Highlights on CMS tracker and calorimeter reconstruction improvements for Run II

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on behalf of the CMS Collaboration

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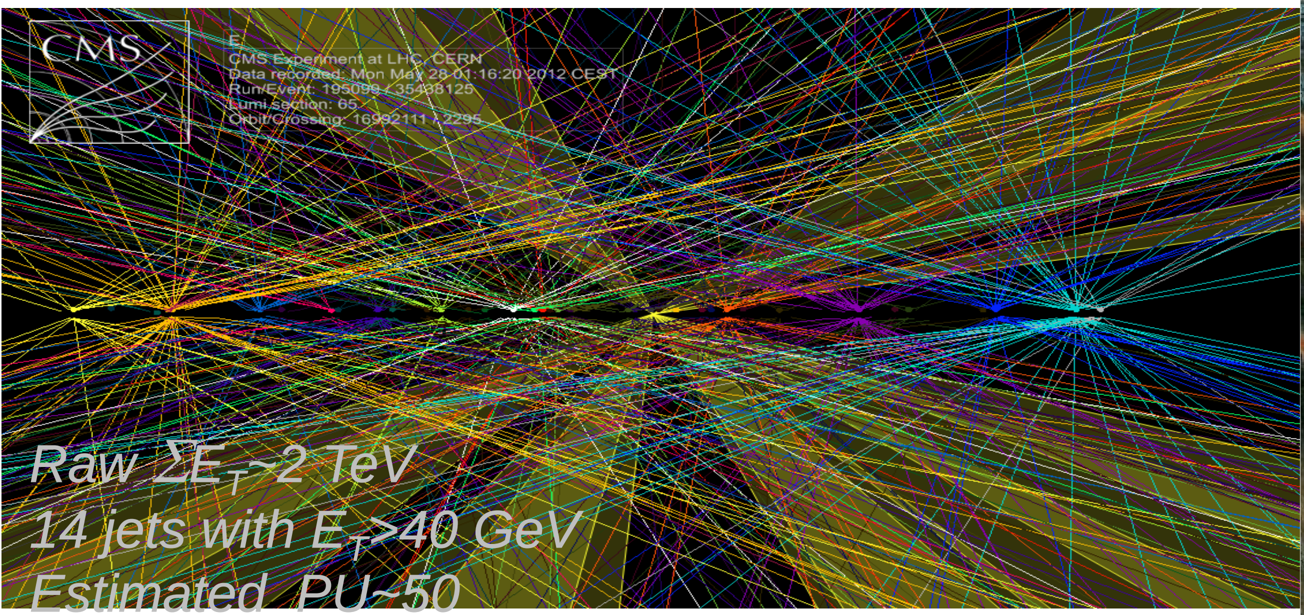
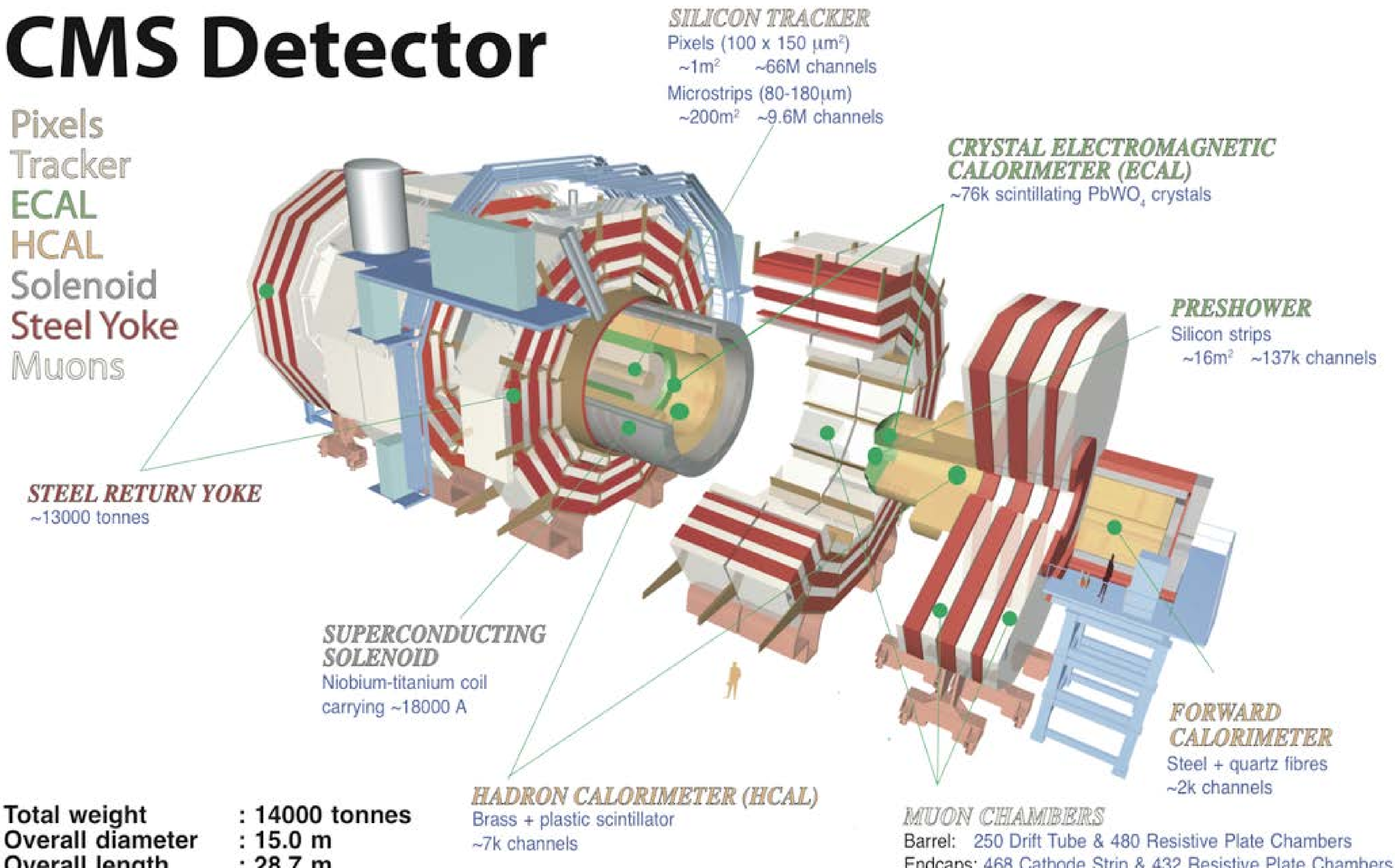
RunII challenge

- LHC energy: 7-8 TeV in RunI → 13 TeV in RunII
- Peak luminosity: 0.7×10^{34} $cm^{-2}s^{-1}$ → 1.4×10^{34} $cm^{-2}s^{-1}$
- Bunch spacing: 50 ns → 25 ns
- Average PileUp (<PU>): 25 → 40



~ 10 cm

CMS Detector



Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

RunI legacy papers

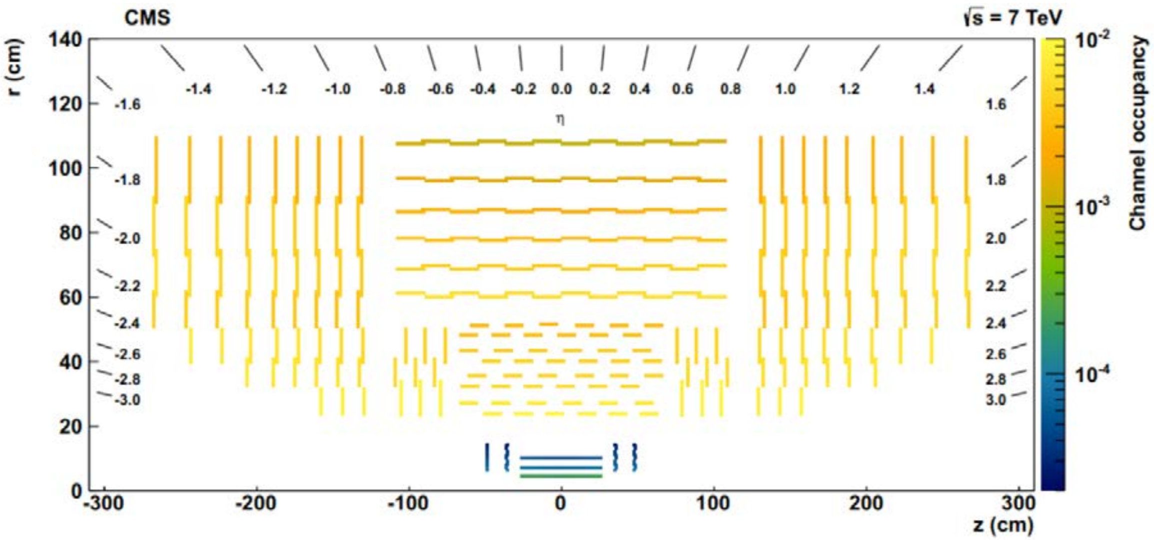
- **EGM-14-001** - “*Performance of photon reconstruction and identification with the CMS detector in proton-proton collisions at* $\sqrt{s}$ *= 8 TeV*”, JINST 10 (2015) P08010
- **EGM-13-001** – “*Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at* $\sqrt{s}$ *= 8 TeV*”, JINST 10 (2015) P06005
- **JME-13-003** – “*Performance of the CMS missing transverse momentum reconstruction in pp data at* $\sqrt{s}$ *= 8 TeV*”, JINST 10 (2015) P02006
- **MUO-11-001** - “*The performance of the CMS muon detector in proton-proton collisions at* $\sqrt{s}$ *= 7 TeV at the LHC*”, JINST 8 (2013) P11002
- **EGM-11-001** – “*Energy calibration and resolution of the CMS electromagnetic calorimeter in pp collisions at* $\sqrt{s}$ *= 7 TeV*”, JINST 8 (2013) P09009
- **TRK-11-001** – “*Description and performance of track and primary-vertex reconstruction with the CMS tracker*”, JINST 9 (2014) P10009
- **MUO-10-004** - “*Performance of CMS muon reconstruction in pp collision events at* $\sqrt{s}$ *= 7 TeV*”, JINST 7 (2012) P10002
- **JME-10-009** – “*Missing transverse energy performance of the CMS detector*”, JINST 6 (2011) P09001
- **TRK-10-001** – “*CMS Tracking Performance Results from Early LHC Operation*”, EPJC 70 (2010) 1165

http://cms-results.web.cern.ch/cms-results/public-results/publications/DET
full list of CMS publications on detector and reconstruction performance

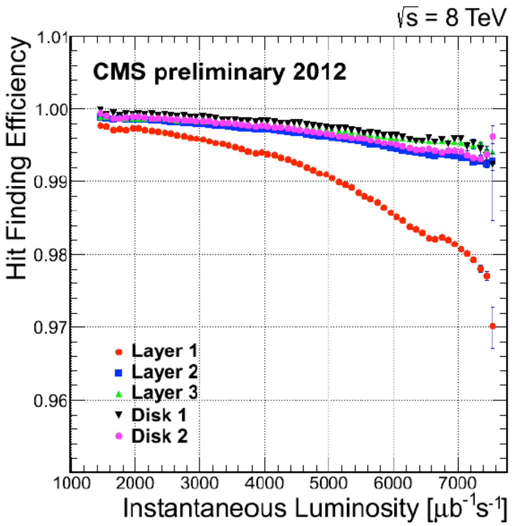
Tracker reconstruction

- Tracking is a challenge with high PU and 25 ns bunch spacing due to the increase occupancy (affecting timing and fake rate)
  - +5% in pixel
  - +45% in strip !!!

the effect of pile-up is dramatic on tracking iterations seeded by pairs of strip matched hits (focused on displaced tracks)



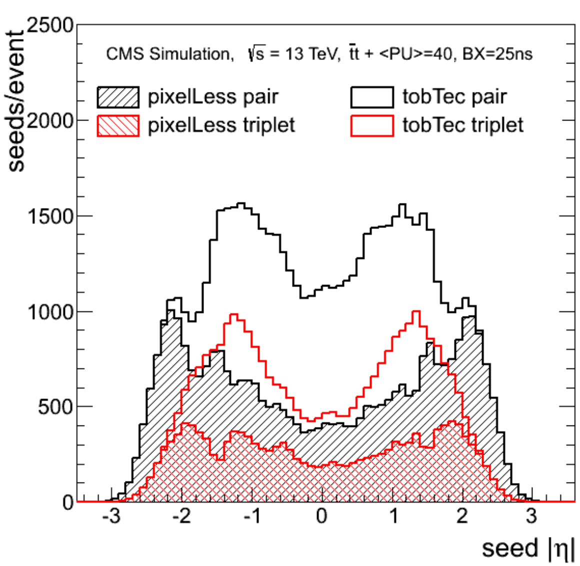
Tracker occupancy with ~10 PU and 50 ns BX

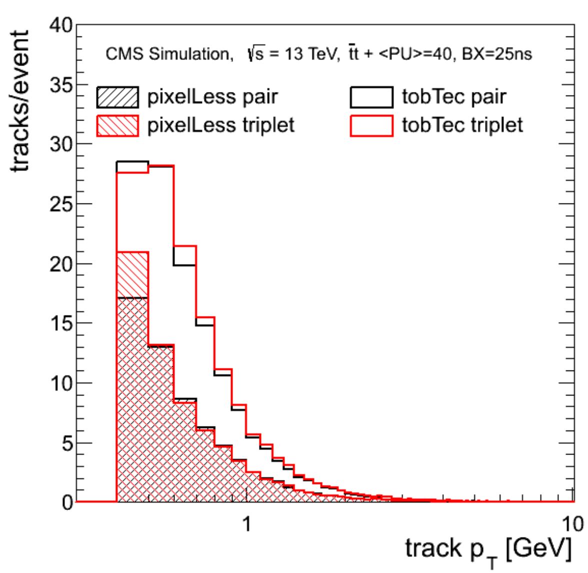


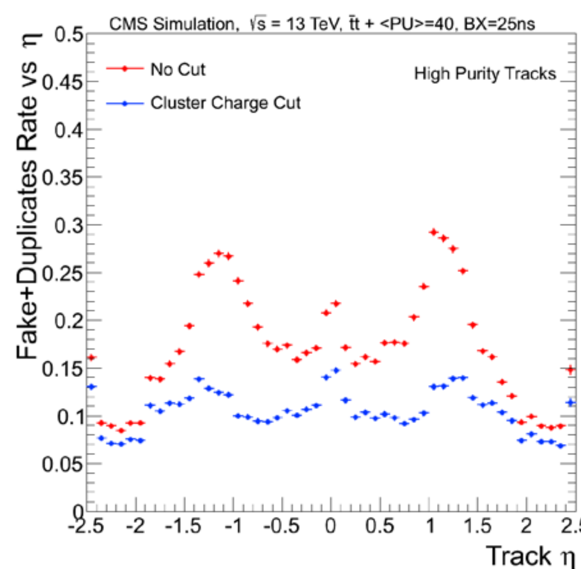
Pixels are affected by dynamic inefficiency due to saturation of chip readout buffer.

Tracking improvement in RunII

- New algorithm for strip-seeded tracking steps
  - main feature is the X^2 cut from straight line fit of 3 points in the RZ plane
  - rejects half of the seeds without introducing any inefficiency in track reconstruction.
- Strip cluster charge cut
  - cluster generated by OOT PU have low collected charge
  - cutting on cluster charge largely improves timing and fake rate performance





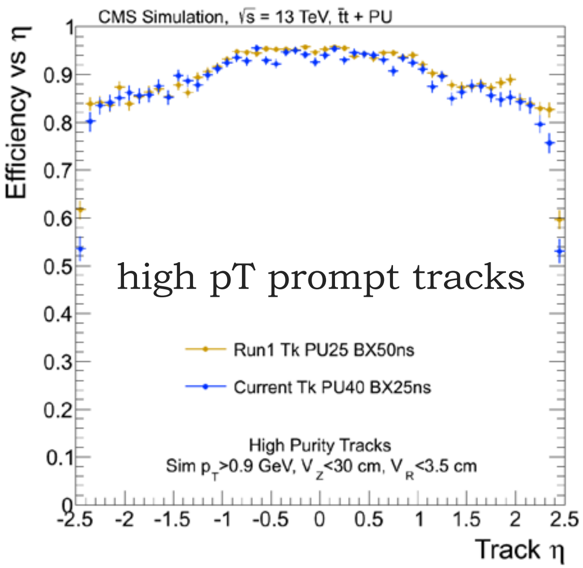


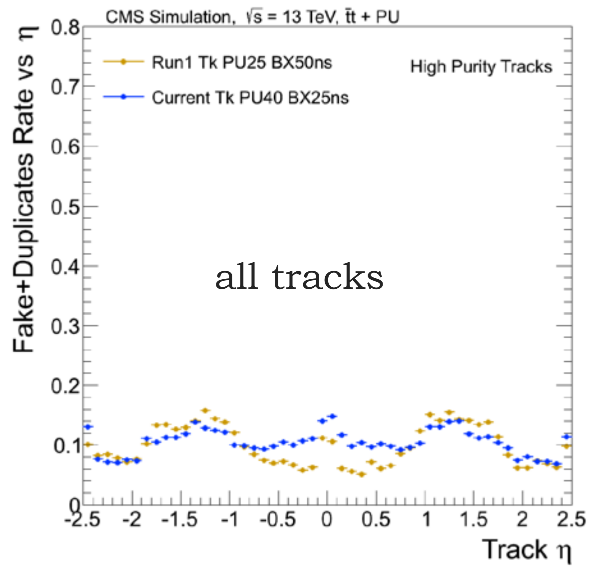
Tracking improvement in RunII: performance vs PU

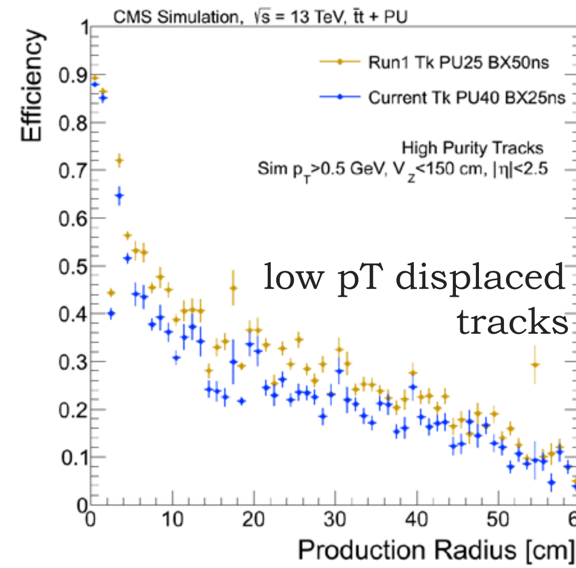
Many other improvements in RunII tracking:

- two new muon iterations to recover efficiency loss observed in 2012 data at high PU
- pixel dynamic inefficiency recently included in the simulation
- tracking at High Level Trigger: 4x time reduction at PU=40 with similar performance

Performance comparison with RunI vs RunII nominal PU conditions





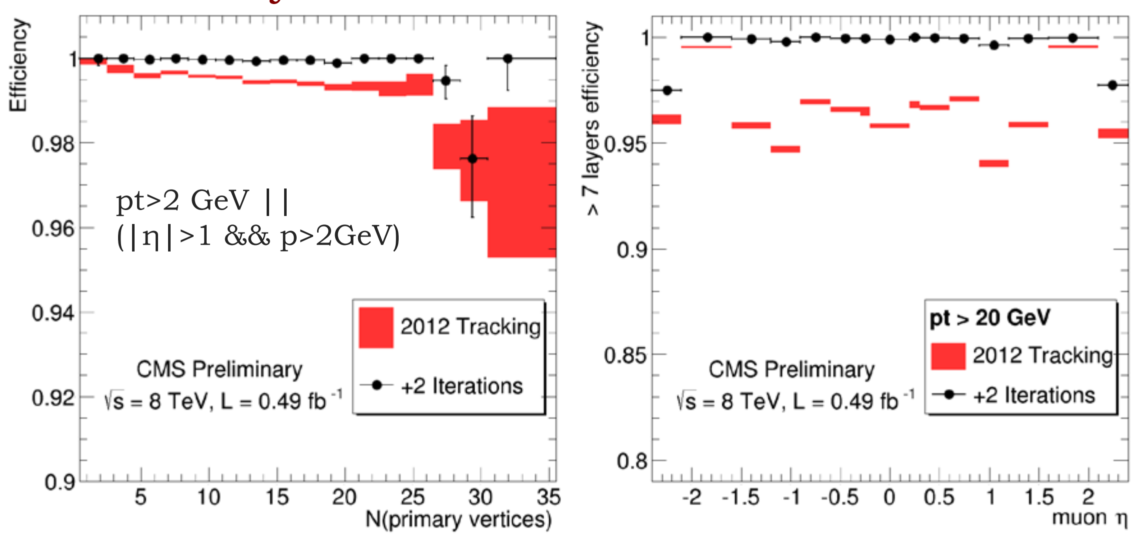


- Very similar CMS physics performance for reconstruction objects based on tracks in RunII w.r.t. RunI despite large PU increase and 25 ns BX.

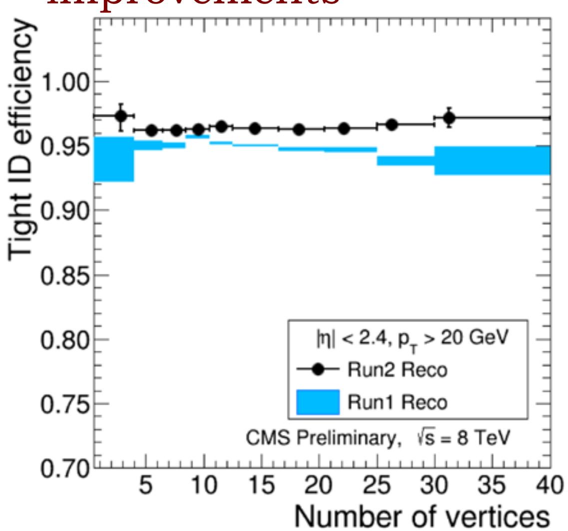
Muon tracking improvement

- Loss in muon reconstruction efficiency in the tracker observed in 2012 with pile-up.
- Two muon-specific tracking iterations developed to recover it:
  - **Outside-in** → seeded by the muon system to recover the missing muon-track in the tracker
  - **Inside-out** → re-reconstruct muon-tagged tracks with looser requirements to improve the hit collection efficiency

Full efficiency recovered for muon tracks in the tracker.



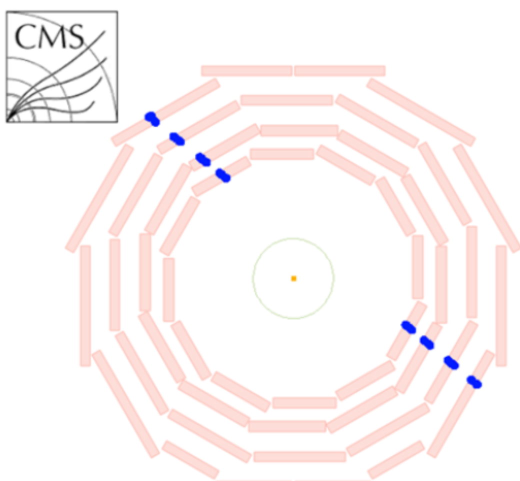
Z→μμ tight ID efficiency improvements



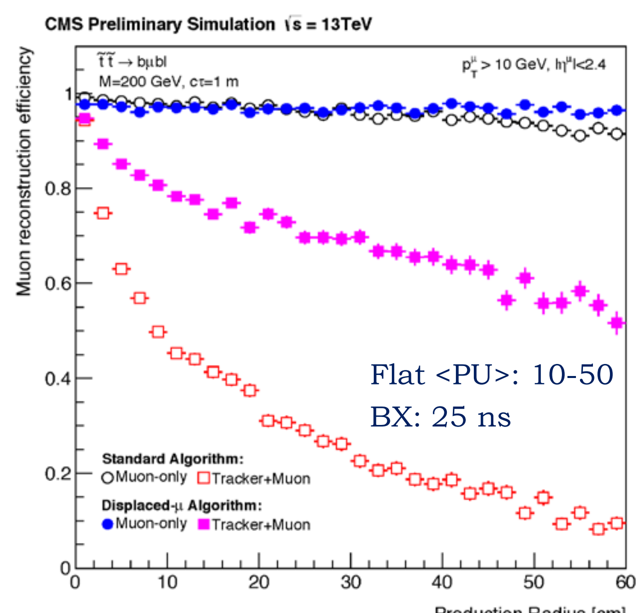
New displaced-muon reconstruction in RunII

- Two new muon reconstruction algorithms for displaced-muons in RunII.
  1) designed for muons produced in decays happening very far from the interaction point and eventually with significant delay → use only muon chamber hits
  2) designed for muons displaced in time and produced within the inner-tracker volume → use both the inner-tracker and muon chamber hits
- Constraint on the interaction point removed in both algorithms.

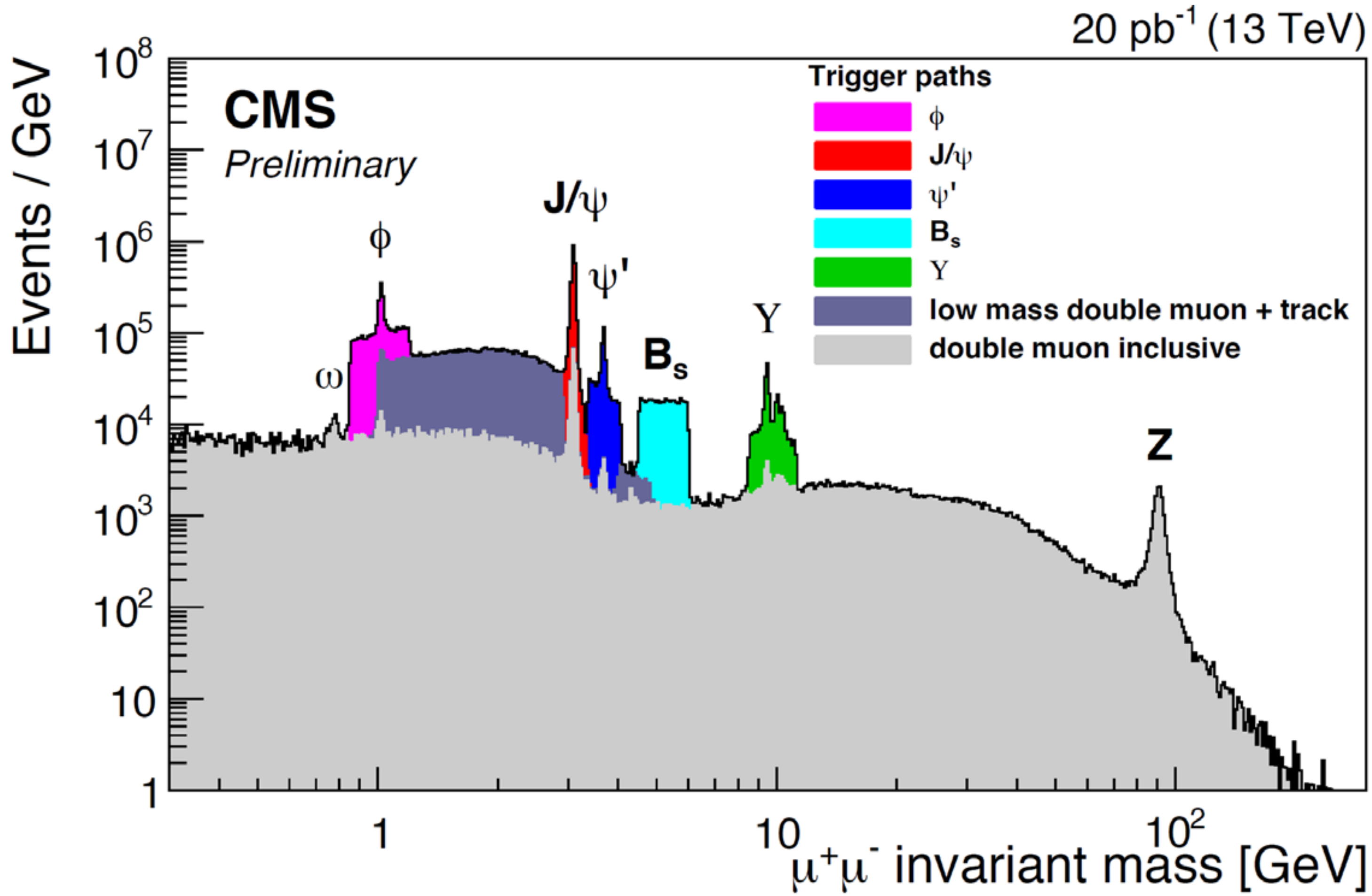
Example of exotic signature:
long-lived massive (m=500 GeV) particle, stopping within the detector at R>1 m and decaying to 2 muons



Efficiency improvement of the two algorithms with muon from stop decay



The dimuon invariant mass spectrum with 13 TeV data

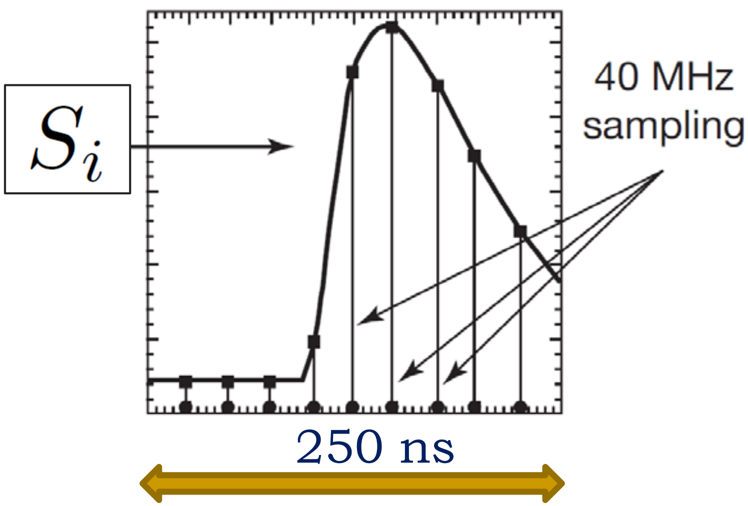


CMS DP2015/018

Data collected with different dimuon triggers.

ECAL pulse shape reconstruction

- Electrical signal from the photodetectors amplified and shaped by a multi-gain preamplifier.
- The output is digitized at 40 MHz and N=10 consecutive samples are readout and used to reconstruct the signal amplitude.
- In RunI (LHC bunch spacing of 50 ns) a digital filtering algorithm was used to filter the electronic noise:
  - both in online and offline reconstruction
  - noise estimated event-by-event by averaging the first 3 samples.



$$\hat{A} = \sum_{i=1}^{N} w_i \times S_i$$

The weights w_i are derived by minimizing the variance of amplitude A

ECAL pulse shape reconstruction in RunII

- Pile-up (mainly OOT) affects the performance of RunI algo.
- Several methods investigated during LS1 to mitigate the effect of pile-up, maintaining optimal energy resolution and noise filtering.

New reconstruction method: MULTI-FIT

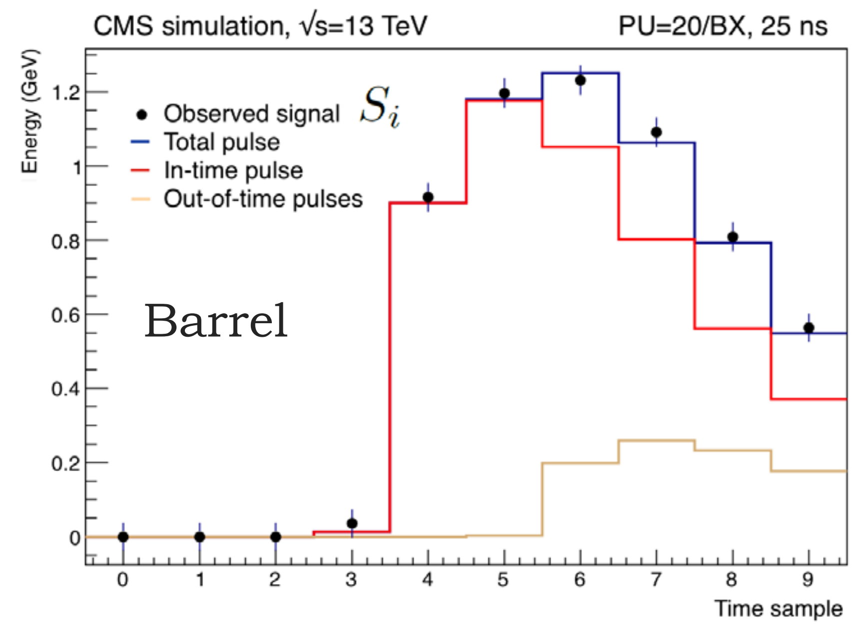
- estimates the IT signal amplitude and up to 9 OOT amplitudes by minimization of:

$$\chi^2 = \sum_{i=1}^{N} \frac{\left(\sum_{j=1}^{M} A_j p_{ij} - S_i\right)^2}{\sigma_{S_i}^2}$$

A_j : amplitudes of up to M = 10 interactions

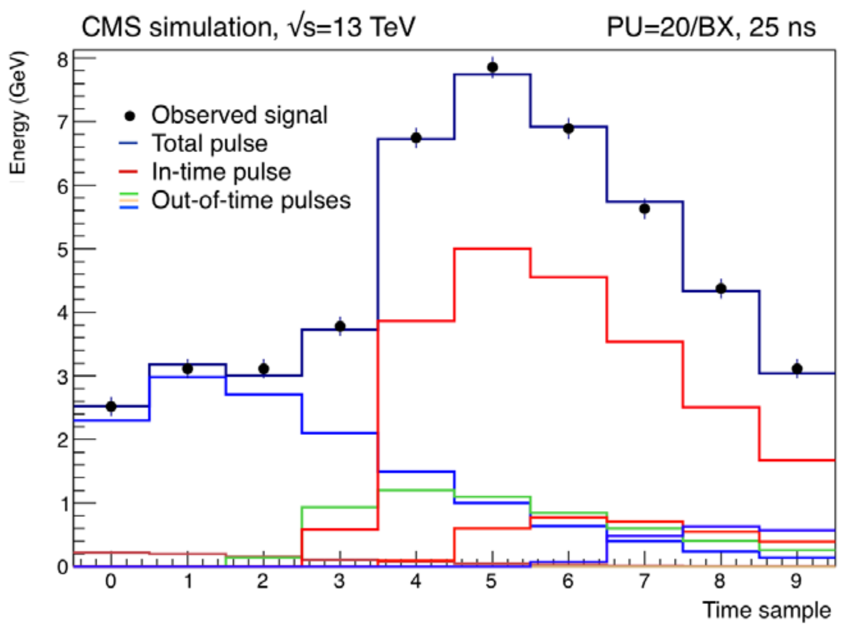
p_{ij} : pulse templates for bunch crossing j
same shape but shifted in time of multiple of 25 ns (taken from very low PU runs)

$\sigma_{S_i}^2$: electronic noise covariance matrix
(from dedicated pedestal runs)



ECAL pulse shape reconstruction in RunII

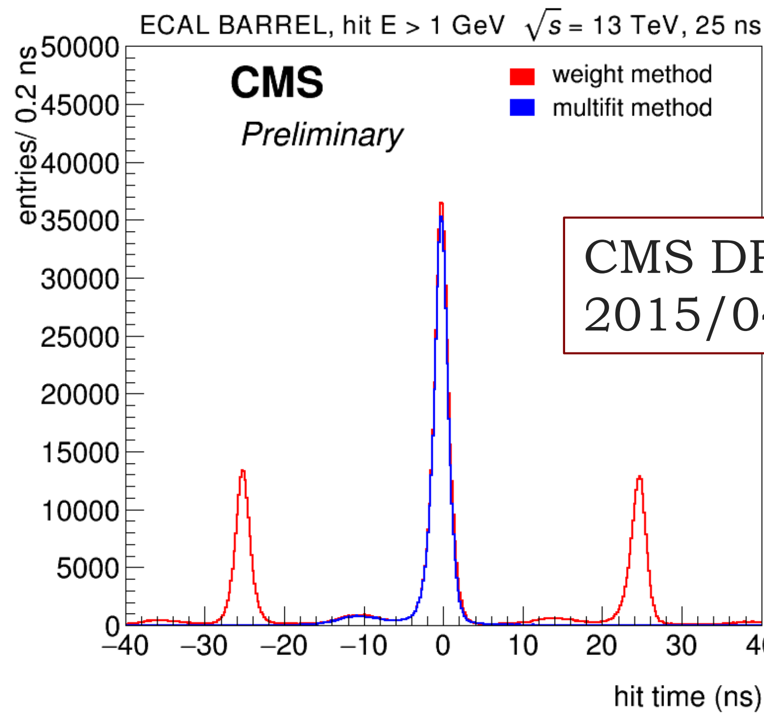
Examples of fitted pulses for simulated event in the Endcap



Improvement in energy resolution w.r.t. the Run I especially for low transverse energy but still significant at high ET (>50 GeV).

Crucial for the search of narrow resonances decaying in photons or electrons.

Timing distribution of the rechits with reconstructed energy > 1 GeV

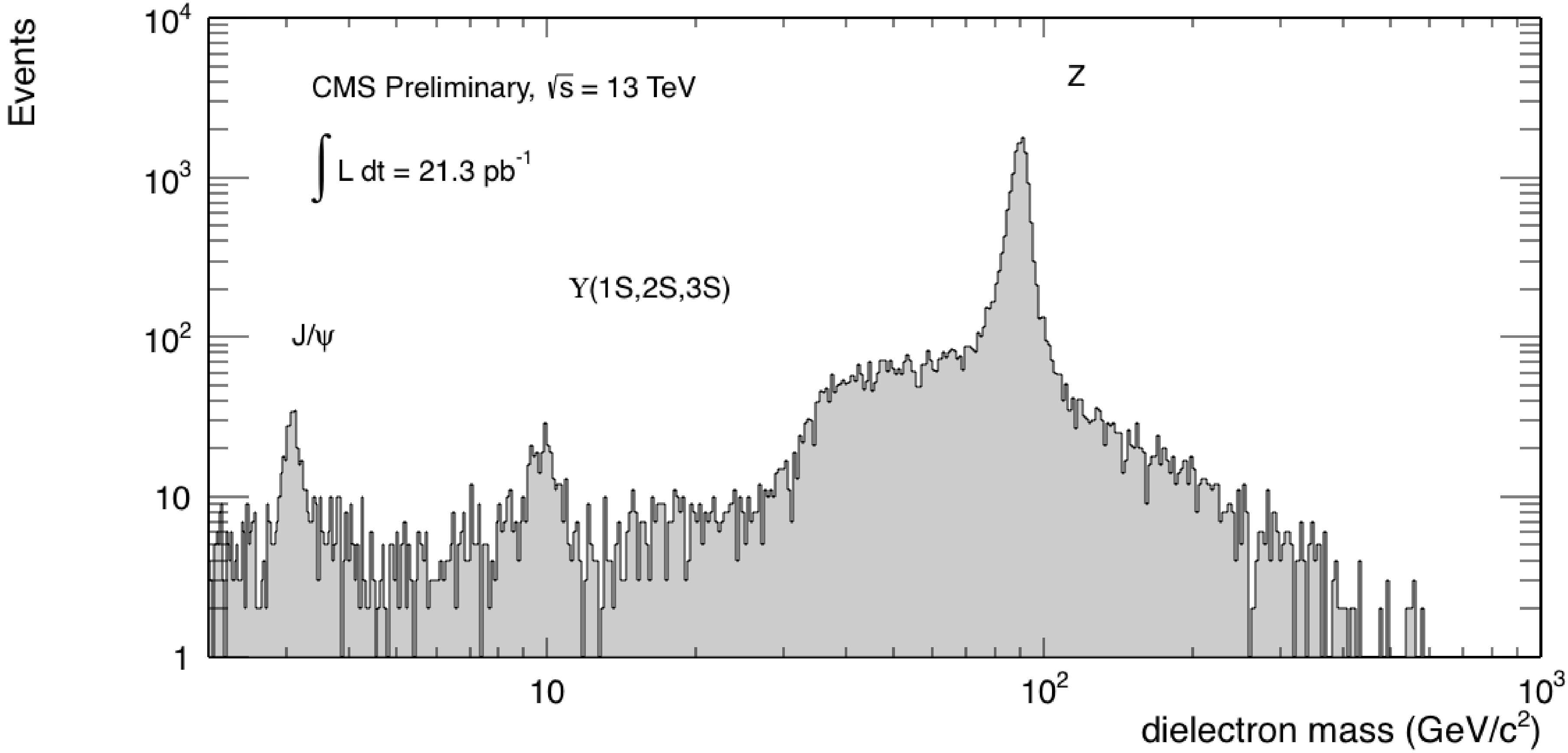


CMS DP 2015/040

Suppression of the contribution from energy deposited in OOT BX thanks to the multifit method.

The dielectron invariant mass spectrum with 13 TeV data

CMS DP2015/013

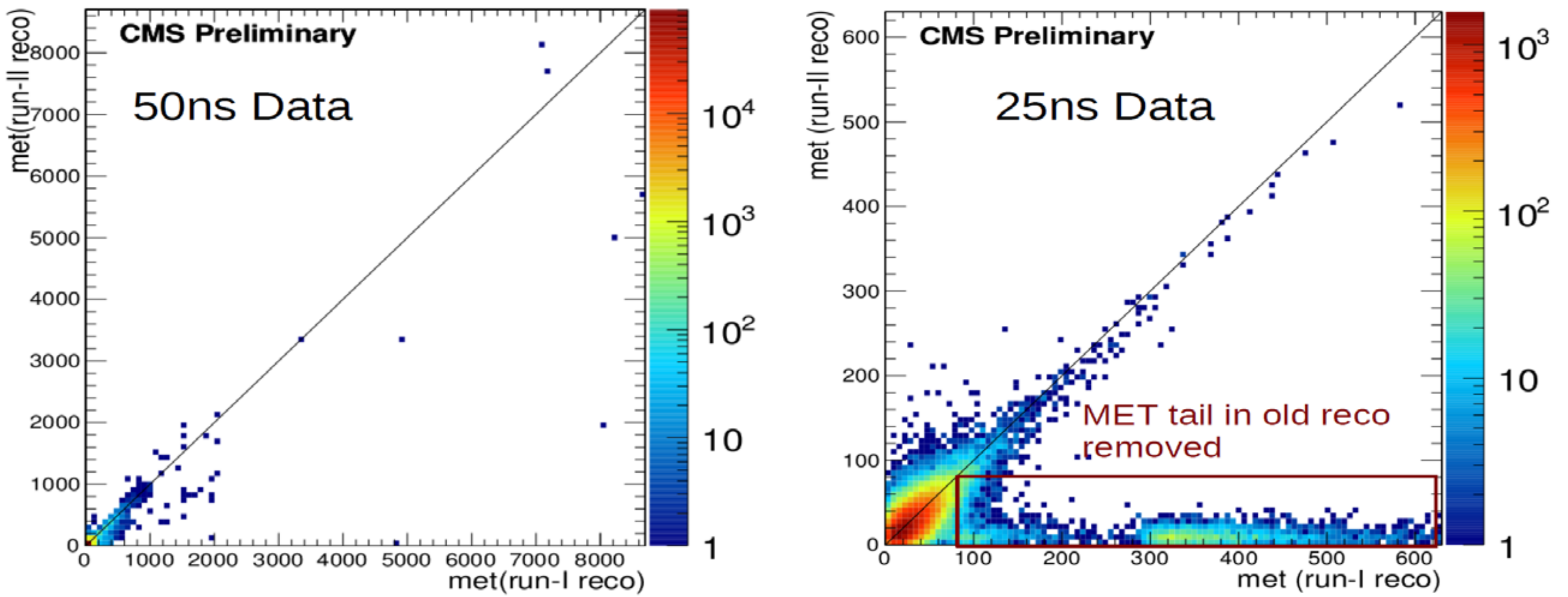


Missing Transverse Energy

- Missing Energy in the plane transverse to the beam direction is strategic to any SUSY analysis and also a key element of several Exotica searches.
- Instrumental and non-physical MET to be reduced and kept under control.

Event by event MET comparison in RunI and RunII reconstruction:

- largely exploiting also the new HCAL reco method to mitigate OOT PU (similar to ECAL, three amplitudes with floating timing).
- Outliers reduced in 50 ns data and large tail in 25 ns data removed.



Conclusions

- LHC RunII conditions (high PU, 25 ns BX, …) pose severe requirements to tracking and calorimeter reconstruction.
- Huge effort during LS1 to improve the reconstruction performance:
  - tracking fake rate, and timing are under control without affecting tracking efficiency and capability of tracking inside jets
  - new algorithms in muon tracking and reconstruction of displaced tracks to enlarge the physics reach in many searches
  - new reco amplitude methods in calorimeters to mitigate the effect of OOT PU on the energy measurements preserving excellent energy resolution in ECAL and improving MET reconstruction
  - many other significant reconstruction improvements on Jets, b-tagging, and tau-tagging side not covered in this talk.

In general, new reconstruction performance comparable or better than RunI despite the higher PU and reduced BX separation of RunII

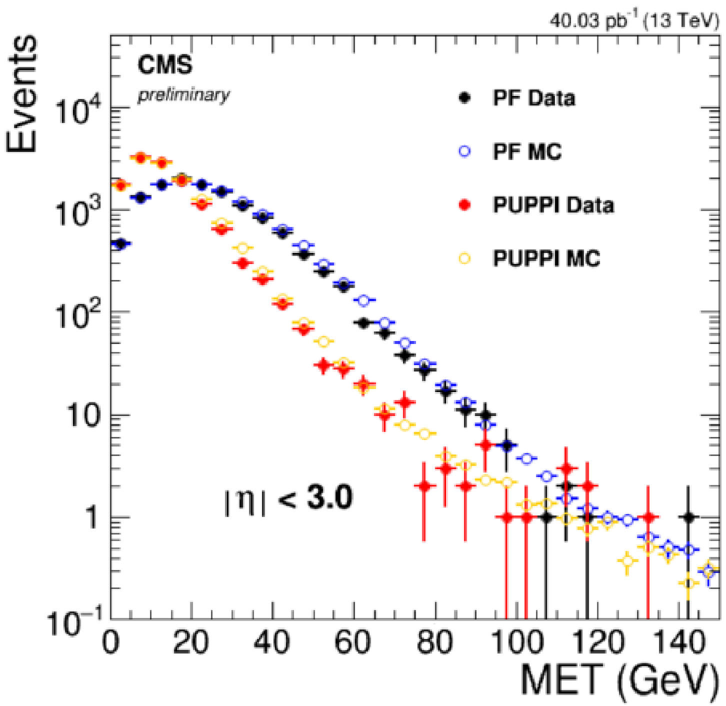
Backup

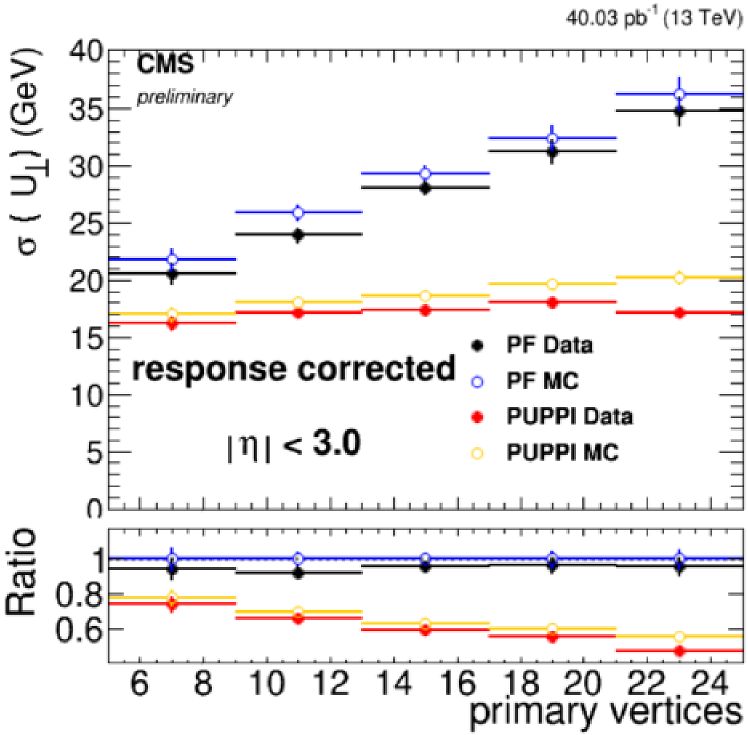
Missing Et performance

PF: standard Particle Flow reconstruction

PUPPI: Pile Up Per Particle Identification (http://arxiv.org/abs/1407.6013, CMS-PAS-JME-14-001)

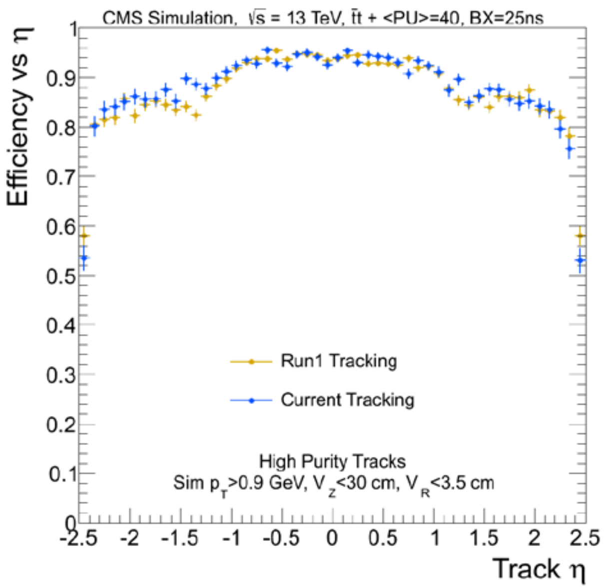
- any particle flow candidate is weighted according to the surrounding activity
- the weights are optimized to discriminate particles from hard scattering vs particle from pile-up.



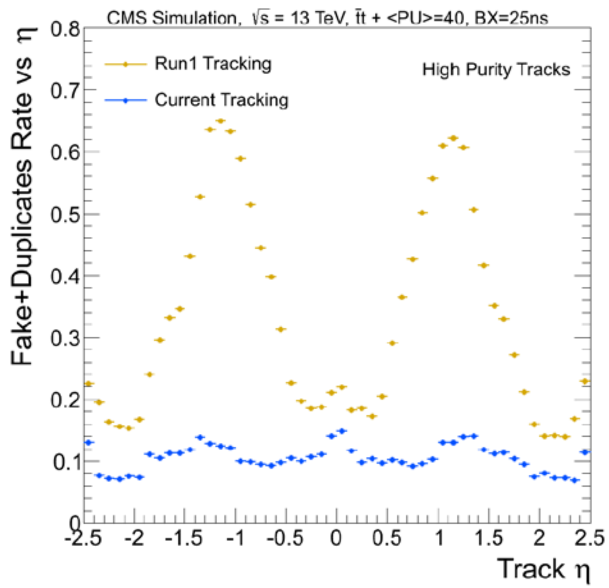


Tracking improvement in RunII: performance vs PU

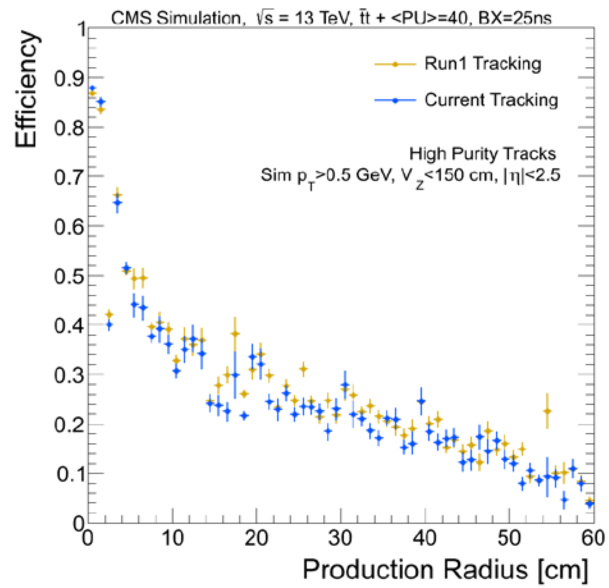
Performance vs PU: ttbar events with <PU>=40 and BX=25 ns



high p_T prompt tracks



all tracks



low p_T displaced tracks

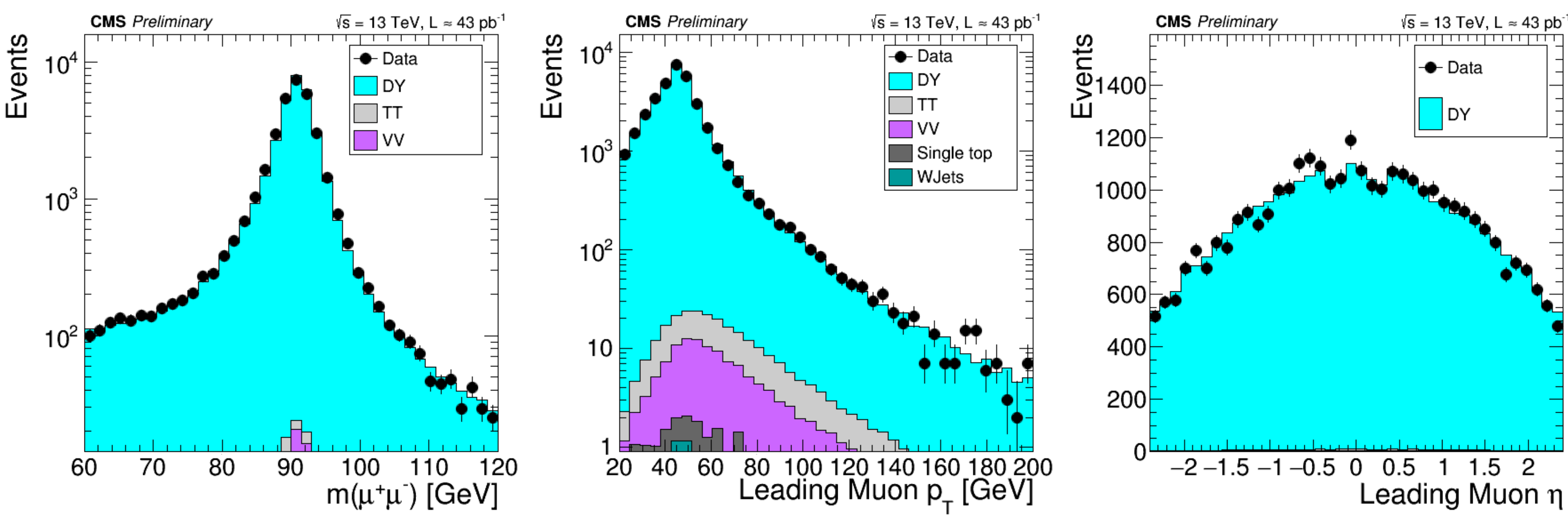
Method

- Efficiency of triggers HLT_Mu40, HLT_IsoMu24 vs p_T, η, vertex multiplicity w.r.t. tight muon ID
  - tight muon ID:
    - Particle Flow (PF) && Global Muon ID
    - Global track's χ^2_{GLB} / dof < 10
    - # valid muon hits > 0, # matched muon stations > 1
    - Impact parameters of tracker track w.r.t. primary vertex: $|d_{xy}| < 0.2$ cm, $|d_z| < 0.5$ cm
    - # valid pixel hits > 0, # tracker layers with measurements > 5
- Method: tag-and-probe with Z resonance
  - tag:
    - tight muon ID, $p_T > 15$ GeV/c
    - matched with HLT_IsoMu24(_eta2p1)
  - probe:
    - tight muon ID
    - (only for IsoMu24 efficiency) Loose combined-relative PF isolation:
      $[\Sigma E_T(\text{ch-hadr from PV}) + \Sigma E_T(\text{neutr-hadr}) + \Sigma E_T(\text{phot})] / p_T^\mu < 0.2$ ($\Delta R = 0.4$)
      "$\Delta\beta$ correction" on neutral component, estimated using the charged particles in the isolation cone originating from non-primary vertexes, and the neutral-to-charged ratio
- MC: $Z \rightarrow \mu\mu$, with pileup reweighting to observed number of reconstructed vertices

Z→μμ in 13 TeV collisions

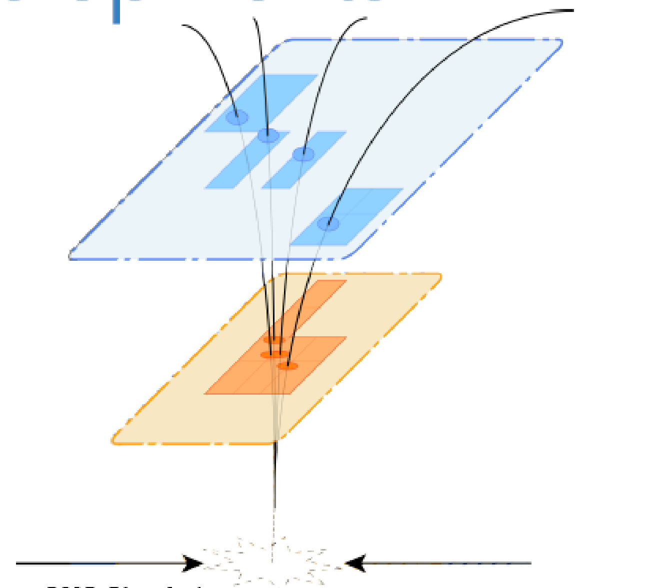
- Collision data at 13 TeV and 50 ns bunch spacing
- Overall normalization of simulated distributions scaled to the data
- No event re-weighting is applied to match the pileup distribution in data yield

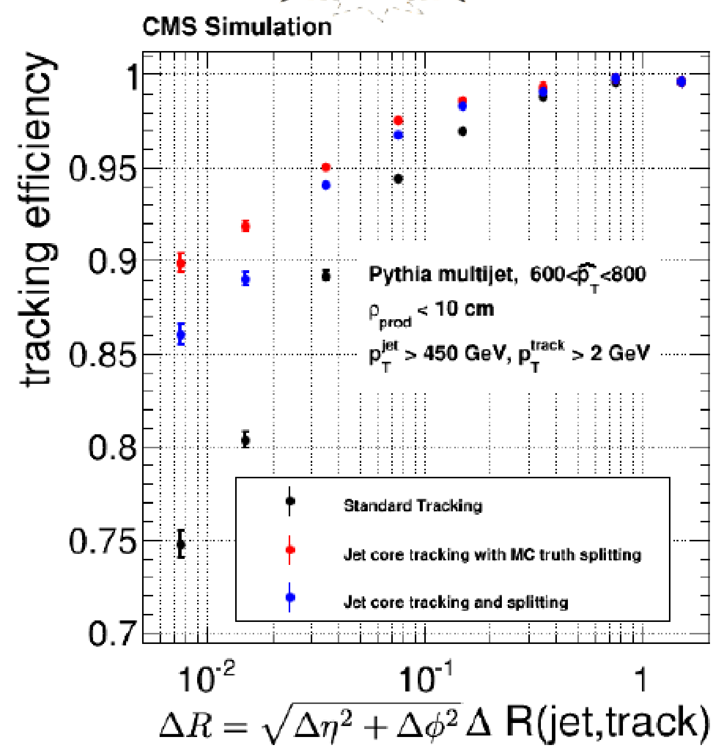
CMS DP2015/015



Tracking Physics oriented developments
High-p_T Jets

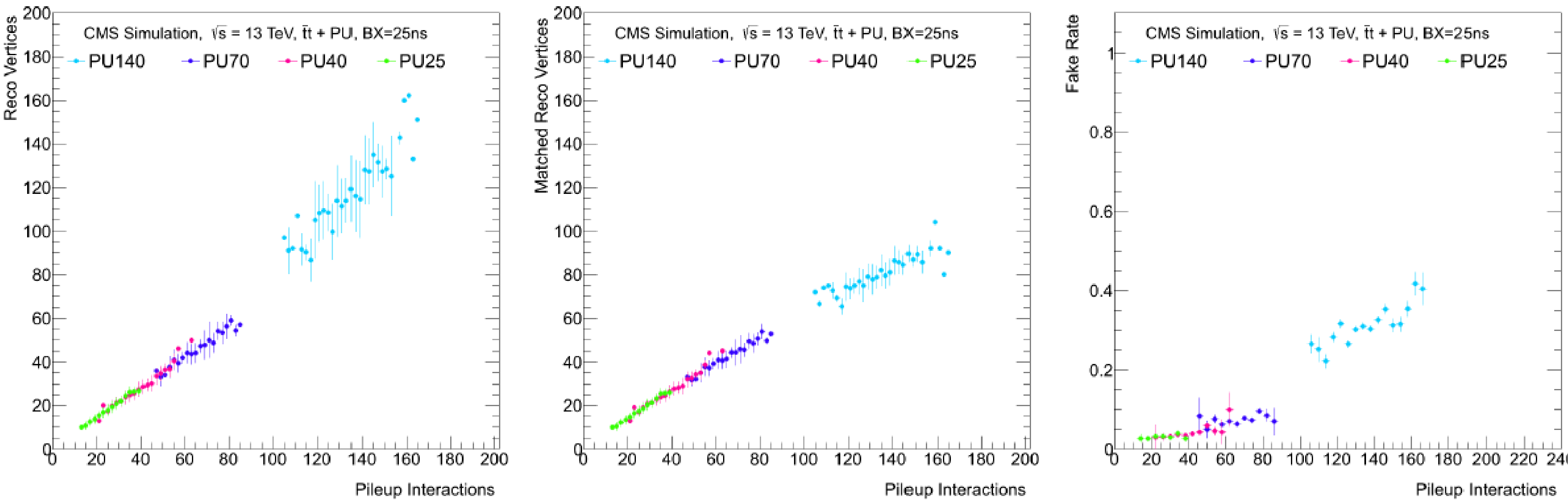
- Tracking in high p_T jets is crucial for b- and τ-tagging efficiency
- Dense environment:
  - small two-track separation
  - merged clusters: only one hit with bad estimated position and uncertainty
- A new dedicated iteration has been developed
  - regional, along high p_T calo jets
  - threshold trade-of between timing and physics
  - cluster splitting
  - looser tracking cuts to follow combinatorial expansion
- improved efficiency at small ΔR





Primary Vertex Performances

- The reconstructed vertices vs PU shows a linear trend with slope ~0.7 up to PU70.
  - Excess of reconstructed vertices for PU140
- The number of matched vertices has linear trend over all range
  - vertex matches a simulated if $|\Delta z|<1$ mm and $|\Delta z|<3\sigma_Z$
- These results are the effect of a faster than linear increase in fake rate and a linear decrease in efficiency



Muons in 13 TeV Collisions
Data and MC

- Data
  - Collision data at 13 TeV and 50 ns bunch spacing
  - Prompt reconstruction, certified only on the basis of DCS detector status
  - DoubleMuon dataset
  - Integrated luminosity ~ 43 pb^{-1}

- Monte Carlo
  - Samples of Drell–Yan, W + jets, top-top, single-top, dibosons generated with MadGraph_aMC@NLO
  - Detector alignment and calibration conditions as expected after about 1 fb^{-1} of integrated luminosity
  - Overall normalization of simulated distributions scaled to the data yield
  - No event re-weighting is applied to match the pileup distribution in data

Muons in 13 TeV Collisions Selection

- Trigger
  - double-muon trigger with p_T thresholds of 17 and 8 GeV on higher- and lower-p_T muon, loose tracker-based isolation on each muon

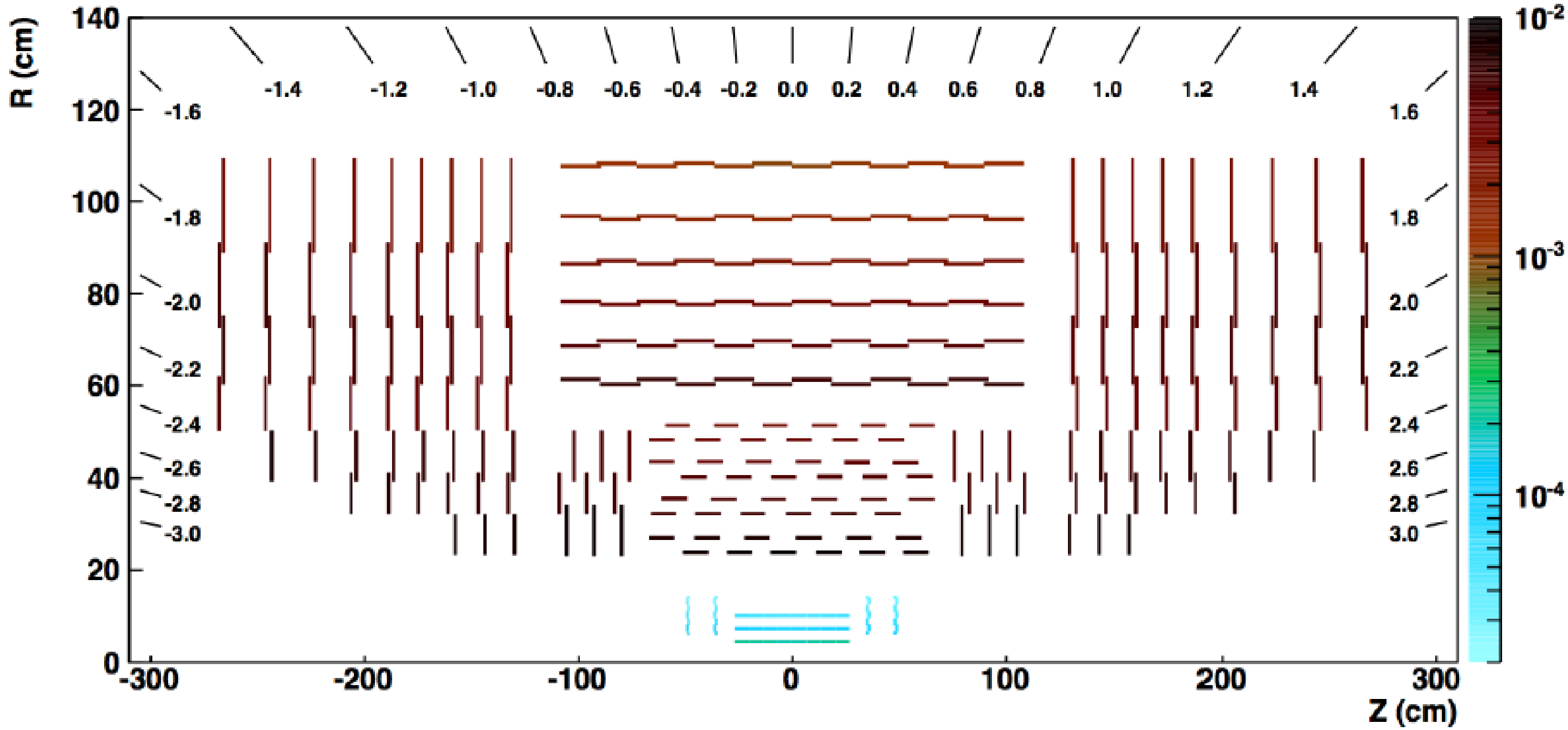
- Offline selection
  - at least two opposite-sign muons passing the Loose ID
  - $p_T > 20$ and 10 GeV, $|\eta| < 2.4$
  - both muons passing a loose isolation requirement:
    $\Sigma\, p_T(\text{tracks}) + \max(0, \Sigma\, E_T(\text{ECAL}) + \Sigma\, E_T(\text{ECAL}) - k \cdot \rho) < 0.2 \cdot p_T(\text{muon})$
    (where ρ is the average energy density in the event)
  - di-muon invariant mass between 60 and 120 GeV
  - if more than one muon pair satisfies the requirements above, the pair with invariant mass closest to the nominal Z boson mass is selected

Occupancy/granularity

Despite the position, the channel occupancy in the pixel detector is typically an order-of-magnitude smaller than in the strip detector.
Occupancy decreases stronger than area/r^2 (magnetic field confines softer particles inside)

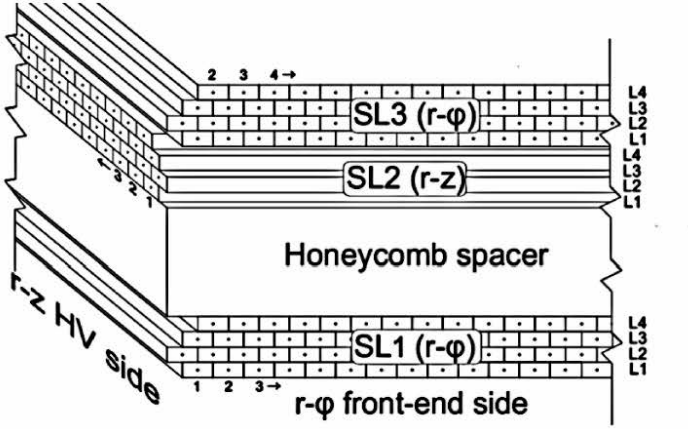
- single pixel area = 100μm×150μm = 1.5×10^{-2}mm^2
- typical strip area = 10cm×100μm = 10mm^2

This plot explains why CMS tracking is heavily pixel driven (seeding).

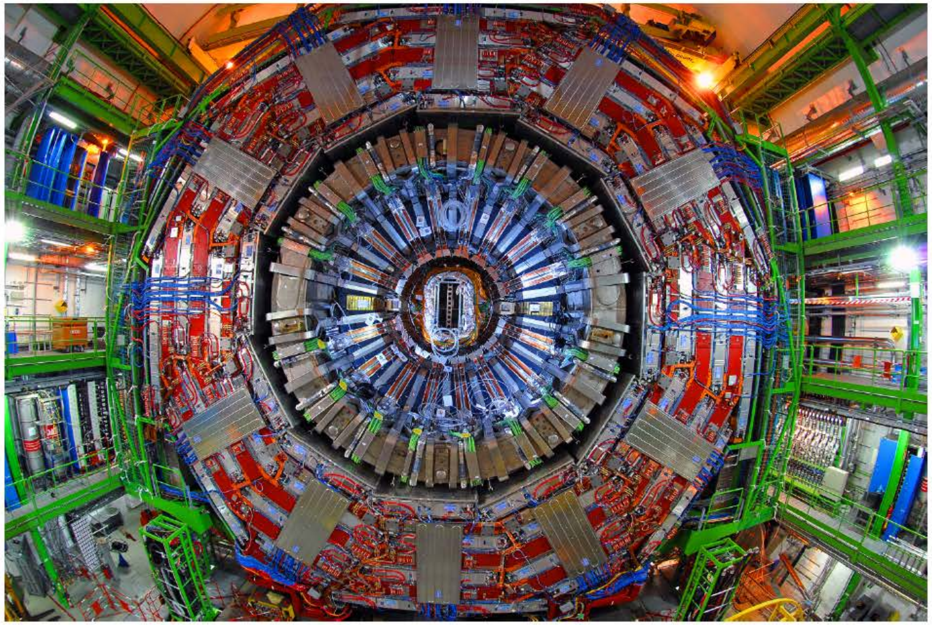


DT (Drift Tube chambers)

$|\eta|<1.2$

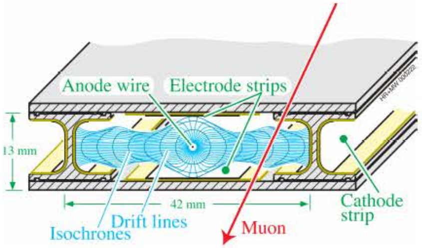


BARREL: 4 cylindrical stations divided in 5 wheels, each one 12 sectors (TOT 250 chambers)



- ✧ Each chamber has 12 detection layers: 4+4 r-ϕ, 4 r-z, except in the outermost station with only r-ϕ view (8 layers)

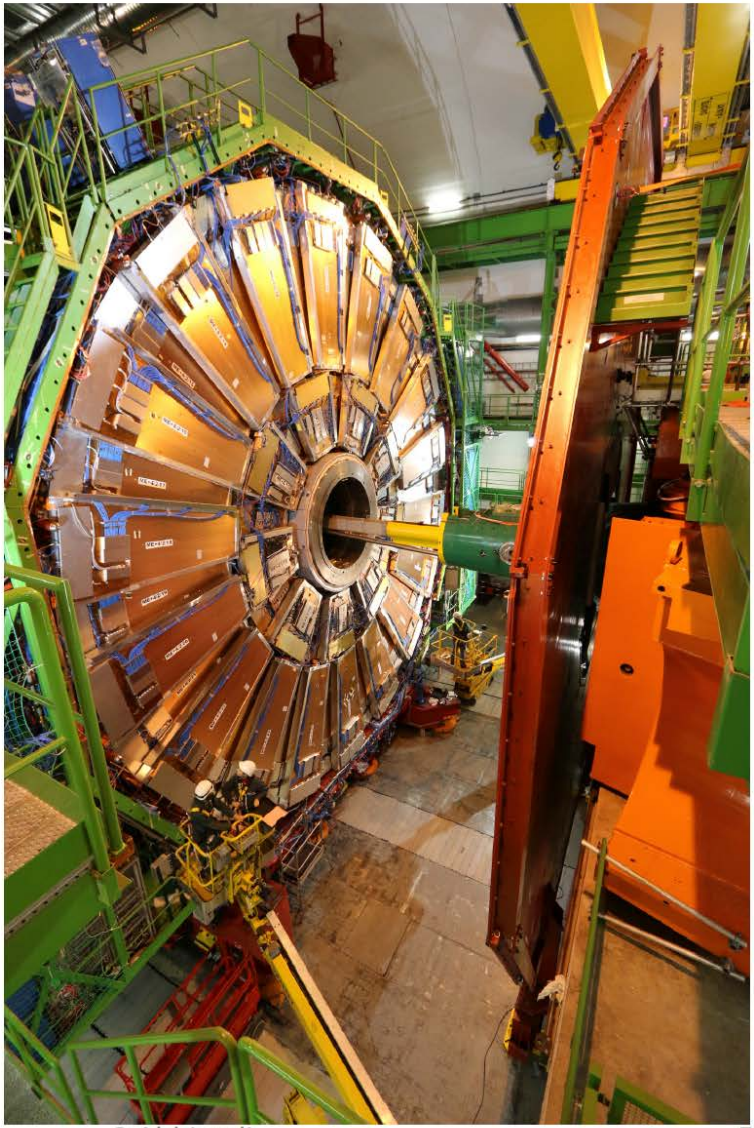
- ✧ Muon segment on a chamber: time resolution < 3ns, position resolution ~100 μm in the bending plane (r-ϕ)



Drift cell 42x13 mm^2
gas mixture 85% Ar, 15% CO_2
drift velocity ~ 55 μm/ns,
max. drift time ~ 400 ns
Hit resolution ~250 μm

CSC (Cathode Strip Chambers)

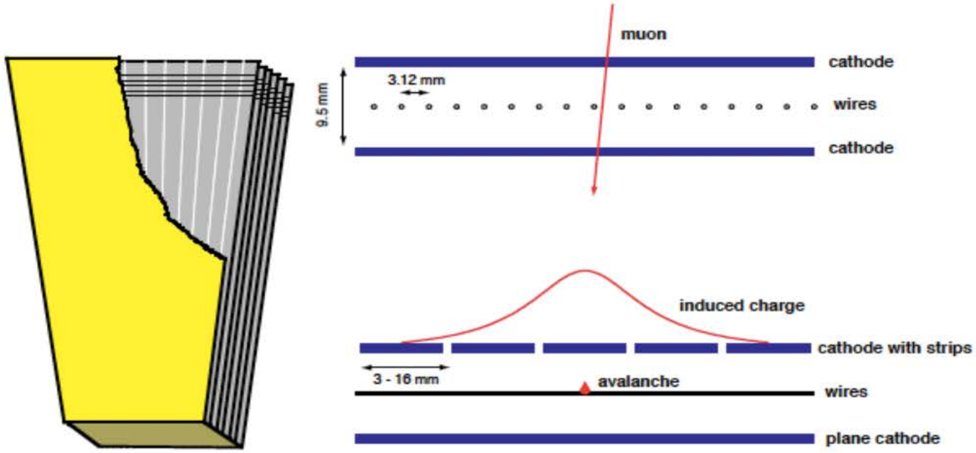
0.9<|η|< 2.4



Two ENDCAPS: 4 stations (disks), each one made of 2-3 rings, each ring with 18/36 sectors (TOT 540 chambers)

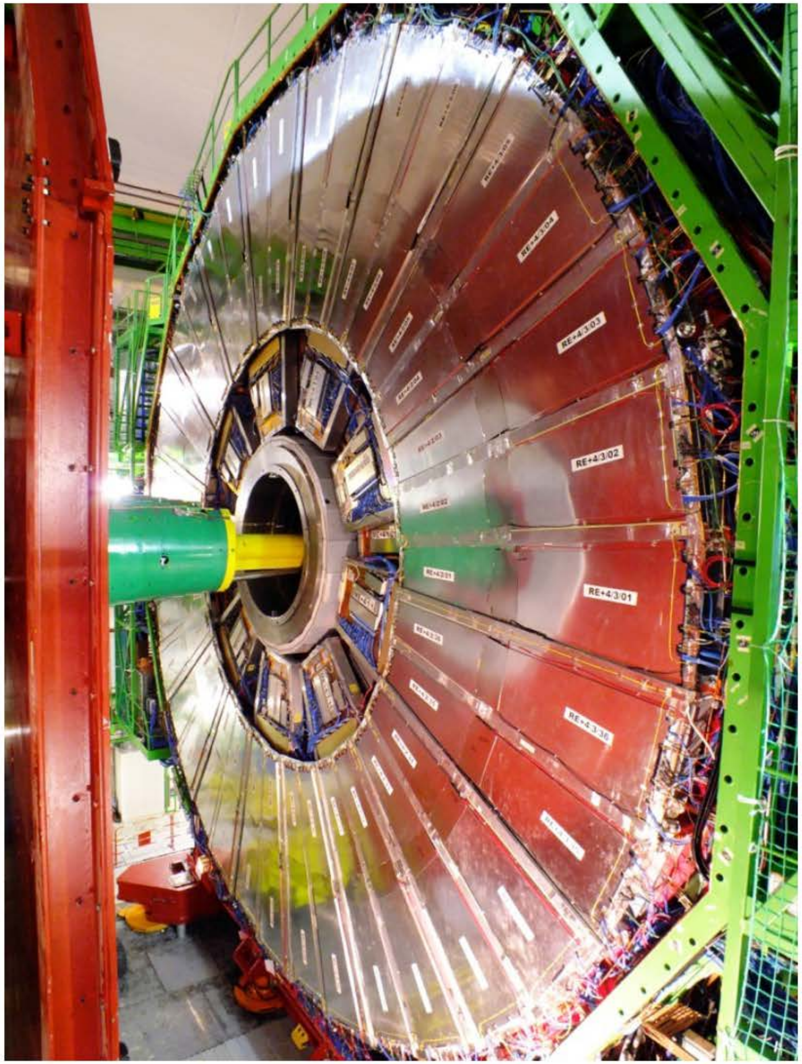
MWPC plus cathode strip read-out

- Each chamber: 6 layers, strips measure bending in r-φ, wires radial coordinate
- Resolution on segments: time ~3ns, spatial 50-150 μm in r-φ



Gas mixture 40% Ar, 50% CO2, 10% CF4

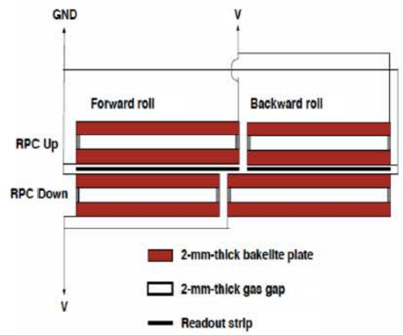
RPC (Resistive Plate Chambers)



Fast independent trigger ($|\eta|<1.6$) with excellent time resolution <3ns

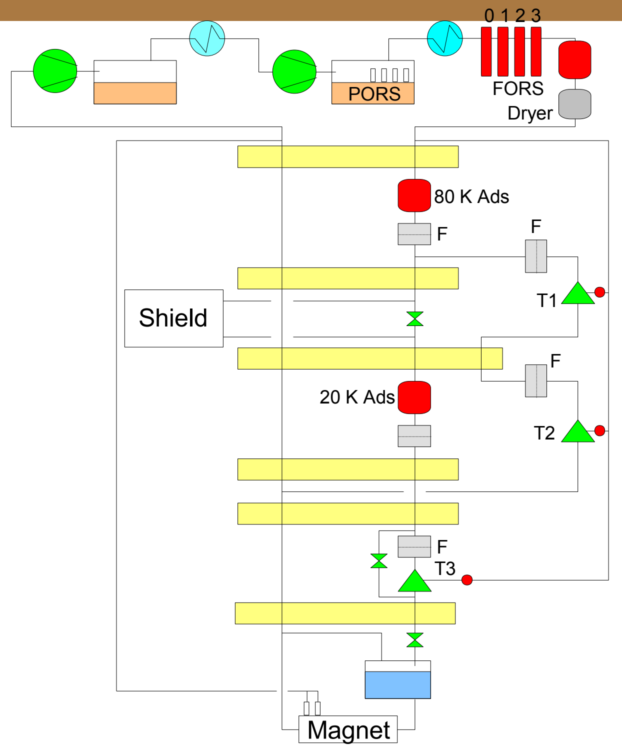
Barrel and endcap RPC with similar geometries as DT and CSC
TOT: 480 Barrel chambers, 576 Endcap chambers (hits up to $|\eta|=1.8$)

Coarse position resolution ~ 1cm in the bending plane



- ✧ Double-gap chambers in avalanche mode (high-rate tolerant)
- ✧ Gas 95.2% Freon, 4.5% Isobutane, 0.3% SF6

Magnet Cryogenics



- The restart of the CMS magnet after LS1 was more complicated than anticipated due to problems with the cryogenic system in providing liquid Helium.
- Inefficiencies of the oil separation system of the compressors for the warm Helium required several interventions and delayed the start of routine operation of the cryogenic system.
- The data delivered during the first two weeks of LHC re-commissioning with beams at low luminosity have been collected with B=0
- Currently the magnet can be operated, but the continuous up-time is still limited by the performance of the cryogenic system requiring more frequent maintenance than usual.
- A comprehensive program to re-establish its nominal performance is underway. These recovery activities for the cryogenic system will be synchronized with the accelerator schedule in order to run for adequately long periods.
- Consolidation and repair program is ongoing during the technical stop while a full cleanup of the Cold Box is foreseen for the long Technical Stop at the end of the year.