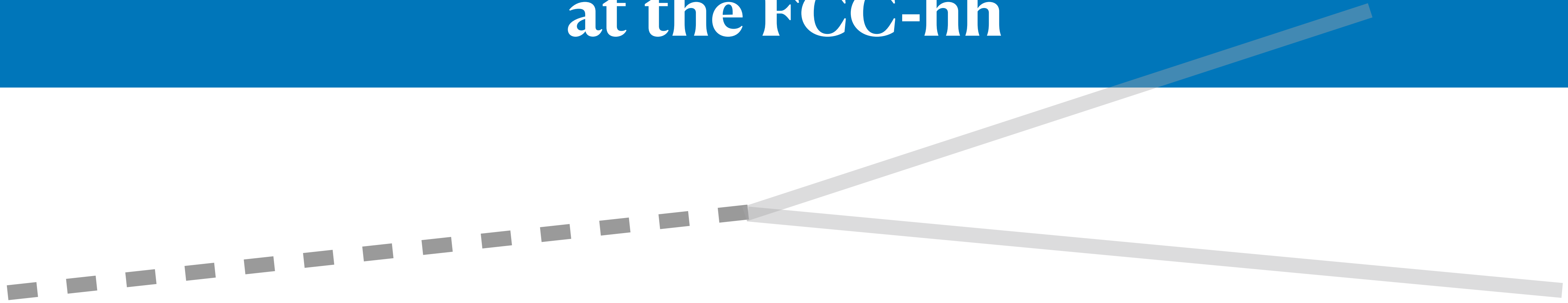
Higgs portal long-lived particle searches at the FCC-hh



Rhitaja Sengupta

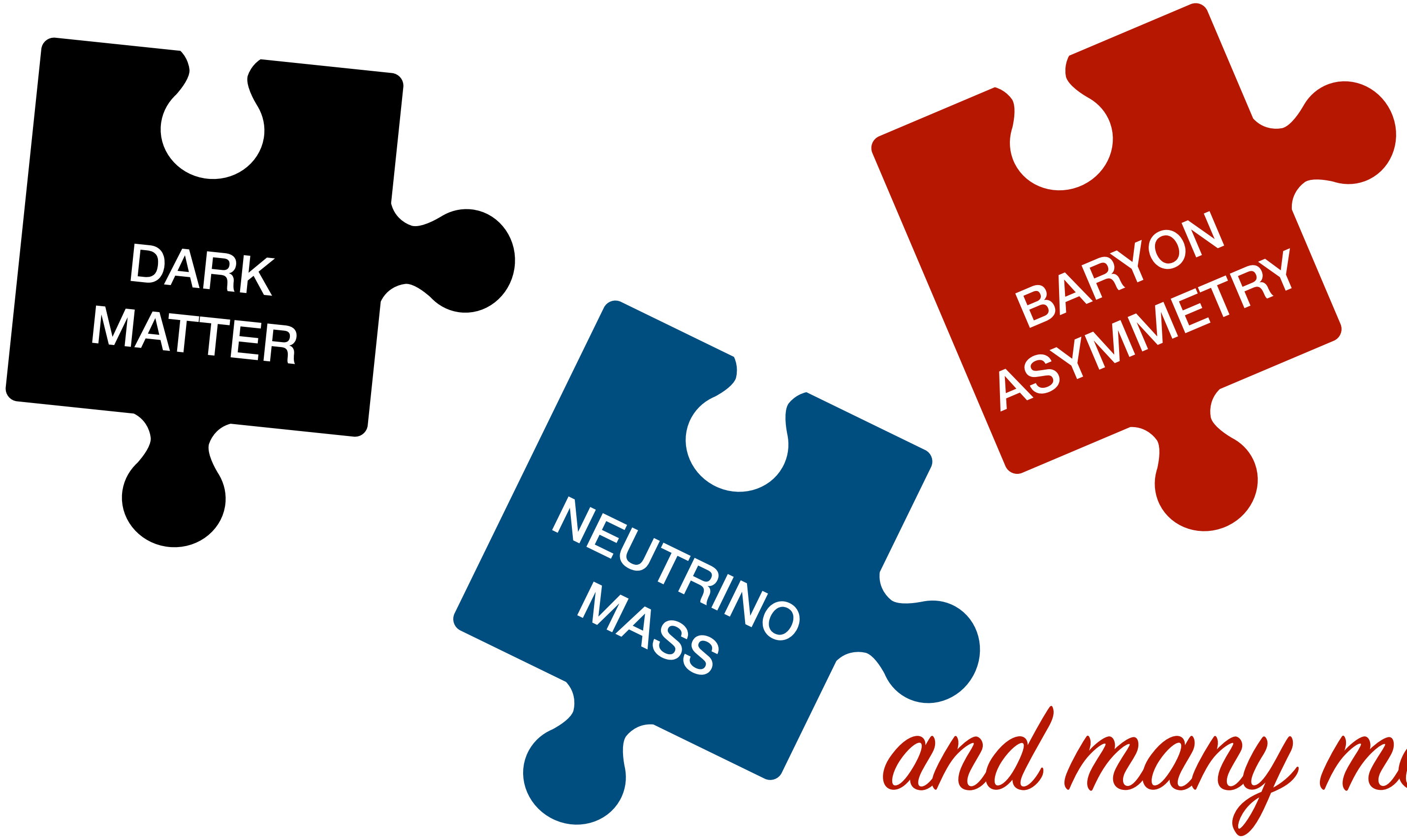
BCTP and Physikalisches Institut
Universität Bonn

Bonn Fall HEP Meeting 2024:
Embracing Diversity in High Energy Physics

October 8, 2024

Standard Model of particle physics (**SM**) *successfully explains many fundamental phenomena of particles*

Still many pieces **missing from the SM**, like



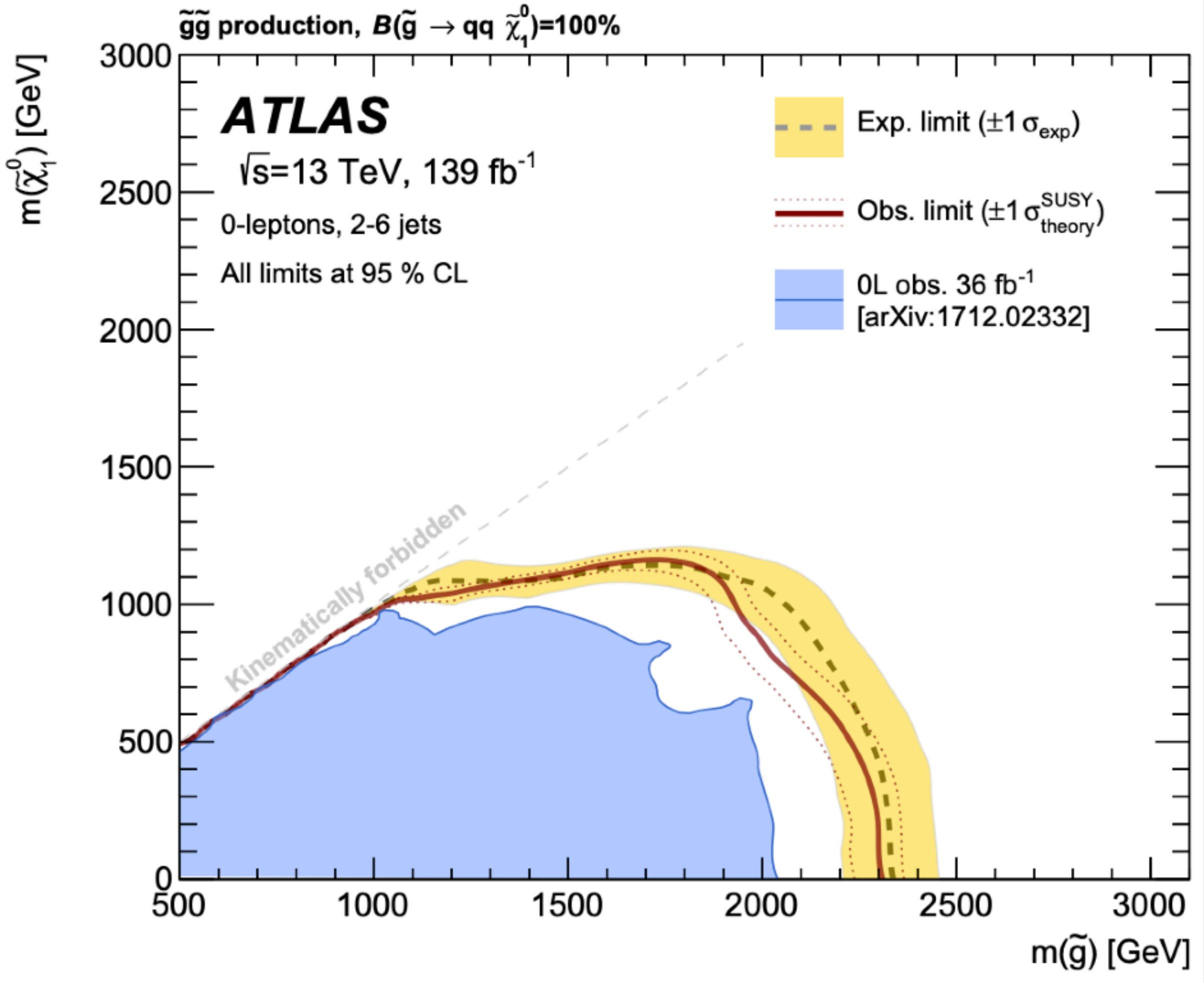
and many more...

We need to look beyond the SM (BSM)

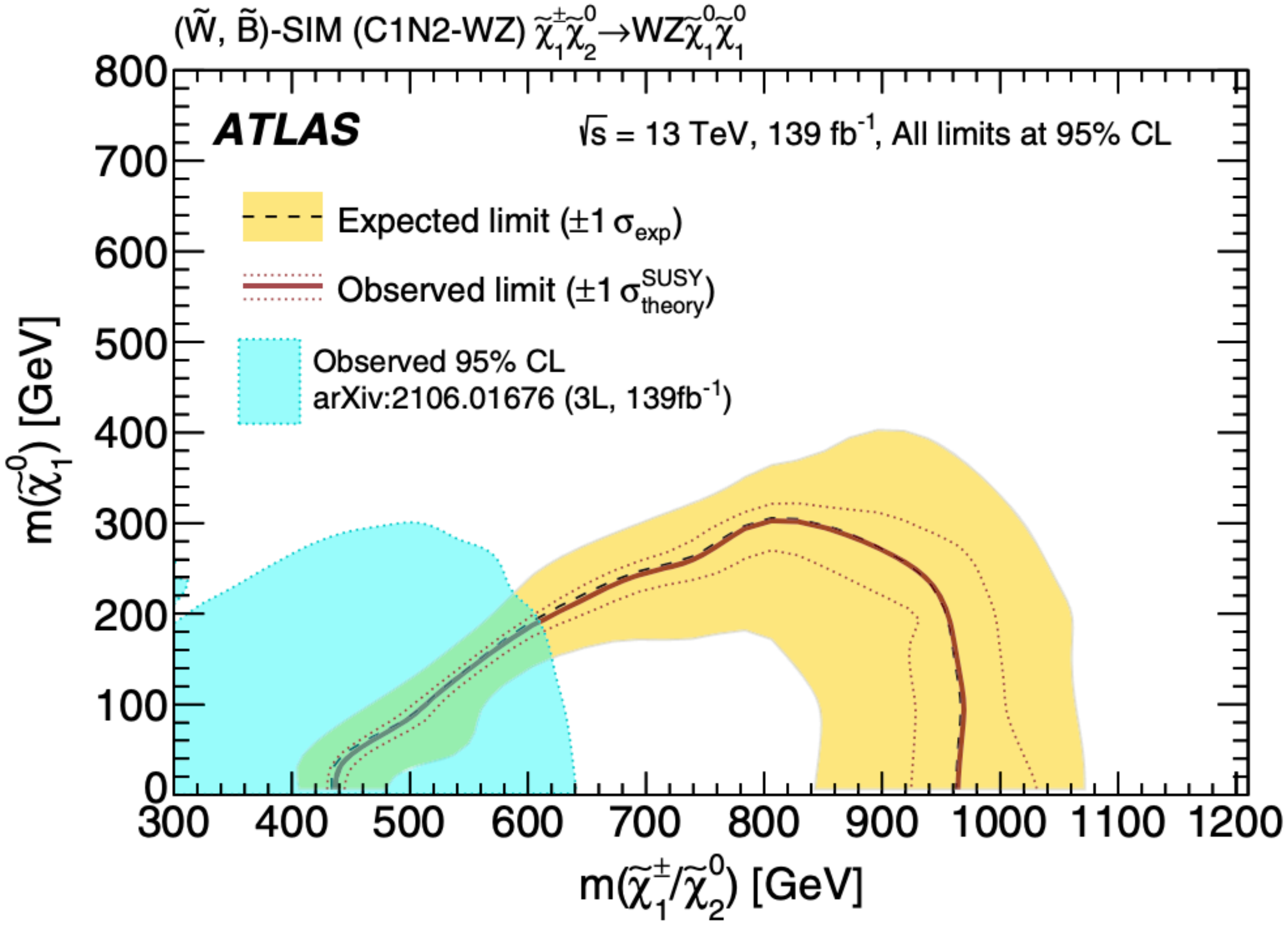
Experiments provide exhaustive bounds on where new physics cannot be and precise measurements of the SM

This gives us directions to look further…

For example, limits on supersymmetric particles at the LHC



ATLAS, *JHEP* 02 (2021) 143



ATLAS, *PRD* 104 (2021) 11, 112010

Takeaway Message

Experiments are putting **stronger constraints on the nature of new physics, especially for the conventional scenarios**

1 New physics appears at a scale beyond LHC or HL-LHC's reach

Extend mass reach by increasing centre of mass energy or with higher precision

2 Scale is within LHC's reach, but the process is very rare or have large backgrounds

Increase luminosity or more sophisticated analyses to reduce backgrounds

3 Their signatures are so unusual that they are overlooked in the present searches

More inclusive or smarter trigger strategies

Takeaway Message

3

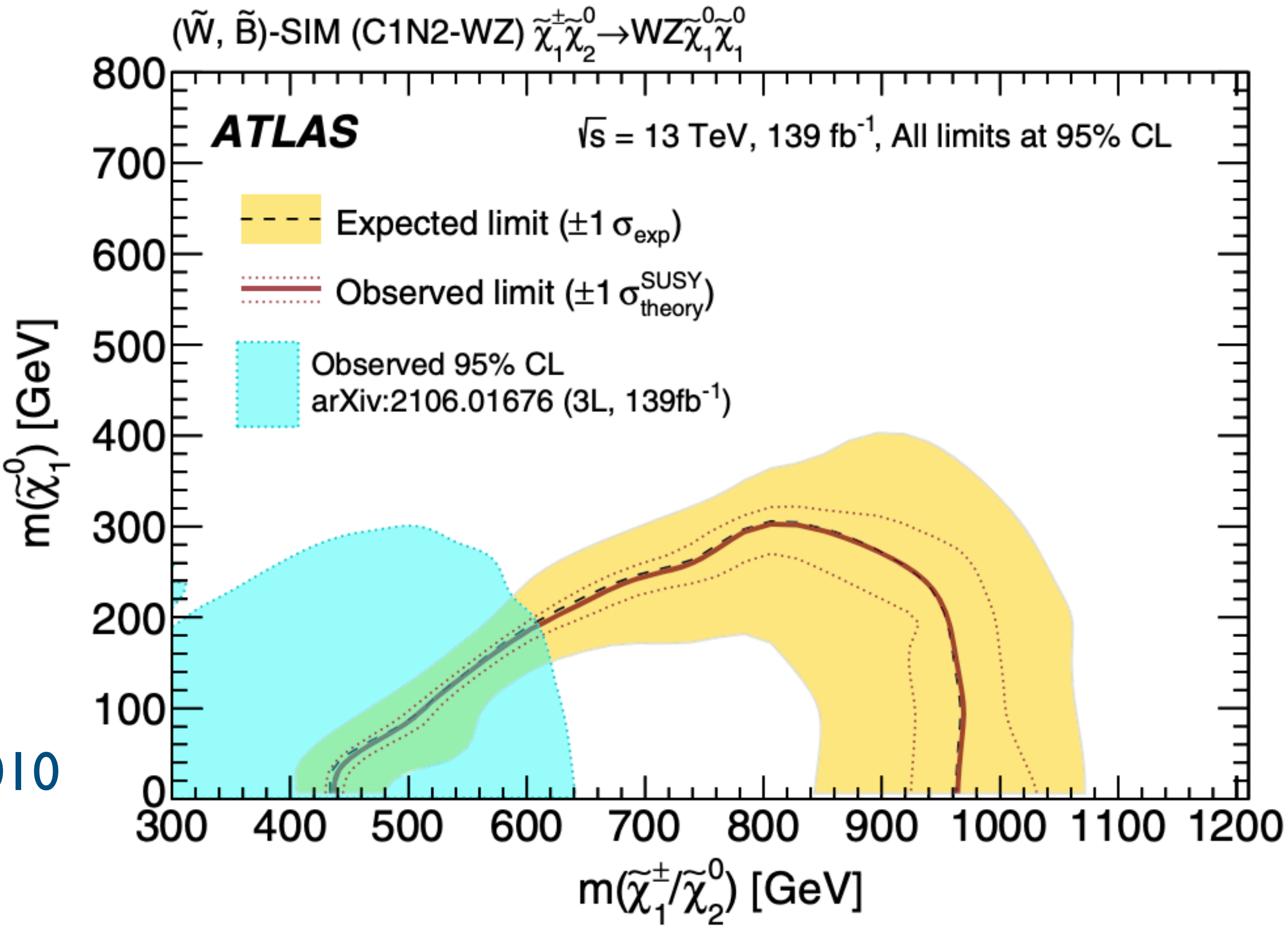
Their signatures are so unusual that they are overlooked in the present searches

More inclusive or smarter trigger strategies

Are we covering the full phase-space of new physics?
Or are we missing something?

Let us revisit some of the assumptions in our search results…

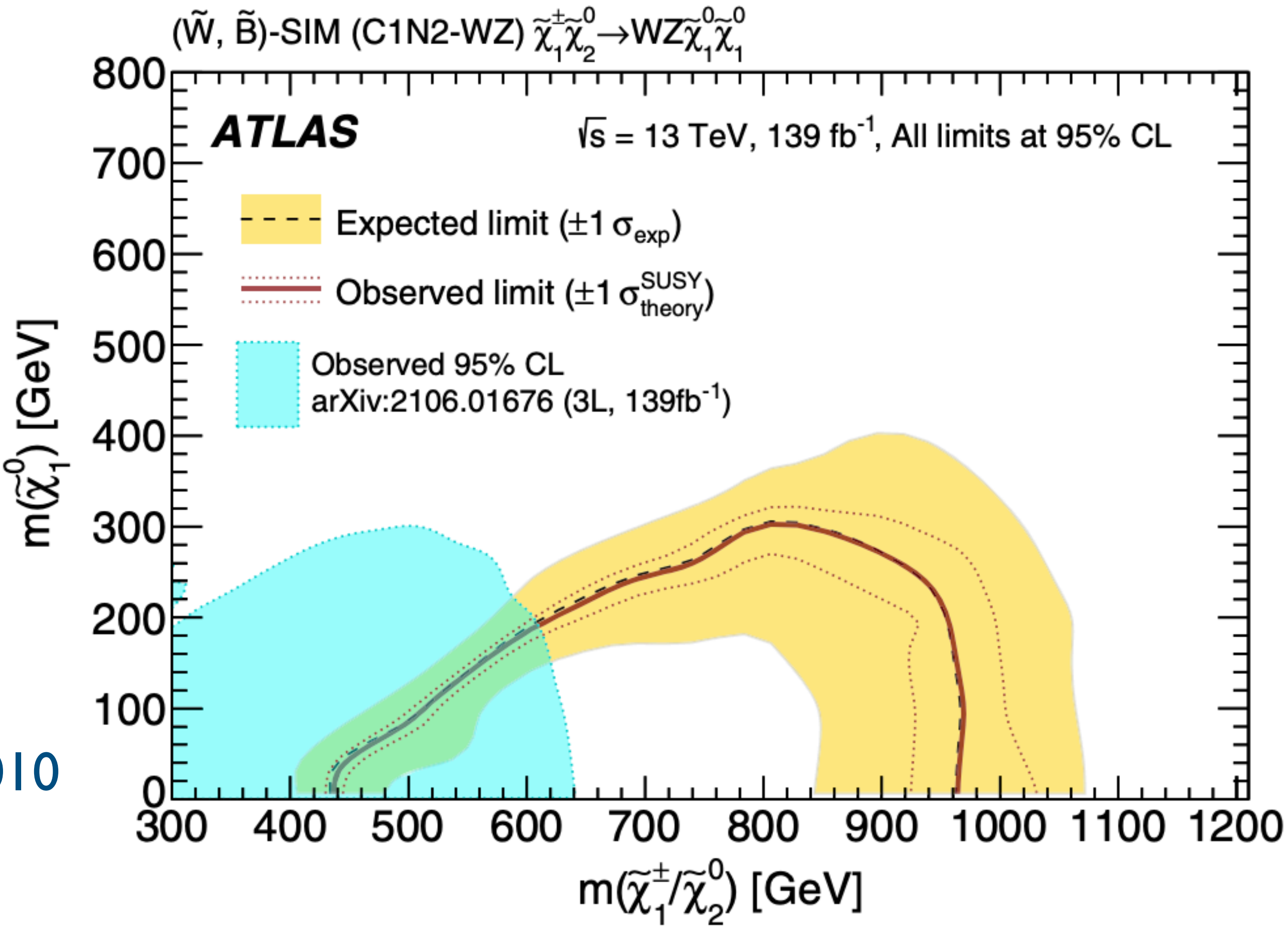
Illustration



ATLAS, PRD.104.112010

Wino-like EWinos are excluded up to masses of 960 GeV

Illustration



ATLAS, PRD.104.112010

Wino-like EWinos are excluded up to masses of 960 GeV

only if

— there is large mass difference between the LSP (bino-like neutralino) and the NLSP (wino-like EWinos)

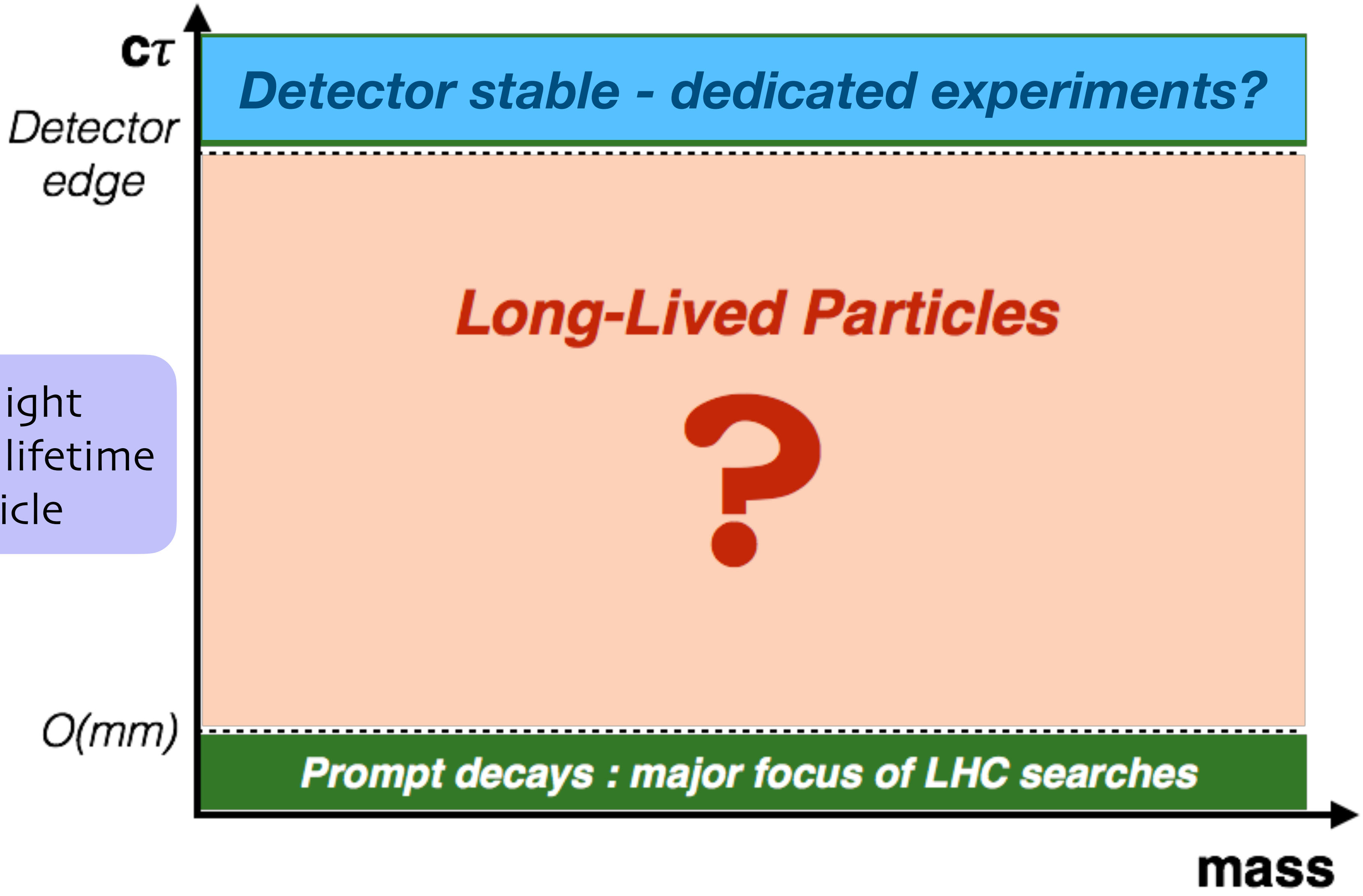
— Br($\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow WZ\tilde{\chi}_1^0\tilde{\chi}_1^0$) = 100%

— only wino and bino are present in the spectrum, other particles are decoupled and $M_2 > M_1$

— the decay is **prompt**

Most of the conventional LHC searches focus on **prompt decay** of particles.

like top quark, W/Z bosons in SM $\tau \sim 10^{-25}$ s
($\Gamma \sim 2.5$ GeV)



c: speed of light
τ: proper mean lifetime of the particle

Lifting up the assumption of prompt decays

open the door to the **Lifetime Frontier**

well motivated in many BSM scenarios **largely unexplored**

LLPs

WHAT ARE LONG-LIVED PARTICLES?

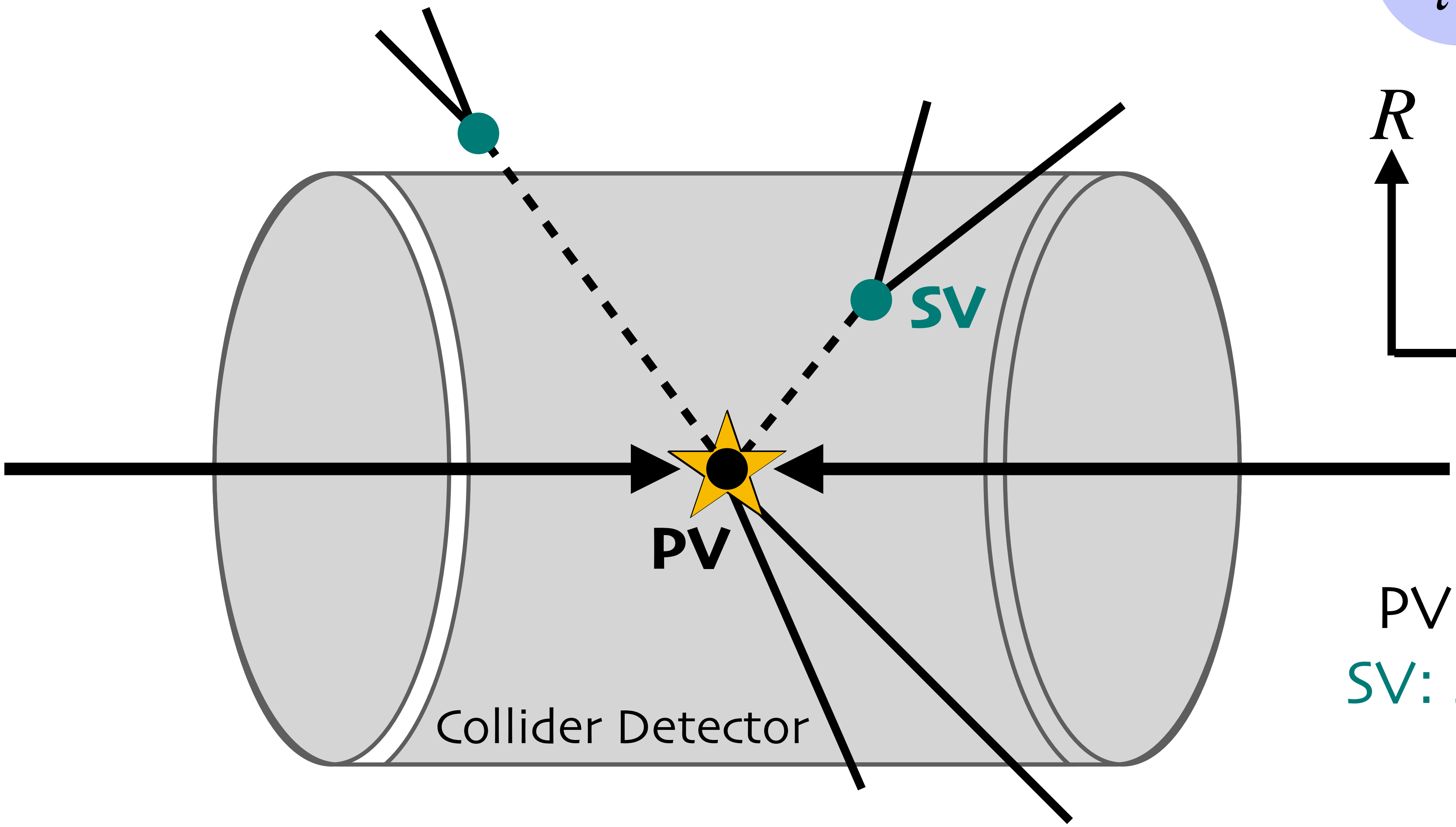
Particles with **large lifetimes (τ)**

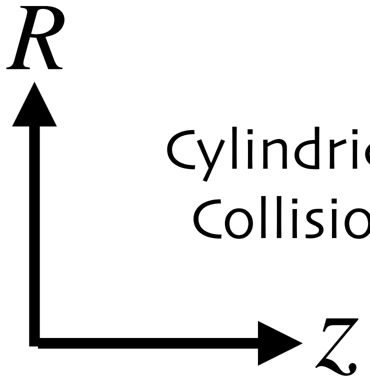
— decays after traversing a macroscopic distance in the collider detectors

— or, decays outside the detector

$c\tau \gtrsim \mathcal{O}(\mathrm{mm})$

$\tau \gtrsim \mathcal{O}(10\,\mathrm{ps})$





Cylindrical coordinates
Collision along z axis

PV: Primary Vertex
SV: Secondary Vertex

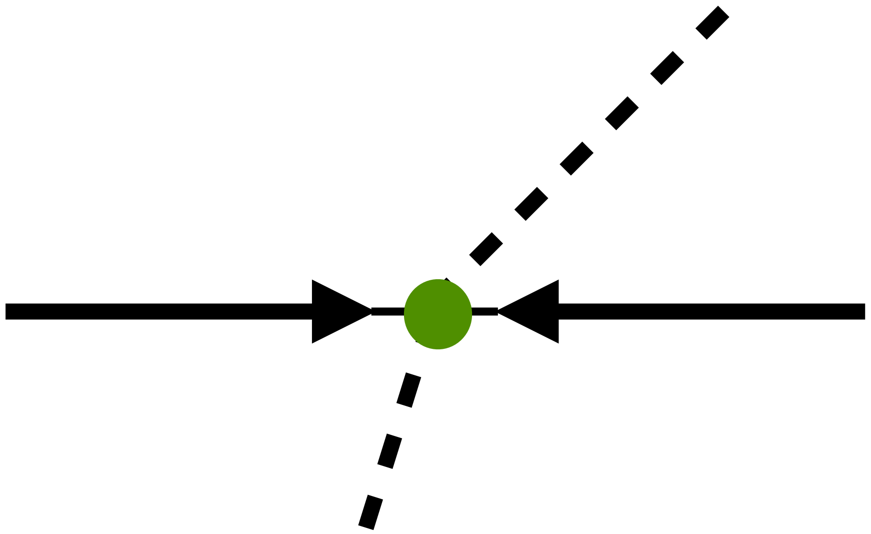
Effect of magnetic field not shown

LLPs in colliders: the 3 major ingredients

THEORY

PRODUCTION

- Production rate, σ
- Boost and direction

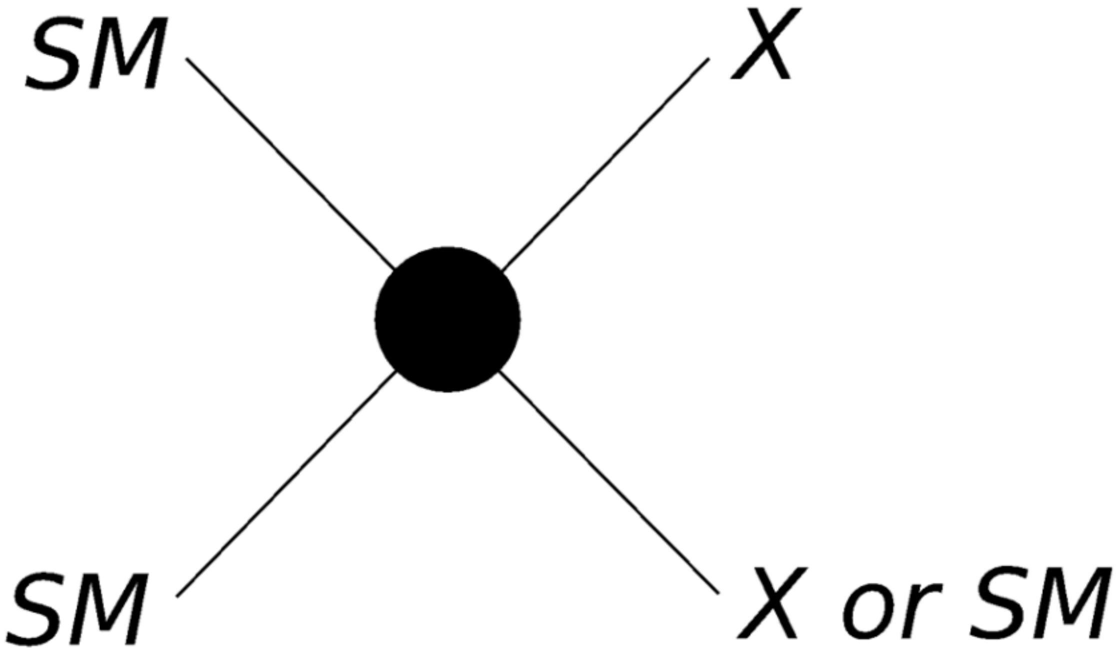


Production of LLPs in colliders

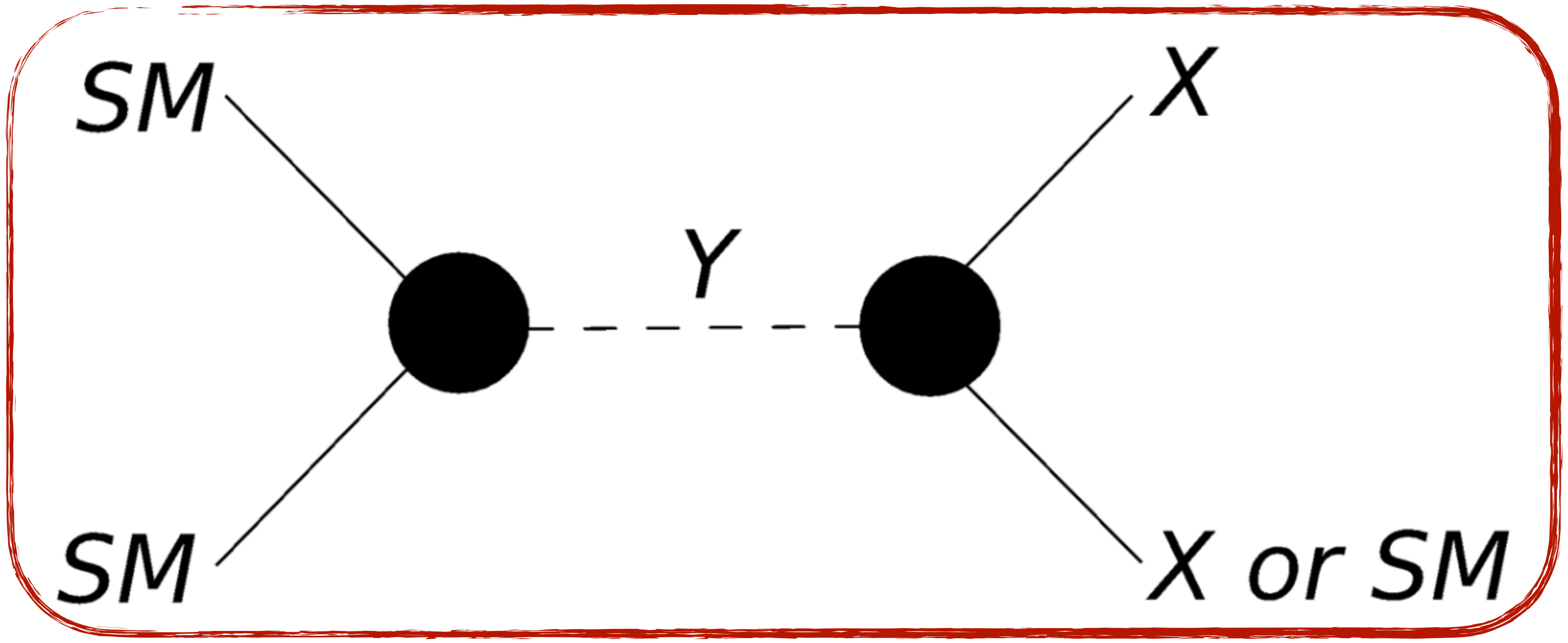
X - LLP

Y - SM/new particle

Direct Production



From the decay of a resonance



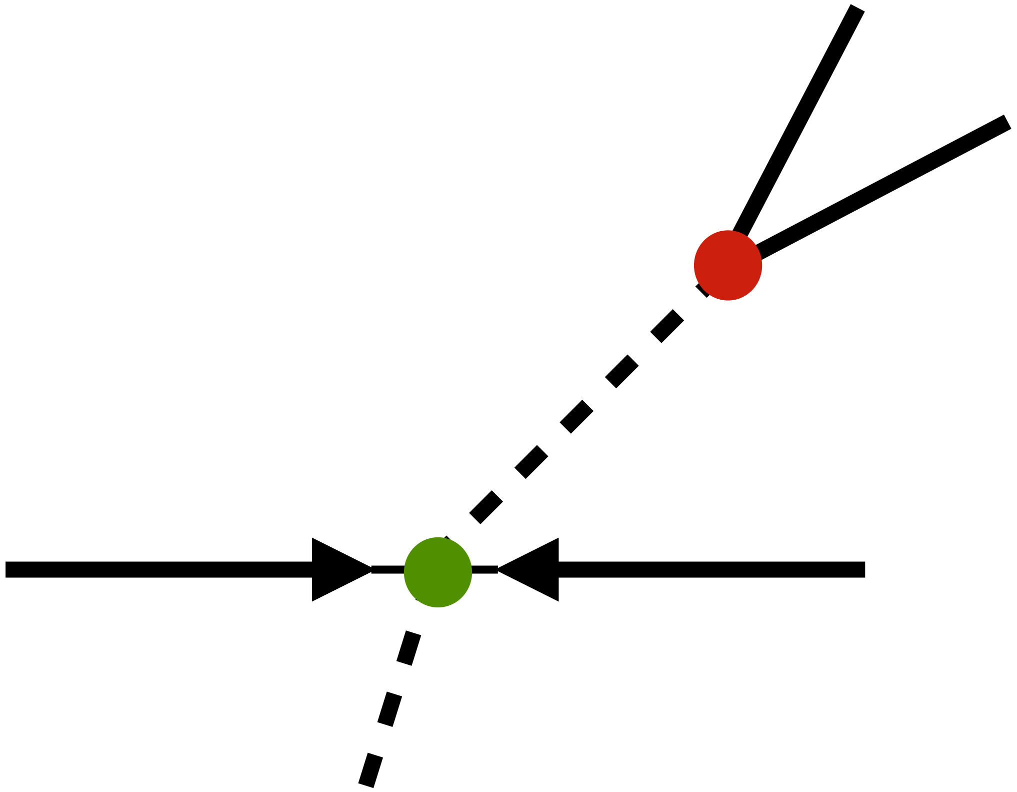
LLPs in colliders: the 3 major ingredients

THEORY
PRODUCTION

- Production rate, σ
- Boost and direction

THEORY
DECAY

- Decay width, Γ or Lifetime, τ
- Decay modes



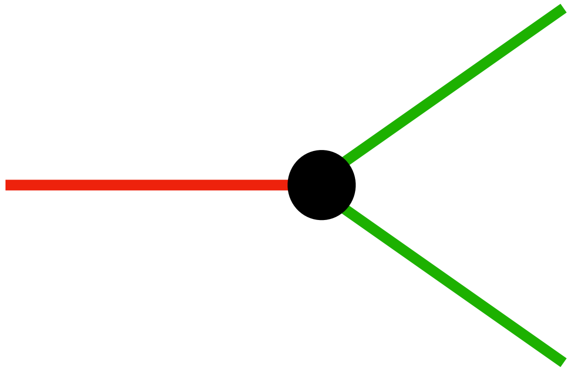
Reasons behind long lifetimes

?

$$\Gamma\left(\text{or } \frac{1}{\tau}\right) \propto |\,\text{Amplitude}\,|^2 \times (\text{Phase space factor})$$

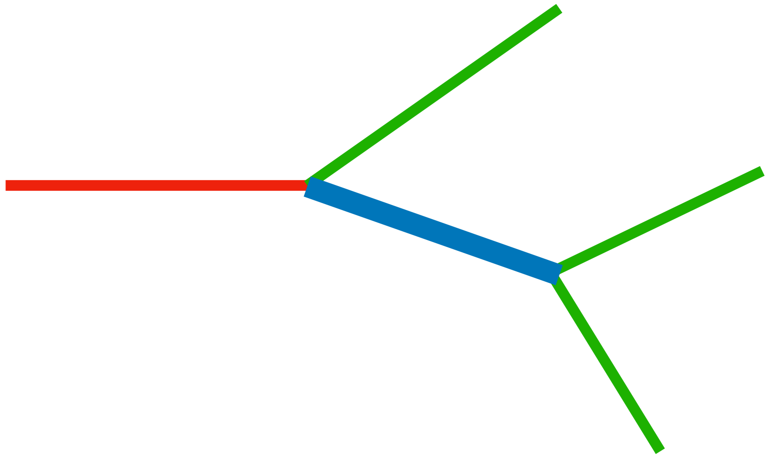
Small couplings

e.g., c and b quarks (SM),
RPV SUSY (BSM)



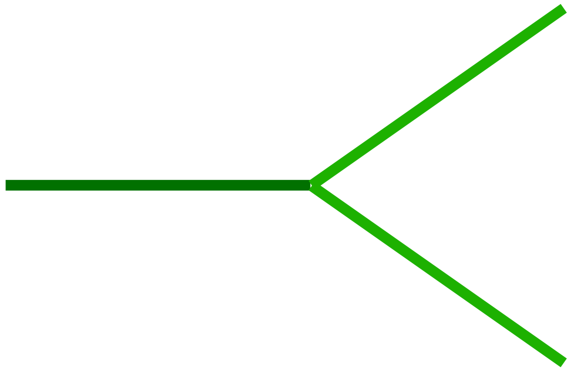
Heavy scales, $\Gamma \sim \frac{m^5}{M^4}$

e.g., muon (SM),
gluino in Split-SUSY (BSM)



Kinematic squeezing

e.g., neutron (SM),
compressed SUSY
scenarios (BSM)



LLP decays in colliders

Decay length in the detector

d is the **product** of $\beta\gamma$ and $c\tau$ **distributions**

LAB FRAME

$$\boxed{d = \beta\gamma c\tau}$$

from PRODUCTION mode

from DECAY width

$$\boxed{\beta\gamma = \frac{p}{m} : \text{boost factor}}$$

c : speed of light

τ : proper mean lifetime of the particle

Lighter particles ⇒ more displaced as compared to heavier ones for the same lifetime

LLPs in colliders: the 3 major ingredients

THEORY

PRODUCTION

- Production rate, σ
- Boost and direction

THEORY

DECAY

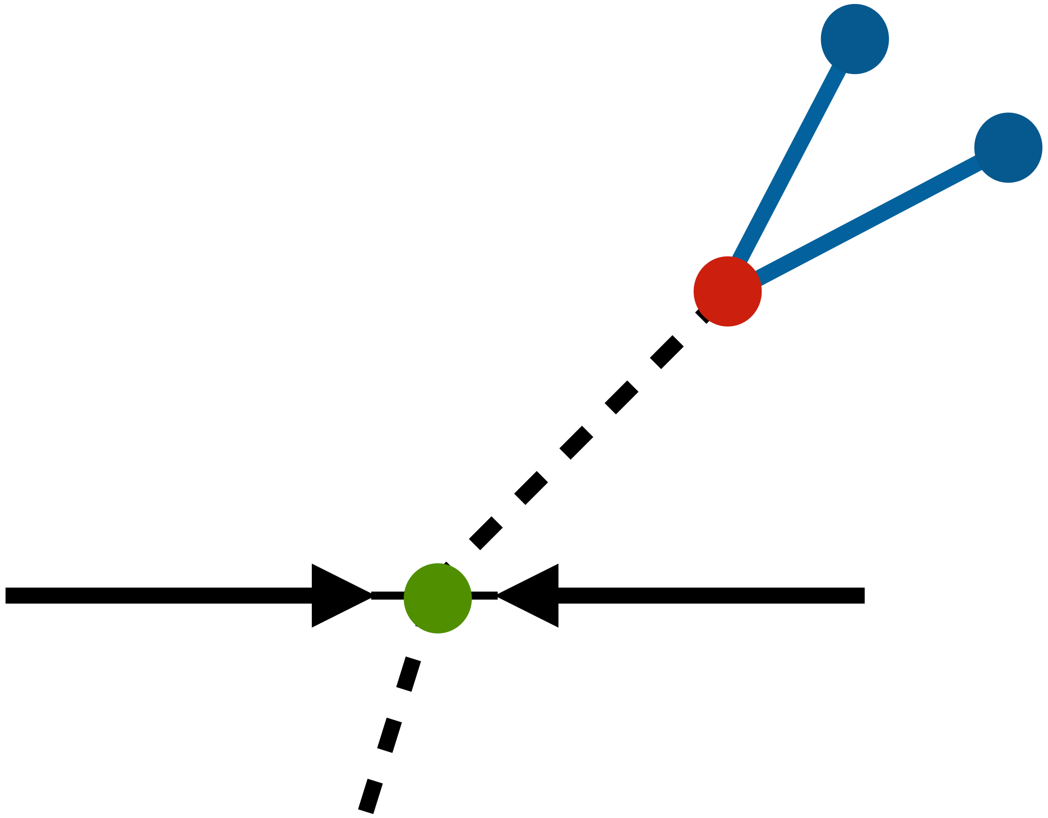
- Decay width, Γ or Lifetime, τ
- Decay modes

EXPERIMENT

DETECTION

depends on

- what it decays into
- where it decays



The 3 major ingredients

THEORY
PRODUCTION

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THEORY
DECAY

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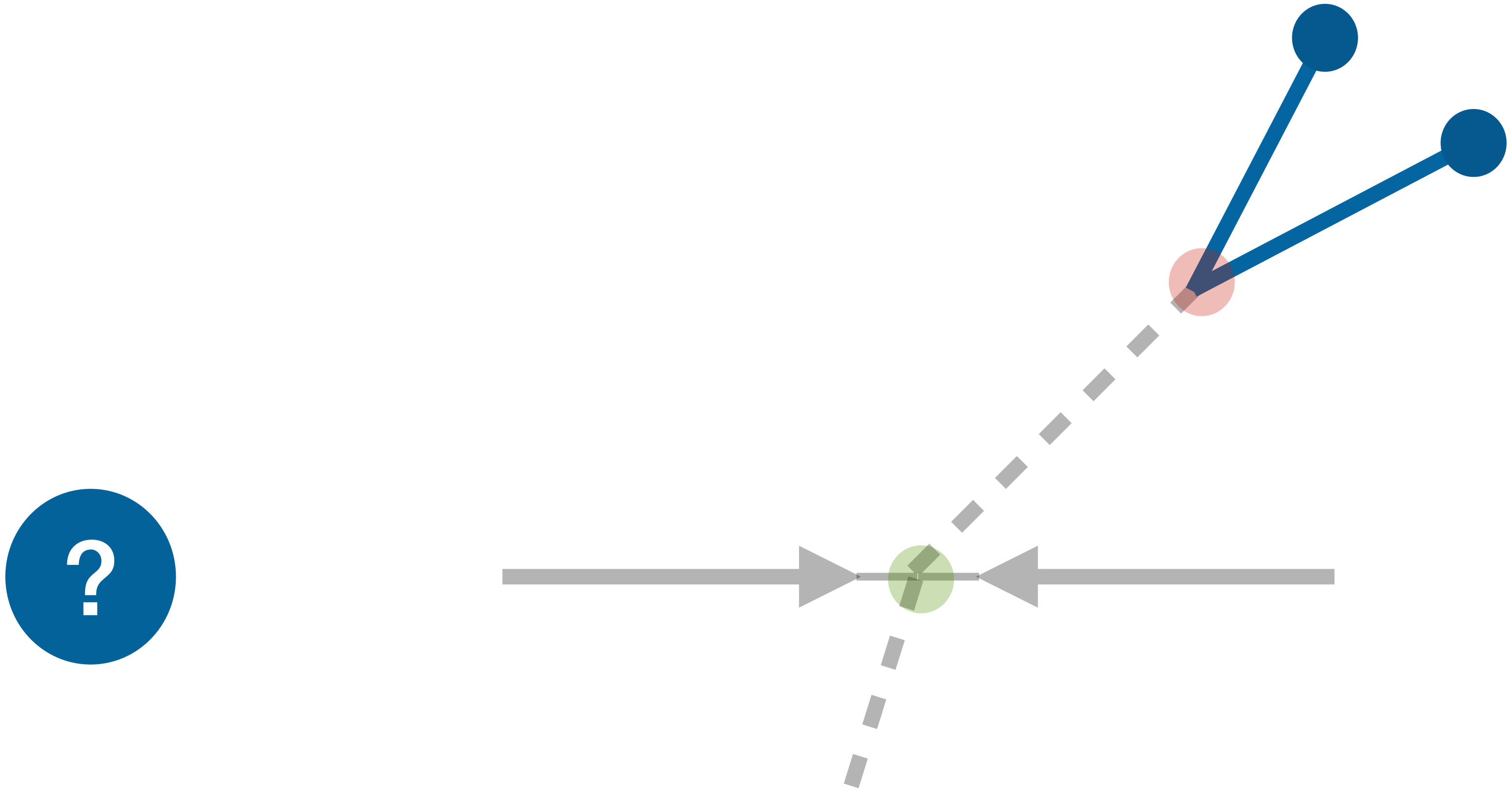
EXPERIMENT
DETECTION

depends on
- what it decays into
- where it decays

similar for prompt decays as well



The 3 major ingredients

THEORY
PRODUCTION

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THEORY
DECAY

- Decay width, Γ or Lifetime, τ
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DETECTION

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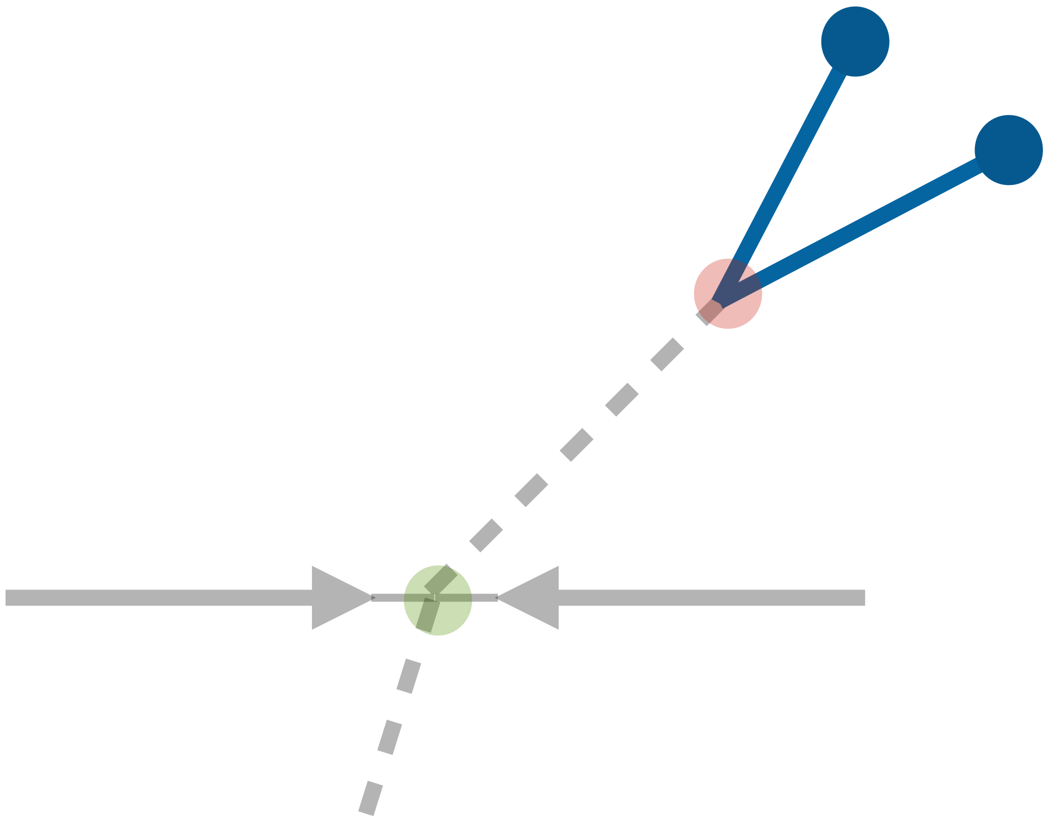
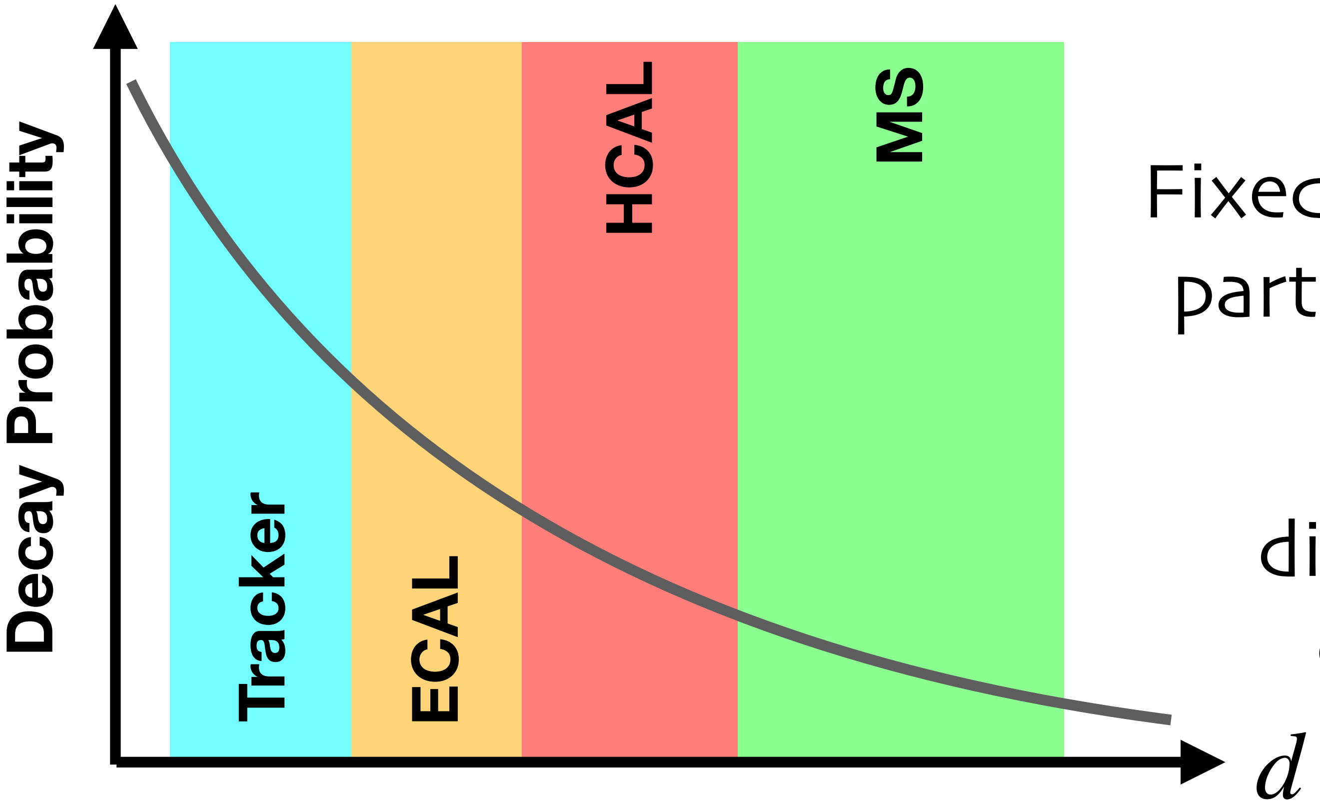
- what it decays into
- where it decays



Decay position of the LLP



Fixed m and $c\tau$ of a BSM particle with a particular production and decay mode

$\Downarrow$

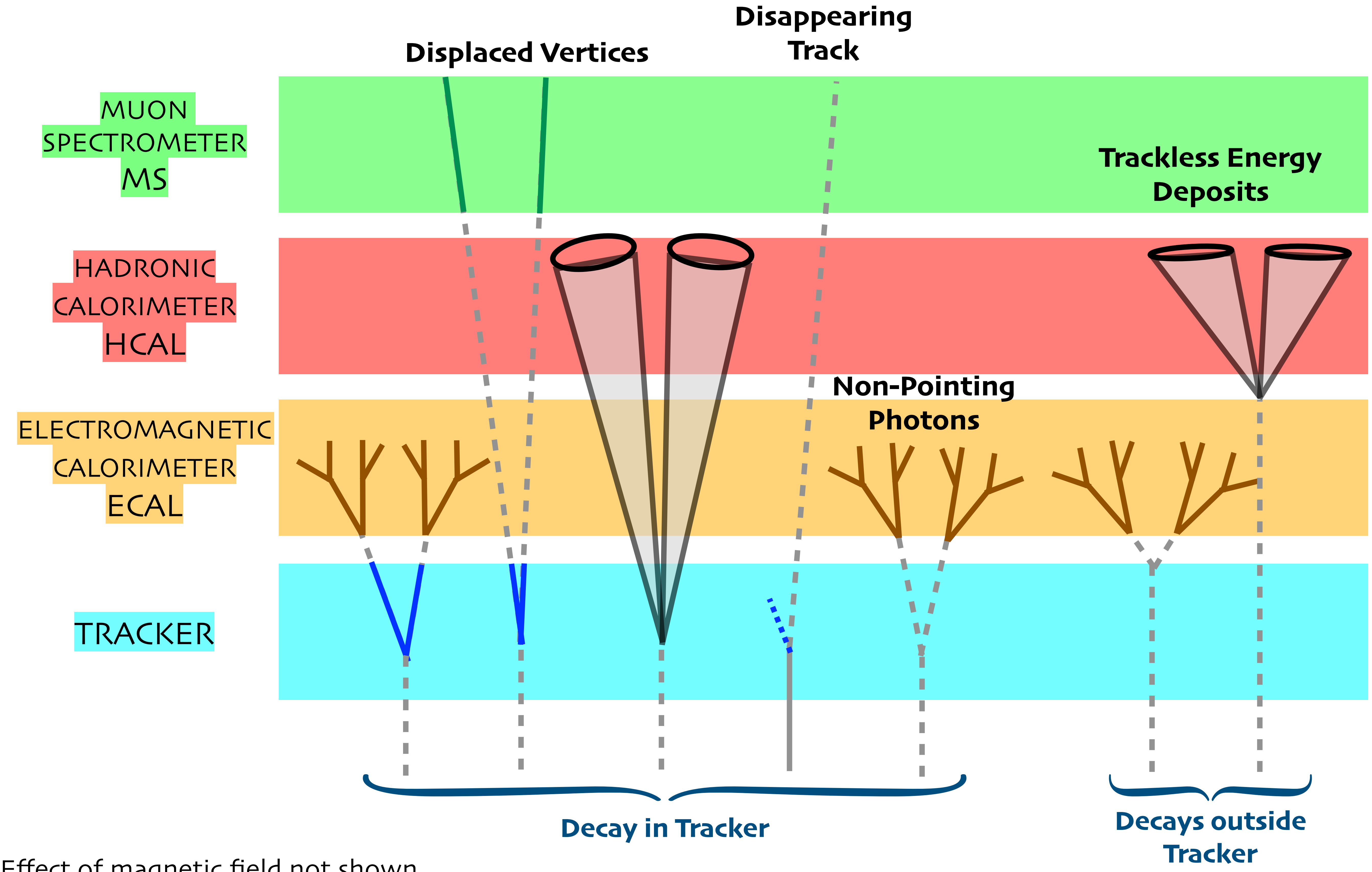
different probabilities to decay in different parts of the detector

Say, a BSM particle decays to two electrons

Prompt scenario	**LLP**
Final state signature fixed 2 electrons ⇒ energy deposits in the ECAL with associated tracks in the Tracker	**DECAYS WHERE?** **Tracker:** displaced vertex **ECAL:** trackless energy deposit **HCAL/MS:** ?

A Peek in to the Exotic Signatures of LLPs

not a complete list



Effect of magnetic field not shown

Rhitaja Sengupta

Long-lived particles in the Higgs portal

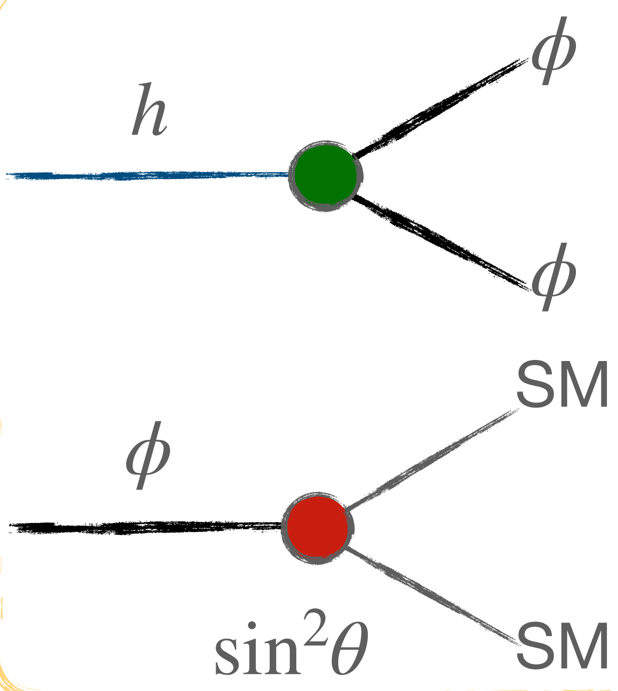
Shigeki Matsumoto, et al., *JHEP* 07 (2019) 050

Light Scalar Mediator

$$\mathcal{L} \subset -m_\phi^2\phi^2 - \sin\theta\,\frac{m_f}{v}\phi\bar{f}f - \lambda_{h\phi\phi}h\phi\phi + \ldots$$

Mixing highly constrained

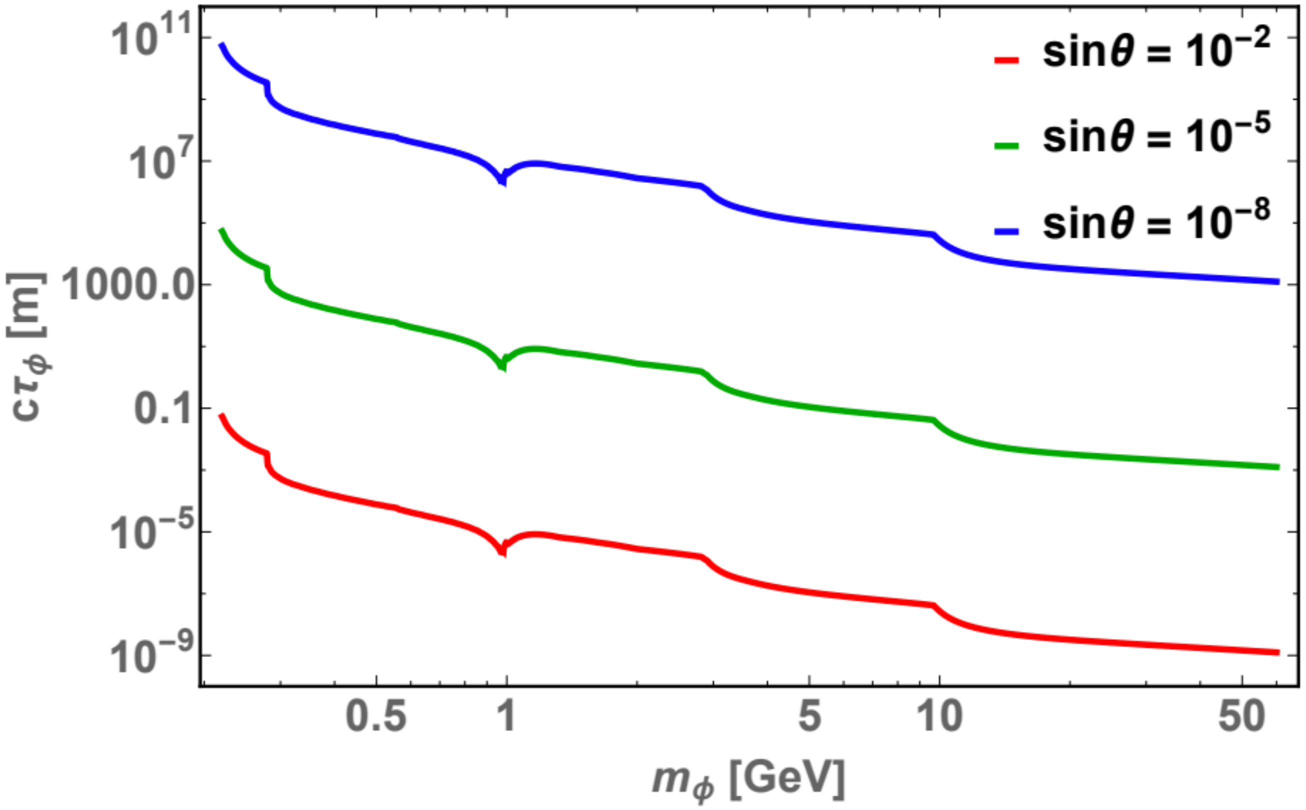
Not severely constrained so far



Production of ϕ has a different coupling than its decay

$\sin^2\theta$ ↓ $c\tau_\theta$ ↑

Long-lived mediator



Long-lived particles in the Higgs portal

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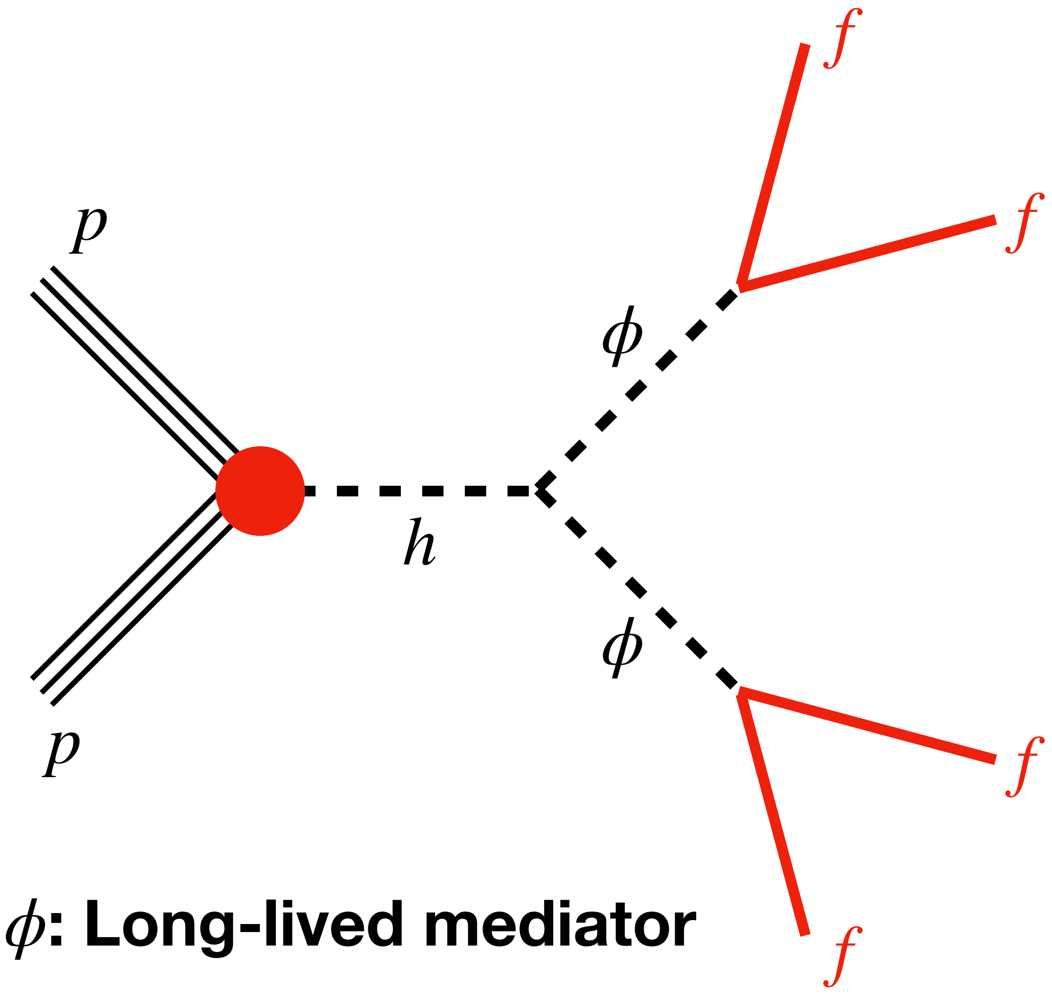
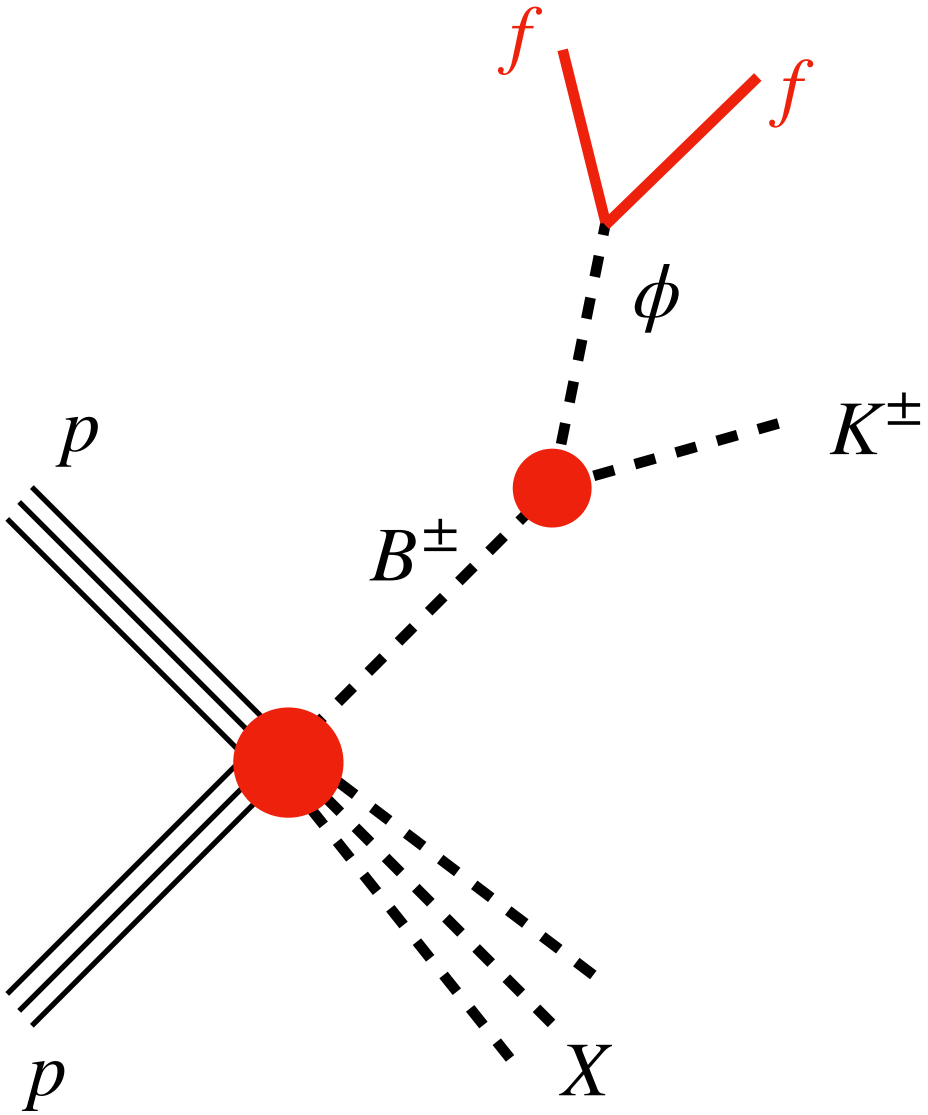


ϕ: **Long-lived mediator**



Light Long-Lived Particles

produced from decay of SM particles, like the Higgs boson, $m_{LLP} \leq m_h/2$

Decay products often have low p_T

Not much radiation associated with production

Triggering?

Difficult to trigger if there are no associated prompt hard particles

Primary vertex identification?

More chances of incorrect assignment of primary vertex

$$\beta\gamma = \frac{p}{m}$$

High boost for small m

Displaced vertices?

Larger decay length in the detector - secondary vertex reconstruction difficult as efficiency of Tracker decreases with increasing displacement

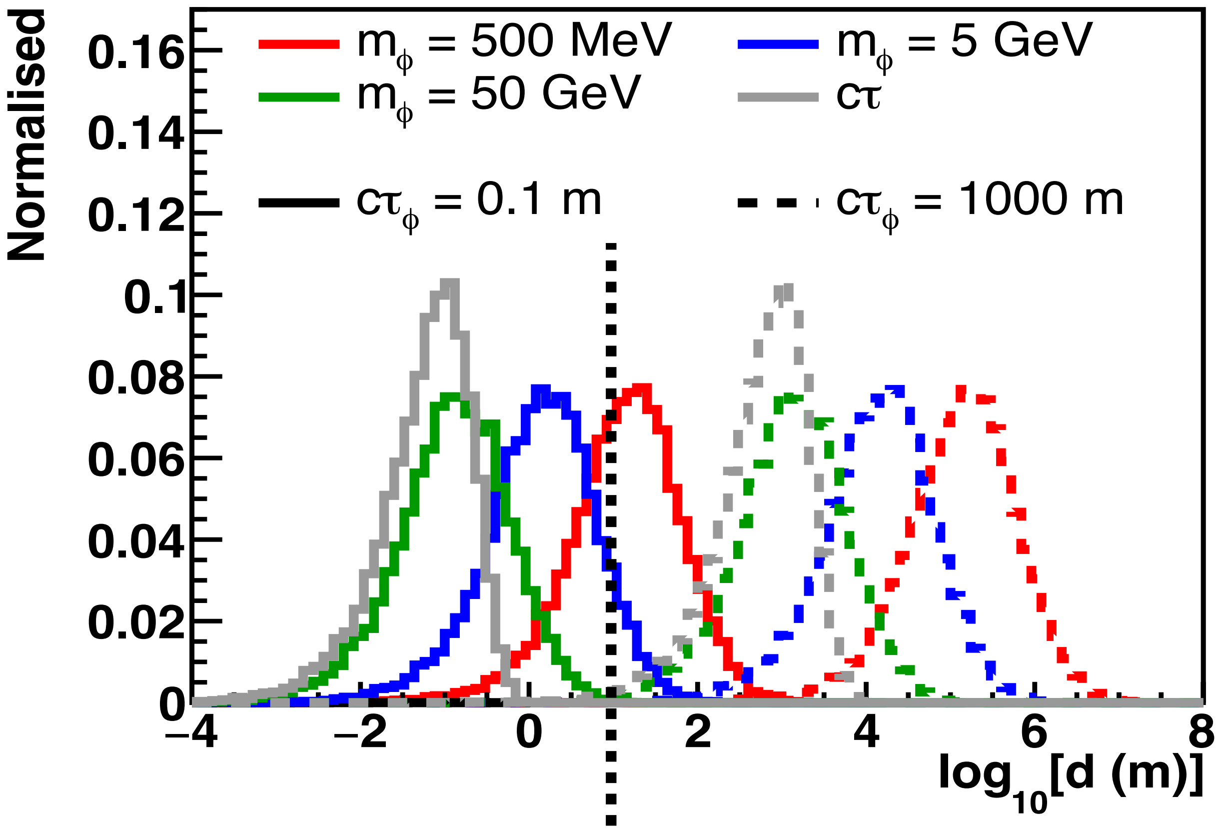
Delayed decay products?

Relativistic LLP - no significant time delay in decay products

Decays outside the collider detector?

Dedicated detectors for LLPs

Distribution of decay length in the lab frame, $d = \beta\gamma c\tau$



ATLAS and CMS main detectors can probe

after $\mathcal{O}(10)$ m, ATLAS and CMS main detectors lose sensitivity

HL-LHC:

FASER	1811.12522
FACET	2201.00019
MATHUSLA	1901.04040
CODEX-b	1911.00481
ANUBIS	1909.13022
AL3X	1810.03636

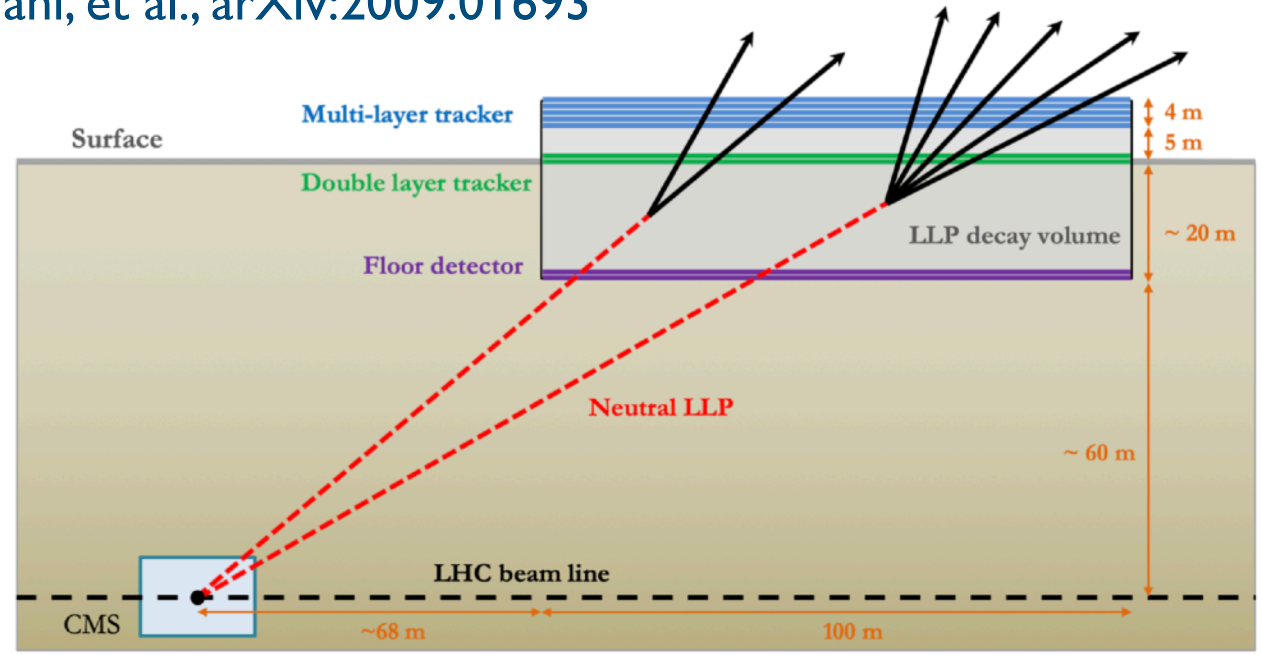
FCC-ee: HECATE 2011.01005

ILC: near/far detectors 2202.11714

BELLE-II: GAZELLE 2105.12962

MATHUSLA and CODEX-b

Cristiano Alpigiani, et al., arXiv:2009.01693

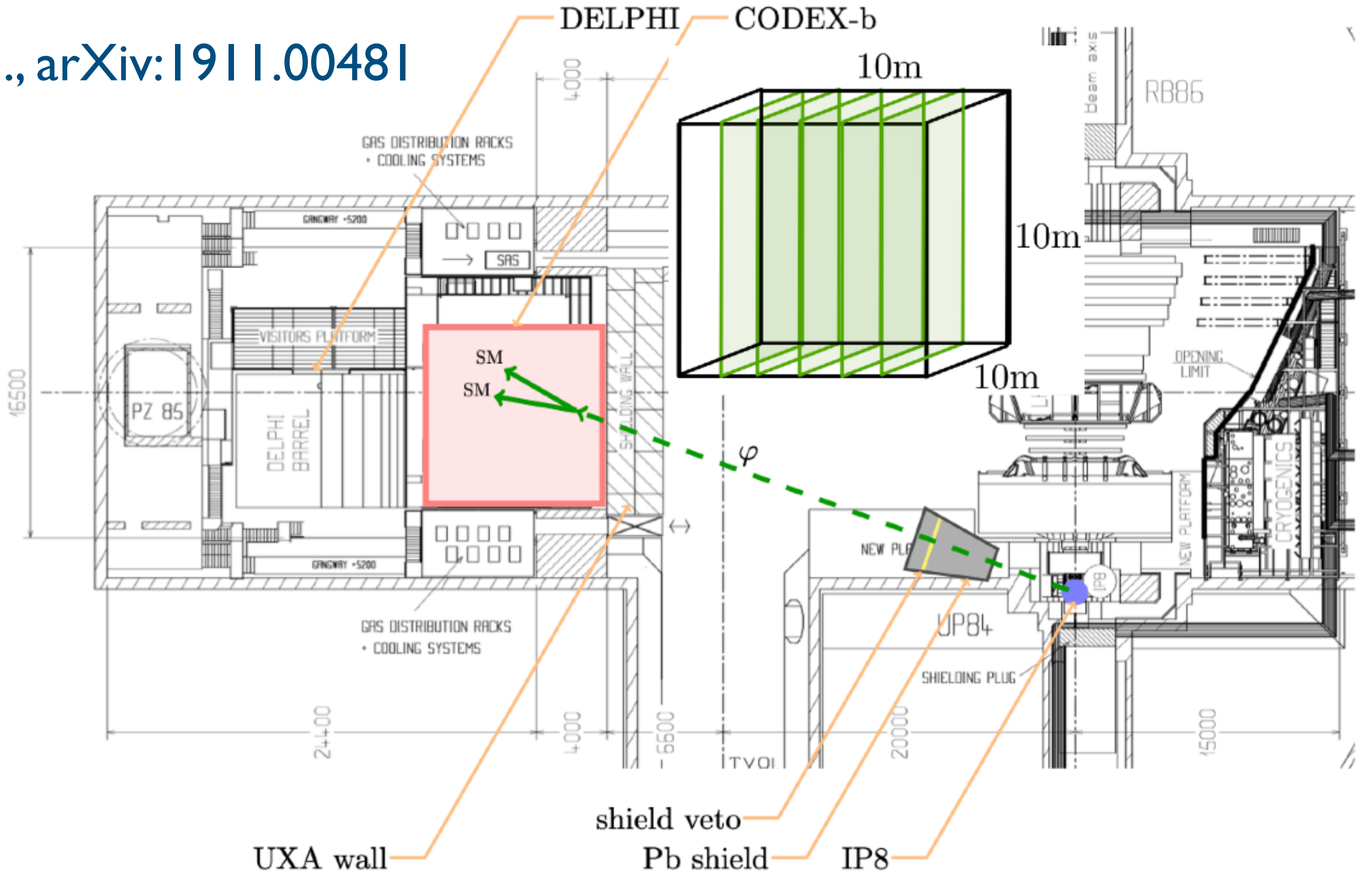


BACKGROUND FREE!

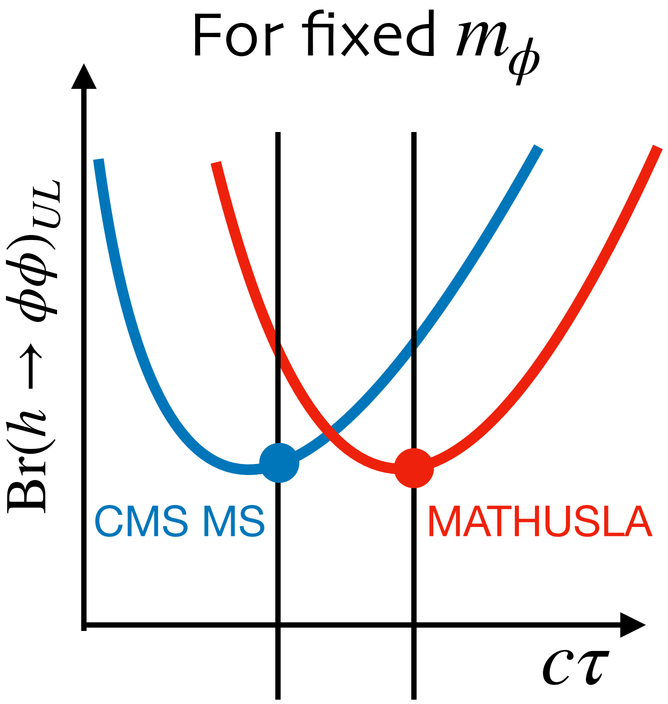
observation of few events (~4) enough to claim discovery

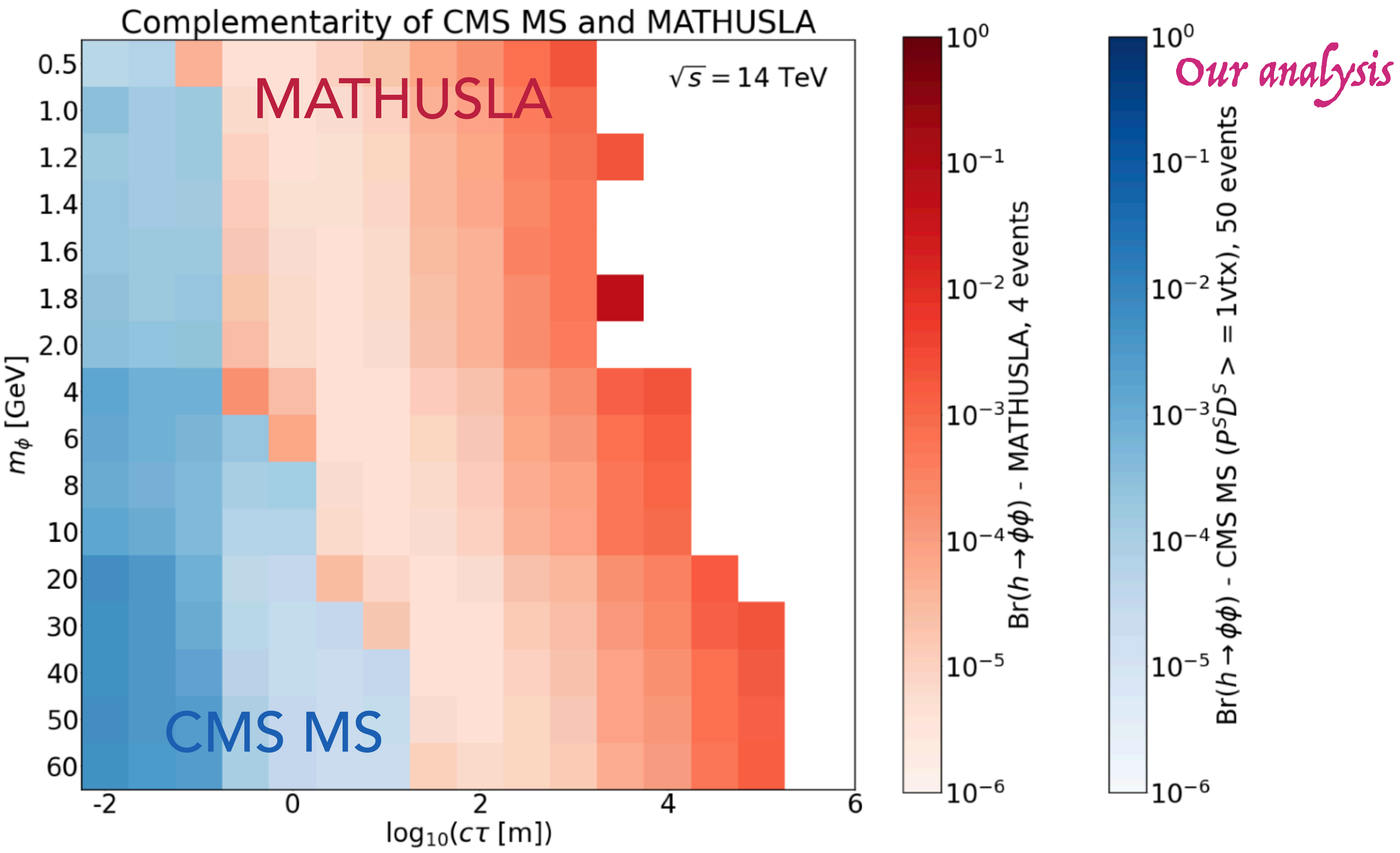
validated and extended analysis for our benchmarks

Giulio Aielli, et al., arXiv:1911.00481



CMS MS and MATHUSLA


For fixed m_ϕ


Complementarity of CMS MS and MATHUSLA

Our analysis

CMS MS + MATHUSLA:

can probe $c\tau \lesssim 10^5\,\mathrm{m}$ for $m_\phi = 60\,\mathrm{GeV}$,

without any gap if $\mathrm{Br}(h \to \phi\phi) \gtrsim 0.1\,\%$

Precise measurements - precursors to discoveries

Looking back...

1970's: precision measurements of neutral currents → the existence of W and Z bosons and hints of their masses

1980's: W and Z bosons observed in the CERN Sp$\bar{p}$S collider

1990's: CERN LEP measured properties of W and Z bosons with high precision → inferring the mass of the still undiscovered top quark

1995: Top quark observed at the Tevatron

With the measured top quark mass, precision measurements at the LEP, SLAC Linear Collider and Tevatron led to a better prediction of the Higgs boson mass

2012: Higgs boson discovered at the LHC

Electron-positron colliders

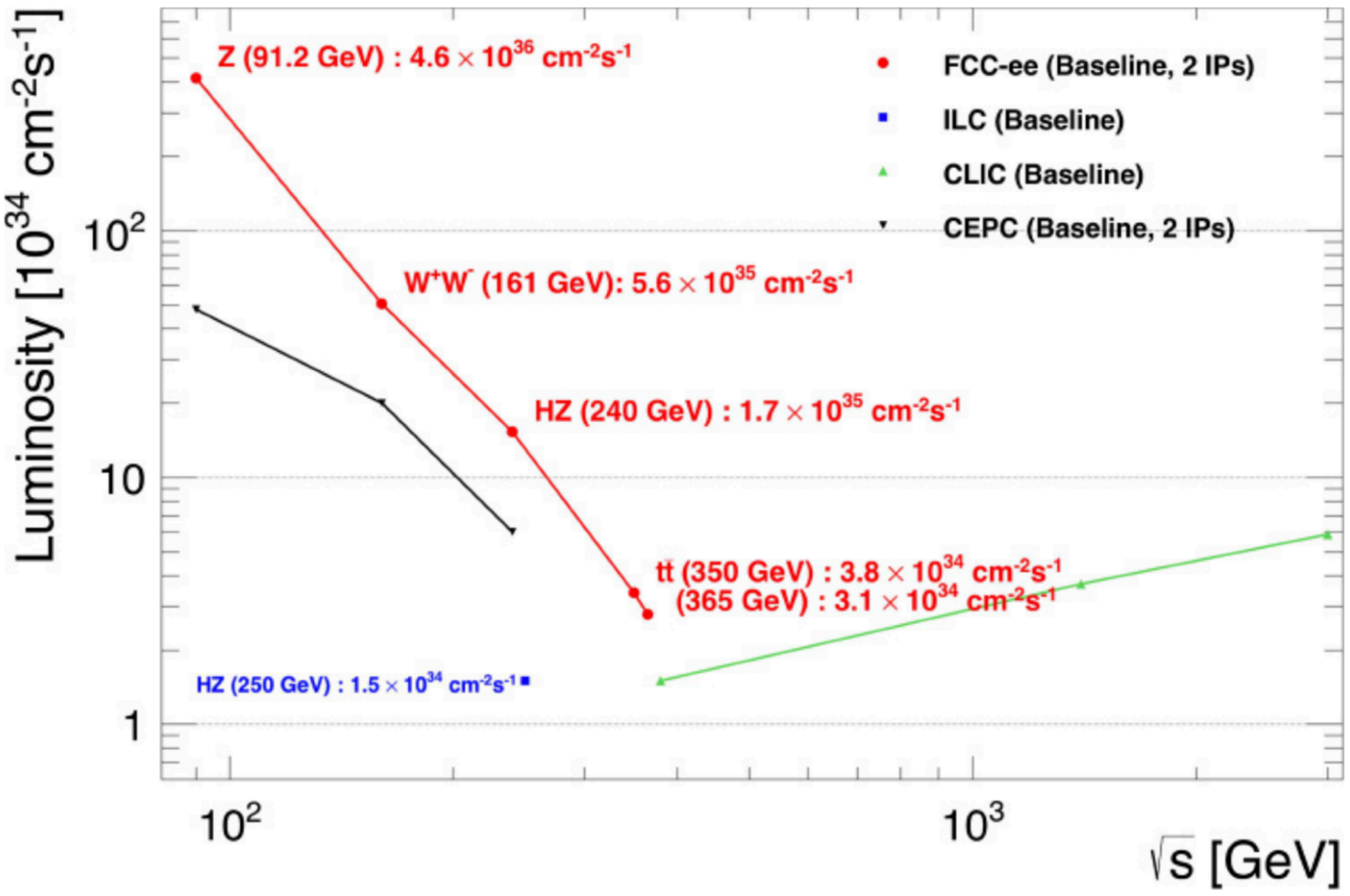
Towards more precision…

International Linear Collider (ILC)

Circular Electron Positron Collider (CEPC)

Compact Linear Collider (CLIC)

Future e^+e^- Circular Collider (FCC-ee)

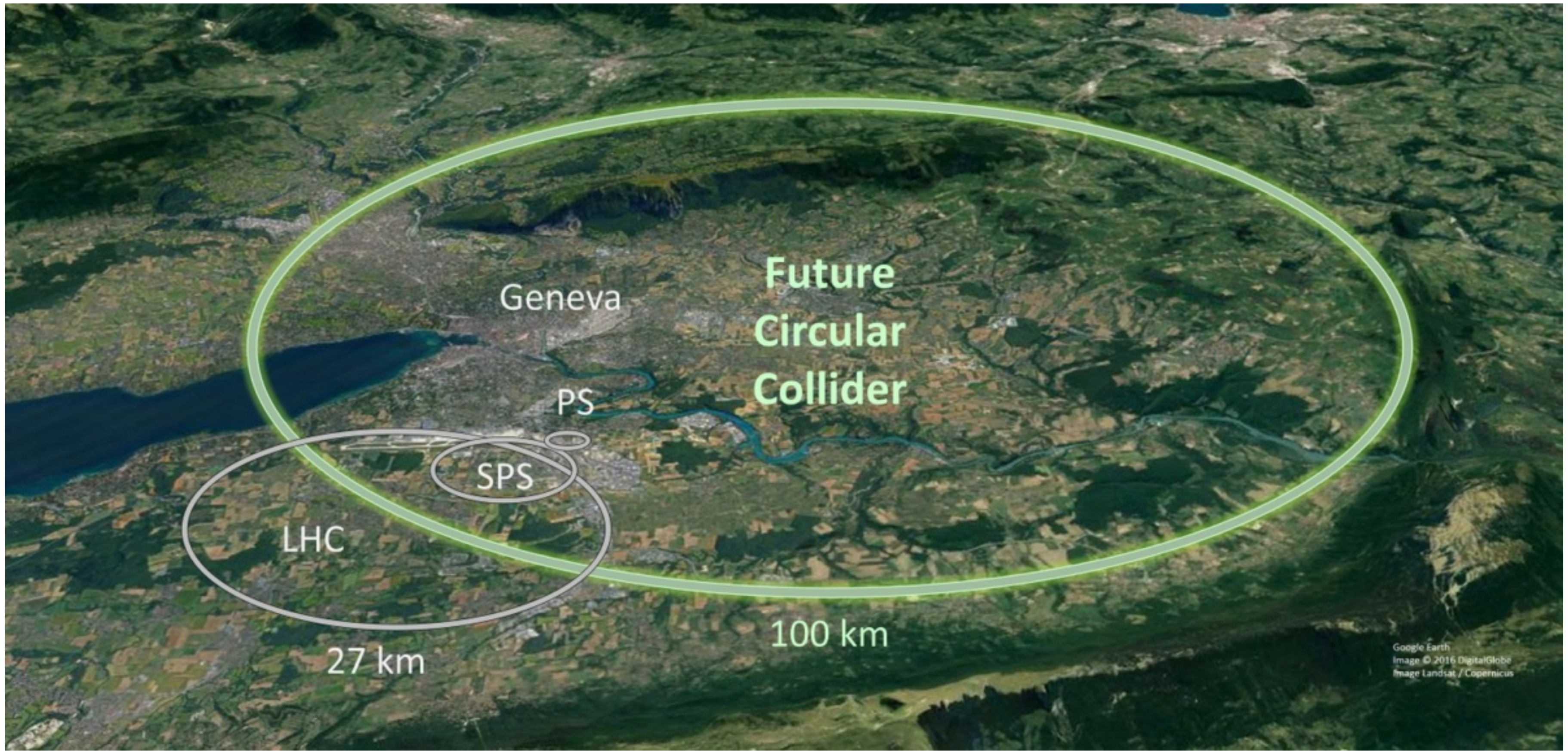


FCC-ee TDR

FCC-ee: More surprises

The FCC-ee 100 km tunnel is designed to host subsequently a future circular hadron collider (FCC-hh) of increased centre-of-mass energy:

100 TeV compared to the 14 TeV HL-LHC



FCC study, CERN

Discovery after indirect evidence

Even when precision measurements provides indirect evidence of particles, we need to produce them directly to understand its properties

As is true for the EW gauge bosons, Higgs boson and the top quark - at least we had the SM to extract their properties from indirect measurements

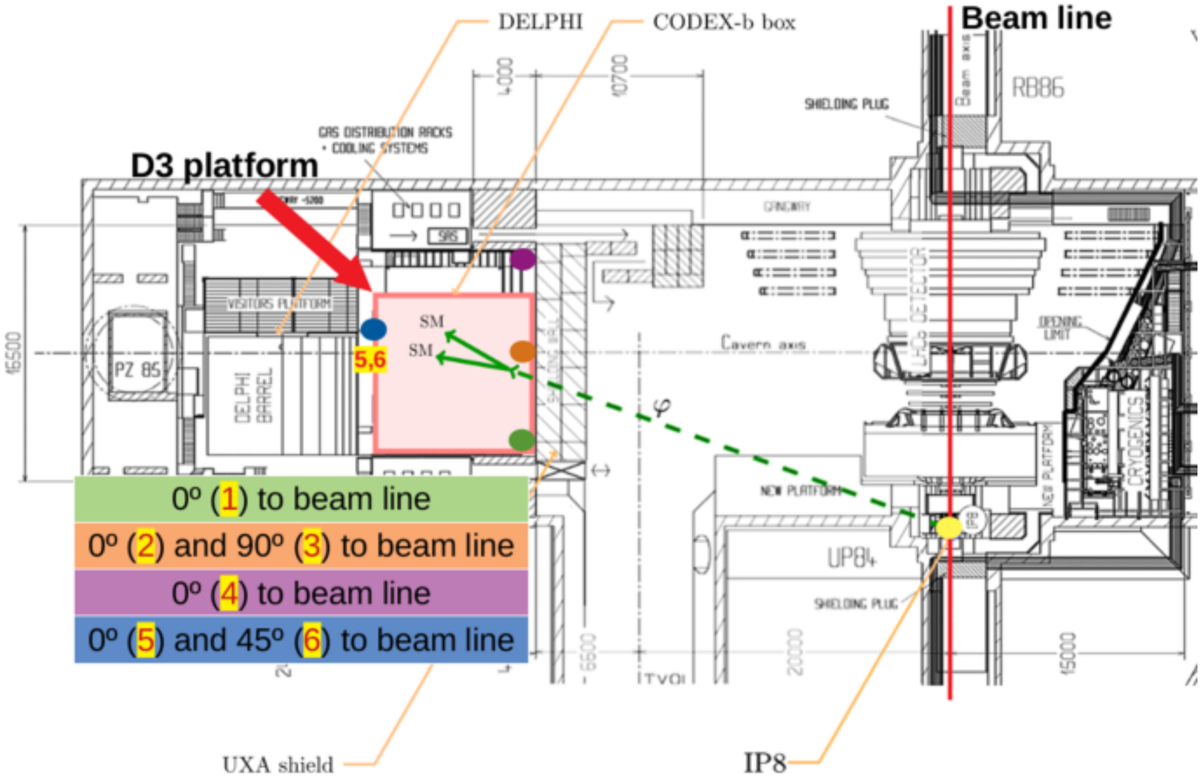
FCC-ee will be sensitive to new phenomena at scales of tens of TeV

With the current technology, direct particle production at this scale can only be achieved by a hadron collider of around 100 TeV energy range

Why should we talk about dedicated detectors at FCC-hh now?

For LHC or HL-LHC, the dedicated detectors are accommodated in empty shafts or available halls around the main detectors

For example, see for CODEX-b



EPJC 80, 1177 (2020)

But this might not be optimal for the LLP models beyond the SM

The Future Colliders are in their conceptual design phase now

Optimise and integrate dedicated LLP detectors with the main detector design

Proposal for DELIGHT and FOREHUNT @ FCC-hh

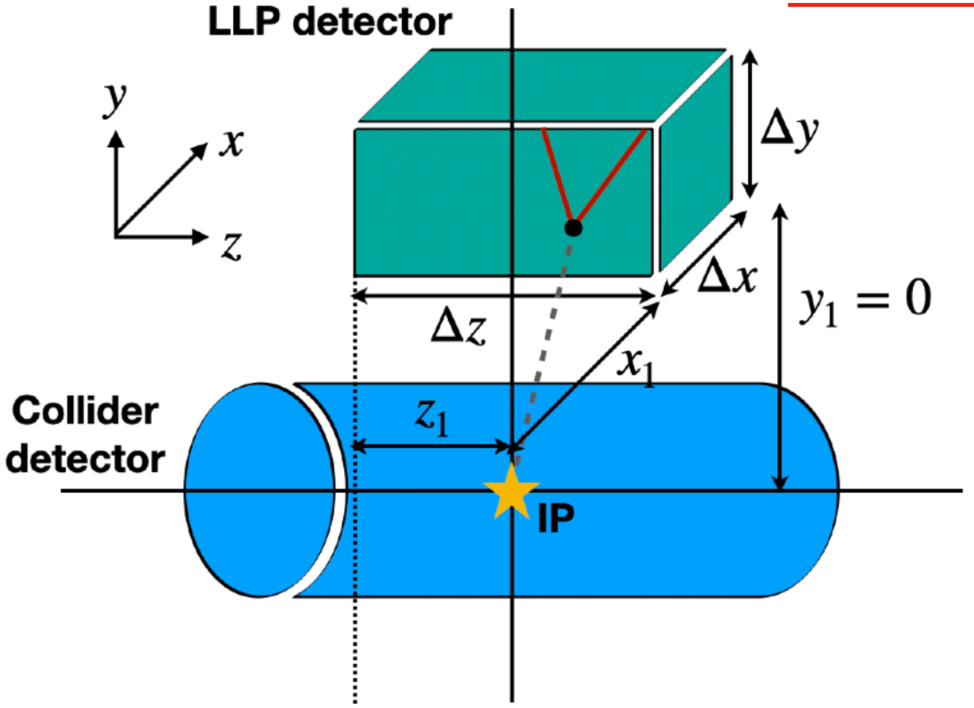
FCC-hh design under study — Room for optimisation

Bhattacherjee, Matsumoto, RS, PRD 106 (2022) 9, 095018

(A) Transverse detector:

DELIGHT

Detector for **l**ong-**li**ved particles at hi**gh** energy of 100 **T**eV



$x_1 = 25$ m

$y_1 = 0$ m

$z_1 = -\Delta z/2$

$\Delta x, \Delta y, \Delta z$

DELIGHT (A): The same as the dimensions of the MATHUSLA detector, i.e. $\Delta x \times \Delta y \times \Delta z = 25 \times 100 \times 100\,\mathrm{m}^3$.

DELIGHT (B): Four times bigger than the MATHUSLA detector, i.e. $\Delta x \times \Delta y \times \Delta z = 100 \times 100 \times 100\,\mathrm{m}^3$.

DELIGHT (C): The same decay volume as the MATHUSLA detector with different dimensions, i.e. $\Delta x \times \Delta y \times \Delta z = 200 \times 50 \times 50\,\mathrm{m}^3$.

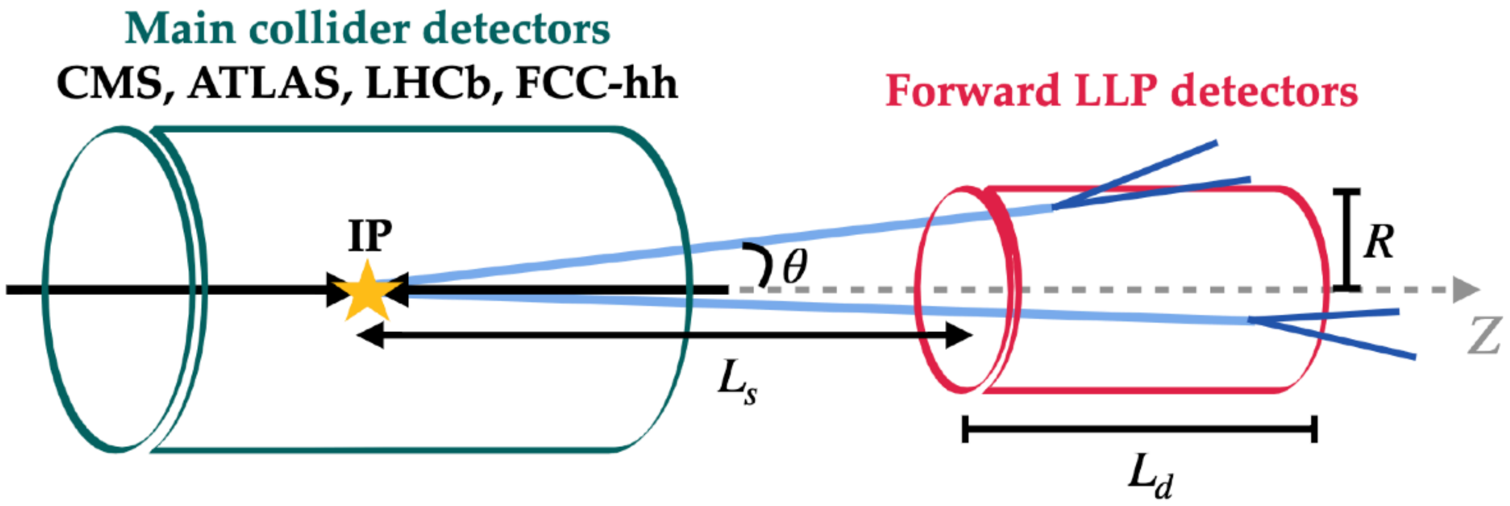
Proposal for DELIGHT and FOREHUNT @ FCC-hh

FCC-hh design under study — Room for optimisation

(B) Forward detector:

FOREHUNT

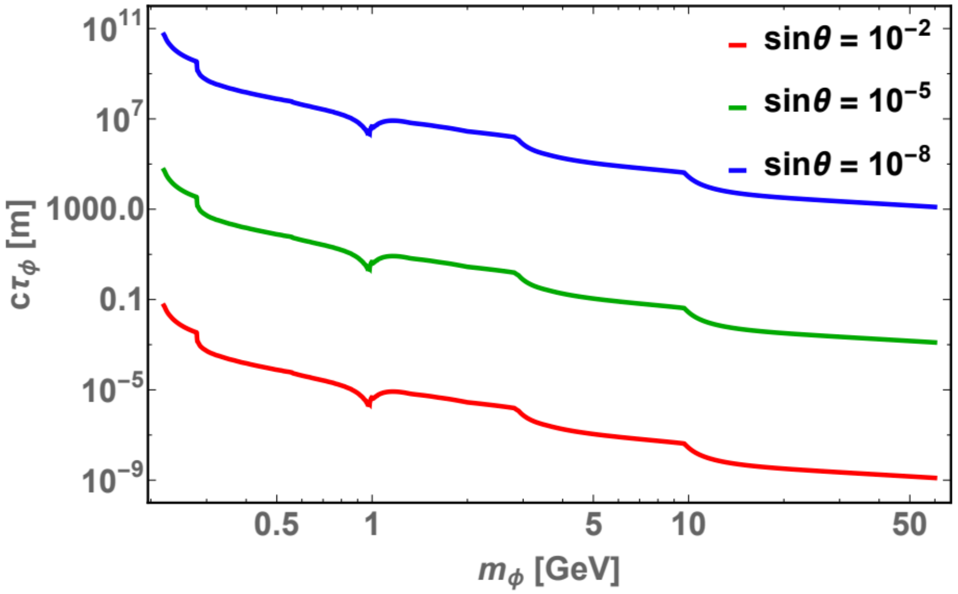
Forward **E**xperiment
for **Hun**dred **T**eV



L_s
R
L_d

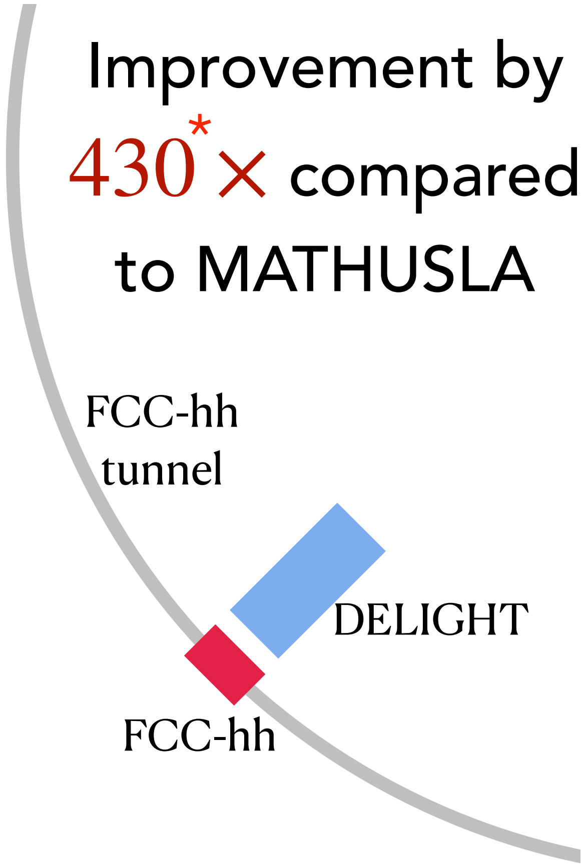
Bhattacherjee, Dreiner, Ghosh, Matsumoto, RS, Solanki,
PRD 110 (2024) 1, 015036

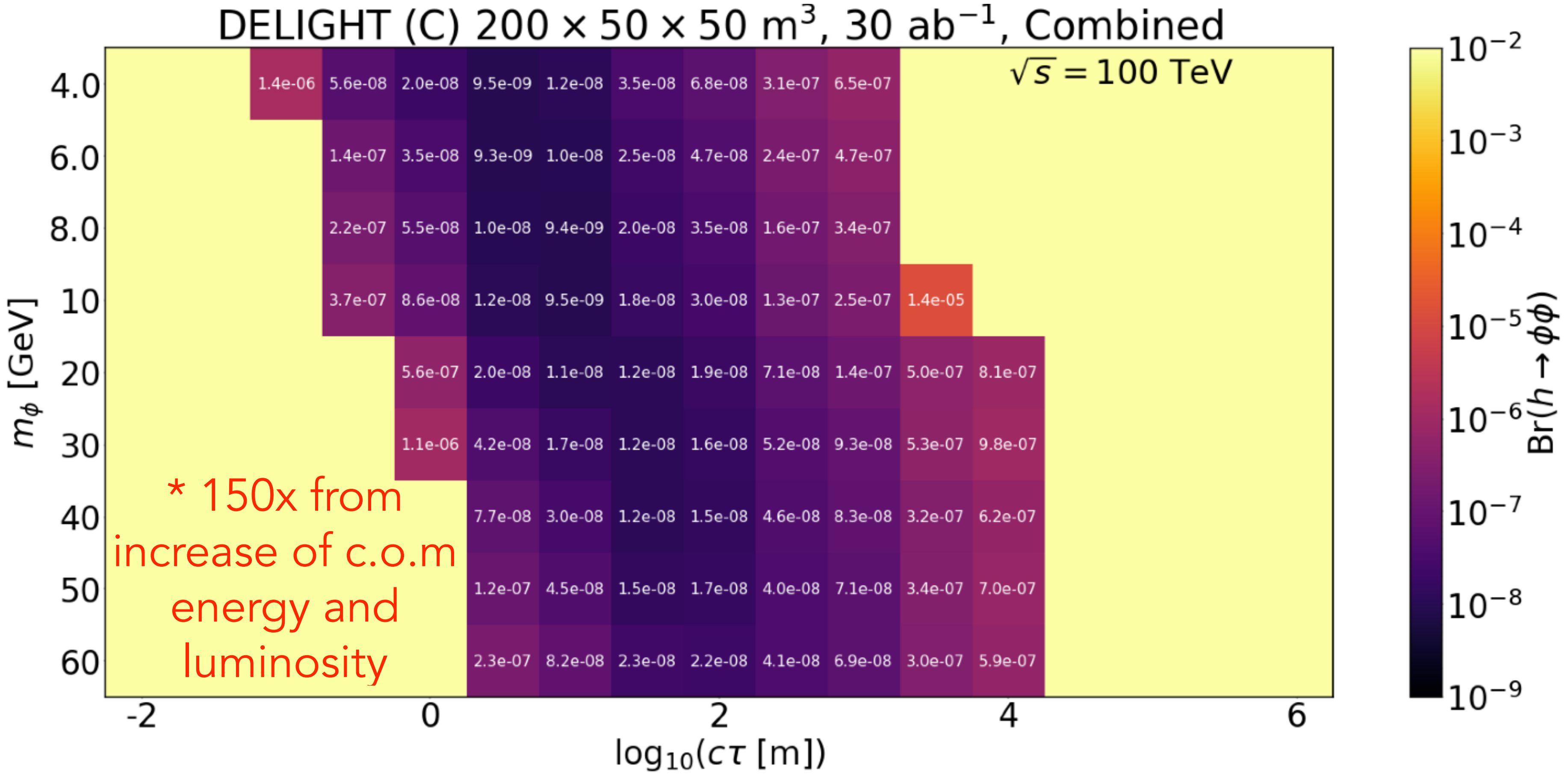
LLPs from Higgs boson decay in DELIGHT



- long tunnel-like detector - better shielding against cosmic rays
- closer to IP - use of materials with high shielding power & active veto components to reduce background
- RPCs and possibility of a calorimeter element
- integration with the trigger system of FCC-hh

Improvement by 430* × compared to MATHUSLA





4.0	1.4e-06	5.6e-08	2.0e-08	9.5e-09	1.2e-08	3.5e-08	6.8e-08	3.1e-07	6.5e-07		
6.0		1.4e-07	3.5e-08	9.3e-09	1.0e-08	2.5e-08	4.7e-08	2.4e-07	4.7e-07		
8.0		2.2e-07	5.5e-08	1.0e-08	9.4e-09	2.0e-08	3.5e-08	1.6e-07	3.4e-07		
10		3.7e-07	8.6e-08	1.2e-08	9.5e-09	1.8e-08	3.0e-08	1.3e-07	2.5e-07	1.4e-05	
20			5.6e-07	2.0e-08	1.1e-08	1.2e-08	1.9e-08	7.1e-08	1.4e-07	5.0e-07	8.1e-07
30			1.1e-06	4.2e-08	1.7e-08	1.2e-08	1.6e-08	5.2e-08	9.3e-08	5.3e-07	9.8e-07
40				7.7e-08	3.0e-08	1.2e-08	1.5e-08	4.6e-08	8.3e-08	3.2e-07	6.2e-07
50				1.2e-07	4.5e-08	1.5e-08	1.7e-08	4.0e-08	7.1e-08	3.4e-07	7.0e-07
60				2.3e-07	8.2e-08	2.3e-08	2.2e-08	4.1e-08	6.9e-08	3.0e-07	5.9e-07

* 150x from increase of c.o.m energy and luminosity

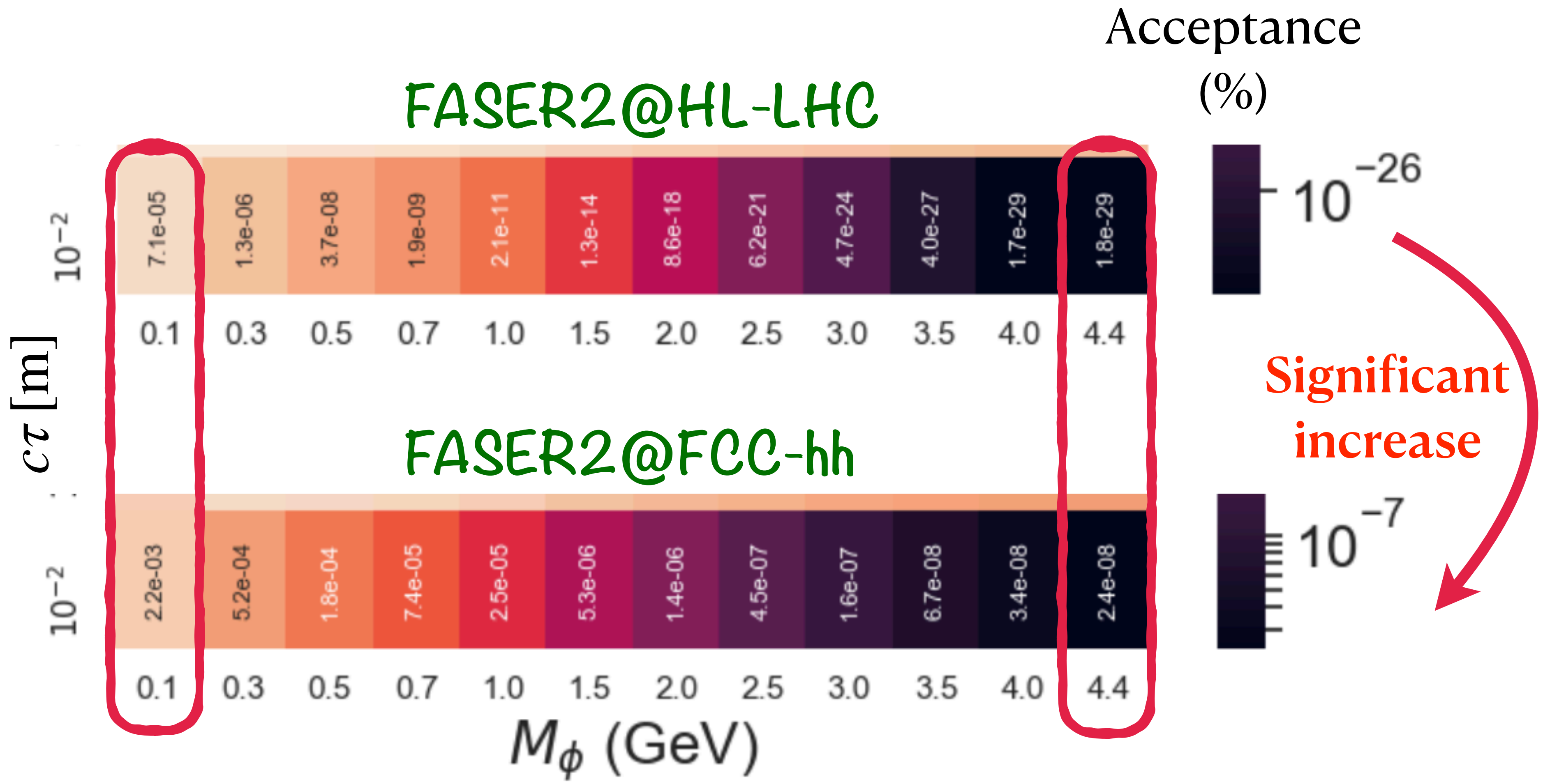
FASER-2 @ HL-LHC vs FASER-2 @ FCC-hh

$B^\pm \to K^\pm \phi$

FASER2

$L_s = 480$ m
$R = 1$ m
$L_d = 5$ m

$p_\phi > 100$ GeV

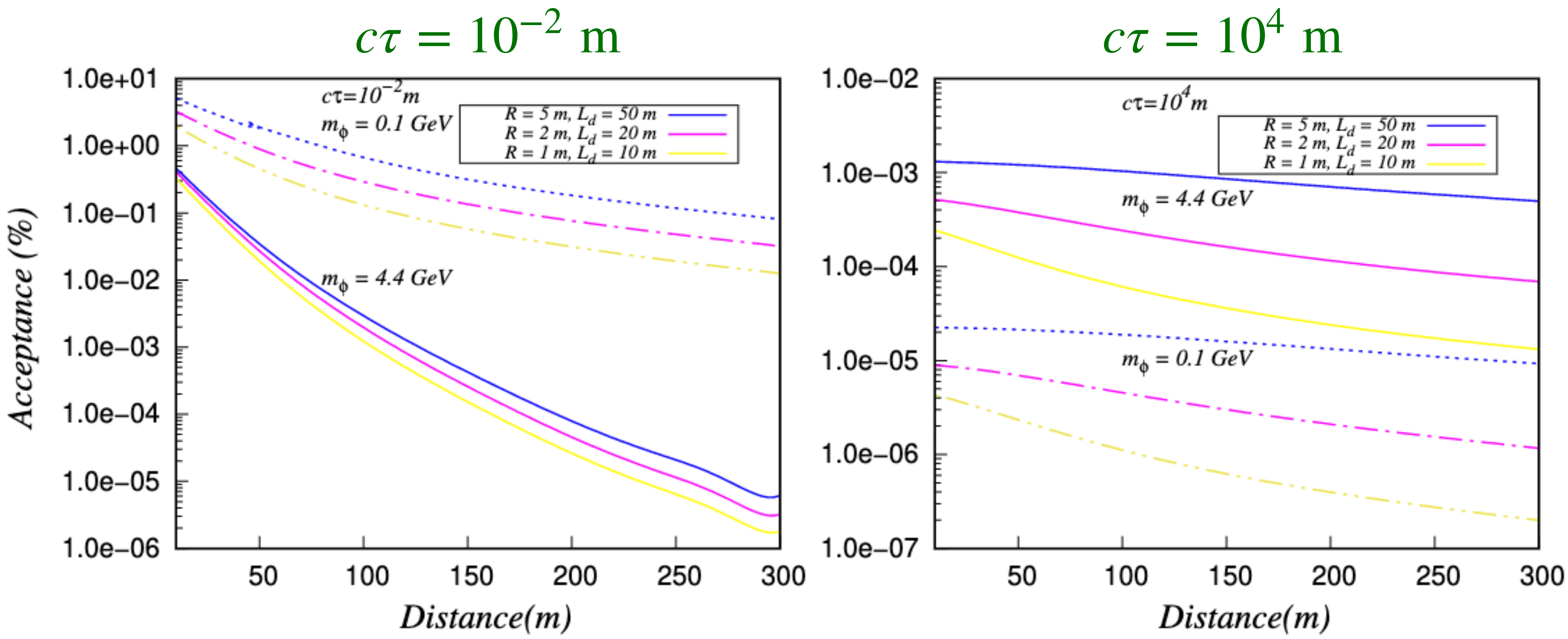


B-mesons more energetic at 100 TeV collider

The LLP coming from *B*-meson decay has larger boost

Increased efficiency for smaller decay lengths and heavier masses

Optimising FOREHUNT for LLPs from B-meson decay



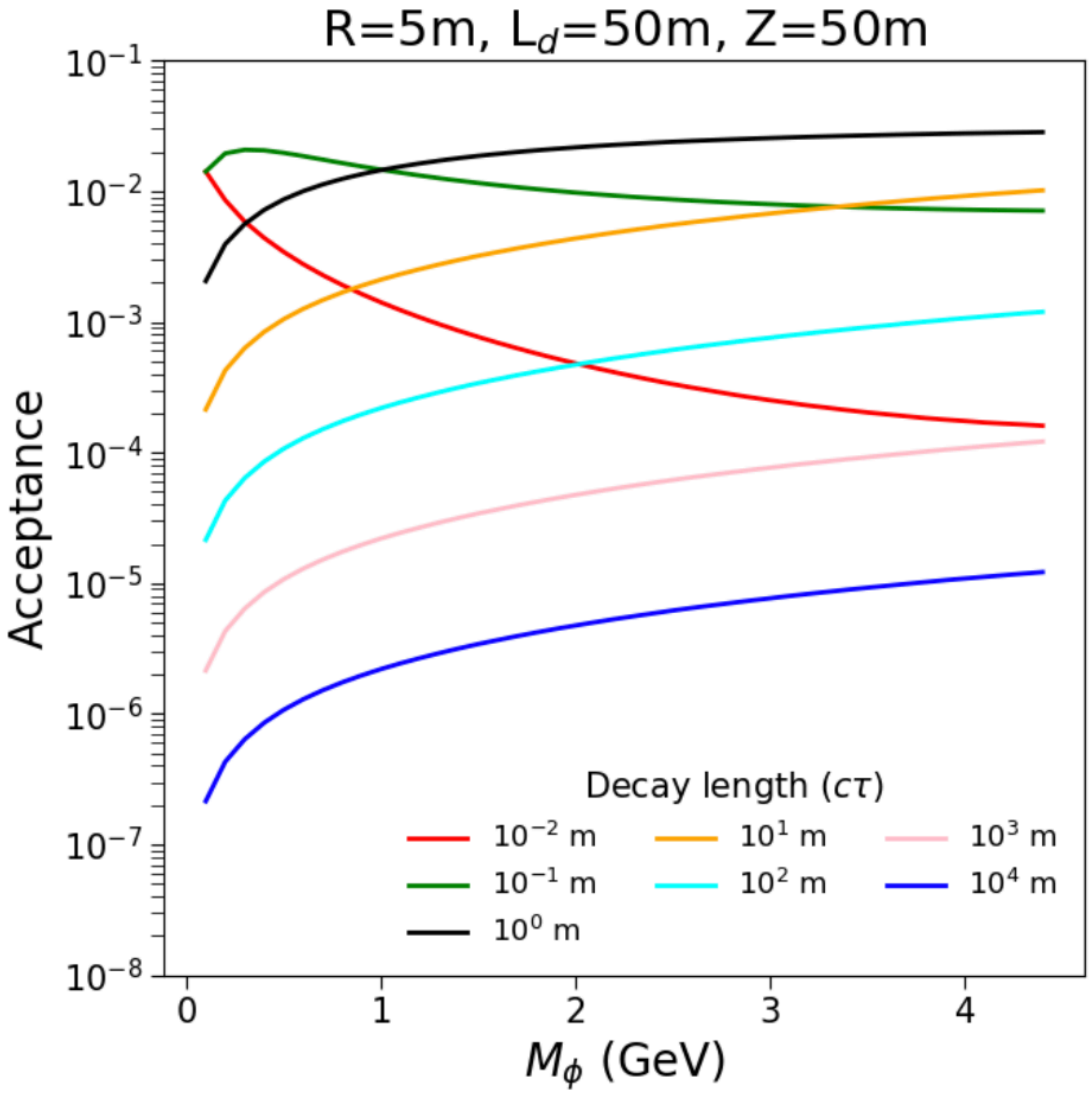
$c\tau = 10^{-2}$ m

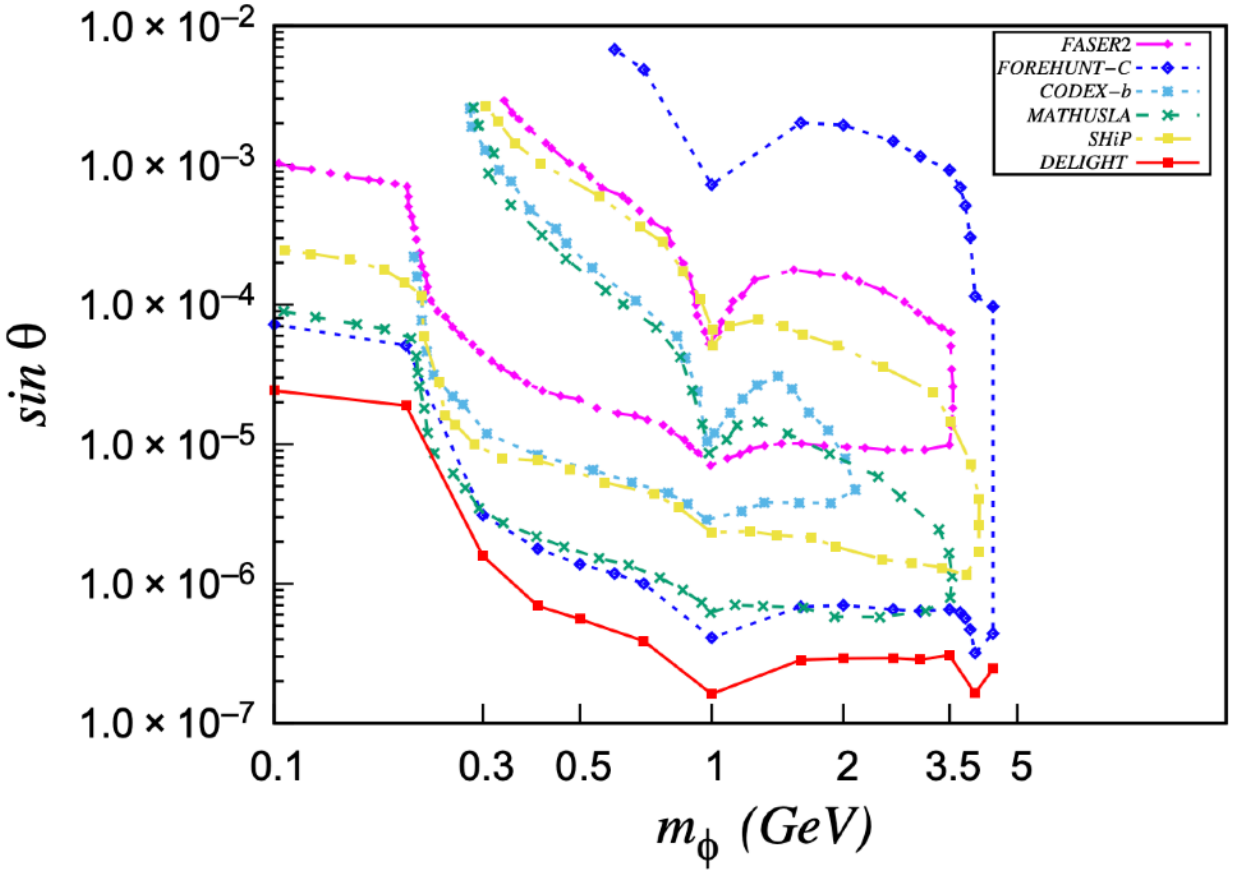
$c\tau = 10^{4}$ m

- Decrease of acceptance with increasing distance of the detector is **more prominent for smaller decay length**
- Small decay length: higher acceptance for lighter LLP
  Large decay length: higher acceptance for heavier LLP

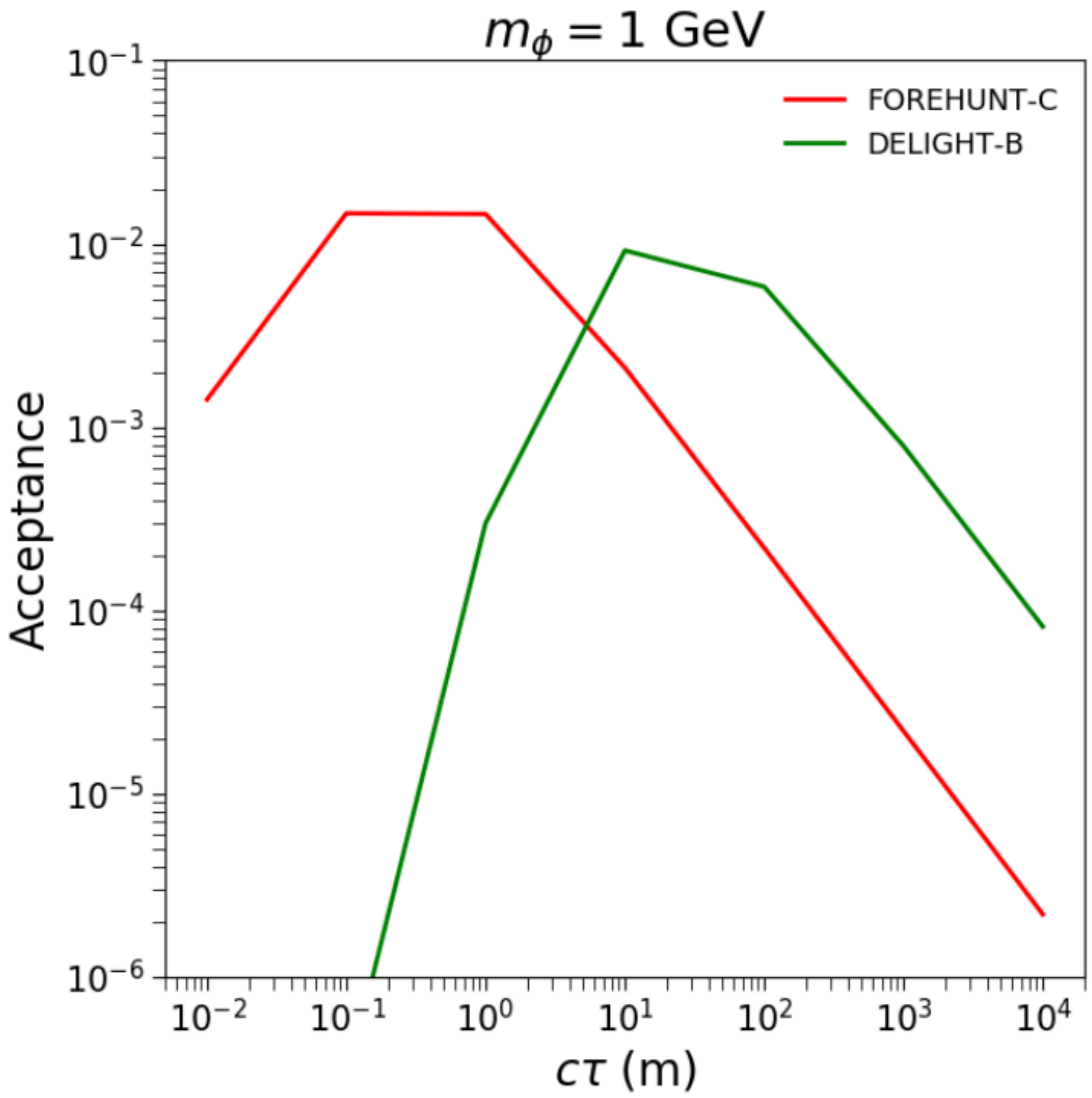
LLPs from B-meson decay in FOREHUNT

Detector Configuration @100 TeV	Radius (R)	Length (L_d)	Position (Z)
FOREHUNT-A	1 m	10 m	50 m
FOREHUNT-B	2 m	20 m	50 m
FOREHUNT-C	5 m	50 m	50 m
FOREHUNT-D	2 m	20 m	75 m
FOREHUNT-E	5 m	50 m	75 m
FOREHUNT-F	5 m	50 m	100 m





LLPs from B-meson decay in FORREHUNT and DELIGHT



LLPs more in *forward direction* for lower $c\tau$ at a particular distance from the interaction point

$$d = \beta\gamma c\tau$$

$$\downarrow$$

$$\uparrow$$

More boost in the forward direction

For smaller decay lengths, FOREHUNT performs better than DELIGHT

Complementarity between forward and transverse detectors

More on FOREHUNT…

(A) Bending and width of the beampipe

- Placing the detector at 50 m might still contain the beampipe within it - reduces acceptance

(B) Off-axis forward detector

- In case placement along the beamline close to the IP is not feasible, place the detector off-axis – 1 m off-axis reduces acceptance by a factor of 2
- Placing the detector 300 m along the beamline is better than shifting it 5 m off-axis

(C) Multiple detectors in the forward direction

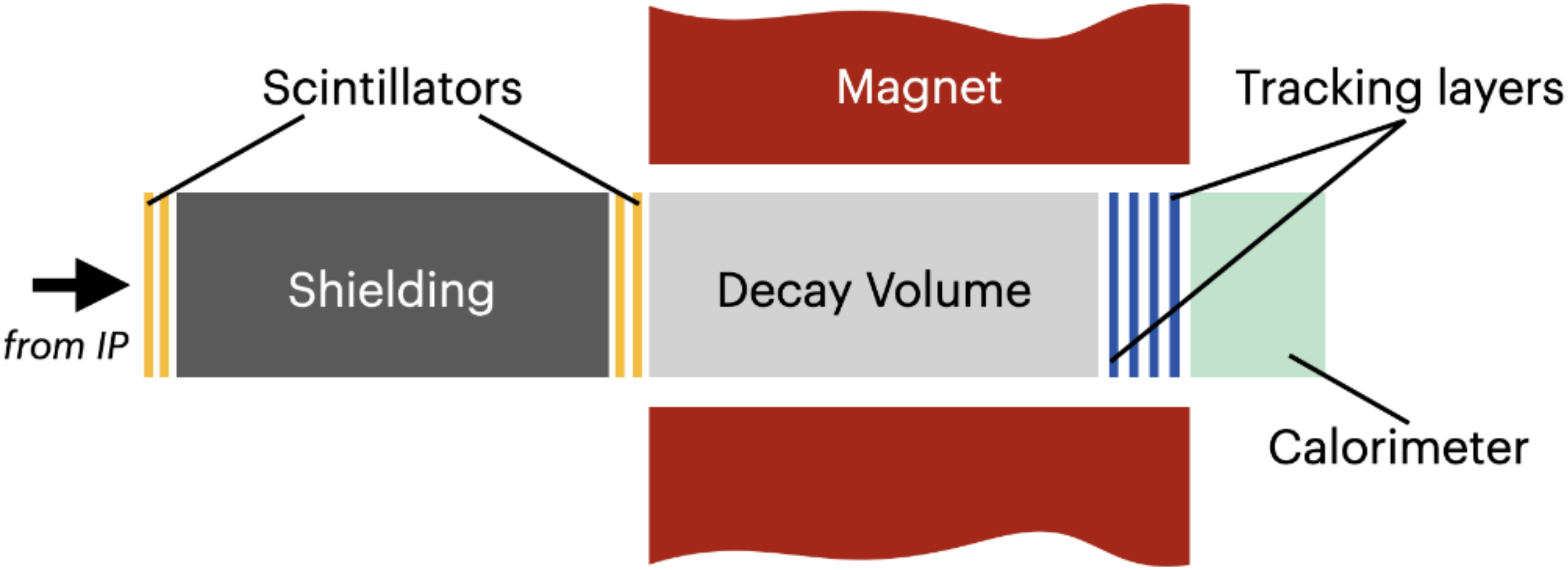
- A second detector at 300 m increases overall signal acceptance by 50%
- Energy threshold of the second detector can be reduced as the first detector plays the role of an active veto

(D) Elements of the detector

- Layers of RPCs: for 5 m radius of the detector, cost per layer of RPC would be around 245 k€
- Triplet RPC layers: 0.1 cm spatial and 0.4 ns temporal resolutions 1909.13022
- Possibility of adding calorimeter and integration with FCC-hh trigger system being studied

Backgrounds and possible detector design

1. Muons from the IP
2. Neutral hadrons
3. Neutrinos

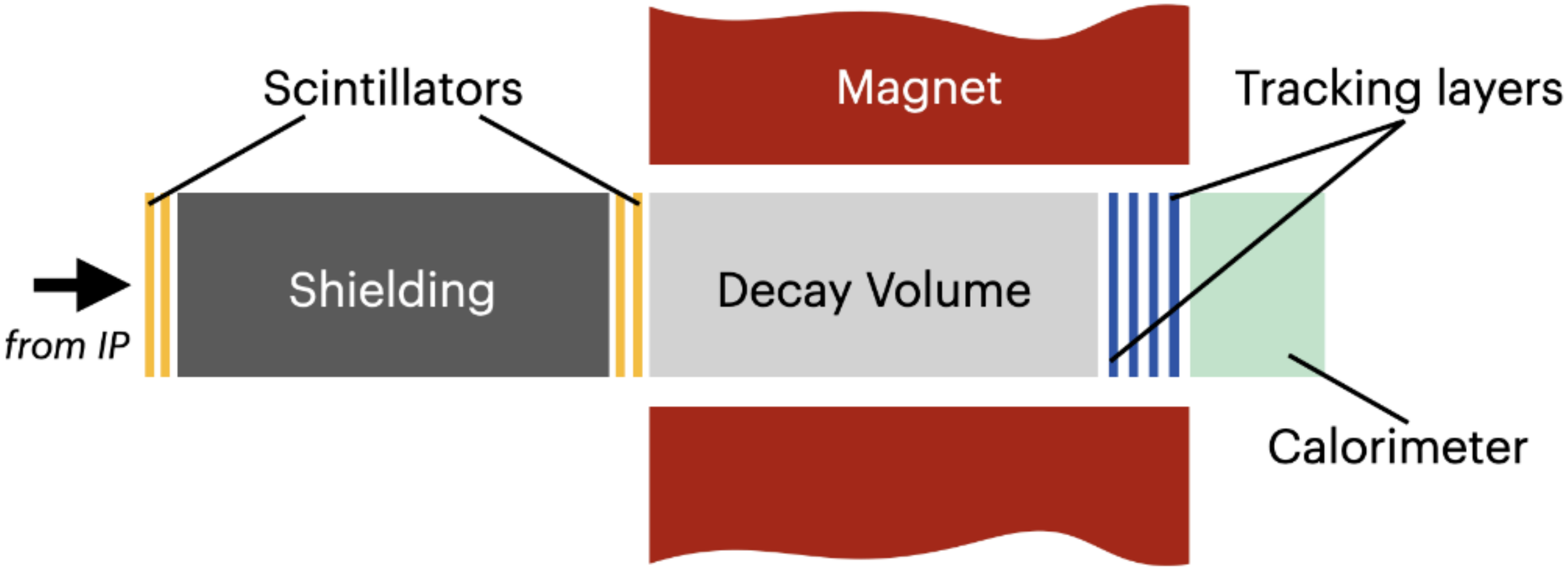


Backgrounds and possible detector design

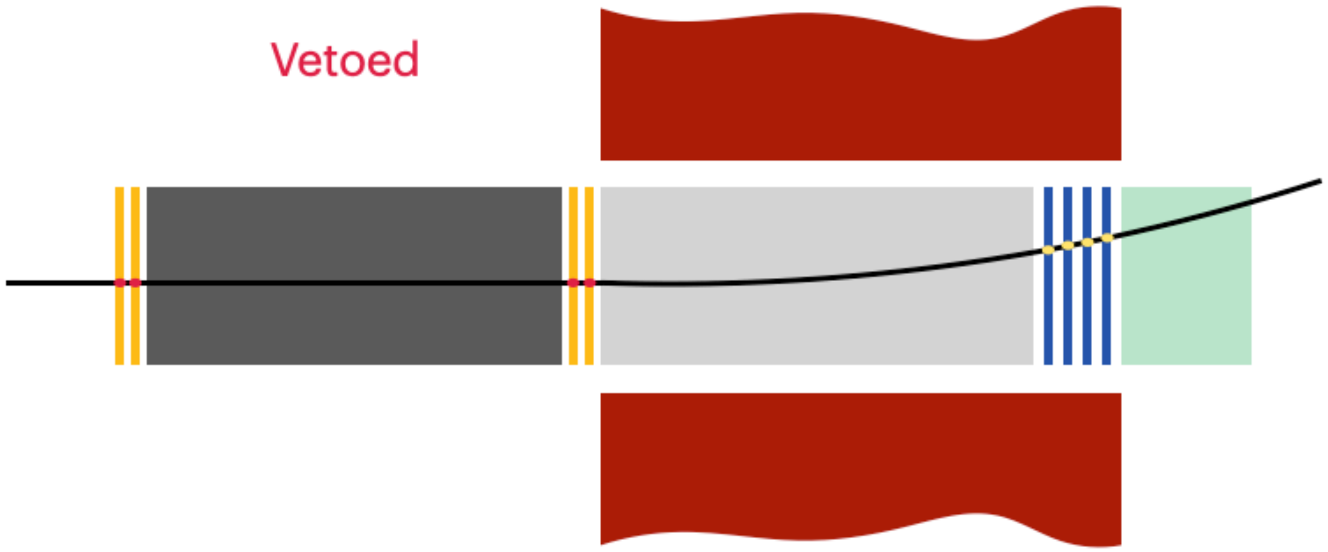
① Muons from the IP

② Neutral hadrons

③ Neutrinos



Muons from the IP



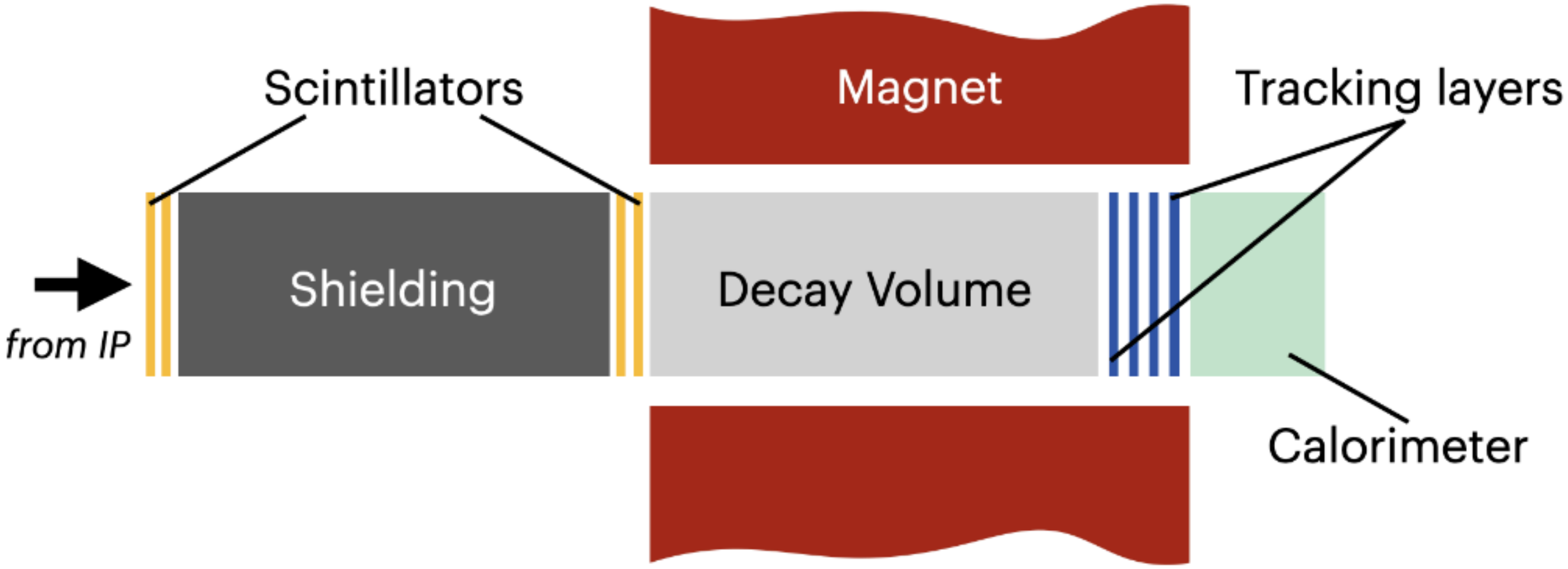
Veto events with hits in any of the four scintillator planes

Backgrounds and possible detector design

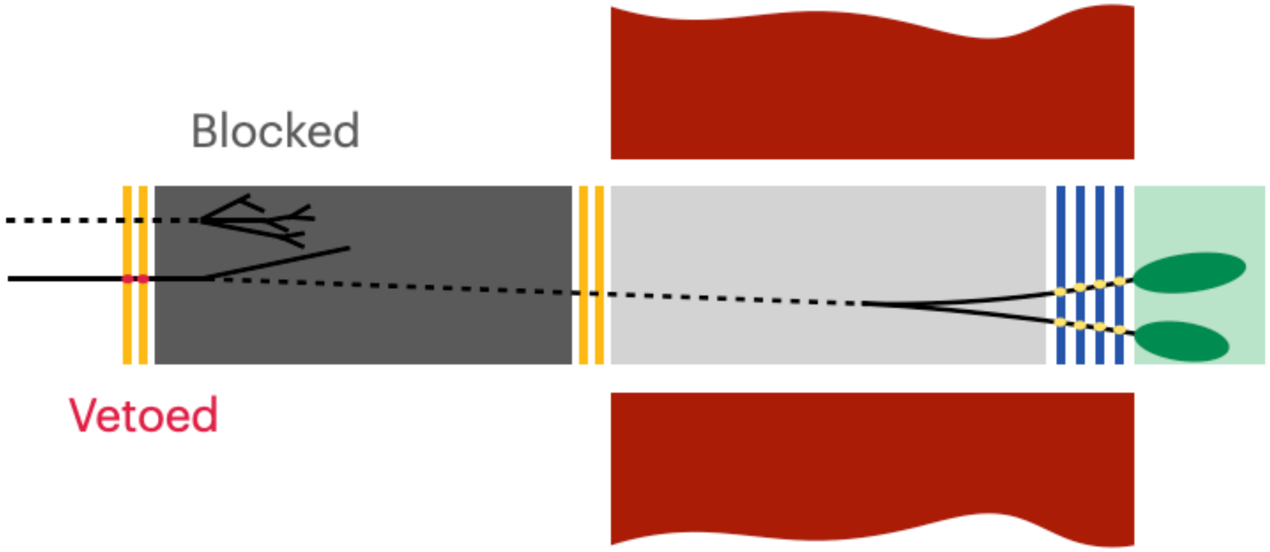
① Muons from the IP

② Neutral hadrons

③ Neutrinos



Neutral hadrons



Veto events with hits in any of the four scintillator planes

Backgrounds and possible detector design

1. Muons from the IP
2. Neutral hadrons
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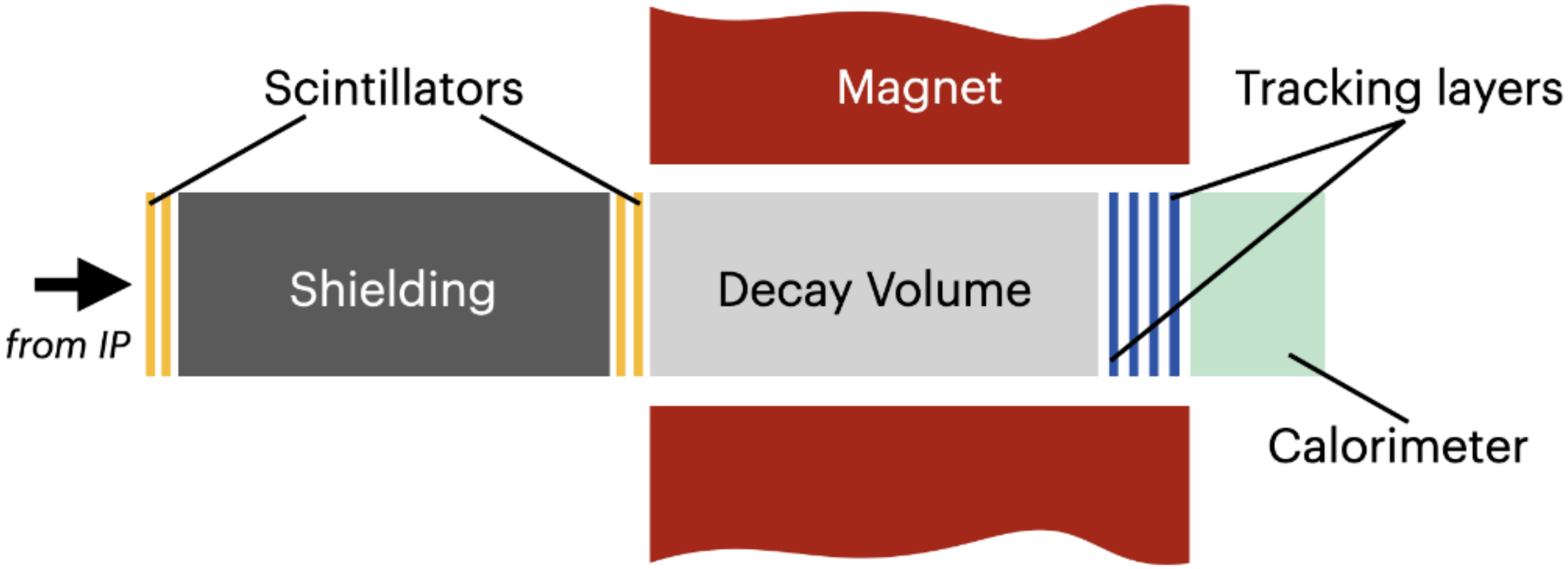
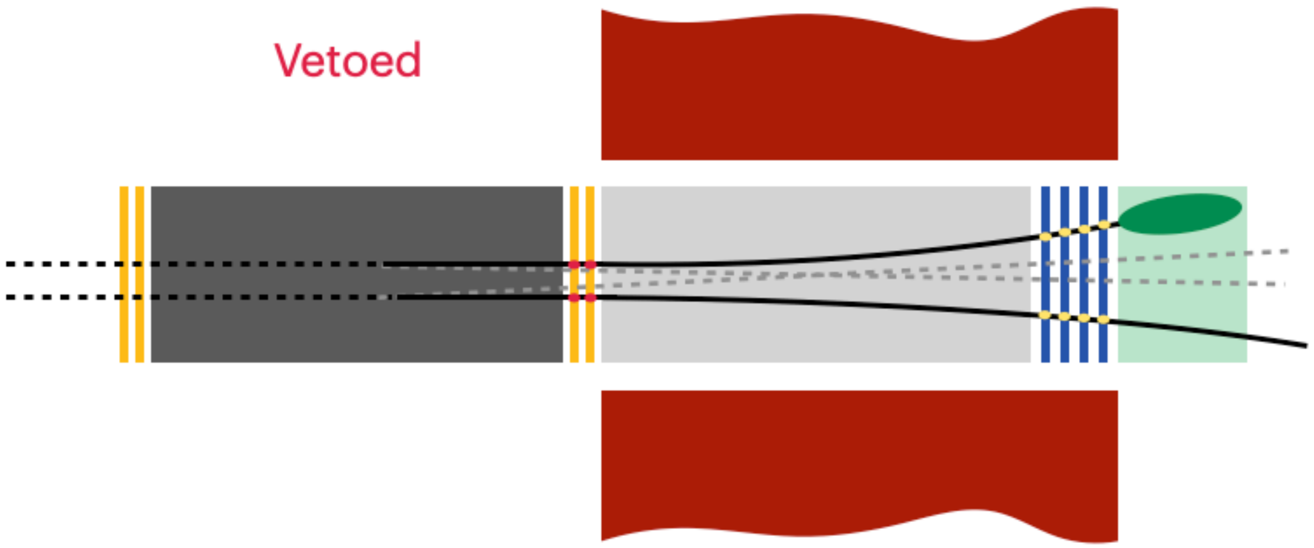


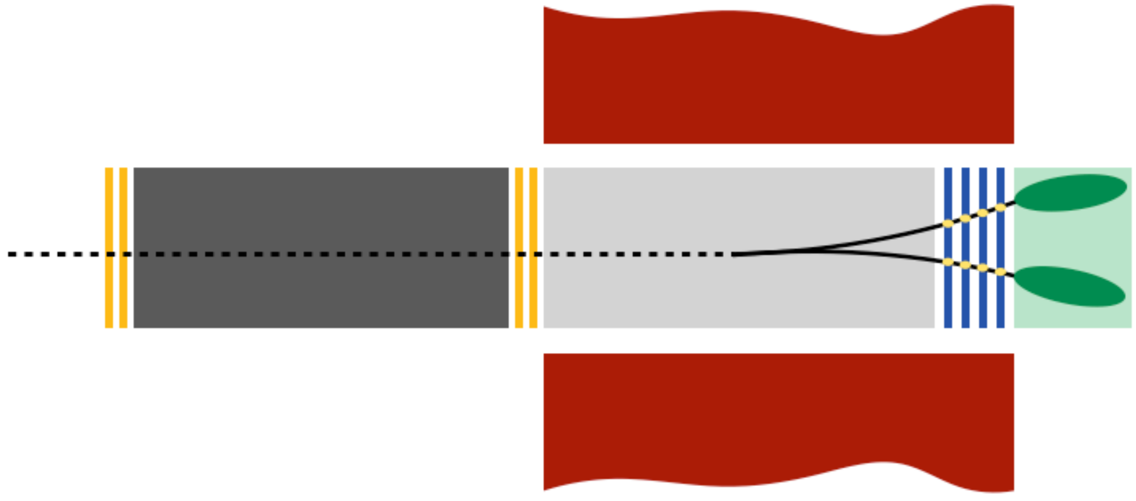
Neutrino interactions



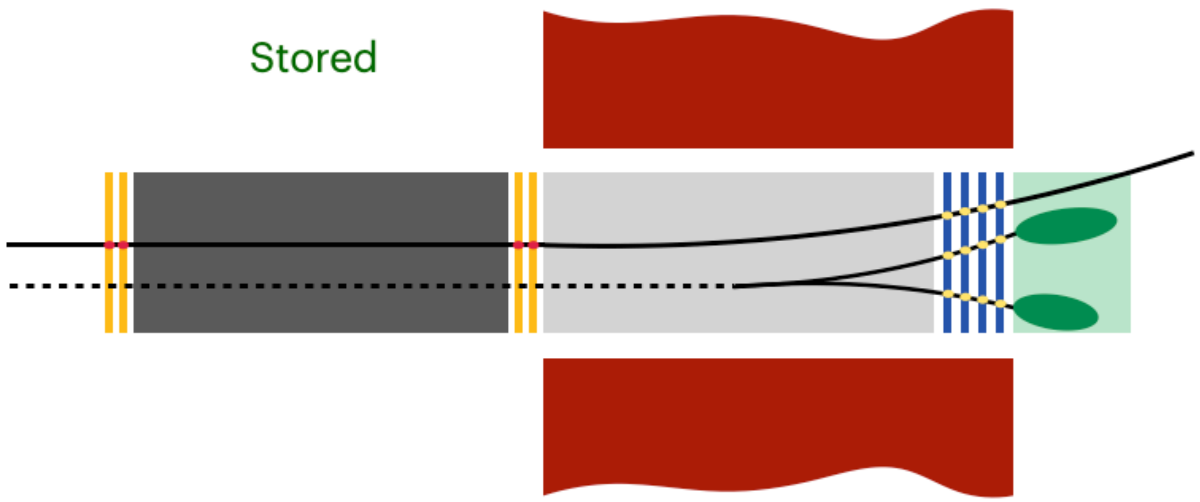
Veto events with hits in any of the four scintillator planes

Signal and backgrounds

LLP signal

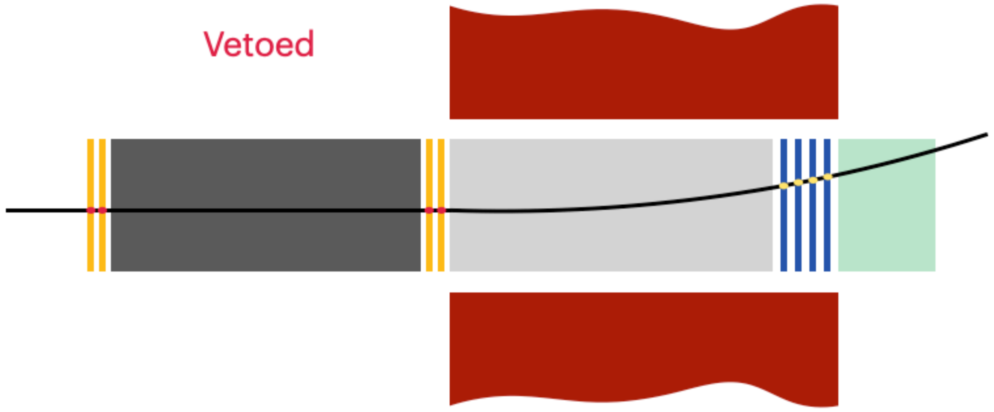


Muons from the IP with a coincident signal

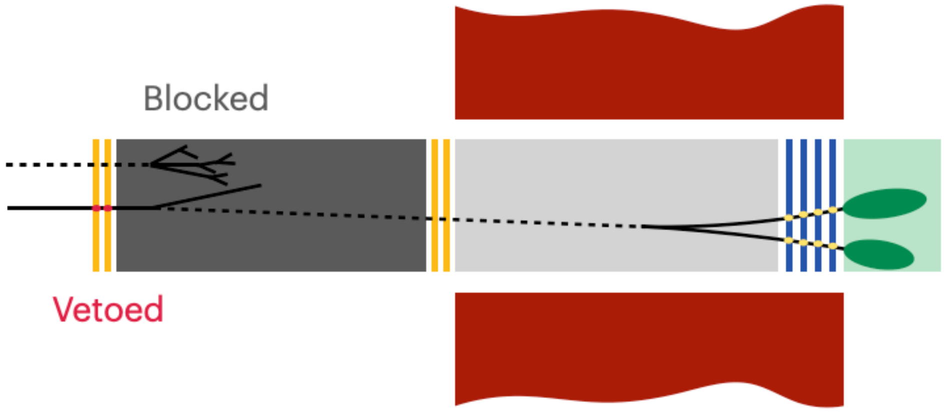


Veto events with hits in any of the four scintillator planes which do not have any calorimeter deposit other than ones which are consistent with the direction of the muon track inferred from the scintillator hits.

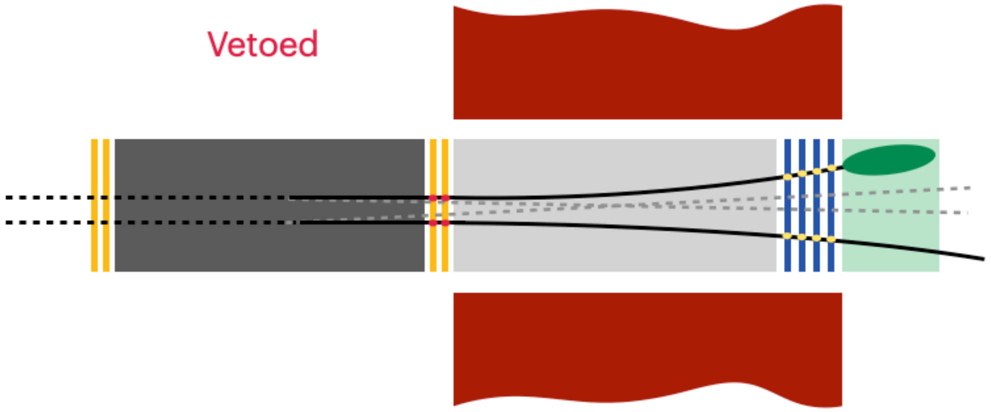
Muons from the IP



Neutral hadrons



Neutrino interactions



Summary

- Why study long-lived particles?

  Strong limits from conventional searches - look carefully at the assumptions
- Long-lived particles - a brief introduction

  Displaced decays of BSM particles - plethora of novel signatures
- Dedicated LLP detectors
  - Importance of future colliders
  - Proposals for dedicated LLP detectors at the FCC-hh
  - DELIGHT and FOREHUNT show promise and further detailed studies required

A Rich Program Ahead to Hunt Down LLPs

Collider Main Detectors

- ATLAS
- CMS
- LHCb

Forward Detectors

- FASER
- Forward Physics Facility
- MAPP-MoEDAL

Transverse Detectors

- CODEX-b
- MATHUSLA
- ANUBIS

Charged LLPs

- MoEDAL
- MilliQan

Future Colliders

- FCC-ee
- FCC-hh
- DELIGHT
- FOREHUNT

Keep looking out for new possibilities!

Thank you for your attention

BACK UP

Nature of the Higgs potential

Two important questions that will remain even after HL-LHC and FCC-ee are:

How does the Higgs couple to itself?
What was the nature of the EWPT?

Both depend on the parameters of the Higgs potential

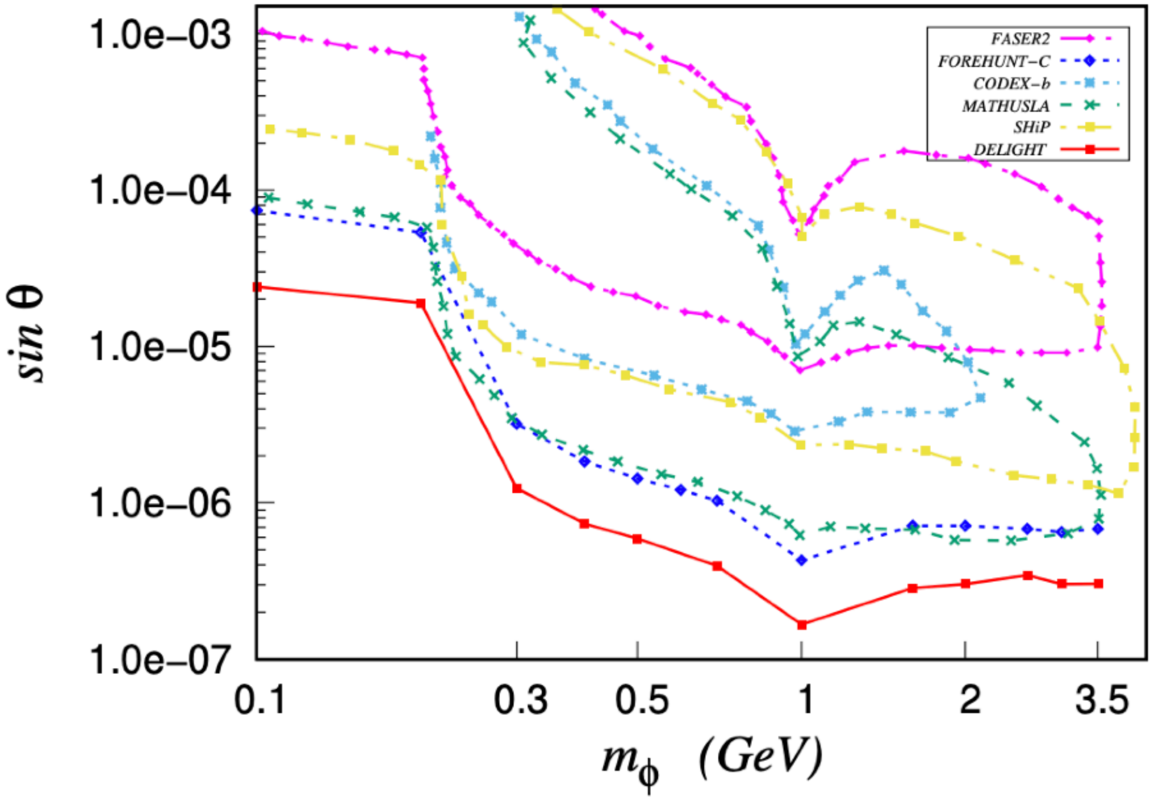
They are known in the SM, but BSM can modify them

Implications for explaining the baryon asymmetry in the Universe

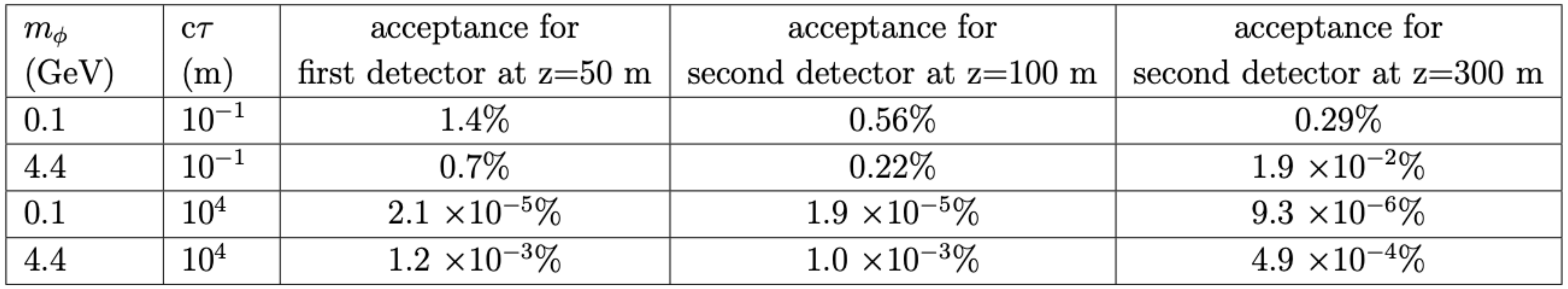
A 100 TeV FCC-hh targets to measure the Higgs cubic self-coupling in the SM with 5% precision, compared to $\mathcal{O}(50\%)$ sensitivity with HL-LHC

Also, the 100 TeV FCC-hh will have a better mass reach for the additional particles that could affect the EWSB

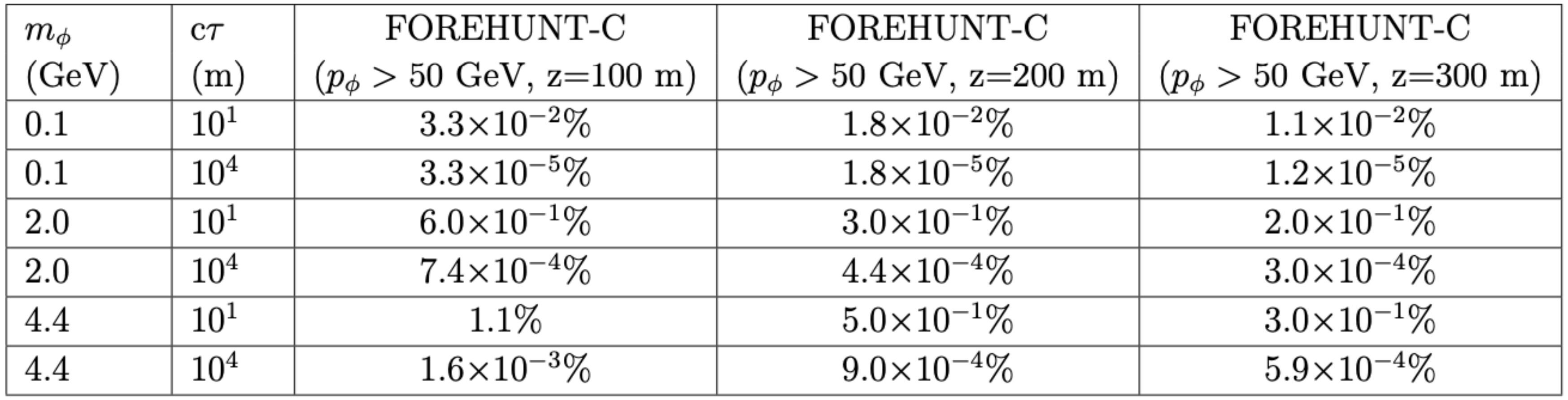
m_ϕ (GeV)	$c\tau$ (m)	FASER2 ($p_\phi > 100$GeV)	CODEX-b ($E_\phi > 1$GeV)	MATHUSLA ($E_\phi > 1$GeV)	FOREHUNT-C ($p_\phi > 100$GeV)	DELIGHT-B ($E_\phi > 1$GeV)
0.1	10^1	$1.6 \times 10^{-5}\%$	$1.0 \times 10^{-2}\%$	$1.3 \times 10^{-1}\%$	$2.1 \times 10^{-2}\%$	$\mathbf{6.5 \times 10^{-1}}\%$
0.1	10^4	$1.5 \times 10^{-8}\%$	$1.1 \times 10^{-5}\%$	$2.1 \times 10^{-4}\%$	$2.1 \times 10^{-5}\%$	$\mathbf{9.2 \times 10^{-4}}\%$
2.0	10^1	$3.6 \times 10^{-4}\%$	$1.8 \times 10^{-2}\%$	$4.4 \times 10^{-2}\%$	$4.4 \times 10^{-1}\%$	$\mathbf{5.3 \times 10^{-1}}\%$
2.0	10^4	$4.8 \times 10^{-7}\%$	$1.9 \times 10^{-4}\%$	$3.4 \times 10^{-3}\%$	$4.7 \times 10^{-4}\%$	$\mathbf{1.5 \times 10^{-2}}\%$
4.4	10^1	$8.6 \times 10^{-4}\%$	$9.2 \times 10^{-3}\%$	$1.3 \times 10^{-2}\%$	**1.0%**	$2.5 \times 10^{-1}\%$
4.4	10^4	$1.5 \times 10^{-6}\%$	$2.3 \times 10^{-4}\%$	$5.0\% \times 10^{-3}\%$	$1.2 \times 10^{-3}\%$	$\mathbf{1.9 \times 10^{-2}}\%$



Multiple forward detectors



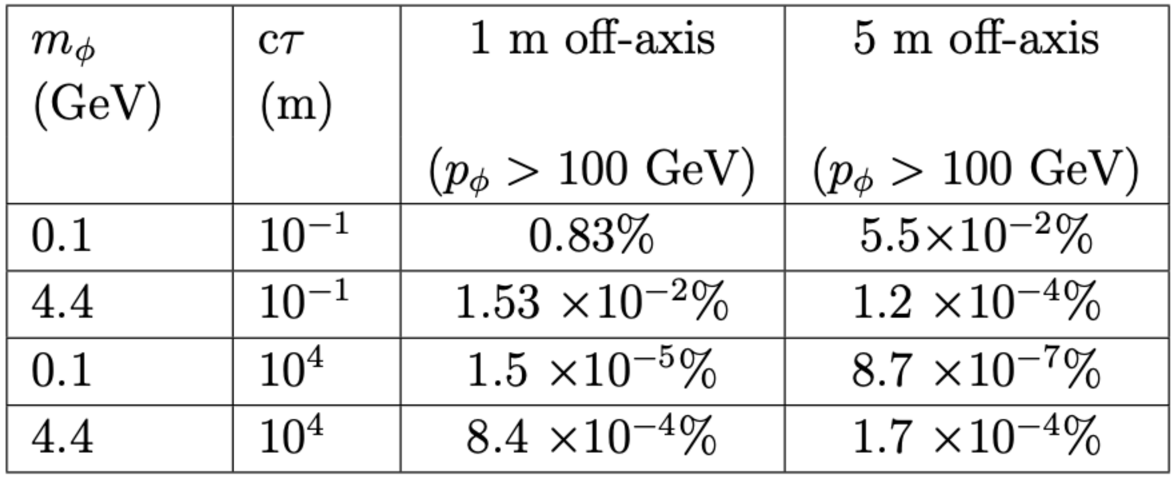
m_ϕ (GeV)	$c\tau$ (m)	acceptance for first detector at z=50 m	acceptance for second detector at z=100 m	acceptance for second detector at z=300 m
0.1	10^{-1}	1.4%	0.56%	0.29%
4.4	10^{-1}	0.7%	0.22%	1.9×10^{-2}%
0.1	10^4	2.1×10^{-5}%	1.9×10^{-5}%	9.3×10^{-6}%
4.4	10^4	1.2×10^{-3}%	1.0×10^{-3}%	4.9×10^{-4}%



m_ϕ (GeV)	$c\tau$ (m)	FOREHUNT-C ($p_\phi > 50$ GeV, z=100 m)	FOREHUNT-C ($p_\phi > 50$ GeV, z=200 m)	FOREHUNT-C ($p_\phi > 50$ GeV, z=300 m)
0.1	10^1	3.3×10^{-2}%	1.8×10^{-2}%	1.1×10^{-2}%
0.1	10^4	3.3×10^{-5}%	1.8×10^{-5}%	1.2×10^{-5}%
2.0	10^1	6.0×10^{-1}%	3.0×10^{-1}%	2.0×10^{-1}%
2.0	10^4	7.4×10^{-4}%	4.4×10^{-4}%	3.0×10^{-4}%
4.4	10^1	1.1%	5.0×10^{-1}%	3.0×10^{-1}%
4.4	10^4	1.6×10^{-3}%	9.0×10^{-4}%	5.9×10^{-4}%

Reduced threshold for the second detector

Off-axis detectors



m_ϕ (GeV)	$c\tau$ (m)	1 m off-axis ($p_\phi > 100$ GeV)	5 m off-axis ($p_\phi > 100$ GeV)
0.1	10^{-1}	0.83%	5.5×10^{-2}%
4.4	10^{-1}	1.53×10^{-2}%	1.2×10^{-4}%
0.1	10^4	1.5×10^{-5}%	8.7×10^{-7}%
4.4	10^4	8.4×10^{-4}%	1.7×10^{-4}%