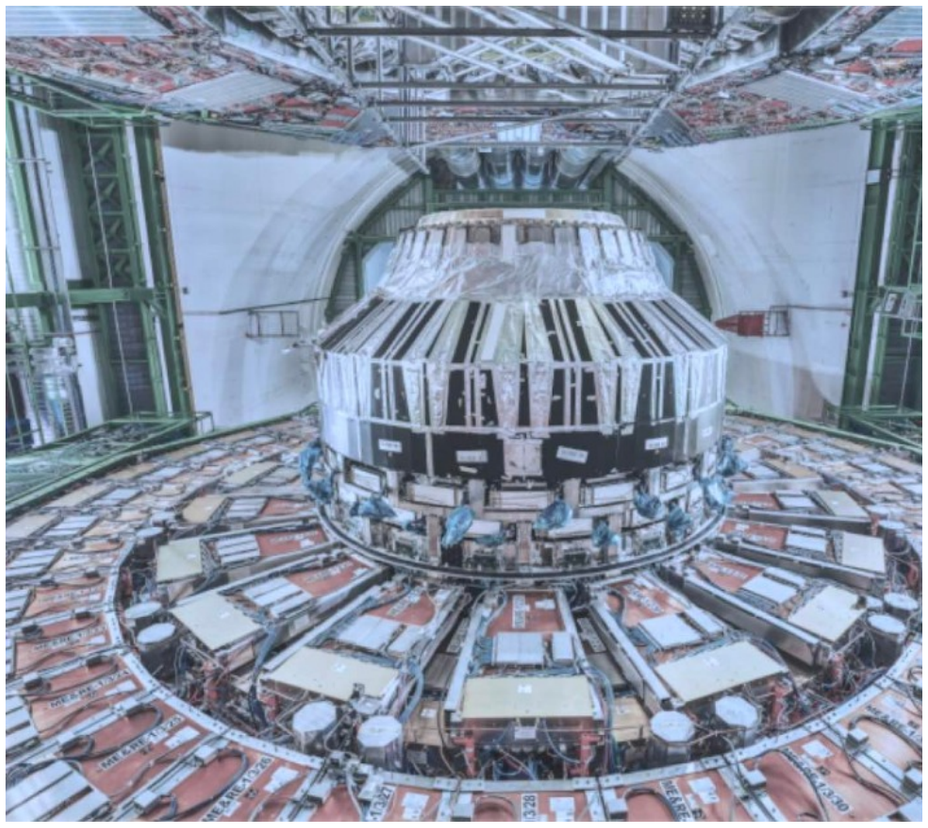
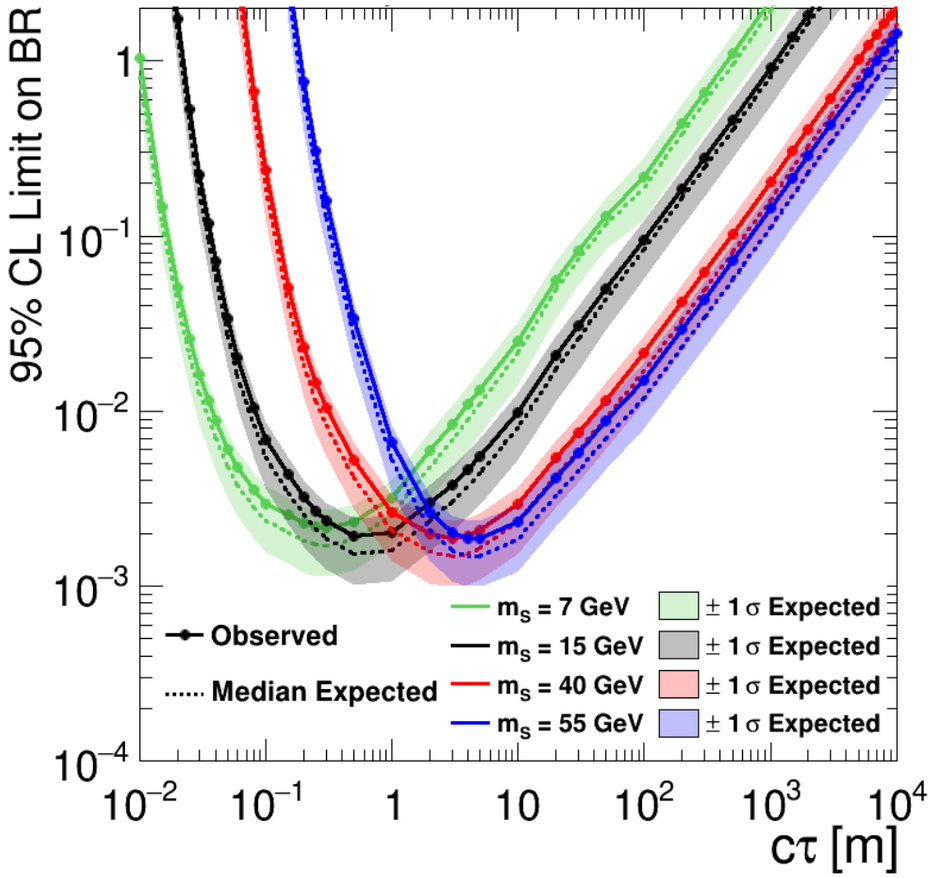
Unlocking the CMS Experiment to Catch Long-lived Particles





Cristián H. Peña

Fermilab

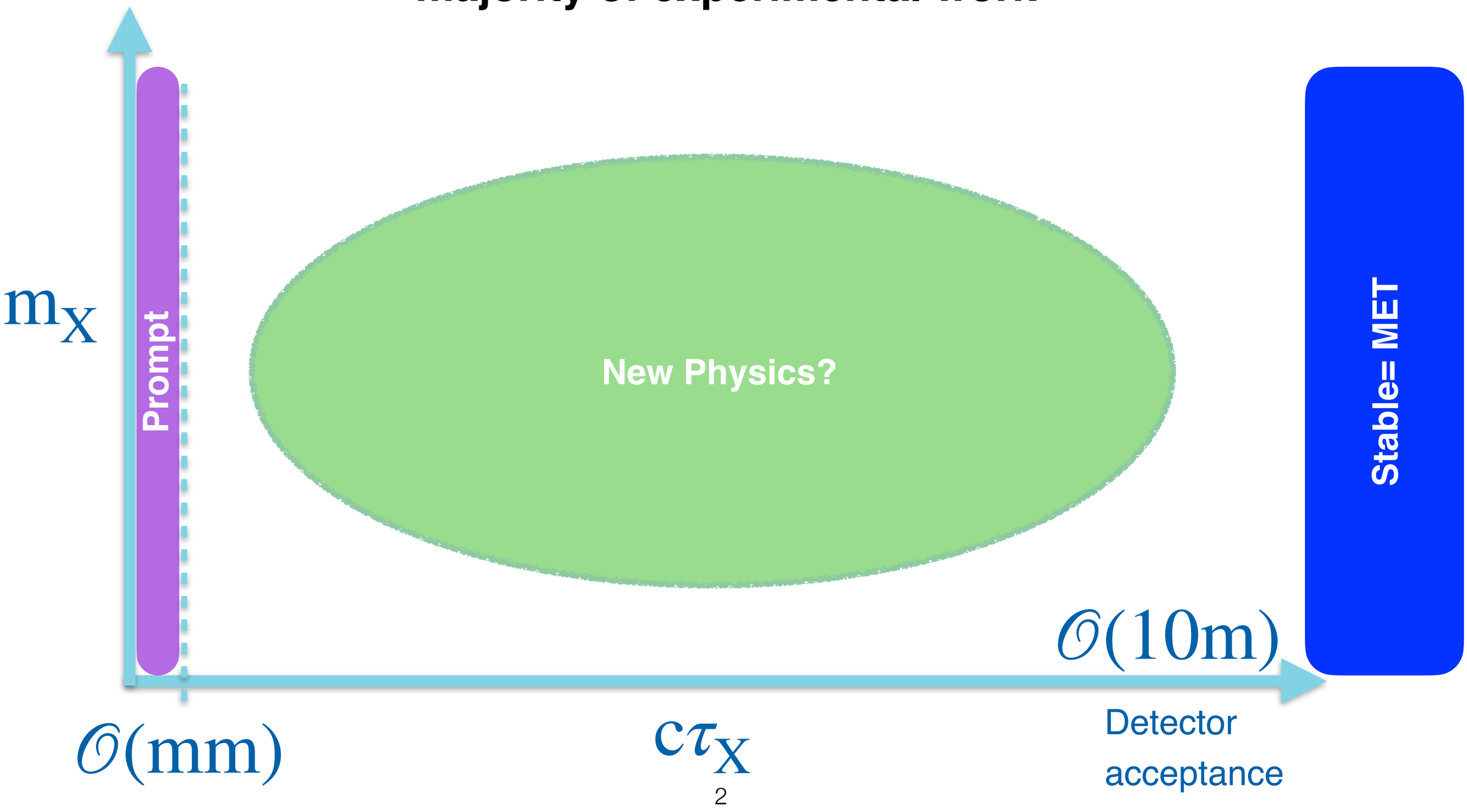
February 7 2022

High Energy Physics Seminars

Caltech The Division of Physics, Mathematics and Astronomy

New Physics at LHC: long-lived particles

Searches for new states up to now:
majority of experimental work



The Case for Long-lived Particles

Small decay width (Γ) gives rise to sizable lifetimes

$$\Gamma \sim \frac{g^2}{8\pi} \left(\frac{m}{M}\right)^{2n} m$$

Three general mechanisms:

1. Feeble coupling to SM
2. Scale suppression
3. Light new particle (m) — phase space suppression

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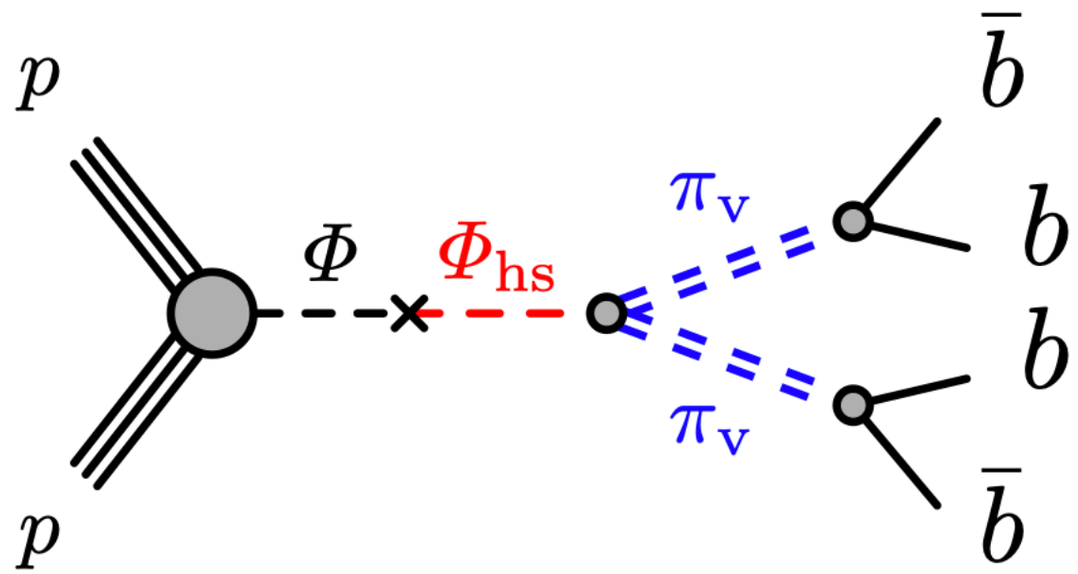
Three general mechanisms:

1. Feeble coupling to SM

e.g: Higgs portal to hidden sectors

Accessing dark matter/sectors



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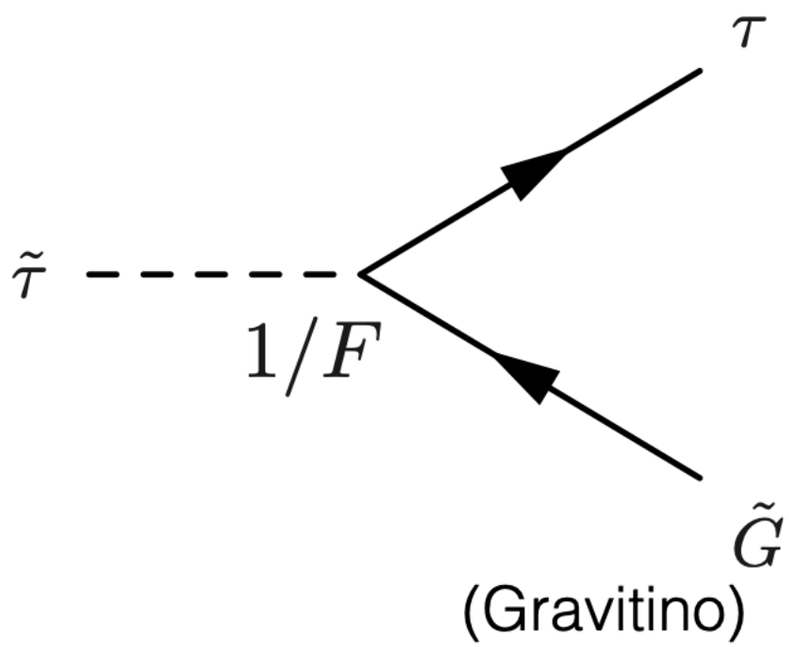
2. Scale suppression

e.g: Gauge mediated SUSY

Decay to gravitino ($\tilde{G}$) suppressed by SUSY-breaking scale (F)



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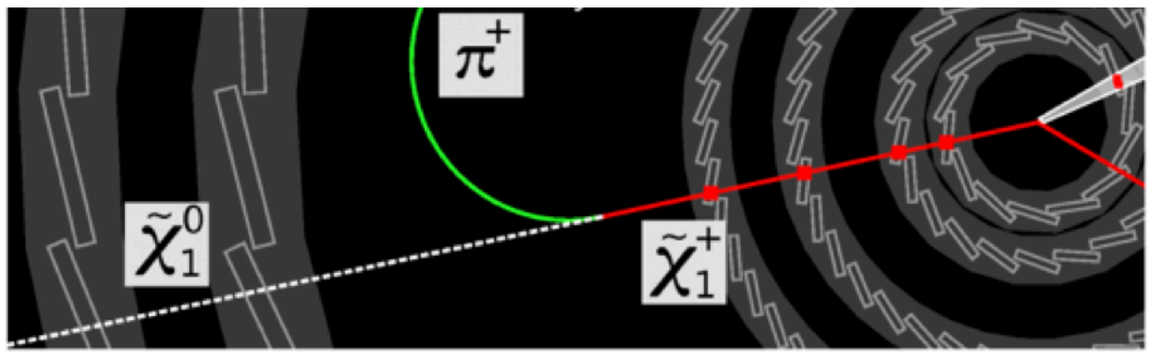
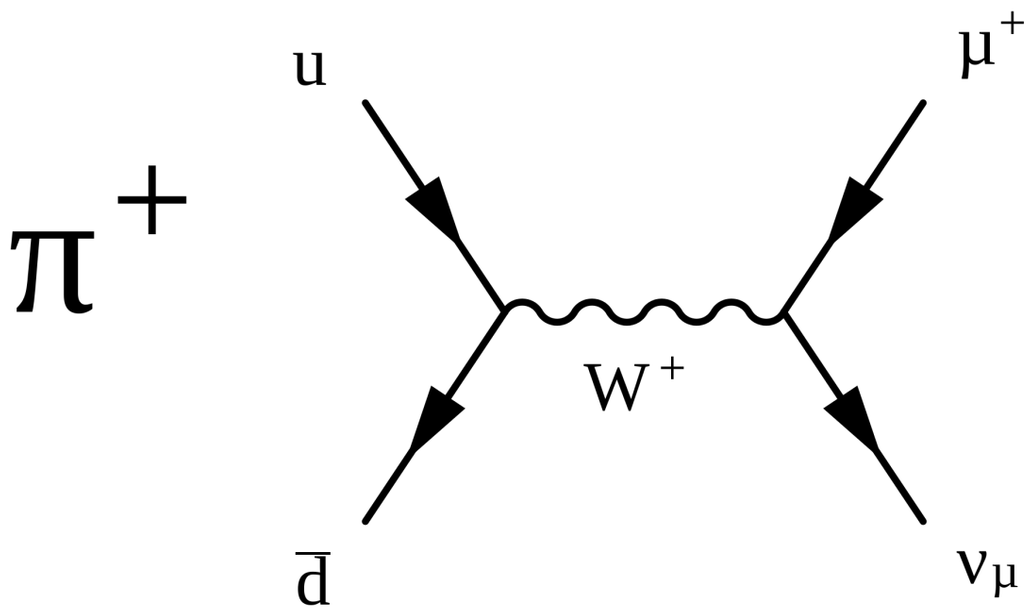
Small mass splitting between NLSP and LSP



Long-lived Particles in SM

The $\pi^{\pm}$ decay



e.g. $\pi^{\pm} \rightarrow \mu^{\pm}\nu_{\mu}$ ($c\tau_0 \sim 7.8$m)

small coupling

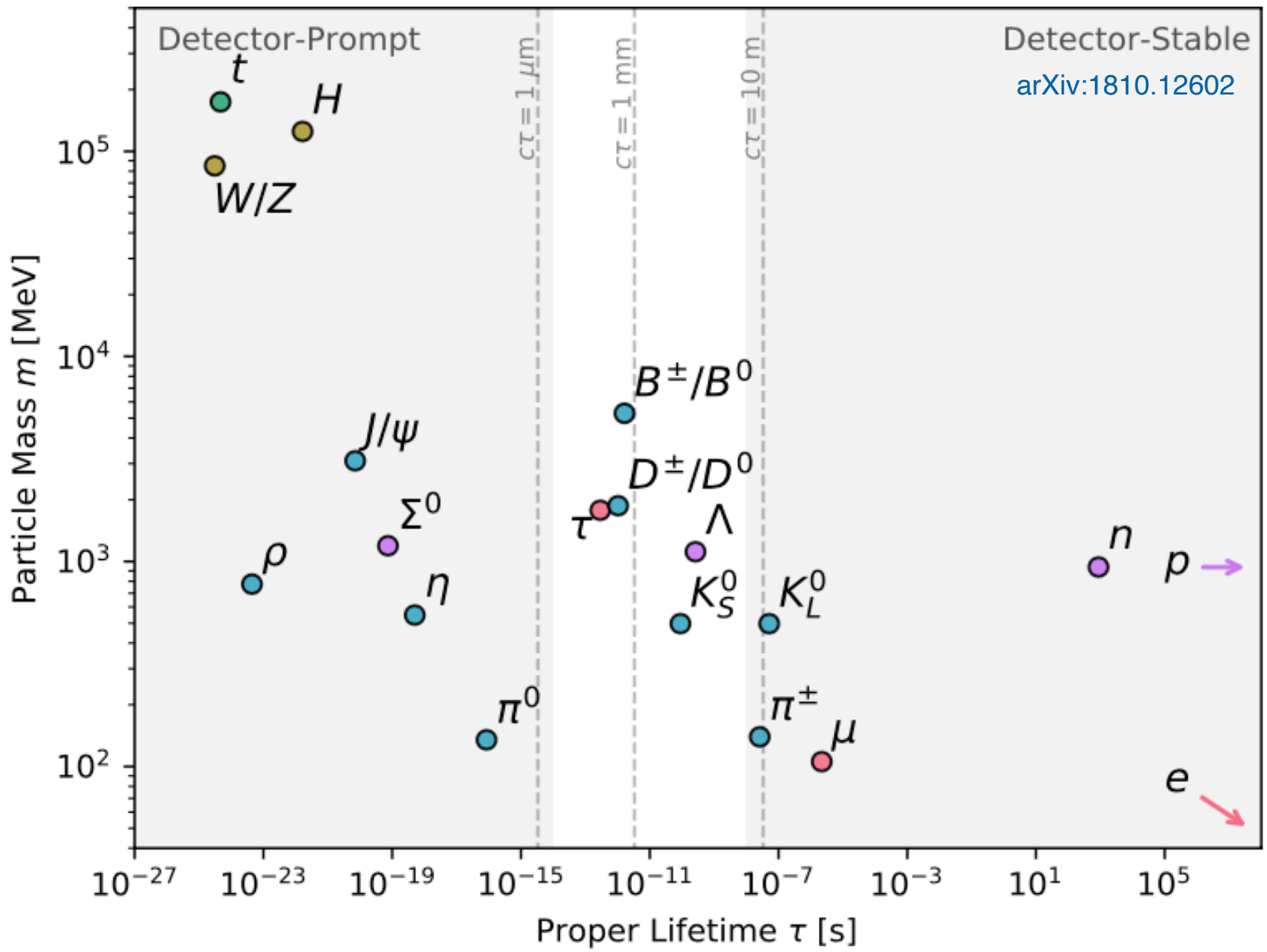
$$\frac{1}{\tau} = \frac{f_\pi^2 |V_{ud}|^2}{256\pi m_\pi} \left[\frac{g^2}{M_W^2} \frac{m_\mu}{m_\pi} (m_\pi^2 - m_\mu^2) \right]^2$$

heavy mediator

compressed spectra

$\pi^{\pm}$ lifetime due to all three mechanisms

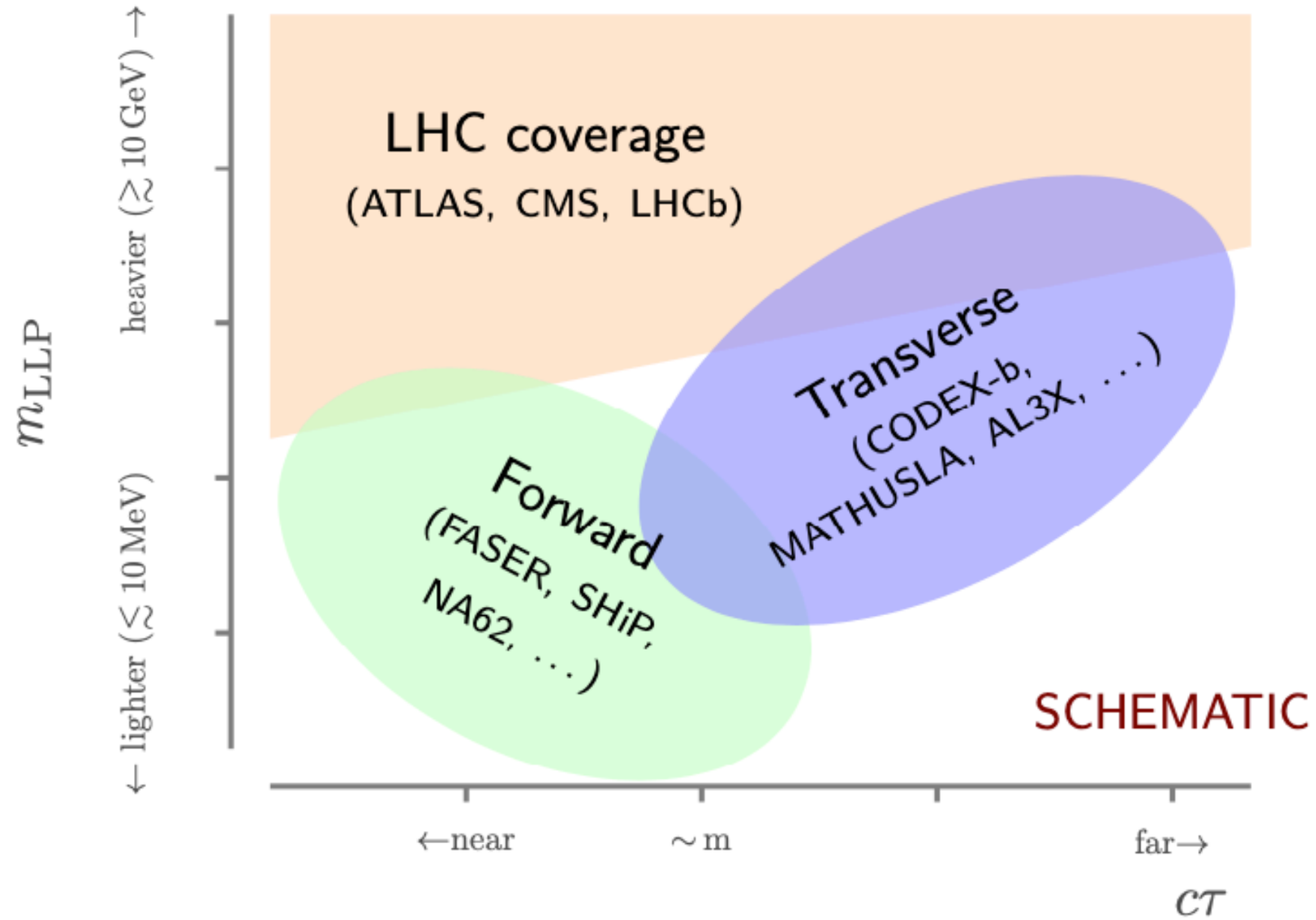
Long-lived Particles in SM



SM great example of fundamental laws giving rise to LLP

LHC and LLPs

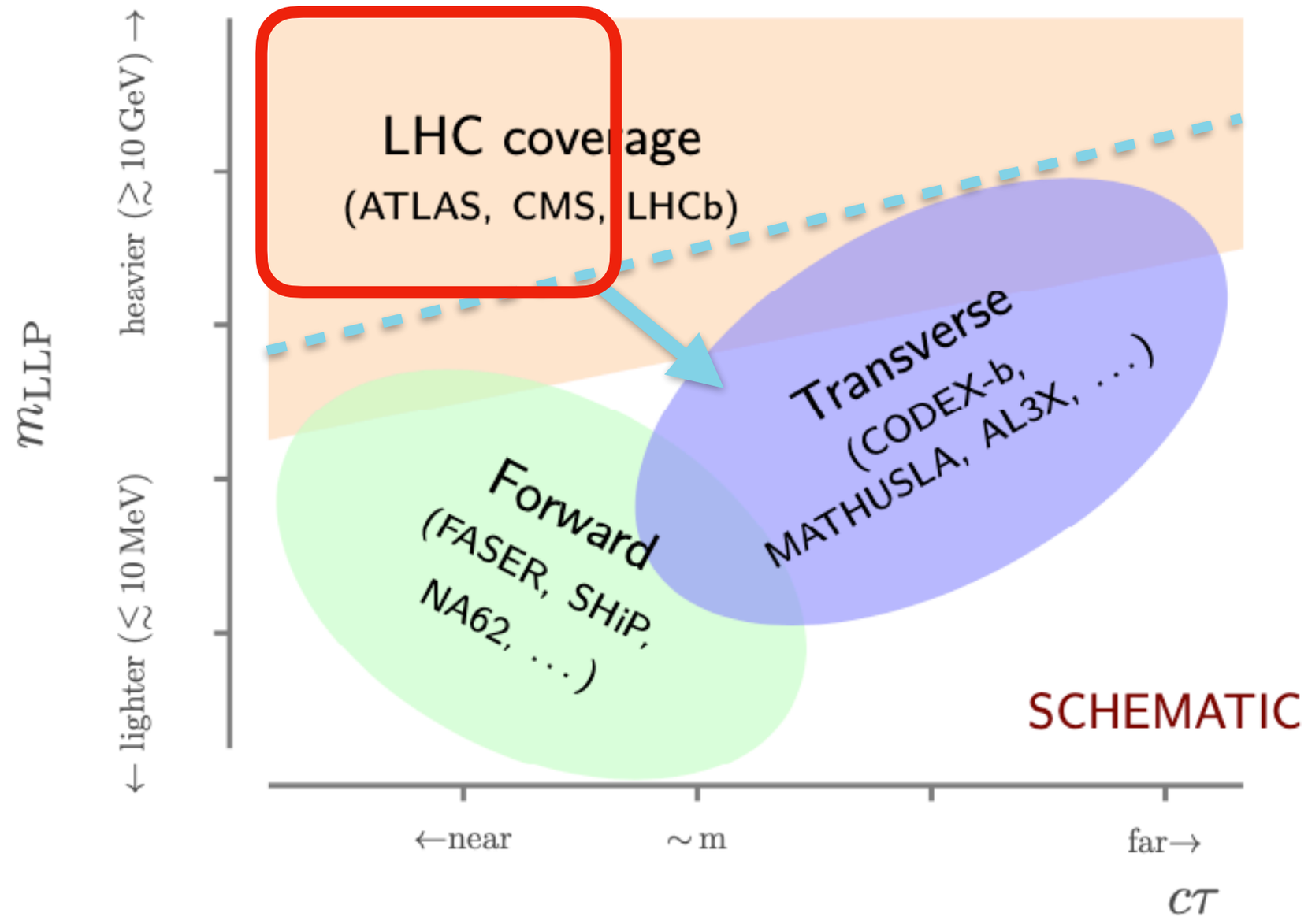
arxiv:1911.00481 — CODEX-b



- 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 is doing well for **cτ < 1m** and **m_{LLP} > 50 GeV**
- Enabled by precision tracker: displaced jets

CMS Plays a Crucial Role on LLPs

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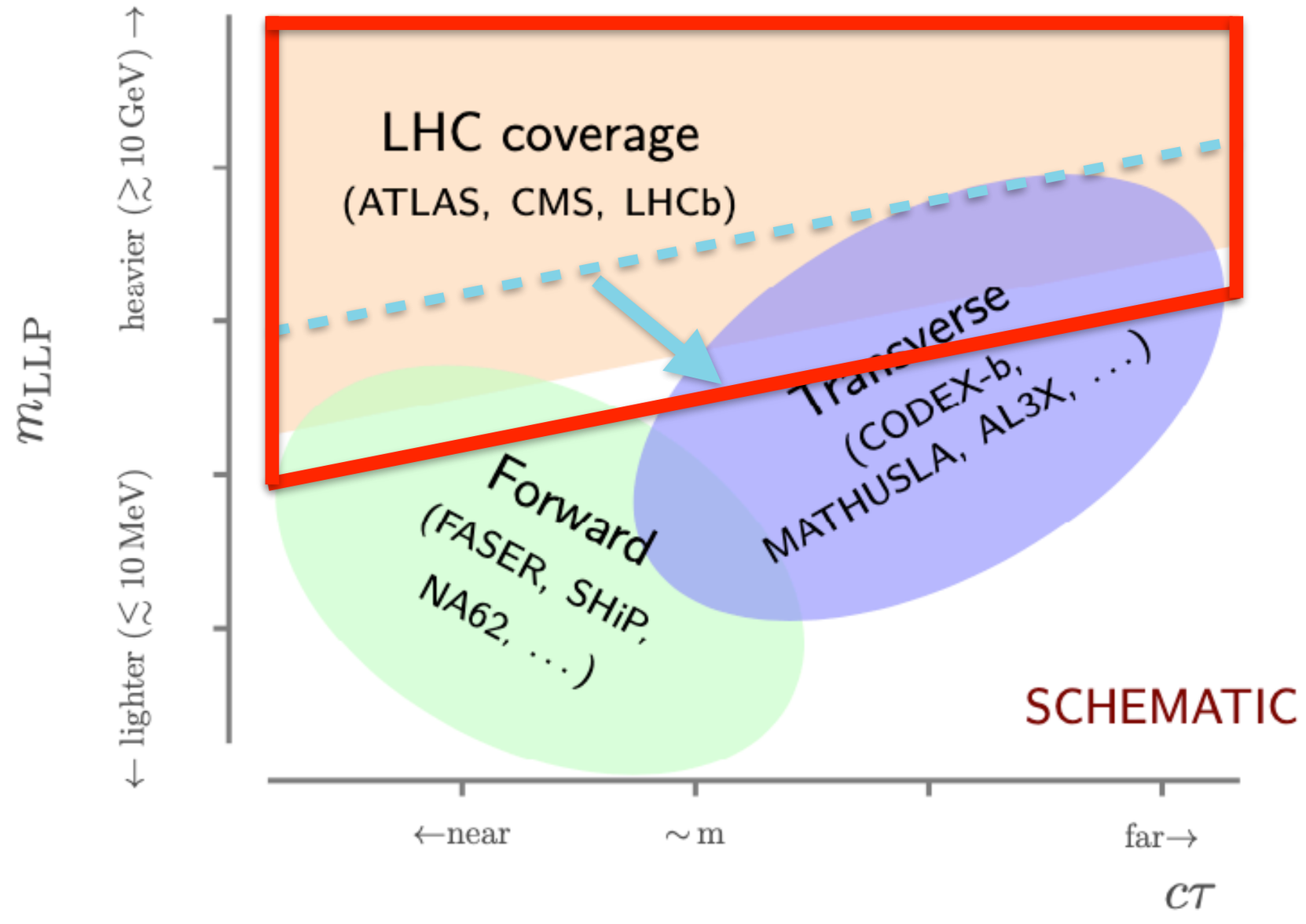
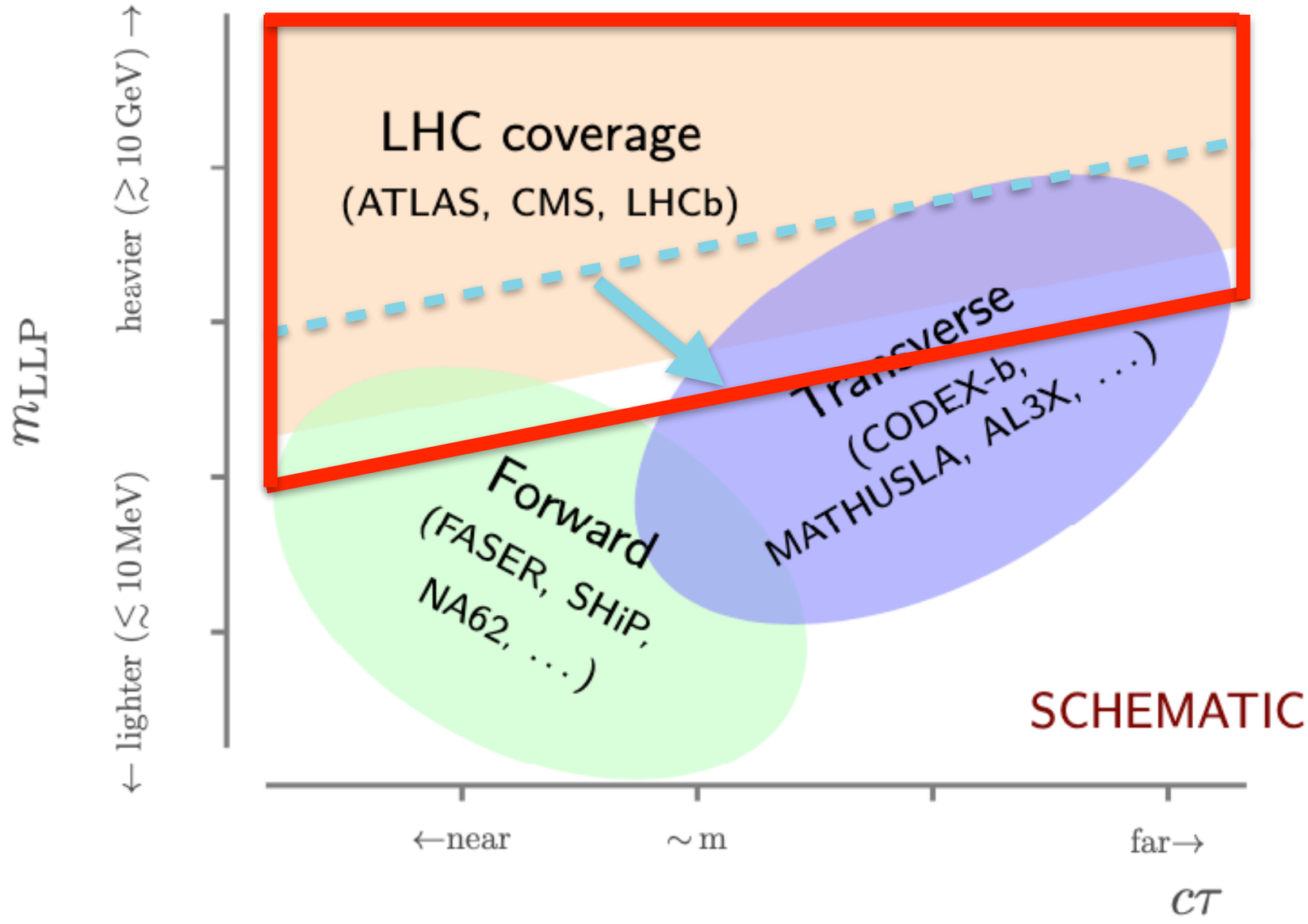


- Goal: close coverage gaps and extend CMS reach
- Strategy: Enable a large cτ and light LLP searches

CMS Plays a Crucial Role on LLPs

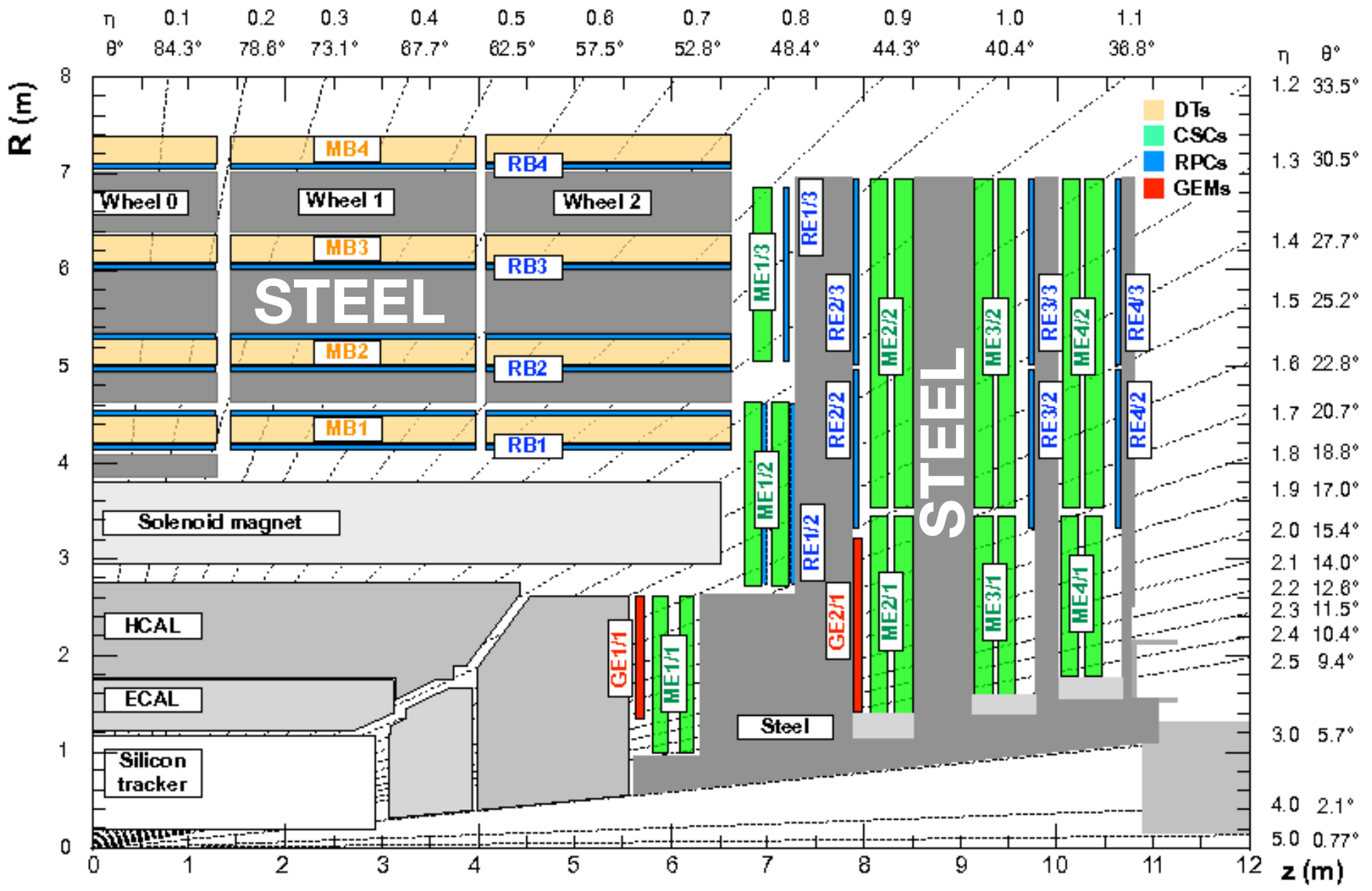
arxiv:1911.00481 — CODEX-b



- Started LPC-LLP group in 2018 to push the frontier to cover light LLP and large lifetime
- Has become a vibrant effort from 10 institutes

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

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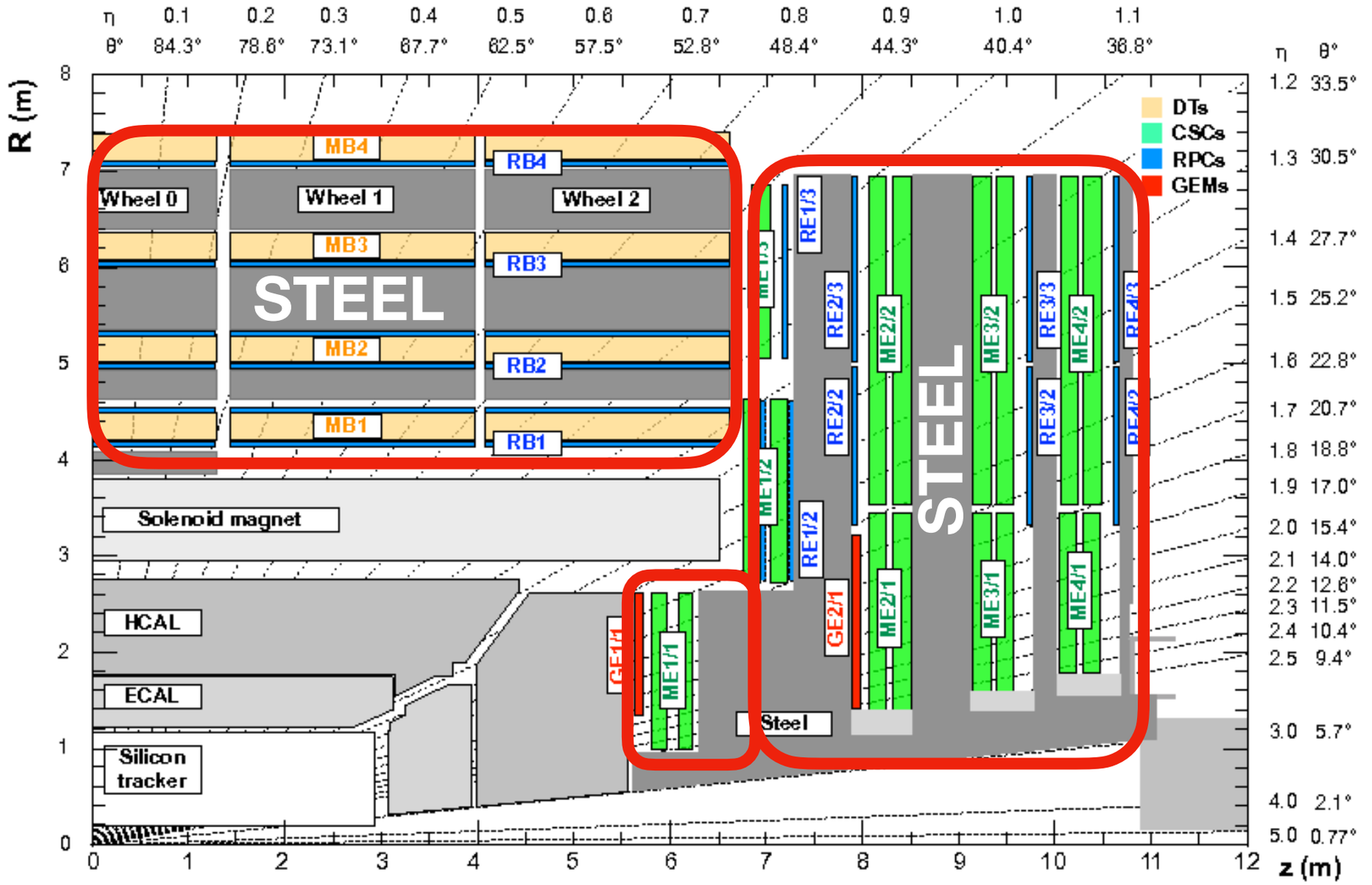

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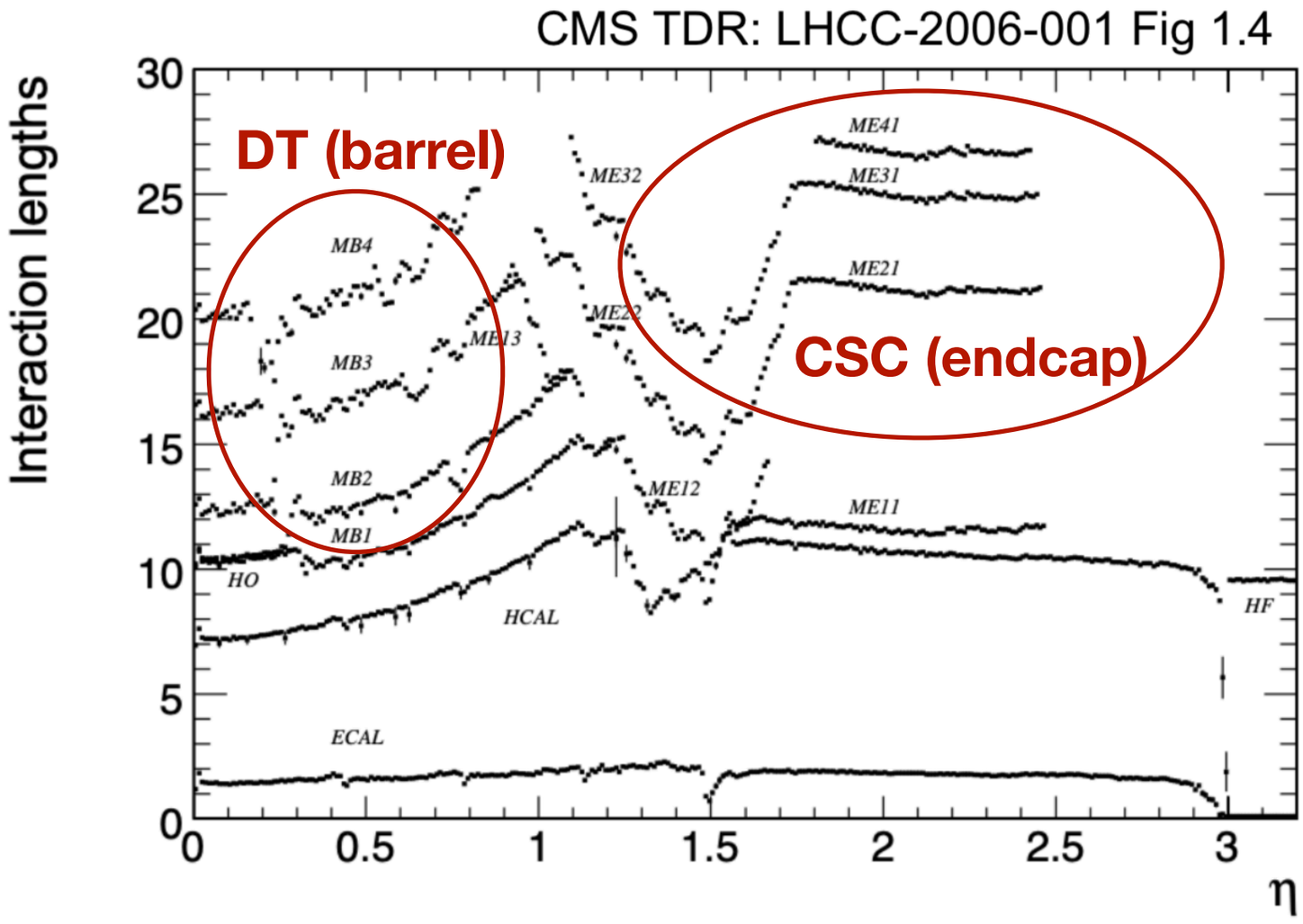
LLP Muon System Analysis

- 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**



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

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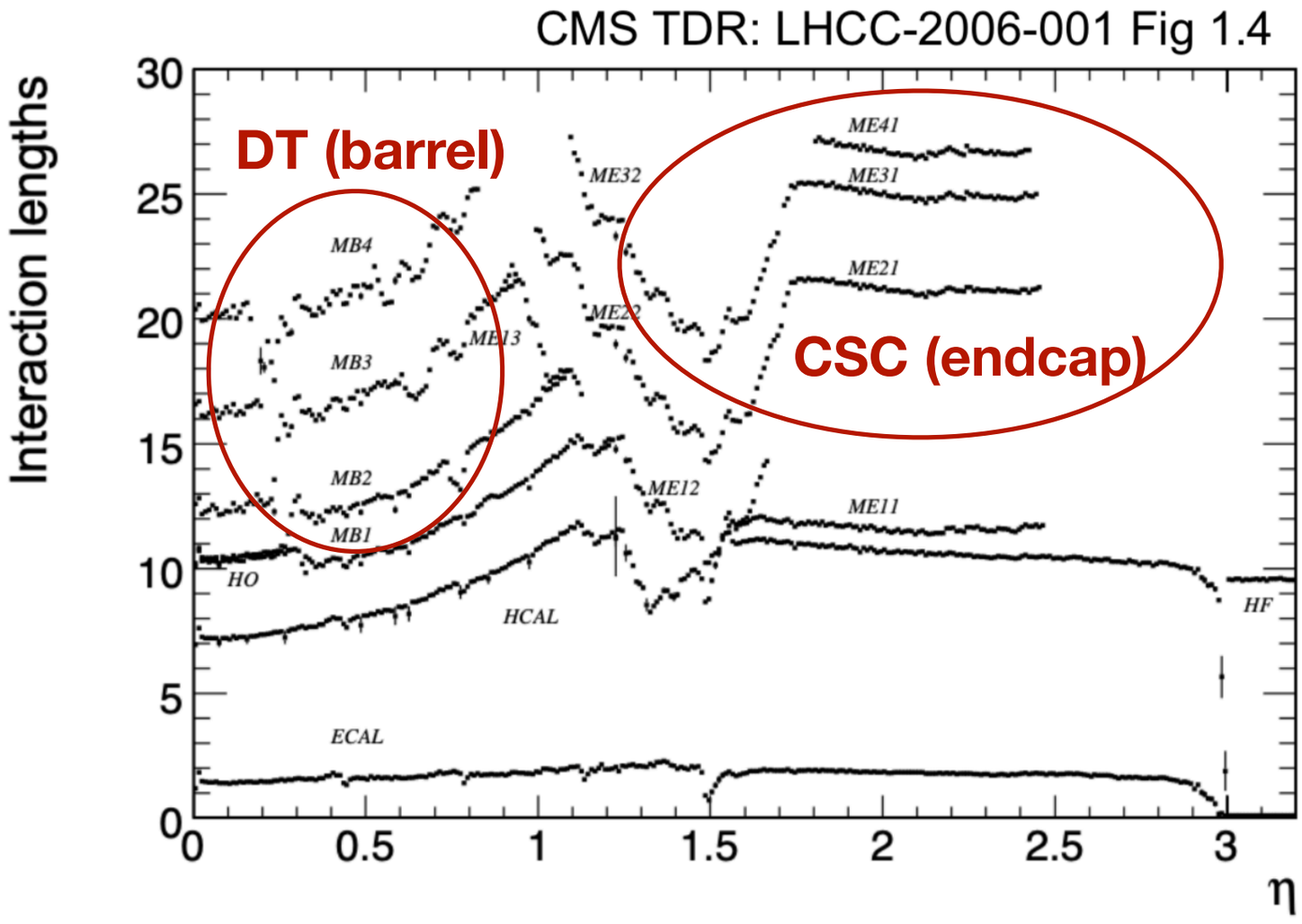
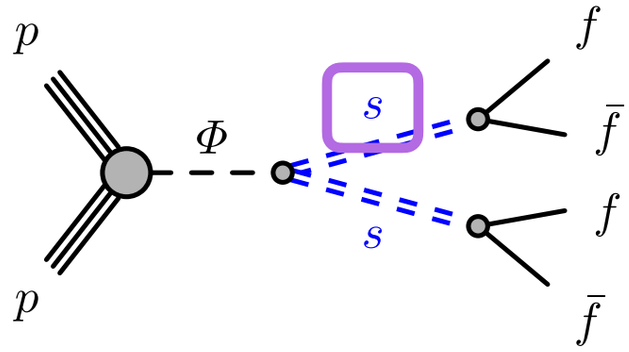
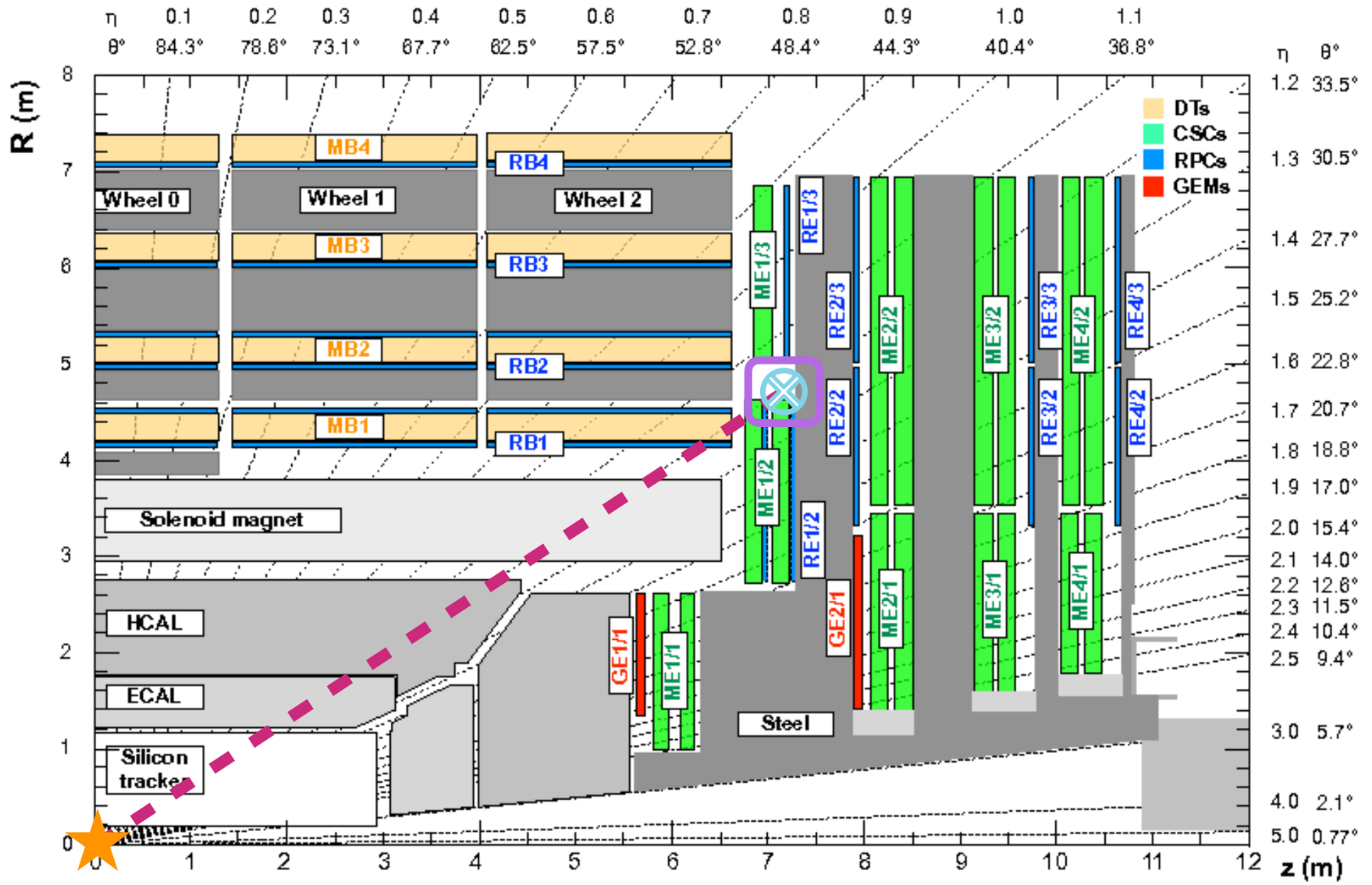


- Opportunity to **extend discovery reach at large lifetimes (> ~few meters)**

Search for LLPs in Muon System

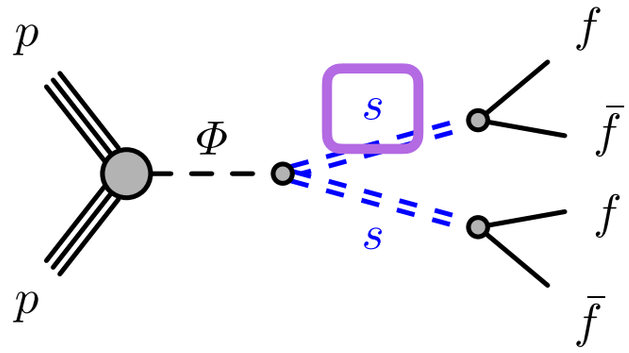
LLP decays in MS → shower





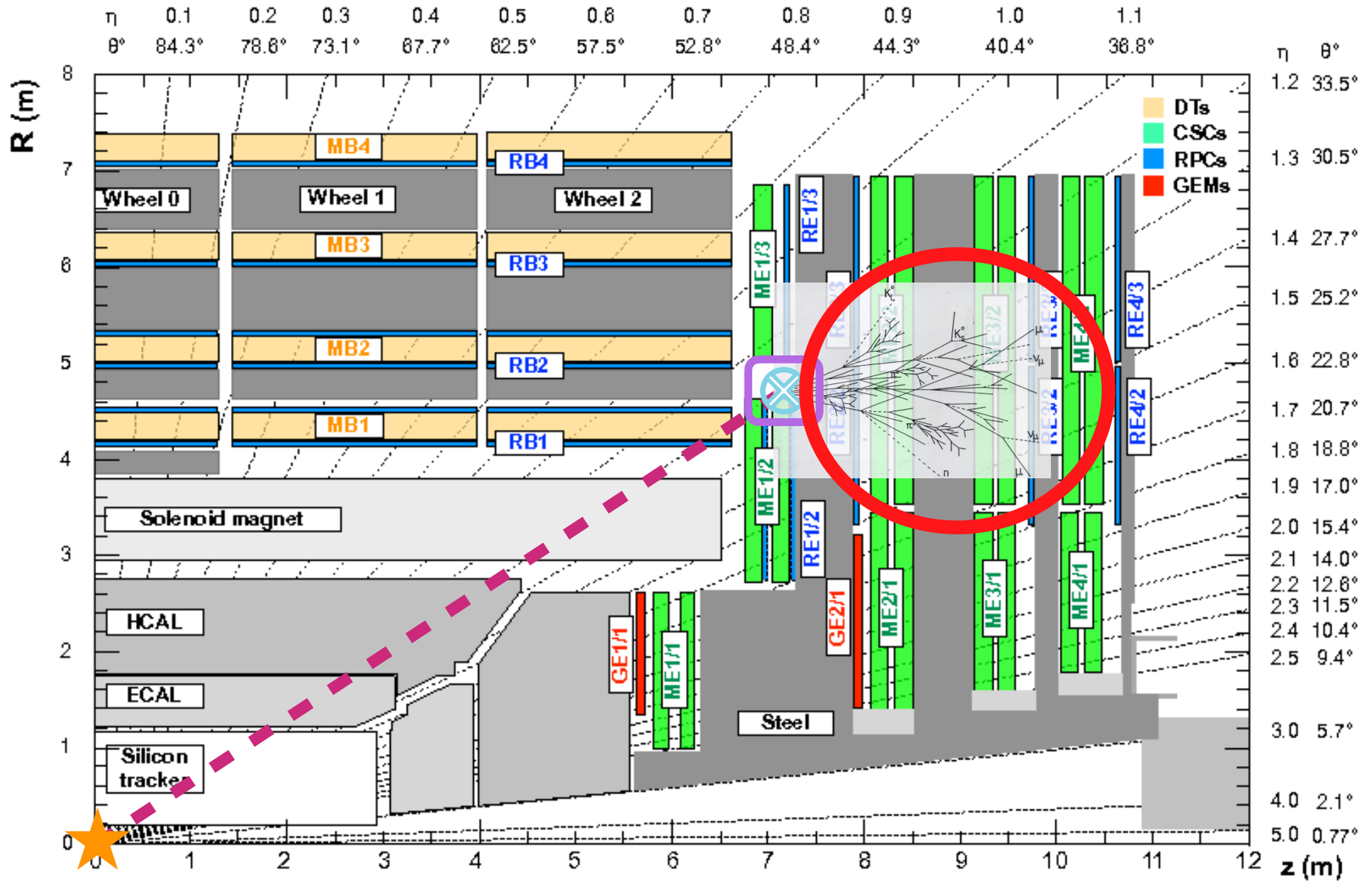
→ LLP (s) decay

Search for LLPs in Muon System



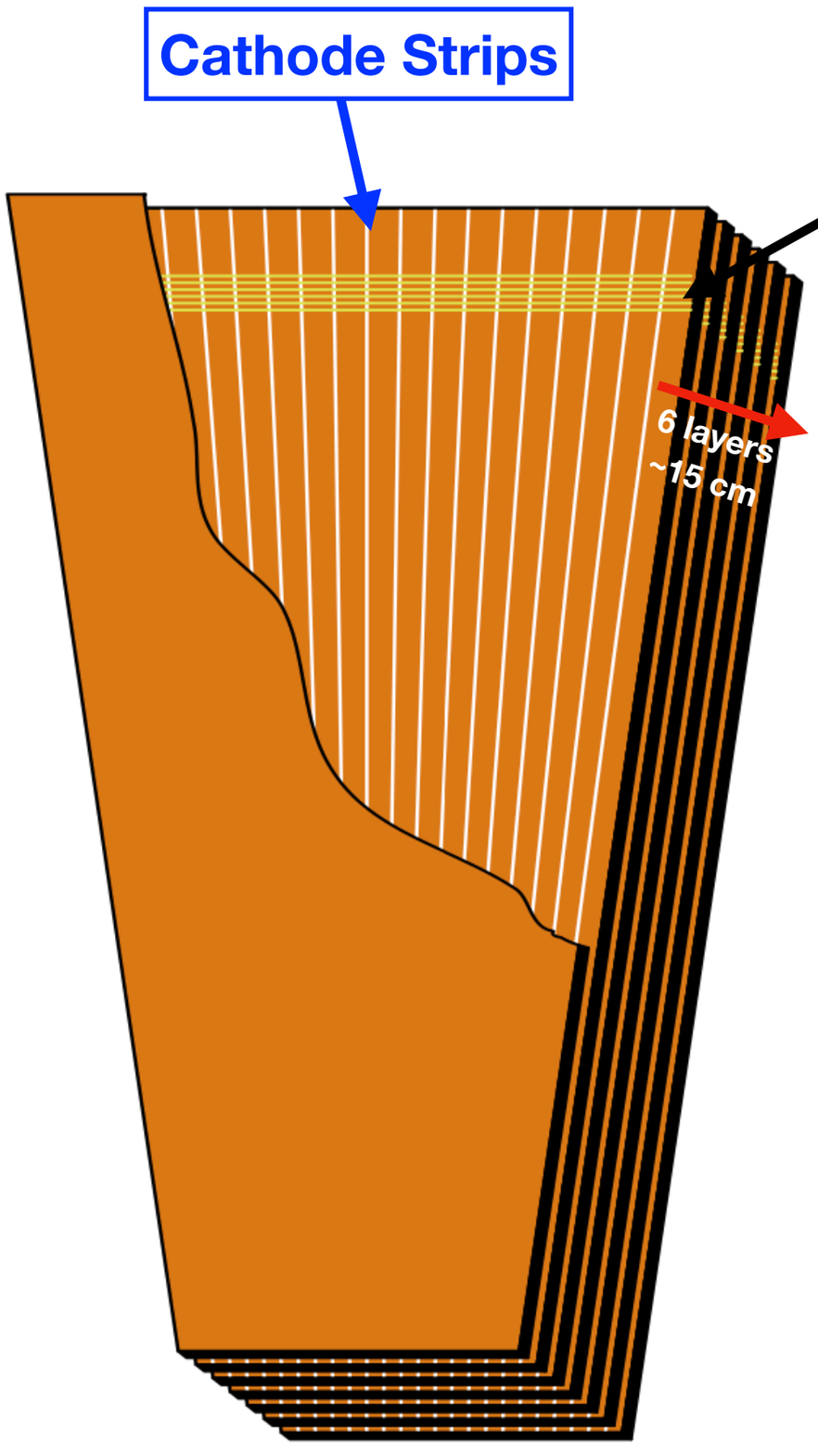
LLP decays in MS → shower

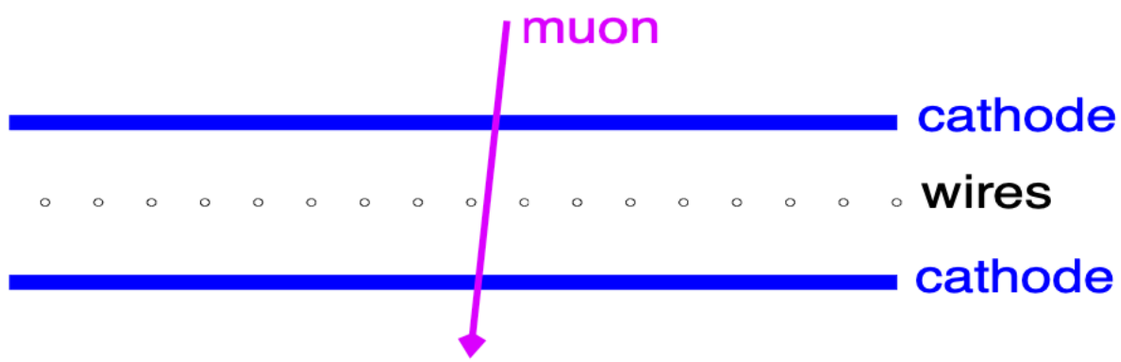
Muon System acts as sampling calorimeter

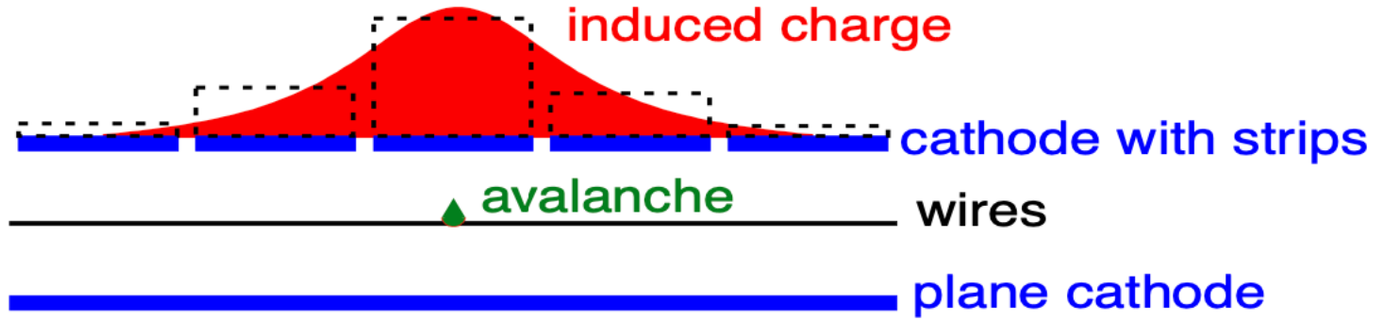


Sensitive to a broad range of LLP decays

Gas Detector



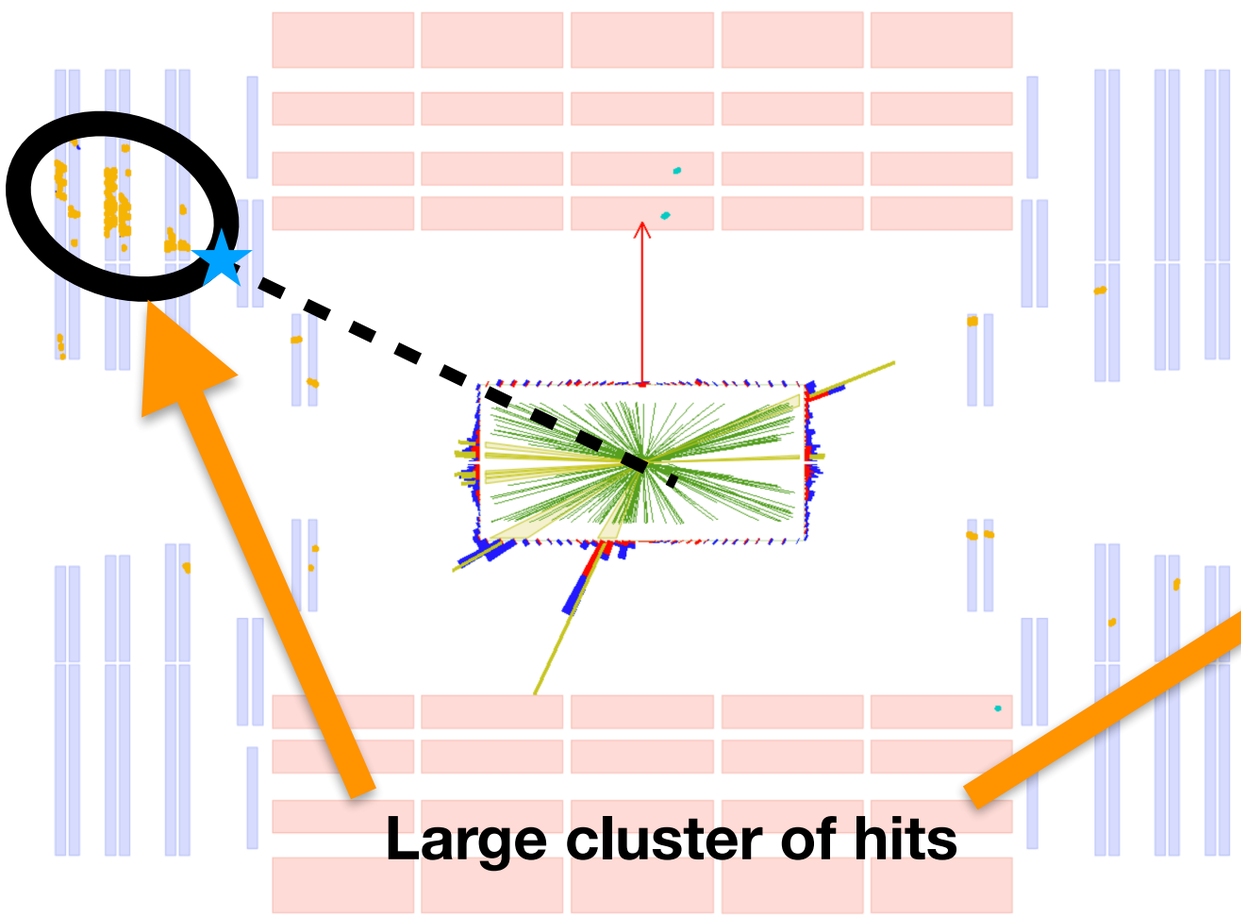


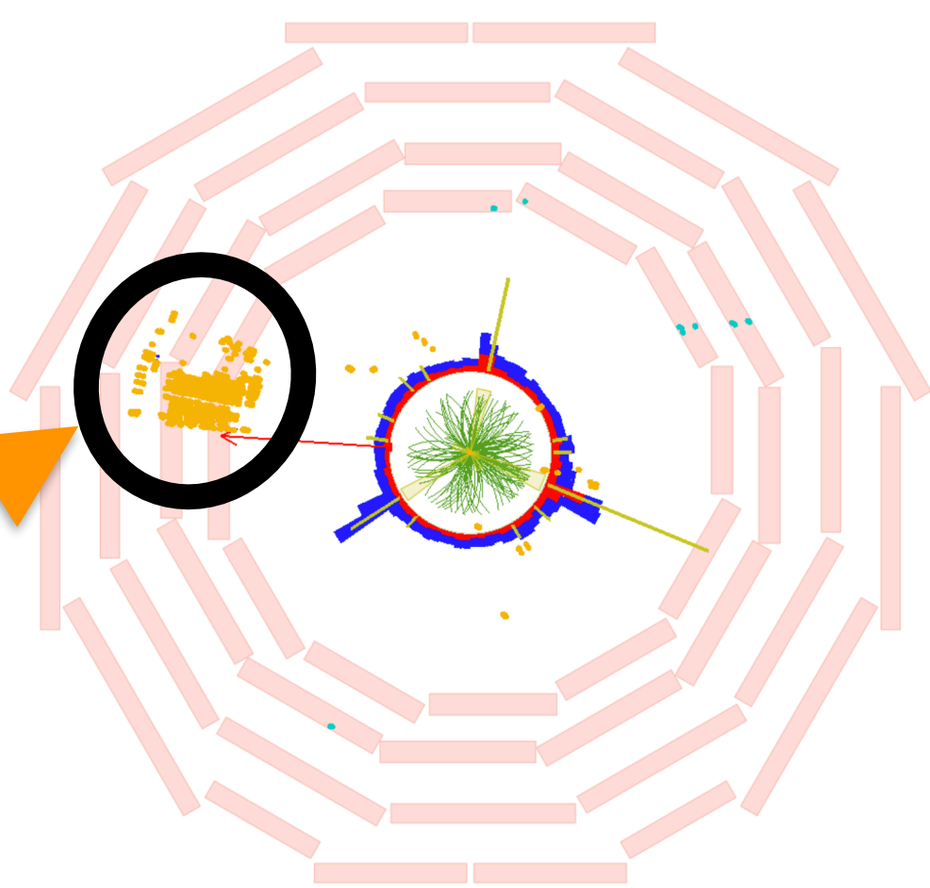


LLP Signature in Muon System

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)**



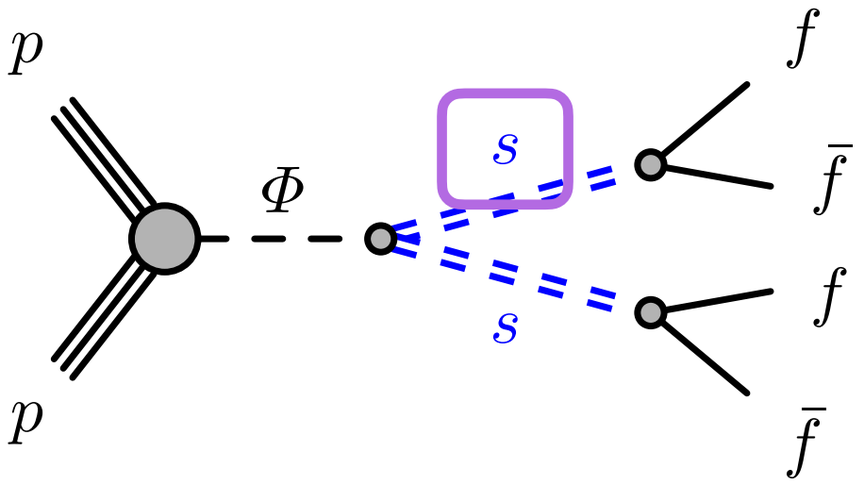


Phys. Rev. Lett. **127**, 261804

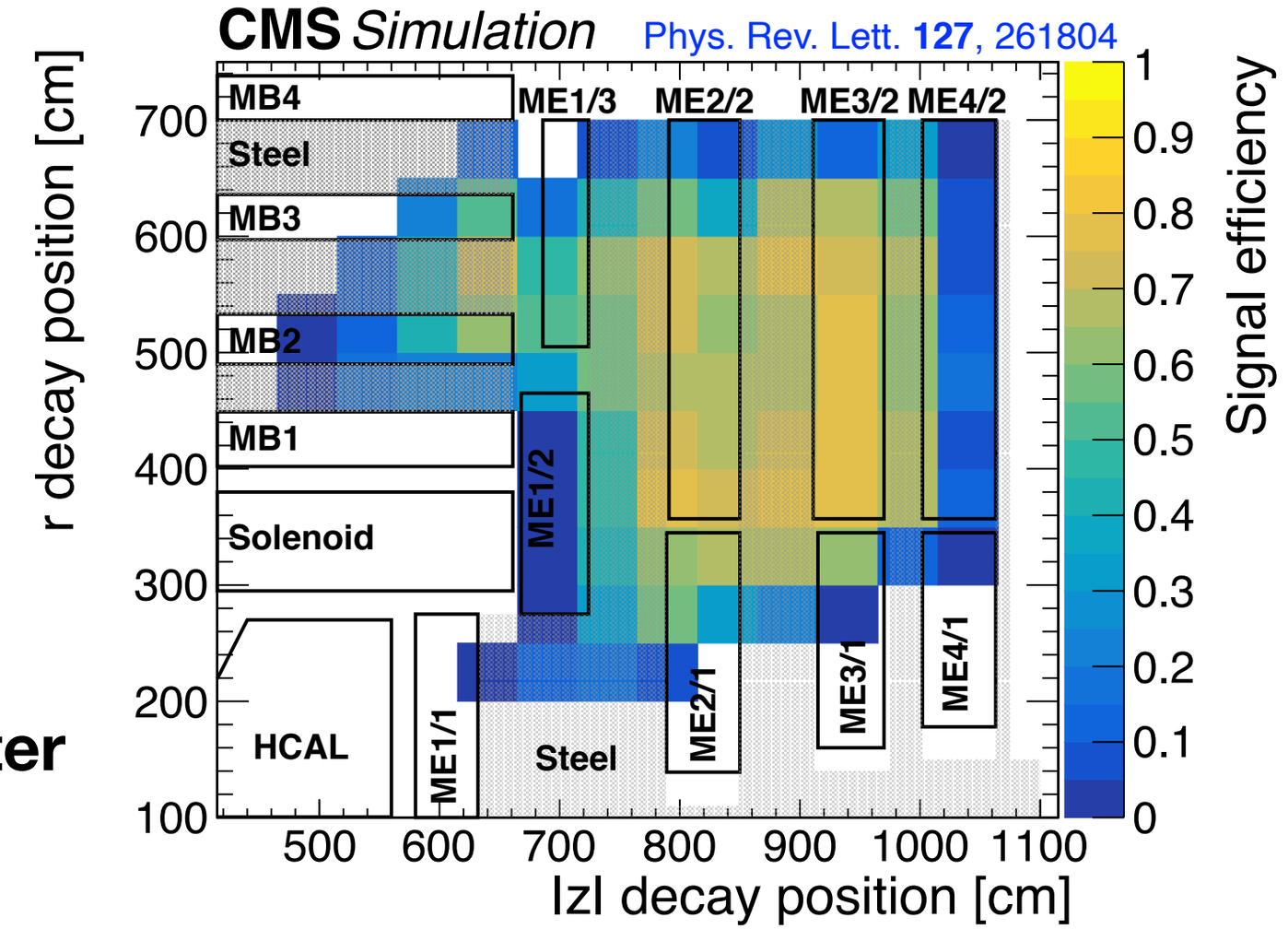
LLP Efficiency in Muon System

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

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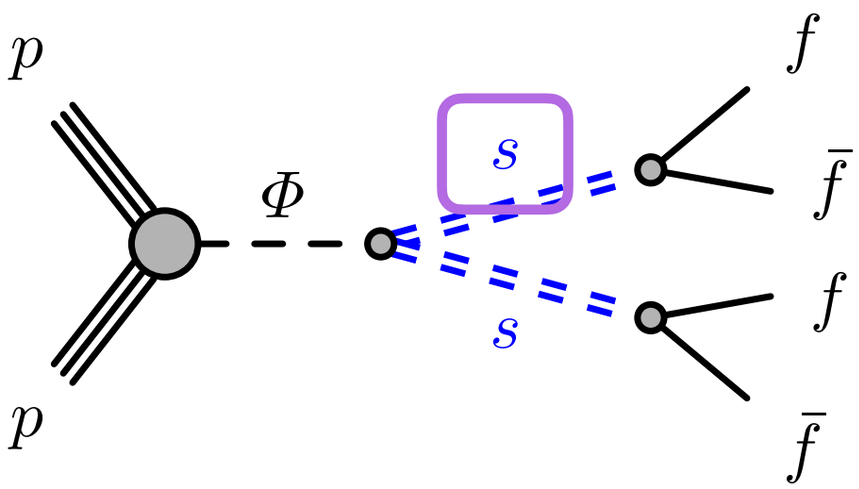

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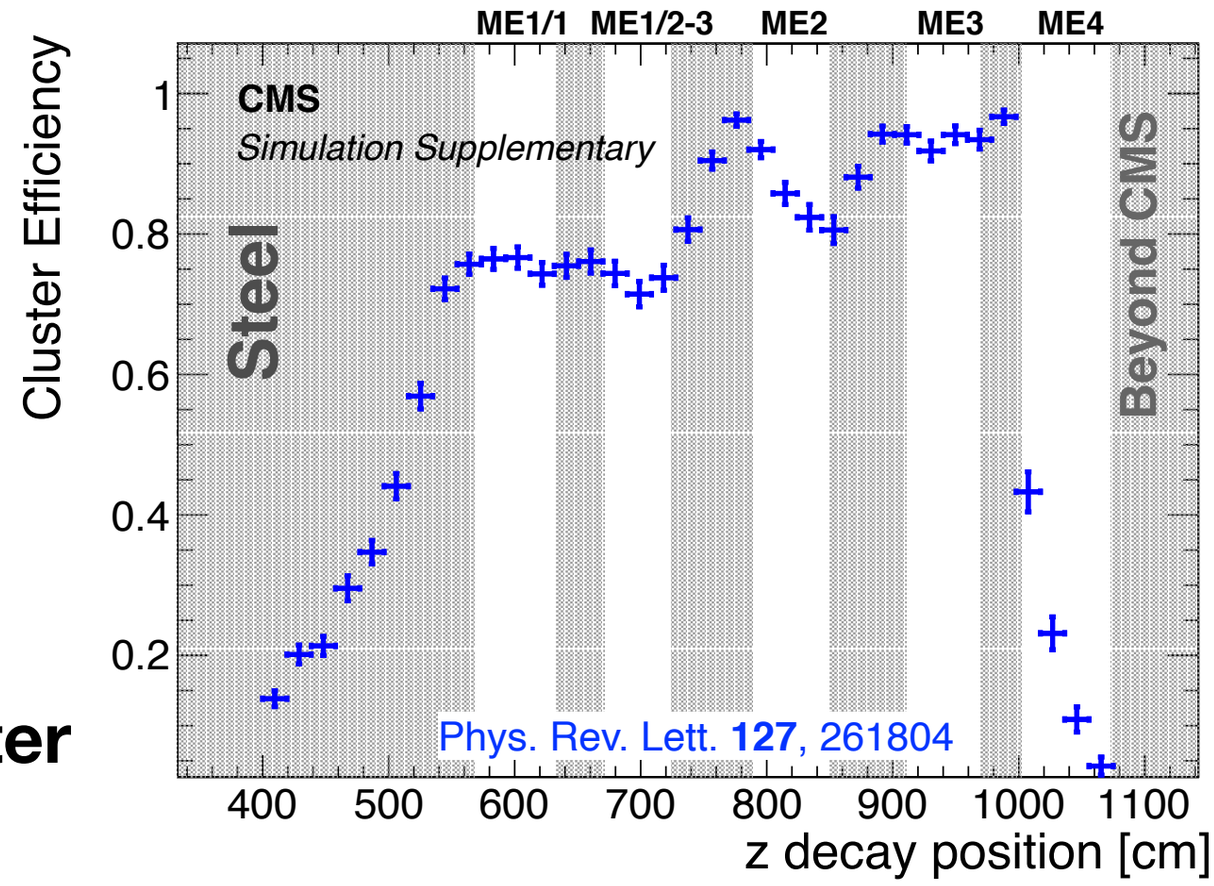
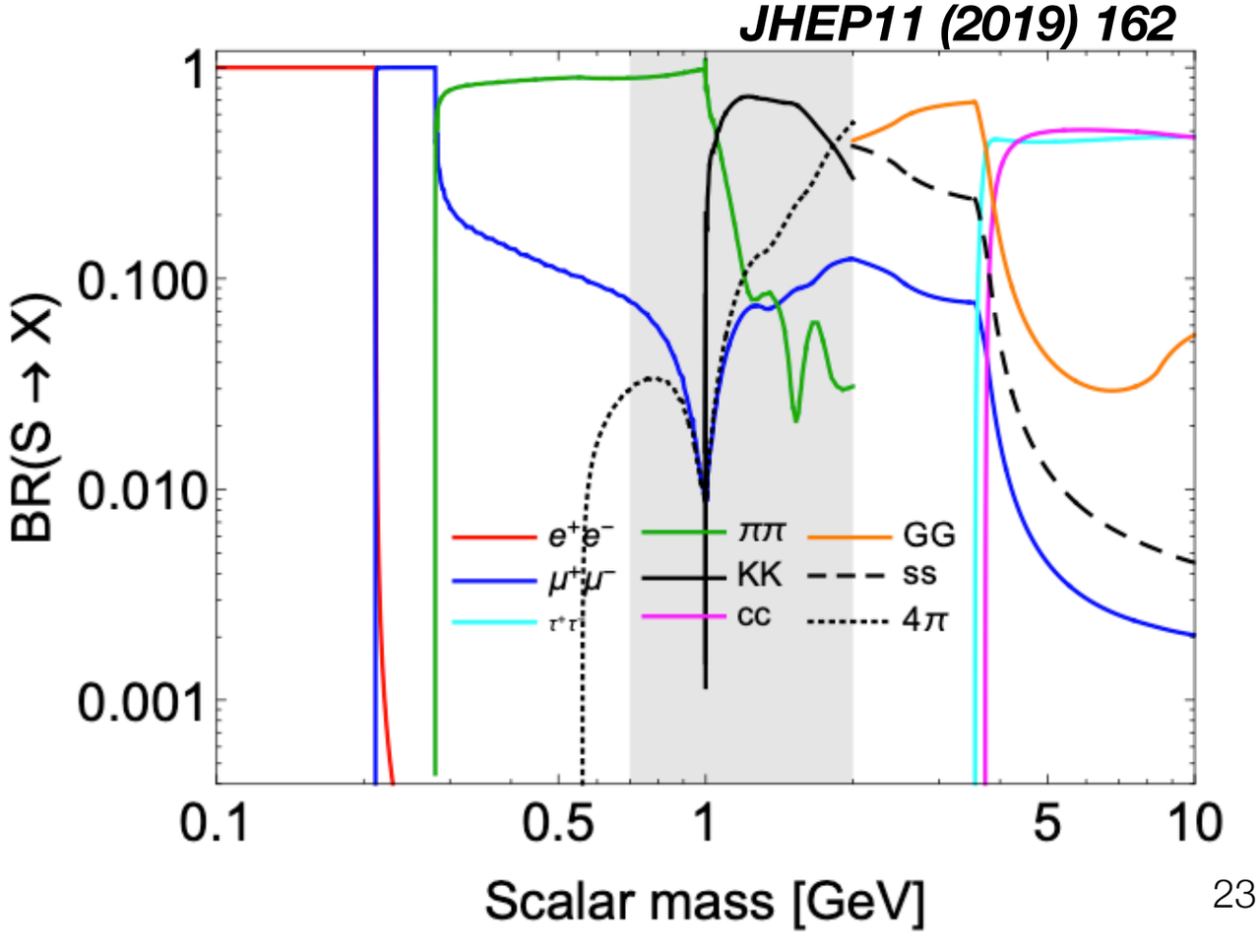
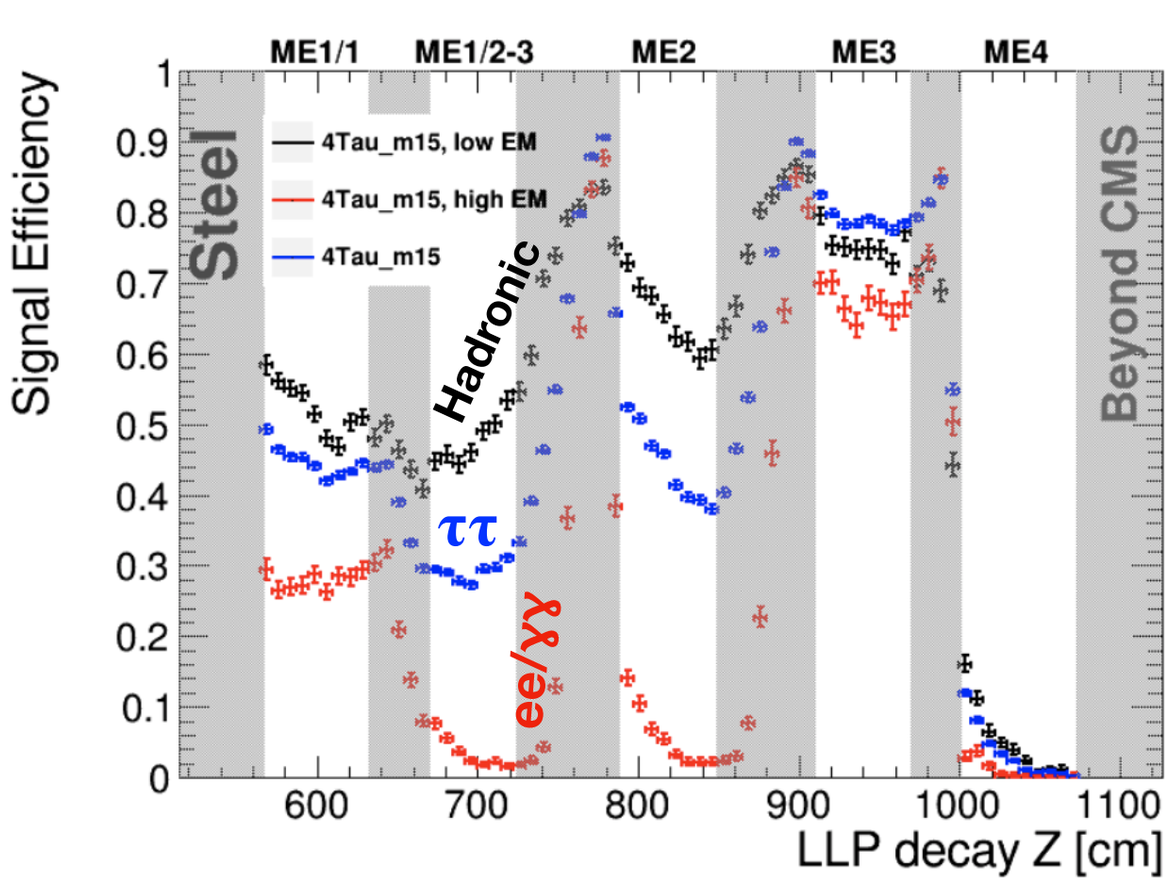


- Strong dependence on decay position (Z)
- Highly correlated with amount of steel in front of CSC

Muon System Enables Broad LLP Reach

- 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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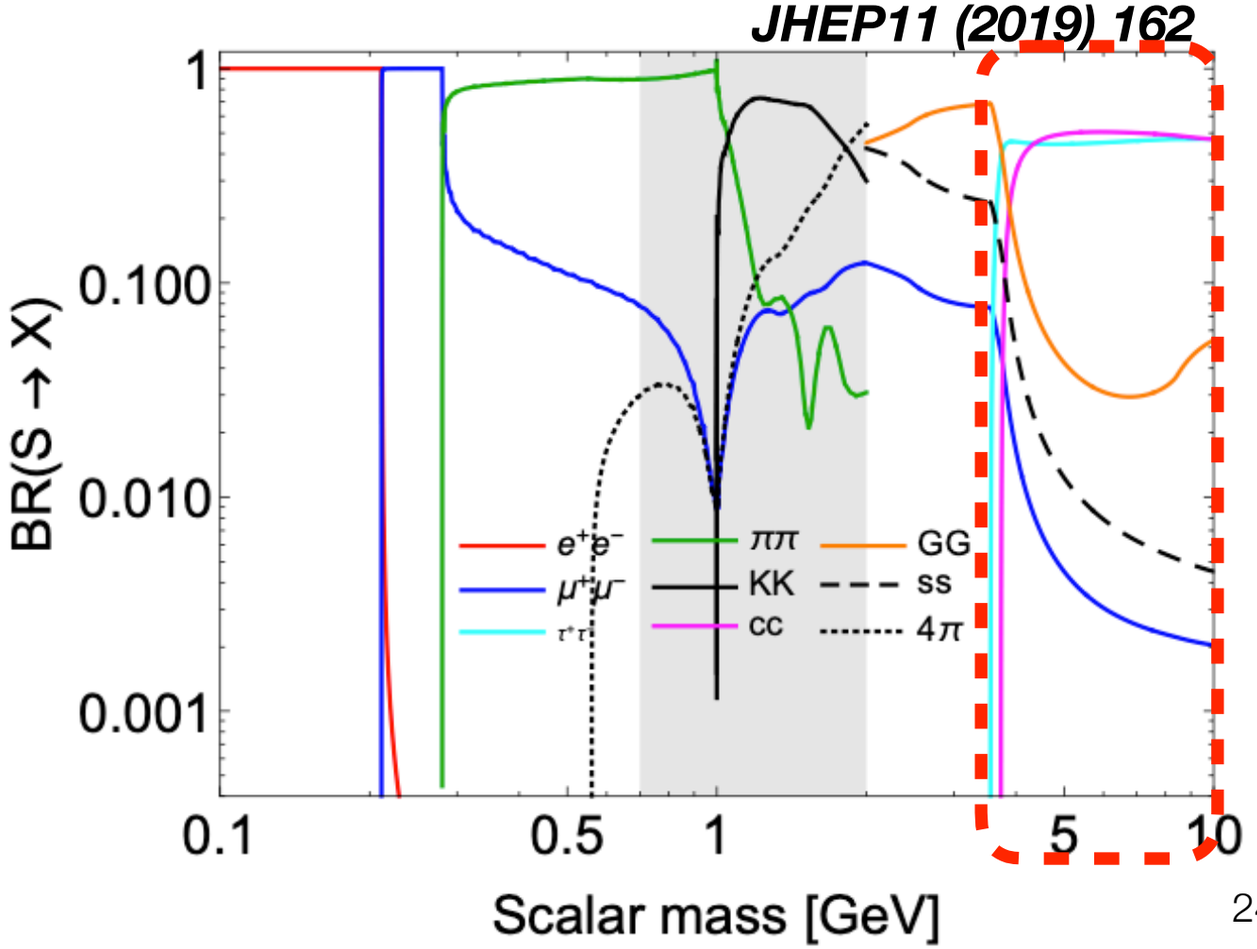

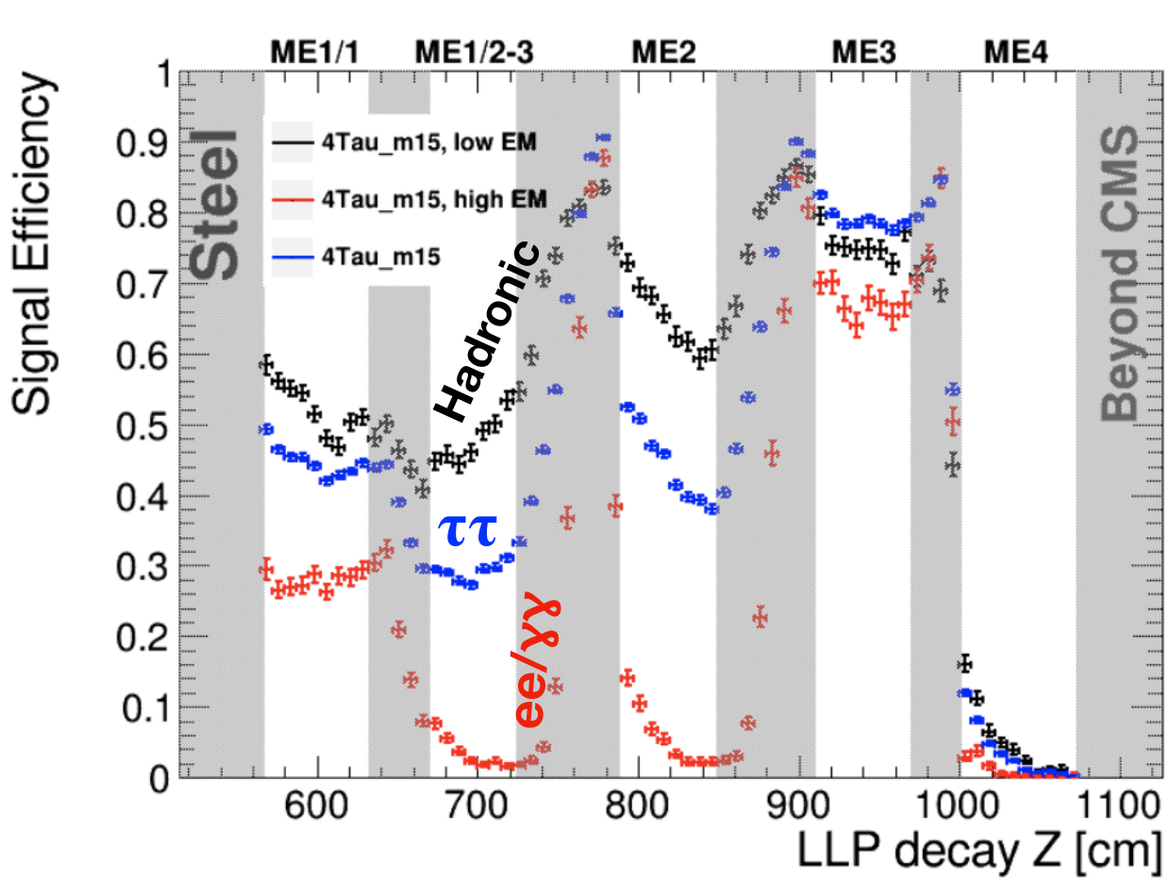

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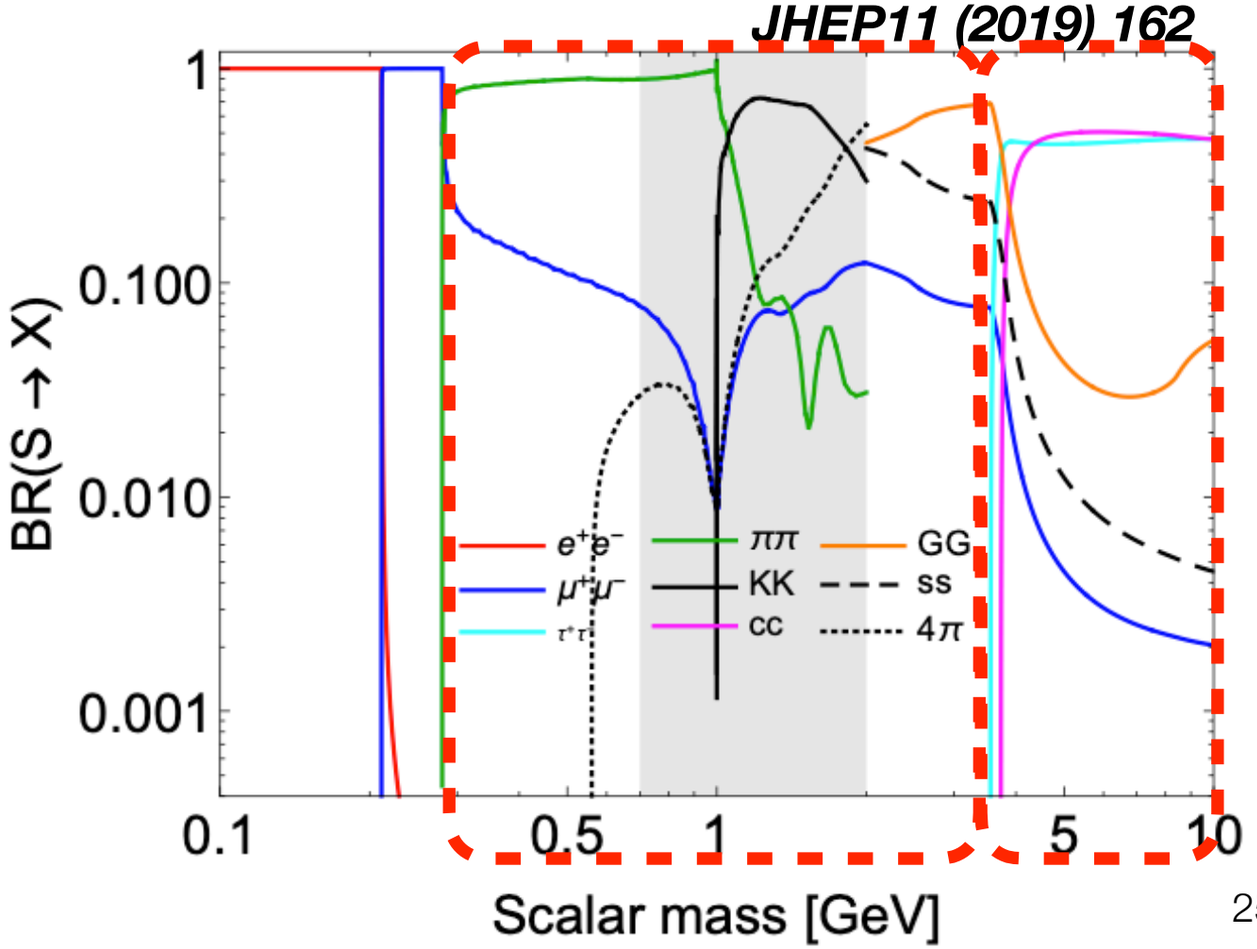

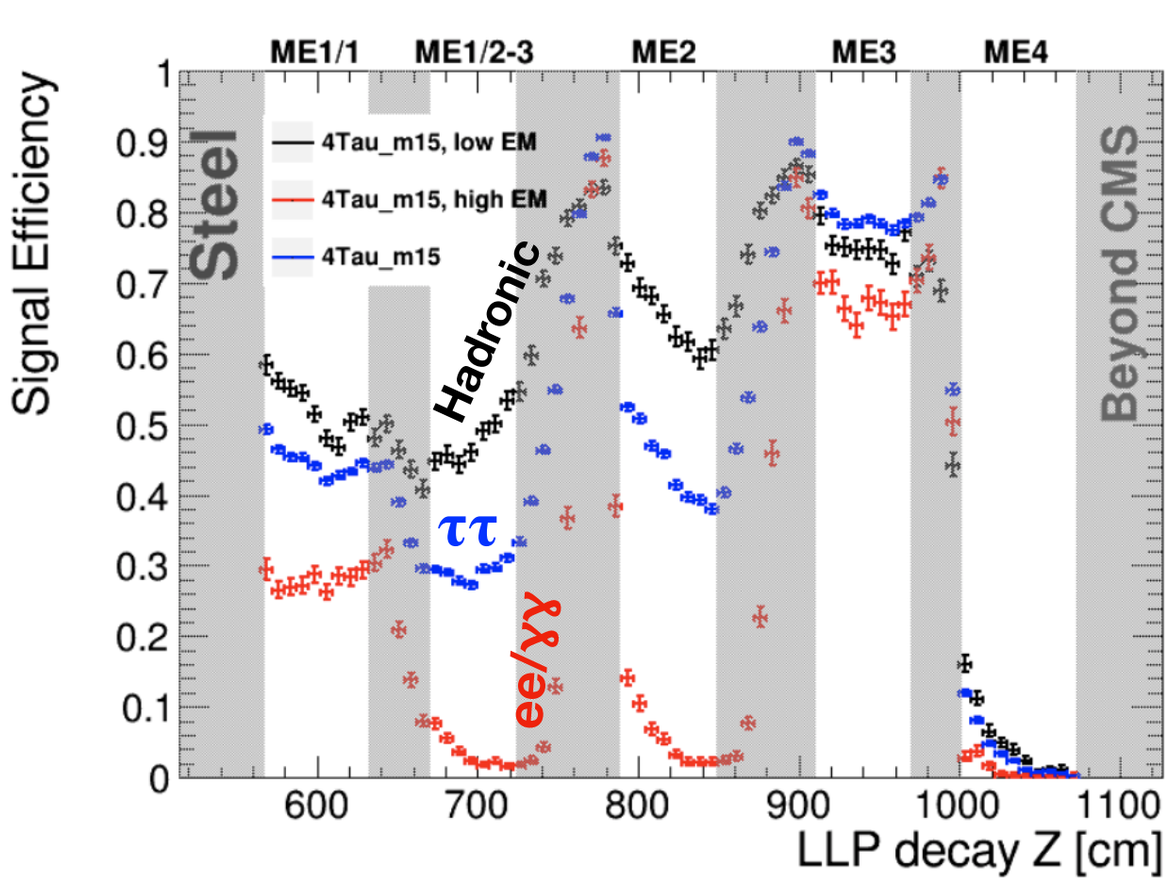

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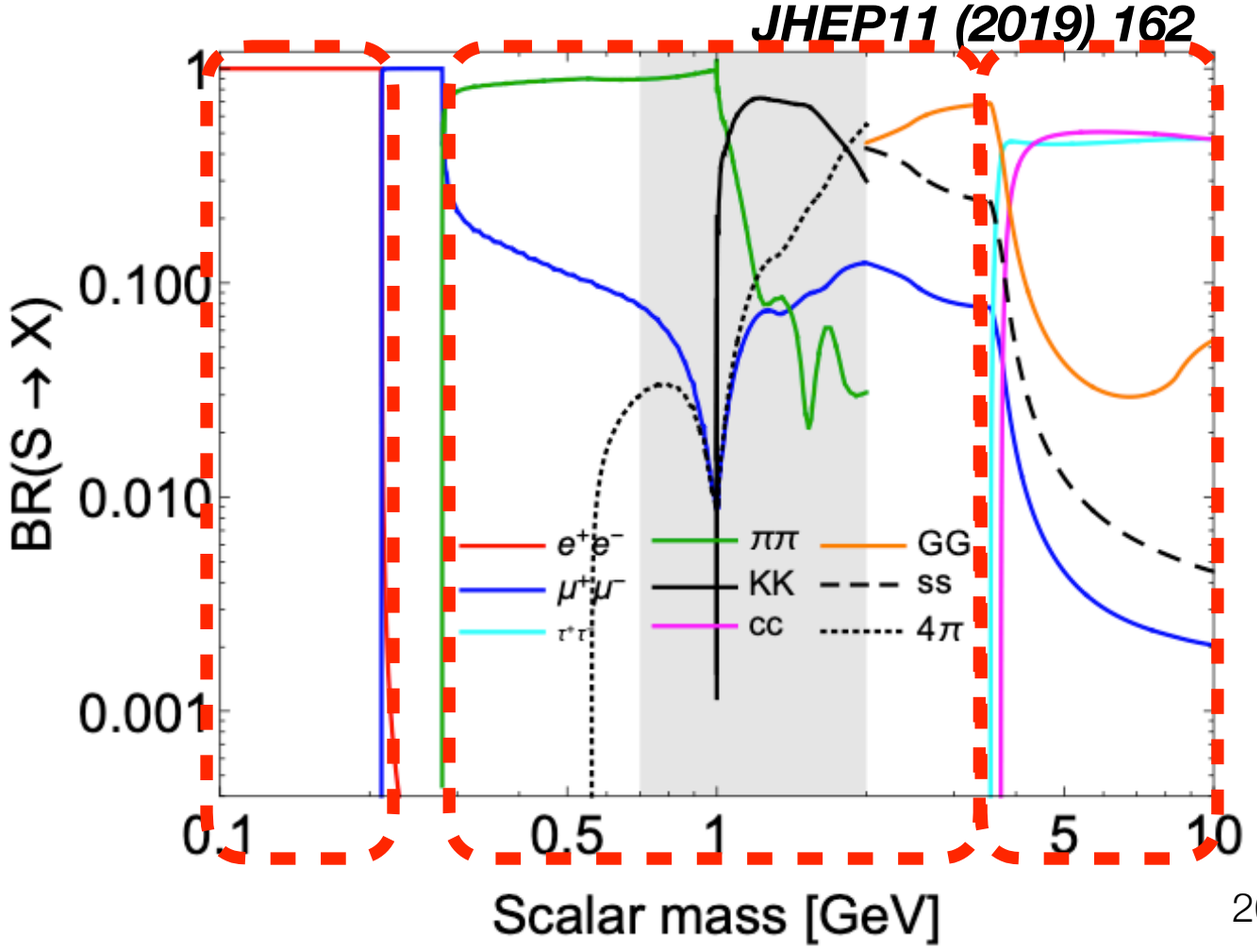
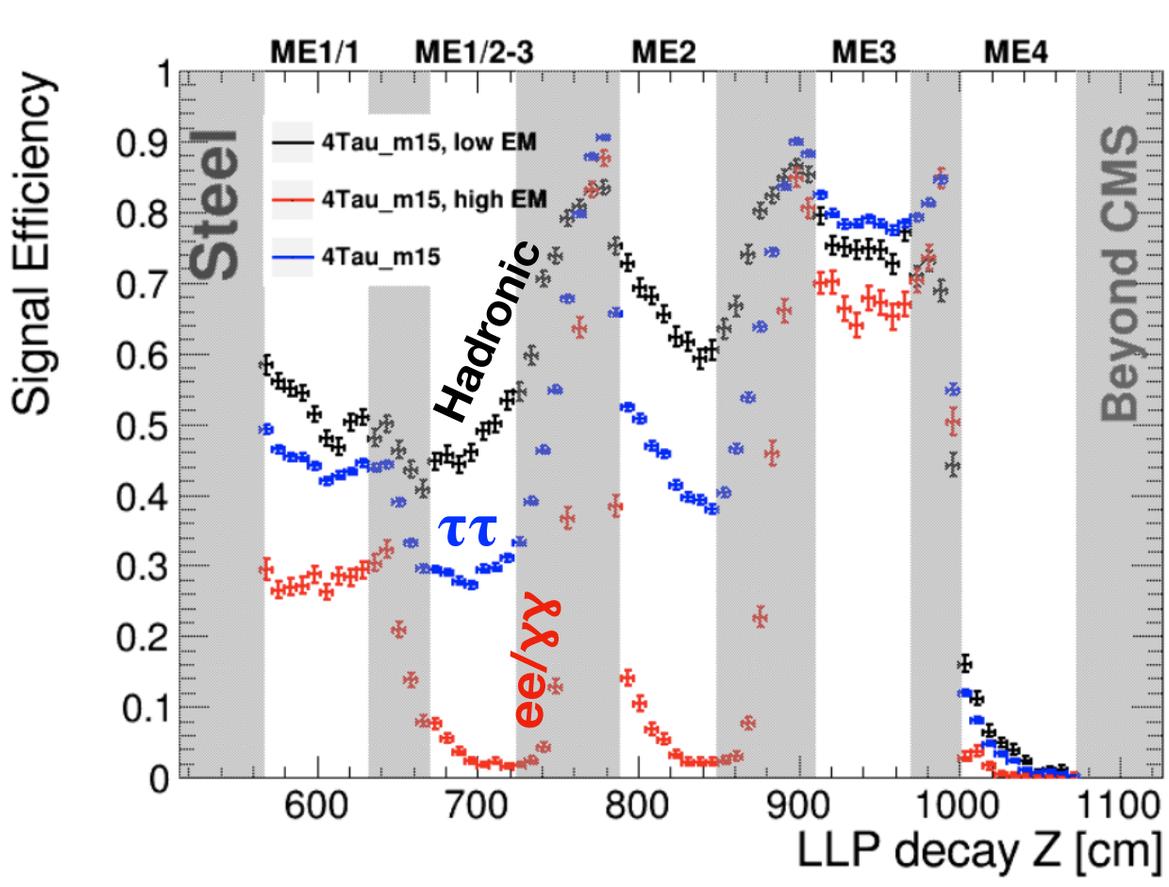




CMS Data Analysis Re-imagined

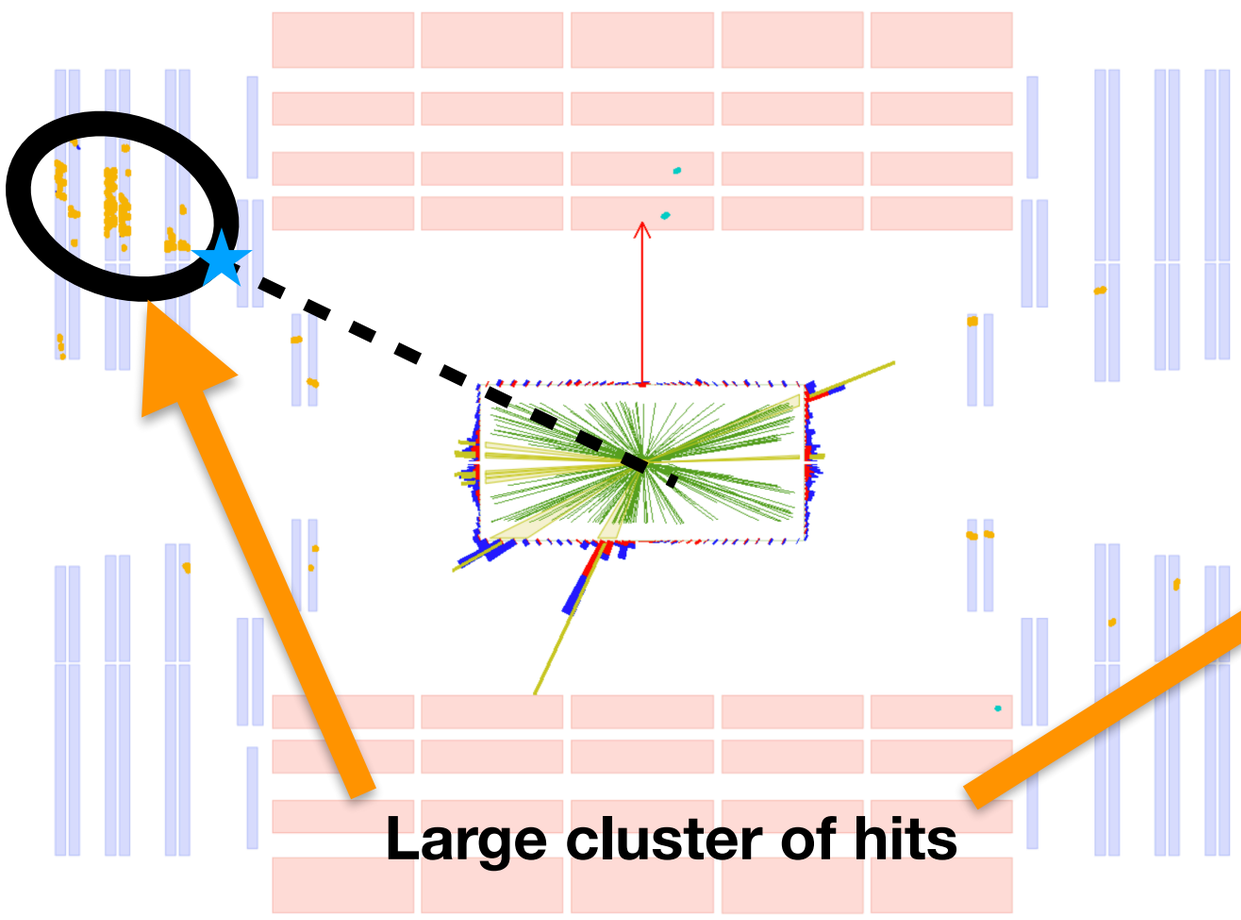
Current CMS data analysis chain
is
broken when LLPs are present

LLP Signature in Muon System

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)**

CMS *Simulation Supplementary*



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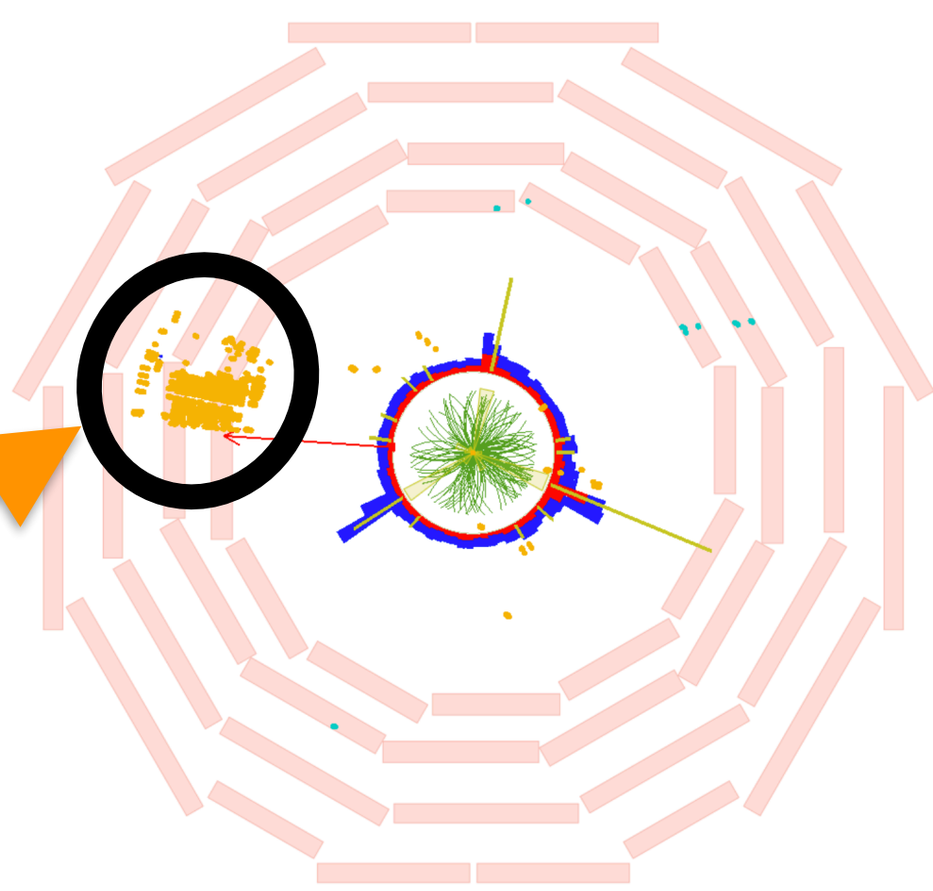
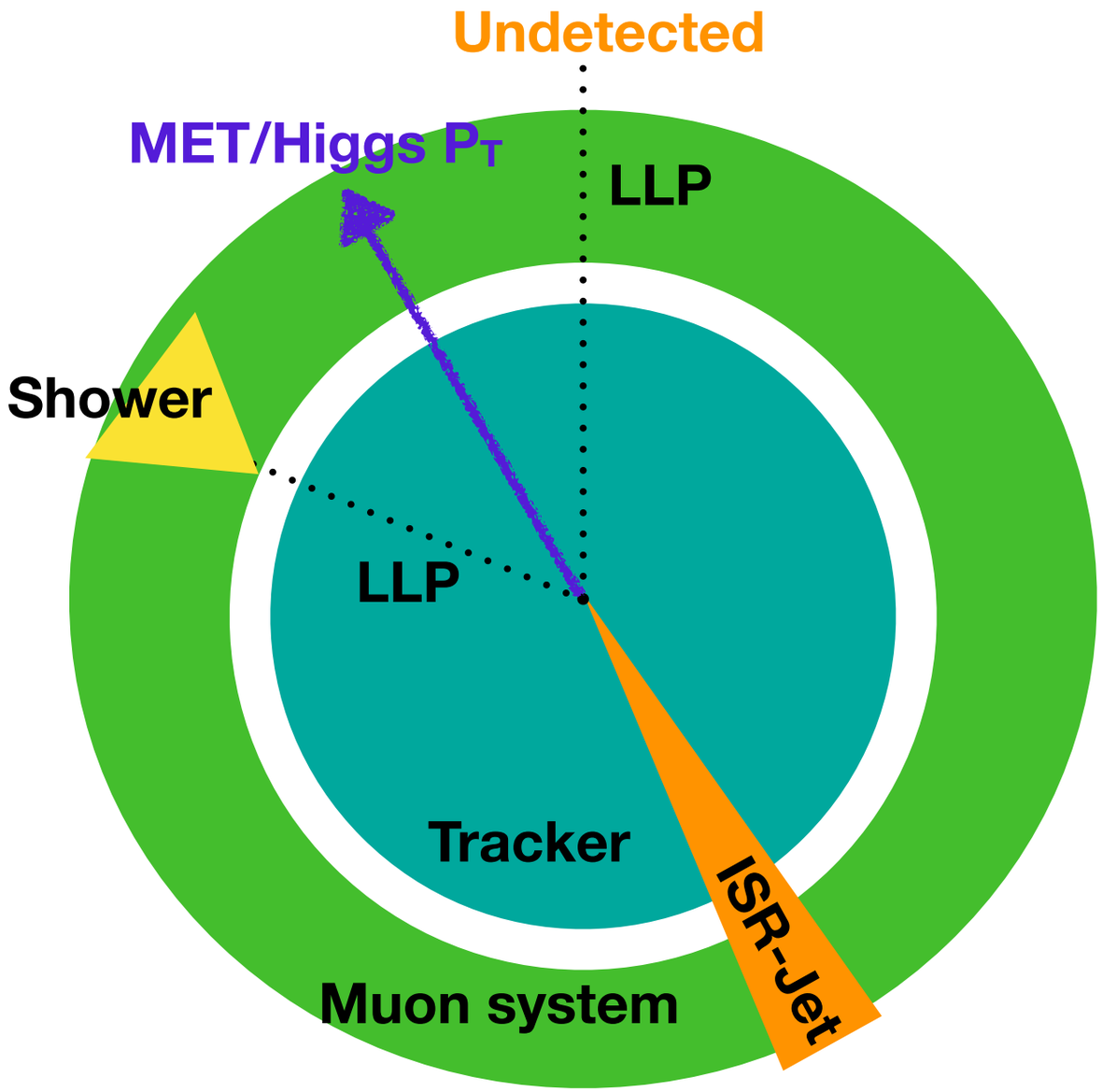


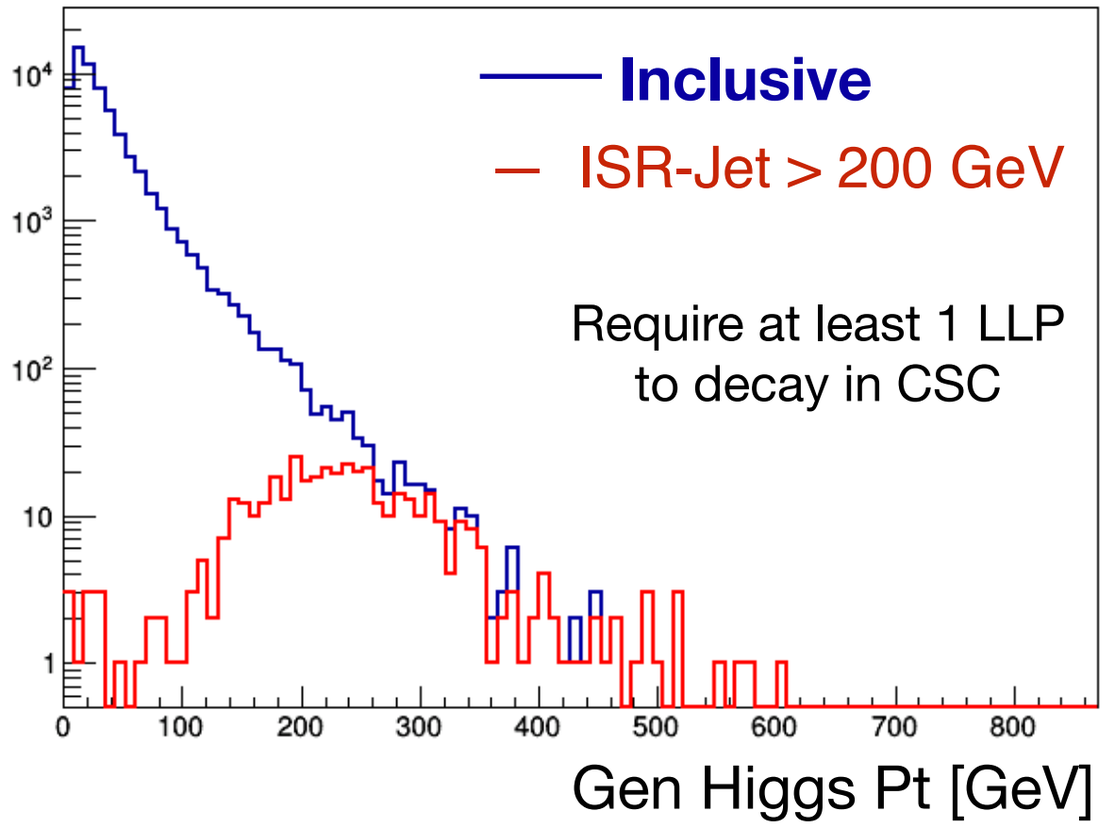
Phys. Rev. Lett. **127**, 261804

LLP Muon System Analysis

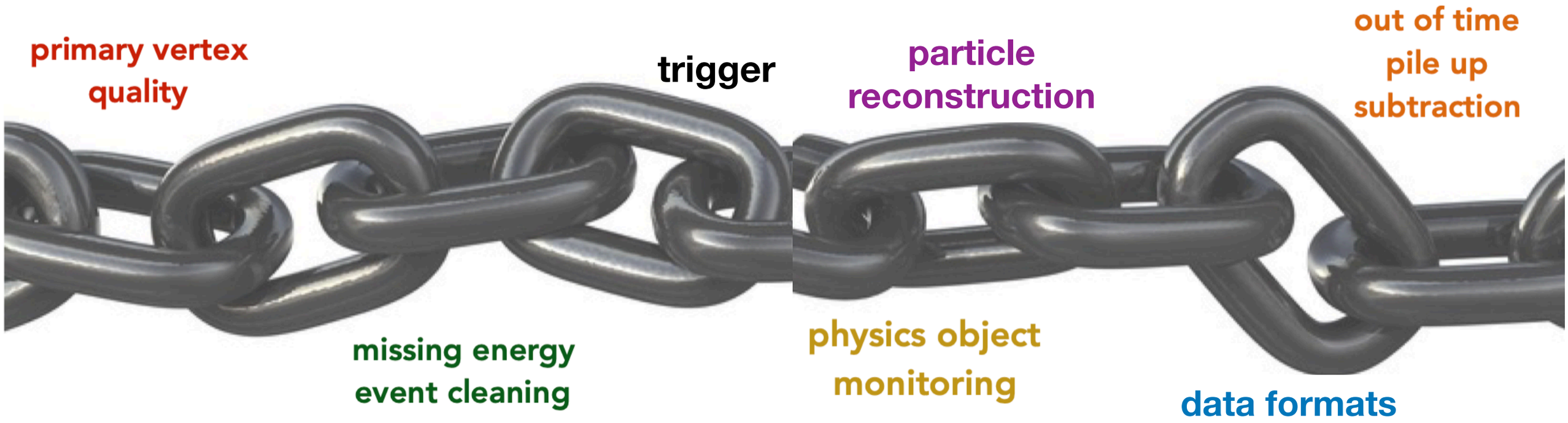
- Start with ggH production mode — largest cross section
- Trigger on **MET (lack of dedicated trigger)** — recoil of Higgs against ISR
  - For large cτ one of the LLPs will decay outside the calorimeter



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



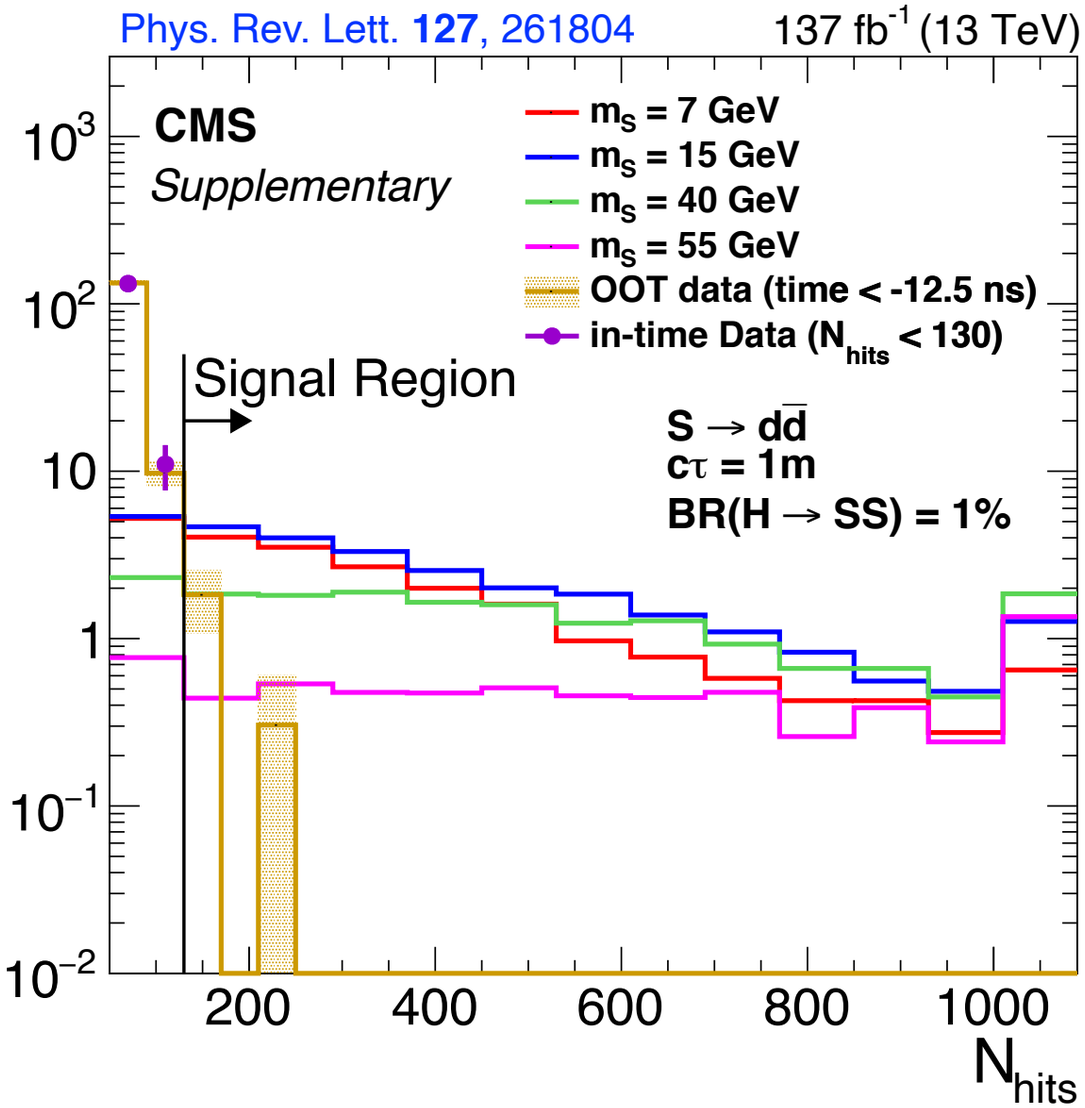
CMS Data Analysis Re-imagined



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 Muon Systems



SR Expected Bkg:
2.0 ± 1.0

Large signal to bkg separation

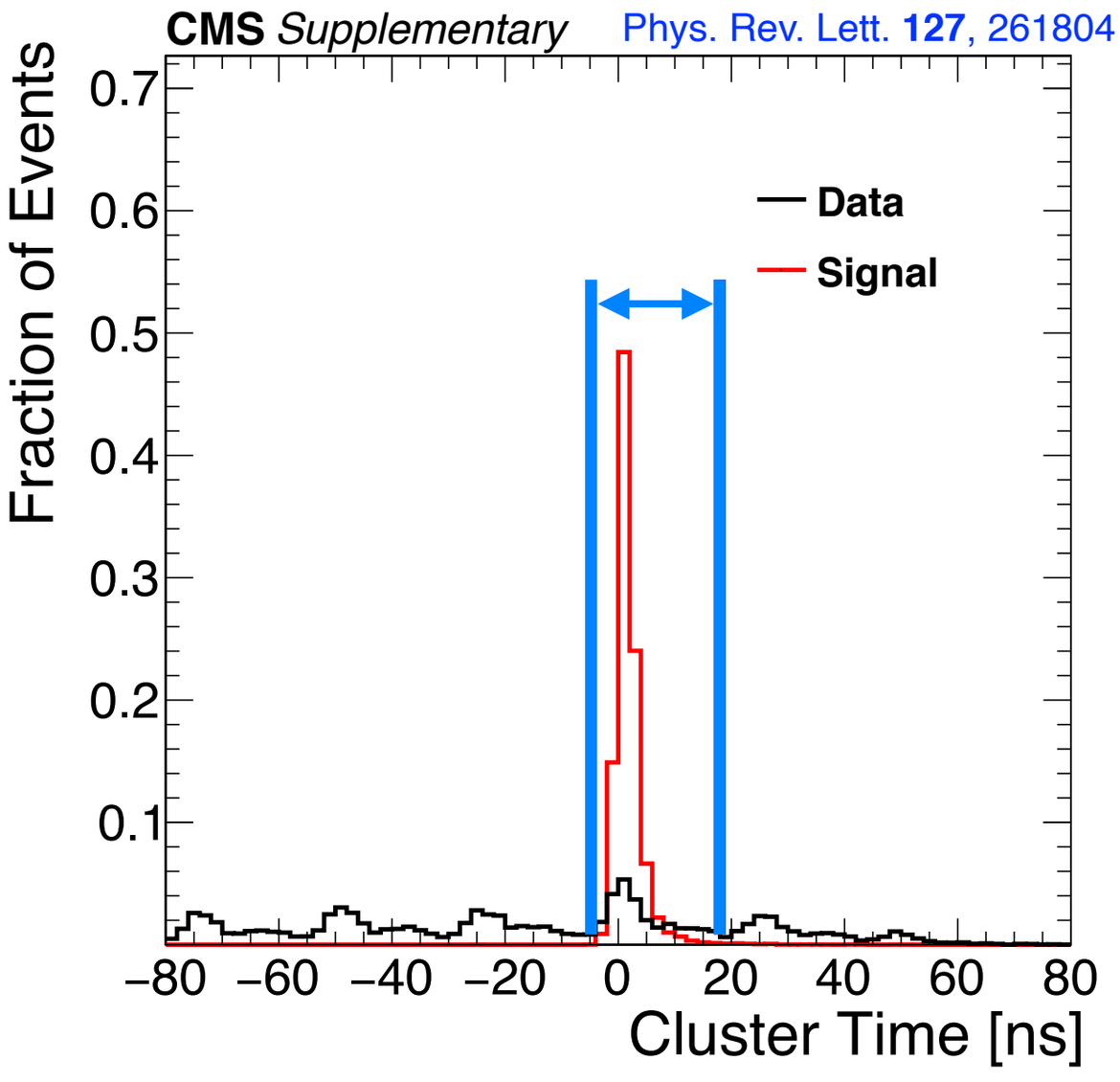
- Signal: clusters with high hit-multiplicity
  - signal-clusters with up to 1k-hits
- Bkg: quickly falling distribution
  - Nearly no bkg in signal region (SR)

Expect sensitivity to BR(H→SS) < 1%

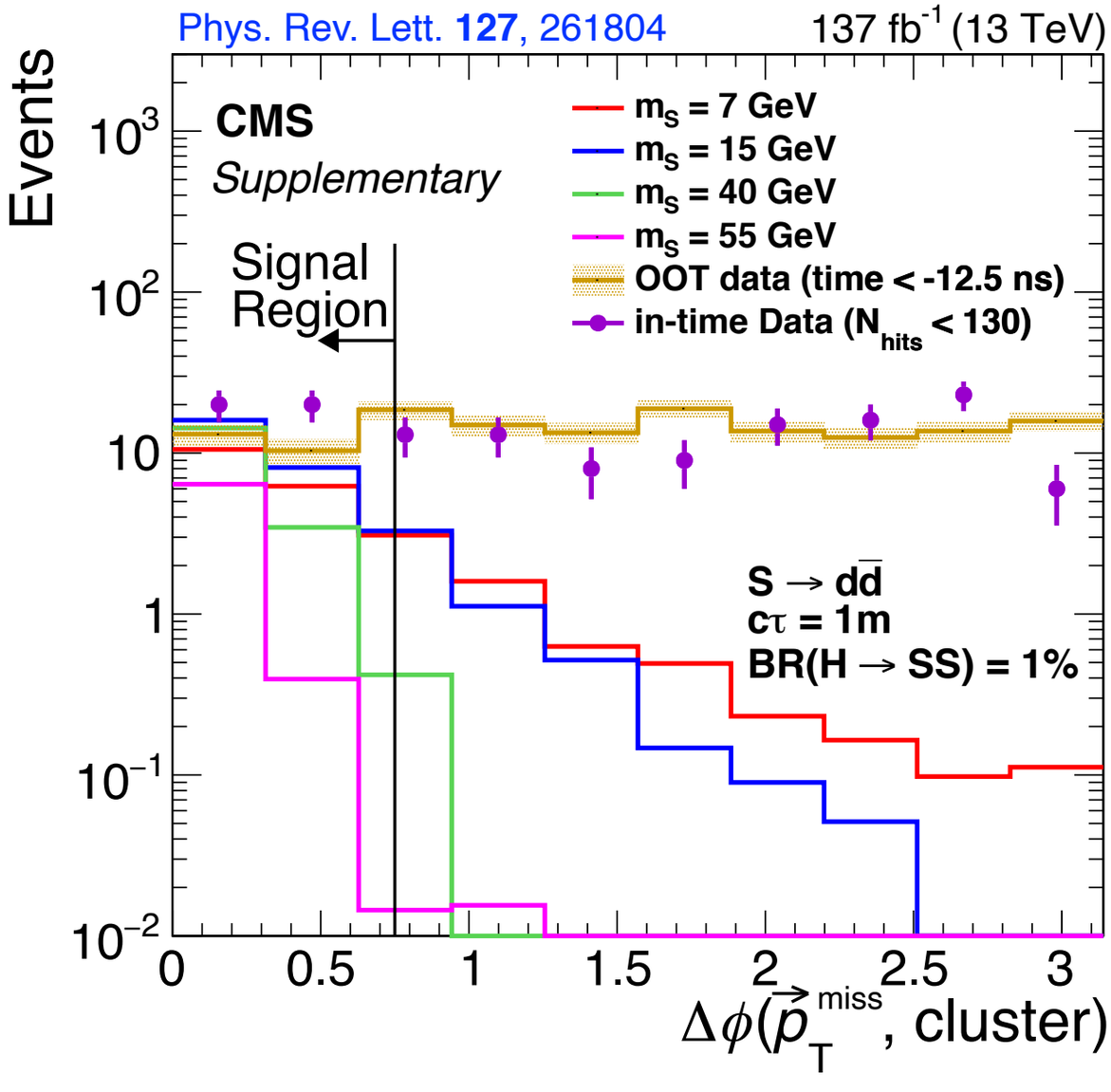
LLP with MS: other key selection

Many bkg cluster from OOT interactions

Signal cluster are in-time

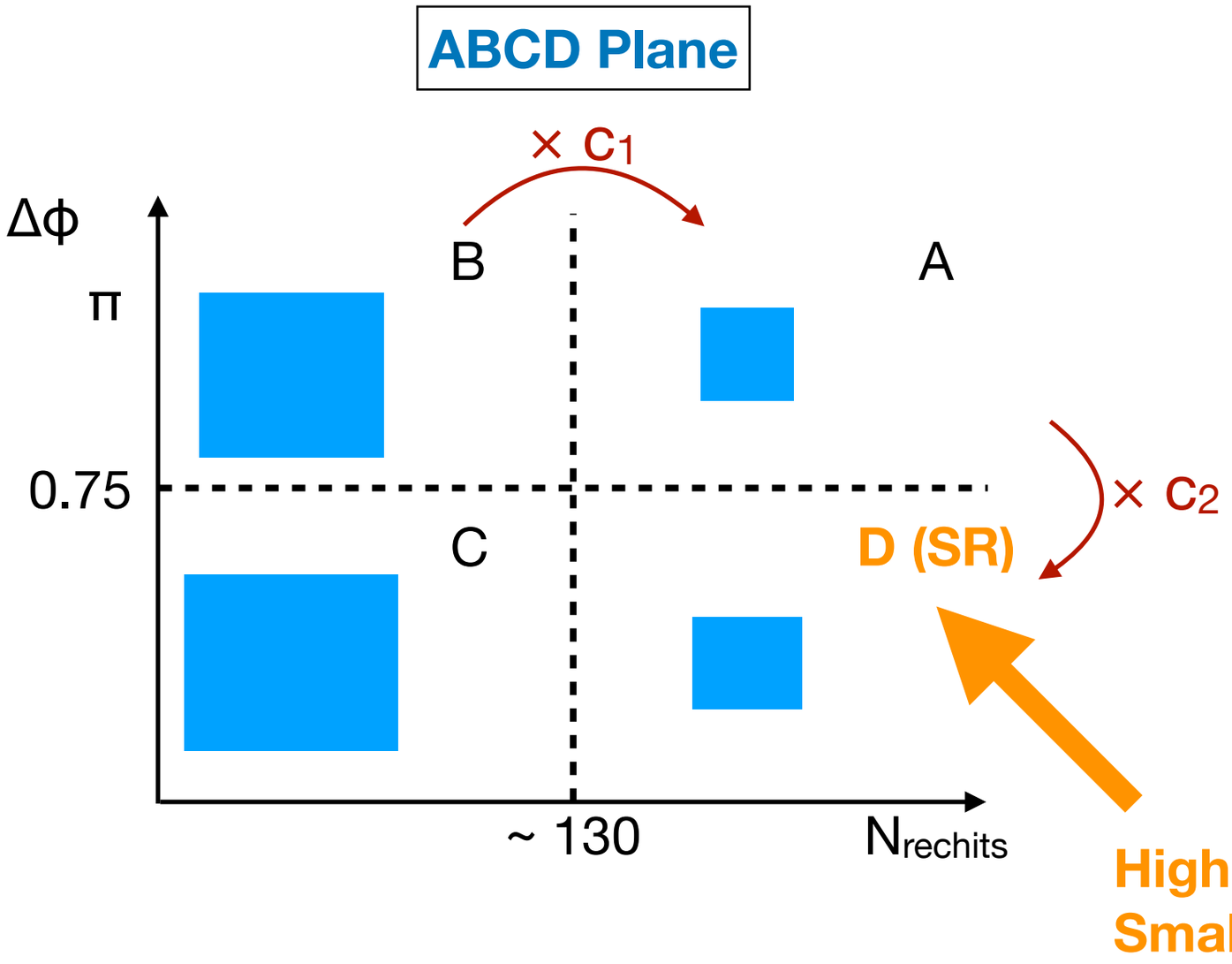


Signal: angle between pT_{miss} and cluster position is aligned



Combined 20x bkg rejection power

Background Estimation

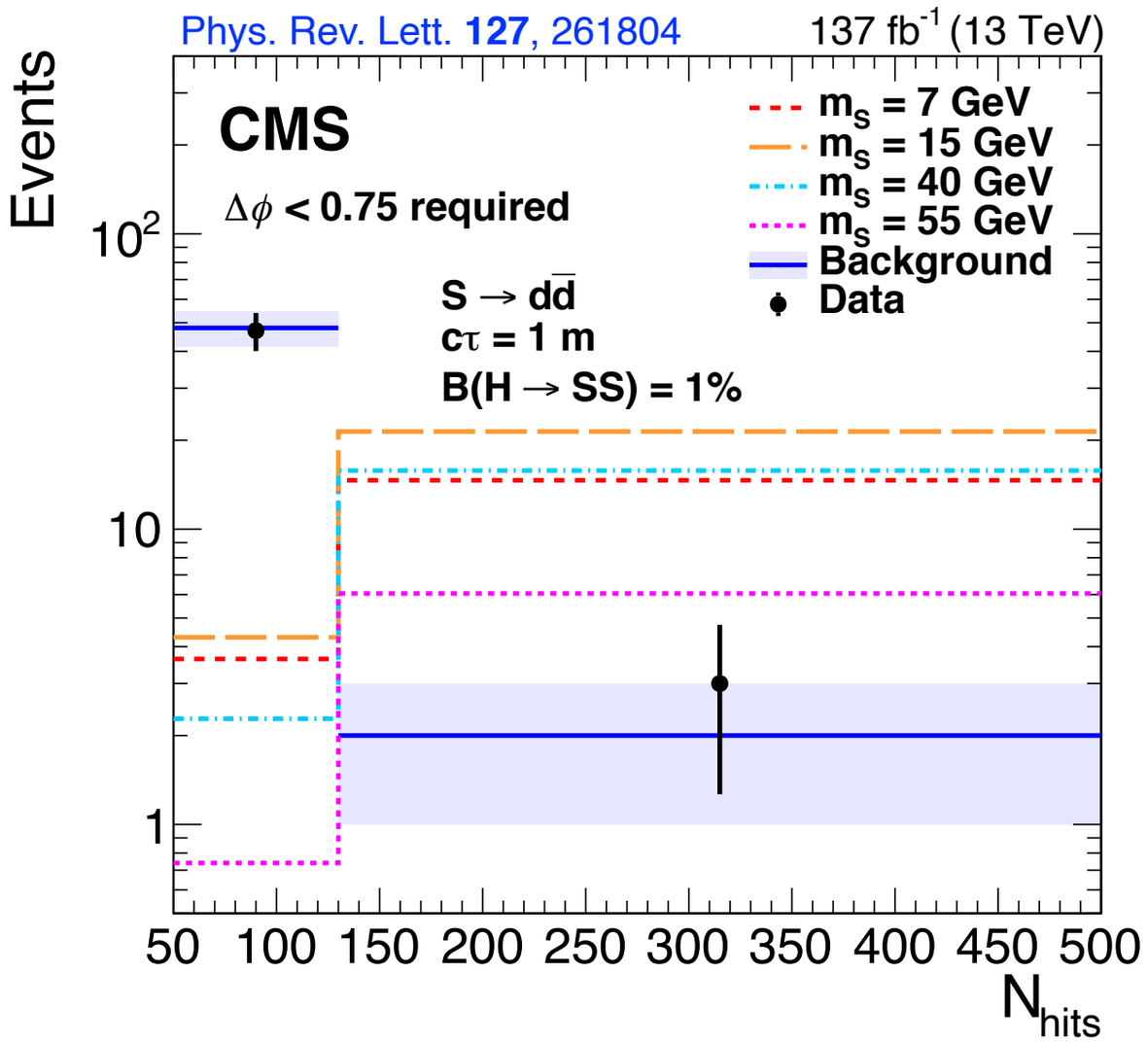


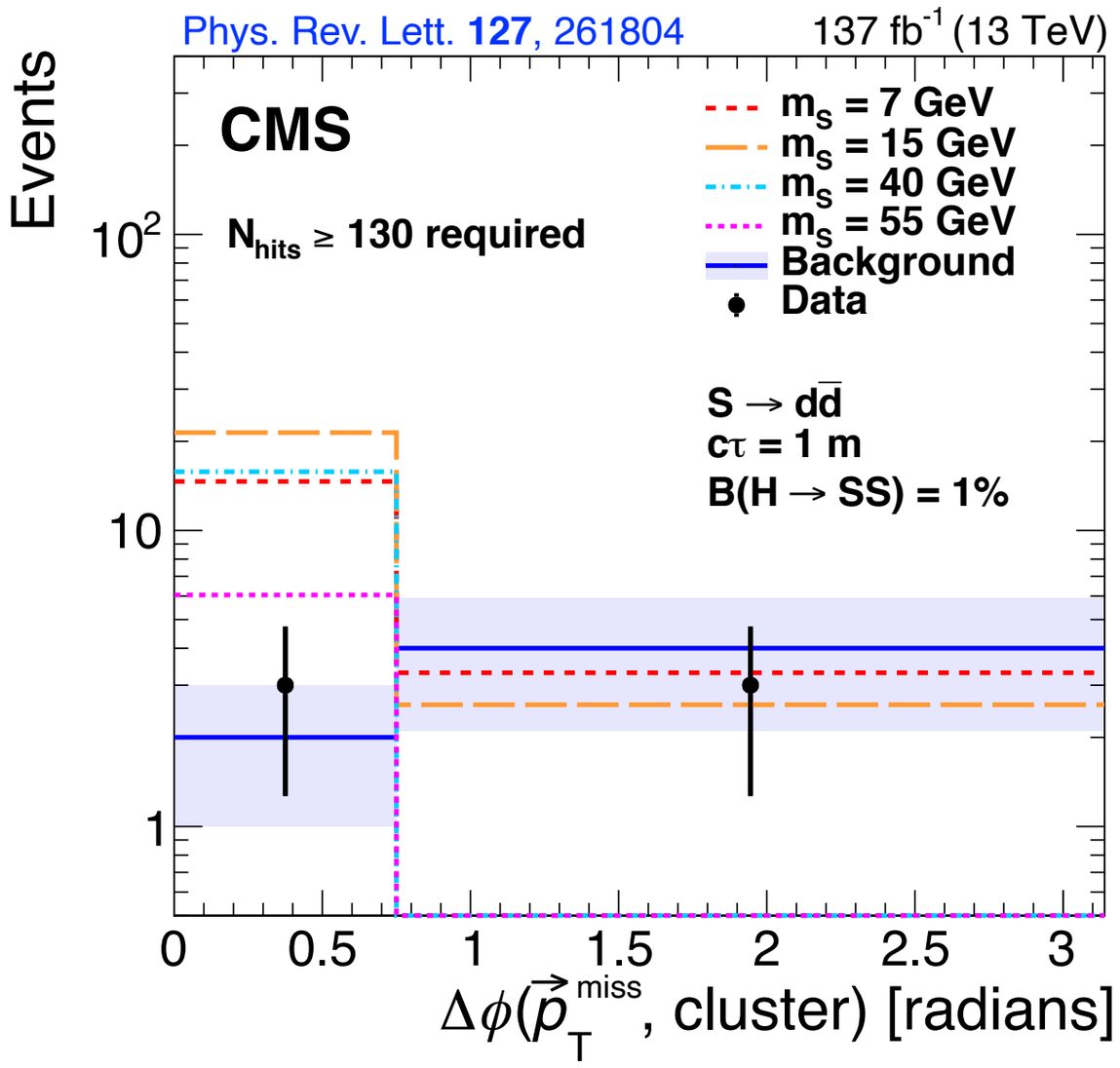
$$N_A = c_1 \times Bkg_B + \mu \times SigA$$
$$N_B = Bkg_B + \mu \times SigB$$
$$N_C = c_2 \times Bkg_B + \mu \times SigC$$
$$N_D = c_1 \times c_2 \times Bkg_B + \mu \times SigD$$

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

LLP with Muon Systems

Unblinded Results



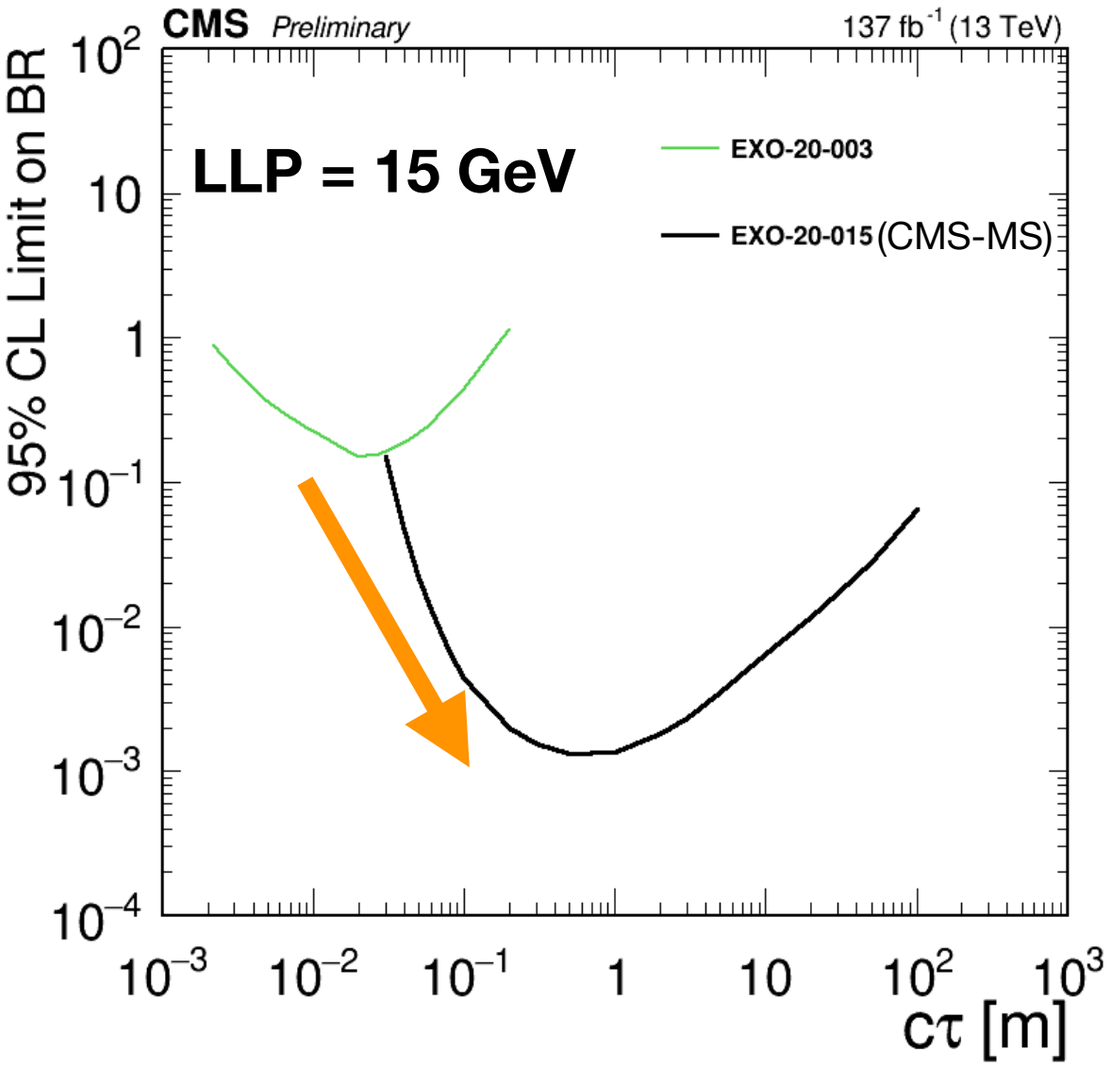


SR Expected Bkg (post-fit):
2.0 ± 1.0

SR Observed: 3

LLP with Muon Systems

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

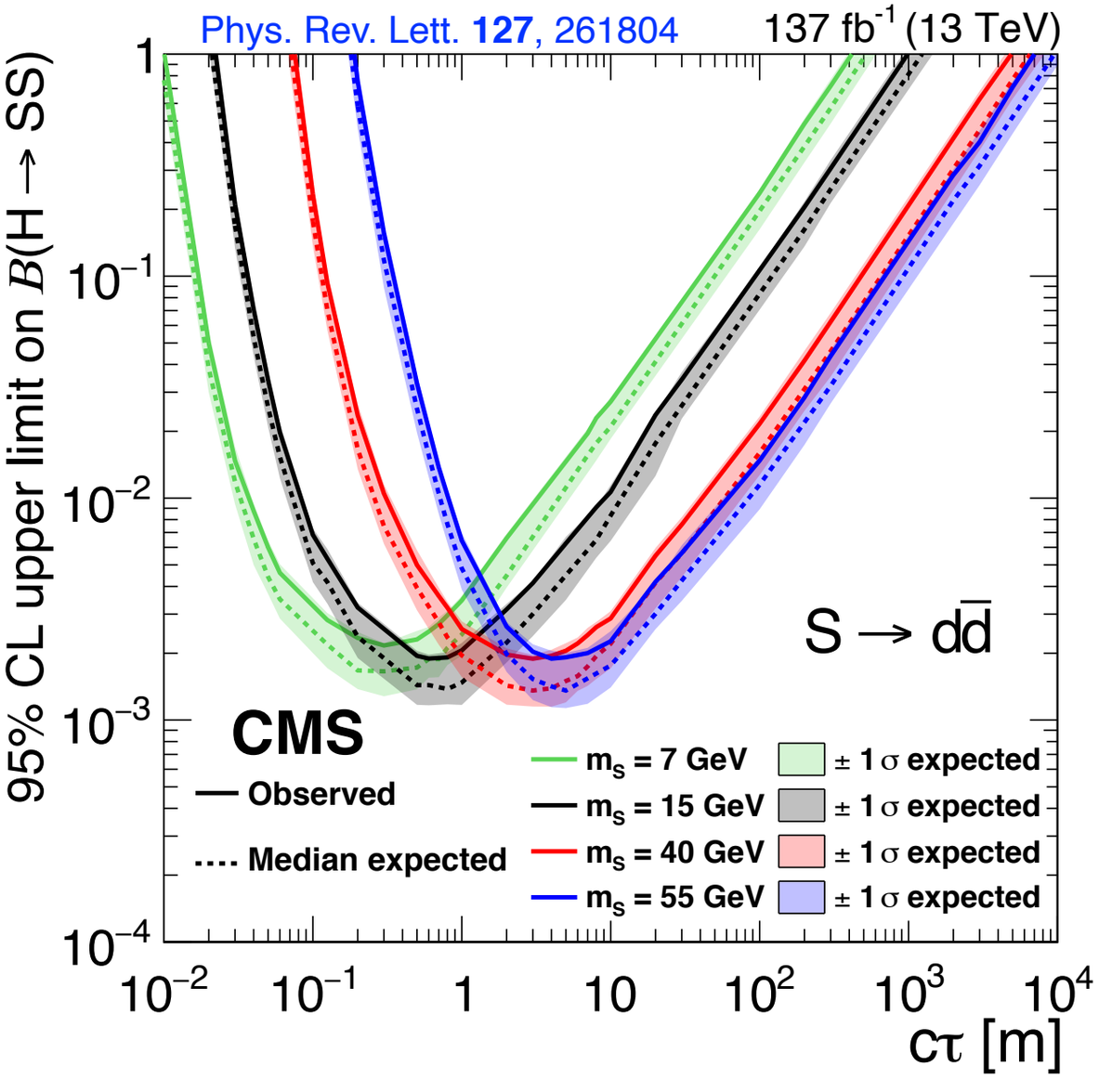


- **ENABLED CMS LLP sensitivity to larger cτ**
- **Access to light LLPs (< 15 GeV)**
  - **Sensitivity to all masses**
  - **Calorimeter: sensitive to LLP energy**

New cτ Reach and 100x better sensitivity

LLP with Muon Systems

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



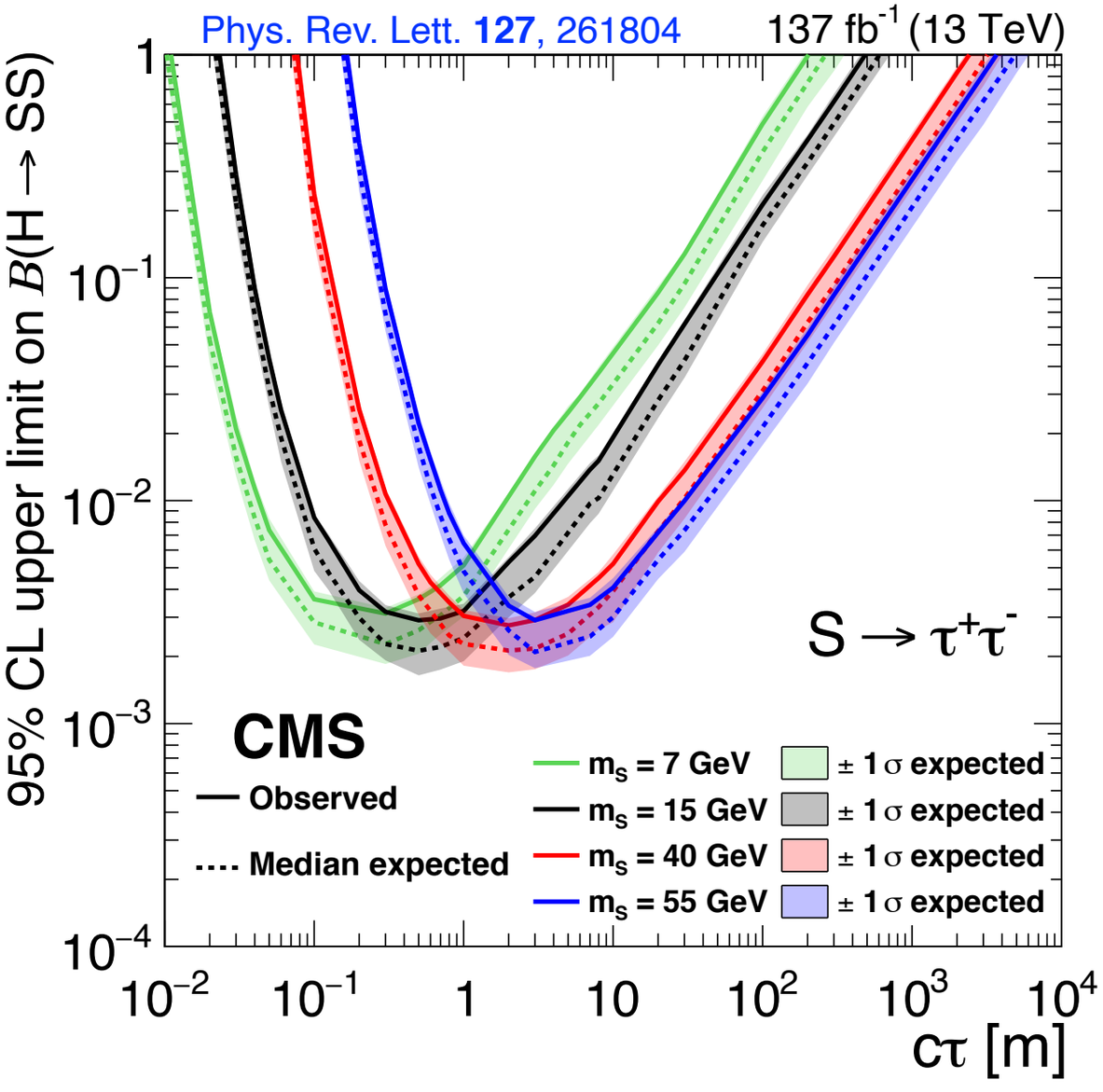
One of the CMS latest results

- **ENABLED CMS LLP sensitivity to larger cτ**
- **Access to light LLPs (< 7 GeV)**
  - **Sensitivity to all masses**
  - **Calorimeter: sensitive to LLP energy**

world-best results for cτ > 25 m

LLP with Muon Systems

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



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- **ENABLED CMS LLP sensitivity to larger cτ**
- **Access to light LLPs (< 7 GeV)**
  - **Sensitivity to all masses**
  - **Calorimeter: sensitive to LLP energy**

world-best results for cτ > 25 m

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 | Phys. Rev. Lett. **127**, 261804 | About | Submission Help | Sign in

Browse all | Tumasyan, Armen et al. | Last updated on 2021-09-24 14:16 | Accessed 480 times | Cite | JSON

Hide Publication Information

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 $...

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 $...

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 $...

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 $...

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 $...

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

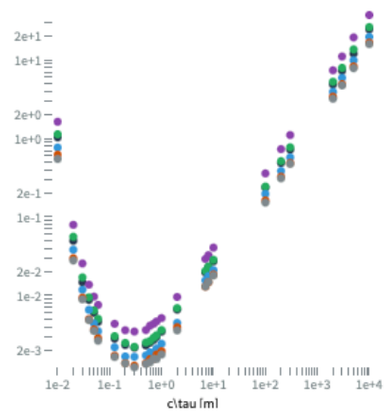
The 95% CL observed and expected limits on the branching fraction B(H → SS) for 7 GeV mass and $S \to d\bar{d}$ decay mode.

cmenergies: 13000.0

observables: CLS

Quantile	-2 σ	-1 σ	Median expected	+1 σ	+2 σ	Observed
cτ [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



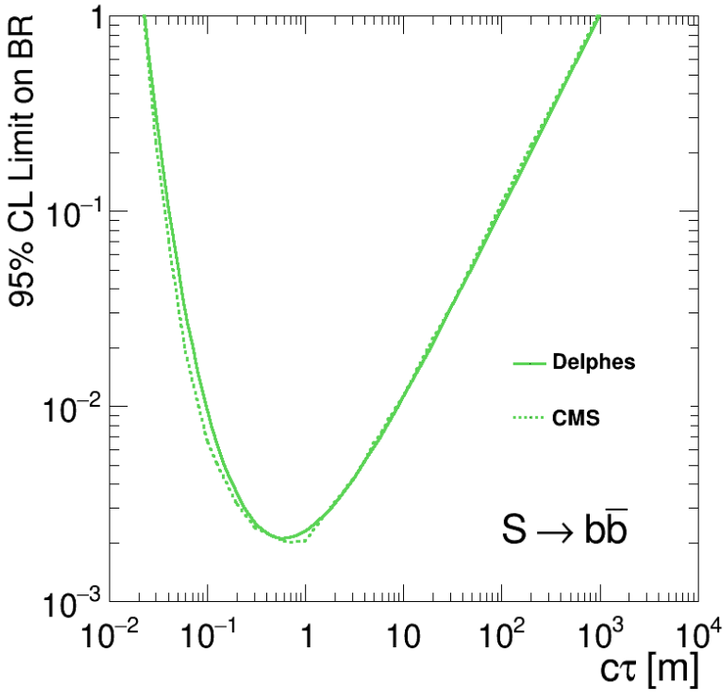
Sum errors | Log Scale (X) | Log Scale (Y)

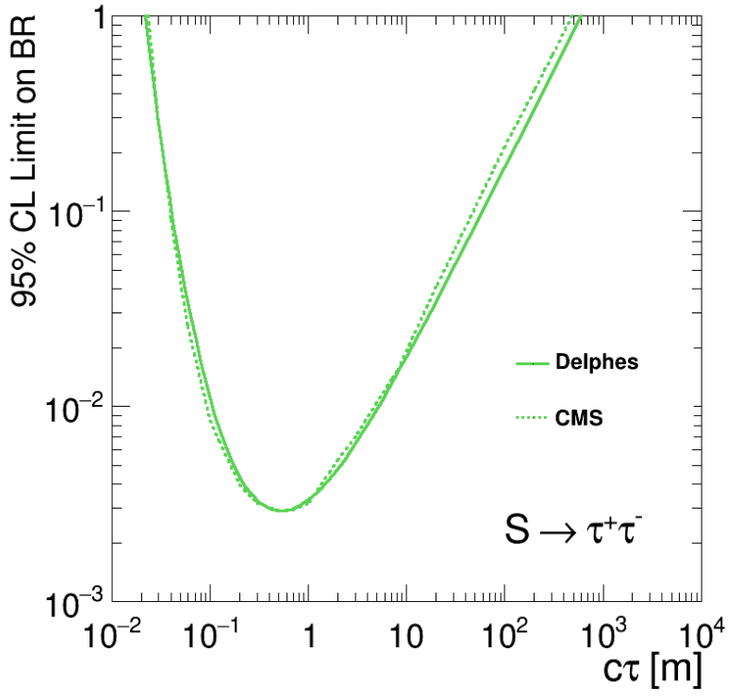
Deselect variables or hide different error bars by clicking on them.

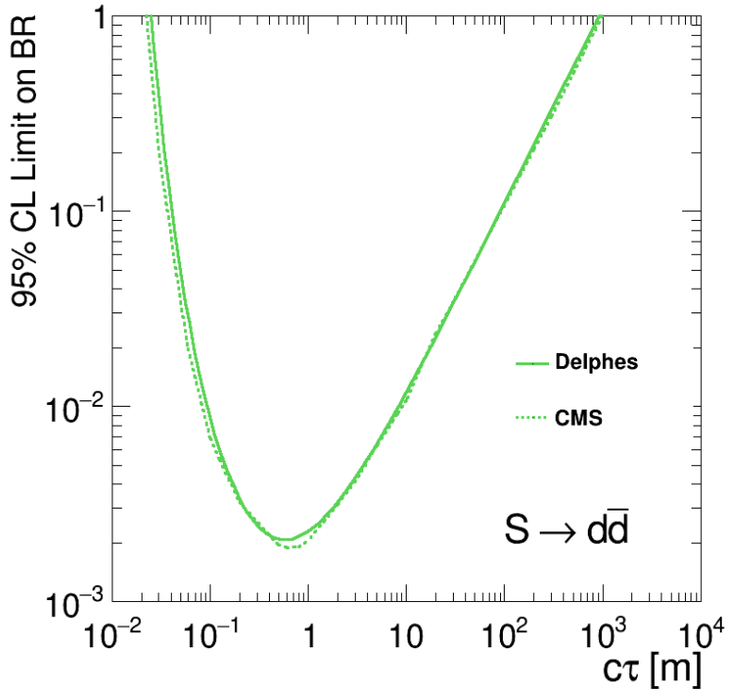
First Results Validation

- **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

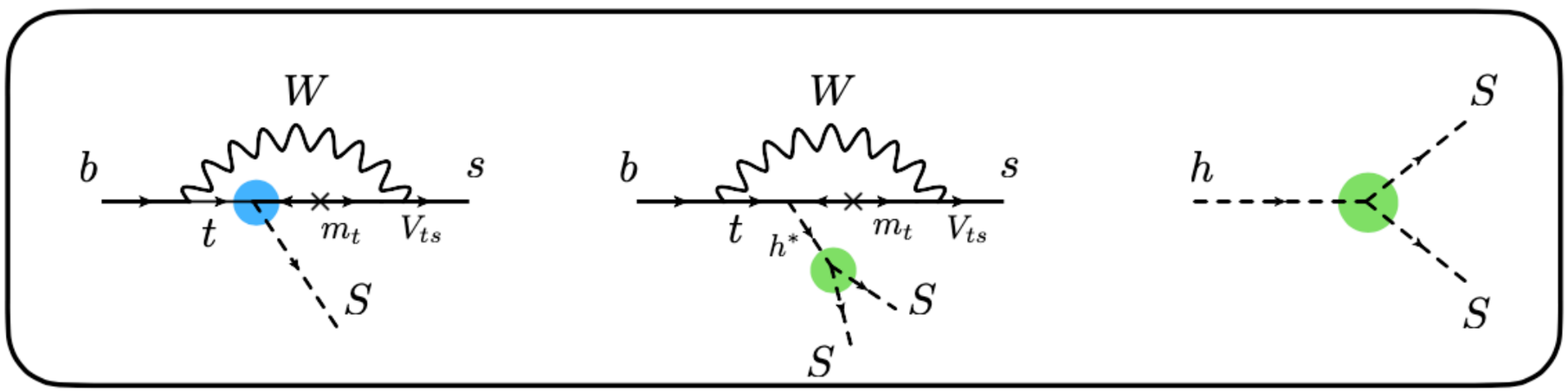
$$\mathcal{L}_{SH} = \mathcal{L}_{\rm SM} + \overbrace{\frac{1}{2}\partial_\mu \hat{S}\,\partial^\mu \hat{S} - \frac{\mu_S^2}{2}\hat{S}^2}^{\mathcal{L}_{\rm DS}} - \overbrace{\left(A_{HS}\,\hat{S} + \lambda_{HS}\,\hat{S}^2\right)\hat{H}^\dagger \hat{H}}^{\text{Higgs portal}}$$

controls the $\hat{H} - \hat{S}$ mixing

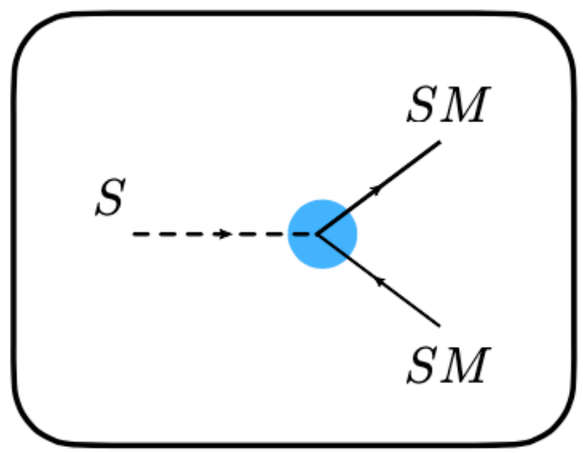
controls $Br(H \to SS)$

Long-lived Scalar (S) couple to Higgs

production



decay



A. Mitridate at LLPX workshop

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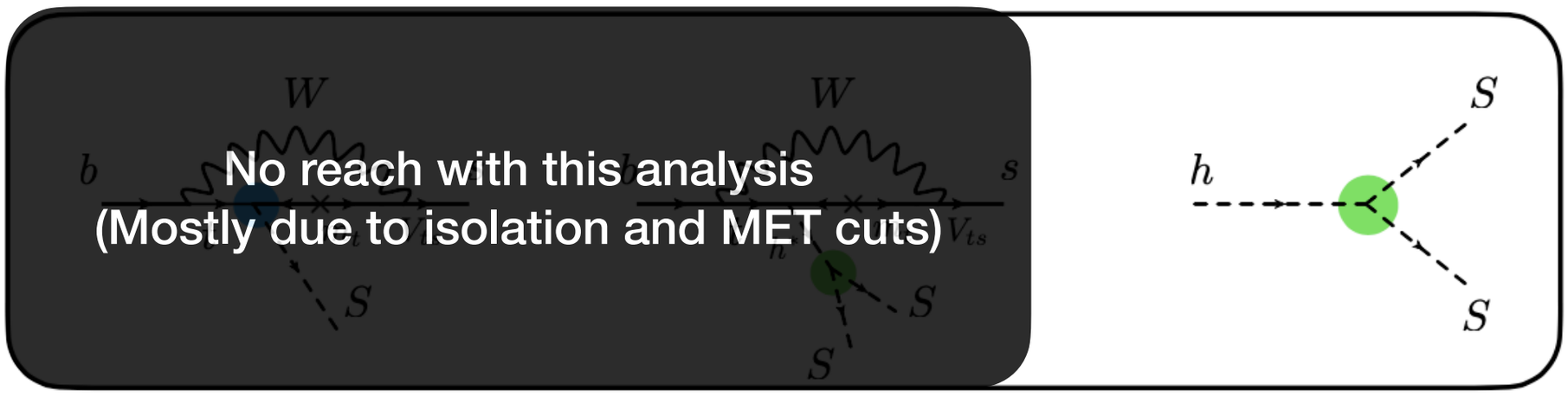
controls the $\hat{H} - \hat{S}$ mixing

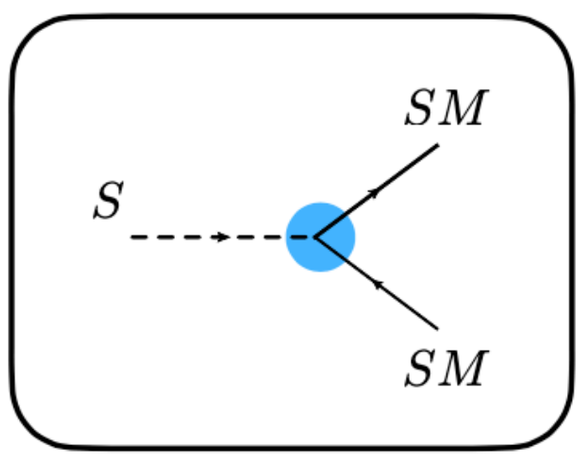
controls $Br(H \to SS)$

Very similar to CMS main interpretation

production

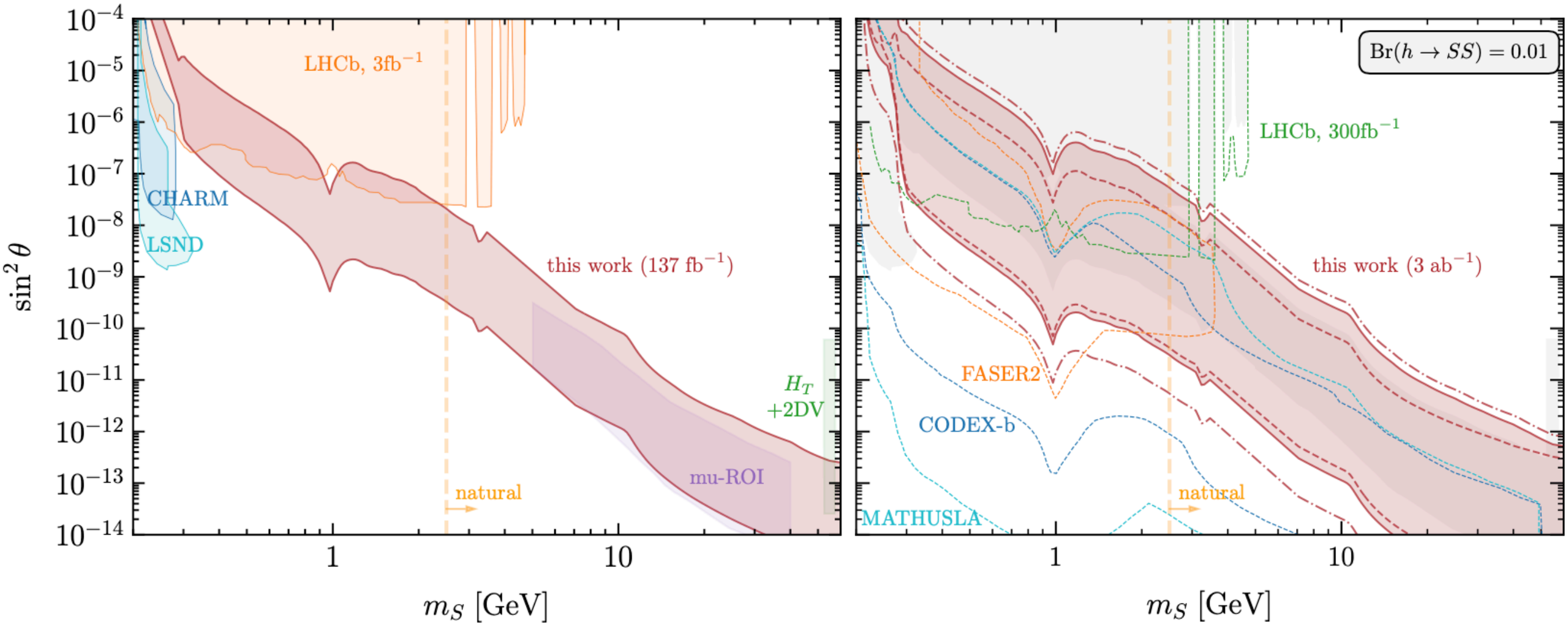


decay



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

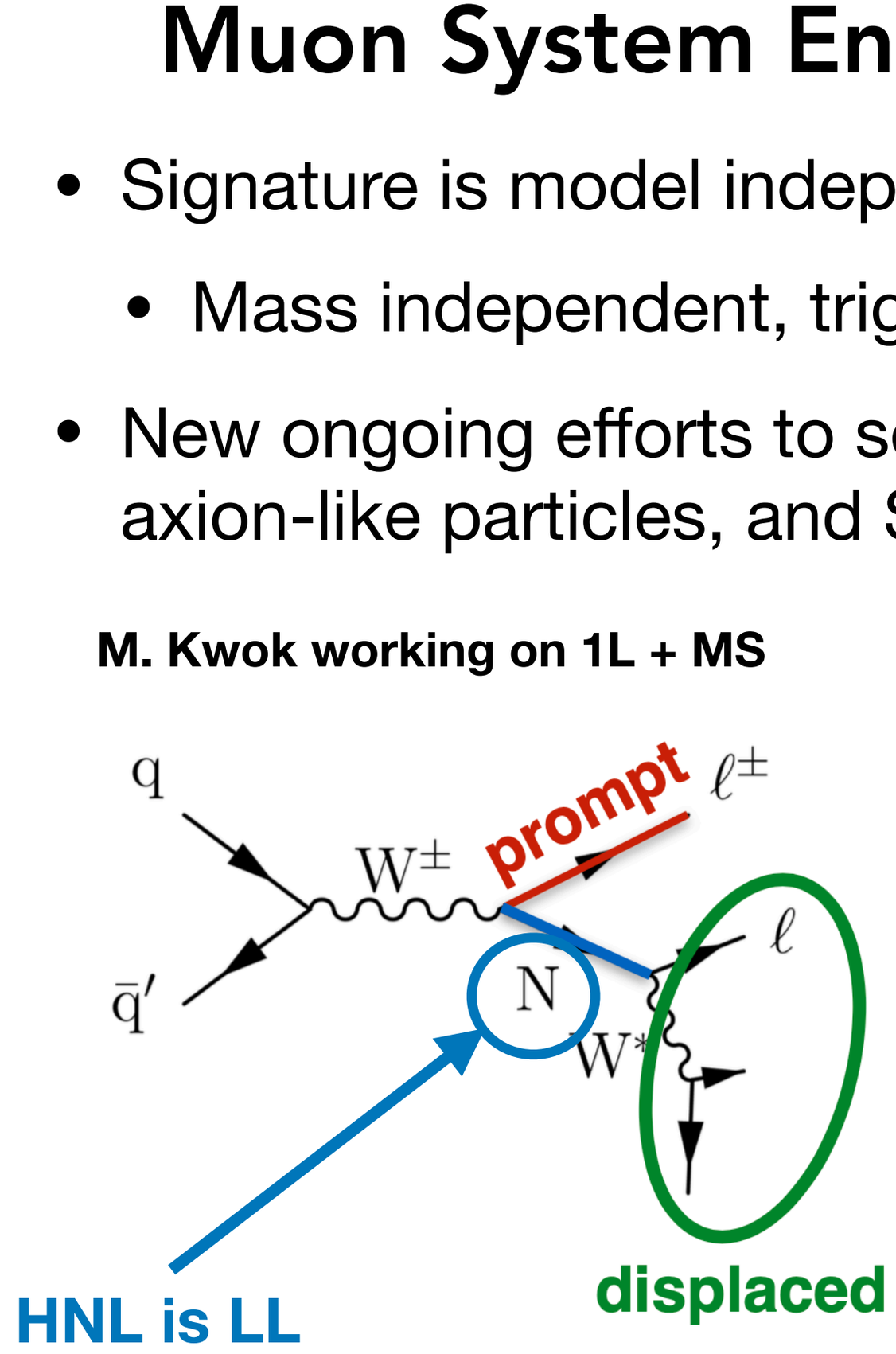


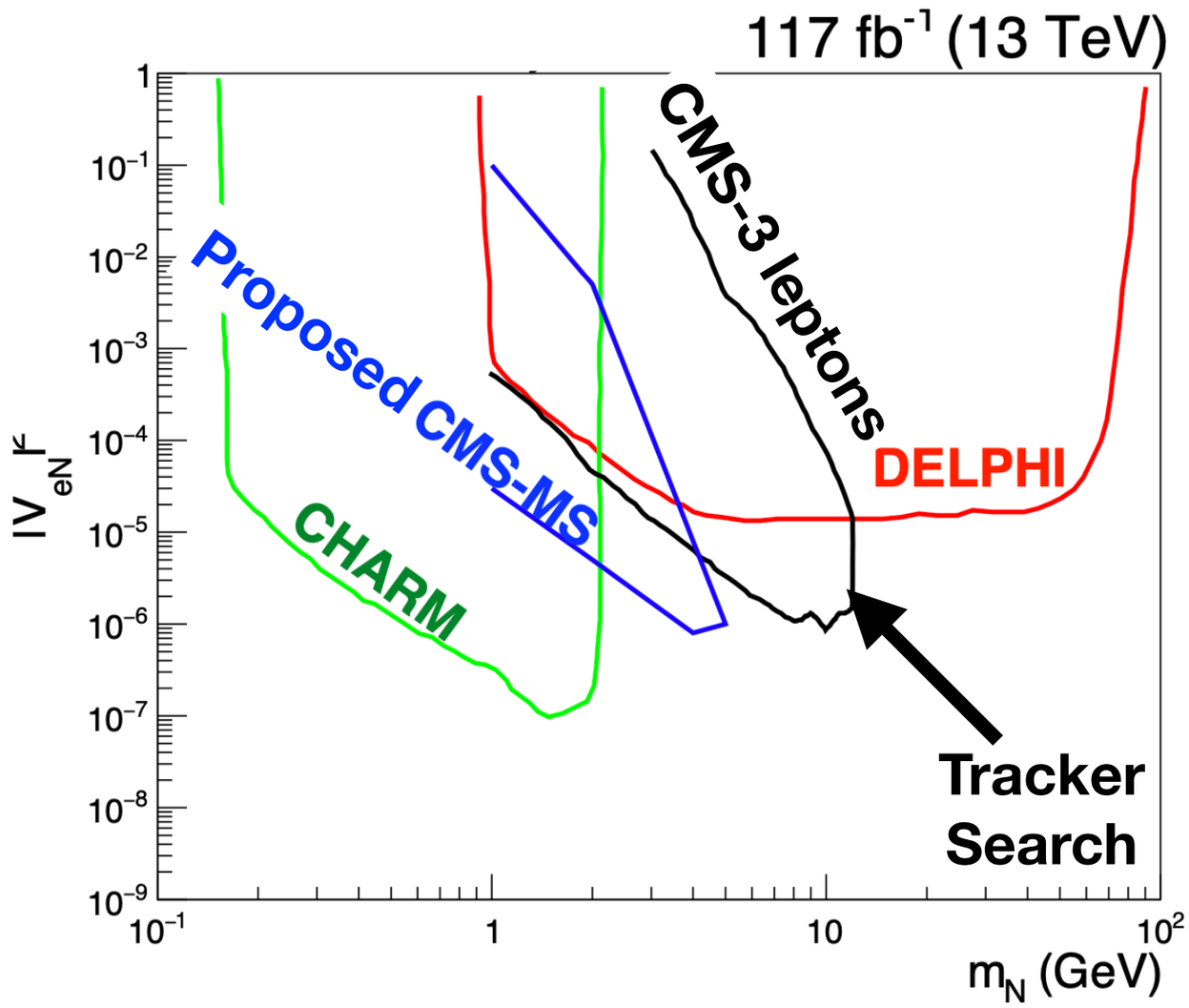
- Current best sensitivity in a large region of phase space ✓
  - Confirms reach to light LLPs (< 1 GeV) for CMS
- Highly complementary to dedicated LLP experiments ✓

Muon System Enables Broad LLP Reach

- Signature is model independent
  - Mass independent, triggerable signature
- New ongoing efforts to search **LLPs in neutrino portals**, axion-like particles, and SUSY s-tau models

M. Kwok working on 1L + MS

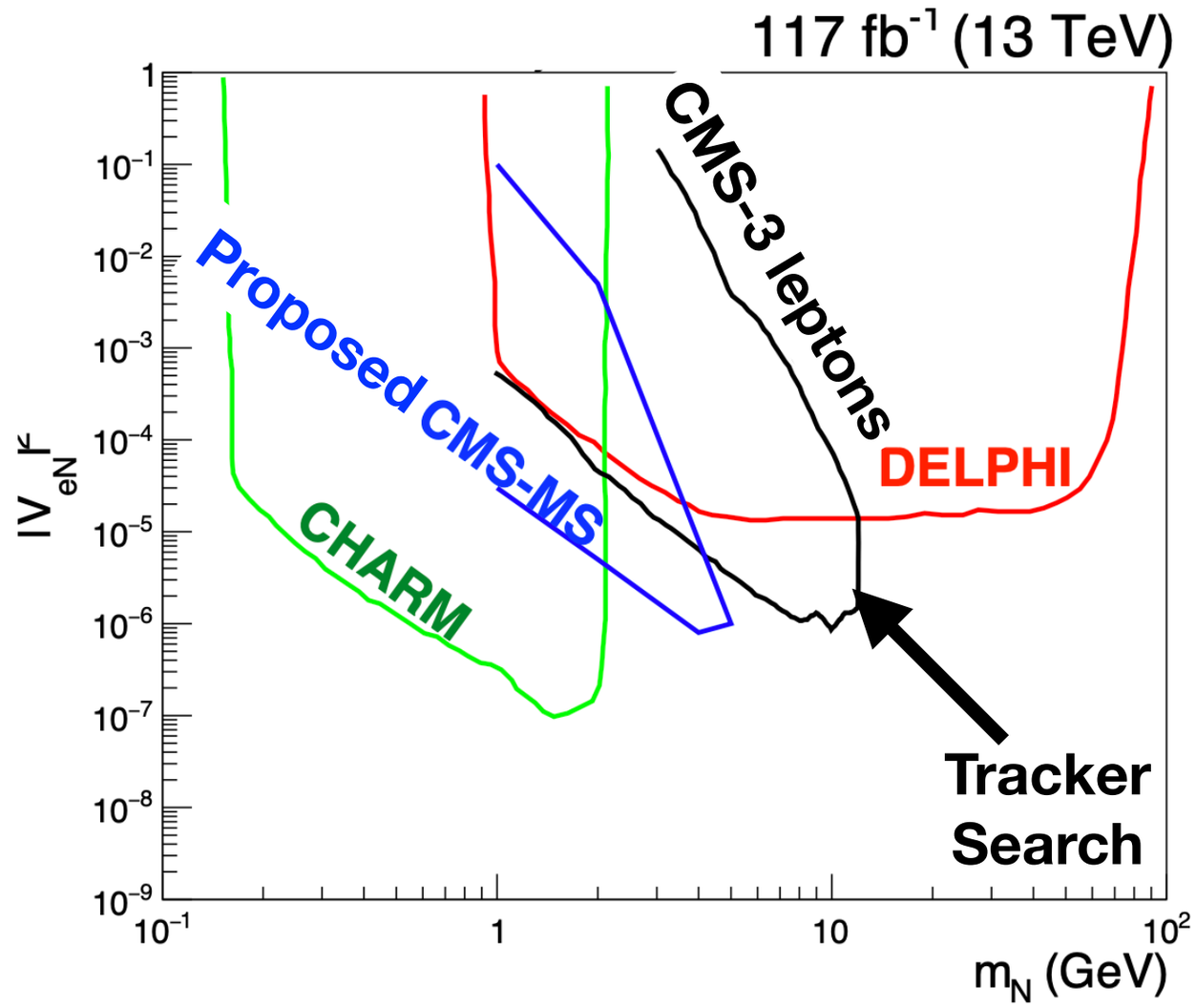




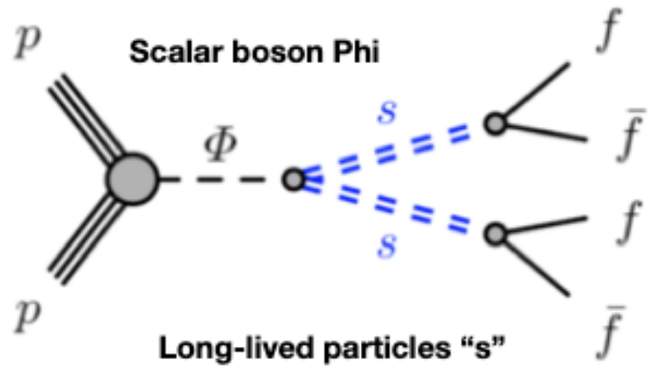
Muon System Enables Broad LLP Reach

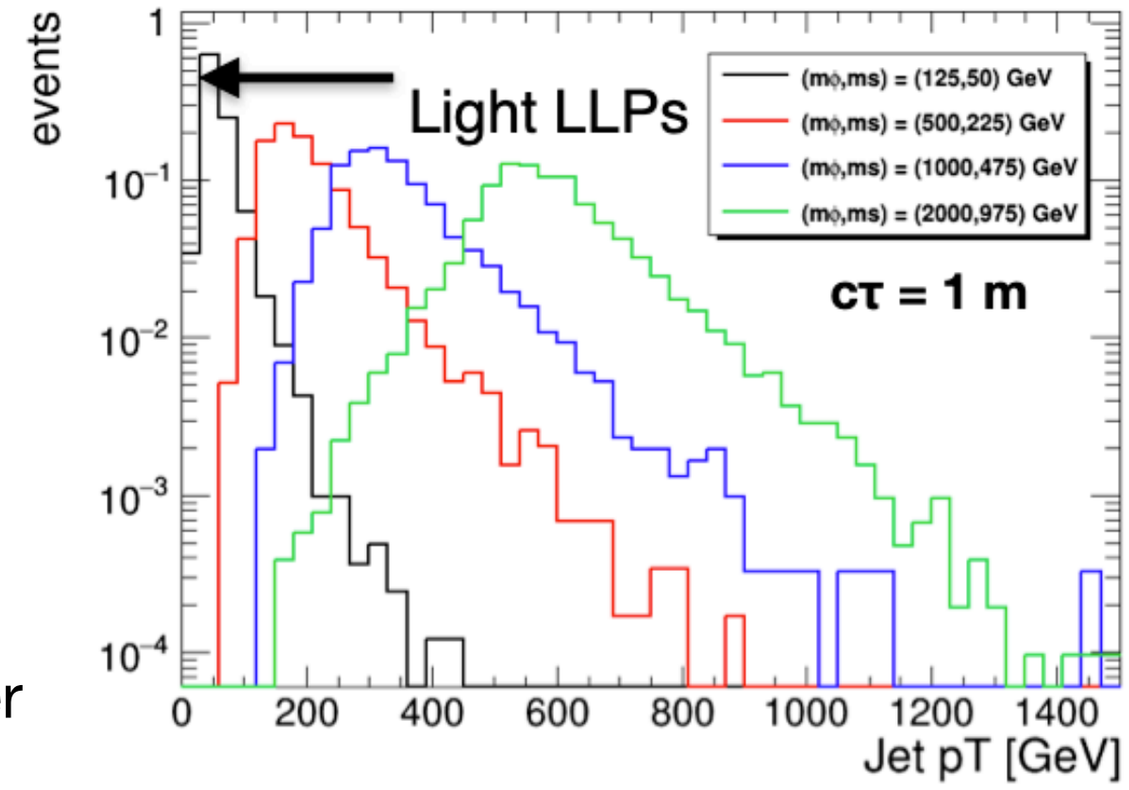
- Signature is model independent
  - Mass independent, triggerable signature
- Using 1L triggers and using the interplay between mass and lifetime MS is uniquely sensitive to HNLs

$$c\tau_N \sim 3.7 \left(\frac{1\ \text{GeV}}{m_N}\right)^5 \left(\frac{0.1}{|V_{lN}|^2}\right) \quad [\text{mm}].$$

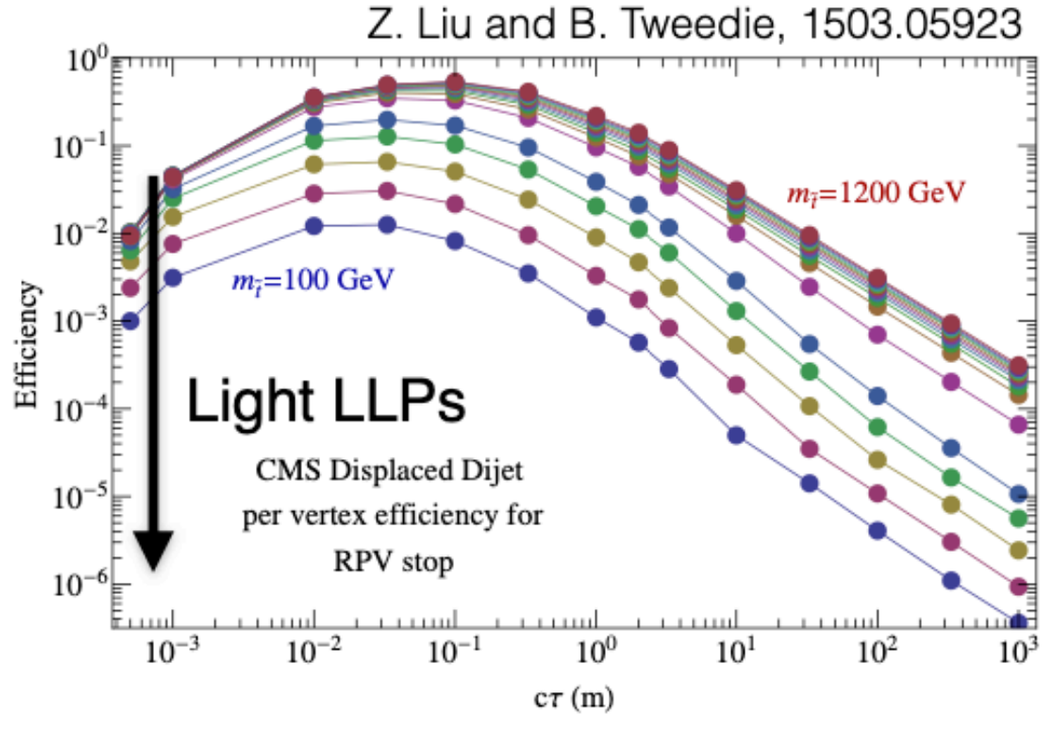


Triggers: the new LLP frontier



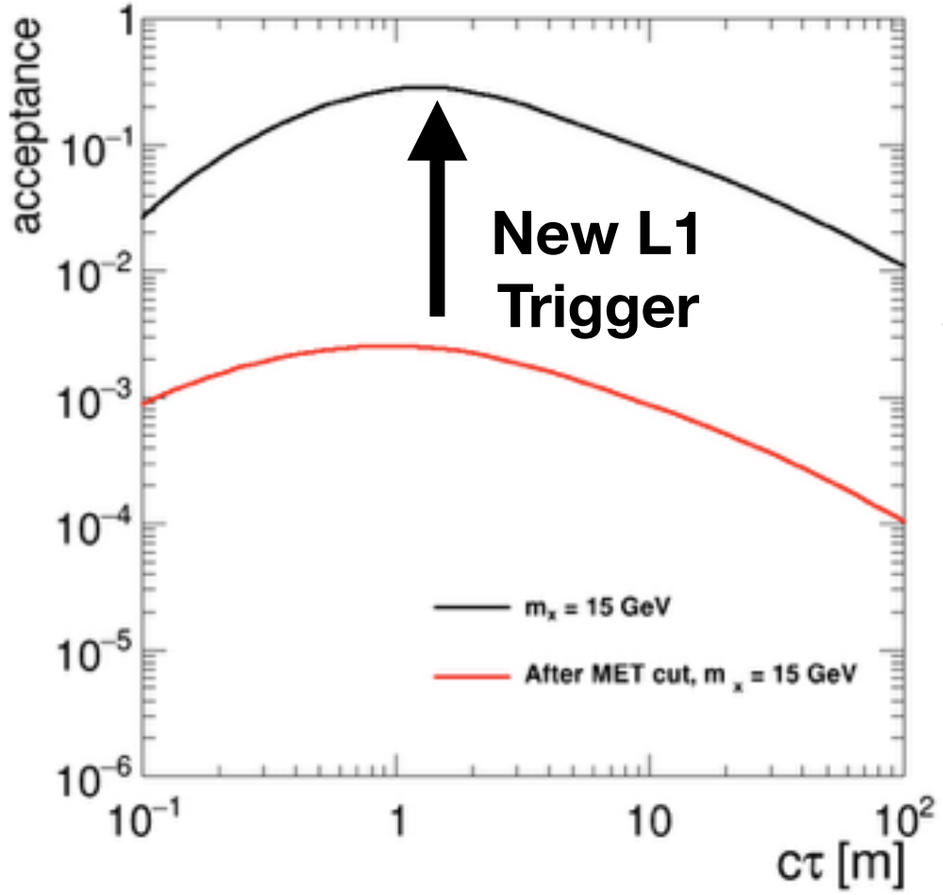


- LL scalar decay position determines signature and strategy:
  - Inside calorimeters: displaced jets
  - Outside calorimeters: no jets — hard to trigger
- Current L1 trigger have high-threshold: highly detrimental to light LLPs
  - HT > 300 GeV and jet pT > 200 GeV ✗
  - Trigger efficiencies below ~1% for light LLPs ✗
  - No seeds for beyond calorimeter signatures ✗
- **Critical need and opportunity for LL Trigger in CMS during Run3**



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

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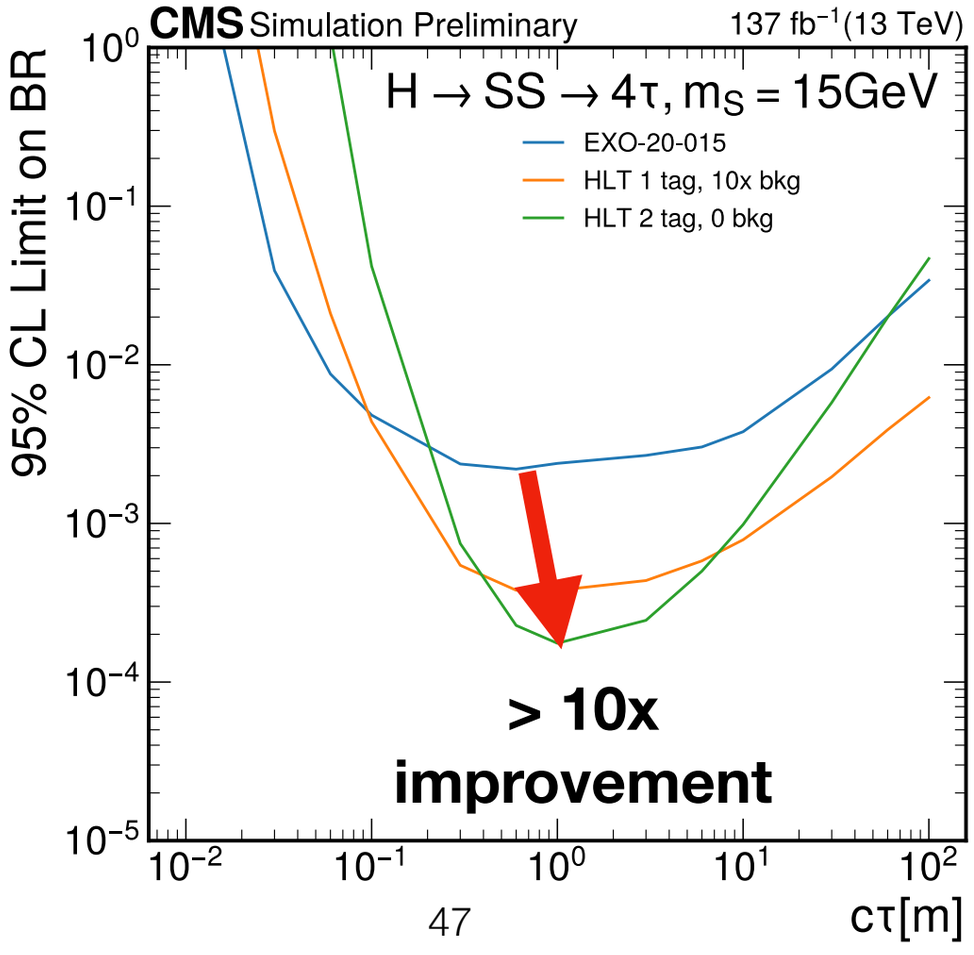
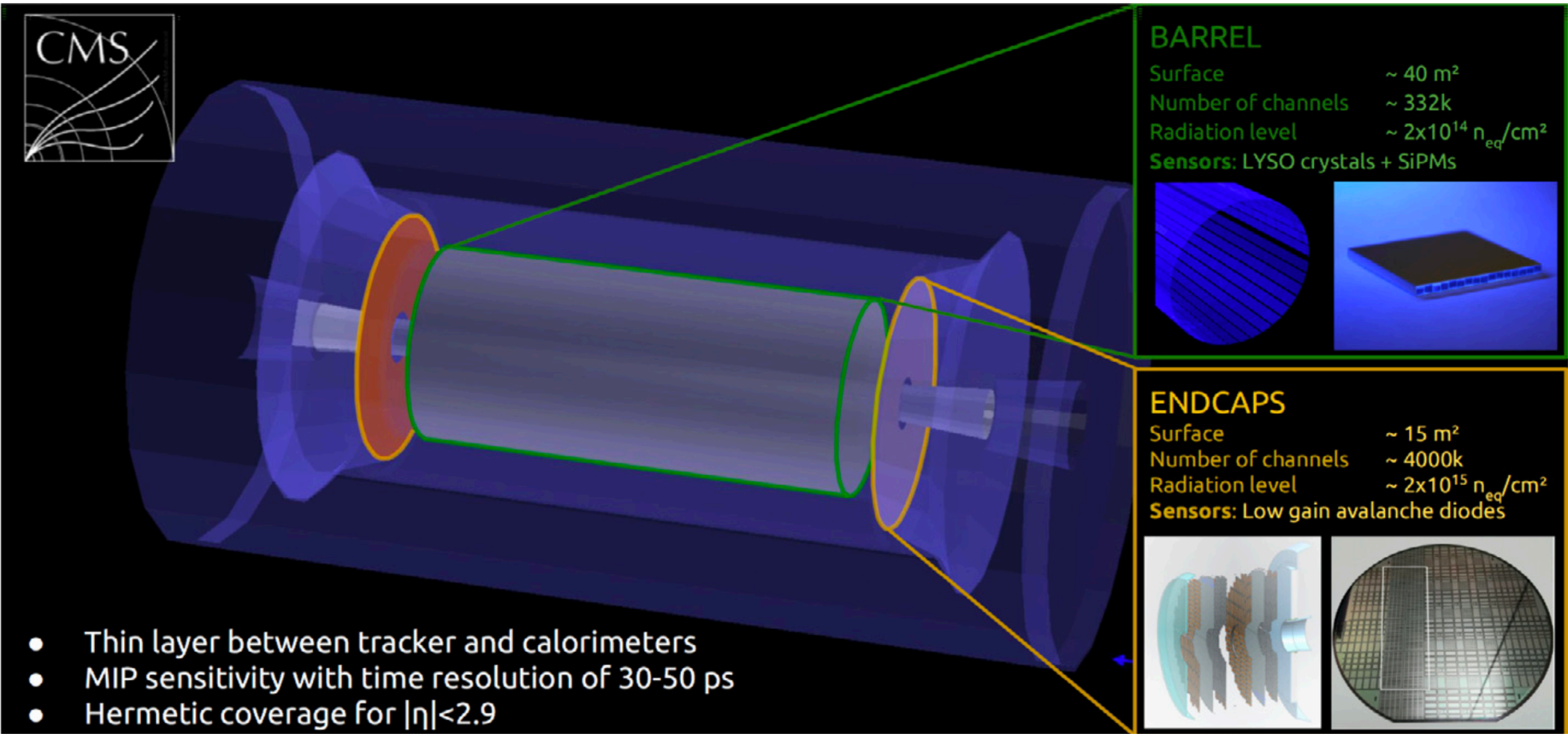
Improvement in sensitivity from new MS trigger

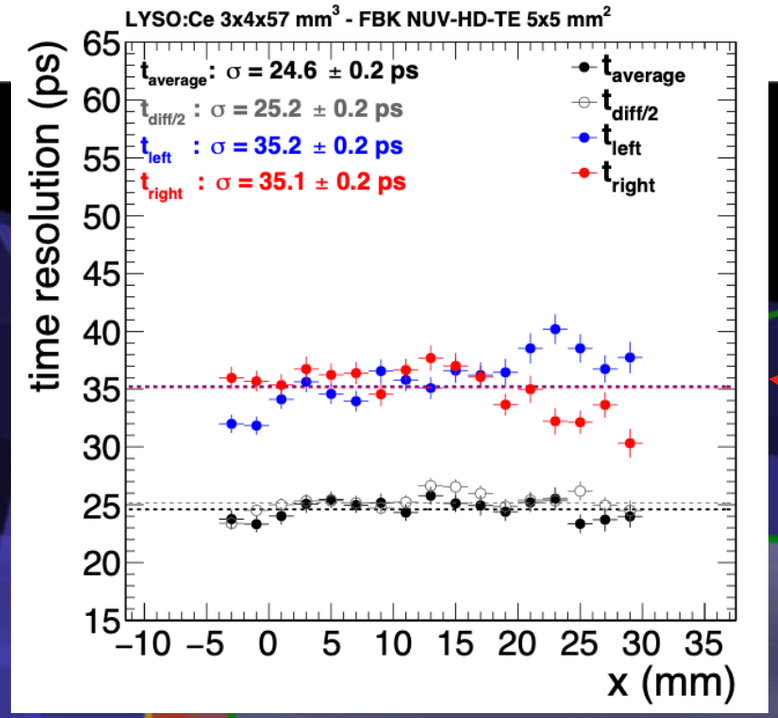


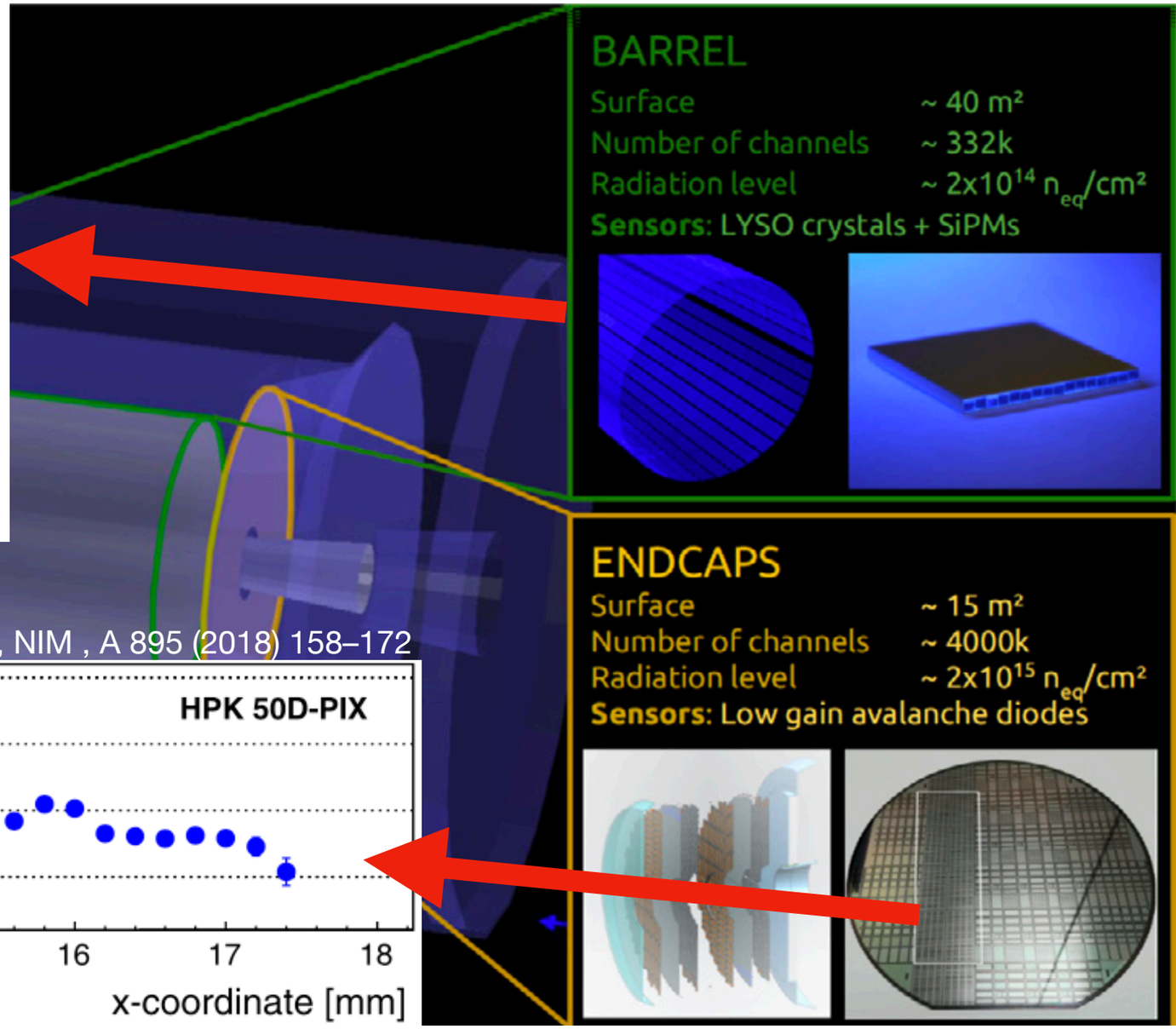
The MIP Timing Detector



A Large Scale Precision Detector

The MIP Timing Detector

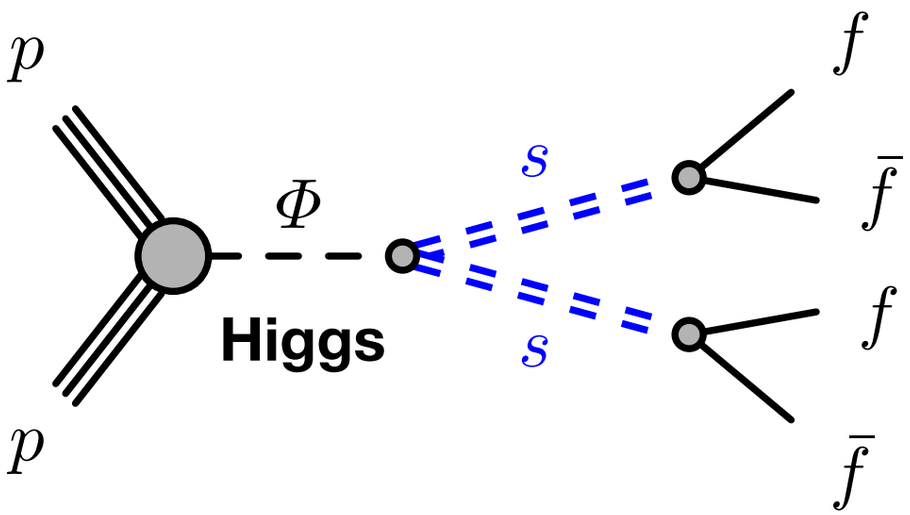




A. Apresyan, S. Xie, C. Peña, et al., NIM , A 895 (2018) 158–172

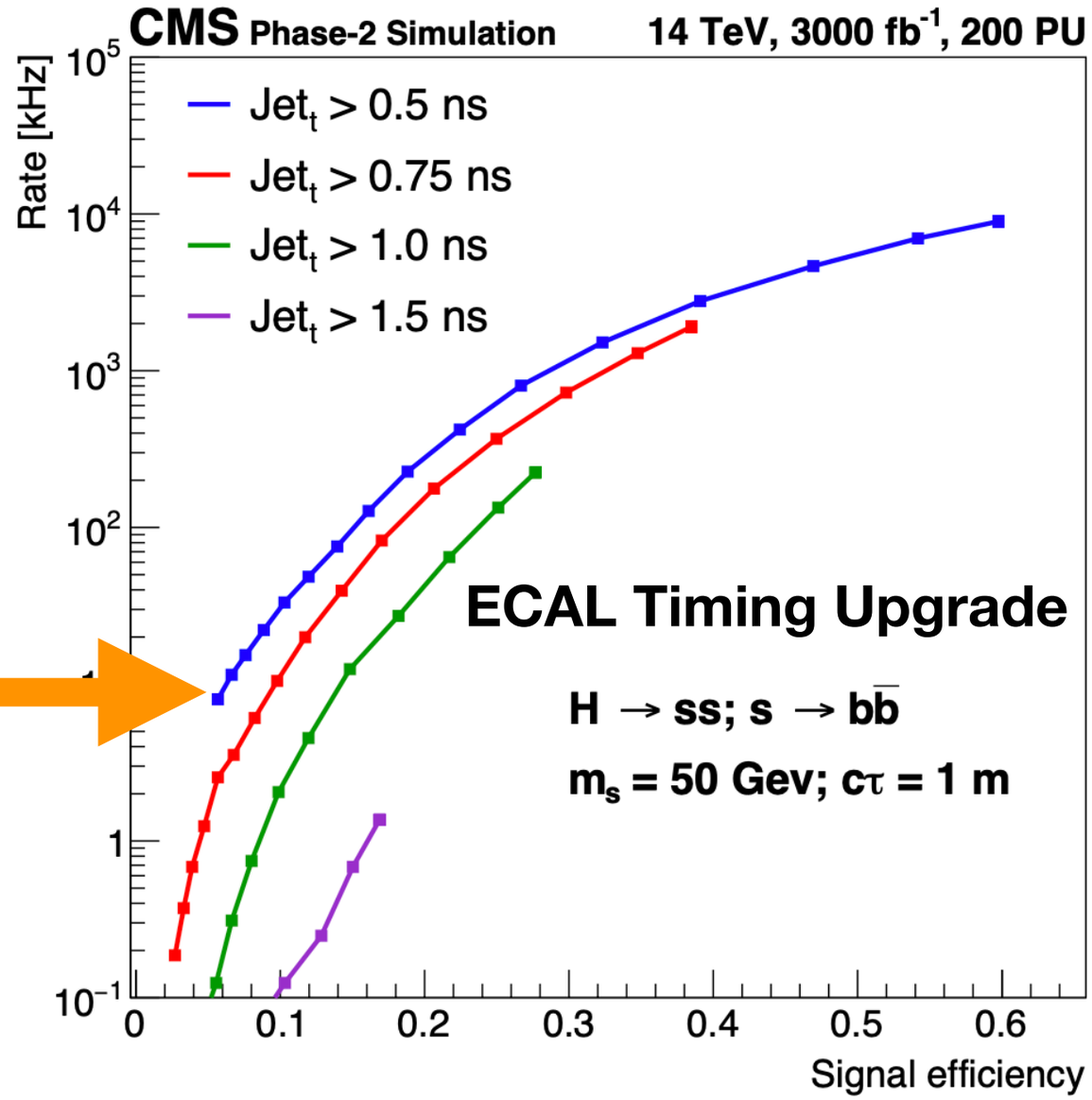
A Large Scale Precision Detector

Precision Timing Enables L1 Triggers



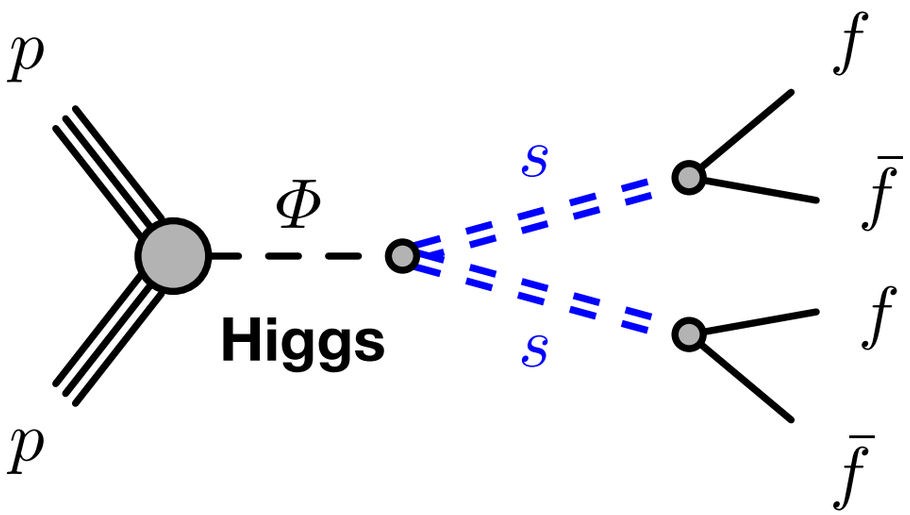
Greater than 10x increase in signal acceptance!

CMS L1 TDR (2020)



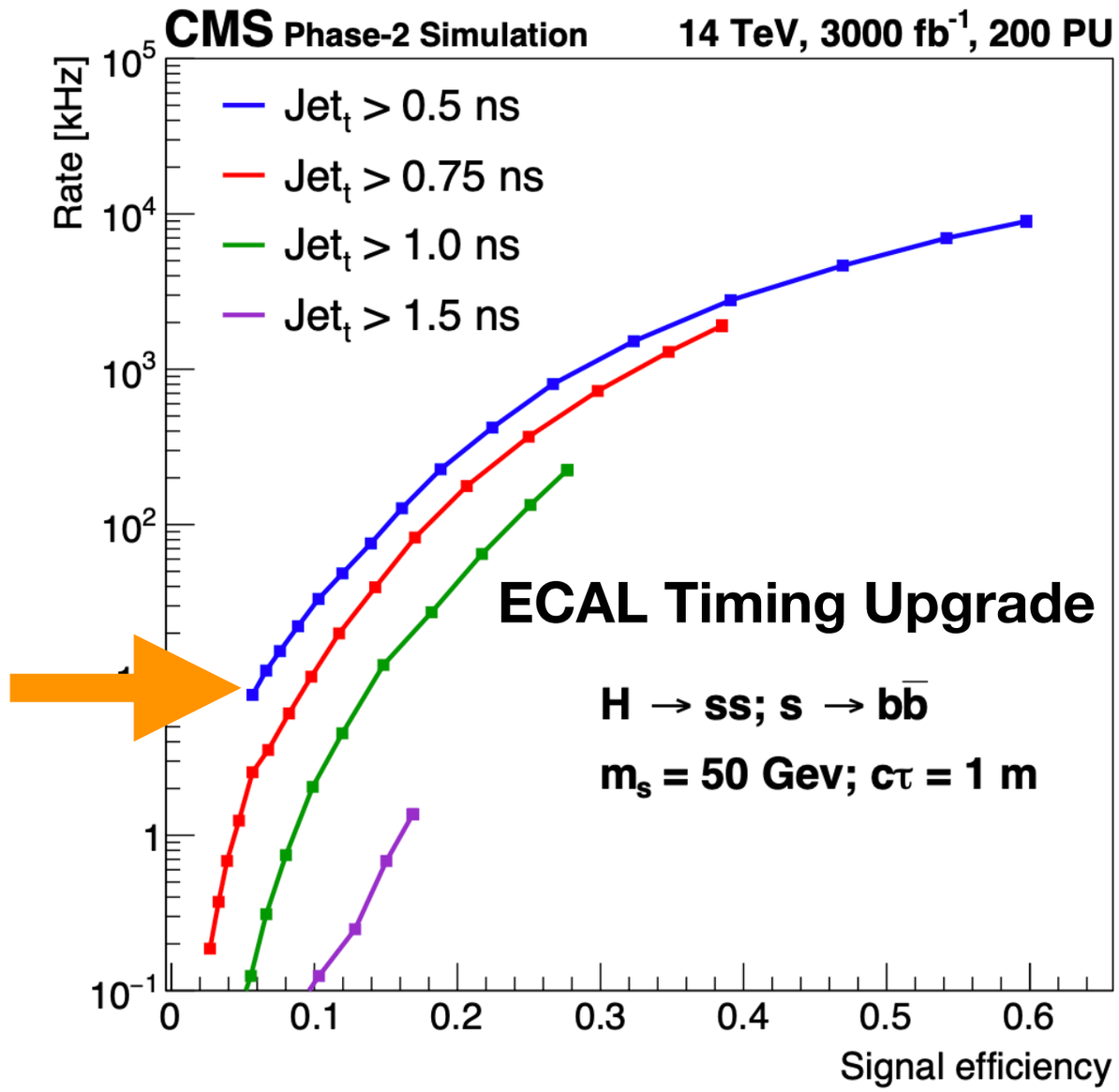
15% efficiency for @ 10 kHz L1 rate

Precision Timing Enables L1 Triggers



Combined with MTD will significantly boost LLPs with ~1m cτ

CMS L1 TDR (2020)



15% efficiency for @ 10 kHz L1 rate

Outlook

- 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

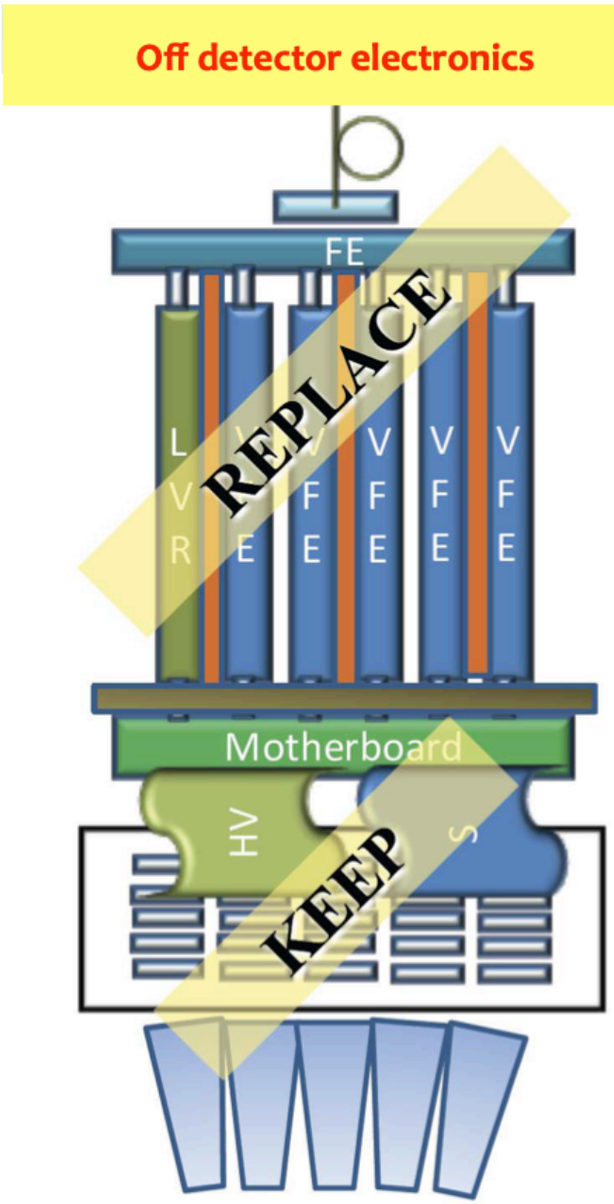
- A decade-long research program ahead that could presents us with possible fundamental discoveries

Thank you!

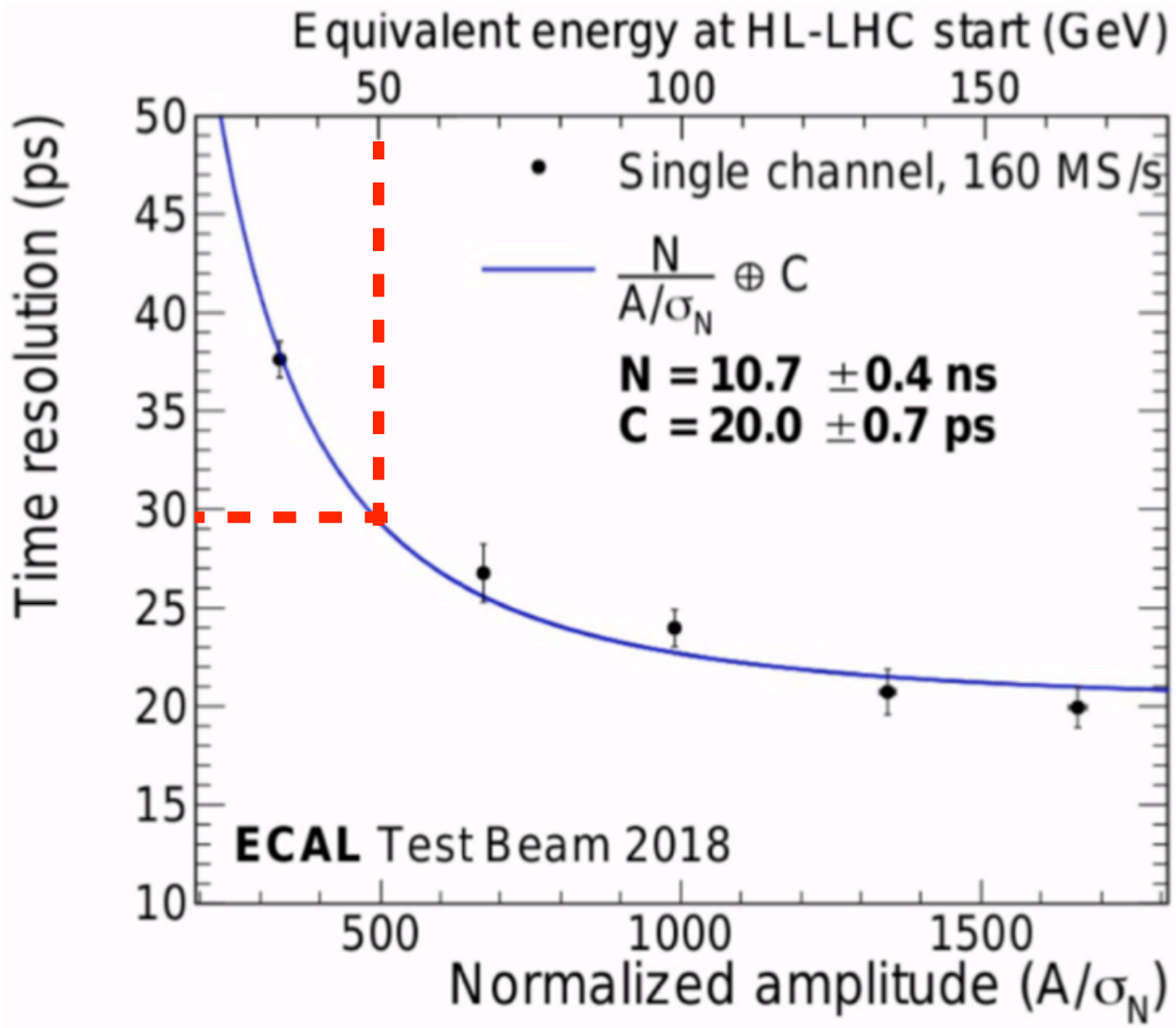
- Backups

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

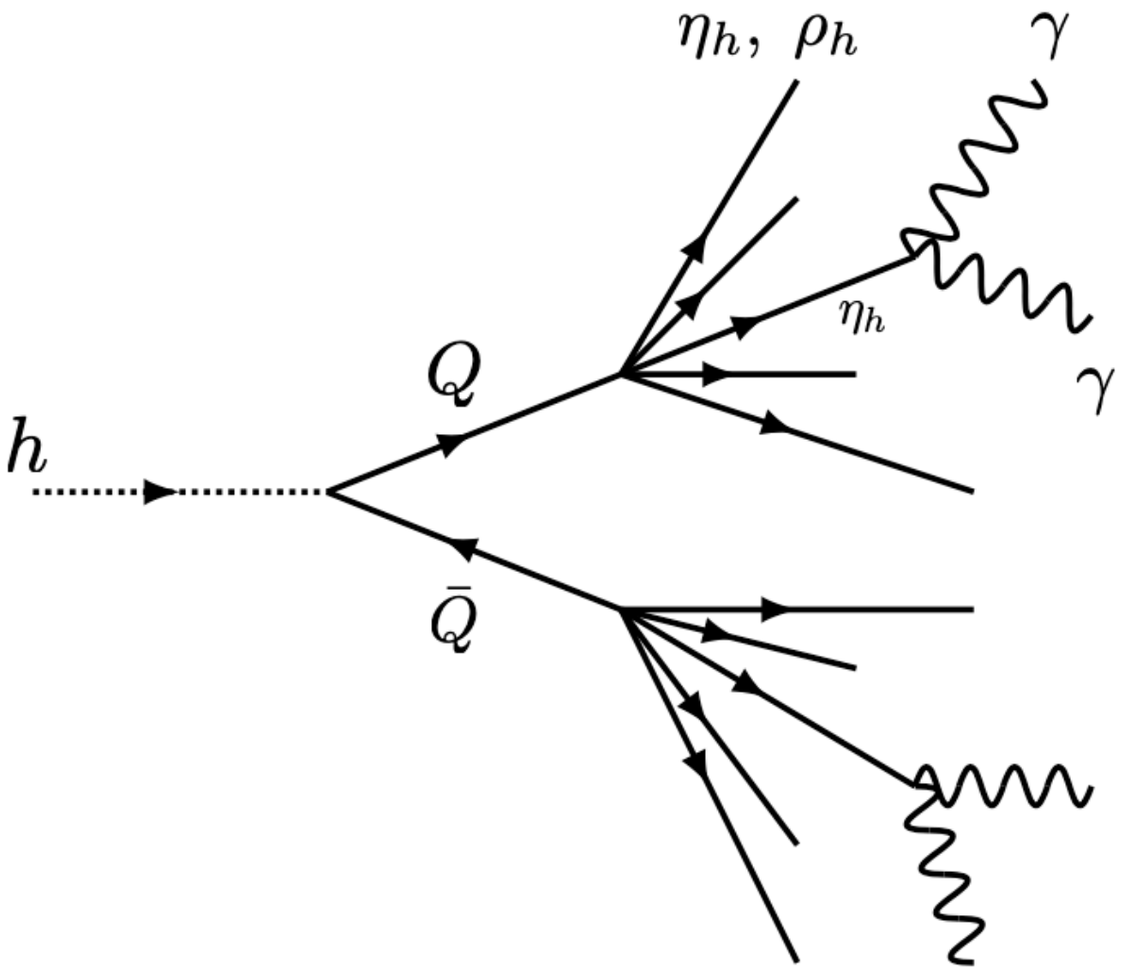


ECAL Barrel upgrade achieves **30 ps resolution for 50 GeV energy deposits**

Hidden Valley Reinterpretation

HIDDEN VALLEY

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

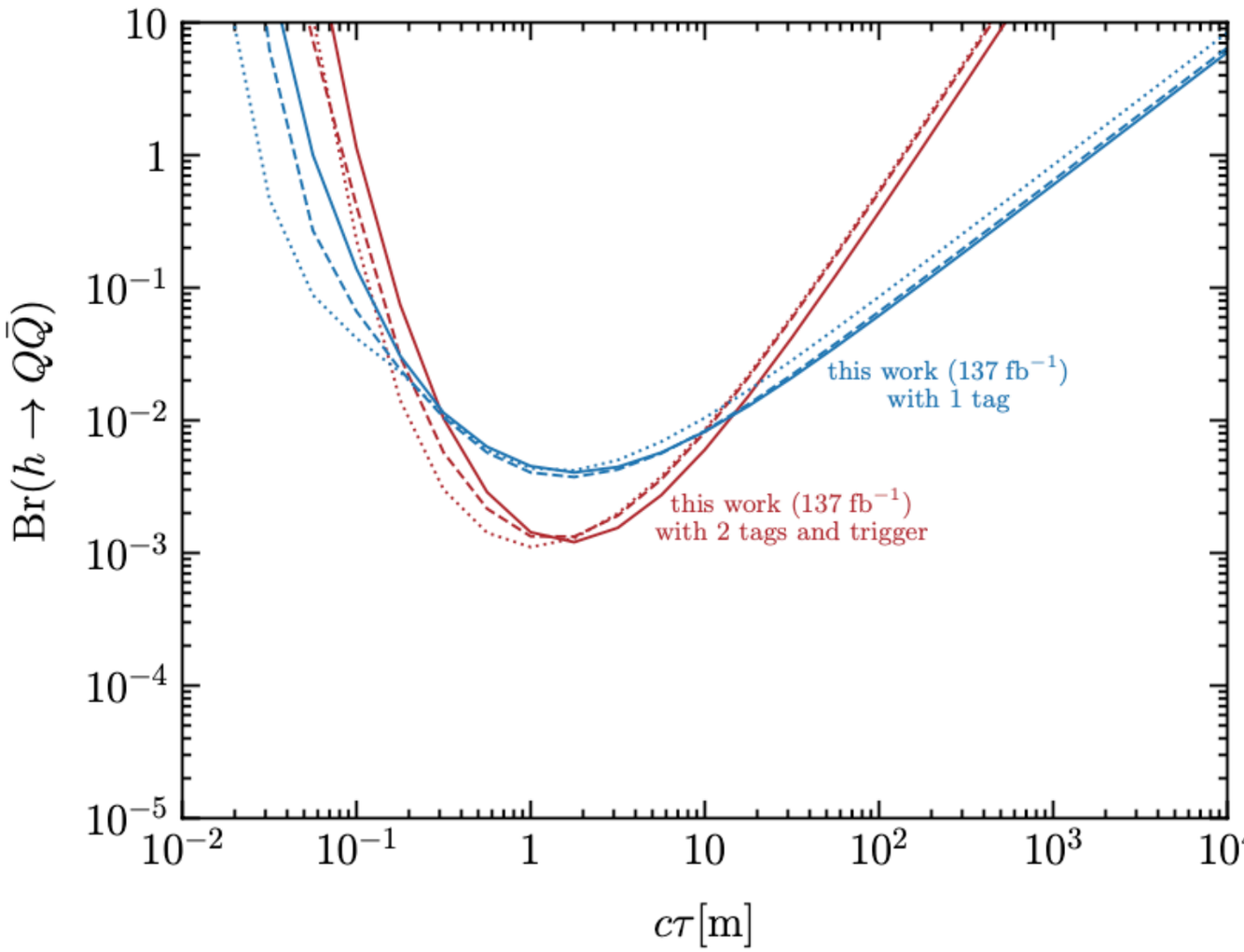


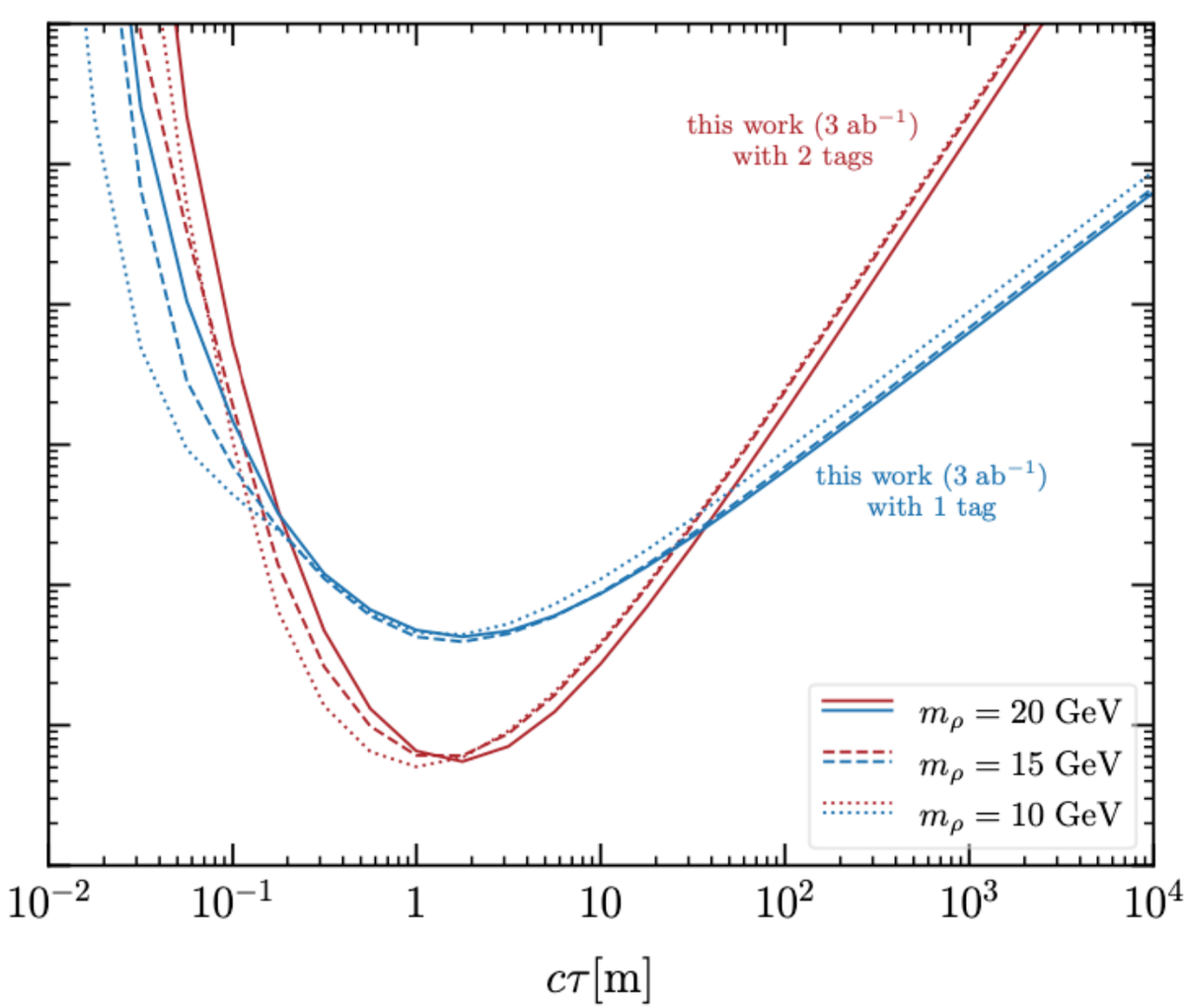
- we treat the η_h lifetime as a free parameter
- we take $\mathrm{Br}(\eta_h \to \gamma\gamma) = 1$ (hard to probe with other searches)
- we assume ρ_h to decay into $\eta_h \eta_h$ to maximize self-veto effects
- we implement the dark shower with Pythia treating η_h as a pion

Diphoton decay sensitivity due to unique signature of this search

Hidden Valley Reinterpretation

Exciting new possibilities with a model independent search





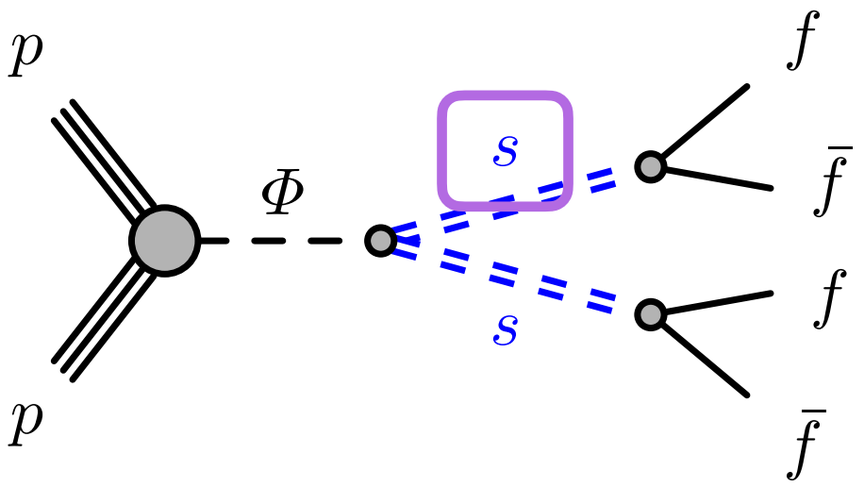
- CMS Results: Good sensitivity for challenging BSM signature
- Re-intepretation shows importance of **double tag search**
- Projected Br exclusion at 1e-4 at HL-LHC → NEEDS TRIGGERS!

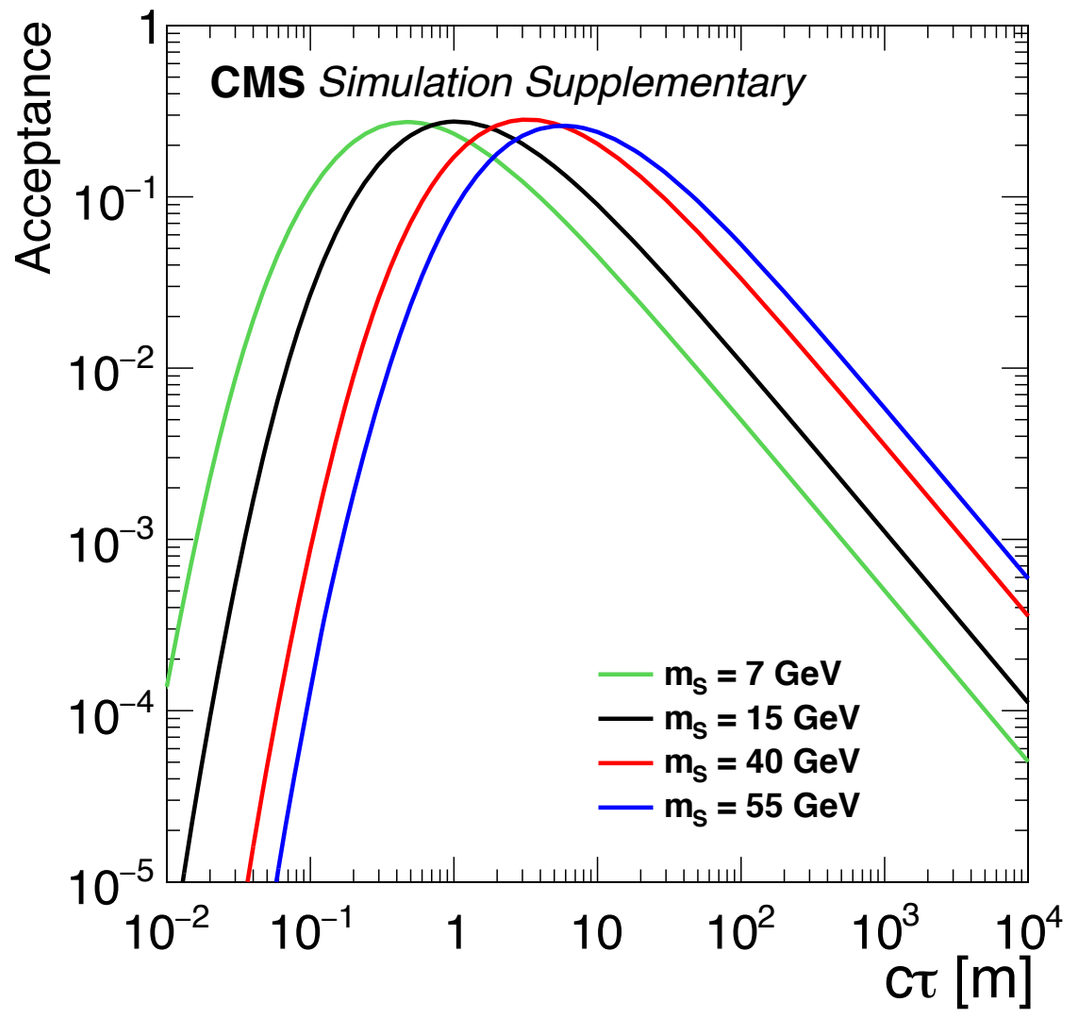
A. Mitridate at LLPX workshop

LLP Acceptance in Muon System

Acceptance in muon system peaks at a few meters

At least one LLP in CSCs





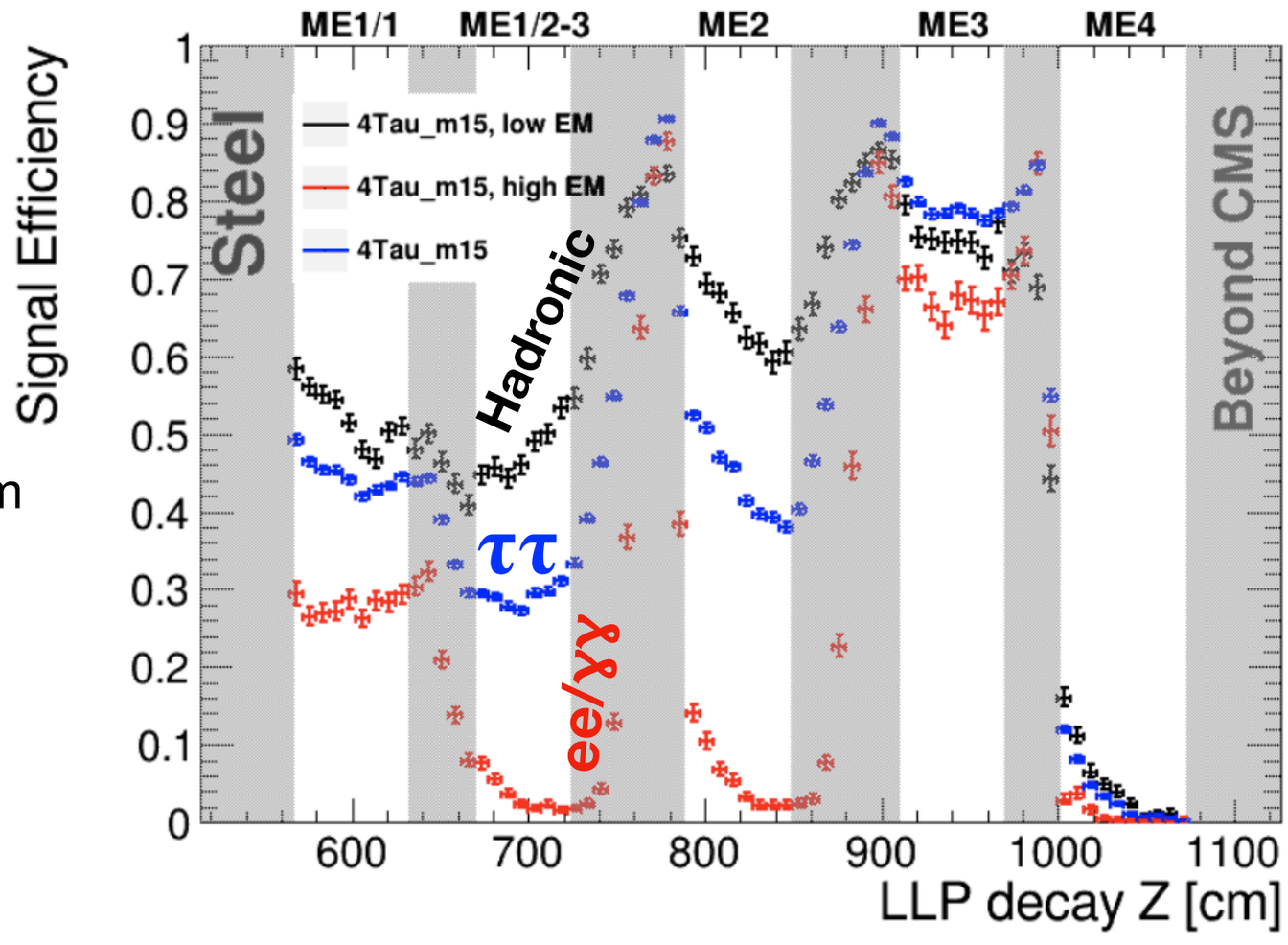
- LLP mass shifts peak acceptance location

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

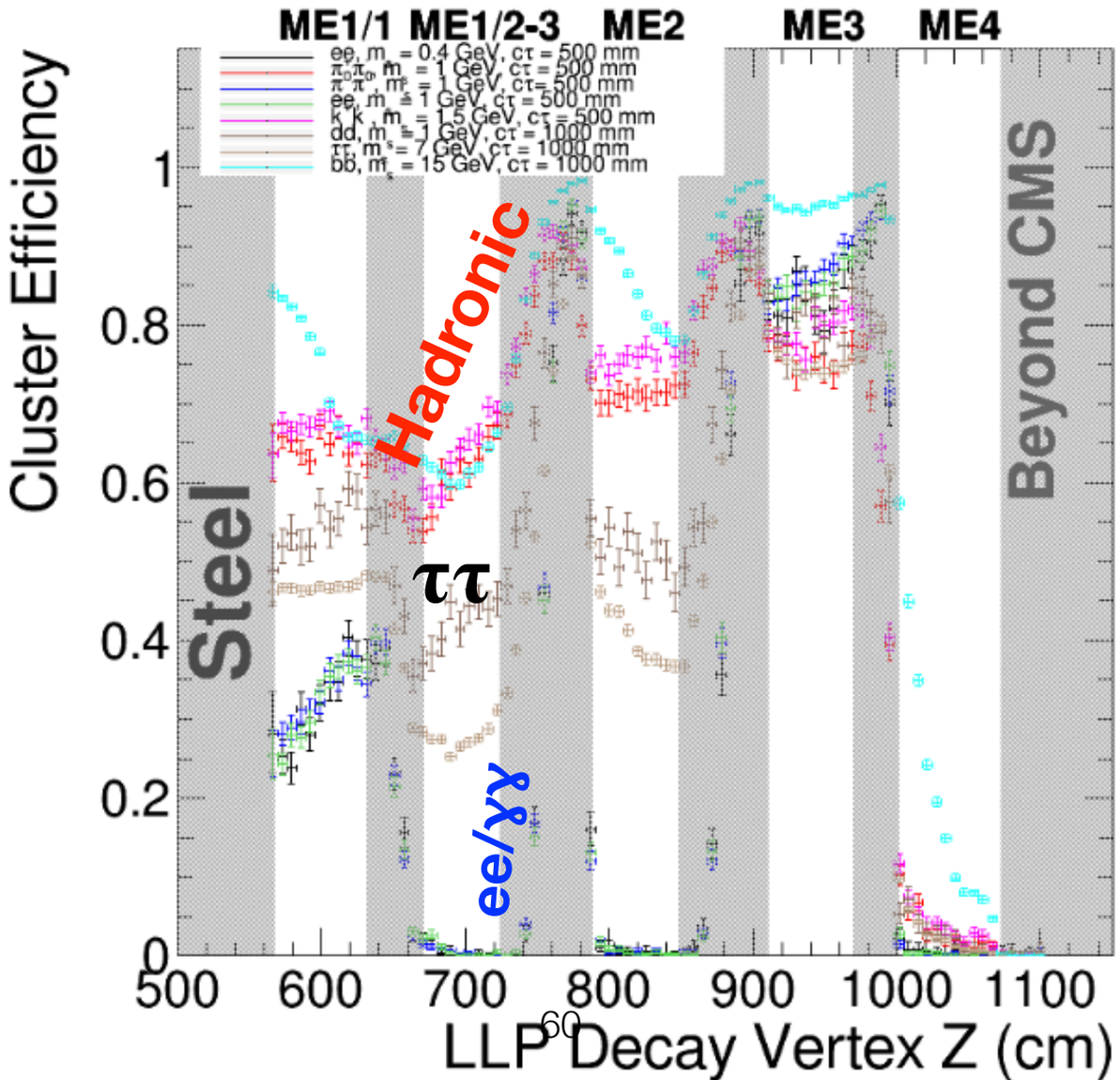
Γ_5 $e^- \overline{\nu}_e \nu_\tau$

Γ_9 $\pi^- \nu_\tau$

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

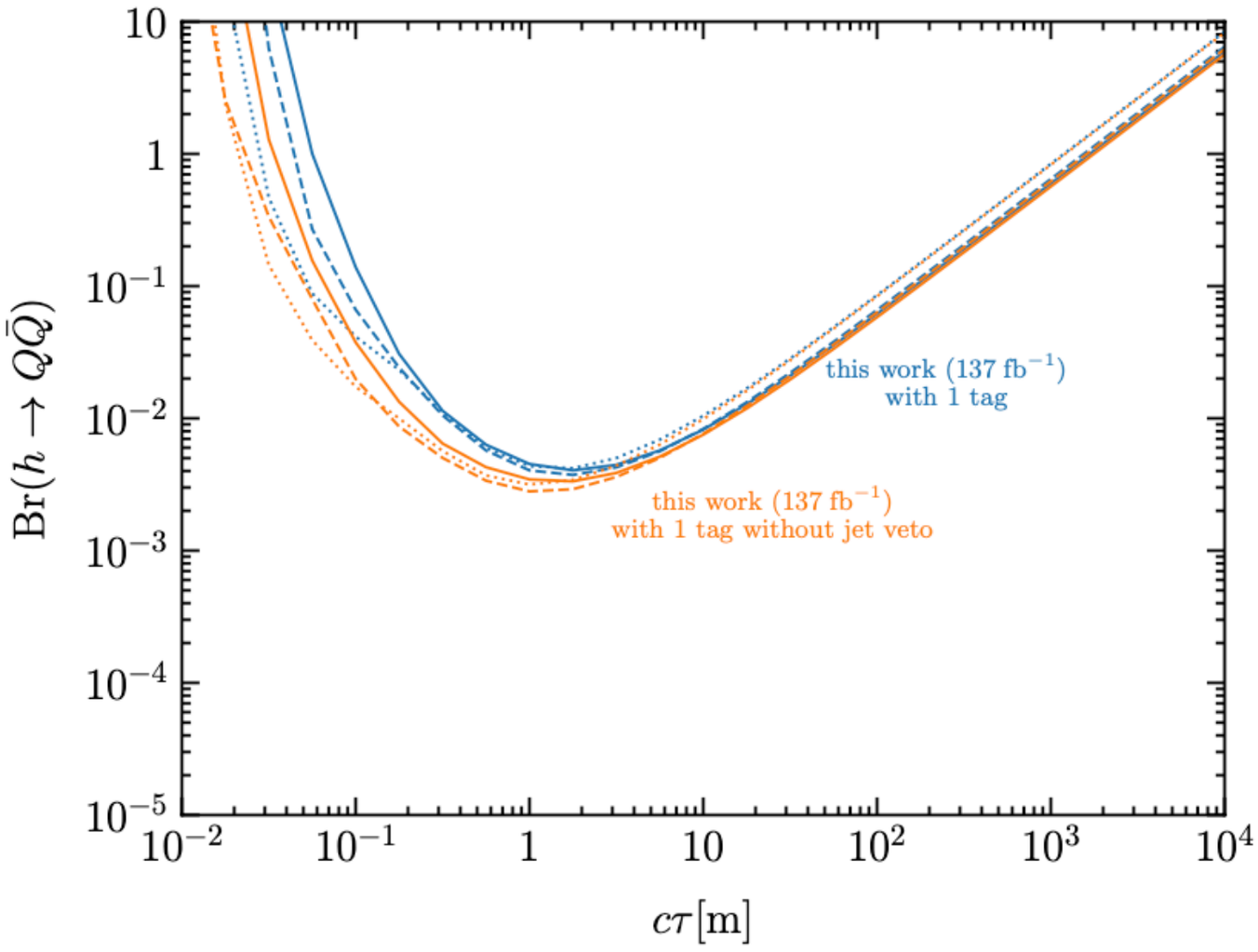
EM/Had LLP Efficiency in Muon System

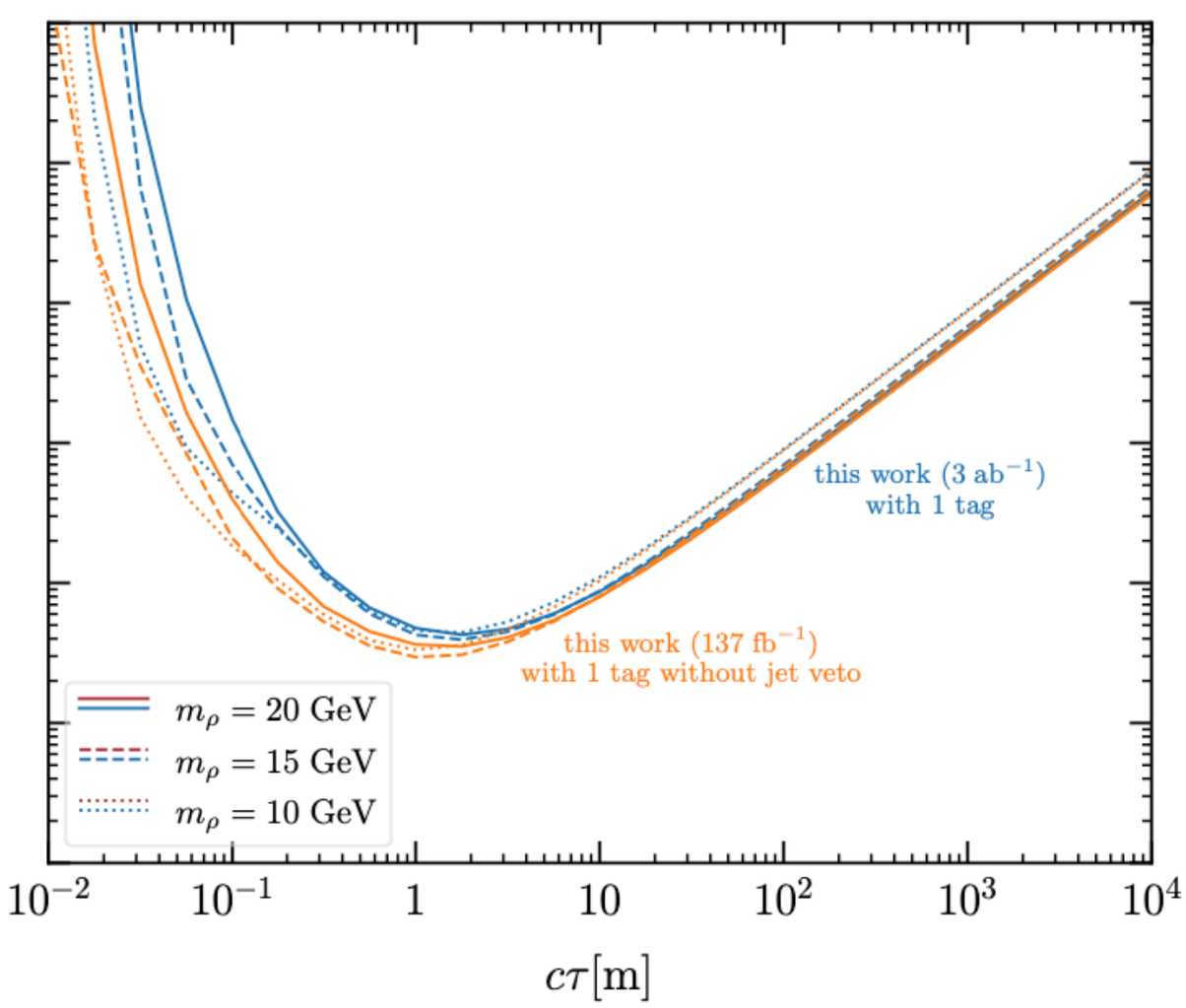
- Confirm efficiency to EM decays using LLPs events decaying to **ee, γγ, $\pi^0\pi^0$**
- Confirm efficiency to Hadronic decays using LLPs events decaying to **k^+k^- and $\pi^+\pi^-$**



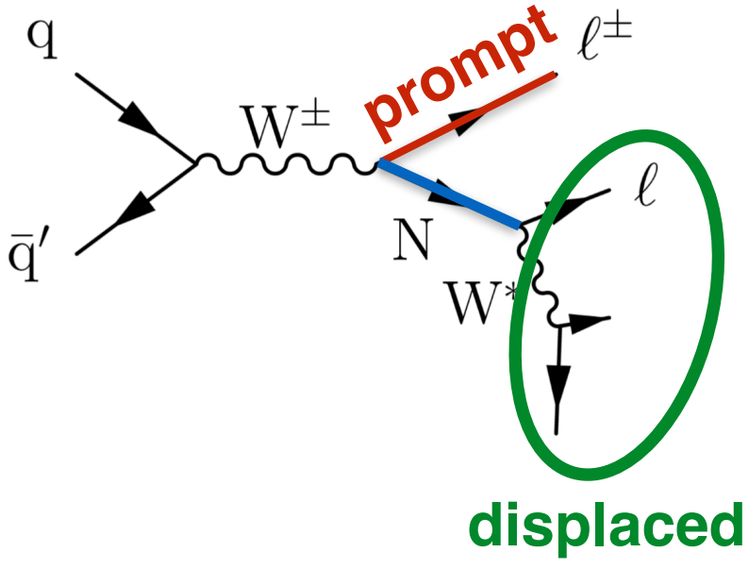
Hidden Valley Reinterpretation

Effect of the Jet veto is explored

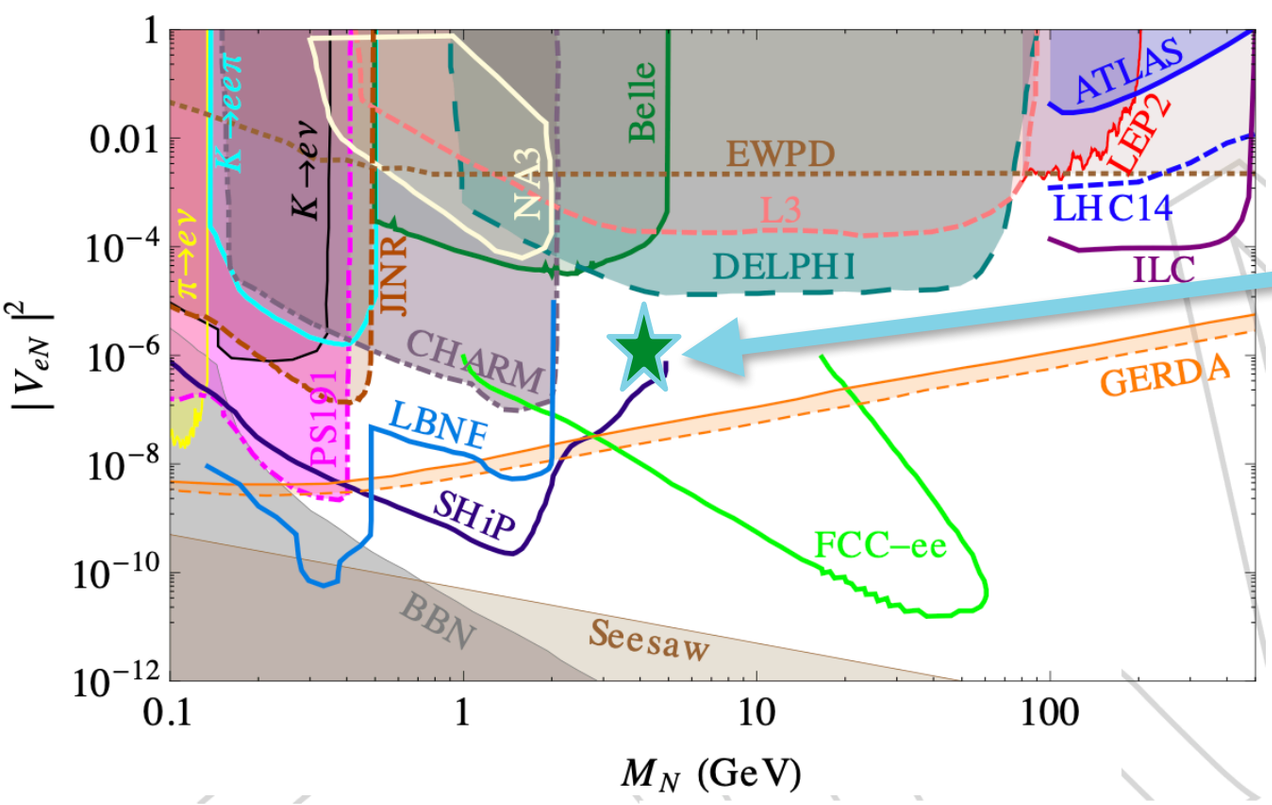




HNLs in Muon System

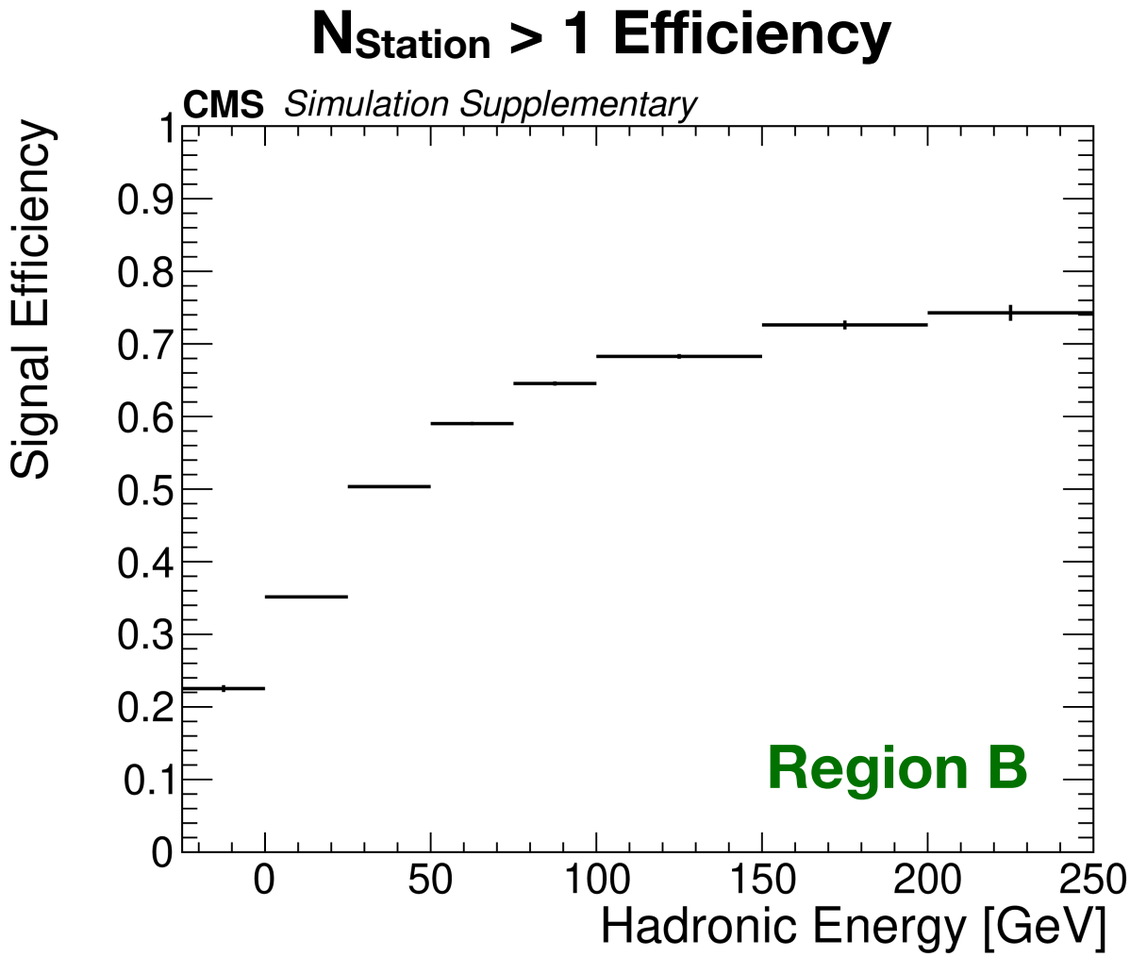


$$c\tau_N \sim 3.7 \left(\frac{1\ \text{GeV}}{m_N} \right)^5 \left(\frac{0.1}{|V_{lN}|^2} \right) \quad [\text{mm}].$$



- 4 GeV HNL @ $|V_{\ell n}|^2$ = 1e-6 → xsec ~ 15 fb
- HNL lifetime ~ 0.4 m → acc in MS ~ 7%
- Events in MS @ 137/fb ~ 150
- HNL decaying at 5-10m, will create shower in the muon system
- Sufficient to probe this parameter-space

Cut-based ID Efficiency



- Implemented a dedicated CscClusterID, which implements the cut-based ID function provided in HEPData entry
- **Only gen-level LLP η , decay position, and hadronic energy are needed as input**
- ID requirement in analysis:
  - If $N_{station} > 1$: $|\eta| < 1.9$
  - If $N_{station} = 1$: apply $|\eta| < X$, where X = 1.6 or 1.8 depending on the Average Station Number
- ID efficiency is 100% for clusters in region A ($|\eta| < 1.3$)
- ID efficiency for region B is calculated using:
  1. Efficiency of $N_{station} > 1$ requirement
  2. Transfer function that takes gen-level LLP decay position to RECO-level cluster Average Station (Only for clusters with $N_{station} = 1$),
  3. LLP η as a proxy for cluster η
- **The full simulation signal yield prediction reproduced using this procedure to within 10%.**

Other Cuts

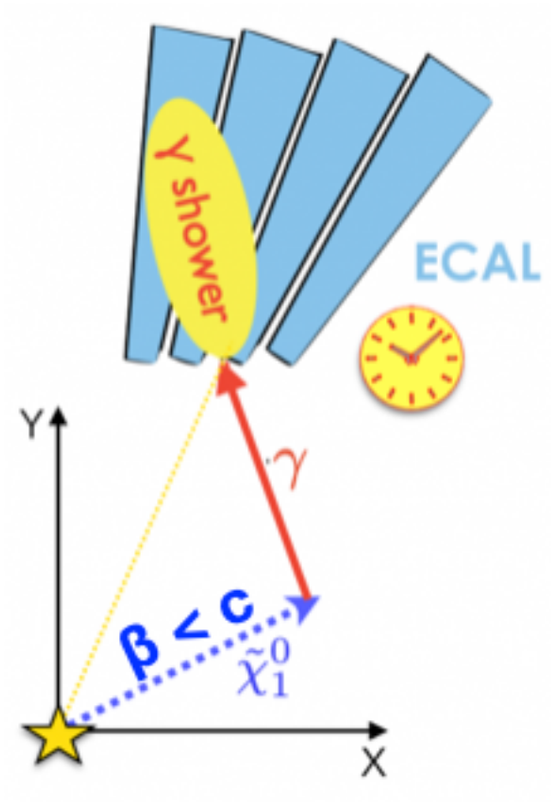
- **The following cuts applied in the analysis are model dependent, and are not provided in HEPData entry**
- **Time cut**
  - -5 ns < $t_{cluster}$< 12.5 ns
  - Travel time highly depends on the lifetime and boost of the LLP
  - $t_{cluster}$ calculated using gen-level LLP travel time from IP to decay vertex and is stored as a variable of the CscCluster class
- **Jet Veto**
  - Clusters matched (ΔR < 0.4) to jets (>10 GeV) are vetoed in the analysis
  - This variable is not implemented as a variable of CscCluster, but is calculated in analysis workflow by matching the cluster to the jet collection from Delphes
- **Δϕ (cluster, MET)**
  - abs(Δϕ (cluster, MET)) < 0.75
  - This variable is not implemented as a variable of CscCluster, but is calculated in analysis workflow by matching the cluster to the MET collection from Delphes

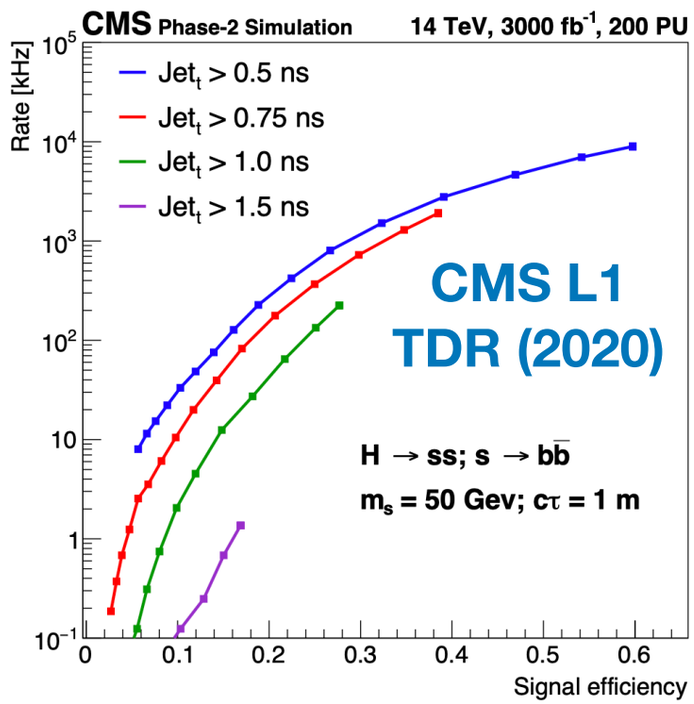
Example: new LLP ideas now

- Trackless jets with precision timing: best executive sensitivity at $c\tau$ ~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

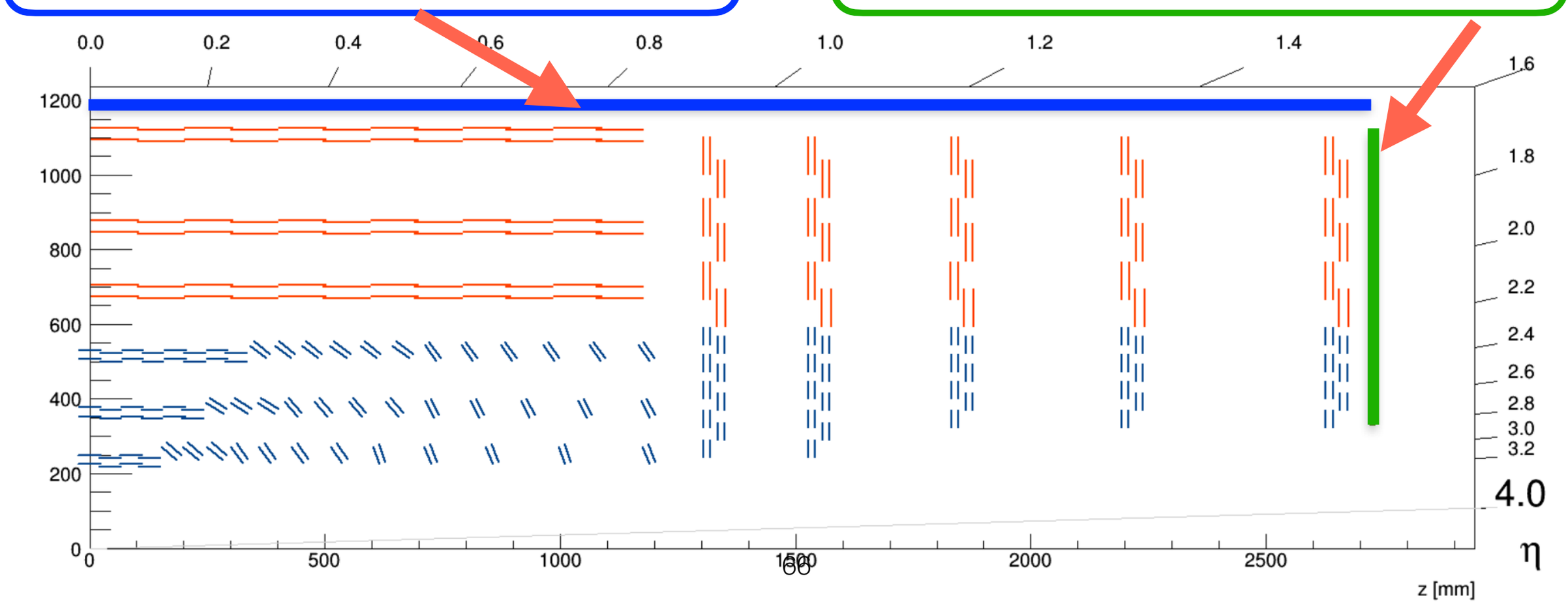
- **Caltech CMS** group the leader of this project since 2012 (with FNAL)
- Sustained effort and progress in precision timing R&D

Barrel Timing Layer:

Scintillating crystal + SiPM

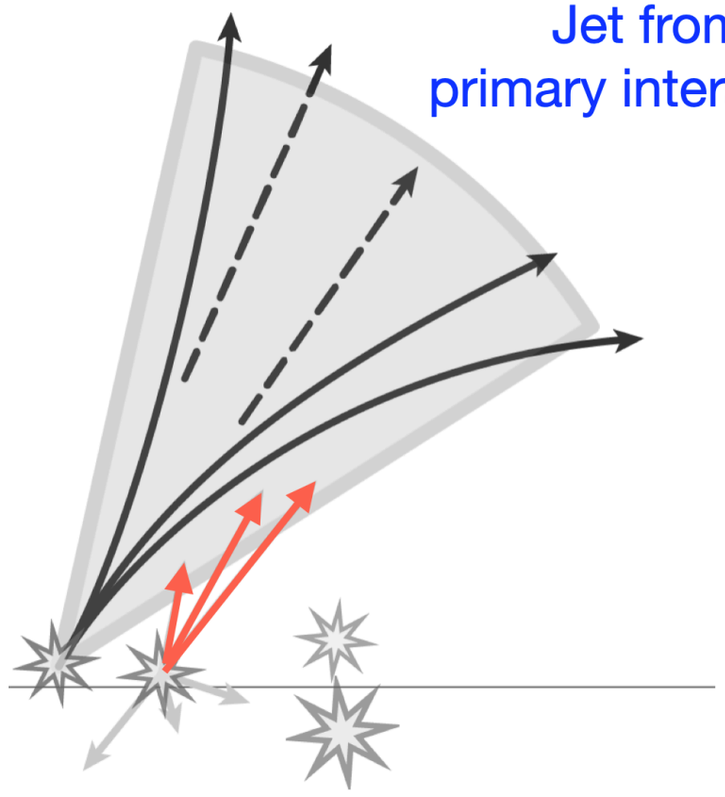
Endcap Timing Layer:

Silicon Sensor with Gain

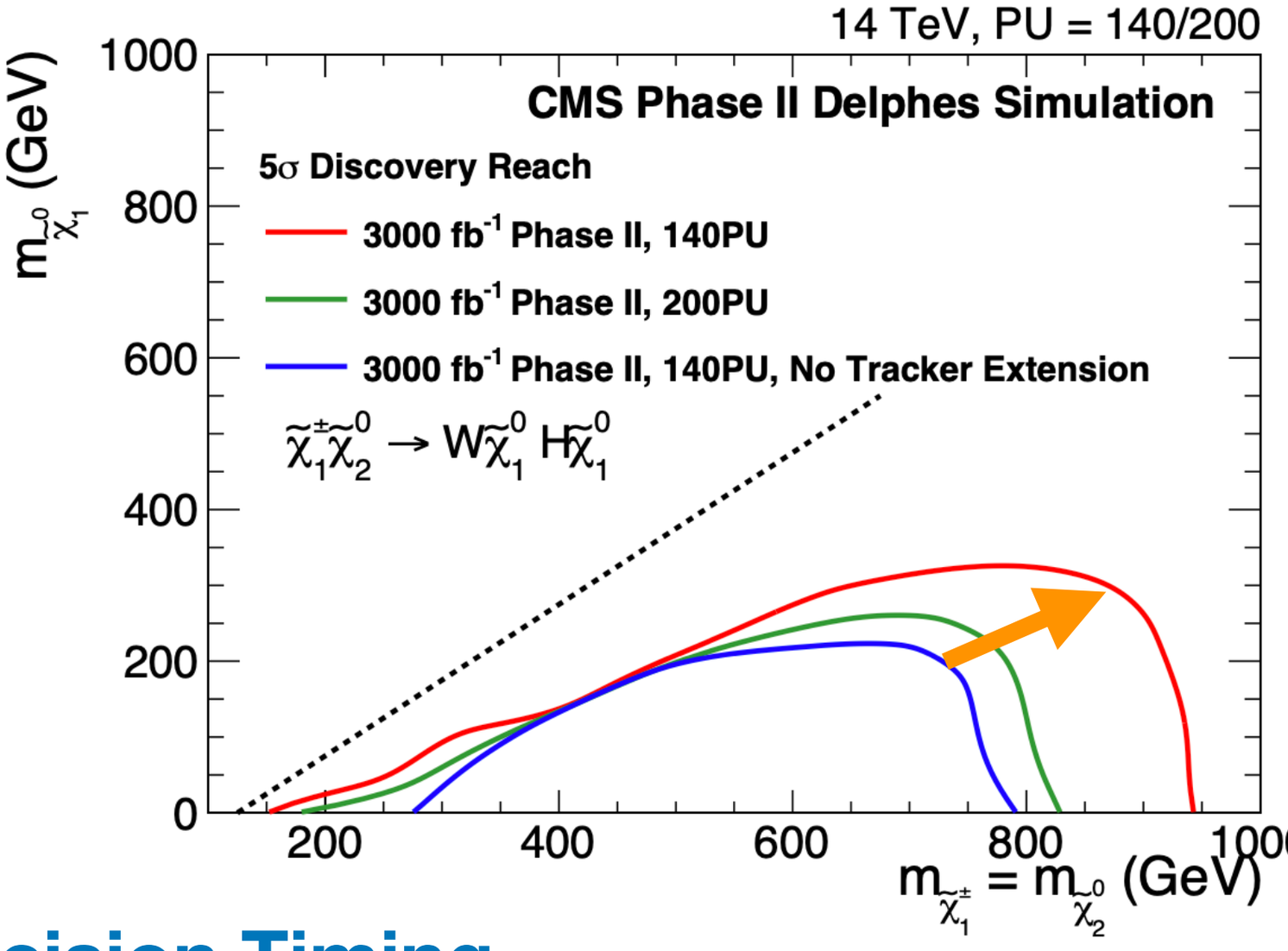


Enhanced Physics Reach

Pileup degrades <u>missing energy resolution</u>



For SUSY searches: timing significantly reduces background

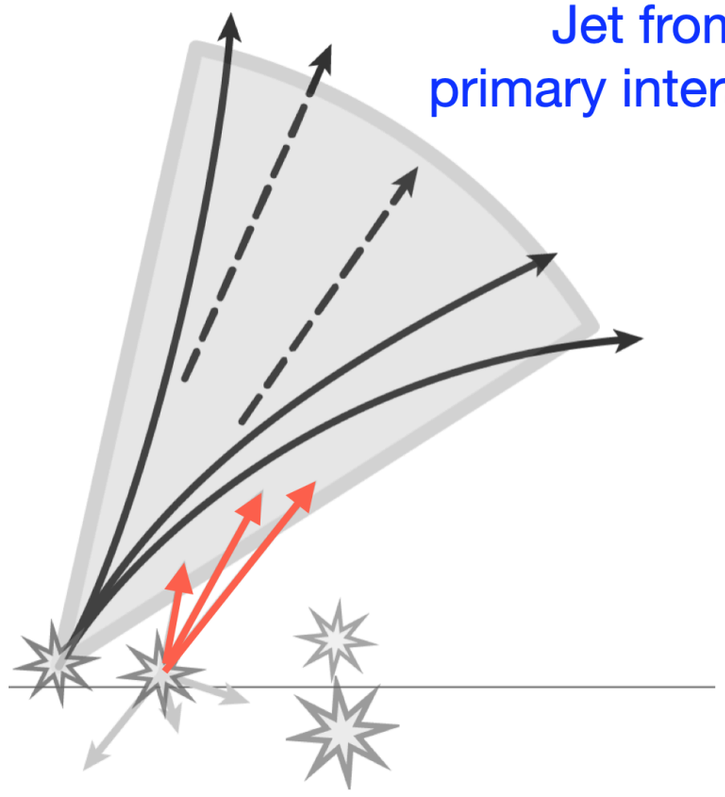


Precision Timing

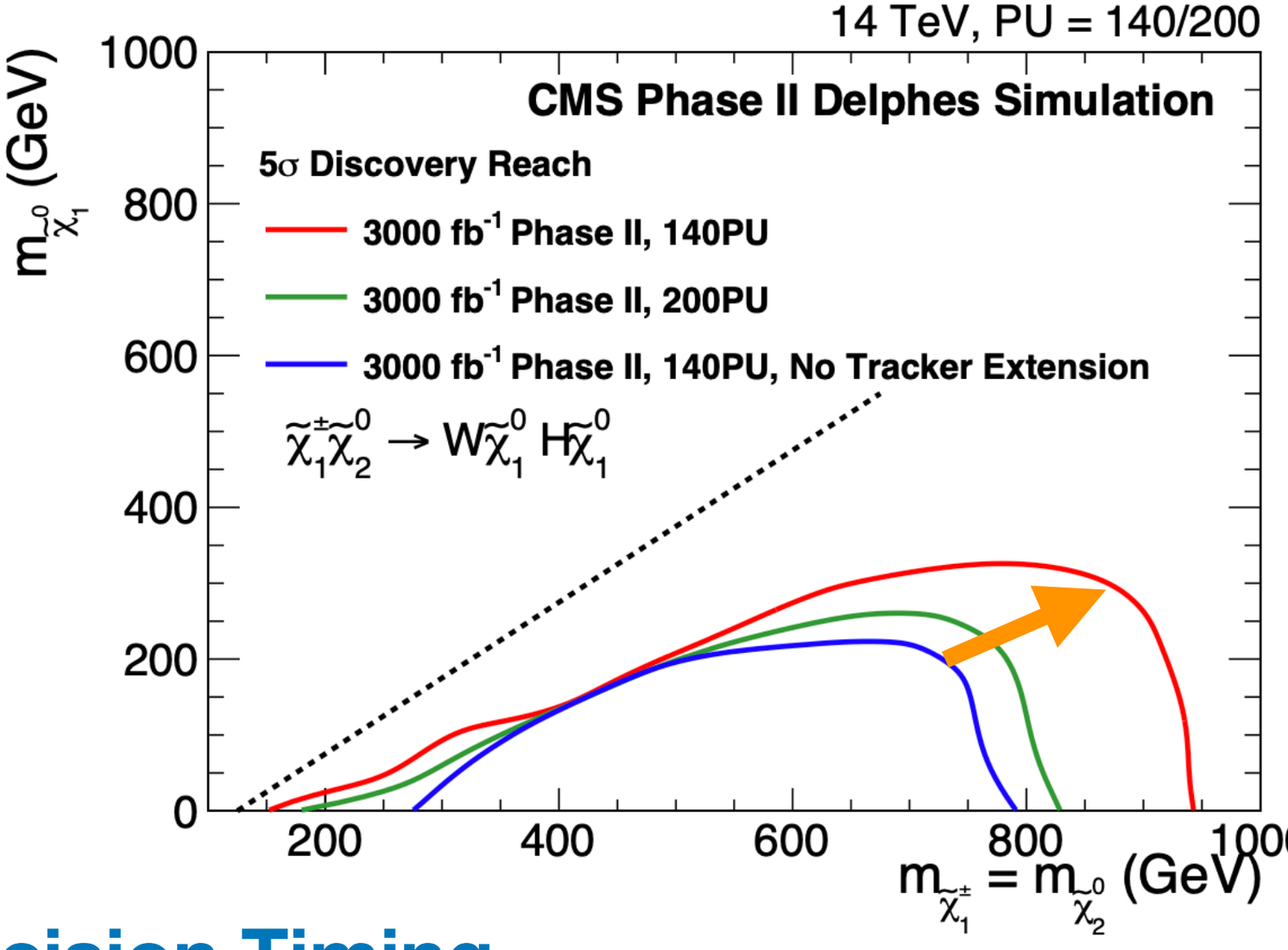
Increase EWK-SUSY mass discovery reach by ~150 GeV

Enhanced Physics Reach

Pileup degrades missing energy resolution



For SUSY searches: timing significantly reduces background



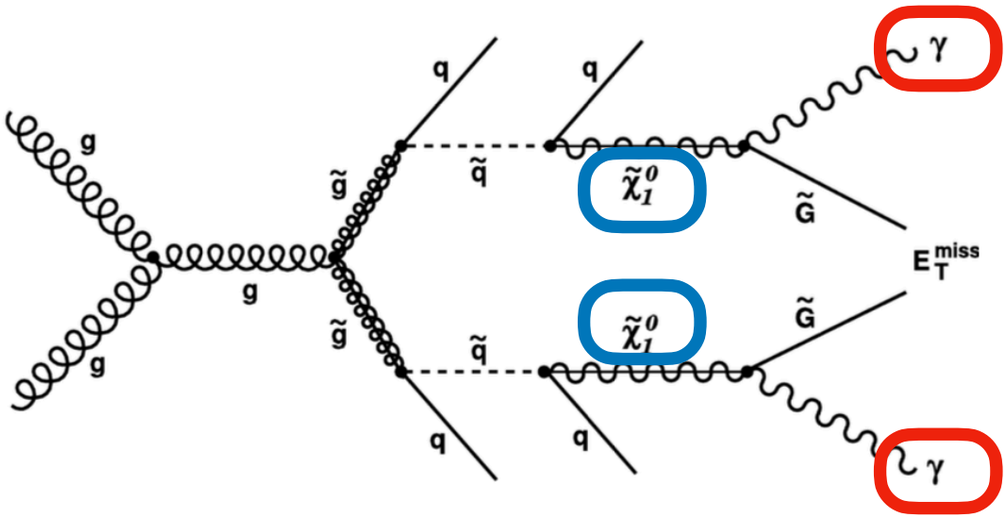
Precision Timing

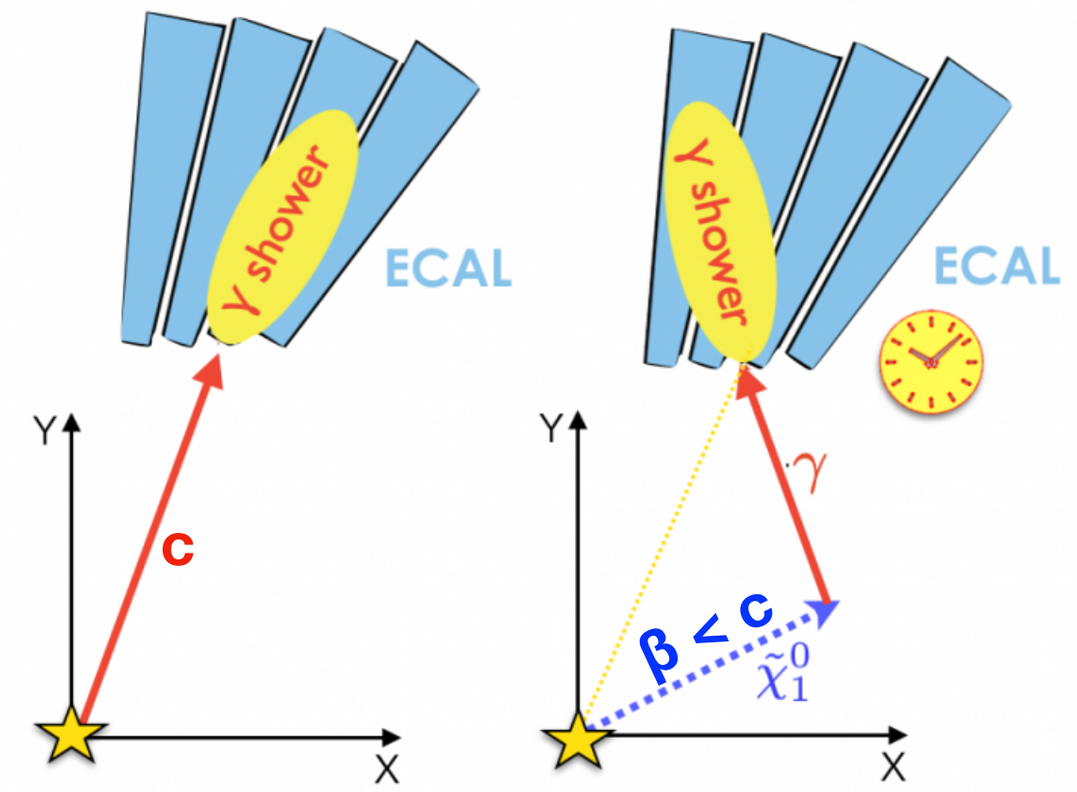
↓

Accessing 3x smaller production rates!

In-flight SUSY

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



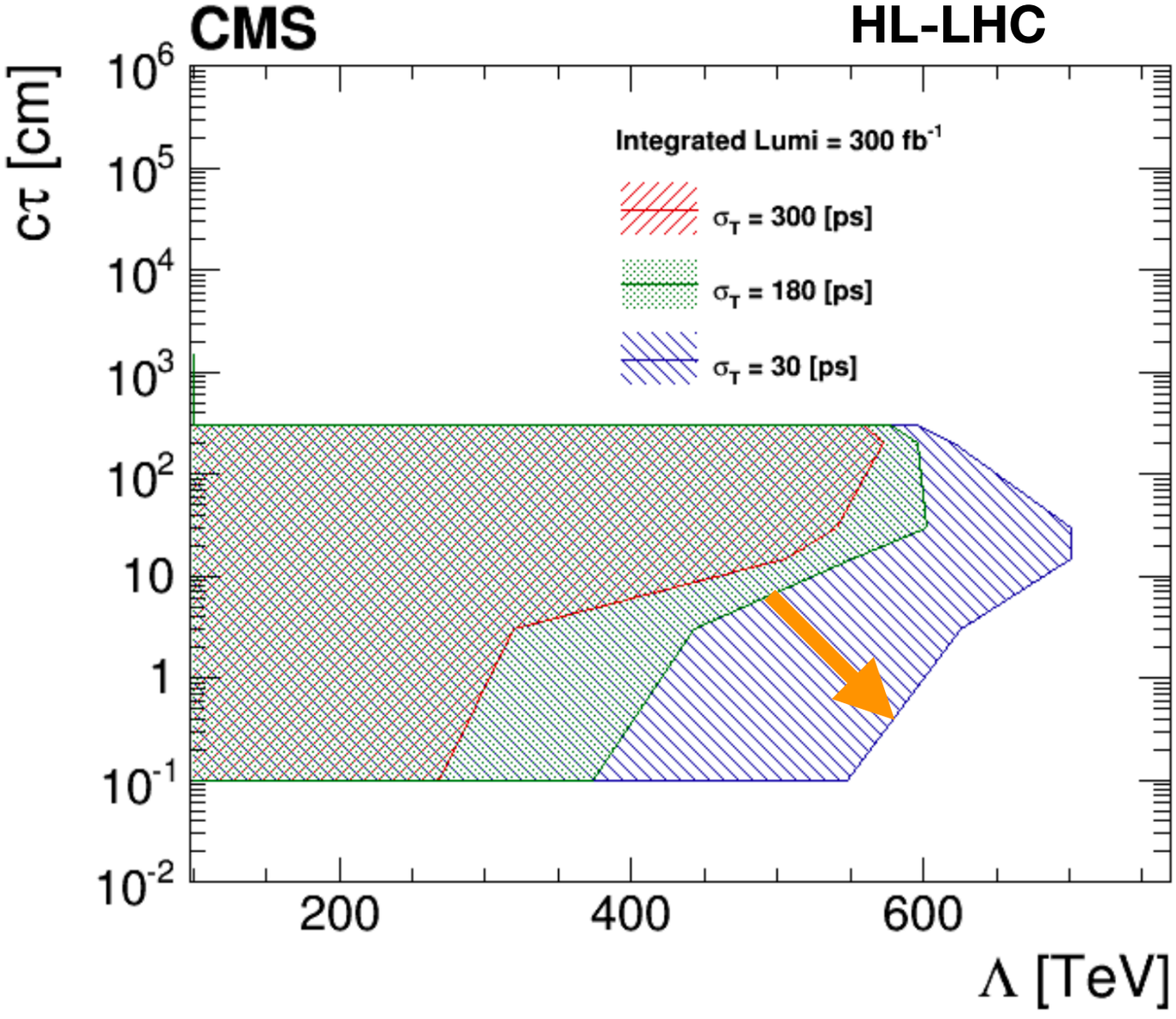


Neutralino travels slower than speed of light: time-delay

Signature: delayed photon

In-flight SUSY

MTD improves beam spot time-spread by 6x



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