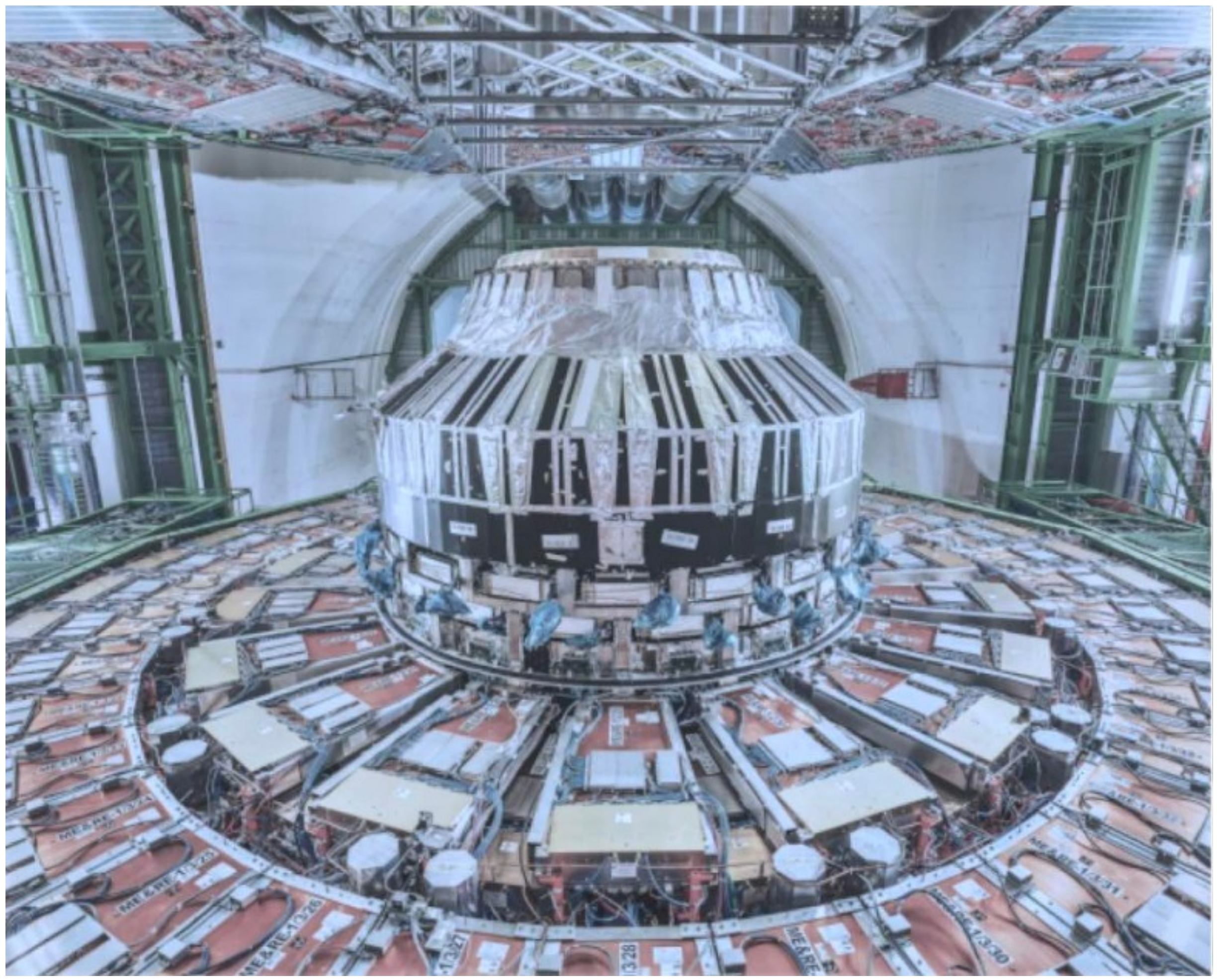
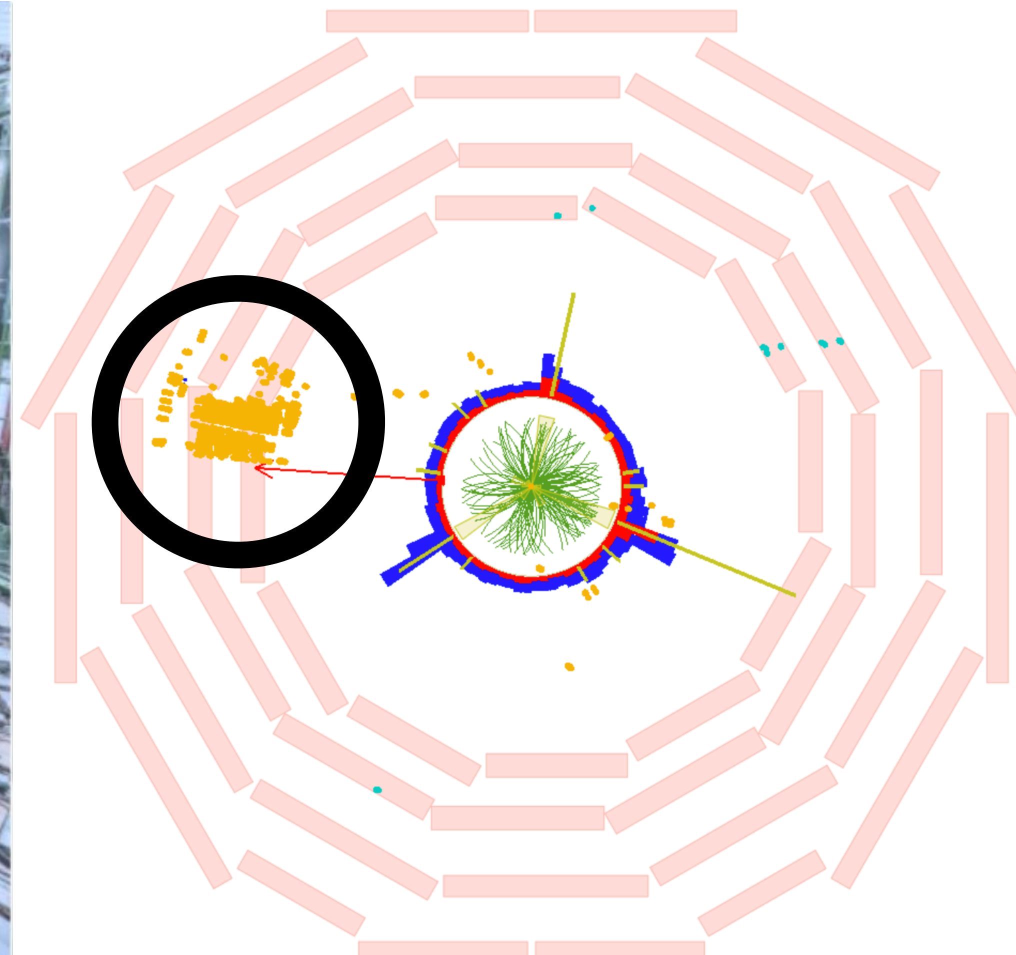
Unlocking the CMS Experiment to Catch Long-lived Particles





Cristián H. Peña

Sapienza — Seminari INFN

November 27, 2023

SAPIENZA UNIVERSITÀ DI ROMA

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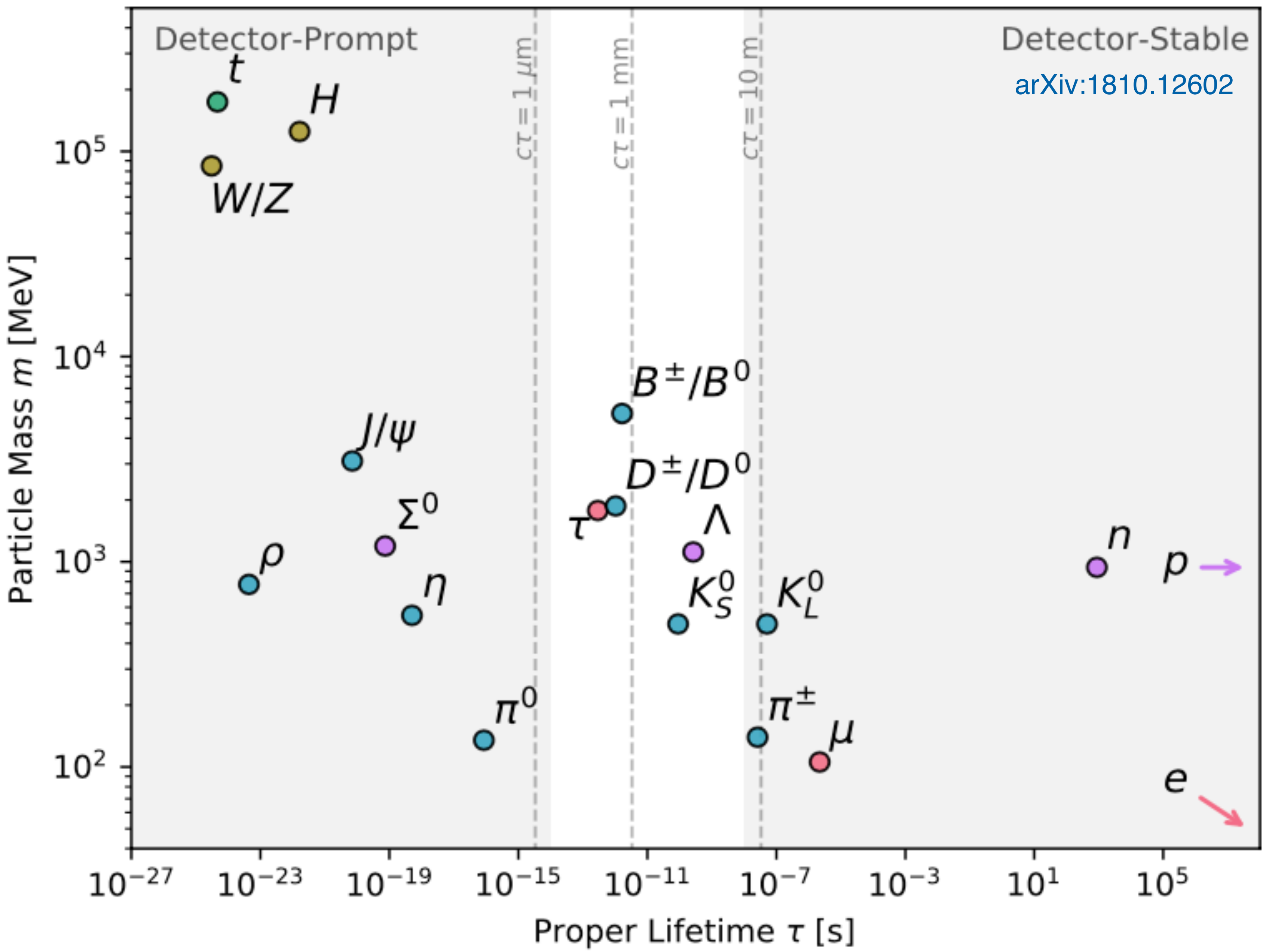
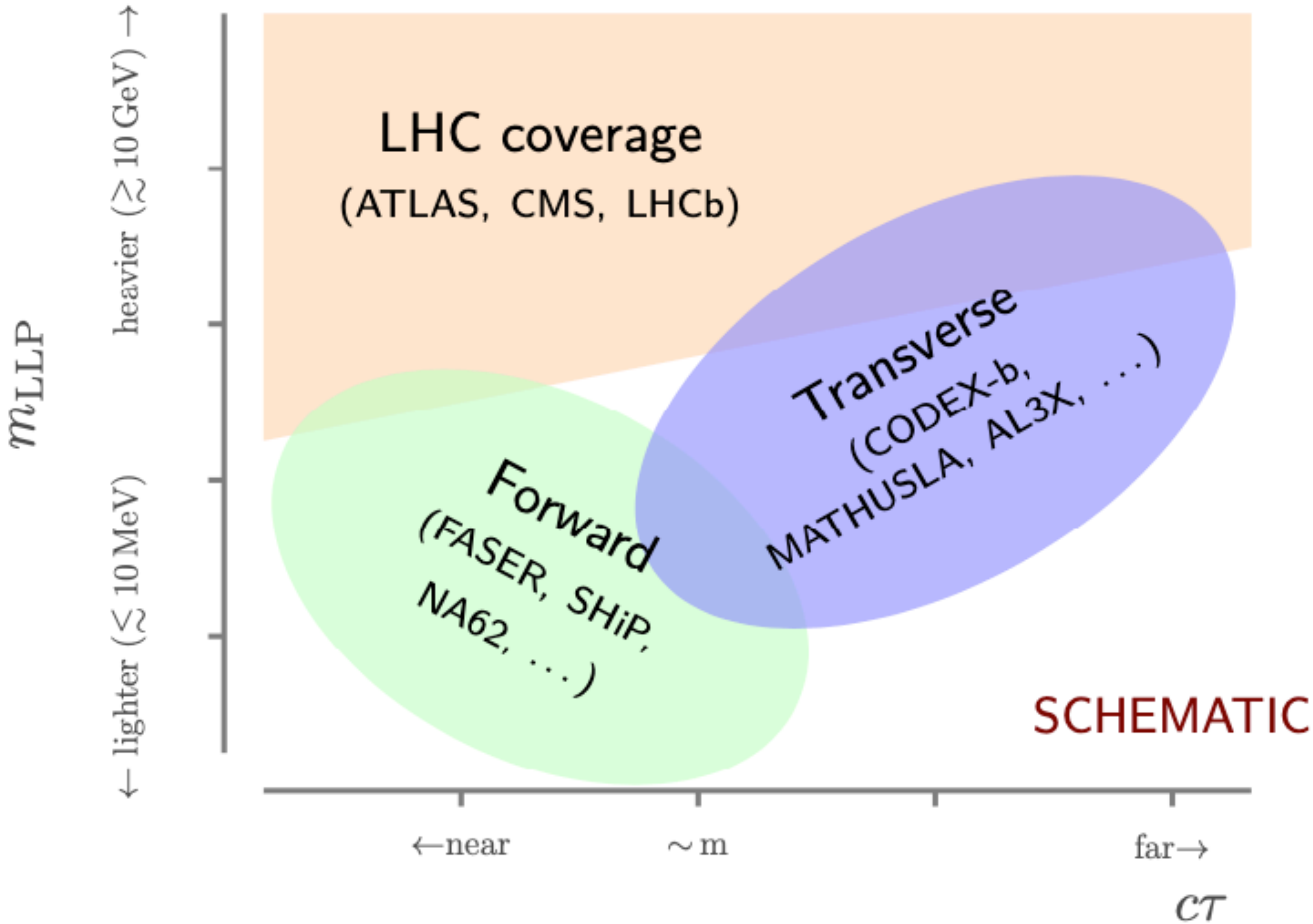
Long-lived Particles in SM



SM great example of fundamental laws giving rise to LLP

LHC and LLPs

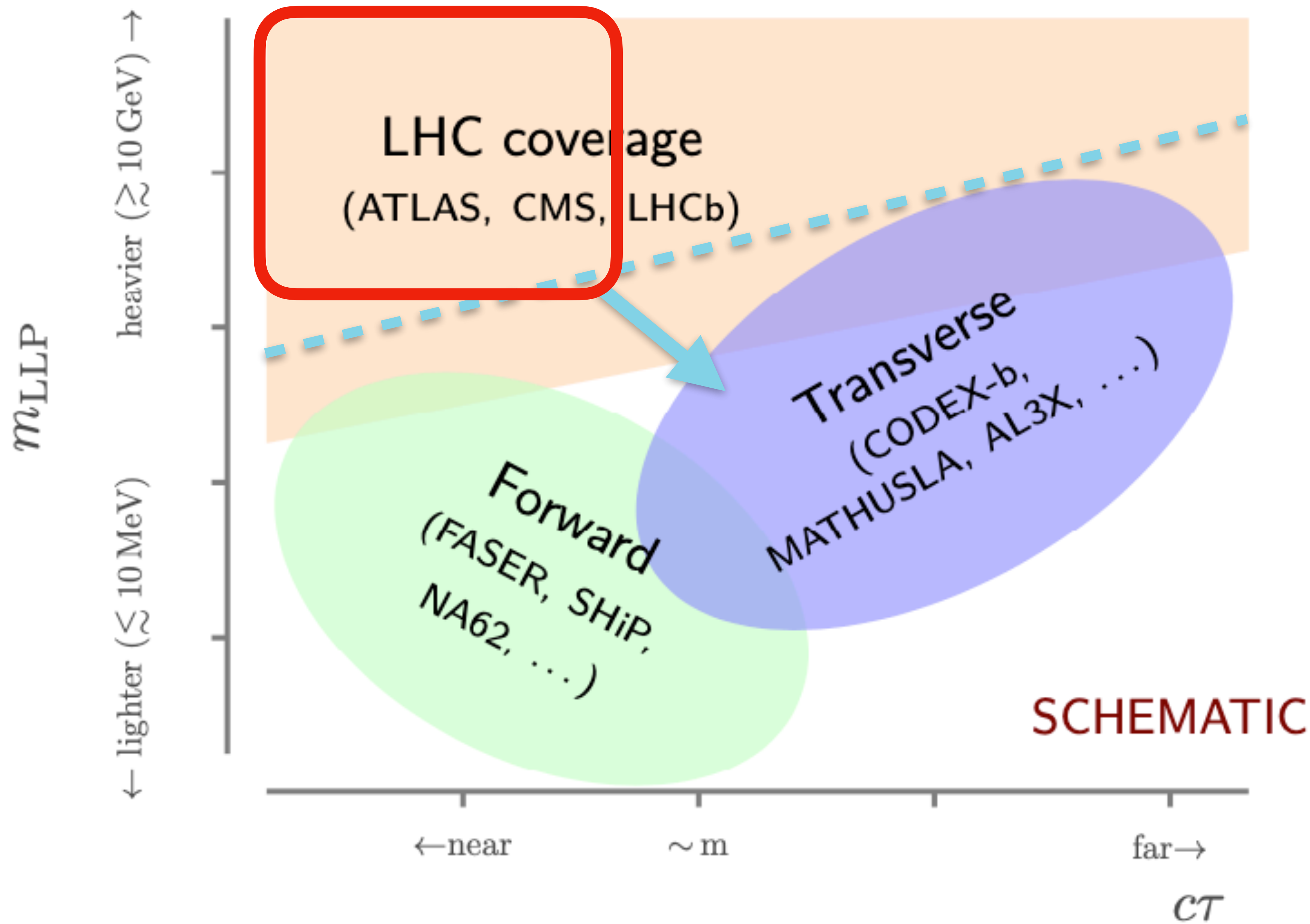
arxiv:1911.00481 — CODEX-b



- How to unlock CMS' full LLP discovery reach?
- How far can we extend the mass and lifetime?

CMS Plays a Crucial Role on LLPs

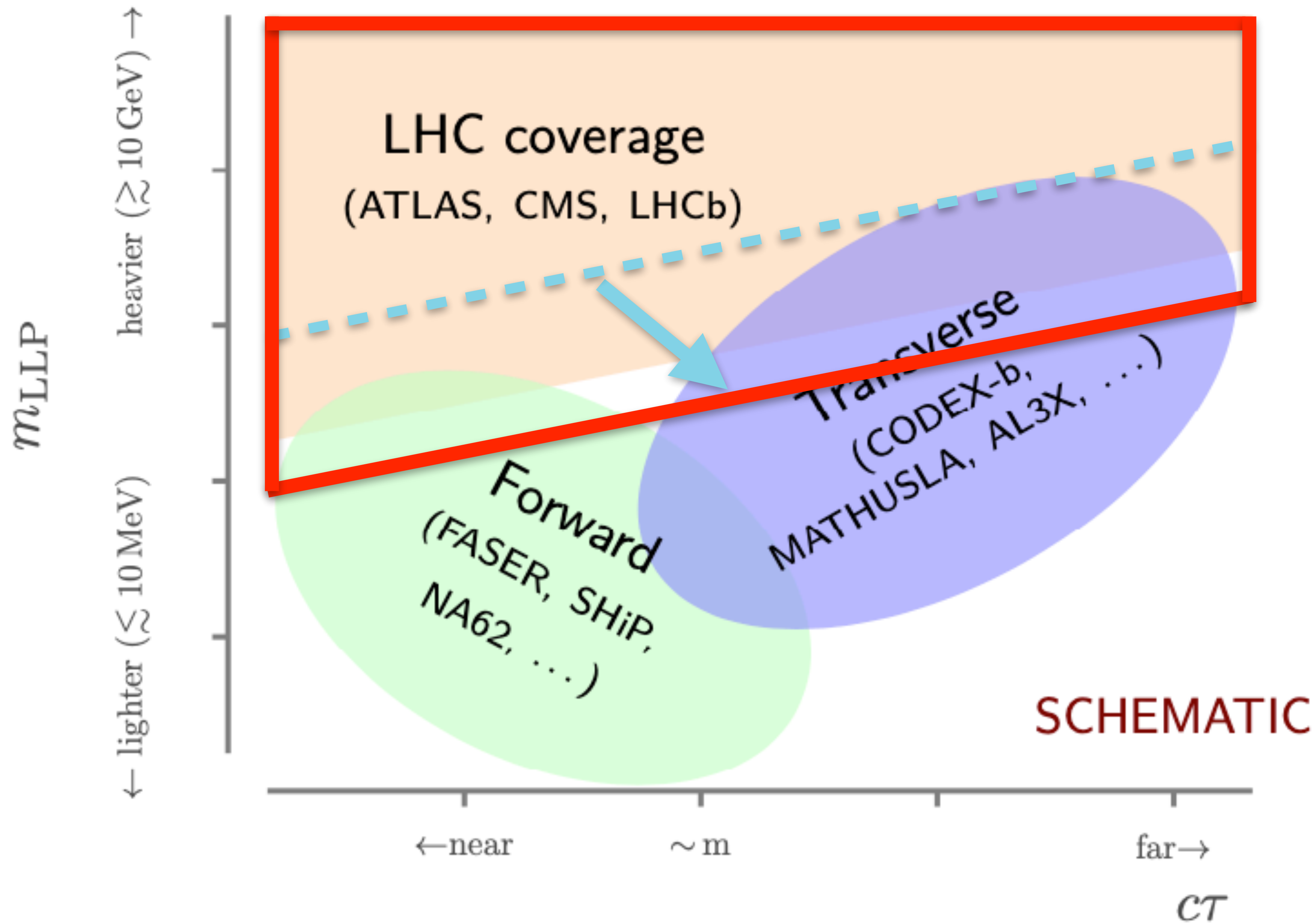
arxiv:1911.00481 — CODEX-b



- CMS was doing well for **$c\tau$ < 1m** and **m_{LLP} > 50 GeV**
- Enabled by precision tracker: displaced jets

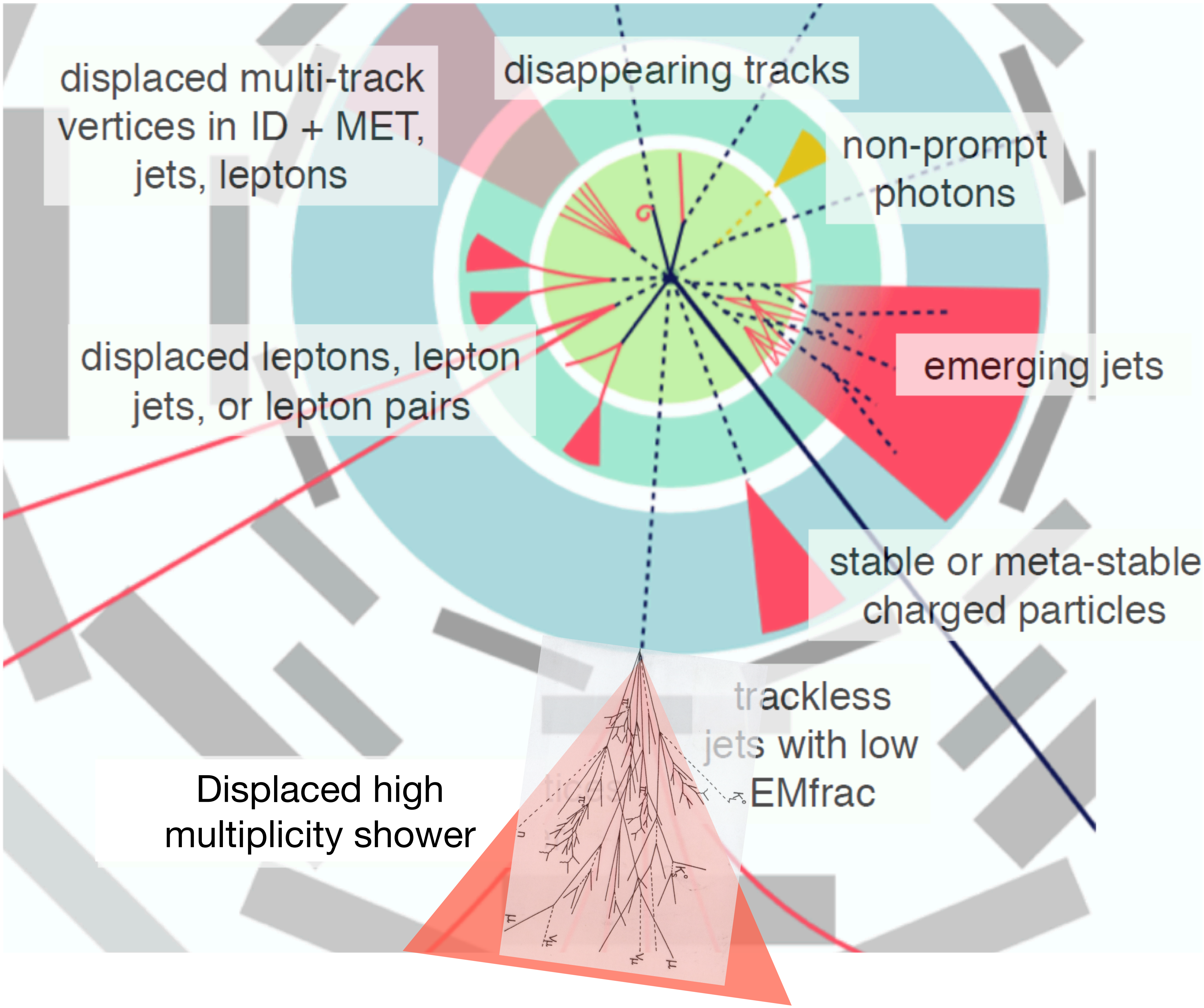
CMS Plays a Crucial Role on LLPs

arxiv:1911.00481 — CODEX-b

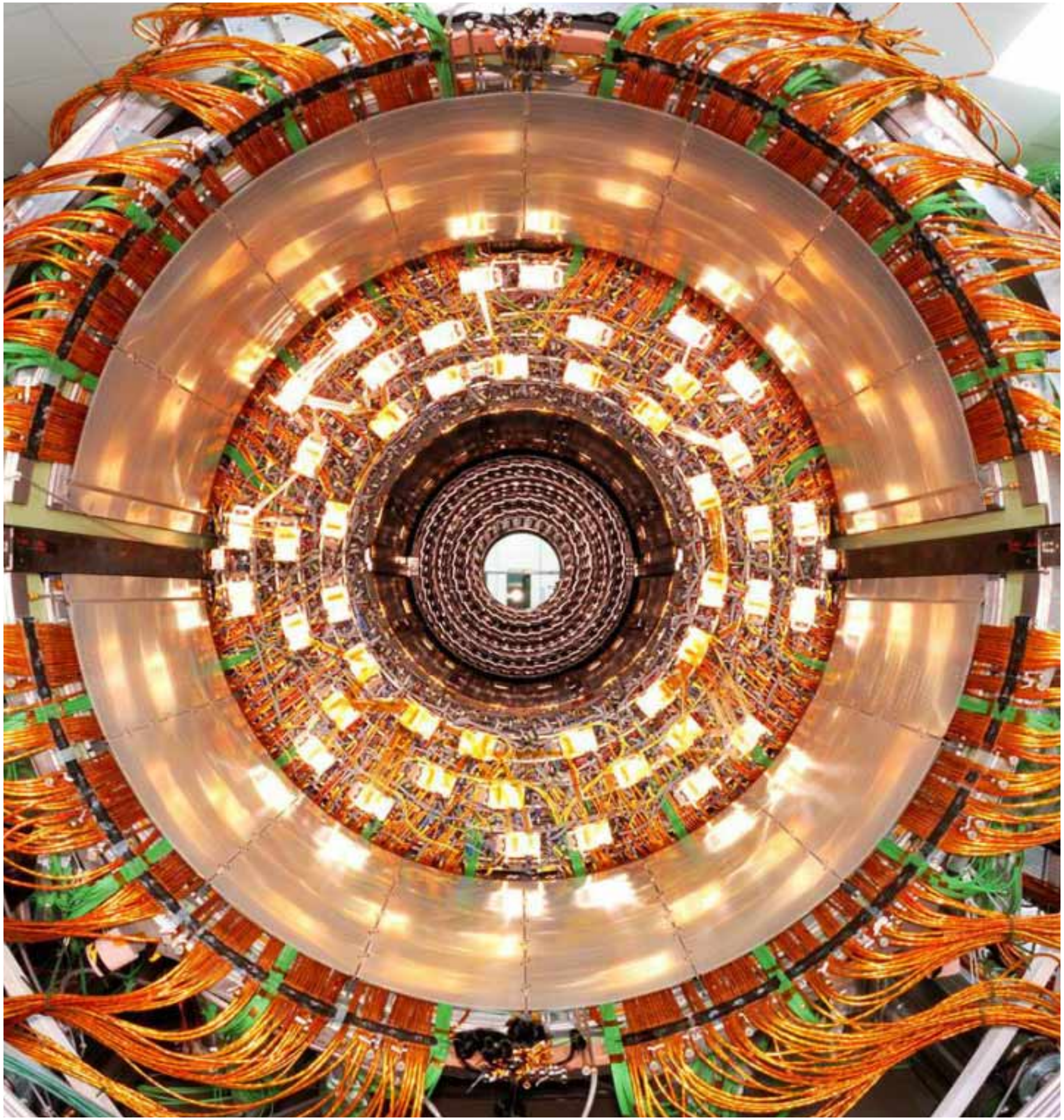


- Goal: close coverage gaps and extend CMS reach
- Strategy: Enable a large cτ and light LLP searches

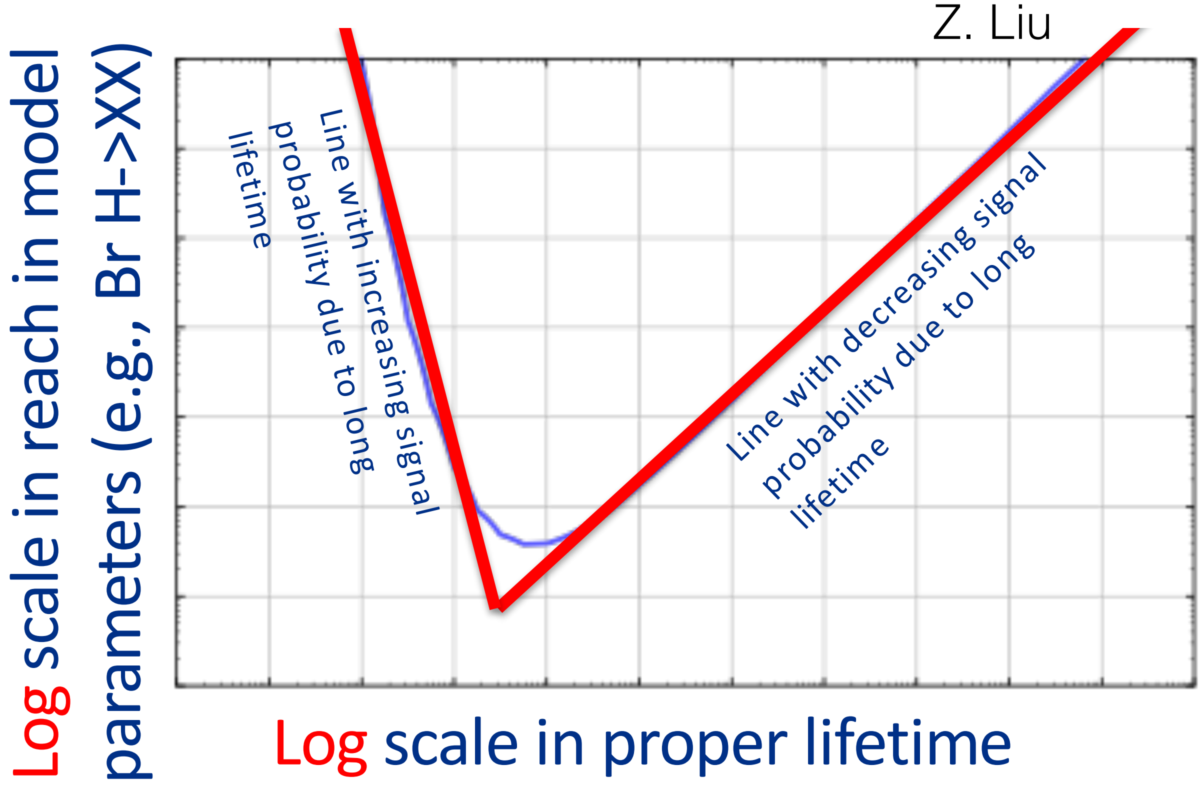
Long-lived Particles in CMS

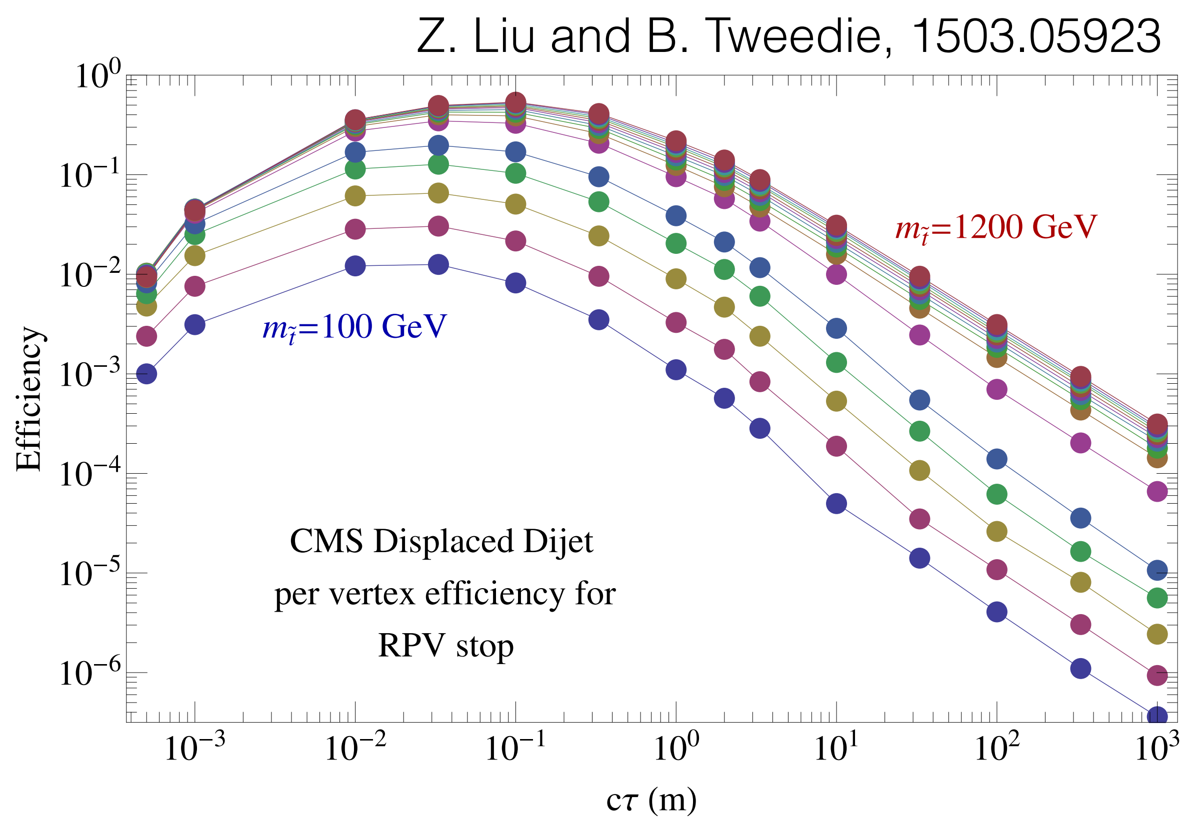


Tracker Based Searches



LLP Experimental Considerations





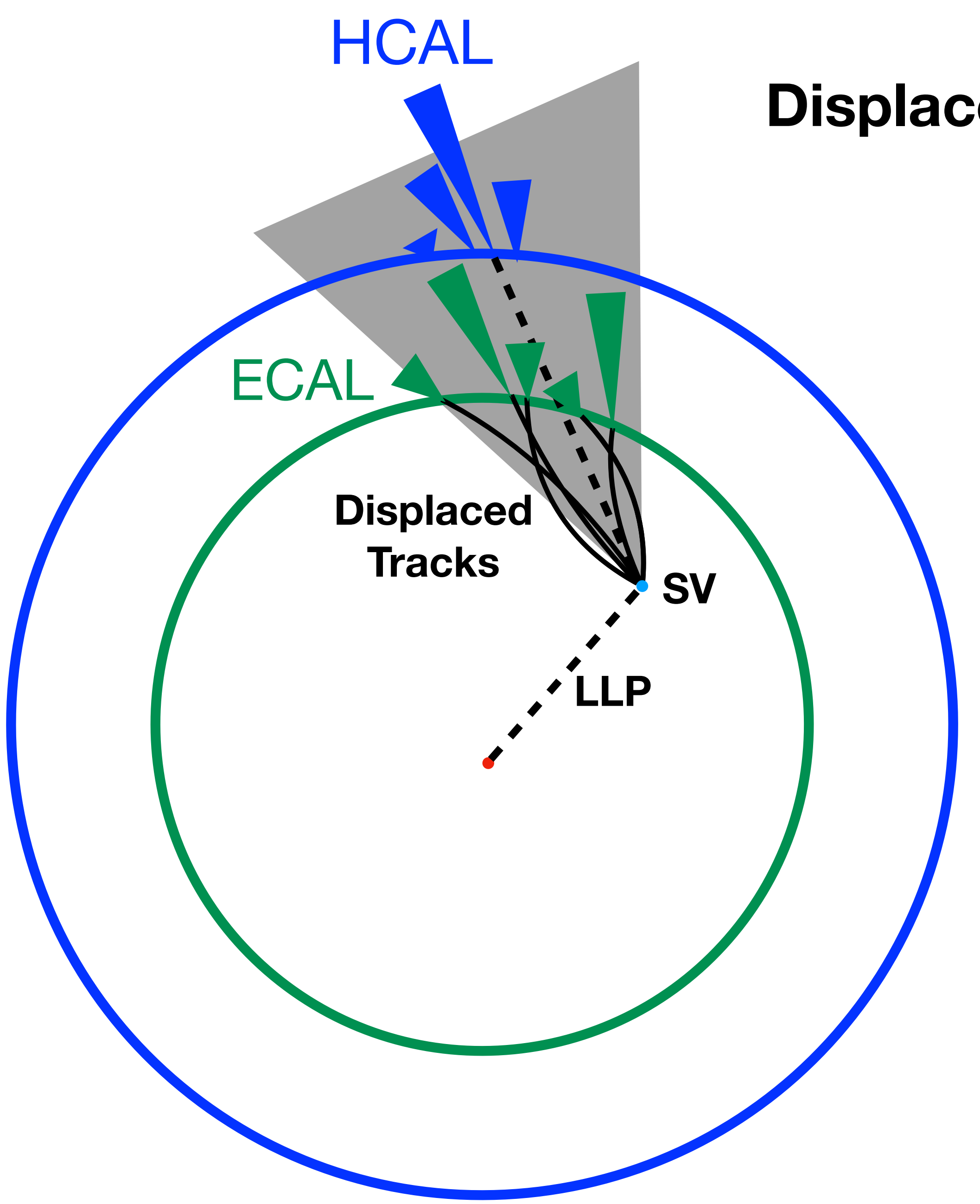
← Larger SM Bkg

Reduced detector Acceptance →

LLP mass is very important:
large drop on efficiency at low masses due to low trigger efficiency.

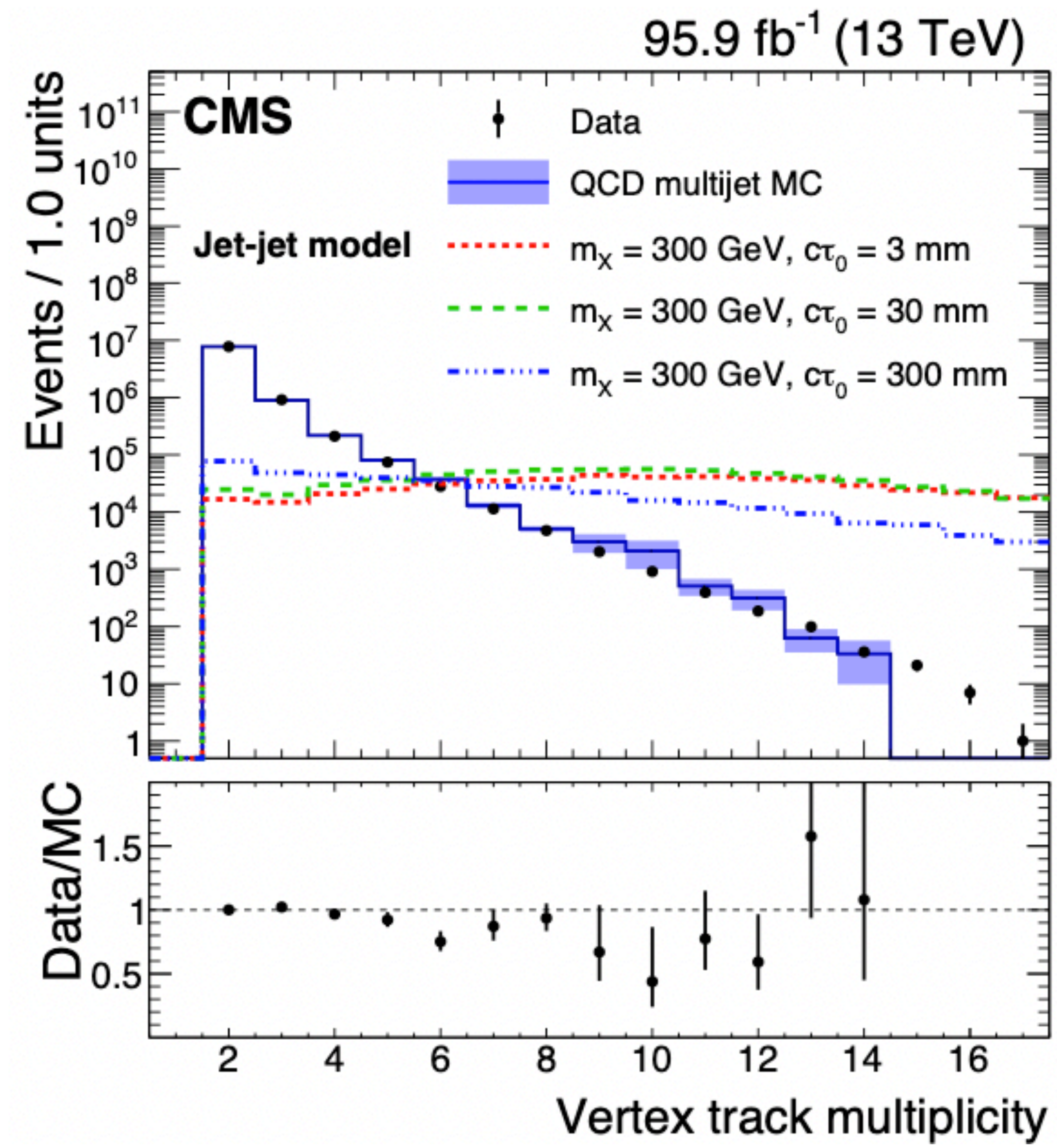
Low LLP masses are motivated in Higgs portal models: e.g $h^0 \to \chi(jj)\chi(jj)$

Tracker Based Searches



Signature:
Displaced Jets & Vertices

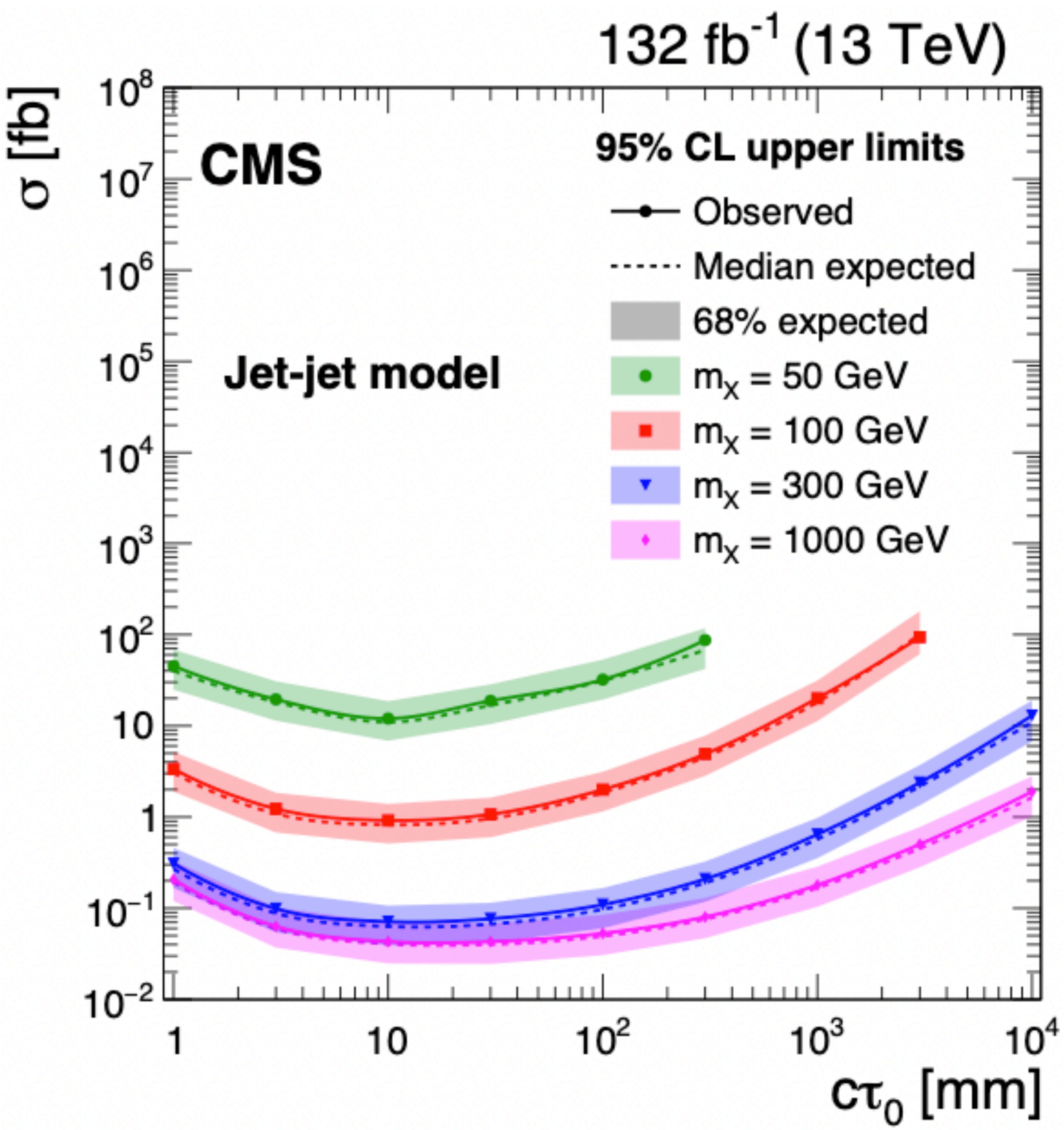
EXO-19-021



Key detector feature: reconstruction of displaced tracks and SV

Tracker Based Searches

EXO-19-021

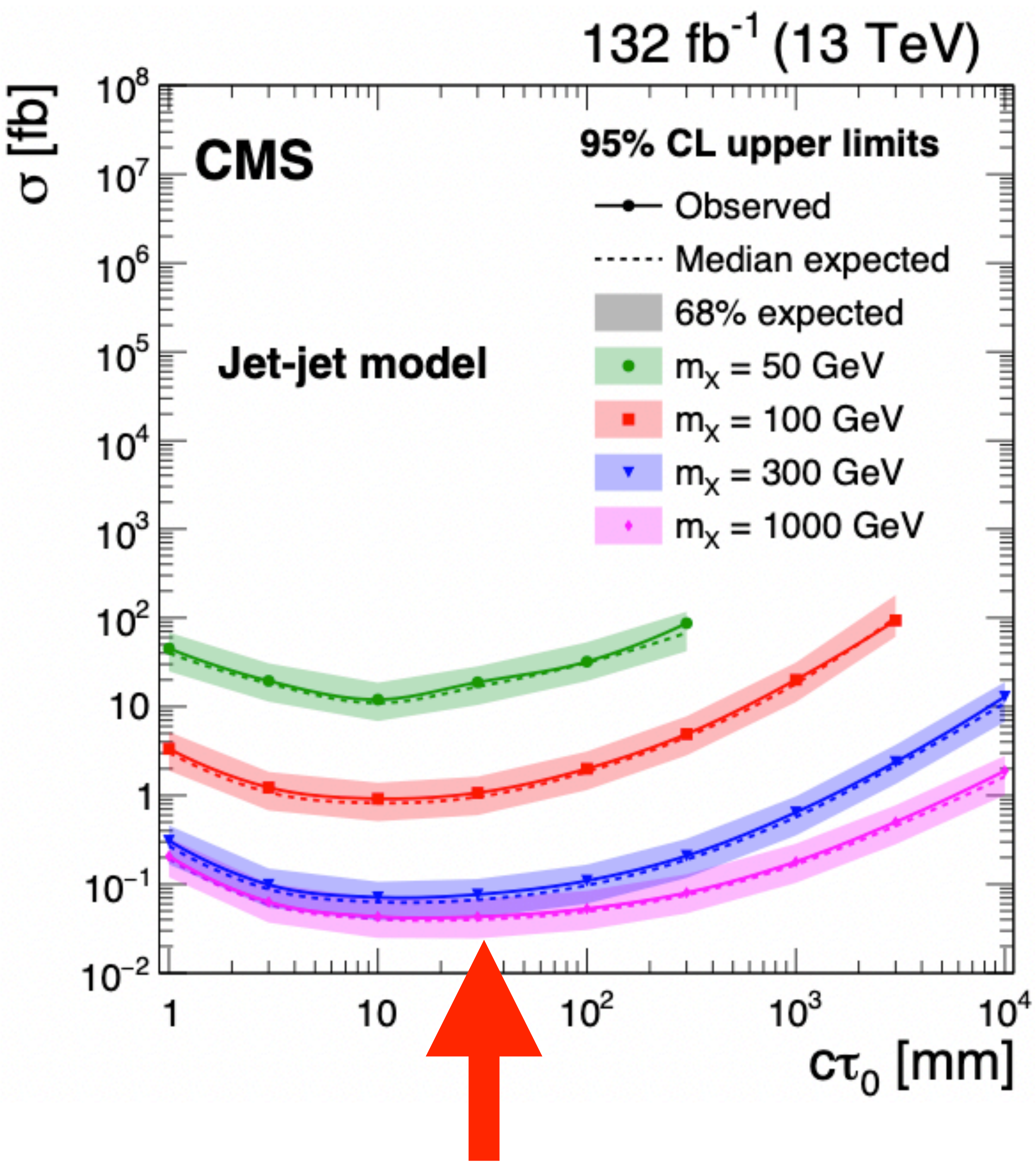


Takeaways

- Most sensitive analysis at cτ ~few cm

Tracker Based Searches

EXO-19-021

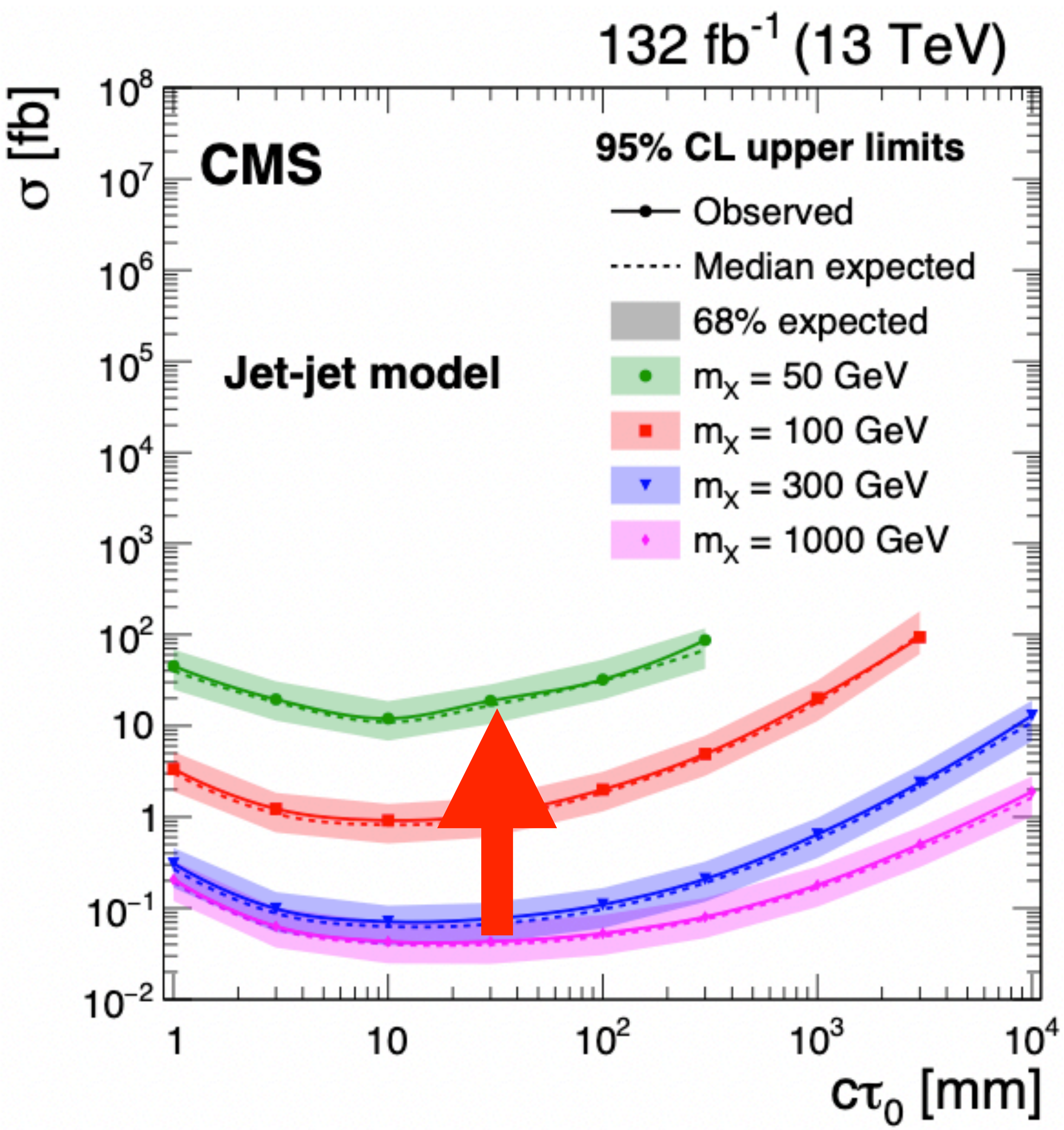


Takeaways

- Most sensitive analysis at $c\tau$ ~few cm
- Peak sensitivity determined by tracker acceptance

Tracker Based Searches

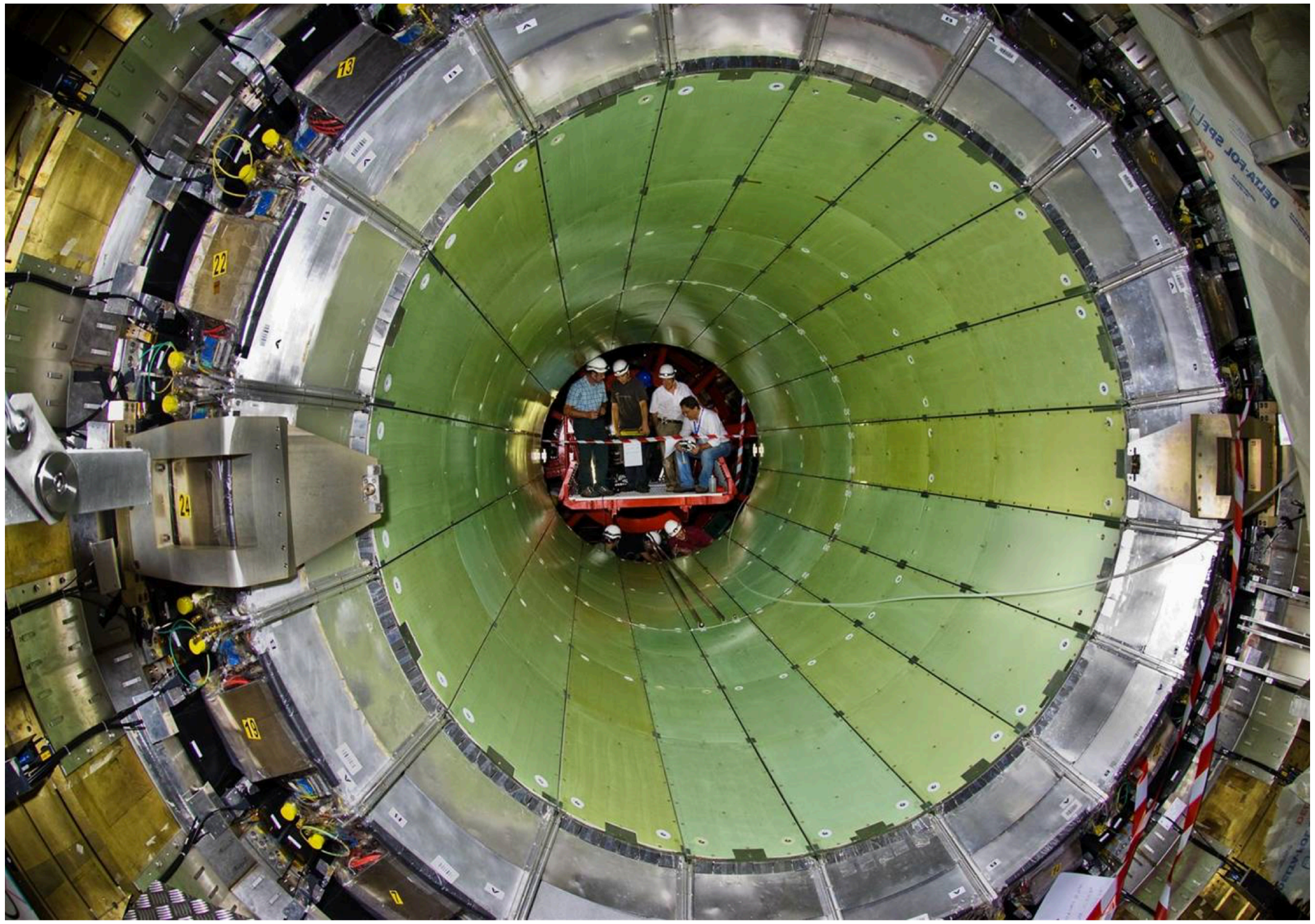
EXO-19-021

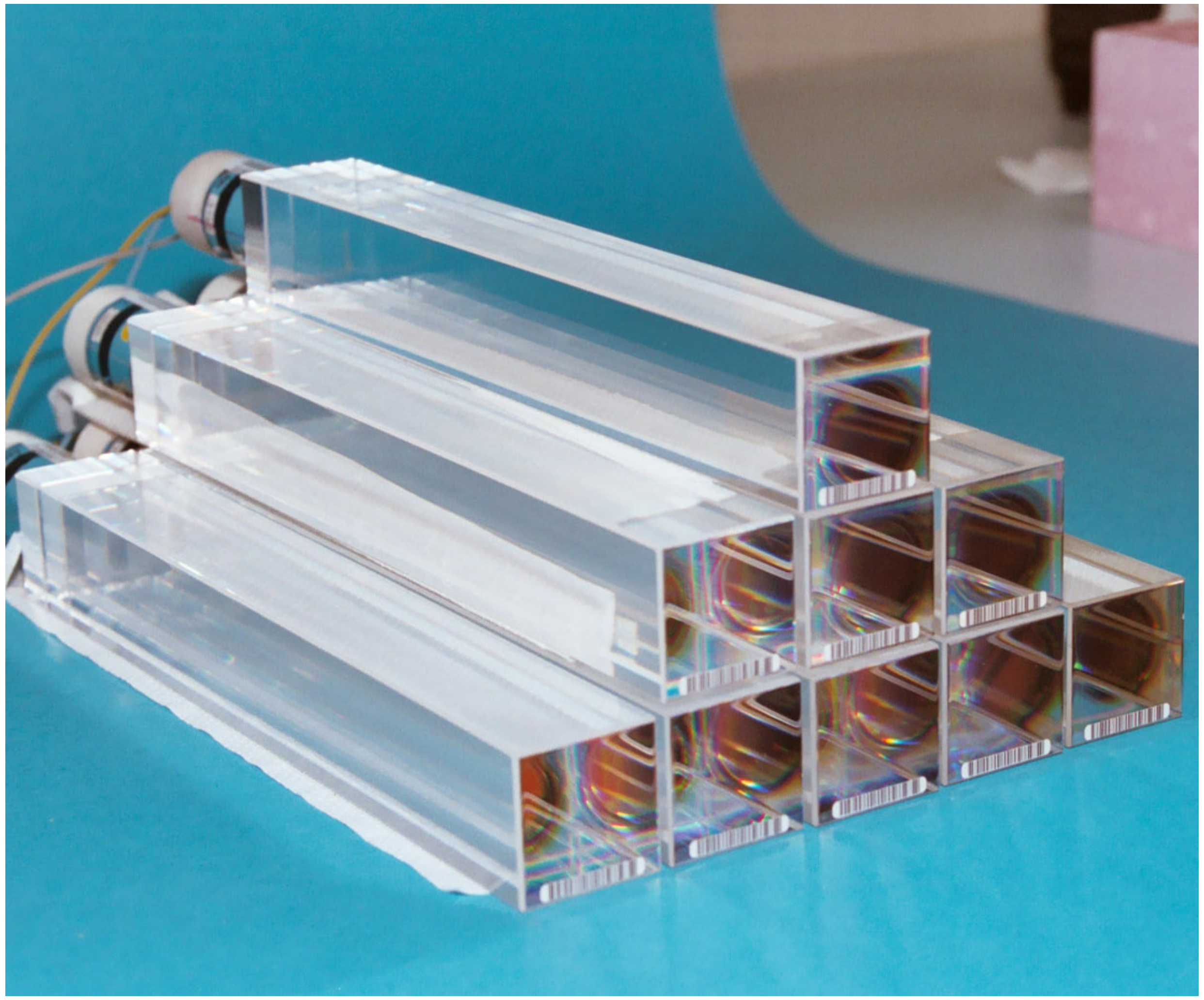


Takeaways

- Most sensitive analysis at $c\tau$ ~few cm
- Peak sensitivity determined by tracker acceptance
- Clear drop in acceptance at lower mediator masses
  - Main limitation: high threshold HT triggers

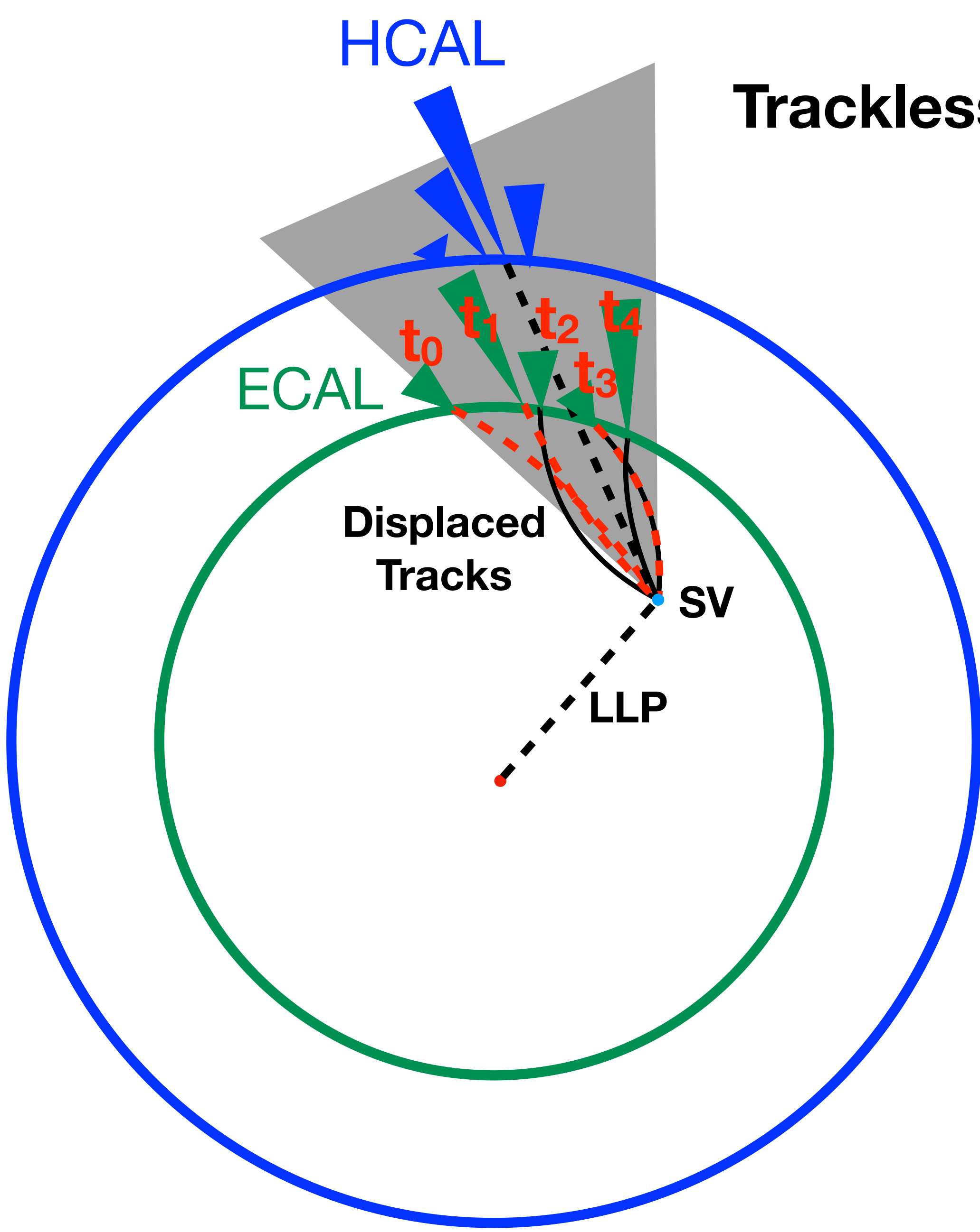
Calorimeters



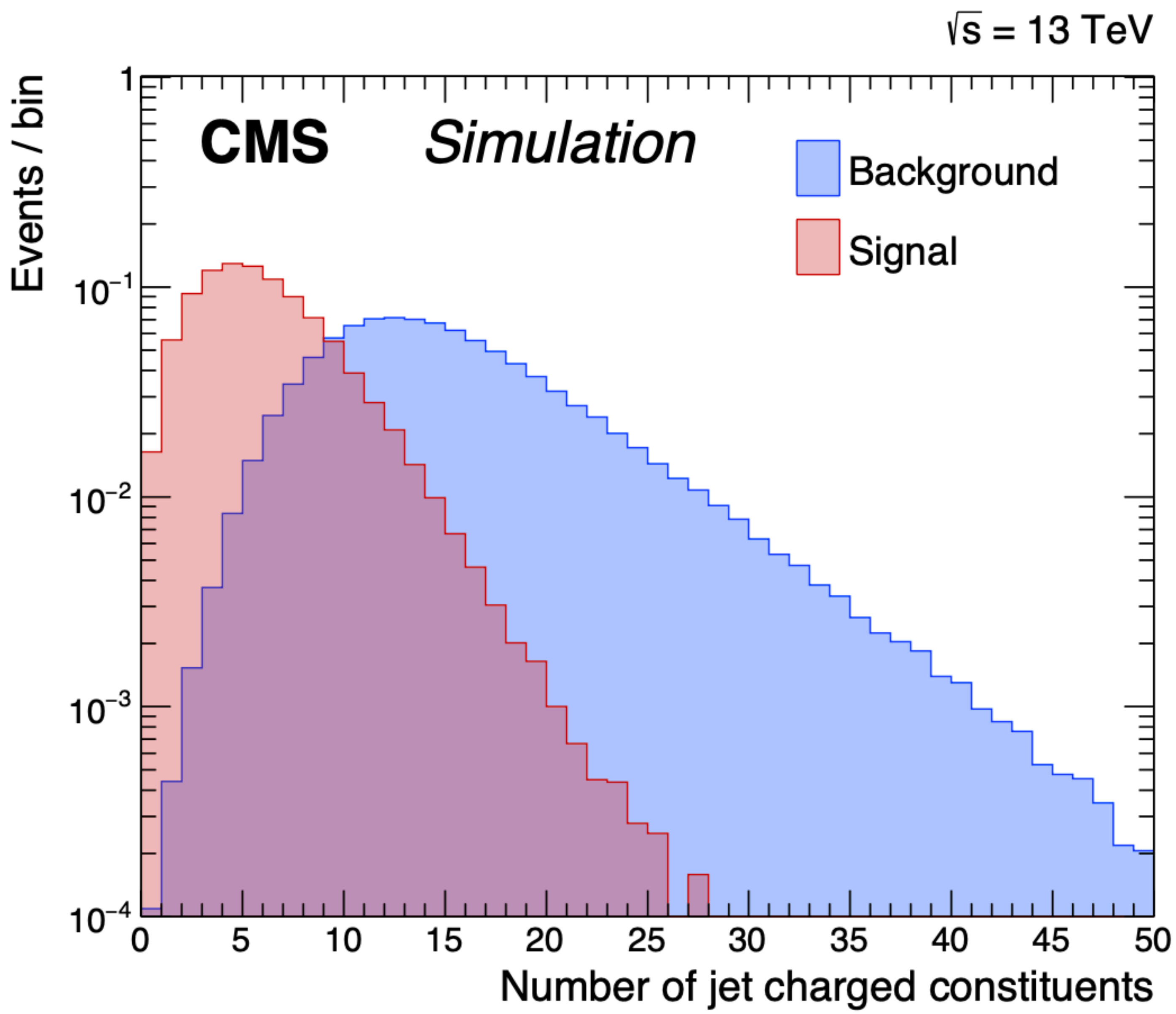


Calorimeter Based Searches

EXO-21-014 & EXO-19-001



Signature:
Trackless jets & delayed ECAL hits

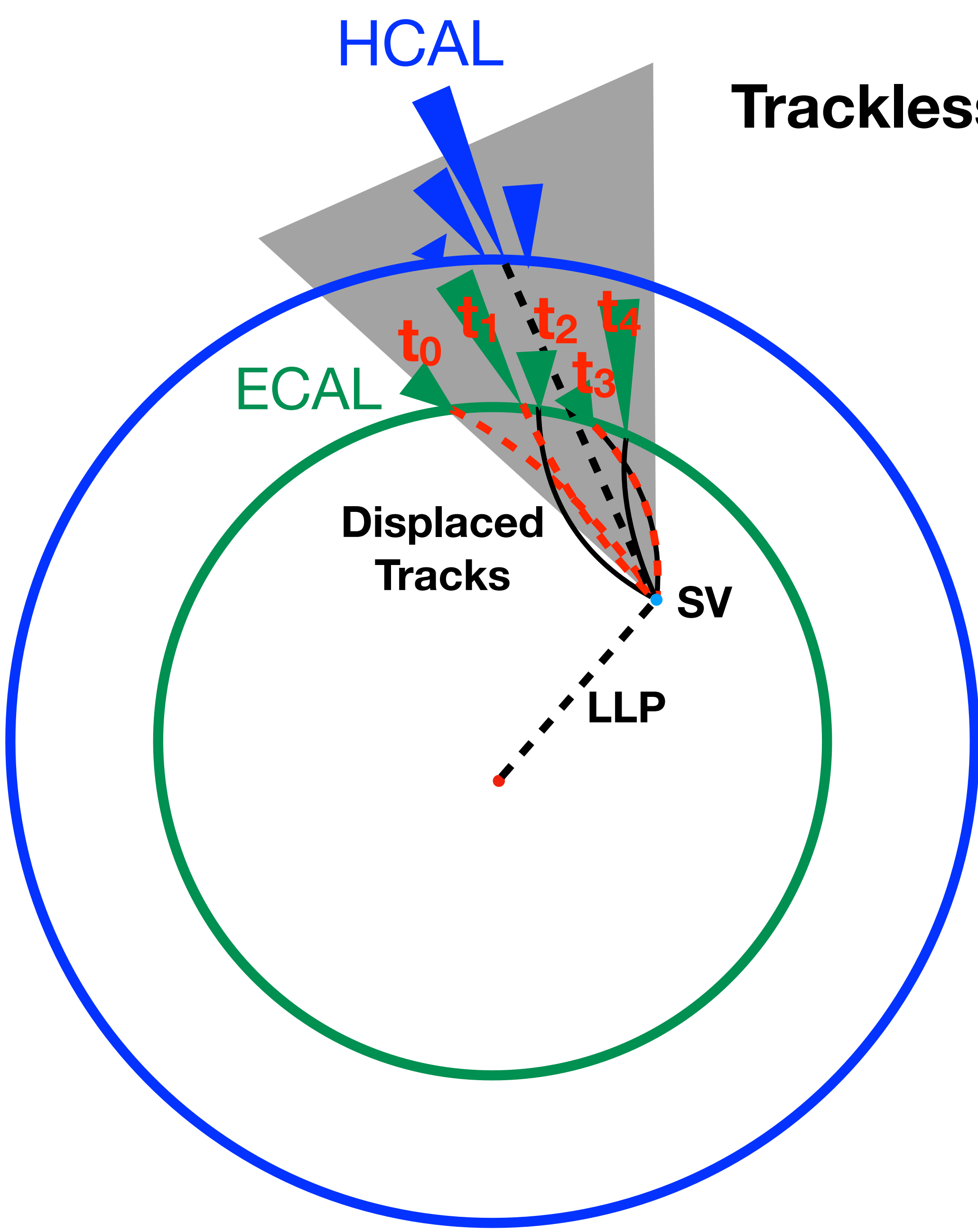


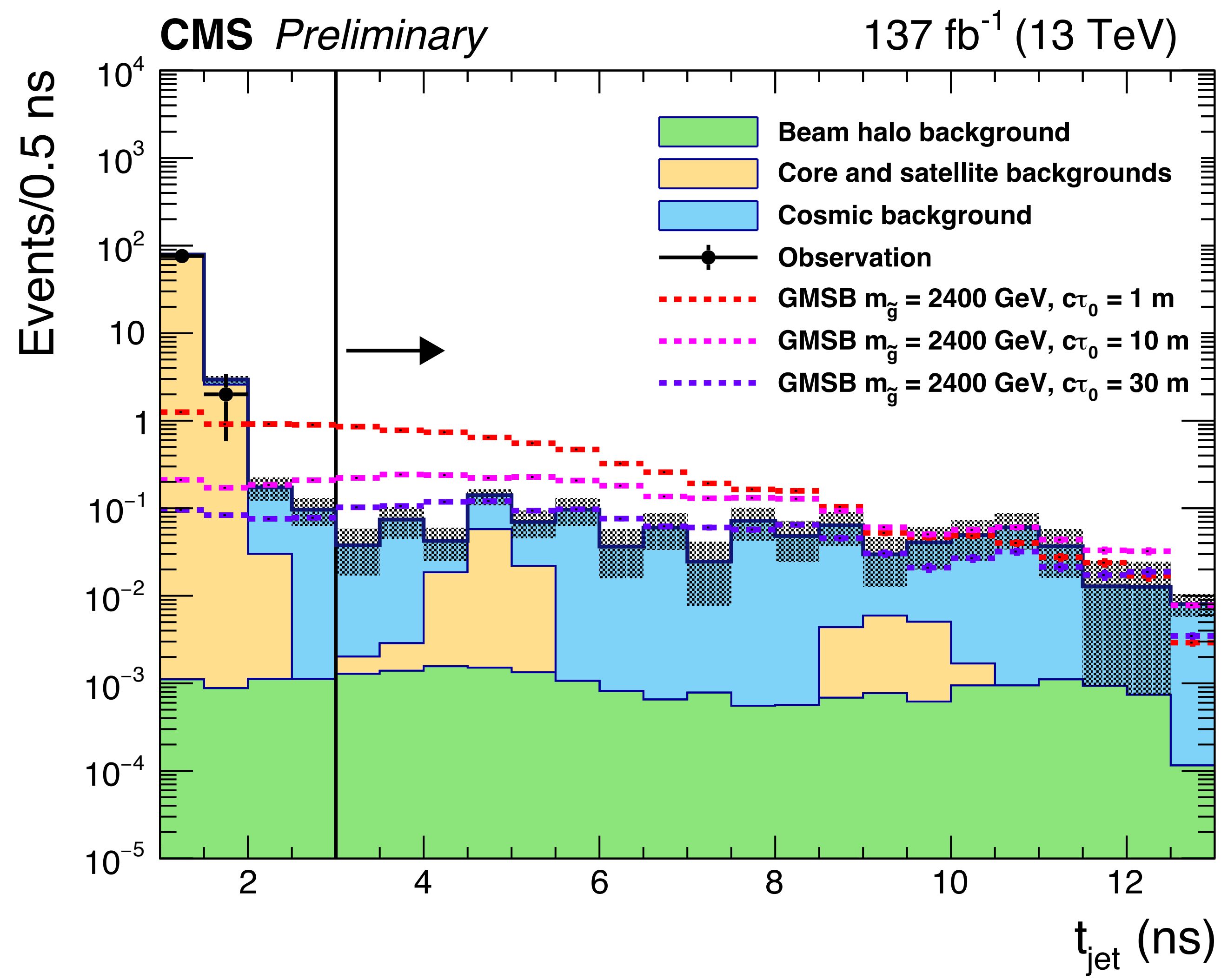
Key feature: Lack of associated tracks and precision timing

Calorimeter Based Searches

EXO-21-014 & EXO-19-001

Signature:
Trackless jets & delayed ECAL hits





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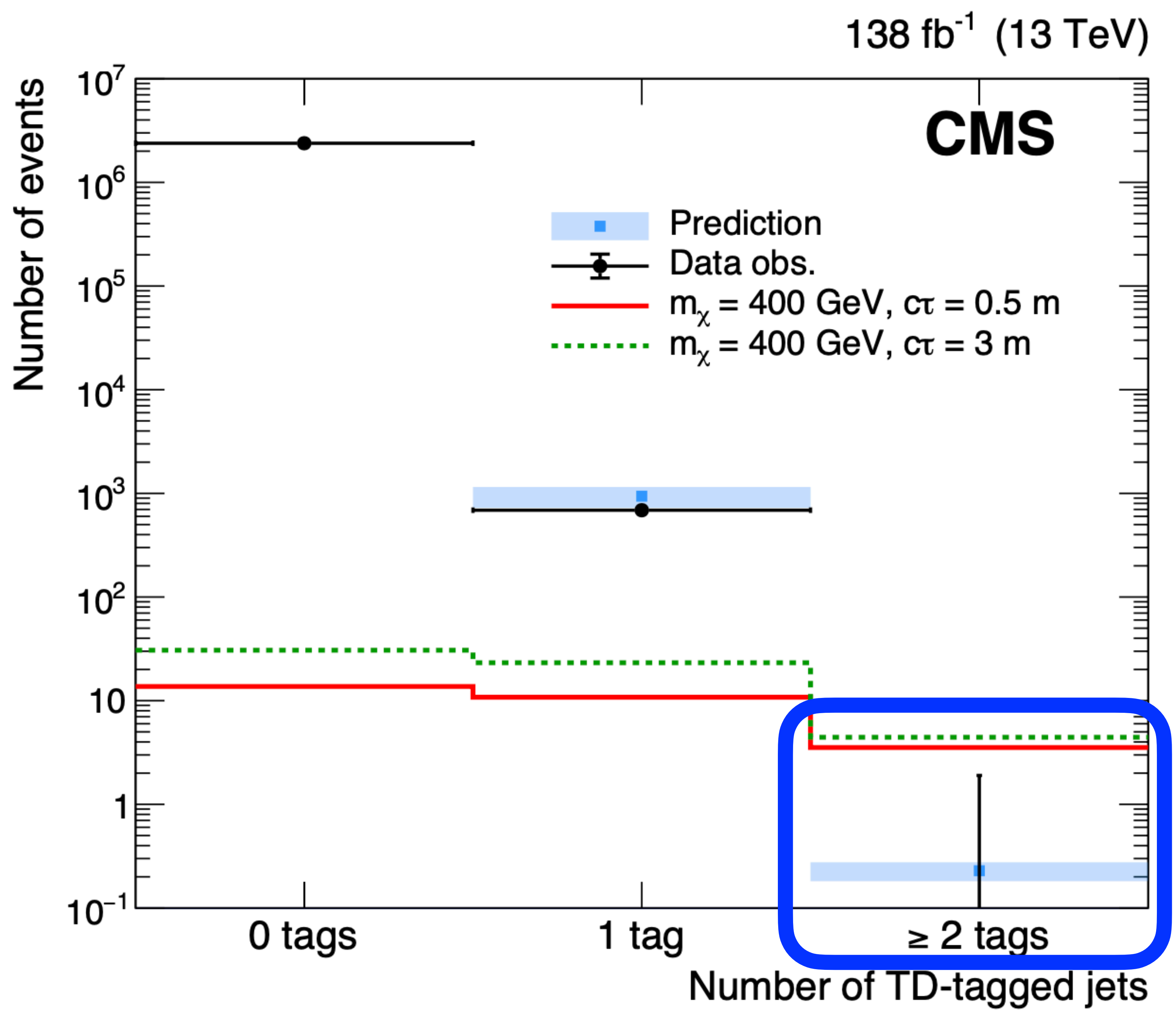
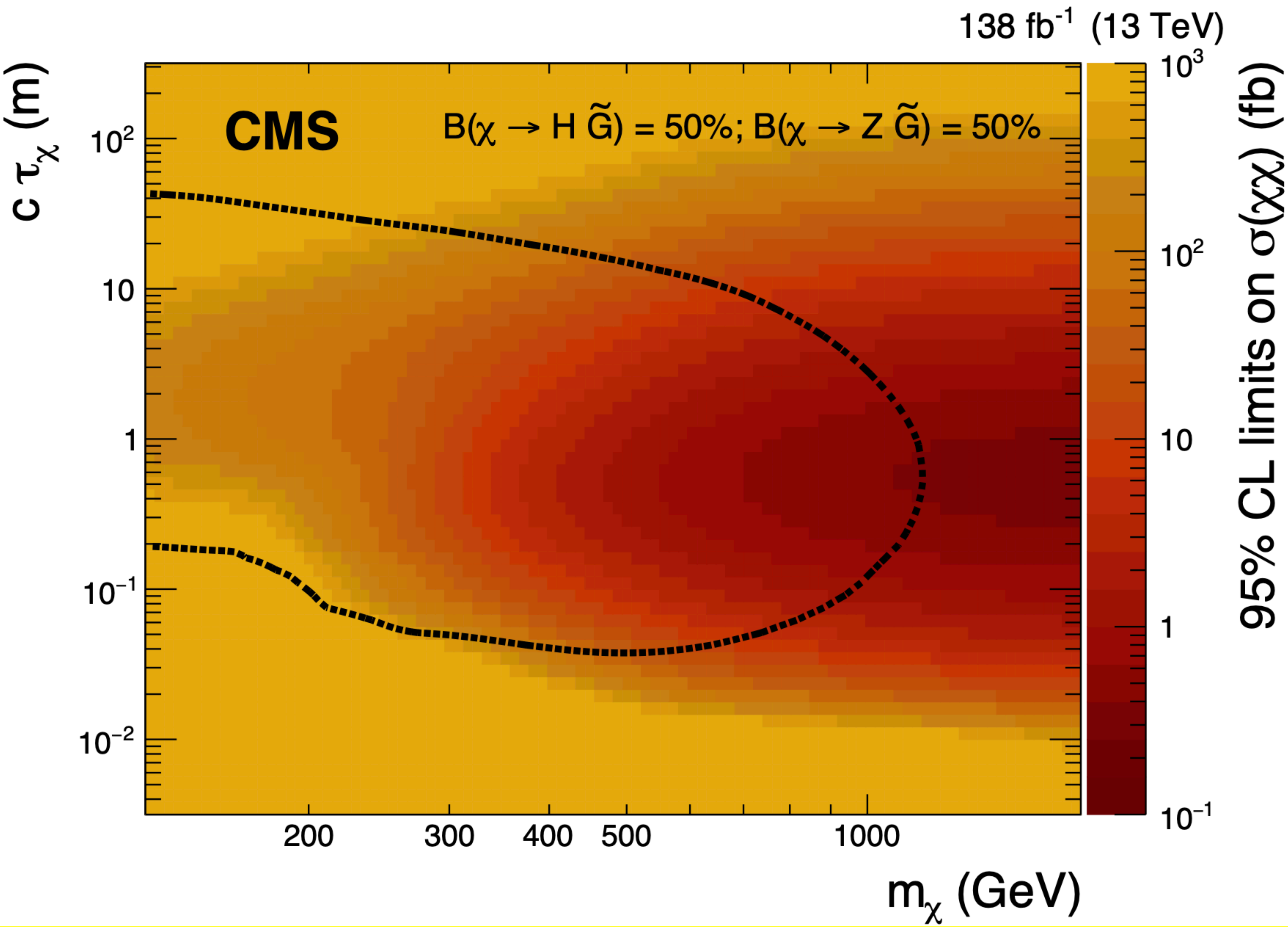
EXO-21-014



Search strategy: count number of displaced ("tagged") jets

Calorimeter Based Searches

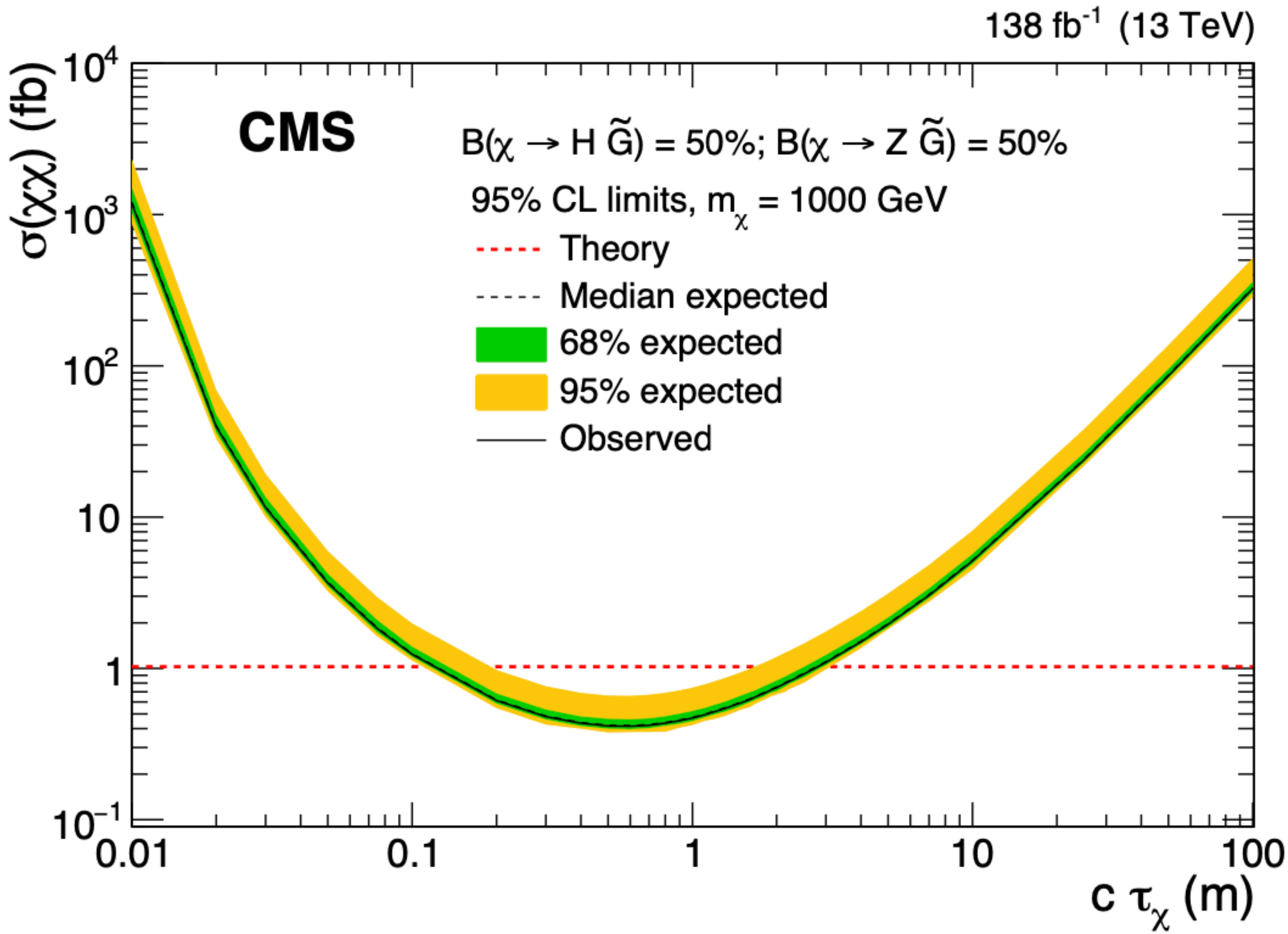
EXO-21-014



Long-lived neutralinos (χ) excluded up to 1 TeV at $c\tau$ ~1m

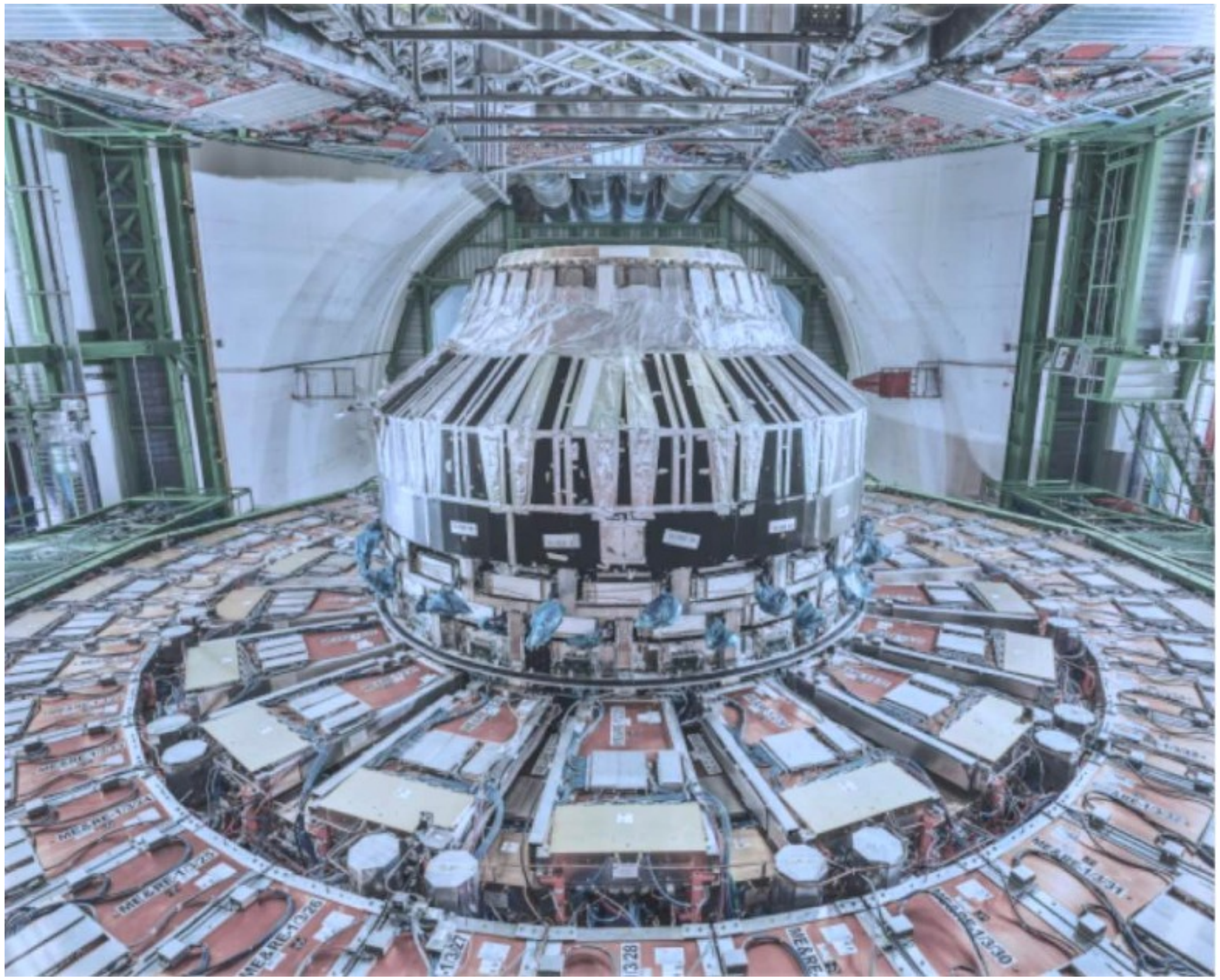
Calorimeter Based Searches

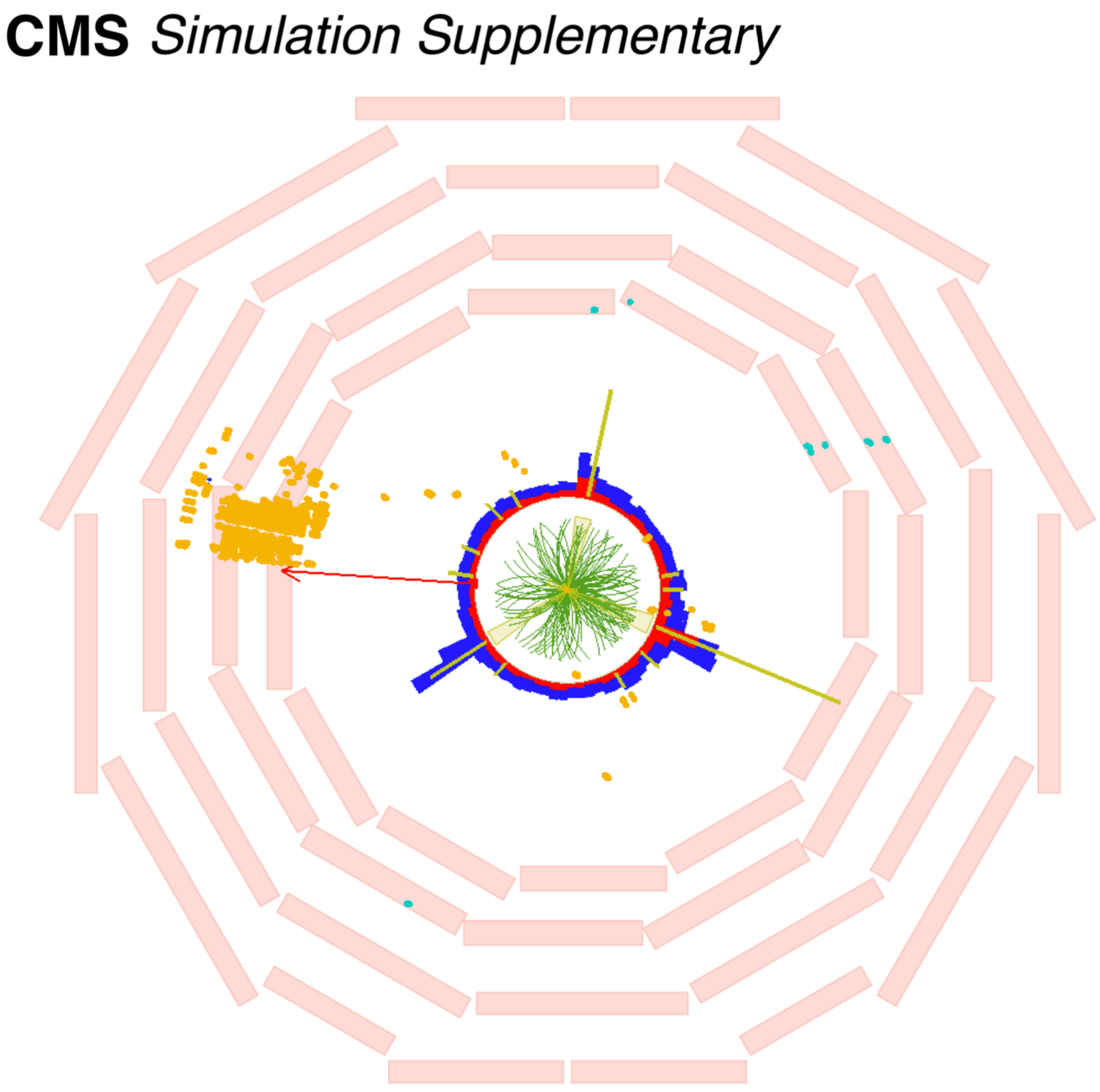
EXO-21-014



Peak sensitivity at cτ ~1m: complementary to tracker-based

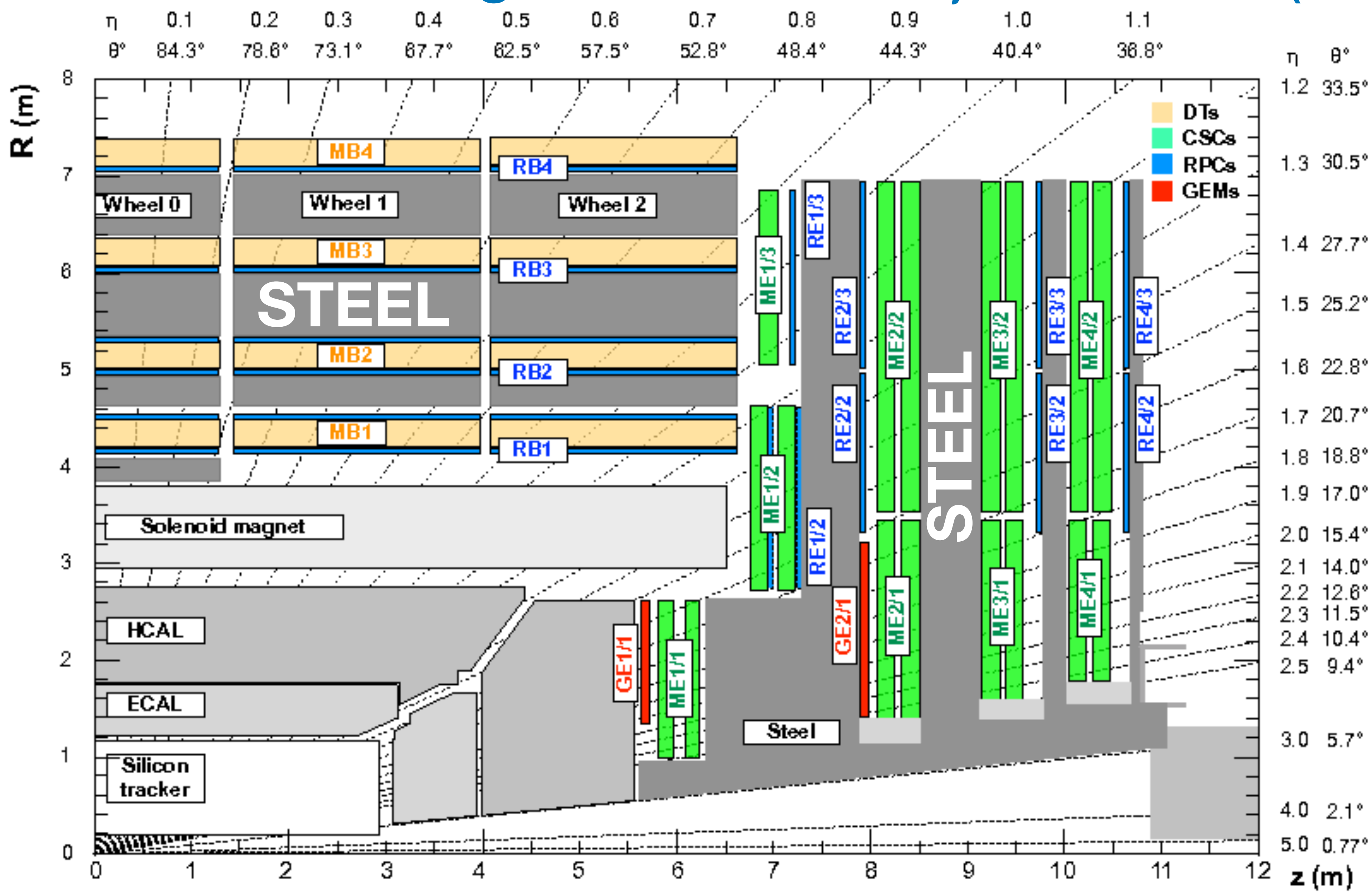
Muon System





Compact Muon Solenoid

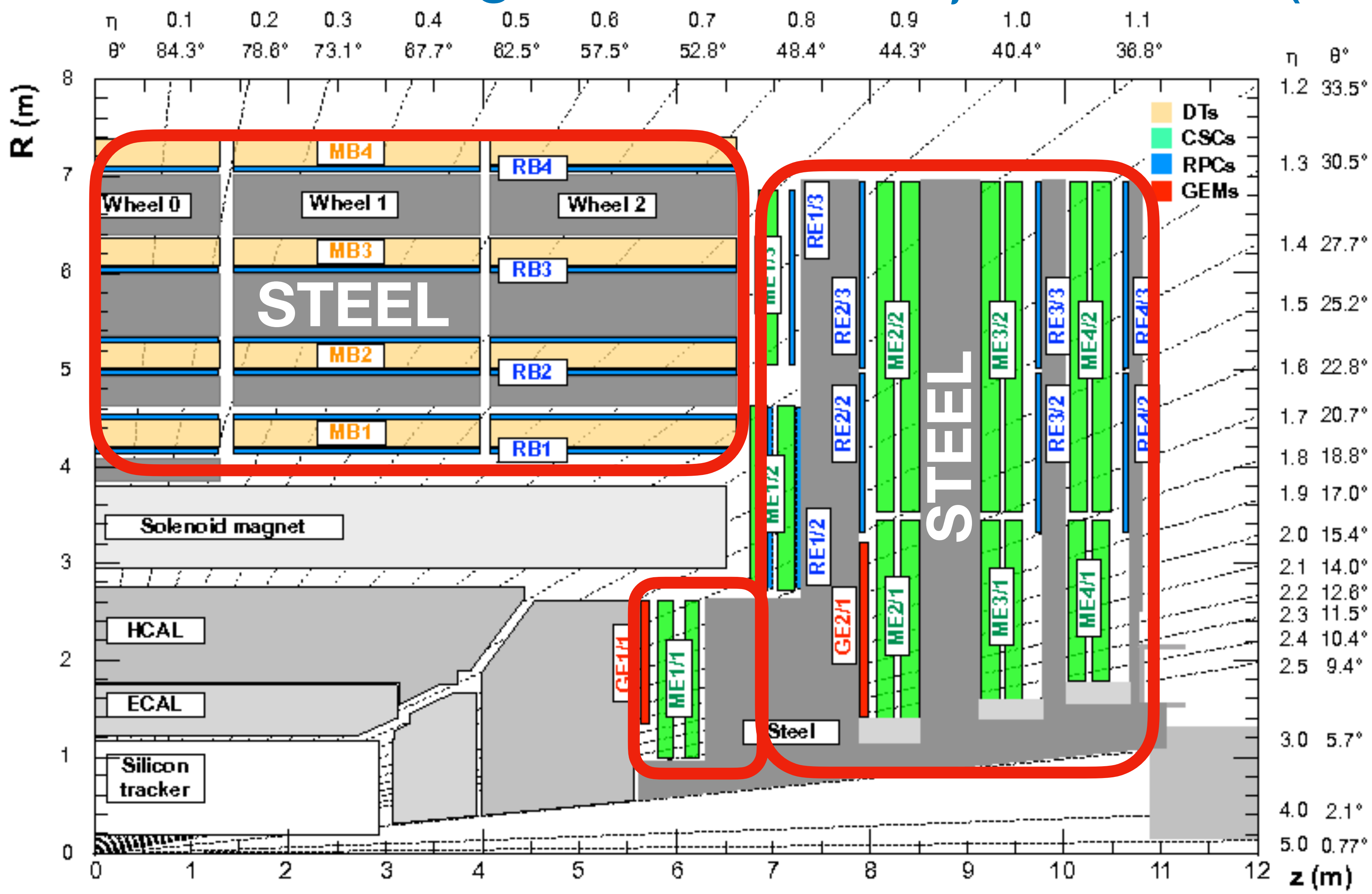
COMPACT Design + Small $\pi \rightarrow \mu$ mis-ID (10^{-3})



- Lots of STEEL →bkg suppression → Ideal for LLP searches
- 4-layers of highly segmented active element → LLP signal

Compact Muon Solenoid

COMPACT Design + Small $\pi \rightarrow \mu$ mis-ID (10^{-3})

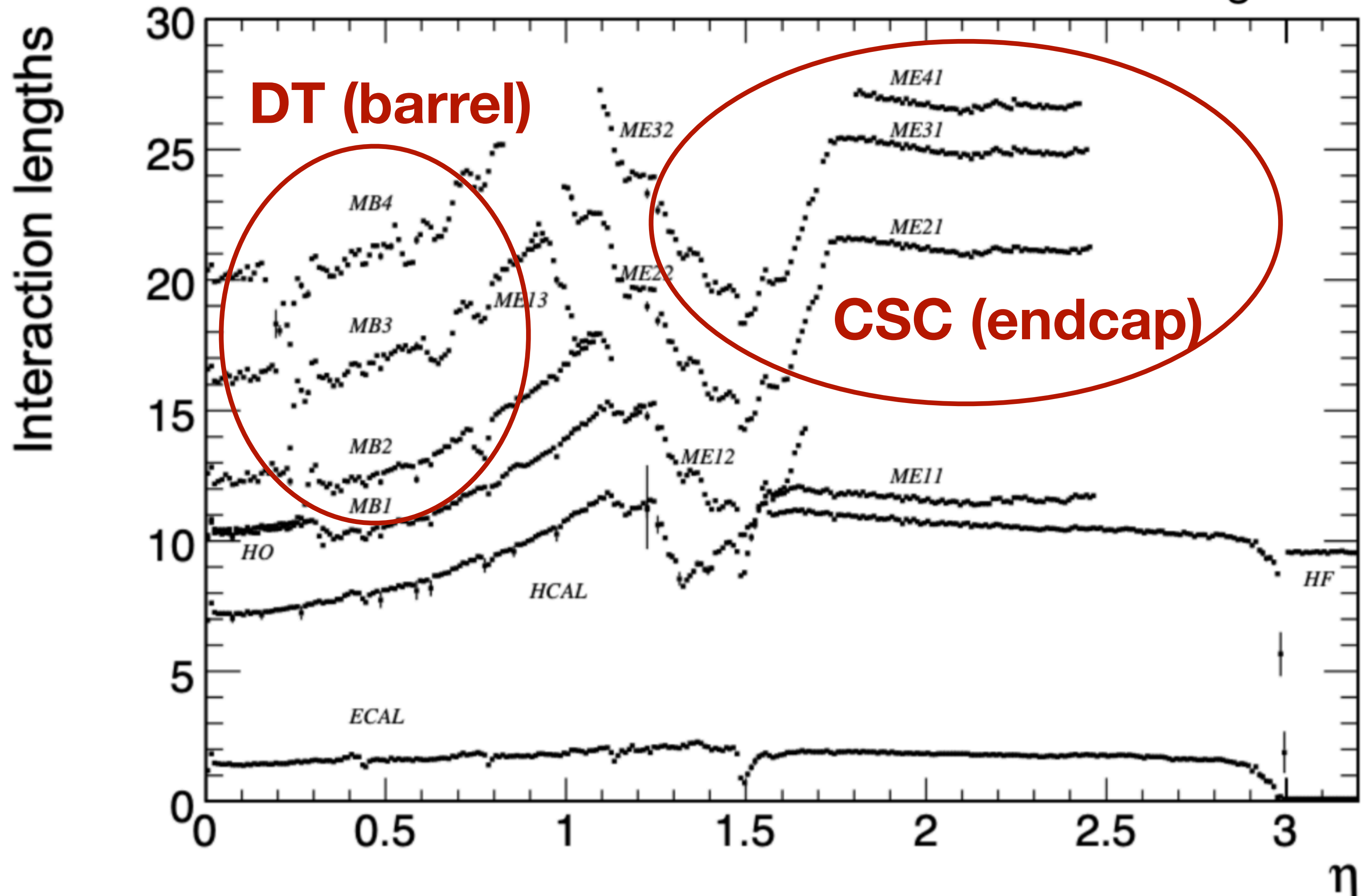


- Lots of STEEL →bkg suppression → Ideal for LLP searches
- 4-layers of highly segmented active element → LLP signal

LLP Muon System Analysis

- Despite the lack of a dedicated trigger, CMS had opportunity to provide better sensitivity for 1 displaced vertex search. **CMS has more steel to reject background**

CMS TDR: LHCC-2006-001 Fig 1.4

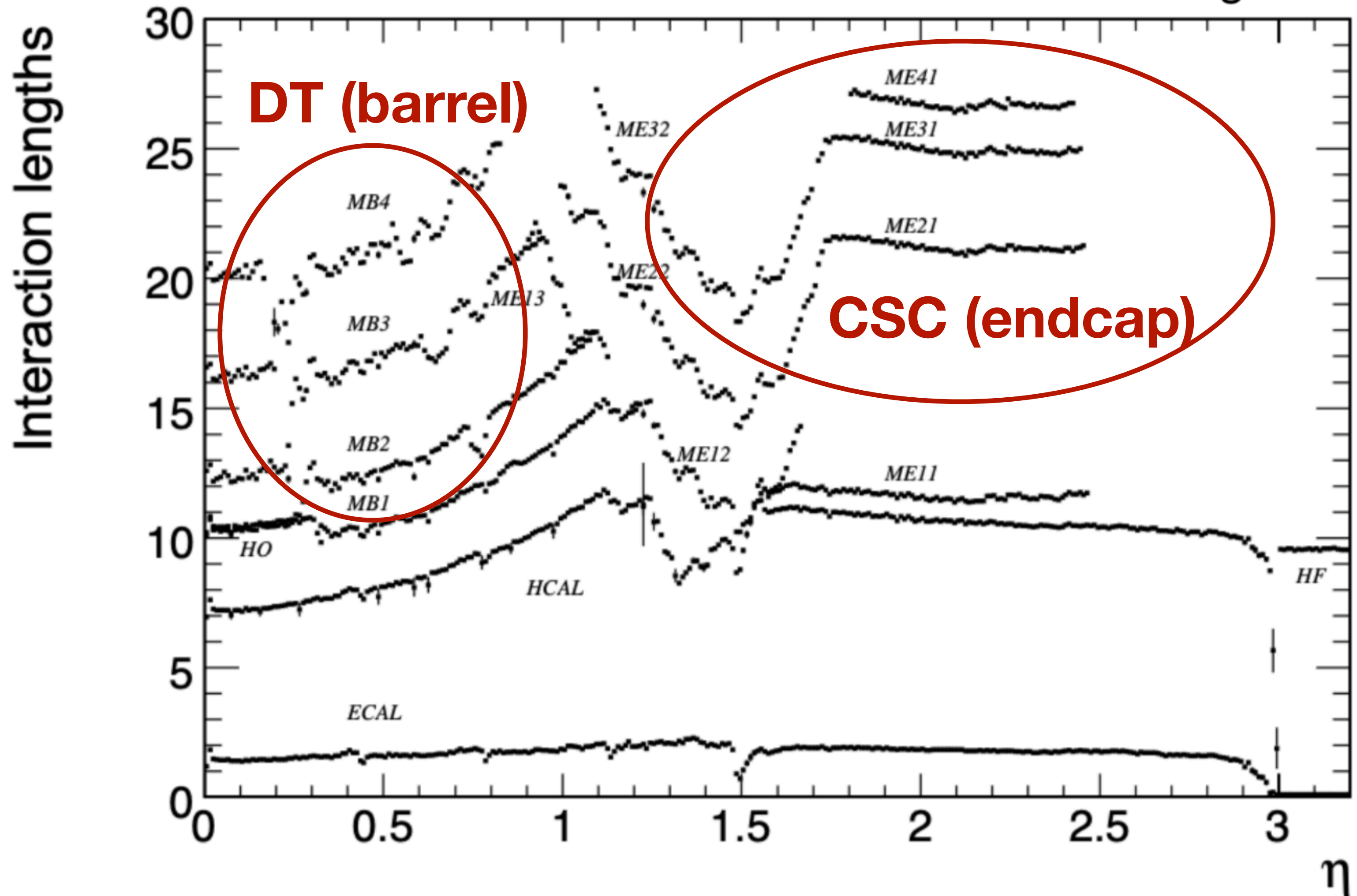


- **Large shielding against backgrounds: 12-27 nuclear interaction lengths**

LLP Muon System Analysis

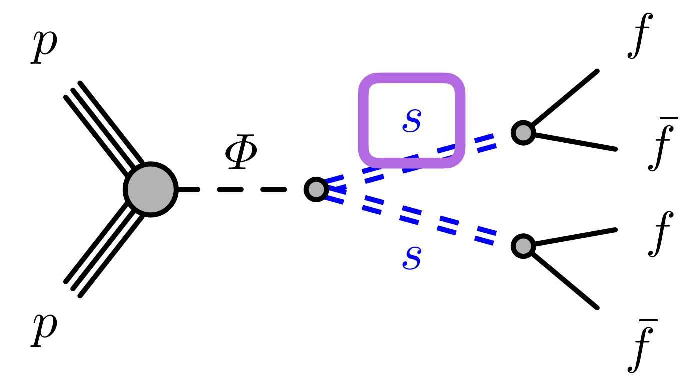
- Despite the lack of a dedicated trigger, CMS has opportunity to provide better sensitivity for 1 displaced vertex search. **CMS has more steel to reject background**

CMS TDR: LHCC-2006-001 Fig 1.4

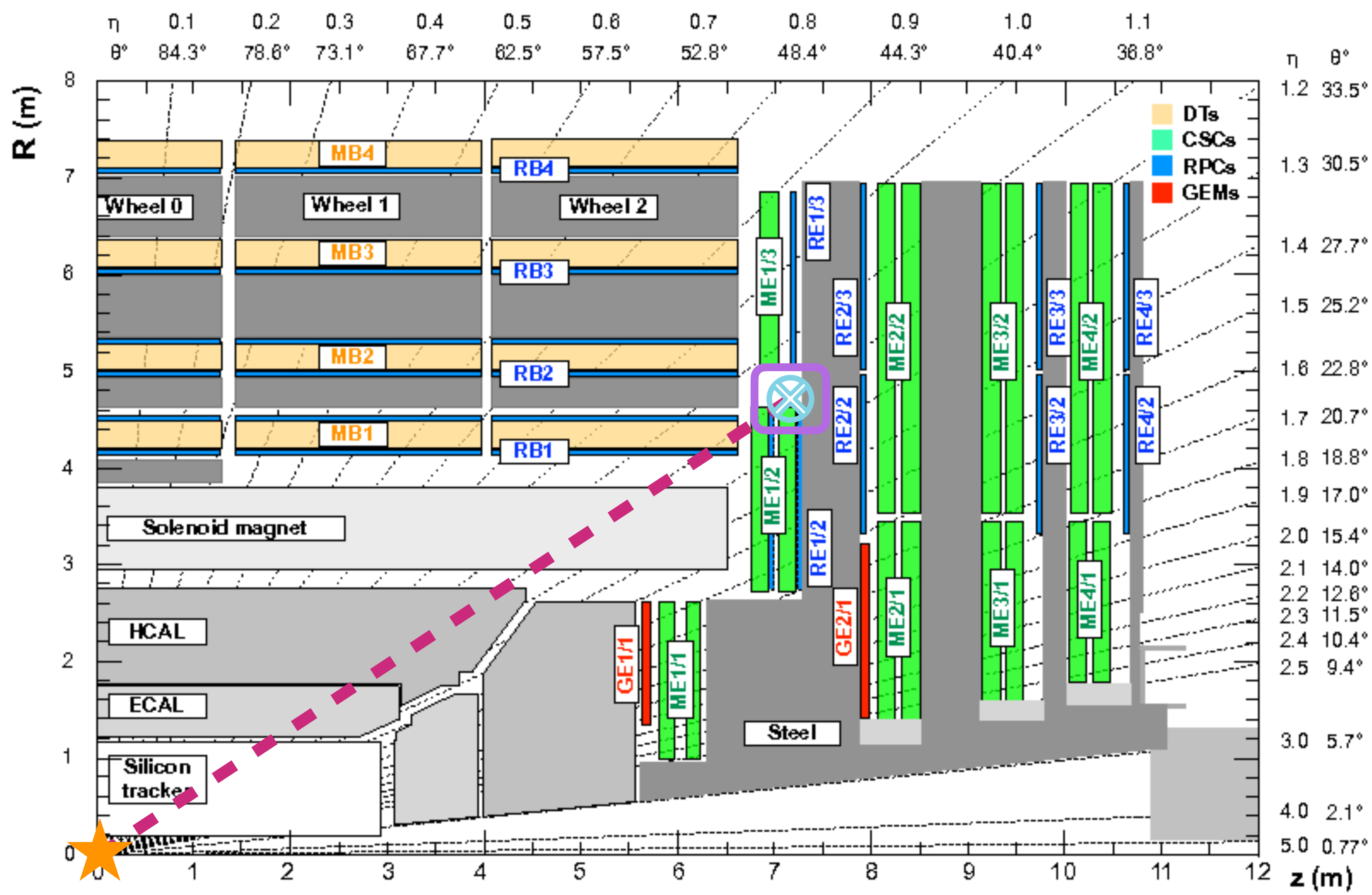


- Opportunity to **extend discovery reach at large lifetimes (> ~few meters)**

Search for LLPs in Muon System

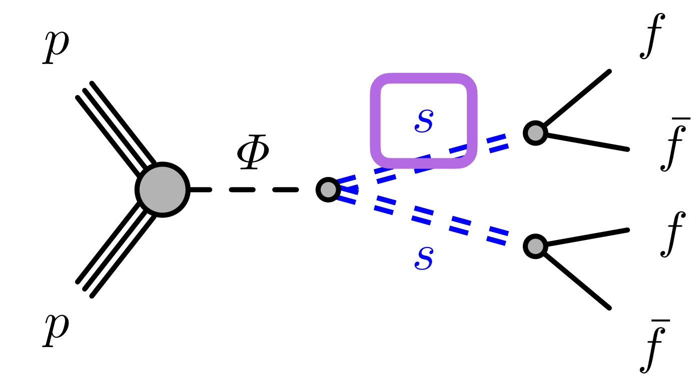


LLP decays in MS → shower



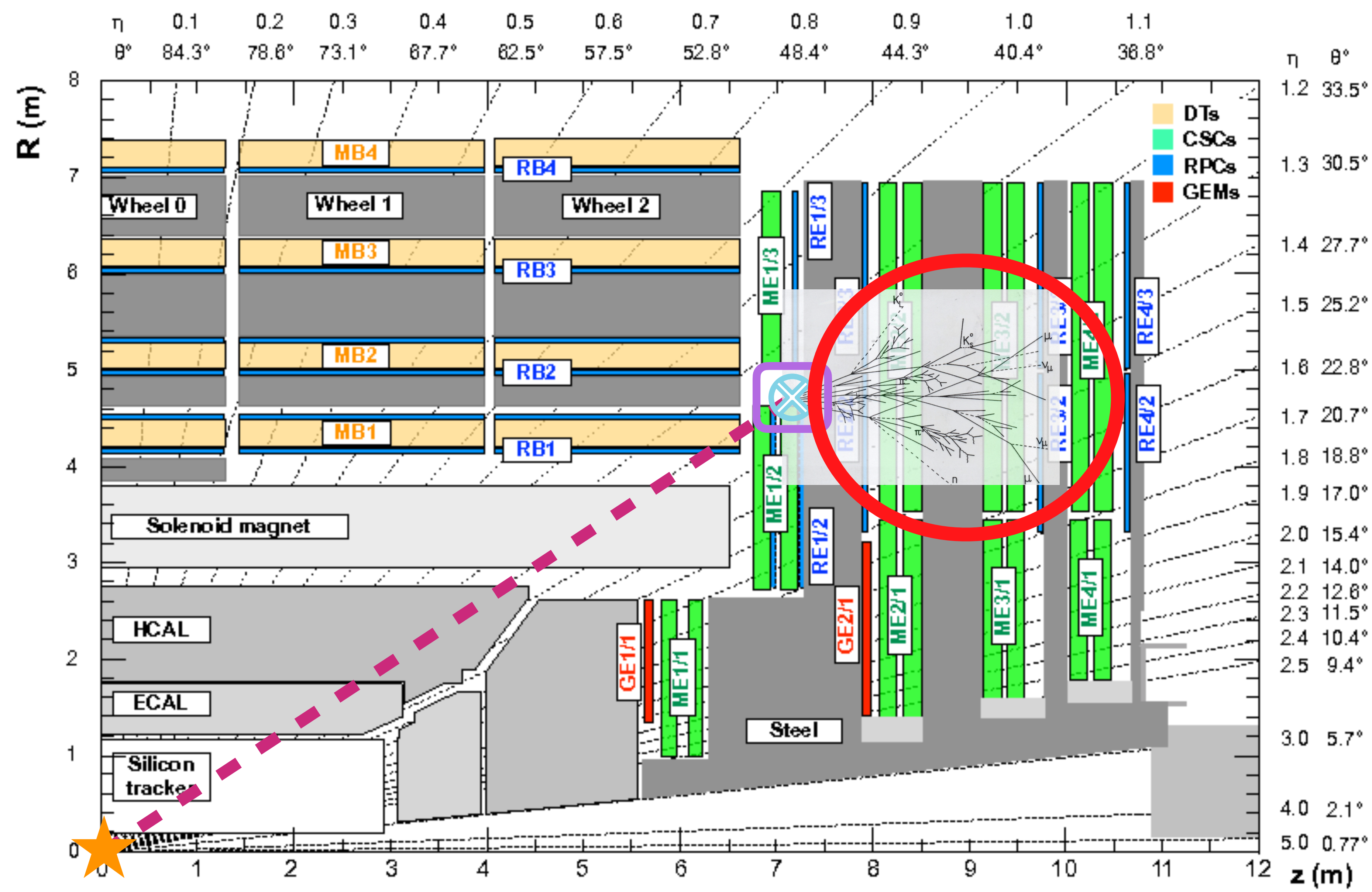
→ LLP (s) decay

Search for LLPs in Muon System



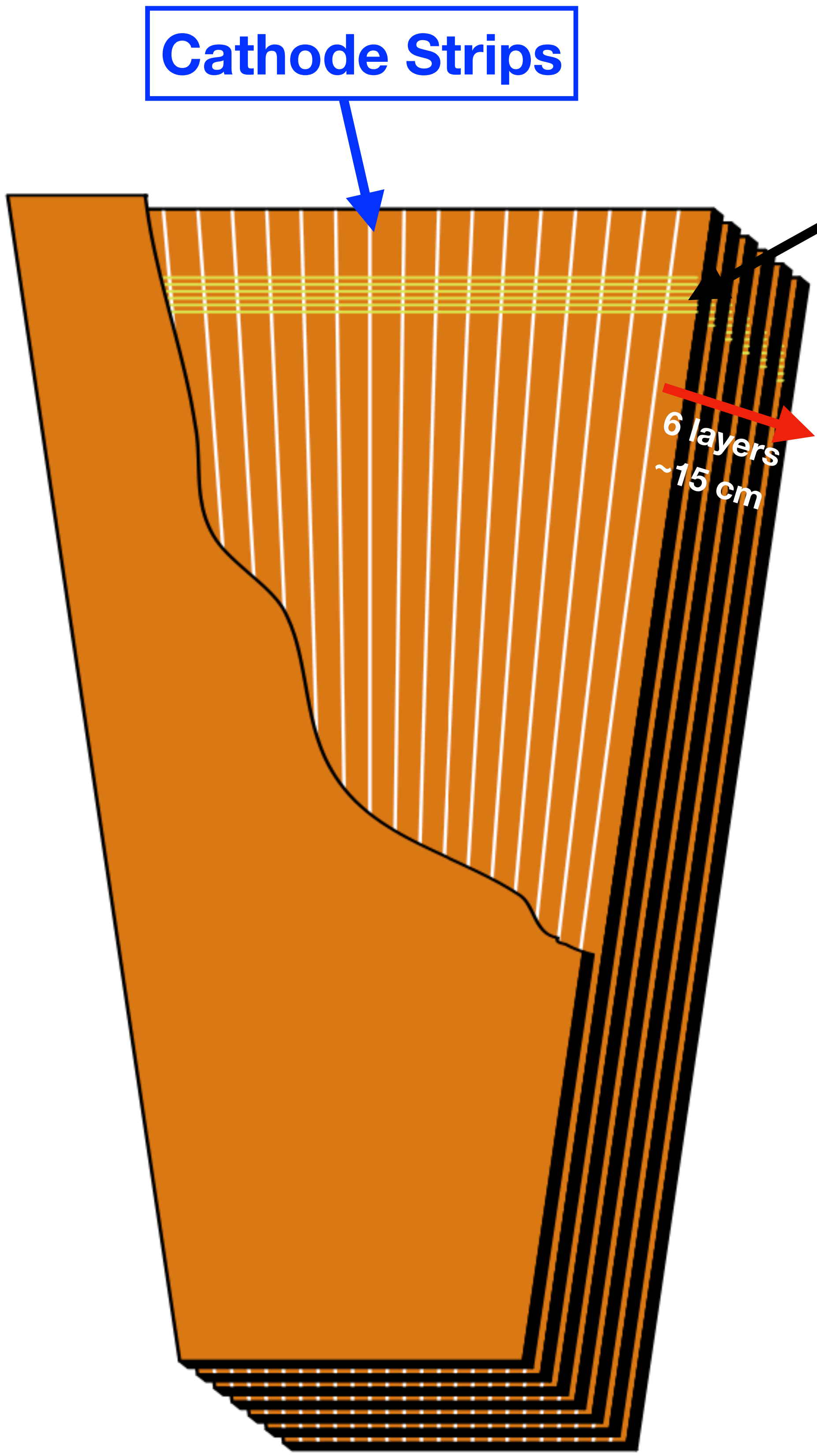
LLP decays in MS → shower

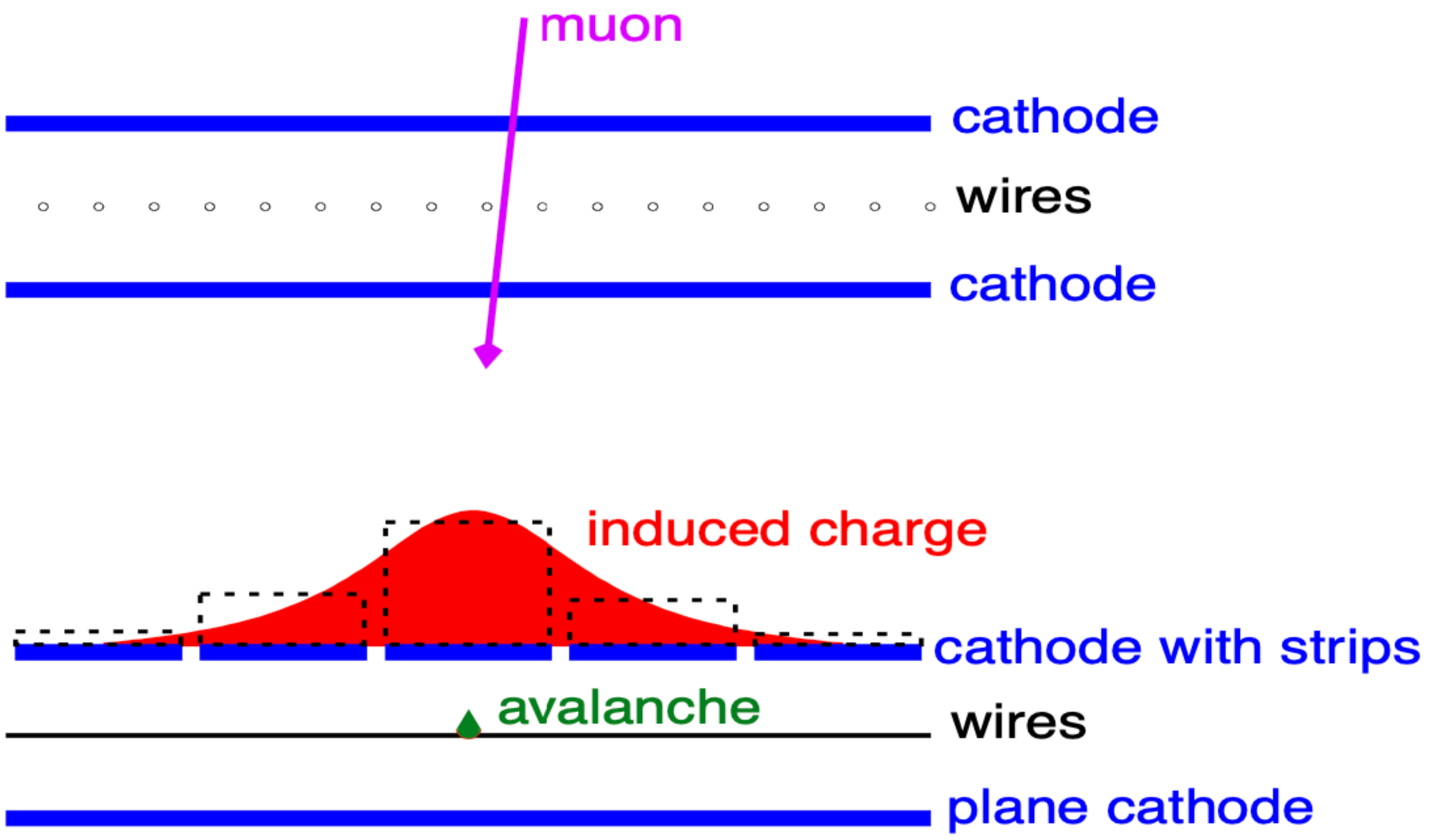
Muon System acts as sampling calorimeter



Sensitive to a broad range of LLP decays

Gas Detector



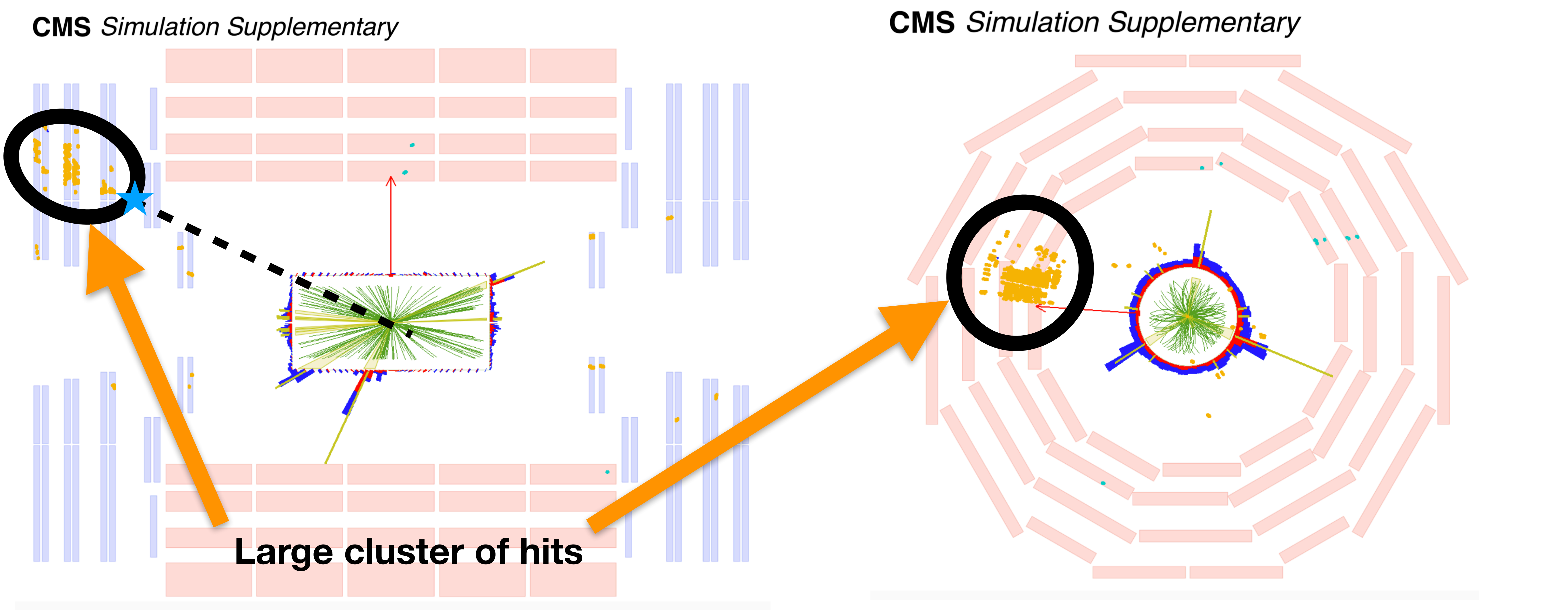


LLP Signature in Muon System

EXO-21-008

First time this signature is explored at the LHC

- LLPs that decay in the muons system leave a signature of:
  - **Large cluster of hits** in the muon chambers
- Muon system acts as a **sampling calorimeter (new)**

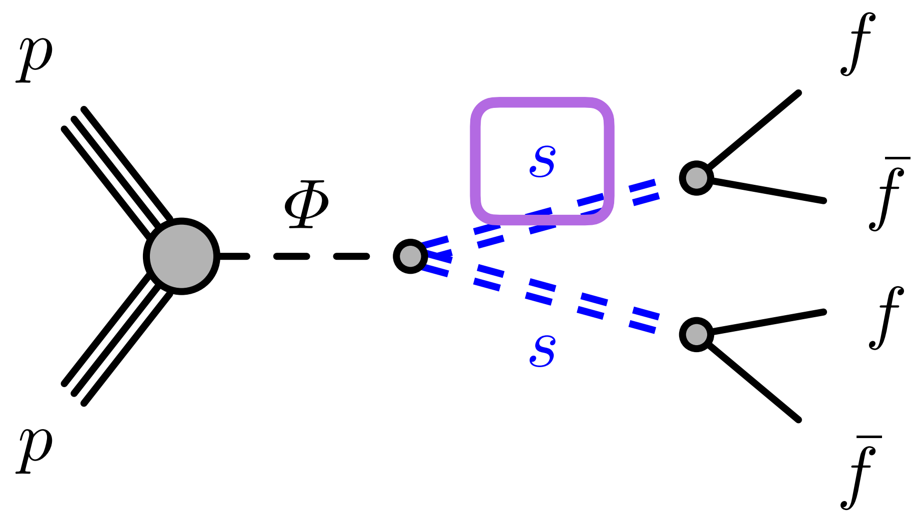


Muon Detector Shower (MDS) Efficiency

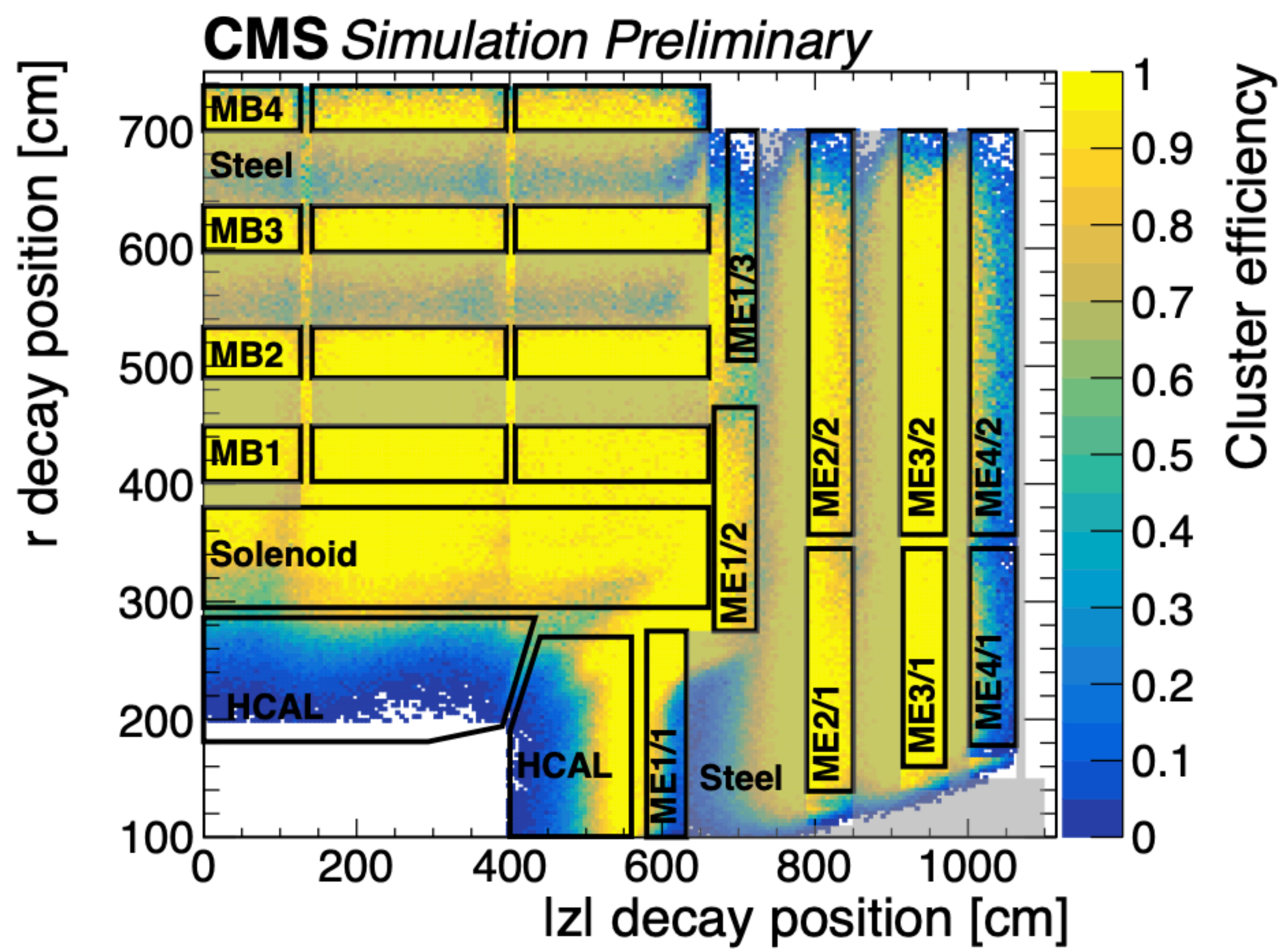
EXO-21-008

Muon system acts as a **sampling calorimeter**

LLP decay position is plotted



At least 50 hit reconstruction cluster



- High cluster reconstruction — up to 80-90%
- Dependence on LLP decay position

Muon Detector Shower (MDS) Efficiency

EXO-21-008

Muon system acts as a **sampling calorimeter**

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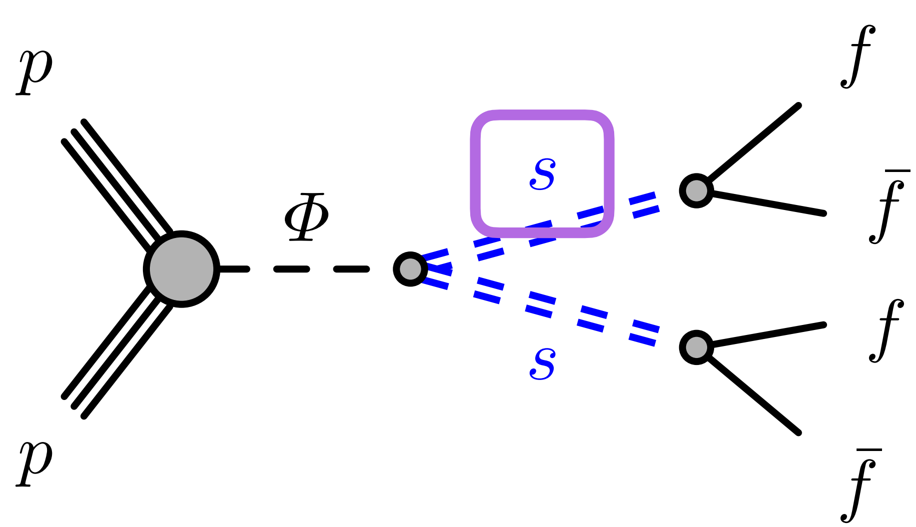

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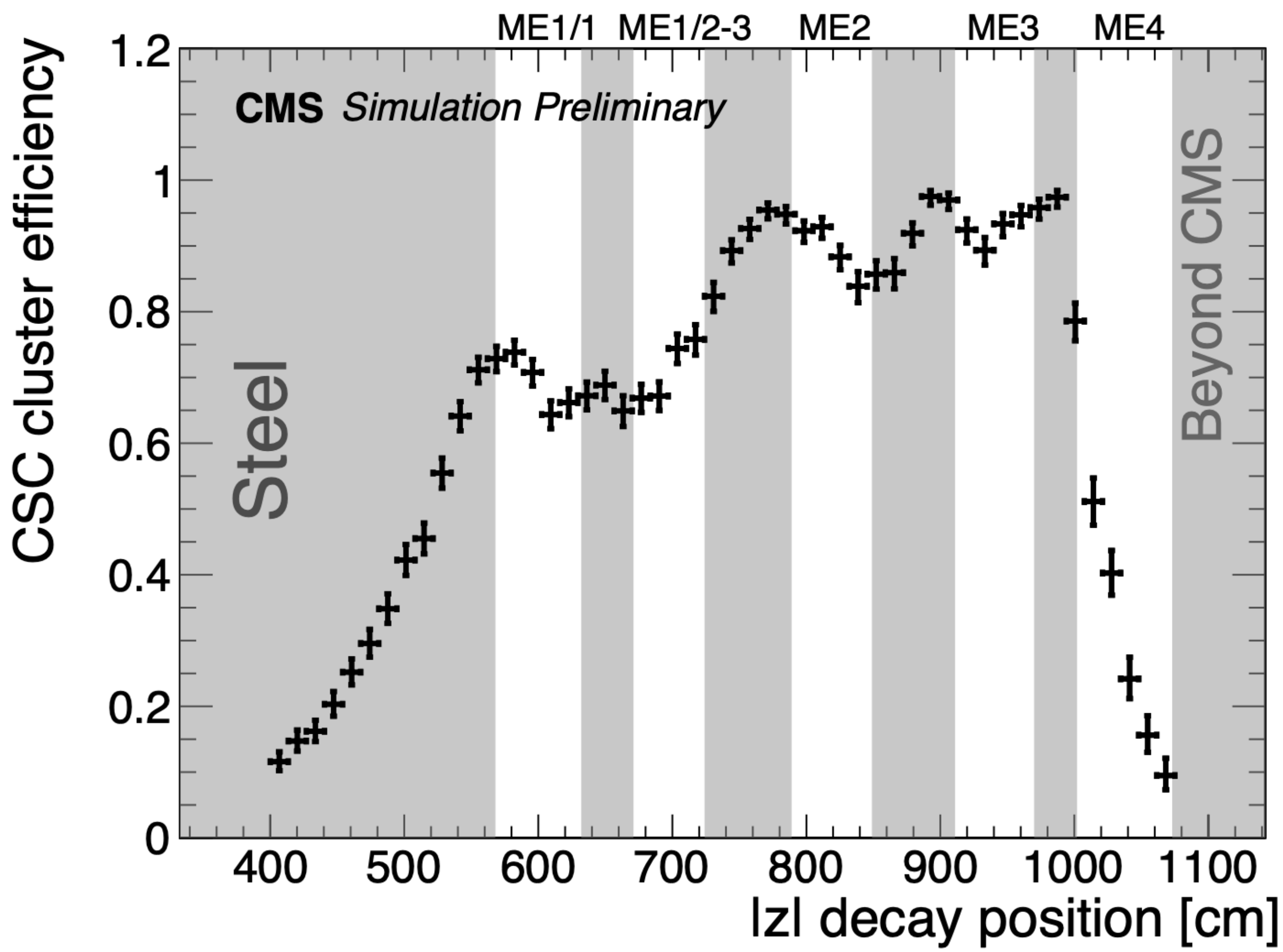
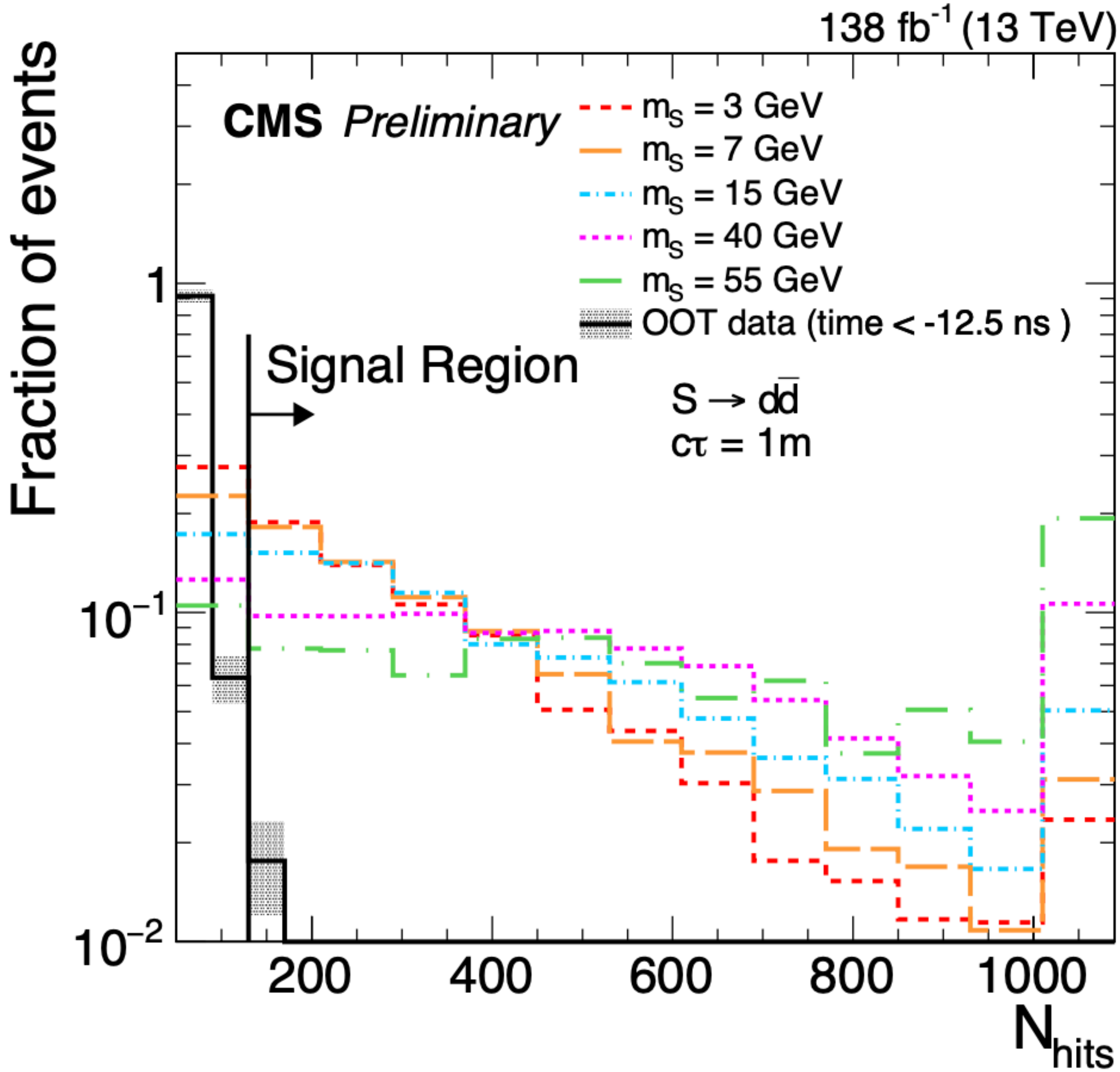


- Strong dependence on decay position (Z)
- Highly correlated with amount of steel in front of CSC

MDS Search Strategy

EXO-21-008

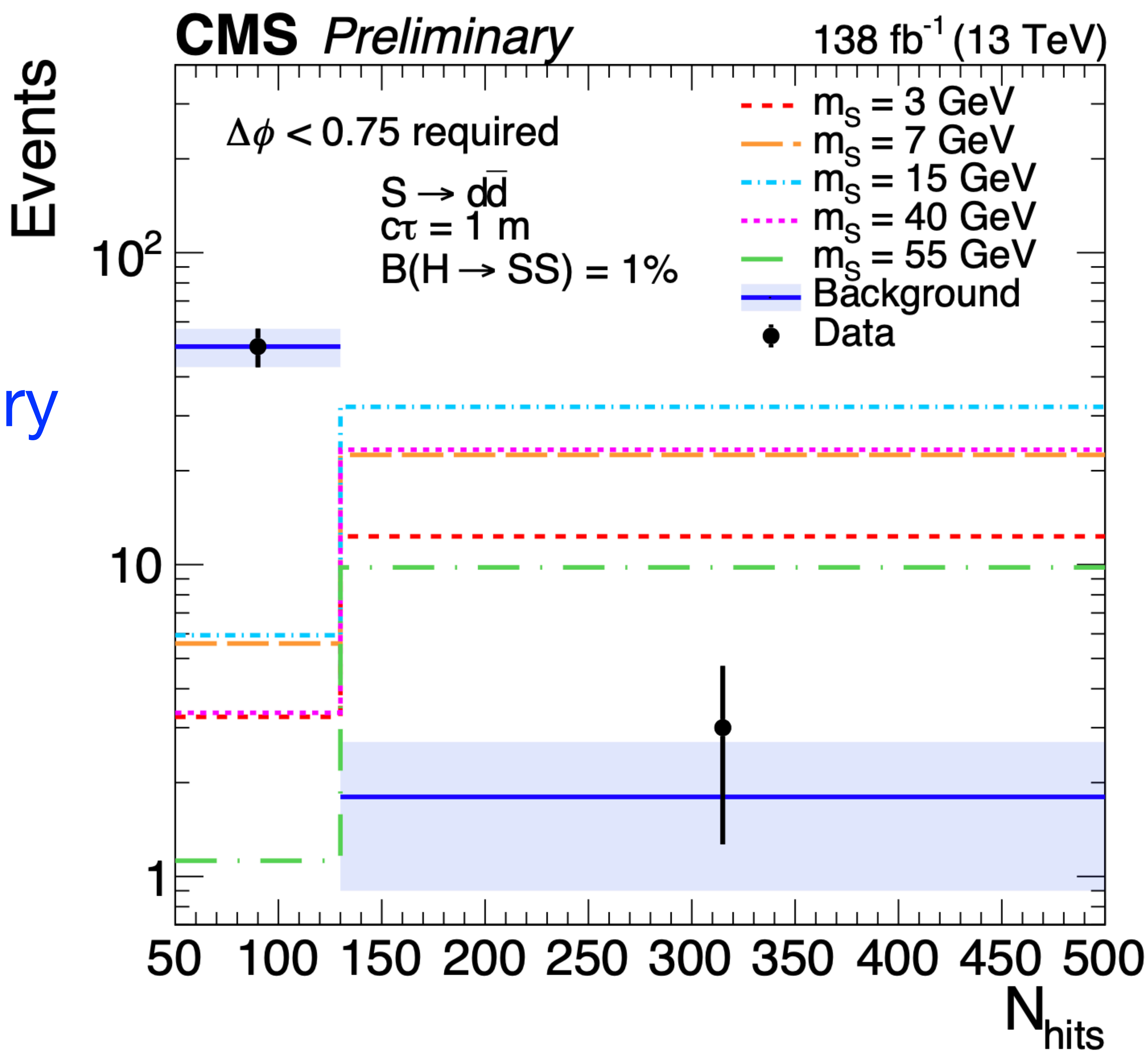


Search strategy: look for high-multiplicity MDS

MDS Search Results

EXO-21-008

CSC Category Unblinded Results



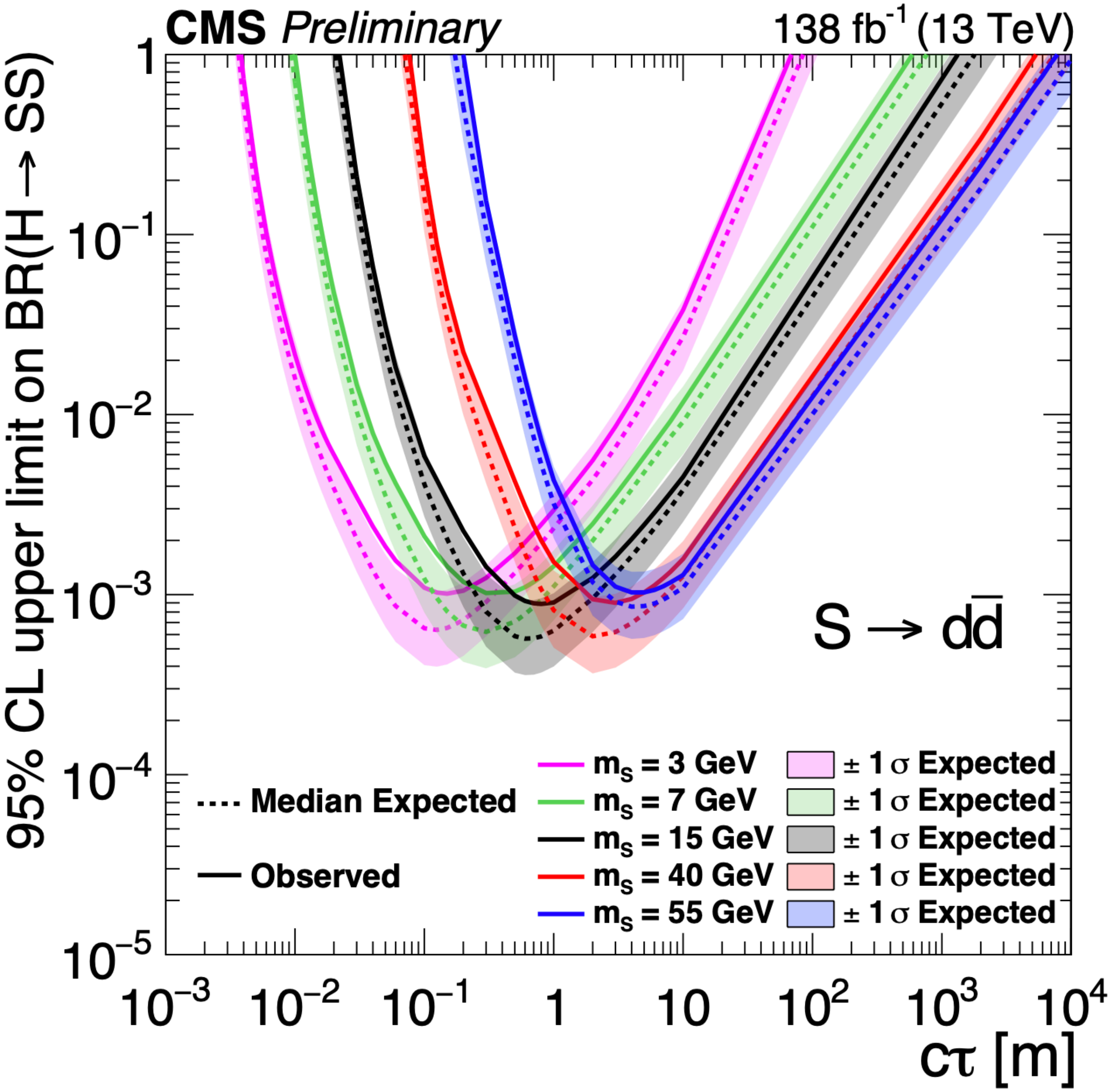
SR Expected Bkg (post-fit): 1.8 ± 0.8

SR Observed: 3

MDS Search Results

EXO-21-008

Best sensitivity at BR(H→SS) ~ 10^{-3} !!



One of the CMS latest results

- **ENABLED CMS LLP sensitivity to larger cτ**
- **Access to light LLPs (< 3 GeV)**
  - **Sensitivity to all masses**
  - **Calorimeter: sensitive to LLP energy**

world-best results for cτ > 25 m

Muon System Enables Broad LLP Reach

EXO-21-008

- Strong reach when LLPs are light — critical to have **sensitivity to all decay modes**
- Strong reach for elusive LLPs decay to SM taus. Enables sensitivity unexplored BSM : e.g **LL SUSY staus, heavy neutral lepton (HNL)**

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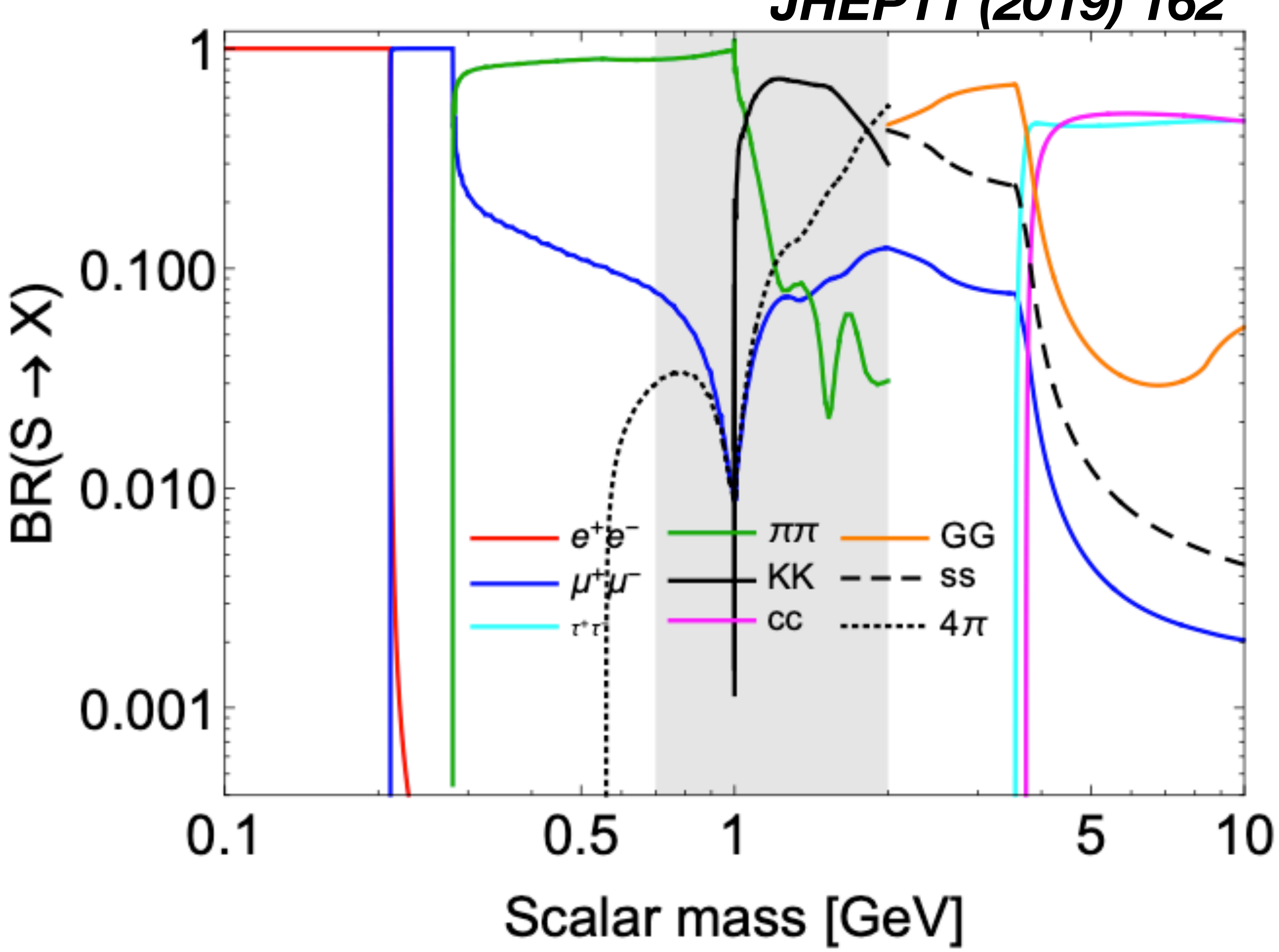
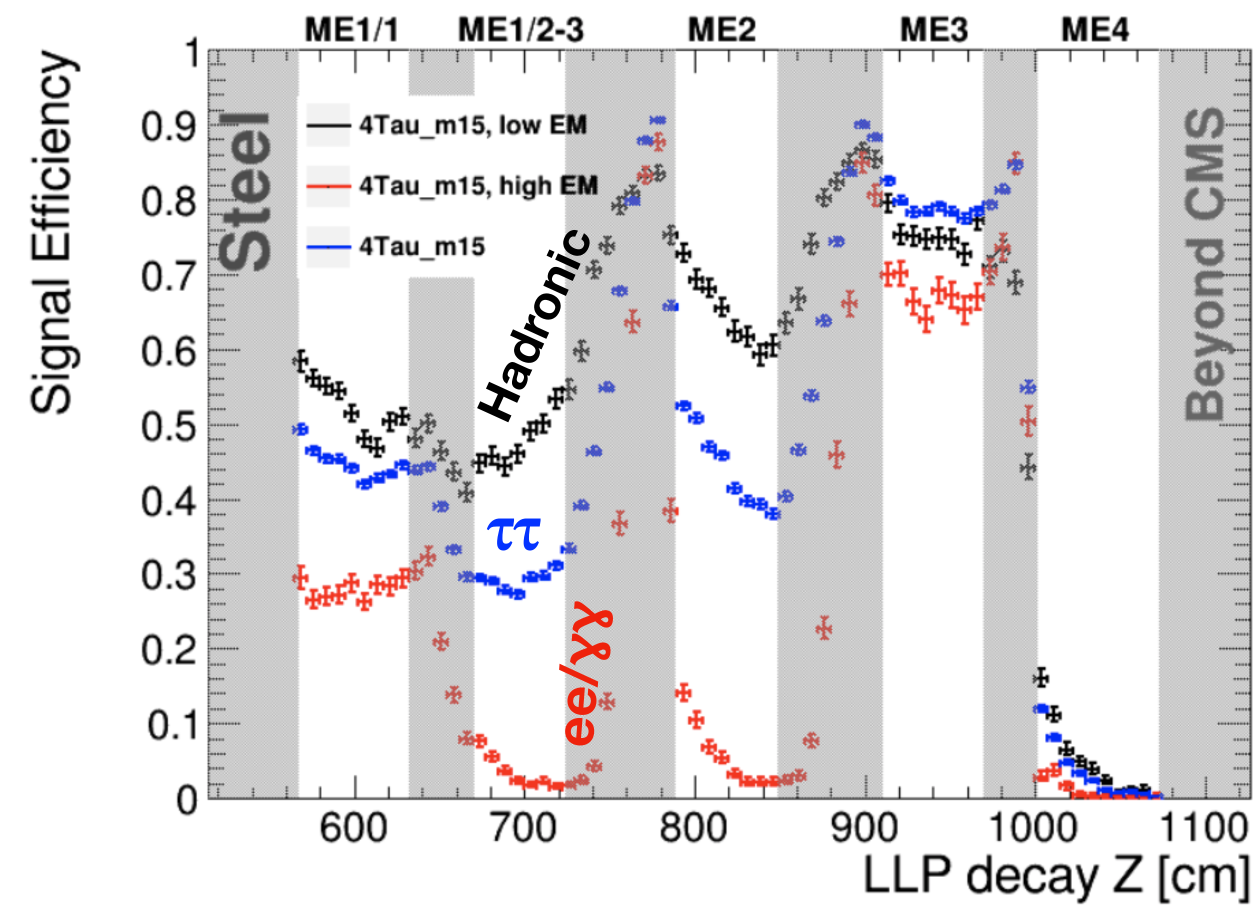
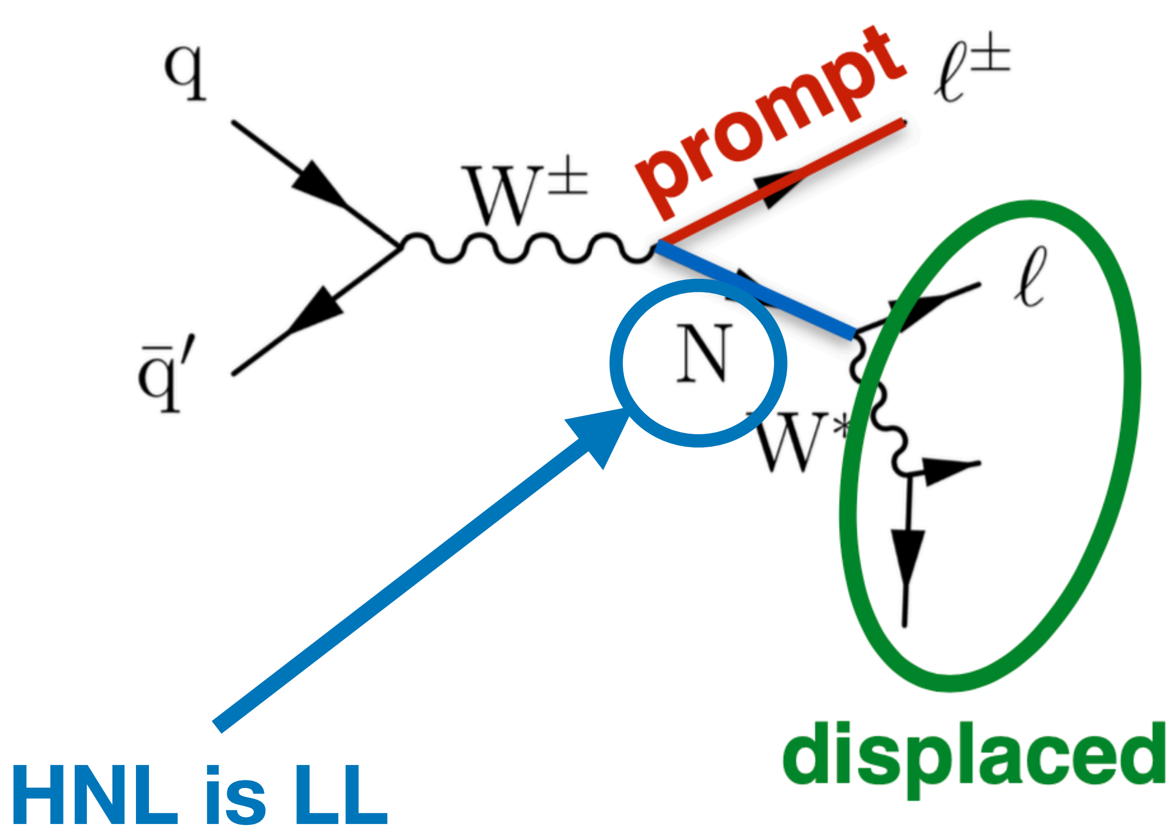


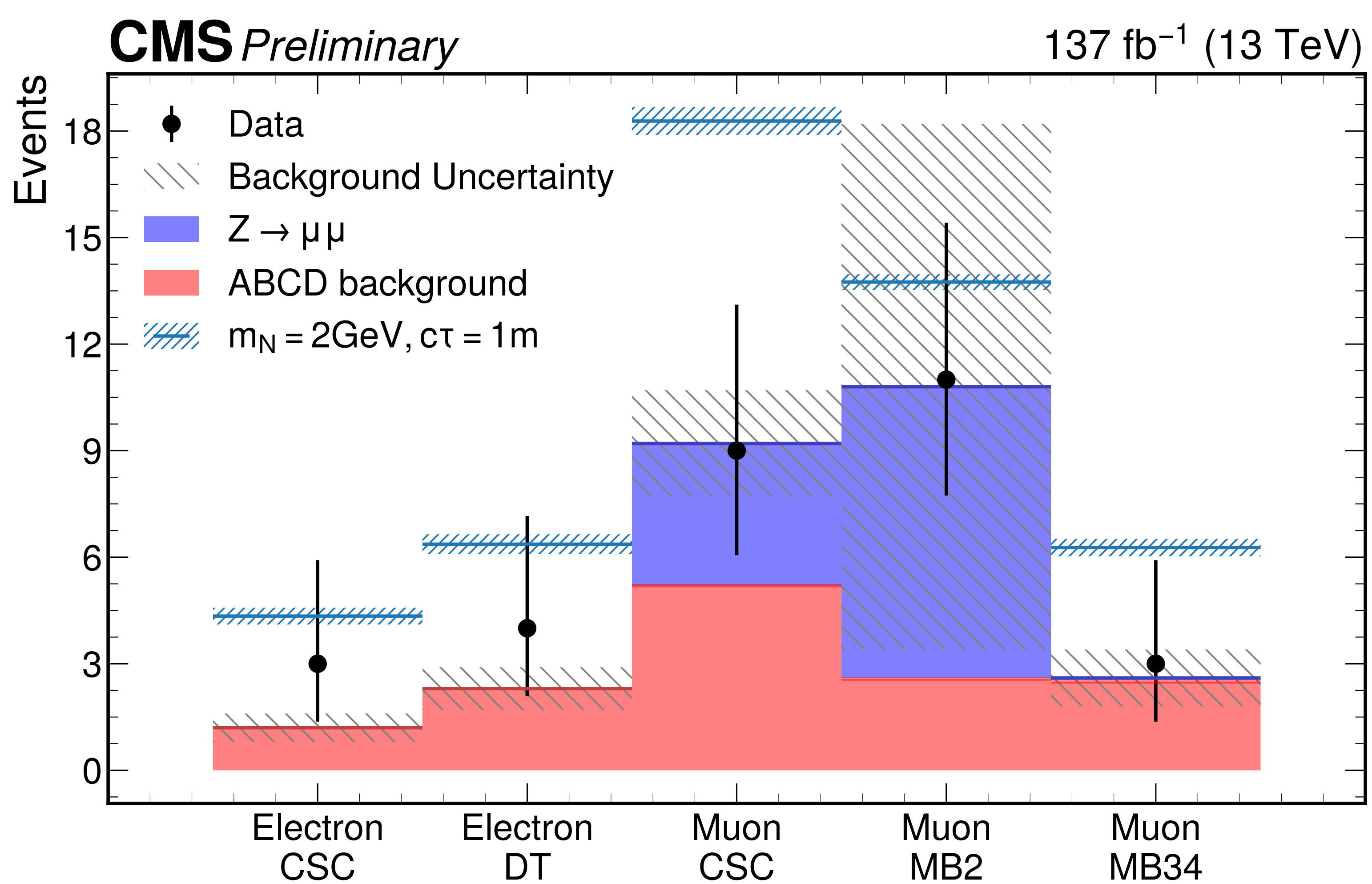


Heavy Neutral Leptons using MDS

EXO-22-017

- MDS broad sensitivity enables searches for **LLPs in neutrino portals**
- Heavy Neutral Leptons (HNLs) are naturally LL and displaced





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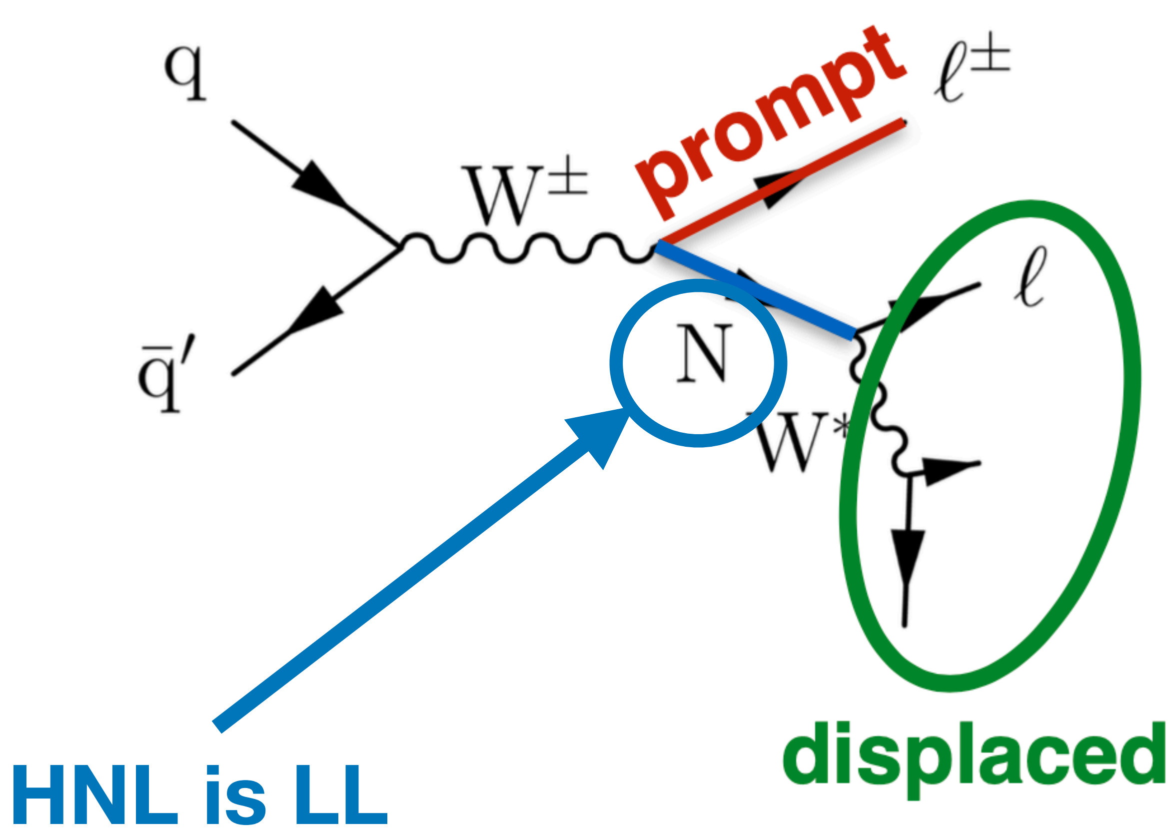

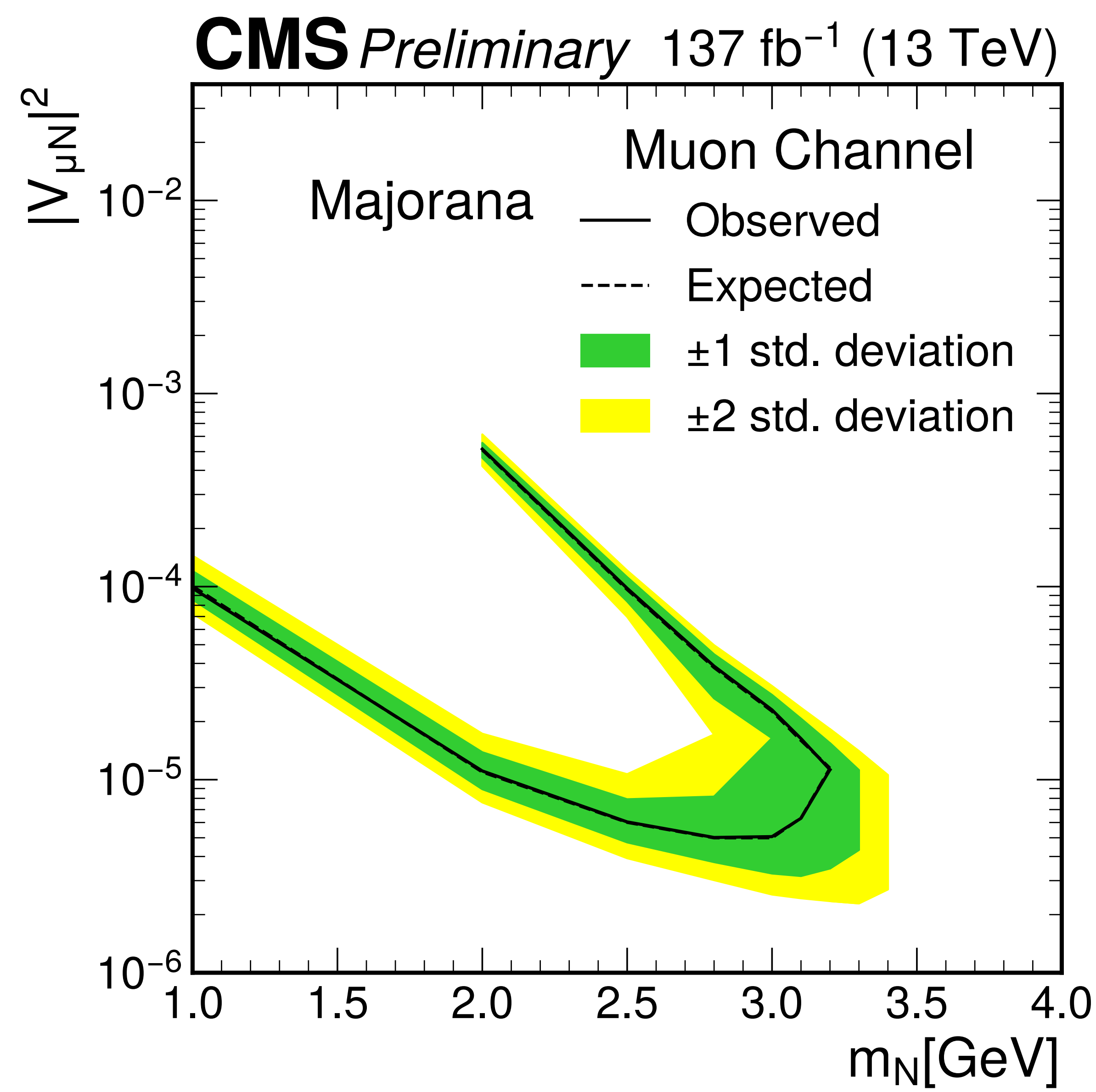

MDS HEPData Publication

- HEPData is a great tool to allow reinterpretation of CMS results
- Digitized figures and additional material such as signal efficiencies
- HEPData for EXO-20-015 allows to reinterpret in many BSM models

HEPData | Search HEPData | Search | About | Submission Help | Sign in

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Search for long-lived particles decaying in the CMS endcap muon detectors in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS collaboration

Tumasyan, Armen , Adam, Wolfgang , Andrejkovic, Janik Walter , Bergauer, Thomas , Chatterjee, Suman , Dragicevic, Marko , Escalante Del Valle, Alberto , Fruehwirth, Rudolf , Jeitler, Manfred , Krammer, Natascha

CMS-EXO-20-015, 2021.

https://doi.org/10.17182/hepdata.104408.v2

INSPIRE | Resources

Abstract

A search for long-lived particles (LLPs) produced in decays of standard model (SM) Higgs bosons is presented. The data sample consists of 137 fb^{-1} of proton-proton collisions at $\sqrt{s} = 13$ TeV, recorded at the LHC in 2016-2018. A novel technique is employed to reconstruct decays of LLPs in the endcap muon detectors. The search is sensitive to a broad range of LLP decay modes and to masses as low as a few GeV. No excess of events above the SM background is observed. The most stringent limits to date on the branching fraction of the Higgs boson to LLPs subsequently decaying to quarks and $\tau^+\tau^-$ are found for proper decay lengths greater than 6, 20, and 40 m, for LLP masses of 7, 15, and 40 GeV, respectively.

Download All | Version 2 | Filter 15 data tables

Figure 3-a (7 GeV)
Figure 3-a
10.17182/hepdata.104408.v2/t1
The 95% CL observed and expected limits on the branching fraction B(H → SS) for 7 GeV mass and S...

Figure 3-a (15 GeV)
Figure 3-a
10.17182/hepdata.104408.v2/t2
The 95% CL observed and expected limits on the branching fraction B(H → SS) for 15 GeV mass and S...

Figure 3-a (40 GeV)
Figure 3-a
10.17182/hepdata.104408.v2/t3
The 95% CL observed and expected limits on the branching fraction B(H → SS) for 40 GeV mass and S...

Figure 3-a (55 GeV)
Figure 3-a
10.17182/hepdata.104408.v2/t4
The 95% CL observed and expected limits on the branching fraction B(H → SS) for 55 GeV mass and S...

Figure 3-b (7 GeV)
Figure 3-b
10.17182/hepdata.104408.v2/t5
The 95% CL observed and expected limits on the branching fraction B(H → SS) for 7 GeV mass and S...

Figure 3-b (15 GeV)

Version 2 modifications: Added new table for additional figure 9.

Figure 3-a (7 GeV) 10.17182/hepdata.104408.v2/t1 | https://www.hepdata.net/rec | JSON

Figure 3-a

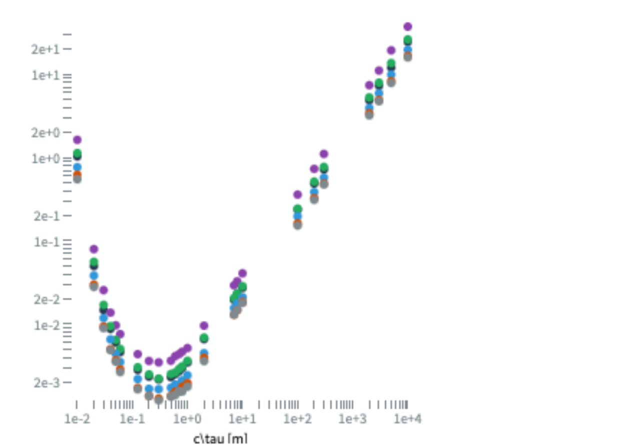
The 95% CL observed and expected limits on the branching fraction B(H → SS) for 7 GeV mass and $S \to d\bar{d}$ decay mode.

cmenergies: 13000.0

observables: CLS

Quantile	-2σ	-1σ	Median expected	$+1\sigma$	$+2\sigma$	Observed
$c\tau$ [m]	95% CL upper limit on B(H → SS)					
0.01	0.5468	0.61962	0.76532	1.1302	1.629	1.0282
0.02	0.027933	0.029842	0.038265	0.055958	0.079302	0.049691
0.03	0.0089284	0.0093833	0.011834	0.017022	0.025549	0.014732
0.04	0.0048704	0.004997	0.006564	0.0094621	0.013723	0.0087544
0.05	0.0035369	0.0037016	0.0044156	0.0064652	0.0096709	0.0059986
0.06	0.0026527	0.0028657	0.0035041	0.0050343	0.0075821	0.0046053
0.125	0.0016474	0.0017129	0.002189	0.0030361	0.0043606	0.0028215
0.2	0.0013649	0.0013779	0.0016728	0.0024945	0.0036087	0.0023424
0.3	0.0012162	0.0012793	0.0016575	0.0022169	0.0034752	0.0021674
0.5	0.0013472	0.0013755	0.0017238	0.0025211	0.0036287	0.0023074
0.6	0.0014066	0.0015516	0.0018828	0.0026288	0.0041192	0.0025032

Visualize



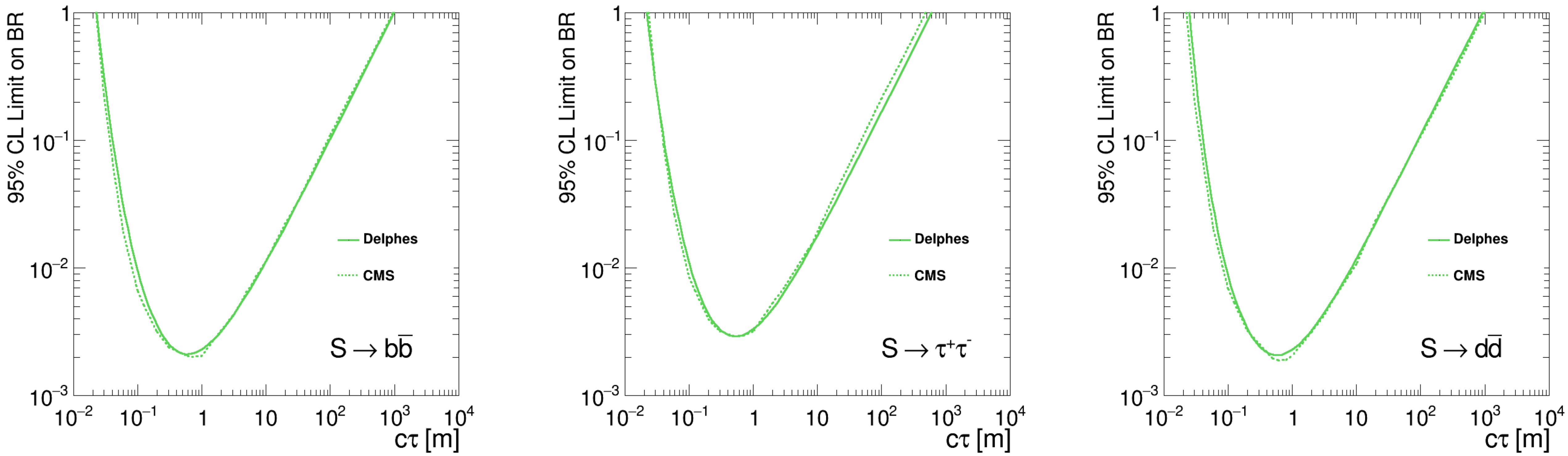
Sum errors | Log Scale (X) | Log Scale (Y)

Deselect variables or hide different error bars by clicking on them.

First Results Validation

- **Use the dedicated Delphes class/module** and implement all cuts applied in the CMS paper
- Use the **data** and expected **background** yield in signal region provided in CMS paper
- **Validated that the standalone workflow** is able to reproduce the limits from the CMS analysis for all 3 decay modes to within 30%

LLP mass = 15 GeV



C. Wang at LLPX workshop

Light Scalar (S) Reinterpretation

Long-lived Scalar (S) couple to Higgs

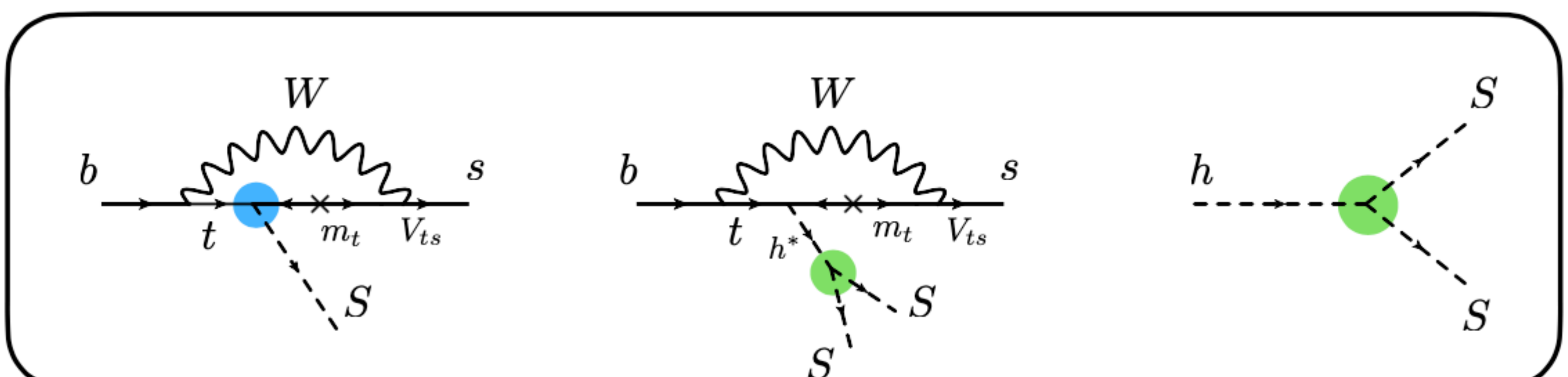
$$\mathcal{L}_{SH} = \mathcal{L}_{\rm SM} + \overbrace{\frac{1}{2}\partial_\mu \hat{S}\,\partial^\mu \hat{S} - \frac{\mu_S^2}{2}\hat{S}^2}^{\mathcal{L}_{\rm DS}} - \overbrace{\left(A_{HS}\,\hat{S} + \lambda_{HS}\,\hat{S}^2\right)\hat{H}^\dagger \hat{H}}^{\text{Higgs portal}}$$

A_{HS}: controls the $\hat{H}-\hat{S}$ mixing

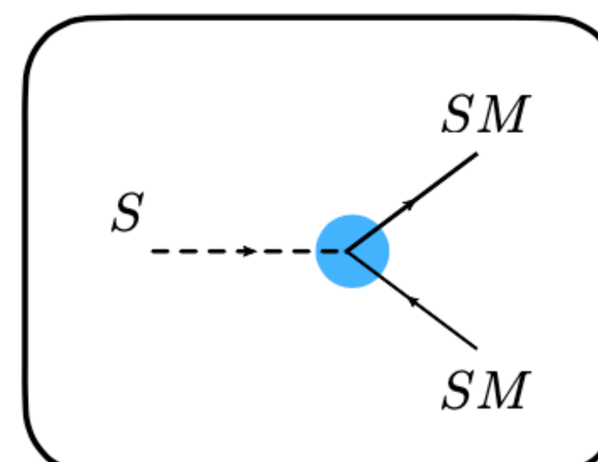
λ_{HS}: controls $Br(H \to SS)$

Long-lived Scalar (S) couple to Higgs

production



decay



A. Mitridate at LLPX workshop

Light Scalar (S) Reinterpretation

Long-lived Scalar (S) couple to Higgs

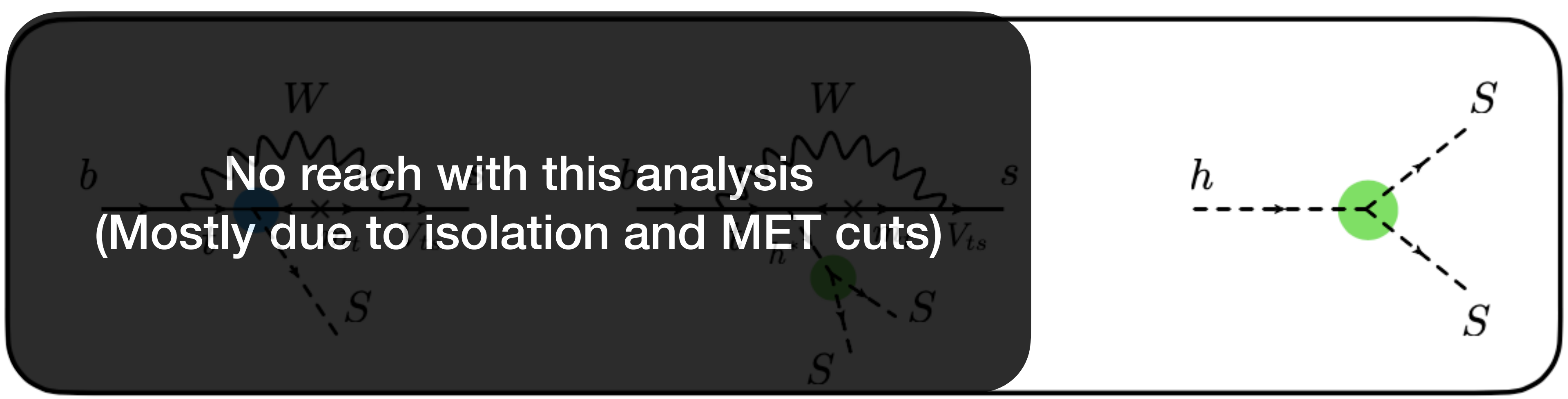
$$\mathcal{L}_{SH} = \mathcal{L}_{\rm SM} + \overbrace{\frac{1}{2}\partial_\mu \hat{S}\,\partial^\mu \hat{S} - \frac{\mu_S^2}{2}\hat{S}^2}^{\mathcal{L}_{\rm DS}} - \overbrace{\left(A_{HS}\,\hat{S} + \lambda_{HS}\,\hat{S}^2\right)\hat{H}^\dagger \hat{H}}^{\text{Higgs portal}}$$

A_{HS}: controls the $\hat{H} - \hat{S}$ mixing

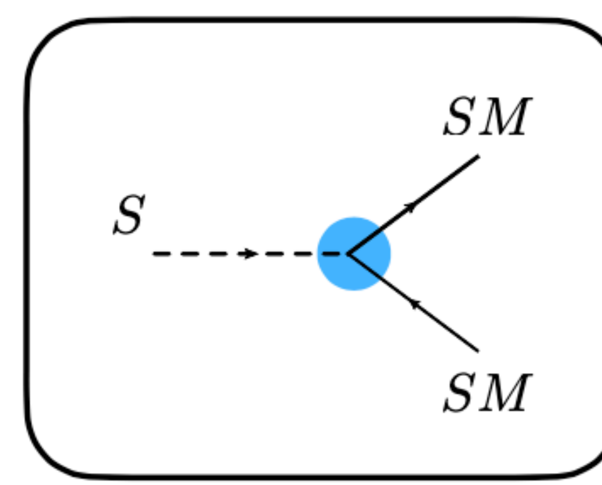
λ_{HS}: controls $Br(H \to SS)$

Very similar to CMS main interpretation

production



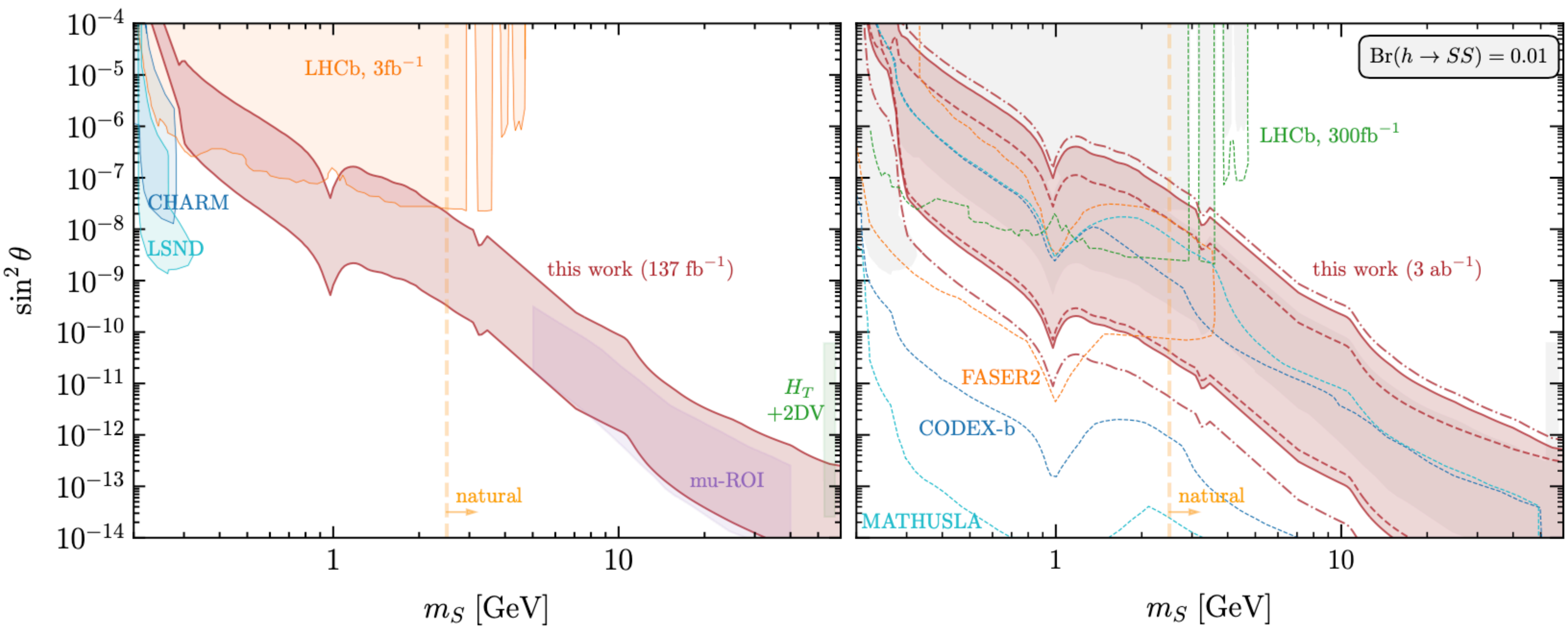
decay



A. Mitridate at LLPX workshop

Light Scalar (S) Reinterpretation

- Mixing angle (θ) controls the scalar lifetime
- Exclusion obtain at 1% Br(h→SS): fixes production cross section × BR
- Scalar mass controls the decay mode and affects the acceptance

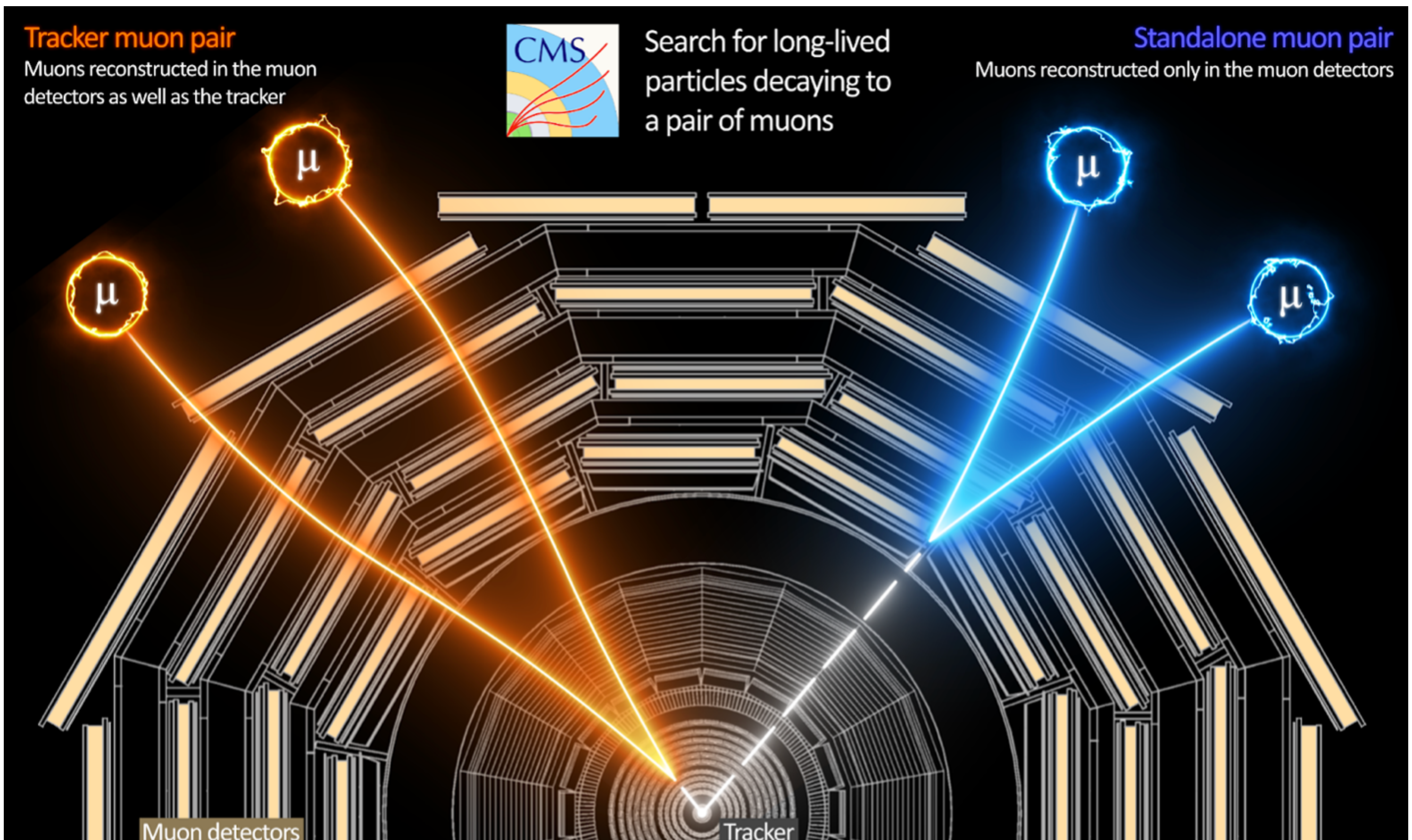


- Current best sensitivity in a large region of phase space ✔
  - Confirms reach to light LLPs (< 1 GeV) for CMS
- Closing the gap to dedicated LLP experiments ✔

Muon System: Displaced Muons

EXO-23-014

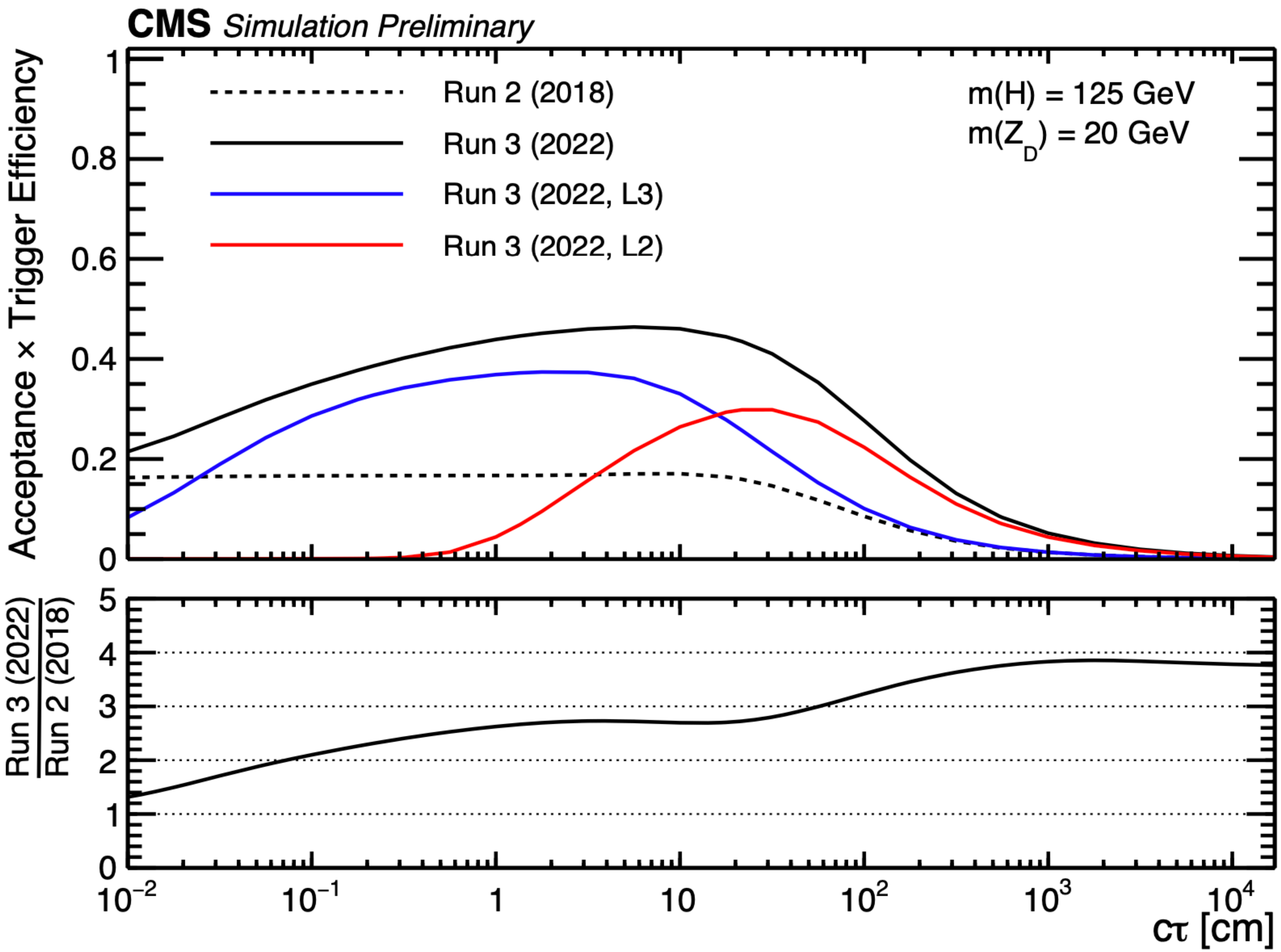
- Displaced Muons are a powerful signature for LLP
- 2 types of reconstructed muons: **tracker muons** and **standalone muons**



Muon System: Displaced Muons

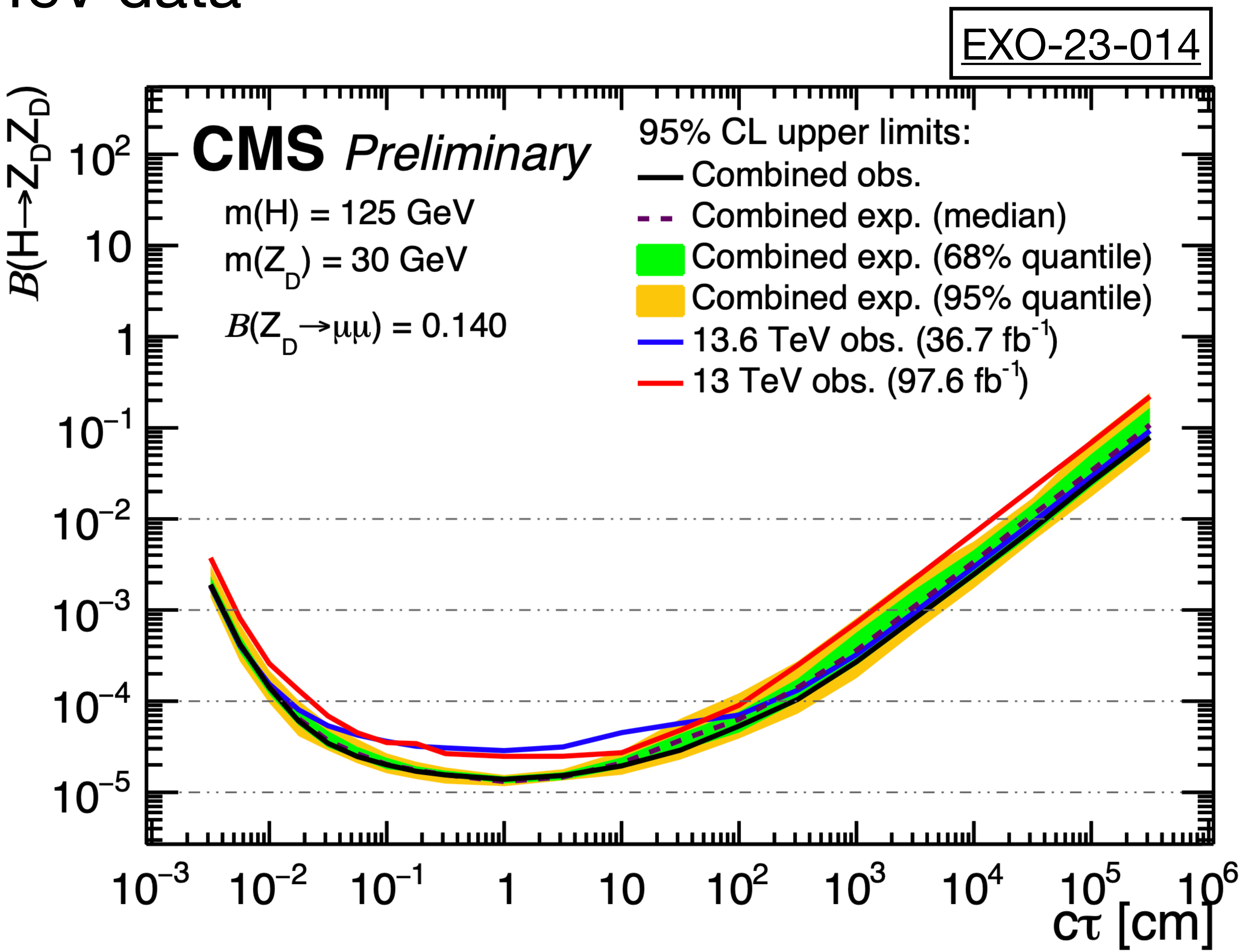
EXO-23-014

- Brand new search using 13.6 TeV (Run3) data
- New optimized trigger using displaced muon signature

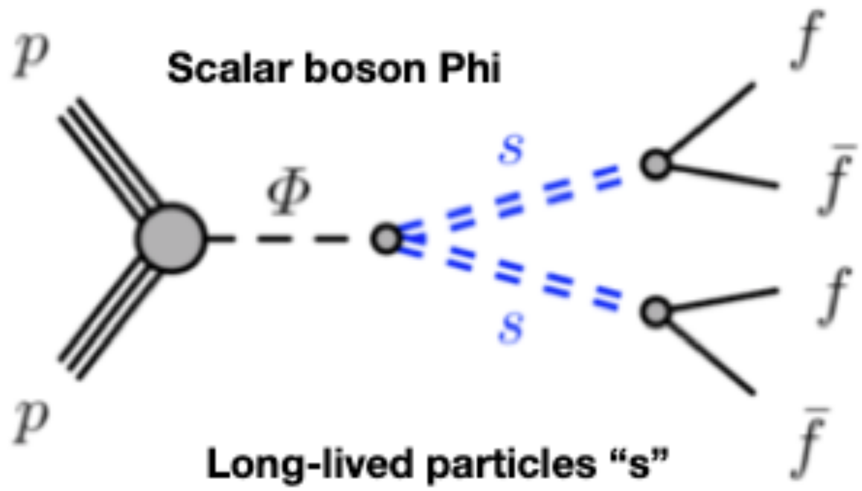


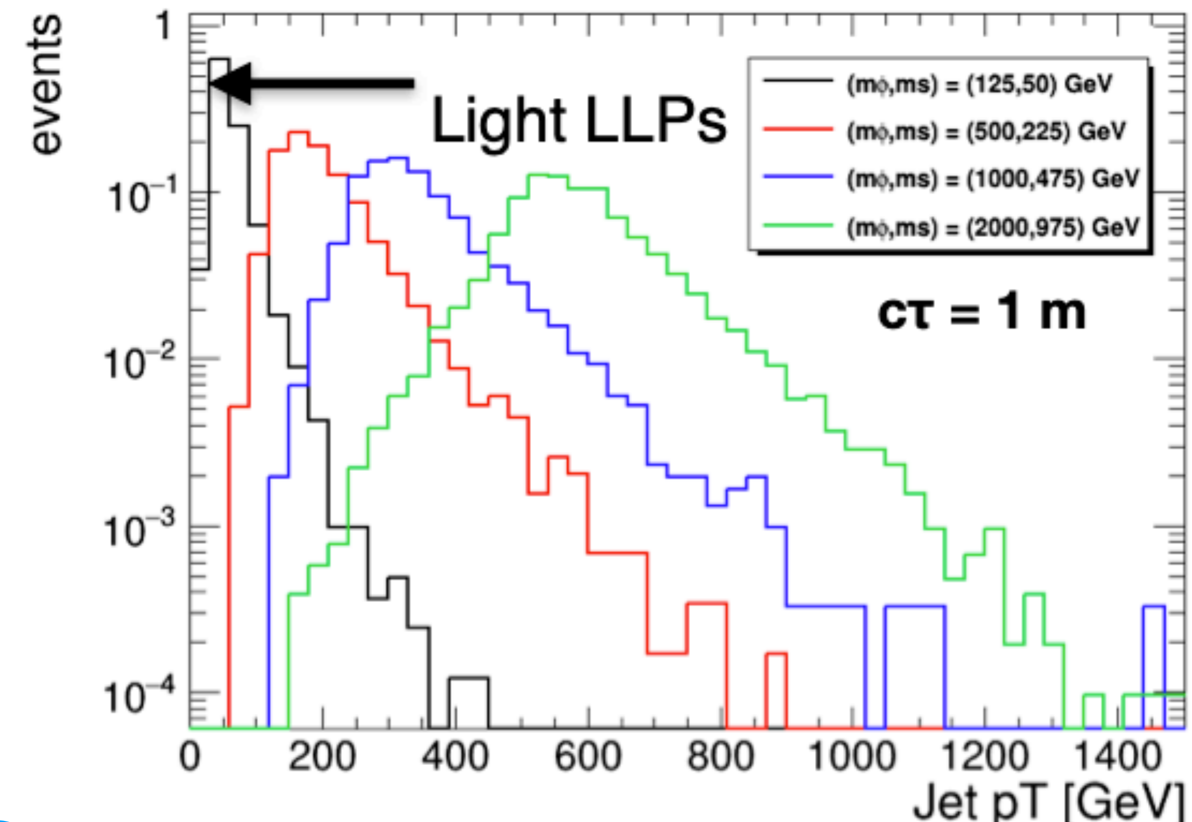
Muon System: Displaced Muons

- Best sensitivity for LLPs decaying to a pair of muons
- New triggers enable large sensitivity gain even with 1/3 of the 13 TeV data



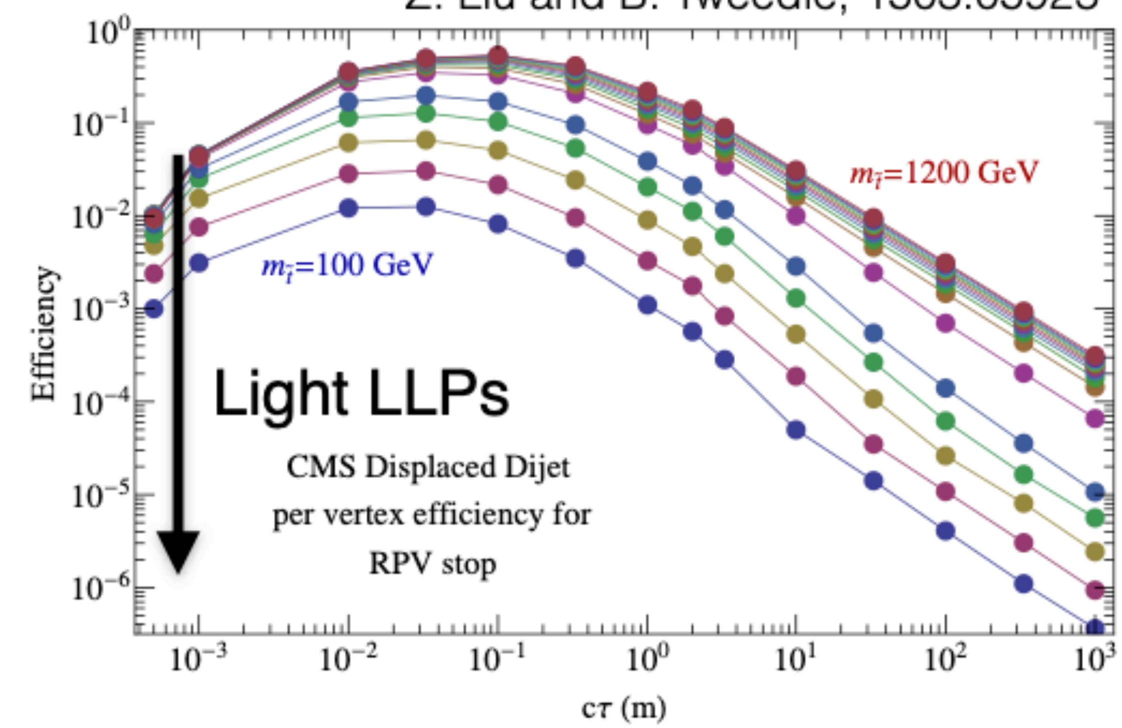
Triggers: the new LLP frontier





- Current L1 trigger have high-threshold: highly detrimental to light LLPs
  - HT > 300 GeV and jet pT > 200 GeV
  - Trigger efficiencies below ~1% for light LLPs
  - No seeds for beyond calorimeter signatures
- **Critical need and opportunity for LL Trigger in CMS during Run3 and HL-LHC**

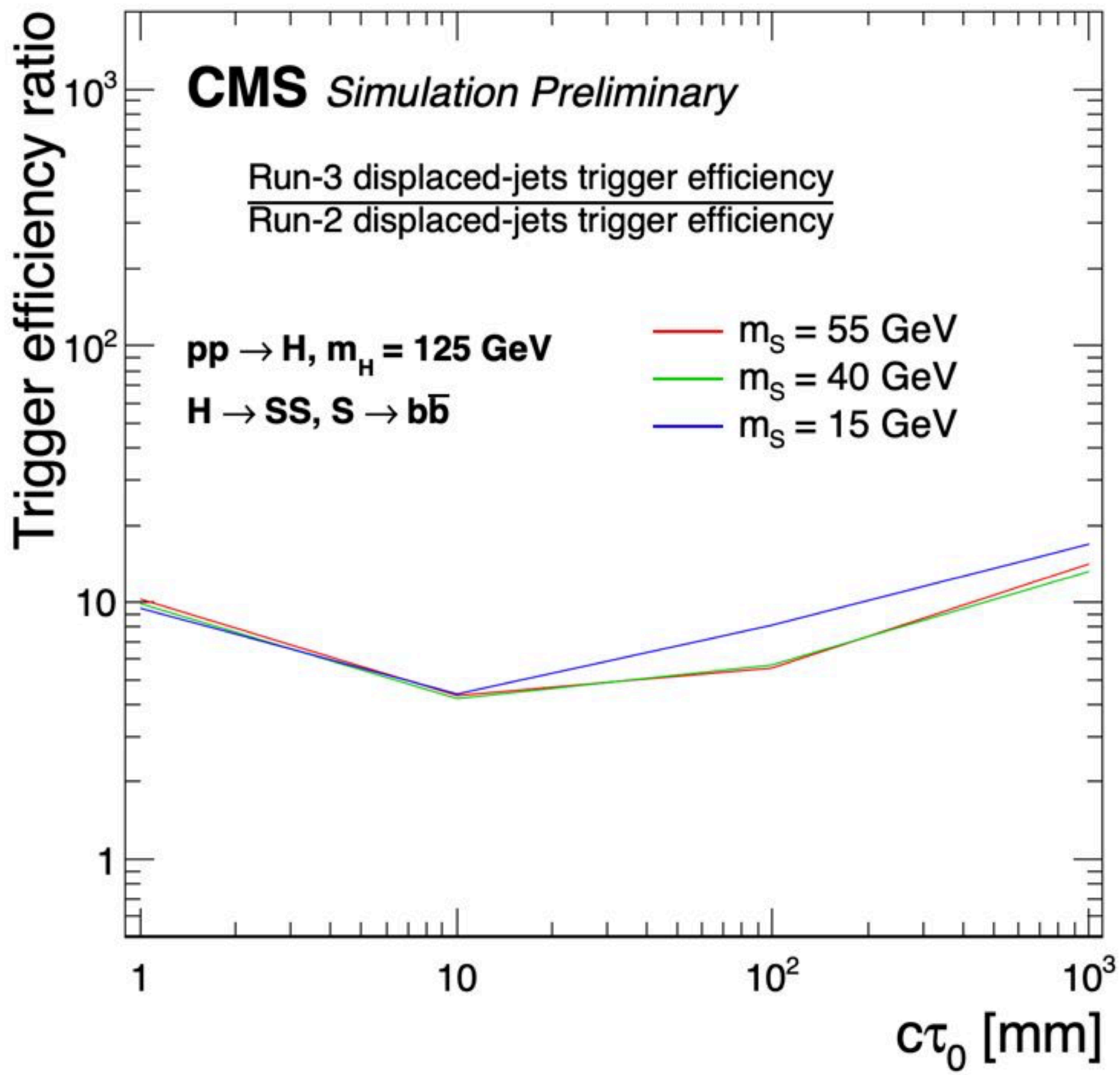
Z. Liu and B. Tweedie, 1503.05923




The
Future is
NOW

New Run3 Triggers: Tracker

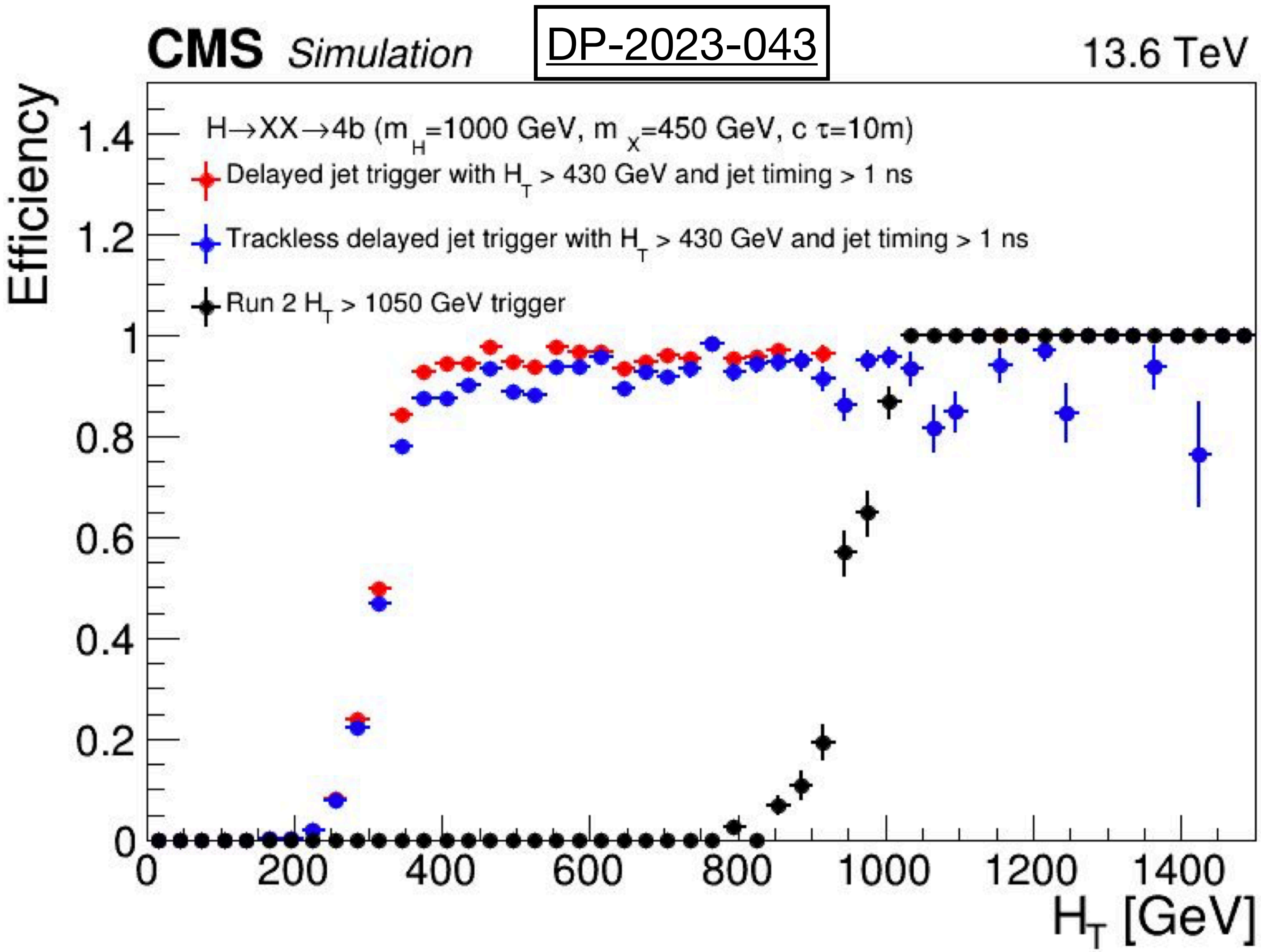
Strategy: lowered jet-pT threshold by requiring no prompt-tracks



DP-2023-043

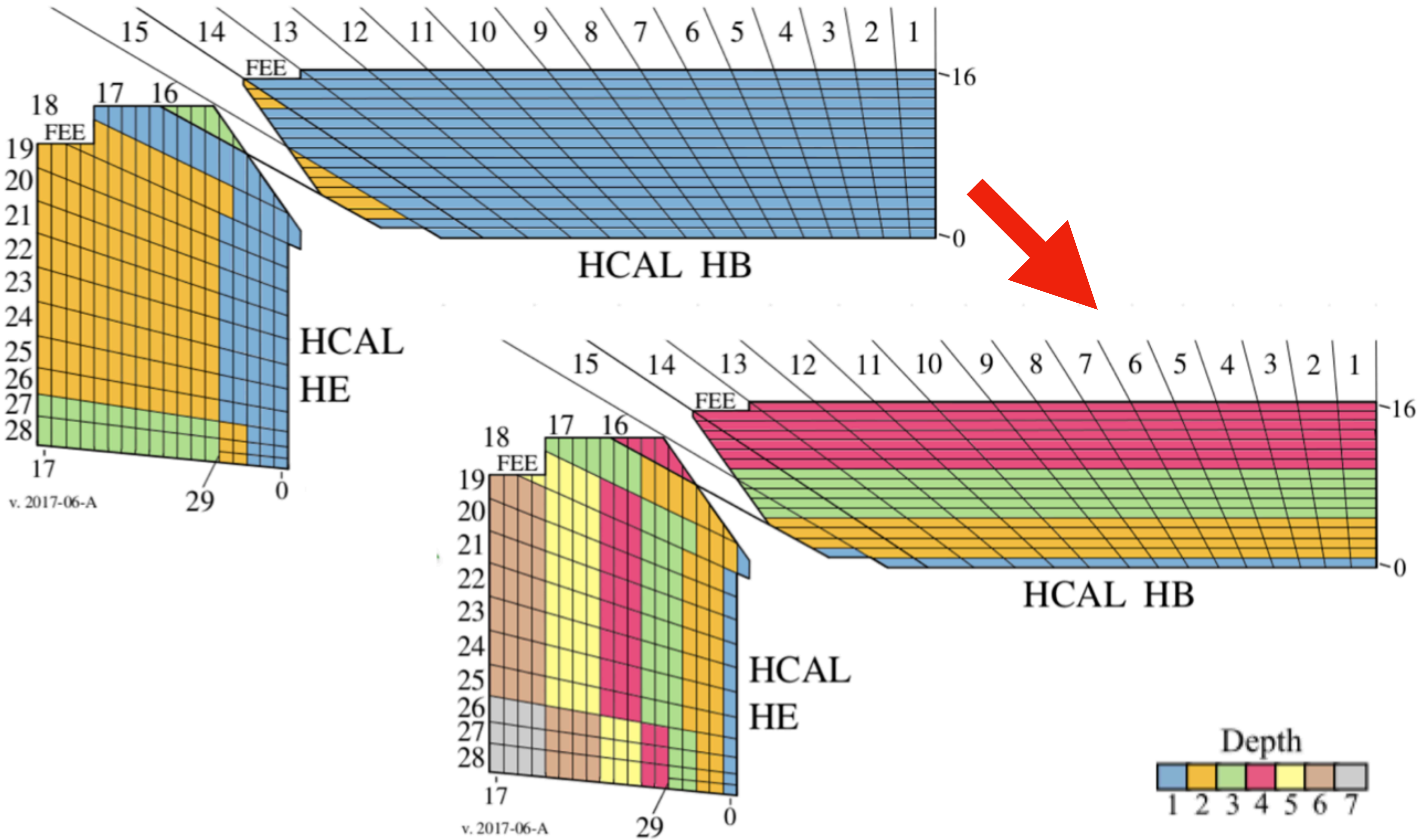
New Run3 Triggers: delayed jets

Strategy: lowered HT threshold by requiring time delay



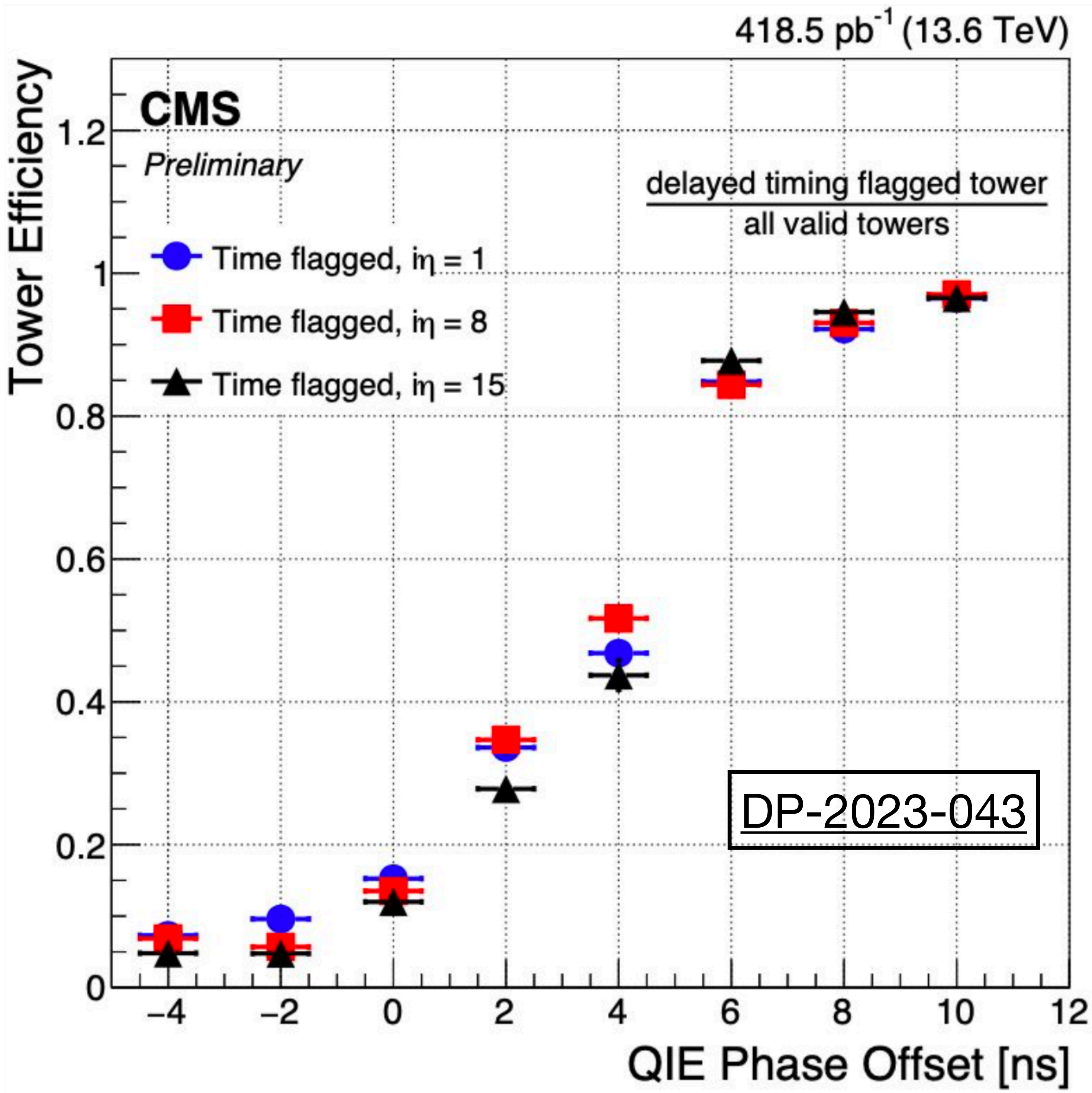
New Run3 Triggers: HCAL delayed jets

HCAL Upgrade provides segmentation and timing information



New Run3 Triggers: HCAL delayed jets

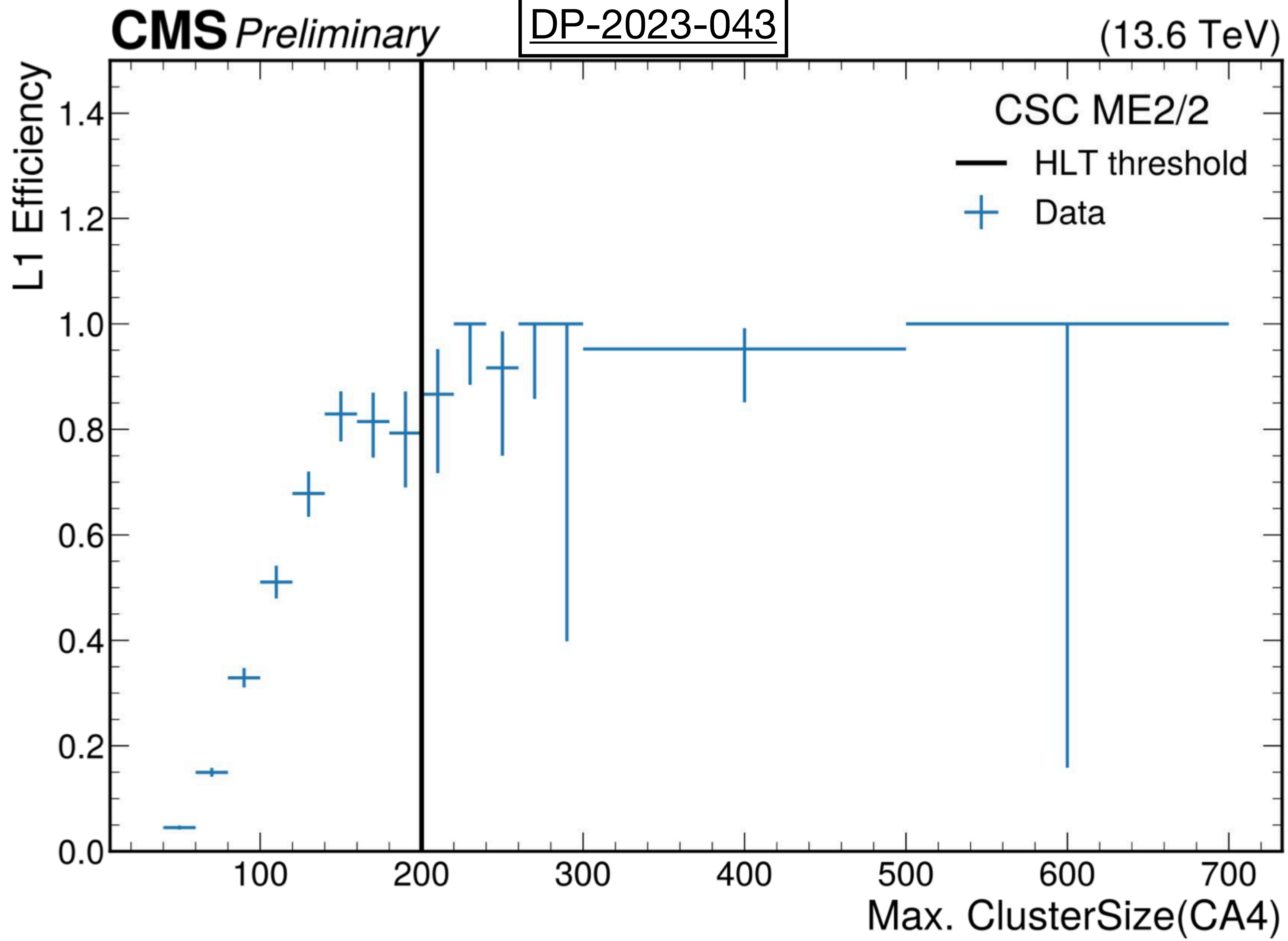
Timing and segmentation at L1 (hardware) to trigger LLPs!



New Run3 Triggers: Muon System

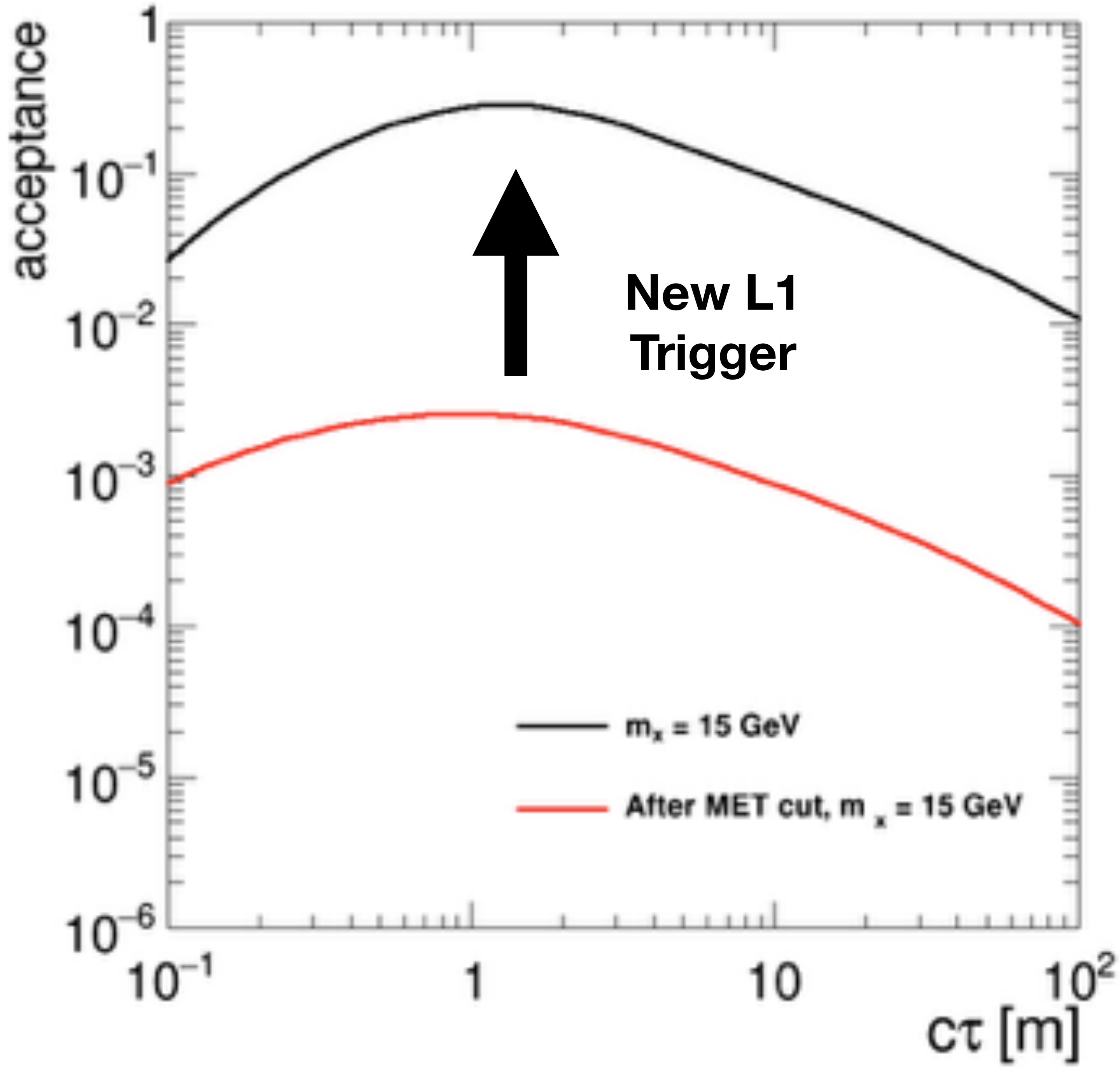
Brand new L1 (hardware) trigger using muon detector shower (MDS)

DP-2023-043



New Run3 Triggers: Muon System

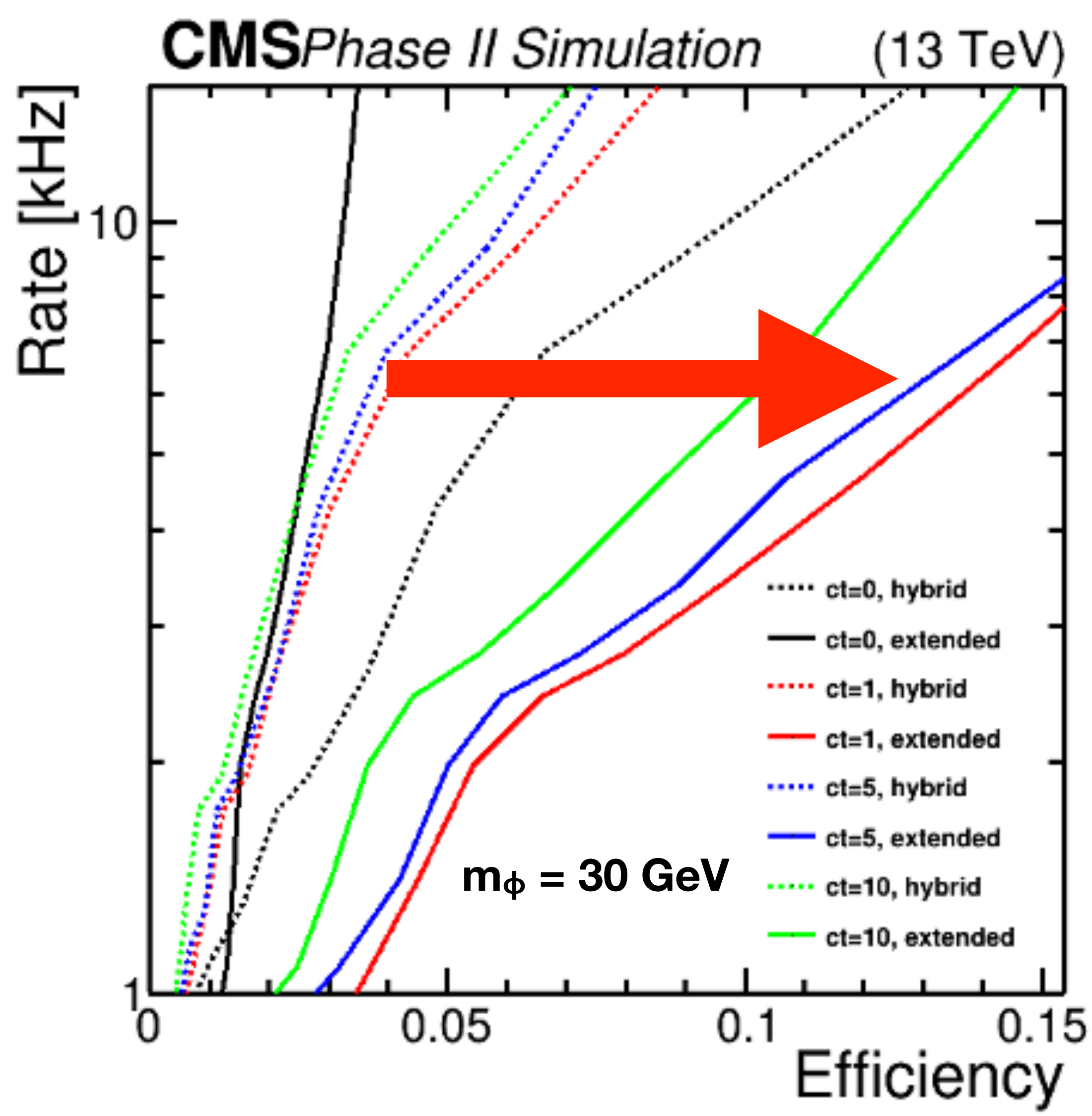
Brand new L1 (hardware) trigger using muon detector shower (MDS)

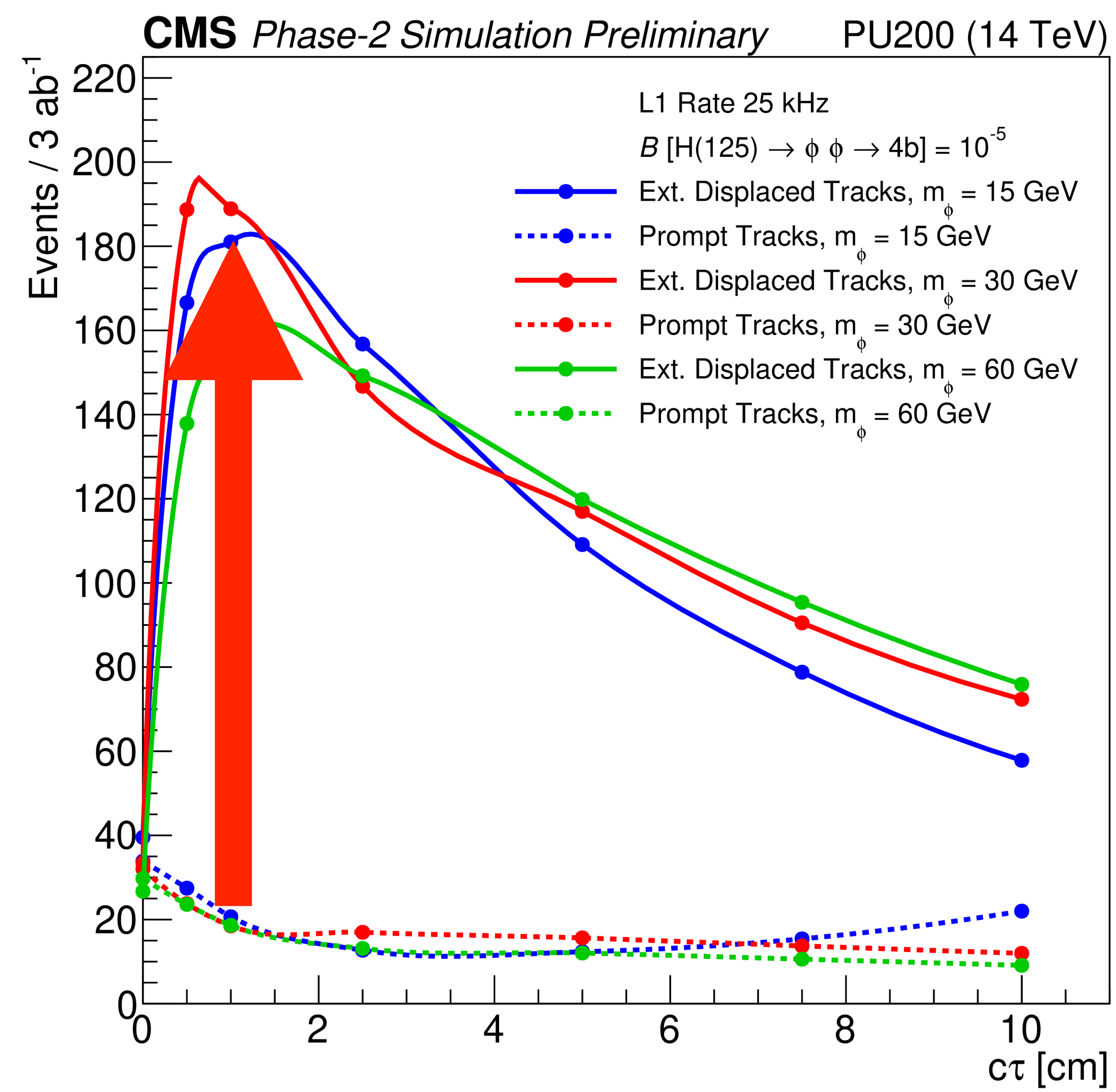


10x LLP signal acceptance gains in Run3!

HL-LHC New Enabler: CMS Track Trigger

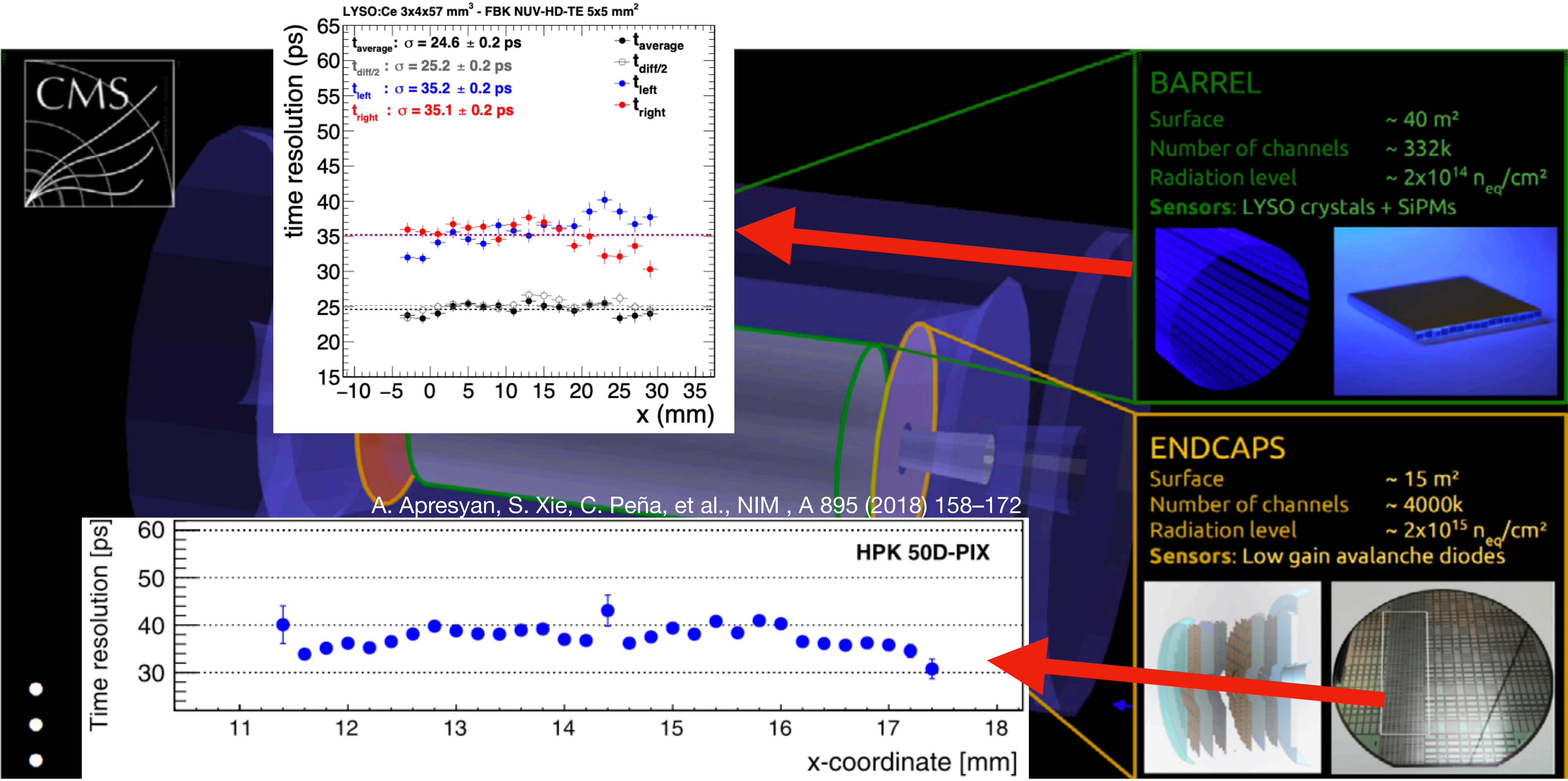
Triggering at L1 in the LLP signature itself





- **Additional L1 track finder for off-pointing tracks**
- **New displaced-tracks at L1 provides large gains (>5x) in acceptance**
  - **Allows to probe rare processes (smaller cross-sections) ~ 10^{-2} fb**

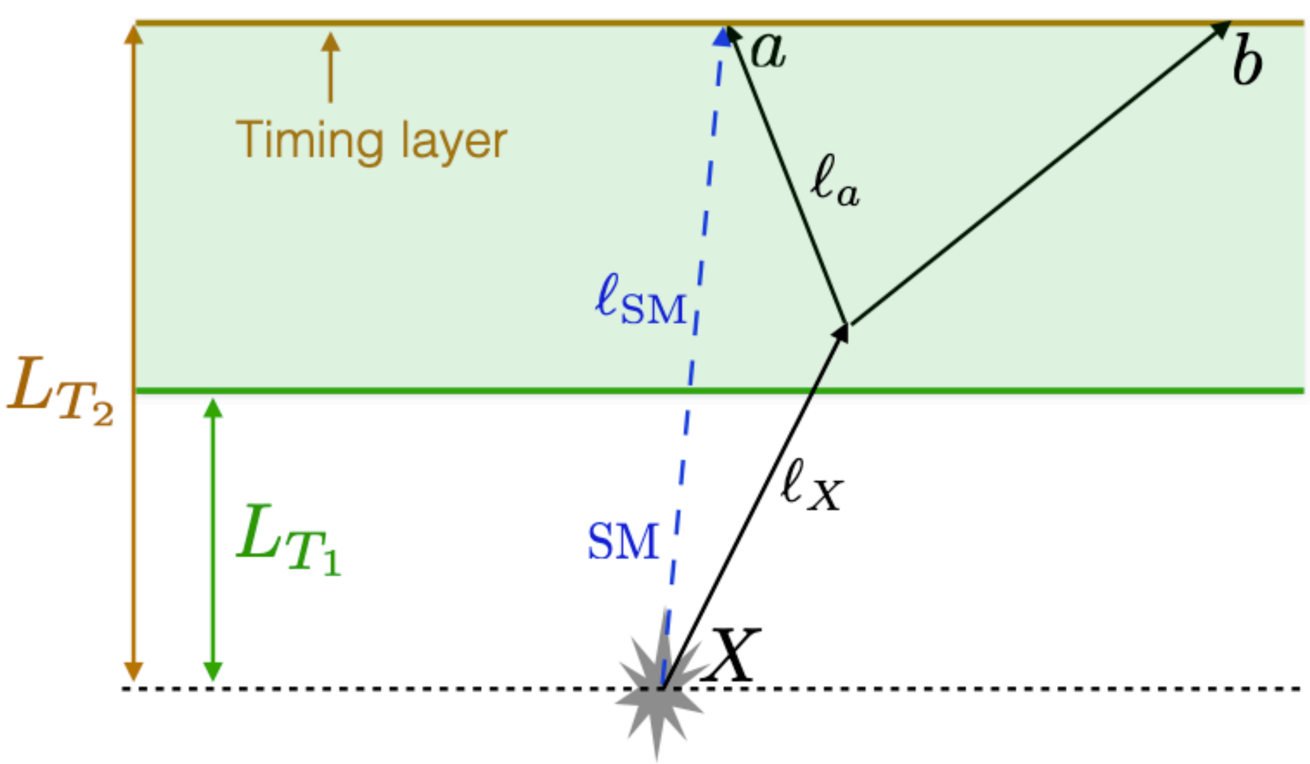
HL-LHC: The MIP Timing Detector



A Large Scale Precision Detector

HL-LHC: Catching LLPs with MTD

Phys. Rev. Lett. 122, 131801

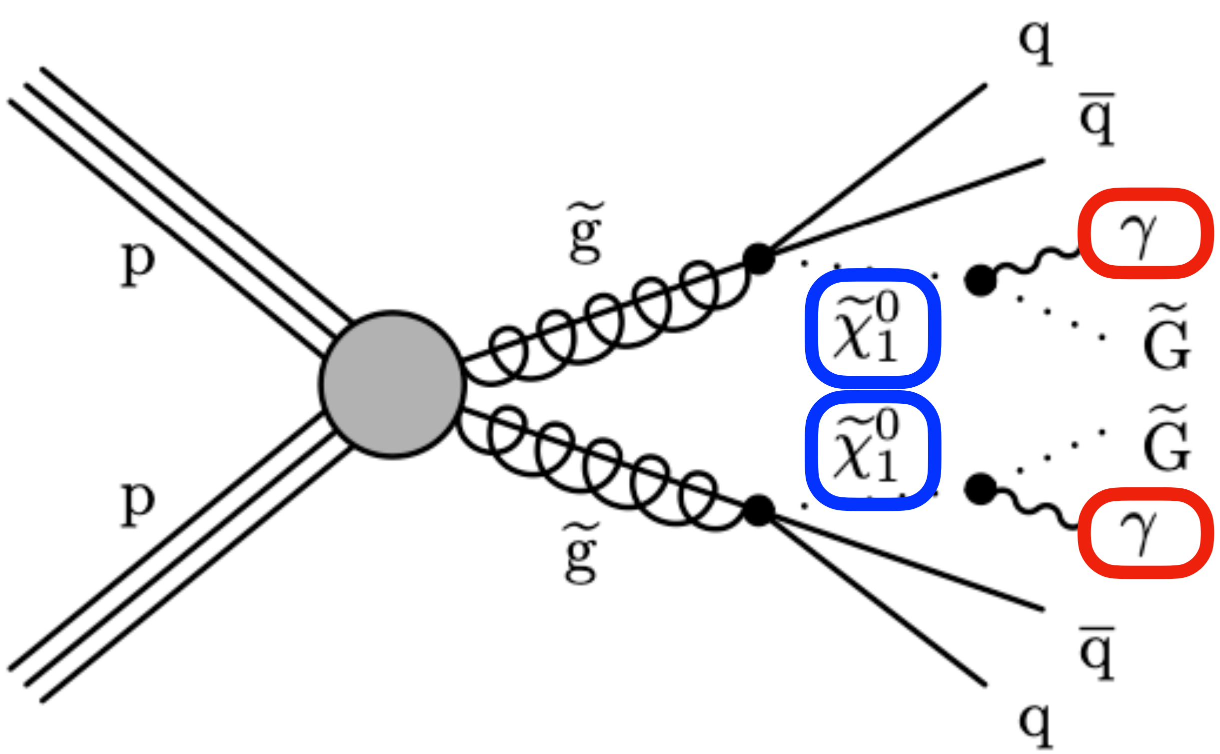


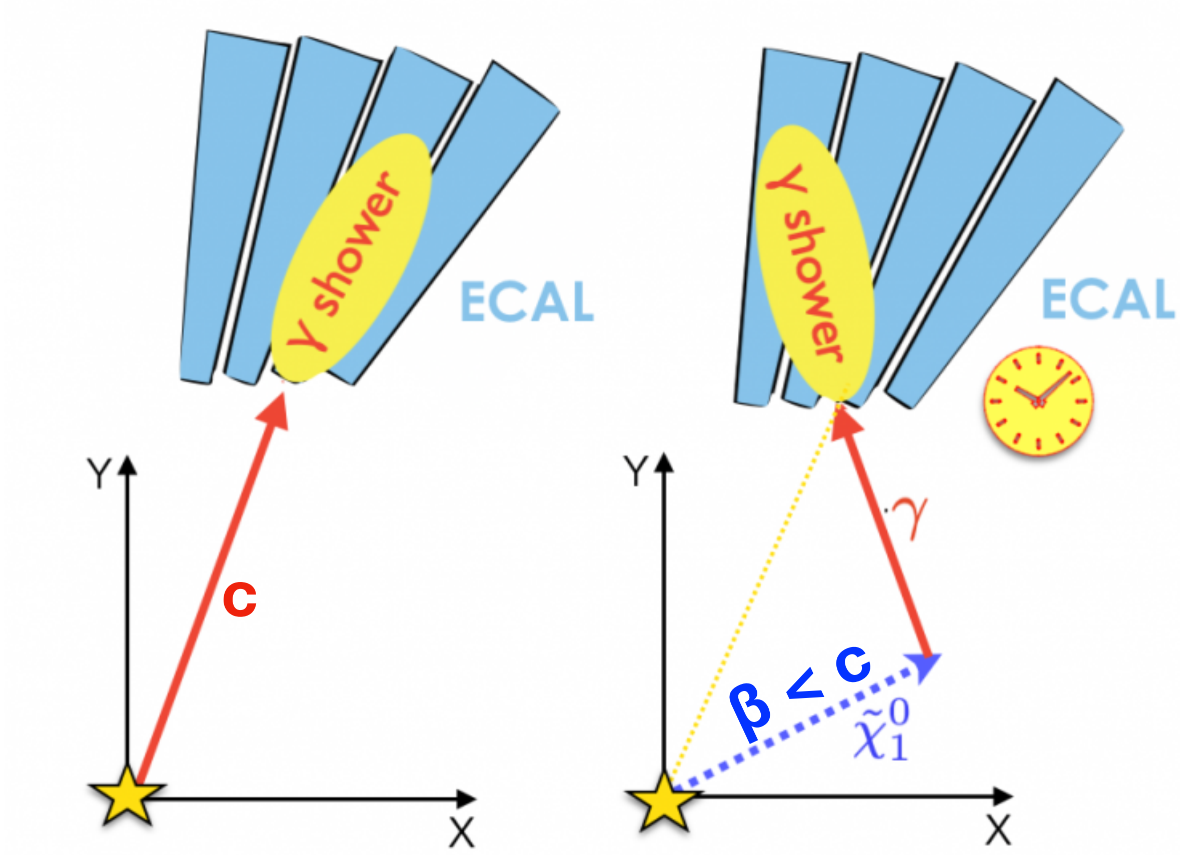
$$\Delta t_{\rm delay} = \frac{l_X}{\beta_X} + \frac{l_a}{\beta_a} - \frac{l_{\rm SM}}{\beta_{SM}}$$

- Time delay arises due to two possible effects
  - Heavy new states travel at speeds (β) only a fraction of speed of light
  - Additional time delay due to increased path length to reach wrt to SM
- MTD measures the combined effect to discriminate agains SM bkgs

In-flight SUSY

New particle (neutralino) is **massive** and **displaced** from interaction point



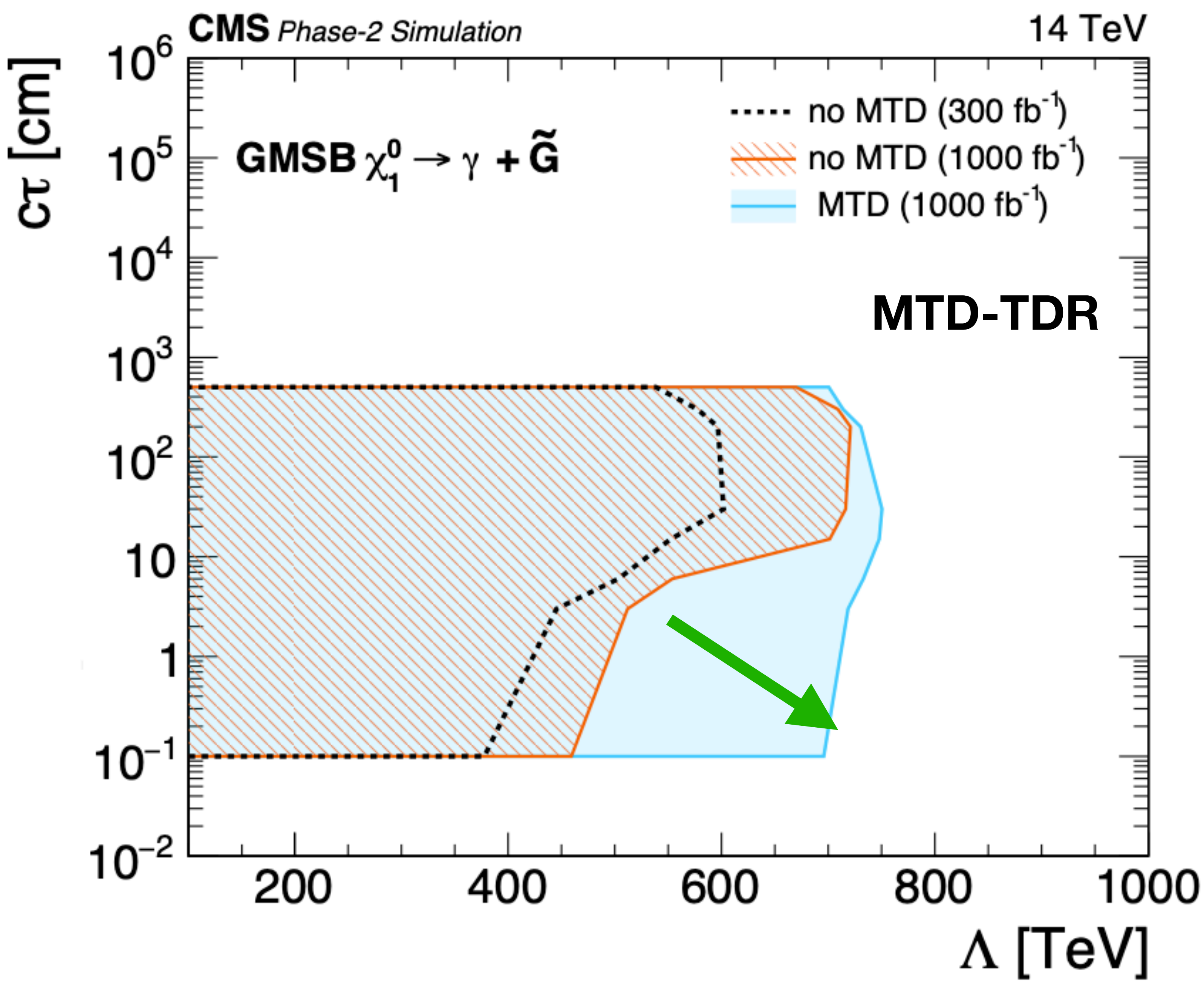


Neutralino travels slower than speed of light: time-delay

Signature: delayed photon

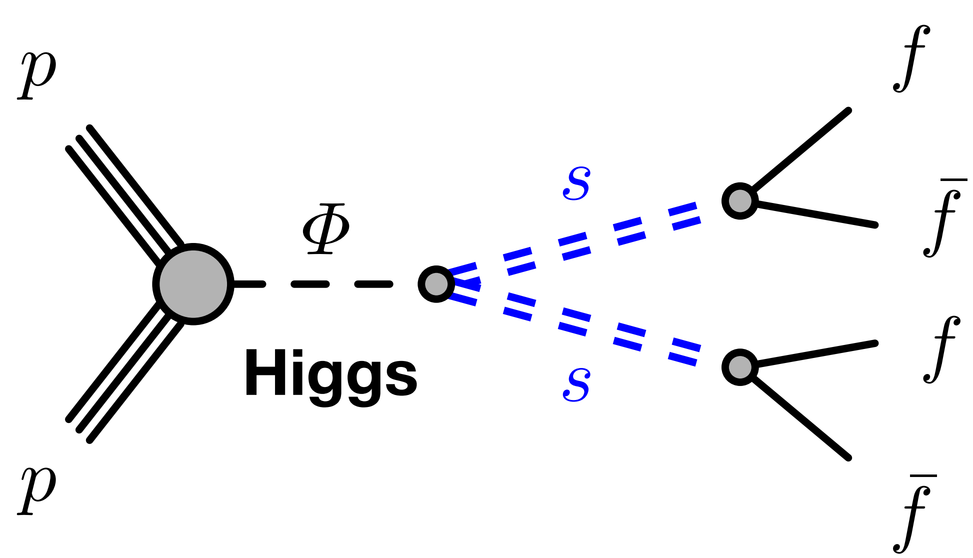
In-flight SUSY

MTD improves beam spot time-spread by 6x

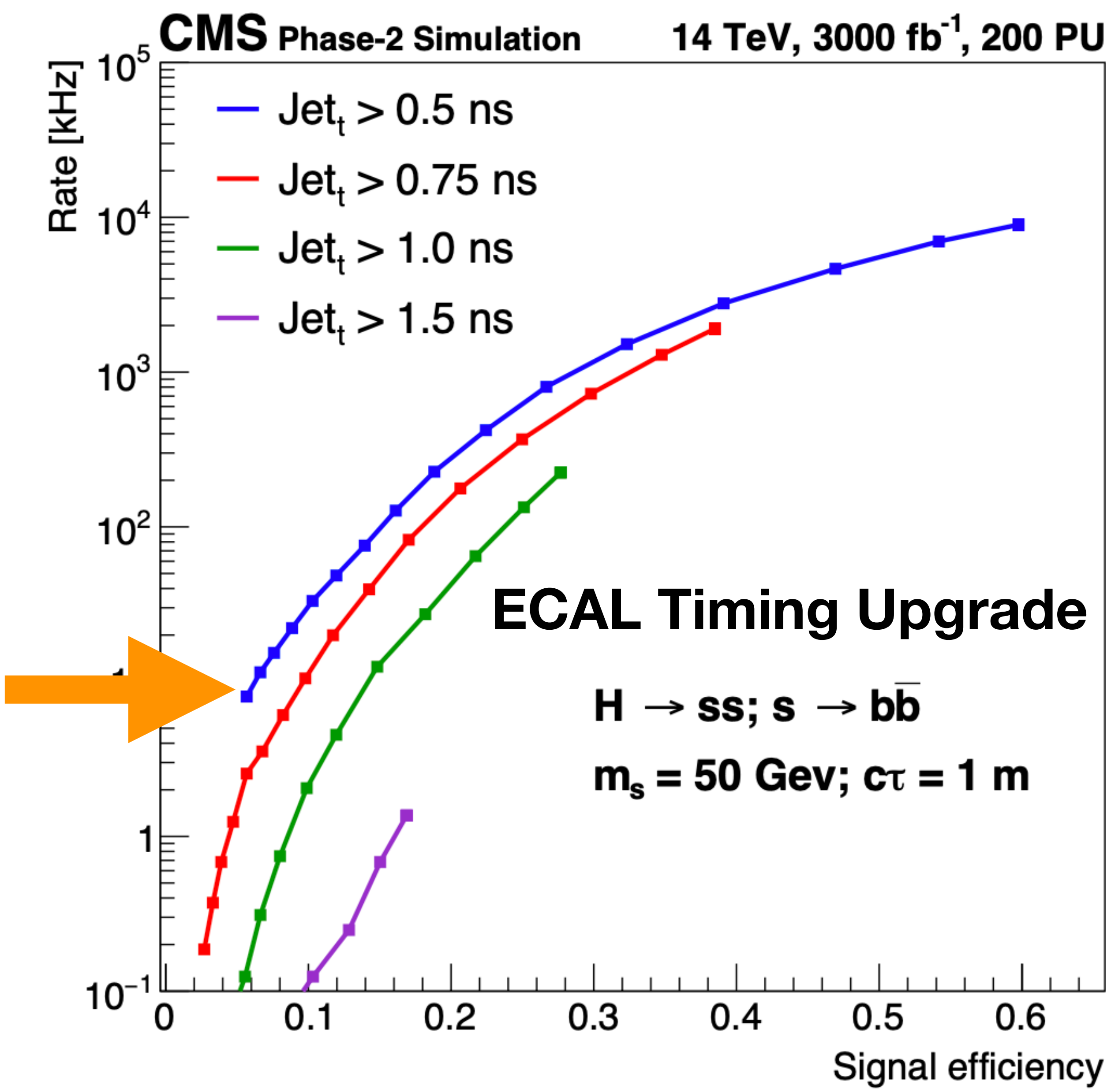


Large gains in decay length ($c\tau$) and mass

Precision Timing Enables ECAL L1 Triggers



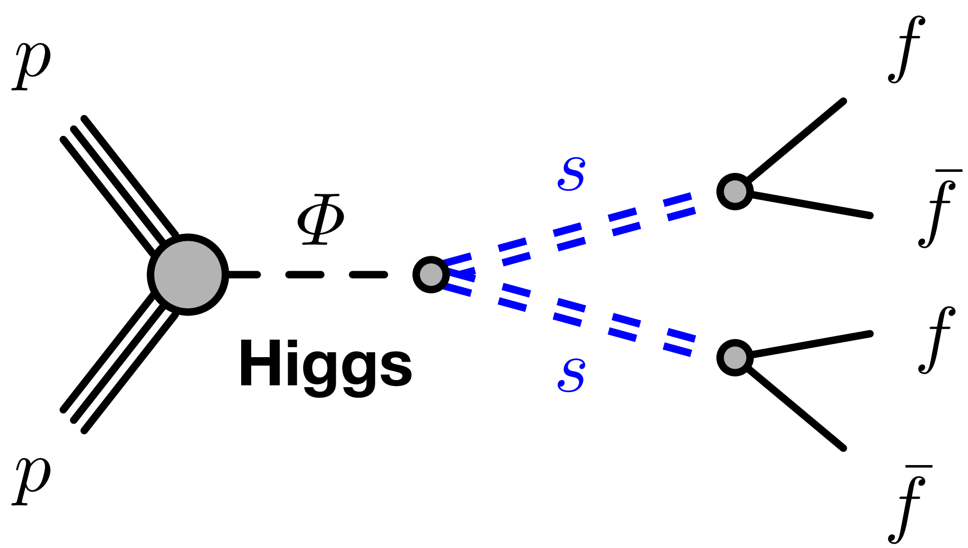
CMS L1 TDR (2020)

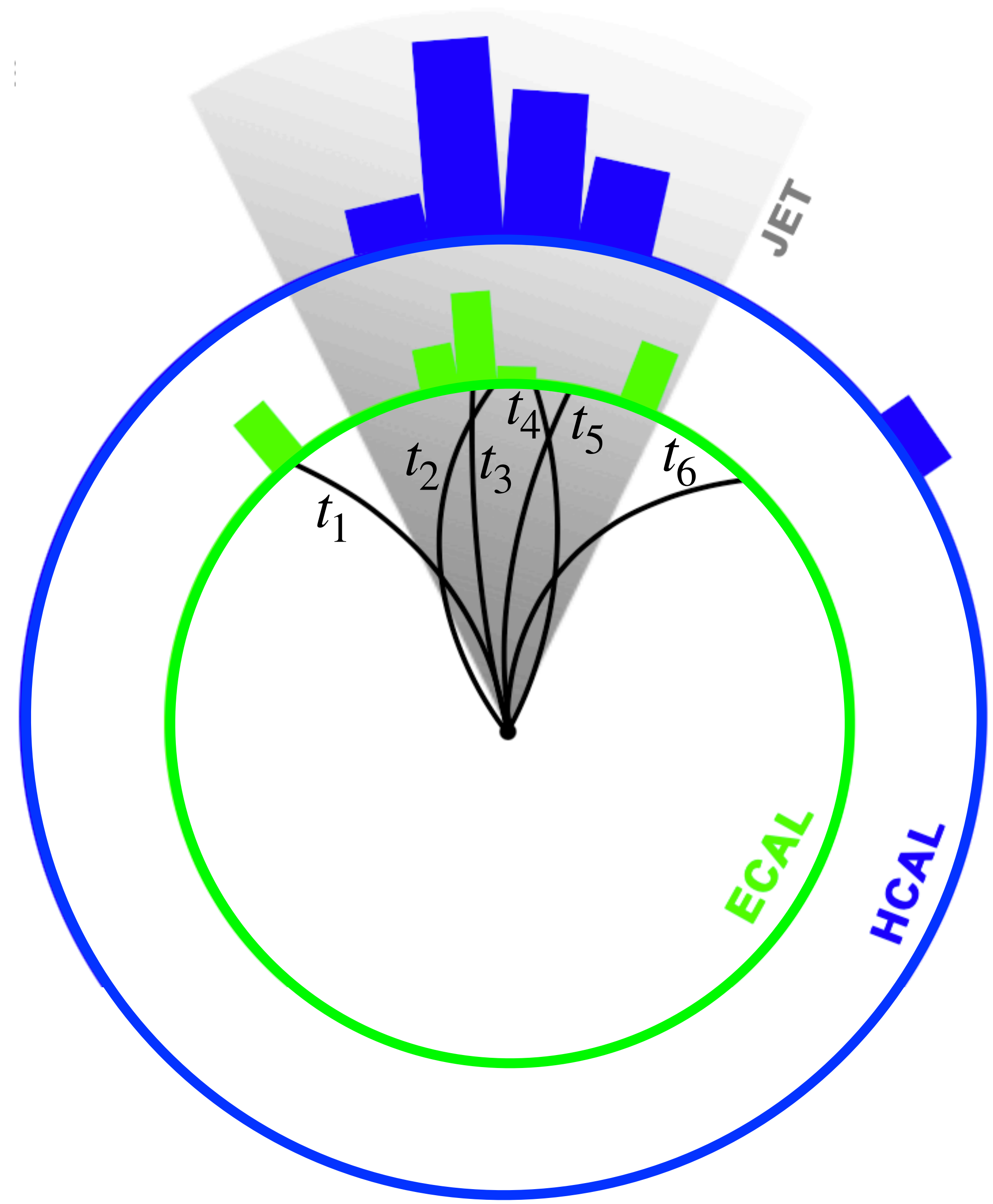


Greater than 10x increase in signal acceptance!

- 15% efficiency for @ 10 kHz L1 rate
- 10x improvement over current triggers

Precision Timing Enables L1 ECAL Triggers





MTD will significantly boost LLP reconstruction by combining multiple time measurements

- **Average jet contains 2/3 charged particles**
- **Time combination important for low-pt jets of Higgs portal models**

- MTD critical to achieve realistic HLT rate
- Possible ECAL seeding to MTD @ L1: improve signal efficiency, beam spot resolution, robustness

Outlook

- CMS is advancing LLP frontier **now**, **Run3** and **HL-LHC** at CMS
- **Instrumentation** (detector/sensor), **trigger**, and **edge processing** (front-end) paradigms are crucial elements for the implementation and improved new physics program with LLPs
- **Vertically integrated effort**: theory, triggers, analysis, data management, algorithms, and impactful publications
- LLP physics is incredible rich and requires **cutting edge detector R&D** (precision timing & others)
- LLPs at CMS provide an **exciting research program** ahead of us that could presents us **with fundamental discoveries**

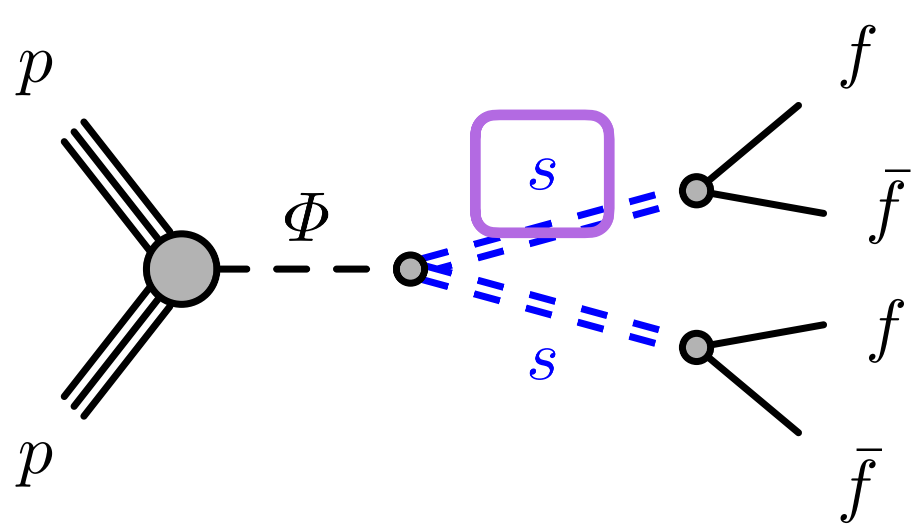
Thank you!

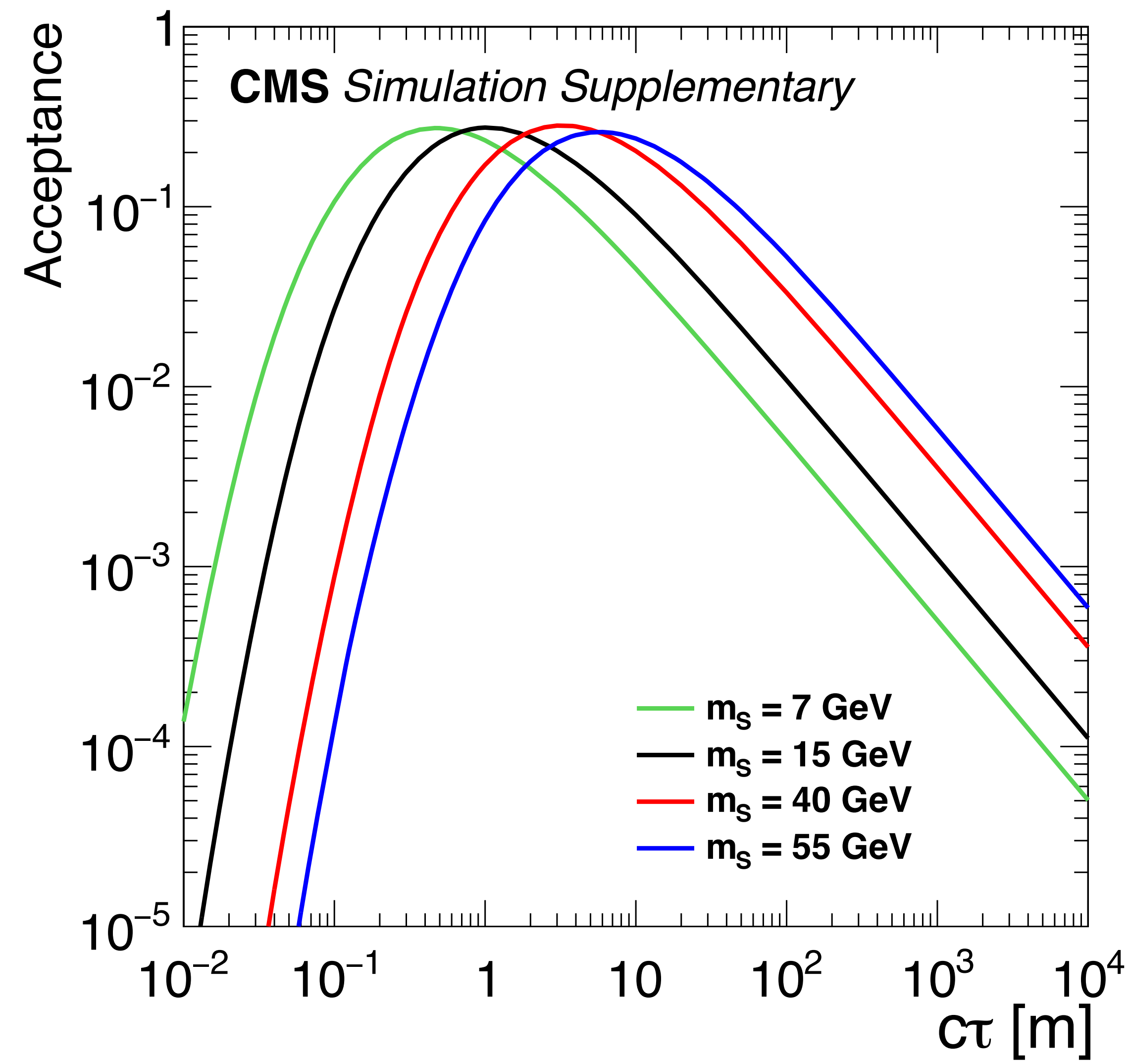
- Backups

LLP Acceptance in Muon System

Acceptance in muon system peaks at a few meters

At least one LLP in CSCs





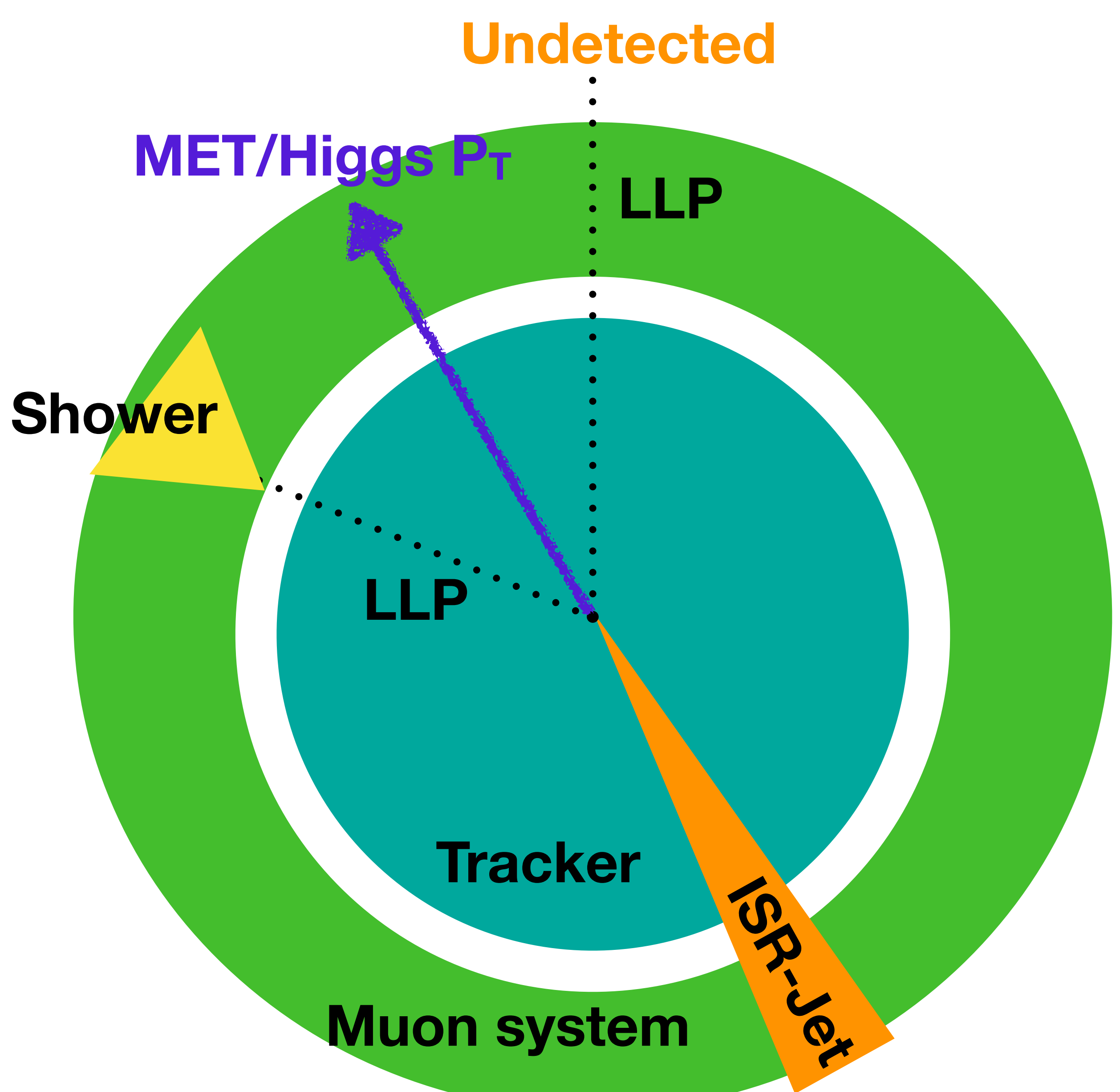
- LLP mass shifts peak acceptance location

CMS Data Analysis Re-imagined

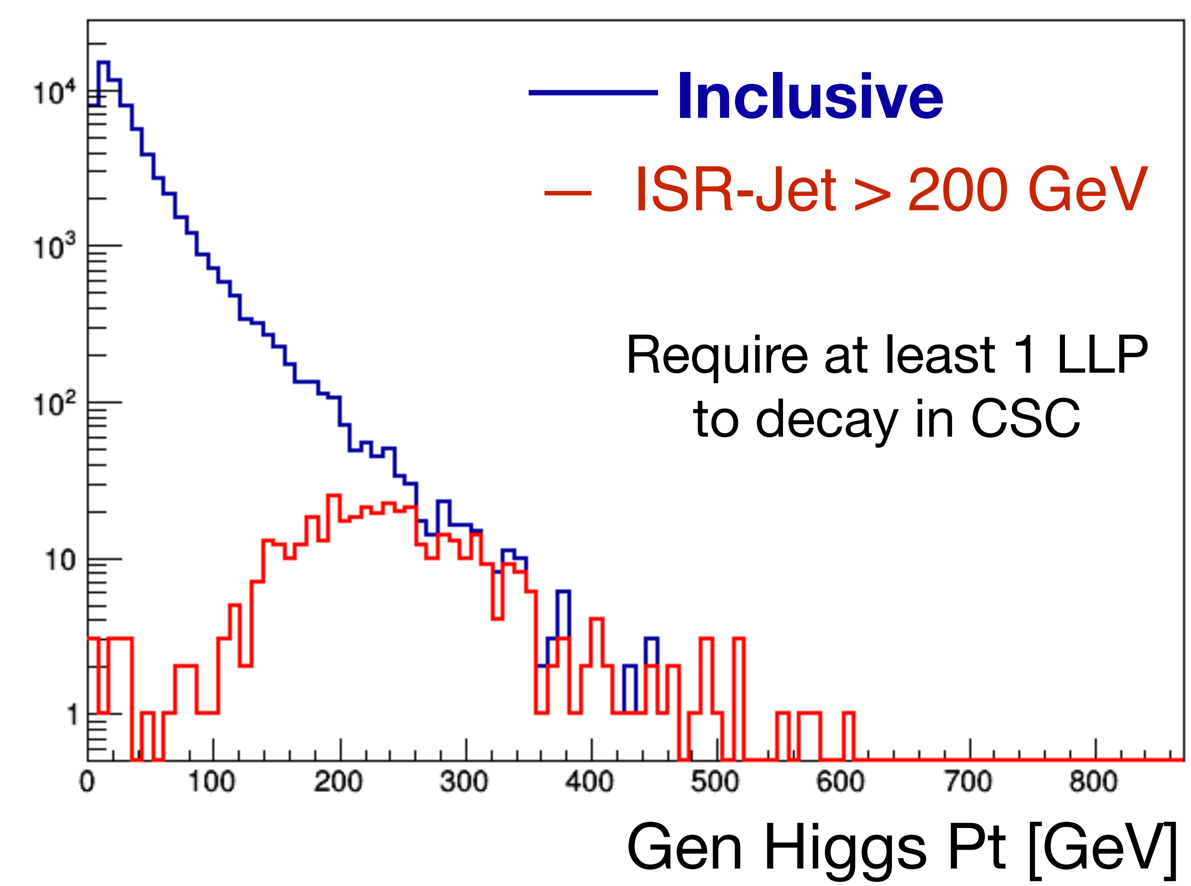
Current CMS data analysis chain
is
broken when LLPs are present

LLP Muon System Analysis

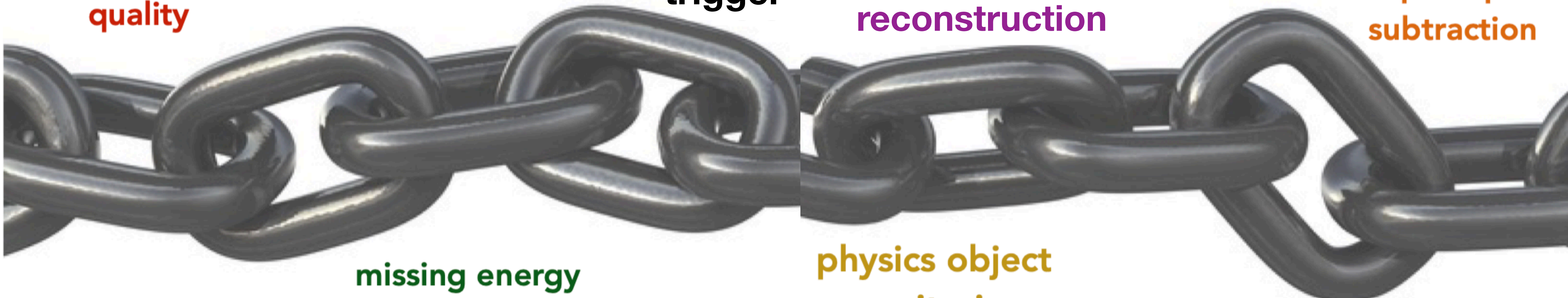
- Start with ggH production mode — largest cross section
- Trigger on **MET (lack of dedicated trigger)** — recoil of Higgs against ISR
  - For large cτ one of the LLPs will decay outside the calorimeter



- ~1% signal events kept after MET cut
- **~4500 events in acceptance**



CMS Data Analysis Re-imagined



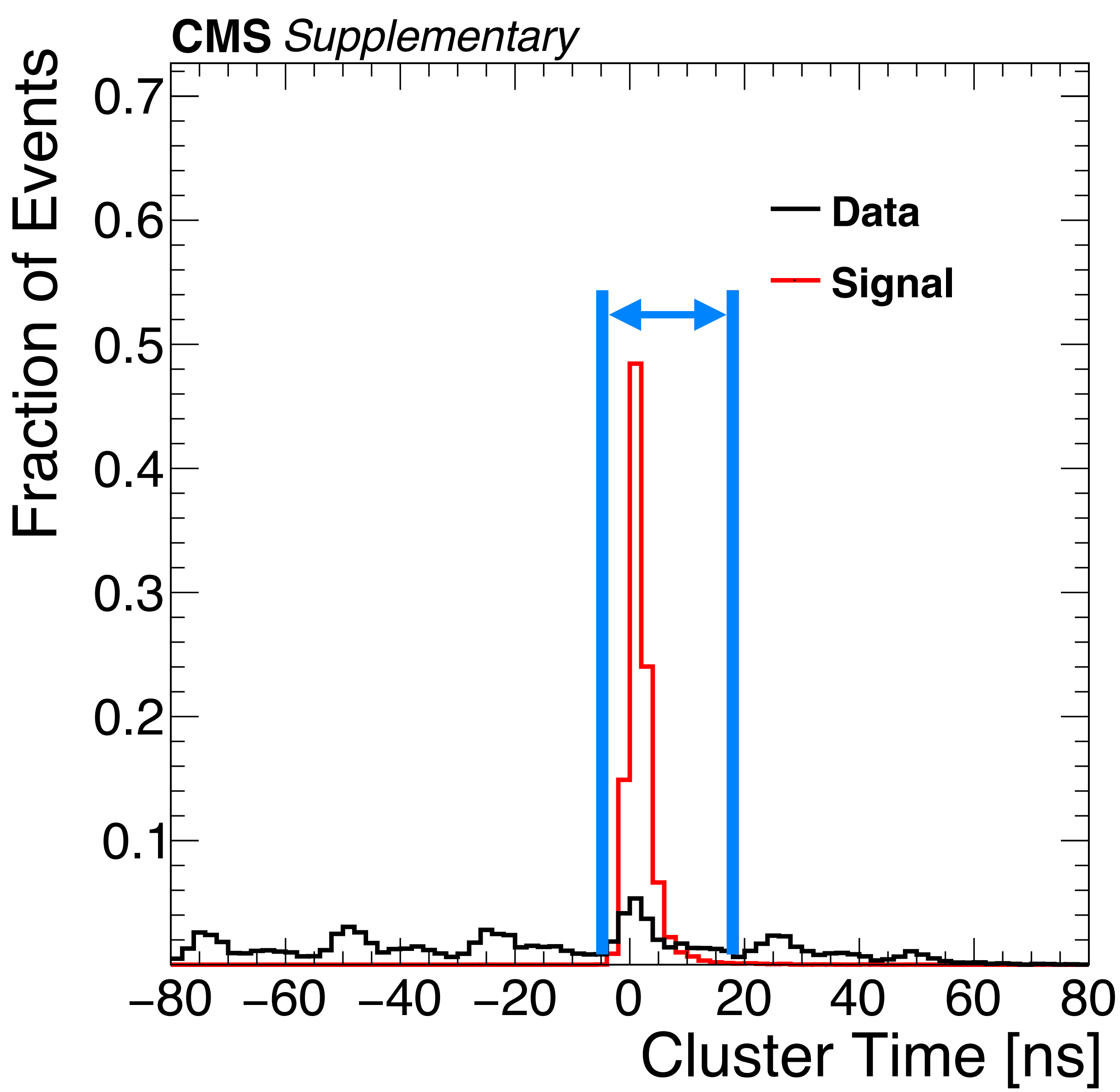
Data analysis chain fixed

- New trigger for LLP in MS; **new dedicated LLP triggers (@2022/Run3)**
- **Re-designed muon system reconstruction** to allow LLP-shower signature
- **Designed new data formats** to overcome limited content for LLP searches

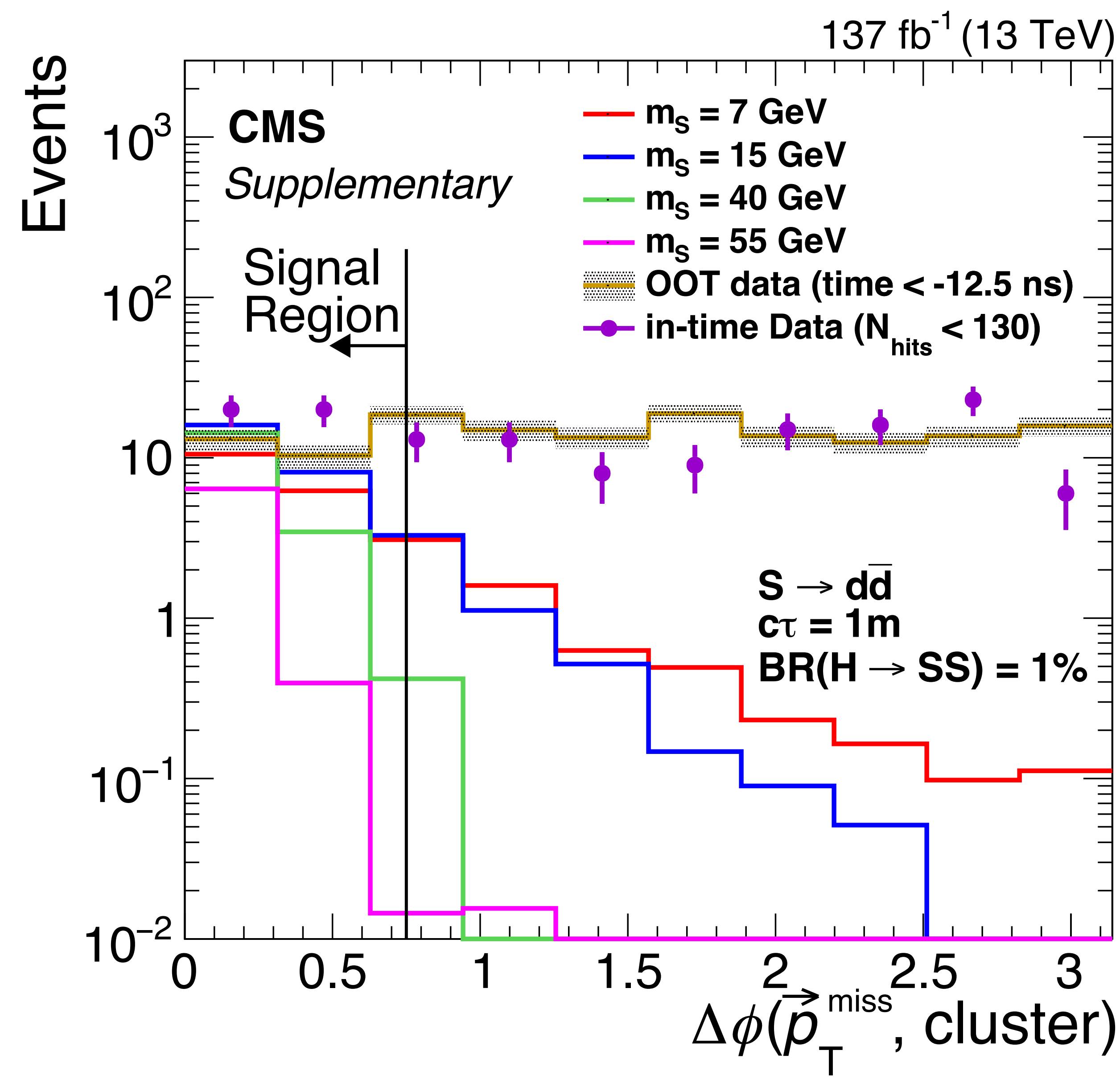
LLP with MS: other key selection

Many bkg cluster from OOT interactions

Signal cluster are in-time

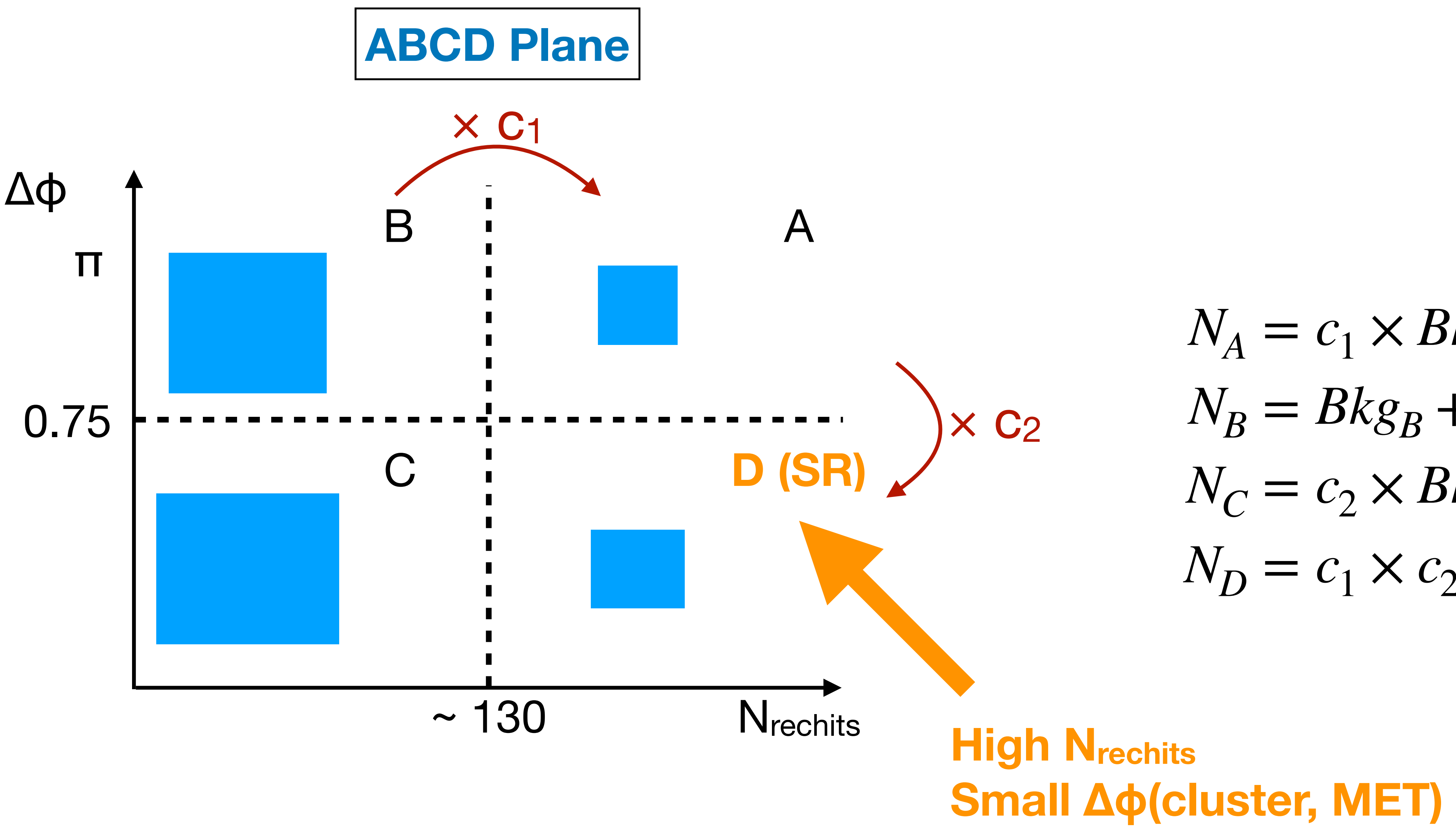


Signal: angle between pTmiss and cluster position is aligned



Combined 20x bkg rejection power

Background Estimation

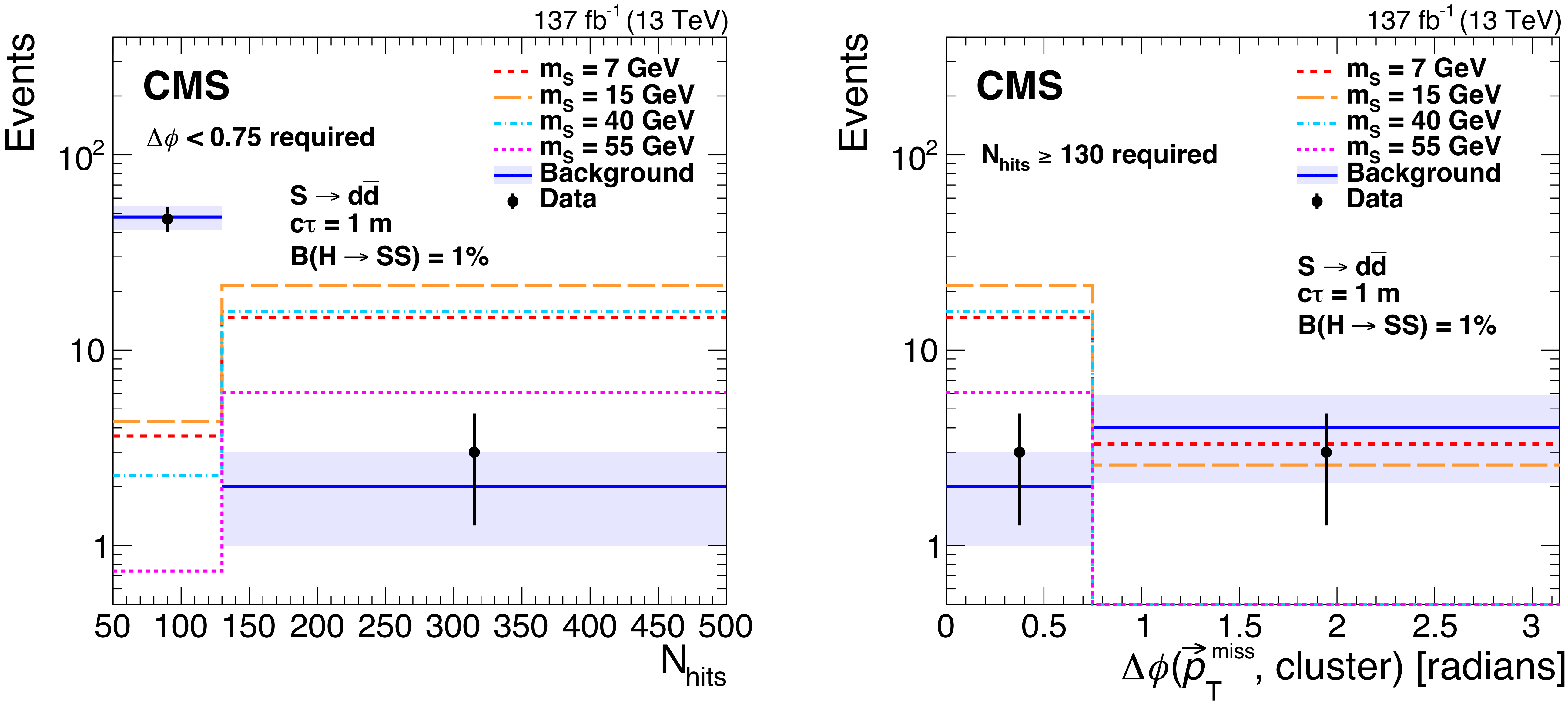


$$N_A = c_1 \times Bkg_B + \mu \times SigA$$
$$N_B = Bkg_B + \mu \times SigB$$
$$N_C = c_2 \times Bkg_B + \mu \times SigC$$
$$N_D = c_1 \times c_2 \times Bkg_B + \mu \times SigD$$

- **Δϕ(cluster, MET)** and **$N_{rechits}$** are independent
- Validate the method in two separate validation regions

LLP with Muon Systems

Unblinded Results

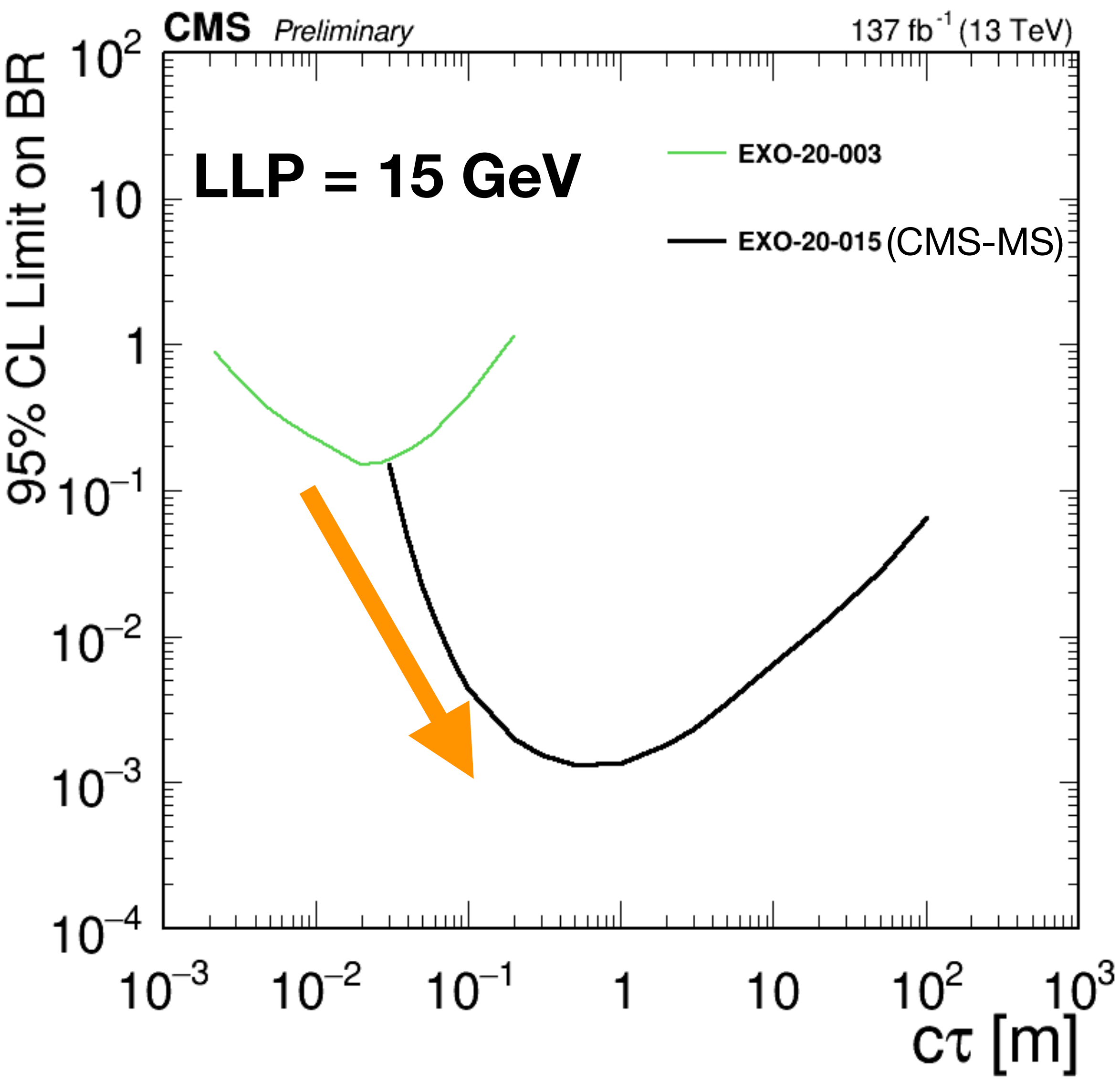


SR Expected Bkg (post-fit):
2.4 ± 0.9 (stat) ±1.5(syst)

SR Observed: 3

LLP with Muon Systems

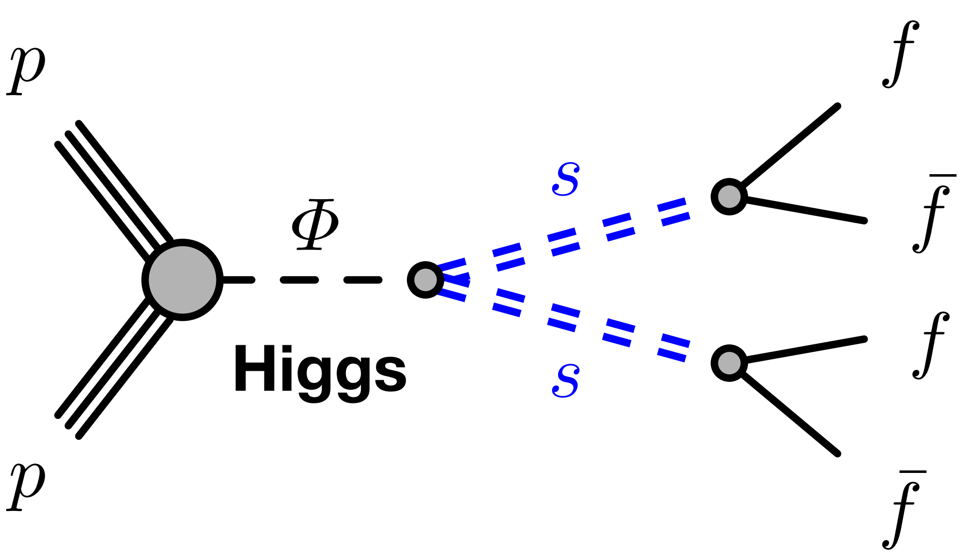
Best sensitivity at BR(H→SS) ~ 10^{-3} !!

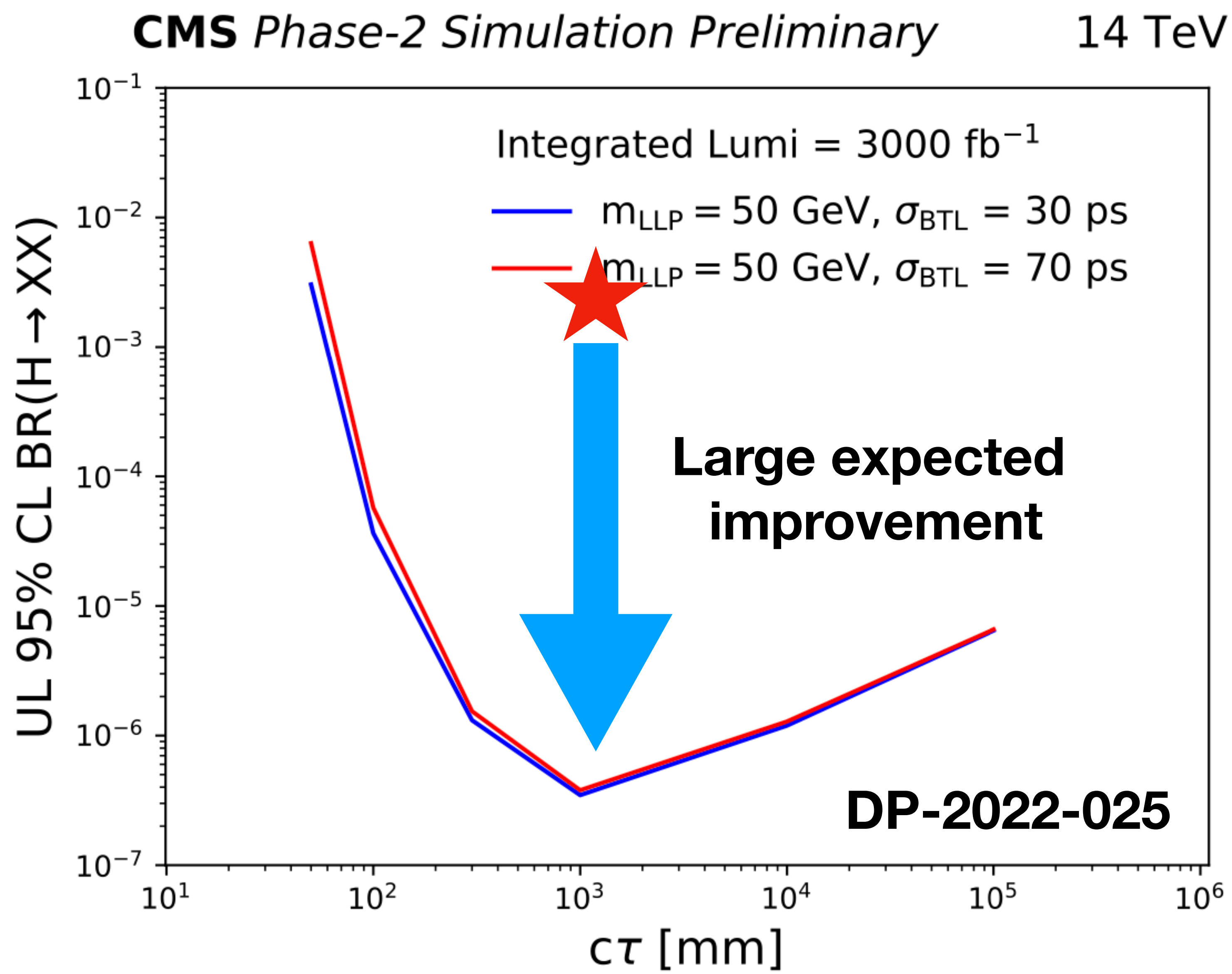


- **ENABLED CMS LLP sensitivity to larger cτ**
- **Access to light LLPs (< 15 GeV)**
  - **Sensitivity to all masses**
  - **Calorimeter: sensitive to LLP energy**

New cτ Reach and 100x better sensitivity

Higgs Portal to LLP

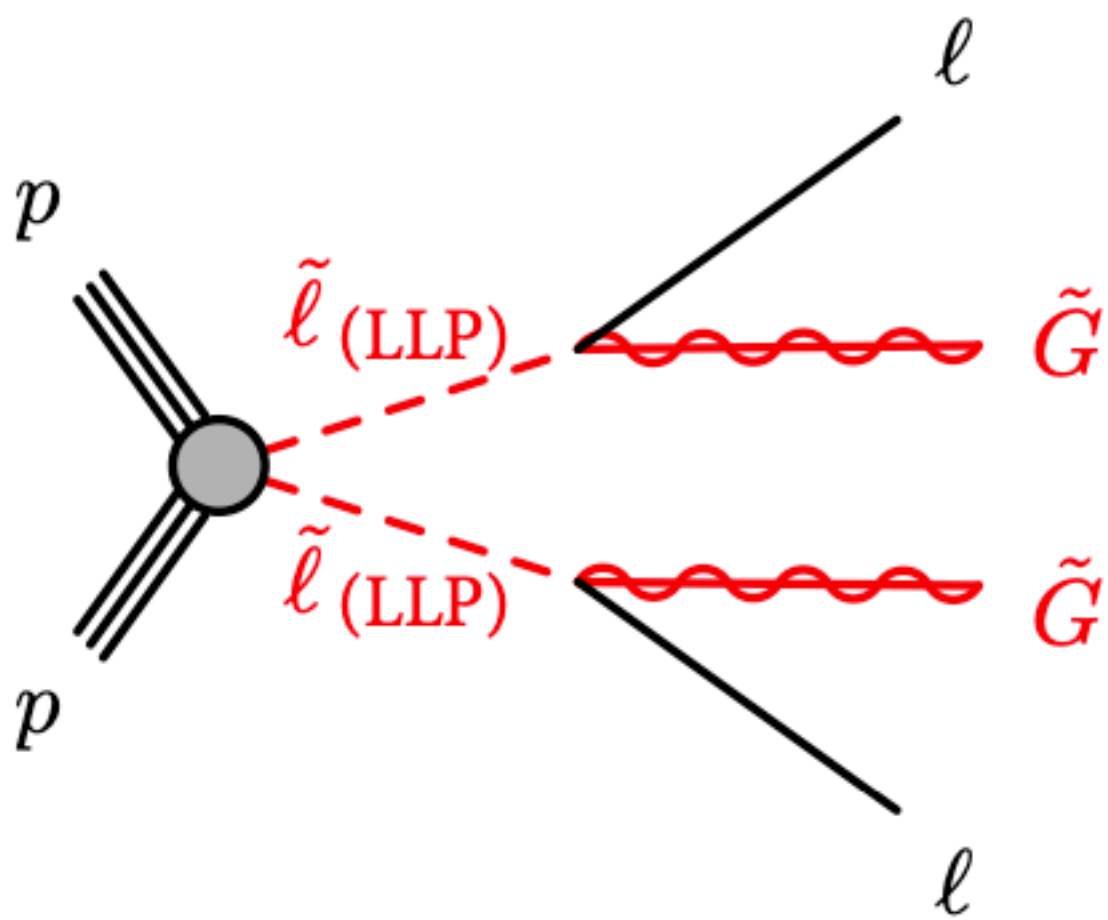


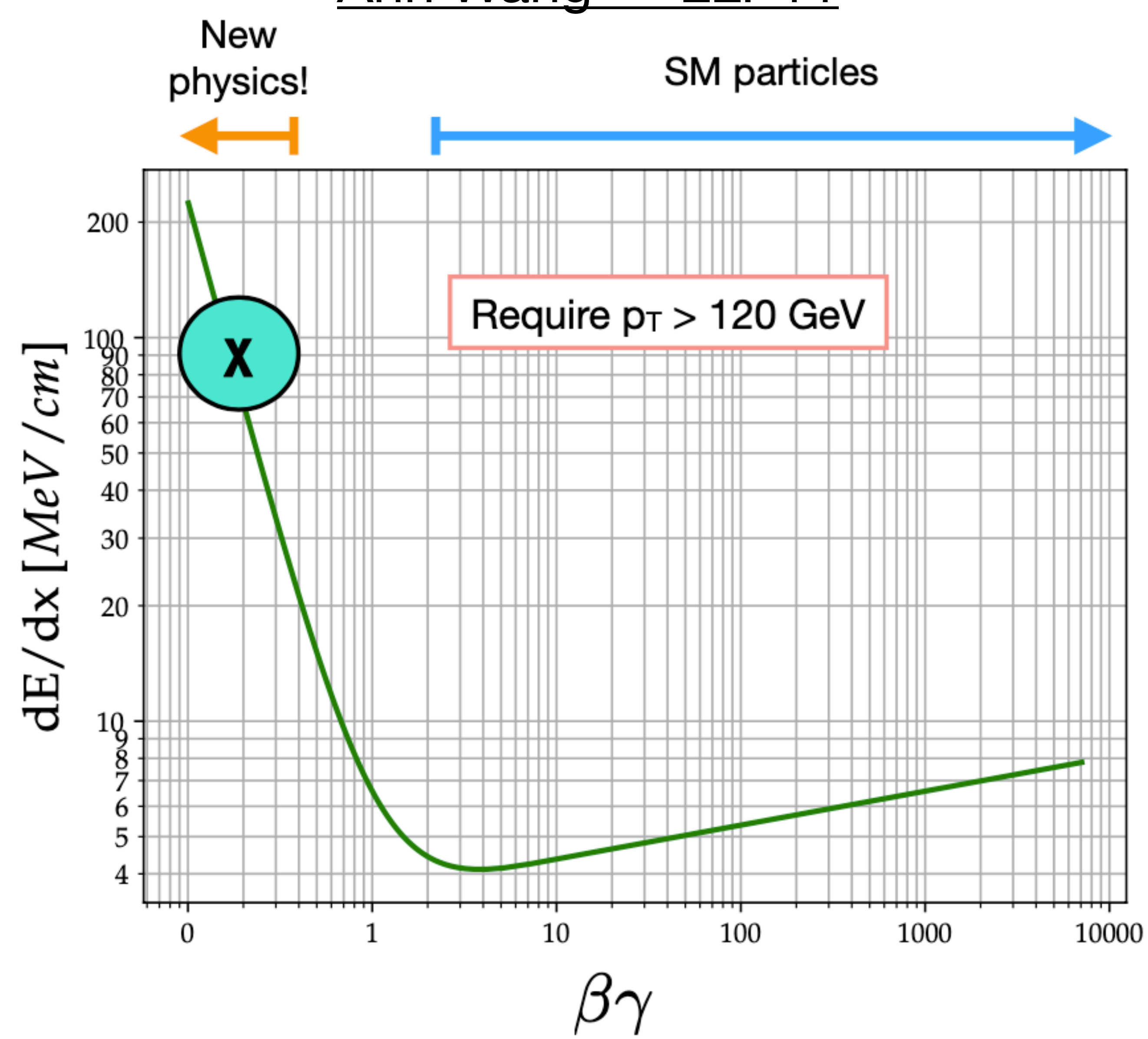


- MTD expected to probe BR(H→ss) below 1e-6!
- Caveat: trigger strategy used for the study needs to be optimized

Heavy Stable Charged Particles

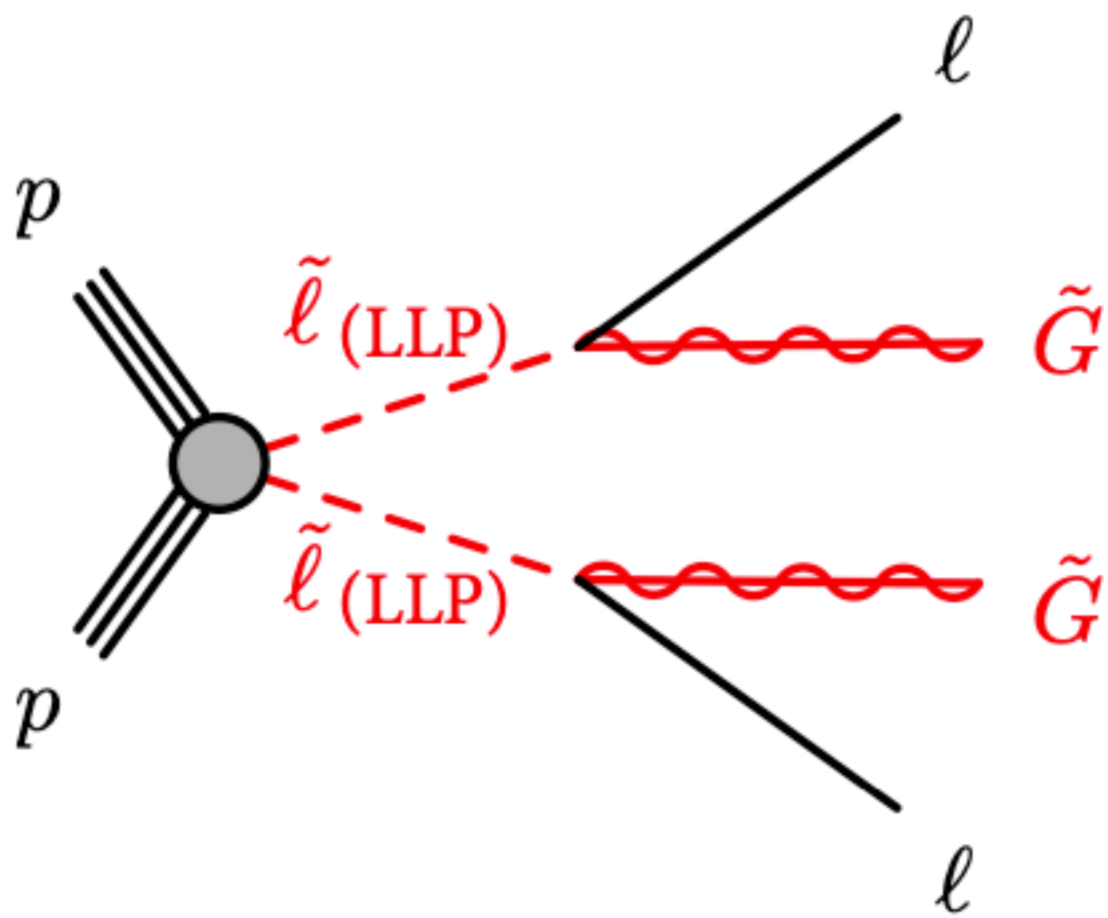
Ann Wang — LLP11

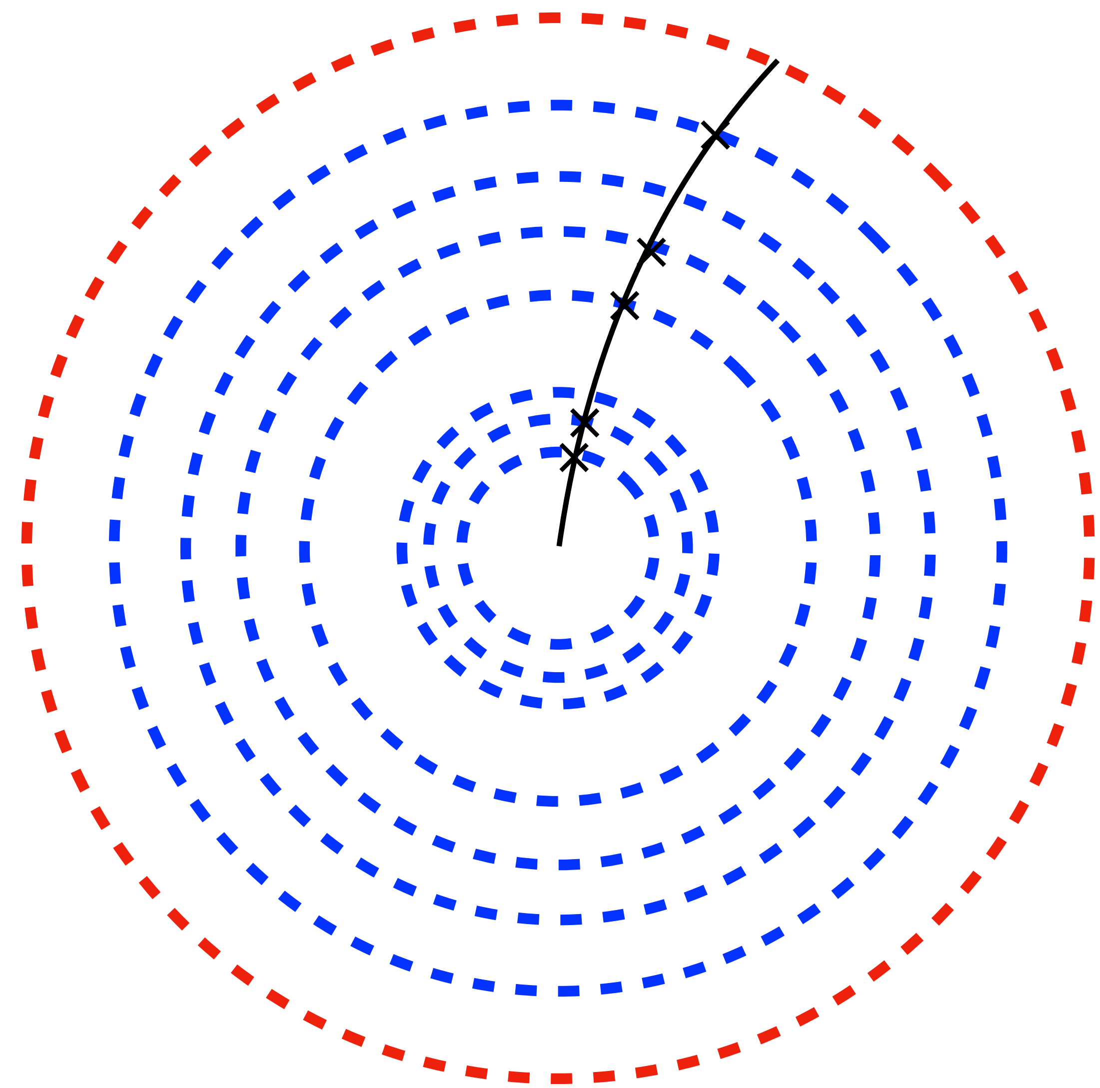




- Ionization loss (dE/dx) depends on particles velocity (βγ)
- Heavy new particles travel slowly — small βγ
- Large dE/dx expected according to Bethe-Bloch

Heavy Stable Charged Particles



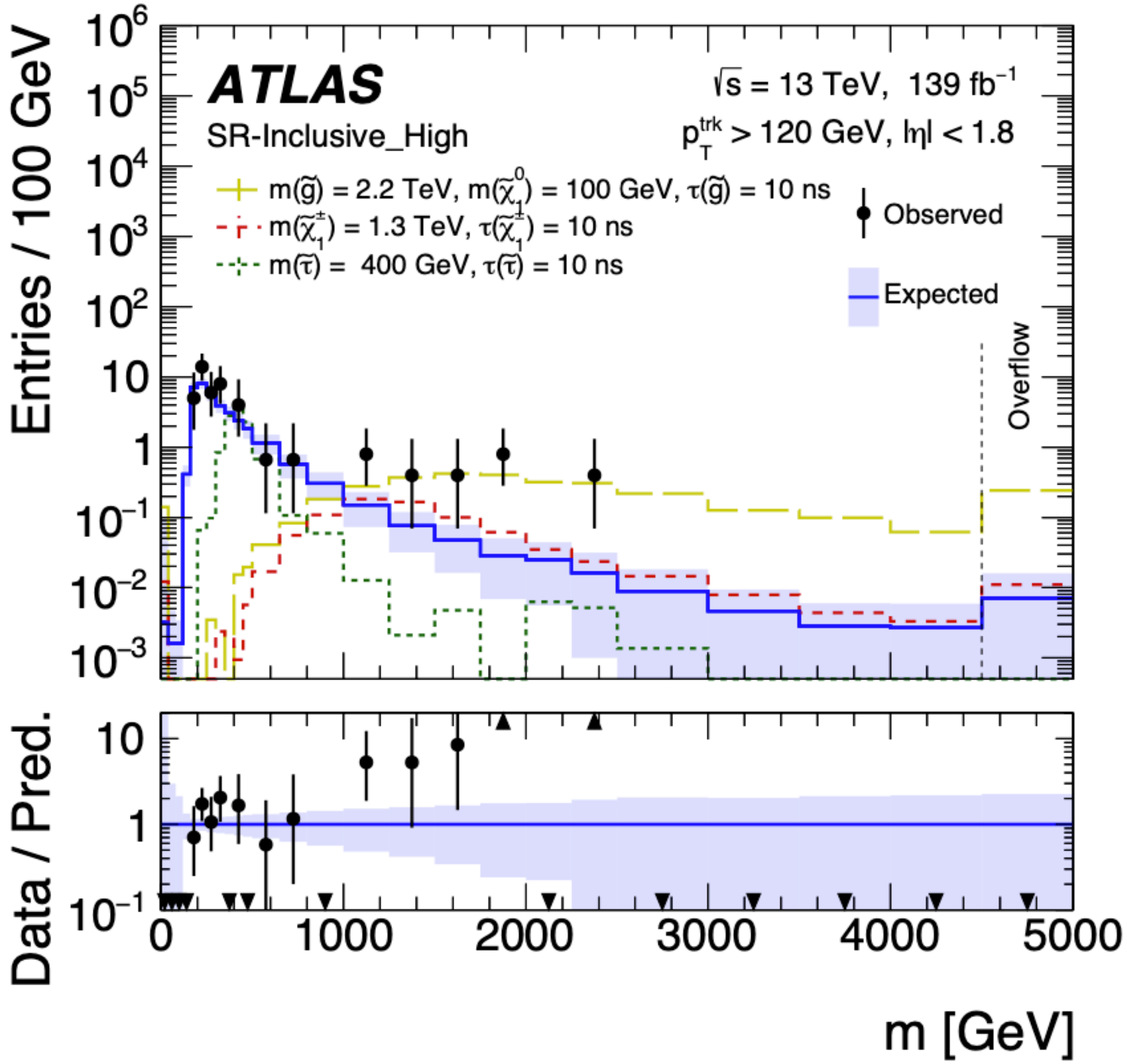


- Precision tracking allows precise momentum (|p|) reconstruction
- Access to dE/dx measurement in silicon → β measurement
- **Mass reconstruction: |p| + β measurements from silicon tracker**

$$|p| = \gamma m \beta$$

Heavy Stable Charged Particles

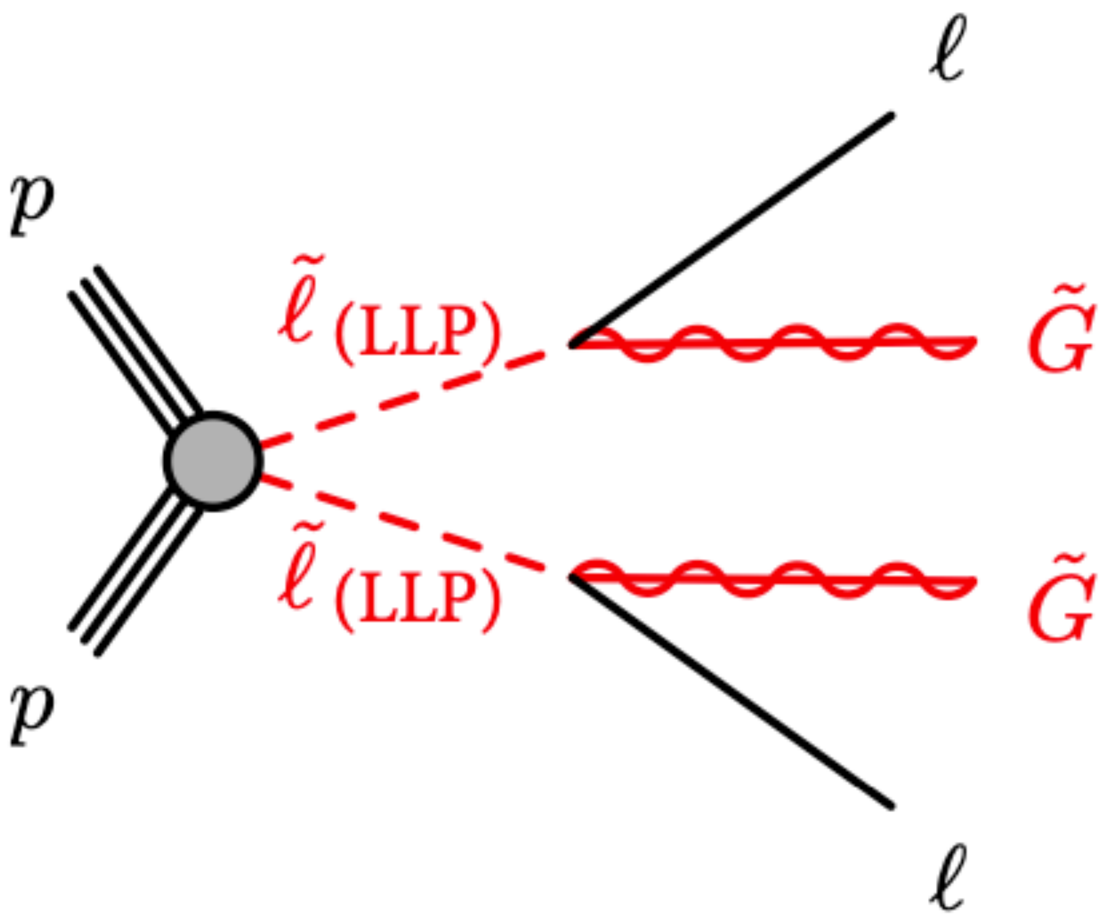
arXiv:2205.06013
Ann Wang — LLP11

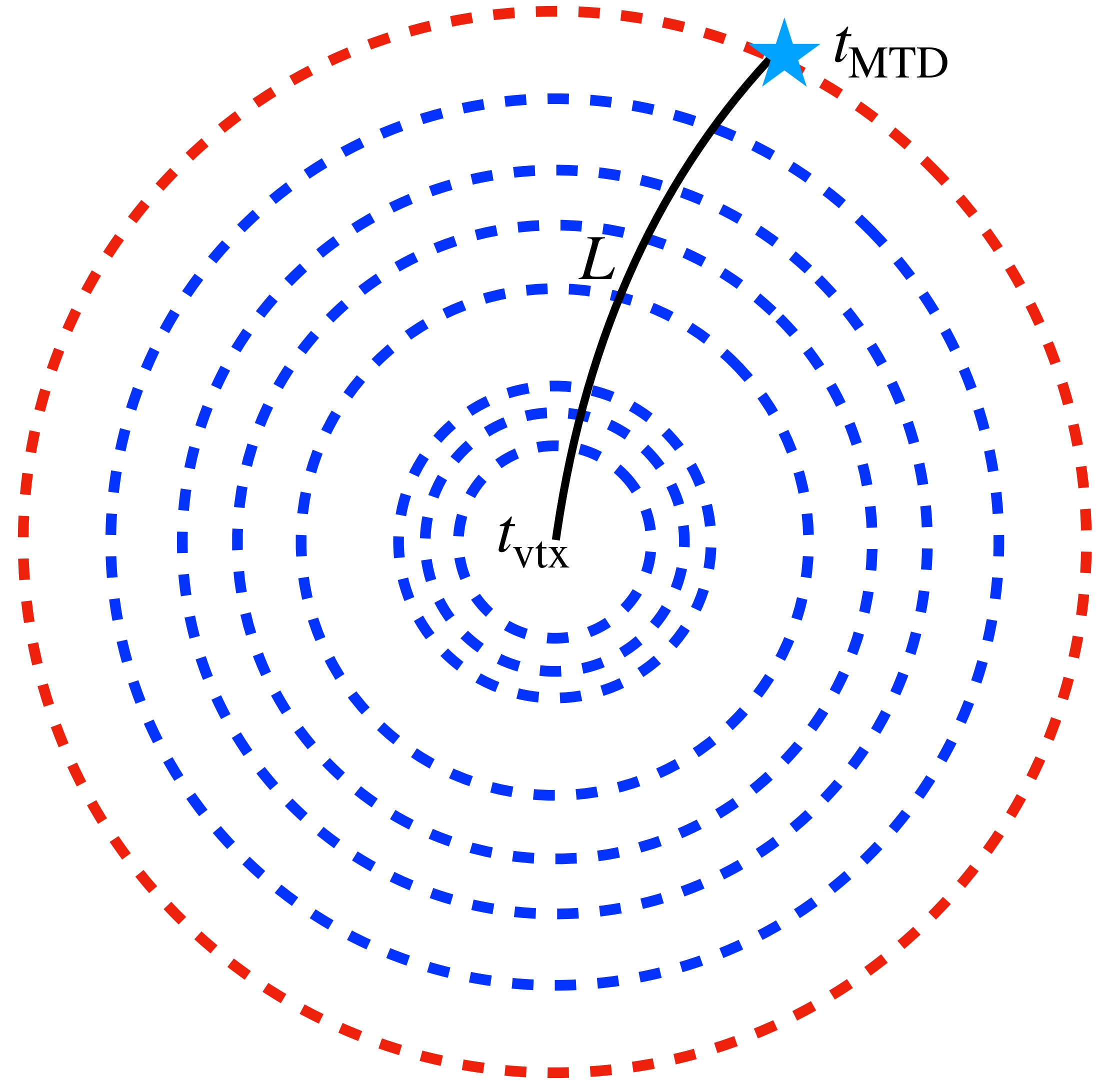


- dE/dx allows for small background level above ~ 800 GeV
- Exciting excess at large dE/dx consistent with heavy HSCP (3.3 σ)
- **Timing is critical to unravel nature of the excess**

Heavy Stable Charged Particles

$$\frac{L}{c\beta} = t_{\mathrm{MTD}} - t_{vtx}$$

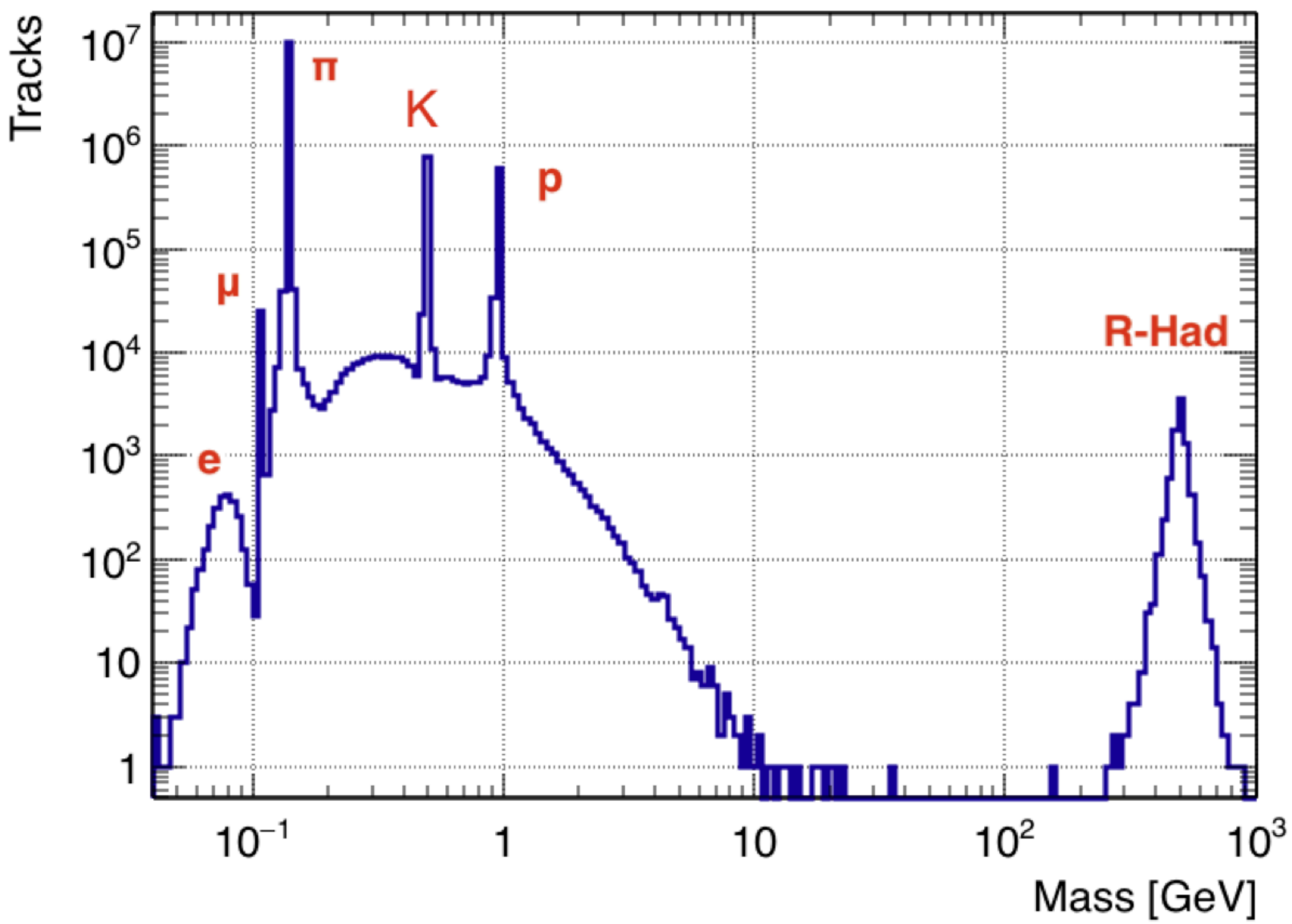


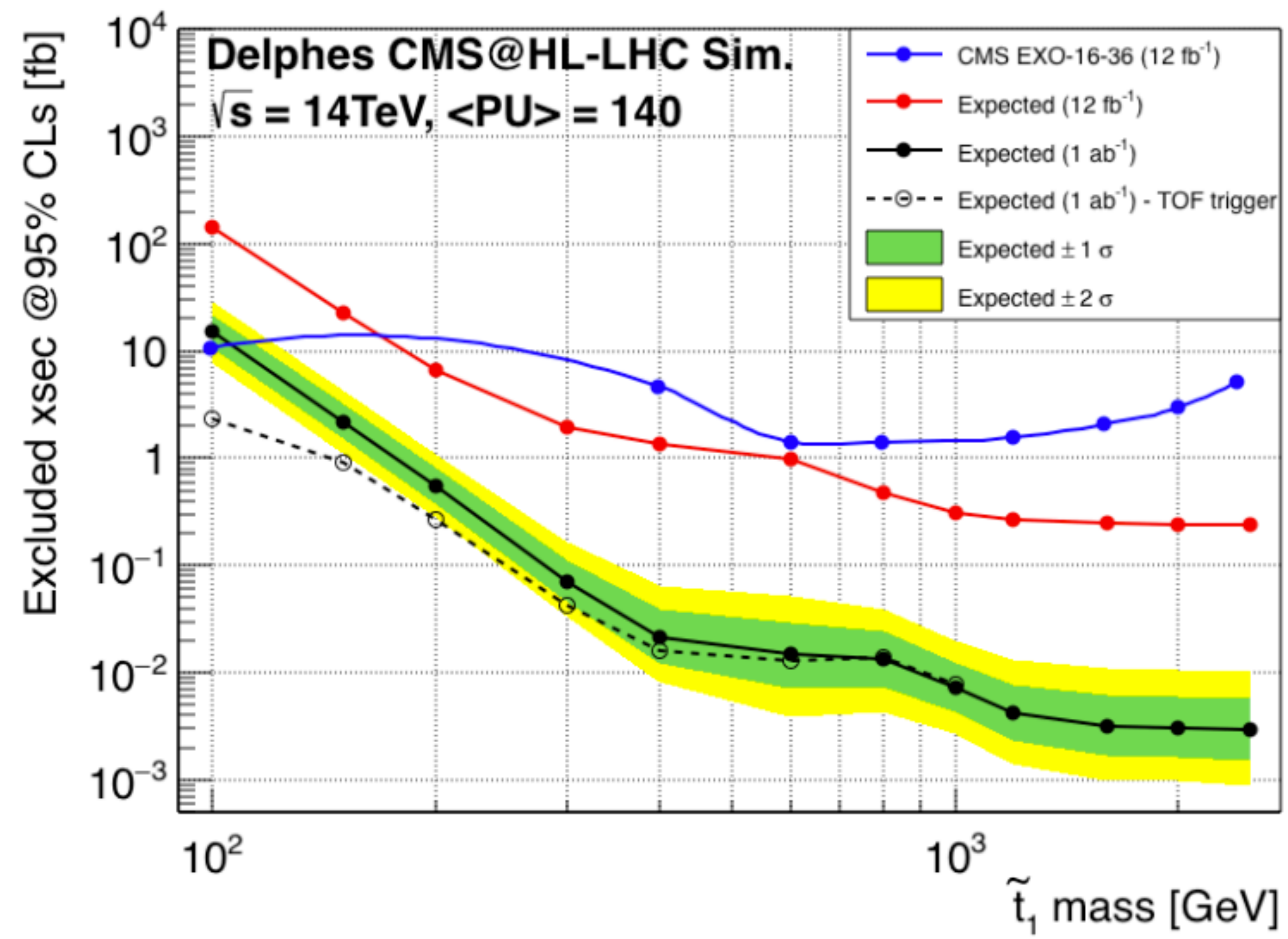


- Precision timing can also measure β — TOF particle ID
    - Independent HSCP mass reconstruction!
- **MTD adds new capabilities to complement/enhance dE/dx**

MTD TOF: Heavy Stable Charge Particle

J. High Energ. Phys. **2019,** 37 (2019)

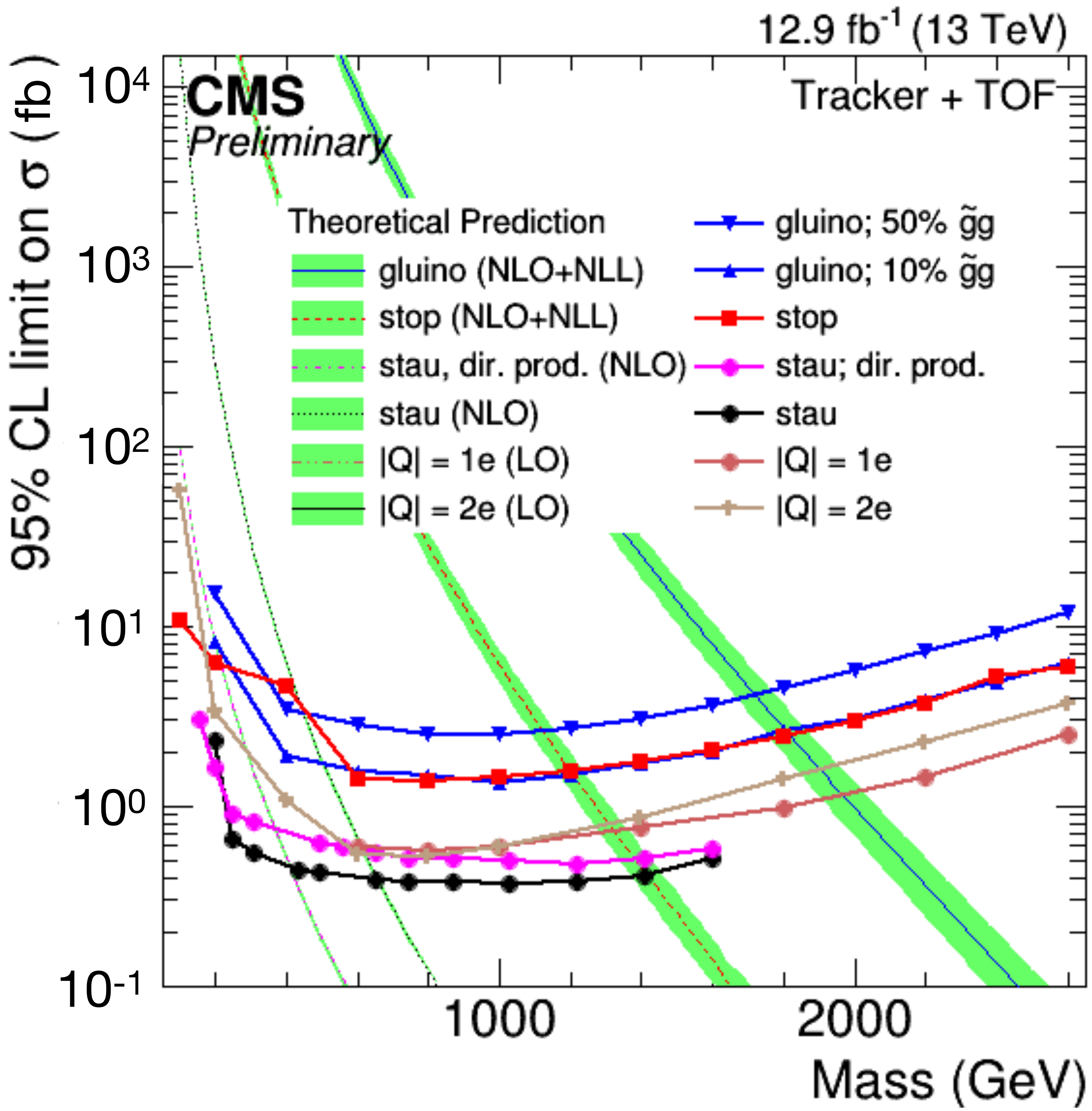


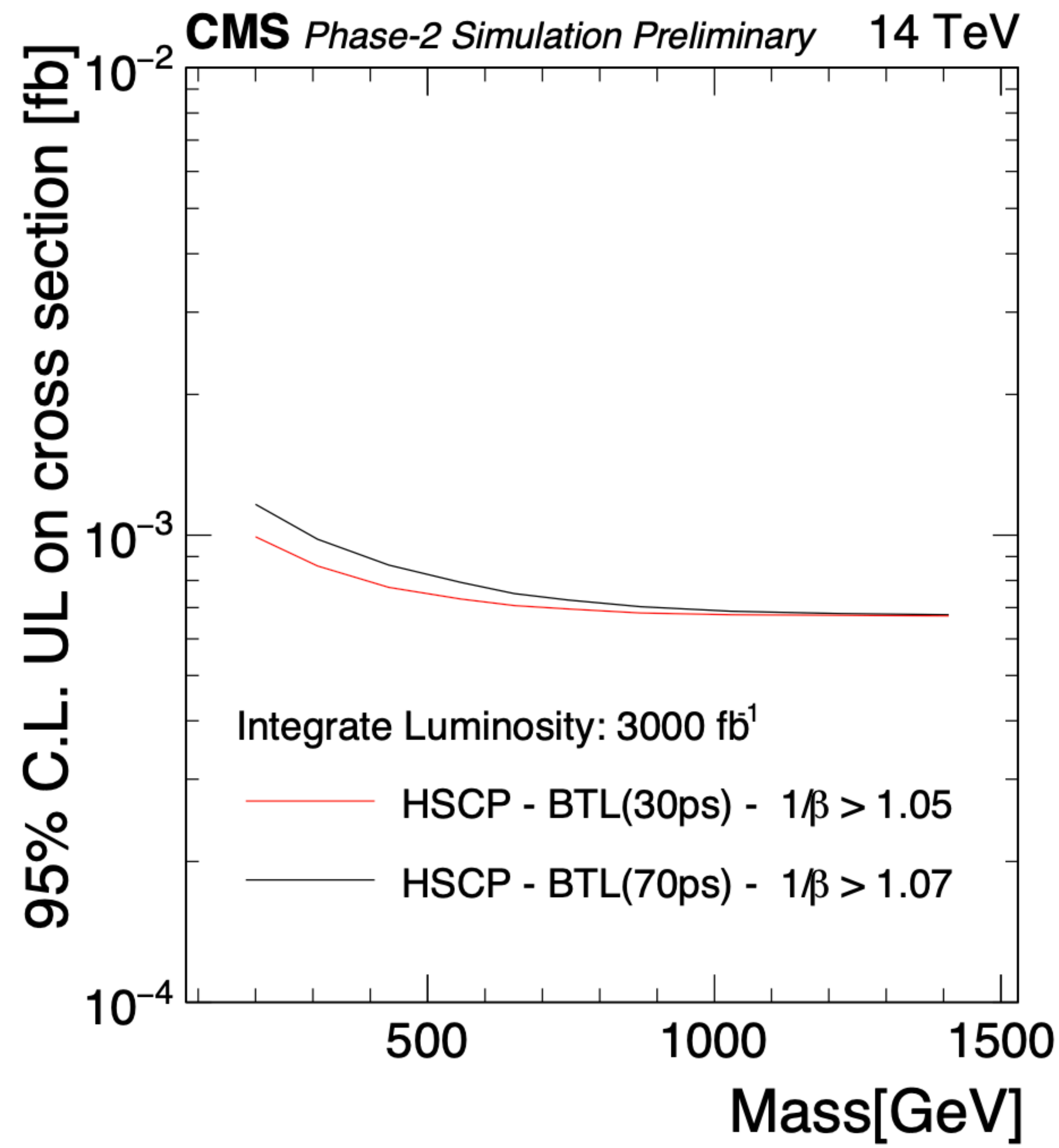


500 GeV HSCP will typically have delay of 1ns
→ timing @ 100 ps 10 σ bkg rejection

- 4D reconstruction allows PID and competitive HSCP discovery potential
- Precision timing dominates sensitivity for large HSCP masses

MTD TOF: Heavy Stable Charge Particle

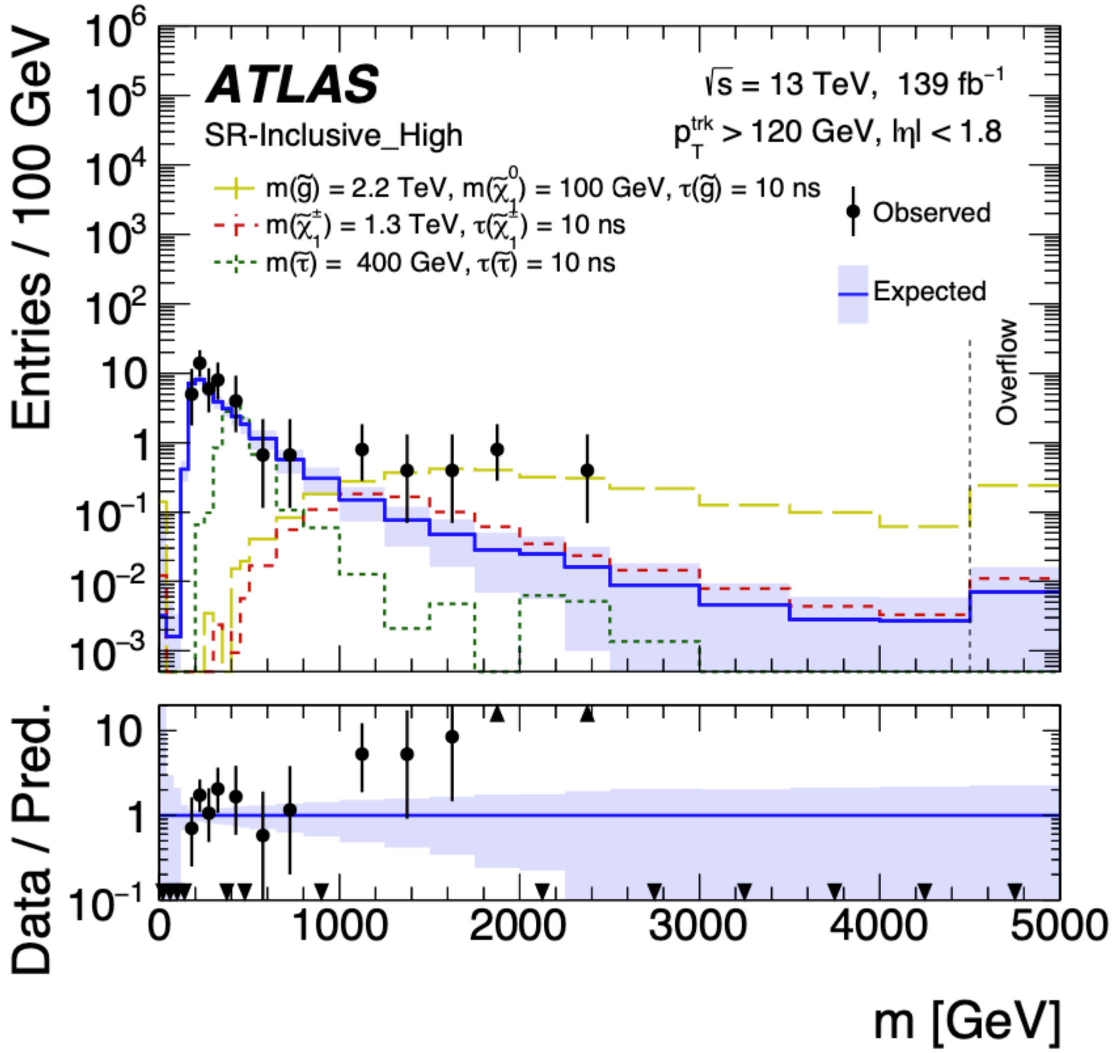




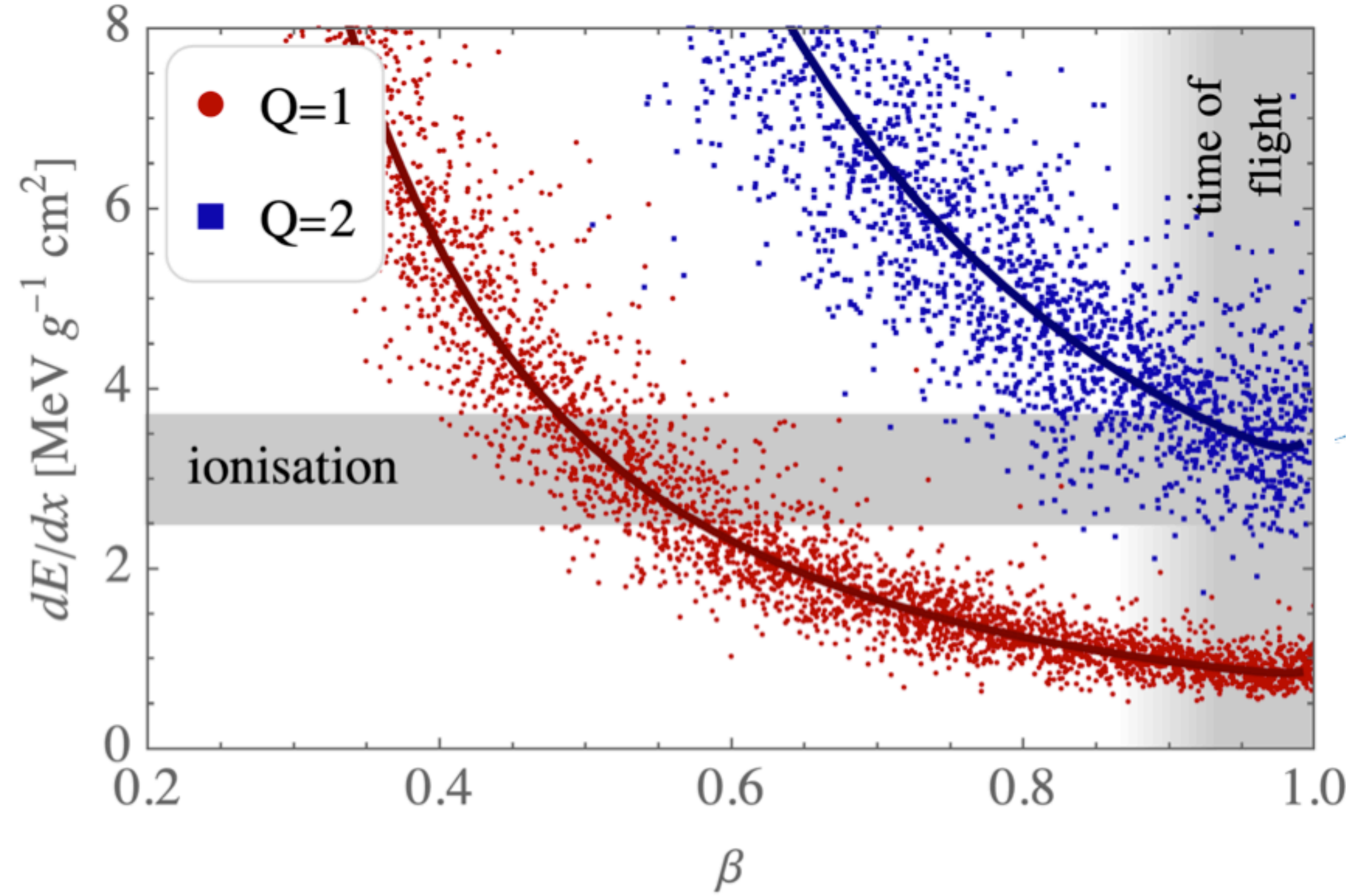
Large expected gain in sensitivity with MTD precision timing

Detector Complementarity

D. Teresi — LLP11



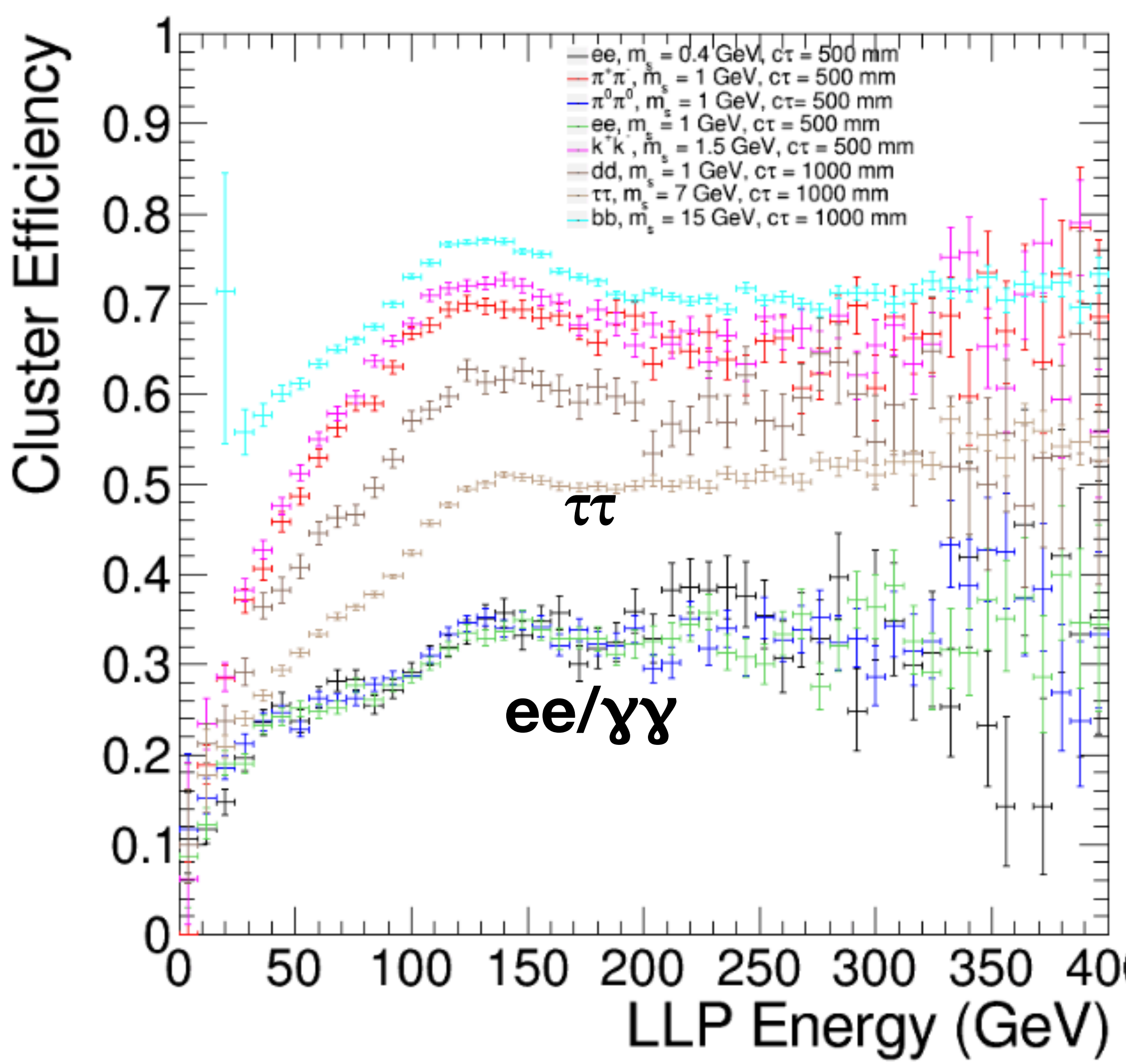
$$-\left\langle \frac{dE}{dx} \right\rangle = 4\pi m_e n_e r_e^2 Q^2 \left(-1 + \frac{2}{\beta^2} \ln \frac{\beta\gamma}{I_e} \right)$$

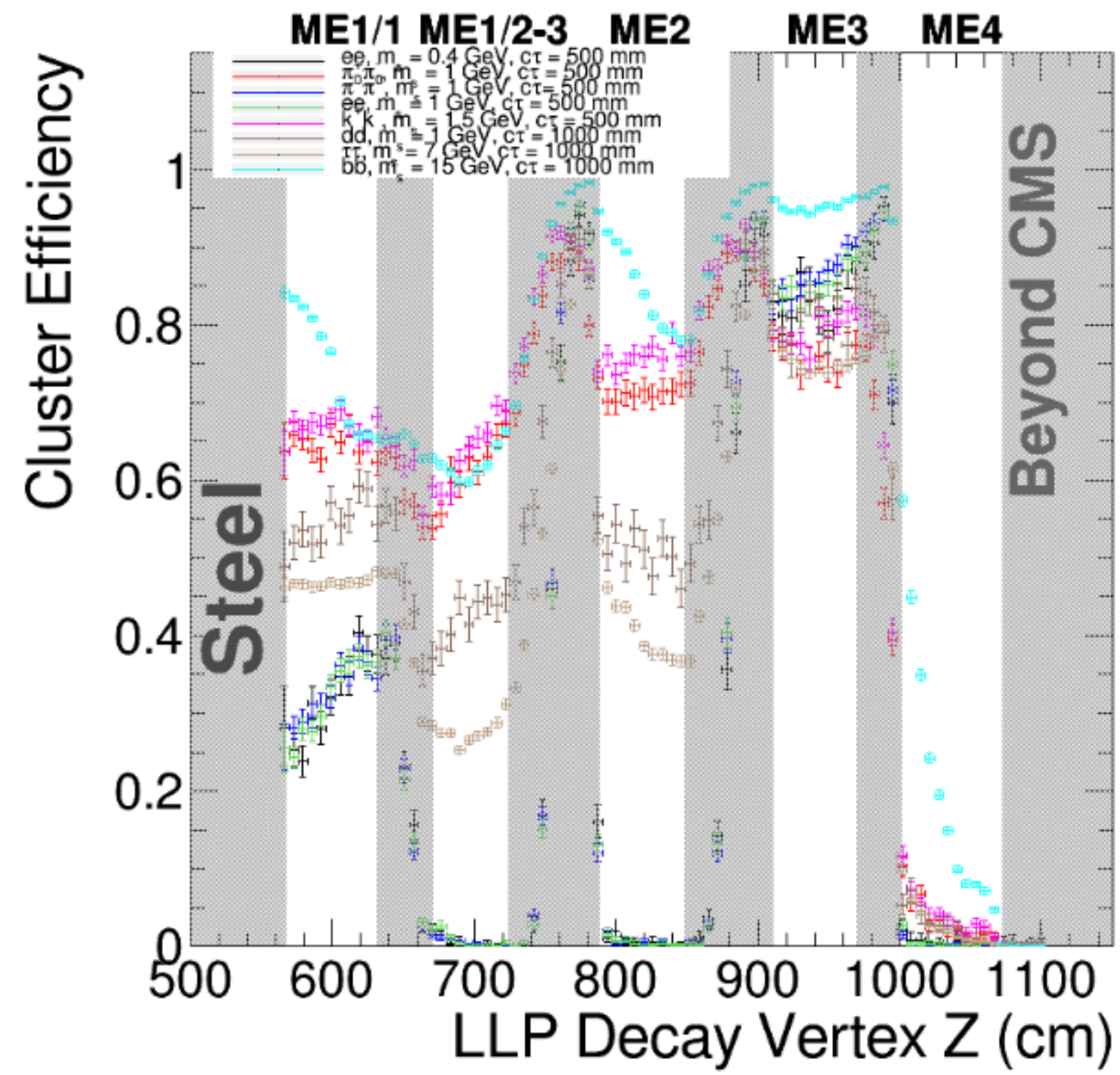


- When looking at the nature of an excess MTD TOF has lots to say
- If TOF is not compatible with dE/dx new physics could have Q > 1
- **Precision timing provides unique insight to signal properties in case of discovery**

Muon System Enables Broad LLP Reach

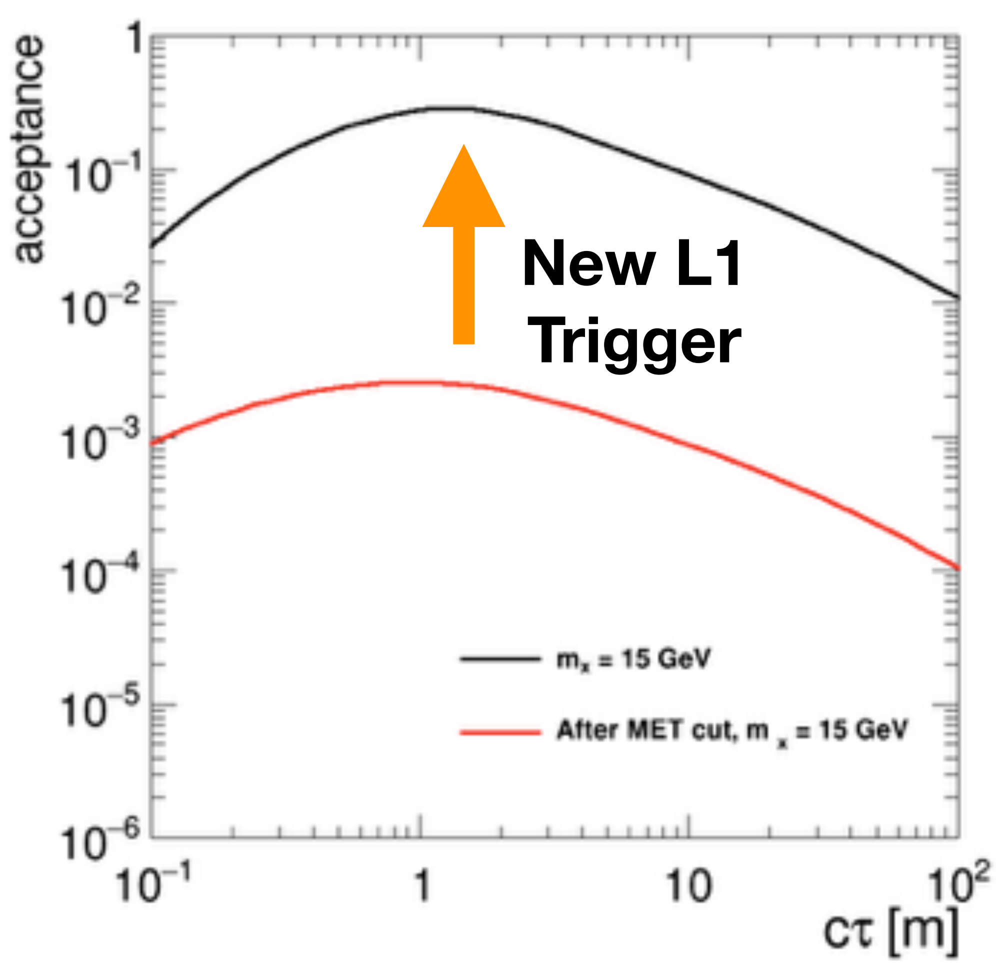
- Strong reach when LLPs are light — below di-muon threshold, target **unexplored ee and γγ decays**
- Strong reach when LLPs decay to SM taus. Enables reach for unexplored SUSY parameter space: e.g **LL staus**



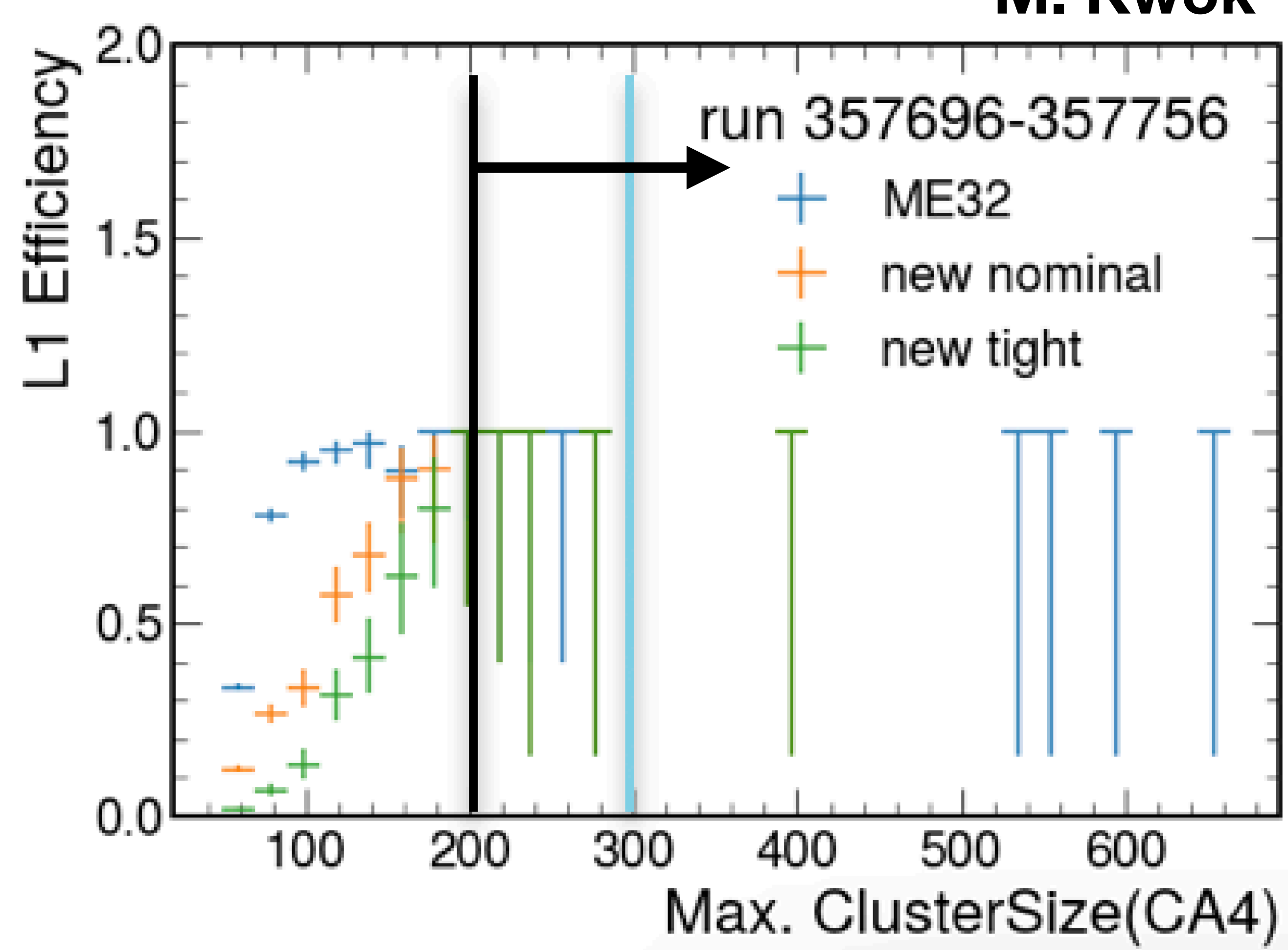


High Multiplicity Trigger (HMT)

- **NEW L1 trigger with MS signature (HMT)**:
  - NEW L1 seed will provide 20x increase in signal efficiency
  - Will enable completely new search signatures **MS-MS, MS-ECAL, MS-Tracker**

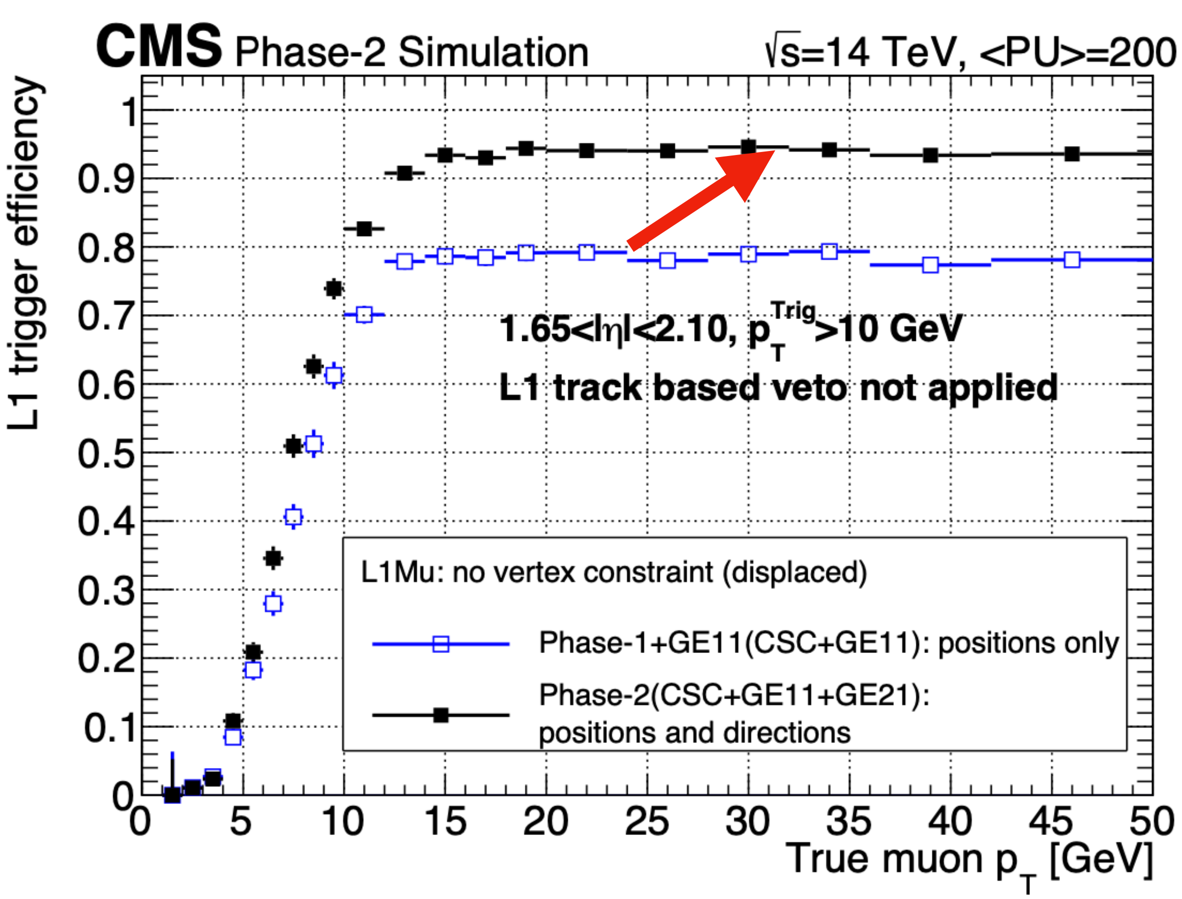


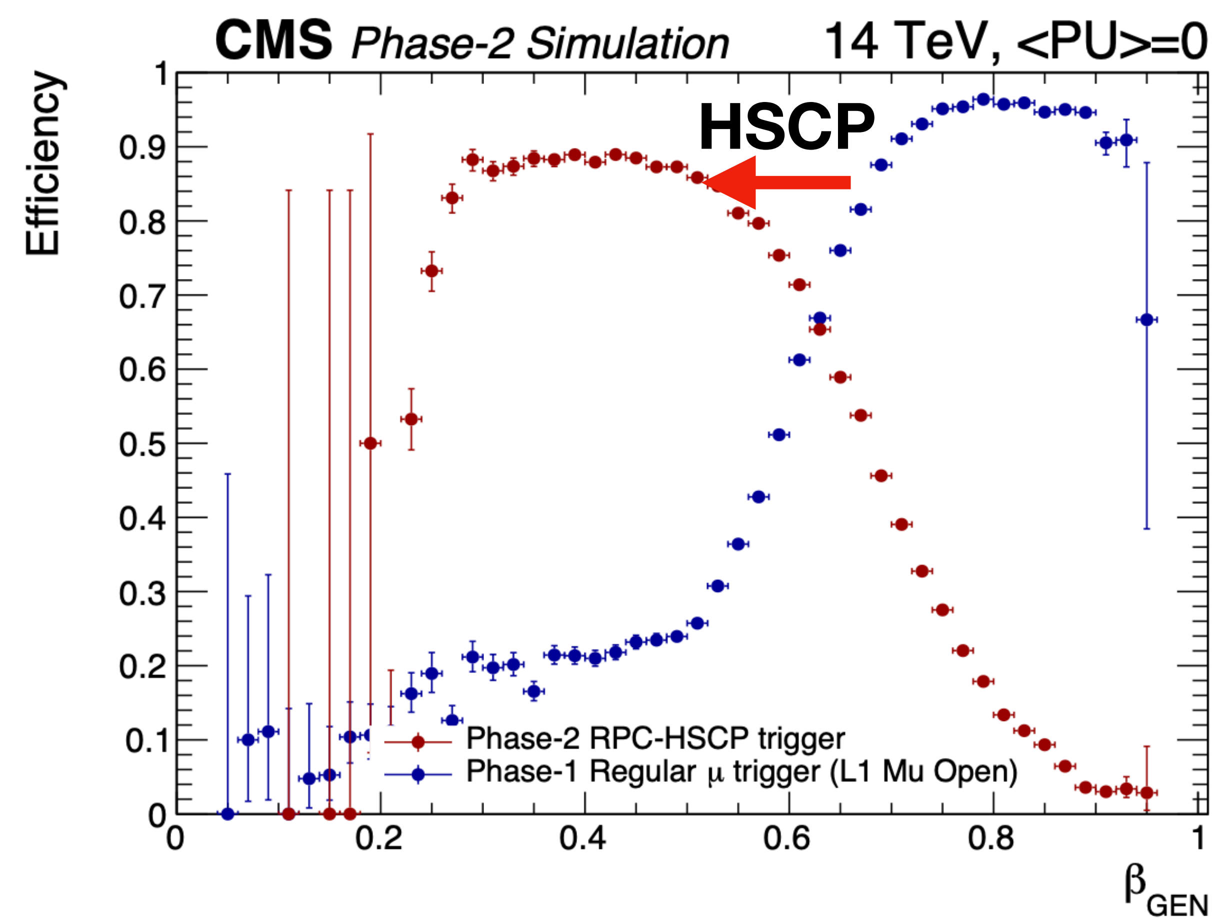
M. Kwok



Muon System Phase-II Upgrade

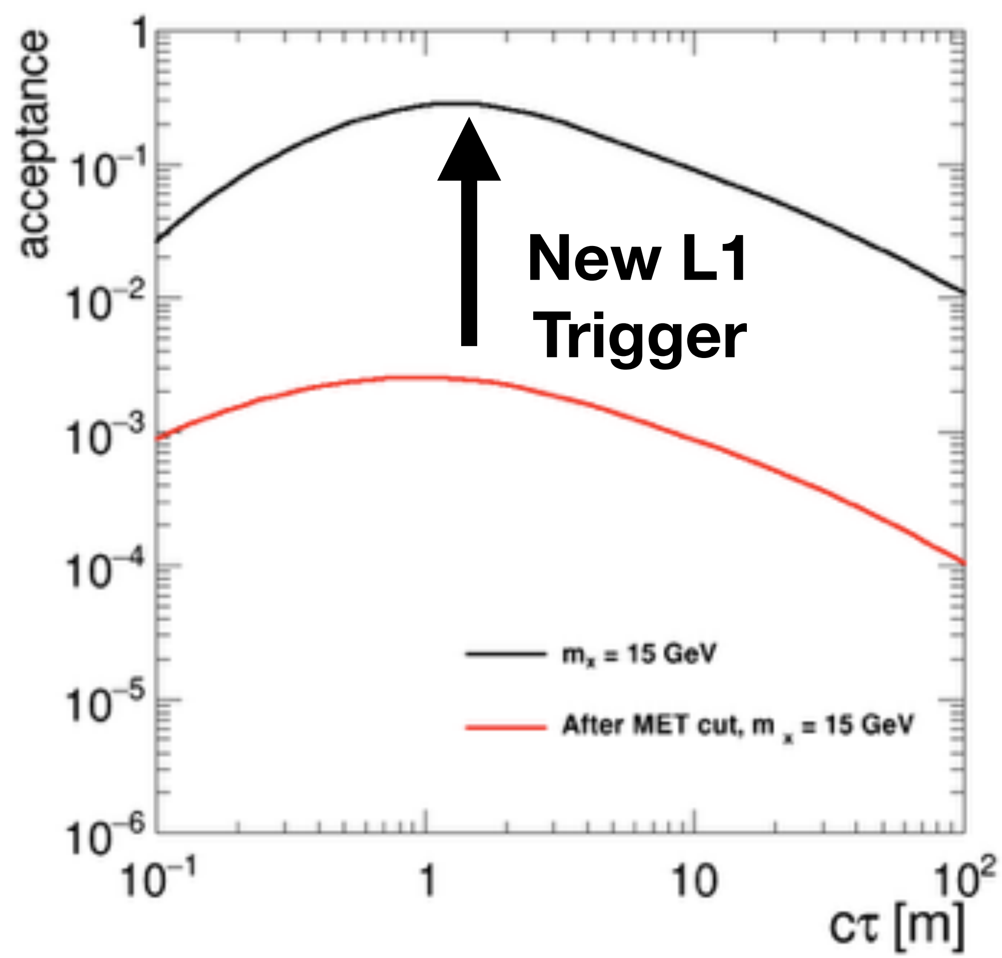
- **Phase-II upgrade will provide significant gains for displaced muon reconstruction**
- **Improved RPC timing will enable new HSCP trigger**
- **Phase-II upgrade will enable HMT in DT (Barrel)**
  - **Will boost acceptance for central LLPs and double LLP searches (peak sensitivity)**
  - **TMB upgrade (under discussion) will improve HMT(cathode) in Ring2 and Rin3**
  - **New/improved RPC and GEMS ME0 will go**





New L1 trigger with Muon System

- **NEW L1 (Hardware) trigger with MS signature**:
  - NEW L1 seed will provide 20x increase in signal efficiency
  - Will enable completely new search signatures **MS-MS, MS-ECAL, MS-Tracker**

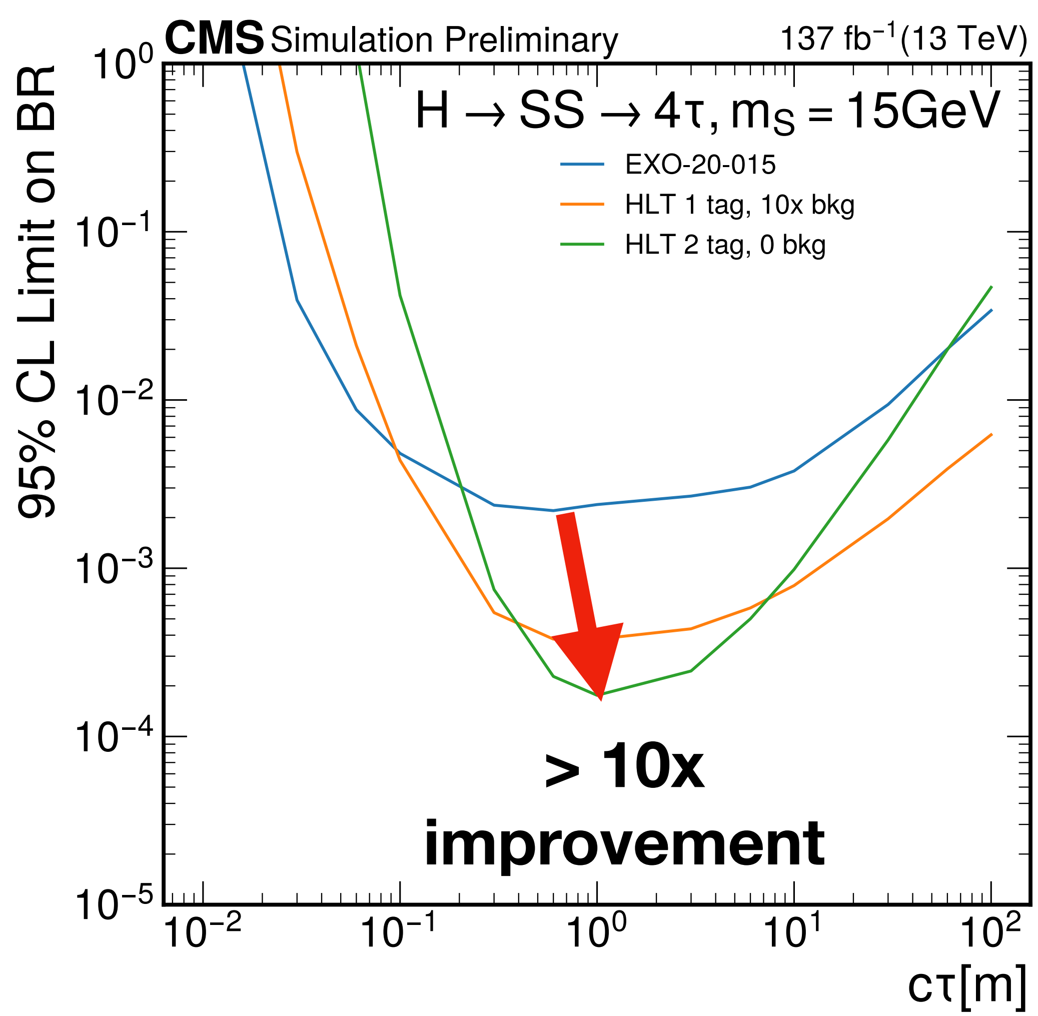


S. Dildick, M. Kwok, N. Menendez, D. Acosta, S. Jindariani, P. Padley

New L1 trigger with Muon System

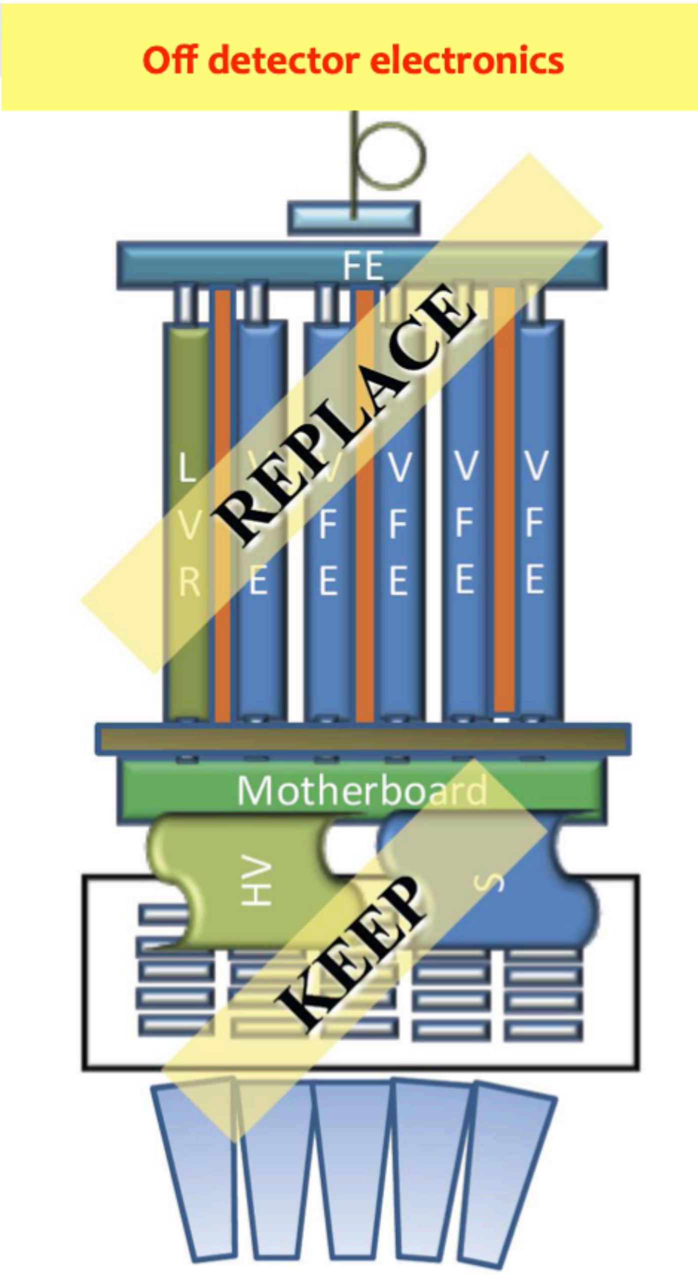
- **NEW L1 (Hardware) trigger with MS signature:**
  - NEW L1 seed will provide 20x increase in signal efficiency
  - Will enable completely new search signatures **MS-MS, MS-ECAL, MS-Tracker**

Improvement in sensitivity from new MS trigger

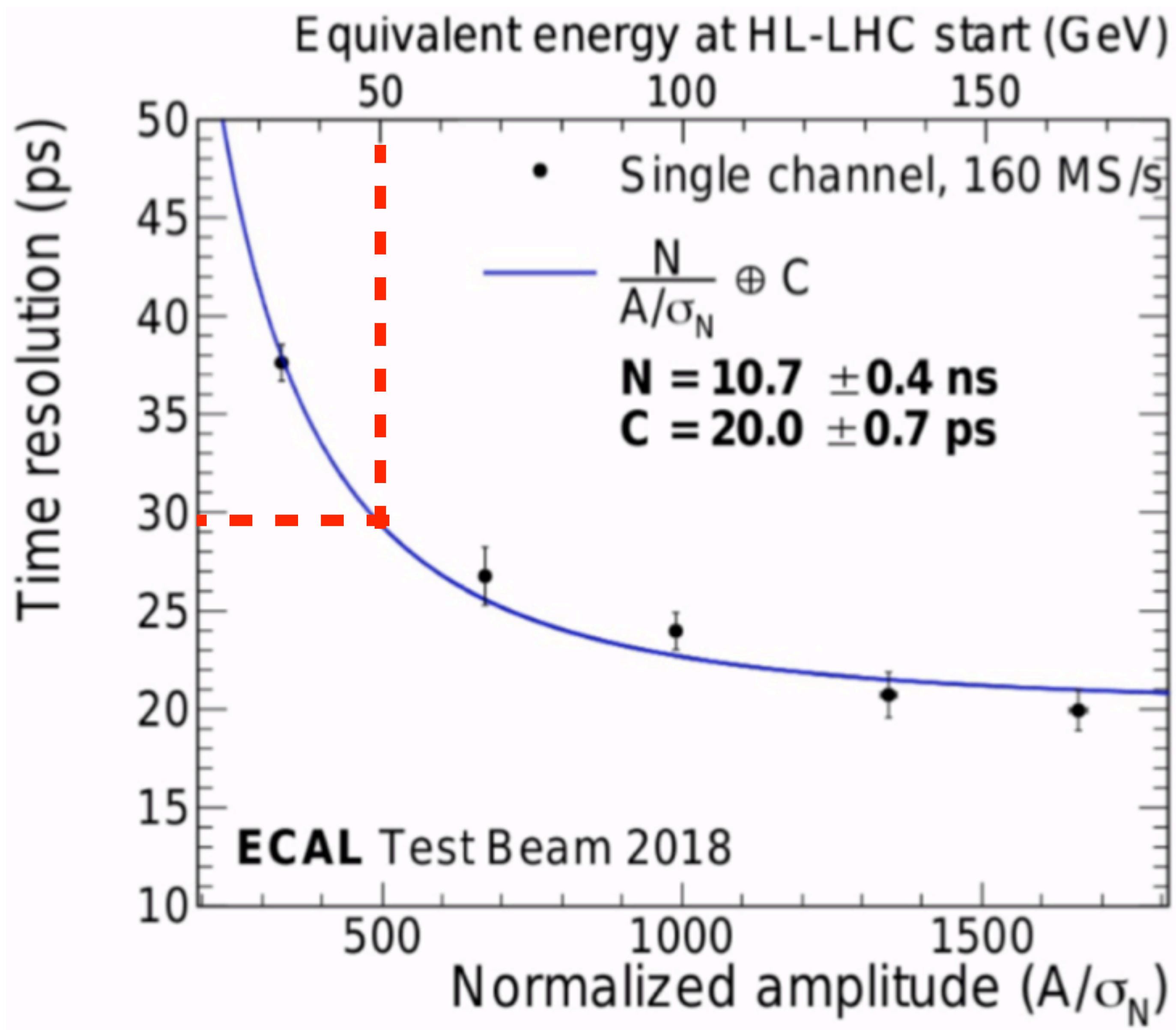


ECAL Barrel HL-LHC Upgrade

- $PbWO_4$ crystals, APDs, mother boards, & overall mechanical structure will not change
- The FE and VFE electronics readout will be replaced:
  - to satisfy the increased trigger latency (up to 12.5 μs) and L1 **accept rate** (750 kHz) requirements
  - to cope with HL-LHC conditions (increased APD dark current, anomalous APD signals, higher PU)
- **VFE** maintains similar purpose, but **reduce shaping time+ digitization** ➜ reduce out-of-time PU contamination, electronics noise and spikes
- FE card becomes streaming readout, moving most processing off-detector



ECAL Barrel HL-LHC Upgrade

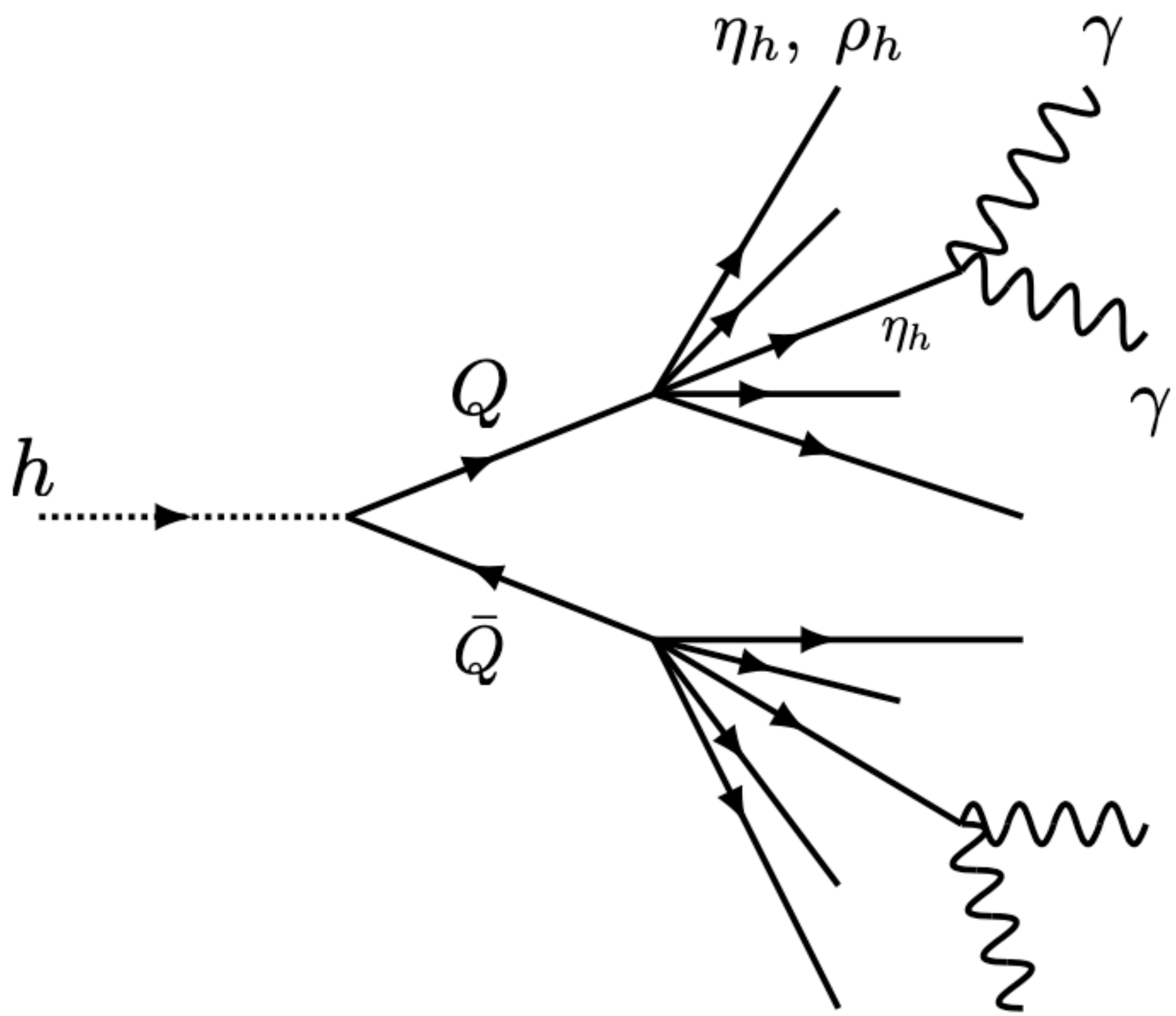


ECAL Barrel upgrade achieves **30 ps resolution for 50 GeV energy deposits**

Hidden Valley Reinterpretation

HIDDEN VALLEY

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \lambda h \bar{Q} Q$$



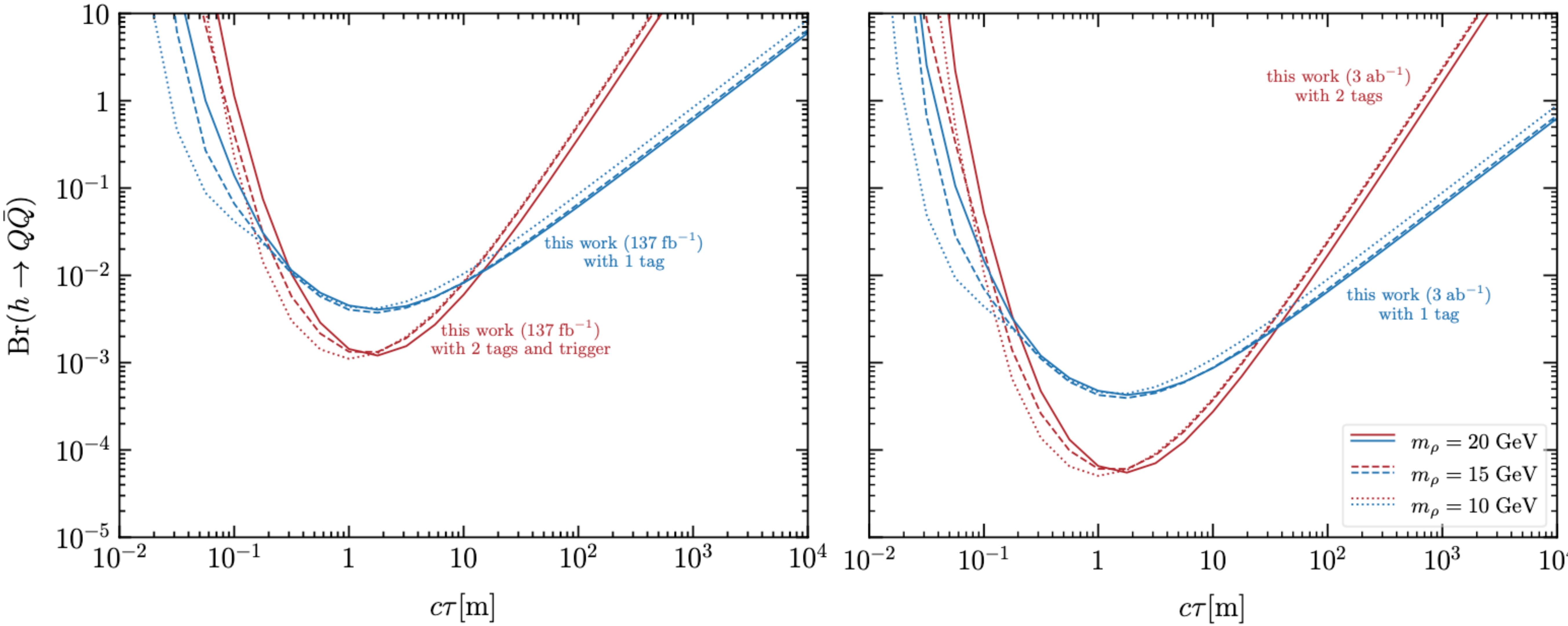
- we treat the η_h lifetime as a free parameter
- we take $\mathrm{Br}(\eta_h \to \gamma\gamma) = 1$ (hard to probe with other searches)
- we assume ρ_h to decay into $\eta_h \eta_h$ to maximize self-veto effects
- we implement the dark shower with Pythia treating η_h as a pion

Diphoton decay sensitivity due to unique signature of this search

A. Mitridate at LLPX workshop

Hidden Valley Reinterpretation

Exciting new possibilities with a model independent search



- CMS Results: Good sensitivity for challenging BSM signature
- Re-intepretation shows importance of **double tag search**
- Projected Br exclusion at 1e-4 at HL-LHC → NEEDS TRIGGERS!

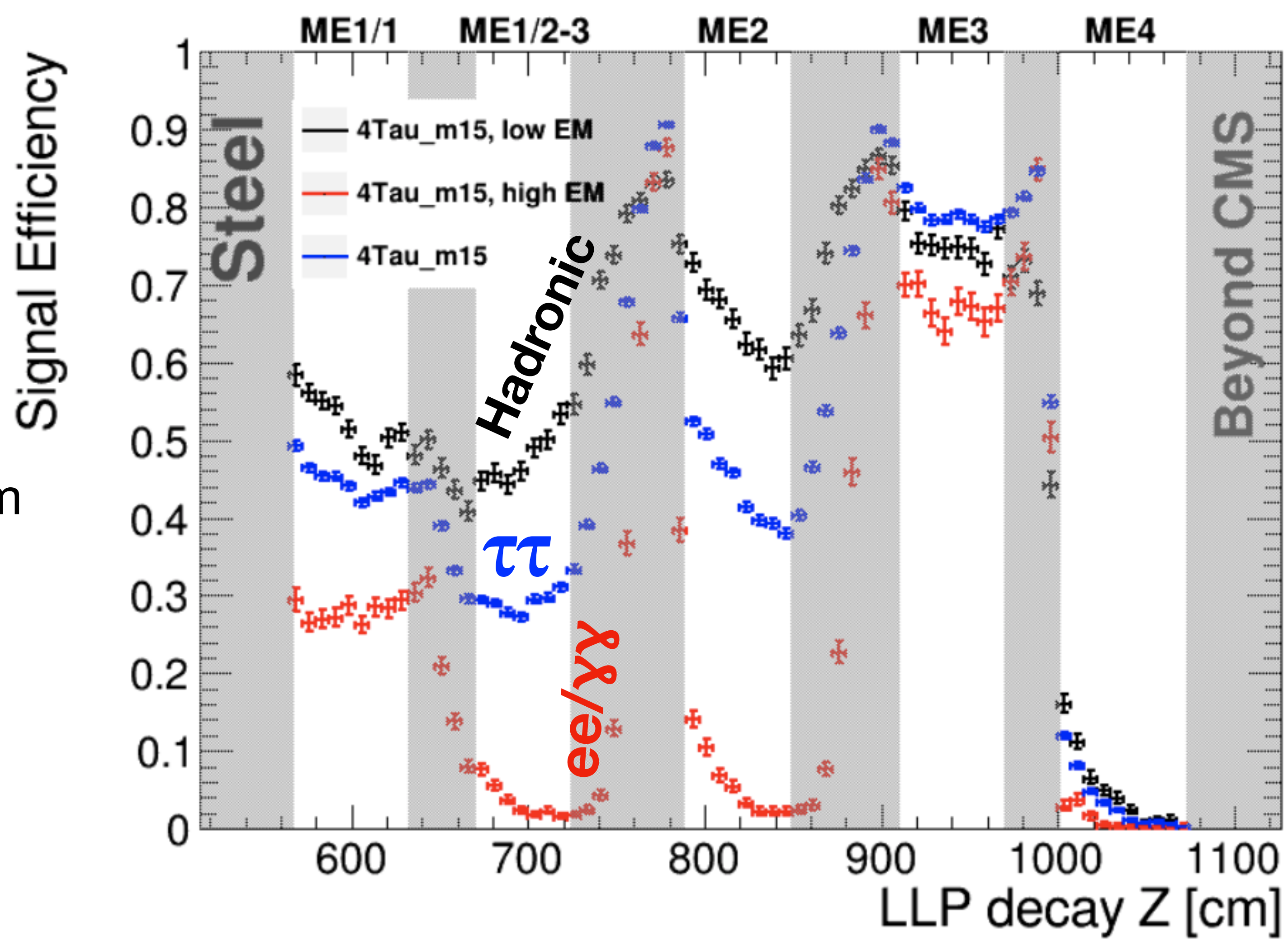
A. Mitridate at LLPX workshop

EM/Had LLP Efficiency in Muon System

LLP to $\tau\tau$ decays probes EM vs hadronic dependence

$s \rightarrow \tau\tau$

N. Interaction L = 16.8 cm
Radiation L = 1.8 cm



For example

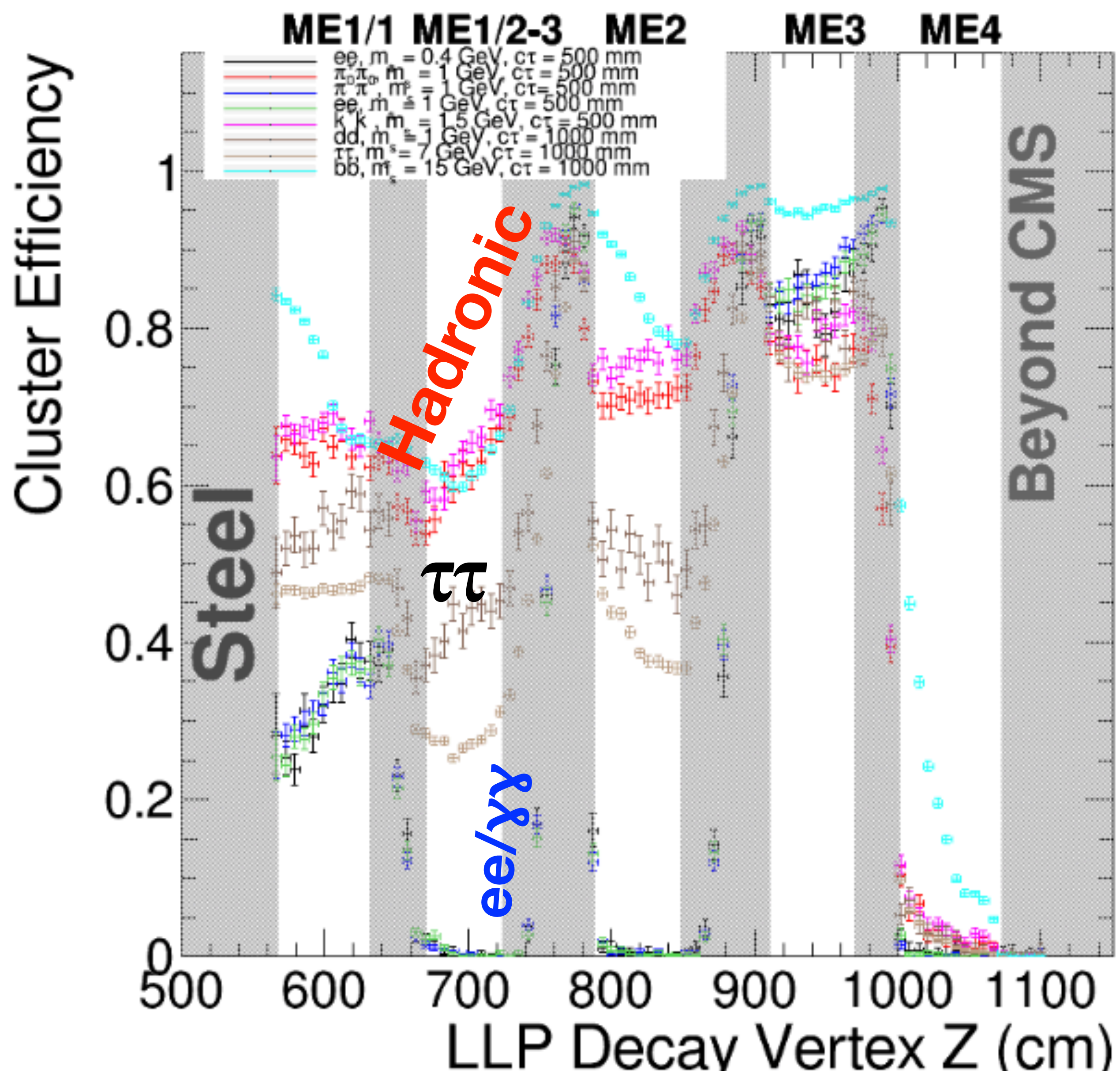
Γ_5 $e^- \overline{\nu}_e \nu_\tau$

Γ_9 $\pi^- \nu_\tau$

- Decays with high-hadron energy fraction resembles s→bb
- Decays with high-EM energy fraction are less penetrating

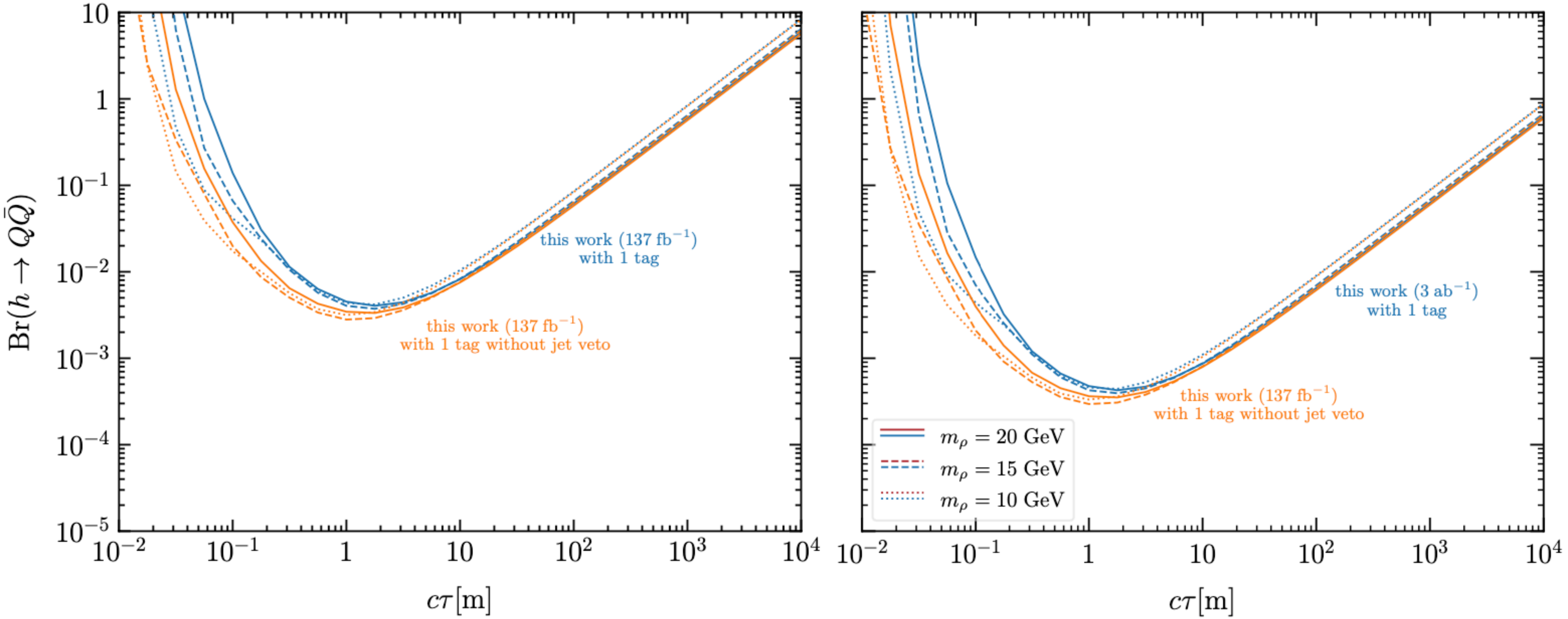
EM/Had LLP Efficiency in Muon System

- Confirm efficiency to EM decays using LLPs events decaying to **ee, γγ, $\pi^0\pi^0$**
- Confirm efficiency to Hadronic decays using LLPs events decaying to **k^+k^- and $\pi^+\pi^-$**



Hidden Valley Reinterpretation

Effect of the Jet veto is explored



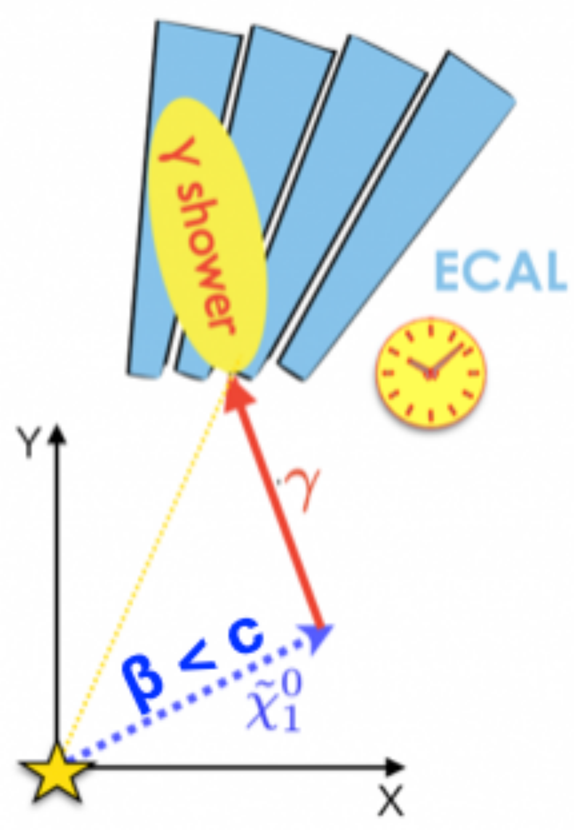
A. Mitridate at LLPX workshop

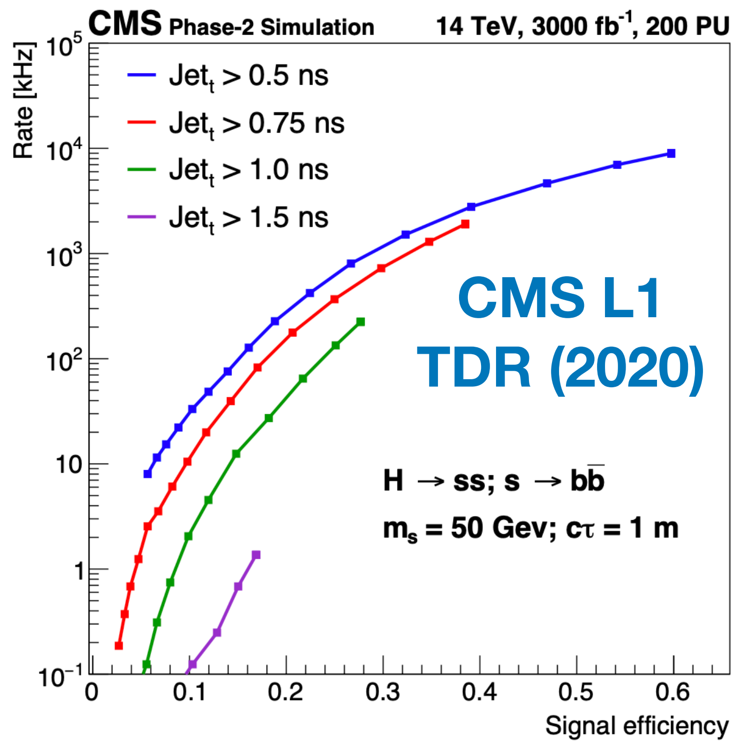
Example: new LLP ideas now

- Trackless jets with precision timing: best sensitivity at cτ ~1m

- Delayed photons with ECAL timing: unique coverage with photon signatures

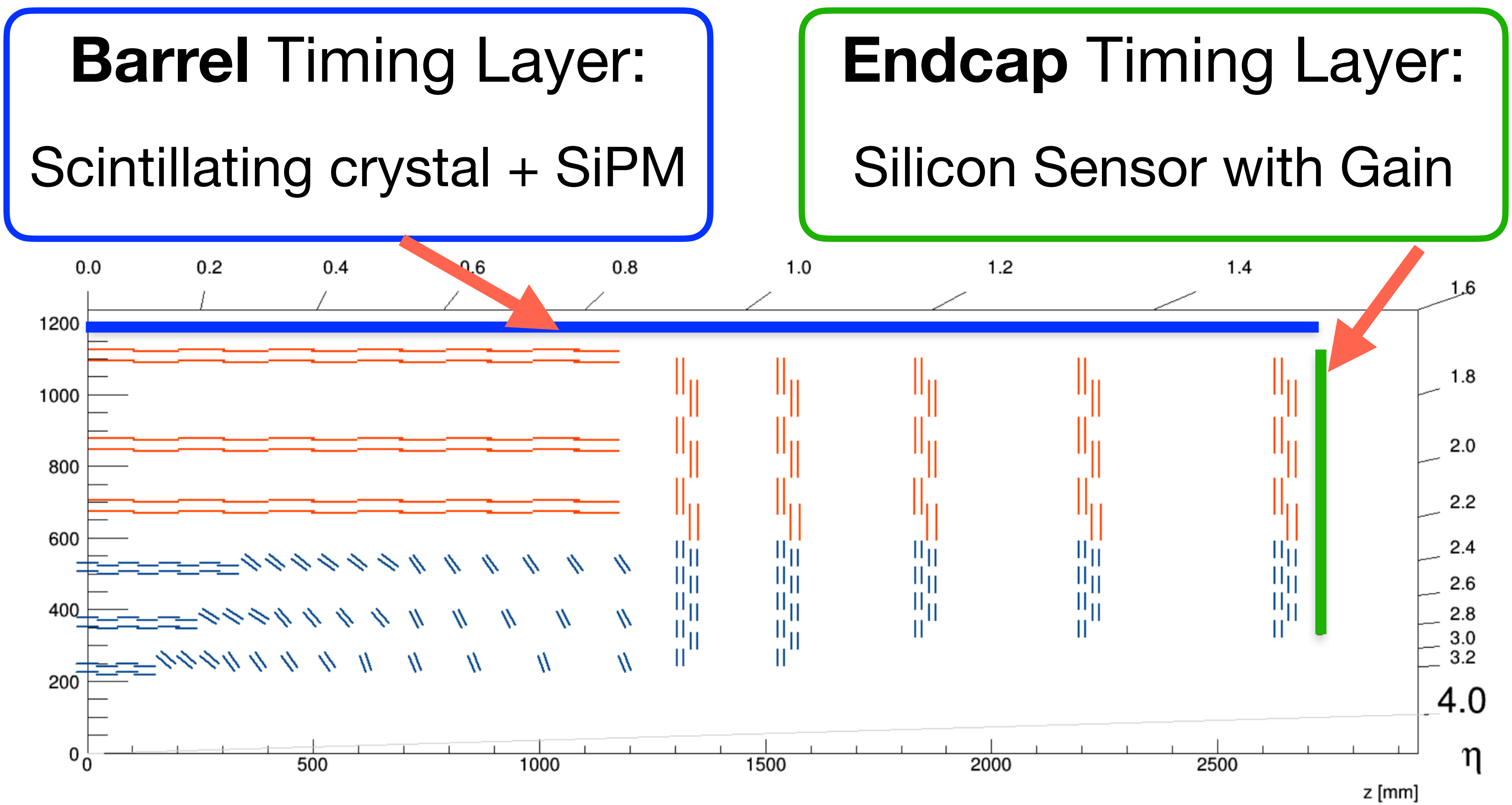
- New trigger for **HL-LHC**: ECAL timing at 50 ps level





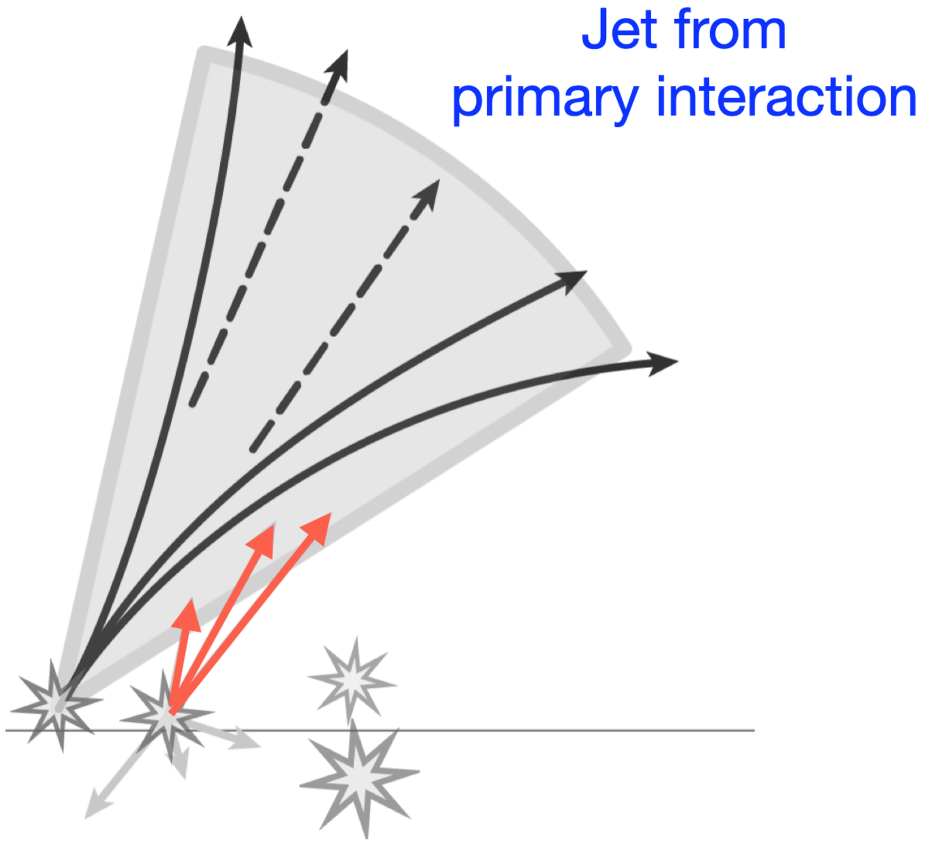
CMS Timing Detector

- **Caltech CMS** group the leader of this project since 2012 (with FNAL)
- Sustained effort and progress in precision timing R&D

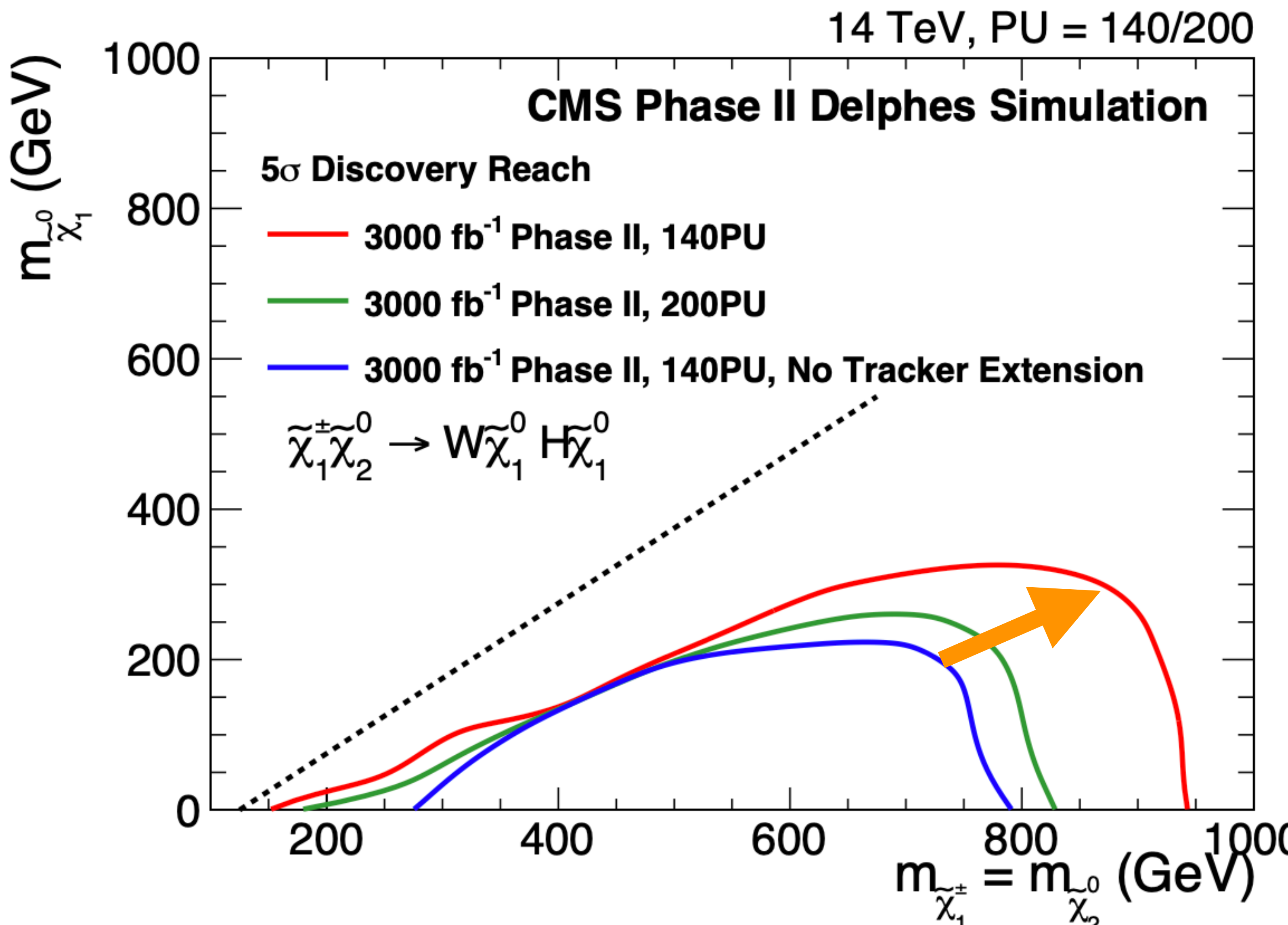


Enhanced Physics Reach

Pileup degrades missing energy resolution



For SUSY searches: timing significantly reduces background



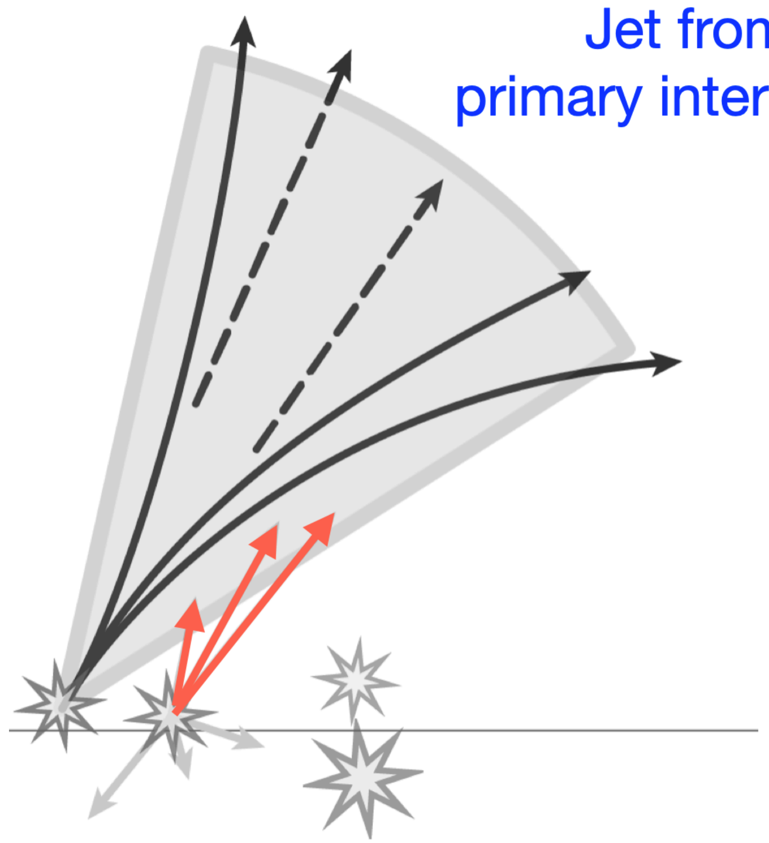
Precision Timing

↓

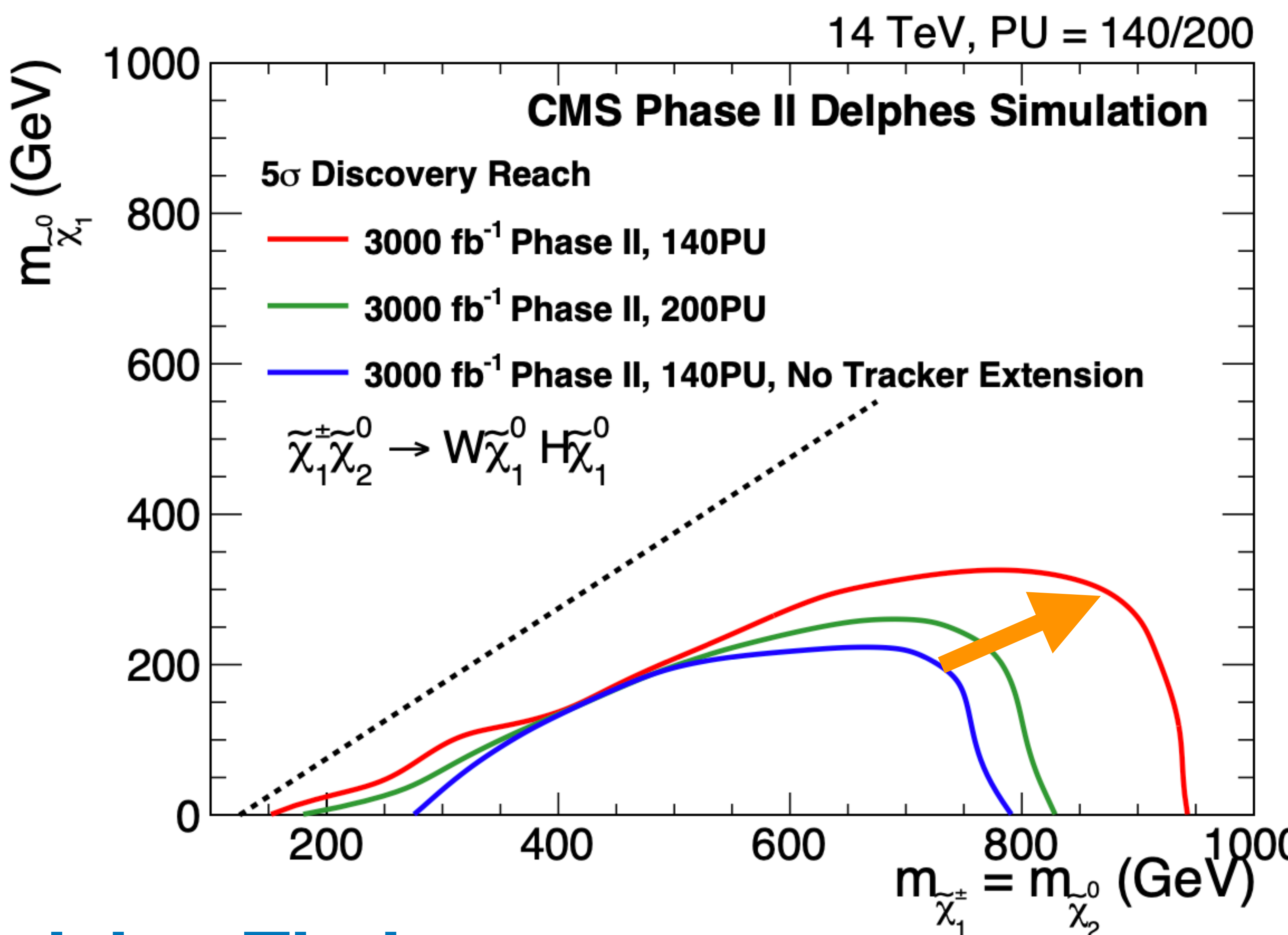
Increase EWK-SUSY mass discovery reach by ~150 GeV

Enhanced Physics Reach

Pileup degrades missing energy resolution



For SUSY searches: timing significantly reduces background



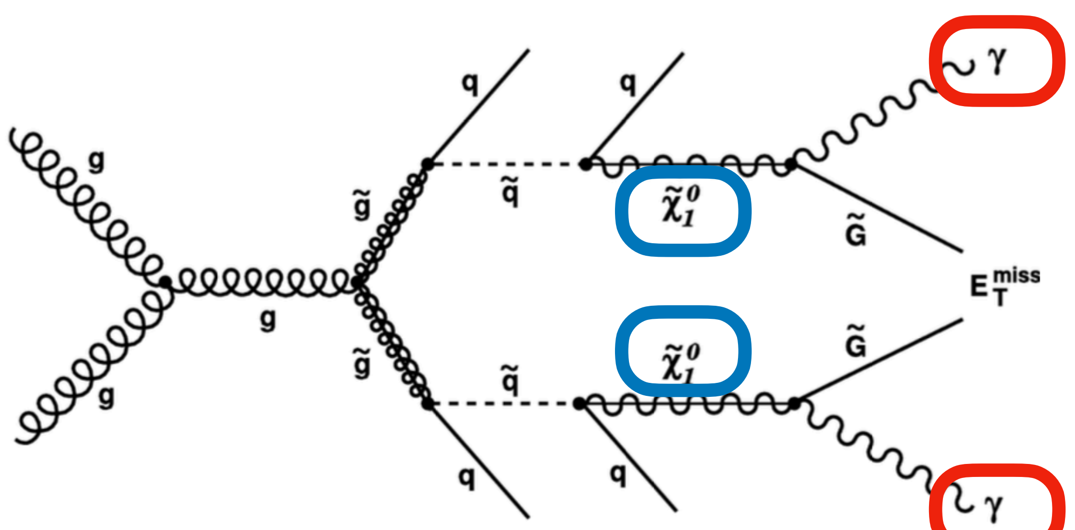
Precision Timing

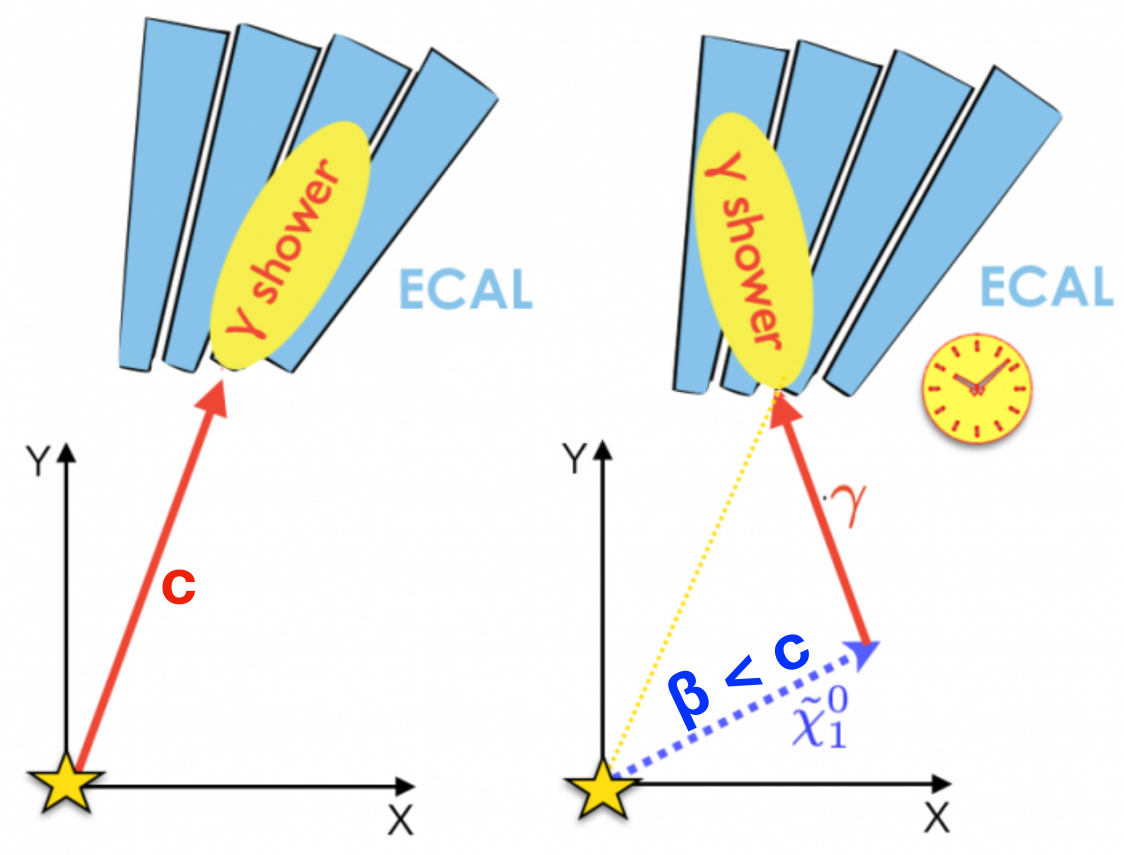
↓

Accessing 3x smaller production rates!

In-flight SUSY

New particle (neutralino) is **massive** and **displaced** from interaction point



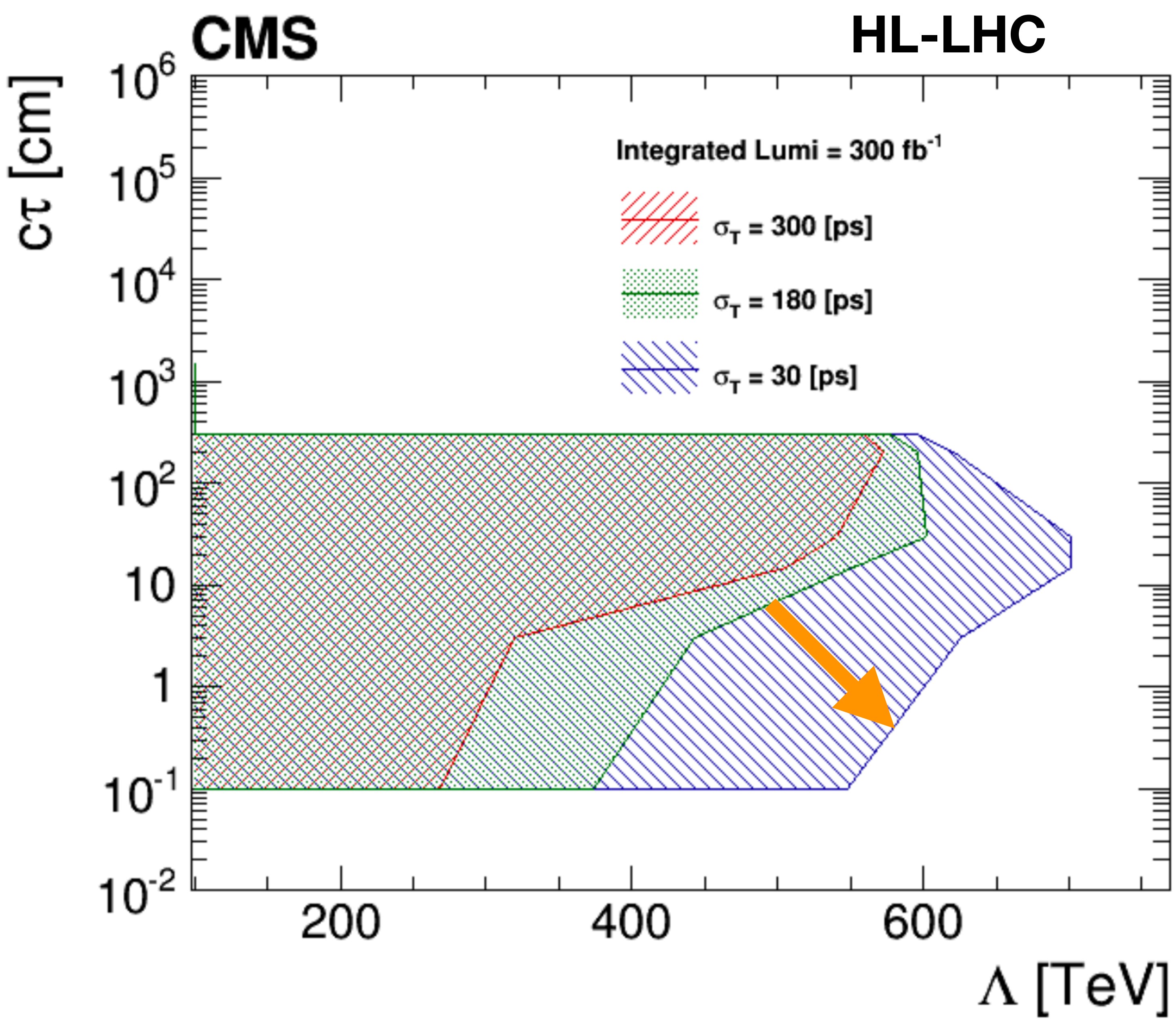


Neutralino travels slower than speed of light: time-delay

Signature: delayed photon

In-flight SUSY

MTD improves beam spot time-spread by 6x



Large gains in decay length ($c\tau$) and mass