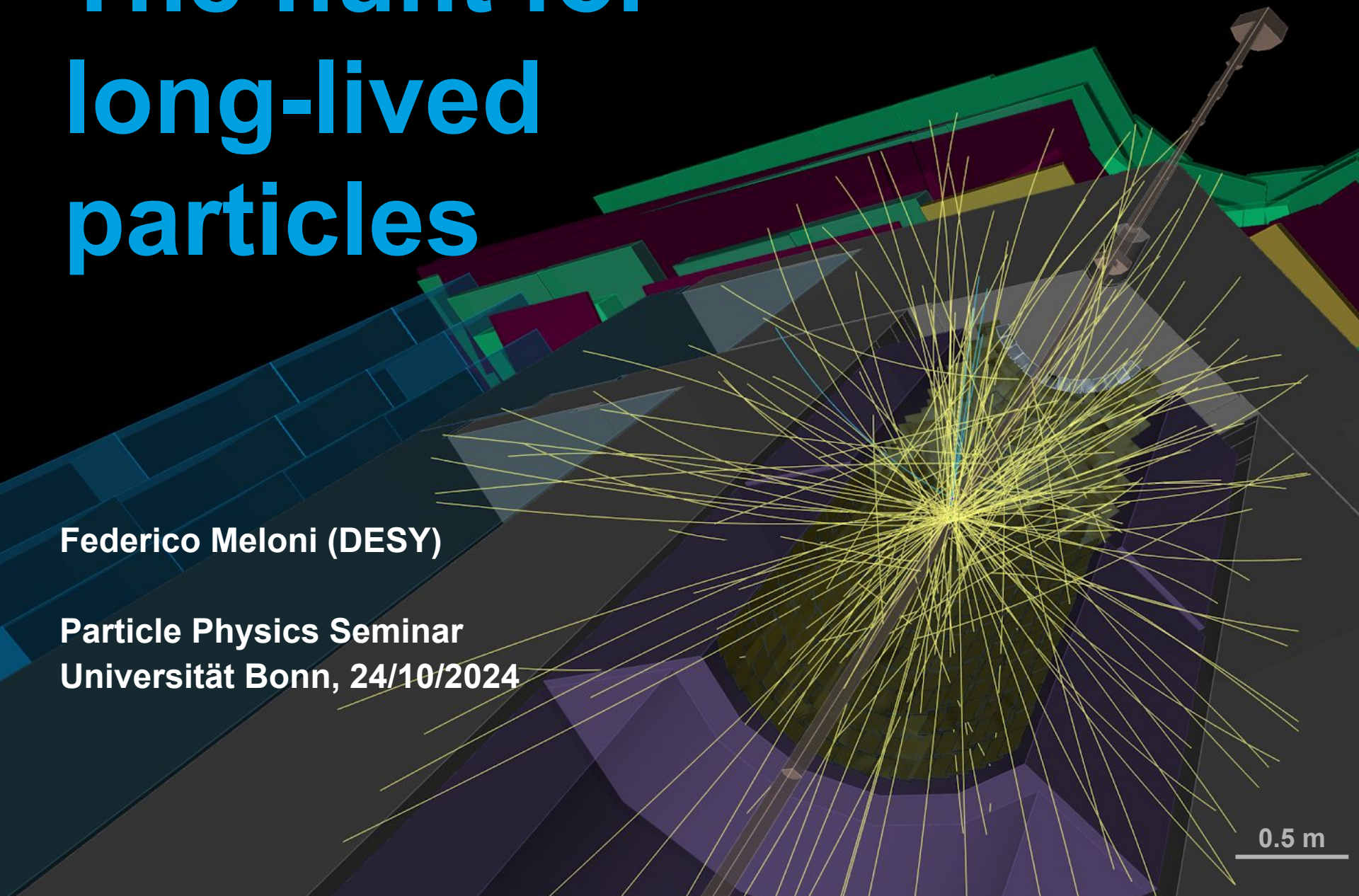
The hunt for long-lived particles

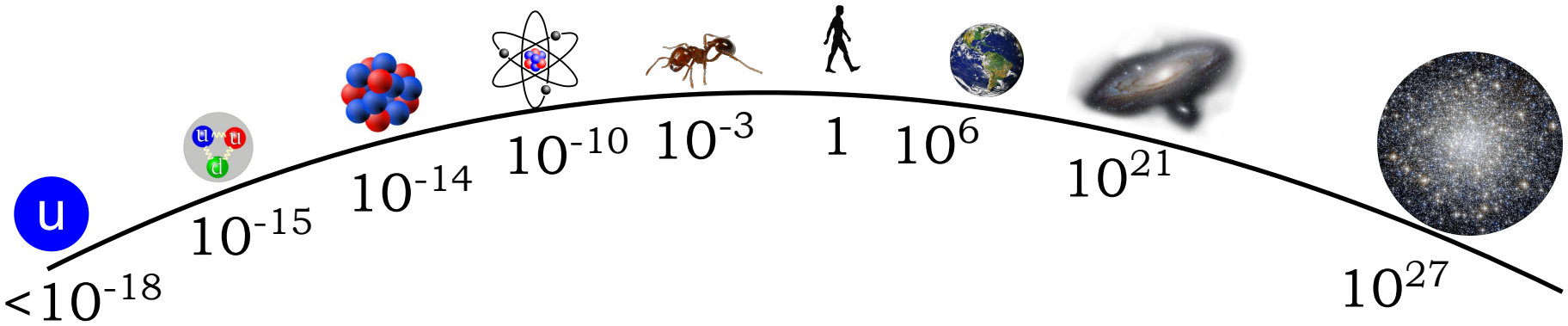


Federico Meloni (DESY)

Particle Physics Seminar
Universität Bonn, 24/10/2024

Physics at the energy frontier

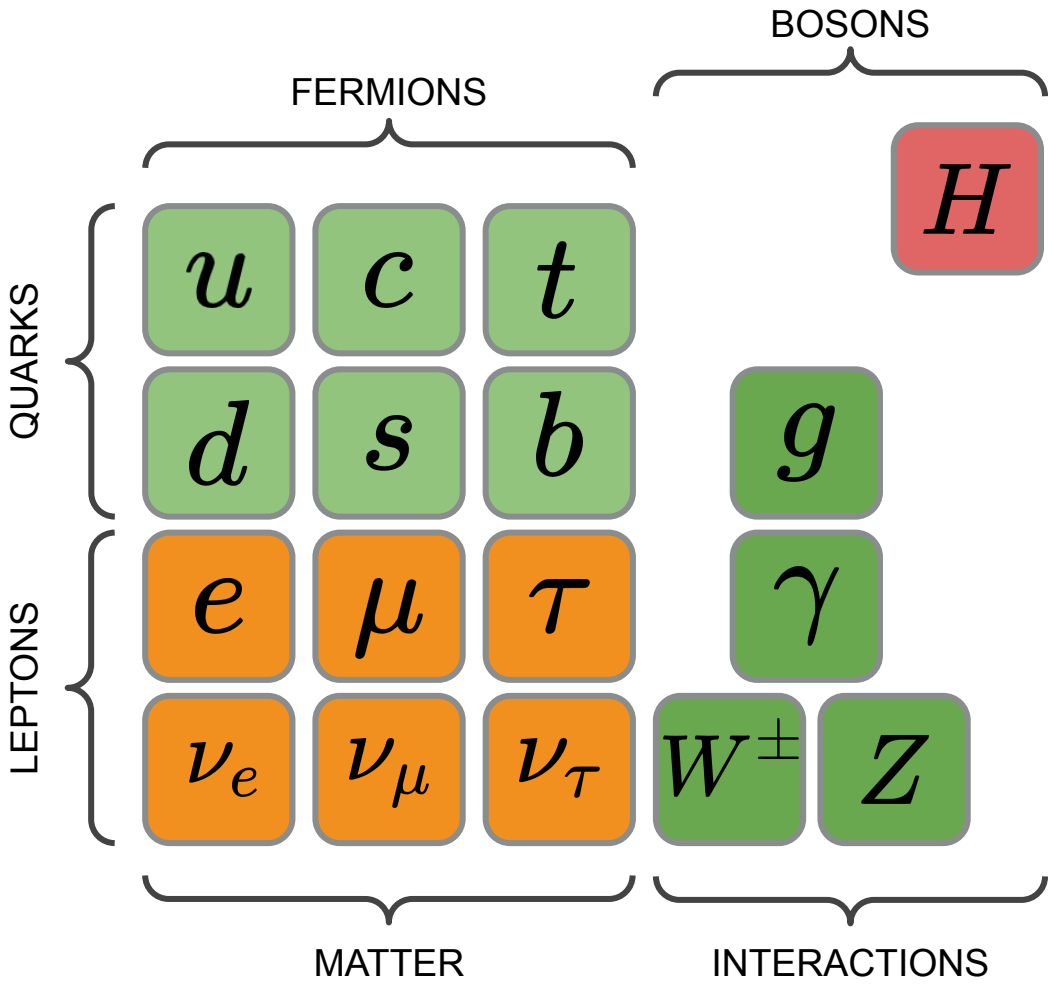
Universe scales in metres



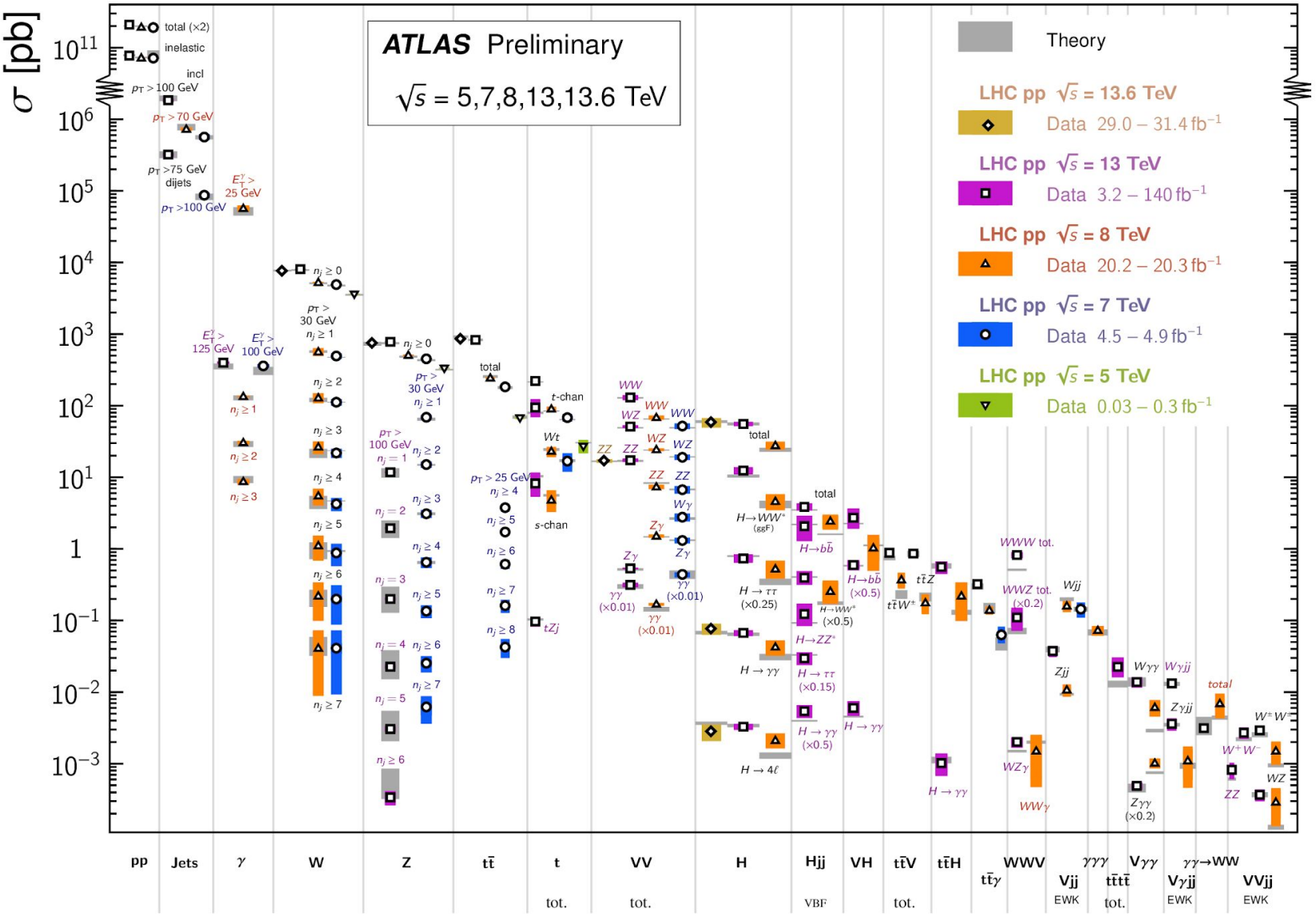
$$\lambda \sim \frac{1}{p}$$

$$E = mc^2$$

The Standard Model



The part that matches



The part that doesn't match too well

The part that doesn't match too well

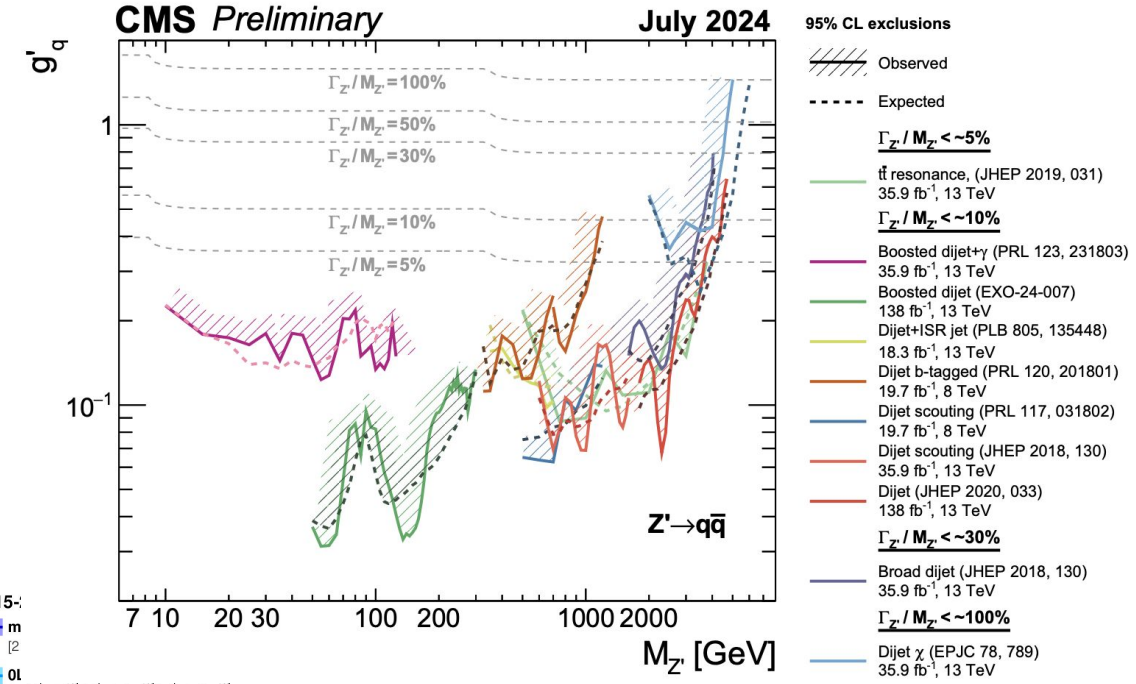
Fundamental open questions:

- Gravity
- Dark matter / energy
- Unification of forces
- Matter-antimatter imbalance
- Hierarchy problem
- …

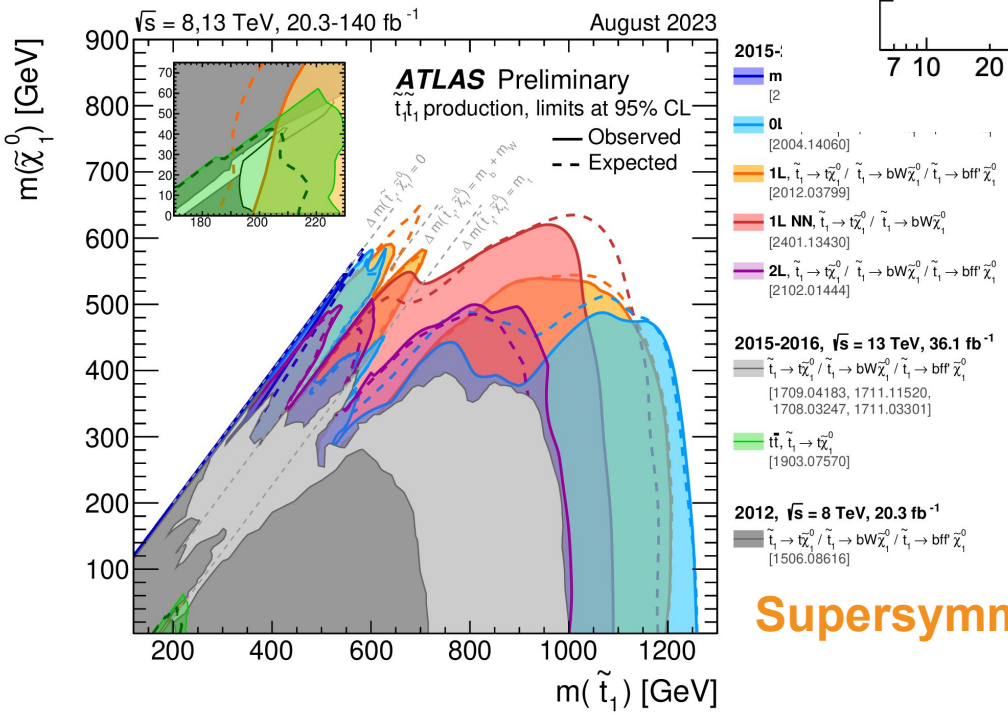
Exploring the unknown

Samples of our exploration

New resonances

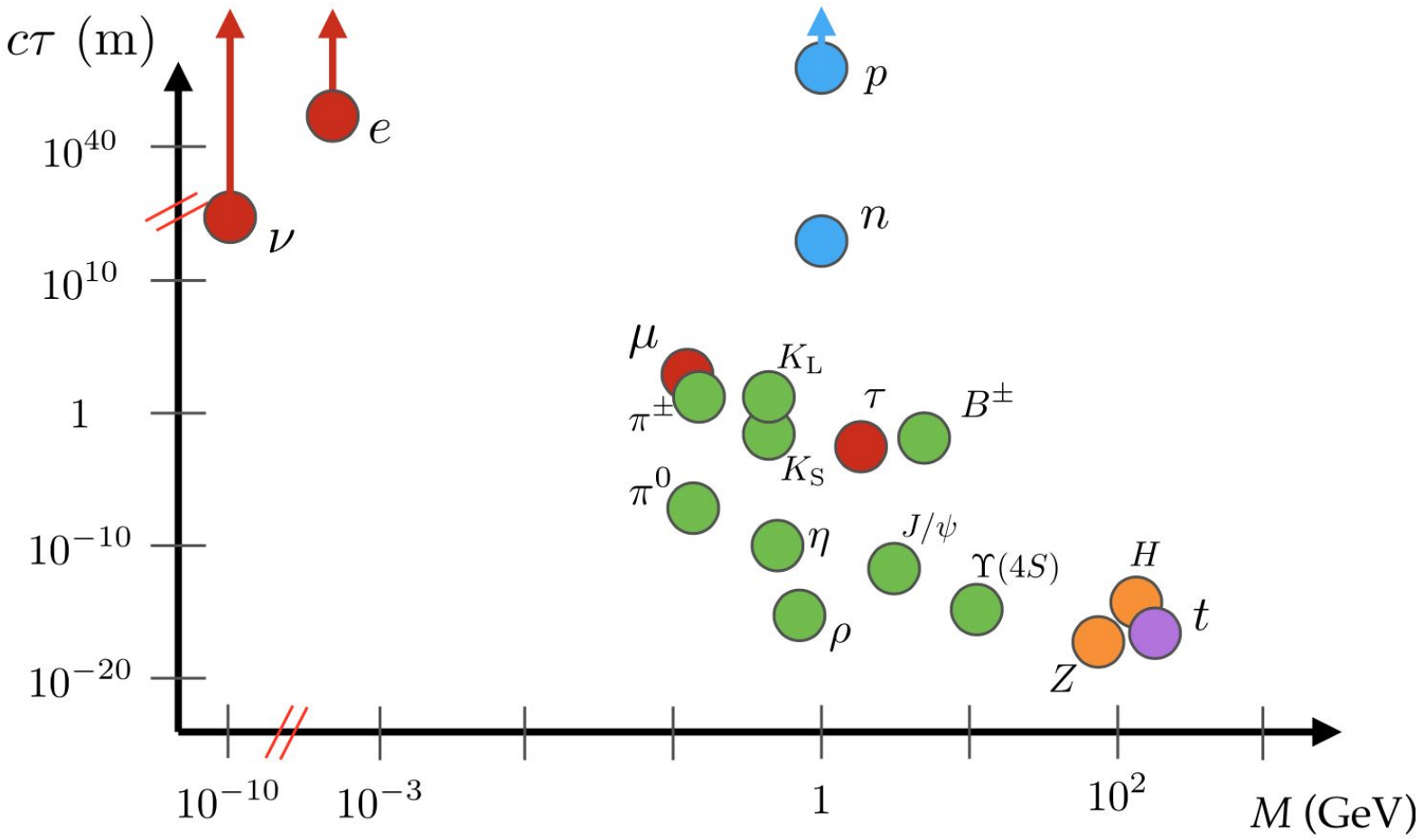


Supersymmetry



1903.04497

Long-lived particles



Long-lived mechanisms

$$\Gamma \sim \varepsilon^2 \, (m/\Lambda)^{2n} \, \Phi$$

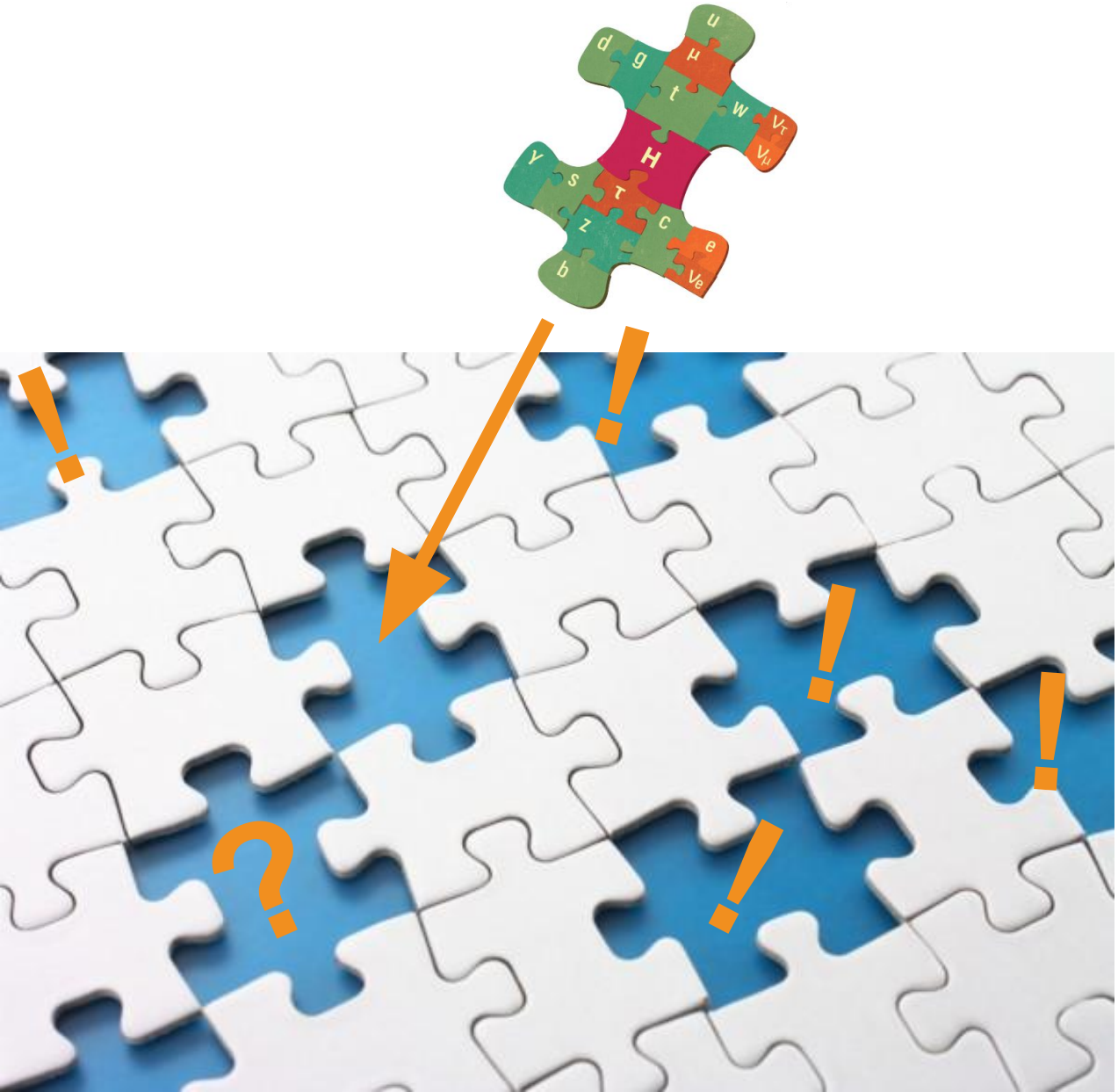
Small couplings

Mass hierarchies (suppressed loops)

Phase space

$$\tau \propto 1/\Gamma$$

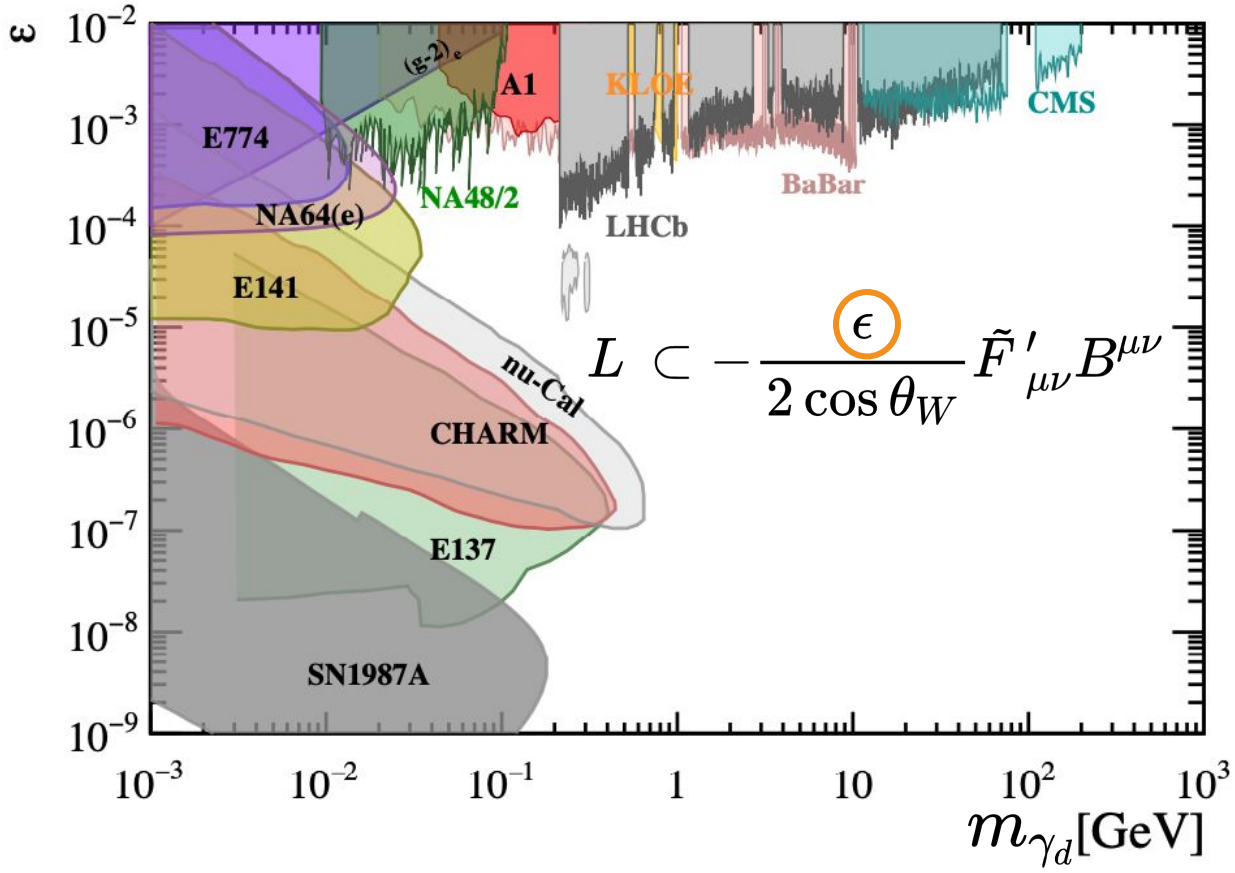
What makes them worth pursuing



- Gravity
- **Dark matter** ✓
- Unification of forces ✓
- Matter-antimatter imbalance ✓
- Hierarchy problem ✓

1412.0018
2005.01515

Massive dark photons



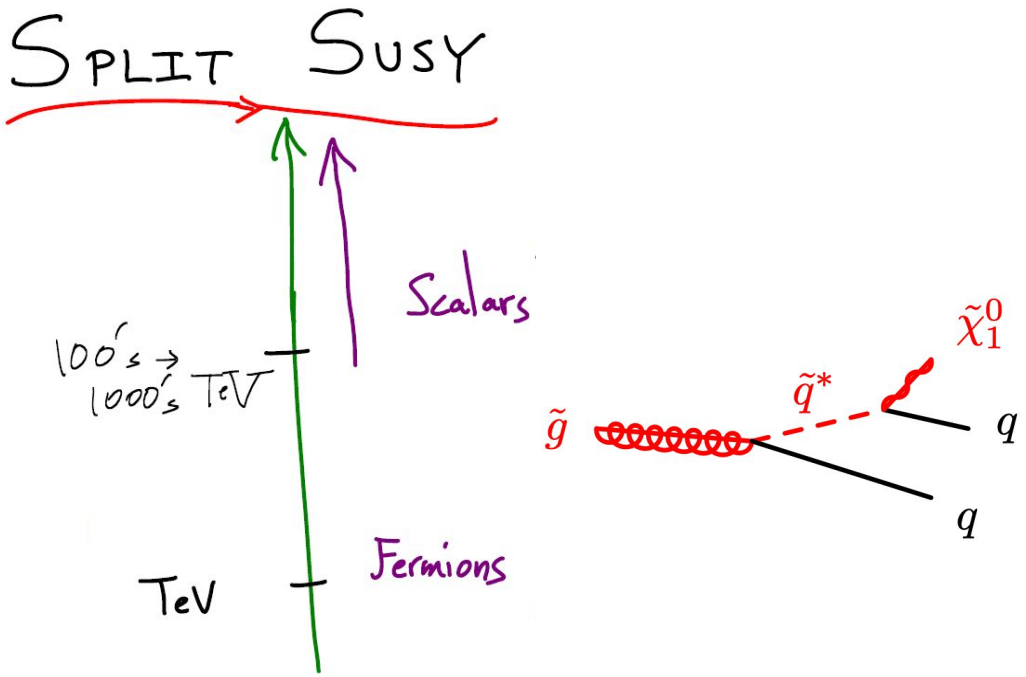
$$\tau_{\gamma_d} \sim \left(\frac{10^{-4}}{\epsilon}\right)^2 \left(\frac{100\,\text{MeV}}{m_{\gamma_d}}\right)$$

Small couplings

- Dark matter ✓ (~)

Split supersymmetry

hep-ph/0406088
hep-th/0405159



Sketch: N. Arkani-Hamed

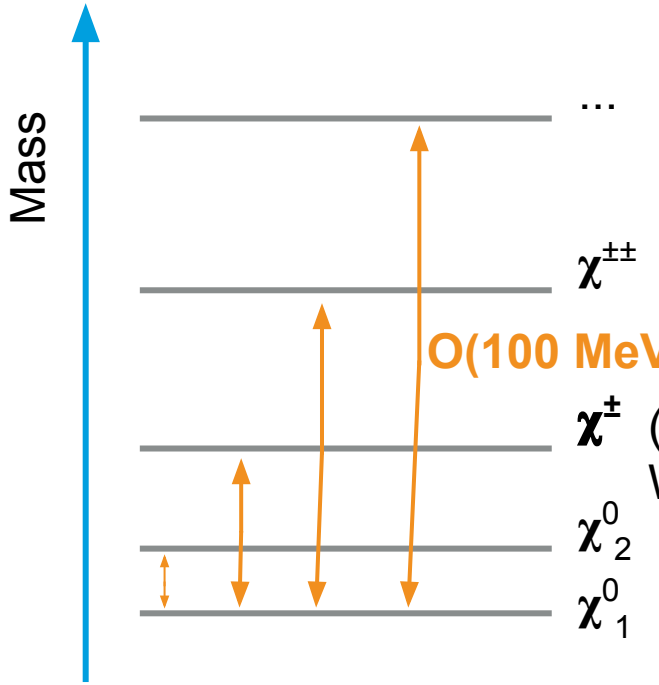
Mass hierarchies

- Dark matter ✓
- Unification of forces ✓
- Hierarchy problem ~

$$\tau = 3 \times 10^{-2} \text{sec} \left(\frac{m_S}{10^9 \text{ GeV}} \right)^4 \left(\frac{1 \text{ TeV}}{m_{\tilde{g}}} \right)^5$$

hep-ph/0512090

Minimal dark matter



Phase space

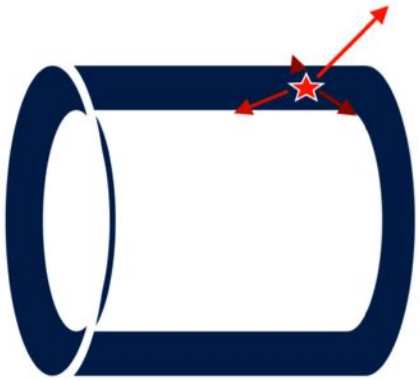
- Dark matter ✓

$$\tau_{\chi^\pm} \sim \frac{44\,cm}{(n^2-1)}$$ for Y=0 and multiplet dimension ≥ 3

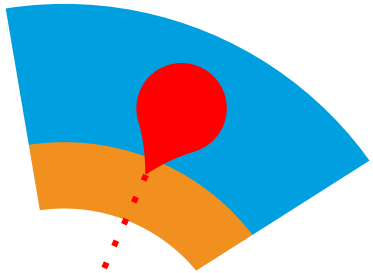
The searches: everything is “non-standard”

IN THIS SEMINAR:

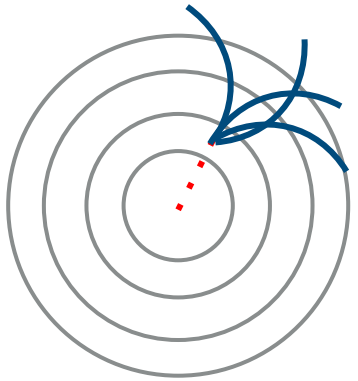
LHC



LATE DECAYS

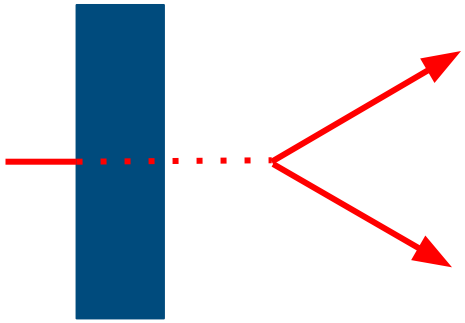


UNUSUAL SHOWERS

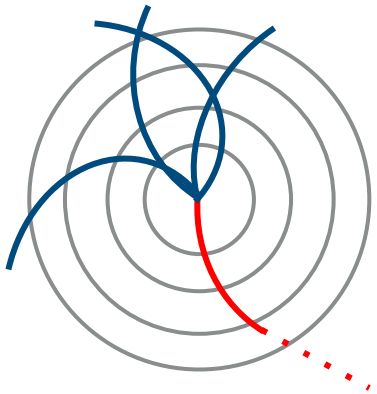


DISPLACED VERTICES

BEYOND LHC



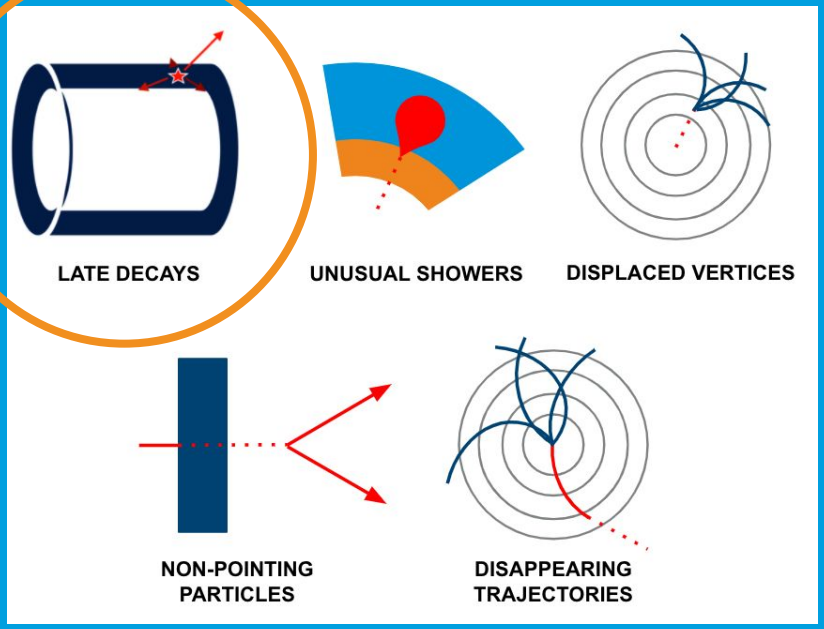
NON-POINTING PARTICLES



DISAPPEARING TRAJECTORIES

2104.03050

Searches at the LHC



JHEP

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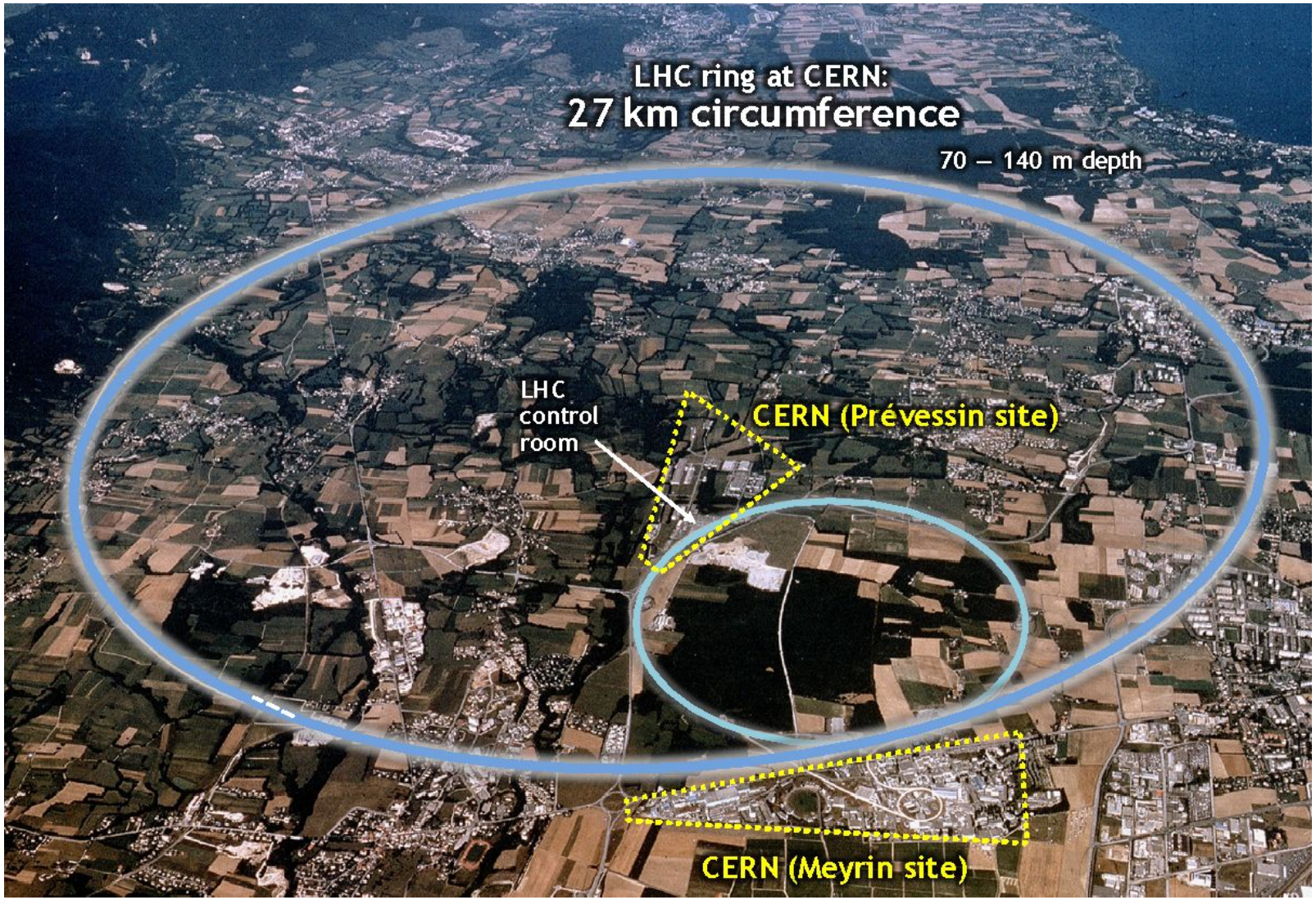
A search for the decays of stopped long-lived particles at $\sqrt{s} = 13$ TeV with the ATLAS detector

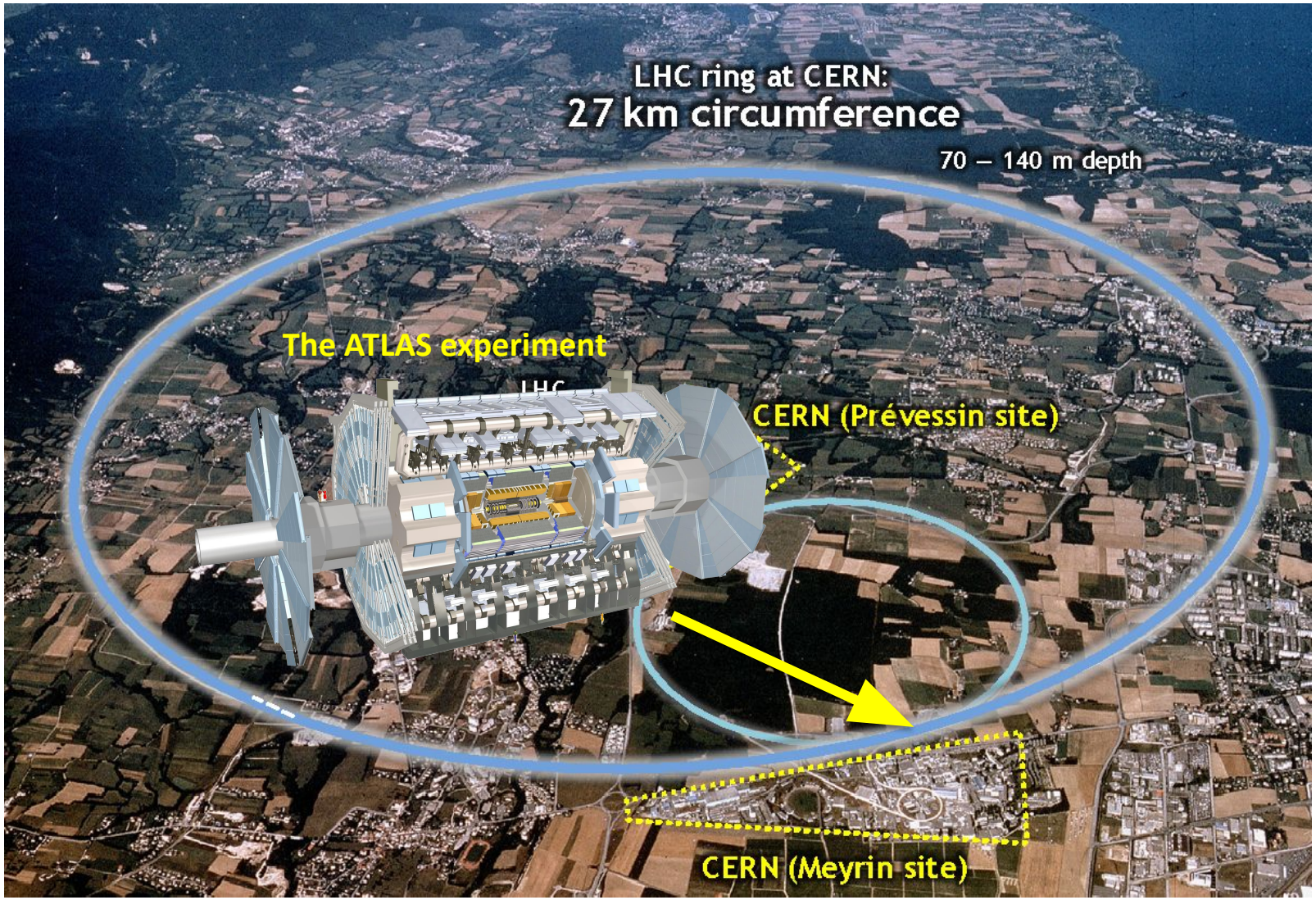
ATLAS EXPERIMENT

The ATLAS collaboration

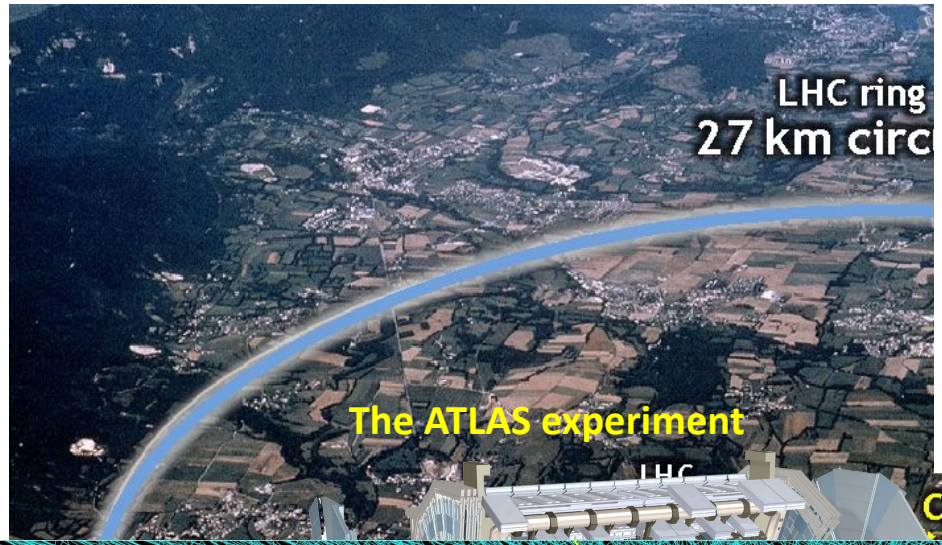
The energy frontier today

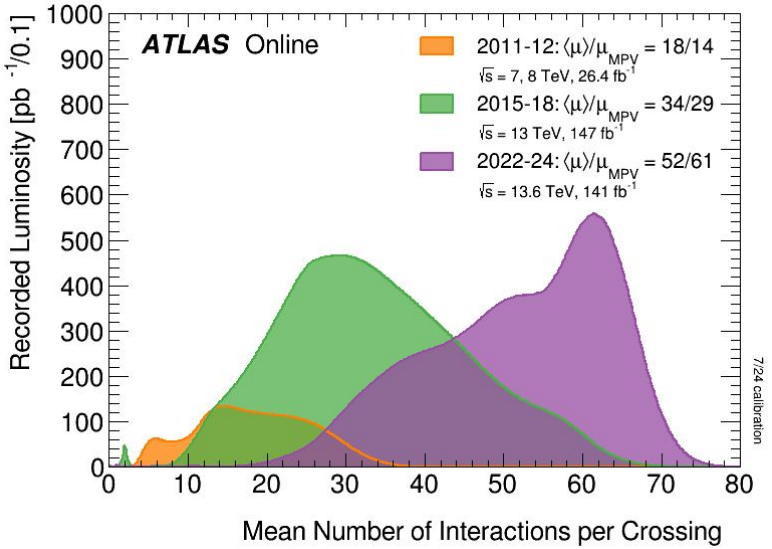


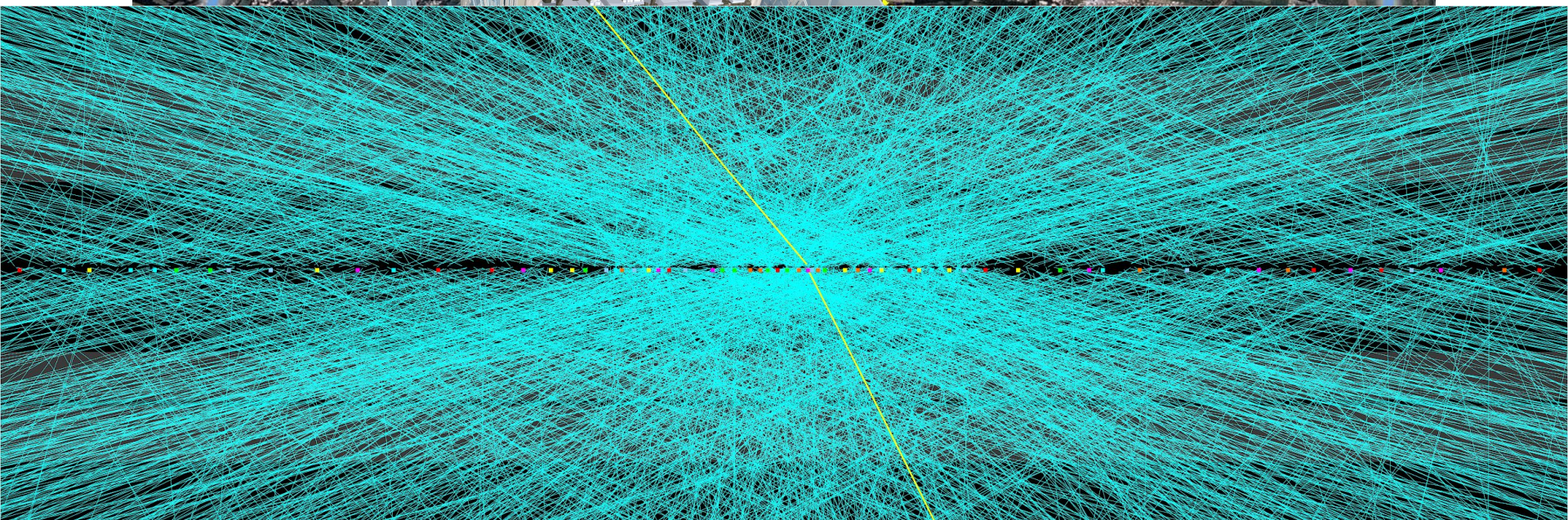
The energy frontier today



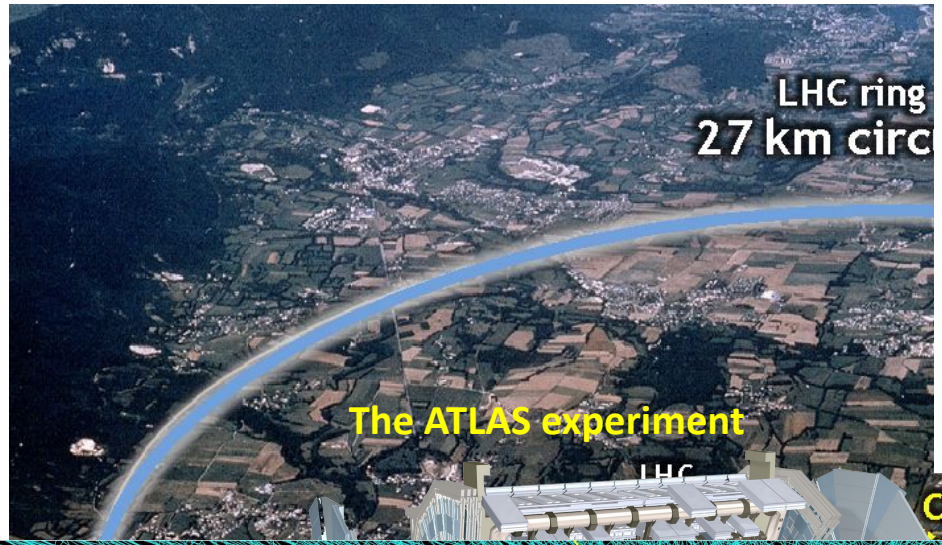
The energy frontier today

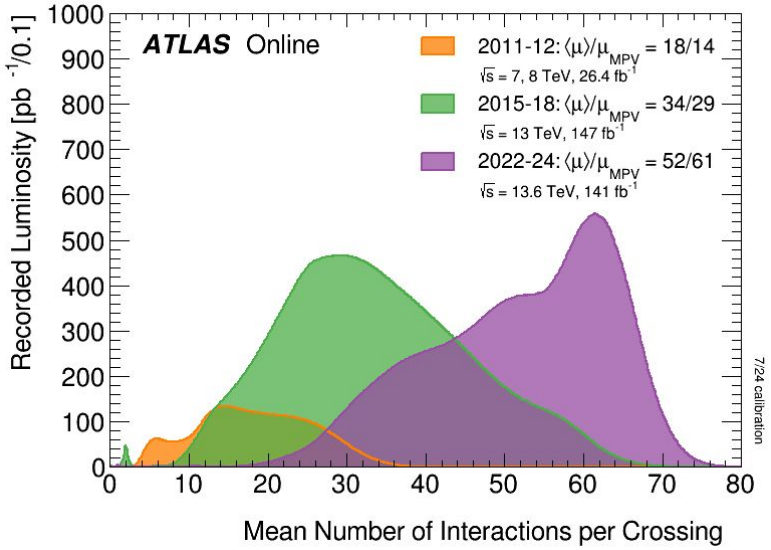


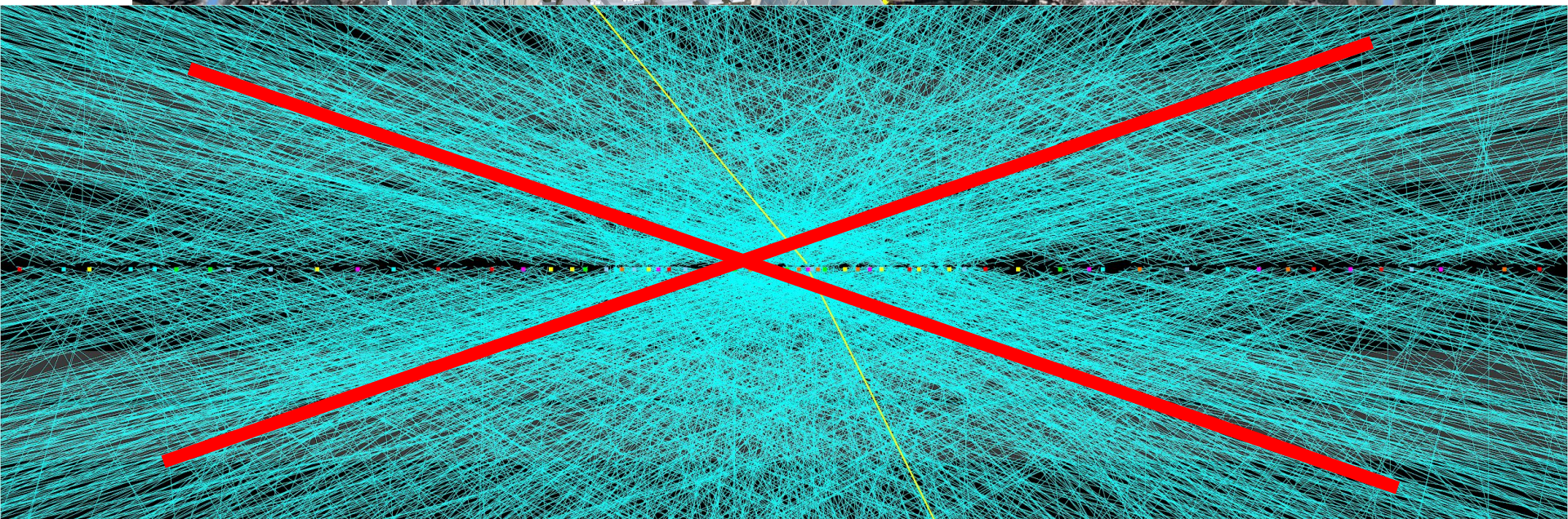




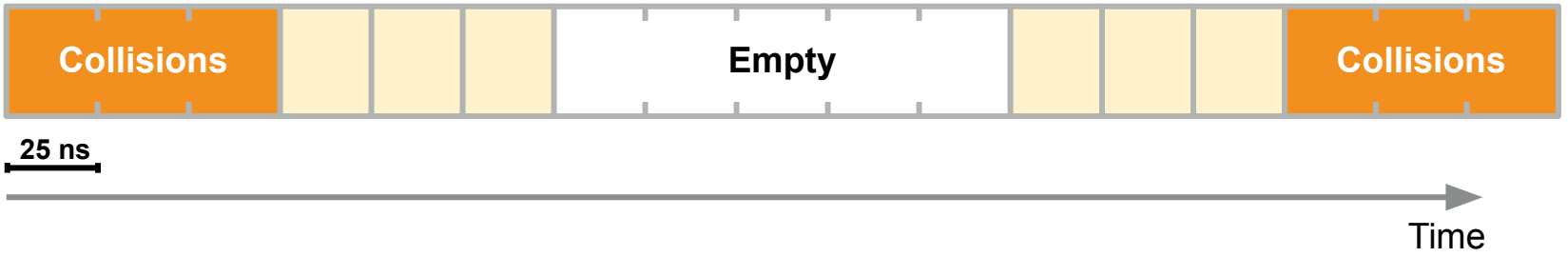
The energy frontier today



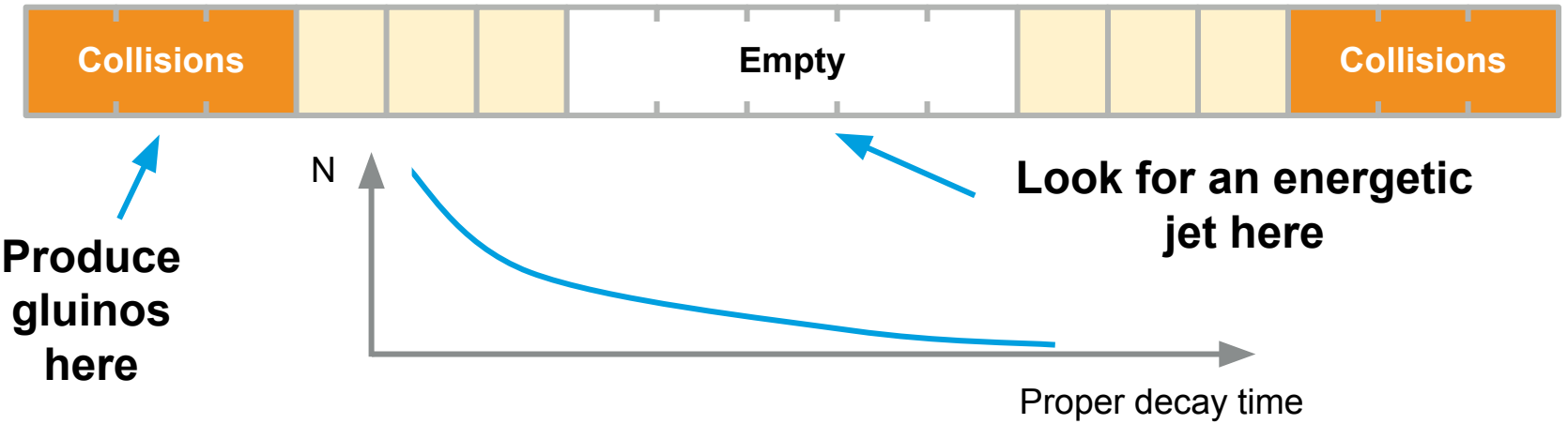


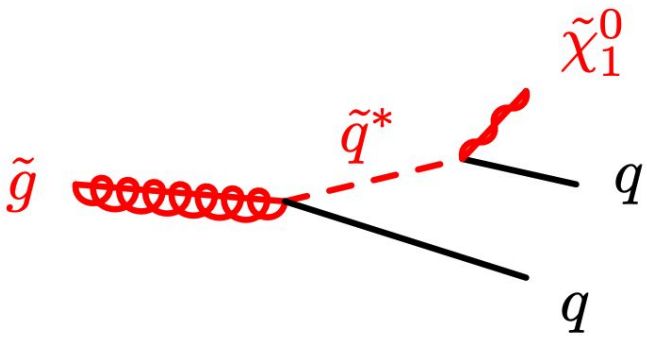


A completely different strategy



A completely different strategy



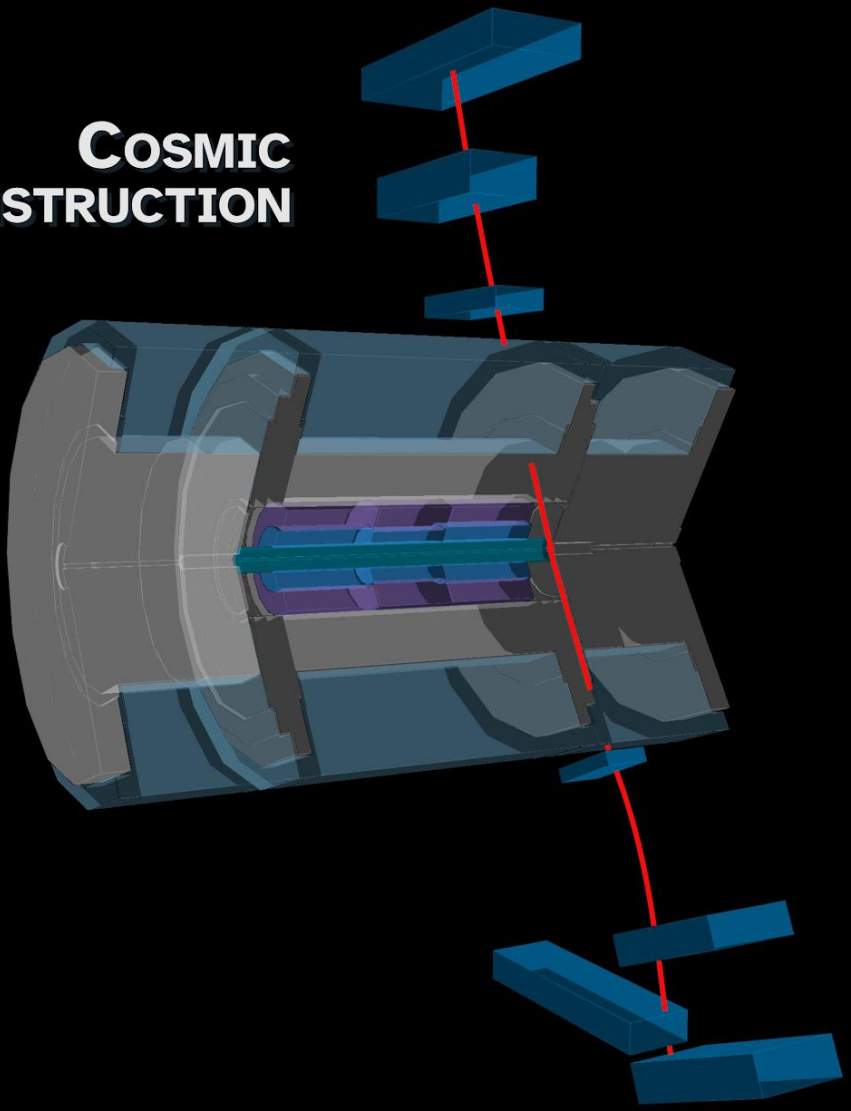


ATLAS EXPERIMENT

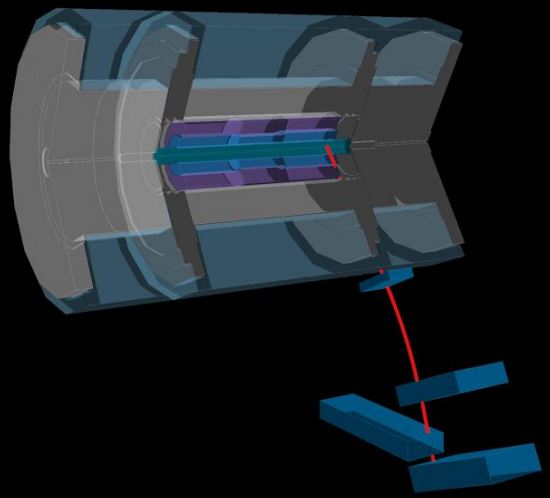
Run 306147
Event 16519

2016-08-11 21:51:33 CEST

Cosmic Reconstruction



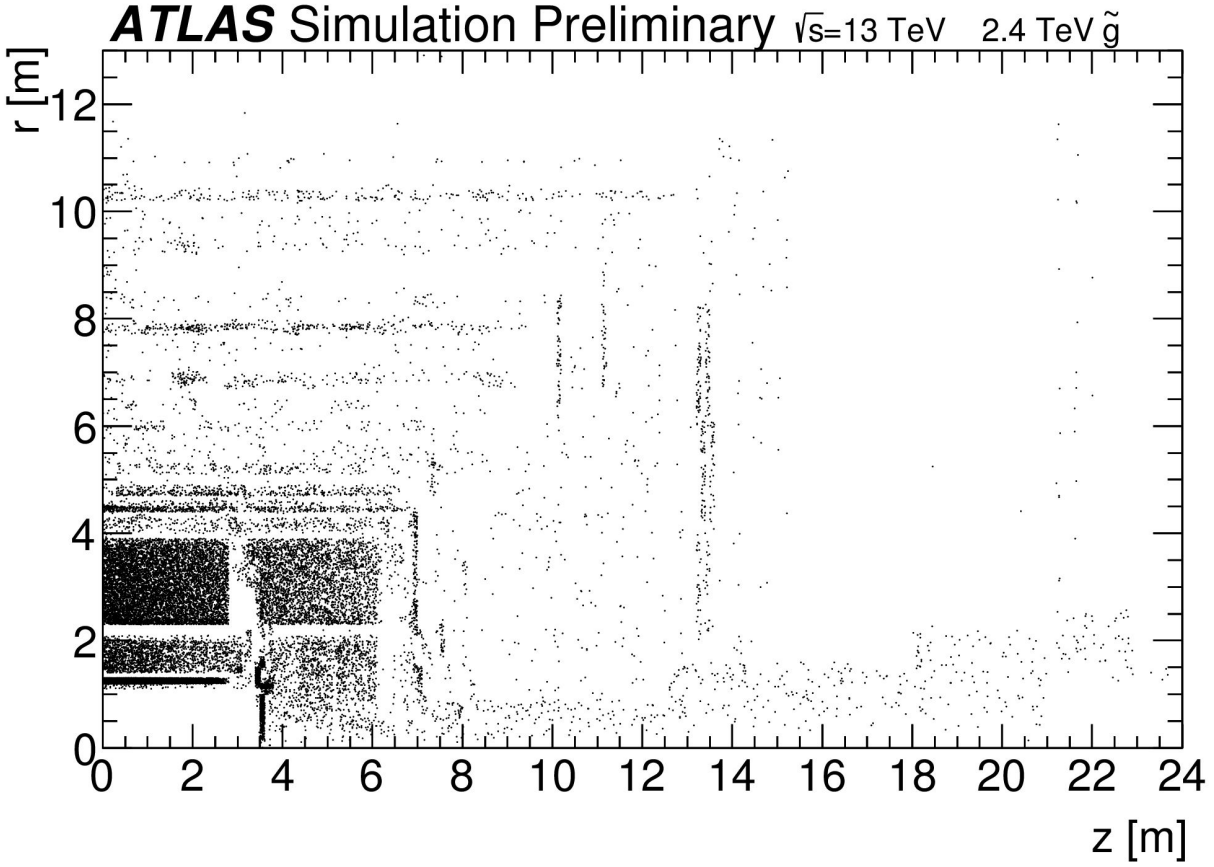
Collision Reconstruction



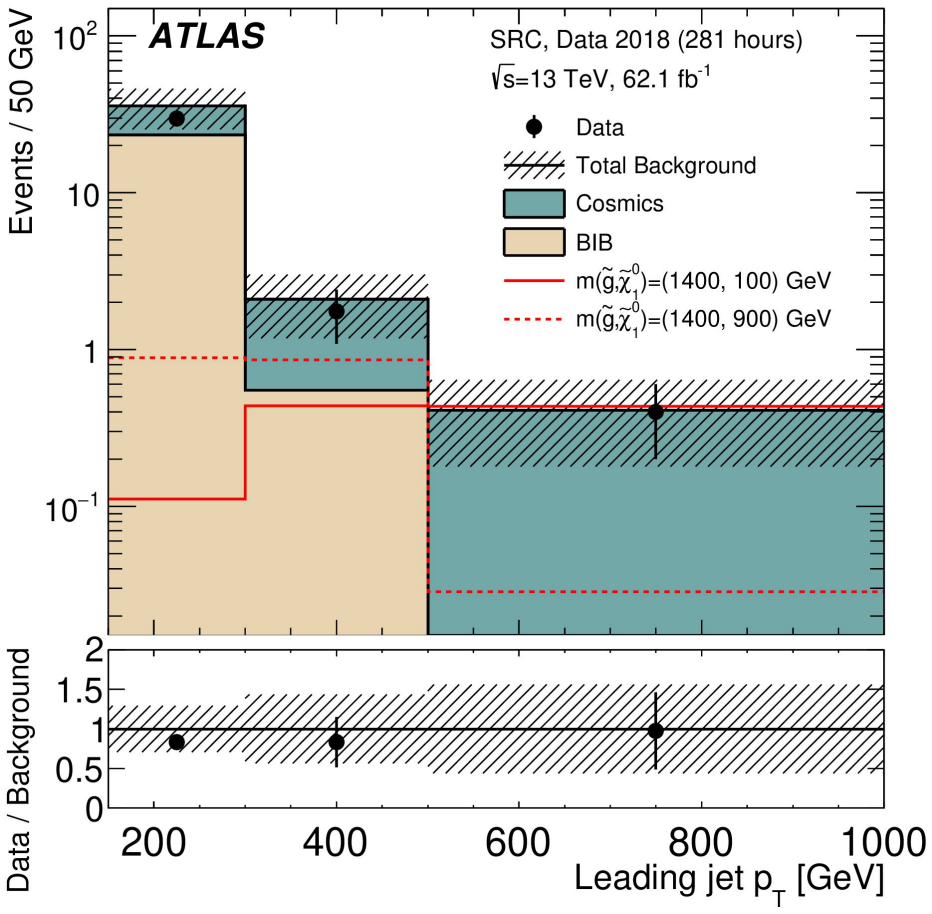
DESY.

Estimating stopped signal yields

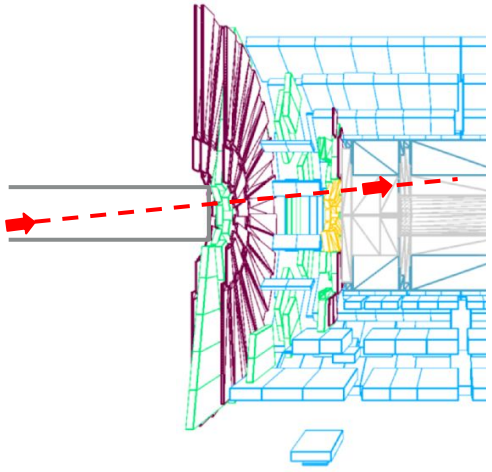
$$N_{\text{events}}^{\text{SR}} = L^{\text{int}} \times \sigma_{\tilde{g}\tilde{g}} \times 2 \times \epsilon^{\text{SR}} \times f_{\text{stopping}} \times (\text{live fraction})$$



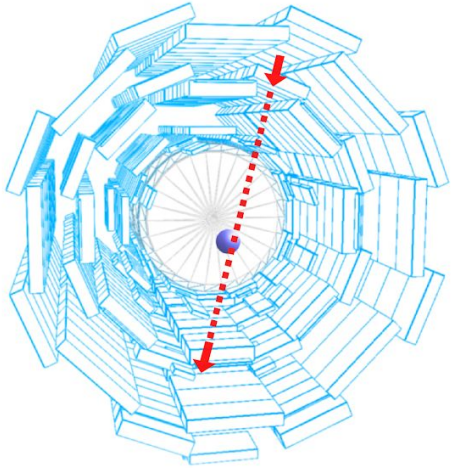
The result



BEAM-INDUCED BACKGROUNDS (BIB)

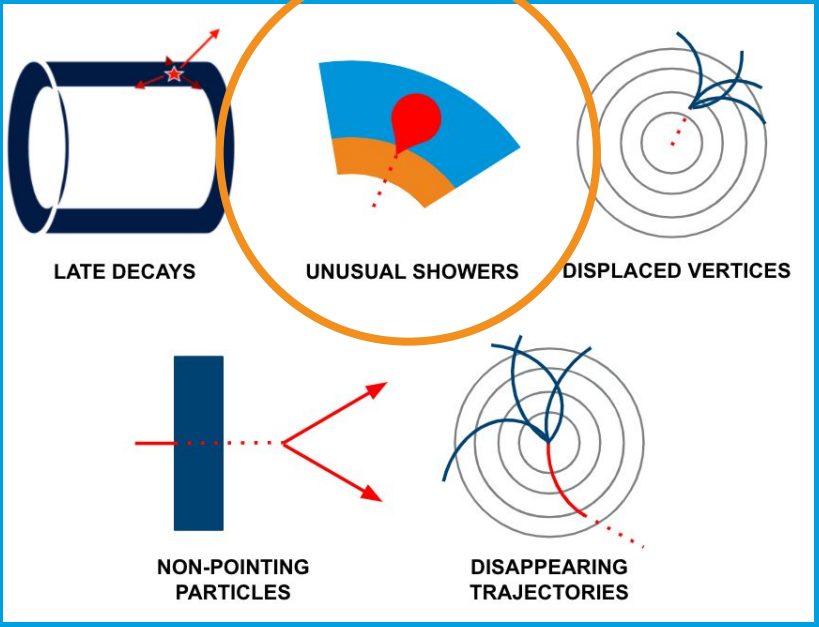


COSMICS



2206.12181

Searches at the LHC



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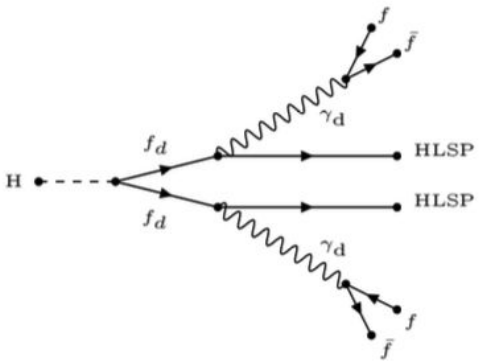
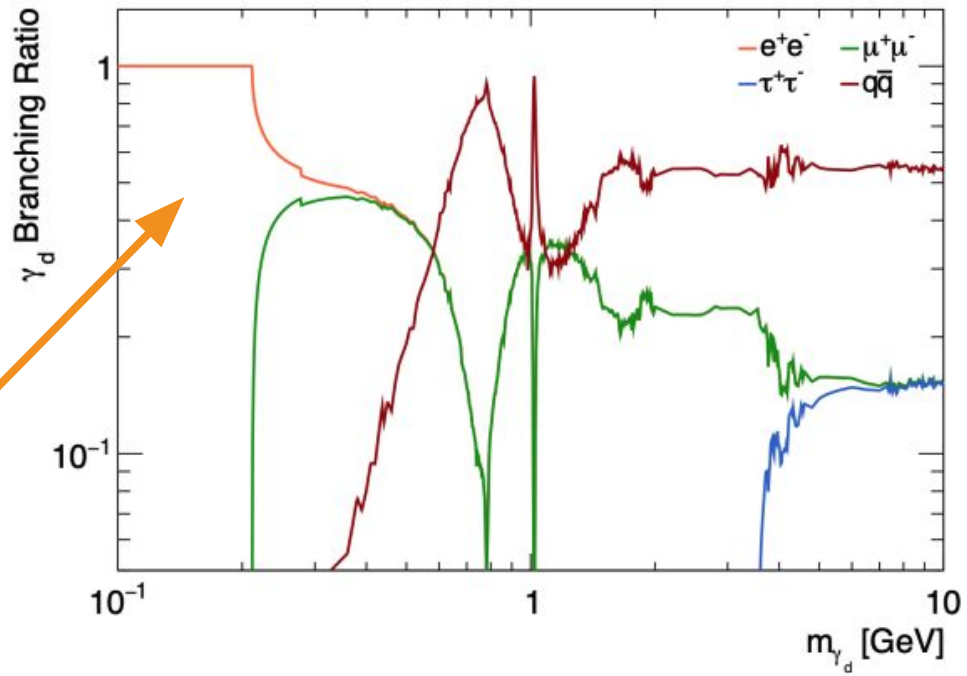
Search for light long-lived neutral particles that decay to collimated pairs of leptons or light hadrons in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

ATLAS EXPERIMENT

The ATLAS collaboration

Dark photons in Higgs boson decays



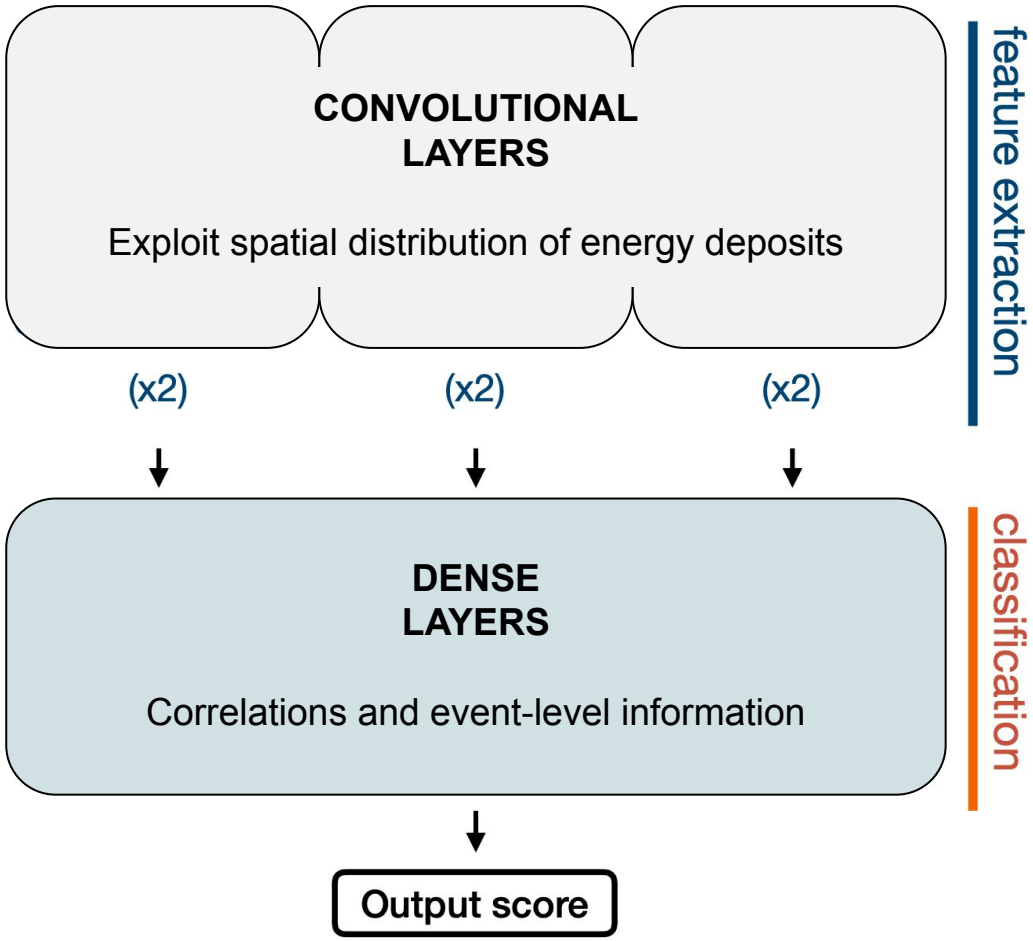


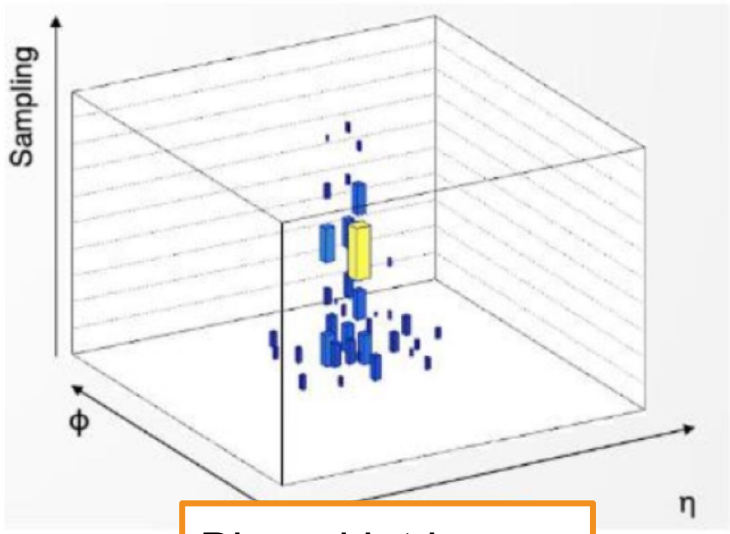
$$m_{\gamma_d} < 2m_\mu$$

Unprobed
(no online selections)

→ exploit WH production

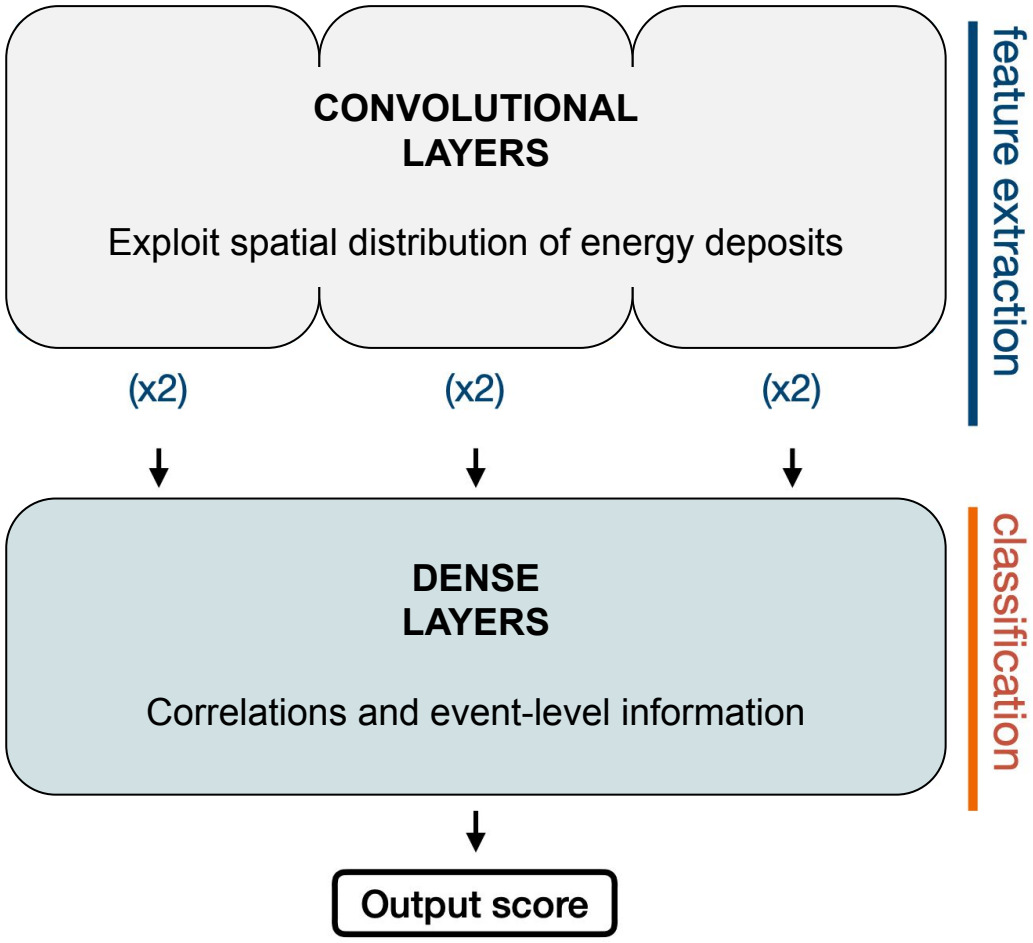
Separating dark photon jets from QCD

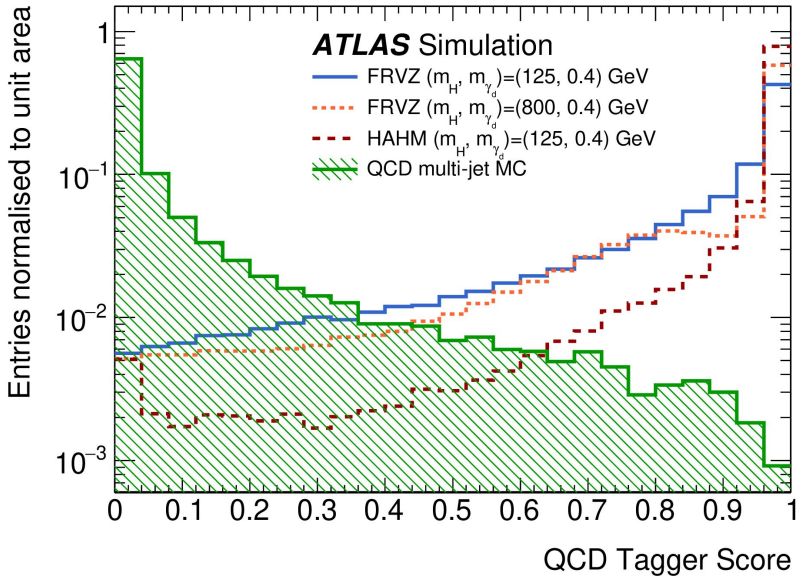




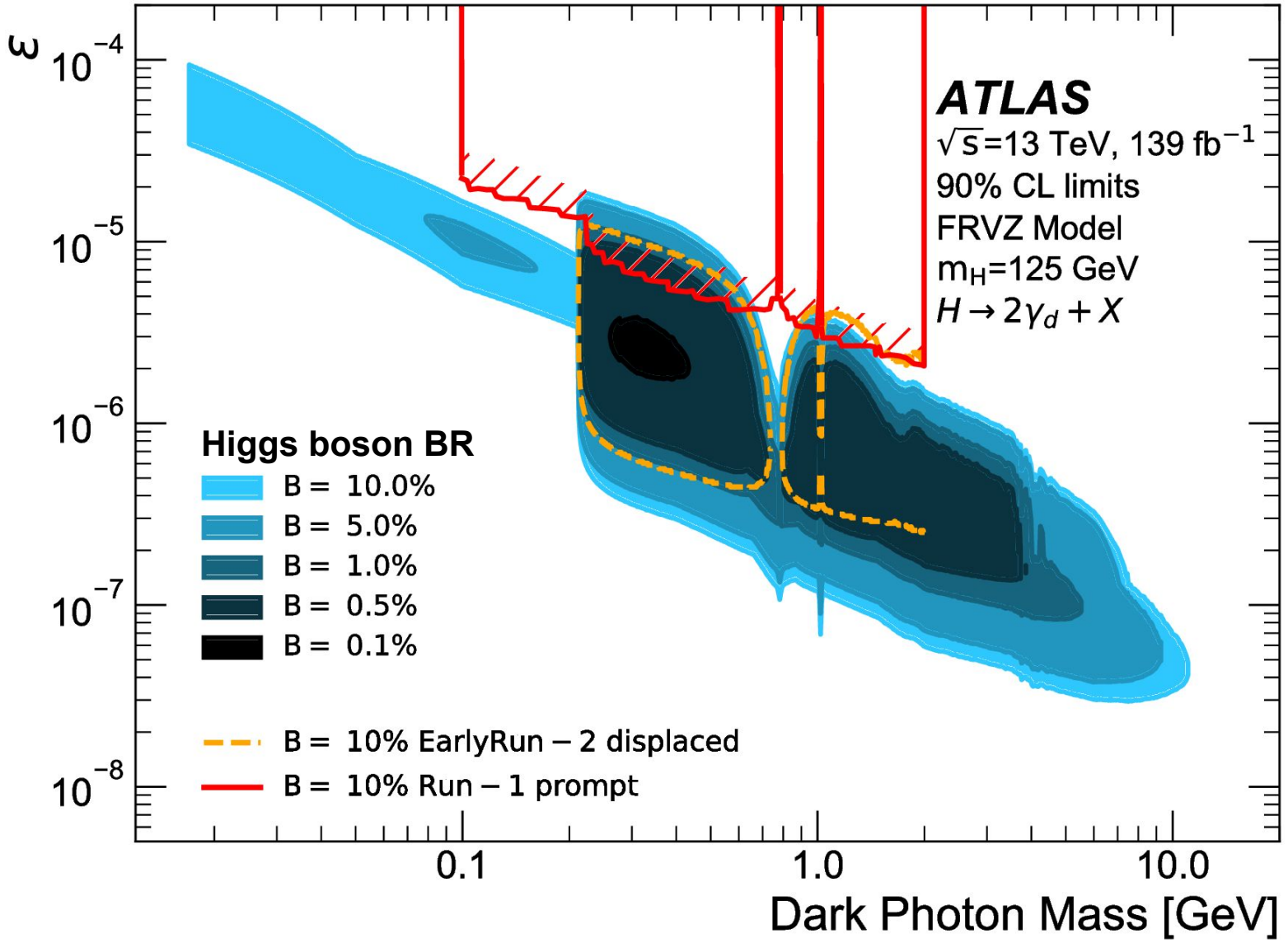
Binned jet image

Separating dark photon jets from QCD



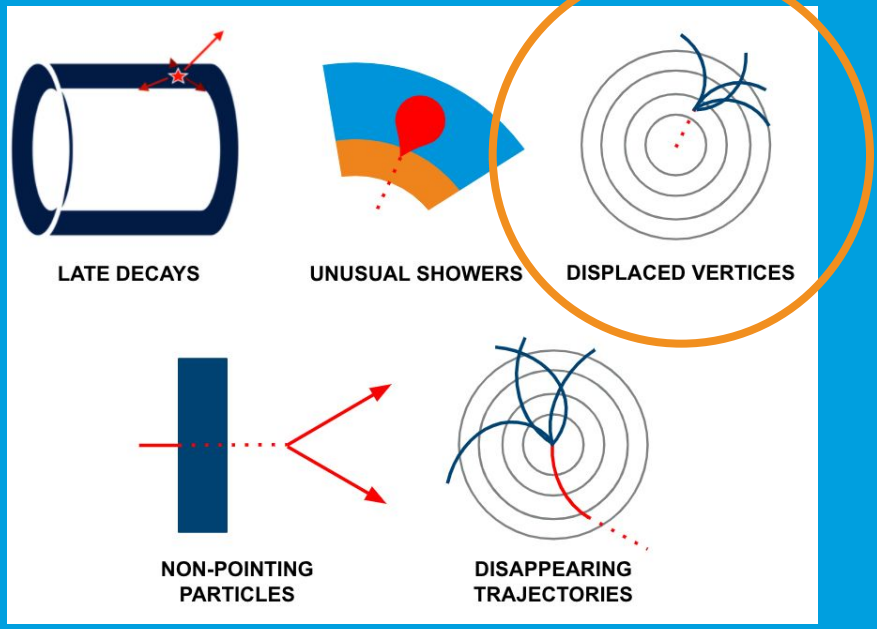


Extending sensitivity to low masses



2301.13866

Searches at the LHC



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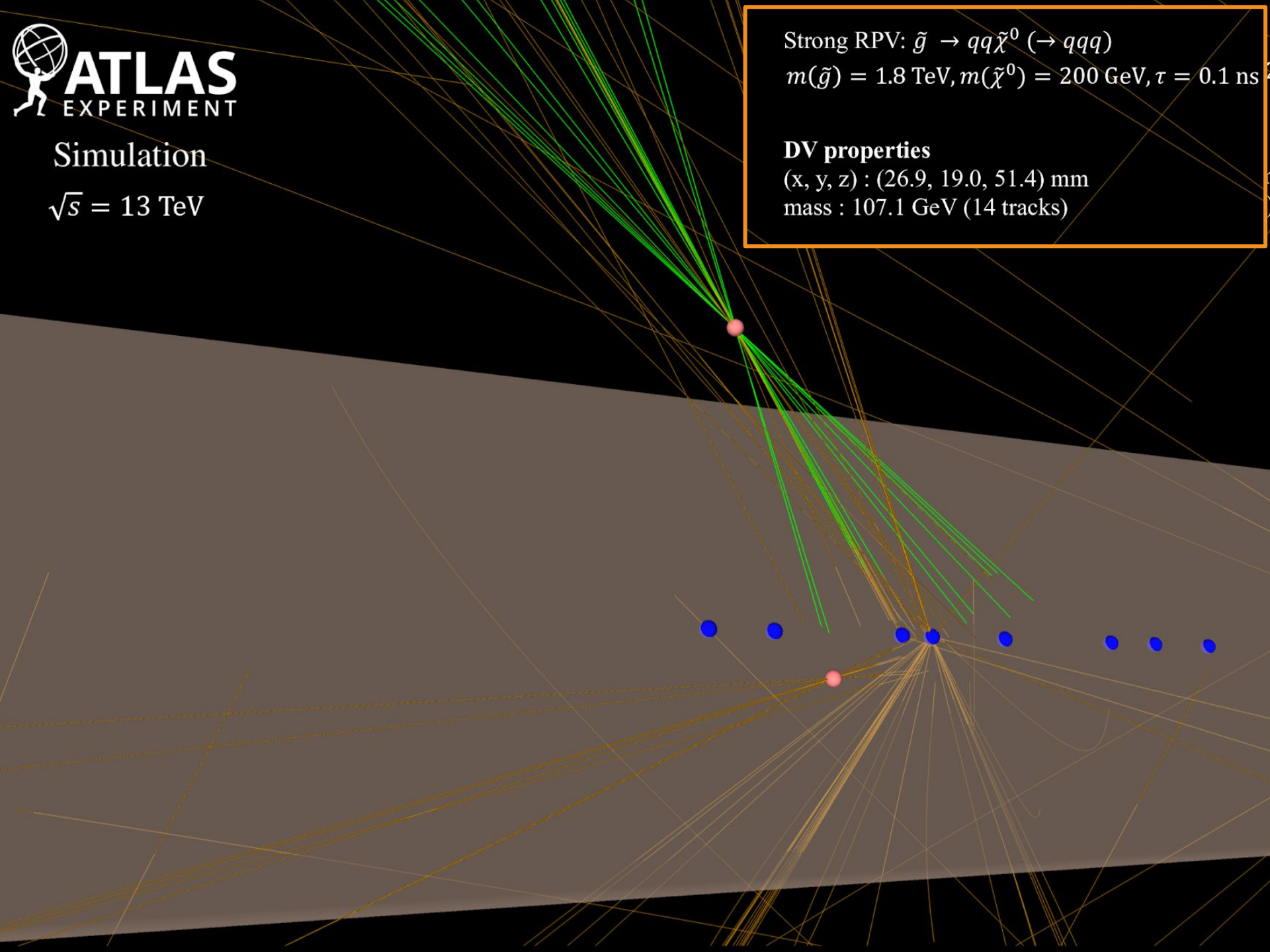
Search for long-lived, massive particles in events with displaced vertices and multiple jets in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

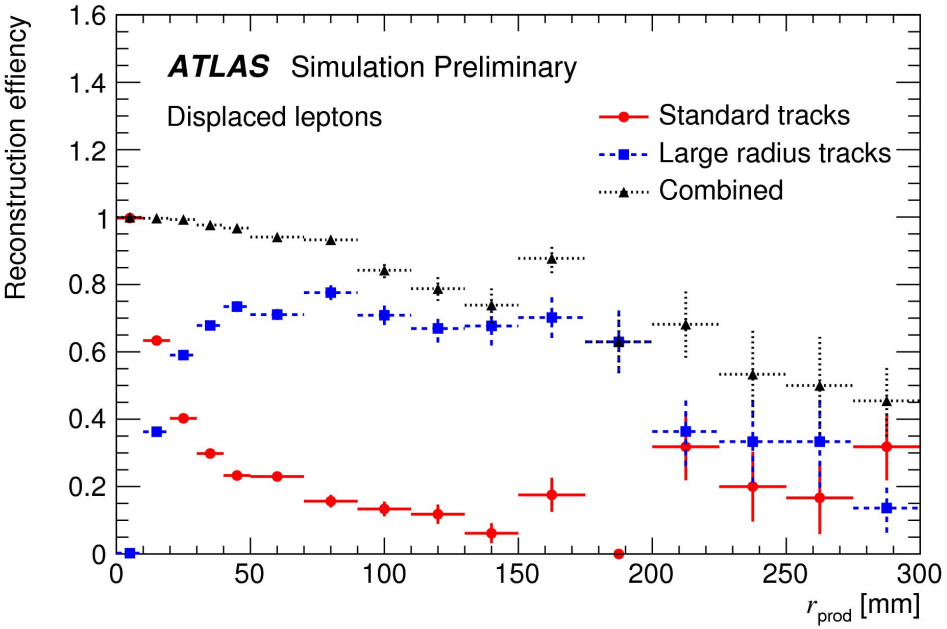
ATLAS EXPERIMENT

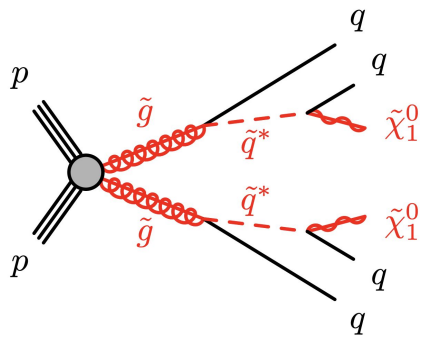
The ATLAS collaboration

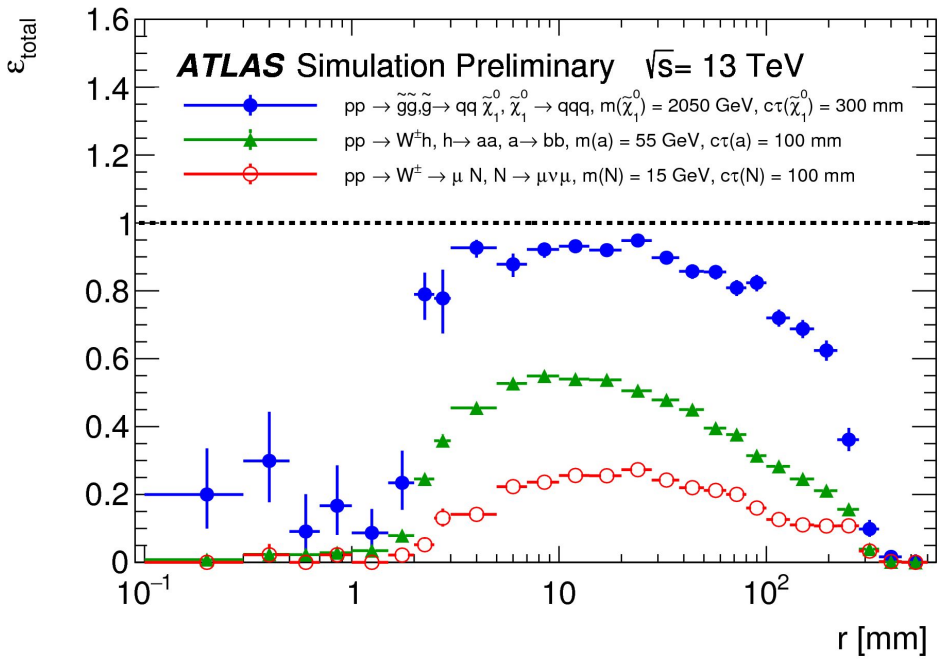

ATLAS
EXPERIMENT
Simulation
$\sqrt{s} = 13$ TeV
Strong RPV: $\tilde{g} \rightarrow qq\tilde{\chi}^0 (\rightarrow qqq)$
$m(\tilde{g}) = 1.8$ TeV, $m(\tilde{\chi}^0) = 200$ GeV, $\tau = 0.1$ ns
DV properties
(x, y, z) : (26.9, 19.0, 51.4) mm
mass : 107.1 GeV (14 tracks)

ATL-PHYS-PUB-2017-014
ATL-PHYS-PUB-2019-013

Displaced vertex reconstruction

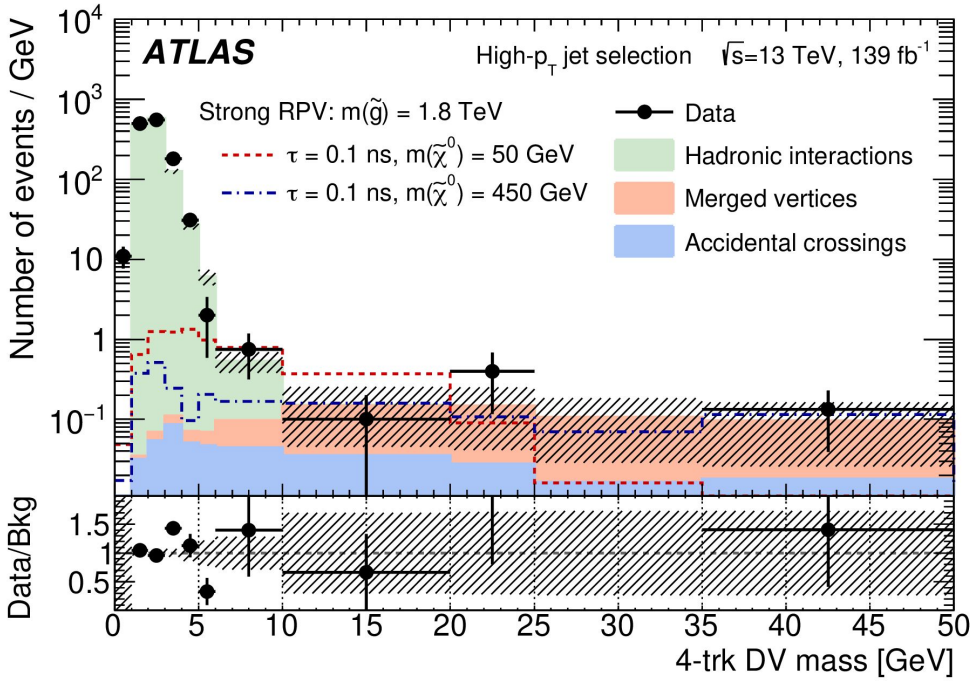




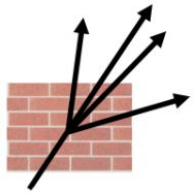


The backgrounds

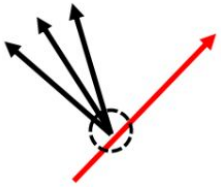
There are no SM processes producing high-mass displaced vertices



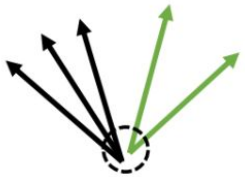
Hadronic interactions



Accidental crossings



Merged vertices



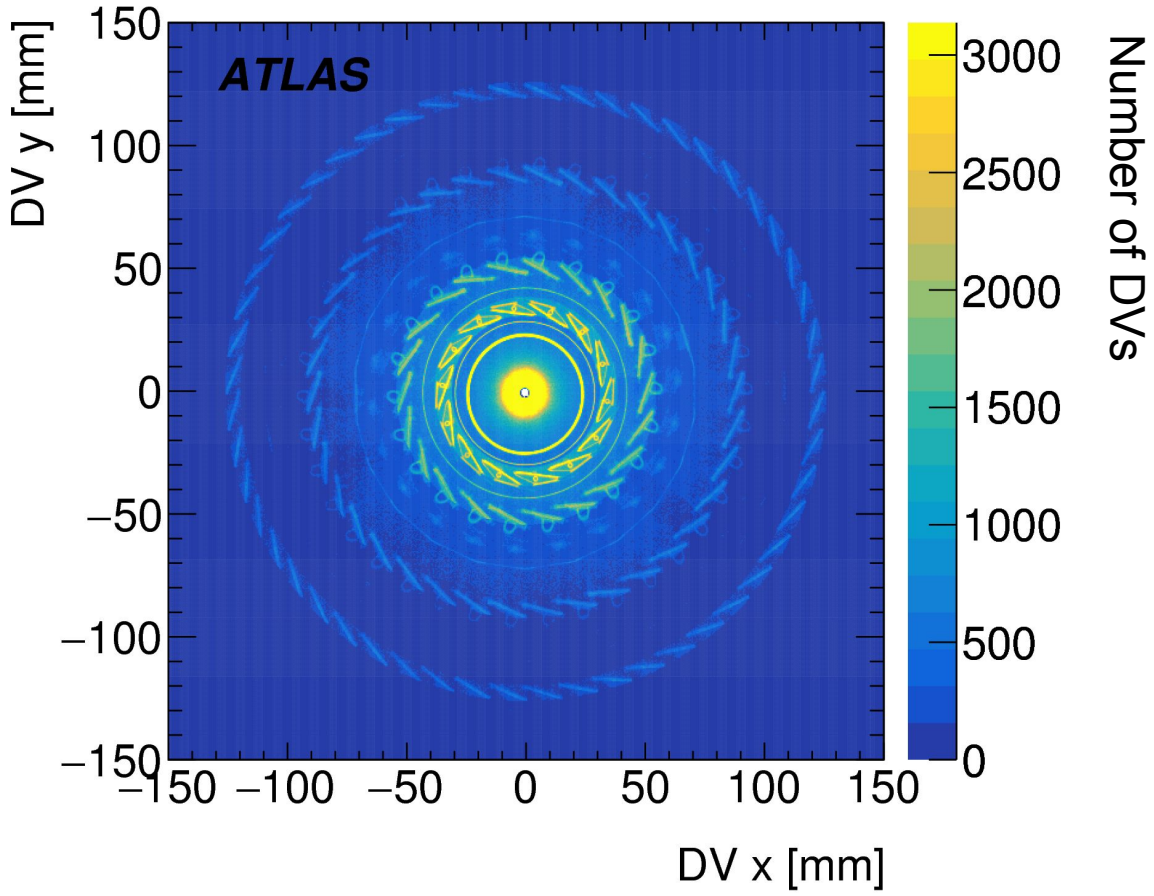
Displaced vertex selections

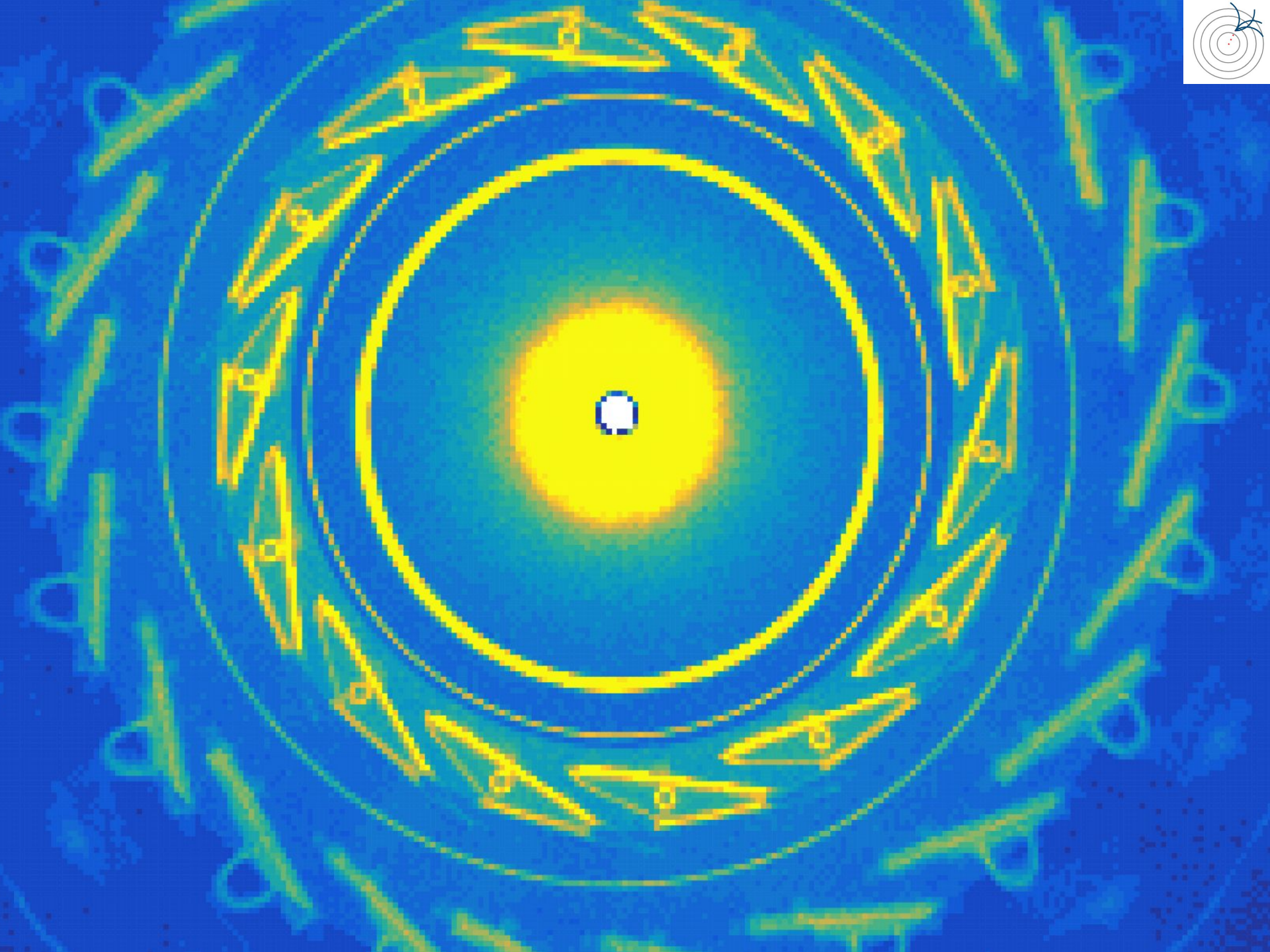
R_{xy} > 4 mm

Hadronic interactions veto

≥ 5 tracks

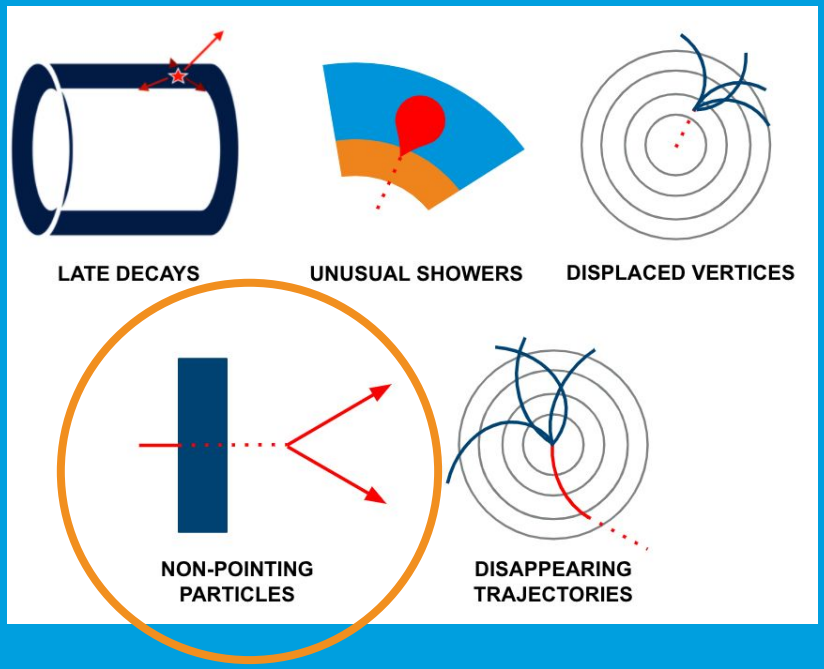
m_{vis} > 10 GeV





2308.00515

Beyond the LHC



Eur. Phys. J. Spec. Top.
https://doi.org/10.1140/epjs/s11734-024-01164-9

THE EUROPEAN PHYSICAL JOURNAL SPECIAL TOPICS

Review

Technical Design Report for the LUXE experiment

LUXE Collaboration, H. Abramowicz[1], M. Almanza Soto[2], M. Altarelli[3], R. Aßmann[4], A. Athanassiadis[4,27], G. Avoni[5], T. Behnke[4], M. Benettoni[6], Y. Benhammou[1], J. Bhatt[7], T. Blackburn[8], C. Blanch[2], S. Bonaldo[6], S. Boogert[9,10], O. Borysov[4,28], M. Borysova[4,11,28], V. Boudry[12], D. Breton[13], R. Brinkmann[4], M. Bruschi[5], F. Burkart[4], K. Büßer[4], N. Cavanagh[14], F. Dal Corso[6], W. Decking[4], M. Deniaud[15], O. Diner[16], U. Dosselli[6], M. Elad[1], L. Epshteyn[16], D. Esperante[2], T. Ferber[17], M. Firlej[18], T. Fiutowski[18], K. Fleck[14], N. Fuster-Martinez[2], K. Gadow[4], F. Gaede[4], A. Gallas[13], H. Garcia Cabrera[2], E. Gerstmayr[14], V. Ghenescu[19], M. Giorato[6], N. Golubeva[4], C. Grojean[4,29], P. Grutta[6], G. Grzelak[20], J. Hallford[4,7], L. Hartman[4,30], B. Heinemann[4,21], T. Heinzl[22], L. Helary[4], L. Hendriks[4,7], M. Hoffmann[4,21,31], D. Horn[1], S. Huang[1], X. Huang[4,21,23], M. Idzik[18], A. Irles[2], R. Jacobs[4,a], B. King[22], M. Klute[17], A. Kropf[4,21], E. Kroupp[16], H. Lahno[11], F. Lasagni Manghi[5], J. Lawhorn[17], A. Levanon[1], A. Levi[16], L. Levinson[16], A. Levy[1], I. Levy[24], A. Liberman[16], B. Liss[4], B. List[4], J. List[4], W. Lohmann[4,32], J. Maalmi[13], T. Madlener[4], V. Malka[16], T. Marsault[4,33], S. Mattiazzo[6], F. Meloni[4], D. Miron[1], M. Morandin[6], J. Moroń[18], J. Nanni[12], A. T. Neagu[19], E. Negodin[4], A. Paccagnella[6], D. Pantano[6], D. Pietruch[18], I. Pomerantz[1], R. Pöschl[13], P. M. Potlog[19], R. Prasad[4], R. Quishpe[17], E. Ranken[4], A. Ringwald[4], A. Roich[16], F. Salgado[23,25], A. Santra[16], G. Sarri[14], A. Sävert[23,25], A. Sbrizzi[5], S. Schmitt[4], I. Schulthess[4], S. Schuwalow[4], D. Seipt[23,25], G. Simi[6], Y. Soreq[26], D. Spataro[4,21], M. Streeter[14], K. Swientek[18], N. Tal Hod[16], T. Teter[23,25], A. Thiebault[13], D. Thoden[4], N. Trevisani[17], R. Urmanov[16], S. Vasiukov[6], S. Walker[4], M. Warren[7], M. Wing[4,7], Y. C. Yap[4], N. Zadok[1], M. Zanetti[6], A. F. Żarnecki[20], P. Zbińkowski[20], K. Zembaczyński[20], M. Zepf[23,25], D. Zerwas[13,34], W. Ziegler[23,25], and M. Zuffa[5]

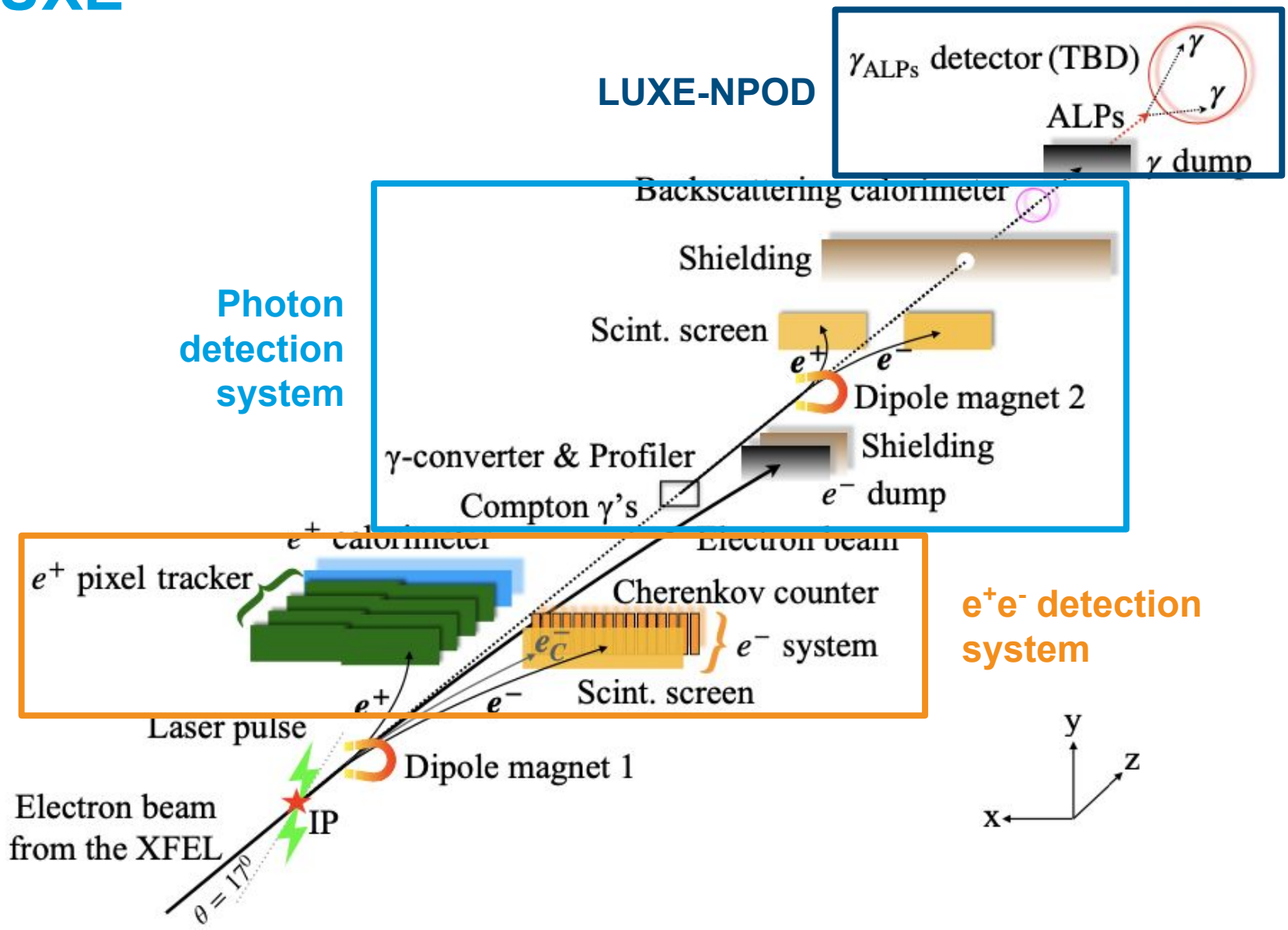
The LLP community

Figure credit: J. Beacham

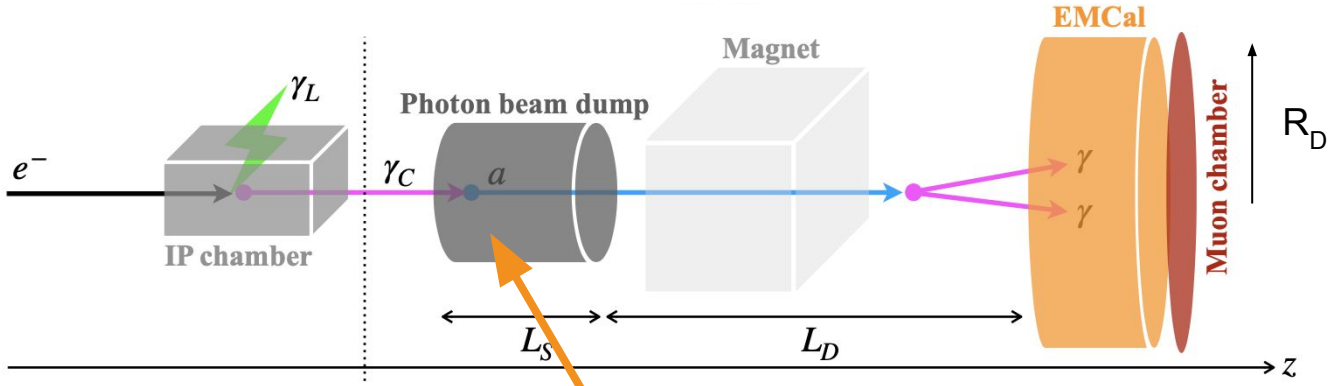
The focus on LLP searches has only grown in the past ~decade

Significant programme beyond the LHC

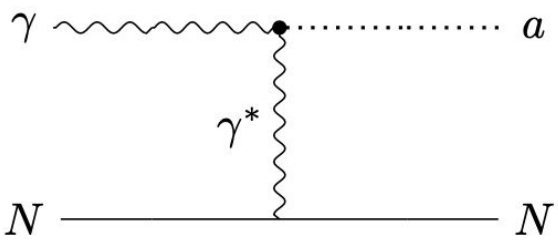
LUXE


LUXE-NPOD
γ_{ALPs} detector (TBD)
ALPs
γ dump
Backscattering calorimeter
Shielding
Photon detection system
Scint. screen
e^+
e^-
Dipole magnet 2
γ-converter & Profiler
Compton γ's
Shielding
e^- dump
e^+ pixel tracker
Cherenkov counter
e^- system
Scint. screen
e^+
e^-
Laser pulse
Dipole magnet 1
Electron beam from the XFEL
IP
$\theta = 17^0$
e^+e^- detection system
y
z
x

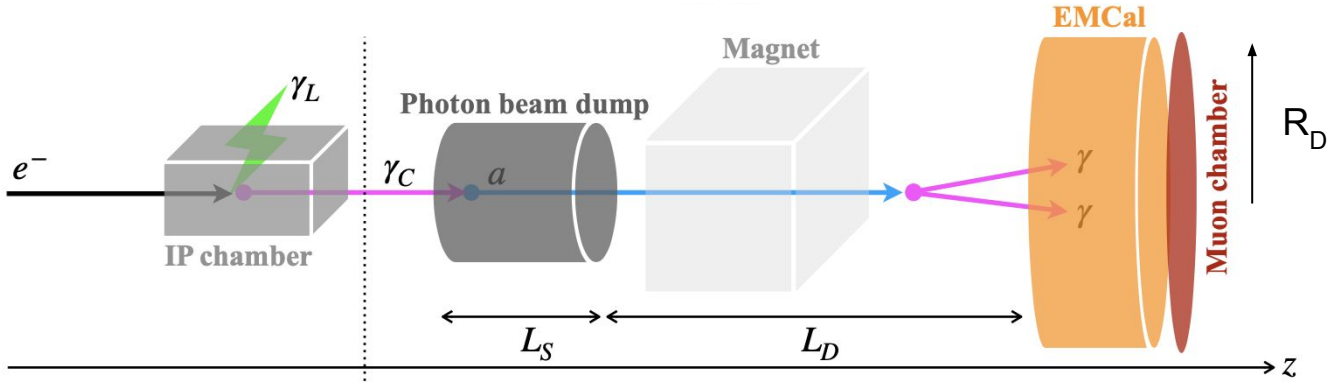
LUXE-NPOD: experimental setup

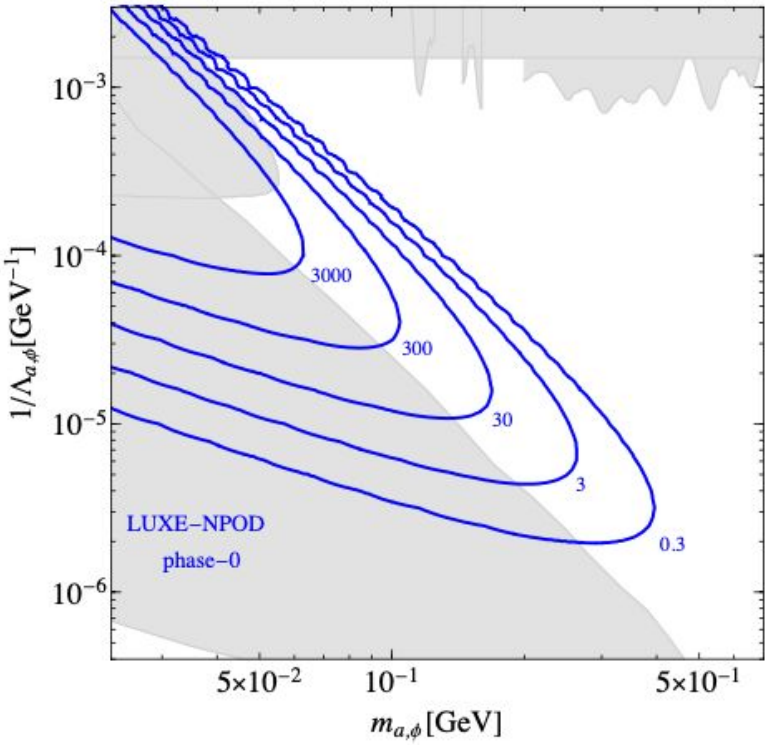


Production via Primakoff effect



Expected signal yields





$$N_a \approx \mathcal{L}_{\text{eff}} \int dE_\gamma \frac{dN_\gamma}{dE_\gamma} \sigma_a \left(e^{-\frac{L_S}{L_a}} - e^{-\frac{L_D+L_S}{L_a}} \right) \mathcal{A}$$

E_e = 16.5 GeV

N_e = 1.5×10^9

N_{BX} = 10^7

Eu.XFEL parameters

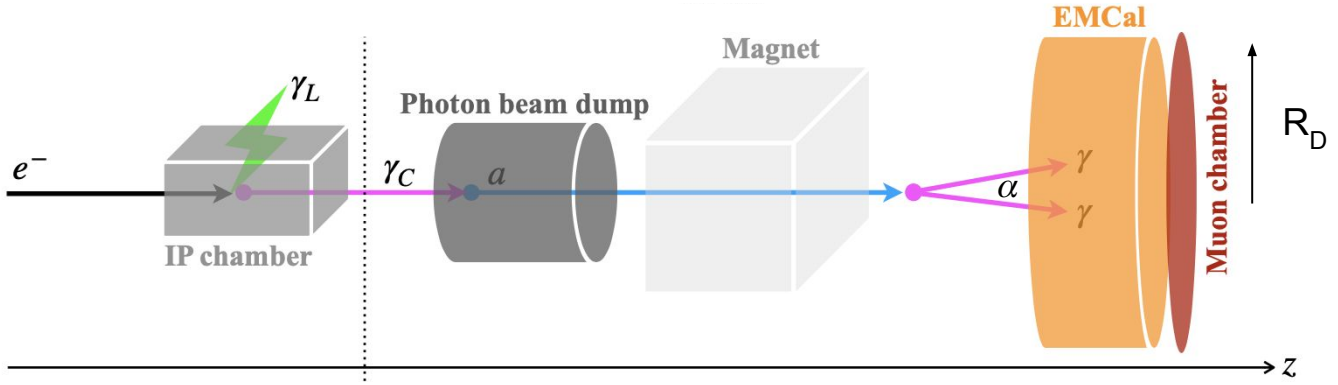
Dump depth L_S = 1.0 m

Decay path L_D = 2.5 m

R_D = 1.0 m

Experimental design

LUXE-NPOD: detection



Plan to measure:

- Decay position
- Mass $m = \sqrt{2\,E_1 E_2 (1 - \cos\alpha)}$

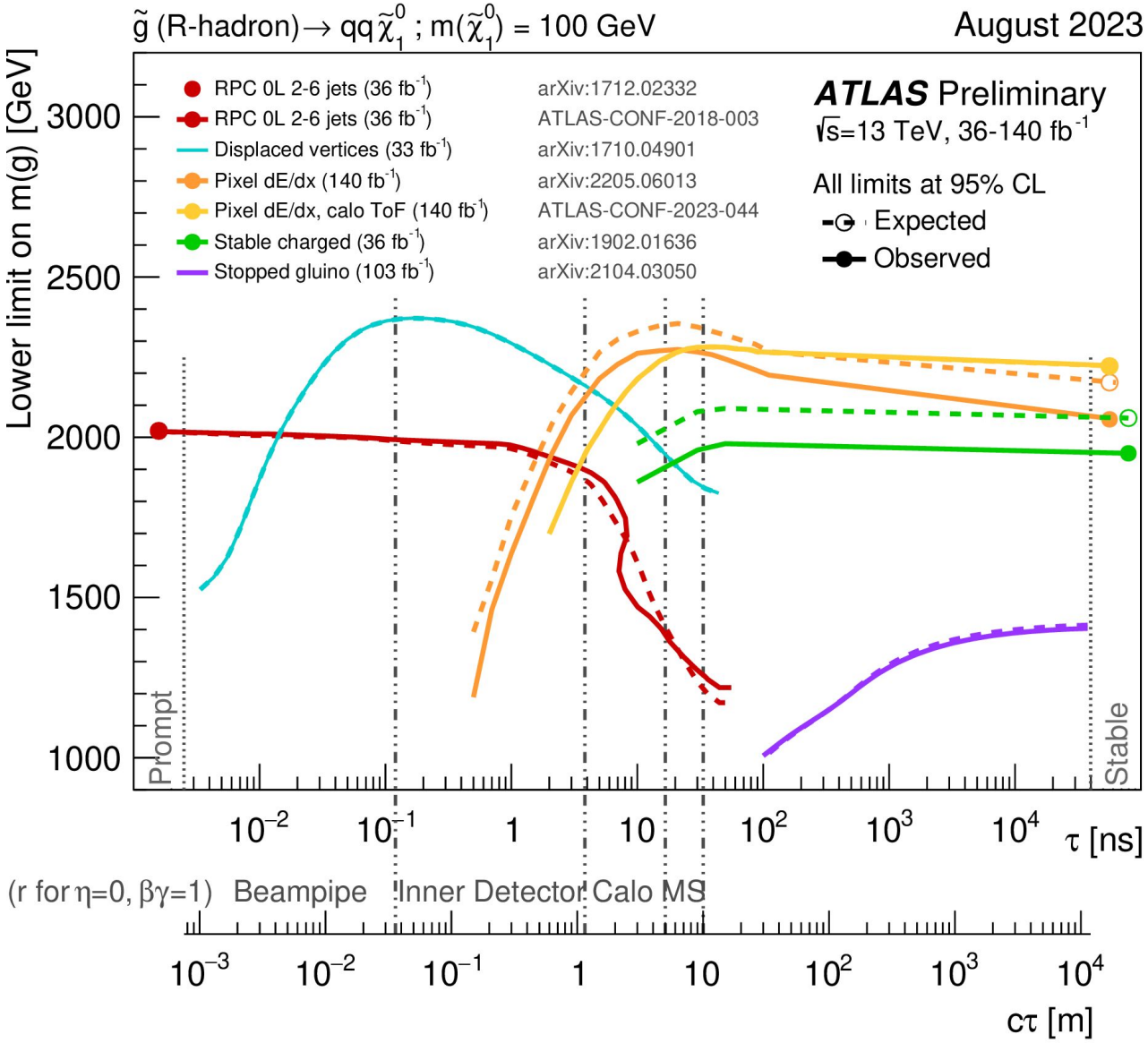
Geant4 simulation of backgrounds to determine target performance

$\sigma_\theta \leq 10$ mrad **$\sigma_t \leq 1$ ns**

ECAL-E prototype

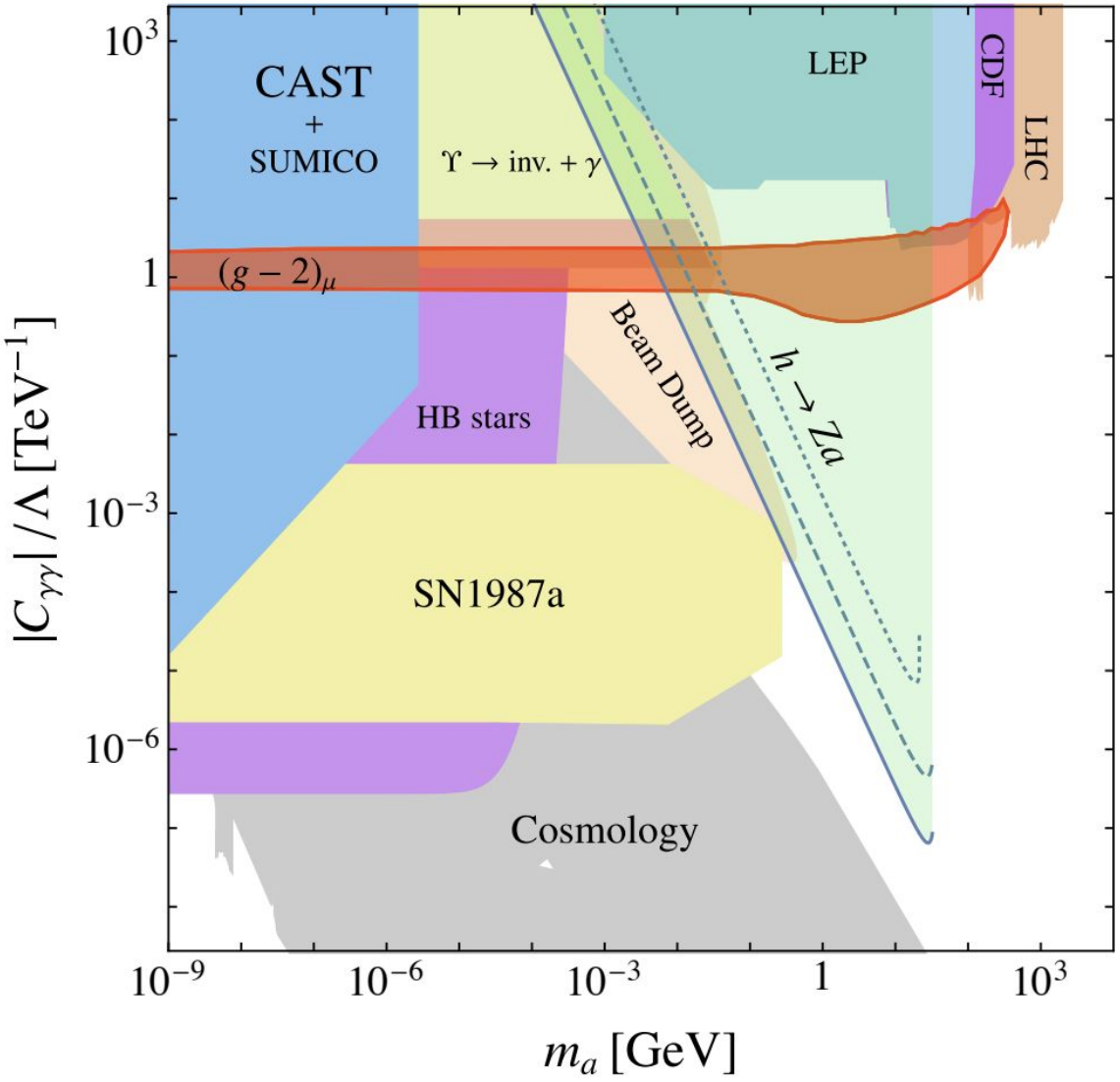
The journey ahead

Beyond the beampipe



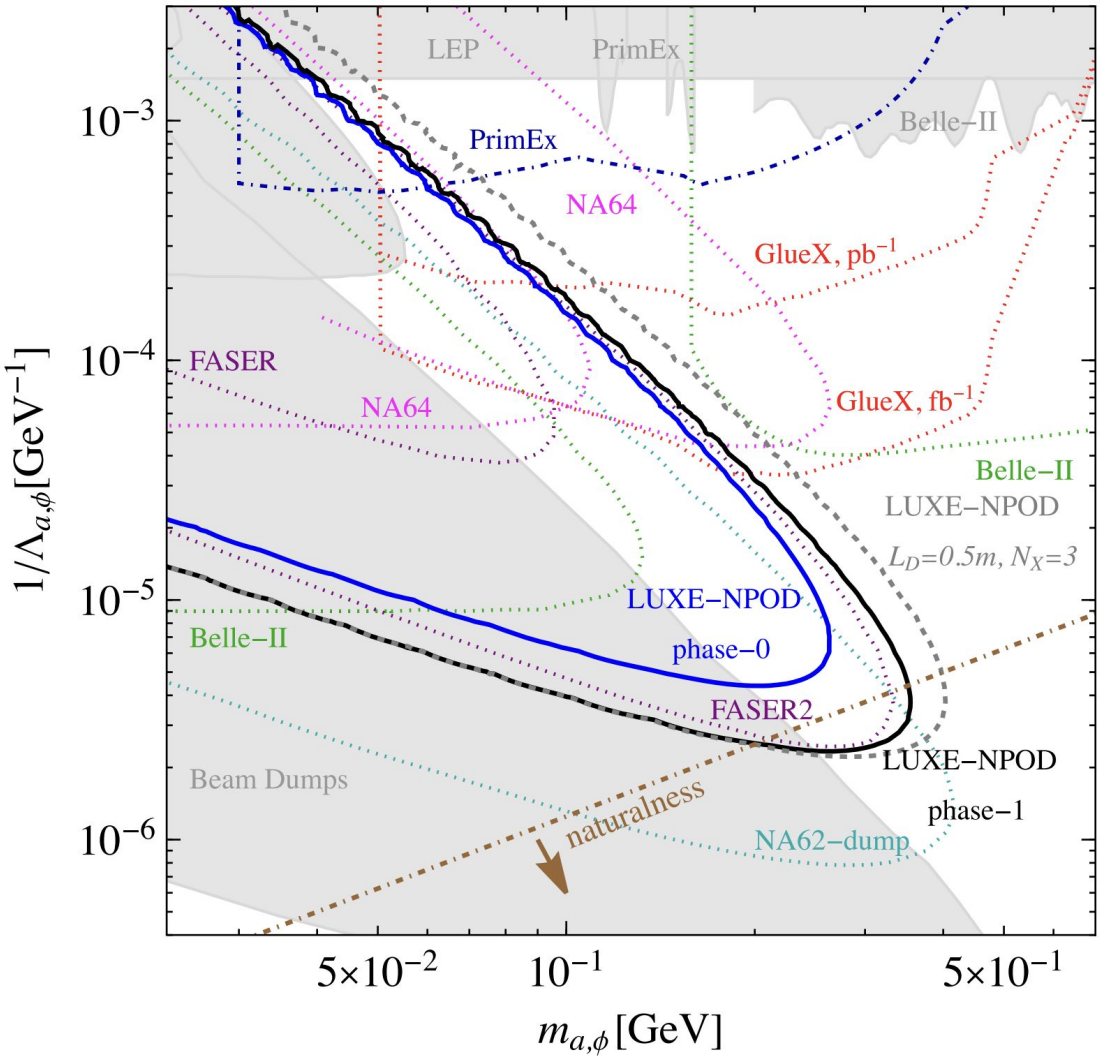
1704.08207

Future 0 - ATLAS potential not exhausted!



2107.13554

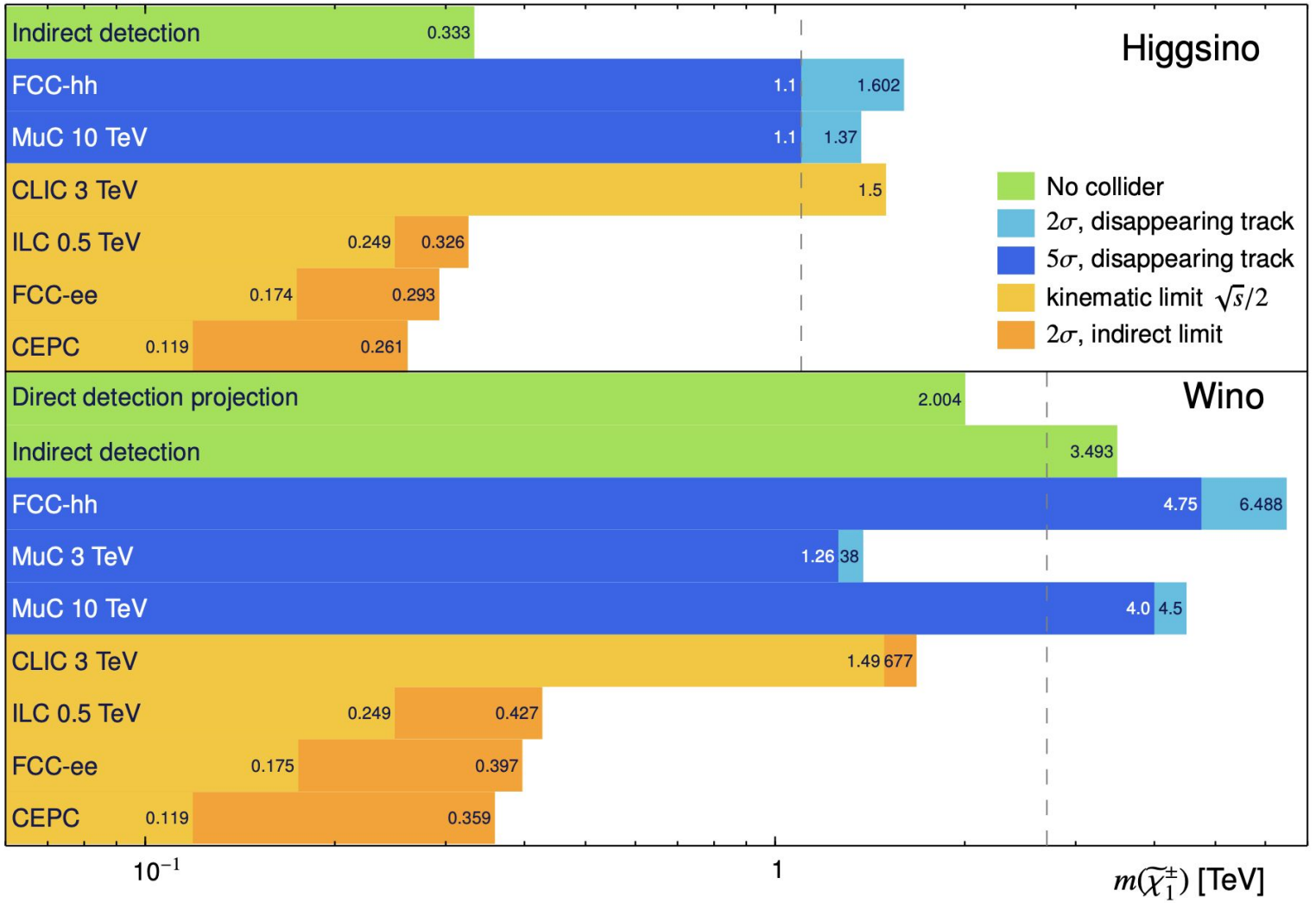
Future I - LLP searches at LUXE



Studied also prospects for a LUXE-NPOD-like experiment at Higgs factories

2303.08533

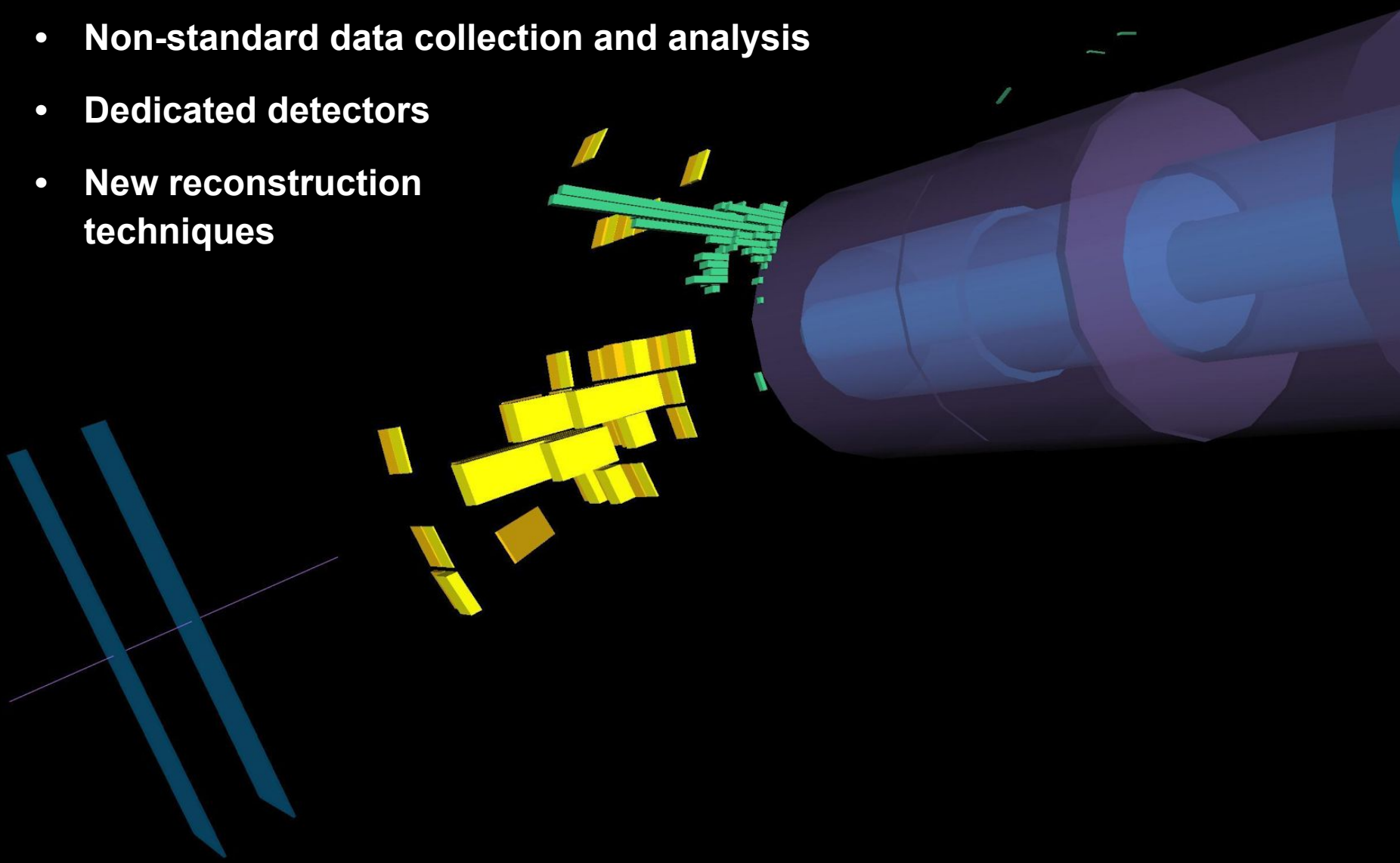
Future II - Future colliders



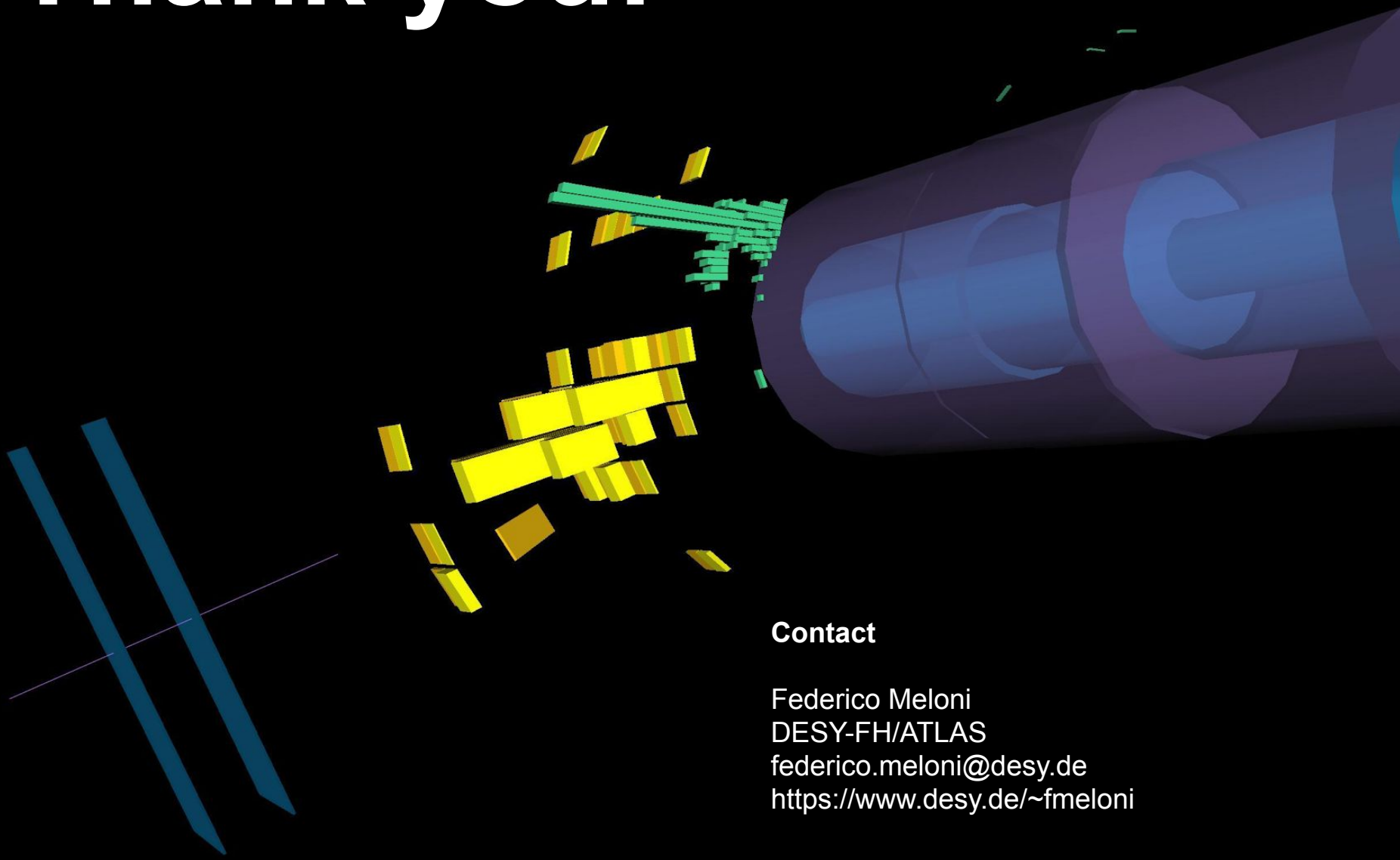
Summary

Long-lived particle searches are a particularly creative field:

- **Non-standard data collection and analysis**
- **Dedicated detectors**
- **New reconstruction techniques**



Thank you!



Contact

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federico.meloni@desy.de
https://www.desy.de/~fmeloni

Re-interpretation

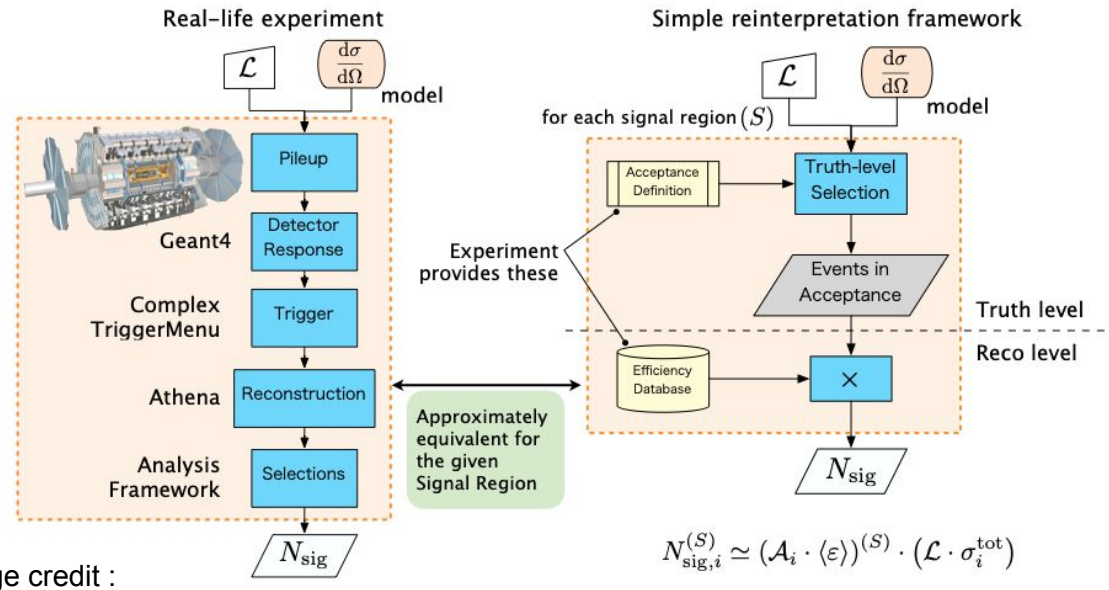
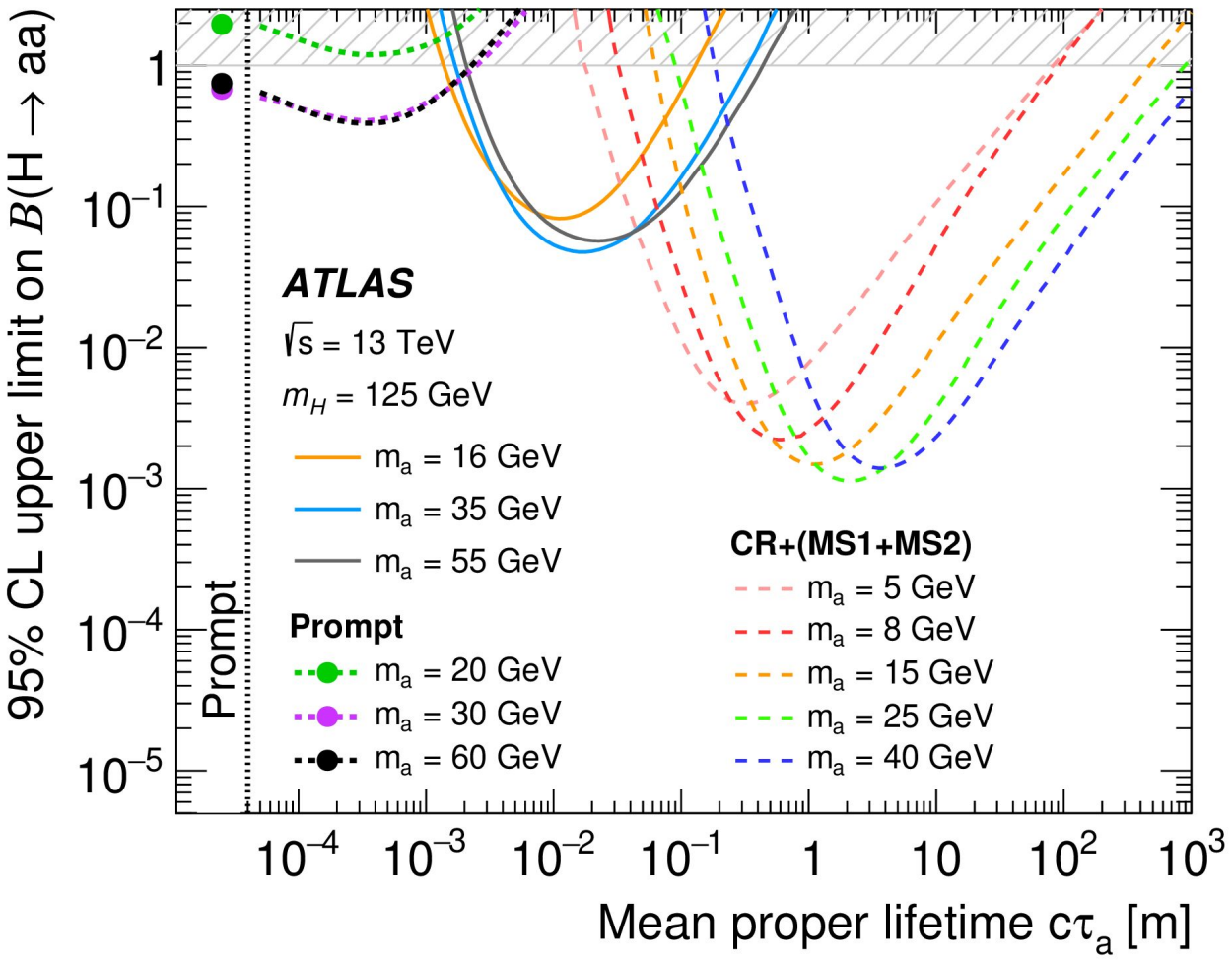


Image credit :
H.Oide

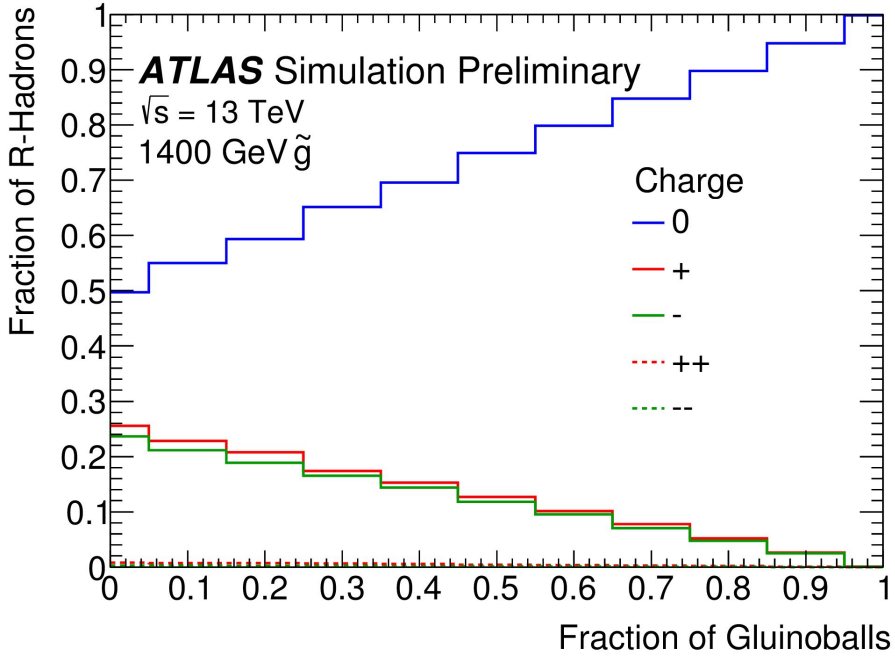
Plots and Tables of HEPDATA information

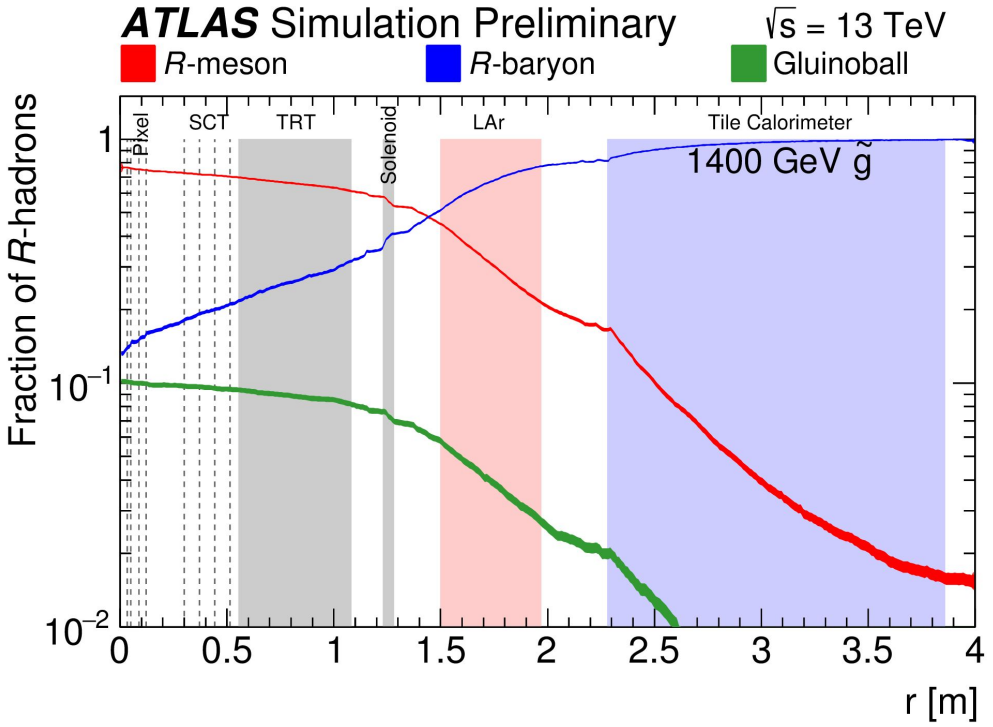
Look for this in the public pages

Exotic Higgs boson decays

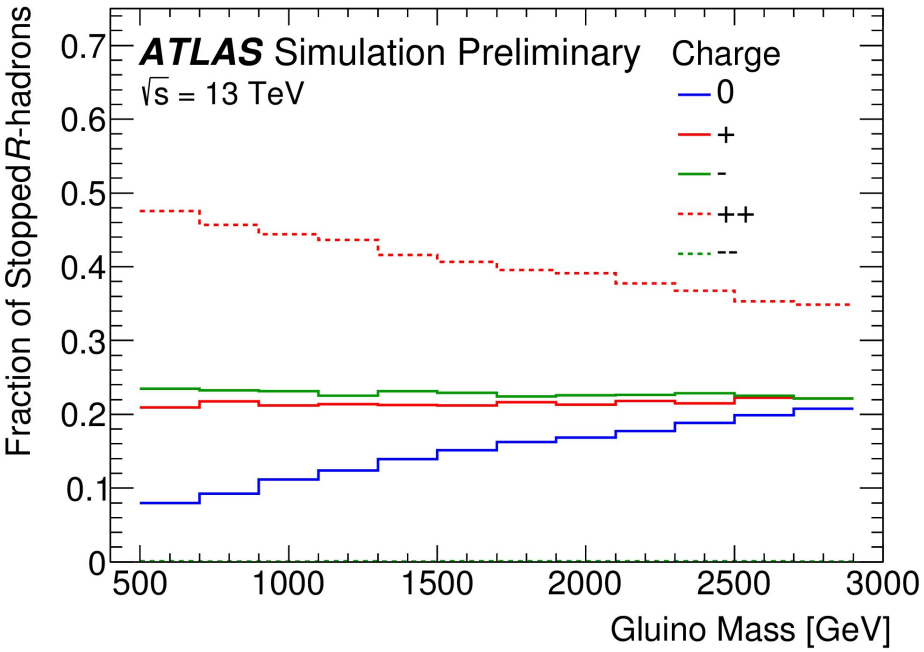


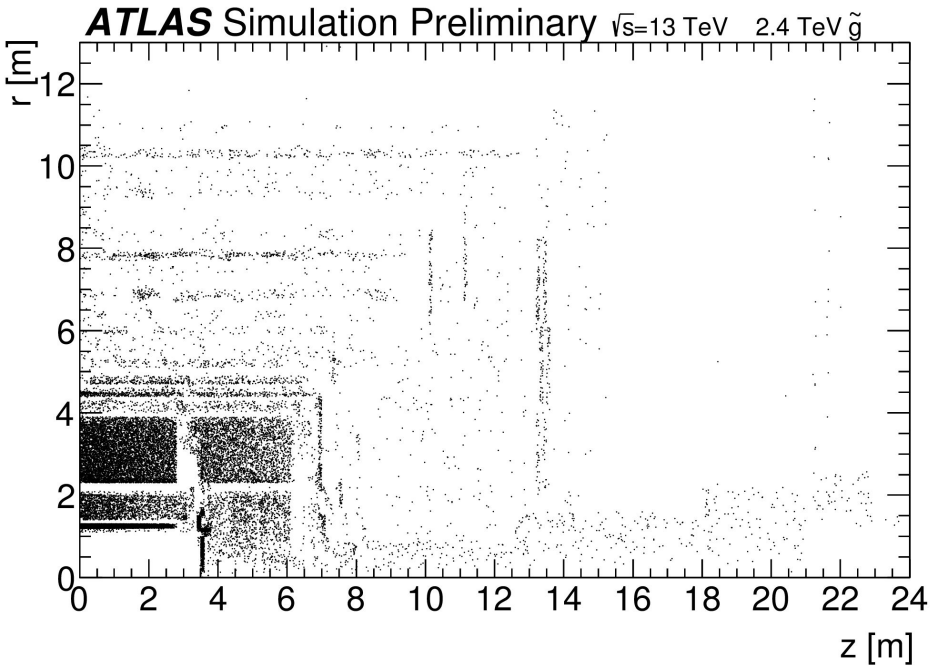
R-hadron generation and simulation



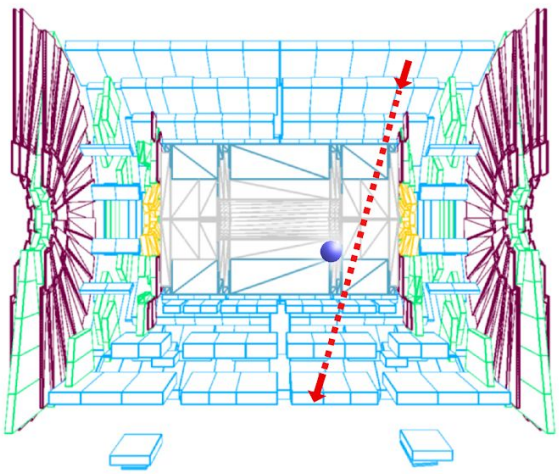


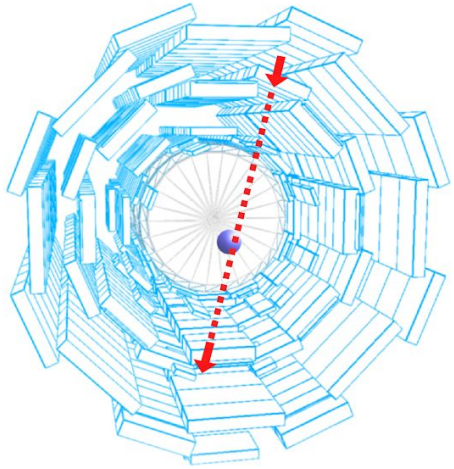
Stopping R-hadrons





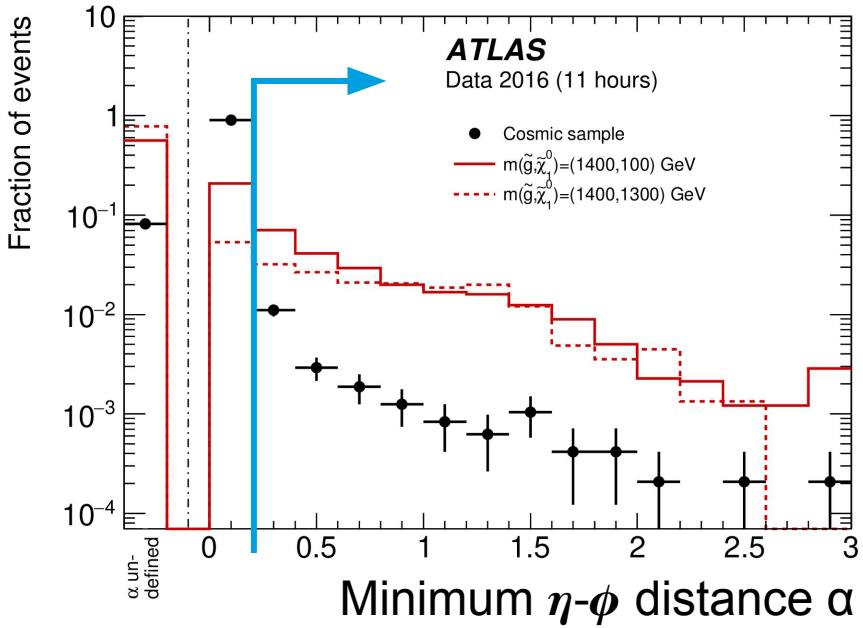
Cosmic-ray background





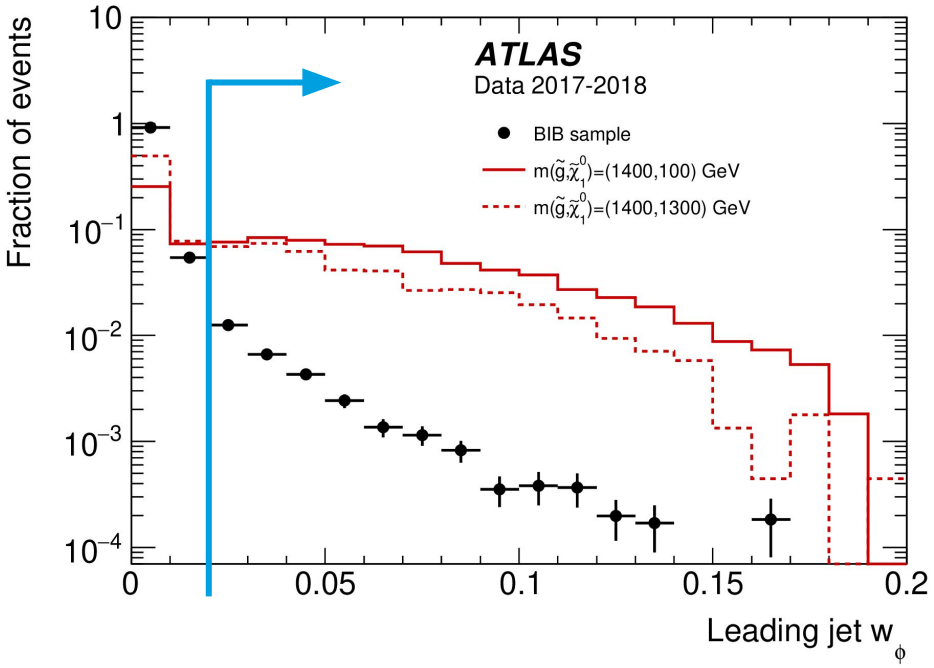
Leading jet

Muon track segments



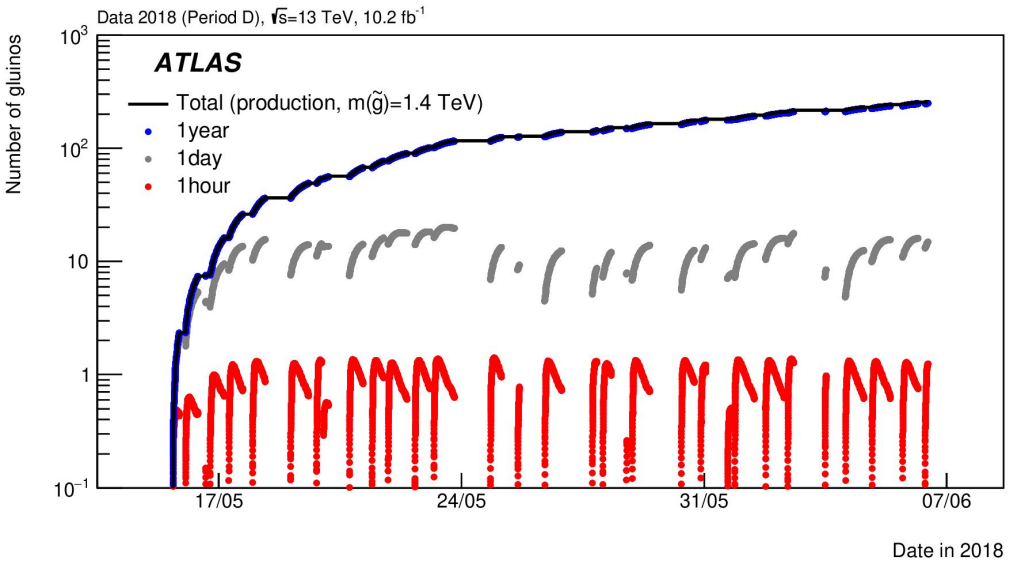
Beam-induced background

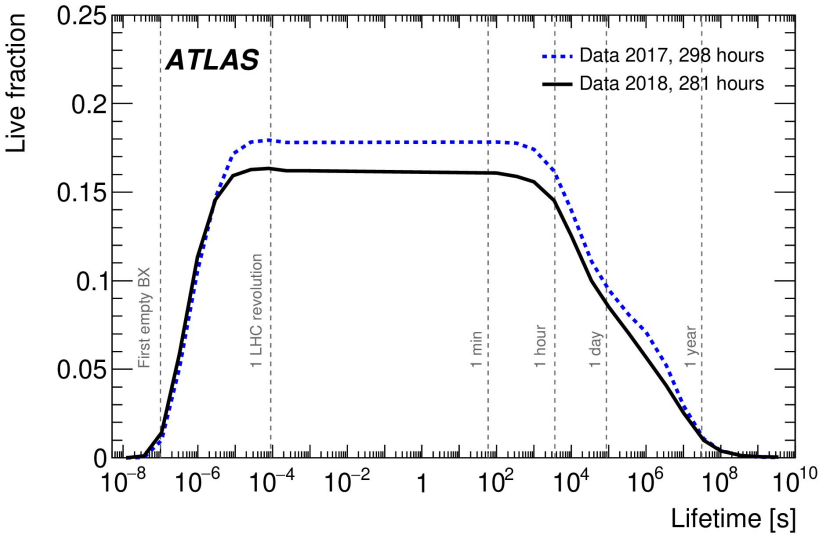
$$w_\phi = \frac{\sum_i p_{\mathrm{T}}(i) \cdot |\Delta\phi(\mathrm{jet}, i)|}{\sum_i p_{\mathrm{T}}(i)}$$



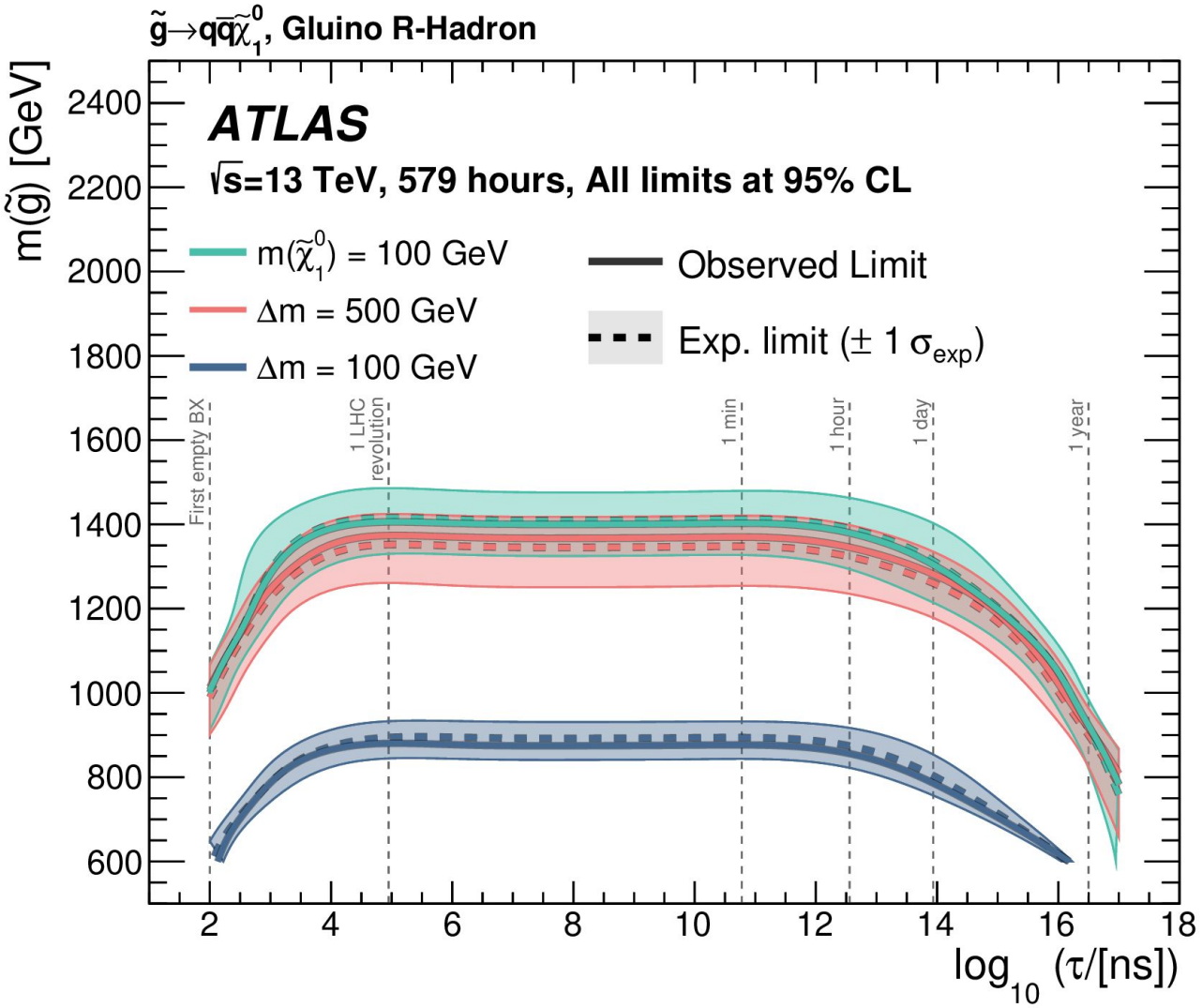
Estimating stopped signal yields

$$N_{\text{events}}^{\text{SR}} = L^{\text{int}} \times \sigma_{\tilde{g}\tilde{g}} \times 2 \times \epsilon^{\text{SR}} \times f_{\text{stopping}} \times (\text{live fraction})$$

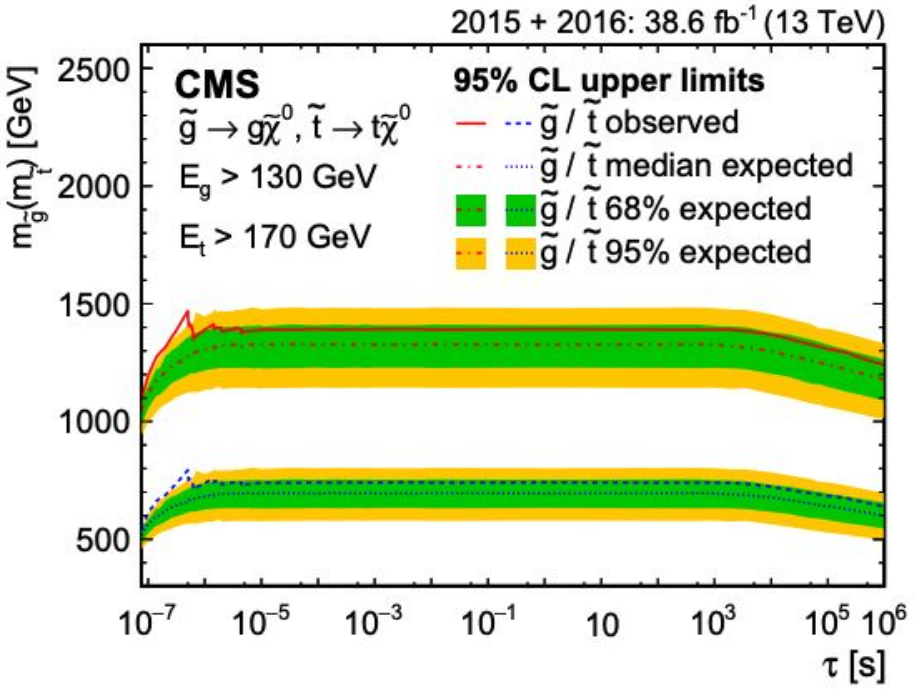


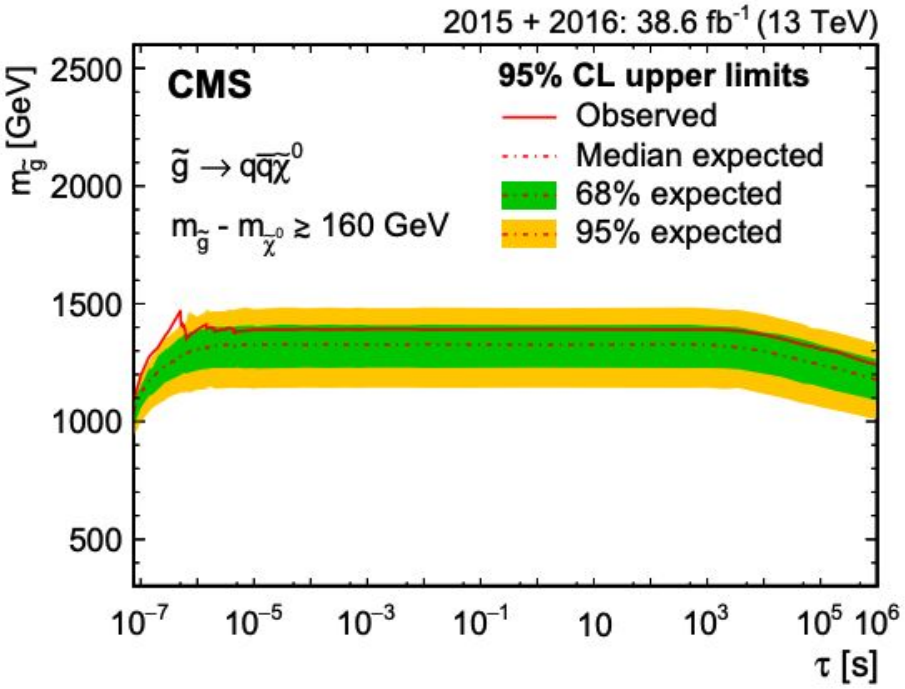


ATLAS stopped particles



CMS stopped particles

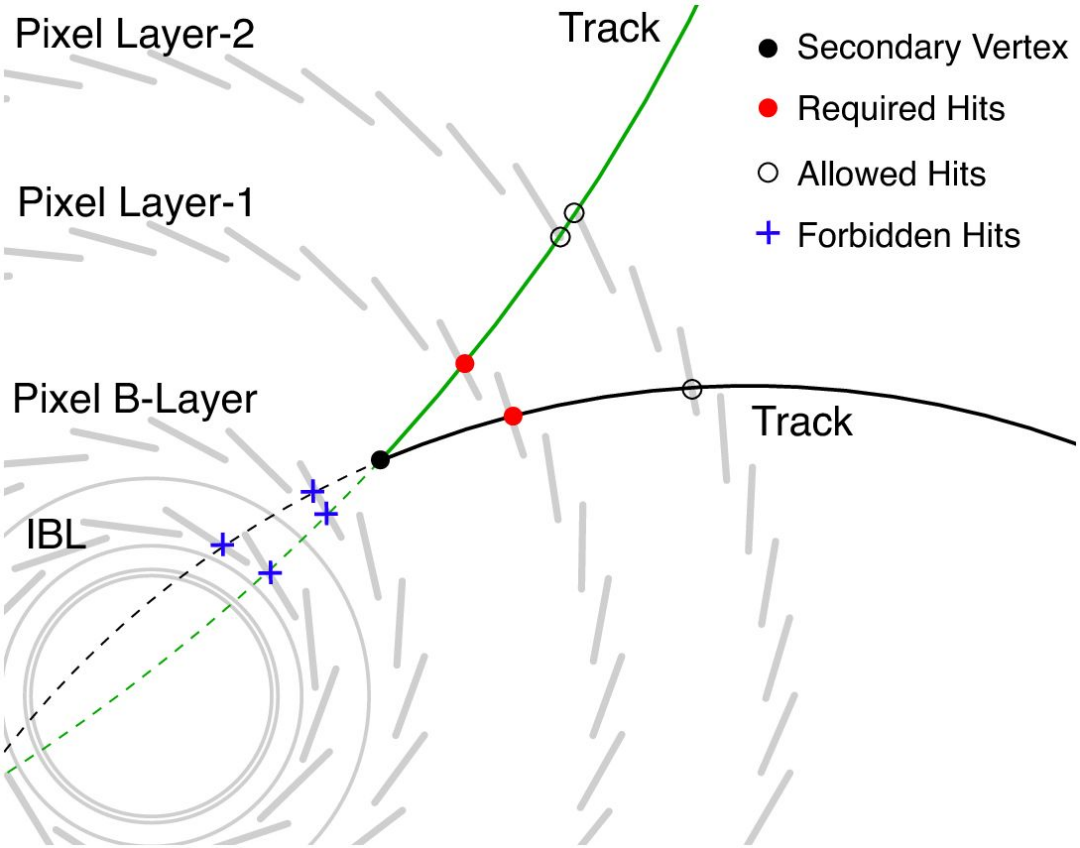




Reconstructing tracks with large displacement

	Standard	Large radius
Maximum d_0 (mm)	10	300
Maximum z_0 (mm)	250	1500
Maximum $\|\eta\|$	2.7	5
Maximum shared silicon modules	1	2
Minimum unshared silicon hits	6	5
Minimum silicon hits	7	7
Seed extension	Combinatorial	Sequential

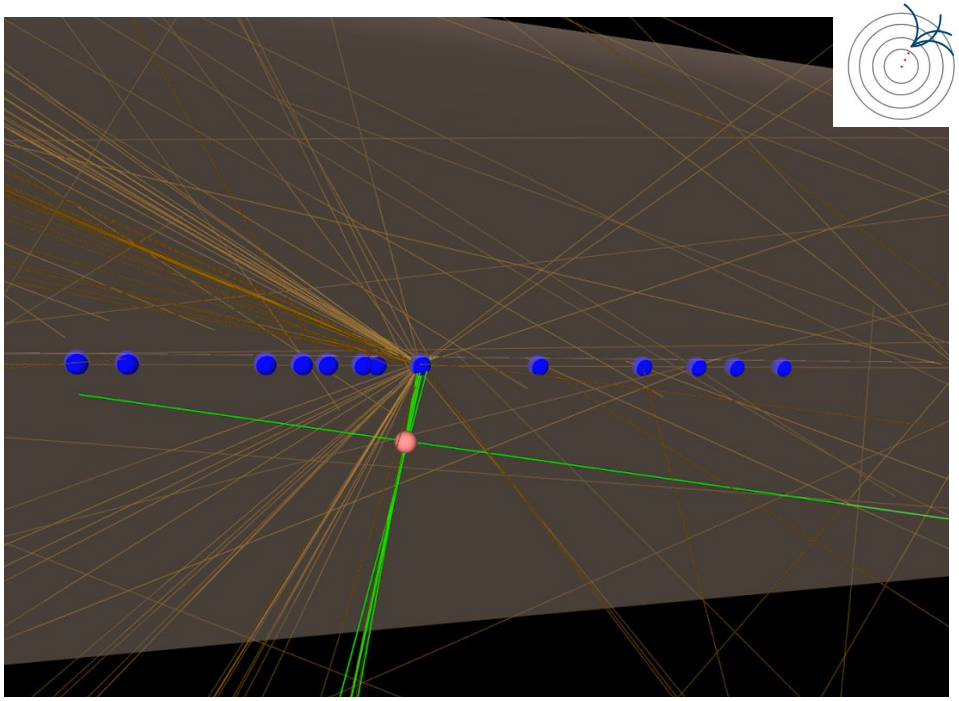
Displaced vertexing

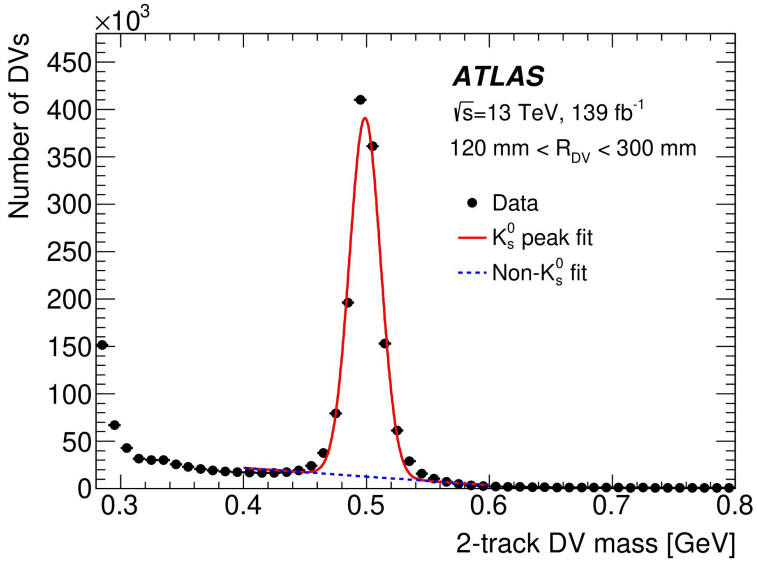


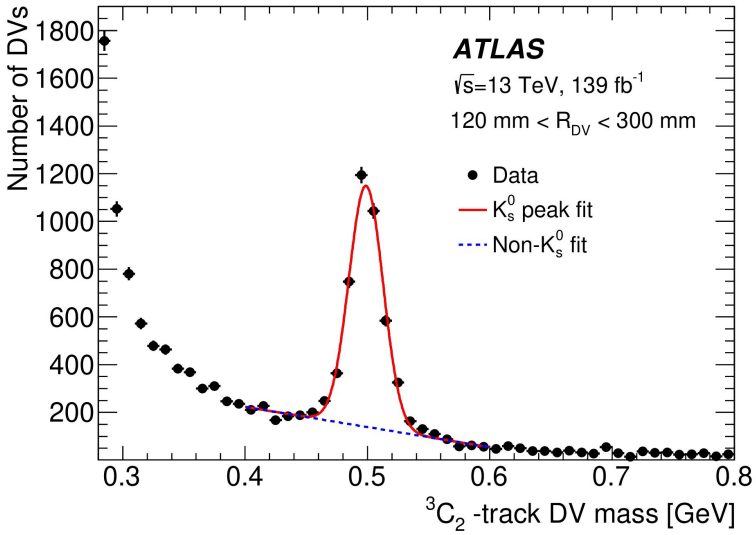
Accidental crossings

Extract **crossing factor** from data exploiting K_s decays

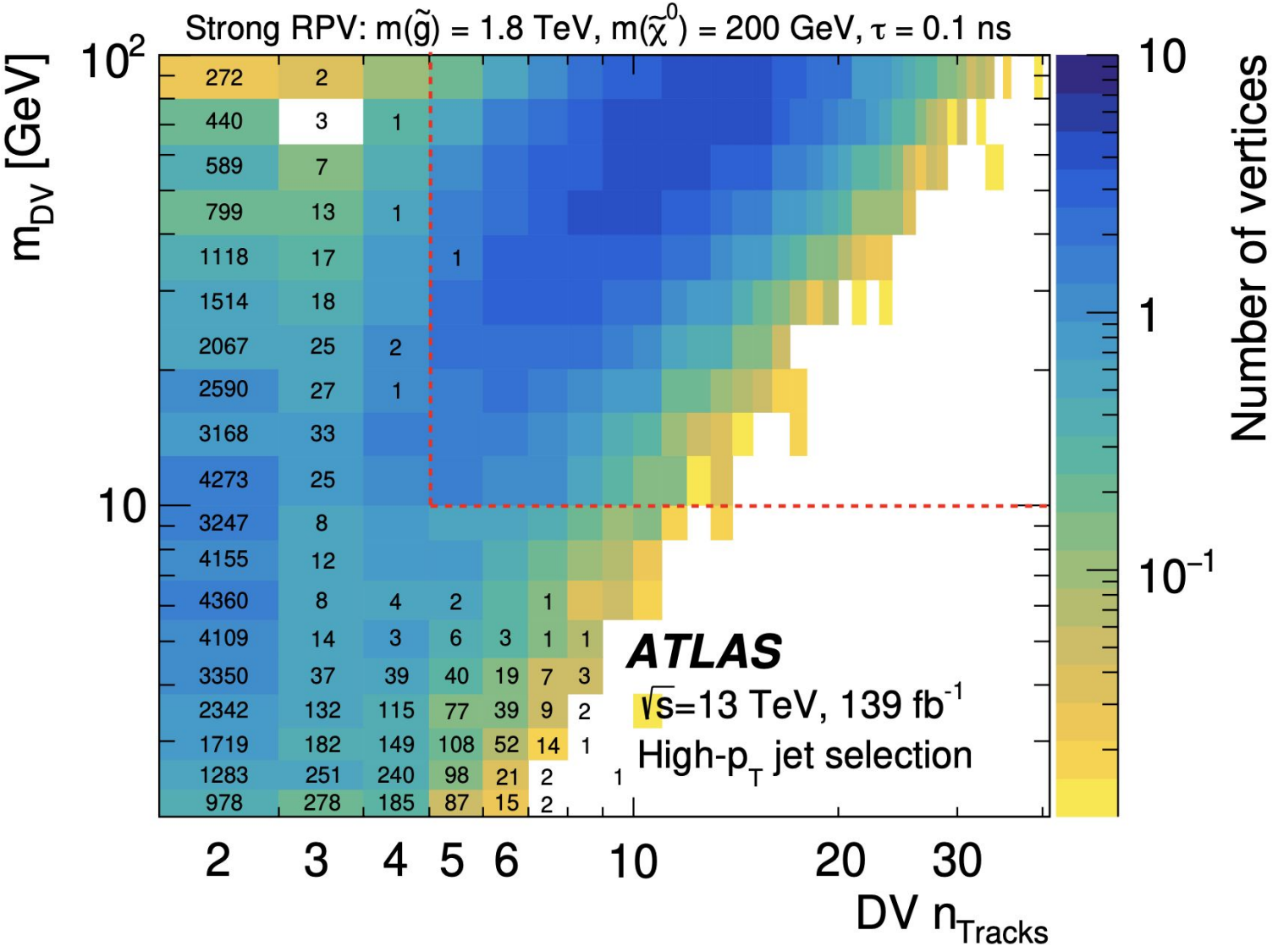
Take crossing tracks to build template of (n+1)-tracks DV mass



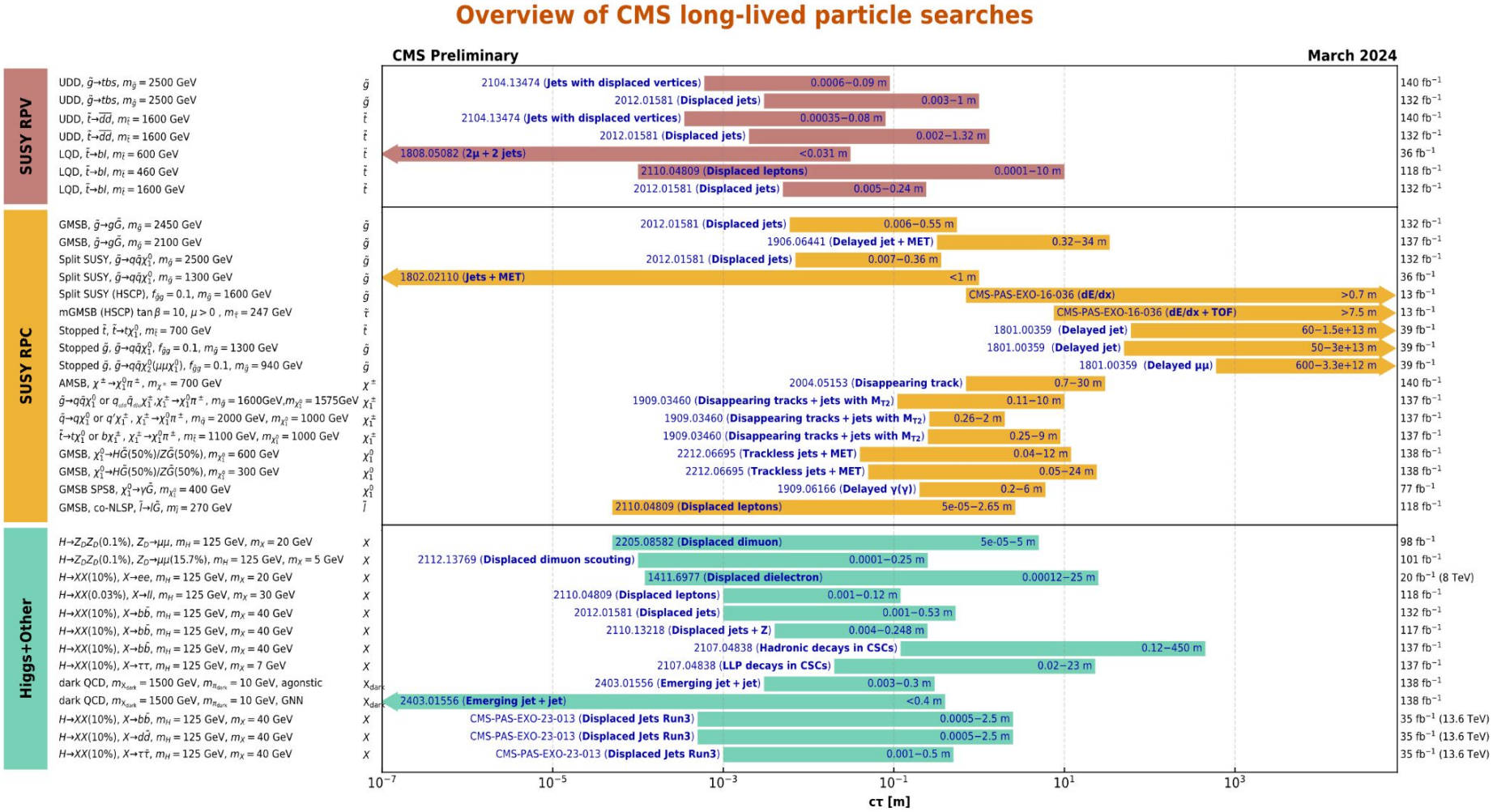




Observations



CMS



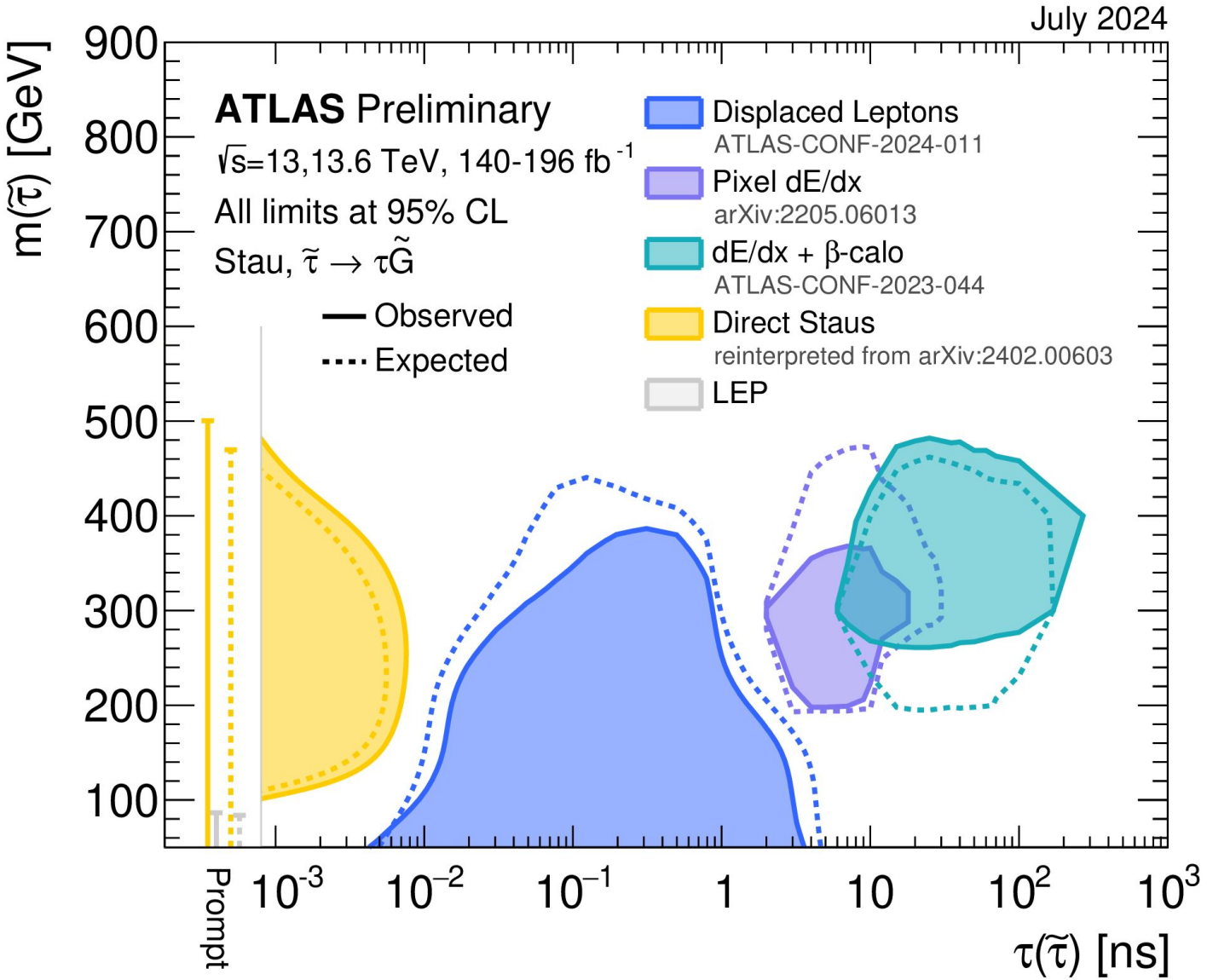
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

Observations

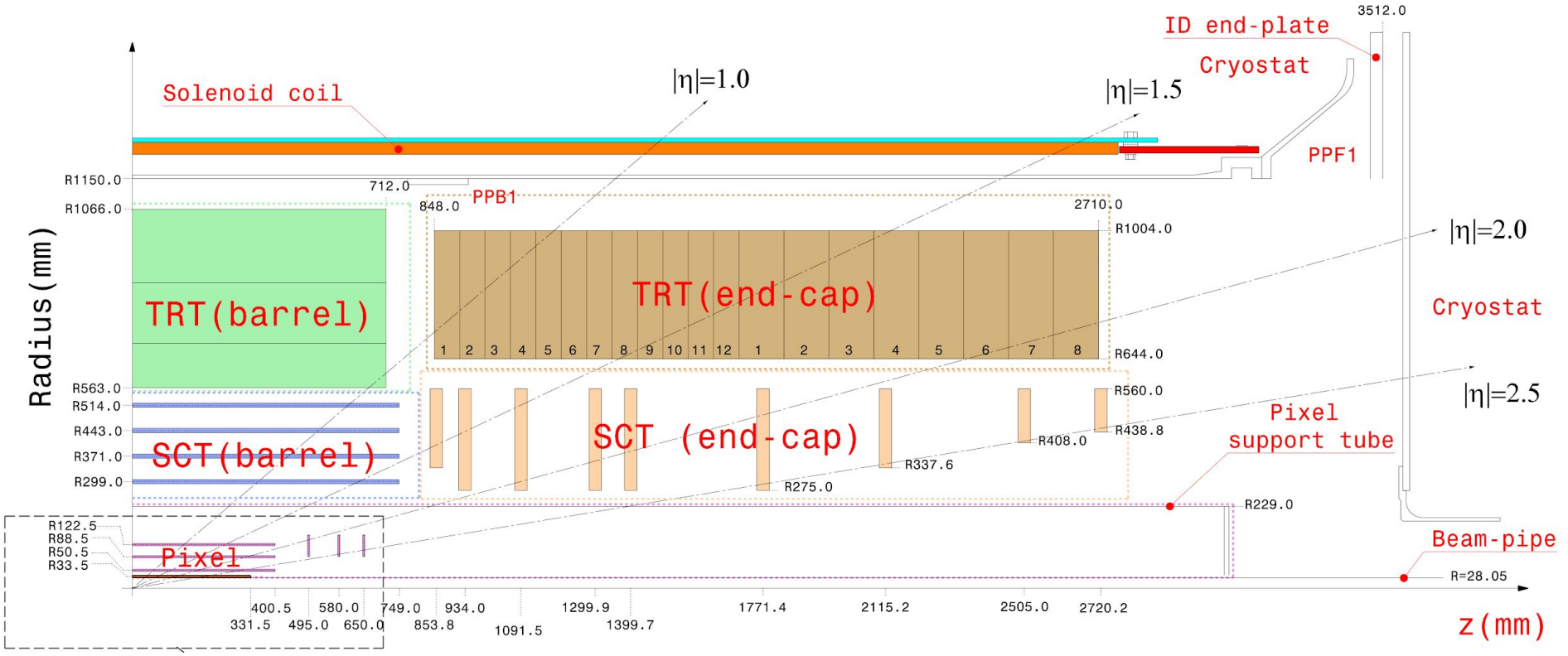
Data-driven “ABCD” background estimation

Selection	Search channel	CRB	CRC	CRD	SR expected	SR observed
ggF	2μ	55	61	389	317 ± 47	269
	c+μ	169	471	301	108 ± 13	110
	2c	97	1113	12146	1055 ± 82	1045
WH	c	1850	3011	155	93 ± 12	103
	c+μ	30	49	31	19 ± 8	20
	2c	79	155	27	14 ± 5	15

Long-lived staus

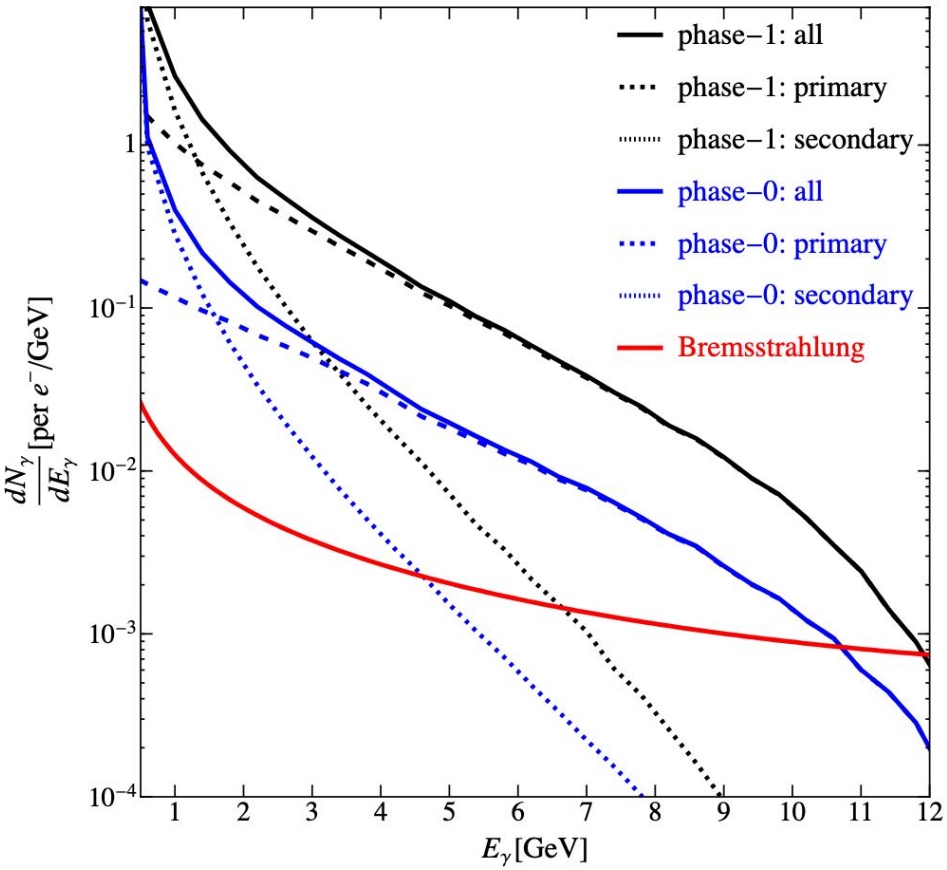


The ATLAS tracking detector

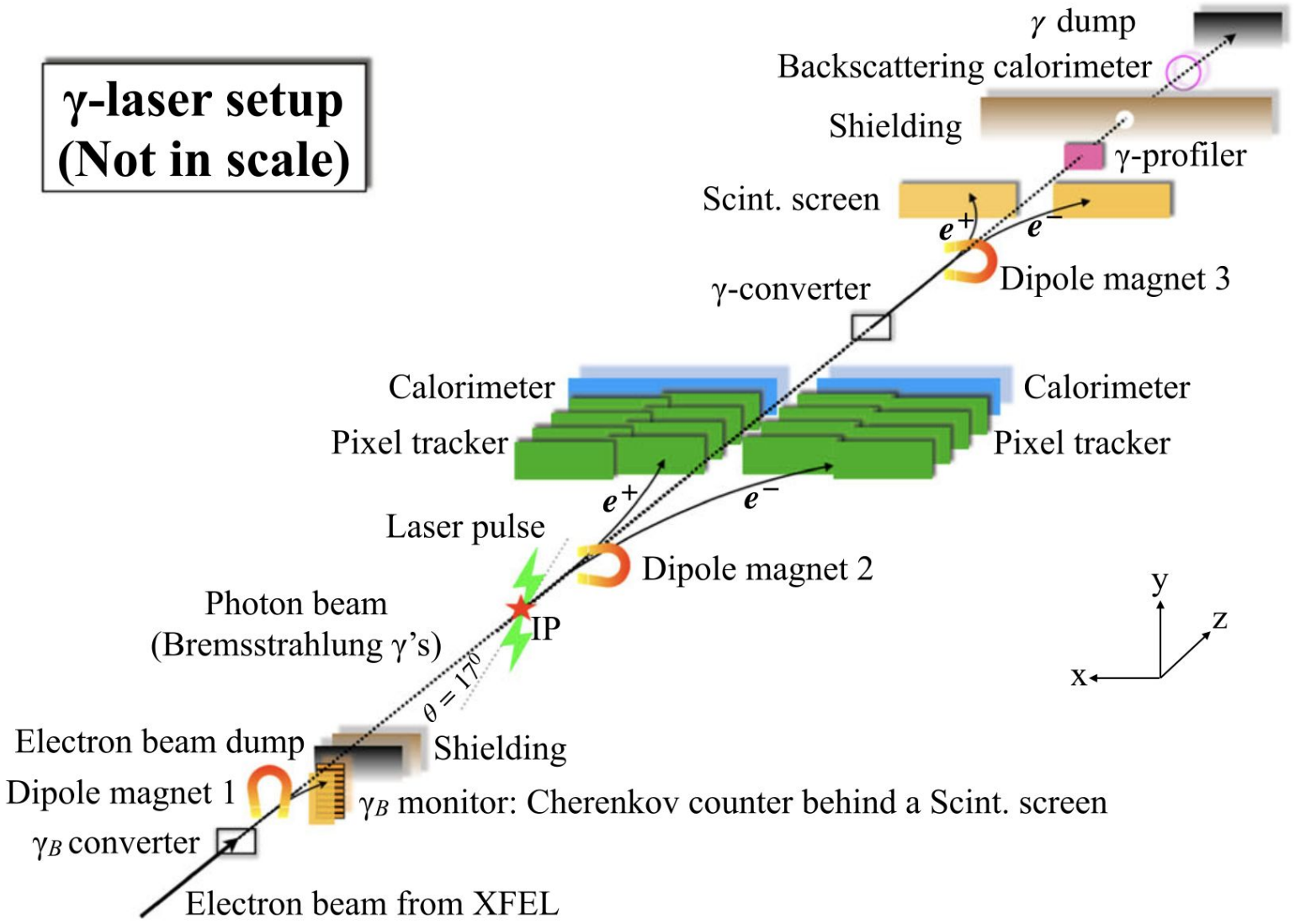


LUXE's "transparent dump"

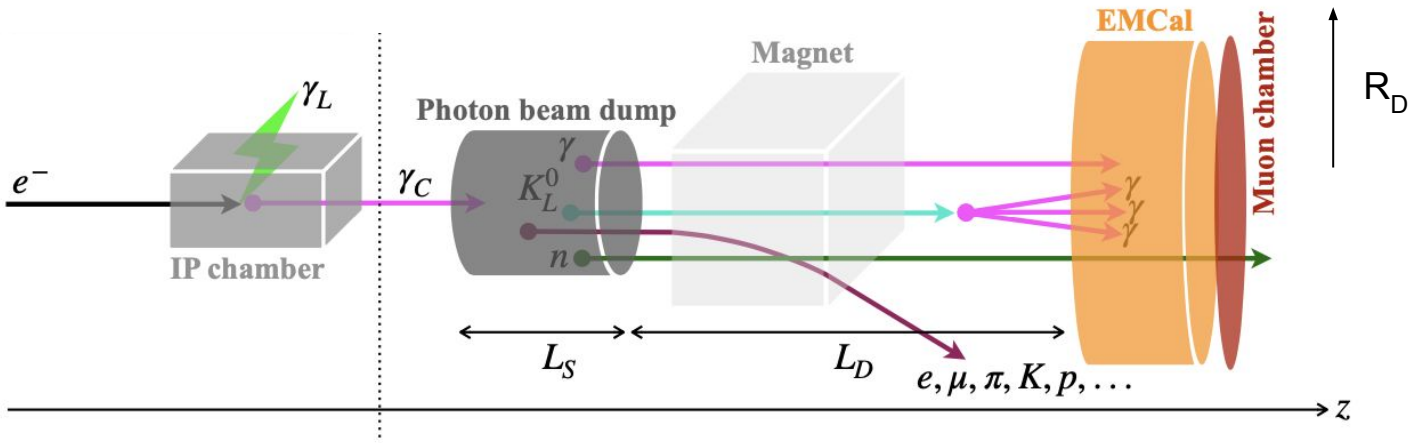
E_γ > 1 GeV	#Photons (per e^-)	Background (per e^-)
LUXE	0.12 / 2.5	~0
Thin e-dump	0.03	~0
Thick e-dump	6.7	x 100



The LUXE experiment



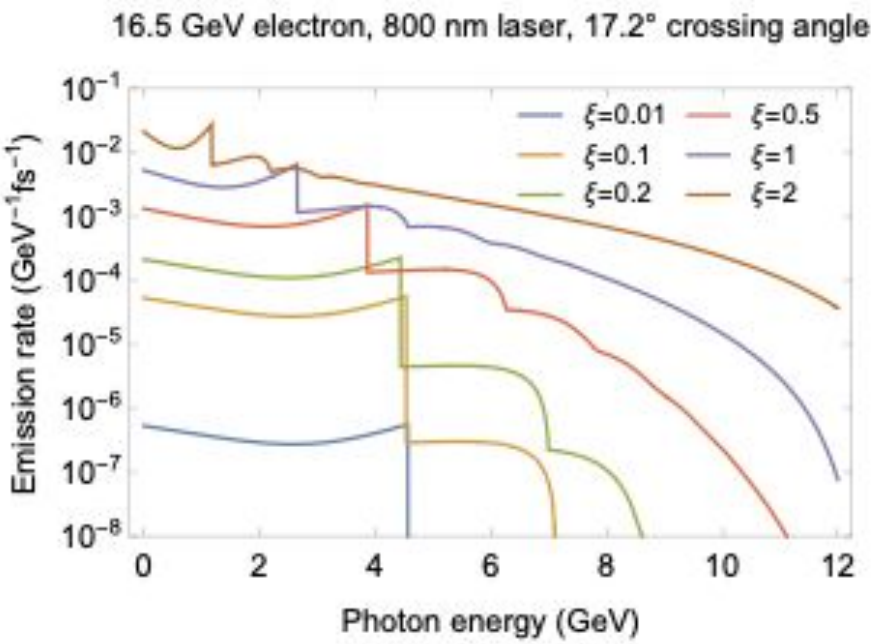
Backgrounds

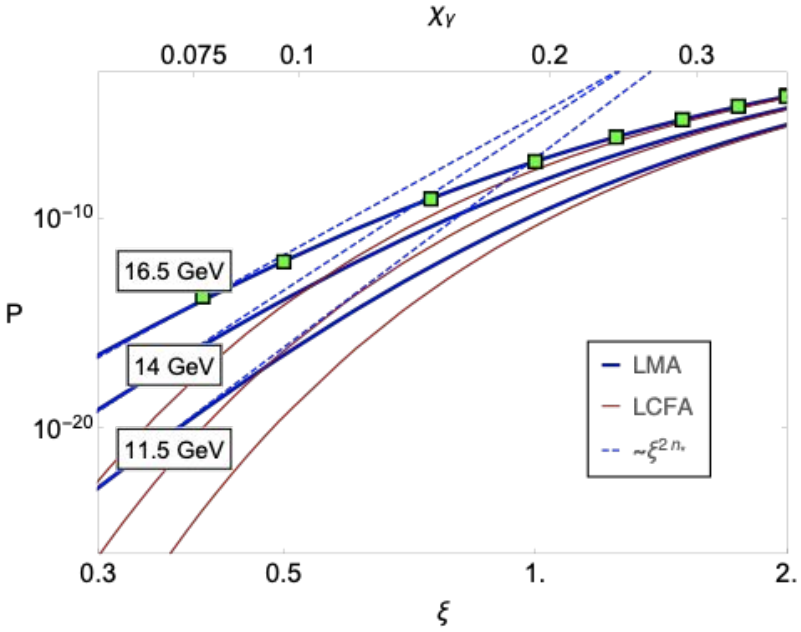


Initial estimation of the backgrounds emerging from the dump with GEANT4:

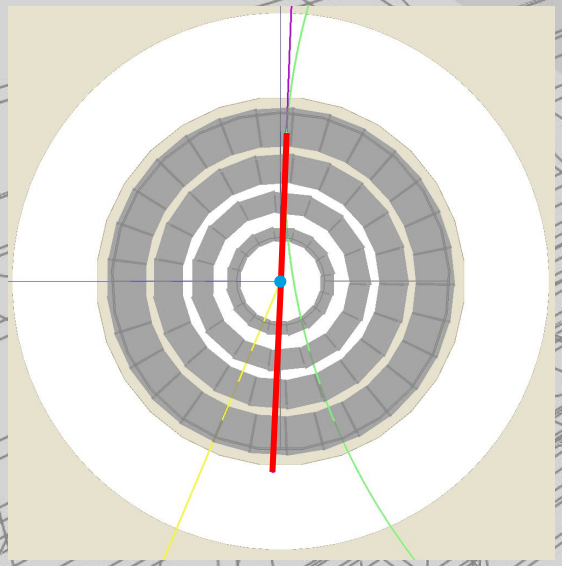
- charged particles → bent by a magnetic field (1.5 T of 1 m)
- real photons → $N_{2\gamma} \approx 8 \times 10^2$
- fake photons → $N_{2n} \approx 5 \times 10^8$
  → $N_{n\gamma} \approx 1 \times 10^6$

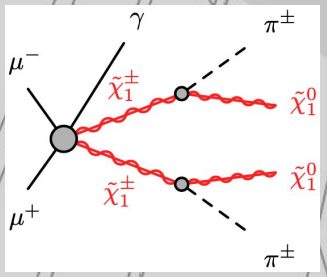
LUXE QED


16.5 GeV electron, 800 nm laser, 17.2° crossing angle
Emission rate (GeV^{-1}fs^{-1})
Photon energy (GeV)
ξ=0.01
ξ=0.1
ξ=0.2
ξ=0.5
ξ=1
ξ=2


χ_γ
P
ξ
16.5 GeV
14 GeV
11.5 GeV
LMA
LCFA
$\sim\xi^{2n_*}$

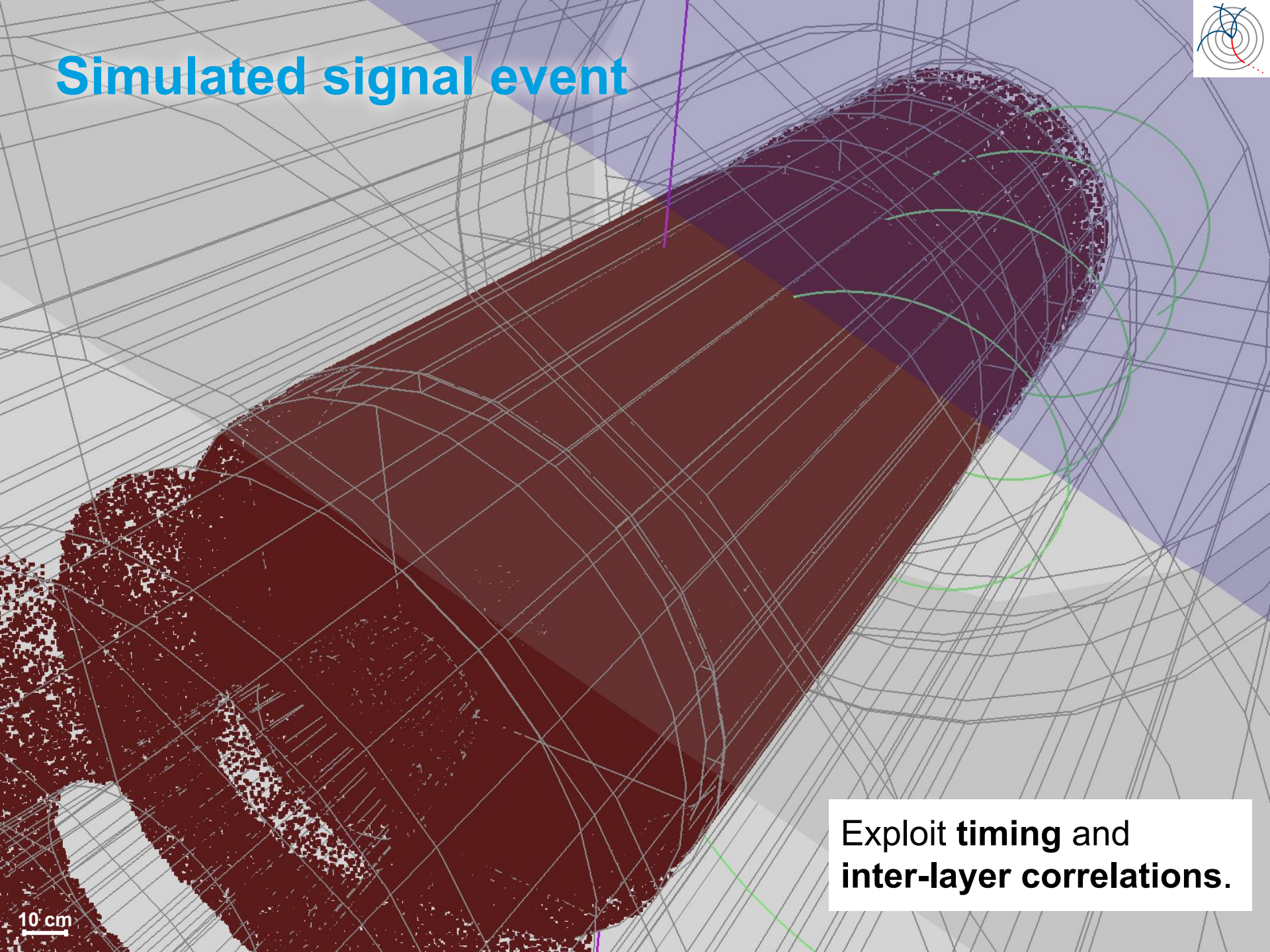
Simulated signal event





10 cm

Simulated signal event



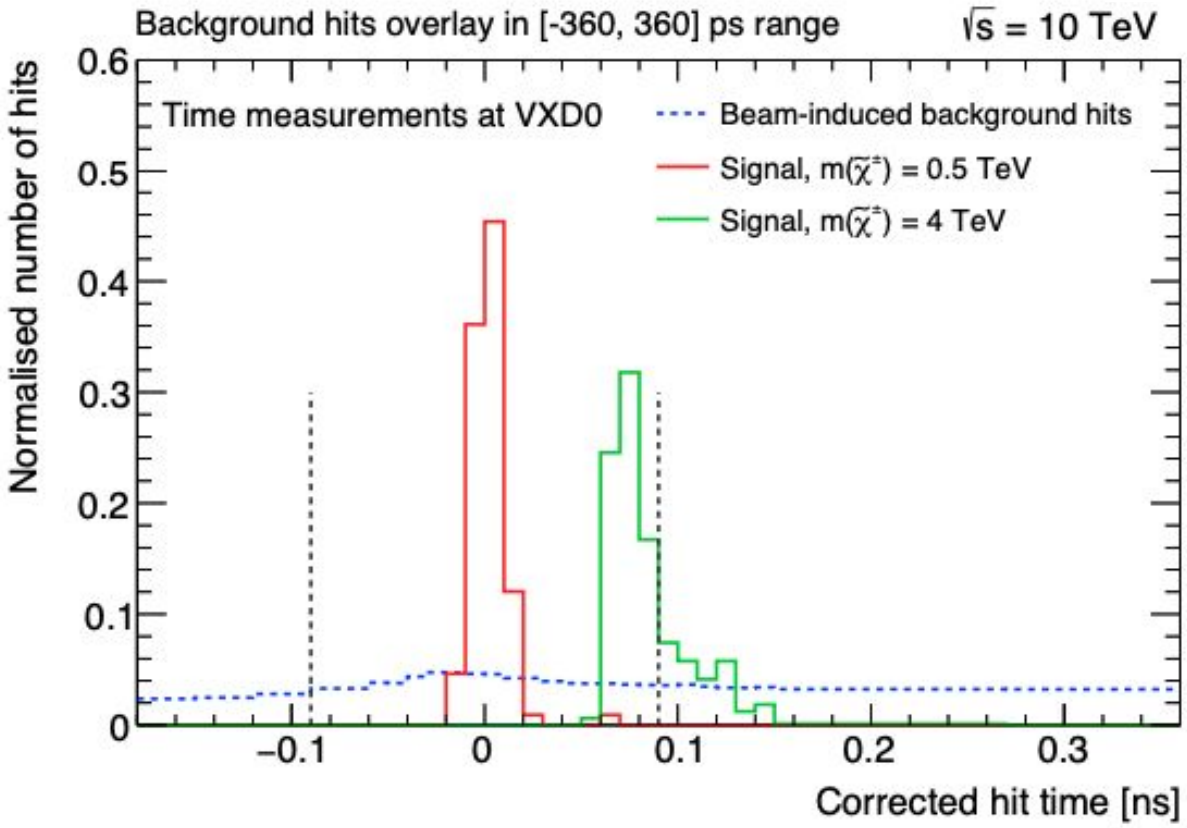
Exploit **timing** and
inter-layer correlations.

BIB characteristics

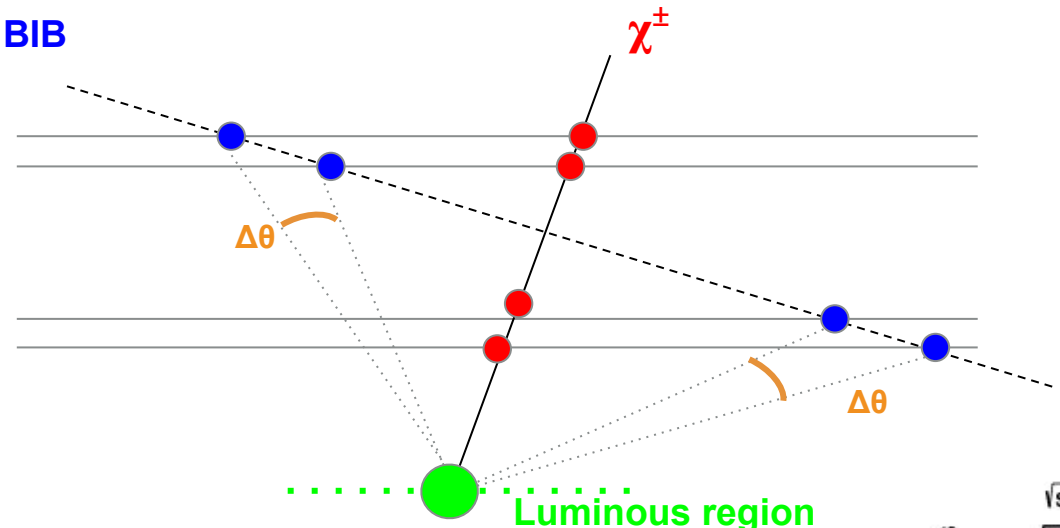
Particle (E_{th}, MeV)	MARS15 25 m	FLUKA 25 m	FLUKA 250 m
Photon (0.2)	$8.3\,10^7$	$4.3\,10^7$	$5.1\,10^7$
Neutron (0.1)	$2.4\,10^7$	$5.4\,10^7$	$5.9\,10^7$
Electron/positron (0.2)	$7.2\,10^5$	$2.2\,10^6$	$2.3\,10^6$
Ch. Hadron (1)	$3.1\,10^4$	$1.5\,10^4$	$2\,10^4$
Muon (1)	$1.5\,10^3$	$1.2\,10^3$	$3.4\,10^3$

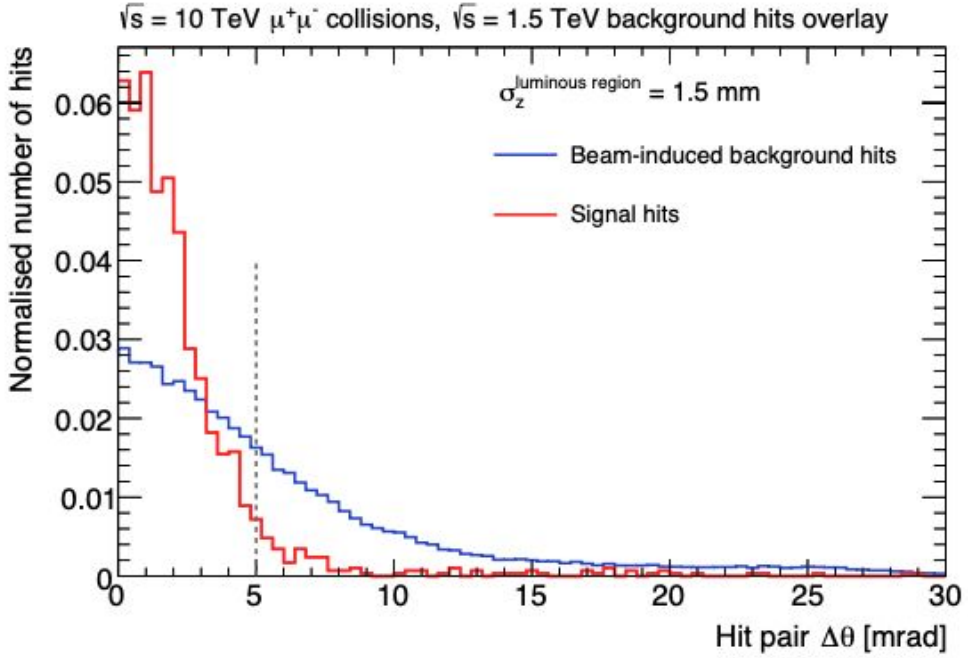
BIB rejection: timing

$$\text{Corrected time} = t_{measured} - \frac{|r|}{c}$$



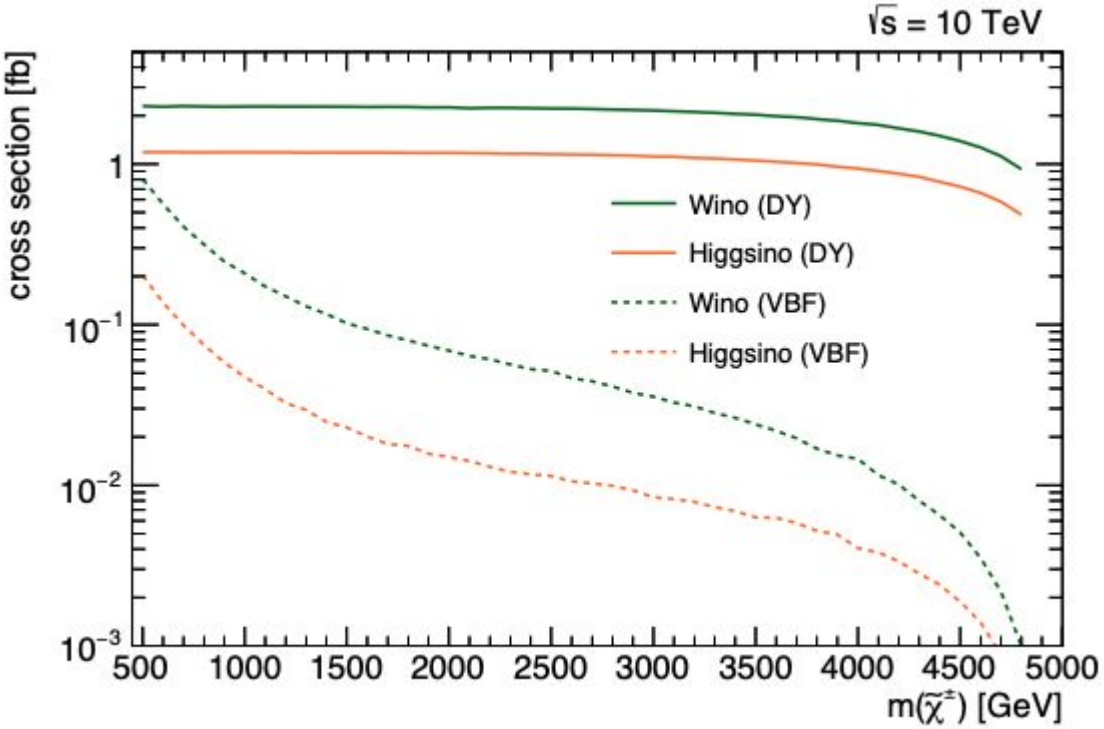
BIB rejection: stub tracks



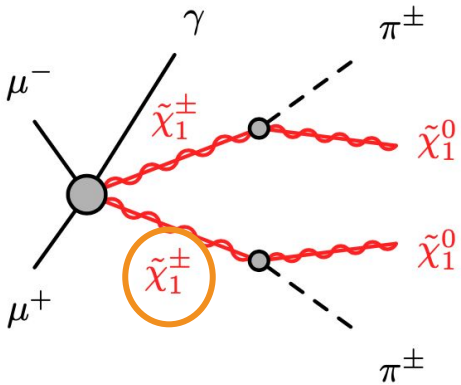


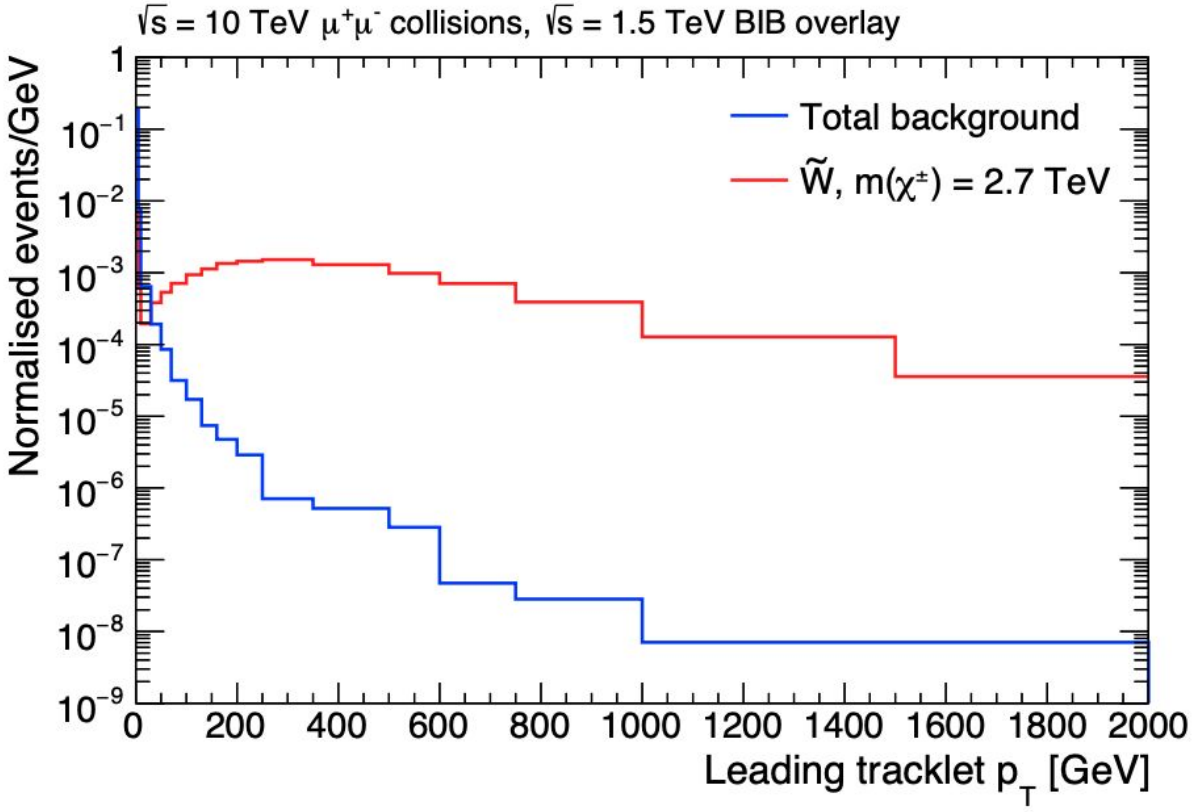
Expected signal production rates

At the MuC 10



Event selection





Expected sensitivity

Pure higgsino models at MuC 10

3 TeV detector
1.5 TeV BIB overlay
Extrapolated to 10 TeV