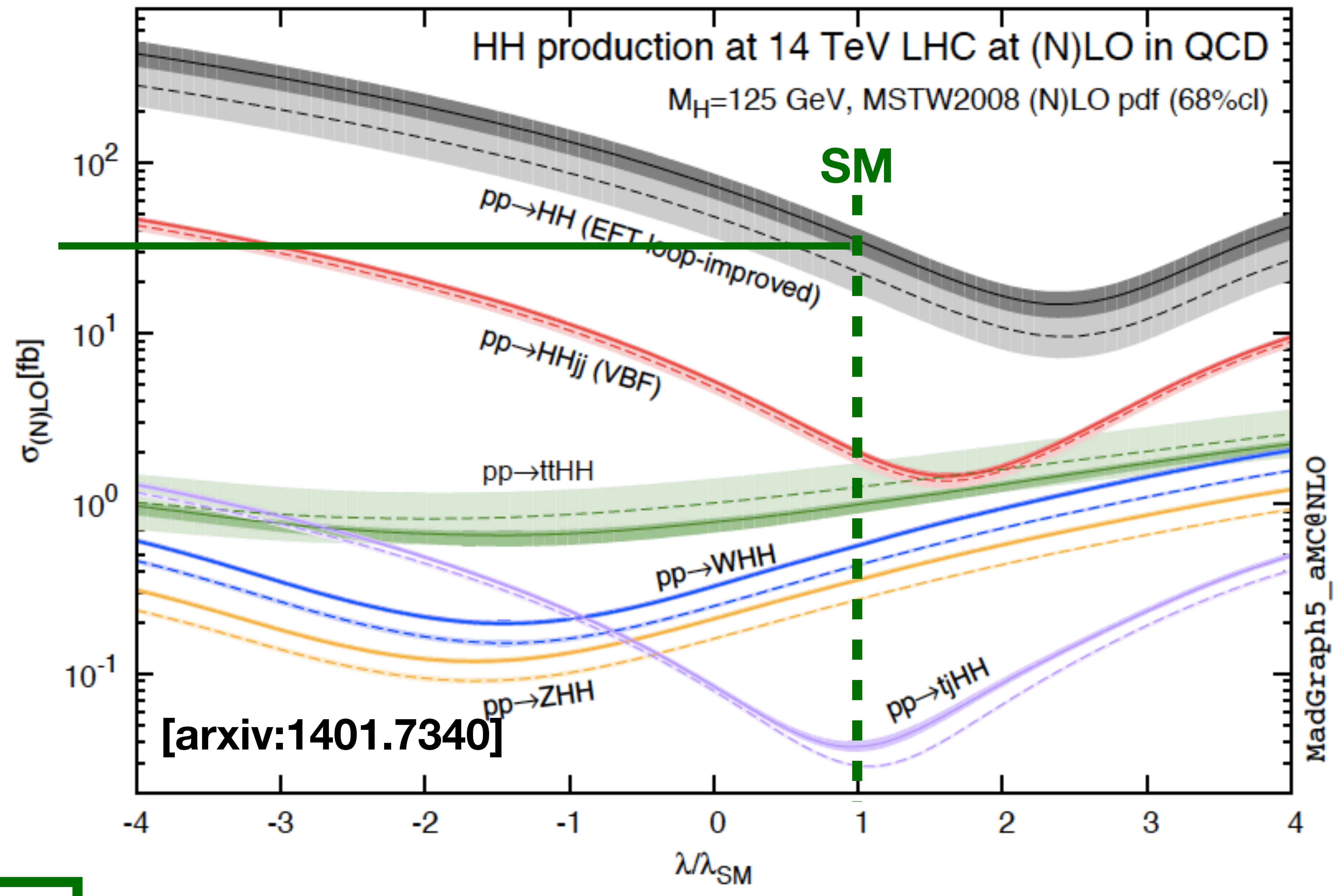

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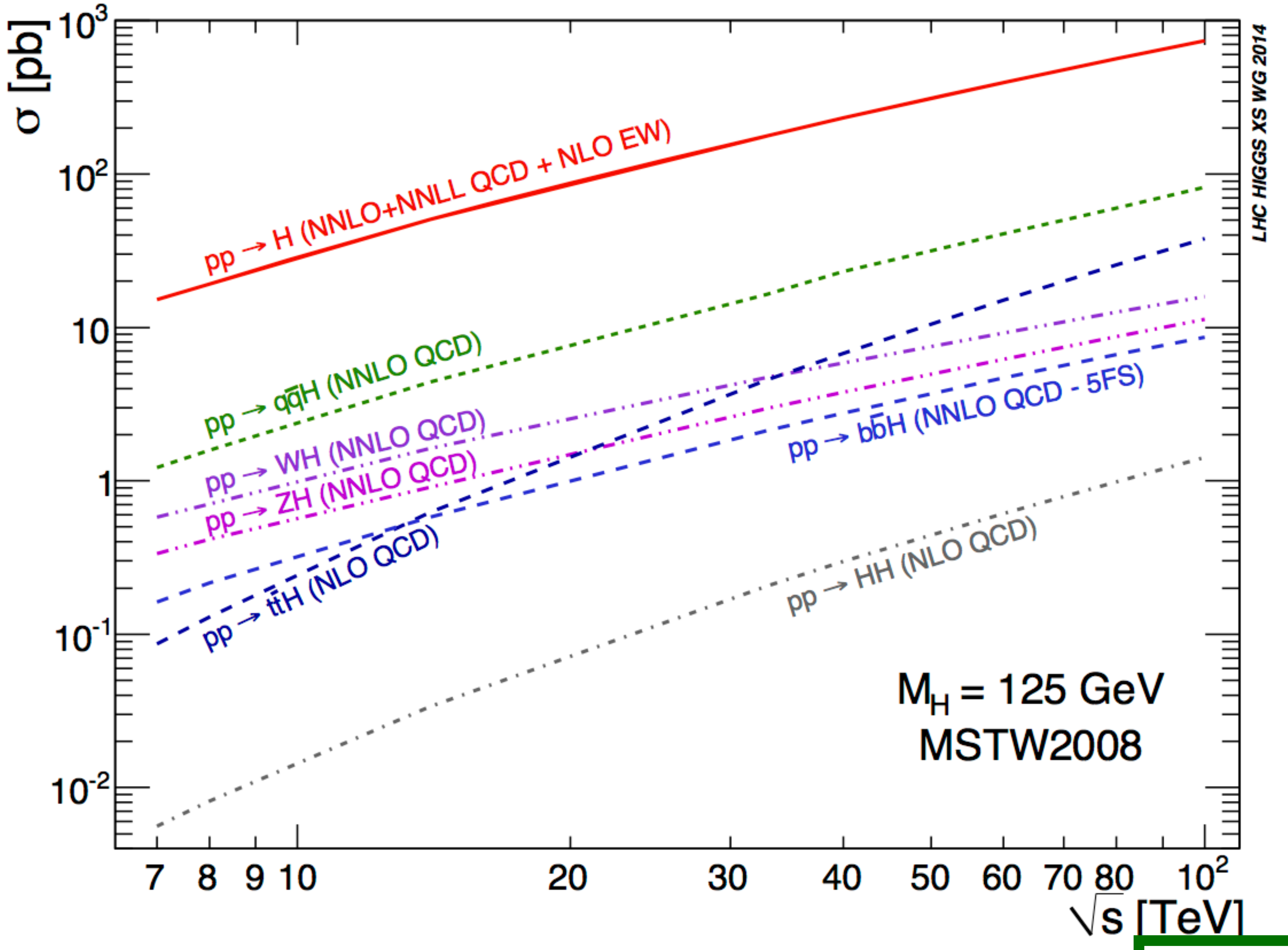

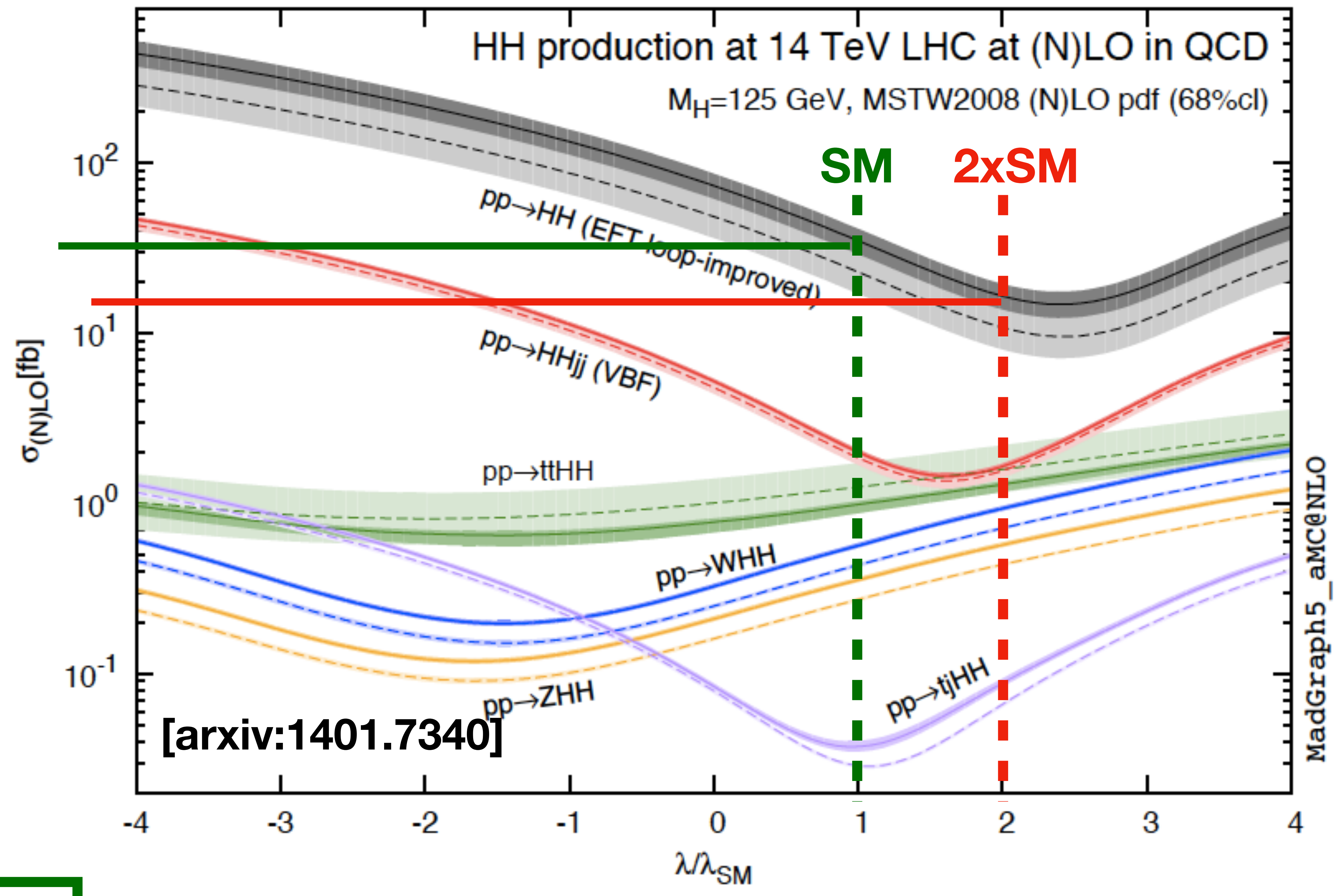

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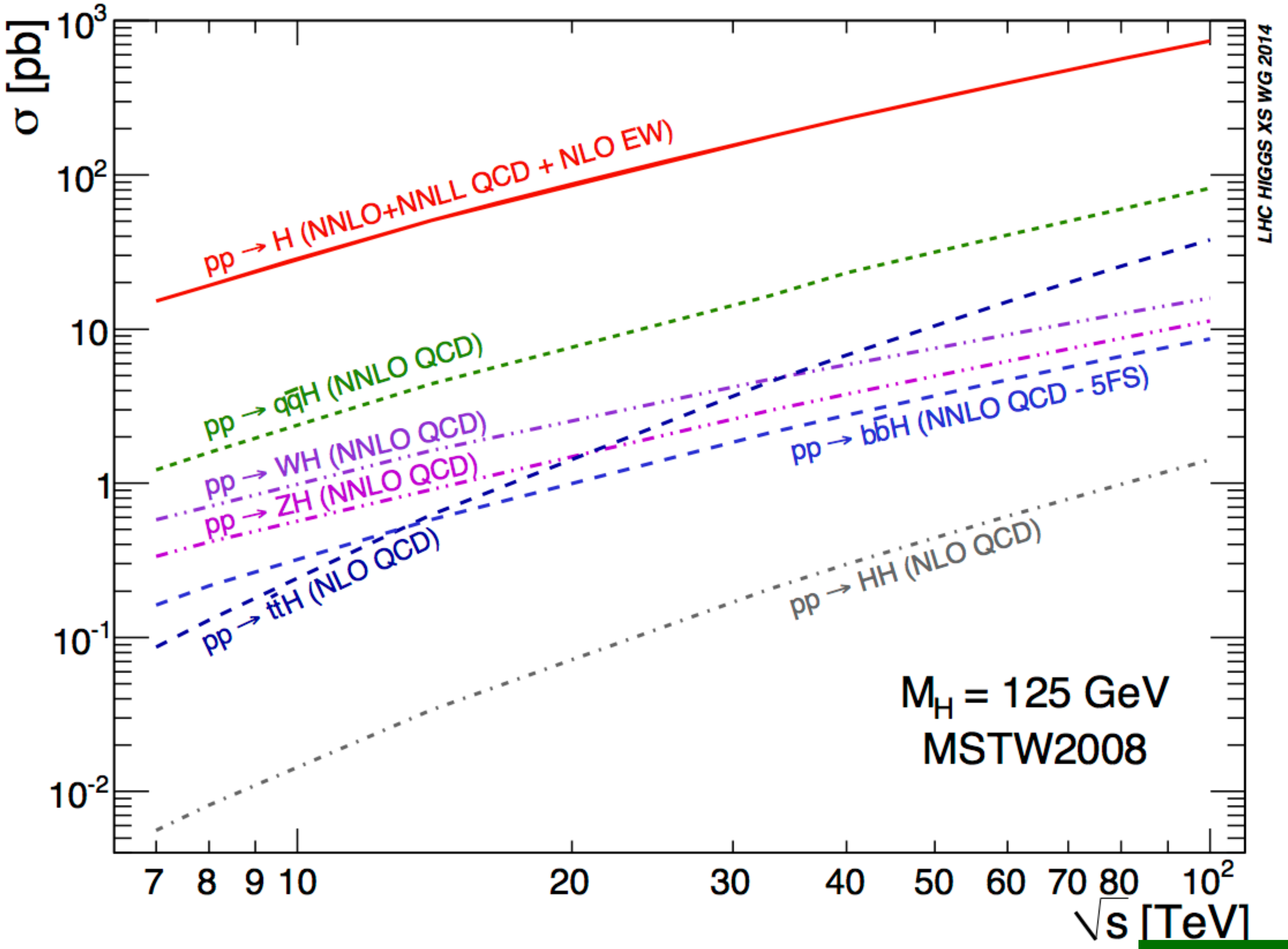

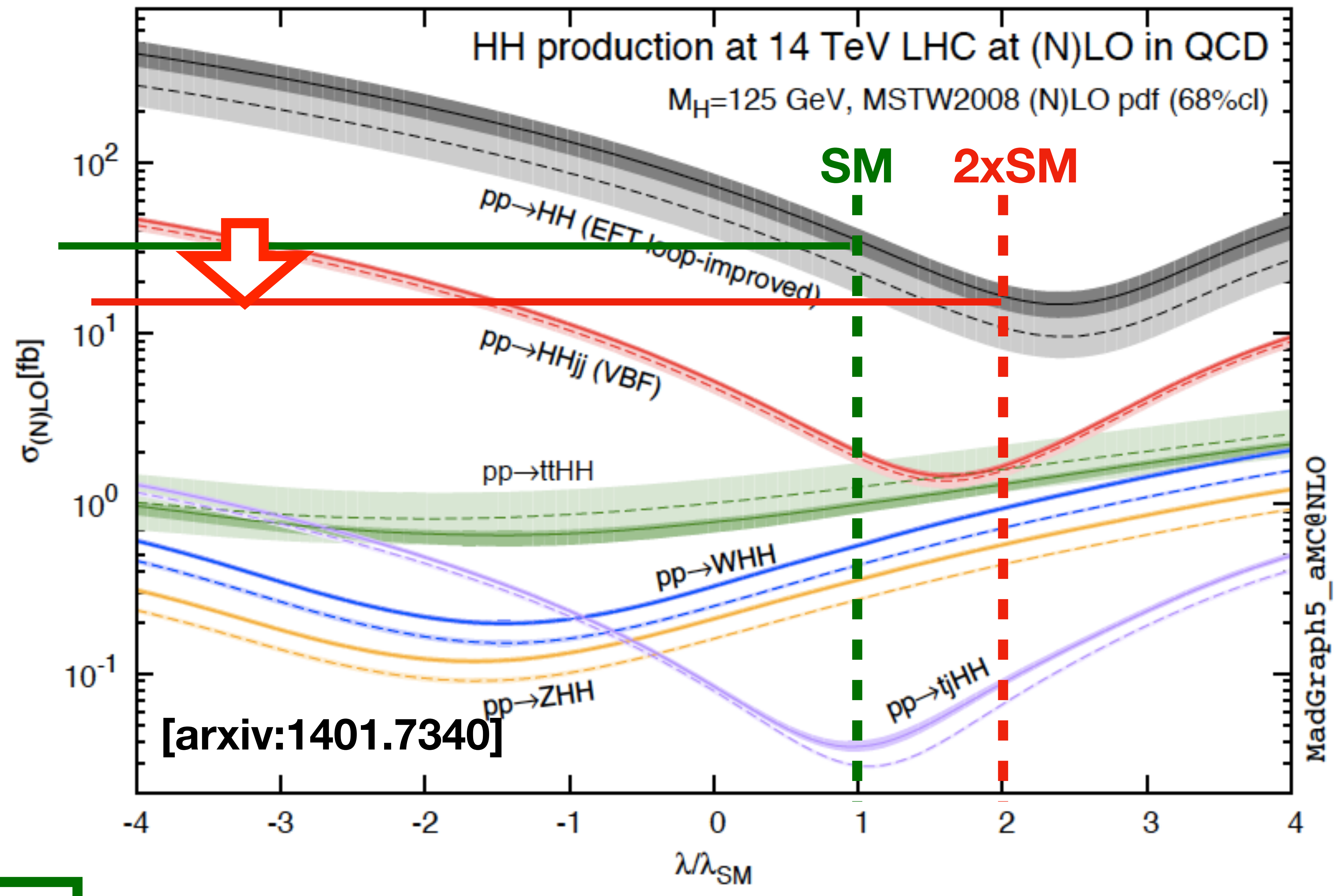

differential distributions!

dependence on ECM:
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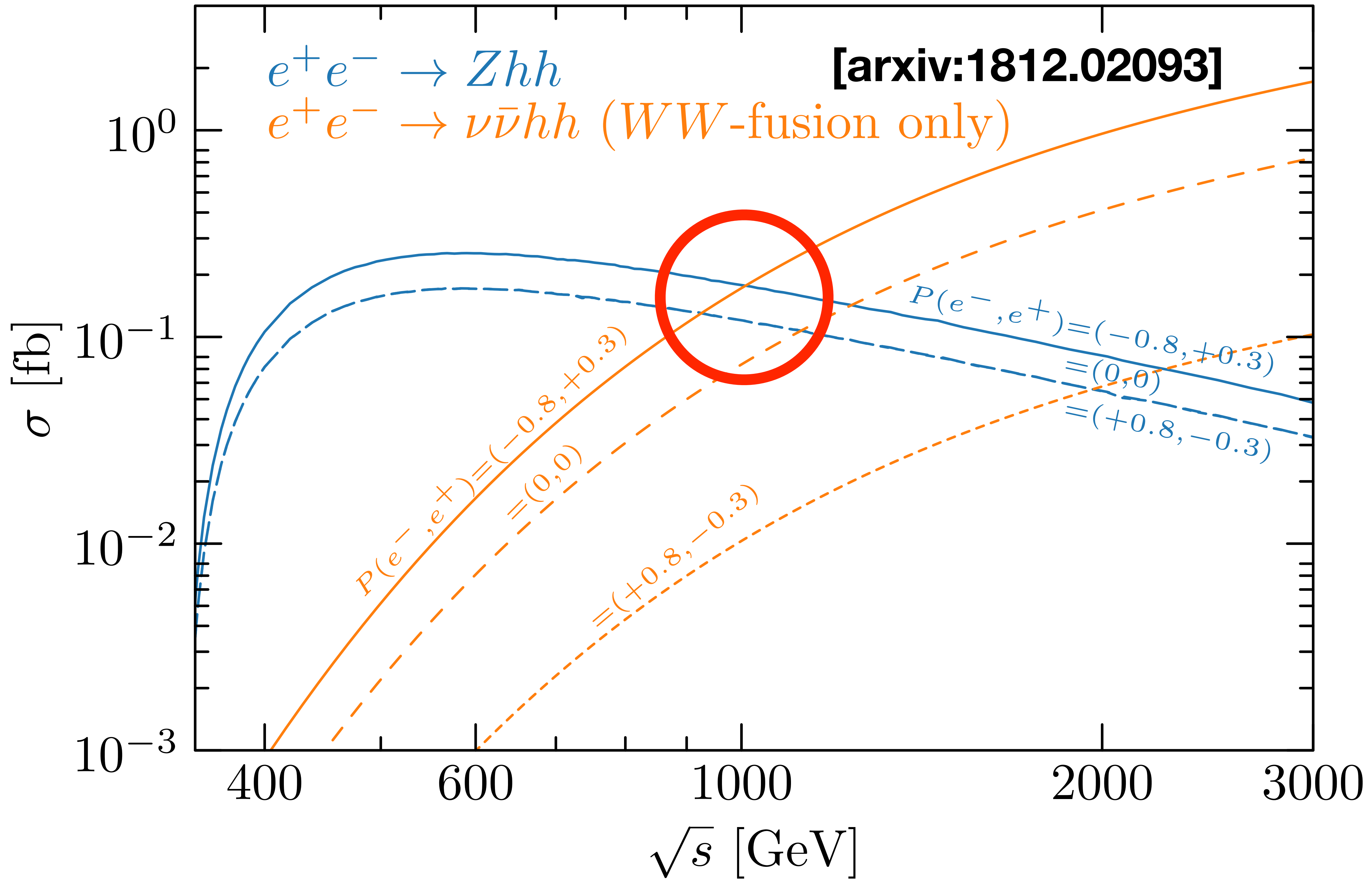
14 TeV -> 38 TeV: ~8 x larger cross section

dependence on λ:
$\lambda > \lambda_{SM}$: cross section drops,
i.e. by factor ~2 for $\lambda = 2\,\lambda_{SM}$

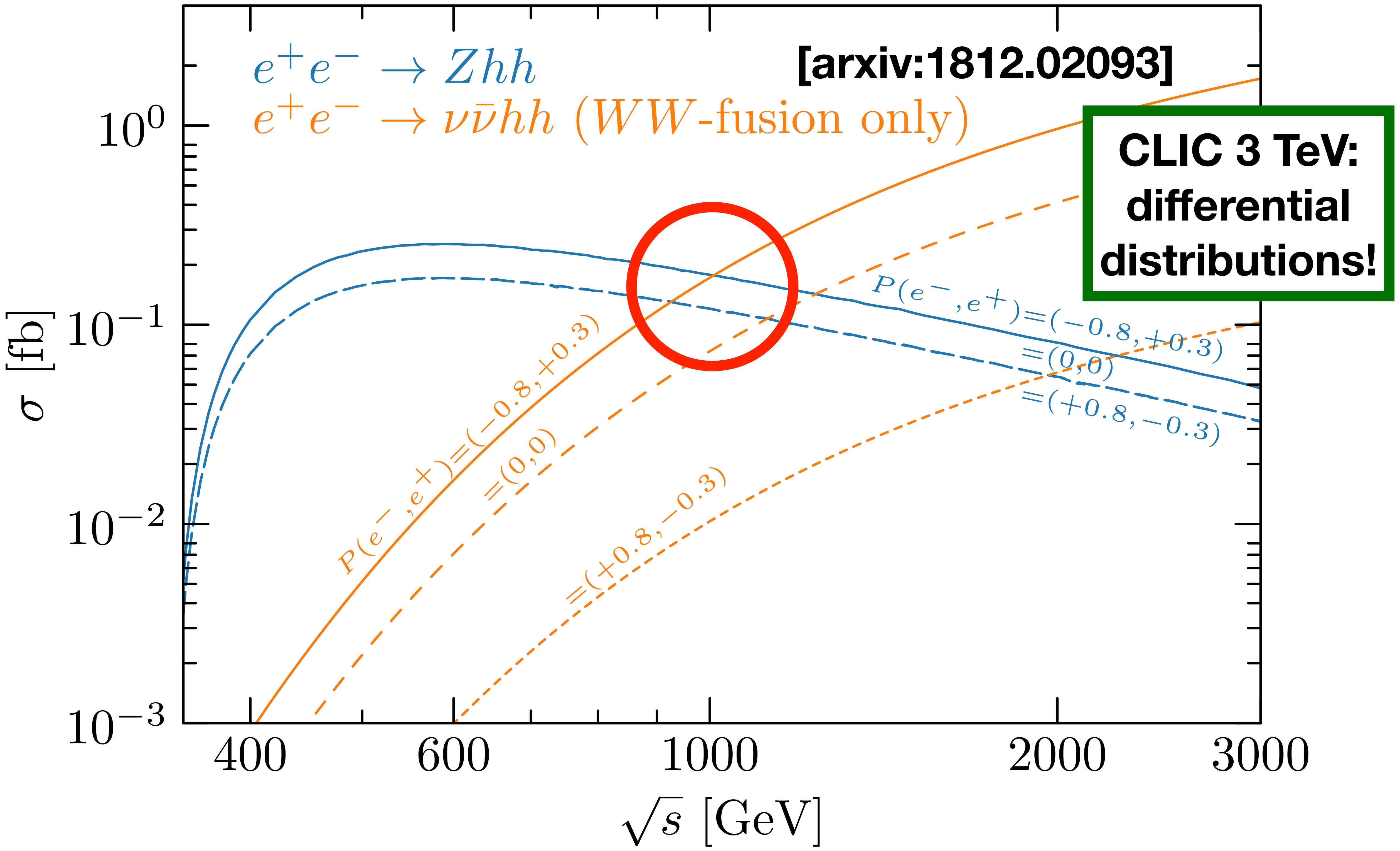
Di-Higgs Production Cross sections - ee



ZHH: P(-80%,+30%) and P(+80%,-30%) give about equal sensitivity

vvHH (fusion): effectively only P(-80%) counts

Di-Higgs Production Cross sections - ee



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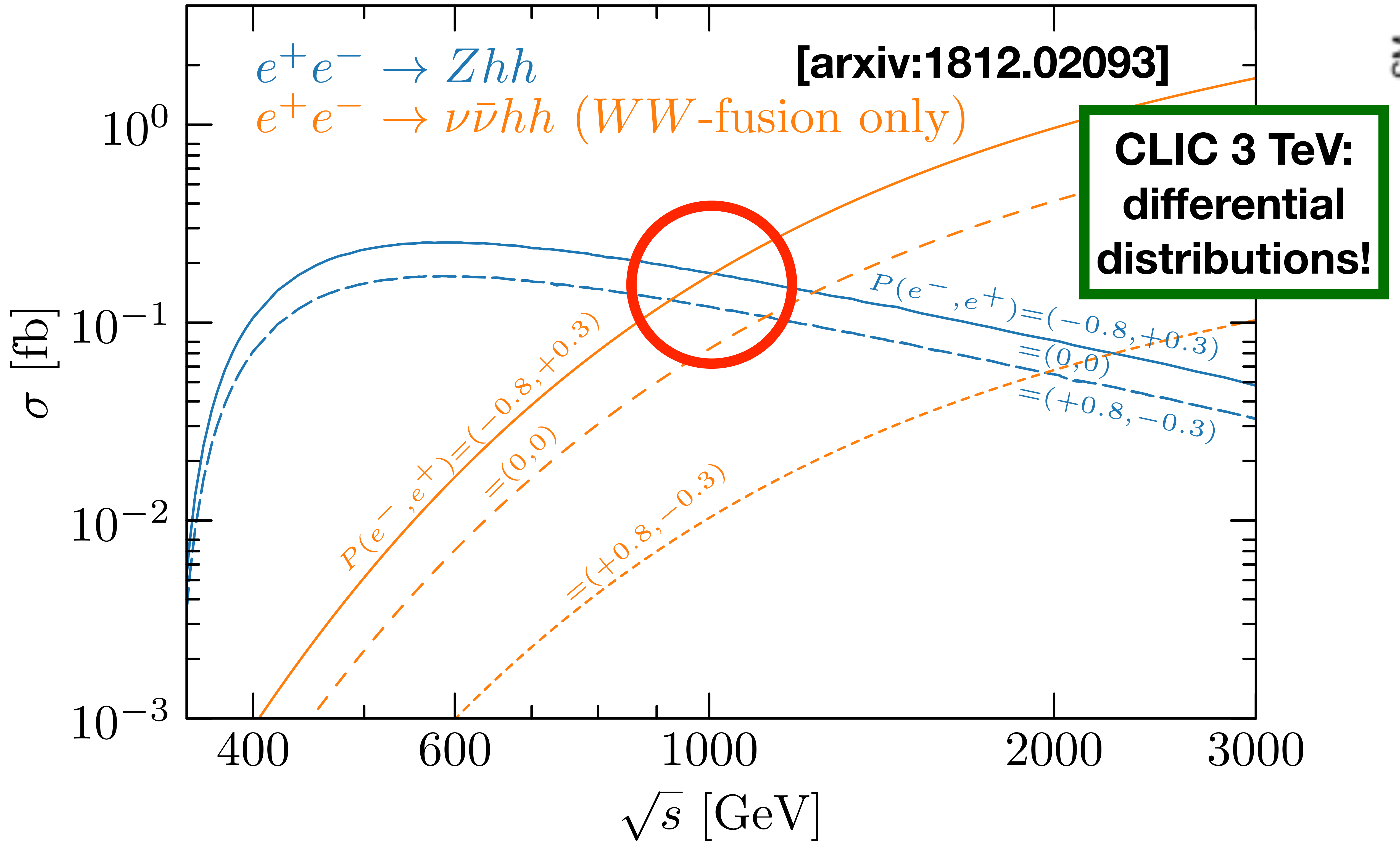

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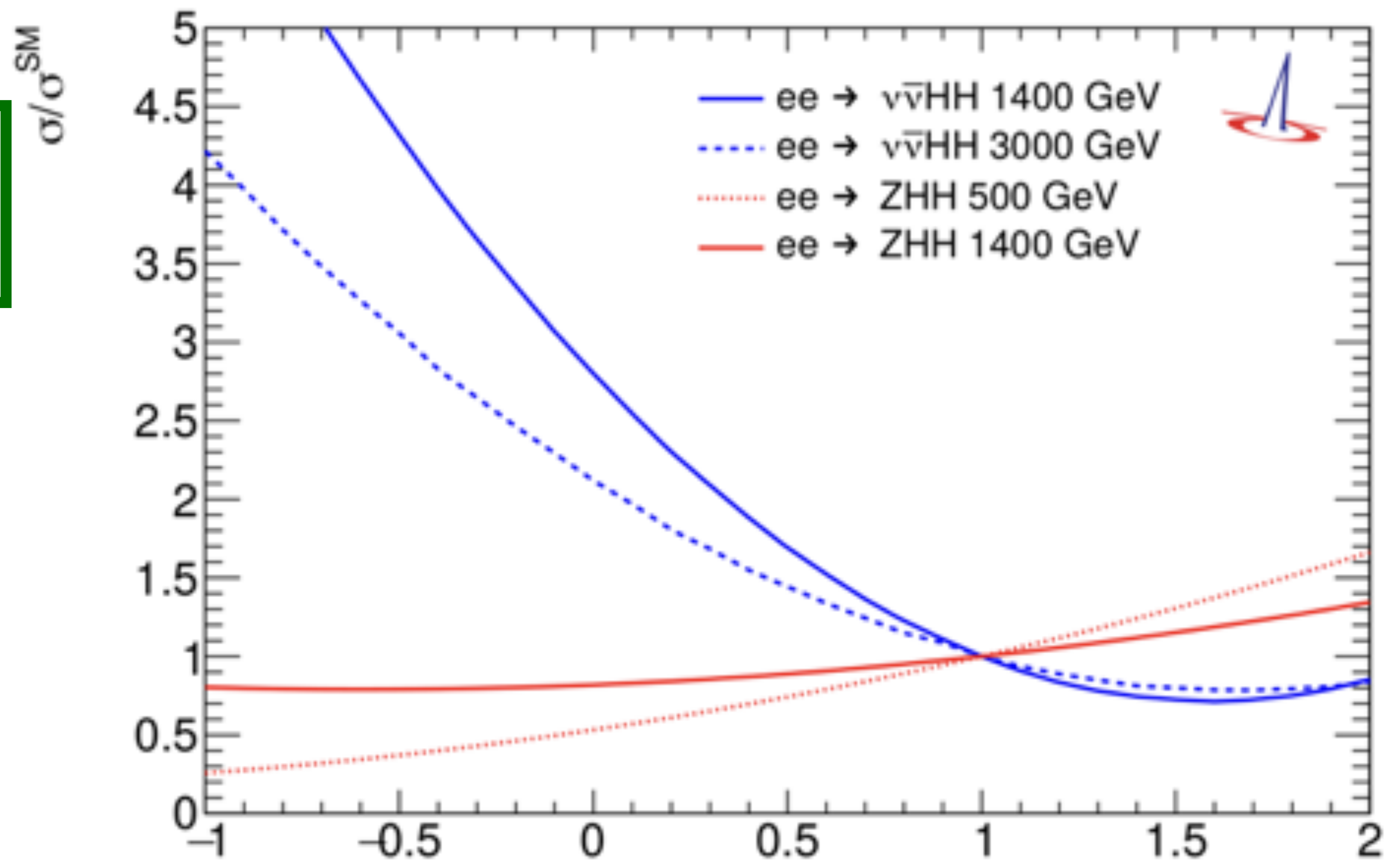

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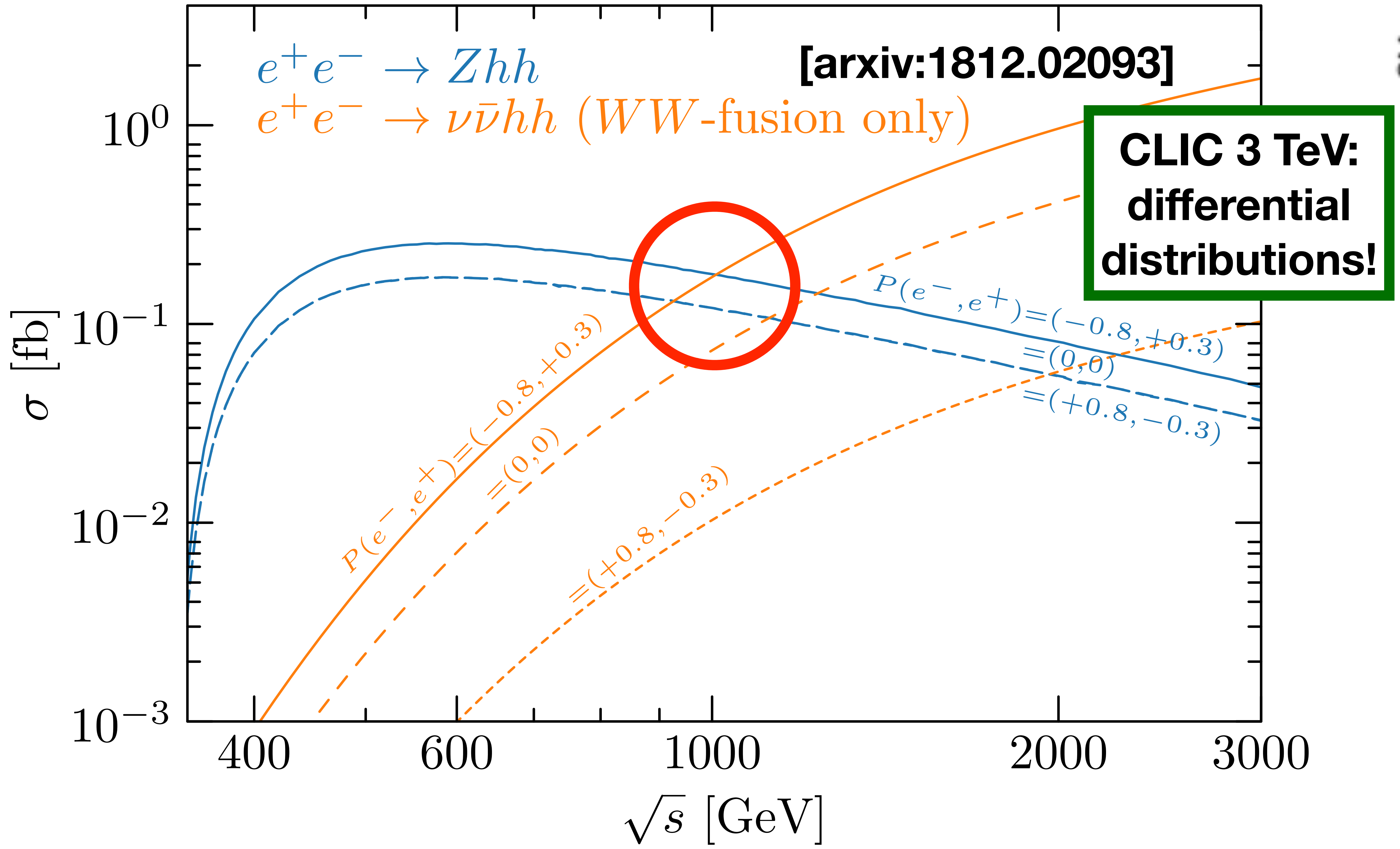

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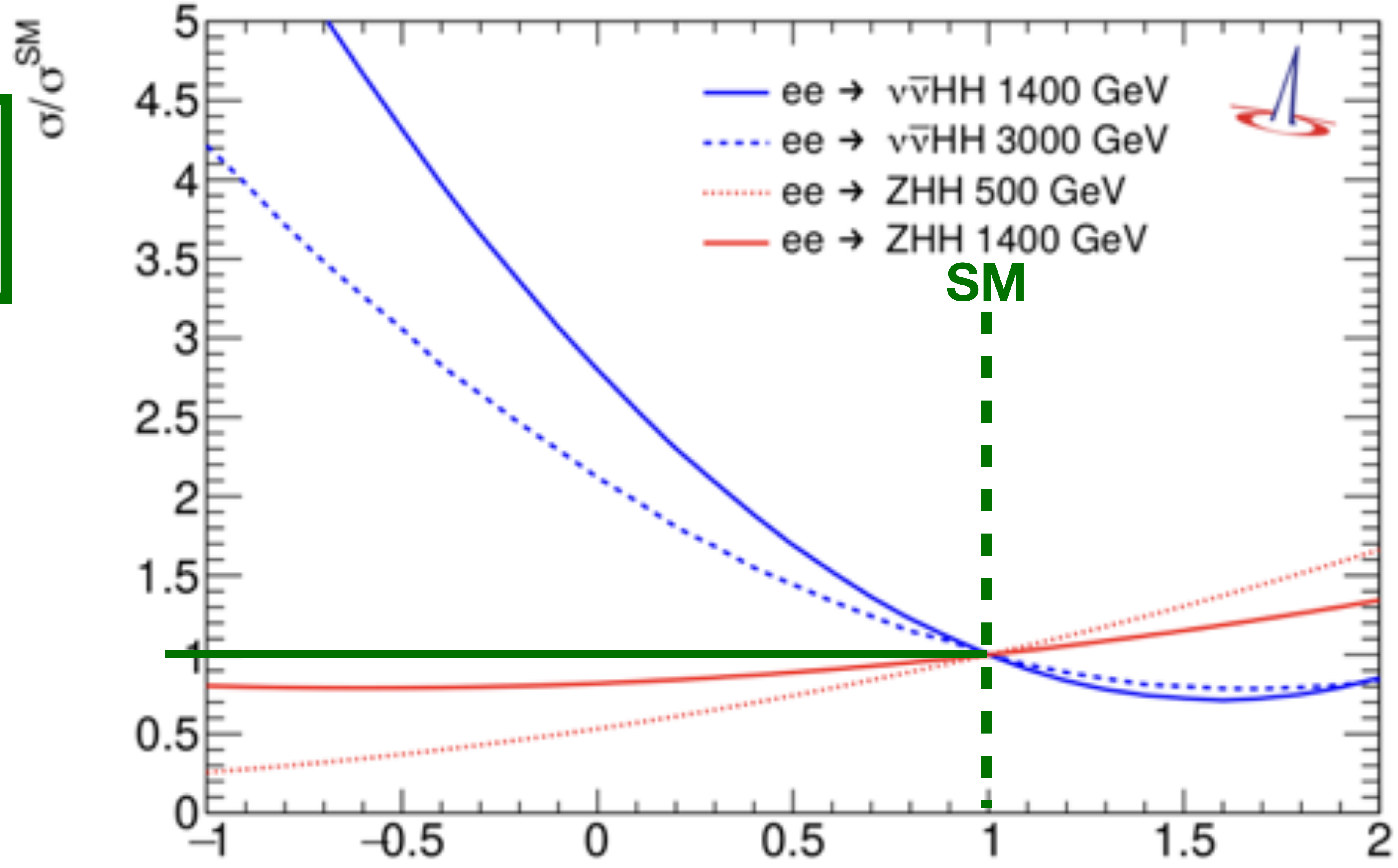

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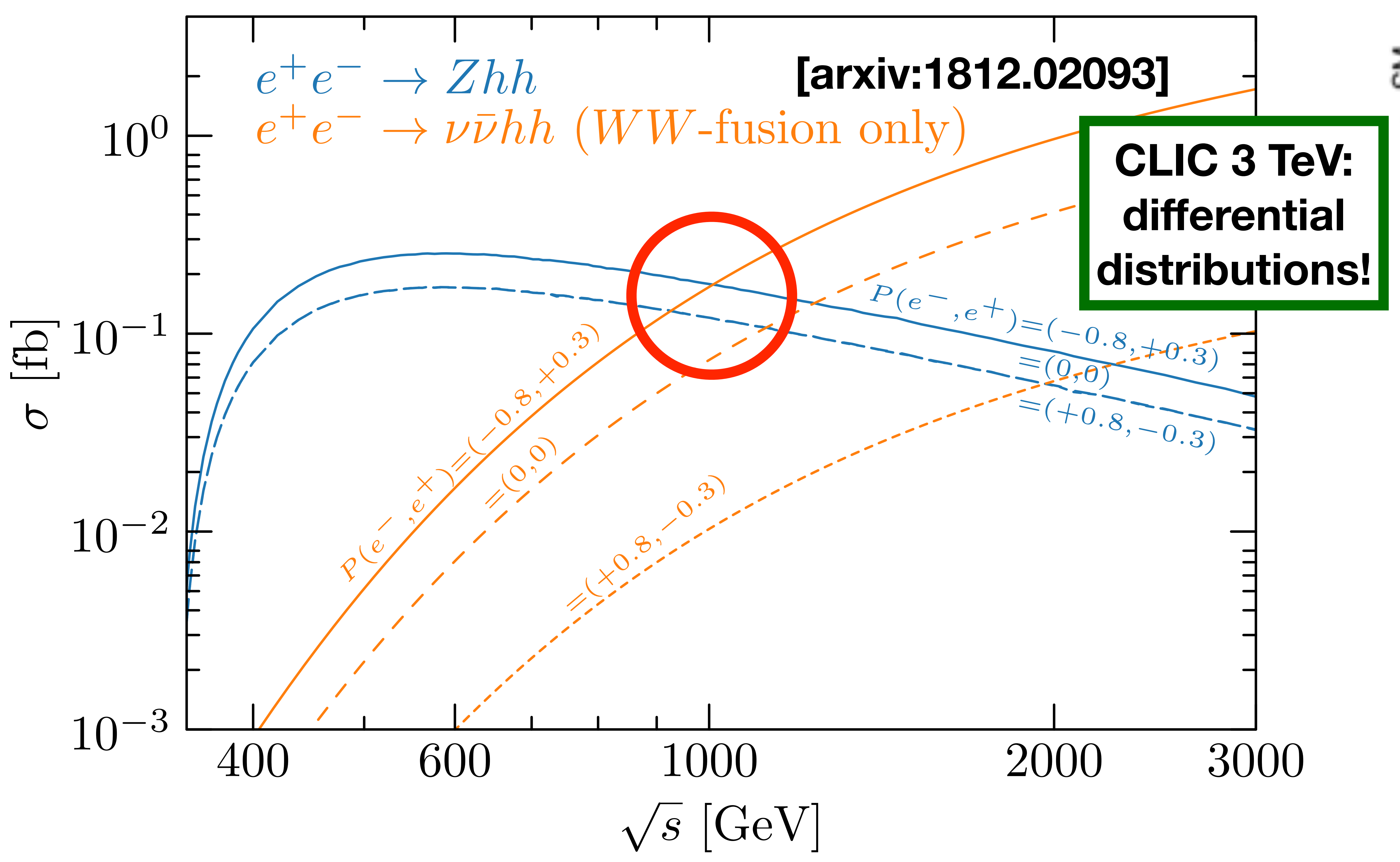

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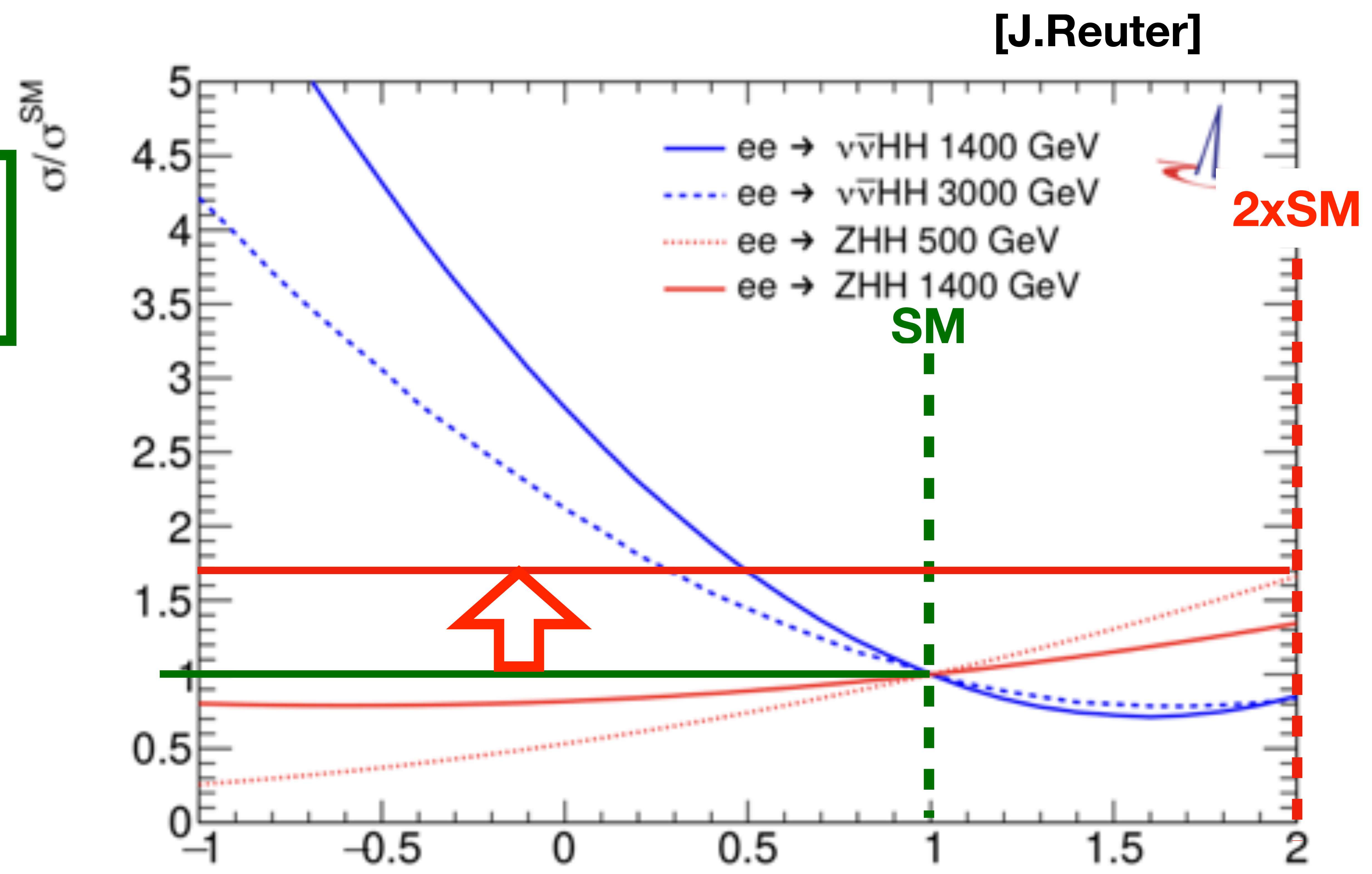

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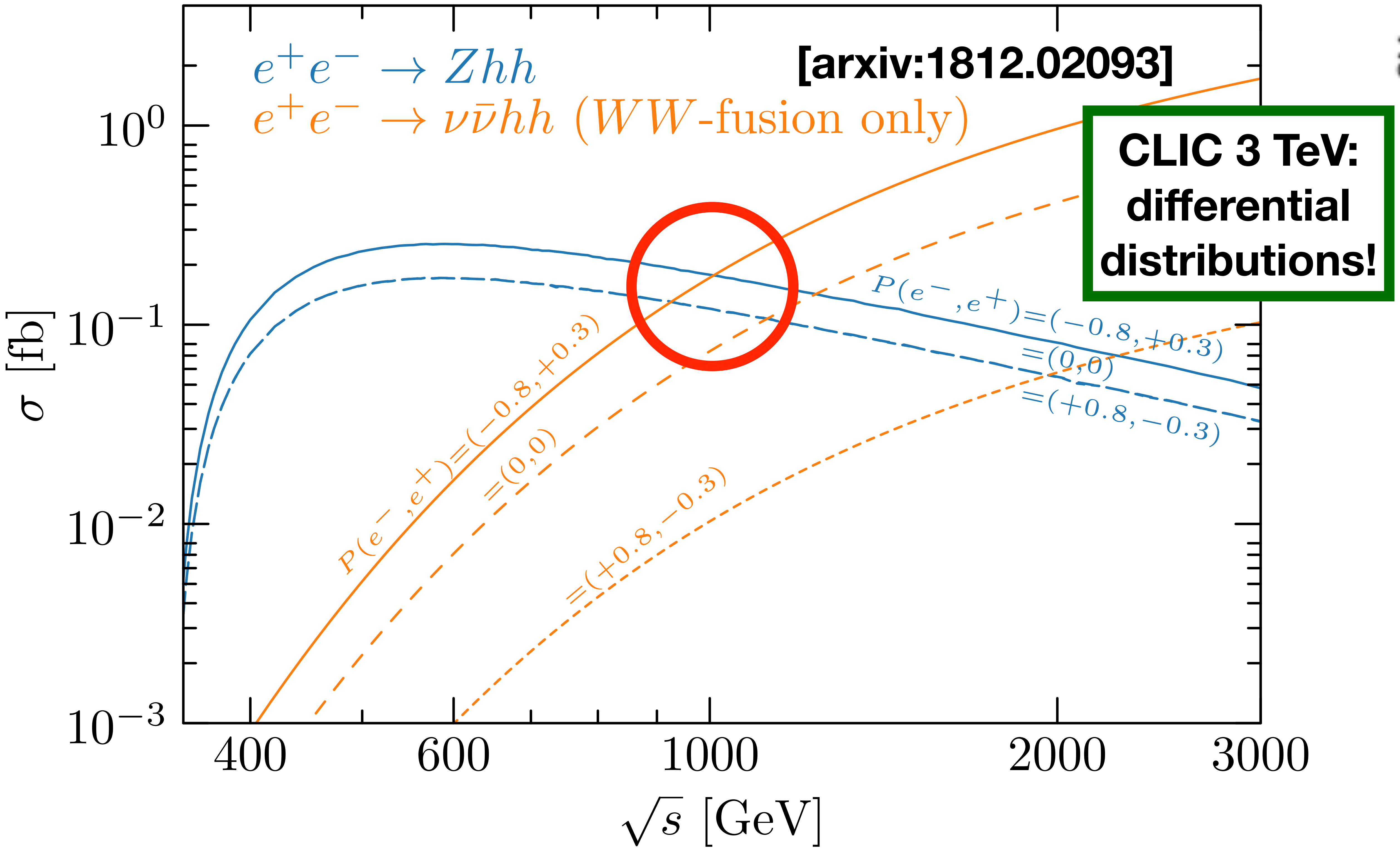

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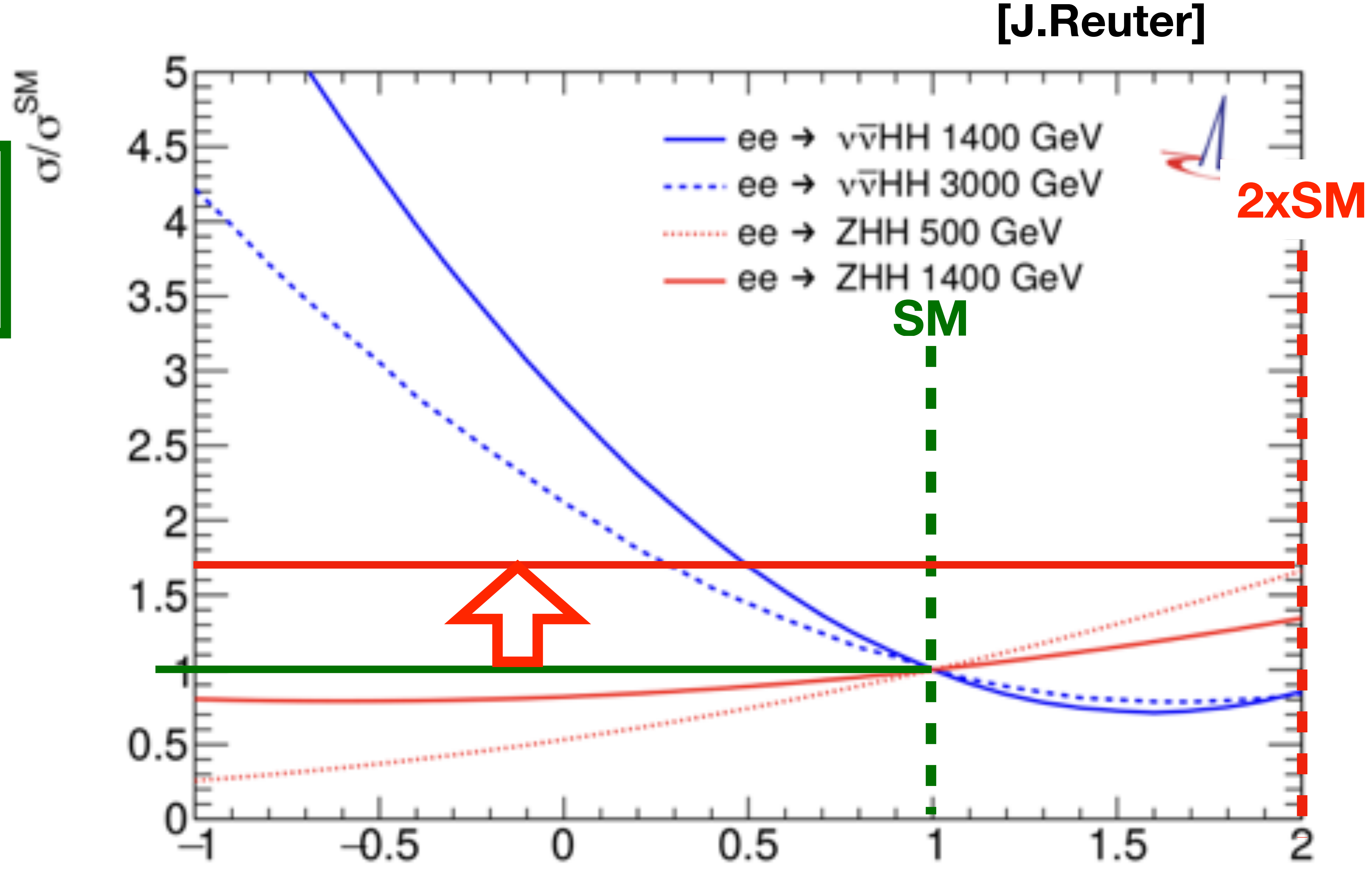


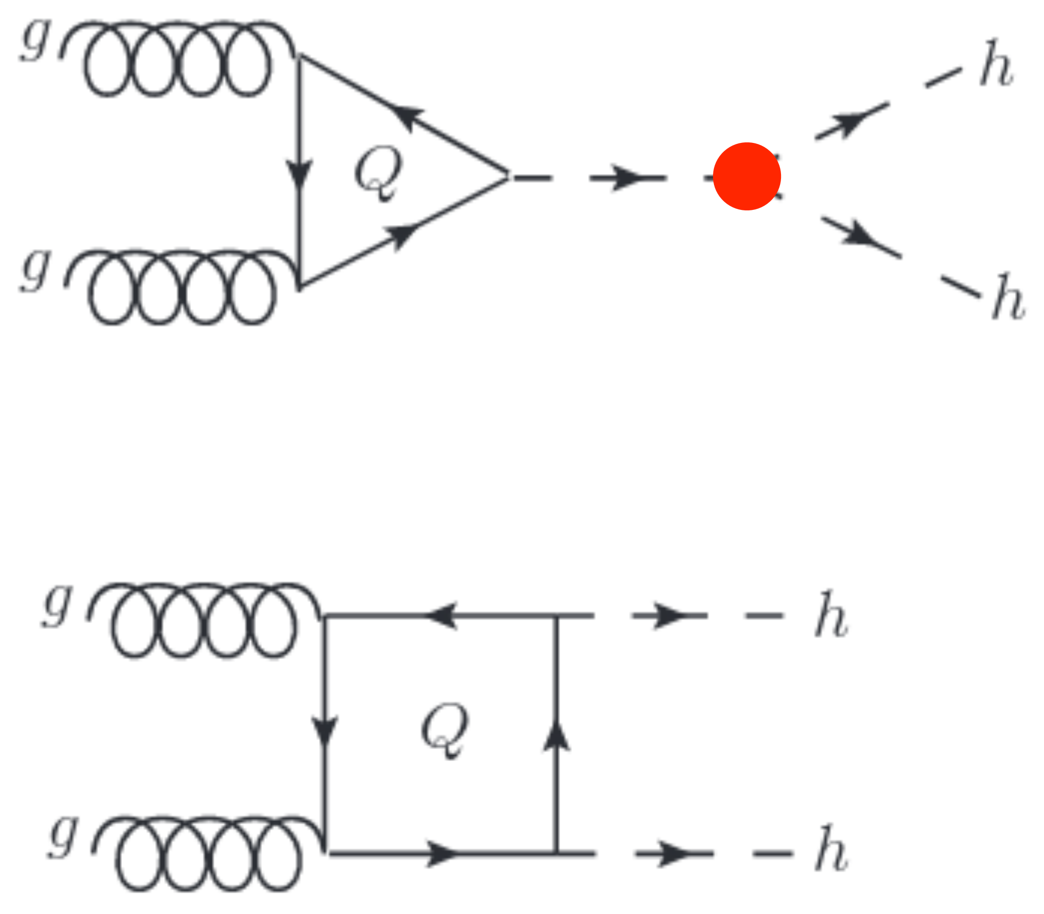
=> VBF(ee/pp)- and Higgsstrahlung (ee) di-Higgs production have orthogonal BSM behaviour

From di-Higgs production to λ

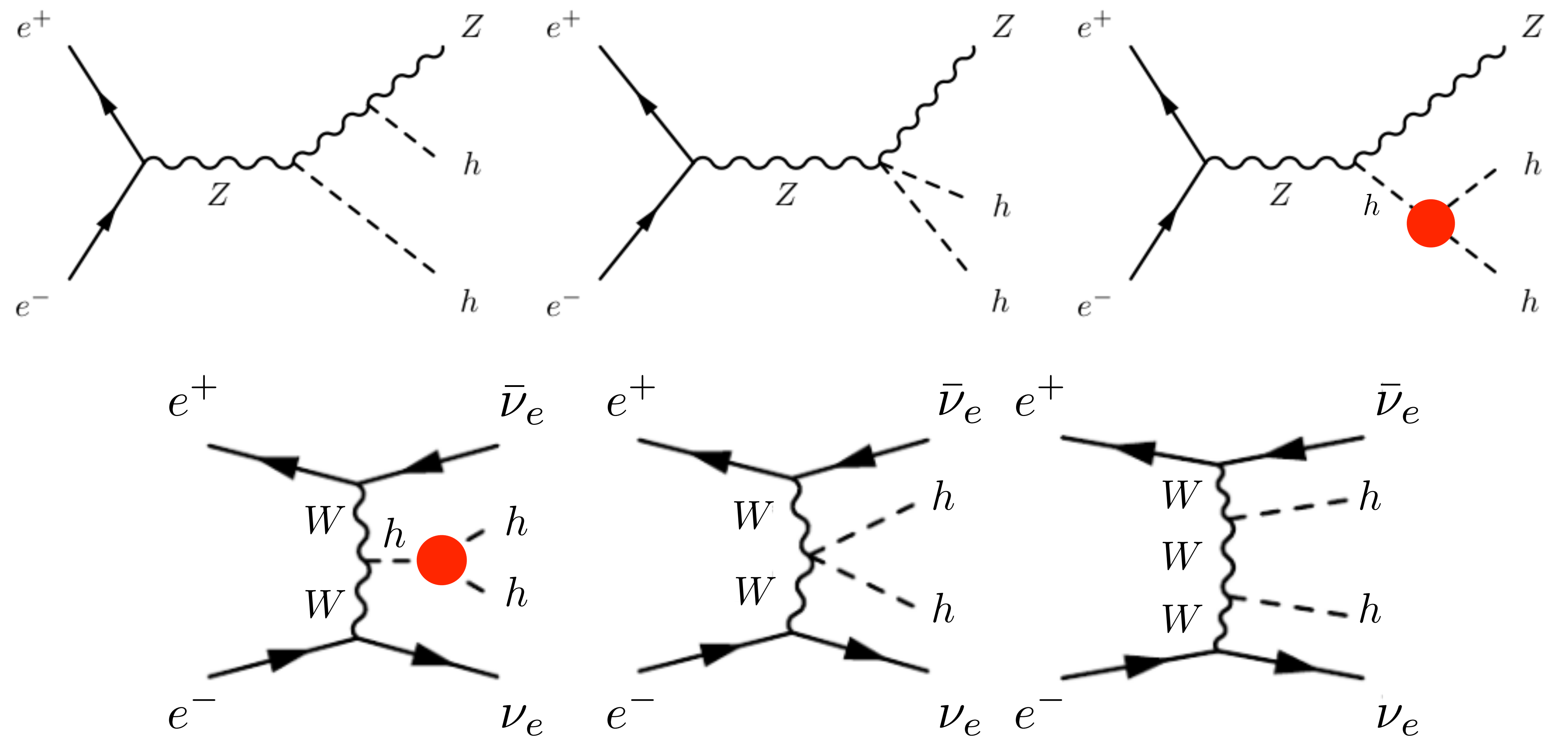
1. Discover di-Higgs production
2. Measure cross section (total and differential!)
3. Extract λ

- Interference of diagrams with / without triple Higgs vertex ●
  => **k:= (δλ/λ)/(δσ/σ) > 1/2**
- k can be "improved" by using *differential* information
- **k depends on: process, *value of λ* and *E_{CM}***

Hadron collider



Lepton collider



ILC Sensitivity vs Lambda

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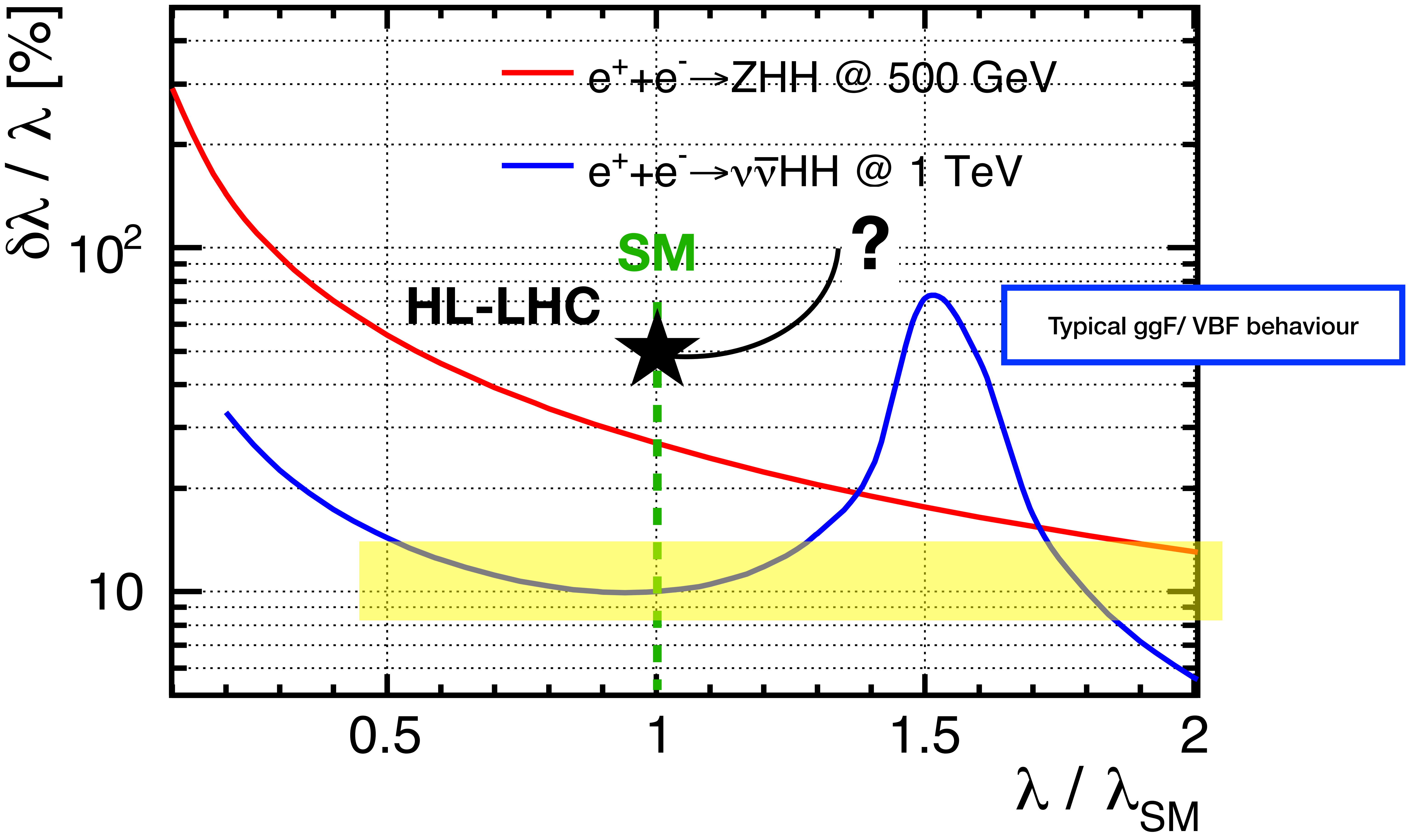
[J.Tian, C.Duerig]



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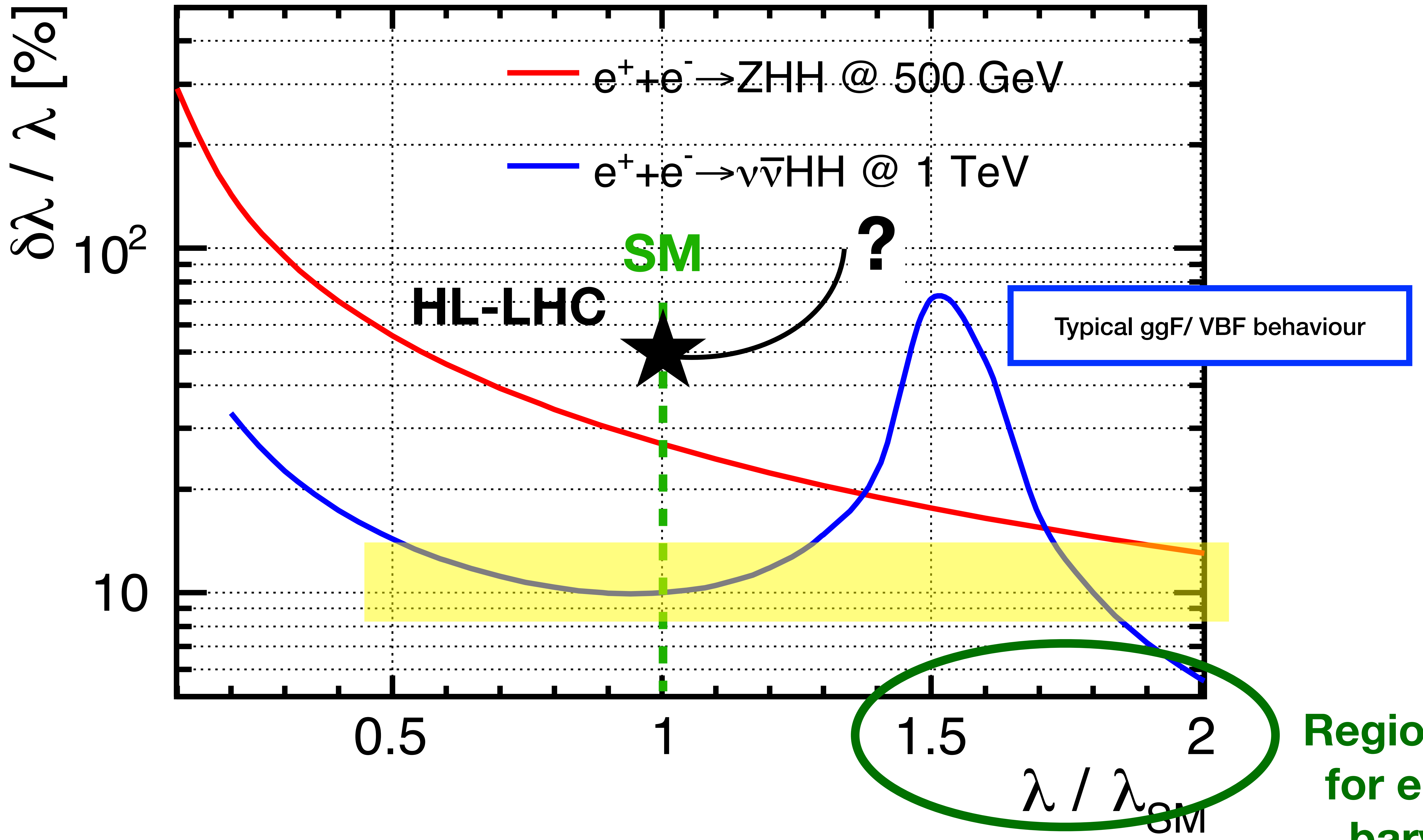
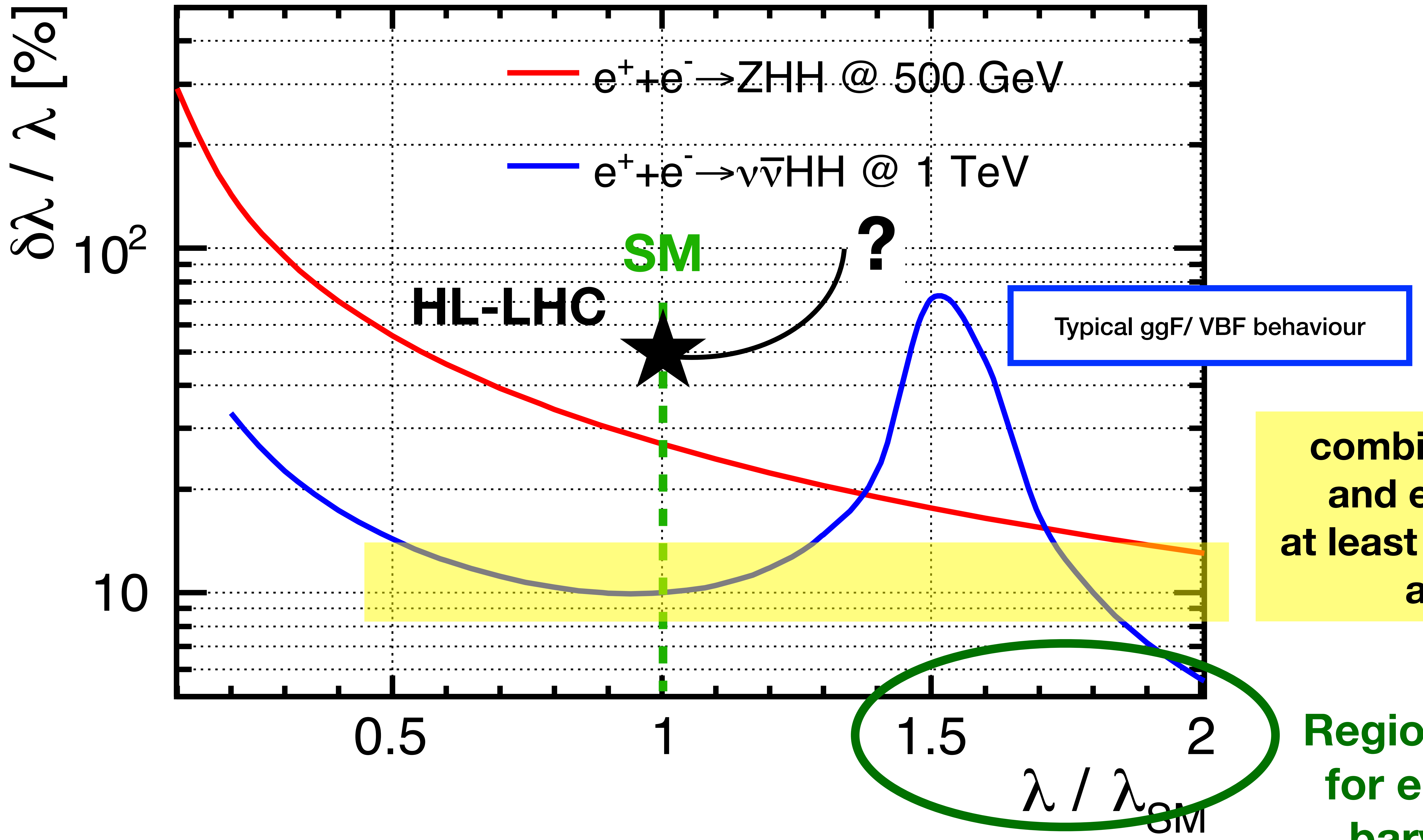


Region of interest for electroweak baryogenesis

ILC Sensitivity vs Lambda

[J.Tian, C.Duerig]

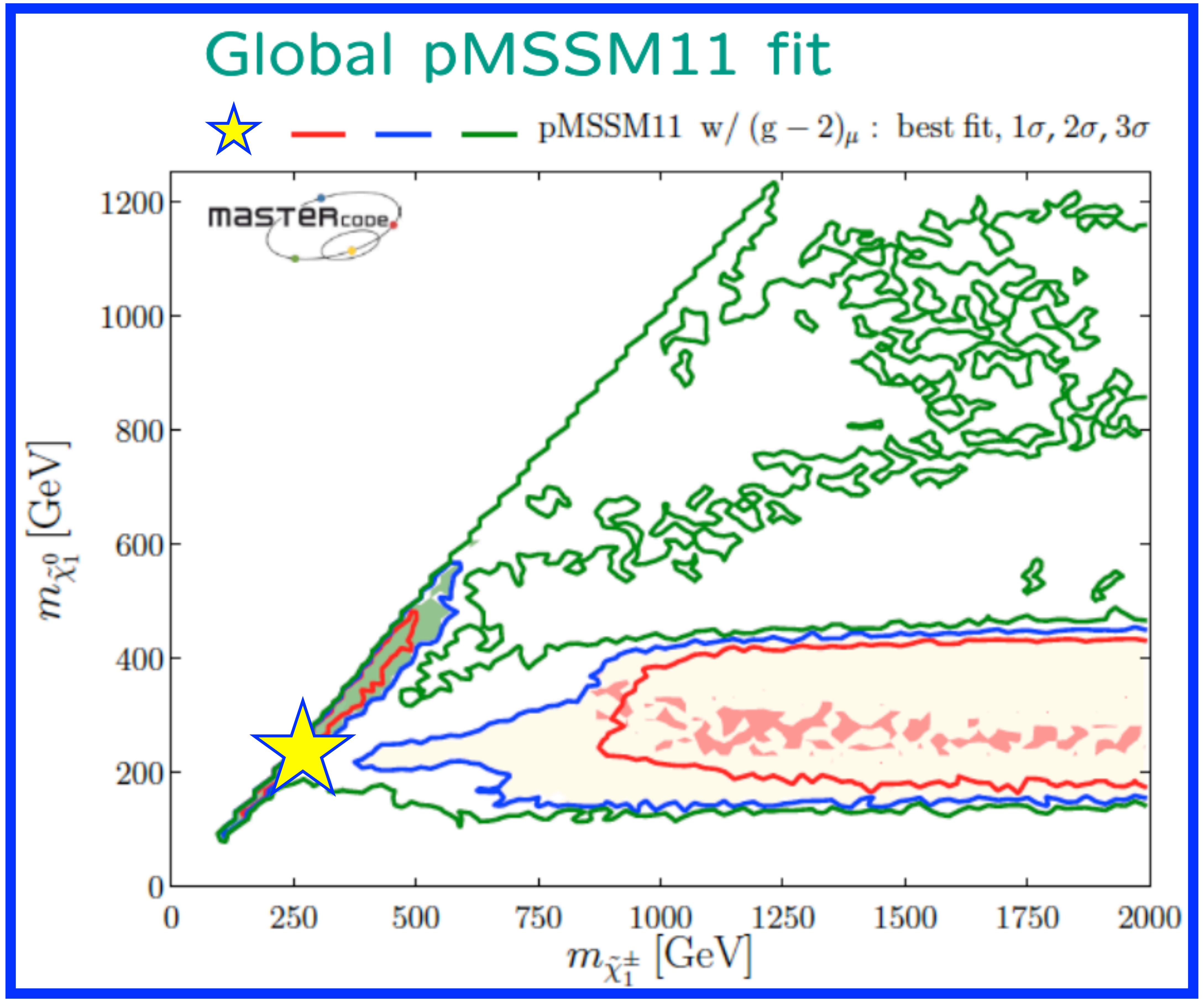


combination of e^+e^- -> ZHH and e^+e^- -> ννHH ensures at least 10-15% precision over a wide range in λ

Region of interest for electroweak baryogenesis

Higgsinos ?

- **lowish ΔM is THE region preferred by data, e.g. for charginos & neutralinos**
  => no *general* limit above LEP



Eur.Phys.J. C78 (2018) no.3, 256

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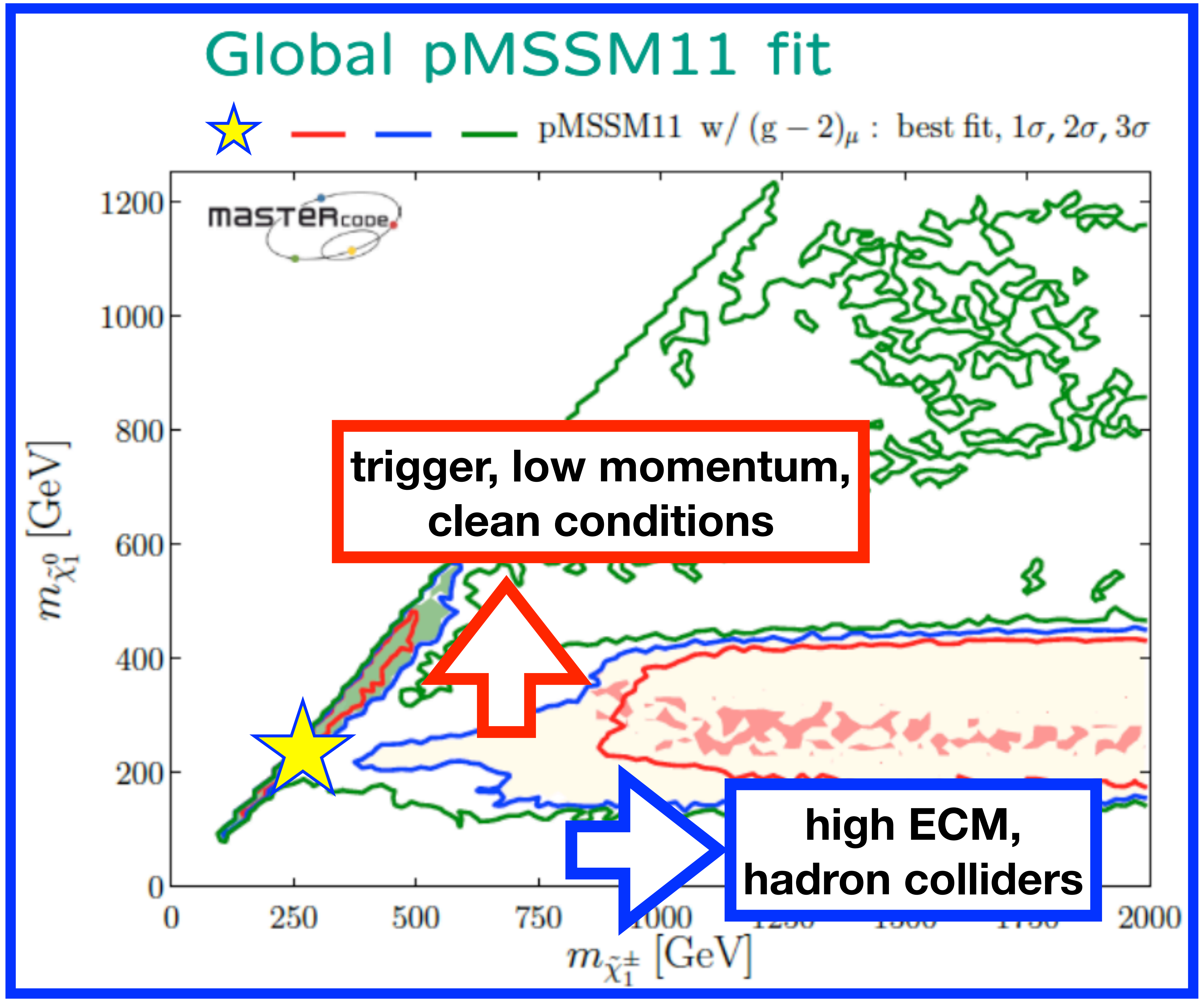

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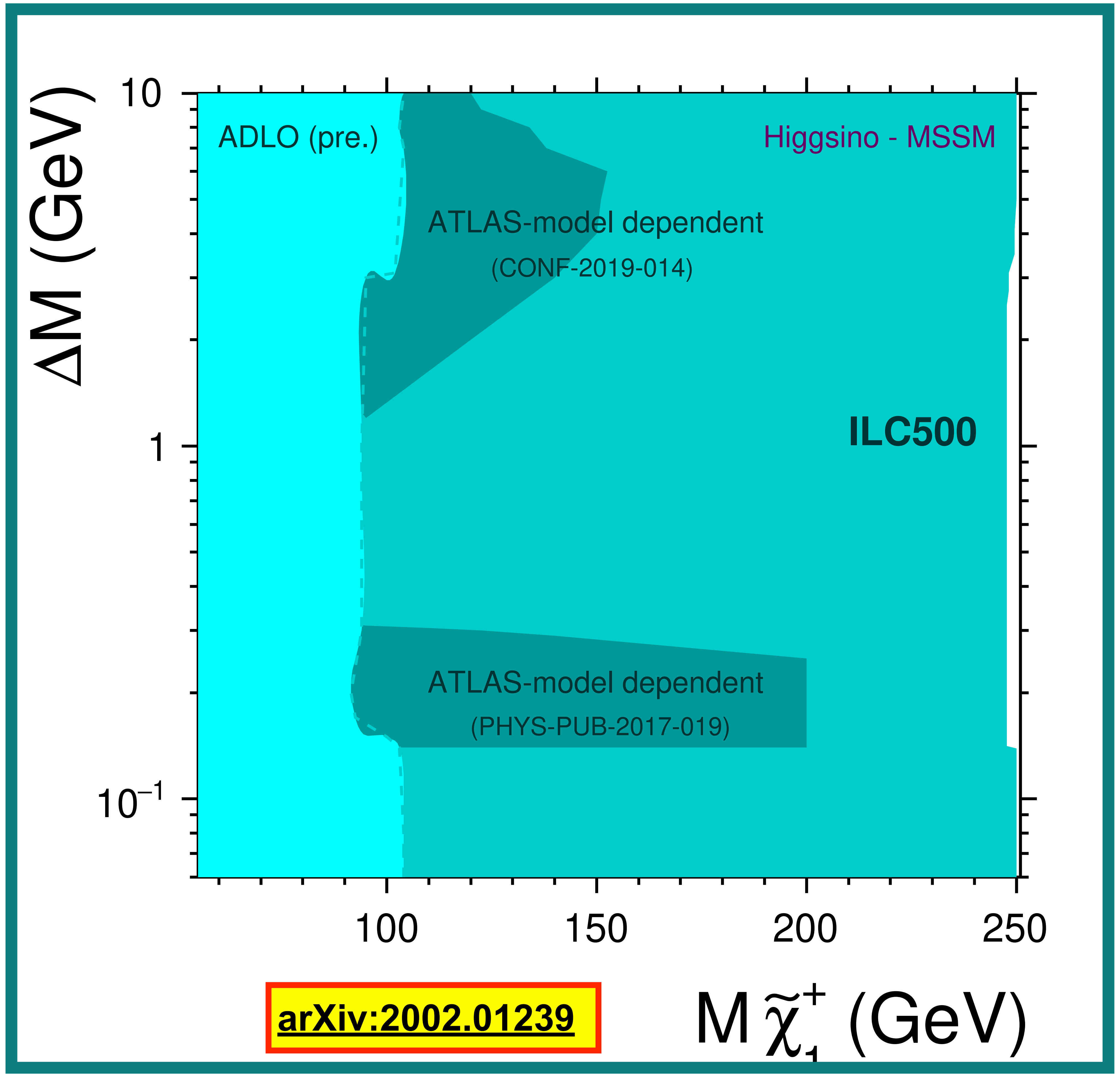
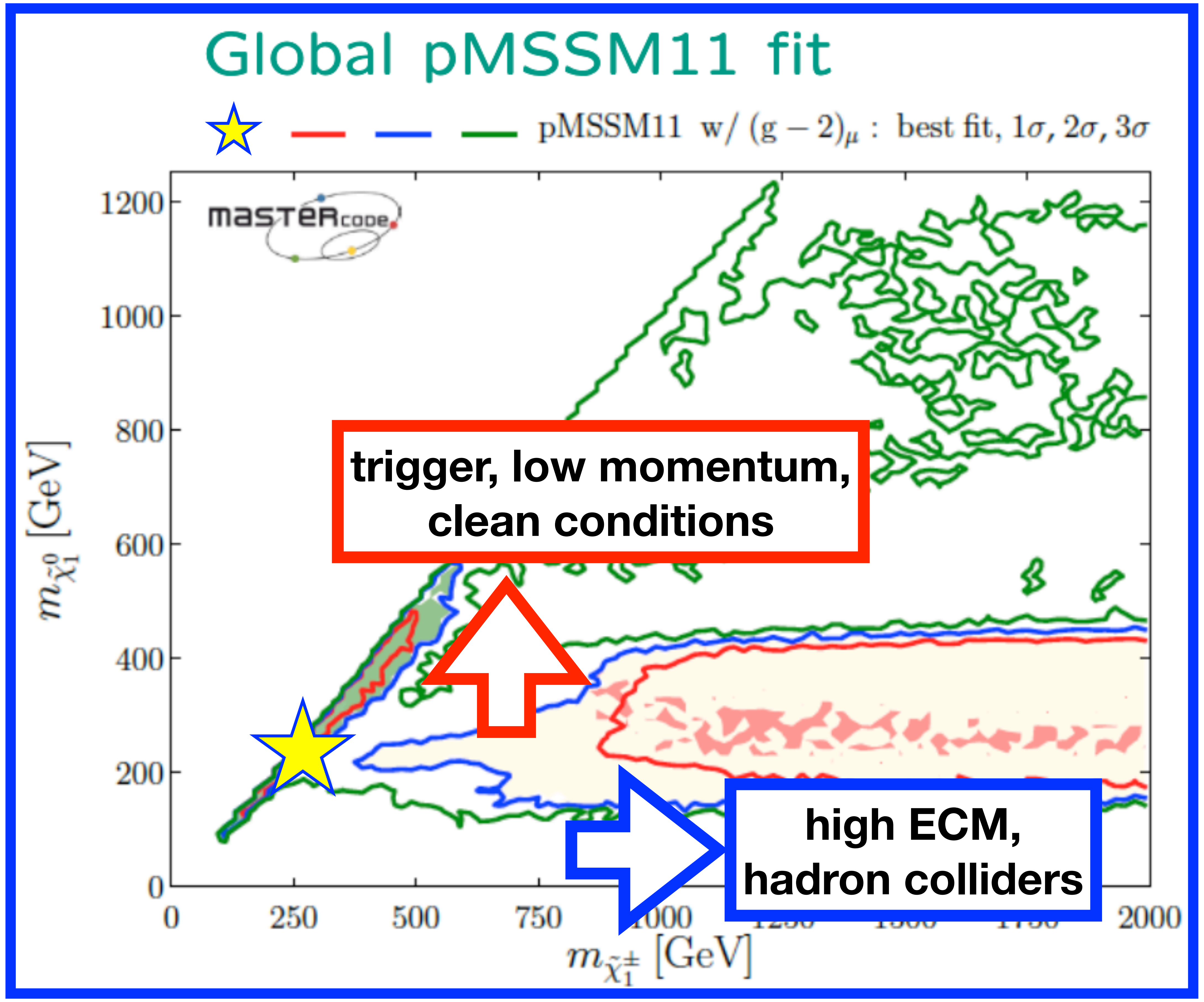


arXiv:2002.01239



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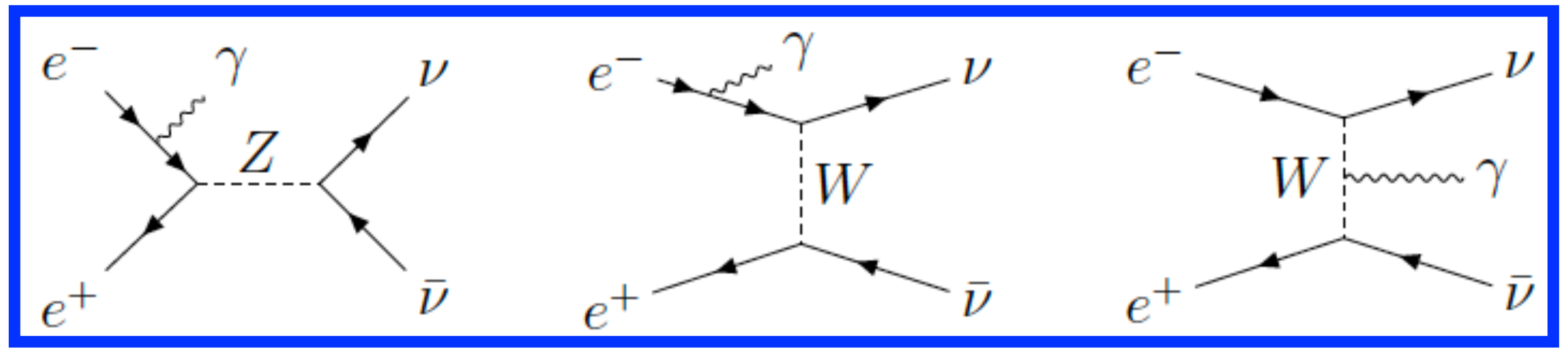
Phys. Rev. D 101 (2020) 7

Polarisation & Beyond the SM: Dark Matter

Background reduction & Systematics

- mono-photon search $e^+e^- \to \chi\chi\gamma$
- main SM background: $e^+e^- \to \nu\nu\gamma$



reduced ~10x with polarisation

- shape of observable distributions changes with polarisation sign
  => combination of samples with sign(P) = (–,+), (+,–), (+,+), (–,–)
  beats down the effect of systematic uncertainties

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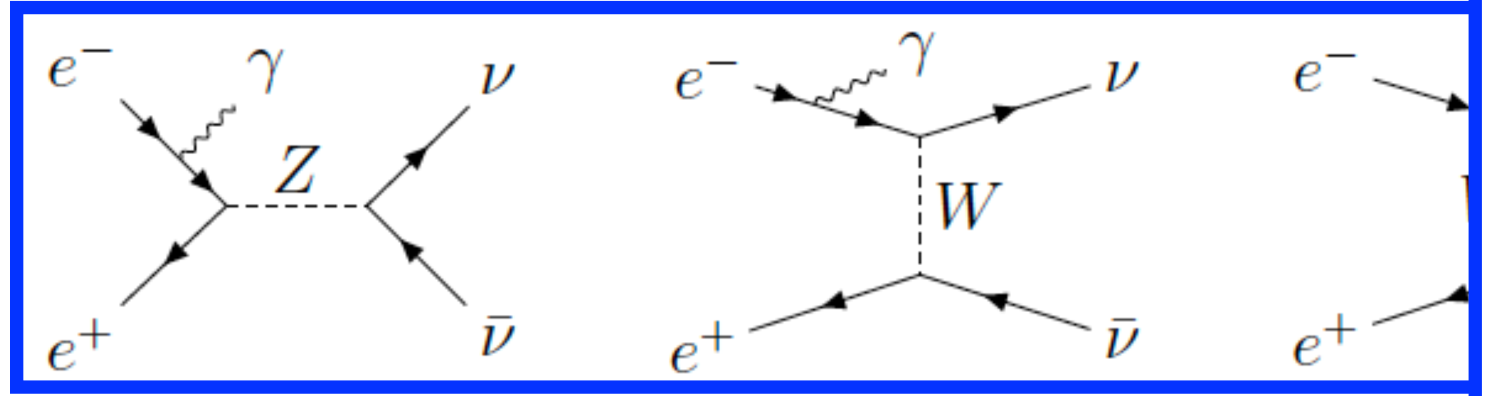

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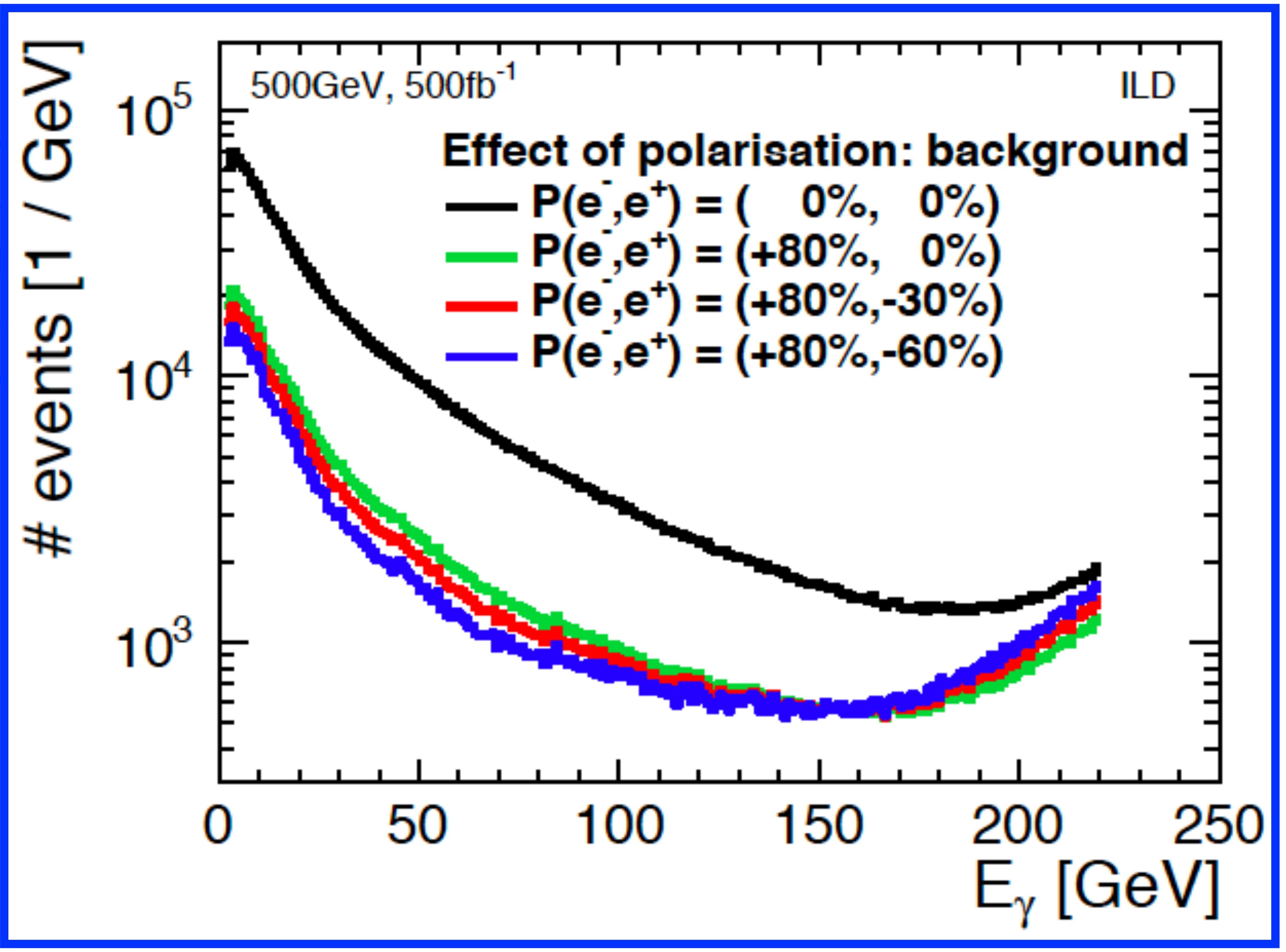

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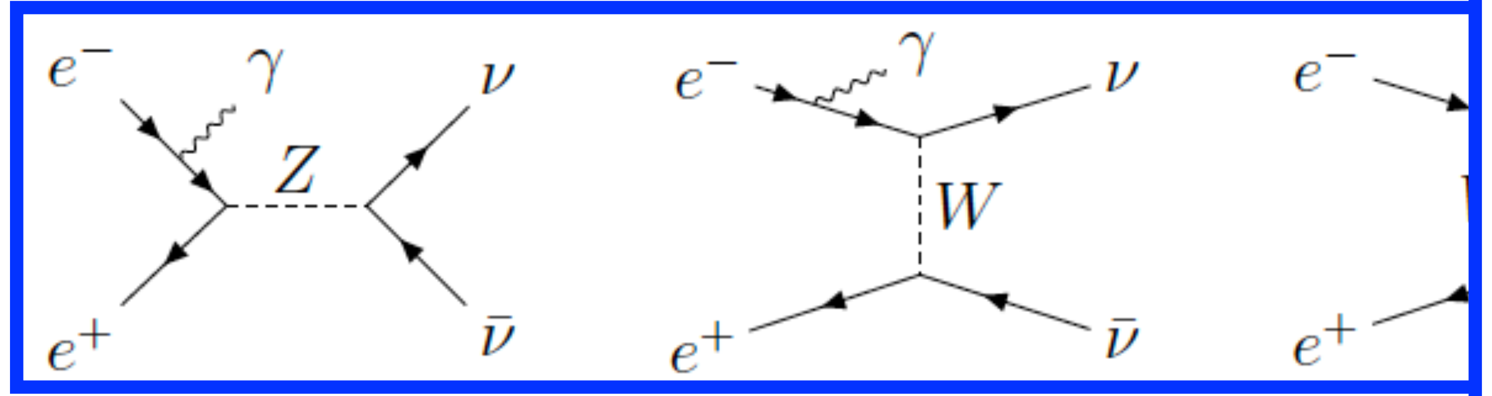

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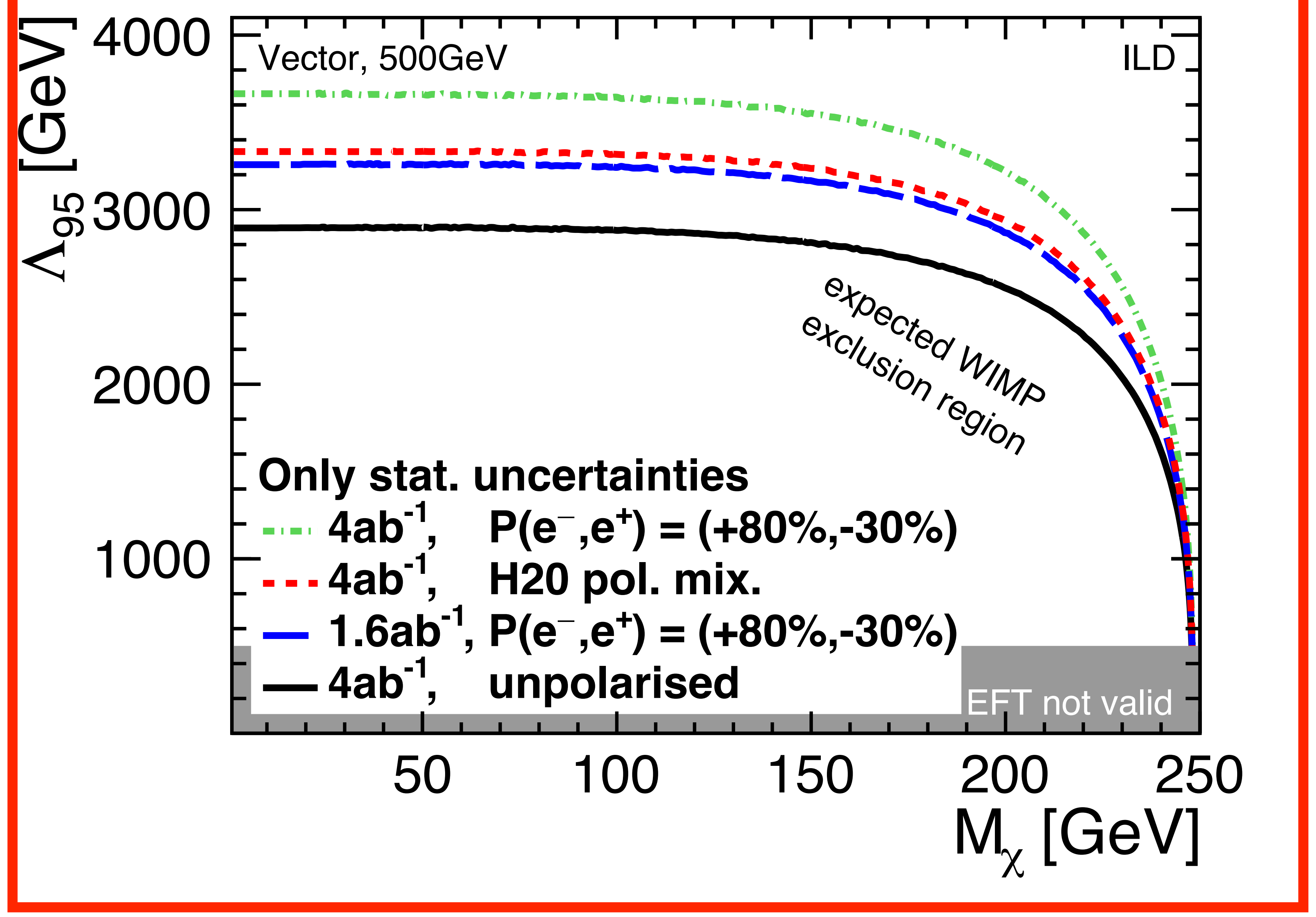

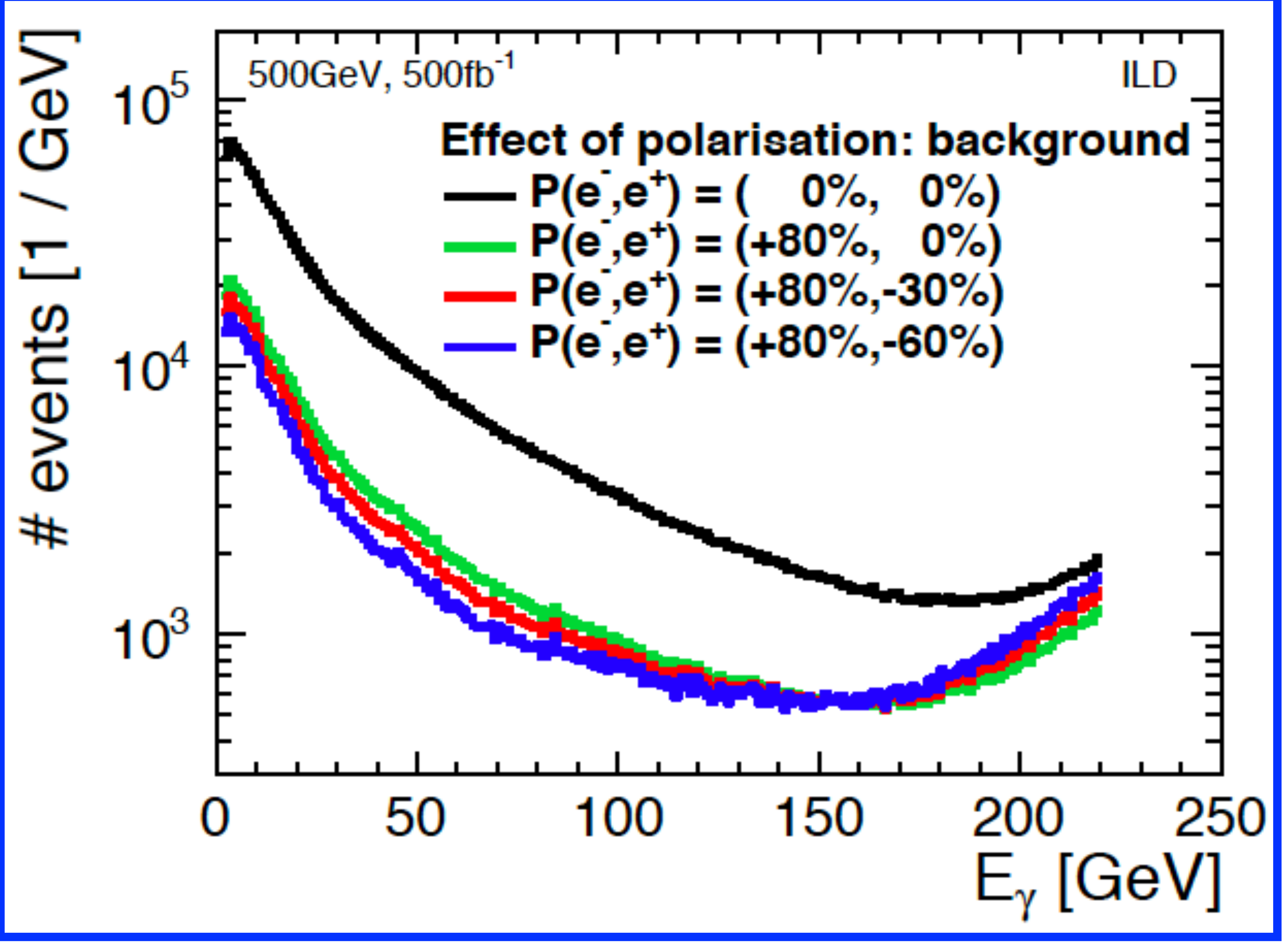

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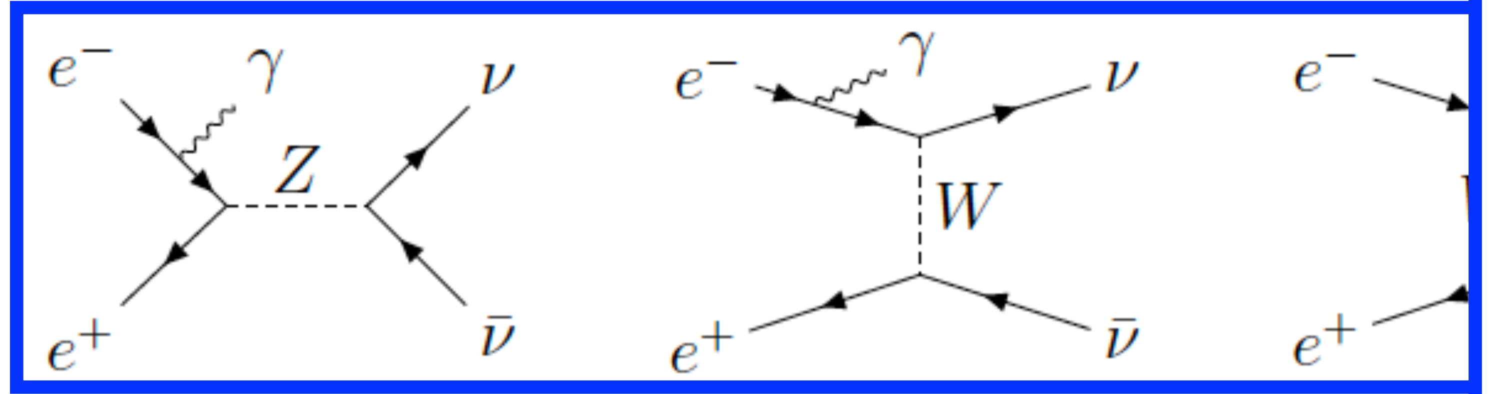

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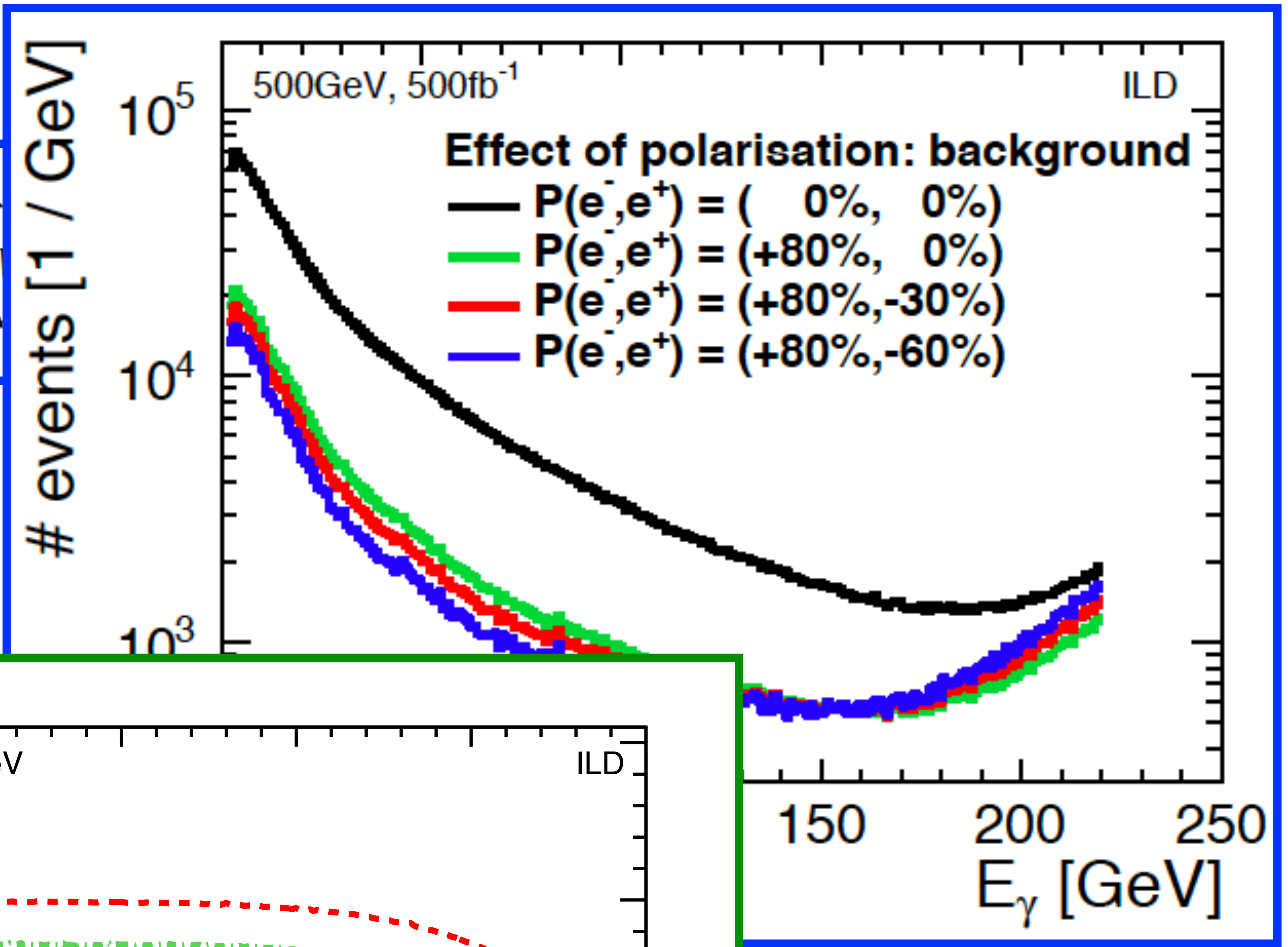
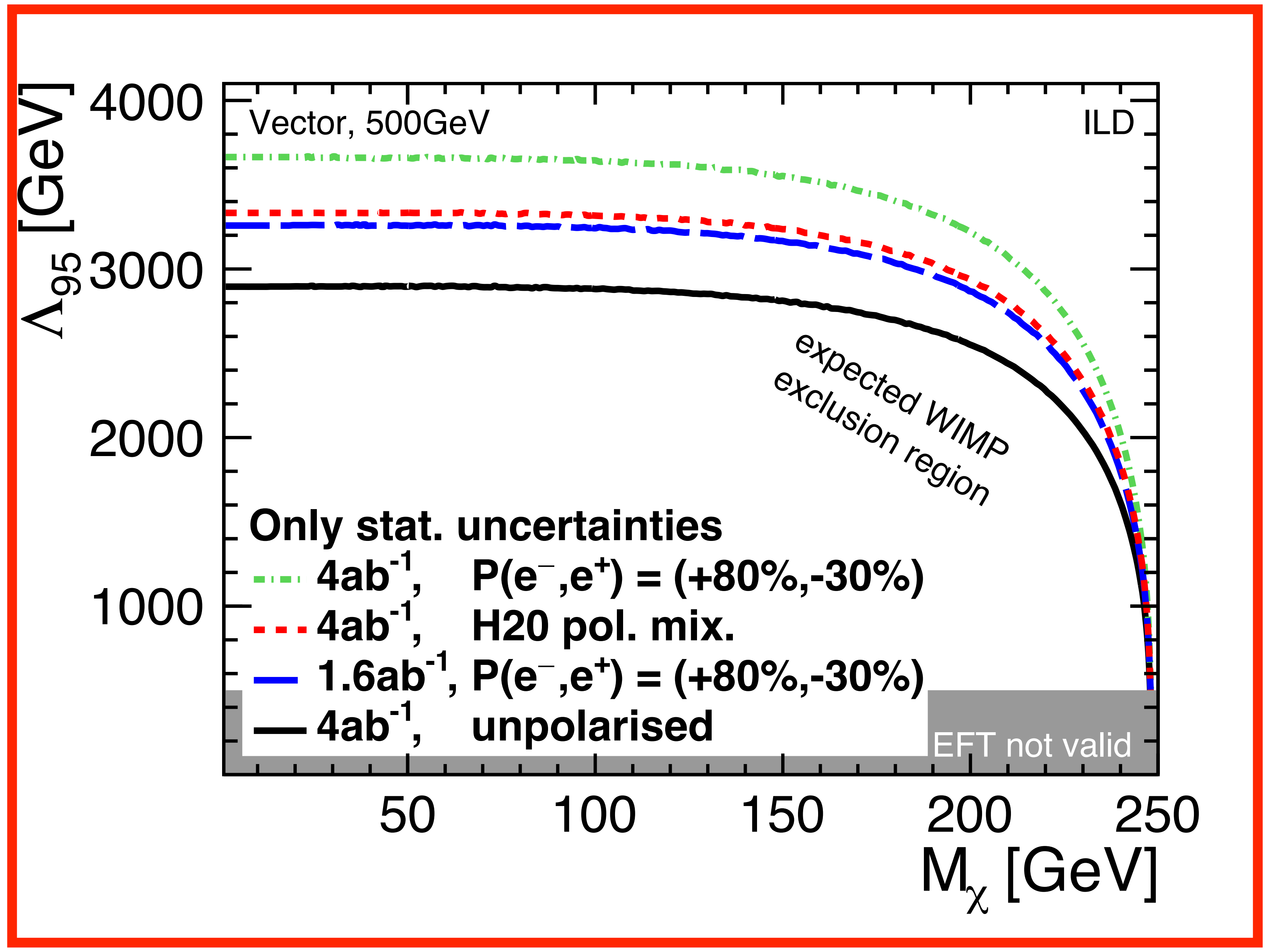
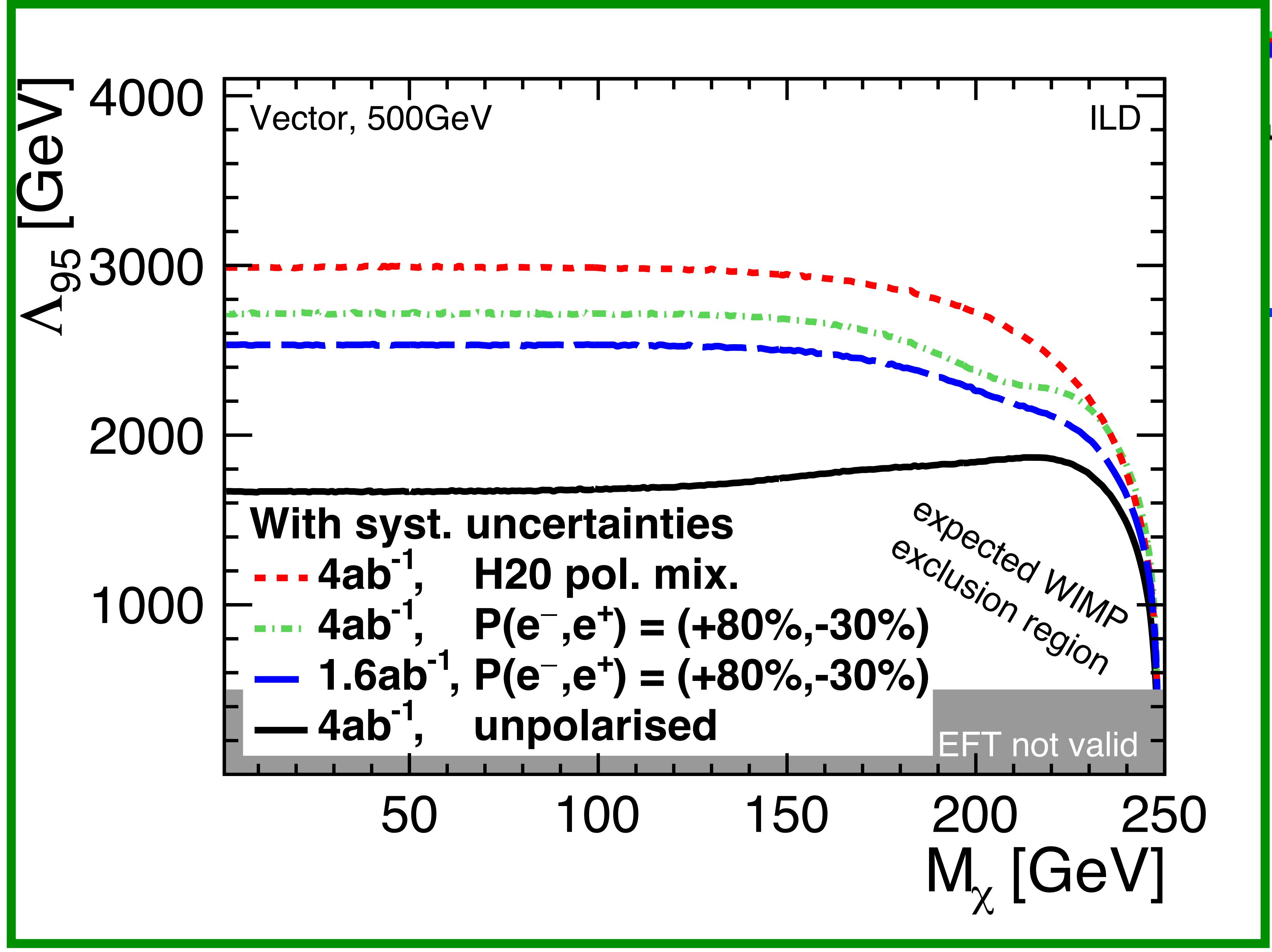






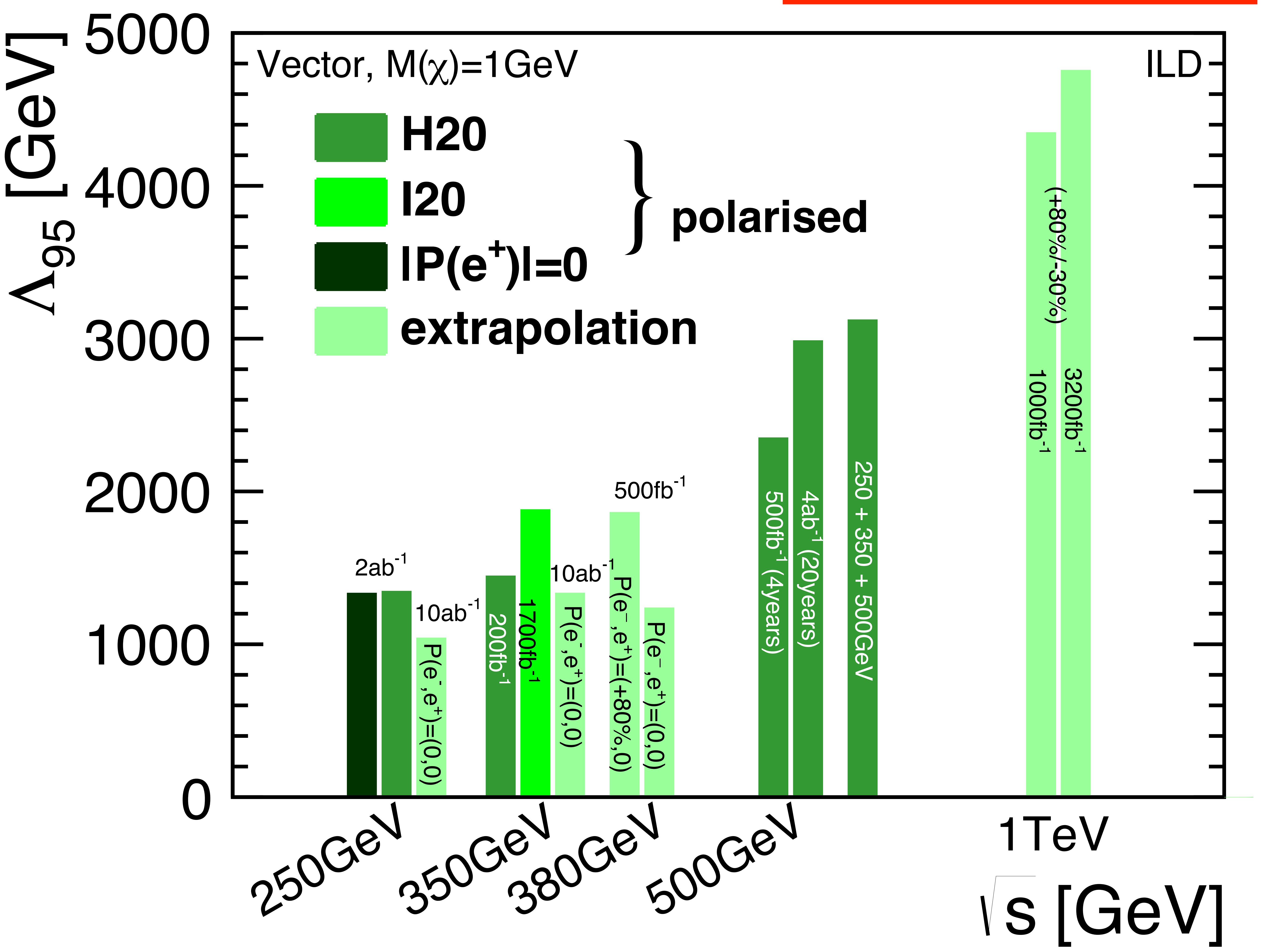
Polarisation & Beyond the SM: Dark Matter

Exmaple: Impact on reach in vector mediator case

Polarisation & Beyond the SM: Dark Matter

Exmaple: Impact on reach in vector mediator case

Phys. Rev. D 101 (2020) 7



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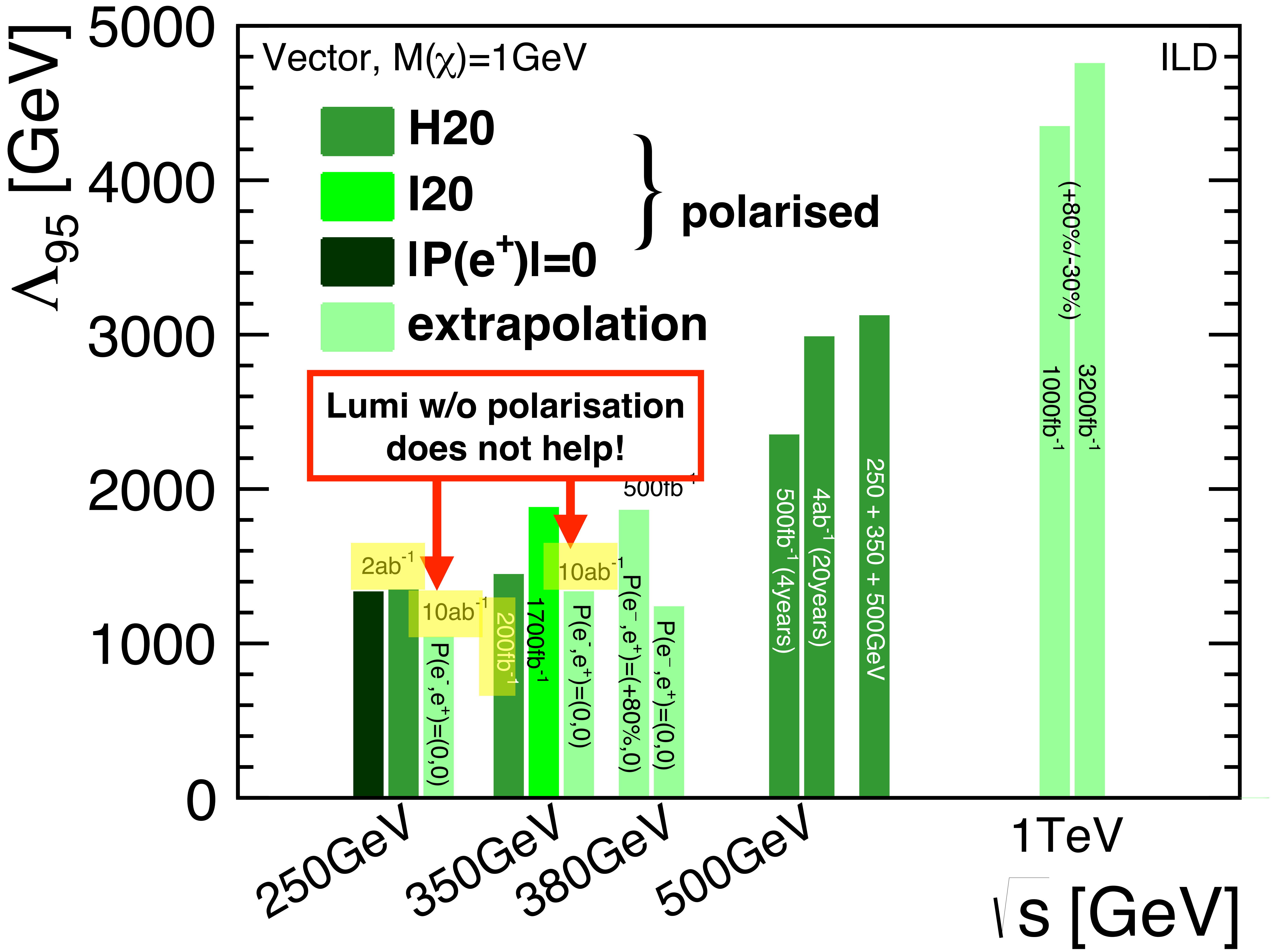
Exmaple: Impact on reach in vector mediator case

Phys. Rev. D 101 (2020) 7



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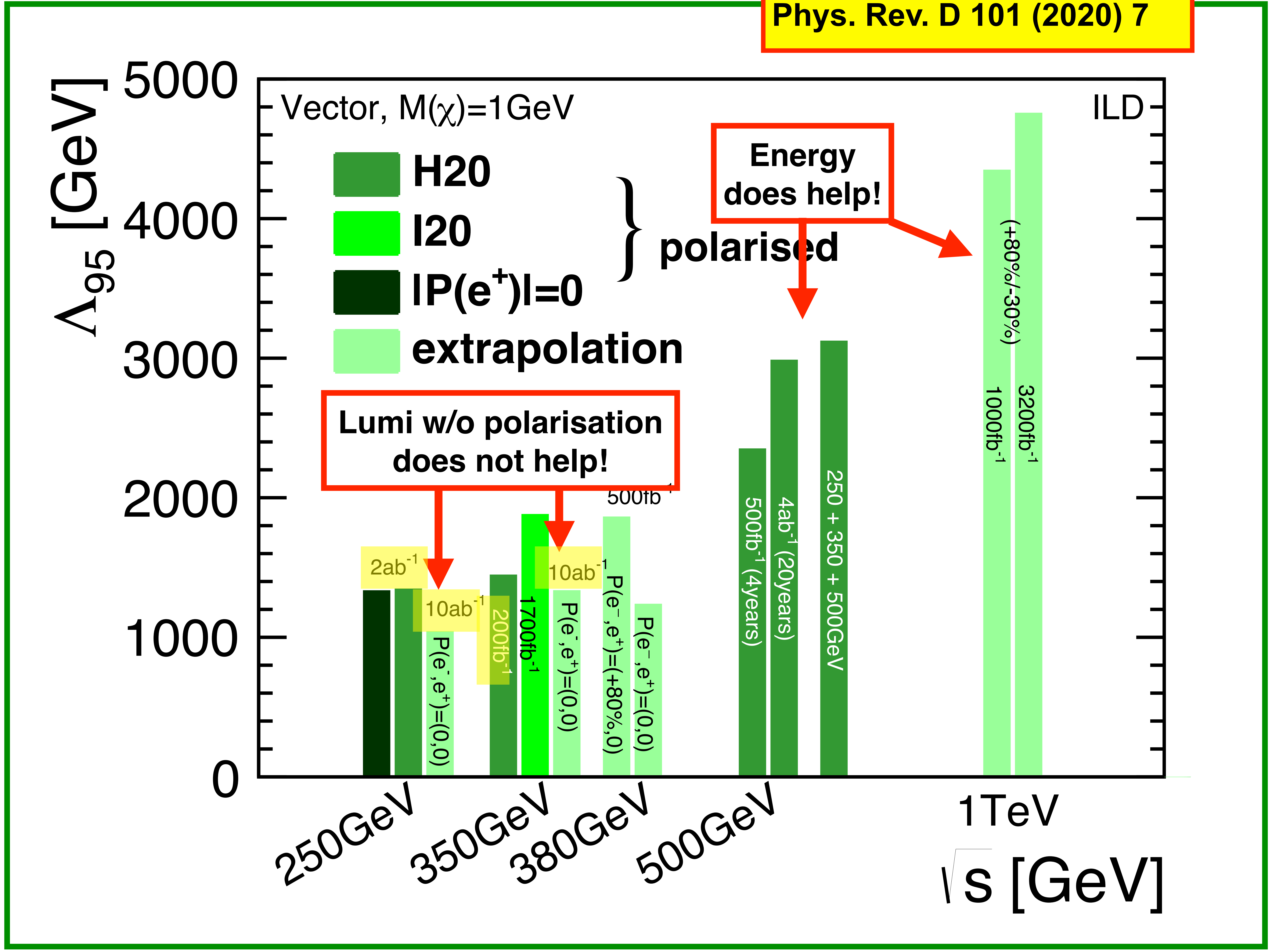

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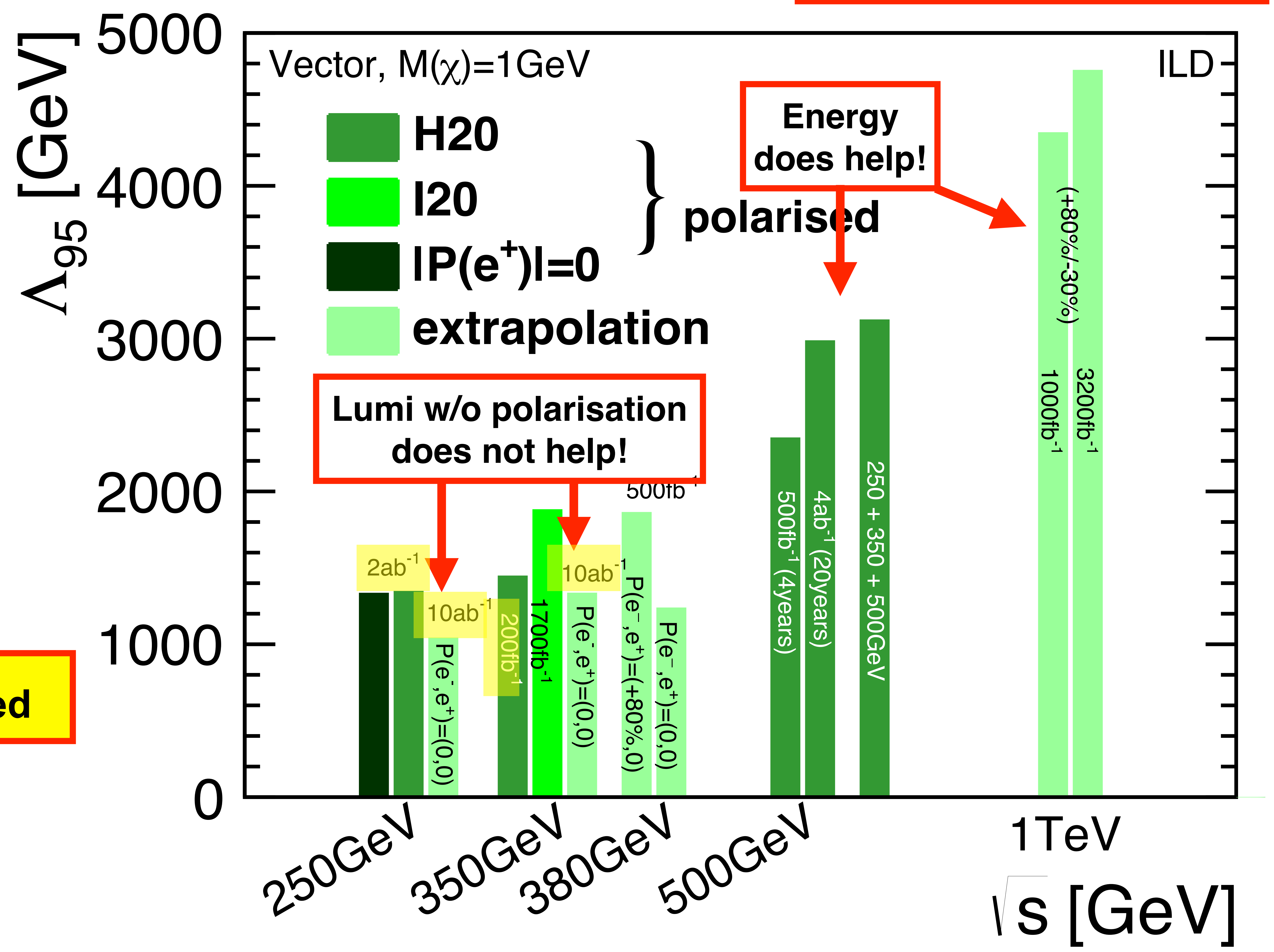
Phys. Rev. D 101 (2020) 7



200 fb^{-1} polarised ≈ 10 ab^{-1} unpolarised

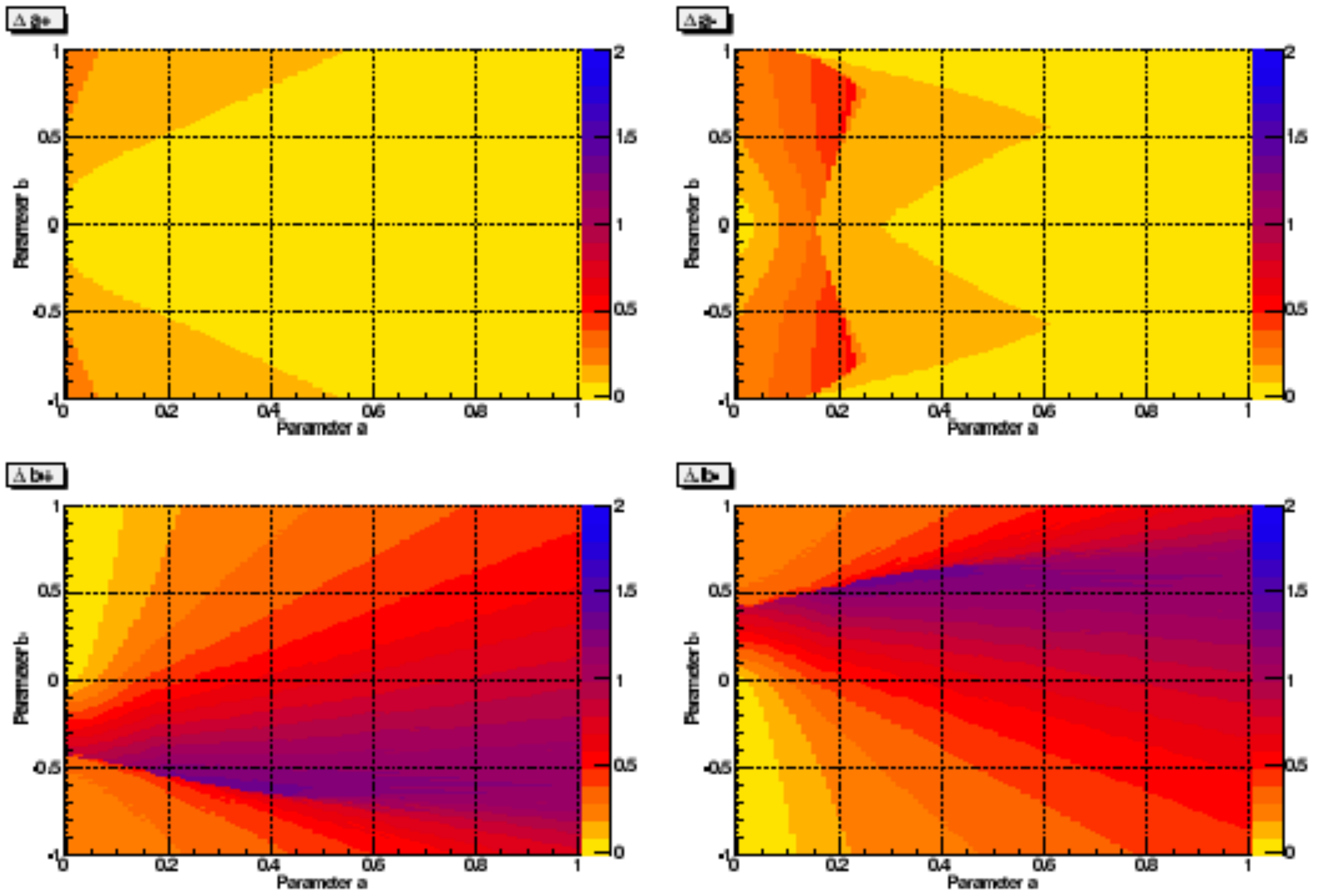
CP odd admixture

- coupling of a general CP-mixed state Φ to $t\bar{t}$: $a, b \in [-1, .., 1]$

$$C_{tt\Phi} = -i\frac{e}{\sin\theta_W}\frac{m_t}{2M_W}(a + ib\gamma_5) \equiv -ig_{ttH}(a + ib\gamma_5)$$

Accuracy on a, b from the Combined Observables σ, P_t, A_ϕ

Godbole, Hangst, MMM, Rindani, Sharma



$\sqrt{s} = 800$ GeV, $\int \mathcal{L} = 500$ fb^{-1}, polarised $e^{\pm}$ beams

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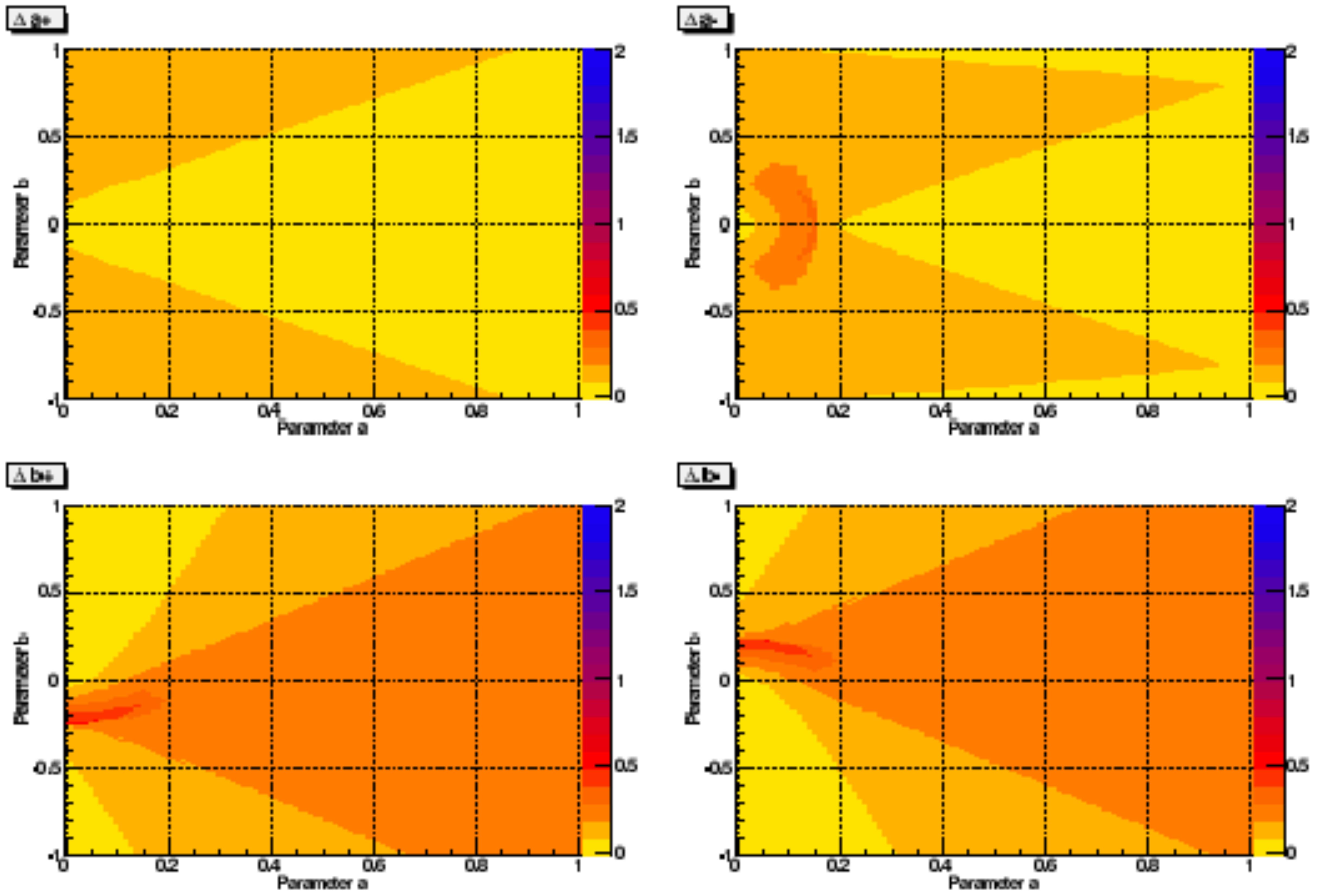
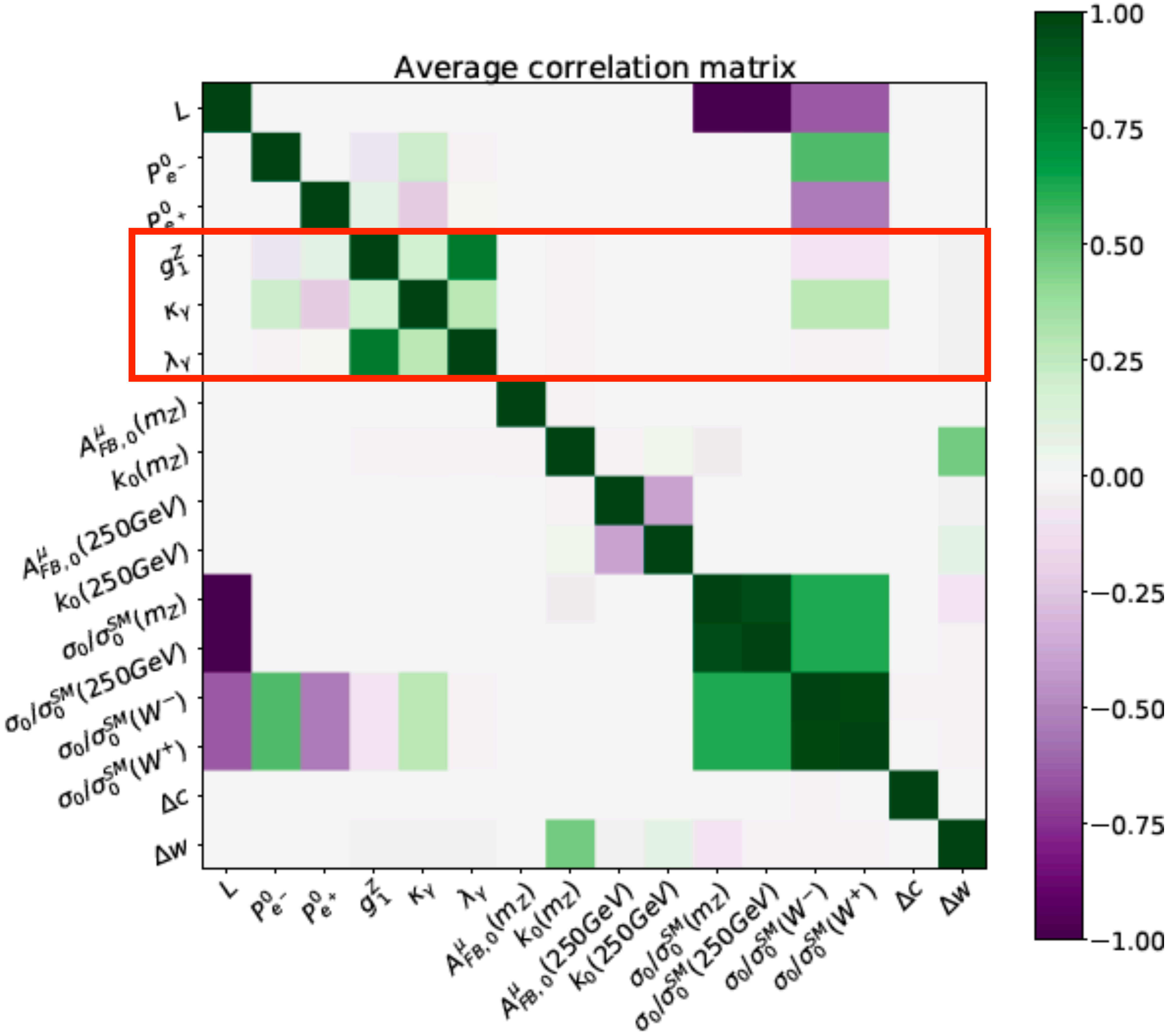
Godbole,Hangst,MMM,Rindani,Sharma

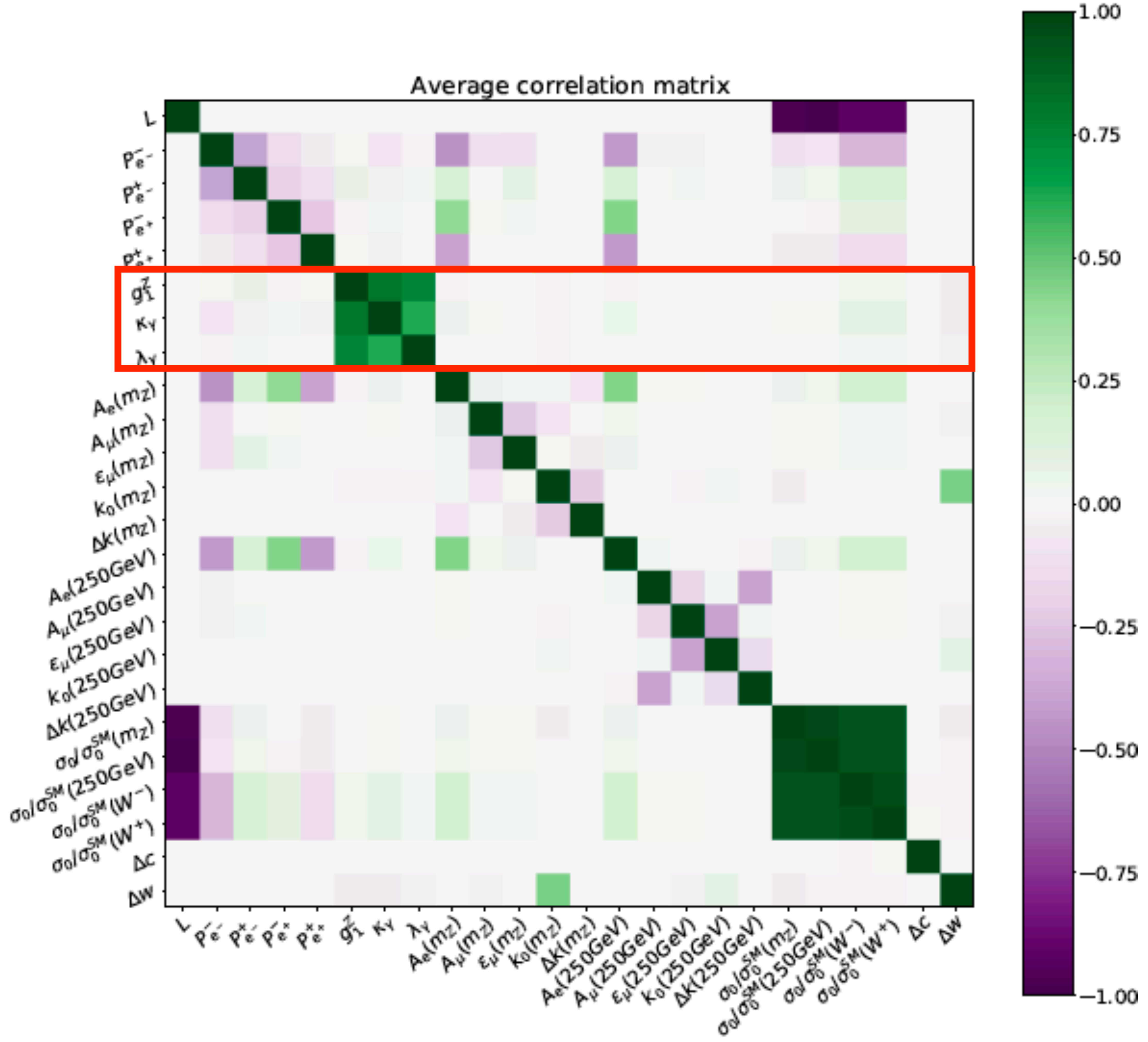


$\sqrt{s} = 3$ TeV, $\int \mathcal{L} = 3$ ab^{-1}, polarised $e^{\pm}$ beams

Can we determine polarisation AND devitions from SM?

P = (0%,0%) vs P = (±80%, ∓30%)





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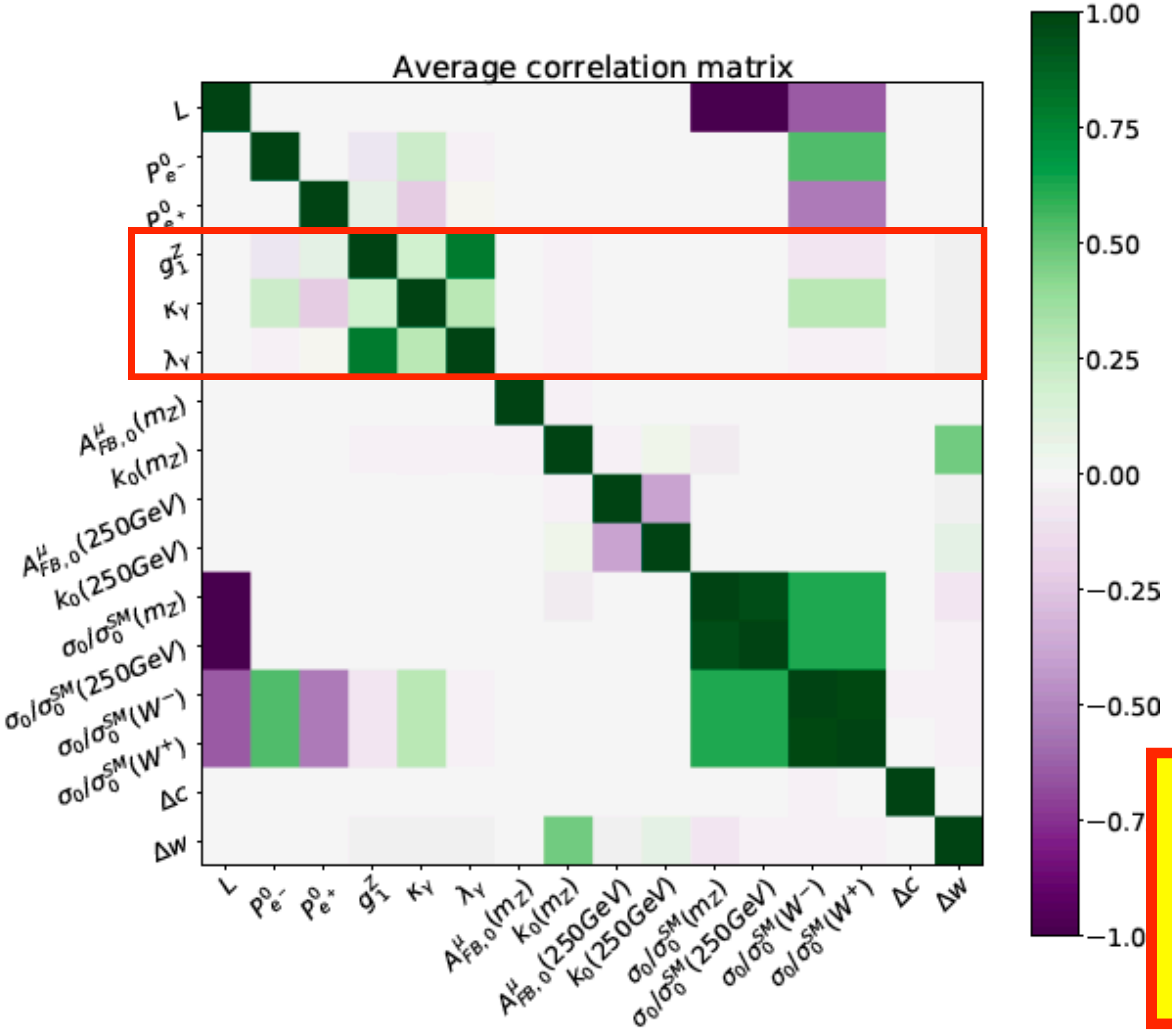
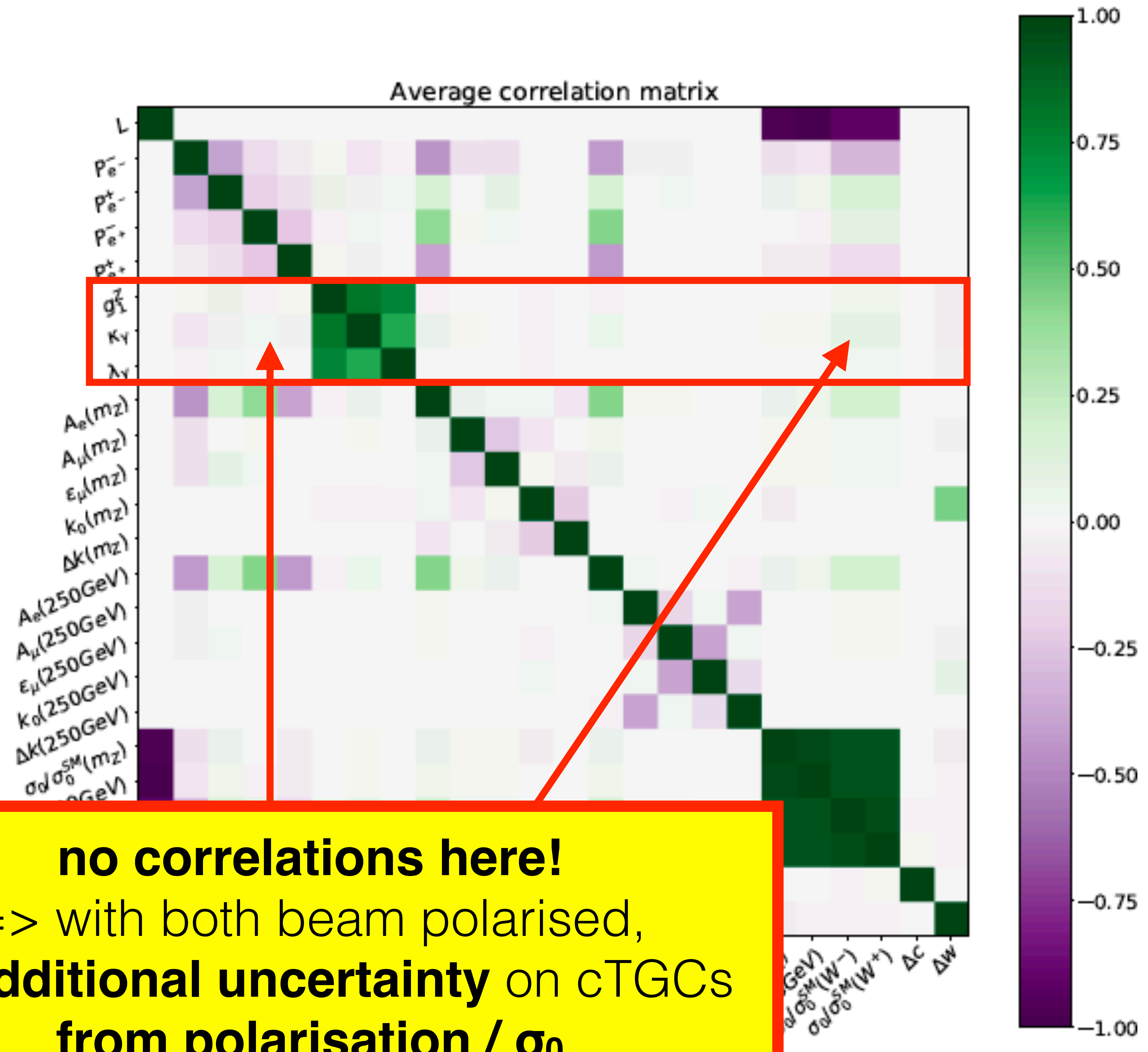
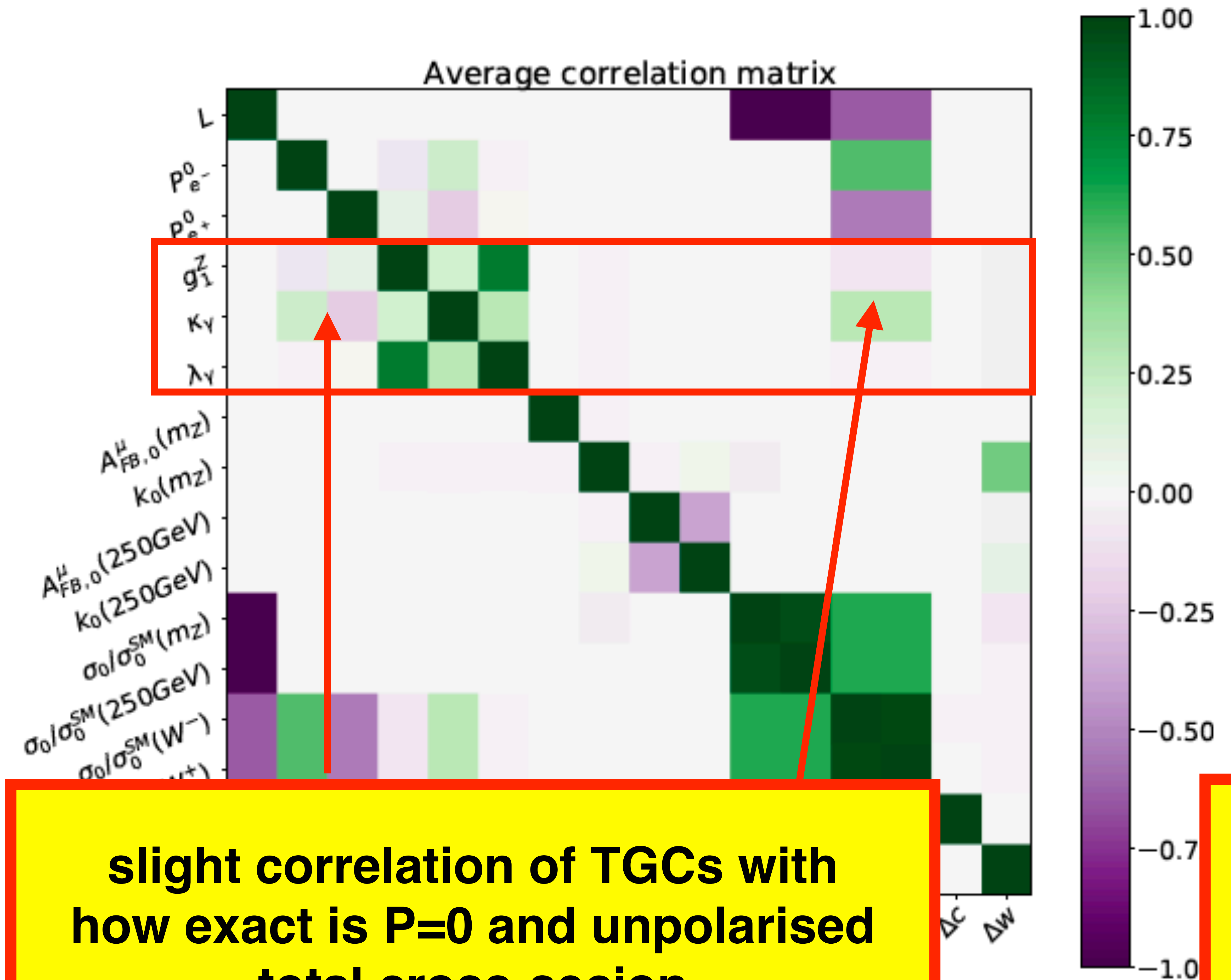


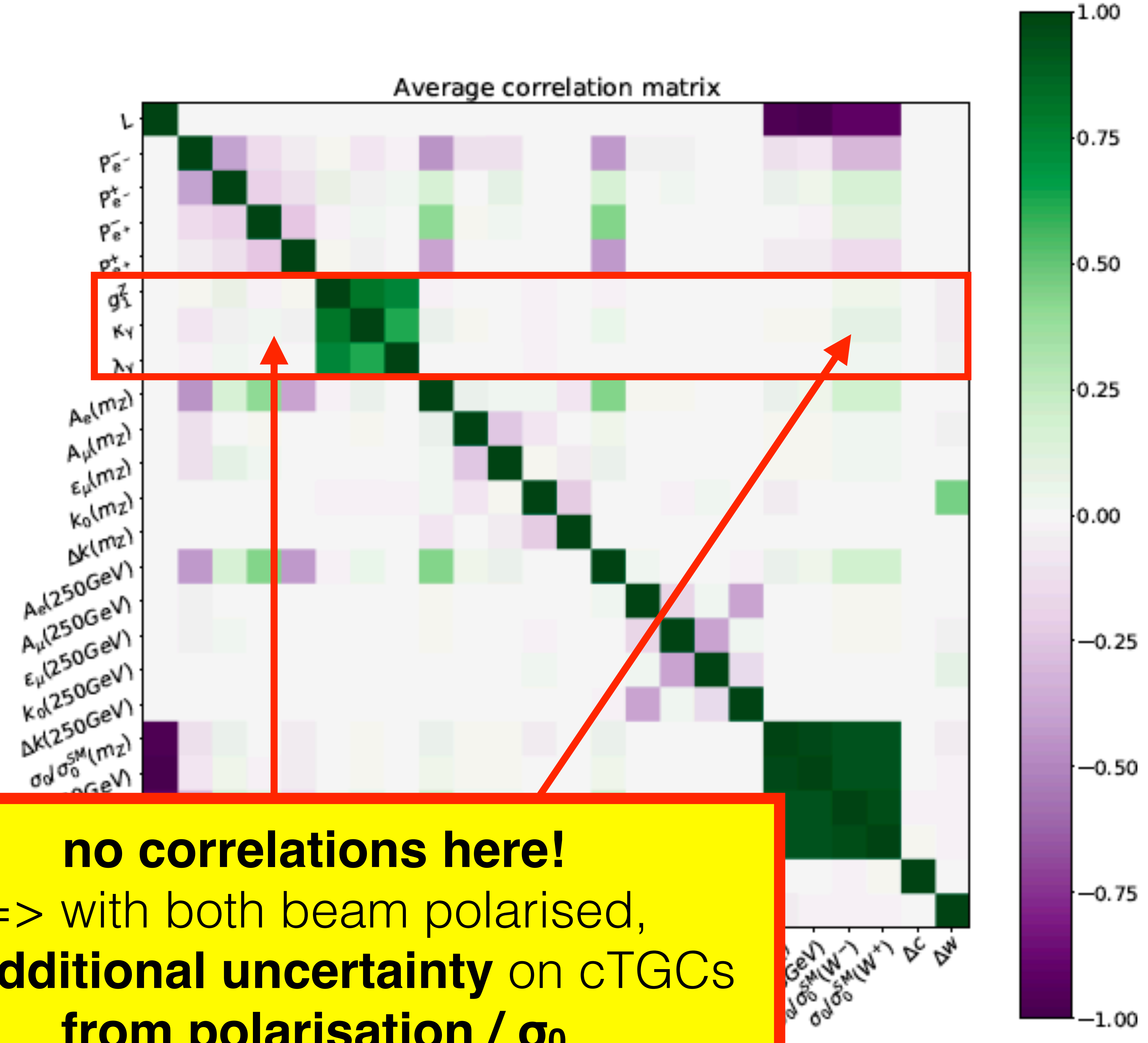


no correlations here!
=> with both beam polarised,
no additional uncertainty on cTGCs
from polarisation / σ0

Can we determine polarisation AND devitions from SM?

P = (0%,0%) vs **P = (±80%, ∓30%)**





slight correlation of TGCs with how exact is P=0 and unpolarised total cross-secion

no correlations here!
=> with both beam polarised,
no additional uncertainty on cTGCs
from polarisation / σ0

Impact of A_{LR}(WW)

- same effect seen in HL-LHC projections
- effect even stronger for HE-LHC

=> will require A_q's from lepton collider!

arXiv:1902.04070

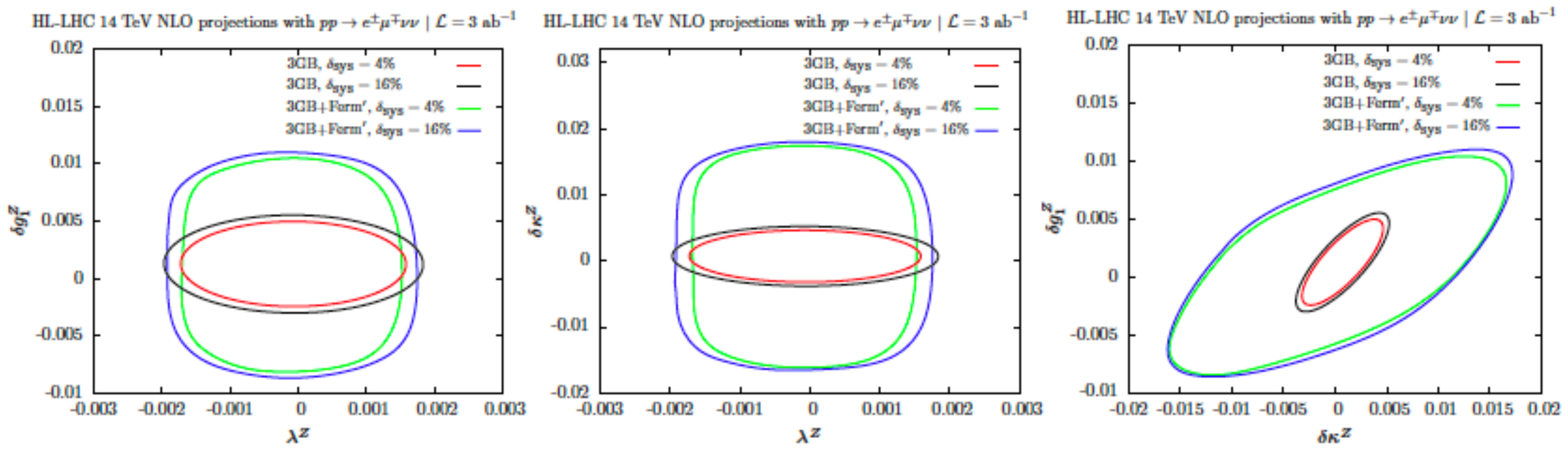


Fig. 40: Projections for 14 TeV with 3 ab^{-1}. $p_{T,cut} = 750$ GeV, corresponding to $\delta_{stat} = 16\%$ with $\delta_{sys} = 4\%$ and $\delta_{sys} = 16\%$. The curves labelled 3GB have SM Z-fermion couplings, while the curves labelled 3GB +Ferm' allow the Z-fermion couplings to vary around a central value of 0.

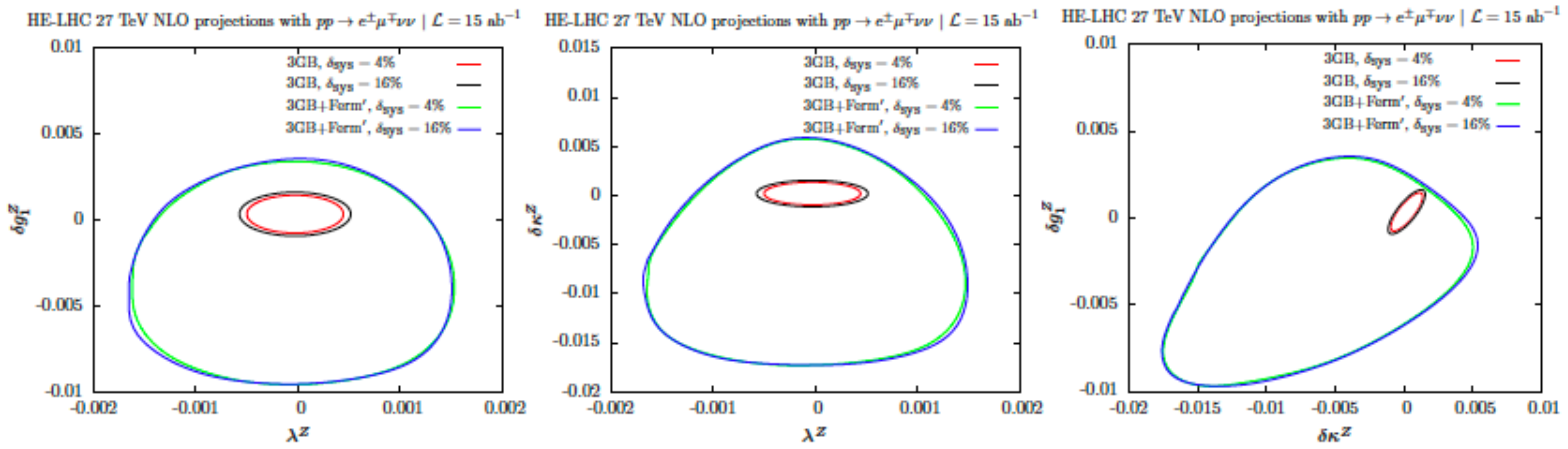


Fig. 41: Projections for 27 TeV with 15 ab^{-1}. $p_{T,cut} = 1350$ GeV, corresponding to $\delta_{stat} = 16\%$ with $\delta_{sys} = 4\%$ and $\delta_{sys} = 16\%$. The curves labelled 3GB have SM Z-fermion couplings, while the curves labelled 3GB +Ferm' allow the Z-fermion couplings to vary around a central value of 0.