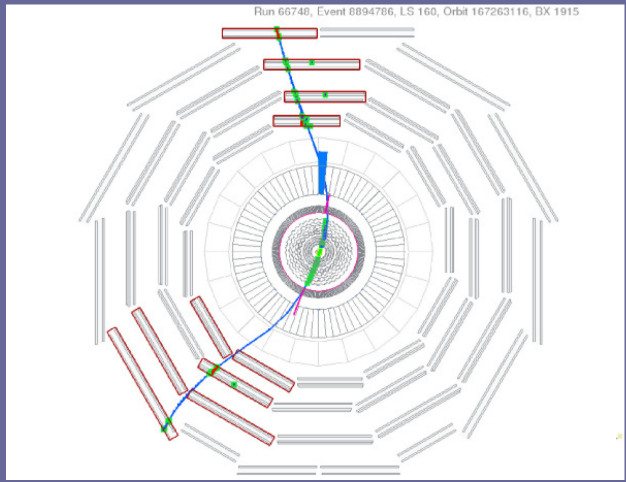
Compact Muon Solenoid (CMS) Muonsystem

1. Design considerations
2. Technology choice and implementation
3. Performance with cosmic rays
4. Efficiencies in collision data
5. Conclusions



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On behalf of the CMS Collaboration

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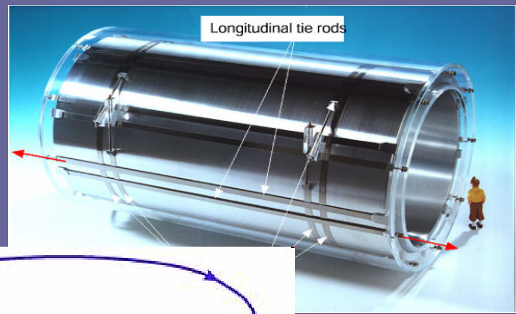
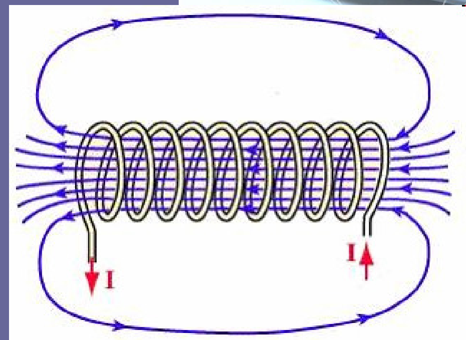
The CMS Original Concept

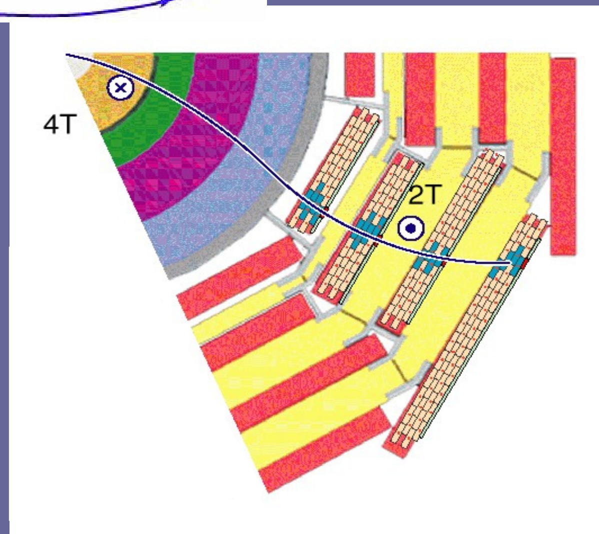
Optimized for high p_T leptons (and γ)

- Good momentum resolution with high B-field
  - High field of B=3.8 T for better momentum resolution $\frac{\Delta p}{p} \sim \frac{p}{B}$
  - For similar bending power solenoidal system is smaller and provides homogeneous field inside tracker
  - Solenoidals fields requires return yoke

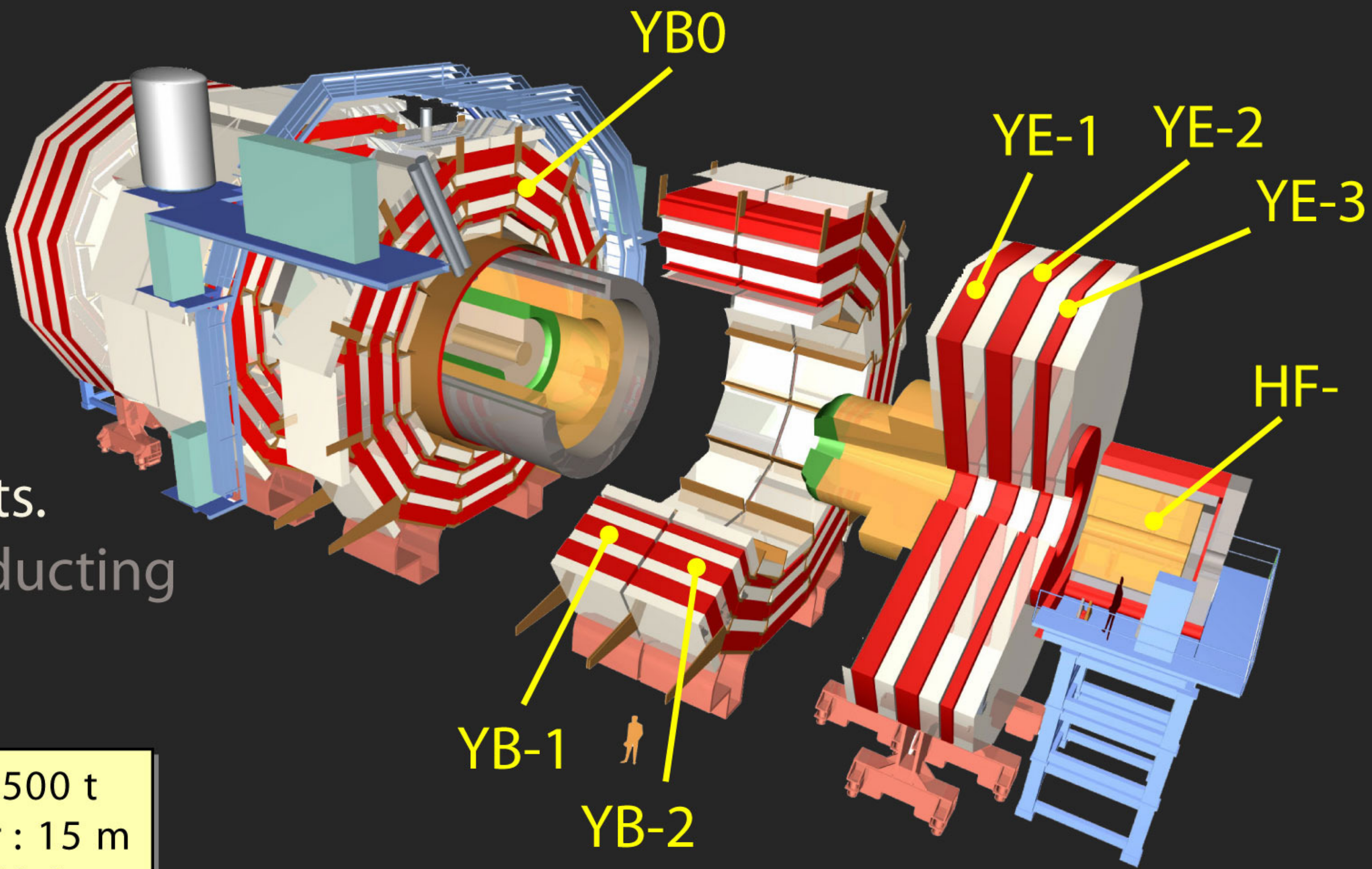
- Excellent and redundant muon identification
  - Muon stations to be interleaved with return yoke, multiple scattering limits overall resolution
  - Four muon stations along the track
  - Redundancy in the muon system, complementary technologies







The CMS Detector

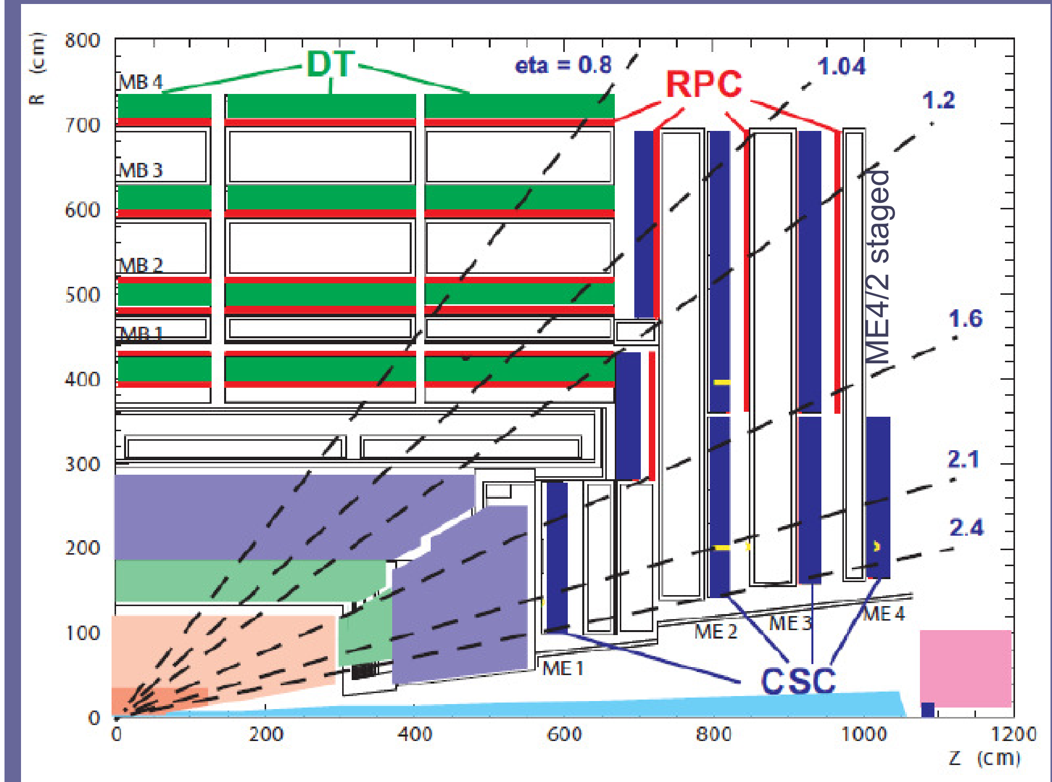


- Pixels
- Tracker
- ECAL
- HCAL
- MUON Dets.
- Superconducting Solenoid

Total weight : 12500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

http://cms.cern.ch

CMS Muon System



Muon Barrel 0 < |η| < 1.2

- 5 barrel wheels, iron return yoke for the solenoid magnet
- Almost no B-field at chamber positions
- 250 Drift Tube (DT) Chambers
- 480 Resistive Plate Chambers (RPC)

Forward Muon 0.9 < |η| < 2.4

- Arranged in 2 x 3 disks
- 4 muon stations in 2/3 rings
- Inhomogenous field with B<1.2 T
- 250 Cathode Strip Chambers (CSC)
- 483 Resistive Plate Chambers (RPC)

Muon-ID By Absorption and Tracking in the Muon System

Charge Curvature in B-Field, Tracker and Muon System

Muon p_T Tracker (~1%) and Muon System (~10%) + Alignment

~0.5 M channels

~10,000 m^2 instrumented

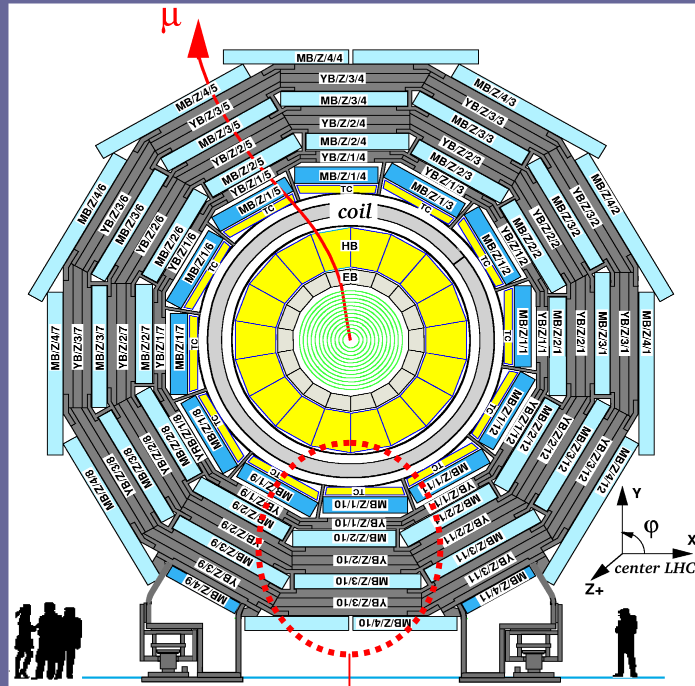
All detectors used for triggering and reconstruction

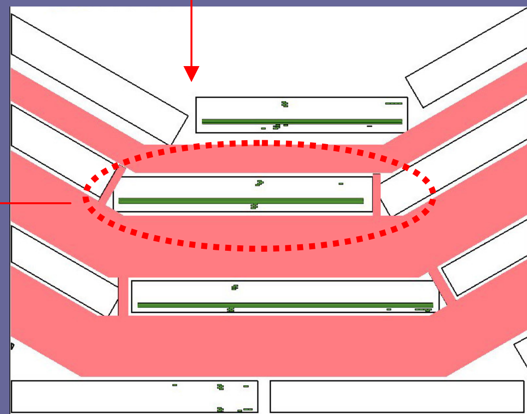
Barrel Drift Tube Chambers (DT)

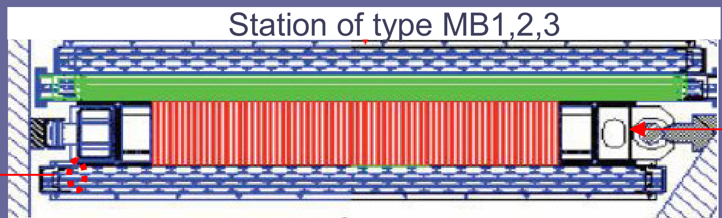
- 250 chambers arranged in 5 wheels, each with 4 stations forming concentric cylinders, 172 k readout channels

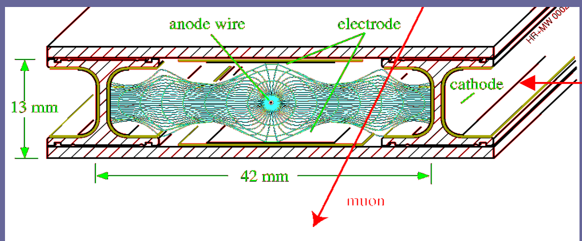
CMS chambers interleaved with iron yoke

- B-field contained in the iron (B~1.9 T) except MB1 of outermost wheels
- B-field in iron for p_T measurement, track curvature flips in MB3
- Punch-through only in first station
- Cell resolution ~250 μm, station resolution ~100 μm (limited by multiple scattering)

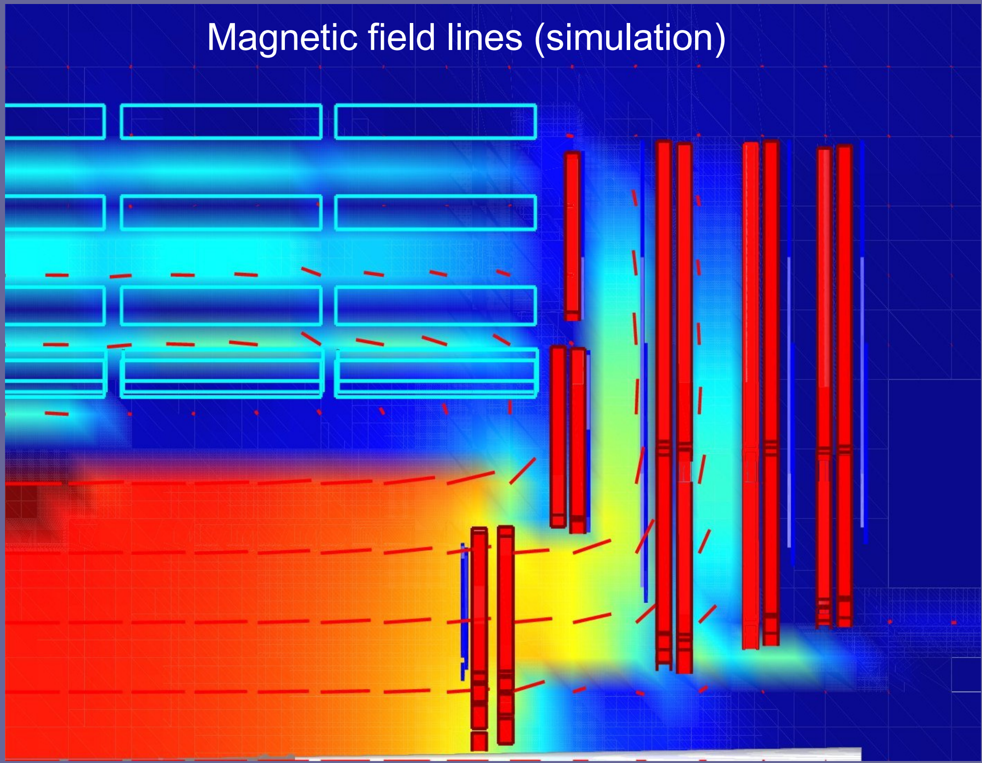


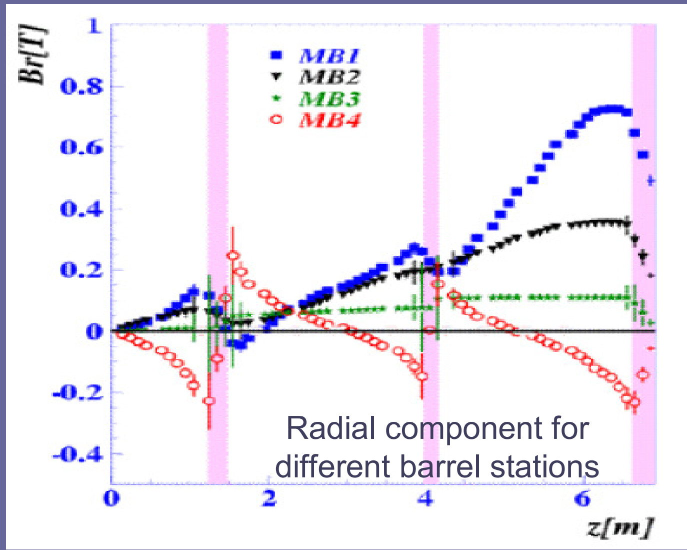


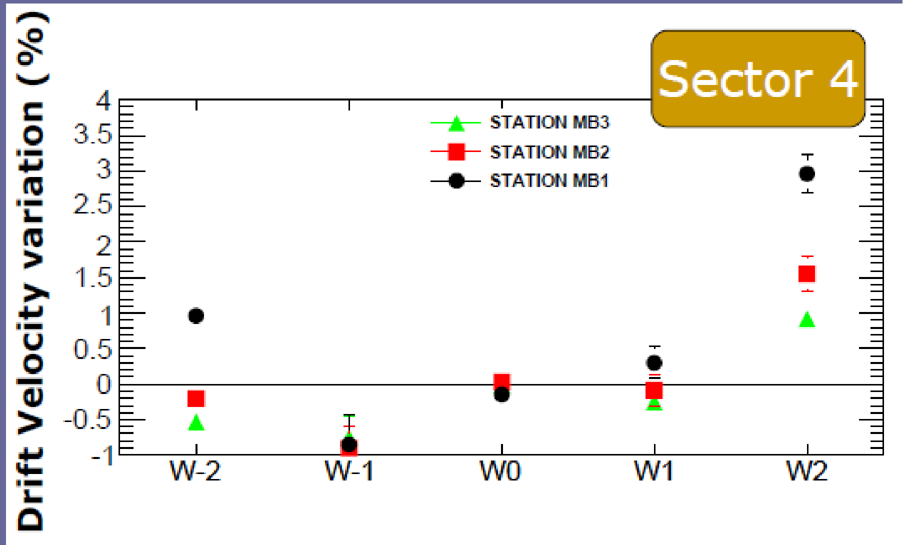




Drift and B-Field



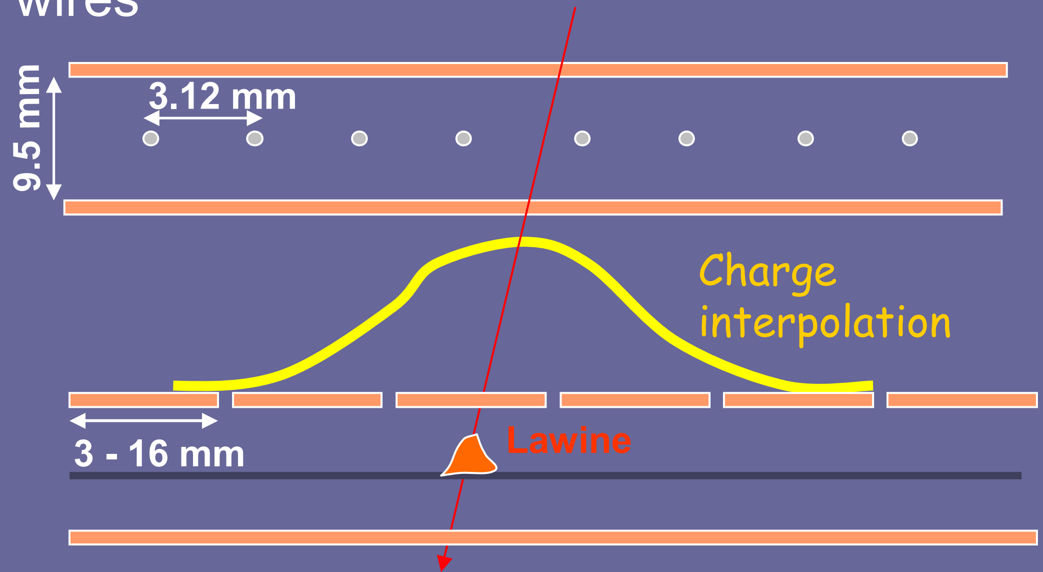




- Residual B-field changes drift velocity
- Has been measured, correction factors are calculated → database for reconstruction
- Monitoring of the effect with calibration runs and gas mixture monitoring system

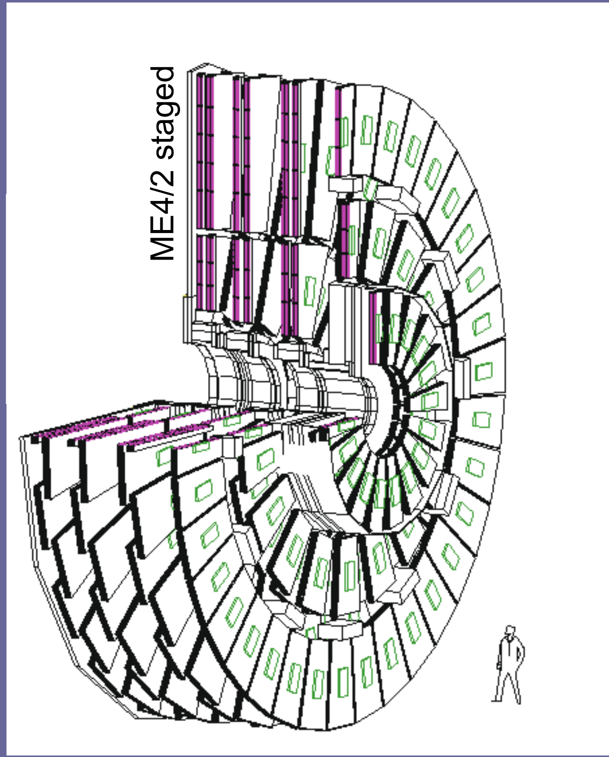
Endcaps: Cathode Strip Chambers

- 468 chambers arranged in 4 disks per endcap
- Chambers composed of 6 gas gaps with a layer of staggered cathode strips and one of anode wires



- Anode wires: fast response (~4 ns) for BX ID, radial coordinate measurement
- Strips: measures bending coordinate ϕ with good spatial resolution (75 - 150 μm)

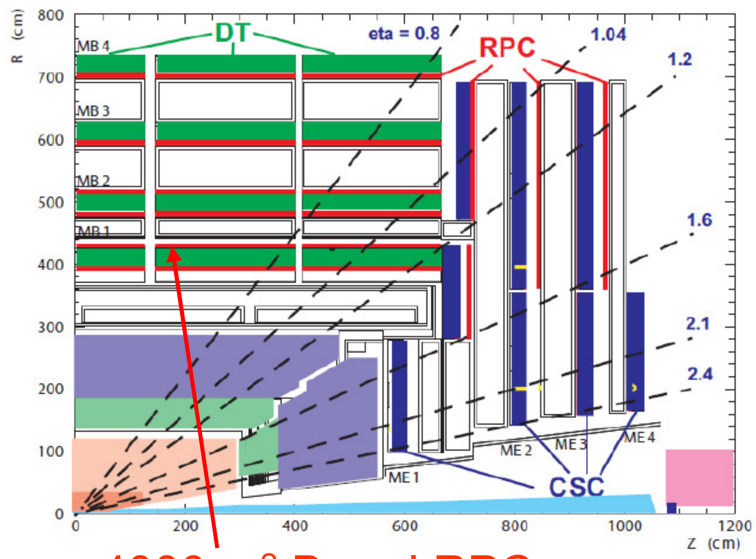
Instrumented up to $|\eta|<2.4$



Gas: Ar/CO2/CF4 (30/50/20)%

CMS RPC System

1500 m² Forward RPCs

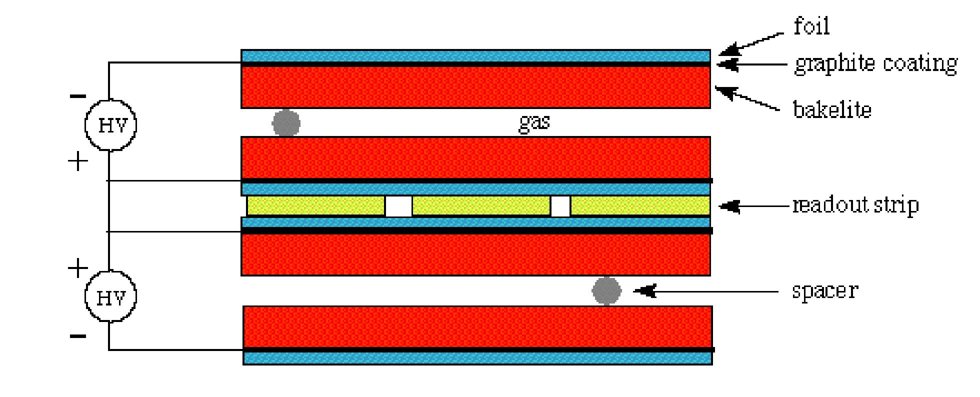


4000 m² Barrel RPCs

- 912 chambers with ~160 k channels
- Barrel with 6 stations (for softer muons), endcap with 3 stations up to $|\eta|<1.6$
- Double gap with single readout strip in OR
- **Avalanche mode to cope with hit rate up to 1 kHz/cm²**
- Gas: 96.2% C2H2F4, 3.5% Iso-Butane, 0.3% SF_6

Strips: measure bending coordinate, resolution ~1cm

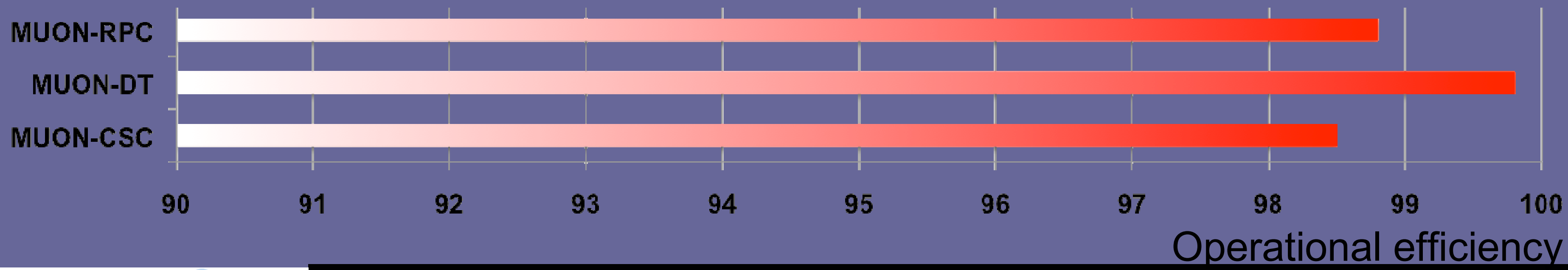
Fast response (~2 ns) for unambiguous BX ID at level-1



Gas gap needs constant width. Signal in pick up electrodes

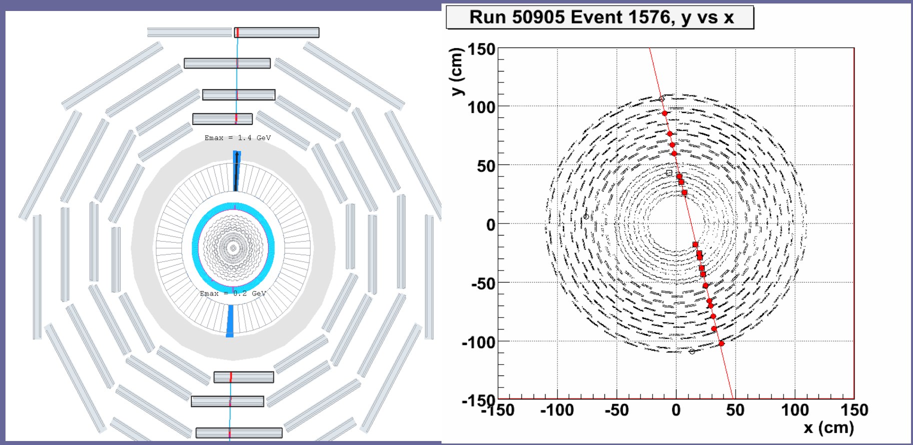
Operation and Commissioning

- Longest production time of all subsystems
  - ~ 5 years production at ~20 different sites incl. first level muon trigger
  - ~ 2 years installation and commissioning
  - ~ 1 for synchronization
- Muon system, especially barrel muon, first to be ready. Provide cosmic muon triggers for MTCC and cosmics data taking
- Continuously running since ~2008
- During pp running, efficiency >98.5%



Commissioning with Cosmic Muons and Beam Splash Events

Vertical Cosmic Muons (CRAFT)

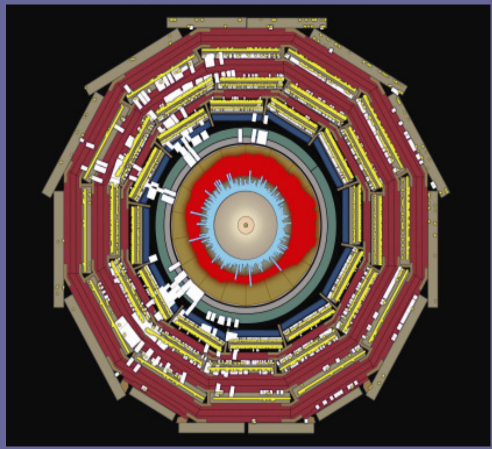


In total ~350 million triggers

Used for studies of

- Reconstruction (tracker, muon, global)
- Trigger performance and efficiency
- Alignment of tracker and muon system and global alignment

Horizontal Beam Splash Events



- For alignment of muon endcaps with respect to each other (cannot be done with cosmics since rate of horizontal cosmics is too low)
- Large energy deposition in calorimeters useful to study performance (although very limited statistics)

Muon Resolution with Cosmics

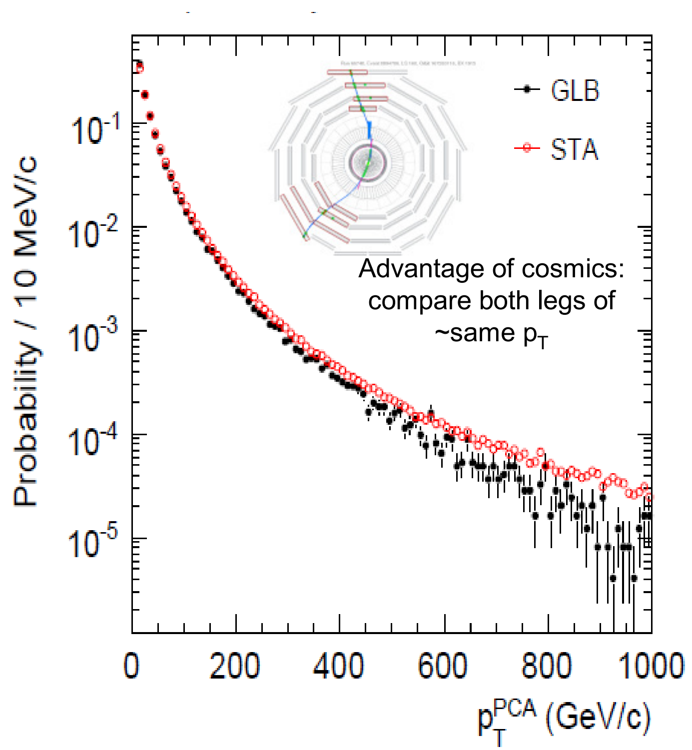
Reconstruction of O(TeV) difficult, showering

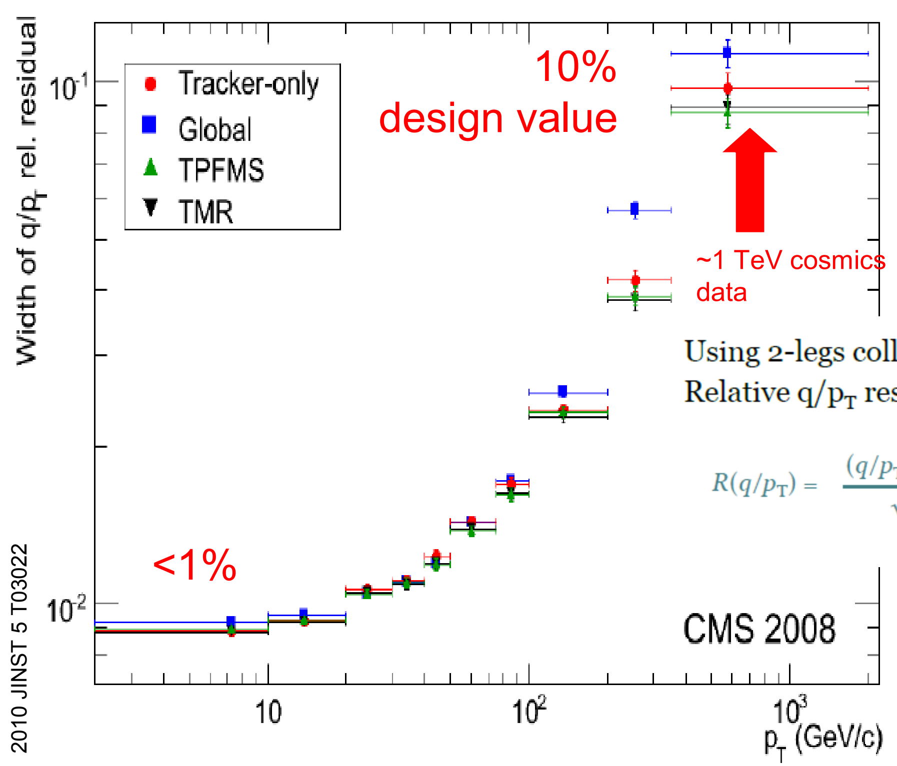
Different algorithms tested and optimized

Width of R(q/pT) distribution for:

- Tracker muons: using only hits in silicon tracker, muon ID
- Global muons: combining tracker and muon hits
- Tracker plus first muon station (TPFMS): profit from long level arm tracker-muon without MS and showering in muon system
- Truncated muon reconstructor: stop when showering in muon system

Cosmics momentum





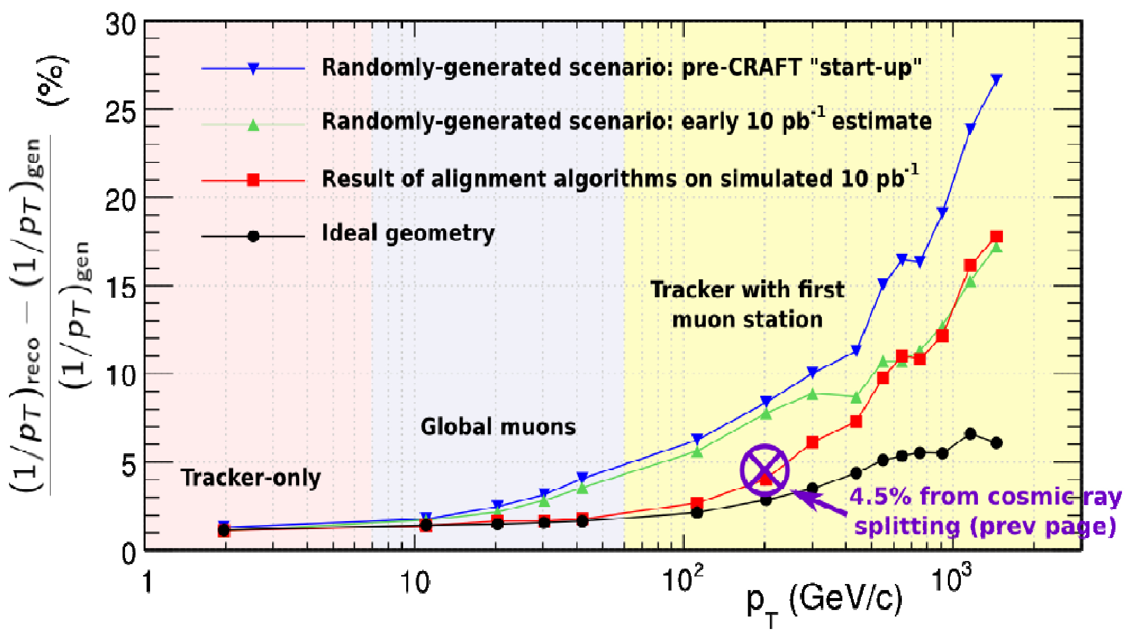
Using 2-legs collision-like muons
Relative q/p_T residual:

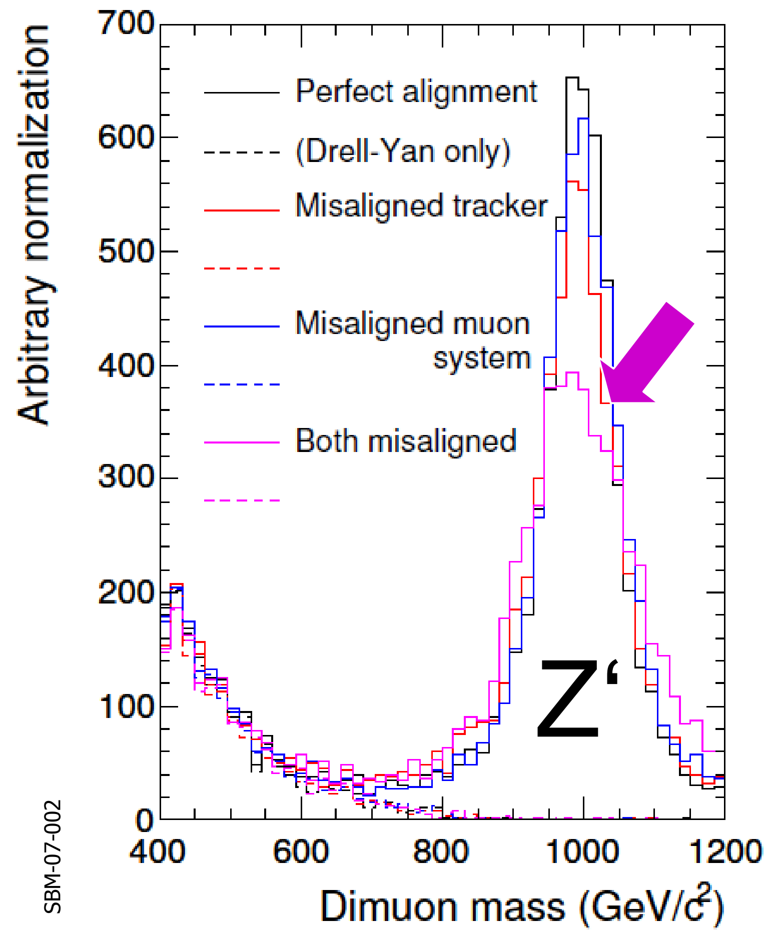
$$R(q/p_T) = \frac{(q/p_T)^{top} - (q/p_T)^{bottom}}{\sqrt{2}(q/p_T)^{bottom}}$$

Impact of Alignment

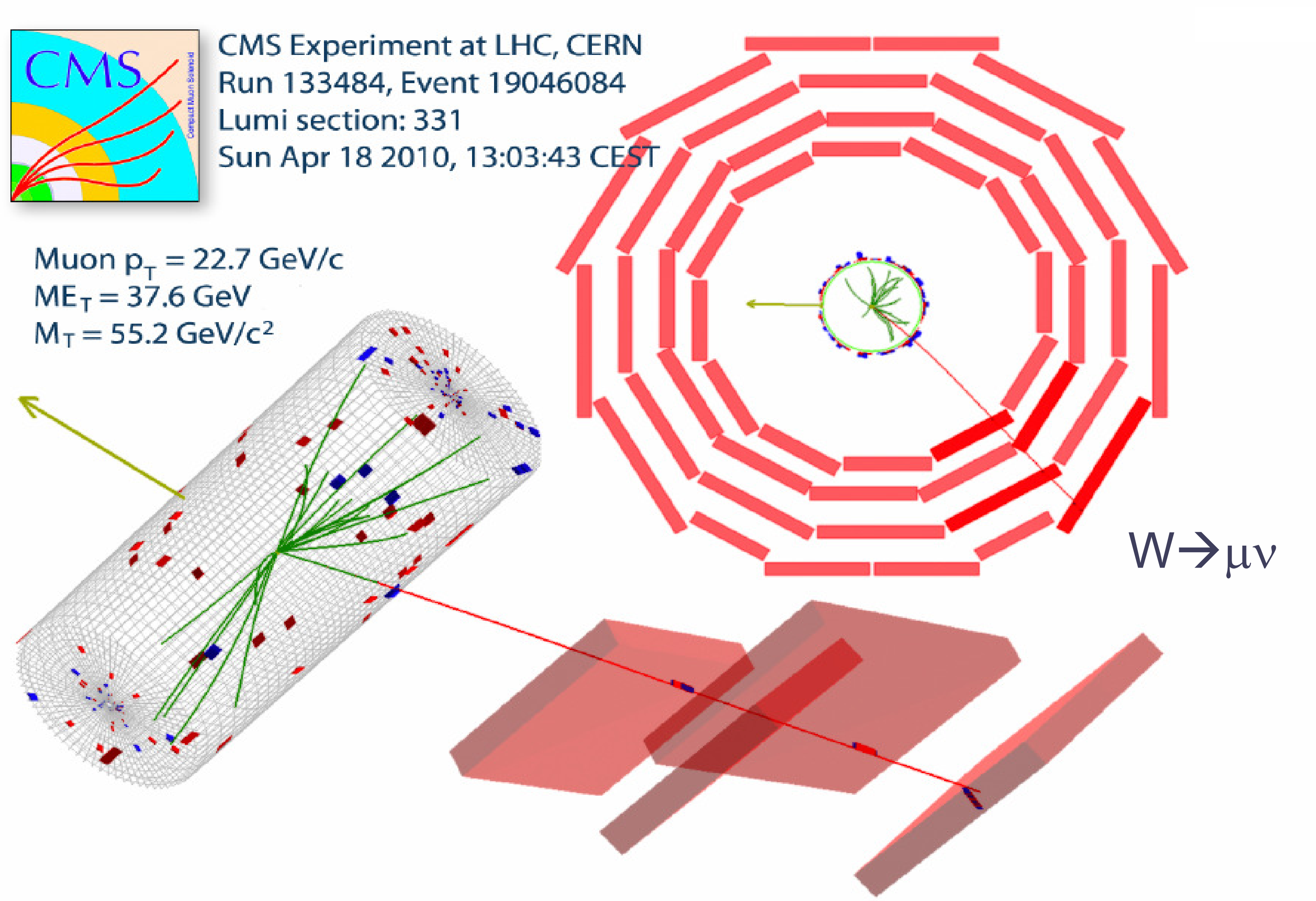
- Big progress in alignment with tracks using cosmic ray tracks
- Complementary to hardware (laser) align.
- Improves the CMS start-up conditions. After cosmics analysis better than earlier estimates for MC samples

Z' → μμ sensitive to tracker – muon alignment



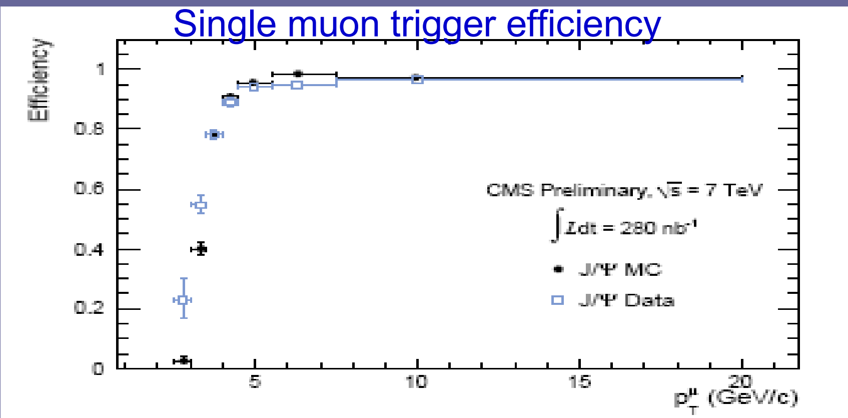


Performance in pp Collisions

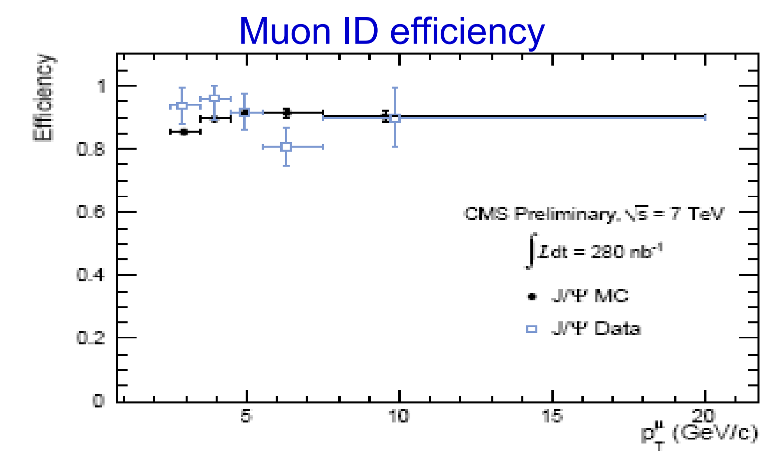


Performance in pp Collisions

Efficiencies determined with tag-and-probe in data and DY MC

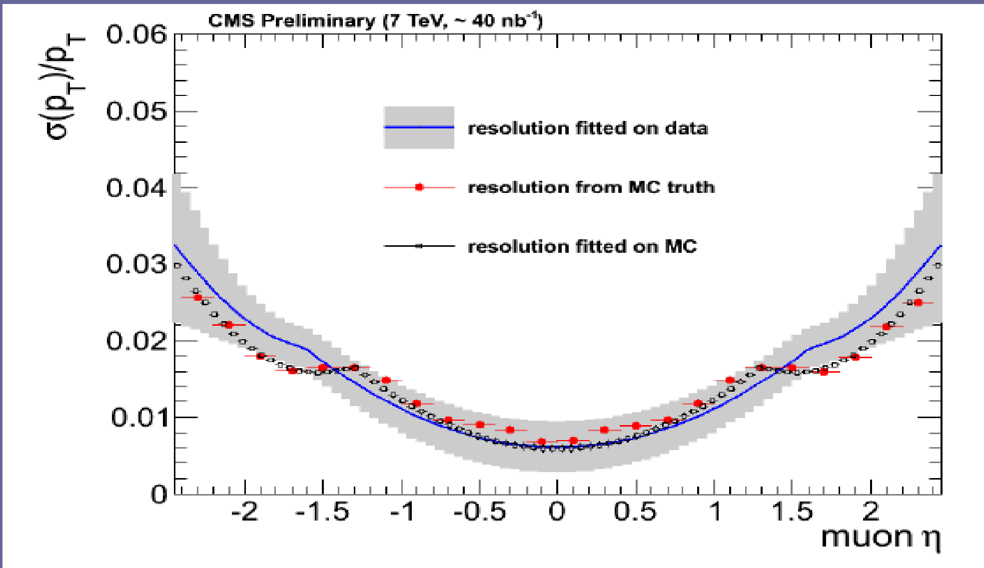


(a) Central region, $|\eta| < 1.2$



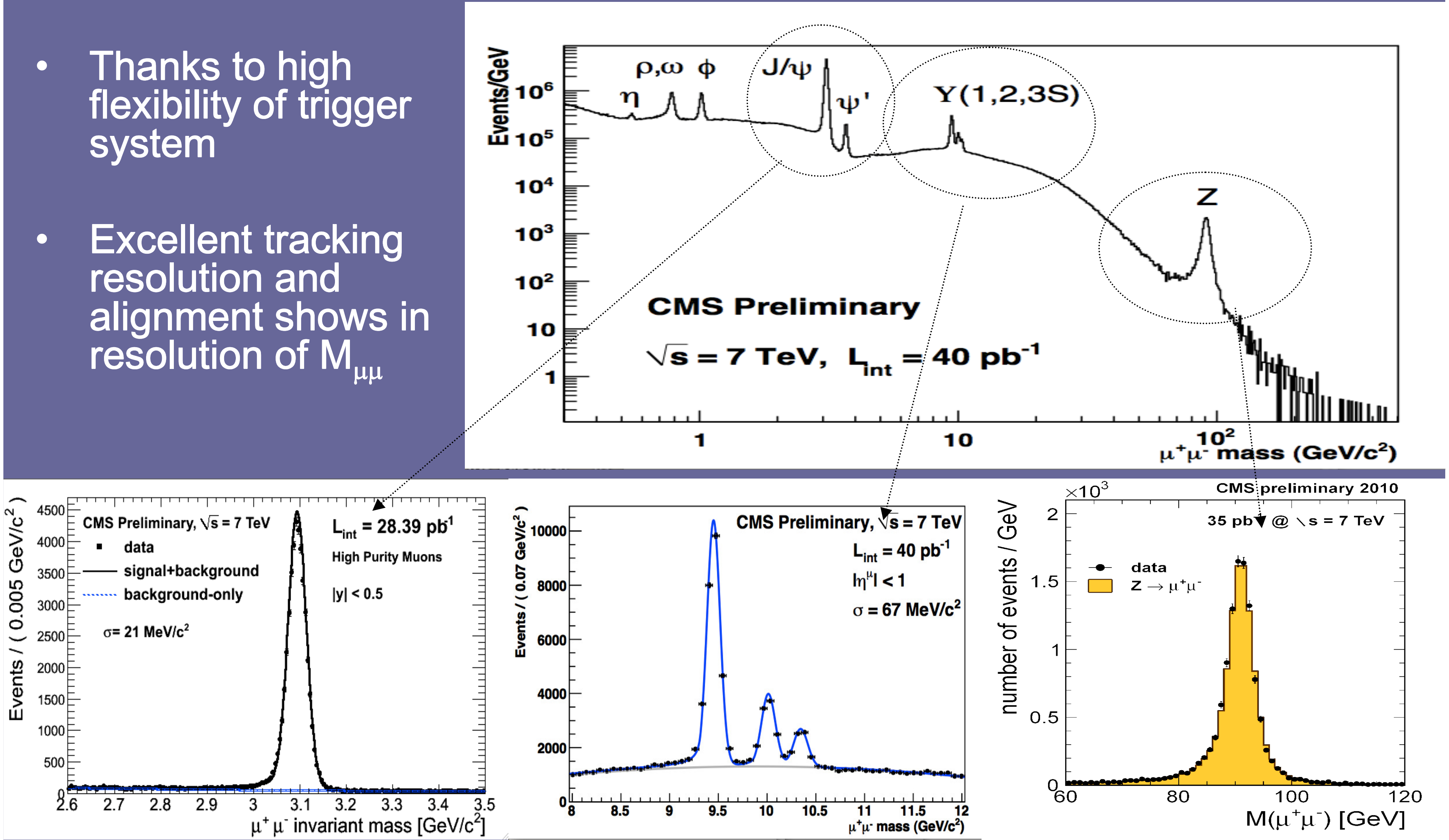
(b) Transition region, $1.2 < \eta^{\mu} < 1.6$

Resolution in pp data for muons with p_T<100 GeV) with 40/nb of data



Tracking and Muon Performance

- Thanks to high flexibility of trigger system
- Excellent tracking resolution and alignment shows in resolution of $M_{\mu\mu}$



Summary

- After 20 years of construction, CMS has began taking collision data
- Muon system continuously operation with >98.5% efficiency
- Very useful alignment and reconstruction studies with cosmics in preparation of pp data taking
- Trigger and muon ID efficiencies ~99% in pp

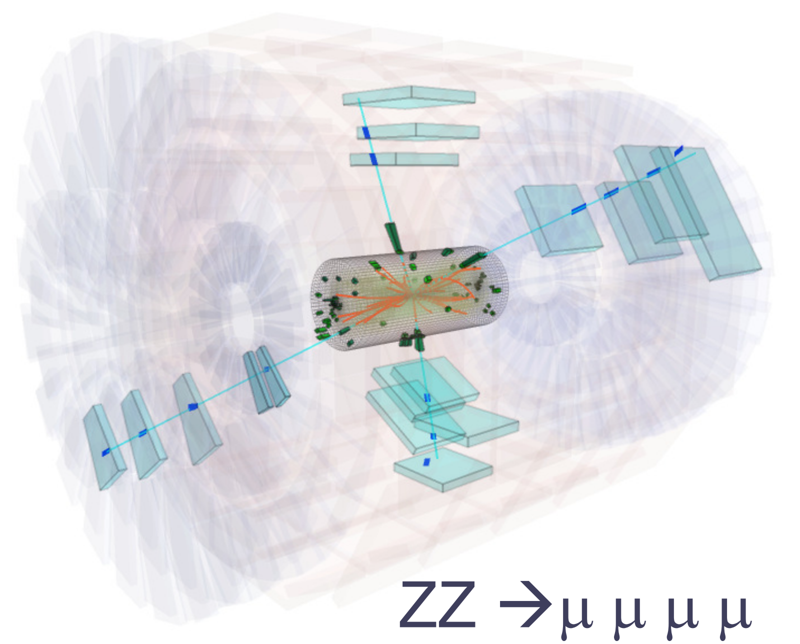
… to detect beautiful events like this ….

CMS Muon system has been build to detect events like this..

Invariant Masses

$\mu_0 + \mu_1$: 92.15 GeV (total(Z) p_T 26.5 GeV, ϕ -3.03),
$\mu_2 + \mu_3$: 92.24 GeV (total(Z) p_T 29.4 GeV, ϕ +.06),
$\mu_0 + \mu_2$: 70.12 GeV (total p_T 27 GeV),
$\mu_3 + \mu_1$: 83.1 GeV (total p_T 26.1 GeV).

Invariant Mass of 4μ: 201 GeV



ZZ → μ μ μ μ