Fermilab

Upgrading the CMS Detector for the High-Luminosity LHC

Christian Herwig, on behalf of the CMS Collaboration

56th Annual Fermilab Users Meeting

June 28, 2023

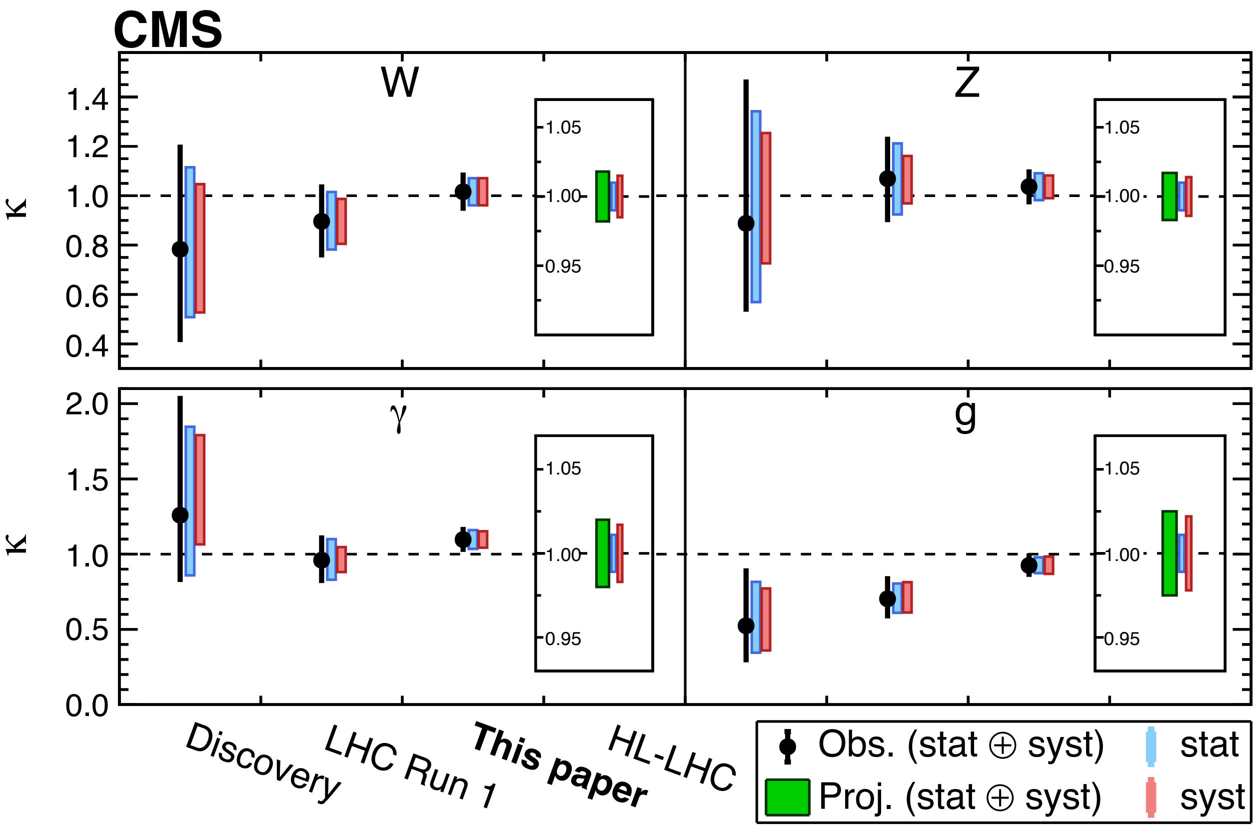
Outline

- **Physics goals:** What's left to learn at the LHC?
- **High-Luminosity:** Opportunities and Challenges
- **Upgrades:** refreshing the CMS detector for HL-LHC

What’s left to learn at the LHC?

Physics goals for High-Luminosity (I)

Since the Higgs boson discovery in 2012, CMS has tested the Electroweak theory to *high-precision* and in some of the *most extreme* regimes.



Most couplings known to 10% or better today! **O(%) with HL-LHC!**

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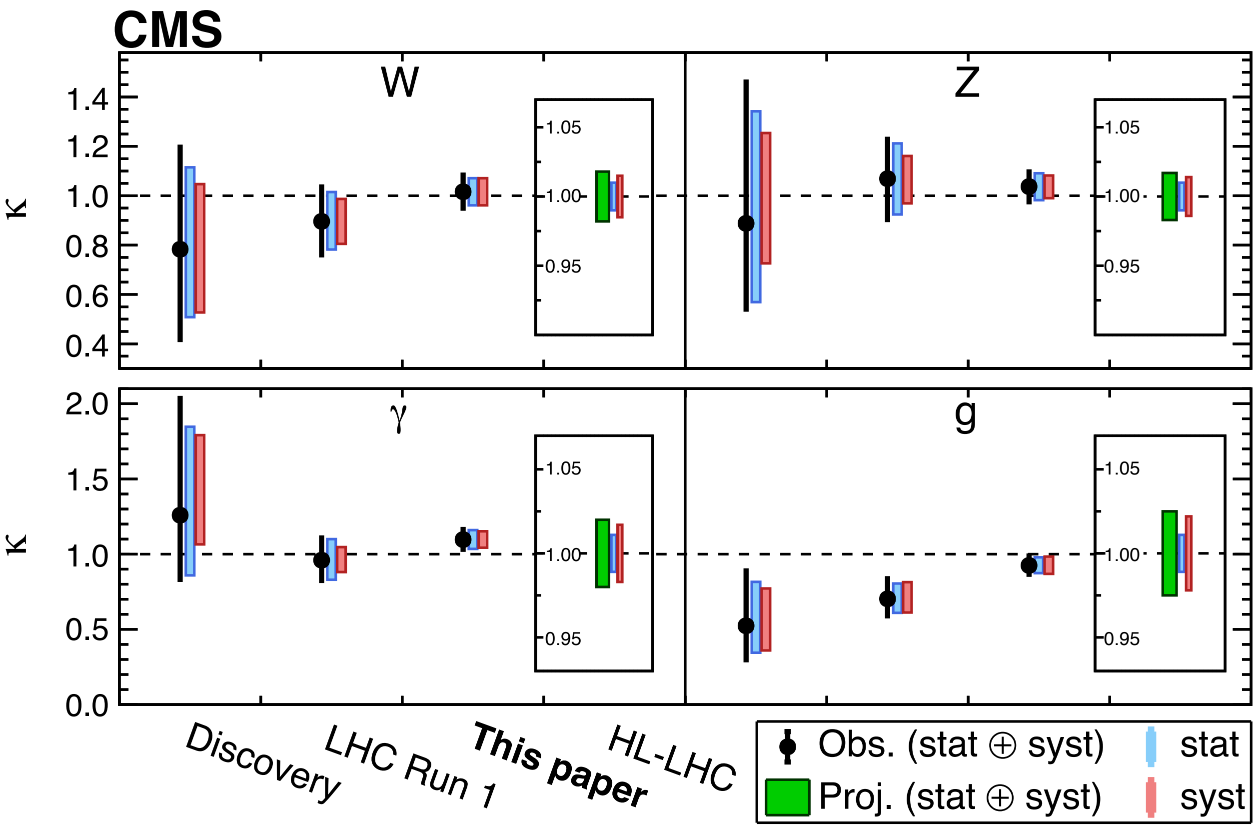

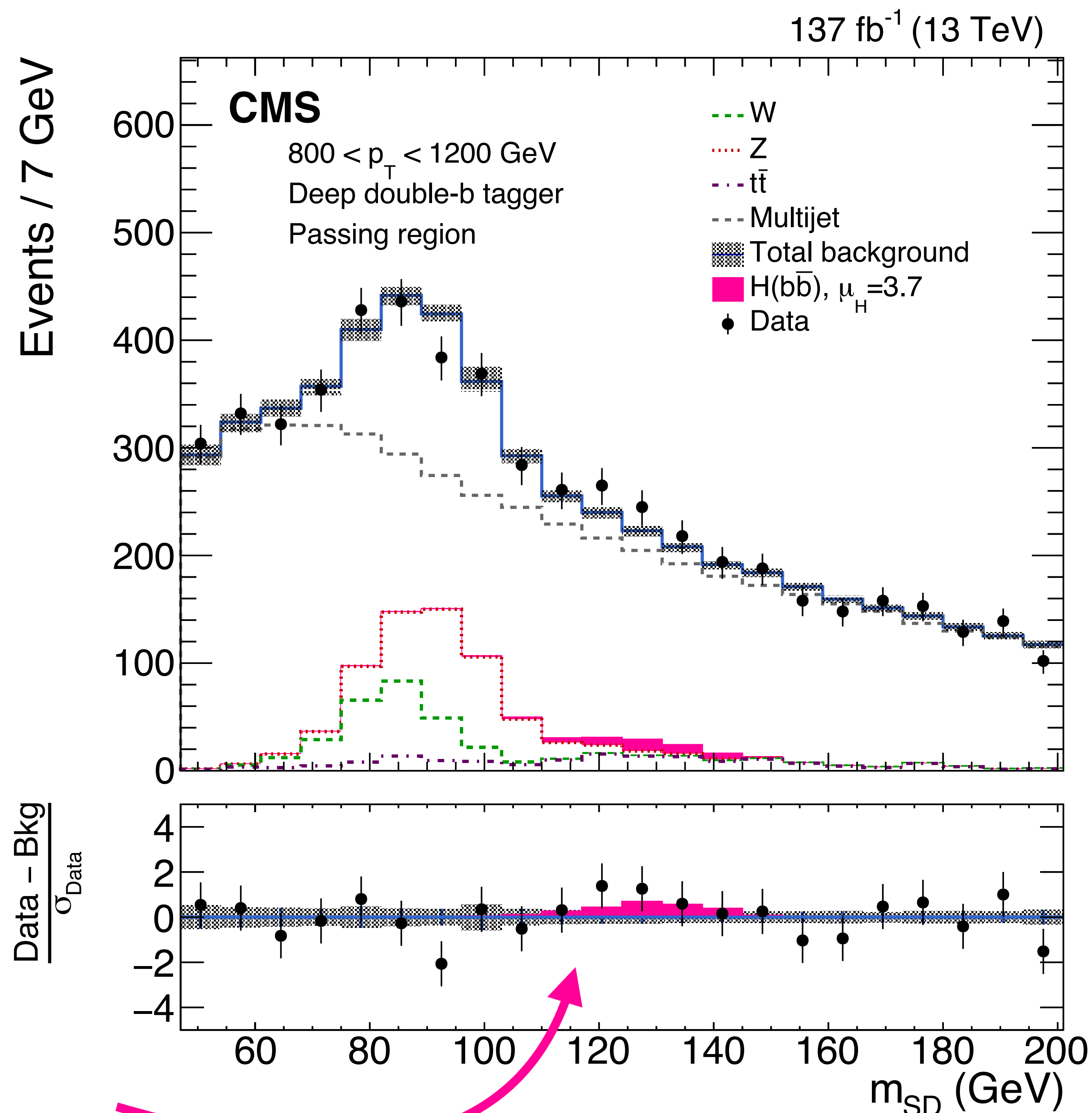

Most couplings known to 10% or better today! **O(%) with HL-LHC!**

Higgs events with ~TeV momenta.

Sensitive to heavy New Physics!

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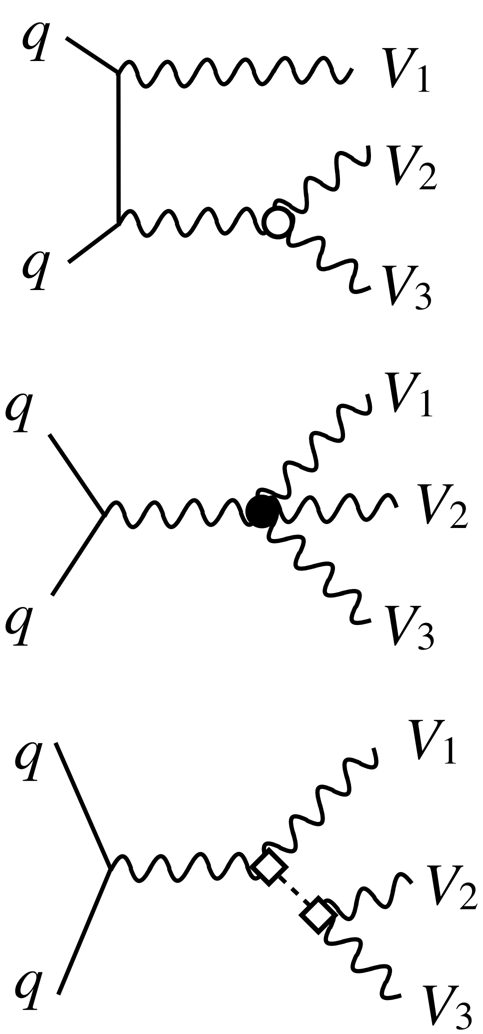
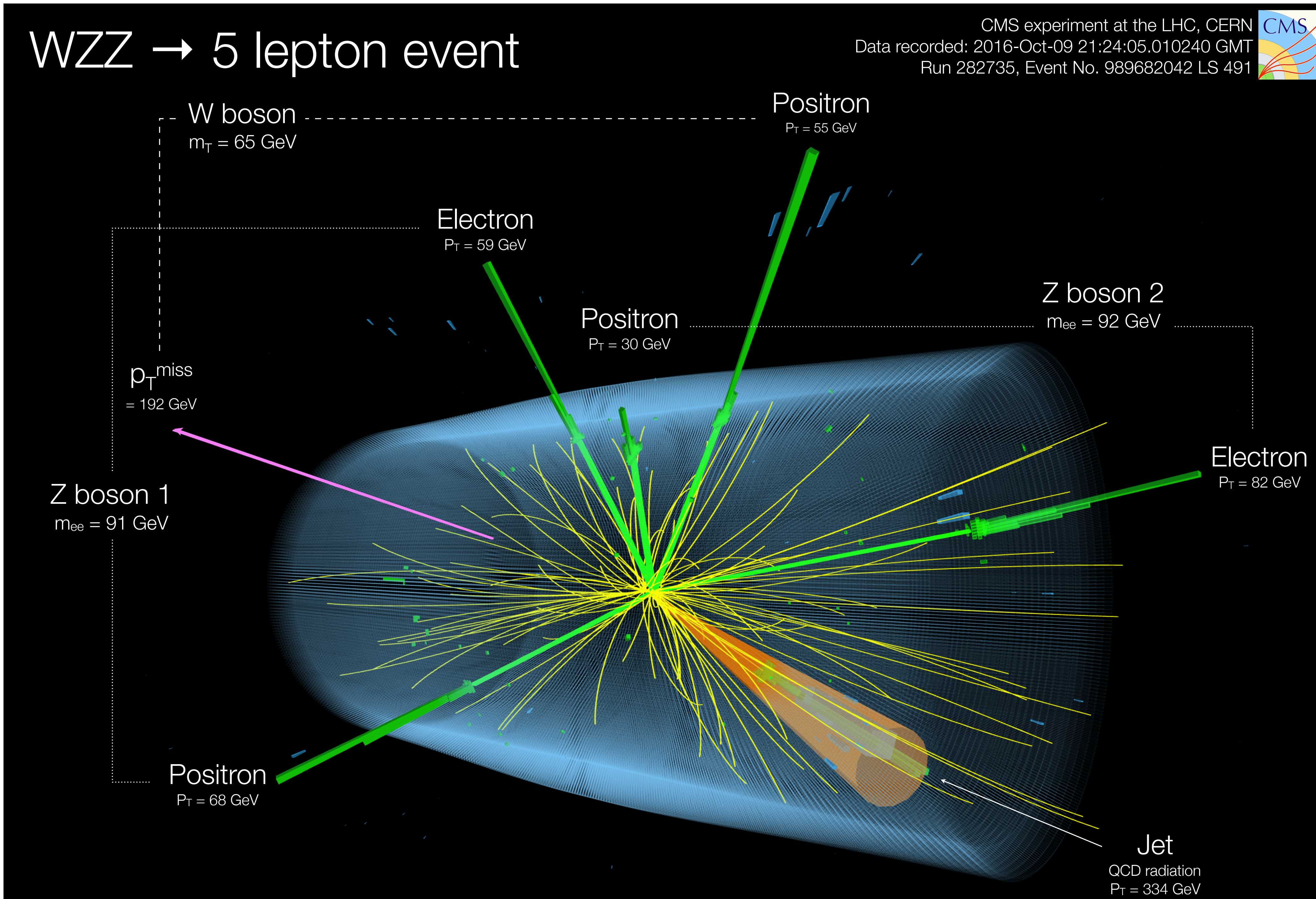
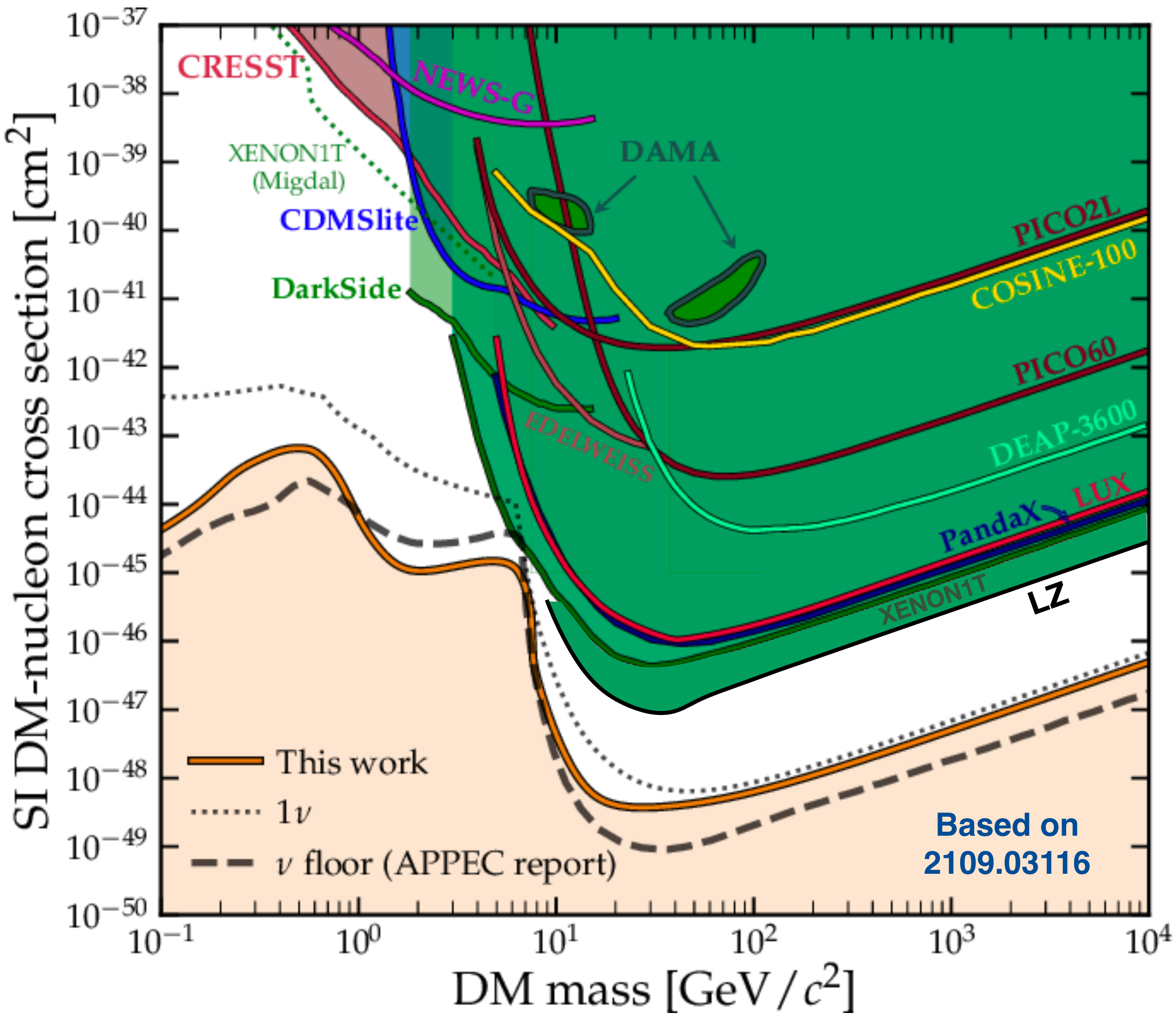


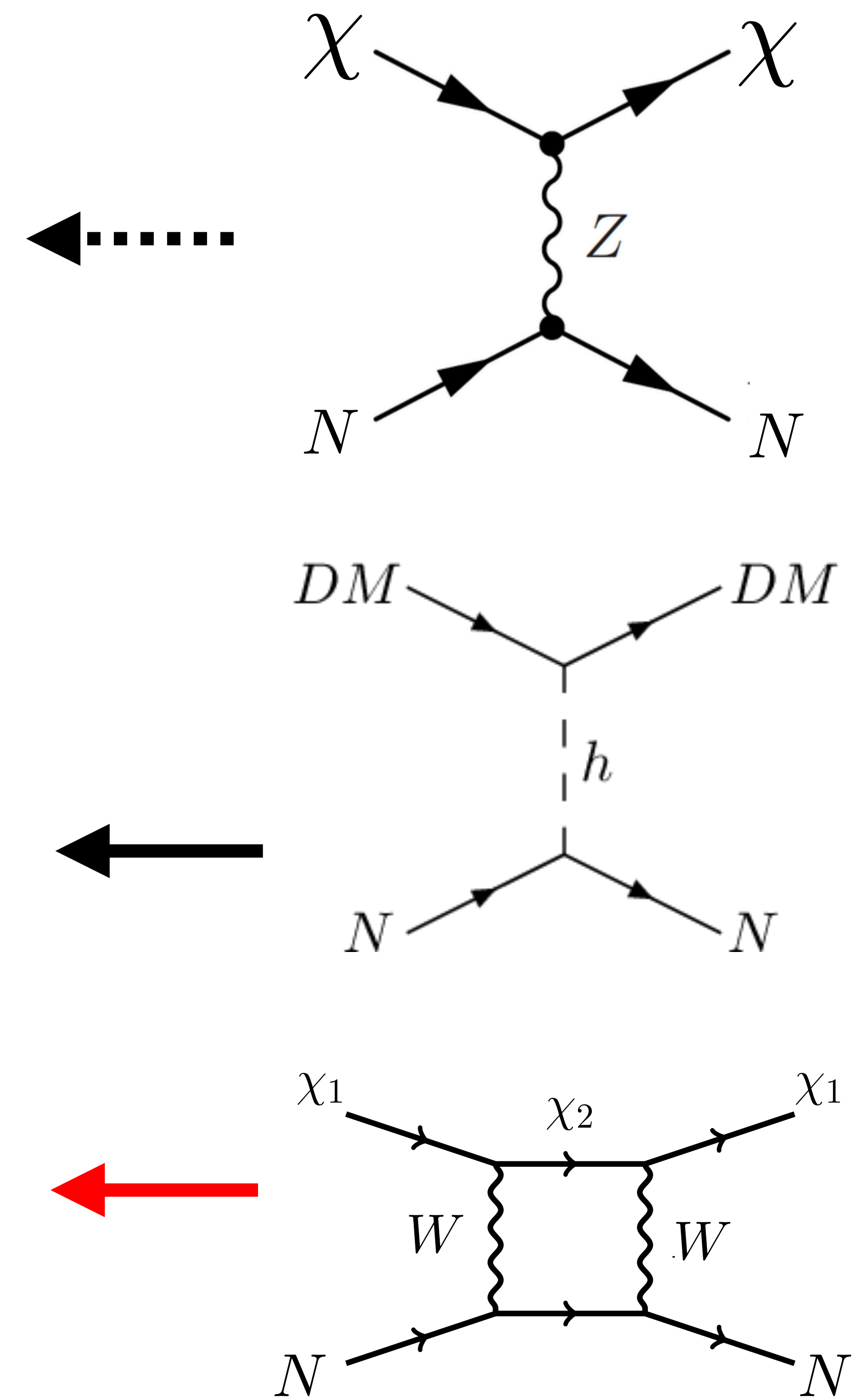
Observed triple gauge boson production!



Physics goals for High-Luminosity (II)

High-energy collisions provide *unique opportunities to detect Dark Matter* beyond the reach of Direct Detection.





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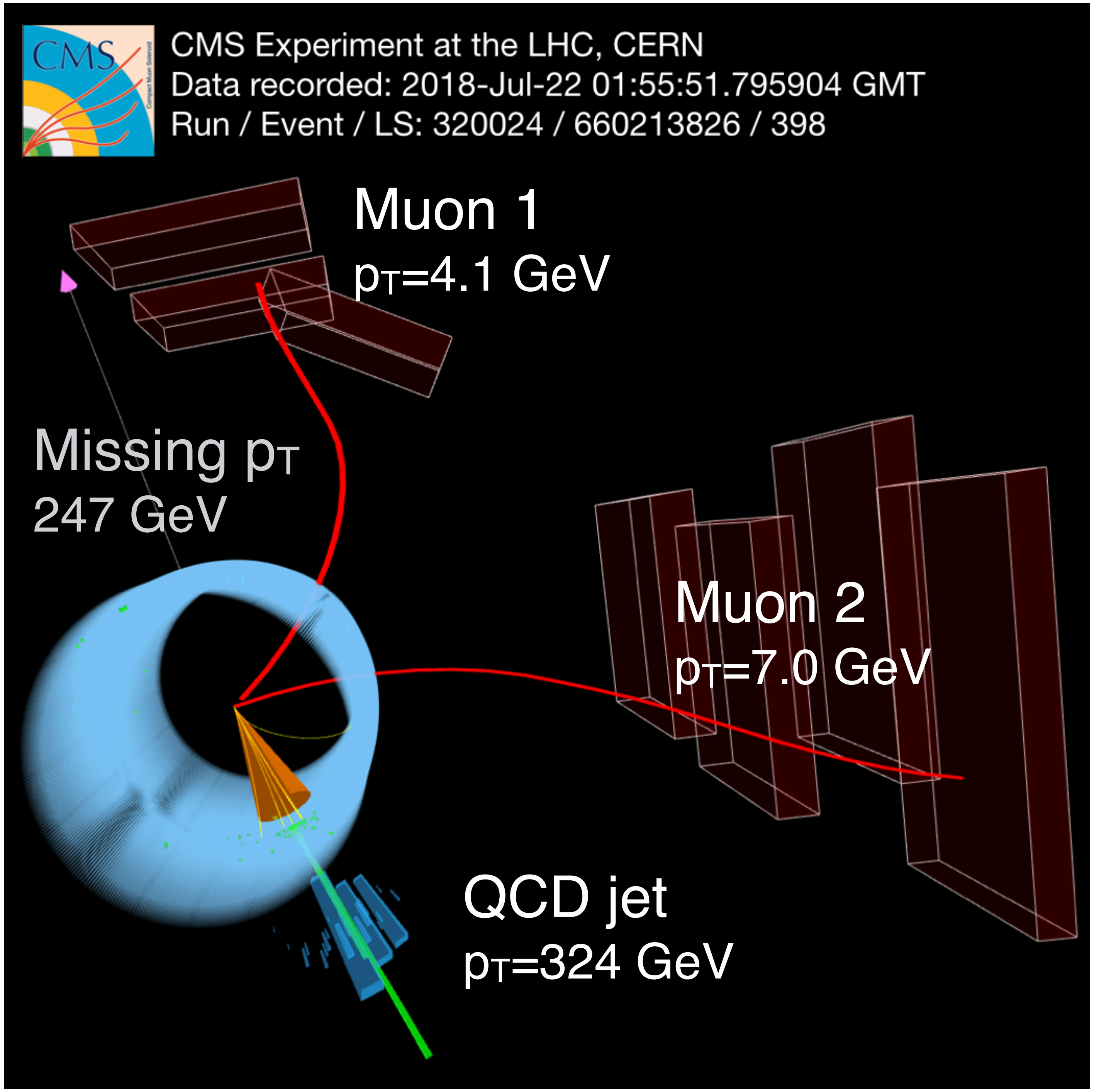

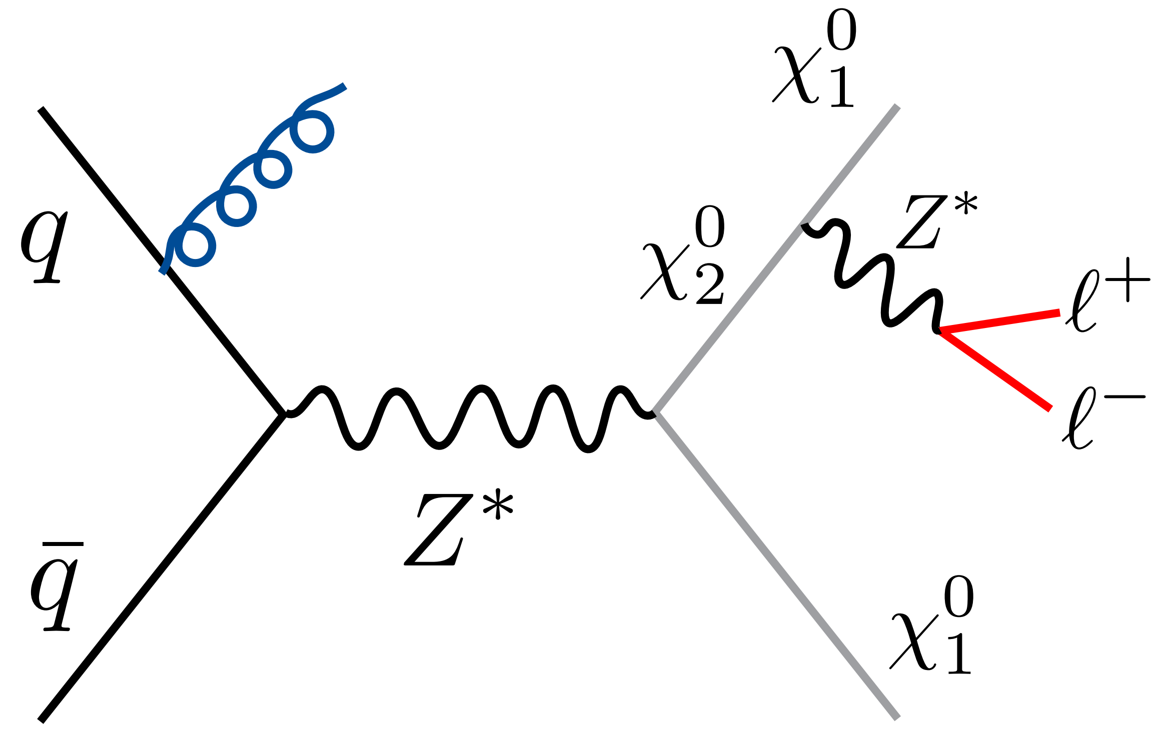

Infer the presence of **invisible particles** from ***extreme momentum imbalance!***

Smoking gun for **Electroweak Dark Matter:** ***Low-p_T leptons***

What's required?

Data: ~10x design luminosity achieves: O(%) couplings, 5% $H \to \chi\chi$, 50% λ_h.

Theory: Detailed control over Standard Model processes.

Detectors: Capable of *precision measurement* & *continued exploration*.

What's required?

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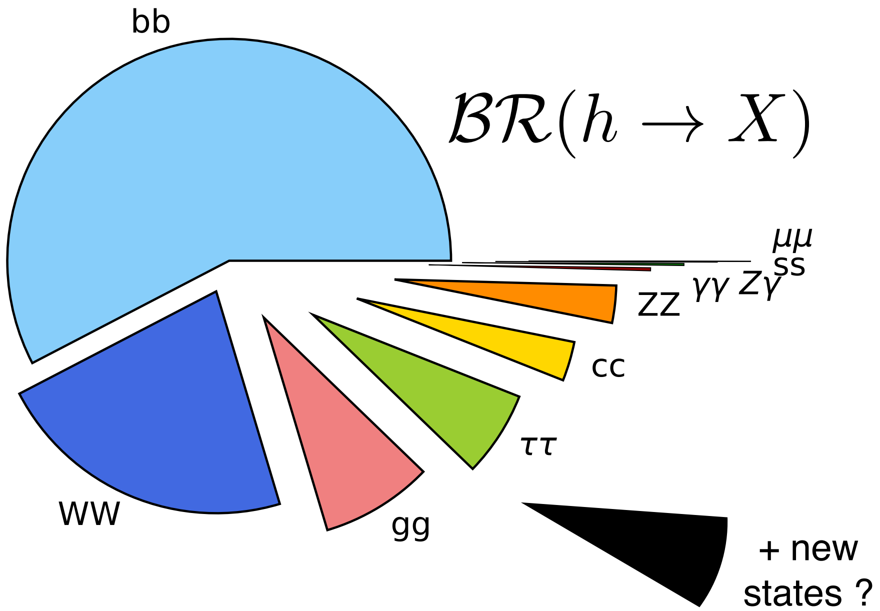
Ultimate Higgs precision requires maintaining broad detector capabilities.

E.g. measure all of e/γ, μ, τ, (b/c-) jets, p_T-miss, over a wide range of momenta.



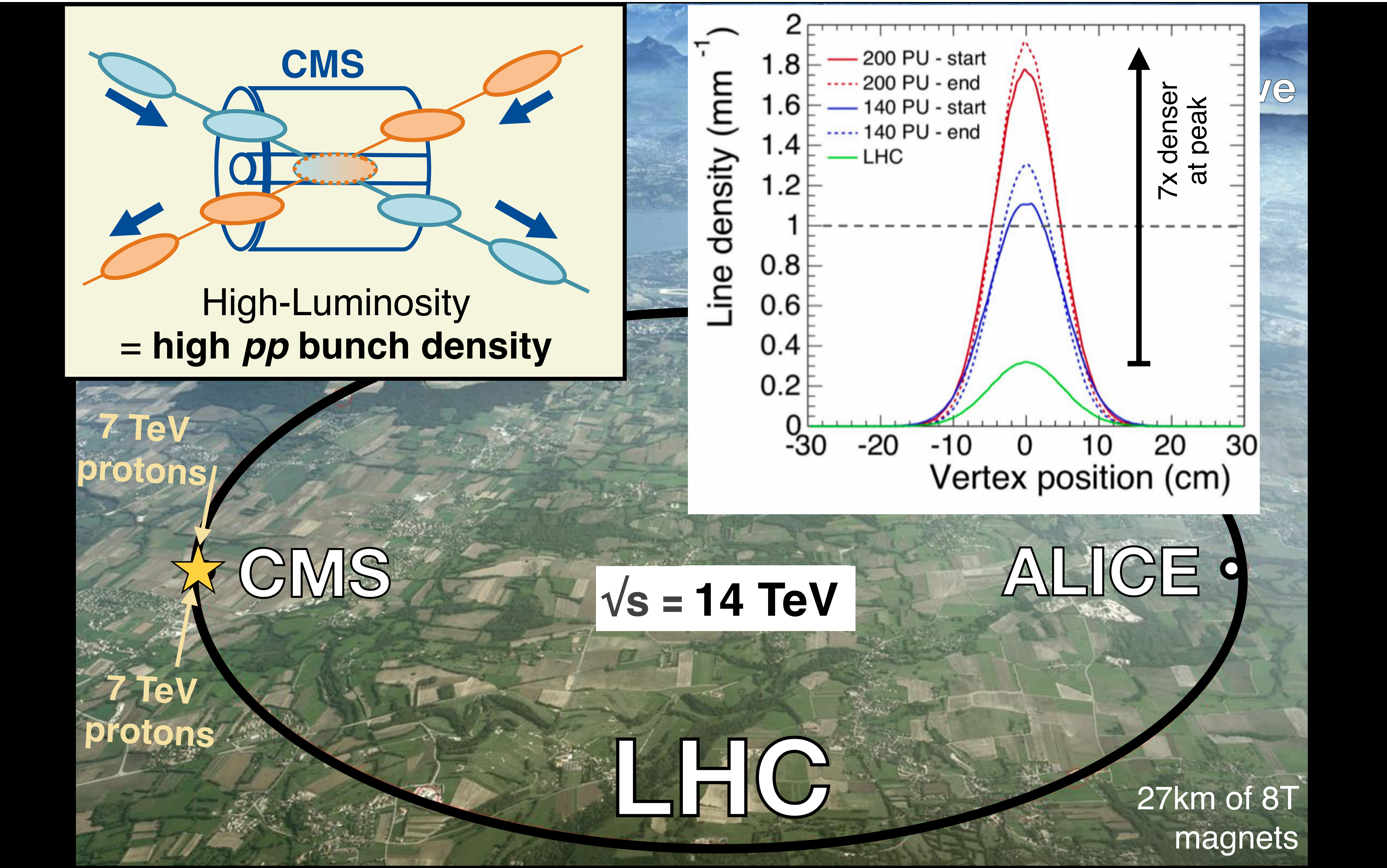
Enable direct searches for New Physics that may stabilize the electroweak scale.

New Higgs doublets, top partners, dark matter?

Maintain **broad sensitivity** to unexpected models of New Physics.

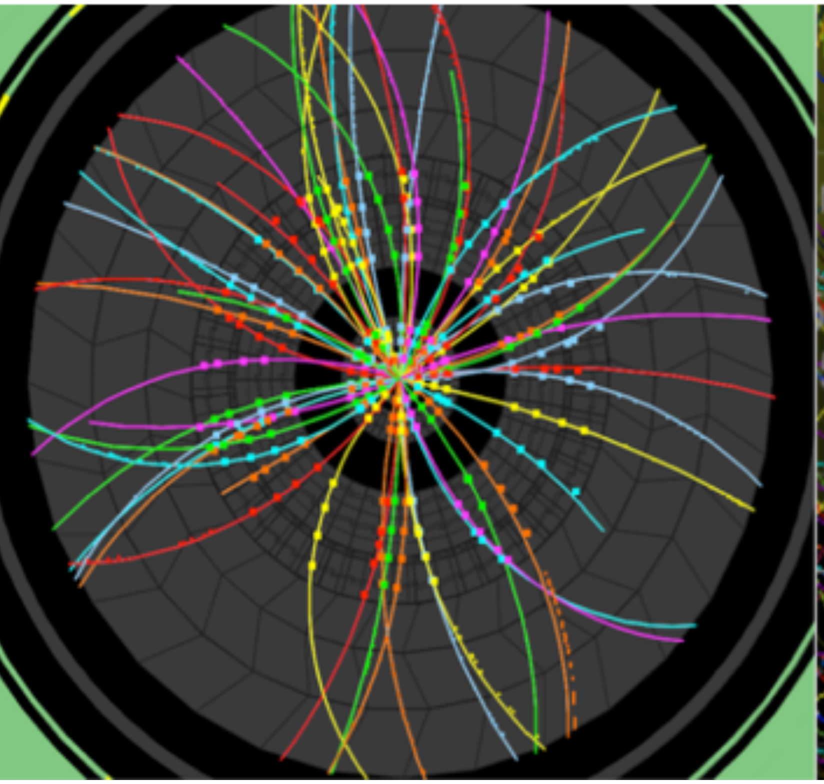
High-Luminosity:
Opportunities and Challenges

Achieving High Luminosity

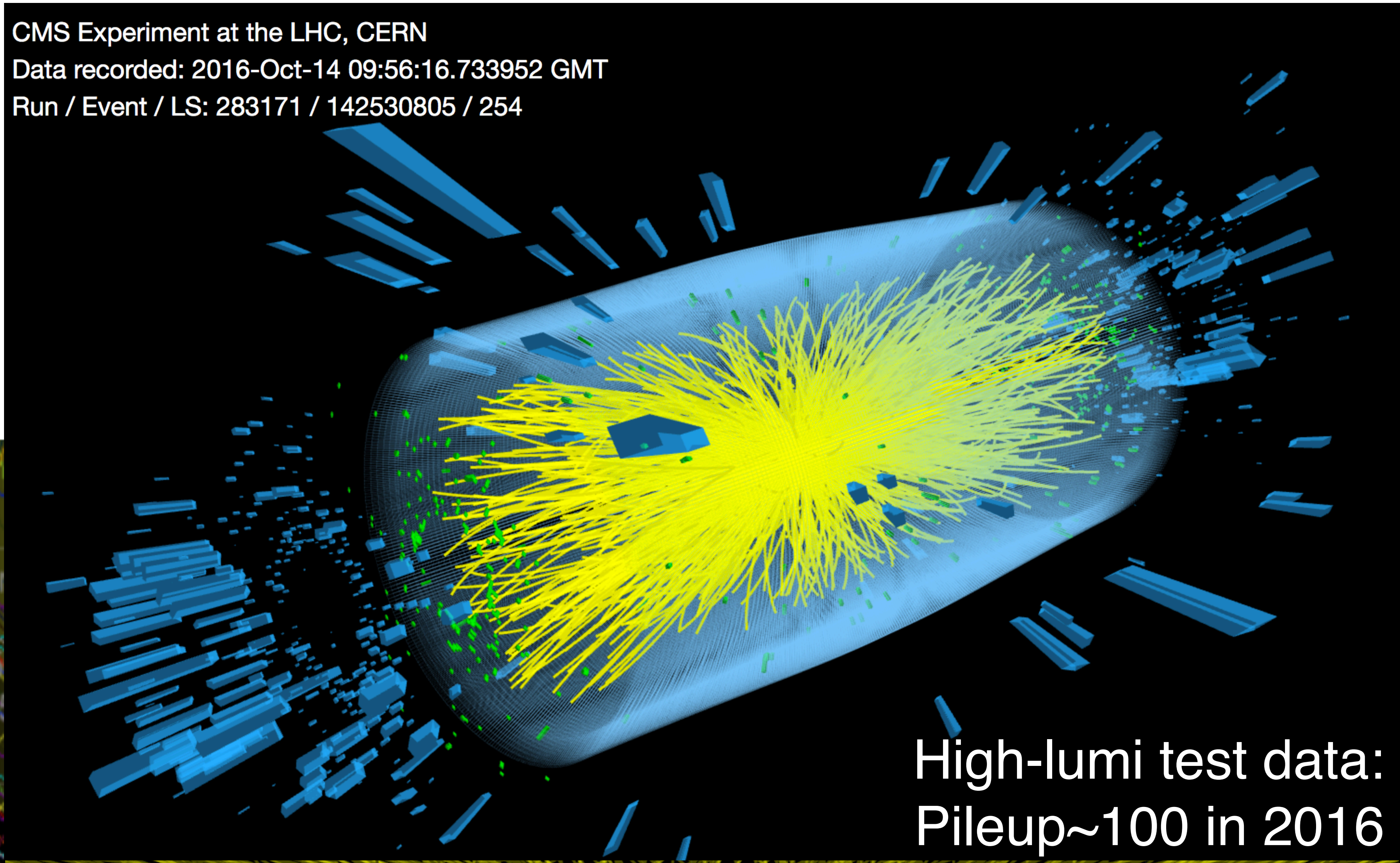


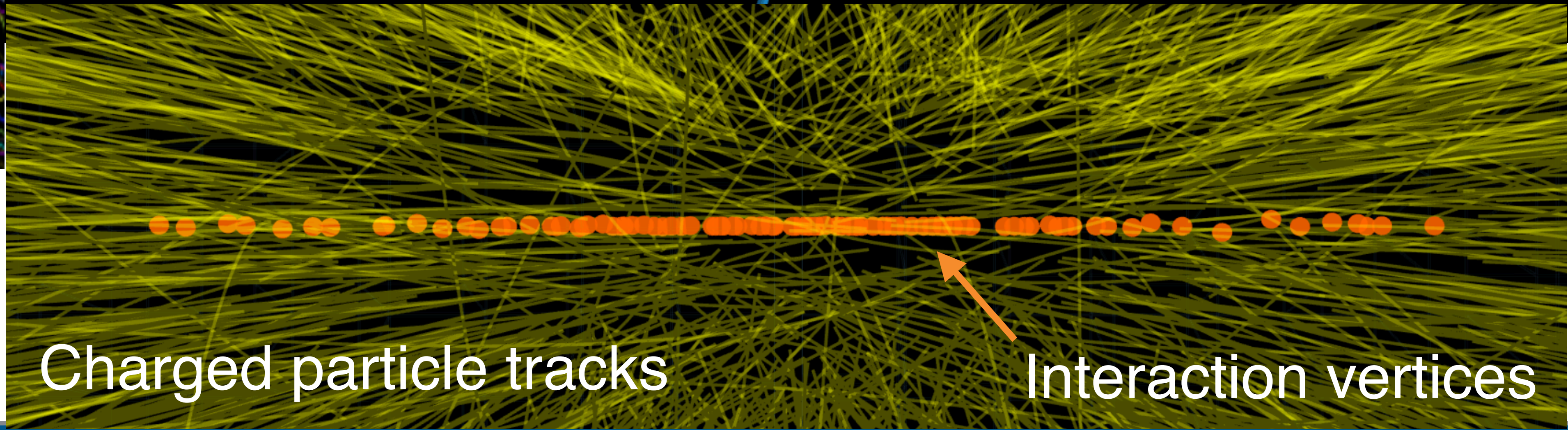
Challenges of High-Luminosity (I)

CMS must disentangle decay products of 200 overlapping collisions.

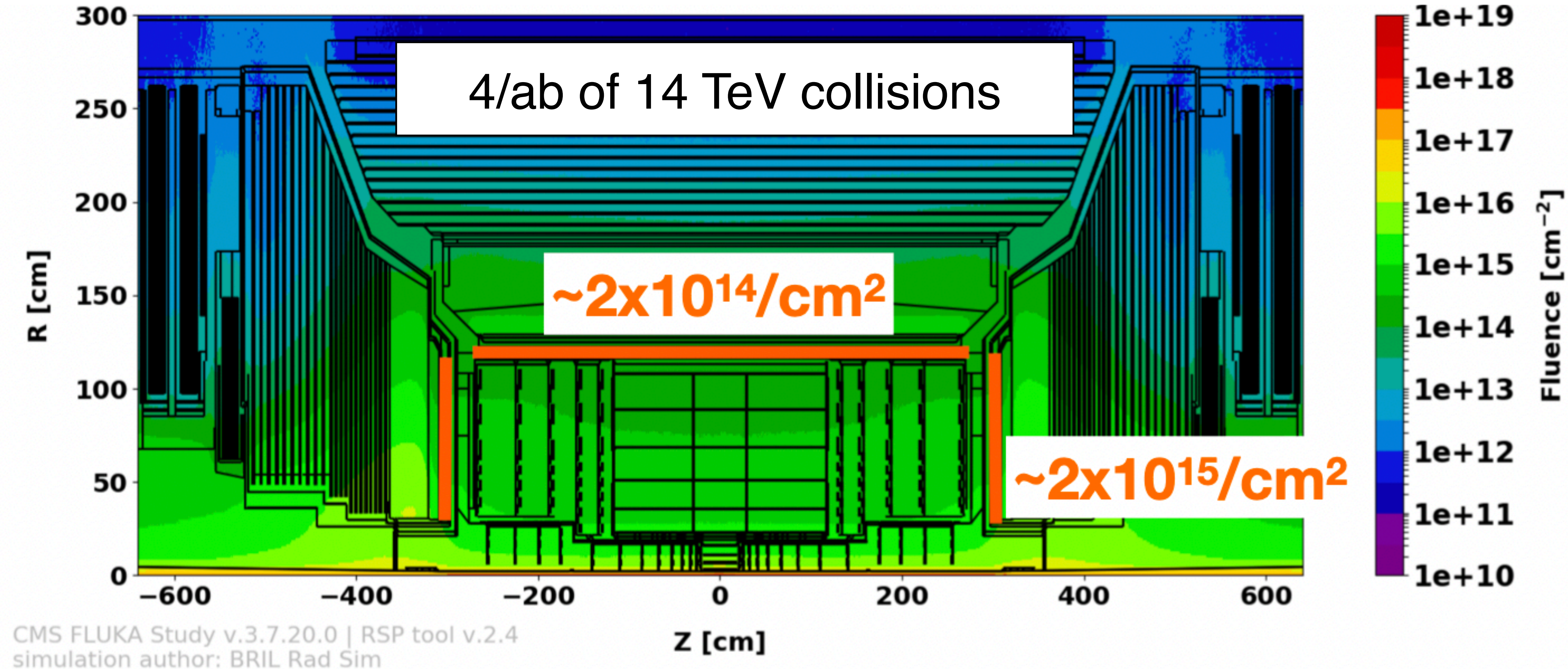


Typical collision at the LHC start (Pileup=2)



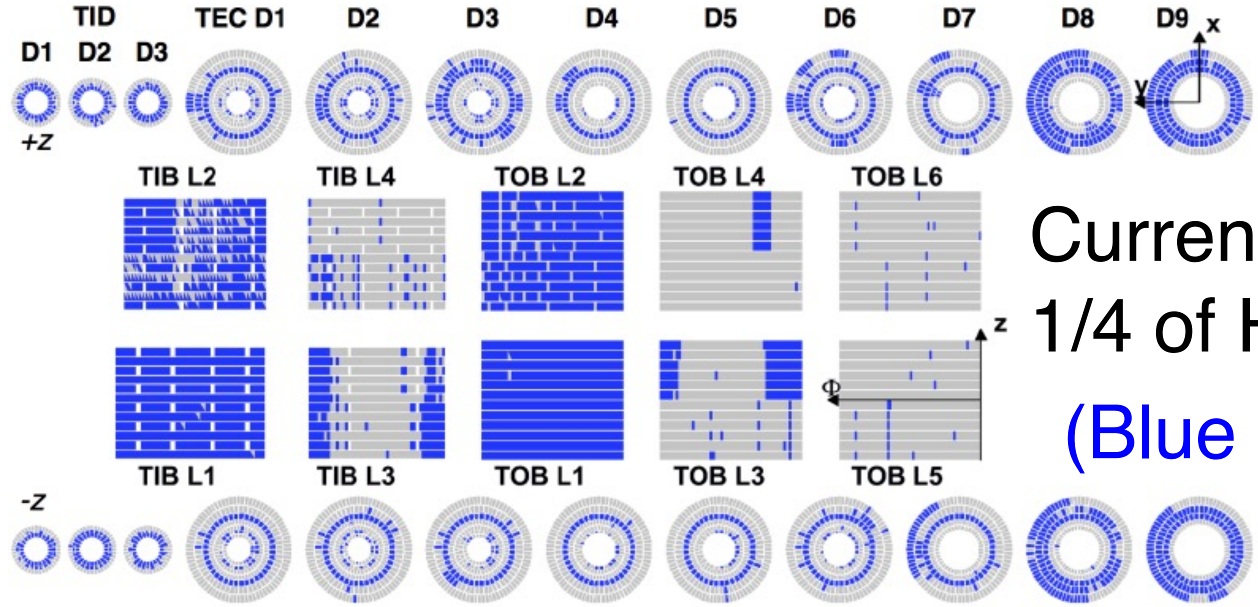


Challenges of High-Luminosity (II)



Detectors must cope with radiation doses up to 12 MGy and 2e16 n_{eq}/cm^2.

Largest burden on tracker and forward calorimeters.



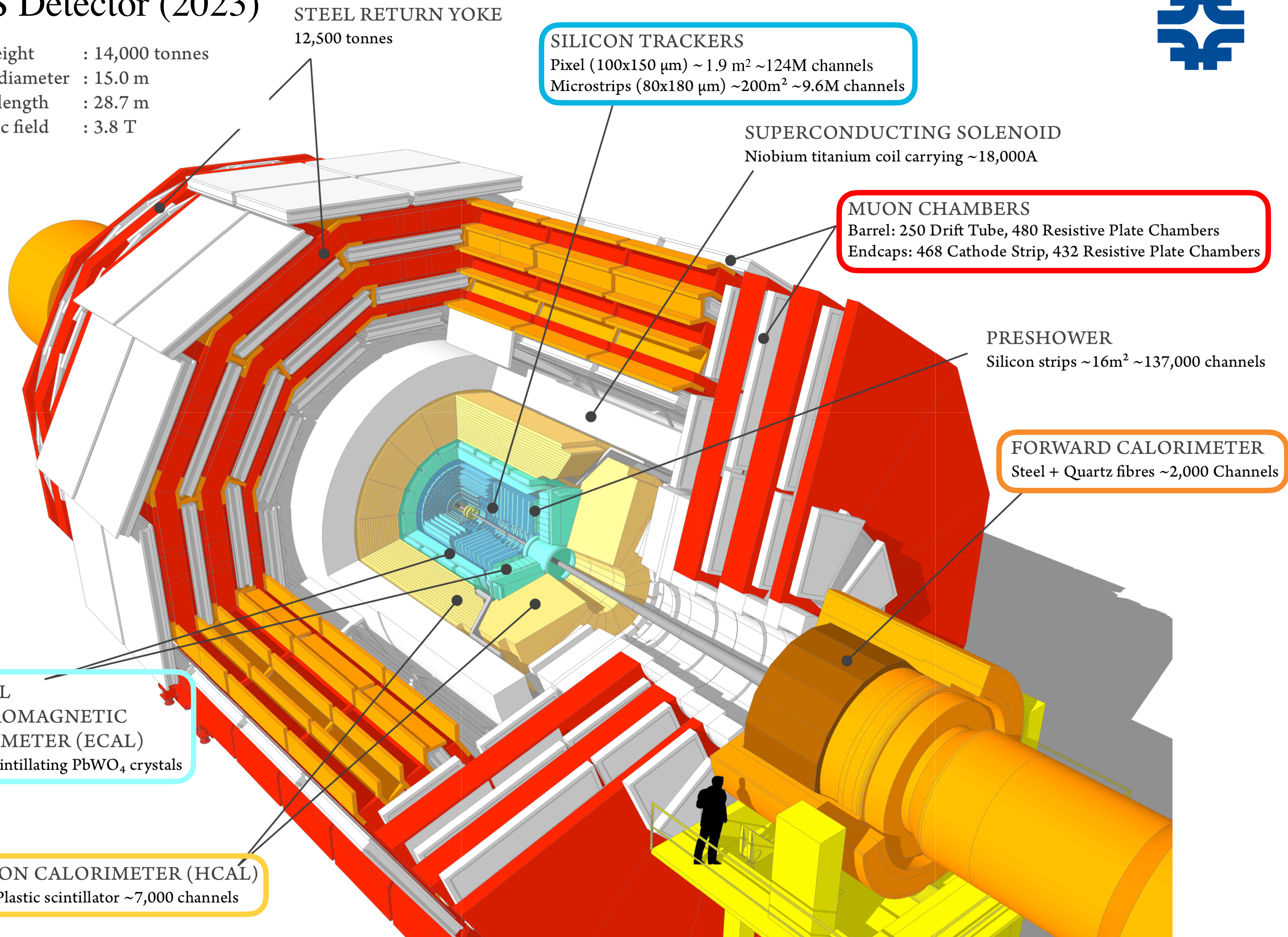
Current tracker after 1/4 of HL-LHC dose!

(Blue don't survive)

Upgrades:
Refreshing CMS for HL-LHC

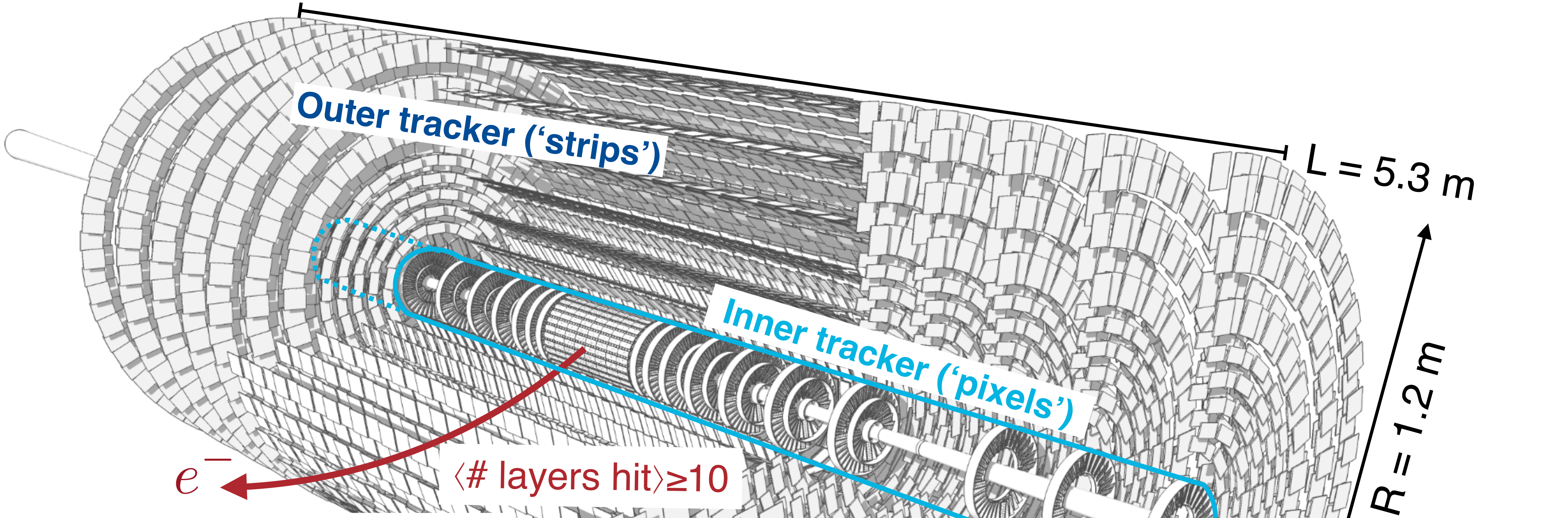
CMS Detector (2023)

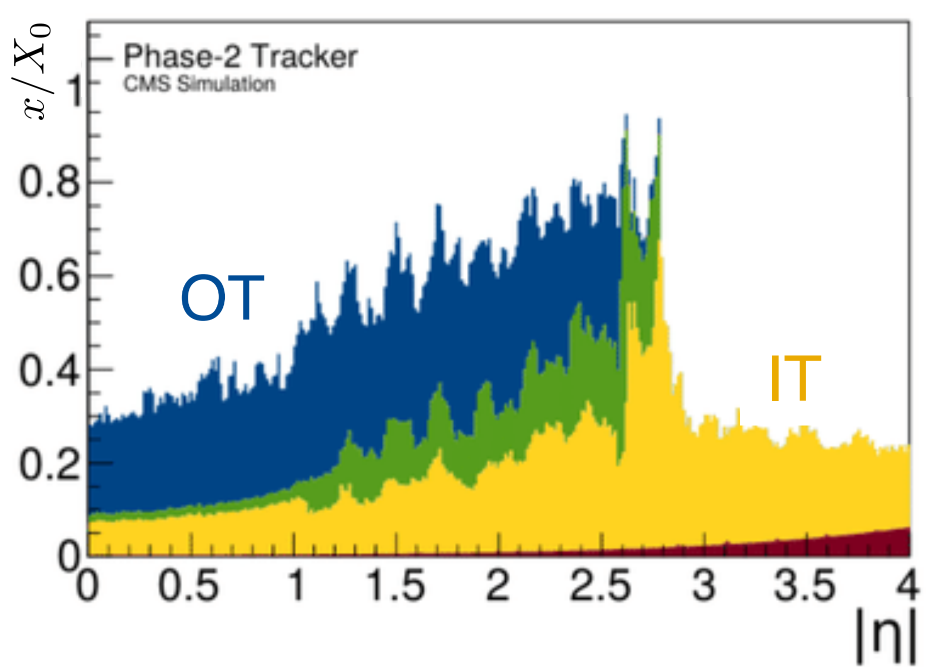
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T



Upgraded silicon tracker

Hermetic cylinders+disks of thin silicon sensors, immersed in a 4T B field.

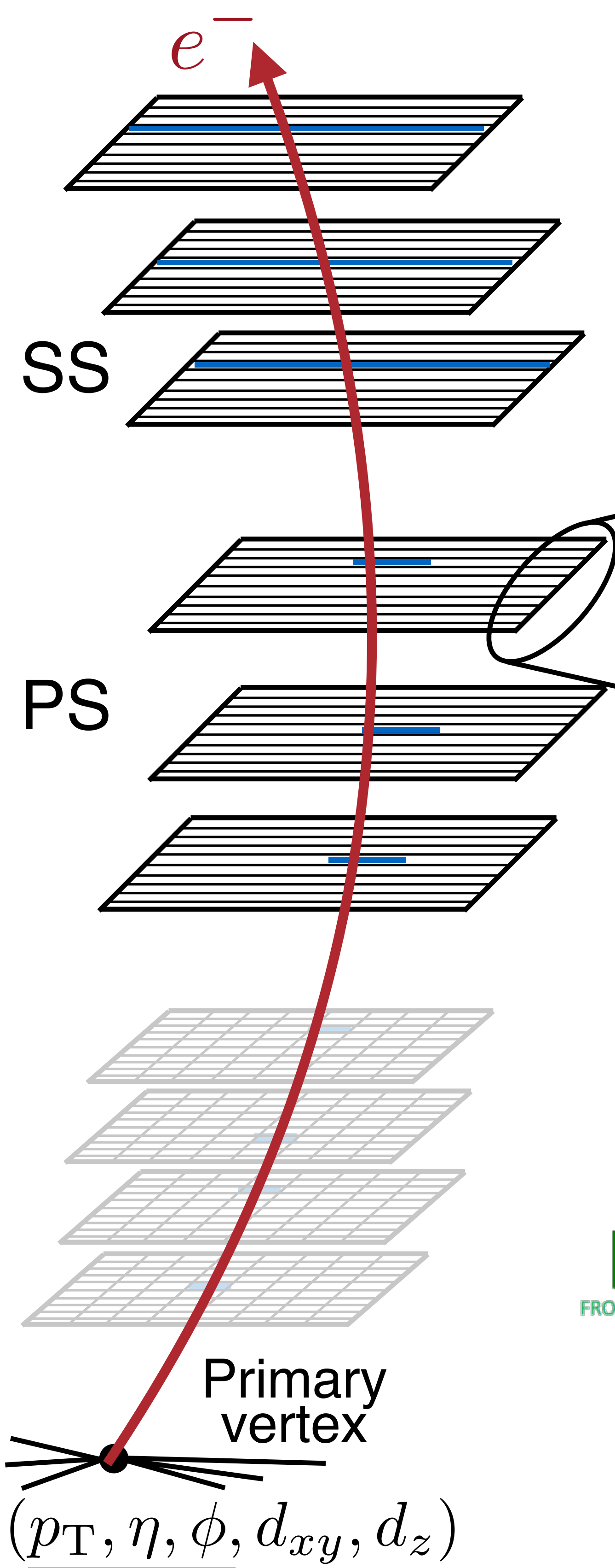




200 m² of active silicon
Low-mass prevents multiple scattering

Outer tracker:
9.6M→**213M channels**
Inner tracker:
124M→**1.9B channels**

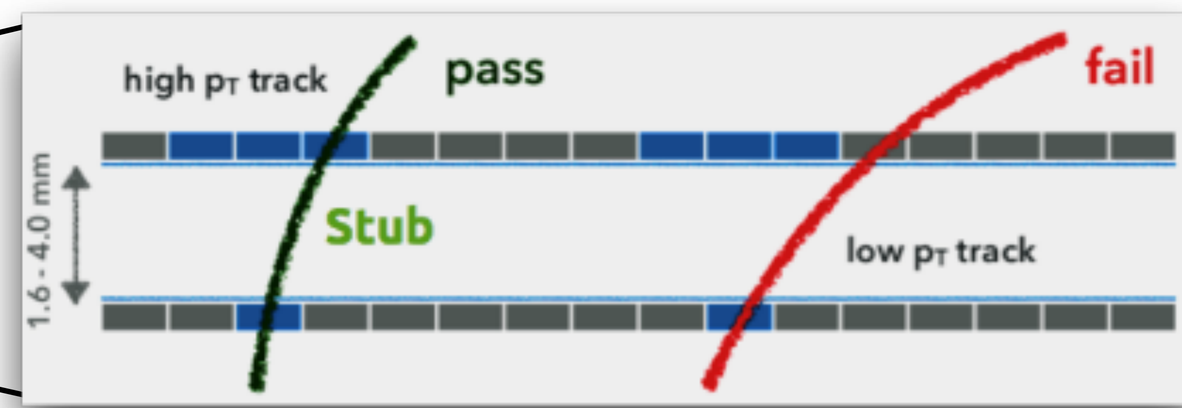
Outer tracker development



Large-radius sensors drive p_T measurement (lever arm).

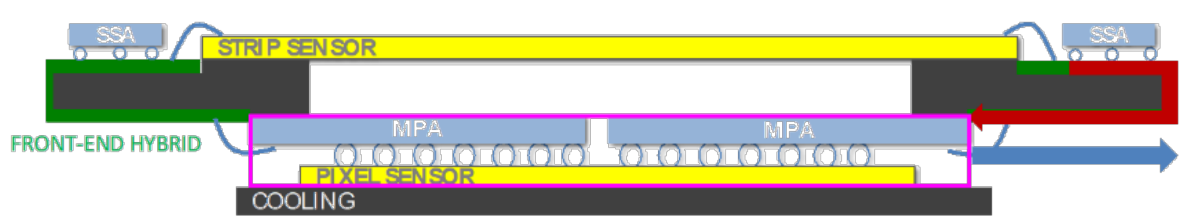
Outer layers: 2 stacked sensors with 5cm strips "SS".

Inner layers: strips (2.4cm) + macro-pixel (1.5mm) "PS".



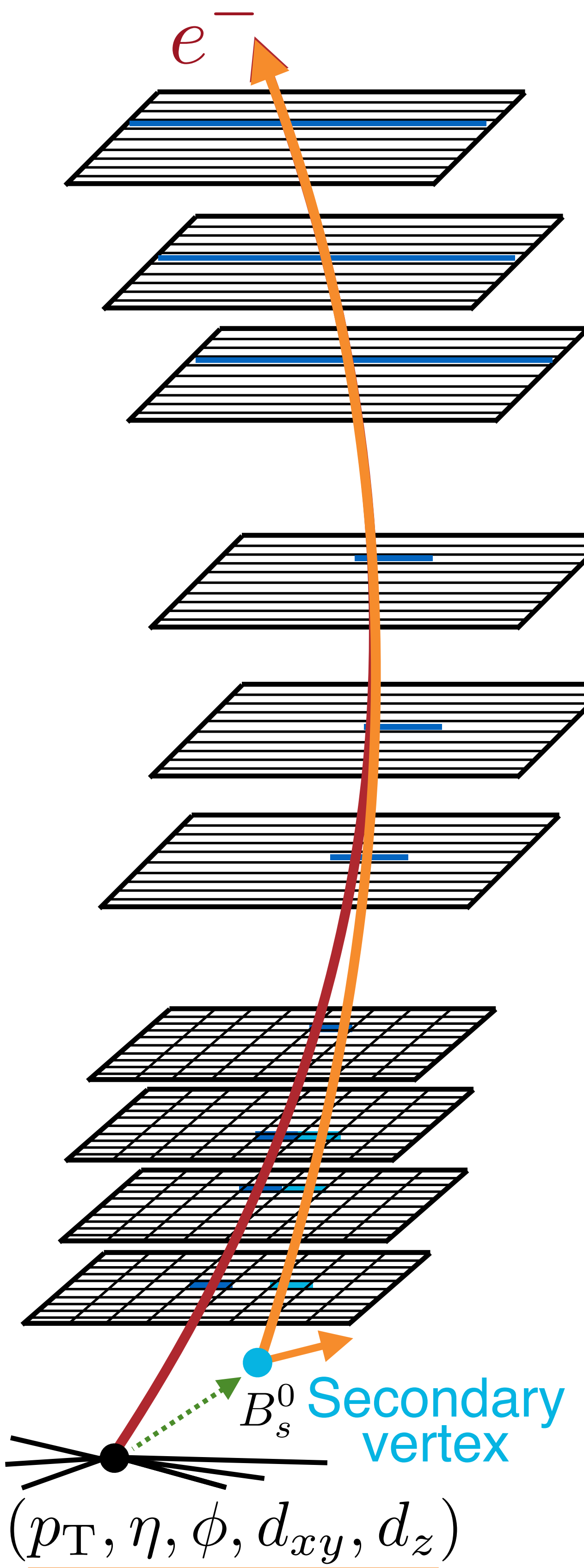
Double-layer strip modules provide local p_T measurement.

→ Intrinsic mechanism to filter hits from low-p_T tracks, allows high-p_T (2 GeV) track-finding in the trigger system!



Schematic and prototype of a "MacroPixel+Strip" module

Inner tracker development



Small-radius sensors drive vertexing capabilities.

→ Primary interaction versus pileup collisions.

→ Secondary vertices from (e.g.) B hadron decays.

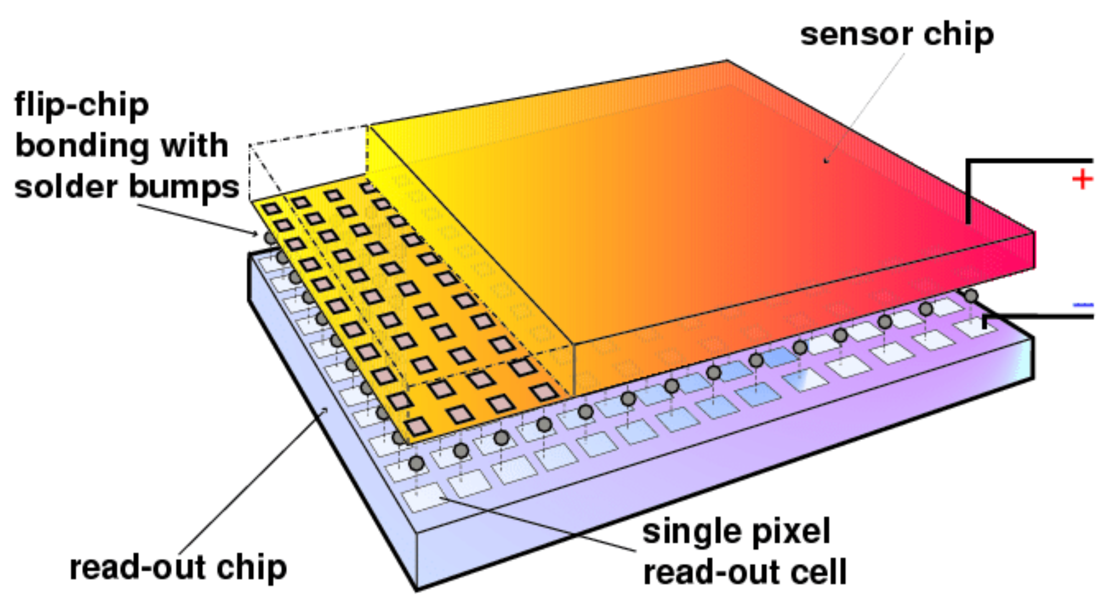
Pixel sensors: 150µm thickness, 50x50µm (100x25) pitch.

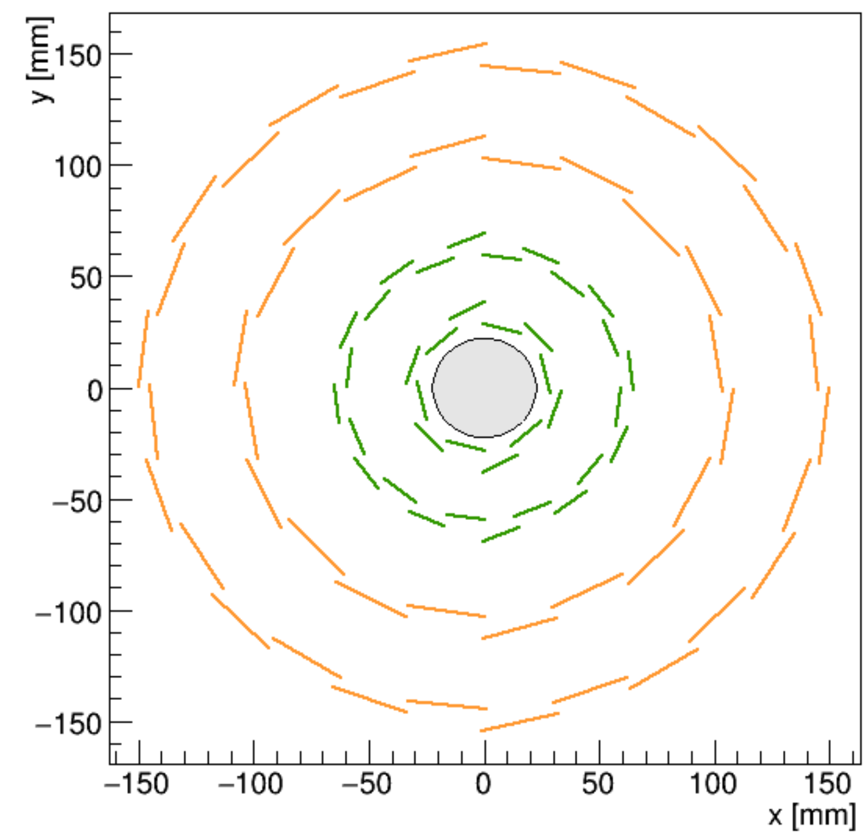
Hit rates up to 3.2 GHz/cm².

12.8µs buffers for trigger.

Thresholds down to 600e⁻.

Serial power distribution.





Innermost layer (r=3cm) on Be vacuum beam-pipe.

High-precision timing detectors

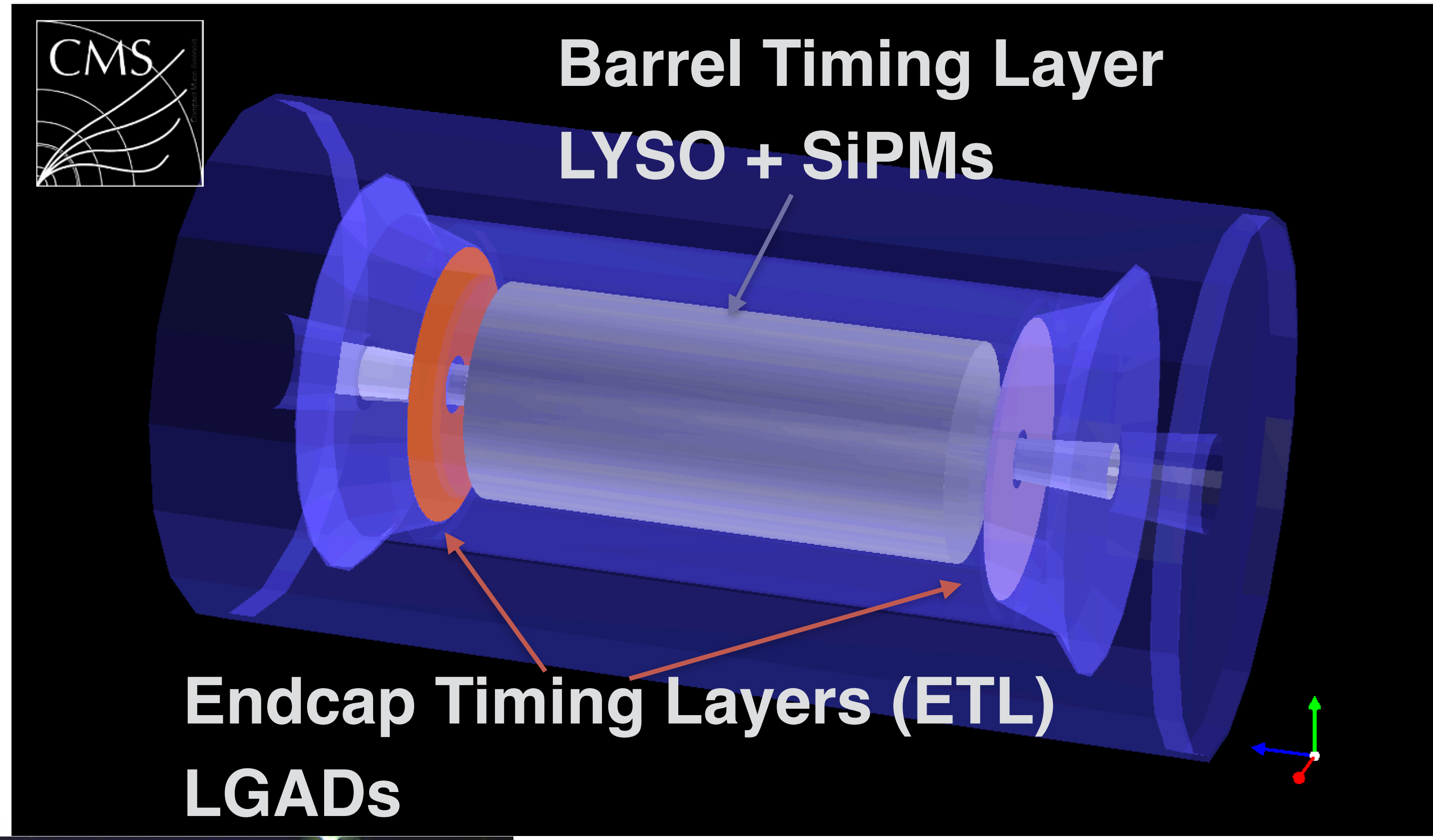
Completely new detector targets 30-40 picosec/track.

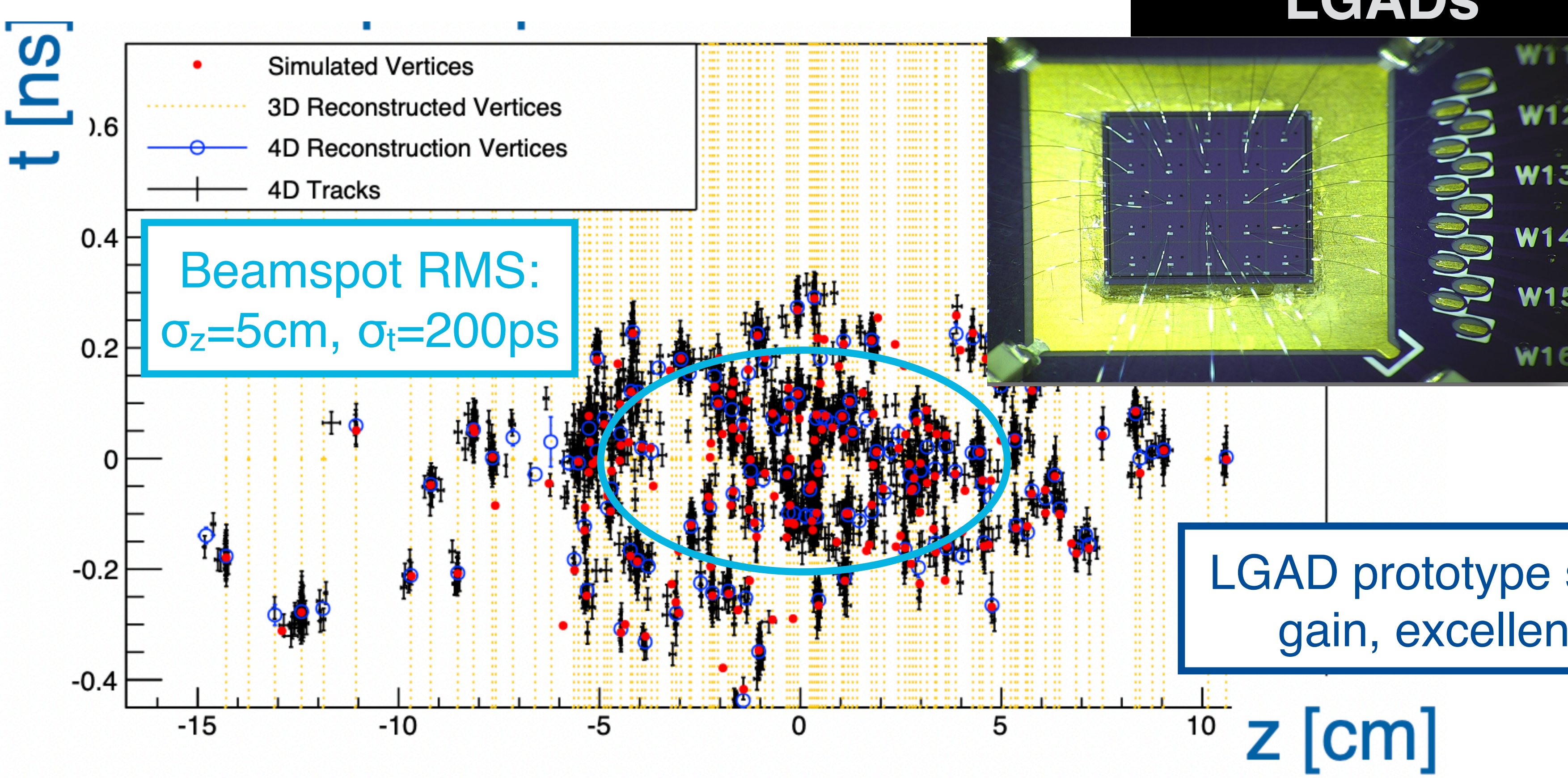
→ Pileup vertex separation

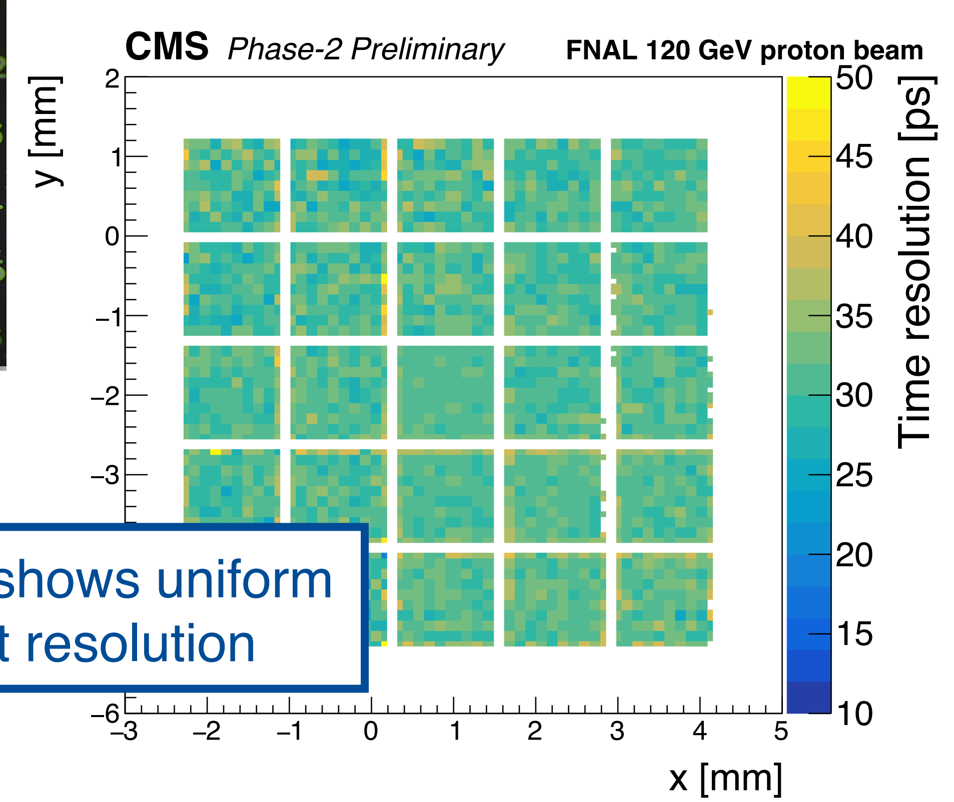
→ Particle ID

→ BSM long-lived particles

Demonstrates key tech for future colliders: 4D tracking (next talk)!







LGAD prototype shows uniform gain, excellent resolution

High-granularity calorimetry

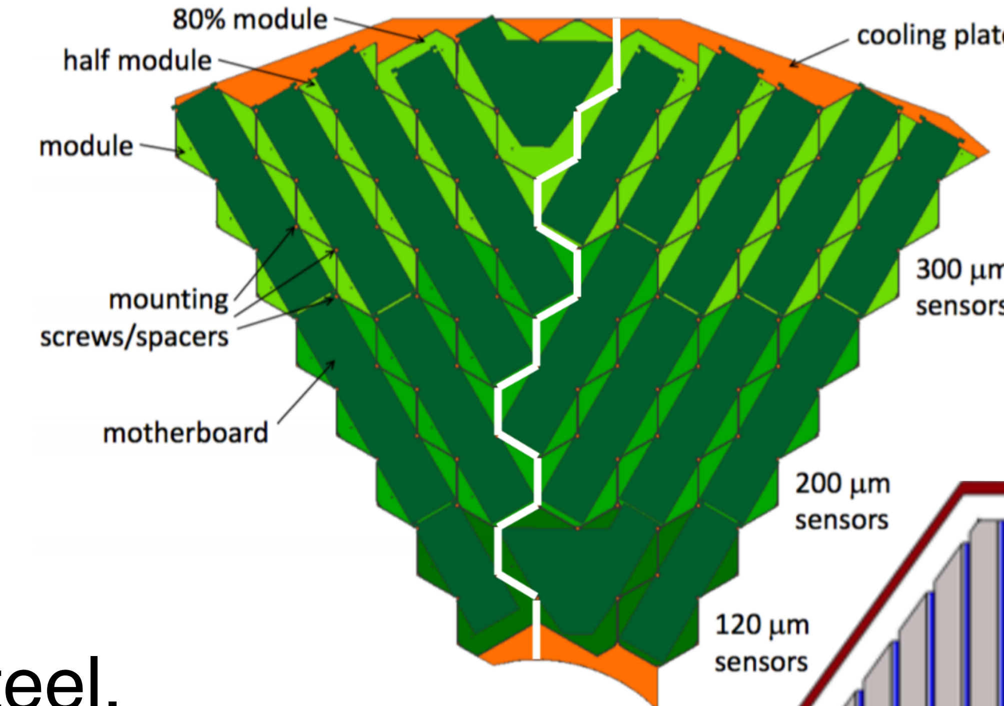
Solve high-radiation w/ Silicon @ -30°C.

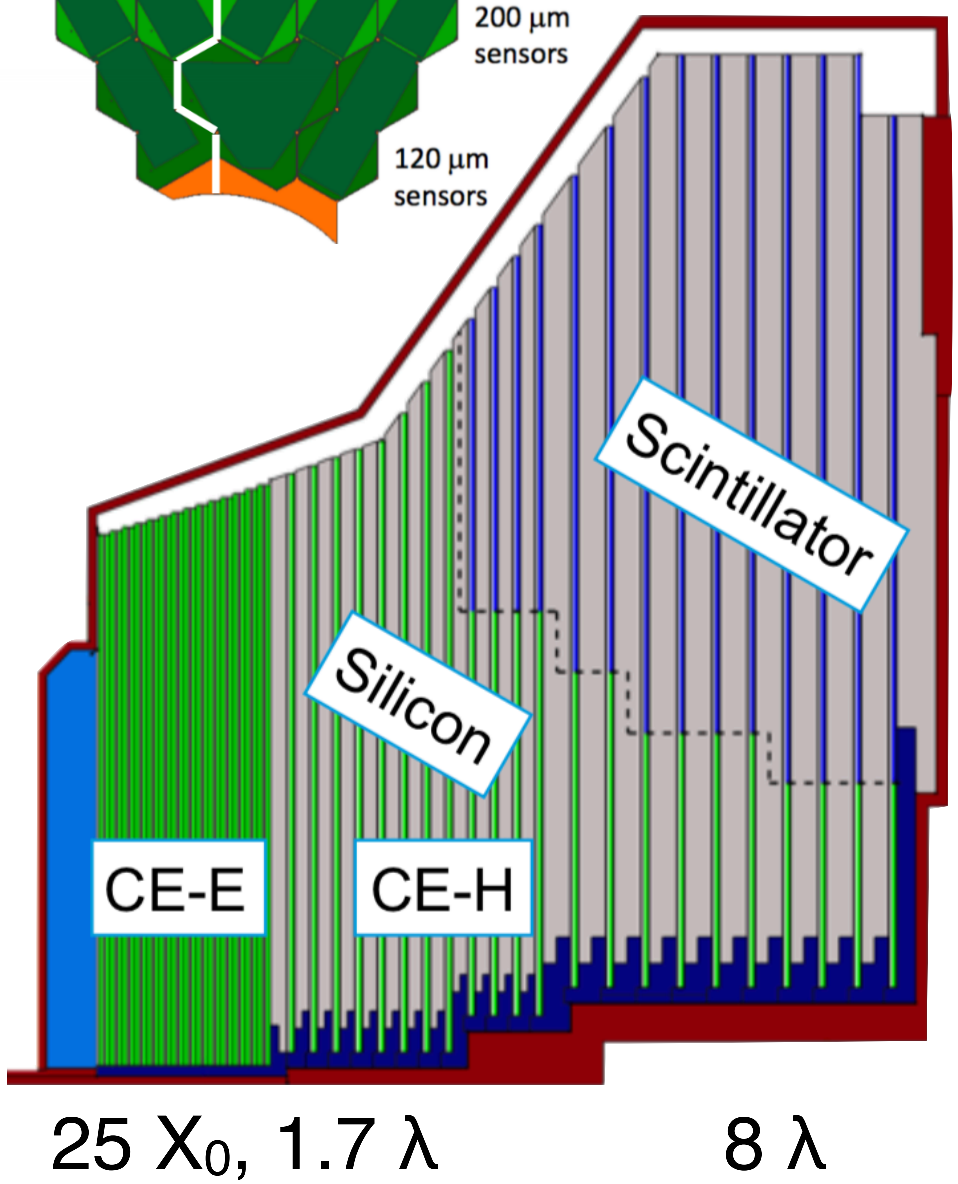
Novel 5D Imaging calorimeter concept:

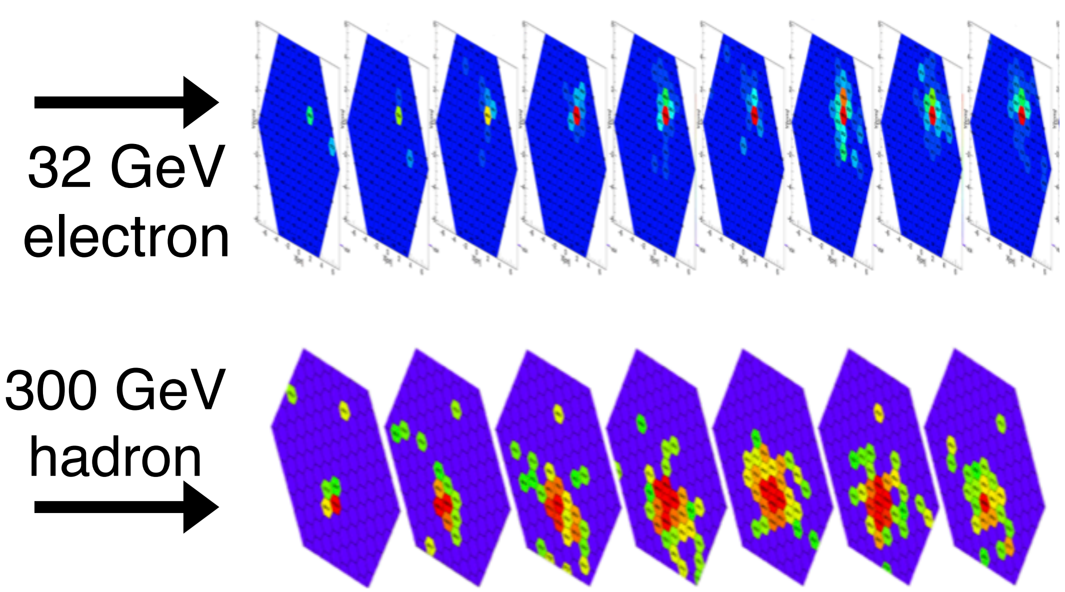
- **6.3M channels:** 0.5-2 cm², σ_t=50ps.
- High dynamic range: 1-100k MIPs
- 28 EM layers: Si w/ CuW/Pb absorber.
- 22 Had layers: 8 Si + 14 SiPM w/ S. Steel.

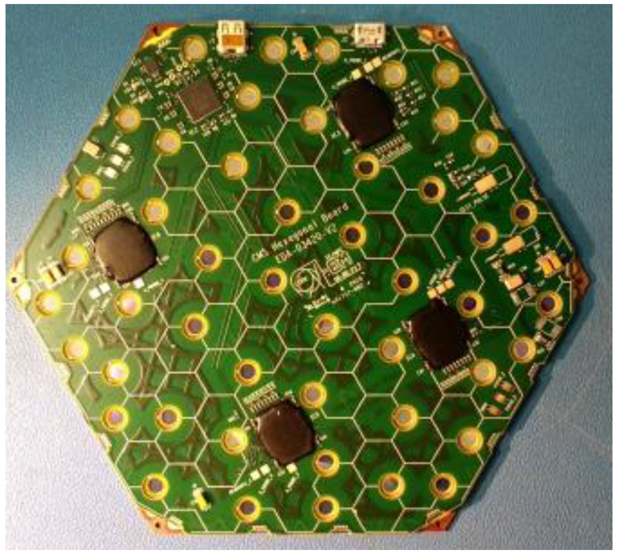
Extends physics capabilities at high-|η|:

- VBF jets, $e^{\pm}$ reco, π^0/γ separation, p_T-miss









New muon detectors, electronics

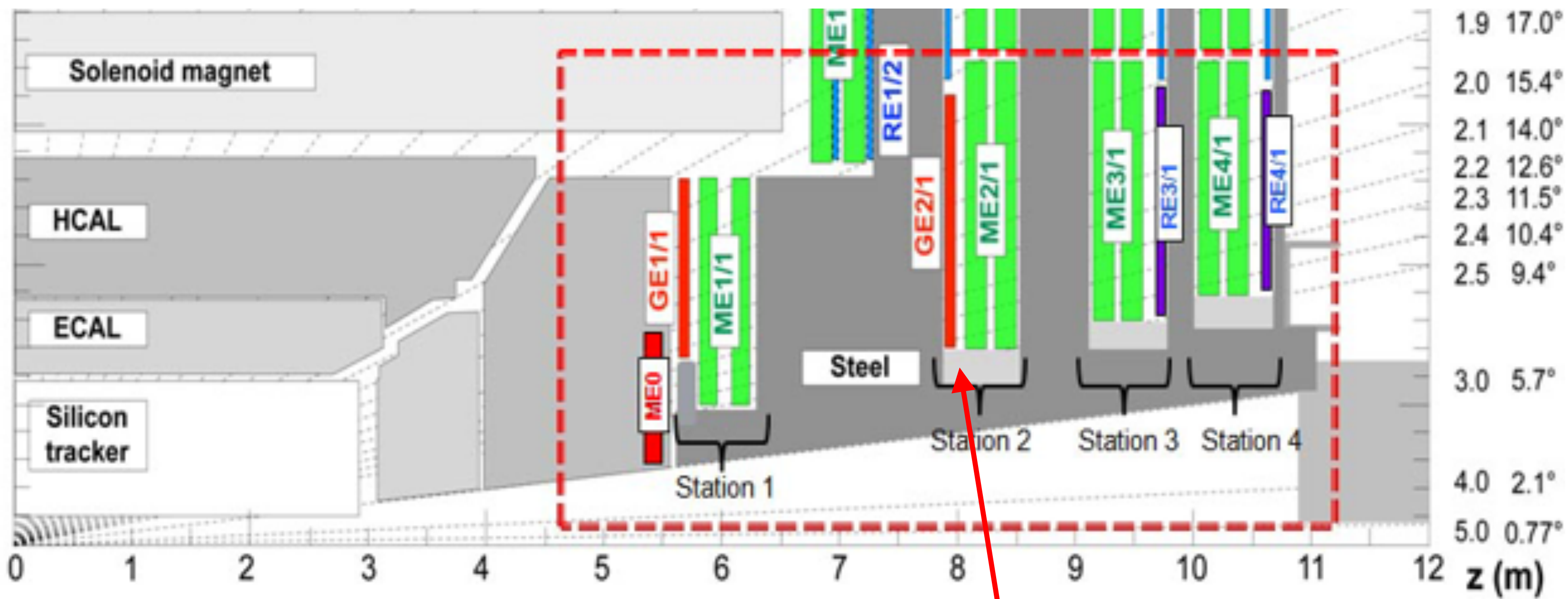
Range of improvements to trigger capabilities and better angular coverage.

New detectors:

→Add RPCs: 1.5<|η|<2.4

→New GEMs: 2.4<|η|<3

Integrating into existing CSC track-finding logic.



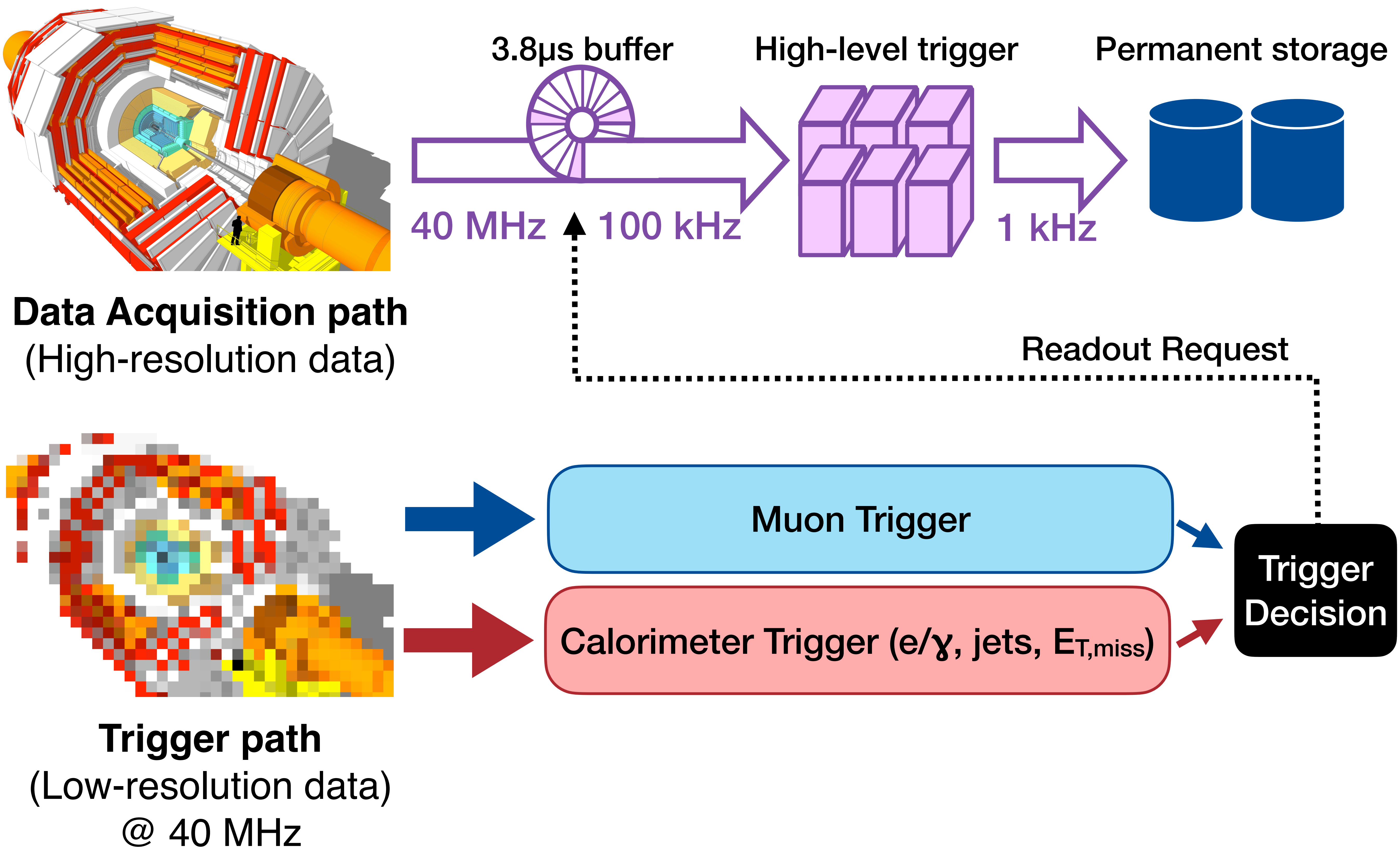
New electronics:

Front-end & back-end replaced for Drift Tube (barrel) and CSCs.

High-speed optics to enable higher rates!

→ Trigger on softer & farther-forward muons!

CMS Trigger Design (2023)



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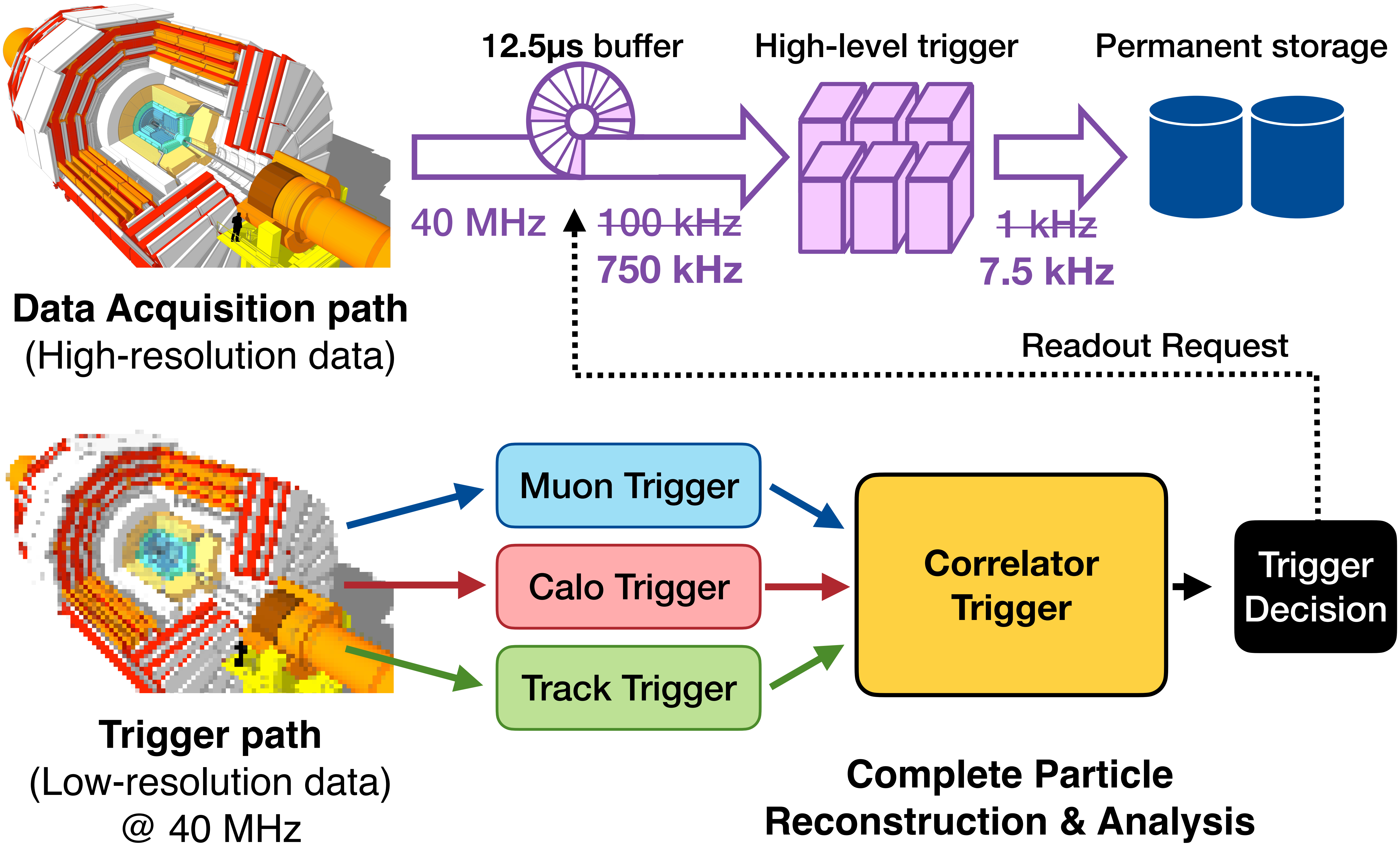
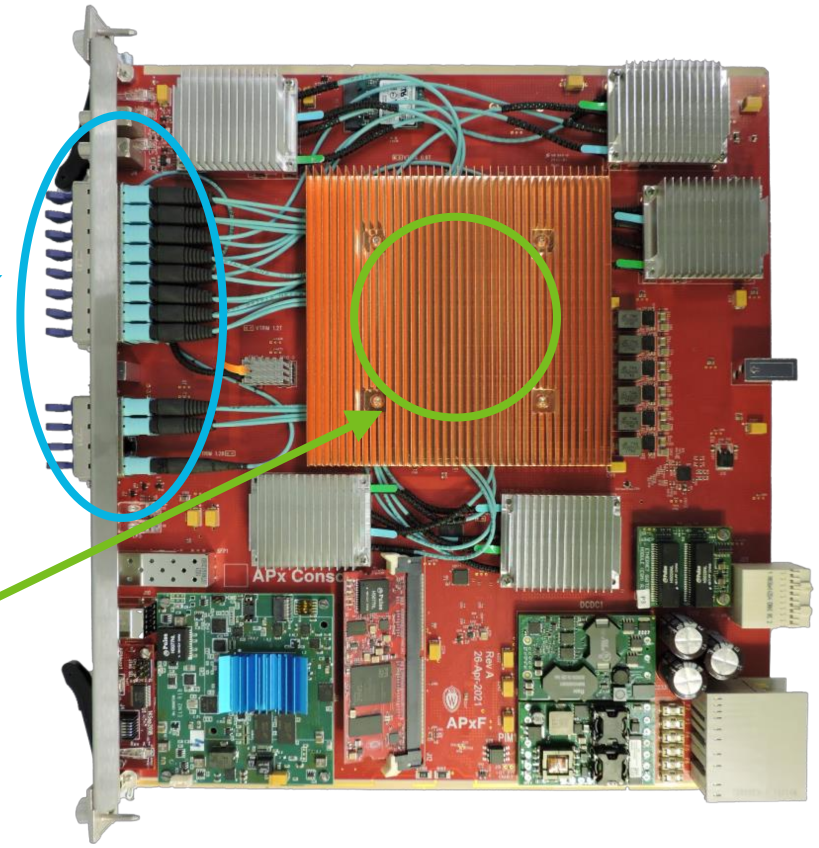


Level-1 Trigger system

One of many trigger processing boards:

- 120 x 28 Gbps optical links
- UltraScale+ FPGA (12k DSP slices)

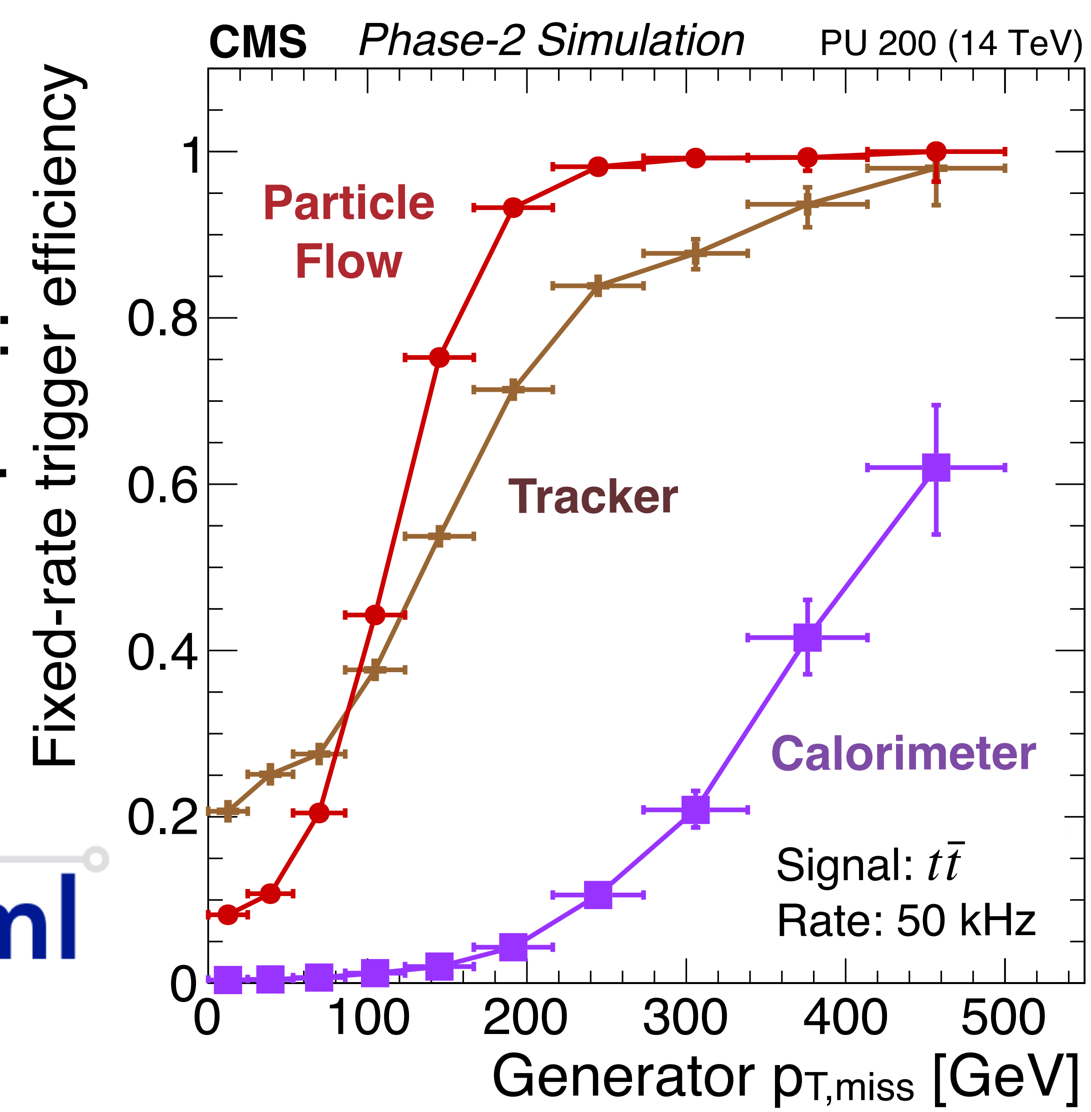


Example: Correlator Trigger

→ 66 processing boards

→ 6-18x time-multiplex factor

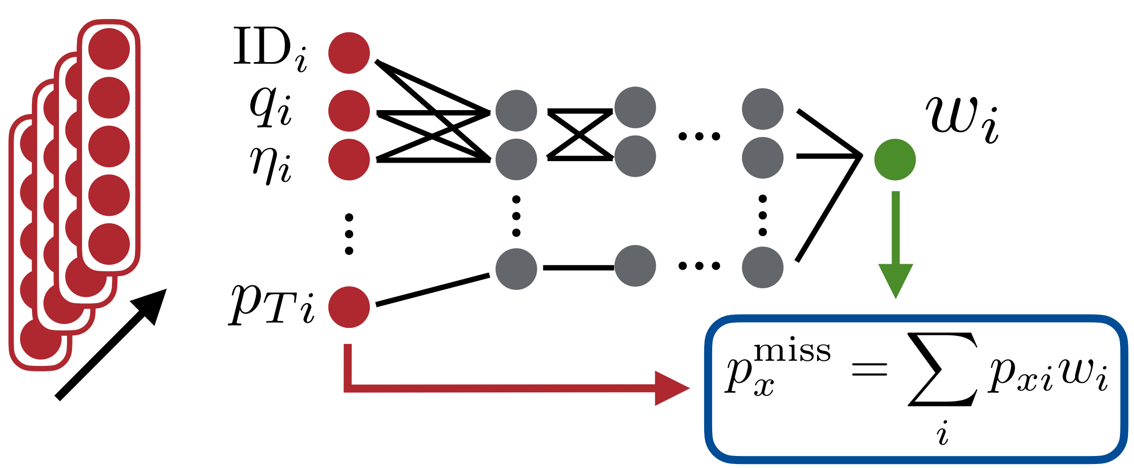
→ 1+1.5μs latency budget



Building all particles allows for complex algos:

Jet-finding, τ ID, missing-p_T w/ neural nets,…

HLS: physicists can program FPGAs w/ C++

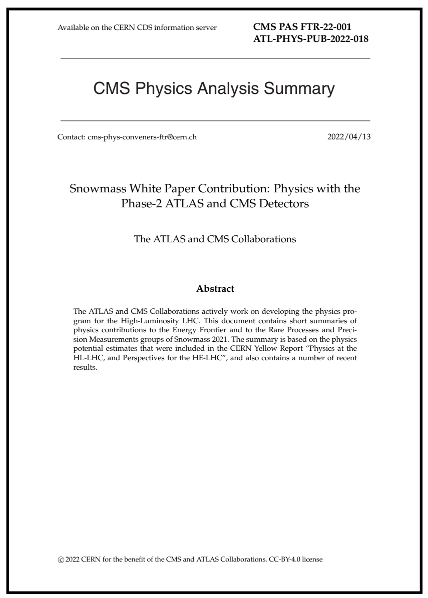


hls4ml

To HL-LHC, and beyond!

High-Luminosity data will dramatically enrich the physics potential of CMS.

Highlights: precision Higgs program & many opportunities for New Physics!


Available on the CERN CDS information server

CMS PAS FTR-22-001
ATL-PHYS-PUB-2022-018

CMS Physics Analysis Summary

Contact: cms-phys-conveners-ftr@cern.ch 2022/04/13

Snowmass White Paper Contribution: Physics with the Phase-2 ATLAS and CMS Detectors

The ATLAS and CMS Collaborations

Abstract

The ATLAS and CMS Collaborations actively work on developing the physics program for the High-Luminosity LHC. This document contains short summaries of physics contributions to the Energy Frontier and to the Rare Processes and Precision Measurements groups of Snowmass 2021. The summary is based on the physics potential estimates that were included in the CERN Yellow Report "Physics at the HL-LHC, and Perspectives for the HE-LHC", and also contains a number of recent results.

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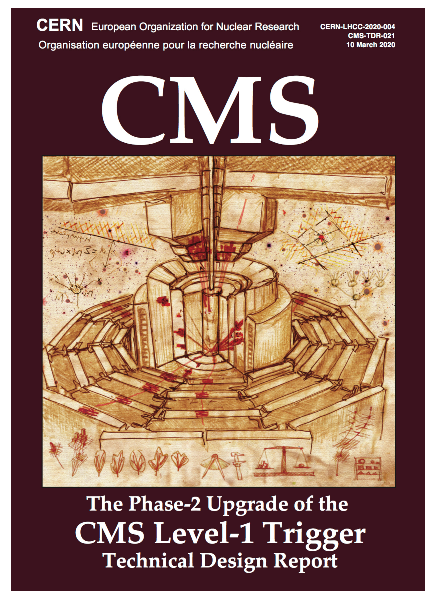

For more details:

→ CERN Yellow Report

→ ATLAS/CMS Snowmass reports

→ TDRs for each detector upgrade

Upgrade projects are in a critical construction period, targeting **data in 2029!**

Fermilab & US CMS are leading efforts in many areas: see SiDet tour!

The legacy of the HL-LHC looms large over Future Collider discussions:

What measurements are needed to complement LHC results?

Can Future Detectors build on LHC tech? Where is more R&D needed?