



# Precision timing detector for CMS at the HL-LHC

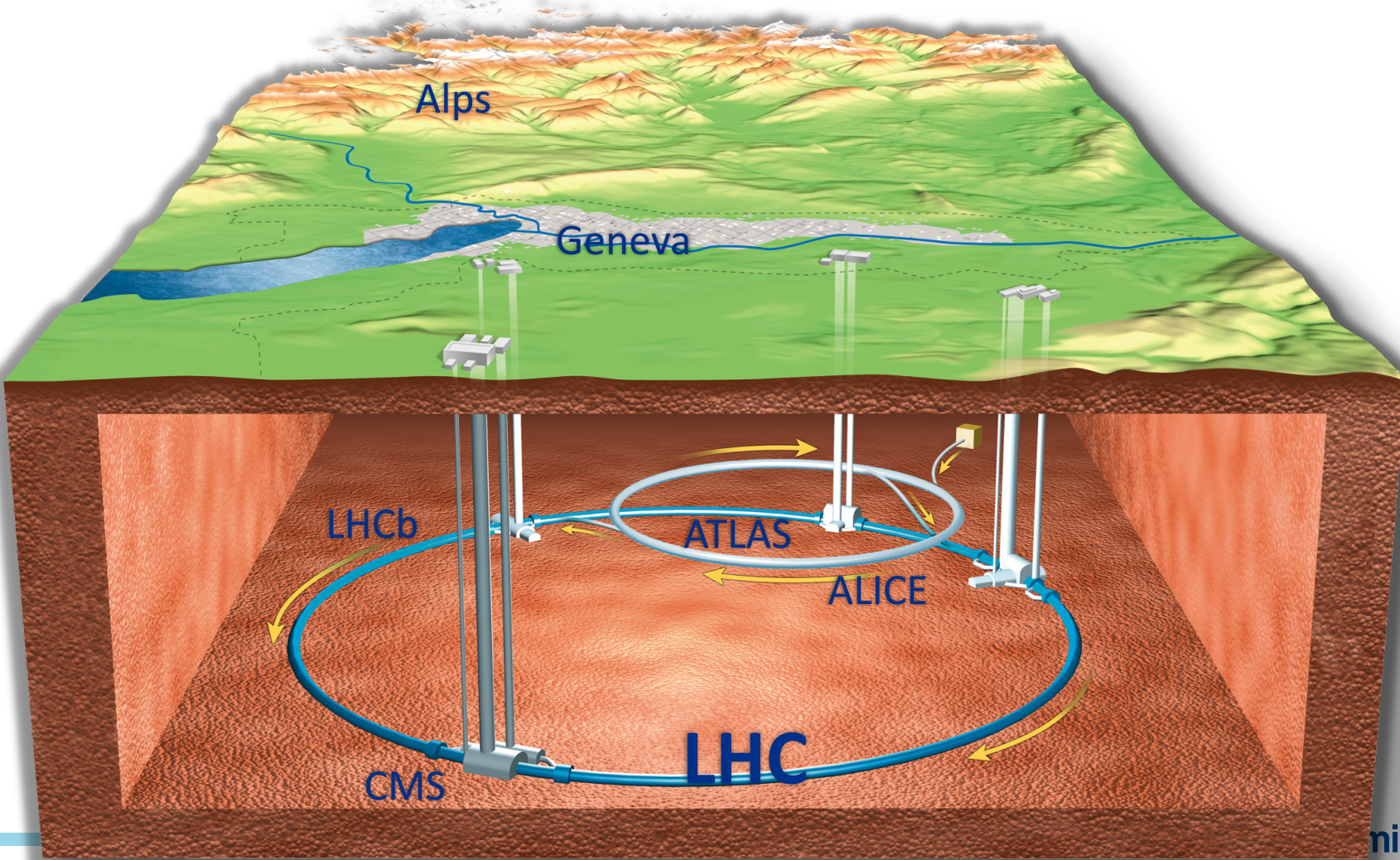
*Artur Apresyan*

*SLAC Experimental Seminar*

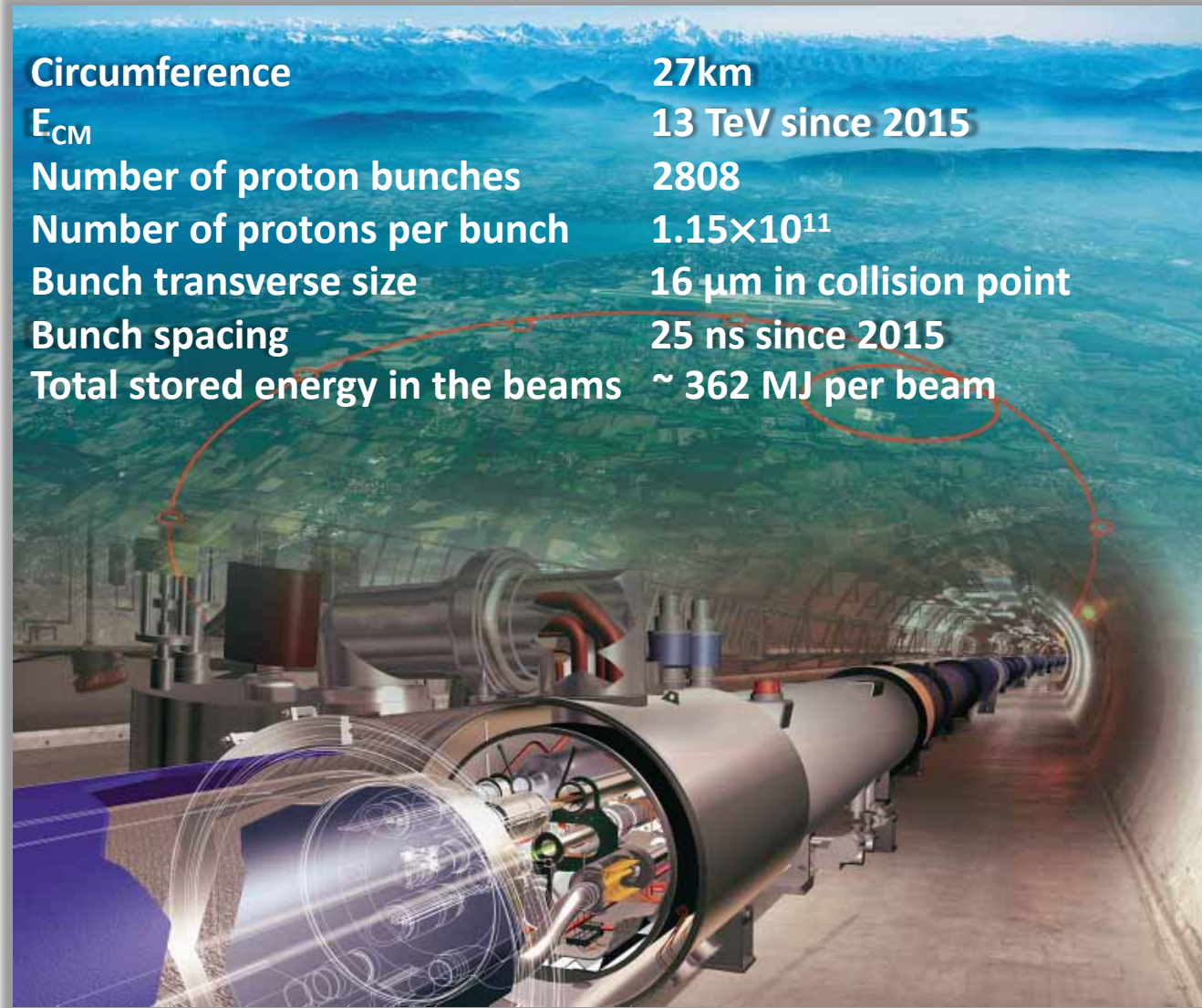
*July 14, 2020*

# The Large Hadron Collider

Four large experiments: **ATLAS**, **CMS**, **ALICE**, and **LHCb**

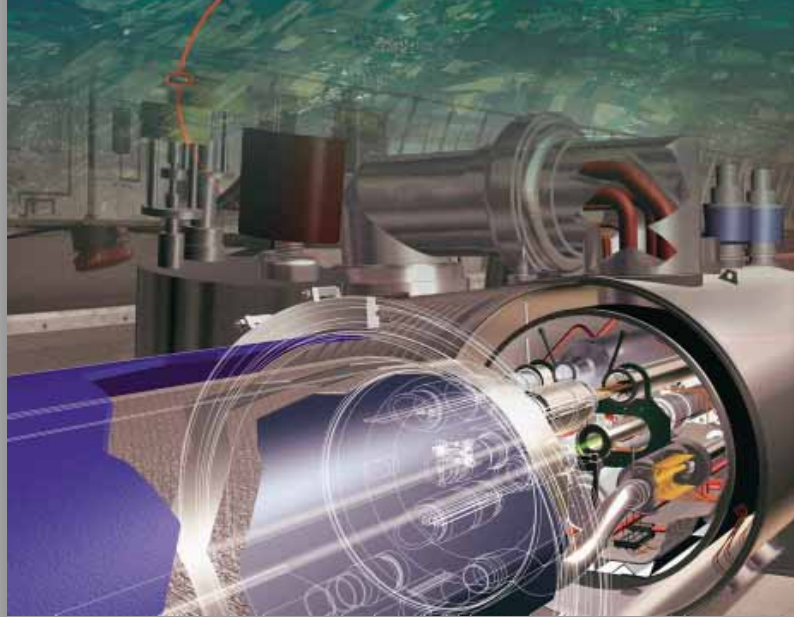


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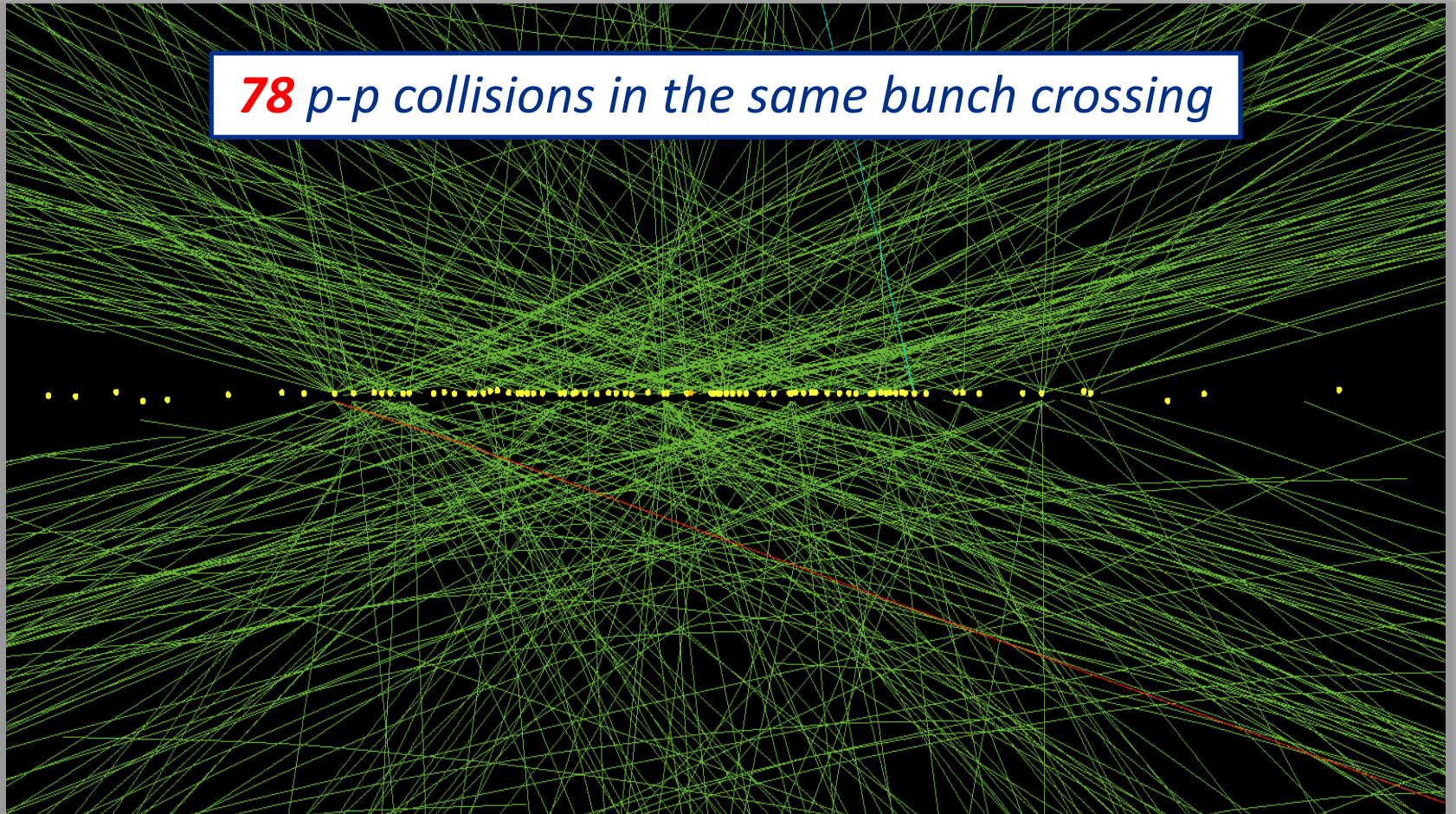
|                                  |                                     |
|----------------------------------|-------------------------------------|
| Circumference                    | 27km                                |
| $E_{\text{CM}}$                  | 13 TeV since 2015                   |
| Number of proton bunches         | 2808                                |
| Number of protons per bunch      | $1.15 \times 10^{11}$               |
| Bunch transverse size            | 16 $\mu\text{m}$ in collision point |
| Bunch spacing                    | 25 ns since 2015                    |
| Total stored energy in the beams | $\sim 362$ MJ per beam              |



10,000-ton carrier at 30 km/h

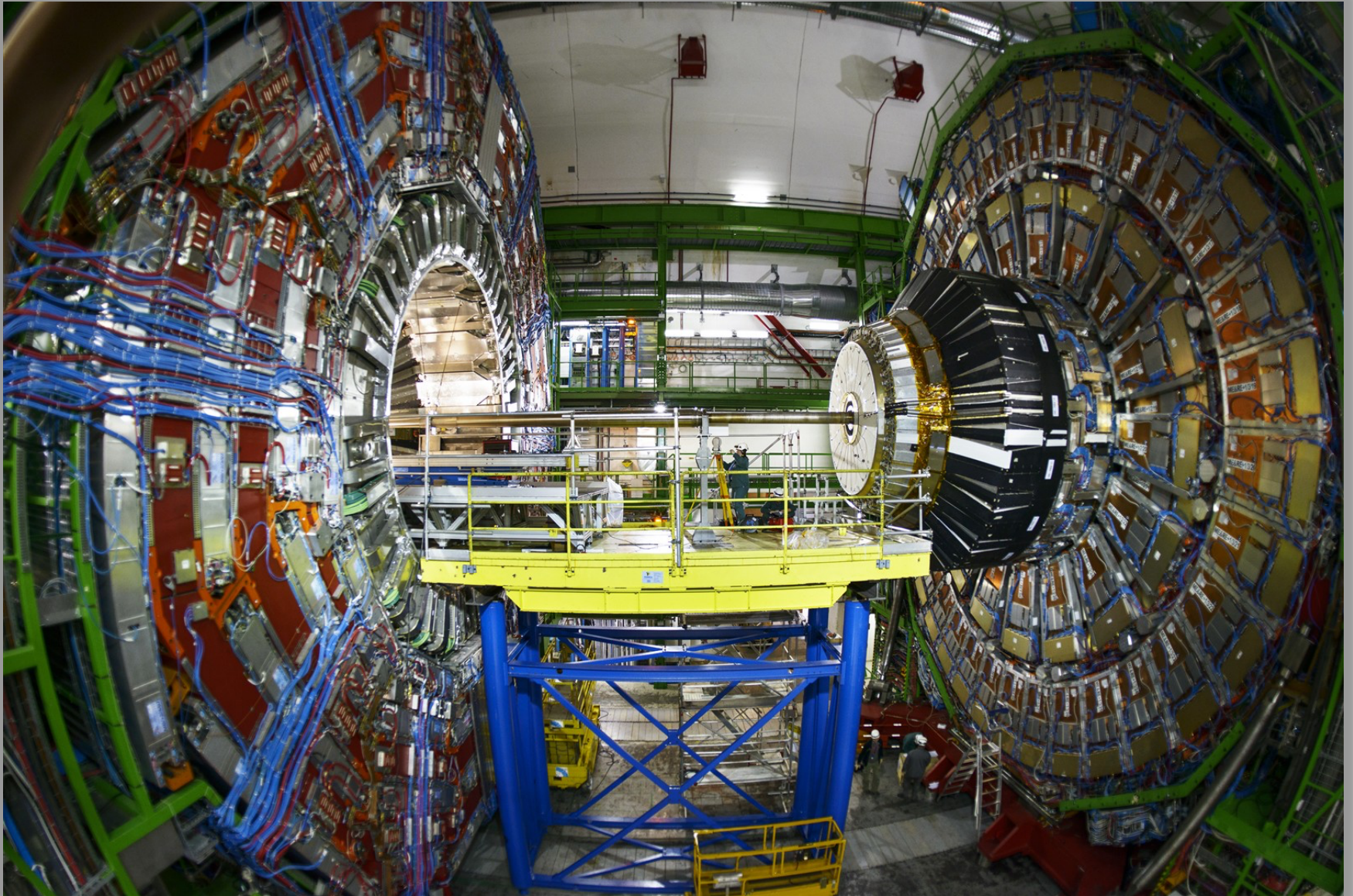
# Proton-proton collisions

**78** *p-p collisions in the same bunch crossing*



Collect lots of proton-proton collisions data

# The Compact Muon Solenoid (CMS)



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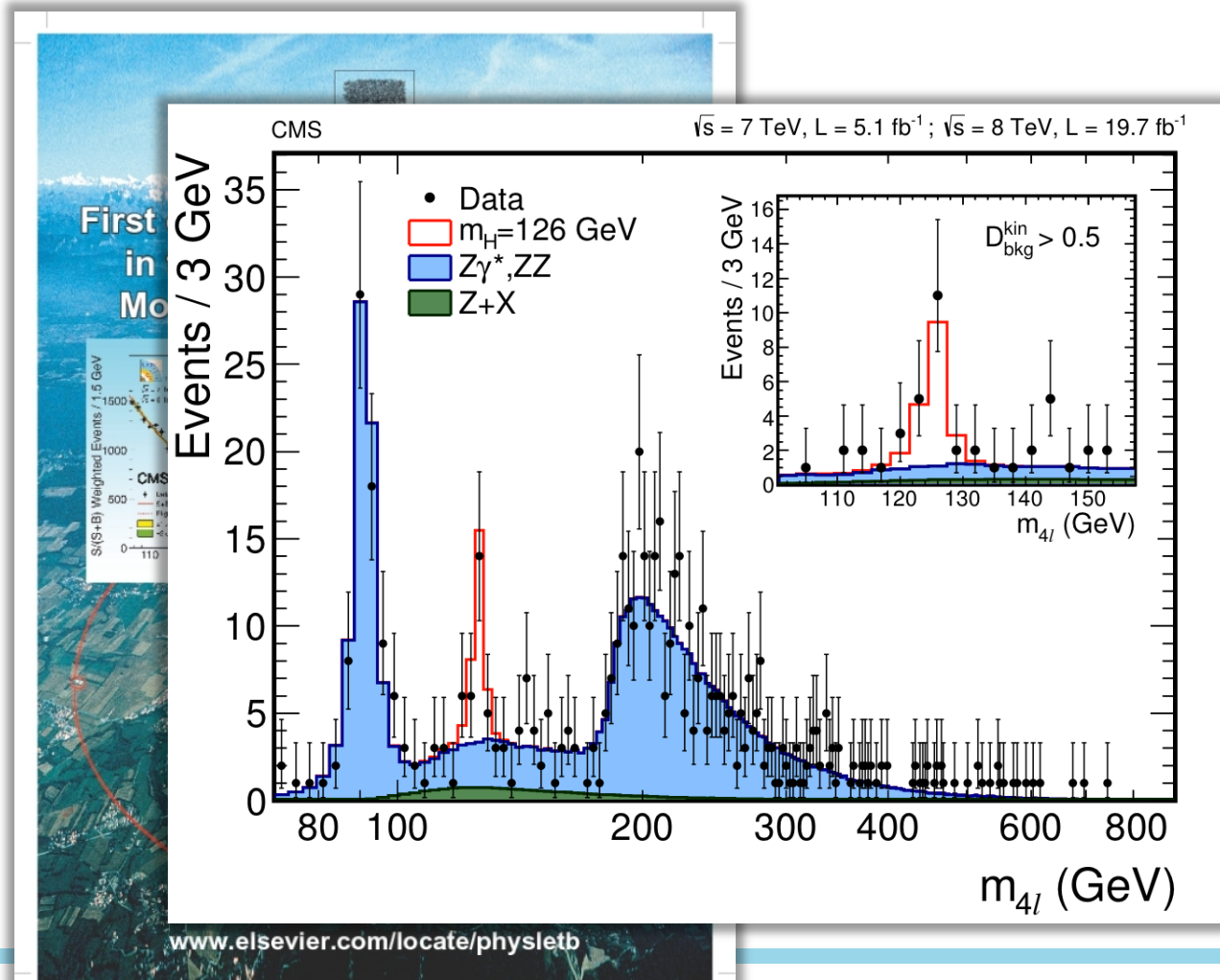


**2700** physicists, **180** institutions from **43** countries



# The crown jewel

- The Higgs boson discovery announced in 2012



# The crown jewel

- The Higgs boson discovery announced in 2012

The image is a collage celebrating the Higgs boson discovery. It features a plot of 'Events / 3 GeV' vs 'Events / 3 GeV' with a peak at 125 GeV, a photo of two men shaking hands on a blue carpet, and a Nobel Prize medal.

Events / 3 GeV

Events / 3 GeV

First in Mo

St(S+B) Weighted Events / 1.5 GeV

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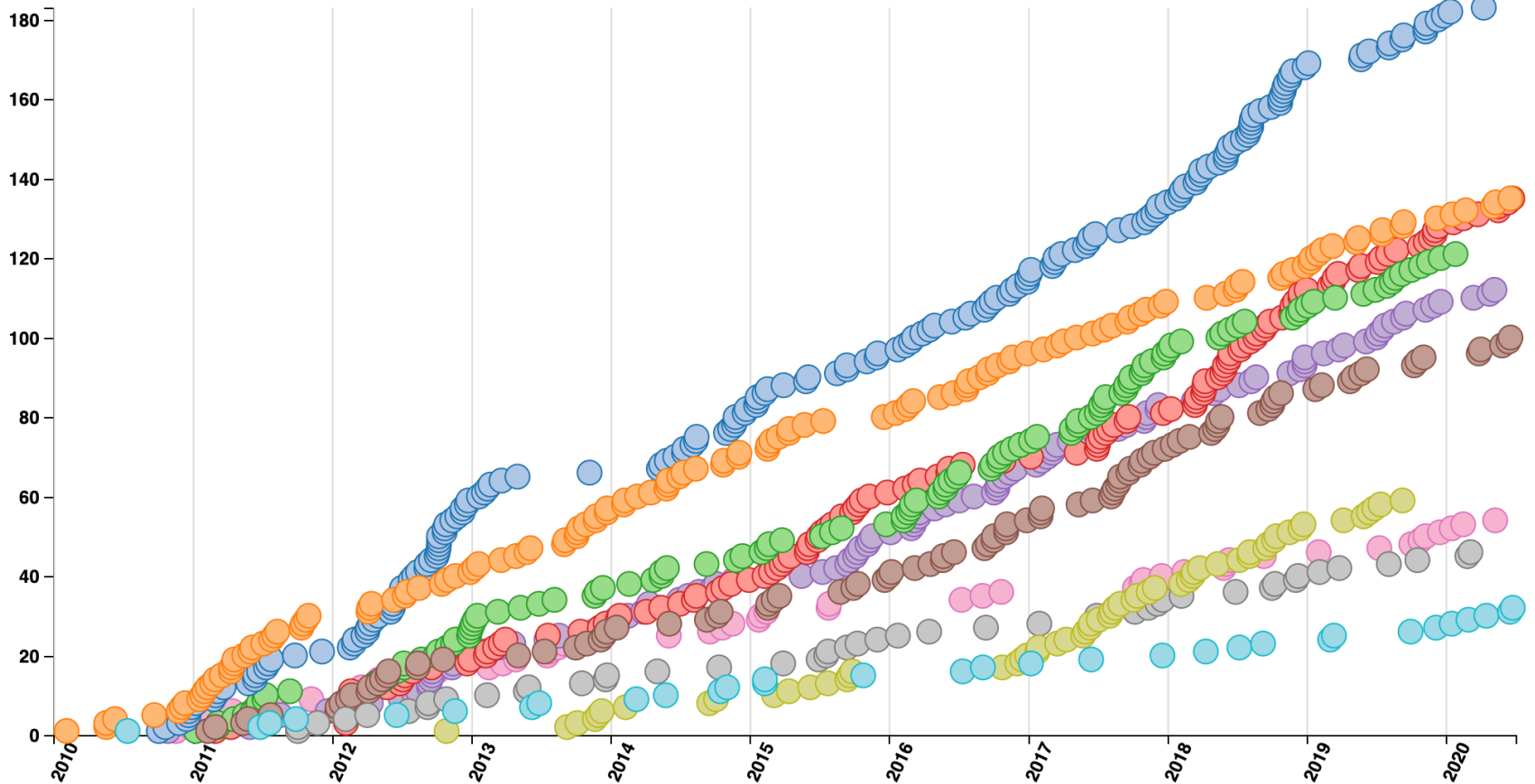
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# CMS Publications

Buttons for publication categories: Show all, Total, Exotica, Standard Model, Supersymmetry, Higgs, Top, Heavy Ions, B and Quarkonia, Forward and Soft QCD, Beyond 2 Generations, Detector Performance.

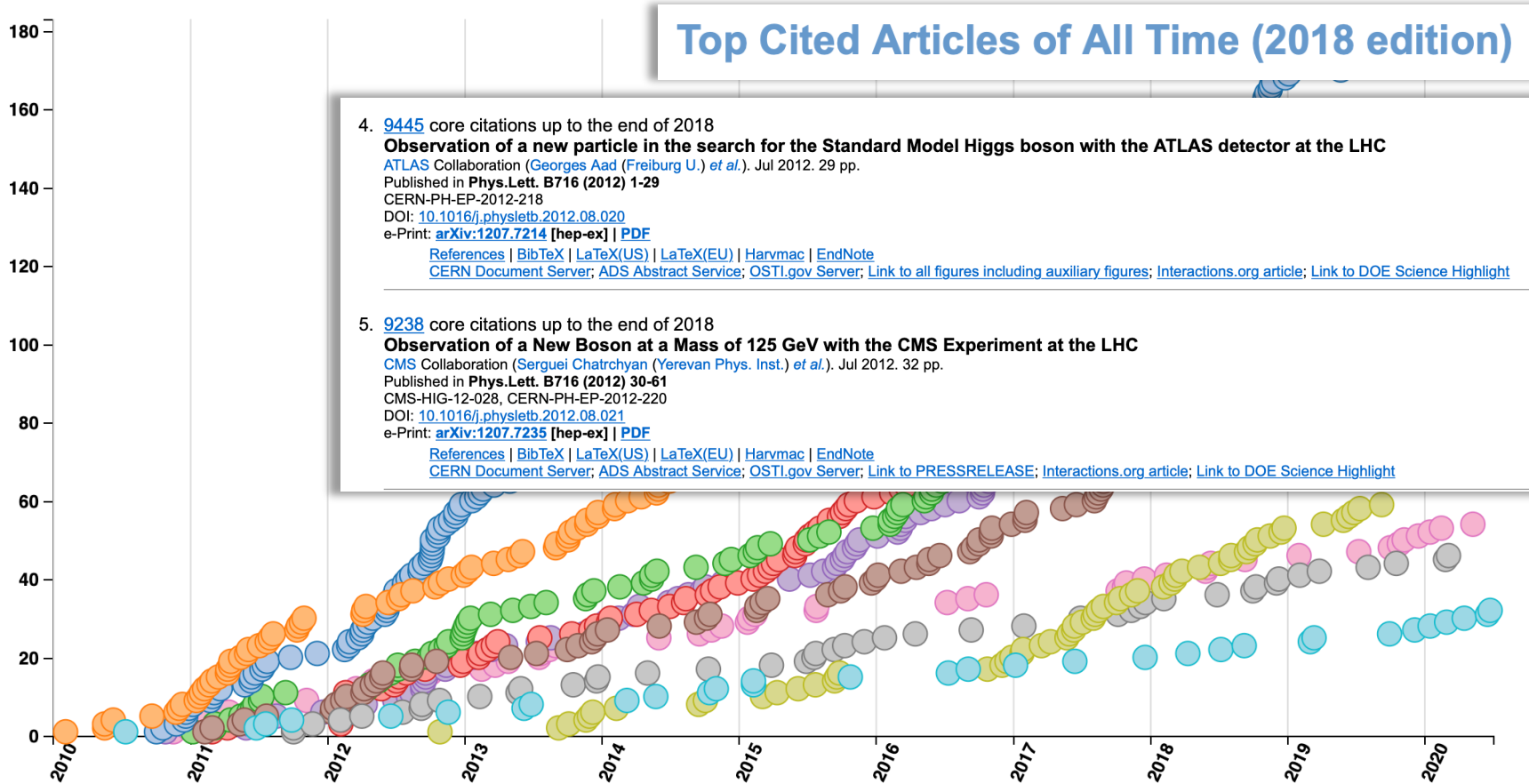
977 collider data papers submitted as of 2020-06-25



# CMS Publications

- Show all
- Total
- Exotica
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- B and Quarkonia
- Forward and Soft QCD
- Beyond 2 Generations
- Detector Performance

977 collider data papers submitted as of 2020-06-25



# What can Tera-scale teach us?

- The LHC: a tool to explore the structure of matter on a scale that is an order of magnitude smaller than previously achieved
- We need to use all its potential to explore all the corners accessible

## Seeing the infinitely small

Instruments at the Musée d'histoire des sciences of Geneva trace the history of microscopy



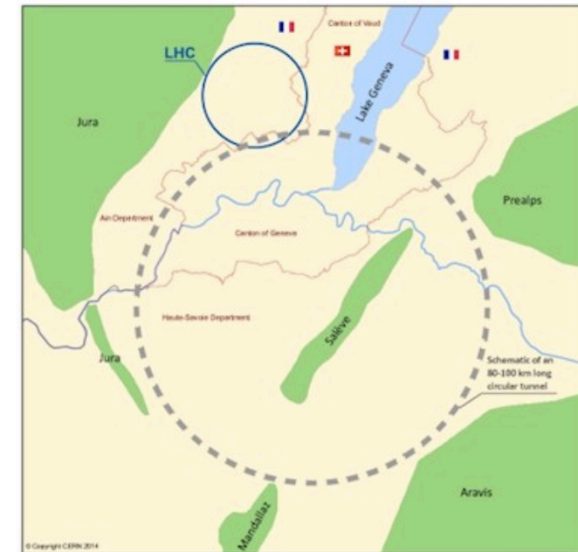
# Extend the reach

- How can we increase the reach of searches?
  - Increase collisions to a **higher energy**
  - Take much **more data** with the existing machine
- Since we have not found it yet, New Physics is a **low rate process**
  - High instantaneous luminosity is required, well in excess of current LHC
- Need to advance detector technologies to reap all physics from the future machines



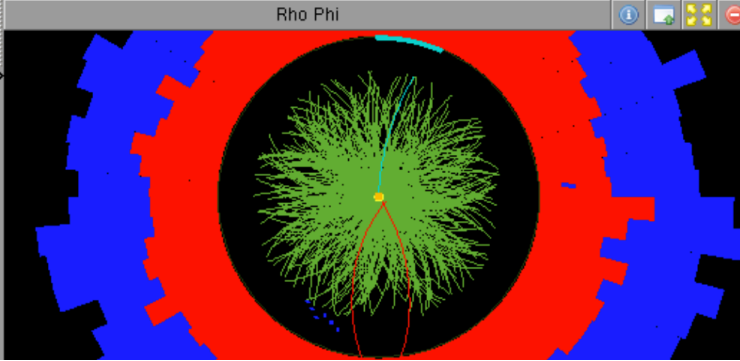
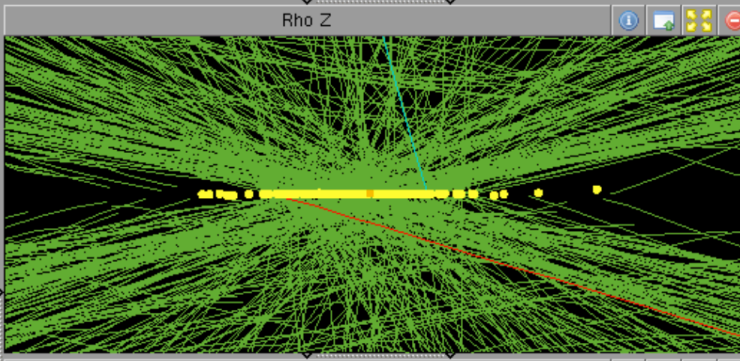
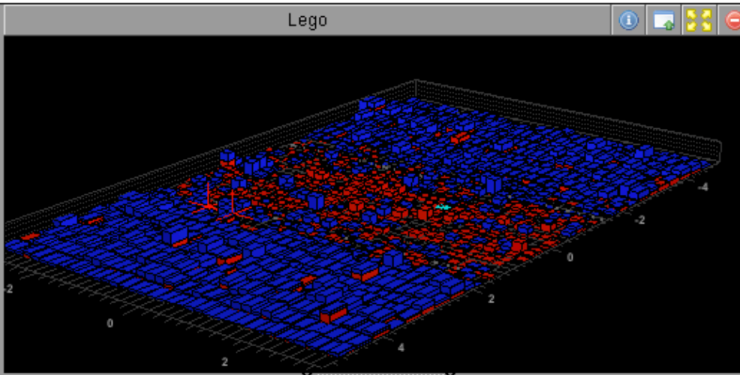
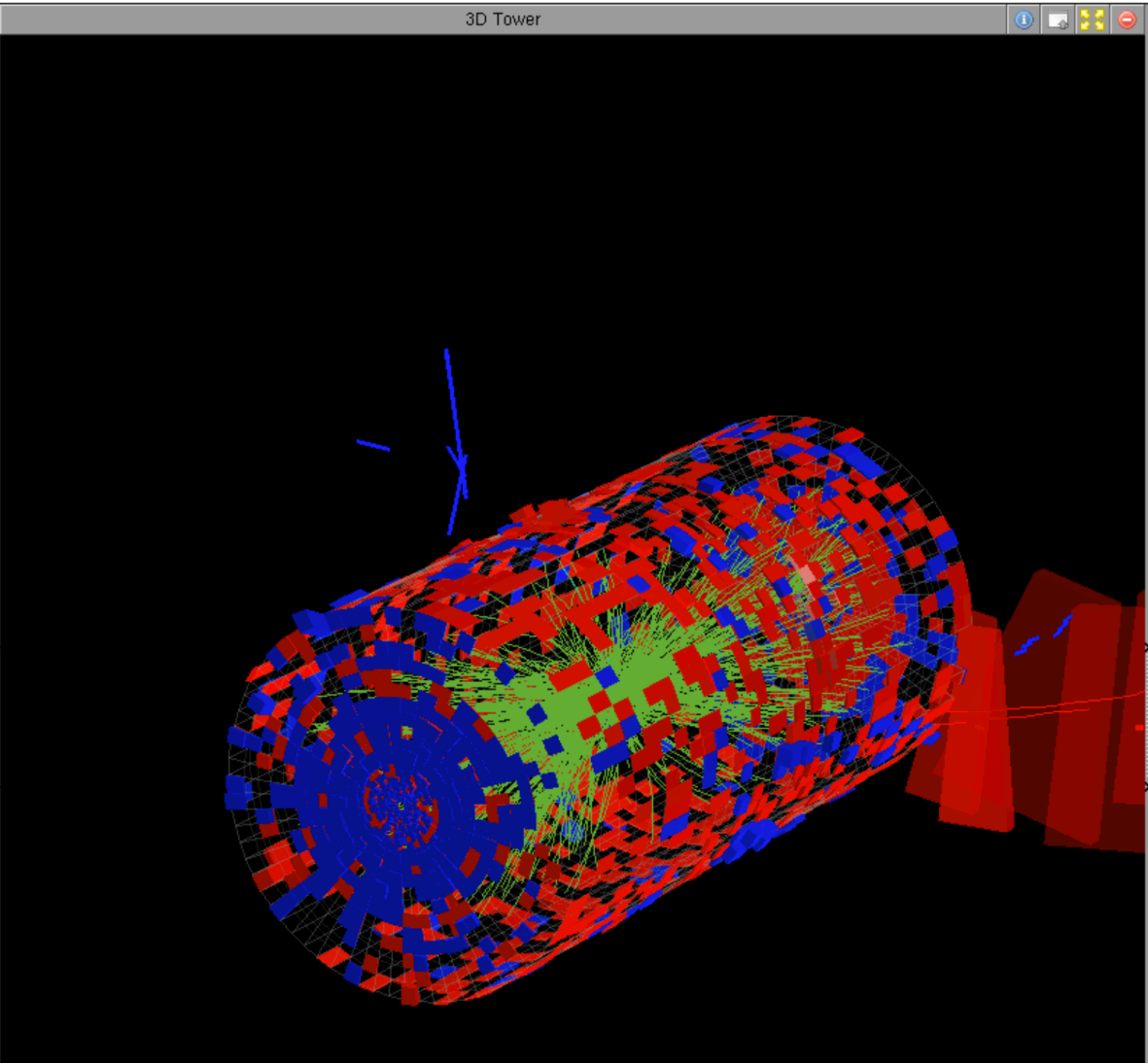
# LHC & Future Colliders

- Luminosities in excess of  $10^{34} \text{ cm}^{-2}\text{s}^{-1}$  is required
  - HL-LHC : towards  $10^{35} \text{ cm}^{-2}\text{s}^{-1}$
  - Future Higher Energy Colliders: **even higher to probe even more rare processes: up to 1000 pileup**

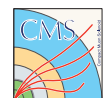


Google earth

# High Luminosity $\rightarrow$ High Pileup!



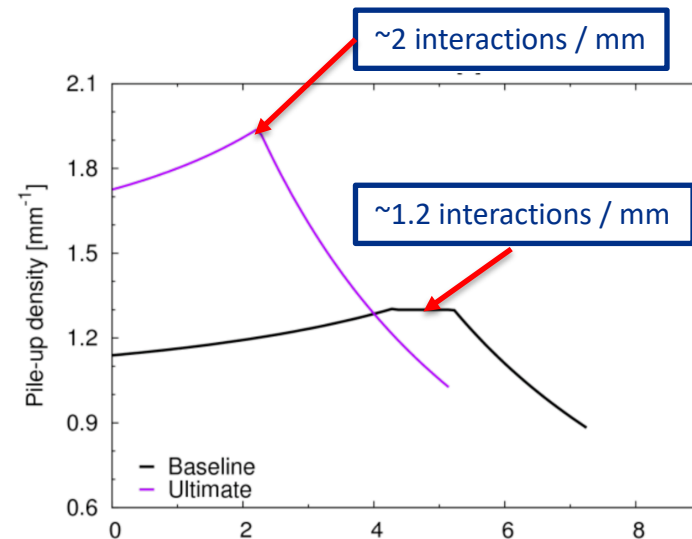
# HL-LHC upgrades schedule



# HL-LHC Luminosity scenarios

- Leveling luminosity:
  - $5.3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$  and 140 pileup (**Baseline**)
  - $7.6 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$  and 200 pileup (**Ultimate**)
- Collect 3 to 4  $\text{ab}^{-1}$  of pp data at 14 TeV

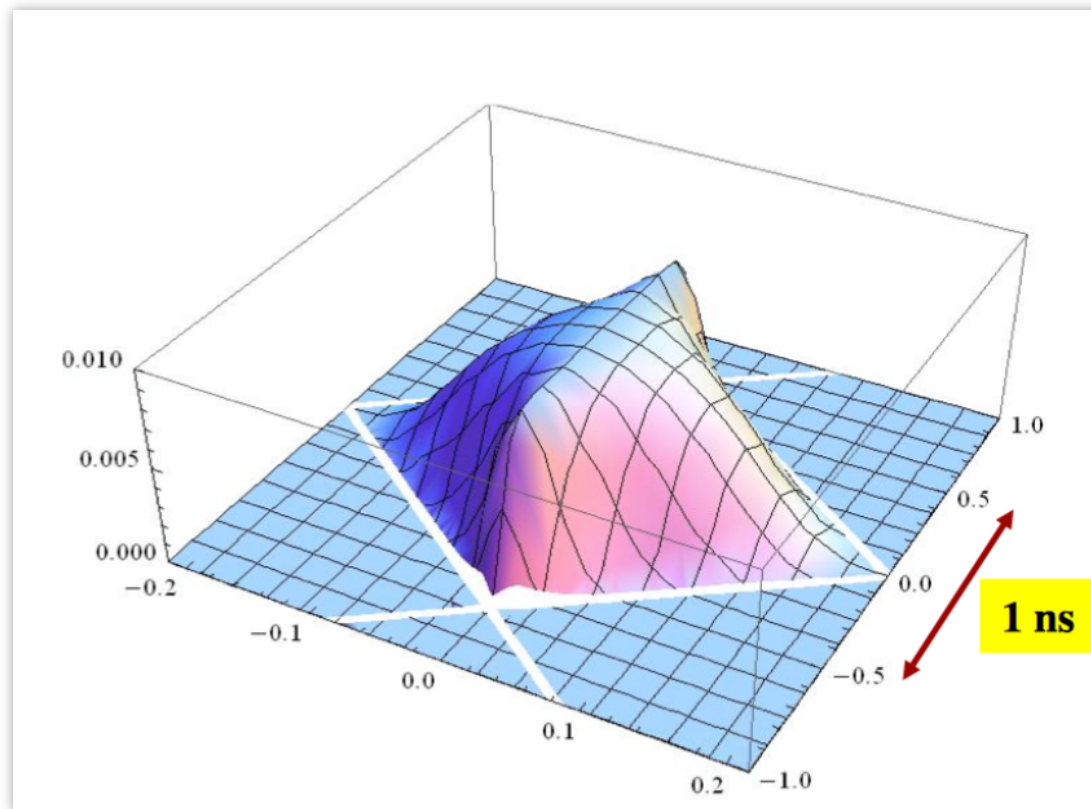
| Scenario     | Max. PU [events/xing] | Max. PU density [events /xing/mm] | Luminous Region long. r.m.s. size [cm] | $\Delta L_{\text{int}}/L_{\text{nom}}$ [%] | Additional HW [Y/N] |
|--------------|-----------------------|-----------------------------------|--|--|---------------------|
| Nominal      | 140                   | 1.3                               | <4.8                                   | 0  | N                   |
| Ultimate     | 200                   | 1.9                               | <4.5                                   | +33  | N                   |
| 8b+4e        | 140                   | 1.3                               | <5                                     | -25  | N                   |
| 200 MHz      | 140                   | 1.3                               | <4.8                                   | -14  | Y                   |
| Flat         | 140                   | 1.1                               | <5.5                                   | 0  | May be              |
| Crab kissing | 140                   | 0.6-0.65                          | <7                                     | -5   | Y                   |



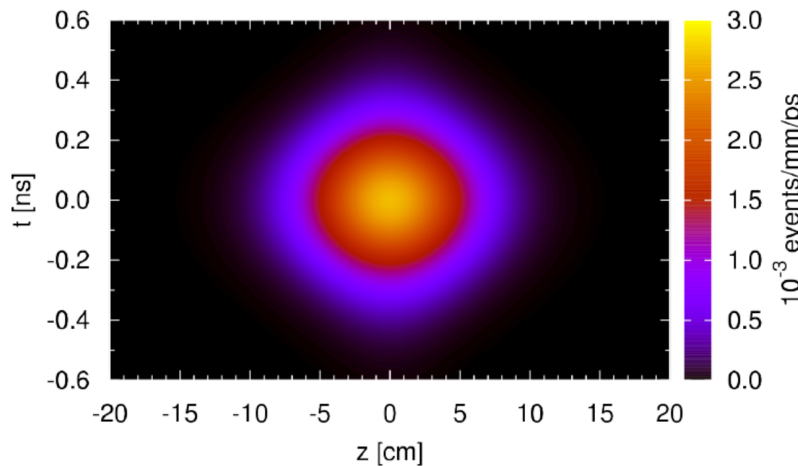
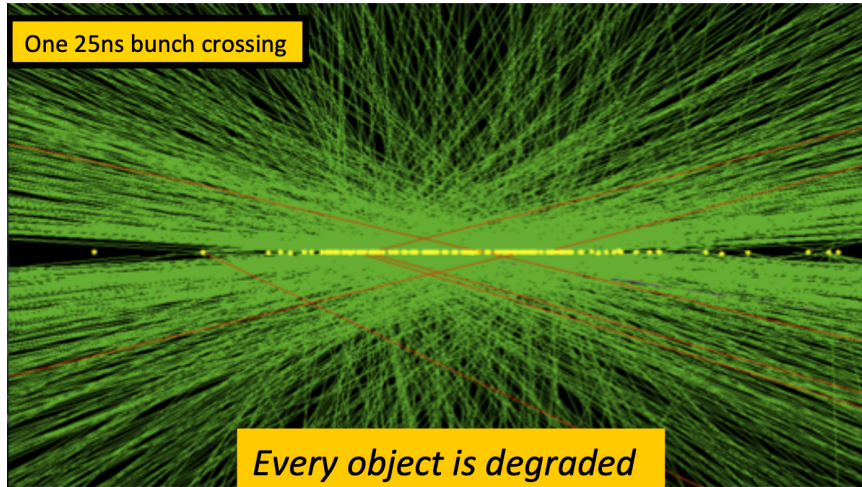
G. Arduini, R. Thomas, ECFA 2016

# HL-LHC beam spread

- Beamspot width in time is several hundred ps (**RMS = 200 ps**)
  - A detector with 20-30 psec timing resolution could meaningfully distinguish between interactions on the basis of timing



# The Challenge of the HL-LHC era



- Dealing with the effects of pileup interactions will be a major challenge of the HL-LHC era
  - PU interactions are separable in space + time.
- 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.
- Per-particle timing provided by the MIP Timing Detector (MTD) allows 4D track and vertex reconstruction
  - PU reduced in each time slice
  - Every object is improved
  - Significant benefit to CMS physics program

# CMS Phase 2 Upgrades

## L1 Trigger/HLT/DAQ NSF and DOE

- L1 40 MHz in/750 kHz out with tracking for PF-like selection
- HLT 7.5 kHz out

Beam Radiation and Luminosity, Common Systems, Infrastructure

## Calorimeter Endcap DOE

- Si, Scint + SiPM in Pb-W-SS
- 3D shower imaging with precise timing

Also known as HGCAL

## Tracker

- Si Strip Outer Tracker designed for L1 Track Trigger DOE
- Pixelated Inner Tracker extends coverage to  $|\eta| < 3.8$  NSF

## Barrel Calorimeters NSF

- ECAL single crystal granularity in L1 Trigger with precise timing for  $e/\gamma$  at 30 GeV
- ECAL and HCAL new back-end electronics

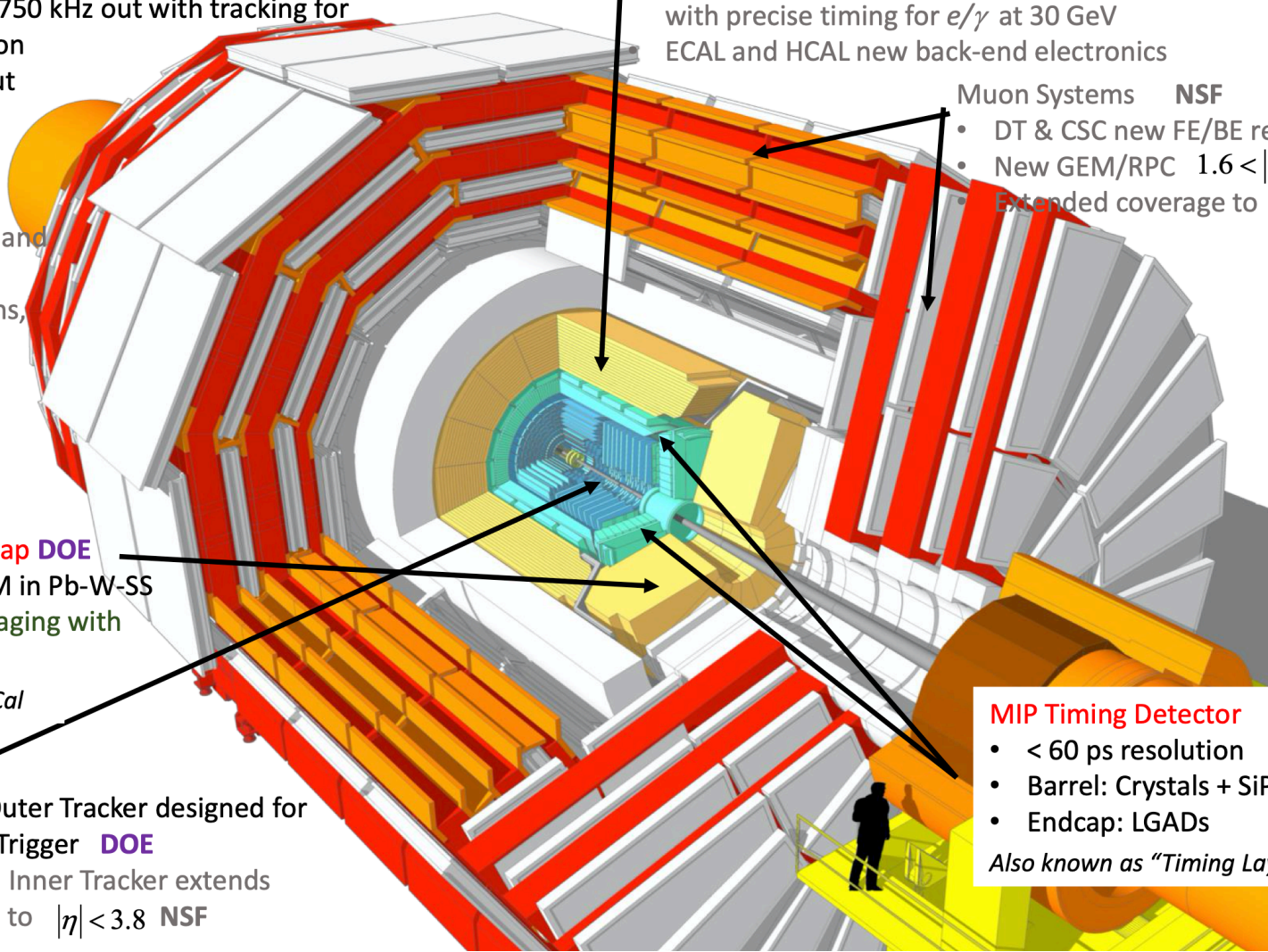
## Muon Systems NSF

- DT & CSC new FE/BE readout
- New GEM/RPC  $1.6 < |\eta| < 2.4$
- Extended coverage to  $|\eta| < 3.0$

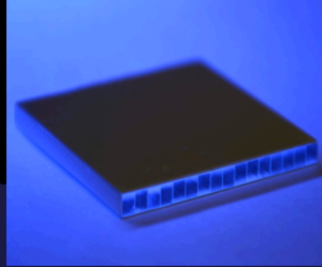
## MIP Timing Detector DOE

- $< 60$  ps resolution
- Barrel: Crystals + SiPMs
- Endcap: LGADs

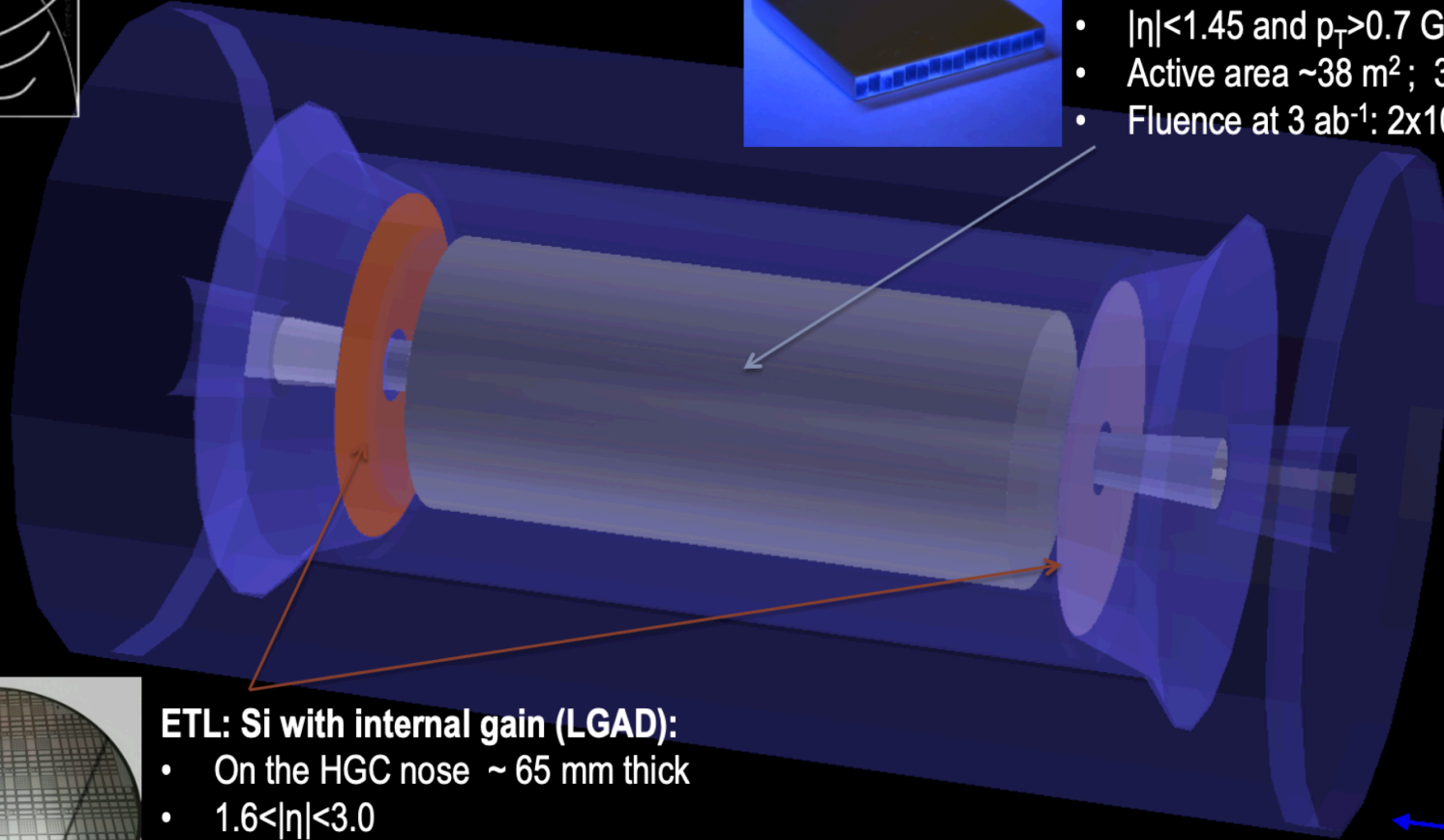
Also known as "Timing Layer" (TL)



# CMS MIP timing detector (MTD)

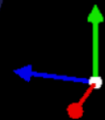
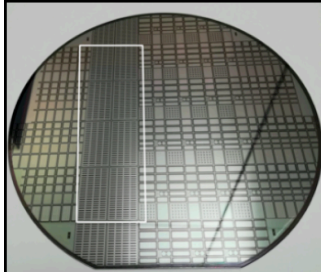


- BTL: L(Y)SO bars + SiPM readout:**
- TK/ ECAL interface  $\sim 45$  mm thick
  - $|\eta| < 1.45$  and  $p_T > 0.7$  GeV
  - Active area  $\sim 38$  m<sup>2</sup>; 332k channels
  - Fluence at  $3 \text{ ab}^{-1}$ :  $2 \times 10^{14} n_{\text{eq}}/\text{cm}^2$



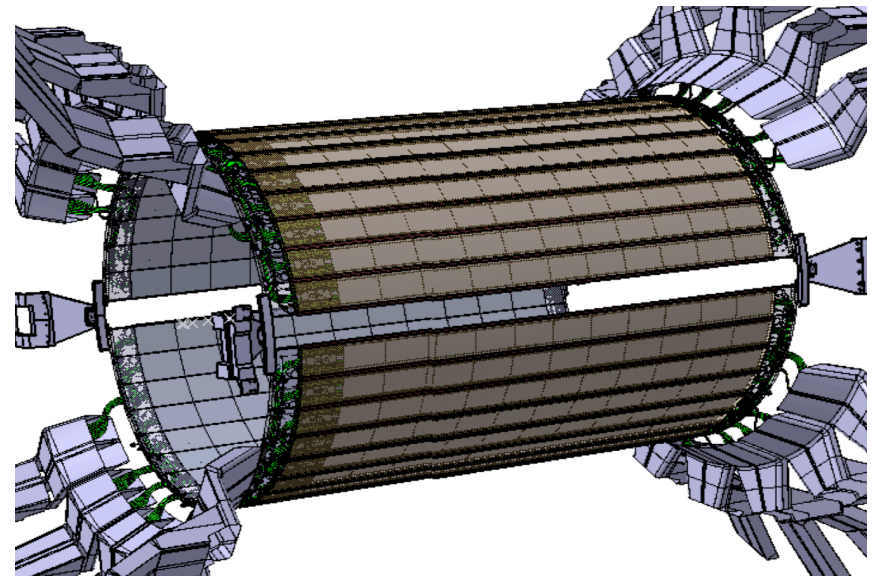
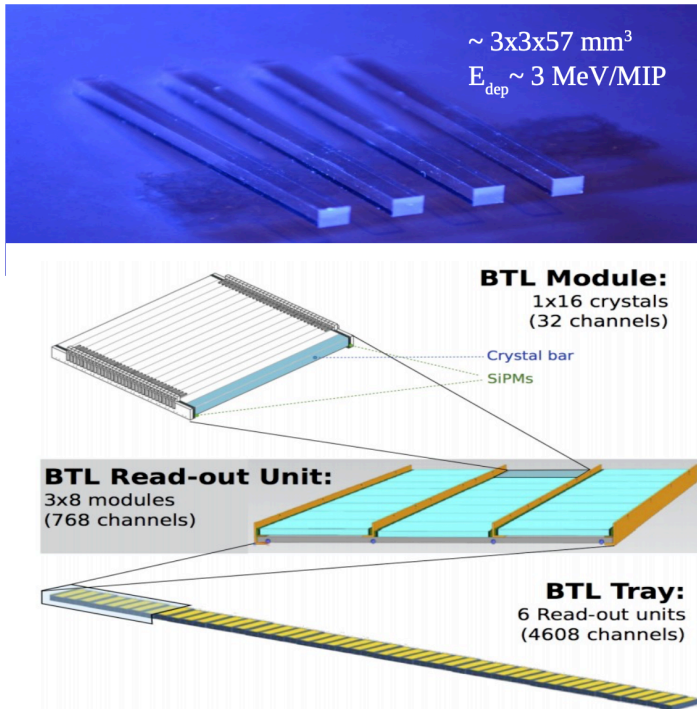
**ETL: Si with internal gain (LGAD):**

- On the HGC nose  $\sim 65$  mm thick
- $1.6 < |\eta| < 3.0$
- Active area  $\sim 14$  m<sup>2</sup>;  $\sim 8.5$ M channels
- Fluence at  $3 \text{ ab}^{-1}$ : up to  $2 \times 10^{15} n_{\text{eq}}/\text{cm}^2$



# Barrel Timing Layer (BTL) design

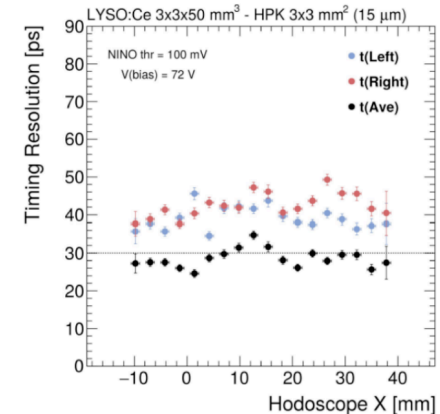
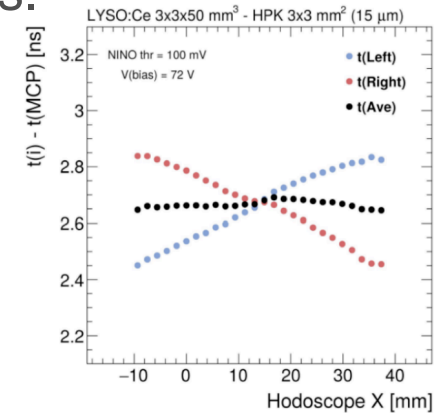
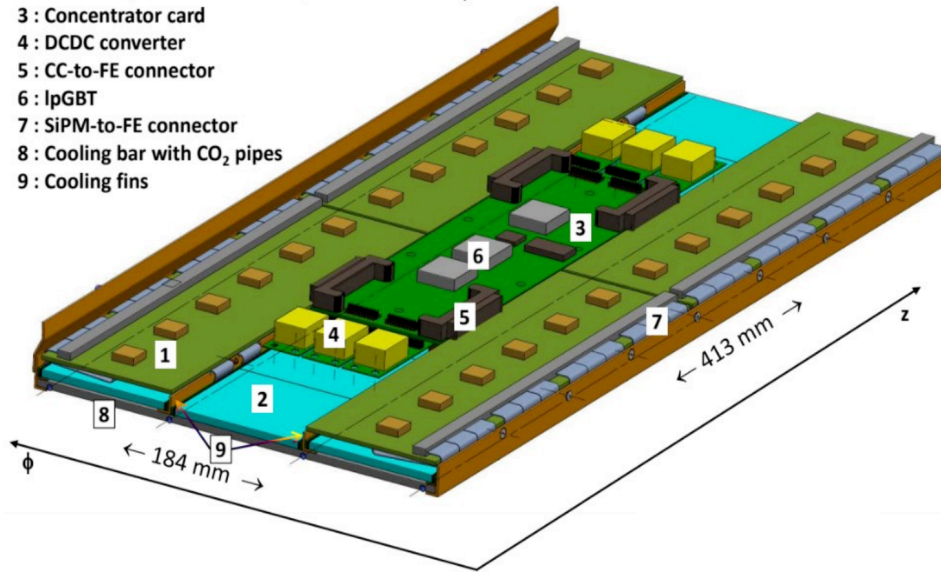
- LYSO crystals as scintillator with an excellent radiation tolerance and fast rise and decay times.
  - Attached to the inner wall of the Tracker Support Tube (TST).
  - 332k channels, organized in 6 Readout Units per tray.
- Time resolution of 35 ps at the beginning of lifetime and 60 ps by the end.



# Barrel Timing Layer (BTL) design

- Small SiPM cells: fast readout, robust vs. magnetic field/radiation and low power consumption.
- Readout using TOFHIR board with 6 ASICs each reading up to 16 crystals (32 channels).
  - Uniform time response and resolution in test-beams.
  - Improved resolution by combining the two SiPMs.

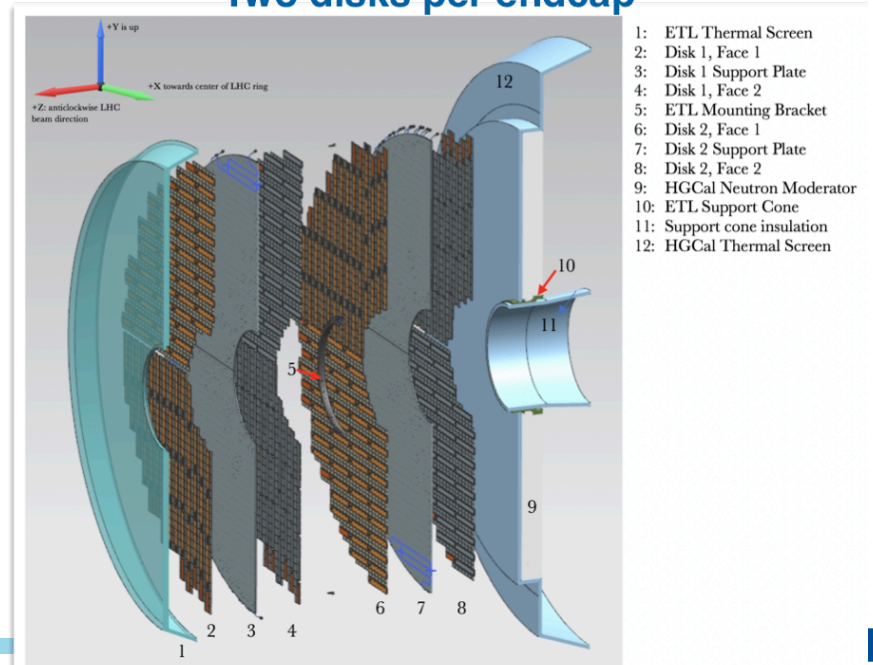
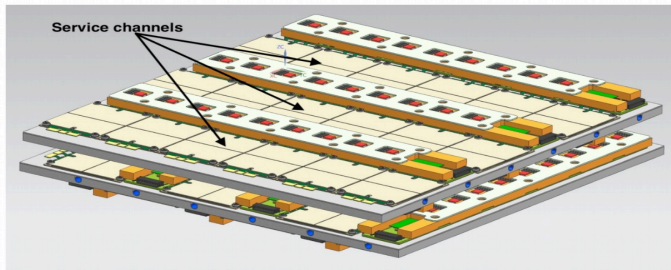
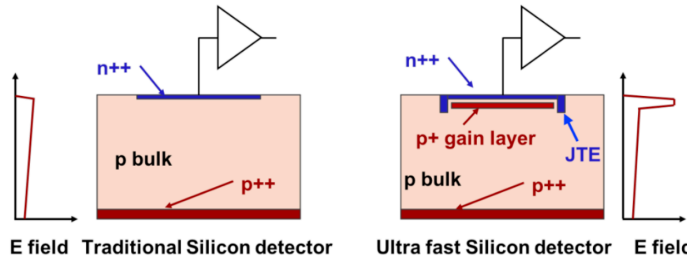
- 1: TOFHIR board with 6 ASICs
- 2: LYSO array with 16 LYSO bars, bars oriented in  $\phi$
- 3: Concentrator card
- 4: DCDC converter
- 5: CC-to-FE connector
- 6: IpGBT
- 7: SiPM-to-FE connector
- 8: Cooling bar with CO<sub>2</sub> pipes
- 9: Cooling fins



# 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 ( $< 2 \times 10^{15} n_{eq}/cm^2$ )
  - Very good timing response and resolution (30-45 ps at the beginning-end of lifetime)
- A total of  $\sim 14 m^2$  detector with two double-sided layers for each endcap
- Small  $1.3 \times 1.3 mm^2$  pixels for low capacitance,  $\sim 8.5M$  channels

## Two disks per endcap

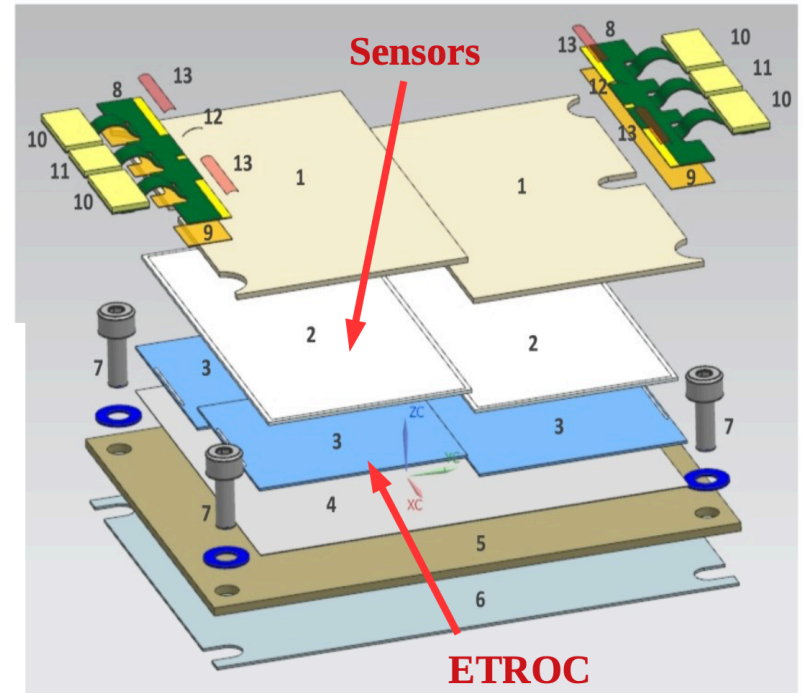
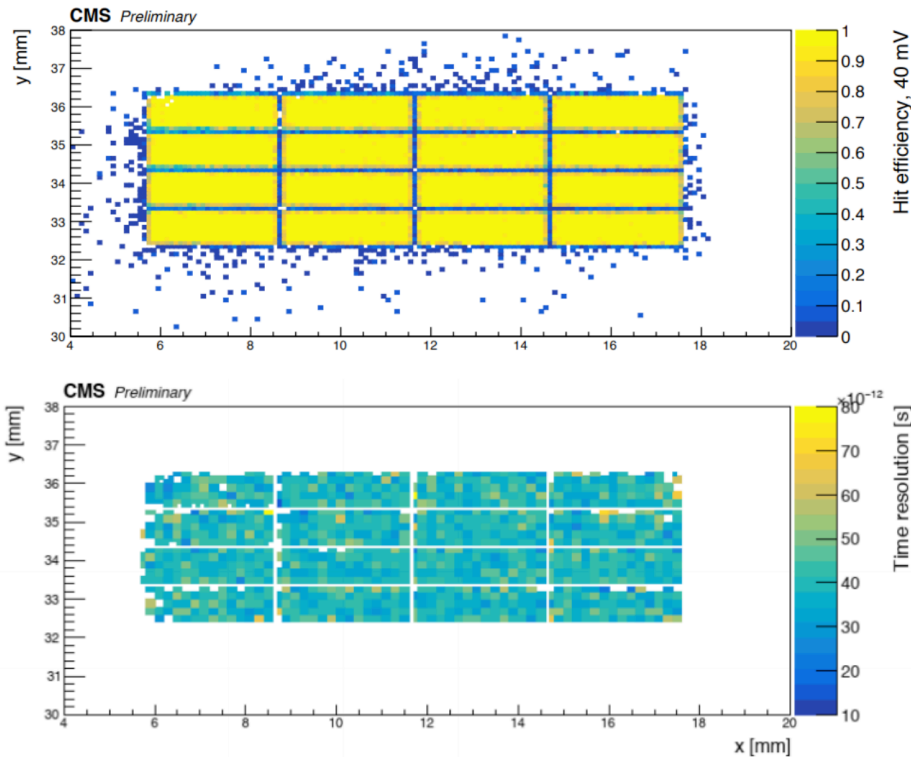


4.5 cm thick!

b

# Endcap Timing Layer (ETL) design

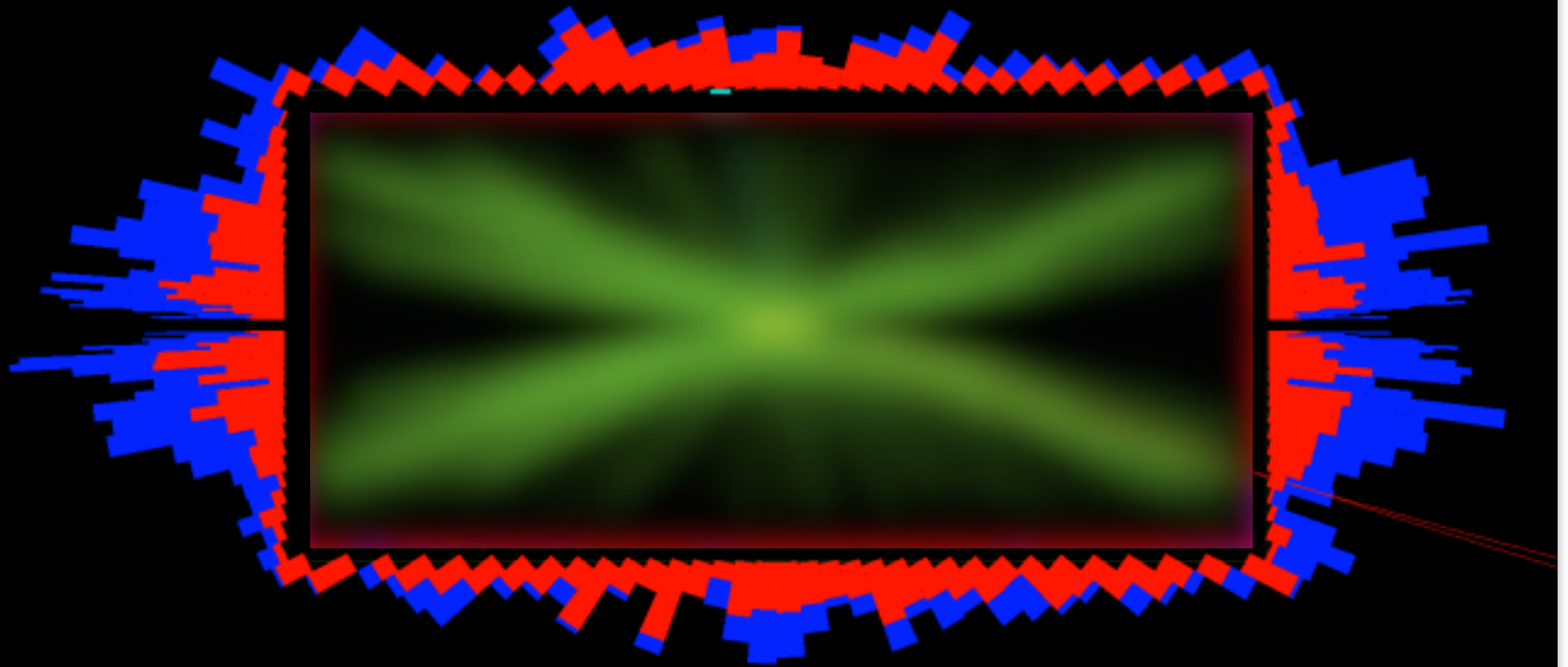
- Sensors are each  $21 \times 42 \text{ mm}^2$  and contain  $16 \times 32$  pixels
- Two ETL ASICs (ETROC) needed to readout one sensor (each ETROC has  $16 \times 16$  channels).
  - Each ETROC consists of pre-amplifier, discriminator and a TDC.
- Excellent efficiency ( $> 99\%$ ) and uniform time resolution in test beams



# Event reconstruction at HL-LHC

78 pp collision

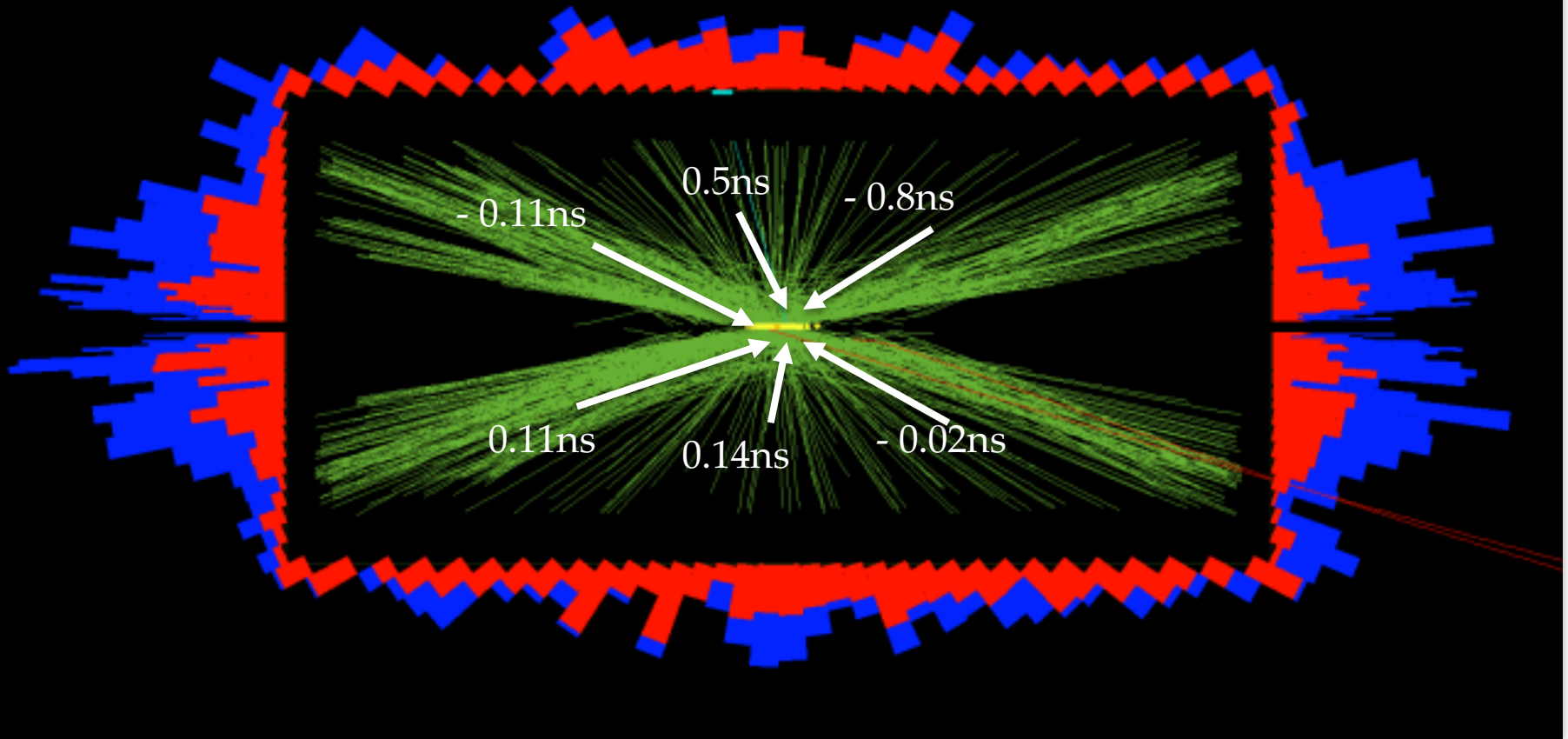
HL-LHC bunch crossing  
1 ns interval



# Event reconstruction at HL-LHC

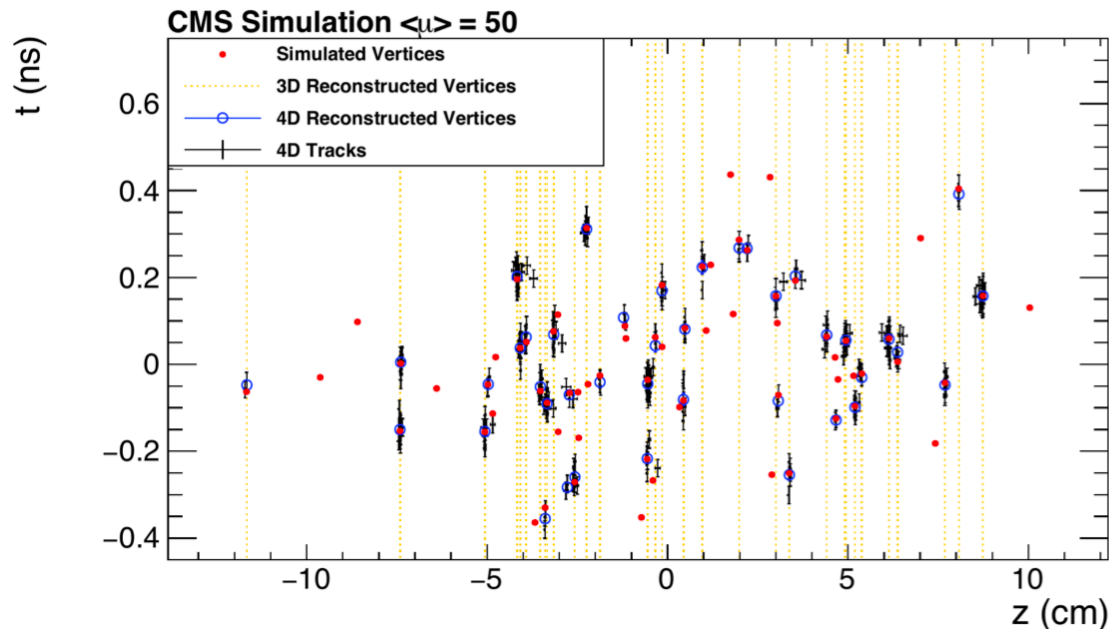
78 pp collision

HL-LHC bunch crossing  
1 ns interval



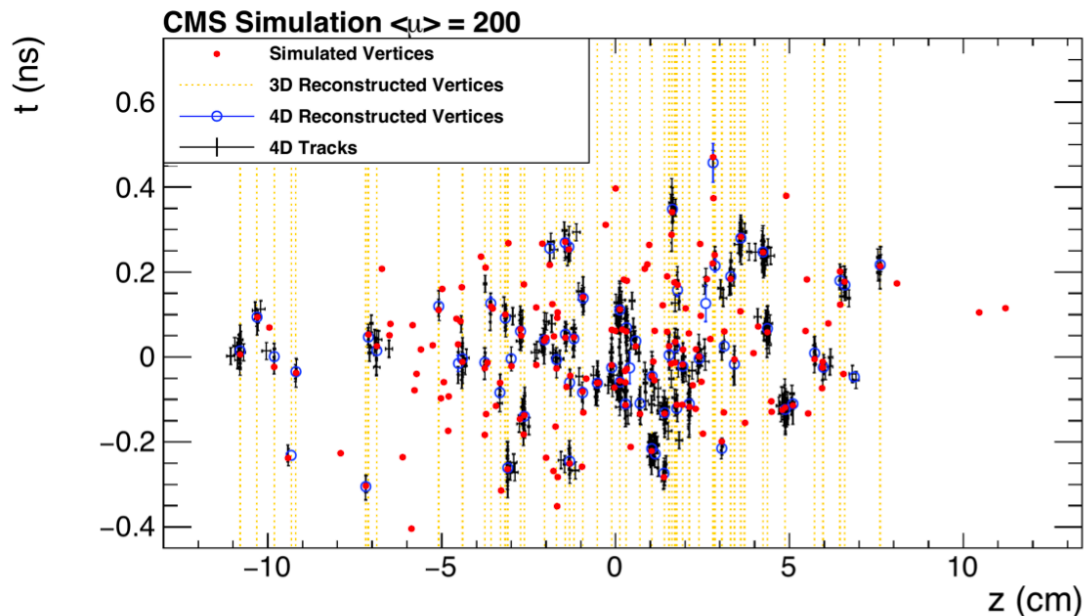
# Precision timing for charged particles

- Traditional **three-dimensional** vertexing can be upgraded to a **four-dimensional** fit
  - Pileup vertices explicitly reconstructed in position **along the beamline** and **time** within the bunch crossing
- Further suppression of charged particles from pileup for jets, MET, lepton isolation, etc...

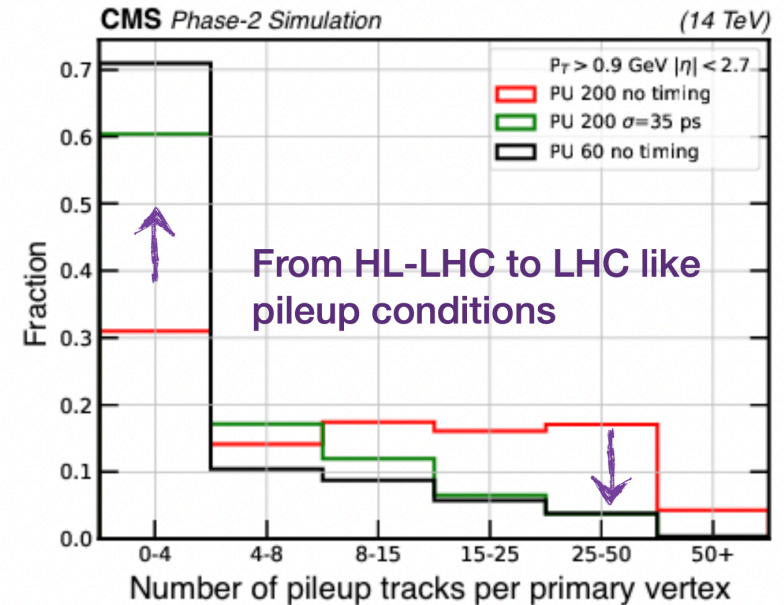
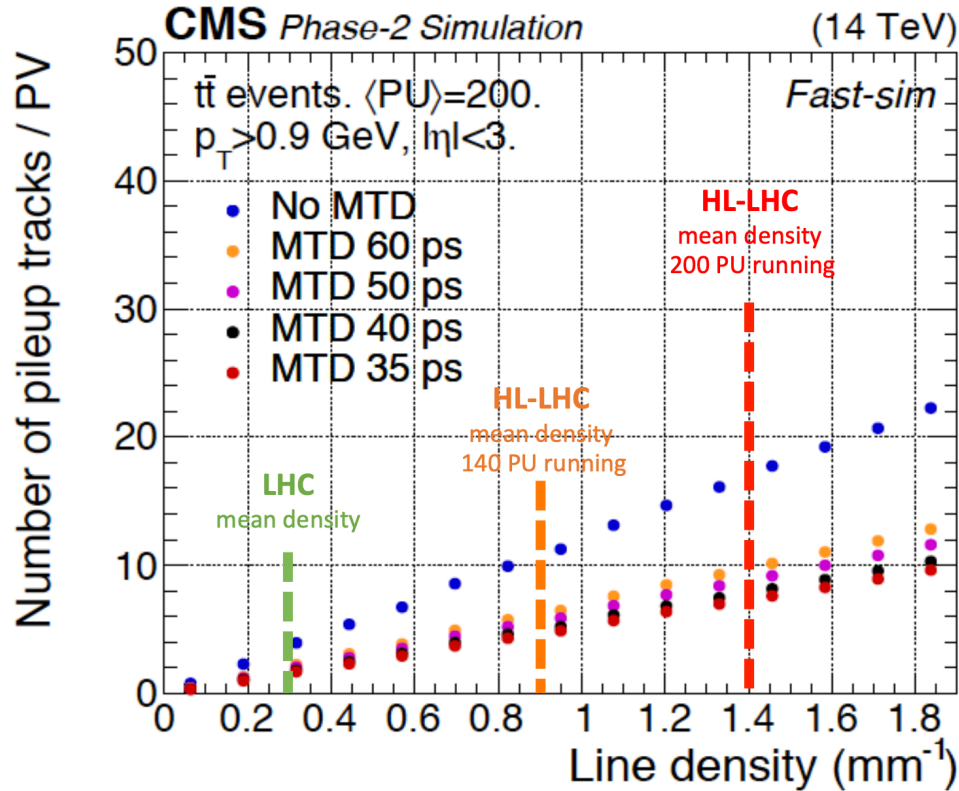


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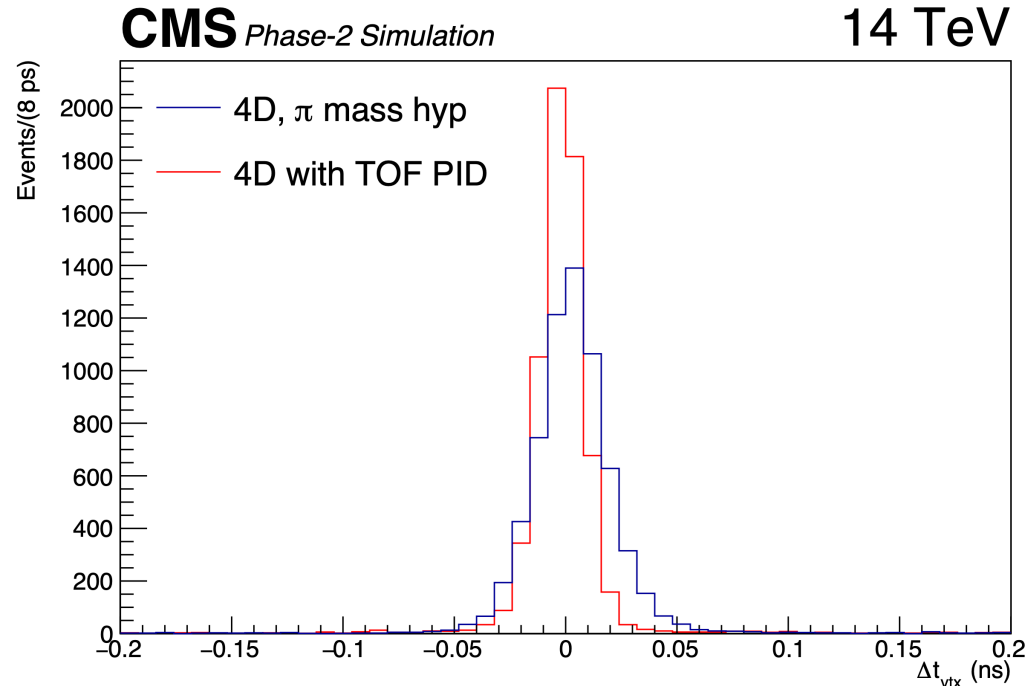
# Pileup rejection



- Time-aware primary vertex reconstruction reduces incorrect association of tracks from nearby pileup interactions by a factor of 2:
  - Fully offsets the impact of the transition from 140  $\rightarrow$  200 PU running
  - Brings per-vertex track purity close to typical current LHC running conditions

# Vertexing

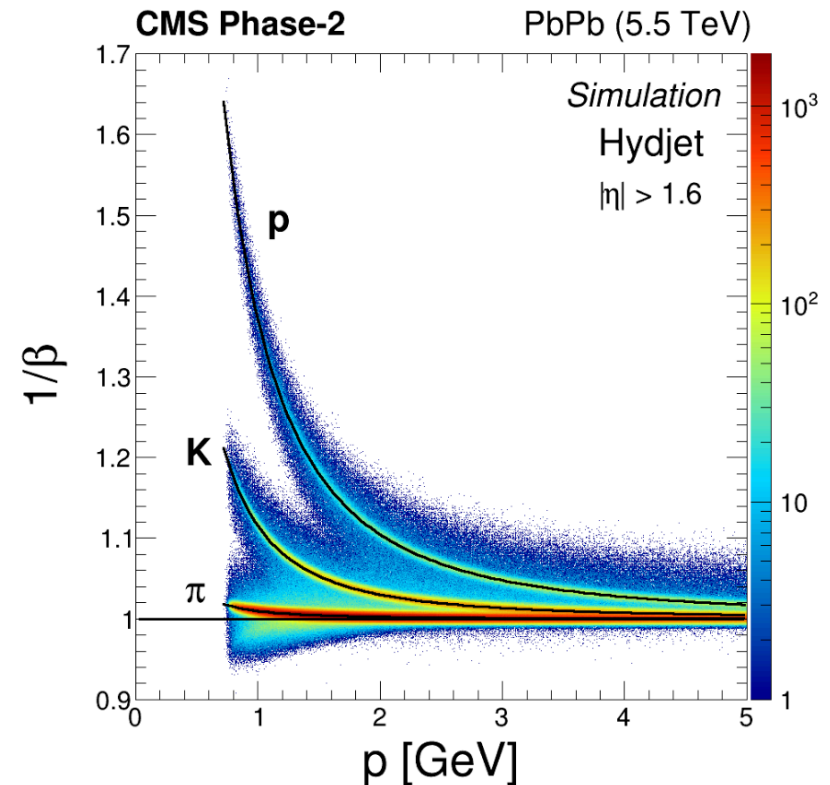
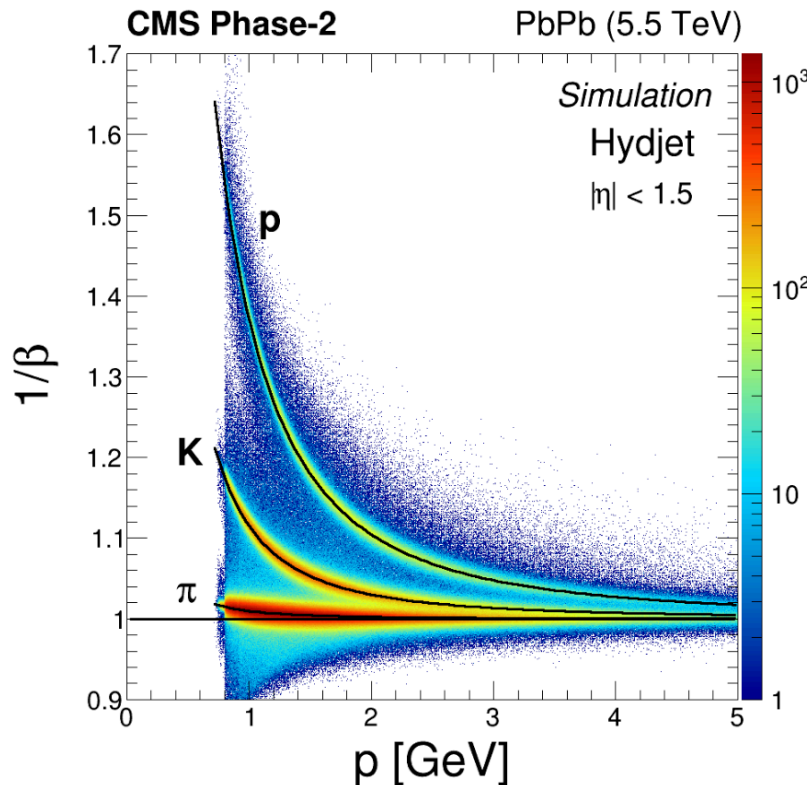
- Iterative 4D vertex reconstruction with TOFPID assignment to handle K/p at low  $p_T$
- Vertex time resolution  $< 10\text{ps}$ , no tails from slow hadrons
- Vertex merging rate @PU200 reduced from 15% to 1% from 3D to 4D vertex



# Time-of-flight Particle ID

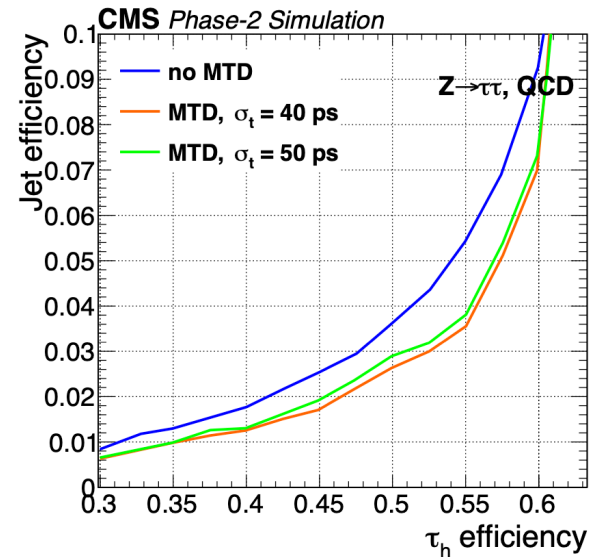
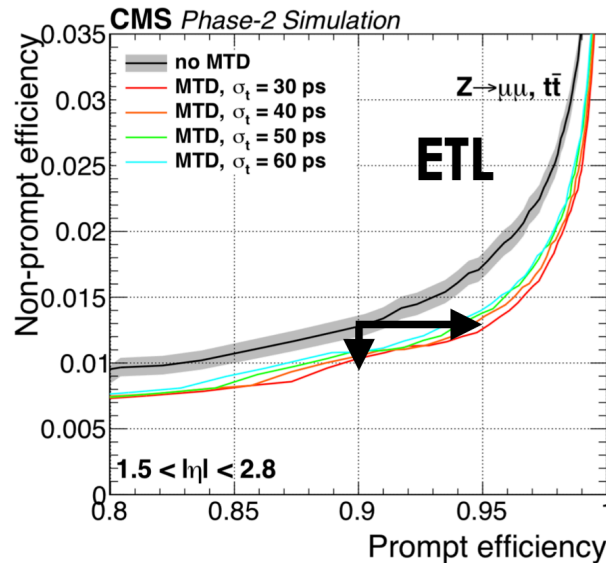
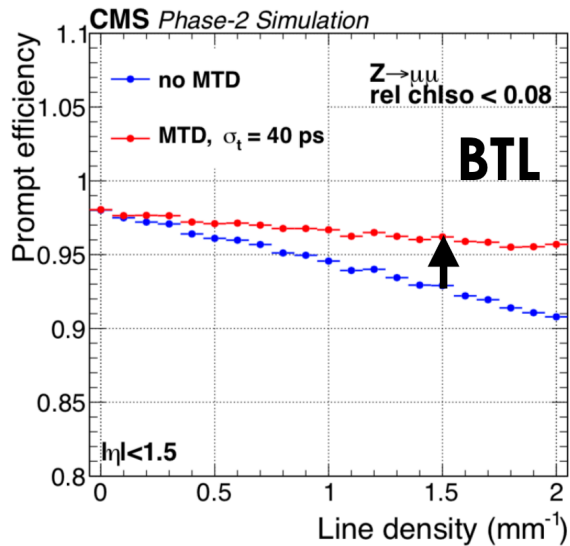
- Time-of-flight particle identification:  $2\sigma$   $\pi/K$  separation up to  $p \sim 2$  GeV and  $K/p$  up to  $p \sim 4$  GeV
  - New handle for CMS for heavy flavor physics

$$\frac{1}{\beta} = \frac{c(t_0^{\text{MTD}} - t_0^{\text{evt}})}{L}$$

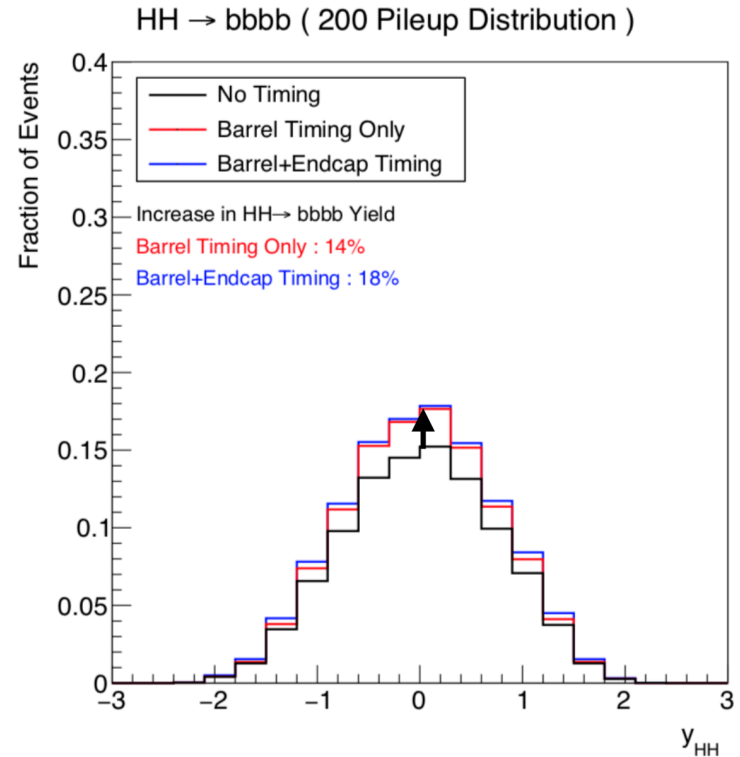
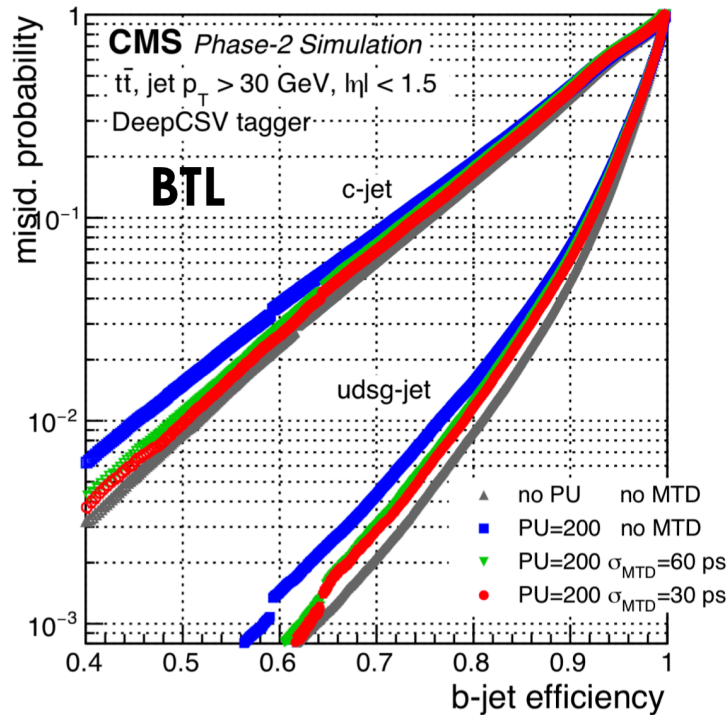


# Lepton isolation

- Gain is combined for multiple leptons in final states, e.g.  $H \rightarrow ZZ \rightarrow 4l$ 
  - Higher gains in forward region, higher line densities – tighter isolation
- Relative gain on efficiency improves at lower  $p_T$ , up to 20-25% going at  $p_T$  around 10-20 GeV
  - Critical to maintain low  $p_T$  thresholds for multi-leptons final states:  $H \rightarrow 4l$ : lowest  $p_T$  cut  $>5$  GeV
  - b-physics analyses ( $B(d,s) \rightarrow \mu\mu$ ,  $B \rightarrow K^* \mu\mu$ , ...)
- Higher gains (10-15%) for  $\tau$  (looser  $dz$  cuts, tighter isolation).  $\tau$  ID not yet fully optimized for Phase-2 reconstruction

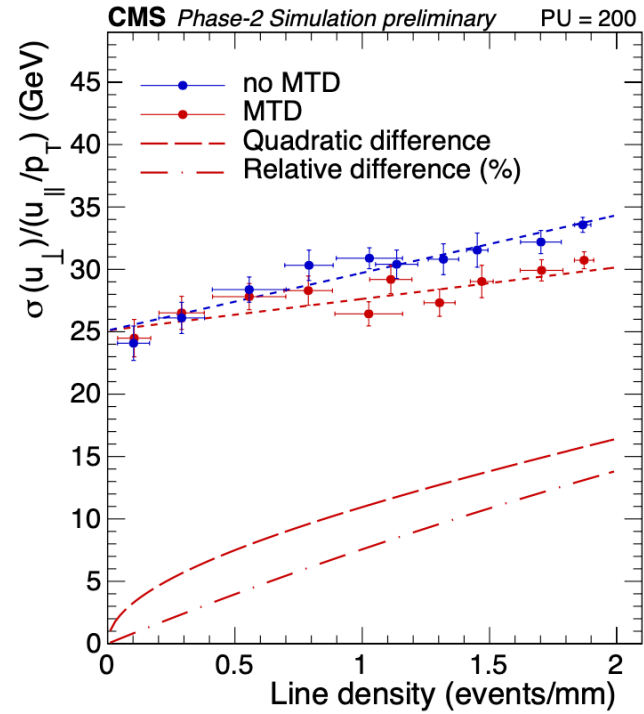
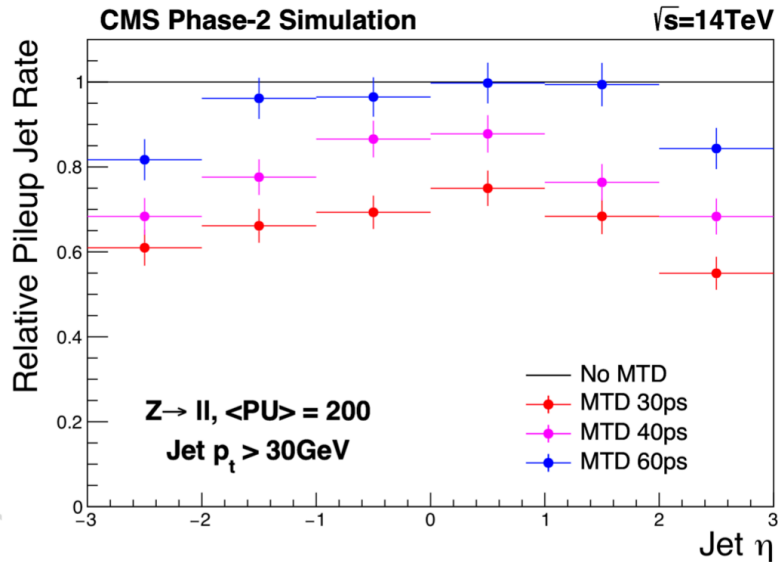


# B-tagging



- Efficiency improvements for b-tagging: 3%(BTL) 6%(ETL)
  - b-tagging not yet fully optimized for Phase-2
  - timing used only for track selection
- Significant acceptance gains in a critical HL-LHC final states with several b:  $HH \rightarrow bbbb$

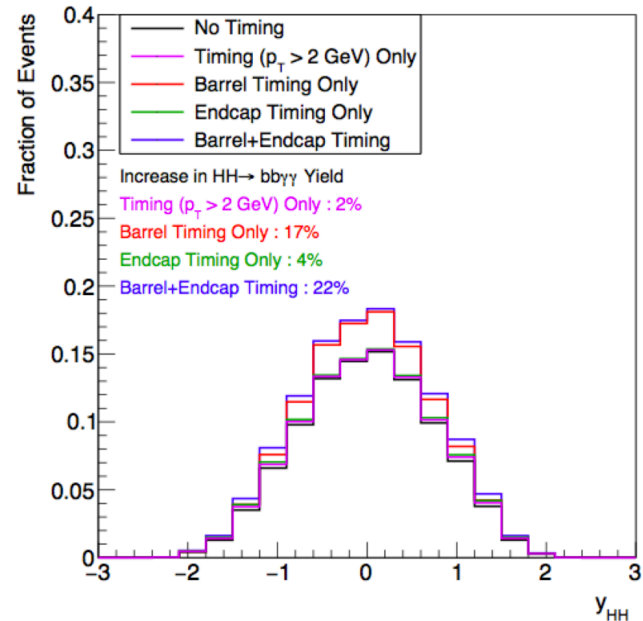
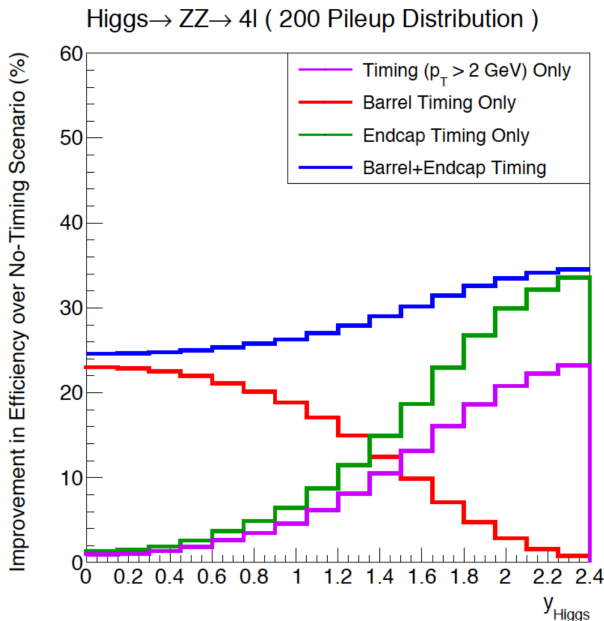
# Jets and Missing Transverse Energy



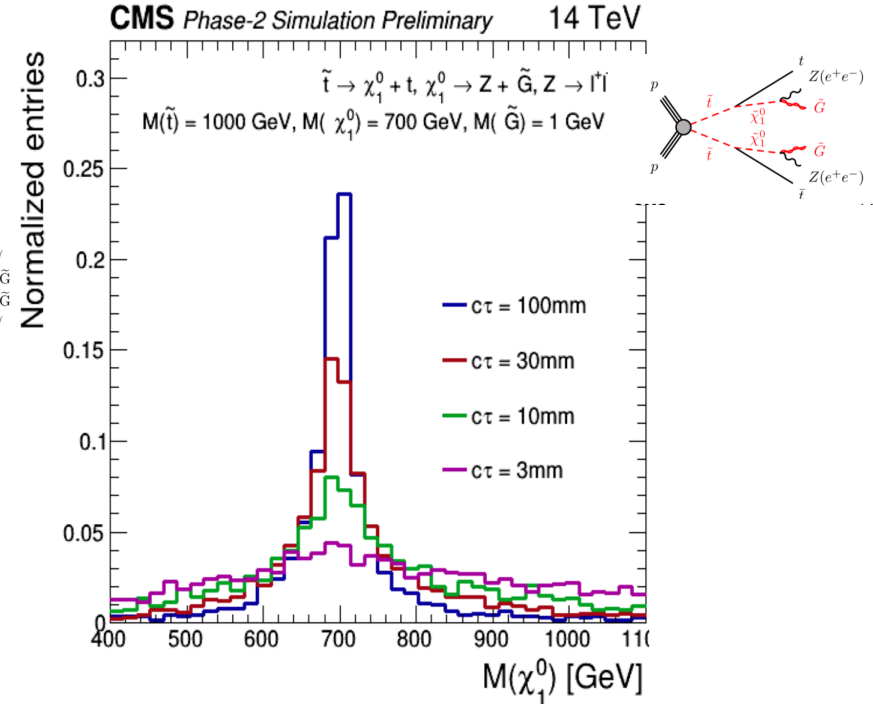
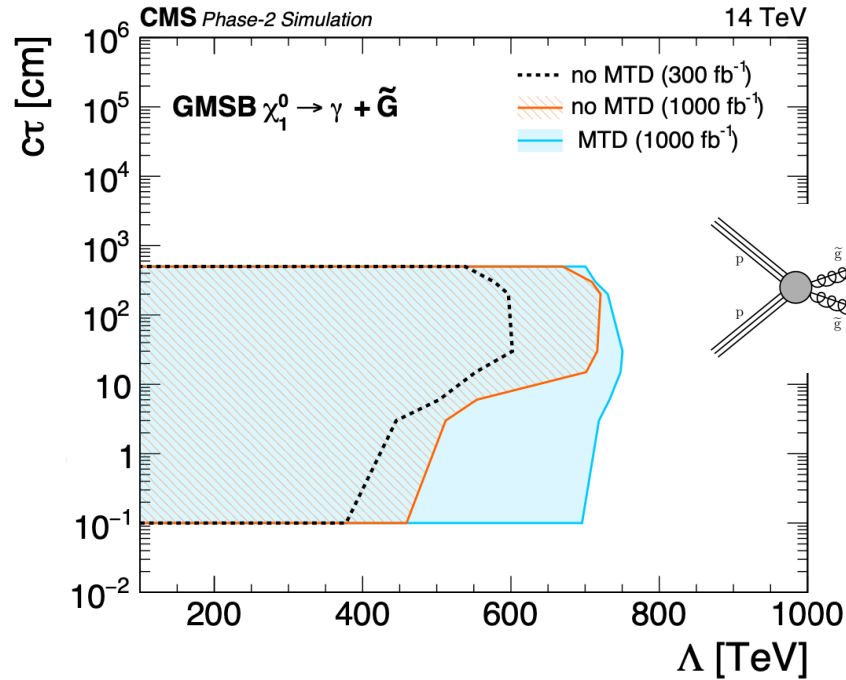
- Up to 40% PU jets reduction especially in forward region
  - Z+jets background reduced by 20-30% for  $p_T$  cuts at 20-30 GeV
- 12% relative gain for MET resolution from charged PU mitigation
  - 40% in background reduction if requiring large MET e.g.  $>150$  GeV

# Physics impact: Higgs physics

- Significant impact on HL-LHC Higgs program
  - 26% increase in effective luminosity for  $H \rightarrow ZZ \rightarrow 4\ell$
  - 22% increase in effective luminosity for  $H \rightarrow ZZ \rightarrow b\bar{b}\gamma\gamma$
  - 25% increase in effective luminosity for VBF  $H \rightarrow \tau\tau$
- Further improvements:
  - resolution improvements (e.g.  $m_{\tau\tau}$ ); run at higher instantaneous luminosity

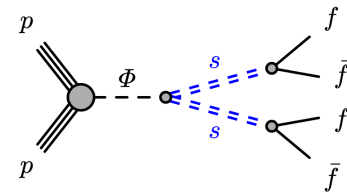


# Physics impact: long-lived particles



- 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.  $\chi_0$ )

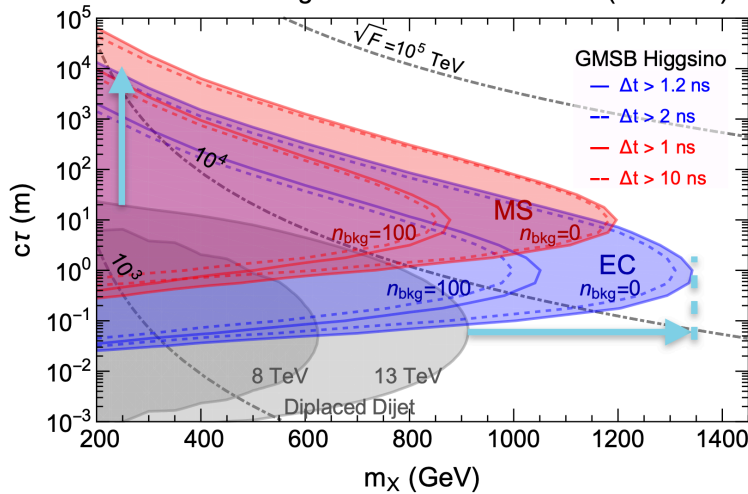
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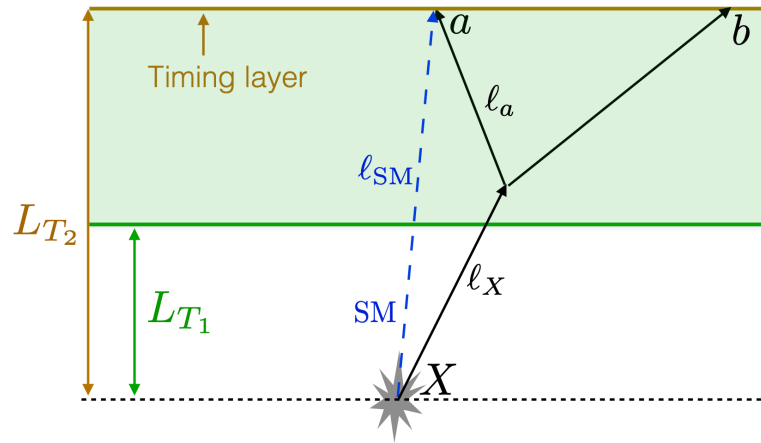
study by Zhen Liu et al.

<https://arxiv.org/abs/1805.05957>

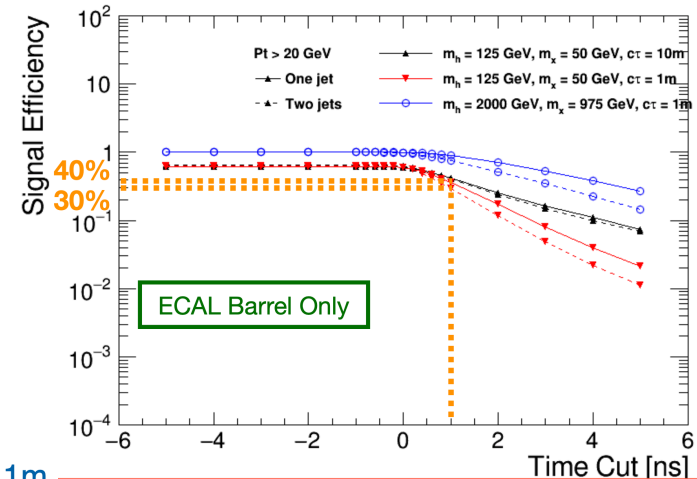
Precision Timing Enhanced Search Limit (HL-LHC)



$$\Delta t = \frac{l_X}{\beta_X} + \frac{l_a}{\beta_a} - \frac{l_{SM}}{\beta_{SM}}$$



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



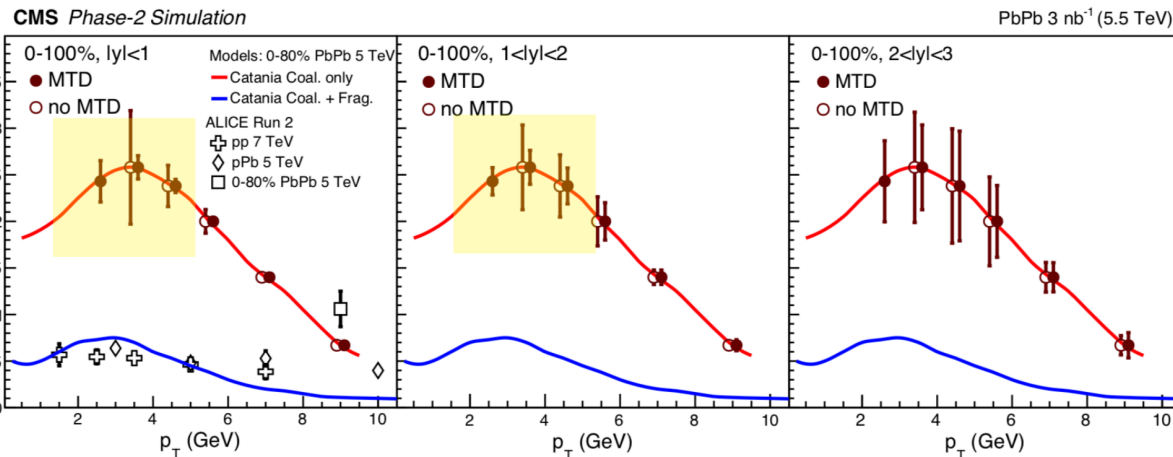
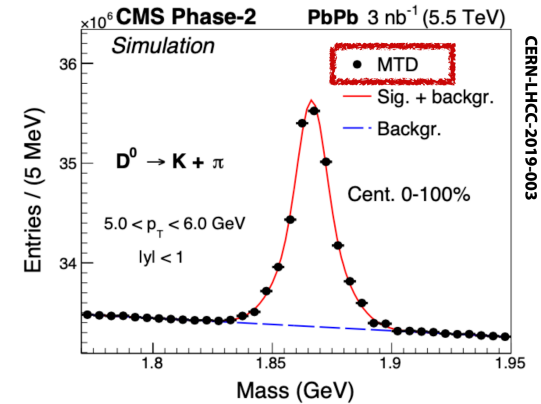
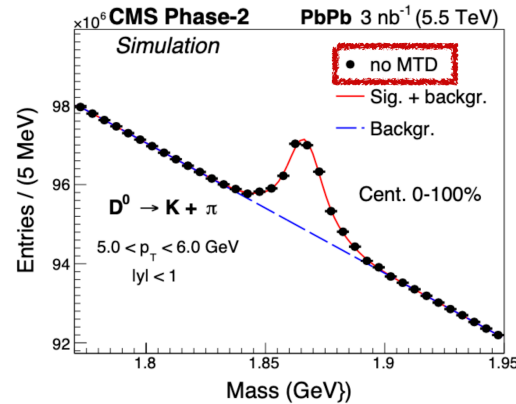
$M_h = 125 \text{ GeV}$   
 $M_\chi = 50 \text{ GeV}, c\tau = 1 \text{ m}$



# Physics impact: TOF Particle ID

- Competitive momentum coverage comparable to ALICE and STAR

- Significantly suppressed background candidates
- Signal significance is drastically improved
- The region of  $|\eta| > 1$  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.

# Summary

- Timing is an enabling technology change for future experiments, HL-LHC, FCC, neutrino physics, and beyond
  - Timing precision of 30-40 ps achieved with several Si-based technologies
  - Precision timing for Calorimeters and MIP tracking achievable
- 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