Emery Nibigira

FPD Seminar @SLAC

2025-7-22

This talk

- Motivation to go beyond the Standard Model
- Tracker-based signature: Heavy Stable Charged Particles
- Perspectives

The Standard Model is incredibly accurate

- **For the past half century or so, the SM has proven incredibly successful at describing many features of nature with accurate predictions**
  - The **Higgs boson discovery** marked a major turning point in the history of the knowledge

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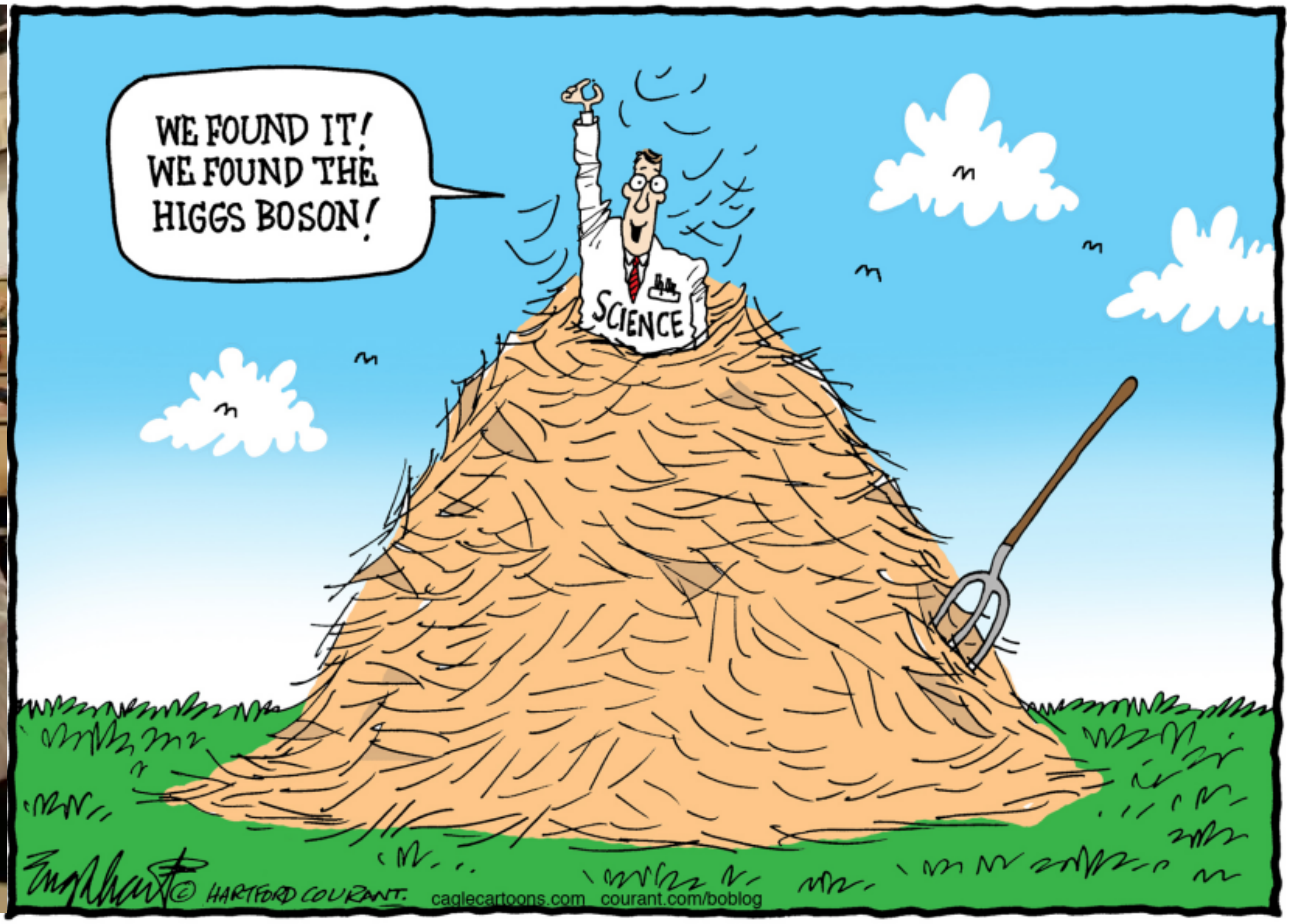
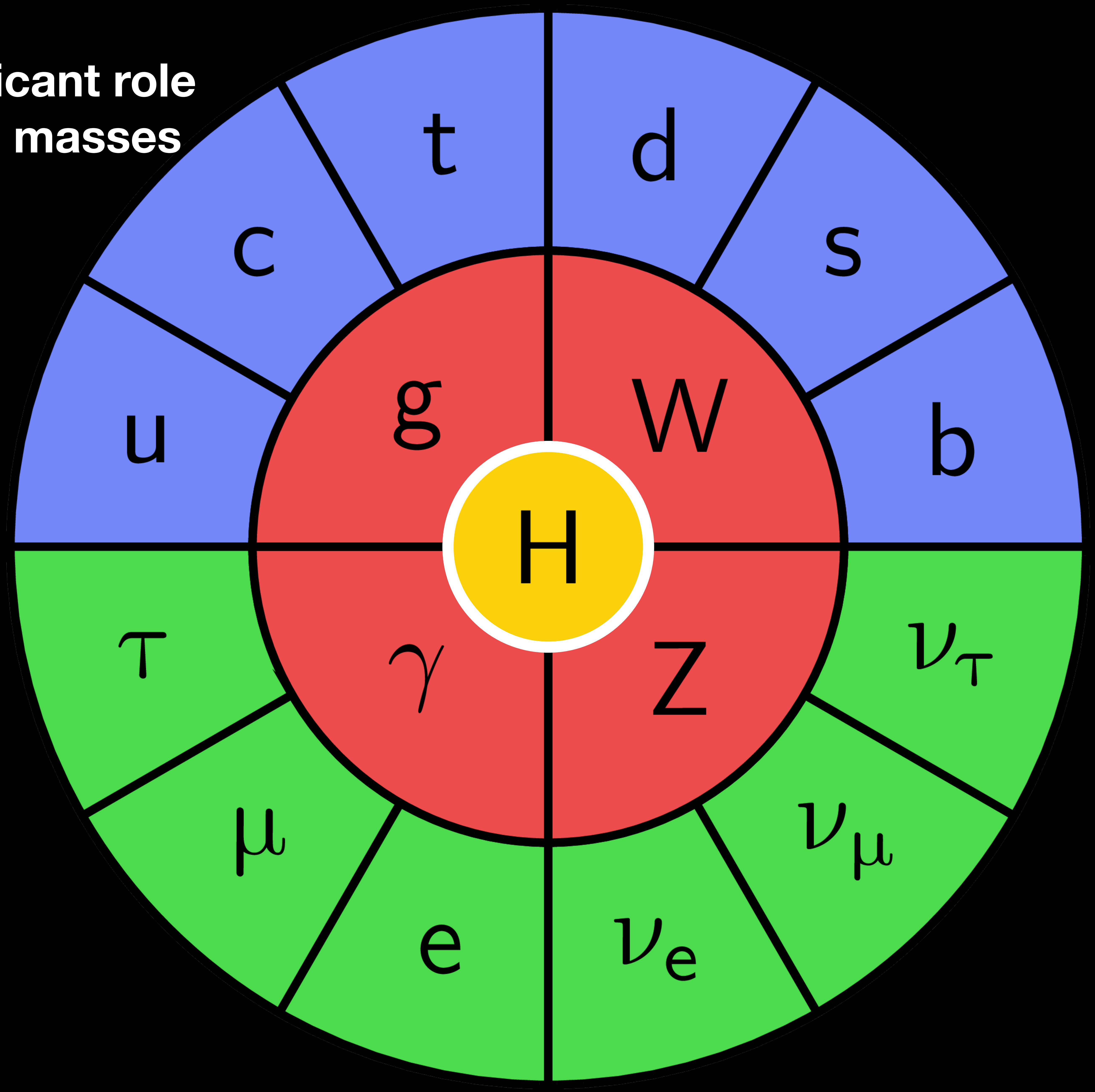


[Source]

The Last Piece of the Puzzle

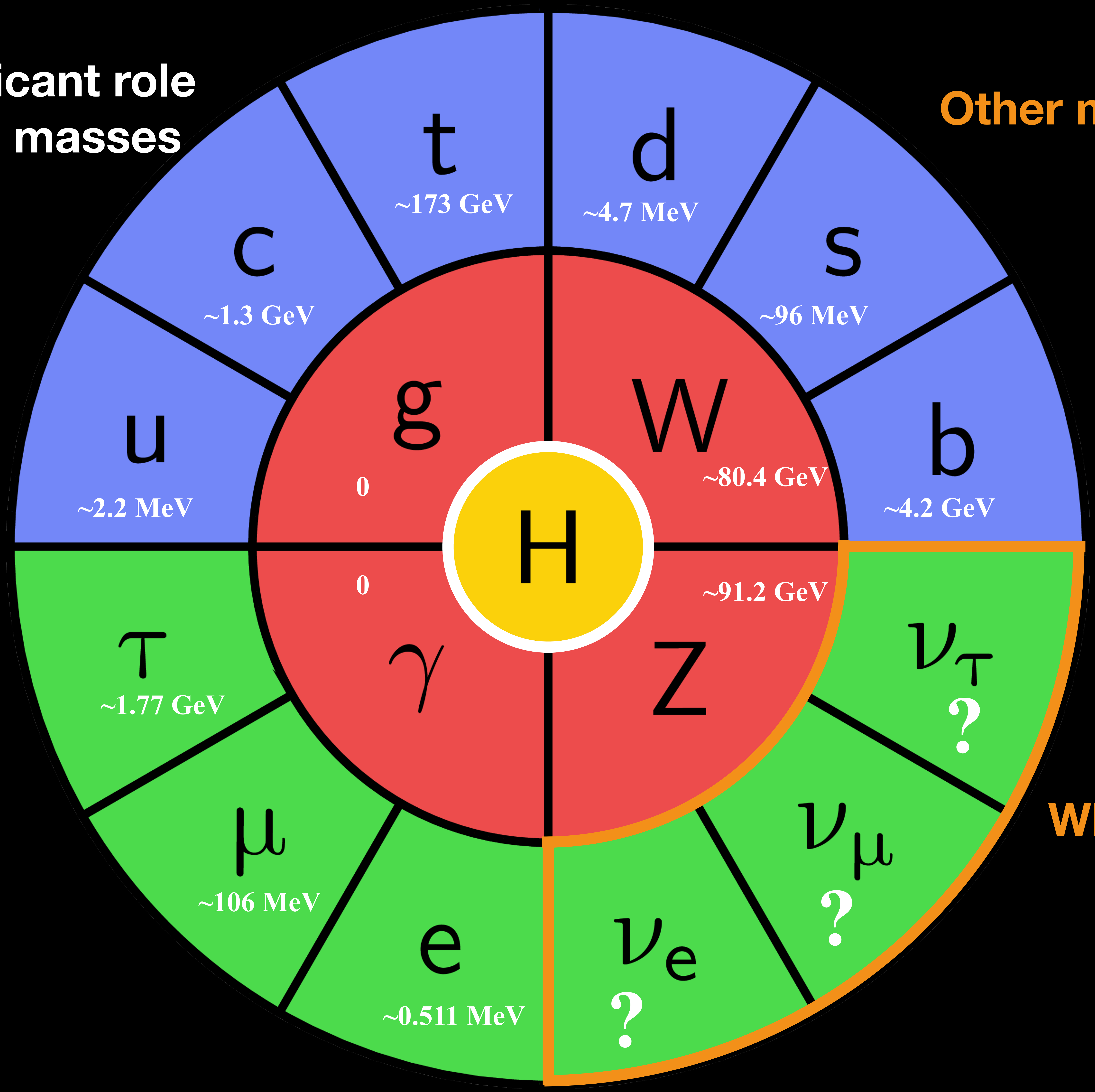
The SM plays a significant role in elementary particle masses



The Last Piece of the Puzzle became a Puzzle

The SM plays a significant role in elementary particle masses

Except for Neutrinos



Other mass giving mechanism?

Why are they left-handed?

The Last Piece of the Puzzle became a Puzzle

Naturally unnatural?

Why is the Higgs boson so light?

Naturally unnatural?

Why is the Higgs boson so light?

$$\left(m_H^{obs}\right)^2 = \left(m_H^{bare}\right)^2 + \Delta m_H^2$$

Naturally unnatural?

The SM has to be valid at up to a certain cutoff scale Λ

$$\left(m_H^{obs}\right)^2 = \left(m_H^{bare}\right)^2 + \delta\left(\Lambda^2\right)$$

The Last Piece of the Puzzle became a Puzzle

Naturally

unnatural?

The SM has to be valid at up to a certain cutoff scale Λ

$$\left(m_H^{obs}\right)^2 = \left(m_H^{bare}\right)^2 + \delta\left(\Lambda^2\right)$$

$\sim 10^4$ GeV

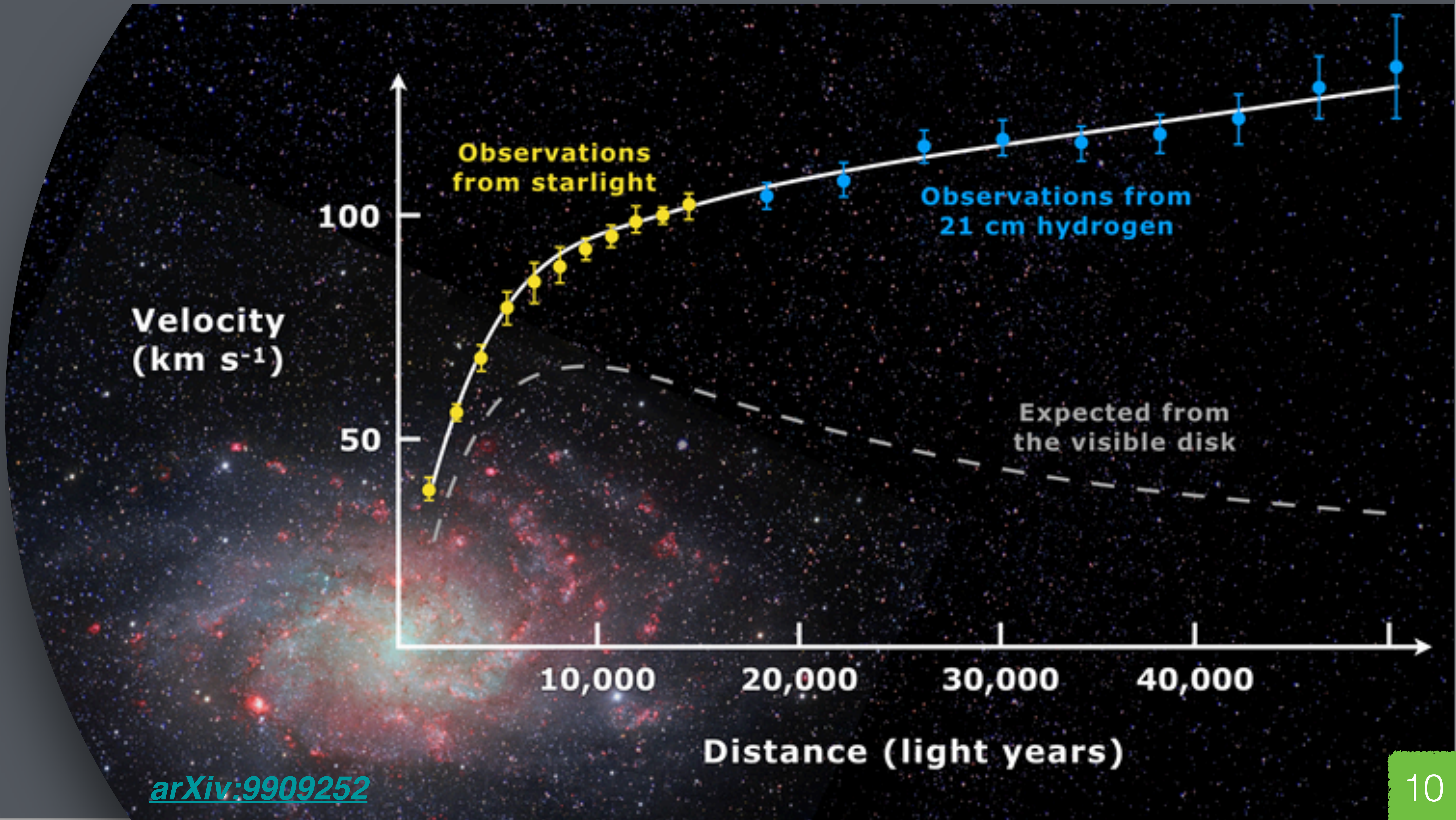
Plank scale

$\sim 10^{-38}$ GeV

extreme fine tuning in order to align predictions with measurements

When you think of SM as a predictive model

Dark Matter was never predicted



arXiv:9909252

… and many more

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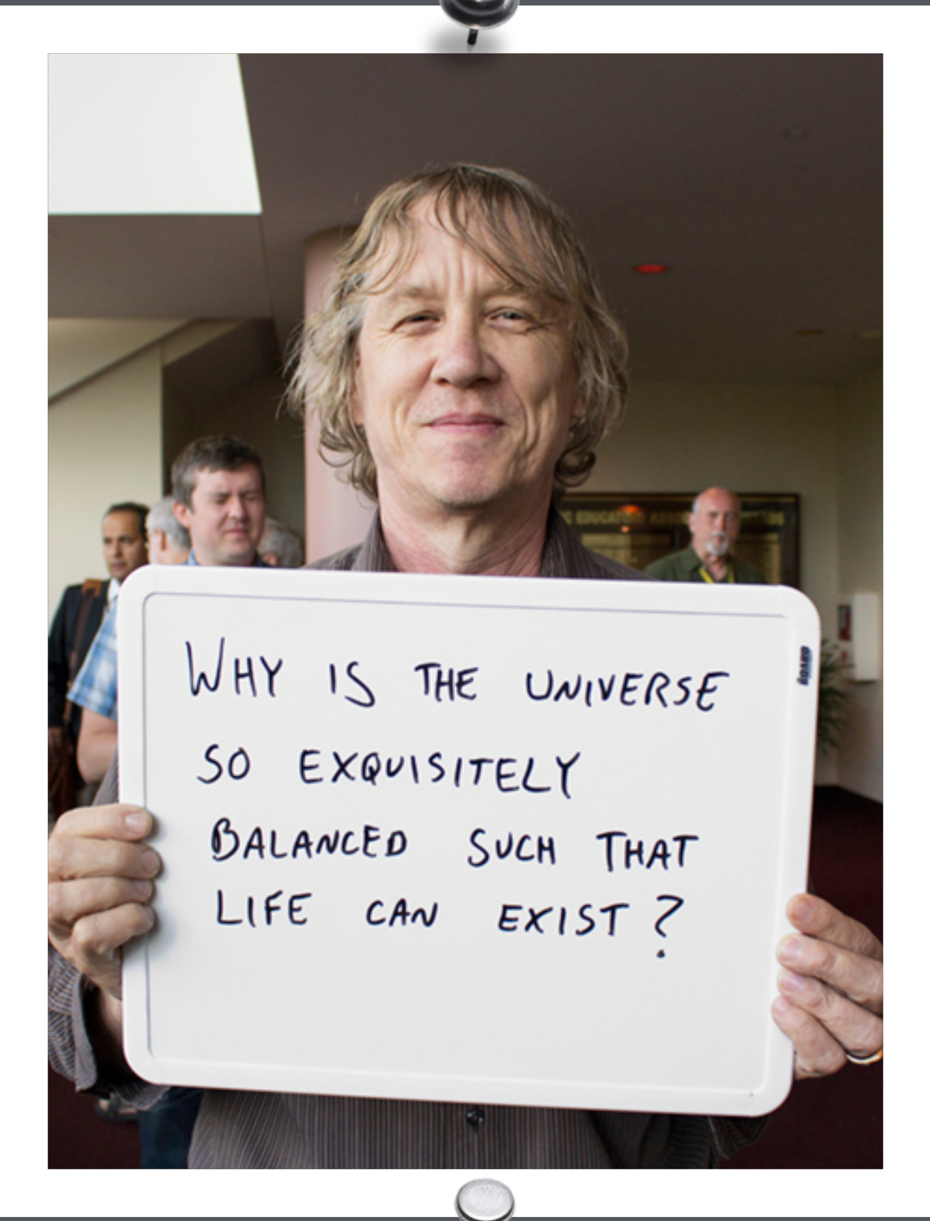
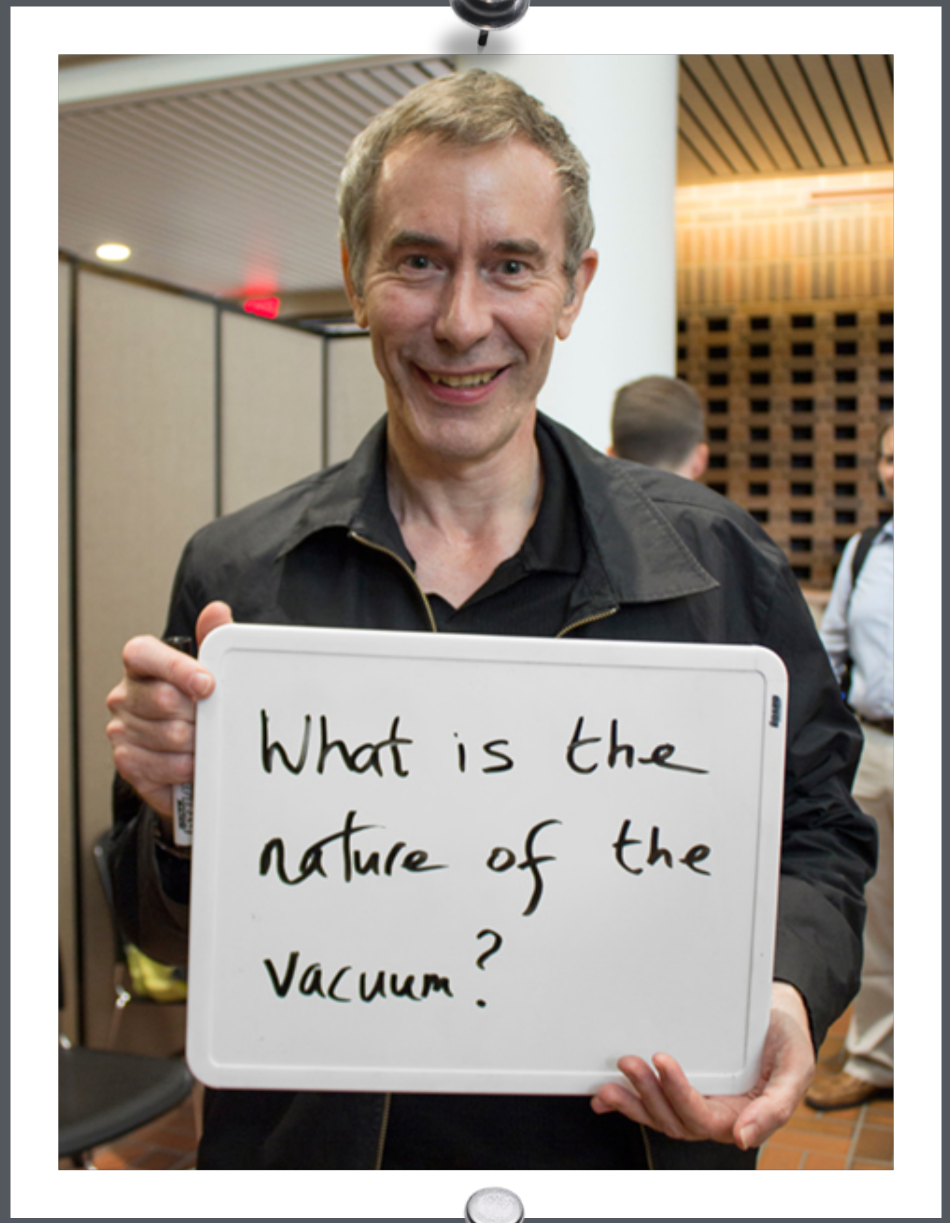
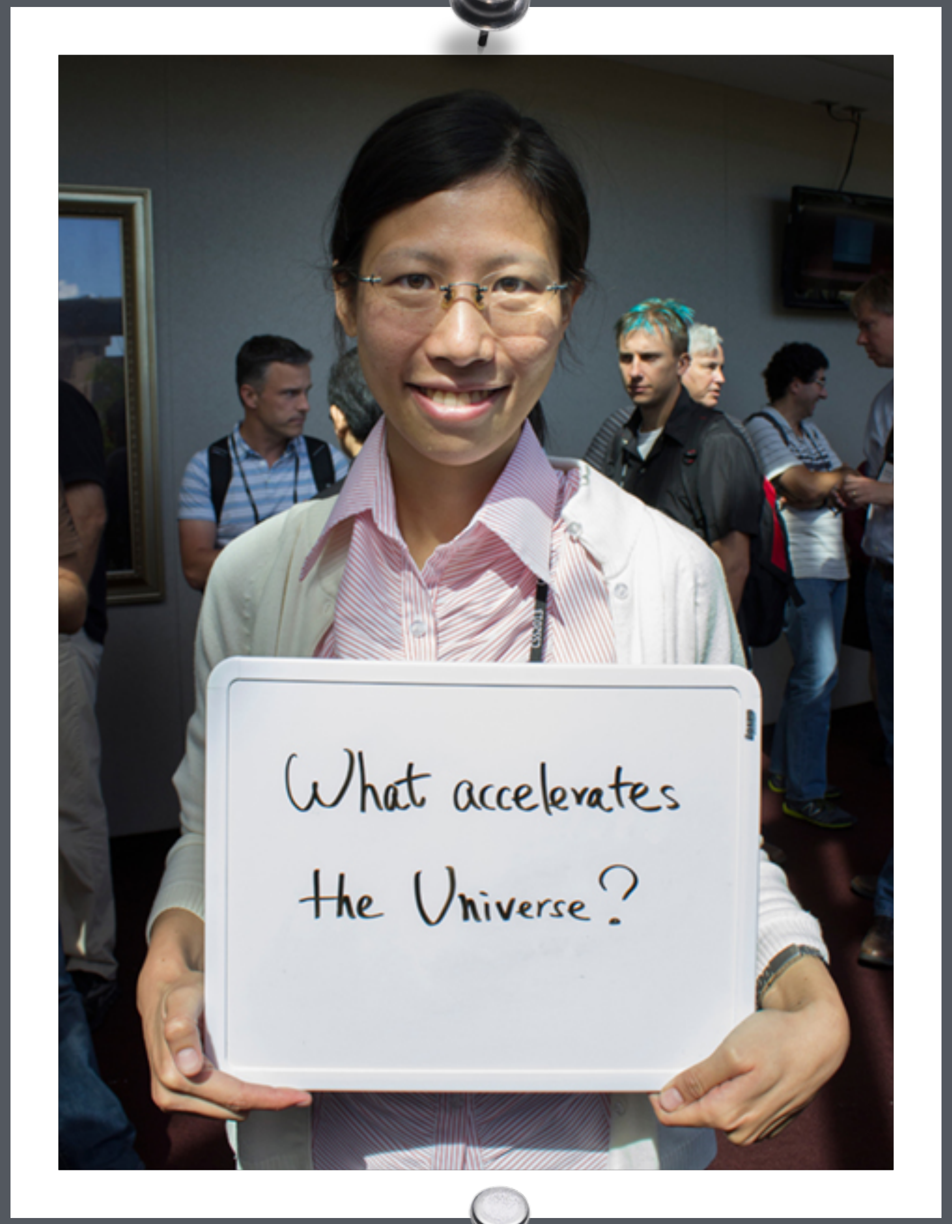
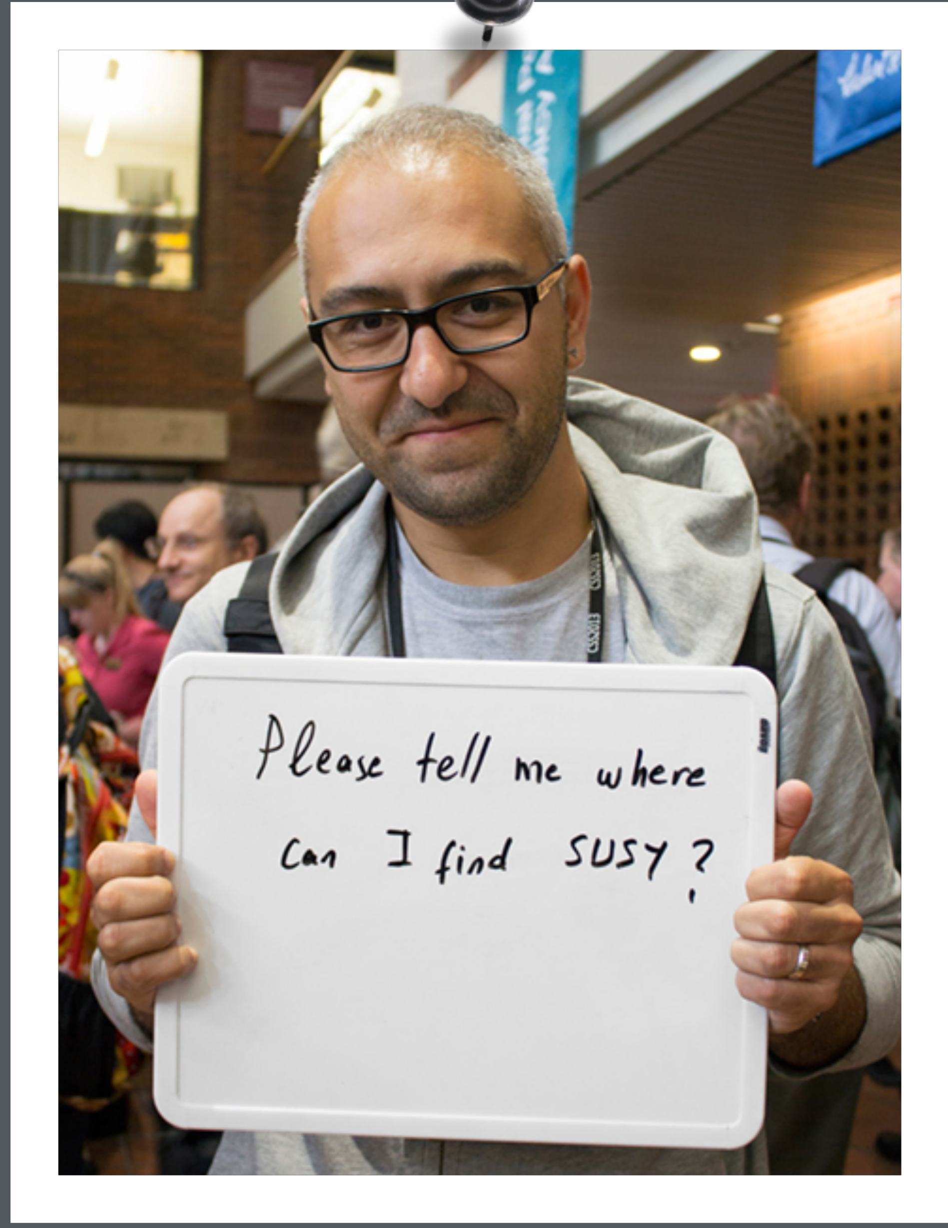
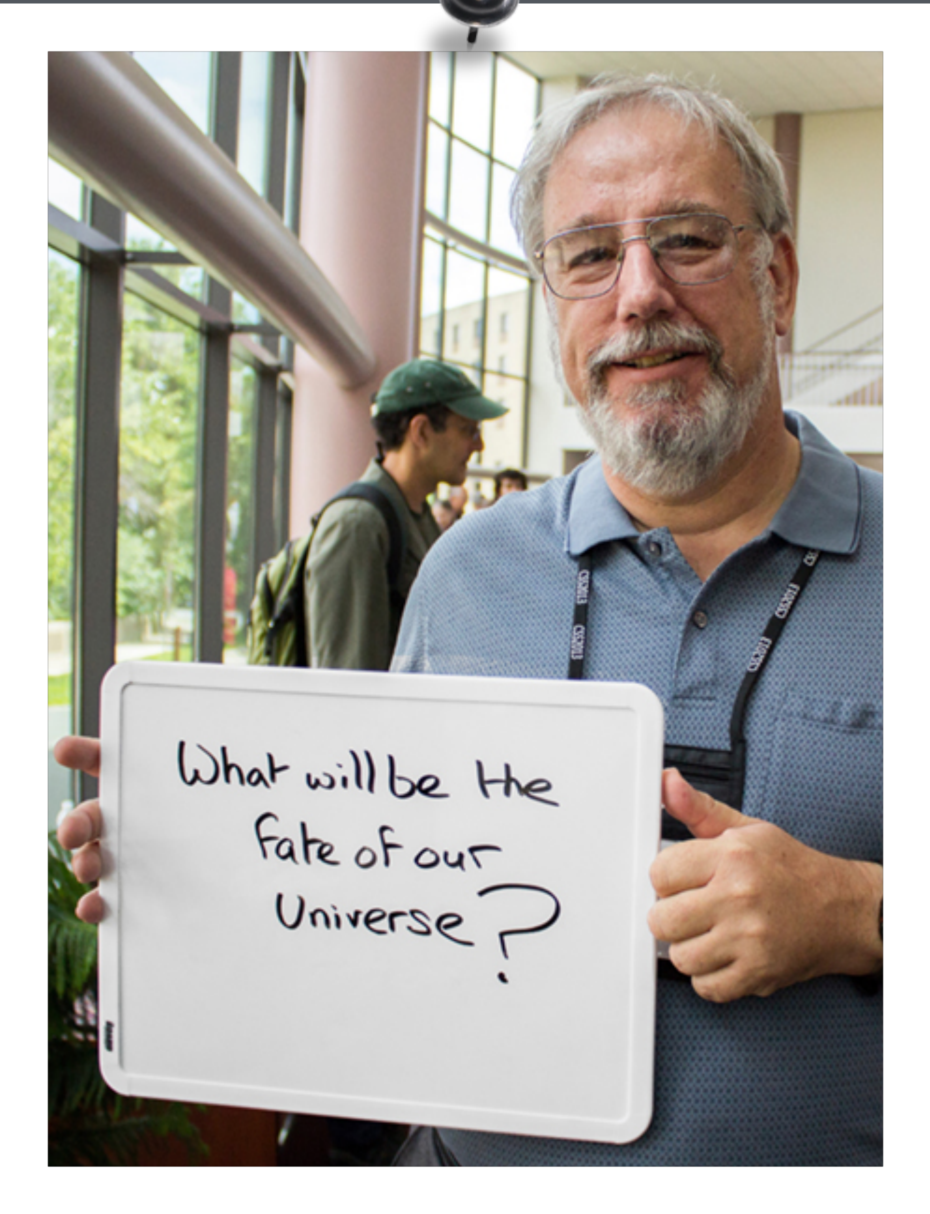






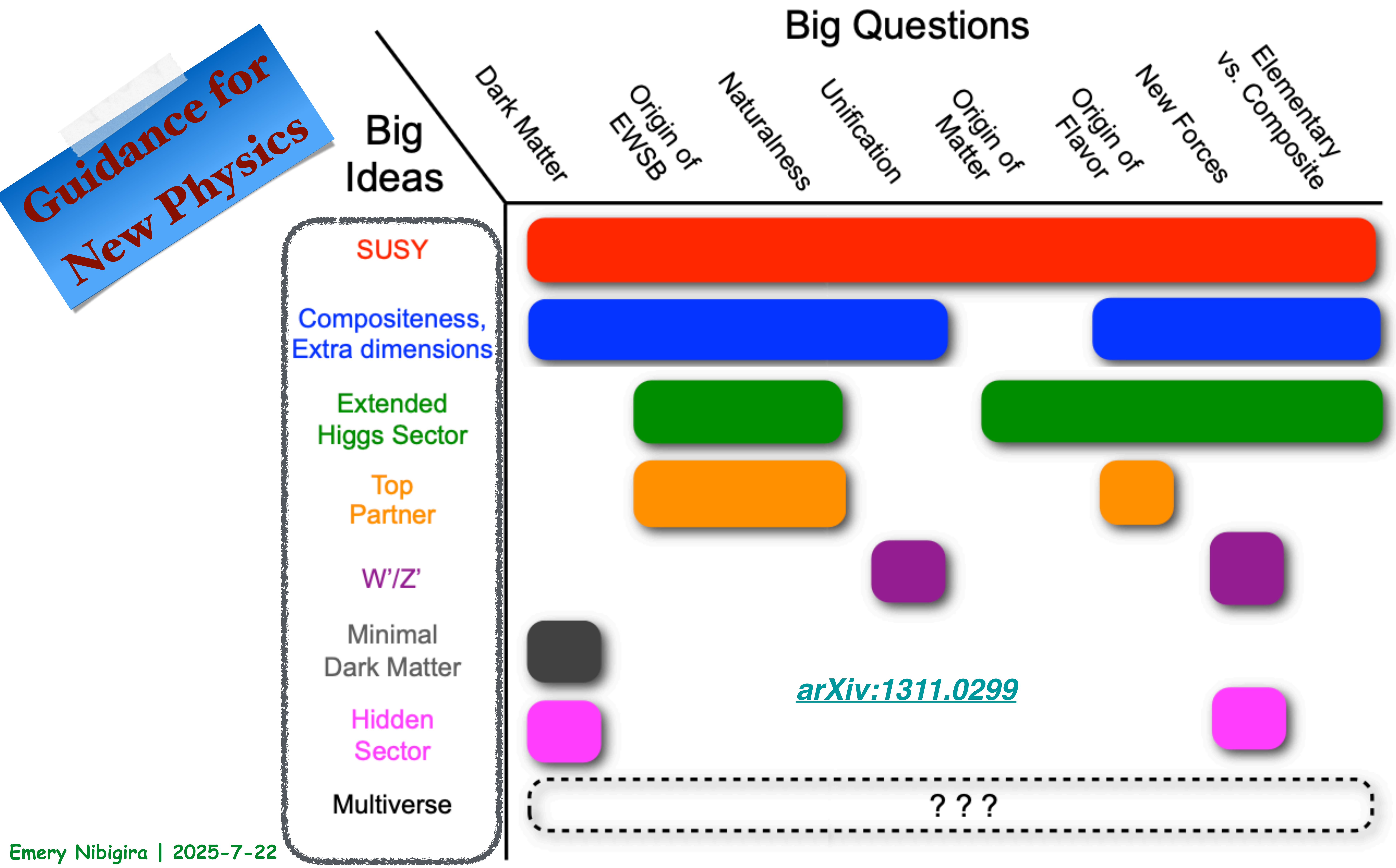




@ Snowmass 2013

Physics Beyond the SM must Exist and Searched For

- Many hypotheses to address the lack of explanation from the SM



@ Snowmass 2013

Physics Beyond the SM must Exist and Searched For

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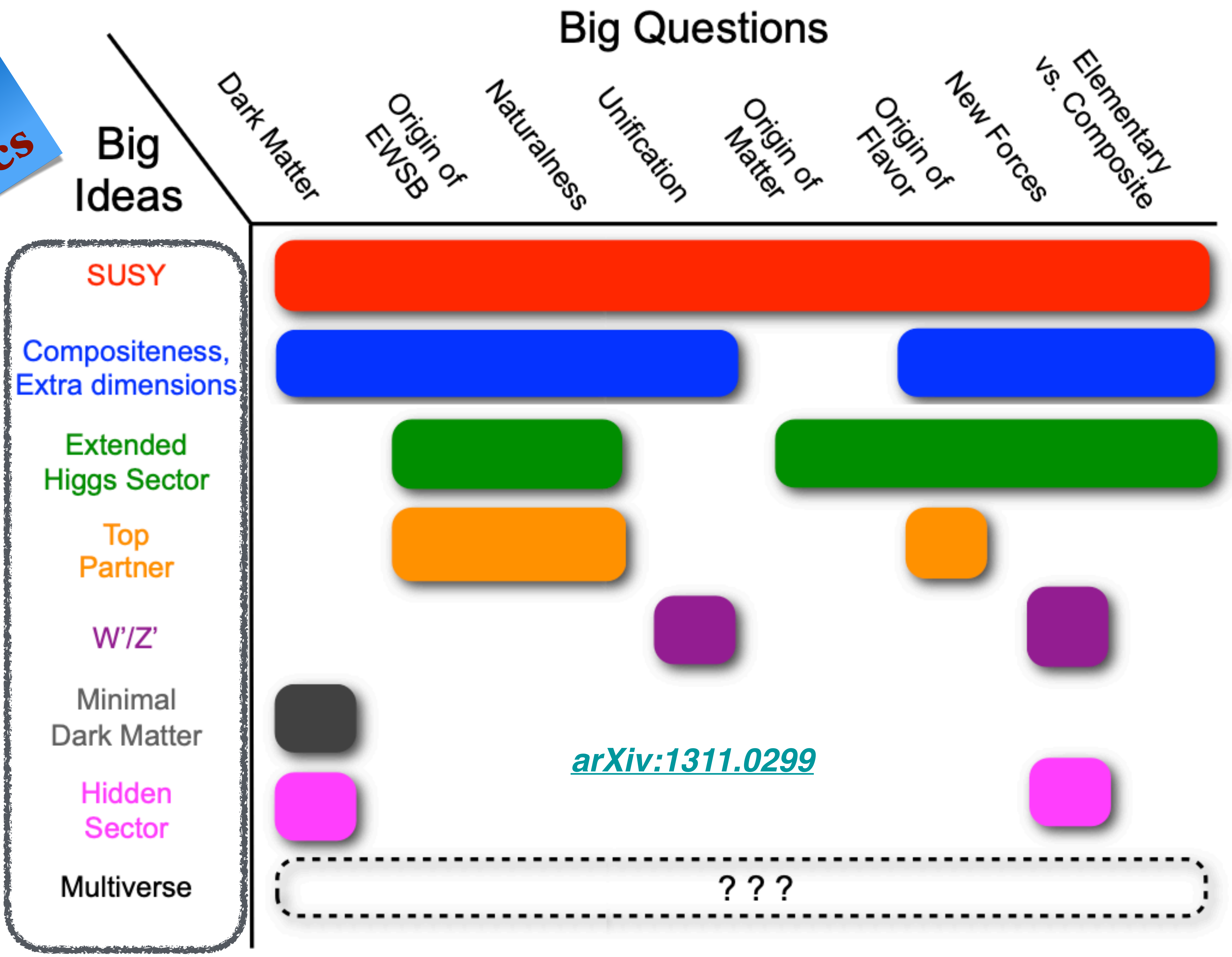
Guidance for New Physics

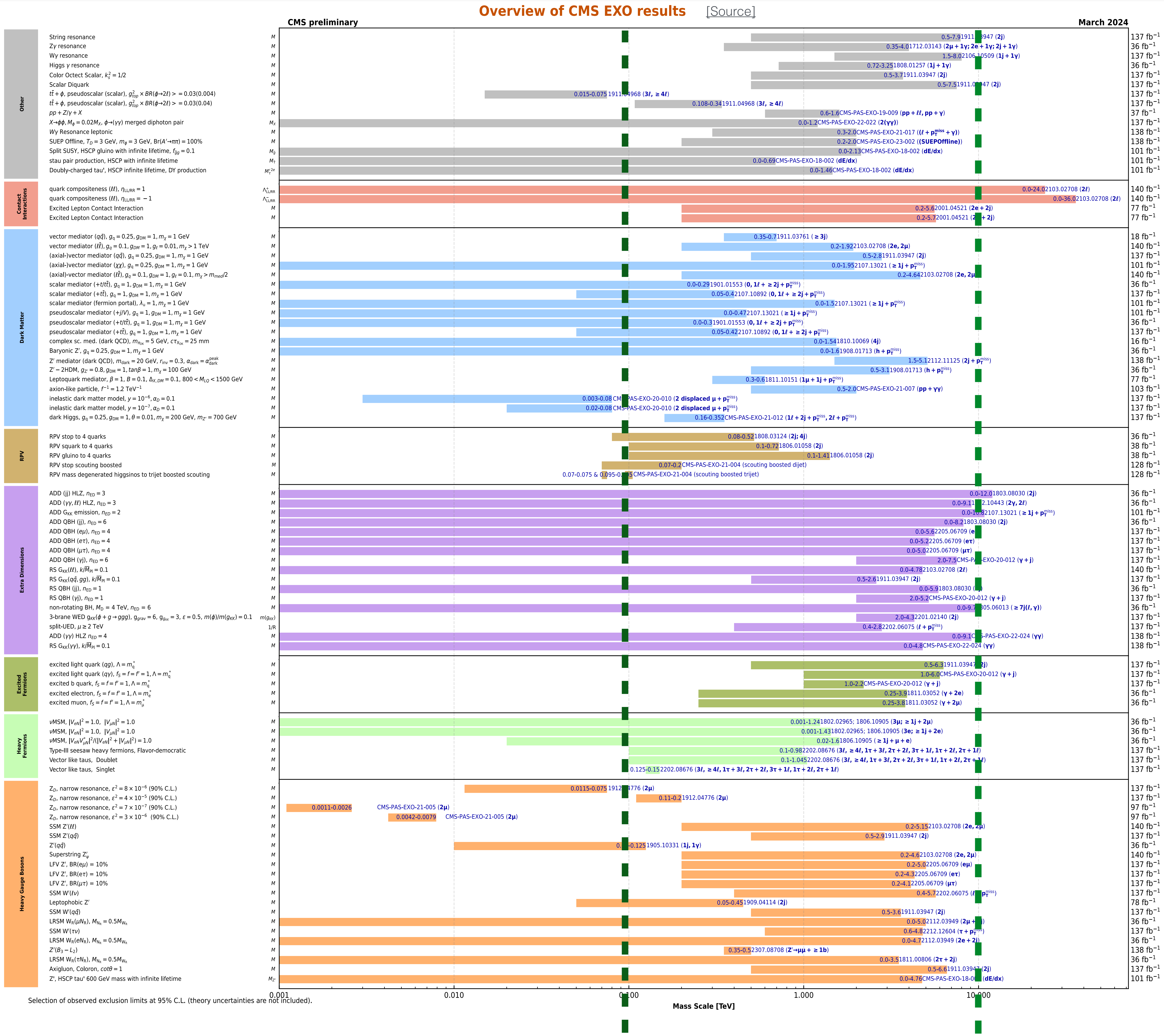


Could exist at TeV scale

@ Snowmass 2013

Why haven't we found New Physics yet???

Probing scales in the range of 1-10 TeV



1 TeV

10 TeV

It could be that New Physics

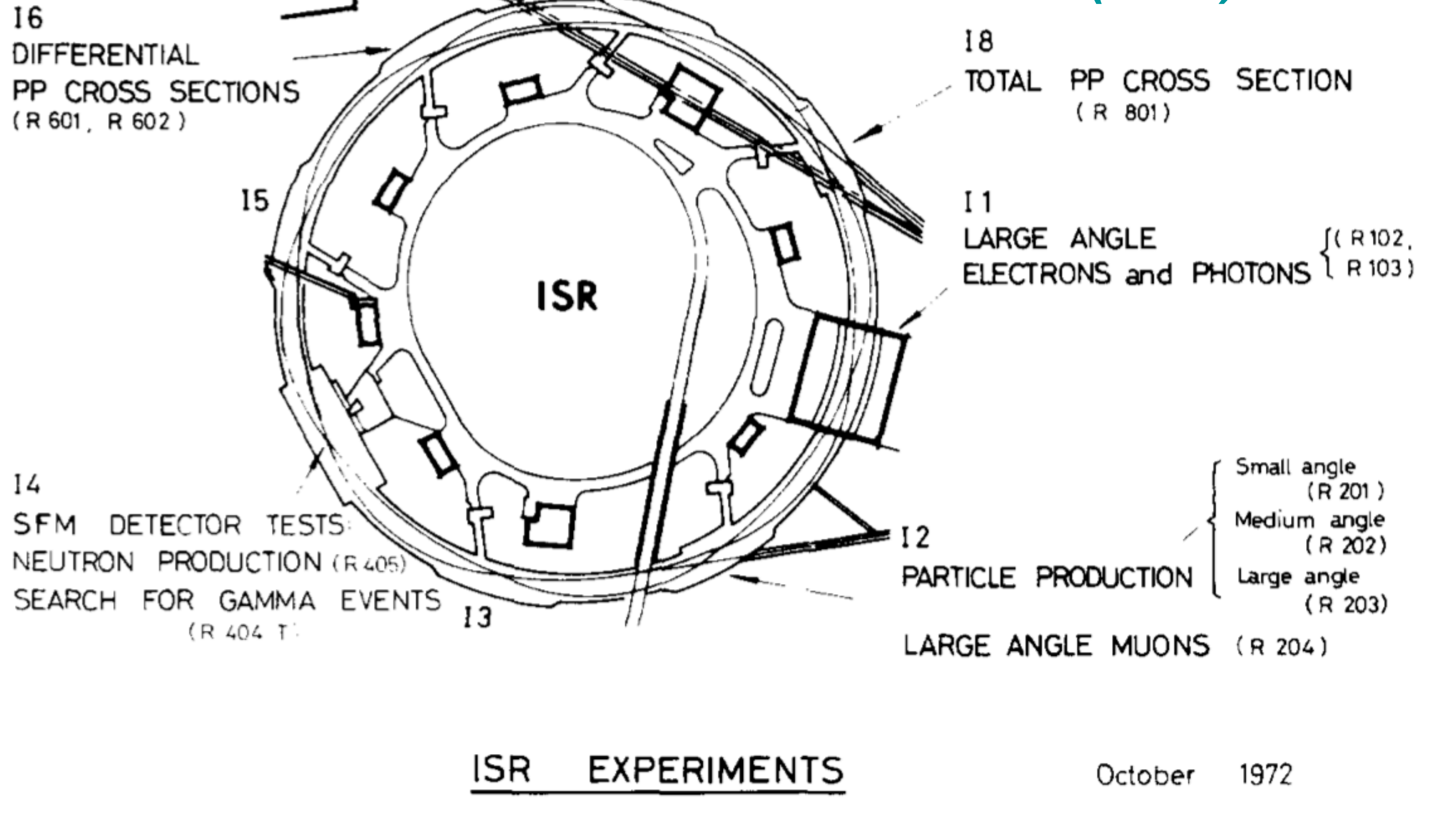
- lies Beyond Energy Frontier
- is within our reach but requires advanced particle detectors and/or particle identification methods
  - may be looking in the wrong way (guidance)

Early 70's

CERN built the first hadron collider:

The Intersecting Storage Rings (ISR)

NIM 108 (1973) 205-223



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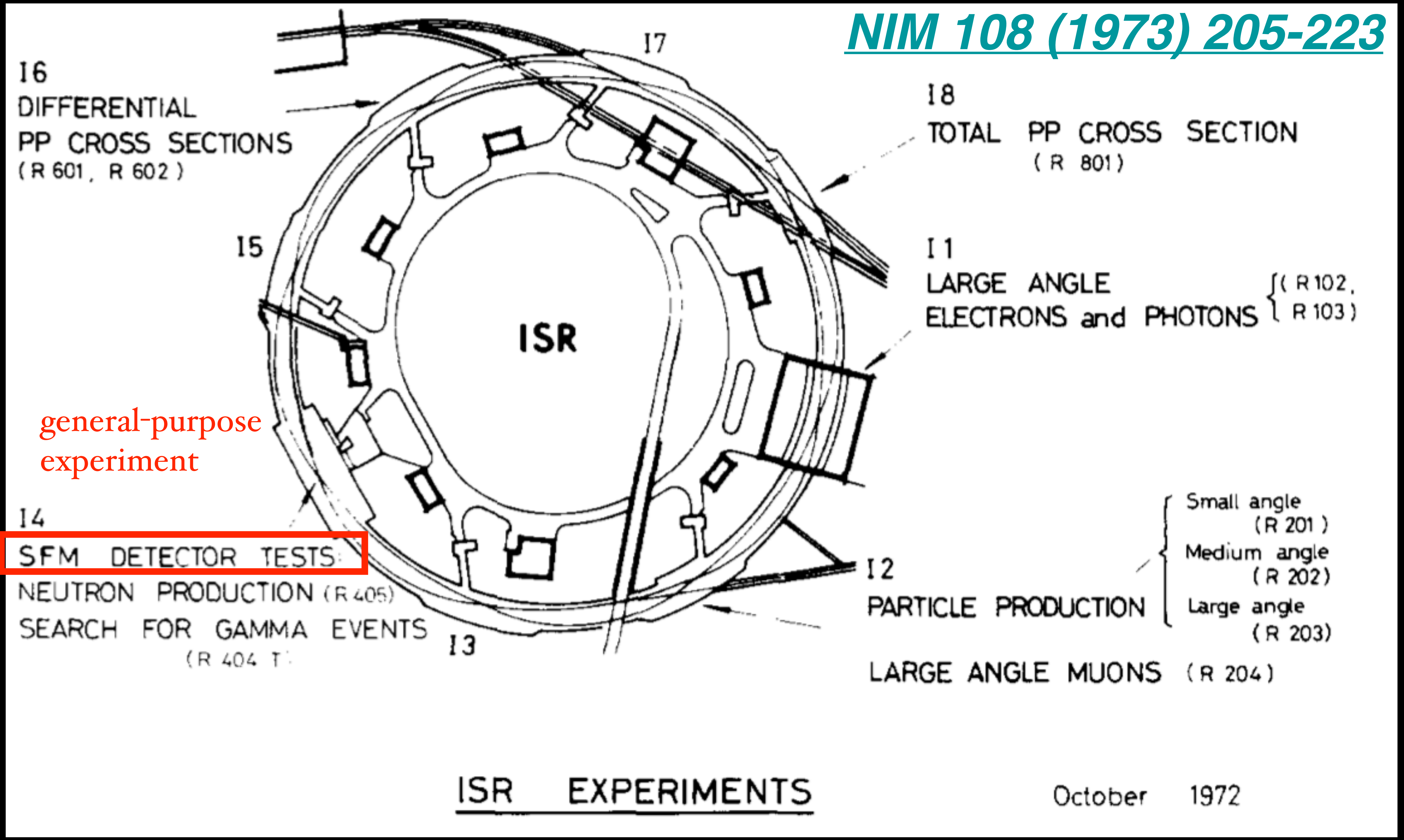


- **SFM** was convinced hadronic physics phenomena would reveal themselves in Forward direction

Unfortunately, did not instrument the Transverse direction

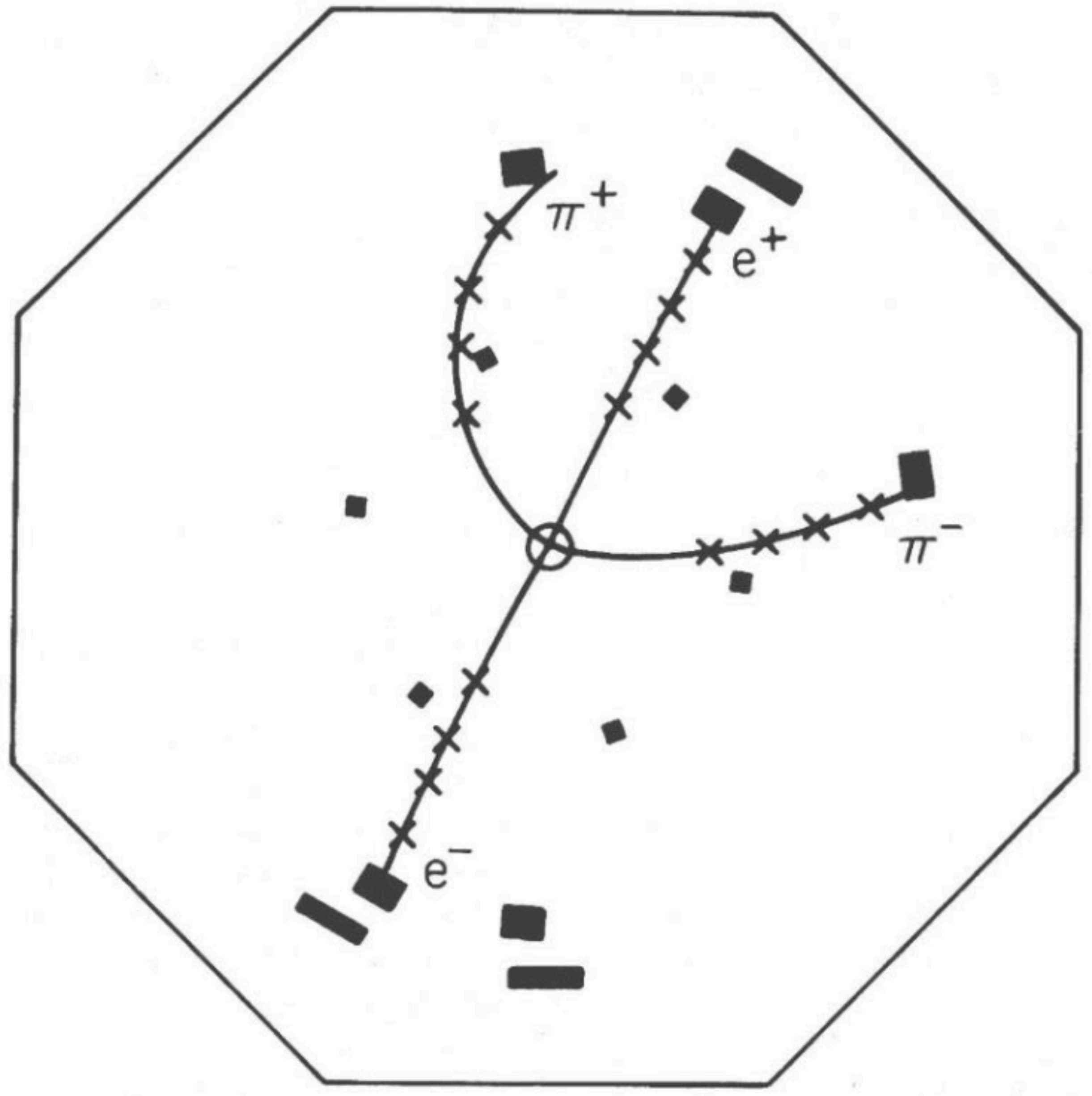
Meanwhile in the US …

at nearly the same time

two independent research groups proved the existence of a fourth quark, charm

Stanford Positron Electron Accelerating Ring at SLAC

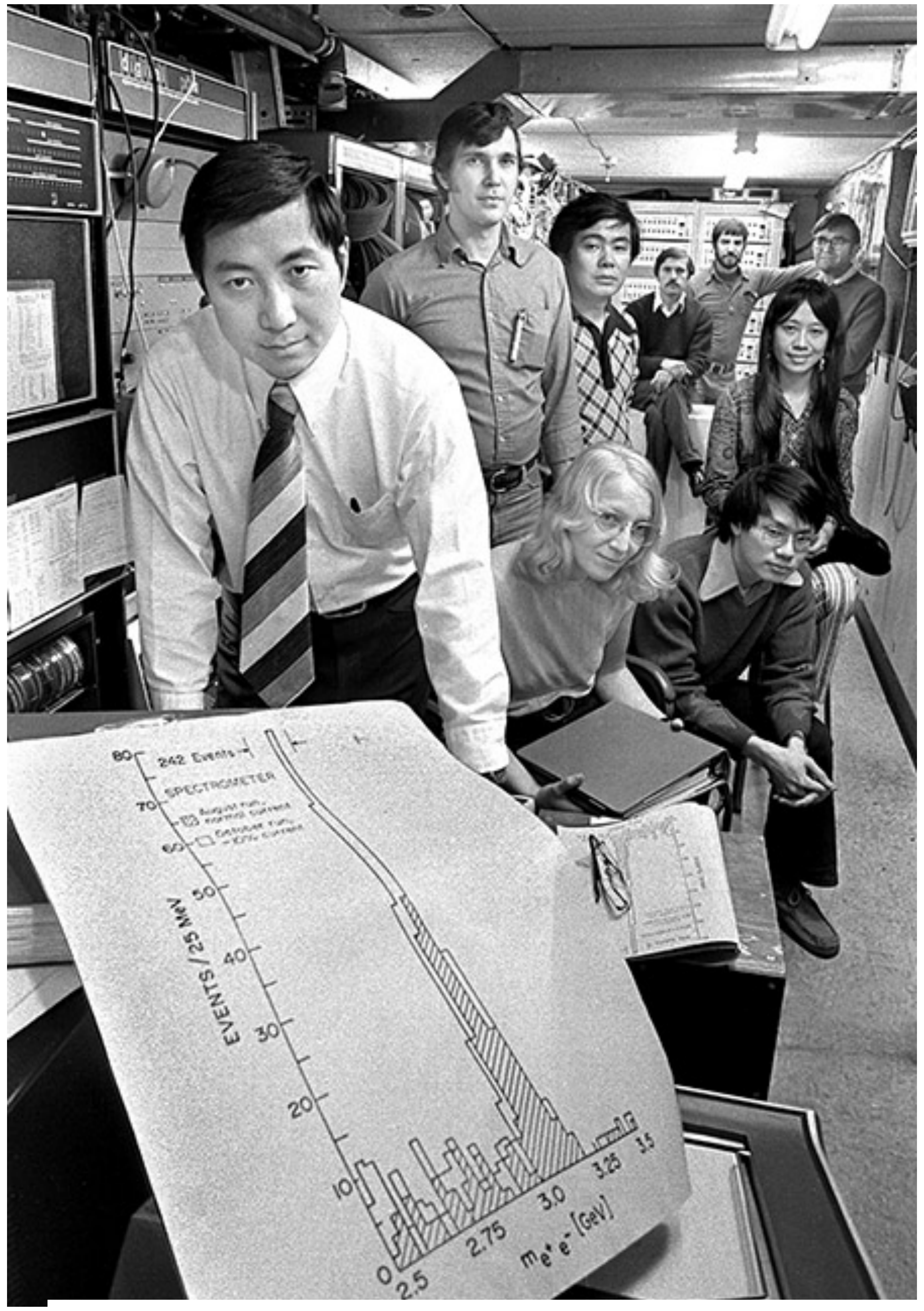
$\sqrt{s}$ = 2.6 to 8 GeV



Computer reconstruction of a psi-prime decay i the Mark I detector, making a near-perfect image of the Greek letter psi. (SLAC)

Alternating Gradient Synchrotron at BNL ~30 GeV

(**J Particle** Experiment)



Samuel Ting and colleagues display a graph showing an excess of events at about 3.1 GeV. Credit: Courtesy of Brookhaven National Laboratory

J/Psi discovery sparked the November Revolution

Why particle detector instrumentation matters

Lessons Learned from the November Revolution

01

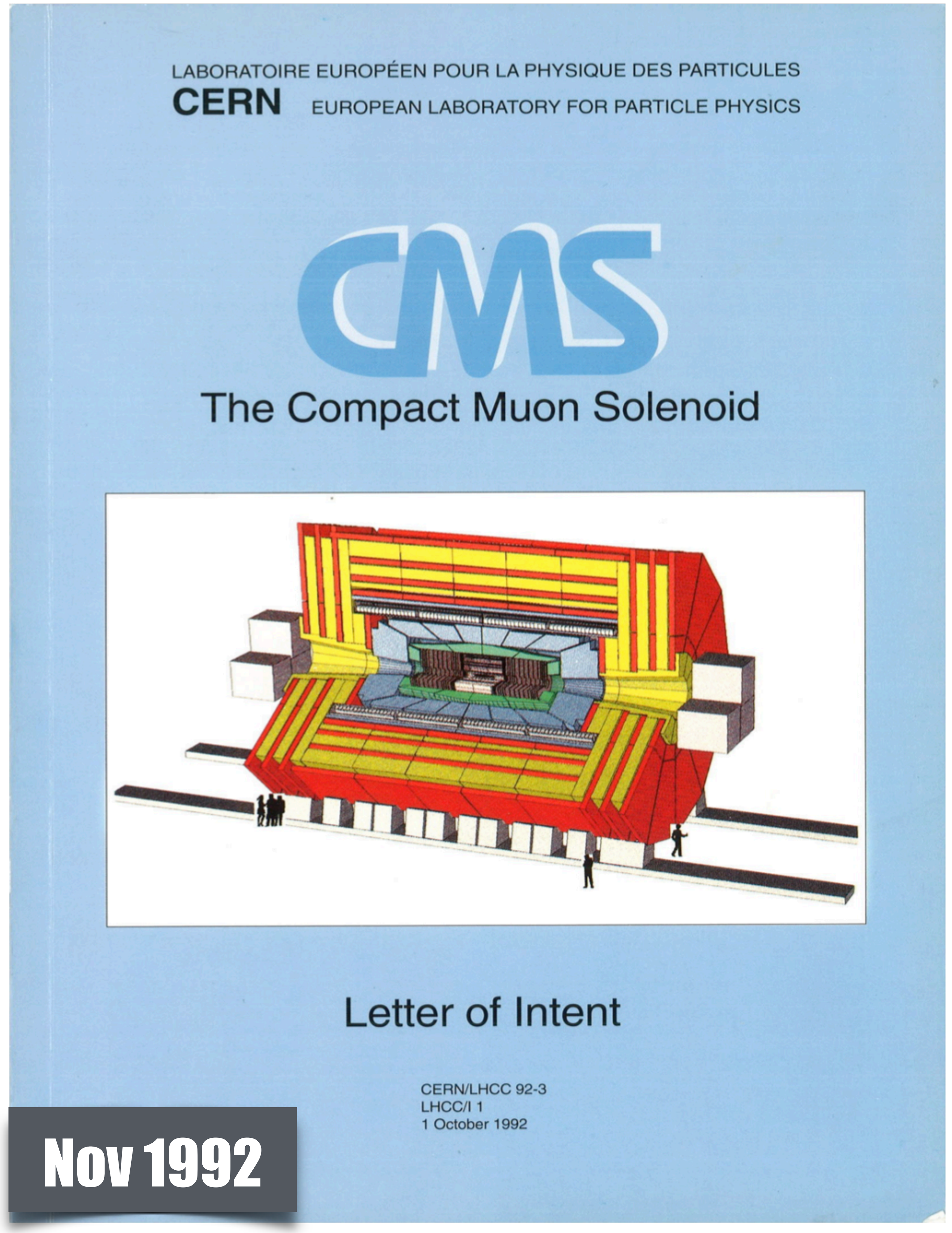
- ISR had enough $\sqrt{s} = 28\ \mathrm{GeV}$ for observing a spectrum of $c\bar{c}$ states. If ISR had a hermetic detector, they could have discovered J/Psi
  - **Model Guidance and Detector capabilities are crucial (physics reach)**

02

- J-particle experiment was rejected (CERN, Fermilab), thought useless
  - **Robust strategy is essential to success (important for future colliders)**

Birth of the CMS Detector

20 years later



Nov 1992

CMS design objectives

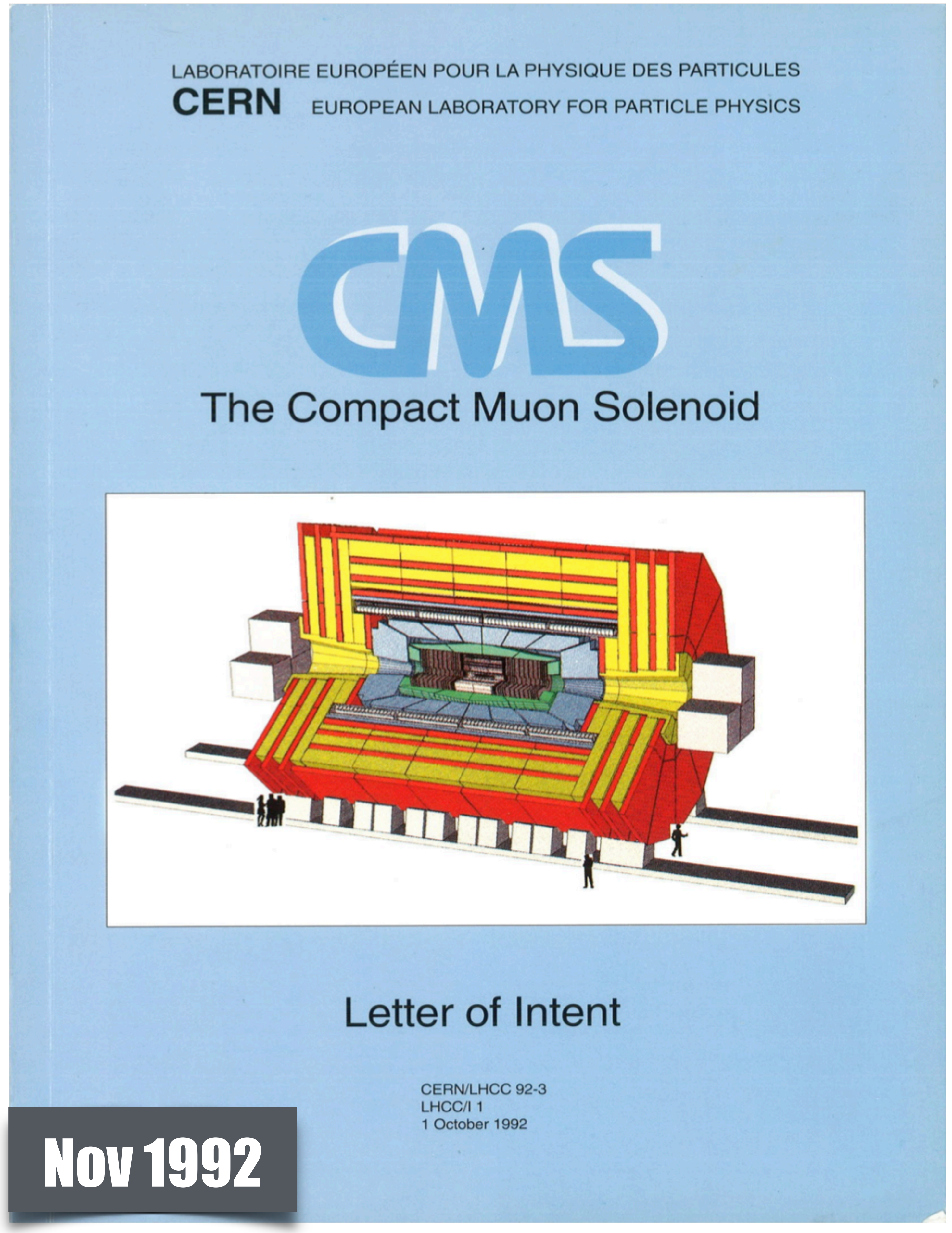
(1) A very good and redundant muon detection system

(2) The best possible e/gamma calorimeter consistent with (1)

(3) High quality central tracking to achieve (1) and (2)

(4) "Hermetic" hadron calorimeter to entirely surround the collision and prevent particles from escaping

20 years later



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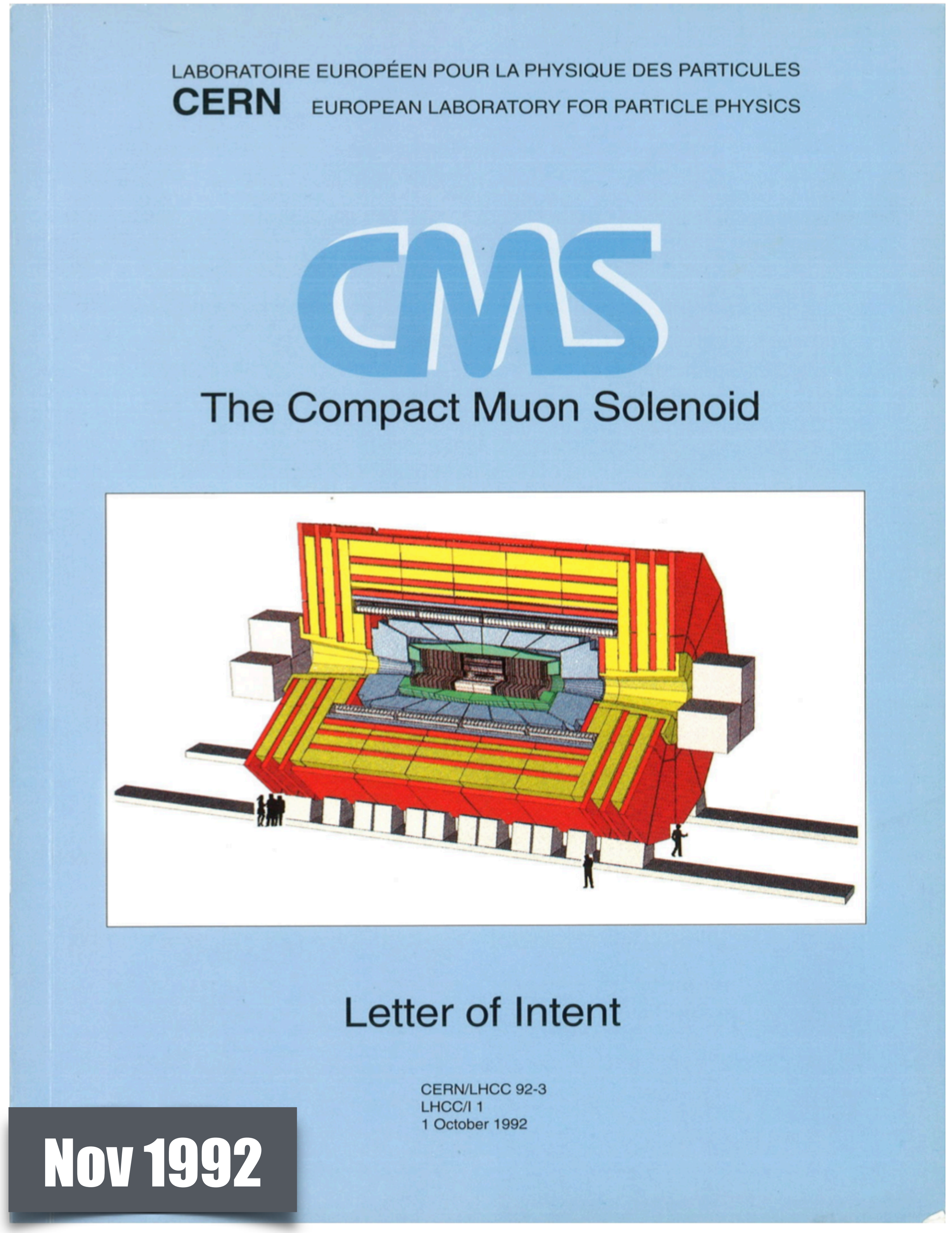
Tracking is crucial to LHC physics

20 years later



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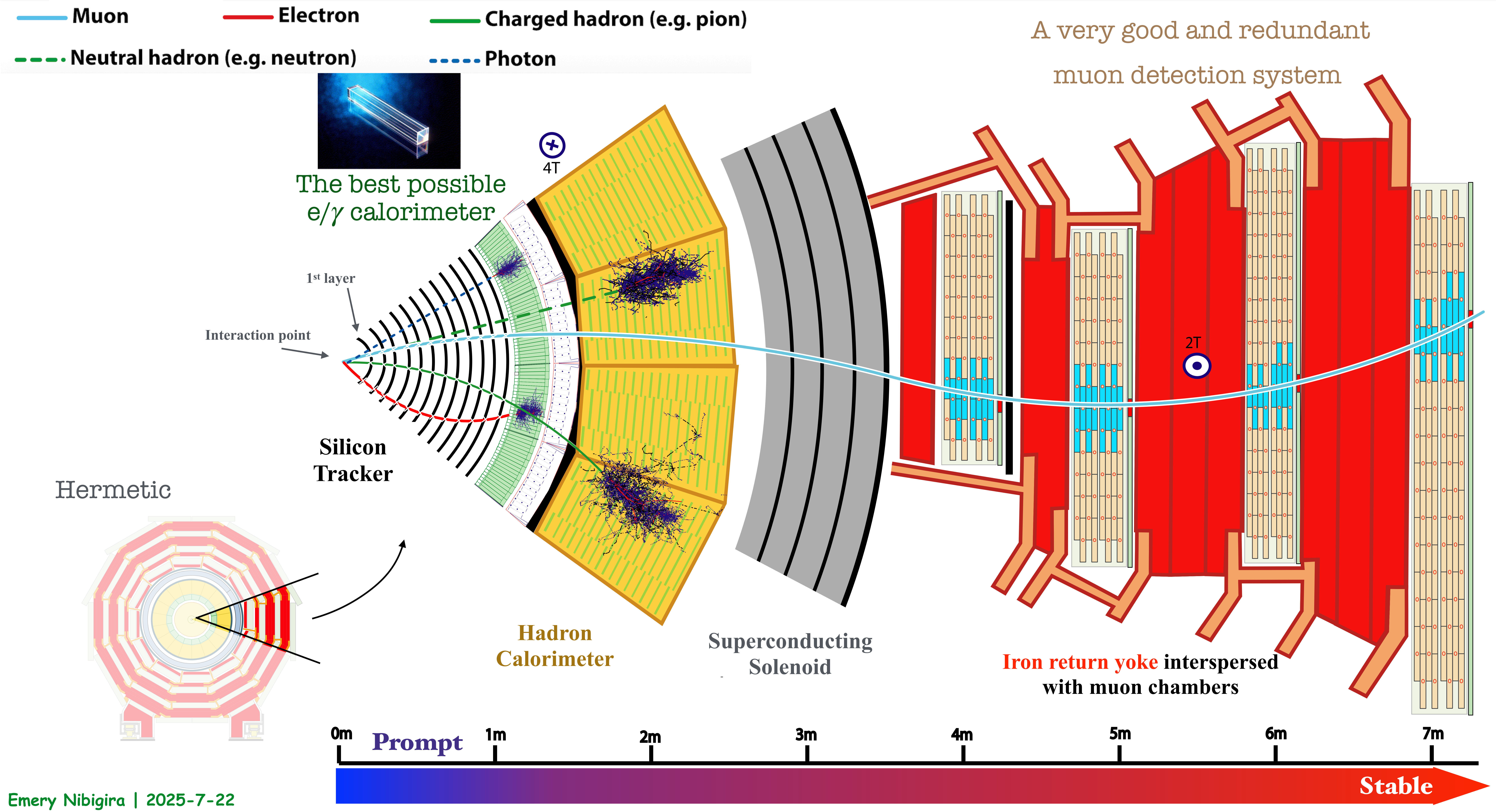
Don't make the same mistake twice!

Let's take a closer look: CMS Detector



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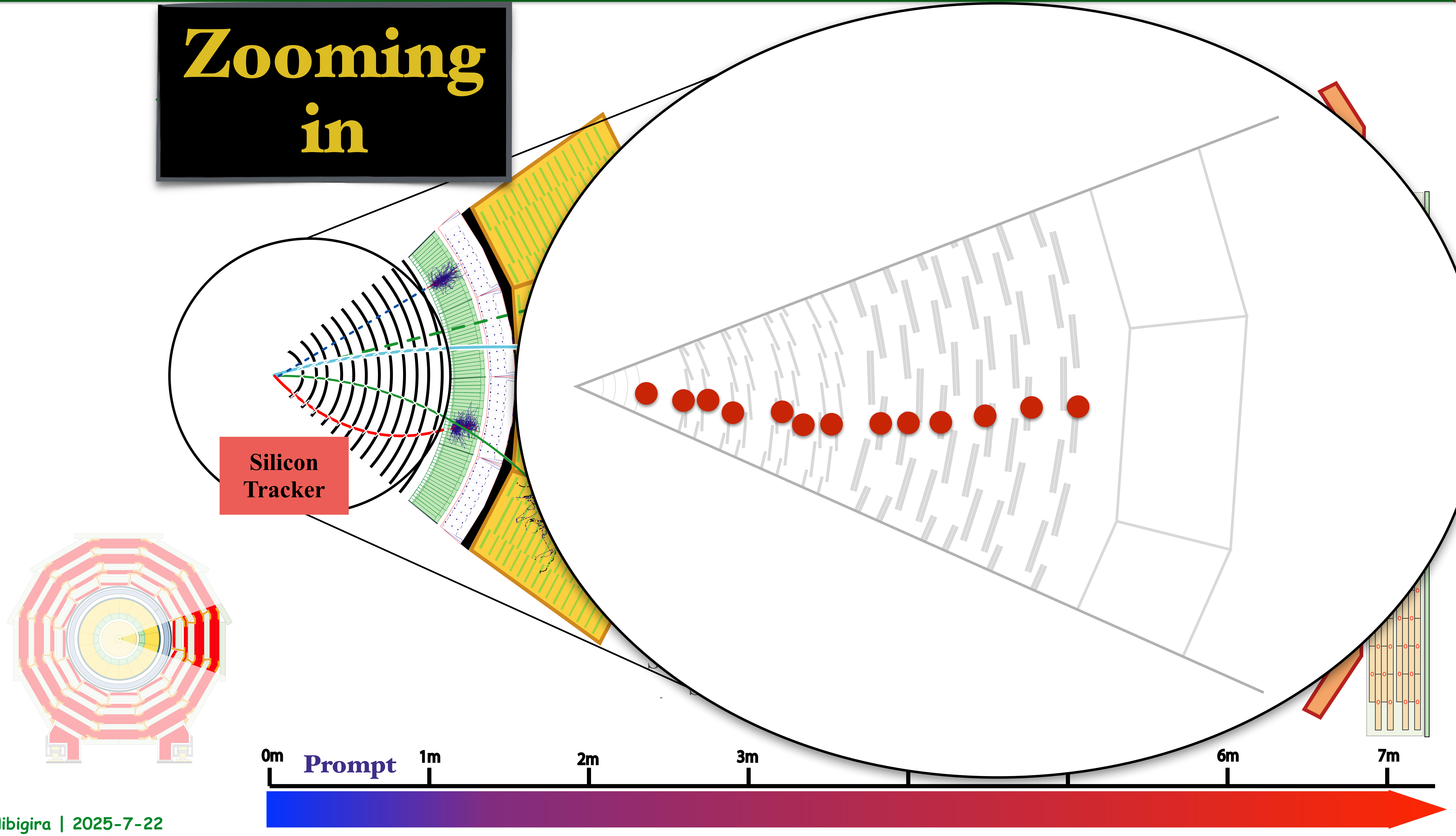

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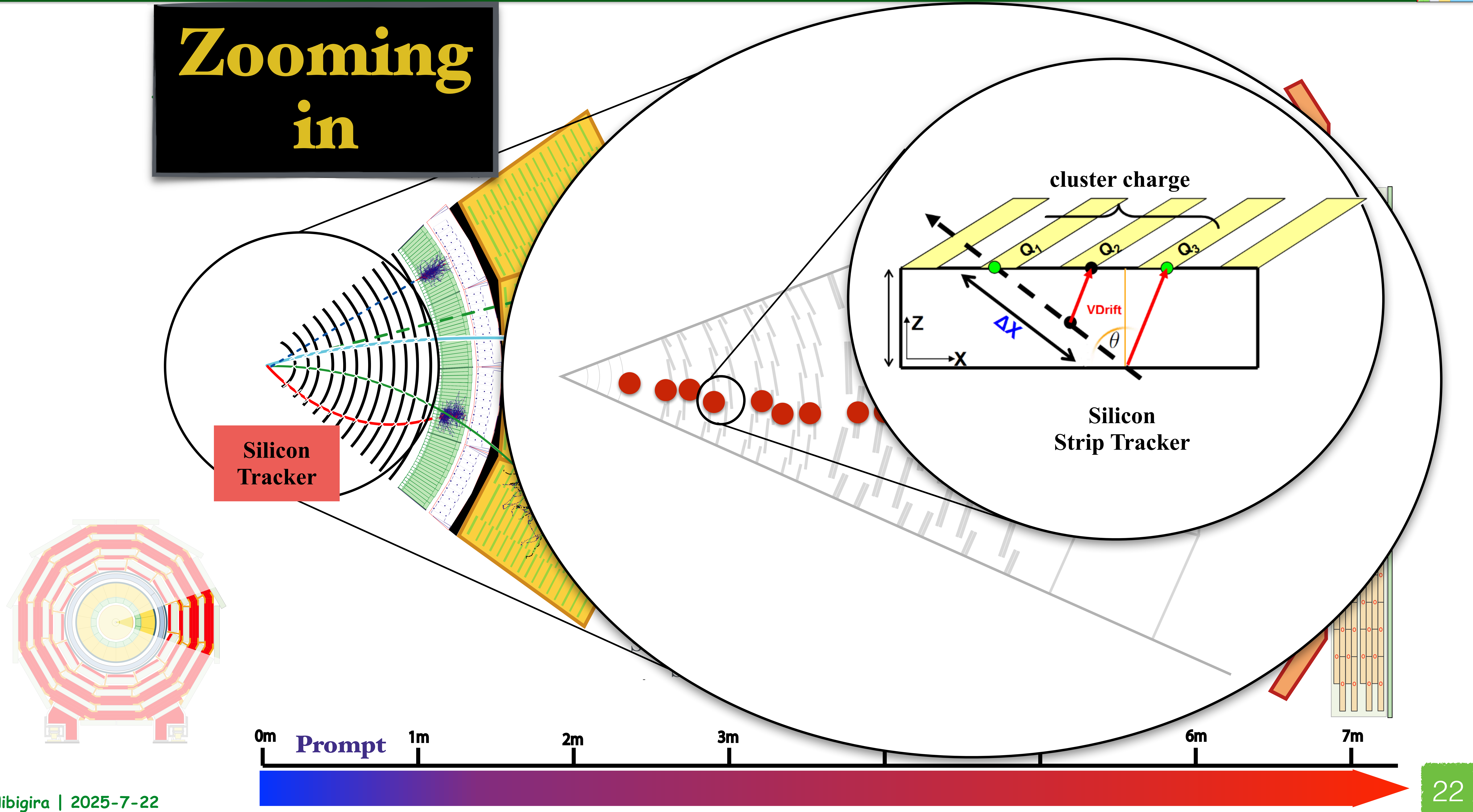

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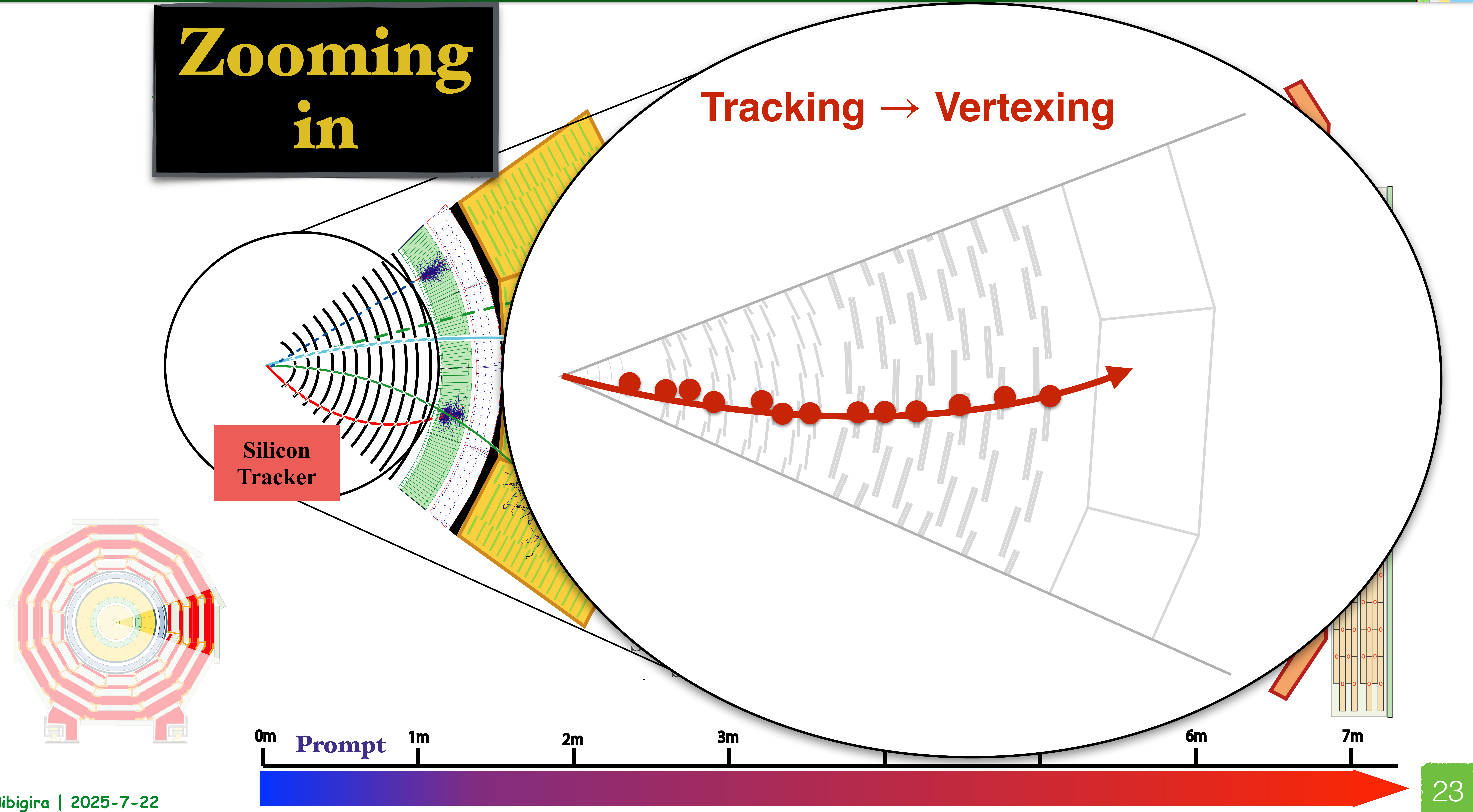
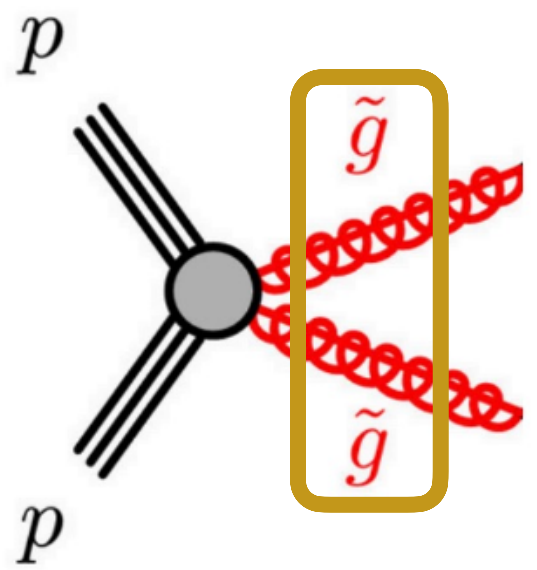


- **Motivation to go beyond the Standard Model**
- **Tracker-based signature: Heavy Stable Charged Particles**
- **Perspectives**

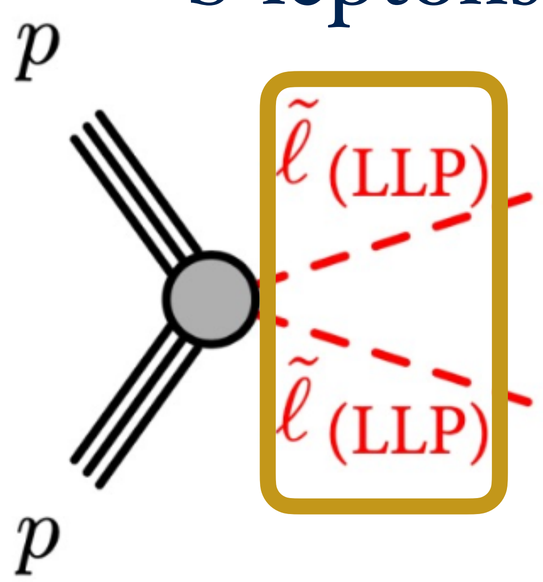
- **Heavy Charged Particles with long lifetime** (may not decay inside the detector)

- **Well motivated**
  - Supersymmetry (SUSY) models, Universal Extra Dimensions, Technicolor, ...

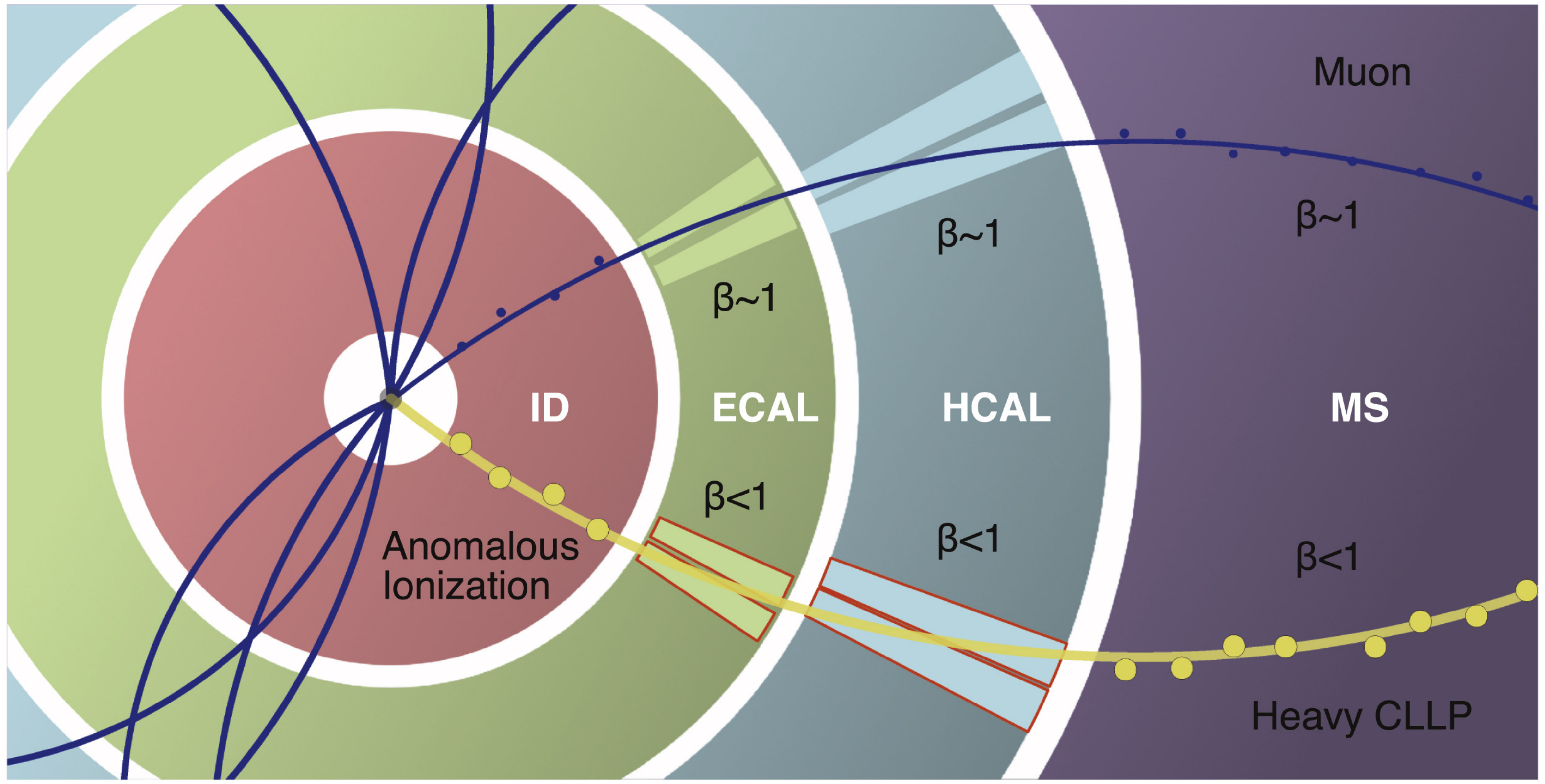
R-Hadrons



S-leptons/S-taus



- **Experimental signature**
  - Large ionization energy loss: **large ionization** inside the Tracker
  - HSCPs travel more slowly: **small** $\beta\gamma$



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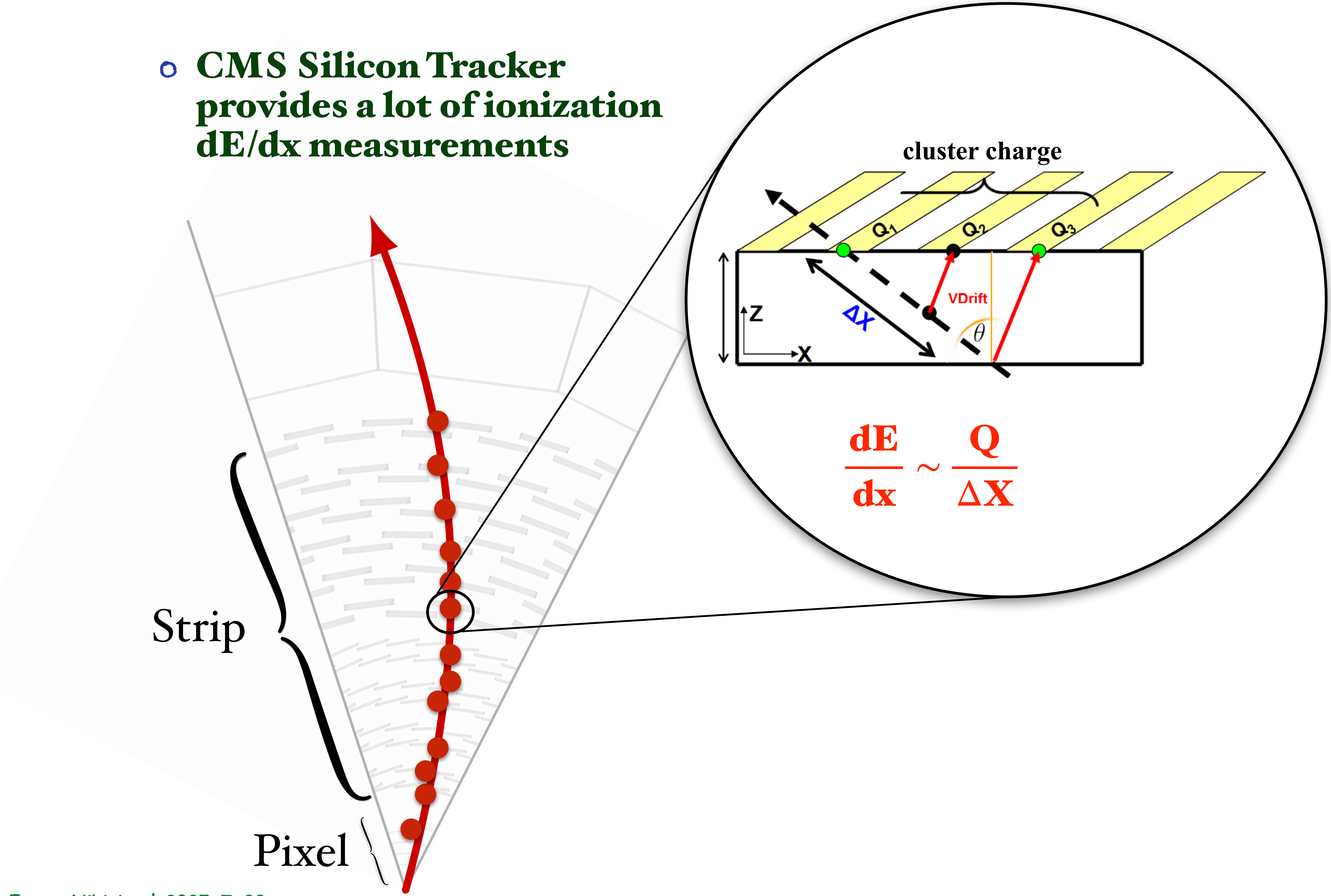
Search for Heavy Stable Charged Particles (HSCP)

- **CMS Silicon Tracker provides a lot of ionization dE/dx measurements**



$$\frac{dE}{dx} \sim \frac{Q}{\Delta X}$$

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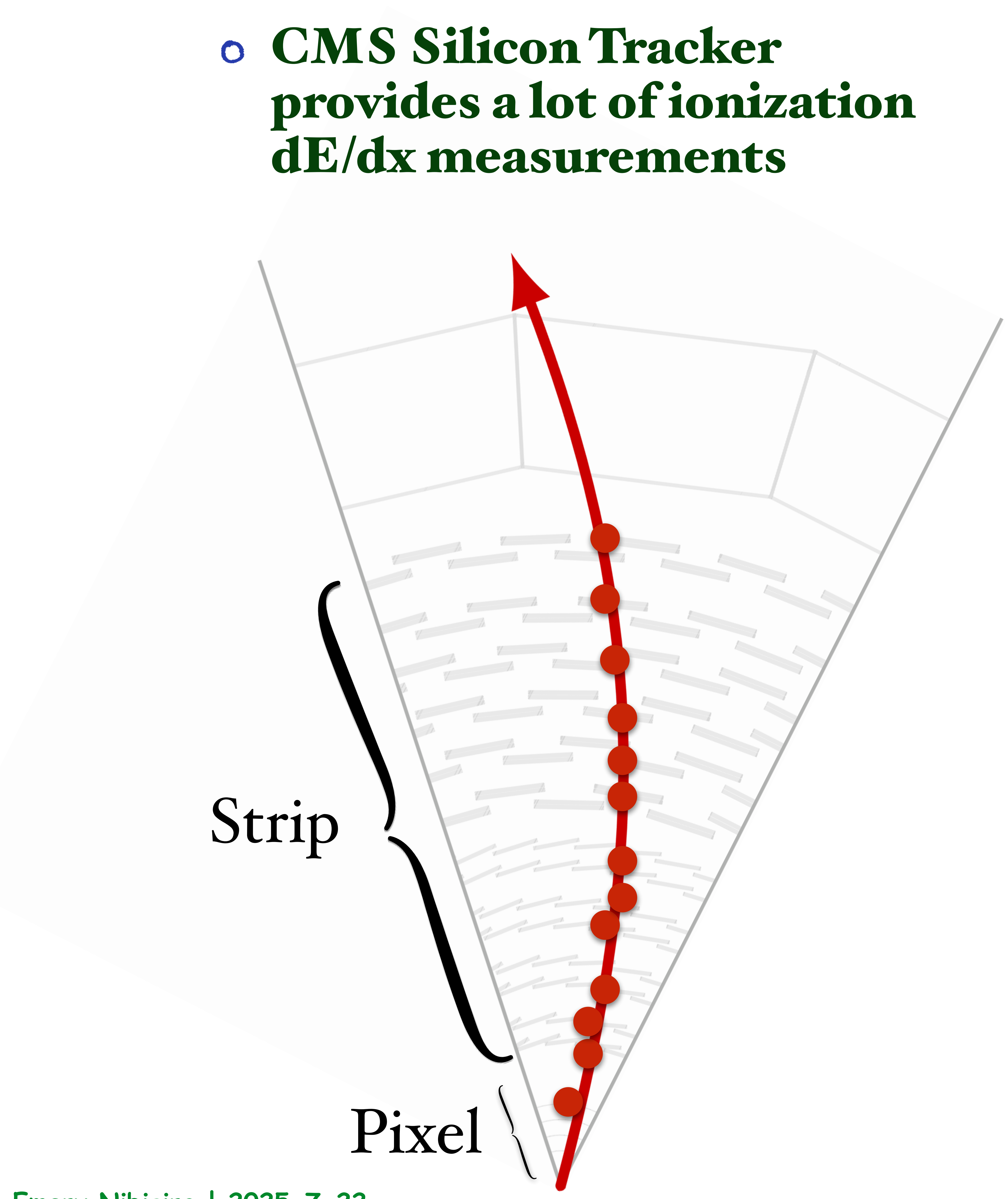
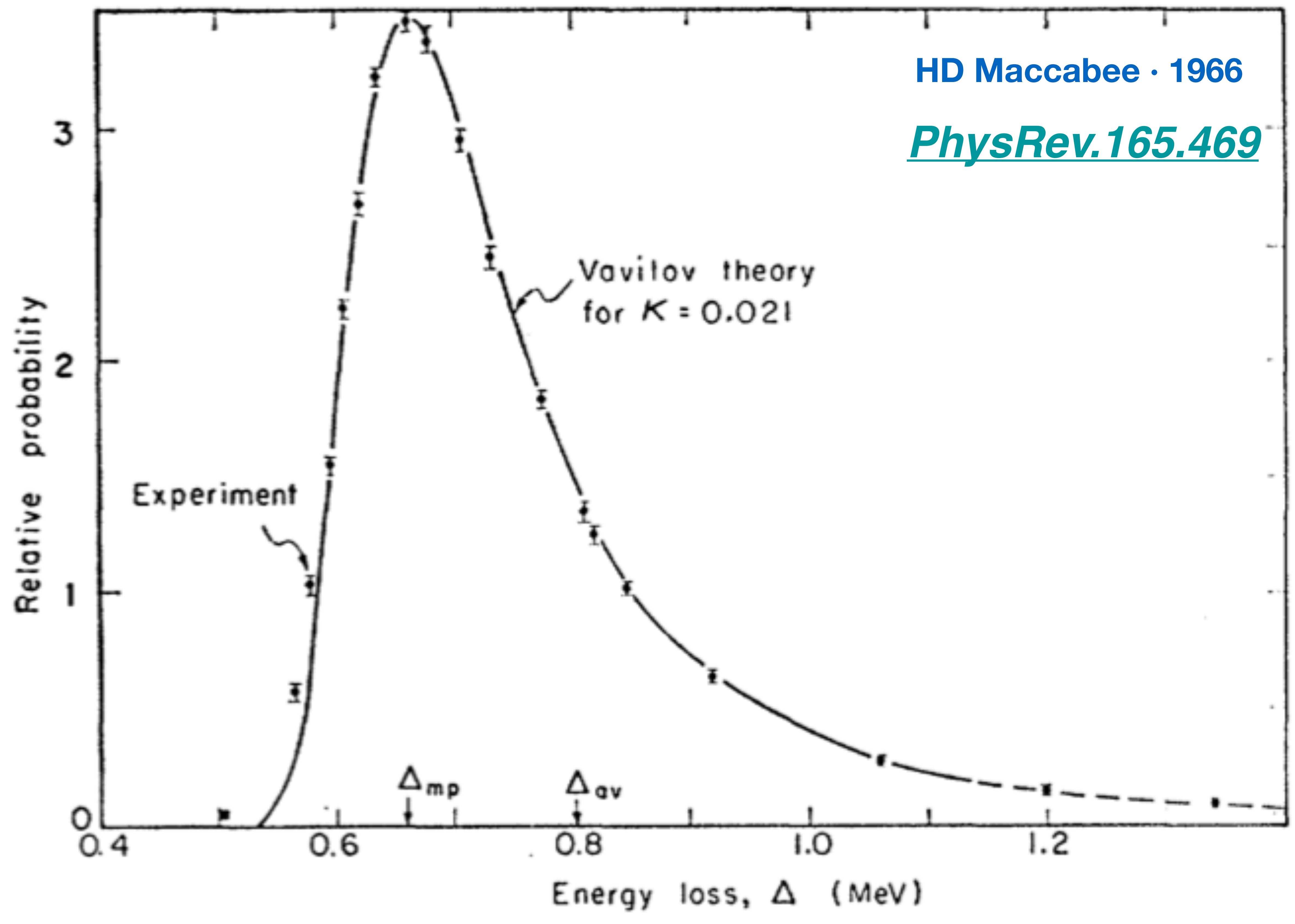


$(dE/dx)_i$ need to be combined to find representative dE/dx of the track: MPV

$(dE/dx)_i$ **follow a Landau distribution**



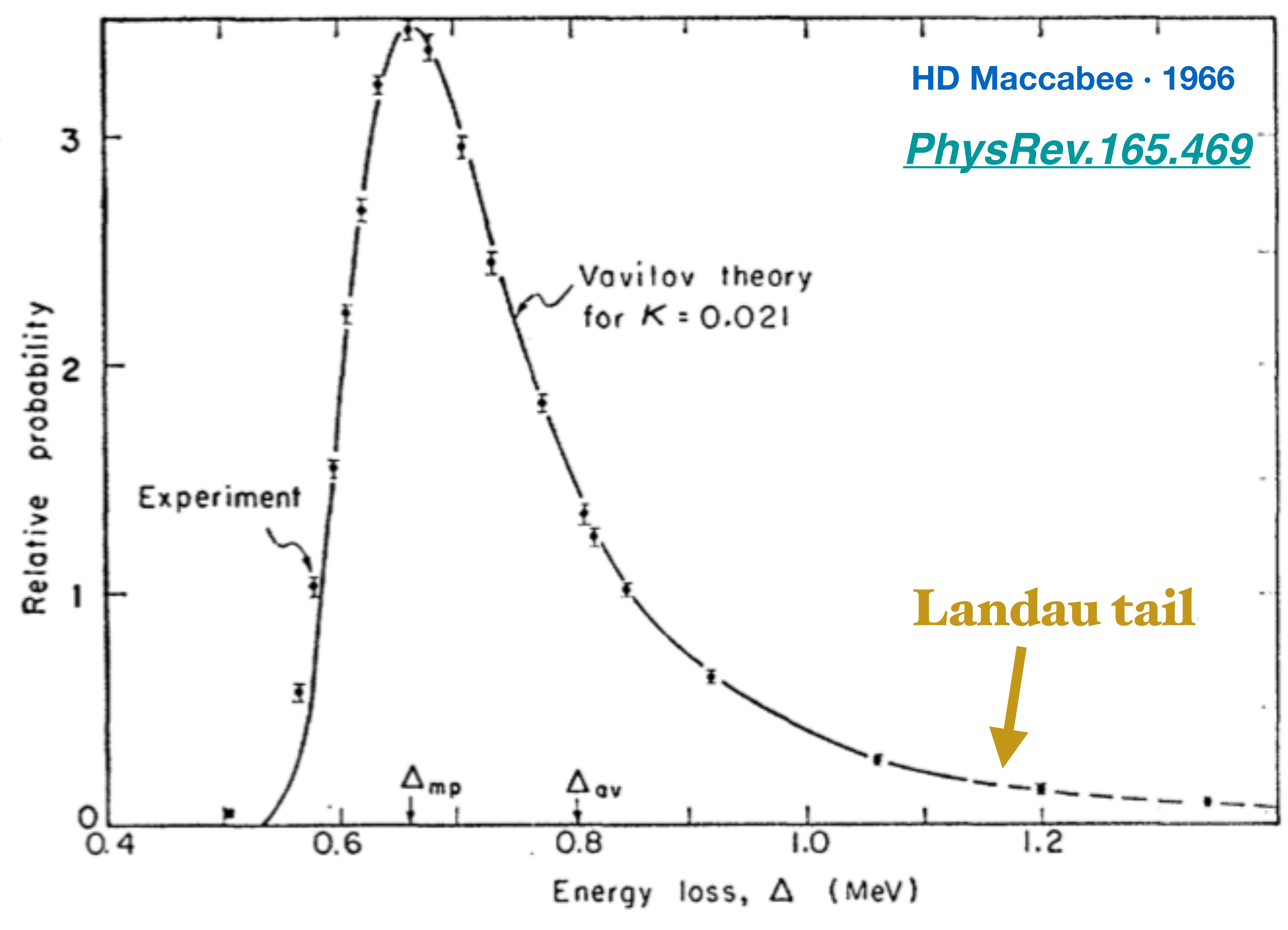
Most Probable Value (MPV) for dE/dx

In CMS we use

Harmonic mean (Inverted quadrature)

$$I_h = \left[\frac{1}{N}\sum_{i=1}^{N}\left(dE/dx\right)_i^{-2}\right]^{-\frac{1}{2}}$$

Known for its power of down-weighting high dE/dx



dE/dx of charged particles traversing a material depends on βγ

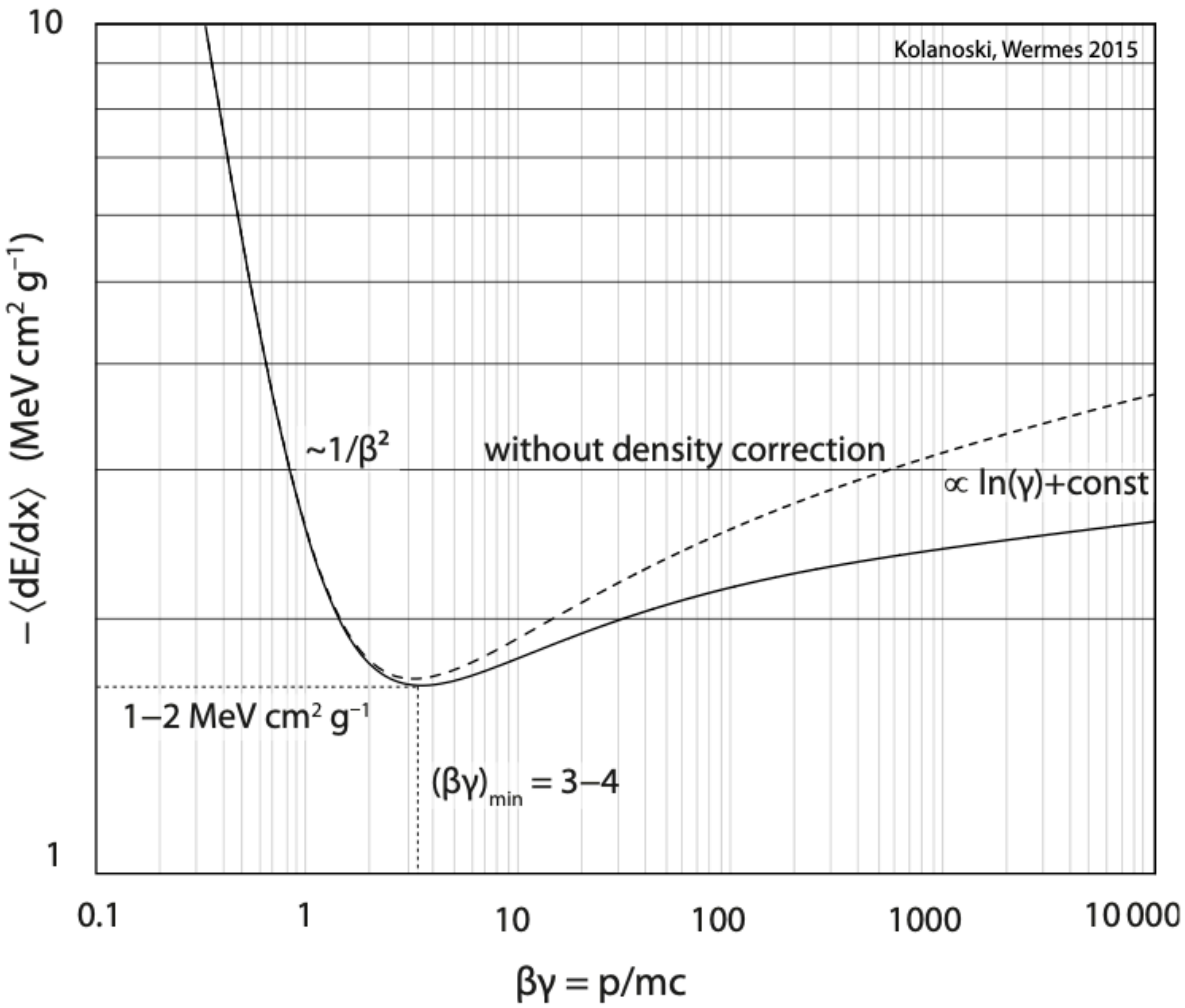
Bethe-Bloch Equation

charge

$$-\langle\frac{dE}{dx}\rangle = kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}ln\frac{2m_ec^2\beta^2\gamma^2T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

Around $\beta\gamma = 3$, lays Minimum Ionizing Particle (MIP).

CMS was designed to look for MIPs



Ionization as described by Bethe-Bloch

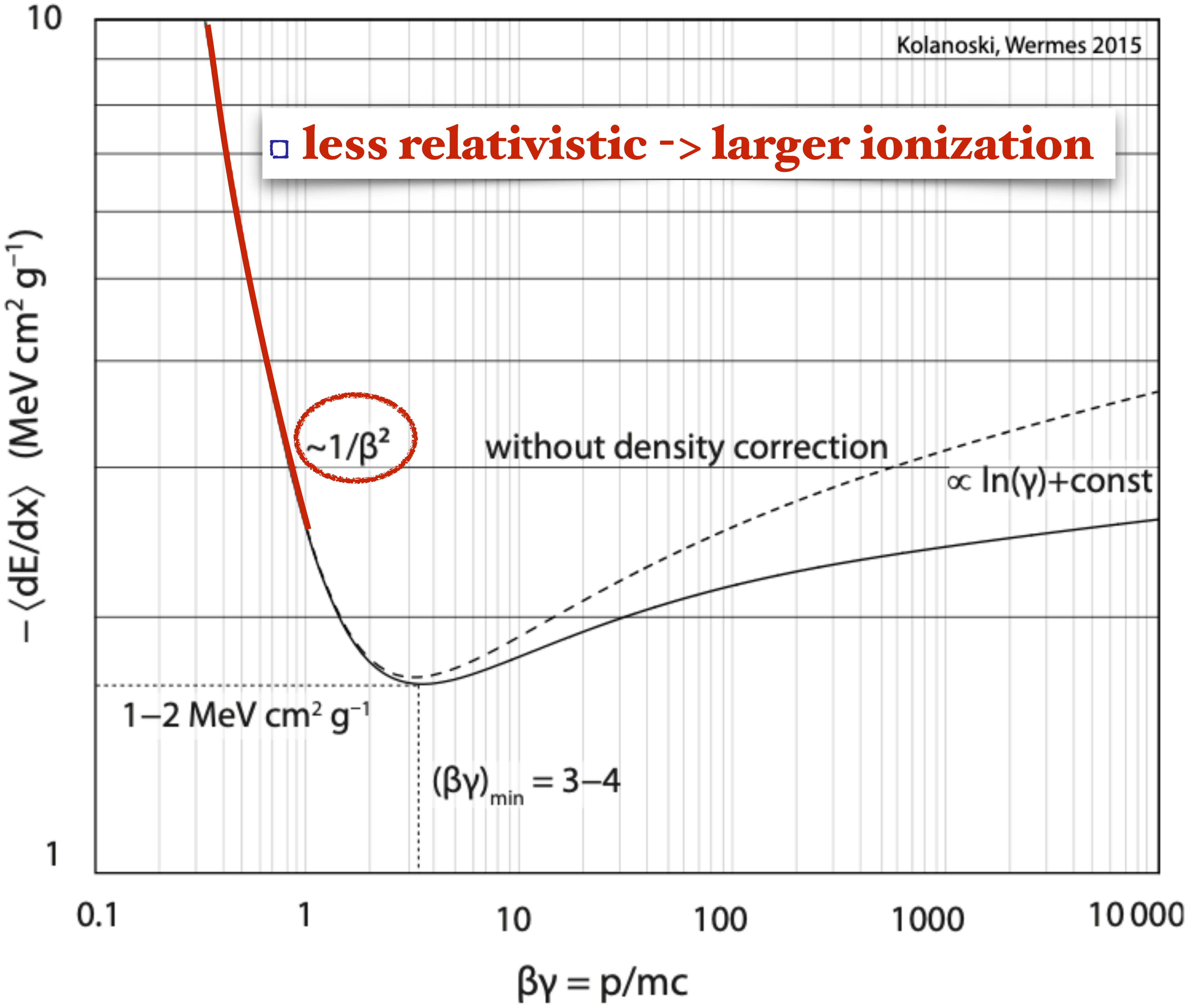
dE/dx of charged particles traversing a material depends on βγ

Bethe-Bloch Equation

charge

$$-\langle \frac{dE}{dx} \rangle = kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

At low β, $-\langle dE/dx \rangle$ scales as $1/\beta^2$



CMS was designed to look for MIPs

and may fail to detector less relativistic particles

Trigger constrain , Readout dynamic range constrain

Two different approaches:

- **Mass Method**
- **Ionization Method**

Using dE/dx Estimator and momentum

$$-\langle \frac{dE}{dx} \rangle \approx f\left(\frac{1}{\beta^2}\right) \approx f\left(\frac{m^2}{p^2}\right)$$ (Bethe-Bloch)

First order approximation

$$I_h = K\frac{m^2}{p^2} + C$$

Using dE/dx Estimator and momentum

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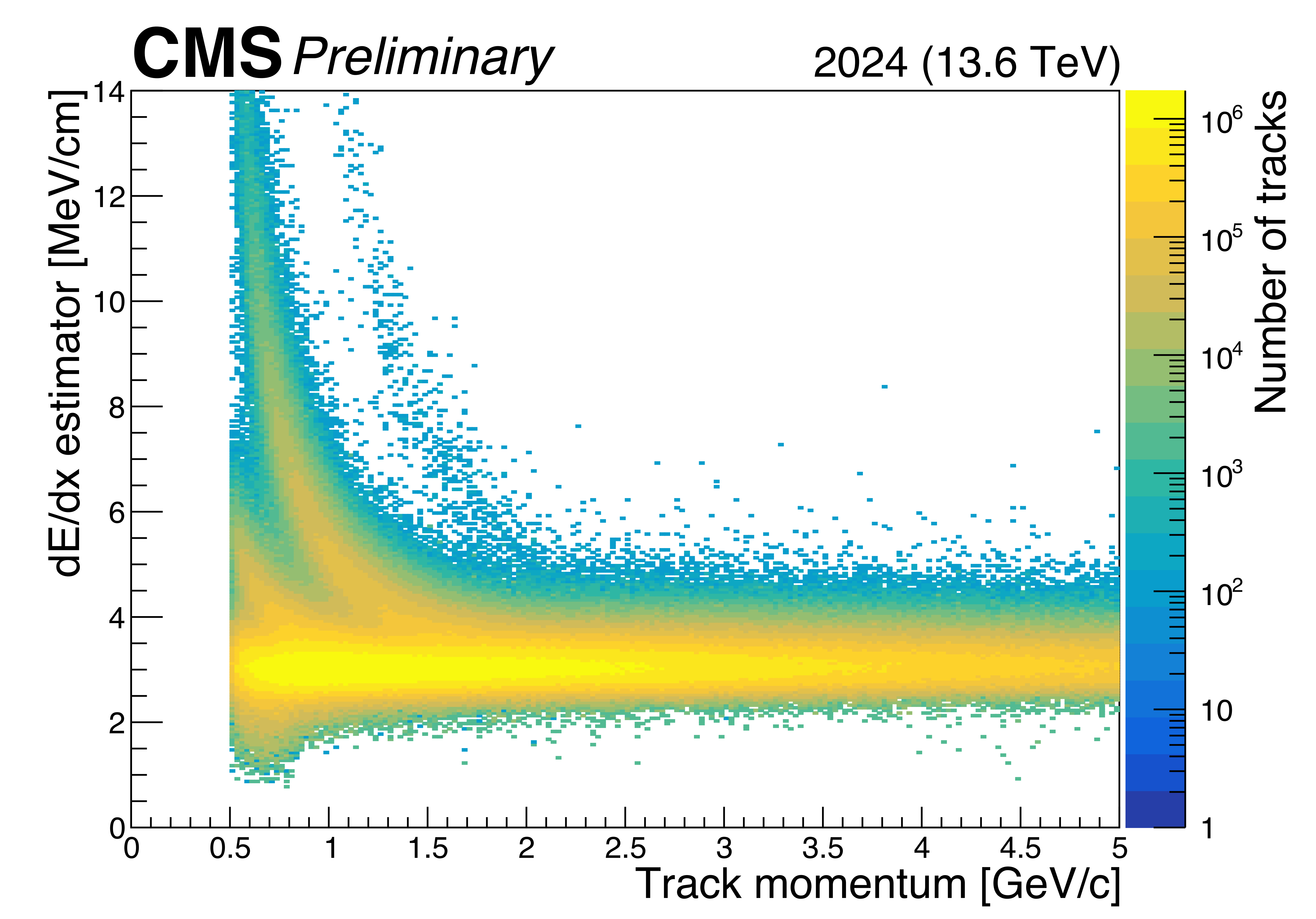

CMS-DP-2025-020

Mass Reconstruction Method

Using dE/dx Estimator and momentum

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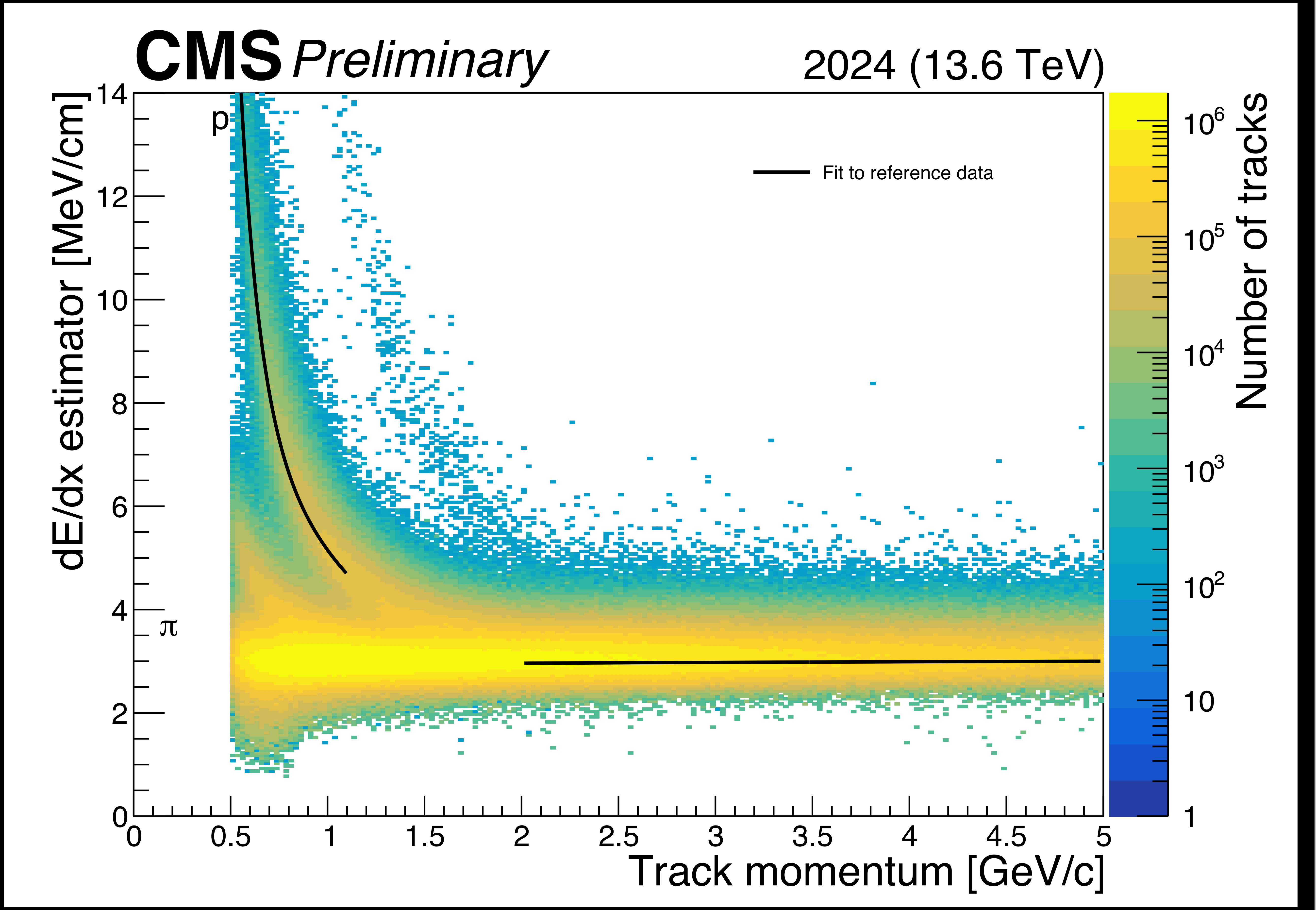
First order approximation

$$I_h = K\frac{m^2}{p^2} + C$$

K and *C* from fit parameters (low momentum)



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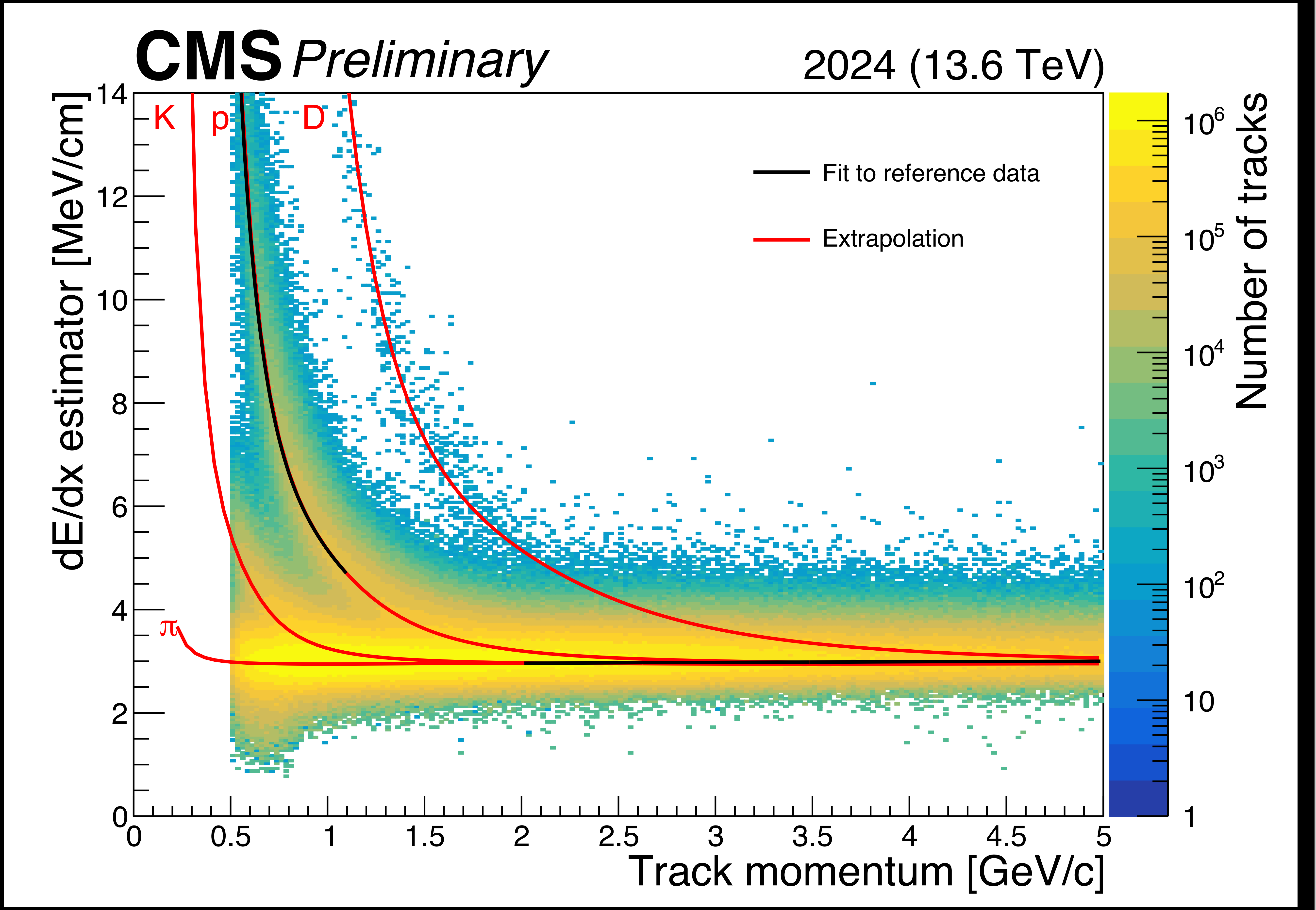
First order approximation

$$I_h = K\frac{m^2}{p^2} + C$$

Extrapolation to any masses

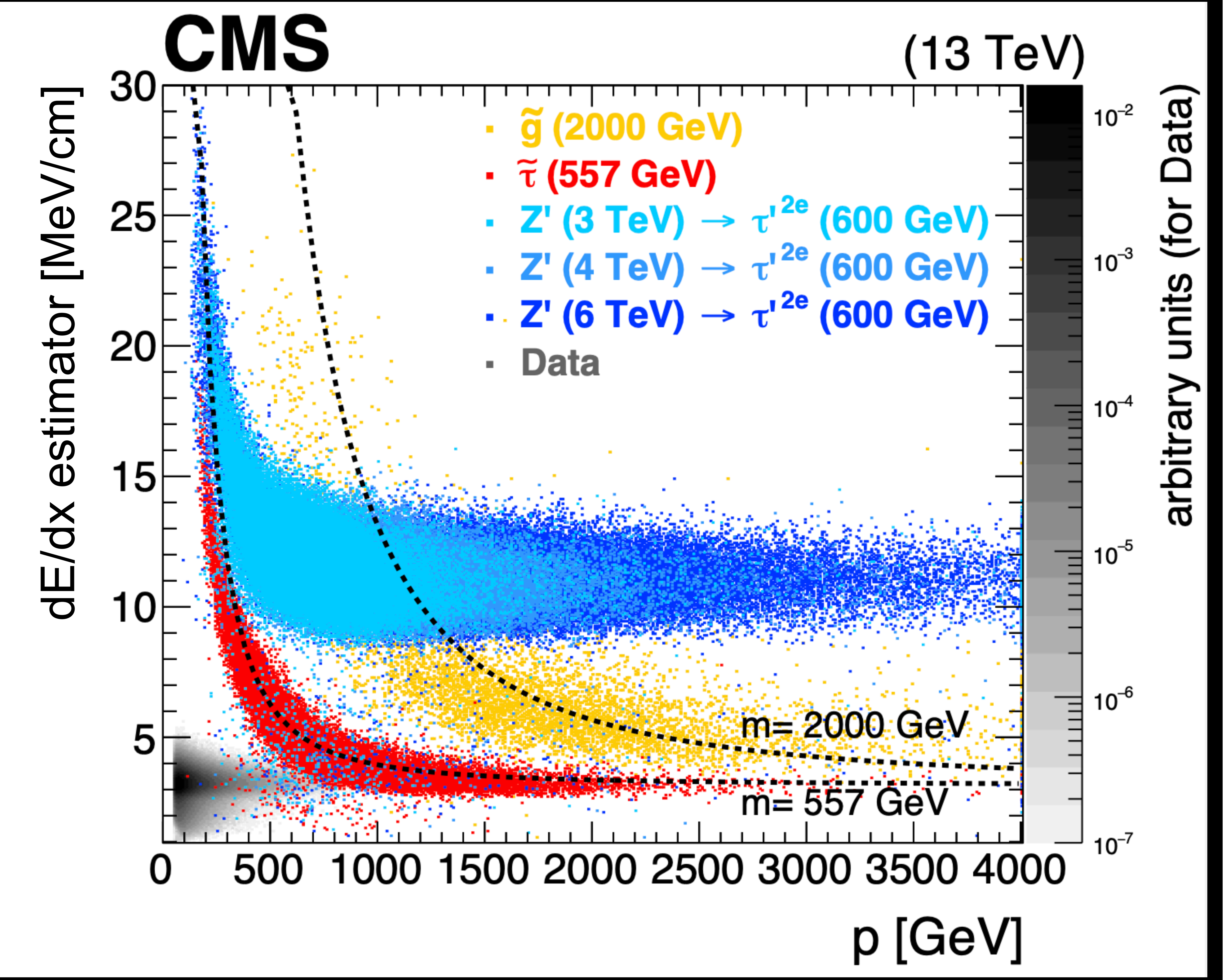
$$m = p\sqrt{\frac{I_h - C}{K}}$$



CMS-DP-2025-020

Extrapolation to Heavy Charged Long-Lived Particles

→ high momentum



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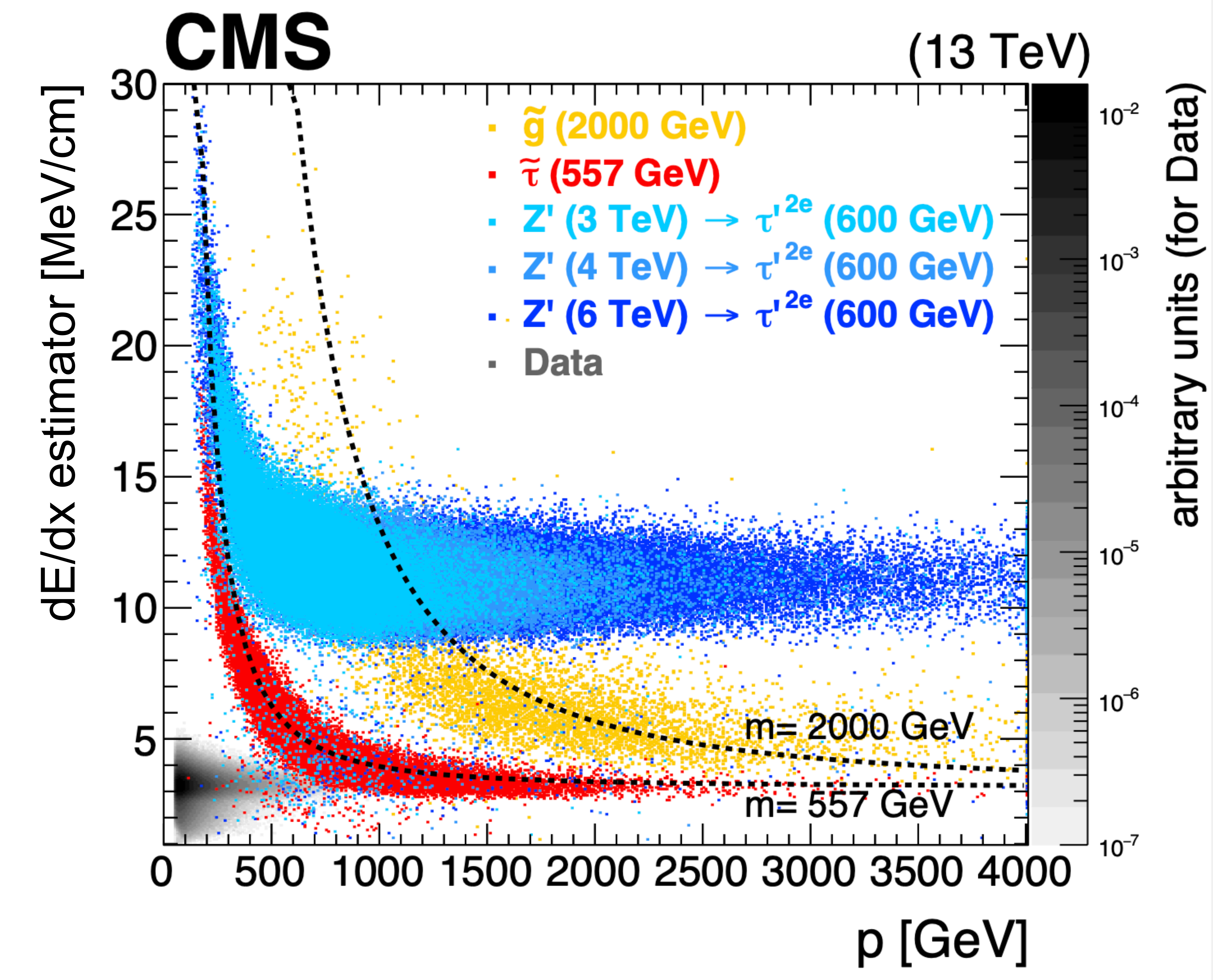
Extrapolation to Heavy Charged Long-Lived Particles

→ high momentum

- Most of our backgrounds come from mis-reconstructed tracks, bad ionization measurement, landau tails



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Predict the mass spectrum in the Search Region

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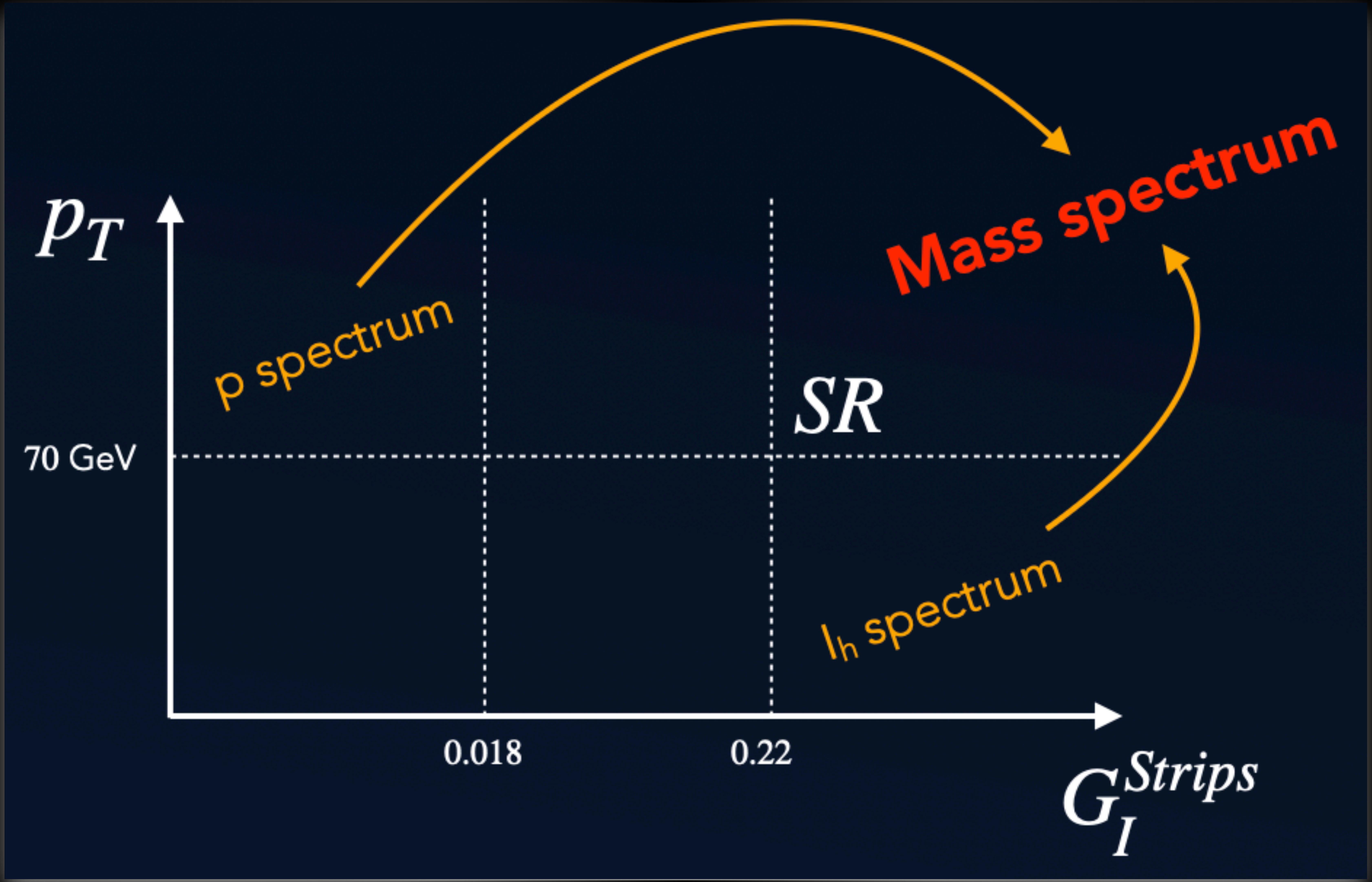
G^{strip} :

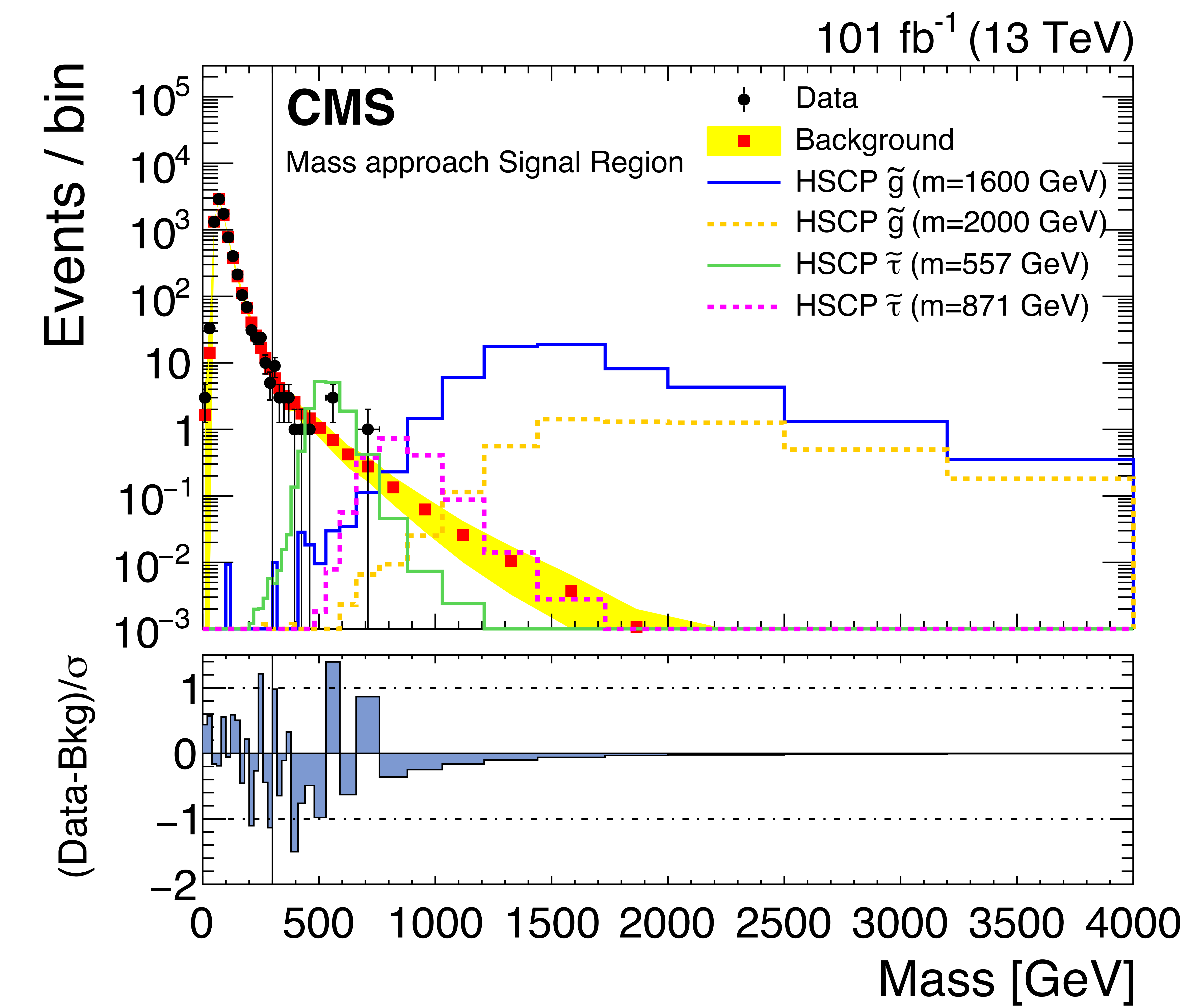
dE/dx Discriminator

Probability that a track is not a MIP

- p_T and G^{strip} should be uncorrelated



Mass Reconstruction Method: Background Estimation



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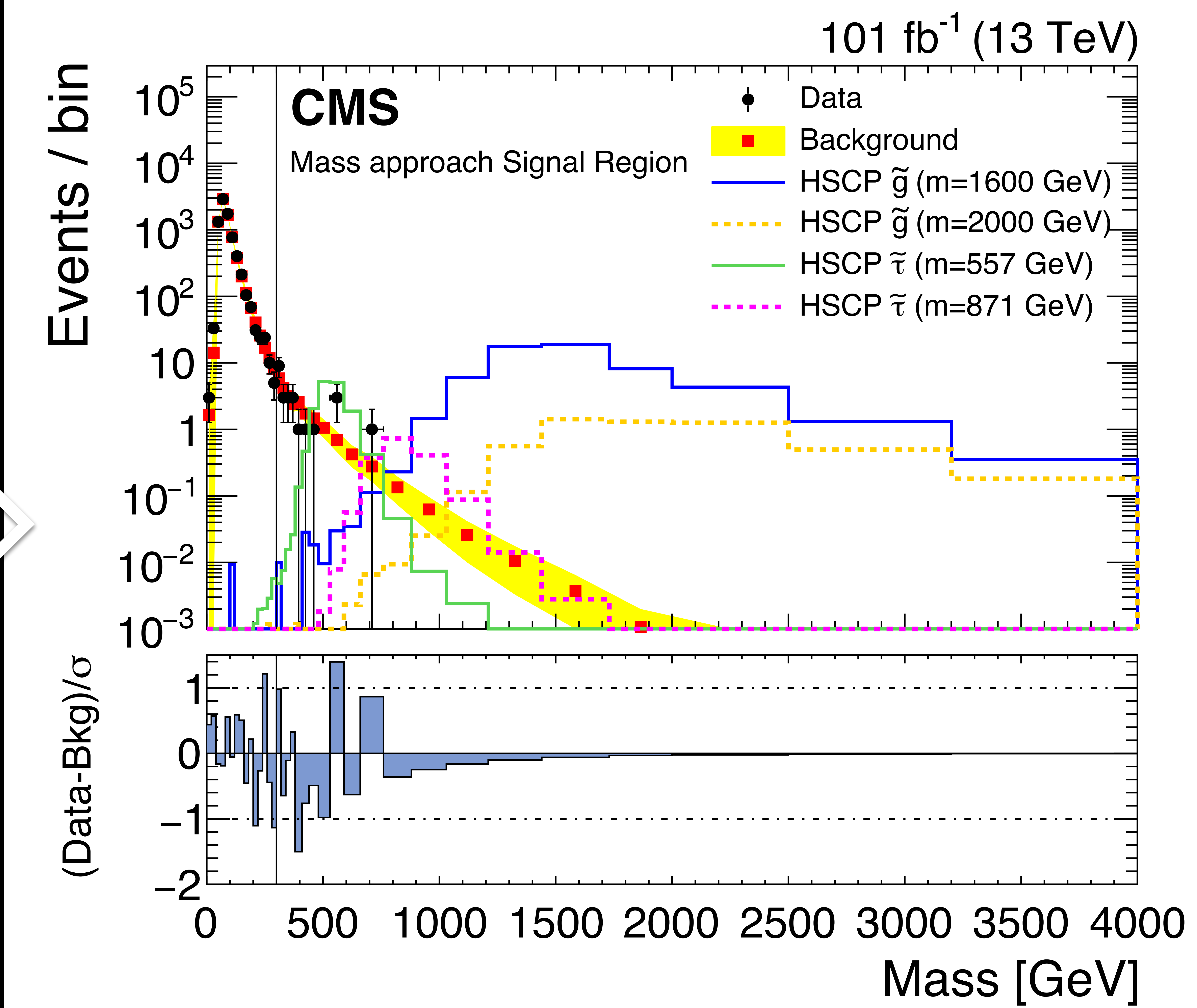
Mass Reconstruction Method: Background Estimation

No significant excess above SM



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What about the Ionization Method?

Two discriminators to combine cluster ionization information

2 Discriminators
(MIP probabilities)

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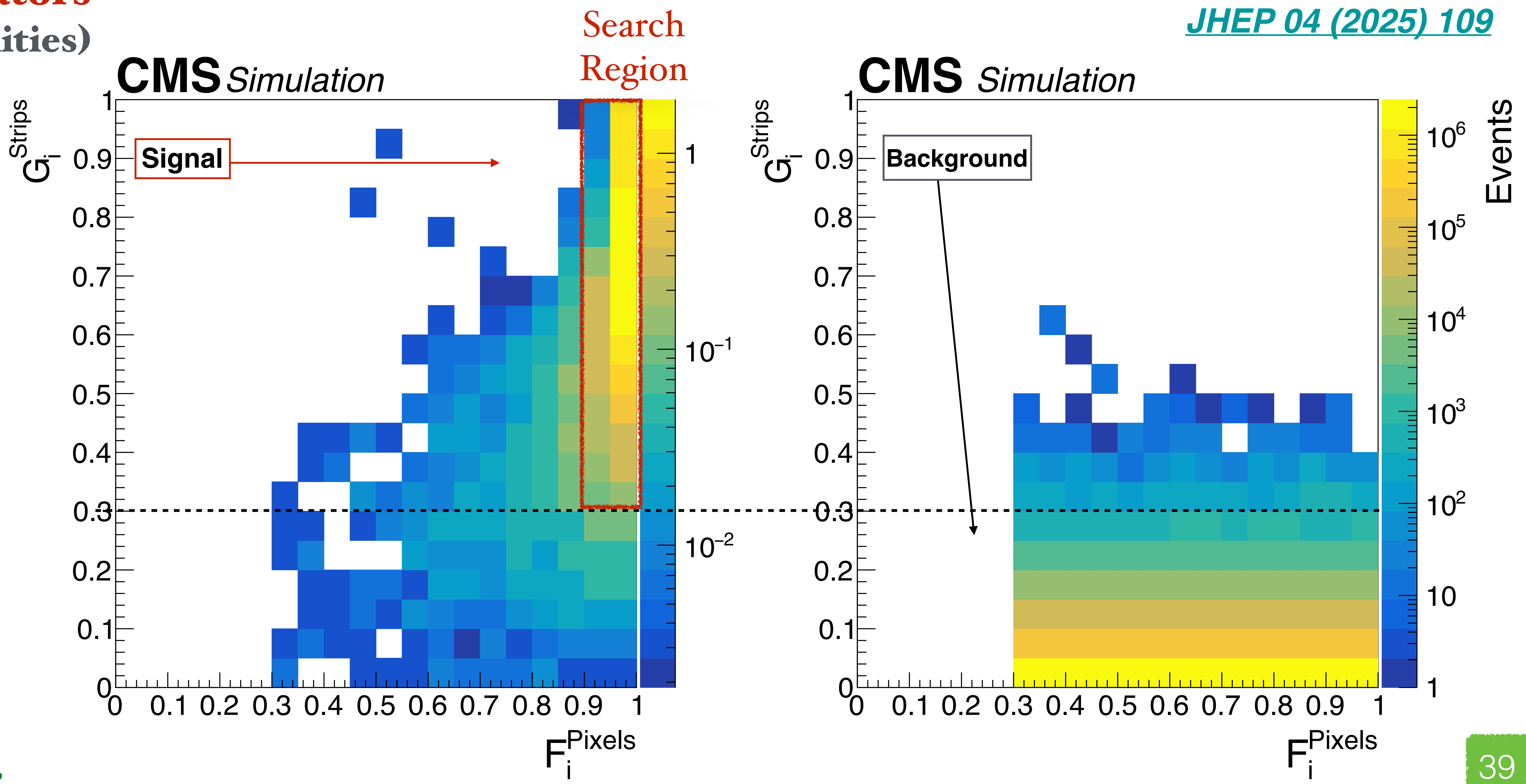
G^{Strips}

&

F^{Pixels}



Ionization Method: Background Estimation

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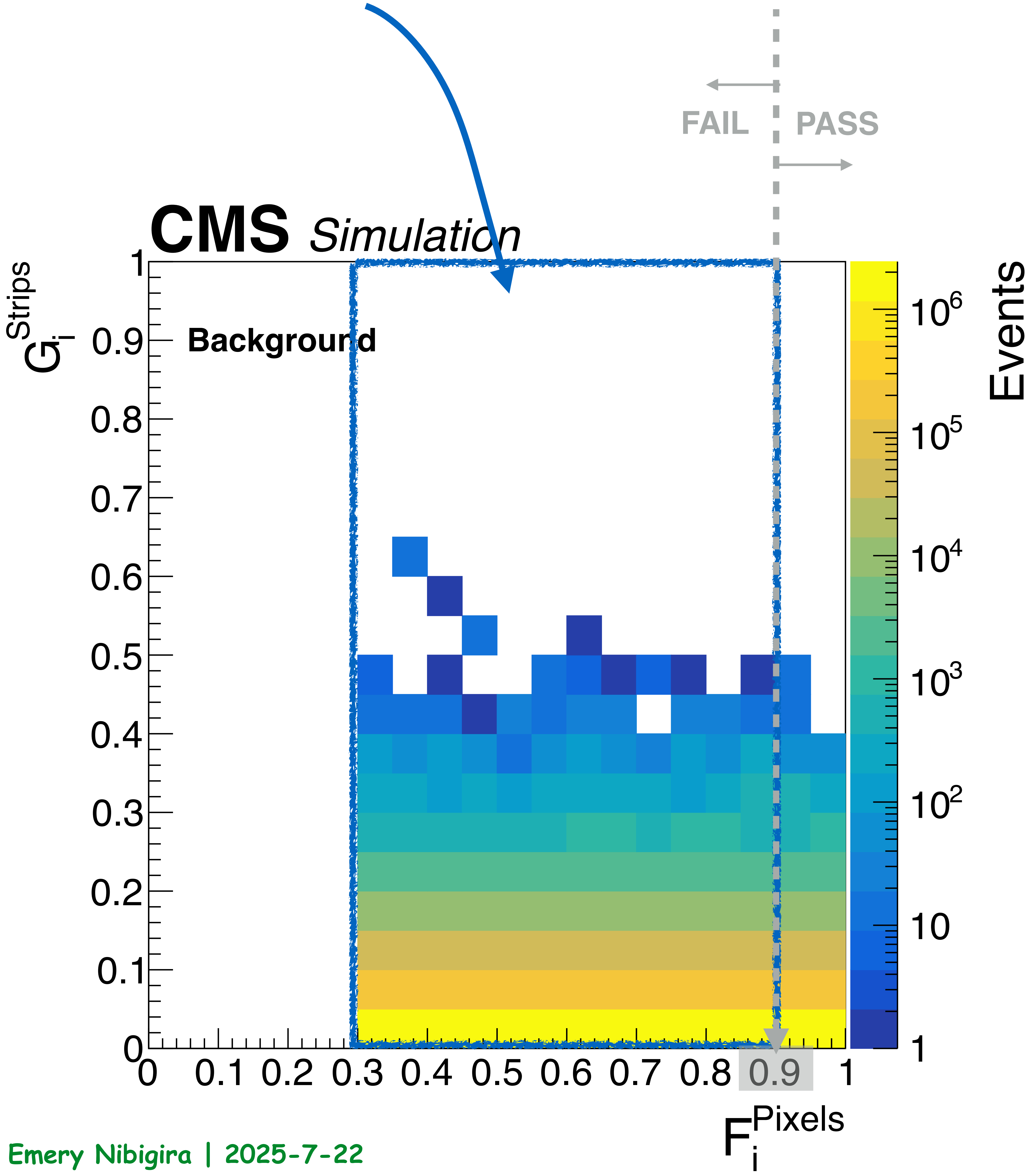
Use Sideband of F^{Pixels} to predict shape of G^{Strips} in Search Region



- This method relies on the fact that
  - F^{Pixels} and G^{Strips} are uncorrelated for background
  - F^{Pixels} is flat for background

- **FAIL templates are used to predict the shape of the G_I^{Strips} for background in PASS region using transfer function** $R_{P/F}$

$$N^{bkg}_{PASS}(j) = R_{P/F}(j) \times N^{bkg}_{FAIL}(j)$$

j^{th} bin of G^{Strips}

- Require $p_T > 200$ GeV

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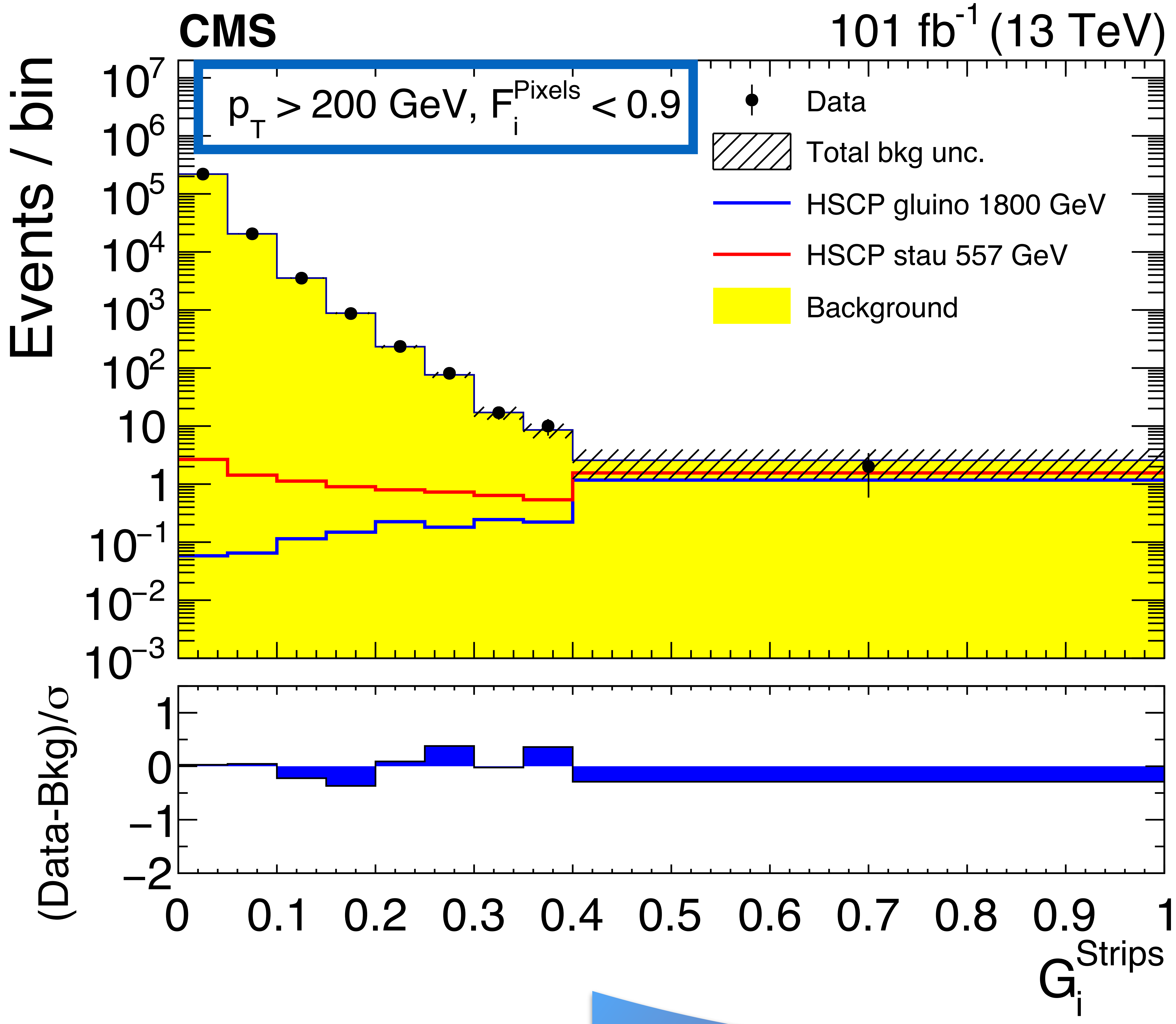
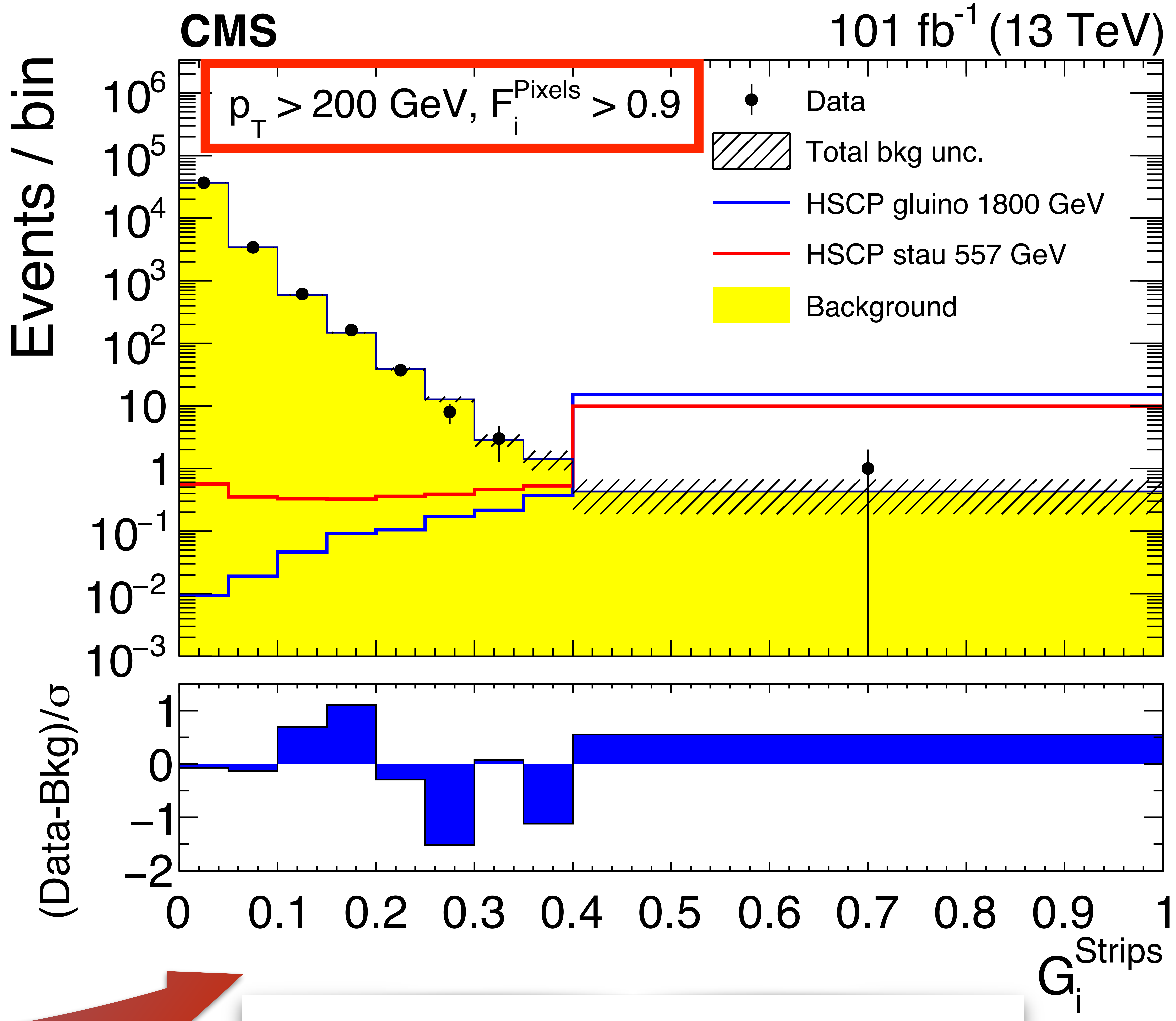
Use Sideband of F^{Pixels} to predict shape of G^{Strips} in Search Region





No significant excess above SM

After all, CMS did not see Excess

Cross section limits set for various models

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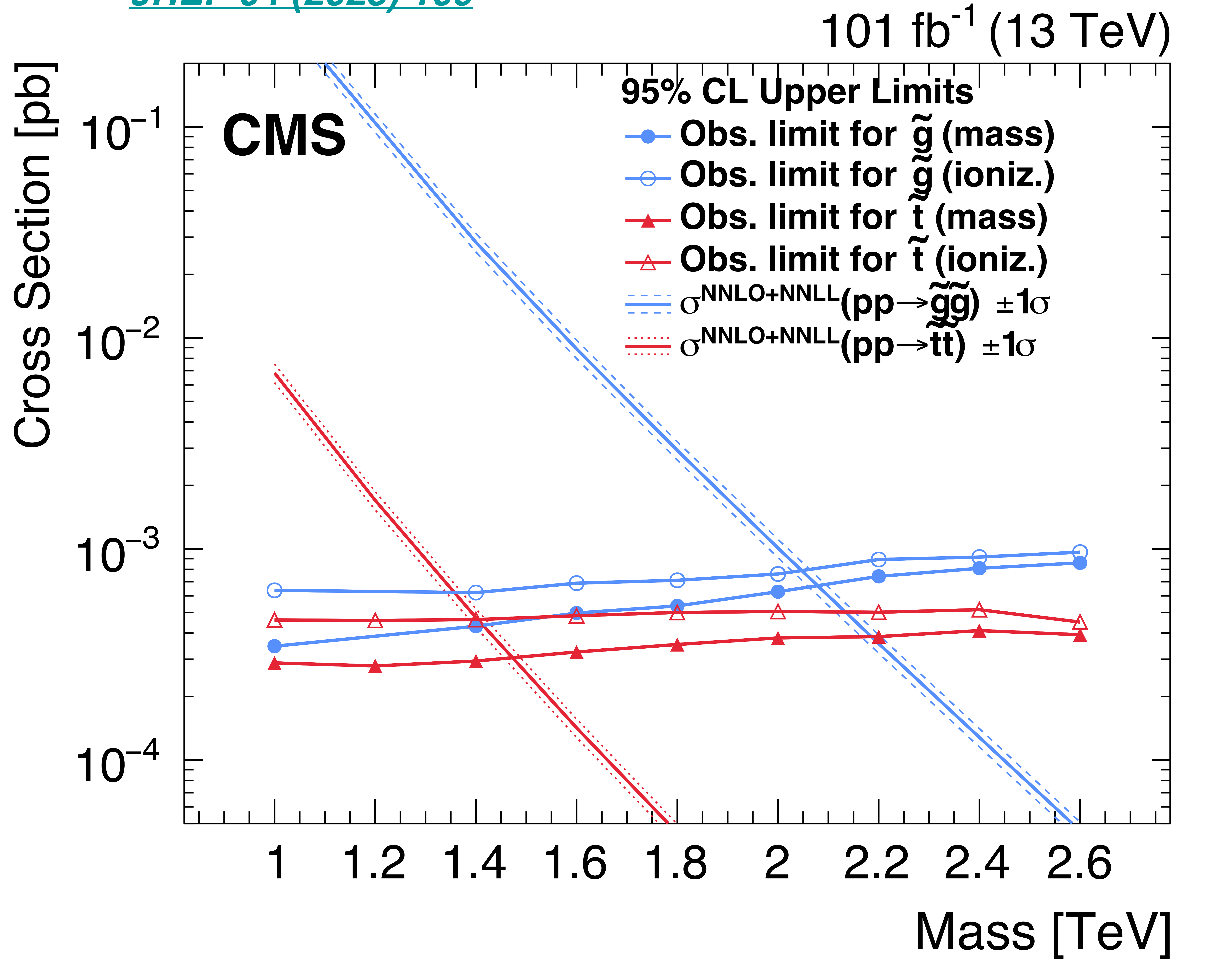

- **Other consideration**
  - **Z' into 4th generation of leptons with Q=2e**

To address ATLAS excess

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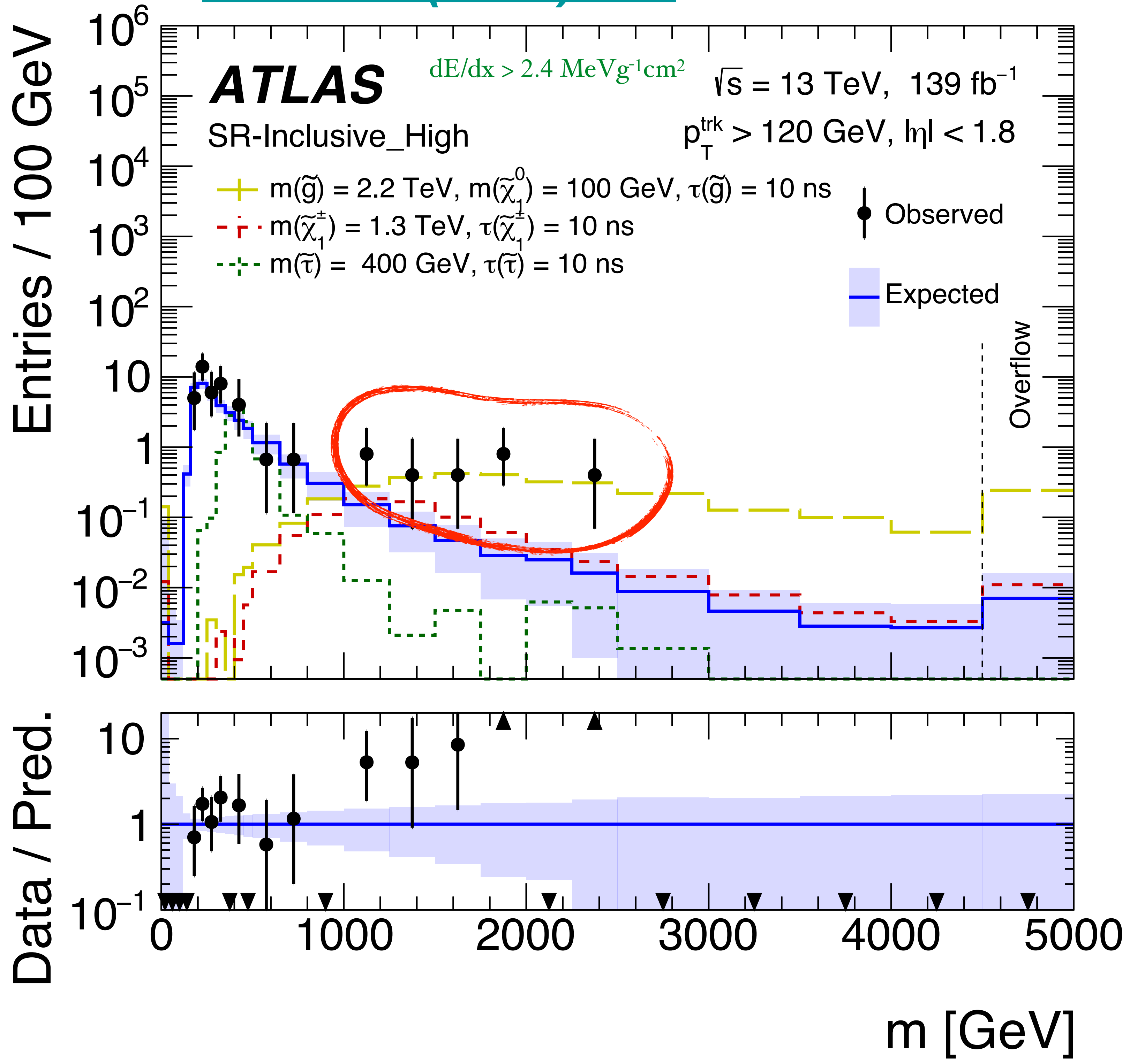

Larger dE/dx but $\beta = 1$

- **Other consideration**
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To address ATLAS excess

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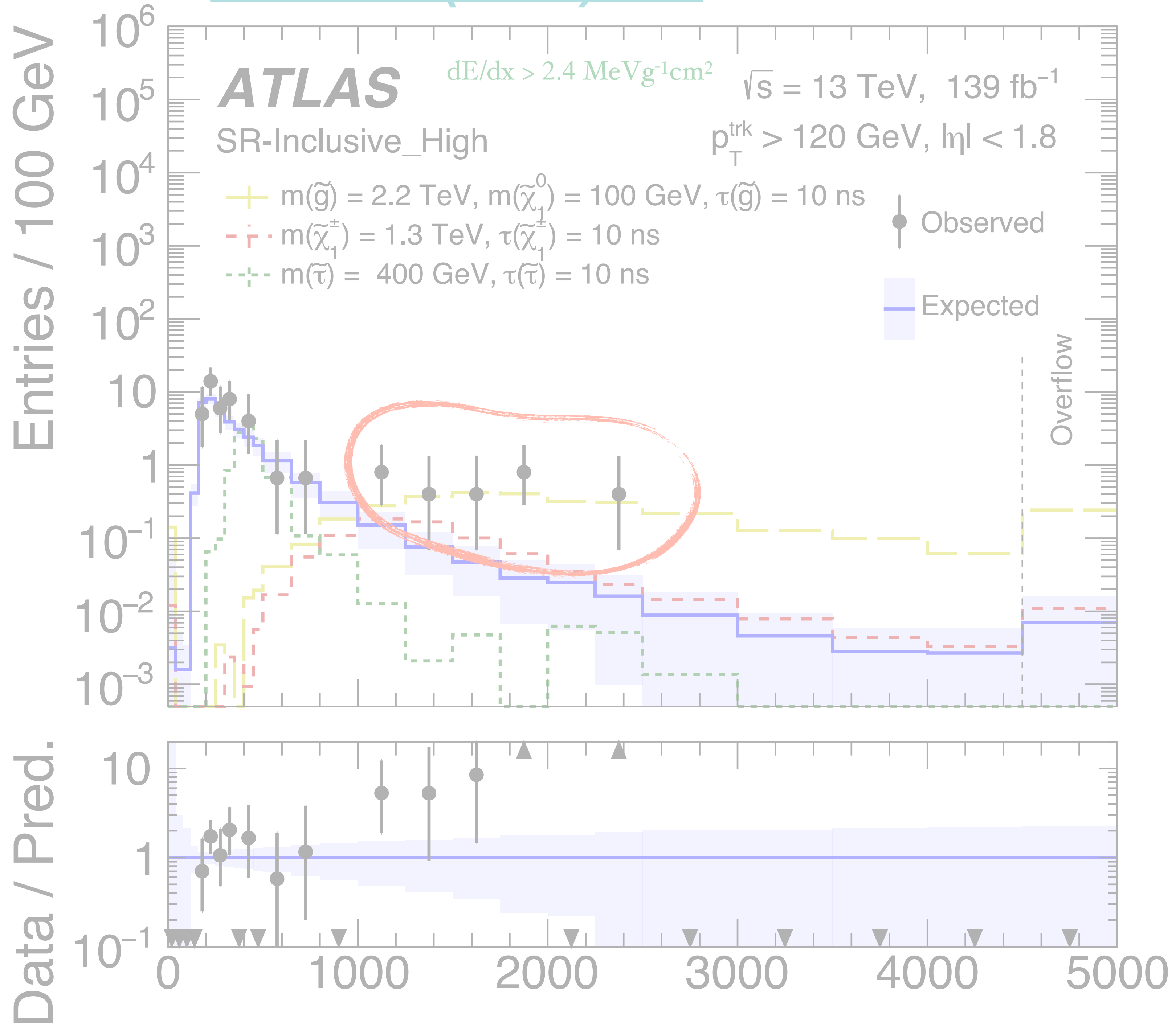

Larger dE/dx but $\beta = 1$

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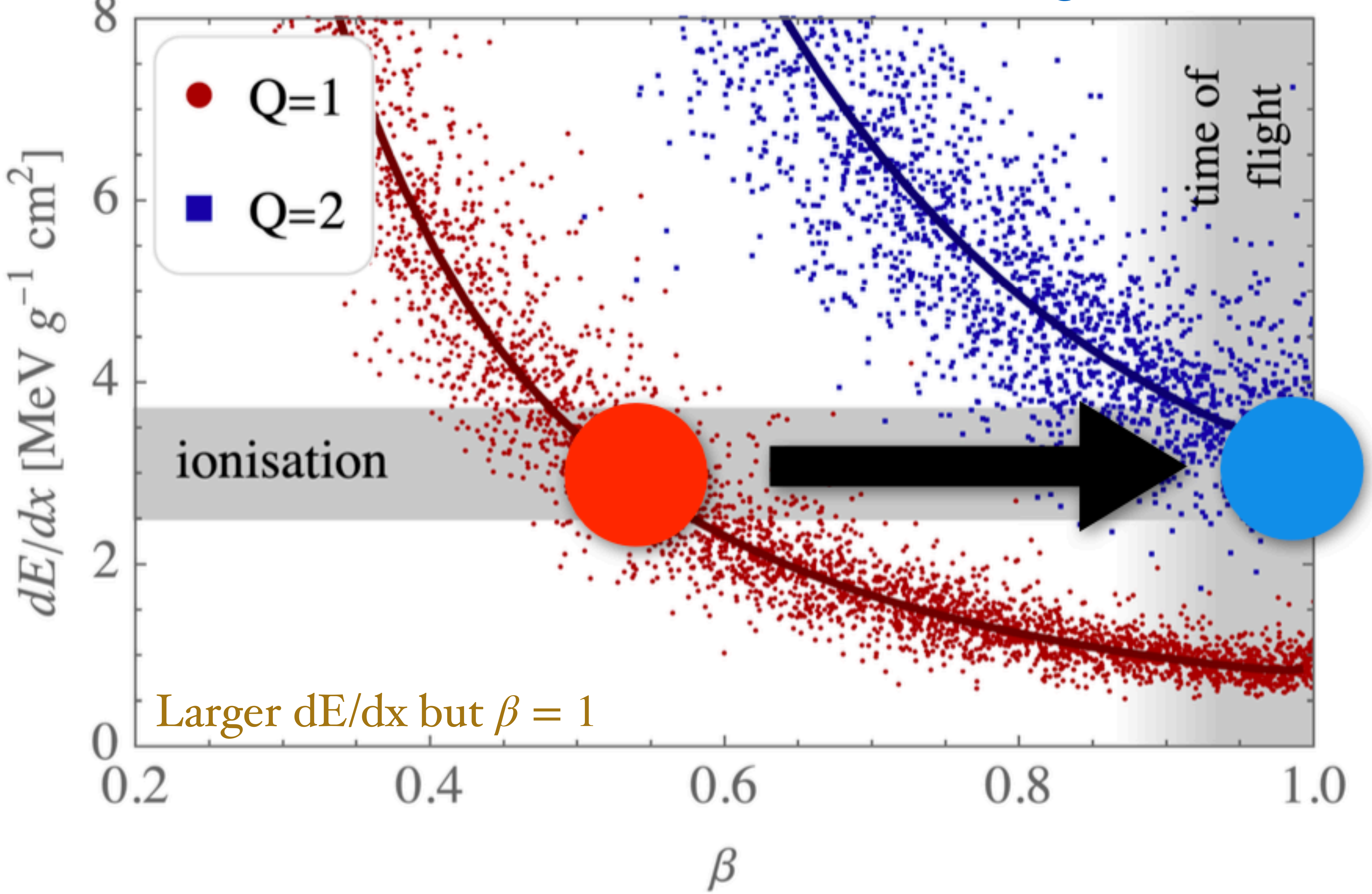
Proposed explanation

- Q=2e



Cross section limits set for various models

Z' into 4^{th} generation of leptons with Q=2e

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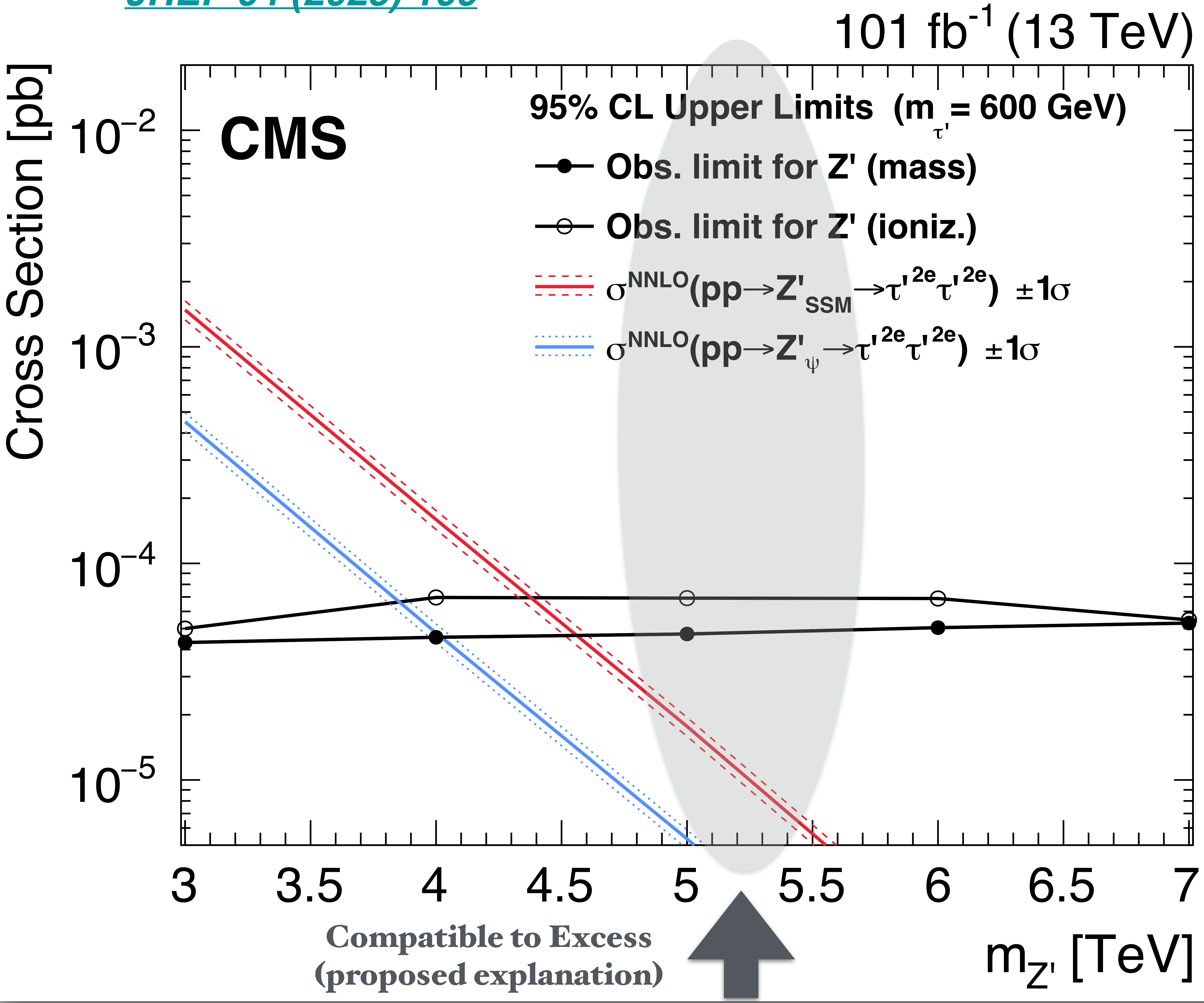

Compatible to Excess
(proposed explanation)

Cross section limits set for various models

Z' into 4th generation of leptons with Q=2e

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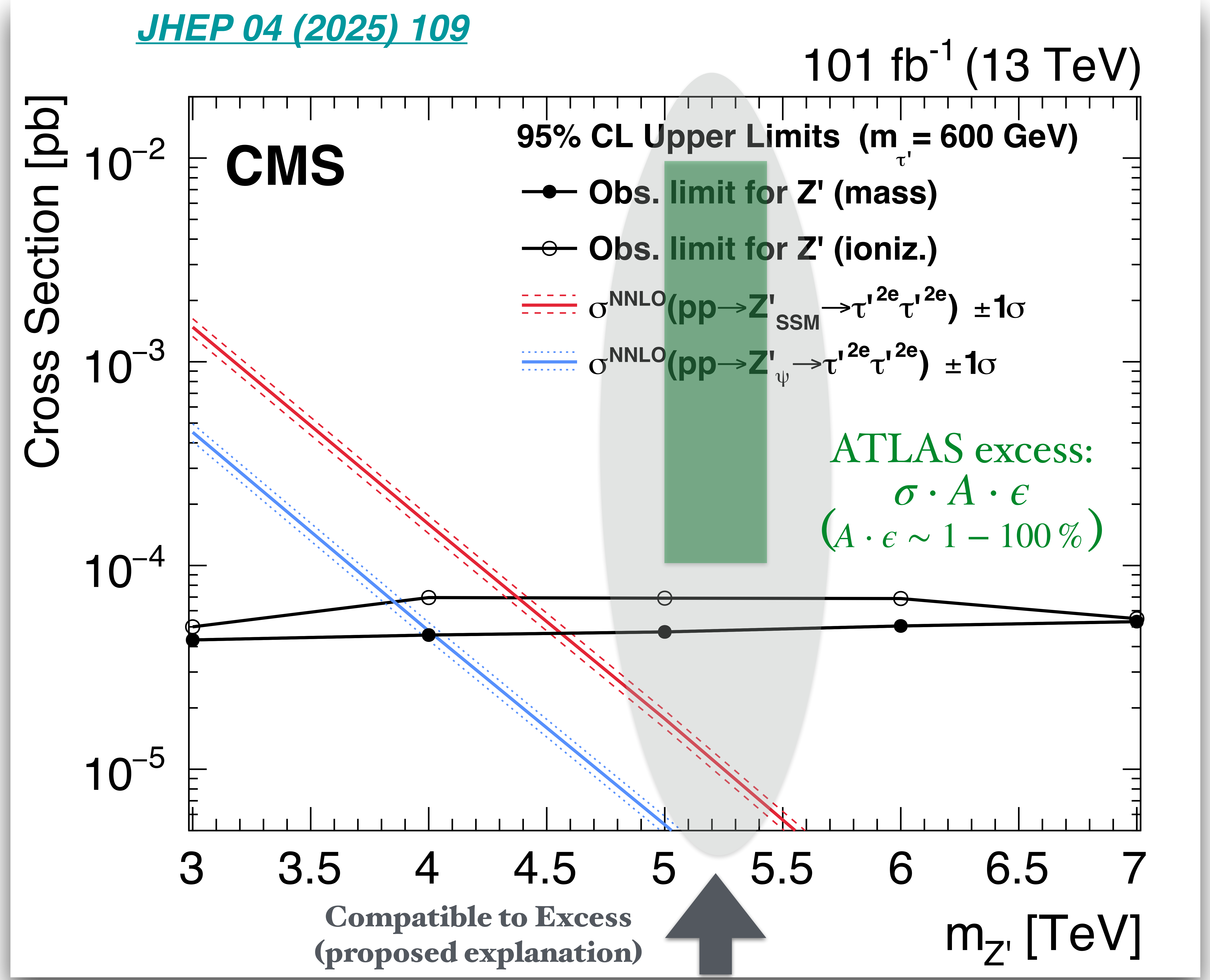
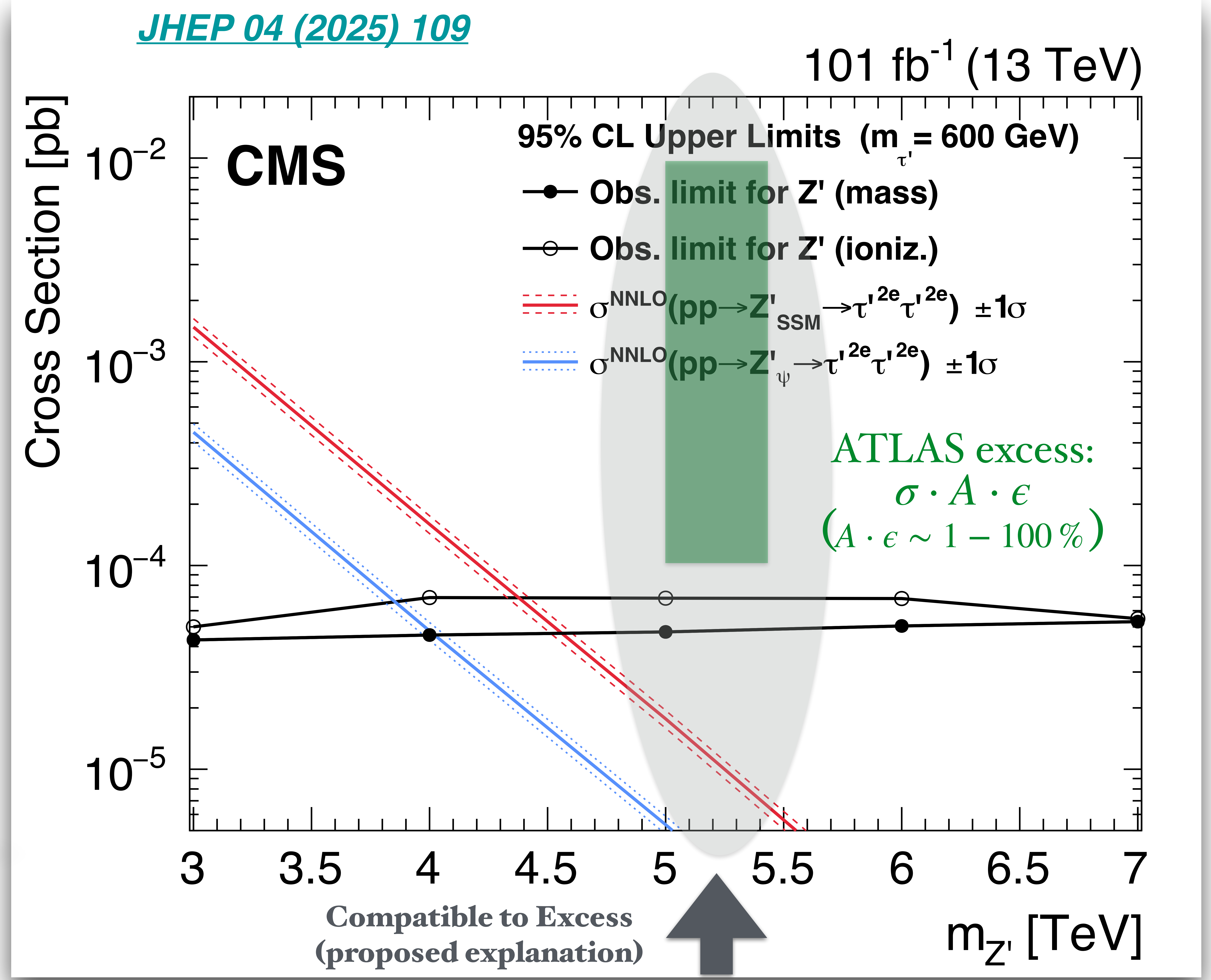


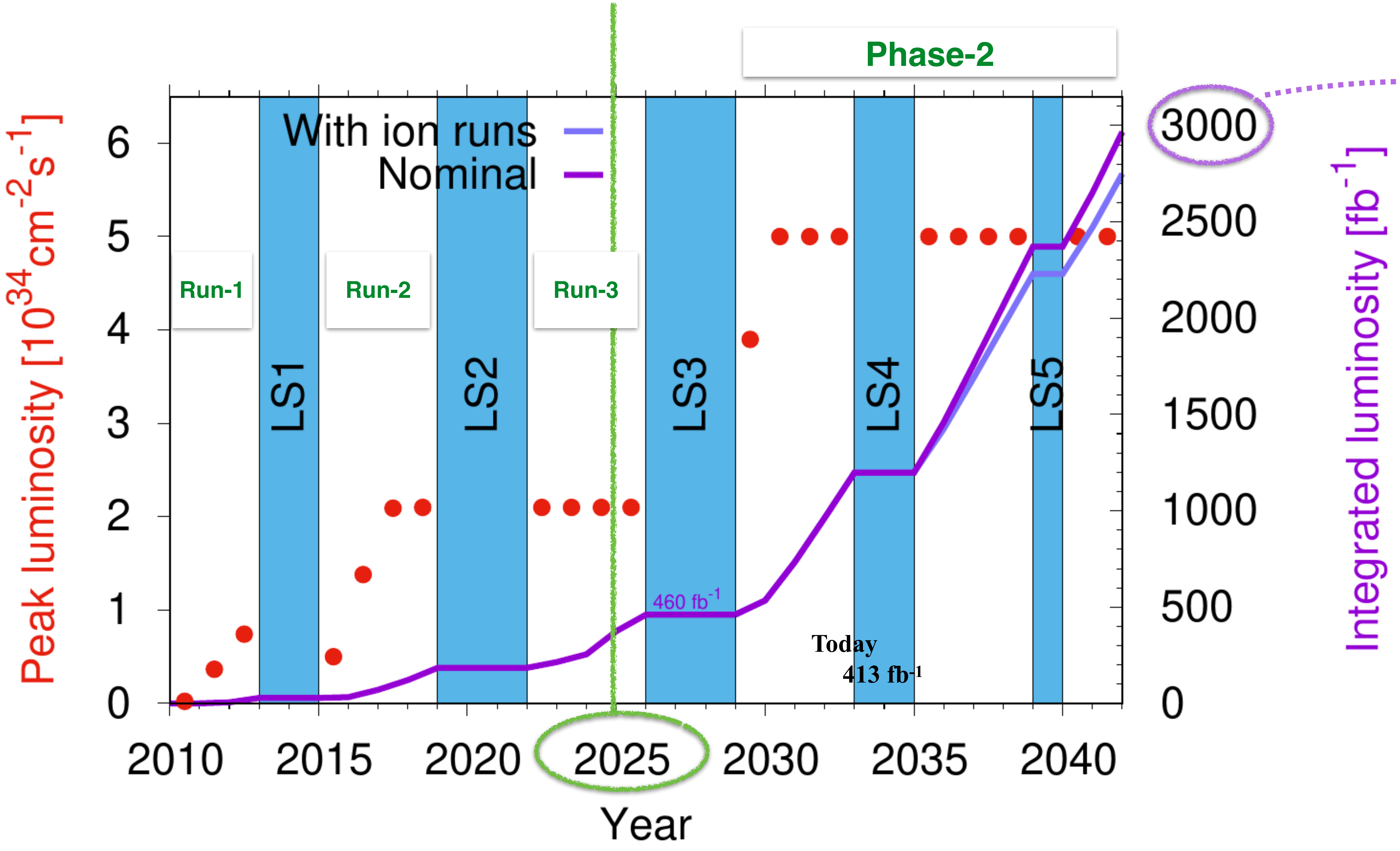
Cross section limits set for various models

Z′ **into 4th generation of leptons with Q=2e**

The proposed explanation is ruled out

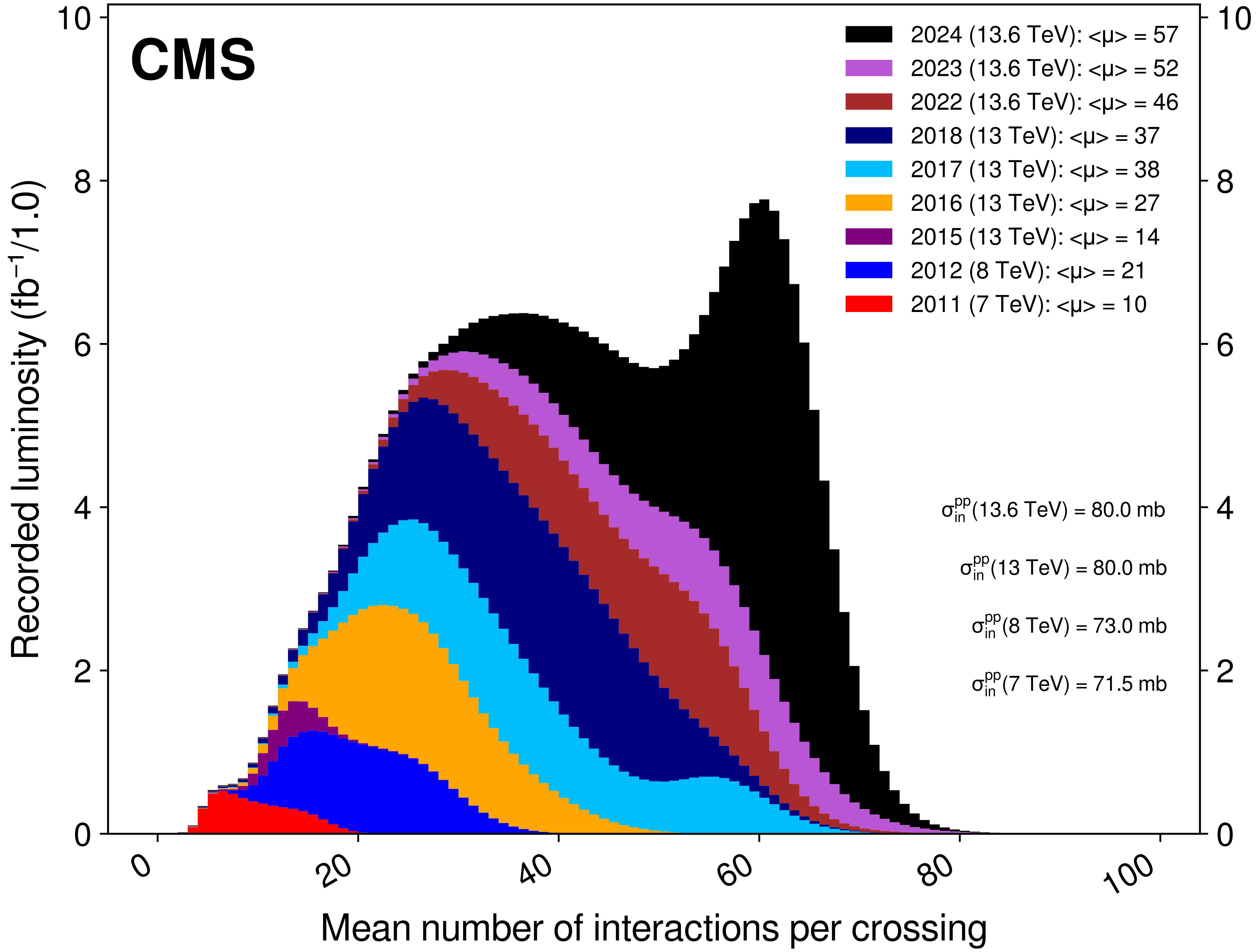


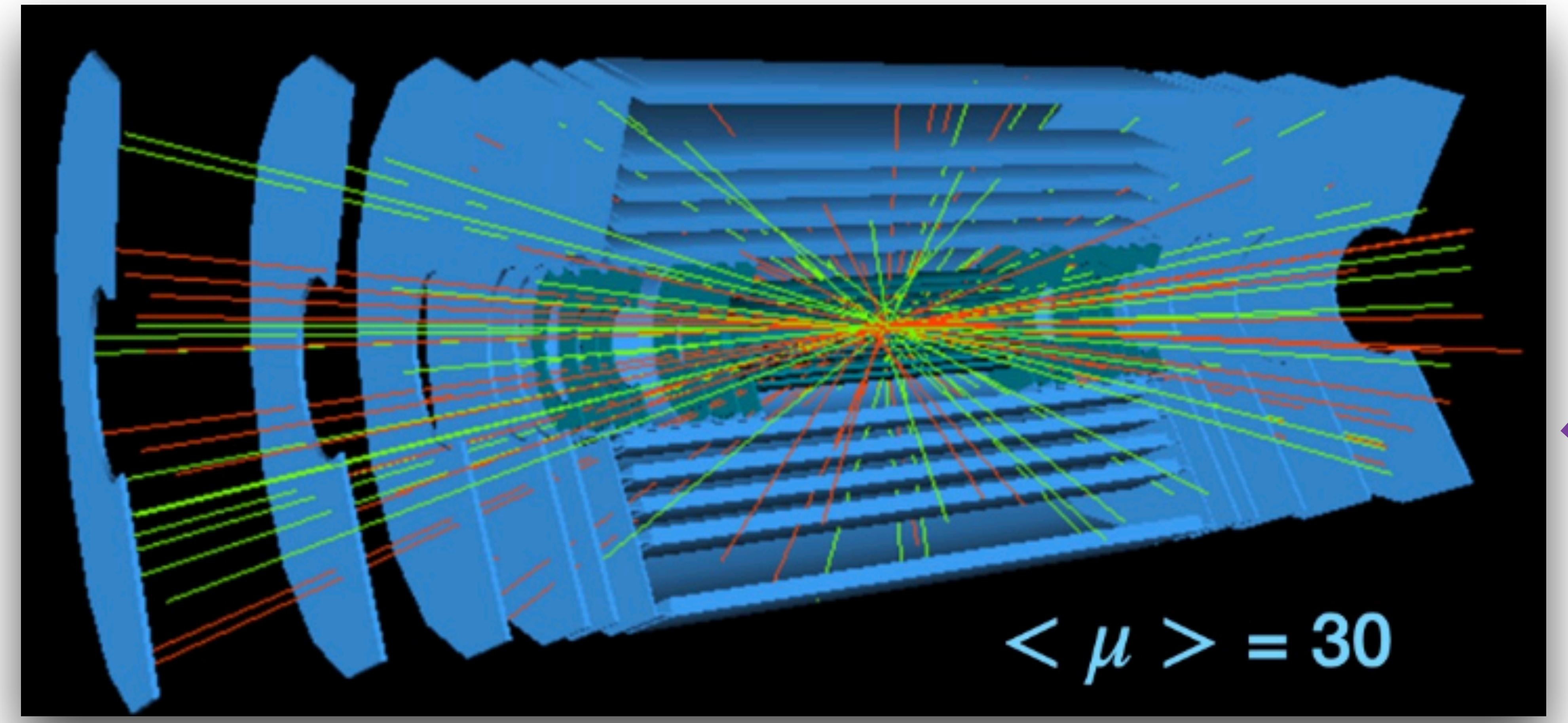
- **Motivation to go beyond the Standard Model**
- **Tracker-based signature: Heavy Stable Charged Particles**
- **Perspectives**



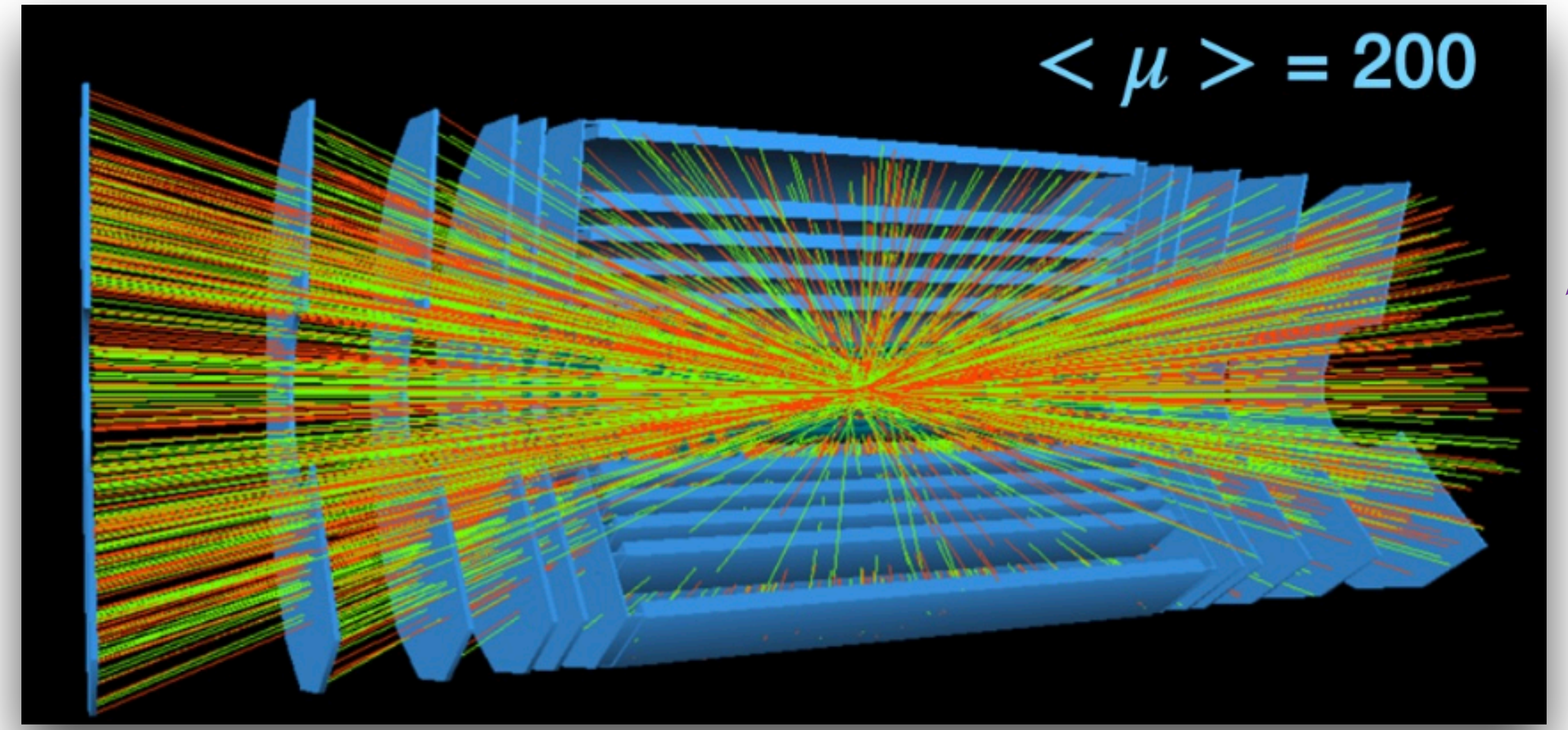
$$N_{evts} = \sigma \cdot L \cdot A \cdot \epsilon$$

- Better precision measurements
- Access to rare processes





- **At HL-LHC**



Larger Data Rates

Higher Pileup

Higher Occupancy

Higher Radiation

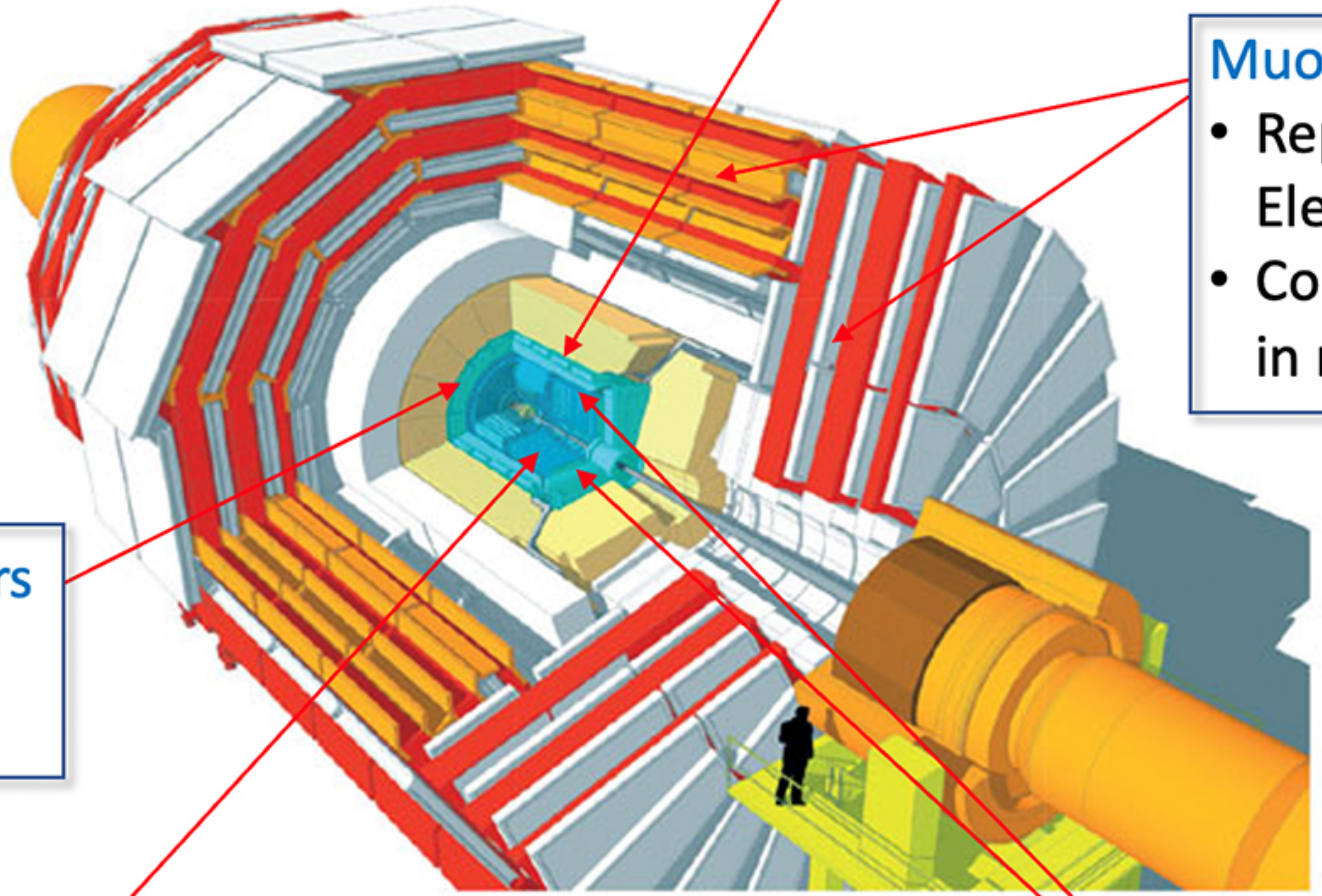
...

HL-LHC: CMS Upgrade to meet the challenges

Trigger/HLT/DAQ
- Track information in L1-Trigger
- L1-Trigger: 12.5 μs latency – output 750 kHz
- HLT output 7.5 kHz

Barrel ECAL/HCAL
- Replace FE/BE electronics
- Lower ECAL operating temp. (8 °C)

Muon Systems
- Replace DT & CSC FE/BE Electronics
- Complete Muon coverage in region $1.5<\eta<2.4$



NEW!

New Endcap Calorimeters
- High granularity
- 3D capable

NEW!

New Tracker
- Rad. tolerant – high granularity – significant less material
- 40 MHz selective readout (p_T>2 GeV) in Outer Tracker for L1 -Trigger
- Extended coverage to $\eta=4$

New Precision Timing Detector
- Barrel: Crystal +SiPM
- Endcap: Low Gain Avalanche Diodes

NEW!

$$N_{evts} = \sigma \cdot L \cdot A \cdot \epsilon$$

The sensitivity ($\mathcal{S}$) in search for resonances

$$\mathcal{S} \backsimeq \frac{S}{\sqrt{B}} \backsimeq \sqrt{L}\frac{\sigma_S}{\sqrt{\sigma_B}}$$

Signal events

Background events

New Detectors & New Capabilities

$\rightarrow A \cdot \epsilon$ improvement

CMS Tracker @HL-LHC

- **Brand New Detector!**
- **Main Goal:**
  - Reduced **Material Budget**
  - Increased **Radiation Hardness**
  - Increased **Granularity**
  - Extended **Tracker Coverage**

CMS Tracker @HL-LHC

- **Brand New Detector!**
- **Main Goal:**
  - Reduced **Material Budget**
  - Increased **Radiation Hardness**
  - Increased **Granularity**
  - Extended **Tracker Coverage**
- **Divided into two:**
  - **Inner Tracker (IT): pixels**
  - **Outer Tracker (OT): modules 2S & PS**

CMS Tracker @HL-LHC

- **Brand New Detector!**
- Main Goal:
  - Reduced **Material Budget**
  - Increased **Radiation Hardness**
  - Increased **Granularity**
  - Extended **Tracker Coverage**

- Divided into two:
  - **Inner Tracker (IT): pixels**
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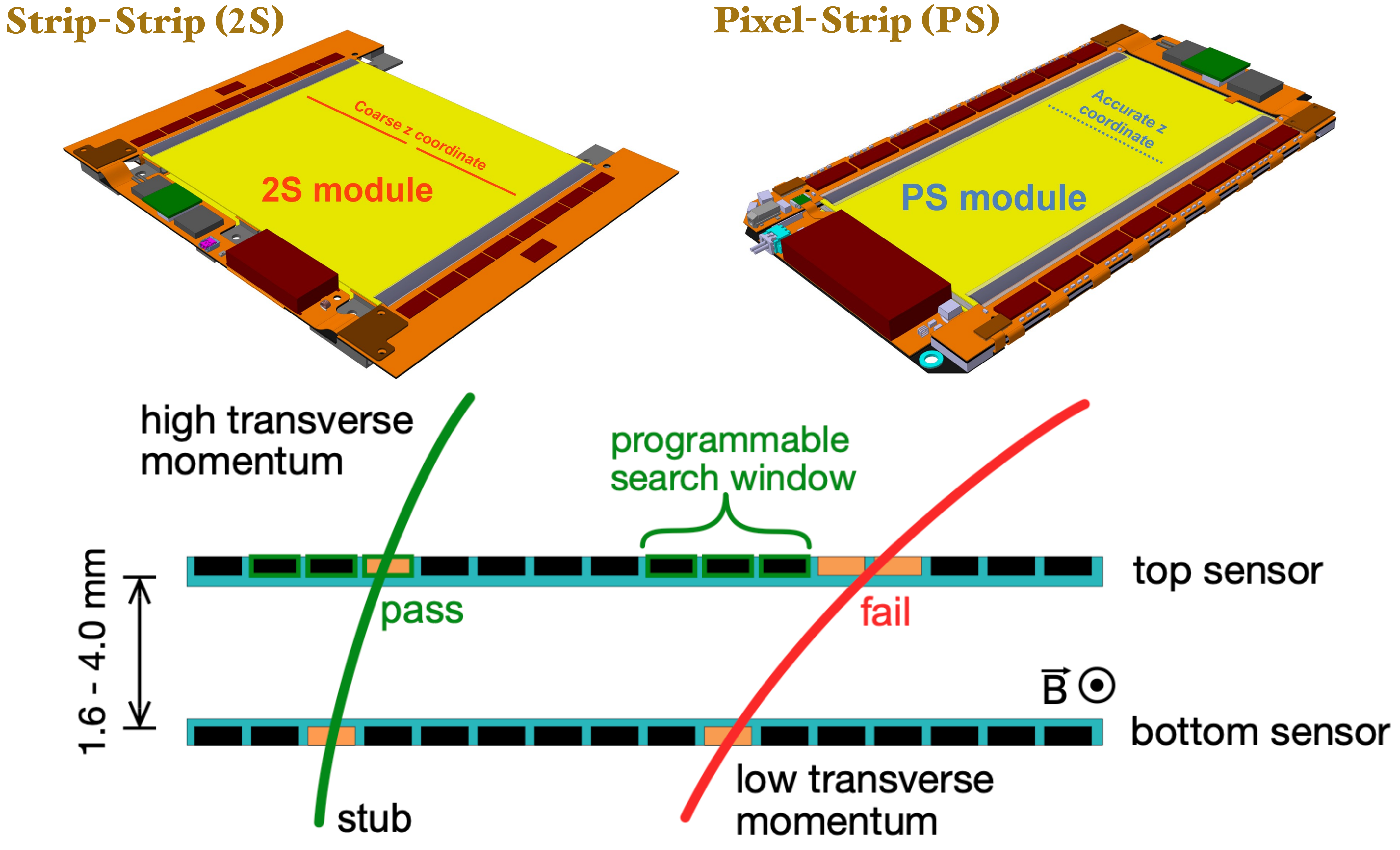


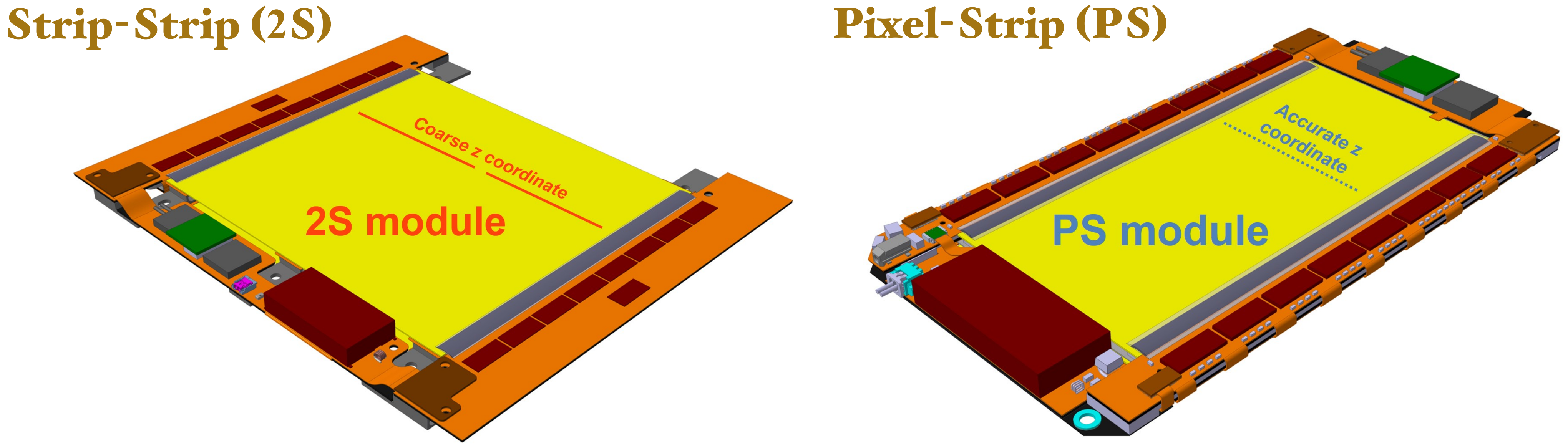
"**Stub**" information is transmitted at **Level-1 Trigger at 40 MHz**

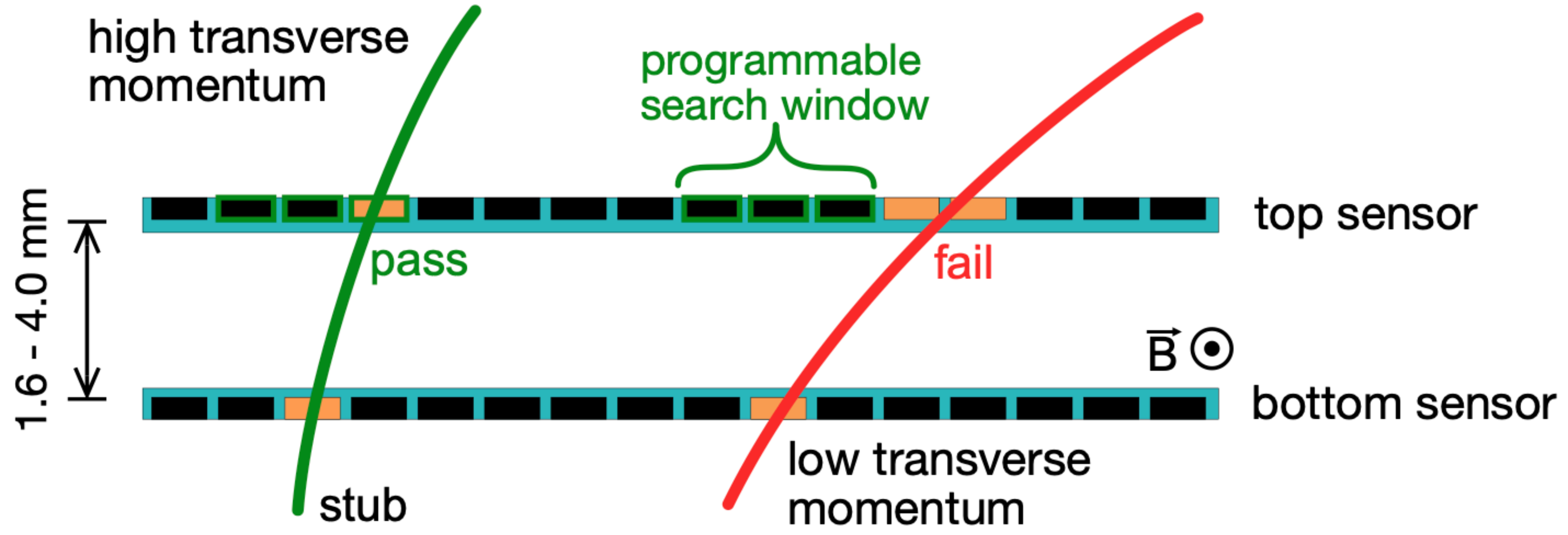
NEW!

- **Brand New Detector!**
- **Main Goal:**
  - Reduced **Material Budget**
  - Increased **Radiation Hardness**
  - Increased **Granularity**
  - Extended **Tracker Coverage**

Vertexing, Jet-tagging, Pileup-rejection at L1, Particle-Flow Reconstruction

- **Divided into two:**
  - **Inner Tracker (IT): pixels**
  - **Outer Tracker (OT): modules 2S & PS**





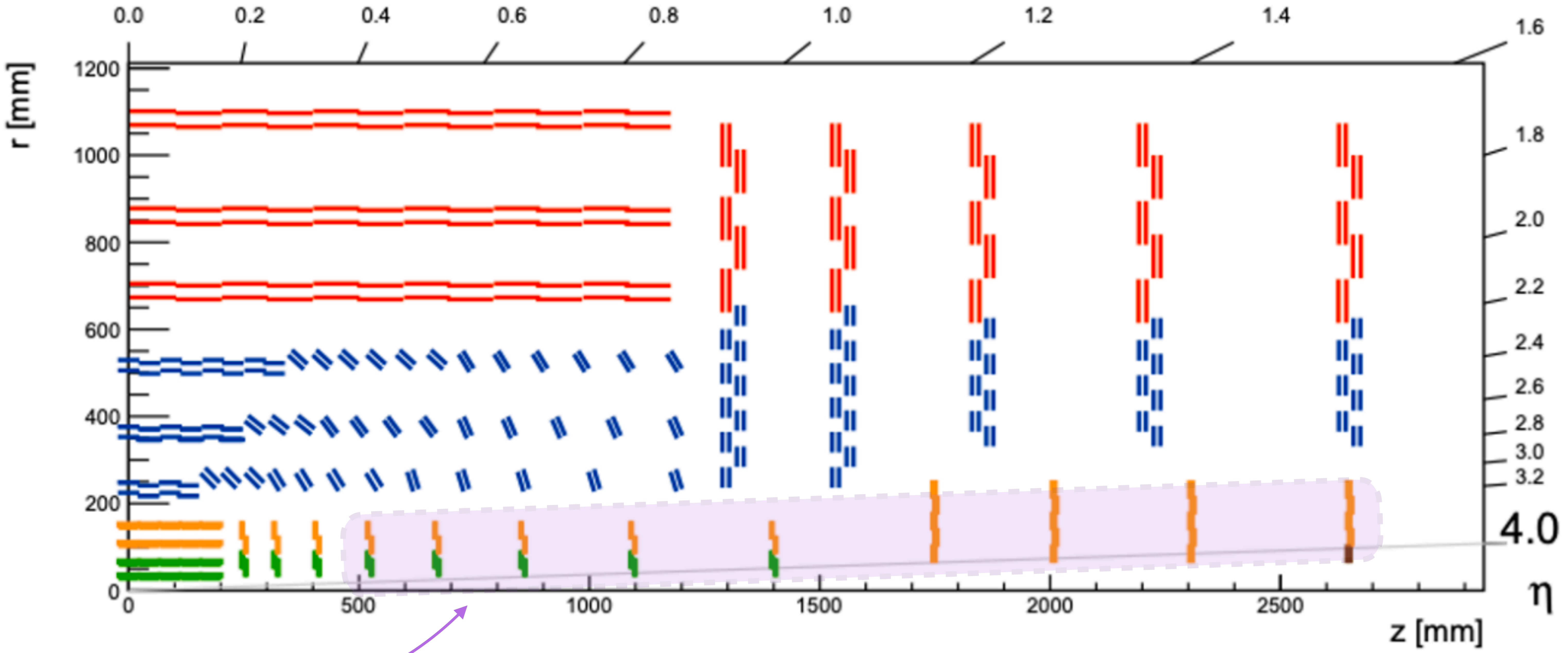
"**Stub**" information is transmitted at **Level-1 Trigger at 40 MHz**

NEW!

- **Brand New Detector!**
- **Main Goal:**
  - Reduced **Material Budget**
  - Increased **Radiation Hardness**
  - Increased **Granularity**
  - Extended **Tracker Coverage** $|\eta| < 4$ (2.5 as of today)

- **Divided into two:**
  - **Inner Tracker (IT): pixels**
  - **Outer Tracker (OT): modules 2S & PS**

where you never looked before

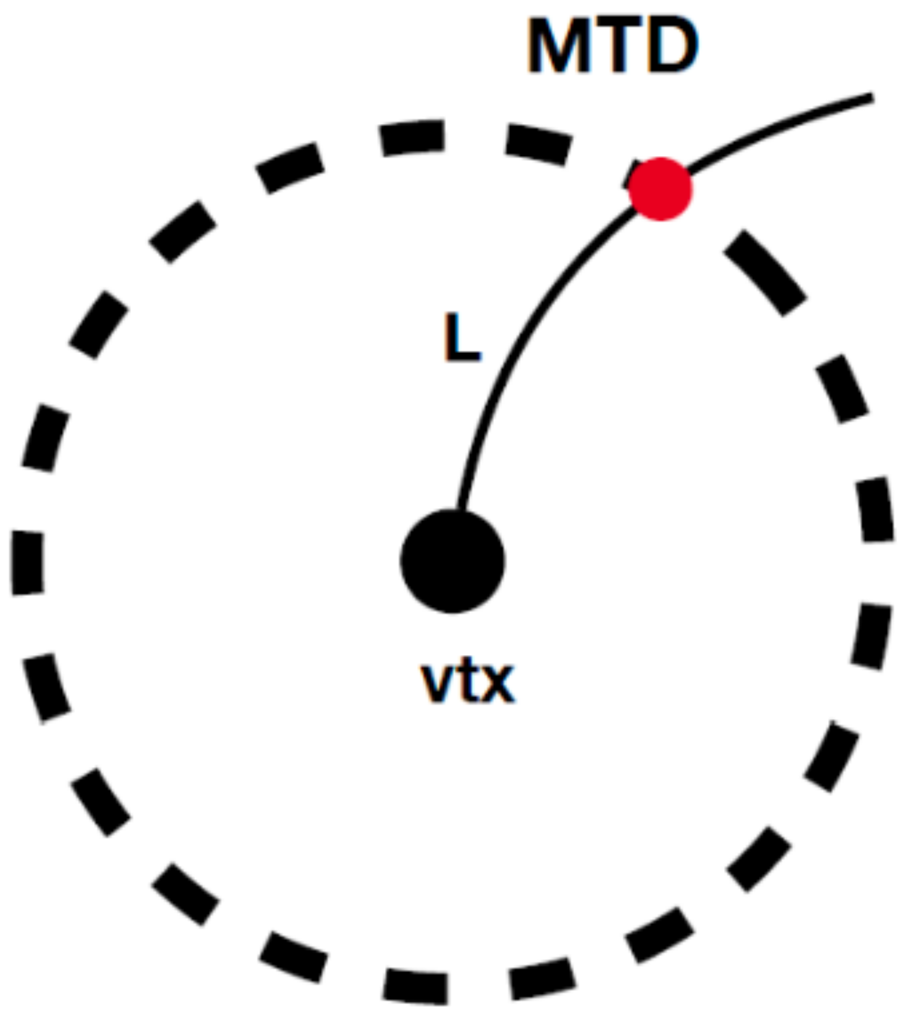


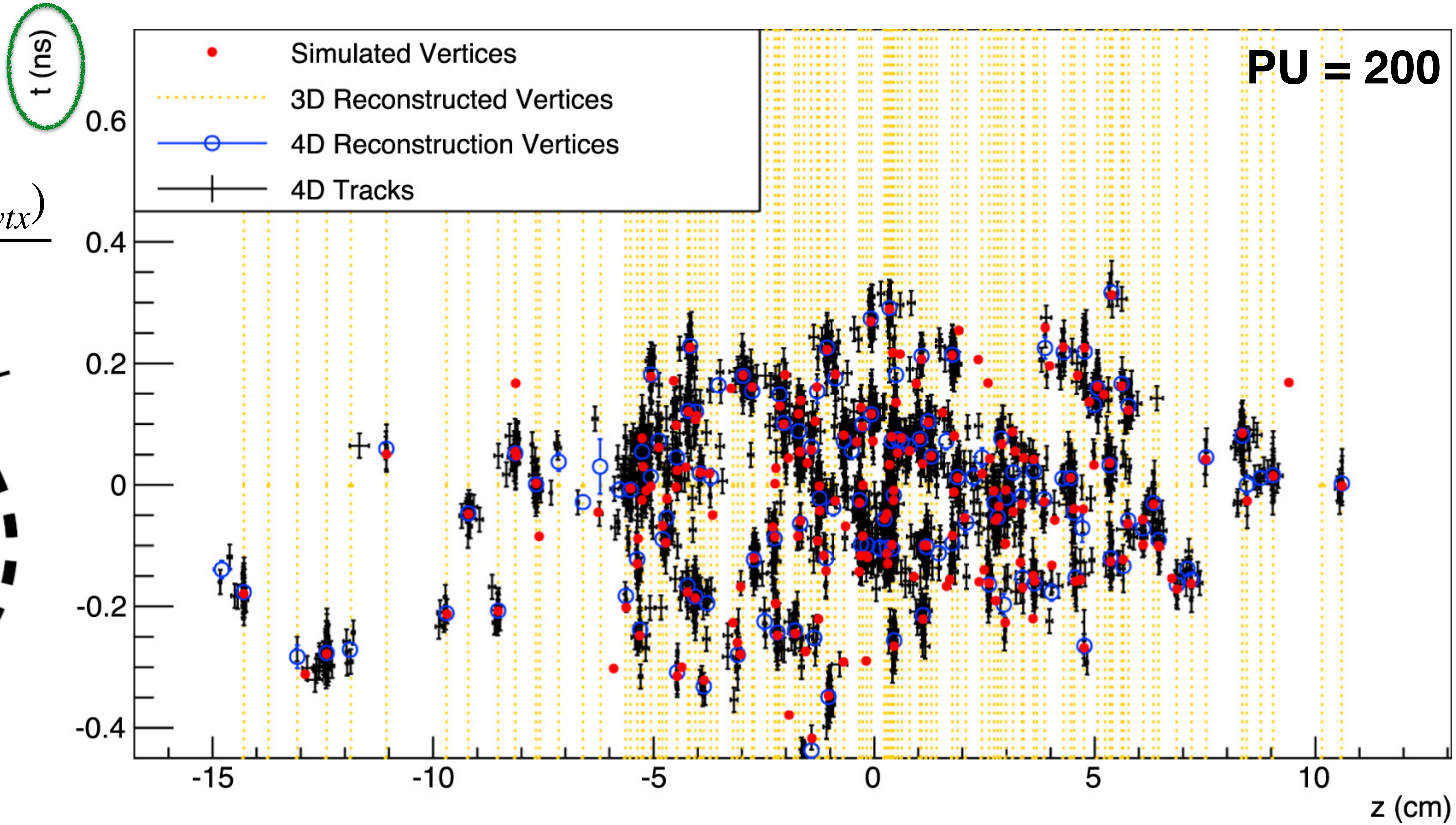
MIP Timing Detector (MTD): Hermetic $|\eta| < 3$

CMS-TDR-020

Enables 4th dimension: timing (30-50 ps time resolution)

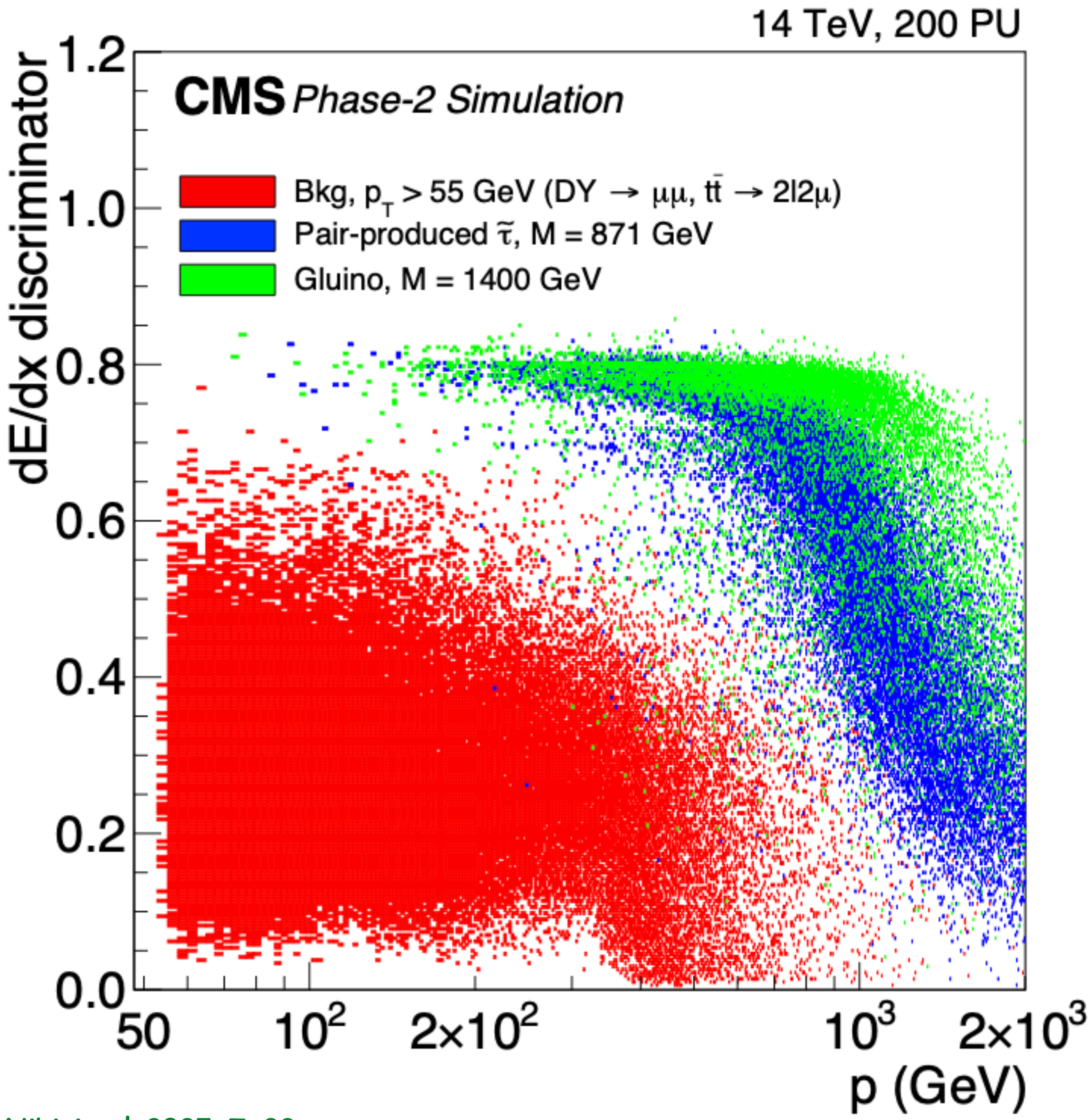
$$\frac{1}{\beta} = \frac{c(t_{MTD} - t_{vtx})}{L}$$

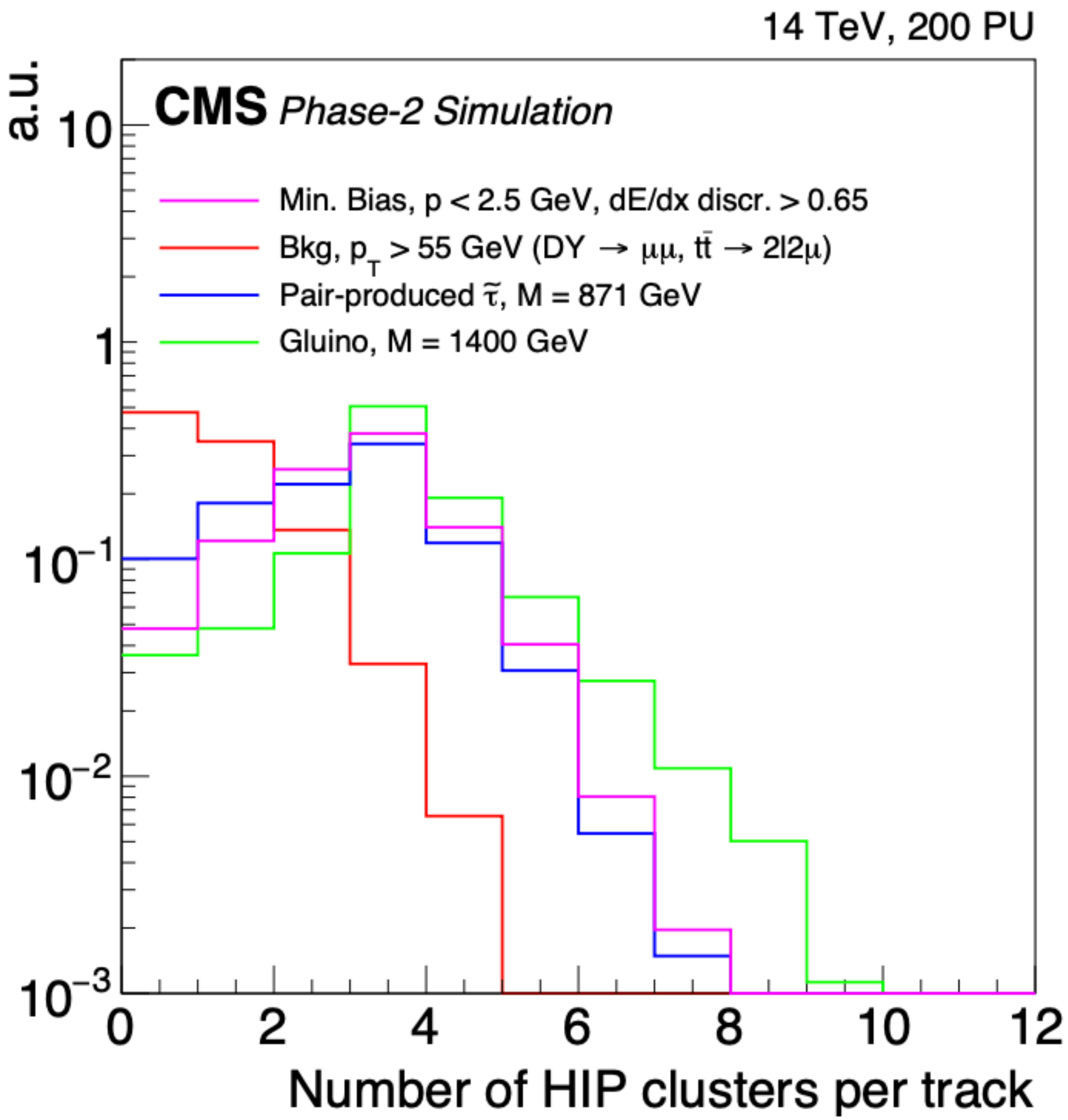




Search for Heavy Stable Charged Particles (HSCP) @HL-LHC

- **Phase-2 IT will still provide dE/dx measurements (time-over-threshold, 4-bit)**
- **Phase-2 OT won't, but will feature an adjustable HIP flag (threshold above MIP)**



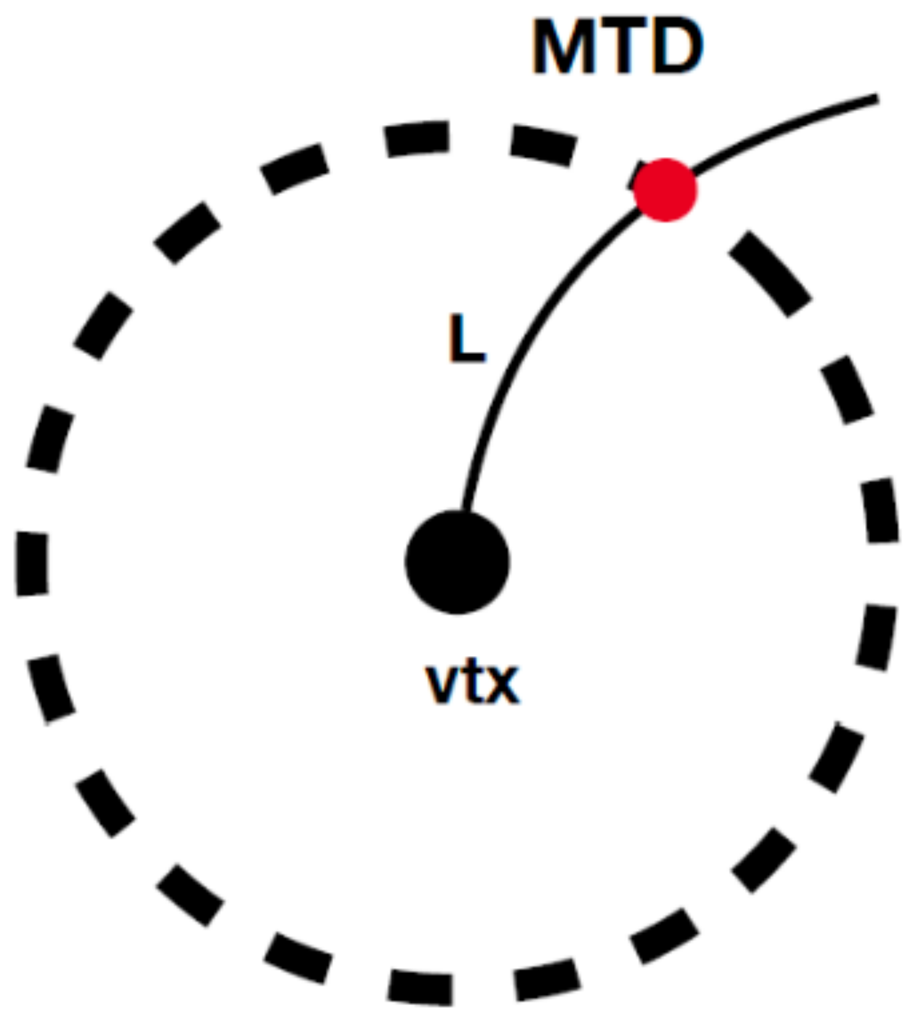


CMS-TDR-014

CMS-TDR-020

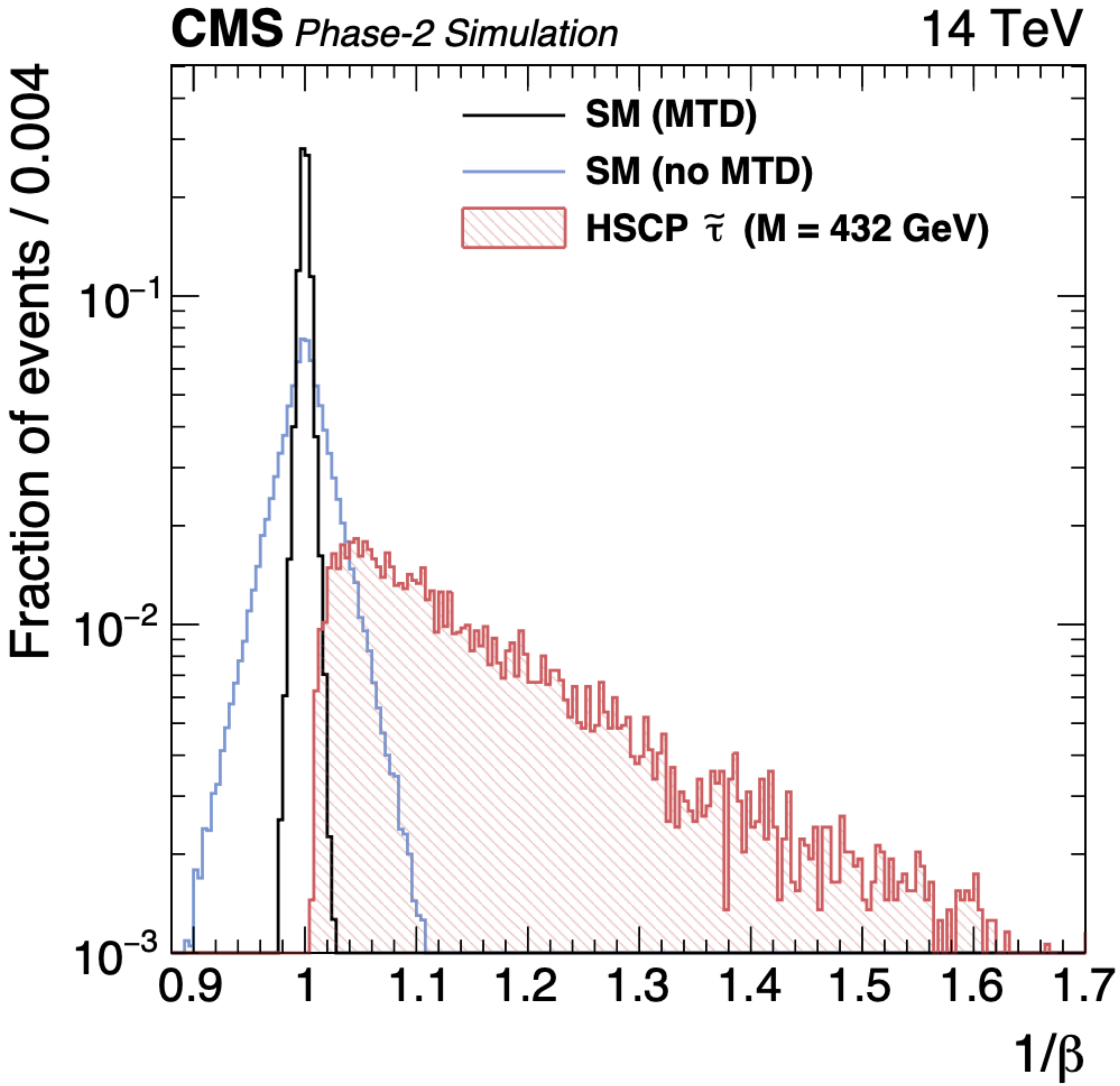
- **Particle identification with the MTD based on the time-of-flight**

$$\frac{1}{\beta} = \frac{c(t_{MTD} - t_{vtx})}{L}$$



Distinguish HSCP from SM

- HSCP associated to delayed hits in MTD



Conclusion

- **Searches with unusual signatures can fill up the gap not covered by conventional signatures**
- **But require enhanced particle detection and identification methods**
  - HL-LHC (new detectors & new capabilities)
  - Futur Colliders
- **Also need robust guidance and strategy to extend the physics reach**
- **CMS Phase-2 Tracker is cool and worth to be explored**

Thank you

Supported by the Department of Energy, Office of Science, under Grant No. DE-SC0020267 and the National Science Foundation, under Award No. 2235028


BACKUP SLIDES

- **Macroscopic lifetime can happen due to various reasons (even in the SM)**
  - Small coupling
  - Heavy mediator
  - Phase-space suppression

Example: charged pion

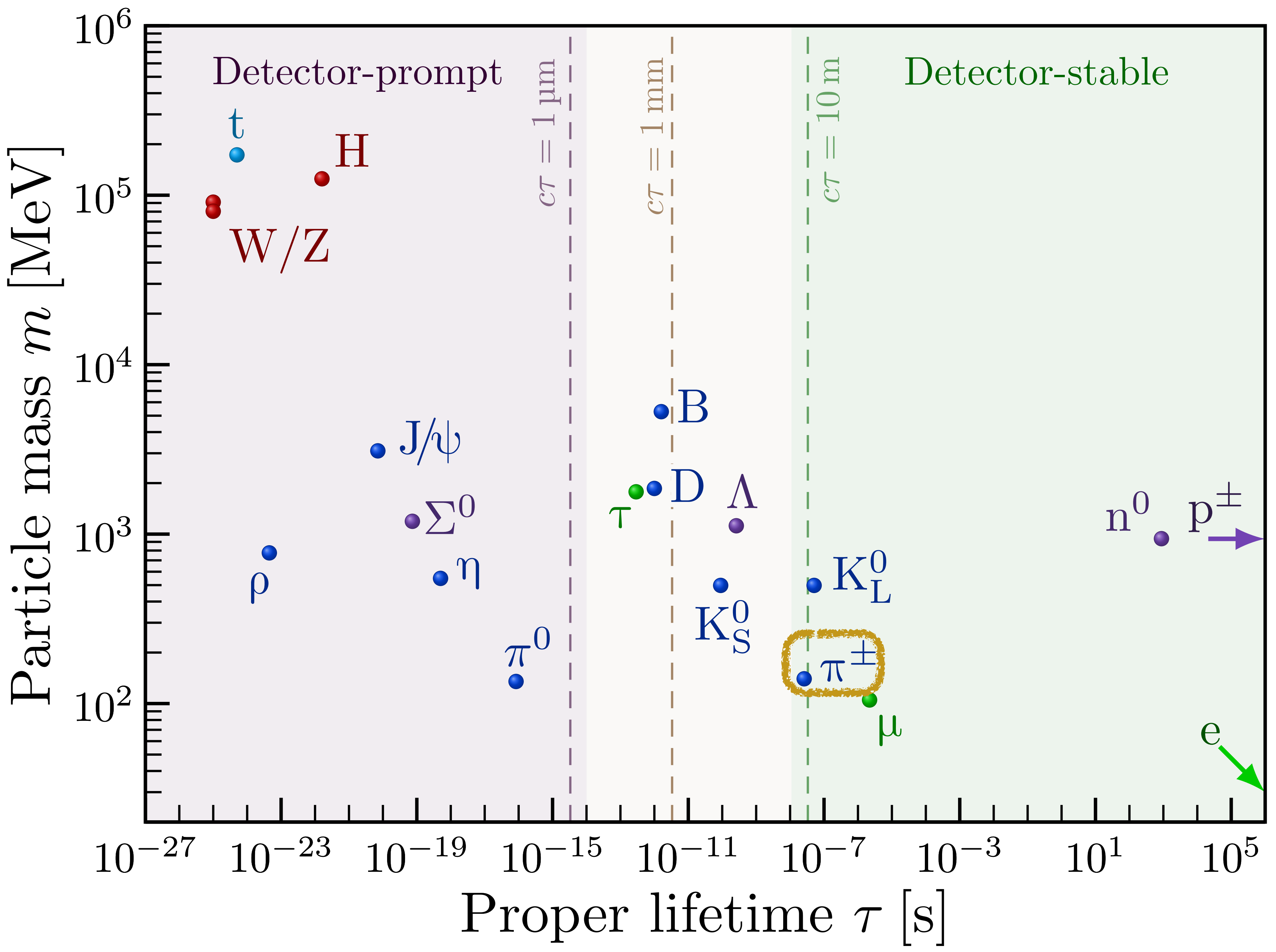
$$\pi^+ \to \mu^+ \nu_\mu$$

$$\frac{1}{\tau_\pi} \sim \left[\frac{g^2}{(M_W)^2} \frac{M_\mu}{M_\pi} \left(M_\pi^2 - M_\mu^2 \right) \right]^2$$

coupling

mediator

compressed mass splitting



HSCP Signal Selection

- **Experimental signature** — **Isolated track with high momentum**

Group	Selection criteria (2017-2018)	Data	$\tilde{g}$ (1.8 TeV)	Pair-prod. $\tilde{\tau}$ (557 GeV)
	All events	1	1	1
	Trigger → Muon Trigger	0.15	0.11	0.86
	$p_T > 55$ GeV	0.11	0.11	0.86
	$\lvert\eta\rvert < 1$	0.059	0.074	0.64
Track Ionization	# of valid pixel hits in L2-L4 ≥ 2	0.056	0.071	0.62
Track Ionization	Fraction of valid hits > 0.8	0.052	0.069	0.62
Track Ionization	# of dE/dx measurements ≥ 10	0.052	0.069	0.62
Track Quality	High-purity track	0.052	0.069	0.62
Track Quality	Track $\chi^2/\mathrm{dof} < 5$	0.052	0.069	0.62
Track Quality	$d_z < 0.1$ cm	0.052	0.069	0.62
Track Quality	$d_{xy} < 0.02$ cm	0.048	0.069	0.62
Track Isolation	$I_{PF}^{rel} < 0.02$	0.014	0.065	0.61
Track Isolation	$I_{trk} < 15$ GeV	0.014	0.065	0.61
Track Isolation	PF $E/p < 0.3$	0.014	0.064	0.61
Track Isolation	$\sigma_{p_T}/p_T^2 < 0.0008$	0.014	0.064	0.61
	$F_i^{Pixels} > 0.3$	0.011	0.064	0.60

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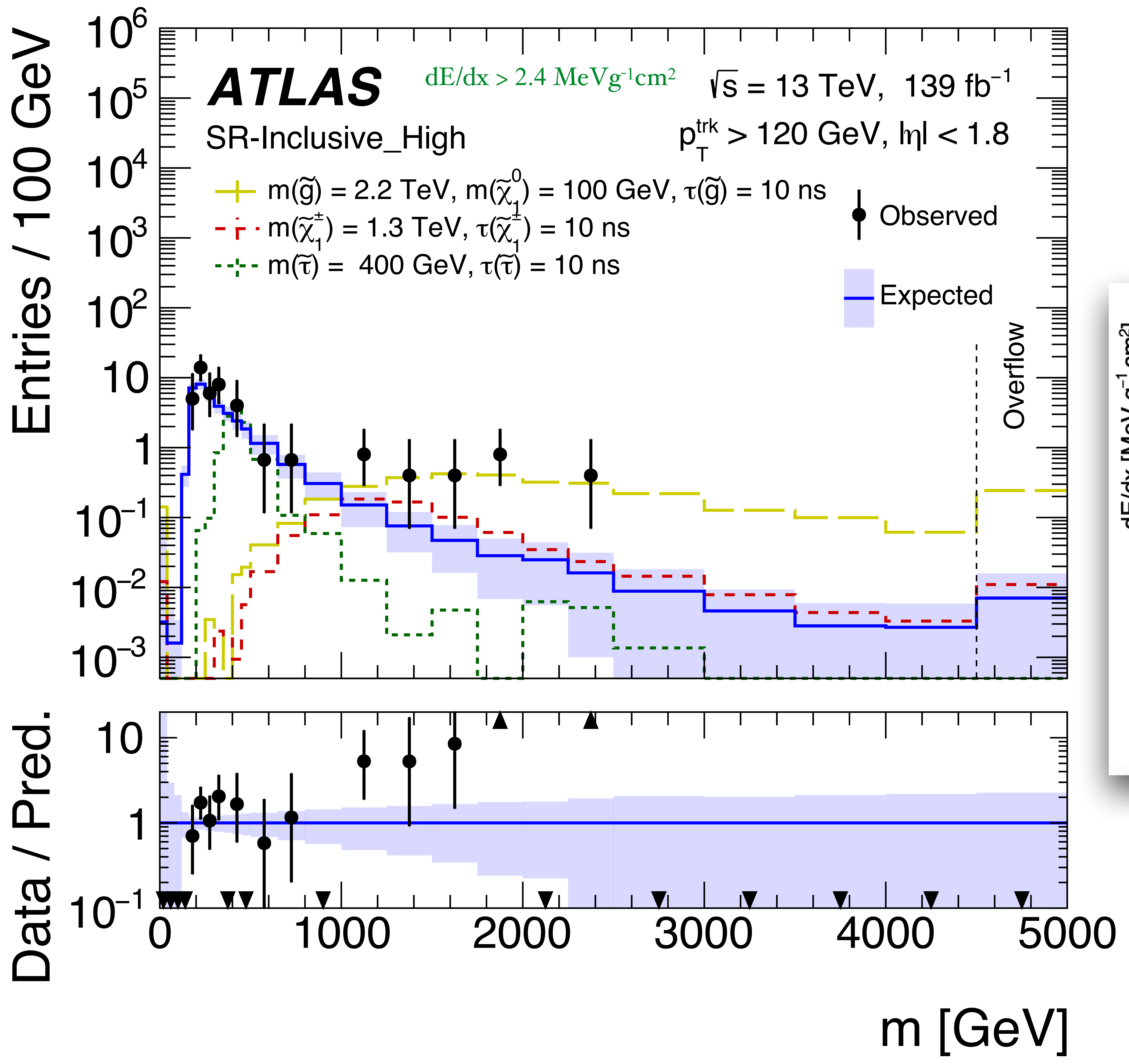
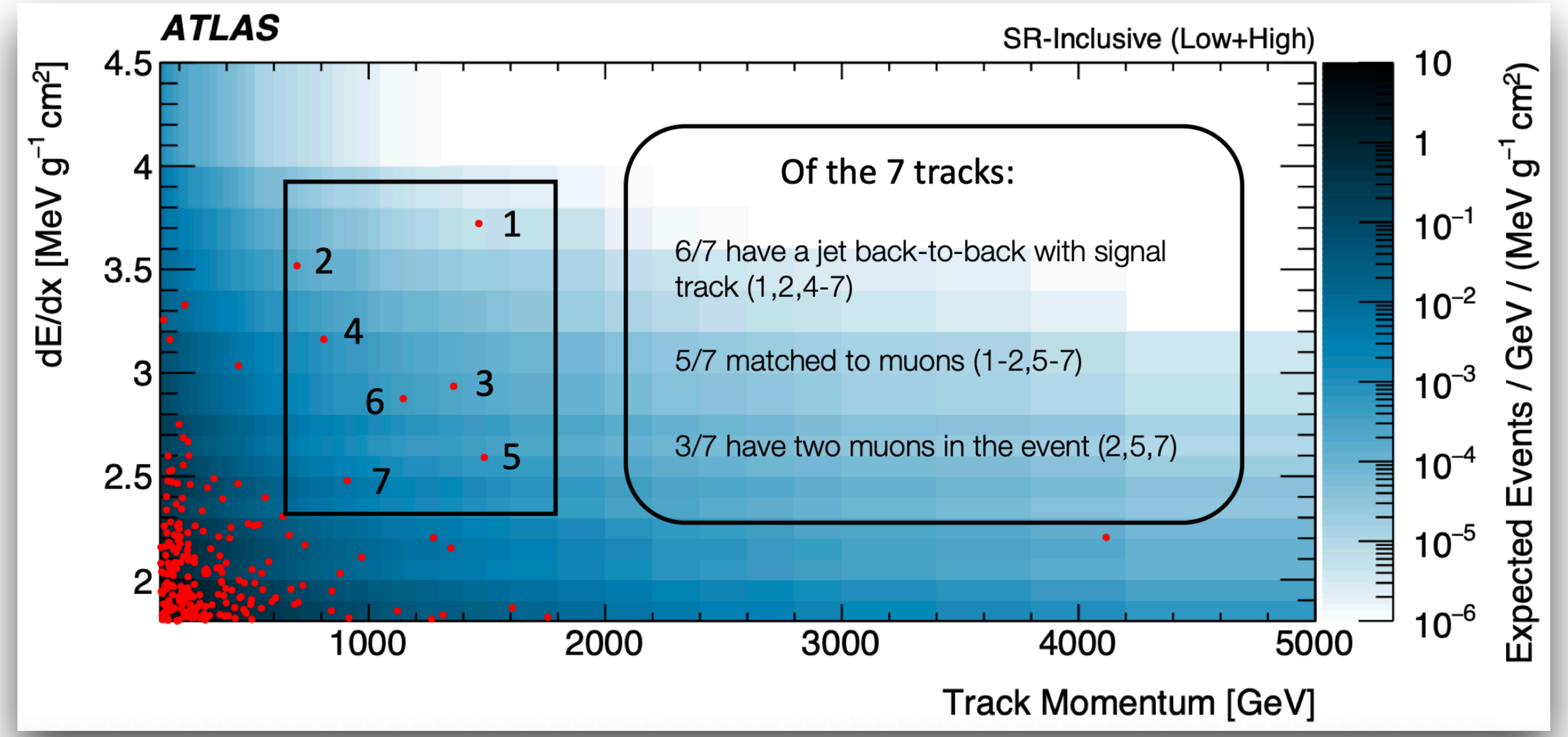


Excess of tracks with local (global) significance of 3.6σ (3.3σ) above m=1 TeV

→ **high dE/dx & high momenta**

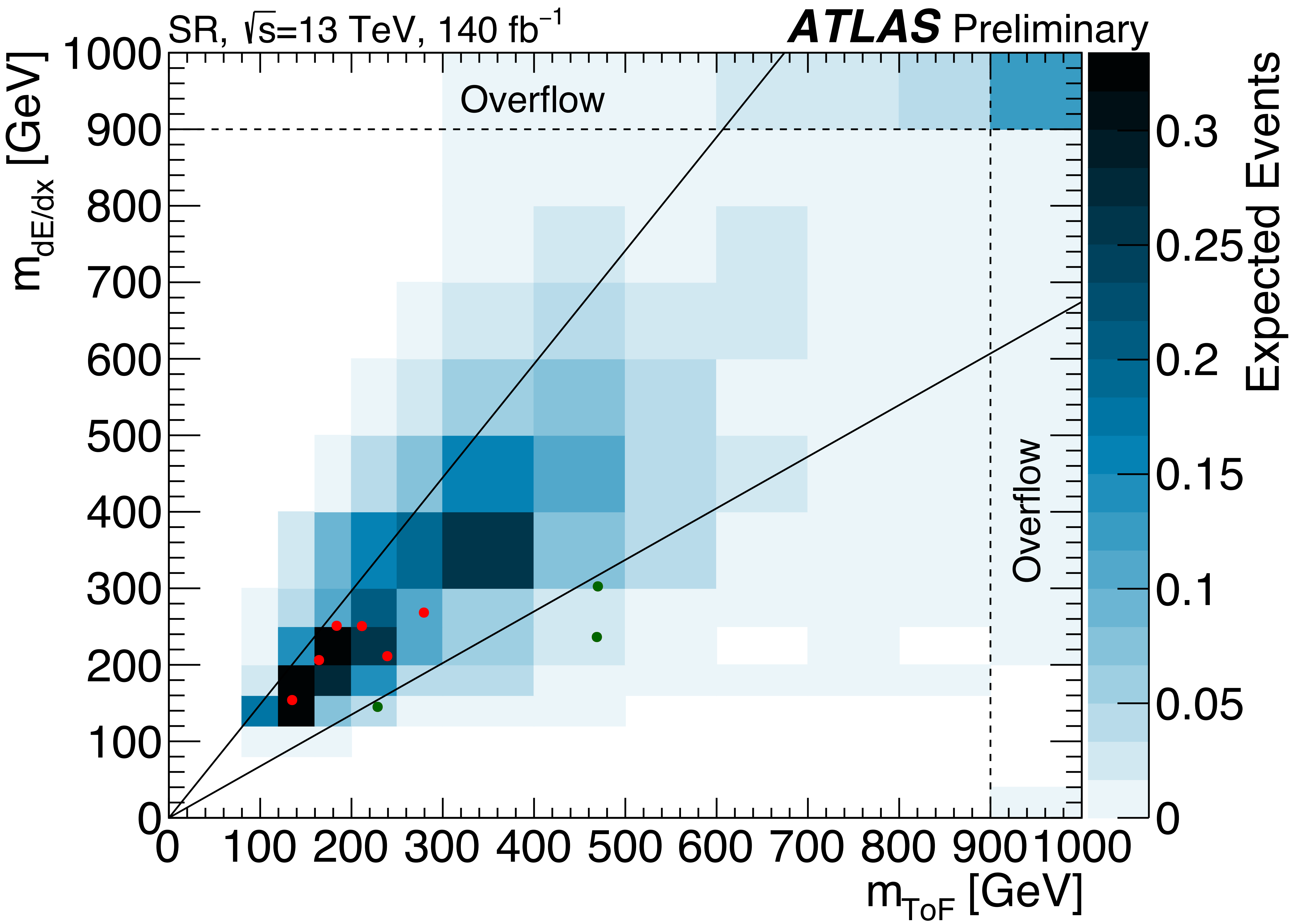


ATL-PHYS-SLIDE-2022-262

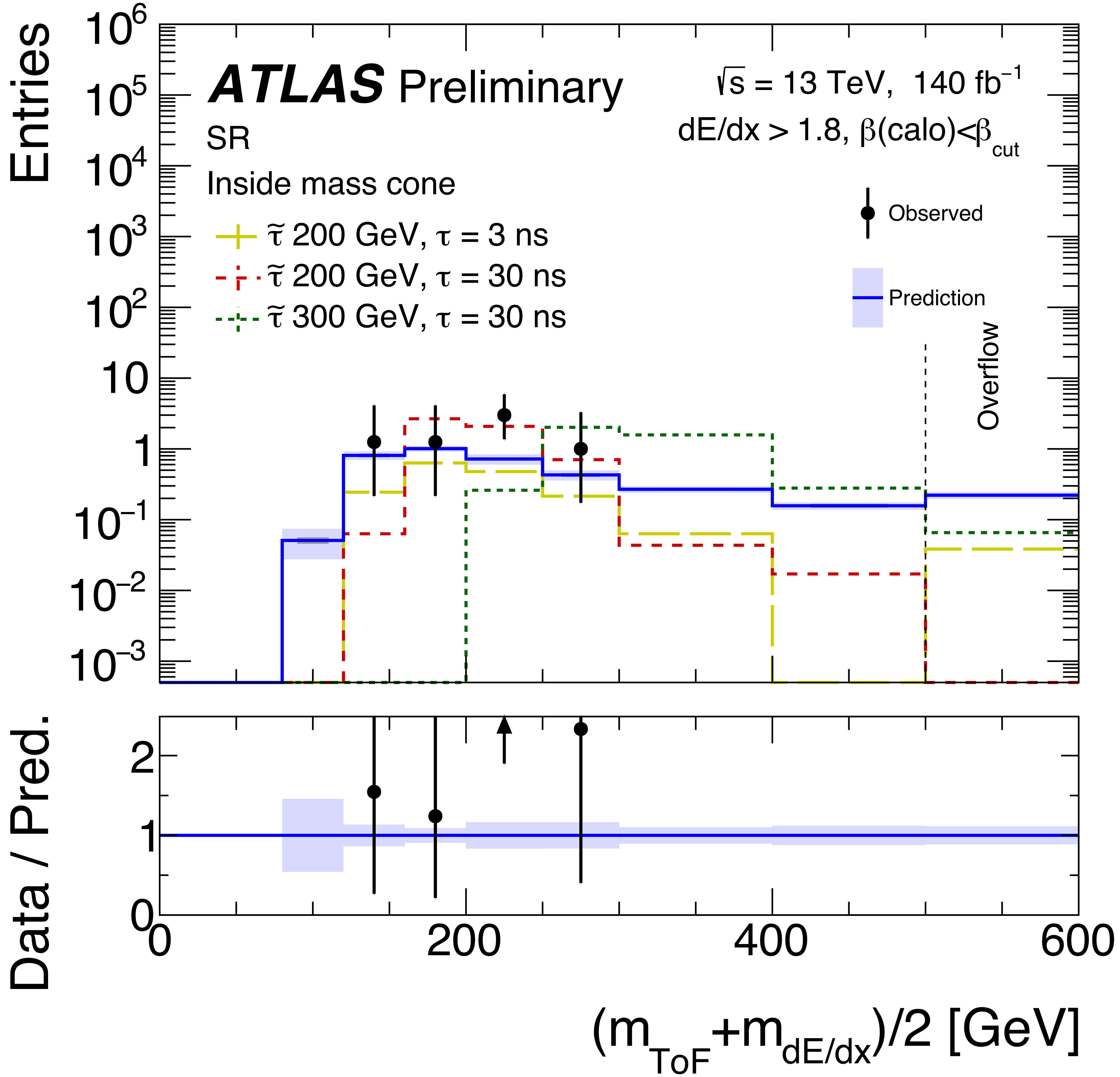
→ **events with excess compatible with $\beta = 1$**

ATLAS 2nd results: Using ToF measurement from Tile Calorimeter

[ATLAS-CONF-2023-044]

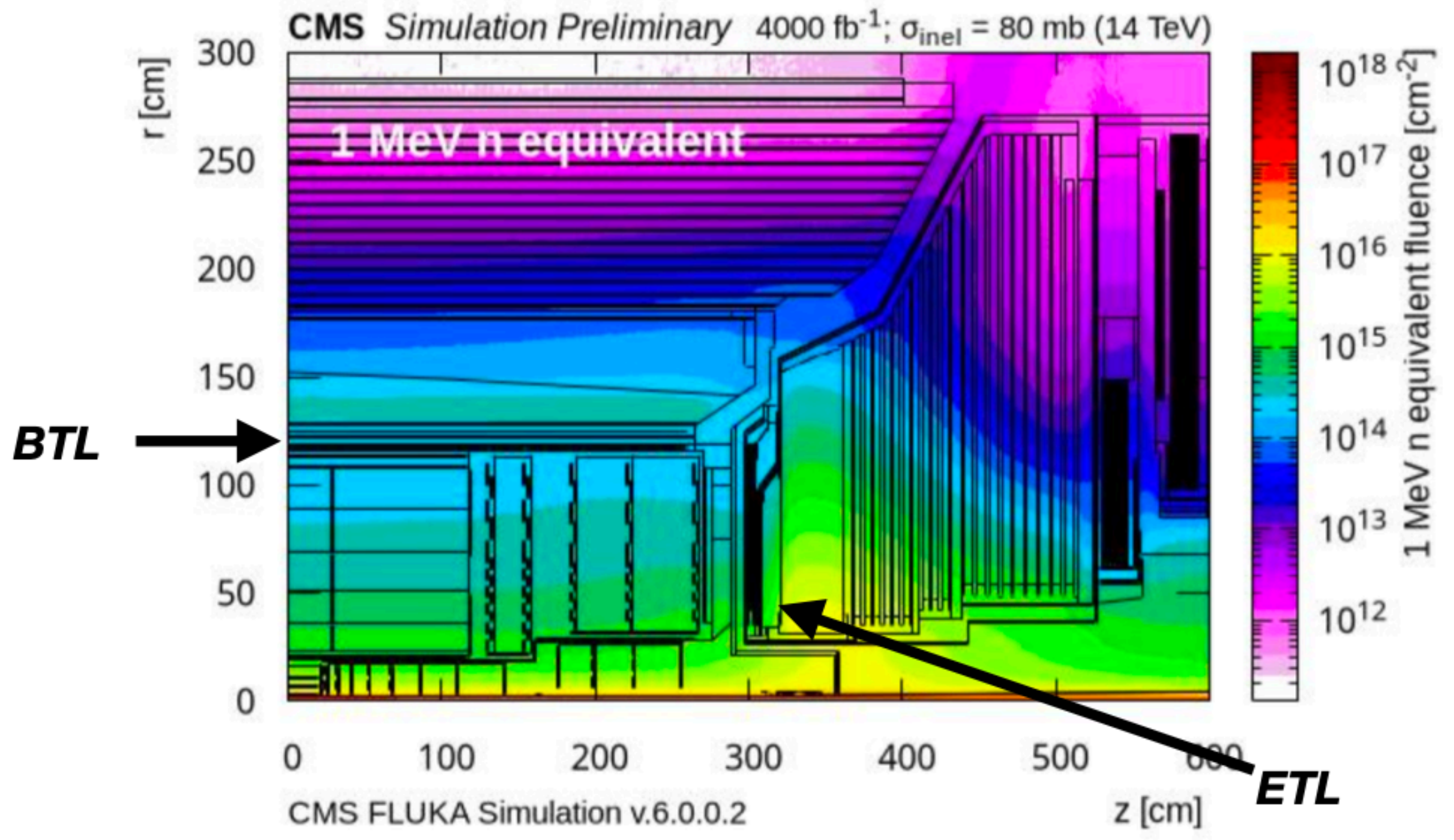


No Excess

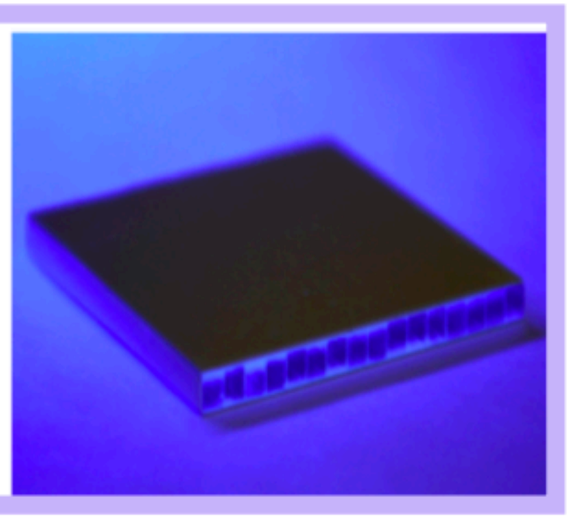


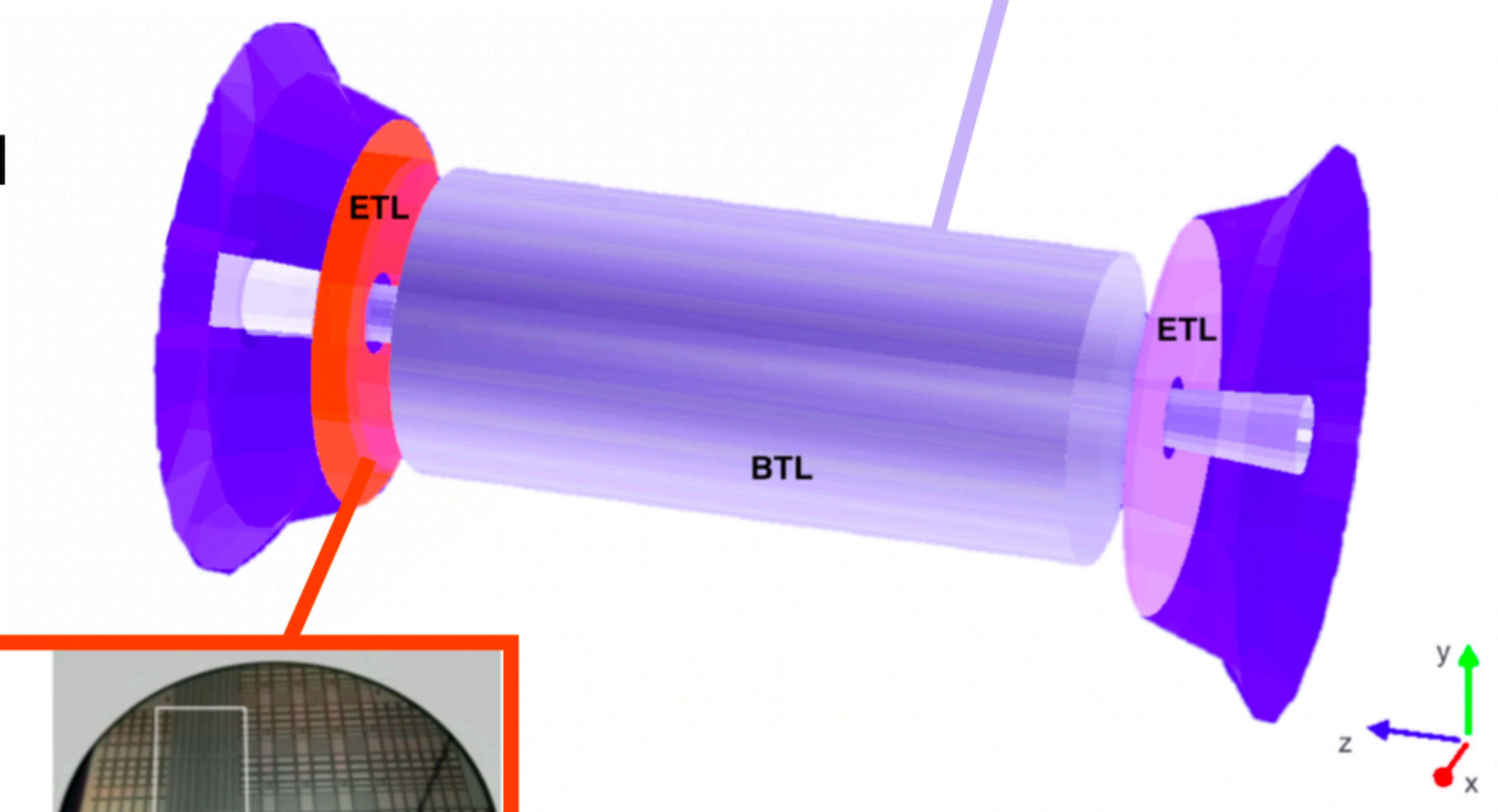
MIP Timing Detector

- **Ultra-thin** detector providing **hermetic coverage** (|η|<3) for charged particles
  - Consists of barrel (|η| < 1.6) and 2×endcap timing layers (BTL & ETL)
  - Installed between tracker and calorimeters
- **Constraints** drive **design**
  - **Radiation hardness** requirements in different regions of CMS
  - **Cost** and **power** effectiveness + **readout** considerations
  - Technology readiness is central consideration: BTL and ETL will **bookend** the upgrade installation

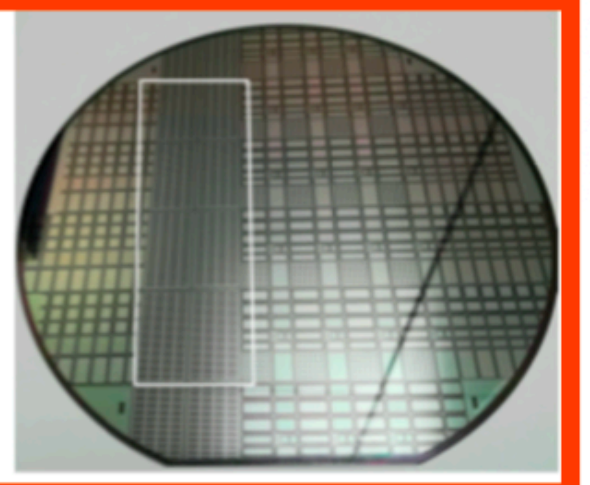


BTL: LYSO bars + SiPM readout:
- TK / ECAL interface: |η| < 1.45
- Inner radius: 1148 mm (40 mm thick)
- Length: ±2.6 m along z
- Surface ~38 m^2; 332k channels
- Fluence at 4 ab^{-1}: 2x10^{14} n_{eq}/cm^2





ETL: Si with internal gain (LGAD):
- On the CE nose: 1.6 < |η| < 3.0
- Radius: 315 < R < 1200 mm
- Position in z: ±3.0 m (45 mm thick)
- Surface ~14 m^2; ~8.5M channels
- Fluence at 4 ab^{-1}: up to 2x10^{15} n_{eq}/cm^2



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