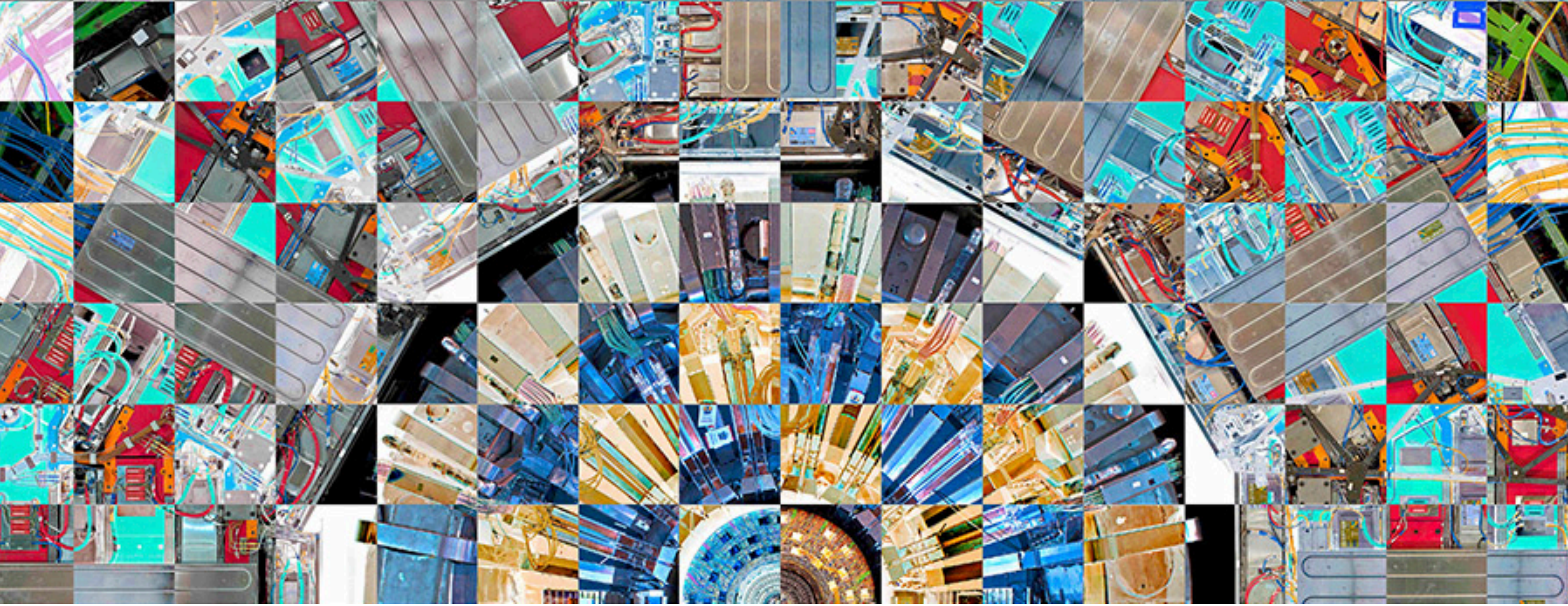


HL-LHC: Long Lived Particles at CMS

Livia Soffi, *on behalf of the CMS Collaboration*

Cornell University

HL/HE LHC Meeting 4-6 April 2018 Fermilab

HL/HE LHC: A Long Term Project

- **HL-LHC upgrade greatly expand physics potential of the LHC**
    - *Rare and statistically limited SM and BSM processes*
    - *New channels w/ low cross sections or small coupling strengths*

PHYSICS PERFORMANCE		DETECTOR UPGRADE
• Increase in **radiation levels**	→	improved **radiation hardness**
• Larger **pileup** and increase in particle density	→	higher detector **granularity** to reduce occupancy, increased **bandwidth** to accomodate higher data rates
• **Trigger rate** at an acceptable level not compromising physics potential	→	higher output rate of interesting events and **improved discriminating power** of the event selection

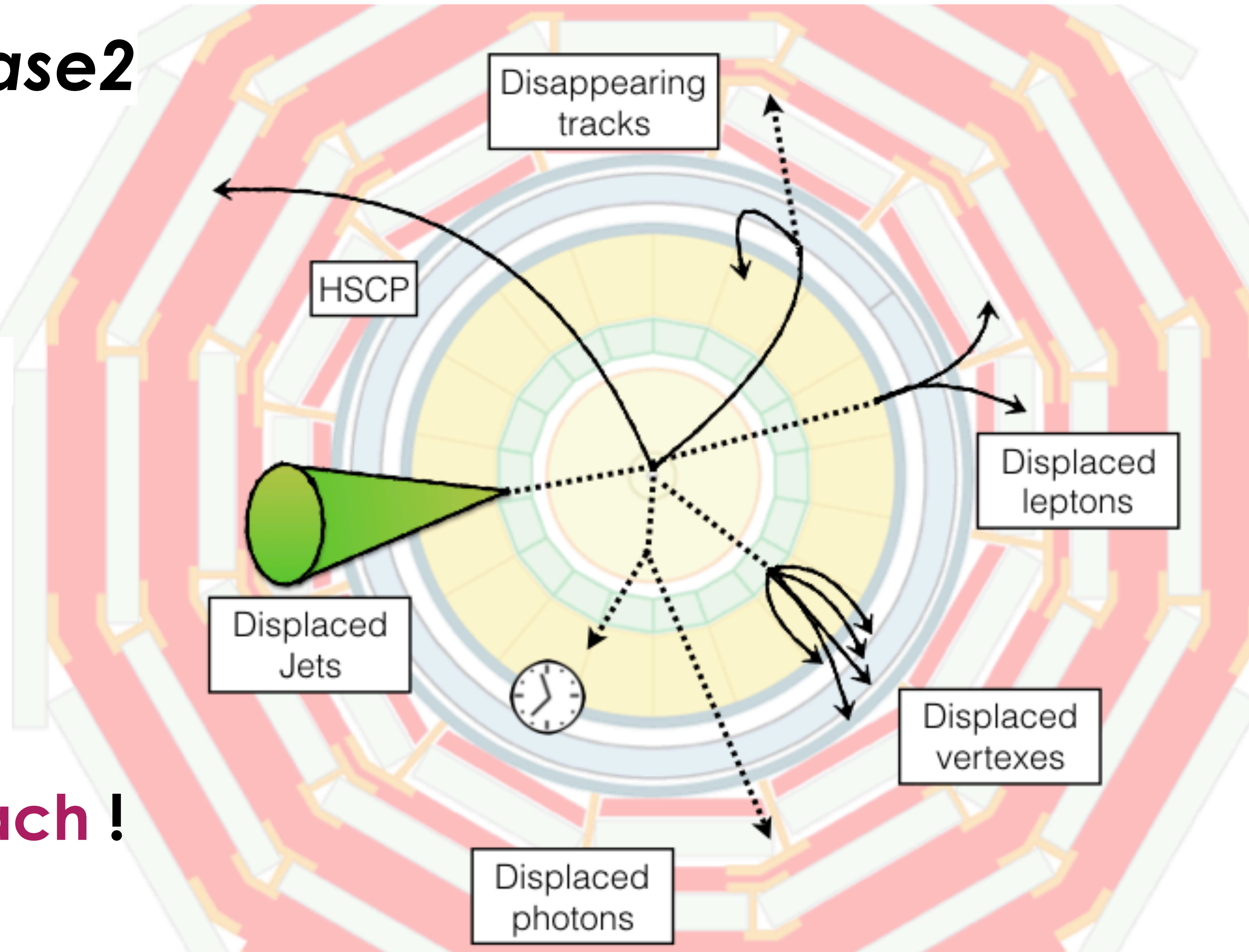
Rediscovered Interest in LLP

- *Strong* ***interest for HL-Phase2***

  - **No hints** of new physics in **prompt searches**

  - Very **small backgrounds** from SM

  - **Dark Matter** related signatures



- **Extend the coverage & reach !**

Explore more final states

Increase luminosity & improve detector performance

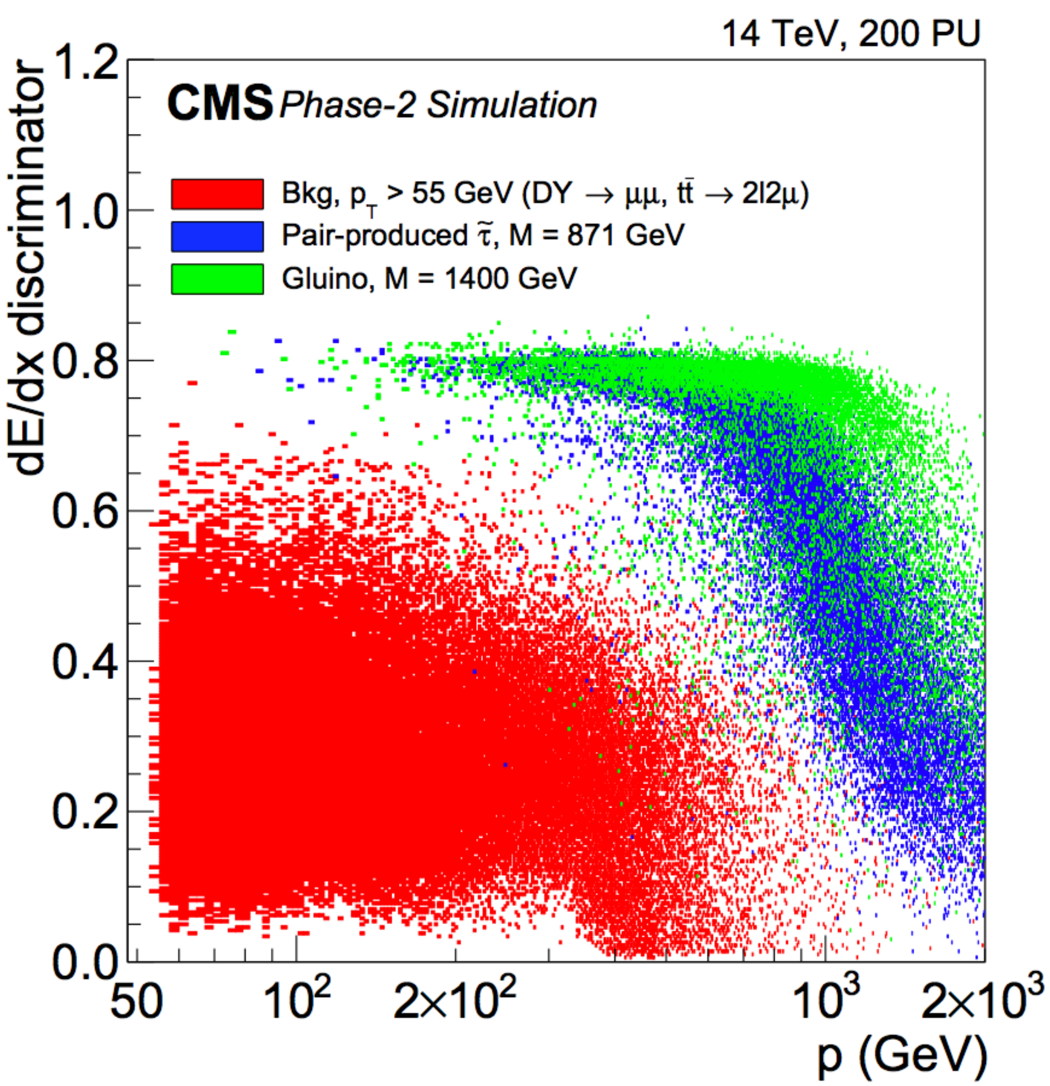
- **Target specific signatures and lifetimes** using dedicated **triggers** and **detectors**

HSCP && Phase2 Tracker Upgrade

Long lifetimes particles moving slowly, heavily ionizing the sensor material as they pass through

SUSY stau and gluino

Depending on mass and charge: **anomalously high dE/dx in the silicon sensors w.r.t. MIP**



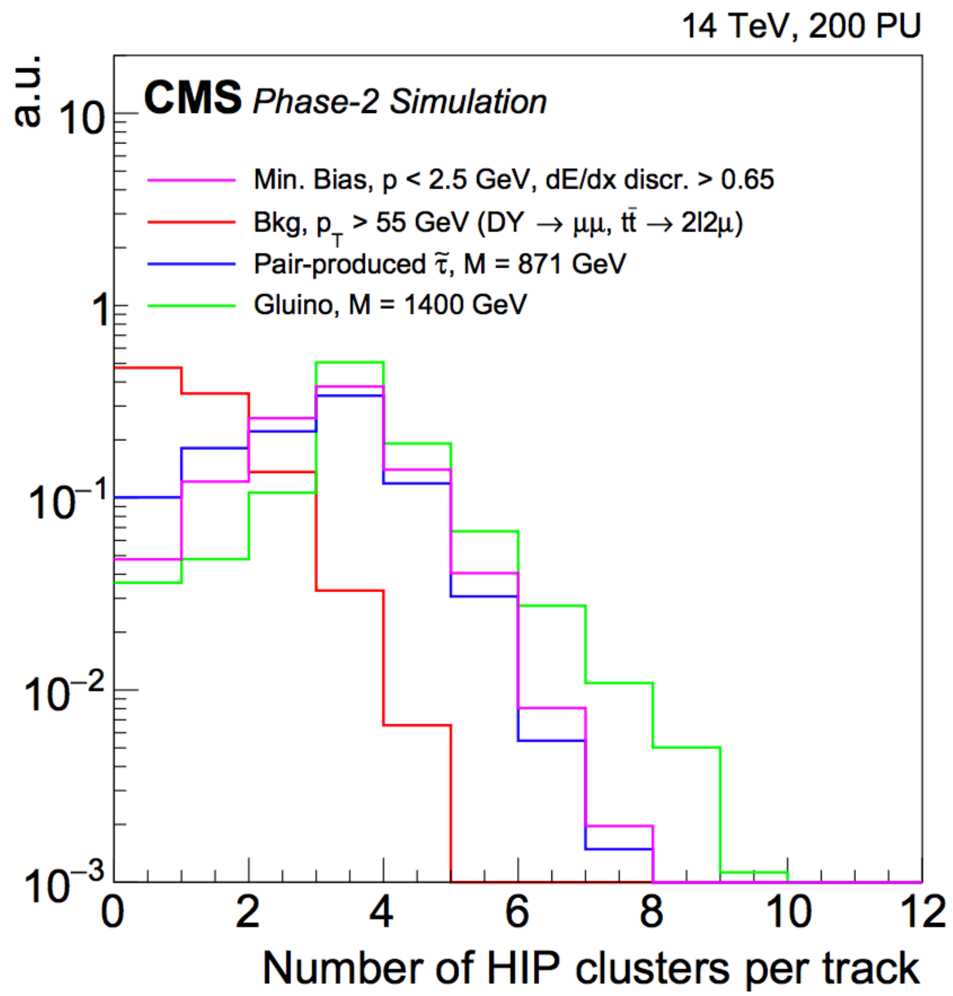
- **Inner Tracker** : dE/dx measurements, enabled by dedicated readout

HSCP && Phase2 Tracker Upgrade

Long lifetimes particles moving slowly, heavily ionizing the sensor material as they pass through

SUSY stau and gluino

Depending on mass and charge: **anomalously high dE/dx in the silicon sensors w.r.t. MIP**



Exploit additional info from OT!!

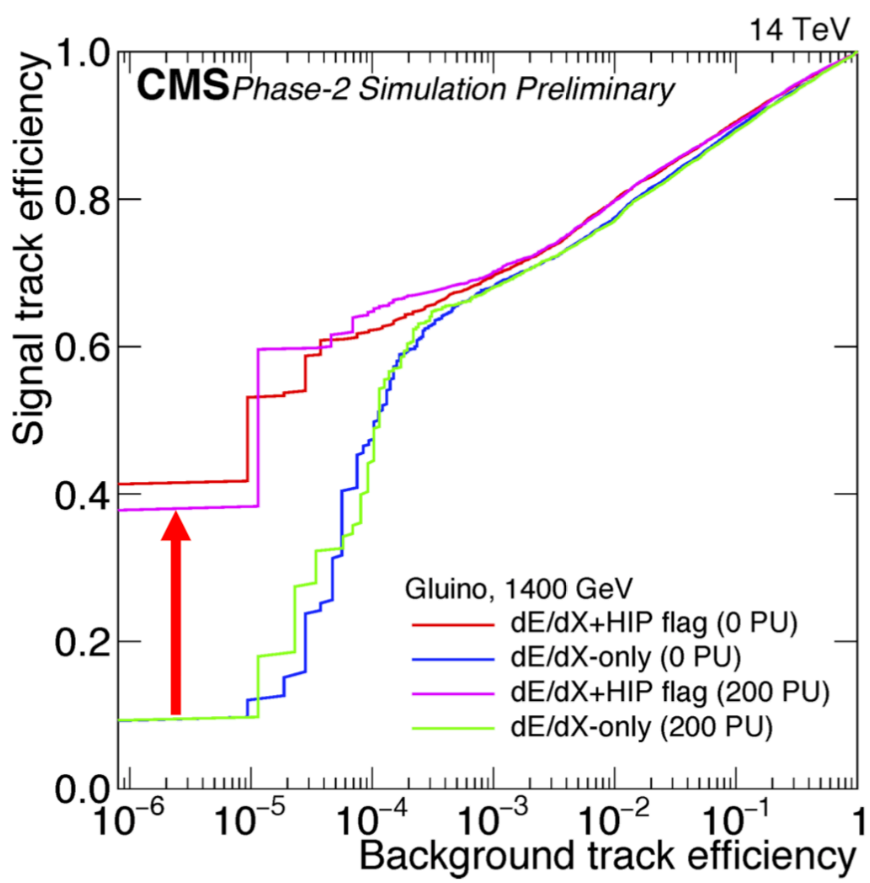
- **Outer Tracker :** threshold implemented in the dedicated readout: **bit signals if a hit is above this threshold: "HIP flag"**

- Energy loss from IT + discriminating HSCPs from MIP w/ "HIP flag" in OT

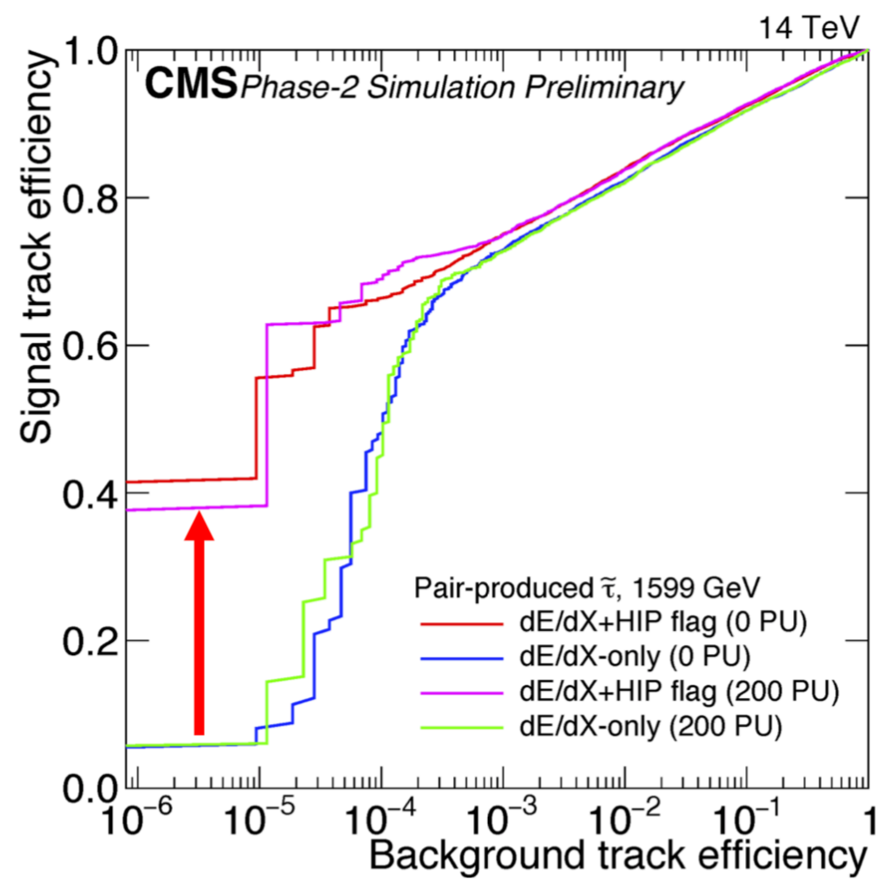
HSCP && Phase2 Tracker Upgrade

- Impact on the HSCP analysis of the Phase-2 inner tracker **dE/dx discriminator and outer tracker HIP flag**
- Evaluate **signal vs background efficiency to identify tracks** from signal events and reject those originating from backgrounds.

Gluino, 1400 GeV



Stau, 1599 GeV



- *Phase-1 sensitivity realized with x4 luminosity and surpassed w/ full expected integrated luminosity of the HL-LHC.*

HIP flag is critical to restore tracker sensitivity to HSCPs in Phase 2

HL-LHC Challenges in muons physics

Major challenges at the HL-LHC for muon physics

Precise momentum *measurement by the* ***Level-1 muon trigger***

- Cope with the HL-LHC luminosity without raising the **trigger thresholds**
- **Standalone Triggering**:reconstructing **long-lived particles** outside the IT as much as O(1m)

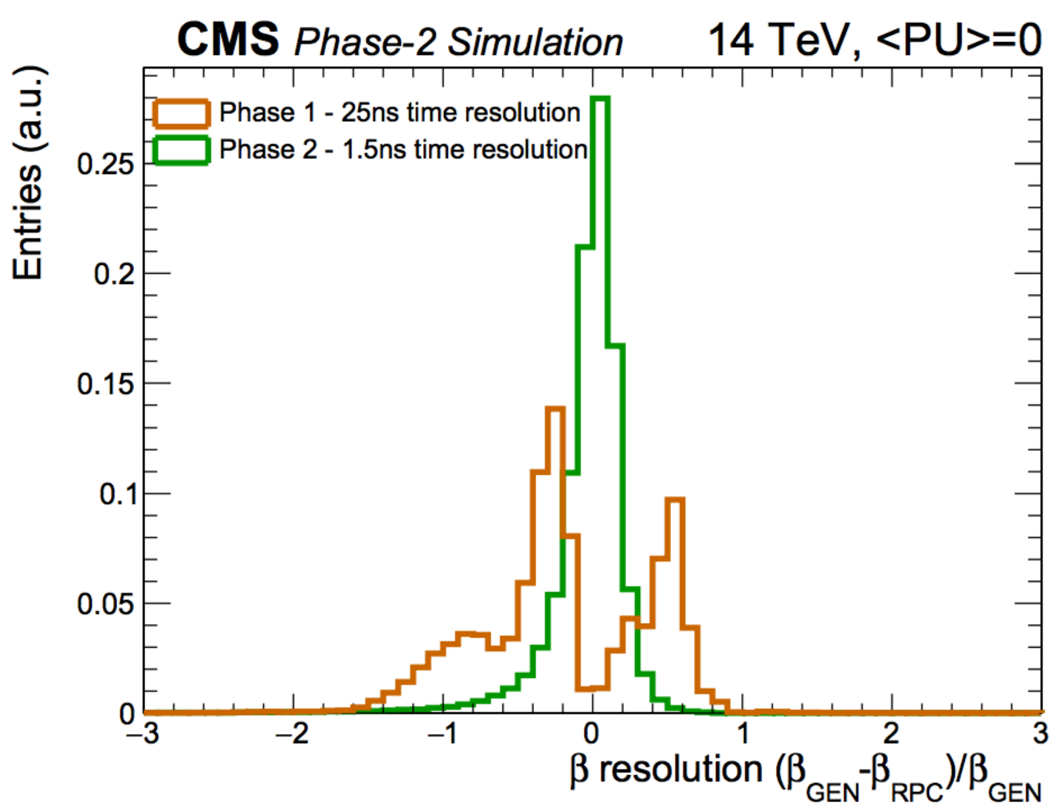
Improve ***redundancy in forward regions***

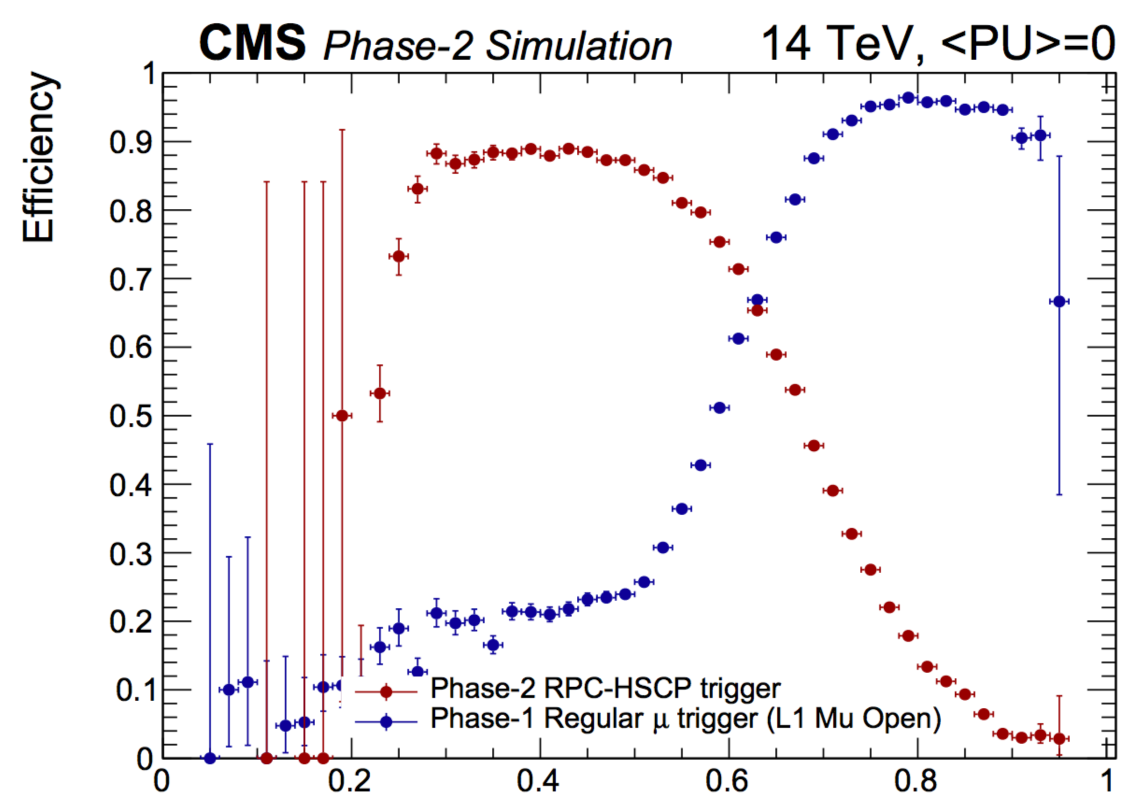
- Good measurement of the **track bending** w/ several **independent direction measurements**
- New forward muon detectors, **GE1/1, GE2/1, RE3/1, and RE4/1 up to eta 2.4**
- Resolve the **track reconstruction ambiguities**

RPC System Upgrade for HSCP

- BSM particles w/ mass > O(1) TeV, mostly produced w/ $\beta \sim 0.3$–0.5
- ***HSCP: electrically charged, no color charge, and long lived -> look like slow muons propagating through the CMS***

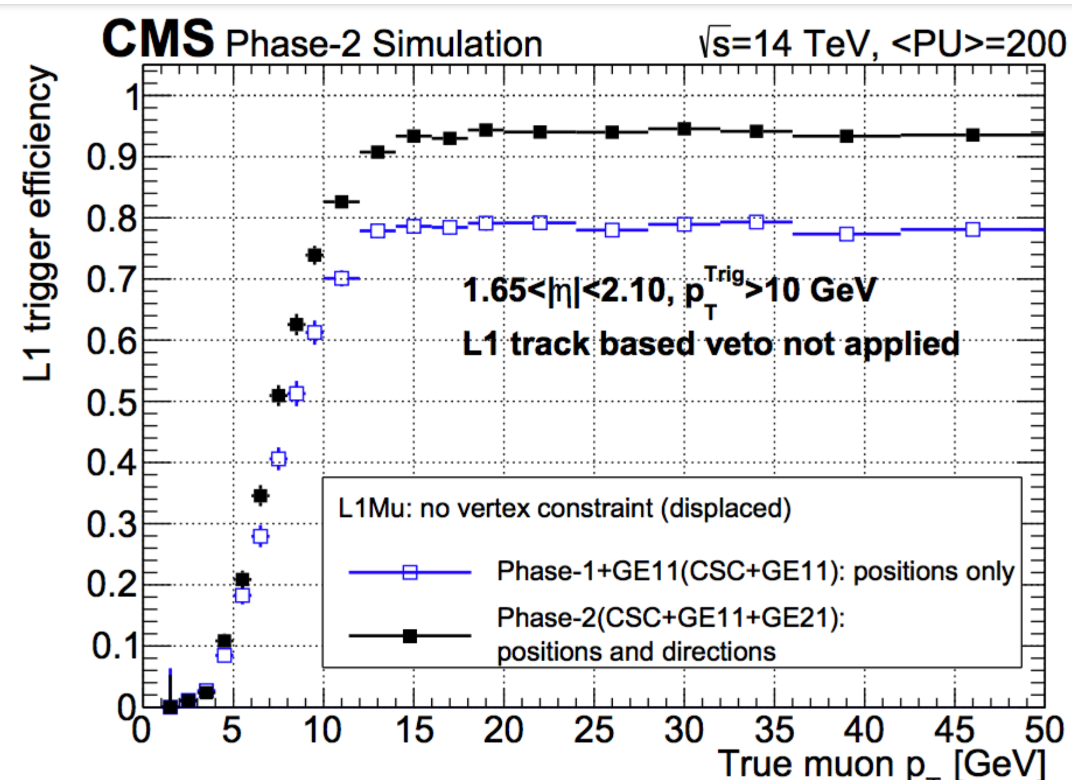
- Exploit **fully the intrinsic time resolution of the RPC chambers O(1.5ns) w/ upgraded RPC Link Board System**
  - *Suppress **OOT background** and improve **BX identification** throughout the entire muon system*
    - Allow to trigger, at the correct BX, HSCPs with **velocities as low as $\beta \sim 0.25$**

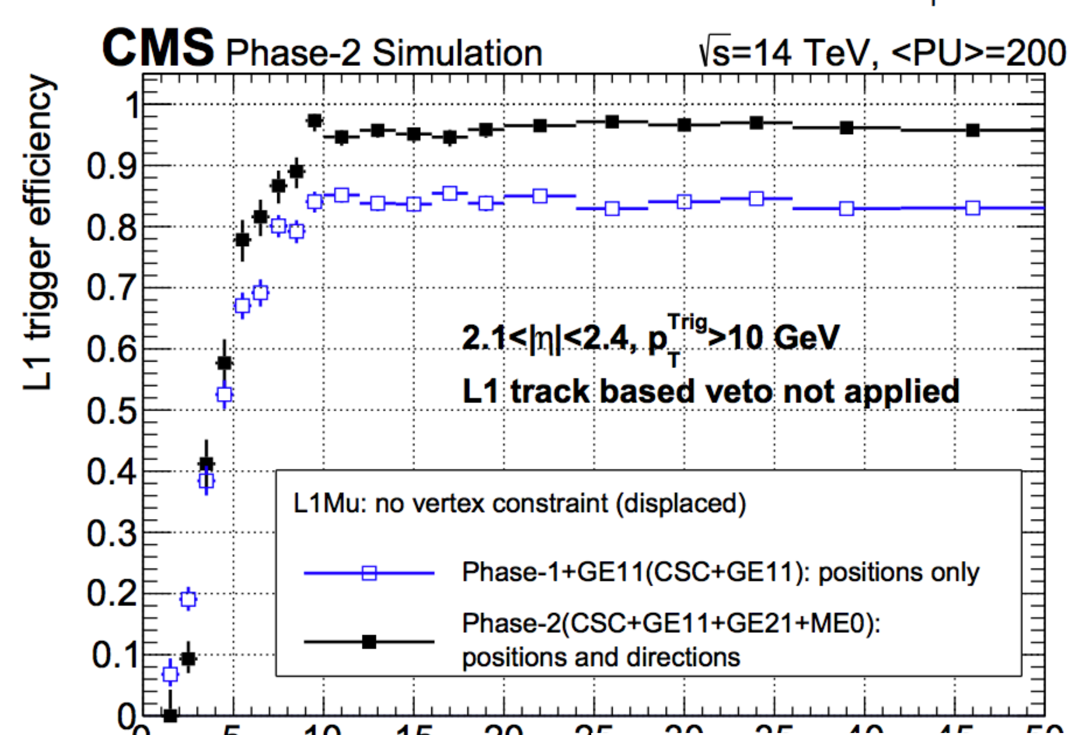




Triggering on highly displaced muons

- **L1 tracking trigger** inefficient for tracks w/ dxy> few mm b/c **beam spot used as a built-in constraint**
  - Dropping this constraint reduces resolution and increases rate
  - **Inclusion of the GE2/1 detectors** improves measurement of the bending angle in **at least two stations** for a suitable endcap trigger on displaced muons
- ***Standalone muon triggering highly efficient for triggering on muons with dxy up to 10–15 cm***





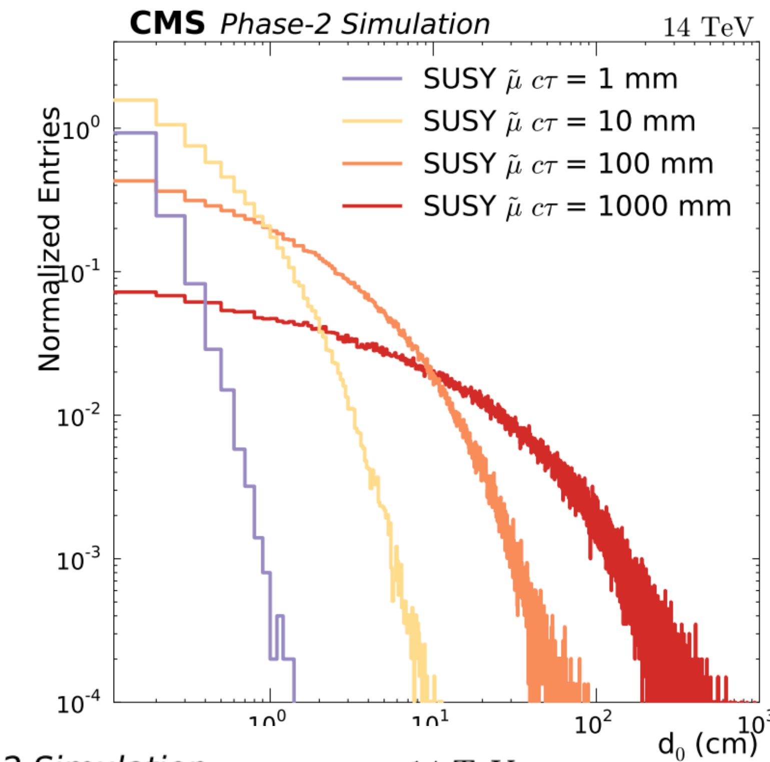
HL-LHC Performance on displaced muons

- Gauge-mediated SUSY breaking model with the **smuon as NLSP** resulting in a **two displaced oppositely charge muons**

- Large MET (> 50 GeV)

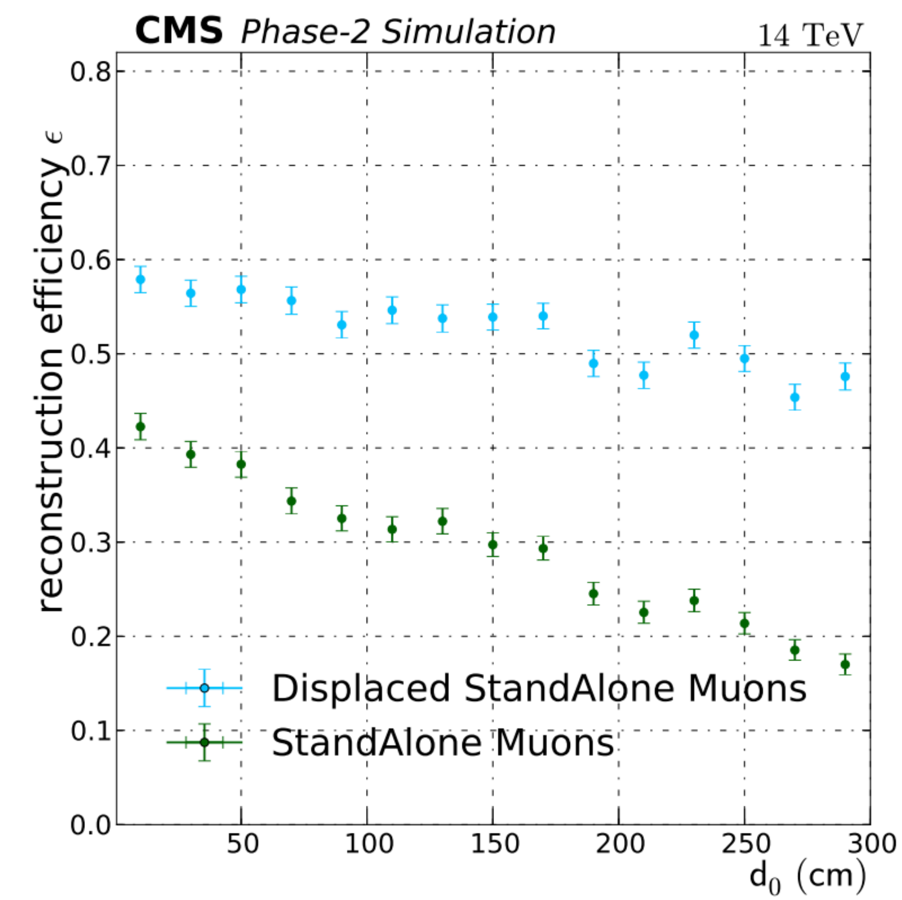
$$q\bar{q} \rightarrow \tilde{\mu}\tilde{\mu}$$

$$\tilde{\mu} \rightarrow \mu\tilde{G}$$



Displaced stand-alone algorithm:

- Tracks reconstructed from only hits in muon chambers
- Muon track reconstructed **w/o constraining the interaction point.**
- Benefits from **additional hits from the Phase-2 muon system forward upgrade**

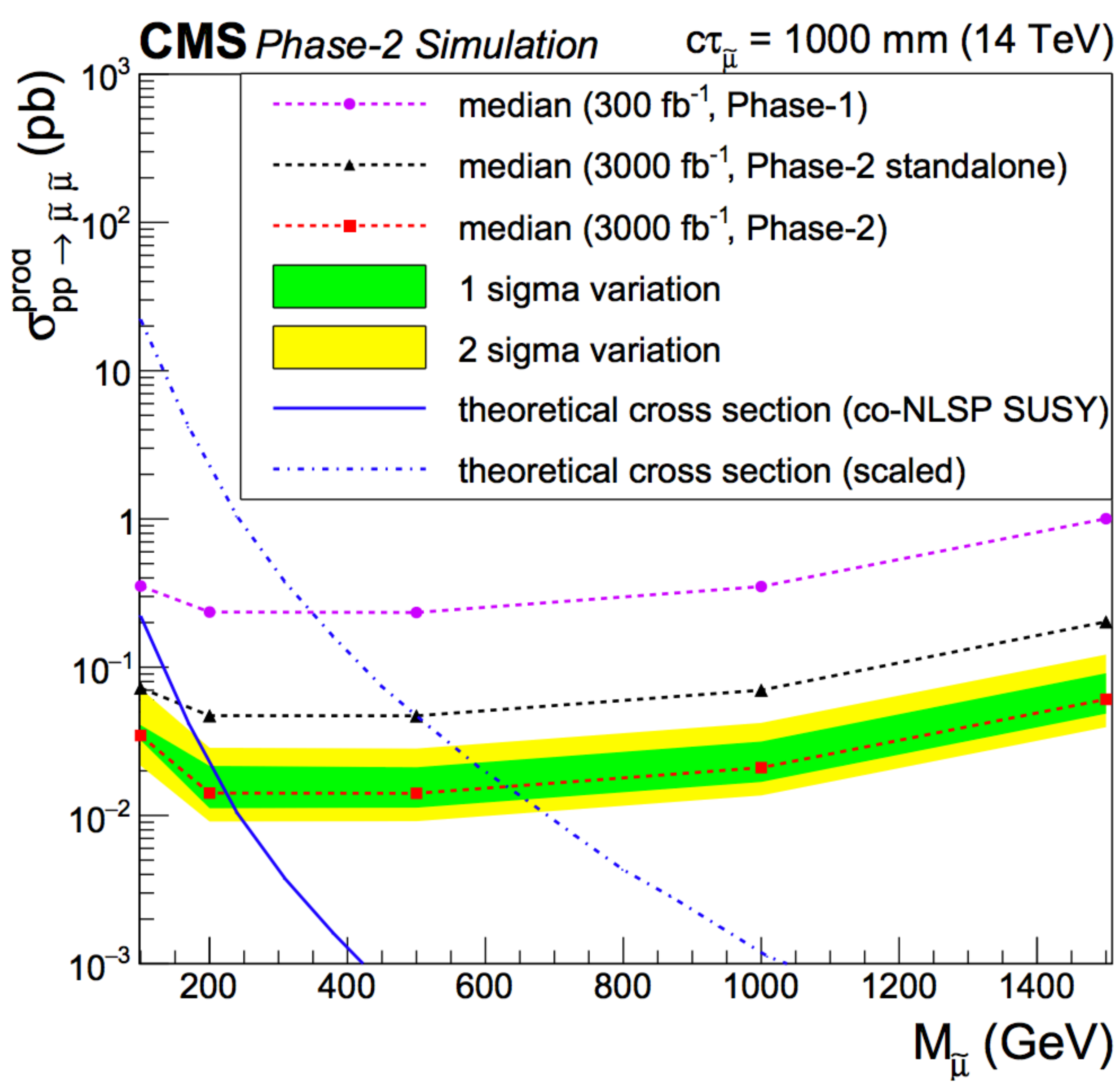


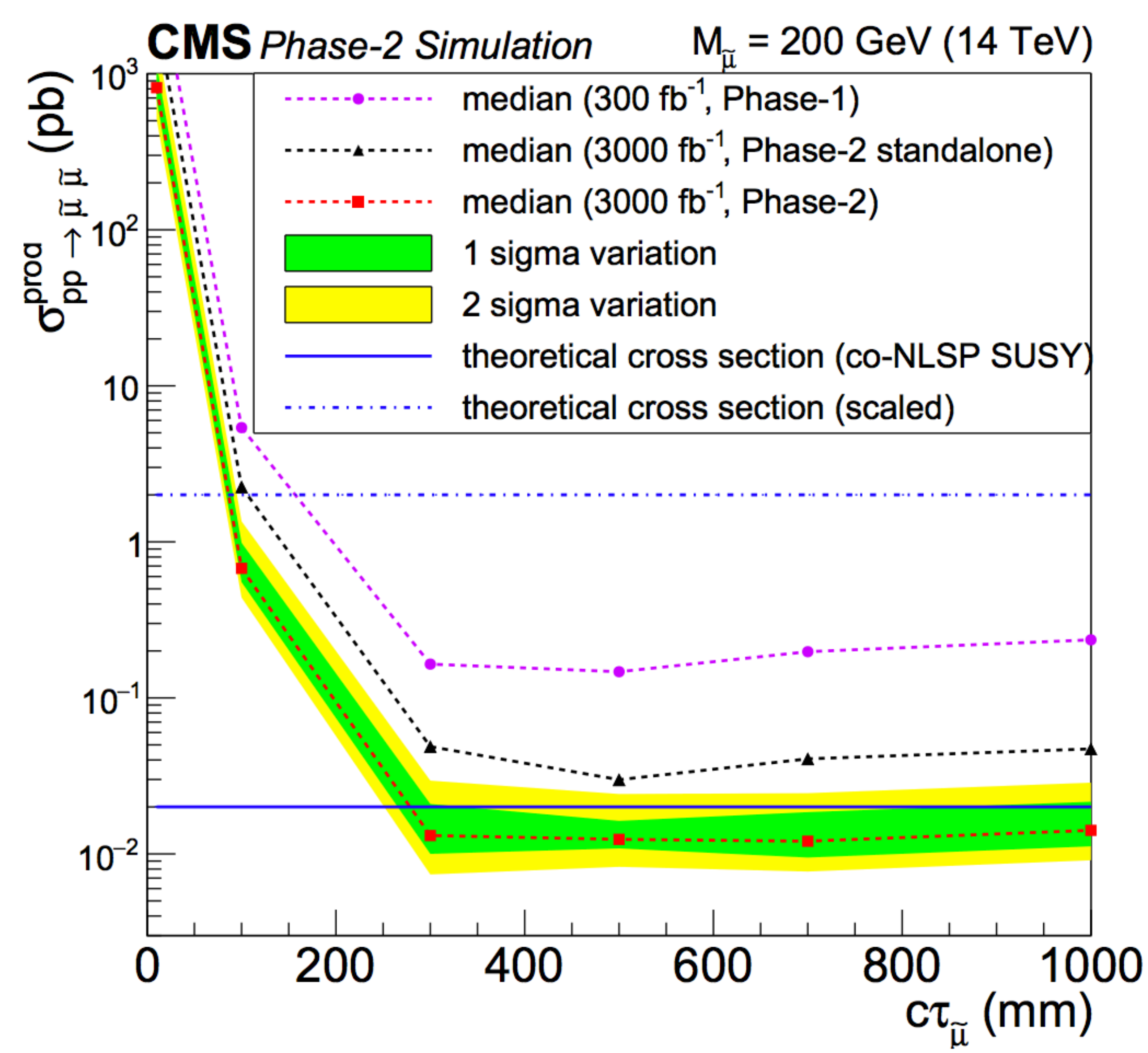
HL-LHC Performance on displaced muons

- Background discriminator: the **impact parameter significance d0/σ(d0)**

- Signal efficiency 4–5% for cτ = 1000 mm vs 10^{-5} – 10^{-4} for QCD, tt, and DY (where large impact parameters are (mis)reconstructed)

- Black line shows sensitivity w/o DSA algorithm which reduces the reconstruction efficiency by a factor three



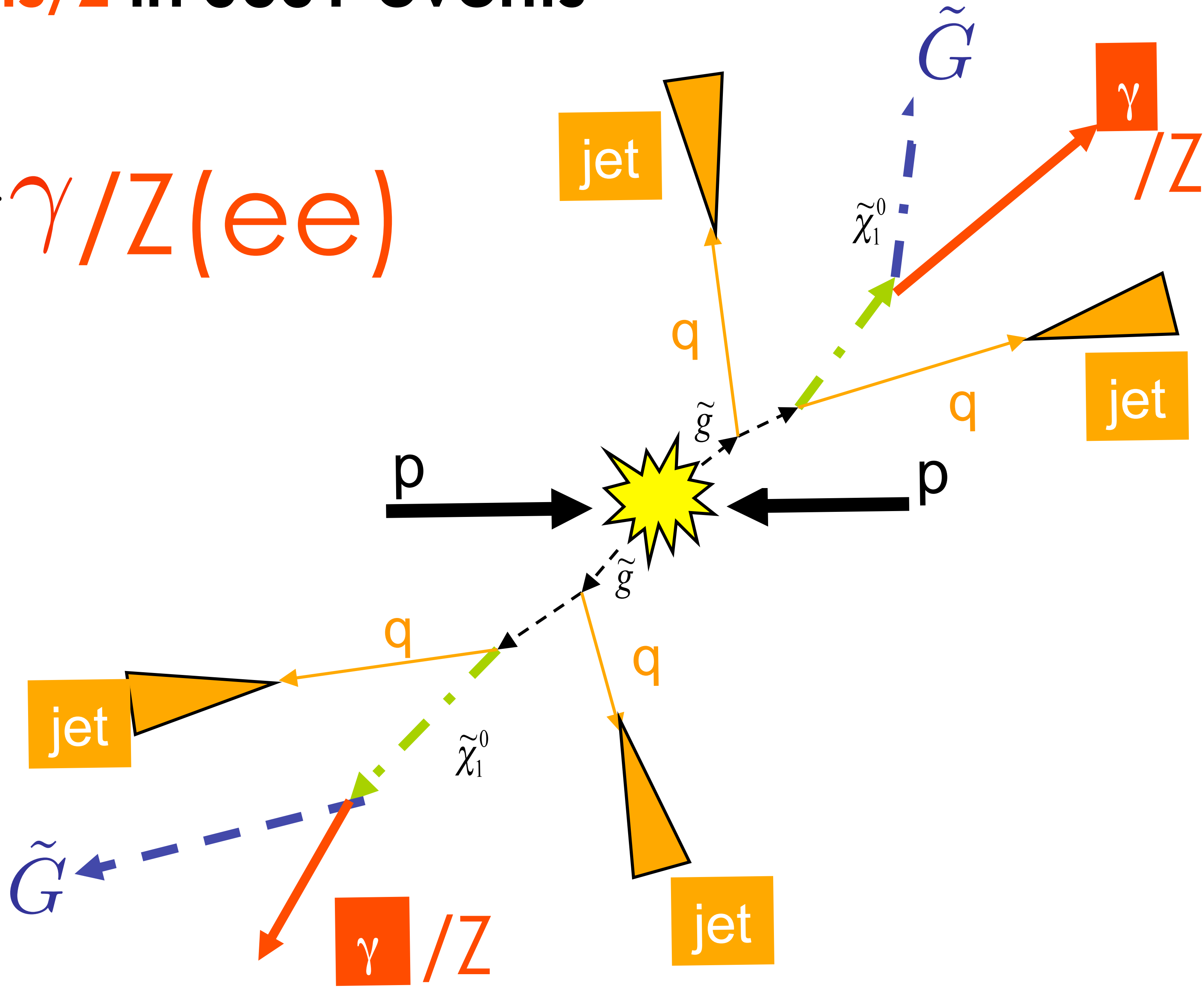


Promising signatures with delayed photons/Z

Search for **delayed photons/Z** in SUSY events

$$\tilde{\chi}_1^0 \rightarrow \tilde{G} + \gamma/Z(ee)$$

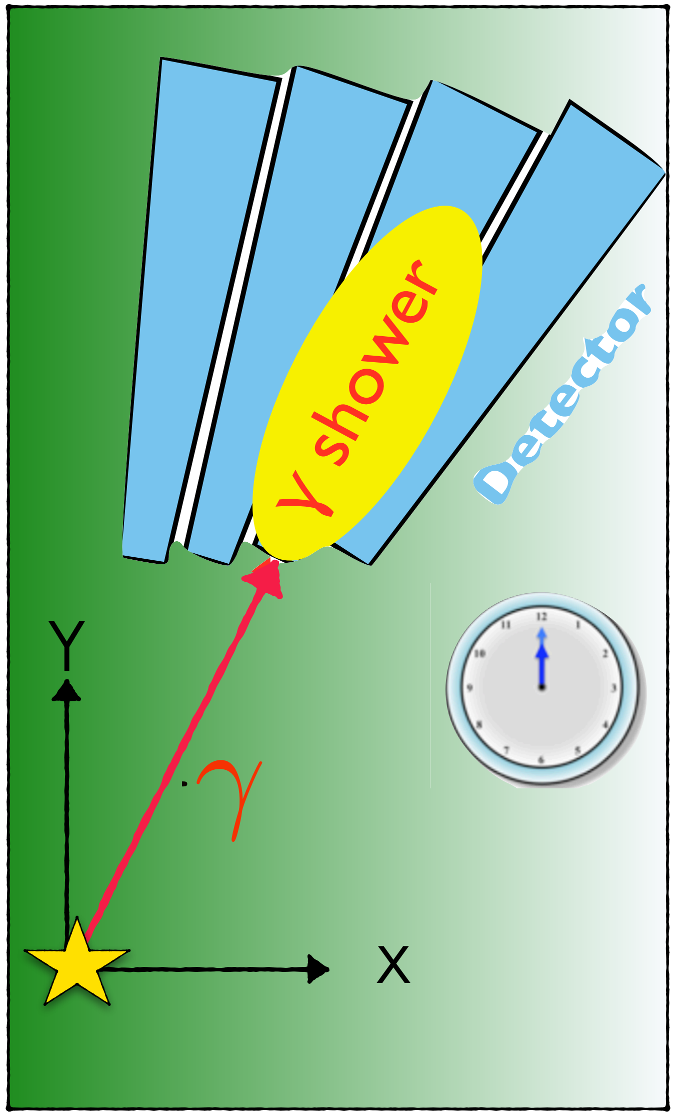
- If **neutralino** is **long-lived**:
  - **Photon/Z (ee)** arrives **on ECAL in delay** w.r.t. prompt particles
  - So far tagging events w/ **ECAL time** information (res 200-300 ps)



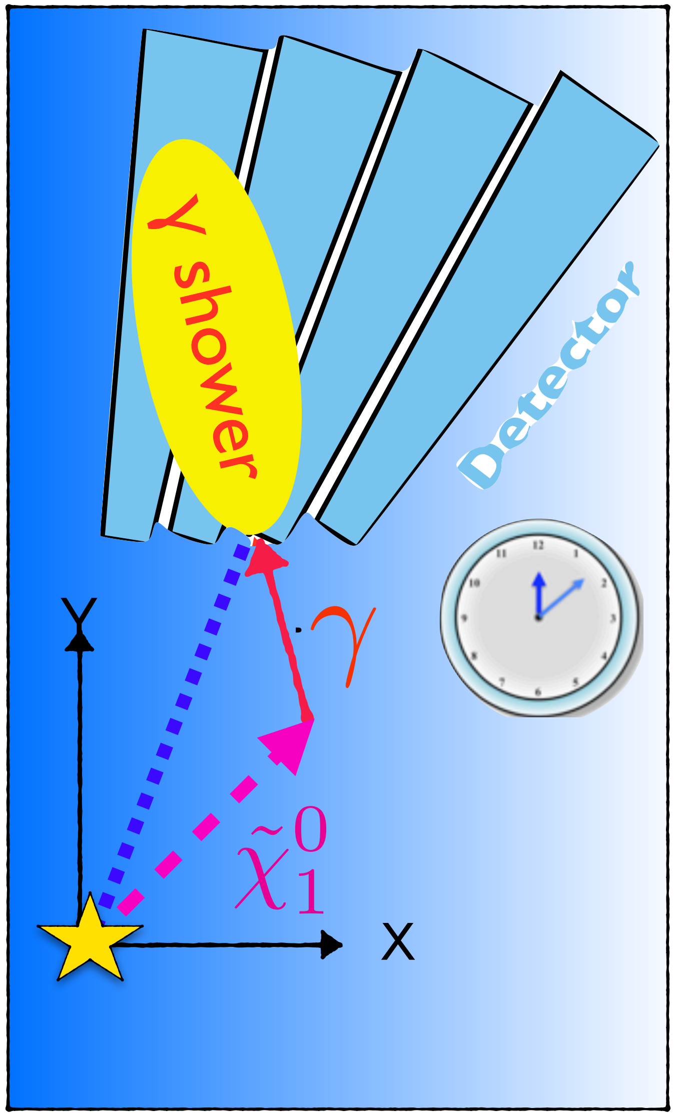
Challenges of the search:

- **Non-standard electromagnetic objects**, customize **trigger/ reconstruction/simulation**

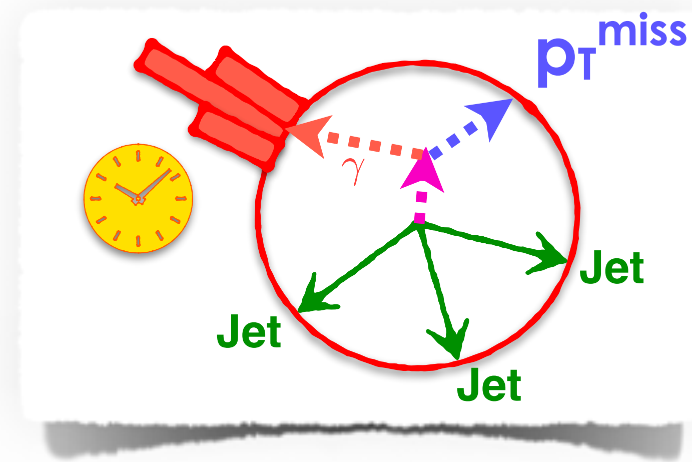
Out Of Time Photons Detection

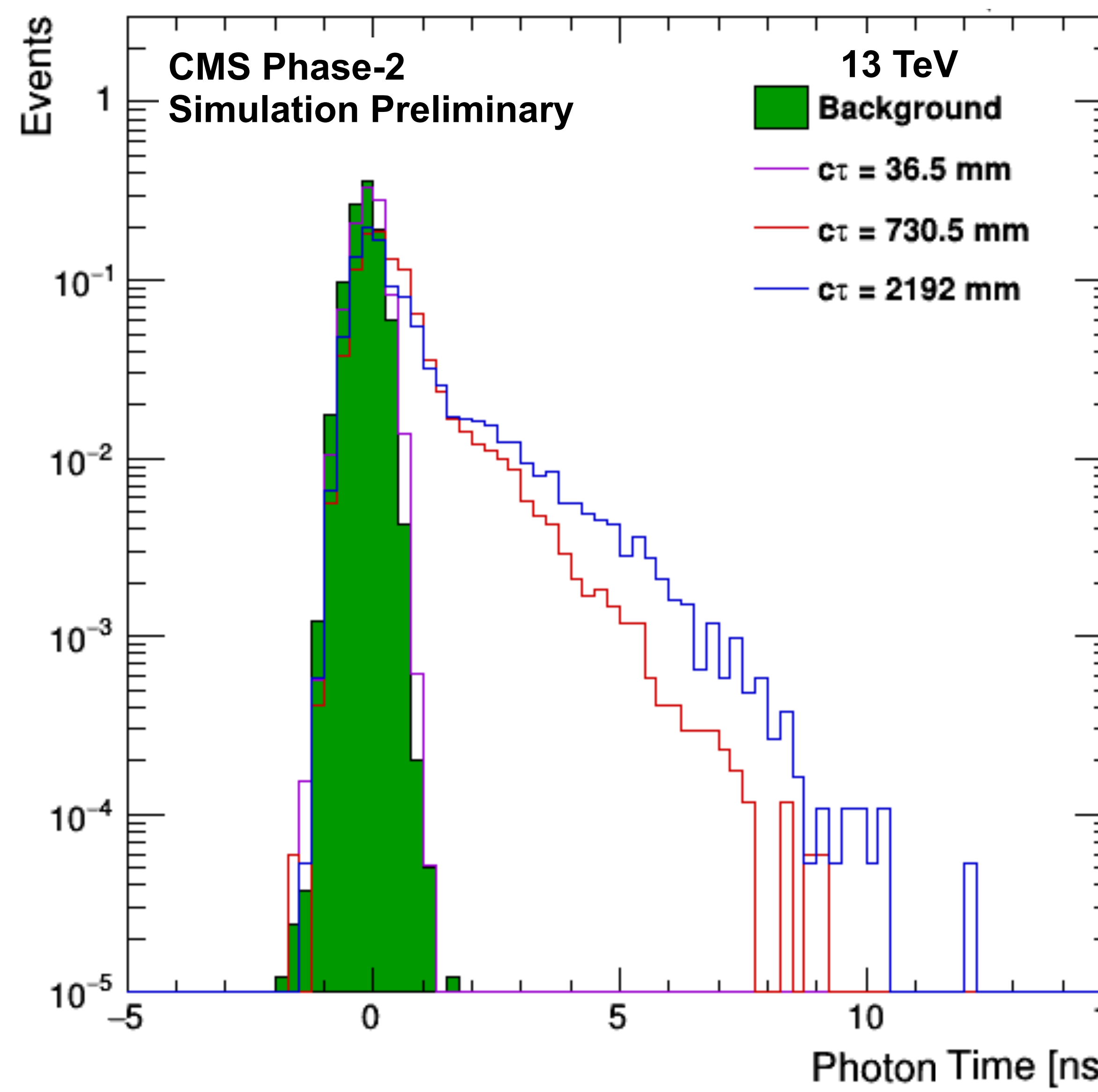


Time compatible with that of a **relativistic particle from the IP**

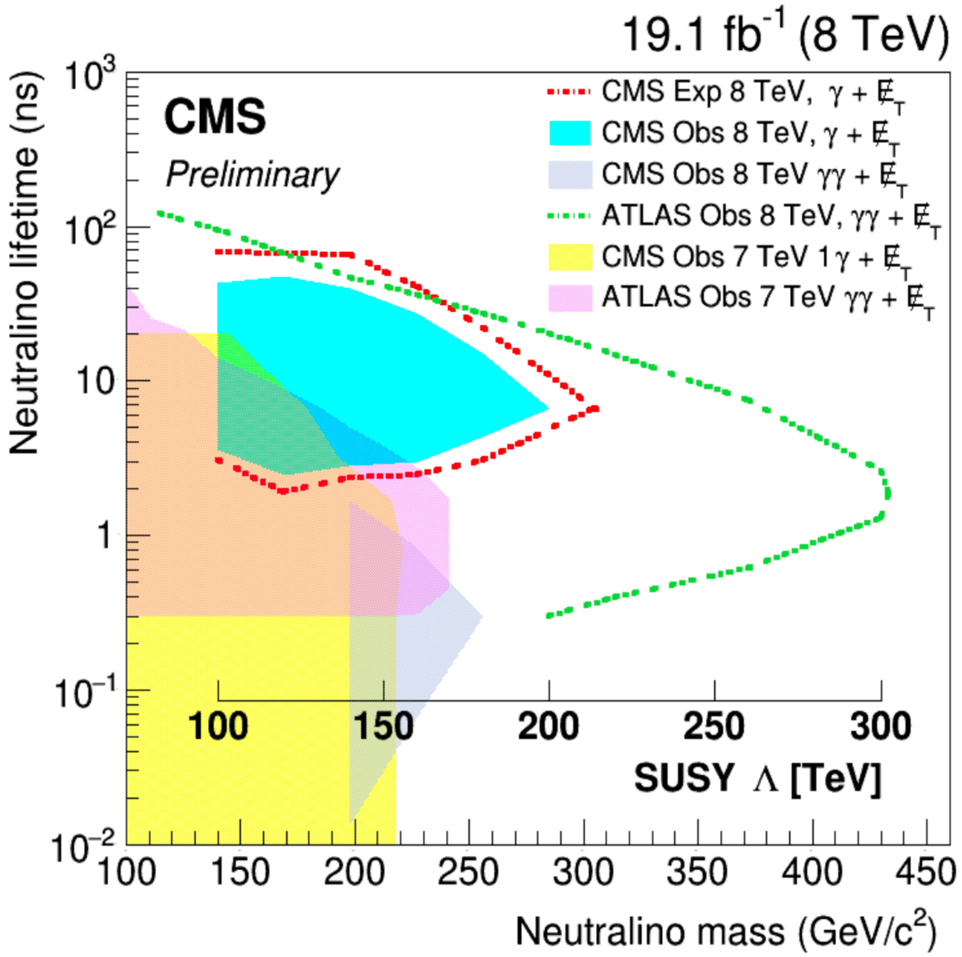


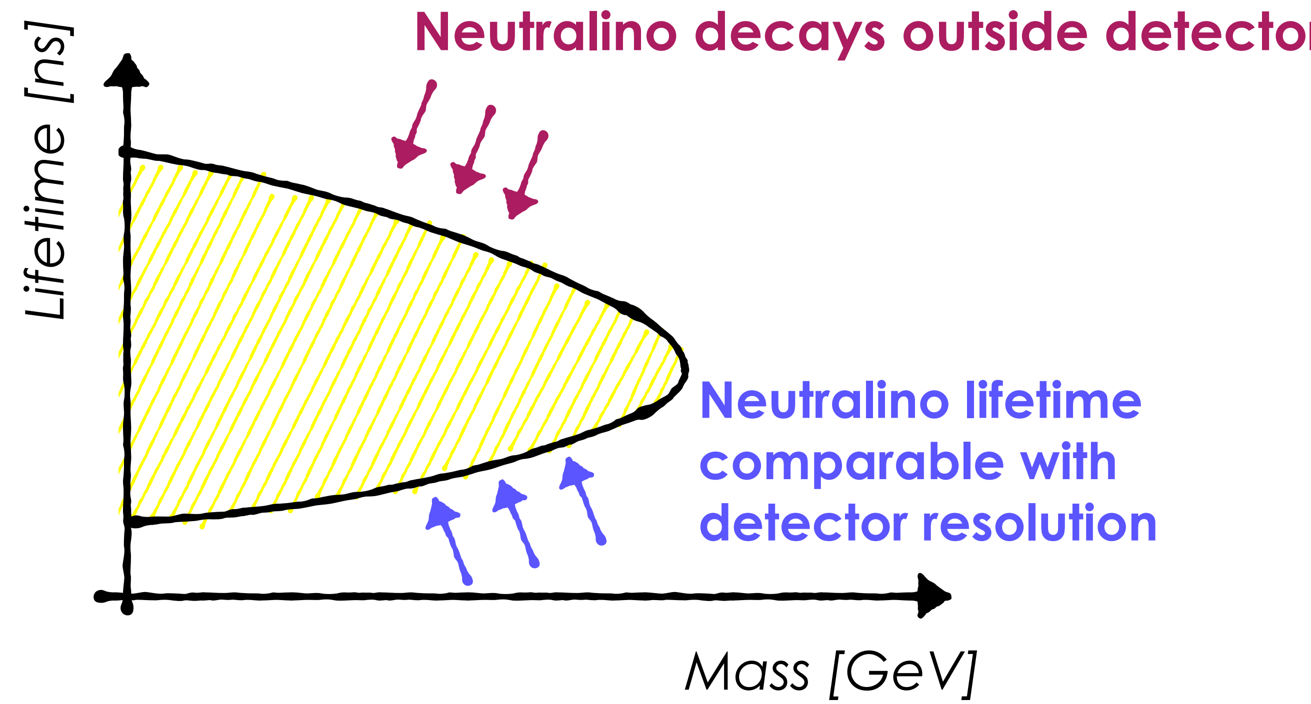
Time sensibly increase with **parent particle lifetime O(ns)**



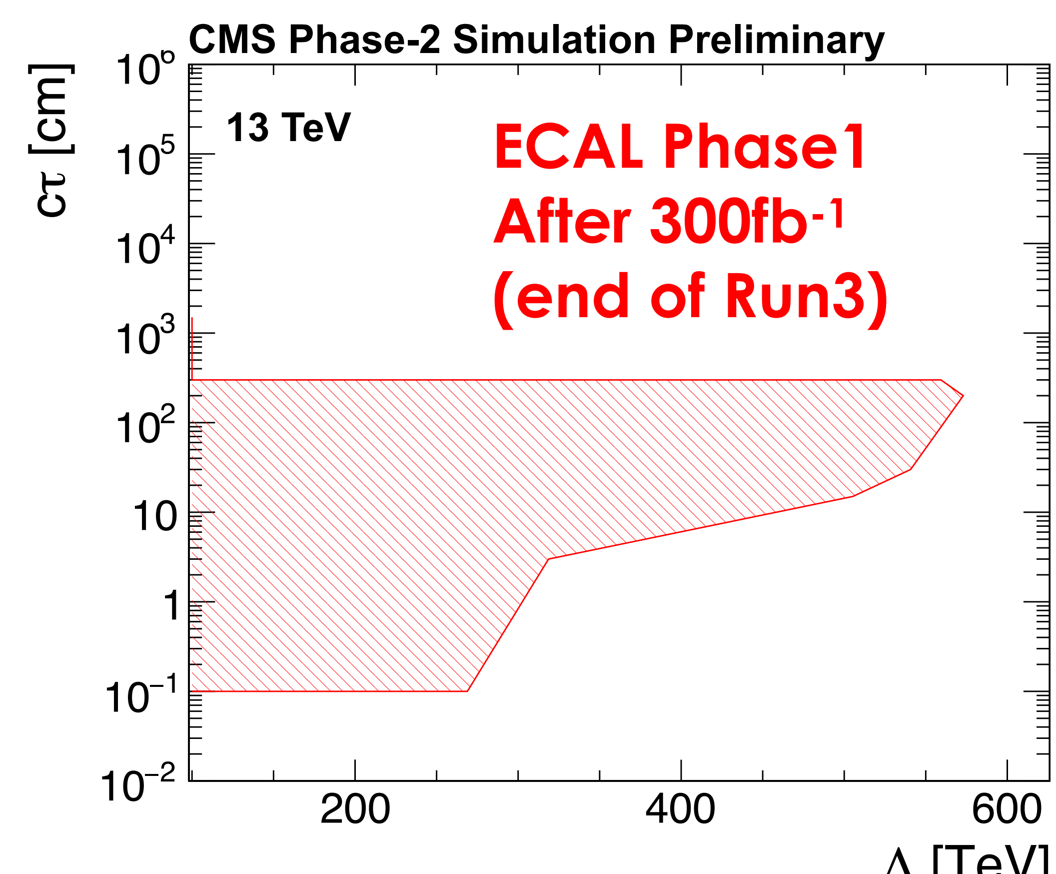


LHC Sensitivity to Displaced Photons





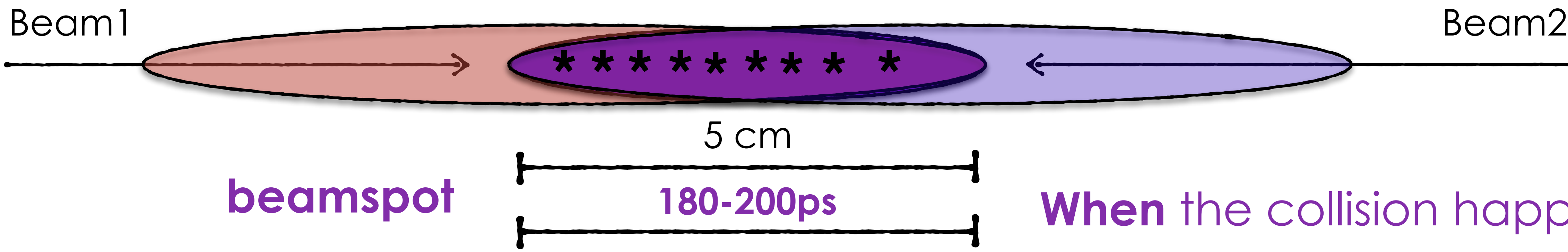
- **Sensitivity to small-lifetimes limited by time resolution**



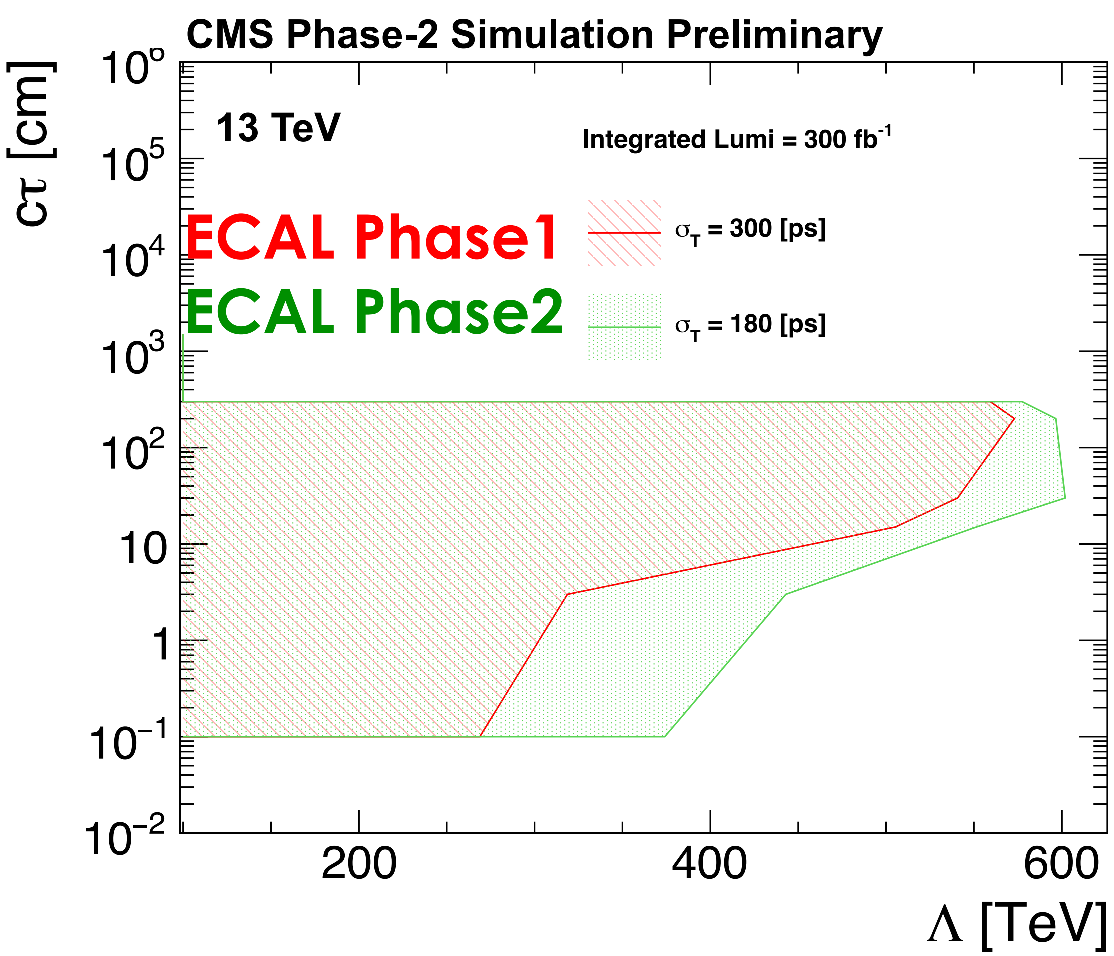
Beam spot limitations to time resolution

Inst Lumi @ HL-LHC: 5.2 or $7.2\times10^{34}\ cm^{-2}s^{-1}$

140 or 200 multiple interactions



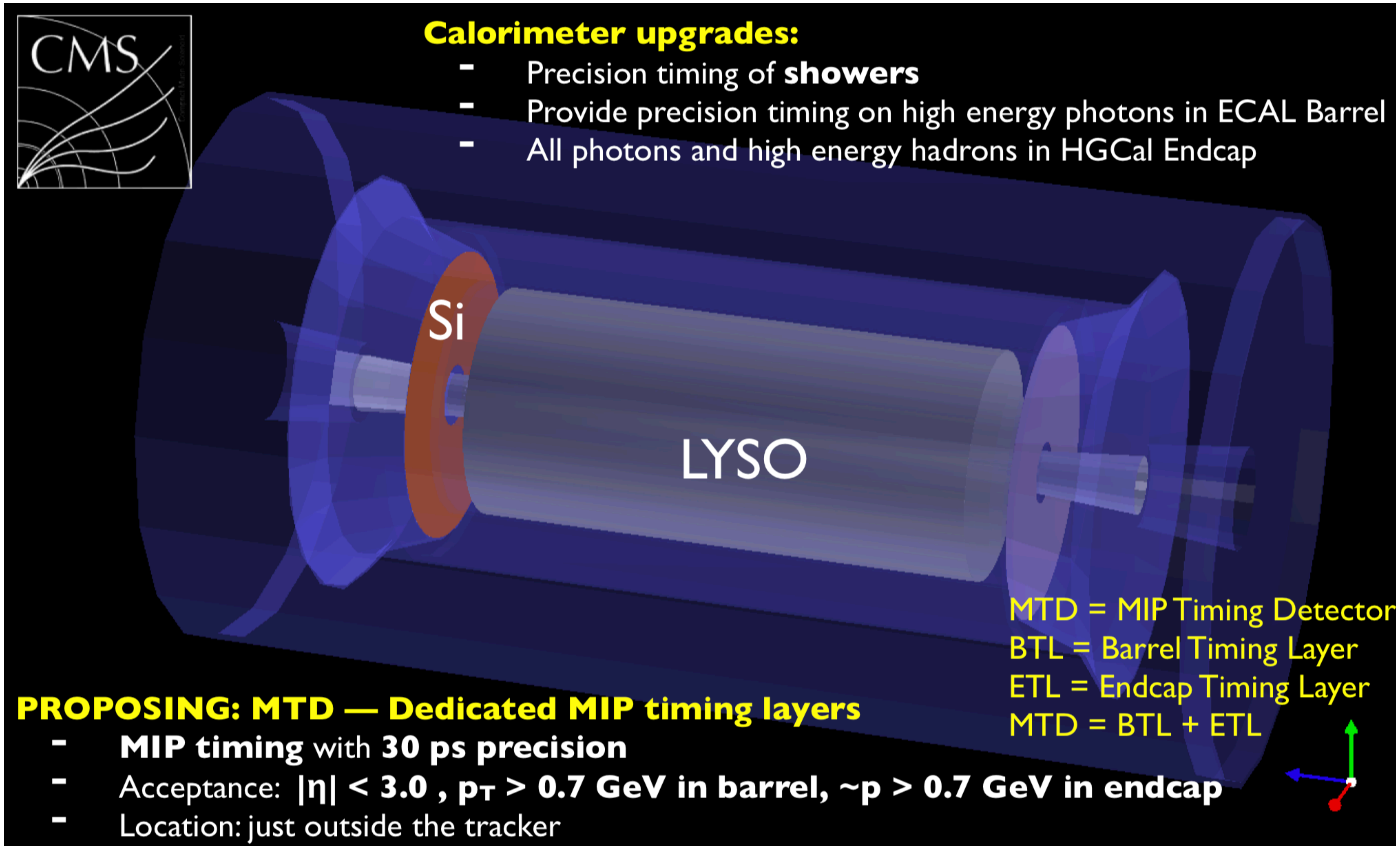
When the collision happens?



- **ECAL Phase2 Upgrade: Time Resolution O(30ps)**
- Time resolution dominated by uncertainty from beamspot
- Performance improves but not optimal

CMS Global Timing Concept

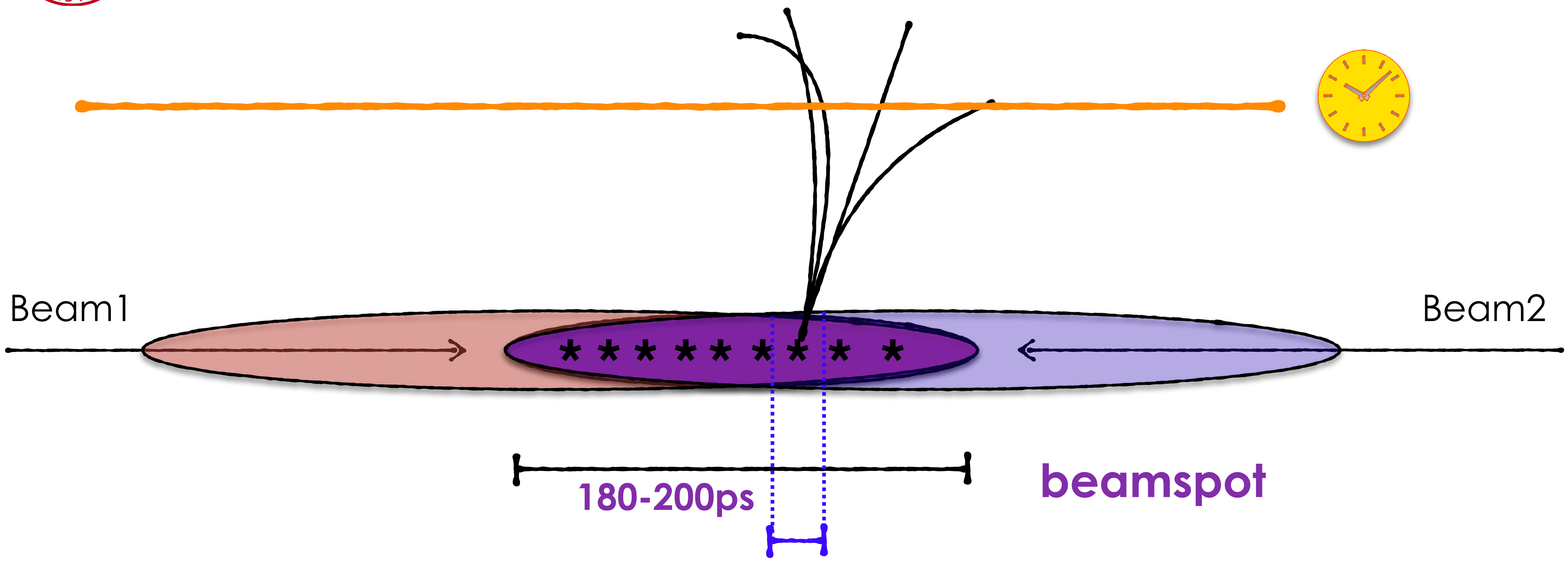
- ***CMS has now included a hermetic precision MIP Timing Detector in the Phase-2 upgrade scope***



132nd LHCC Meeting 30th Nov 2017: https://indico.cern.ch/event/679087

Timing Days 22th Mar 2018 (CMS only): https://indico.cern.ch/event/700775

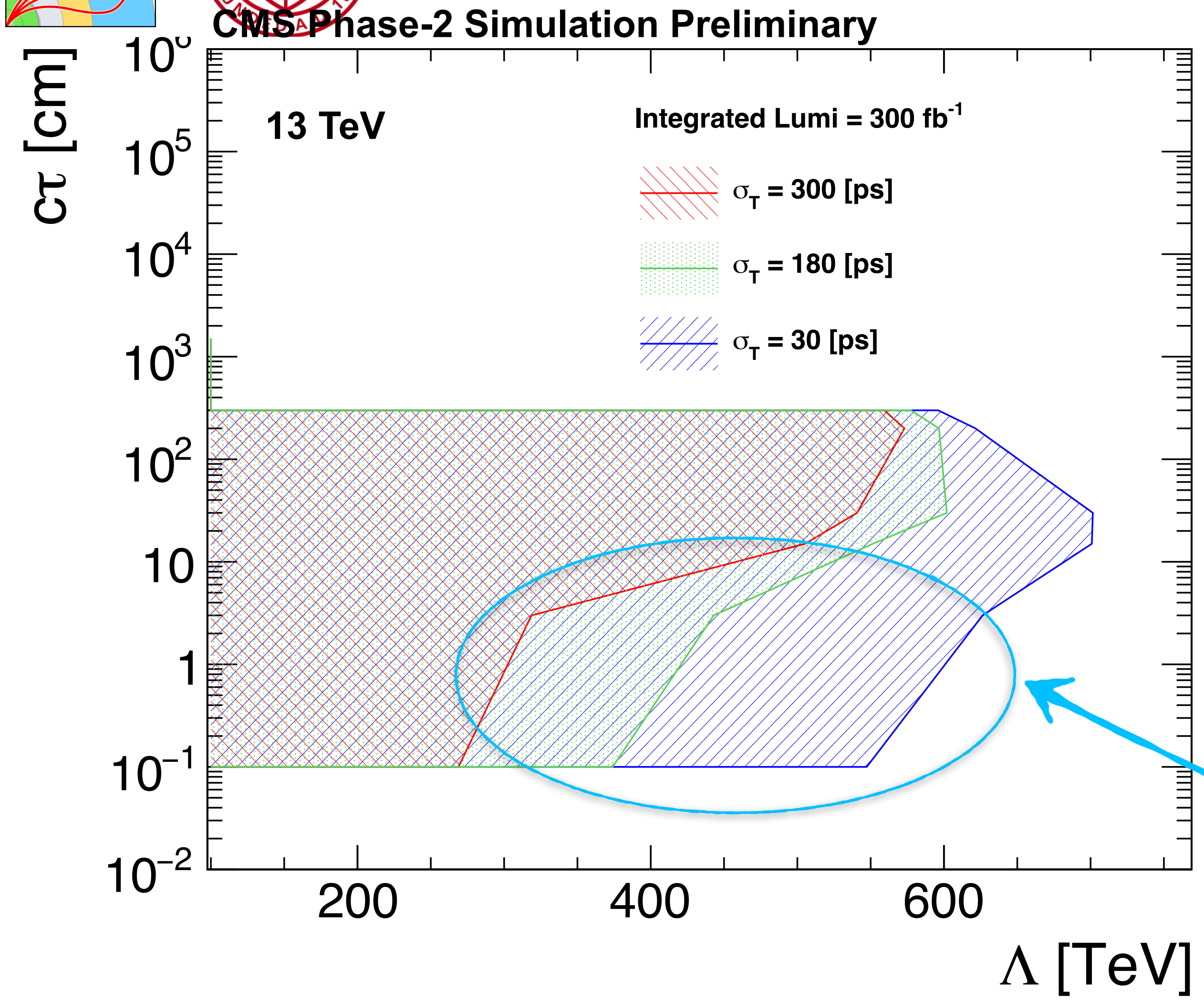
MIP Timing Layer Detector Upgrade



Significant reduction of beamspot uncertainty

- Precision timing **rejects spurious secondary vertices**
- **Remove pileup tracks** from isolation cones
- **Extend the physics reach** in searches for massive invisible particles
- Provides a ***new capability* for LLP searches**

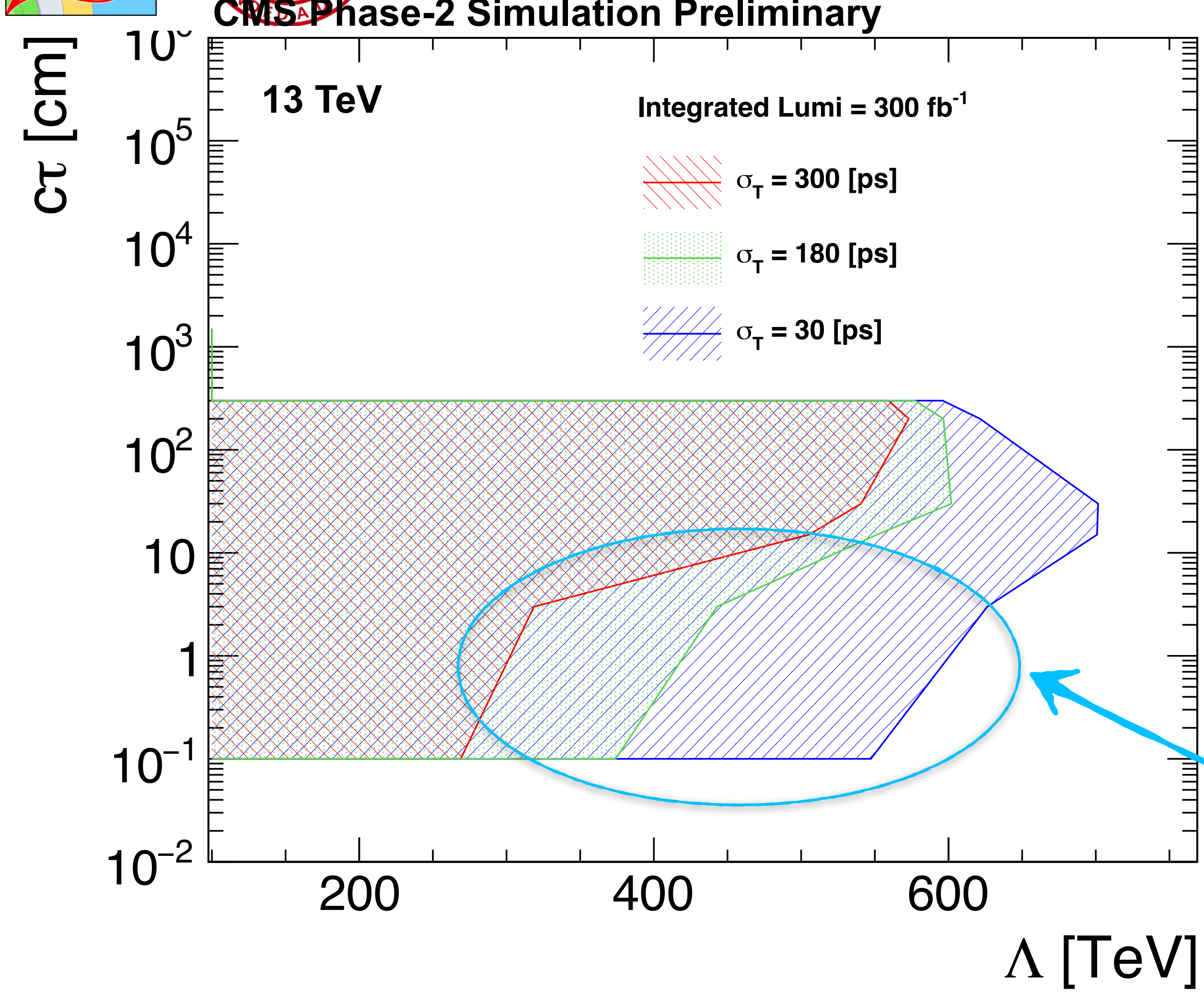
Displaced Photons w/ MTD at HL-LHC



- ECAL Phase1
- ECAL Phase2(beamspot dominant)
- ECAL Phase2 + Timing Layer

- Increase sensitivity to short lifetimes

Displaced Photons w/ MTD at HL-LHC

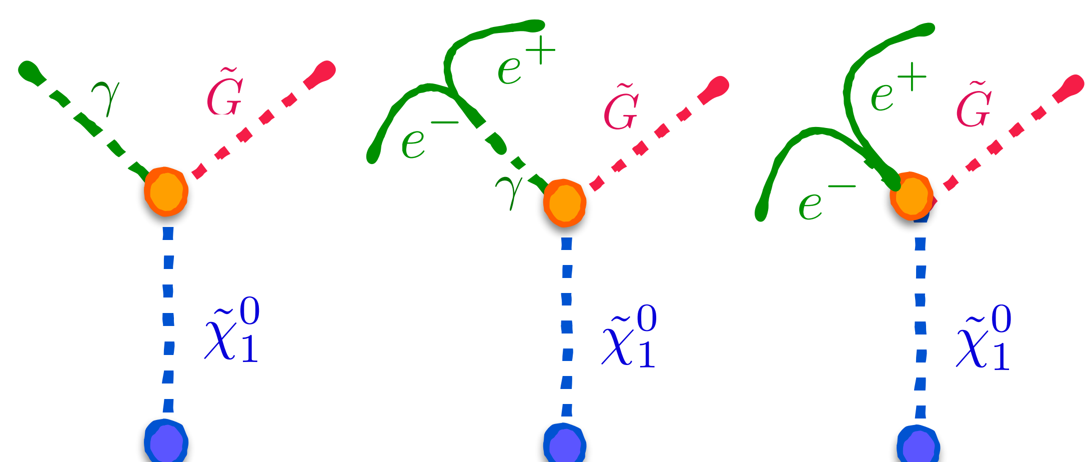


- ECAL Phase1
- ECAL Phase2
- ECAL Phase2 + Timing Layer

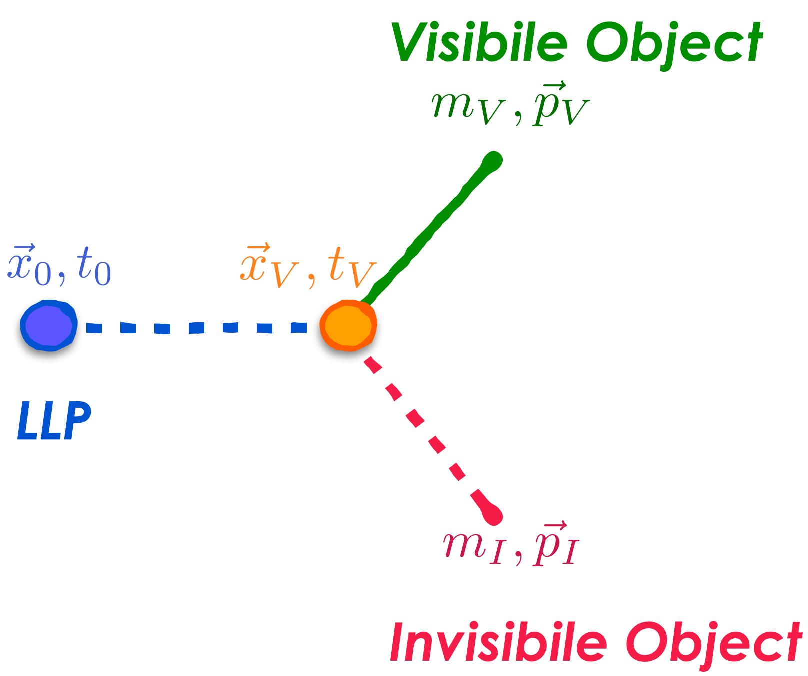
- Increase sensitivity to short lifetimes

- Proposal for **more effective timing detectors for HL-LHC** ⟺ **Significant impact on long-lived particles searches**

  - Possibility to include complementary **out-of-time channels**



Secondary Vertex Reconstruction with MTD



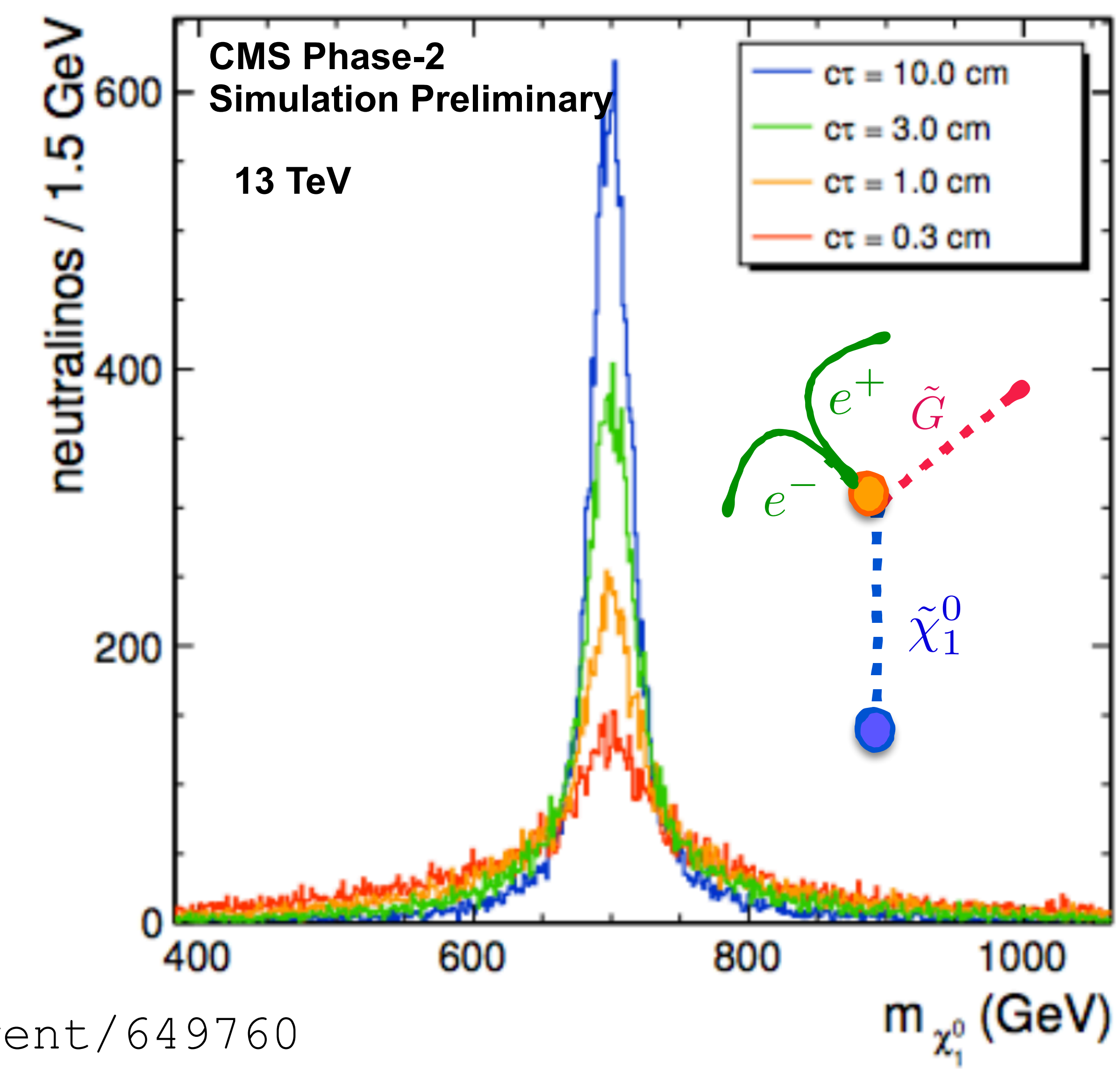
- **Reconstructed vertex to measure the TOF** of LLPs

⇩

- **Kinematic closure:** direct measurement of the **LLP mass**

- **Timing resolution for tracks is 30 ps**

- Model independent: can either **reconstruct mass or mass splitting** depending on how velocity related to model structure



See Sasha`s talk https://indico.cern.ch/event/649760

Conclusions

- **CMS Phase-2 upgrade for HL-LHC:** maintain excellent performance of the detector in efficiency, resolution, and background rejection

  → withstand **radiation damage, trigger thresholds** and **pileup**

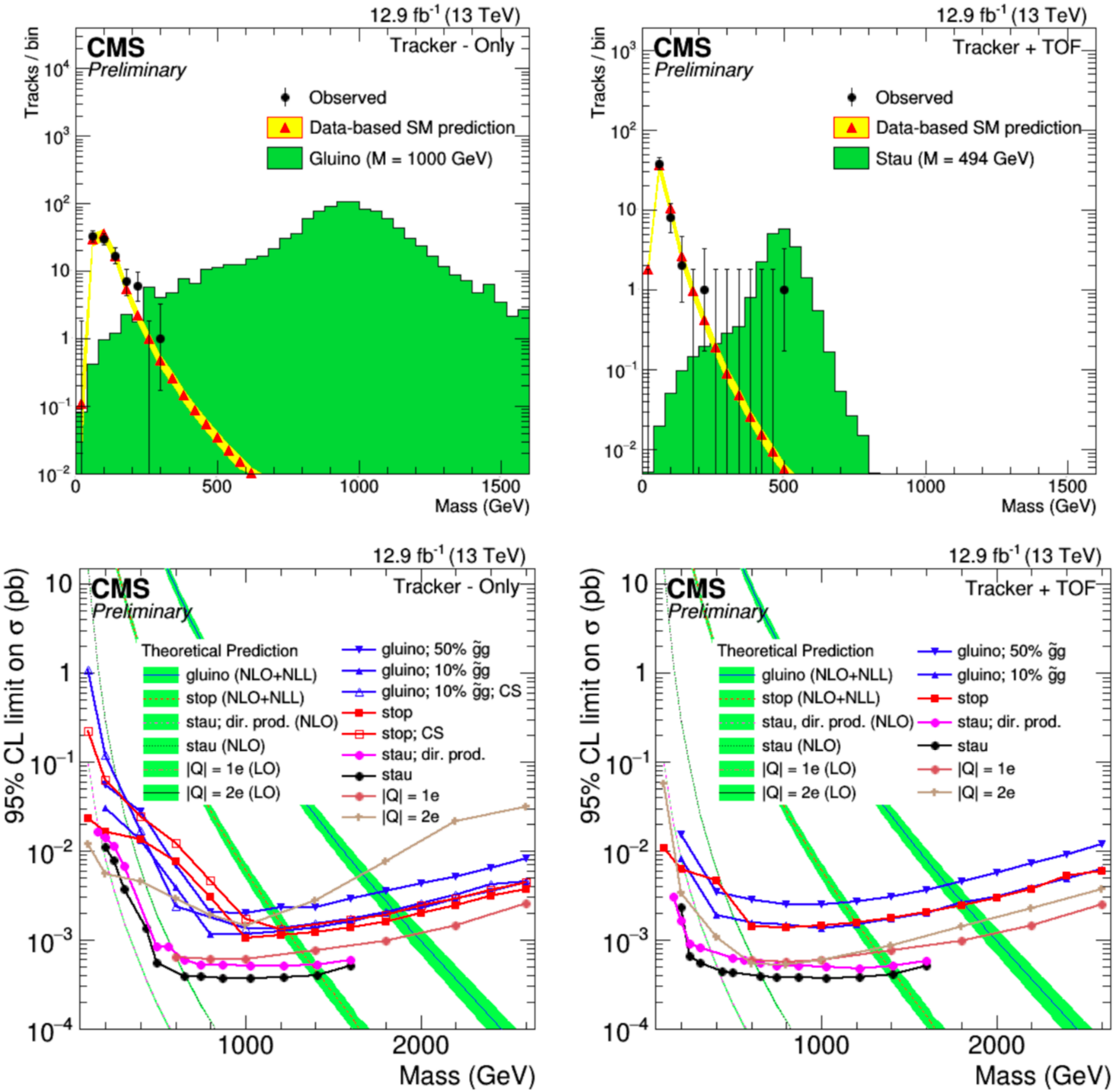
- Many LLP SEARCHES will benefit from **extra info from upgraded detectors and improved tools**

- *HL-LHC Phase2 will fundamentally* ***changes how we execute LL searches***

- Significantly **expand physics program for CMS in HL-LHC**

Backup

HSCP - EXO-16-036



Upgrade Muon System

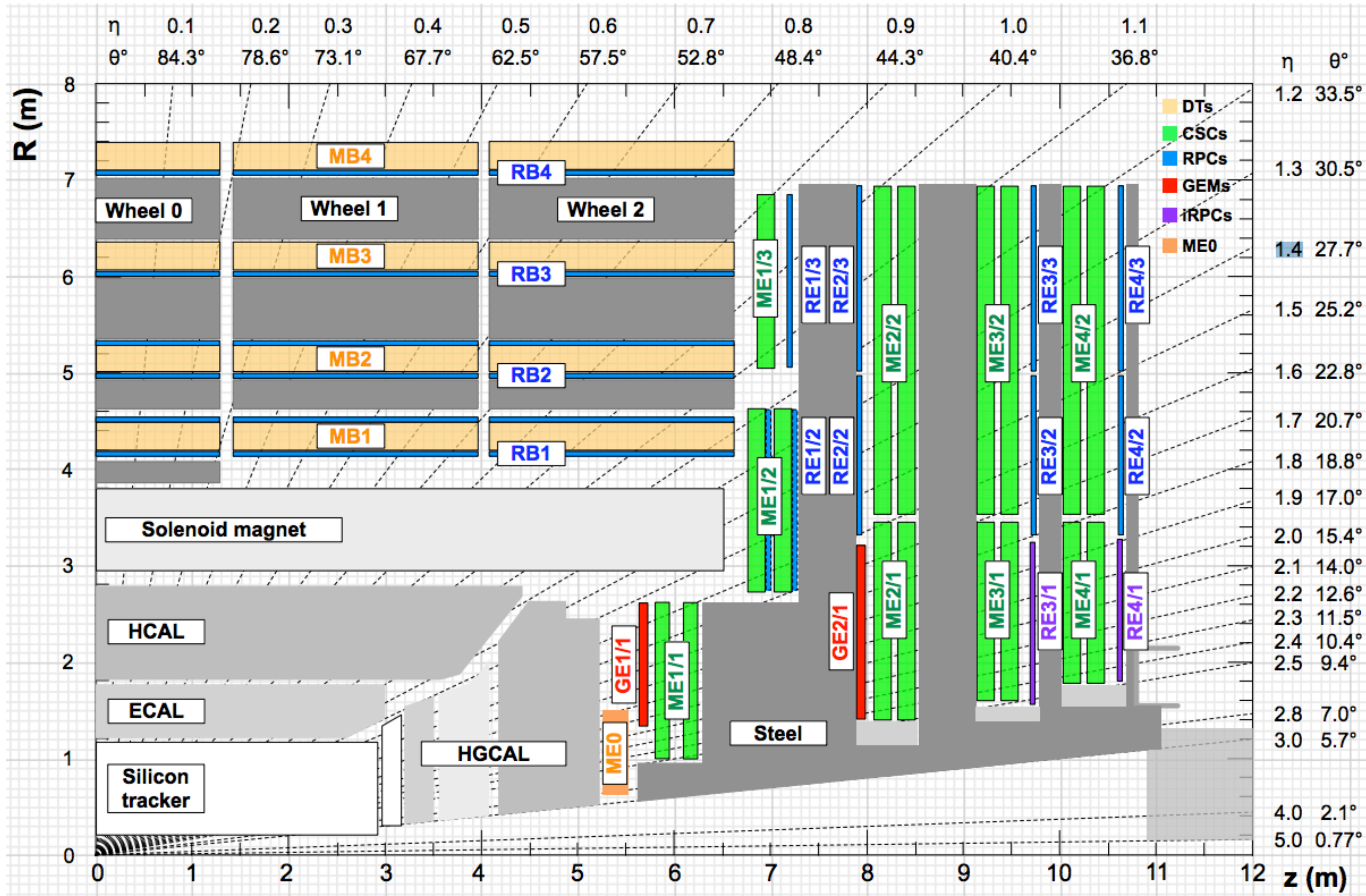


Figure 1.4: An *R*-*z* cross section of a quadrant of the CMS detector, including the Phase-2 upgrades (RE3/1, RE4/1, GE1/1, GE2/1, ME0). The acronym iRPCs in the legend refers to the new improved RPC chambers RE3/1 and RE4/1. The interaction point is at the lower left corner. The locations of the various muon stations are shown in color (MB = DT = Drift Tubes, ME = CSC = Cathode Strip Chambers, RB and RE = RPC = Resistive Plate Chambers, GE and ME0 = GEM = Gas Electron Multiplier). M denotes Muon, B stands for Barrel and E for Endcap. Labelling details are given in Section 1.2.2. The magnet yoke is represented by the dark gray areas.

Neutralino Mass Constraint

Precision timing gives $\vec{\beta}$ of LLP

$$\vec{\beta}_P^{LAB} = \frac{1}{c} \cdot \frac{\vec{D}}{T_v - T_0} = \frac{\vec{P}_P^{LAB}}{E_P^{LAB}}$$

We assume we have measured

$\vec{\beta}_P^{LAB}$ - velocity of parent particle in the lab

E_V^{LAB}, $\vec{P}_V^{LAB}$ - energy and momentum of visible decay products

Can boost visible system to LLP rest frame

$$E_V^P = \gamma_P \left(E_V^{LAB} - \vec{P}_V^{LAB} \cdot \vec{\beta}_P^{LAB} \right)$$

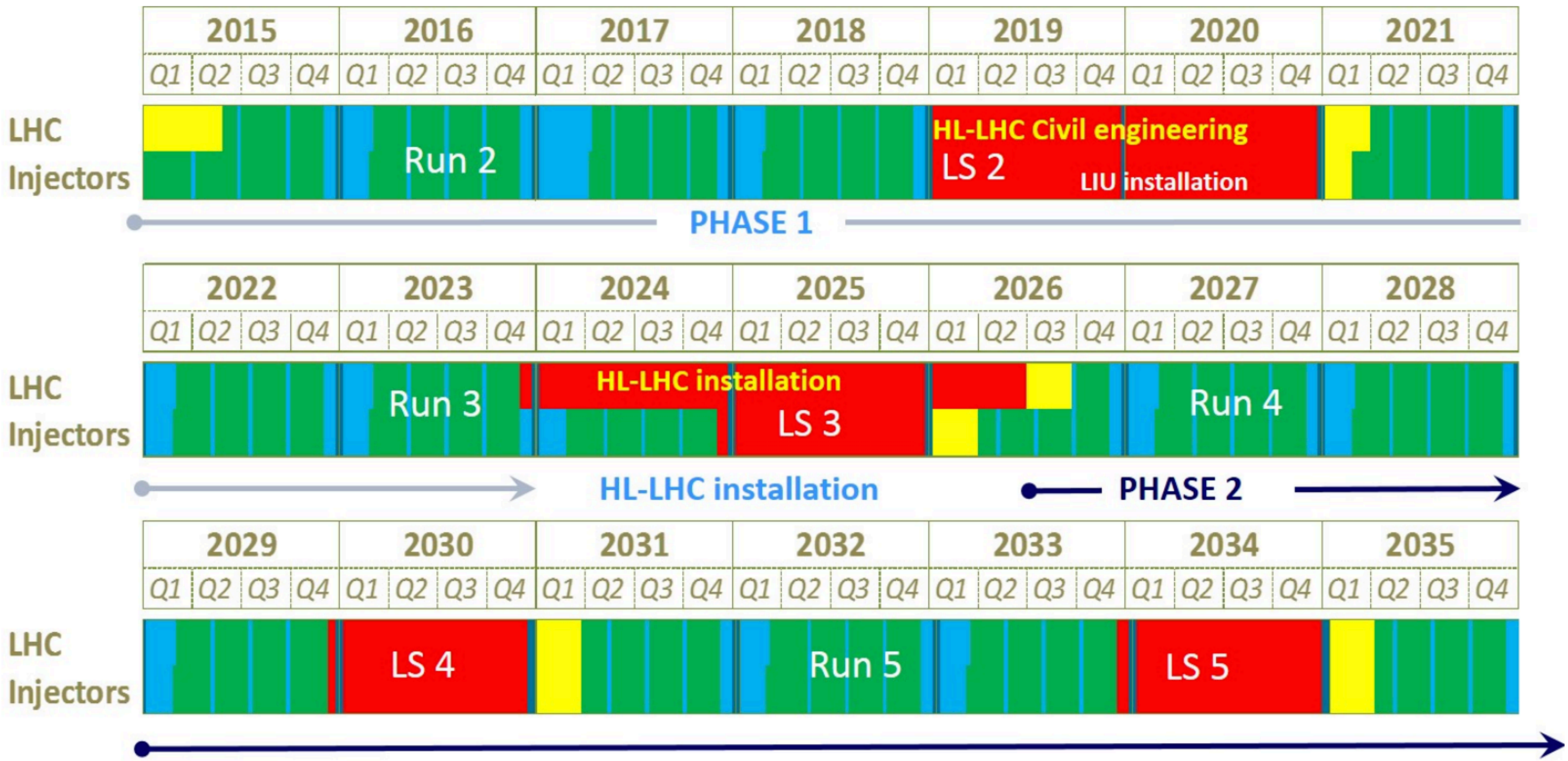
Energy of visible system in LLP rest frame

$$E_V^P = \frac{m_P^2 - m_I^2 + m_V^2}{2m_P}$$

Can **assume** invisible system mass to calculate LLP mass

$$m_P = E_V^P + \sqrt{E_V^{P2} + m_I^2 - m_V^2}$$

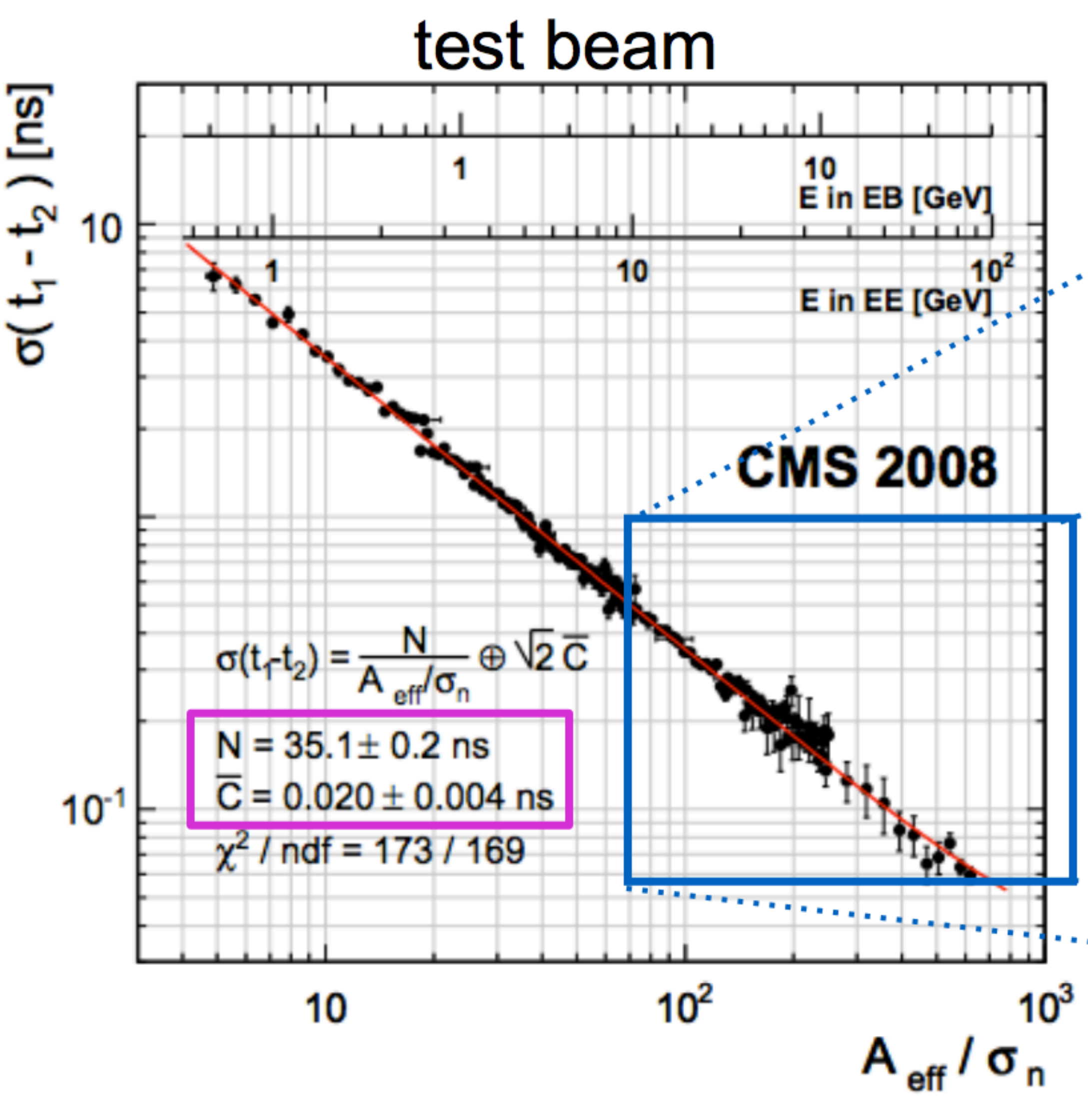
HL/HE LHC Schedule



ECAL timing measurement

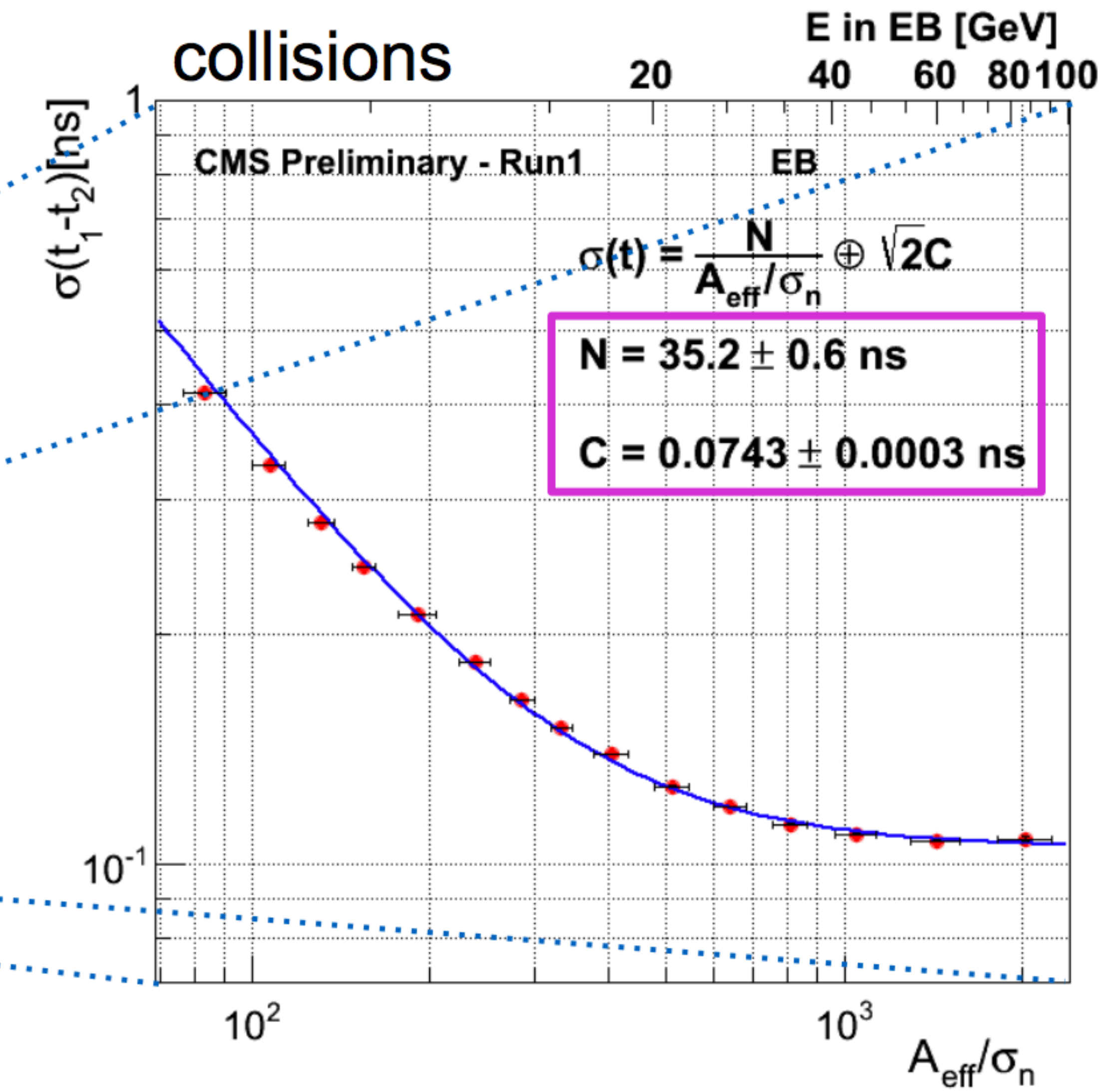
- **Lead tungstate** fast scintillation response – **about 80% of the light emitted in 25 ns**

@ **test beam in 2008** intrinsic ECAL precision measured with electrons



E_{EB} >30GeV σ_T <50ps

@ **collisions** with electrons from Z decay



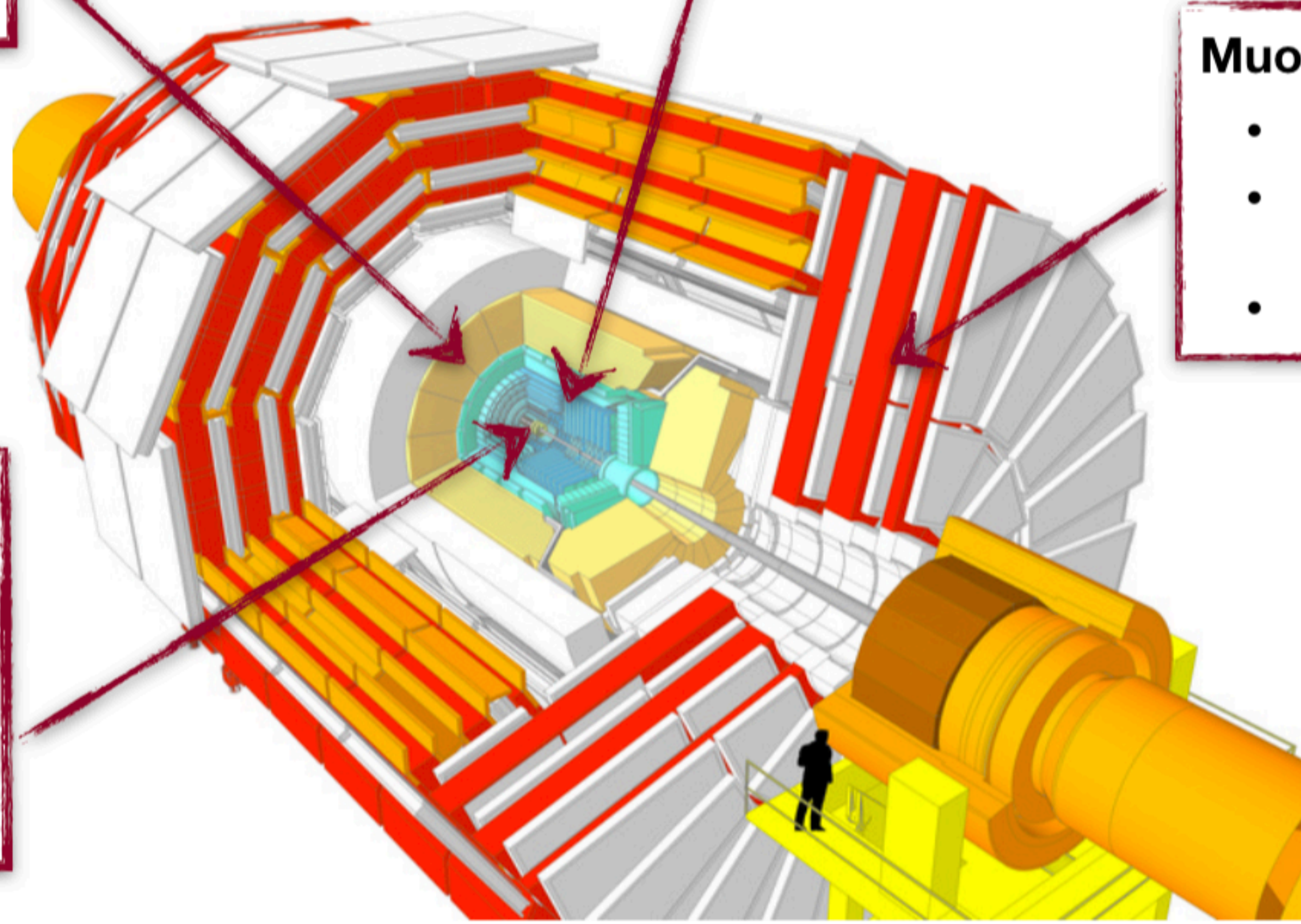
σ_T <150ps

CMS Phase2 Upgrade Plans

New Forward Calorimetry
- Entirely made of silicon
- Radiation tolerant
- ‘5D’ measurement

Central ECAL
- New electronics
- Lower operating temperature (10°C)

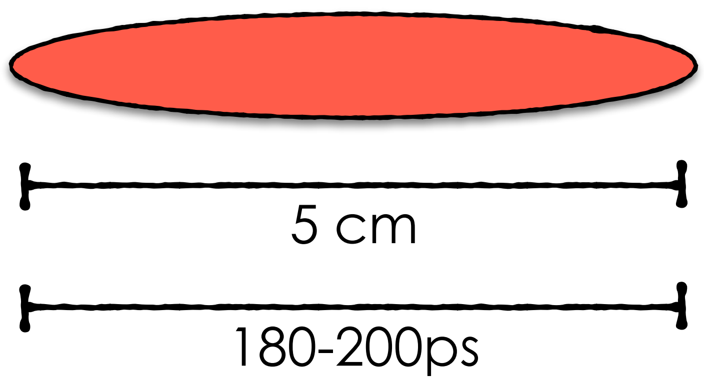
Muon System
- New electronics
- New forward chambers
- Up to |η| = 3

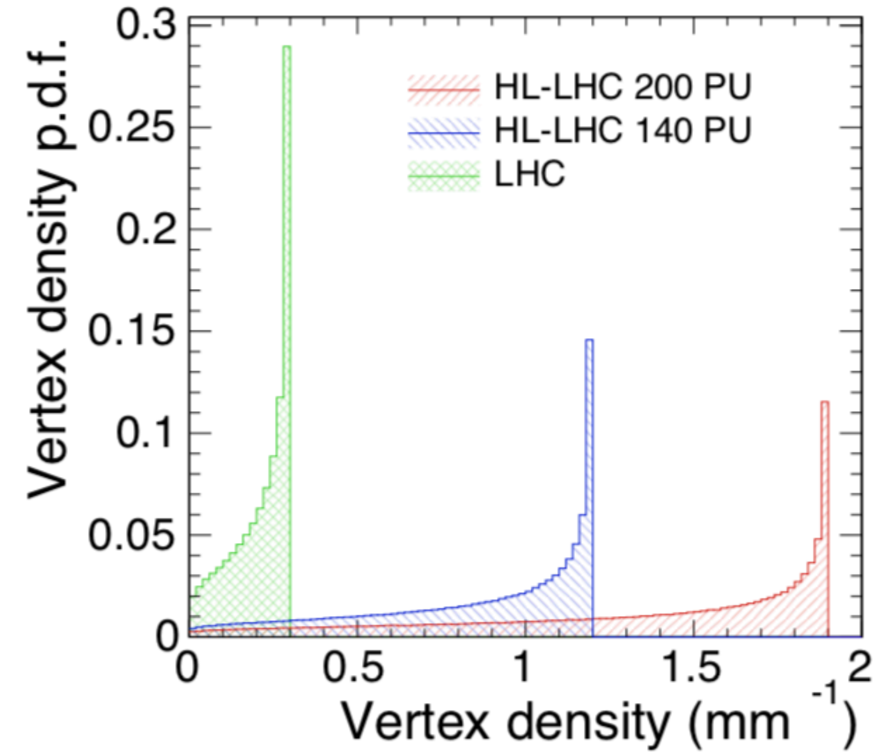


New Tracker
- Radiation tolerant
- Light
- Full-blown tracking at trigger level
- Pixels up to |η| = 4

HL-LHC Pileup

Inst Lumi @ HL-LHC: 5.2 or 7.2×10^{34} $cm^{-2}s^{-1}$, yielding 140 or 200 pileup





- spatial overlap of tracks and energy deposits:

  degrade identification and reconstruction and confuse the **trigger**.

MTD:

- slicing the beam spot in consecutive **time exposures of 30 ps**:

  ⇨ **reduce the 'effective multiplicity'** of pileup recovering the Phase-1 track purity of vertices.

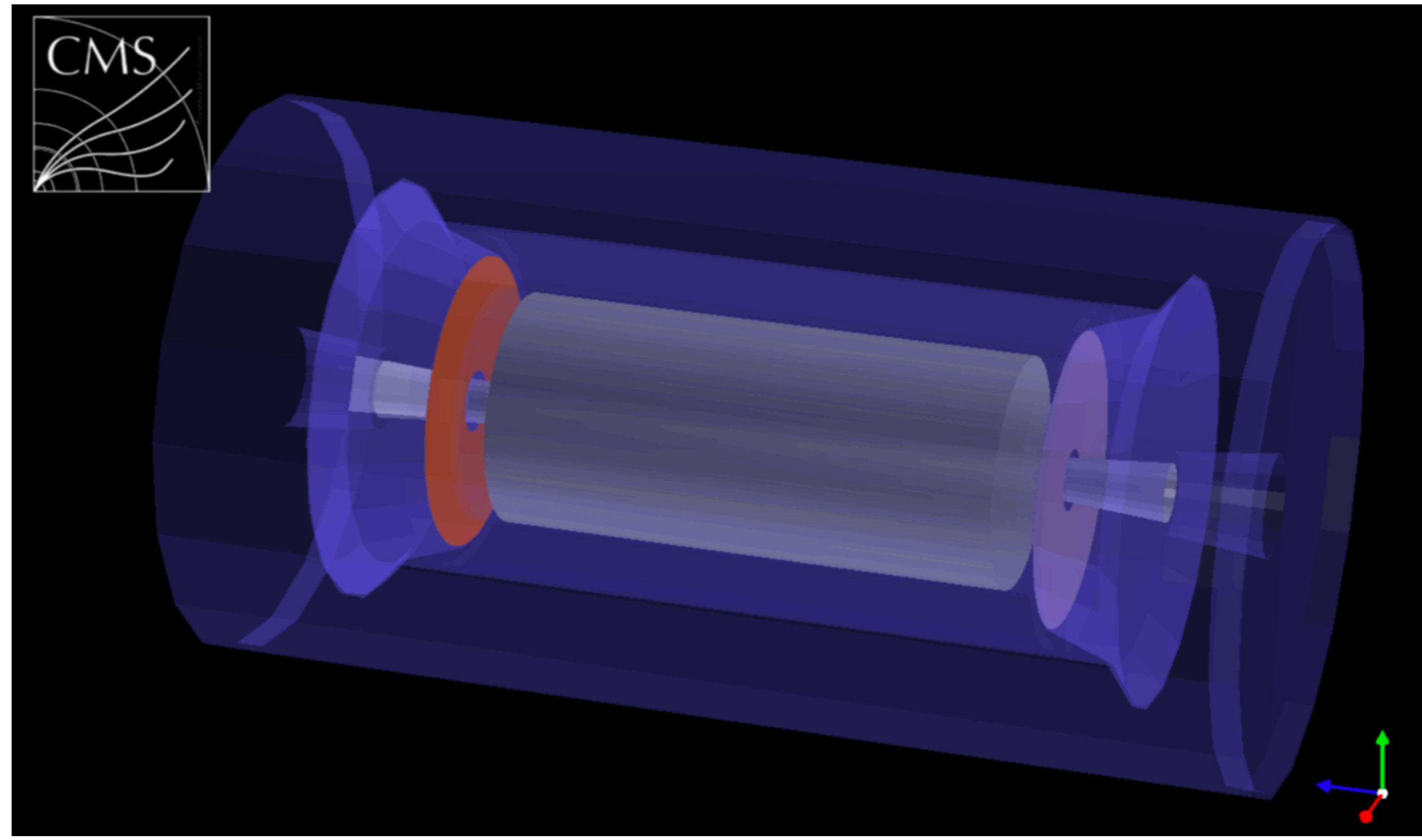
- consolidate the particle-flow performance @140 and extend it up to 200

MTD Overview

- **Thin layer between the tracker and the calorimeters**, divided in a barrel ($|\eta| < 1.5$) and two endcap sections covering up to $|\eta| = 3.0$.

⇨ space and integration constraints

- **hermetic** coverage, with **time resolution of order 30–40 ps**



- Granularity: A channel area of order **1 cm^2 in the barrel**, and **varying in the endcaps down to 3 mm^2** at $|\eta| \sim 3$,

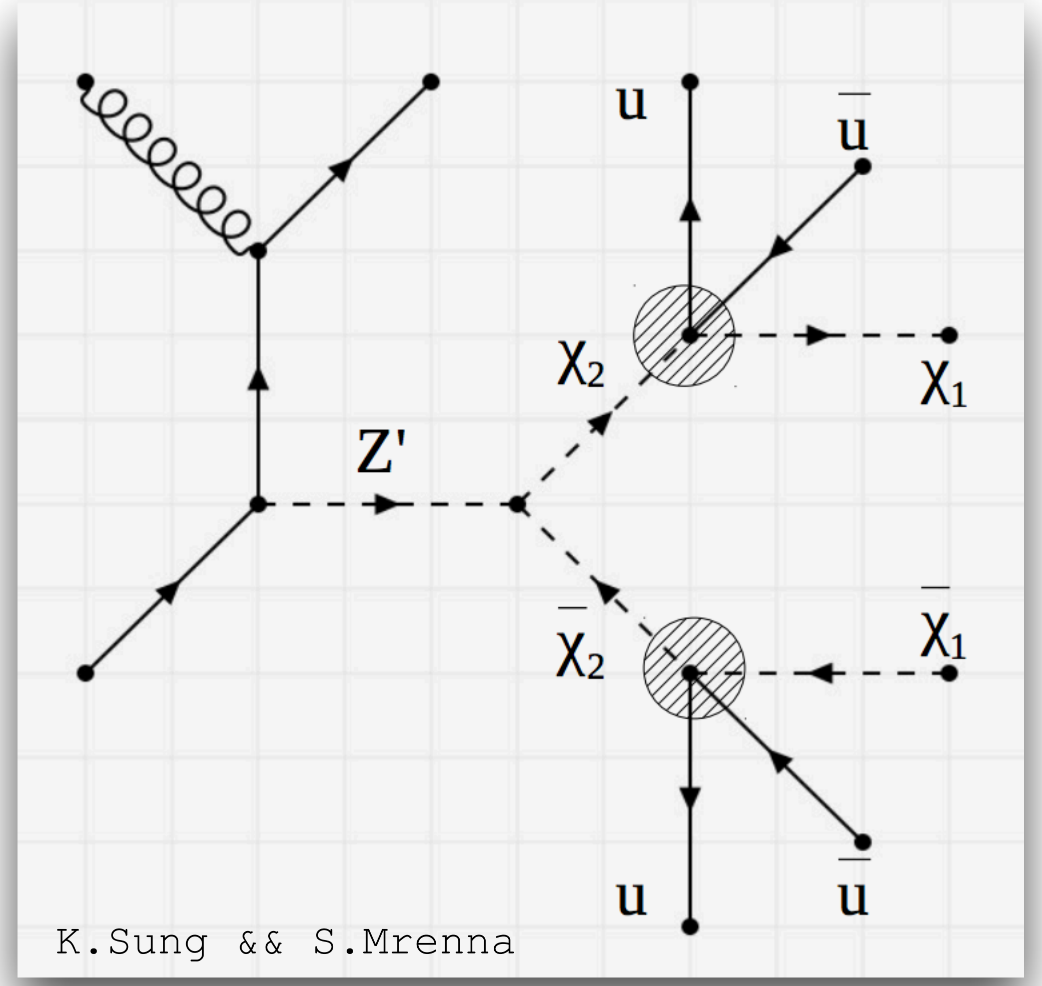
⇩

good compromise between **low time response spread** within a channel, **low occupancy and low channel count**

- Radiation tolerance: The devices must be able to operate **efficiently up to an integrated luminosity of 4000 fb^{-1}**

Displaced Dark Matter Signatures

- **Extend DM model to involve long-lived decays**
- **Primary vertex:** dark matter simplified
- **Displaced secondary vertex:** characterized by the **mass of the long-lived particle and its lifetime**
- Excited dark sector state χ_2
- χ_2 lifetime depends on the masses of the particles involved and their couplings



- Both EFT or Simplified Approach can be used to describe the interaction

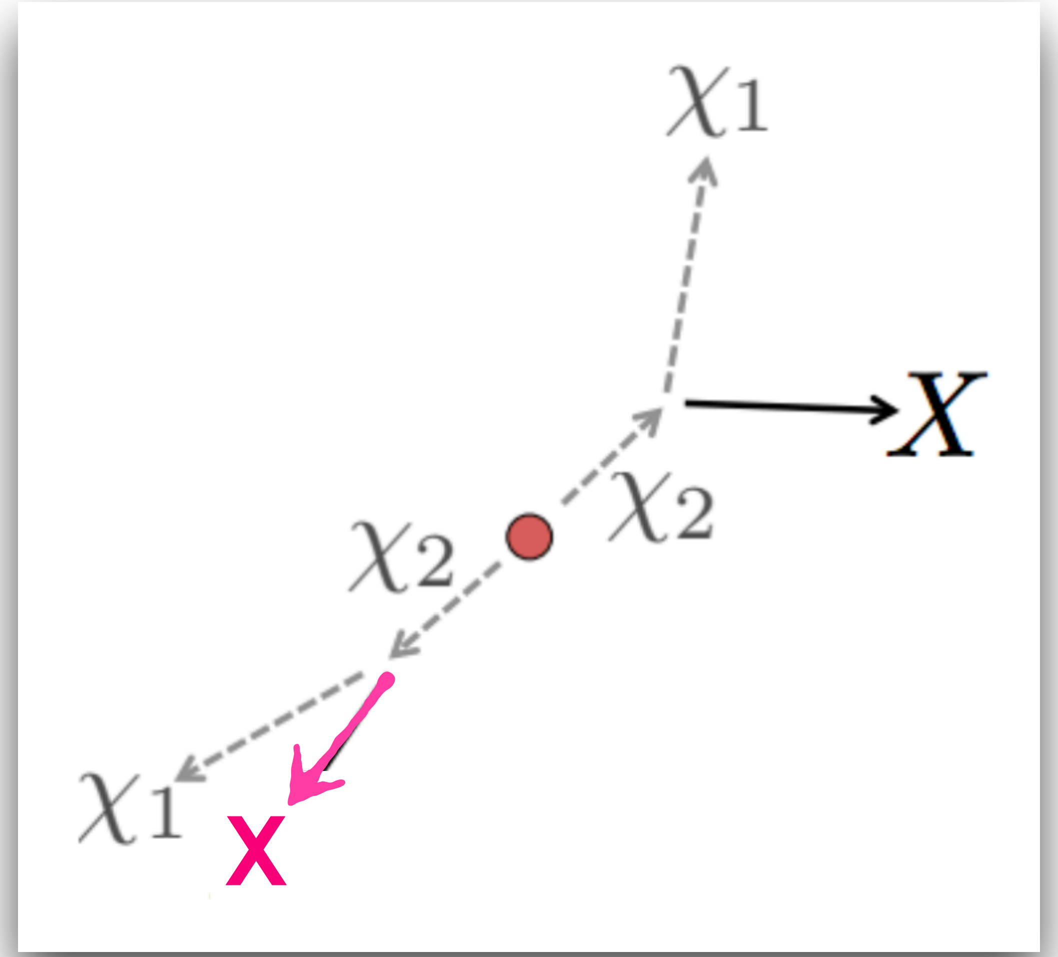
Displaced Dark Matter Signatures

- No backgrounds from SM processes: excellent **target for the HL-LHC**

- Softer-MET spectrum expected: χ_1 gets ~20% of the χ_2 momentum

- DM-recasting: detailed understanding of the **object reconstruction and background estimation**

  - Plan to include this interpretation in **2017 Mono-Jet and Mono-Higgs analyses**



https://arxiv.org/pdf/1704.06515.pdf