Unconventional search and long-lived particles at LHC: signature and experimental challenges

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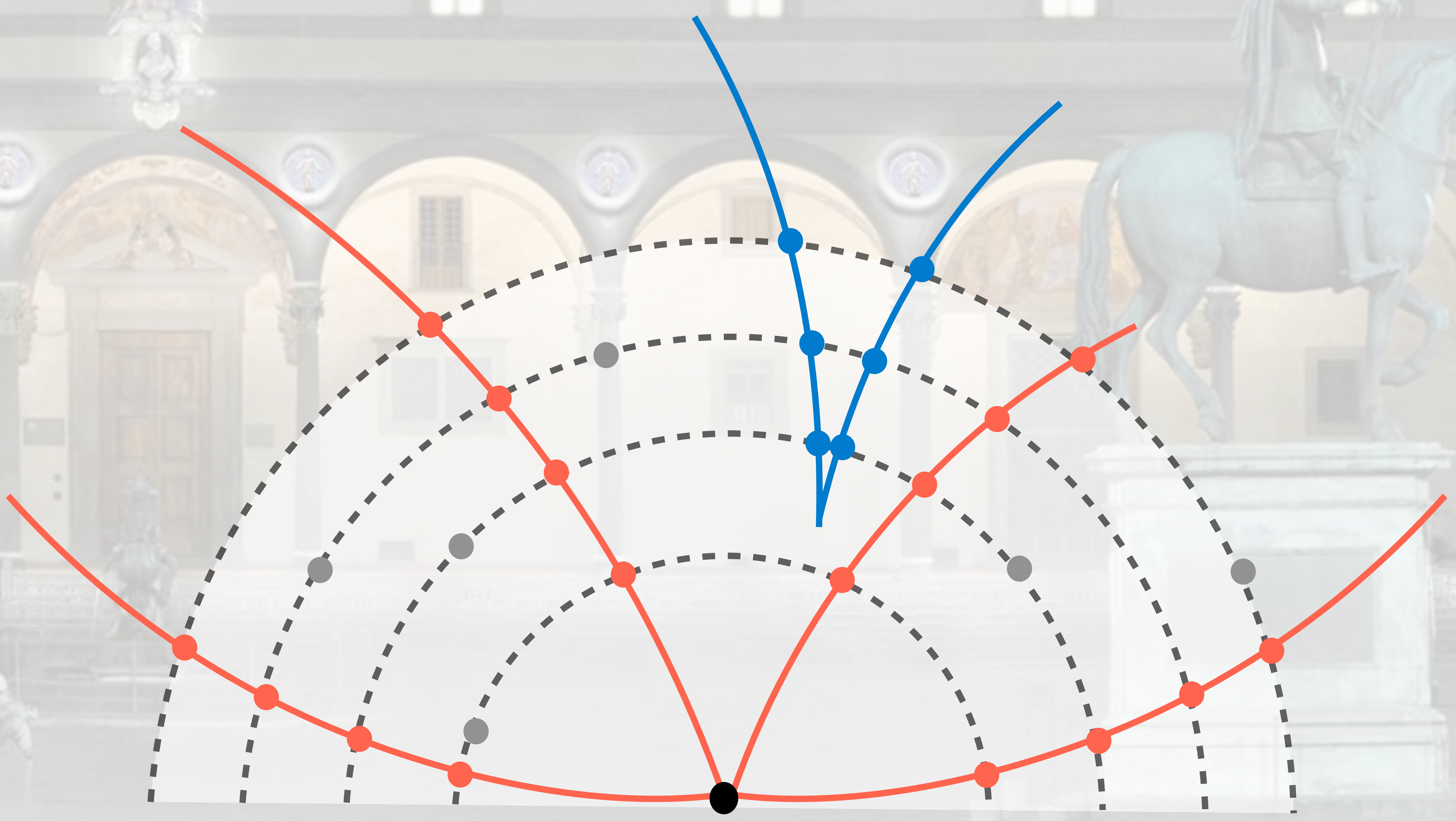
Incontri di Fisica delle Alte Energie



INFN ROMA

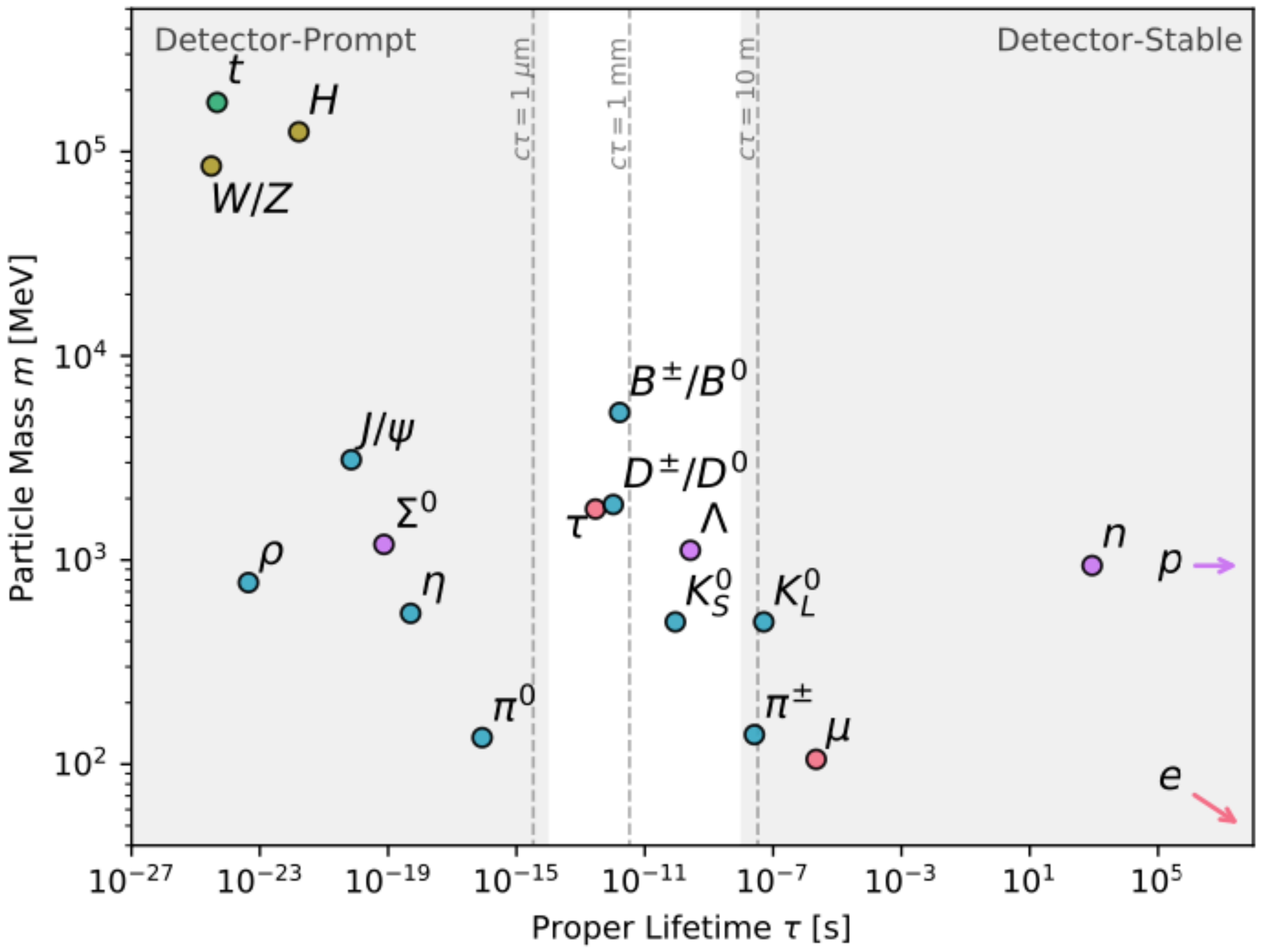
STVDIVM VRBIS

LLP in the SM

Long-lived particles (LLPs) are particles that are effectively stable or travel an observable distance before they decay.

Detector - prompt

Detector - stable



Long-lived particles

LLPs have played an essential role in many of the conceptual breakthroughs that established the SM: e, p, n, μ, K, ν, B, ...

Why long-lived?

INFN ROMA

$$\frac{1}{\tau} = \Gamma \propto g^2 |\mathcal{M}|^2 \Phi$$

LLP w/ macroscopic lifetime can arise when:

- small couplings
- small phase space (suppression, small mass-splitting)
- small matrix element (off-shell suppression)

Standard Model

Feeble Coupling

e.g. b→clv, off-diagonal CKM, τ ~ ps

Mass Scale suppression

e.g. $\mu \to e \nu_\mu \nu_e$, via W-boson, τ~2 μs

Phase space suppression

e.g. $n \to p e^- \nu$, $m_n - m_p$ ~ 1 MeV, τ = 15 min

Beyond the Standard Model

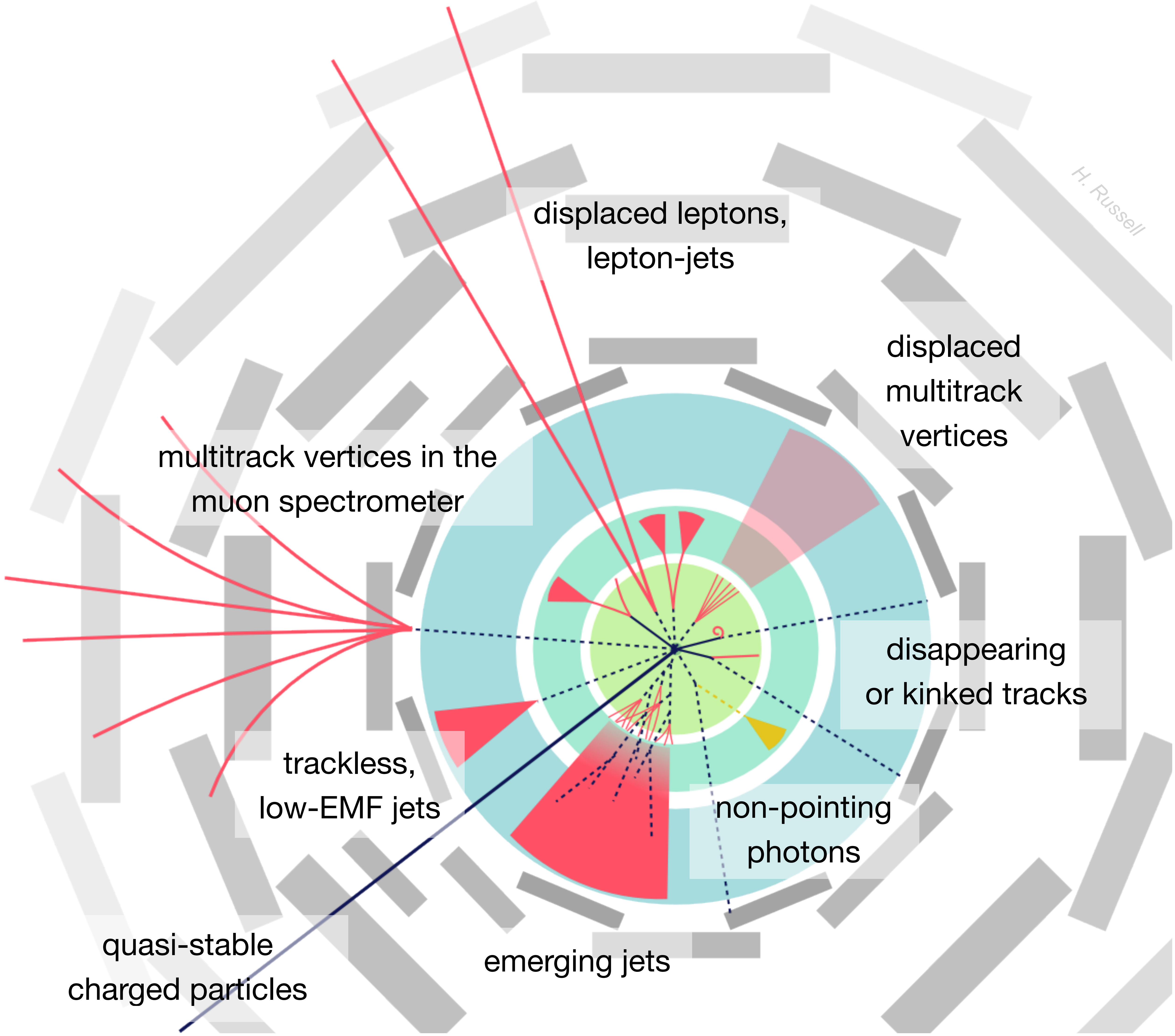
		Small coupling	Small phase space	Scale suppression
SUSY	GMSB			✓
	AMSB		✓	
	Split-SUSY			✓
	RPV	✓		
NN	Twin Higgs	✓		
	Quirky Little Higgs	✓		
	Folded SUSY		✓	
DM	Freeze-in	✓		
	Asymmetric			✓
	Co-annihilation		✓	
Portals	Singlet Scalars	✓		
	ALPs			✓
	Dark Photons	✓		
	Heavy Neutrinos			✓

Why searching for LLP?

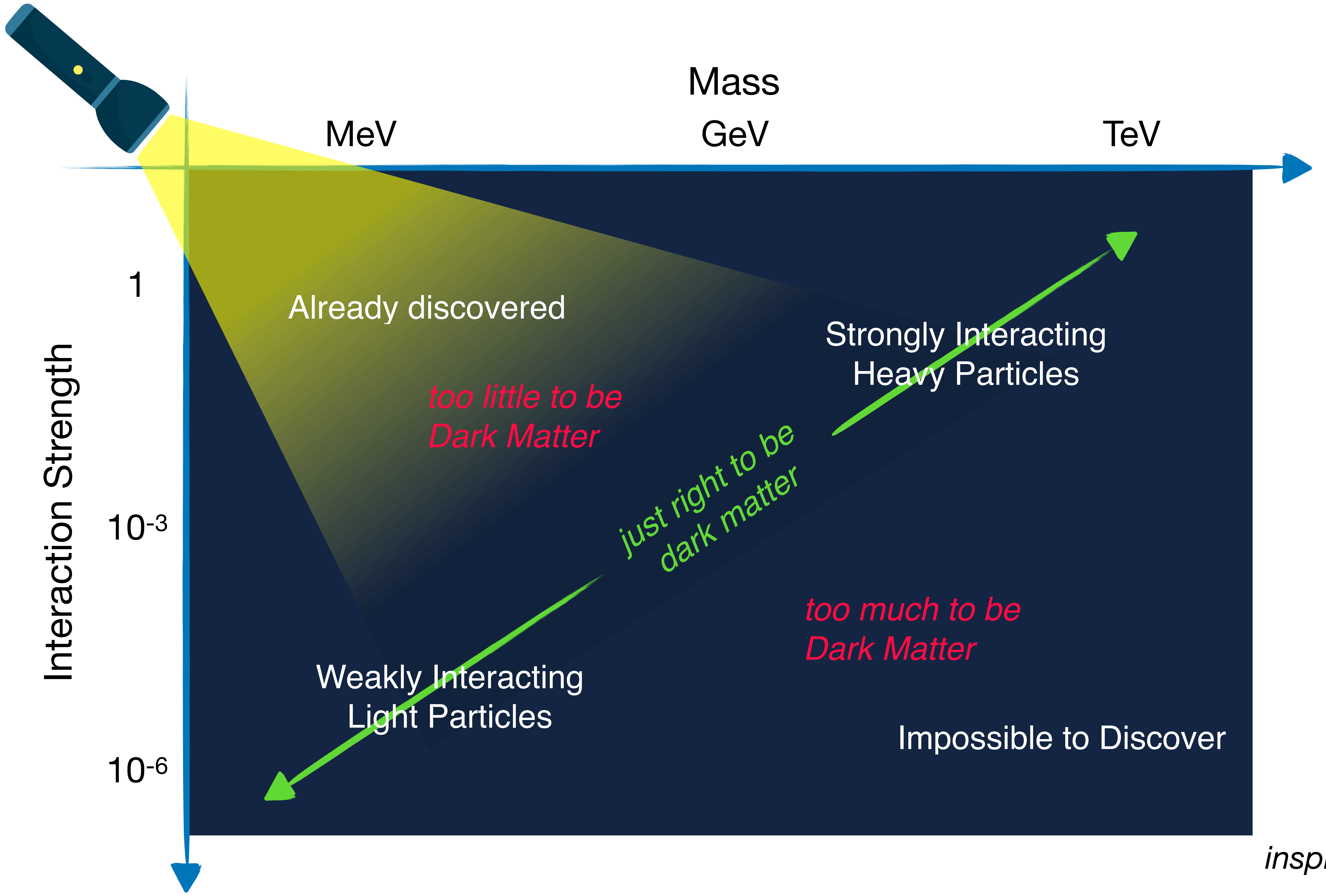
The search for beyond the Standard Model LLPs is

- **well-motivated** from a theoretical perspective
  - upper bounds on $c\tau$ from potentially spoiling BBN ➡ $\tau \sim 0.1 - 10^4$ s
    - way too loose to concern LHC experiments
  - lower bounds depend on the models

- **exciting** from an experimental point of view
  - huge variety of spectacular signatures
  - still largely unprobed scenarios
  - large room for novel ideas
  - many opportunities for new experiments



The cosmological landscape

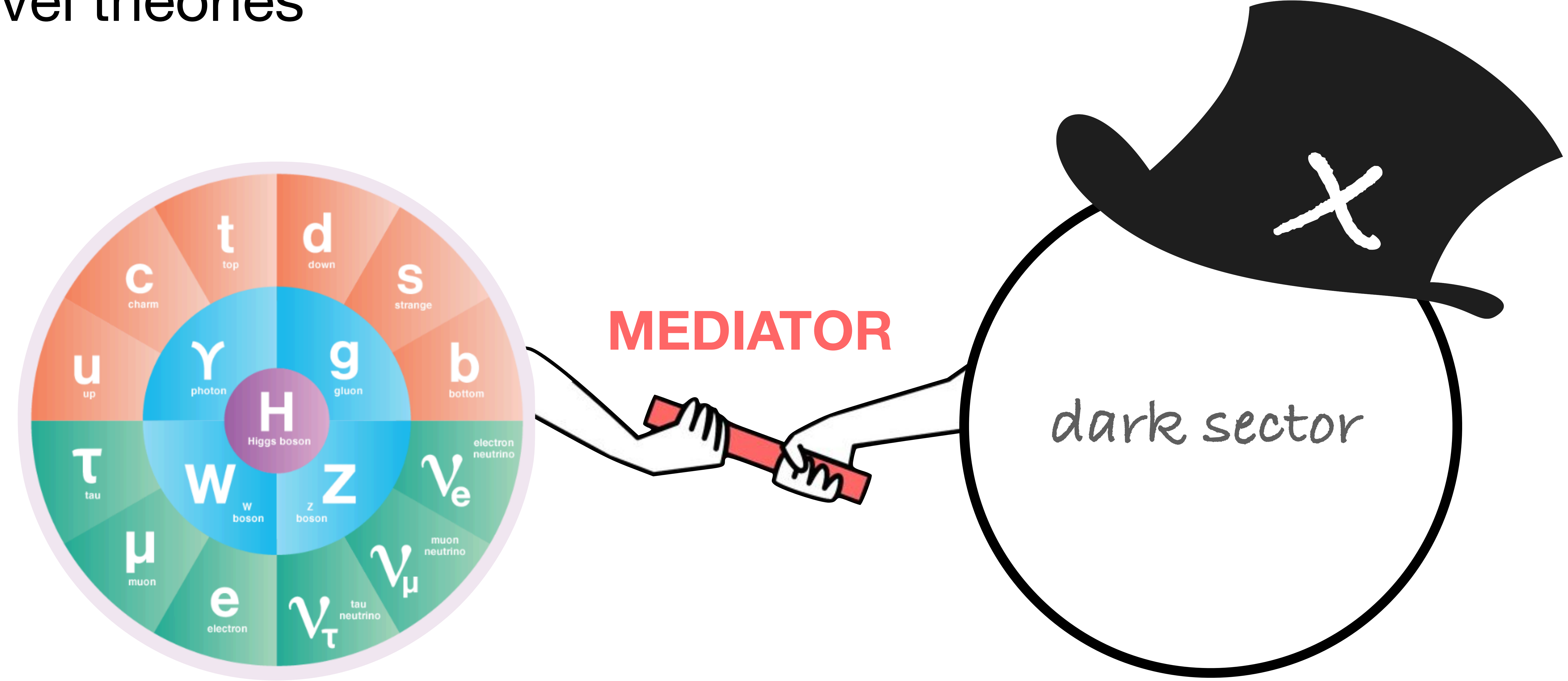


inspired by J. Feng

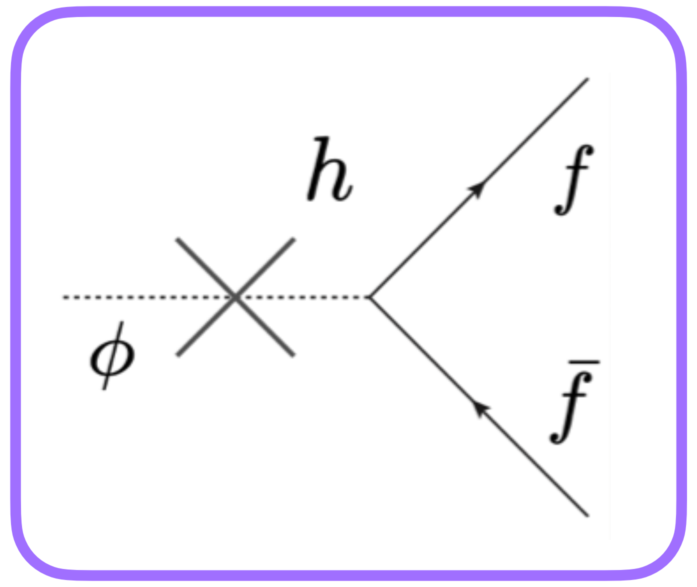
Dark Sectors

Simplified benchmarks are often used to allow a reinterpretation in more complete, complex and novel theories

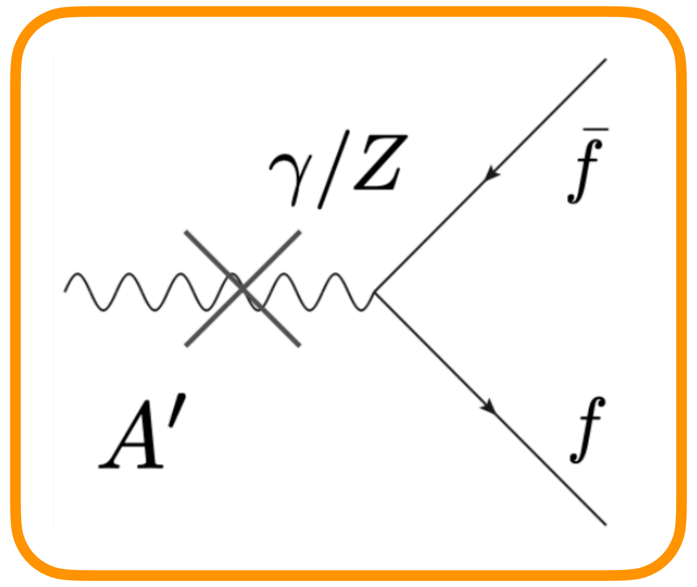
Dark sectors can hide a world of particles, including DM candidates, w/ the right relic abundance



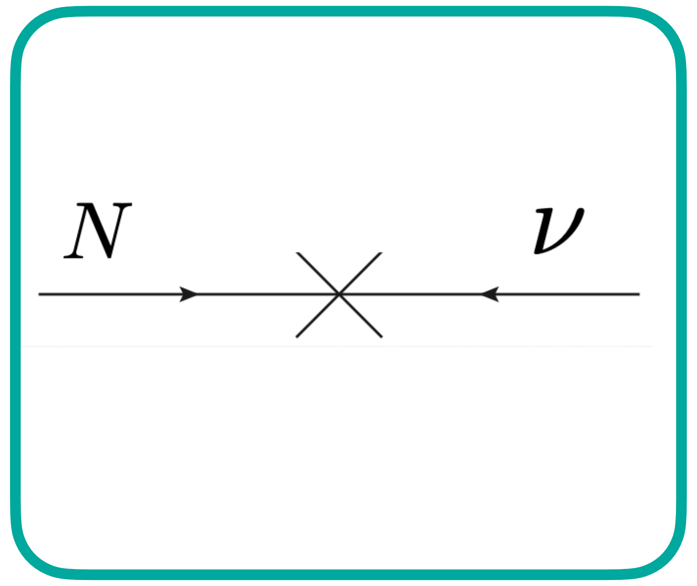
scalar portal
spin-0



vector portal
spin-1



neutrino portal
spin-1/2

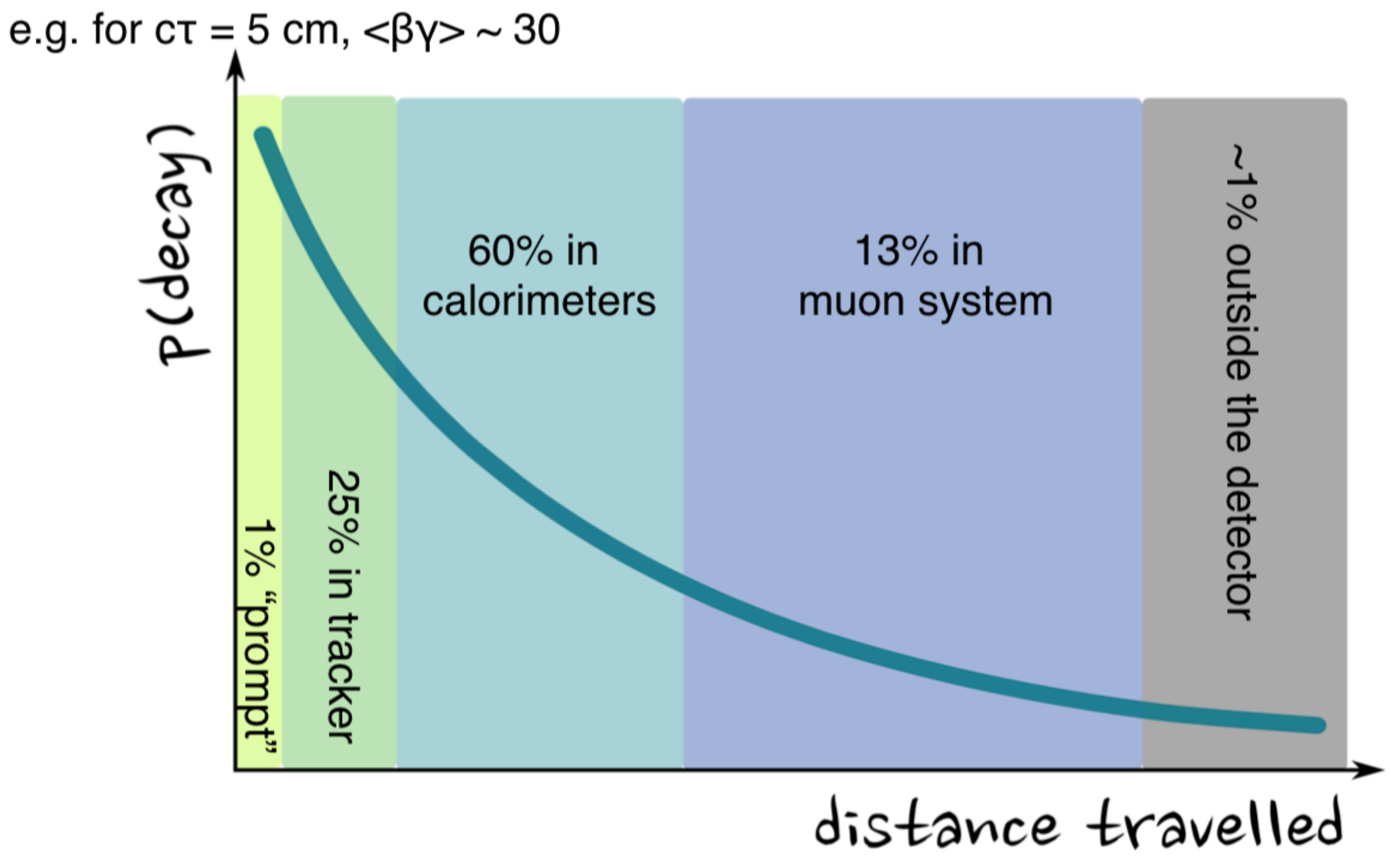


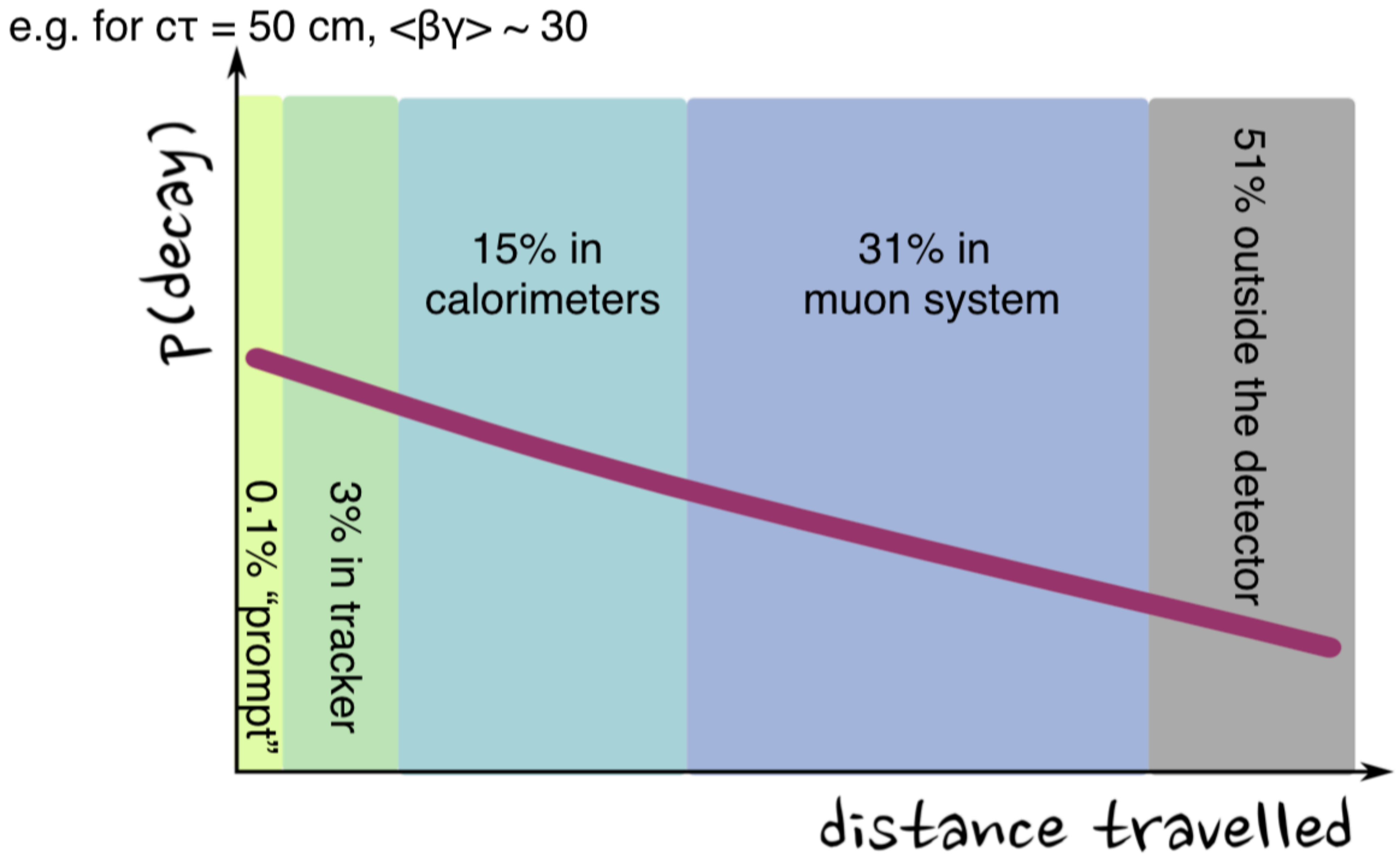
Decay length

Any given particle's lifetime follows an exponential distribution:

particles with a short proper lifetime can decay with a large lab-frame distance

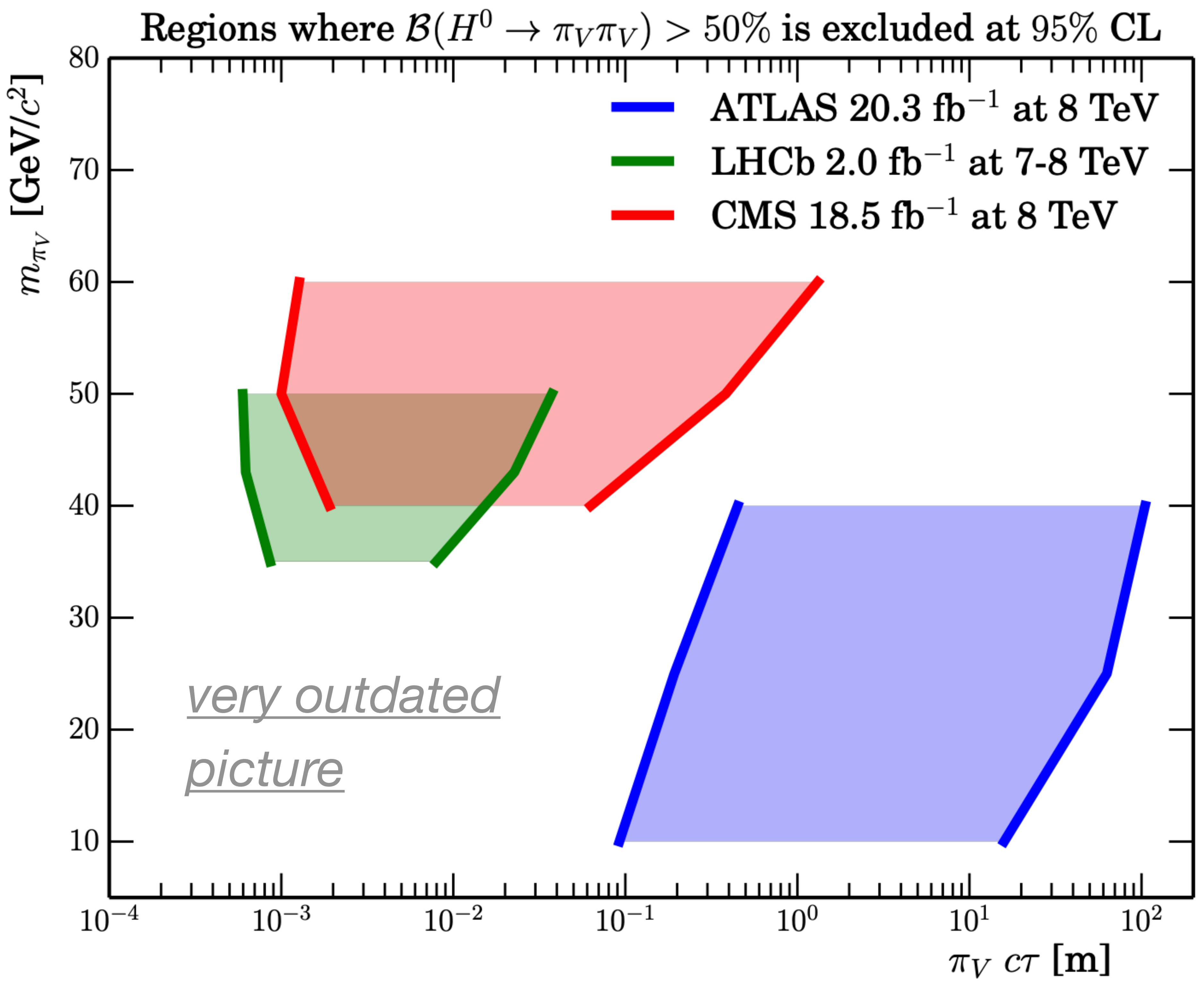
- all subdetectors must be used for optimal results
- **prompt** and **invisible** final states searches can play a fundamental role!



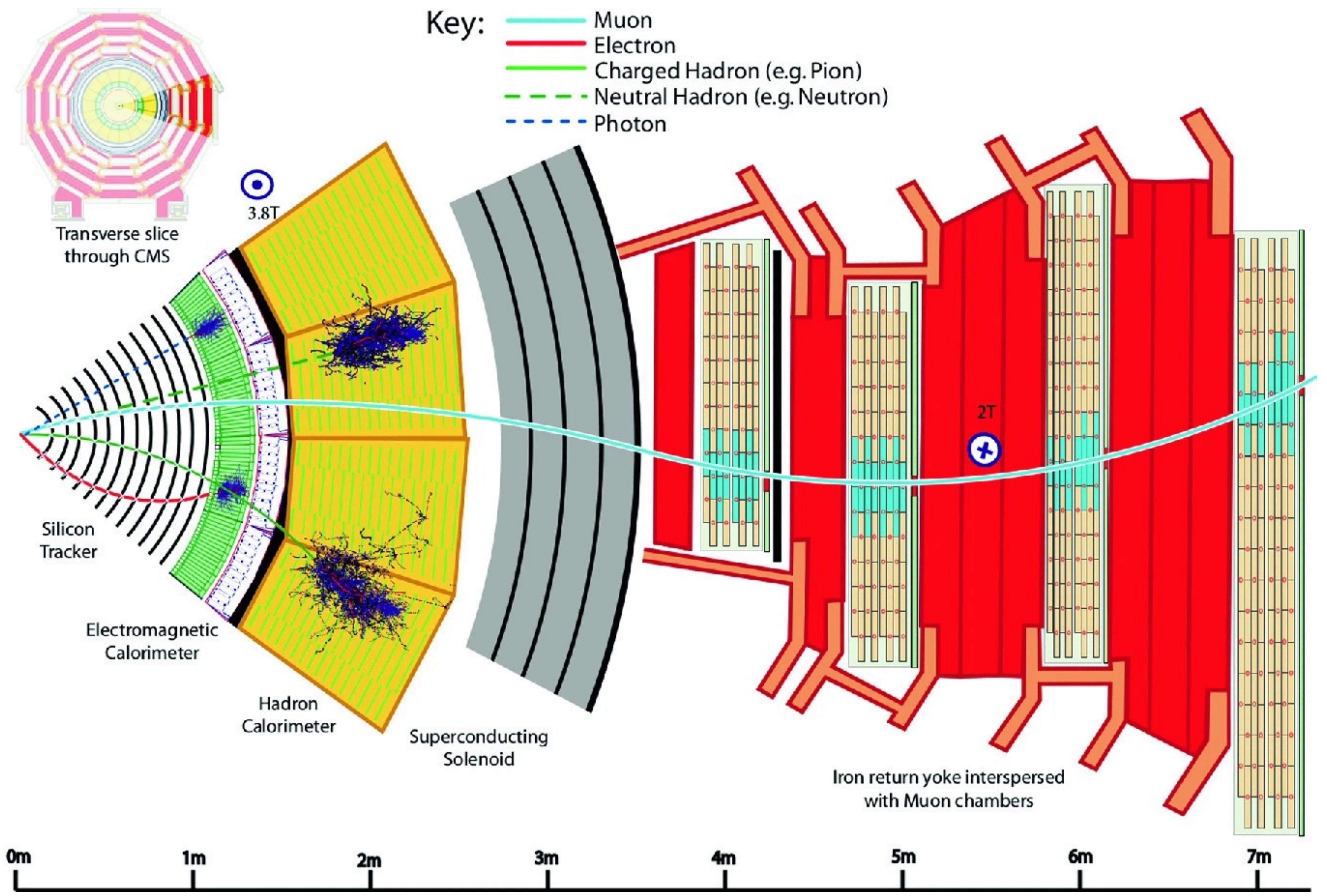


based on the ATLAS geometry

LHC experiments



LHC experiments can probe different phase-spaces

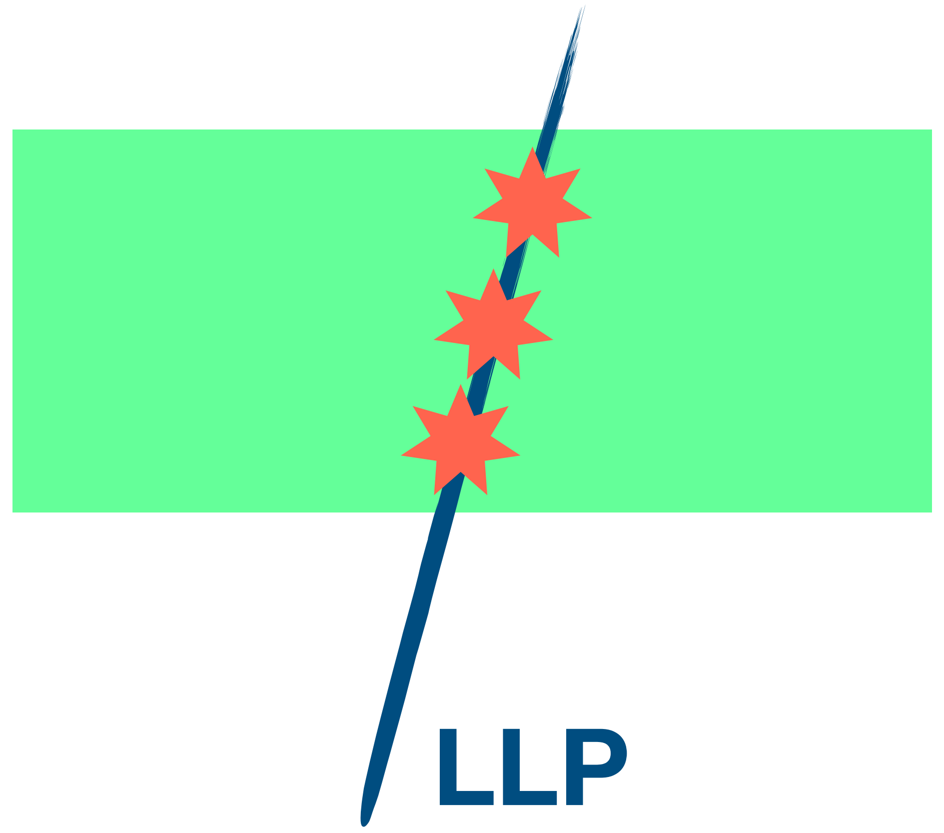


Various sub-detectors are sensitive to different life-time ranges

Hunting LLP

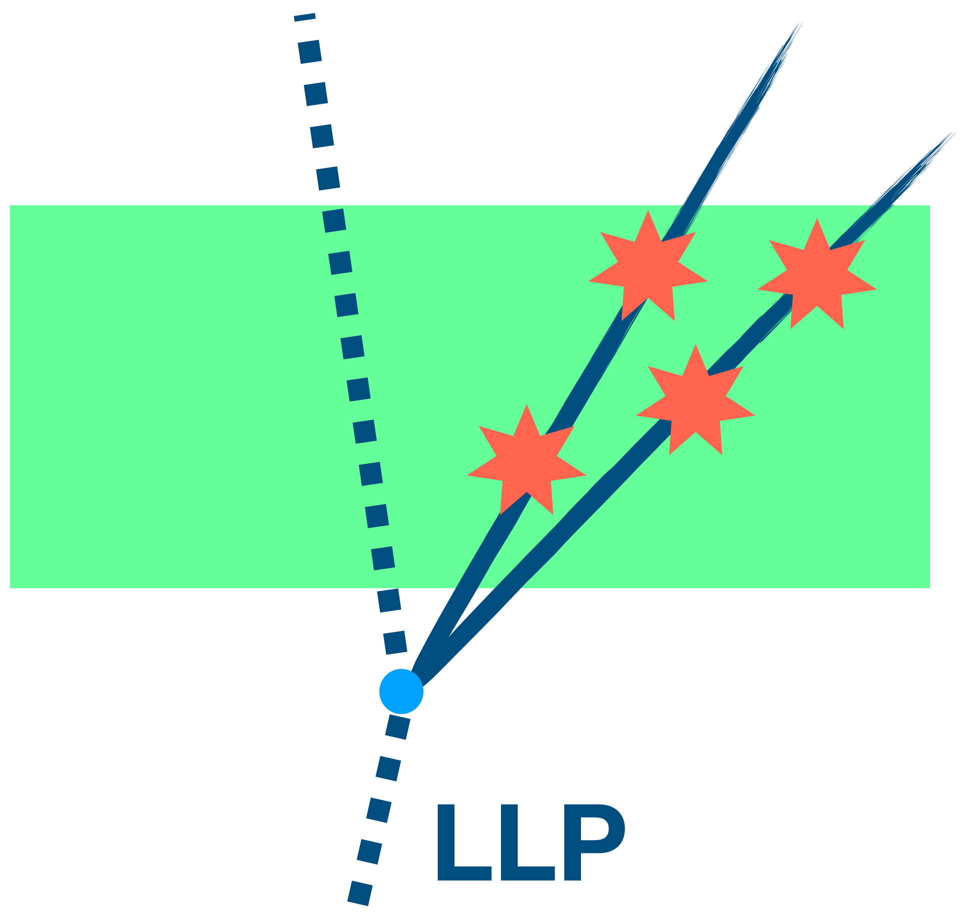
Direct detection

- Through direct interaction w/ the detector
  - Energy loss
  - TOF
  - special track properties
- Mostly fit charged LLP



Indirect detection

- Through SM or invisible decay products
  - "Isolated" activity inconsistent with prompt or expected instrumental / SM
- Natural fit for neutral LLP but also sensitive to charged ones



Main experimental challenges

*Missing transverse energy:
momentum imbalance on the transverse plane

Triggering

- trigger systems (especially Level-1) usually do not have sufficient information to tag LLP particle/decay
- often used ‘prompt’ physics trigger (e.g. ISR jet, MET*, prompt leptons)
  - reducing sensitivity and increasing model dependence of results

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- Unusual background sources
- **Data-driven approach** is adopted
  usually cannot rely on simulation

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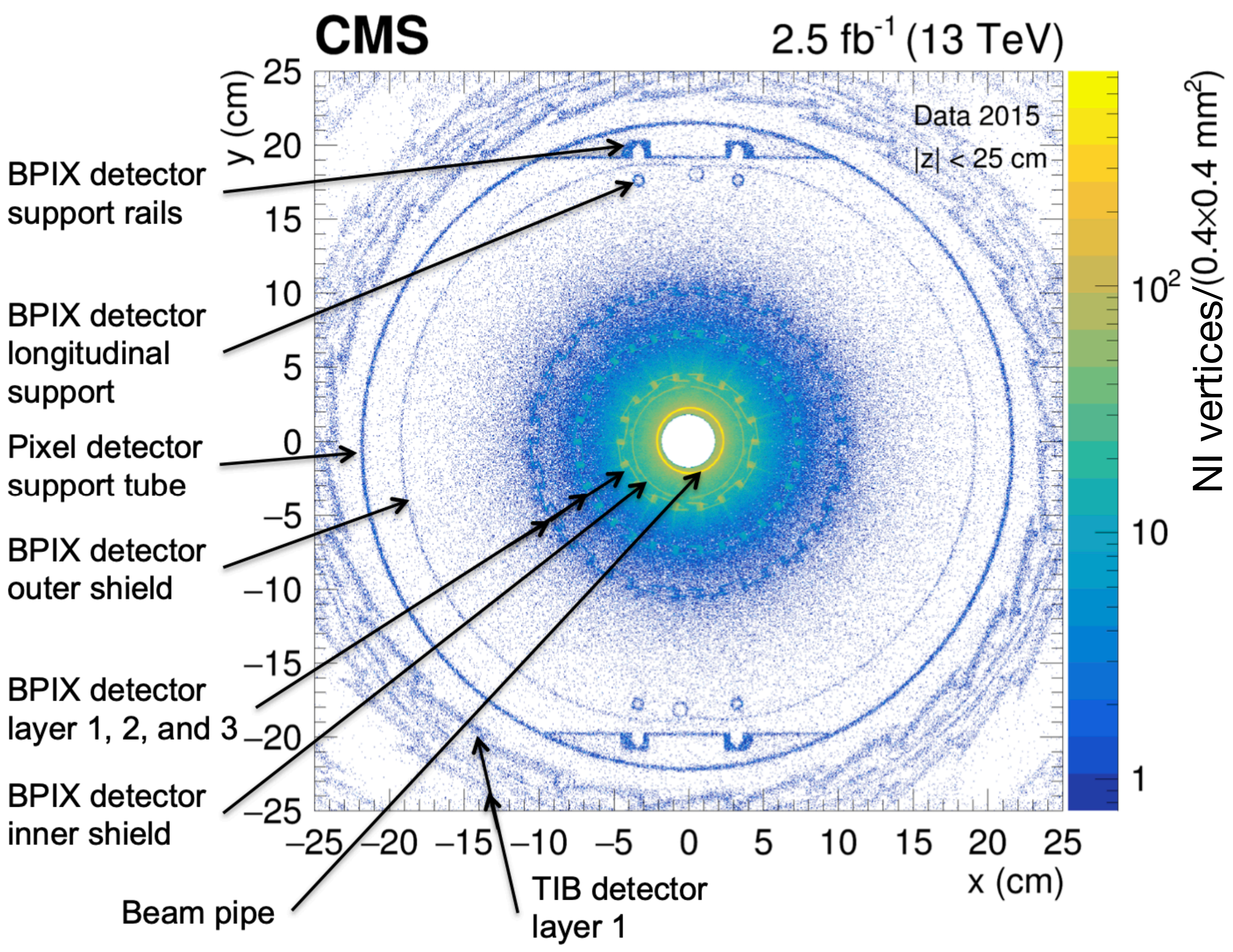

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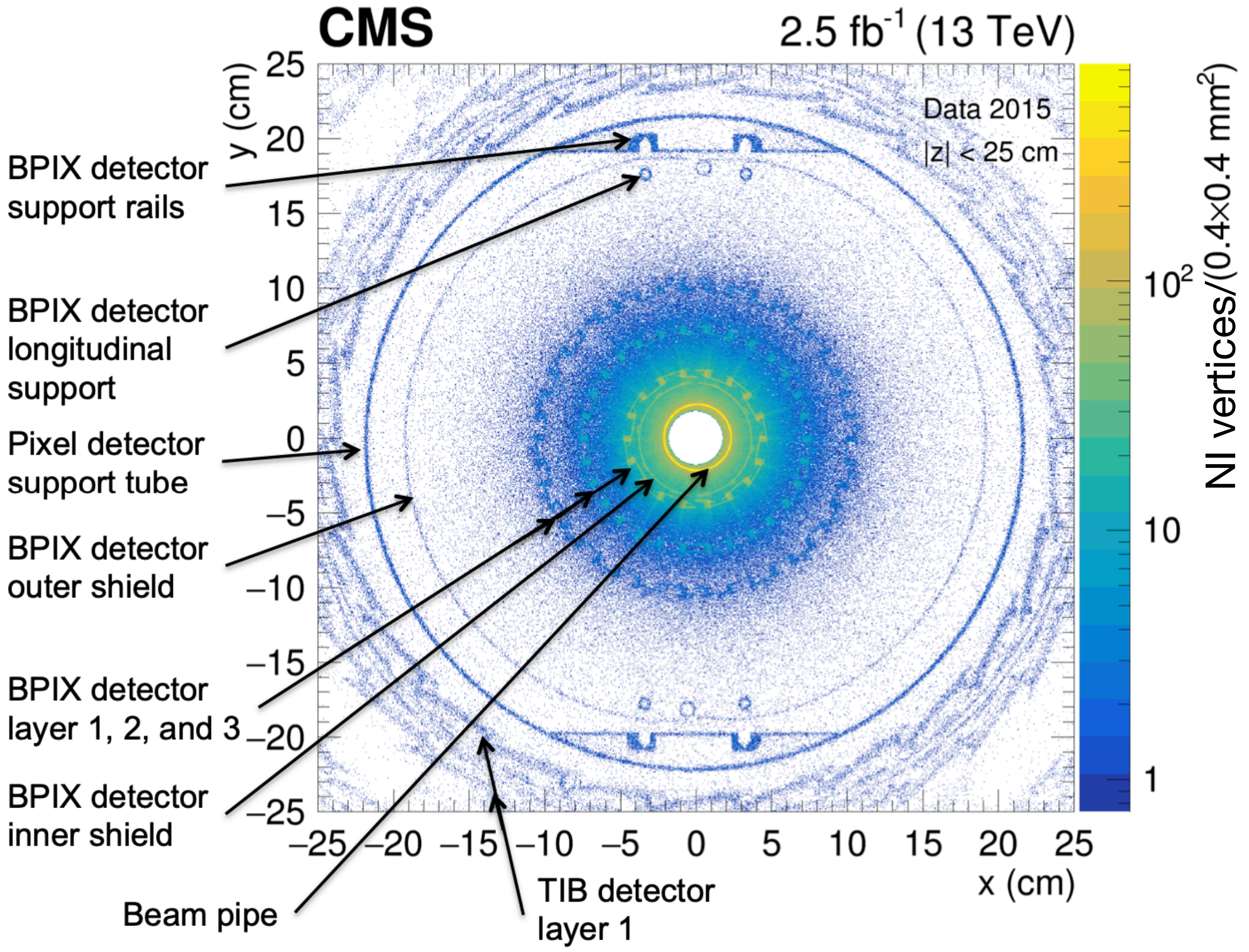

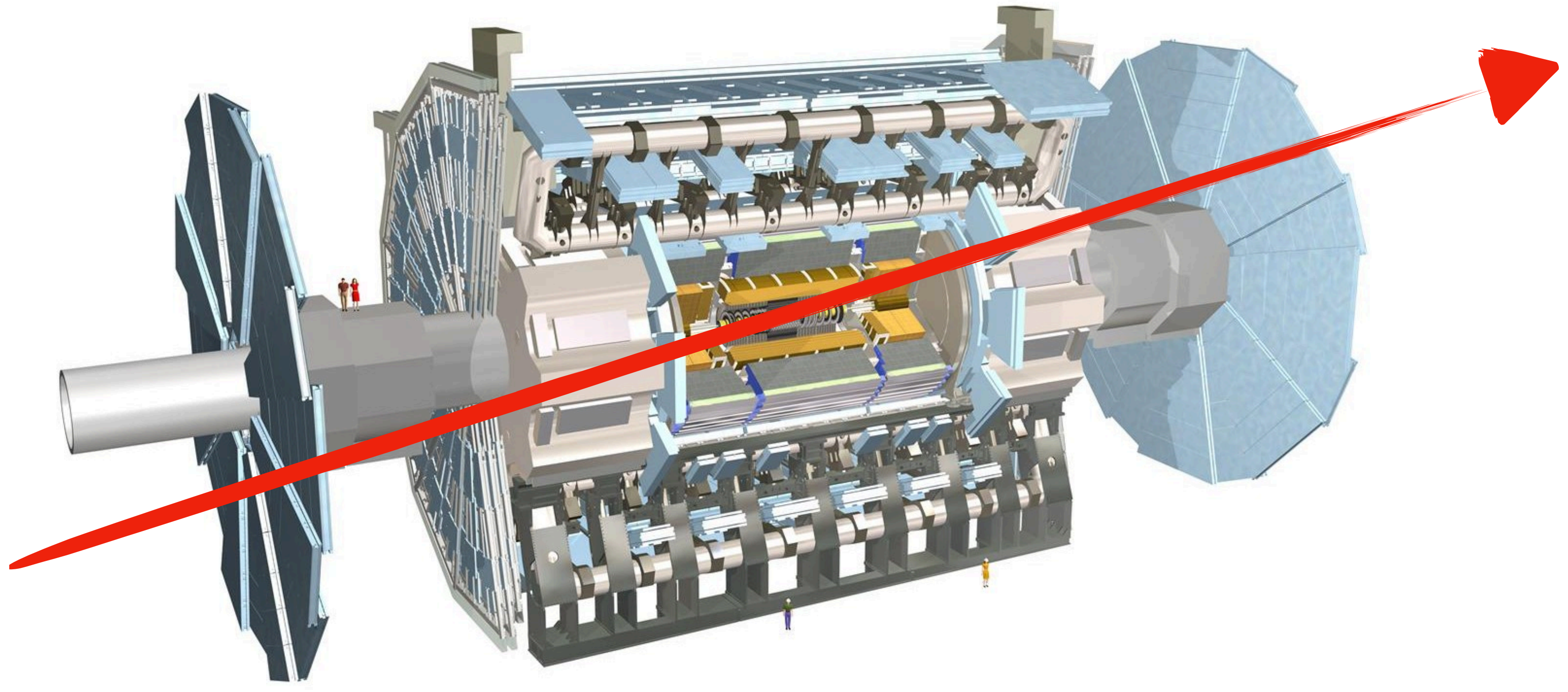

Beam induced background

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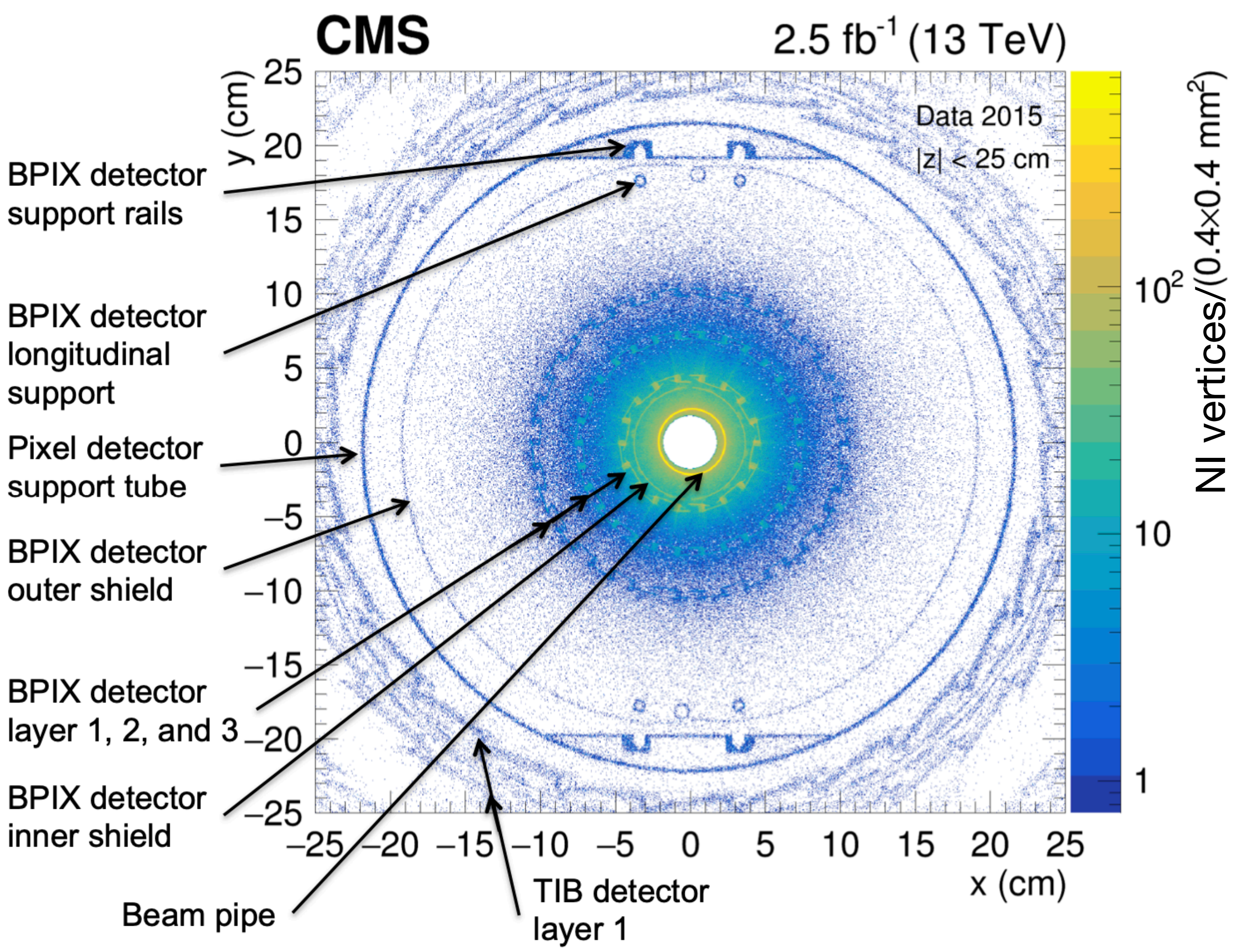
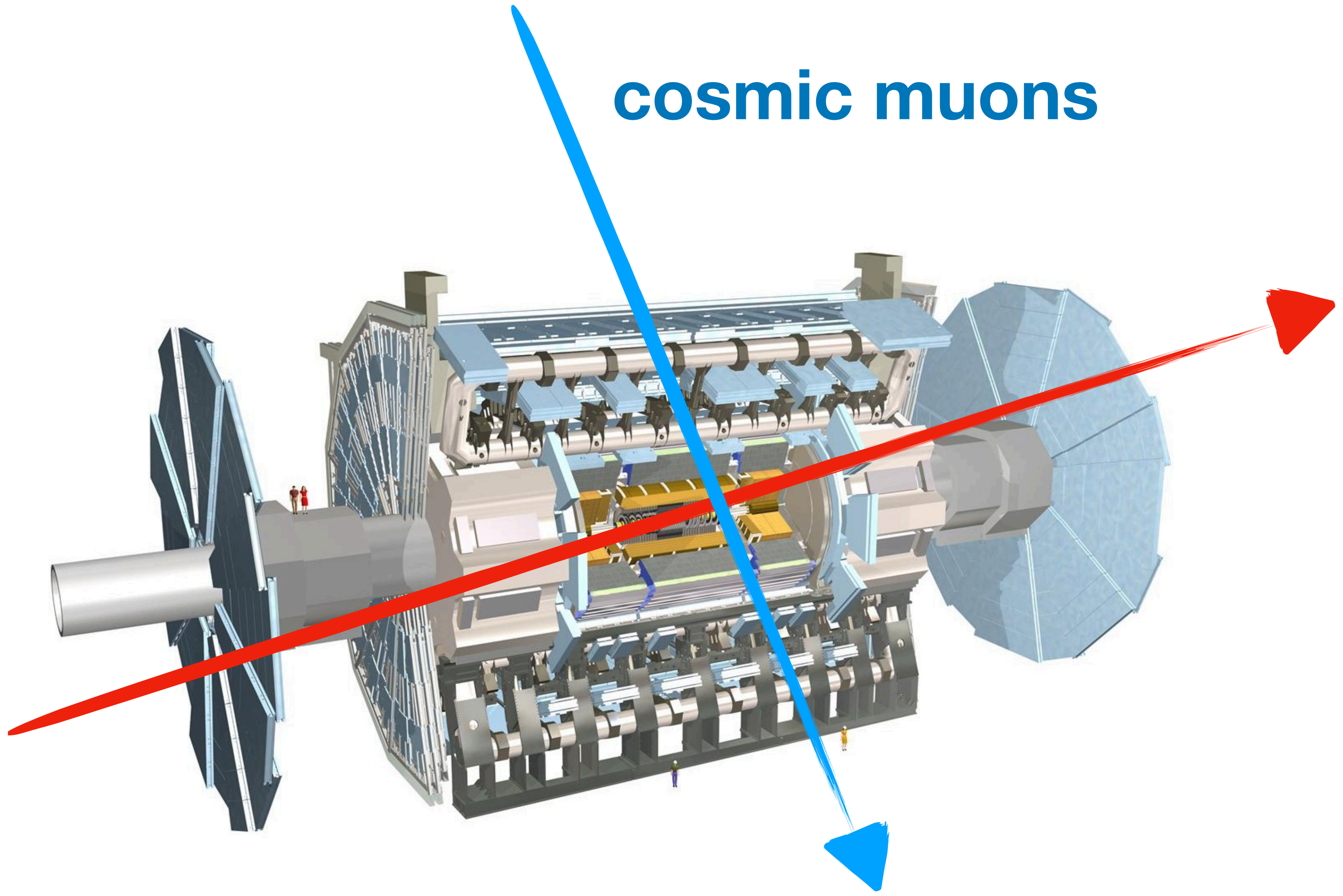


cosmic muons



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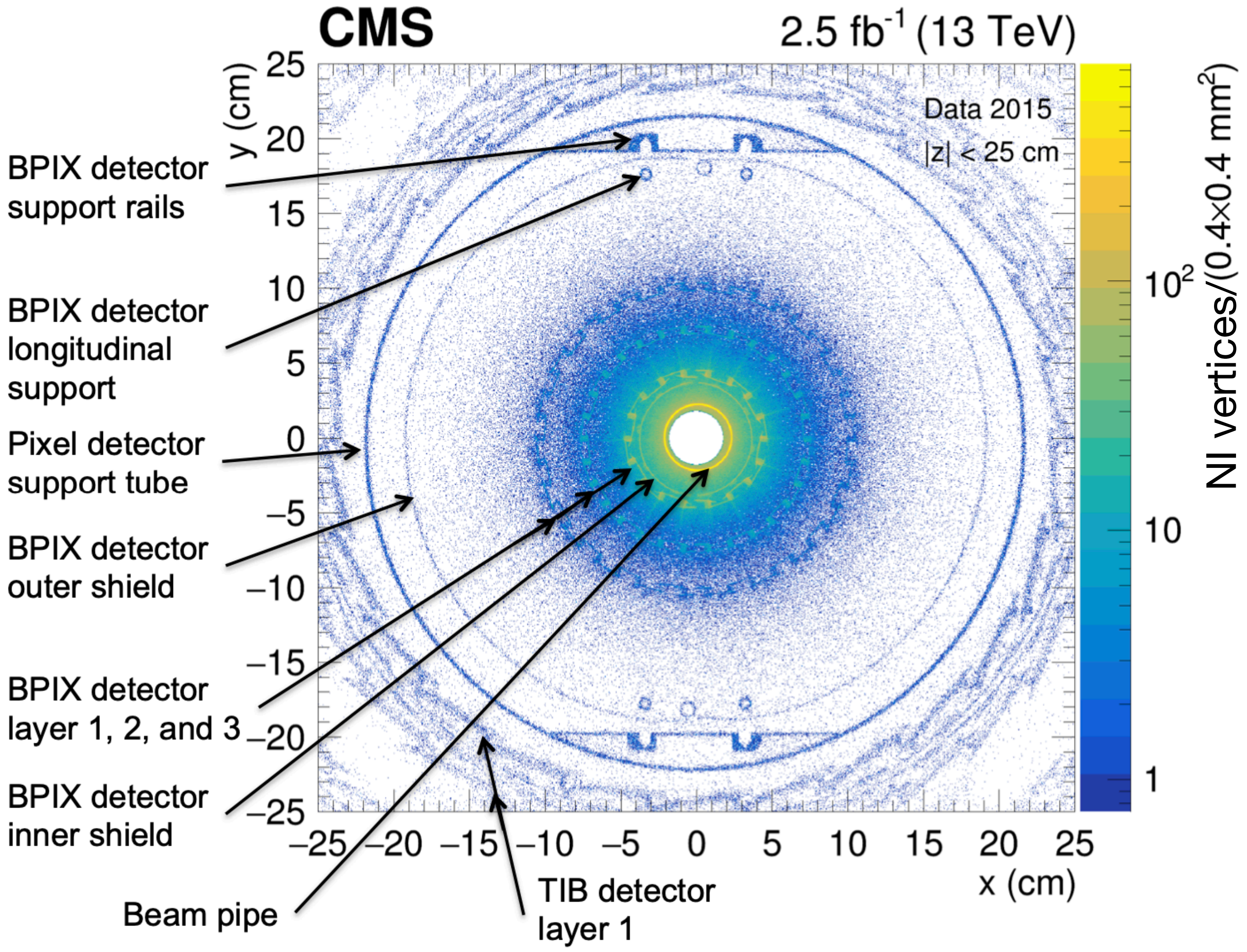

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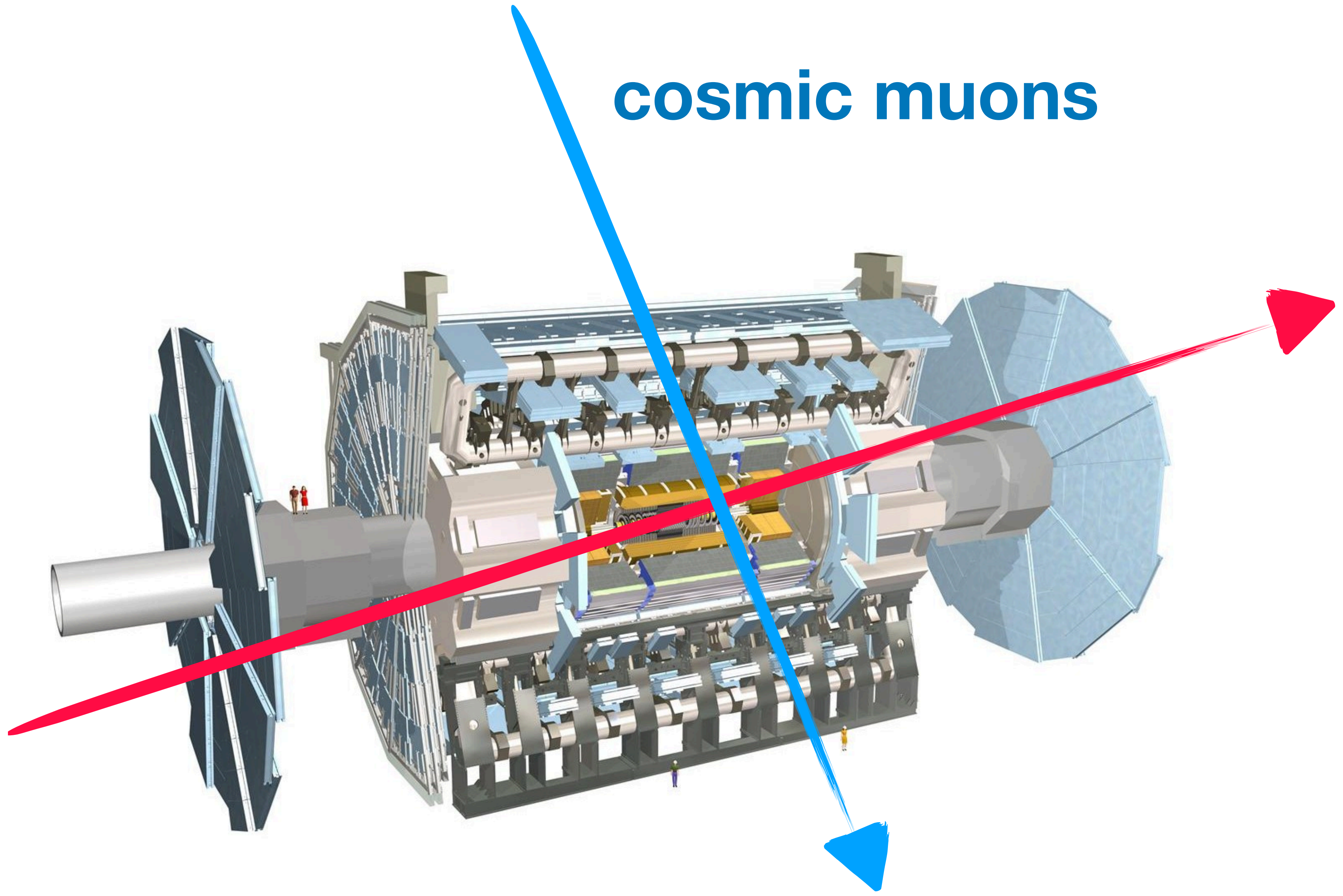
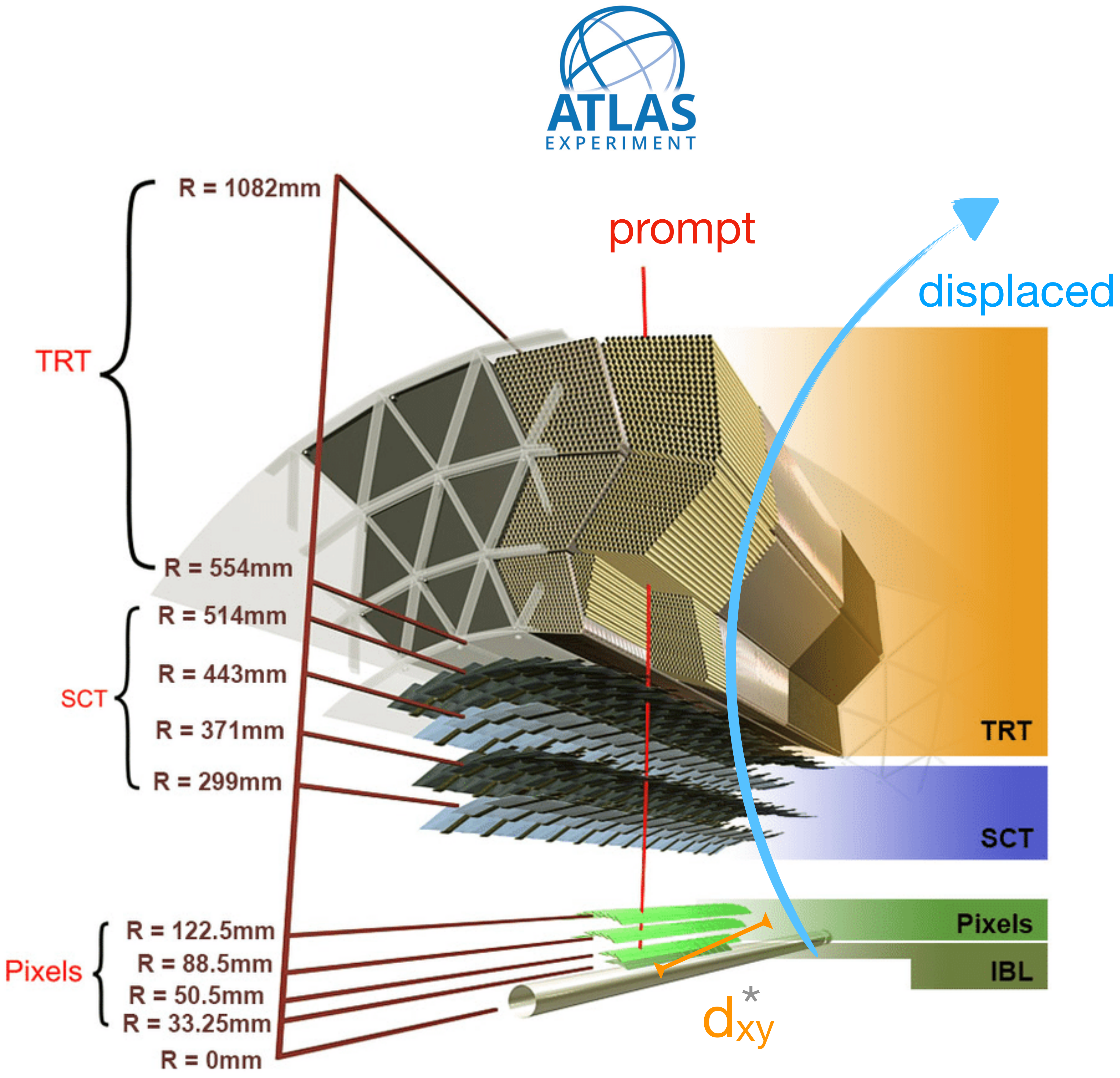


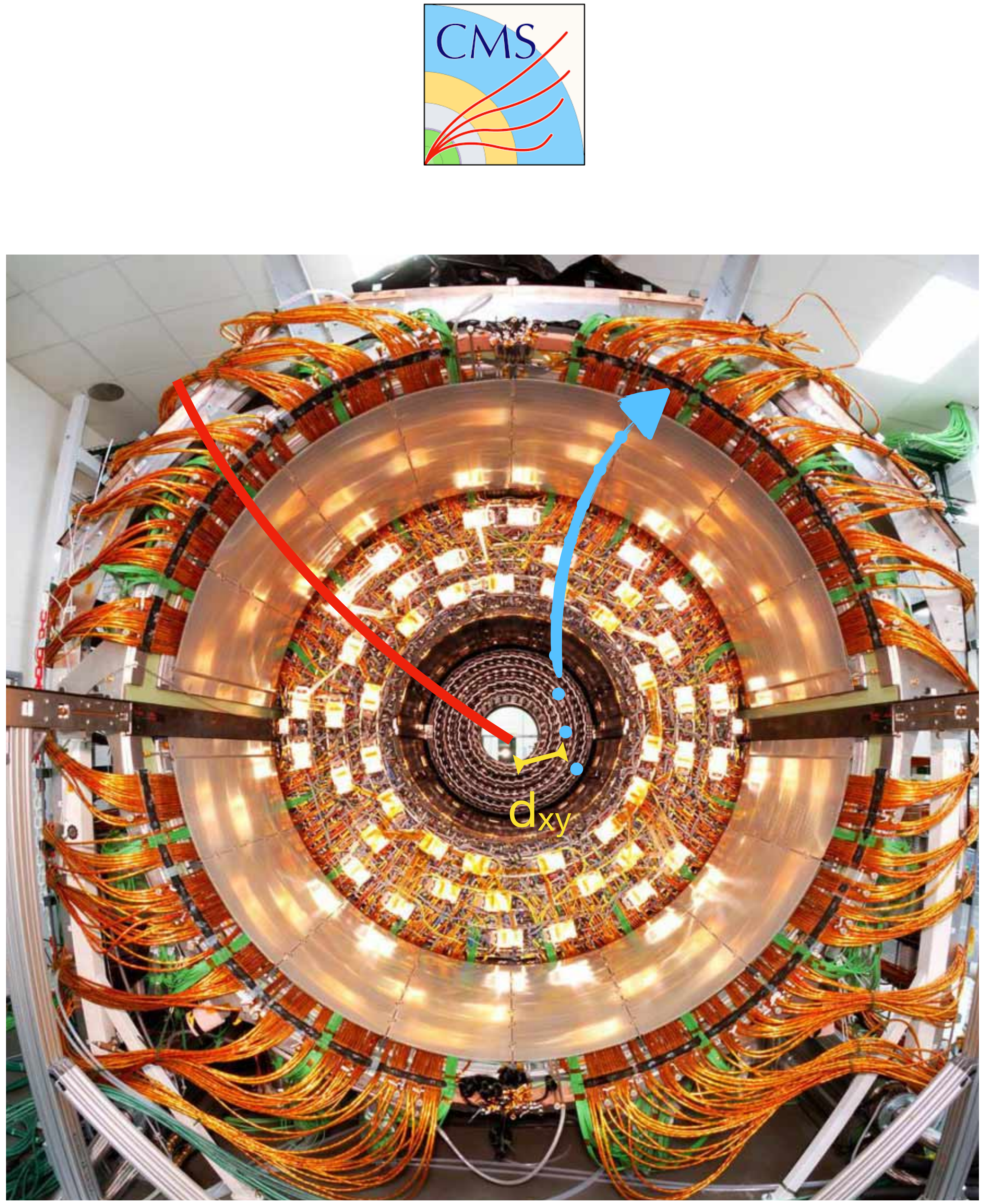
Beam induced background

Estimation of signal efficiency

- Often not possible, as no SM standard candle giving sufficiently LLP signatures / decay signatures

Inner Tracker based searches





probing up to cτ ~ O(dm)

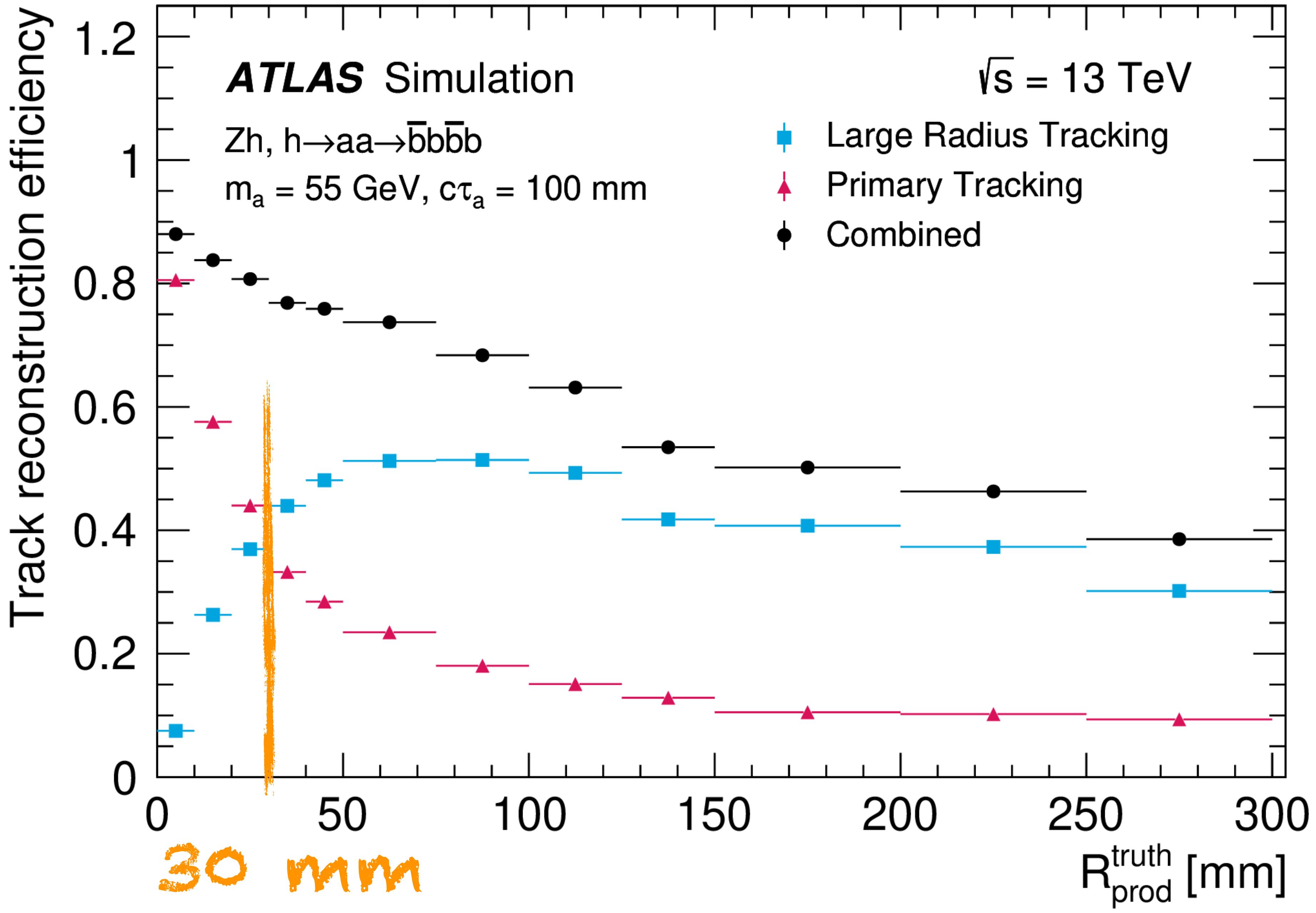
*transverse impact parameter

Inner Tracker based searches

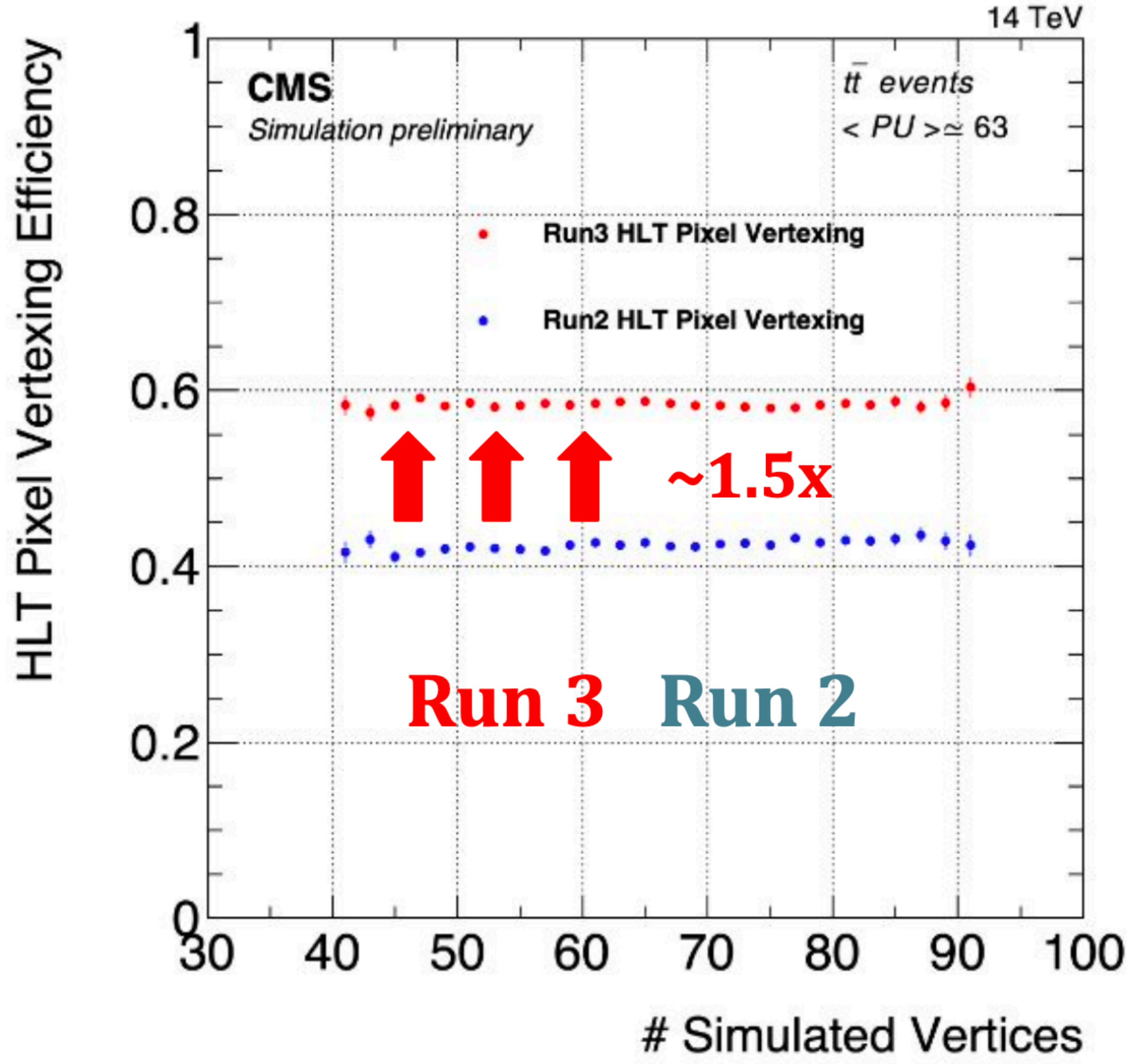
INFN ROMA

New @ Run-3

ATLAS EXPERIMENT



CMS



reconstruction algorithm

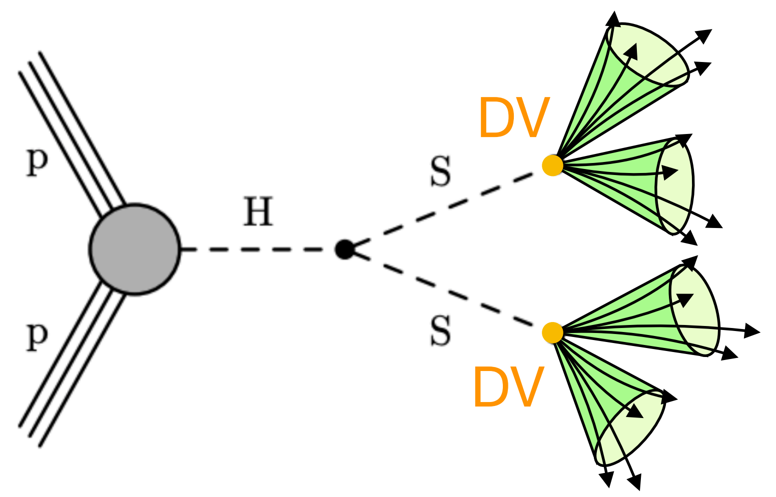
- New **Large Radius tracking algorithm**
  - x20 less fake tracks
  - integrated in the reco-chain
- Integration of tracks @ HLT!

trigger algorithm

- HLT pixel tracking on GPUs
- 1.5x more pixel vertex efficiency!
- 0.5x fakes

Searches for LLP in ID

scalar portal h->ss

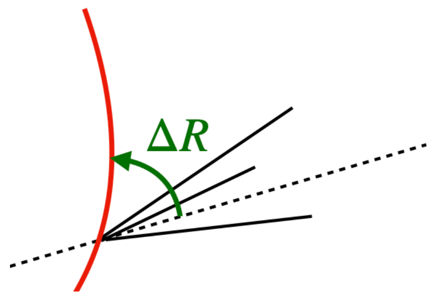


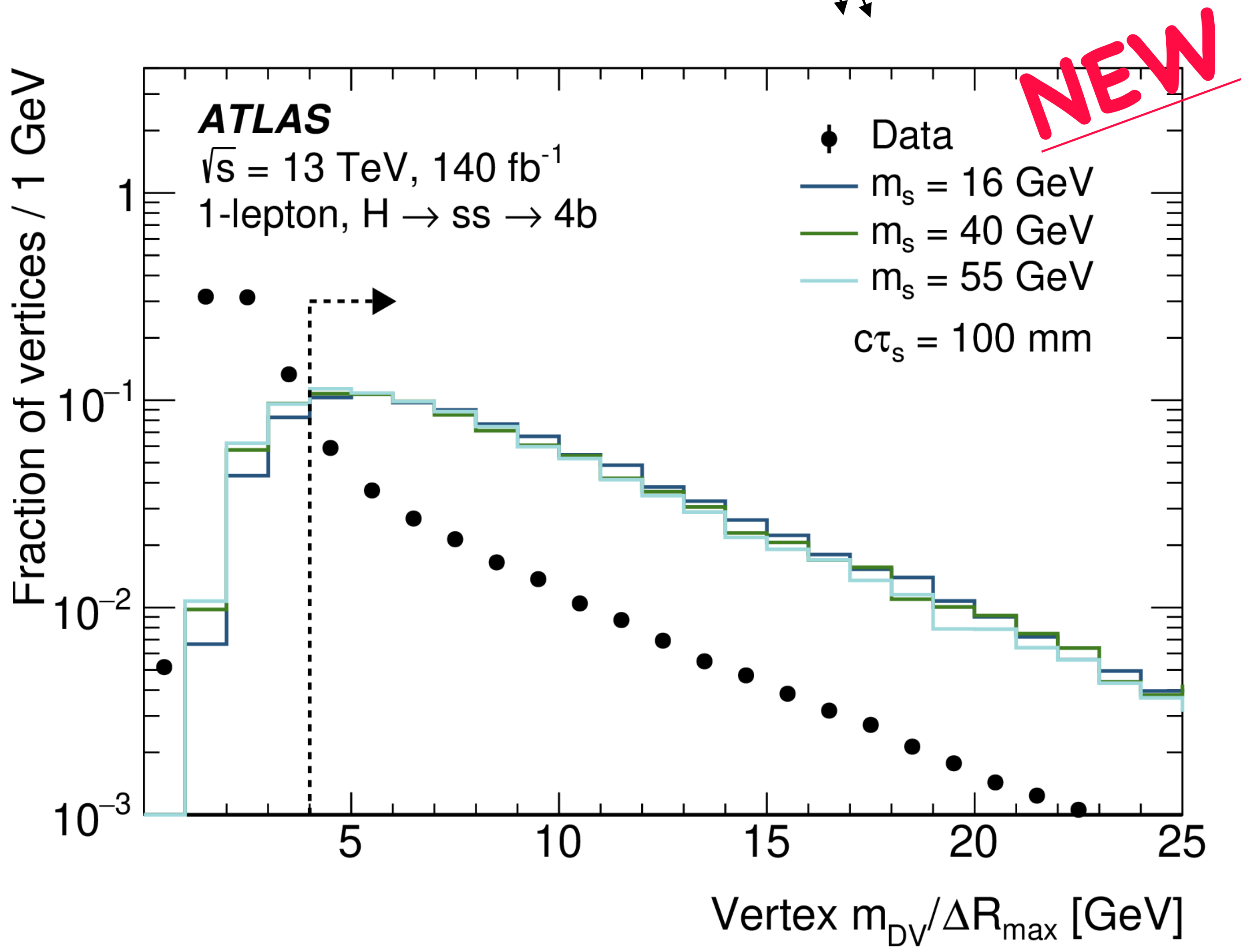
Signature: Displaced Jets & displaced Vertices (DVs) in the ID

BKG: DV from random crossing, heavy flavour jets, material interactions

ATLAS EXPERIMENT

- new production channels (VH, VBF)
- **new LRT algorithm**: x40 s/√b tracks
- analysis strategy requiring **≥1** displaced jet
  - sensitive to more signatures





ATL-EXOT-2021-32

Factor of 10 improvements w/ the same Run-2 dataset

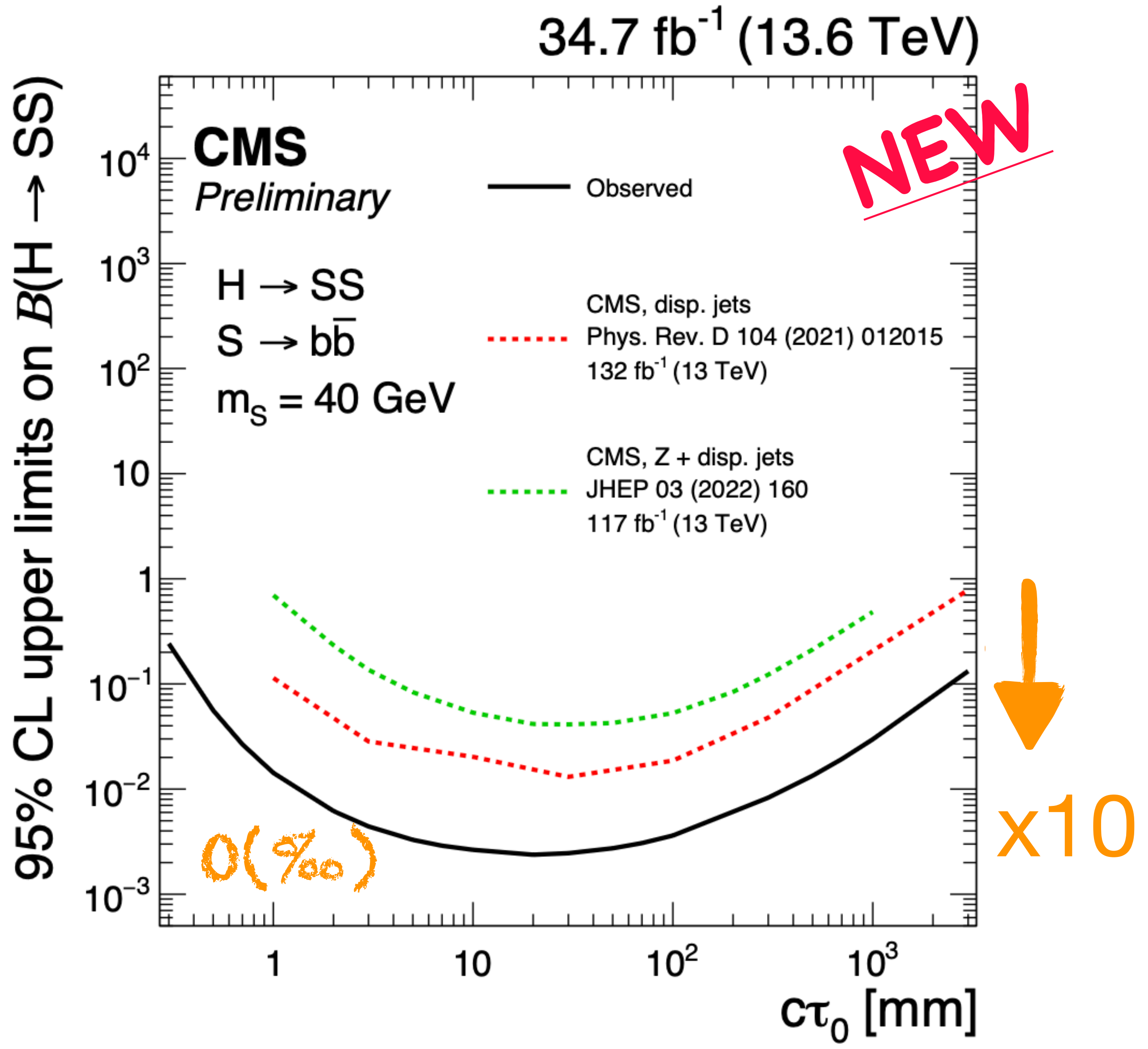
additional gain with new dedicated triggers to exploit ggF production in Run-3

CMS

- **New Run-3 triggers**: 2 jets with ≤1 prompt track (L1 HT or L1 HT+MU6)
  - efficiency 4-17 times higher than Run 2
- new reconstruction for displaced secondary and tertiary vertices
- new displaced jet taggers based on GNN

Factor of 10 improvements w/ 1/4 of the Run-2 stats

Additional gain (+40-100% signal) with 2023 data parking triggers

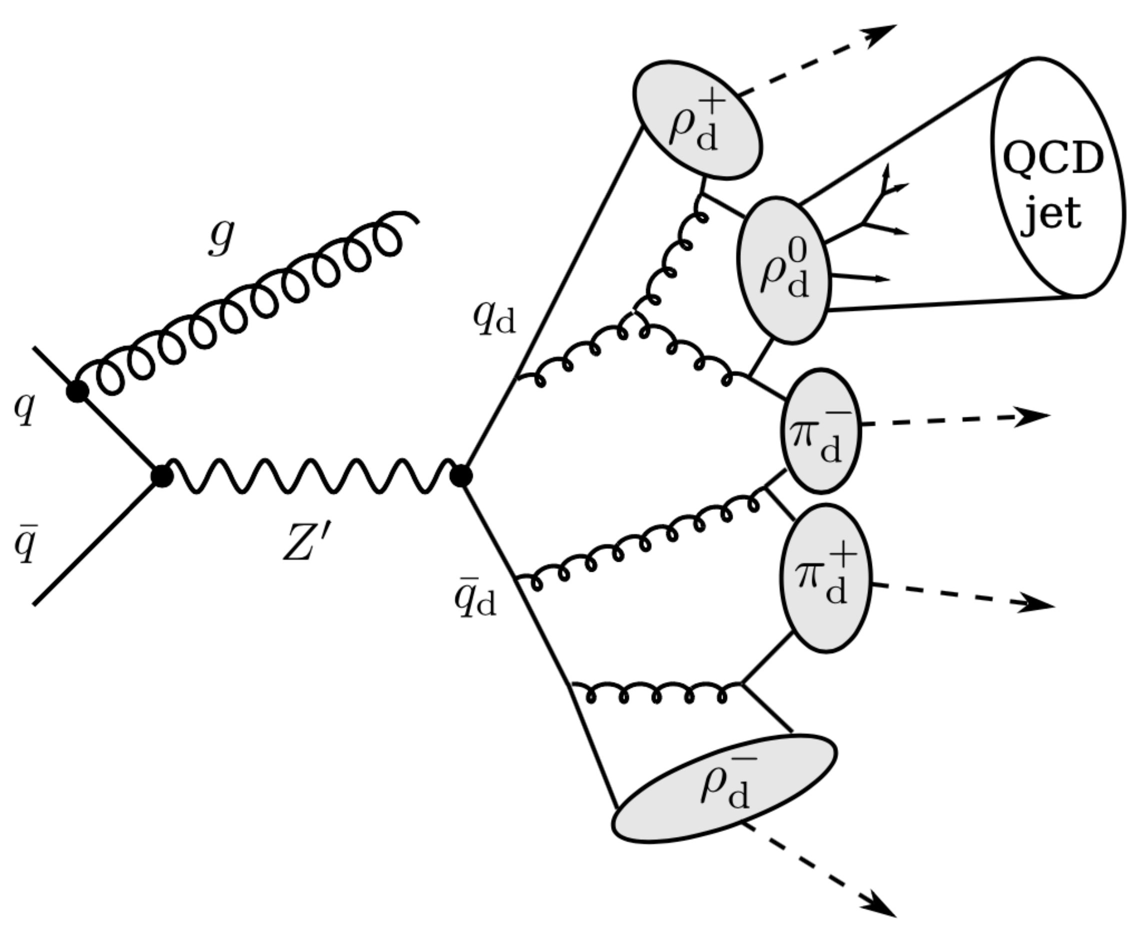


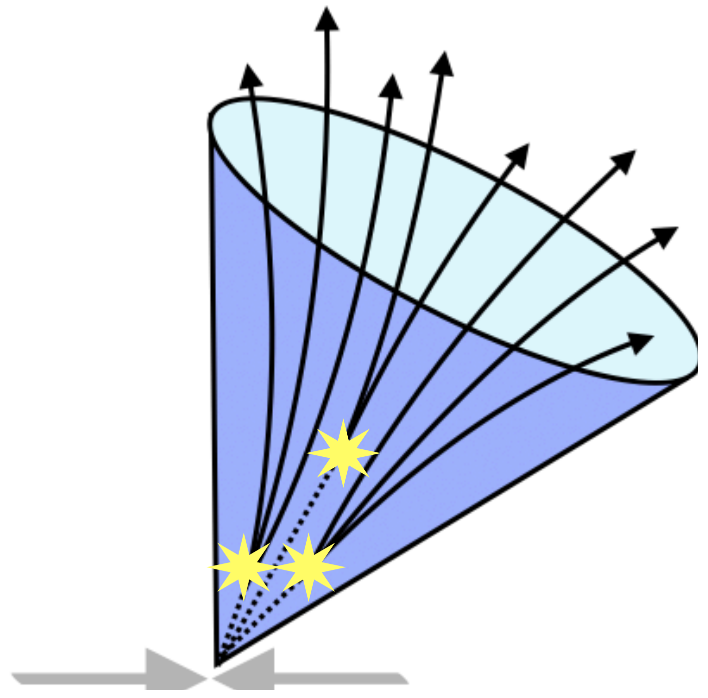
CMS-PAS-EXO-23-013

Emerging jets

QCD-like dark sector producing dark showers

- Dark pions can have a non-null lifetime





Signature: high multiplicity of DVs and displaced tracks

BKG: QCD, HF jets

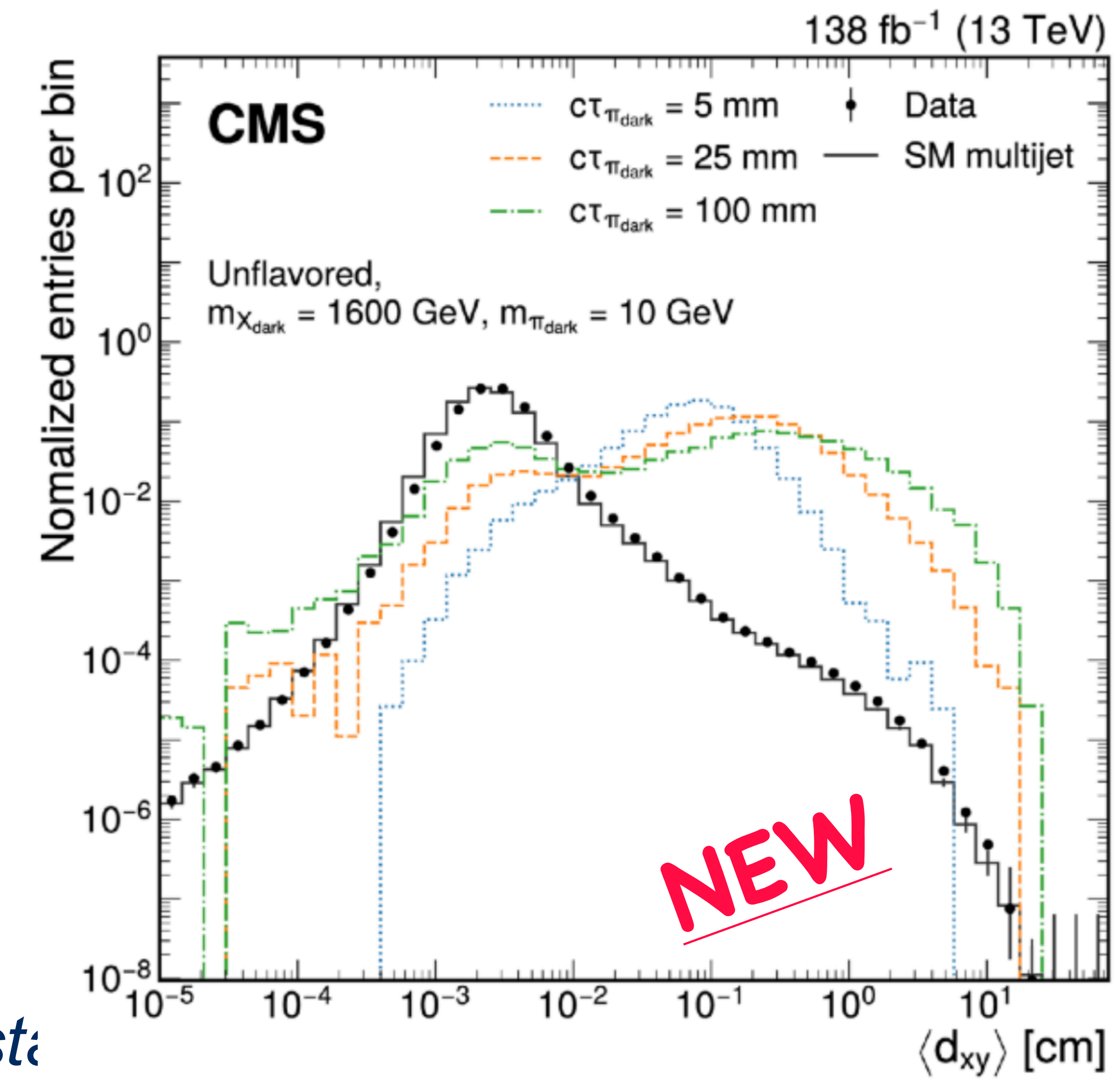
CMS

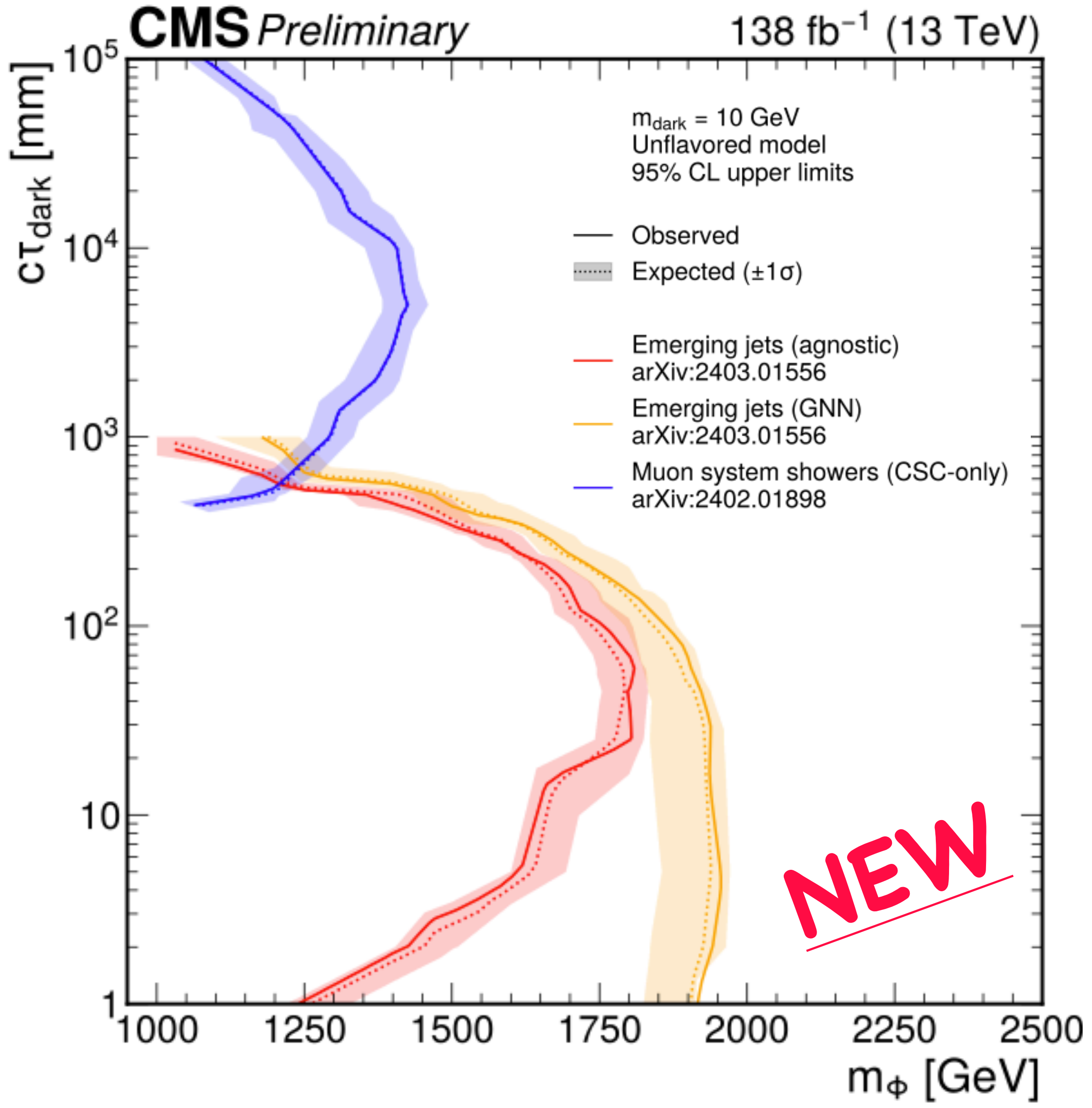
- New Run-2 results
  - GNN discriminates EJ vs QCD jets

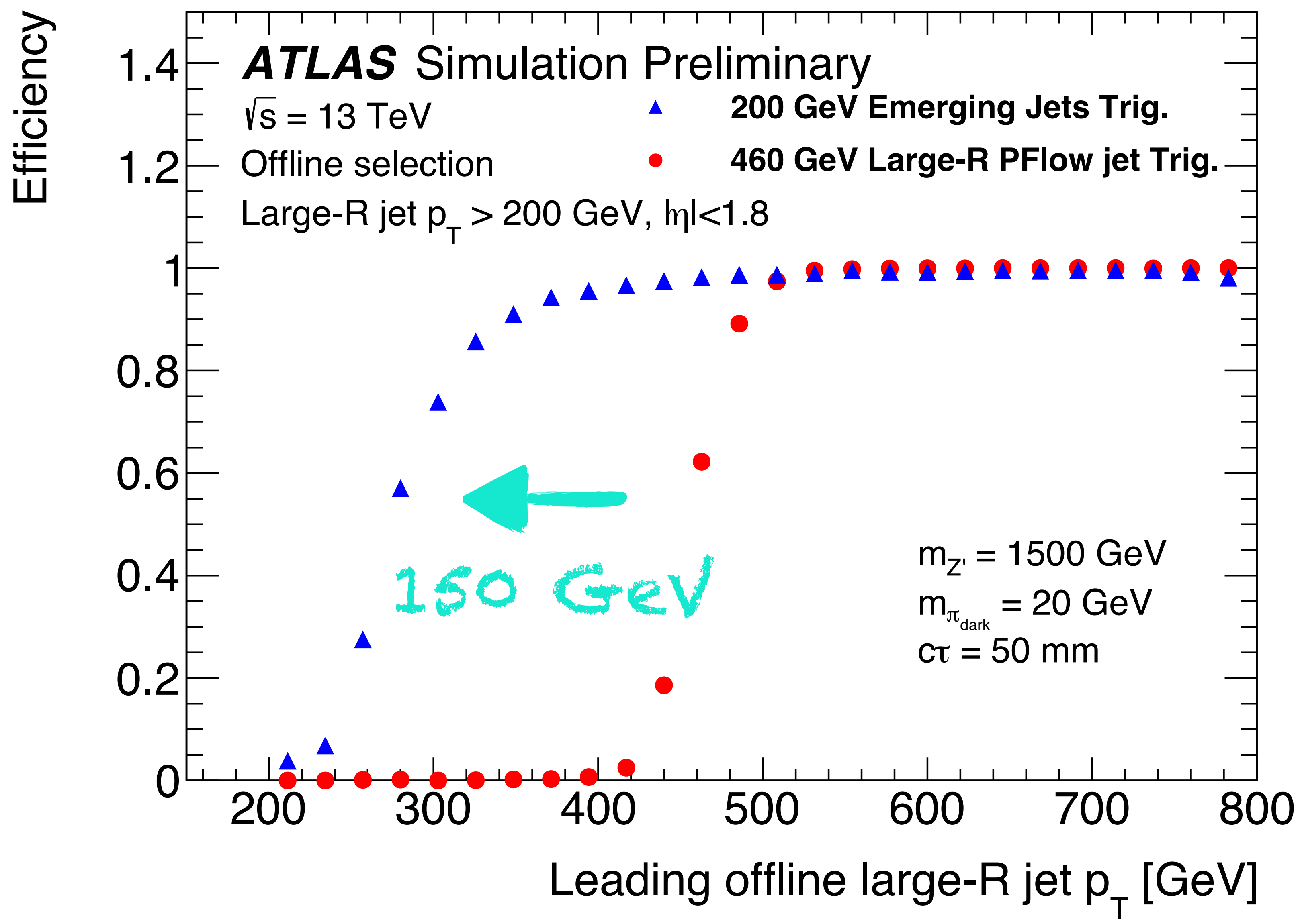
ATLAS EXPERIMENT

- New dedicated trigger in Run-3
  - selecting jets with small prompt track fraction

EXO-22-015







Fractional/multi-charged particles (FCP/MCP) & slow LLPs

LLP direct detection

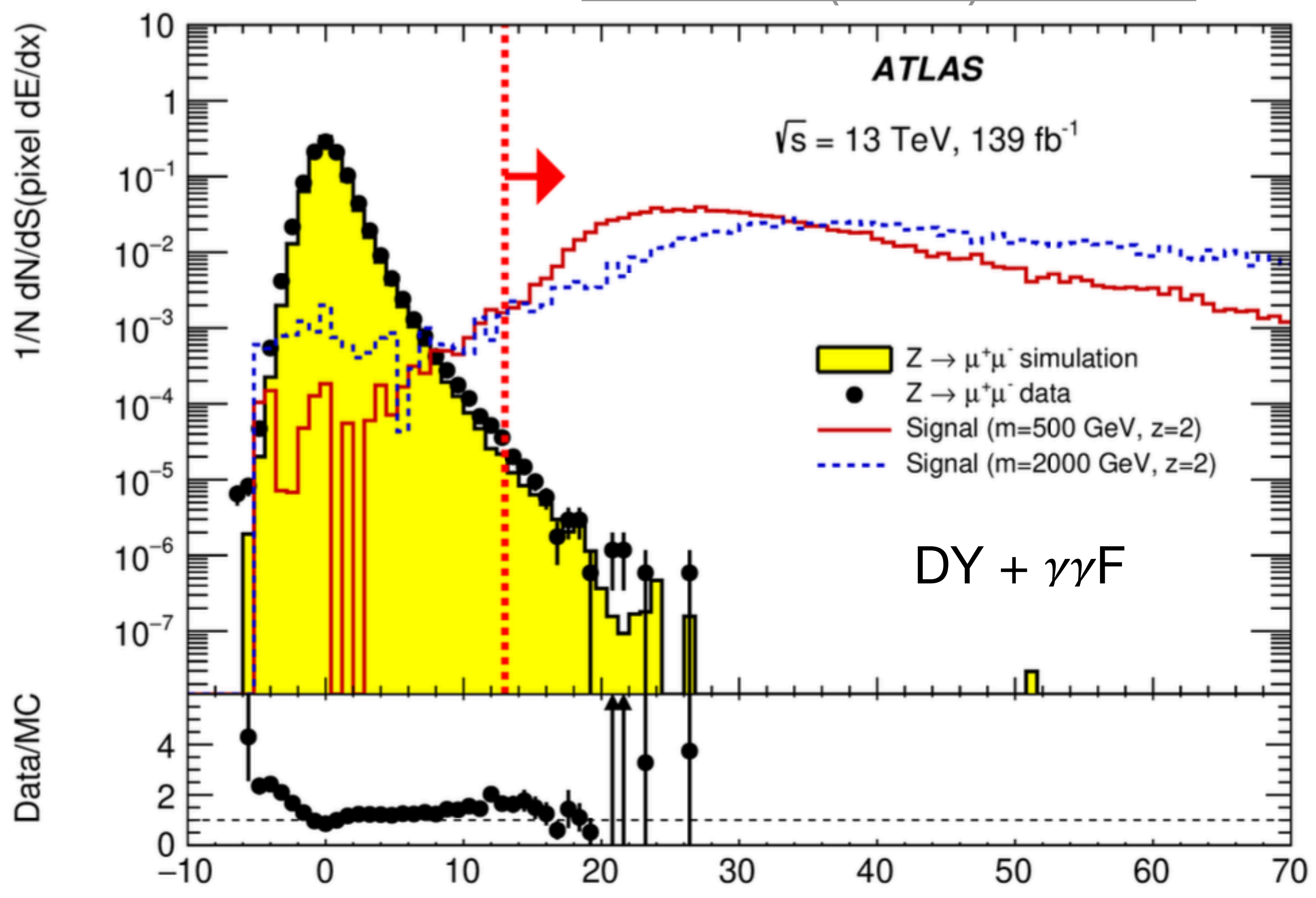
Signature: muon-like tracks with anomalous dE/dx

$$\frac{dE}{dx} \propto \frac{z^2}{\beta^2}$$

BKG: instrumental effects and δ-rays, random large dE/dx from Landau tail

- **MCP**: exploits dE/dx significance & TRT High Thresh. fraction
- **slow LLP**: <dE/dx> in pixel tracker to estimate $\beta\gamma$ using Beth-Bloch
- **FCP**: counting tracks with the number of hits with low dE/dx

PLB 847 (2023) 138316



$$S(dE/dx) = \frac{dE/dx - \langle dE/dx_{\mu}\rangle}{\sigma(dE/dx)_{\mu}}$$

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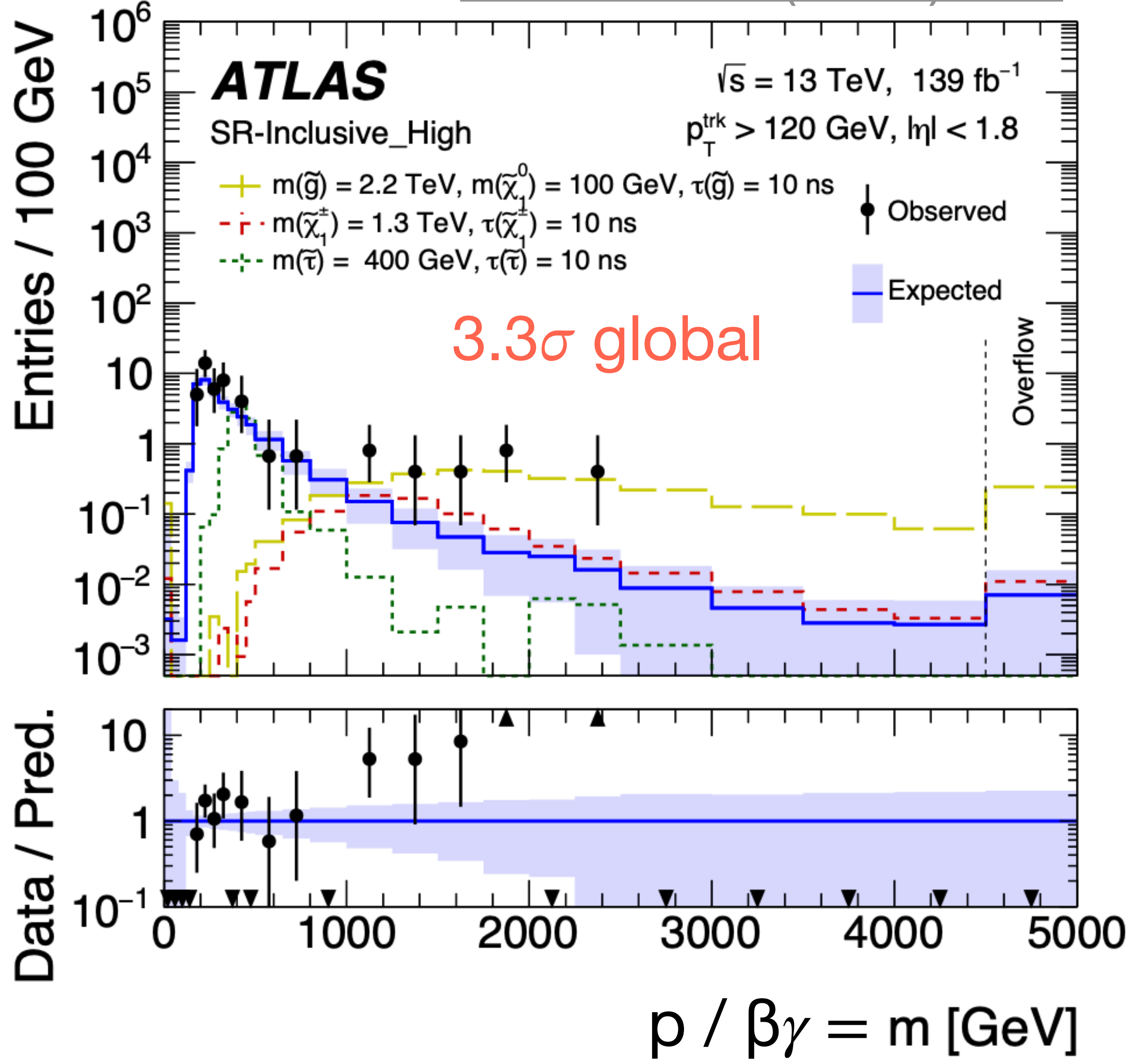

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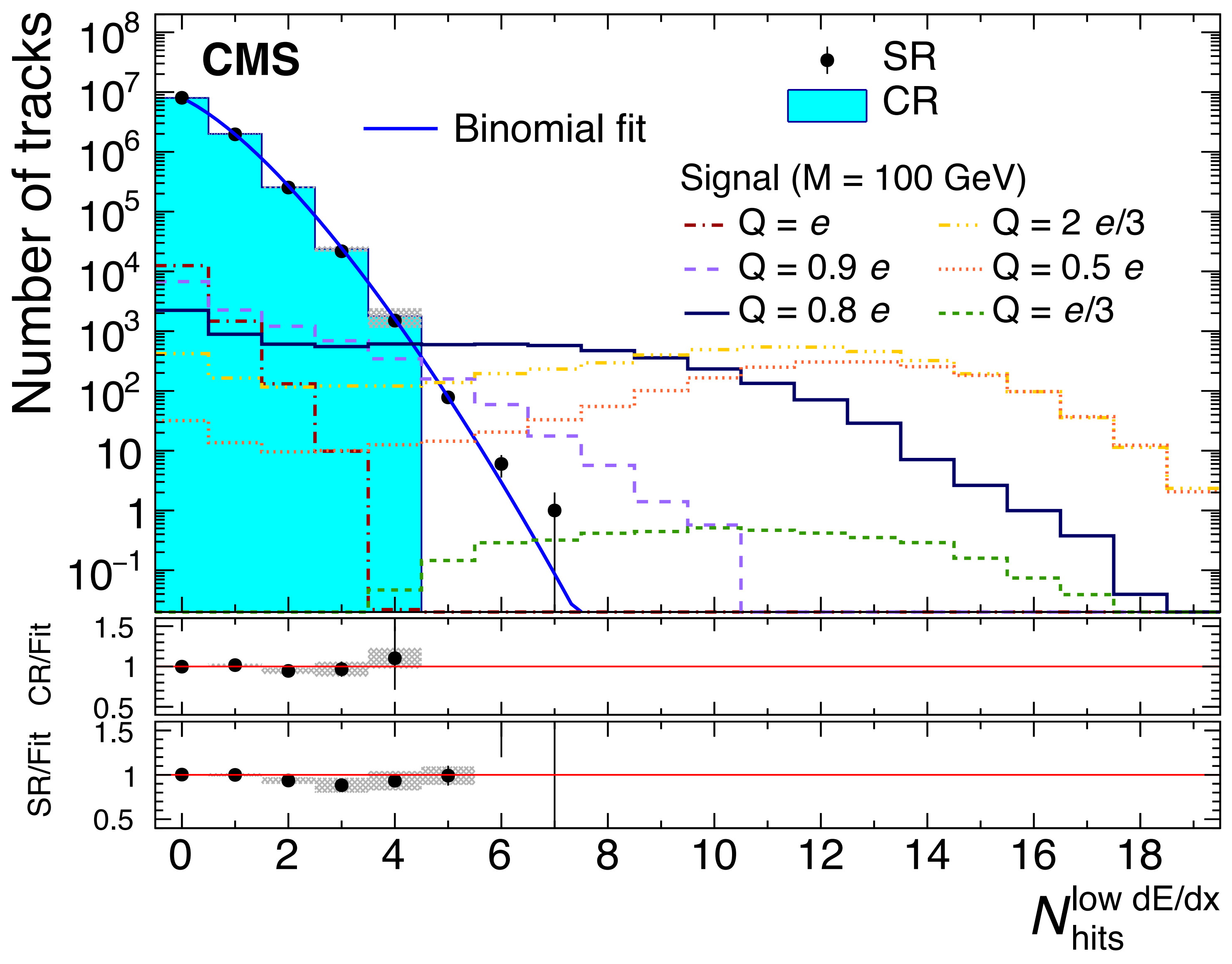
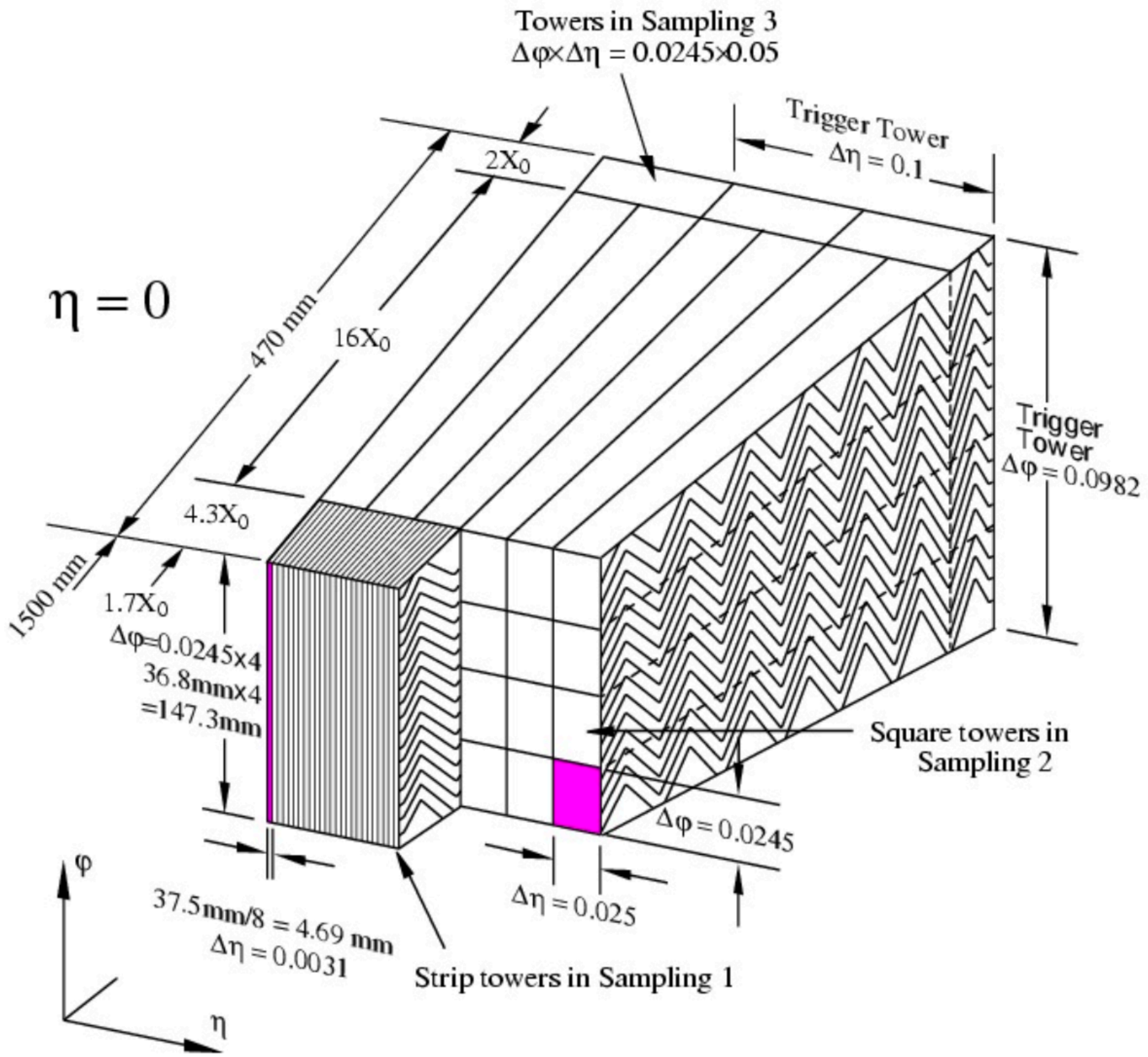
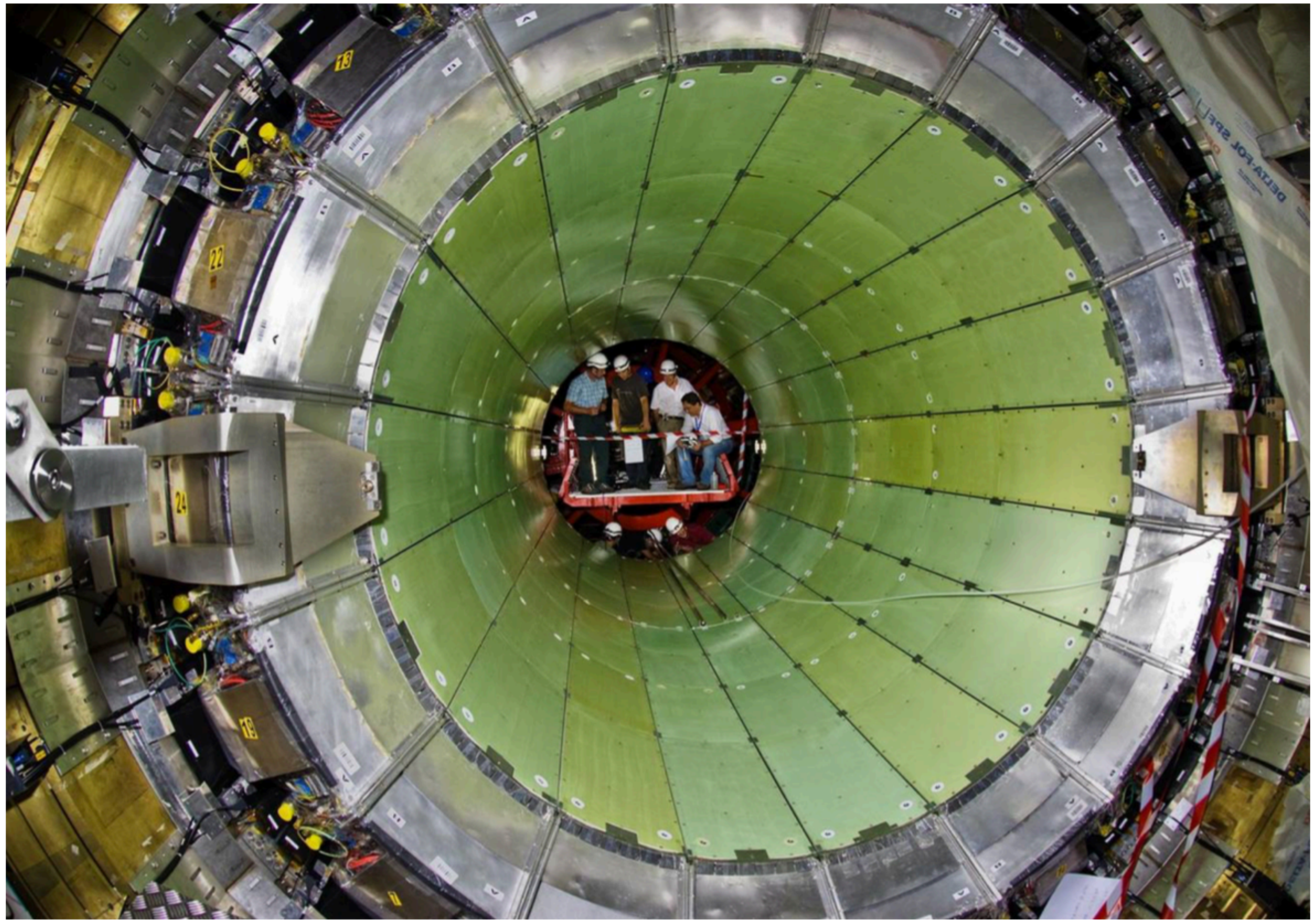


Calorimeter based searches





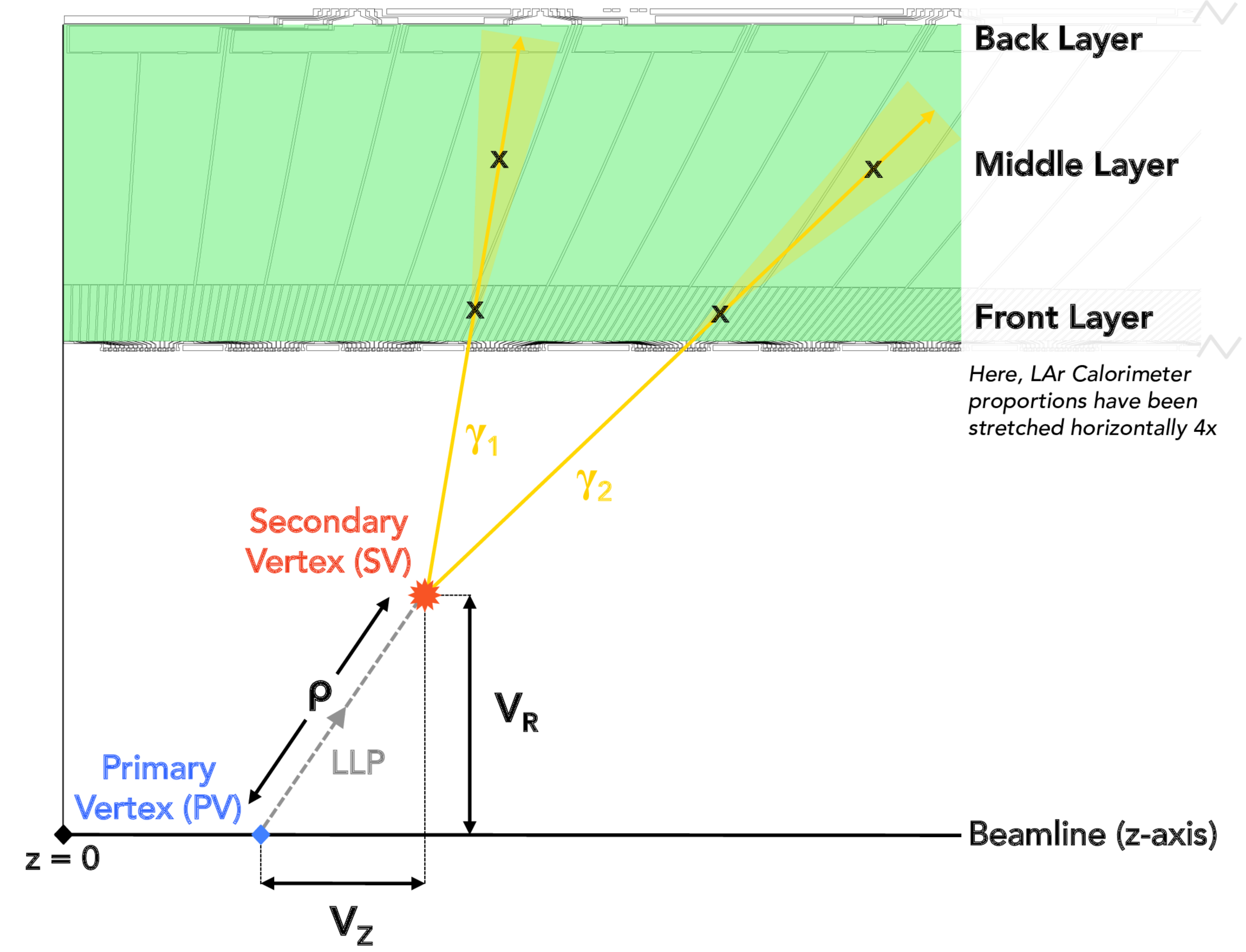
probing up to cτ ~ O(m)

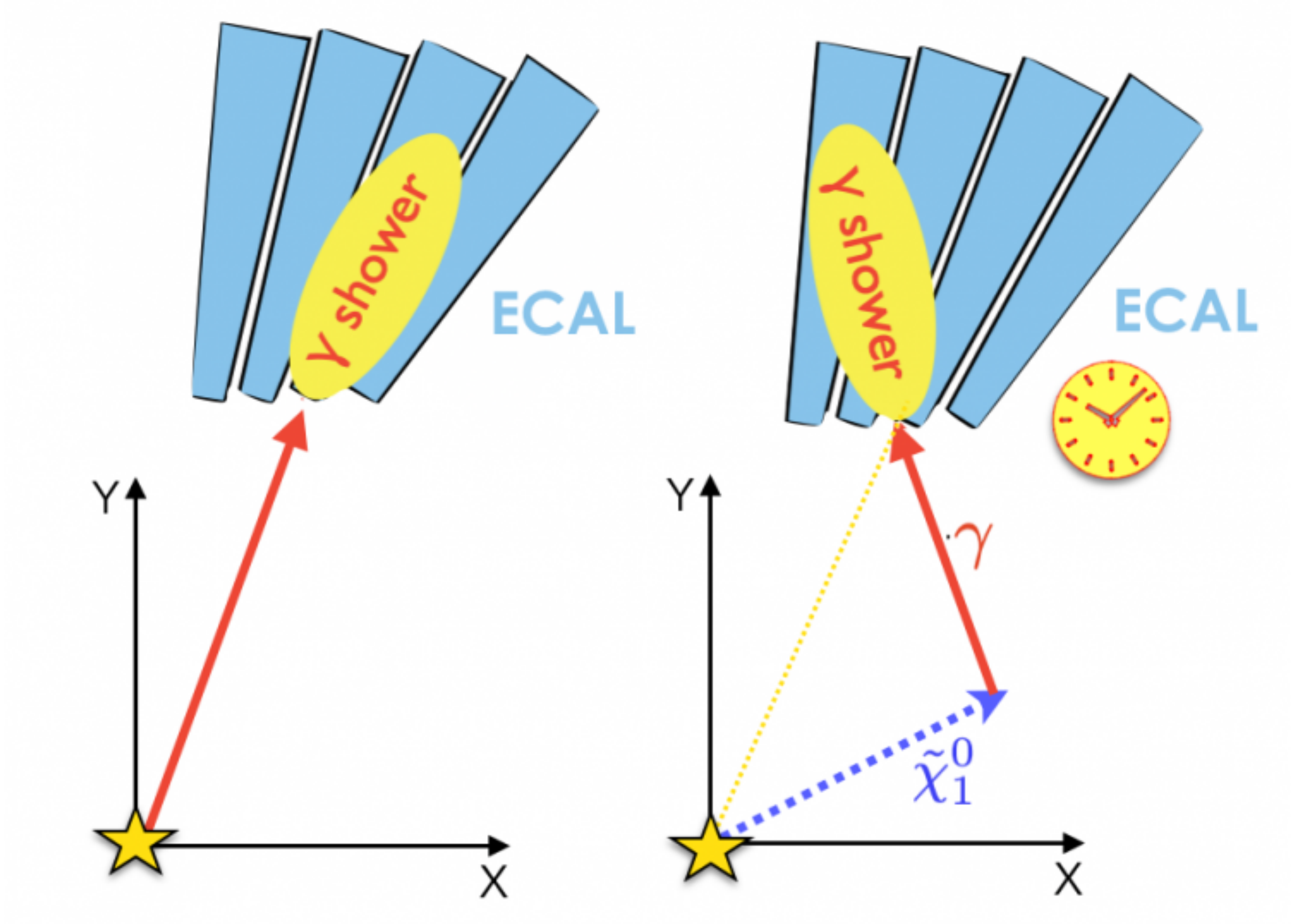
LLP searches in ECAL

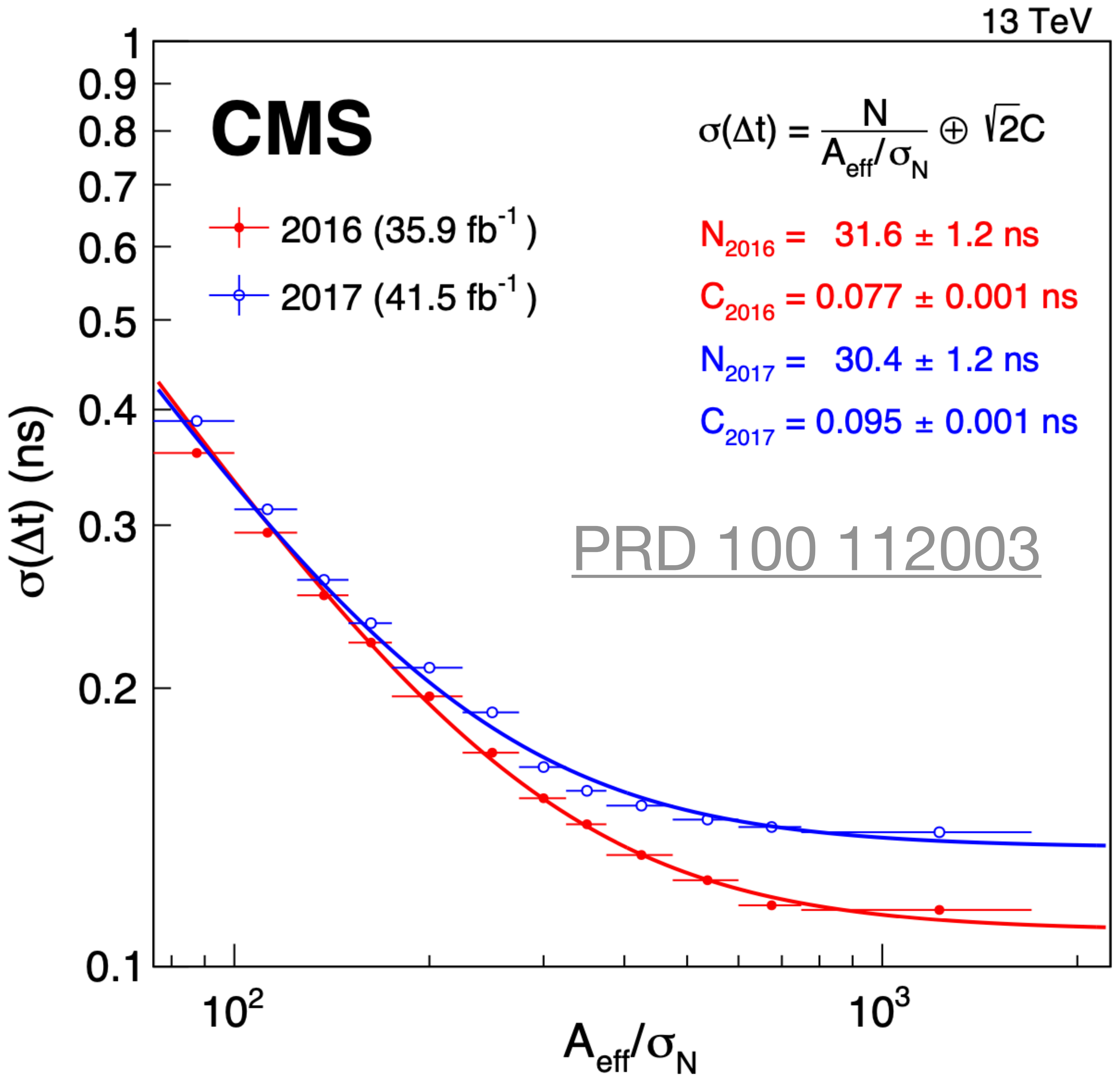
Signature: delayed photons from same or different decays

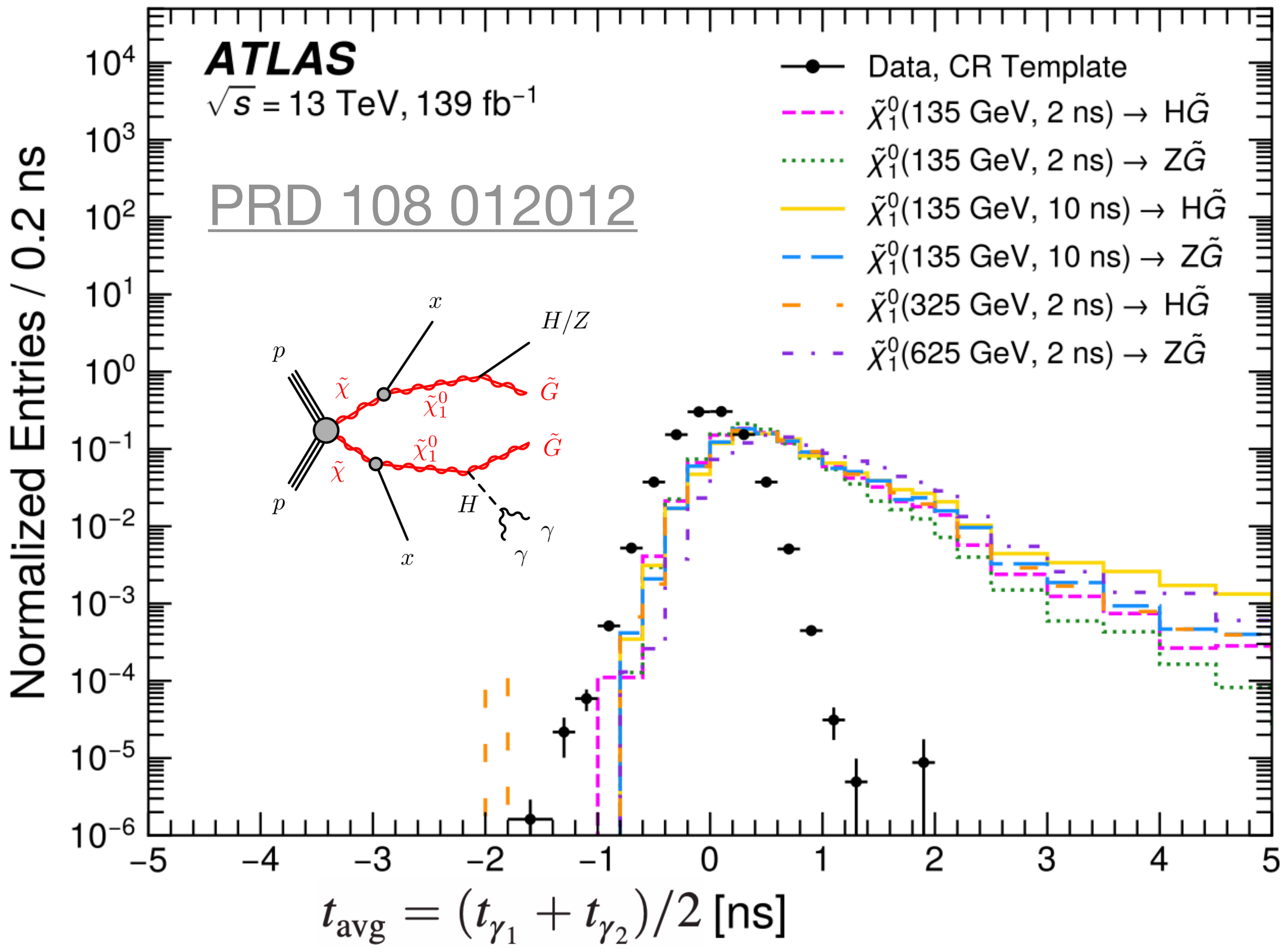
BKG: prompt γ or fake-γ from electrons/jets

Strategy: exploiting EM calorimeter segmentation & time resolutions!
pointing and timing measurements







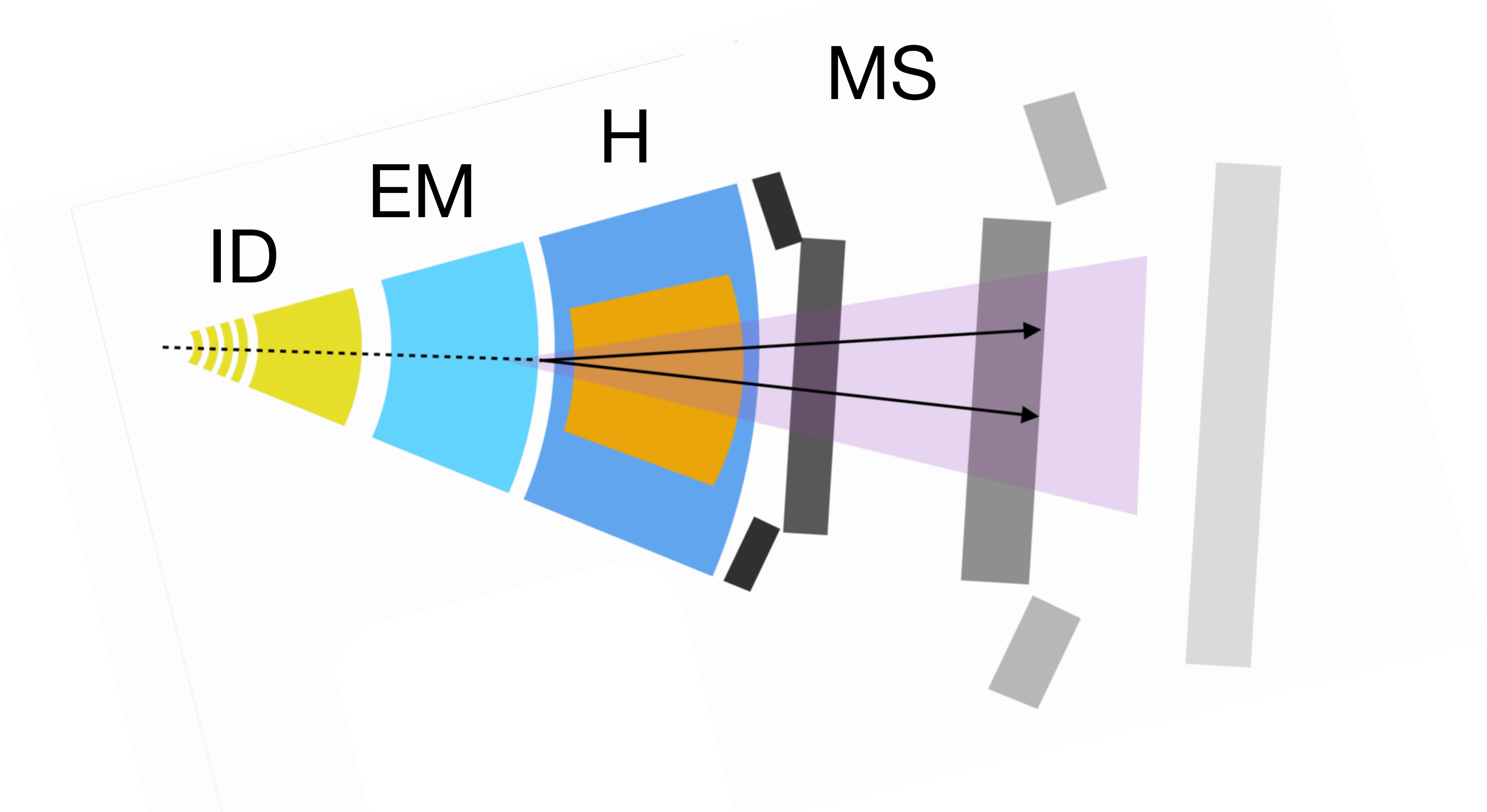


G. Gustavino

LLP searches in calorimeter

Signature: Trackless jets w/ high hadronic calorimeter fraction

BKG: QCD jets, BIB, cosmics

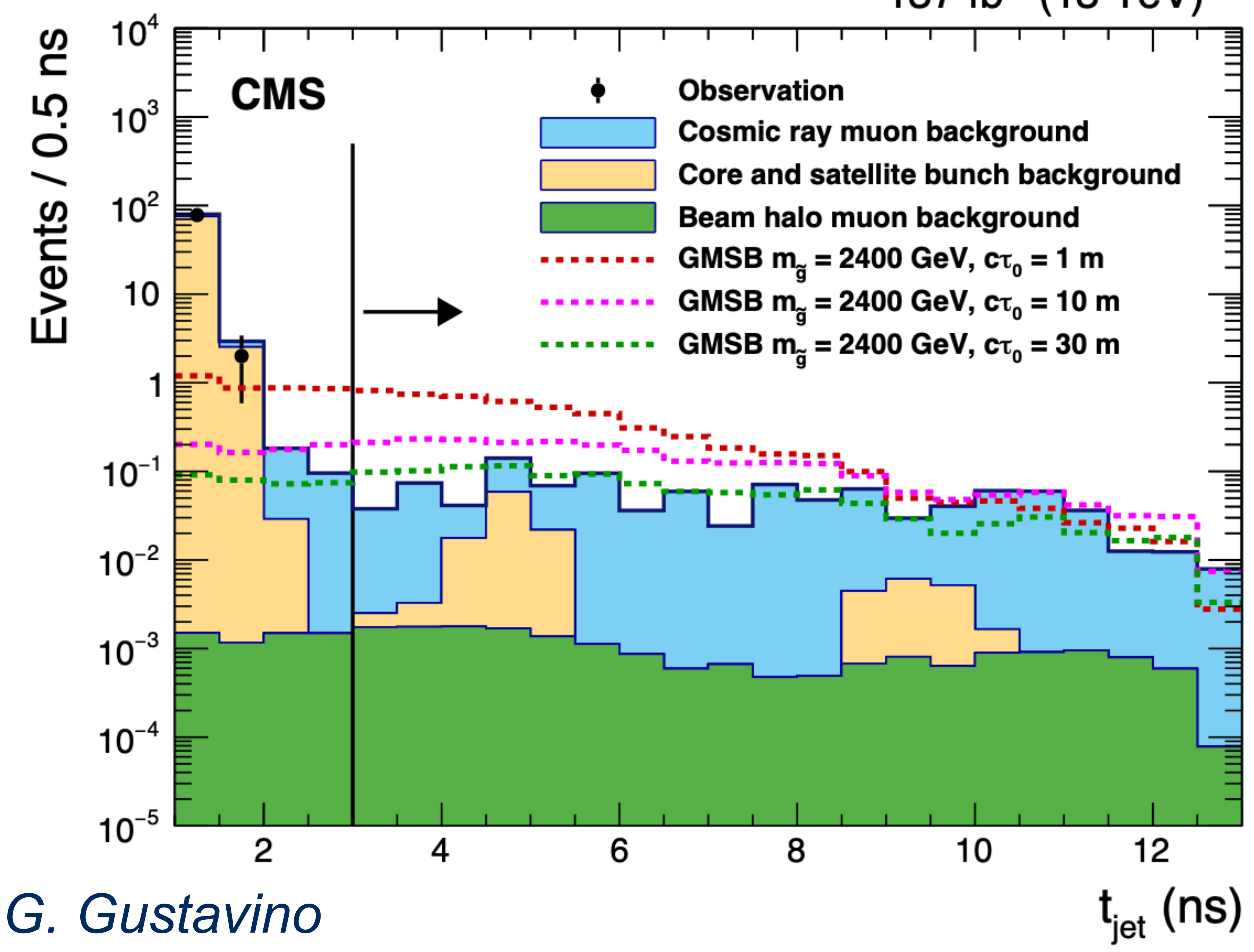


- Lack of associated tracks & precision timing
  - median of ECAL cells in jet

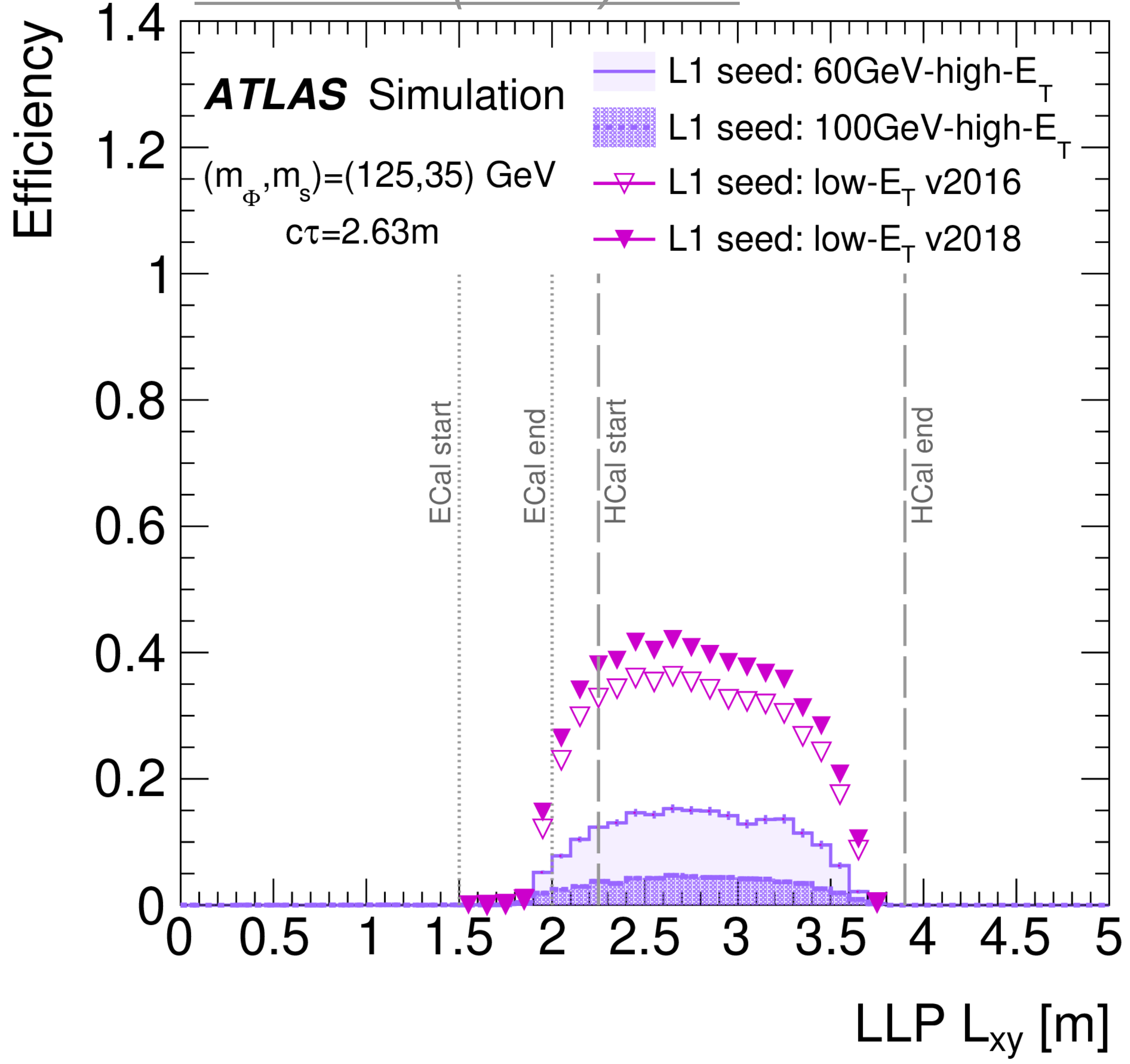
- Dedicated triggers

exploiting E_H/E_{EM} exploiting **jet timing**

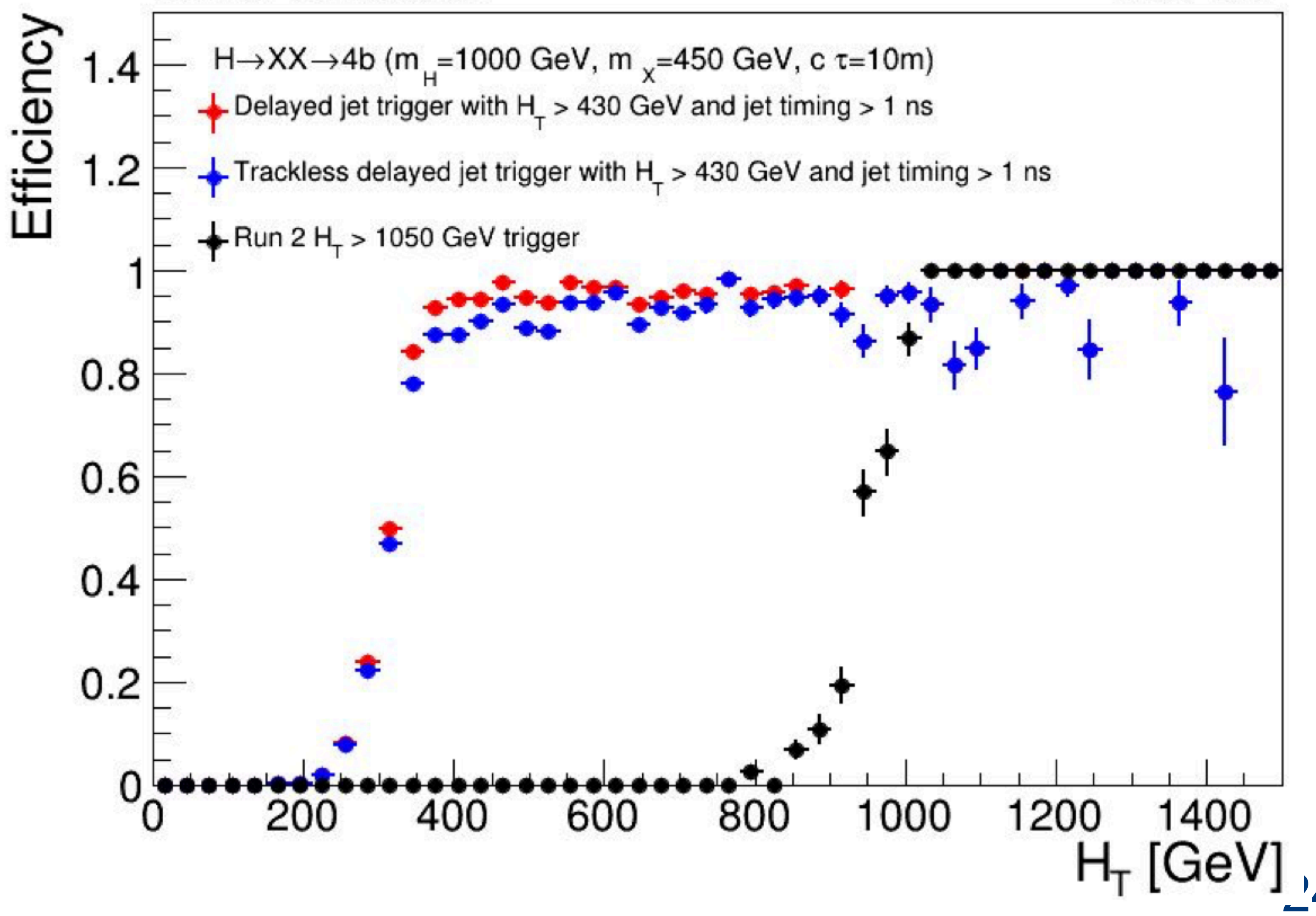
PLB 797 (2019) 134876



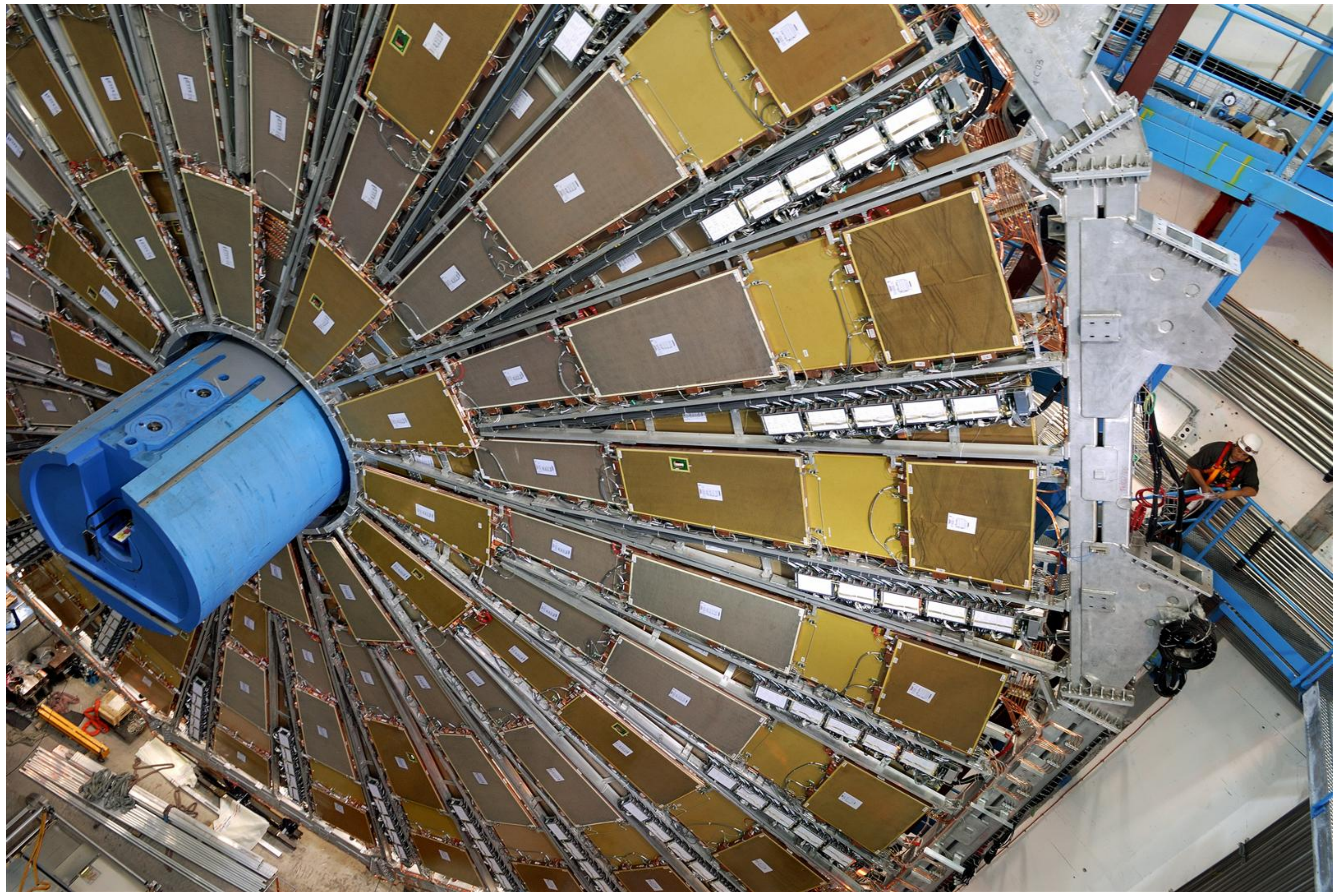
JHEP 06 (2022) 005

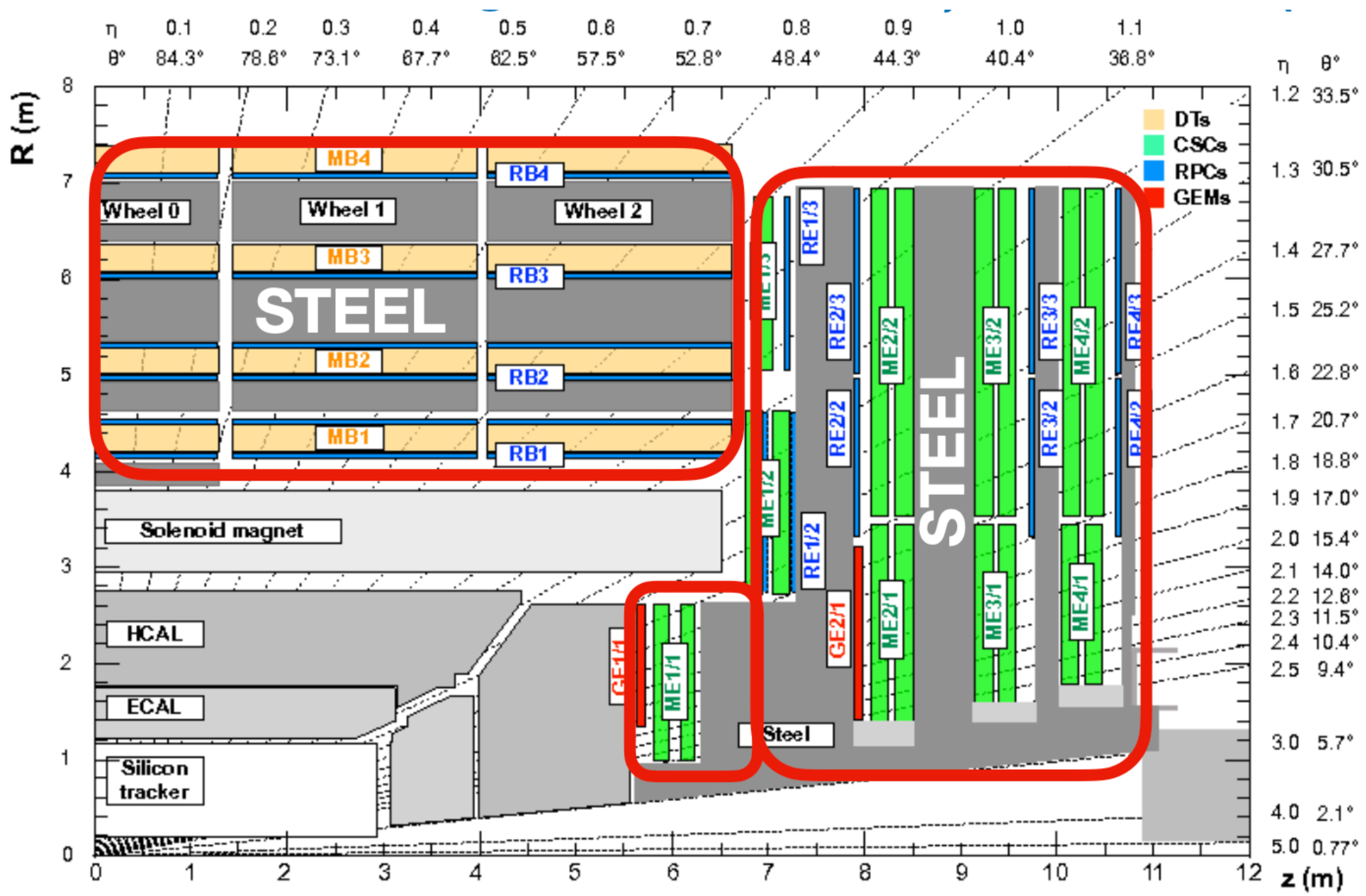


CMS DP -2023/043



Muon Spectrometer based searches





Large fiducial volume with air gaps

- Reconstructing displaced tracks & vertices

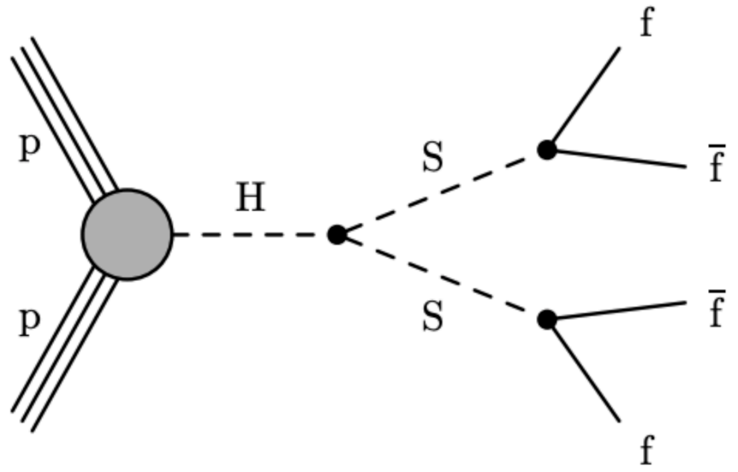
Compact spectrometer with lots of steel

- can be used as a sampling calorimeter searching for shower decays

probing up to cτ ~ O(10 m)

LLP searches in MS

scalar portal h->ss



Signature: high multiplicity hadron showers in MS

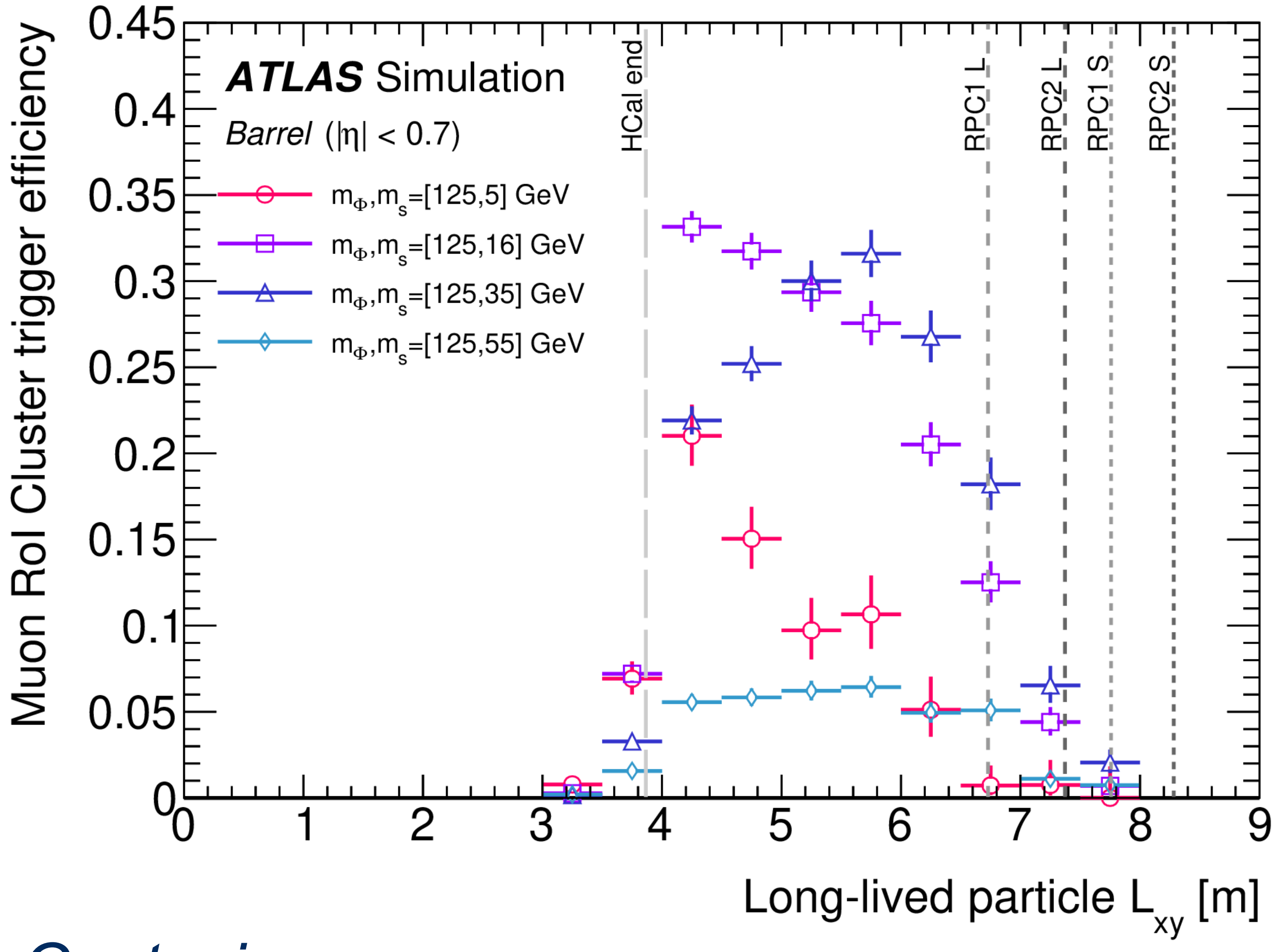
BKG: punch through jets, BIB

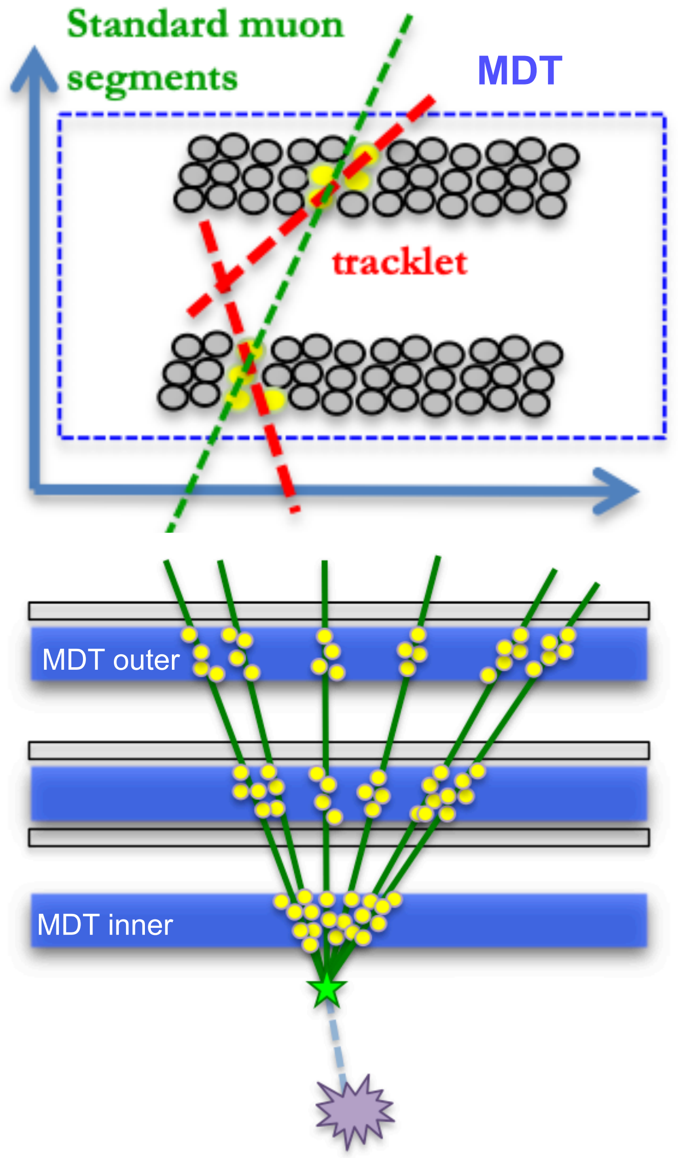
~BKG-zero searches

- Dedicated **Trigger**
  - multiple ROIs
- Dedicated **Vertex algorithm**
  - multiple tracklets in MDTs

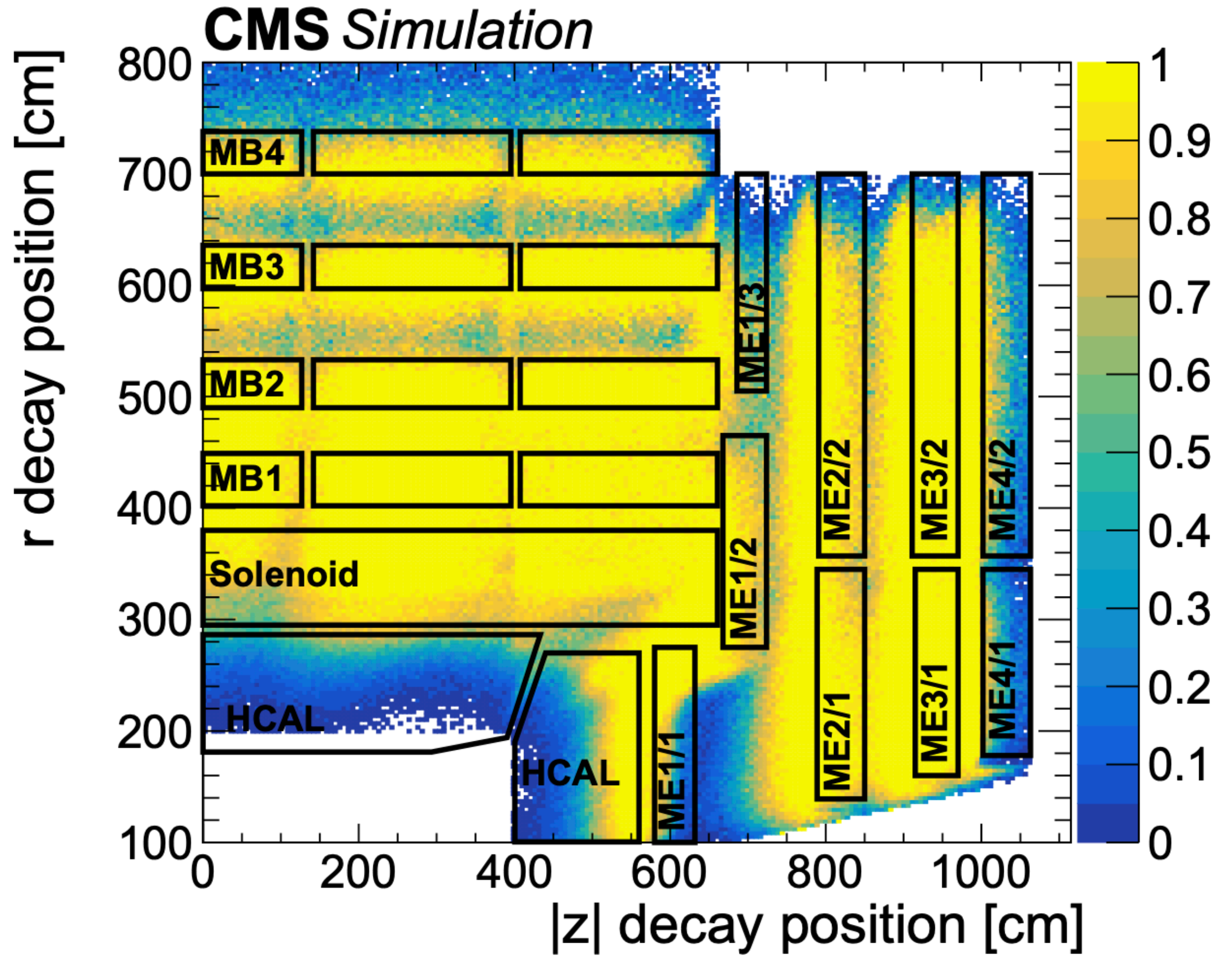
- High cluster reconstruction
  - > 50 hits with ε up to 80-90%
  - Highly correlated with amount of steel in front of CSC

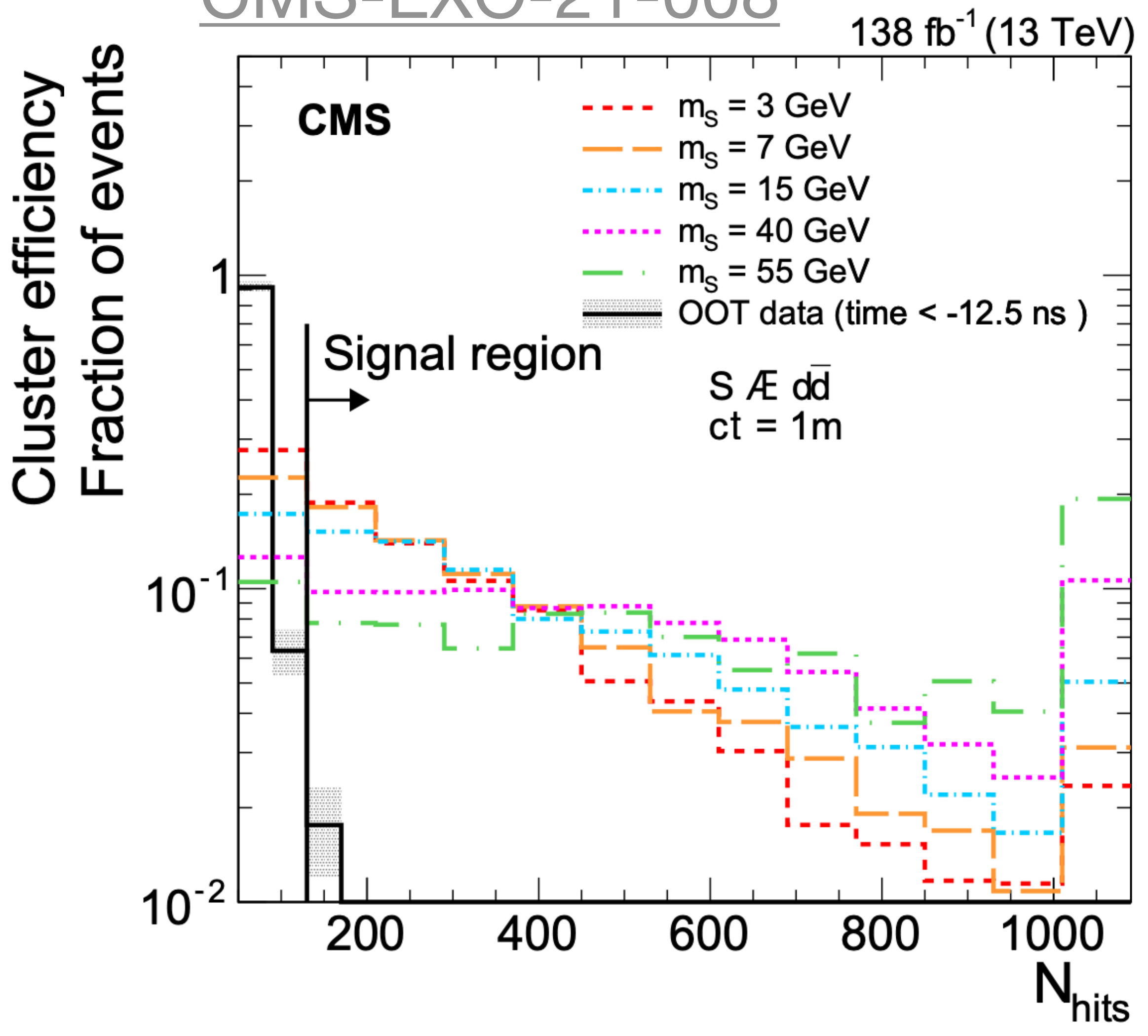
Phys. Rev. D 106, (2022) 032005





CMS-EXO-21-008

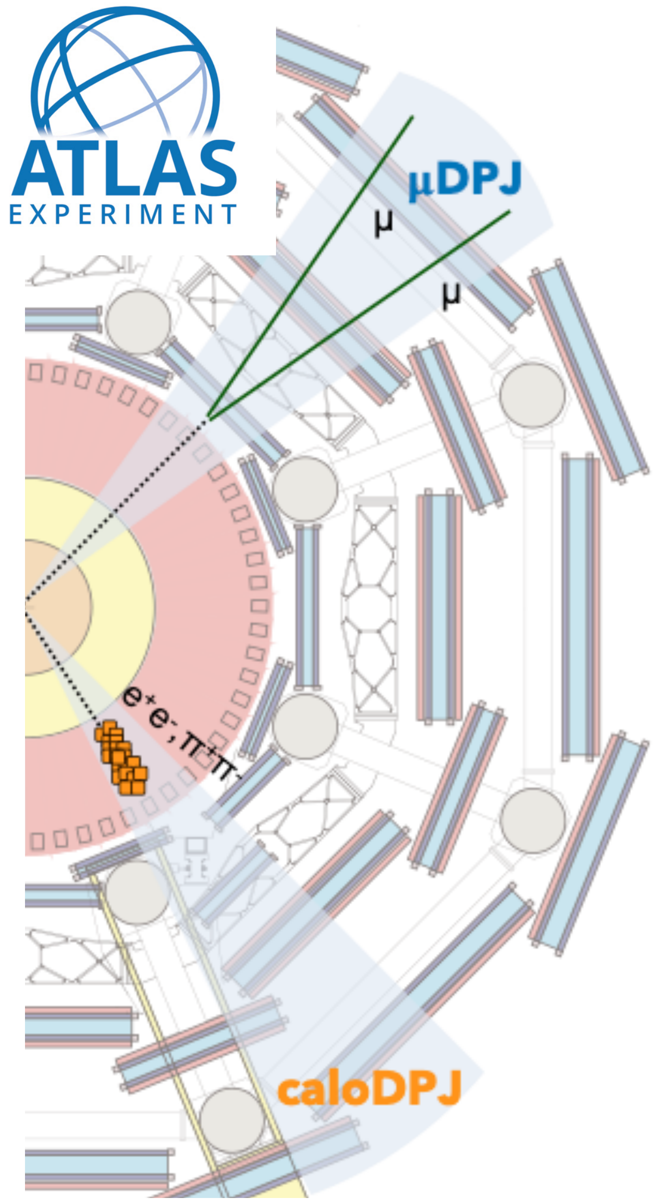




LLP searches in MS

JHEP 06 (2023) 153

ATLAS-EXOT-2022-15



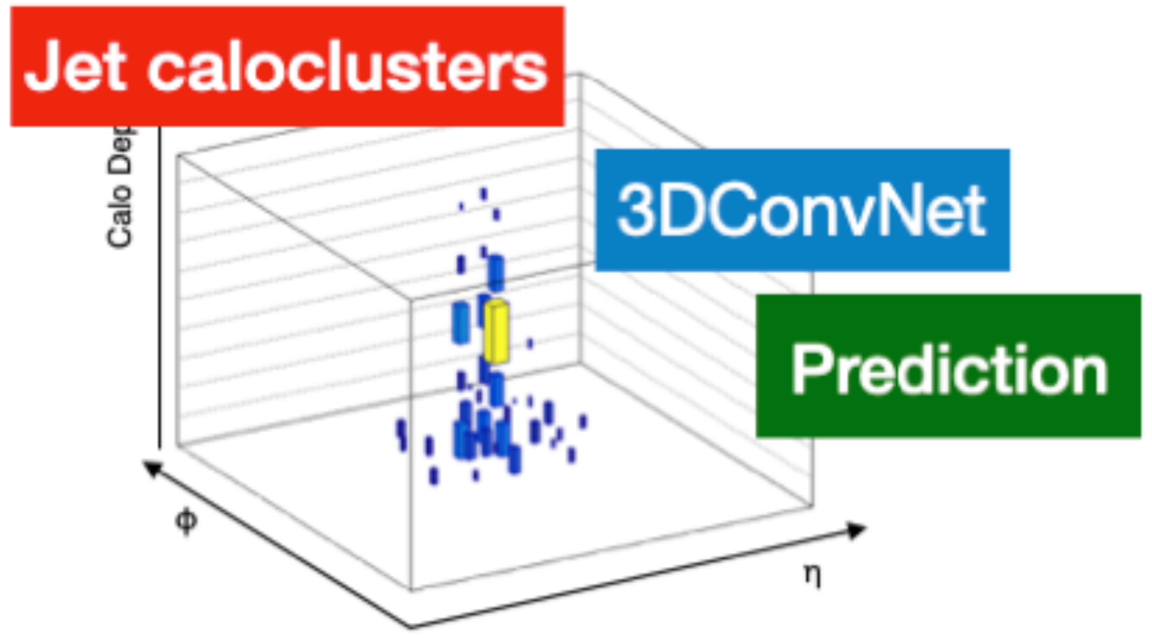
Signature: collimated jet structures of leptons or light hadrons

➡ ***low masses***

- Collimated bunch of SA muons
  - Narrow scan triggers
- Displaced jet w/ large E_H/E_{EM}
  - calo-ratio triggers

→ **Dense NN** (per track) tagger in **μ-channels**

→ **Convolutional NN** tagger in **calo-channels** trained on low-level inputs

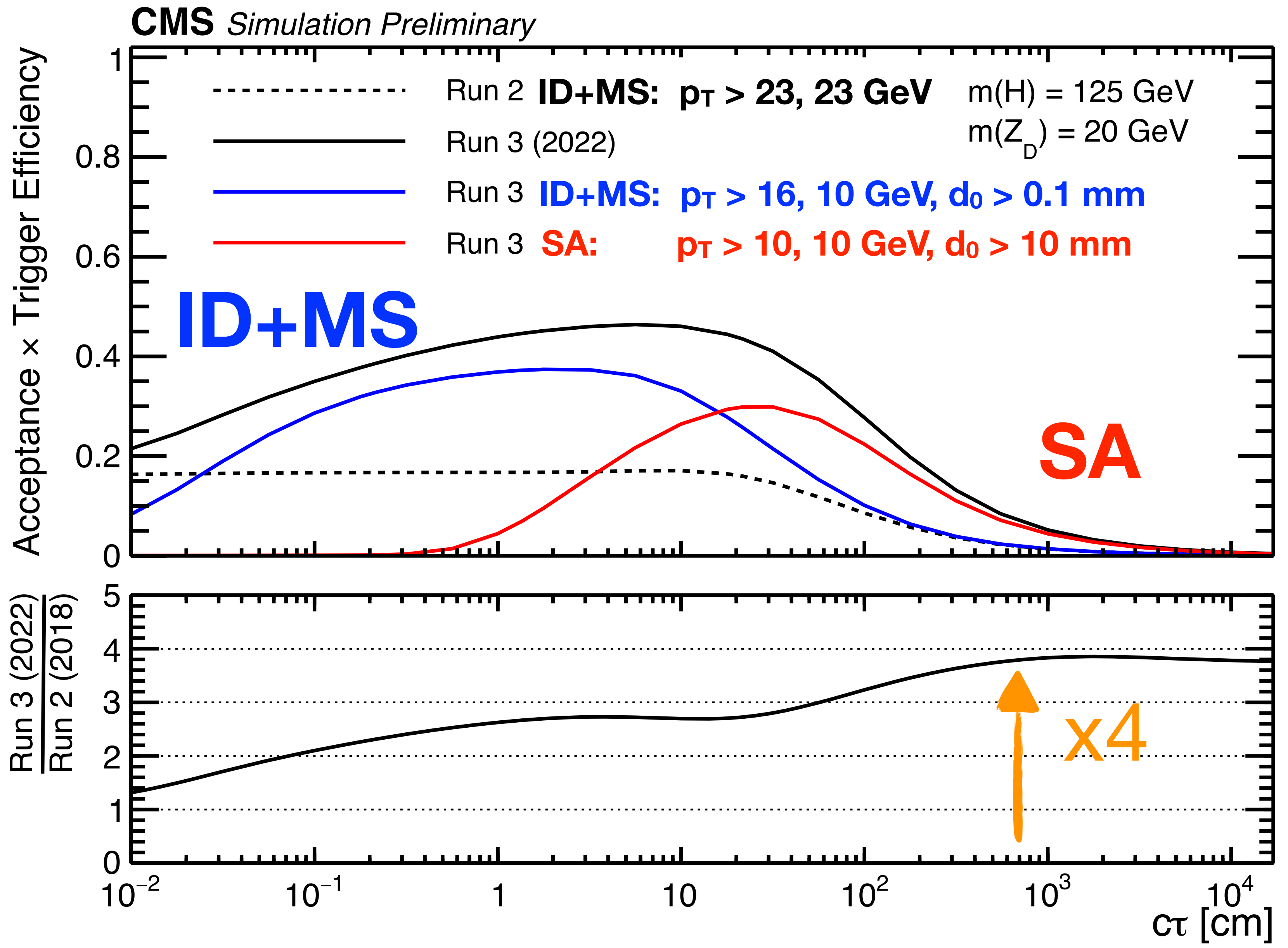


Signature: displaced di-muons

NEW

New Run-3 triggers modifications of hardware L1 and HLT triggers allow for reducing greatly the muon p_T thresholds!

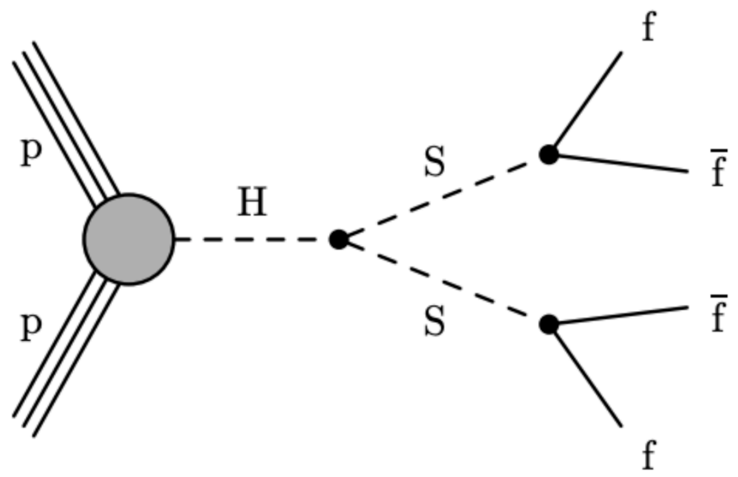
Large sensitivity gain even w/ 1/3 of the 13 TeV data stats!



CMS-EXO-23-014

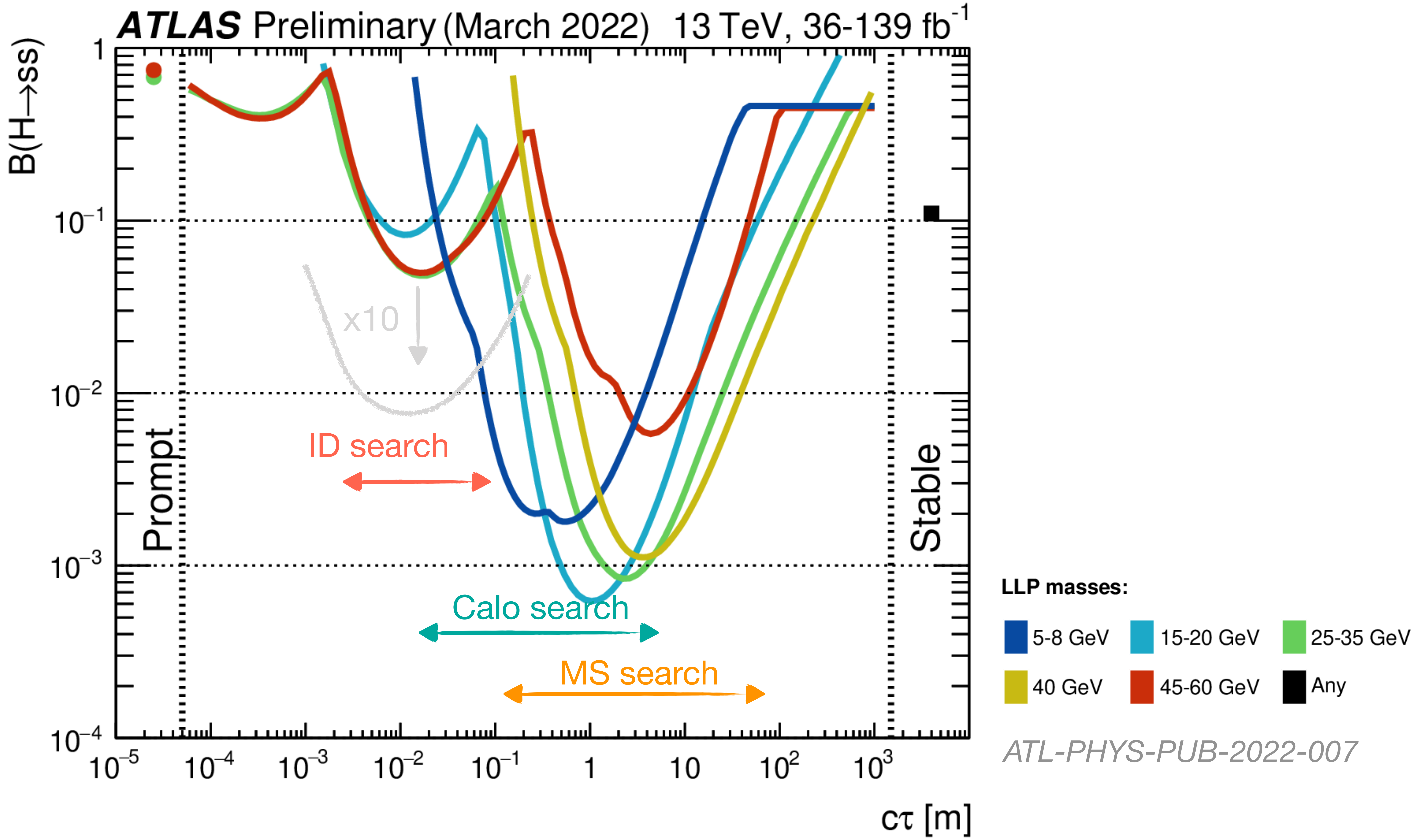
Summary plots

scalar portal
h->ss



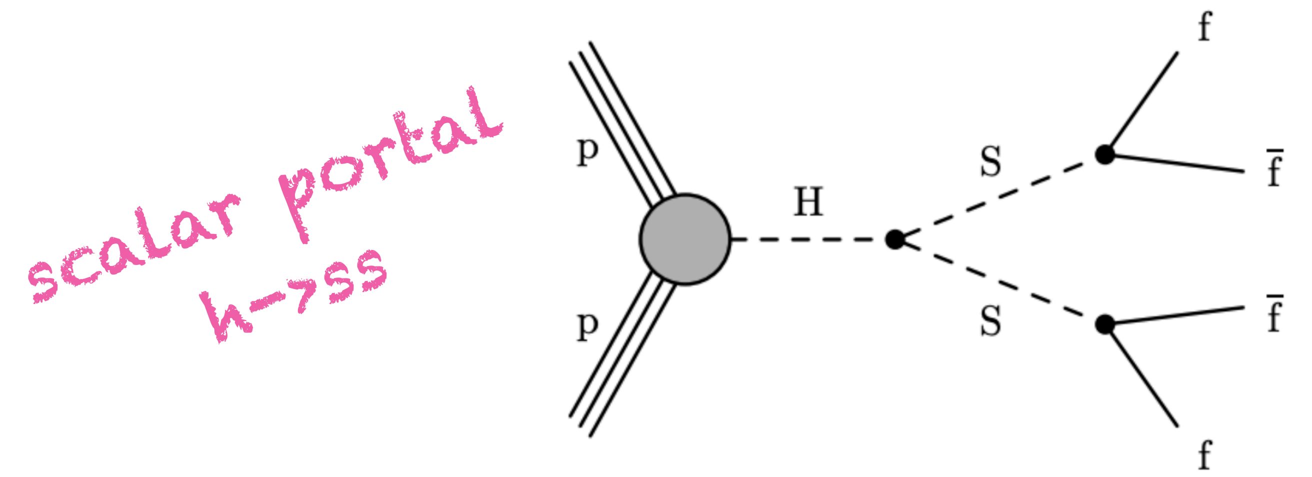
LLP searches are limited by the detector acceptance…

ATL-PHYS-PUB-2022-007



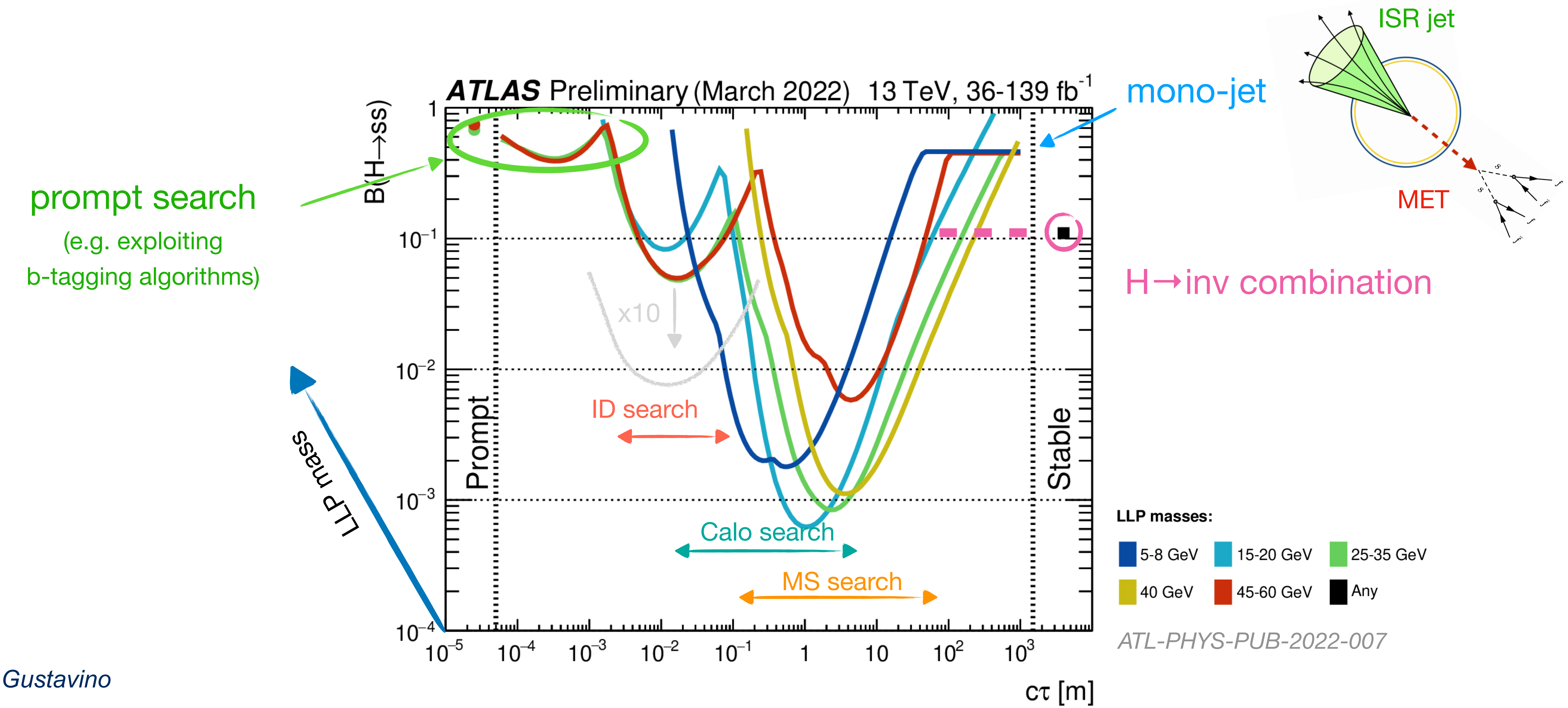
ATL-PHYS-PUB-2022-007

Summary plots



LLP searches are limited by the detector acceptance…

Re-interpretations permits to fill the gap!

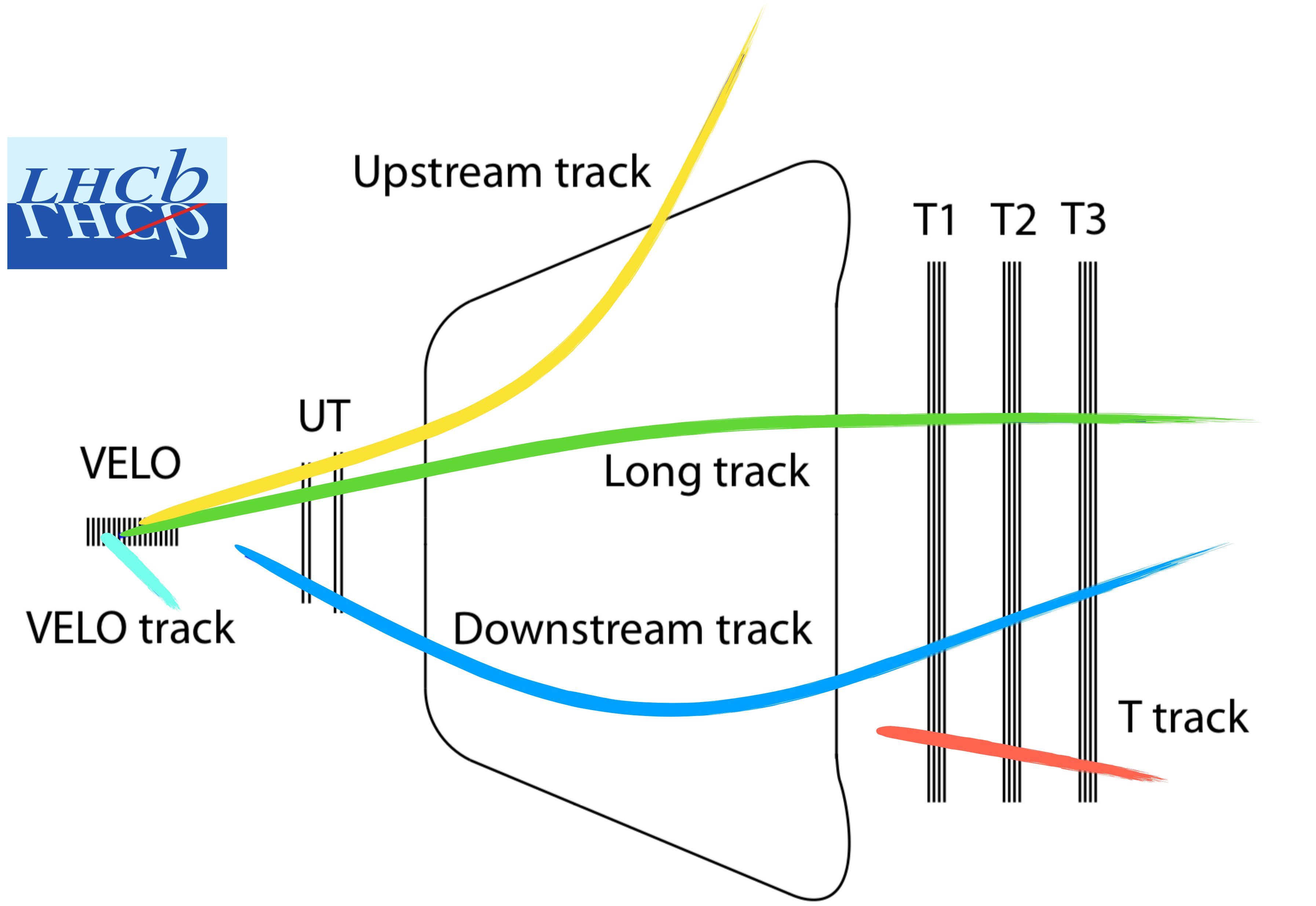


LHCb LLP searches

Forward region: high/low-x partons involved

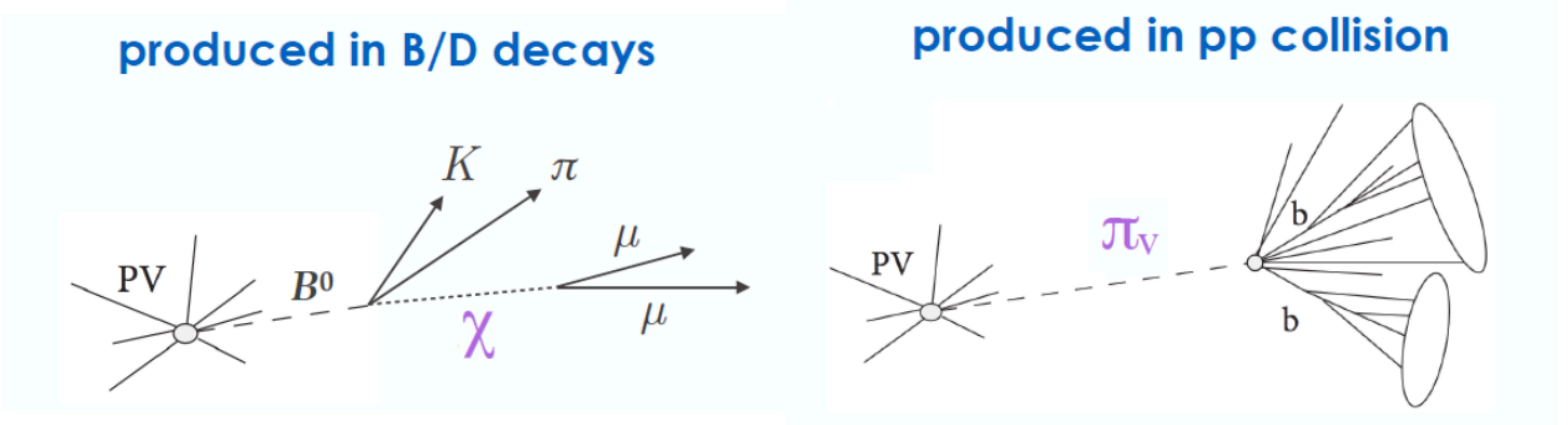
LHCb proved to be competitive in many signatures:

* low lifetimes
* low masses
* LLP from B-decays



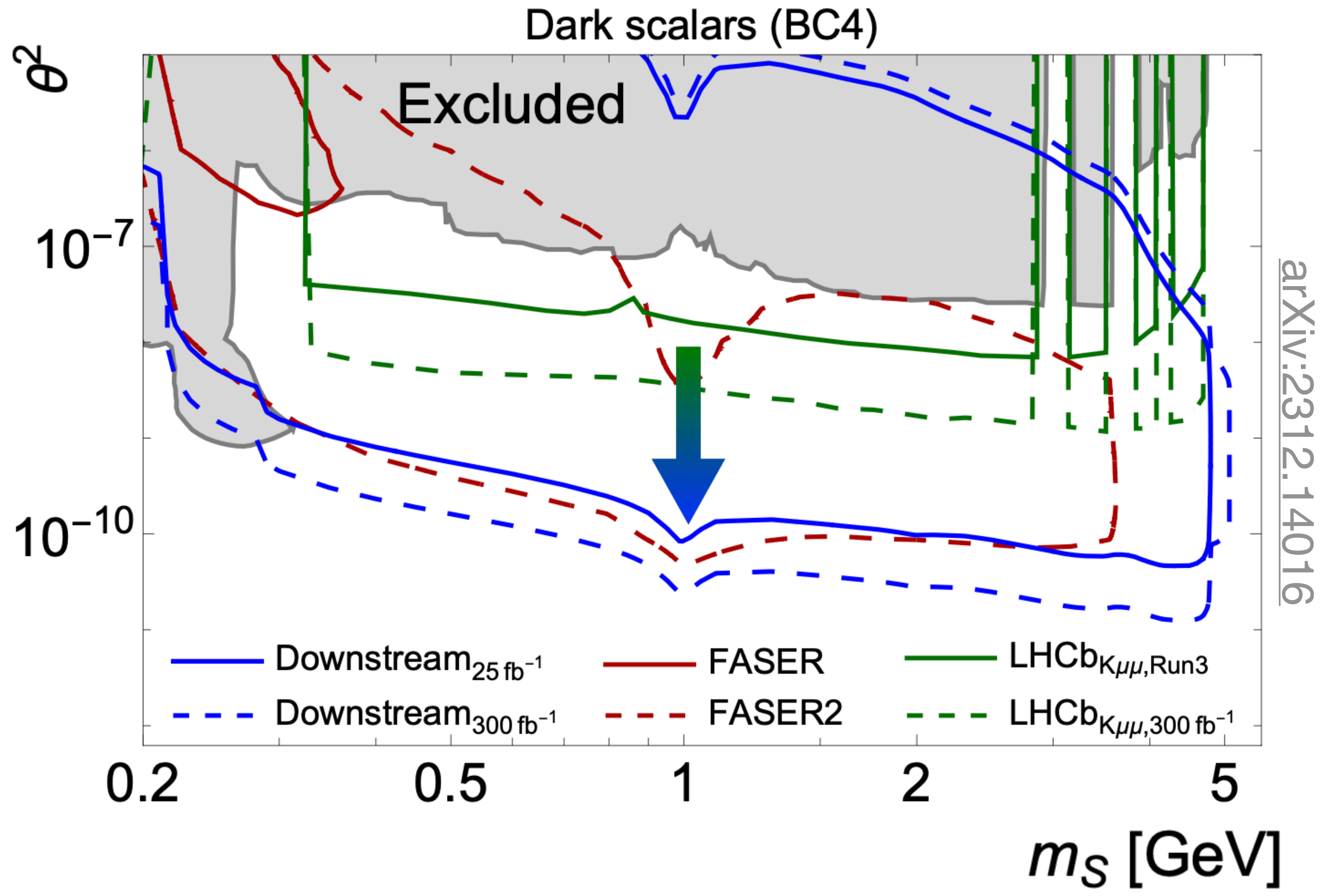
MAX displacement:

Long	~ 1m
Downstream	~2m
T tracks	~8m



displaced di-lepton — PRL 124 (2020) 041801

displaced jets — EPJC 77 (2017) 812

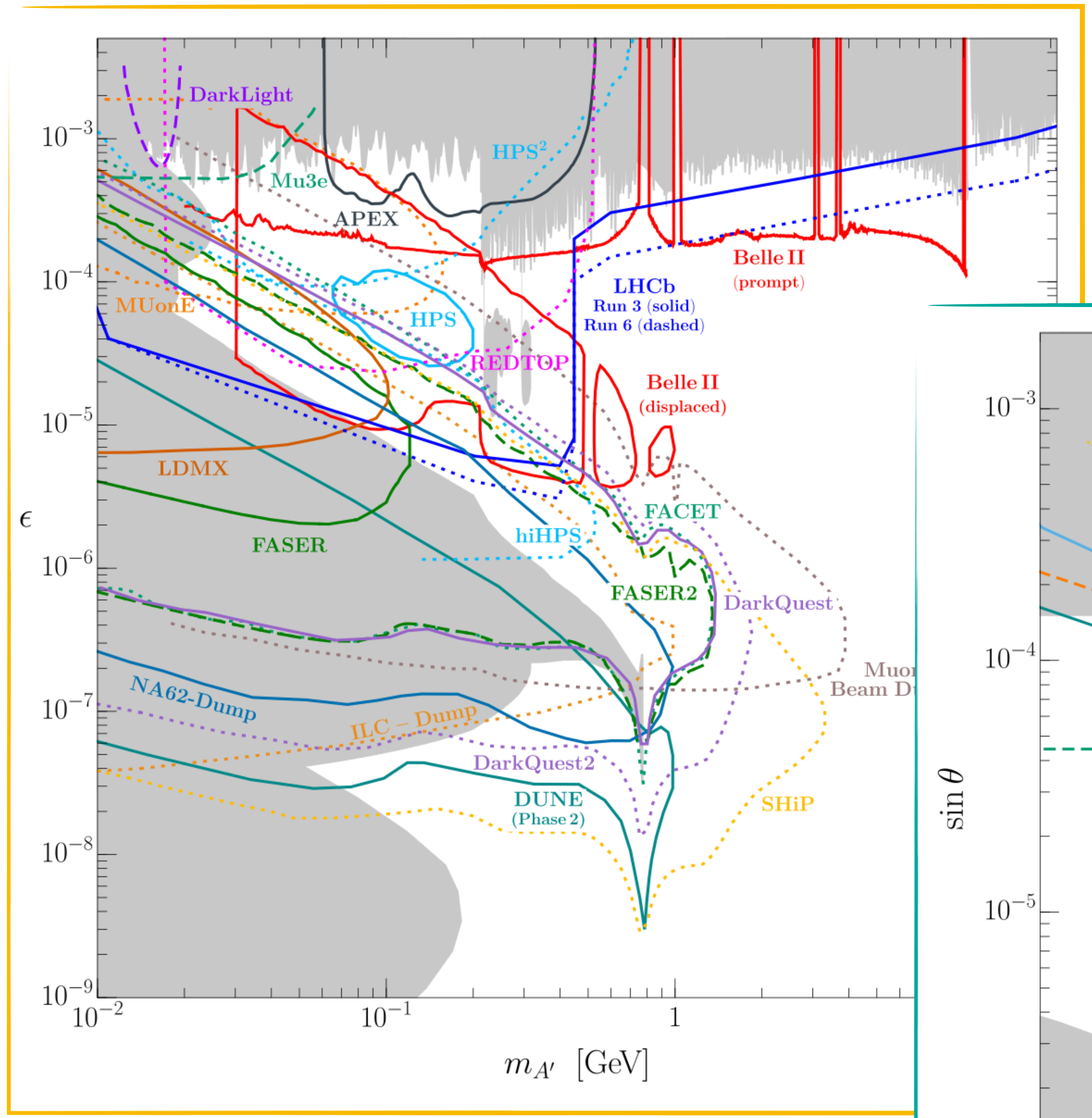


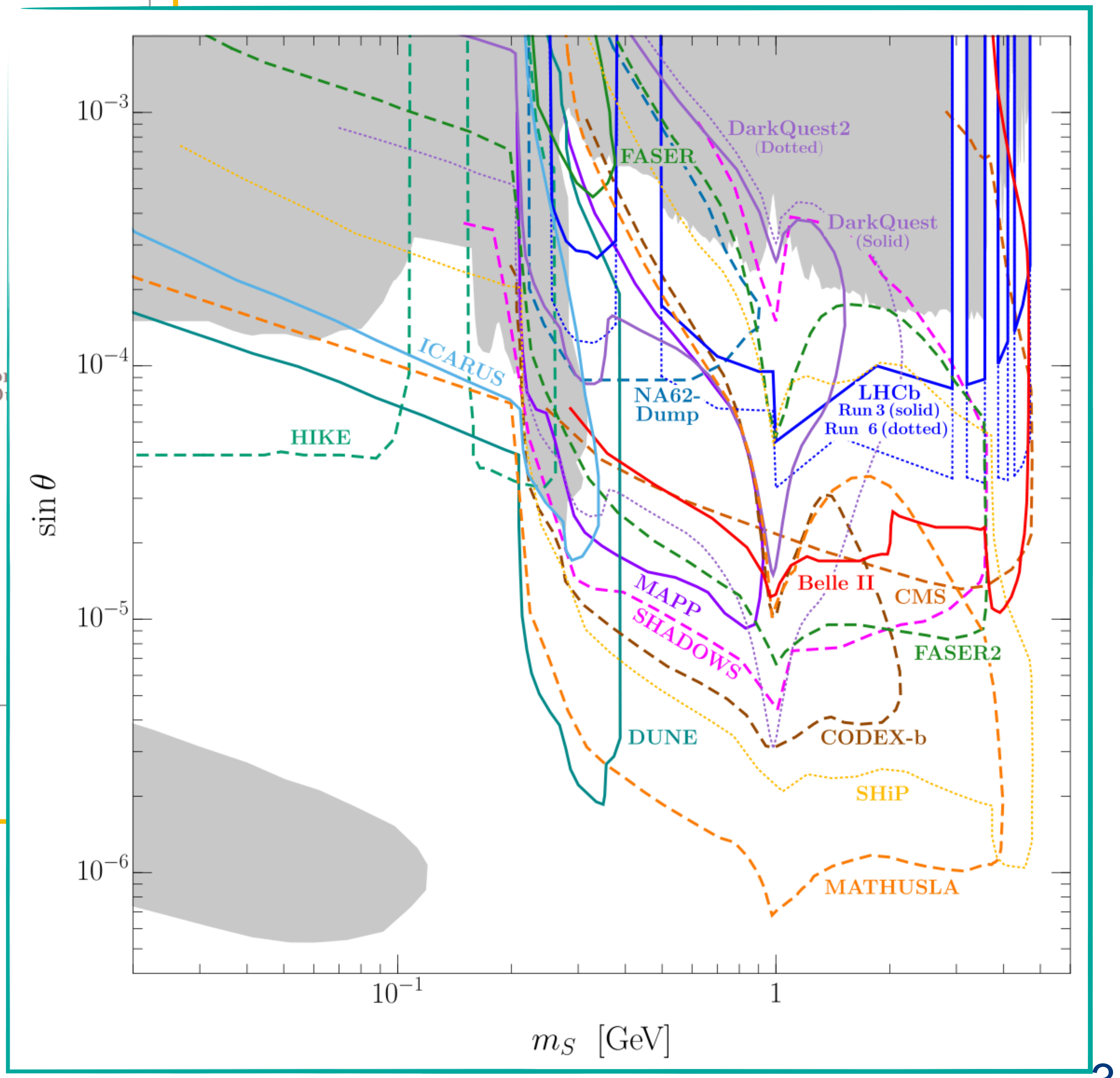
New software-based trigger at L0

- can trigger on downstream tracks [1]
- effort to extend searches with T tracks [2]

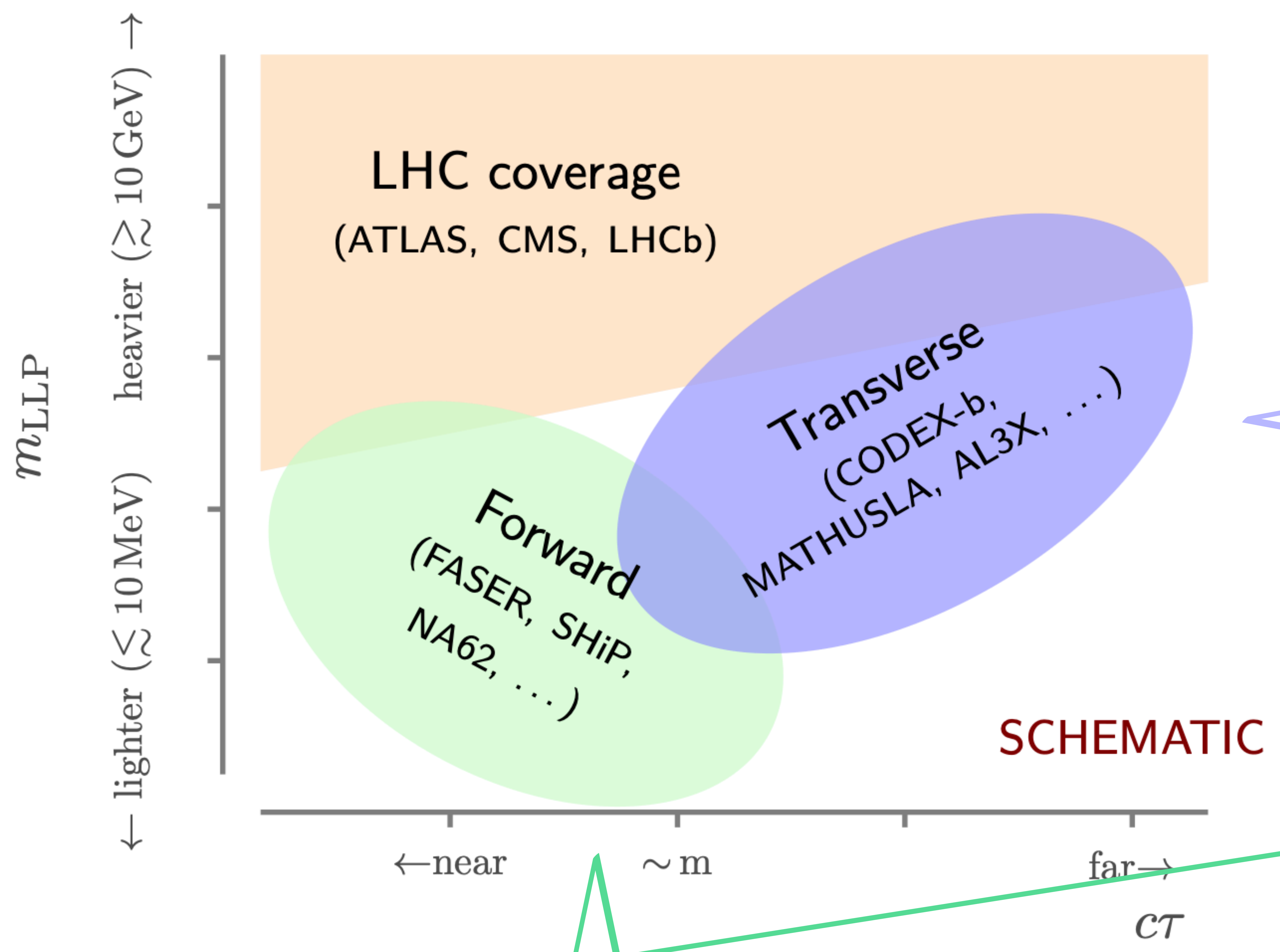
Detectors Overview

Many large community studies (LLP Community, Physics Beyond Collider at CERN, Snowmass in the US...), and many new experiments have been proposed for labs worldwide.

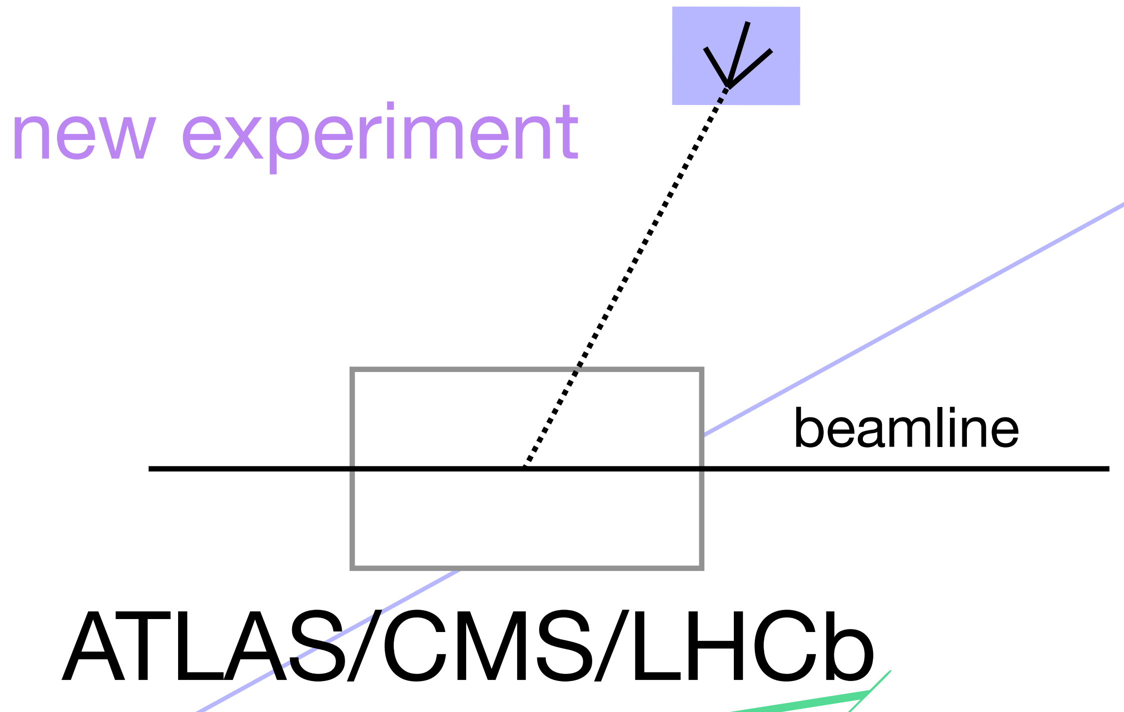




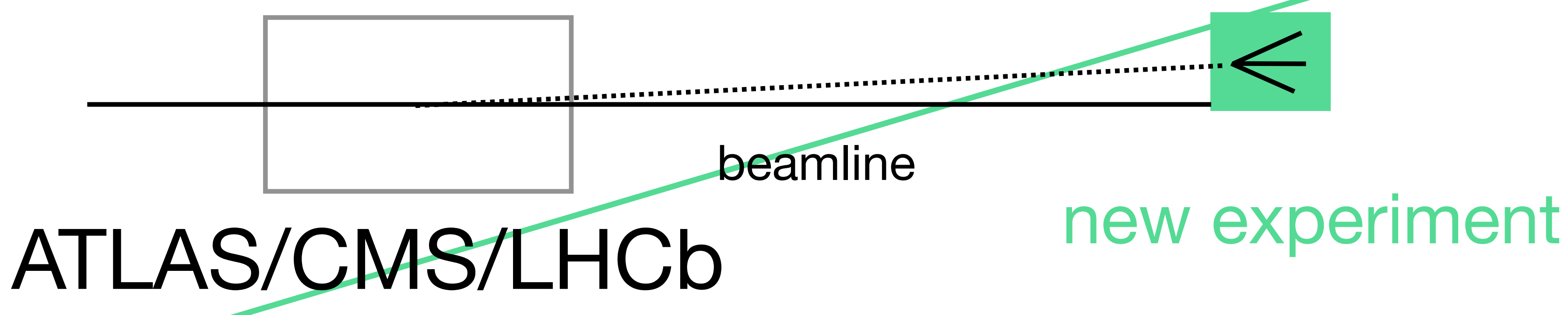
Other LLP detectors



- Dedicated detectors searching for LLPs and milli-charged particles at larger angles



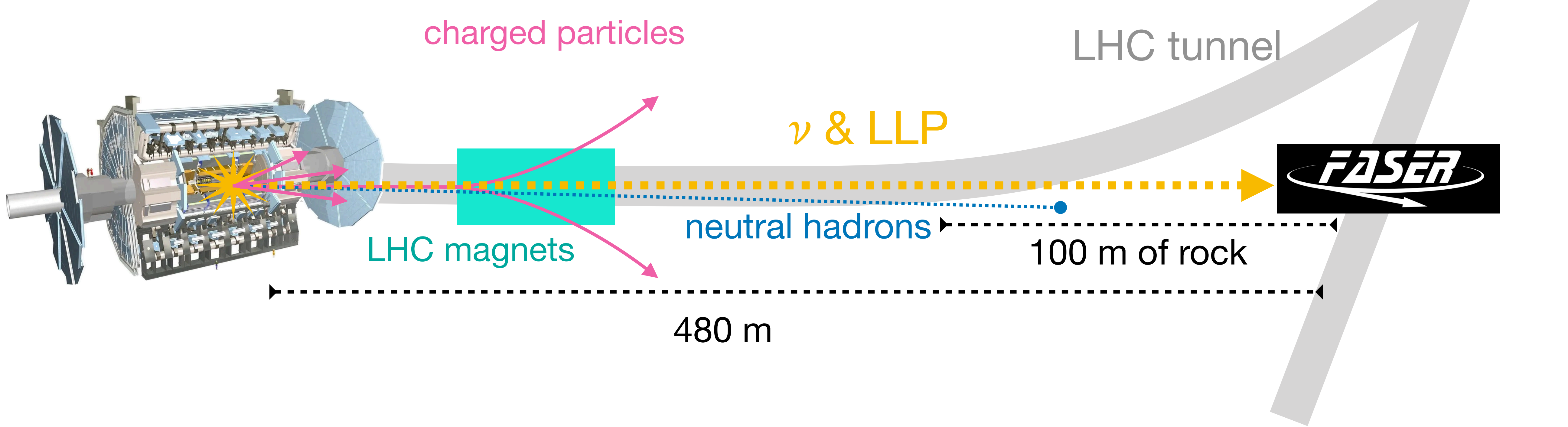
- Fixed target experiments and forward detectors to probe low-mass scenarios



just approved!

and many others targeting Run-4 and beyond!

FASER



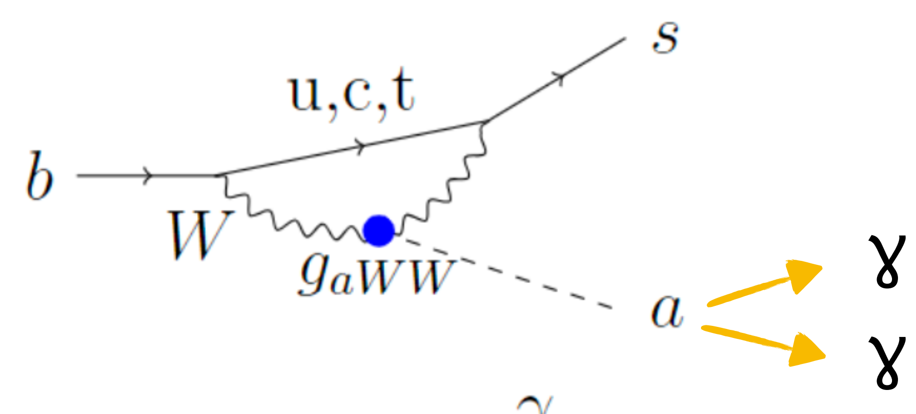
Forward LHC experiment designed to detect

light and weakly interacting particles

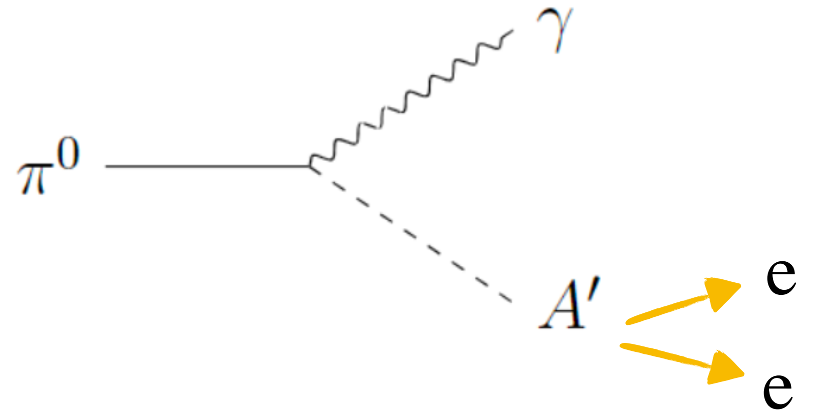
- Situated 480m downstream of the ATLAS IP

First searches for

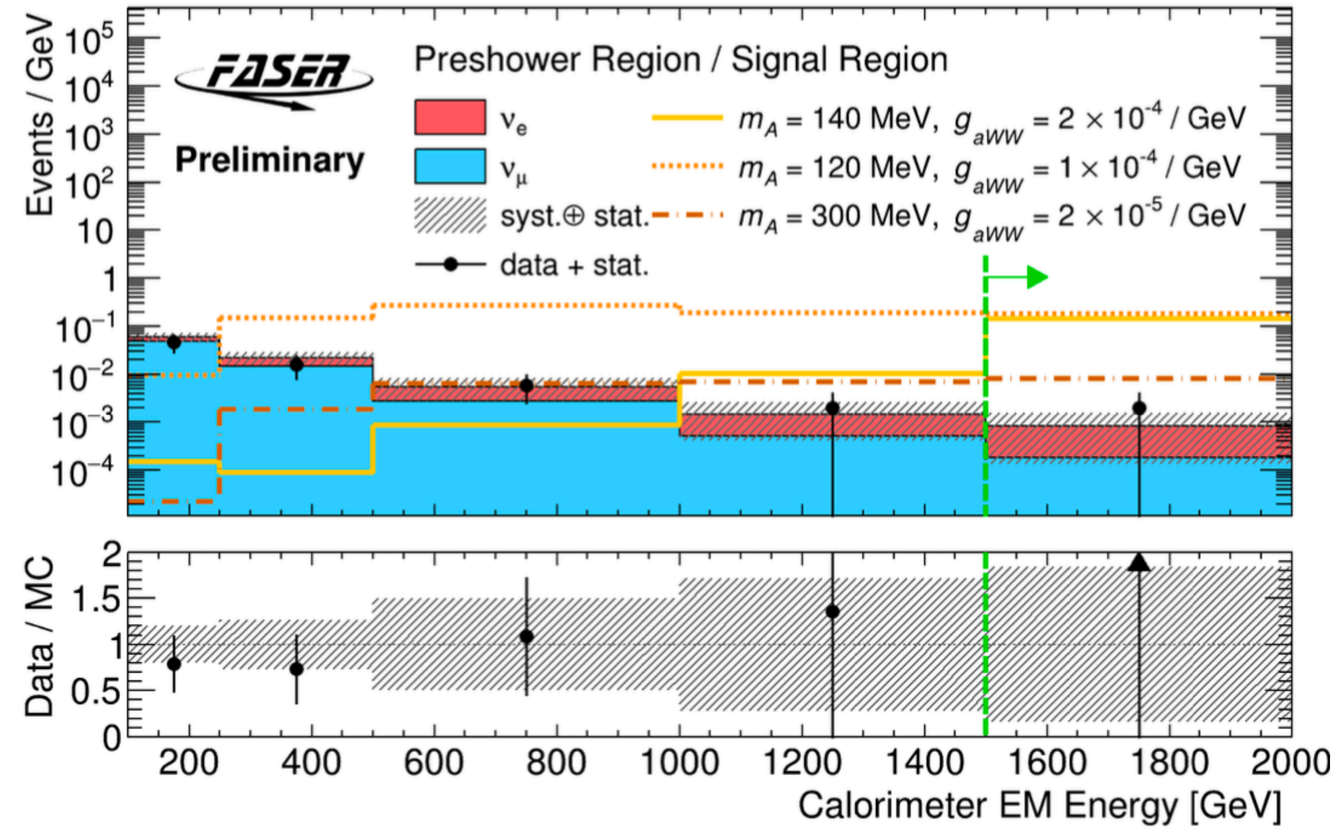
ALPs

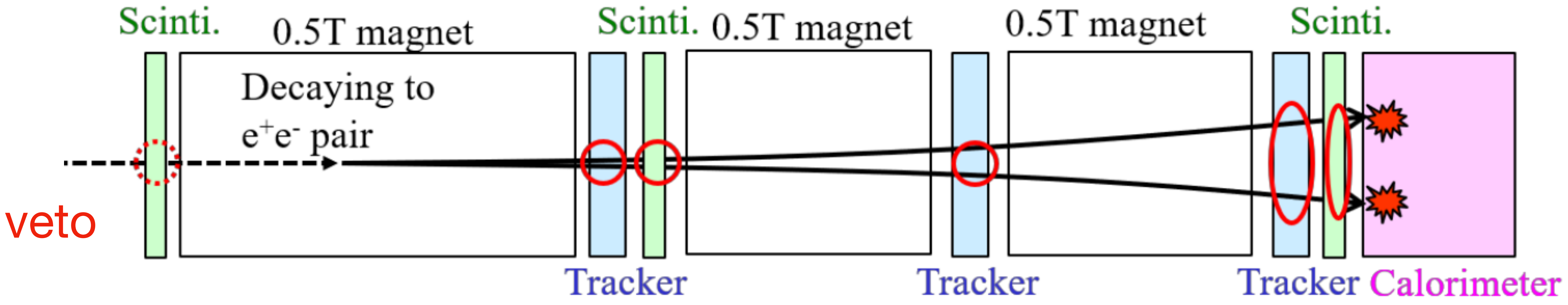


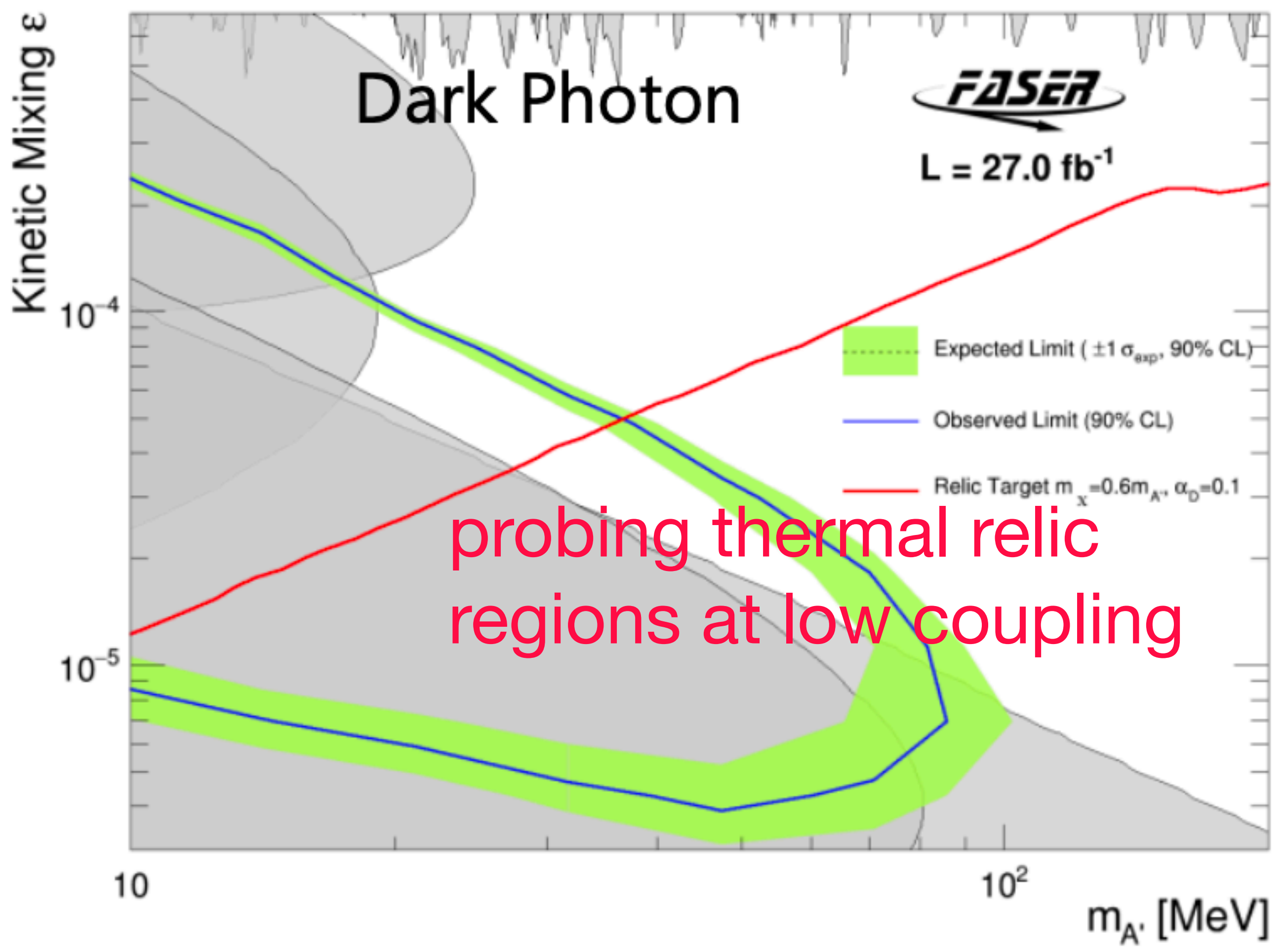
dark-photons



NEW







PLB 848 (2024) 138378

BKG-zero searches dominated by ν-material interactions!

Conclusions

Rich search LLP program @ LHC

Interplay between

* detector technologies

➡ allows to extensively probe different lifetime regimes

LLP searches are often **statistically limited**!

- **BKG-zero searches sensitivity** $\propto \mathcal{L}$

NEW IDEAS to probe such *anomalous* signatures:

- new trigger strategies
  - e.g. data parking, data scouting, lower thresholds [1, 2, 3]
- deep learning ↔ model-independence
- new detectors technologies @ Run-4
- new dedicated experiments!