Precision timing detector for CMS at the HL-LHC

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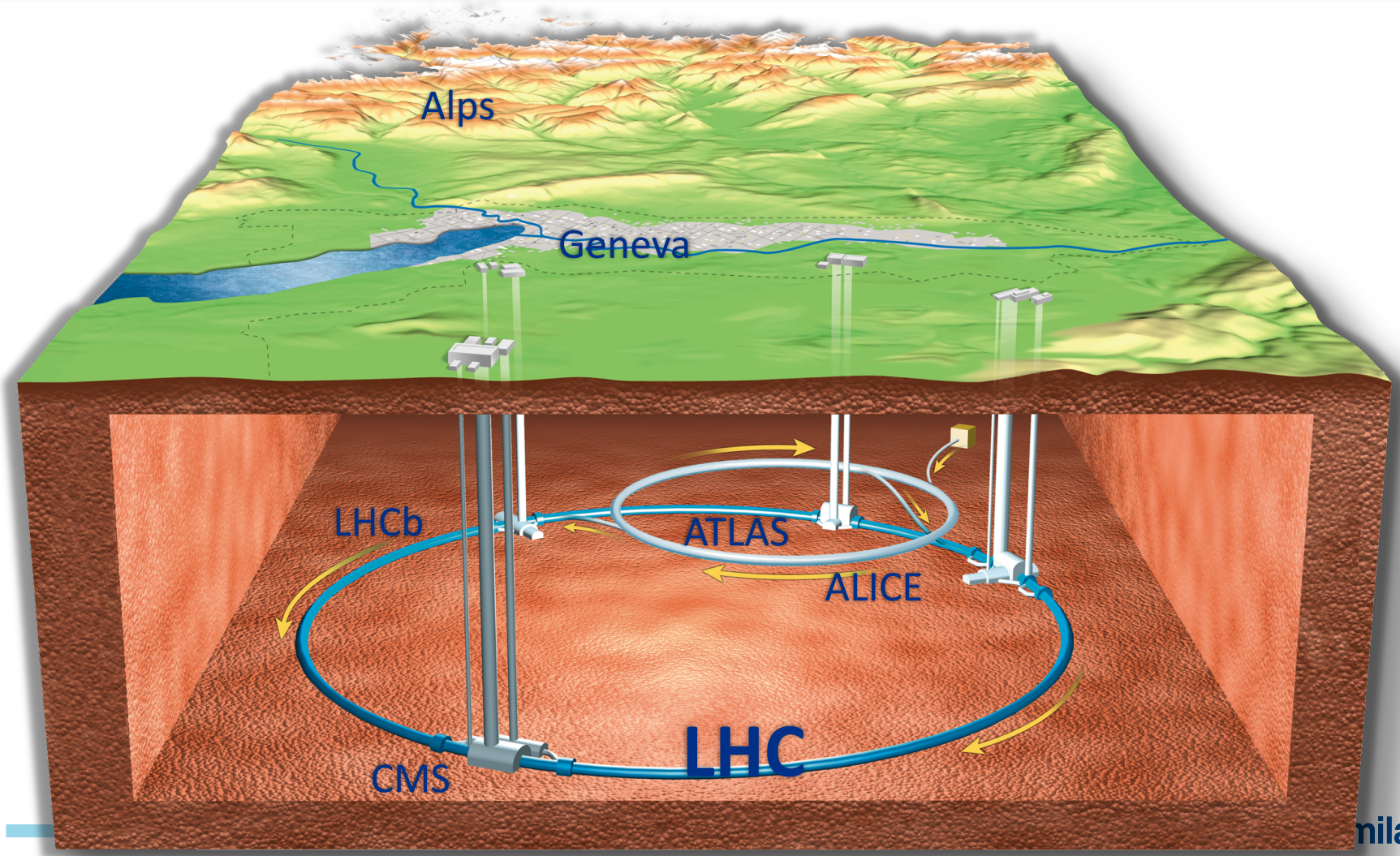
SLAC Experimental Seminar

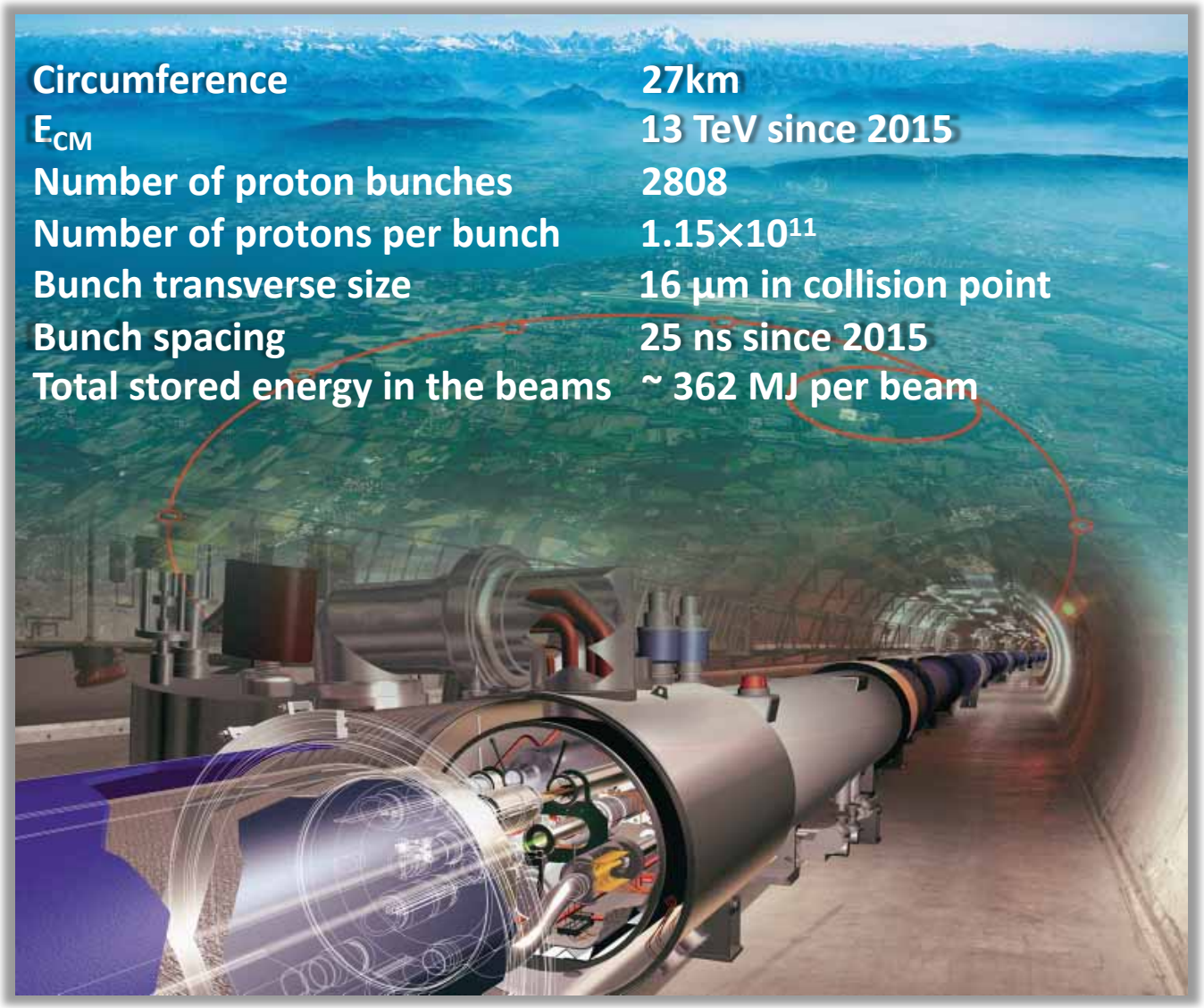
July 14, 2020

The Large Hadron Collider

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



The Large Hadron Collider



Circumference	27km
E_{CM}	13 TeV since 2015
Number of proton bunches	2808
Number of protons per bunch	1.15×10^{11}
Bunch transverse size	16 μm in collision point
Bunch spacing	25 ns since 2015
Total stored energy in the beams	~ 362 MJ per beam

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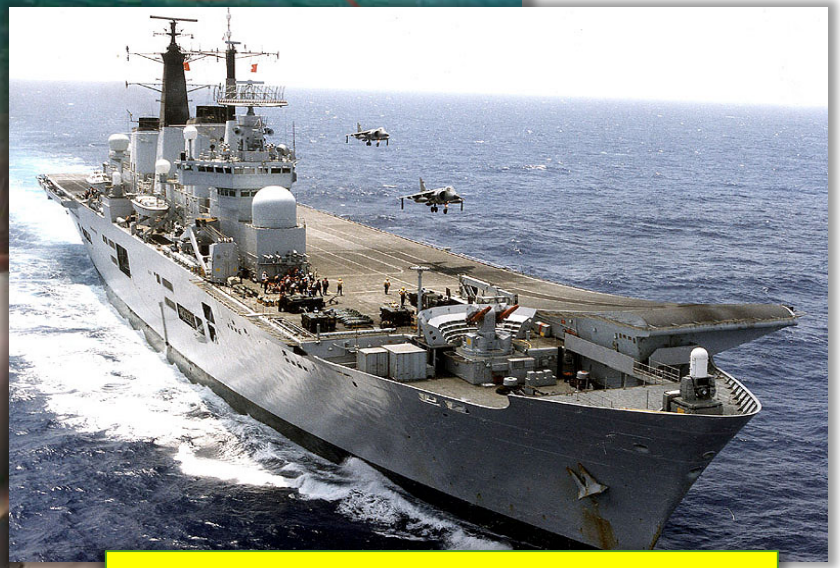
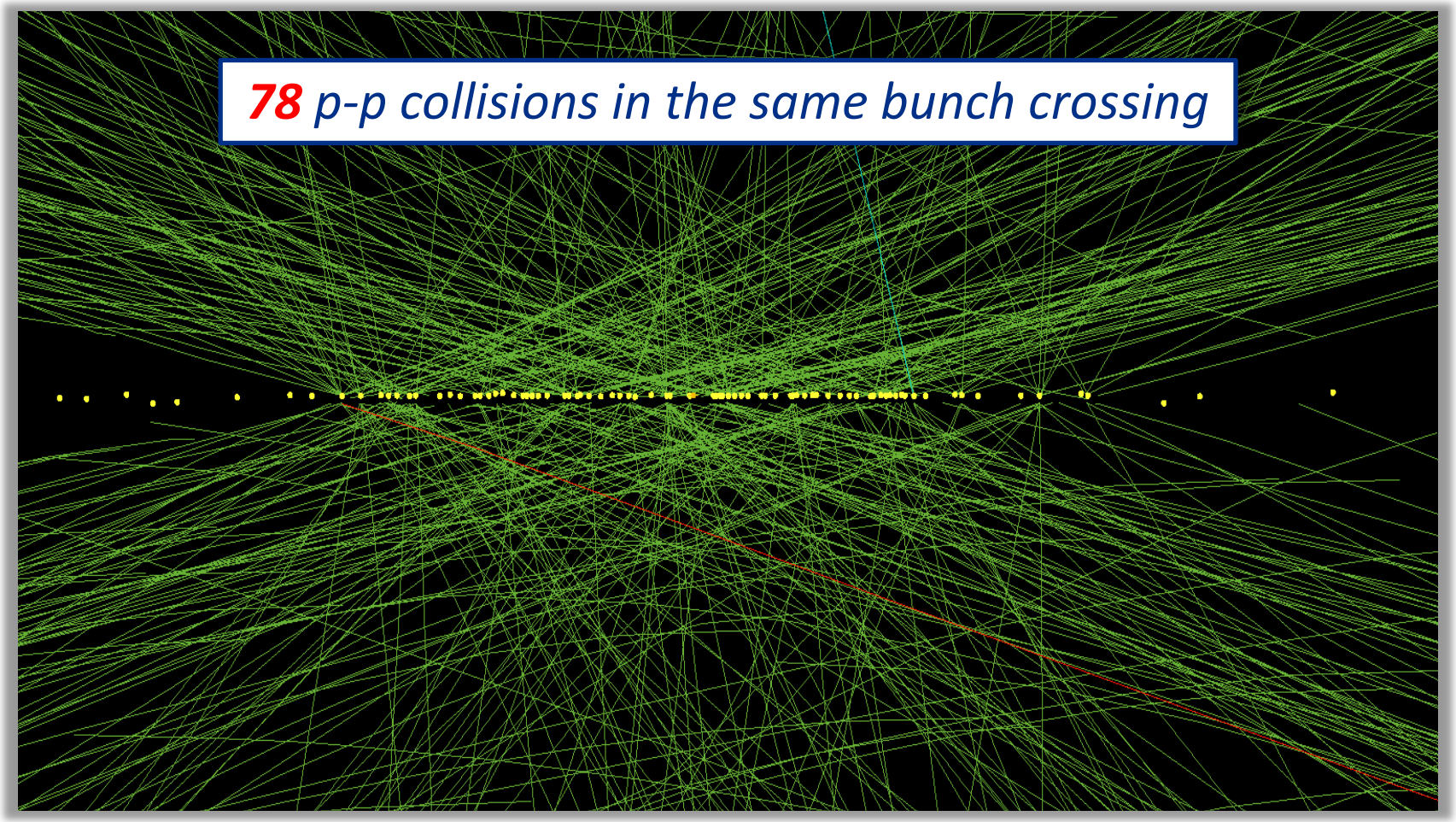


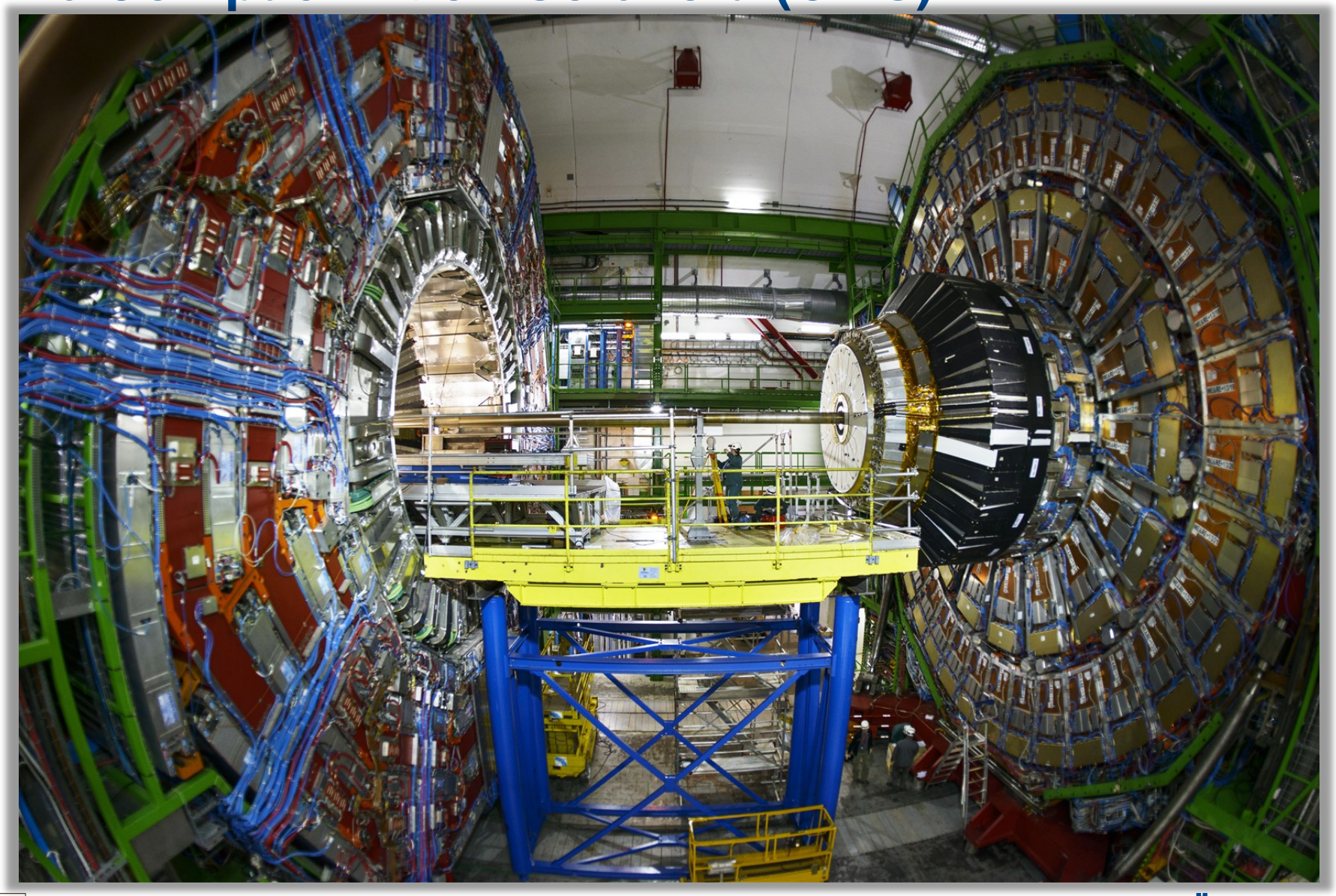
10,000-ton carrier at 30 km/h

Proton-proton collisions



Collect lots of proton-proton collisions data

The Compact Muon Solenoid (CMS)

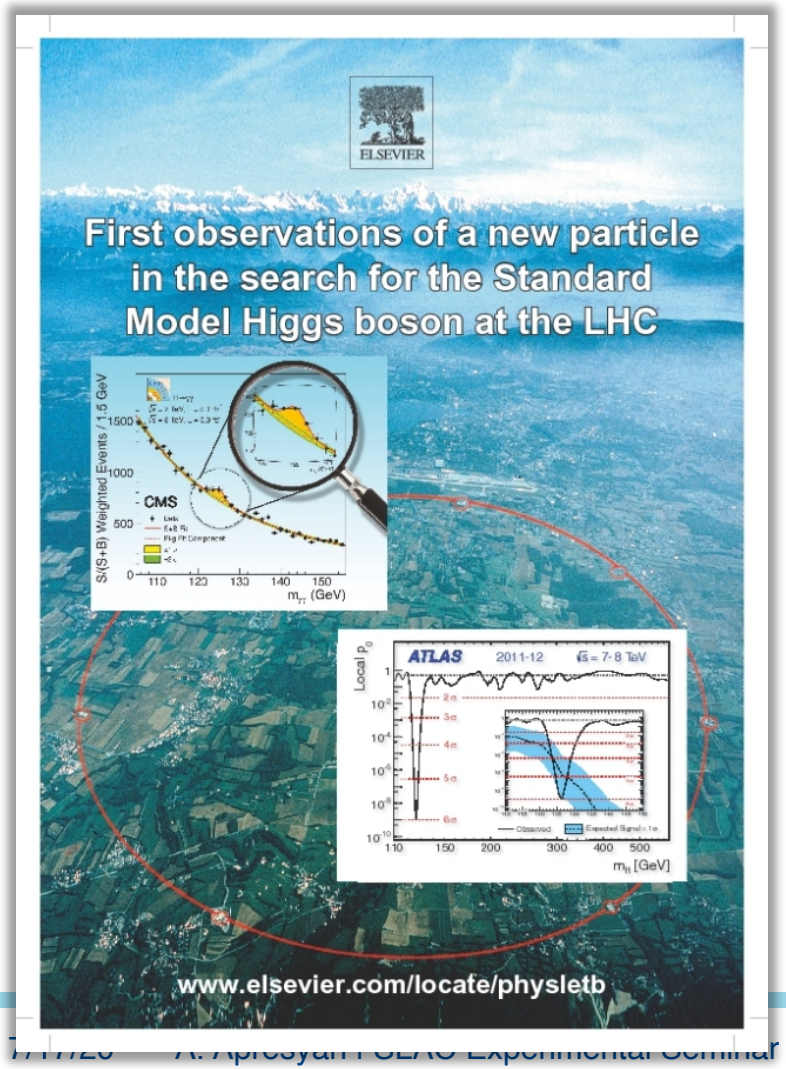


The Compact Muon Solenoid (CMS)

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

The crown jewel

- The Higgs boson discovery announced in 2012



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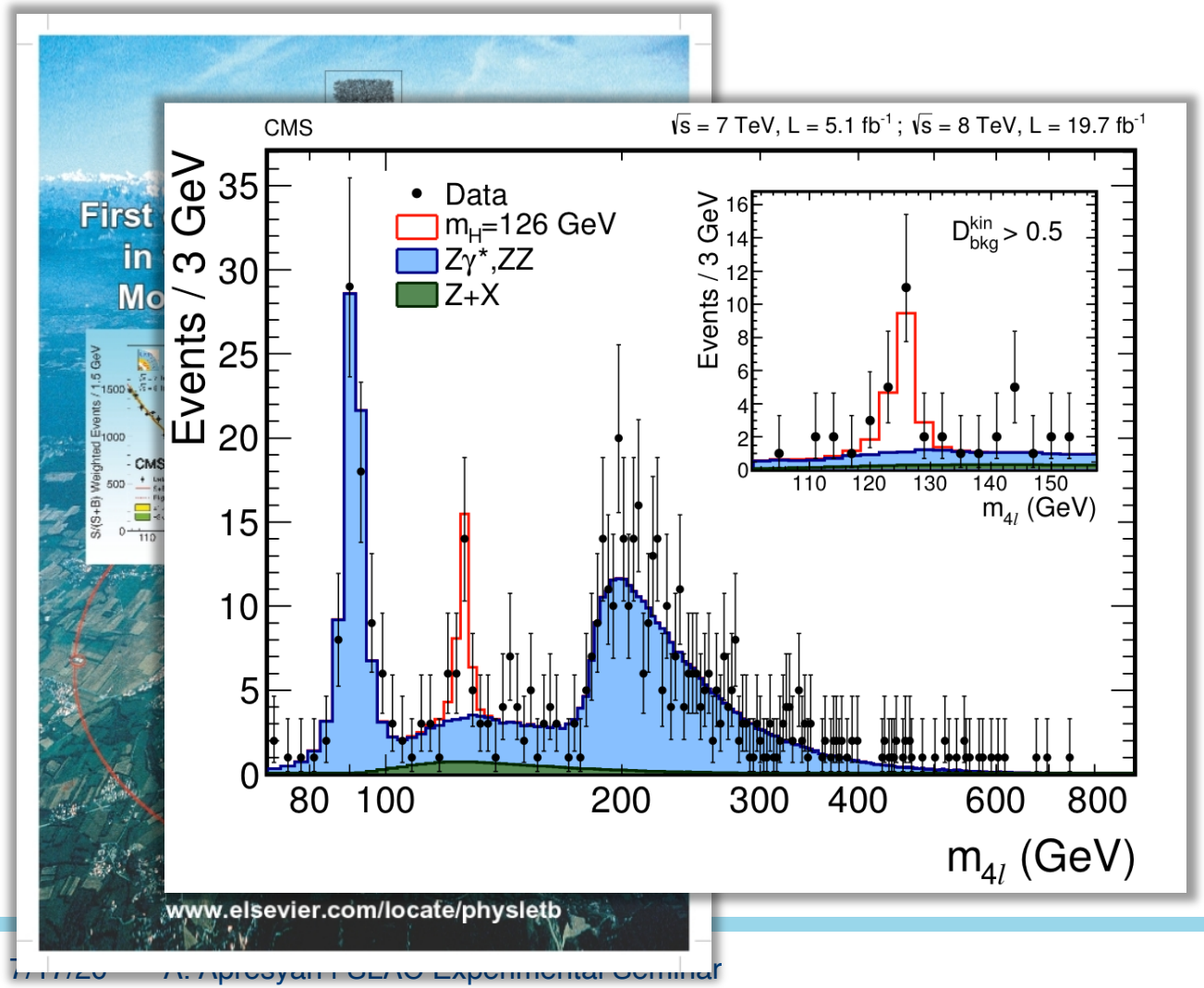

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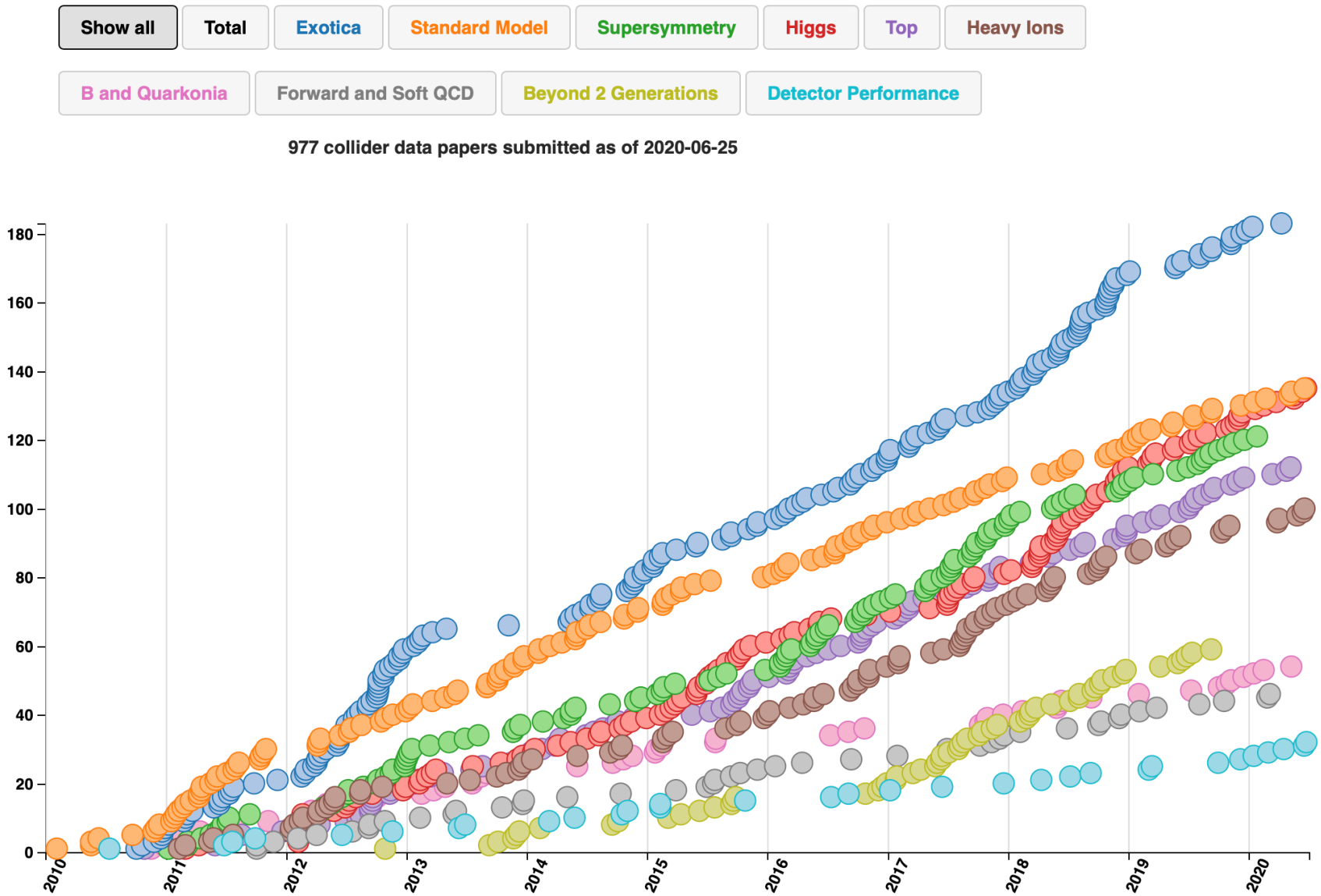
CMS Publications

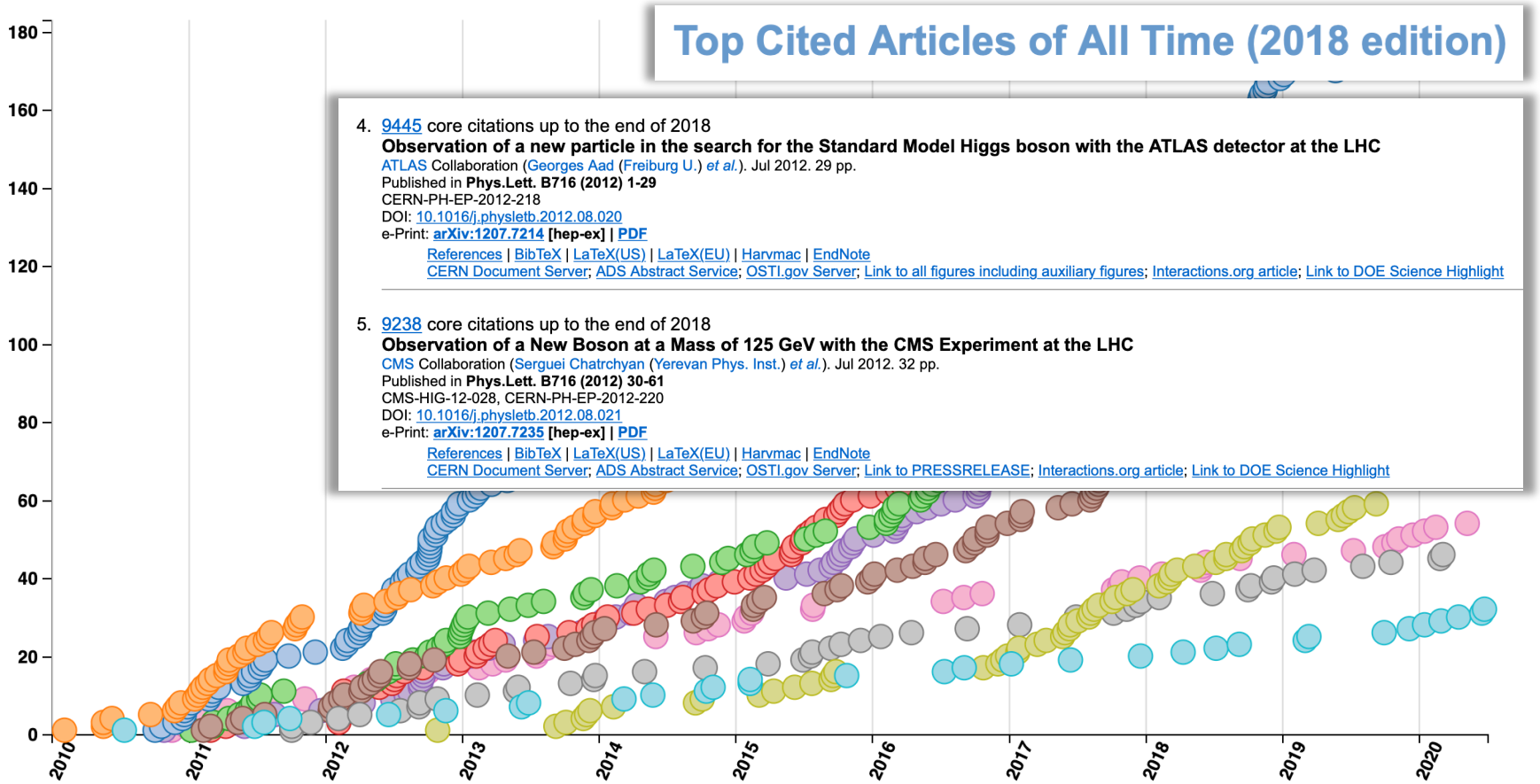


CMS Publications

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



Top Cited Articles of All Time (2018 edition)

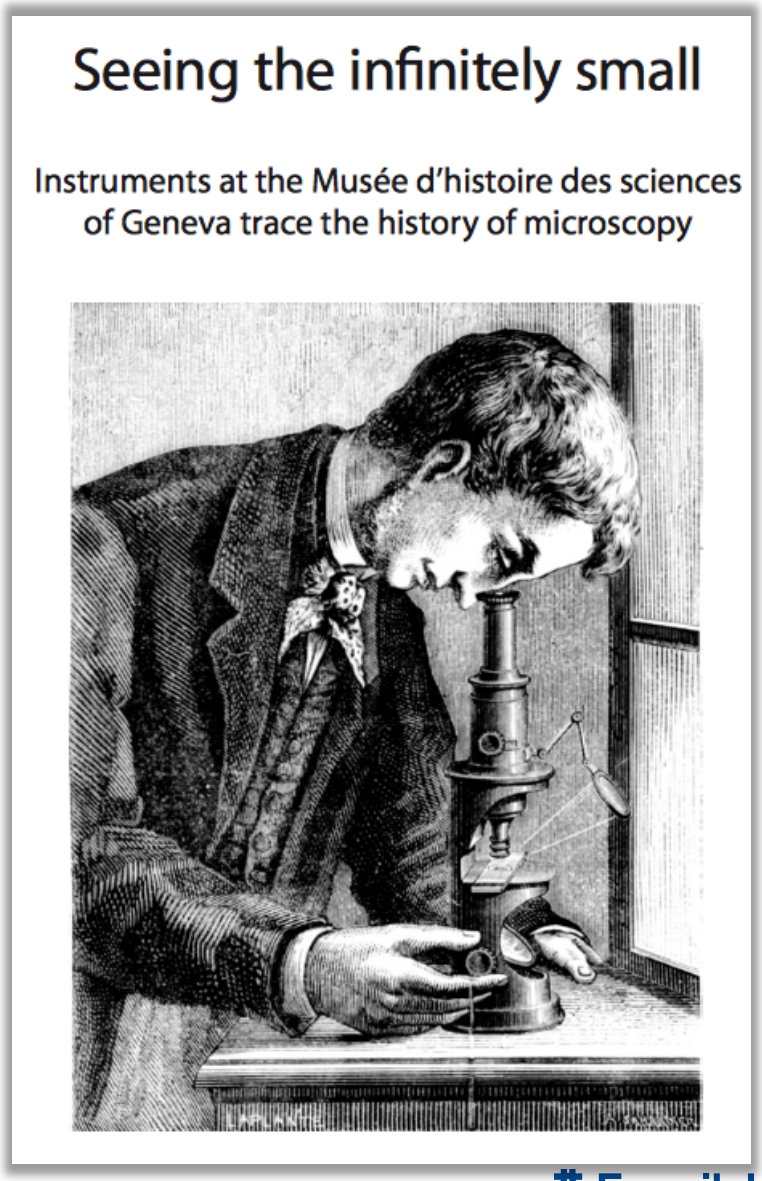
4. 9445 core citations up to the end of 2018
Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC
ATLAS Collaboration (Georges Aad (Freiburg U.) *et al.*). Jul 2012. 29 pp.
Published in **Phys.Lett. B716 (2012) 1-29**
CERN-PH-EP-2012-218
DOI: 10.1016/j.physletb.2012.08.020
e-Print: **arXiv:1207.7214 [hep-ex] | PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service; OSTI.gov Server; Link to all figures including auxiliary figures; Interactions.org article; Link to DOE Science Highlight

5. 9238 core citations up to the end of 2018
Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at the LHC
CMS Collaboration (Serguei Chatrchyan (Yerevan Phys. Inst.) *et al.*). Jul 2012. 32 pp.
Published in **Phys.Lett. B716 (2012) 30-61**
CMS-HIG-12-028, CERN-PH-EP-2012-220
DOI: 10.1016/j.physletb.2012.08.021
e-Print: **arXiv:1207.7235 [hep-ex] | PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server; ADS Abstract Service; OSTI.gov Server; Link to PRESSRELEASE; Interactions.org article; Link to DOE Science Highlight

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



Extend the reach

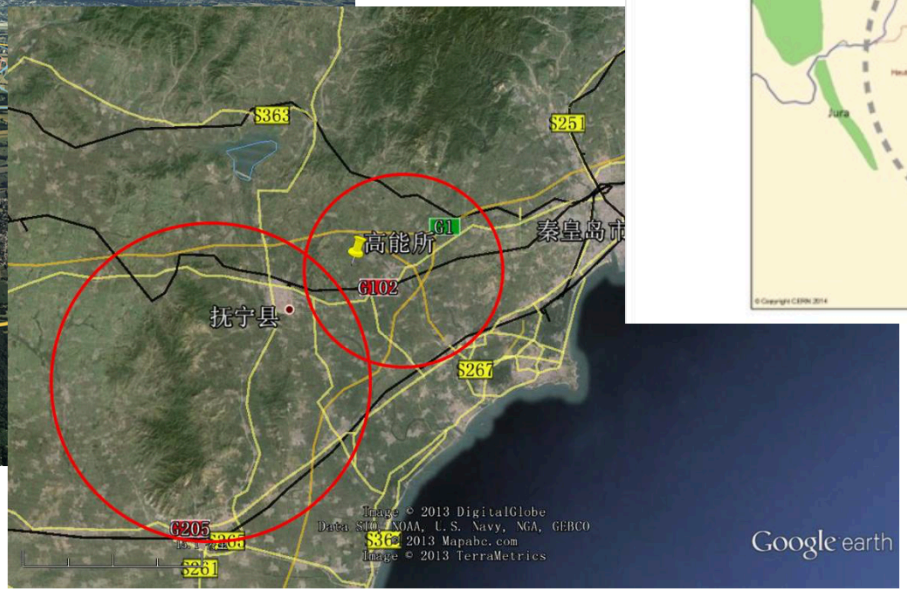
- How can we increase the reach of searches?
  - Increase collisions to a **higher energy**
  - Take much **more data** with the existing machine

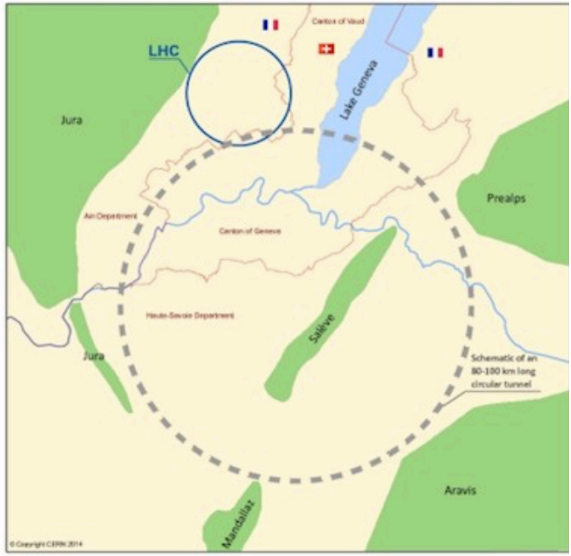
- Since we have not found it yet, New Physics is a **low rate process**
  - High instantaneous luminosity is required, well in excess of current LHC

- Need to advance detector technologies to reap all physics from the future machines

LHC & Future Colliders

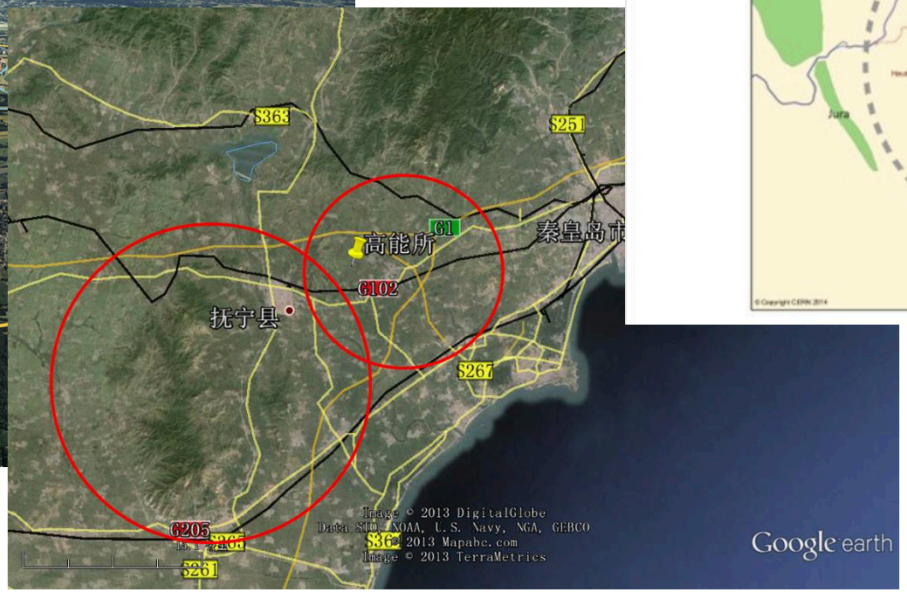
- Future colliders are among the tools to help us answer some of the remaining fundamental questions about Nature:
  - High-Luminosity LHC
  - Hadron Colliders of even higher energy (FCC, SppC)

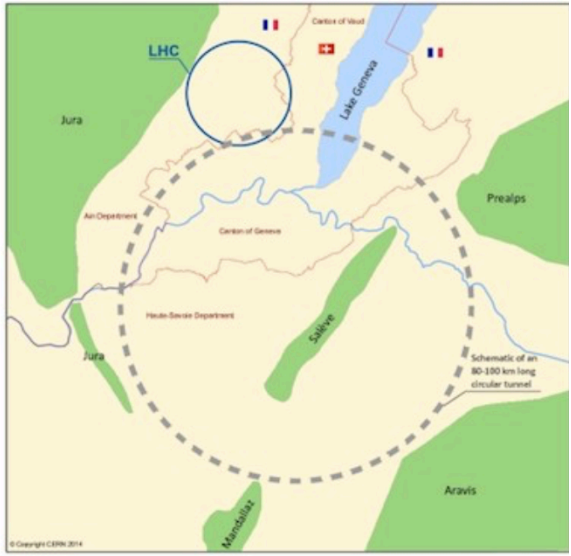




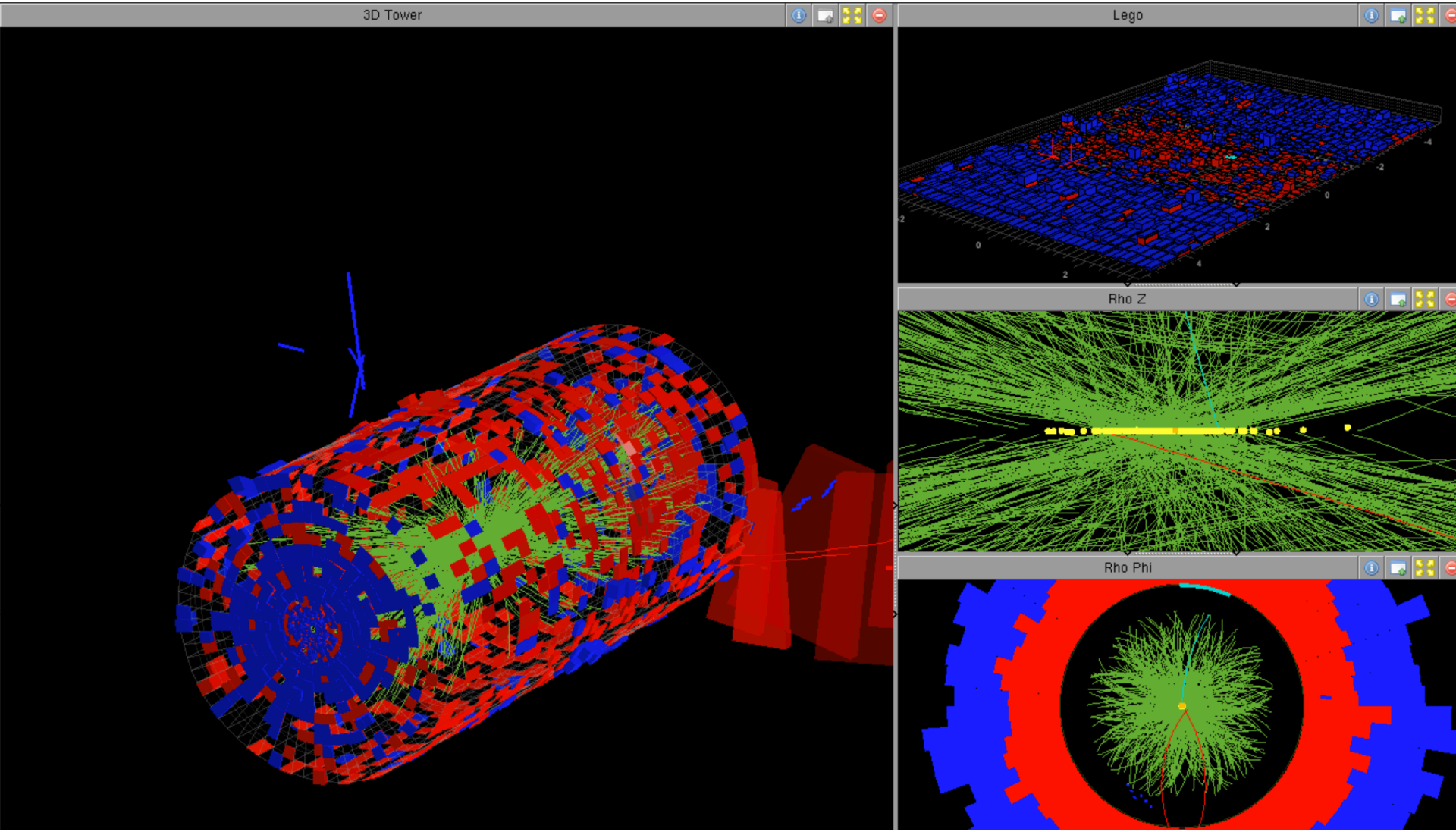
LHC & Future Colliders

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

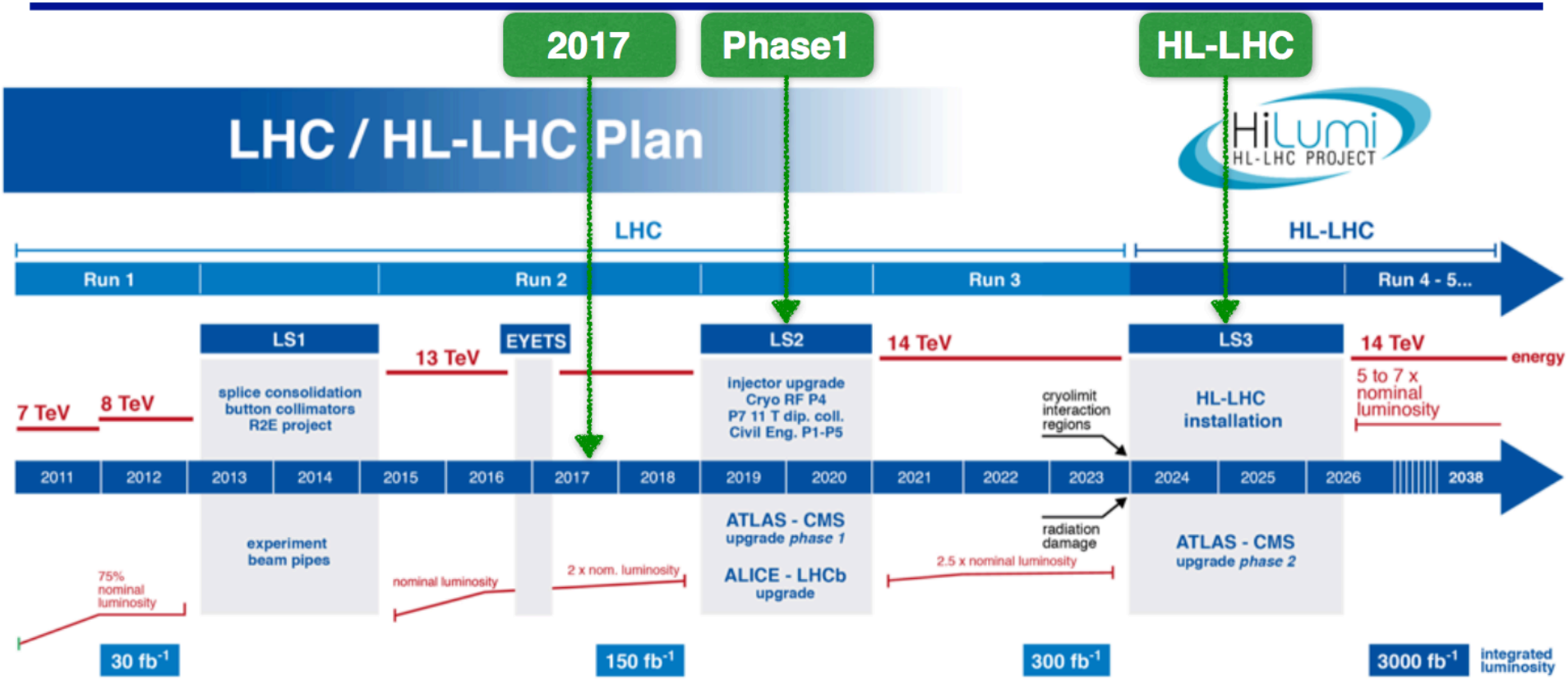




High Luminosity → High Pileup!



HL-LHC upgrades schedule



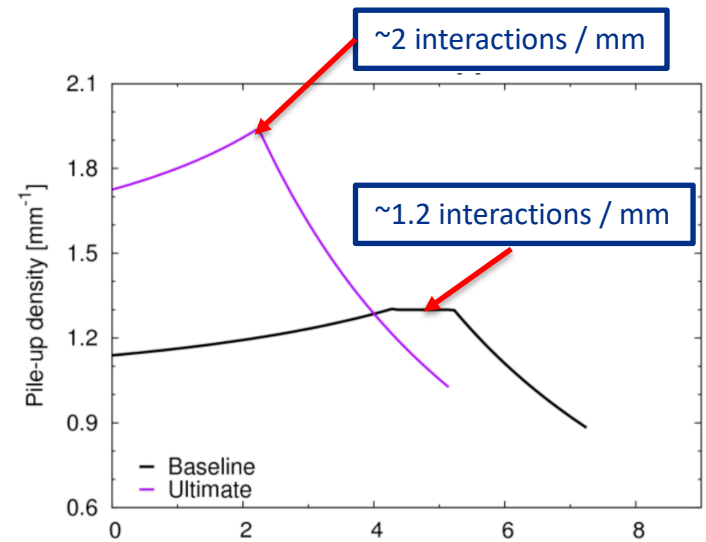
Pile-up ~30 **Pile-up ~60** **Pile-up ~200**

HL-LHC Luminosity scenarios

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

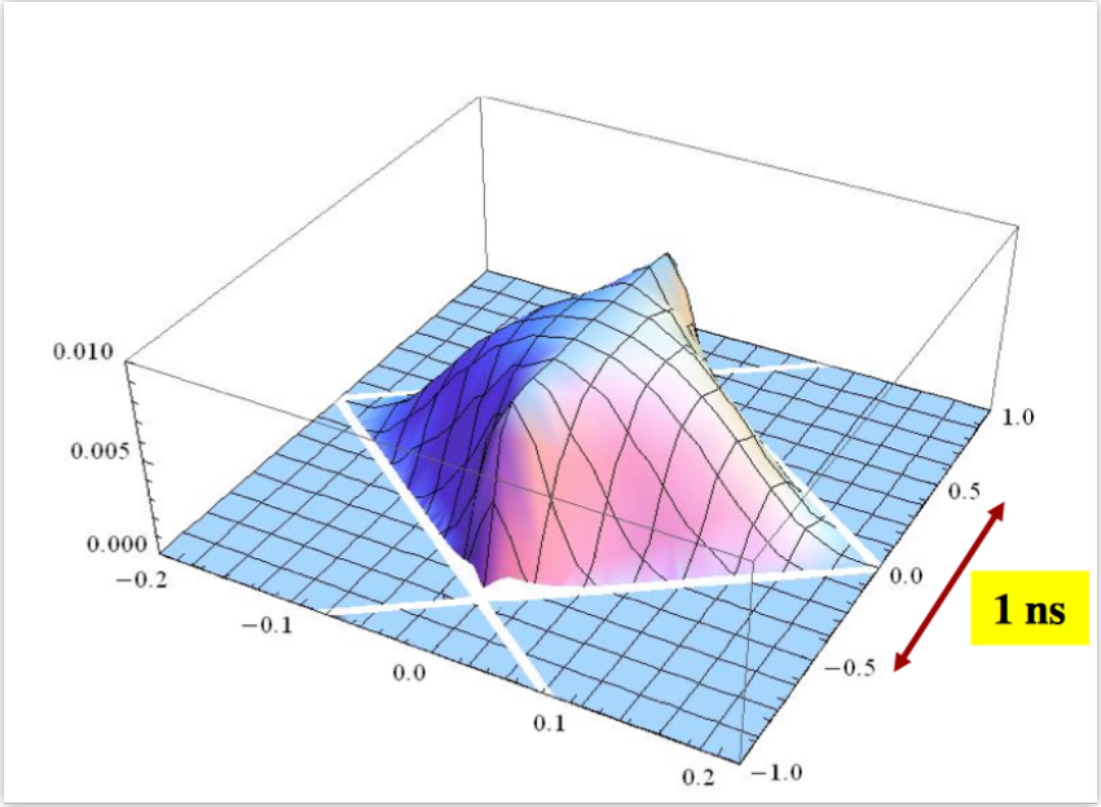
Scenario	Max. PU [events/xing]	Max. PU density [events /xing/mm]	Luminous Region long. r.m.s. size [cm]	$\Delta L_{int}/L_{nom}$ [%]	Additional HW [Y/N]
Nominal	**140**	**1.3**	**<4.8**	**0**	**N**
Ultimate	**200**	**1.9**	**<4.5**	**+33**	**N**
8b+4e	140	1.3	<5	-25	N
200 MHz	140	1.3	<4.8	-14	Y
Flat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

G. Arduini, R. Thomas, ECFA 2016

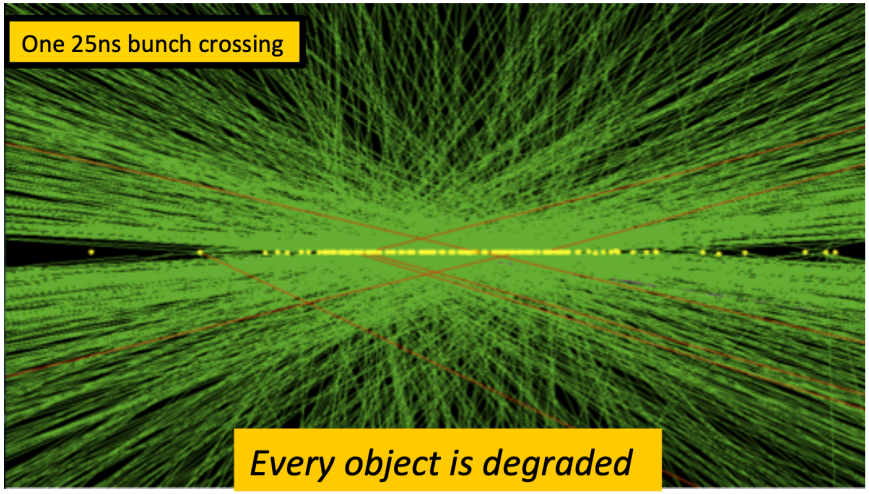


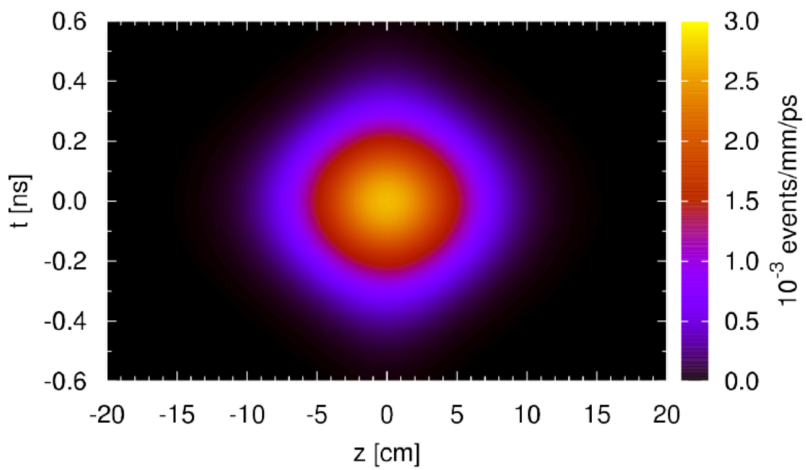
HL-LHC beam spread

- 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

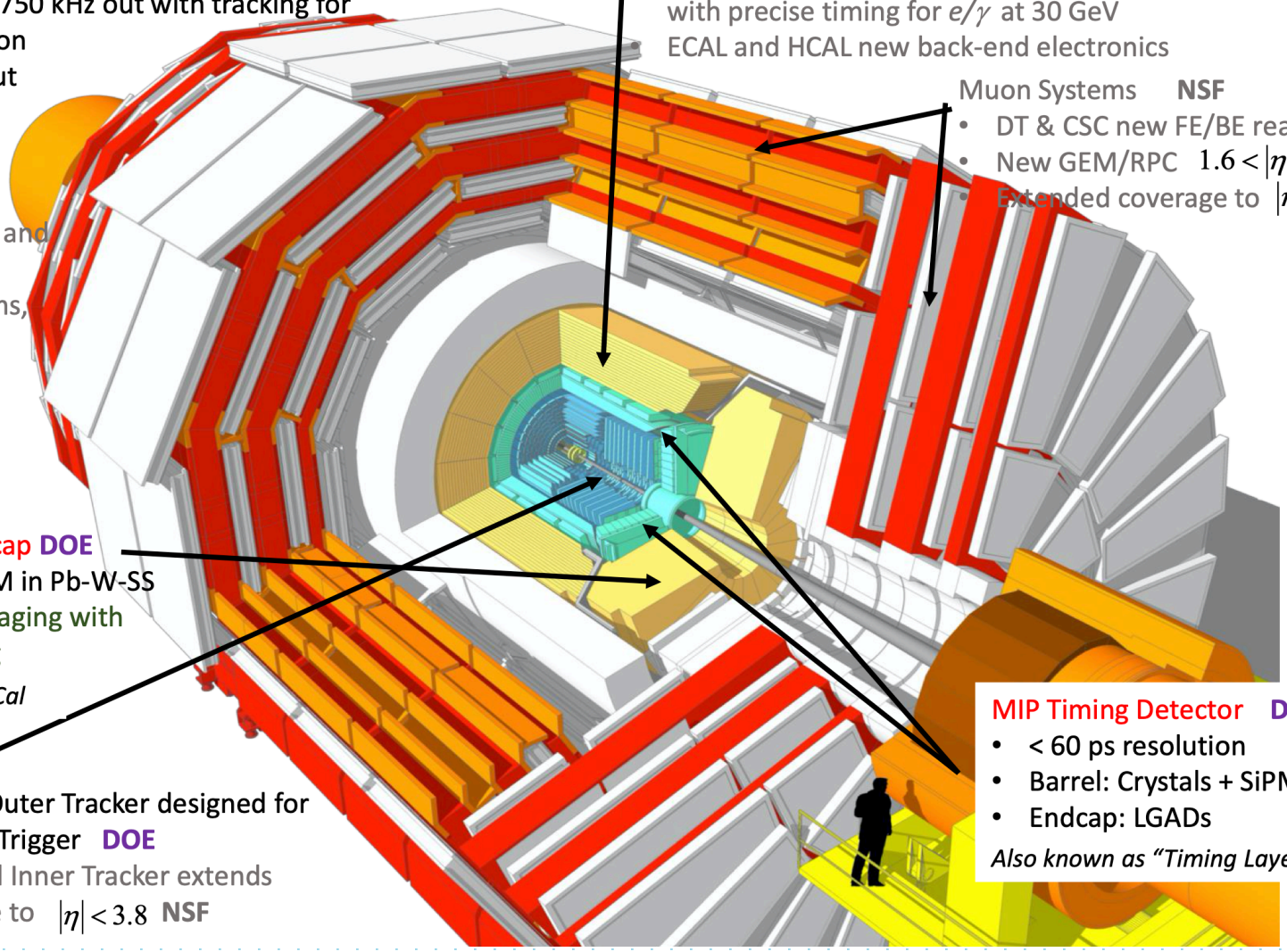
CMS Phase 2 Upgrades

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

Barrel Calorimeters **NSF**
- ECAL single crystal granularity in L1 Trigger with precise timing for e/γ 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 $|\eta| < 3.0$

Beam Radiation and Luminosity, Common Systems, Infrastructure



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

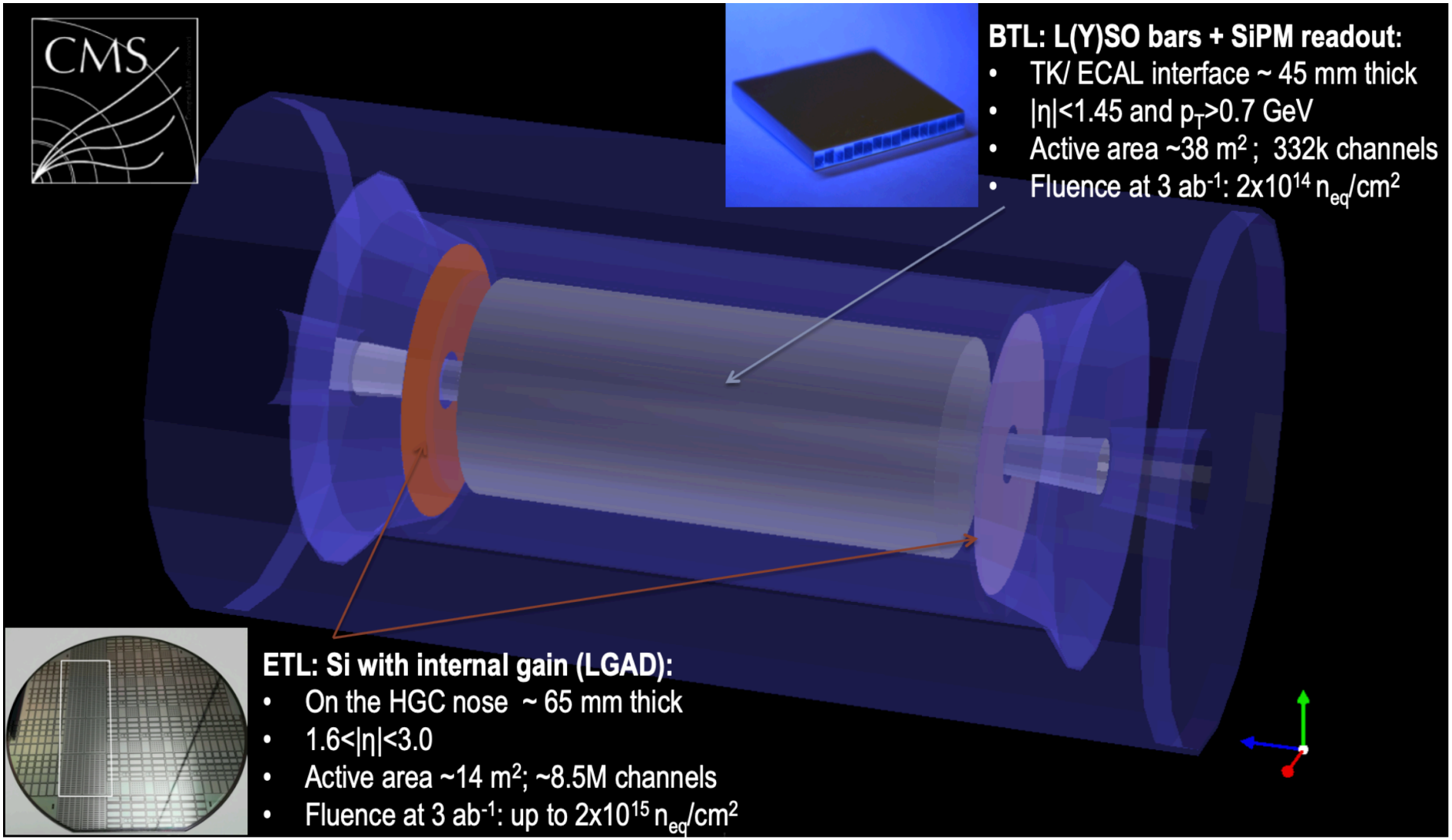
Also known as HGCal

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

MIP Timing Detector **DOE**
- < 60 ps resolution
- Barrel: Crystals + SiPMs
- Endcap: LGADs

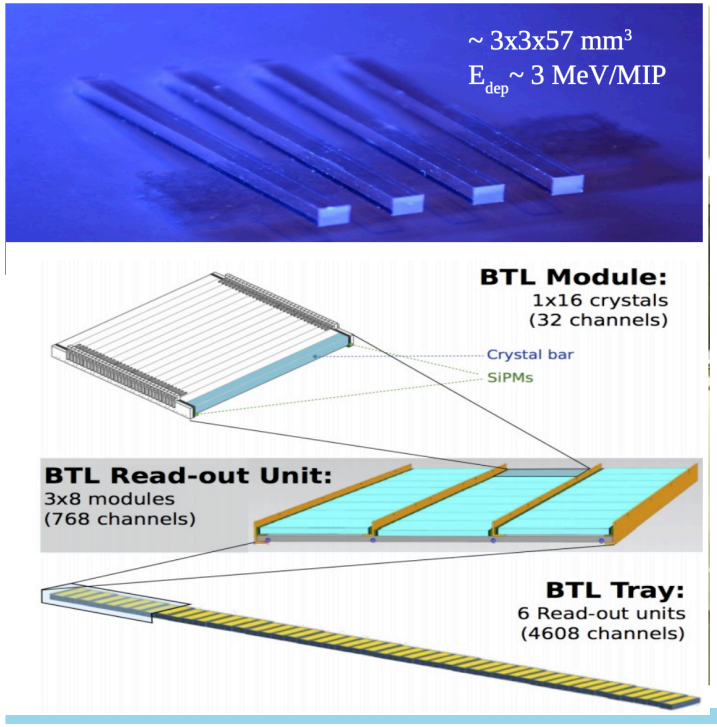
Also known as "Timing Layer" (TL)

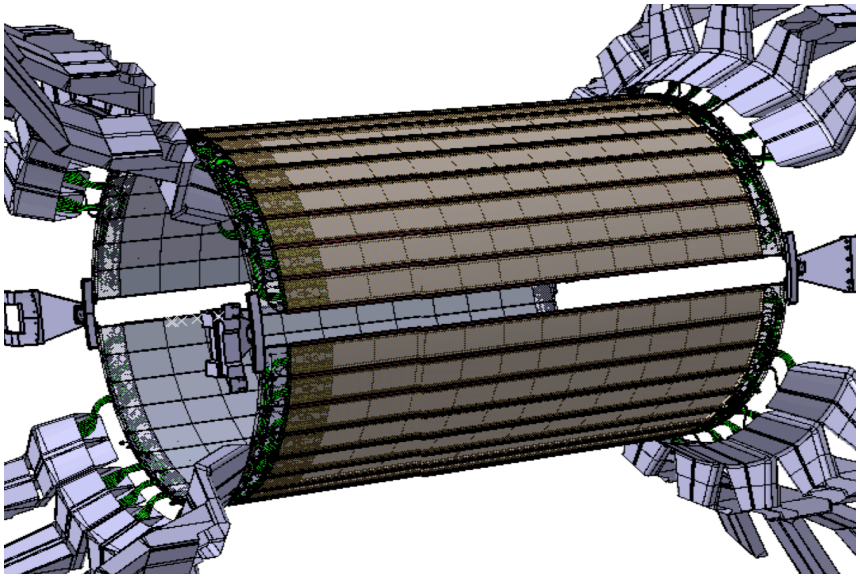
CMS MIP timing detector (MTD)



Barrel Timing Layer (BTL) design

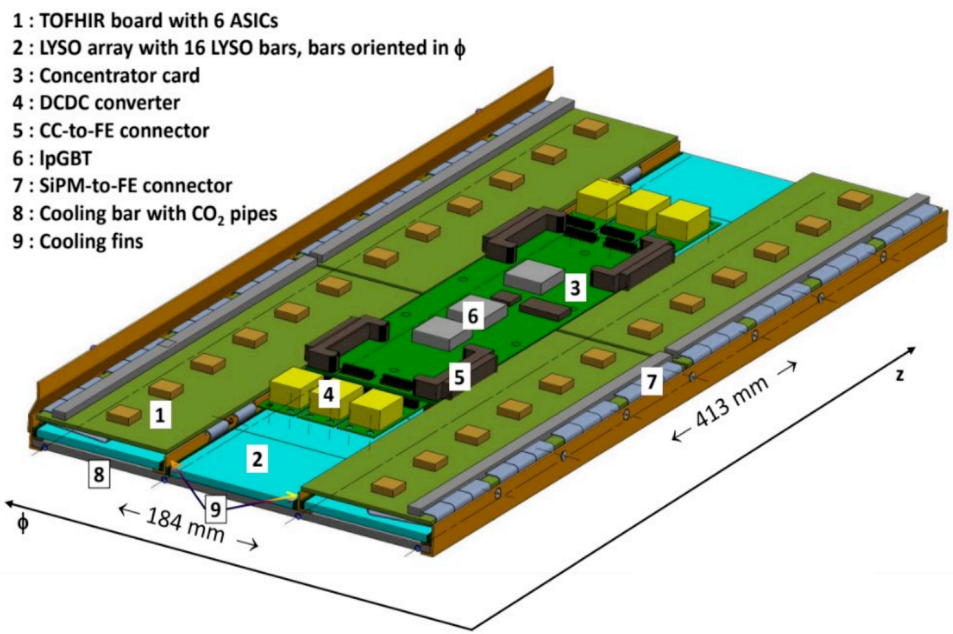
- LYSO crystals as scintillator with an excellent radiation tolerance and fast rise and decay times.
  - Attached to the inner wall of the Tracker Support Tube (TST).
  - 332k channels, organized in 6 Readout Units per tray.
- Time resolution of 35 ps at the beginning of lifetime and 60 ps by the end.

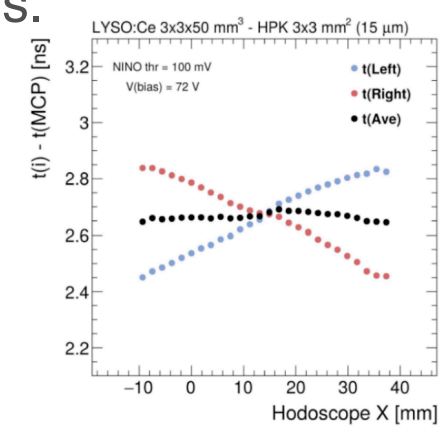


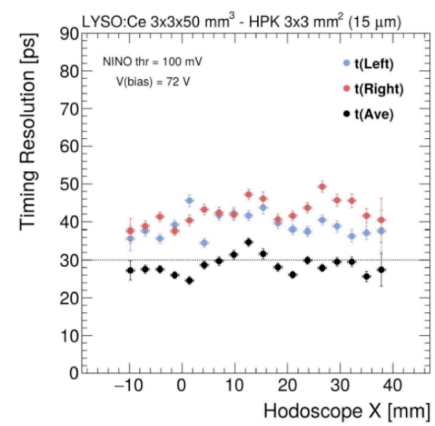


Barrel Timing Layer (BTL) design

- 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.

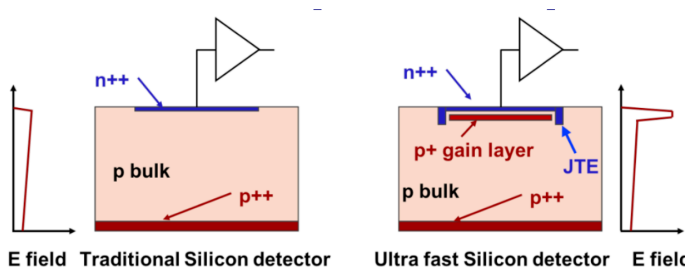


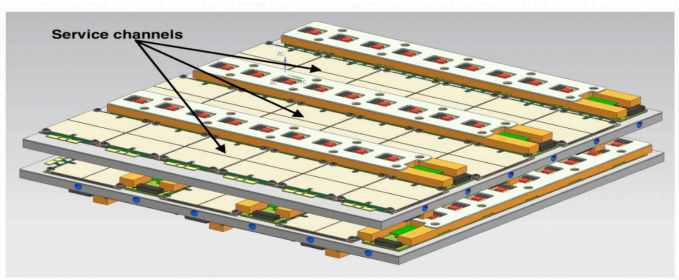




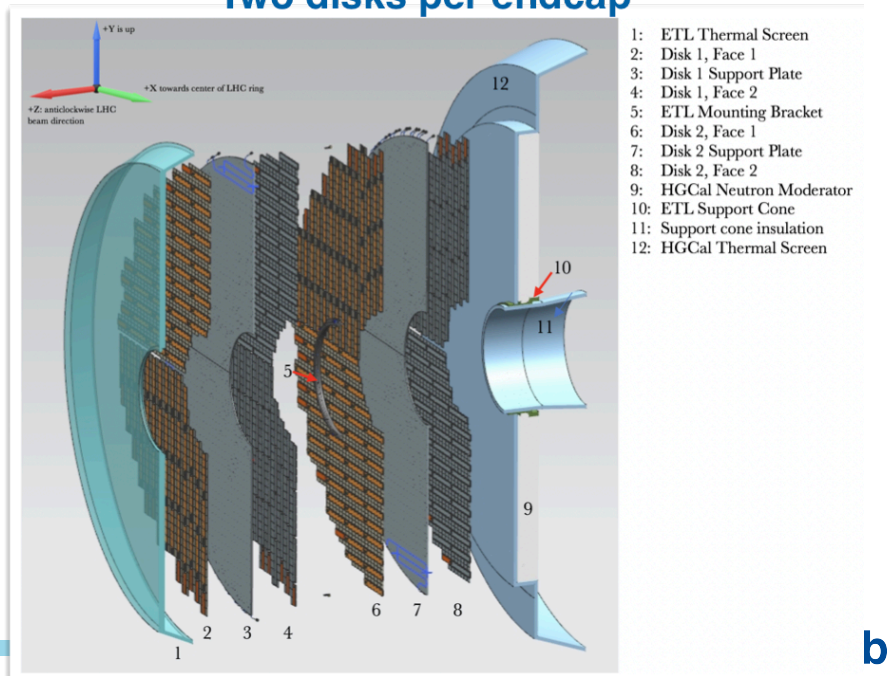
Endcap Timing Layer (ETL) design

- 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





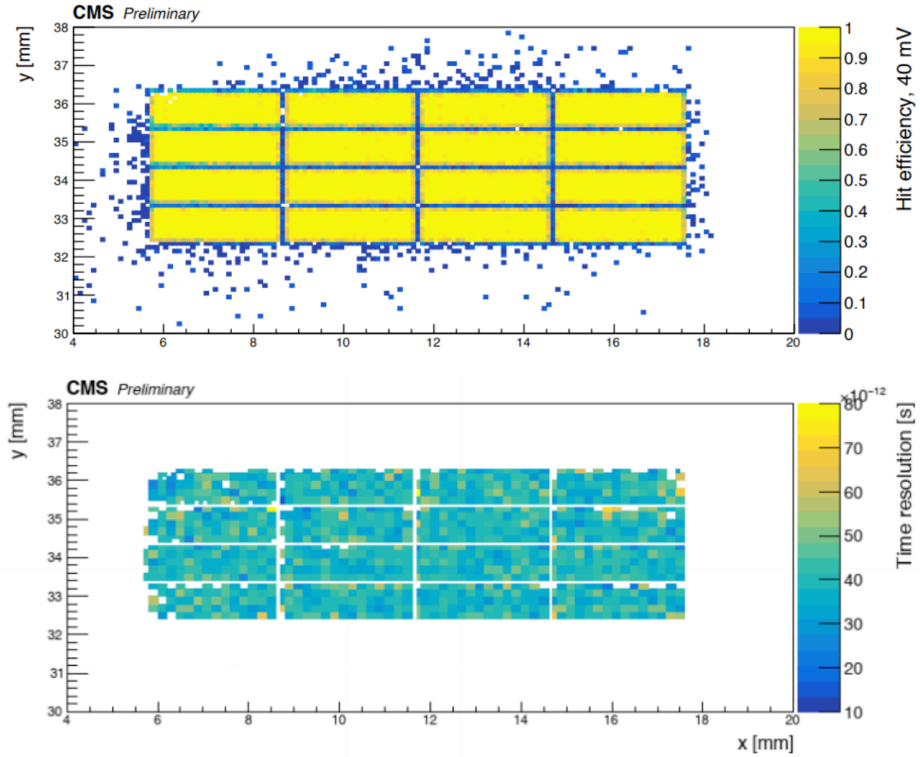
Two disks per endcap

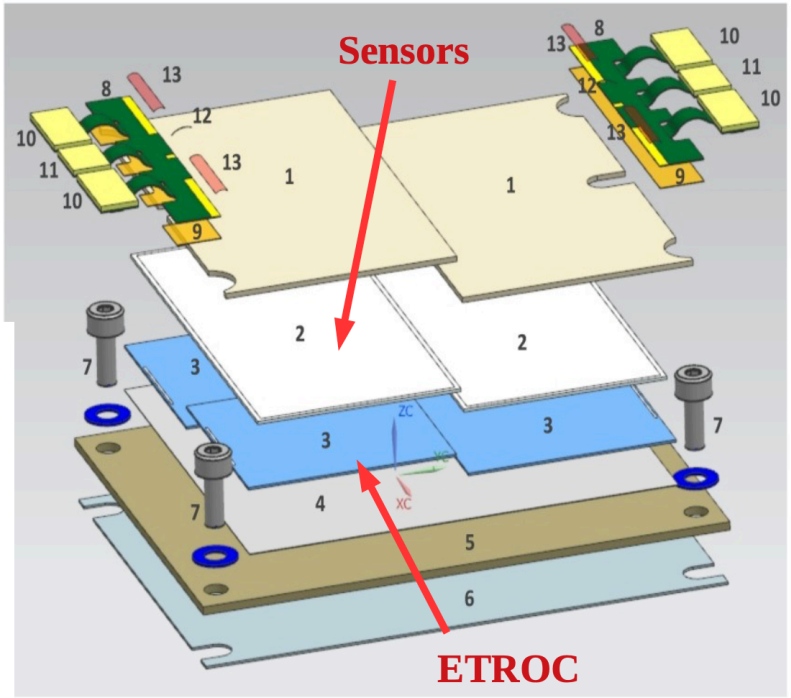


4.5 cm thick!

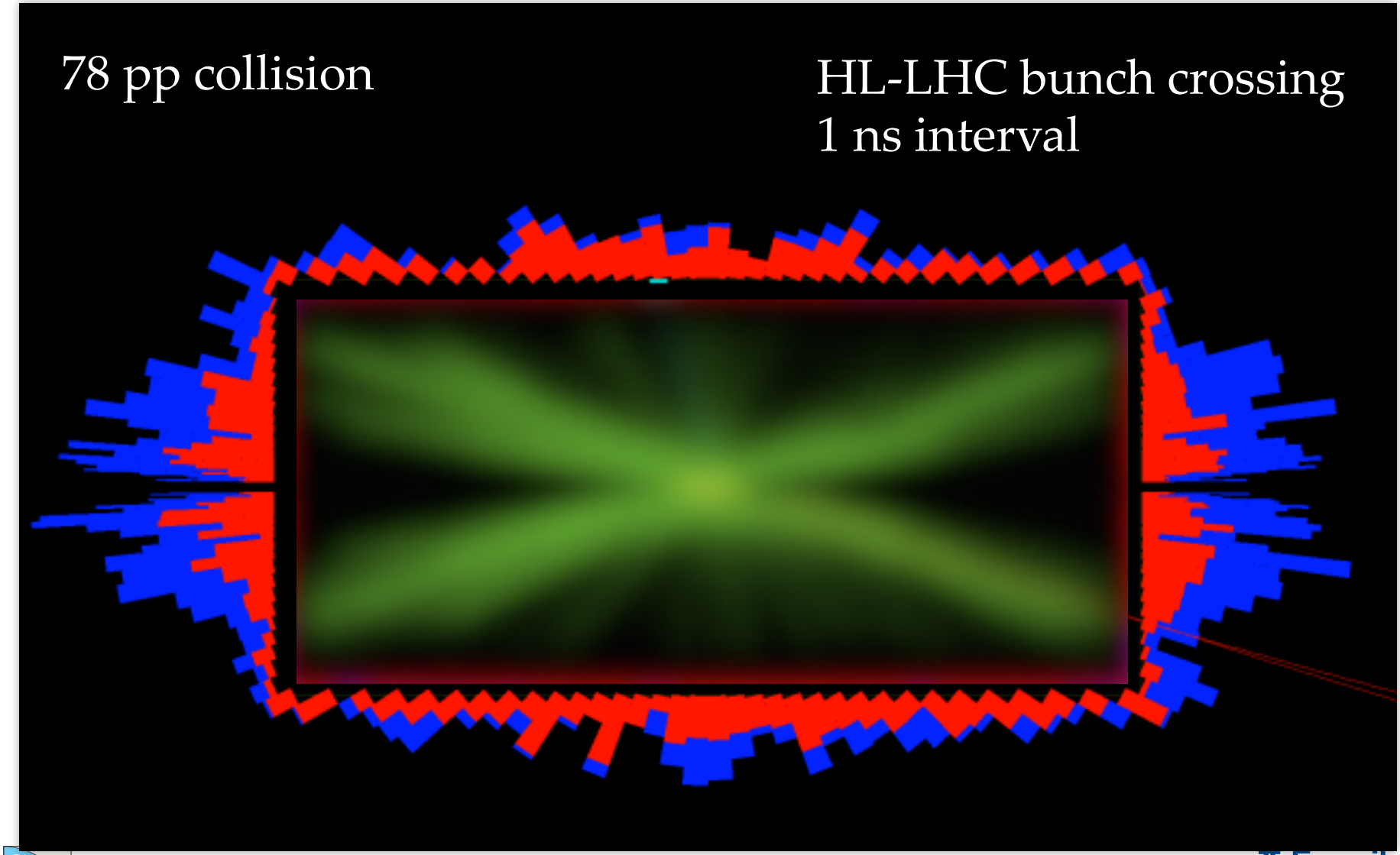
Endcap Timing Layer (ETL) design

- Sensors are each 21x42 mm^2 and contain16x32 pixels
- Two ETL ASICs (ETROC) needed to readout one sensor (each ETROC has 16x16 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



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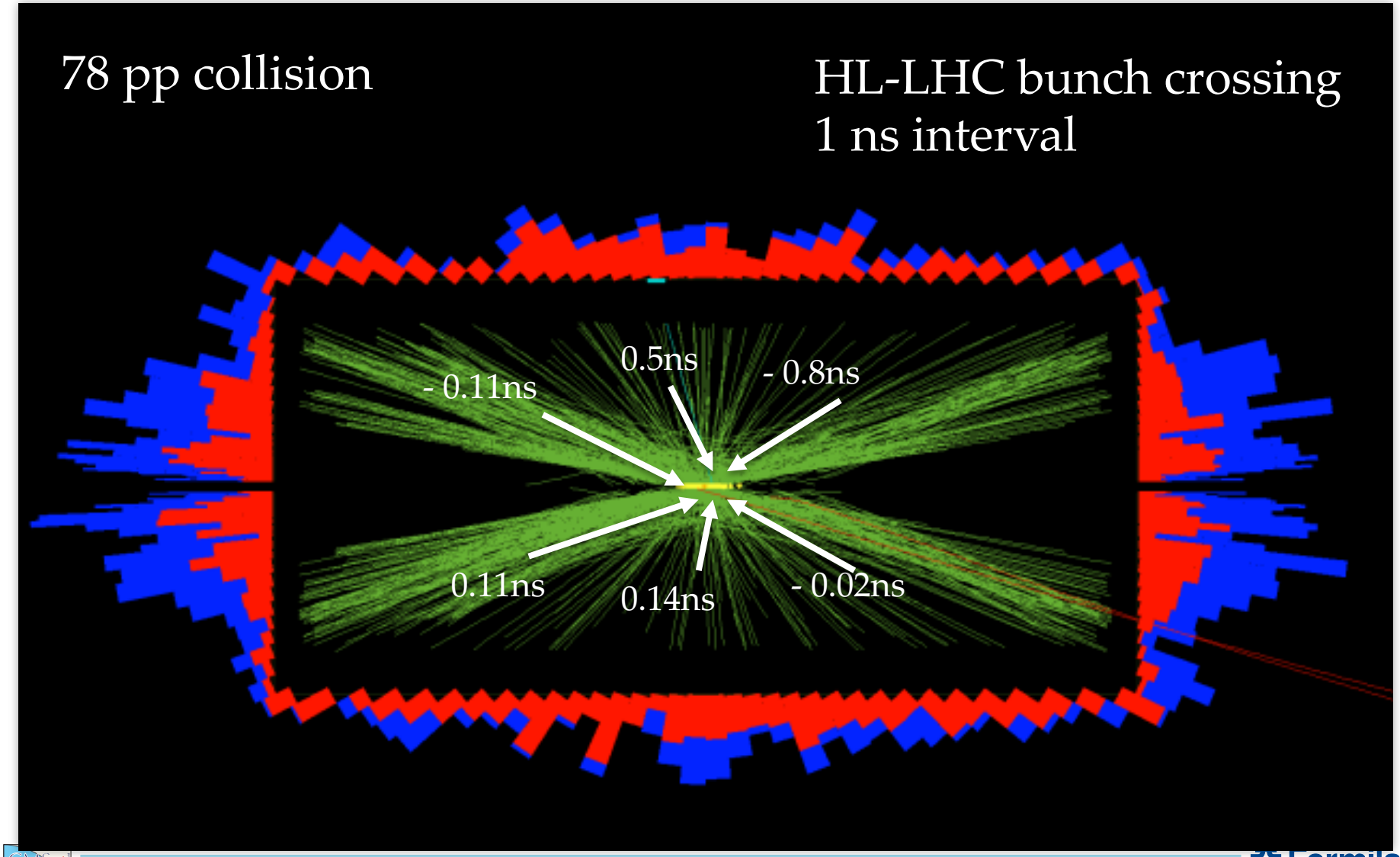
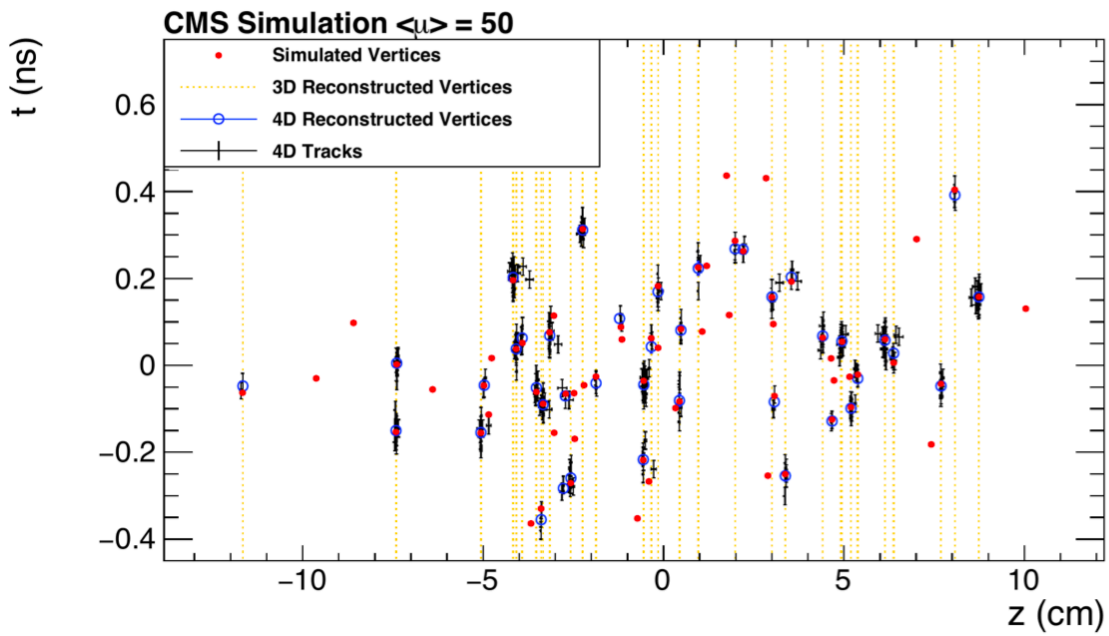


Precision timing for charged particles

- 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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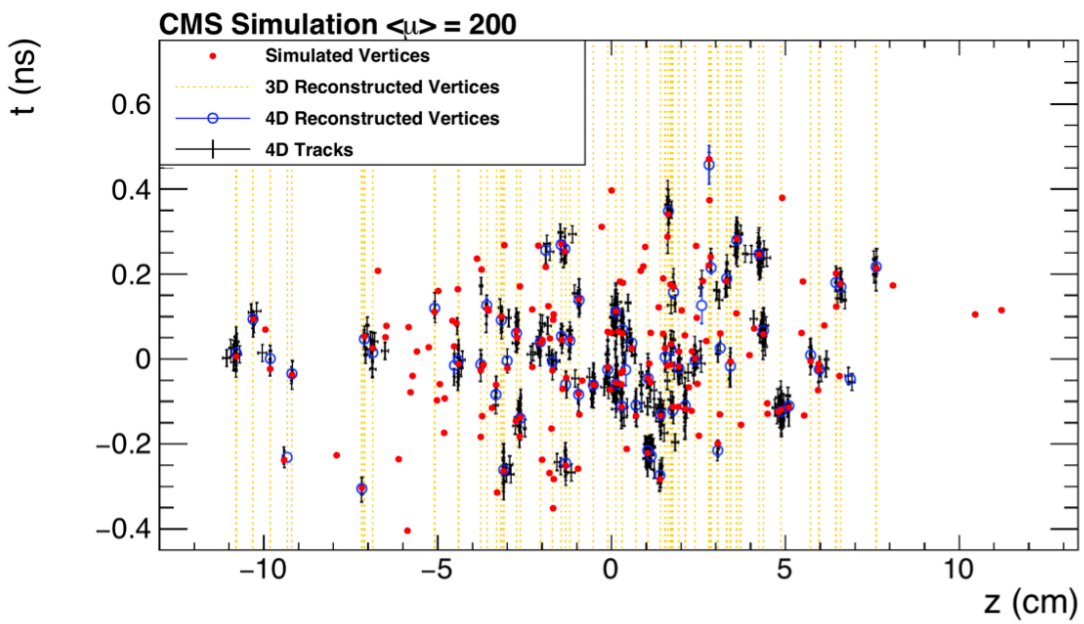
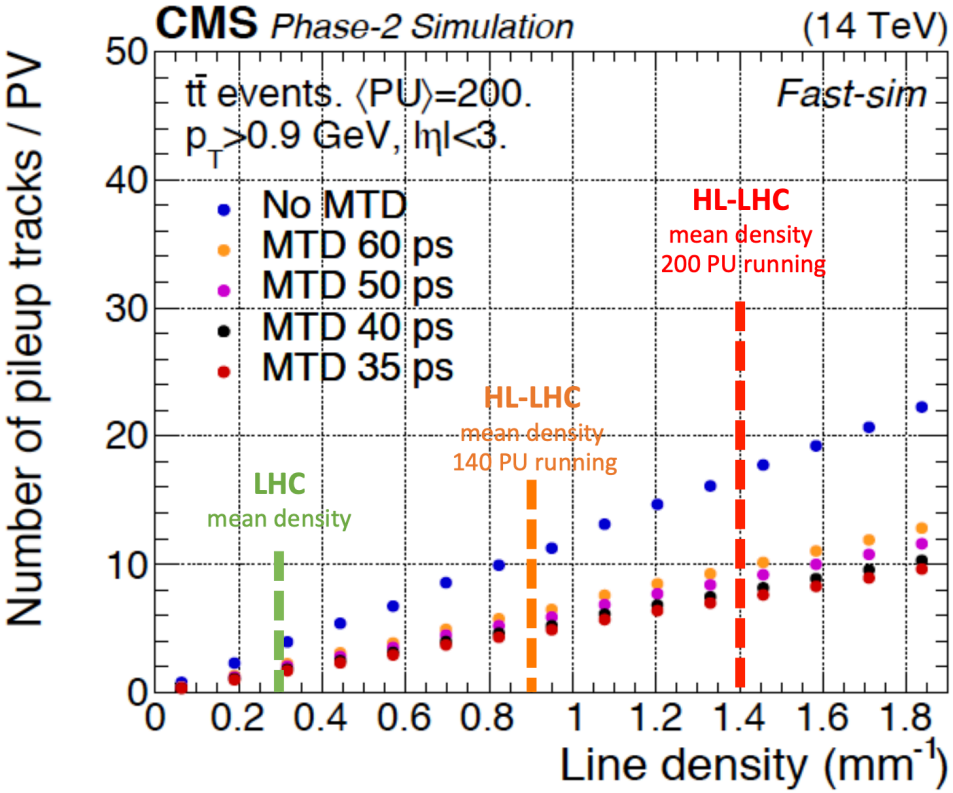
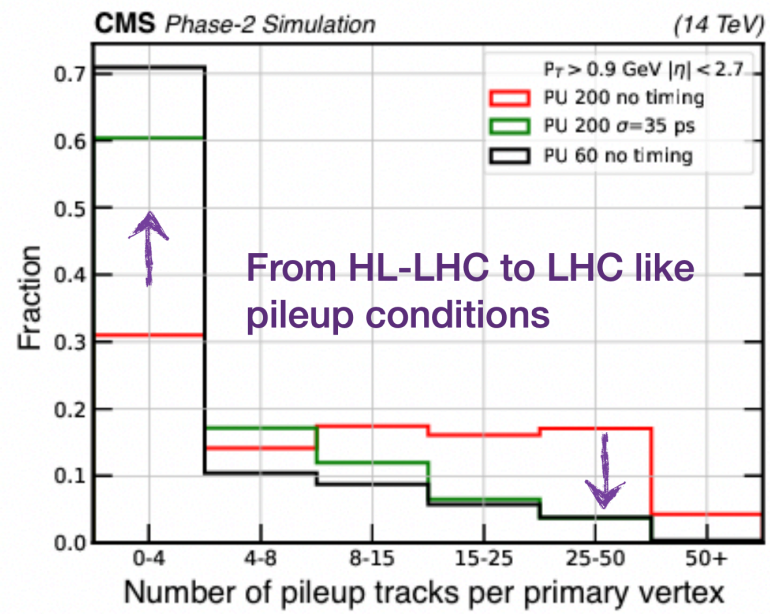


Pileup rejection

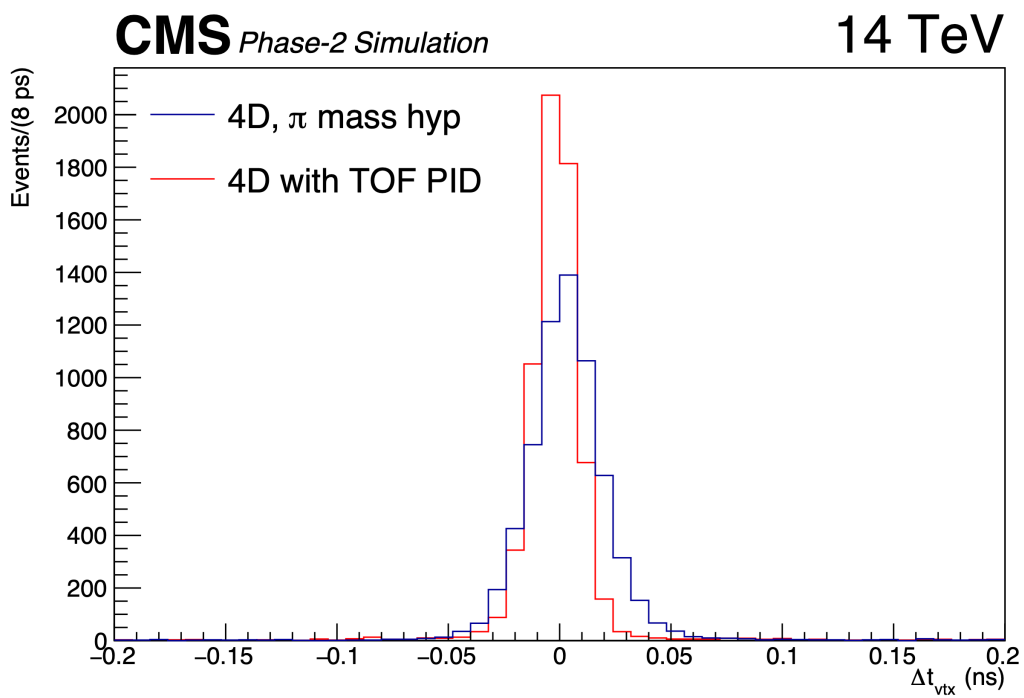




- Time-aware primary vertex reconstruction reduces incorrect association of tracks from nearby pileup interactions by a factor of 2:
  - Fully offsets the impact of the transition from 140→200 PU running
  - Brings per-vertex track purity close to typical current LHC running conditions

Vertexing

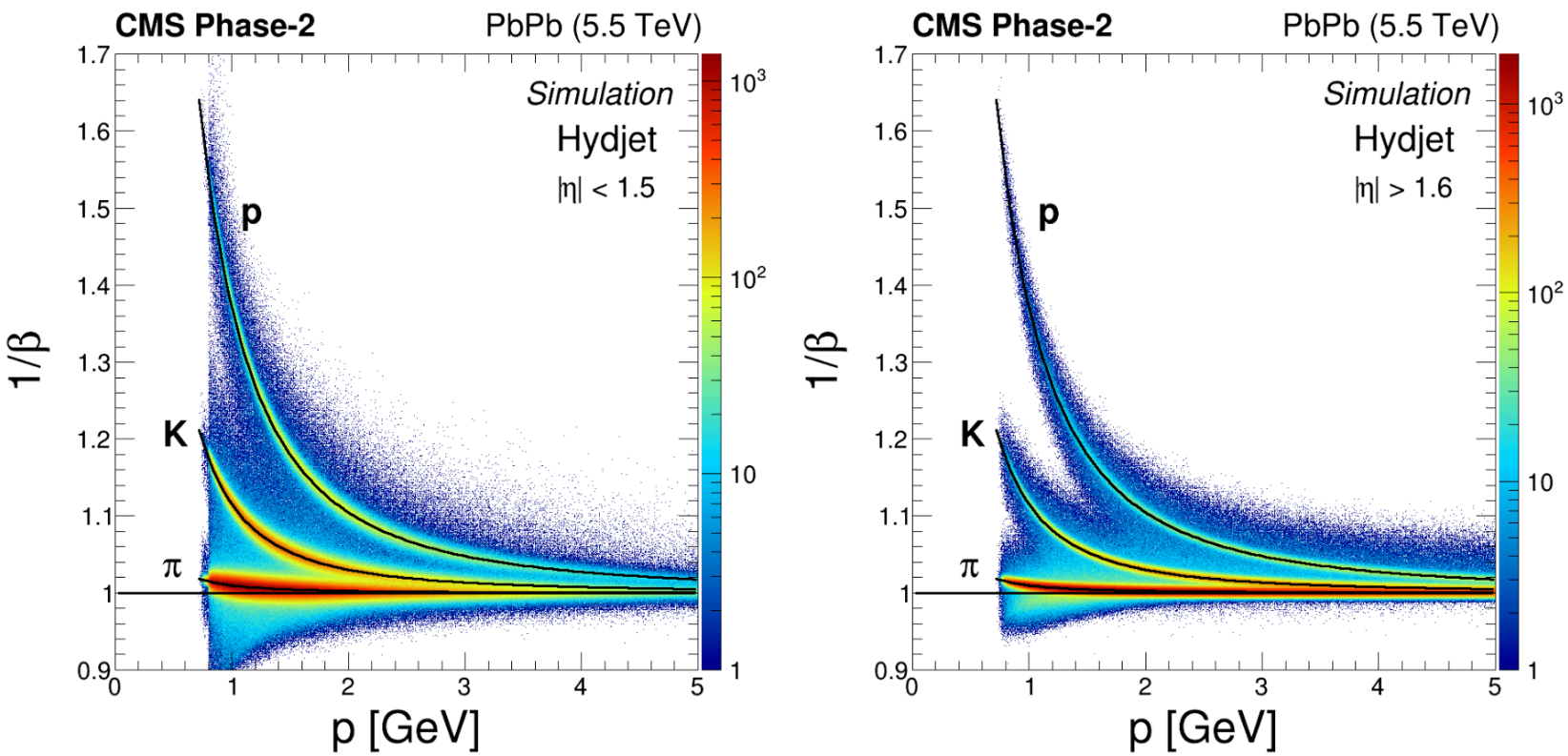
- Iterative 4D vertex reconstruction with TOFPID assignment to handle K/p at low p_T
- Vertex time resolution < 10ps, no tails from slow hadrons
- Vertex merging rate @PU200 reduced from 15% to 1% from 3D to 4D vertex



Time-of-flight Particle ID

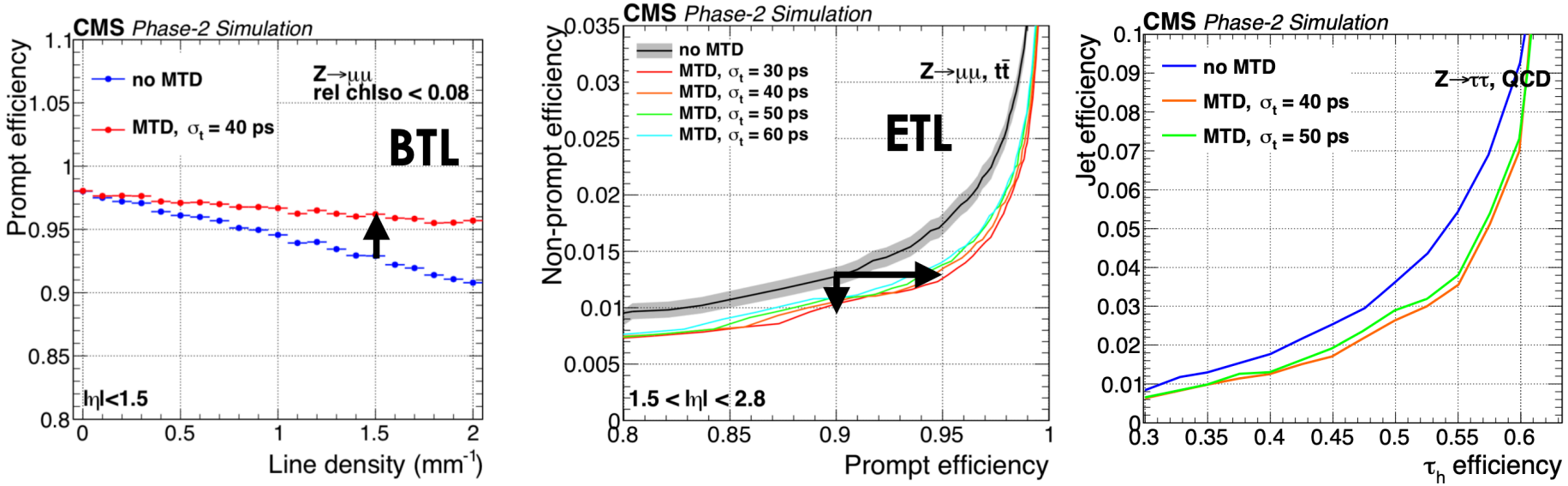
- Time-of-flight particle identification: 2σ π/K separation up to p~2 GeV and K/p up to p~4 GeV
  - New handle for CMS for heavy flavor physics

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

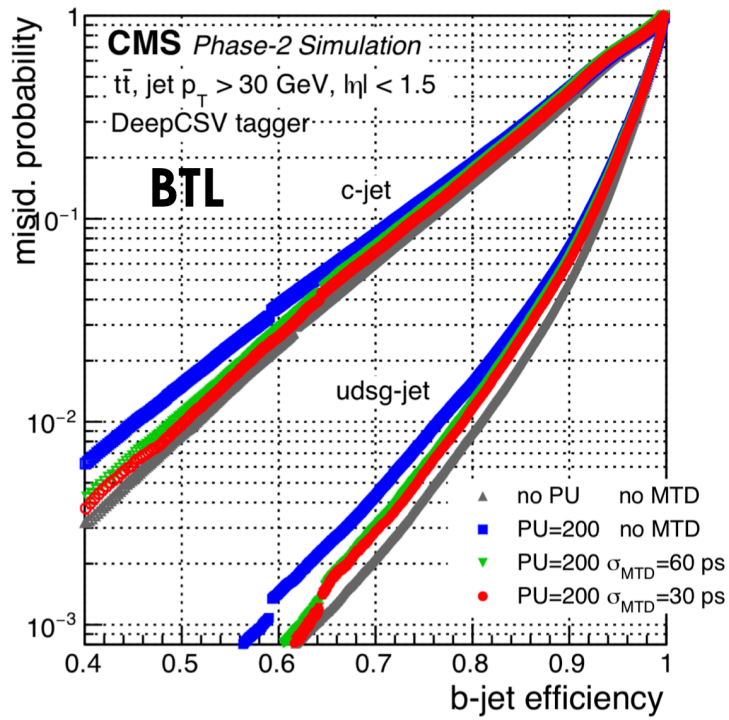


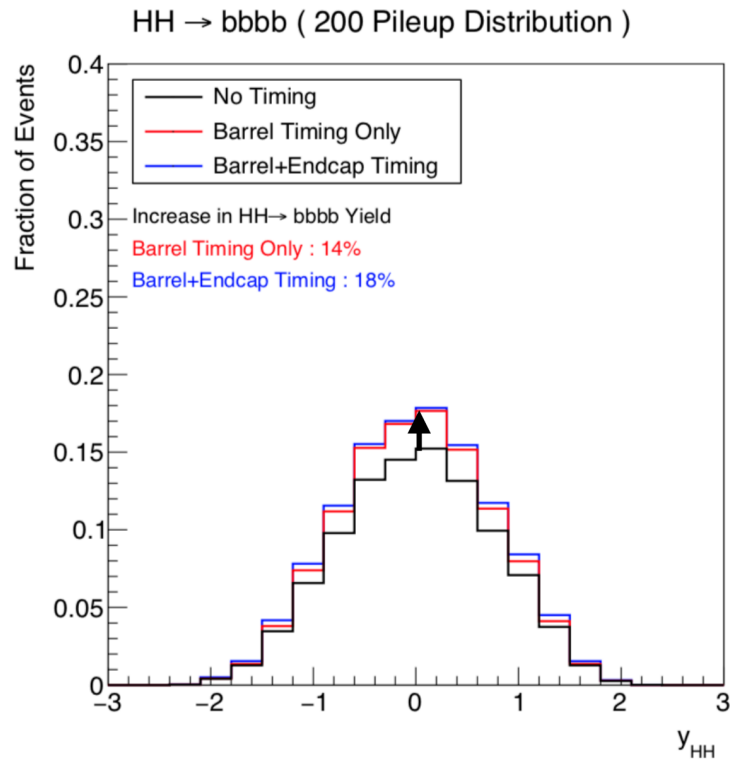
Lepton isolation

- Gain is combined for multiple leptons in final states, e.g. H→ZZ→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 pT thresholds for multi-leptons final states: H→4l: lowest p_T cut >5 GeV
  - b-physics analyses (B(d,s)→μμ, B→K*μμ, ...)
- Higher gains (10-15%) for τ (looser dz cuts, tighter isolation). τ ID not yet fully optimized for Phase-2 reconstruction



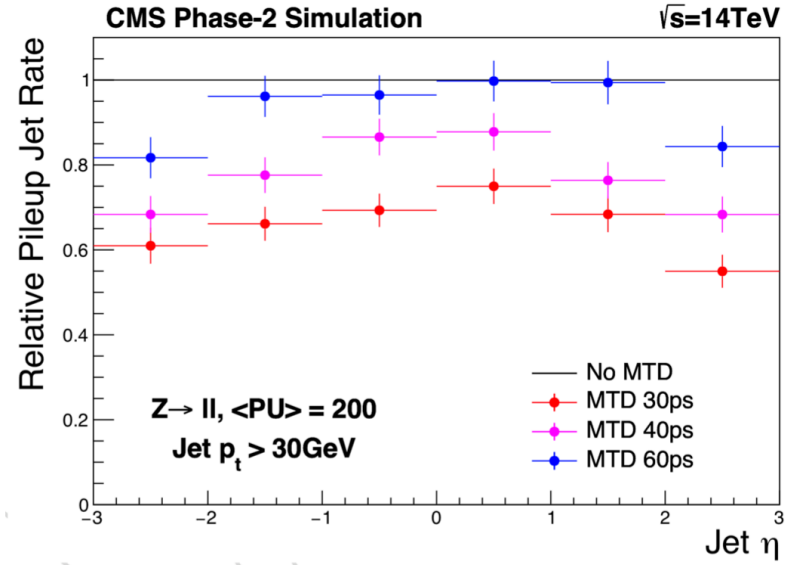
B-tagging

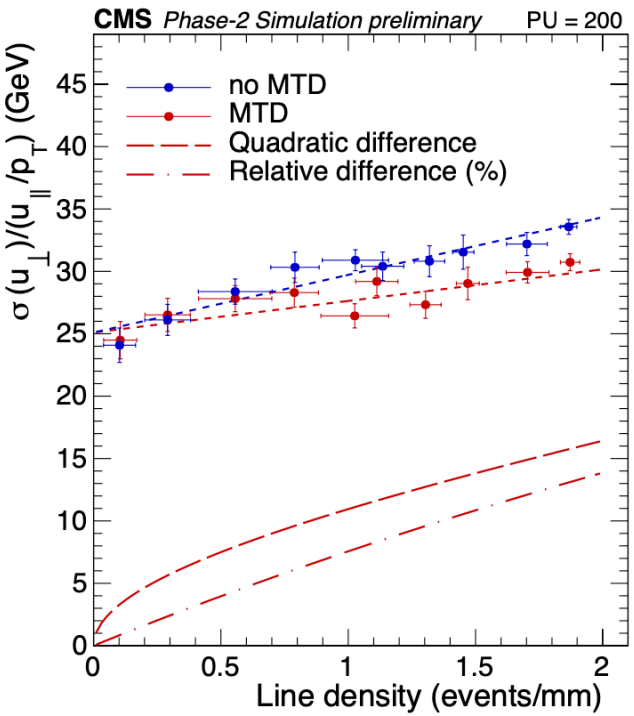




- Efficiency improvements for b-tagging: 3%(BTL) 6%(ETL)
  - b-tagging not yet fully optimized for Phase-2
  - timing used only for track selection
- Significant acceptance gains in a critical HL-LHC final states with several b: HH→bbbb

Jets and Missing Transverse Energy

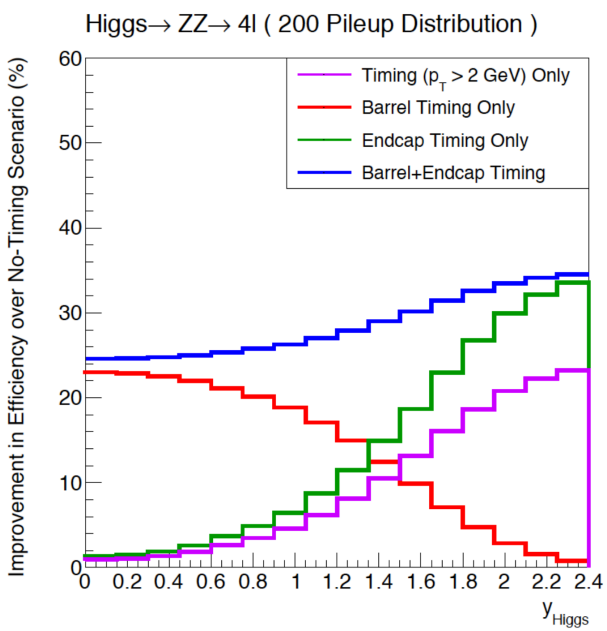


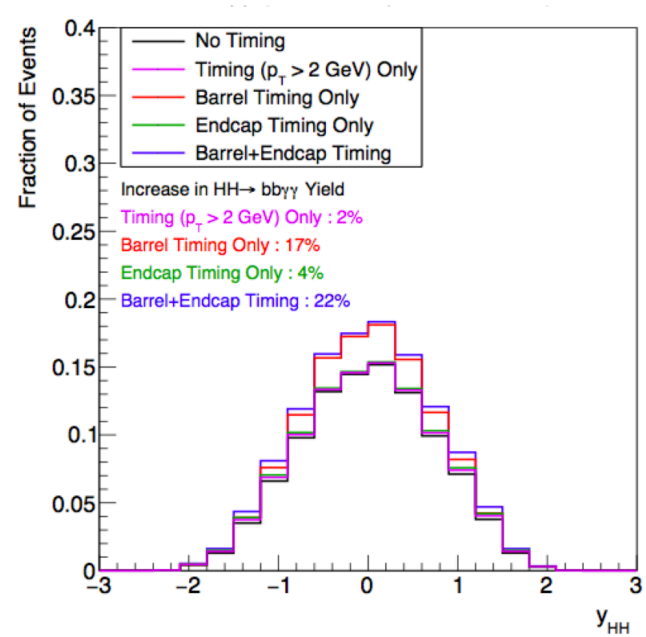


- Up to 40% PU jets reduction especially in forward region
  - Z+jets background reduced by 20-30% for p_T cuts at 20-30 GeV
- 12% relative gain for MET resolution from charged PU mitigation
  - 40% in background reduction if requiring large MET e.g. >150 GeV

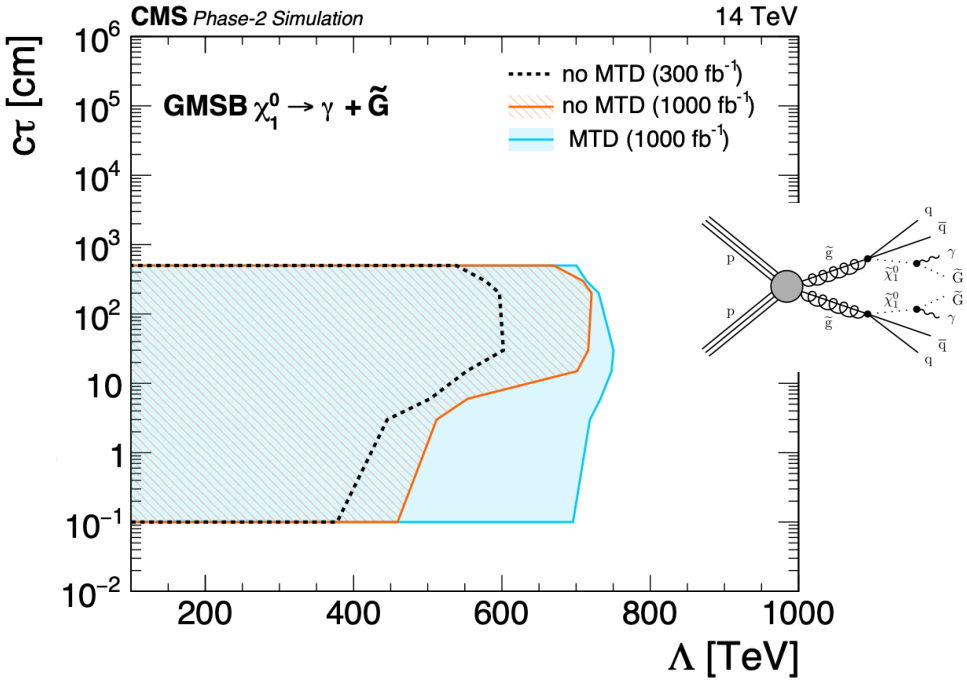
Physics impact: Higgs physics

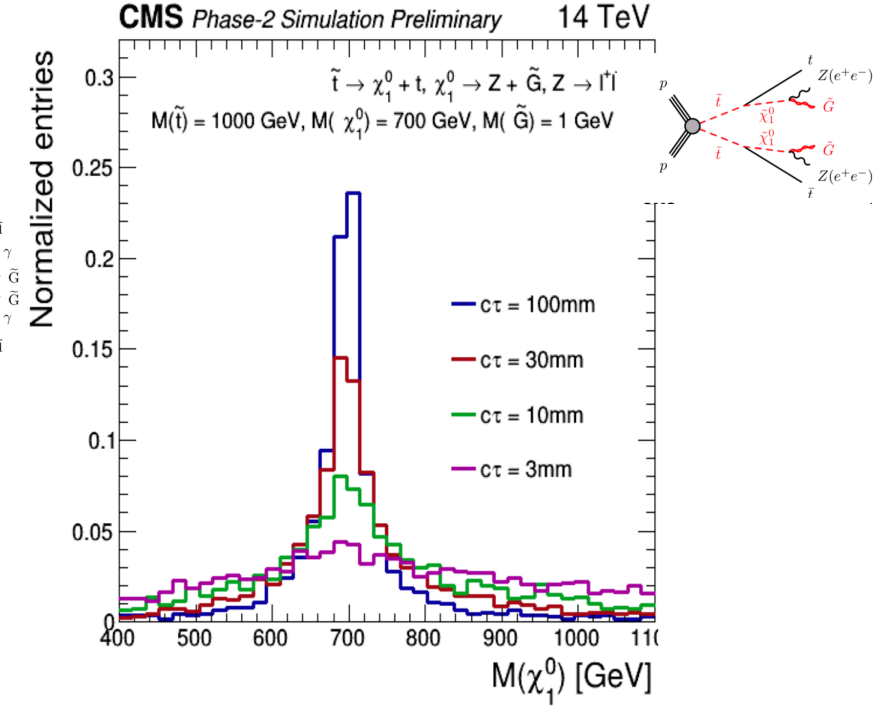
- Significant impact on HL-LHC Higgs program
  - 26% increase in effective luminosity for $H \to ZZ \to 4\ell$
  - 22% increase in effective luminosity for $H \to ZZ \to bb\gamma\gamma$
  - 25% increase in effective luminosity for VBF $H \to \tau\tau$
- Further improvements:
  - resolution improvements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





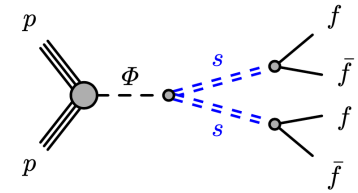
Physics impact: long-lived particles





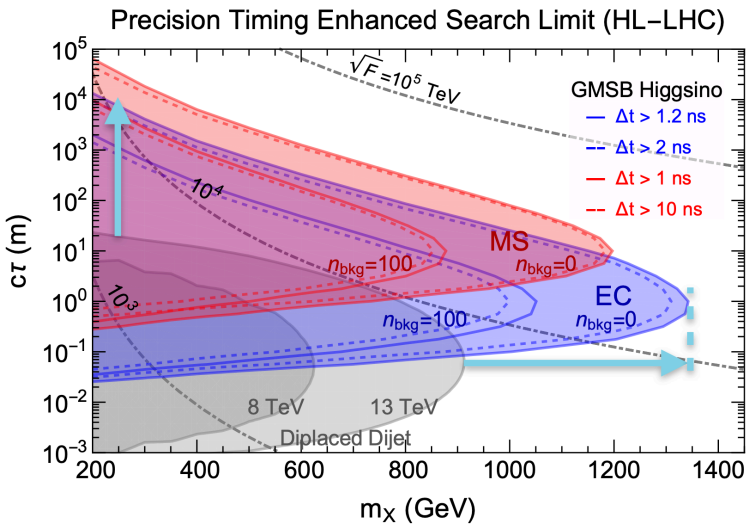
- Vertex timing enhances Long-lived particle physics program
- In topologies involving secondary vertices, MTD provides a unique handle to reconstruct the mass of the long-lived neutral particles (e.g. χ_0)

Physics impact: long-lived particles

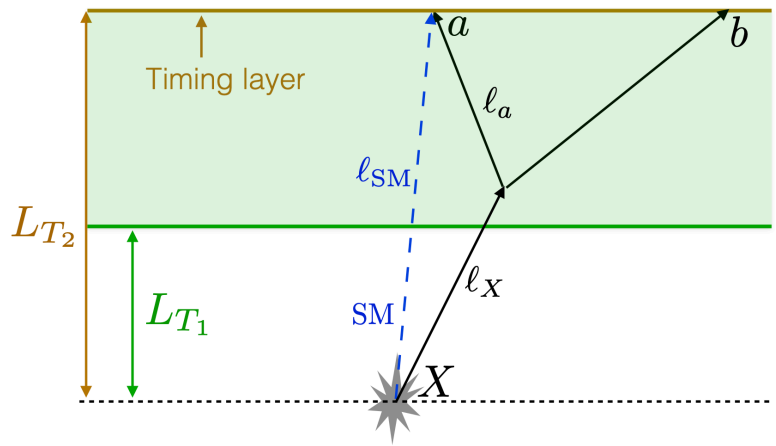


study by Zhen Liu et al.

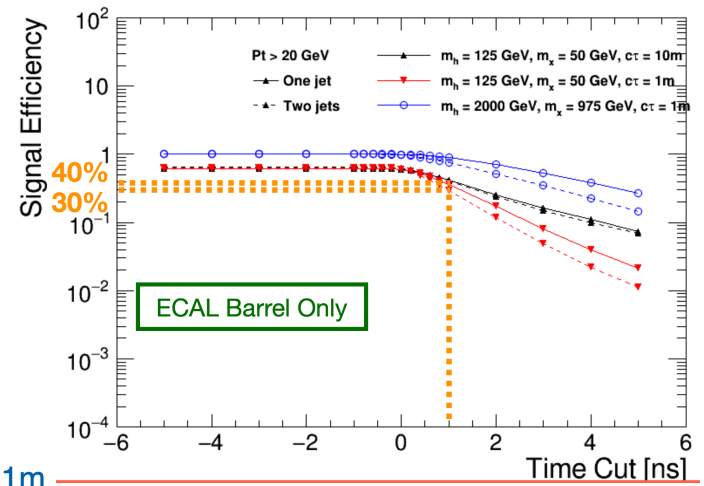
https://arxiv.org/abs/1805.05957



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



- 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

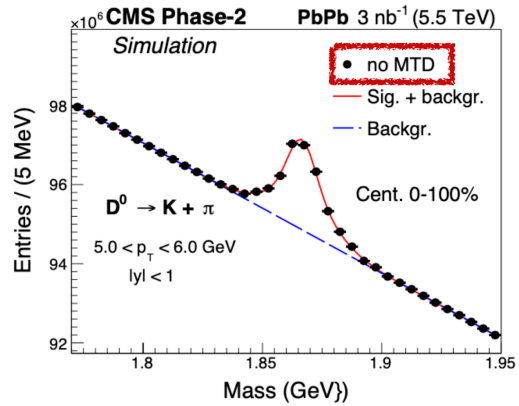


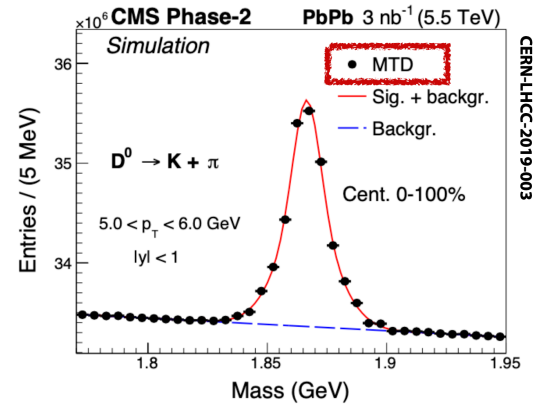
M_h = 125 GeV

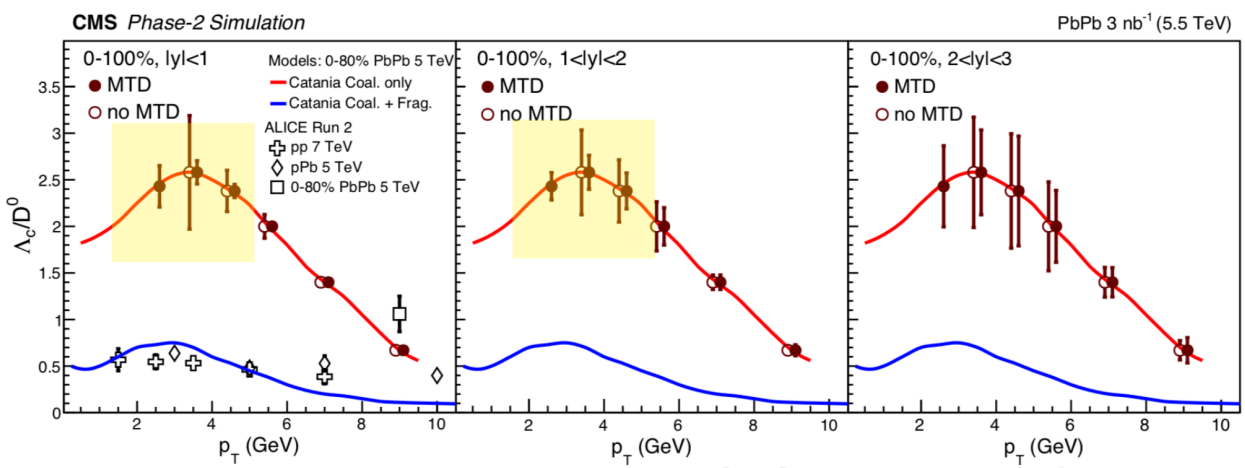
M_x= 50 GeV, $c\tau$ = 1m

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 |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.

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