Run 3 performance of new hardware in CMS

LHCP2023: The 11th annual conference on Large Hadron Collider Physics,

22-27 May 2023, Belgrade (Serbia)

David Walter,
on behalf of the CMS Collaboration

CERN

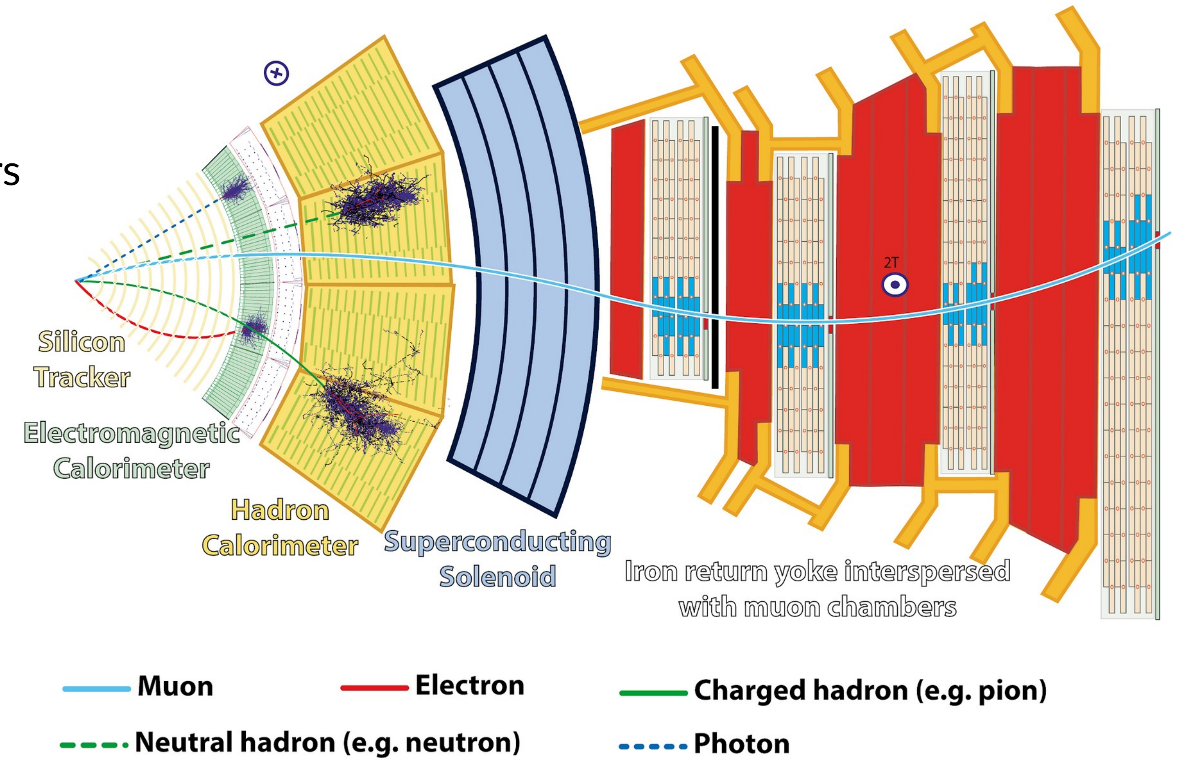
LHCPhysics
Belgrade, 22 - 26 May 2023

CMS
Compact Muon Solenoid

The CMS experiment

Event reconstruction via particle flow

- Combine information from all subdetectors



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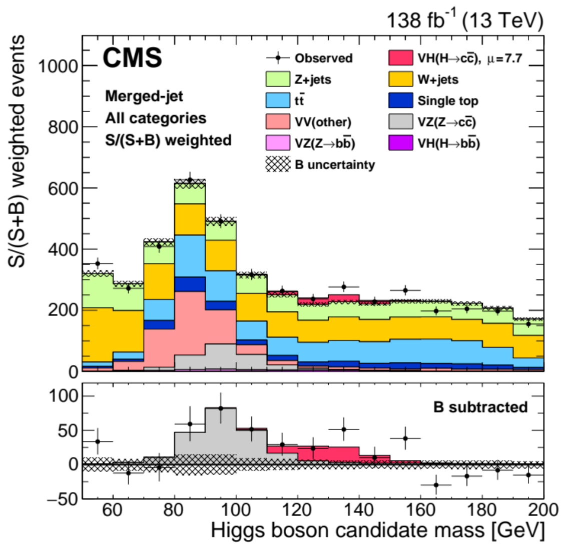
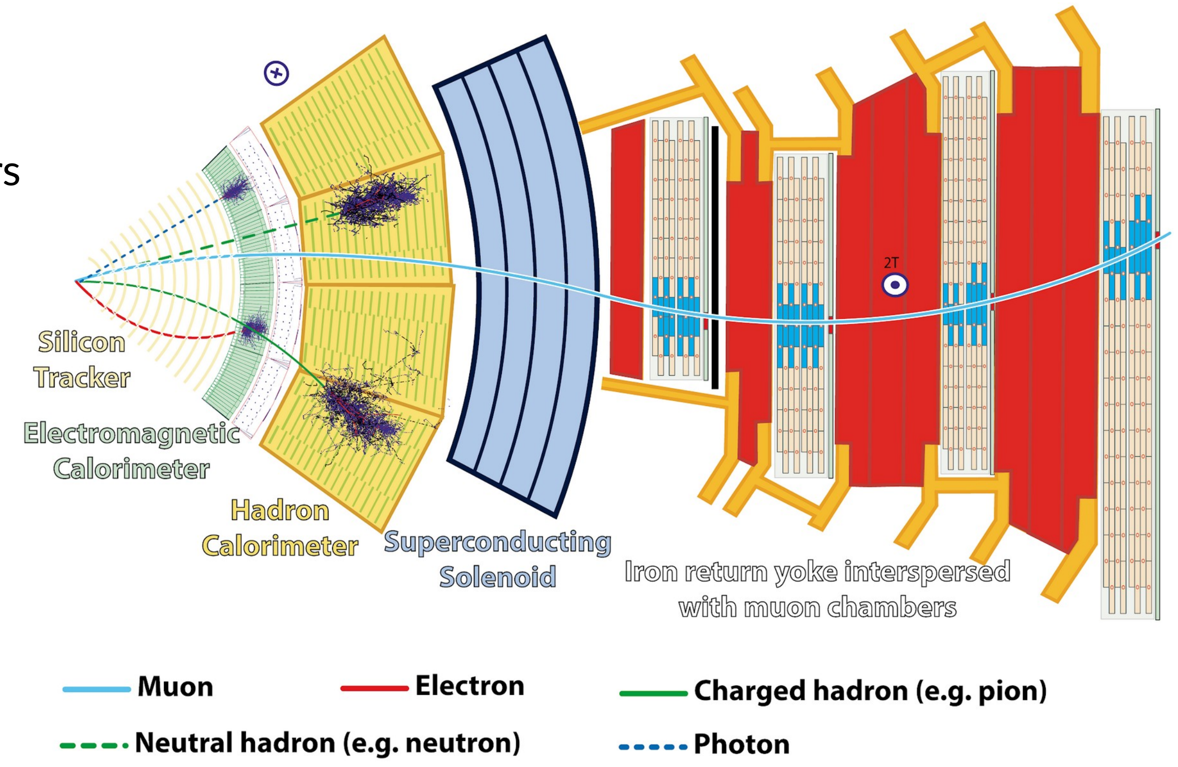
Example physics case:

- H → cc [arXiv:2205.05550]





σ_{obs} (H→cc) < $14\sigma_{SM}$ – observation in Run 3?

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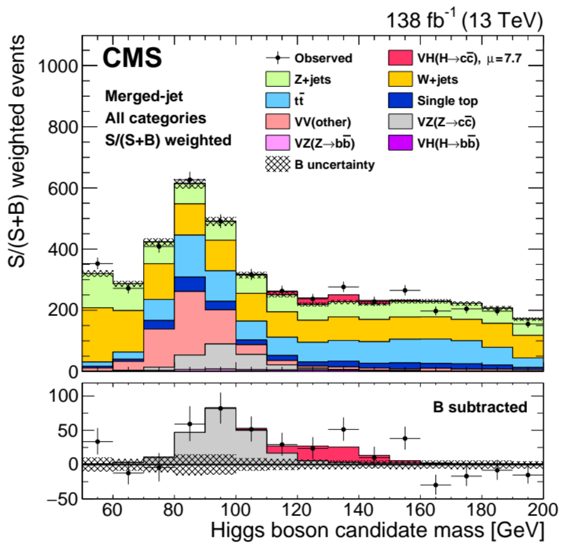
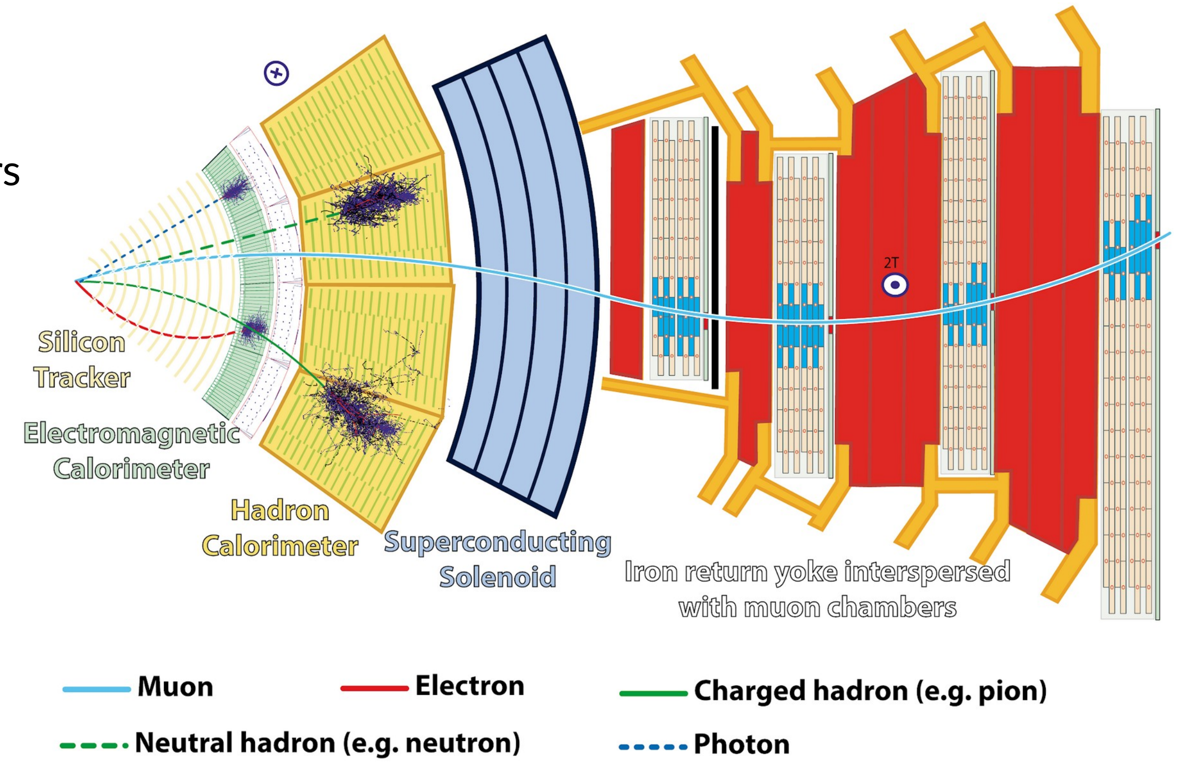


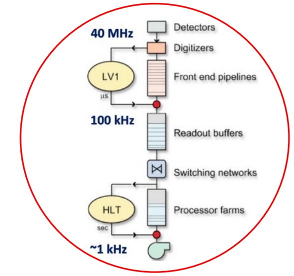


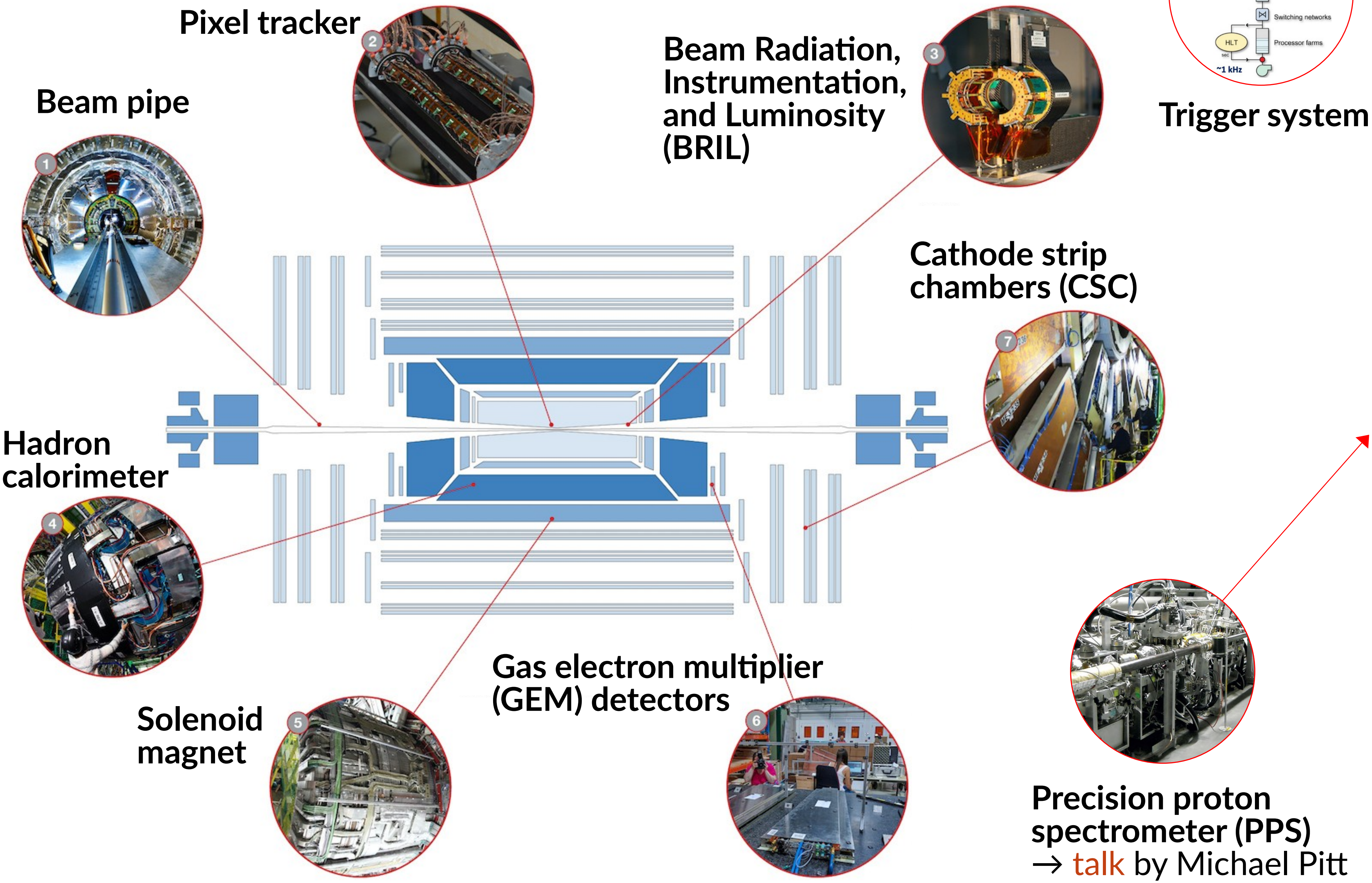
σ_{obs} (H→cc) < $14\sigma_{SM}$ – observation in Run 3?

Challenges for data taking

- Radiation damage from past
- Increasing pileup to ~60
- Recover - Detector maintenance
- Upgrade – Experience / Use technological advancements in hardware & software

CMS after the 2nd long shutdown





[CMS DP 2022/033]

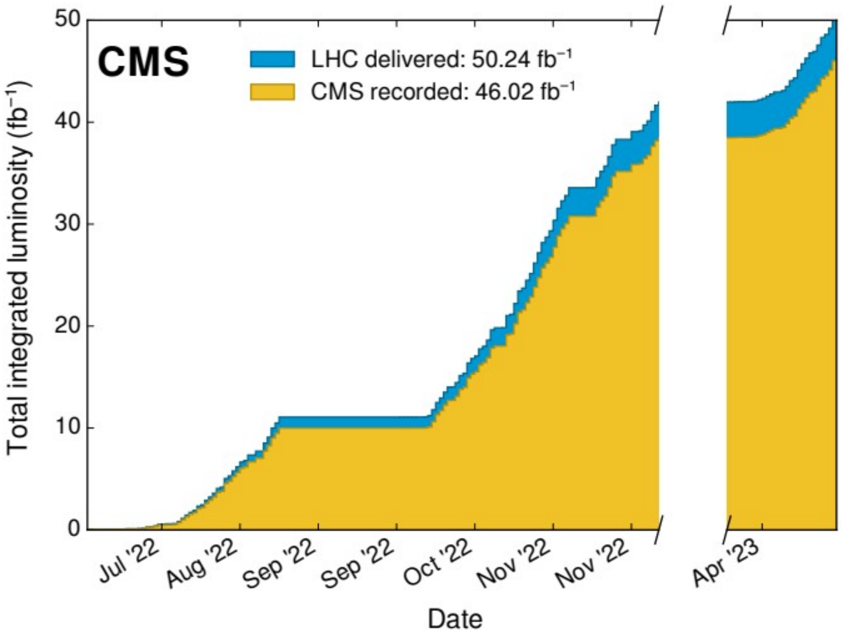
Luminosity

Successful start of Run 3 data taking

- LHC delivered 42fb^{-1} in 2022
- 92% recorded (89 % certified)

Multiple luminosity detectors for cross-checks

→ Preliminary uncertainty for 2022: δL = 2.1%



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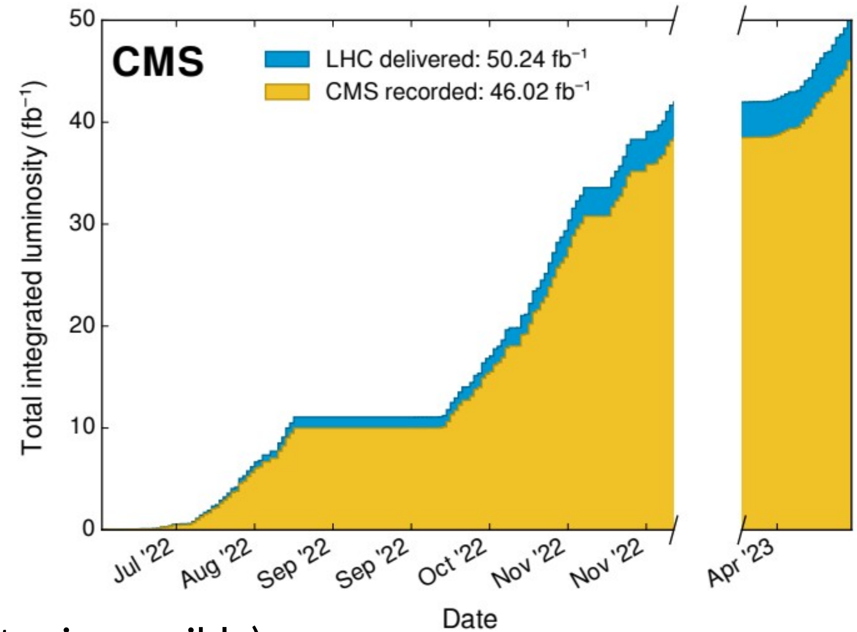
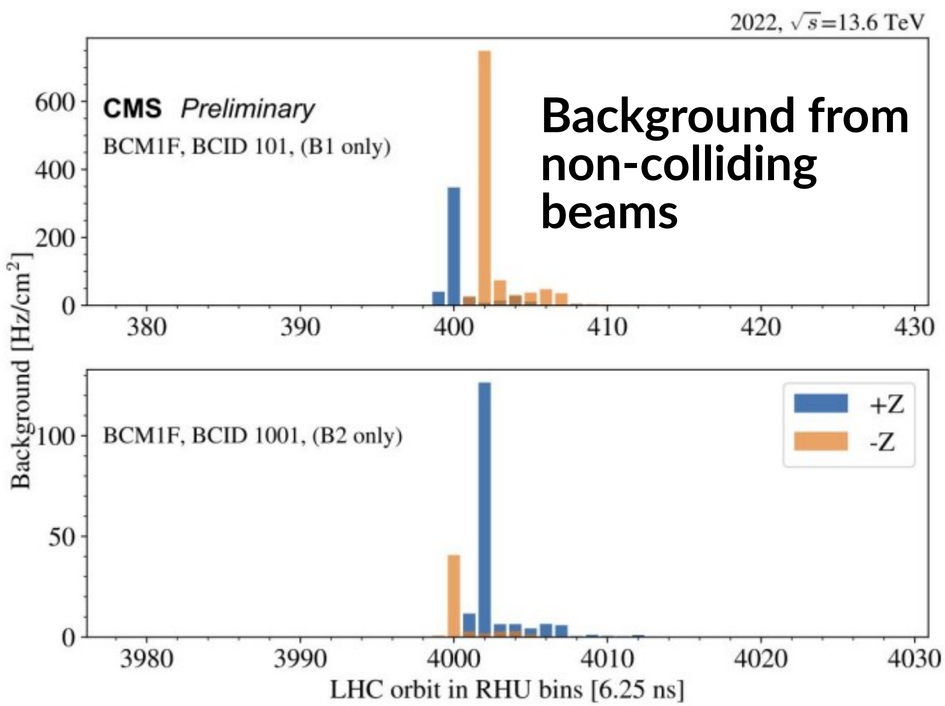
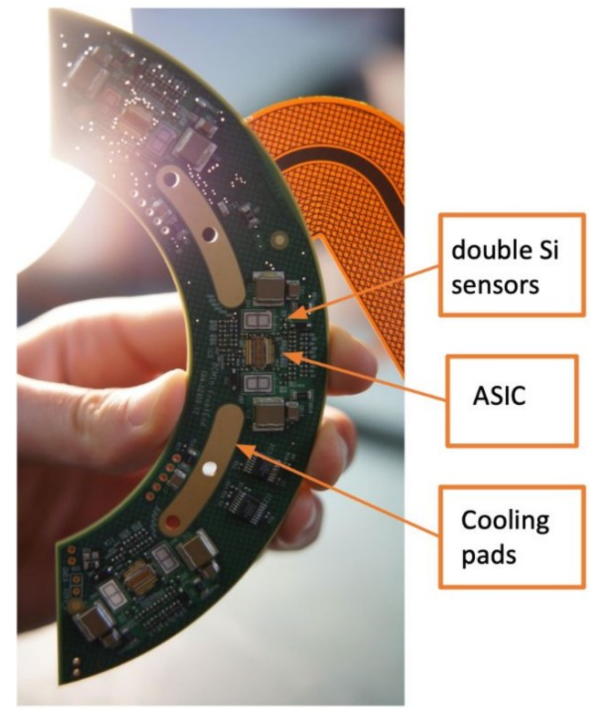
Rebuilt Fast Beam Condition Monitor (BCM1F)

- Measure background rate in 6.25ns (4.167ns in 2023, faster is possible)
- Full silicon based and cooled to -20°C





Background from non-colliding beams



One of four C shapes

Silicon tracker

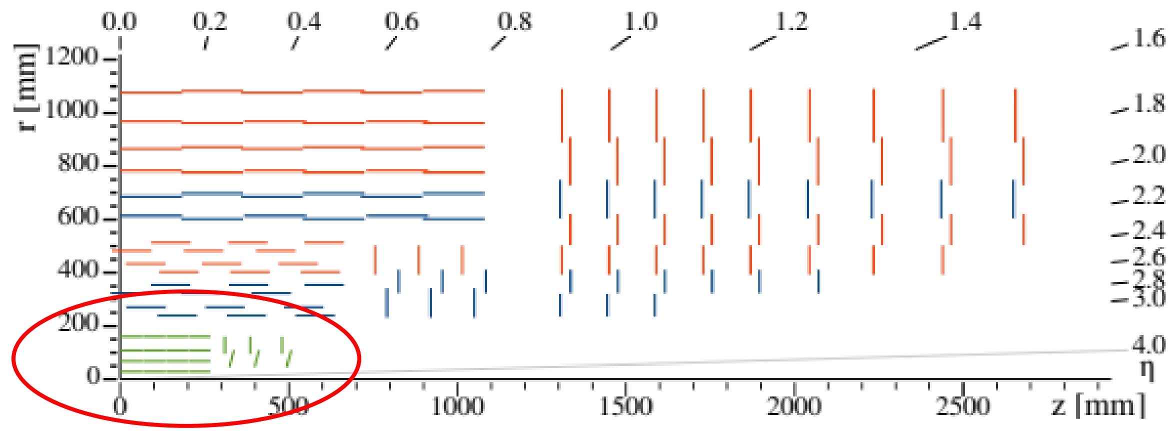
[CMS DP 2022/044]
[CMS DP 2022/047]
[CMS DP 2022/070]

Work on pixel detector

- Extracted after Run 2 for maintenance
- New innermost layer
- Reinstalled in 2021

Functional pixel readout chips > 98.5%

- Compared to ~94% for 2018



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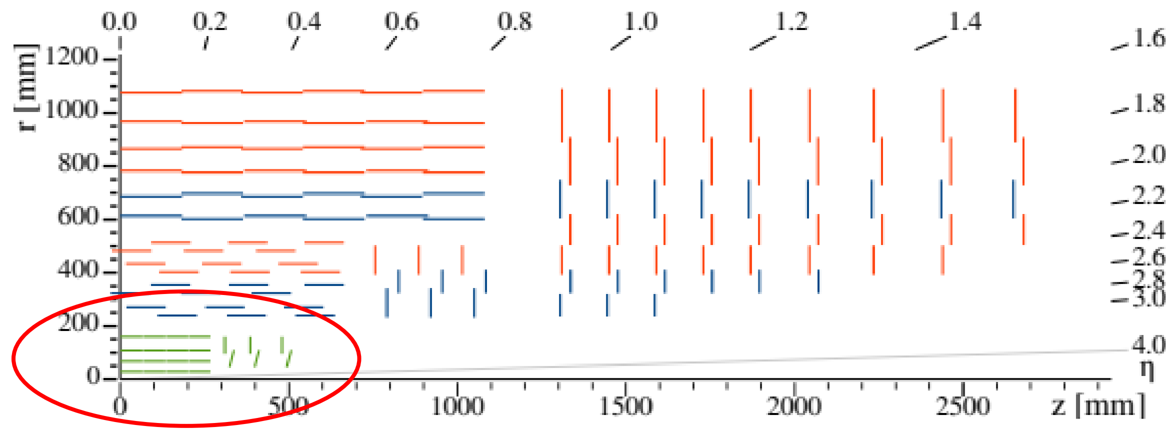
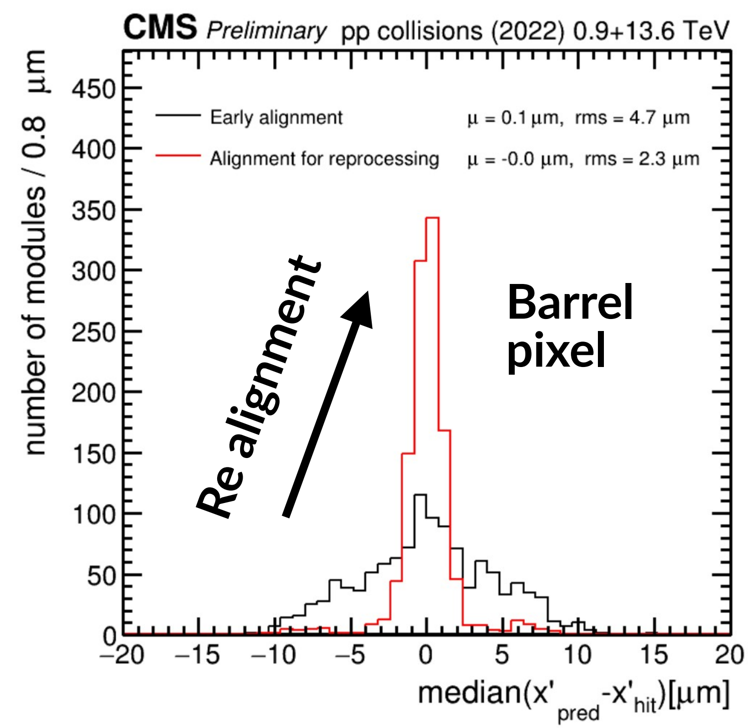
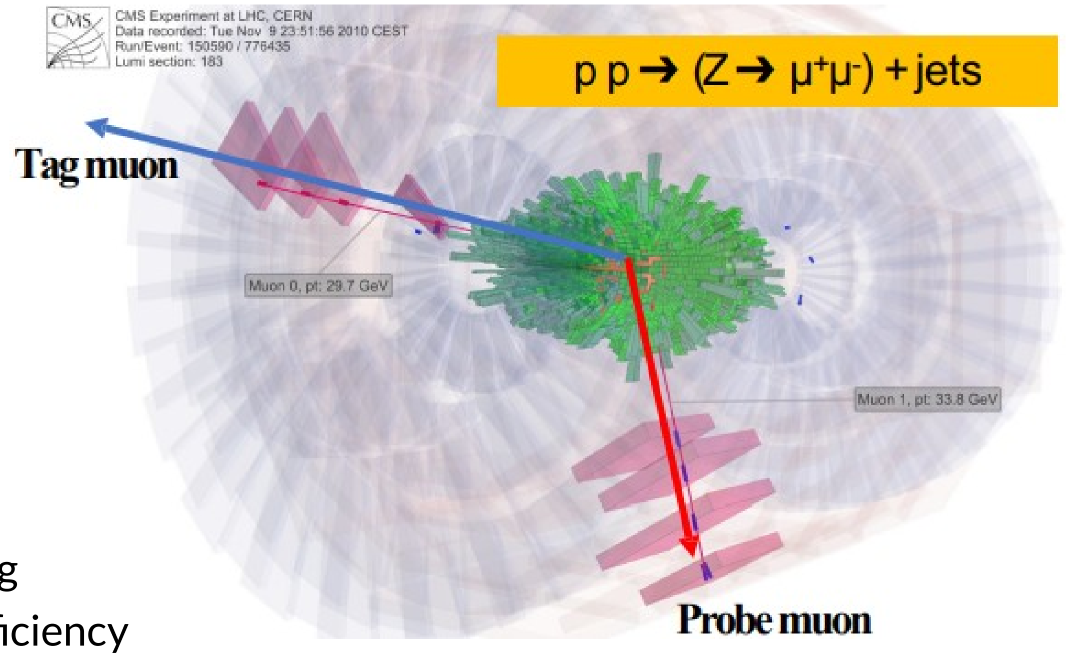
Incremental detector alignment
- Early alignment:
  - 300K cosmic ray tracks
  - 7M pp collision tracks at 900GeV
- Alignment for reprocessing:
  - 9M cosmic ray tracks
  - 120M pp collision tracks at 13.6TeV

→ poster





Tracking efficiency

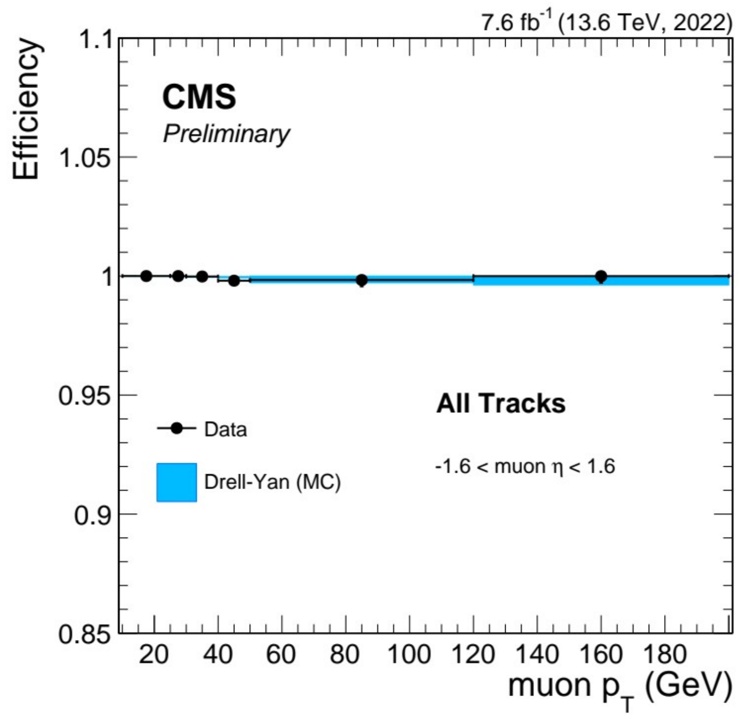


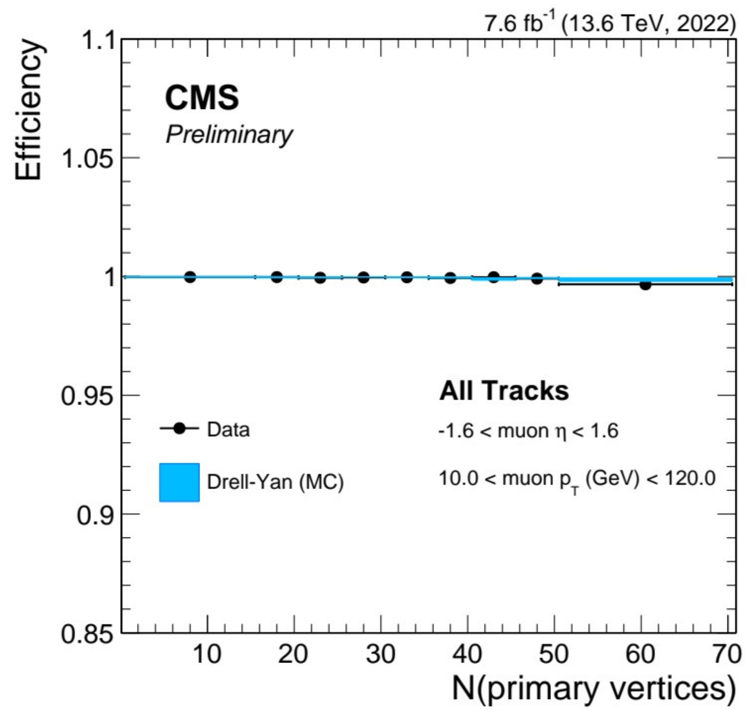
Tracking efficiency measured via tag & probe

- Data until 23 Aug 2022
- Approaches 100%
- Very stable under higher pileup conditions

Other improvements:

- Parallelization for multi core CPU/ GPU for timing
- Track selection DNN replacing BDT for better efficiency

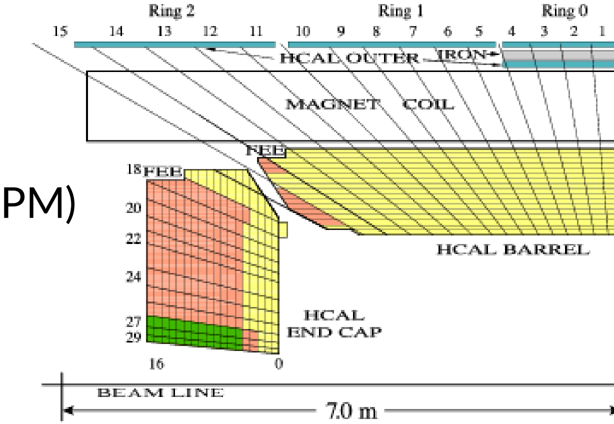




Hadronic calorimeter

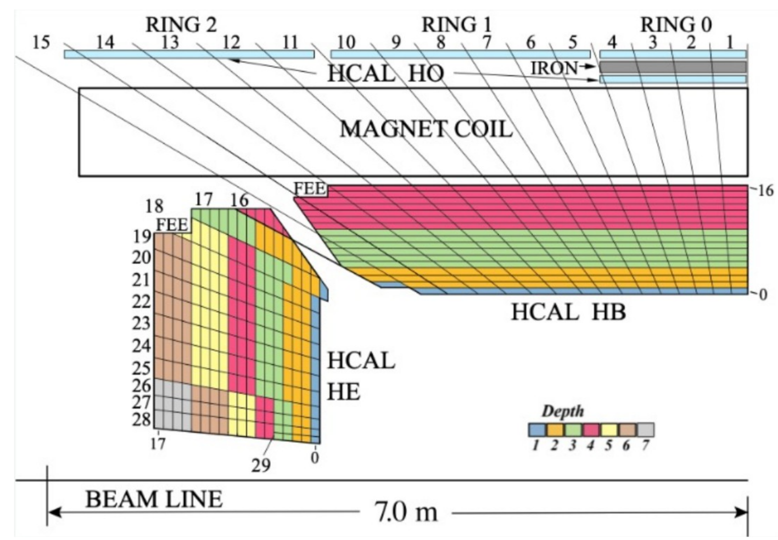
Replacing old hybrid photodetectors (HPD) with new silicon multipliers (SiPM)

- Three times higher photon detection efficiency, 200 times higher gain
- Finer depth segmentation
  - 4 in barrel, up to 7 in endcap
  - 350% increase in the number of readout channels
- Added timing information (0.5ns resolution)



Endcap upgrade before 2018
Barrel upgrade for Run 3

Mitigate radiation damage to the scintillator
Eliminate a source of high-amplitude noise
Maintain physics performance for jets and MET
Enable new triggers (e.g. long lived particles)



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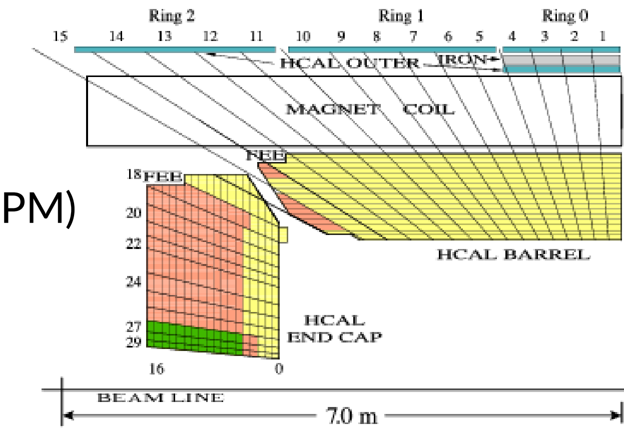

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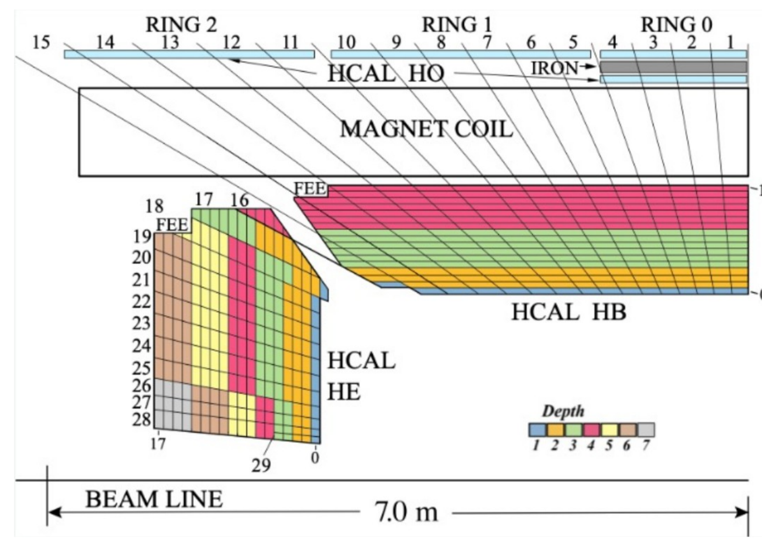
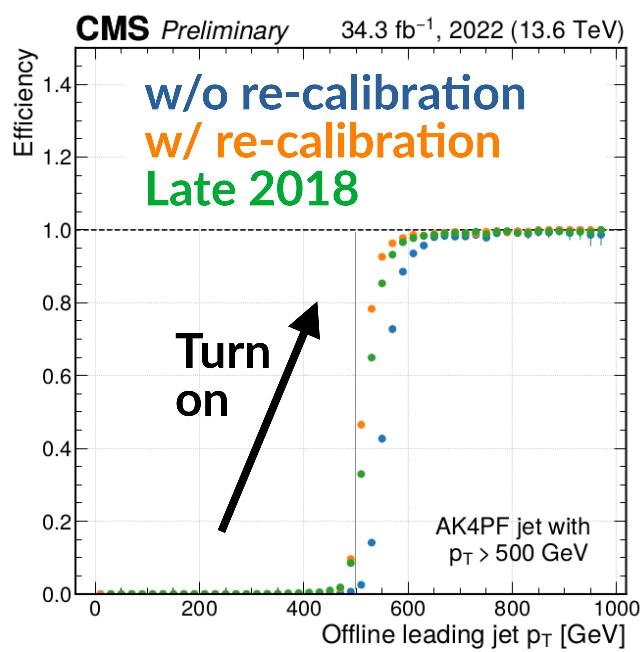


Successful commissioning

- Re-calibration on early data



[CMS DP 2022/069]

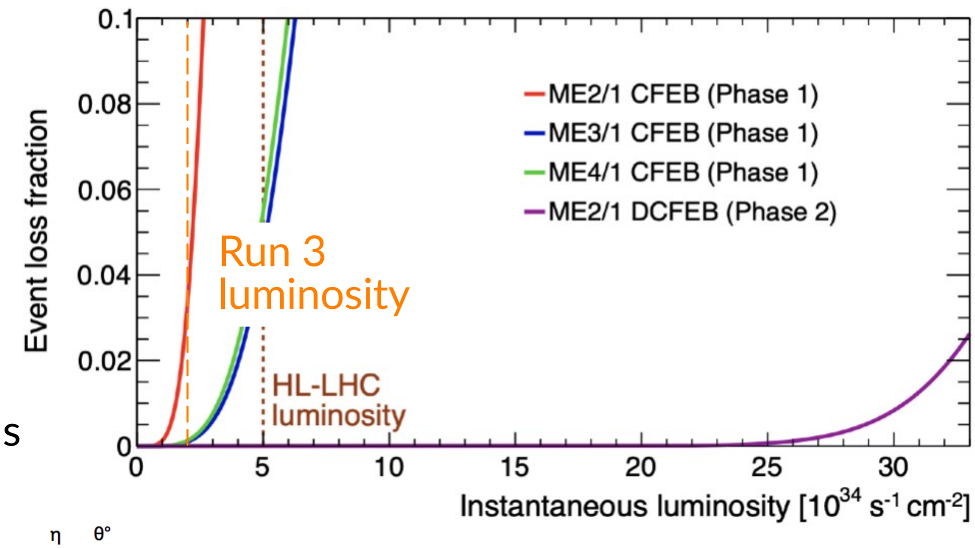
Muon detectors

Cathode strip chamber (CSC) located in 0.9 < |η| < 2.4

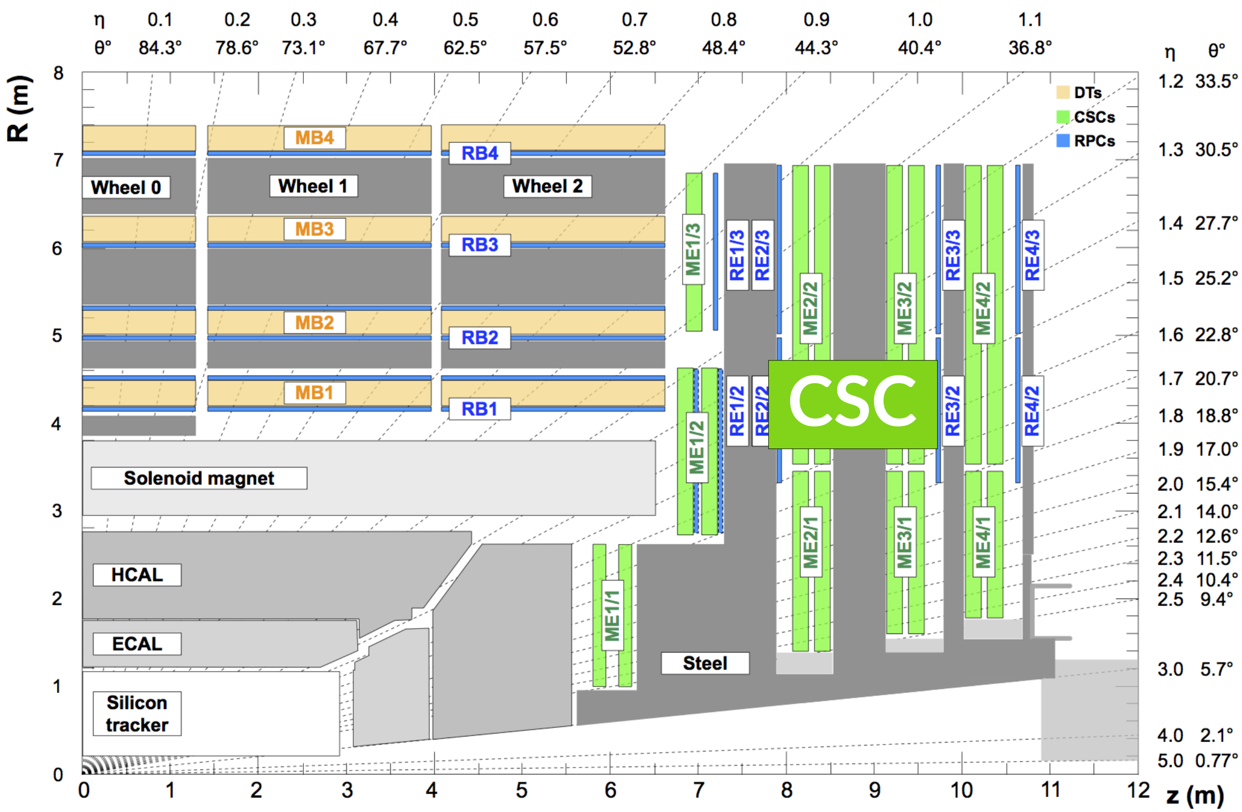
Firmware for new electronics boards deployed

- Handle the higher particle rates with no data loss
  - High speed optical links for trigger data
  - Radiation tolerant
  - More current for new electronics

Successfully commissioned with cosmic and beam muons



Significant loss without upgrade
(~100% loss in ME2/1 at HL-LHC)



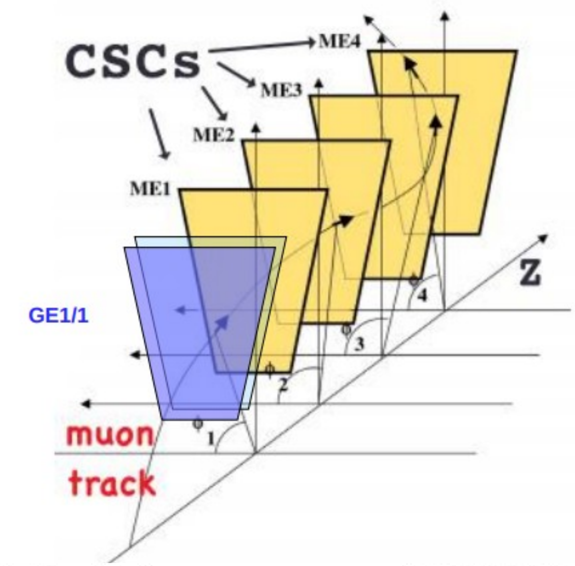
New gas electron multiplier (GEM) stations

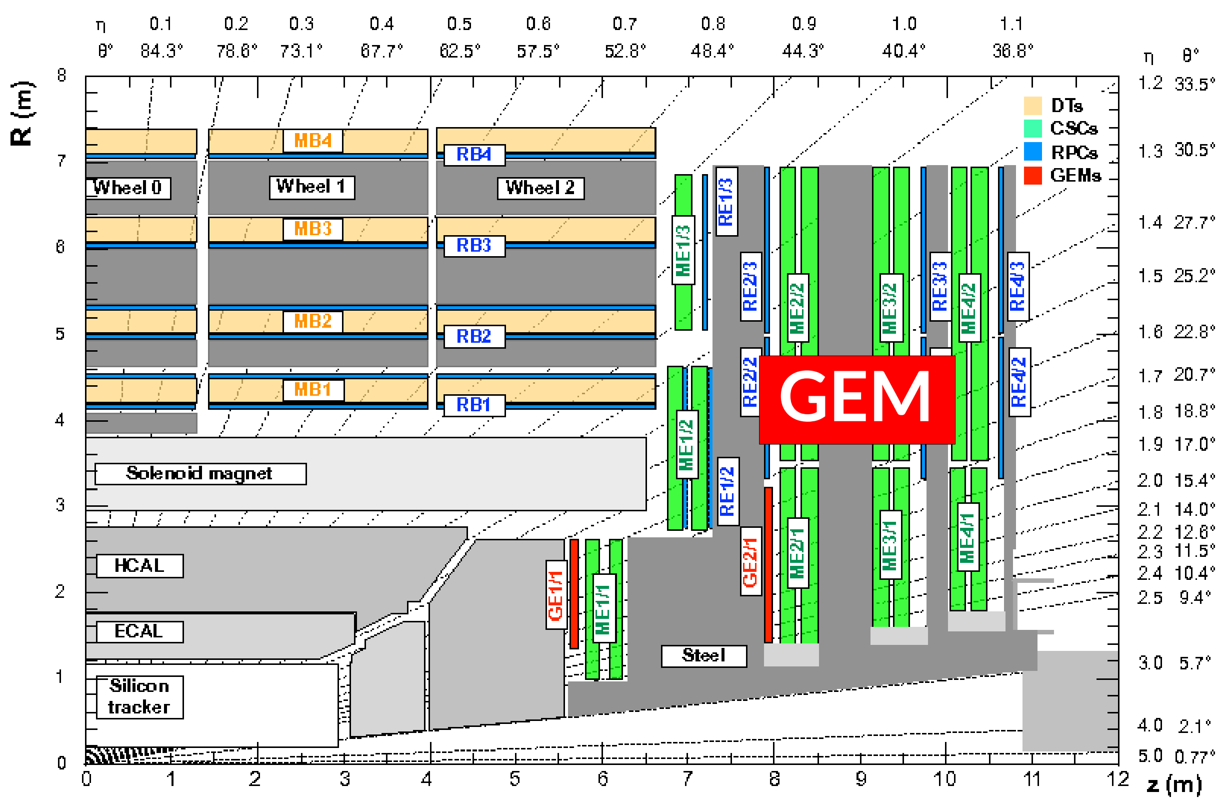
Redundancy for muon detection in endcap region

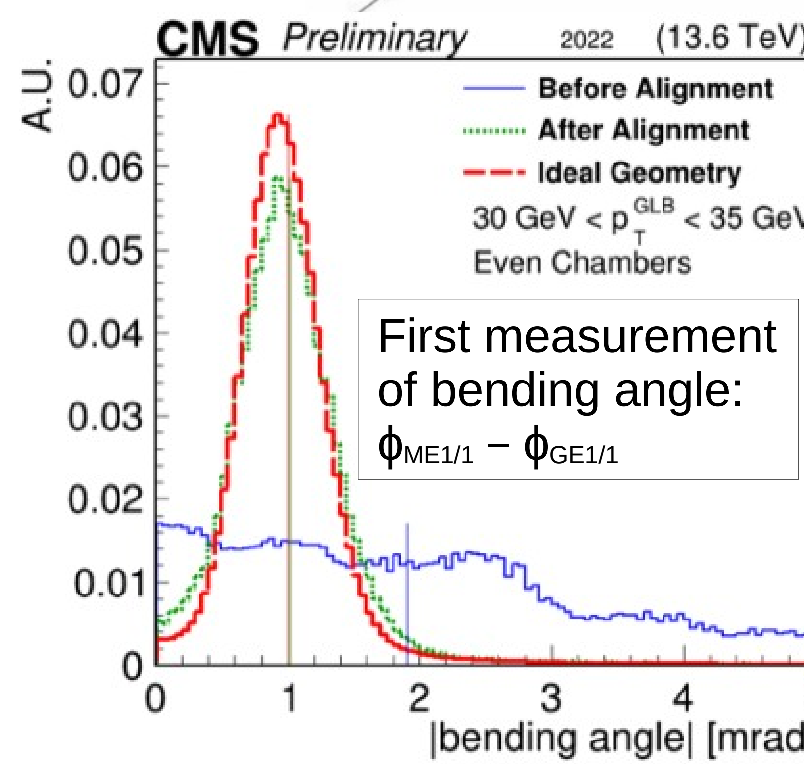
- Retain trigger capability at high occupancy
- Improve momentum scale and resolution

GEM detectors

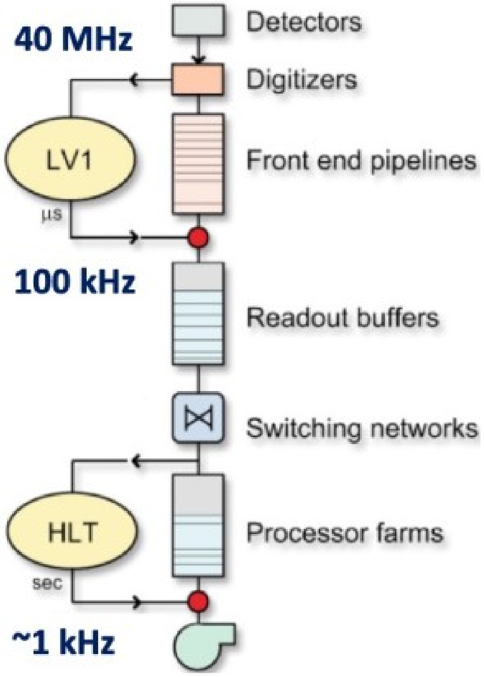
- 144 – Now, covering $1.6 < |\eta| < 2.2$
- 288 – Added in 2023-2024, covering $1.6 < |\eta| < 2.4$
- 216 – After Run 3, covering $|\eta| < 2.8$







CMS trigger system



LHC collision rate at 40 MHz

Two tiered trigger system to filter events

Level 1 (LV1): custom electronics (e.g. FPGAs)

- New trigger paths
  - Delayed/displaced jets using the new HCAL timing capabilities (0.5 ns) and energy deposit information in deep layers
  - Displaced muons (using the Kalmar Muon Track Algorithm)
  - Hadronic muon showers relying on the CSC Muon stations information

High Level Trigger (HLT): streamlined version of CMS reconstruction

- Gain experience with heterogeneous architectures
  - Currently offloading 40% of the event processing
  - calorimeters and pixel local reconstruction, pixel tracking and vertex reconstruction
- New trigger paths
  - Optimized pixel track reconstruction
  - Jet tagging with graph neural networks

CSC High Multiplicity Trigger (HMT) in Run 3

Efficient selection of signatures expected from long-lived particles

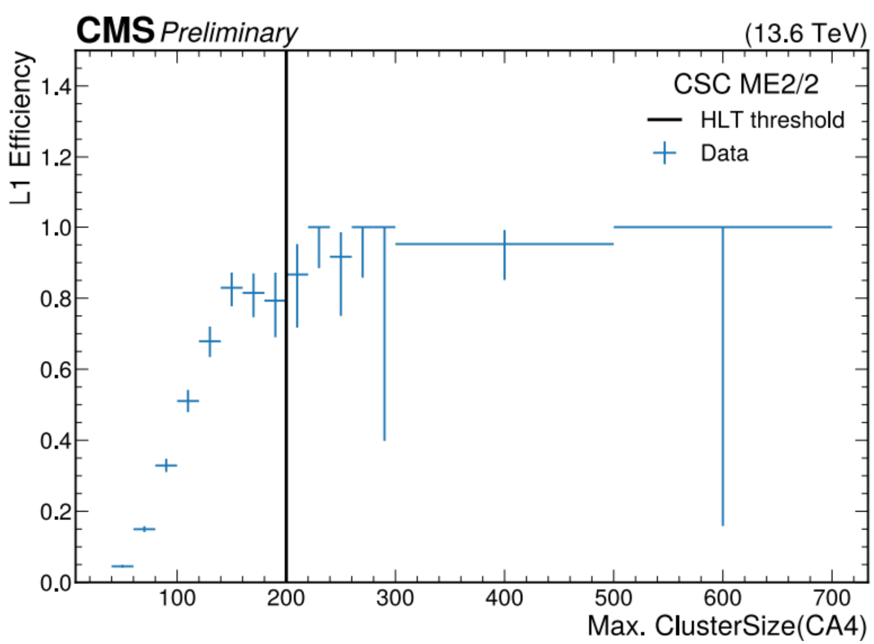
- Previous searches used MET triggered events – large loss in acceptance [PRL 127 (2021) 261804]

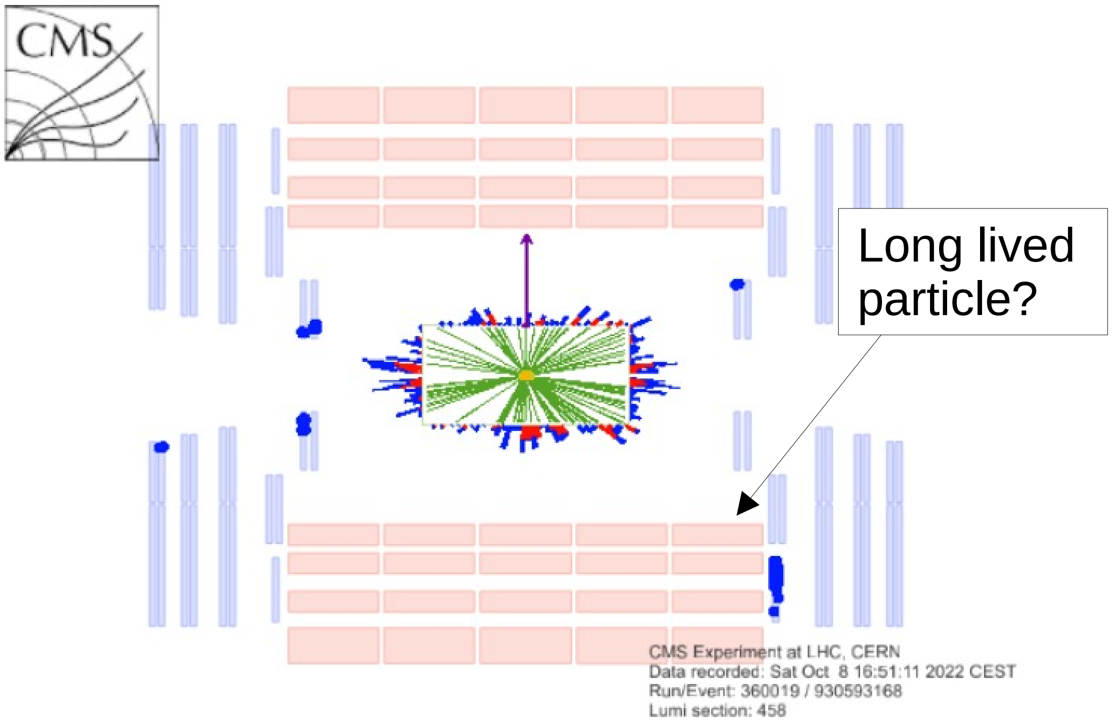
L1 trigger implementation:

- Fires if hit multiplicity in a given CSC chamber above a configurable threshold

HLT trigger implementation:

- Reconstructed CSC hits are clustered within $\Delta R<0.4$
- Selections on cluster properties to suppress backgrounds
  - Number of hits; Number of rings with at least 10 hits

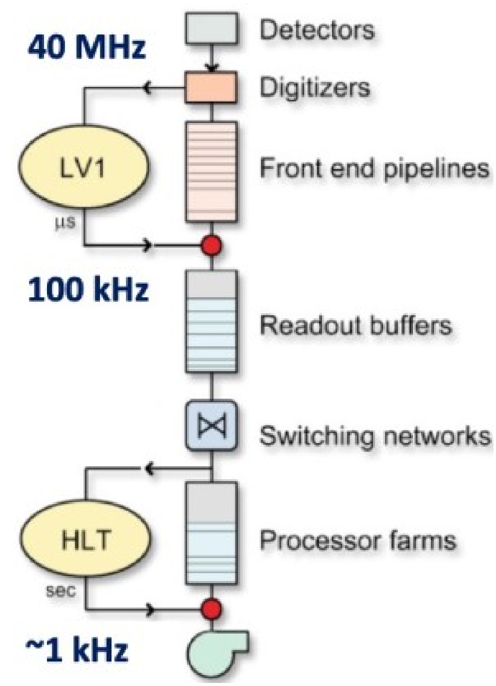




Event recorded on October 8th, 2022.

[CMS DP 2023/004]

CMS trigger system



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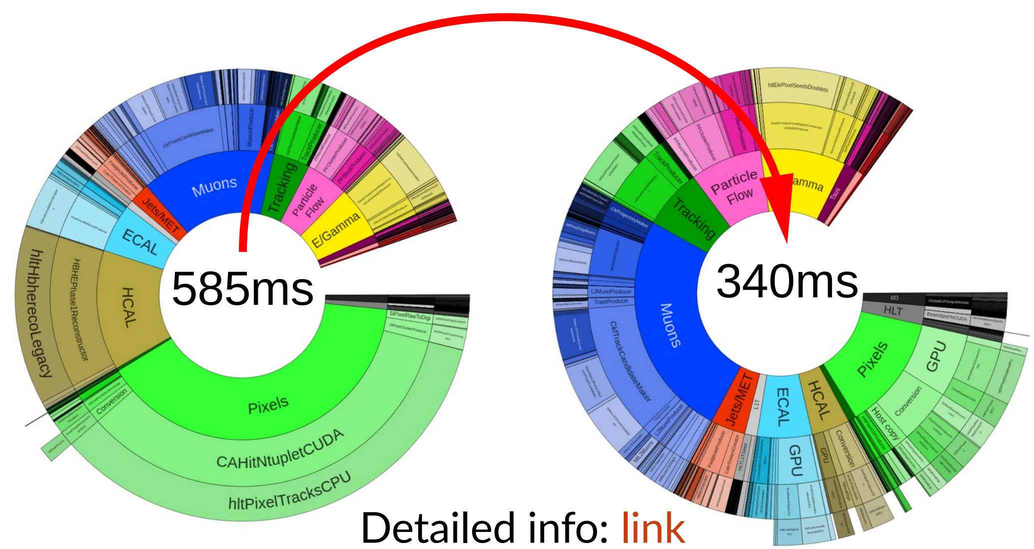


Detailed info: link

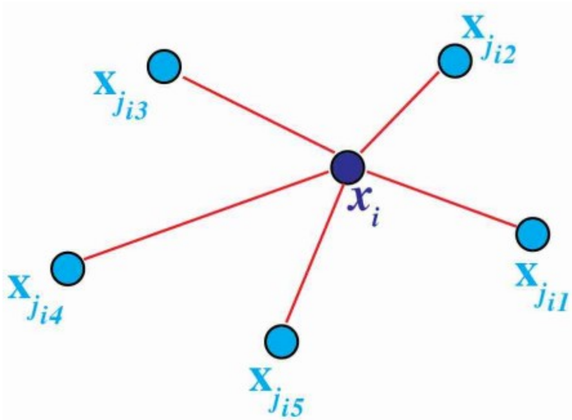
ParticleNet tagger at high level trigger

Particle cloud based on graph neural networks [PRD 101, 056019]

- Improved performance over previously deployed algorithms
- E.g. b tagging: ε≈80% with 1% mistag for udsg

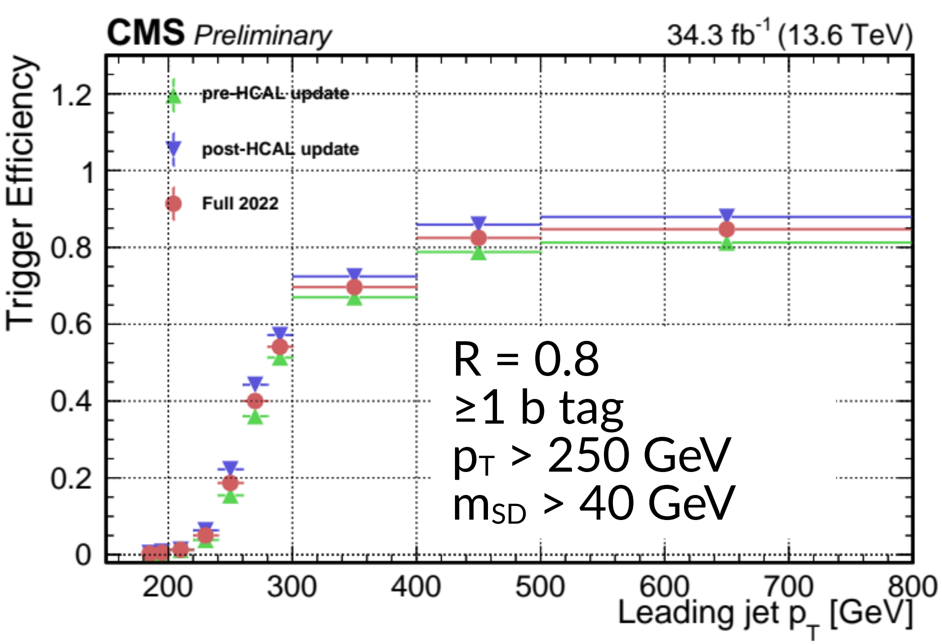
Dedicated training using HLT-level jets

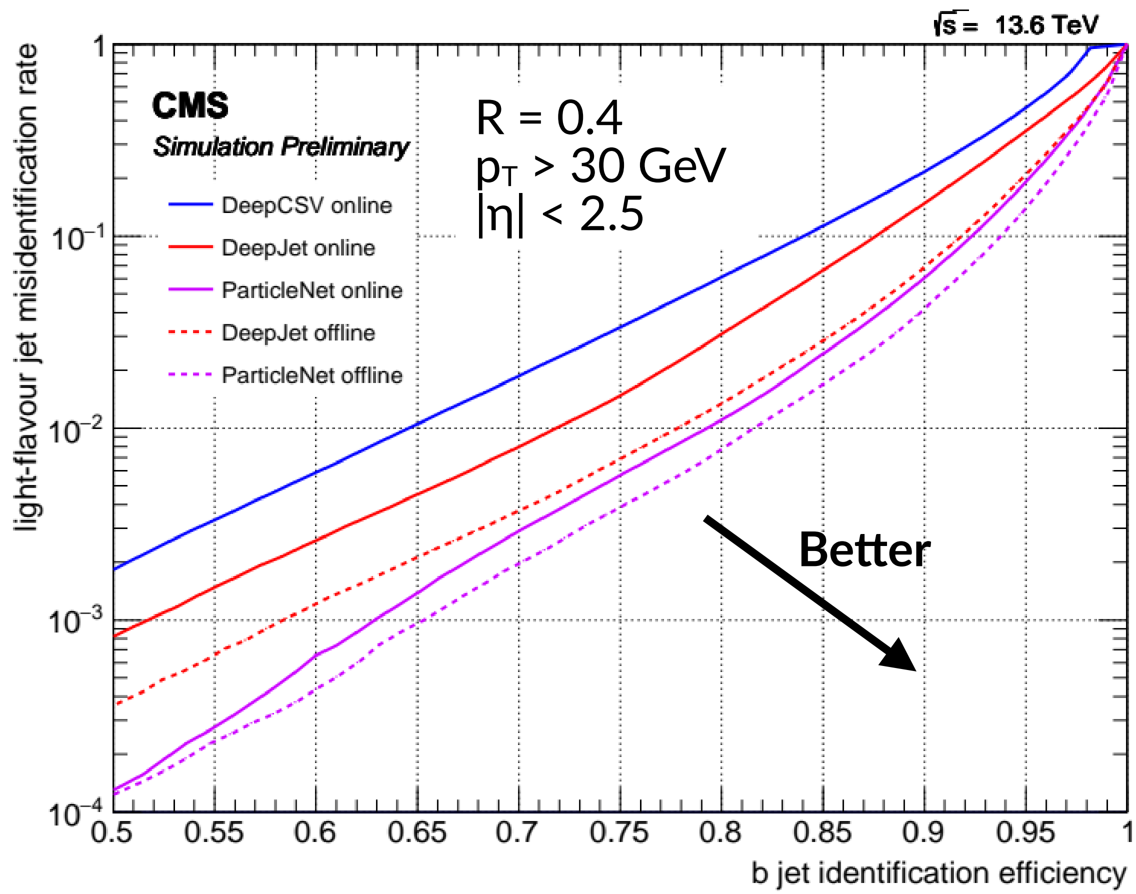
- Mitigating difference between online and offline tagging



Also for large radius jets

- E.g. tagging boosted H→bb for HH→4b events
- Using softdrop mass [CMS DP 2023/013]





Z boson counting for luminosity determination

Measure Z→ μμ production rate in bins of ~20min

$$\mathcal{L} = \frac{N^{Z}}{\sigma^{Z}_{\mathrm{fid}}\epsilon^{Z}}$$

- In situ tag & probe measurement of all efficiency
  - Account for changing detector conditions
- Minimal dependence on simulation

Included in data reconstruction chain

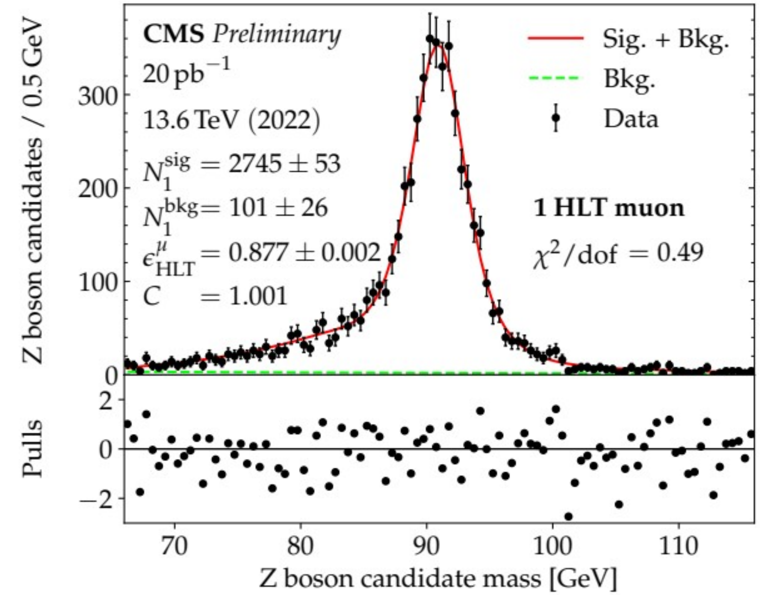
- Runs quasi online
  - results obtained ~1 week after data taking

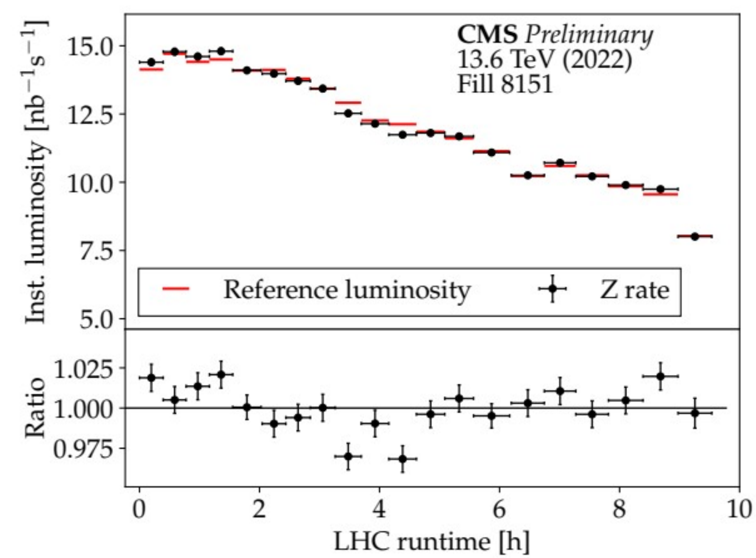
Cross check to reference luminometers
Comparisons with ATLAS luminosity
Coherent test of end to end analysis chain

Method studied in [CMS-PAS-LUM-21-001] with Run 2 data

- First complete estimate of uncertainties

→ poster



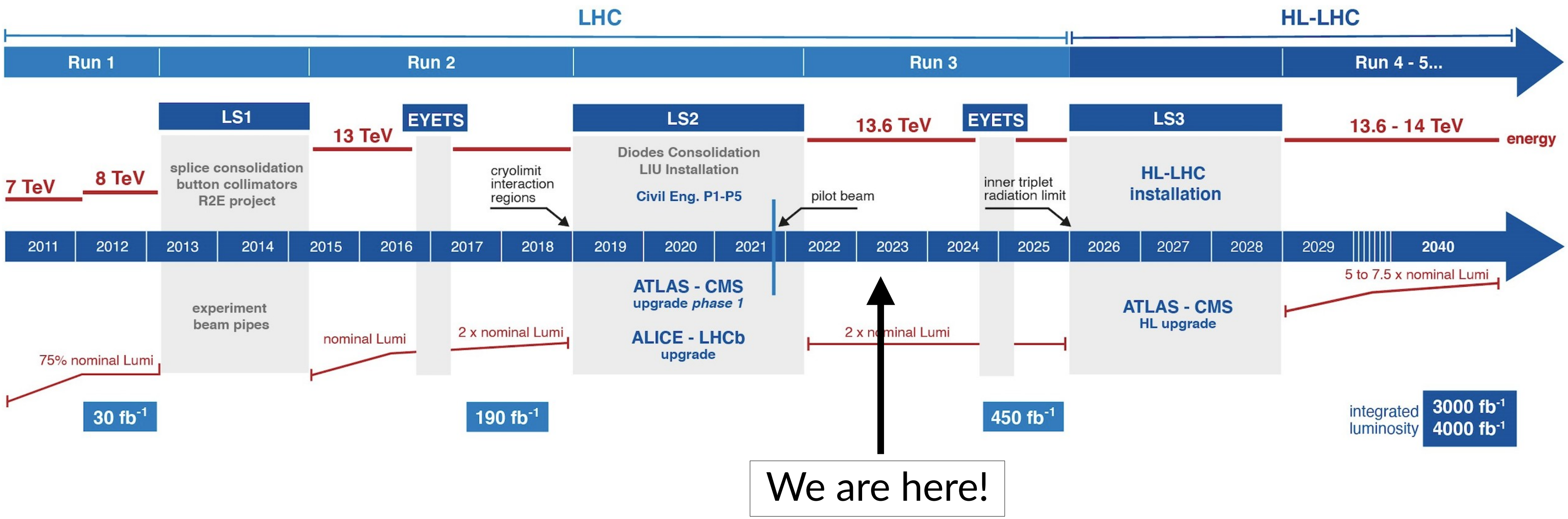


Summary & conclusions

Successful upgrades of the CMS detector

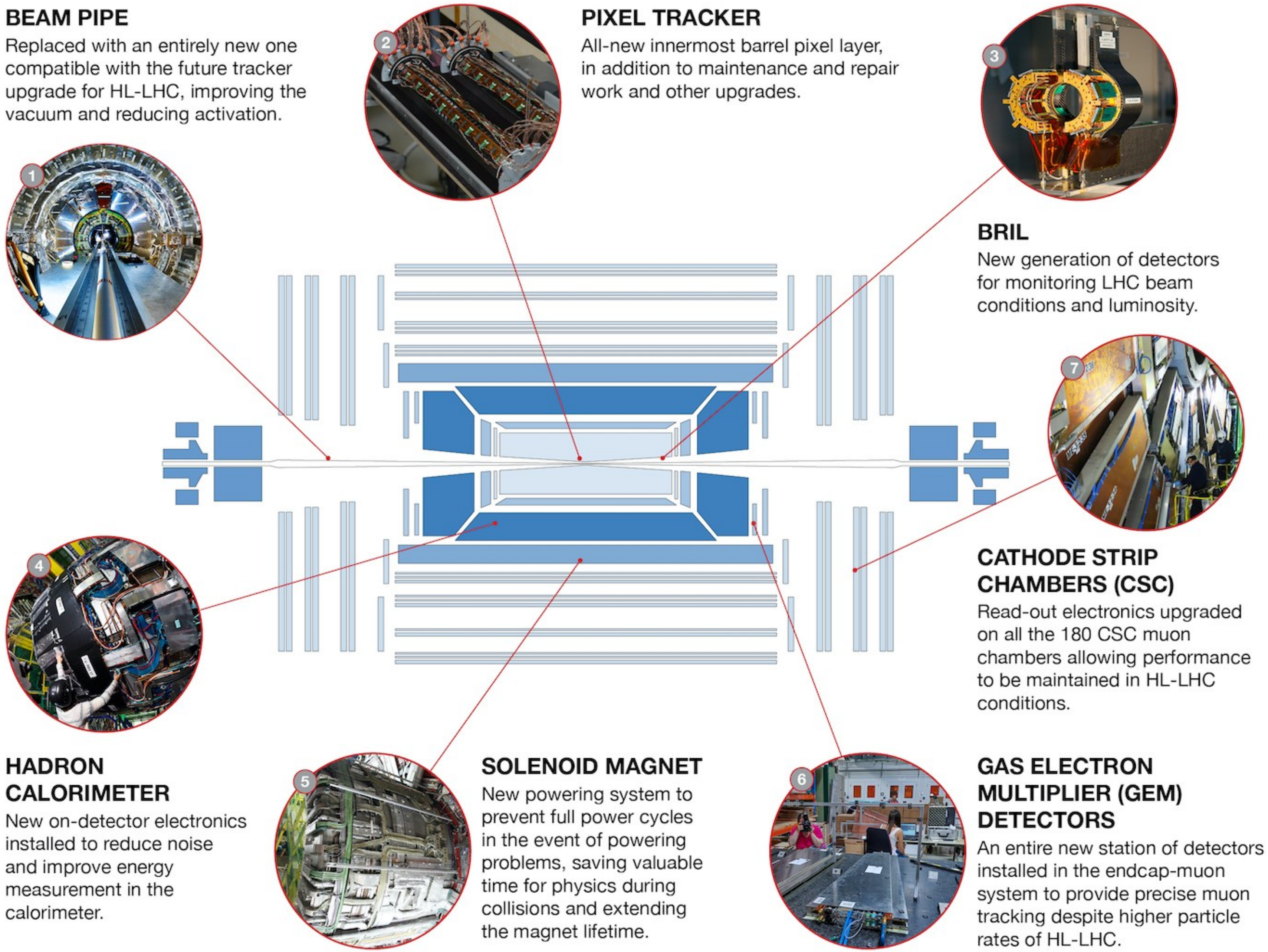
Good quality data taken in 2022 and 2023
- Exploring new regimes – e.g. LLP, HH → 4b
- New computing techniques – Machine learning!
- Many new physics results expected soon!

Important milestones reached with regards to the HL-LHC → talk by Juliette Alimena
- Mutlicore CPU/ GPU processing
- Muon GEM detectors upgrade in commissioning



Backup

CMS after the 2nd long shutdown



New beam pipe

36m long beam pipe

- Compatible with Phase 2 tracker sub-detector
- Cylindrical section of the central chamber, with a diameter of 43.4mm, extended from 1.6m to 3.1m

Aluminium alloy:

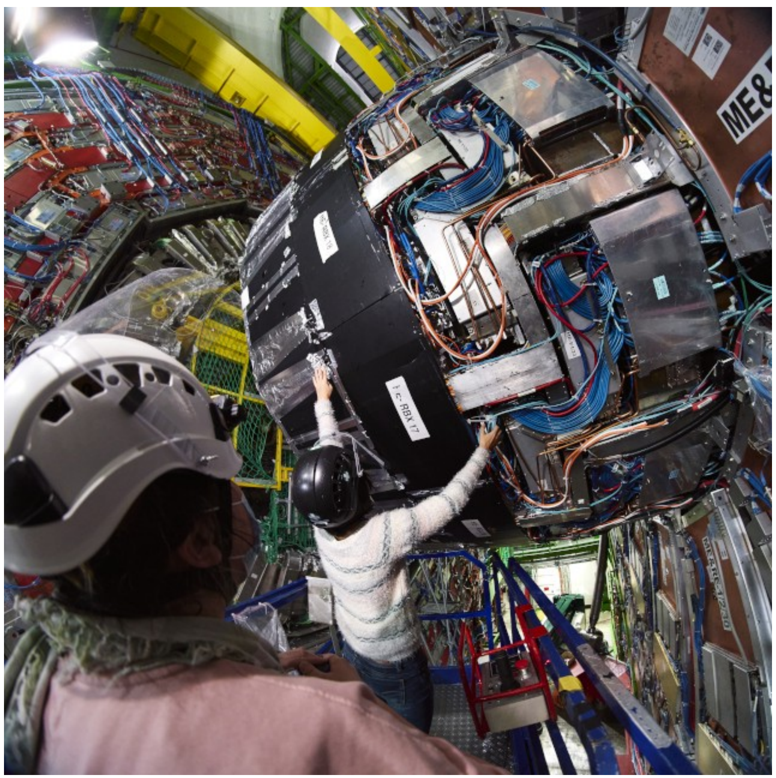
- Reduces the induced radioactivity by a factor of five compared to the previously used stainless steel

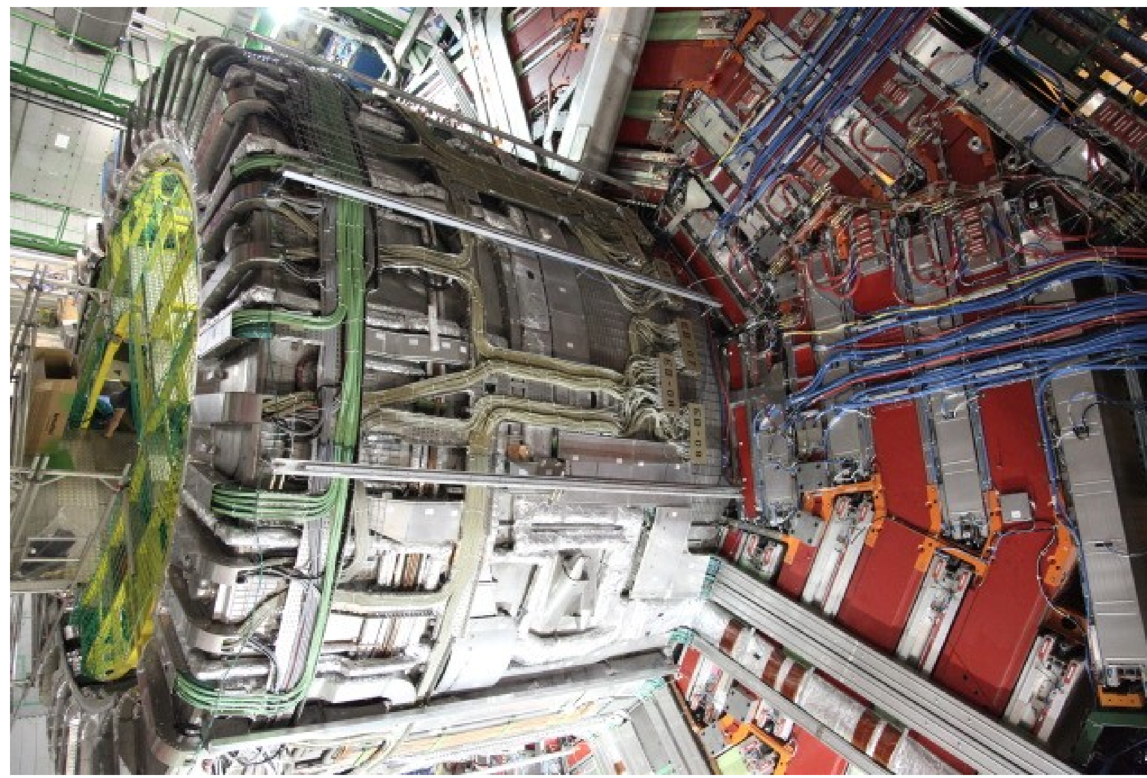
New vacuum pumping group at 16m from the interaction point to facilitate maintenance.

Replaced eight vacuum chambers of four different types.

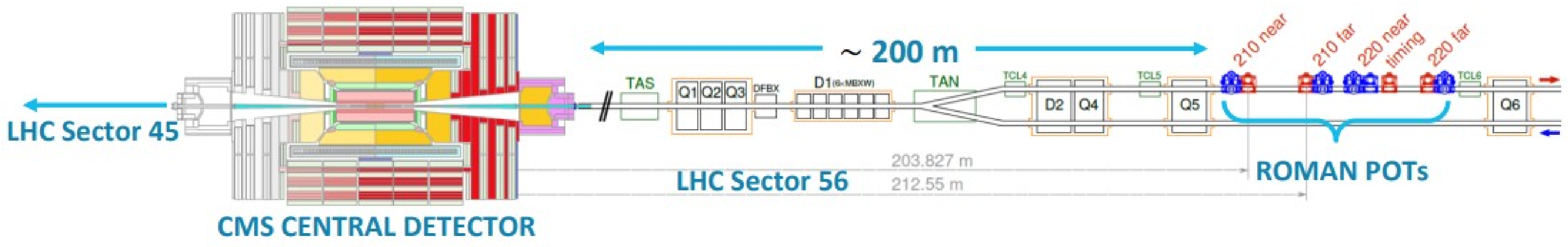
Solenoid magnet upgrade

Control and safety system rebuild
Part of electronic completely renewed
New powering system to control current flow inside the magnet
Faster return back to full field after power power disruption (minutes instead of hours)





Precision proton spectrometer



Measure scattered protons on both sides of CMS

Physics program:

- Exclusive production: pp → pp + X
- Single diffractive production: pp → p + X

Upgrades on

- silicon pixel tracker
- timing systems – goal of <30ps resolution

Now also included in HLT

- Open up new possibilities in the search for uncharted territory or new physics!

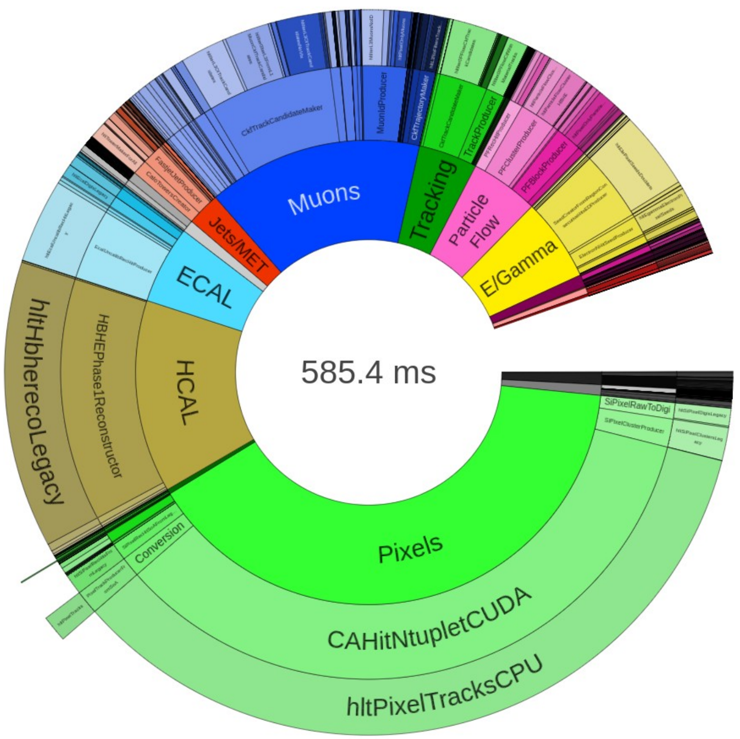
[CMS DP 2023/004]

Online HLT reconstruction with GPUs

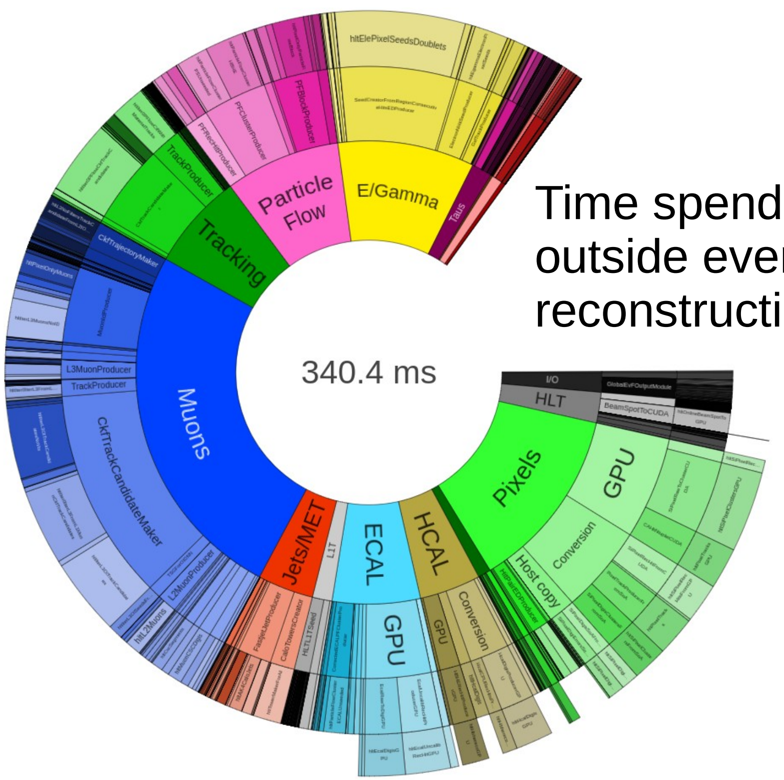
Offload physics reconstruction to NVIDIA GPUs

- Currently HCAL, ECAL, Pixel Local Reconstruction, Pixel-Only Track and Vertex Reconstruction
- The execution time per event reduced by ~ 40%

Detailed info: link



Without GPUs
32 threads, 24 streams



Time spend outside event reconstruction

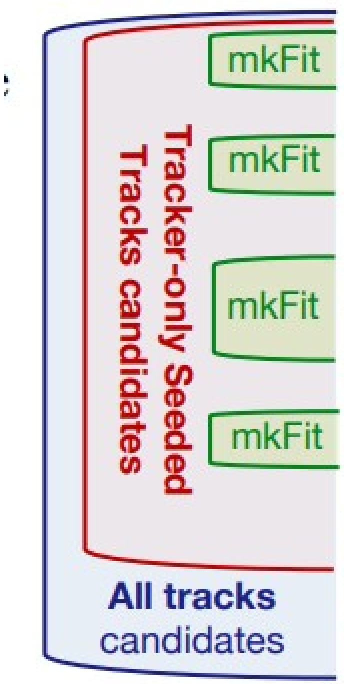
With GPUs
32 threads, 24 streams
(Without Nvidia multi process server)

Iterative tracking at CMS

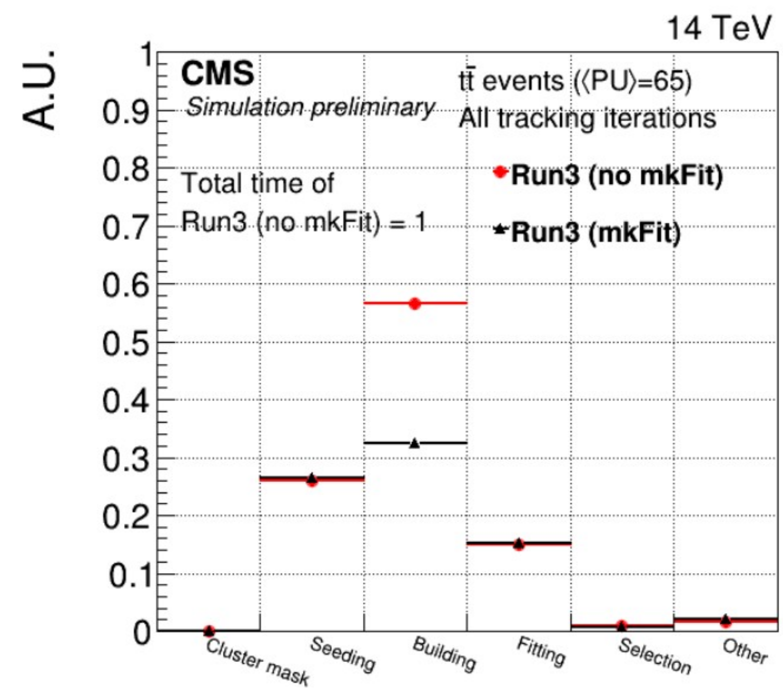
In Run 2: combinatorial Kalman Filter (CKF)

New technique in Run 3: Matriplex Kalman trajectory Fitter (mkFit) [2020 JINST 15 P09030]

- Maximally exploits parallelization and vectorization in multi-core CPU architectures
- ~25% reduction of total tracking time



Iteration	Seeding	Target track
Initial	pixel quadruplets	prompt, high p_T
LowPtQuad	pixel quadruplets	prompt, low p_T
HighPtTriplet	pixel triplets	prompt, high p_T recovery
LowPtTriplet	pixel triplets	prompt, low p_T recovery
DetachedQuad	pixel quadruplets	displaced--
DetachedTriplet	pixel triplets	displaced-- recovery
MixedTriplet	pixel+strip triplets	displaced-
PixelLess	inner strip triplets	displaced+
TobTec	outer strip triplets	displaced++
JetCore	pixel pairs in jets	high-p_T jets
Muon inside-out	muon-tagged tracks	muon
Muon outside-in	standalone muon	muon



New track selection DNN

Each iteration has 4 main steps:

- Seeding → Pattern recognition → Track fit → Track selection
- Removing hits for following iteration

Track selection essential for efficient track reconstruction

DNN for track selection

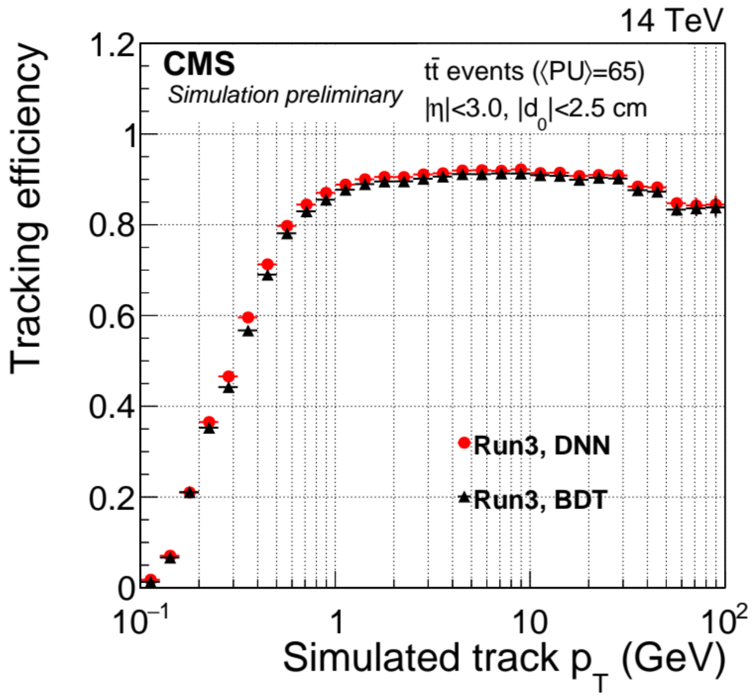
- Replacing previously used BDT
- Feed forward network combining 29 input variables

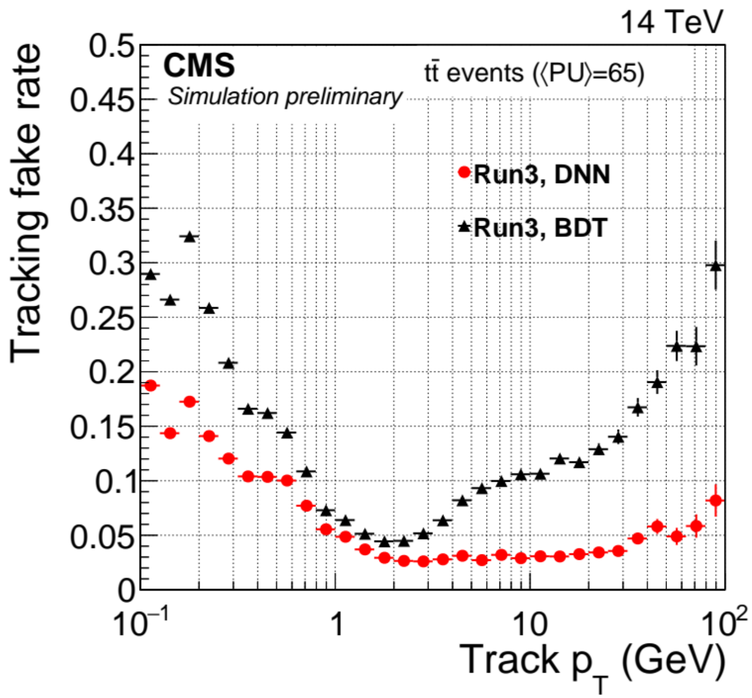
Performance

- Similar tracking efficiency
- Reduction of fake rate

Reduction of time

- Fraction of total tracking time: 4.9% → 0.9%





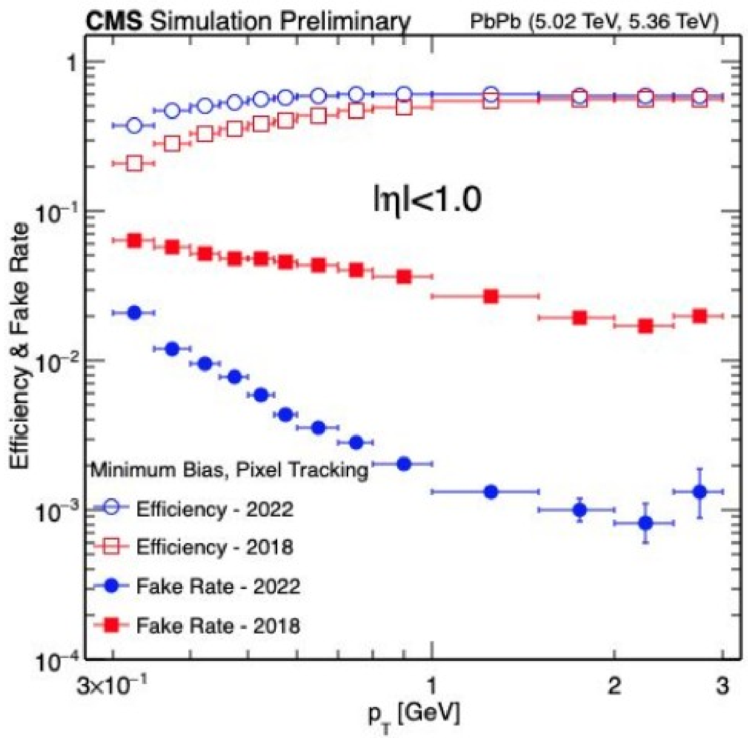
Tracking and L1 performance in PbPb

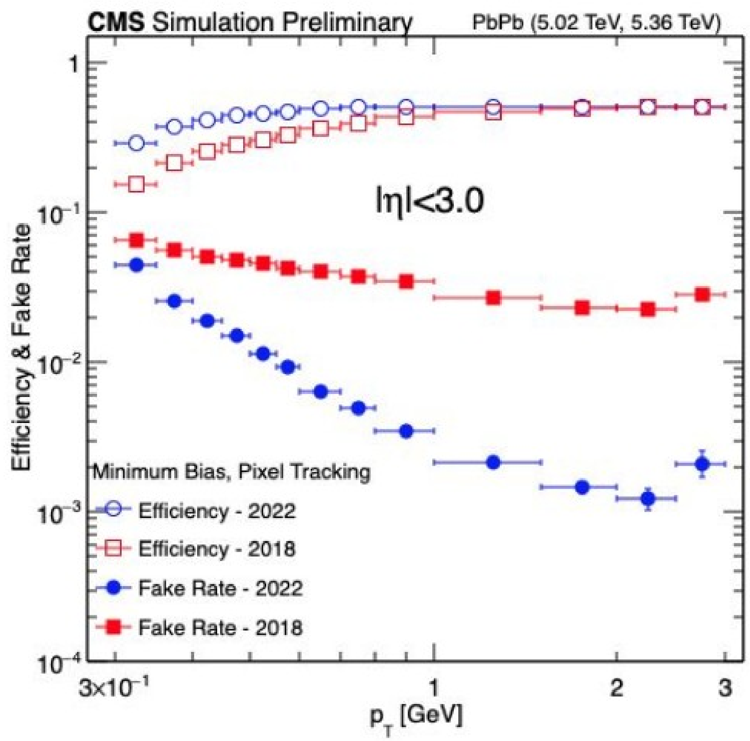
2018 PbPb (5.02 TeV)

- Conformal mapping fitter

2022 PbPb (5.36 TeV)

- Used broken line fitter
- Reduction in the number of inactive detector channels





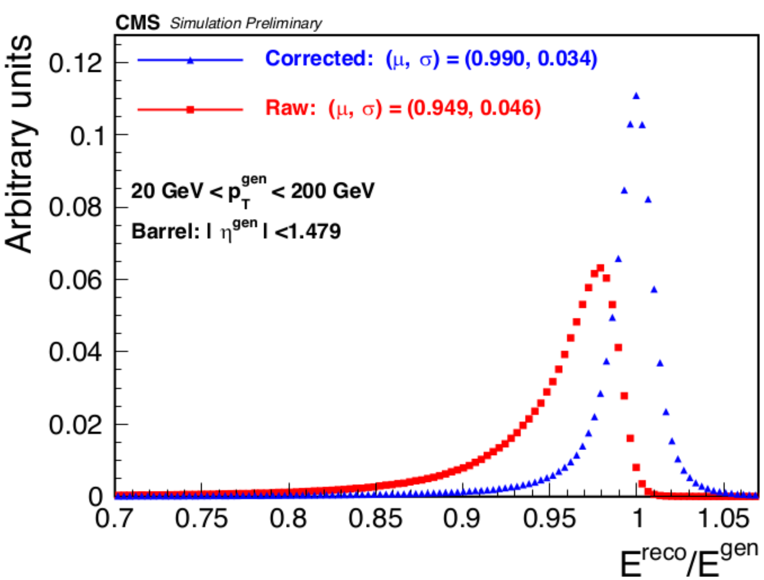
ECAL and e/γ at HLT

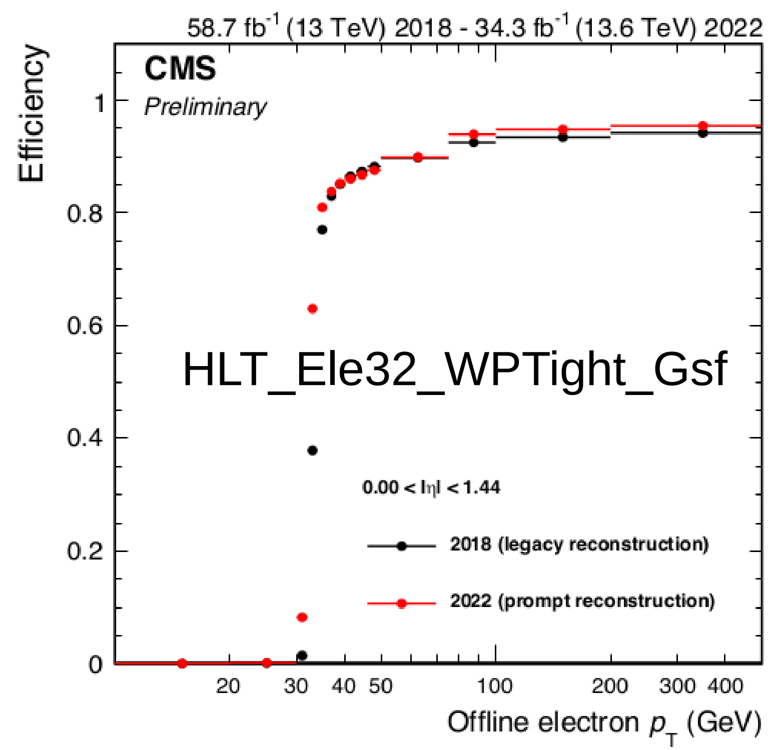
ECAL successfully commissioned with

- updates to noise, pedestals, pulse shapes, calibrations, timing and energy scale

New online regression deployed, improving both the energy scale and the resolution

- Using boosted decision tree, "raw" energy of simulated e/γ is calibrated to the generator-level energy





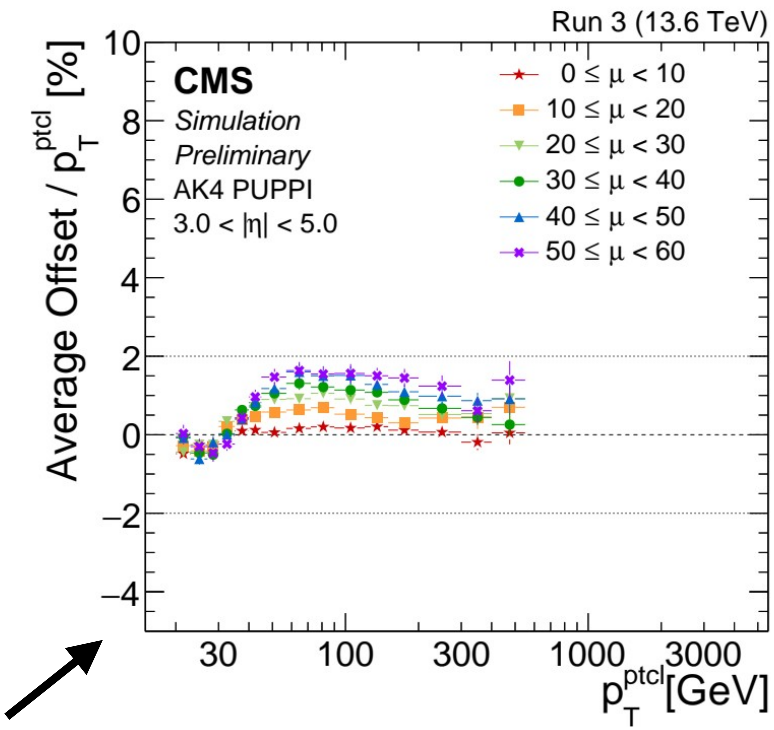
Jet energy scale

Jets using pileup-per-particle identification (PUPPI)

- Weight every particle with pileup probability

Electromagnetic and hadronic calorimeter responses not linear

- Jets are corrected sequentially



Average pileup offset largely reduced due to switch to PUPPI jets

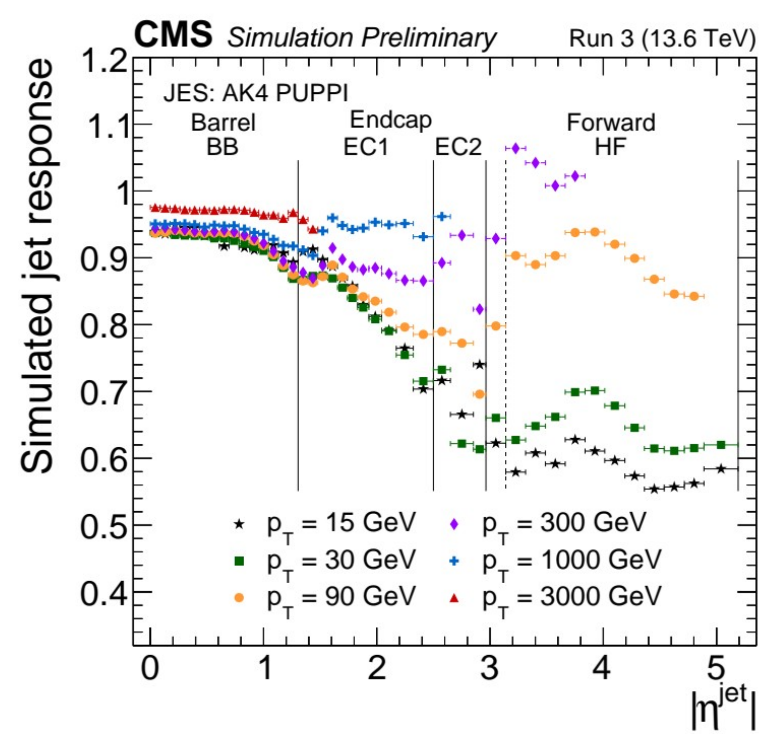
- E.g. <2% in forward region 3 < |η| < 5 (previously ~80%)
- Overall negligible

Response correction from simulation

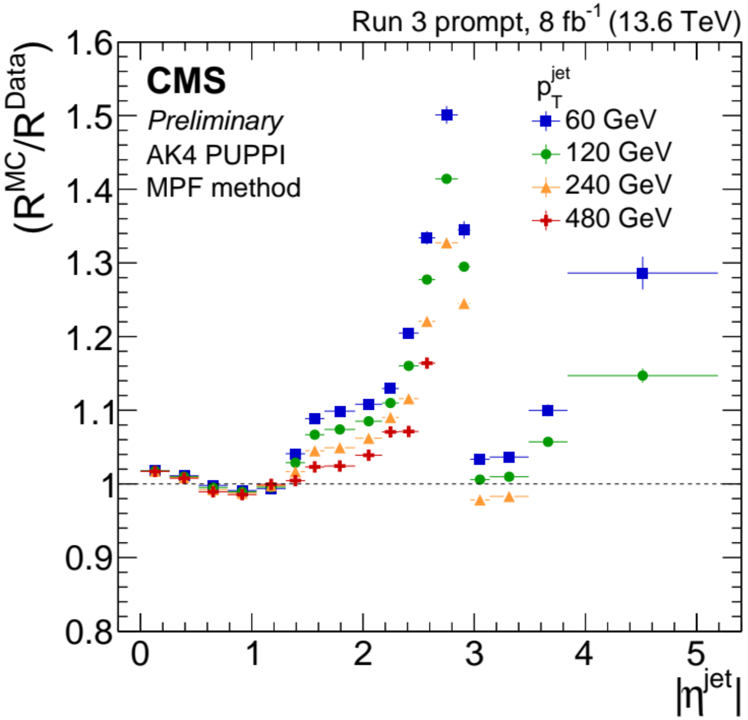
- Stable response in central region
- Lower response for low p_T in forward region
  - Over-subtraction from PUPPI for better scale & resolution

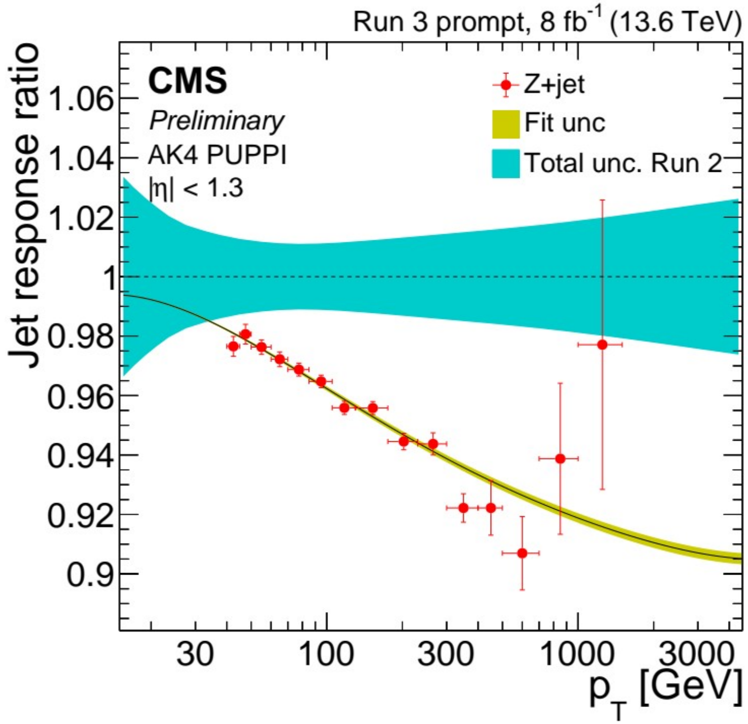
Preliminary further corrections based on data available as well

- Residuals (η): <3% in central and <50% in forward region
- Residuals (p_T): observed p_T dependence <10%



Jet residual corrections





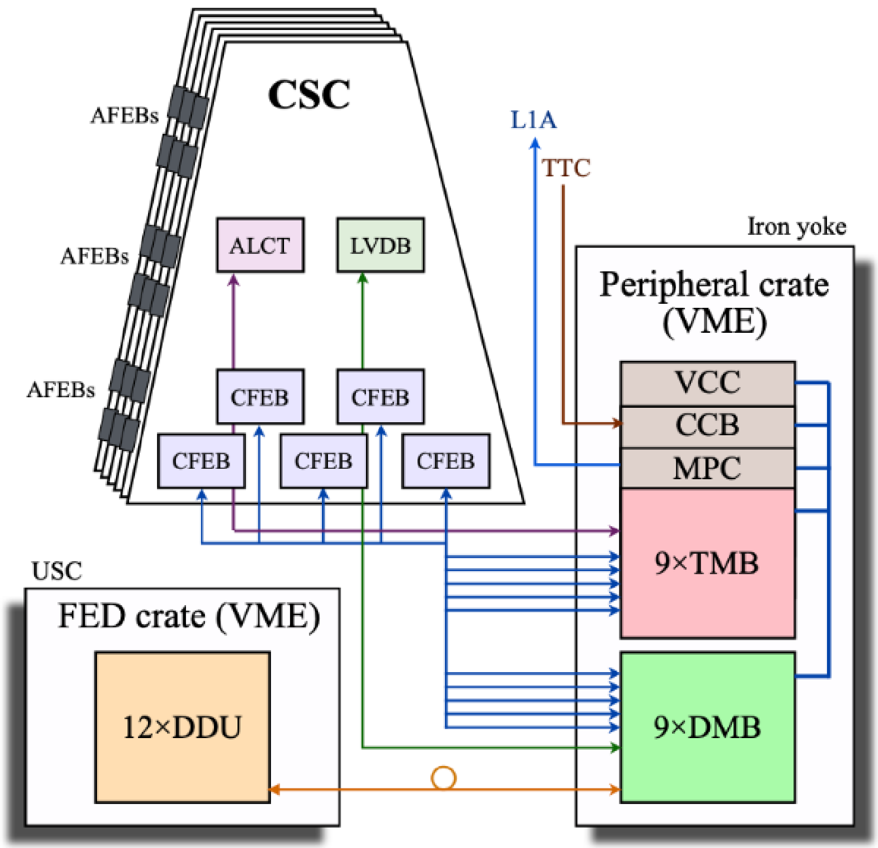
Cathode Strip Chambers – electronics

Wire hits read out by Anode Front End Board

Processing anode hits into multi-layer coincidence in Anode Local Charged Track board

Digital Strip hits read out by Cathode Front End Board

DDU: interface between CSC and CMS data acquisition system within Front End Driver crate



Low Voltage Distribution Board provides power

Clocking, data concentration and other services (VCC, CCB, MPC)

Processing multi-layer coincidences from cathode hits and ALCTs in (Optical) Trigger Motherboard

Optical Data collection by Data Mother Board

[CMS DP 2023/017]

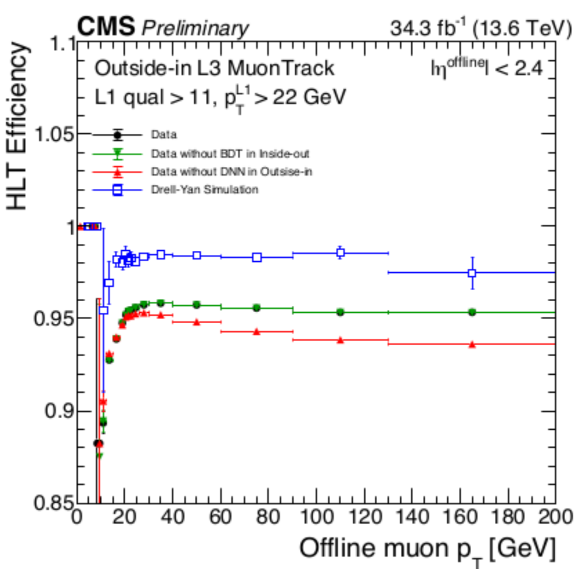
Muon reconstruction at HLT

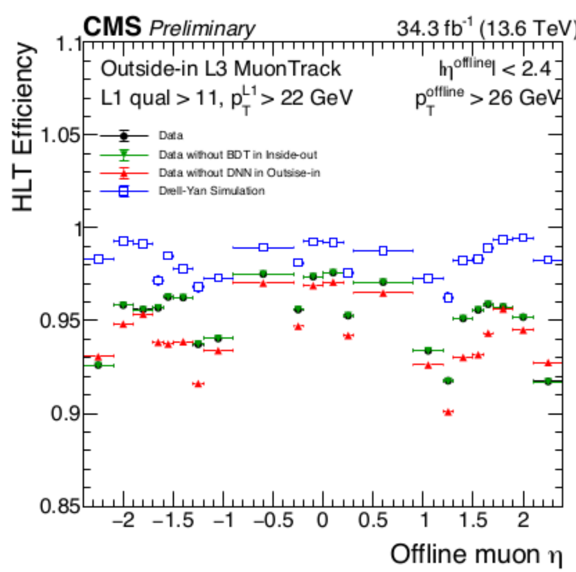
Muon reconstruction algorithm in high level trigger (HLT) updated

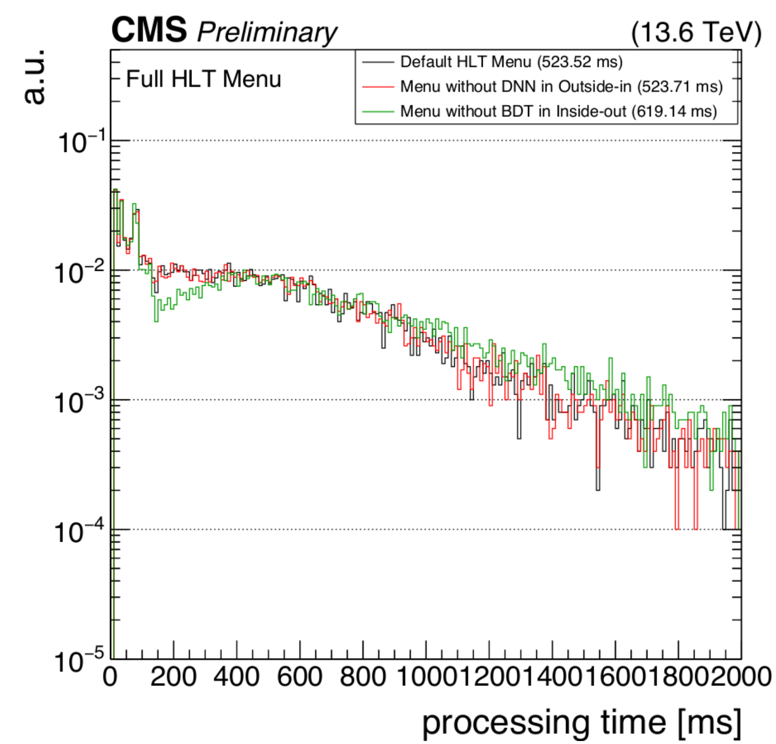
New machine learning techniques

- Deep Neural Network (DNN) to improve track seeding in Outside-In muon track reconstruction
- Bosted Decision Tree (BDT) seed classifier in Inside-Out muon track reconstruction to improve timing

Alignment on October







Soft drop mass jet at HLT

Aiming at jets from boosted resonances produced in pair decays (e.g. X → HH → 4b)

Soft drop technique: recursively removes soft wide-angle radiation from a jet (JHEP05(2014)146)

- Lowering HLT rate and pT thresholds
- Single (Double) Jet pT > 420 (270-270) GeV; mass > 30 GeV; soft threshold > 0.1; jets with ΔR<0.8 and pT > 30GeV