Long-lived Particles

Experimental constraints

Karri Folan DiPetrillo
University of Chicago
IMCC Physics Meeting
6 July 2023

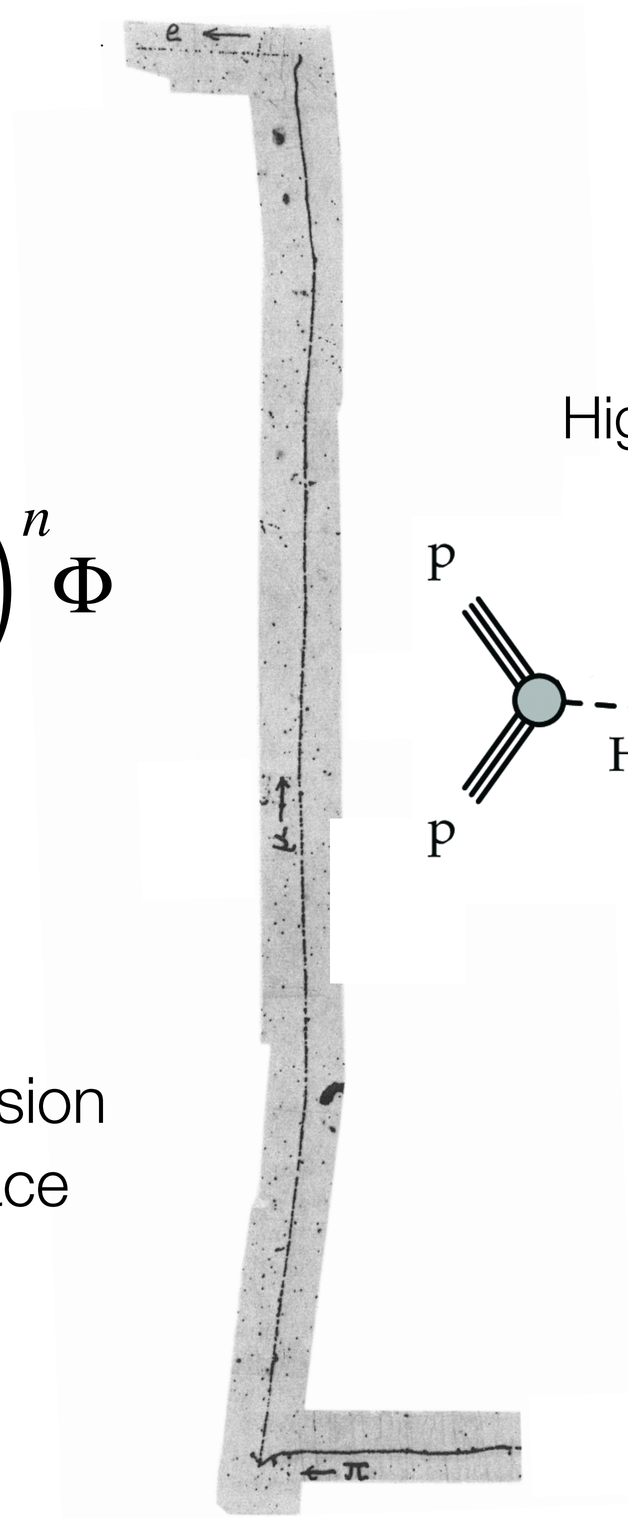
Long-lived particle reminder

LLP benchmarks, Z. Liu

Motivation

$$\tau^{-1} = \Gamma \sim y^2 \left(\frac{m}{\Lambda}\right)^n \Phi$$

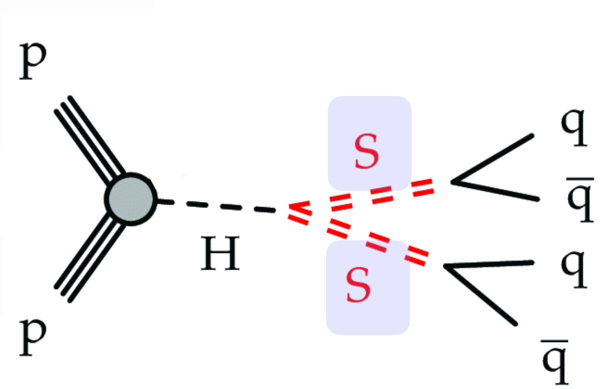
y - small coupling
m≪Λ - scale suppression
Φ - small phase space



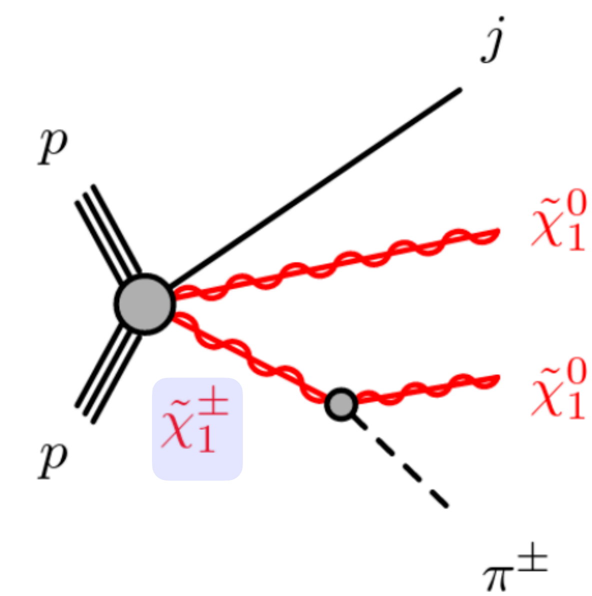
(1949) *Nature* **163**, 82.

Commonly appear in your favorite model

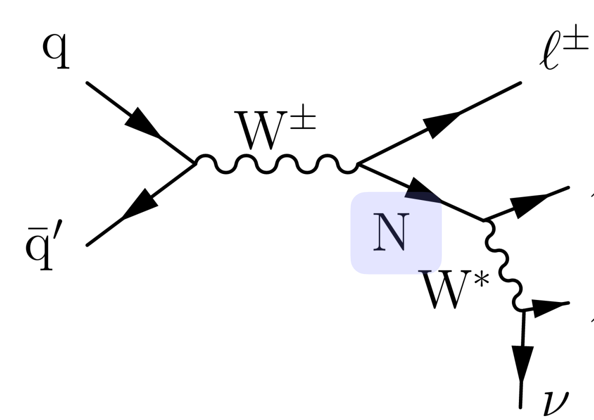
Higgs portal



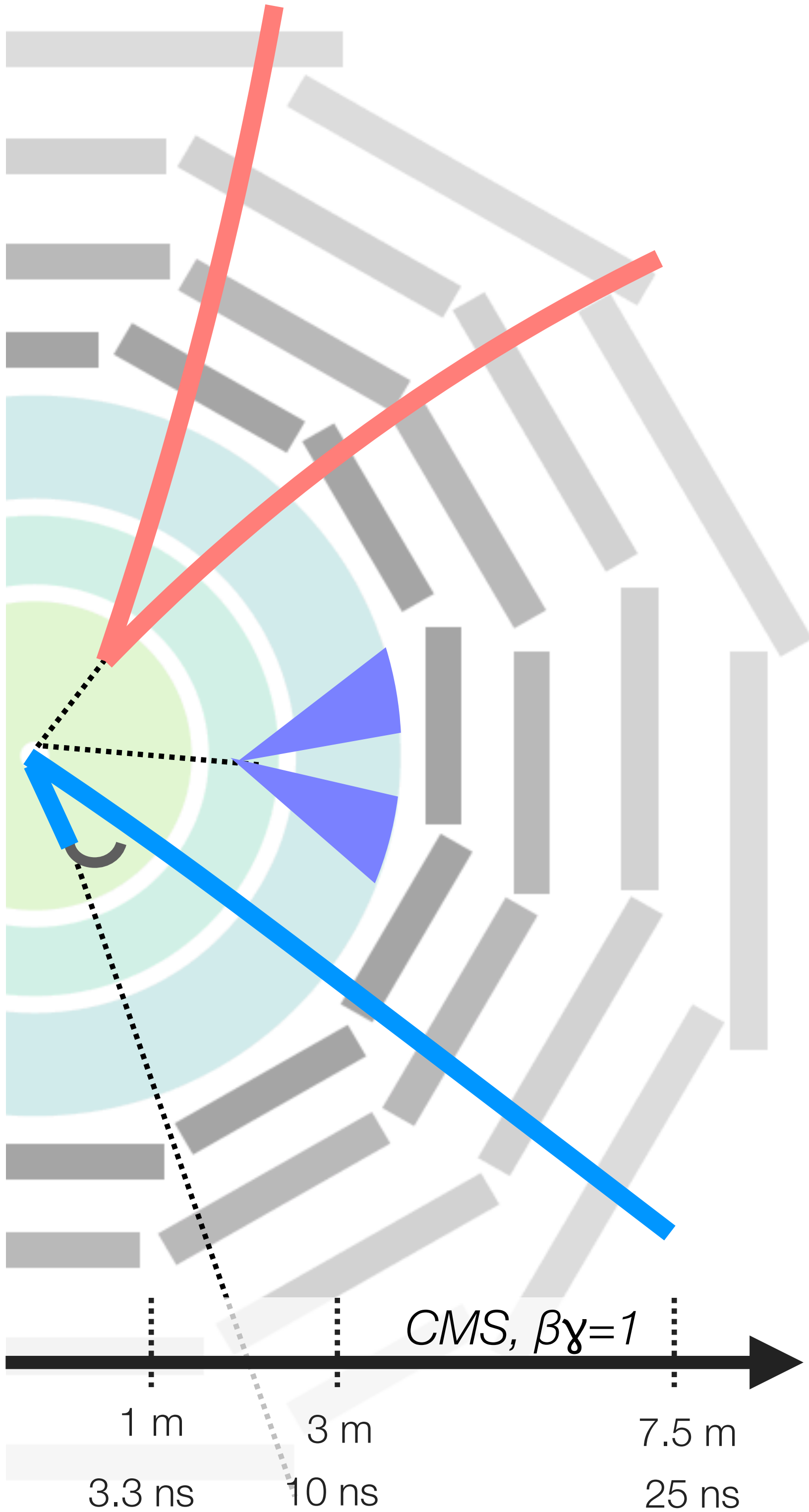
Supersymmetry



Heavy Neutral Leptons



How we've looked for LLPs at the LHC



Indirect Detection via decay products

Tracking

impact parameter

secondary vertex

Calorimetry

shower shape

delay

Direct Detection of Charged long-lived particles

anomalous ionization

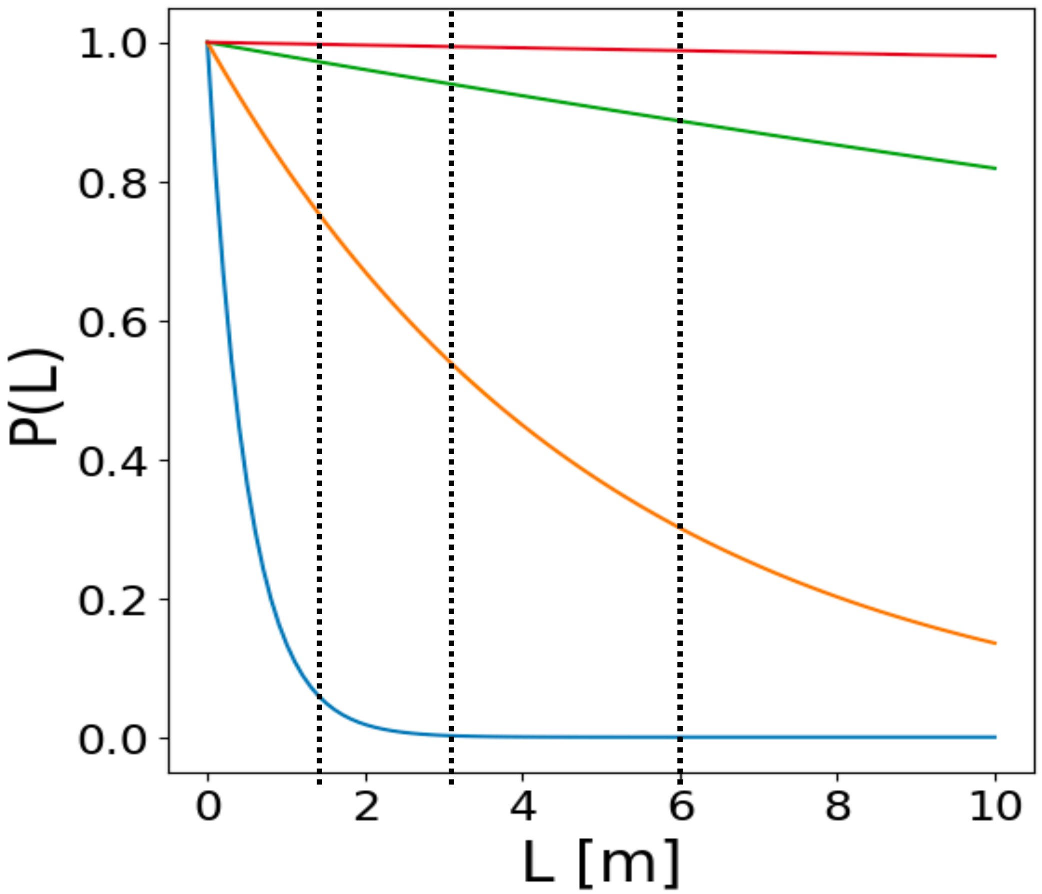
time of flight

infer decay
via missing hits

Understanding sensitivity

Long-lived particle decay position follows an exponential with mean = βγcτ

Acceptance
driven by detector volume



Efficiency
driven by everything else

- Detector technology
- Data Acquisition & Storage
- Reconstruction
- Standard Model Backgrounds
- <u>Non-standard Backgrounds</u>

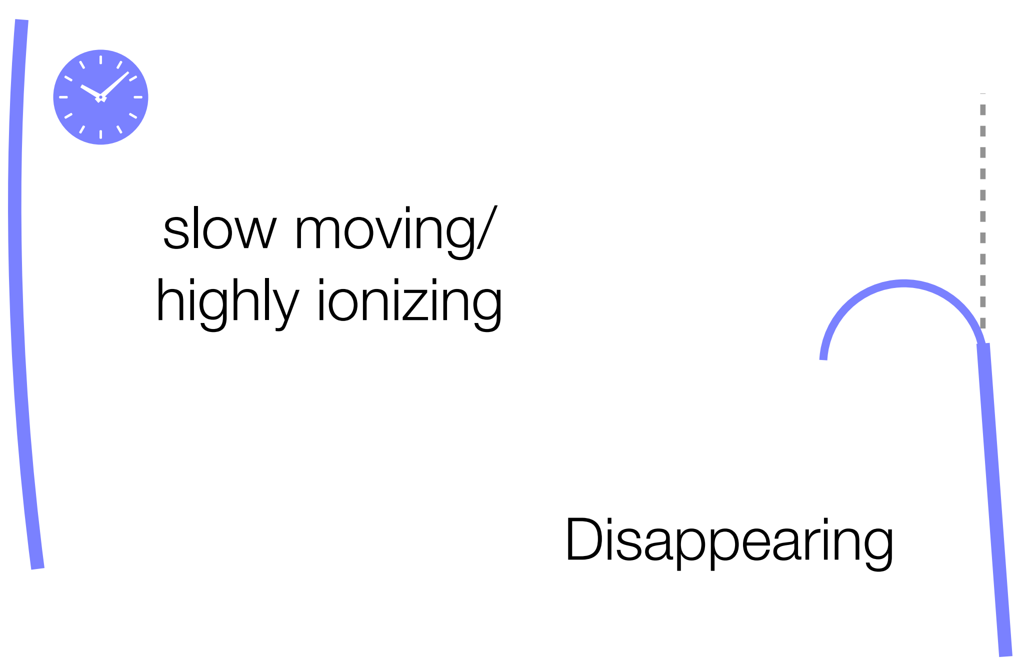
1. Tracker tends to 'win' on acceptance & efficiency
2. All challenges connect to beam induced background

This talk

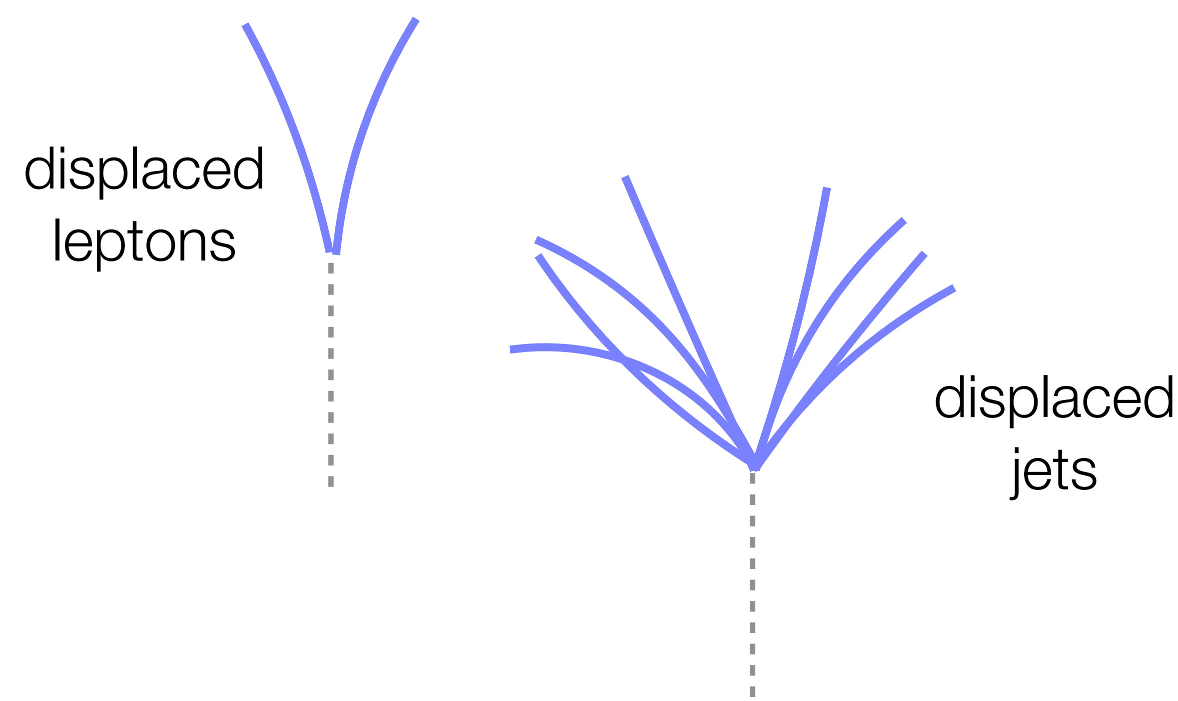
Following strategy of [2211.05720]

Consider a range of well motivated track-based LLP signatures
Map challenges posed by beam induced background to signal sensitivity
Assuming 3 TeV detector design as a baseline

Heavy meta-stable charged particles (HSCPs)



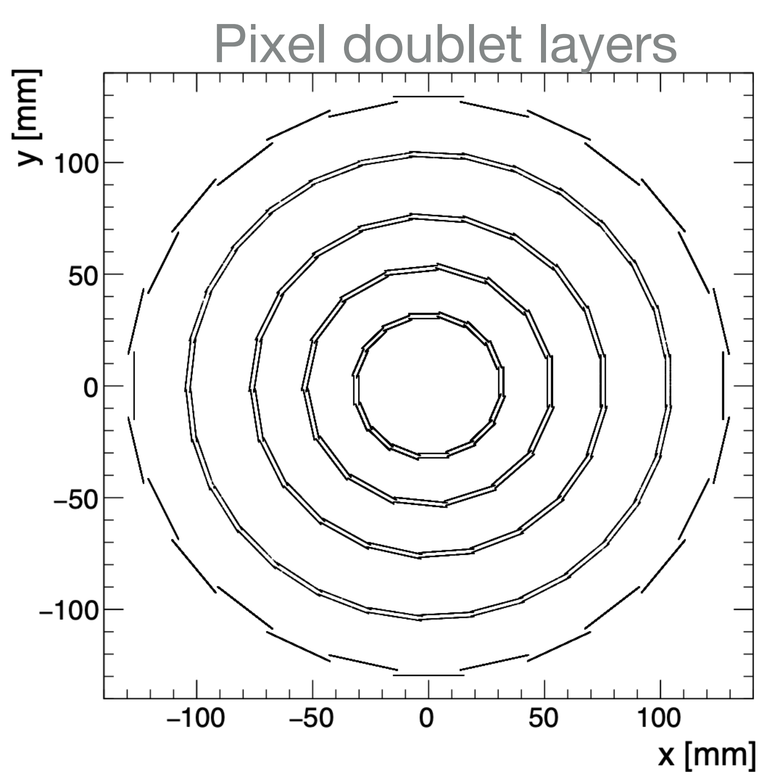
Displaced tracks

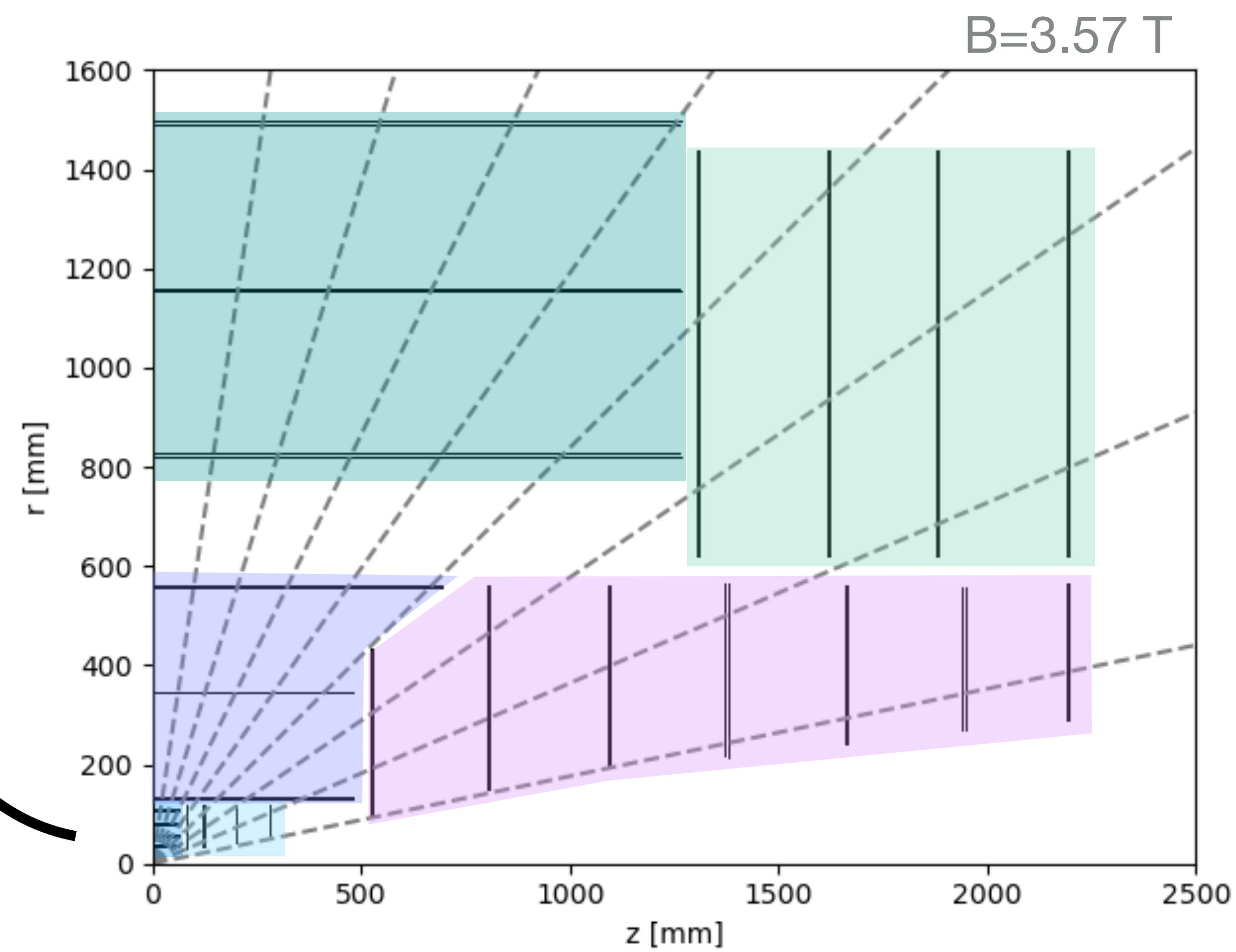


Tracker geometry reminder

I'll mostly focus on the barrel for simplicity

	Vertex Detector	Inner Tracker	Outer Tracker
cell size	25x25 μm^2	50 μm x 1 mm	50 μm x 10 mm
thickness	50 μm	100 μm	100 μm
σ_t	30 ps	60 ps	60 ps

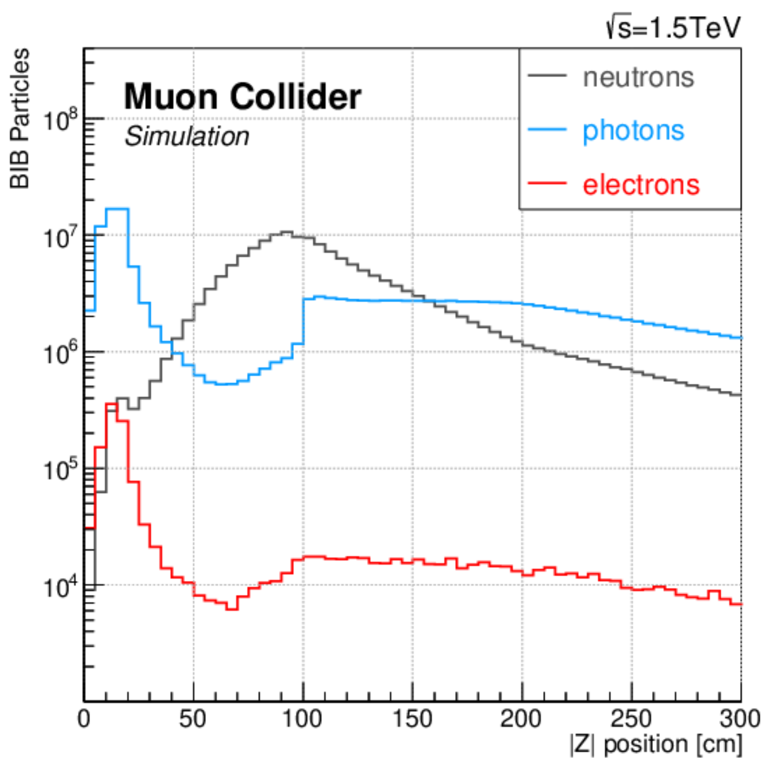




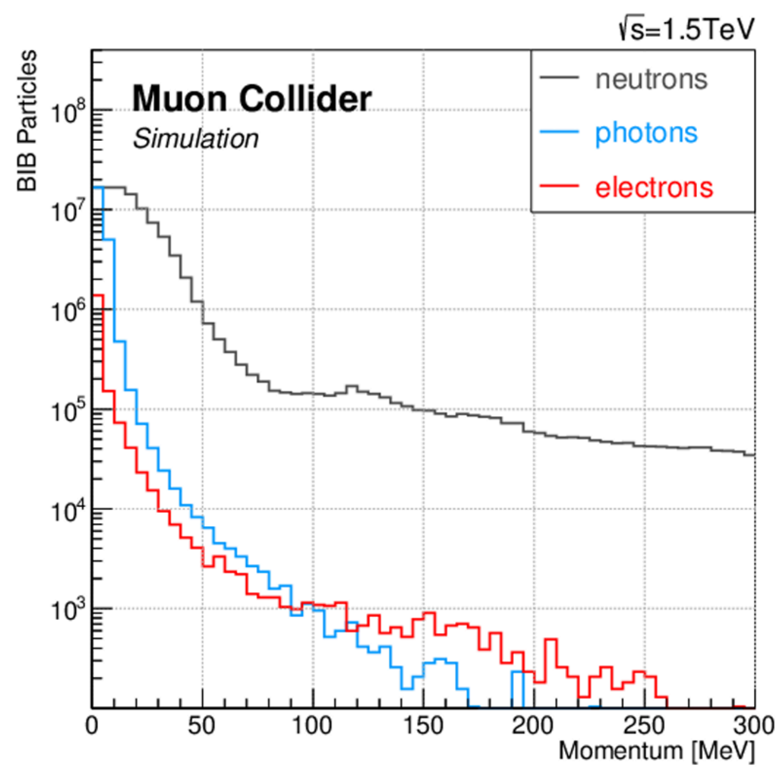
Beam induced background reminder

~10^8 low momentum particles per event
Drives nearly every aspect of detector design

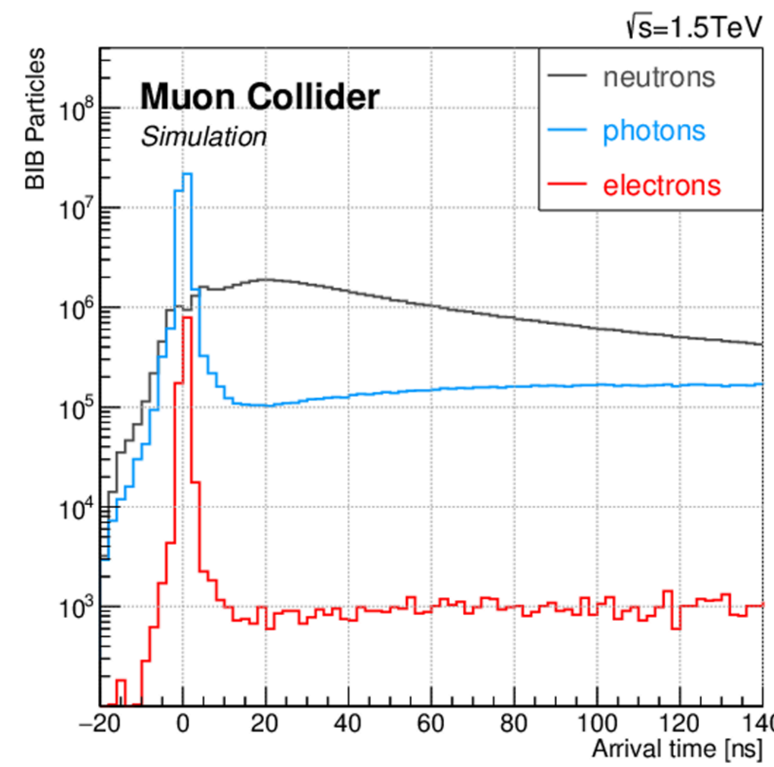
Unusual position & direction



Majority < 200 MeV



Partially out of time



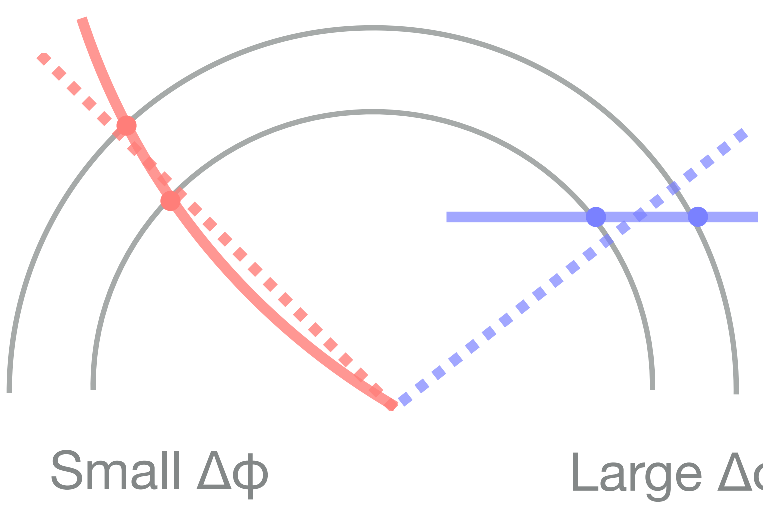
distributions depend on beam energy, nozzle, and magnets

Why the BIB is a problem (hit-level)

2303.08533

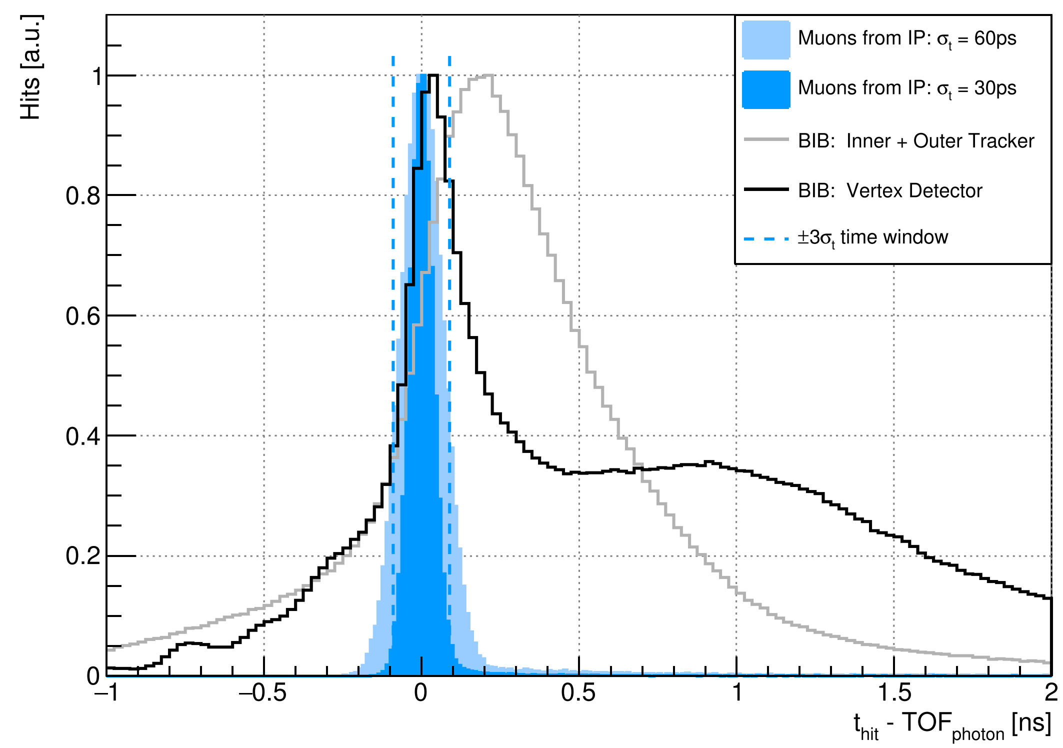
All the handles we use to reject hits from BIB can reject long-lived signal

Pointing requirement



A pointing requirement of
$\Delta\phi < 2\text{-}3$ mrad at R = 30 mm
Corresponds to $d_0 \lesssim 100$ μm*

Corrected time of arrival



Most studies assume
1 ns integration window and
±3σ time of arrival cut

LLP hit efficiency

How do pointing, timing, and charge measurements impact LLP hit efficiency?

Example: meta-stable charged LLP pair production

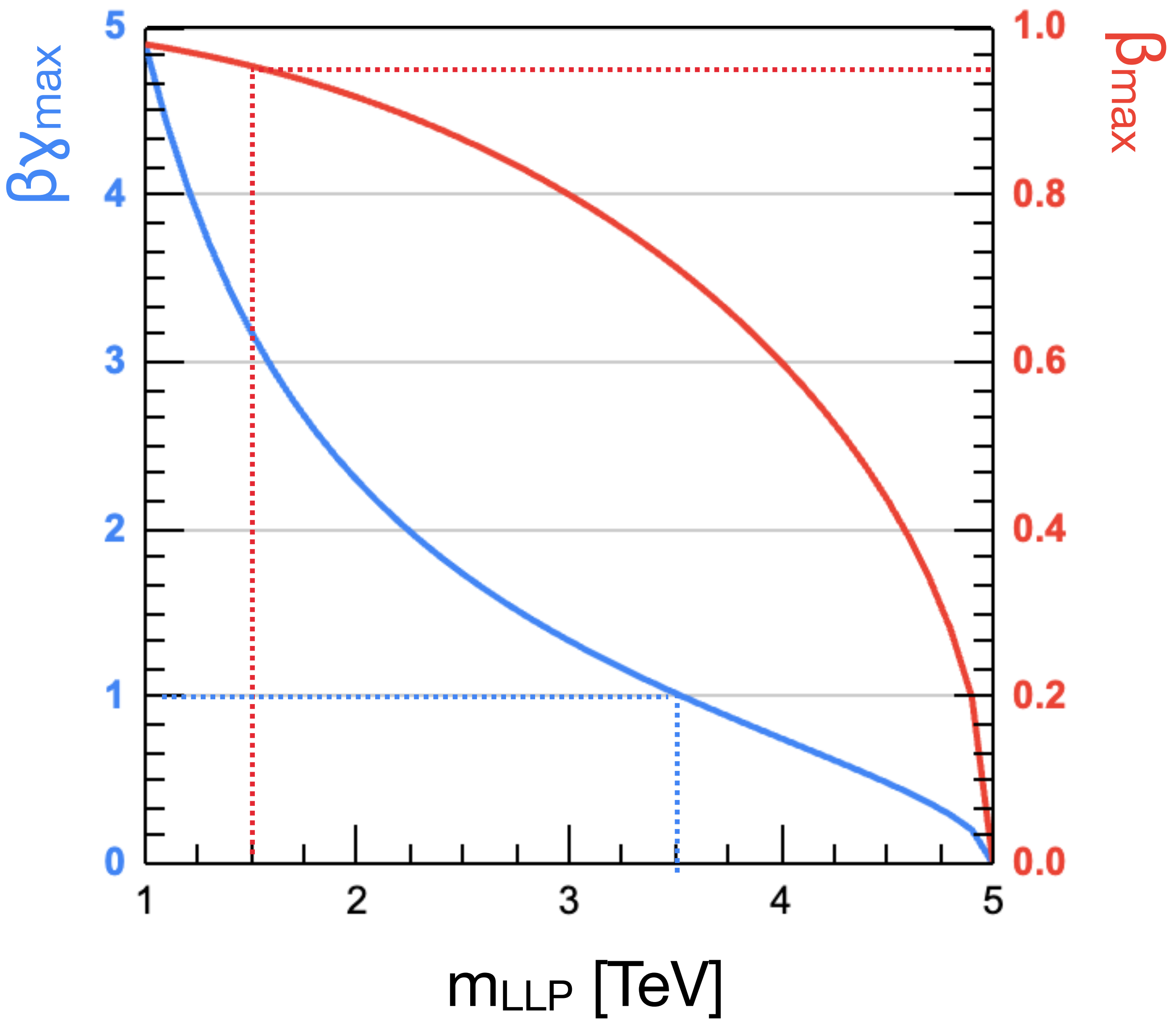
$$p_{\max} = \sqrt{(\sqrt{s}/2)^2 - m_{LLP}{}^2}$$

Pointing: prompt high p_T isolated tracks

Slowly moving: $m_{LLP} \gtrsim 1.5$ TeV

Highly Ionizing: $m_{LLP} \gtrsim 3.5$ TeV

Obtain mass from delay or dE/dx, and track momentum



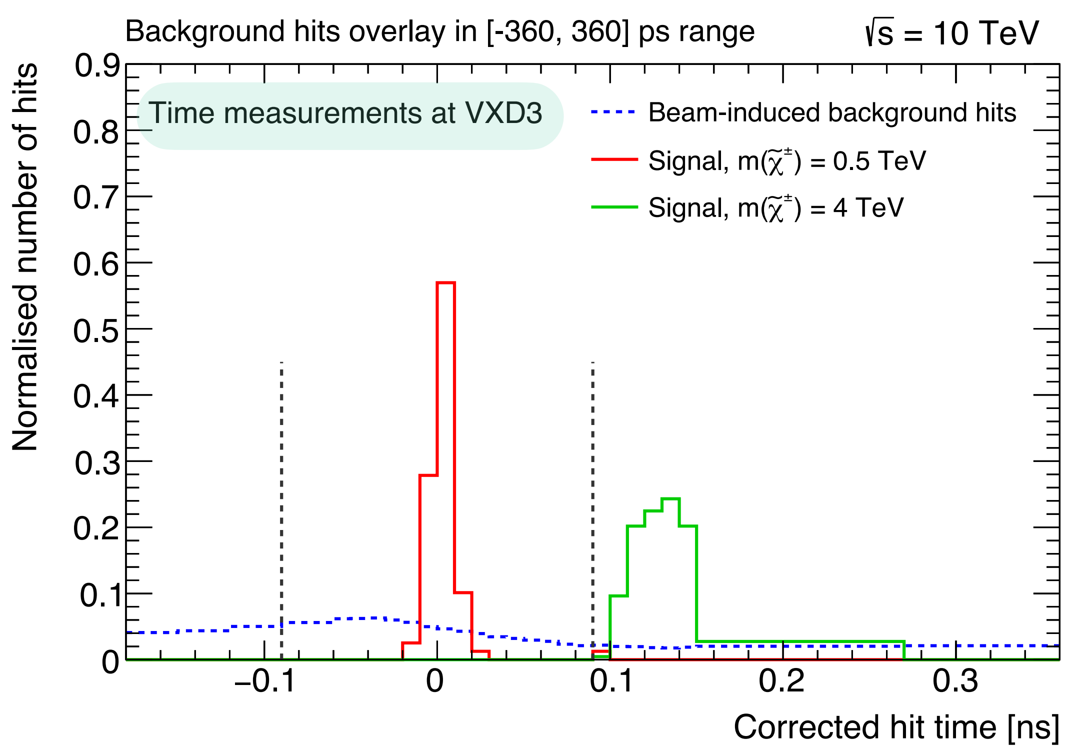
Time of Flight

2102.11292

Massive long-lived particles arrive late with respect to prompt particles

$$t_{\text{delay}} = 30 \text{ ps } (1 - \beta^{-1})\left(\frac{L}{10 \text{ mm}}\right)$$

Layer	Delay for LLPs at η=0 (ns)		
	1.5 TeV	4 TeV	4.8 TeV
VTX0	0.01	0.07	0.23
VTX3	0.01	0.11	0.39
VTX8	0.02	0.26	0.92
IB2	0.1	1.22	4.27
OB0	0.14	1.8	6.31
OB3	0.26	3.29	11.52



To reconstruct tracks from massive LLPs, need to extend timing windows up to O(100 ps) in pixel and O(few ns) in Inner/Outer Tracker

Challenging given beam induced background

Cluster charge & shape

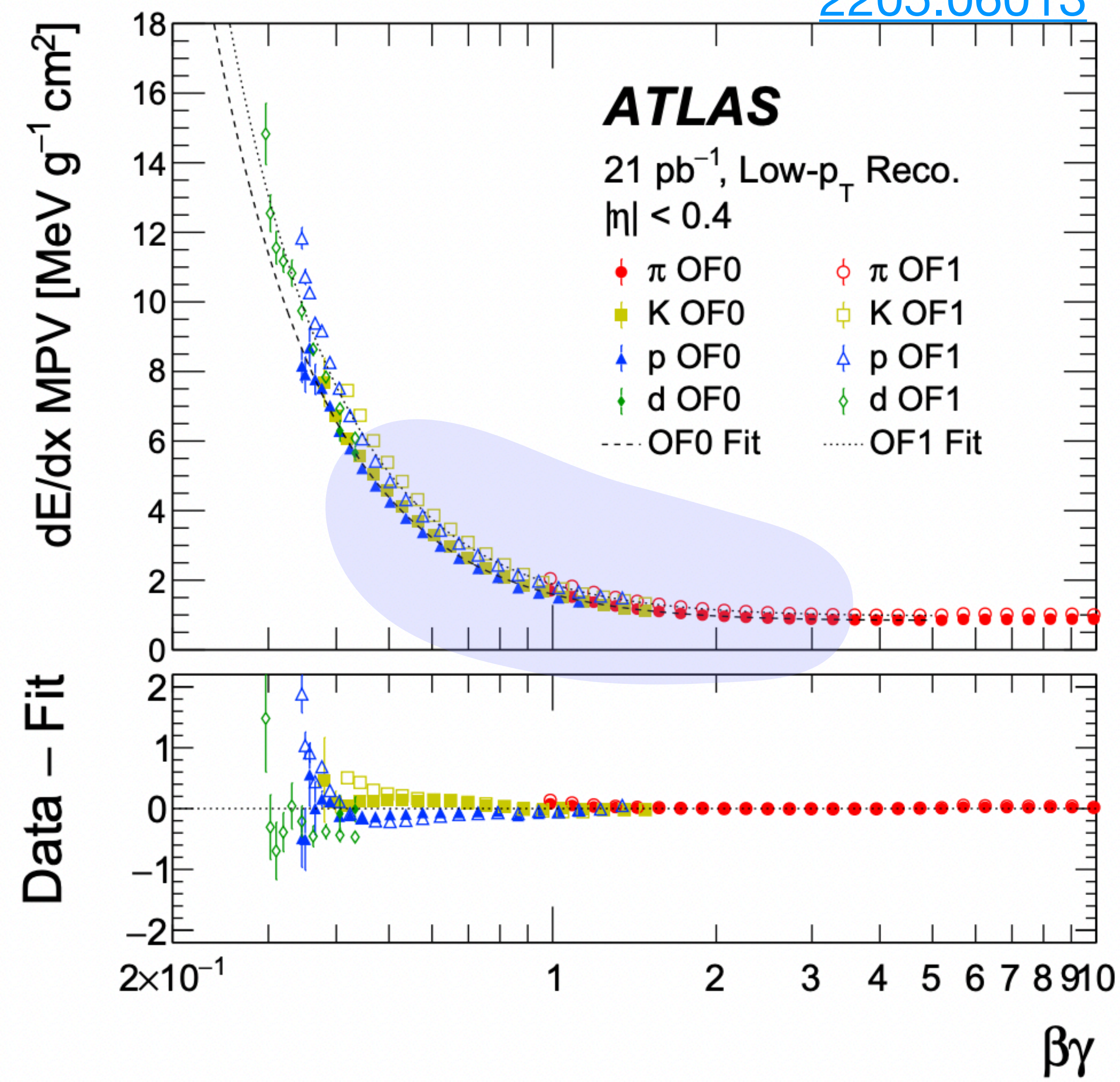
Energy deposited by an incident particle (dE/dx) depends on βɣ
Cluster shape depends on position, incident angle, etc

	Momentum	Mass	dE/dx
LLP	High	High	Moderate
BIB	Low	Low	Moderate
Prompt μ	High	Low	Low

Cannot reject high dE/dx clusters if shape is consistent with high p_T particles

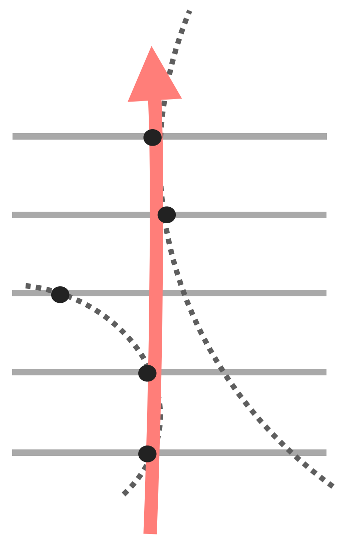
Want coarse dE/dx information at hit or cluster level

2205.06013

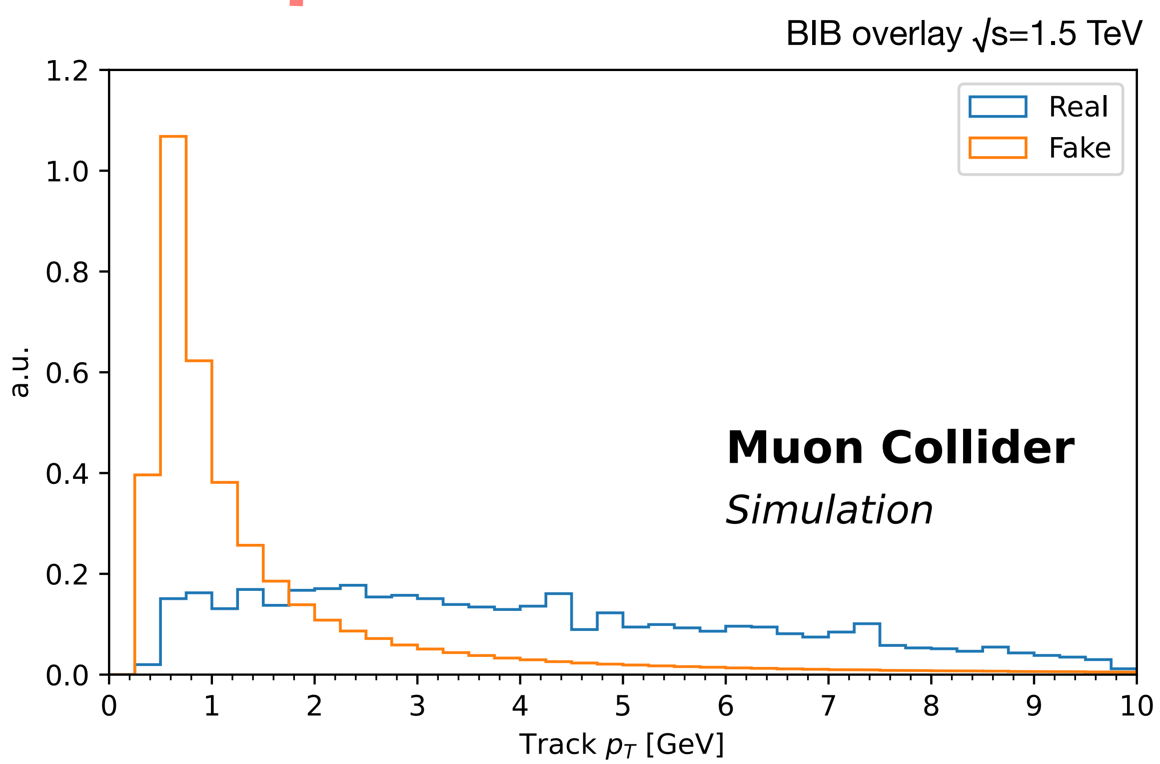


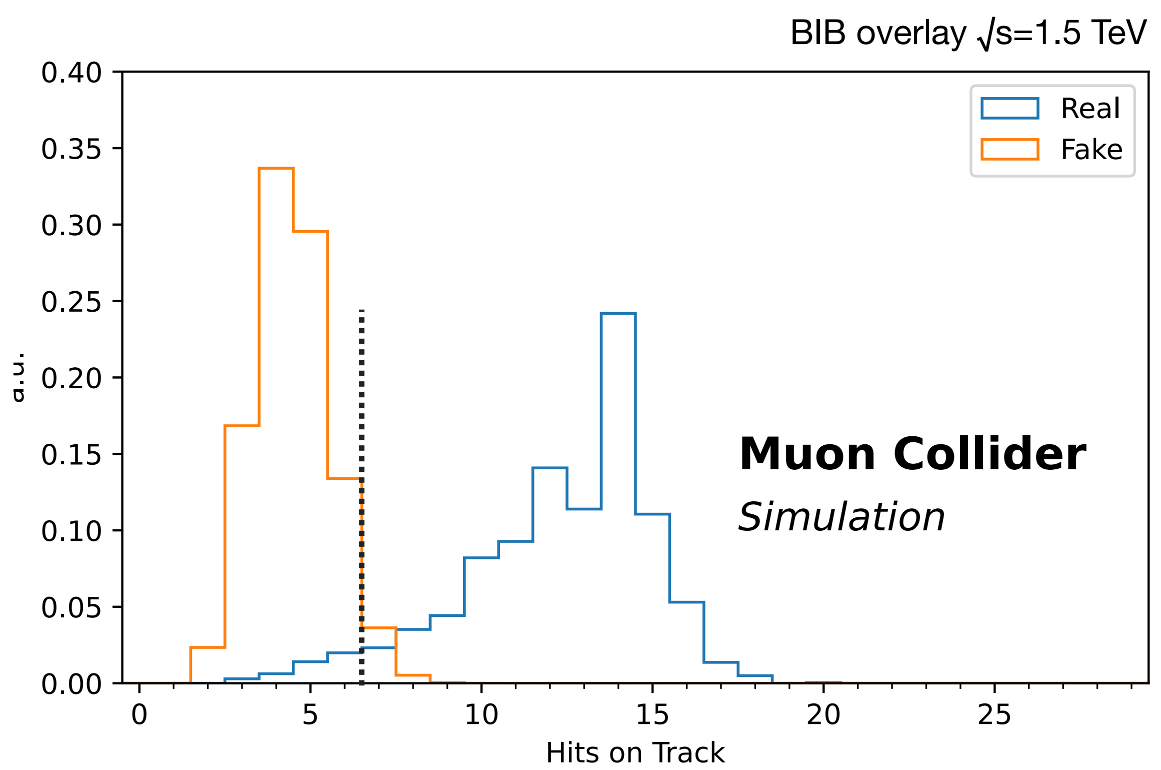
Why the BIB is a problem (track-level)

2303.08533



Remaining hits result in ~100k 'fake' tracks per event
low p_T, poor quality of fit, and <u>low n_{hit}</u>



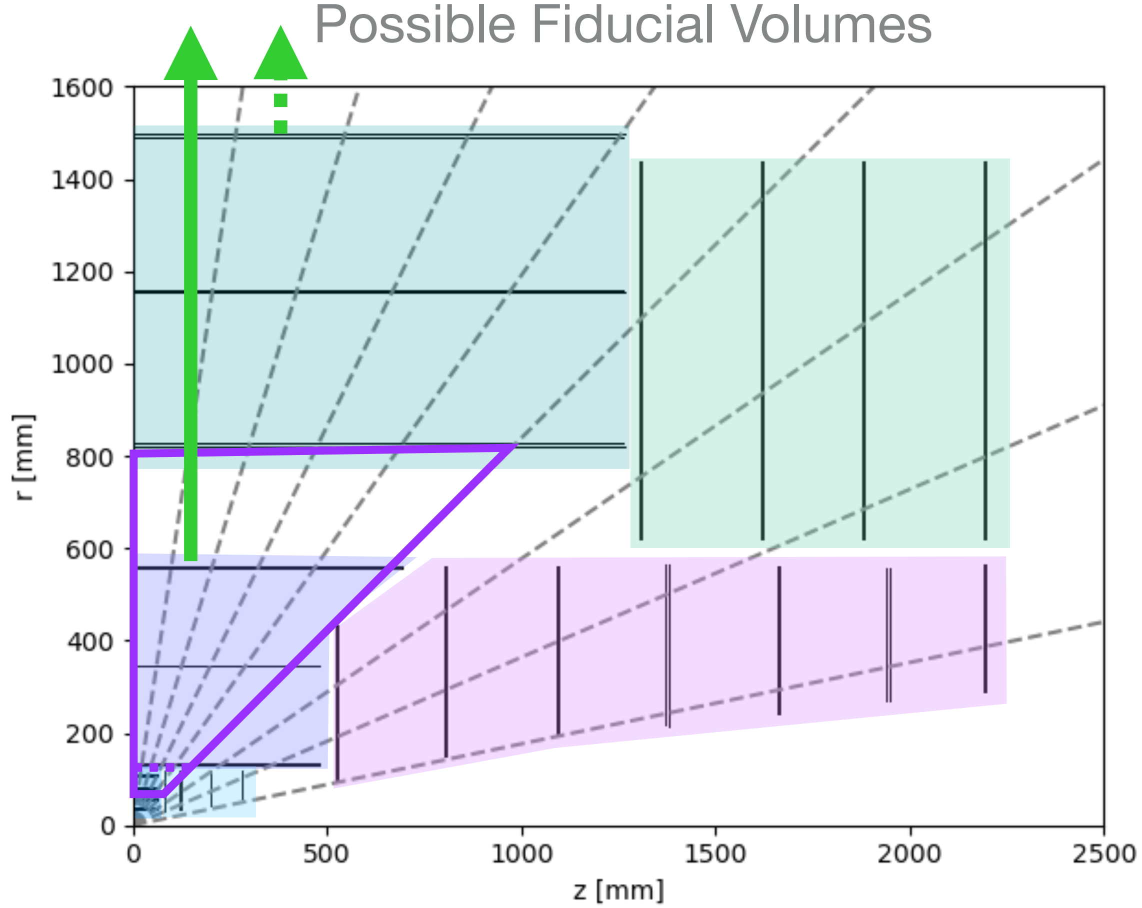


n_{hit} requirements determine fiducial volume for
displaced and disappearing tracks

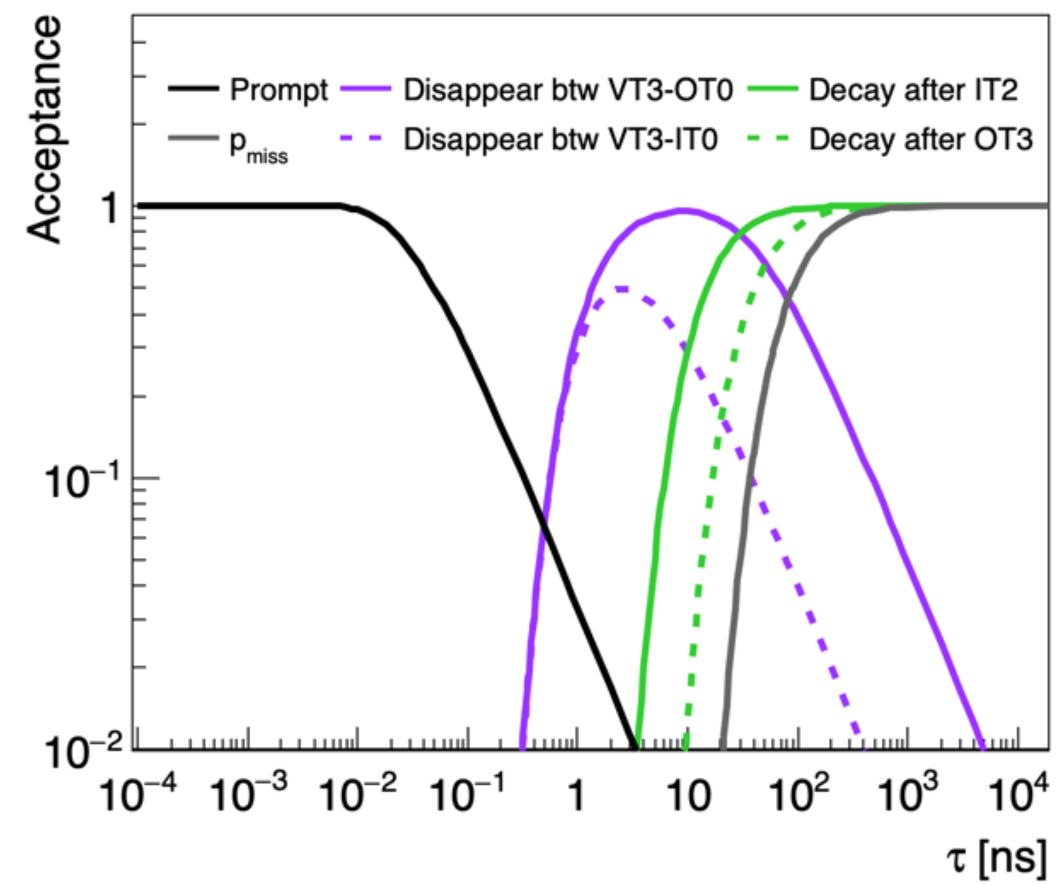
Direct Detection Acceptance

What is the minimum n_{hits} per track for meta-stable charged particles?

Possible Fiducial Volumes



Acceptance versus lifetime

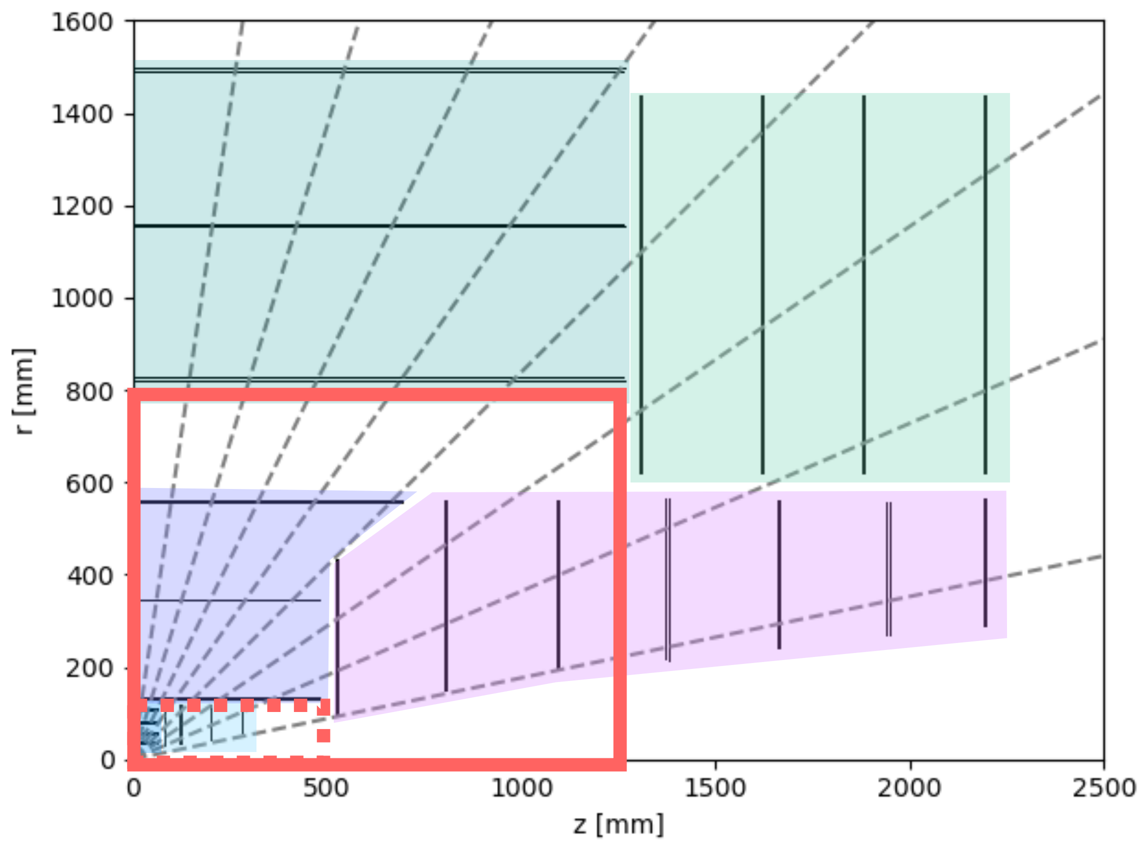


Assume two LLP decays at η=0, βγ=5, require ≥1 decay w/in detector volume
3 TeV Muon Collider Geometry,

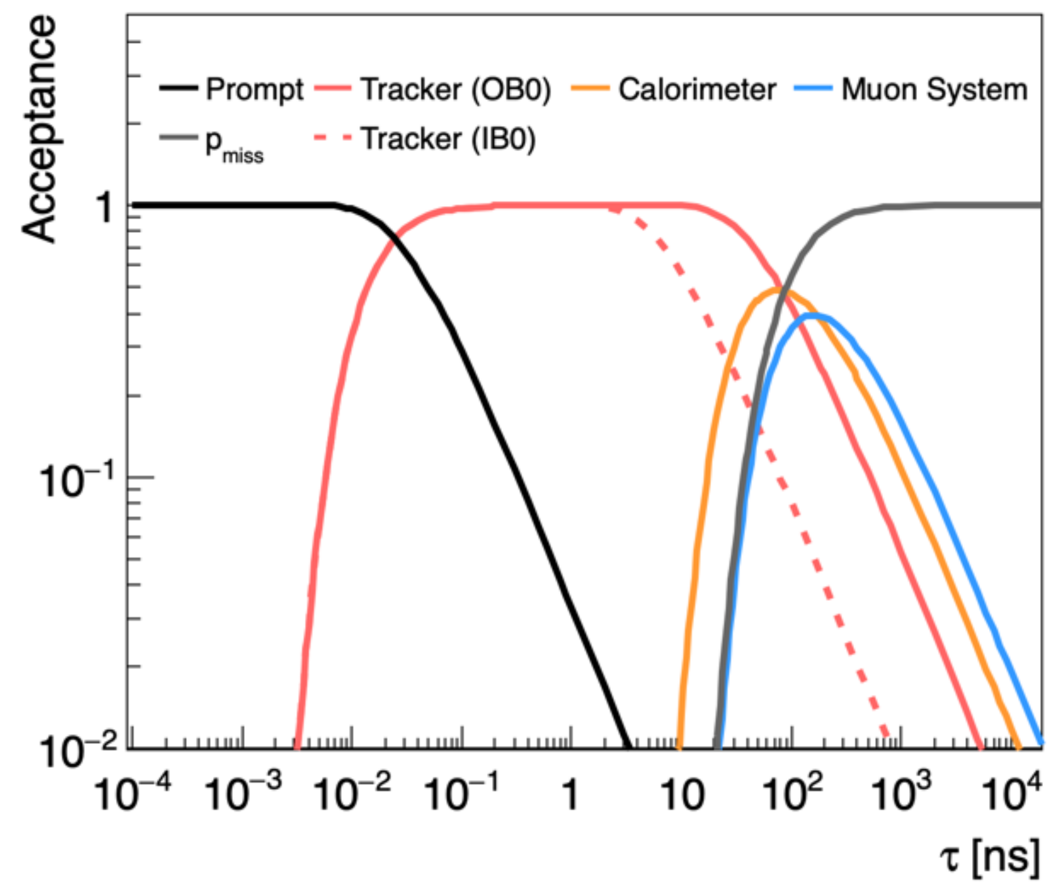
Displaced Track Acceptance

What is the minimum n_{hits} needed for displaced tracks?

Possible Fiducial Volumes



Acceptance versus lifetime



Assume two LLP decays at η=0, βγ=5, require ≥1 decay w/in detector volume
3 TeV Muon Collider Geometry,

Non-standard tracking

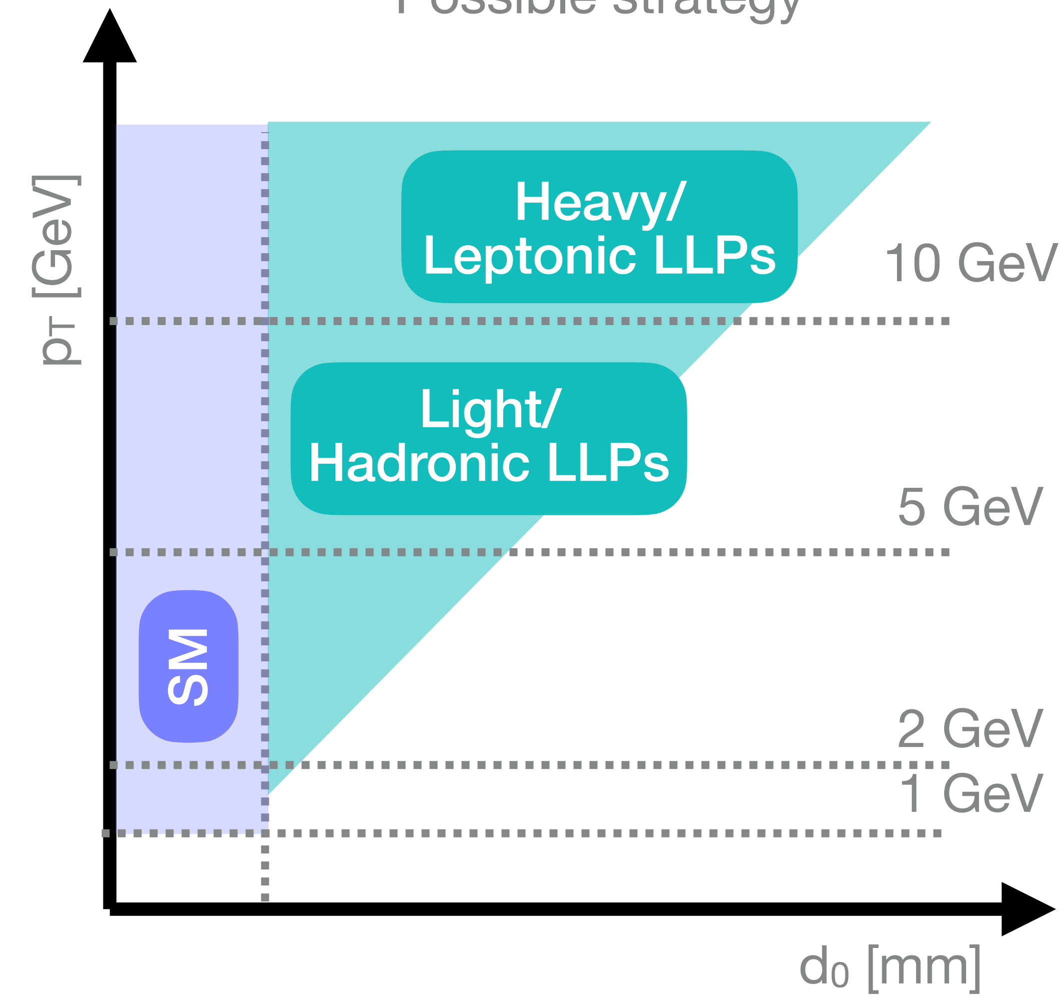
[2211.05720, 2102.11292]

Most (all) studies have focused on prompt tracks
Do we have any hope for displaced or unusual tracks?

Yes, many possible solutions

- Multiple iterations of tracking a la CMS: easiest to most difficult
- For displaced tracks: compensate for increased combinatorics with increased p_T cut
- For slowly moving tracks: compensate for relaxed time windows with tighter pointing, p_T, and n_{hit} requirements, fit to velocity
- Seed regions of interest

Possible strategy

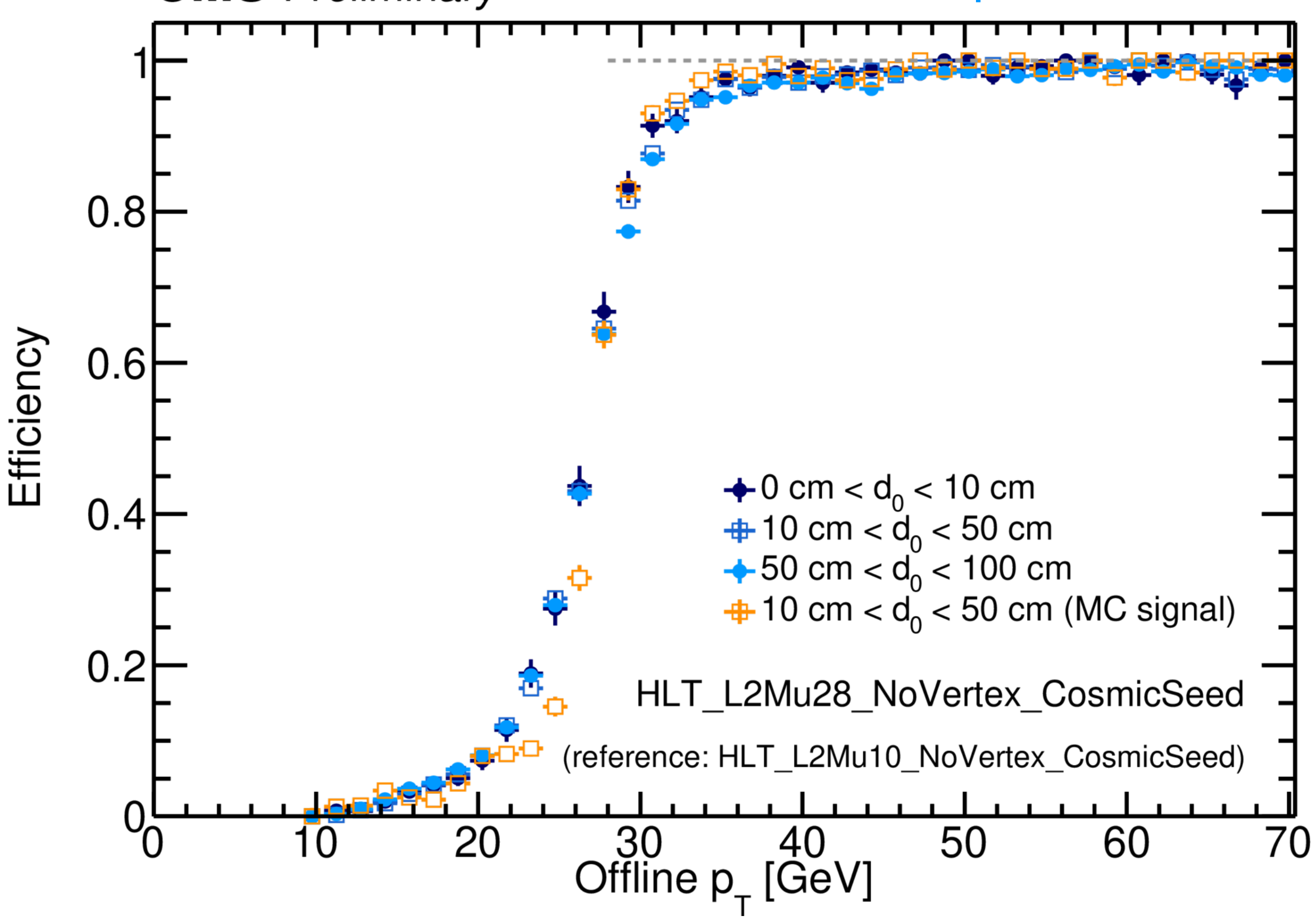


Detector modeling

Need to make sure all custom reconstruction & selections are well modeled

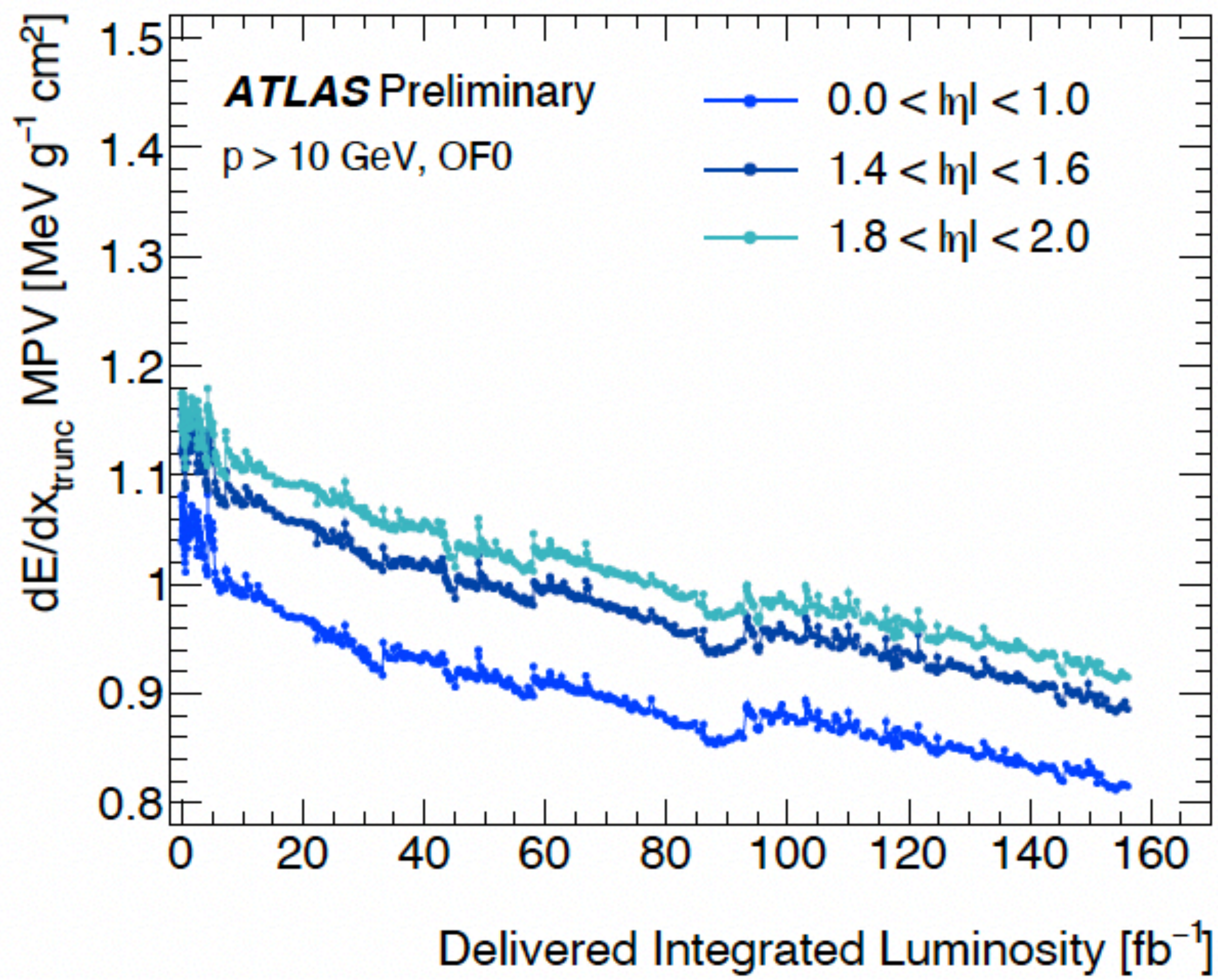
Eg. validating displaced muon trigger efficiency with Cosmics

CMSDisplacedMuons



Eg. Calibrating dE/dx for |η| and detector conditions with SM particles

2205.06013



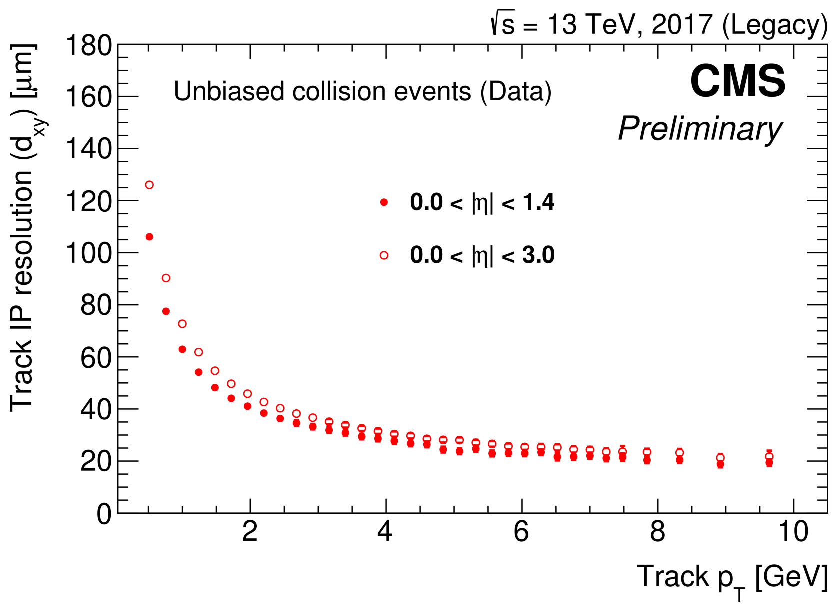
Unusual backgrounds

Go as close to the interaction point as possible

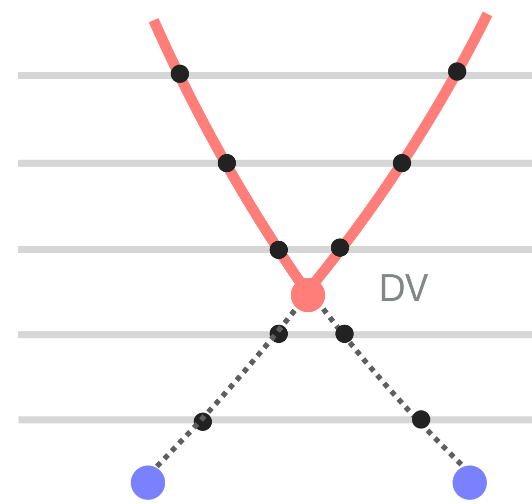
Reject as many displaced backgrounds as possible

d0 tails of prompt SM particles

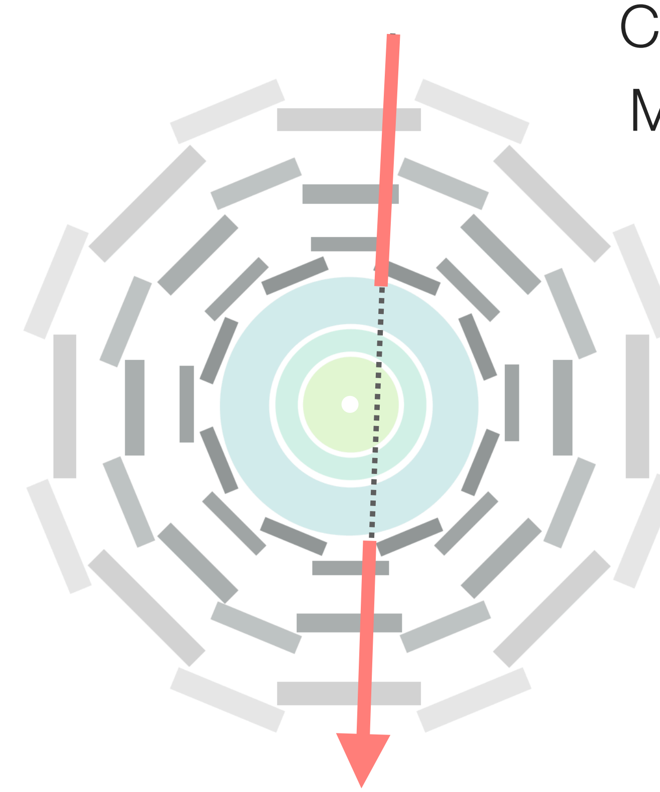
CMSTrackingPOG



Randomly crossing tracks



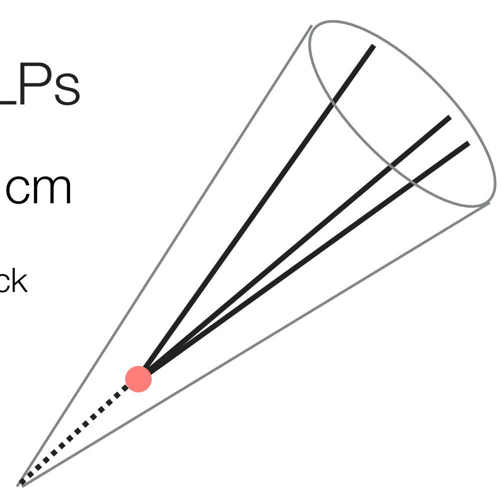
Cosmic Muons



Standard Model LLPs

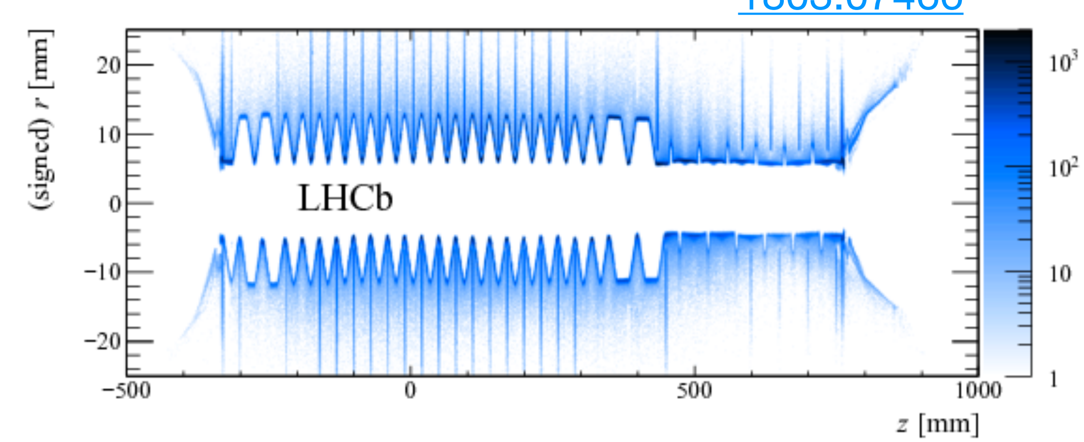
1 TeV b-jet 〈L〉 ~10 cm

Low mass and n_{Track}



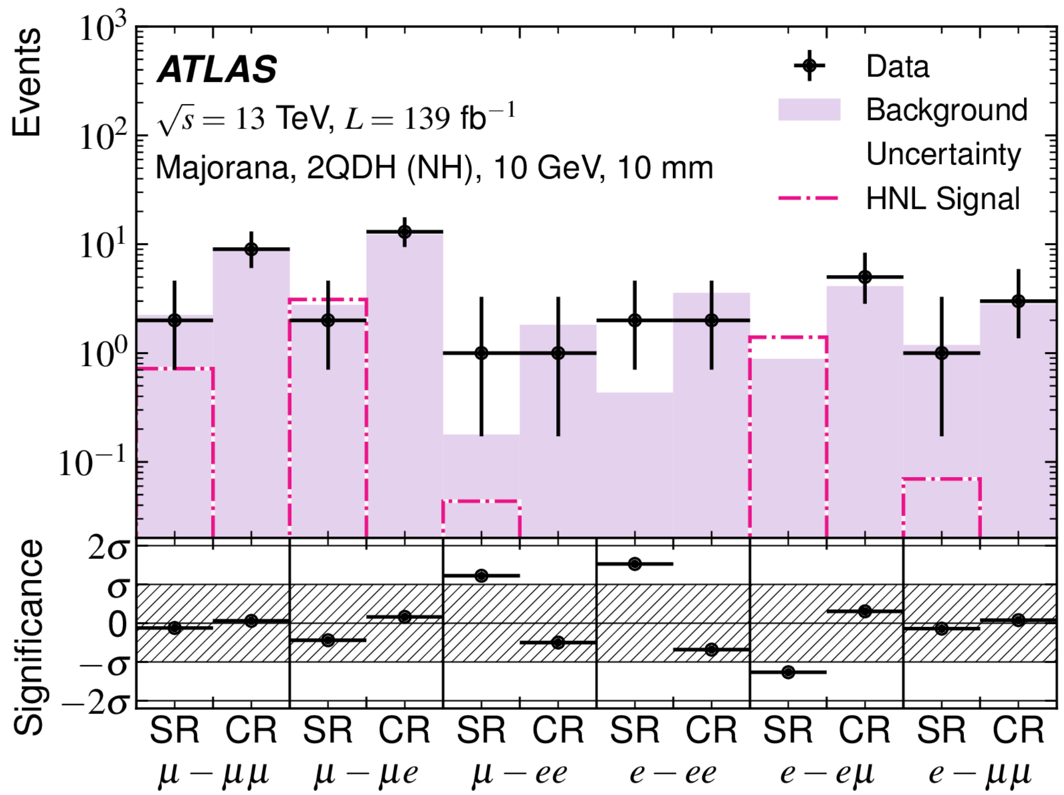
Material interactions

1803.07466



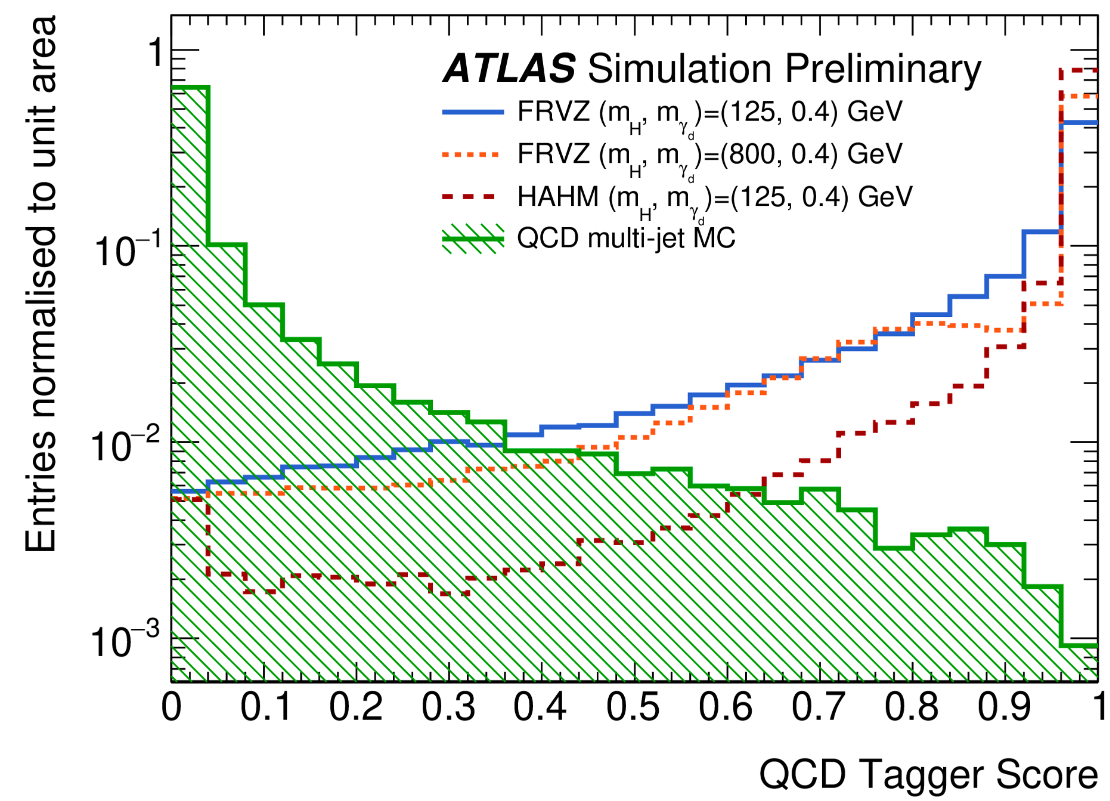
Selection & Analysis Strategy

Past: achieve ~0 background with ~simple selections
Now: sophisticated techniques to access lower masses and probe full lifetime range



eg. Heavy neutral leptons
Categorize in lepton flavor & charge
Vertex Mass & displacement

ATLAS-EXOT-2019-29
CMS: 2201.05578



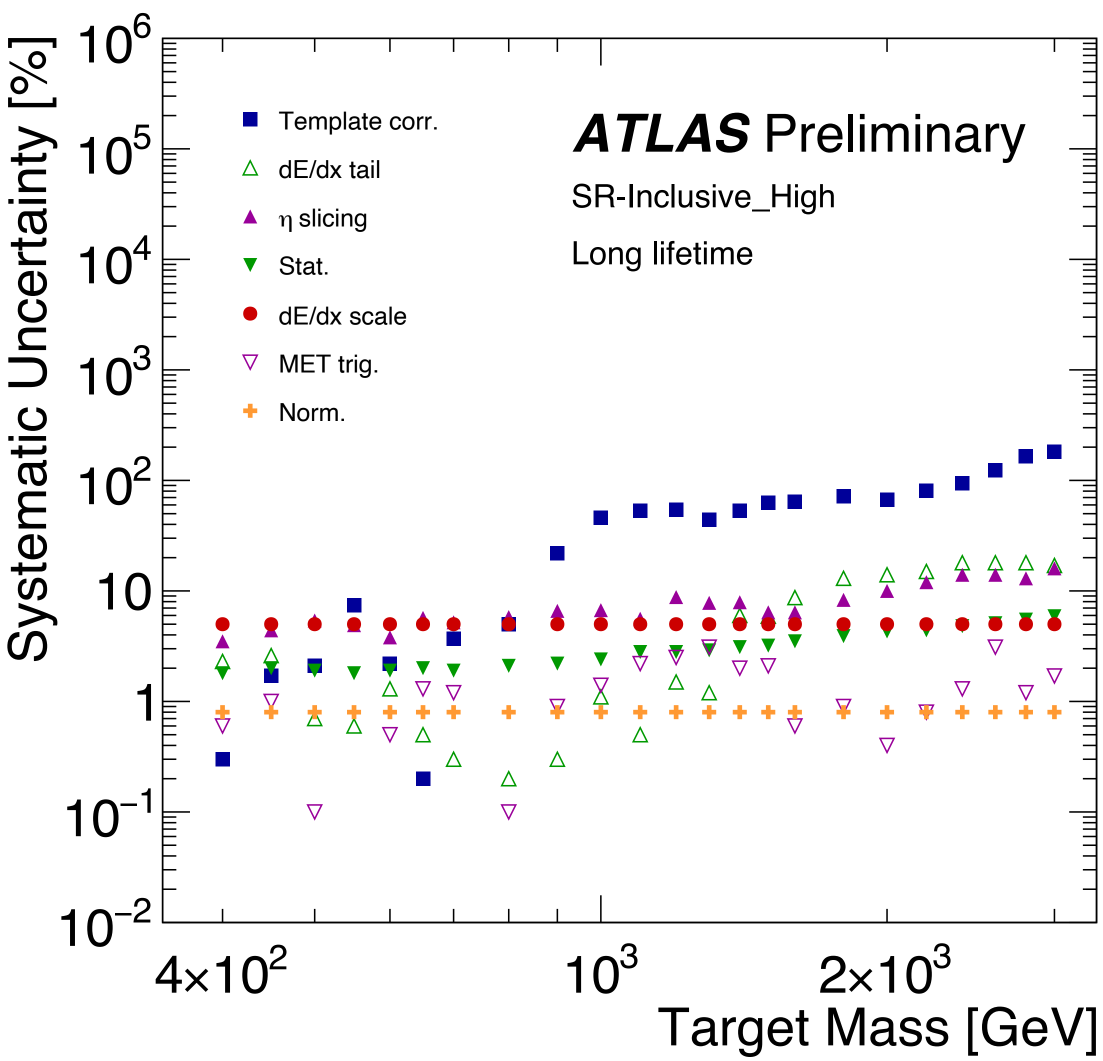
eg. Displaced lepton jets
input calorimeter cells/clusters
into advanced Neural Networks

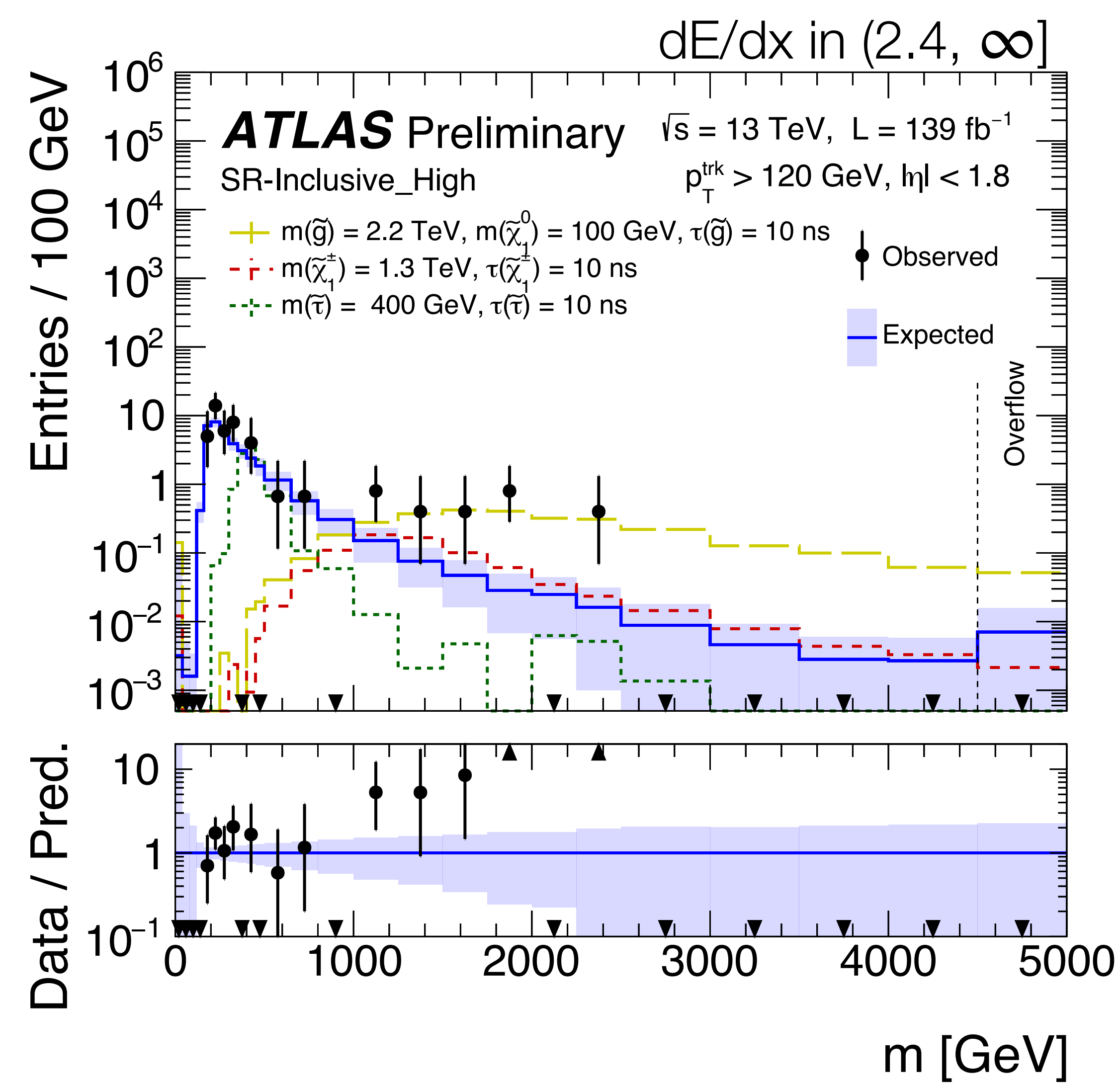
ATLAS-CONF-2022-001

Background estimation

Always data-driven, sometimes very tricky

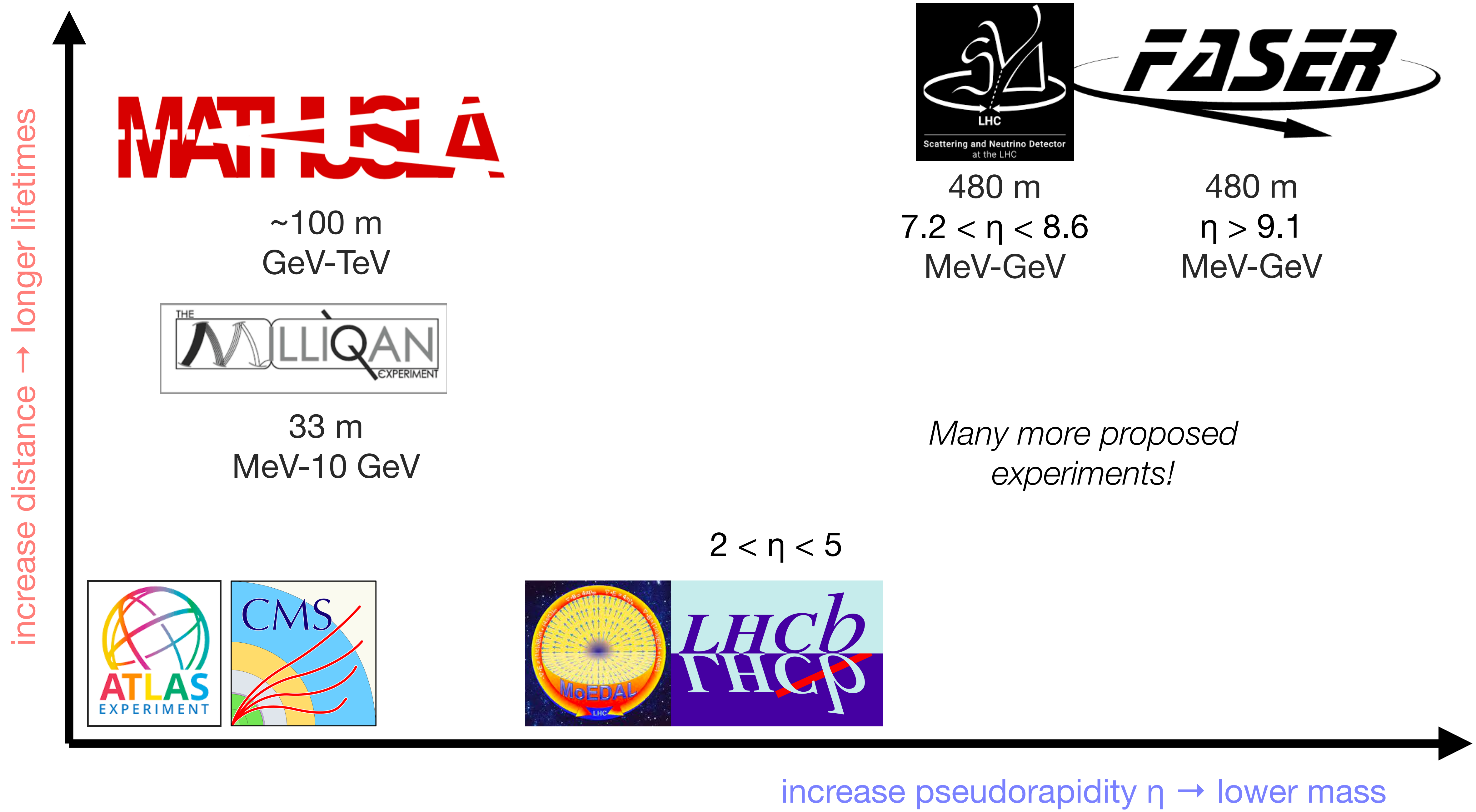
Finding signal free control regions, correlations between key variables, unexpected backgrounds, etc





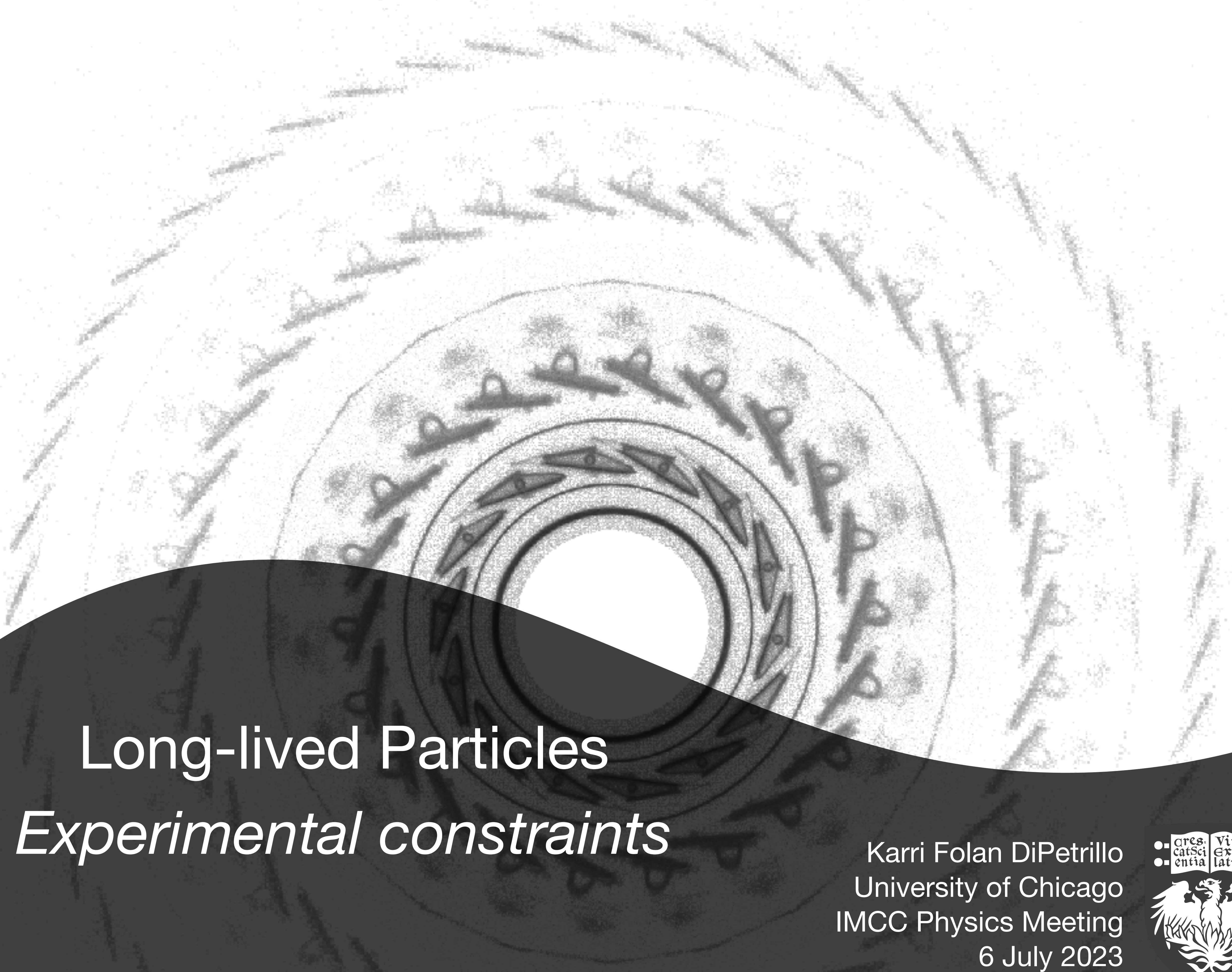
Aux Detectors

Different physics than the LHC…
We should think about how increasing distance or going forward could probe interesting phase space



Conclusions

- Tracker tends to be the most powerful detector volume for LLPs
- Many challenges posed by the beam induced background
- Optimistic we can overcome these challenges
- A lot of exciting work ahead!



Long-lived Particles

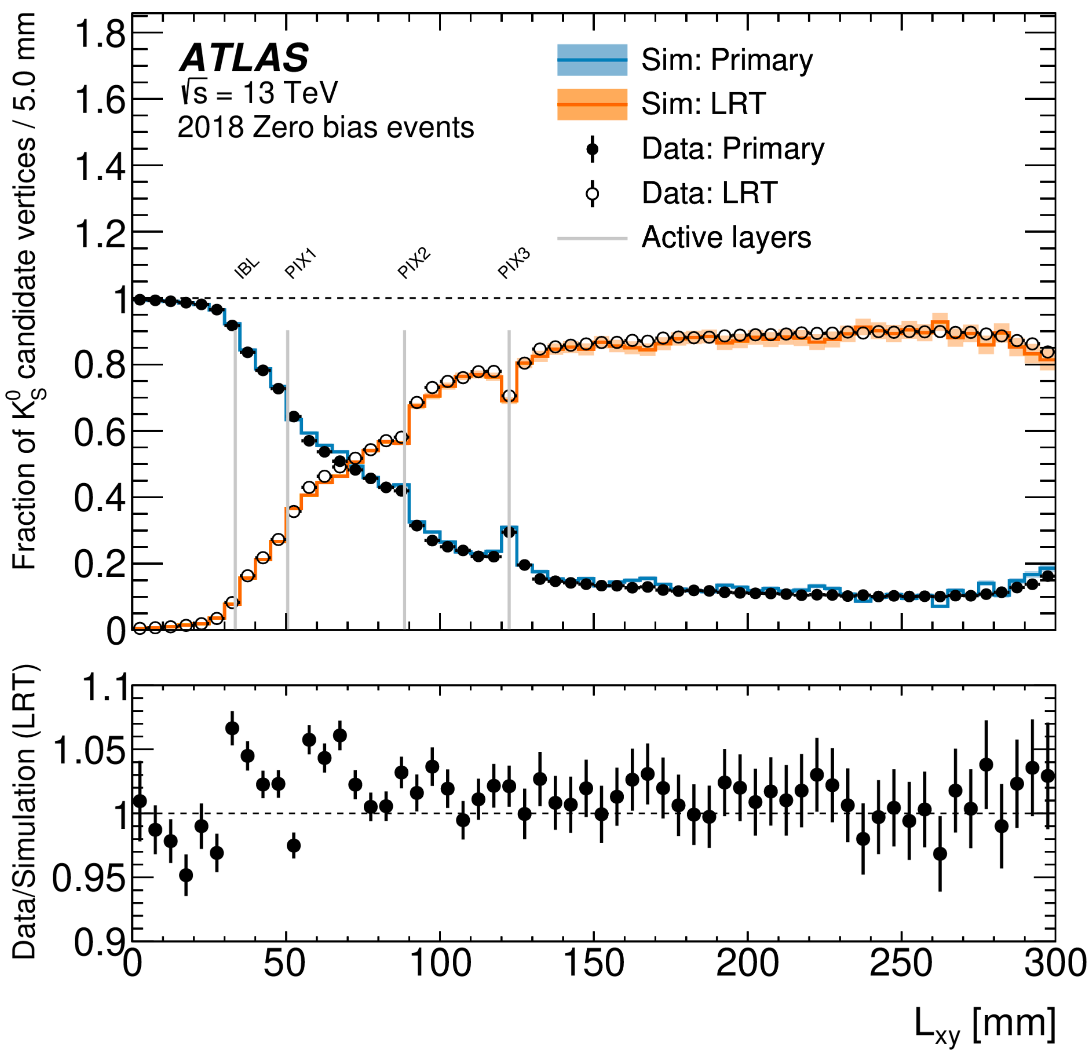
Experimental constraints

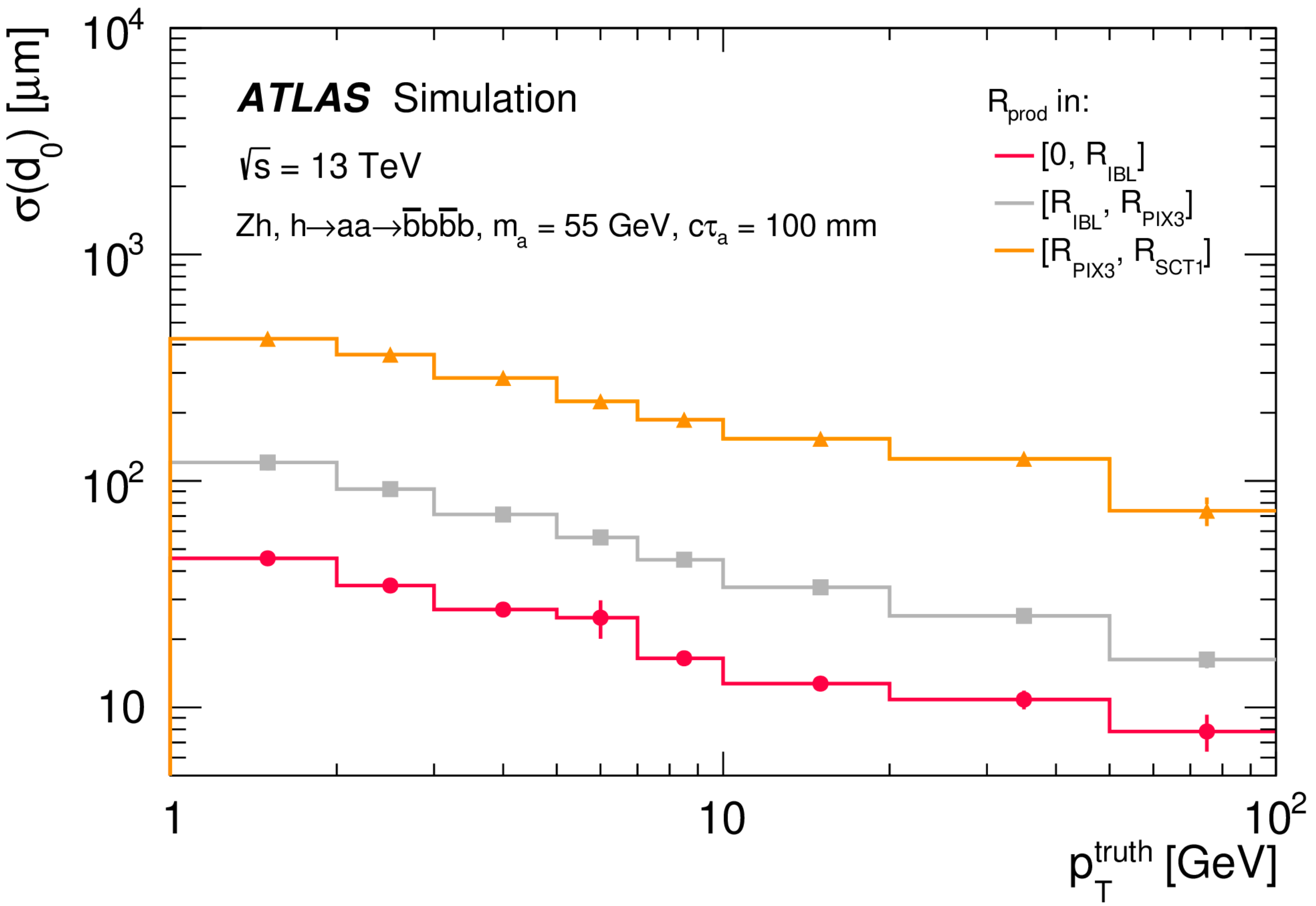
Karri Folan DiPetrillo
University of Chicago

IMCC Physics Meeting
6 July 2023

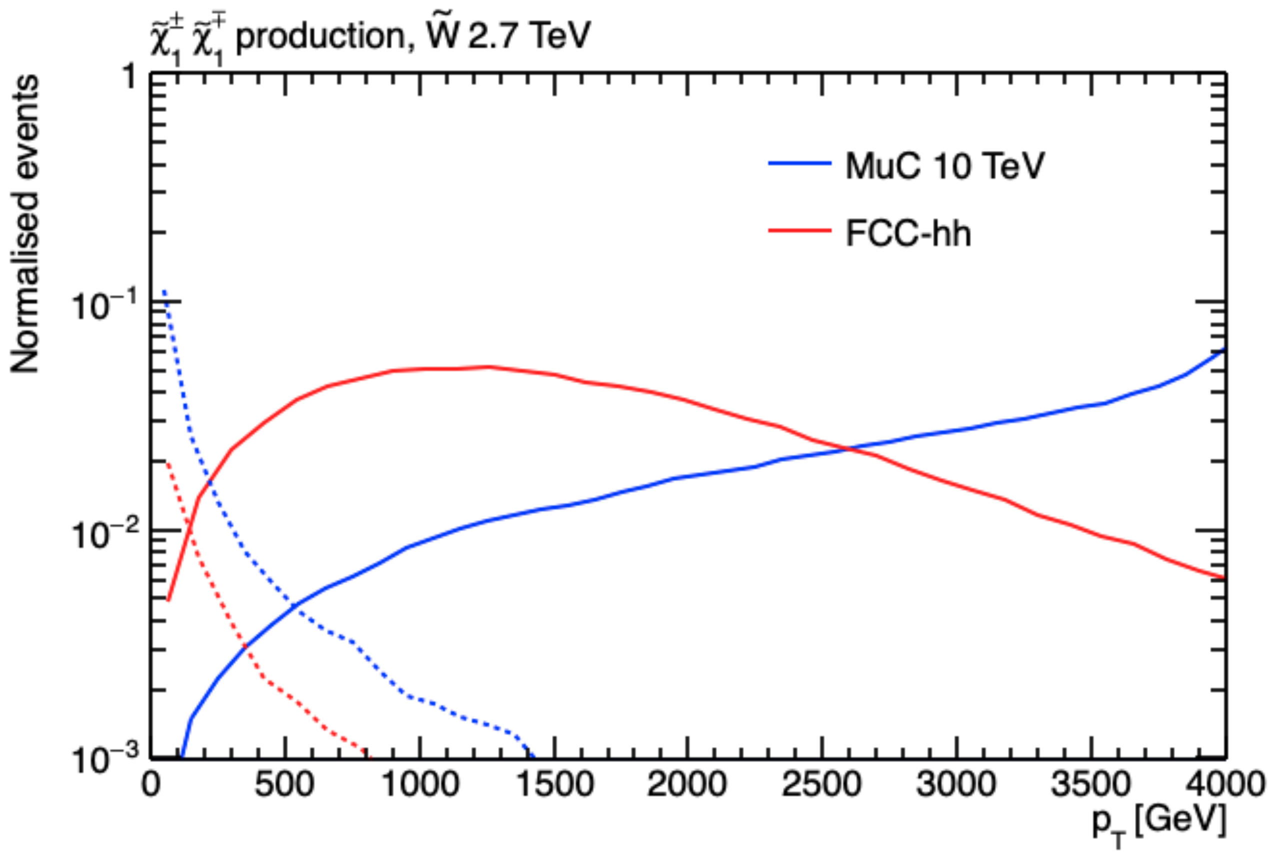
Large radius tracking

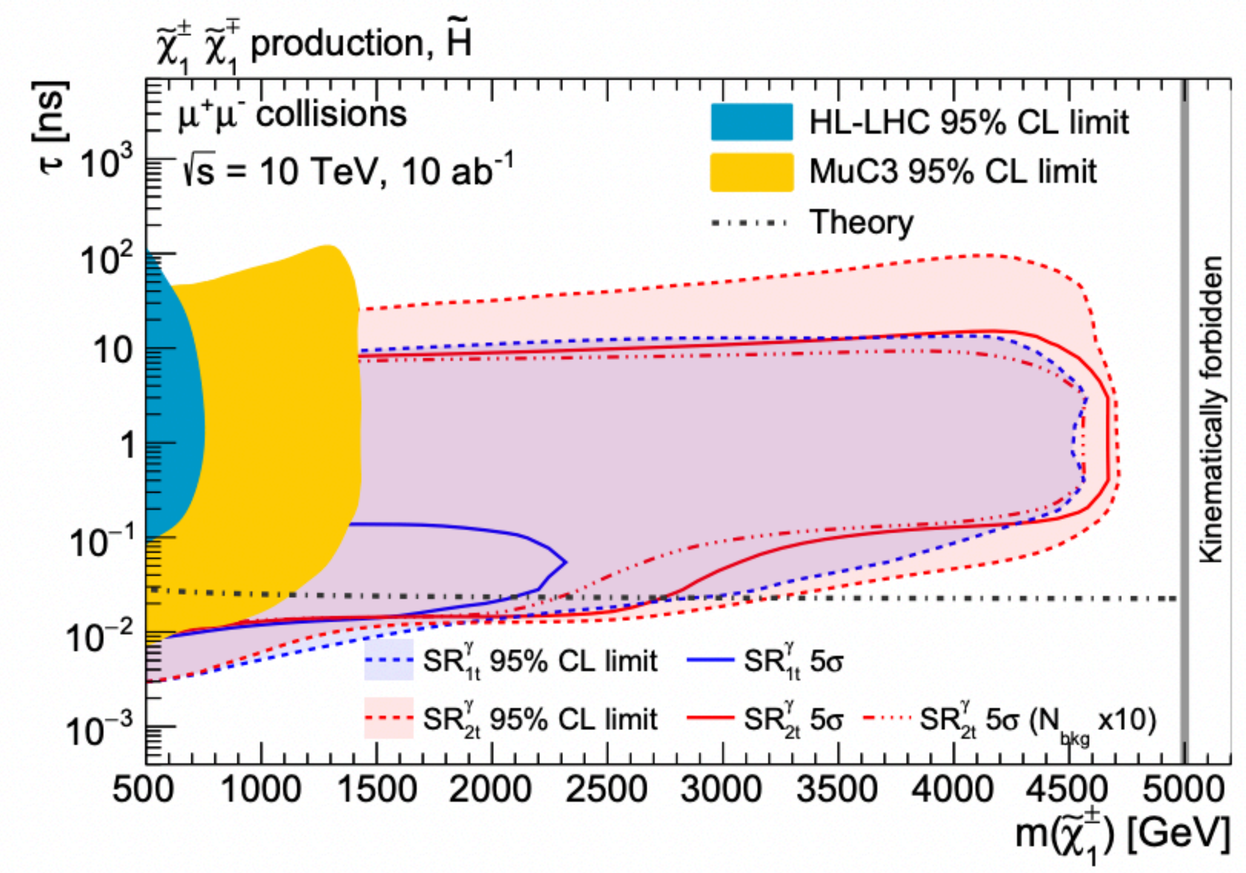
arXiv:2304.12867



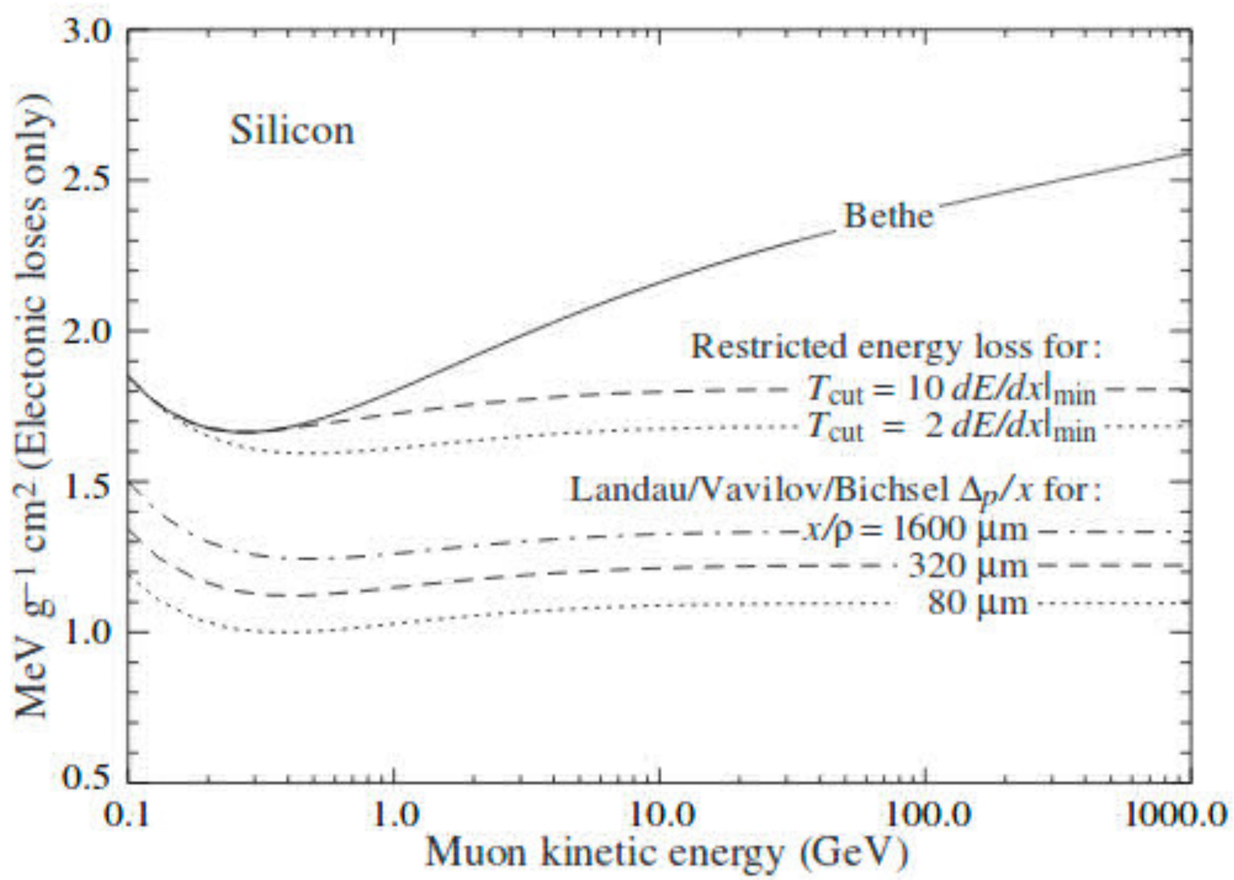


Charged LLPs/Disappearing track



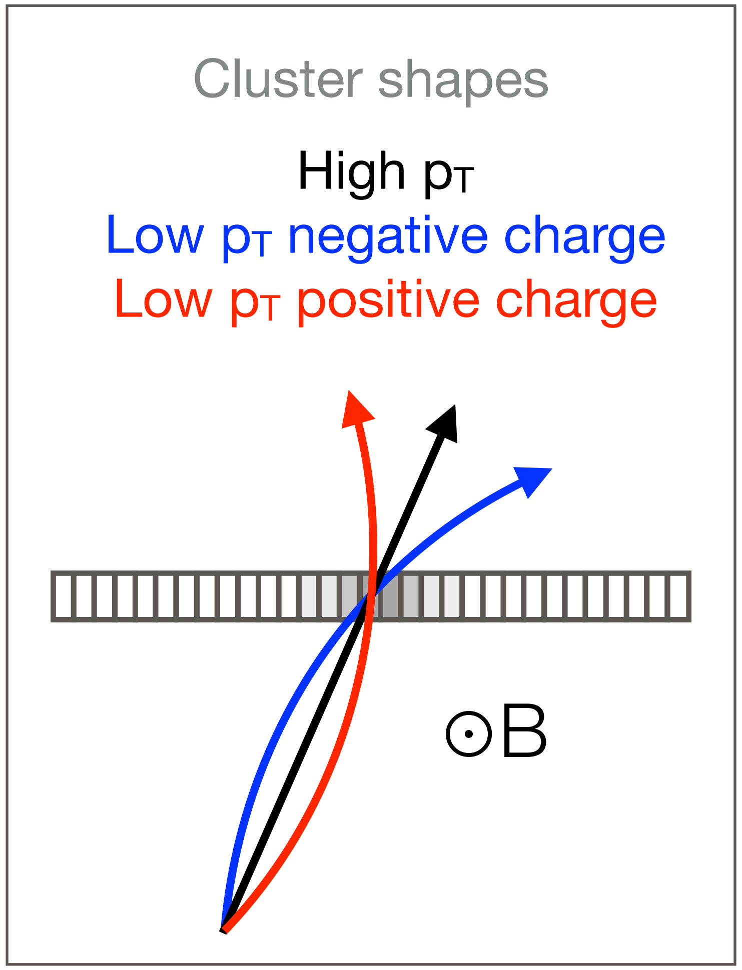


Cluster charge/shape



MPV & shape shifts
w/ detector thickness

MPV = 0.027 × ln(d) + 0.126 [keV]
width =$0.31 \times d^{0.81}$ [keV]



Time of flight

30 ps bunch length sets minimum time resolution (in MAP)

$$\left(\frac{\Delta m_{\mathrm{ToF}}}{m}\right)^2 = \left[\left(\frac{\Delta p_{\mathrm{T}}}{p_{\mathrm{T}}}\right)^2 + \left(\frac{1}{1-\beta^2}\right)^2\left(\frac{\sigma_{t_{\mathrm{hit}}}}{t_{\mathrm{hit}}}\right)^2\right]$$

Improves w/ L

Need good p_T resolution to improve S/B separation and measure mass in case of discovery