INFN ROMA
Istituto Nazionale di Fisica Nucleare
Sezione di Roma

CMS
Compact Muon Solenoid

Precision timing detectors

Quest for new physics at High Luminosity LHC

Livia Soffi

Challenges in the **future of LHC**:

Scientific and experimental problems and a joint solution

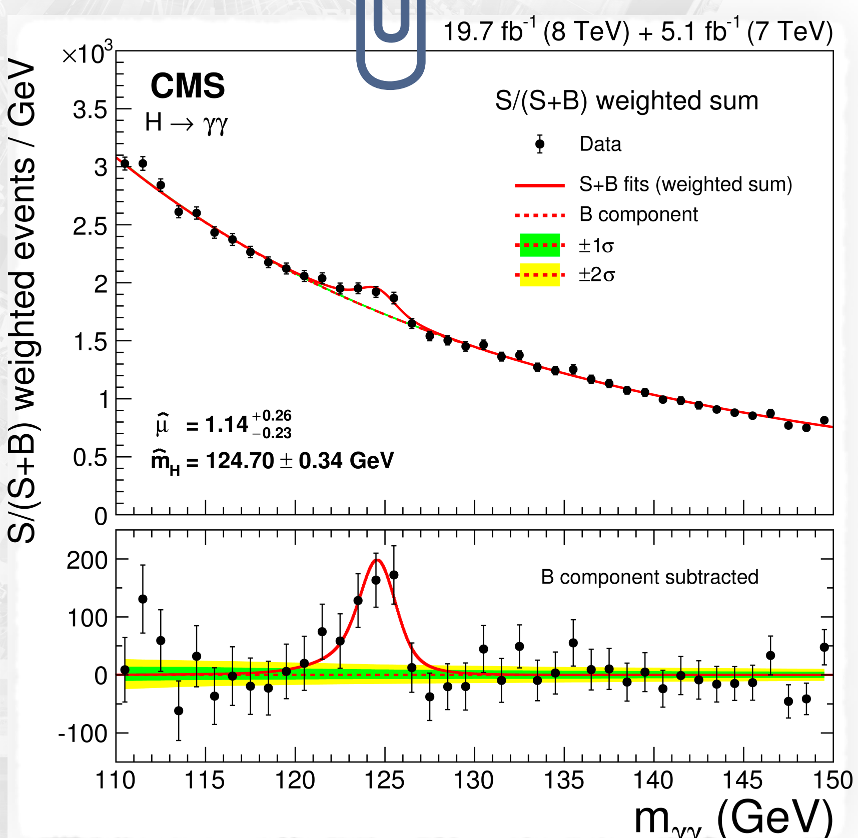
Run 1 & 2 Legacy

2014

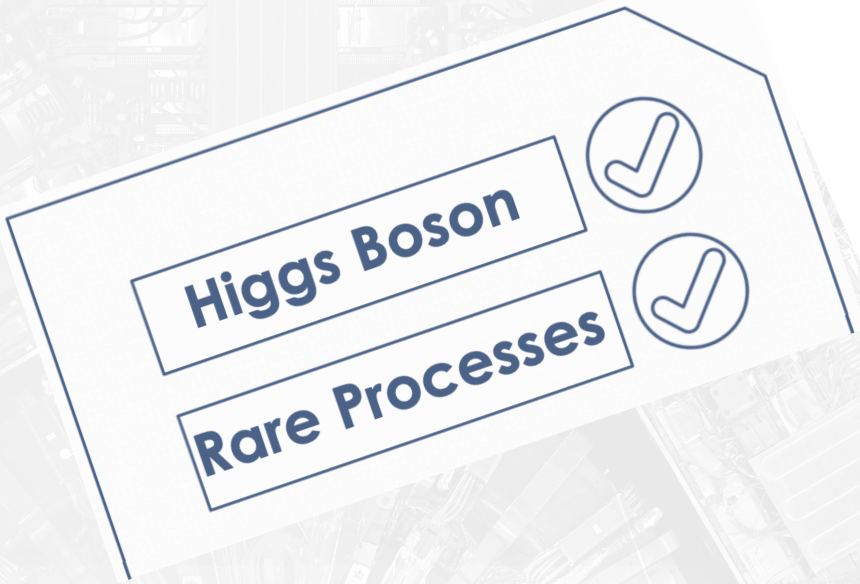
2020

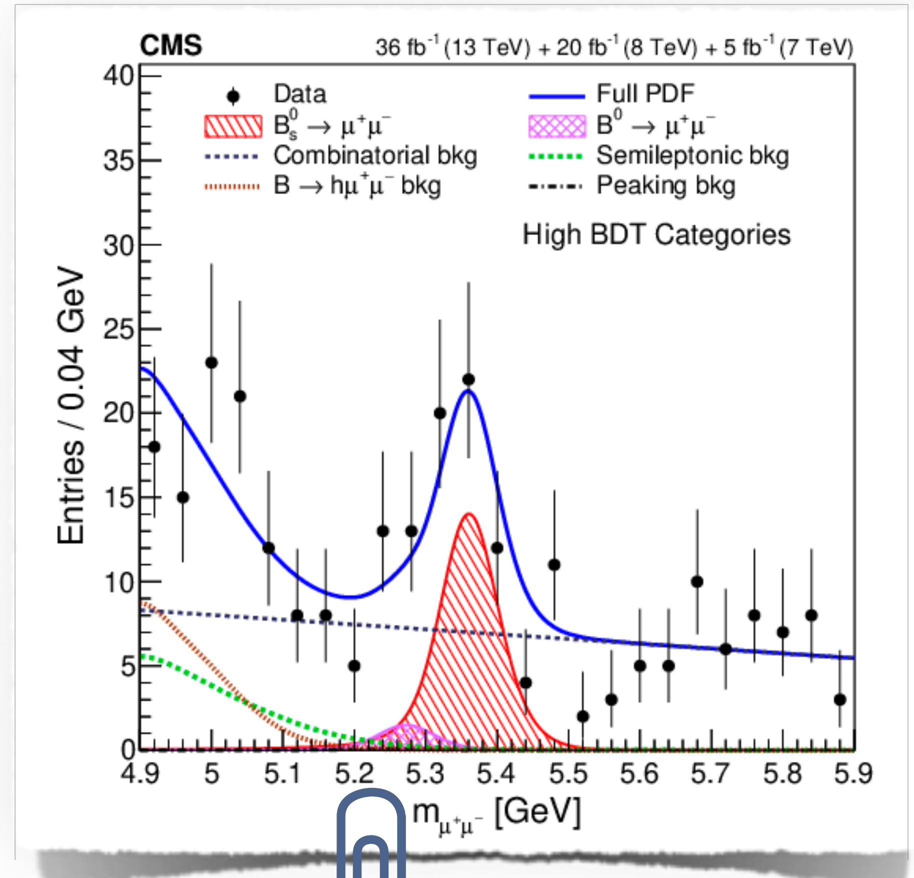
2019

t[years]



Run 1 & 2 Legacy





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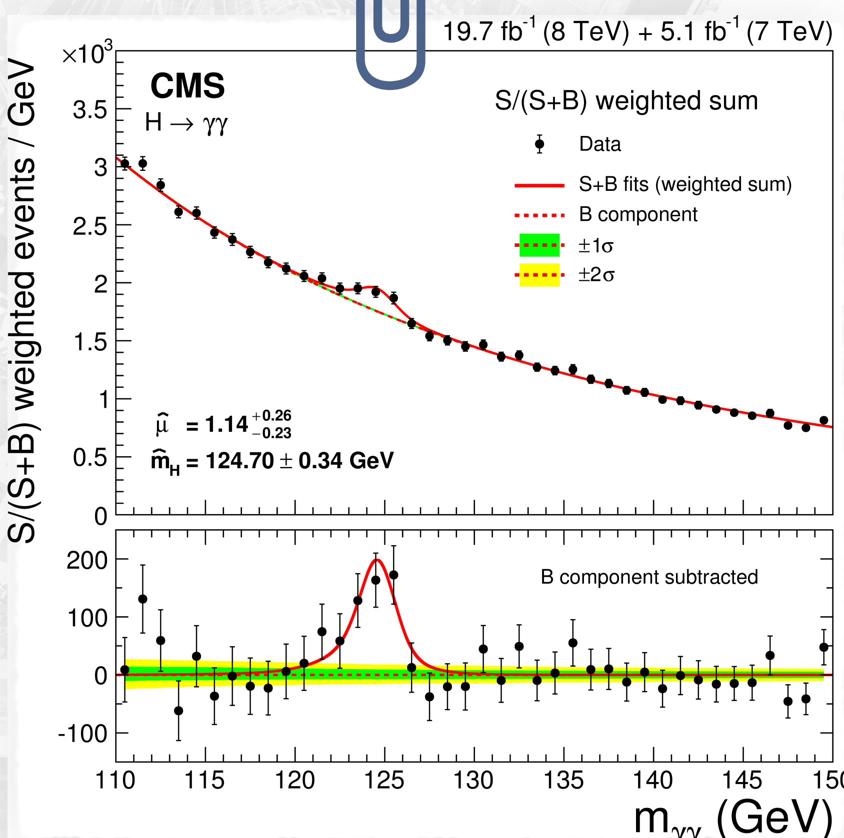

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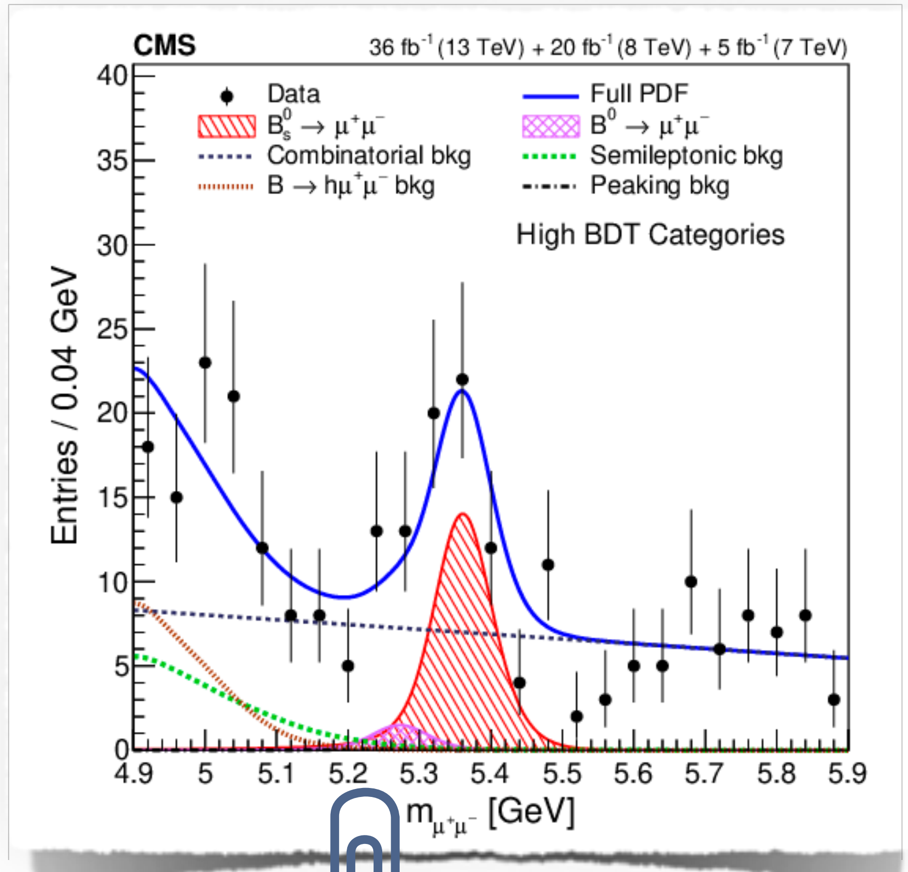

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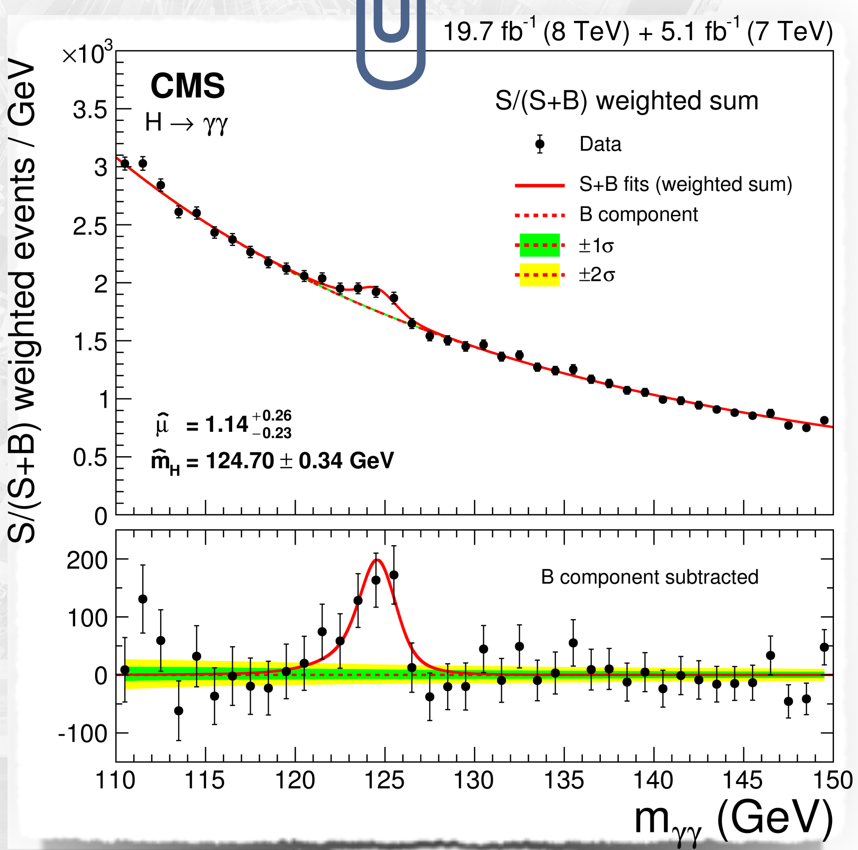
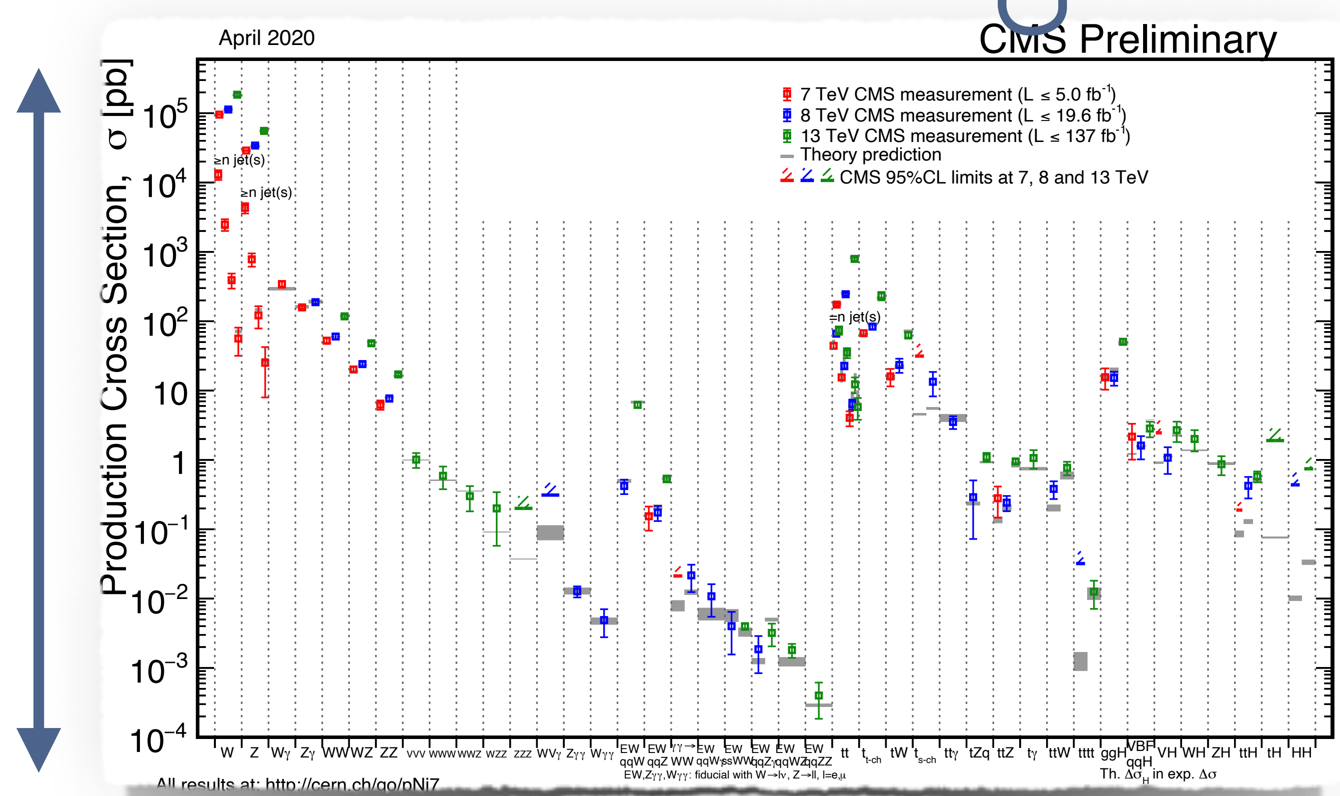
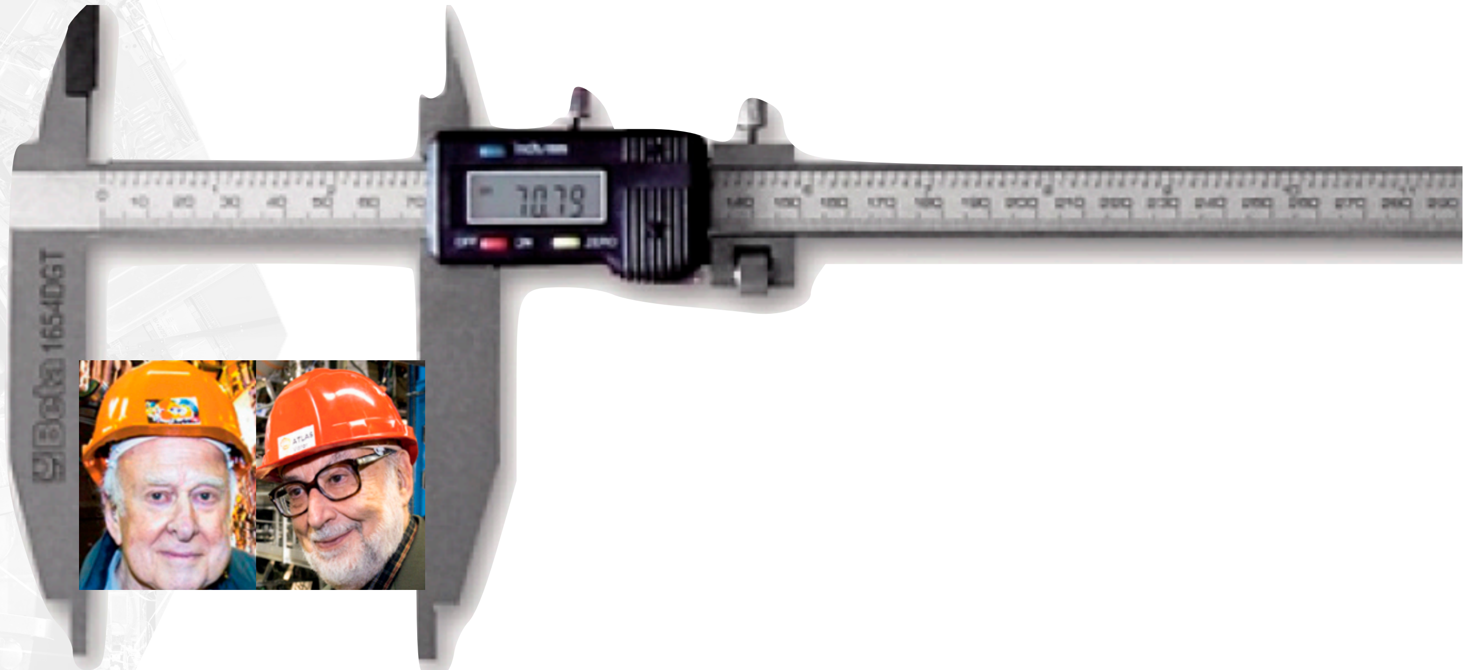


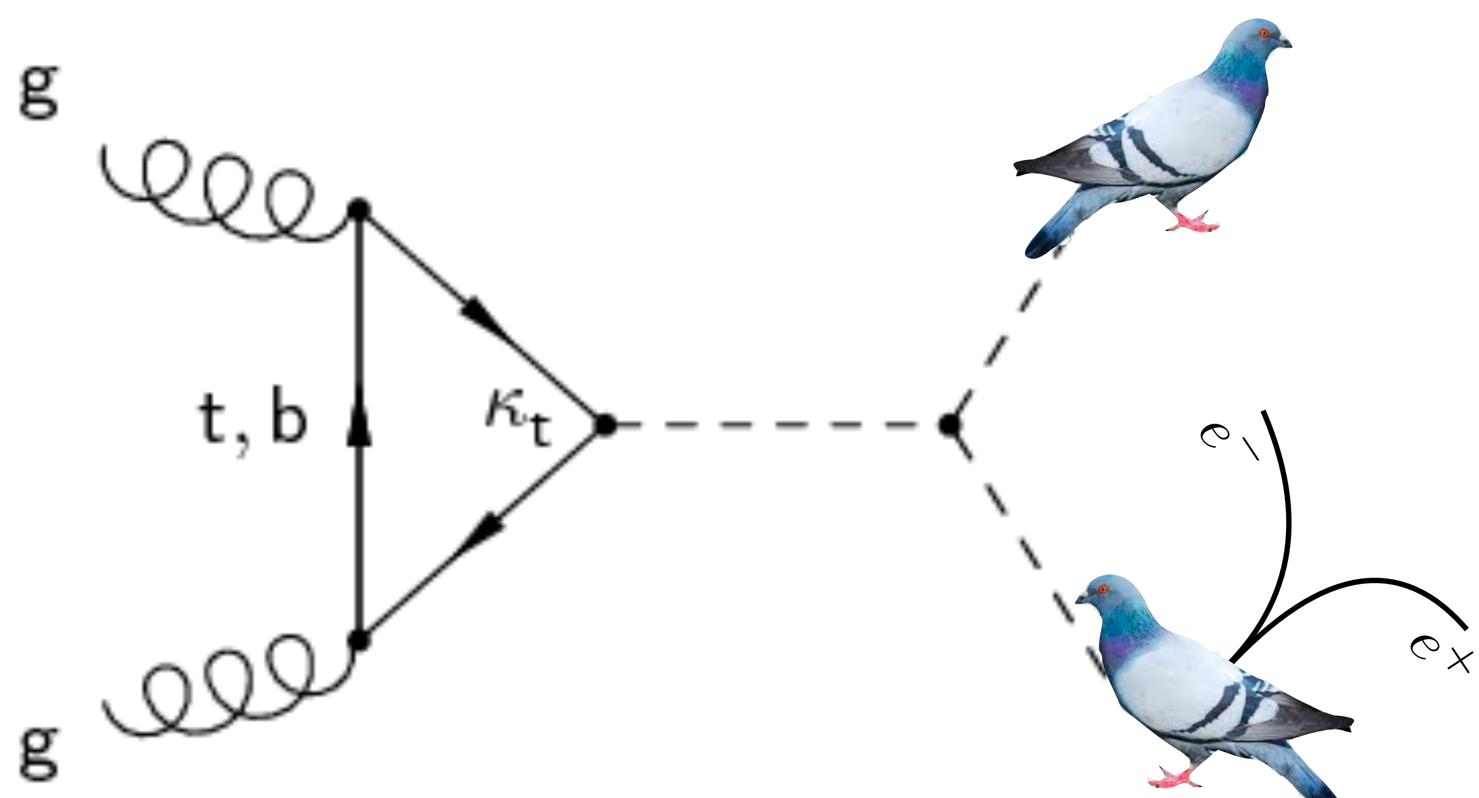


Quest for New Physics at Colliders

- **Indirect searches**: **see effects** caused by potential new particles

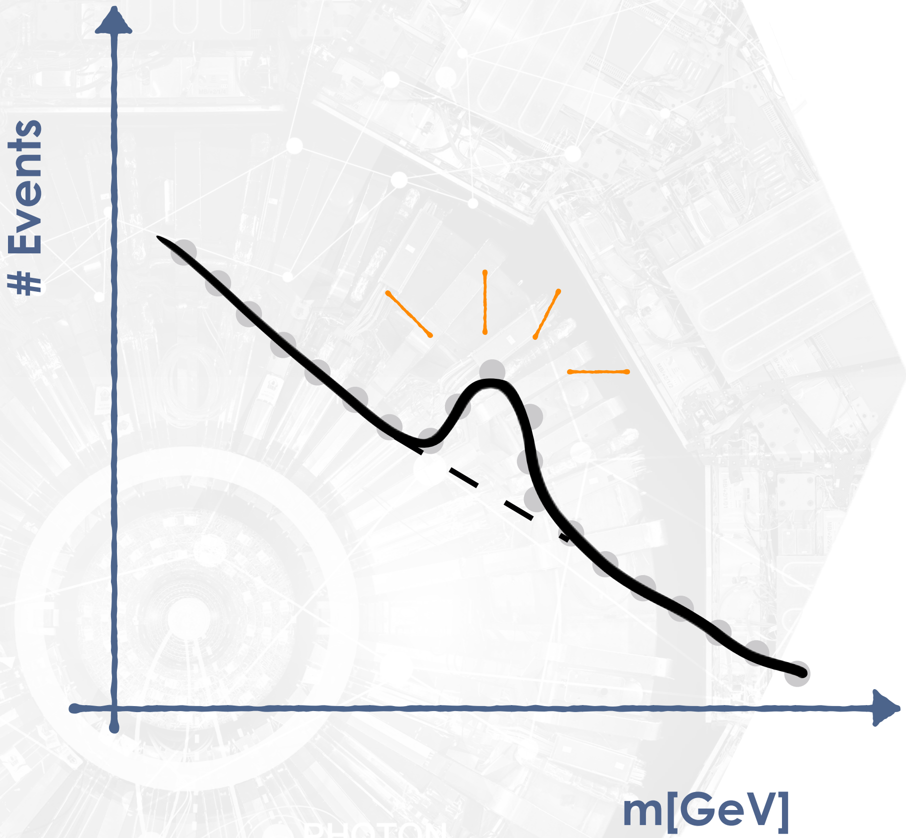


- **Direct searches**: **produce directly** new particles



A Path Toward Discovery at LHC

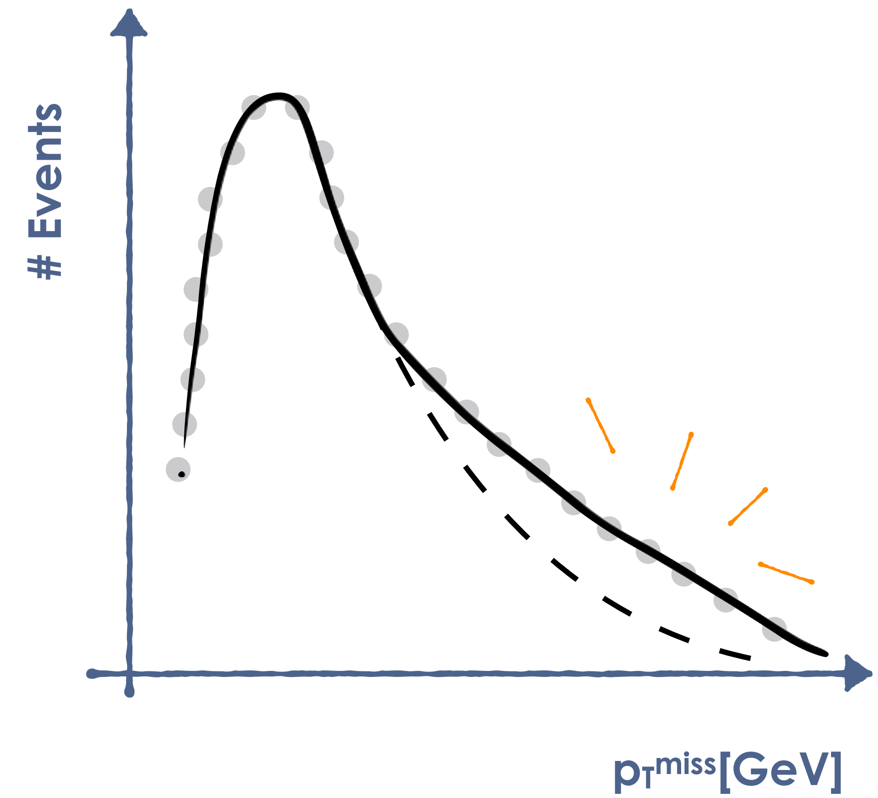
***Bump** searches*



$$m = \sqrt{2E_1E_2(1 - cos\theta)}$$

- **Golden way** for early discovery

***Exotic** signatures*

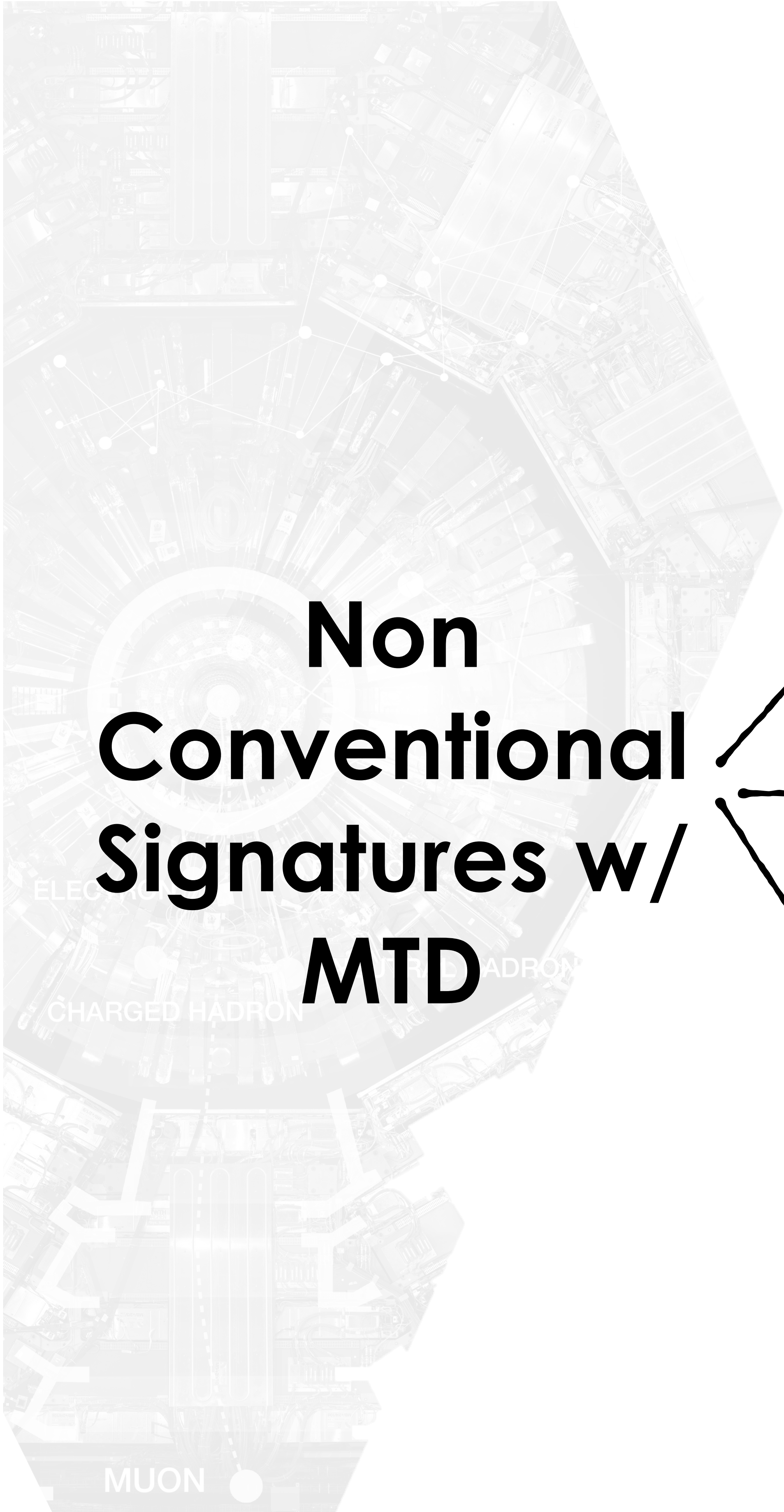


Missing Energy, Time of Arrival, Jet Multiplicity…

- ***Excess in the tail** of kinematic distribution*

Simplicity of final state

Detector Understanding



Non Conventional Signatures w/ MTD

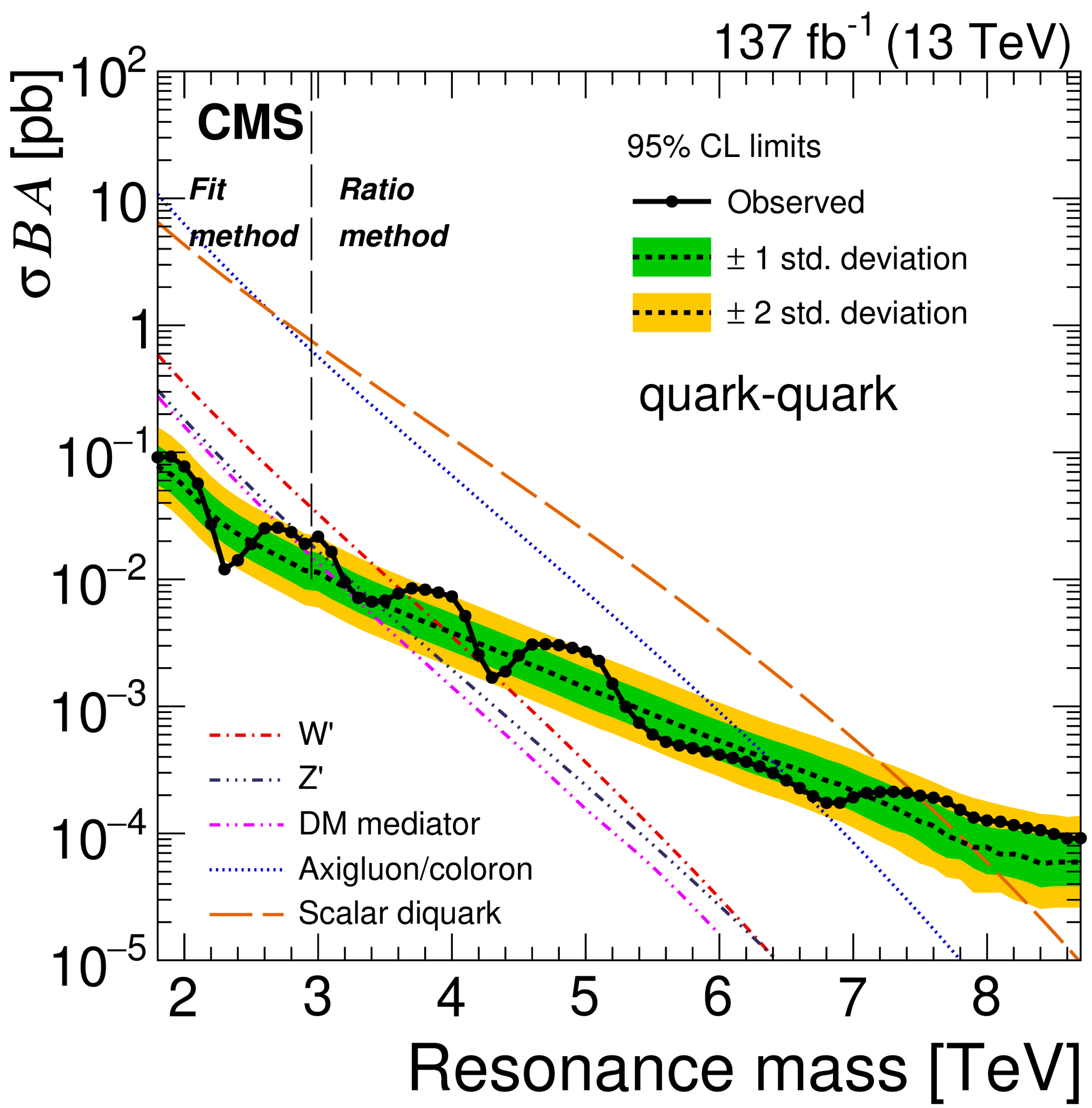
Dedicated **trigger** algorithms

Unique **object reconstruction**, discriminating variables, or **data processing**

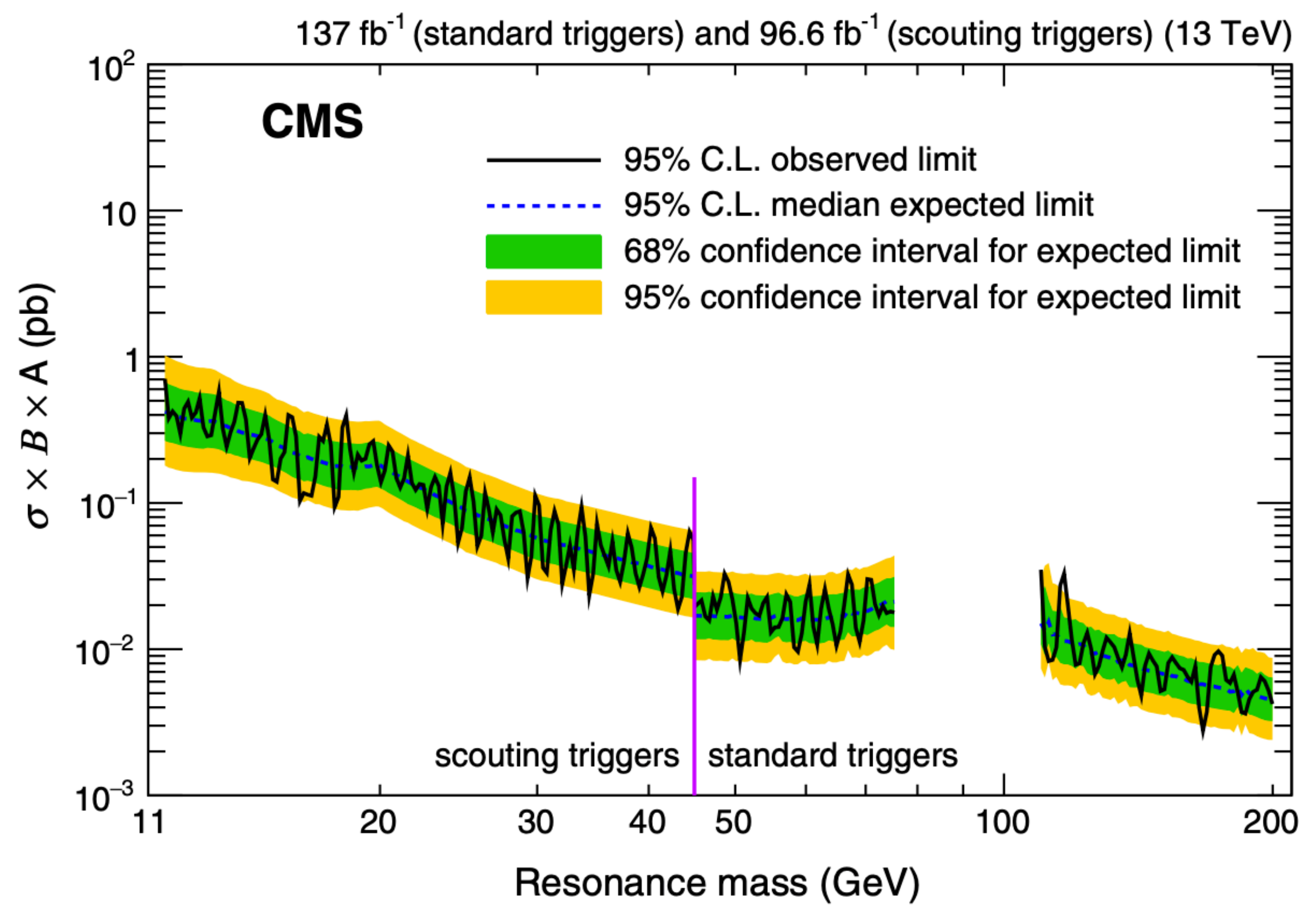
Re-defined **analyses strategies** w/ atypical backgrounds

Top Priorities for Frontier Research

Exploration of TeV scale



Low Mass Region



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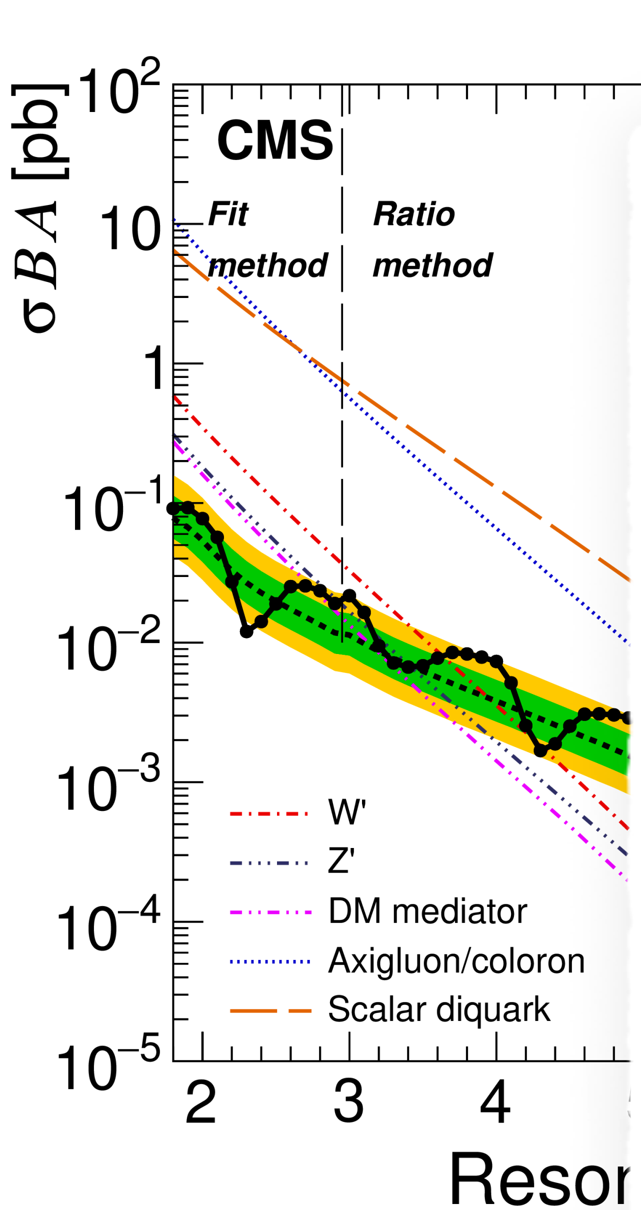

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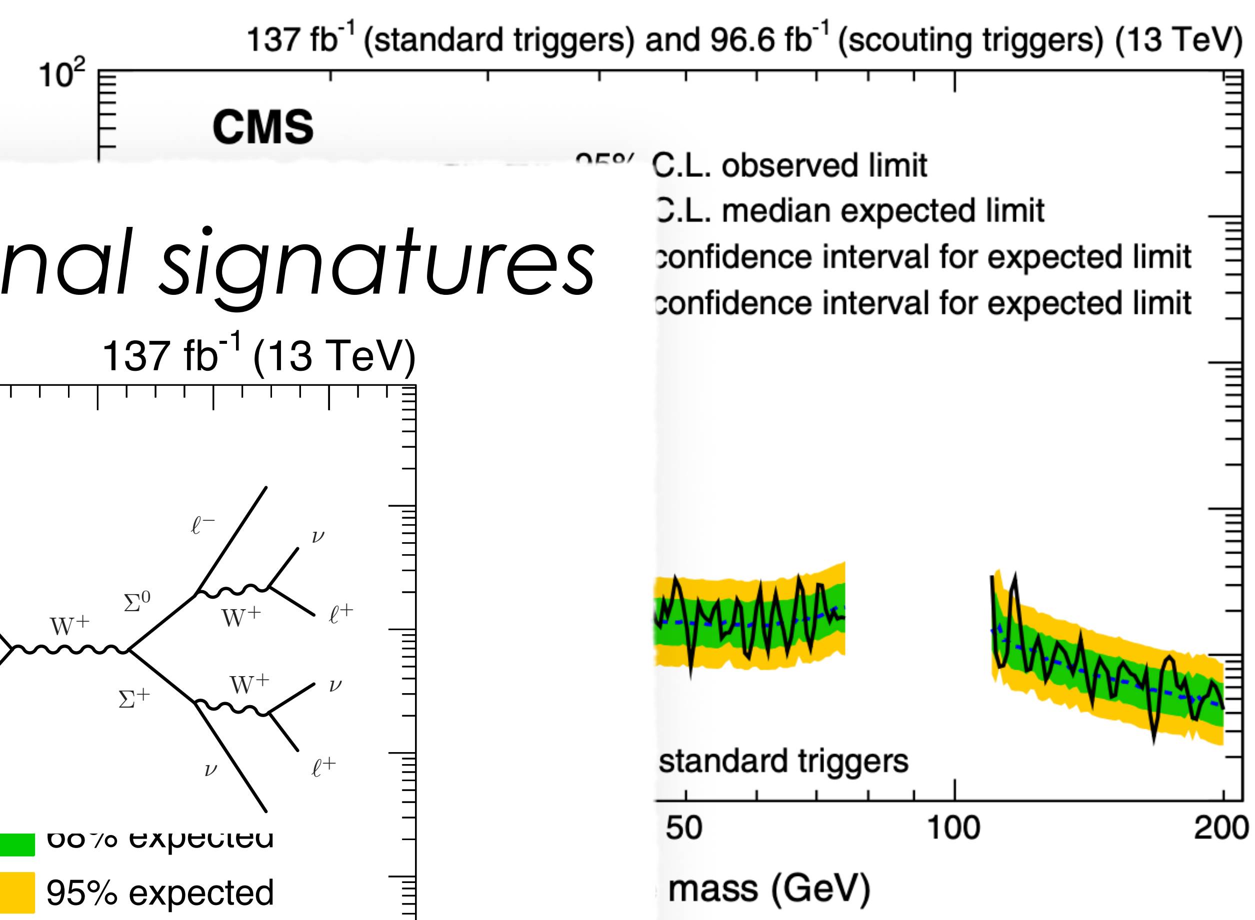
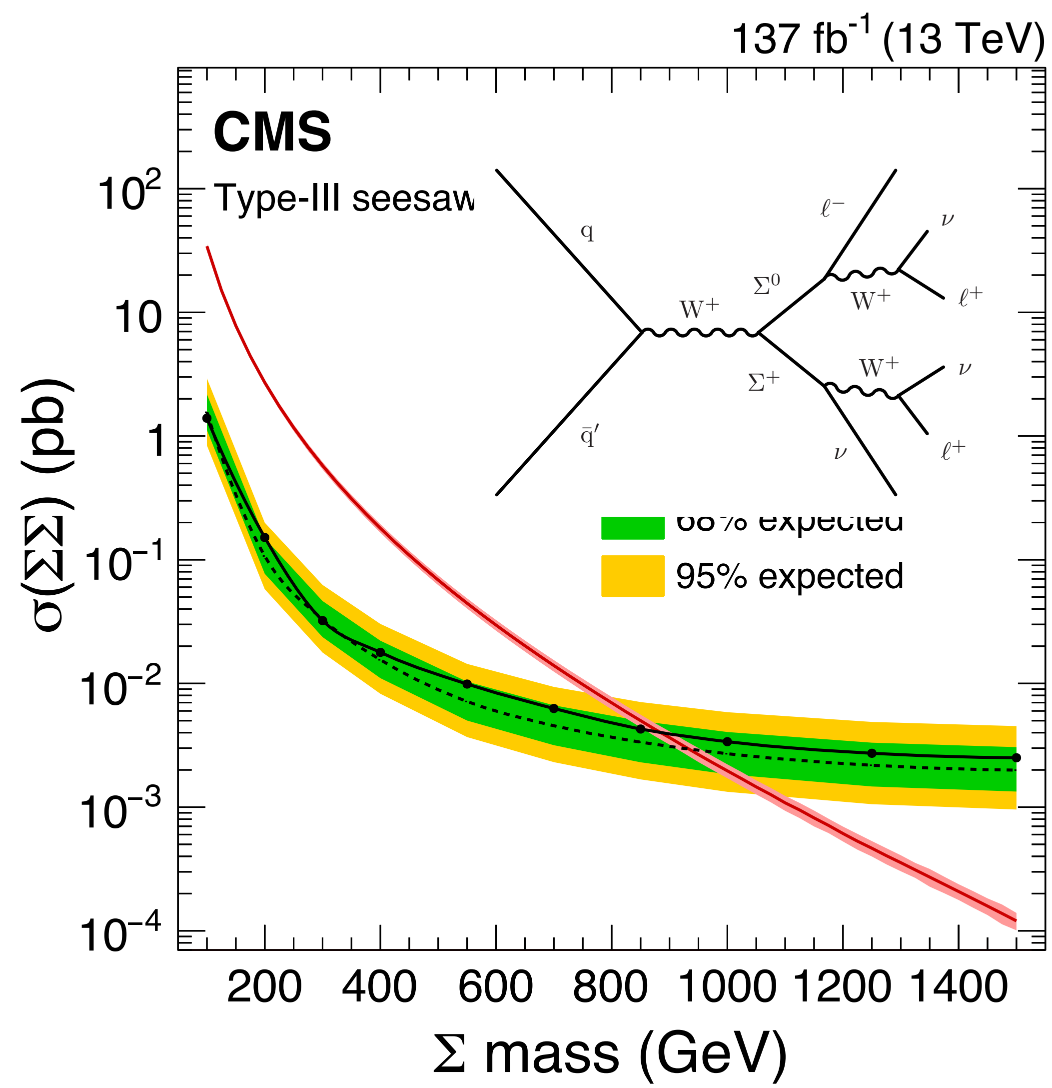


Non Conventional signatures



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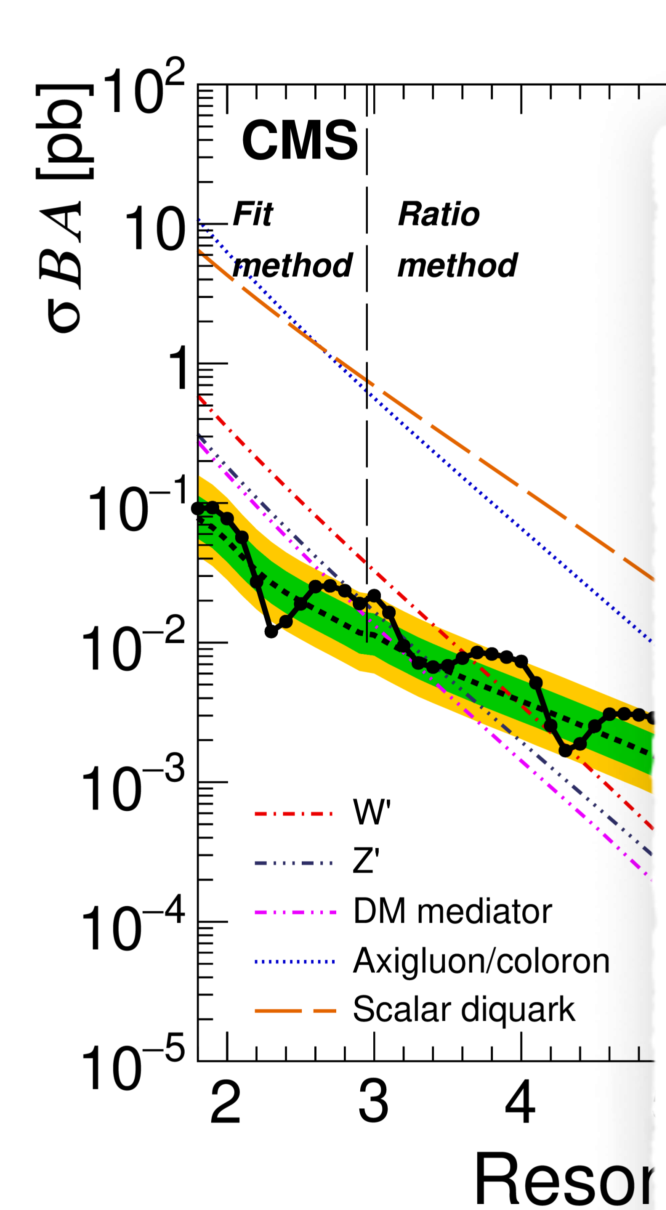

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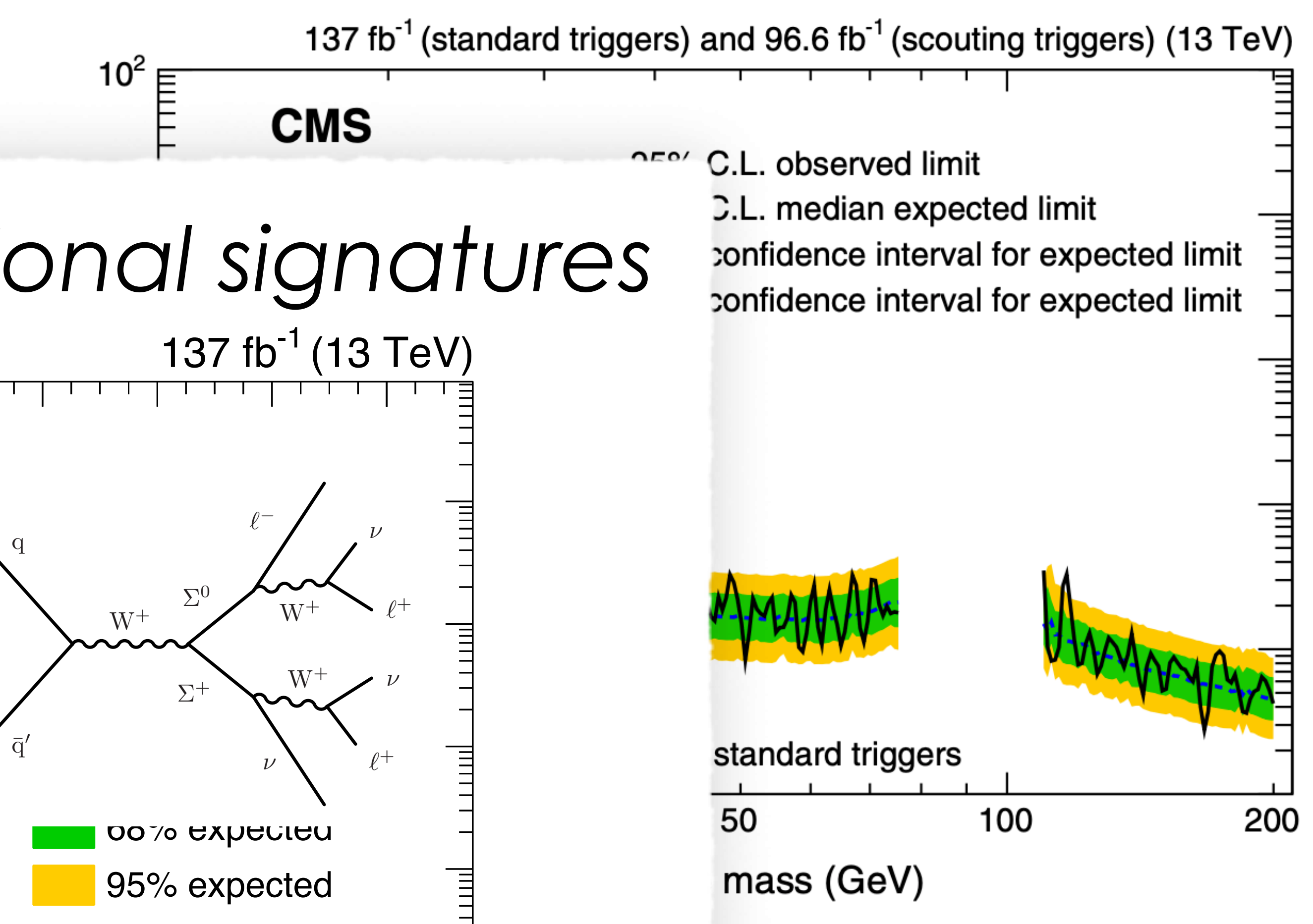
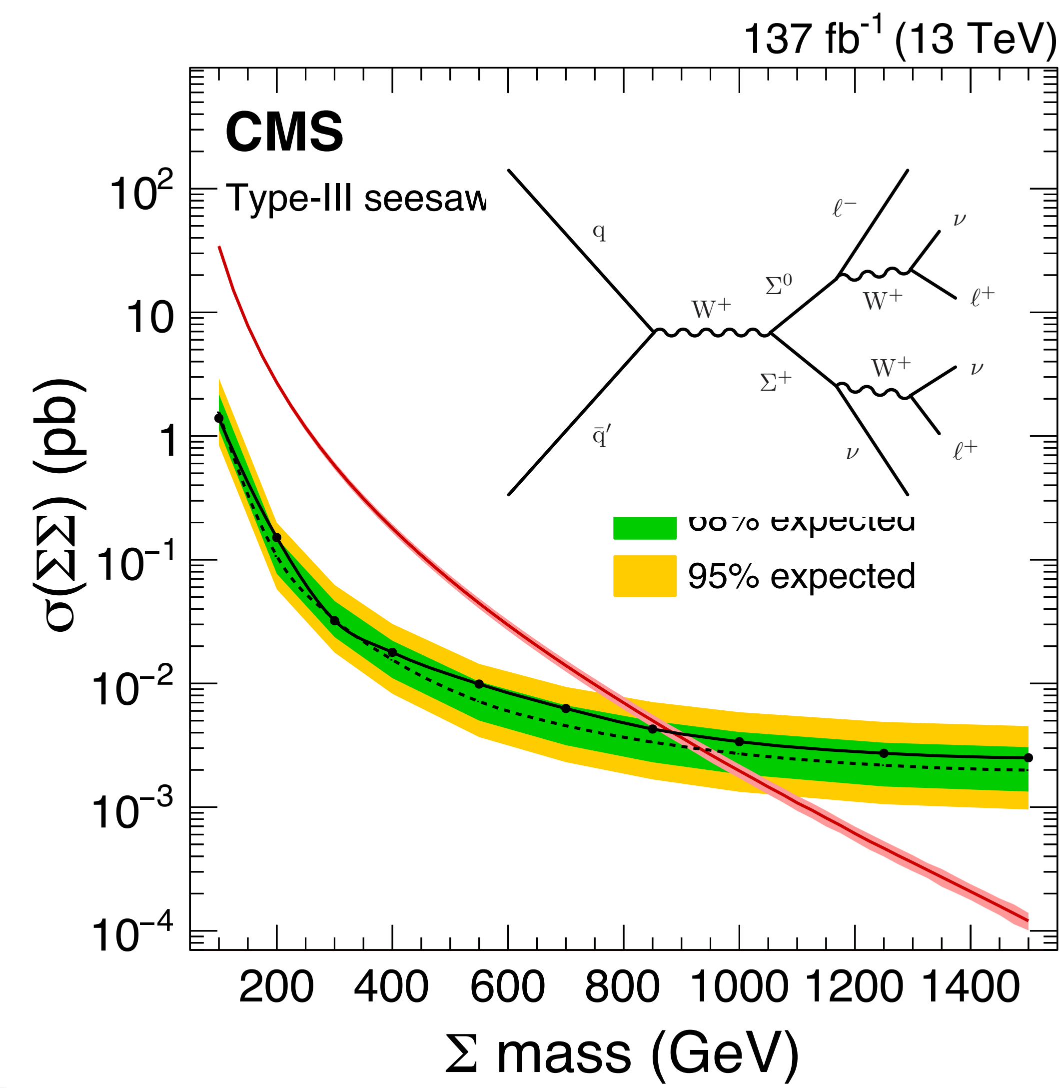


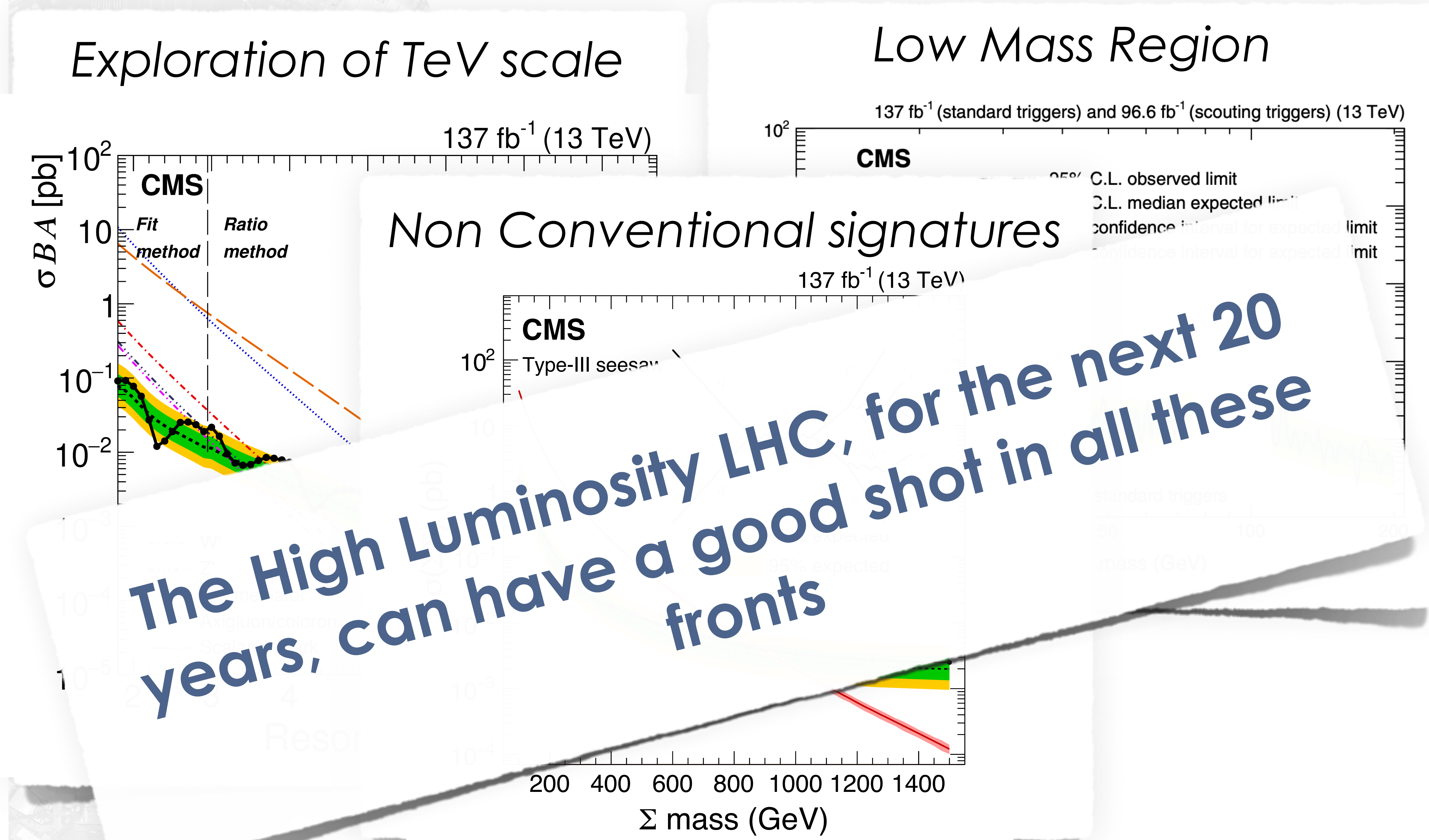
Non Conventional signatures



No sign of BSM physics ⟶ New Physics is heavier, lighter, less abundant or more weird w.r.t. we could detect so far

Top Priorities for Frontier Research

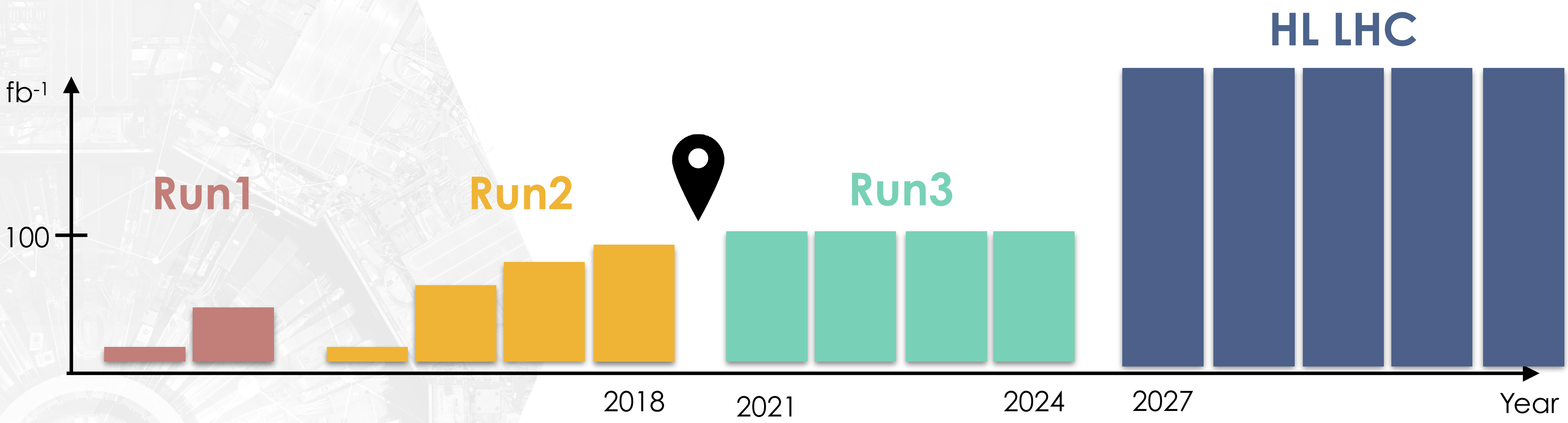
Exploration of TeV scale — *Low Mass Region* — *Non Conventional signatures*



The High Luminosity LHC, for the next 20 years, can have a good shot in all these fronts

No sign of BSM physics → New Physics is heavier, lighter, less abundant or more weird w.r.t. we could detect so far

Heading to the future at LHC



c.o.m. E: **13 TeV** **14 TeV**

Inst. Lumi: **2×10^{34} cm^{-2} s^{-1}** **$5\text{-}7.5\times10^{34}$ cm^{-2} s^{-1}**

Int. Lumi: **~ 150fb^{-1}** **~ 300fb^{-1}** **~ 3000fb^{-1}**

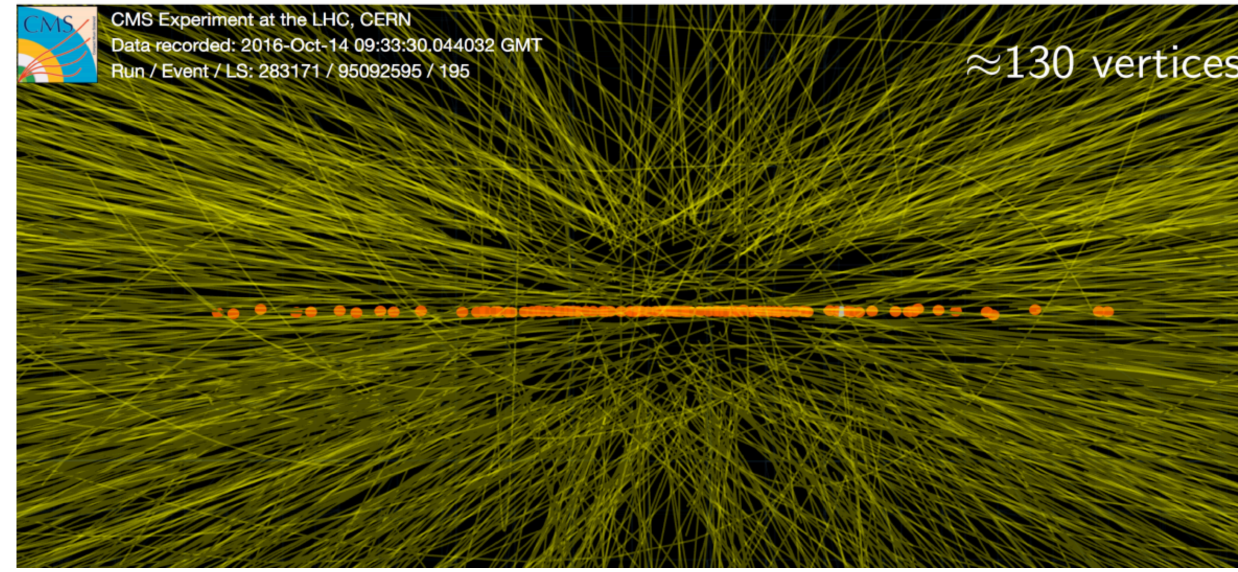
- **HL-LHC upgrade greatly expand physics potential of the LHC**
    - *Rare and statistically limited SM and BSM processes*
    - *New channels w/ low cross sections or small coupling strengths*

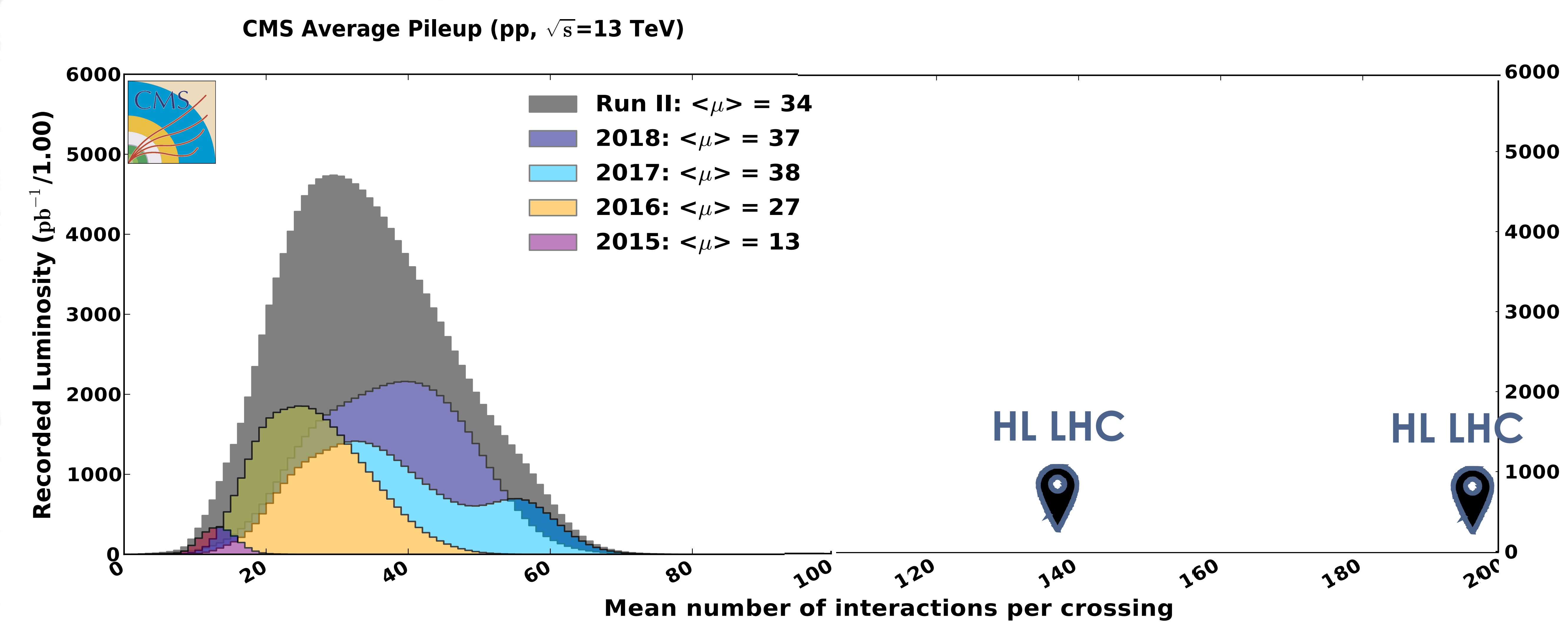
Physics Perfomance & Detector Upgrade

More p-p interaction (pileup - PU)
per bunch crossing

⬇

Need **performant and flexible detector** to allow a deep **exploration of corners of phase space**





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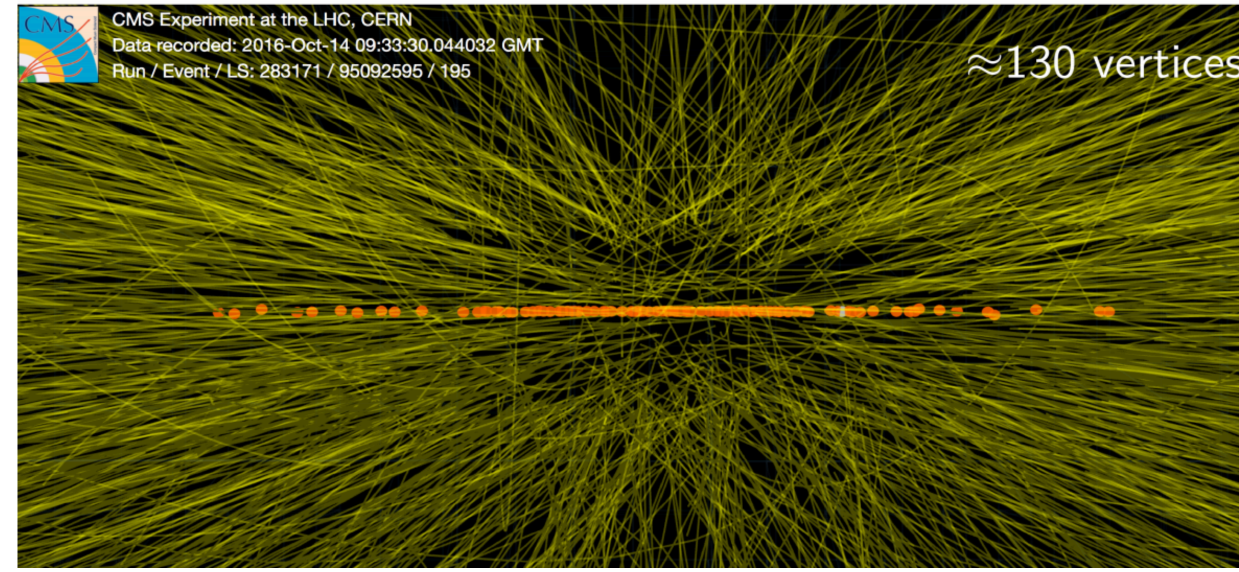
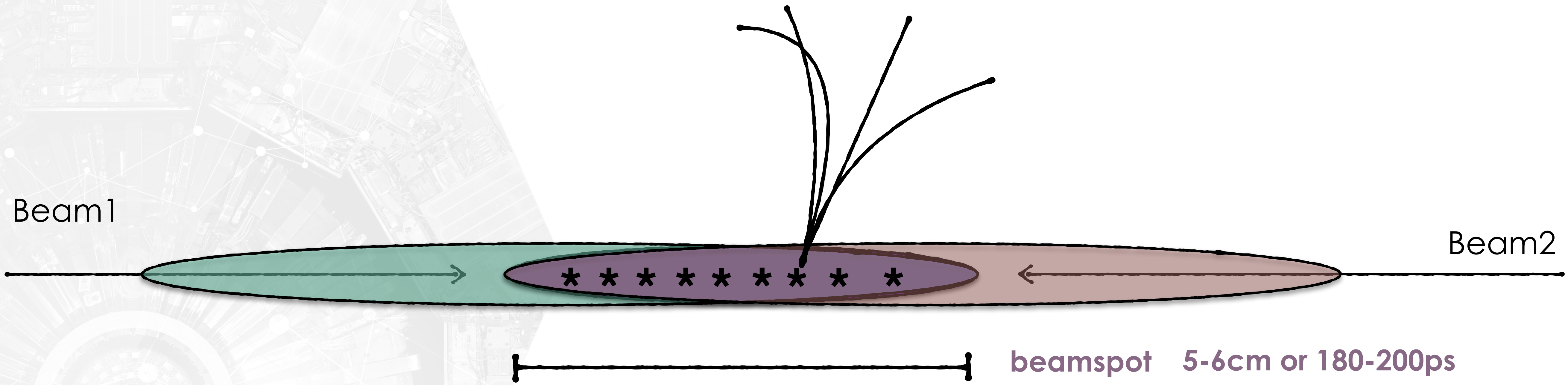


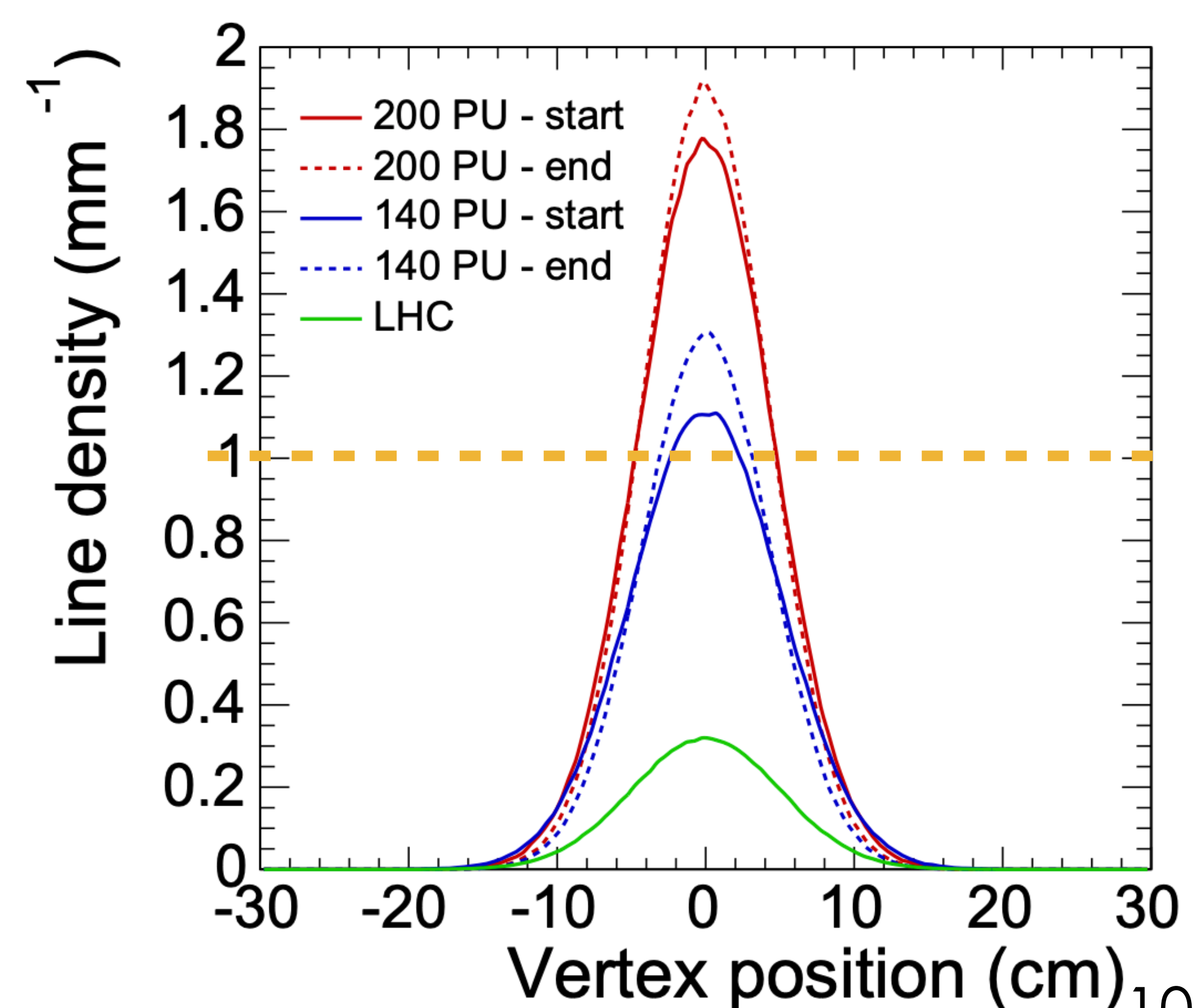
- **Pileup** → higher detector **granularity** to reduce occupancy, increased **bandwidth** to accomodate higher data rates
- **Trigger rates** → higher output rate of interesting events and **improved discriminating power** of the event selection
- **Radiation levels** → improved **radiation hardness**

Extending CMS Performance at High PU

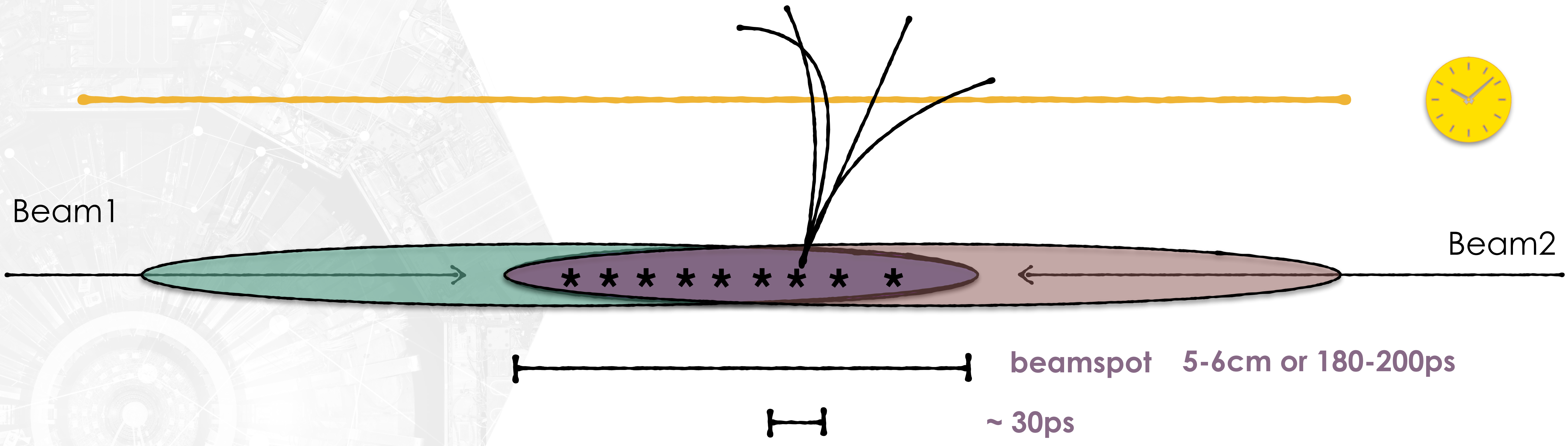


beamspot 5-6cm or 180-200ps

- **LHC today: 30-40 collisions in 5 cm**
- **Optimal cut at 1 mm** for track-vertex compatibility in space
- **HL-LHC: 5x vertex density** = PU contamination and reconstruction degradation



Extending CMS Performance at High PU

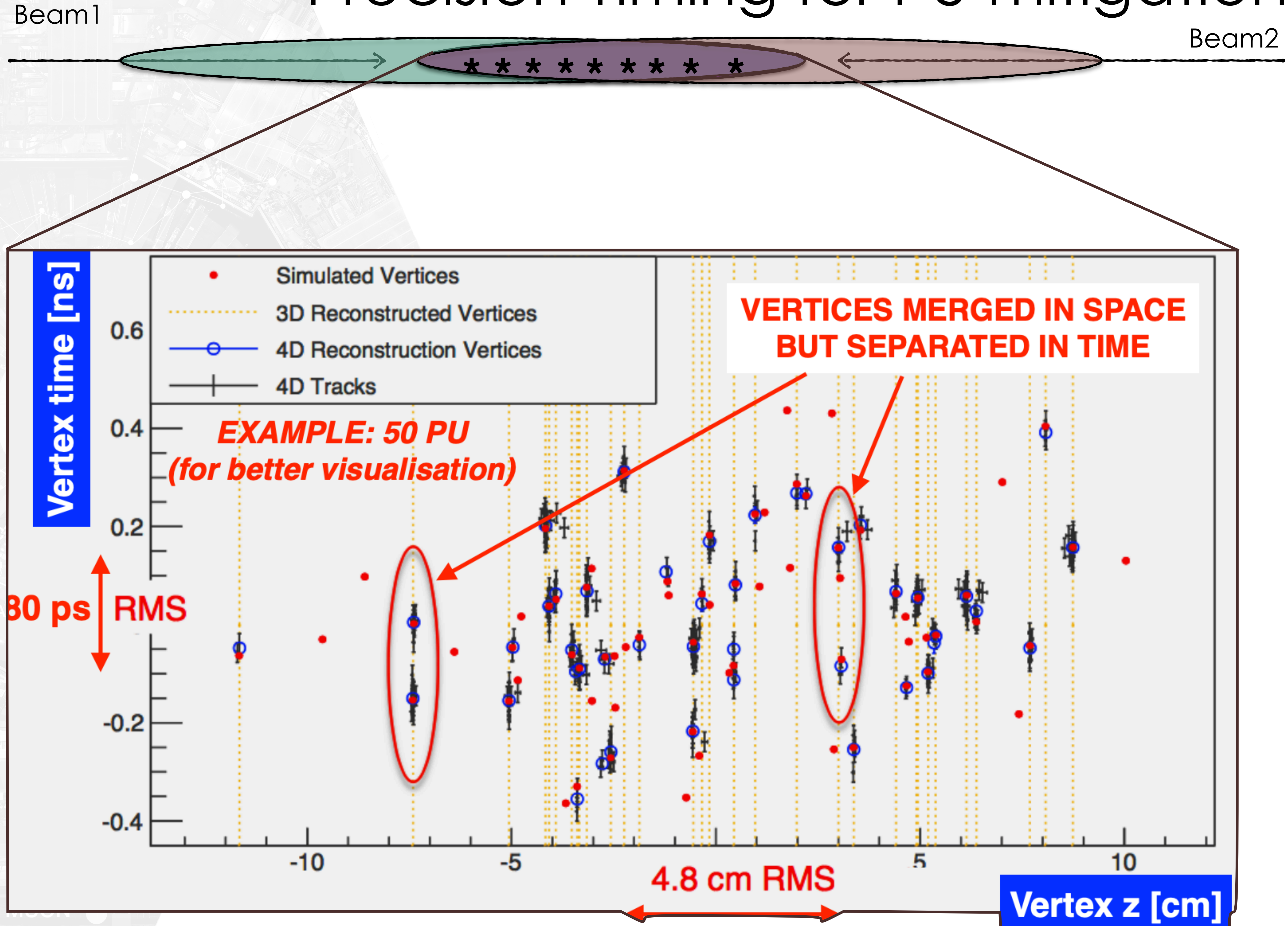


Basic Idea: Use track timing for a 4D vertex reconstruction: correct tracks-vertex association

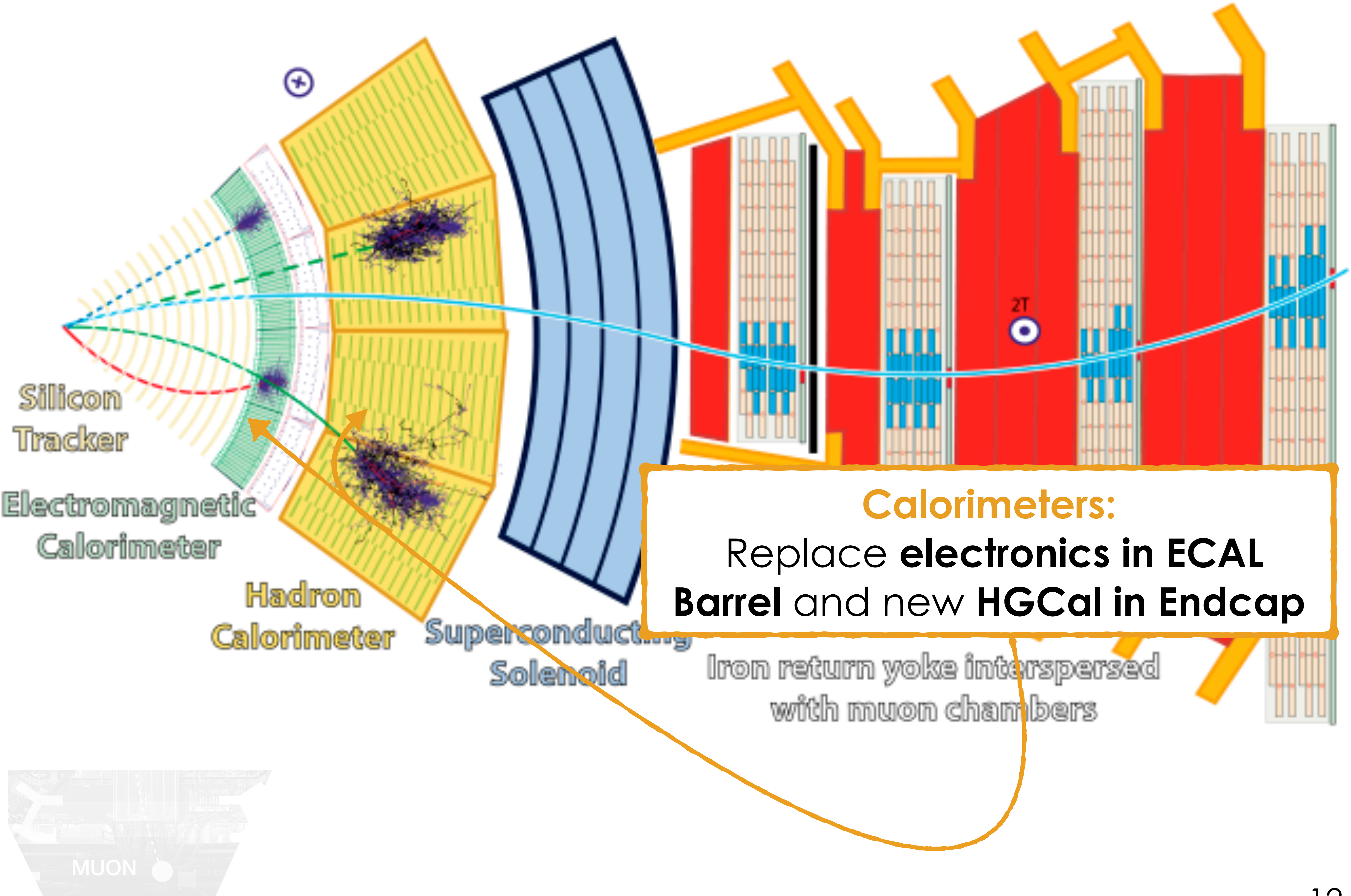
Significantly **reduce “effective” vertex line density**

30 ps needed to recover LHC performance

Precision Timing for PU mitigation

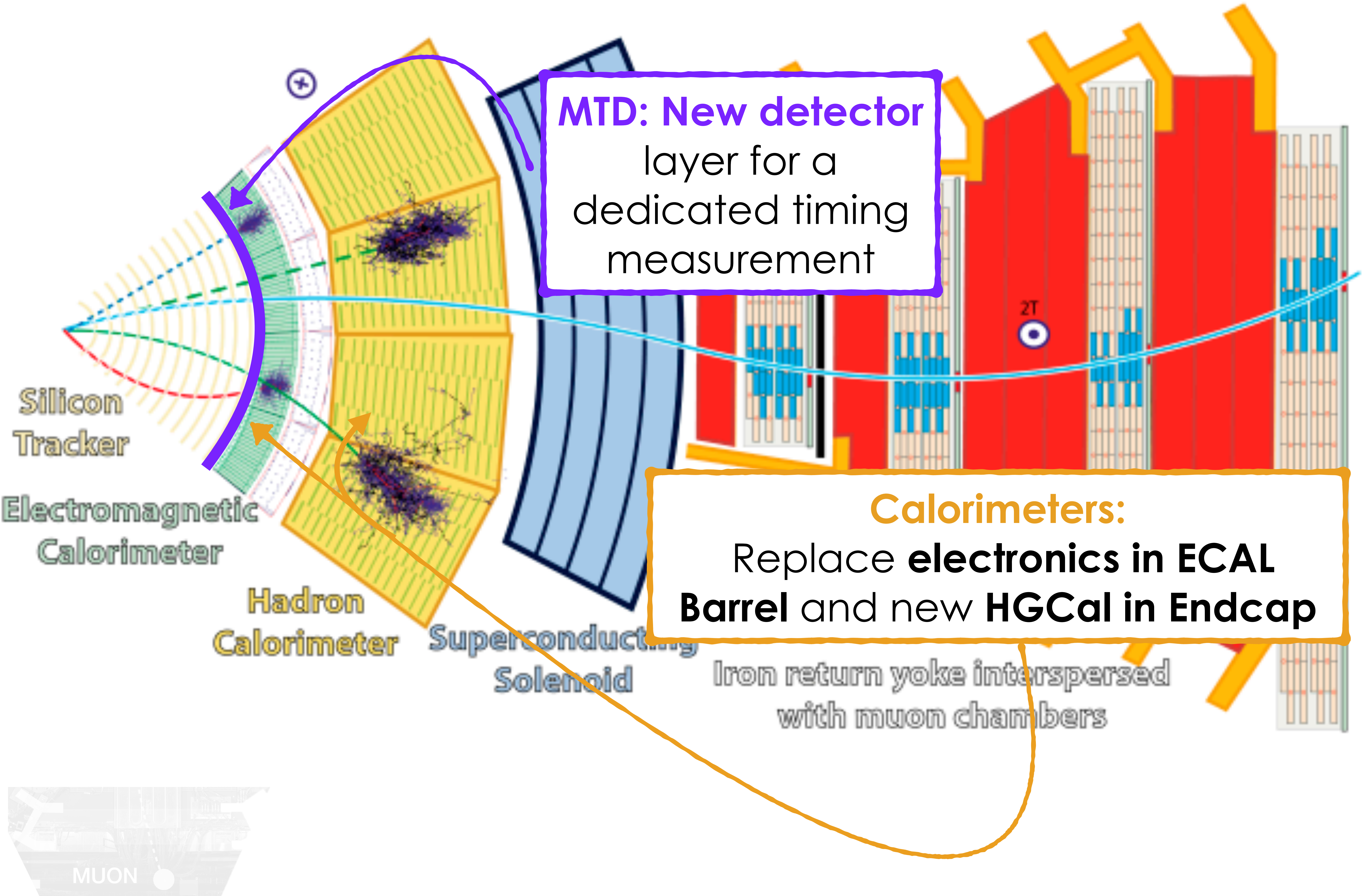


CMS Global Timing Concept at HL-LHC



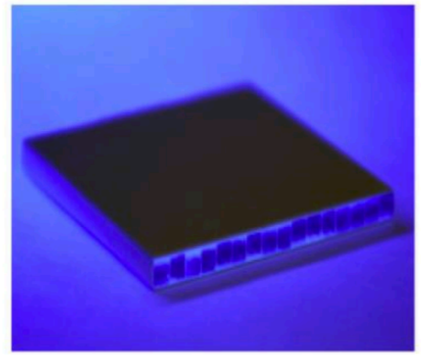
Calorimeters:
Replace **electronics in ECAL Barrel** and new **HGCal in Endcap**

CMS Global Timing Concept at HL-LHC

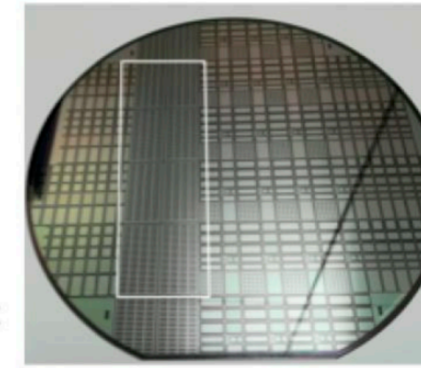


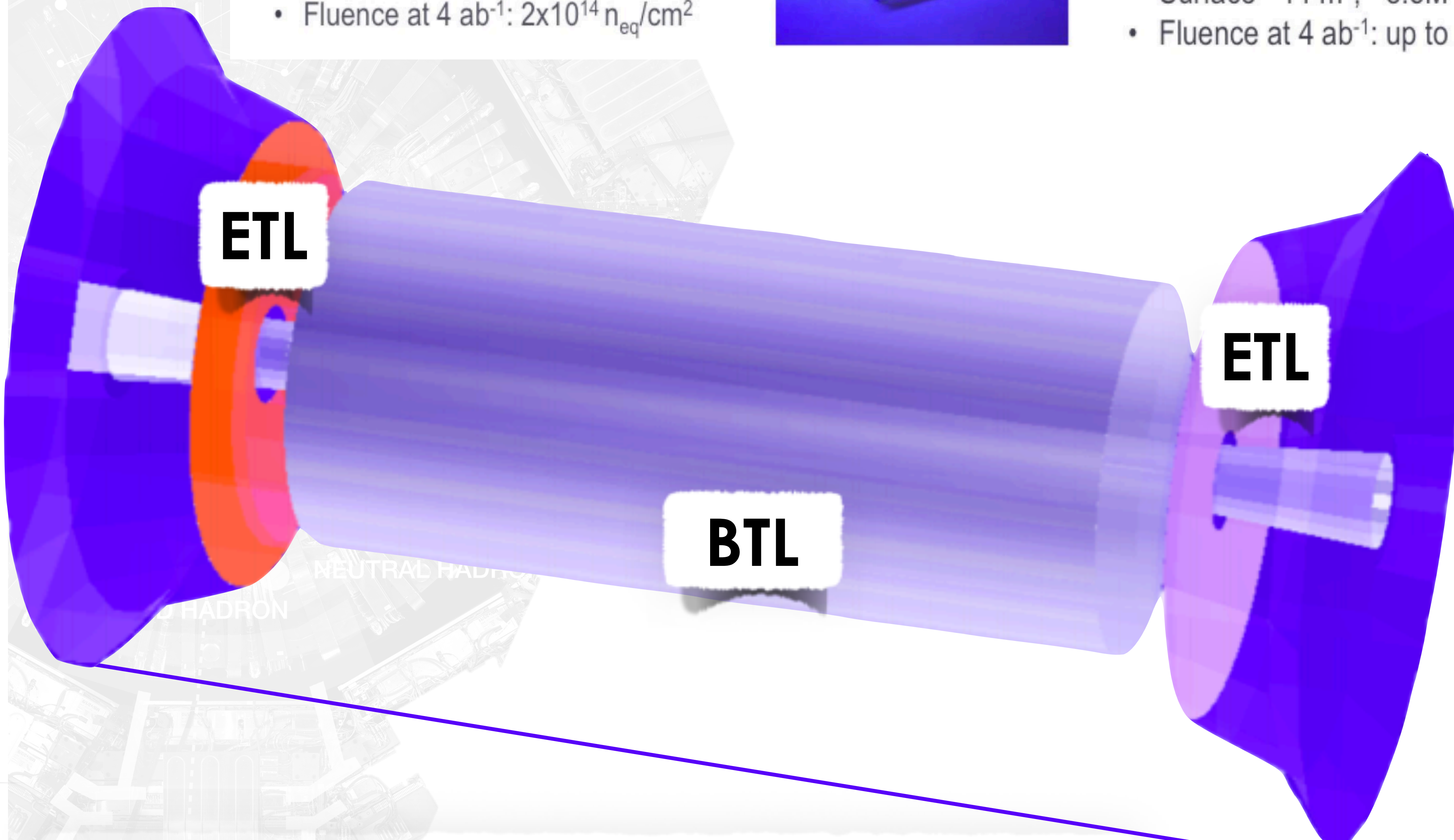
MTD: Mip Timing Detector Design Overview

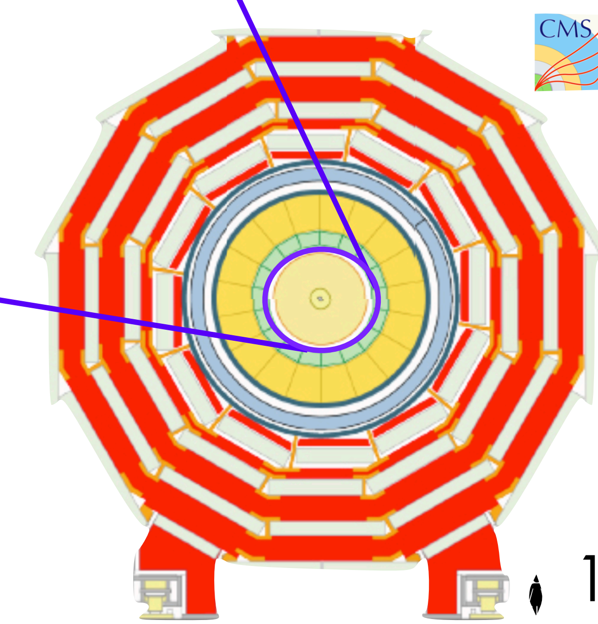
BTL: LYSO bars + SiPM readout:
- TK / ECAL interface: $|\eta| < 1.45$
- Inner radius: 1148 mm (40 mm thick)
- Length: ±2.6 m along z
- Surface ~38 m^2; 332k channels
- Fluence at 4 ab^{-1}: $2\times10^{14}\ n_{eq}/cm^2$



ETL: Si with internal gain (LGAD):
- On the CE nose: $1.6 < |\eta| < 3.0$
- Radius: 315 < R < 1200 mm
- Position in z: ±3.0 m (45 mm thick)
- Surface ~14 m^2; ~8.5M channels
- Fluence at 4 ab^{-1}: up to $2\times10^{15}\ n_{eq}/cm^2$





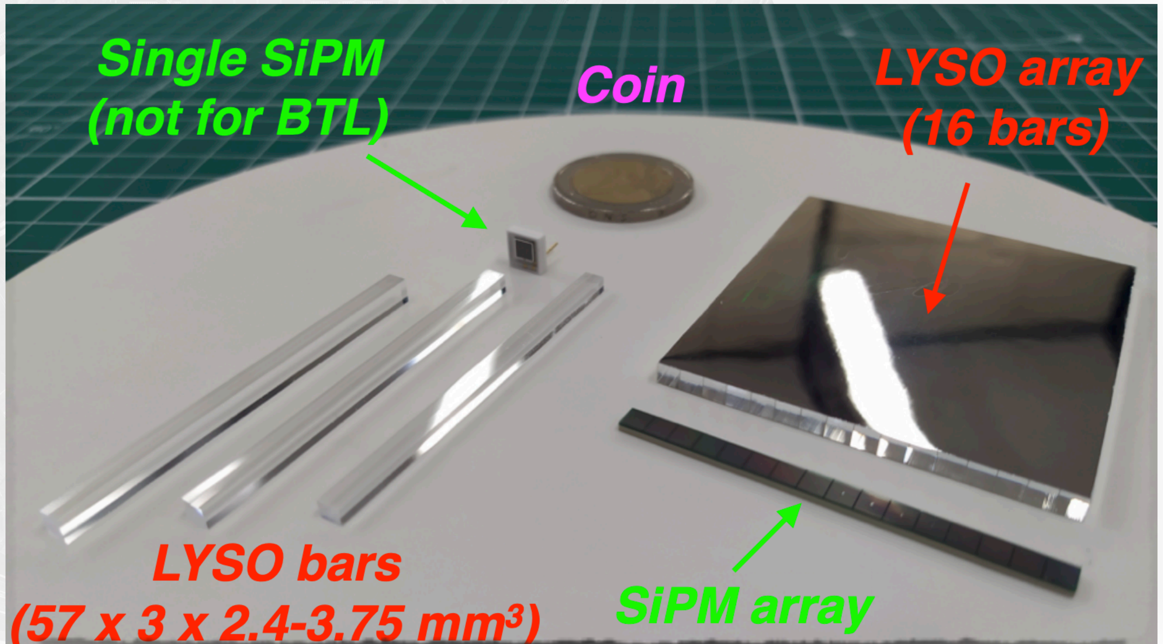


MIP Timing with **~30 ps precision**

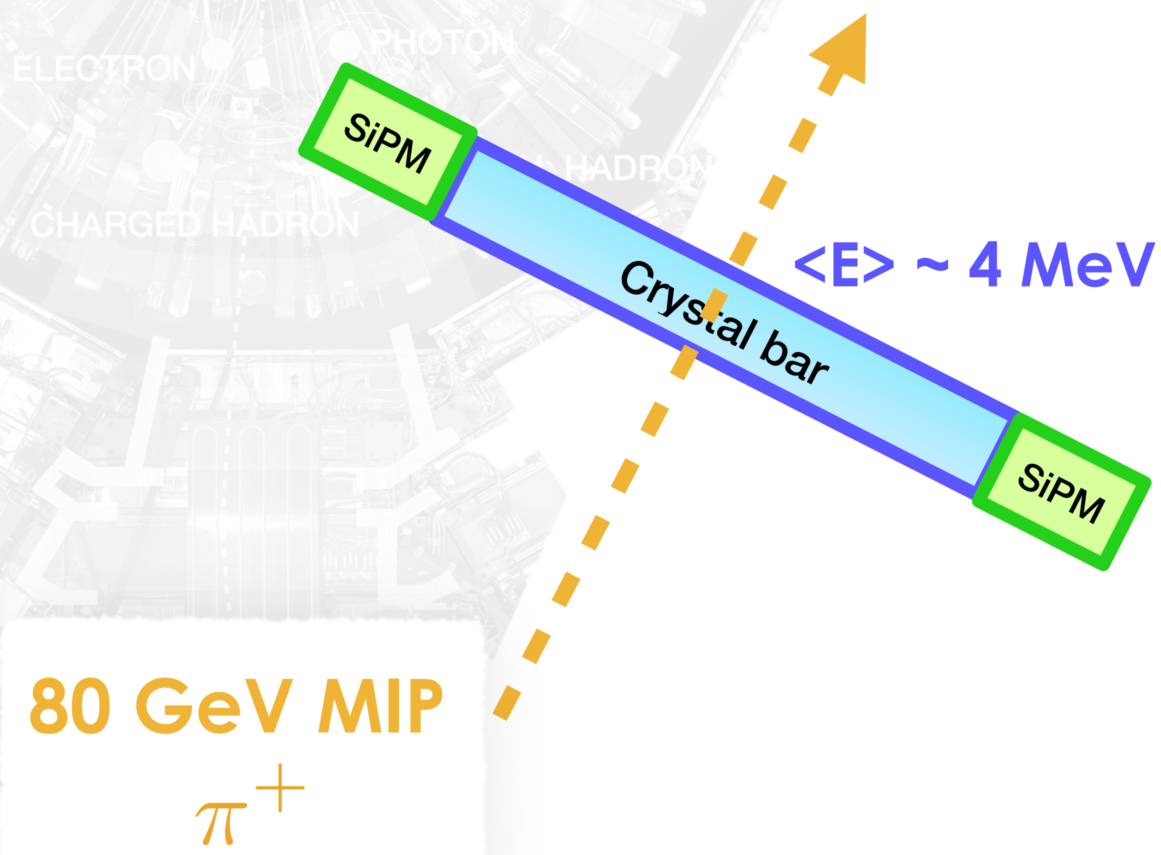
Acceptance: $|\eta| < 3.0, p_T > 0.7 GeV$

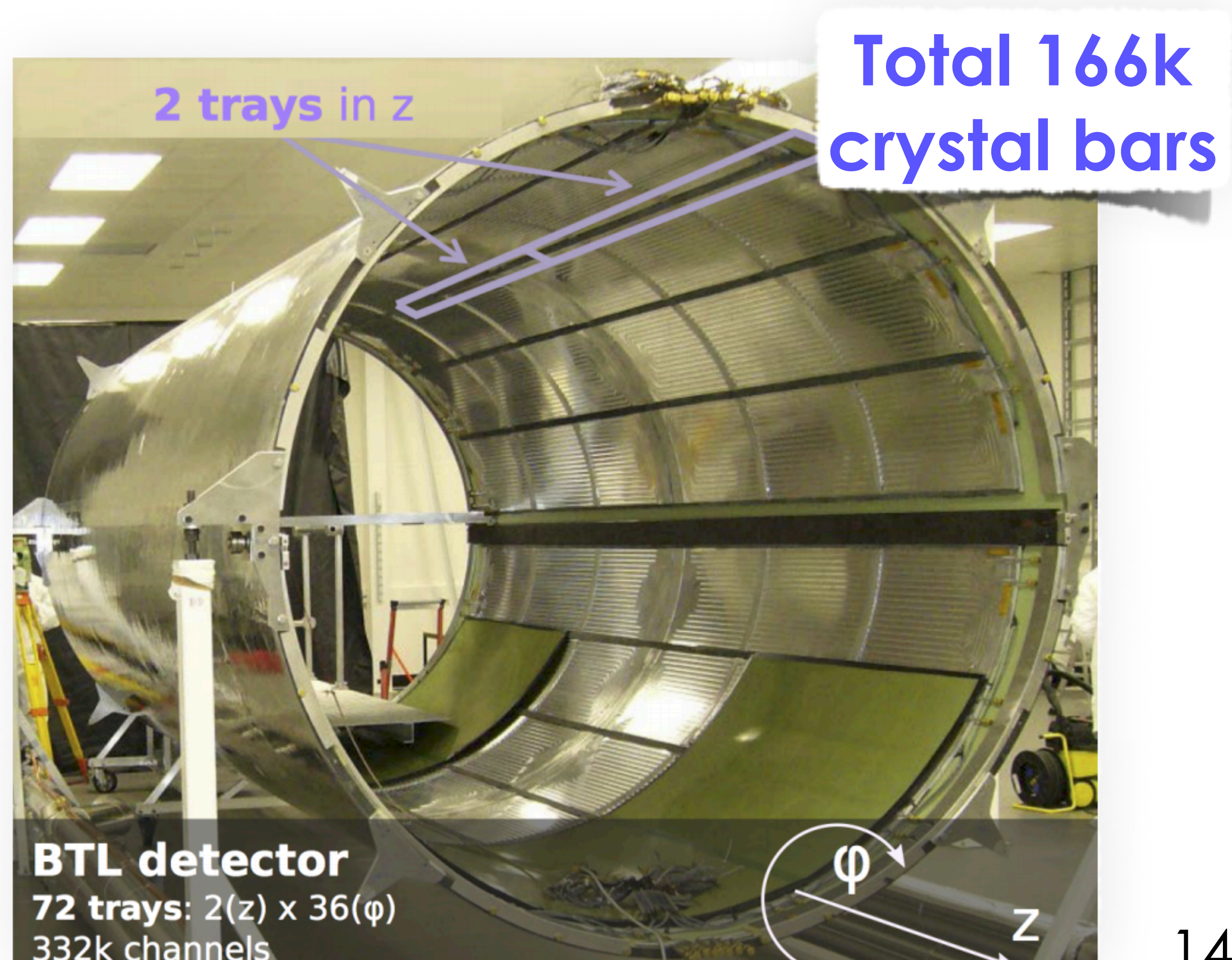
4 mm thick LYSO:Ce layer in Barrel

BTL Geometry and Sensors

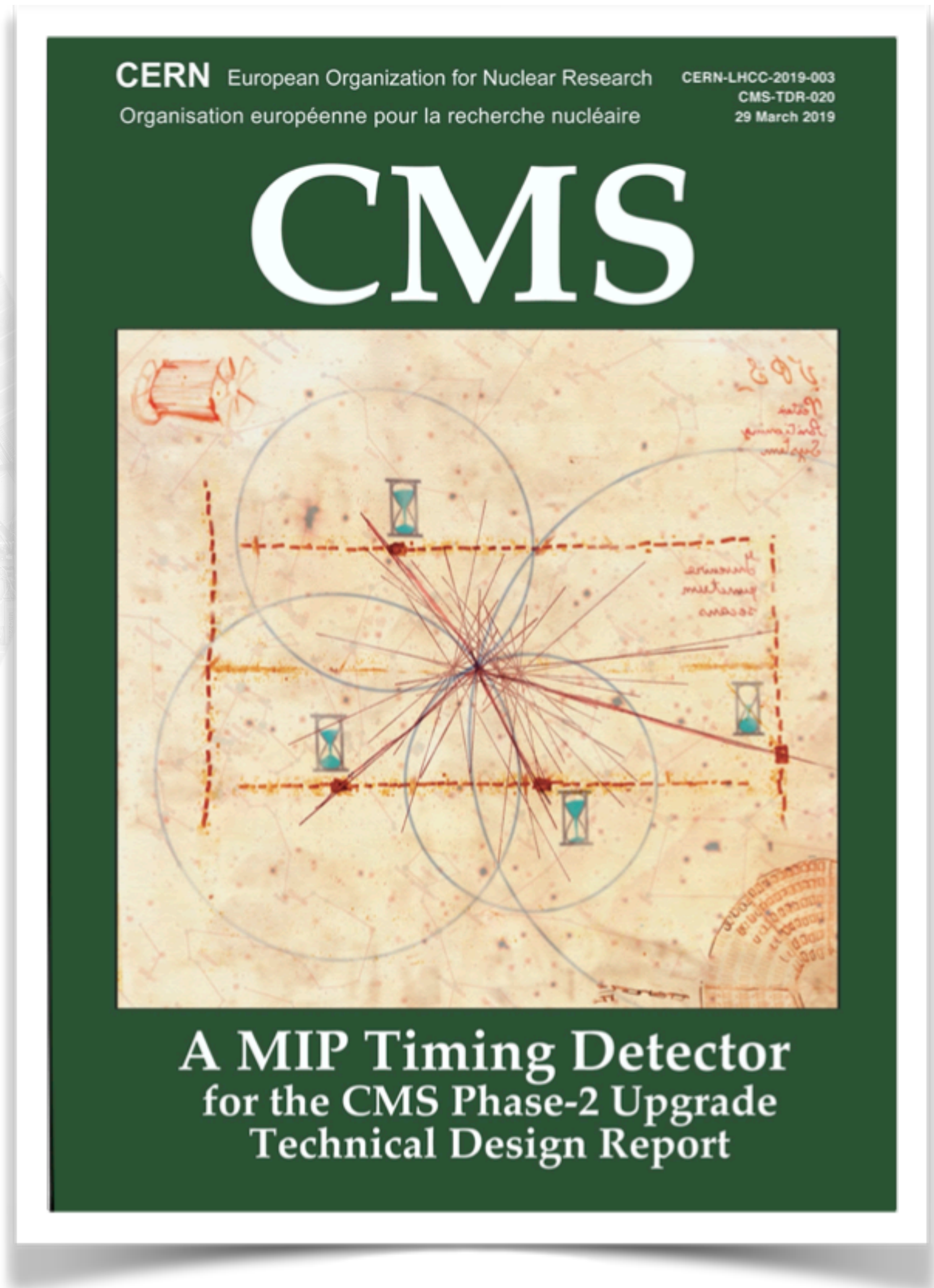


- **LYSO:Ce crystal bars** as scintillators
- **Silicon Photomultipliers** as photo-sensors (one SiPM per bar side)
- **Arrays of LYSO** crystal bars (50×3 mm2) aligned in z direction

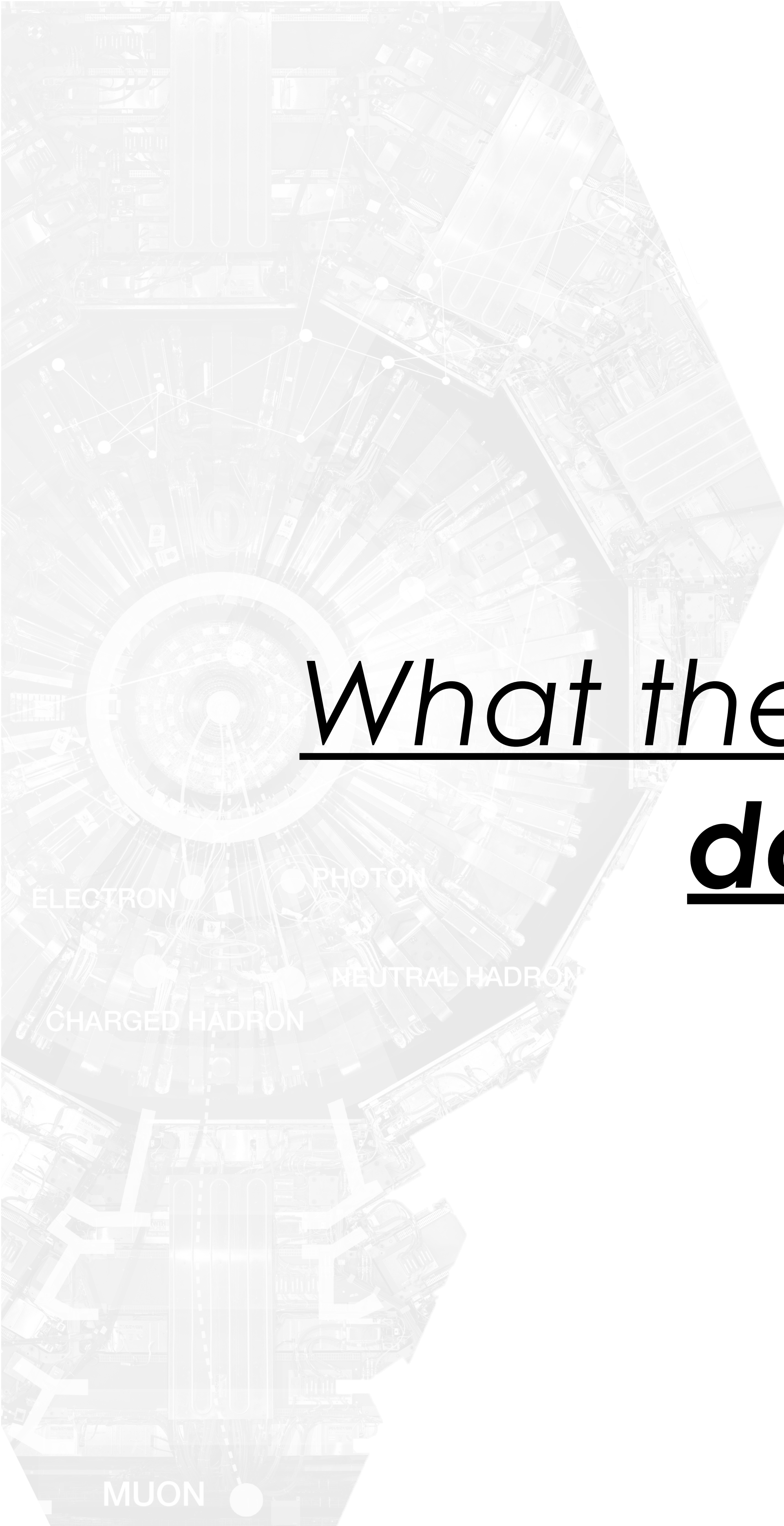




The CMS MTD Project



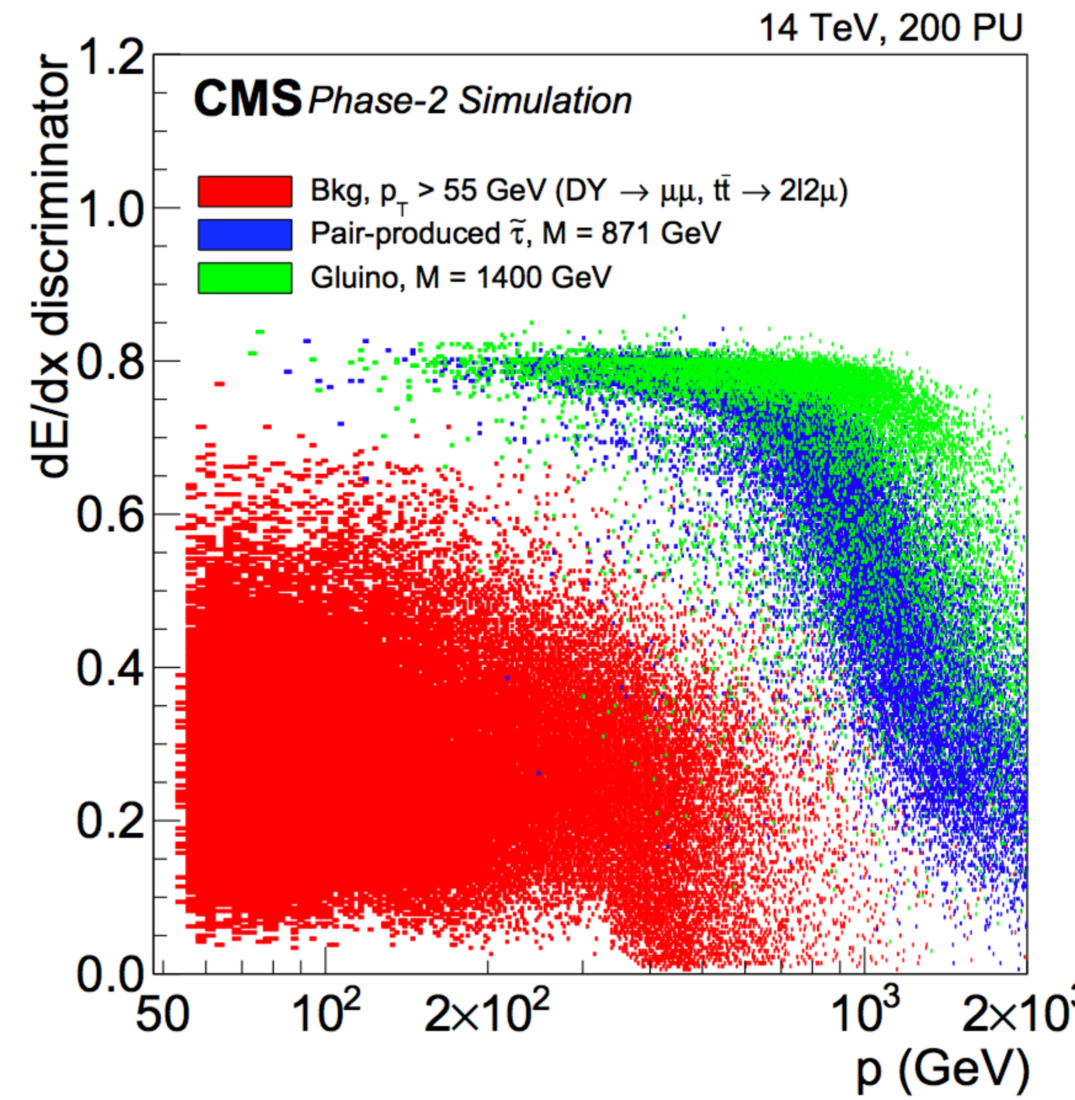
- MTD project **formally approved by CERN Research Board** end of '19.
- R&D to define **detector design completed**
- **CMS Rome** group leading resonsability on **LYSO crystals characterization**



What the **we know we can do with MTD..**

Charged Long Lived Particles at HL-LHC

- **Heavy, long-lived, charged particles**: slow moving compared to SM muons and hadrons



Heavy-Stable-Charged-Particles(HSCP):
SUSY **stau** and **gluino**

- Depending on mass and charge: **anomalously high dE/dx** and **longer time-of-flight**

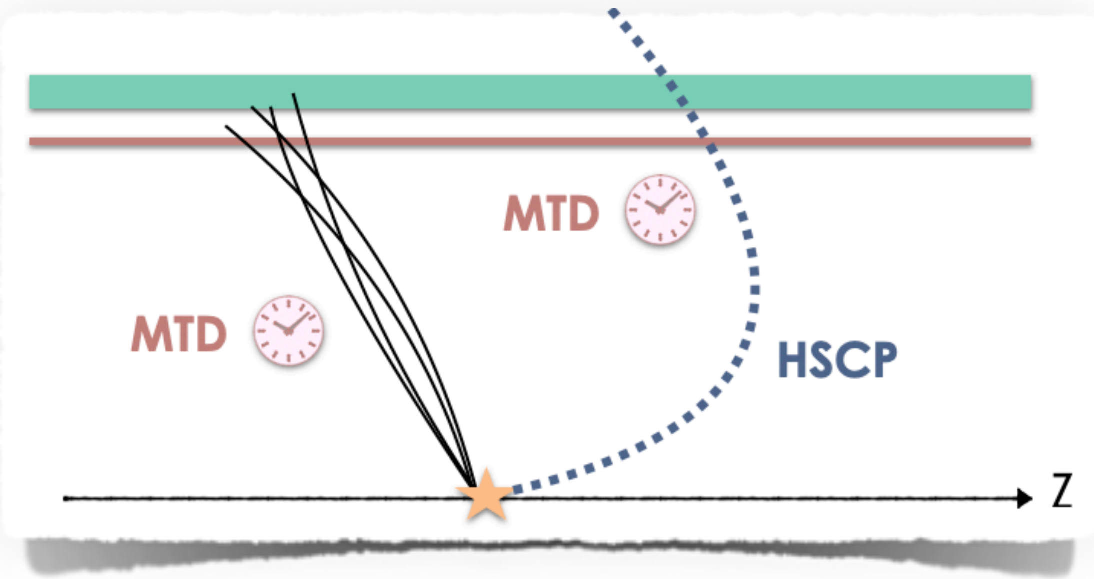
- Today: **tracker dE/dx** and **time-of-flight to the muon system**

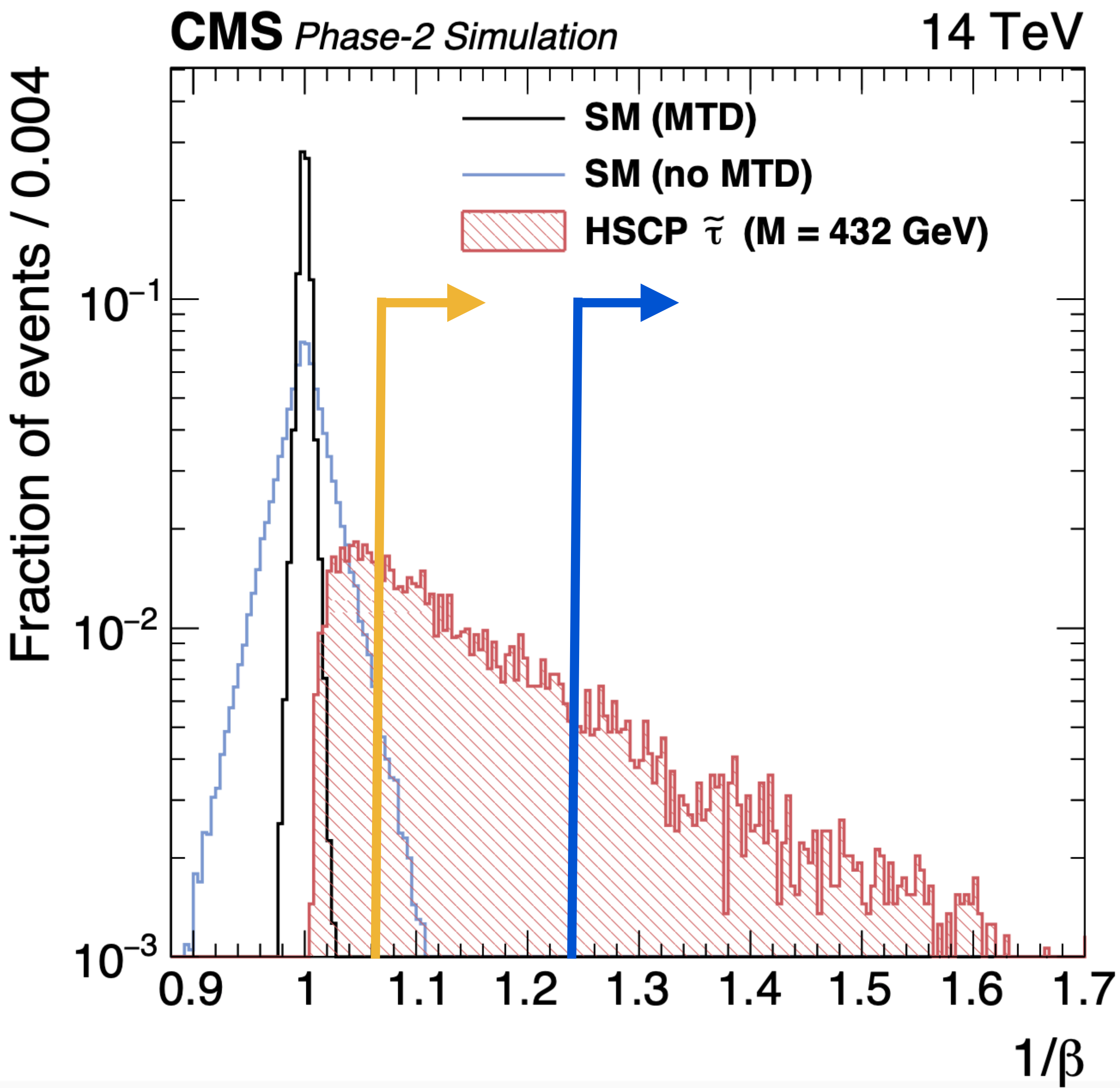
e.g. HSCP masses > 100 GeV → $\beta < 0.9$

σ < 5 ns

HSCP with MTD at HL-LHC

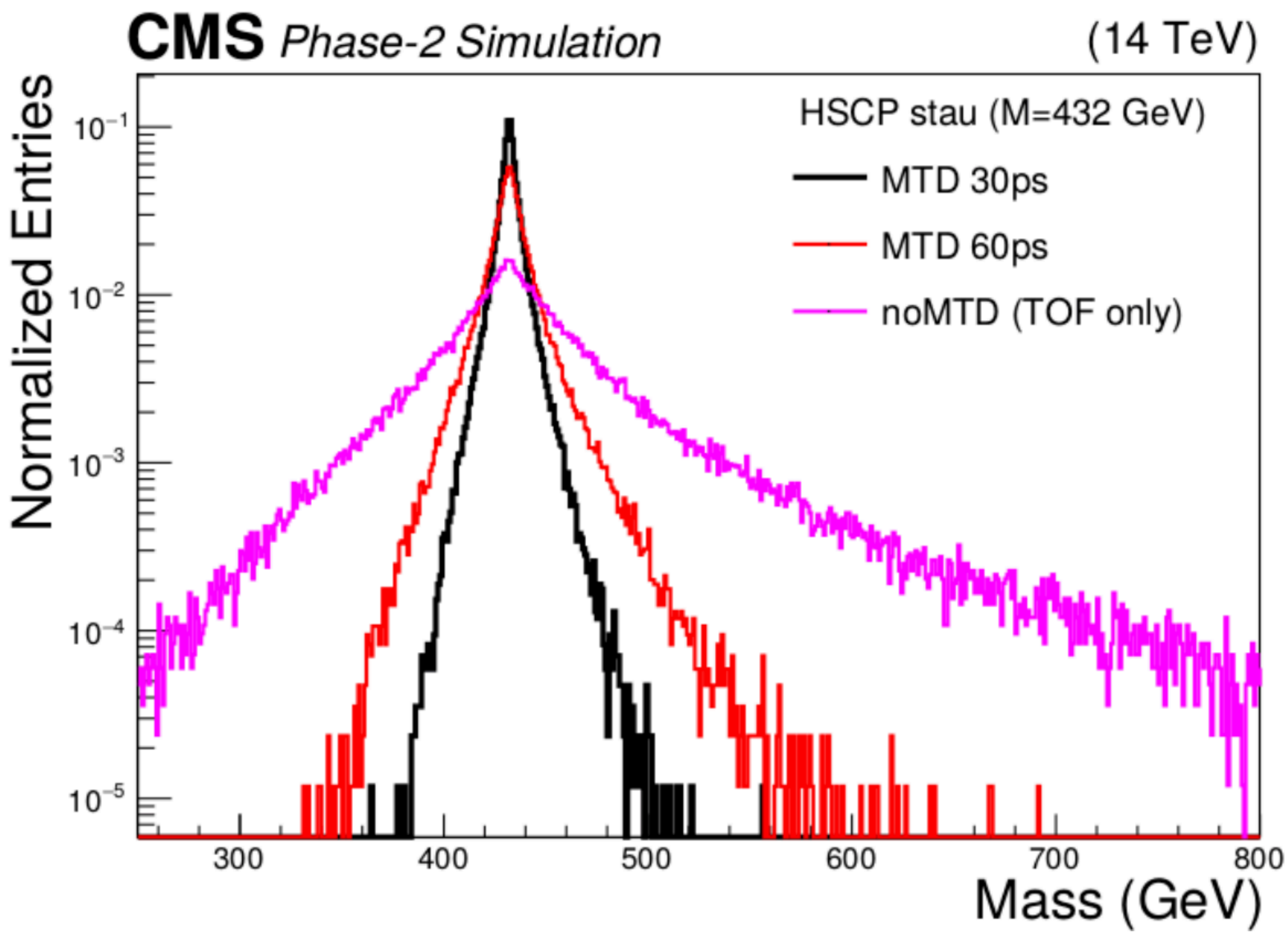
- **MTD** allows to **reduce the uncertainty in 1/ β** to improve the discrimination power and signal efficiency





- Lower selection 1.25 (**w/o MTD**) to 1.05 (**w/ MTD**) (5x resolution)

- **Mass of the HSCP** can also be reconstructed **using β and the 4-momentum**

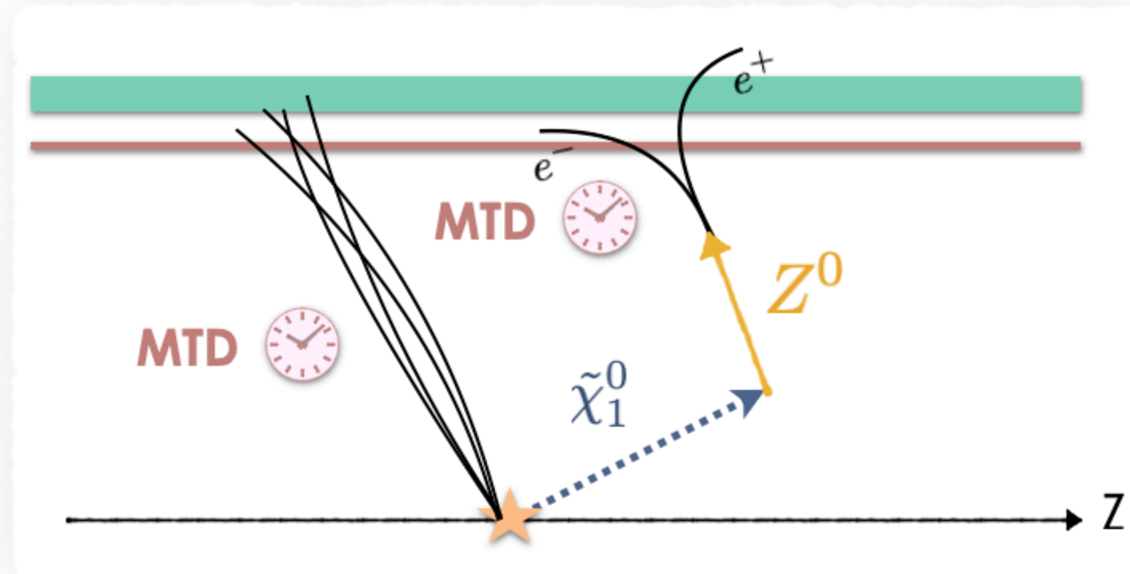


Neutral Long Lived Particles at HL-LHC

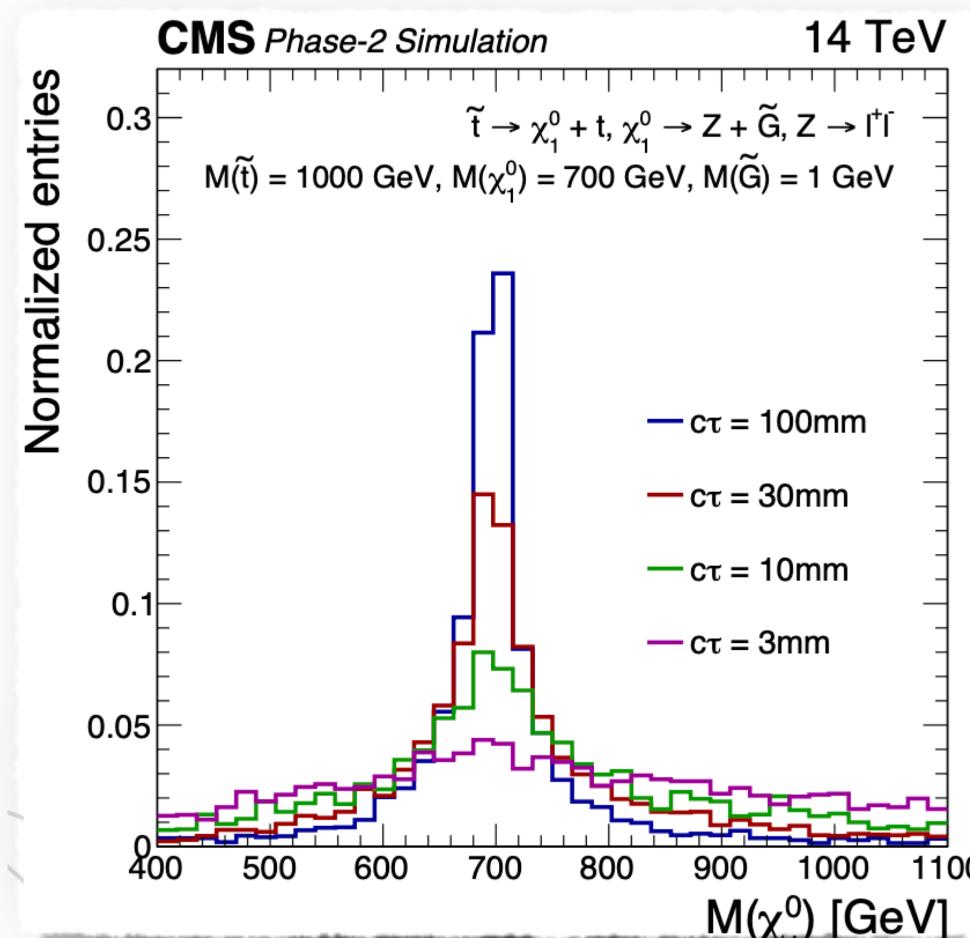
- Measure boost of **neutral long lived particles** from **coordinates and time** of **primary and secondary vertices w/ MTD**:

$$\tilde{\chi}_1^0 \rightarrow \tilde{G} Z^0$$

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



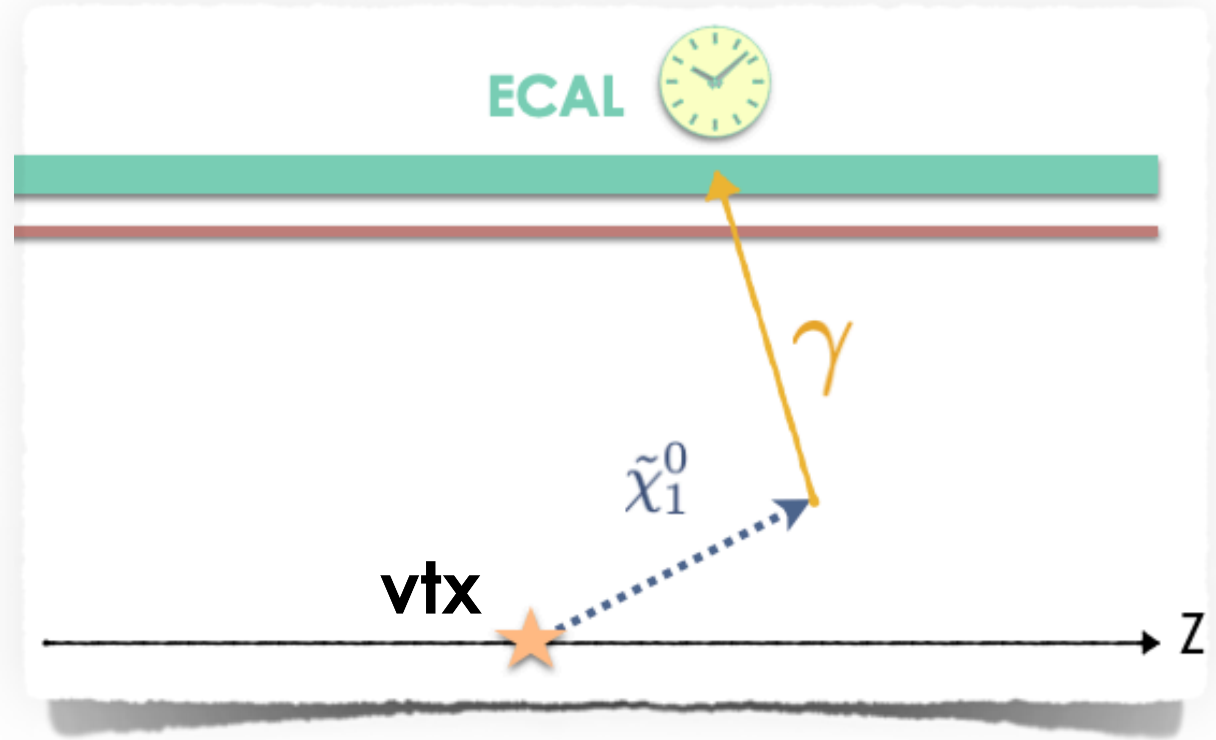
- **Boost** the visible system energy in the LLP rest frame and **compute its mass**
  - Assume mass on invisible object



Signatures with Delayed Photons

- **Gluino production with a Long Lived neutralino** decaying into photon and Gravitino

$$\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma$$



- **Photons** arrive **on ECAL delayed**

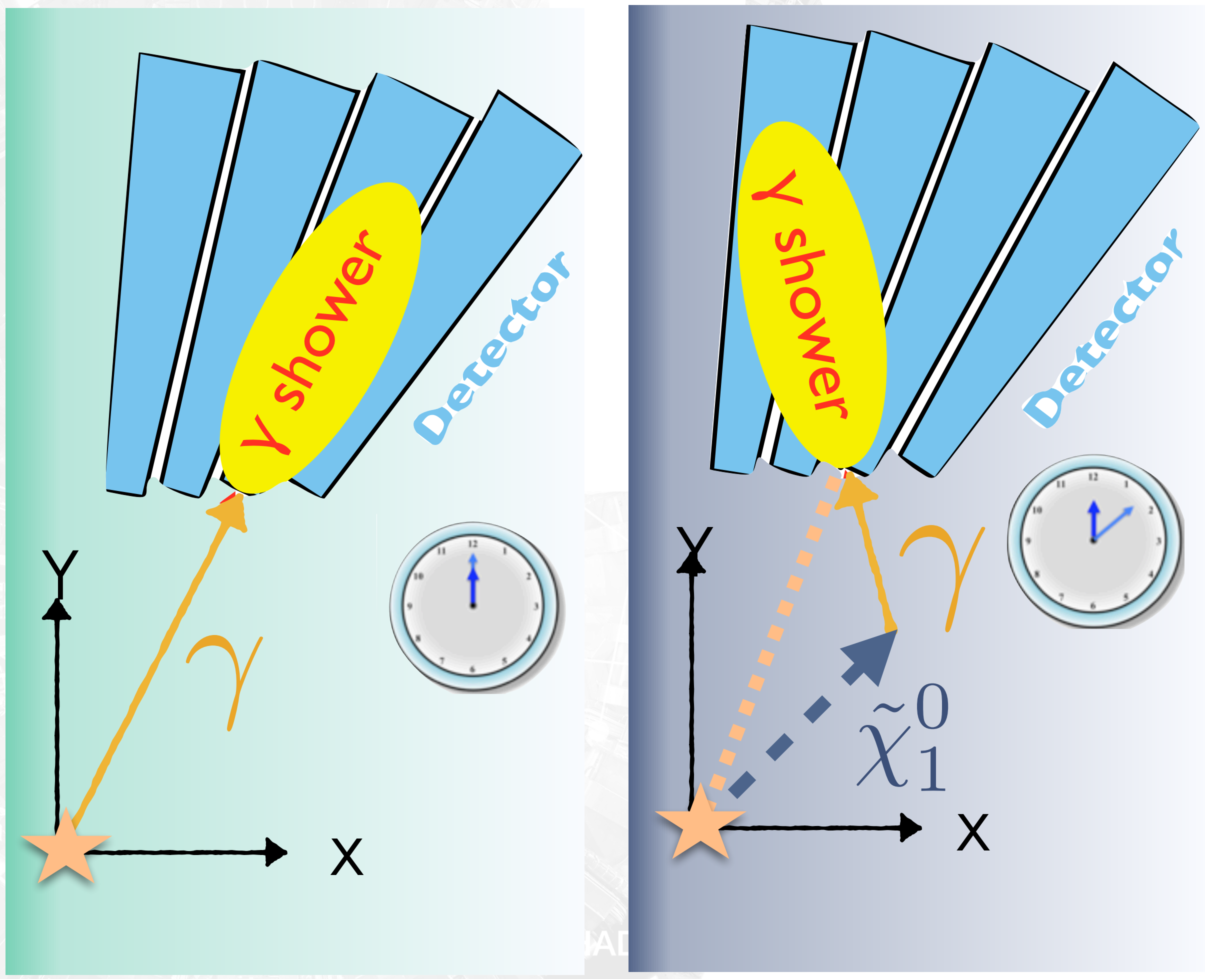
- Today: **ECAL based analysis** using ECAL Timing

$$t_\gamma = t_{vtx} + t_{flight}$$

Dominated by **beamspot: σ = 180 ps**

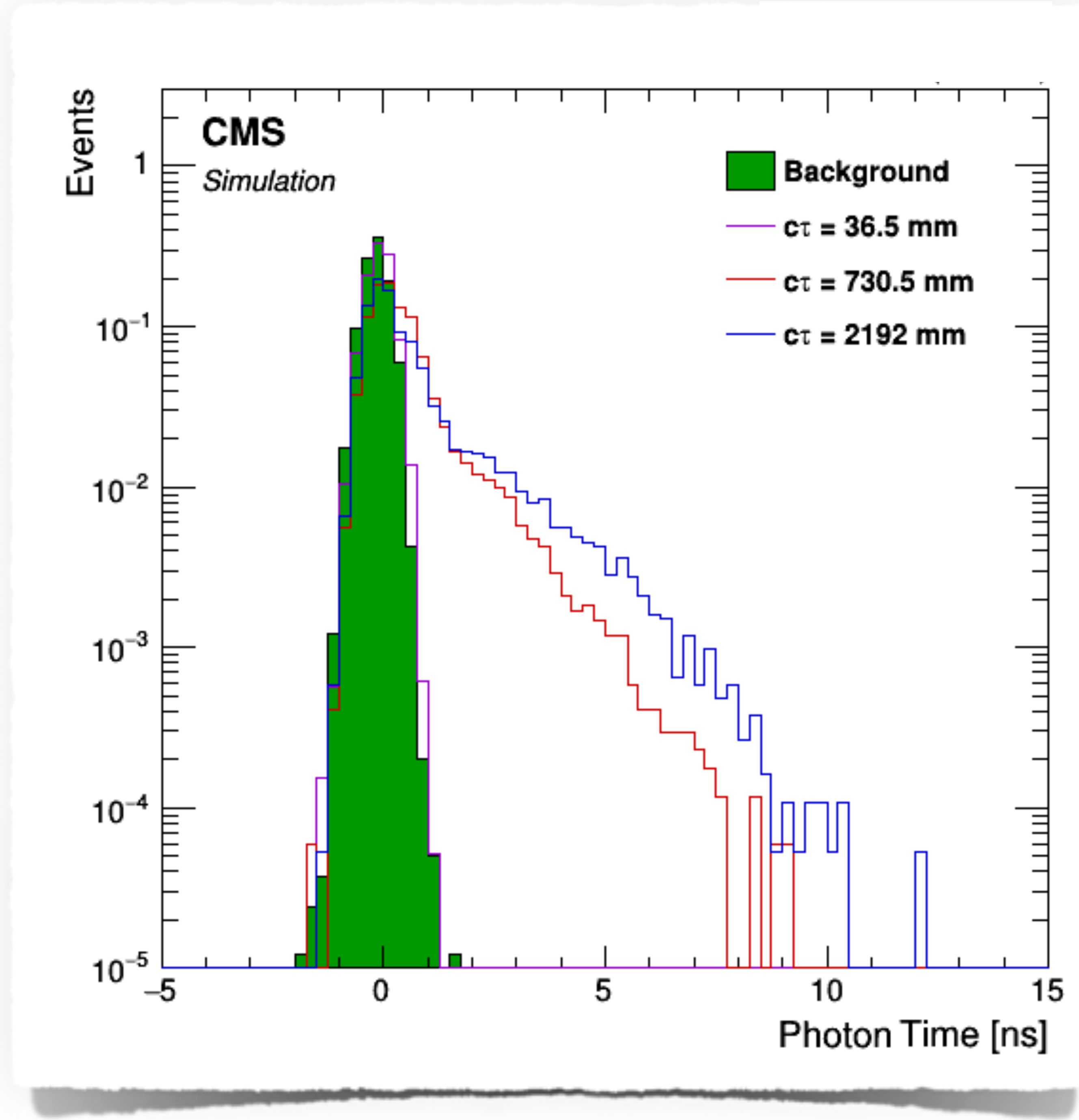
Dominated by **ECAL σ < 100 ps**

Delayed Photons Detection

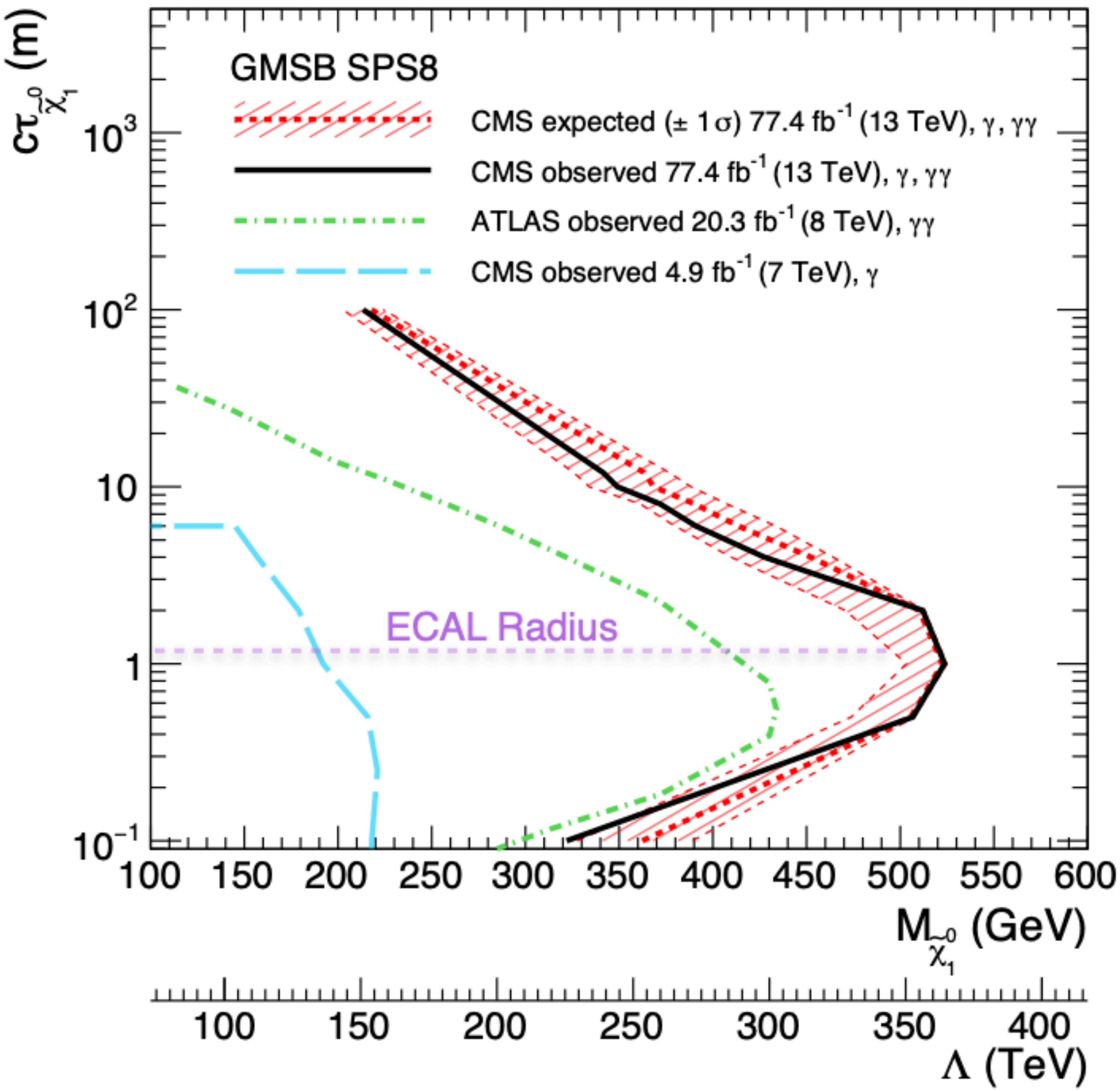


Time compatible with **relativistic particle from IP**

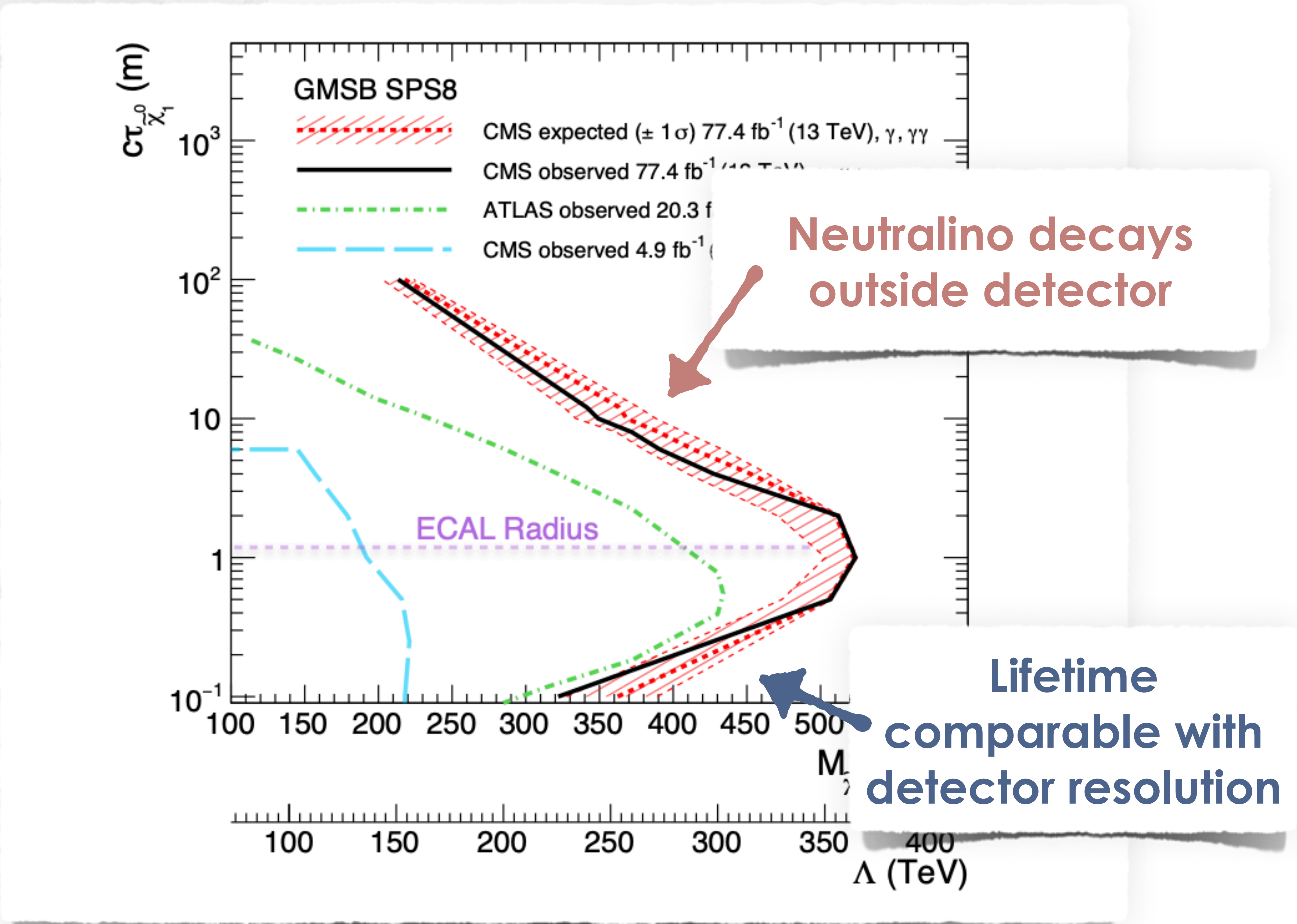
Time sensibly increase with **parent particle lifetime O(ns)**



Delayed Photons Legacy at Run 2



Delayed Photons Legacy at Run 2

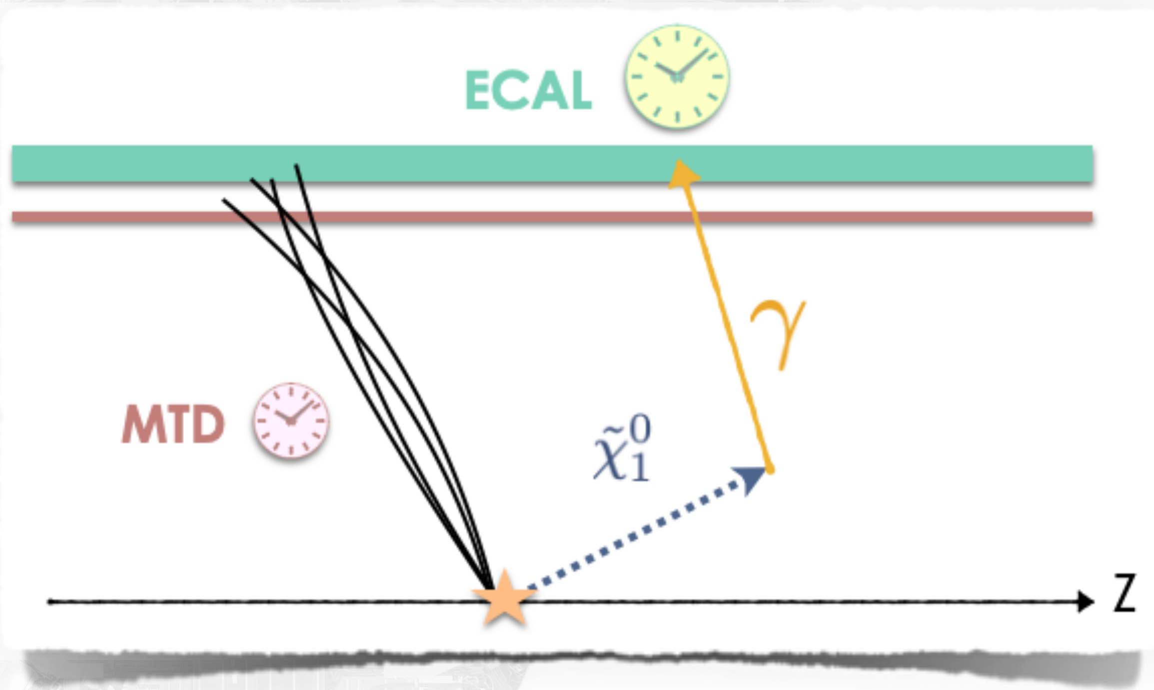


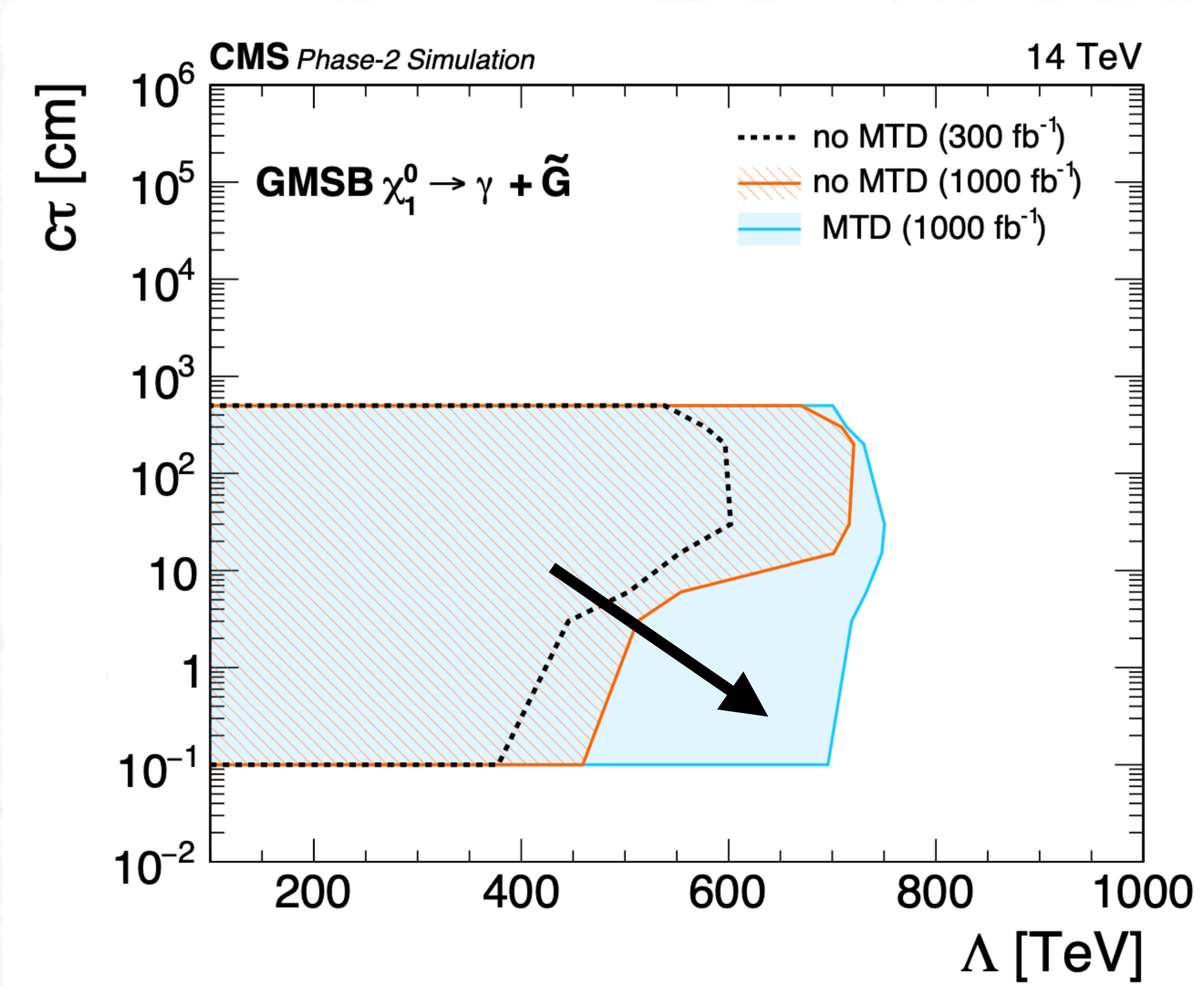
Delayed Photons Opportunity w/ MTD

$$t_\gamma = t_{vtx} + t_{flight}$$

MTD reduces beamspot time spread: σ = 30ps

Phase2 ECAL: σ = 30 ps



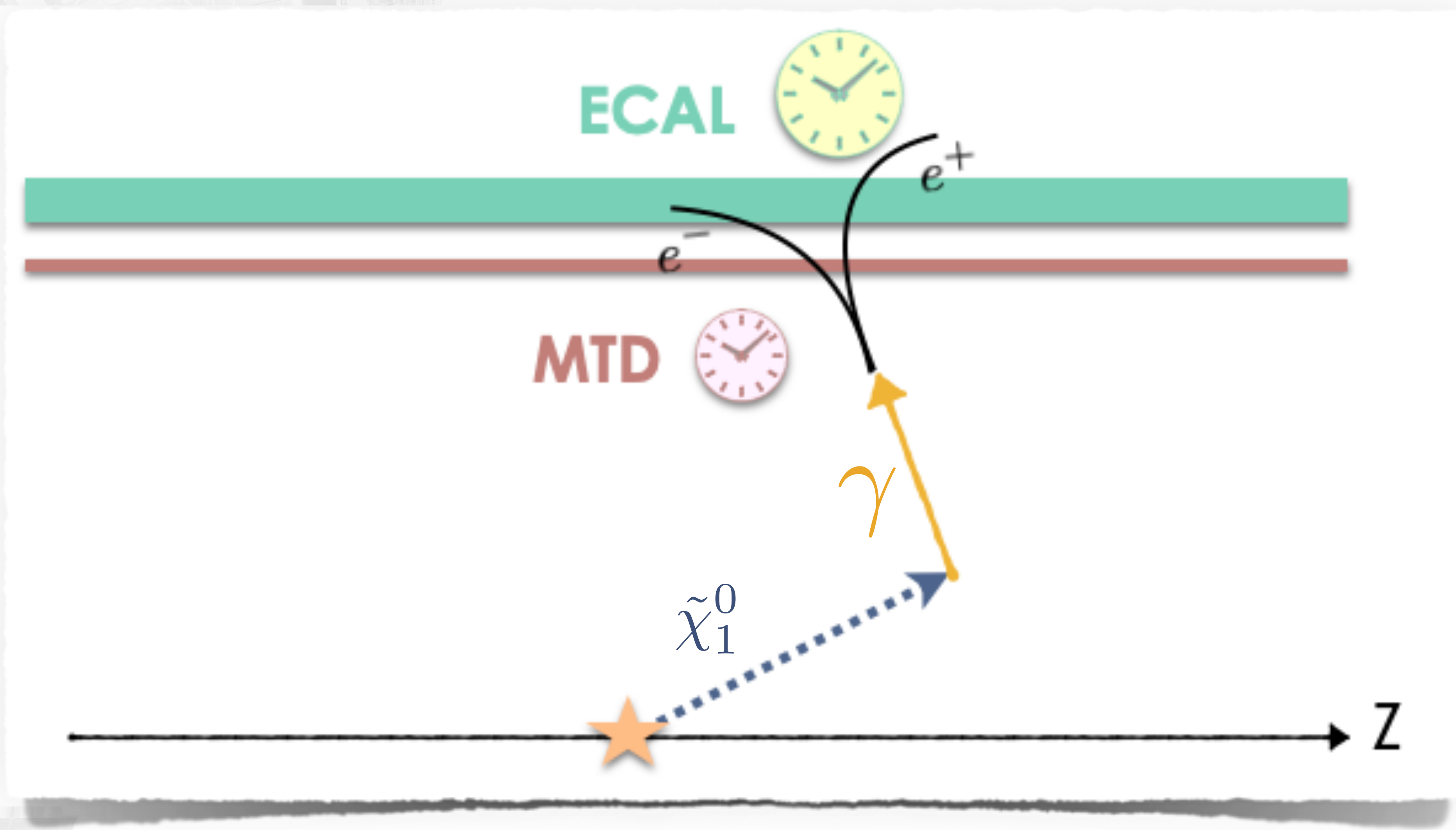


$$Mass \propto \Lambda$$

Converted Delayed Photons w/ MTD

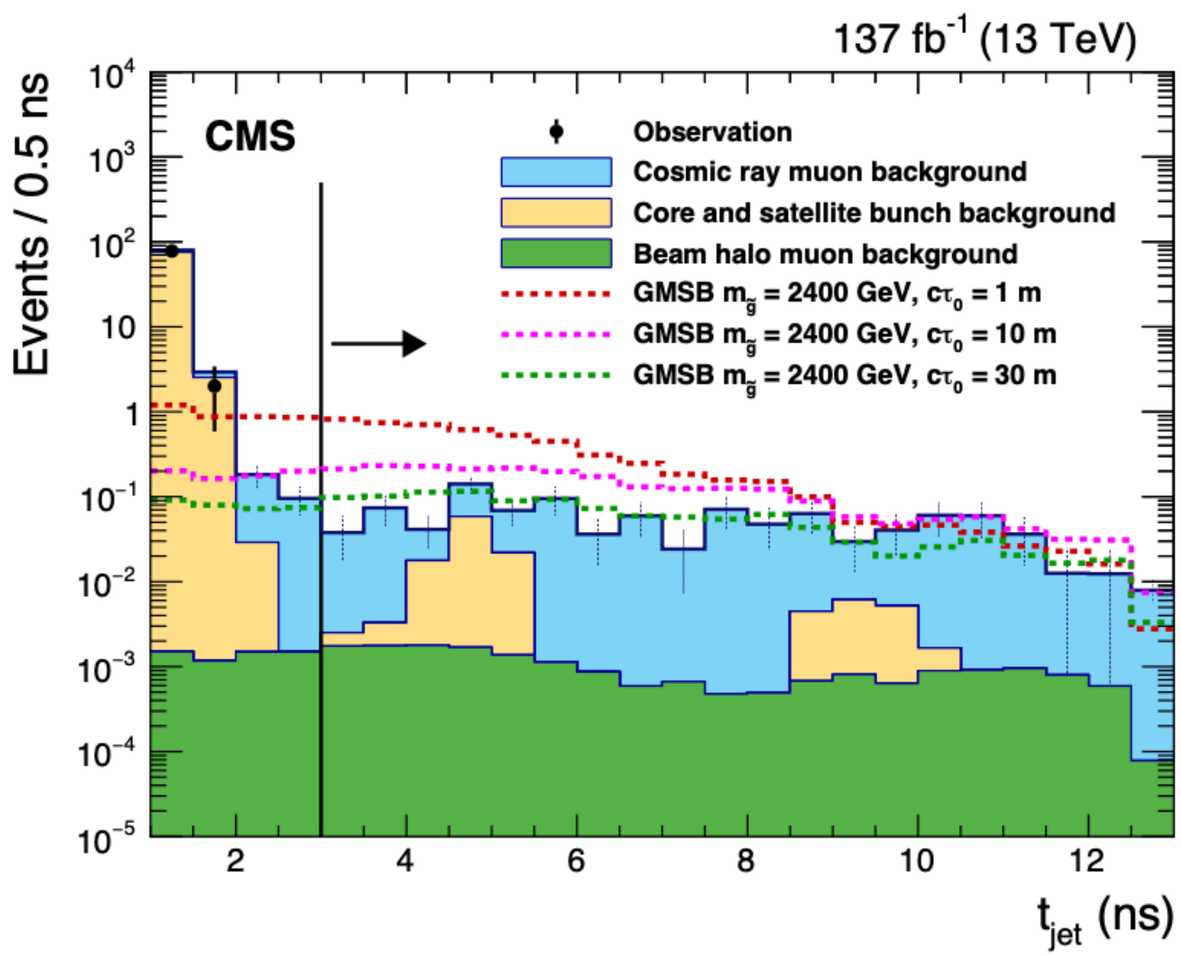
- Last CMS results with **displaced photons using conversions** from 8 TeV

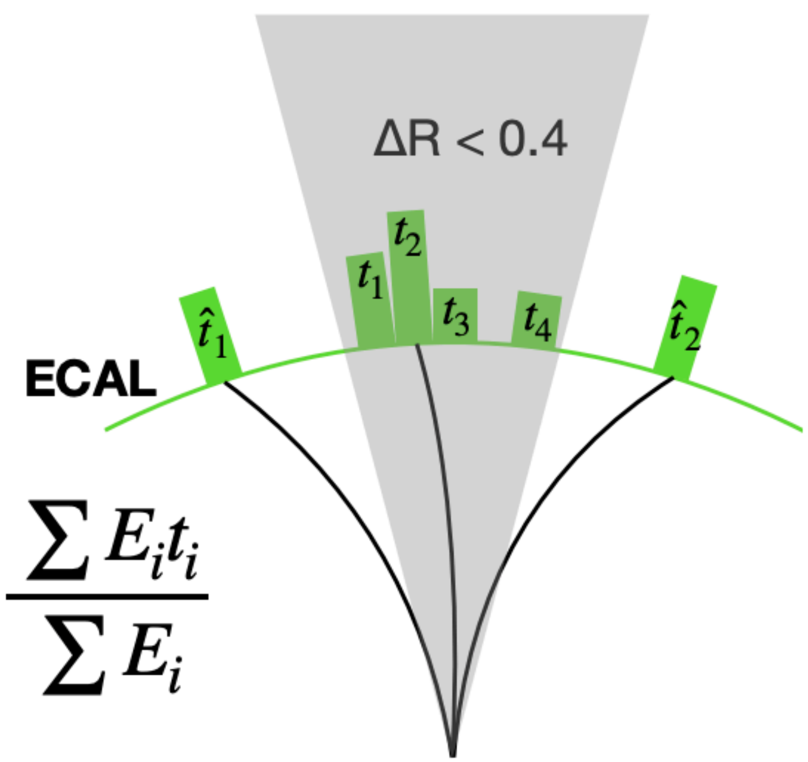
- Eventually extend delayed photons search with **MTD including converted photons**



Displaced Jets at CMS Run 2

- Long-lived gluinos give rise to **jets from displaced vertex**
- Today: Use time from **ECAL cells to match the calo-jets** complementary to tracker-based analysis(> 100 cm)
- **Non Collision Backgrounds**



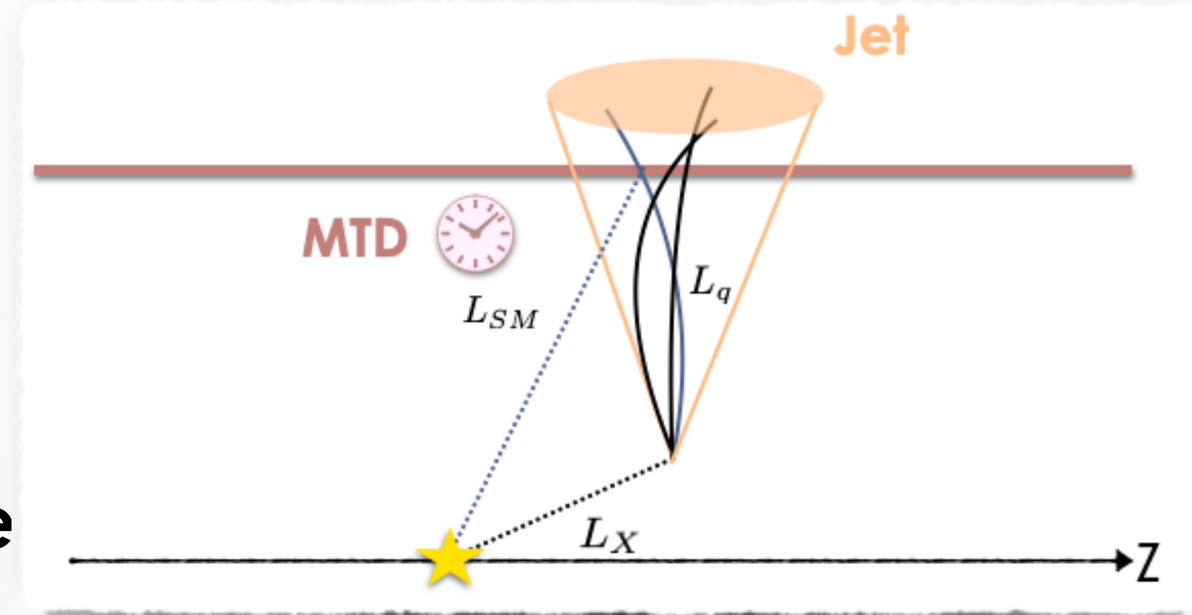


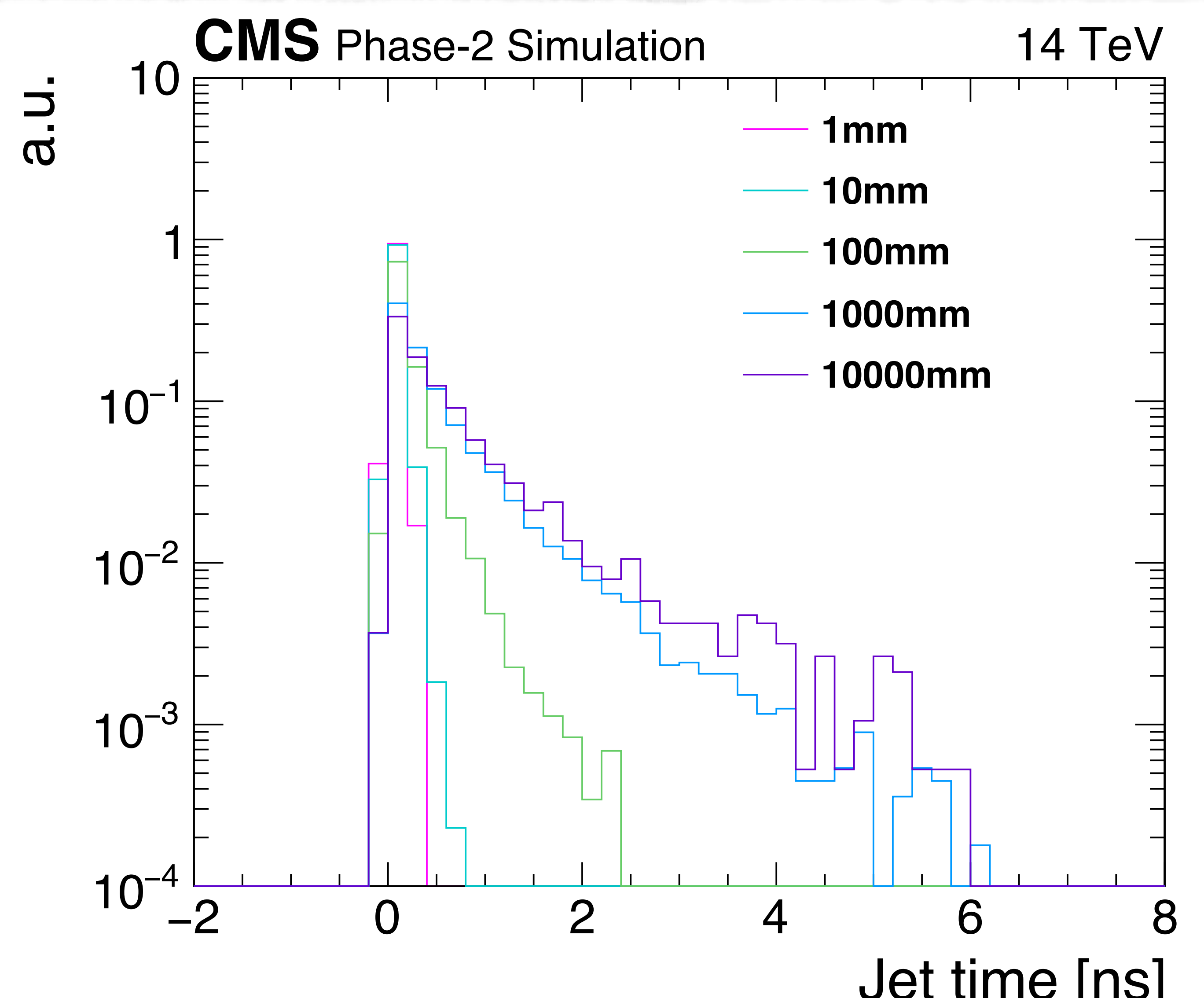
$$t_{reco} = \frac{\sum E_i t_i}{\sum E_i}$$

Displaced Jets w/ MTD I

Generator-level study

- Calculate Δt of arrival to MTD for each jet constituent
- Smear time w/ MTD resolution (30ps)
- **Jet time = average of constituents' time**



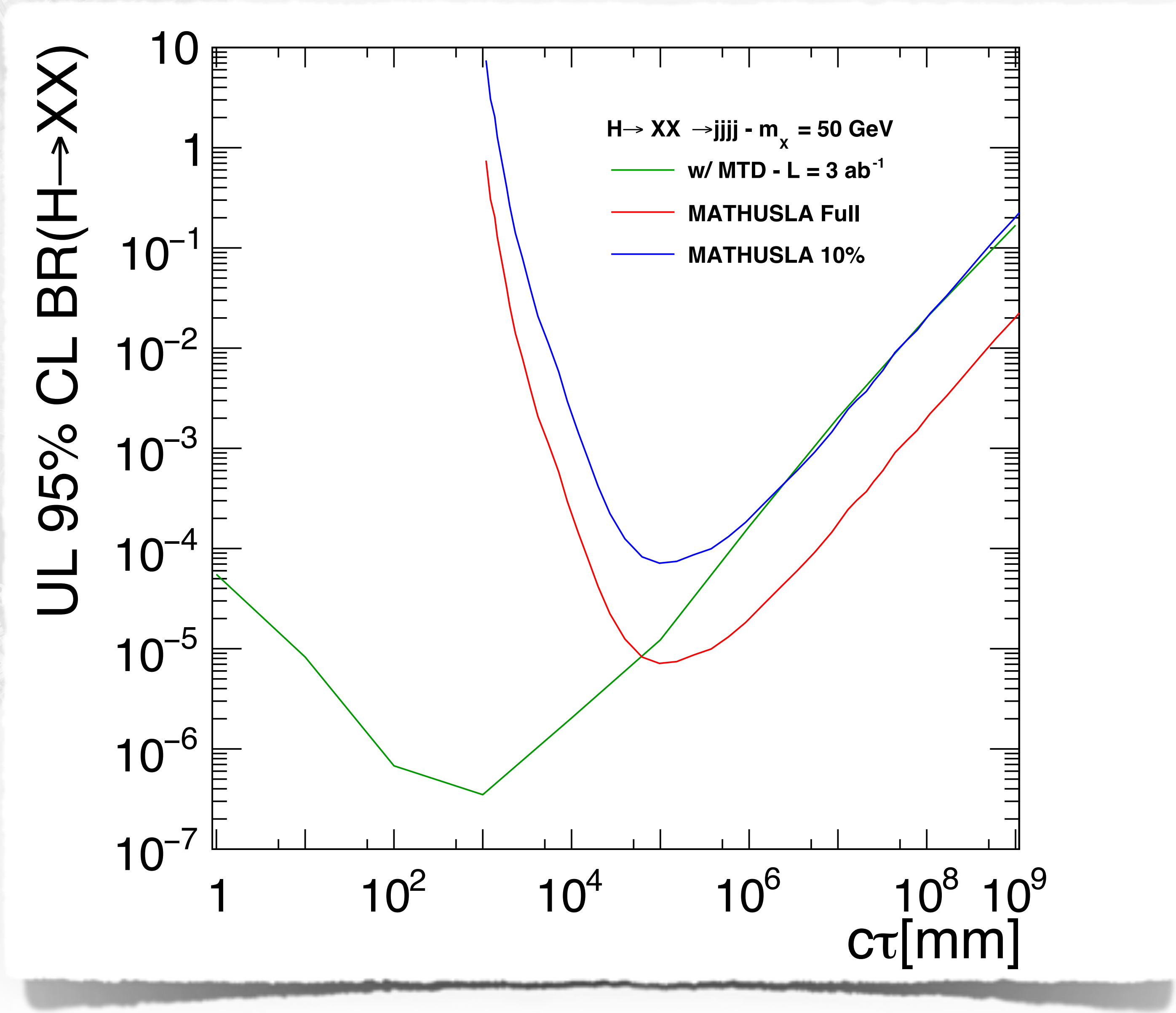


$$\Delta t = \frac{L_X}{\beta_X} + \frac{L_q}{\beta_q} - \frac{L_{SM}}{\beta_{SM}},$$

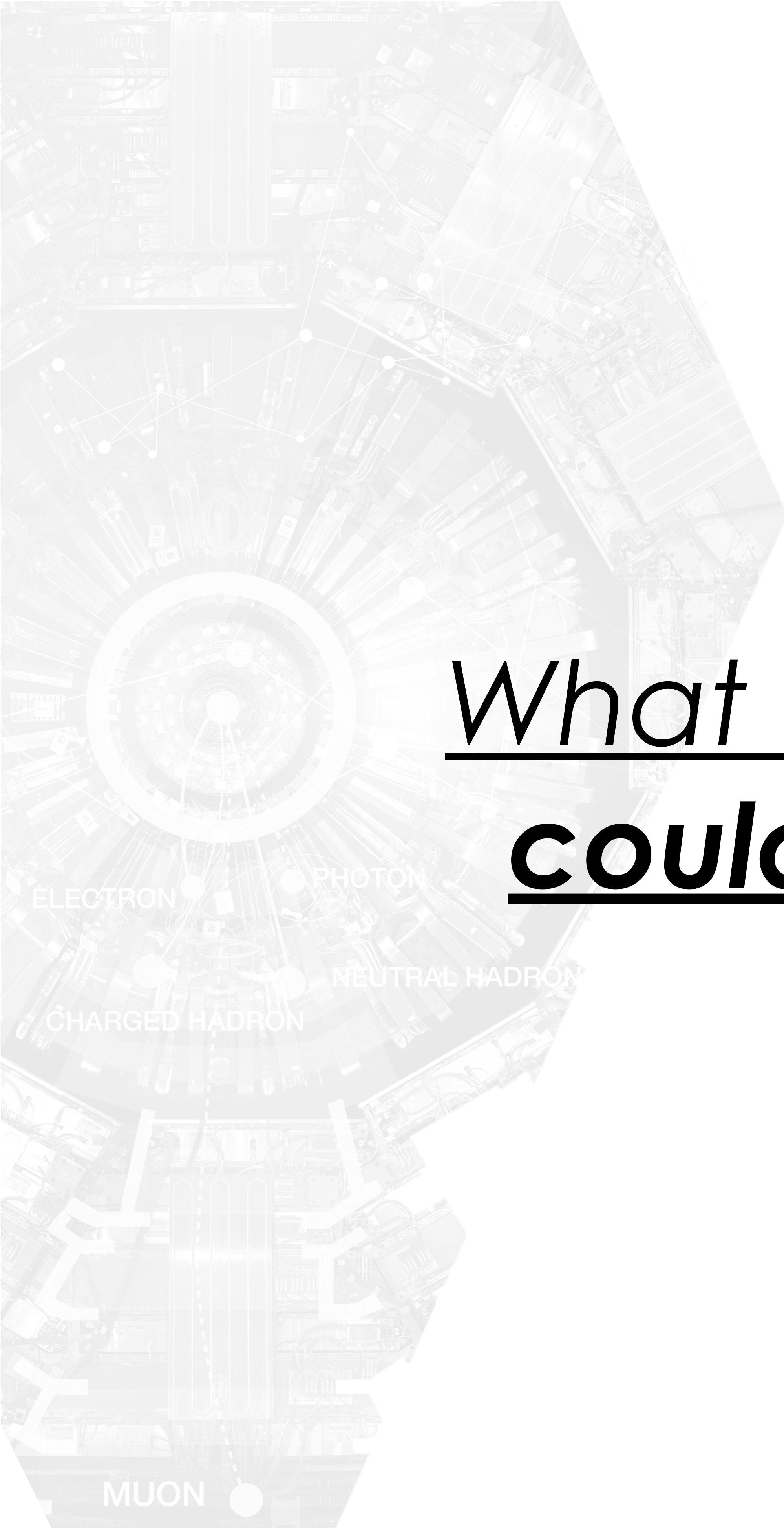
arXiv:1805.05957
arXiv:1806.07396
arXiv:1905.07772

Displaced Jets w/ MTD II

- Upper limits calculated working with a **zero background assumption and L = 3 ab^{-1}**.
- Background effieciency checked with QCD MC to be < 10^{-6}

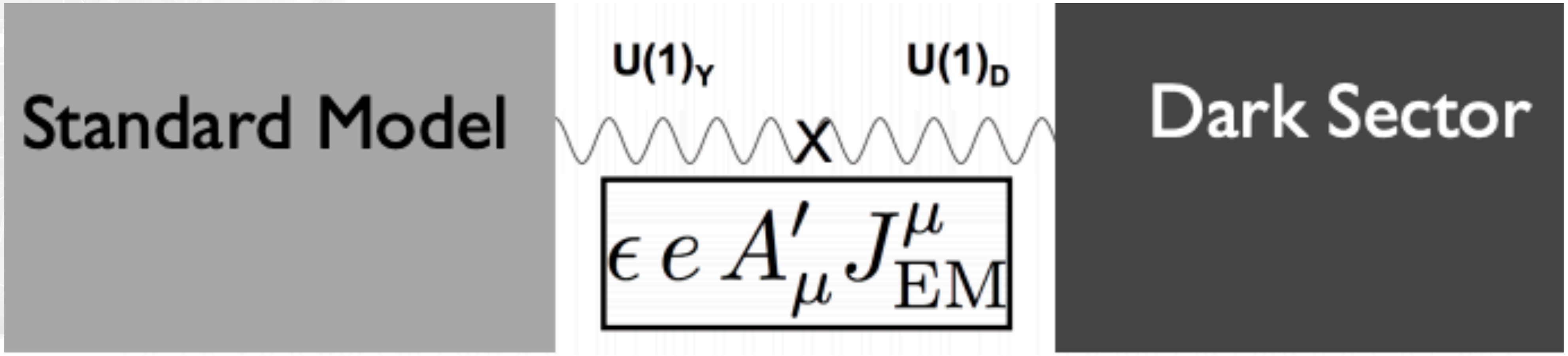


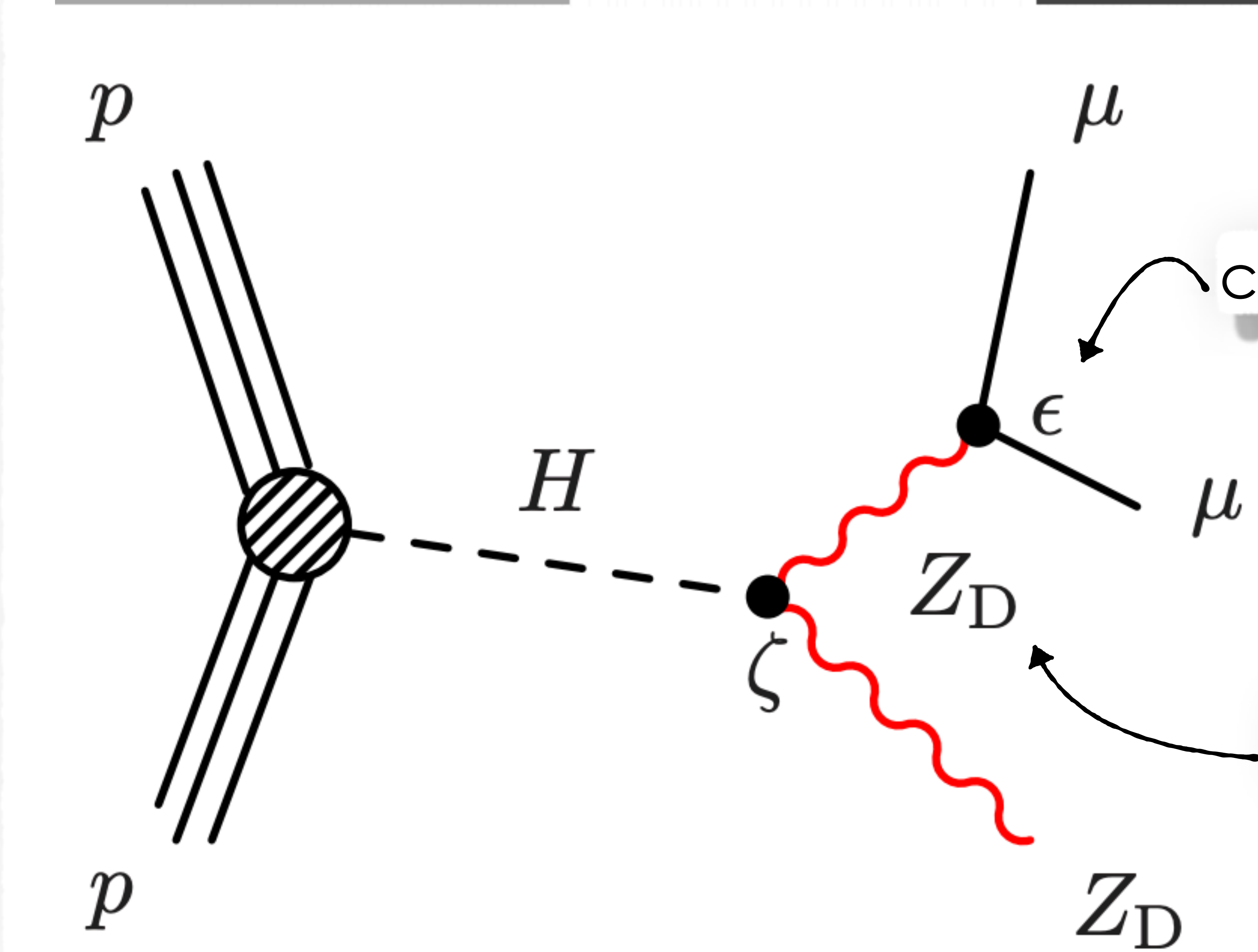
- Limits competitive on the 1000-10000 mm region with dedicated experiments



What the **we think** we could do with MTD..

Delayed Dilepton Signatures



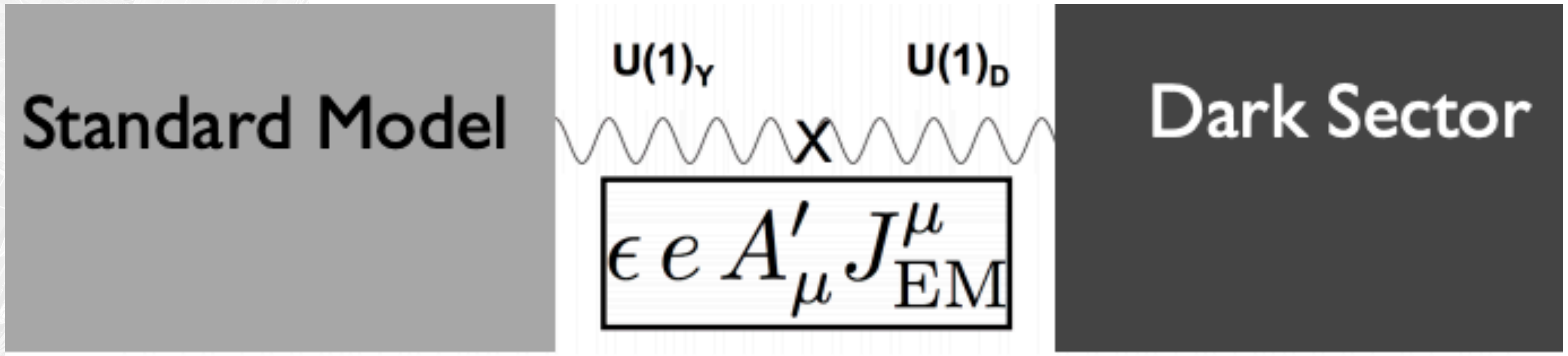


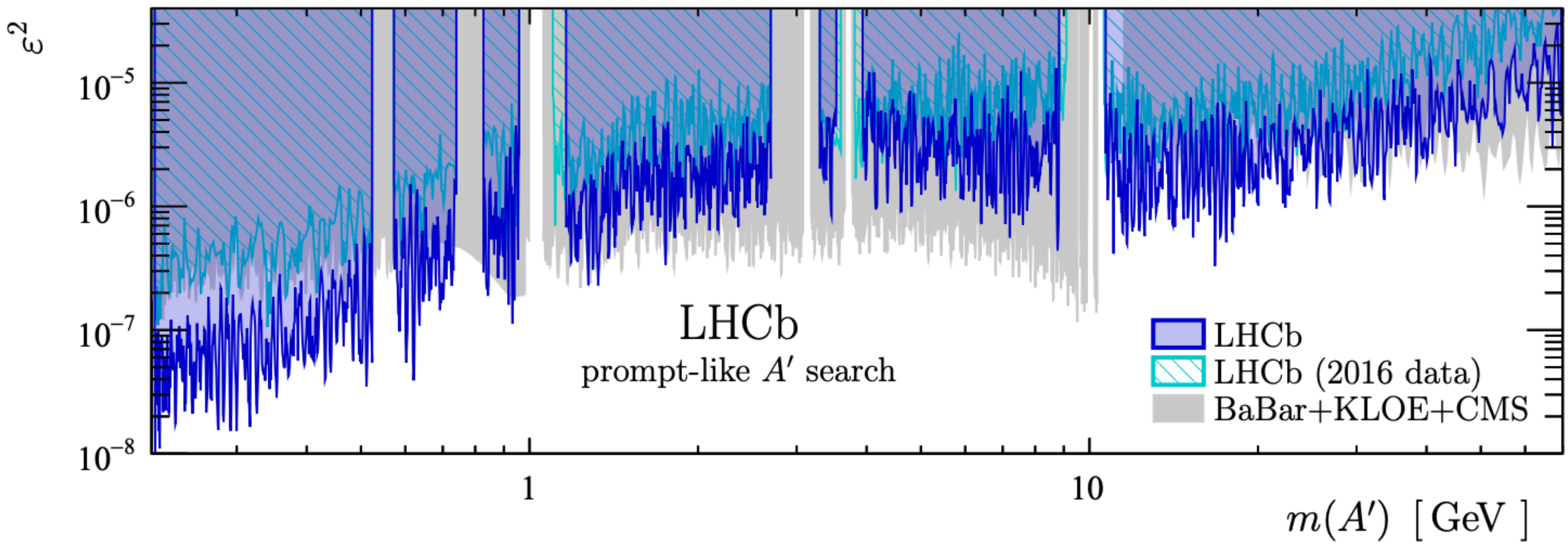
controls Z_D lifetimes

$2m_\mu < m_{ZD} < m_{H/2}$

https://arxiv.org/abs/1412.0018

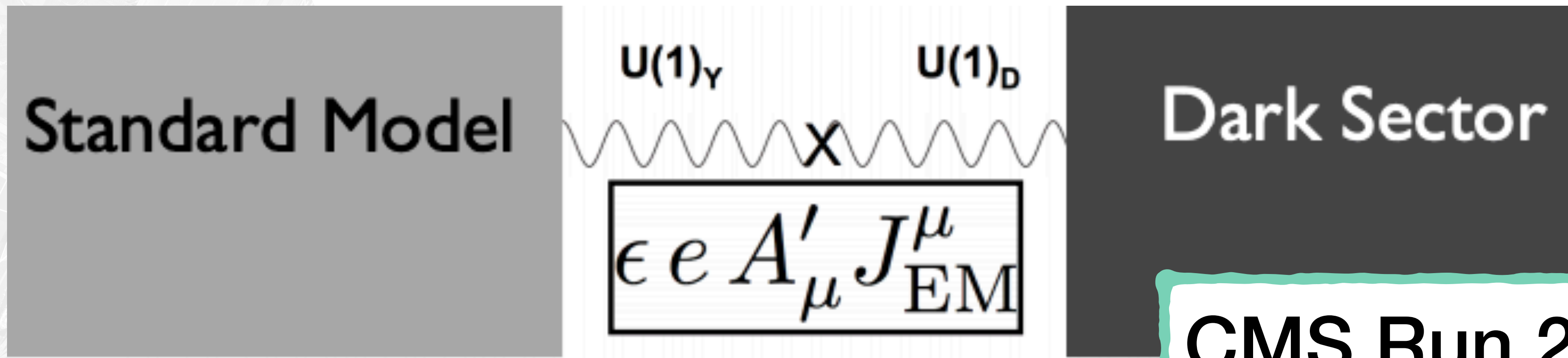
Comparing to LHCb Sensitivity

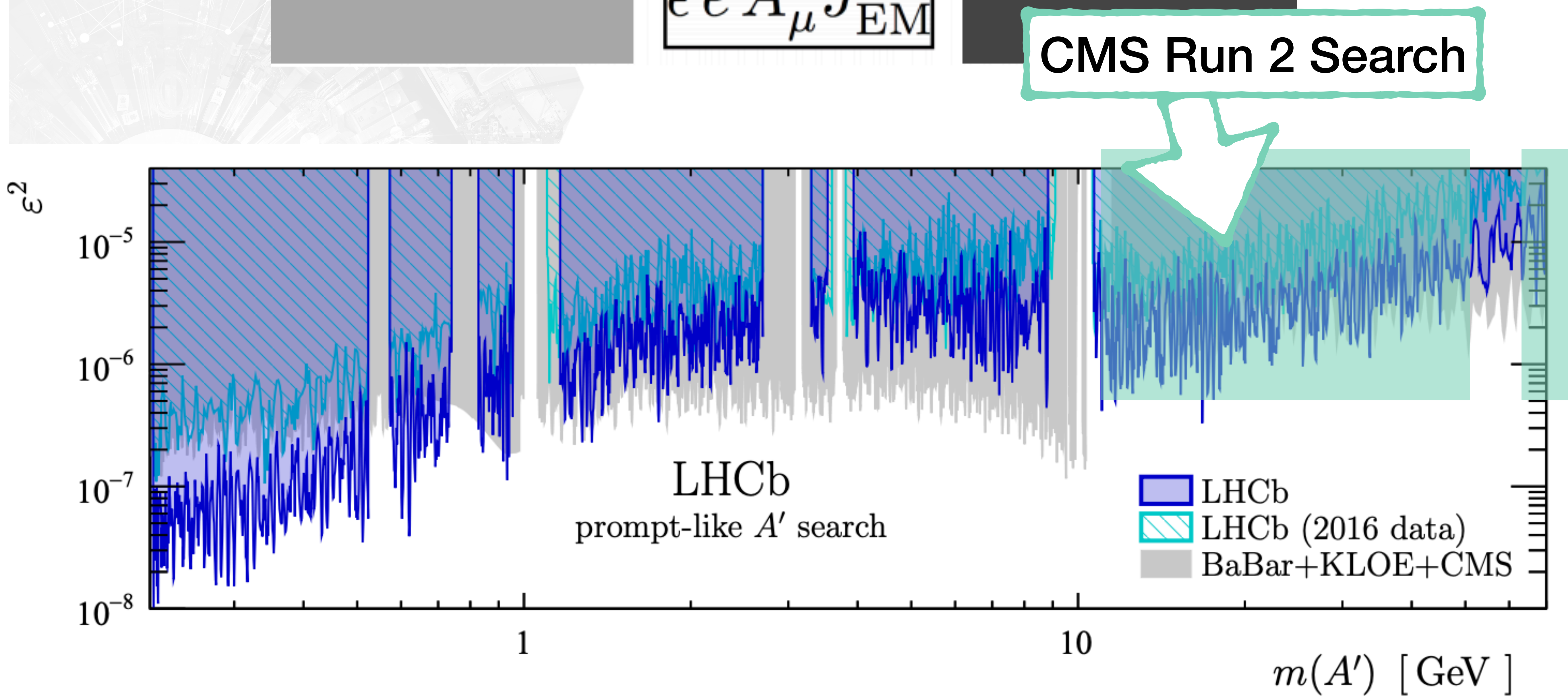




https://arxiv.org/pdf/1910.06926.pdf

Comparing to LHCb Sensitivity





- Today: **Only prompt** bump search with muons reconstructed in **tracker and muon system**

https://arxiv.org/pdf/1910.06926.pdf

Exploring the low mass regions

Trigger Bandwidth = **Event Rate** × **Event Size**

~1 kHz × ~1 MB

If we want to **increase** rate

We need to **decrease** event size

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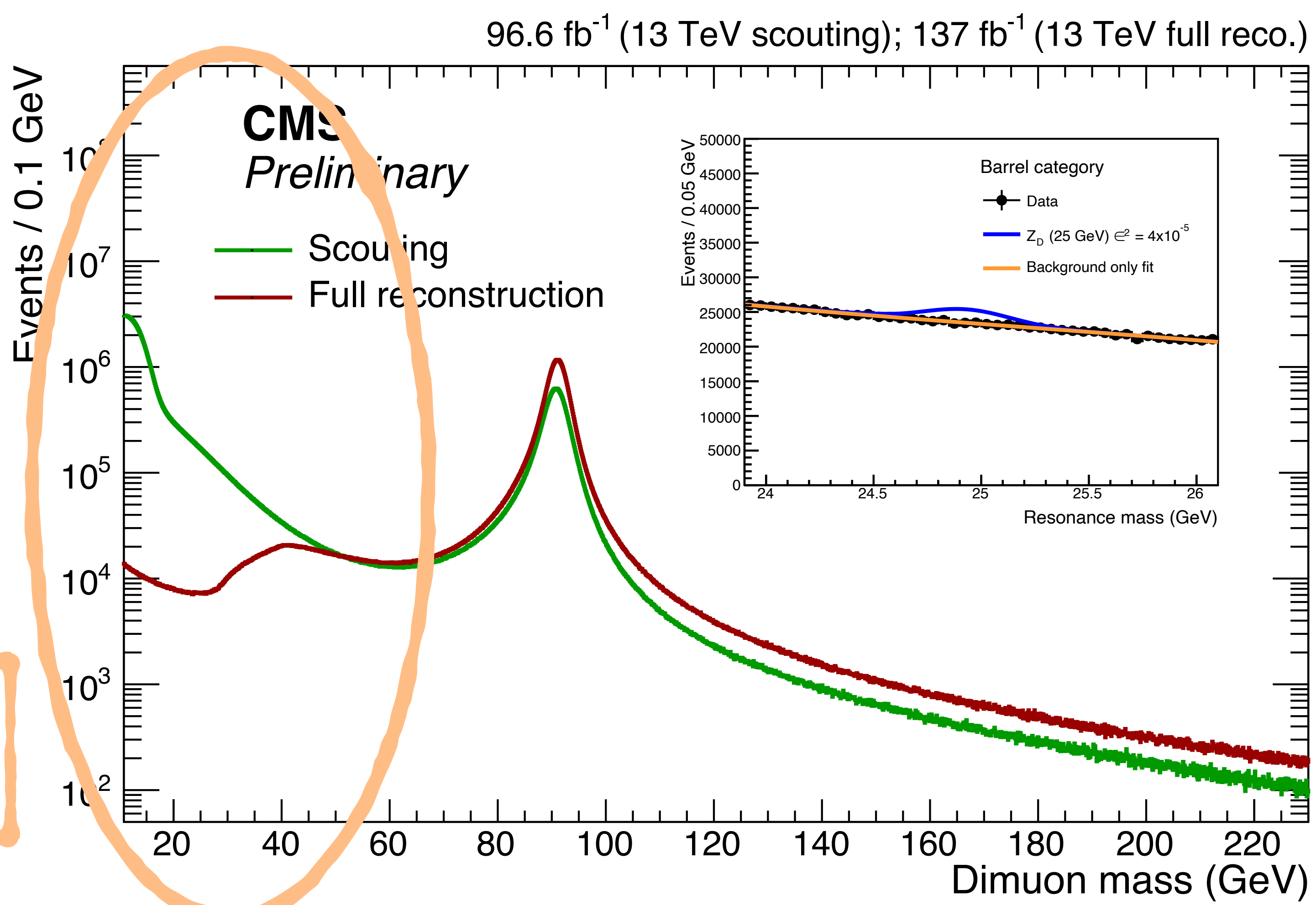
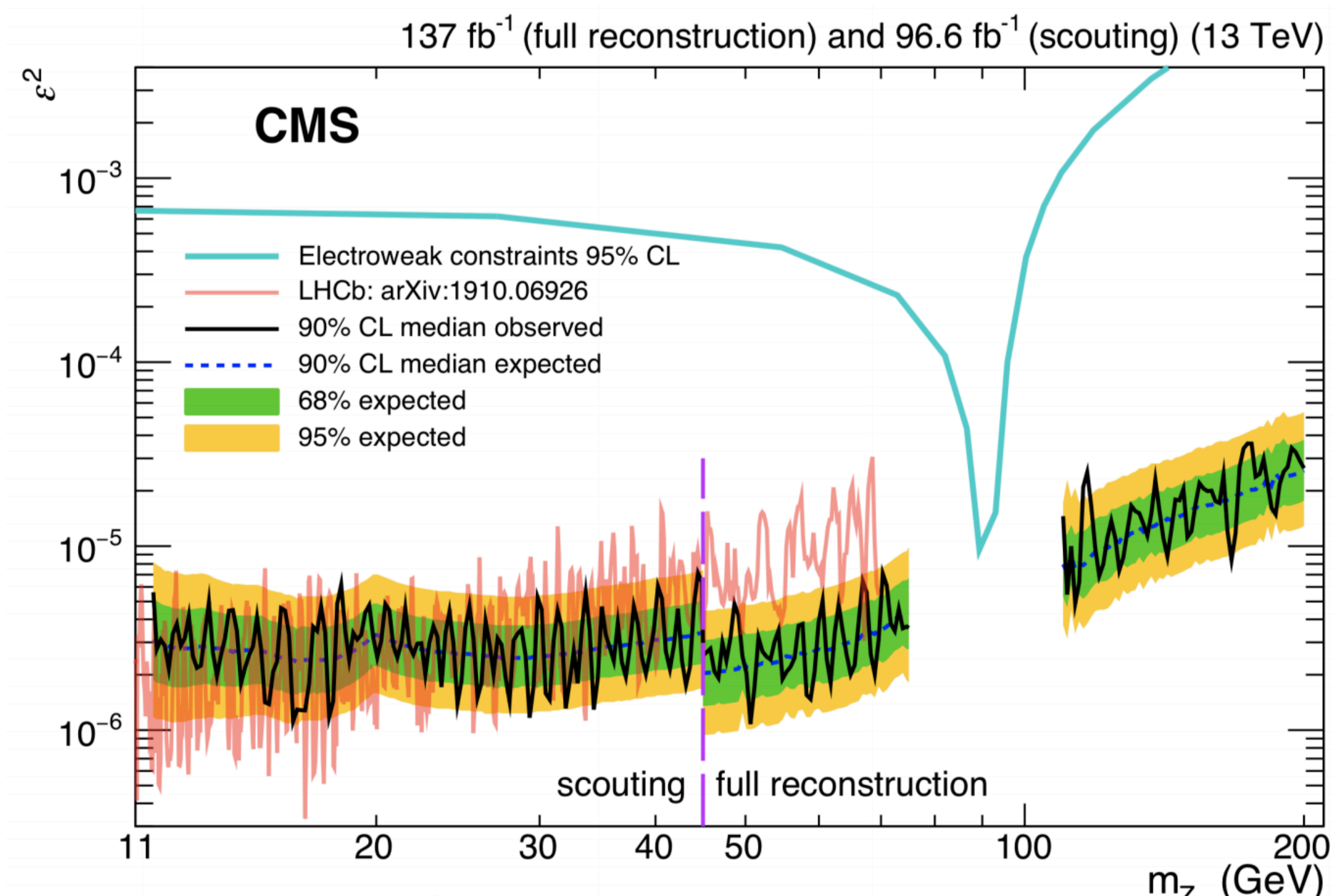


Scouting

Comparing to LHCb Sensitivity



11.5-45 GeV scouting

45 – 75, 110 - 200 GeV: full reconstruction

- Today: **Only prompt** bump search with muons reconstructed in **tracker and muon system**

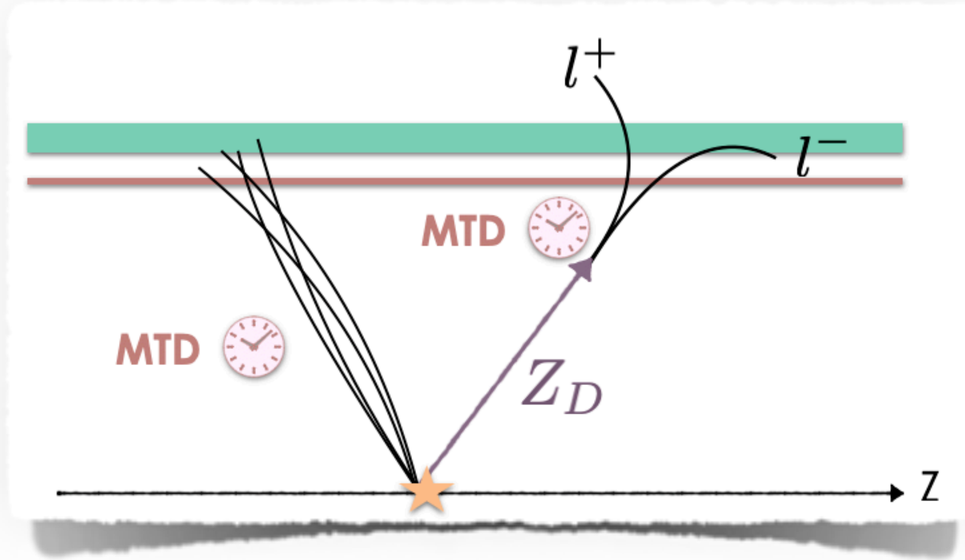
Dark photons with MTD at HL-LHC I

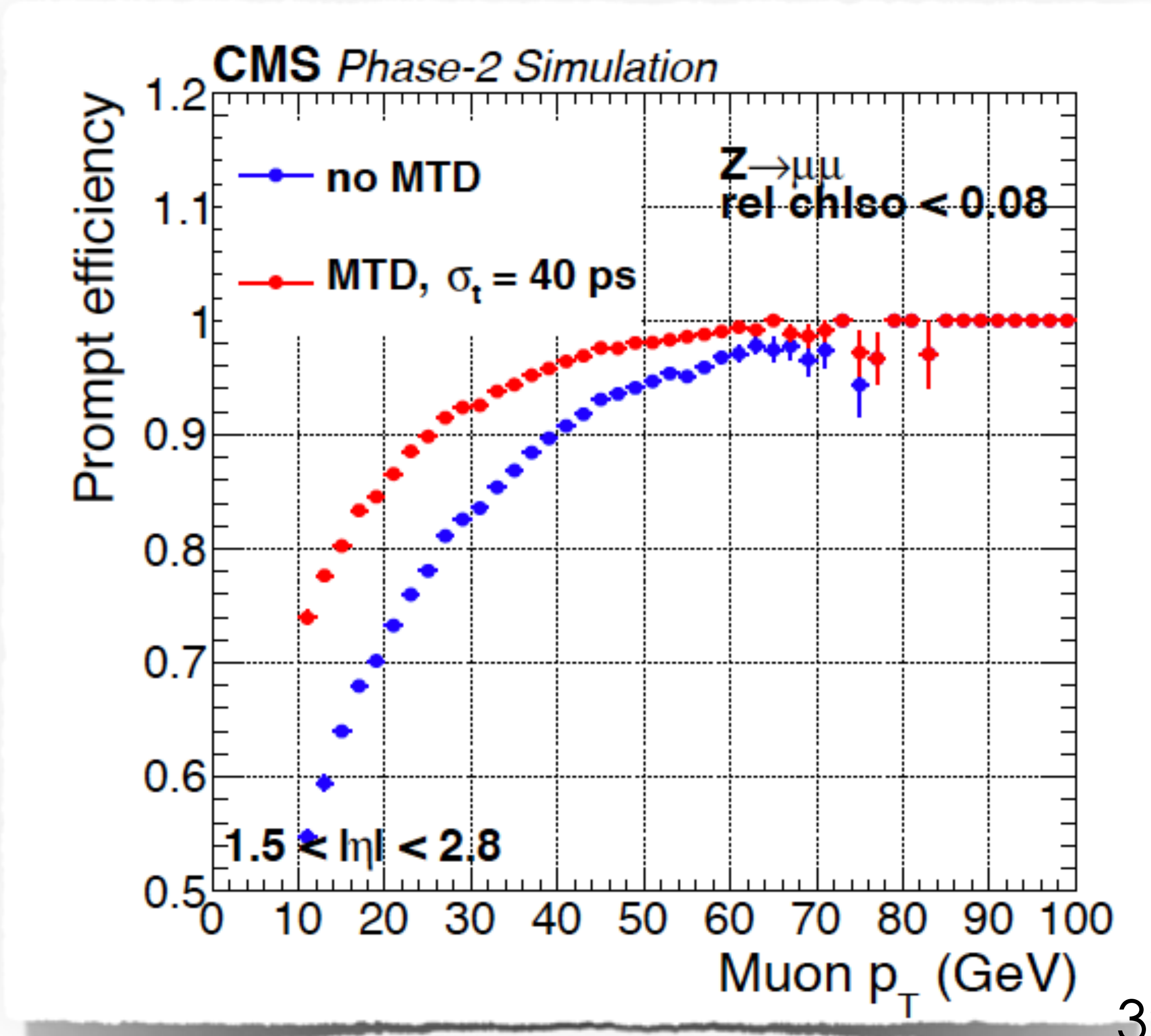
- Improve **lepton performance at low p_T**

  - Extend scouting dataset **acceptance** (up to 3rd pixel layer)

  - **Lepton ID** benefit from additional information **from MTD** and **reject background especially from PU at low p_T**

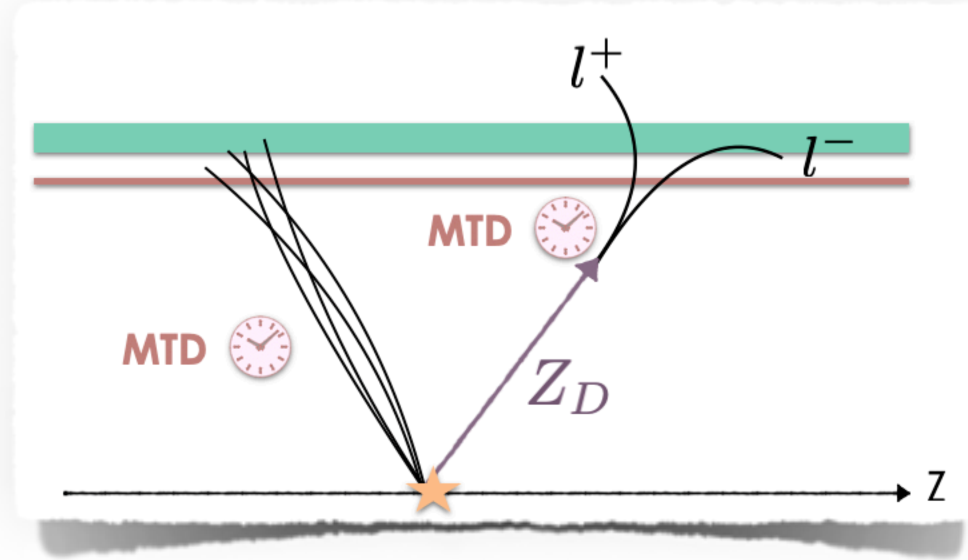
    tracks are **space/time-associated** with the primary vertex

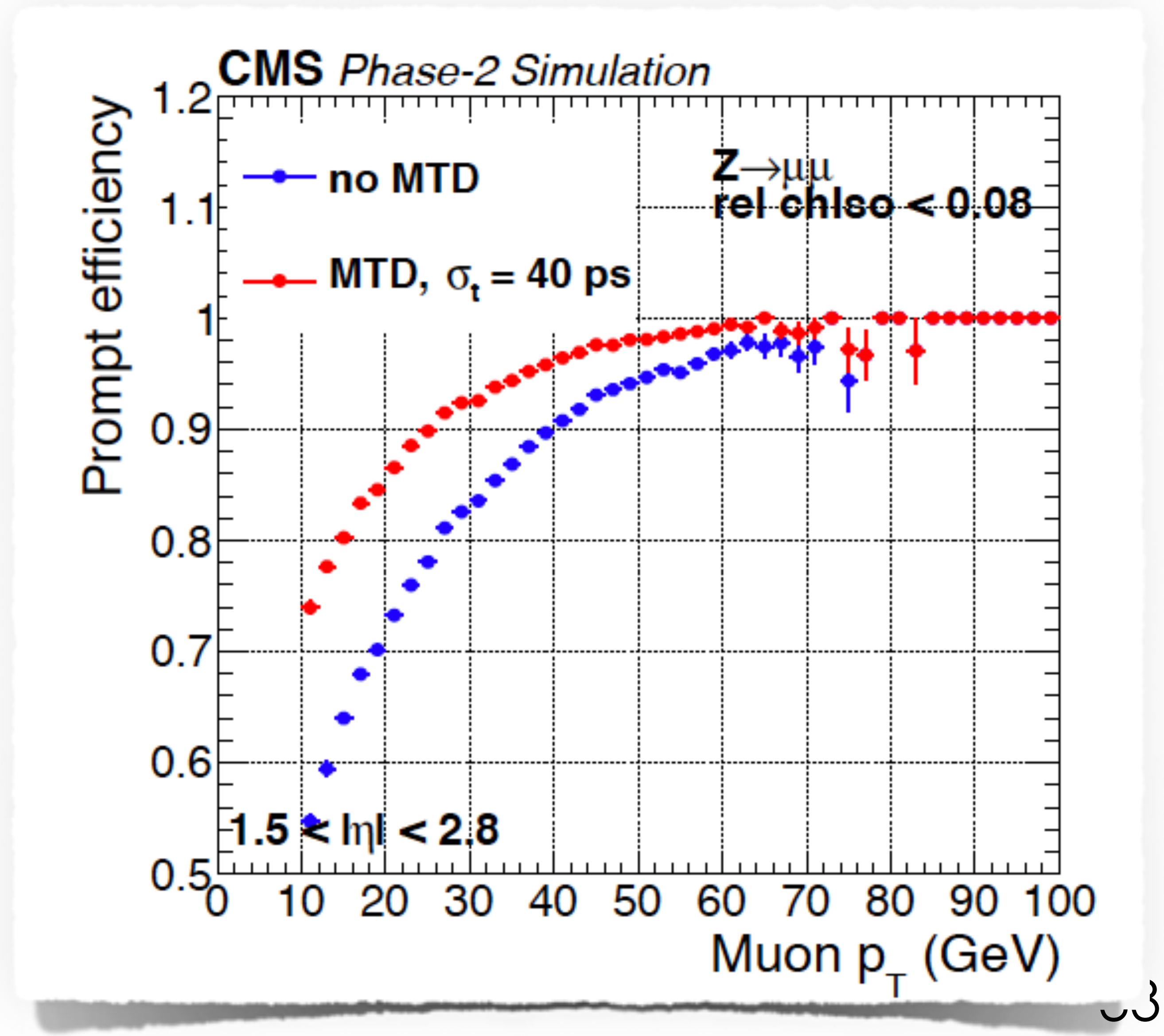




Dark photons with MTD at HL-LHC II

- Improve **lepton performance at low p_T**
- Extend search to **dielectrons channel combining MTD with ECAL measurement**
- Extend dilepton search to **displaced signals** to explore **displaced dark photons production**





What the ***we would like to do*** *with* ***MTD in the future..***

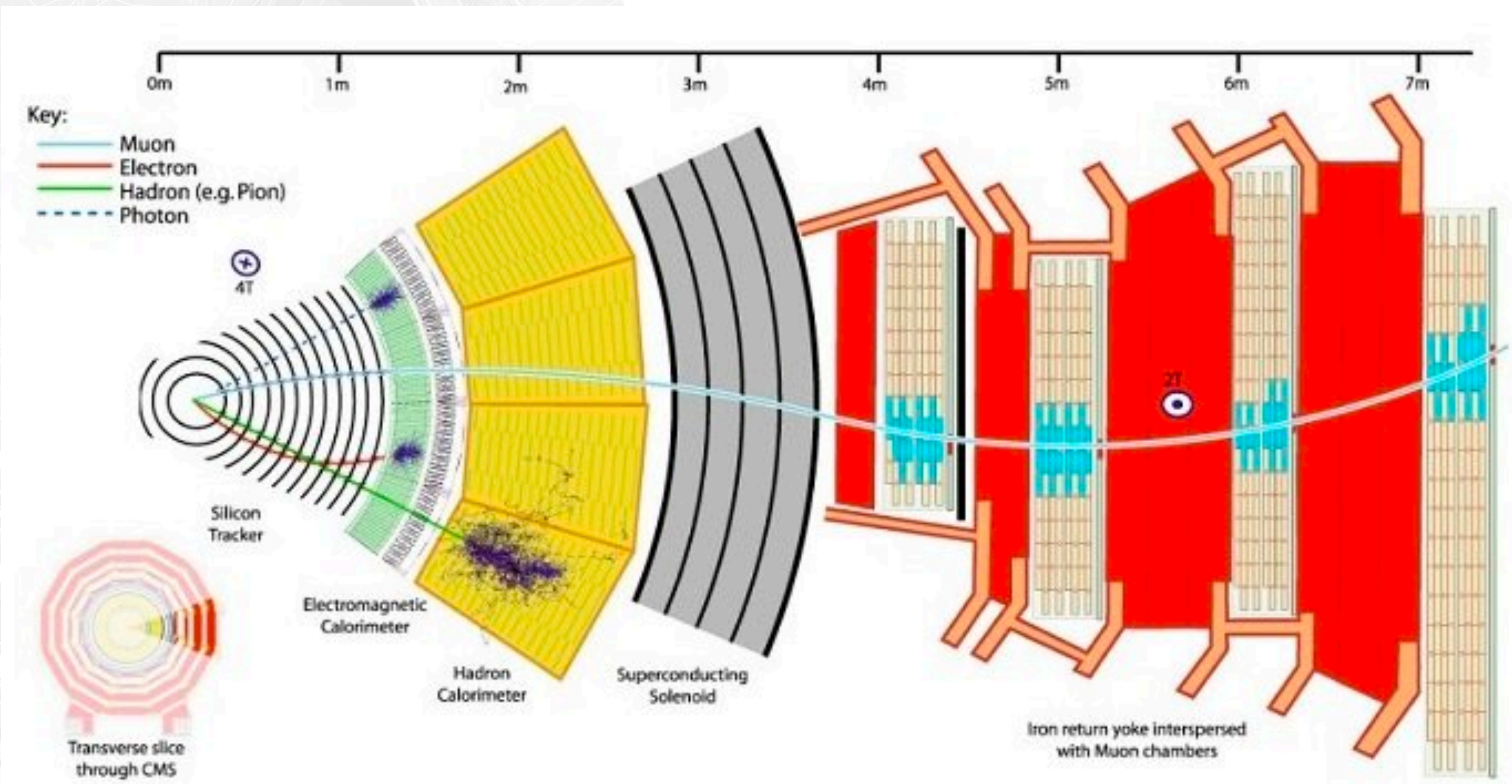
CMS Timing Trigger at HL-LHC

L1 Tracking
up to ~50 mm displacement

ECAL TPs
(only eγ > 20 GeV)
position = 1m
resolution ~1ns

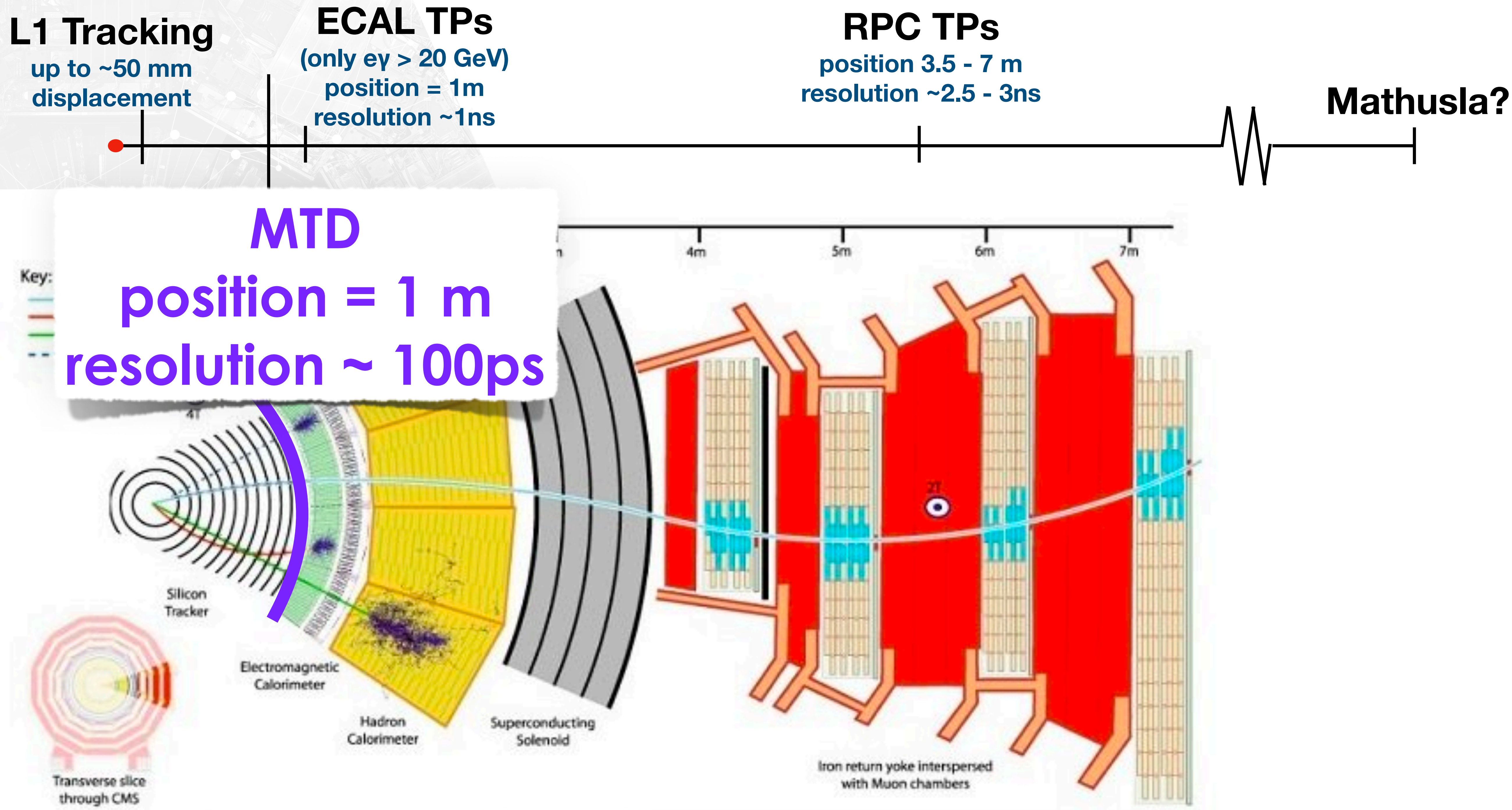
RPC TPs
position 3.5 - 7 m
resolution ~2.5 - 3ns

Mathusla?



- Timing online from the **ECAL, HCAL, RPCs** in the Phase2 L1 Trigger
- Displaced tracks up to ~50 mm will be available at L1

CMS Timing Trigger at HL-LHC

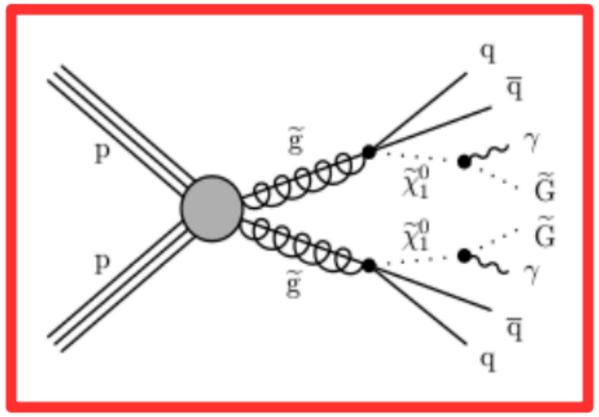


- Timing online from the **ECAL, HCAL, RPCs** in the Phase2 L1 Trigger
- Displaced tracks up to ~50 mm will be available at L1

Motivation for MTD at L1

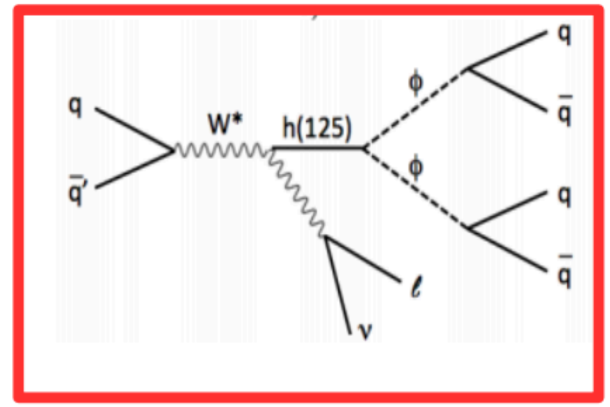
Delay between LL object and PV

- Seed triggering on large time differences between electron/muon/jet/photon and the PV.



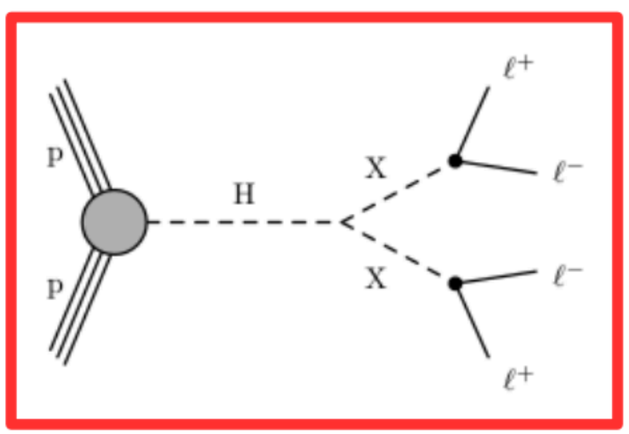
Delay between prompt and LL object

- Seed triggering on large time differences between electron/muon/jet/photon and a prompt object.



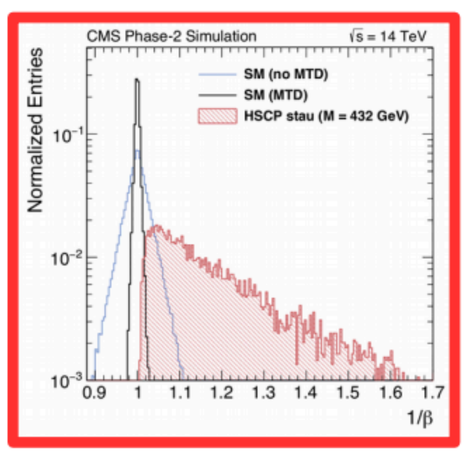
Delay between two LL objects

- Time difference between LLP (which can be also large)



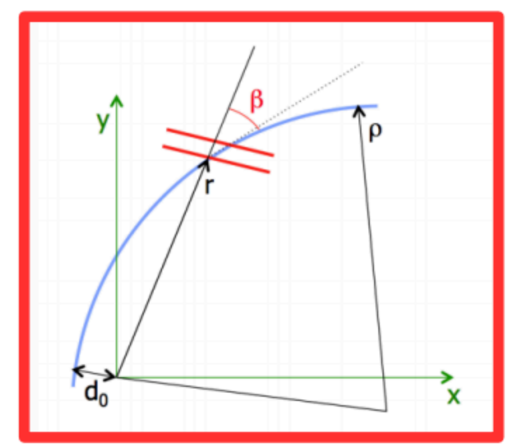
Discrimination on beta

- Seed on low beta particles
- Path length / time diff wrt PV



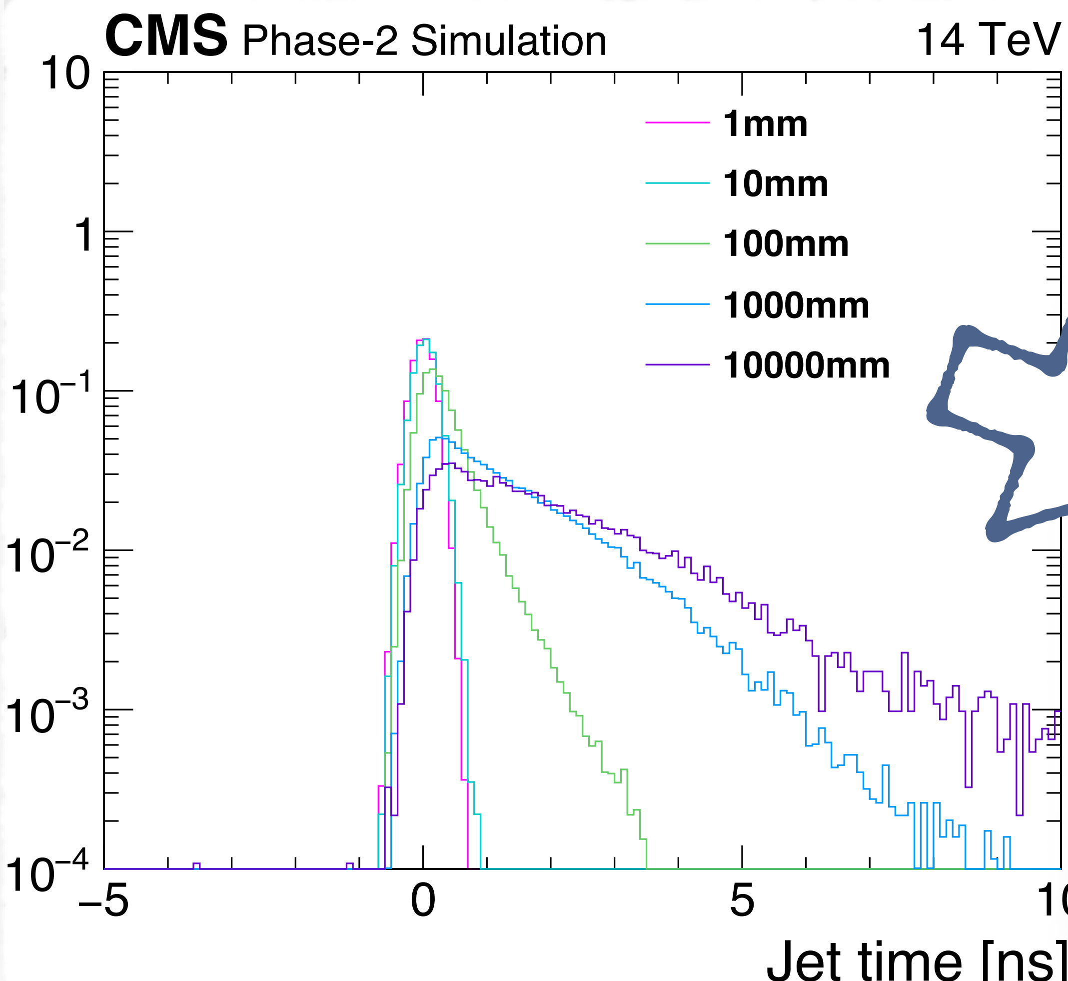
Pile-up cleaning

- Cleaning tracks entering into other displaced object algorithms.



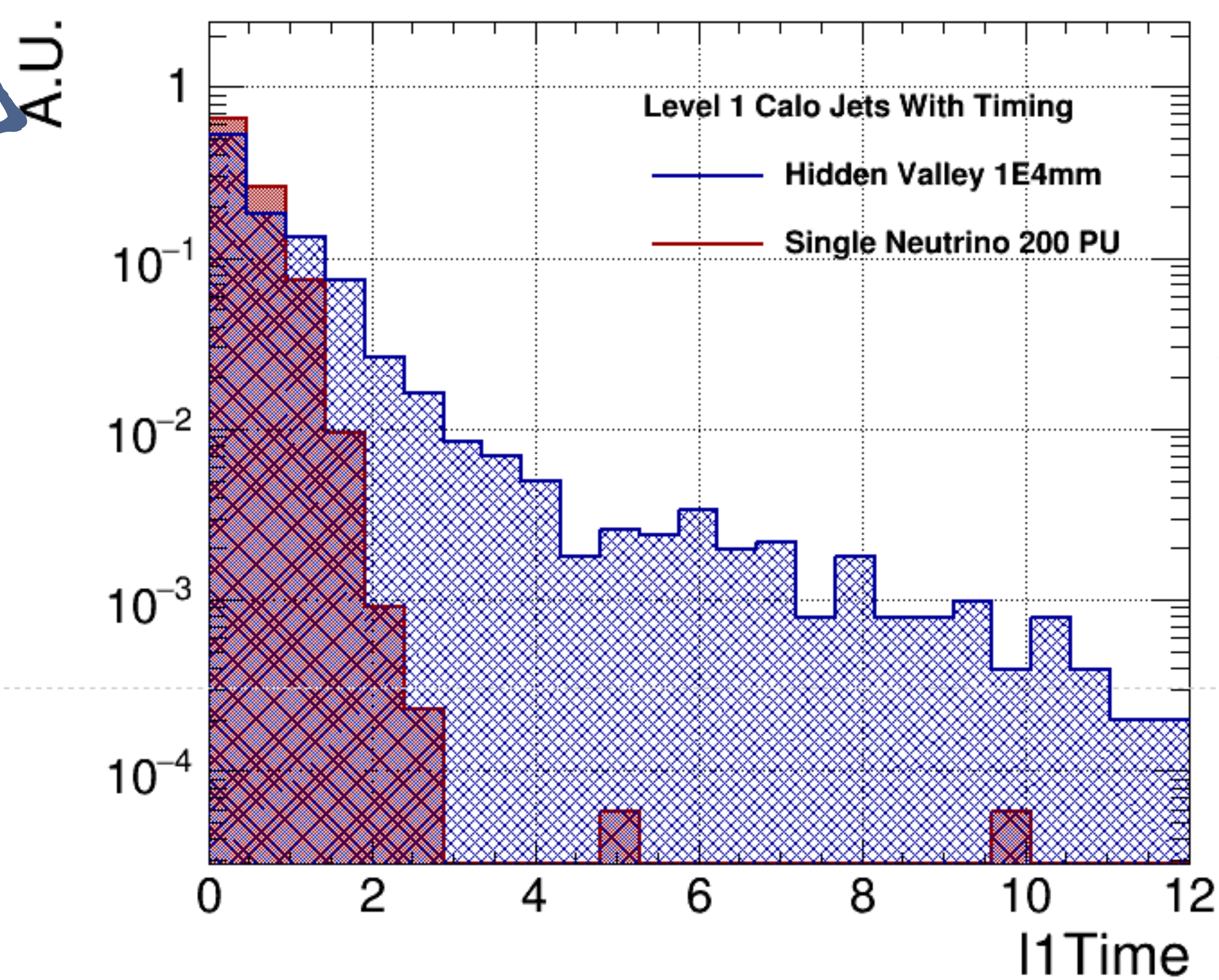
L1 Jet Time with MTD

- **Level-1 Calorimeter Jets** are **matched to MTD timing hits** in a cone of 0.4 around the central axis of the Calo Jet
- The L1 Time of a jet is the **total time / number of hits**



Gen-level

Reco-level



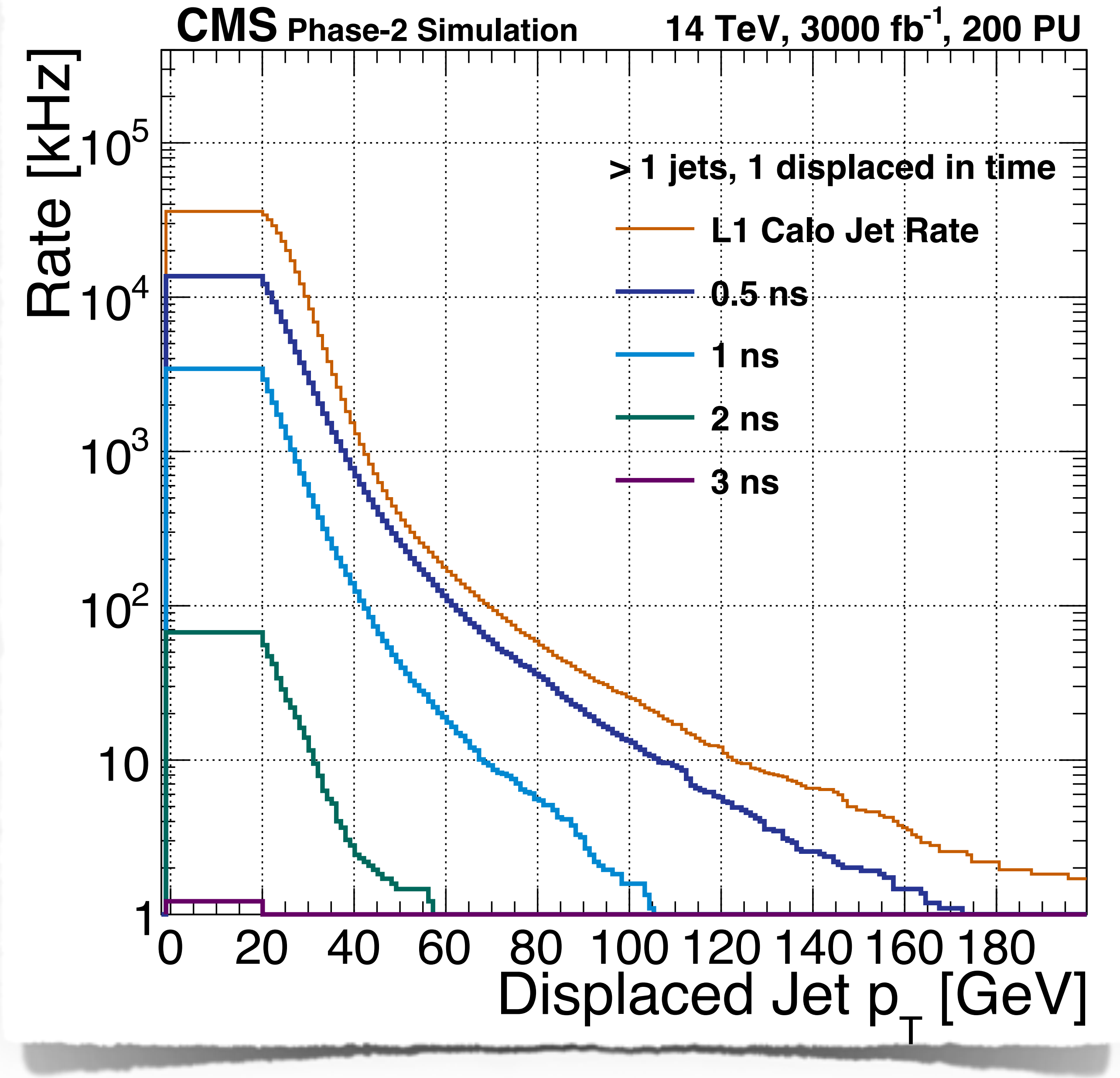
Work w/ Isobel Ojavo

State of the art: CMS MTD @L1

L1 Rates reduction is a compelling reason to allow the MTD to be part of the Level-1 Trigger

- Already the plan for the BTL
- Would need to be added to the ETL

For now it has been decided that this is not within the CMS Phase 2 baseline however there is space to strengthen the physics case for a L1 trigger and we will keep working on it in the next year!

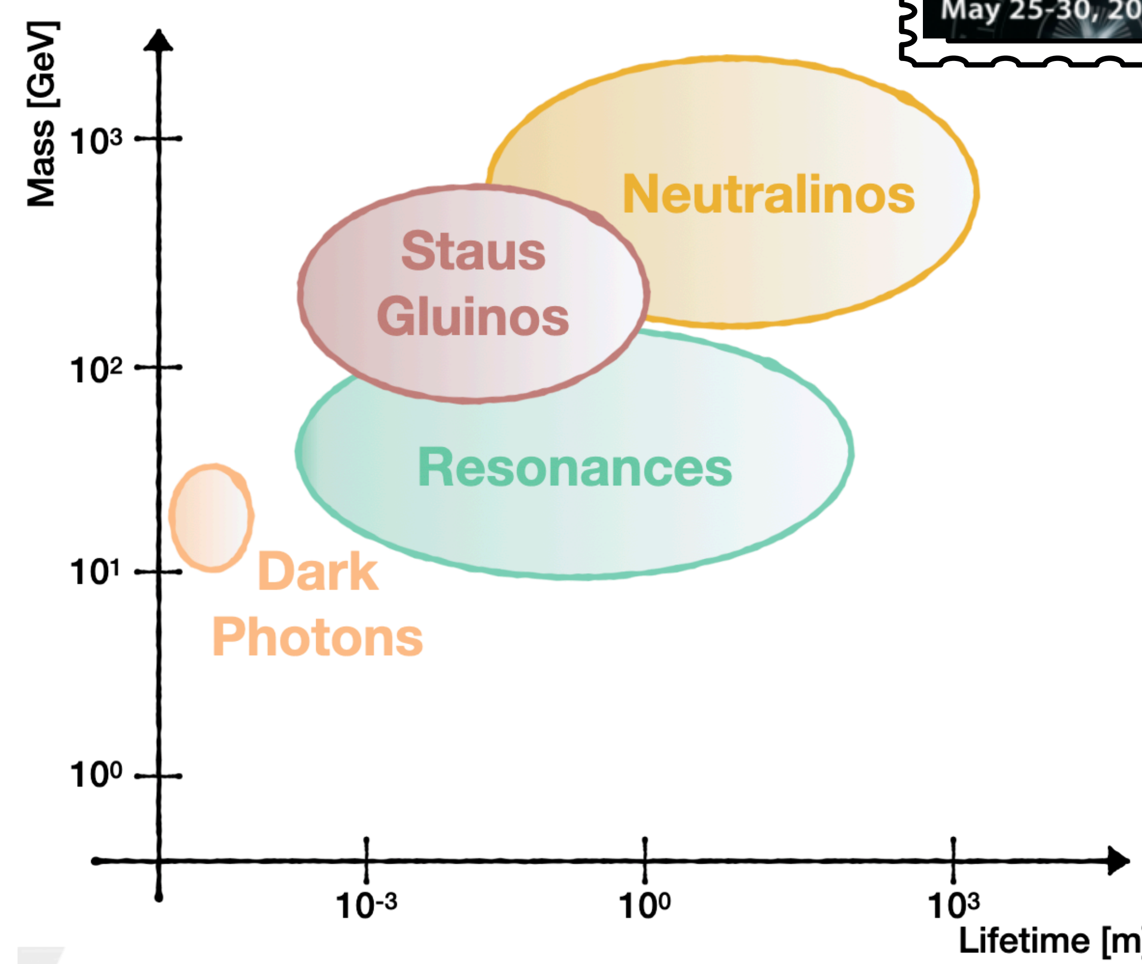


Work w/ Isobel Ojavo

Conclusions

- **CMS MTD** project: **more effective timing detector for HL-LHC**
  - Maintain current LHC **performance**
  - Withstand **radiation damage** effects and **high pileup rate**

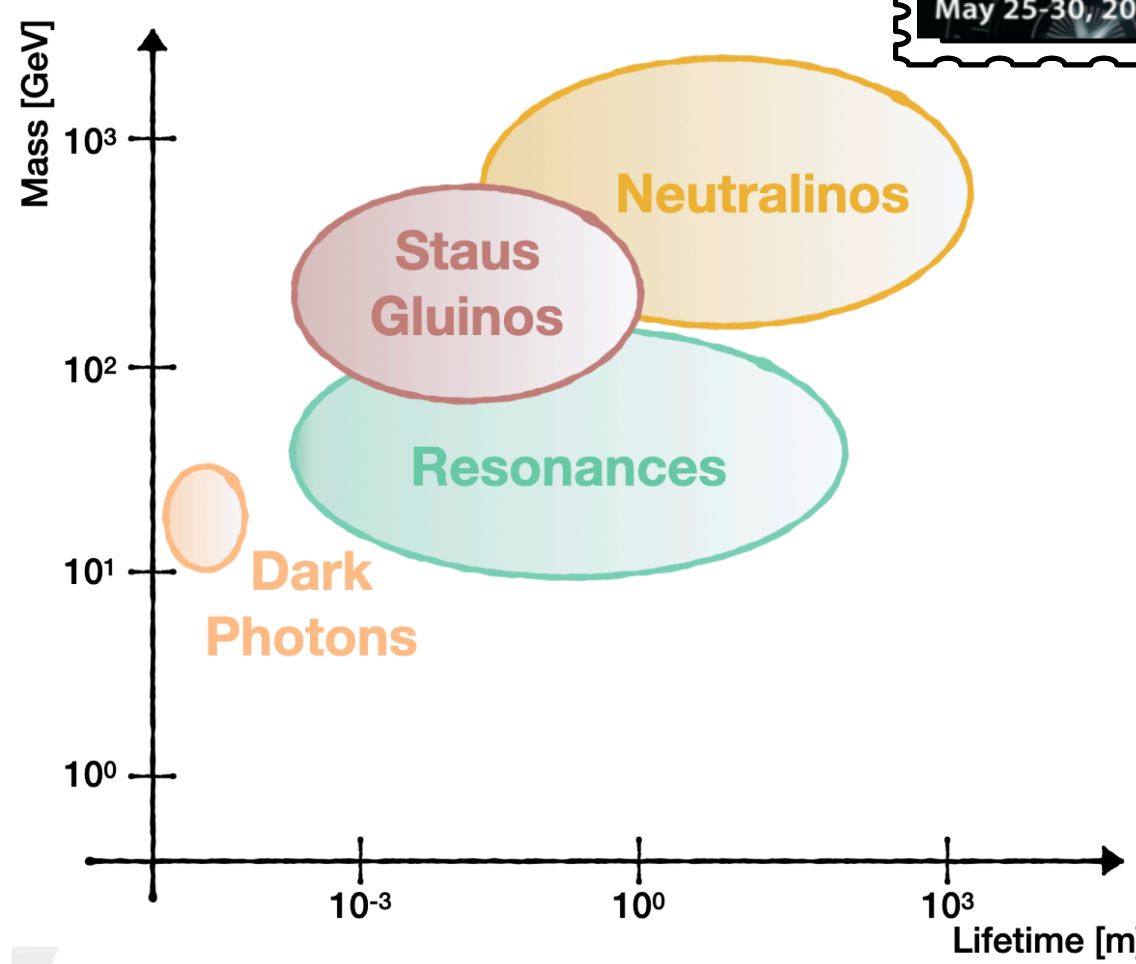
- Rediscovered interested in **long lived particles** and **detector based signatures**



Conclusions

- **CMS MTD** project: **more effective timing detector for HL-LHC**
    - Maintain current LHC **performance**
    - Withstand **radiation damage** effects and **high pileup rate**

- Rediscovered interested in **long lived particles** and **detector based signatures**
    - MTD brings **novel search capabilities**
    - Probe **unexplored phase space regions**
    - **Competitive** with dedicated experiments



Backup