Timing Detectors: Impact on Physics Reach

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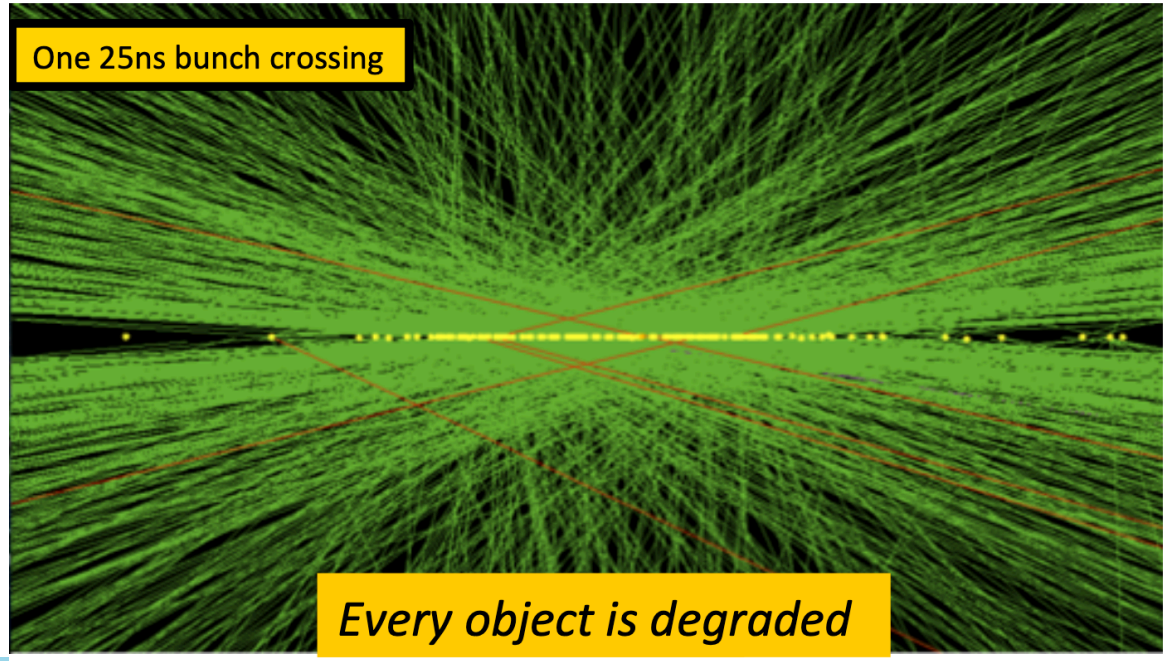
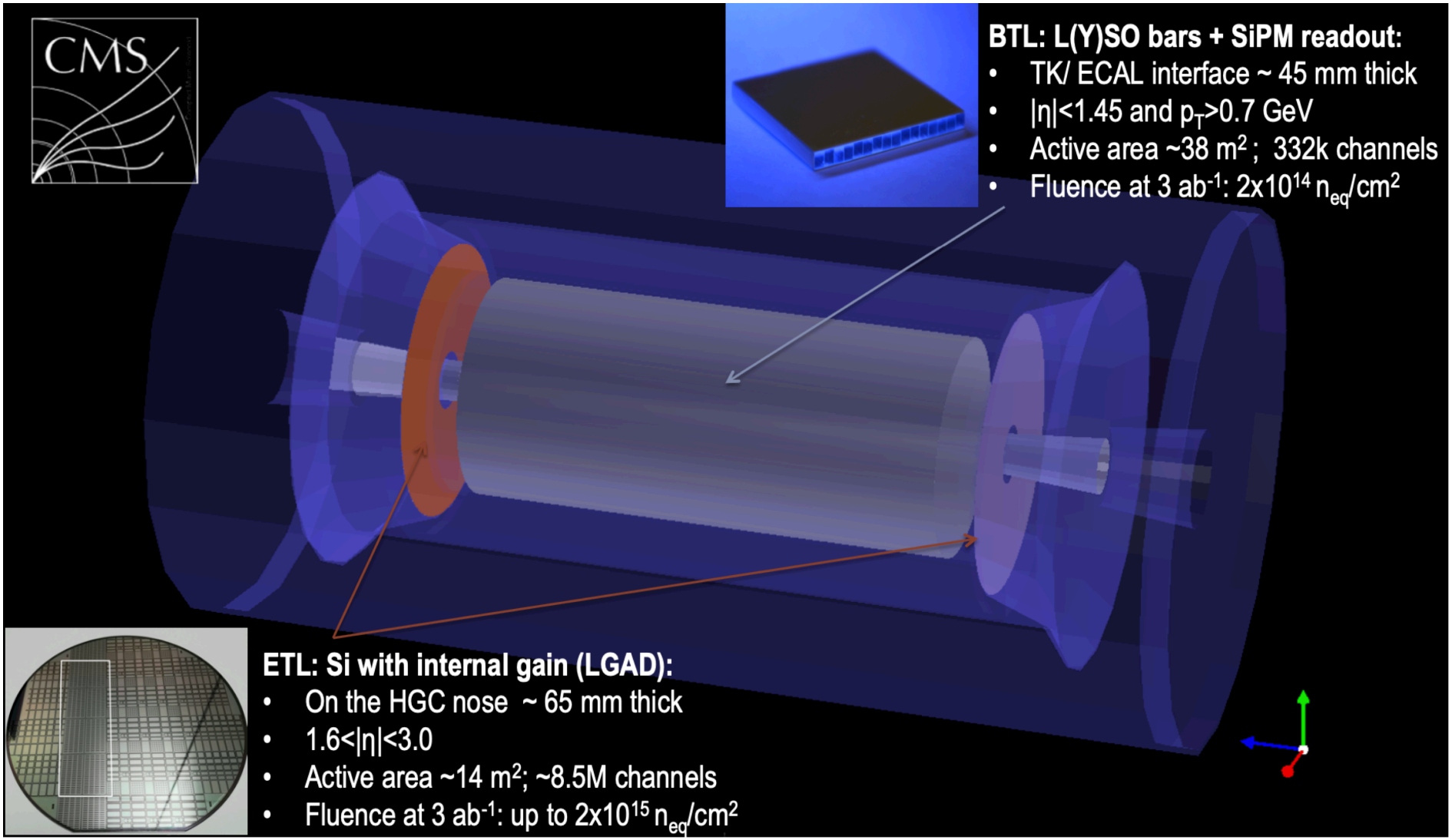
The Challenge of the HL-LHC era

- Imagine separating the 25ns beam crossing into consecutive time slices
  - Each exposure has far fewer vertices than when integrating over an event's complete time profile.
  - Reconstruction and identification of every object is improved

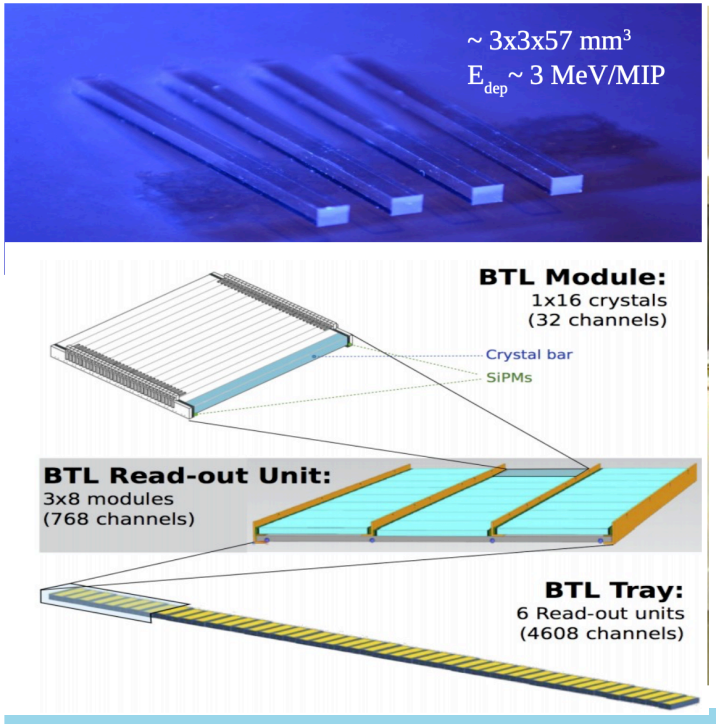


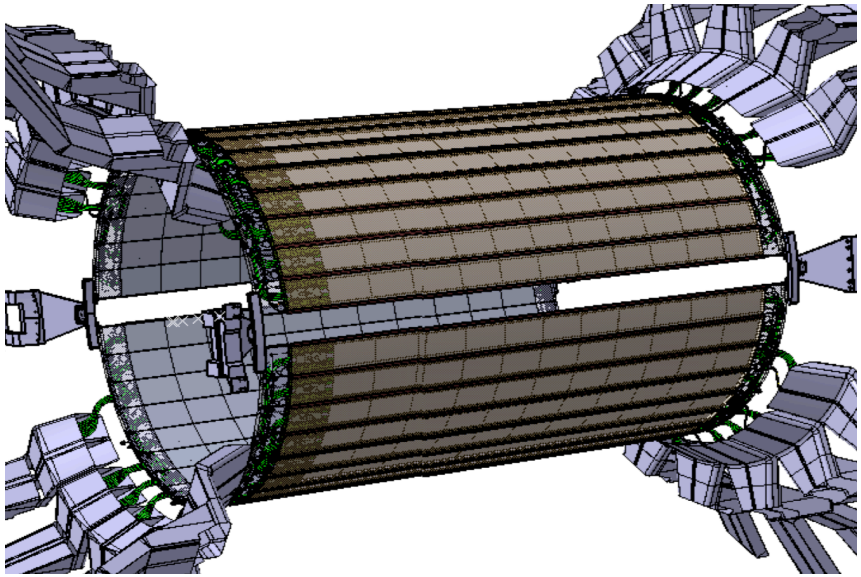
CMS MIP timing detector (MTD)



Barrel Timing Layer (BTL) design

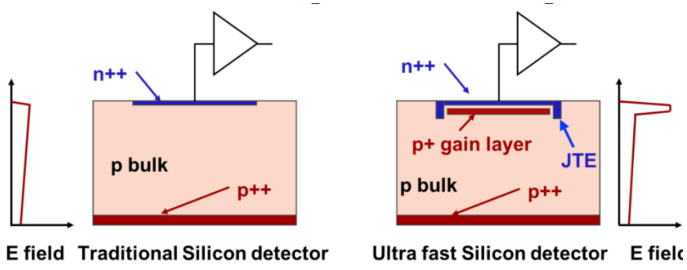
- LYSO crystals as scintillator with an excellent radiation tolerance and fast rise and decay times.
  - Attached to the inner wall of the Tracker Support Tube (TST).
  - 332k channels, organized in 6 Readout Units per tray.
- Time resolution of 35 ps at the beginning of lifetime and 60 ps by the end.

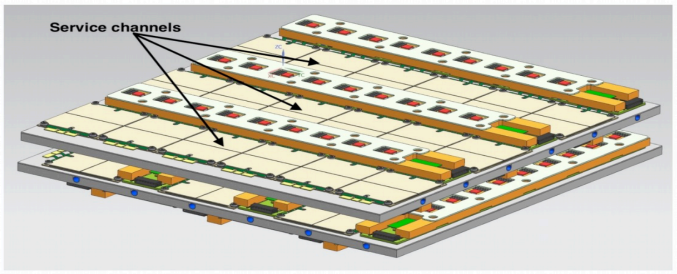




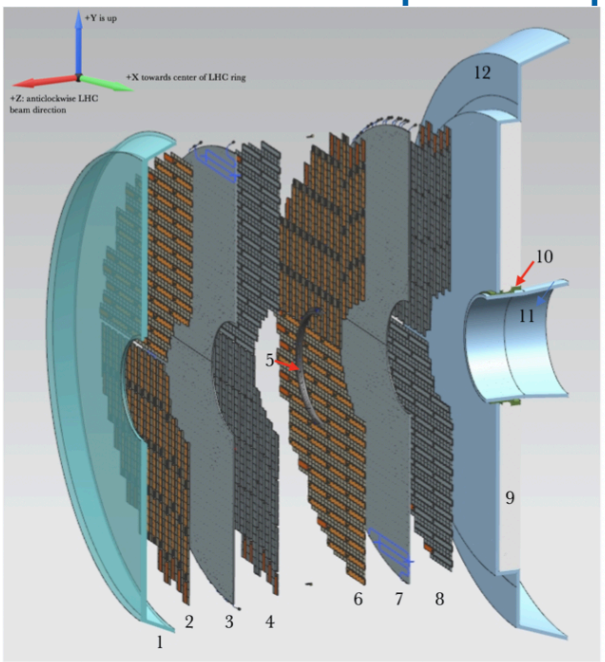
Endcap Timing Layer (ETL) design

- Low Gain Avalanche Diodes (LGADs) with highly doped p+ region just below the n- implants.
  - Radiation tolerance sufficient for endcap fluence (< 2×10^{15} n_{eq}/cm^2)
  - Very good timing response and resolution (30-45 ps at the beginning-end of lifetime)
- A total of ~14 m^2 detector with two double-sided layers for each endcap
- Small 1.3x1.3 mm^2 pixels for low capacitance, ~8.5M channels





Two disks per endcap



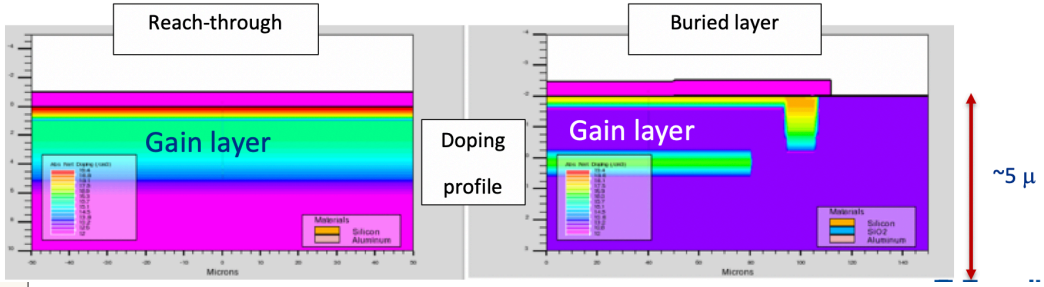
4.5 cm thick!

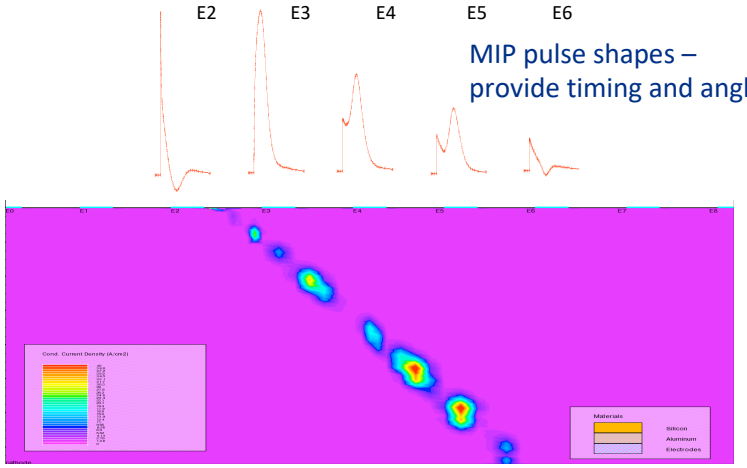
Timing detector technologies

- Other silicon technologies with precision timing:
  - AC-LGAD: good position and timing resolution for MIPs
  - Deep gain layer, or buried junction LGADs for higher radiation tolerance
  - CMS HGCal: silicon calorimeter with excellent timing resolution
  - Several HV-CMOS MAPS with good time resolution
  - Specially designed sensors provide track position, angle and timing
- Common challenge for many technologies: low-power ASICs

Usual reach-through implanted from top – limited options

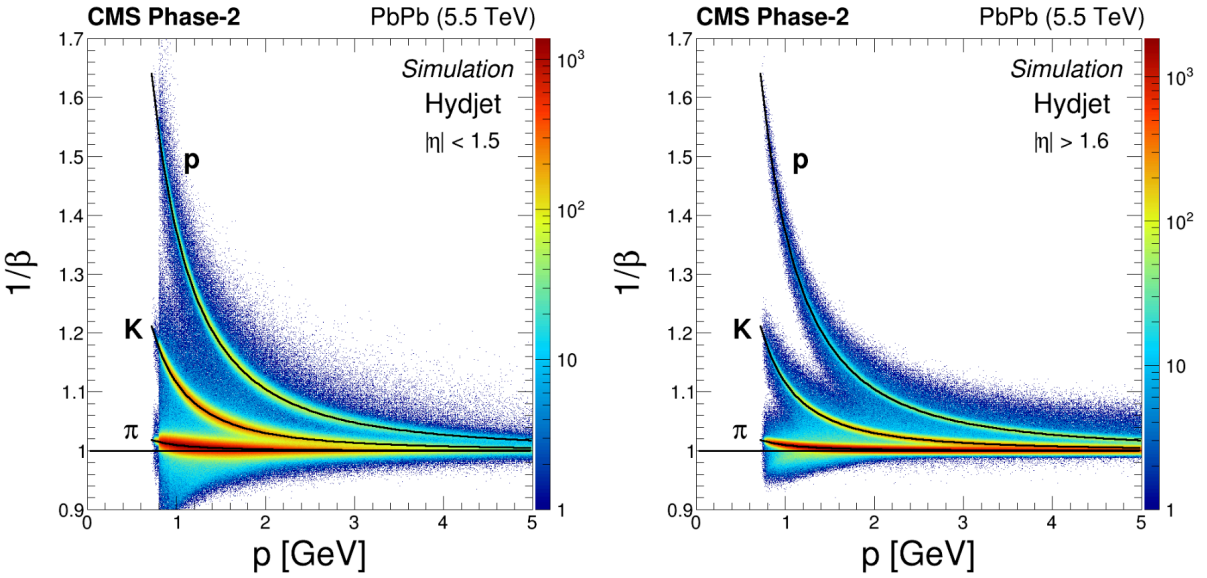
Gain layer grown over implant – can be denser, top can be custom processed





Time-of-flight Particle ID

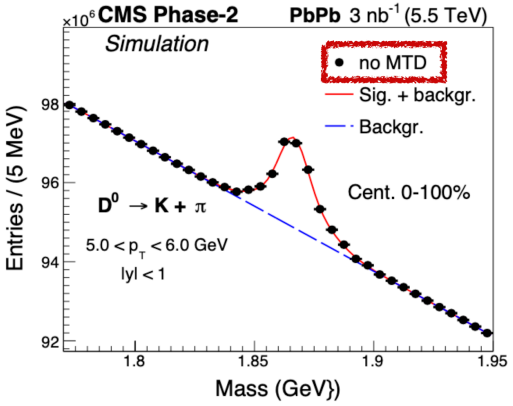
- Time-of-flight particle identification: 2σ π/K separation up to p~2 GeV and K/p up to p~4 GeV
  - New handle for CMS for heavy flavor physics $\frac{1}{\beta} = \frac{c(t_0^{\mathrm{MTD}} - t_0^{\mathrm{evt}})}{L}$

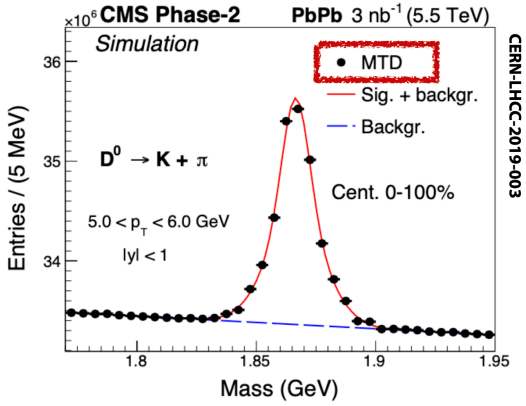


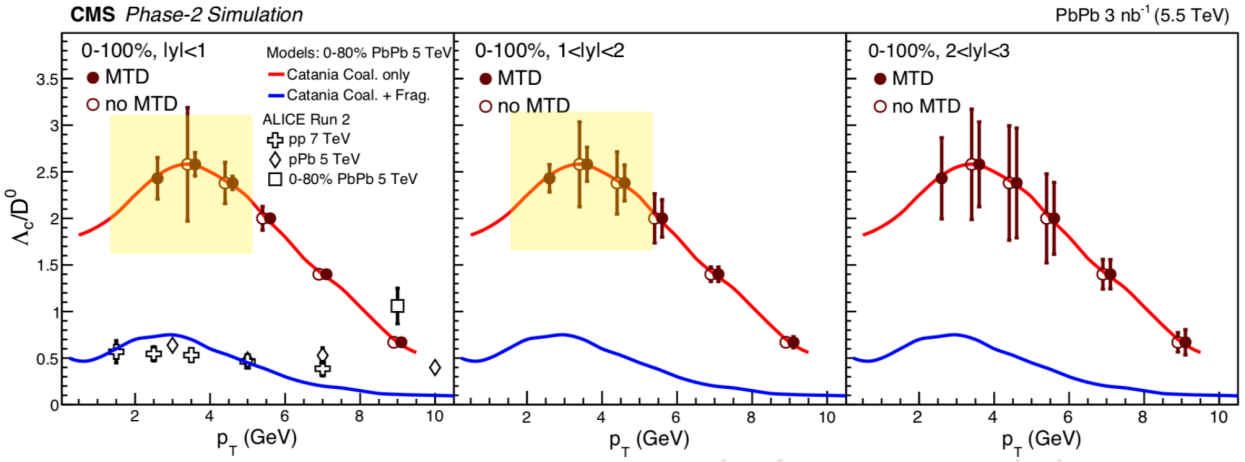
- Use timing for flavor tagging and providing an additional handle for separation between light quarks at linear colliders
  - Intermediate momentum $K^{\pm}$ ID from fast timing can become a significant contributor for b and c decays identification

Time-of-flight Particle ID

- Competitive momentum coverage comparable to ALICE and STAR
  - Significantly suppressed background candidates
  - Signal significance is drastically improved
  - The region of |η|>1 is uncovered by other experiments

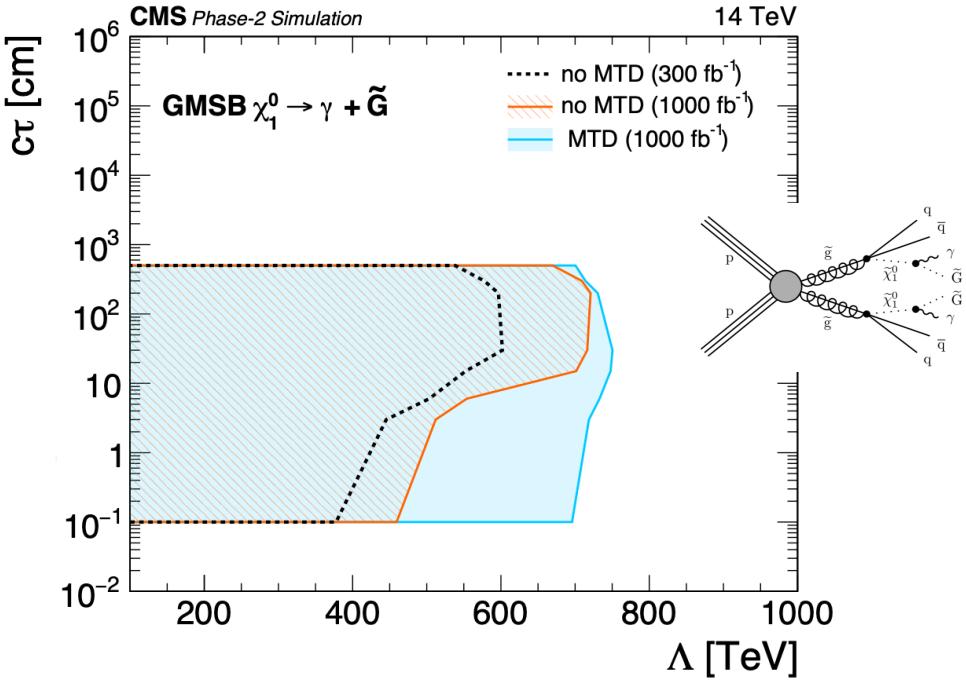


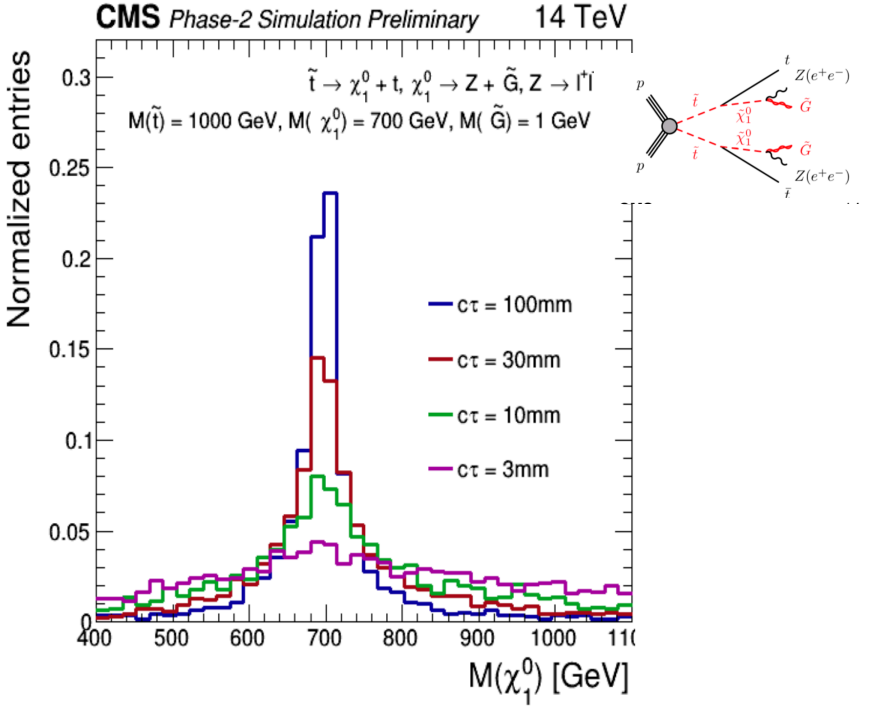




- Unique possibility to study charm and bottom hadrons production over a wide range of p_T and rapidity.
- Low p_T regions inaccessible without MTD should have the largest effect from QGP.

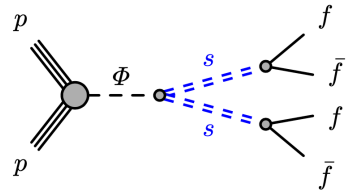
Physics impact: long-lived particles





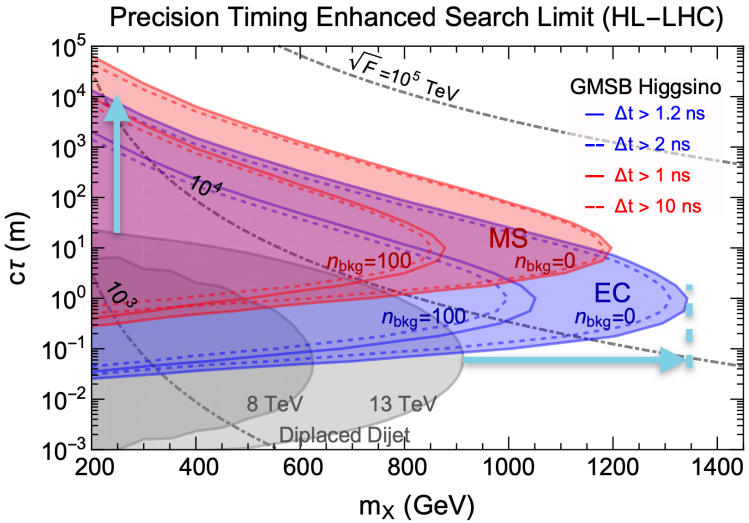
- Vertex timing enhances Long-lived particle physics program
- In topologies involving secondary vertices, MTD provides a unique handle to reconstruct the mass of the long-lived neutral particles (e.g. χ_0)

Physics impact: long-lived particles

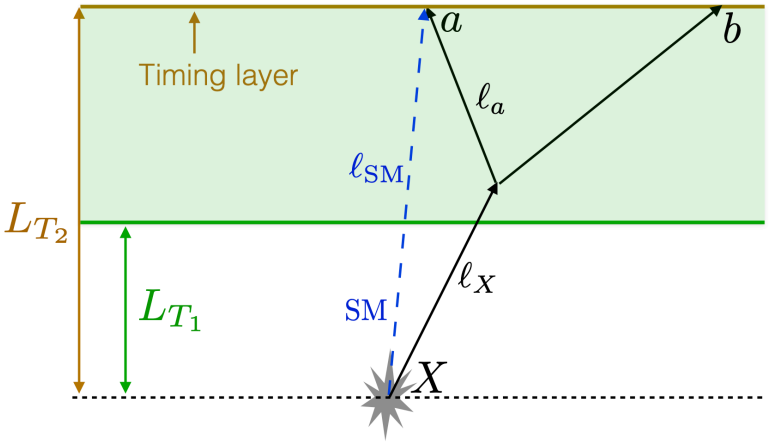


study by Zhen Liu et al.

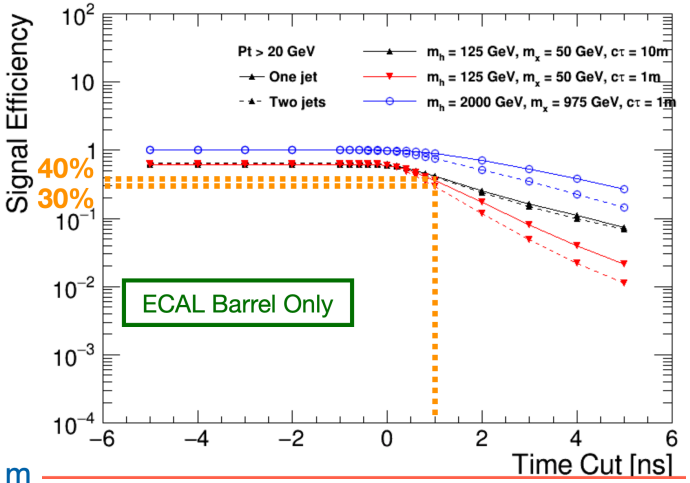
https://arxiv.org/abs/1805.05957



$$\Delta t = \frac{\ell_X}{\beta_X} + \frac{\ell_a}{\beta_a} - \frac{\ell_{\rm SM}}{\beta_{\rm SM}}$$



- Timing results in large gains in cτ and mass reach
- L1-trigger to fully exploit LLP potential
  - MTD and ECAL timing trigger for LLP searches can reach 40% signal efficiency



M_h = 125 GeV

M_x= 50 GeV, $c\tau$ = 1m

Fermilab

Summary

- Timing is an enabling technology change for future experiments
  - Timing precision of 30-40 ps achieved with several Si-based technologies
  - Precision timing for calorimeters and MIP tracking demonstrated at < 30 ps

- New technologies and applications being actively developed
  - The last dimension to be used in precision experiments!
  - Improvements in event reconstruction, and new handles in searches for deviations from the Standard Model
  - Future tracking detectors will likely be required to have significant timing precision