

Discovering new physics with HL-CMS

Seeing LHC collisions through new eyes

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Marietta Blau Institute Monthly Colloquium

Vienna, Austria

9 September, 2026

Goals for today

Introduce CMS and convince you that discovering new physics in existing CMS data is absolutely possible

Introduce the incredible opportunity and challenge of HL-LHC

Introduce HL-CMS and convince you that meeting the HL-LHC challenge will create fundamentally new opportunities for discovery

LHC and CMS

Large Hadron Collider

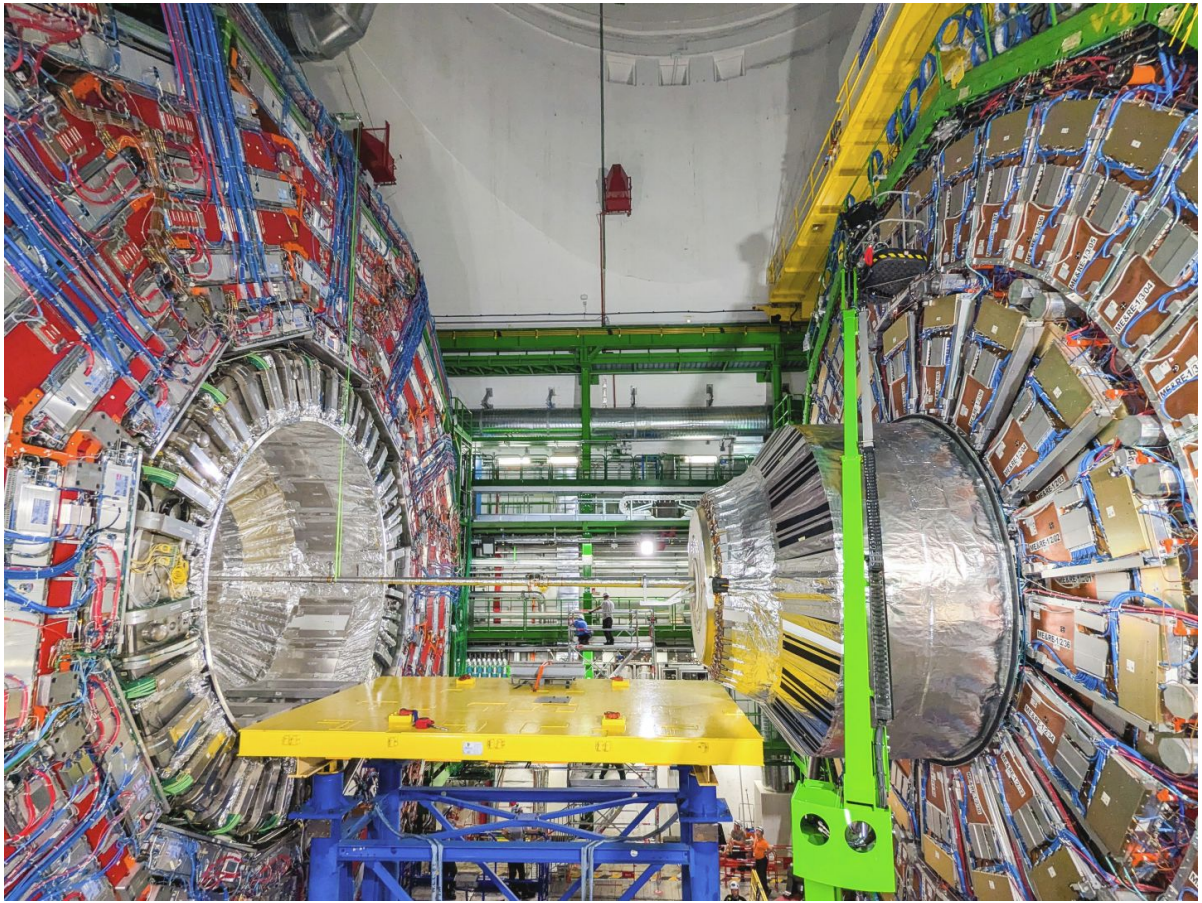


Things to know about LHC to enjoy this talk

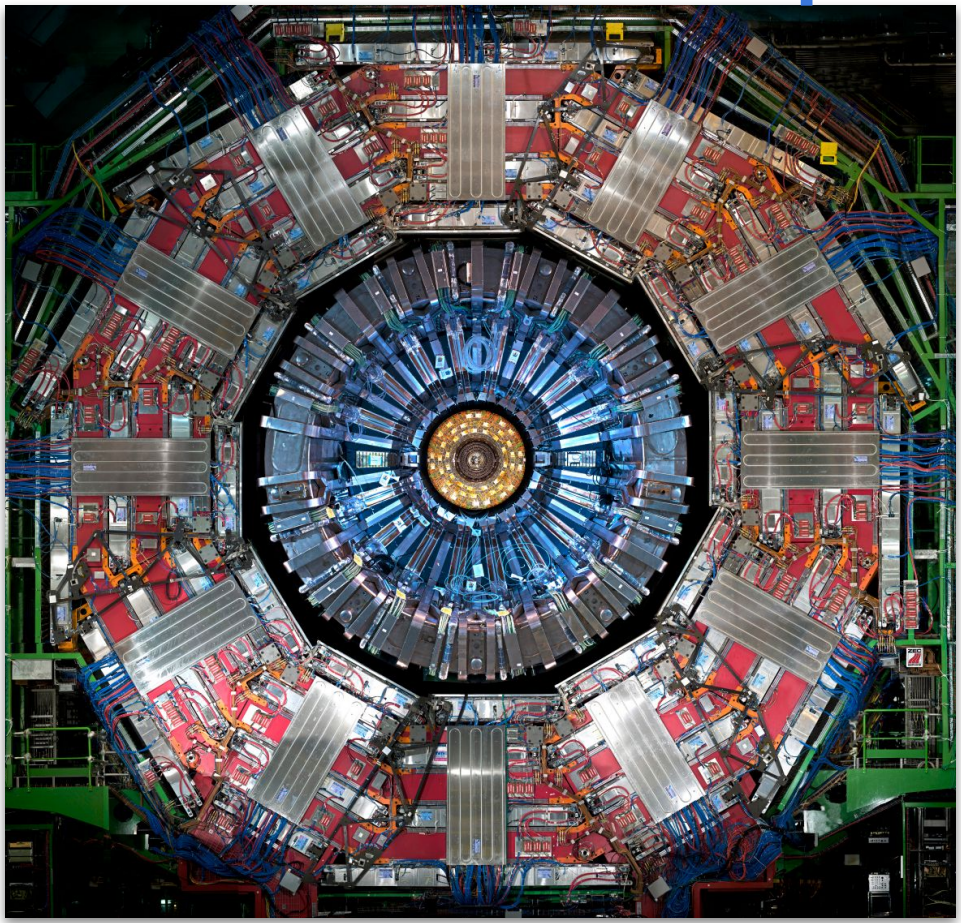
- Humanity's window into the electroweak scale
- Creating opportunities for O(TeV) interactions 40 million times per second since 2010
- Just wrapped up (wildly successful) LHC Run 3
- Upgrading now to massively increase overall collision rate

  → High-Luminosity LHC starts in 2030

CMS

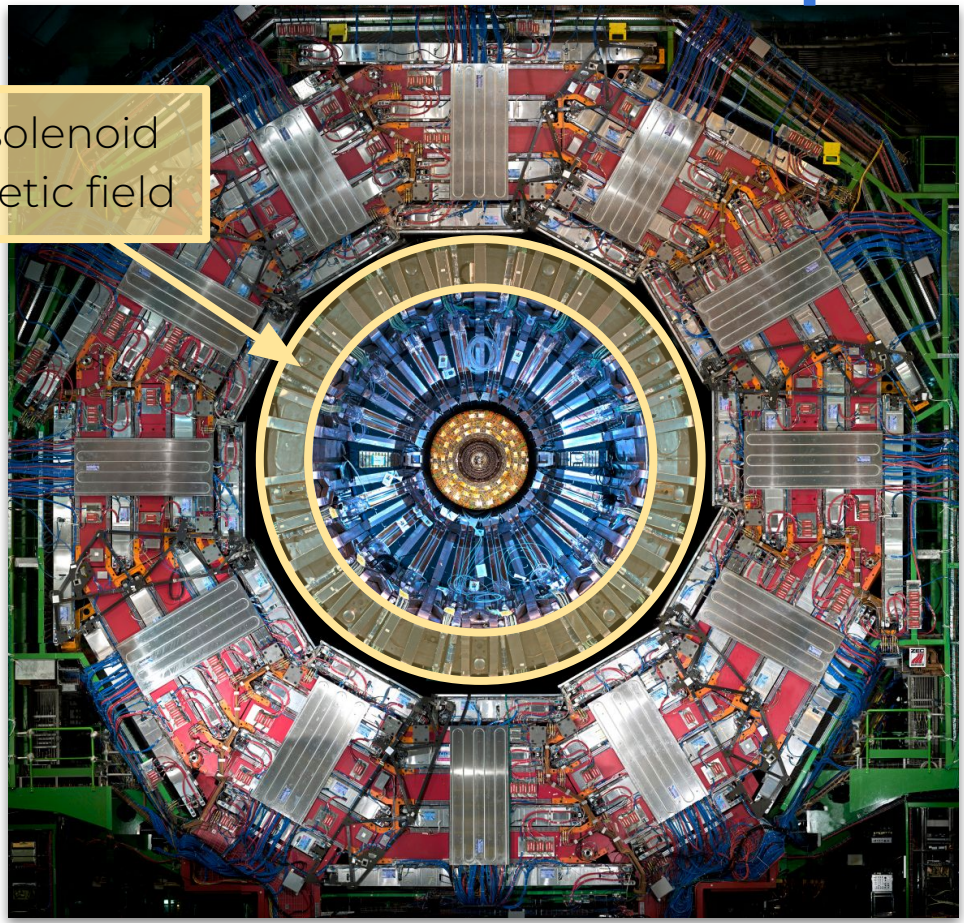


How does CMS detect particles?



How does CMS detect particles?

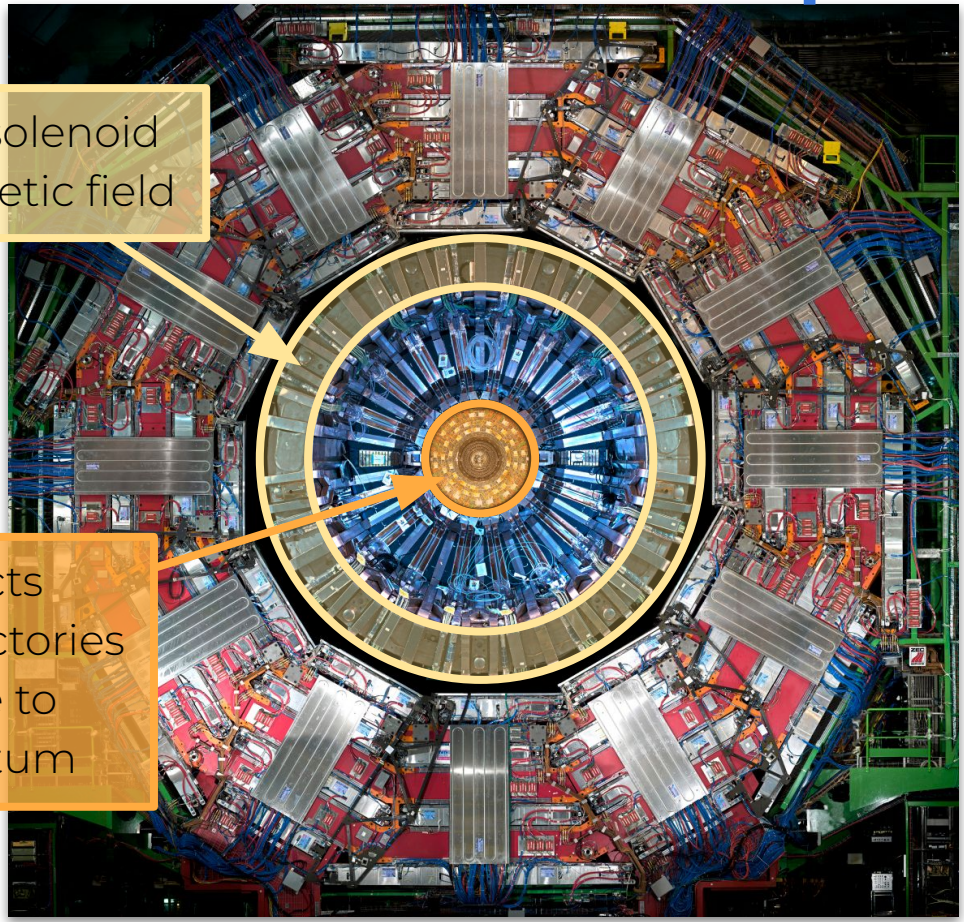
Superconducting solenoid provides 3.8T magnetic field



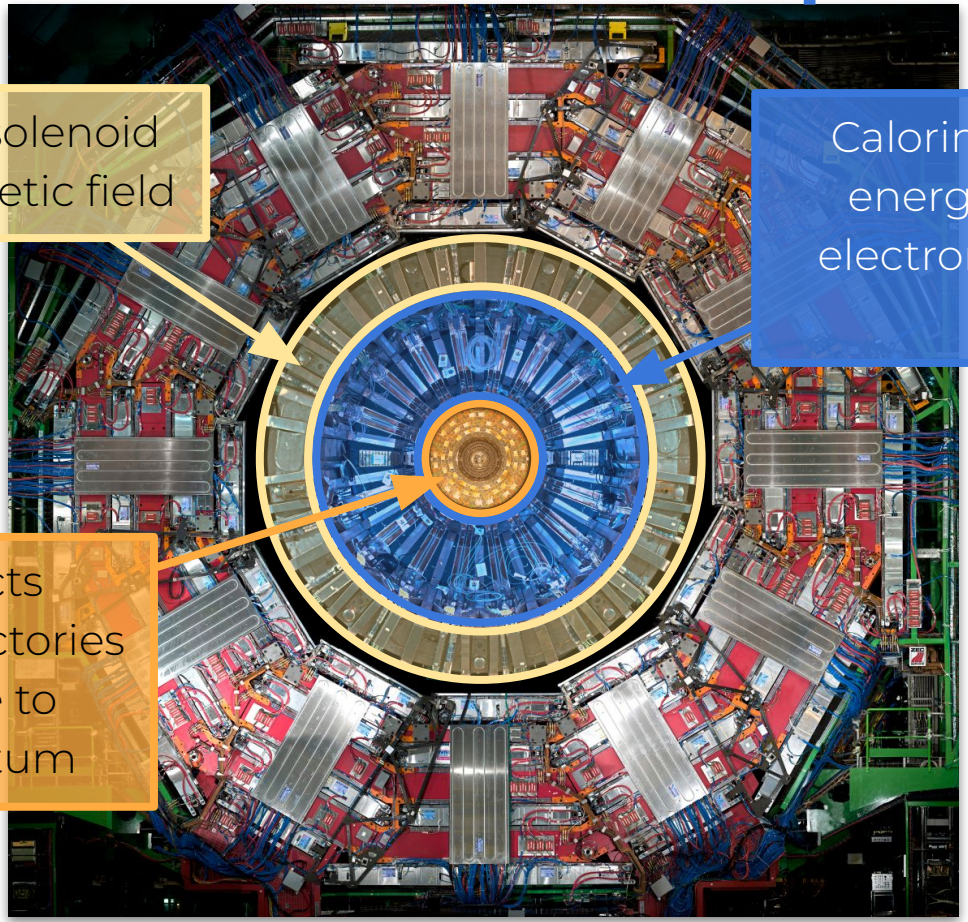
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Tracker reconstructs charged particle trajectories and uses curvature to determine momentum



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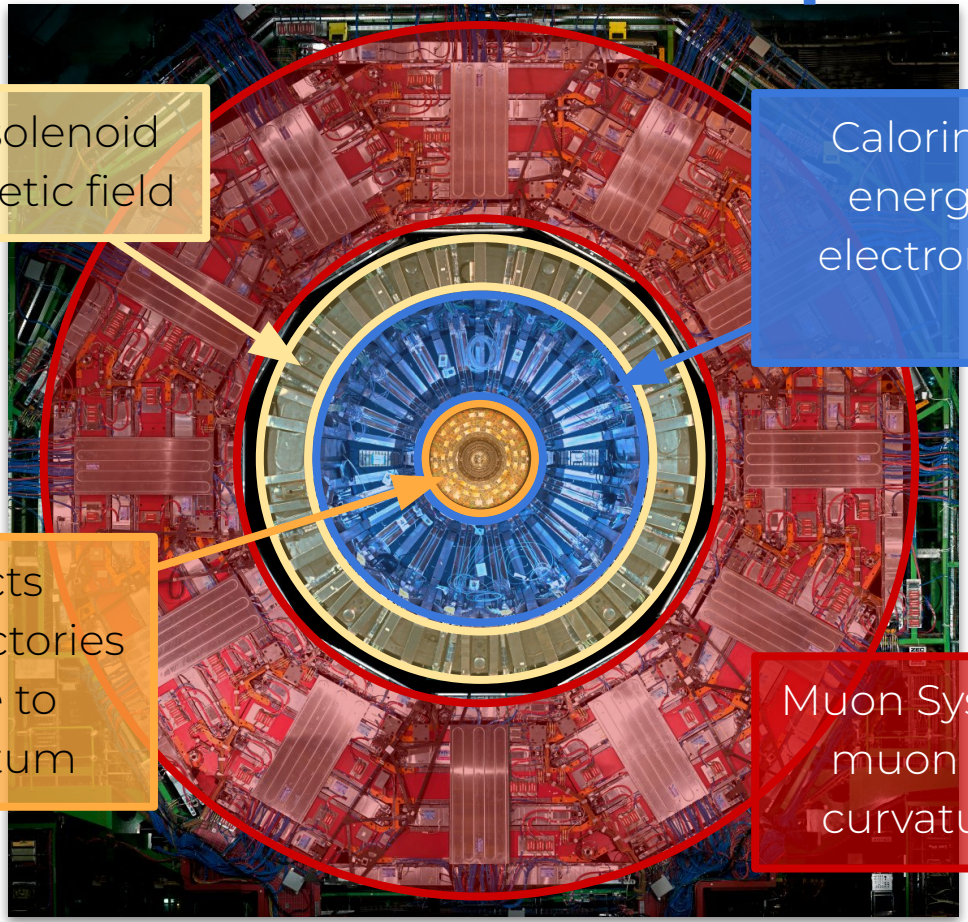


Superconducting solenoid provides 3.8T magnetic field

Calorimeters measure energy of showering electrons, photons, and hadrons

Tracker reconstructs charged particle trajectories and uses curvature to determine momentum

How does CMS detect particles?



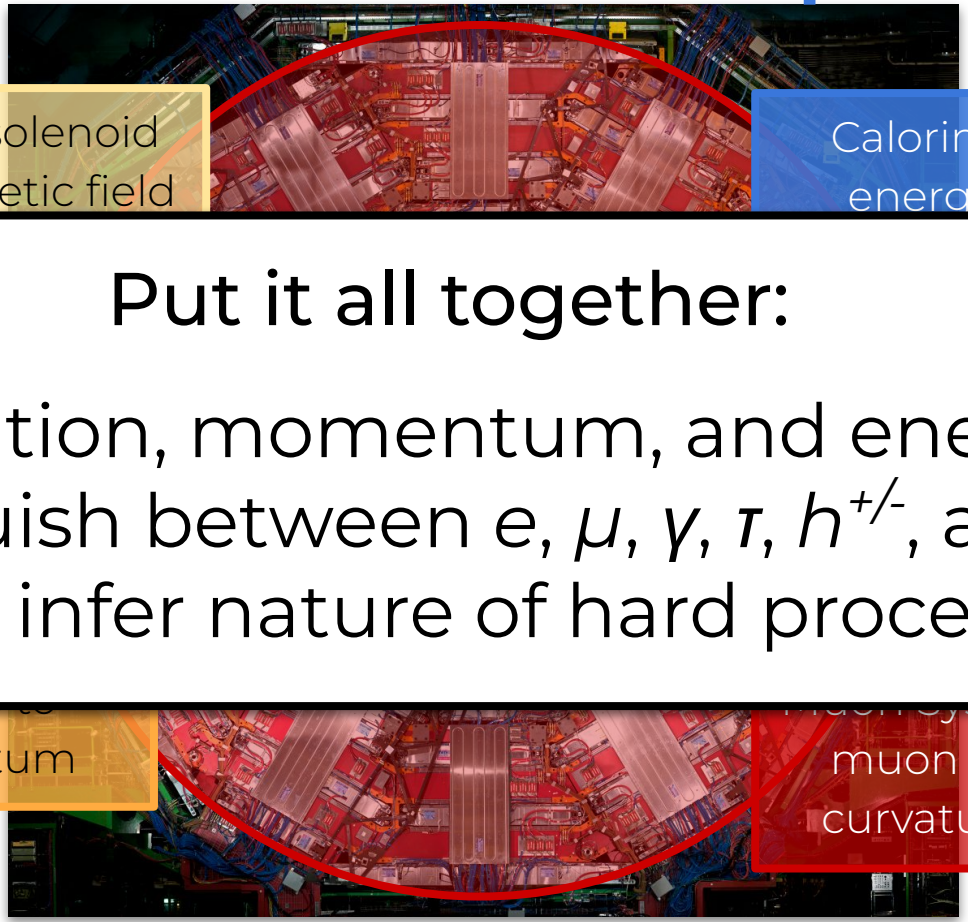
Superconducting solenoid provides 3.8T magnetic field

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Tracker reconstructs charged particle trajectories and uses curvature to determine momentum

Muon System reconstructs muon trajectories and curvature in return flux

How does CMS detect particles?



Superconducting solenoid provides 3.8T magnetic field

Calorimeters measure energy of showering

Tr… charg… an… determine momentum

…ructs muon trajectories and curvature in return flux

Put it all together:

Use position, momentum, and energy to distinguish between e, μ, γ, τ, $h^{+/-}$, and h^{0} and infer nature of hard process

Not pictured: Trigger

Problem: Not possible* to analyze every bunch crossing

- Raw data would be ~10^{10} Terabytes per year
- Also limitations associated with data transfer and computation

*...yet

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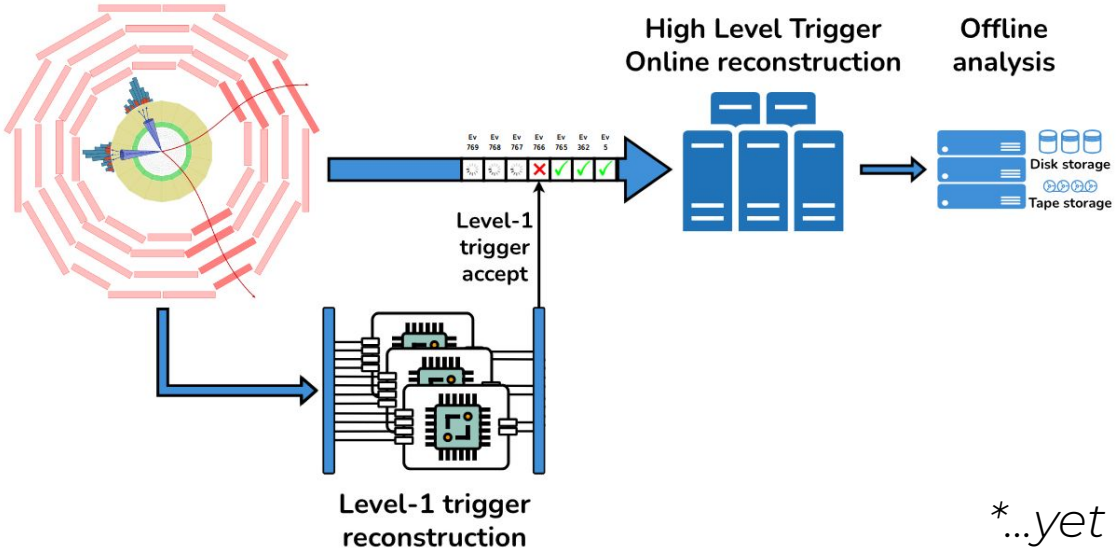
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Solution: use partial event information to select “interesting” events

- L1: Use coarse Calorimeter and Muon System information to go from 40MHz to 100kHz

- HLT: Use complete but imperfectly reconstructed information to go from 100kHz to ~1kHz



*...yet

Not pictured: Trigger

Problem: Not possible* to analyze every bunch crossing

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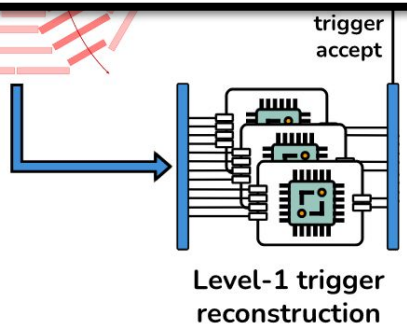
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99.99% of events are thrown away

…a lot rests on our definition of “interesting”

reconstructed information to go from 100kHz to ~1kHz





*…yet

Hunting for new physics with CMS

Three ways to discover new physics at colliders

1. New physics only manifests at higher energy scales
   → Hope to see hints in precision measurements
   → Build O(100TeV) collider ASAP

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   → Continue “standard” searches and measurements at HL-LHC

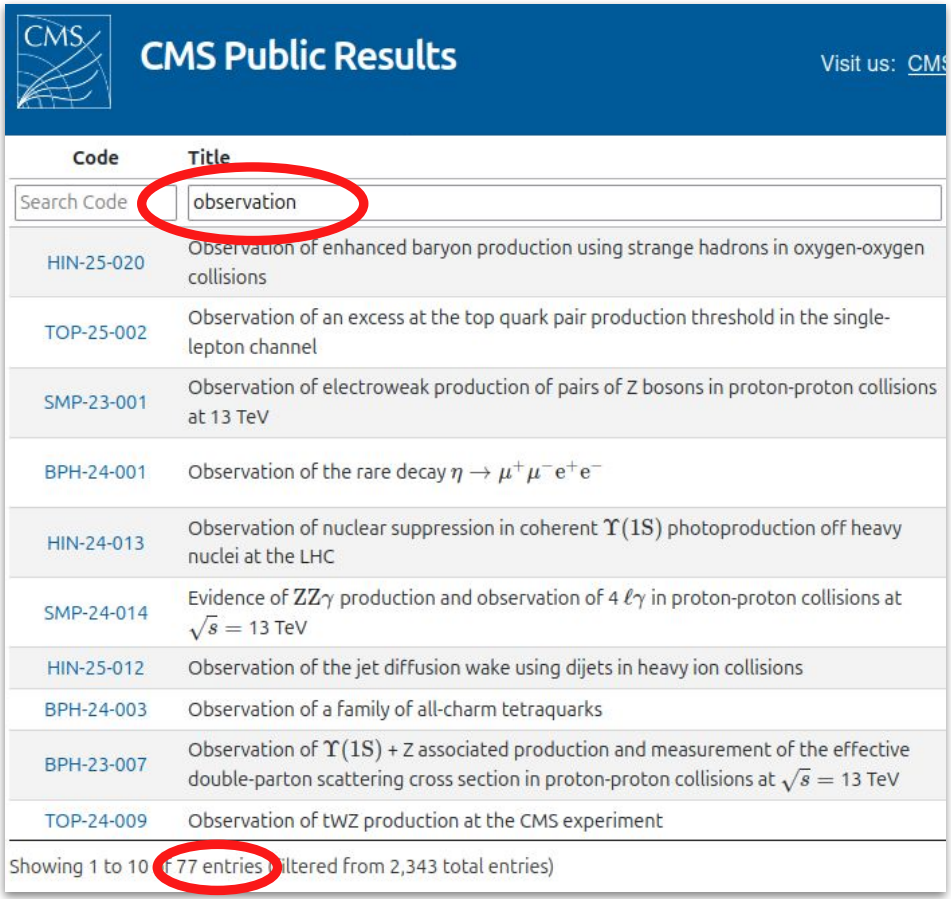
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2. New physics manifests at TeV scale but is very weakly coupled
   → Continue “standard” searches and measurements at HL-LHC

3. New physics manifests at TeV scale in ways we don’t expect
   → Confront the ways our biases, reconstruction algorithms, and detector design may blind us to new physics *already being produced*

An important reminder



CMS Public Results

Visit us: CMS

Code	Title
Search Code	observation
HIN-25-020	Observation of enhanced baryon production using strange hadrons in oxygen-oxygen collisions
TOP-25-002	Observation of an excess at the top quark pair production threshold in the single-lepton channel
SMP-23-001	Observation of electroweak production of pairs of Z bosons in proton-proton collisions at 13 TeV
BPH-24-001	Observation of the rare decay $\eta \to \mu^+\mu^-e^+e^-$
HIN-24-013	Observation of nuclear suppression in coherent $\Upsilon(1S)$ photoproduction off heavy nuclei at the LHC
SMP-24-014	Evidence of $ZZ\gamma$ production and observation of 4 $\ell\gamma$ in proton-proton collisions at $\sqrt{s} = 13$ TeV
HIN-25-012	Observation of the jet diffusion wake using dijets in heavy ion collisions
BPH-24-003	Observation of a family of all-charm tetraquarks
BPH-23-007	Observation of $\Upsilon(1S)$ + Z associated production and measurement of the effective double-parton scattering cross section in proton-proton collisions at $\sqrt{s} = 13$ TeV
TOP-24-009	Observation of tWZ production at the CMS experiment

Showing 1 to 10 of 77 entries (filtered from 2,343 total entries)

CMS observes things humans have never seen before *all the time*

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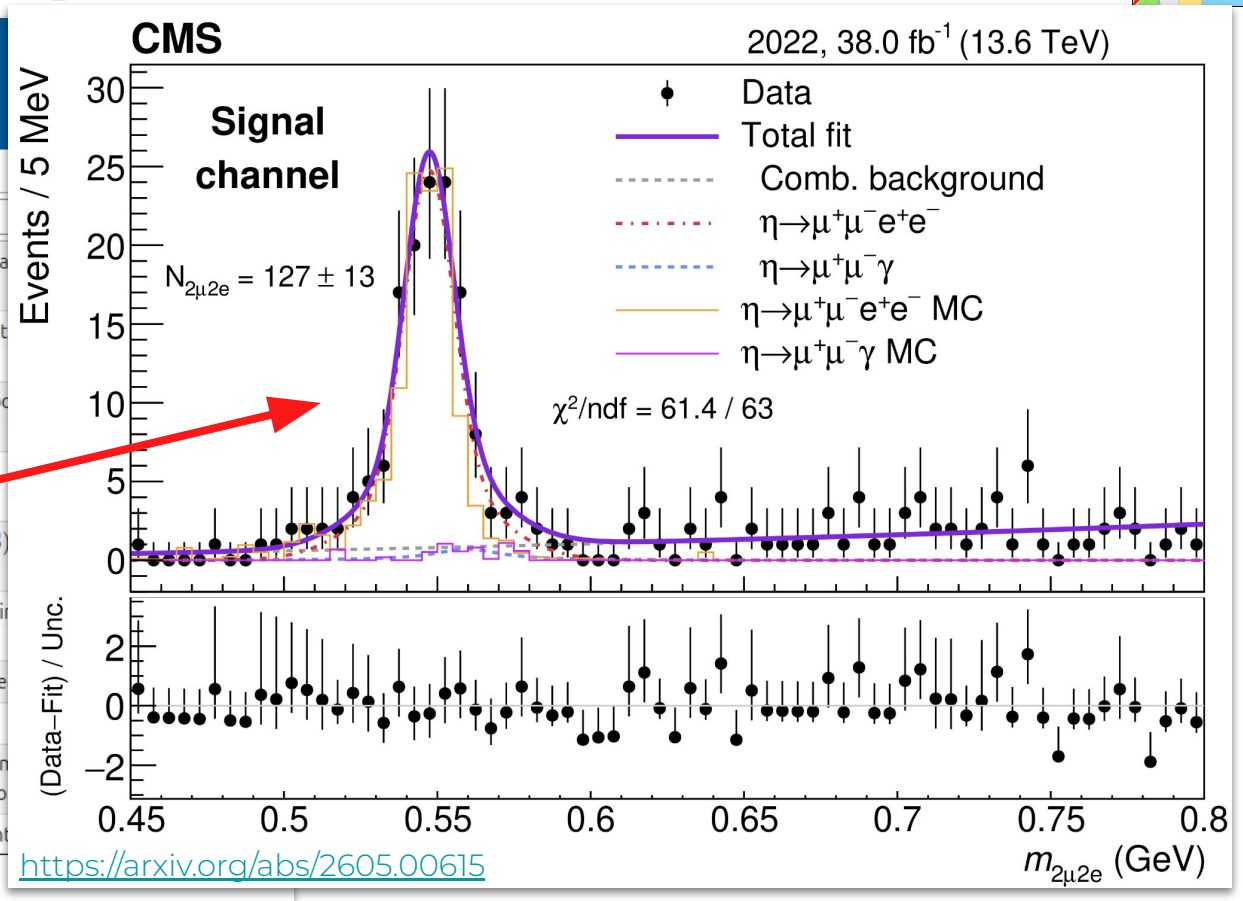
Looking somewhere new for the first time is always an opportunity for discovery

An important reminder

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https://arxiv.org/abs/2605.00615

Confronting experimental biases at CMS

Considering unconventional signatures

Addressing the blind spots in our reconstruction algorithms

Recovering lost collisions

Making sure that what feels “well motivated” isn’t overly constrained but what feels “experimentally possible”

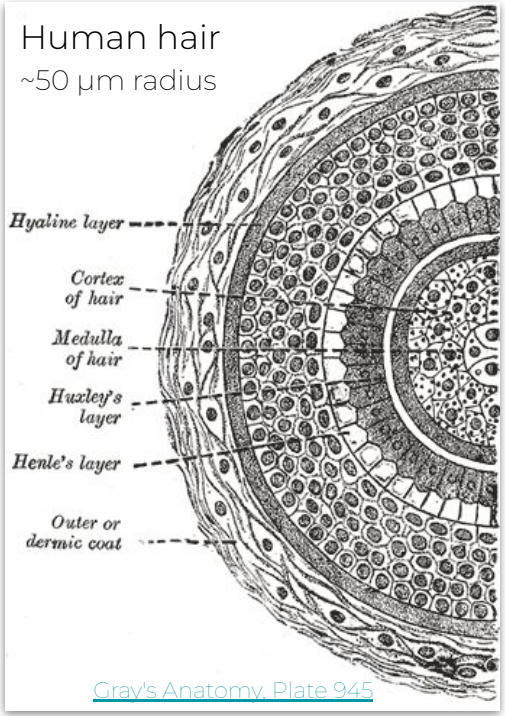
Long-Lived particles (LLPs)

Experimentally: particles with measurable, macroscopic decay lengths

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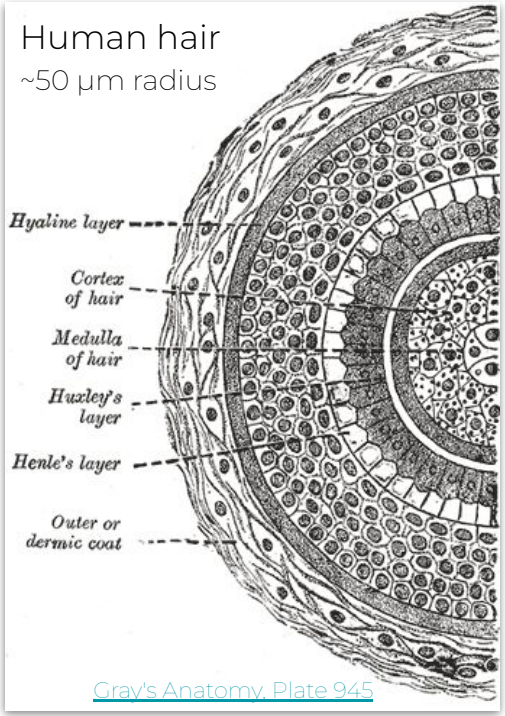
- Lab-frame decay length bigger than a human hair

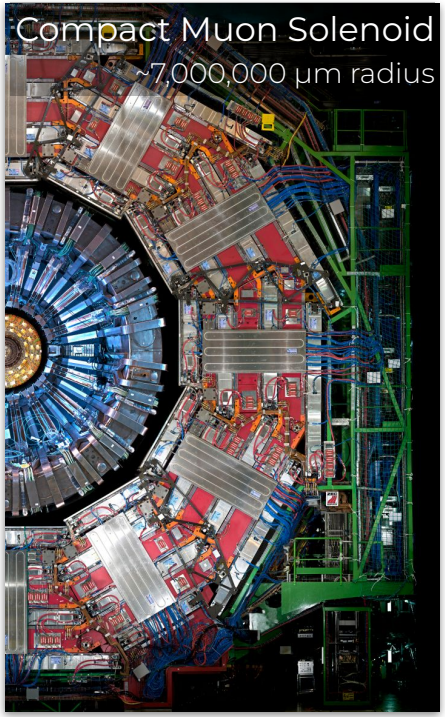


Long-Lived particles (LLPs)

Experimentally: particles with measurable, macroscopic decay lengths

- Lab-frame decay length bigger than a human hair and smaller than CMS

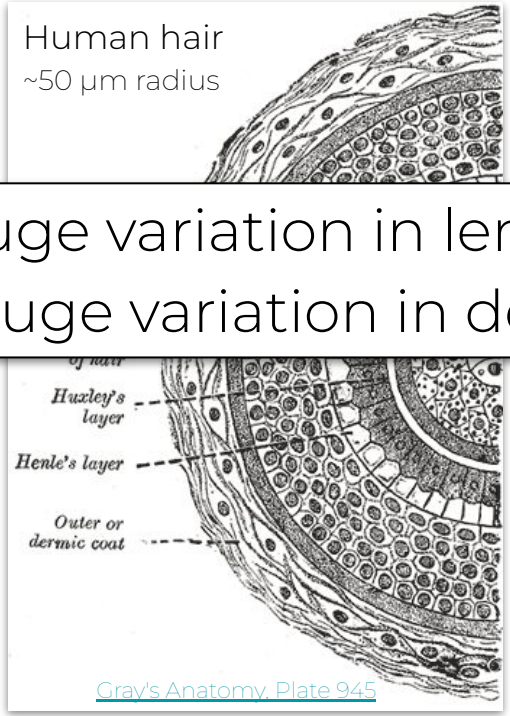




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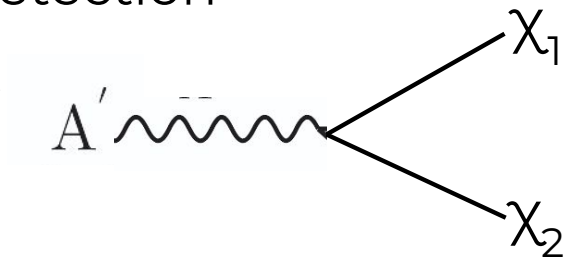
Huge variation in length scale demands huge variation in detection strategies!

Inelastic Dark Matter

arxiv:1508.03050 arxiv:1810.01879 arxiv:0101138

Simple DM model that (mostly) evades direct detection

- Two DM states with small mass splitting: χ_1 and χ_2
- Smaller mass state is *the* astrophysical DM
- Off-diagonal coupling dominates interaction

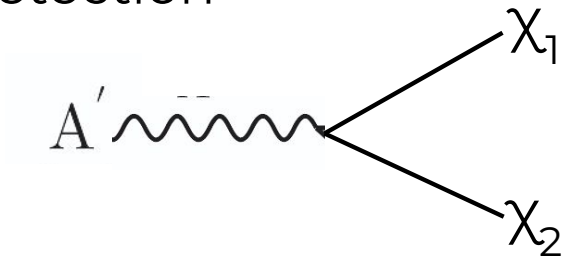


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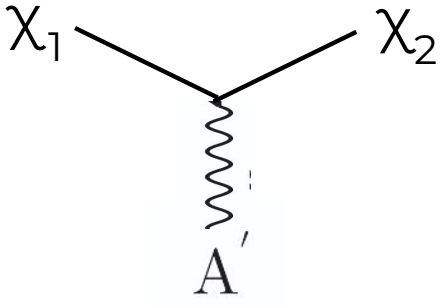
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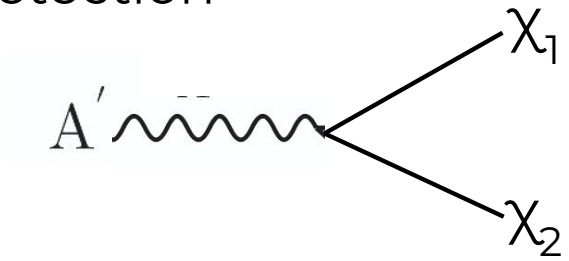


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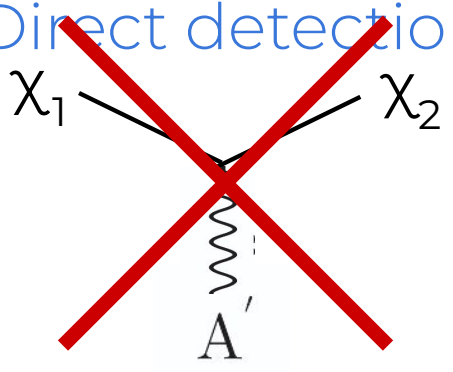
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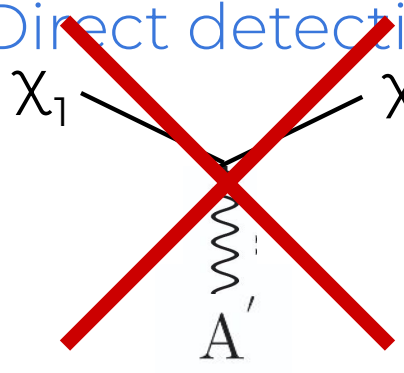
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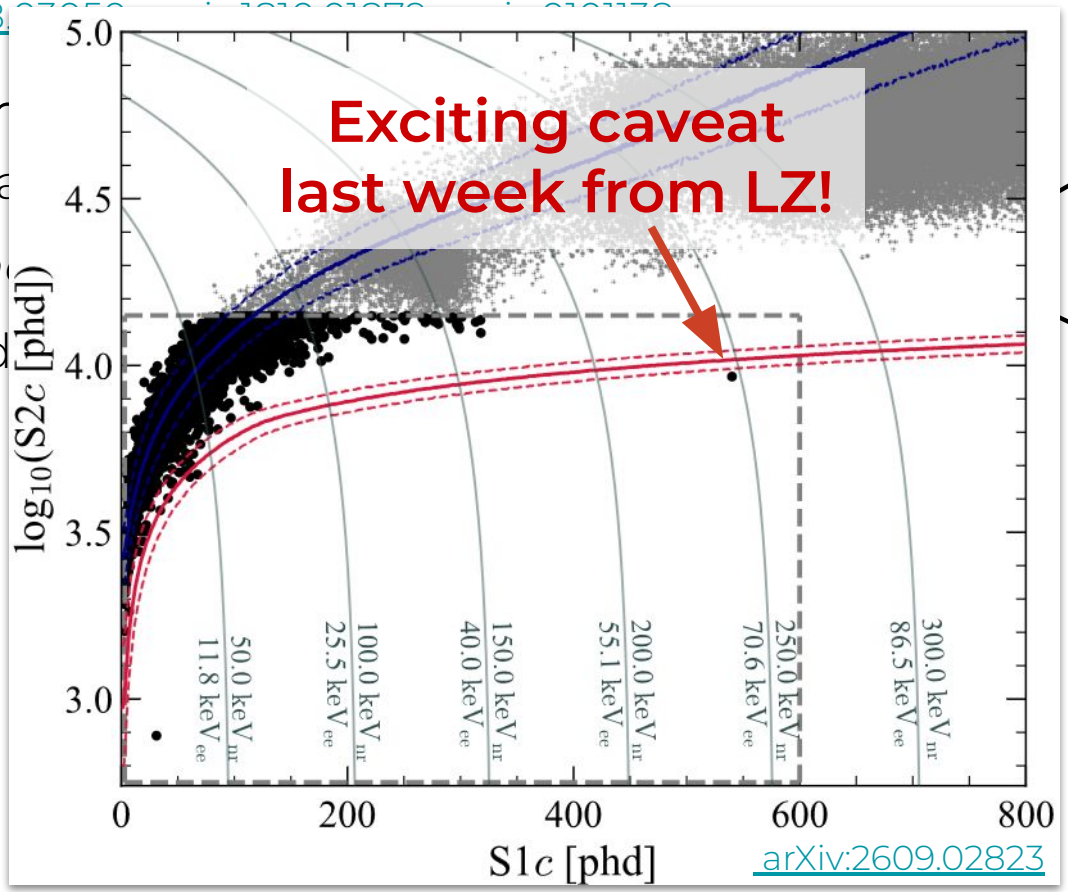
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Direct detection





χ_1

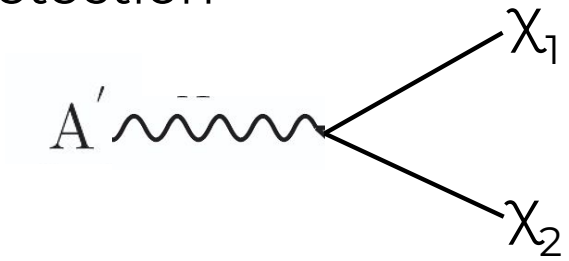
χ_2

Inelastic Dark Matter

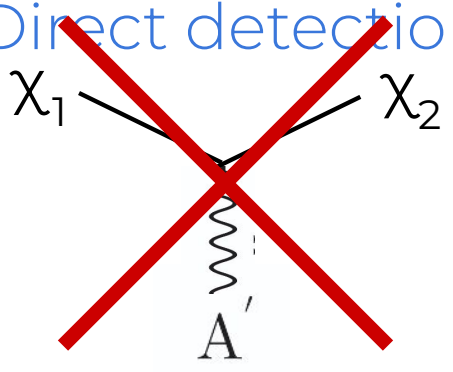
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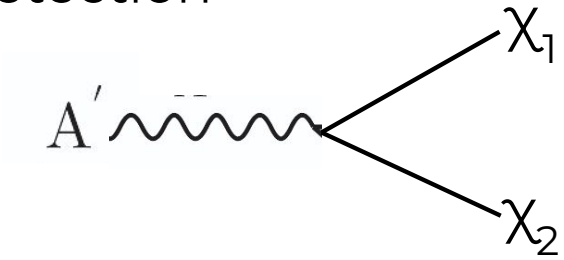


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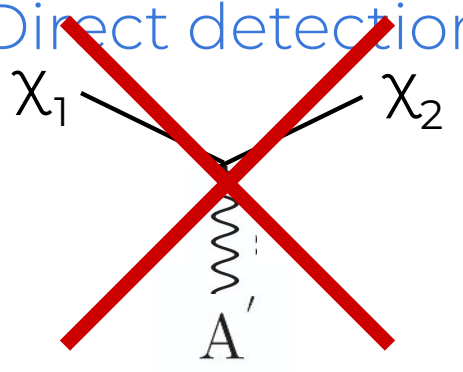
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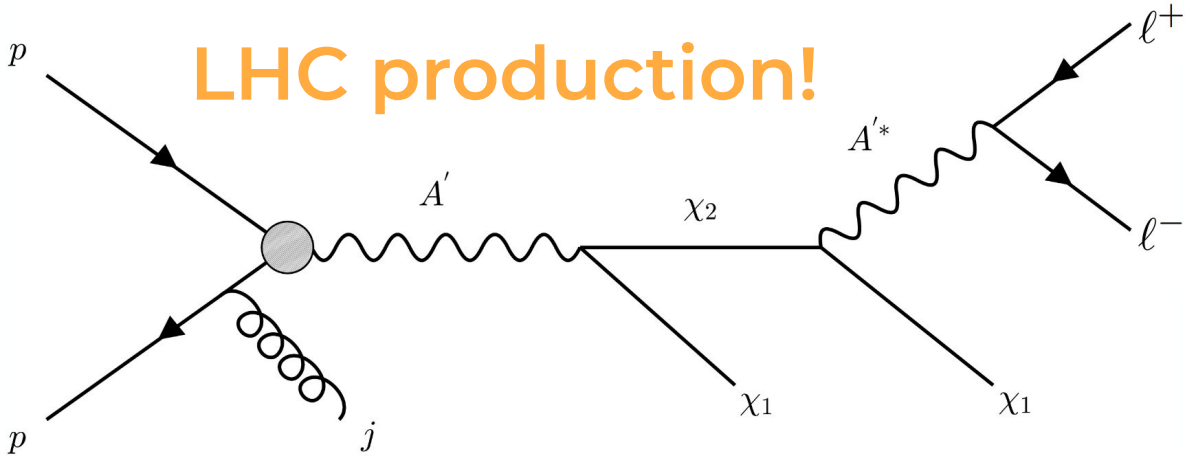
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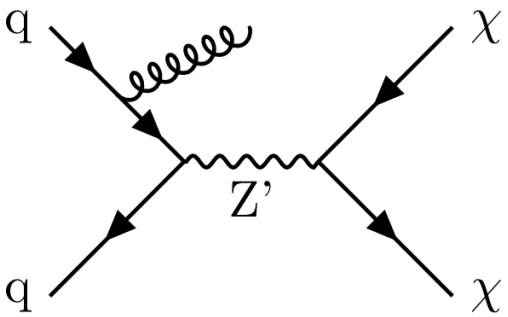
LHC production!

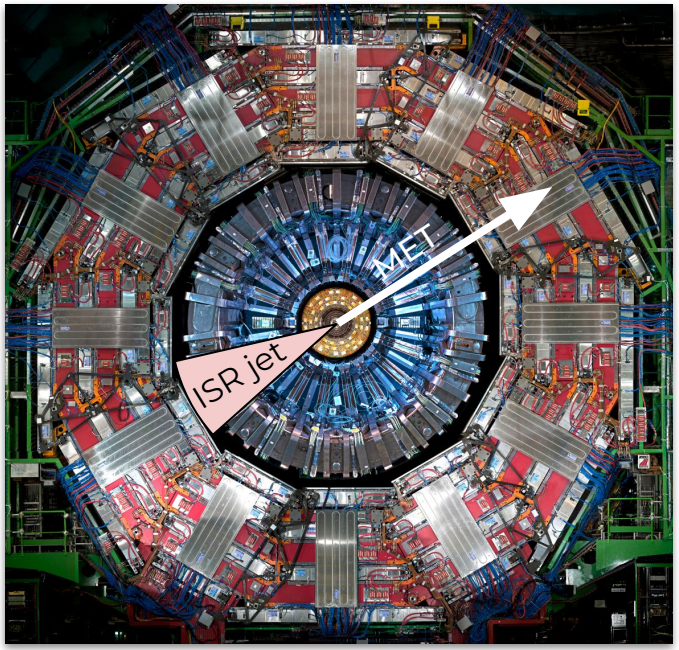


Monojet signature

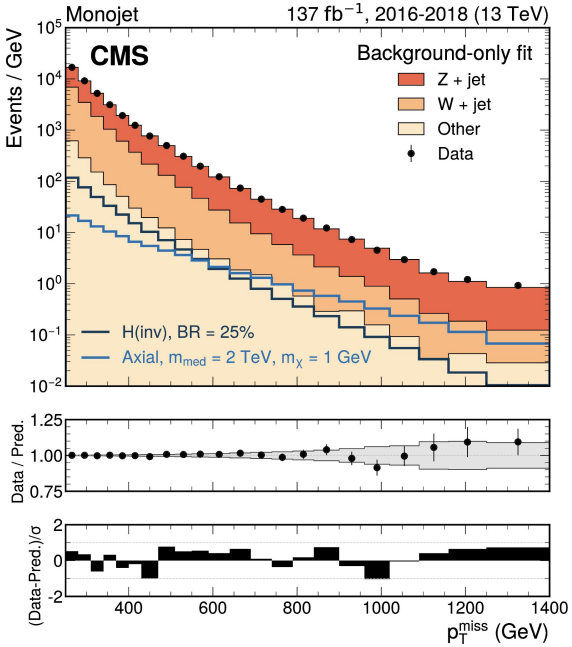
Classic signature of DM (or SUSY or whatever invisible thing you can imagine)

- Initial-state radiation (ISR) jet provides a kick to invisible particles
- Identify potential signal events via large momentum imbalance (MET)
- Powerful, model independent, but large Z→nunu background out to large MET



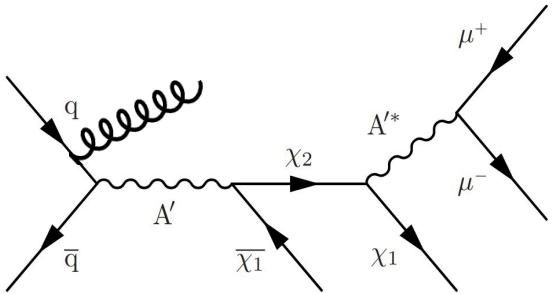


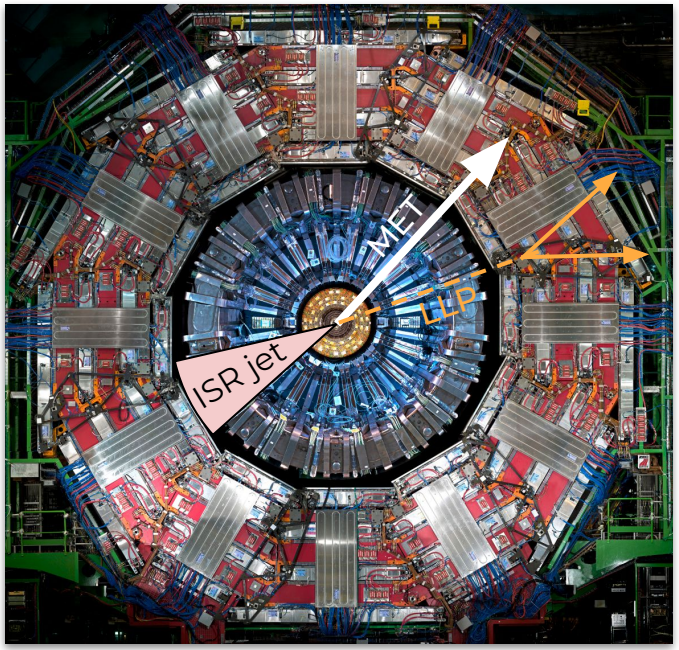
CMS-EXO-20-004



Monojet+LLP signature

- ISR Jet + LLP process w/ visible *and* invisible final state particles
- LLP signature greatly reduces Z→nunu background
- MET provides a way to trigger on signals that would otherwise be too soft or displaced
- Boost from ISR can give otherwise too-soft LLP decay products enough energy to be reconstructed



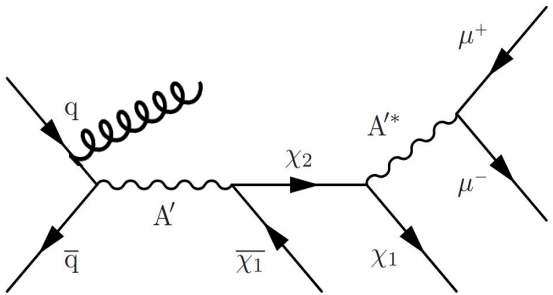


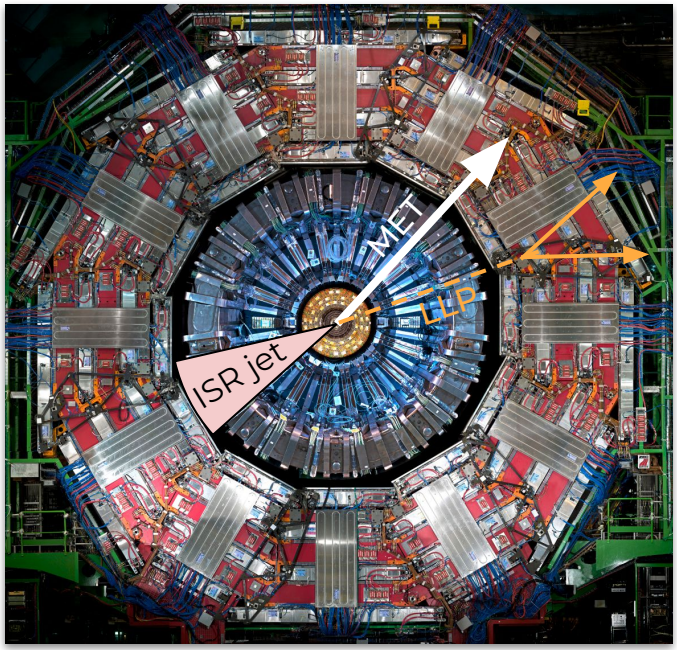
Some CMS examples

Disappearing tracks
Inelastic Dark Matter
Muon Detector Showers
Soft displaced track
Soft displaced vertex

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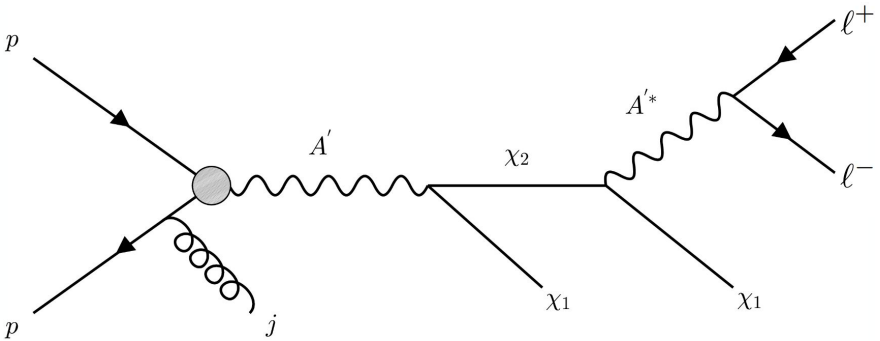
Inelastic Dark Matter at CMS

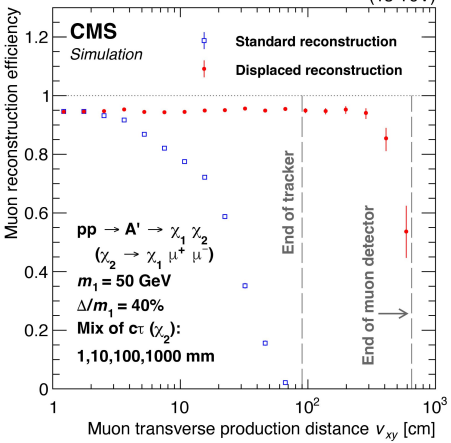
First search targeting μμ final state (PhysRevLett.132.041802)

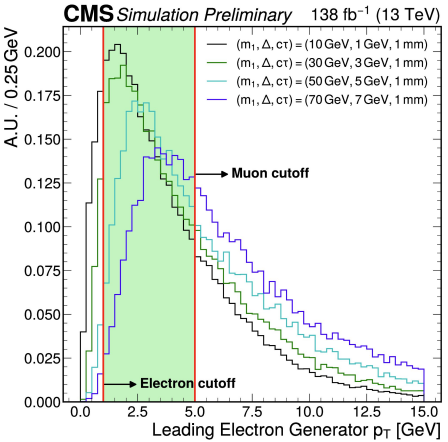
- Dedicated displaced muon reconstruction enables sensitivity to decays all the way out to Muon System

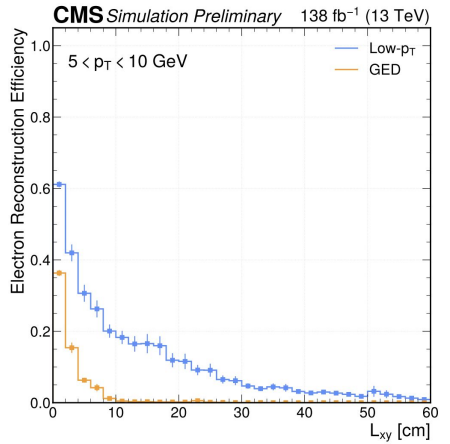
Second search targeting ee final state (CMS-PAS-EXO-24-036)

- Dedicated tracker-driven electron reconstruction enables electron reconstruction down to momenta of 1 GeV
- Tracker-driven reconstruction also dramatically increases ability to reconstruct electrons outside of inner tracker



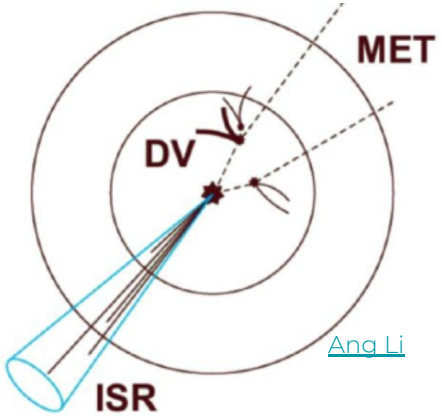




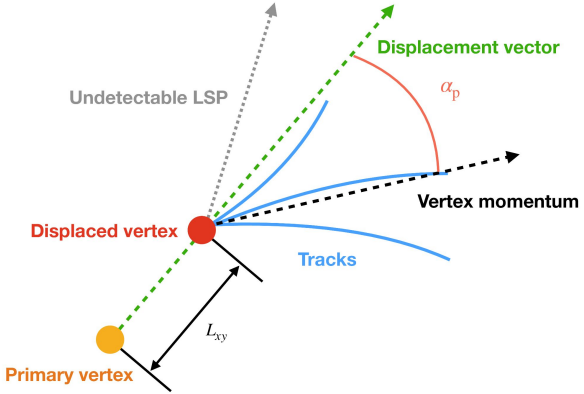


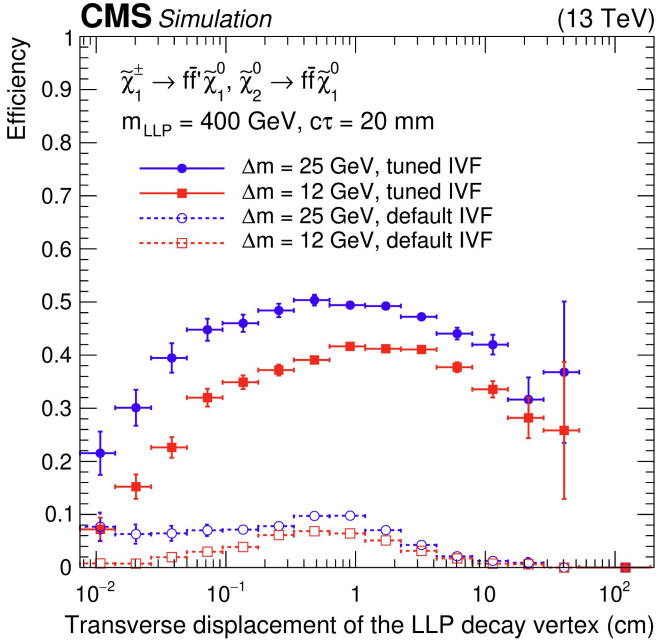
Soft Displaced Vertices

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Ang Li





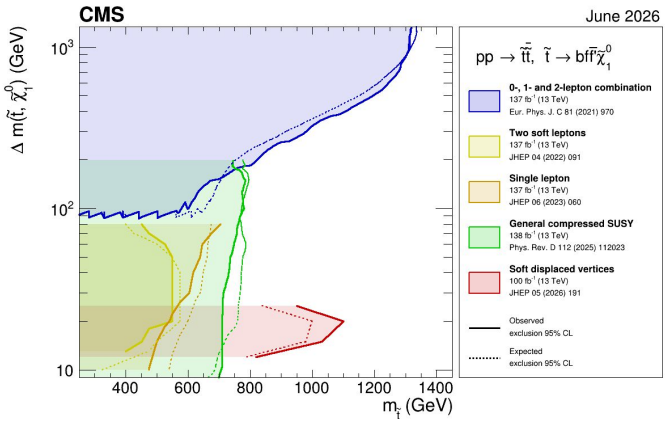
Push Displaced Vertex searches to the limit

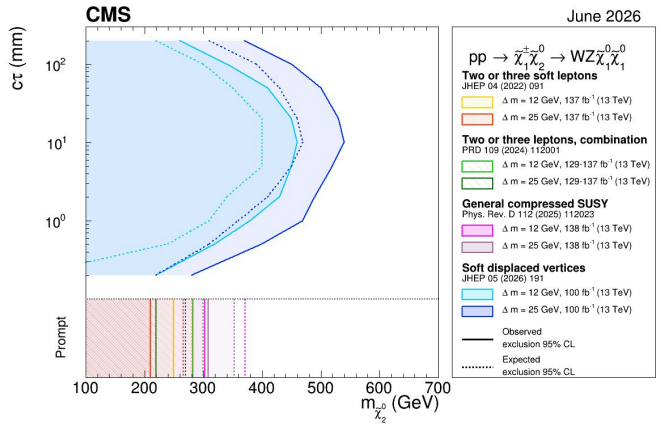
- Fewer (≥ 2), lower momentum (≥ 0.5 GeV) tracks
- Larger displacements (< ~30 cm)
- Weird angles

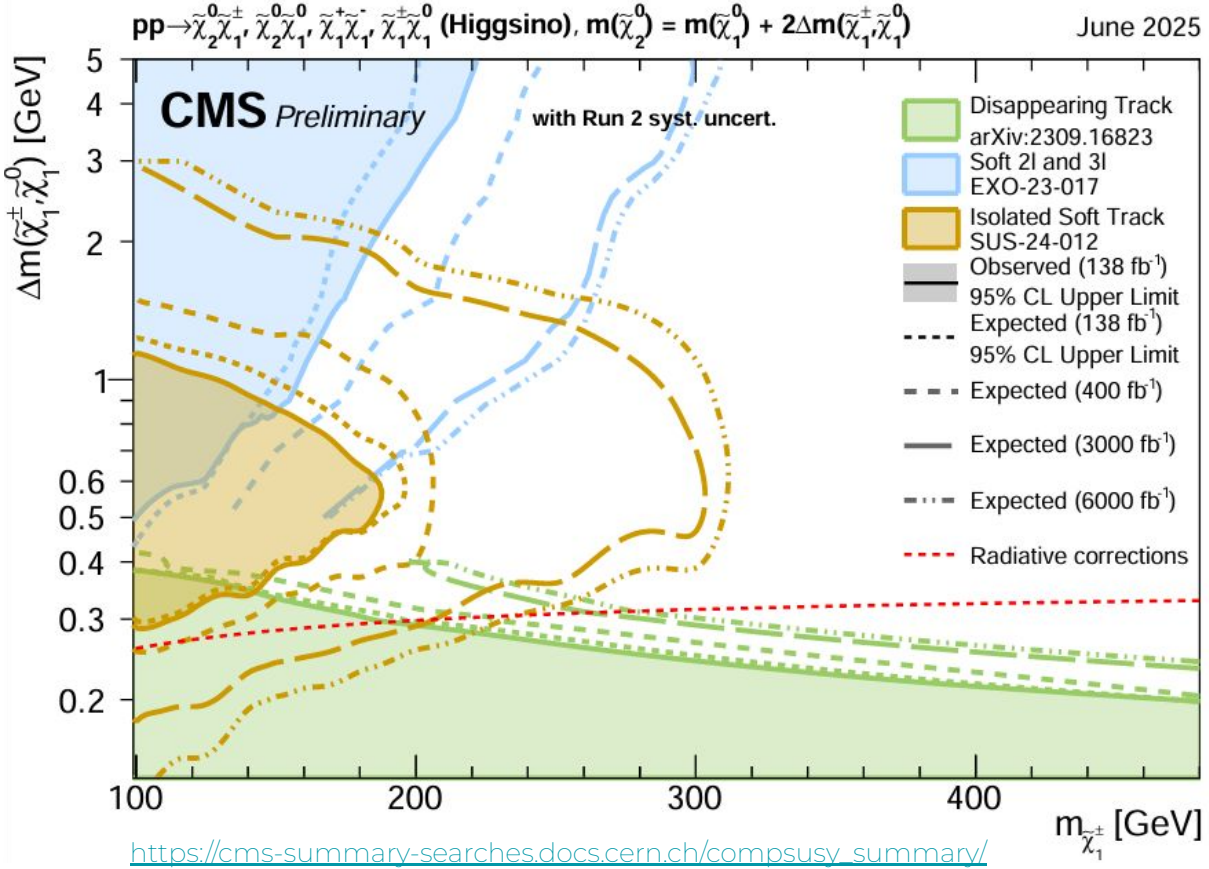
Major challenges:

- Combinatorial background
- Unrelated or mis-reconstructed tracks overlapping genuine SM backgrounds

General theme: compressed mass spectra







https://cms-summary-searches.docs.cern.ch/compsusy_summary/

Recovering lost collisions

What if the “interesting” events are part of the 99.99% we’re throwing away?

Let’s try to save them! Three approaches:

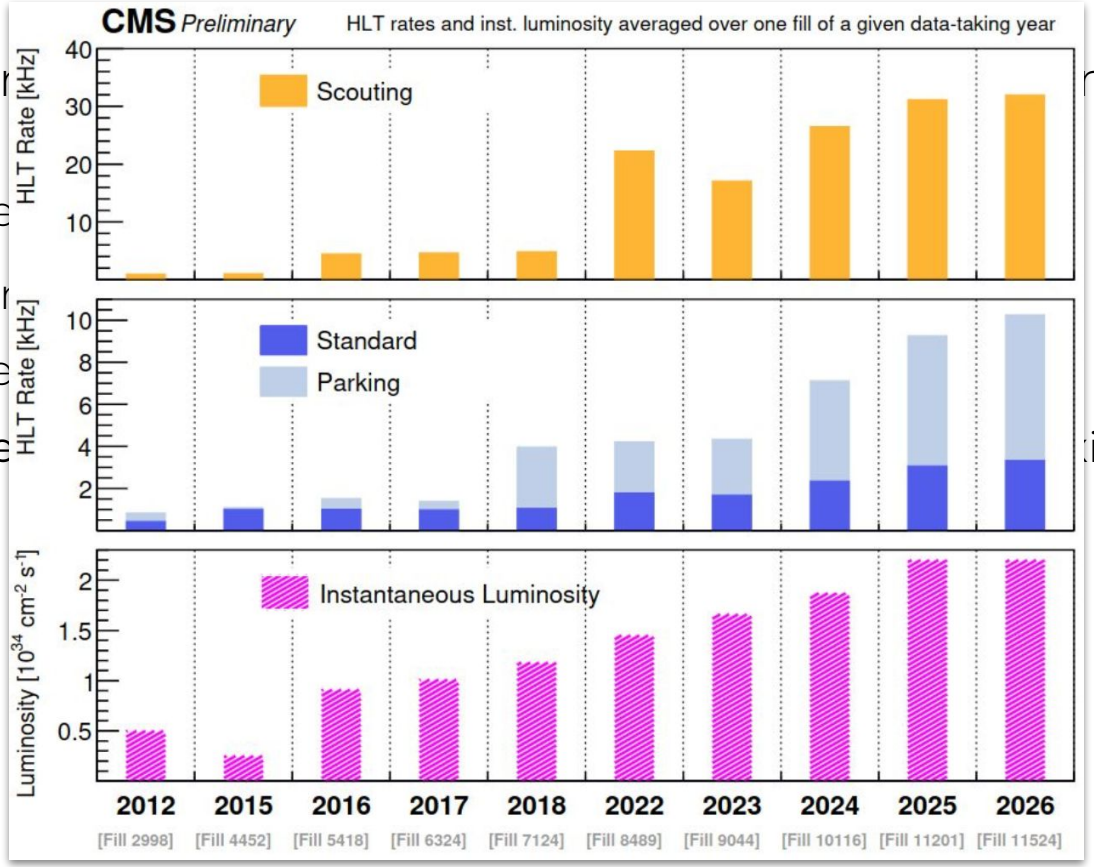
- **Parking**: save more events by delaying reconstruction
- **Scouting**: save more events by reducing data per event
- **Anomaly Detection**: save “weird” events that aren’t targeted by existing triggers

Recovering lost collisions

What if the “inter rowing away?

Let’s try to save the

- **Parking**: save
- **Scouting**: save
- **Anomaly Dete** isting triggers



CMS-DP-2026-023

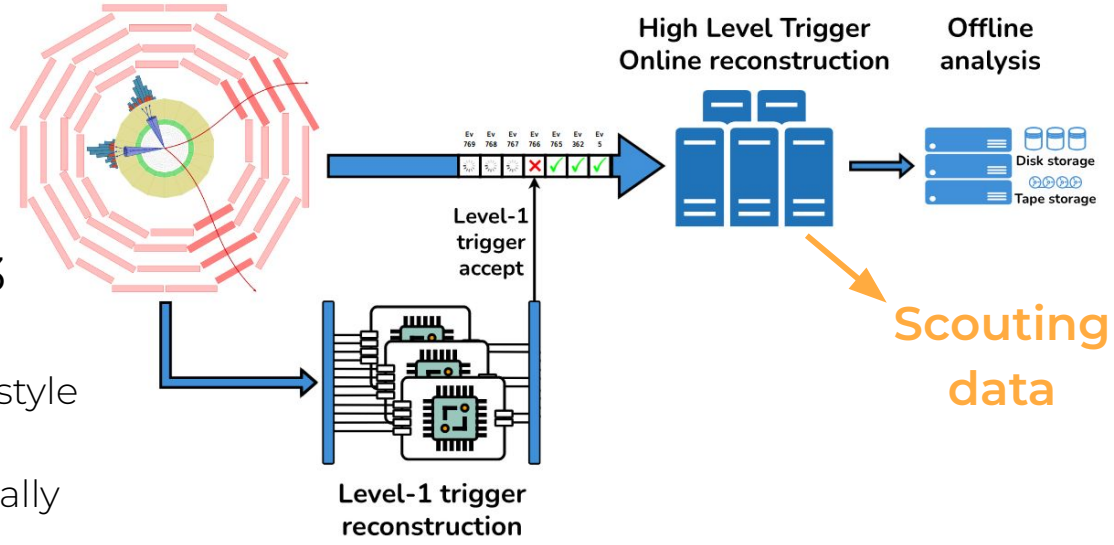
Scouting

Using HLT-level information for analysis

- Imperfect calibrations and reconstruction
- Reduced information to meet data rate constraints
- Lower trigger threads

Matured and expanded in Run 3

- GPUs everywhere
- Adding *e*, *γ*, full tracking, and offline-style reconstruction
- Data rates and data quality dramatically increasing in last years of Run 3

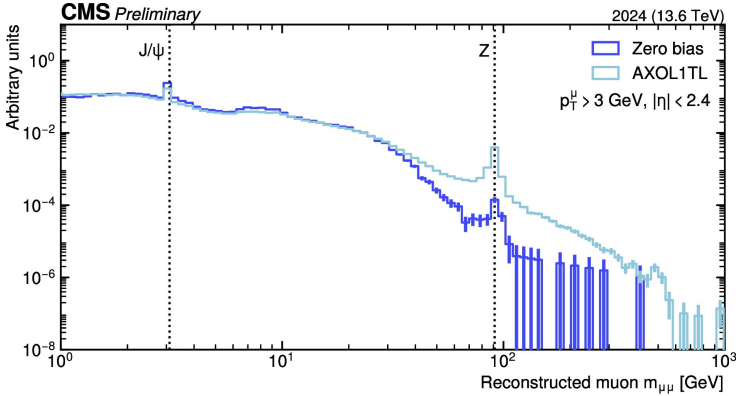


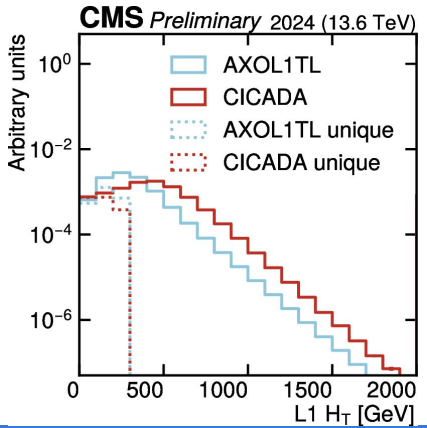
Anomaly Detection

CMS-PAS-MLG-25-001

Two L1 anomaly detection triggers active in CMS: AXOL1TL and CICADA

- Similar concepts:
  - Autoencoder-based
  - Trained on Zero-Bias dataset
  - Running on FPGAs at 40 MHz
  - Very nice logos
- Different inputs:
  - High-level physics objects
  - Low-level calorimeter images





Both taking data since 2024!

- ~740 unique million Anomaly Detection events in 2024
- Exploration and analysis design underway

The opportunity and challenge of HL-LHC

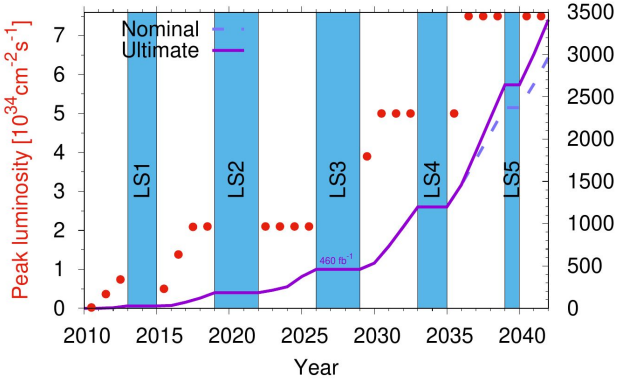
Opportunity

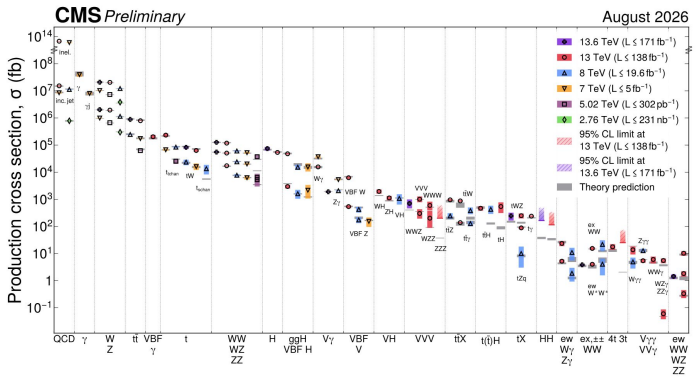
Up to 4000 fb^{-1} of 13.6 TeV collisions

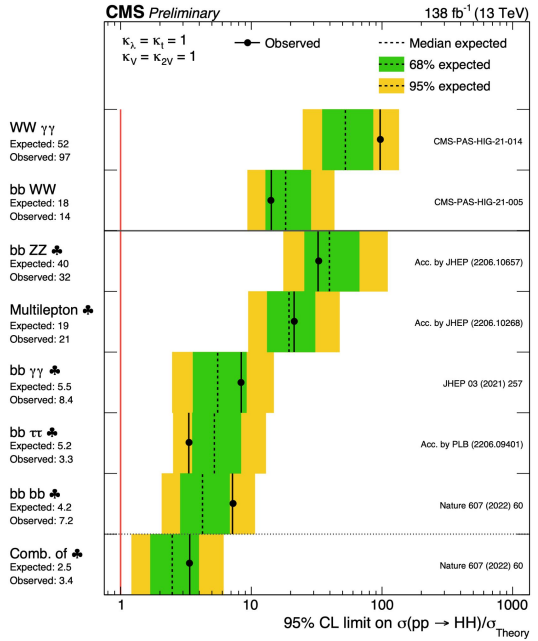
- We may collect more data *every year* than we collected in all of Run 3 (2022-2026)

Unprecedented opportunity for precision measurements and possible observation of rare processes

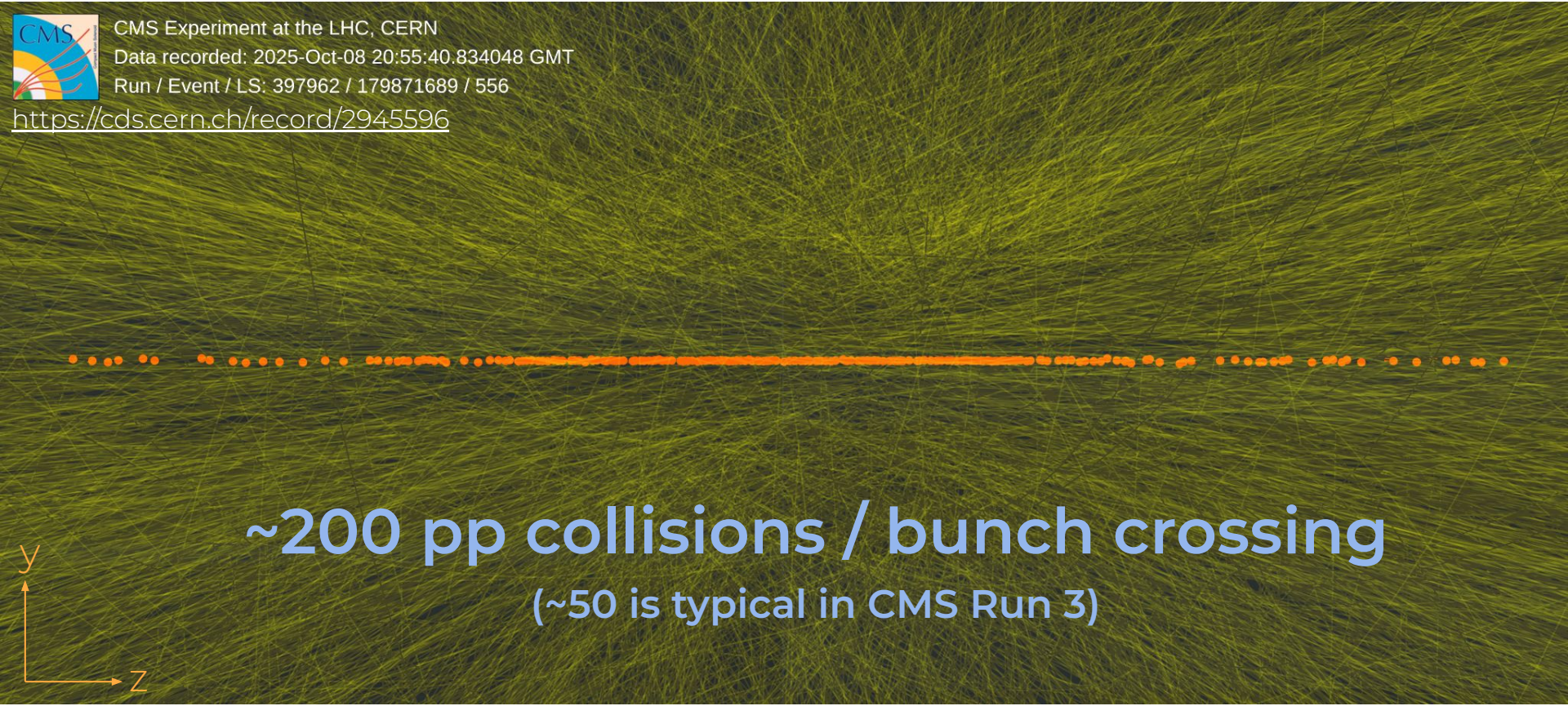
- Aim to produce >100 million Higgs bosons
- Study the Higgs sector in detail and potentially observe Higgs self-coupling



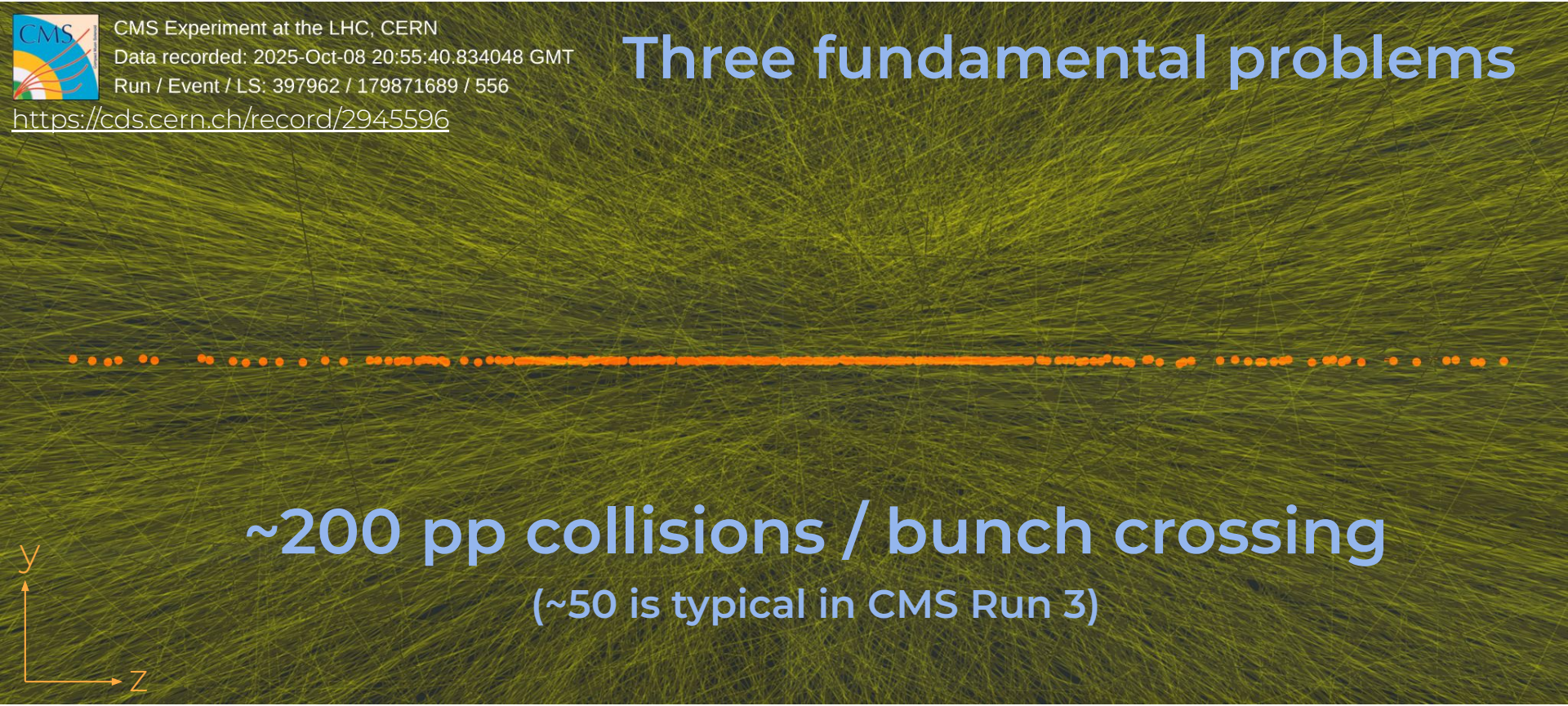




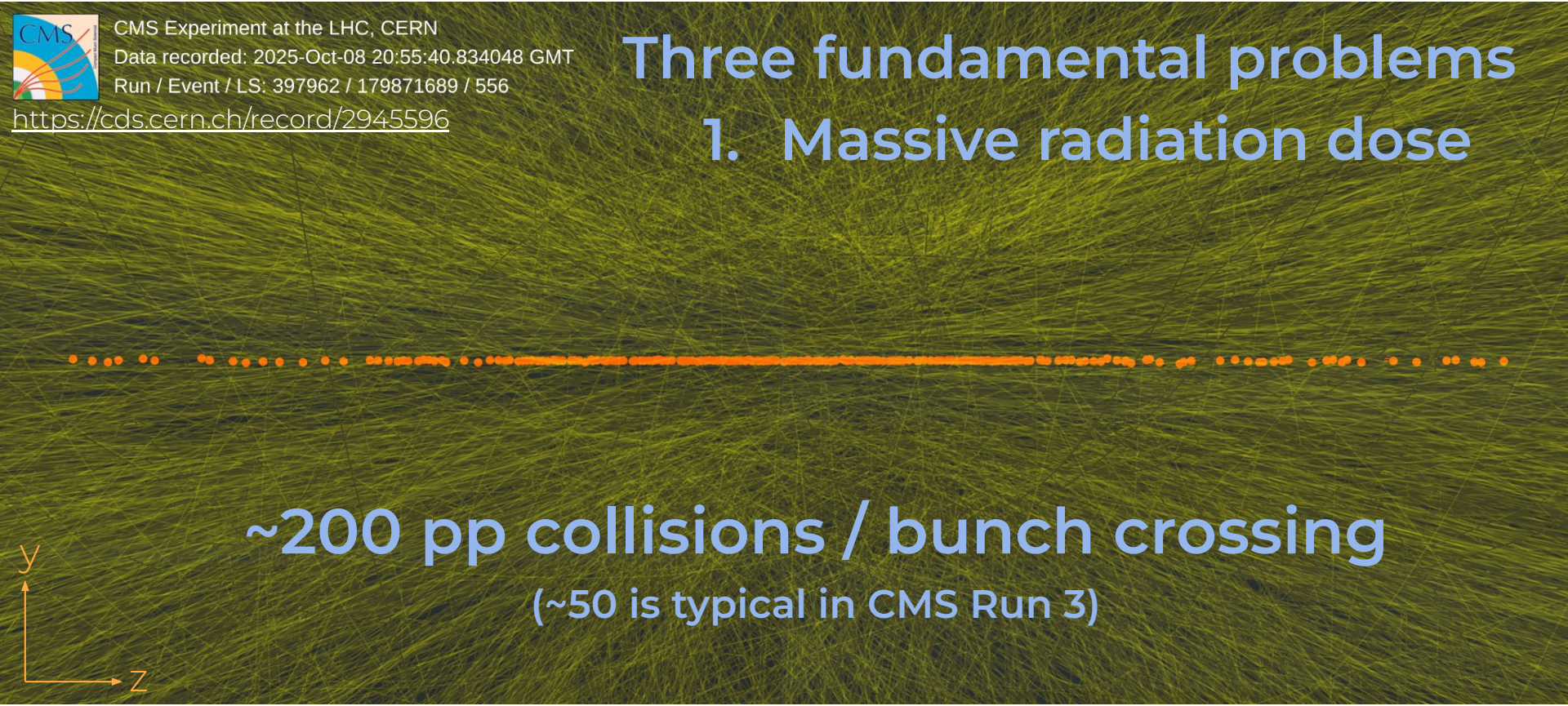
Challenge


CMS Experiment at the LHC, CERN
Data recorded: 2025-Oct-08 20:55:40.834048 GMT
Run / Event / LS: 397962 / 179871689 / 556
https://cds.cern.ch/record/2945596
~200 pp collisions / bunch crossing
(~50 is typical in CMS Run 3)
y
z

Challenge


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Data recorded: 2025-Oct-08 20:55:40.834048 GMT
Run / Event / LS: 397962 / 179871689 / 556
https://cds.cern.ch/record/2945596
Three fundamental problems
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Challenge



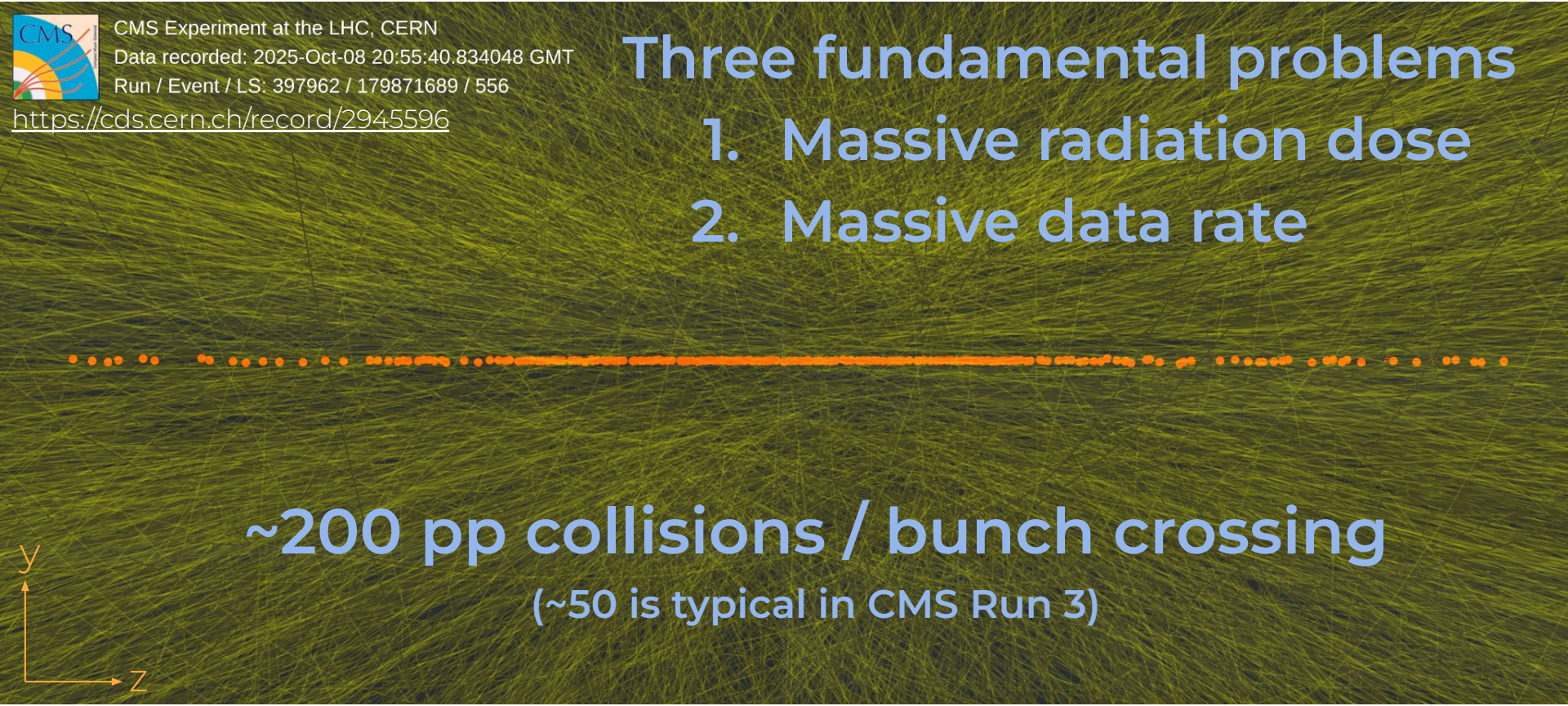
Three fundamental problems

1. Massive radiation dose

~200 pp collisions / bunch crossing

(~50 is typical in CMS Run 3)

Challenge



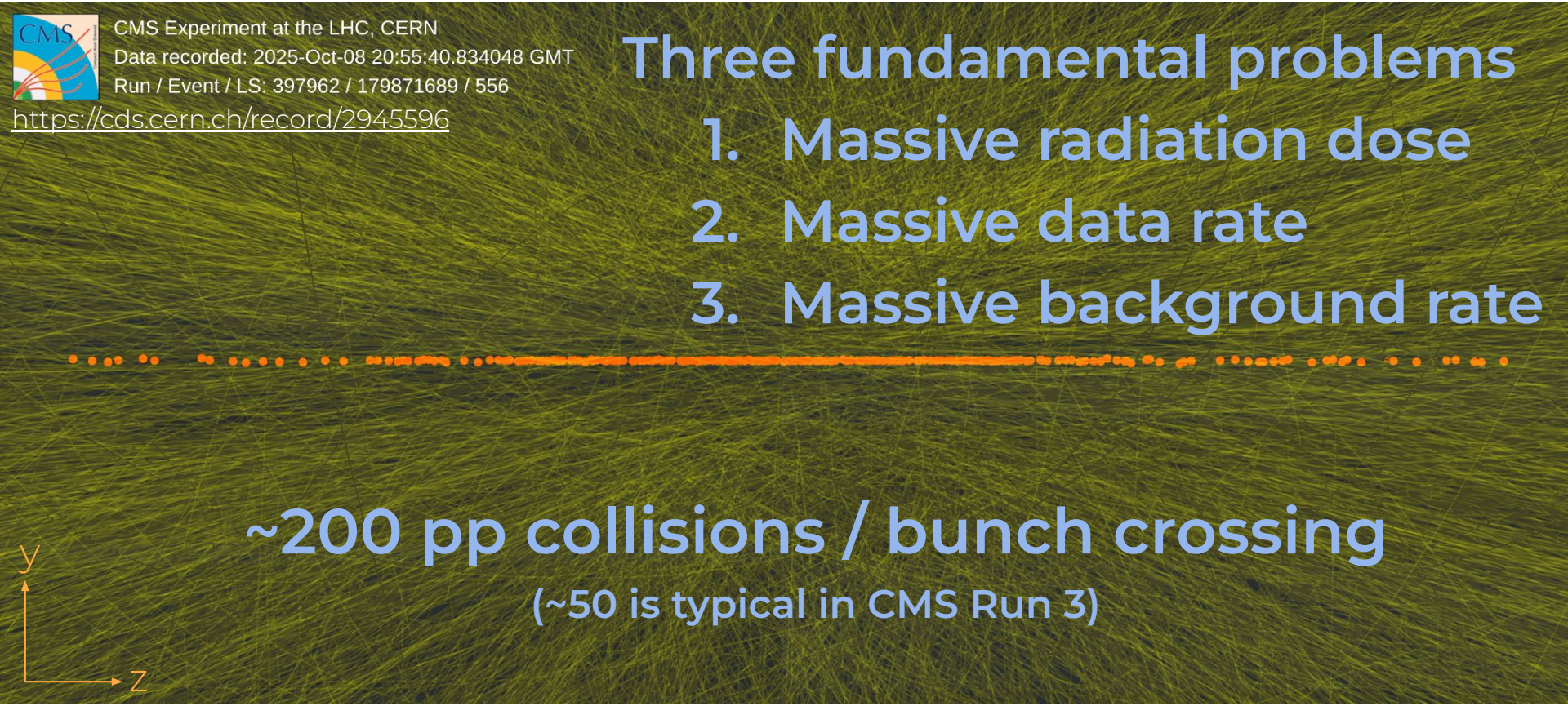
Three fundamental problems

1. Massive radiation dose
2. Massive data rate

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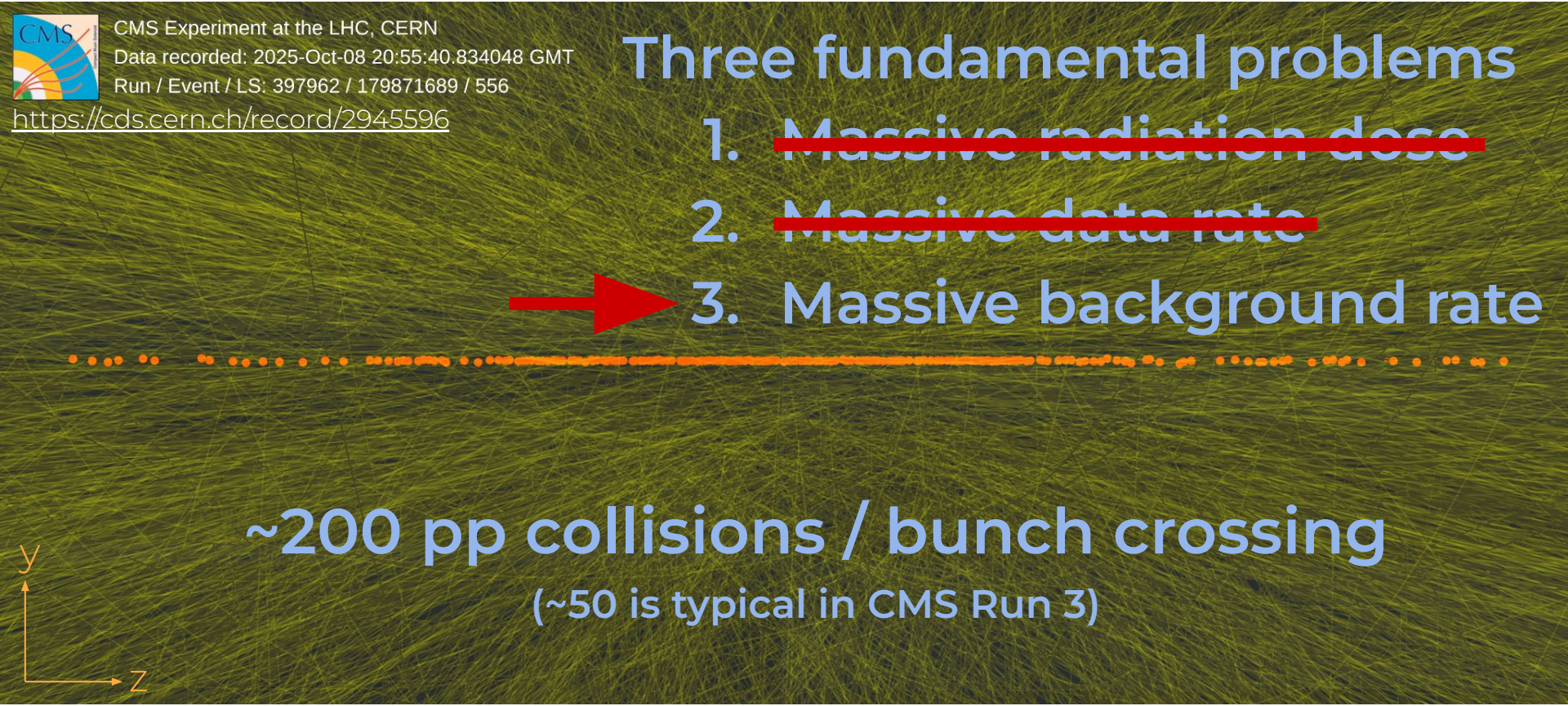
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2. ~~Massive data rate~~
3. Massive background rate

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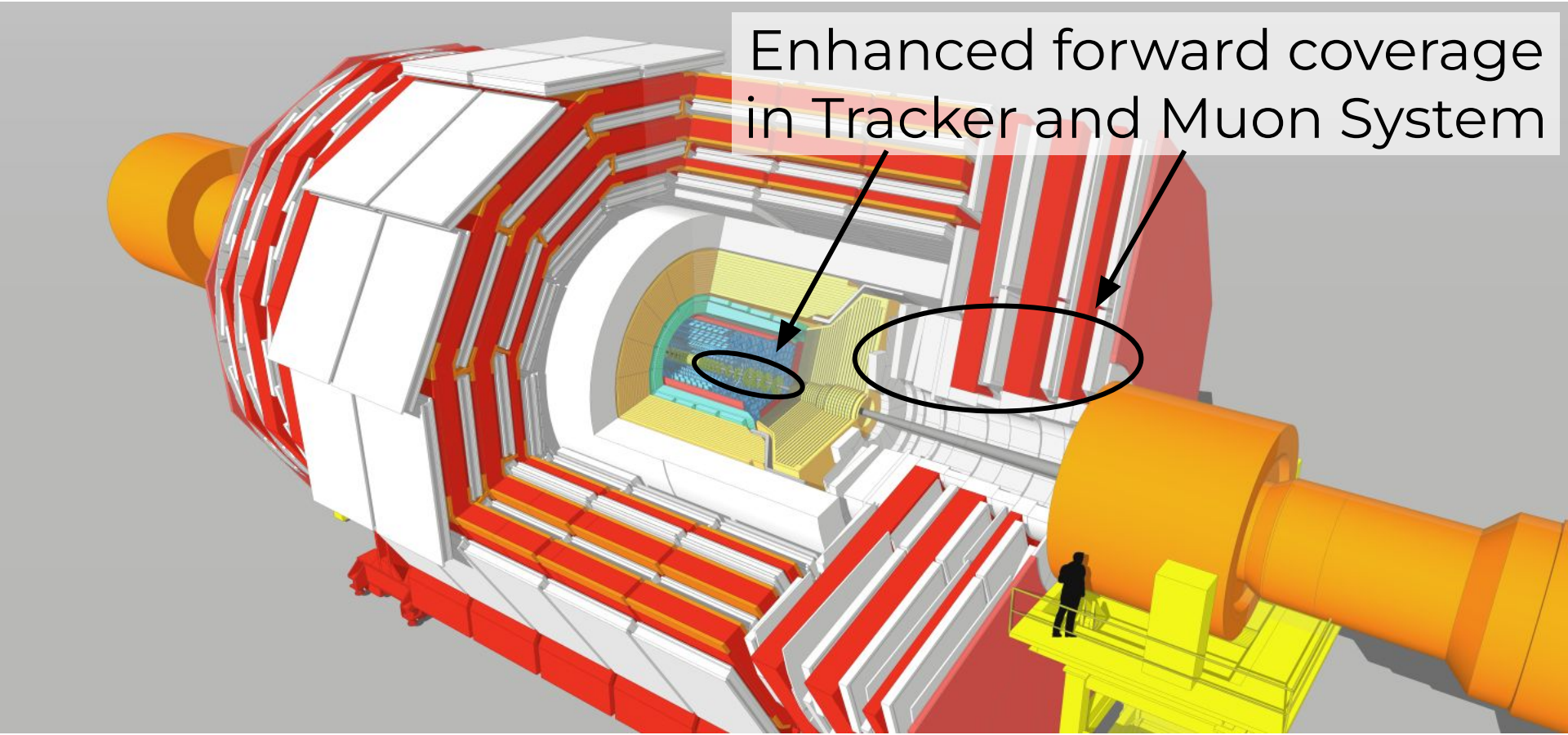


Challenge


CMS Experiment at the LHC, CERN
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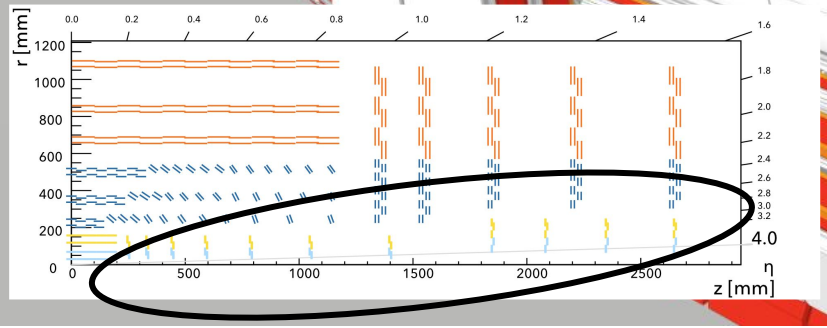
Three ways to reduce background

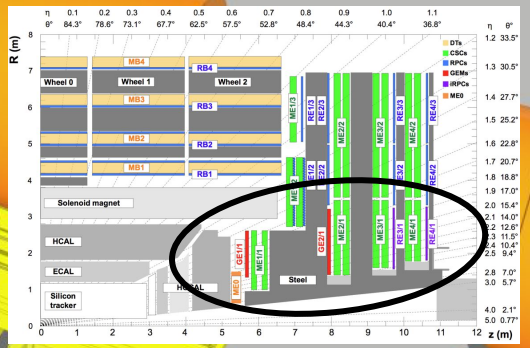
1. More complete coverage



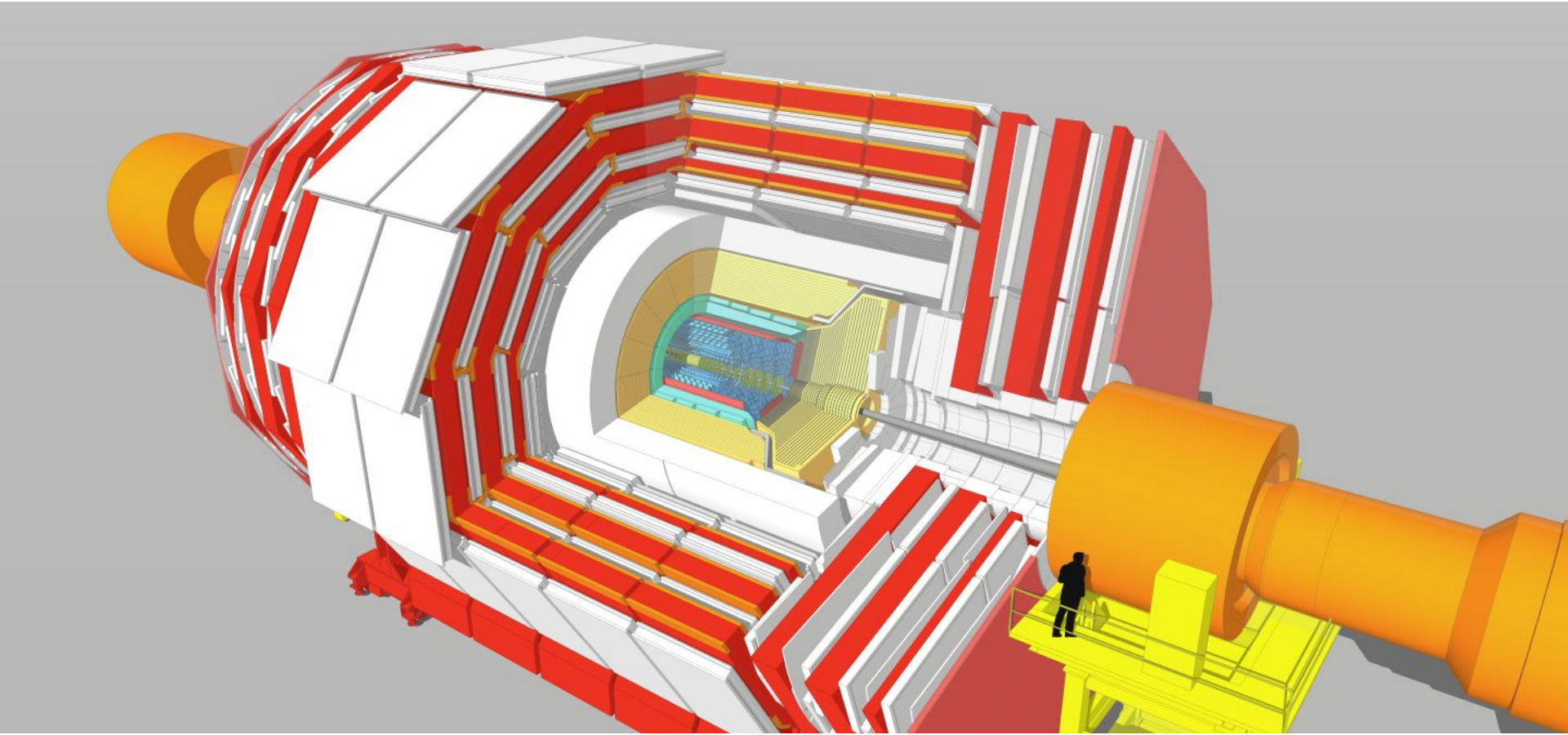
1. More complete coverage

Enhanced forward coverage in Tracker and Muon System

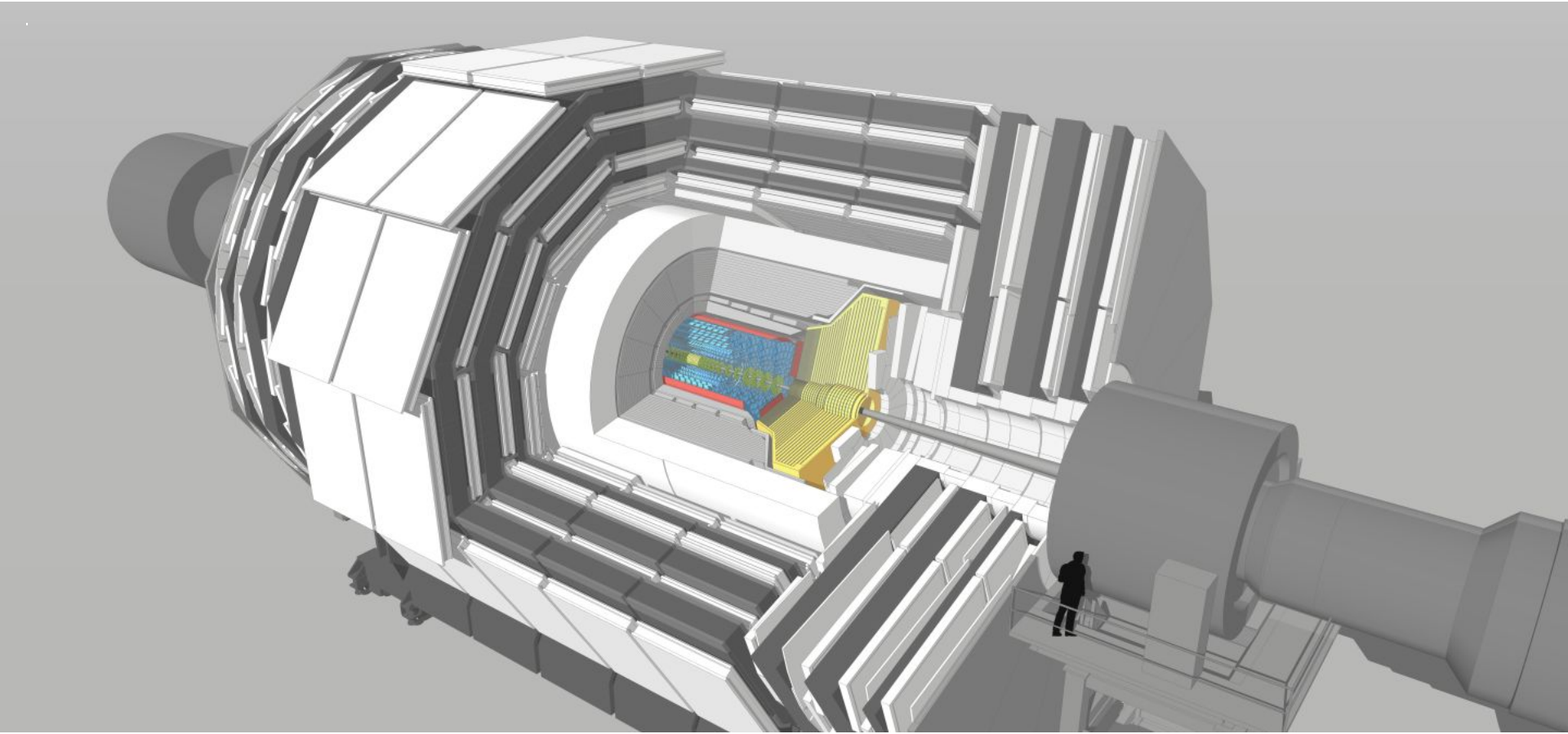




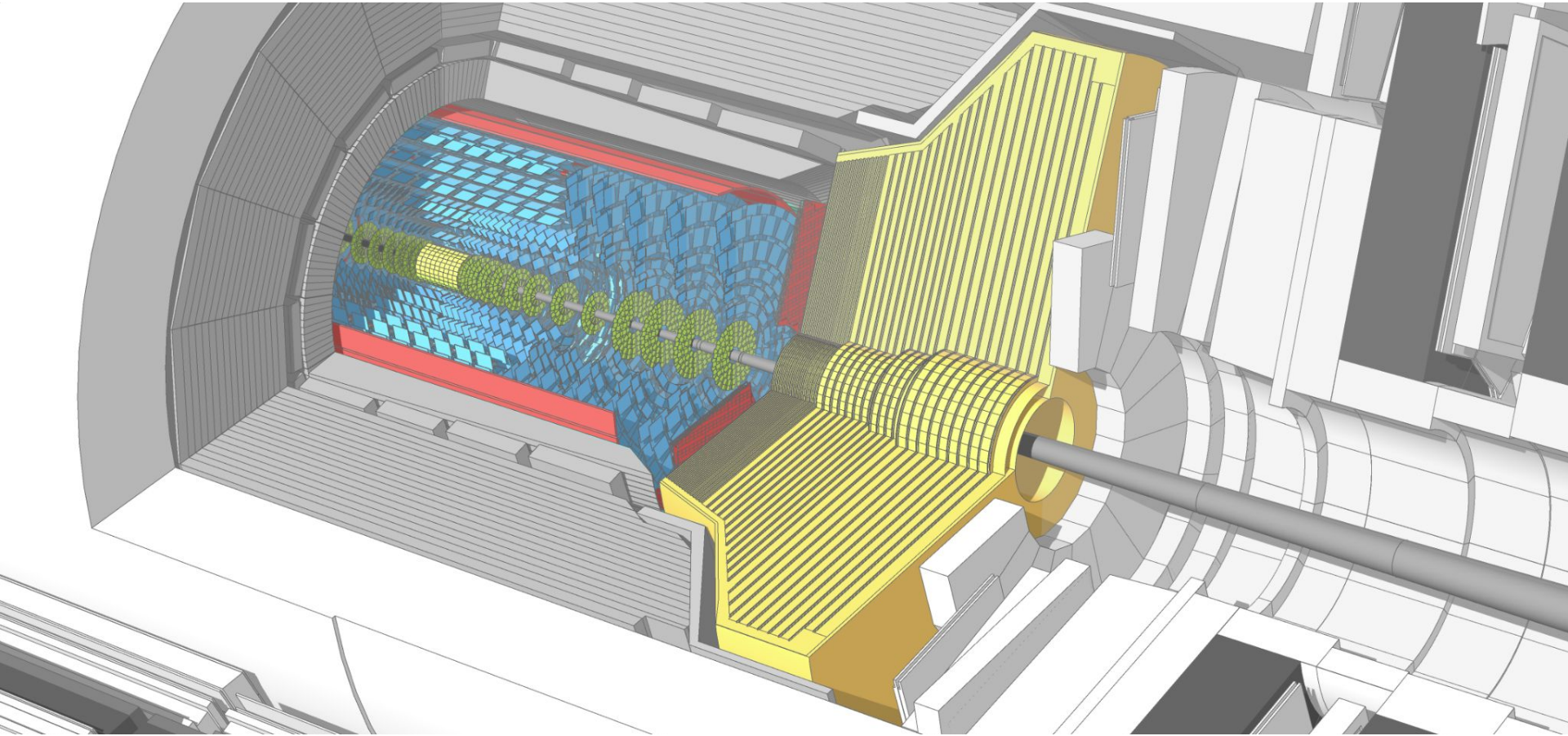
2. Higher granularity



2. Higher granularity



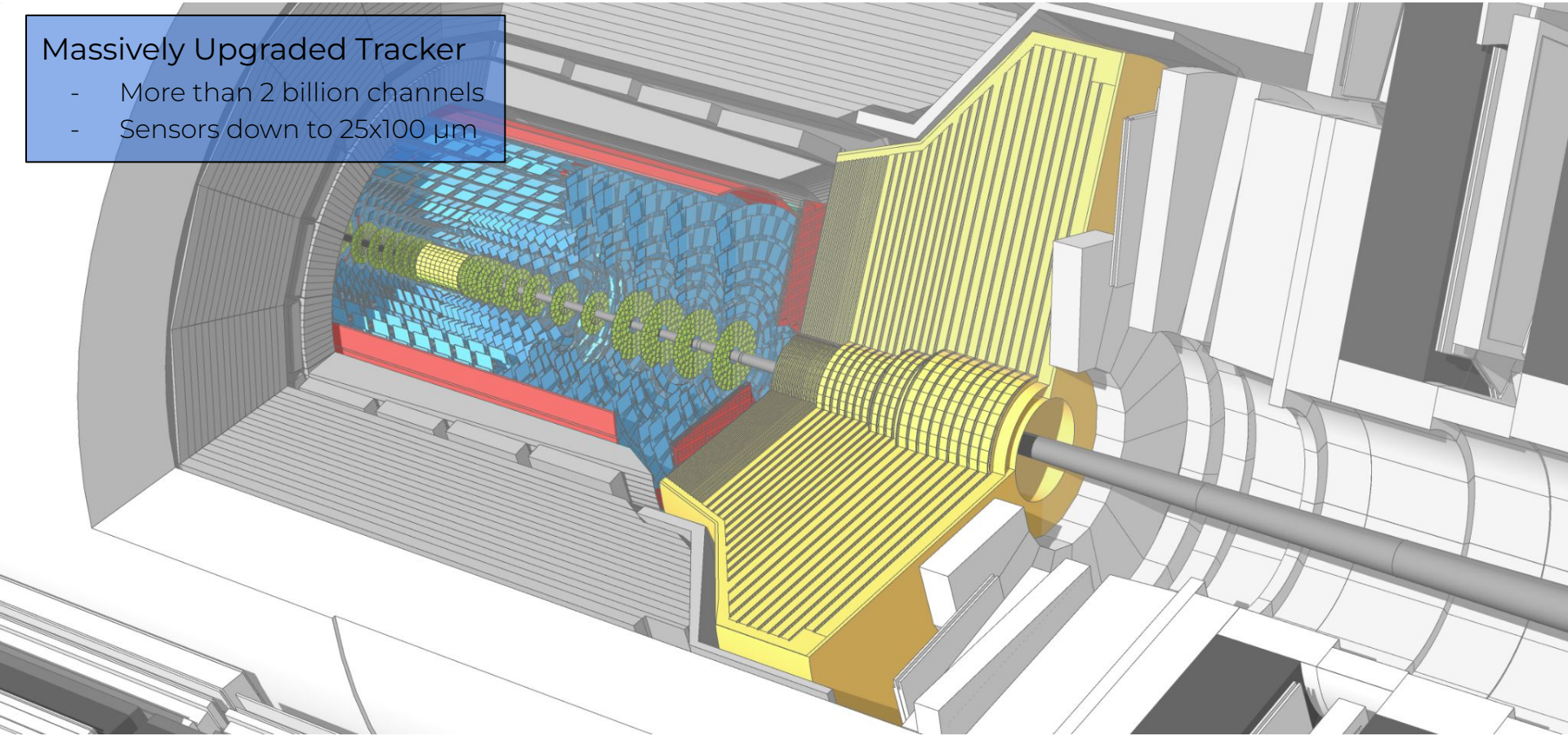
2. Higher granularity



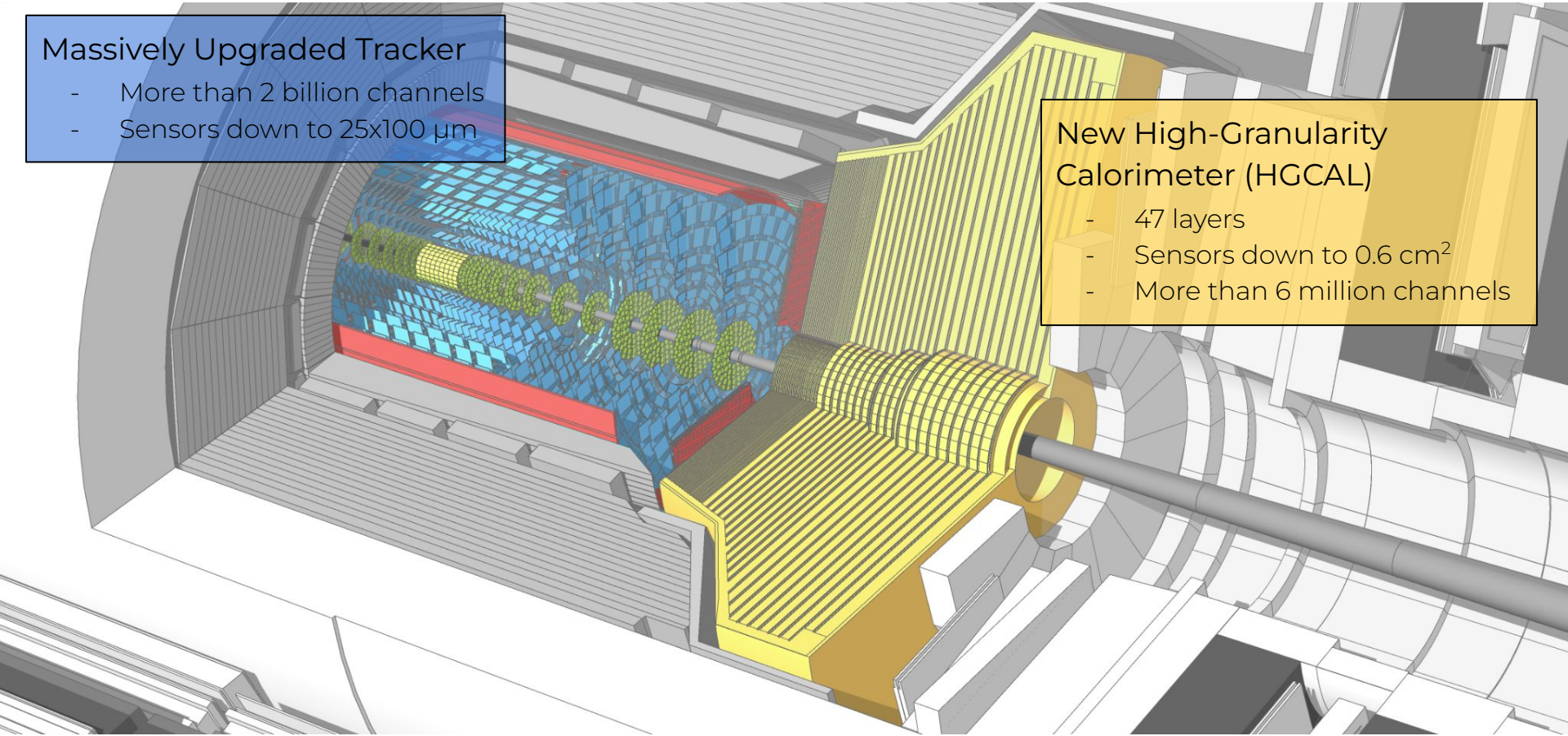
2. Higher granularity

Massively Upgraded Tracker

- More than 2 billion channels
- Sensors down to 25x100 μm



2. Higher granularity



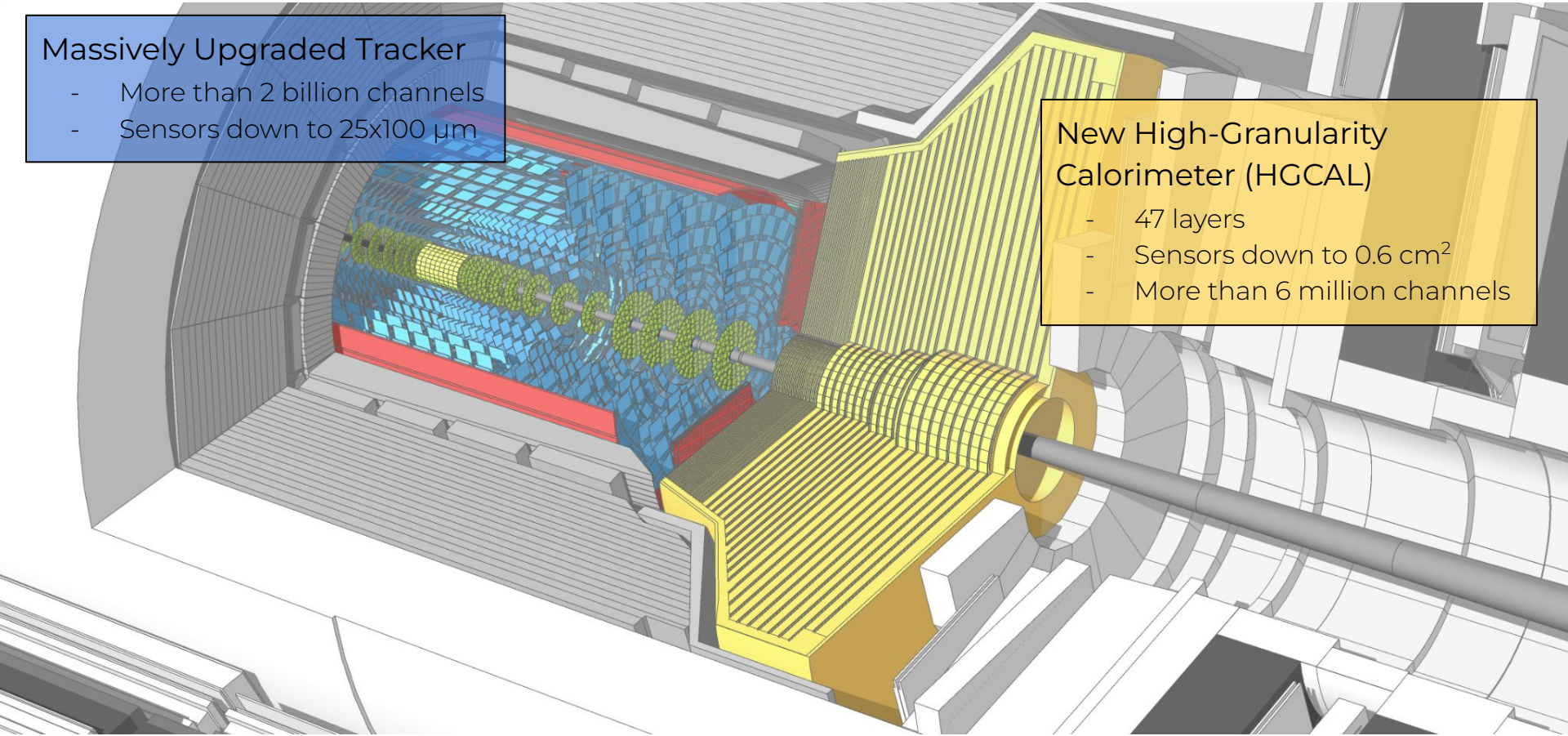
Massively Upgraded Tracker

- More than 2 billion channels
- Sensors down to 25x100 μm

New High-Granularity Calorimeter (HGCAL)

- 47 layers
- Sensors down to 0.6 cm^2
- More than 6 million channels

3. Precision Timing



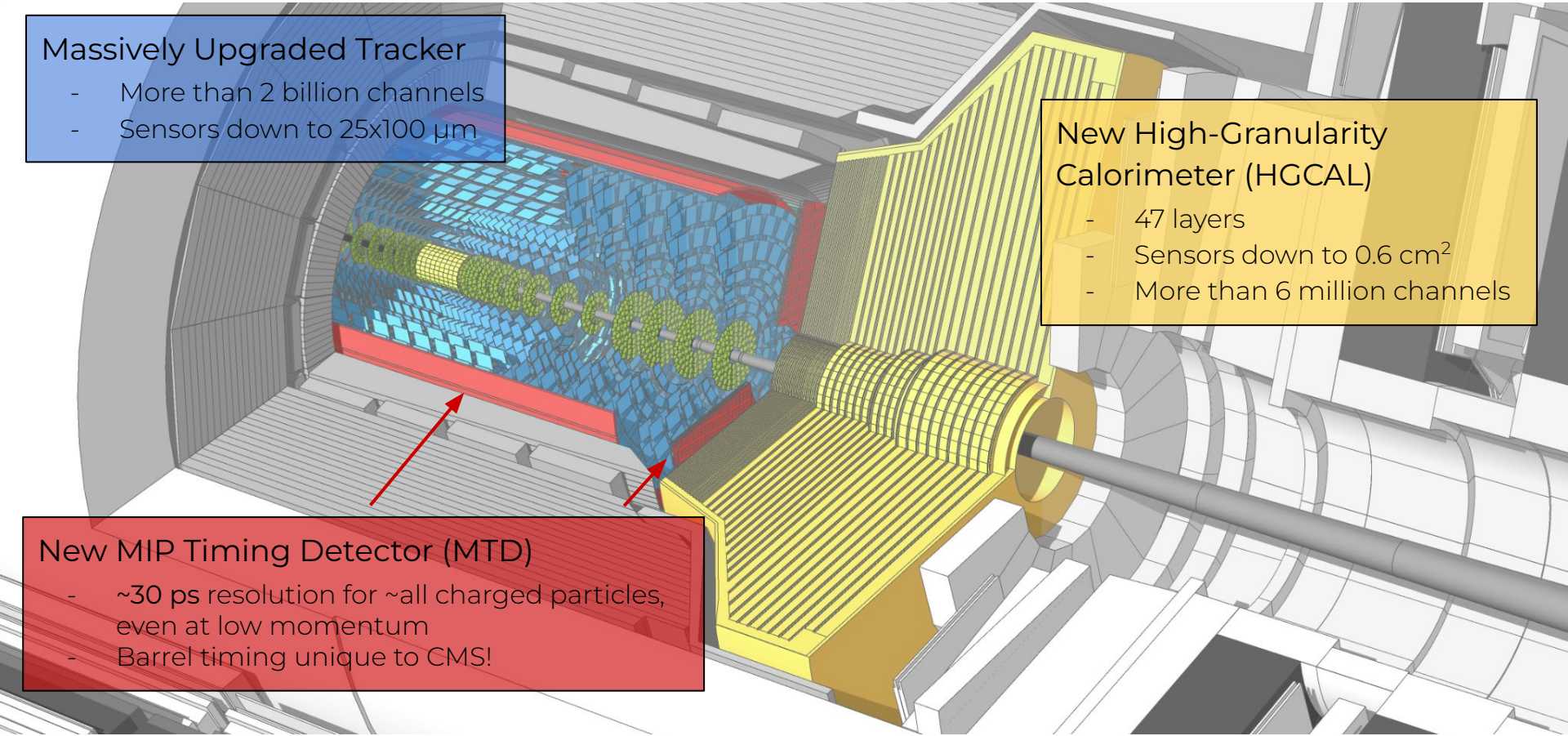
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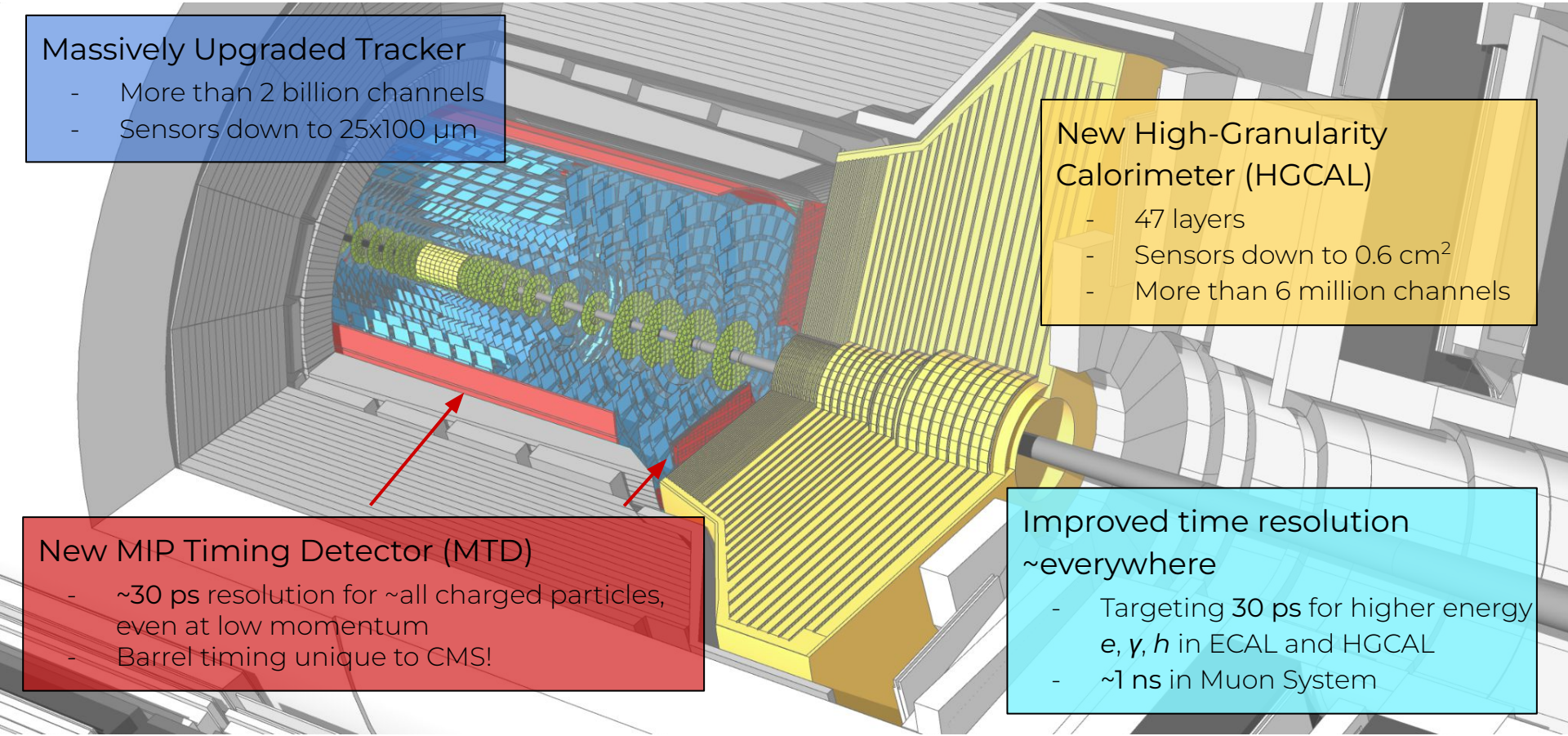
New High-Granularity Calorimeter (HGCAL)

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New MIP Timing Detector (MTD)

- ~30 ps resolution for ~all charged particles, even at low momentum
- Barrel timing unique to CMS!

3. Precision Timing



Massively Upgraded Tracker
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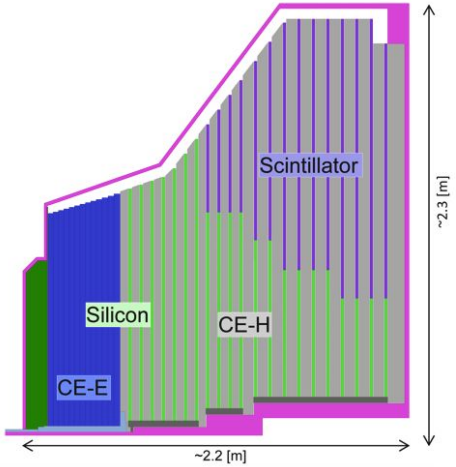
Improved time resolution ~everywhere
- Targeting 30 ps for higher energy *e*, *γ*, *h* in ECAL and HGCAL
- ~1 ns in Muon System

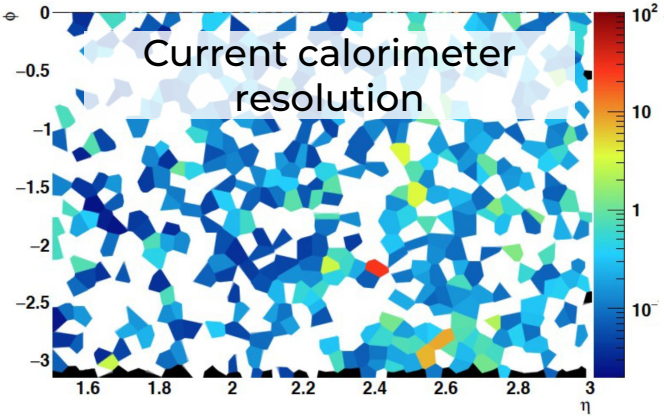
HGCAL

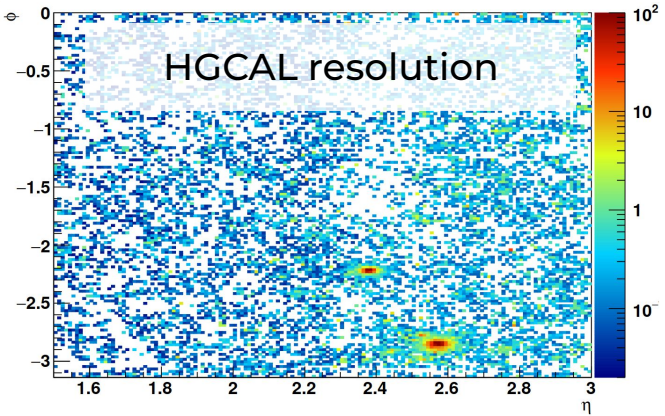
Unprecedented longitudinal and transverse segmentation

Silicon sensors and plastic scintillator + SiPMs

Potential to watch particle showers develop in space and time









MTD

Barrel Timing Layer (BTL):

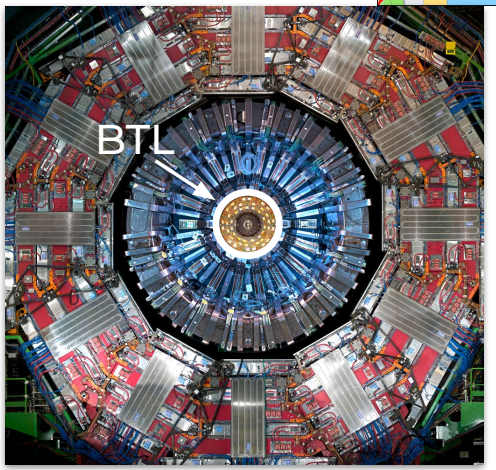
- Scintillating crystals and SiPMs tile surface just outside Tracker

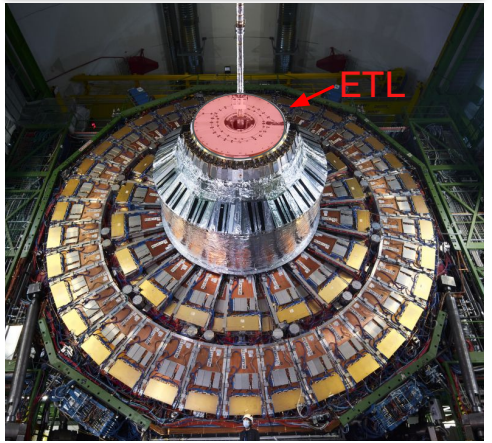
Endcap Timing Layer (ETL):

- Low-Gain Avalanche Diodes (LGADs) just in front of HGCAL

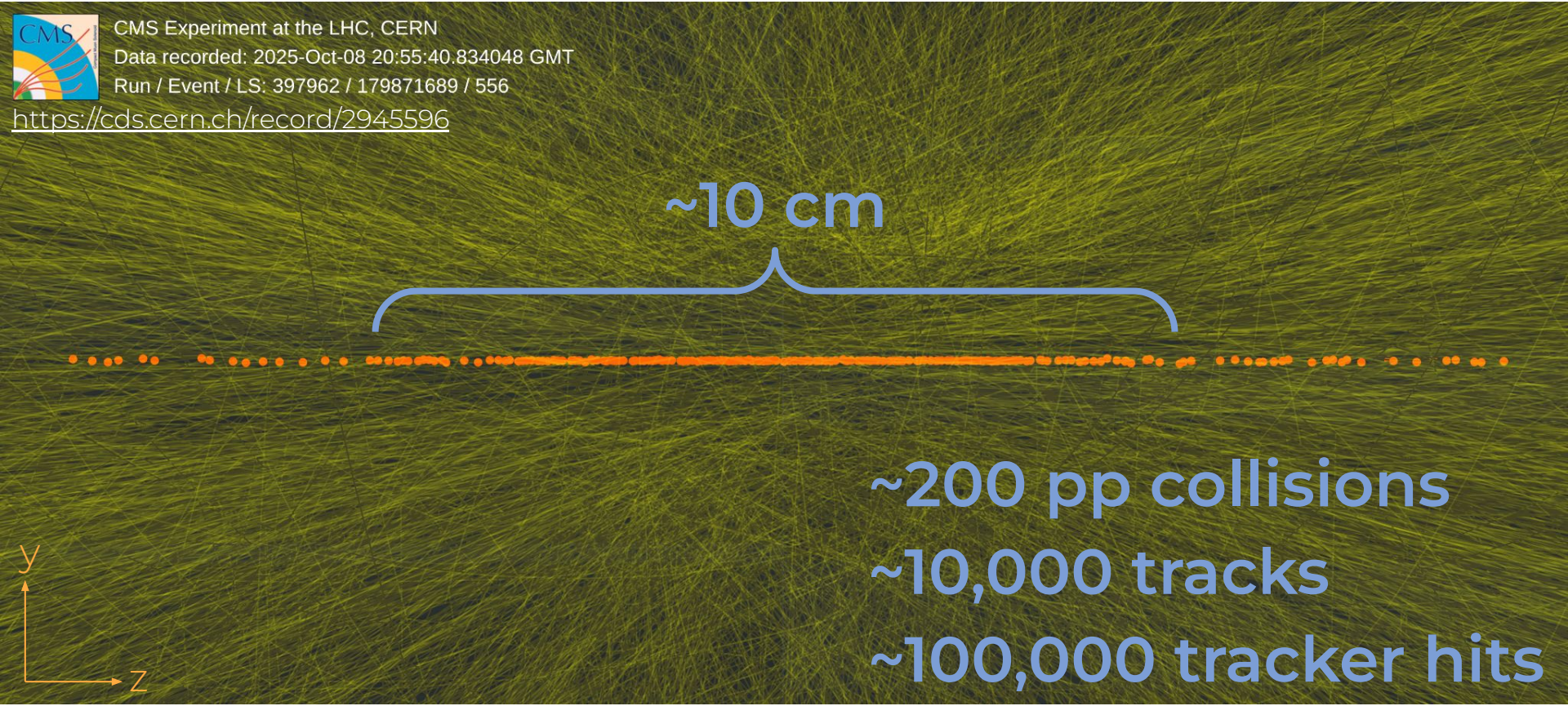
Hermiticity and precise timing for ~all charged particles critical to locate collisions in time



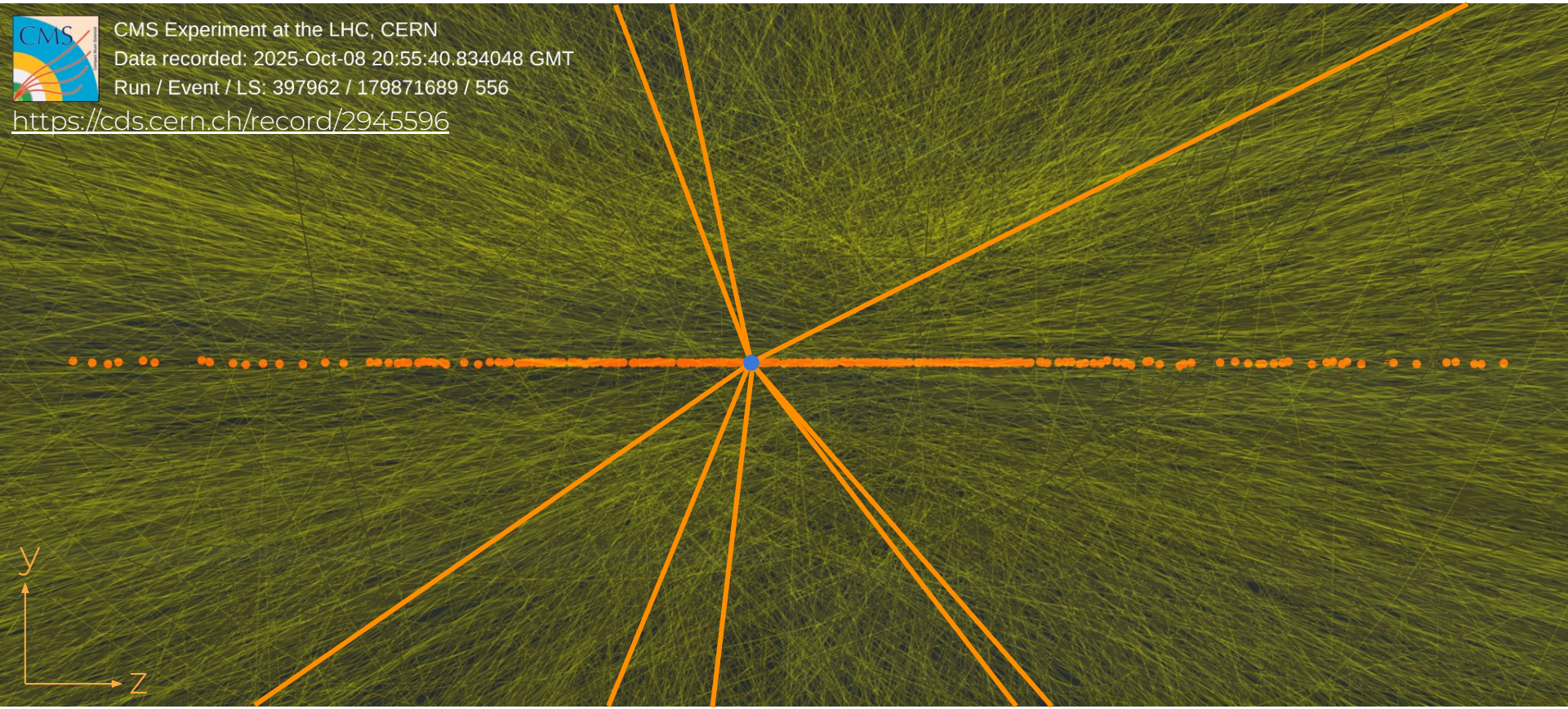




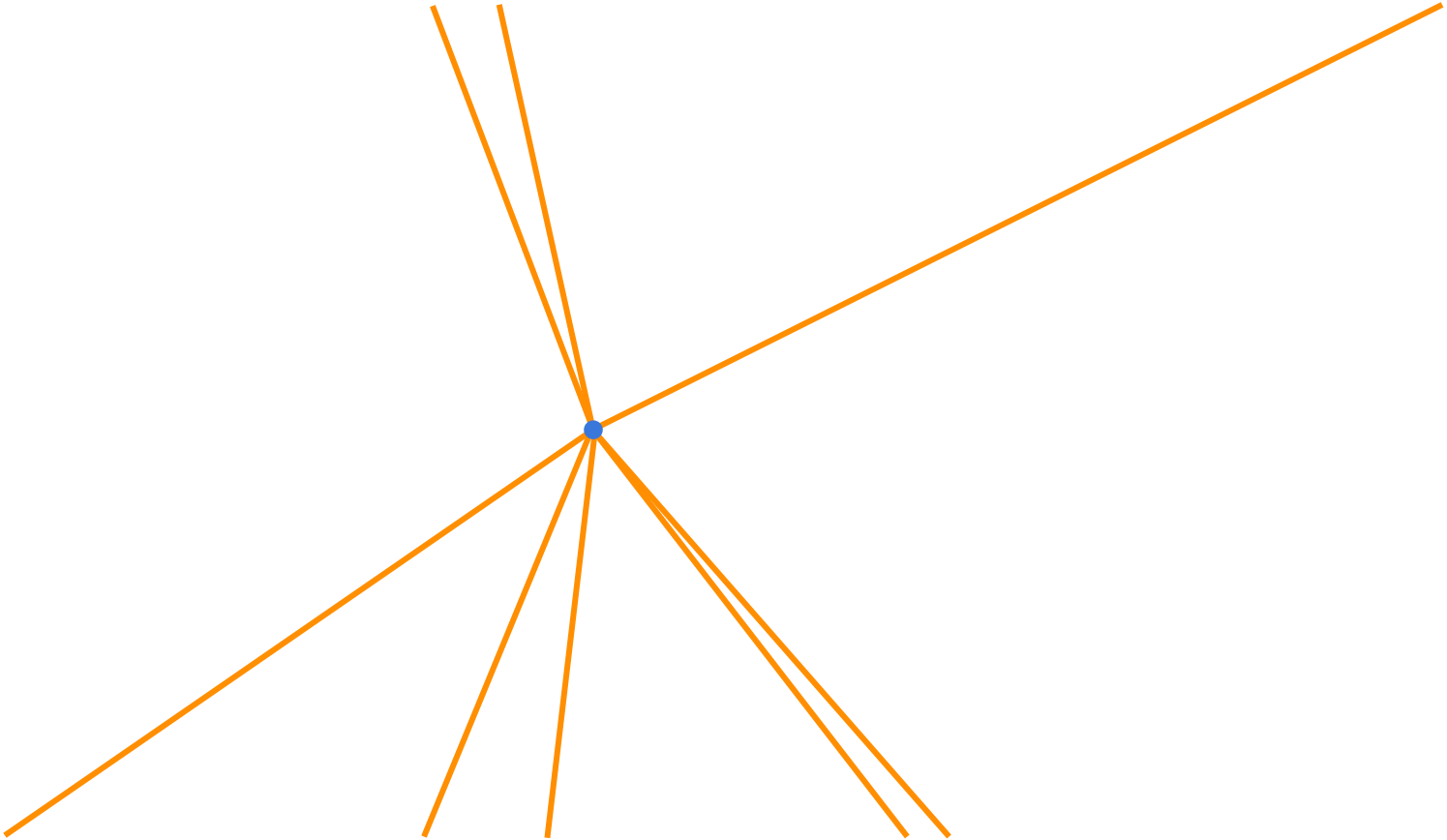
Putting it all together



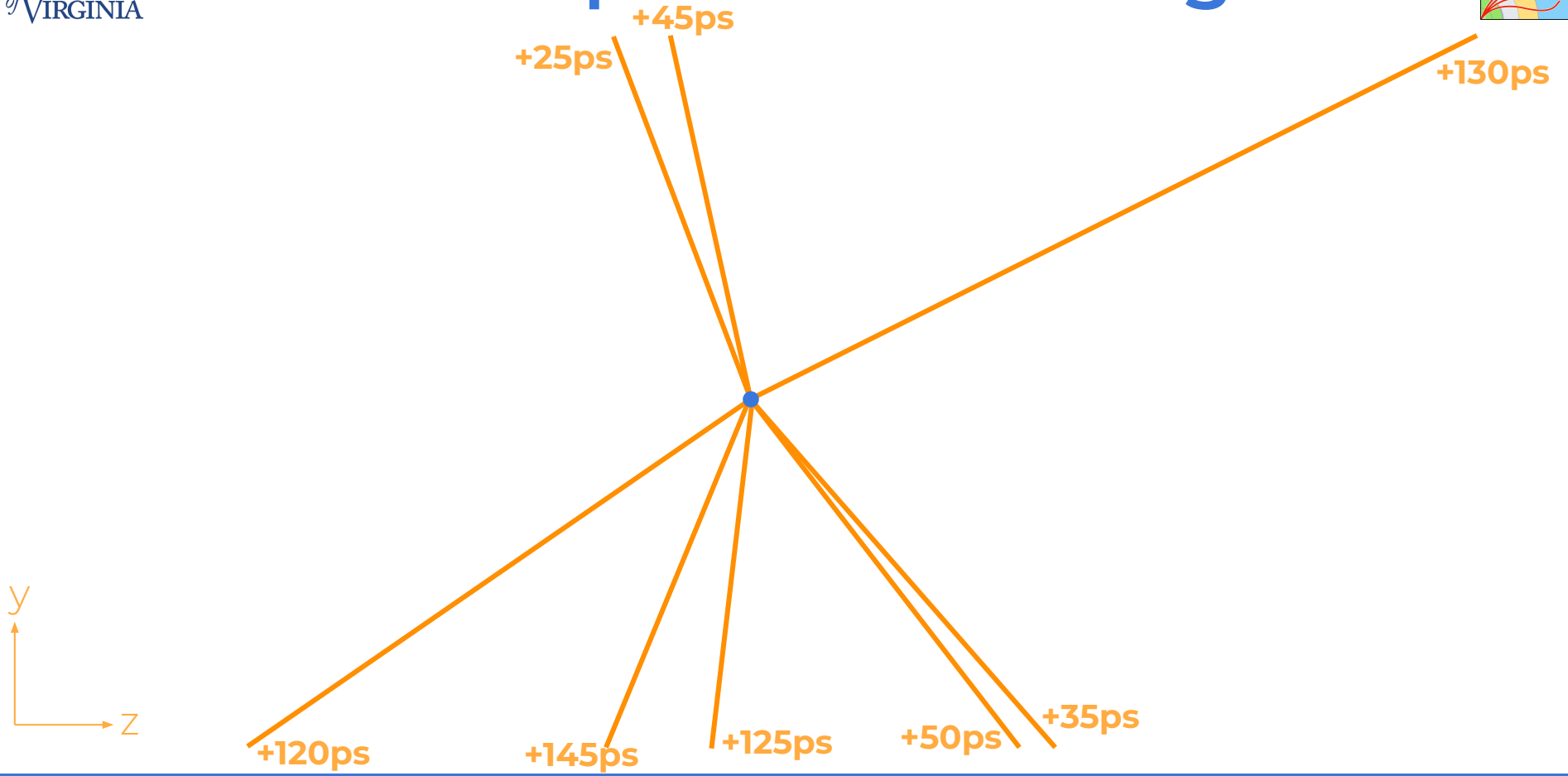
Start with Phase-2 Tracker



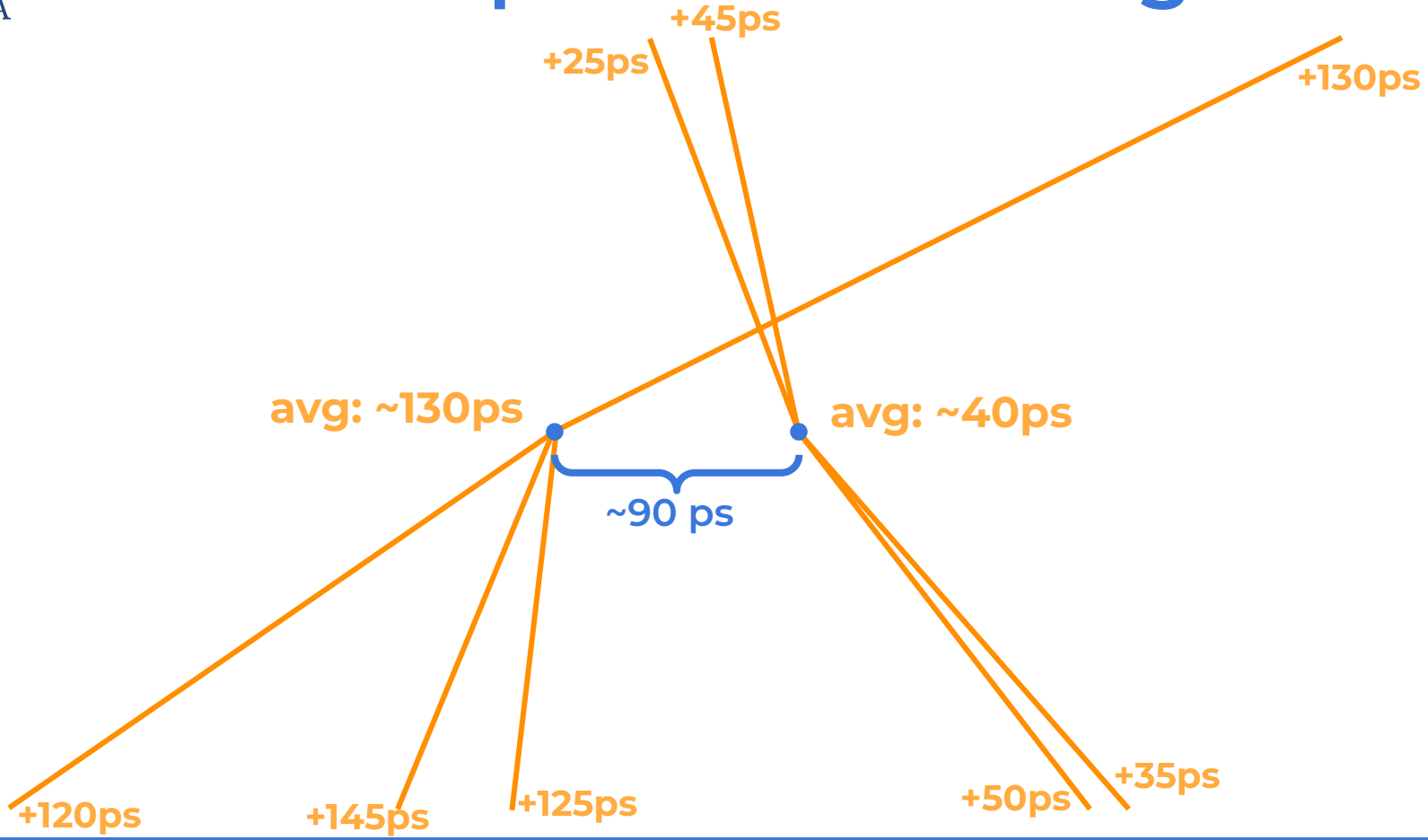
Start with Phase-2 Tracker



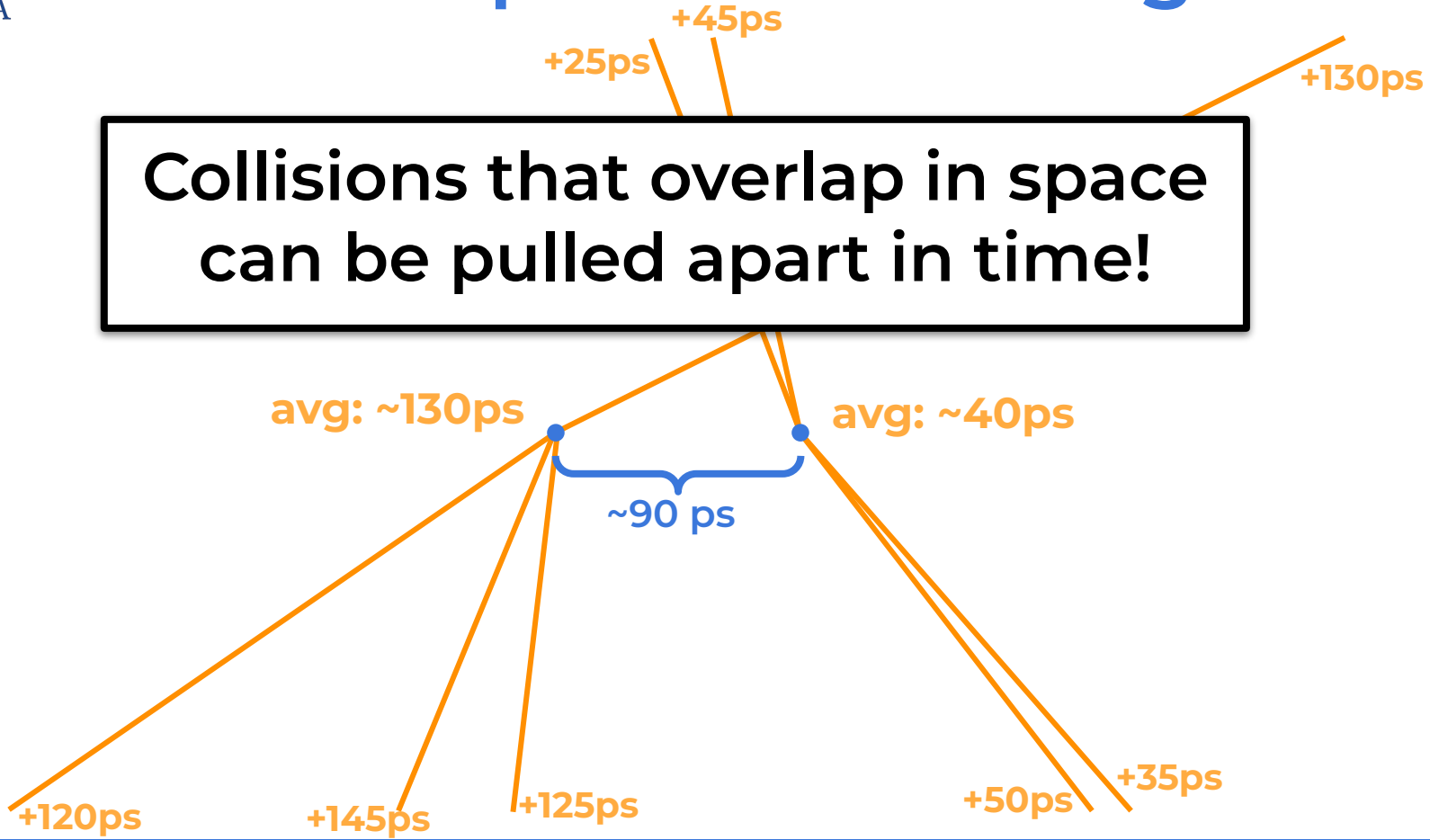
Add precision timing



Add precision timing

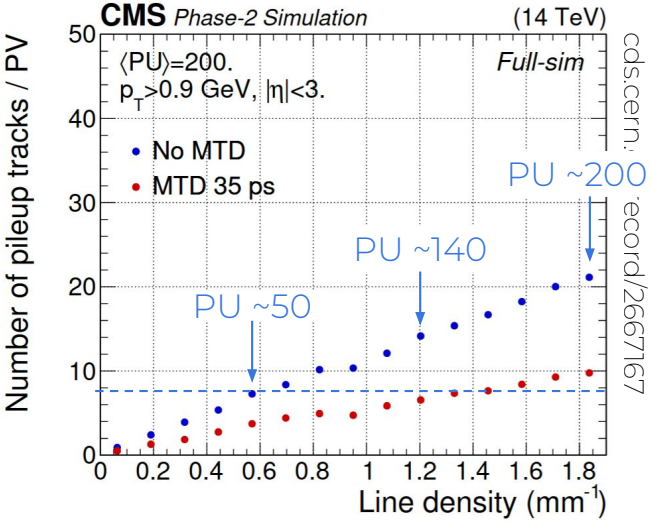


Add precision timing



Why is timing a big deal?

Timing will allow us to reject ~2x as many tracks from pileup vertices

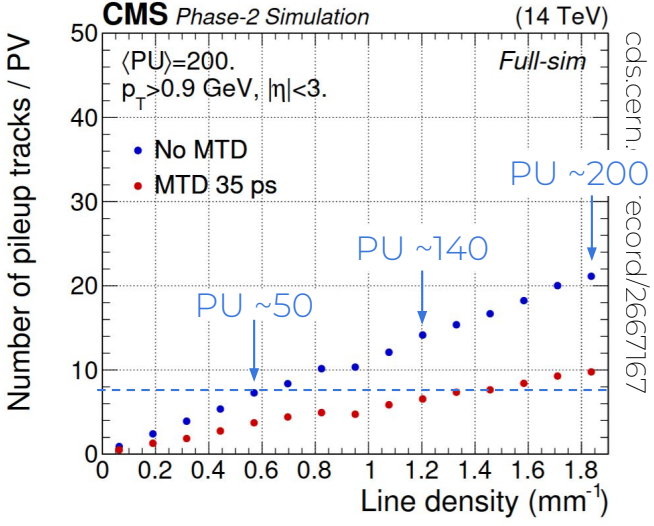


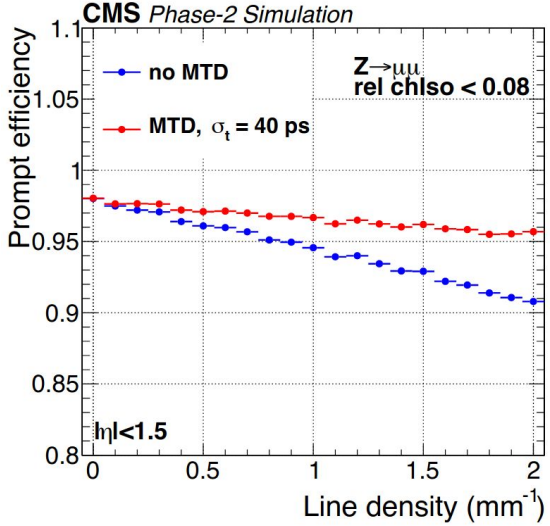
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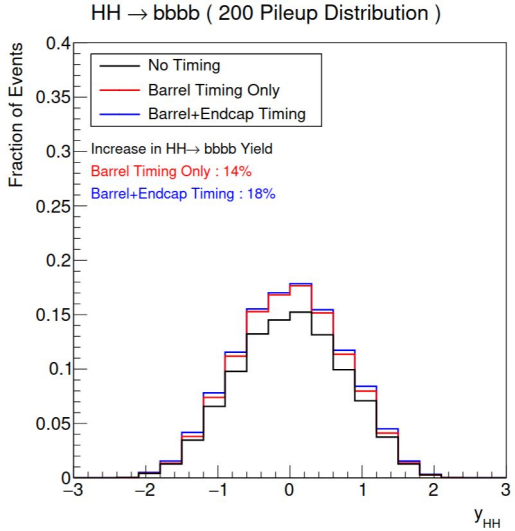
Timing will allow us to reject ~2x as many tracks from pileup vertices

Improves the performance of ~all CMS objects and therefore ~all CMS analyses

- Improved object identification and isolation will improve expected di-Higgs observation significance by as much as ~2-3 additional years of HL-LHC data taking







What else can timing do?

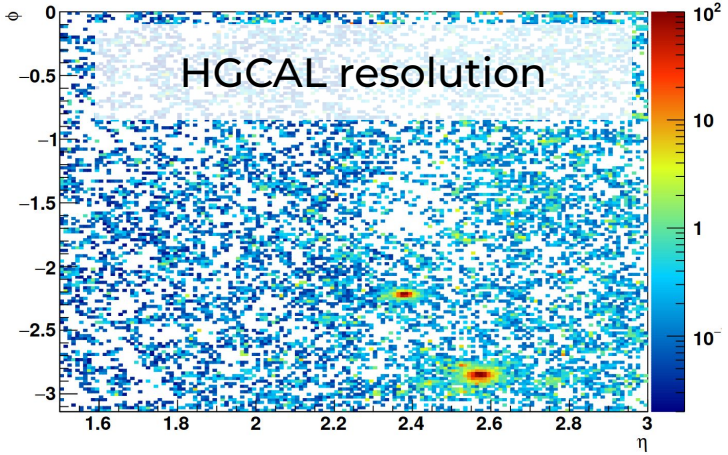
Fundamentally new information enables fundamentally new abilities, for example:

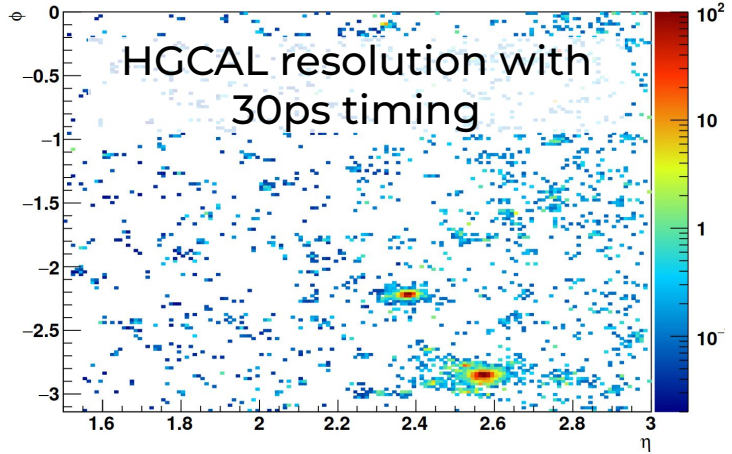
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Work together with other Phase-2 upgrades

- Associate neutral particles to primary vertices by combining MTD vertex time with ECAL+HGCAL time measurements
  - e.g. Identify H→γγ vertex, even at PU=200





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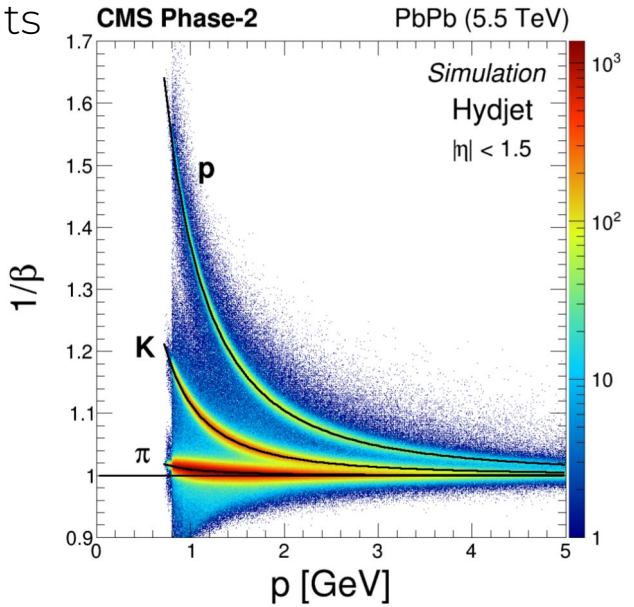
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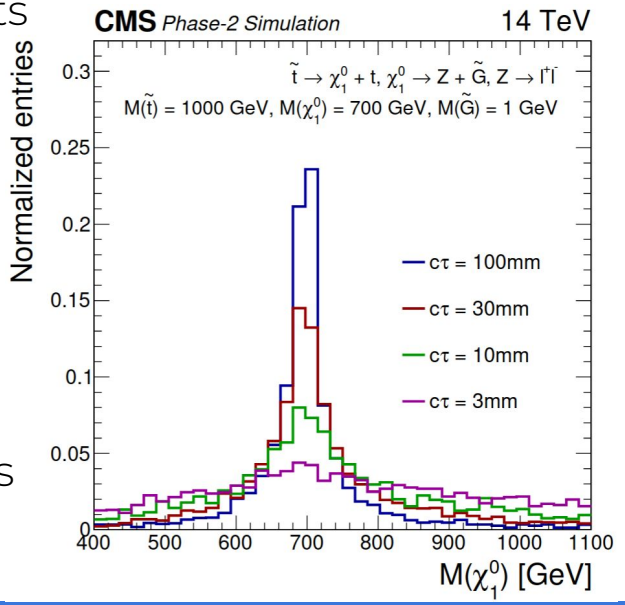
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Long-Lived Particle searches

- Direct handle in Heavy Stable Charged Particle searches
- LLP mass reconstruction via kinematic constraints



Not pictured: Trigger

Huge part of the overall upgrade

Massively increased power and efficiency

- L1 latency: 3.8 μs → **12.5 μs**
- L1 output: 100 kHz → **750 kHz**
- L1: Exploit higher granularity for FPGA-based full offline-like reconstruction
- HLT output: ~1 kHz → **~10 kHz**
- HLT: more GPUs and smarter GPU-friendly reconstruction

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Fundamentally new capabilities

- Dramatically improved HLT scouting →

Aiming to record events at 750 kHz with reduced data format and offline-like reconstruction and quality

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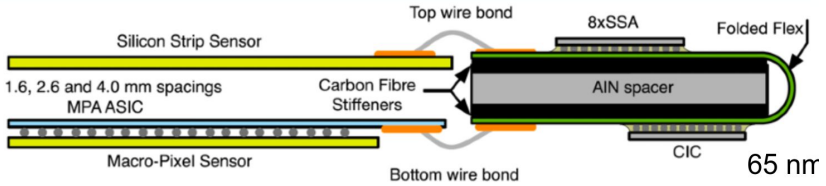
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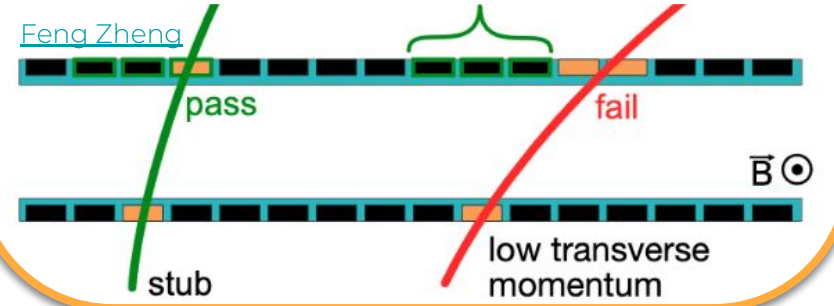
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Fundamentally new capabilities

- Dramatically improved HLT scouting
- Tracking at 40MHz

Phase-2 Tracker design and smarter FPGA-based tracking enable track finding at 40 MHz





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Write ~1 kB of event info for *every* bunch crossing (BX) in LHC orbit

Demonstrator system already running since 2024

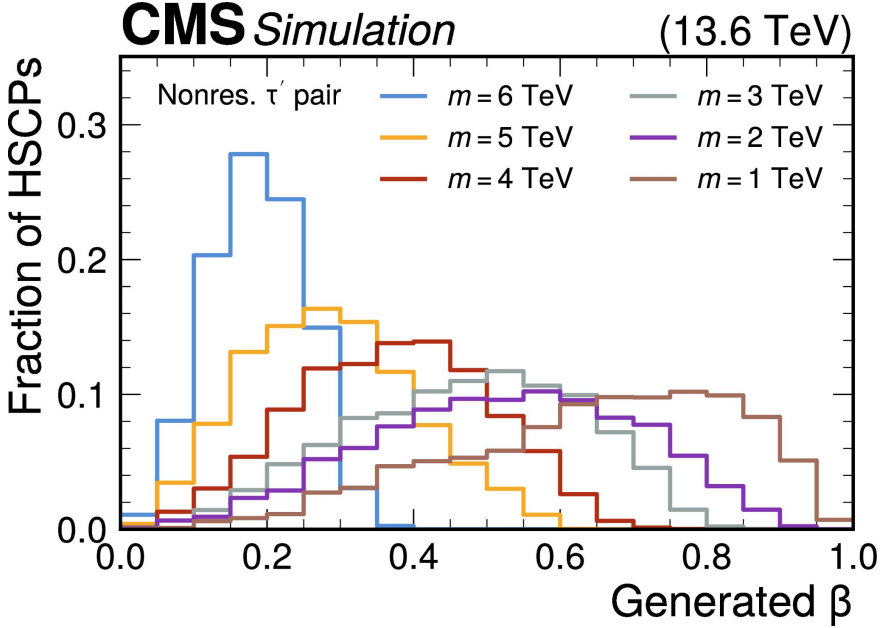
I wonder if we could do anything cool with it…

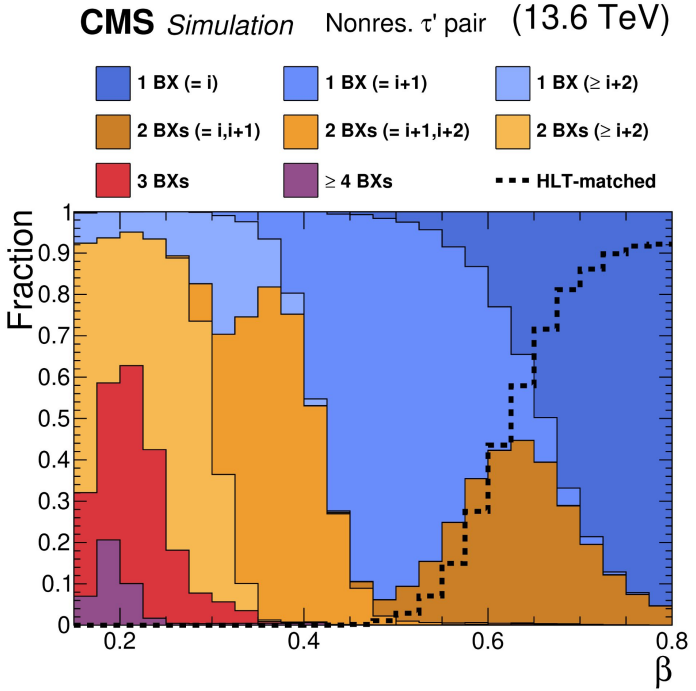
Heavy Stable Charged Particles with 40MHz scouting

arxiv:2601.20063

HSCPs above ~3 Tev take multiple BX to pass through detector

- Search for heavier particles by reconstructing multi-BX tracks in Muon System
- Unique sensitivity to particles with 0.15 < β < 0.5





Heavy Stable Charged Particles with 40MHz scouting

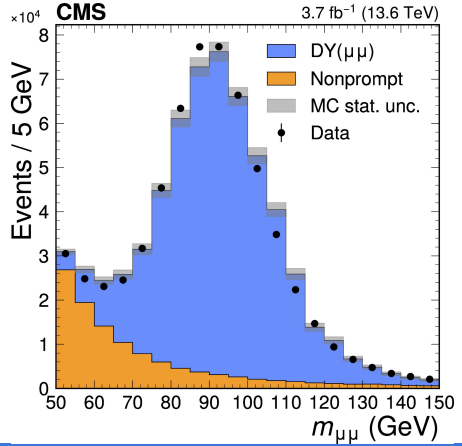
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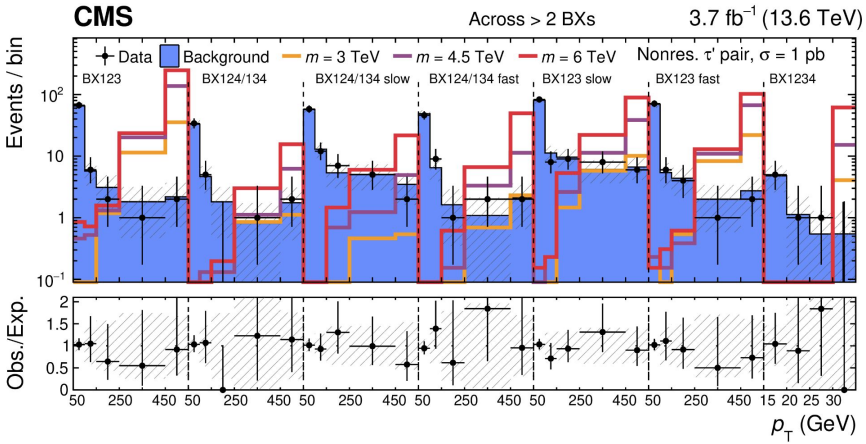
Reconstruct tracks in Muon System that span 2-4 BXs

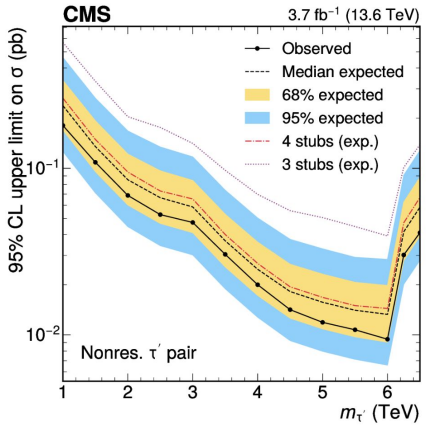
Model background from tracks with asynchronous ordering

Compare track p_T with background model

- World-leading sensitivity to high-mass HSCPs with incomplete system and only 3.7 fb^{-1} of data!







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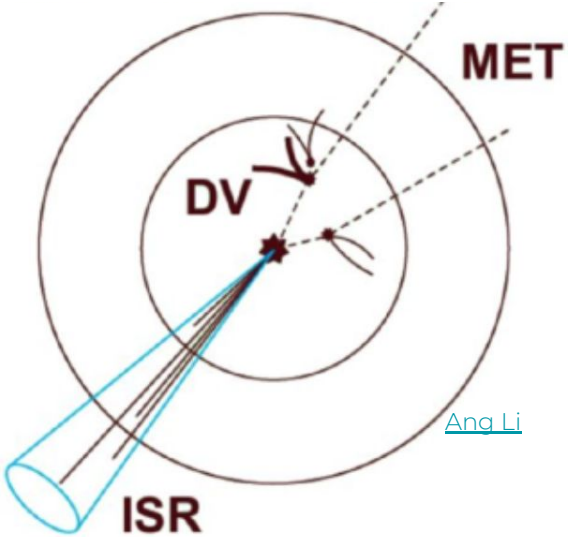
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- When considering these kinds of signals, the massively upgraded trigger, tracking at L1, high granularity, and precision timing have the potential to **fundamentally redefine what is experimentally possible**
- The people who care the most about these upgrades are (rightfully) busy making sure they'll really work – **we as a community need to take stock of their combined impact and recalibrate our imaginations accordingly**

Displaced Vertices with HL-CMS

An imagined Displaced Vertex search, circa 2031

- Events are triggered directly via displaced tracks or vertices
- Vertices are precisely located in time as well as space
- The combinatorial background is reduced by enforcing spatial and temporal consistency
- The SM background processes are clearly identified via timing-based particle ID
- We can *image* decays that occur in HGCAL
- Slow-moving particles are identified via timing and can be tracked across multiple bunch crossings
- ***The combination of all these new handles is used to characterize any observed signal***



Ang Li

Conclusions

CMS continuing to create opportunities for discovery in Run-3 data by redefining what is experimentally possible

(small snapshot today, follow links throughout and see summary plots and CMS review papers)

HL-CMS is prepared to meet the challenge of HL-LHC

Doing so presents an opportunity to view LHC collisions through entirely new eyes – let's take it

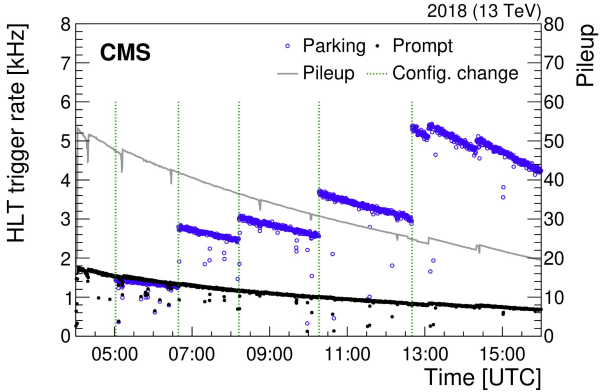
bonus slides

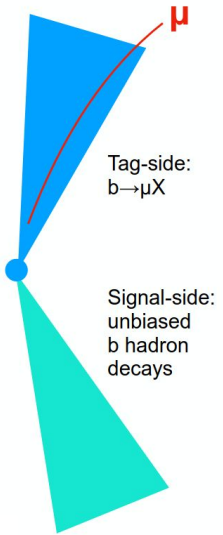
2018 B-Parking dataset

CMS-EXO-23-007

CMS recorded 10 billion events w/ unbiased b-hadron decays during 2018

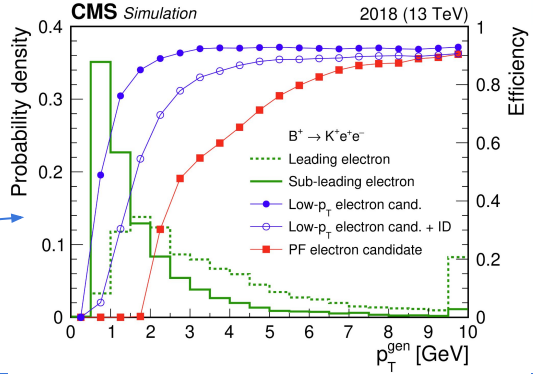
- Motivated by B flavor anomalies
- Triggering on single displaced “tag” muon provides pure, unbiased b-hadron sample
- Vary muon p_T and displacement thresholds throughout LHC fill to maximize acceptance
- Park on disk and reconstruct *after* 2018 run





Also an incredible playground for LLP searches!

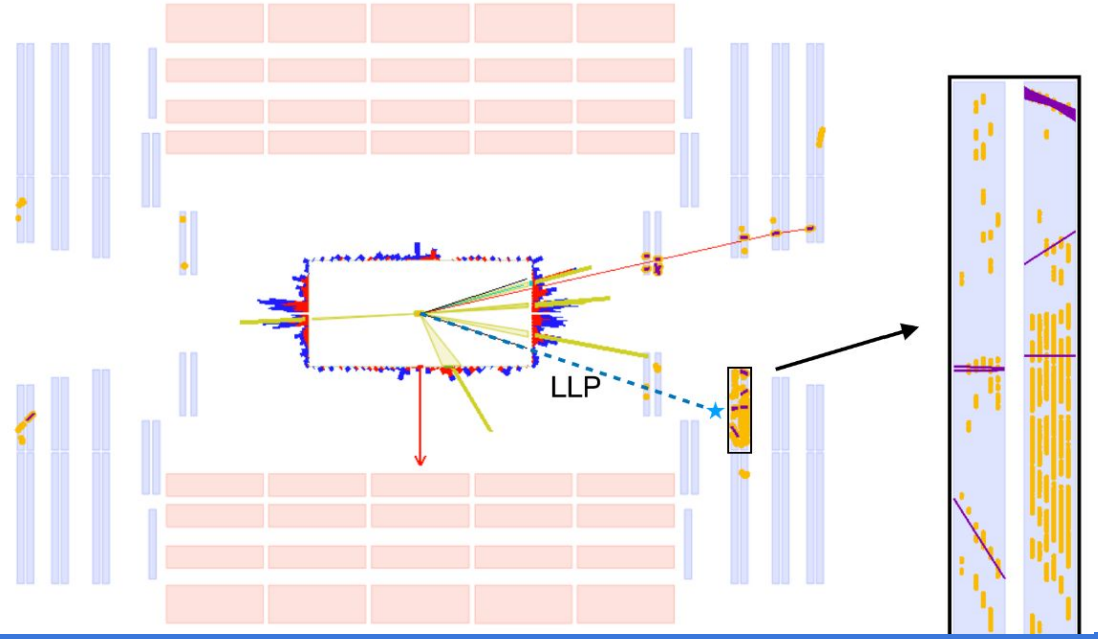
- Access to low-mass and compressed scenarios
- Bonus: low-p_T electron reconstruction algorithm



Muon Detector Showers (MDS)

Use CMS muon system and steel return yoke as a sampling calorimeter

- Large radius, excellent shielding, sensitive to hadronic and EM showers
- Signal sensitive to LLP energy, not mass → sensitivity to very low-mass LLPs



Expanding MDS search program over last few years

- MET triggers: CMS-EXO-20-015
- Lepton triggers: CMS-EXO-22-017
- B-parking: CMS-PAS-EXO-24-004
- With τ: CMS-EXO-23-015

200 vs 80 pp collisions

