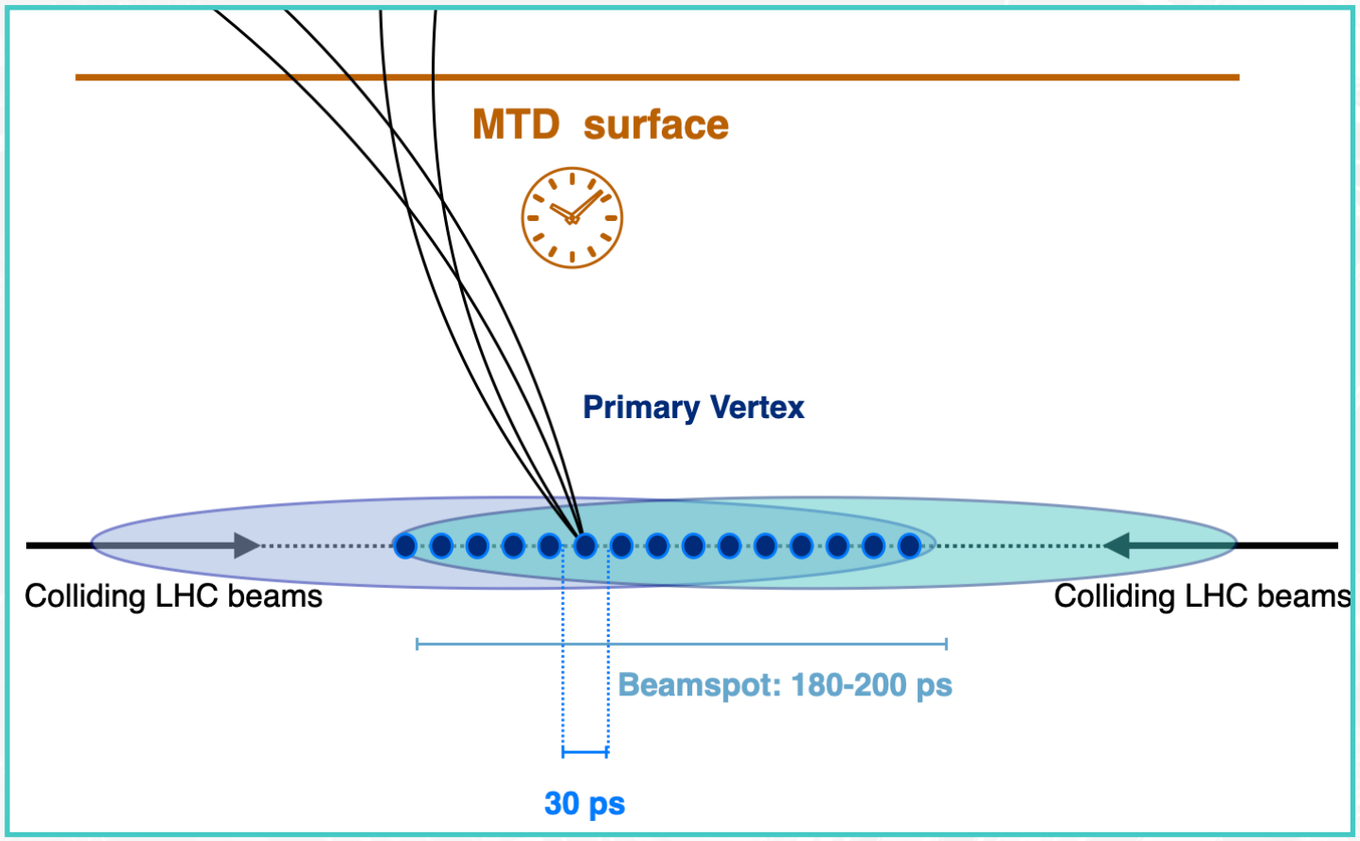
Physics opportunities with a MIP Timing Detector in CMS for HL-LHC

Livia Soffi on behalf of the CMS Collaboration

Introduction

- **Mip Timing Detector (MTD)**: new **30-40 ps timing resolution** detector for CMS at HL-LHC



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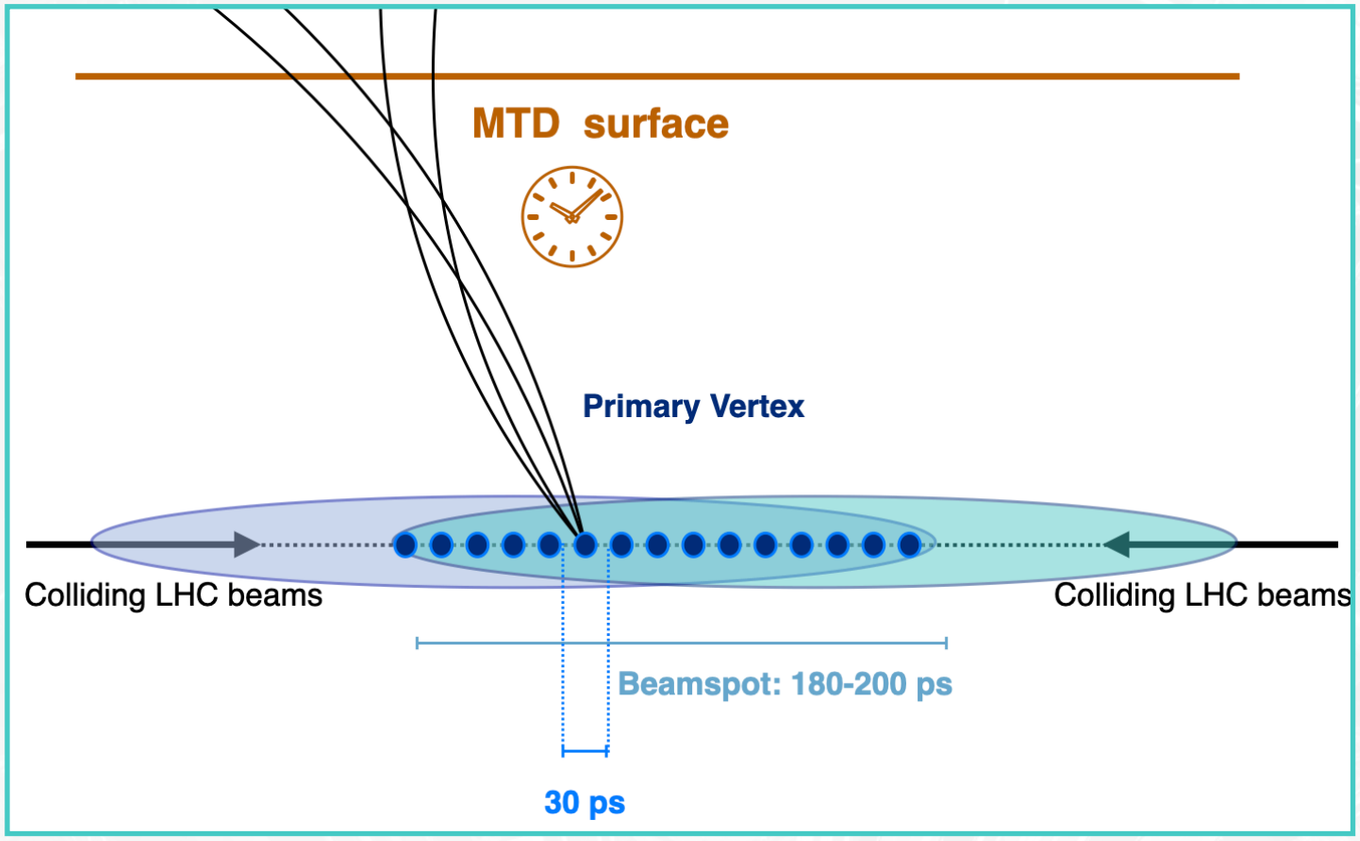

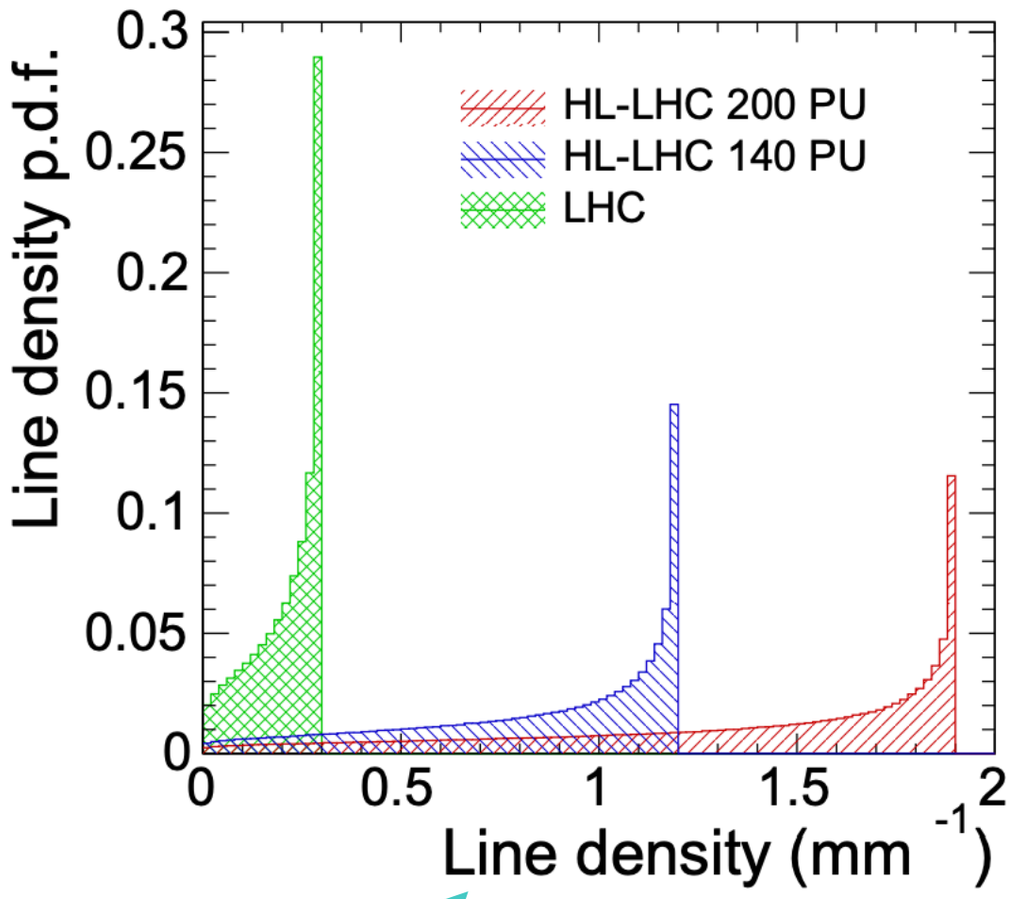

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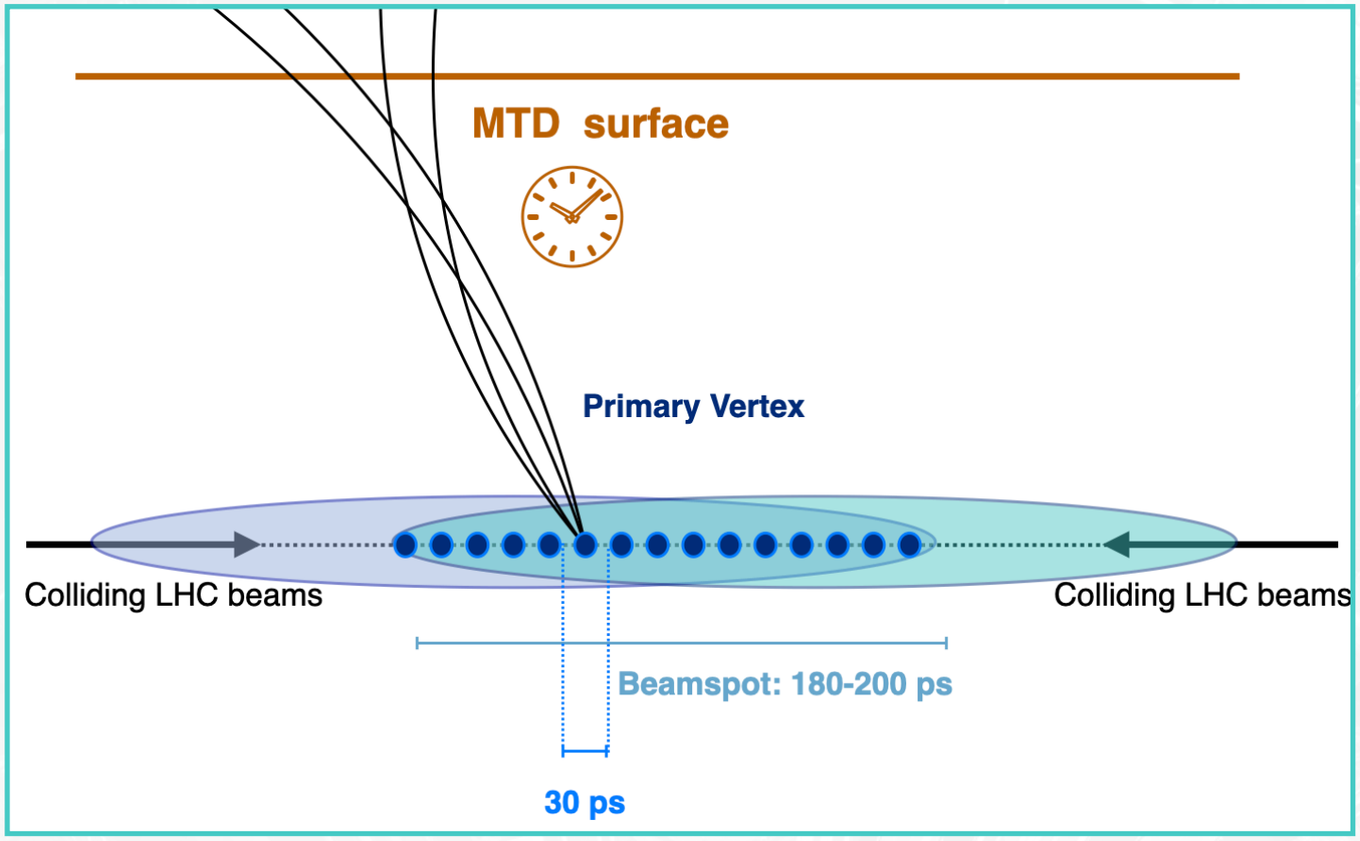

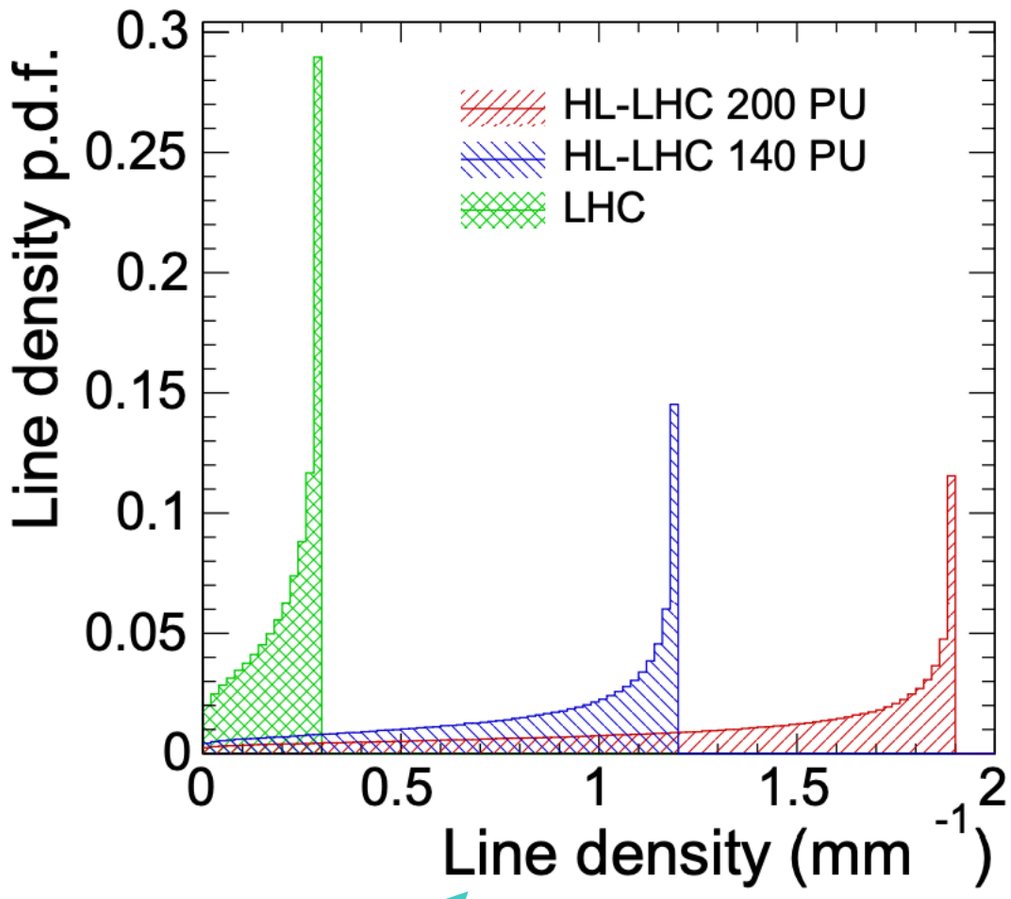

- Recover **Run 2 performances** in harsh pileup (PU) HL-LHC condition

- Improve reconstruction and selection of **physics objects**
- Extends **sensitivity to Long Lived Particles** (LLP) beyond typical analysis strategies
- Provides implicitly **particle identification (PID)** capabilities
- New **opportunities of Heavy Ion** physics (DP2021-037) and **B-physics**

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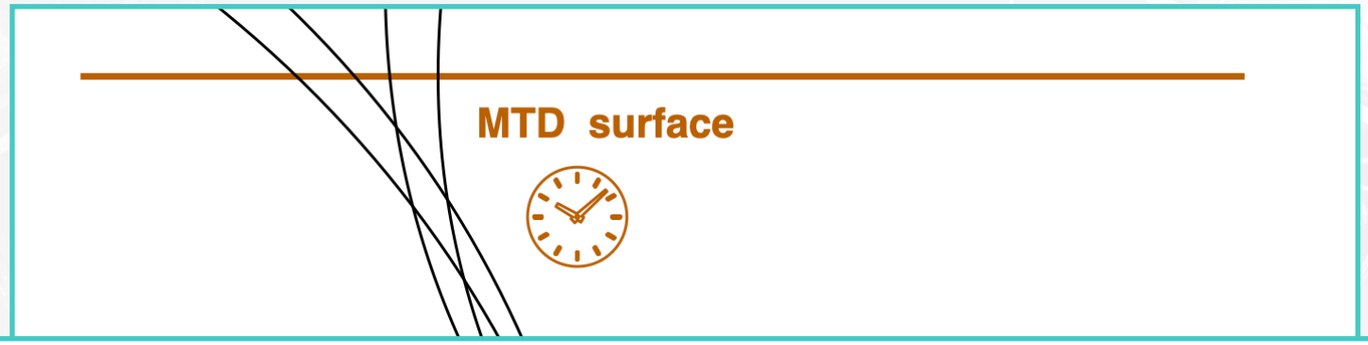

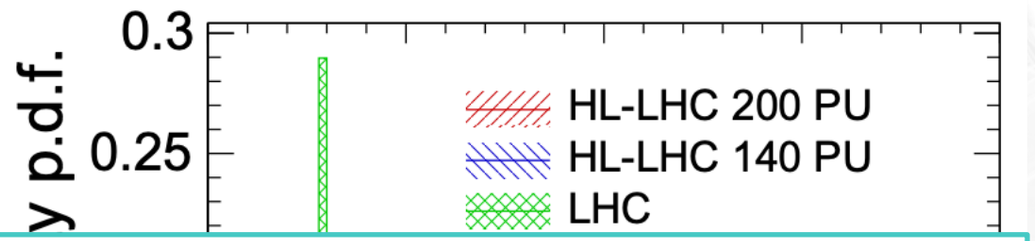

More on MTD @ICHEP2022:

09:53 **The CMS MTD Endcap Timing Layer: Precision Timing with Low Gain Avalanche Detectors**

Speaker: Marta Tornago

10:10 **Precision Timing with the CMS MTD Barrel Timing Layer for HL-LHC**

Speaker: Francesca Maria Addesa (INFN)

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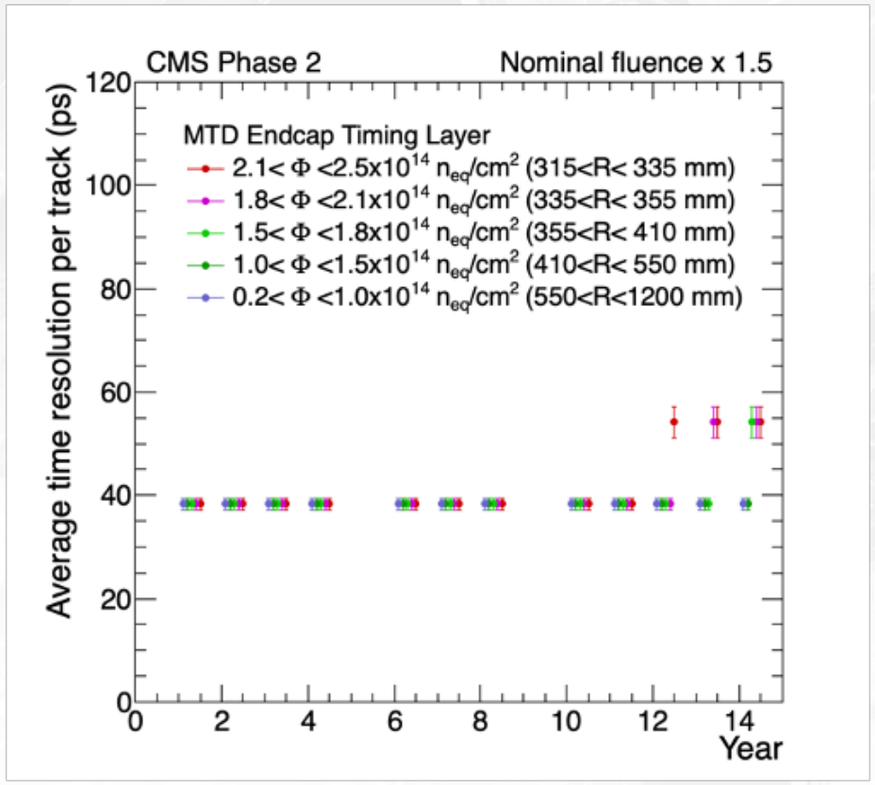
MTD Resolution Scenarios

- **MTD** CMS-TDR-020: MIPs w/ **30–40 ps resolution** degrading **to 50–60 ps** by the end of operations
- New Public Results Released for ICHEP2022: **Additional physics channels** that benefit from timing information: explore **impact of potentially degraded performance**

NEW

- **Barrel** (BTL) Resolution scenarios:
  - → **~35 ps** – Nominal TDR performance
  - → **~50 ps** – Scenario with potential degradated performance due to radiation damage (dark current contribution increases) (*)
  - → **~70 ps** – Extreme scenario with potentially degraded performance and the largest safety margin on radiation level uncertainties

- **Endcap** (ETL): excellent performance maintained



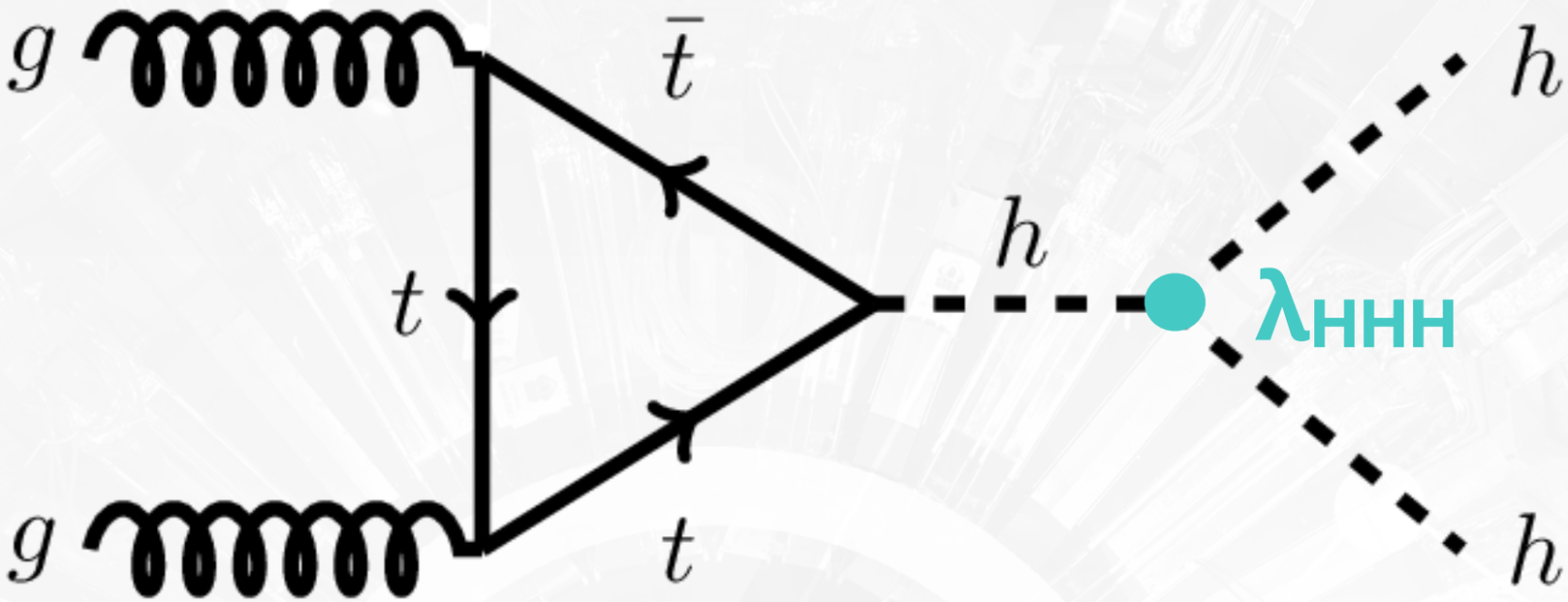
(*)***Current projections***: *based on prototype studies with sensor modules and near-to-final ASICs,* ***close to TDR expectations*** *(optimization in progress till the end of 2022)*

Current projections: *intense LGADs studies marginal degradation in region of less than 5% of the area in the last 10% of the luminosity, including fluence safety margin*

Higgs Bosons Pair Production at HL-LHC

- One of the **main goals of the LHC** physics programme: λ_{HHH}
- Benchmark channel used to gauge the **impact of pileup reduction including time cleaning of events.**

σ_{SM} ggF = 31.05 fb



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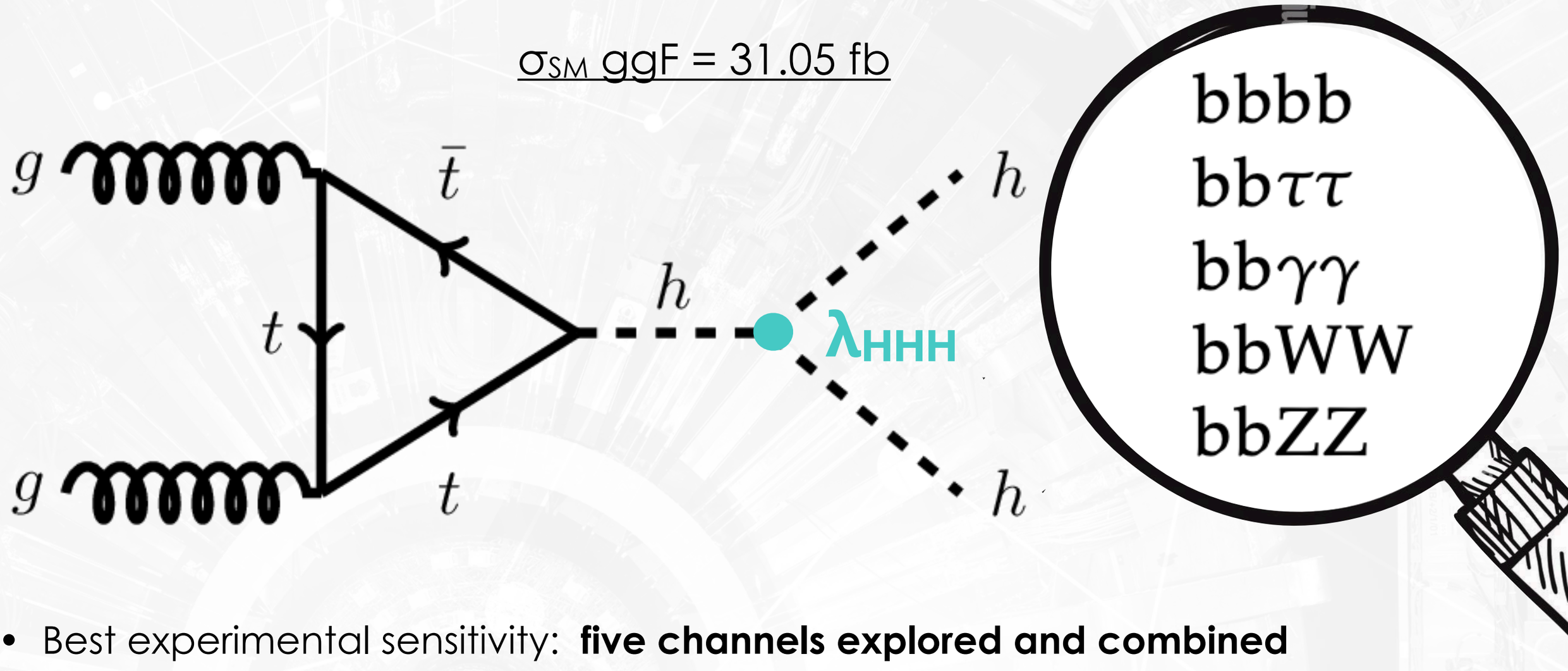
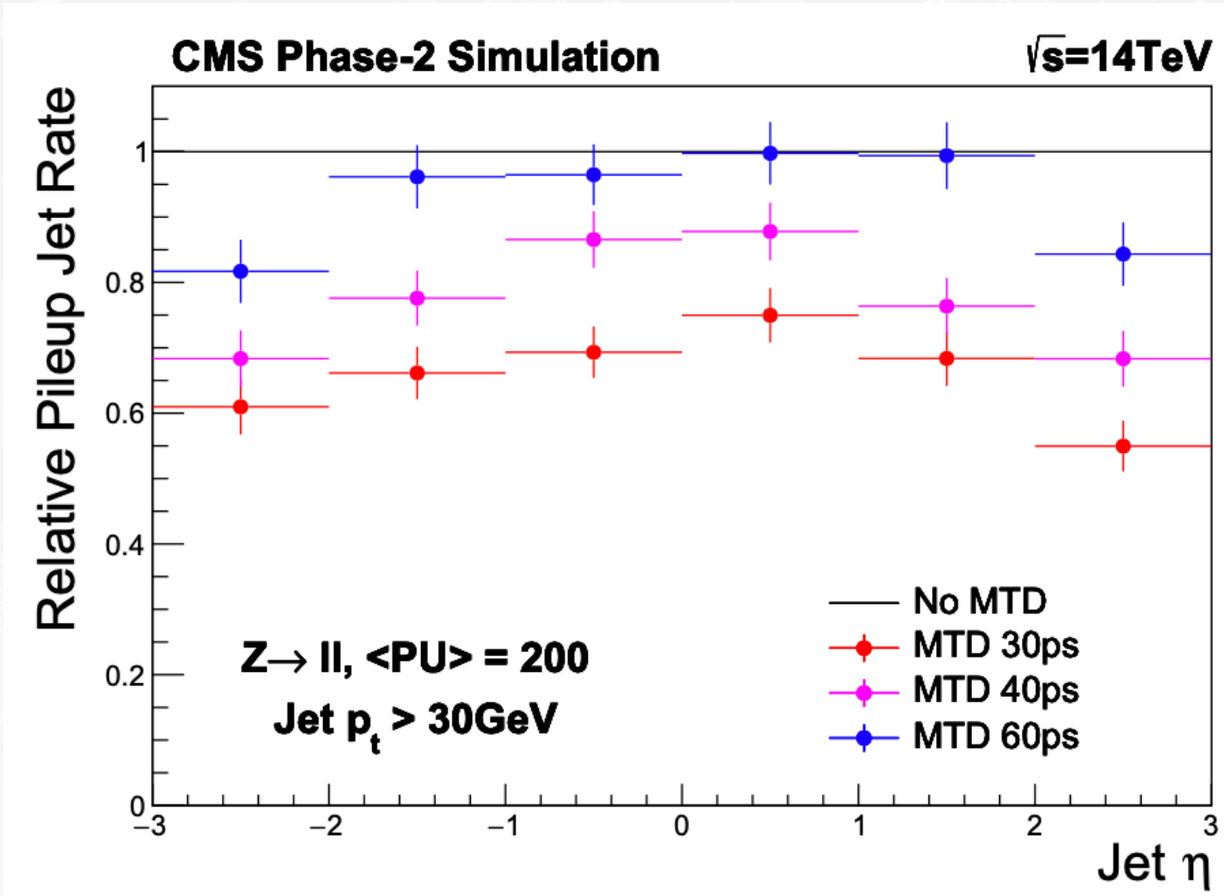


- Best experimental sensitivity: **five channels explored and combined**
- Richness of physics objects: **MTD has large integral effect**

Physics Objects Performance w/ MTD

Pileup mitigation | B-tagging | Lepton isolation | MET resolution



25−40% of reduction

Physics Objects Performance w/ MTD

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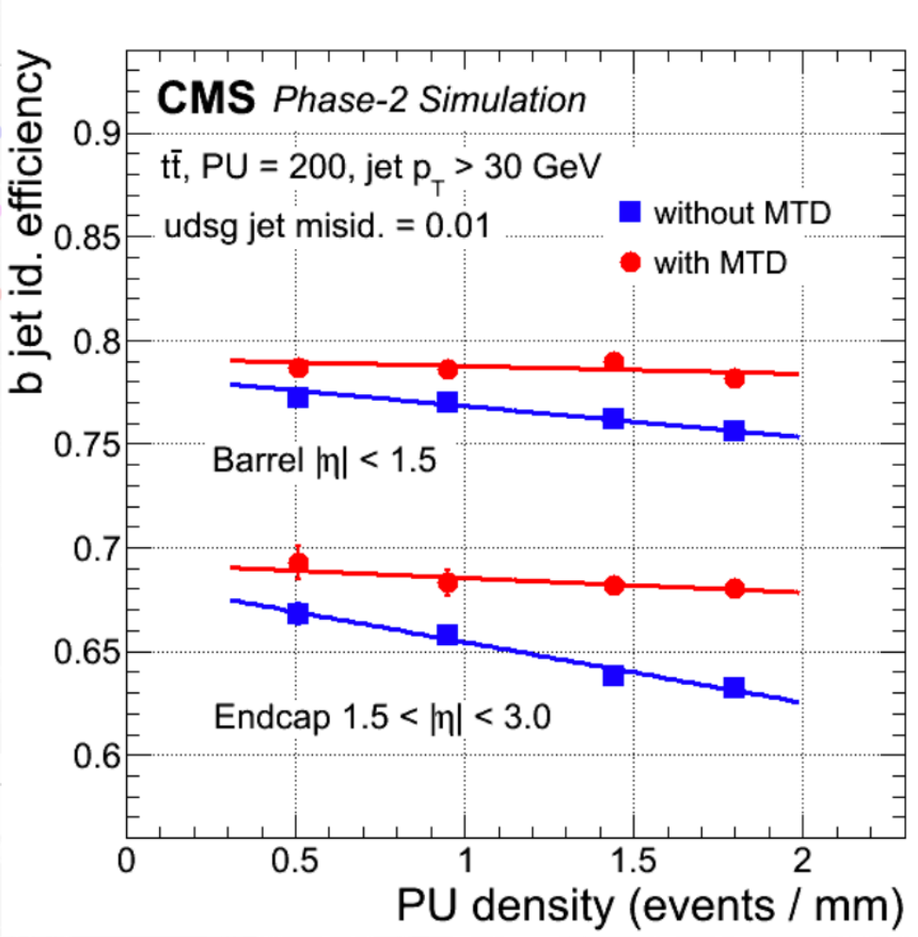
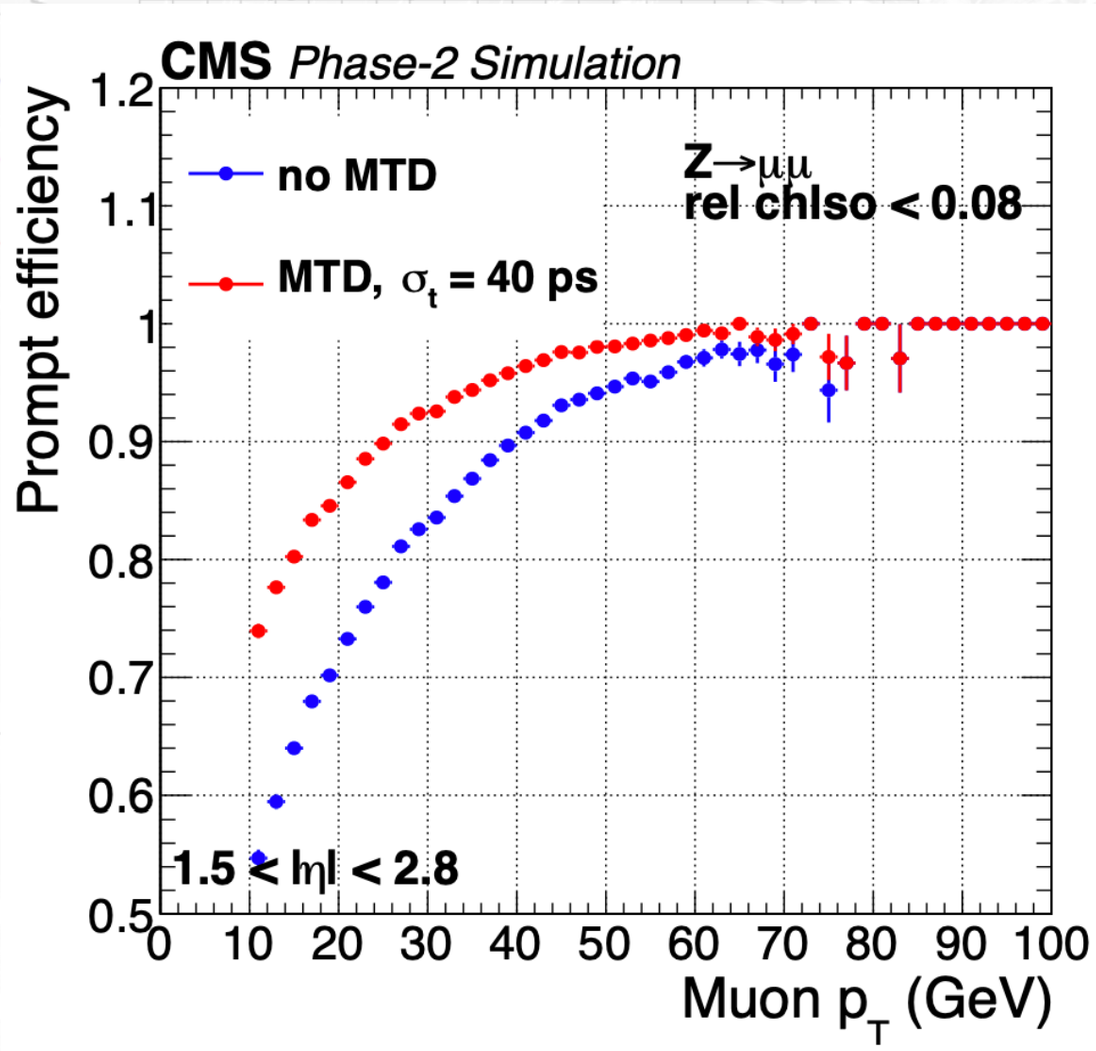


reduction

Spurious secondary vertices reduced by up to 30%

Physics Objects Performance w/ MTD

Pileup mitigation | B-tagging | **Lepton isolation** | MET resolution



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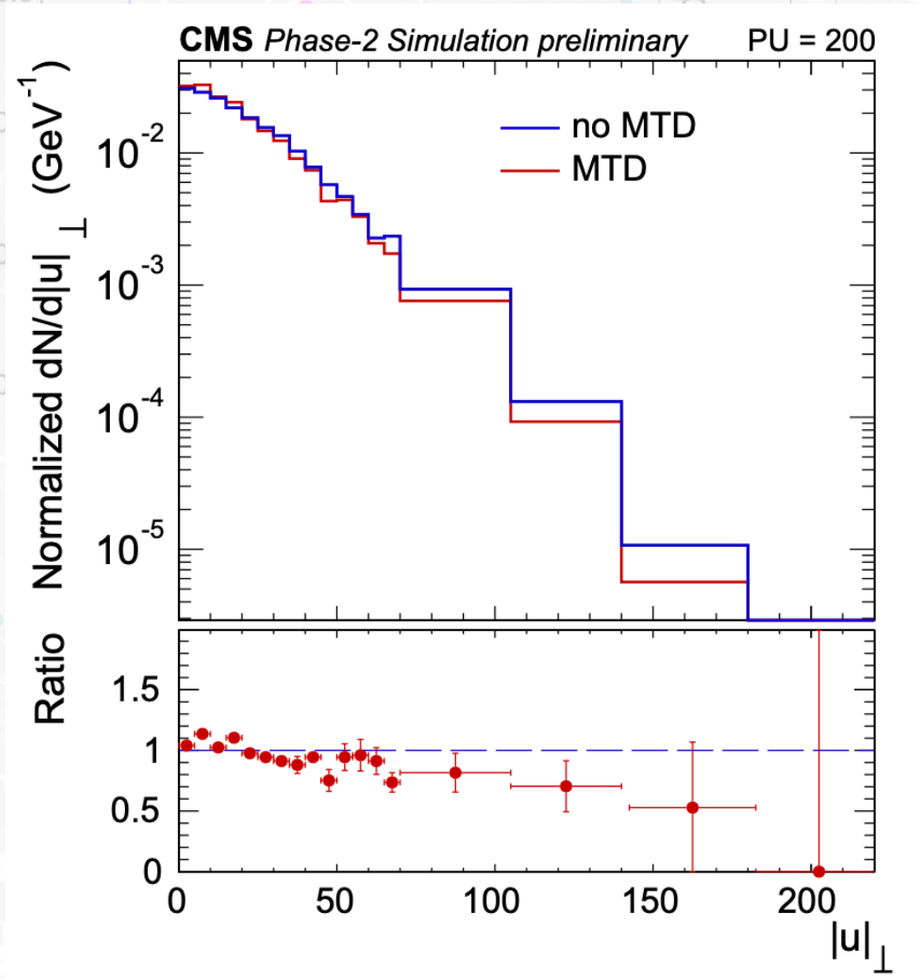
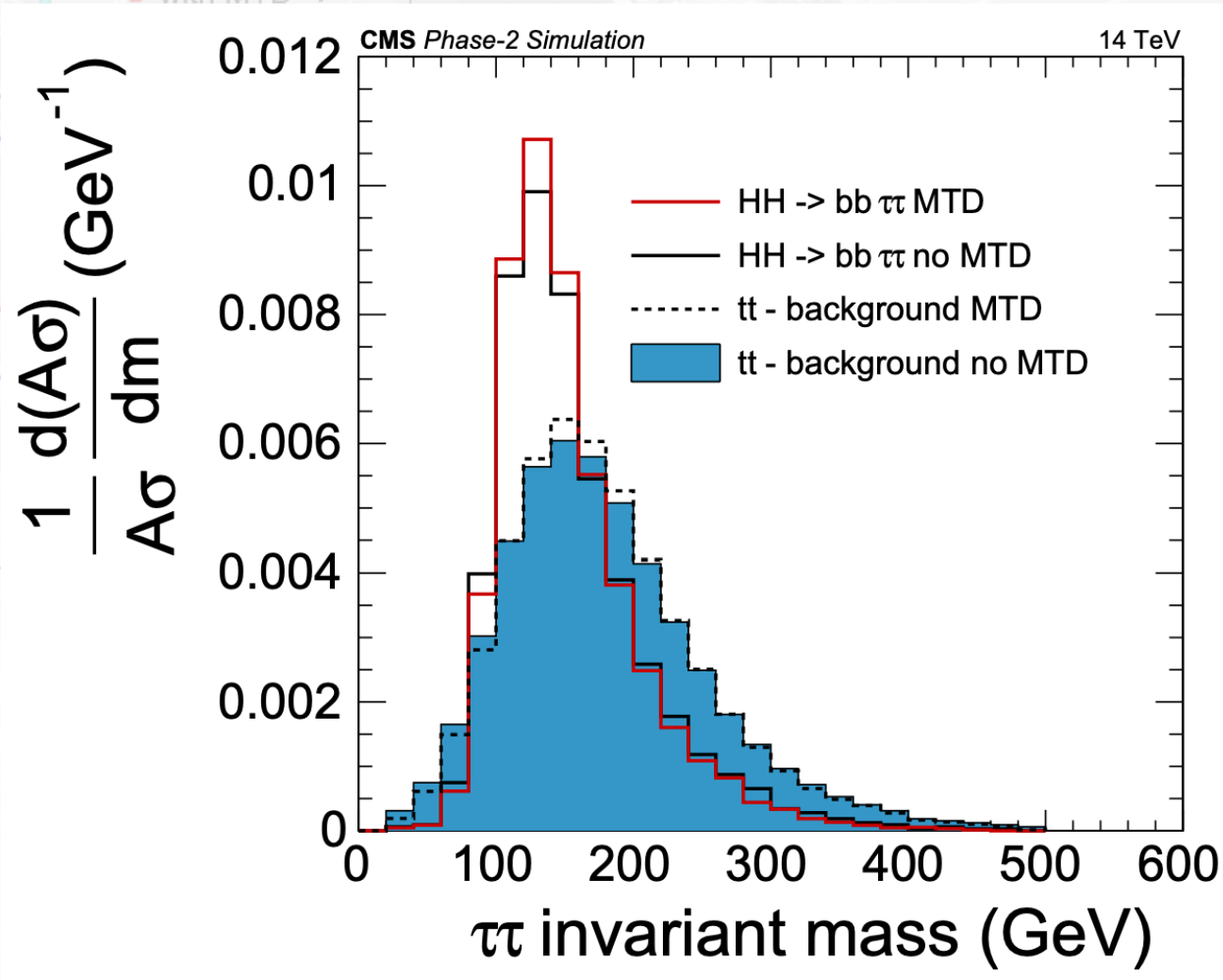
Physics Objects Performance w/ MTD

Pileup mitigation | B-tagging | Lepton isolation | **MET resolution**

10% variation in MET resolution: 10% variation in di-tau mass resolution

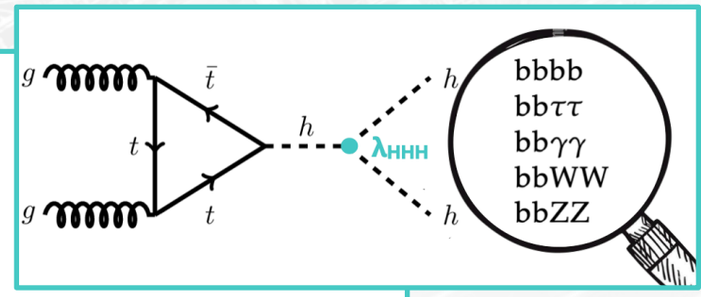




Updated Performance of HL-LHC HH sensitivity with MTD

Update

- The **cumulative effect** of the gains at the single object level translates into an **increase in the signal yield** at constant reducible background



35 ps BTL, 35 ps ETL

Channel	No MTD	ETL Only	BTL Only	MTD
$bbbb$	0.88	0.90	0.93	0.95
$bb\tau\tau$	1.30	1.38	1.52	1.60
$bb\gamma\gamma$	1.70	1.75	1.85	1.90
Combined	2.31	2.40	2.57	2.66

(2.75 w/ bbWW and bbZZ)

50 ps BTL, 50 ps ETL

Channel	No MTD	ETL Only	BTL Only	MTD
$bbbb$	0.88	0.90	0.93	0.95
$bb\tau\tau$	1.30	1.36	1.44	1.50
$bb\gamma\gamma$	1.70	1.72	1.78	1.80
Combined	2.31	2.37	2.47	2.53

(2.63 w/ bbWW and bbZZ)

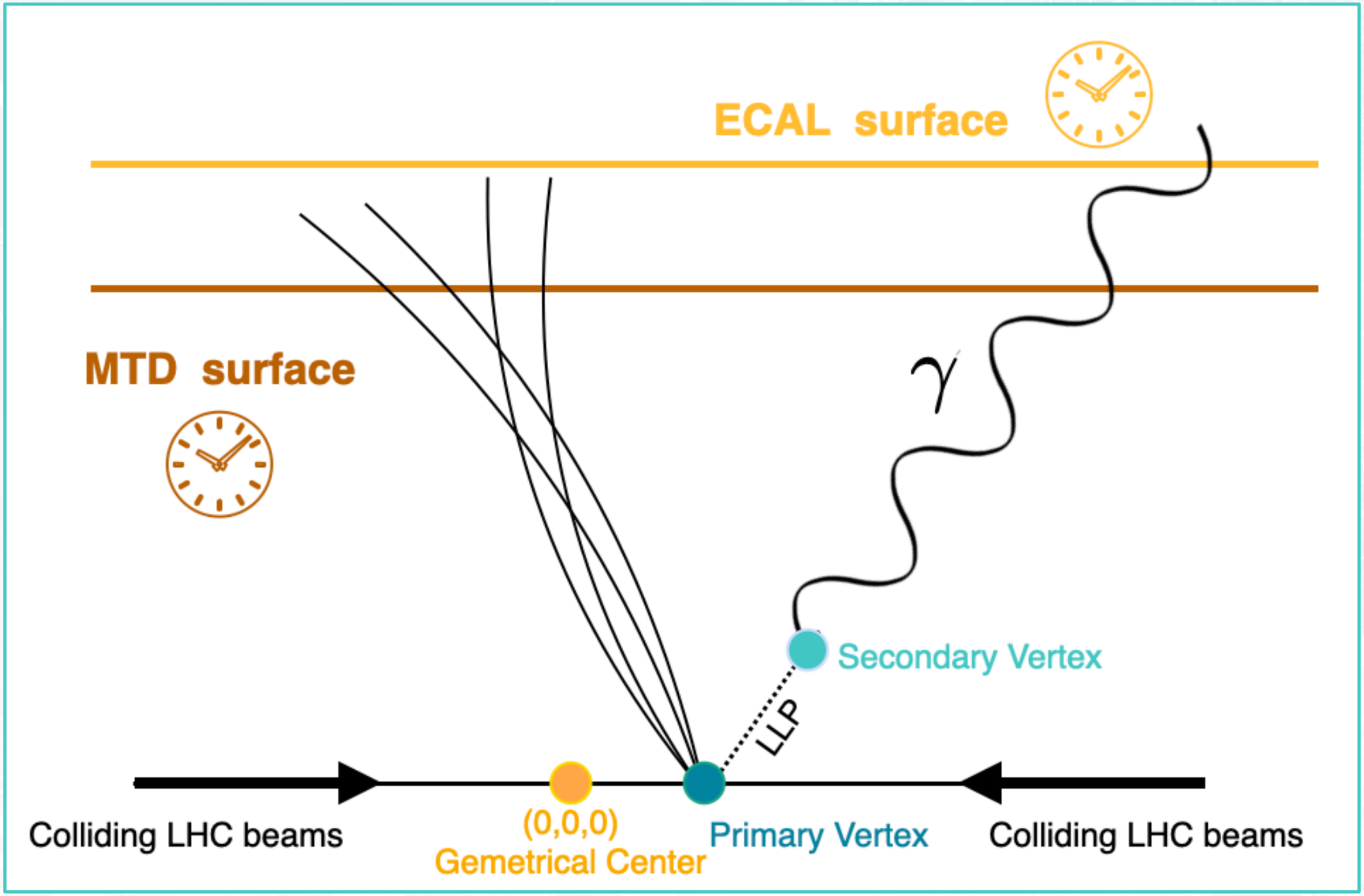
70 ps BTL, 35 ps ETL

Channel	No MTD	ETL Only	BTL Only	MTD
$bbbb$	0.88	0.90	0.92	0.94
$bb\tau\tau$	1.30	1.38	1.36	1.44
$bb\gamma\gamma$	1.70	1.75	1.76	1.81
Combined	2.31	2.40	2.41	2.51

(2.60 w/ bbWW and bbZZ)

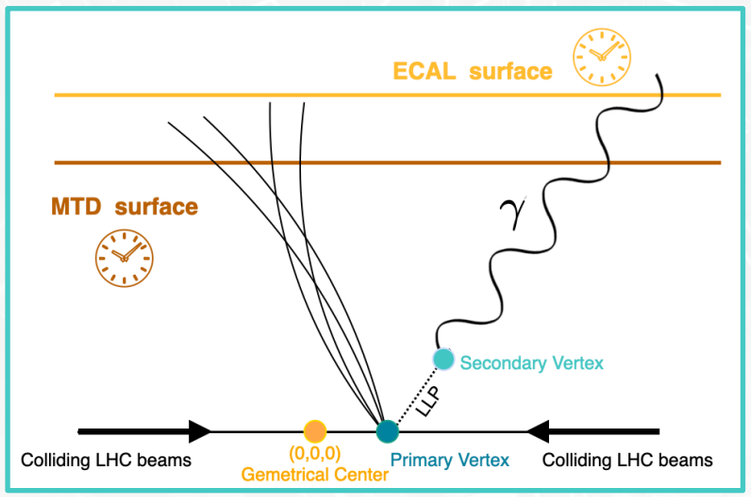
- MTD will enable CMS to (**almost) achieve standalone evidence for HH production**
- These improvements w/o MTD would require 31% more luminosity (+3 y of data taking) w/ nominal scenario and ~20% (+2 y) w/ degraded scenarios

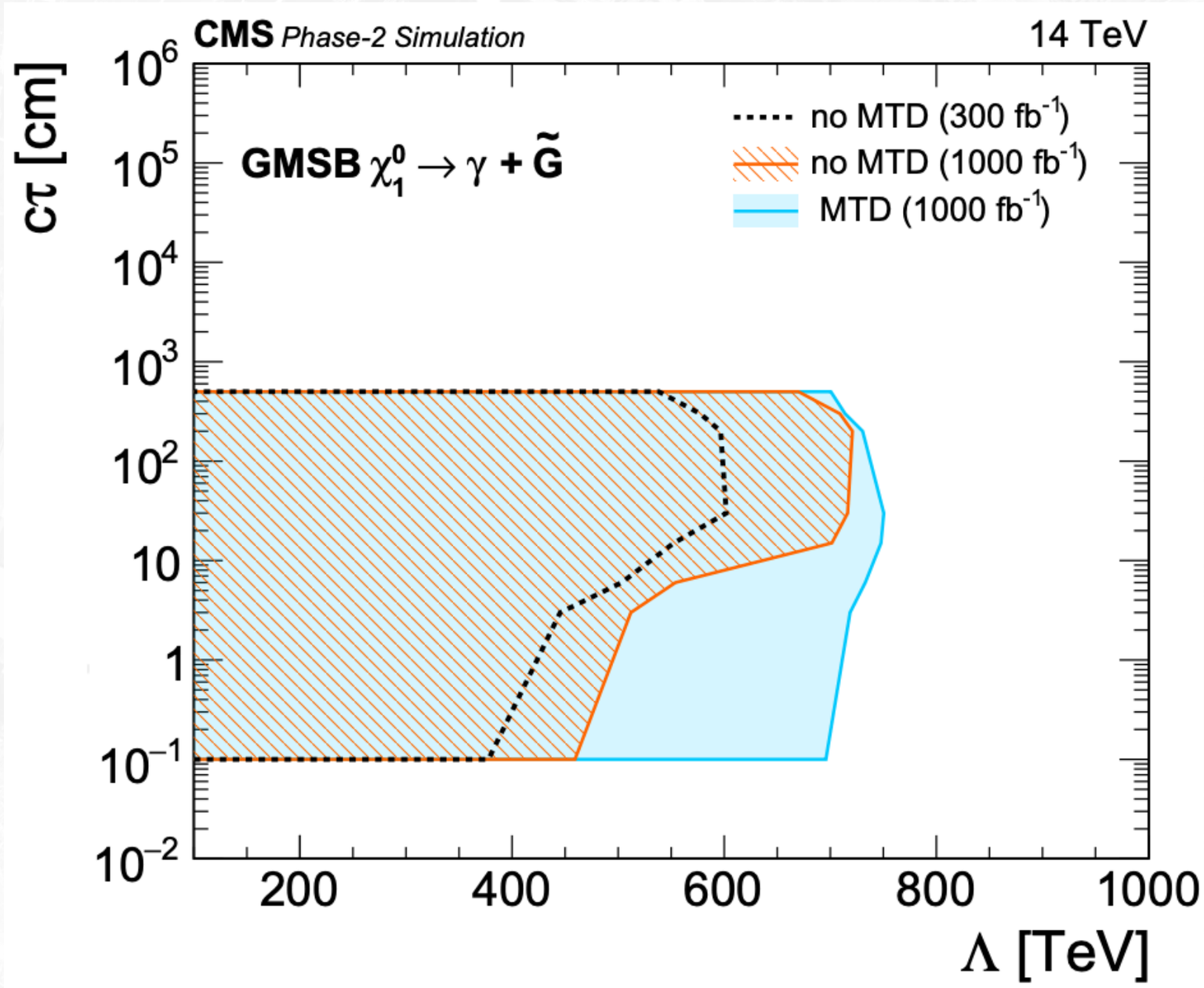
Long Lived Particles detection with MTD



Long Lived Particles decaying to photons

- MTD essential to properly determine the **primary vertex time** (large gain in sensitivity w.r.t. **ECAL only scenario**)
- ECAL time resolution: 30 ps





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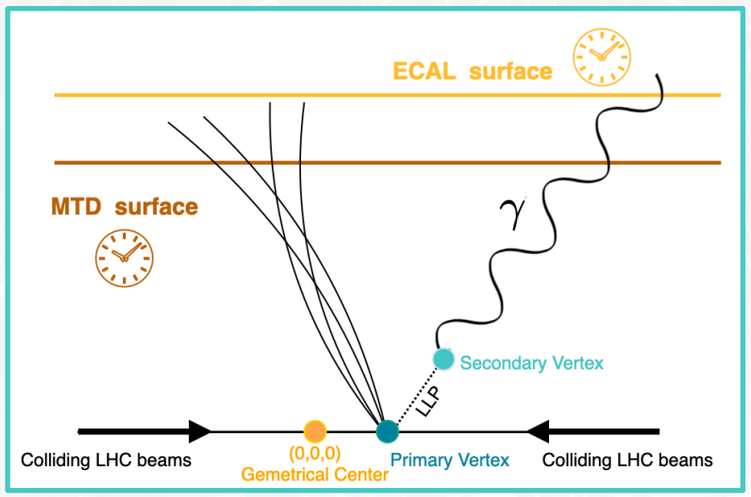
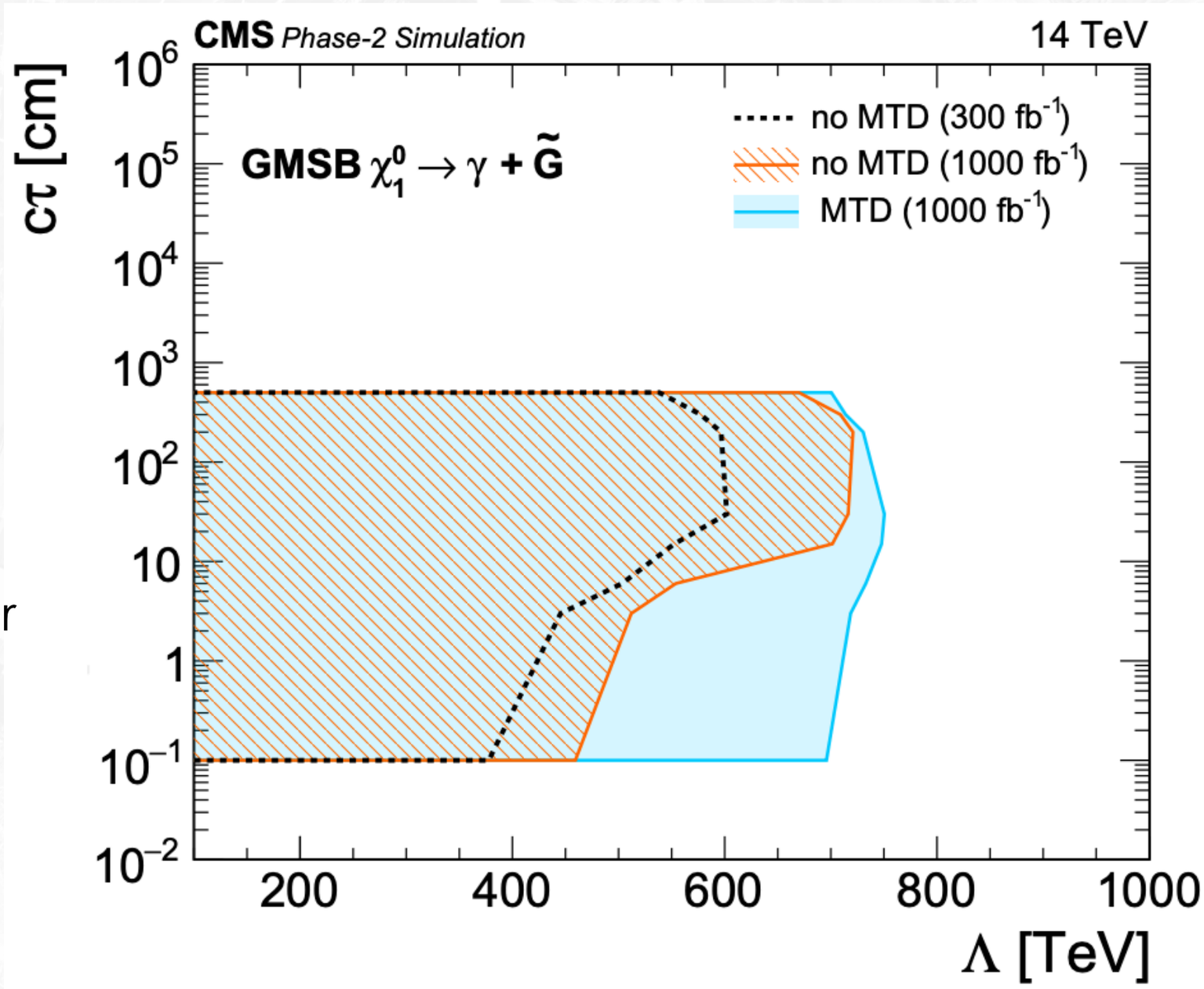


- **Weighted vertex time resolution**: estimating number of tracks in barrel/endcap

- More **realistic estimate of photon TOF resolution**

$$\sigma_{TOF} = \sqrt{\sigma_{vtx}^2 + \sigma_{ECAL}^2}$$



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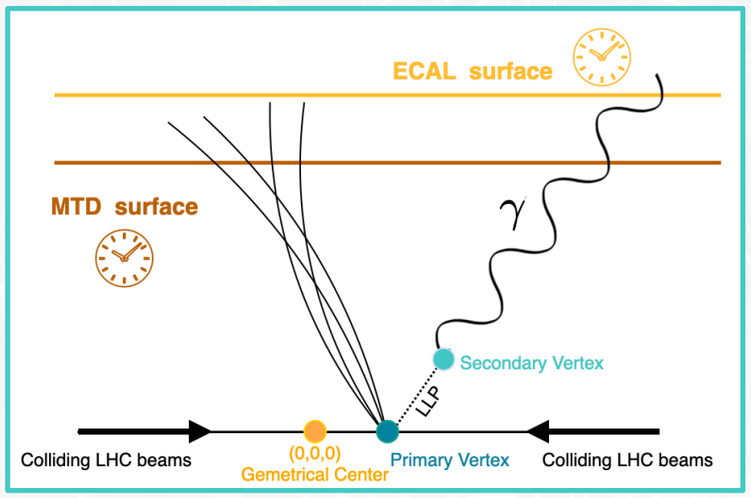
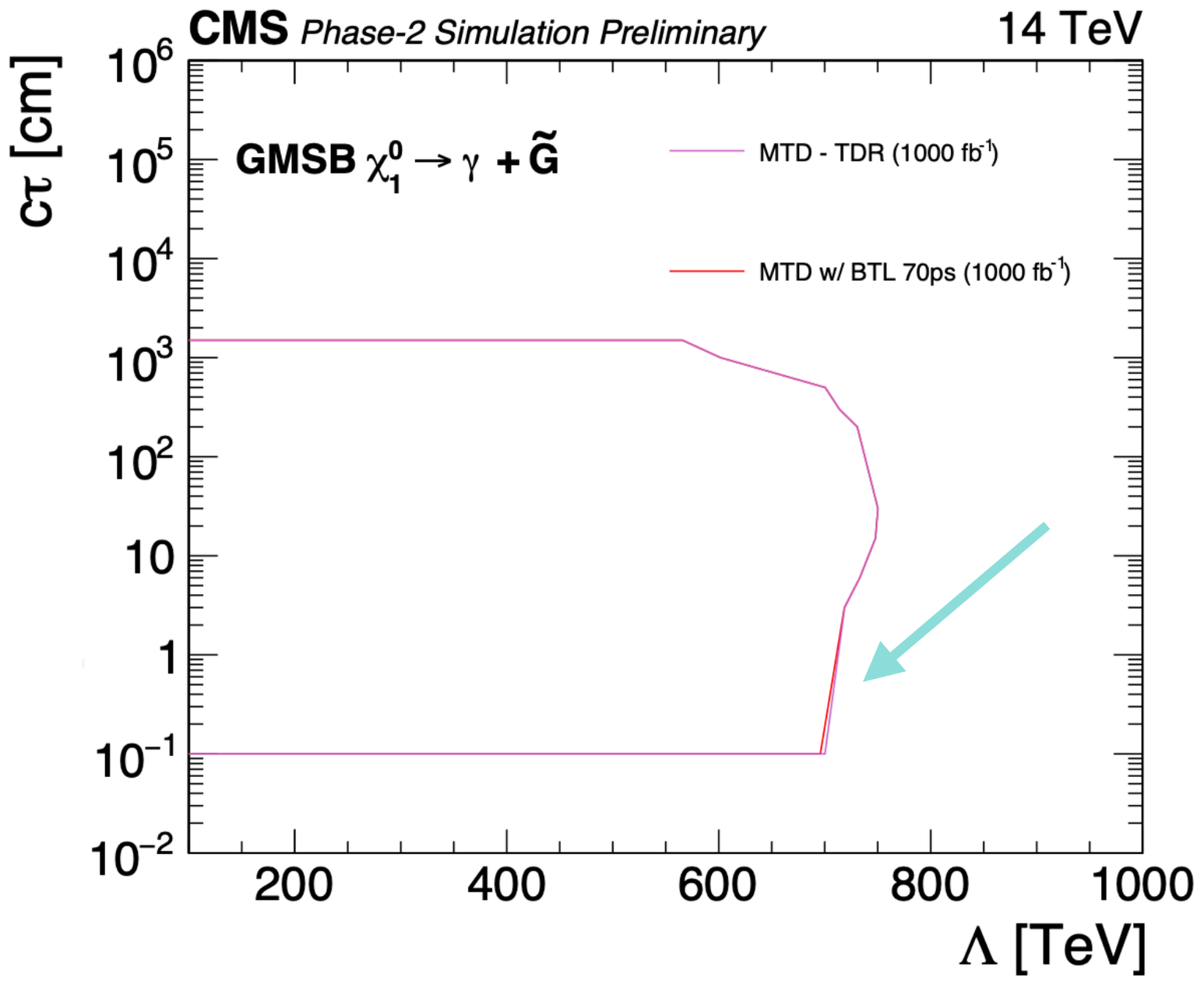
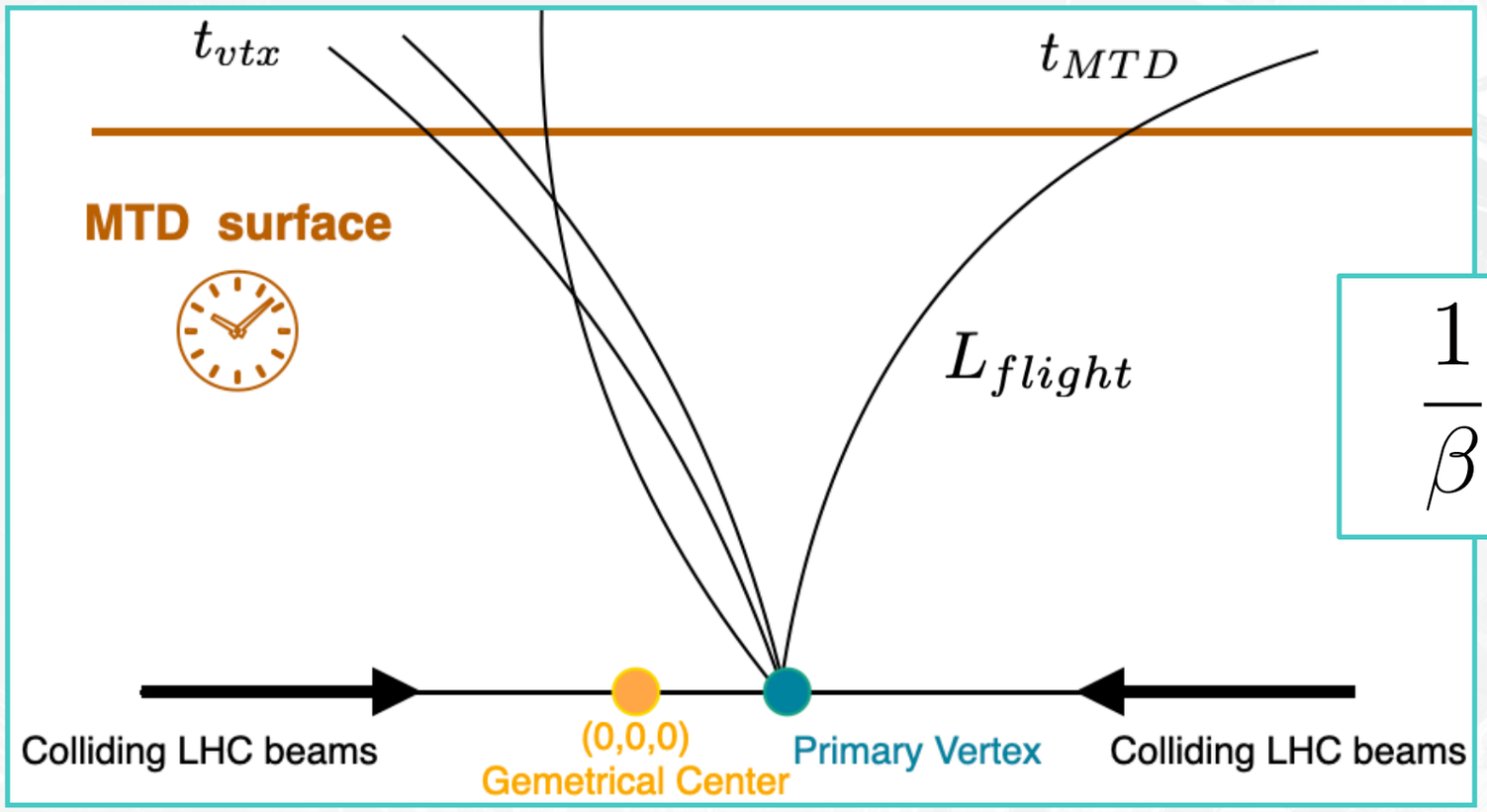


- Explore impact of **different BTL scenarios**

- **High tracks multiplicity** expected: exact **MTD resolution not critical** in this case since TOF dominated by **ECAL**



MTD as a time-of-flight detector



$$\frac{1}{\beta} = \frac{E}{p} = \frac{c(t_{MTD} - t_{vtx})}{L_{flight}}$$

- Detection of **anomalous moving particles** (slow velocities, q!=1 charges): **BSM(CMS-TDR-020)**

- **Particle Identification** (PID): **Heavy Ions(DP2021-037) and B-Physics**

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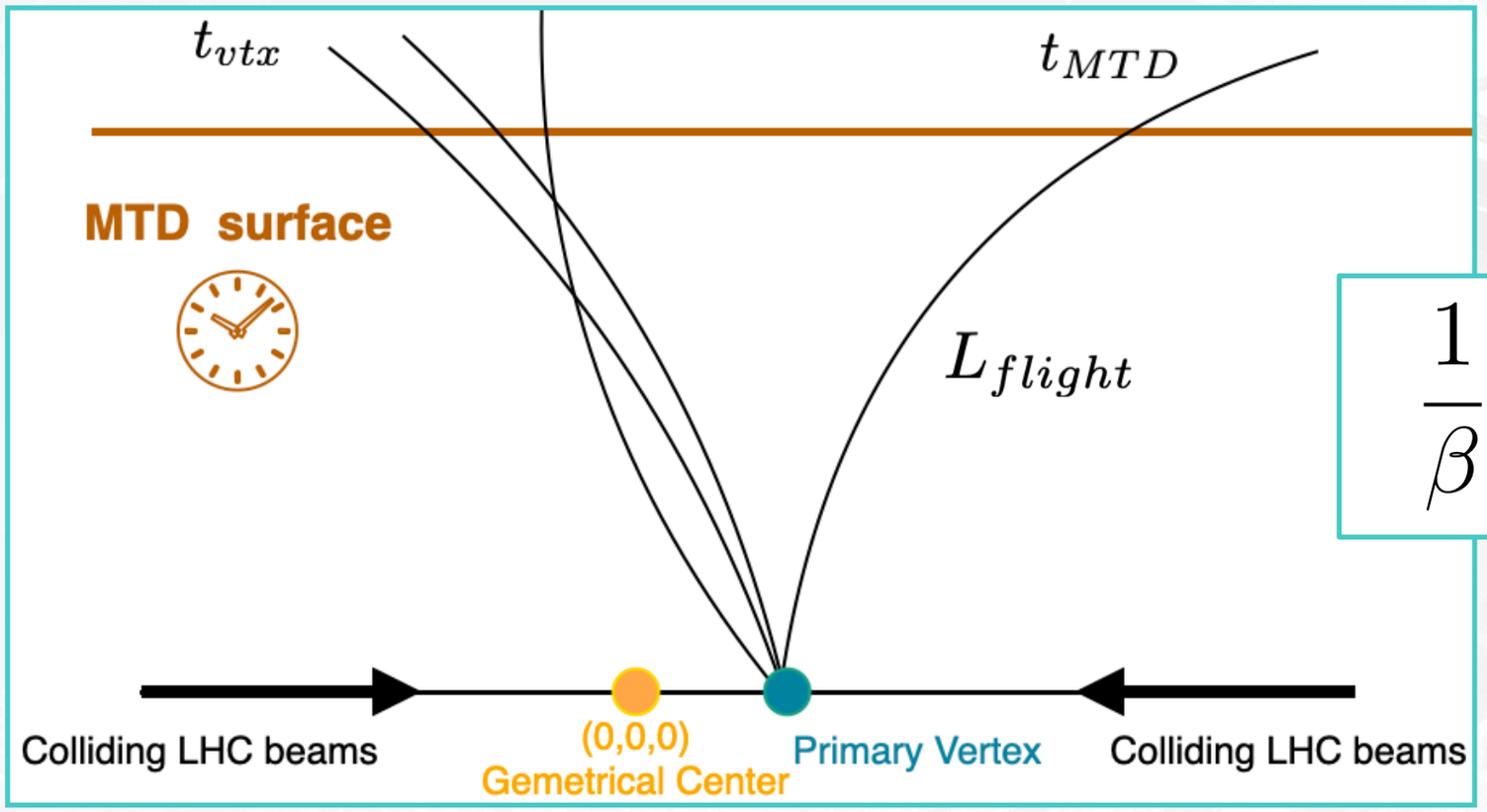

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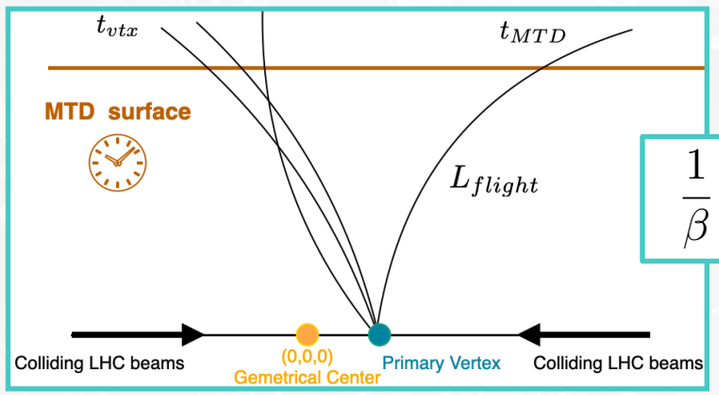
10:28 **New opportunities for understanding high-density QCD matter with CMS PhaseII detector at the High Luminosity LHC era** 17m

Speaker: Yousen Zhang (Rice University (US))

Detection of Slow Moving Particles

Update



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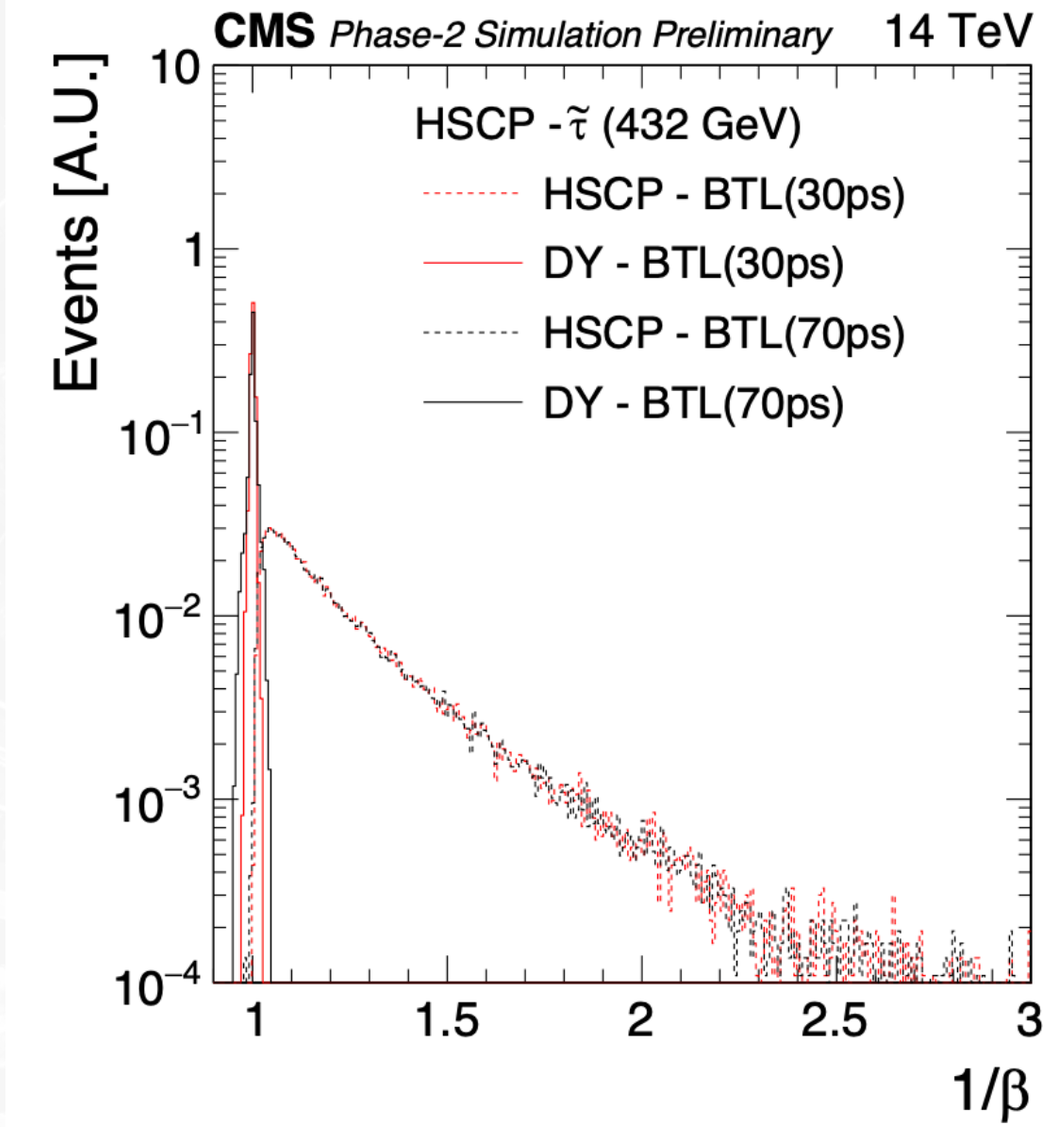
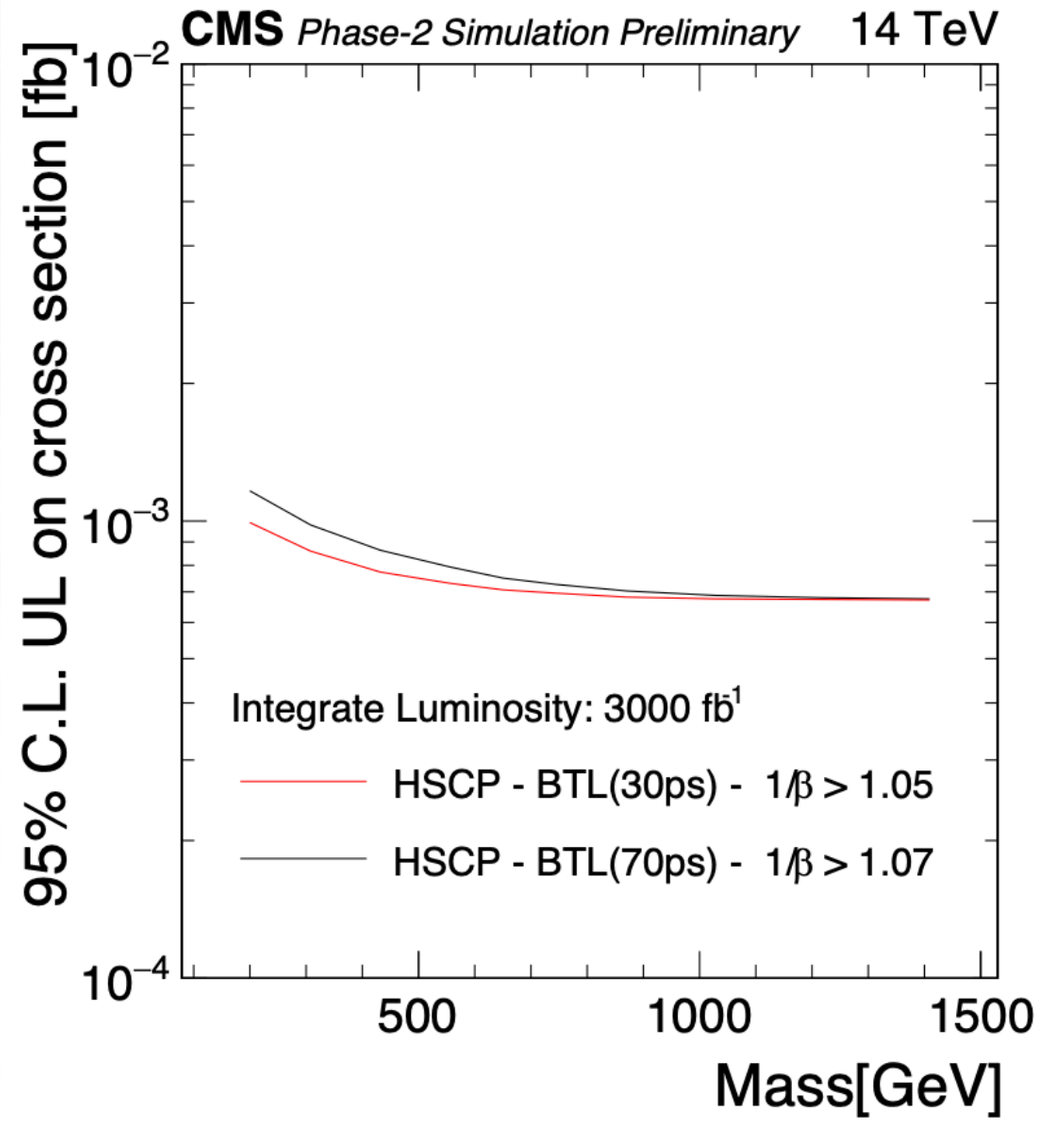
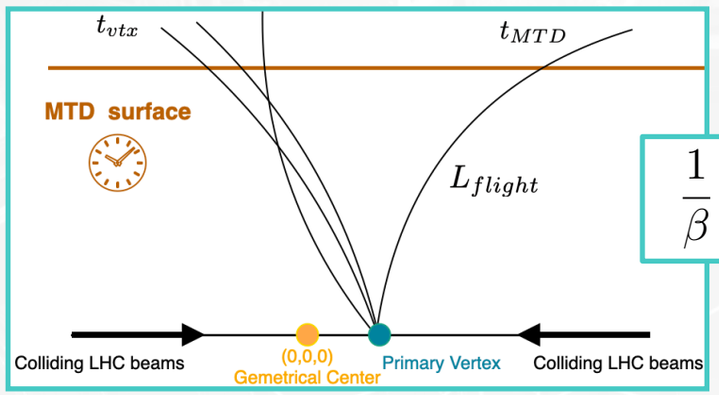
Heavy Stable Charged Particles
with very large lifetime discrimination





MTD Impact in Particle Identification

NEW



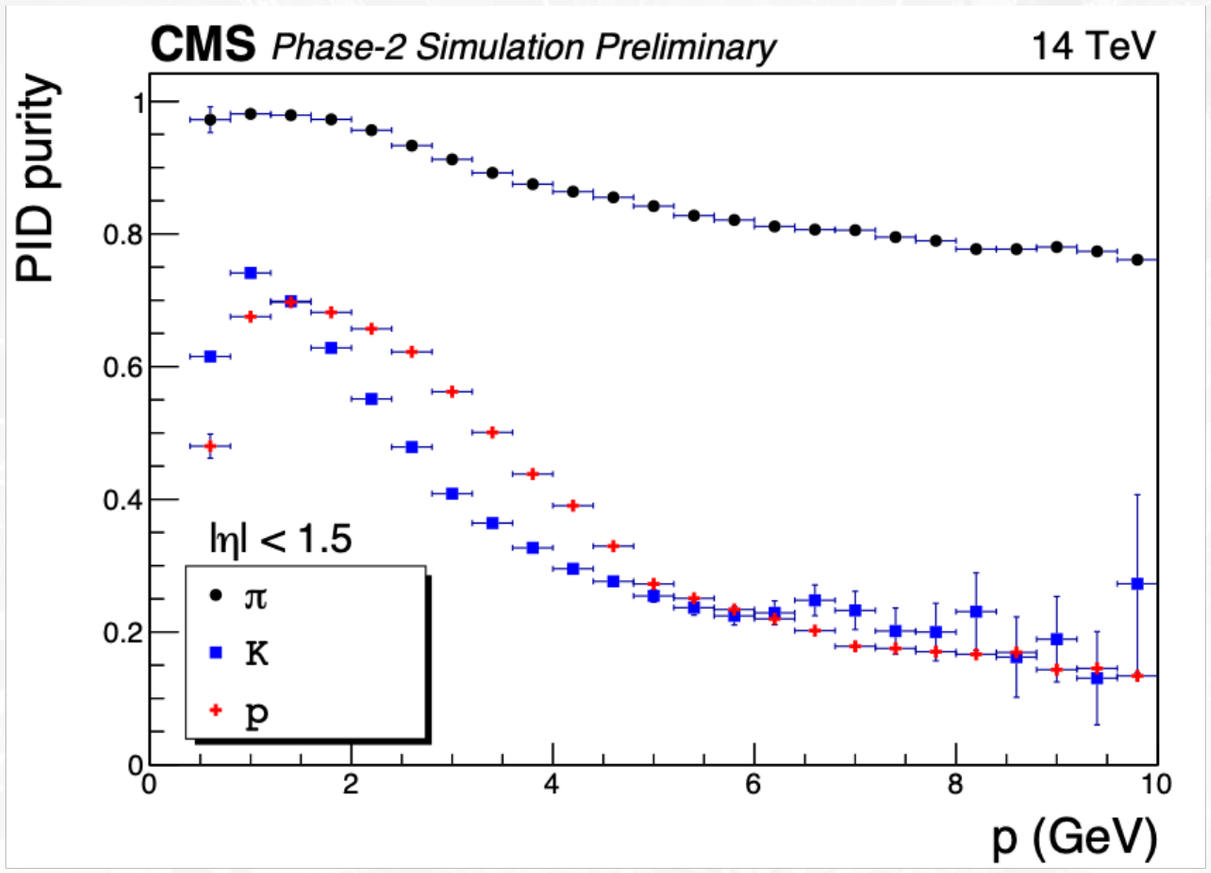
$$\frac{1}{\beta} = \frac{E}{p} = \frac{c(t_{MTD} - t_{vtx})}{L_{flight}}$$

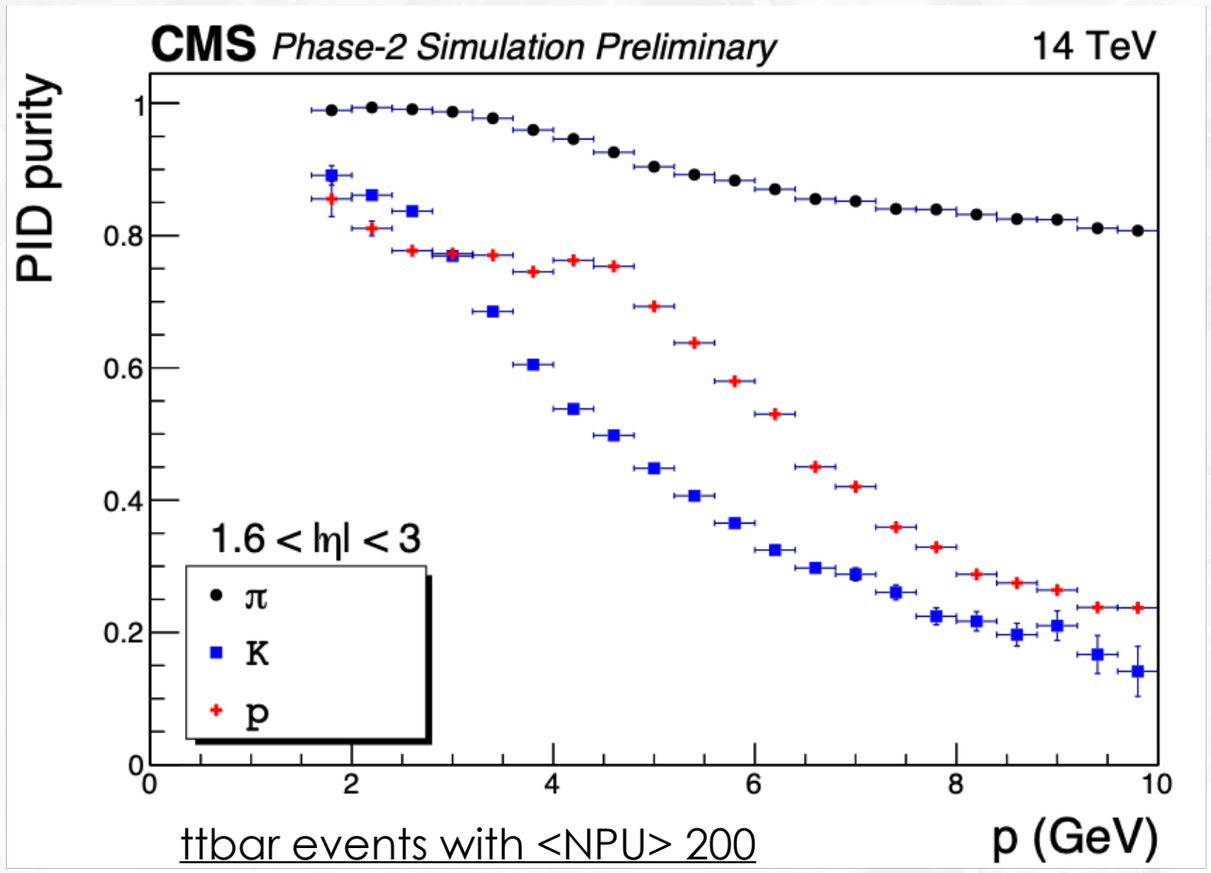
PID provided by MTD exploited in **Heavy Ion and B-Physics** measurements

- Based on the **TOF difference of particles with different masses**

$$\Delta t = \frac{L}{c}\left(\frac{1}{\beta_{meas}} - \frac{1}{\beta_{hyp}}\right)$$

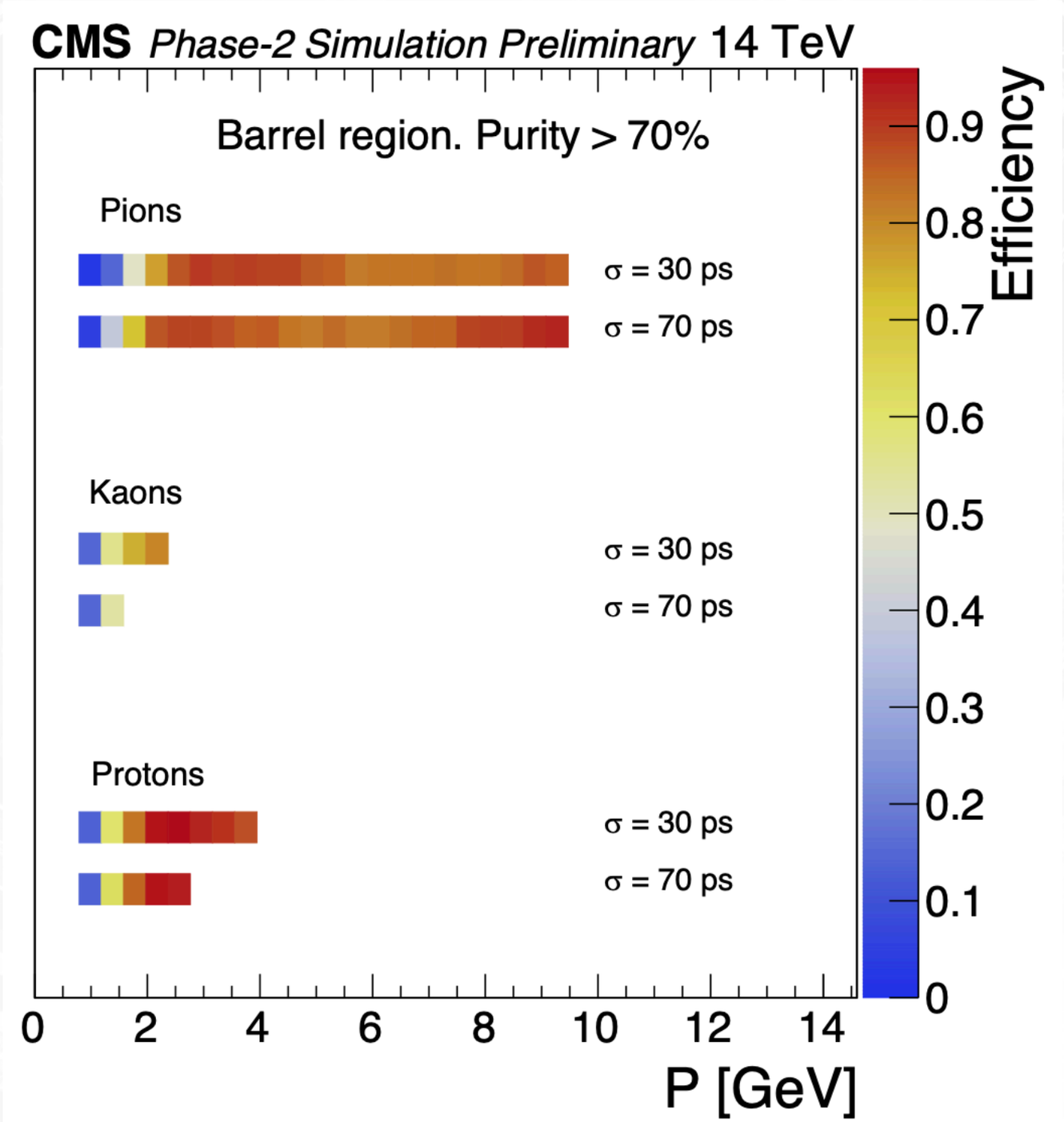
- Detailed detector response model implemented in the **full CMS reconstruction** algorithms





Dependence of PID performances from MTD resolution

NEW



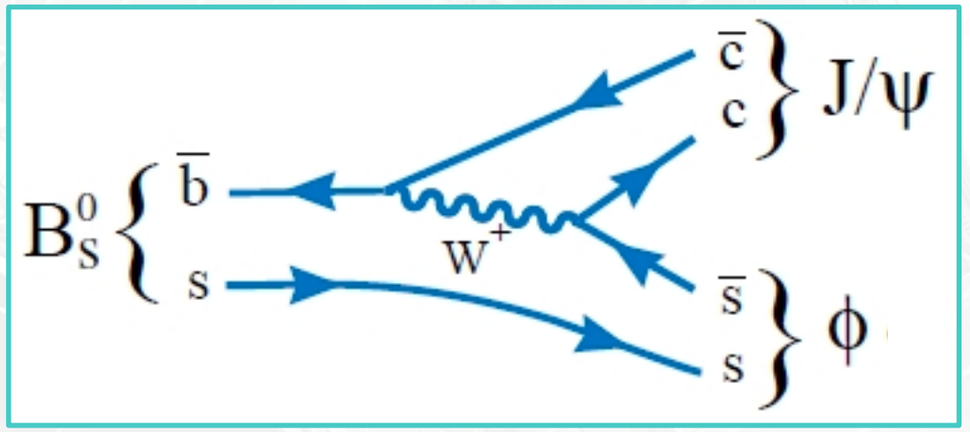
- Studied using a simplified model based on the DELPHES program in order to tune MTD BTL resolutions
- The range of momentum with a purity higher than 70% is shown for different species and time resolution scenarios

PID w/ MTD application in B-Physics

NEW

- CP violation in the $B_{0s} \rightarrow J/\psi\ \phi(1020)$ decay: HL-LHC projection exists w/o PID

  - Benchmark channel to gauge **benefits from timing in flavour tagging**



- Strategy:

  - Initial **B flavour "tagged"** by exploiting the charge correlation between the s-quark sign and the charge of a **soft kaon from the PV** (same-side tagging)

  - **Deep Neural Network tagging algorithm** w/ event-by-event tag decision and expected mis-tag rate

  - Figure of merit to quantitatively compare different tagging techniques

$$P_{\text{tag}} = \epsilon_{\text{tag}}\, D^2_{\text{tag}} = \epsilon_{\text{tag}}(1 - 2\,\omega_{\text{tag}})^2$$

PID scenario	Gains in P_{tag}
MC truth	+66%
PID with σ_{BTL} = 40 ps	+24%
PID with σ_{BTL} = 70 ps	+14%

- Significant **improvement w/ PID from MTD** on top of Phase-2 extrapolation

Conclusions and Outlook

- **MTD** detector design driven by **scientific requirements** which follow from the **physics goals of the HL-LHC program**

- MTD time **resolution**: **30–40 ps at beginning of HL-LHC.** Still effective at the end of operation after degradation due to radiation damage.

  → *Final **optimization of the sensors** is in progress to achieve the **TDR target***

- **New analysis capabilities to CMS** :

  → *Enhance feasibility of **SM precision measurements***

  → *Explore **non conventional signatures with Long Lived Particles***

  → *Boost **Heavy Ions and B-Physics** capabilities with **Particle Identification***