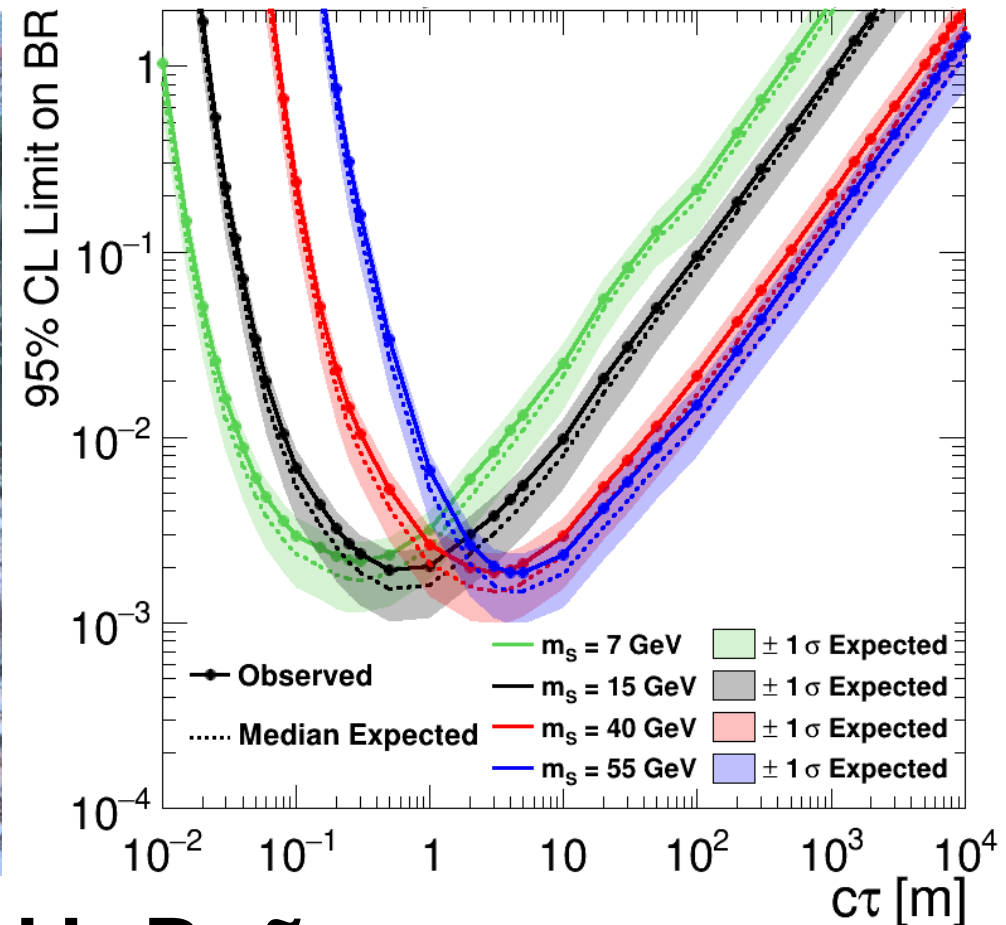
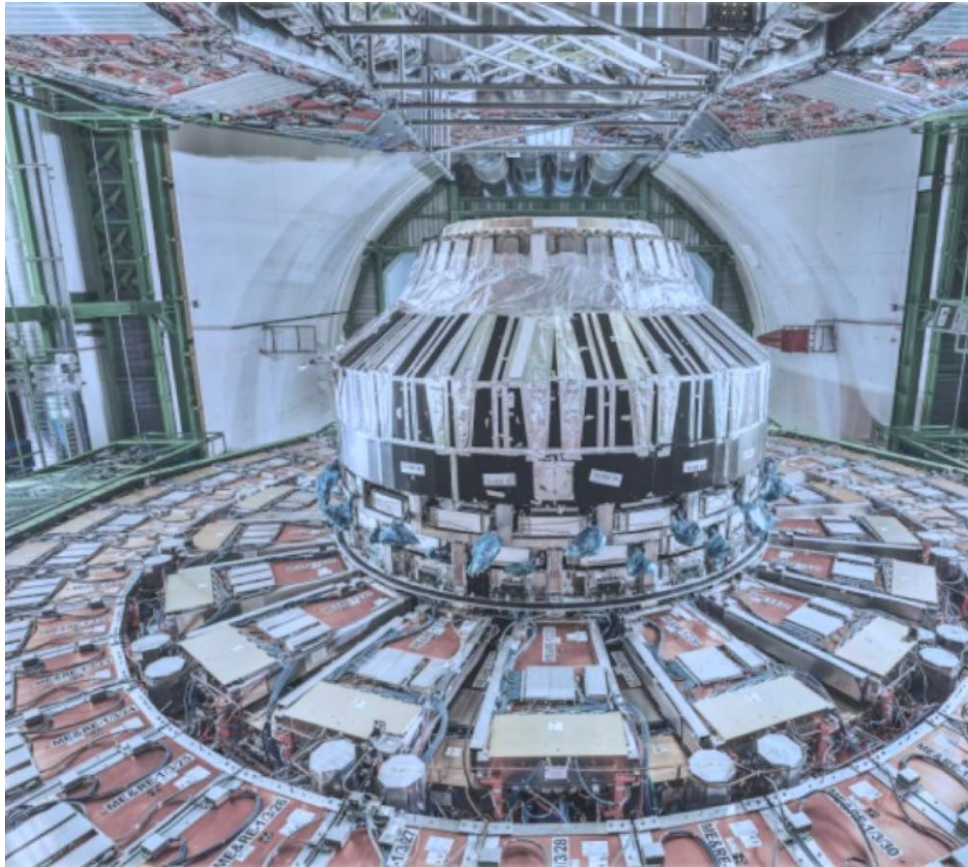


Enabling Searches for Long-lived Particles and The Path Towards Precision Timing



Cristián H. Peña

Fermilab

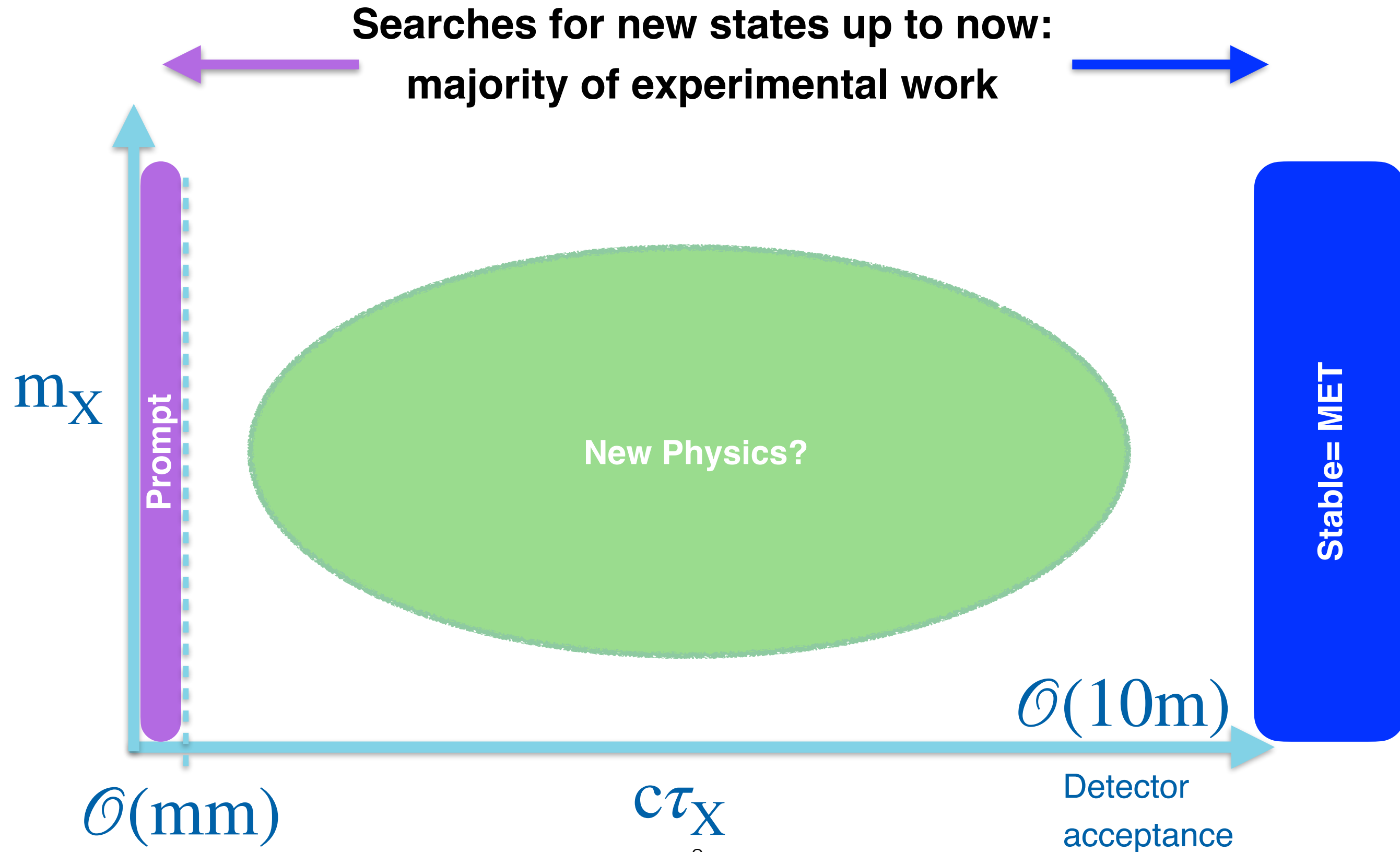
November 5, 2024

FPD Seminar



NATIONAL ACCELERATOR LABORATORY

New Physics at LHC: long-lived particles



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

The Case for Long-lived Particles

Small decay width (Γ) gives rise to sizable lifetimes

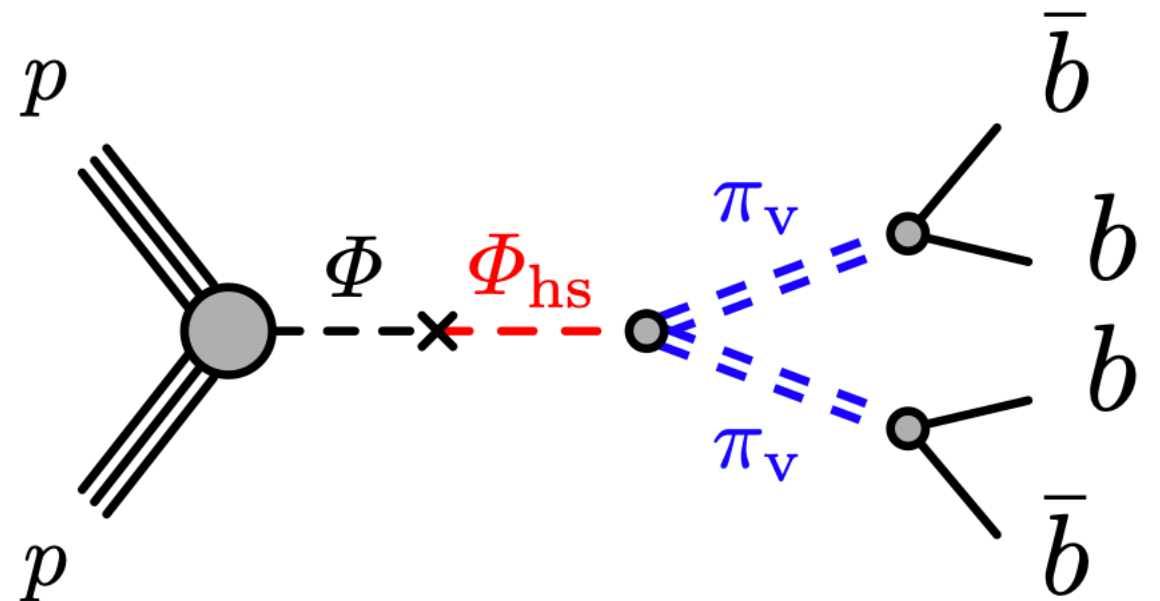
$$\Gamma \sim \boxed{\frac{g^2}{8\pi}} \left(\frac{m}{M}\right)^{2n} m$$

Three general mechanisms:

1. Feeble coupling to SM

e.g: Higgs portal to hidden sectors

Accessing dark matter/sectors



The Case for Long-lived Particles

Small decay width (Γ) gives rise to sizable lifetimes

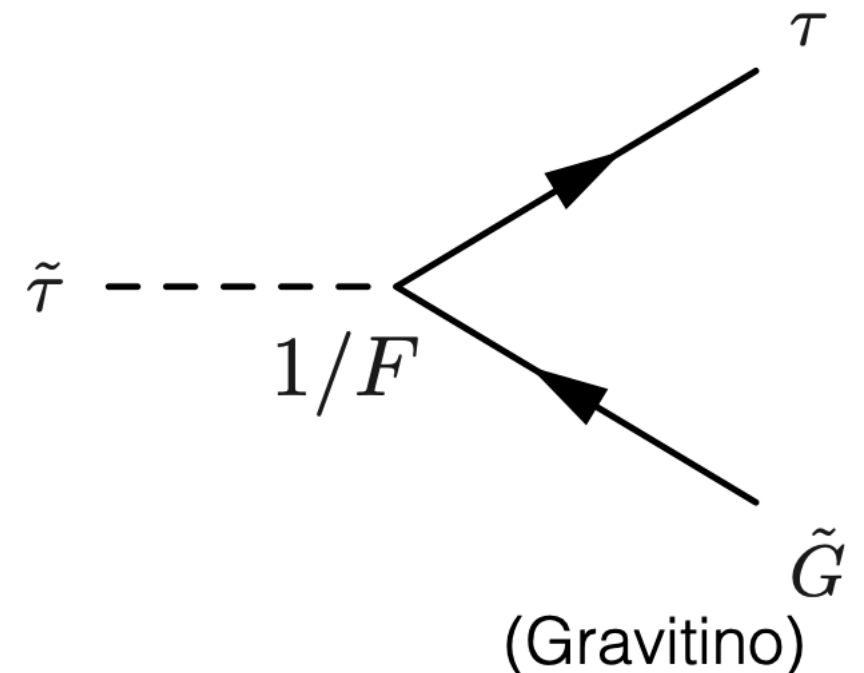
$$\Gamma \sim \frac{g^2}{8\pi} \left(\frac{m}{M} \right)^{2n} m$$

Three general mechanisms:

2. Scale suppression

e.g: Gauge mediated SUSY

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



The Case for Long-lived Particles

Small decay width (Γ) gives rise to sizable lifetimes

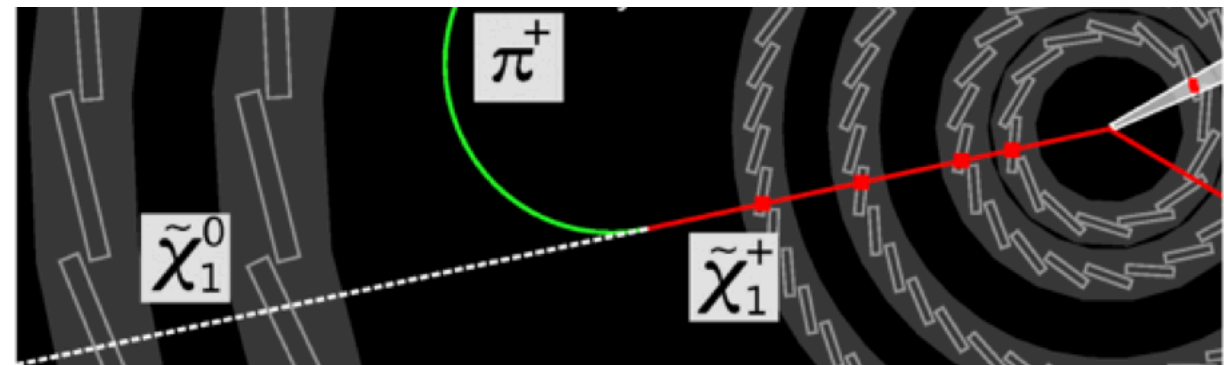
$$\Gamma \sim \frac{g^2}{8\pi} \left(\frac{m}{M} \right)^{2n} m$$

Three general mechanisms:

3. Phase space suppression

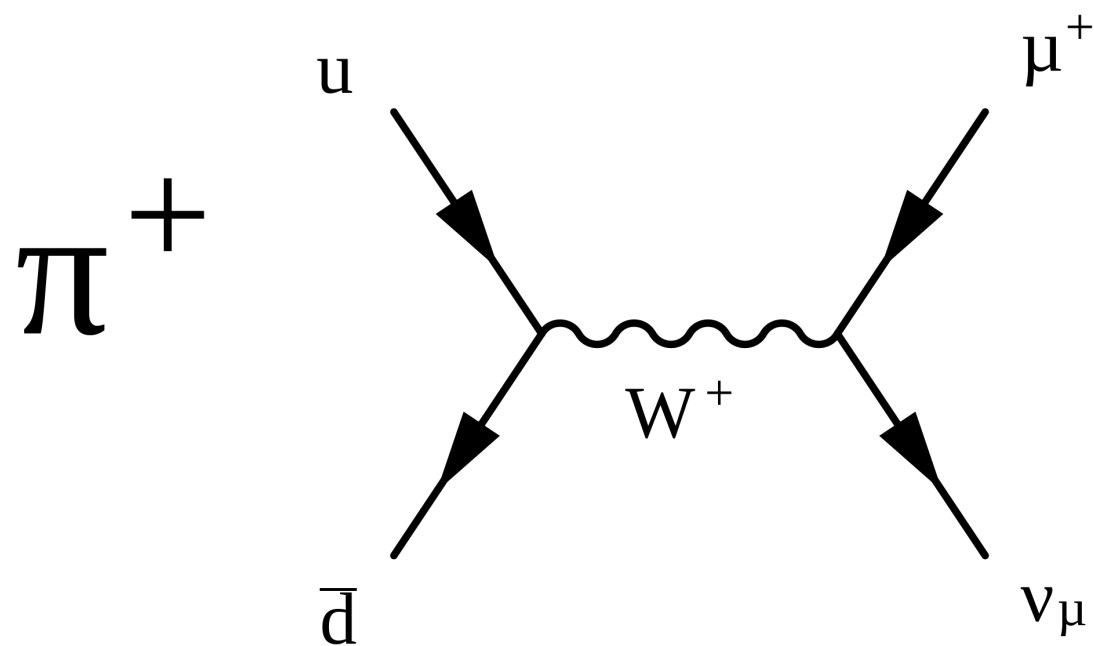
e.g: SUSY

Small mass splitting between
NLSP and LSP



Long-lived Particles in SM

The $\pi^\pm$ decay



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

small coupling

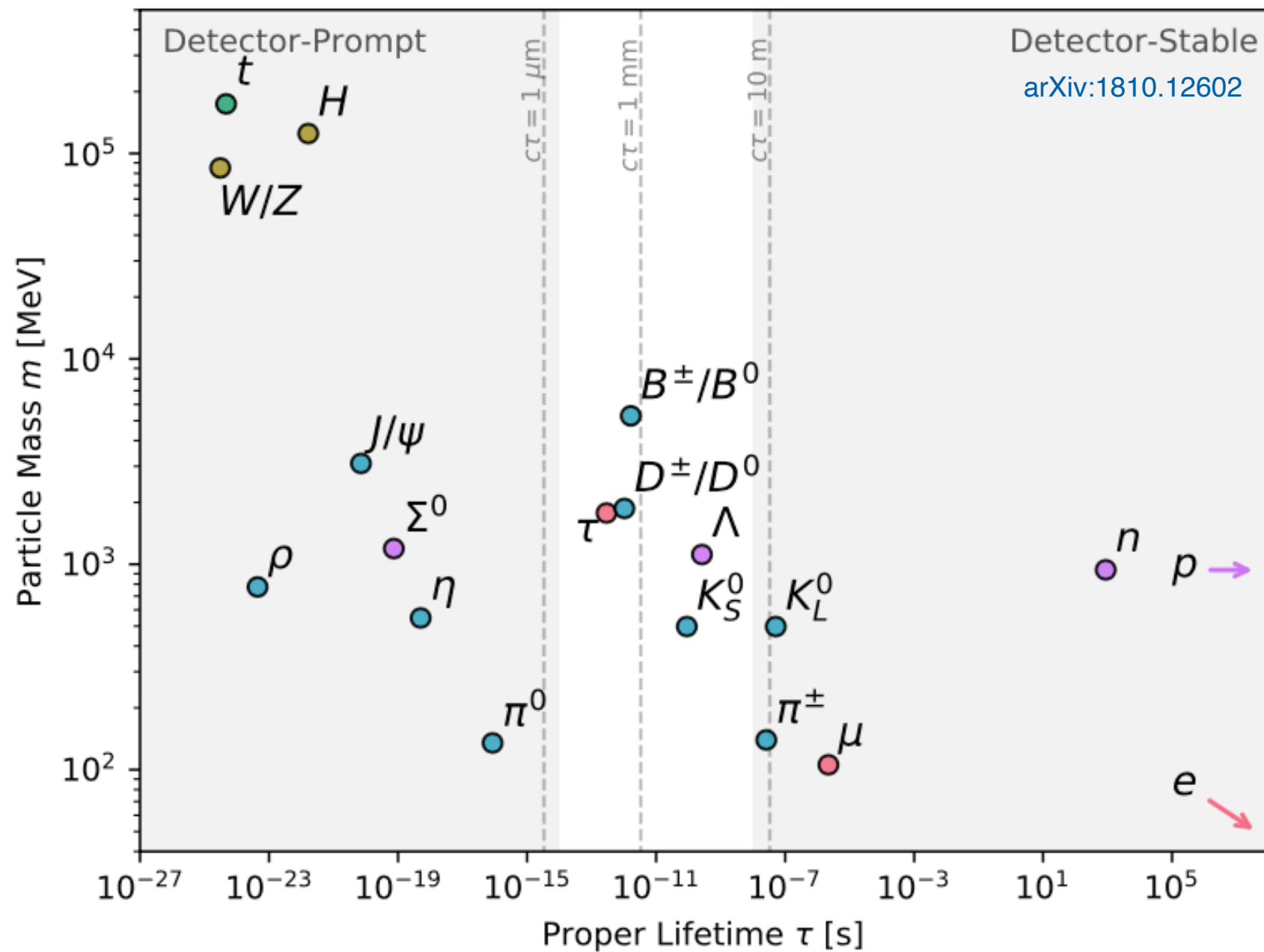
$$\frac{1}{\tau} = \frac{f_\pi^2 |V_{ud}|^2}{256\pi m_\pi} \left[\frac{g^2}{M_W^2} \frac{m_\mu}{m_\pi} (m_\pi^2 - m_\mu^2) \right]^2$$

heavy mediator

compressed spectra

$\pi^\pm$ lifetime due to **all three** mechanisms

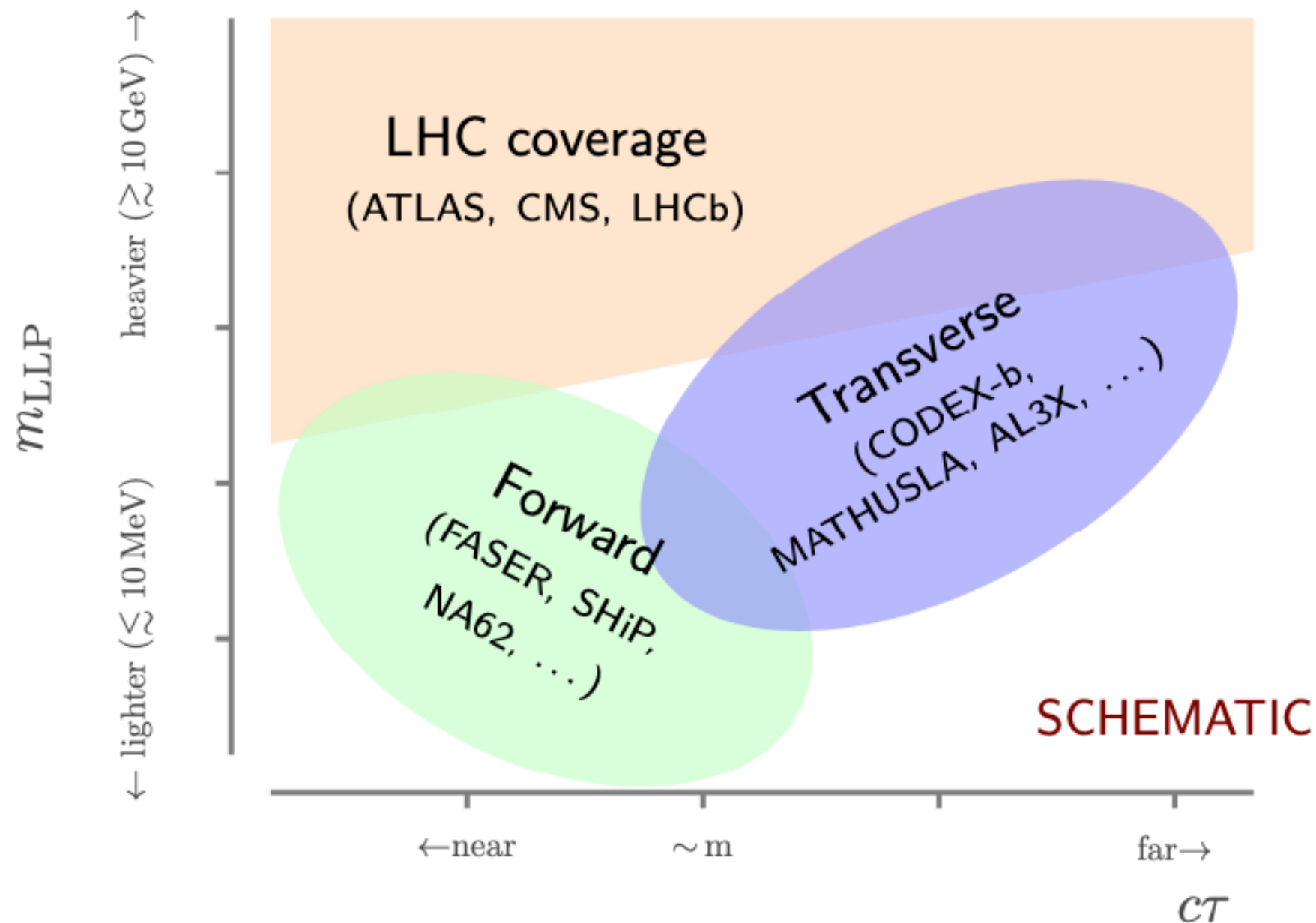
Long-lived Particles in SM



SM great example of fundamental laws giving rise to LLP

LHC and LLPs

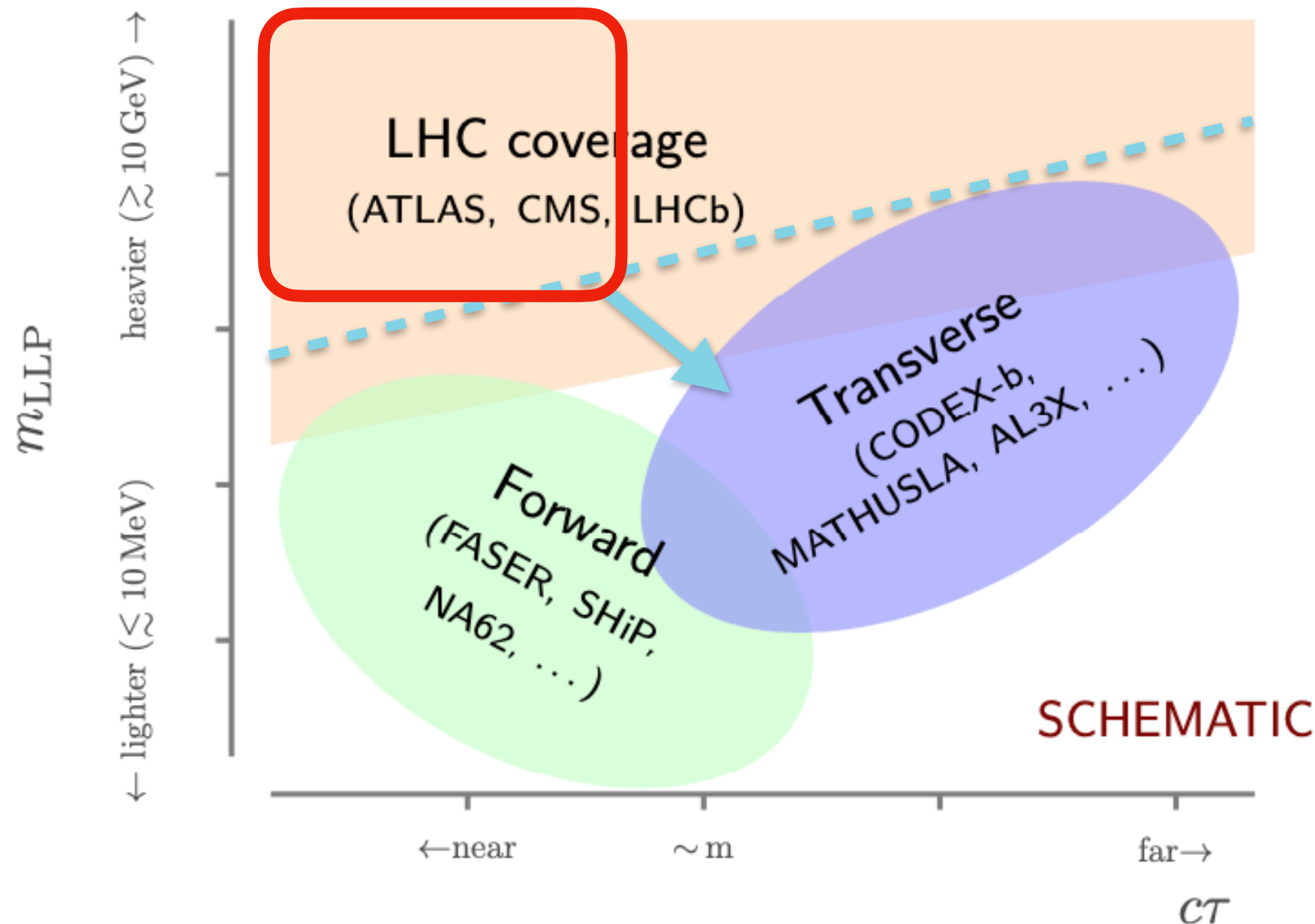
arxiv:1911.00481 — CODEX-b



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

CMS Plays a Crucial Role on LLPs

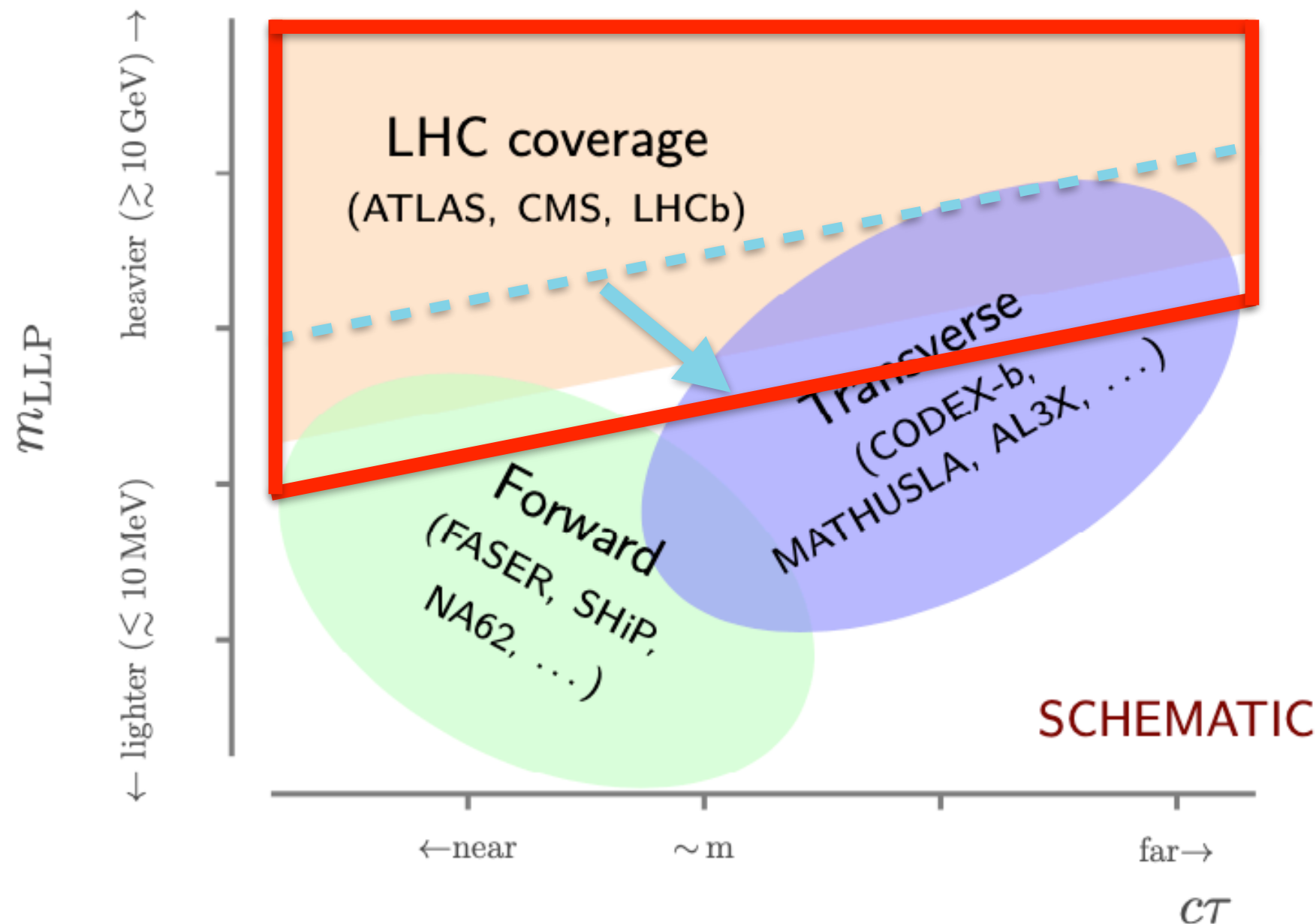
arxiv:1911.00481 — CODEX-b



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

CMS Plays a Crucial Role on LLPs

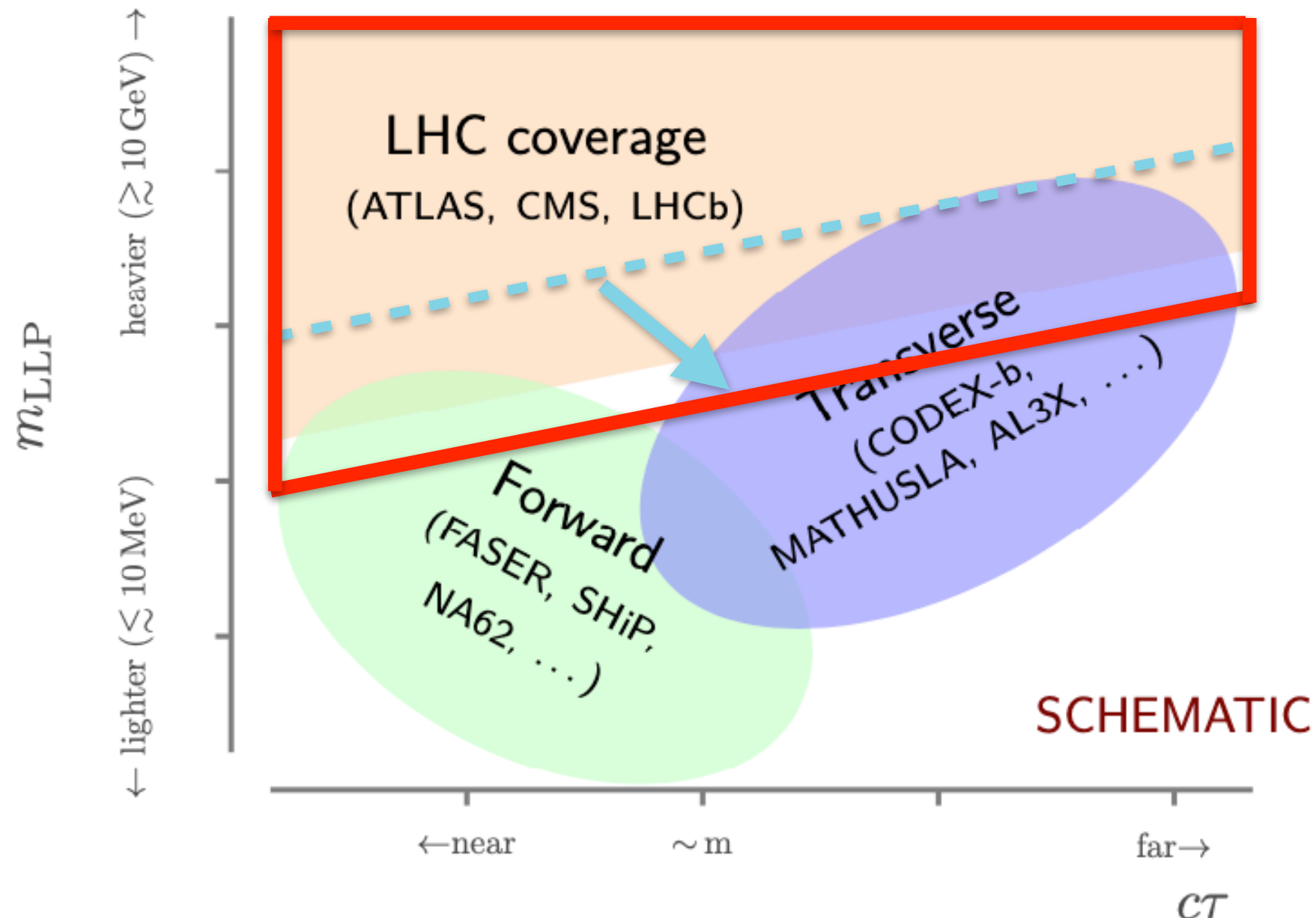
arxiv:1911.00481 — CODEX-b



- Goal: close coverage gaps and extend CMS reach
- Strategy: Enable a large $c\tau$ and light LLP searches

CMS Plays a Crucial Role on LLPs

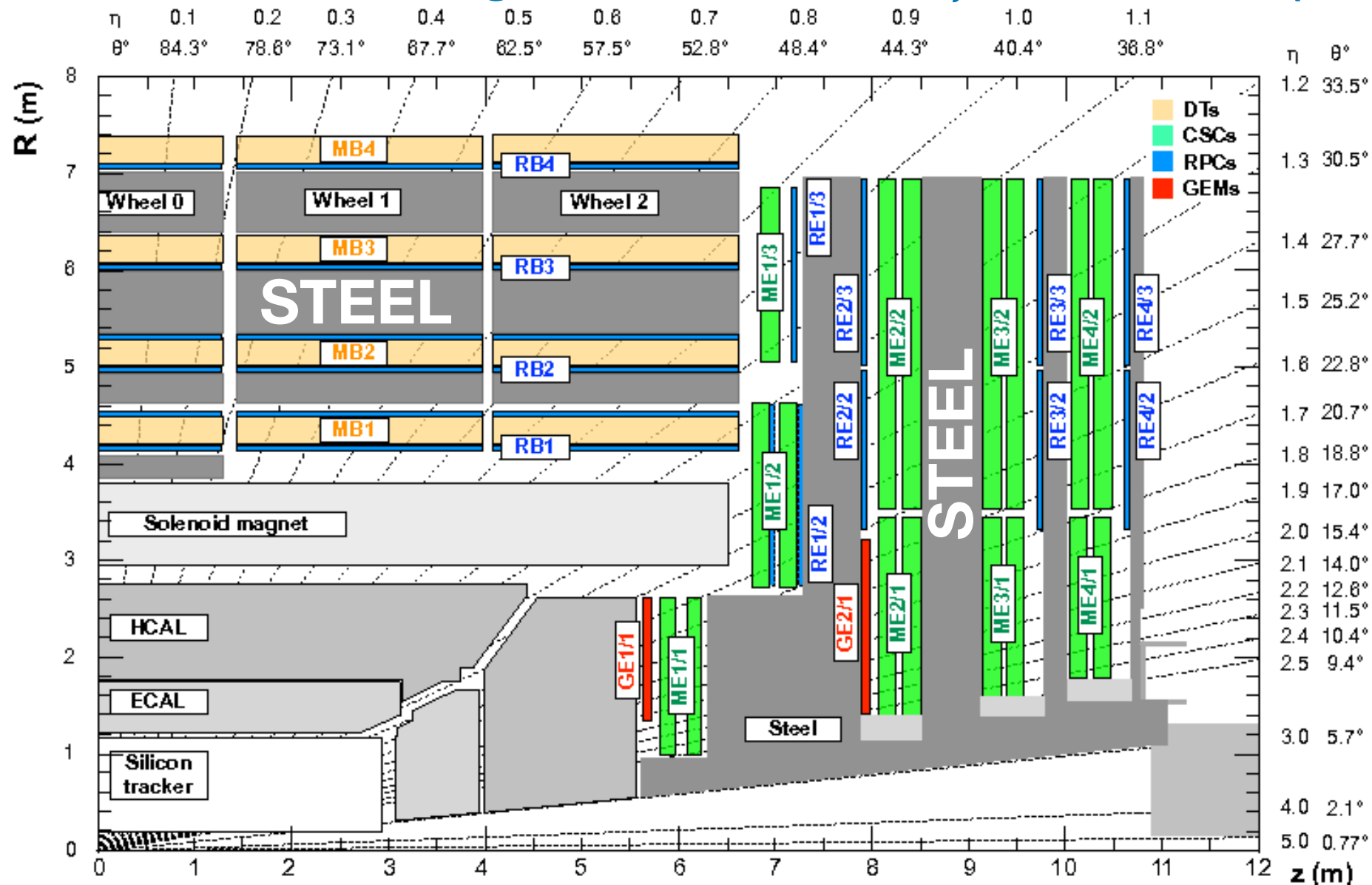
arxiv:1911.00481 — CODEX-b



- 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

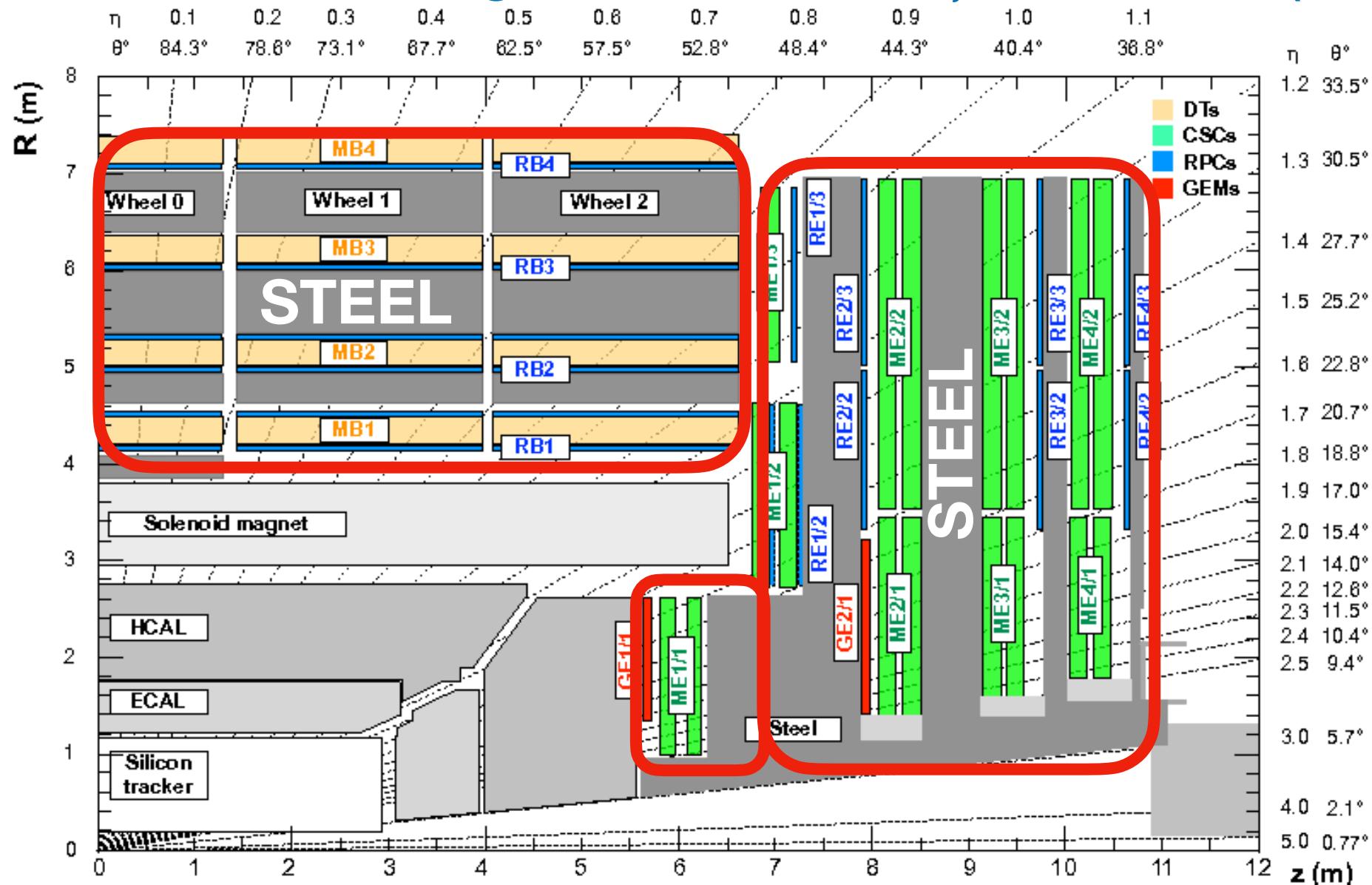
COMPACT Design + Small $\pi \rightarrow \mu$ mis-ID (10^{-3})



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

Compact Muon Solenoid

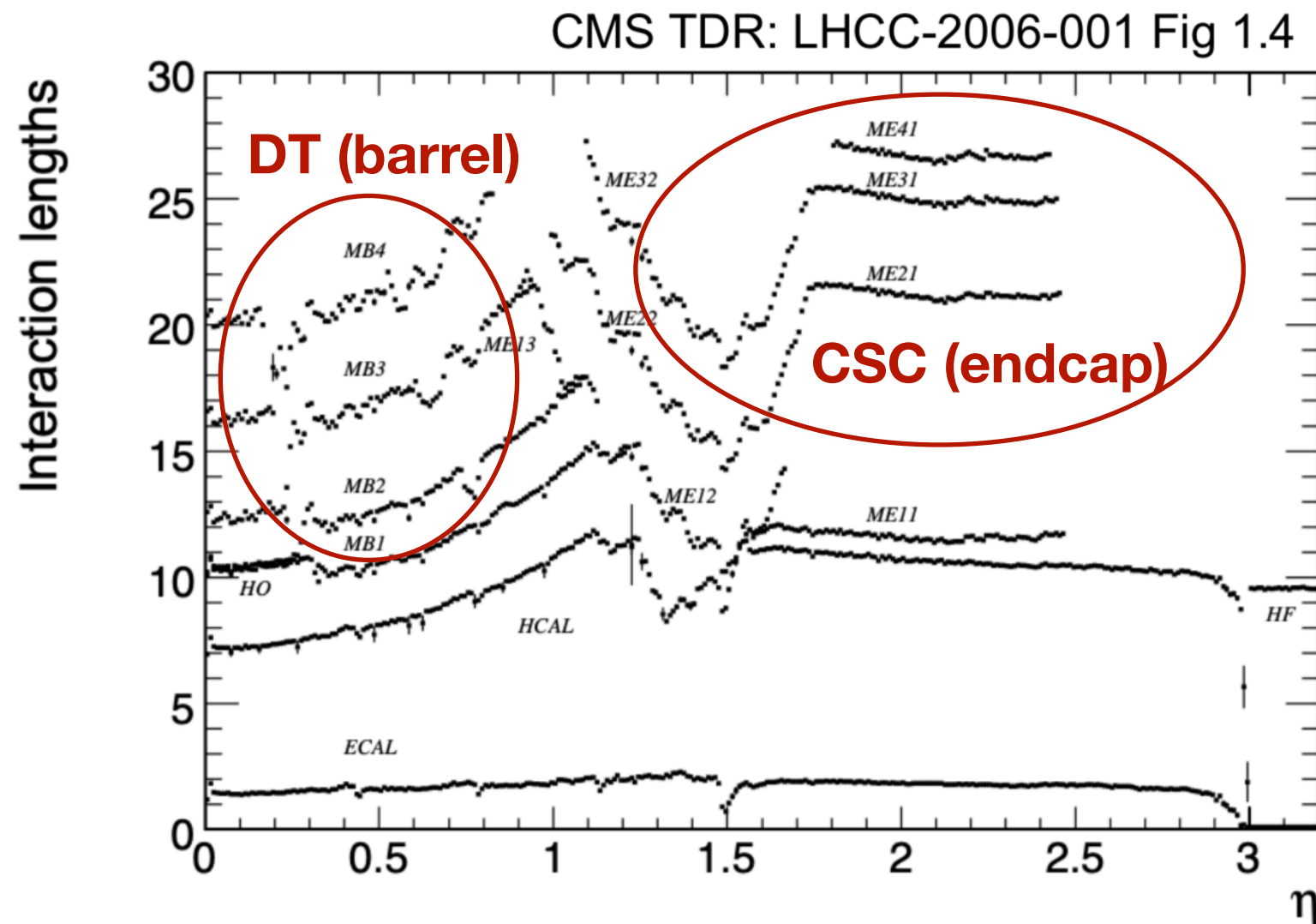
COMPACT Design + Small $\pi \rightarrow \mu$ mis-ID (10^{-3})



- Lots of STEEL → bkg suppression → Ideal for LLP searches ✓
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LLP Muon System Analysis

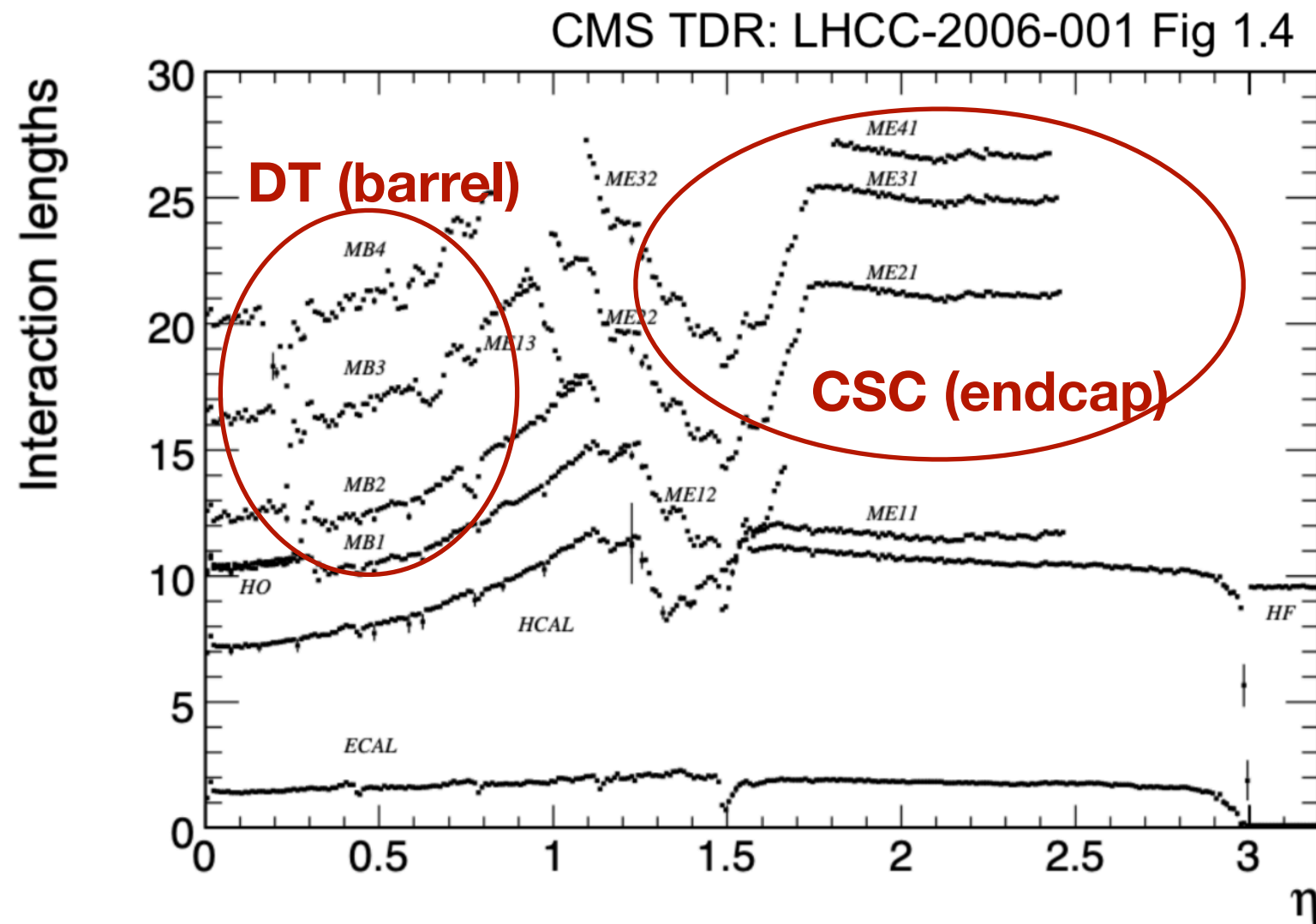
- Despite the lack of a dedicated trigger, CMS has opportunity to provide better sensitivity for 1 displaced vertex search. **CMS has more steel to reject background**



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

LLP Muon System Analysis

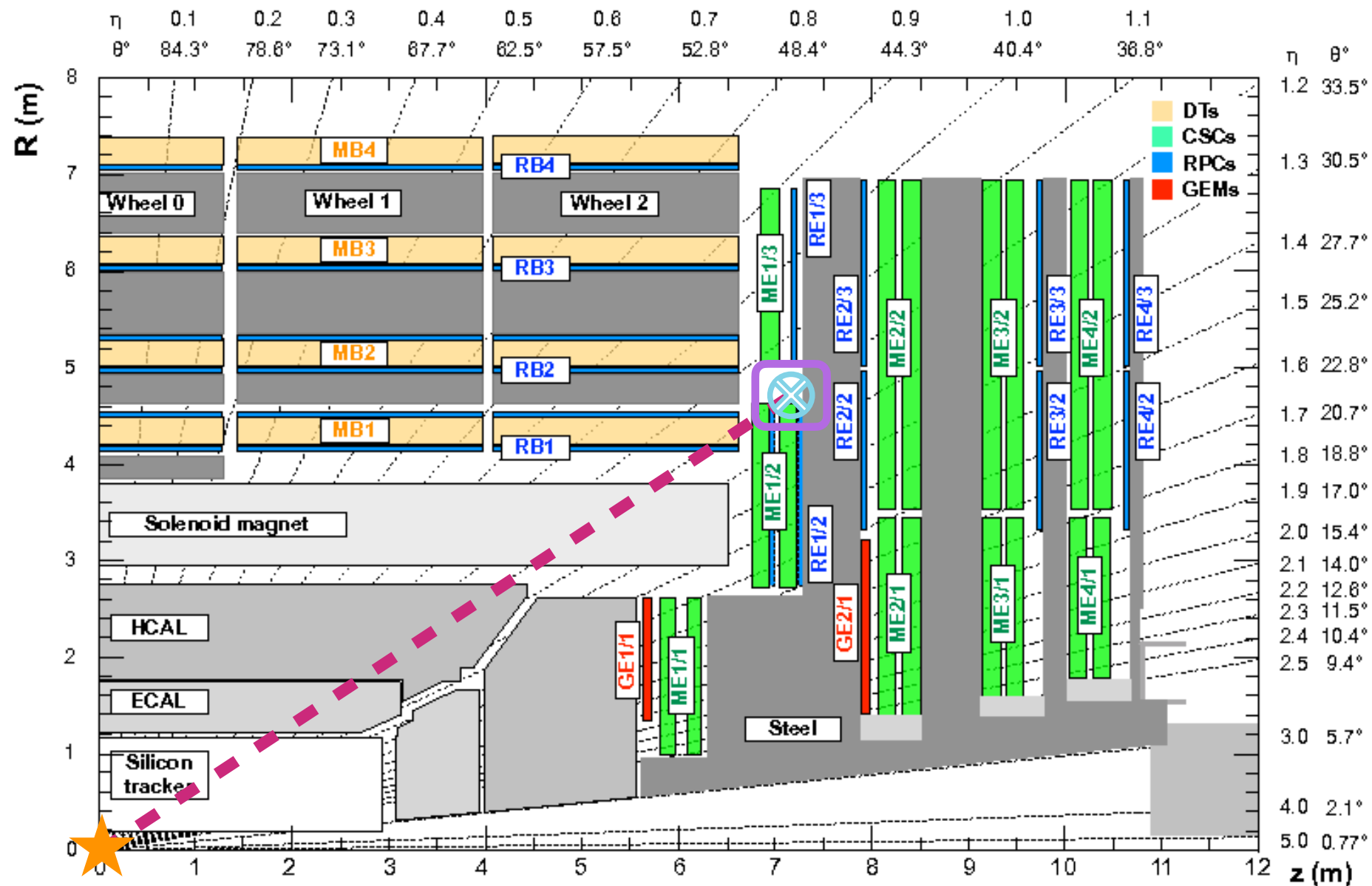
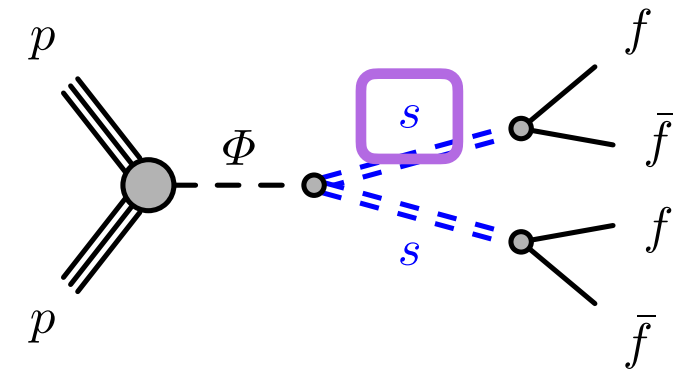
- Despite the lack of a dedicated trigger, CMS has opportunity to provide better sensitivity for 1 displaced vertex search. **CMS has more steel to reject background**



- Opportunity to **extend discovery reach at large lifetimes ($> \sim$ few meters)**

Search for LLPs in Muon System

LLP decays in MS → shower

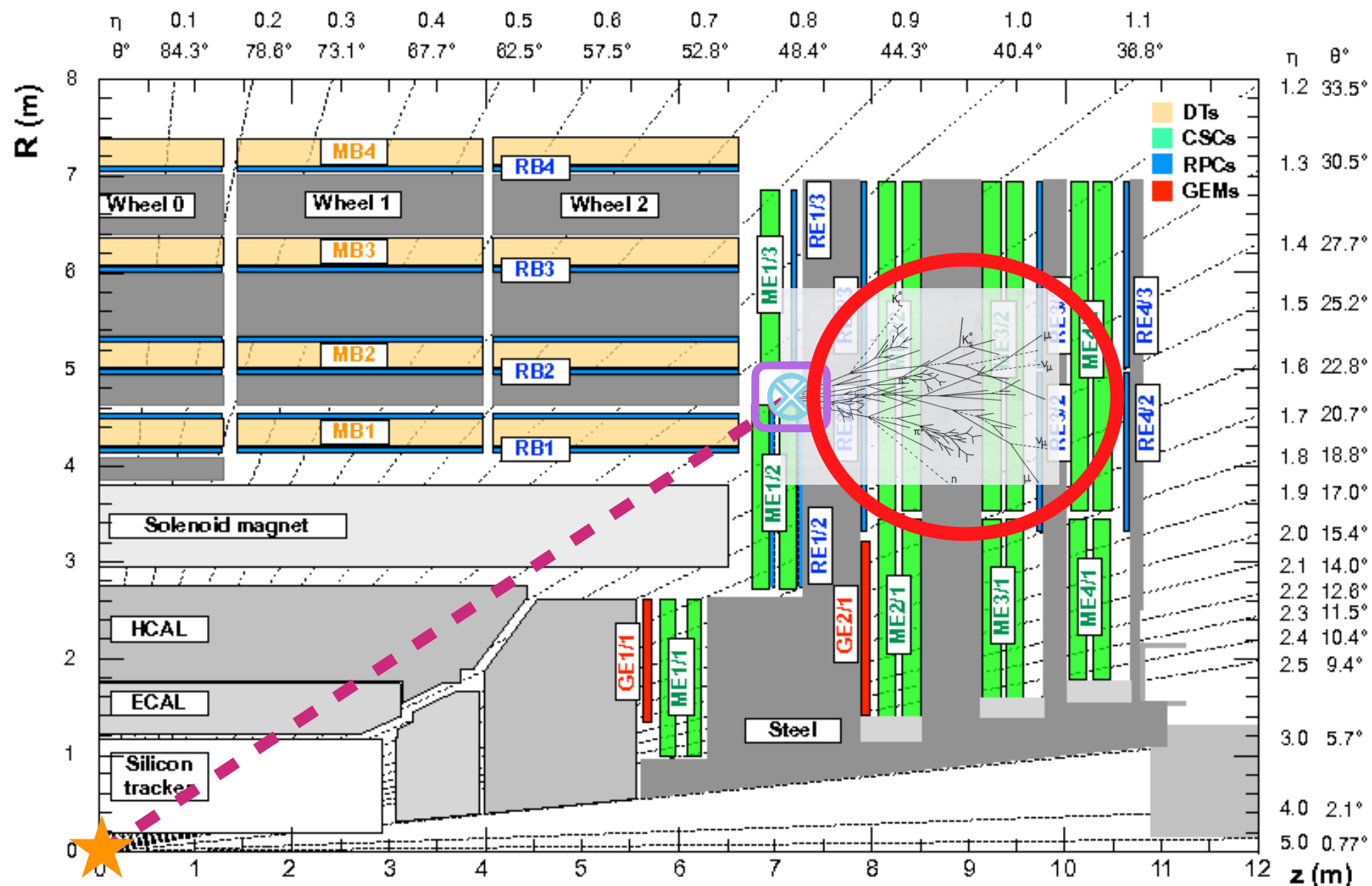
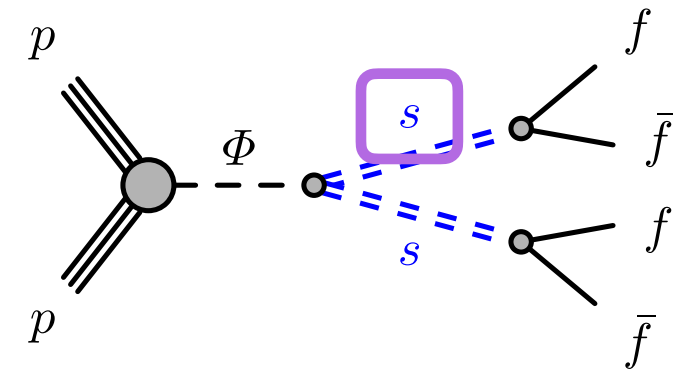


 → LLP (s) decay

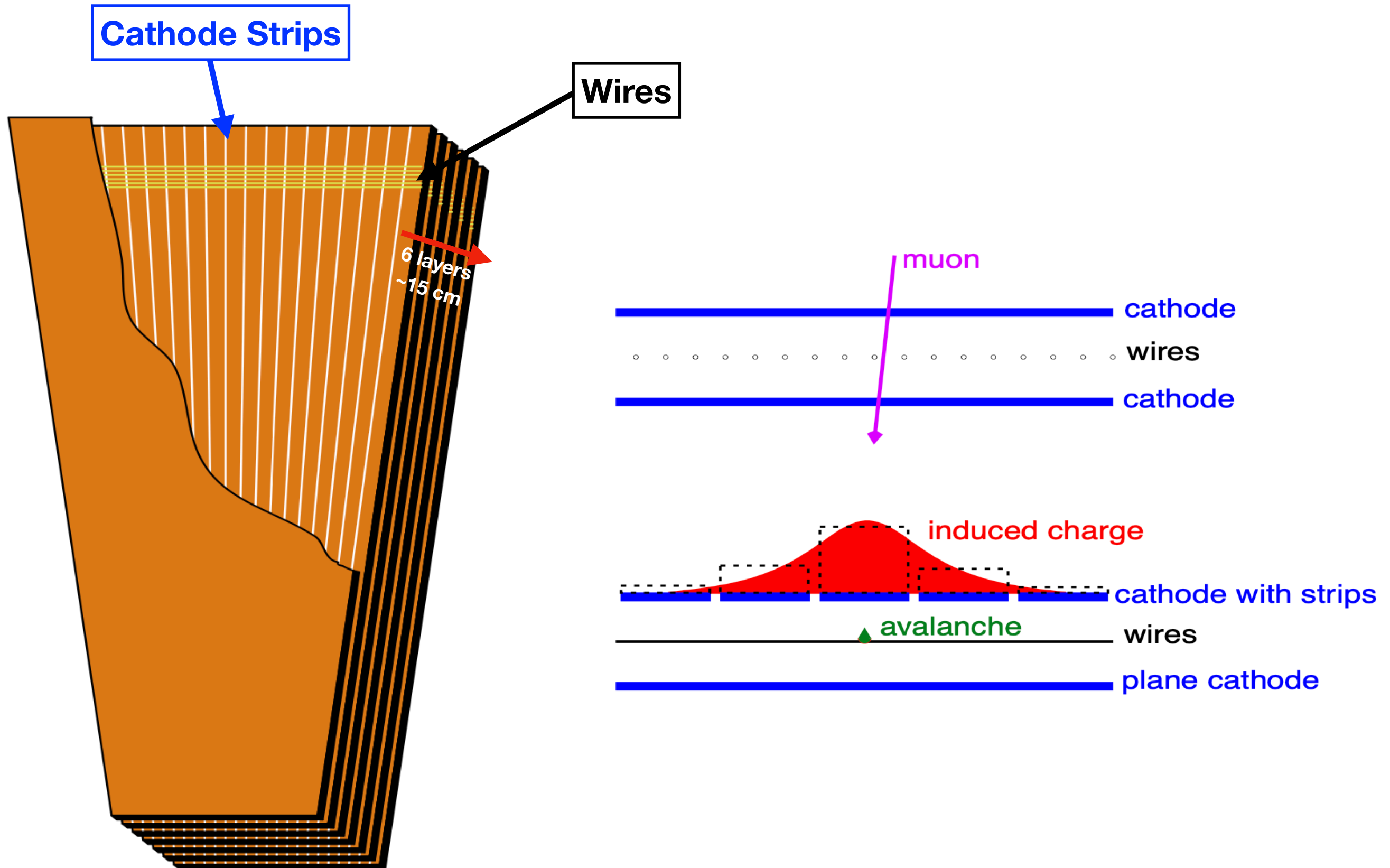
Search for LLPs in Muon System

LLP decays in MS → shower

Muon System acts as sampling calorimeter



Gas Detector

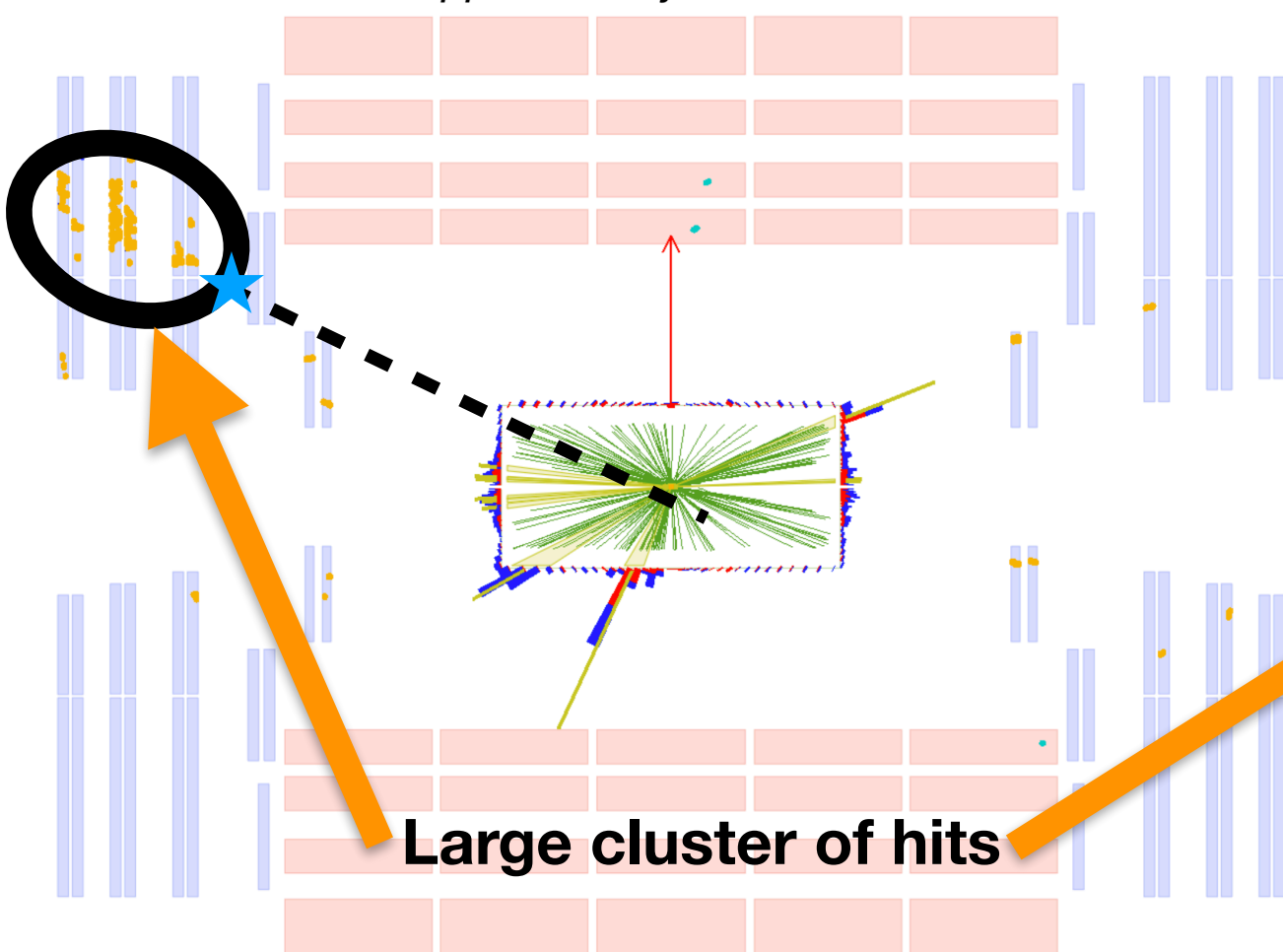


LLP Signature in Muon System

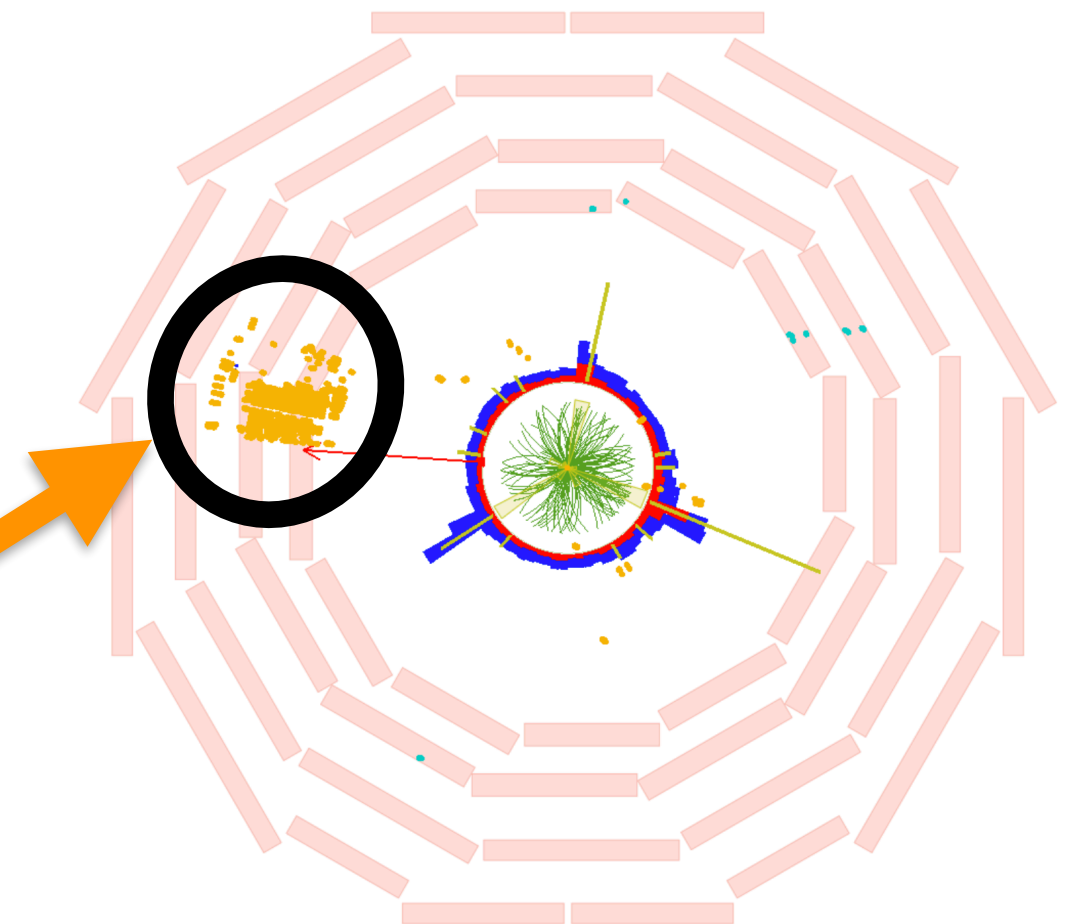
First time this signature is explored at the LHC

- 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)**

CMS Simulation Supplementary



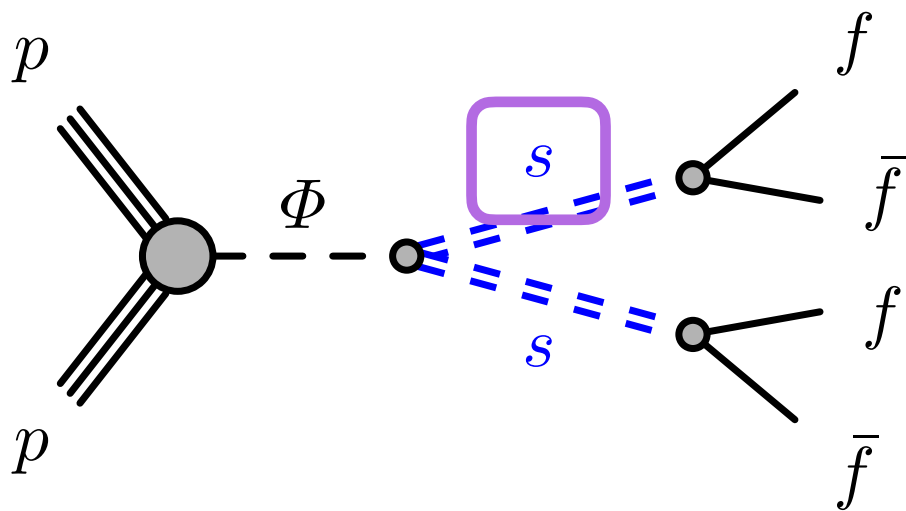
CMS Simulation Supplementary



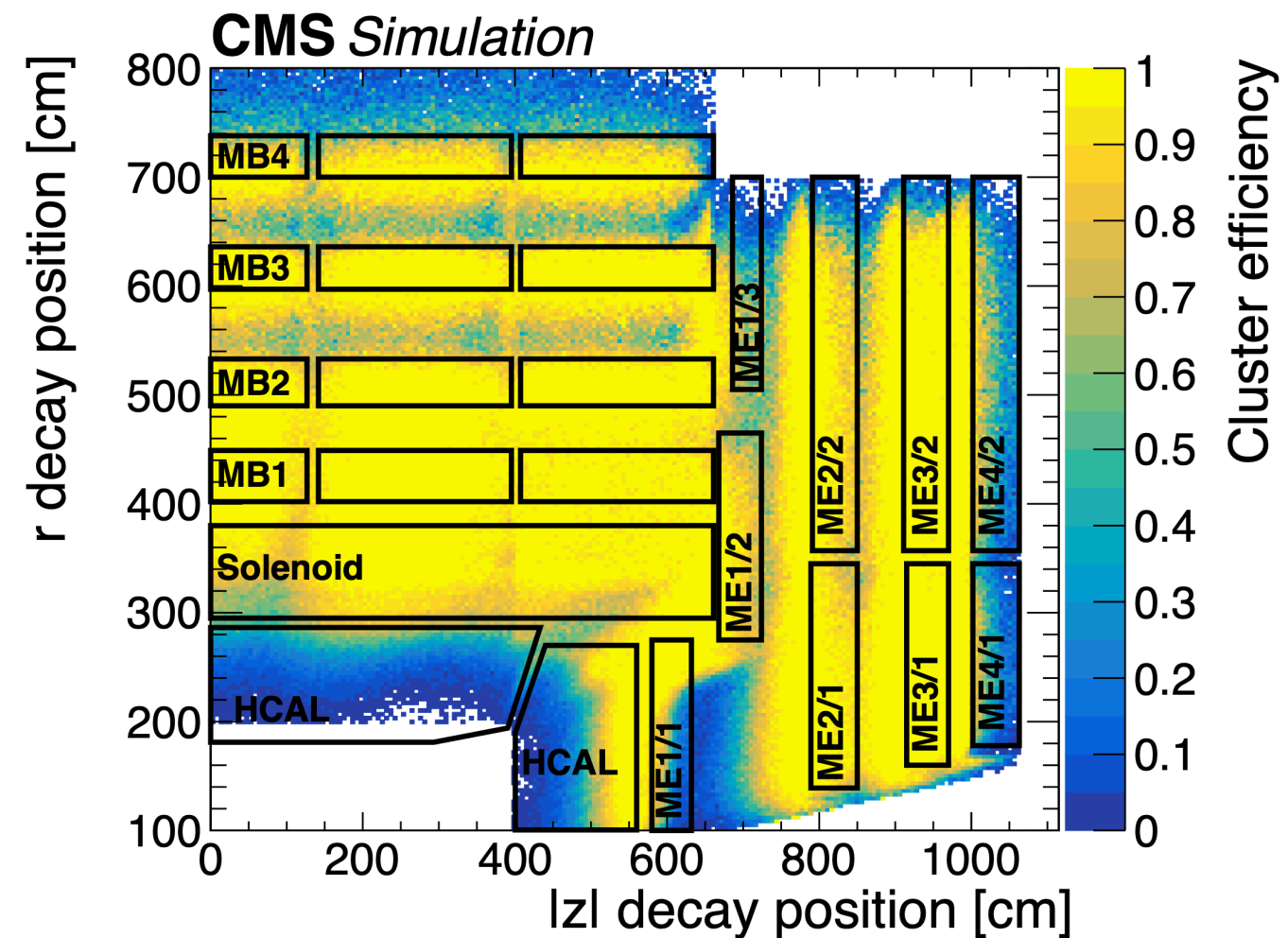
LLP Efficiency in Muon System

Muon system acts as a **sampling calorimeter**

LLP decay position is plotted



At least 50 hit reconstruction cluster

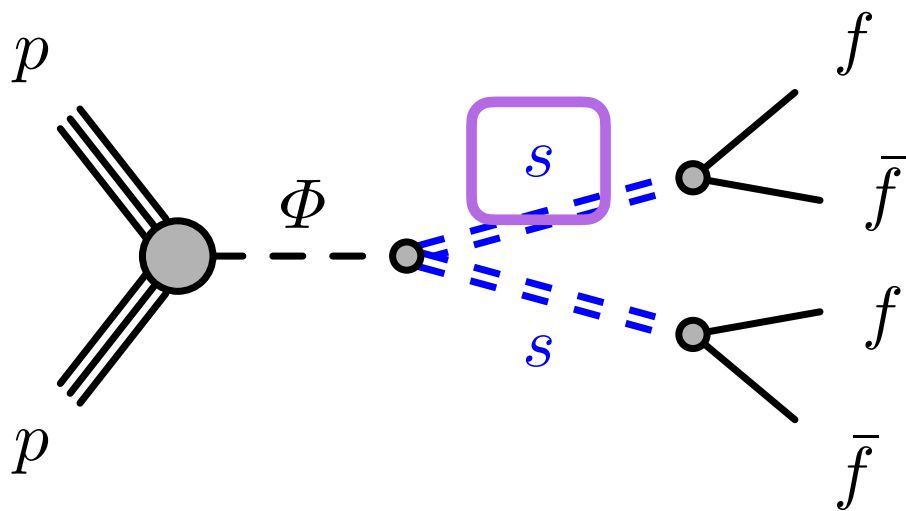


High cluster reconstruction — up to 80-90%

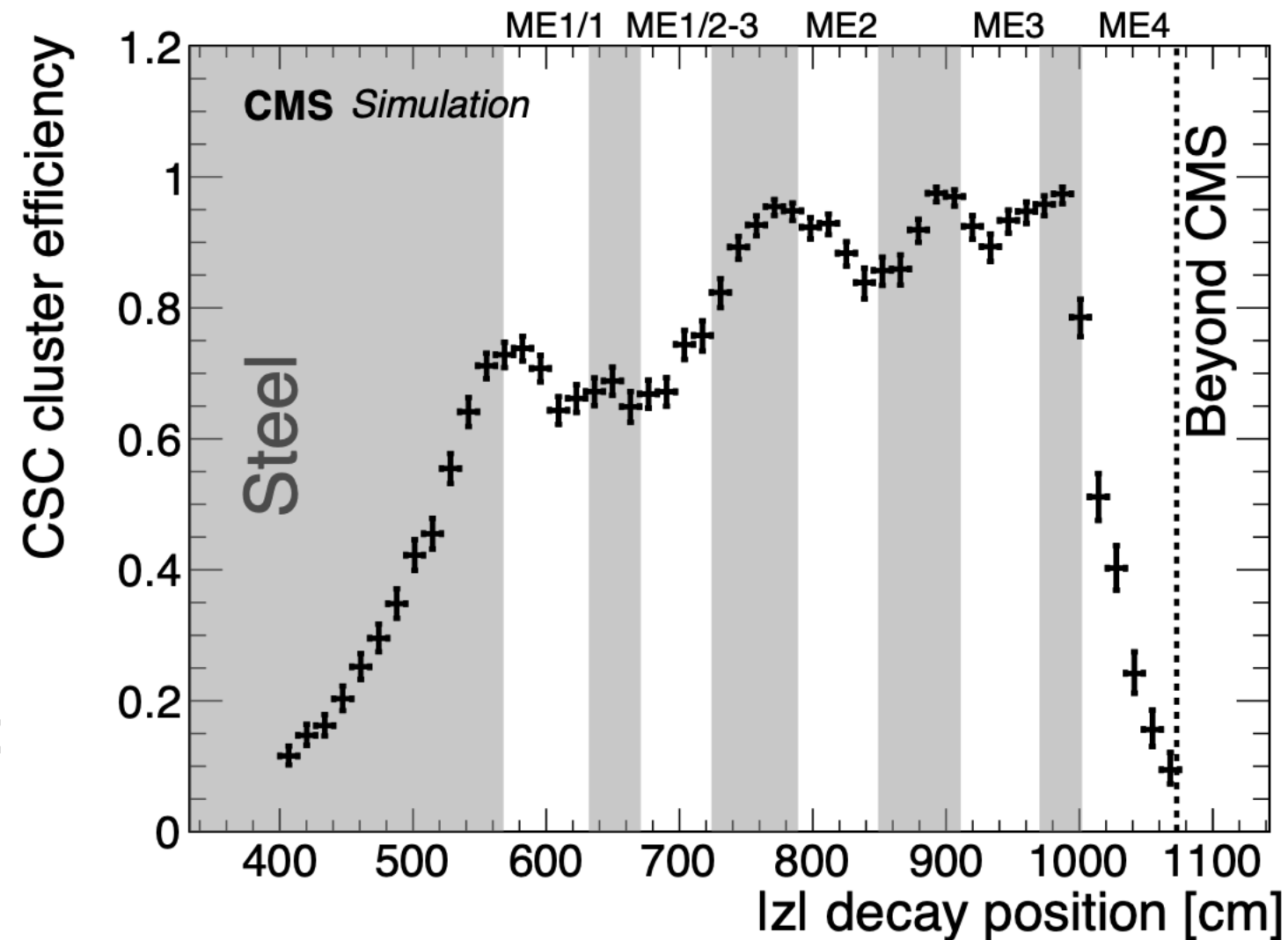
LLP Efficiency in Muon System

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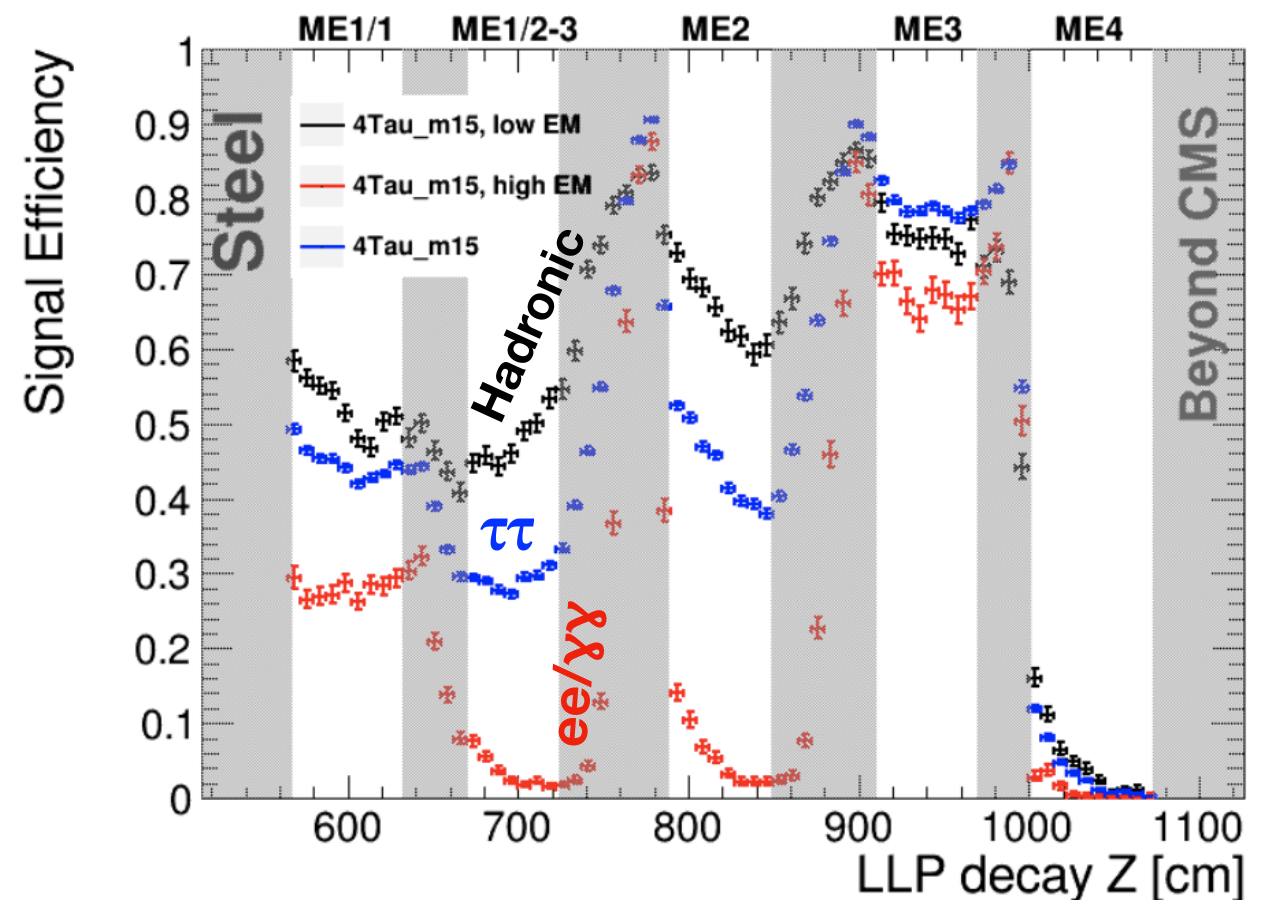
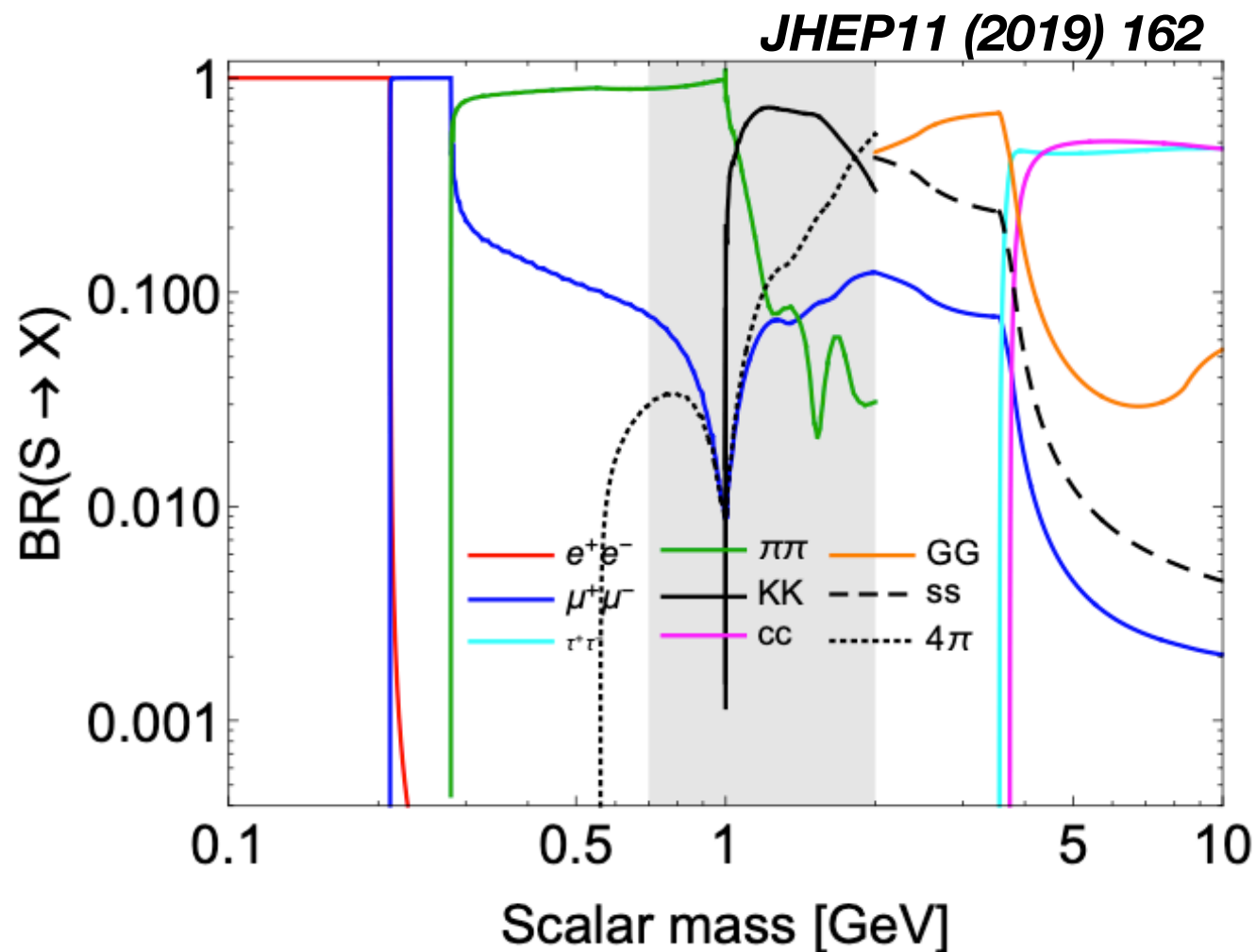
At least 50 hit reconstruction clust



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

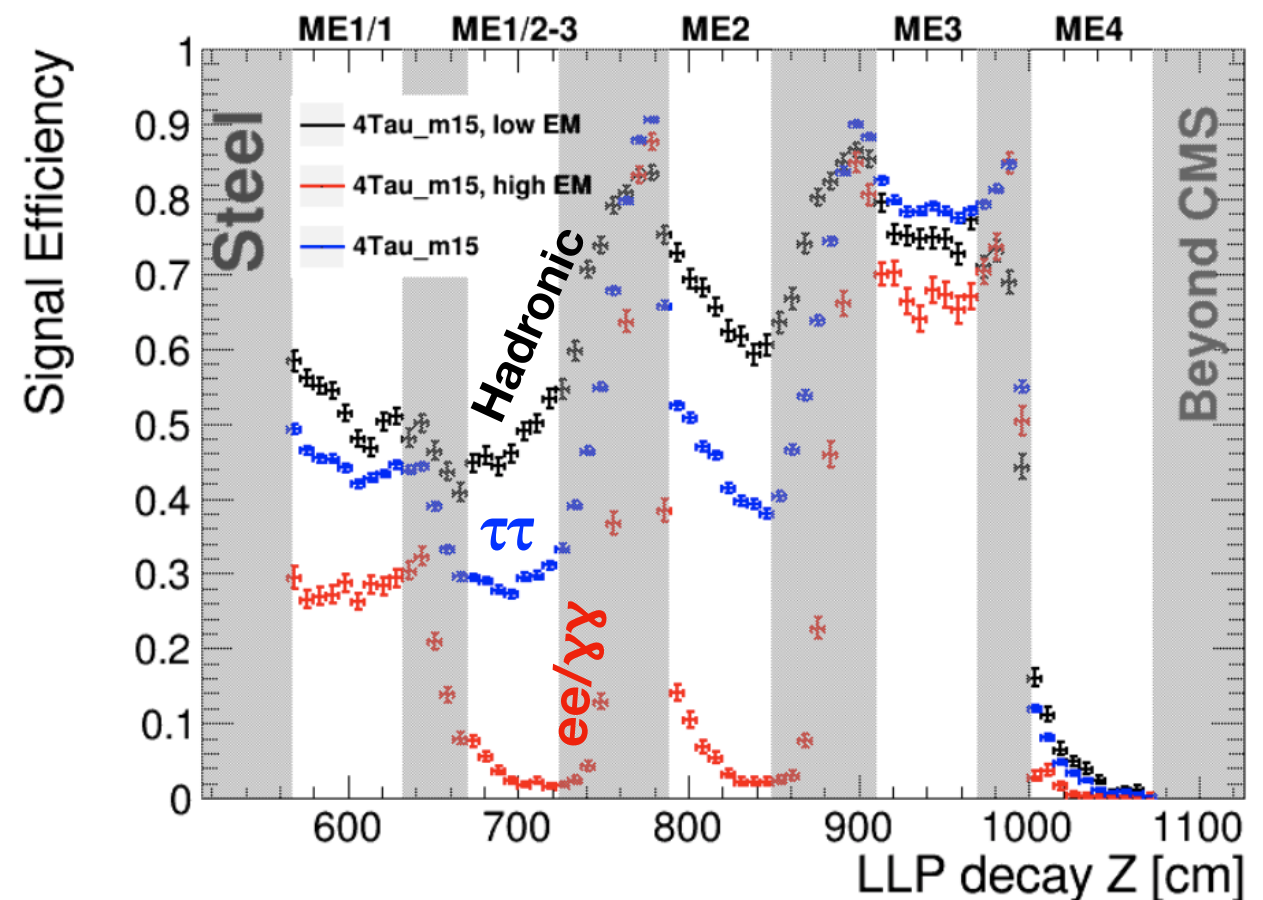
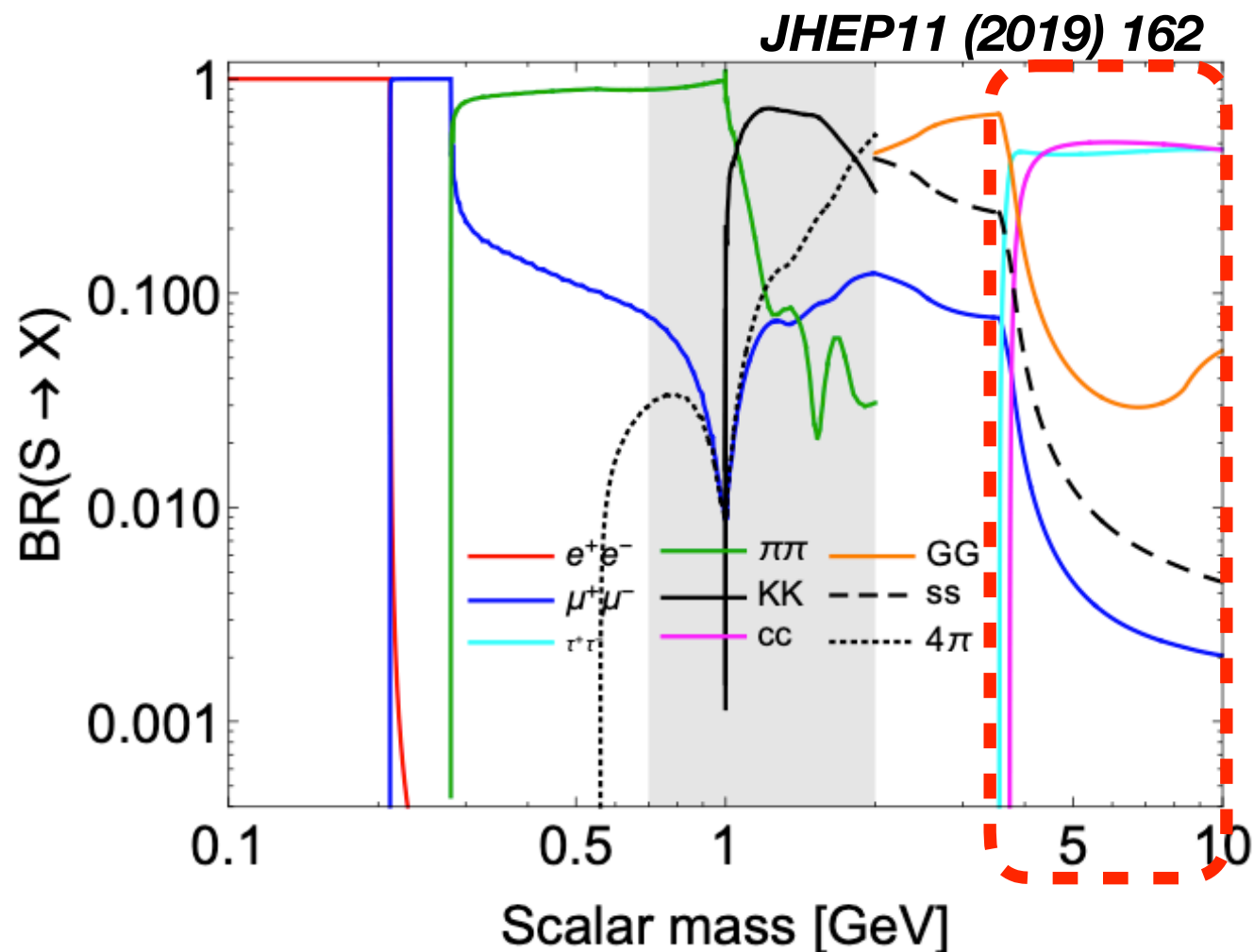
Muon System Enables Broad LLP Reach

- 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)**



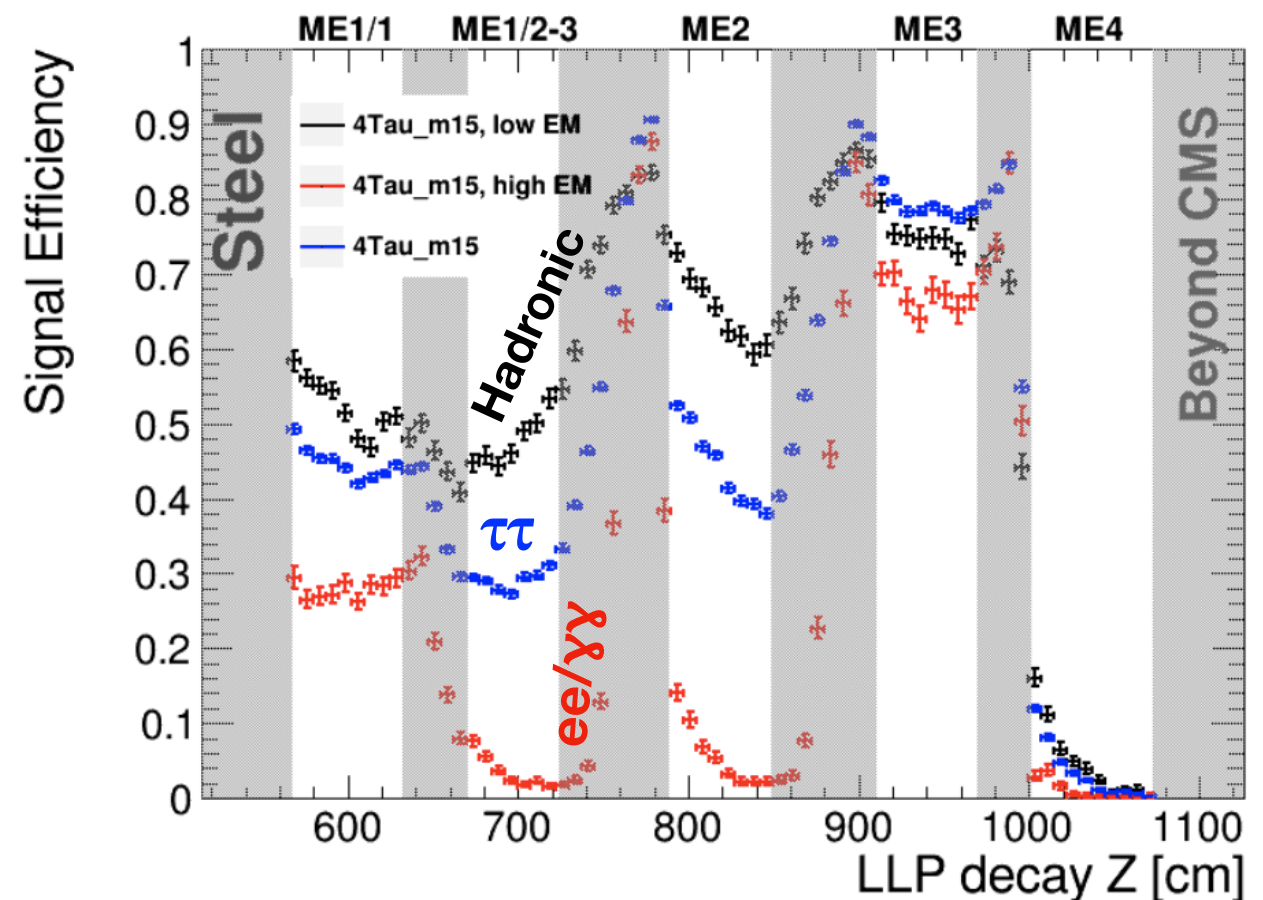
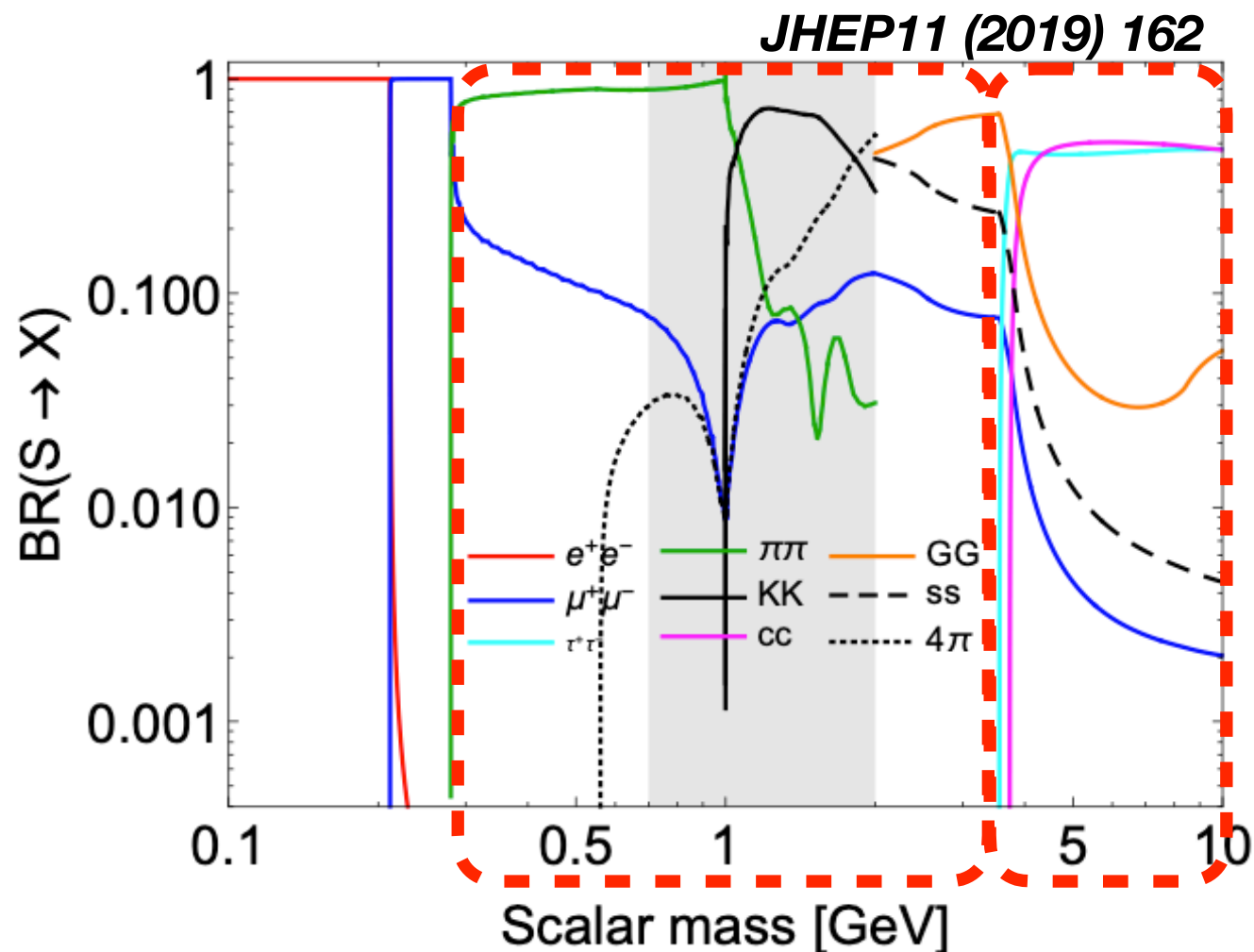
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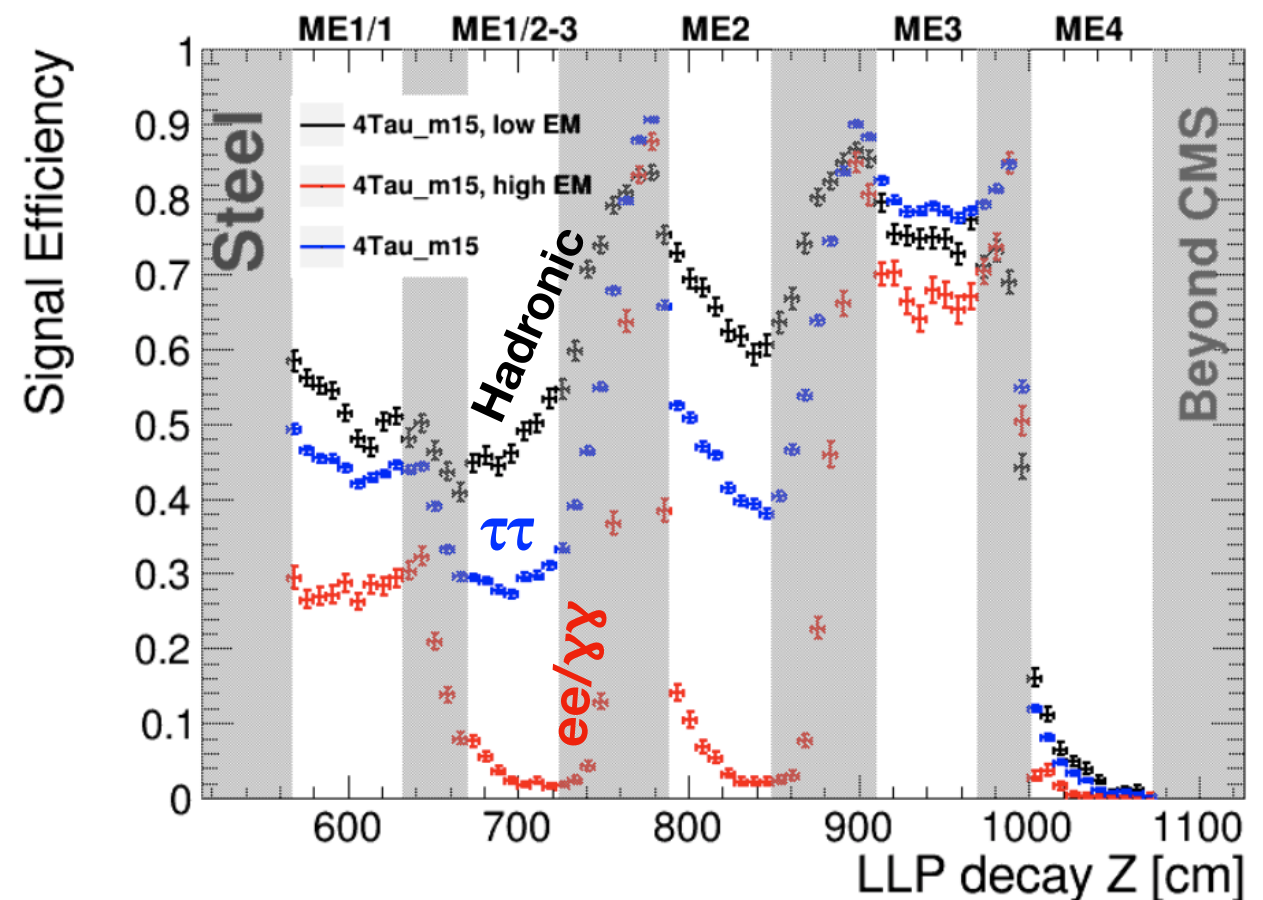
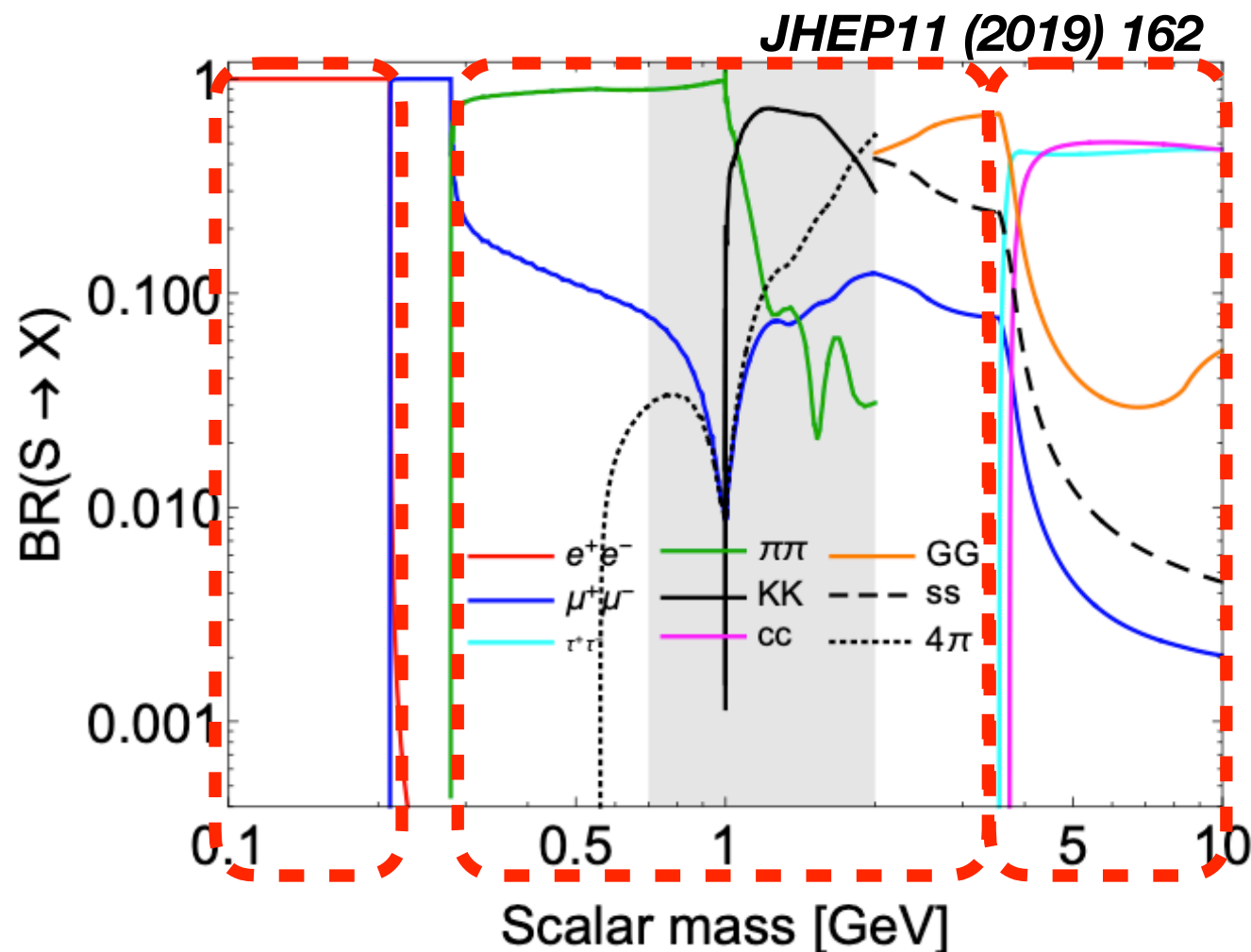
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CMS Data Analysis Re-imagined

Current CMS data analysis chain
is
broken when LLPs are present

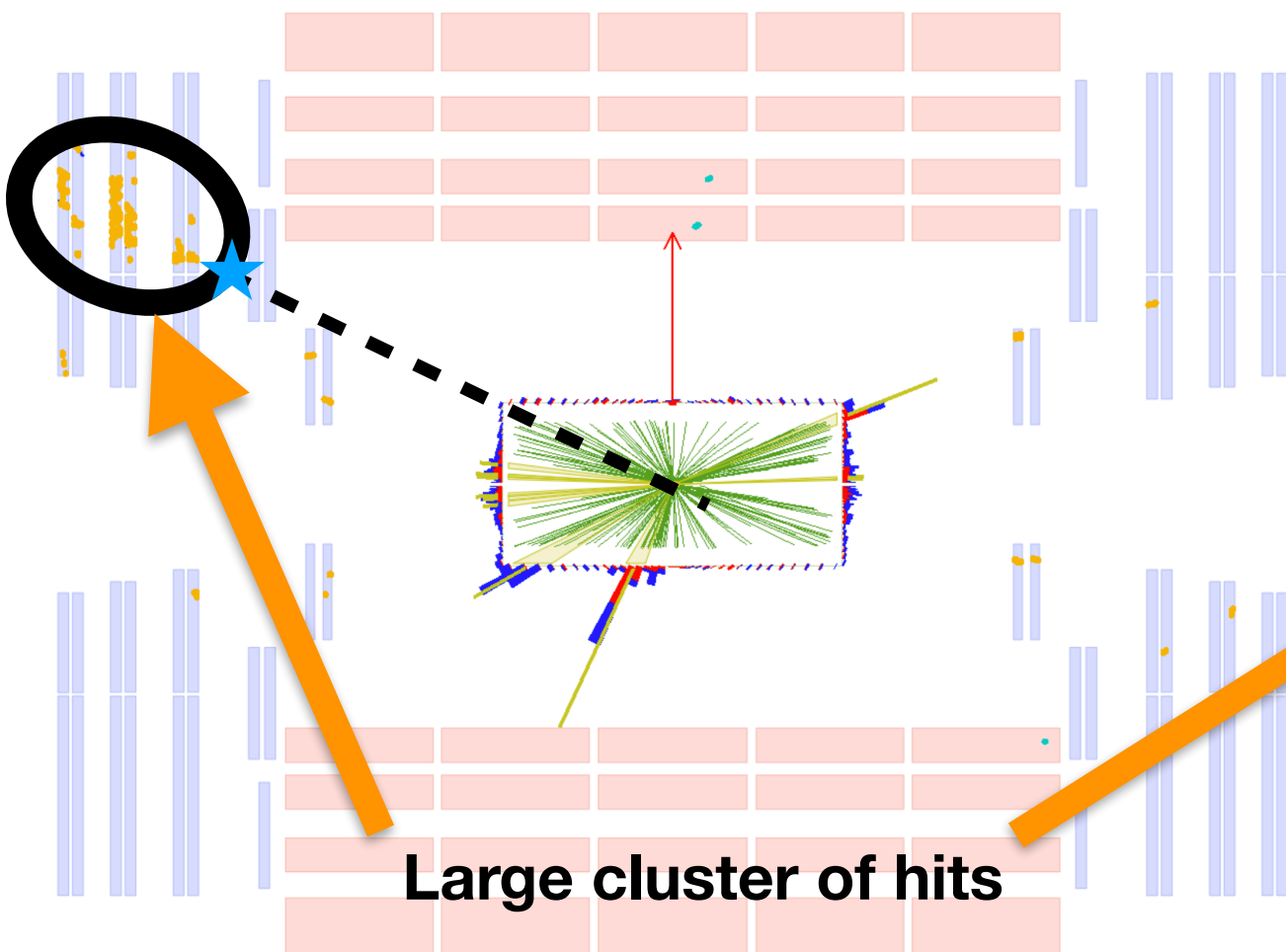


LLP Signature in Muon System

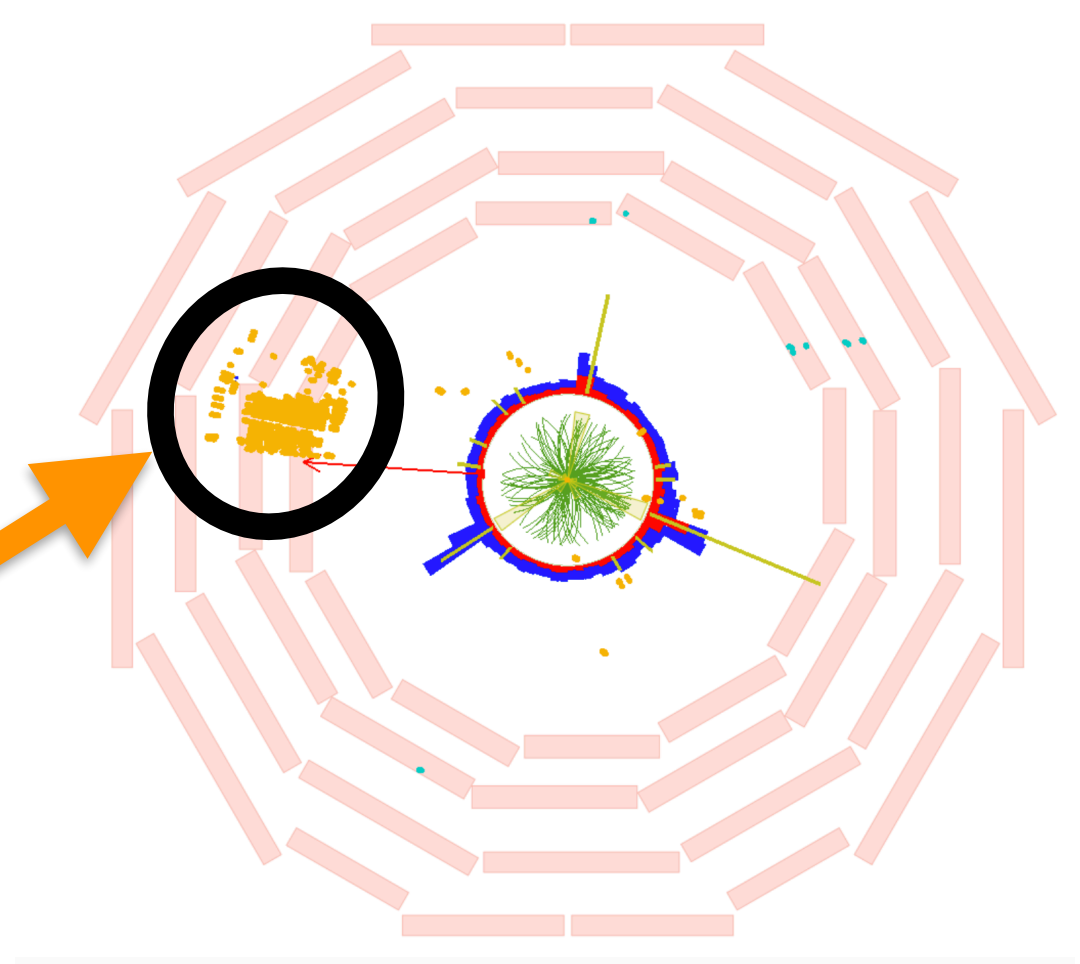
First time this signature is explored at the LHC

- LLPs that decay in the muons system leave a signature of:
 - **Large cluster of hits** in the muon chambers
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CMS Simulation Supplementary

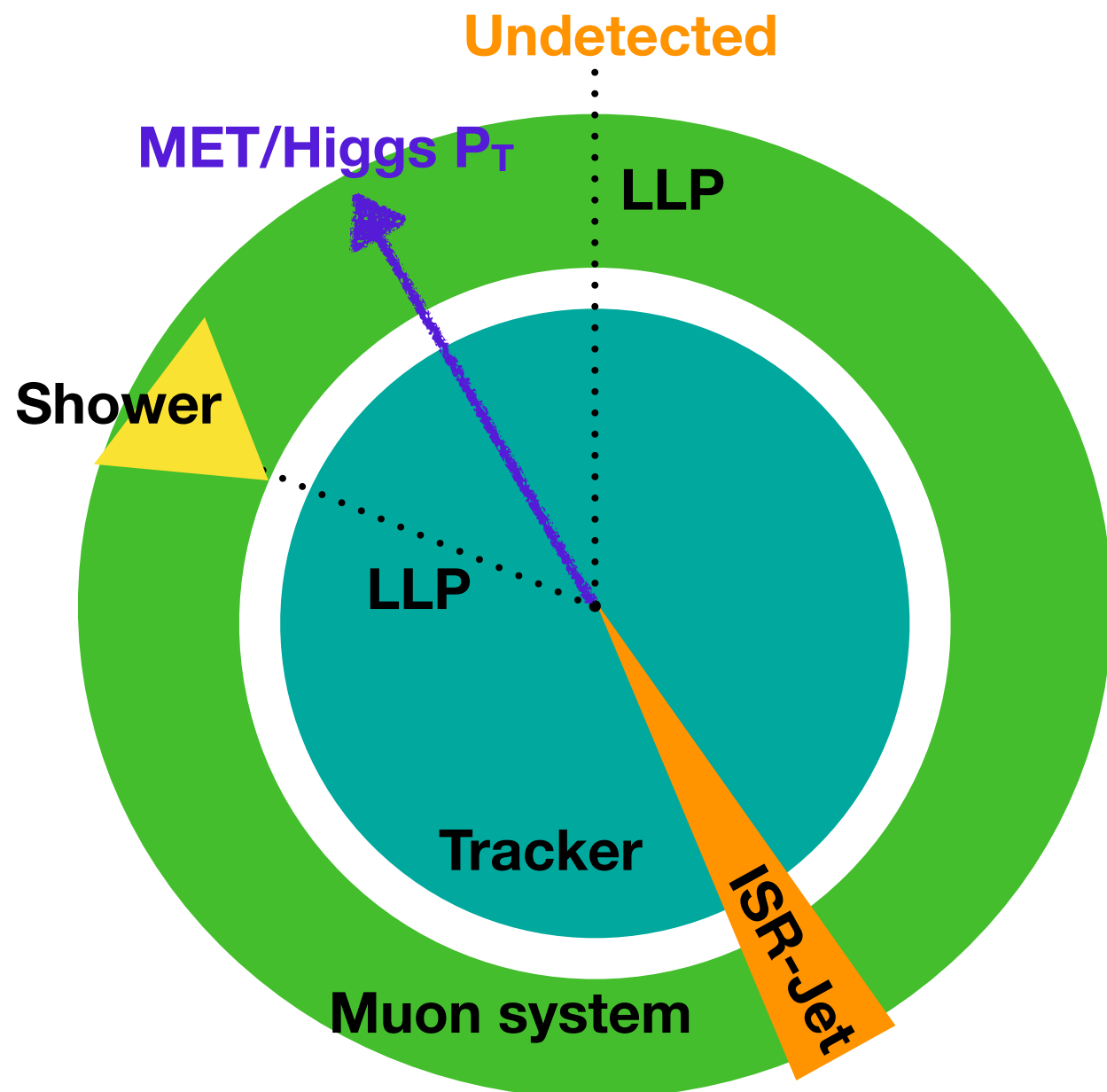


CMS Simulation Supplementary

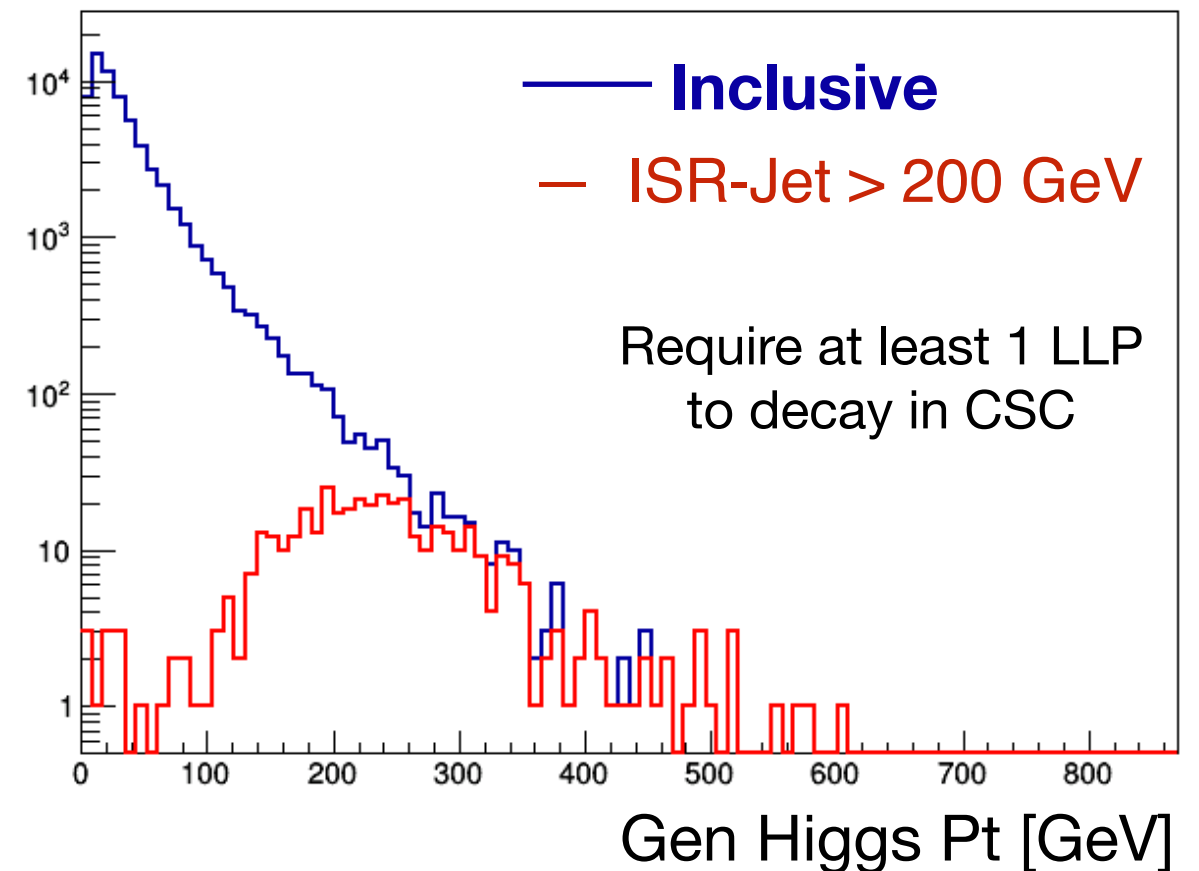


LLP Muon System Analysis

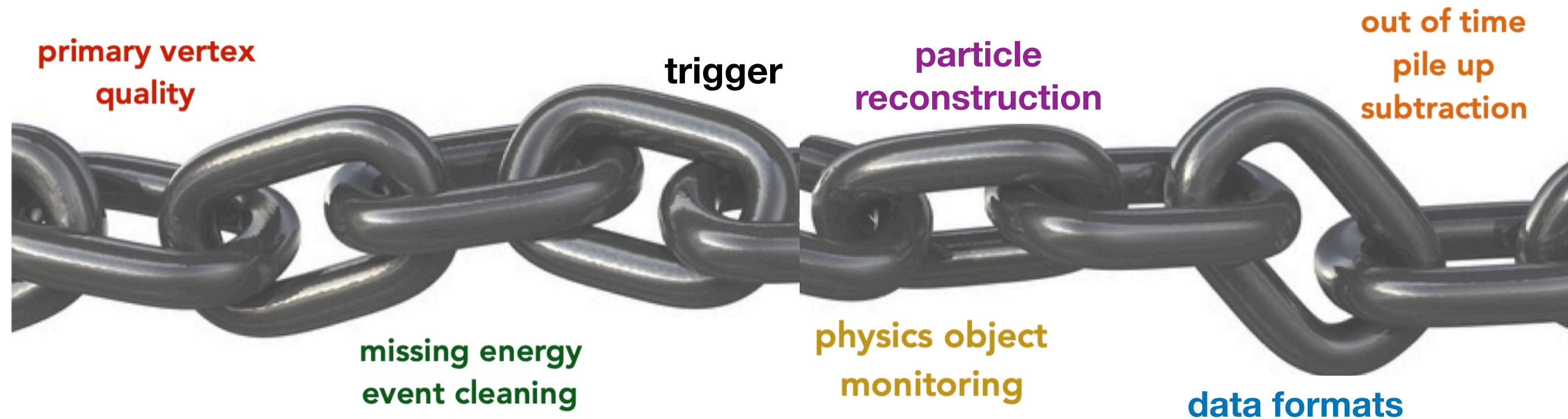
- Start with ggH production mode — largest cross section
- Trigger on **MET** (**lack of dedicated trigger**) — recoil of Higgs against ISR
 - For large $c\tau$ one of the LLPs will decay outside the calorimeter



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



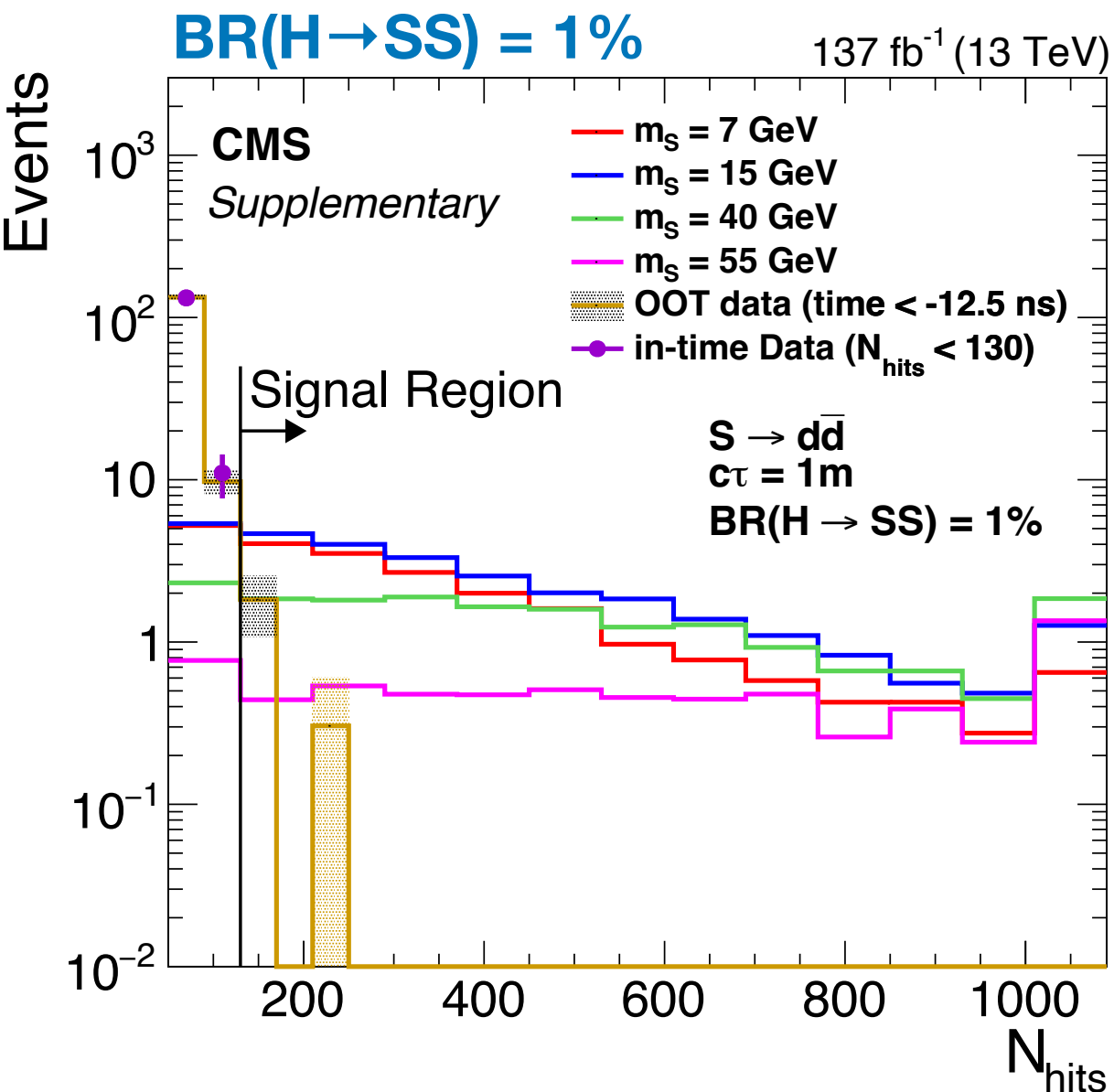
CMS Data Analysis Re-imagined



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:
 1.8 ± 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)

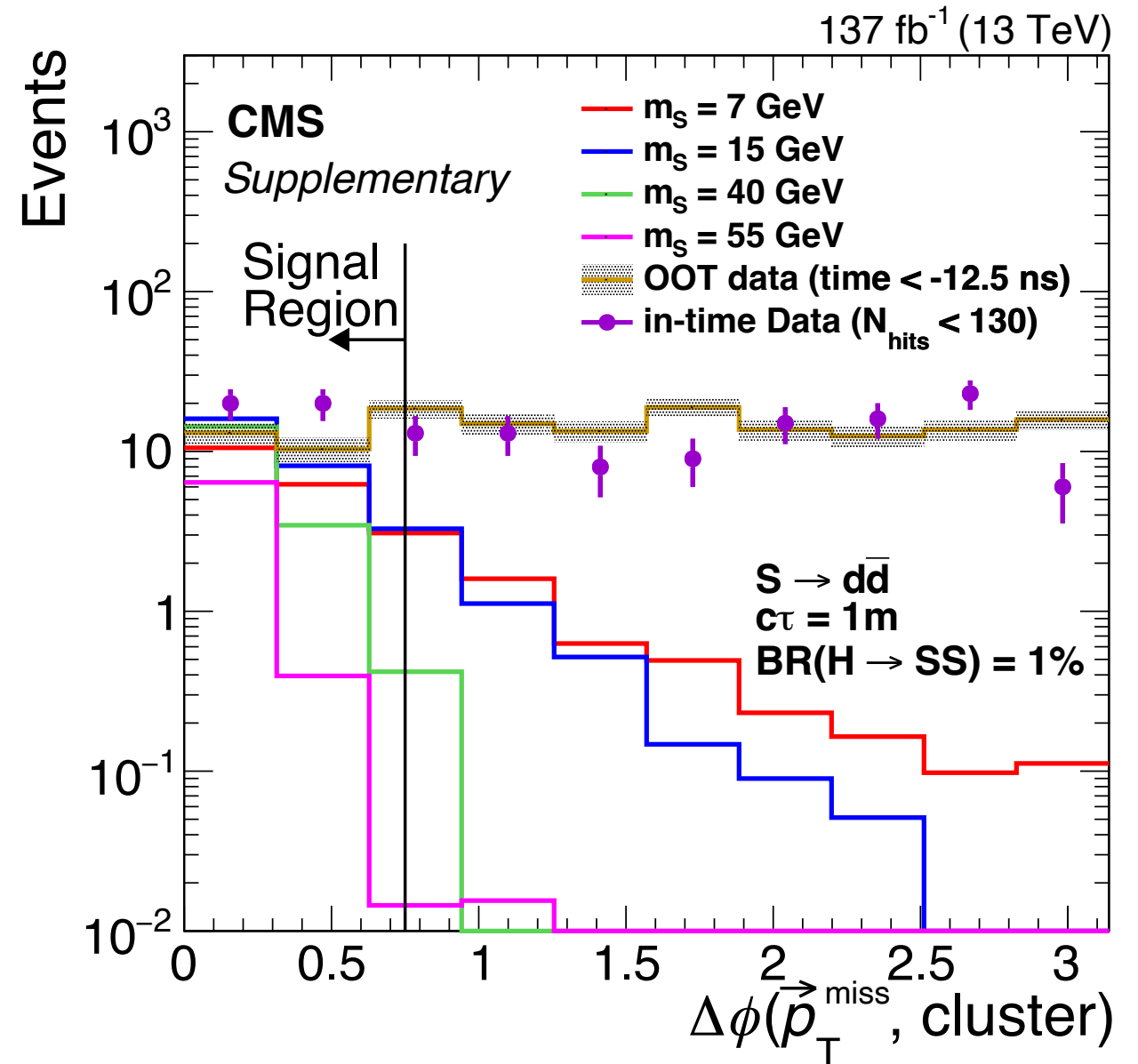
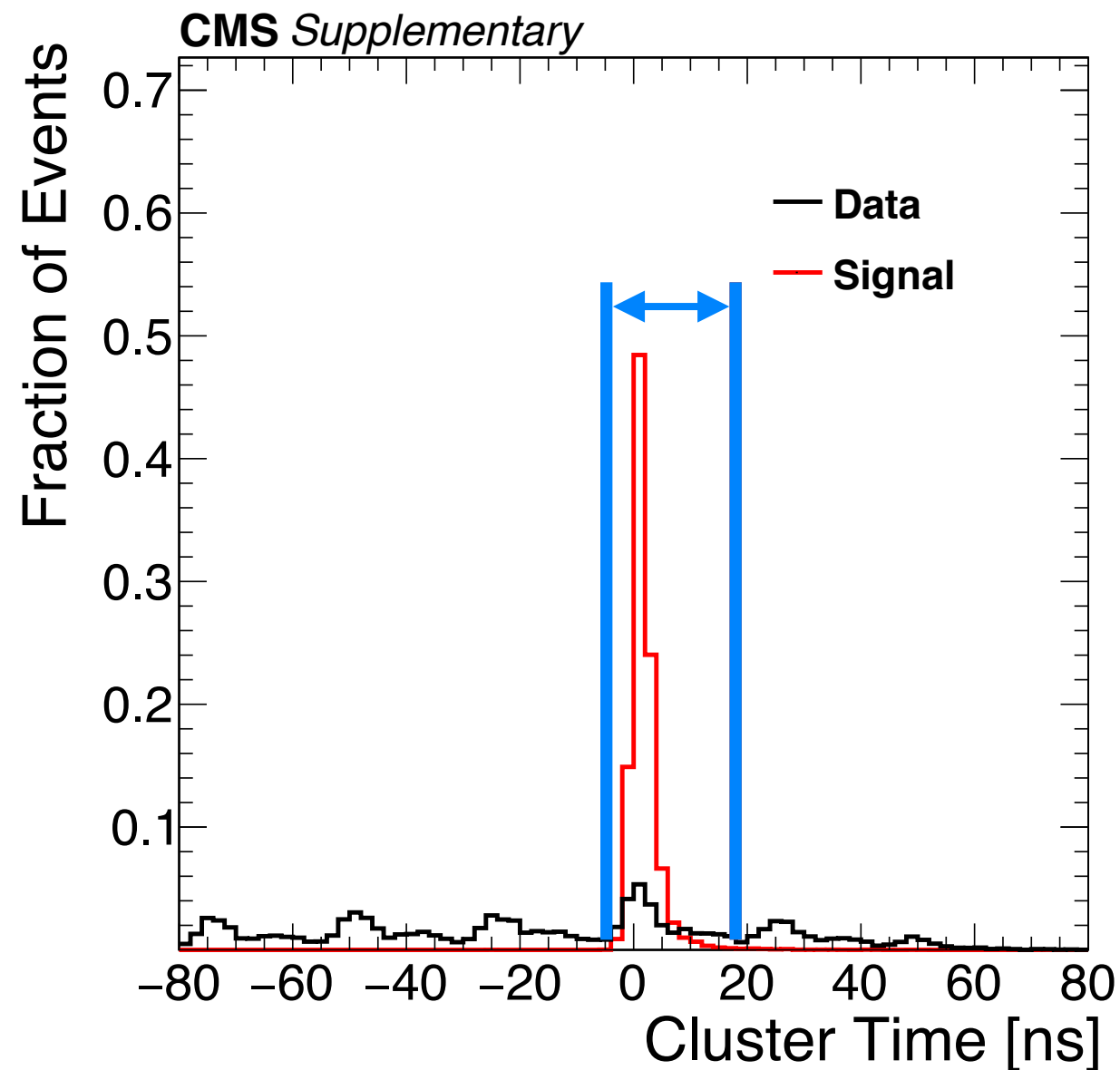
Expect sensitivity to $\text{BR}(H \rightarrow \text{SS}) < 1\%$

LLP with MS: other key selection

Many bkg cluster from OOT interactions

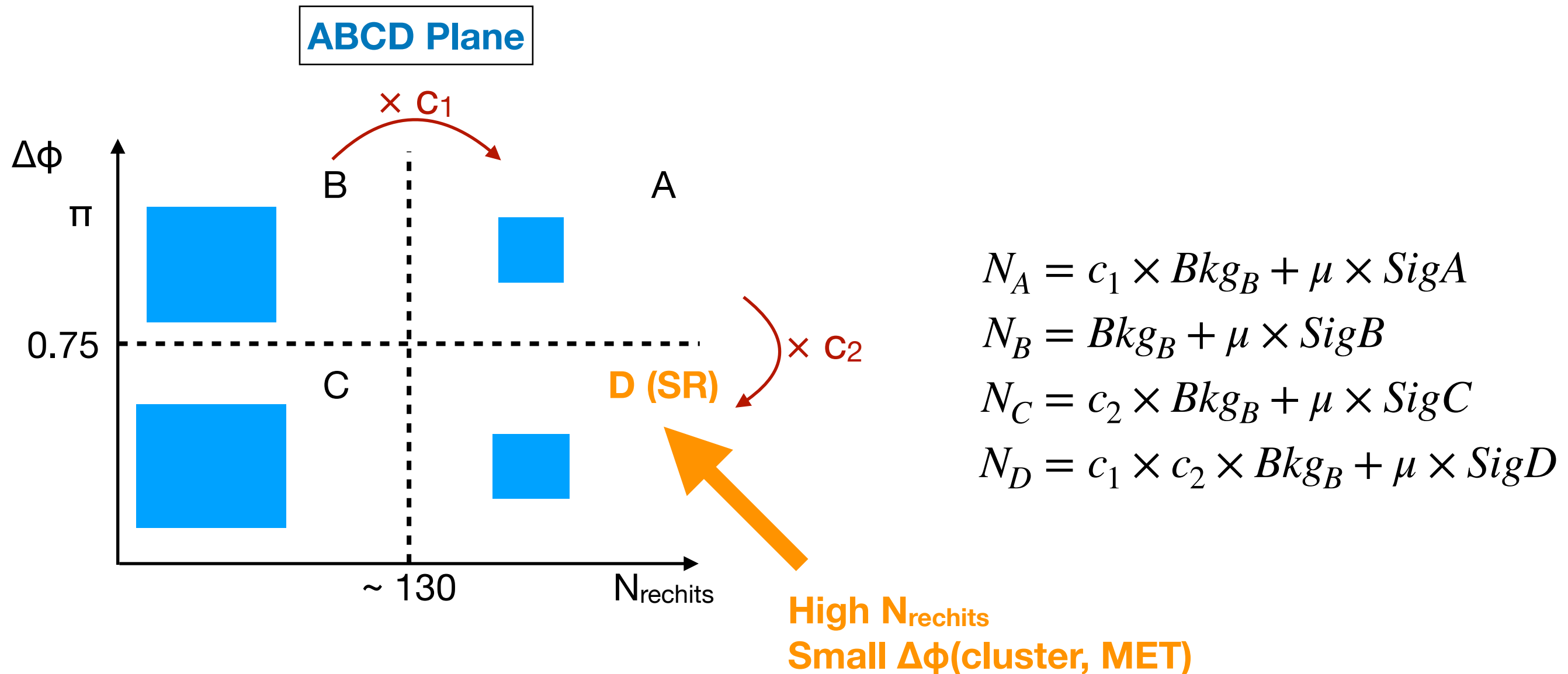
Signal cluster are in-time

Signal: angle between $\vec{p}_{T\text{miss}}$ and cluster position is aligned



Combined 20x bkg rejection power

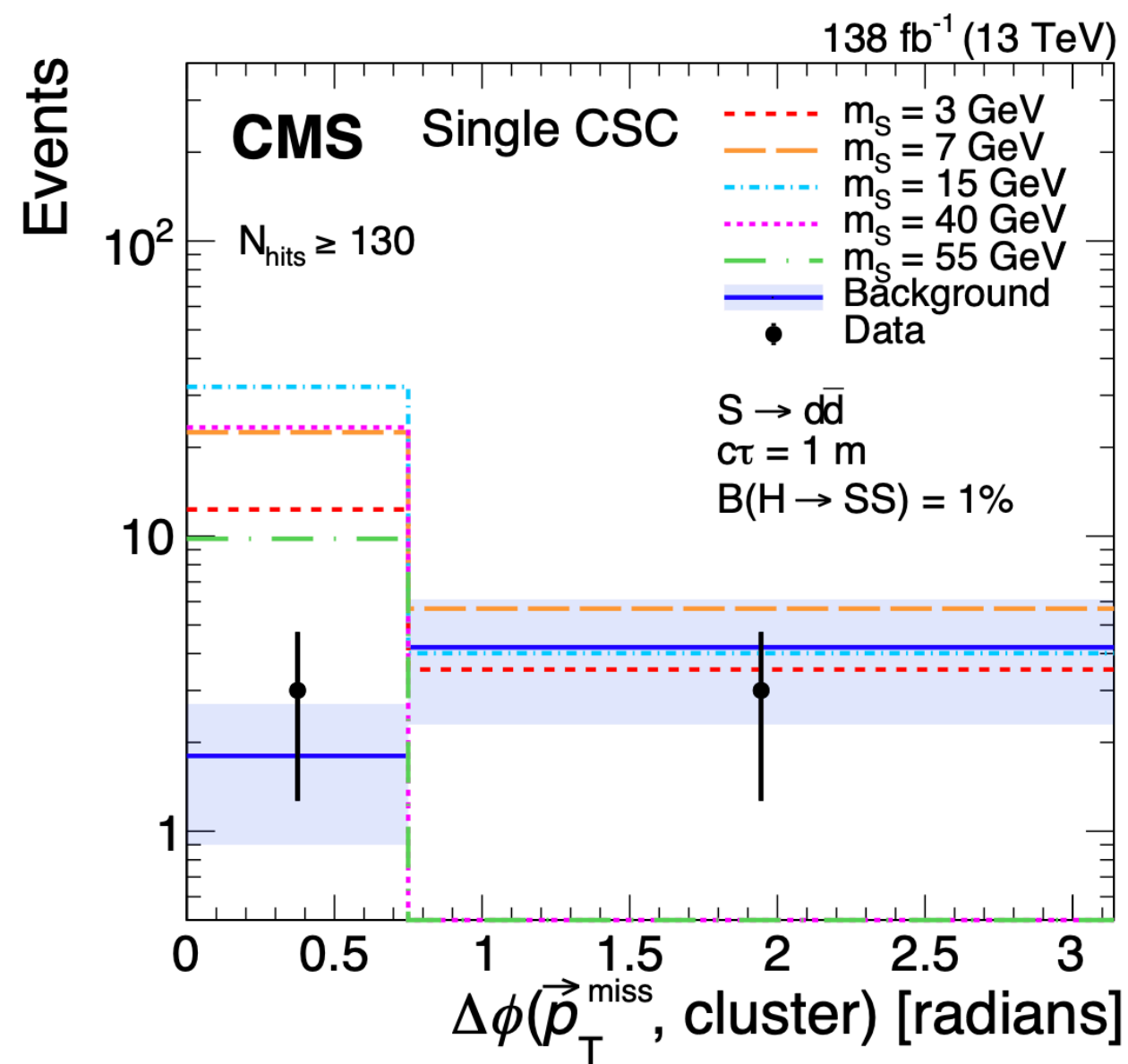
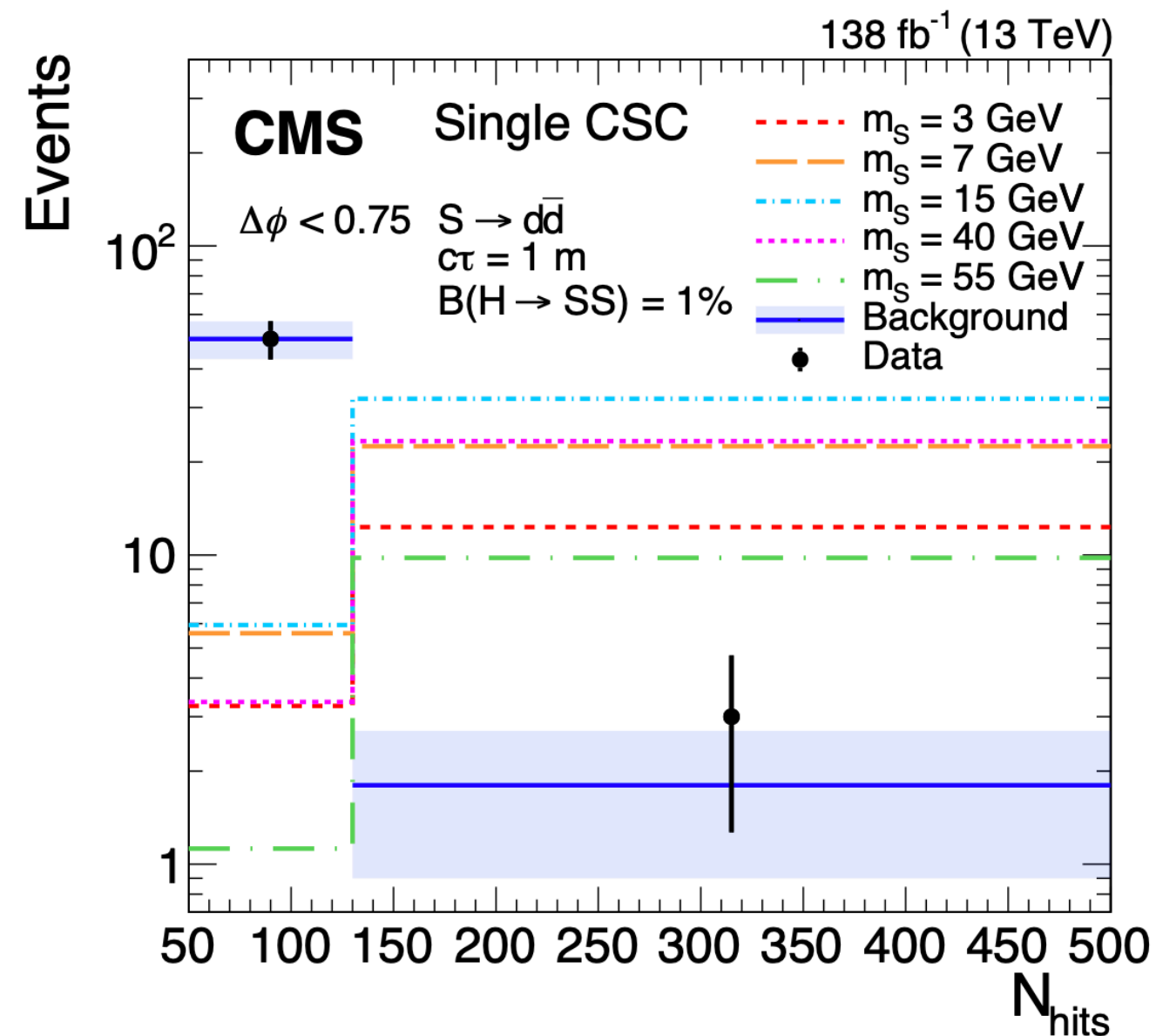
Background Estimation



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

LLP with Muon Systems

Unblinded Results

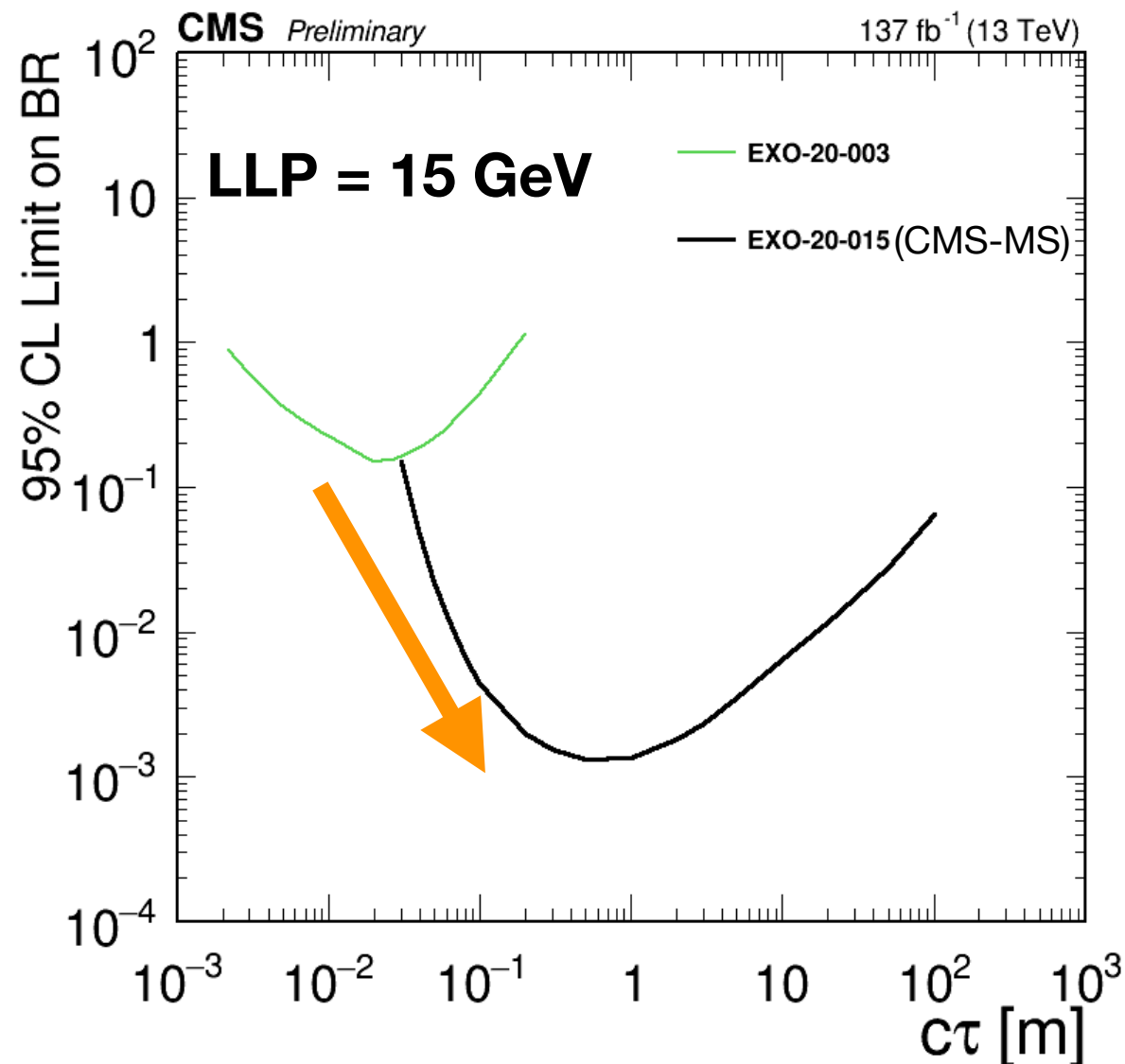


SR Expected Bkg:
 1.8 ± 0.8

SR Observed: 3

LLP with Muon Systems

Best sensitivity at $\text{BR}(\text{H} \rightarrow \text{SS}) \sim 10^{-3}$!!

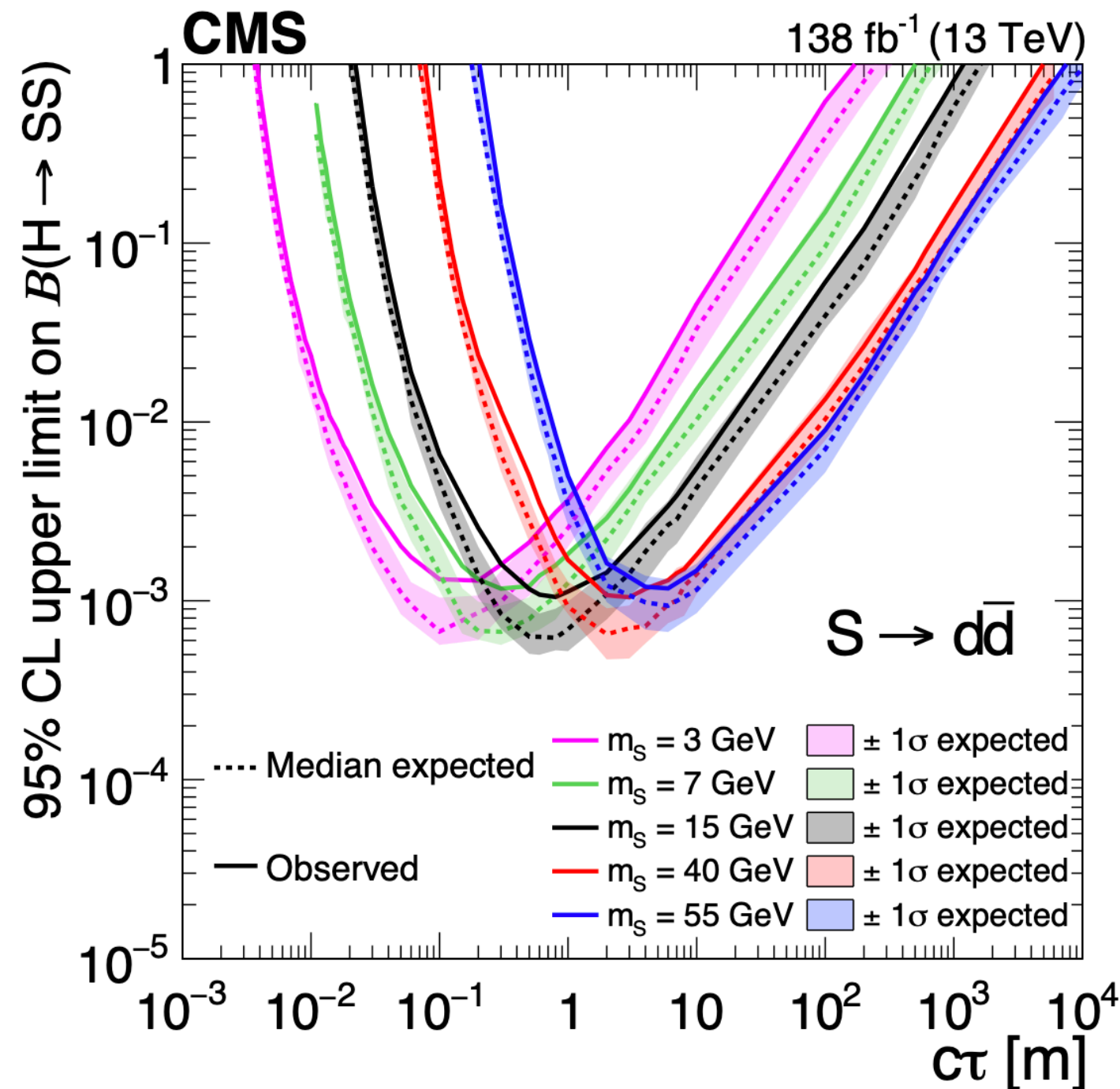


- **ENABLED CMS LLP sensitivity to larger $c\tau$**
- **Access to light LLPs (< 15 GeV)**
 - **Sensitivity to all masses**
 - **Calorimeter: sensitive to LLP energy**

New $c\tau$ Reach and 100x better sensitivity

LLP with Muon Systems

Best sensitivity at $\text{BR}(H \rightarrow SS) \sim 10^{-3}$!!



ENABLED CMS LLP sensitivity to larger $c\tau$

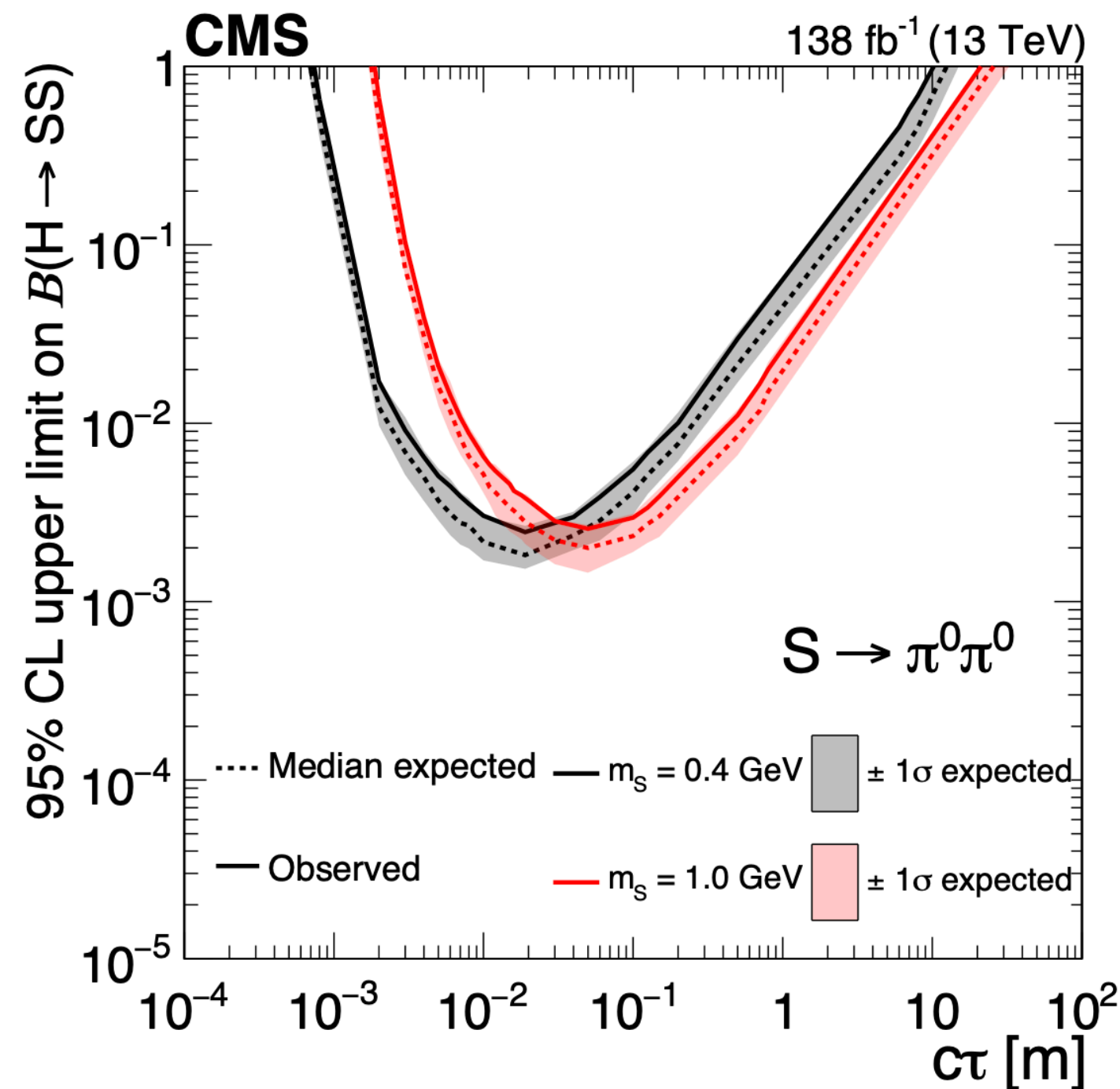
Access to light LLPs (< 7 GeV)

- **Sensitivity to all masses**
- **Calorimeter: sensitive to LLP energy**

**world-best results
for $c\tau > 25$ m**

LLP with Muon Systems

Best sensitivity at $\text{BR}(\text{H} \rightarrow \text{SS}) \sim 10^{-3}$!!



ENABLED CMS LLP sensitivity to larger $c\tau$

Access to light LLPs ($< 7 \text{ GeV}$)

- **Sensitivity to all masses**
- **Calorimeter: sensitive to LLP energy**

**world-best results
for $c\tau > 25 \text{ m}$**

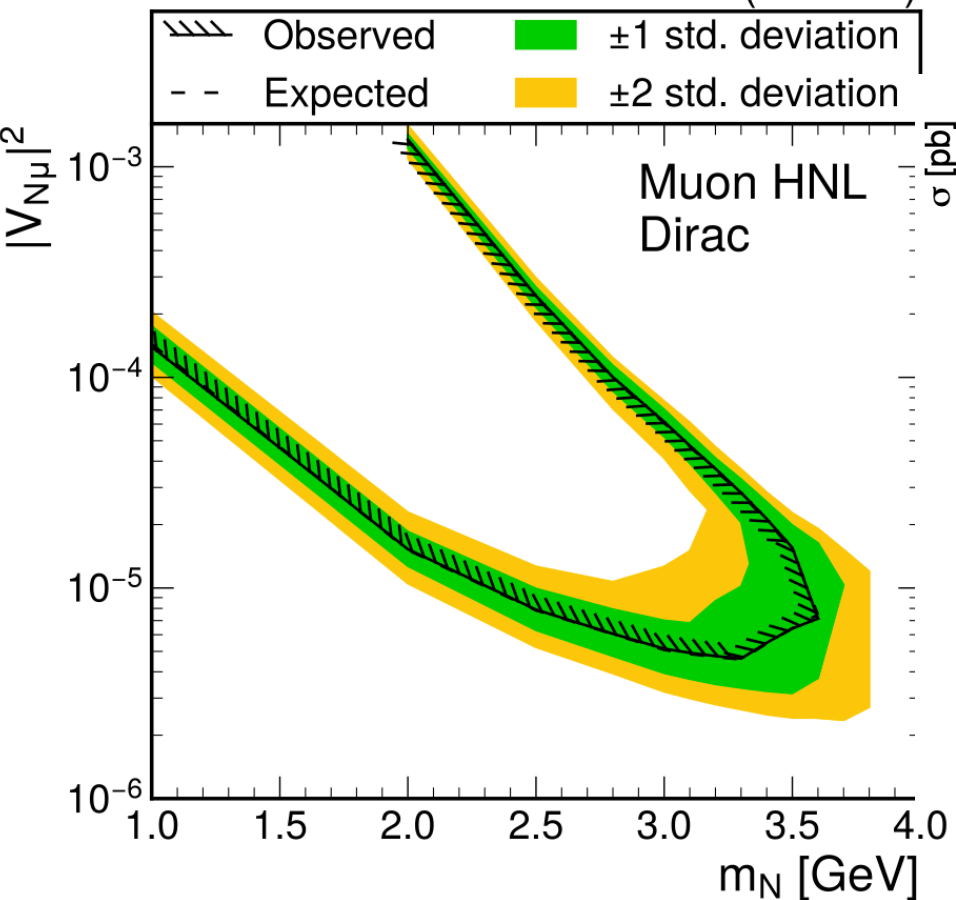
Muon Detector Shower Physics Program

Heavy Neutral Leptons

Phys. Rev. D **110**, 012004

CMS

138 fb⁻¹ (13 TeV)

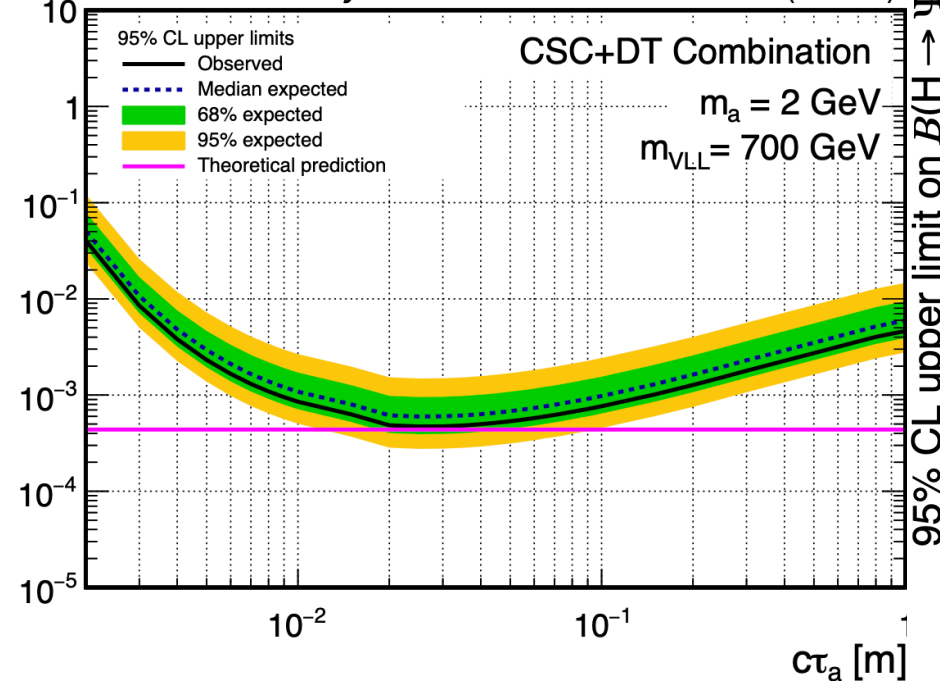


Vector Like Leptons

CMS-PAS-EXO-23-015

CMS Preliminary

138 fb⁻¹ (13 TeV)

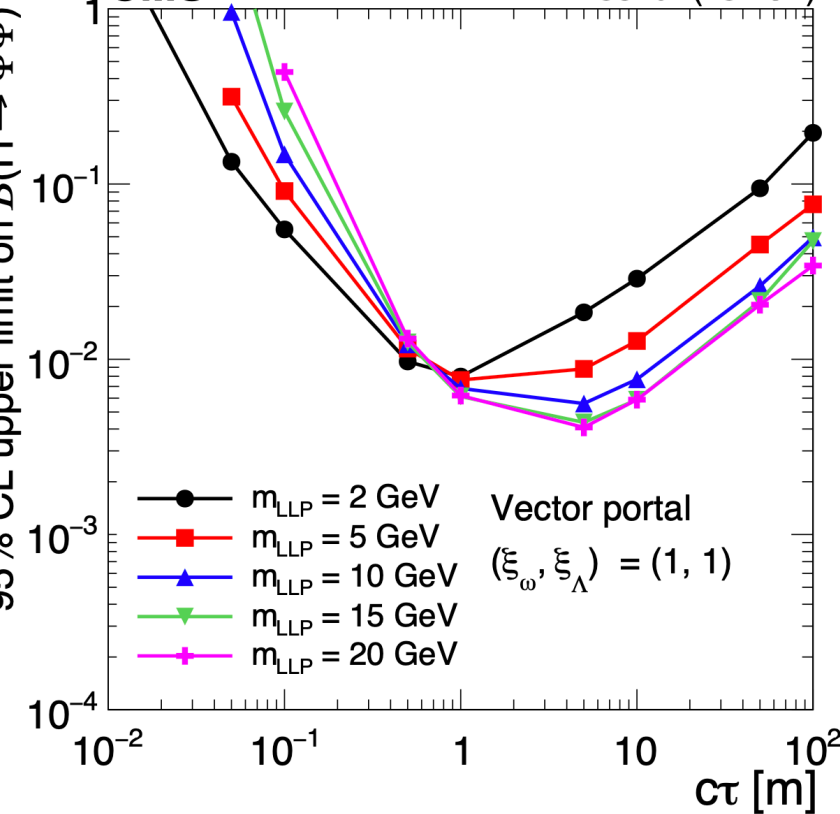


Dark showers

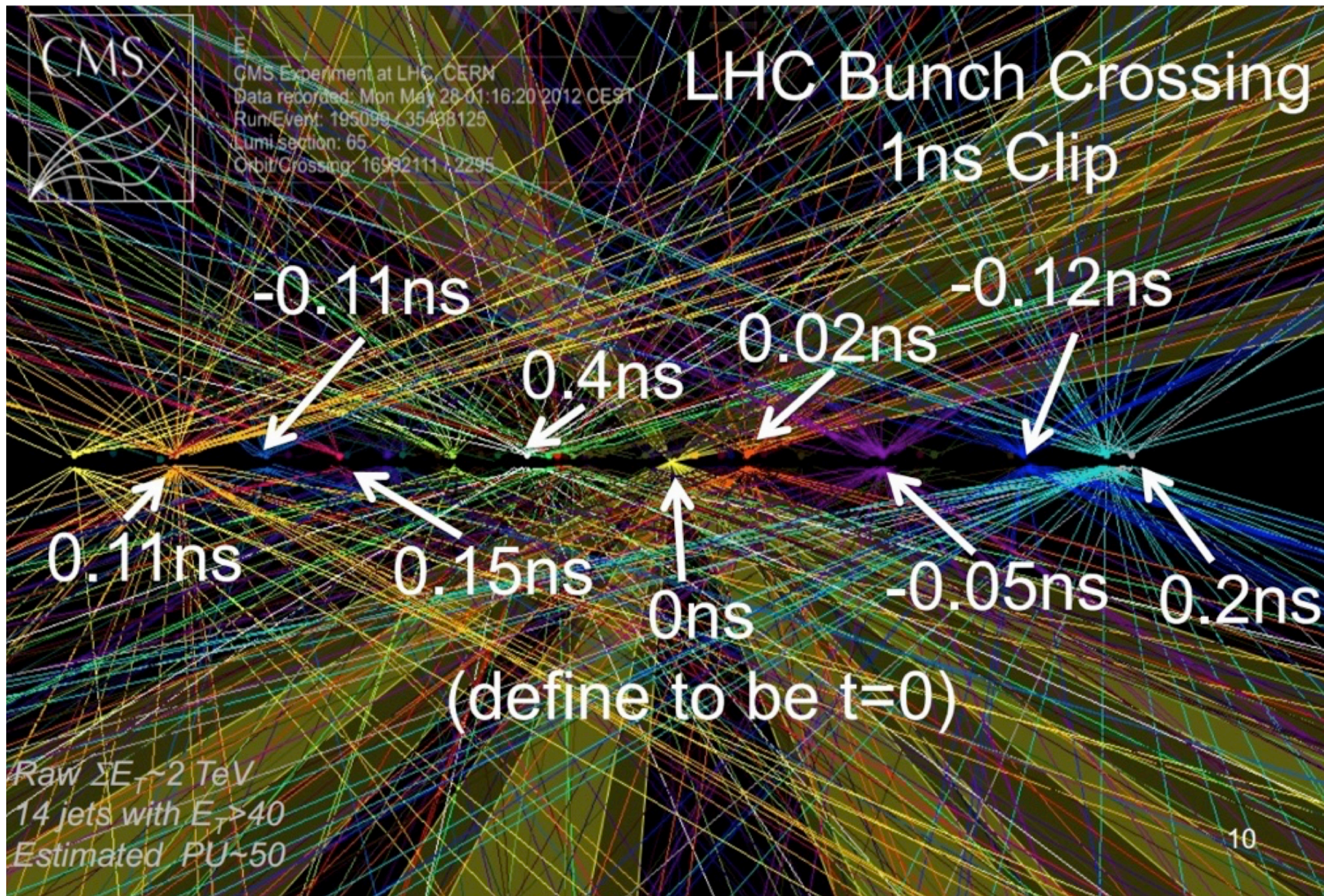
Phys. Rev. D **110**, 032007

CMS

138 fb⁻¹ (13 TeV)

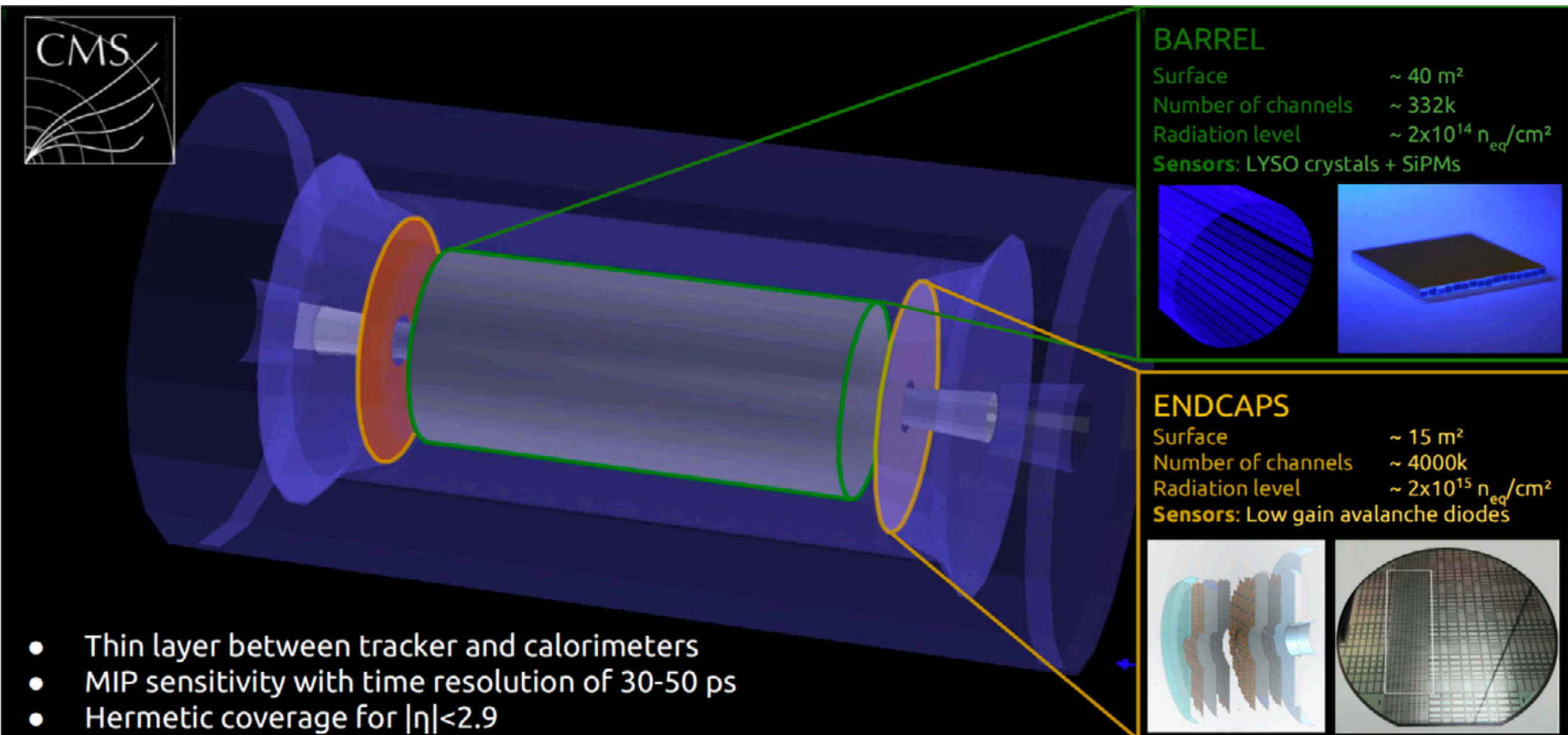


MDS has enabled new LLP sensitivity



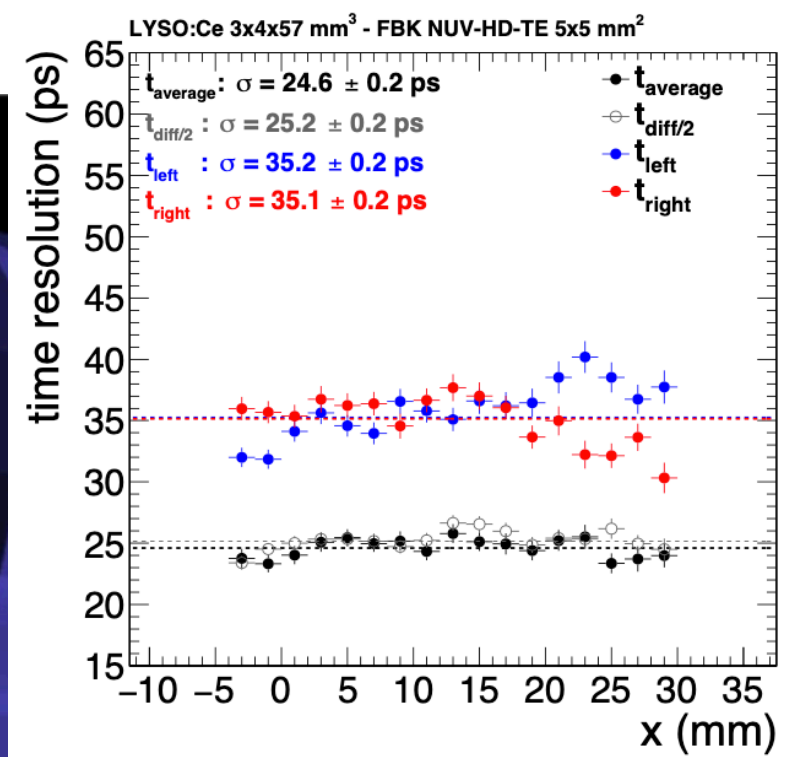
Precision Timing — The Next Frontier

The MIP Timing Detector

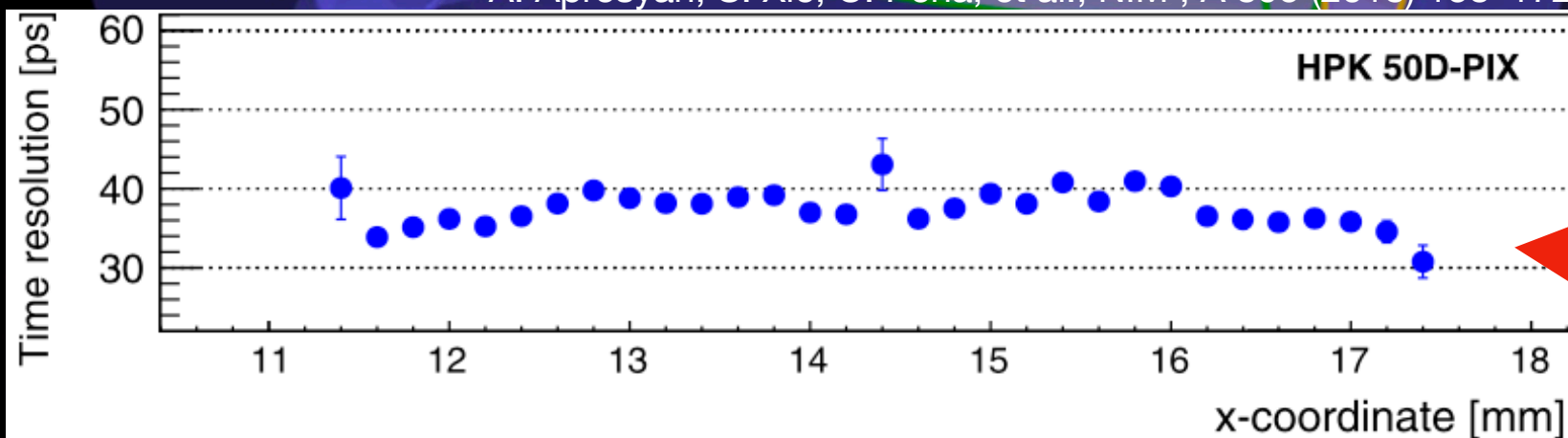


A Large Scale Precision Detector

The MIP Timing Detector

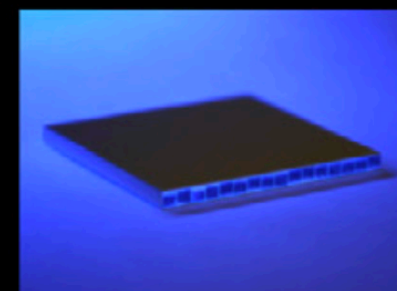
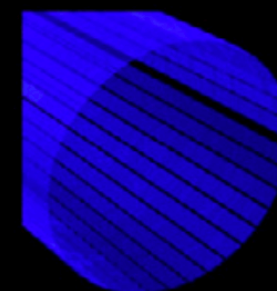


A. Apresyan, S. Xie, C. Peña, et al., NIM , A 895 (2018) 158–172



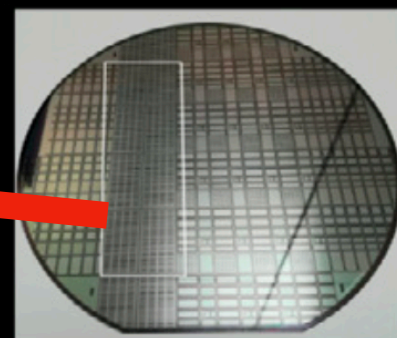
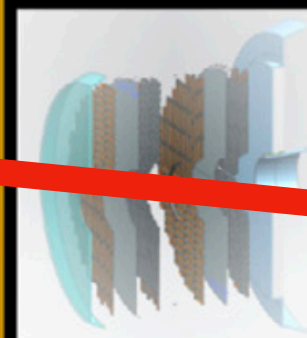
BARREL

Surface $\sim 40 \text{ m}^2$
 Number of channels $\sim 332\text{k}$
 Radiation level $\sim 2 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$
Sensors: LYSO crystals + SiPMs



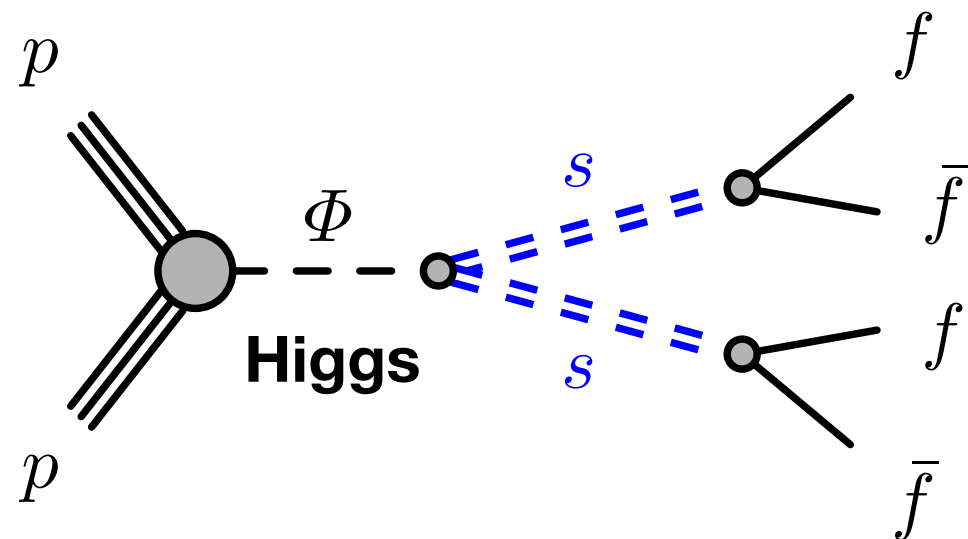
ENDCAPS

Surface $\sim 15 \text{ m}^2$
 Number of channels $\sim 4000\text{k}$
 Radiation level $\sim 2 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$
Sensors: Low gain avalanche diodes

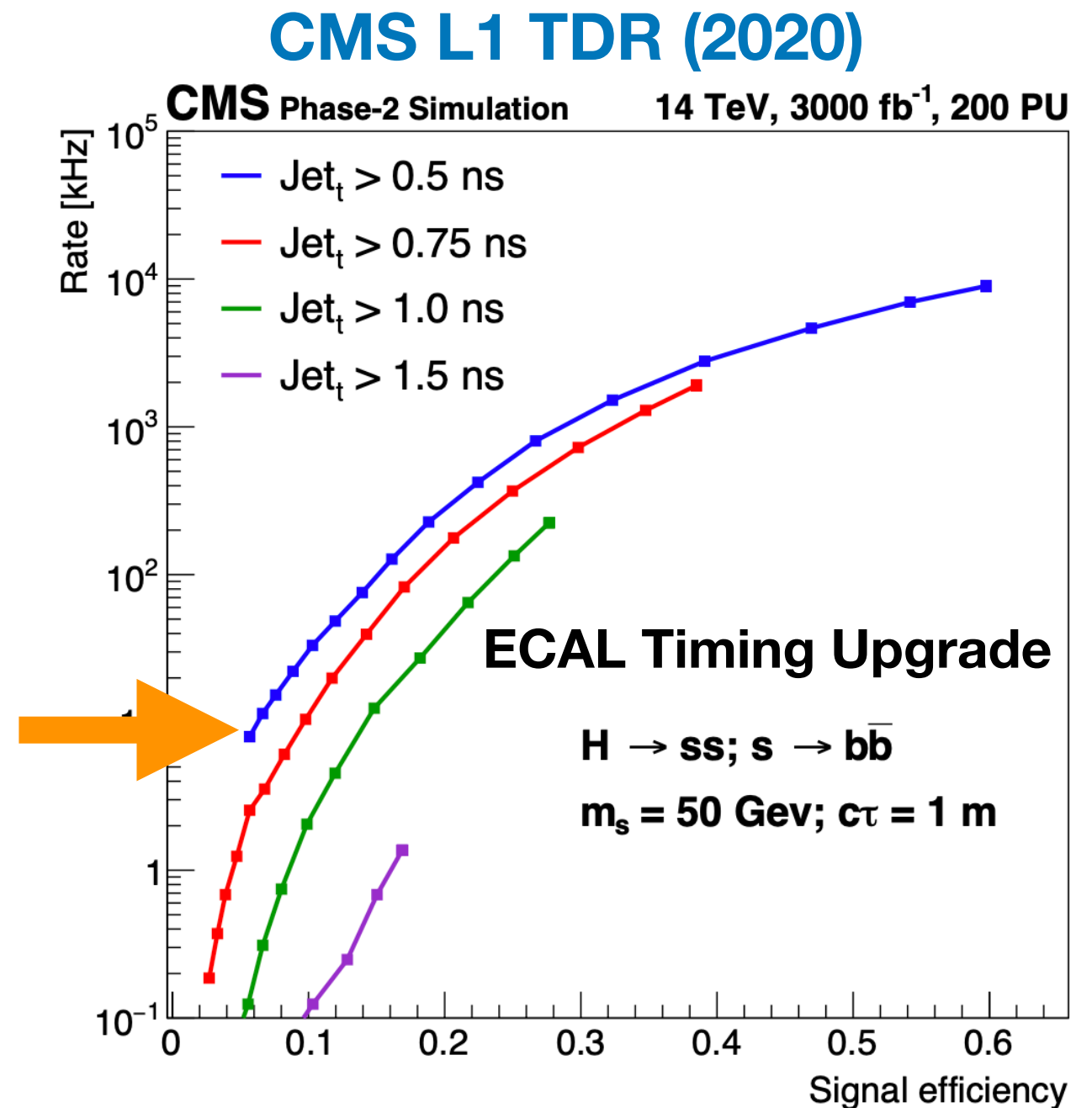


A Large Scale Precision Detector

Precision Timing Enables L1 Triggers

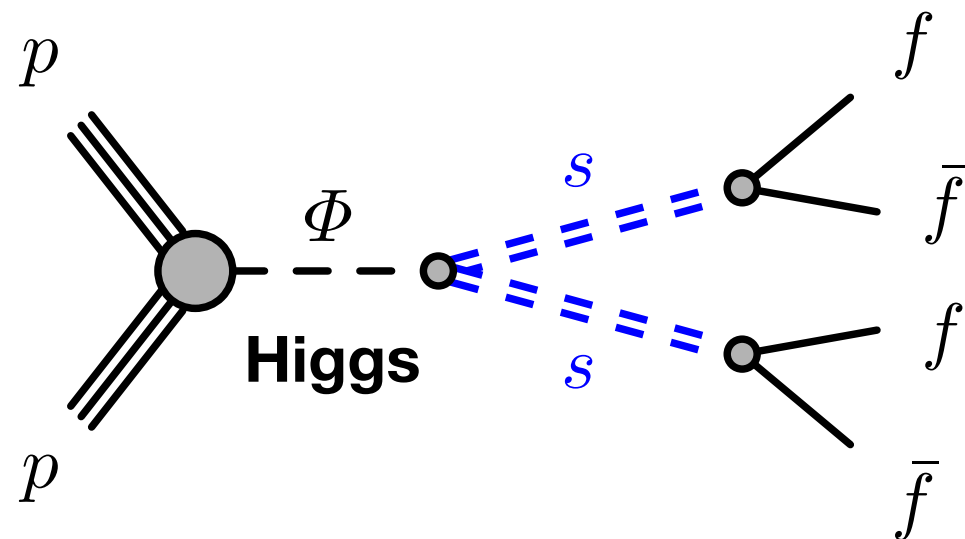


**Greater than 10x increase
in signal acceptance!**

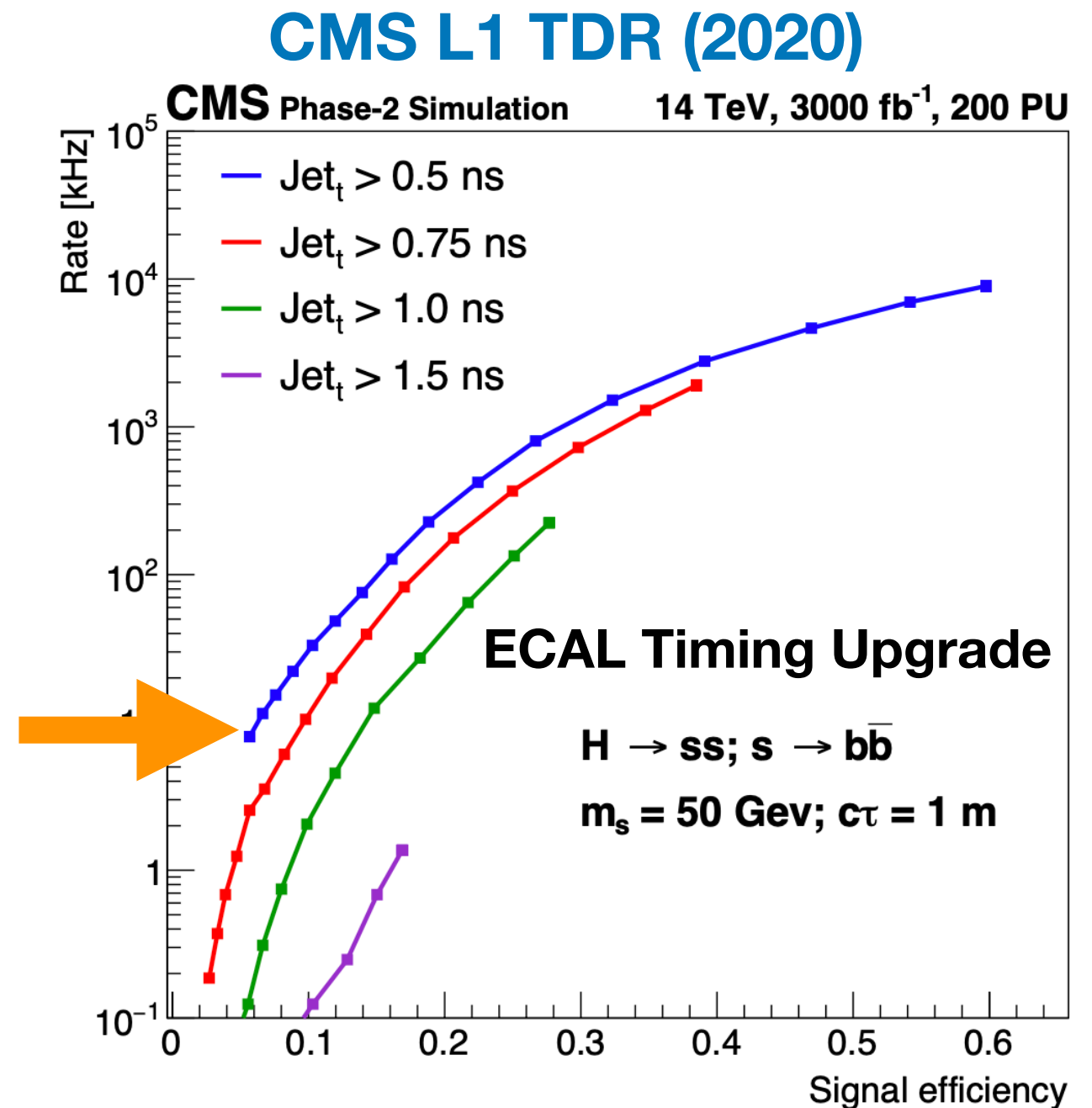


15% efficiency for @ 10 kHz L1 rate

Precision Timing Enables L1 Triggers

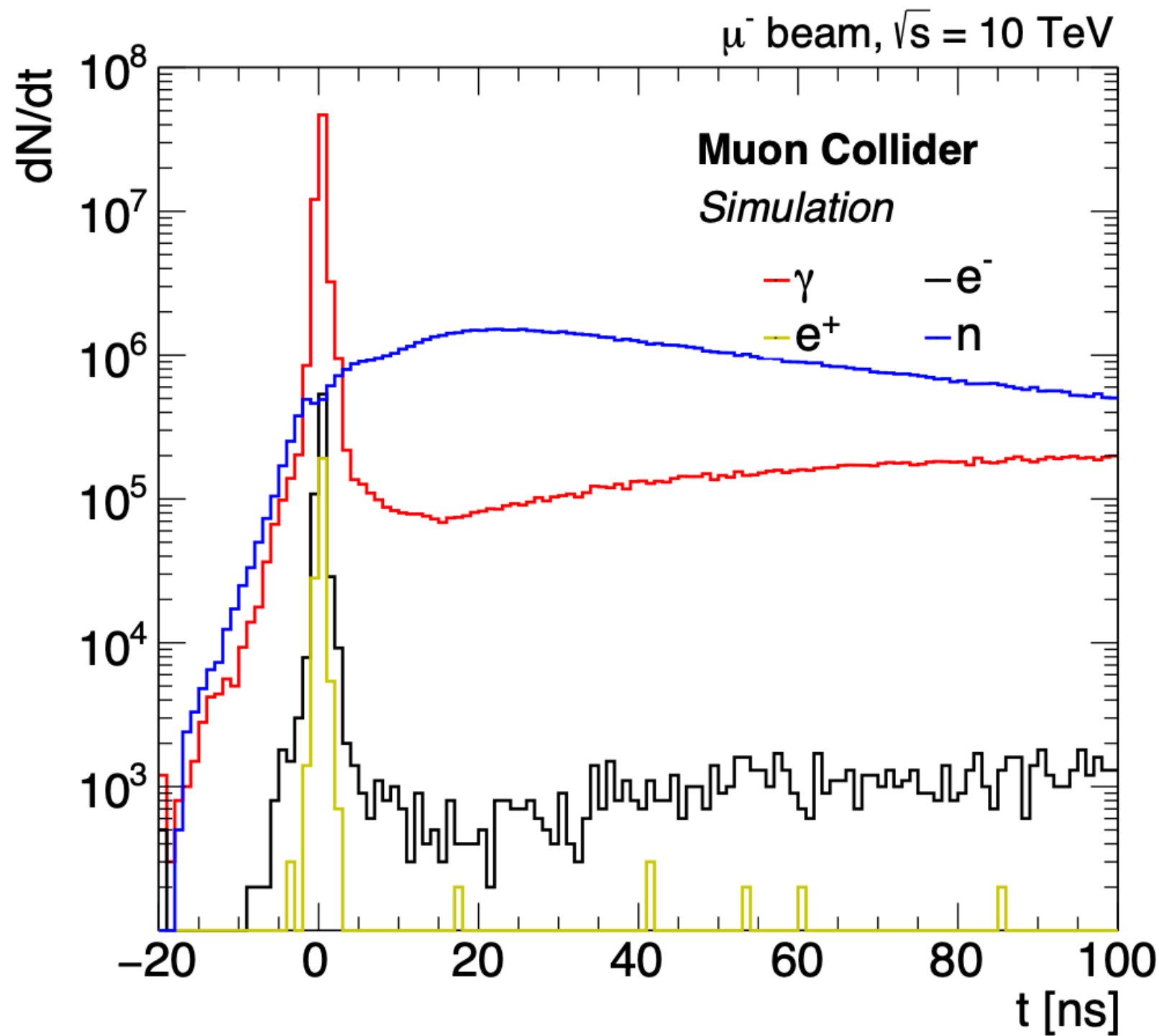


Combined with MTD will significantly boost LLPs with $\sim 1\text{m } c\tau$



15% efficiency for @ 10 kHz L1 rate

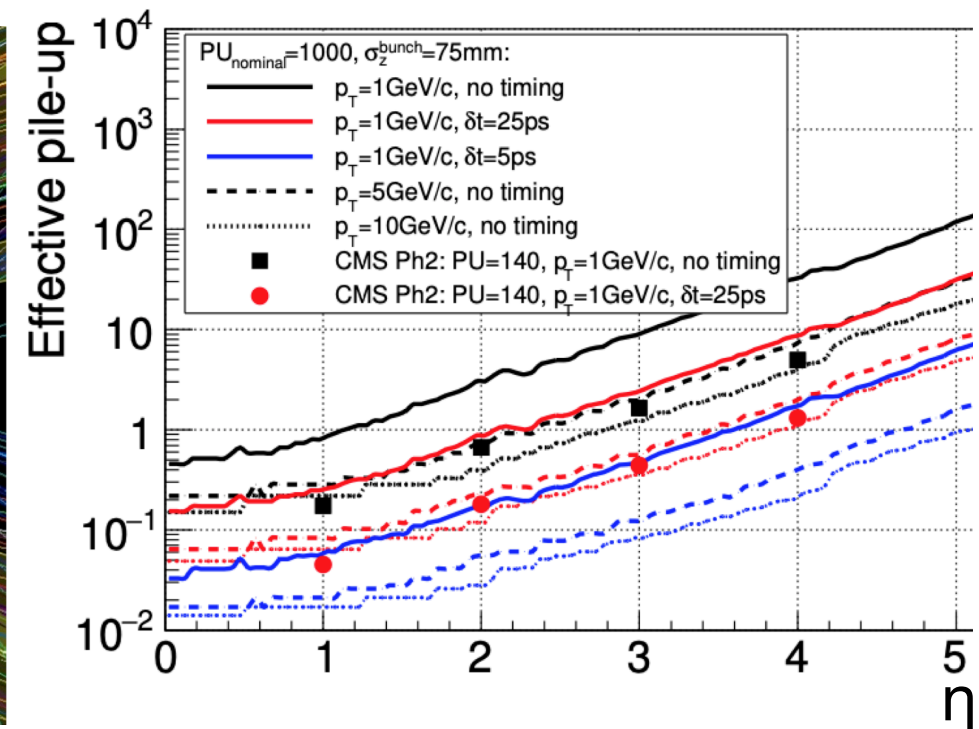
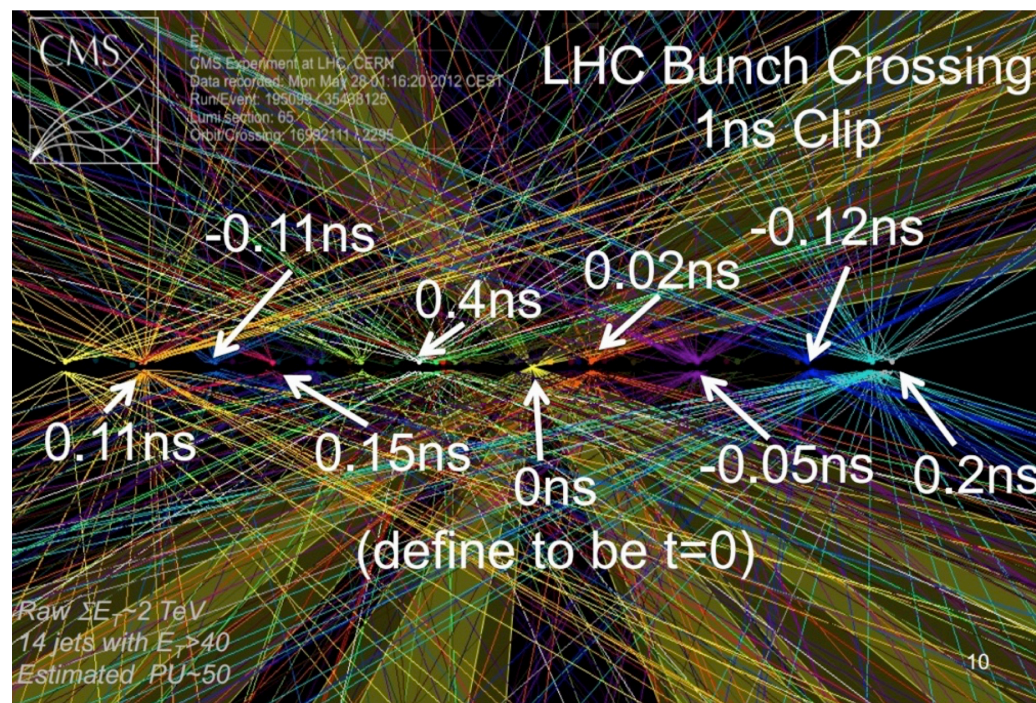
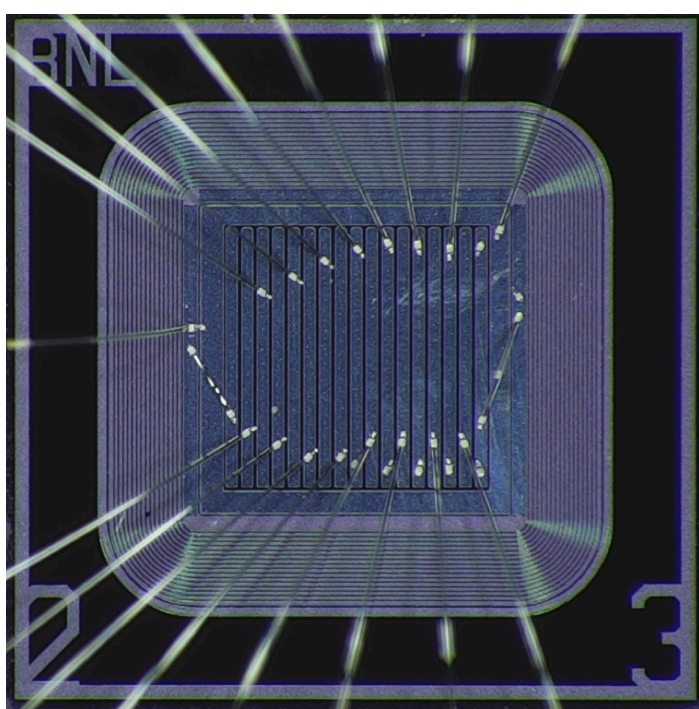
Next Generation Colliders Need Timing



Muon collider case: ~ 10 ps to suppress BIB

Tracker

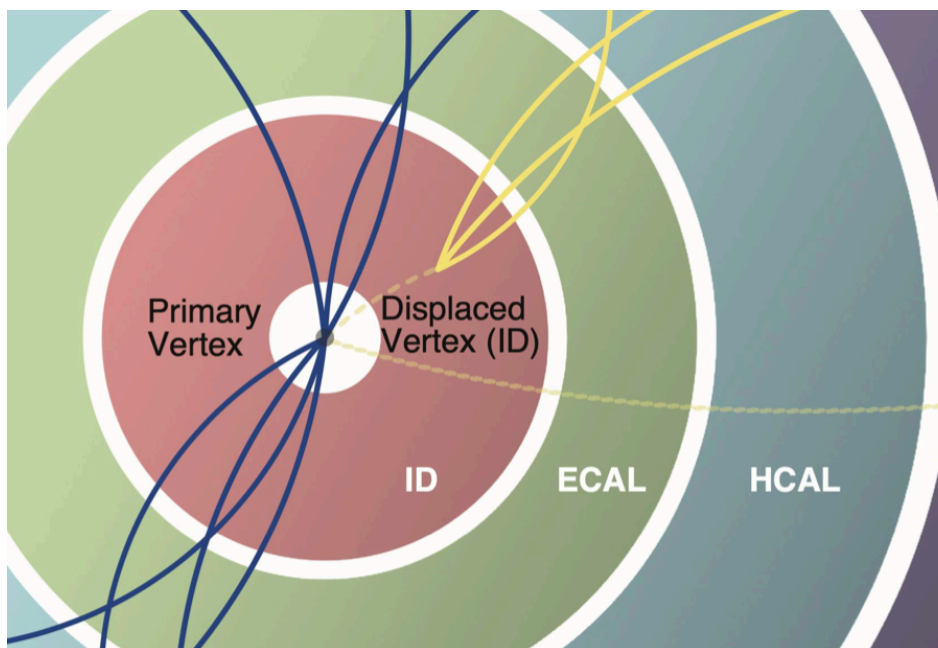
- 4D-Tracking: position+timing (x, y, z, t) in same sensor
- Momentum, 4D-vertexing, pileup and BIB rejection
- Specifications: ~ 10 ps and ~ 10 μm resolution: advance R&D for sensors and ASICs



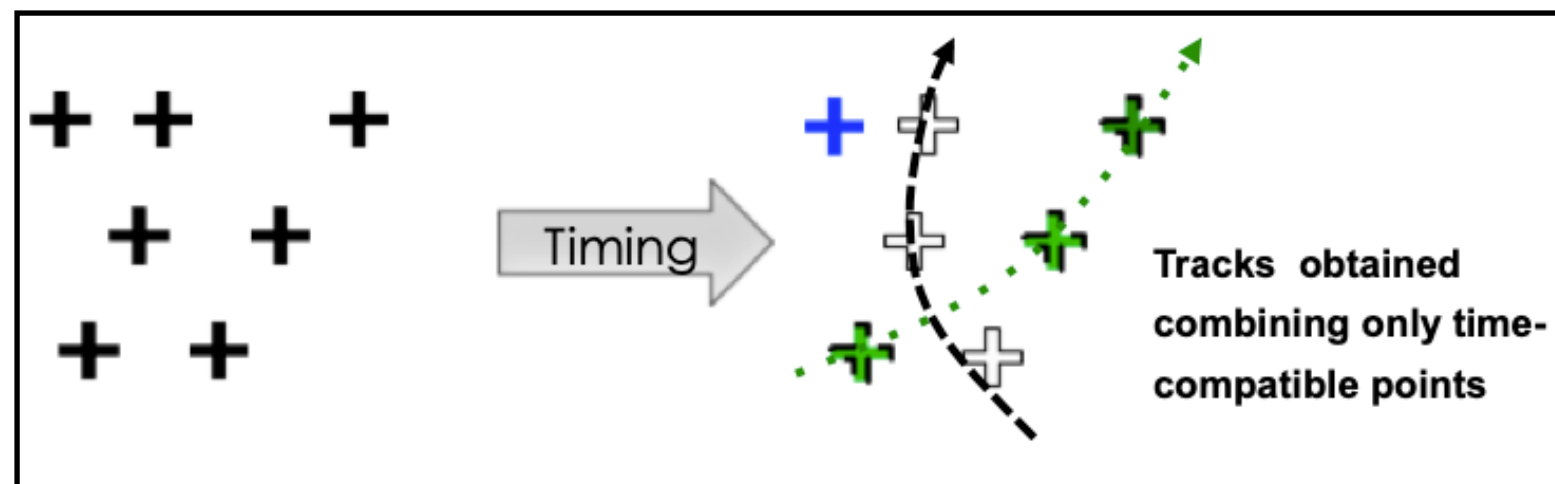
4D Tracking and DV

- 4D-Tracking: position+timing in same sensor
- Key capabilities: **4D-vertexing**
 - Pixels at large radii: enhanced DV capability
 - Smaller inner radius: sensitivity to lower $c\tau$

New capability: Large radii DV



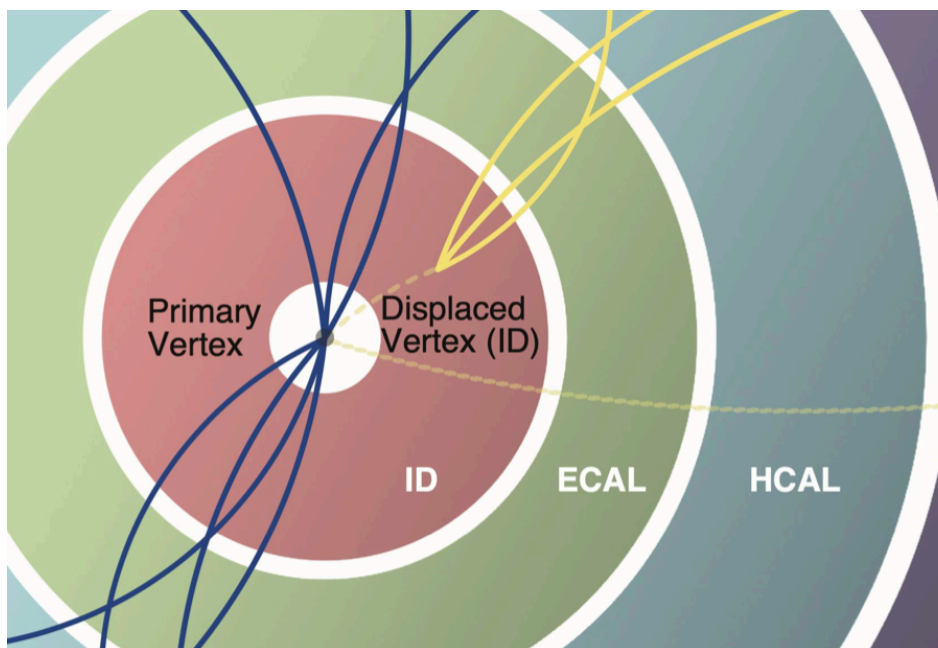
New capability: reduce hit combinatorics



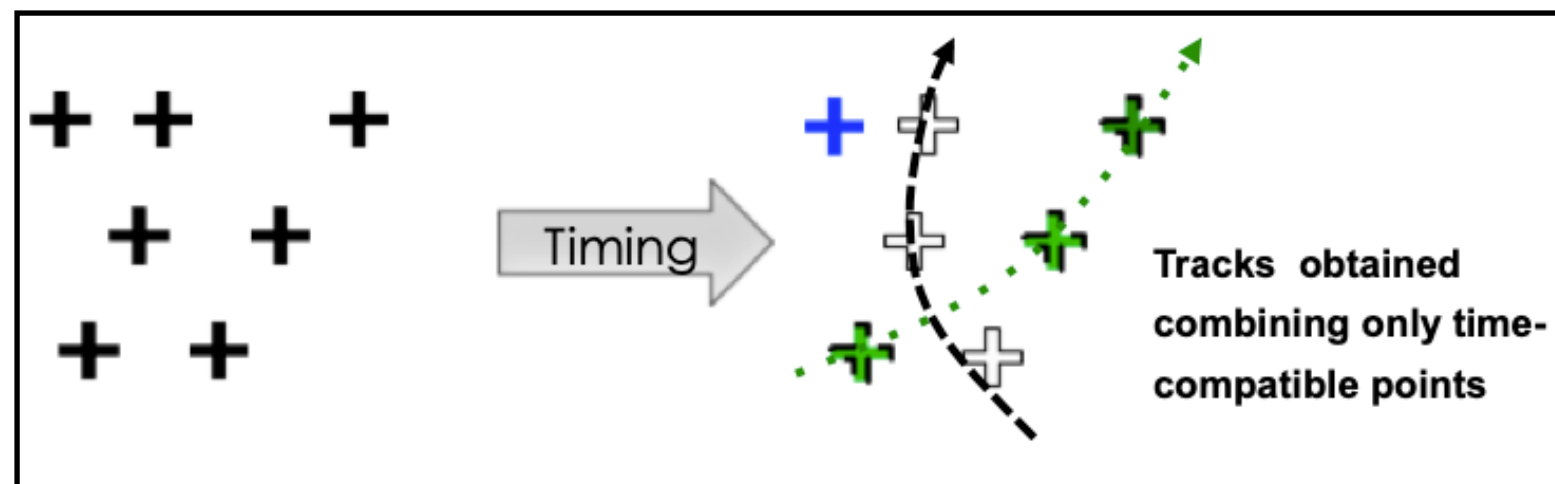
4D Tracking and DV

- 4D-Tracking: position+timing in same sensor
- Key capabilities: **4D-vertexing**
 - Pixels at large radii: challenge for ASIC design
 - Smaller inner radius: challenge rad hard sensor/ASIC

New capability: Large radii DV

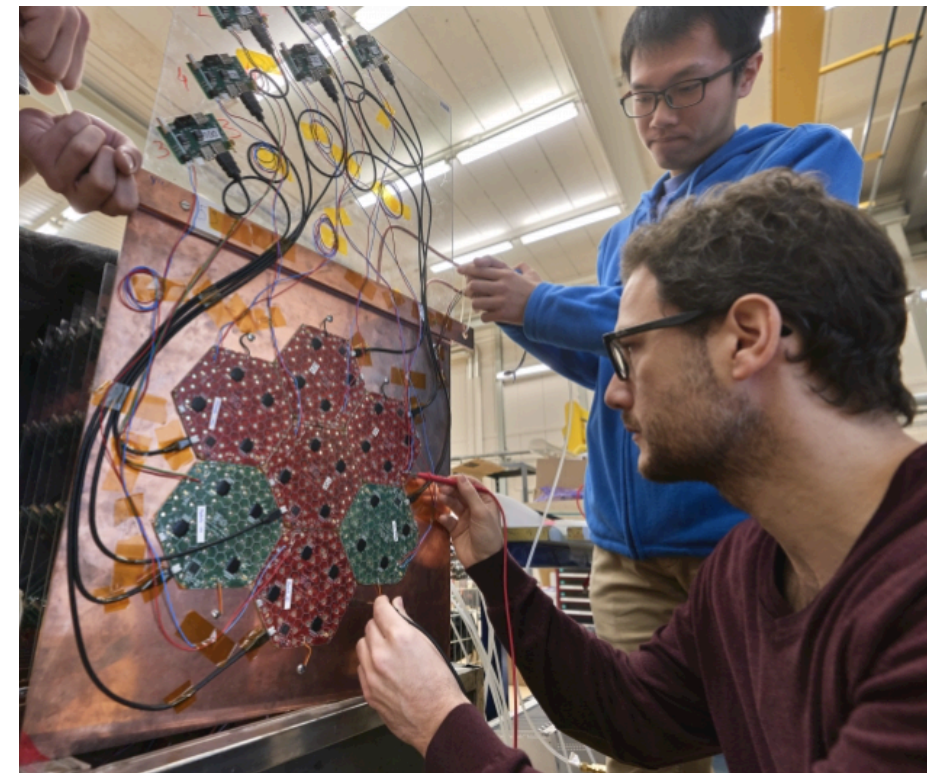
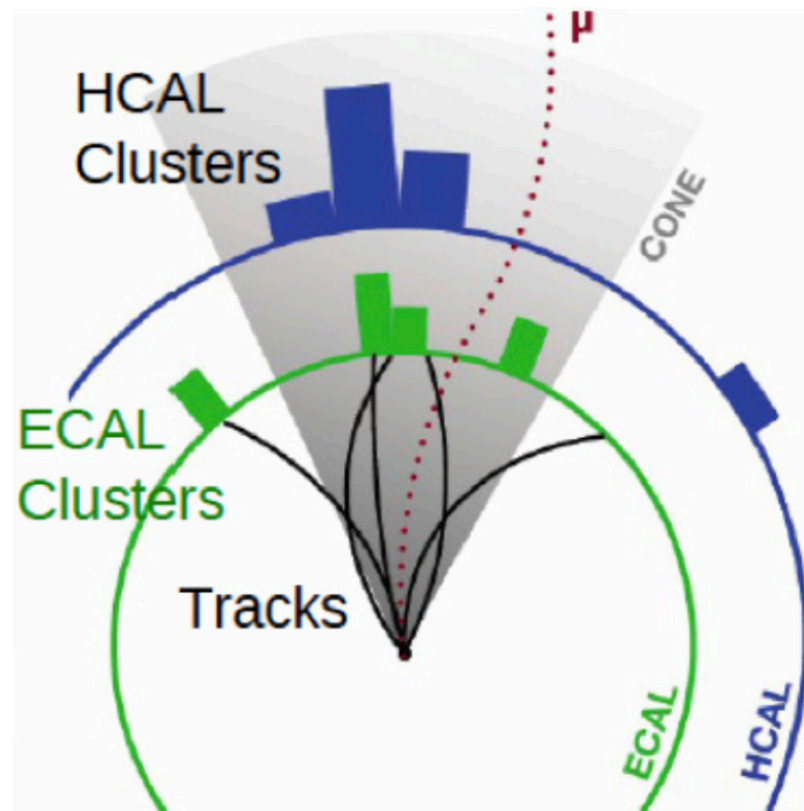
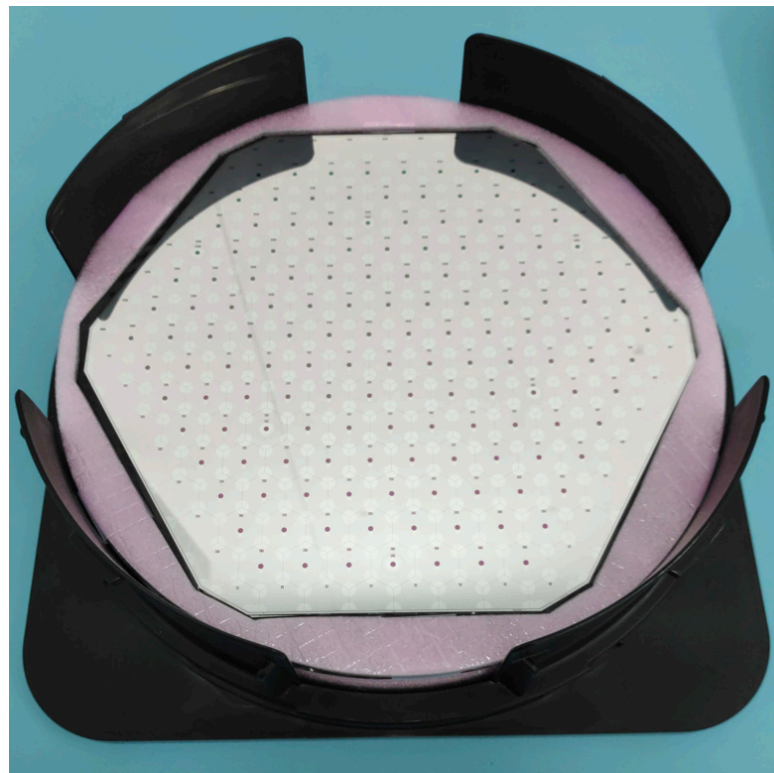


New capability: reduce hit combinatorics



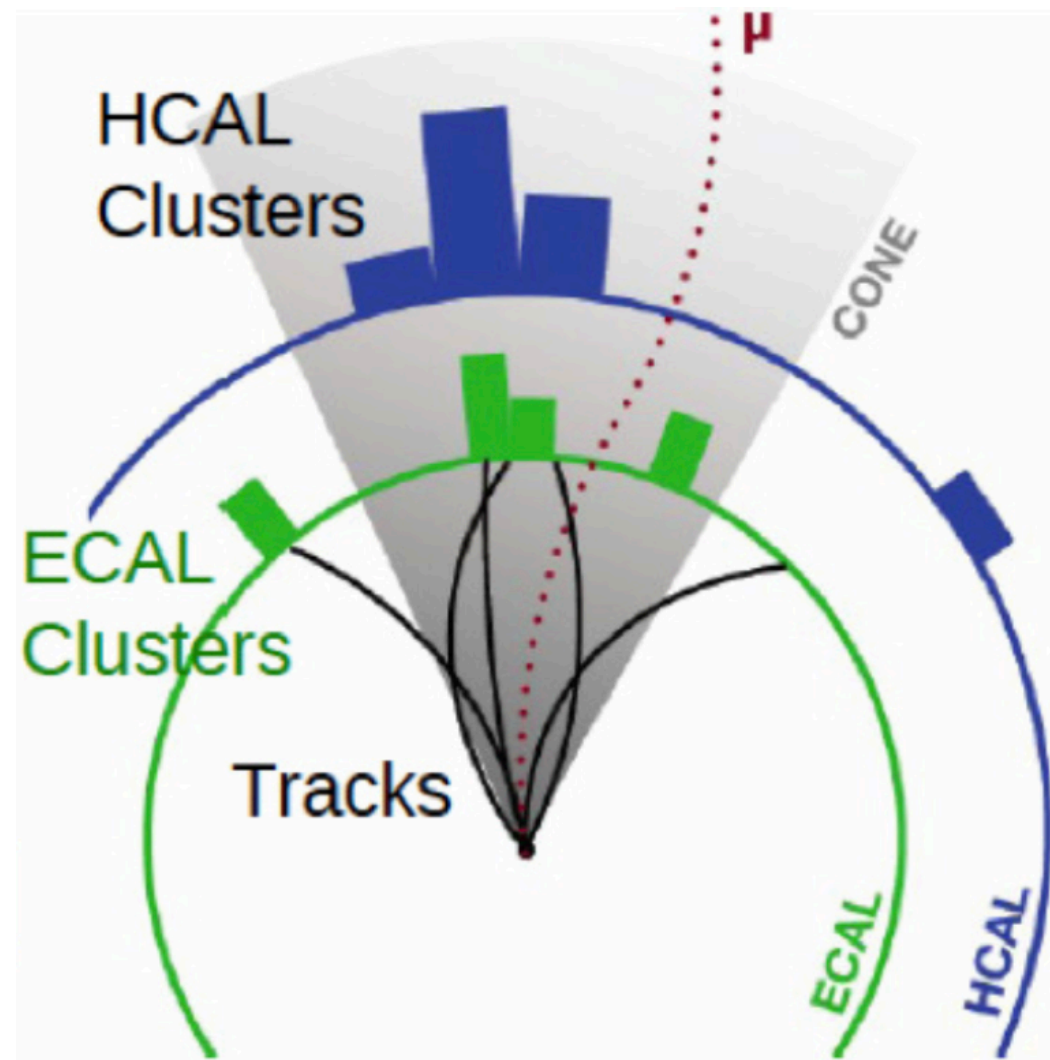
Calorimeters

- **5D-calorimeter:** measure (x, y, z, t, E)
 - Key capabilities: LLP vertex reconstruction and TOF
 - High transverse and longitudinal **segmentation**
 - Excellent timing resolution



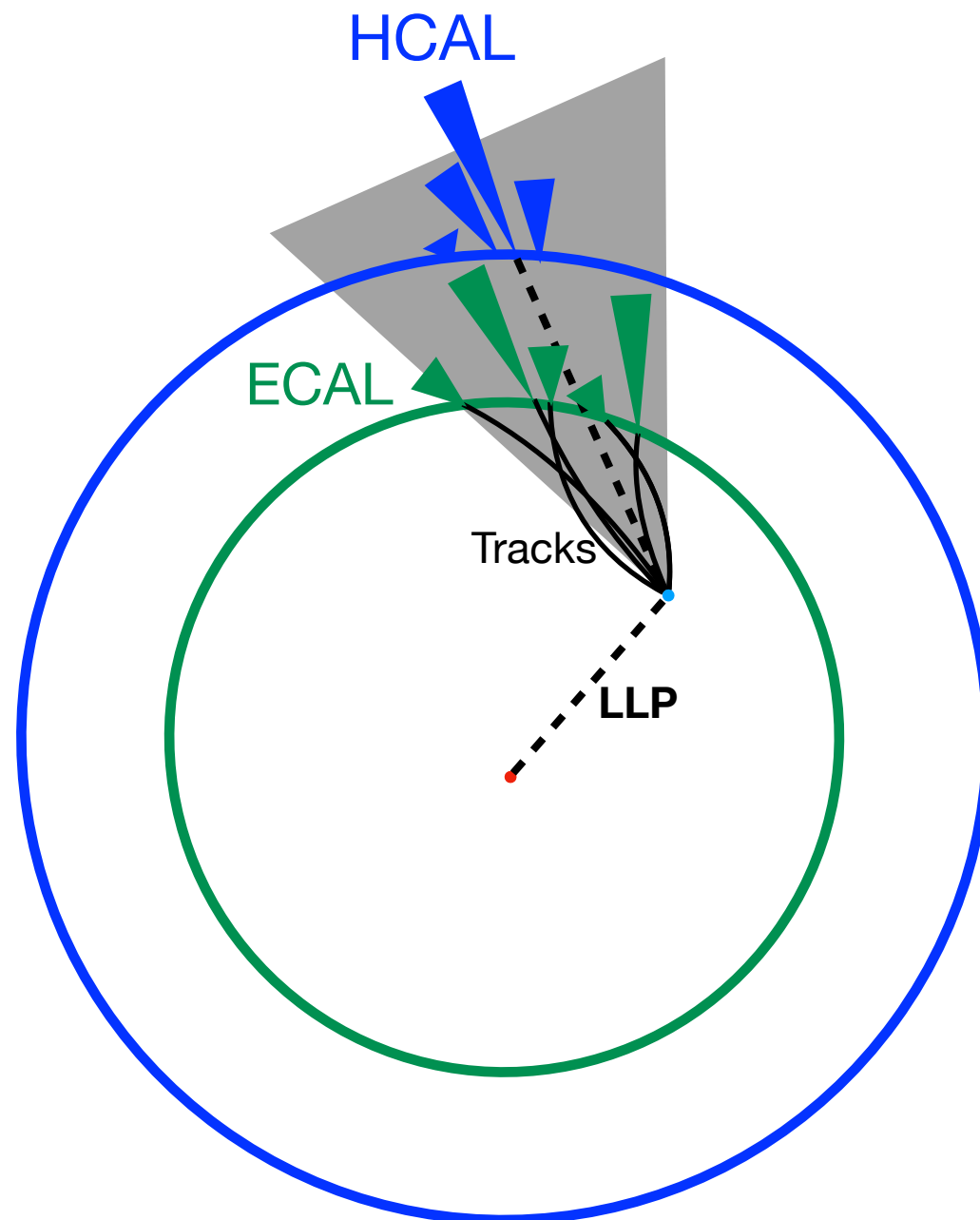
Particle Flow Detector

- Current experiments allow prompt particle flow reconstruction



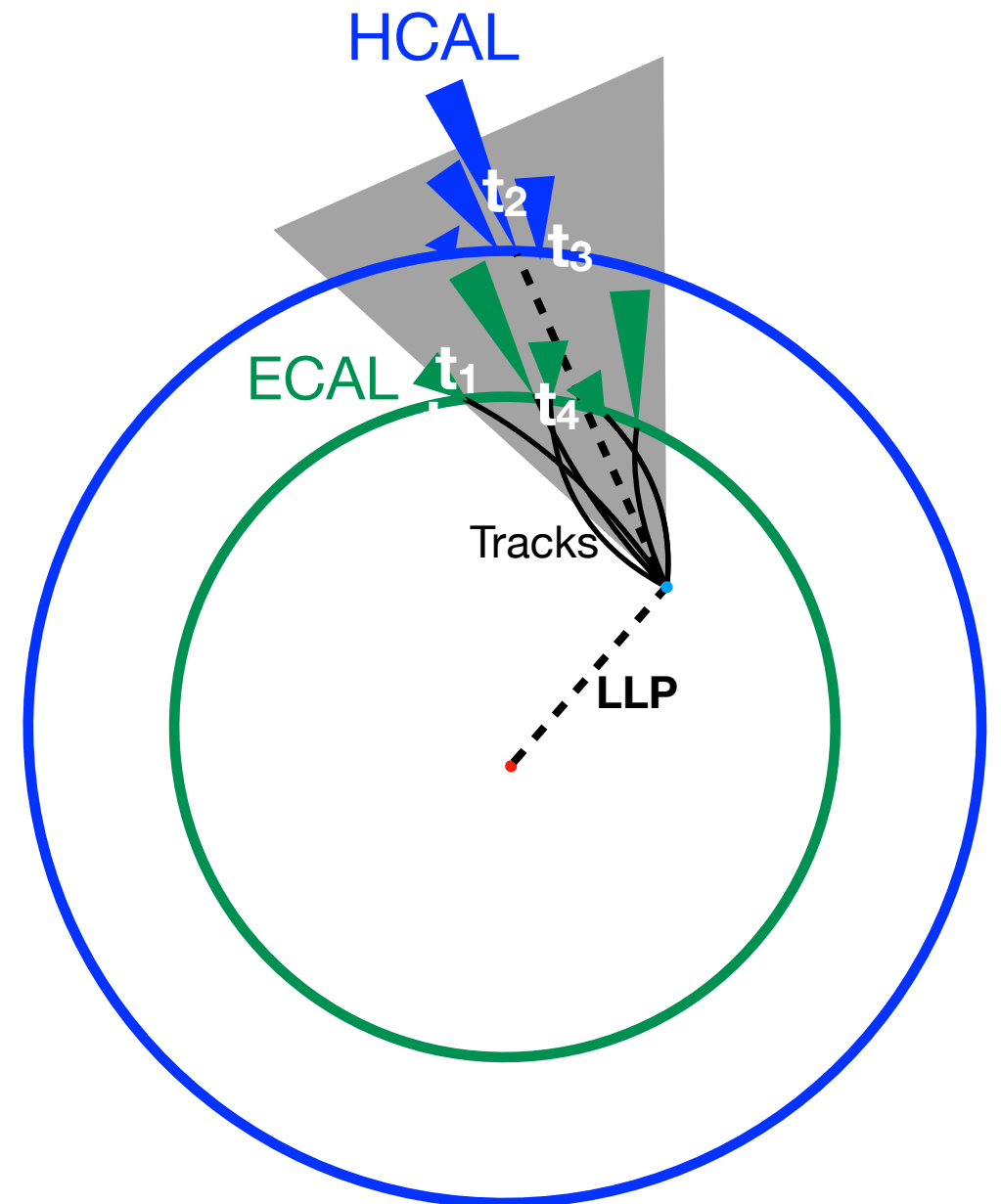
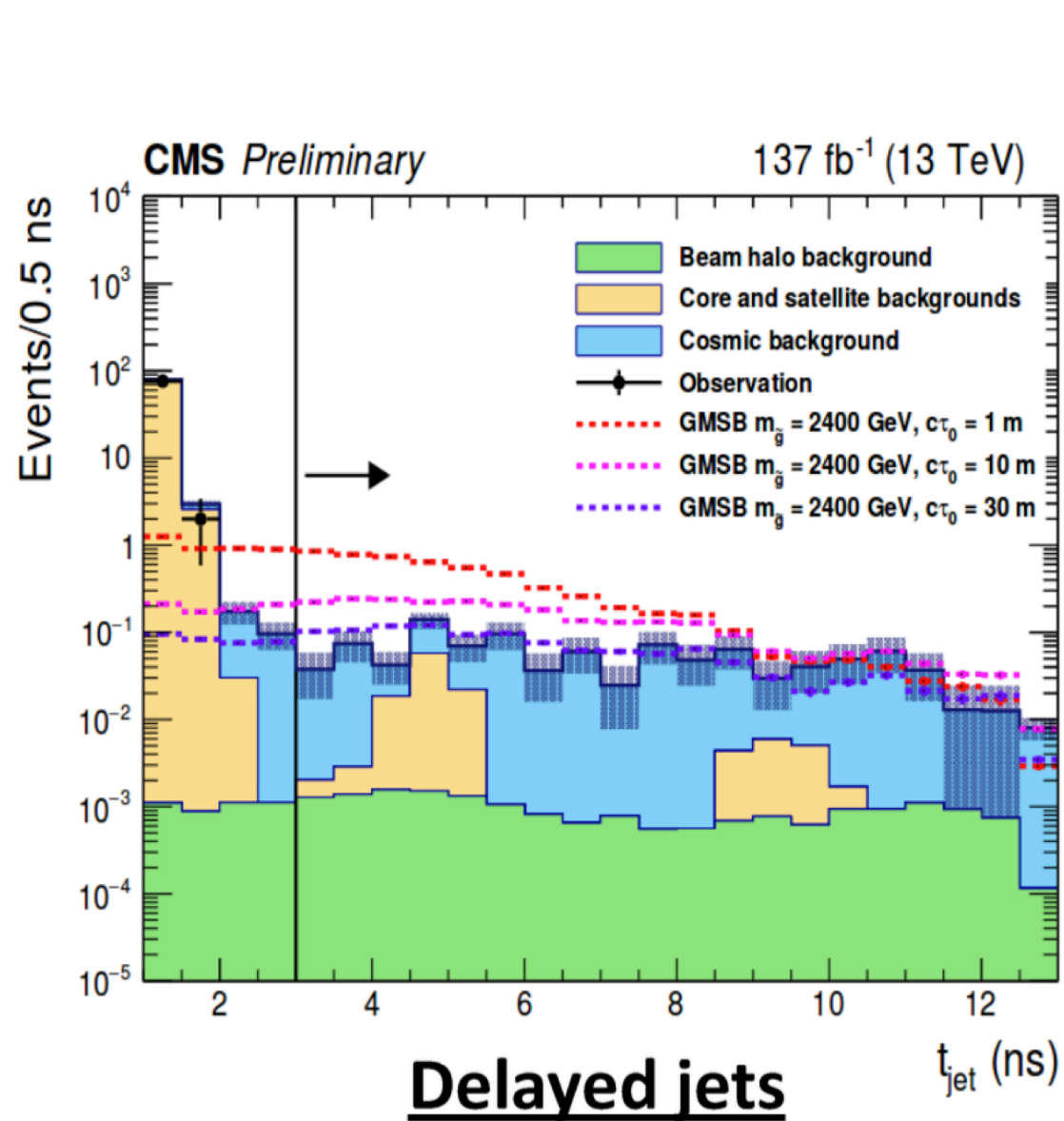
LLParticle Flow Detector

- 5D-calorimeter enables **LLPF** reconstruction



Calorimeter TOF

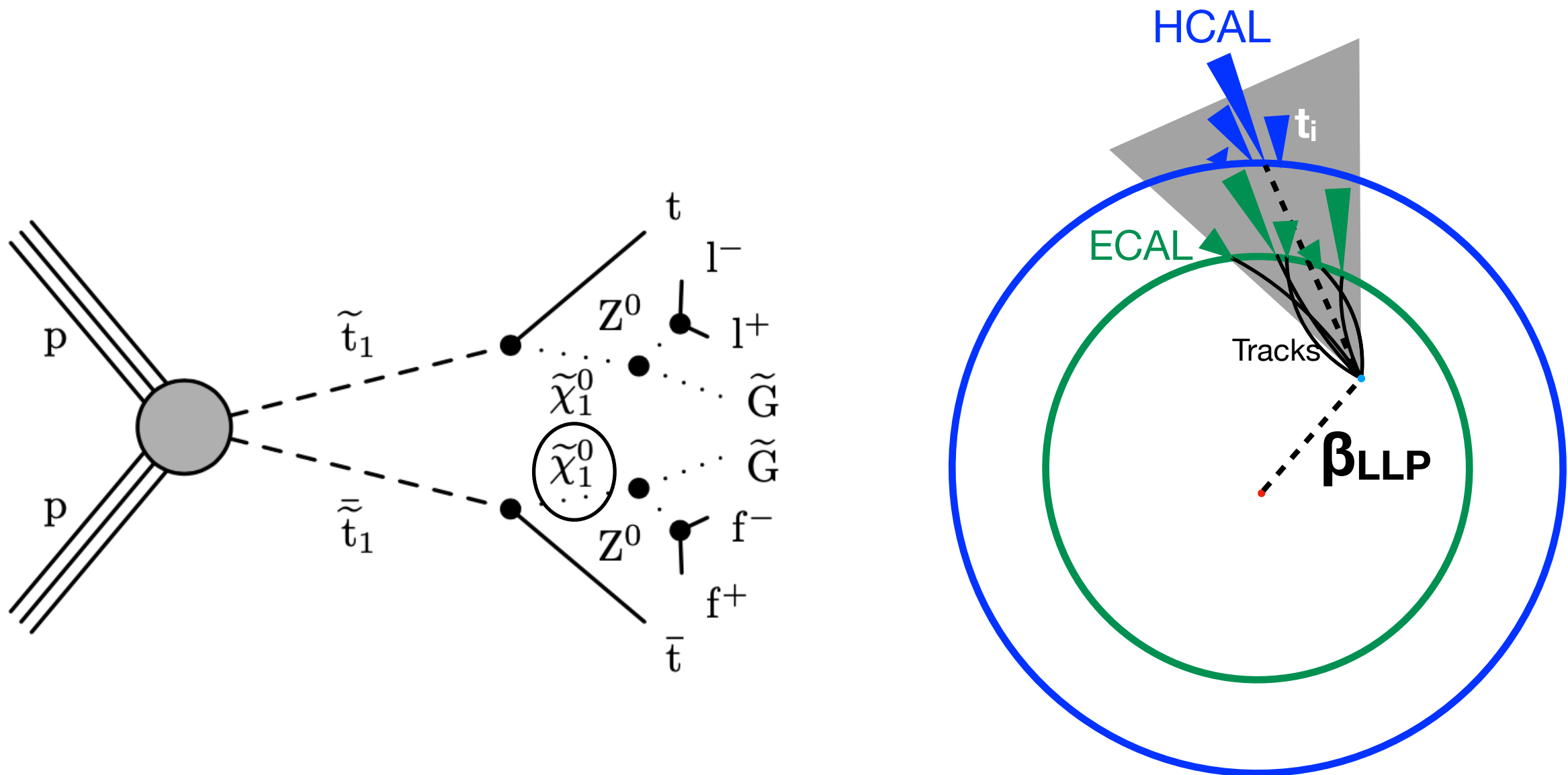
- Enables delayed photon and jet searches for LLPs



Ability to separate signal from backgrounds

Calorimeter TOF

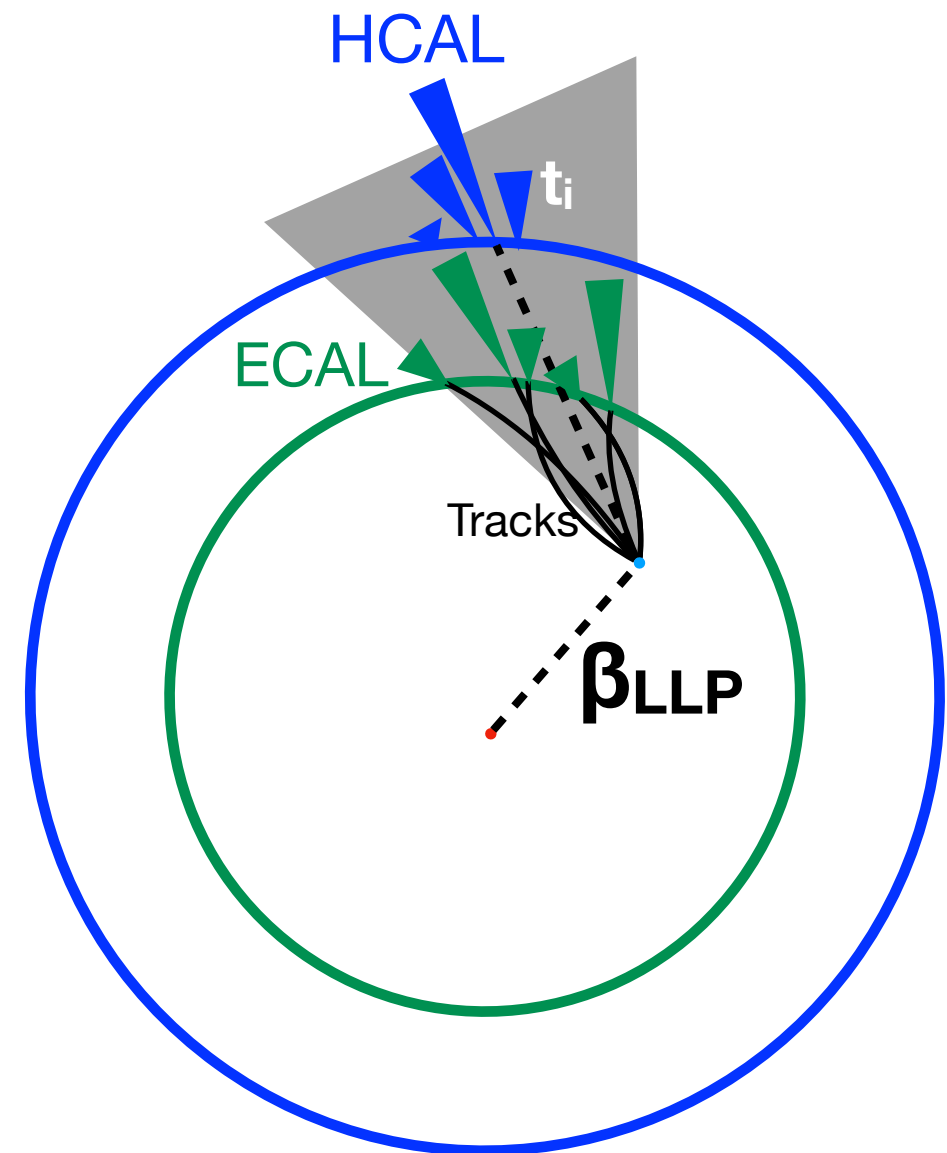
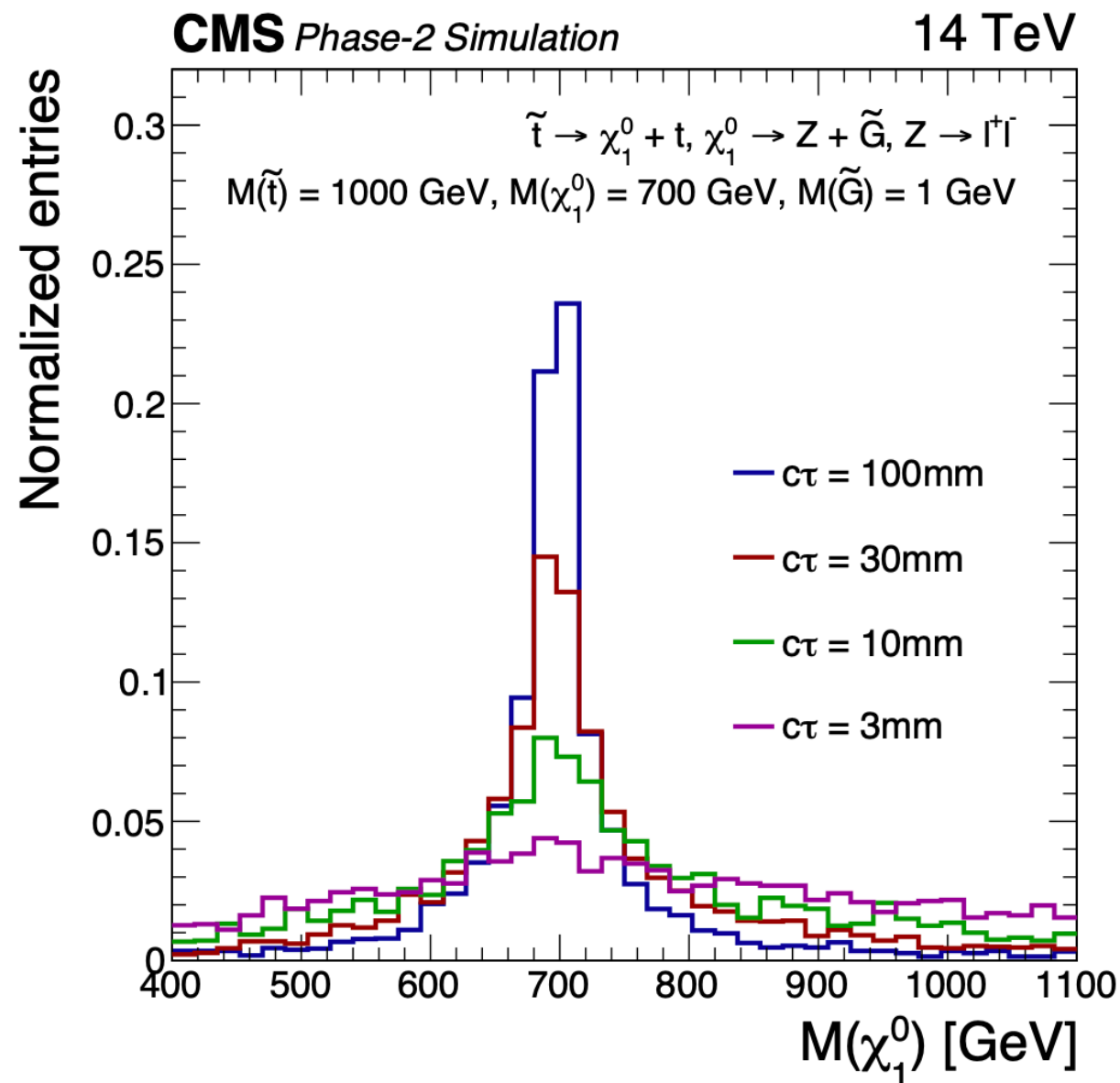
- Full LLP event reconstruction



5D calorimeter enables β_{LLP} measurement

Calorimeter TOF

- Full LLP event reconstruction

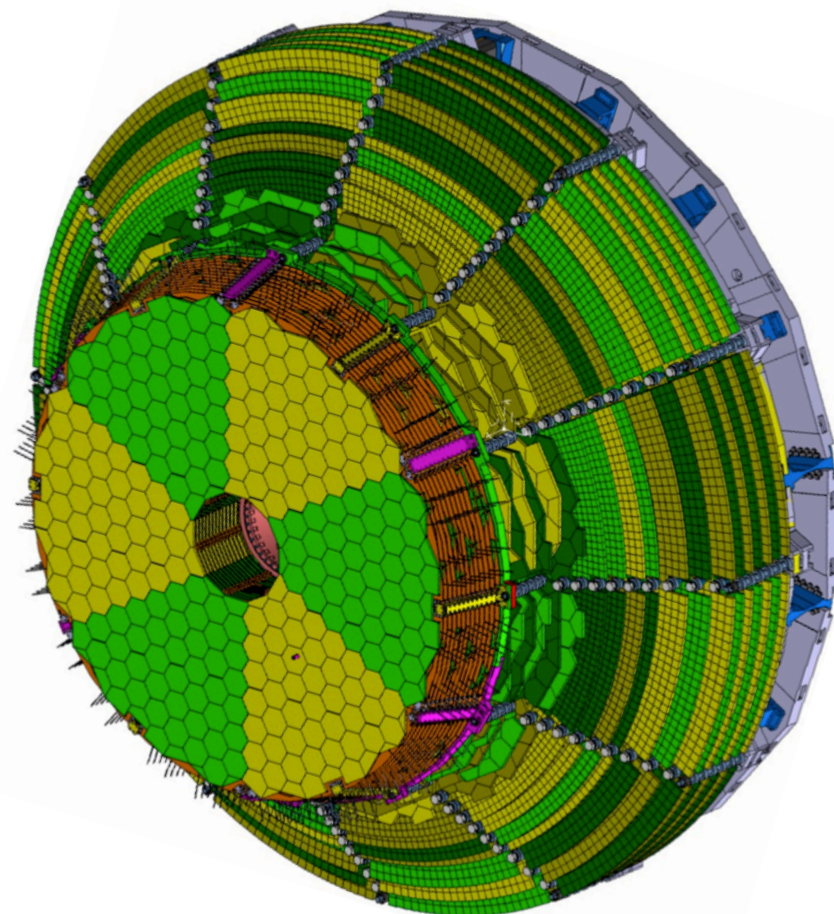
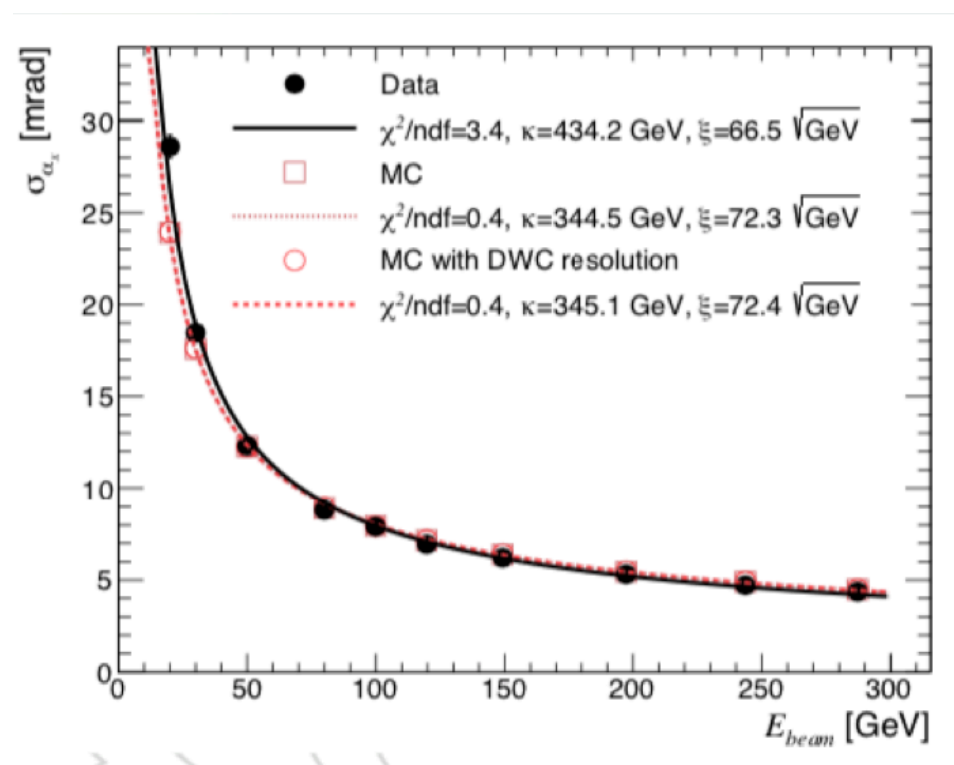
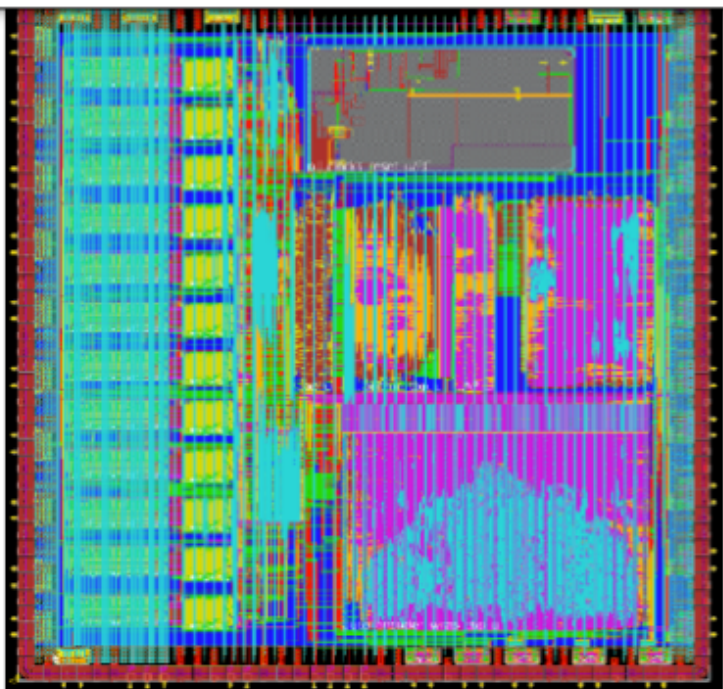


Ability to reconstruct LLP mass resonance

Calorimeter Technologies

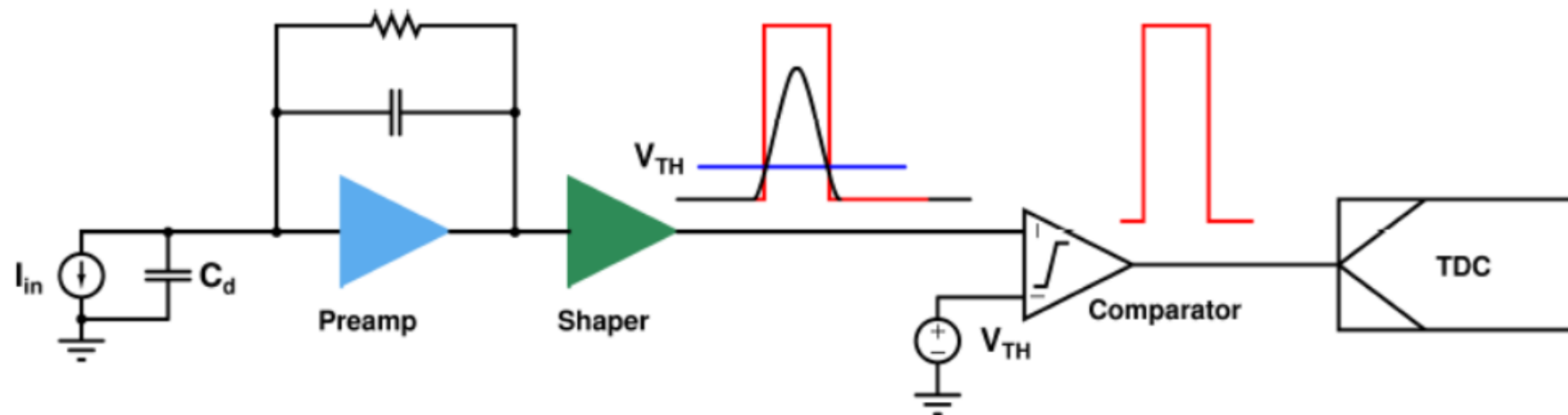
- **Several 5D-calorimeters in construction or proposed:**
 - CALICE R&D, CMS HGCAL, ALICE FoCal
 - **PF concept** enhanced towards **LLPF**
- New front-end processing capabilities (e.g ECON) required for LLP triggering

ECON as concentrator ASIC



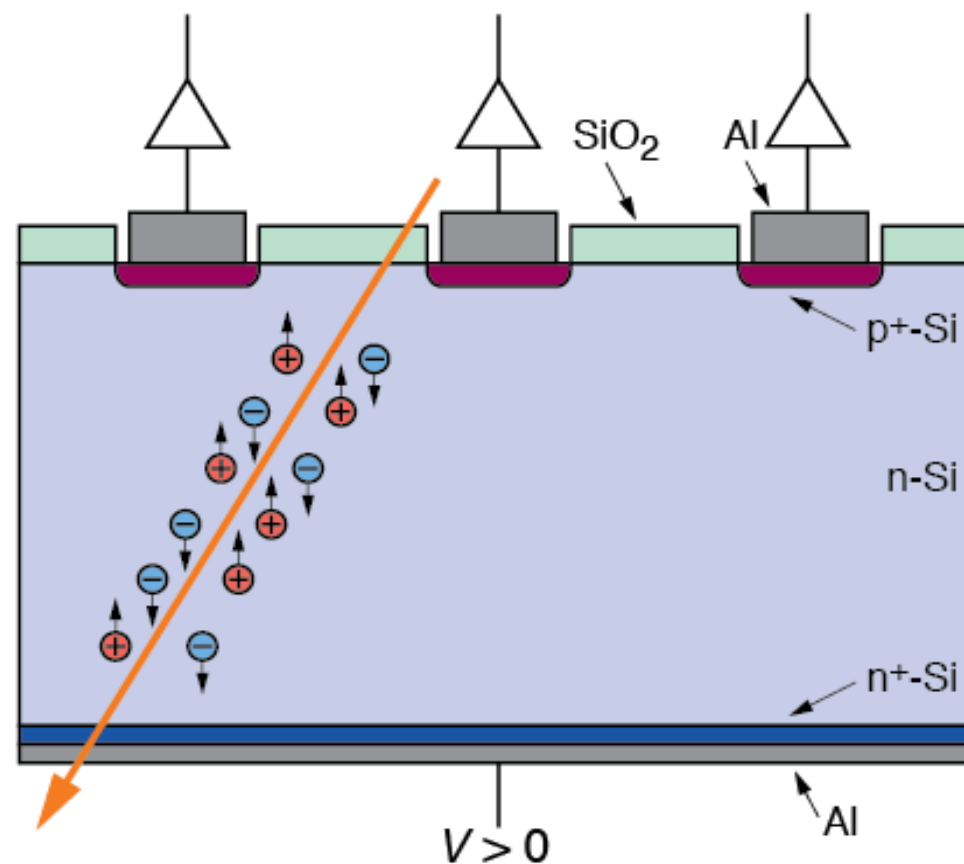
Timing resolution

- Particles passing through medium generate signals which are then measured to *time-stamp* the arrival
 - Depending on detector type (tracker, calorimeter) the dominant effects that impact resolution slightly vary
- The goal is to design sensors that deliver the best timing information, while optimized for a specific application



Signal attributes

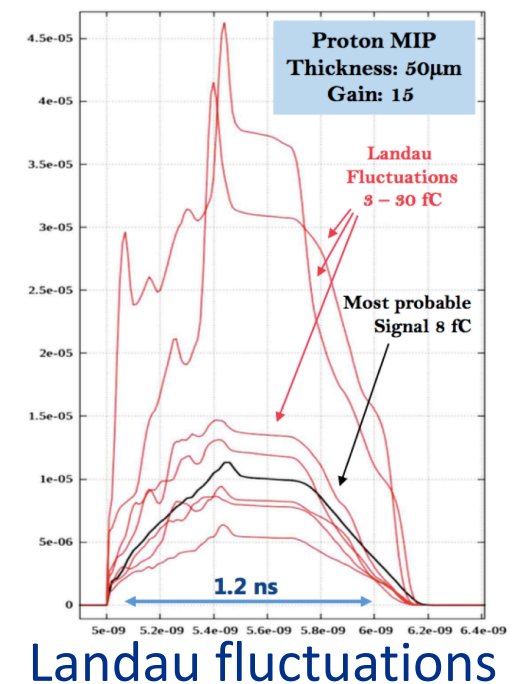
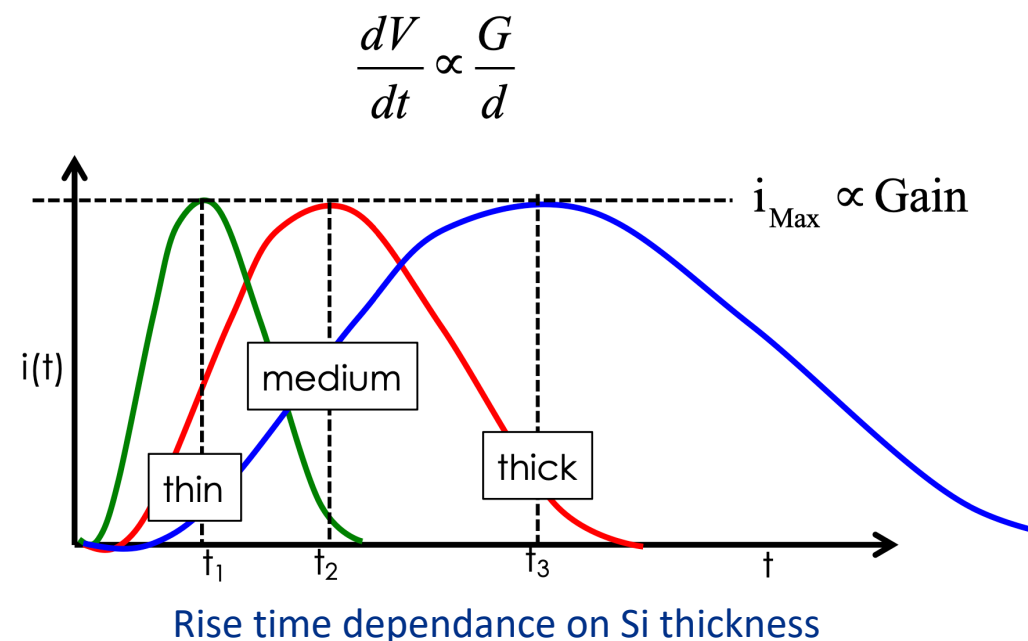
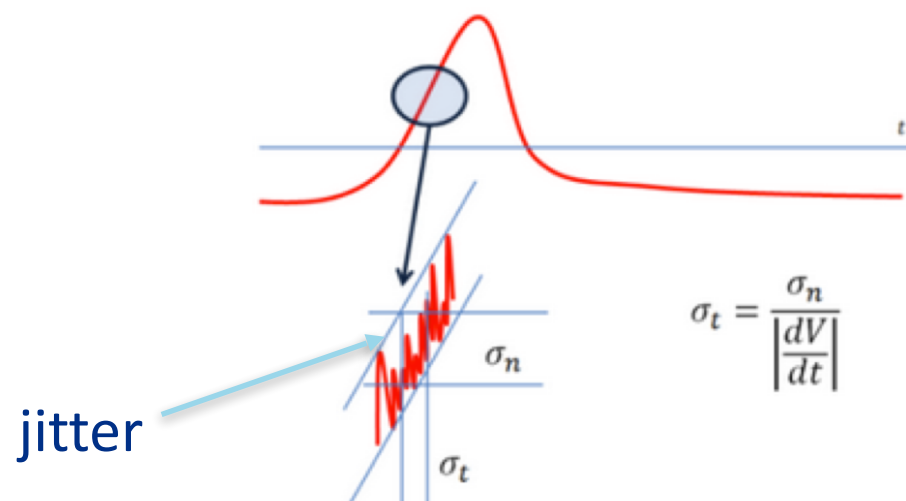
- Signal of MIP passing through a silicon detector depends on the thickness of the depletion zone and dE/dx
- The noise in a silicon detector system depends on various parameters: geometry of the detector, the biasing scheme, the readout electronics, etc.



Time resolution components

- Optimize detector timing resolution
 - Increase **Signal/Noise** to minimize jitter
 - **Fast rise time** to reduce impact of electronic noise: thinner sensor
- Non uniform charge deposition:
 - Landau fluctuations: cause fluctuations in signal shape and amplitude
 - Effect is reduced in thinner sensors

$$\sigma_t = \frac{\sigma_V}{\frac{dV}{dt}} = \frac{N}{\frac{S}{t_r}} = \frac{t_r}{S/N}$$



Timing resolution

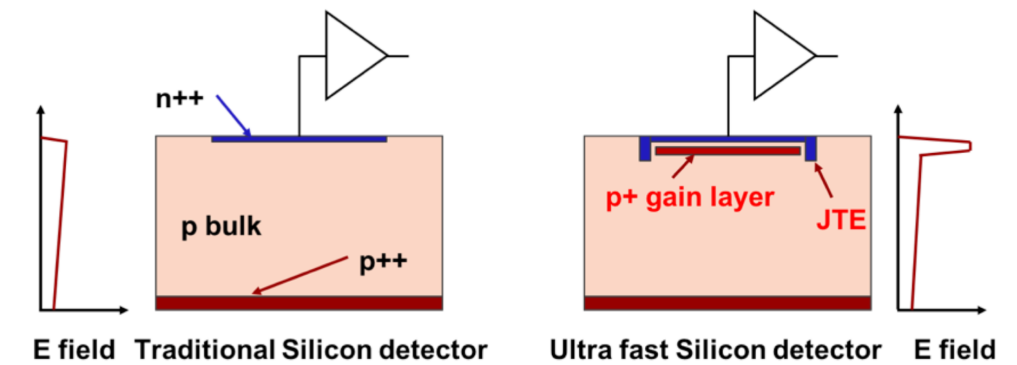
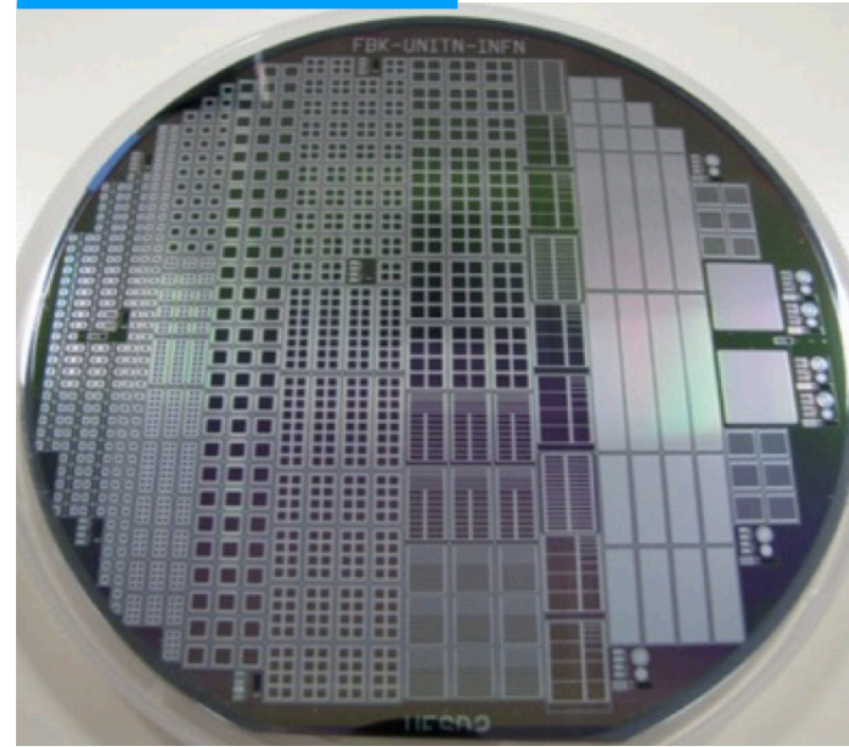
- Putting together various components

$$\sigma_t^2 = \sigma_{Landau}^2 + \sigma_{timewalk}^2 + \sigma_{jitter}^2 + \sigma_{TDC}^2 + \sigma_{clock}^2$$

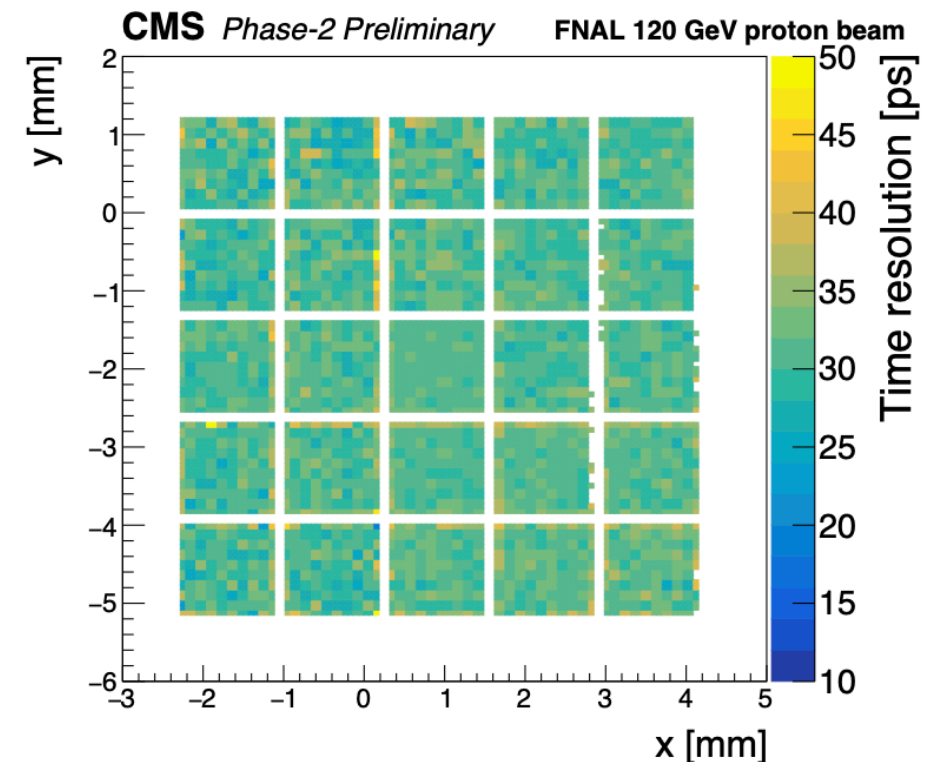
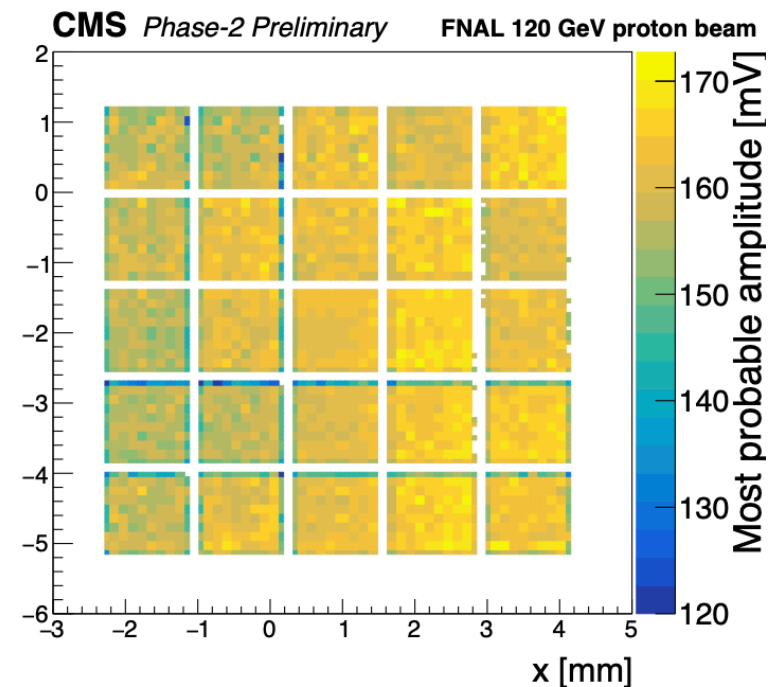
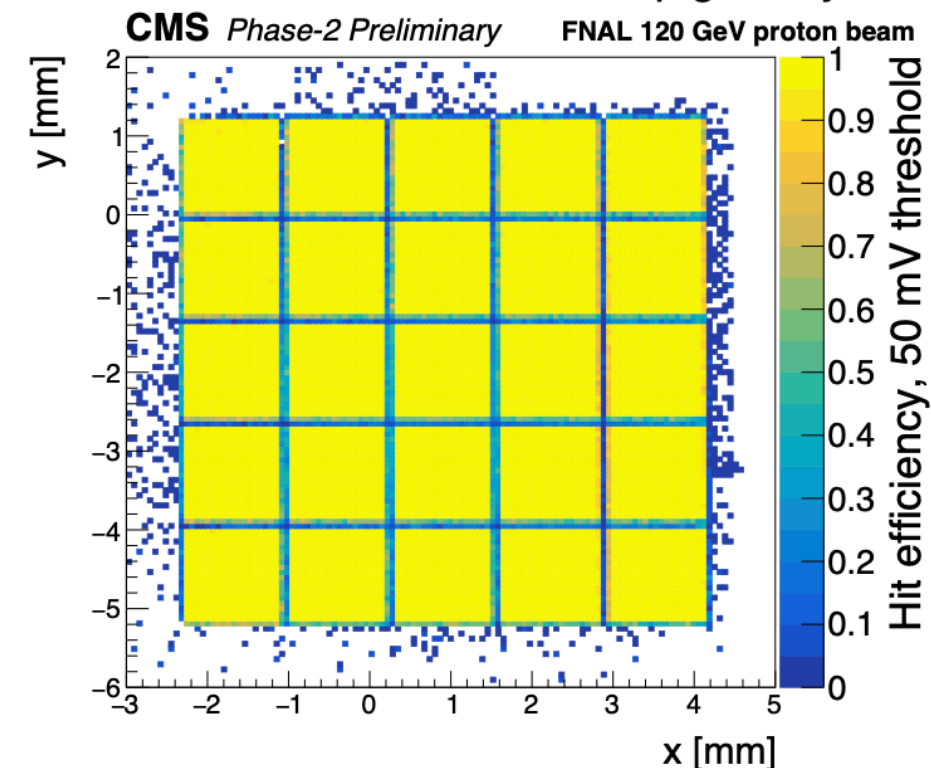
- Ideal detector components
 - Fast signals with large S/N ($\sigma_{jitter} = t_{rise}/(S/N)$)
 - Thin sensors to minimize σ_{Landau}
 - Stable and uniform signals across sensor area
 - Optimized electronics to reduce time-walk and clock jitter
 - Electronics with low power consumption
- Radiation damage complicates things, so all these need to be also resilient to high fluences in hadron colliders

Endcap Timing Layer

LGAD Wafer

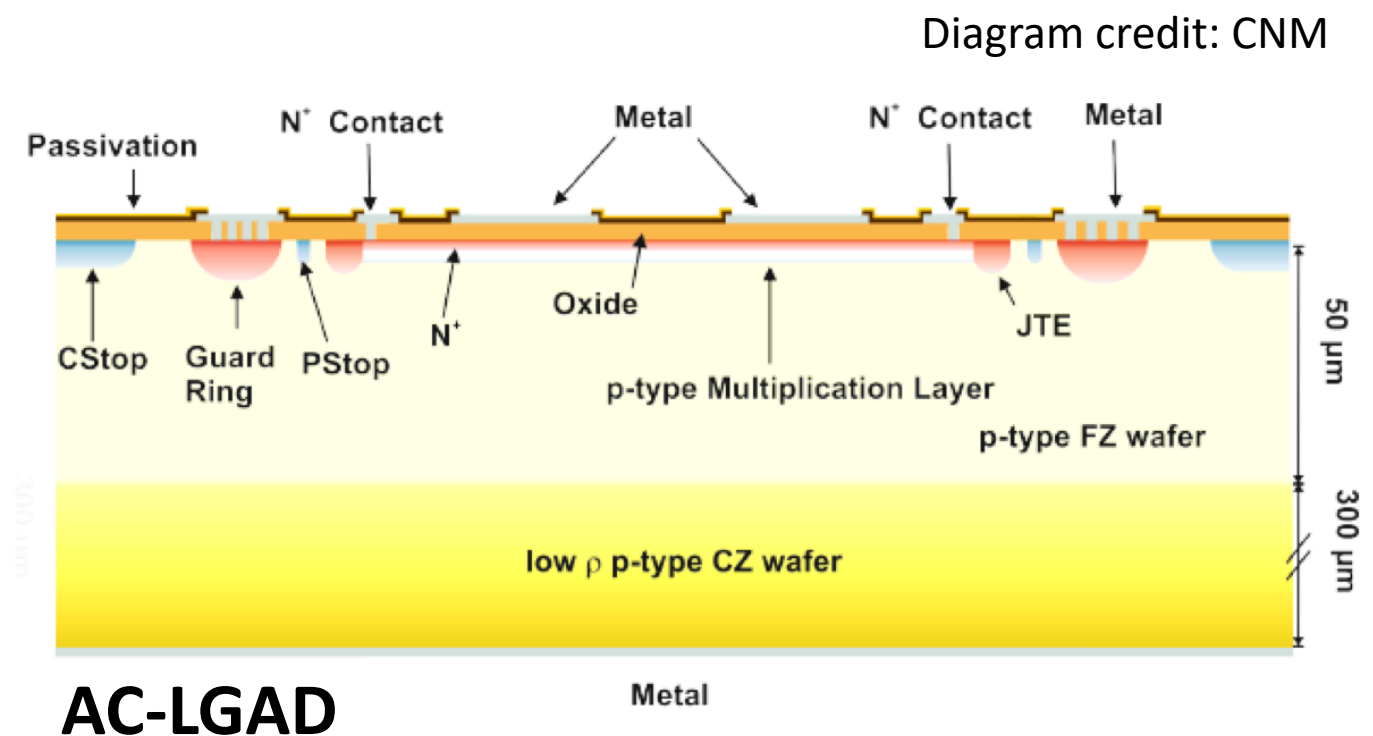
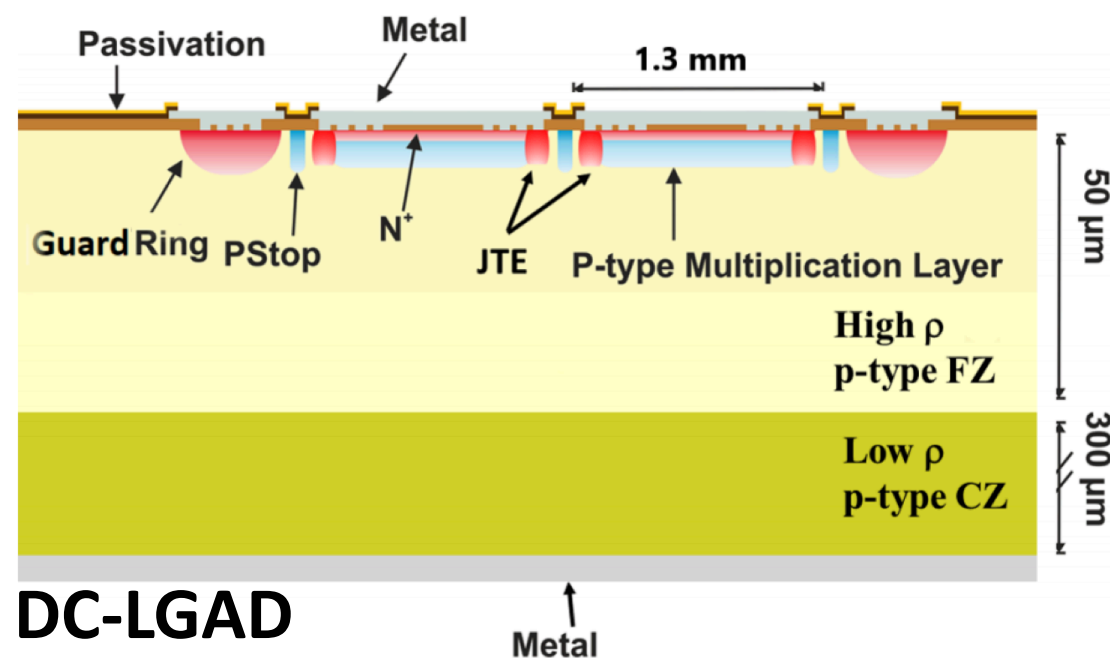


- Breakthrough development of last decade
 - High field in gain region ~ 300 kV/cm, **causes avalanche**
 - High gain $\rightarrow$ high signal $\rightarrow$ faster rise $\rightarrow$ smaller "jitter"
- Sensors demonstrate
 - Efficiency is 100 % inside pixels
 - Signal size uniform across area



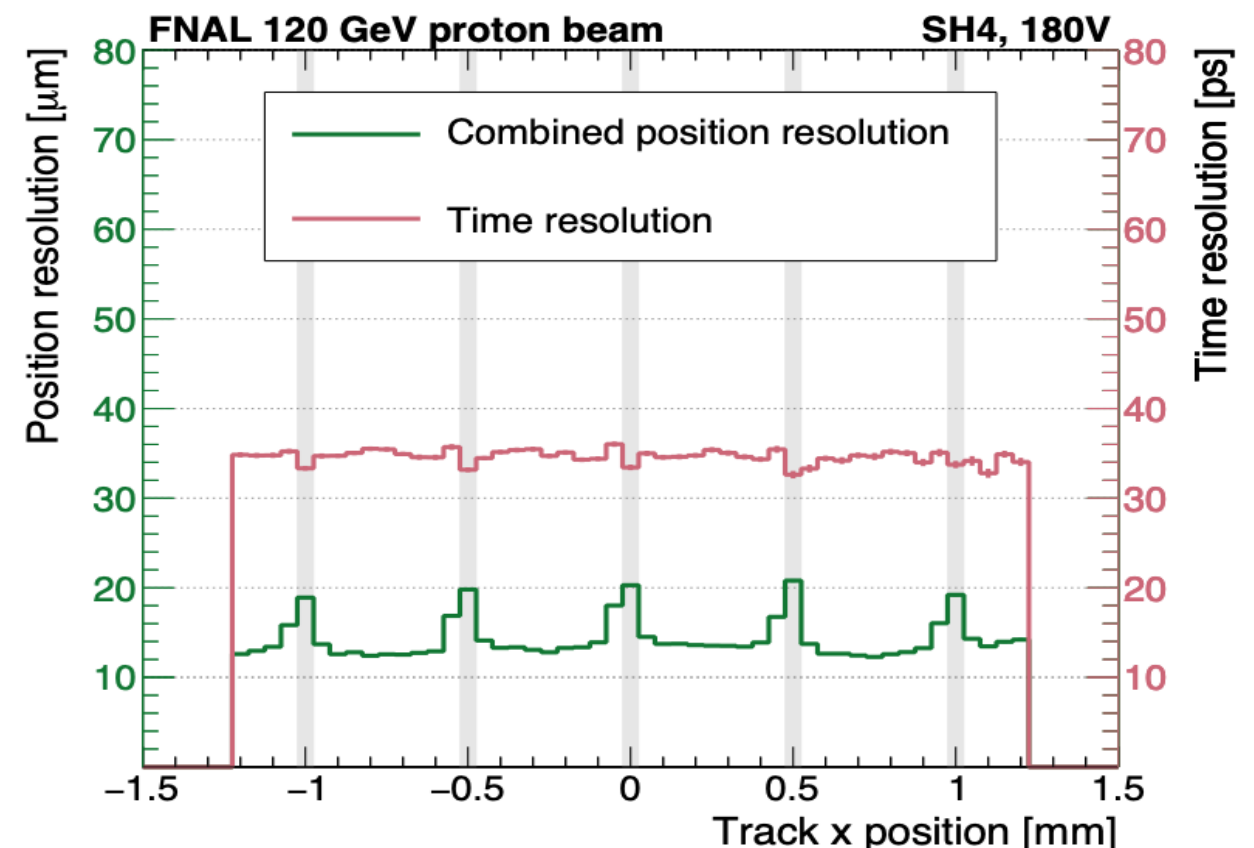
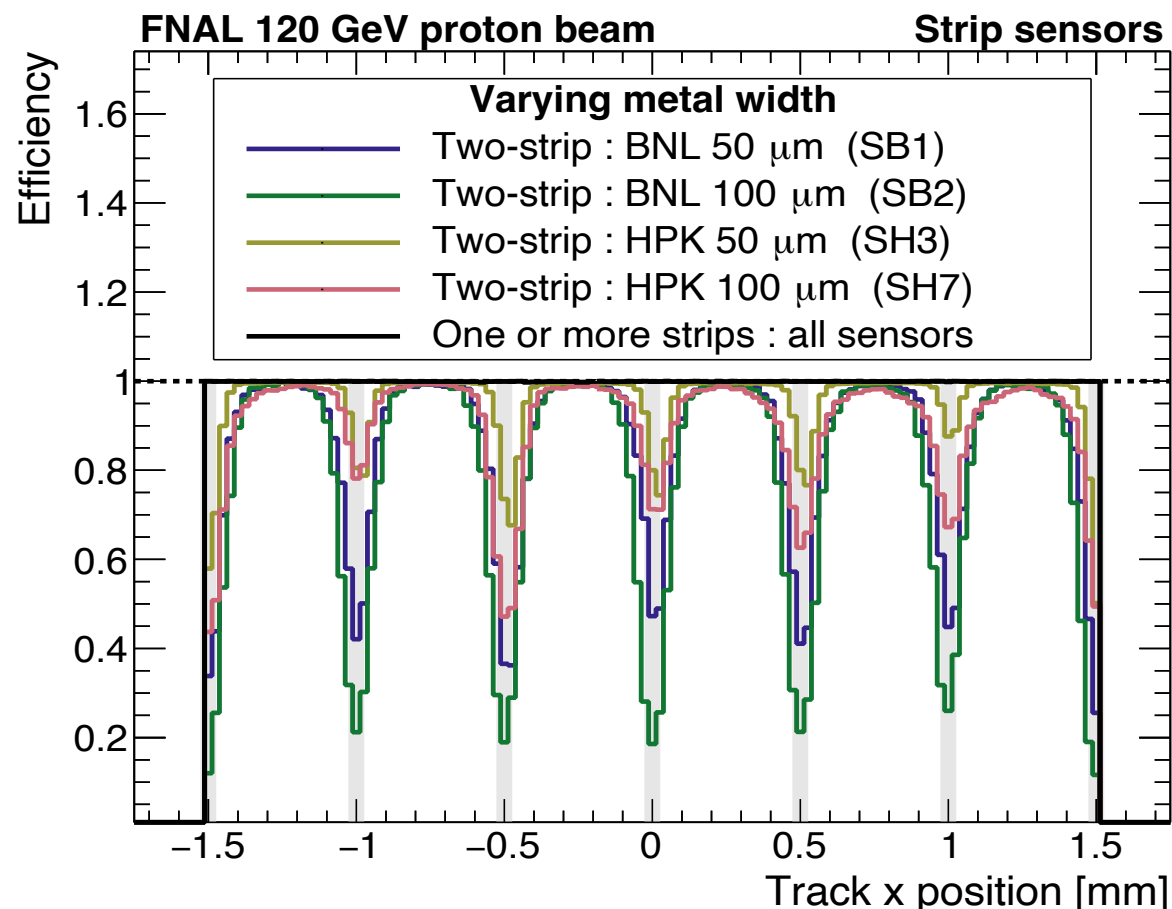
AC-coupled LGADs

- Ongoing R&D to eliminate dead area
 - Simultaneously improve position resolution via charge sharing
- Active R&D at different manufacturers
 - 100% fill factor, and fast timing information at a per-pixel level
 - Signal is still generated by drift of multiplied holes into the substrate and AC-coupled through dielectric



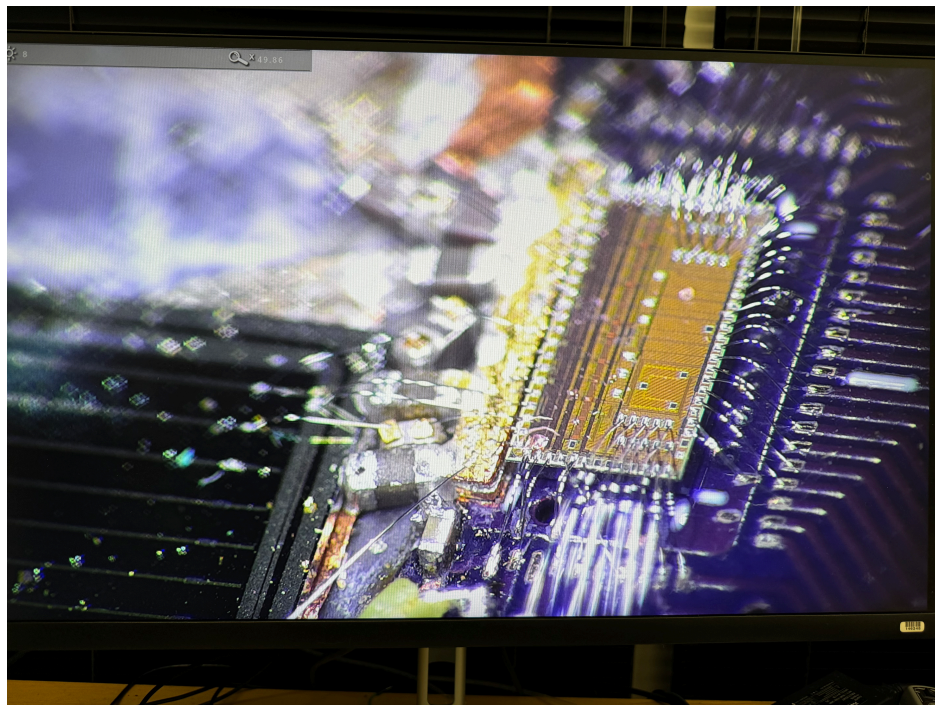
Long AC-LGAD strip sensors performance

- Position reconstruction with ratio of amplitudes
 - Sensor provides 100% efficiency across surface
- Signal sharing: measure position based on ratio in neighbors
 - Achieve 15-20 μm resolution in 10 mm strips with 500 μm pitch
- Excellent time resolution
 - Achieve 30-35 ps for 10 mm strips

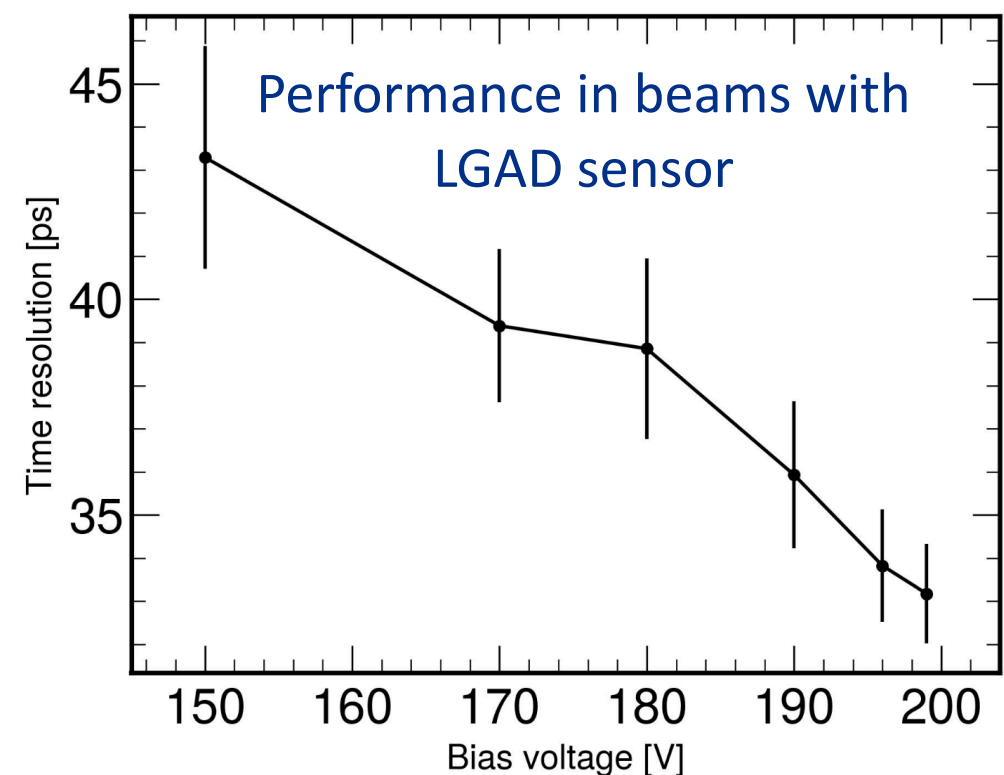


Timing with Constant Fraction Discrimination (FCFD)

- A novel ASIC based on CFD for LGAD fast timing readout
 - Most timing ASICs need time-walk correction: each pixel timing needs to be corrected offline
 - CFD: **No need for time-walk** correction → directly get time-measurement
- Two generations produced, targeting DC- and AC-LGAD
- Excellent performance : ~ 30 ps time resolution and no time-walk demonstrated in beam-tests



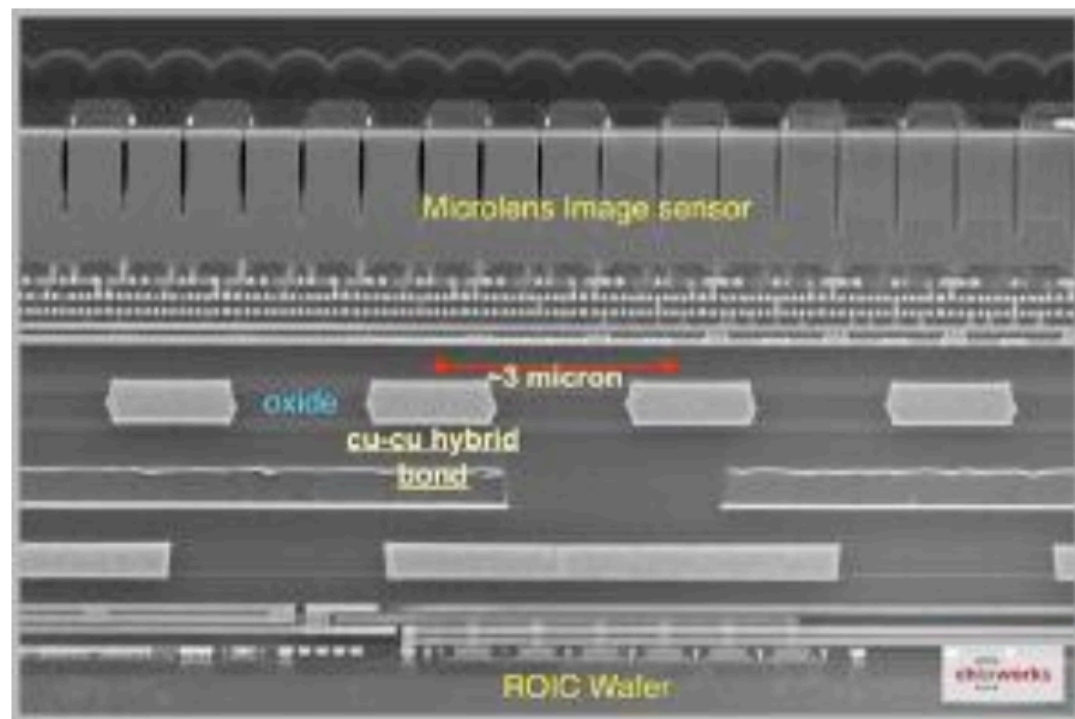
FCFD v1 ASIC with AC-LGAD strip sensor



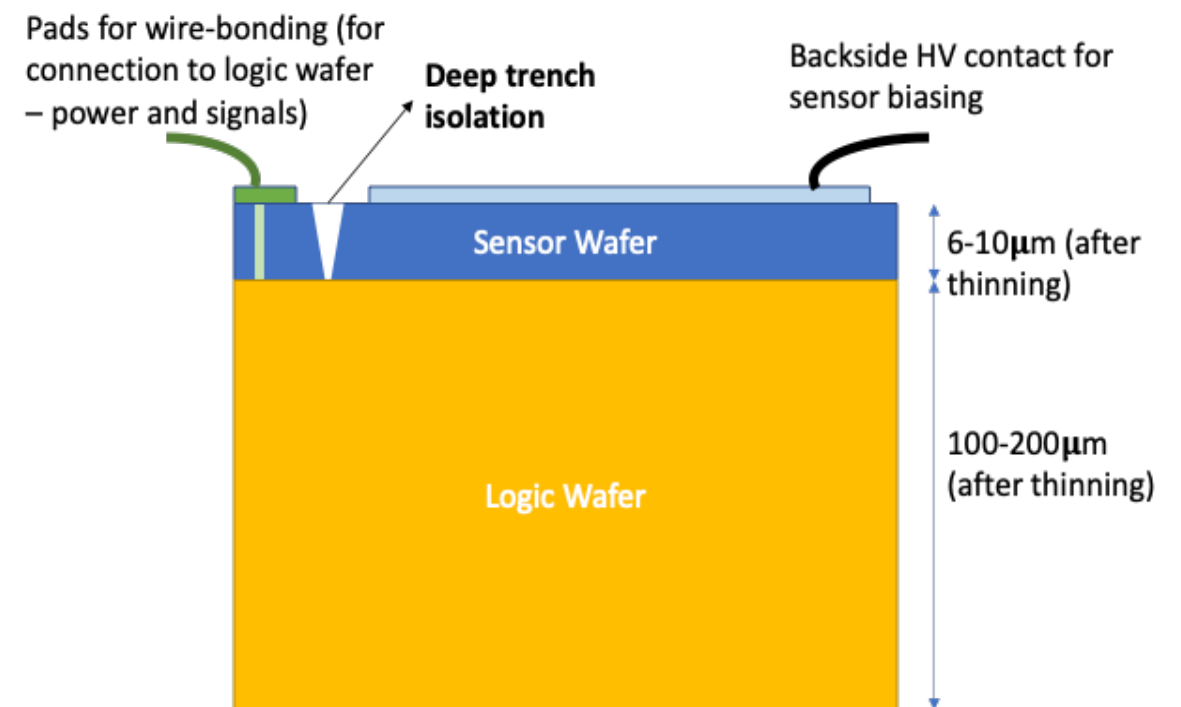
~ 30 ps time resolution — no time walk

3D-Integrated sensors

- Development of low-power, highly granular detectors in $(\vec{x}, t)$
 - Required to achieve breakthroughs across HEP, NP, BES, and FES
 - Adoption of 3D-integration has been cost-prohibitive in academia
- Supported by DOE “Accelerated Innovation in Emerging Technologies”
 - Joint development effort of **SLAC, FNAL** and LLNL
 - Tower Semi to develop process for 12” wafer production, with 28 nm TSMC
 - Design goal is to achieve position resolution $\sim 5 \mu\text{m}$, timing $\sim 5\text{-}10 \text{ ps}$

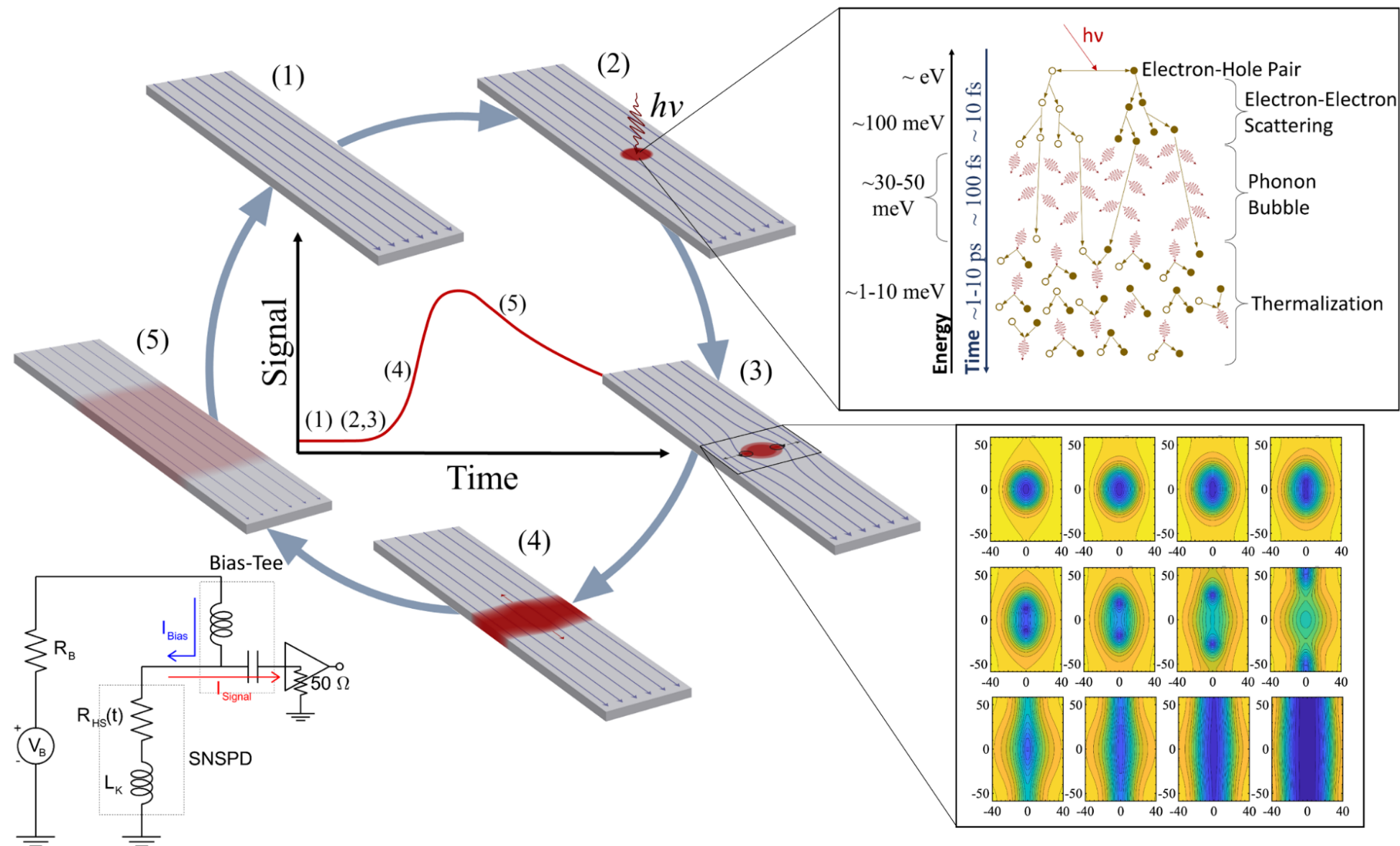


Section of the Sony Exmor camera chip showing the hybrid bond interface



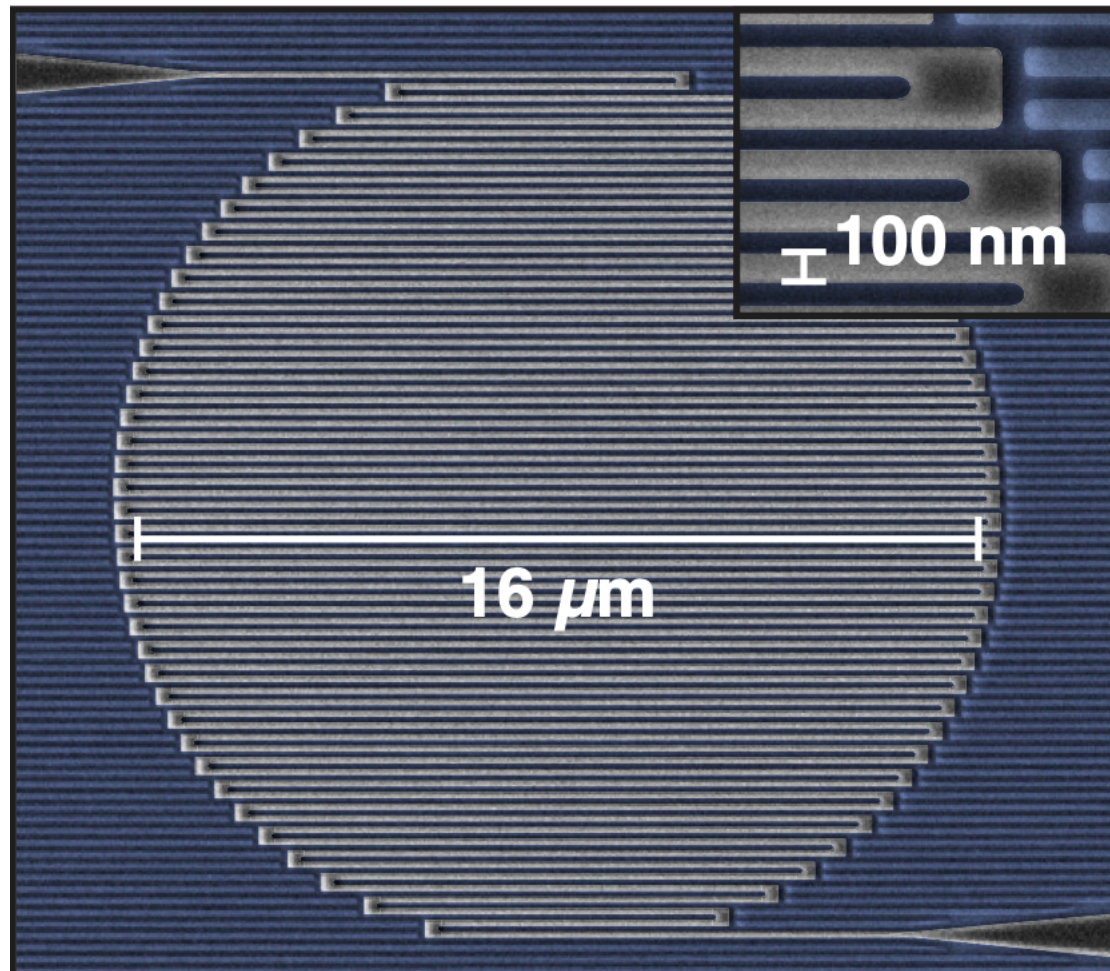
Quantum Sensors (SNSPD)

- Single photon (heat) triggers detector out of superconductor state
- Resistance quickly (ps) jumps to few $k\Omega$ $\rightarrow$ detector current into readout
- Highest performance single-photon detector, from UV to mid-infrared
- Operating temperature : 1-4 Kelvin



more on quantum sensors in A. Chou's presentation

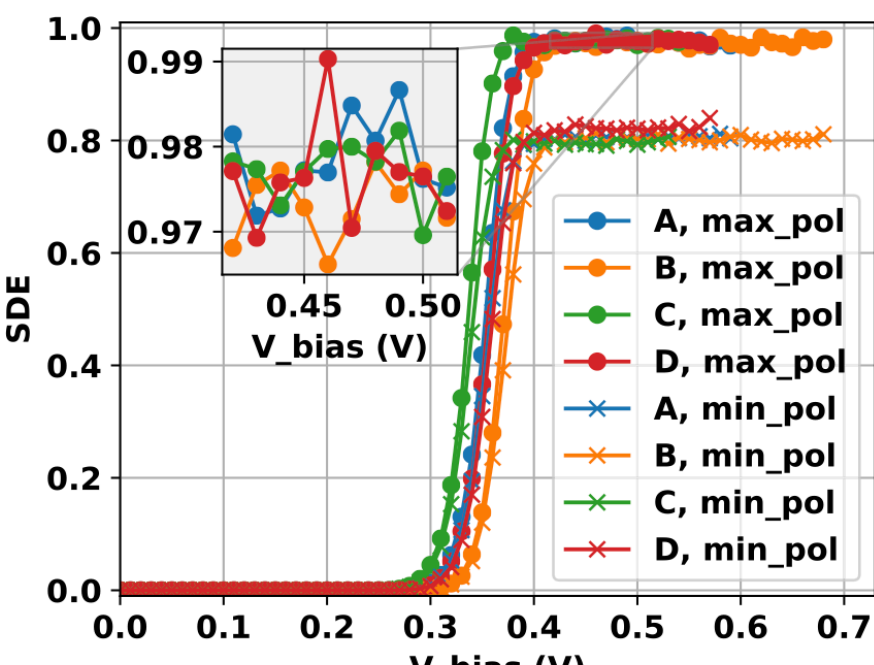
Quantum Communication Enabler: SNSPDs



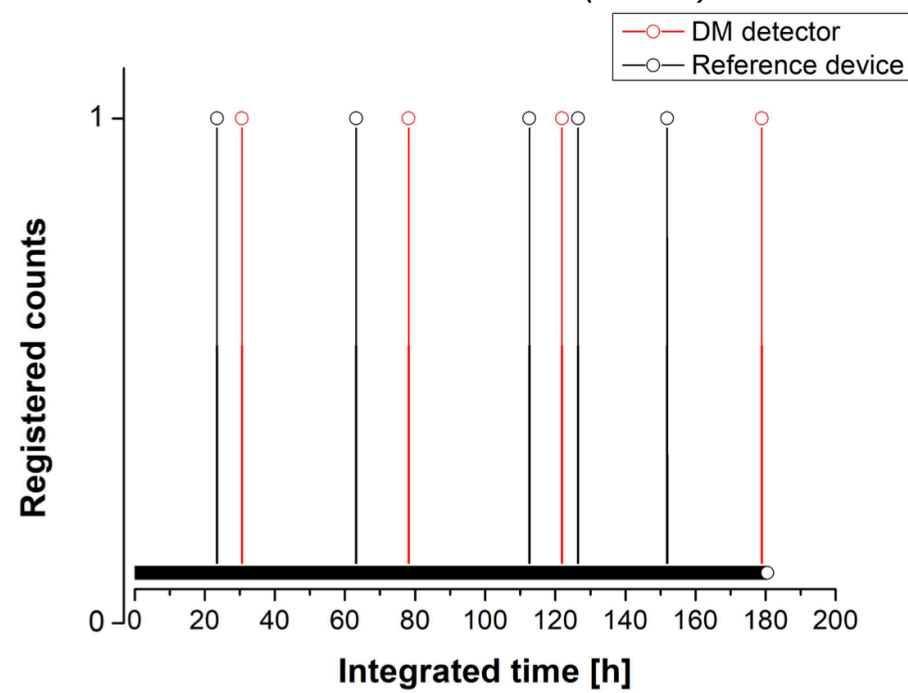
SNSPD Has Achieved:

- **> 90% system efficiency** ✓
- **Low dark count rate 1e-5Hz** ✓
- **Record time resolution ~3ps** ✓

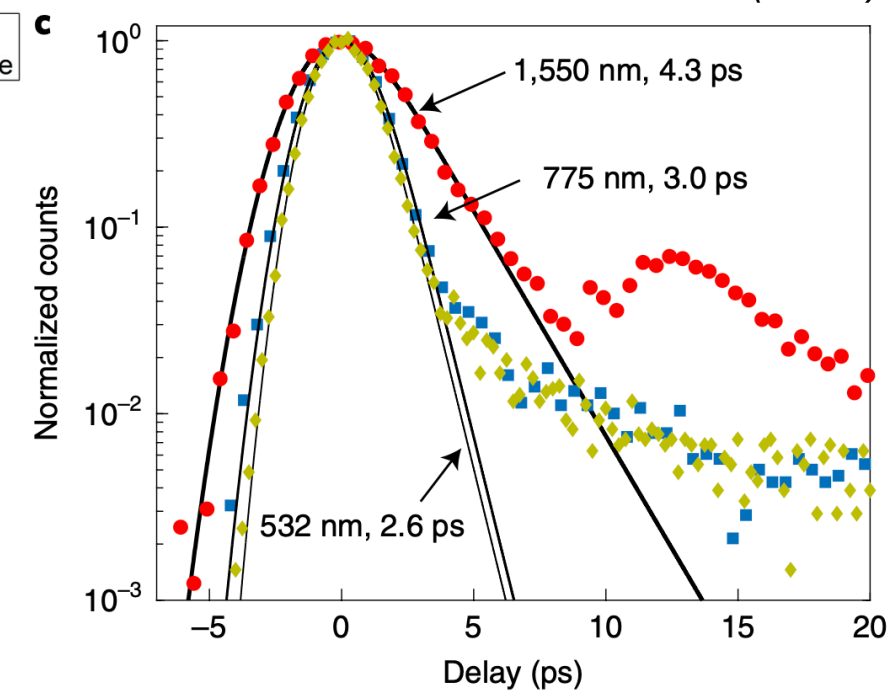
Reddy et al, Optica (2018)



Chiles et al, PRL (2022)



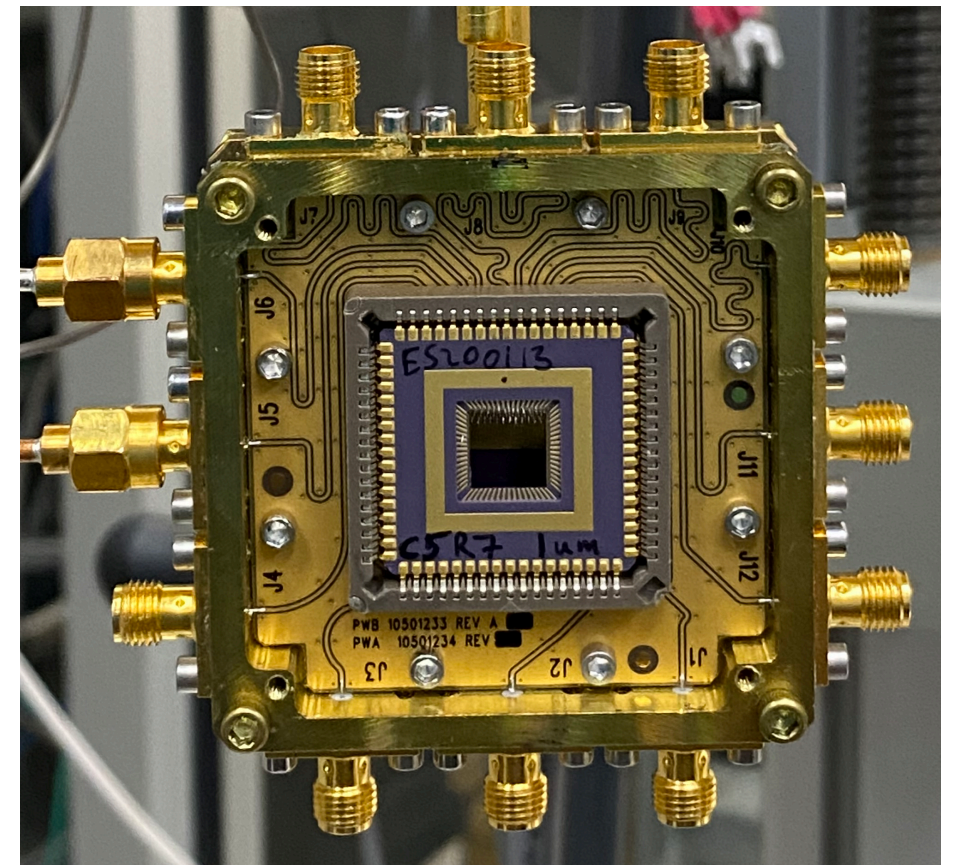
Korzh et al, Nature Photonics (2020)



New R&D program to develop sub-eV space-time (4D) particle detection

Superconducting Nanowire Single Photon Detector

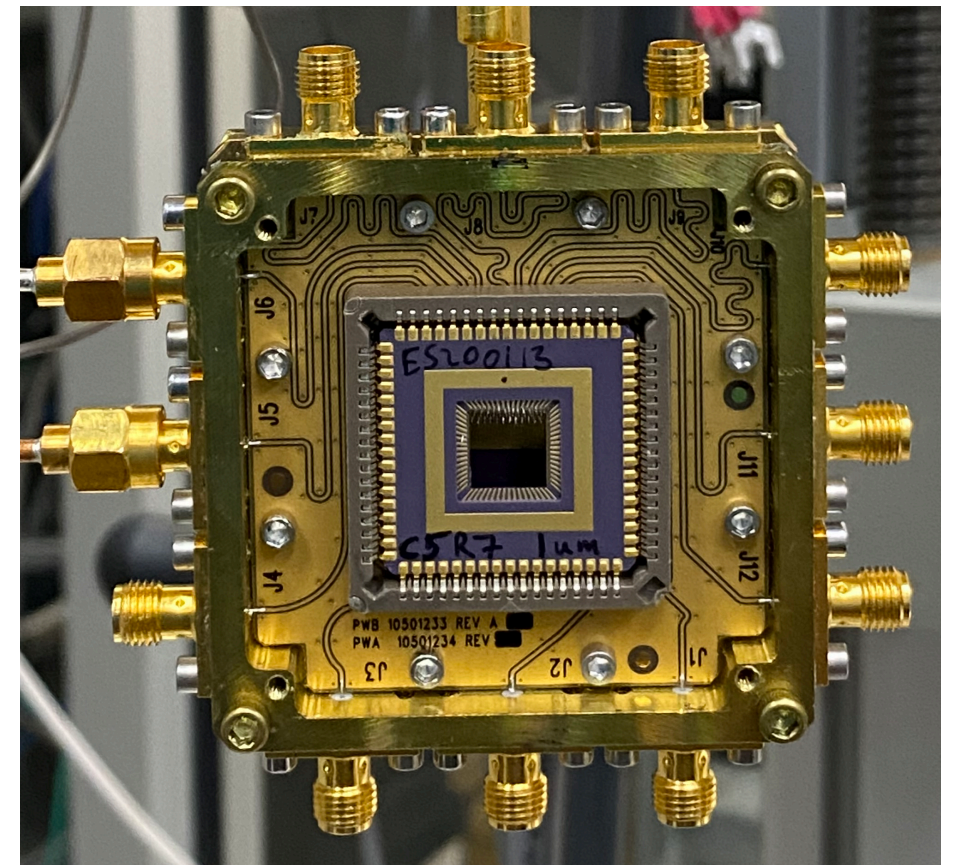
- **Vision :**
 - sub-eV threshold
 - sub-micron spatial resolution
 - picosecond time resolution



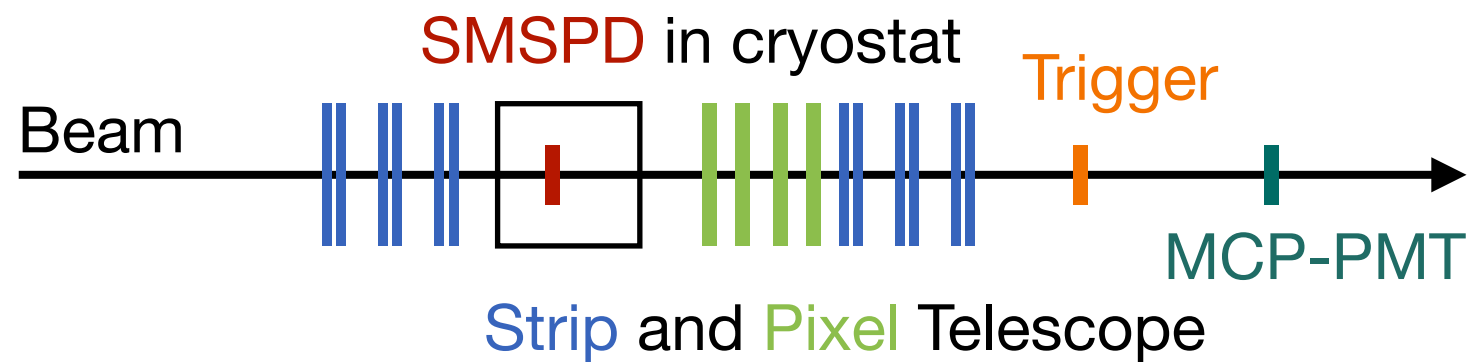
New R&D program to develop sub-eV space-time (4D) particle detection

Superconducting Nanowire
Single ~~Photon~~ Detector
Particle

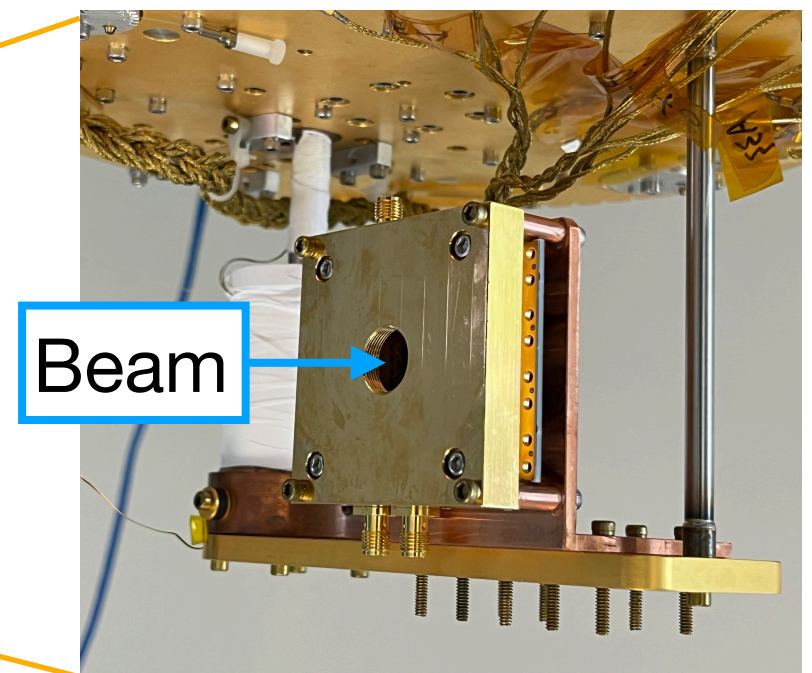
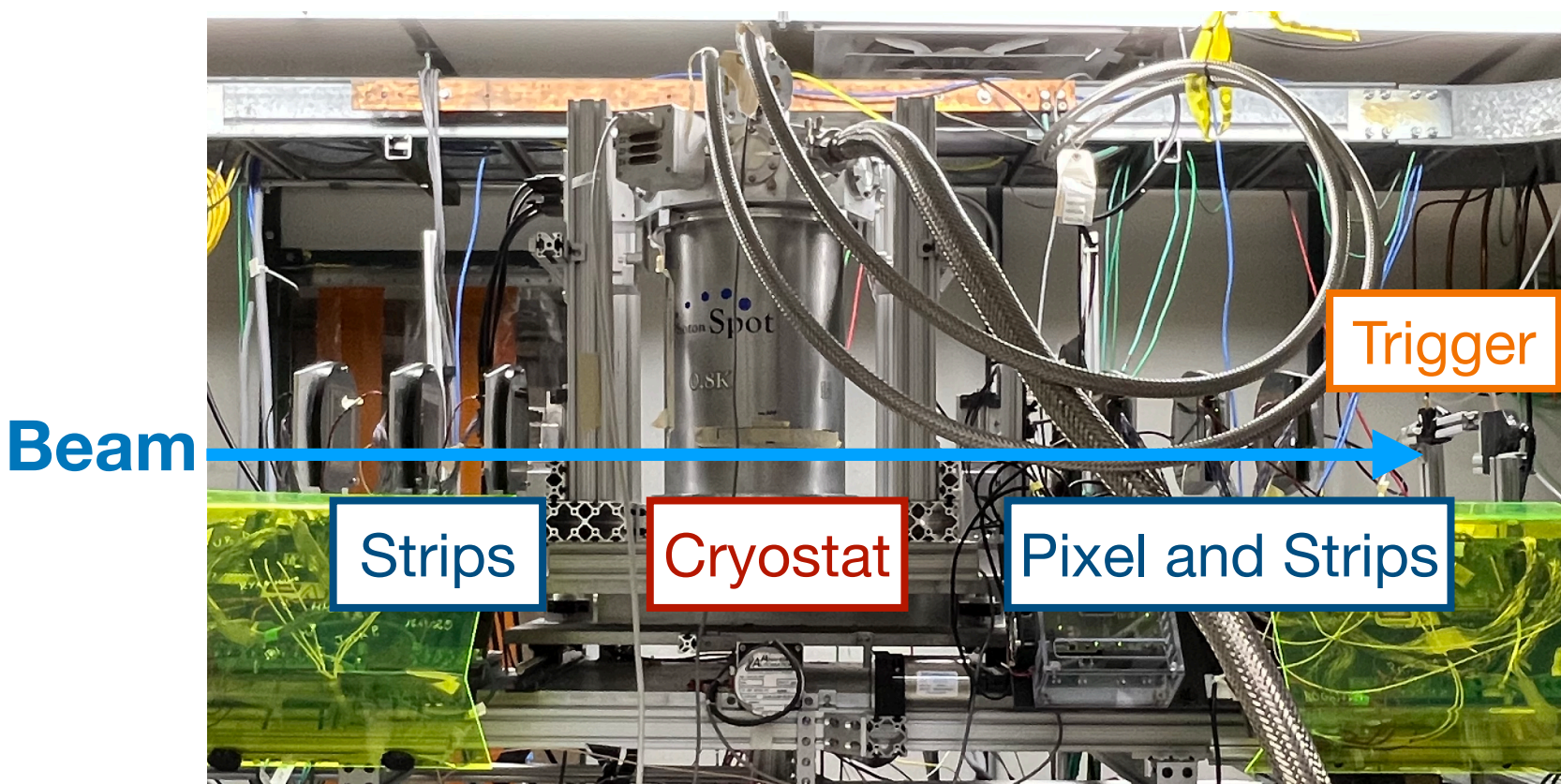
- Vision :
 - sub-eV threshold
 - sub-micron spatial resolution
 - picosecond time resolution



First test beam campaign at Fermilab



Pilot SNSPD characterization system at FTBF developed in Summer 2024 as a proof of concept



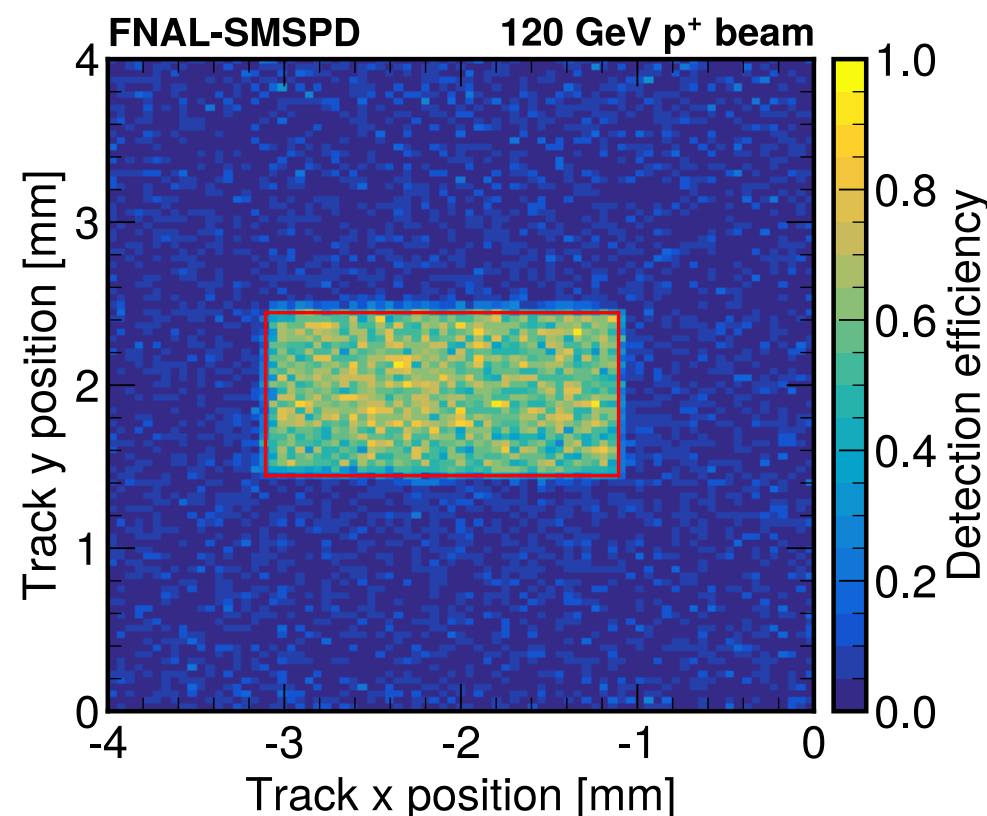
Very successful and interesting initial results

Characterization of SNSPD Response to Particles

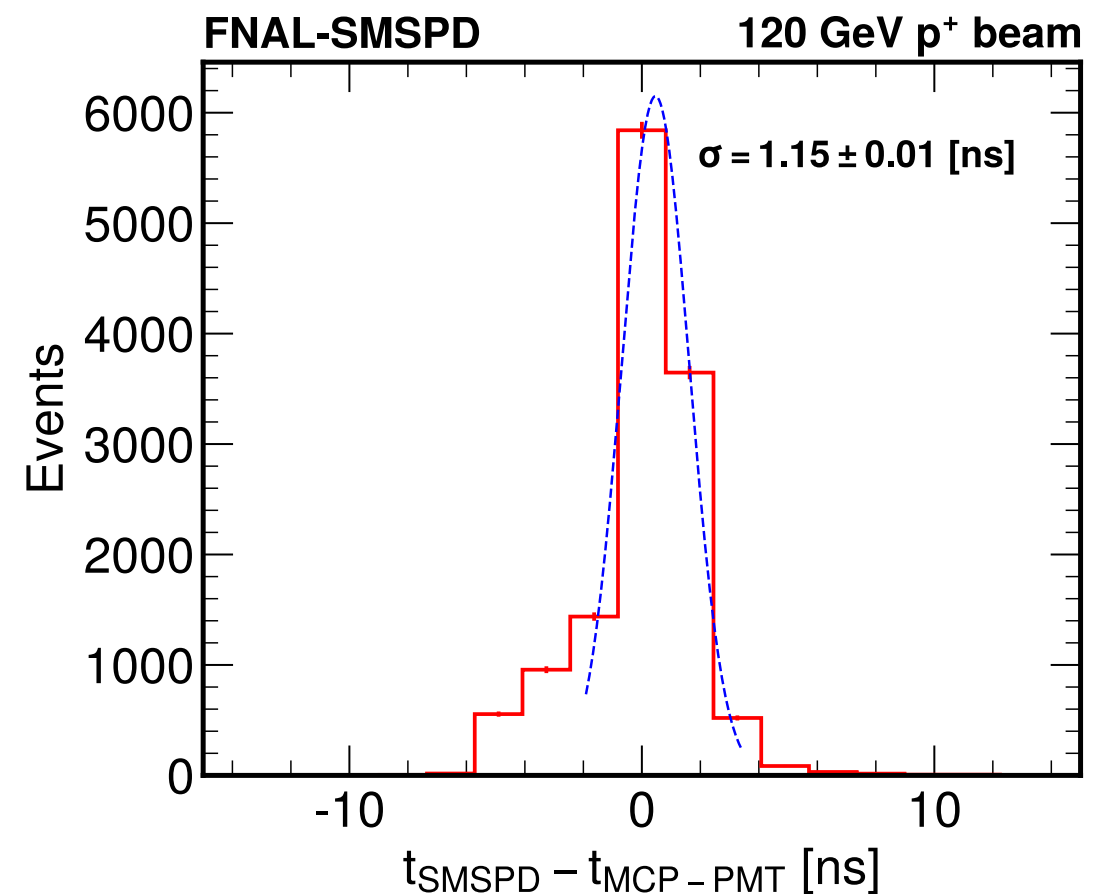
Accepted by JINST: [arXiv:2410.00251](https://arxiv.org/abs/2410.00251)

- Characterized an existing **large-area** ($2 \times 2 \text{ mm}^2$) **multi-pixel** (8-pixel) SNSPD response to proton, electron, and pion

Efficiency wrt particle hit position



Time resolution



World-first SNSPD efficiency measurement for charged particles

Outlook

- Advancing LLP frontier now(Run2 and Run3) and HL-LHC
- 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
- Rich R&D program ongoing to realize the precision timing frontier for next generation experiments: 4D tracking and 5D Calorimeters
- Next generation detectors will be key to unlock the discovery potential of any machine we build.

Thank you!