Muon Tracking and Alignment

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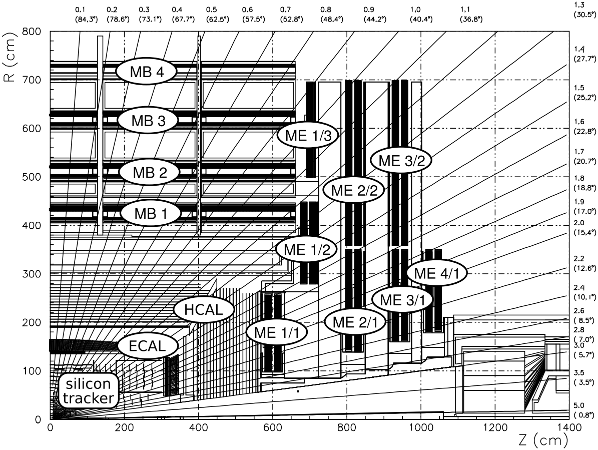
Muon tracking

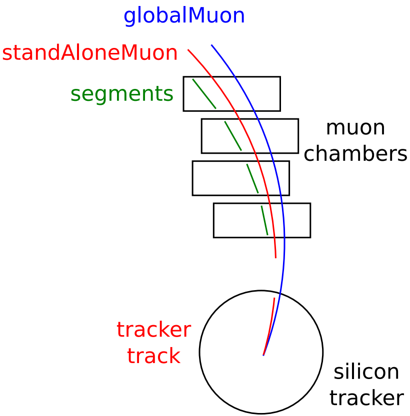
- You just heard about tracking in the silicon tracker; now extend that to the muon system
- Modular tracking environment: tracking in self-contained chambers

map of muon stations (CMS quarter view)



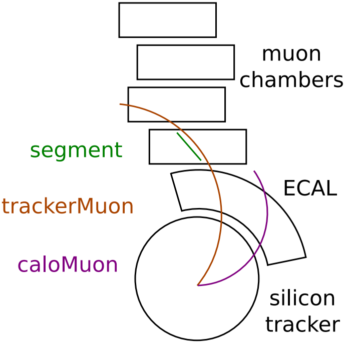
Muon tracking

- Inside of each chamber are 6–12 detector layers sensitive to the positions of passing muons (100–300 μm)
- Each can measure the position and direction of local tangents to the muon's trajectory called segments



- Connect segments into a continuous track called a standAloneMuon (used especially in HLT trigger)
- Match to closest tracker track to form a globalMuon

Muon tracking



Other reconstruction methods

- trackerMuon: starting from a tracker track, find at least one matching segment (traditional method for experiments with smaller muon systems)
- caloMuon: match tracker track to a *calorimeter* shower consistent with a minimum-ionizing particle

- Purpose: high efficiency across the whole momentum range (low-p_T tracks curl in the $\vec{B}$ field, less likely to form standAloneMuon)
- As always, there's a trade-off between efficiency and background rejection
- User can select from different reconstruction algorithms

Muon tracking

Efficiency

(high 90%'s above 10 GeV)

- L1 trigger
- HLT reco and cuts
- offline track seeding
- analysis cuts

Background rejection

(depends on specific analysis)

- $\pi \rightarrow \mu\nu$ decays in flight (so-called "fake muons")
- misidentification, punch-through (actual fake muons are rare)

Resolution

(focus of this talk)

- measuring p_T
- $\vec{B}$-field outside solenoid
- TeV muon showers
- scattering
- chamber alignment

Also relevant for resolution, but not covered in this talk

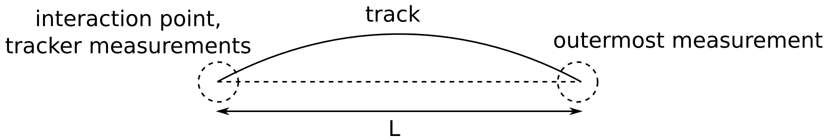
- intrinsic hit resolution
- calibration
- layer alignment
- reconstruction algorithms for TeV muon showers

Resolution

Accuracy of reconstruction track parameters at the interaction point

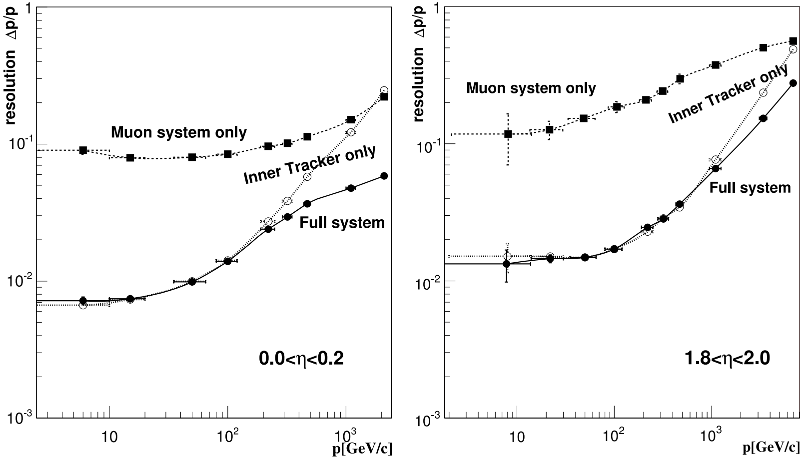
d_{xy}, d_z	point of closest approach	dominated by pixel measurements
ϕ; λ, θ, or η	direction of muon's initial momentum	dominated by strip tracker
$\frac{q}{p_T}$	signed curvature; magnitude of muon's initial momentum	dominated by tracker up to 200 GeV (barrel), 500 GeV (endcap); above that, both are important

- Direction (ϕ, θ) resolution $\sim$ (hit resolution)/L
- p_T resolution $\sim$ (hit resolution)/ $\left(\frac{L}{2}\right)^2$

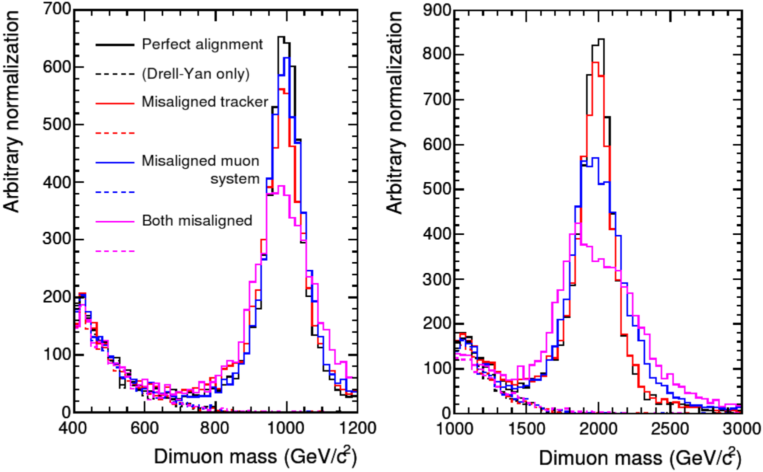


Resolution

(from the TDR)

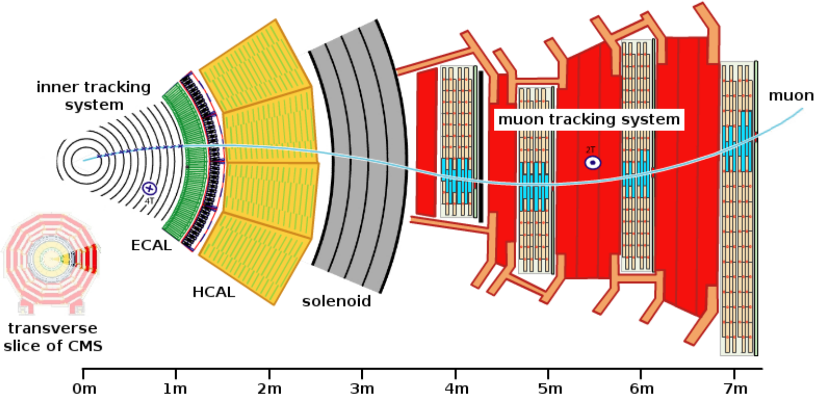


Z' reconstructed with misaligned tracker elements and muon chambers



- Misaligning the muon system (blue) has a greater effect at higher momenta/Z' masses

- Further complicated by the fact that muon tracks are not helices

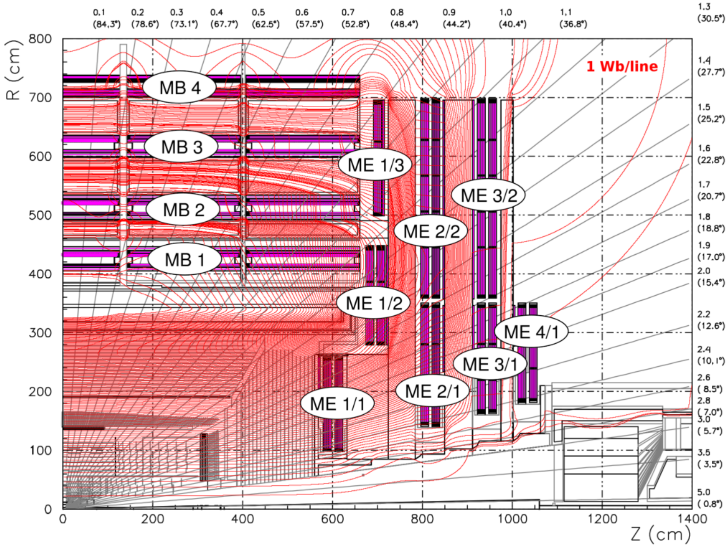


inside the solenoid

outside (field is reversed)

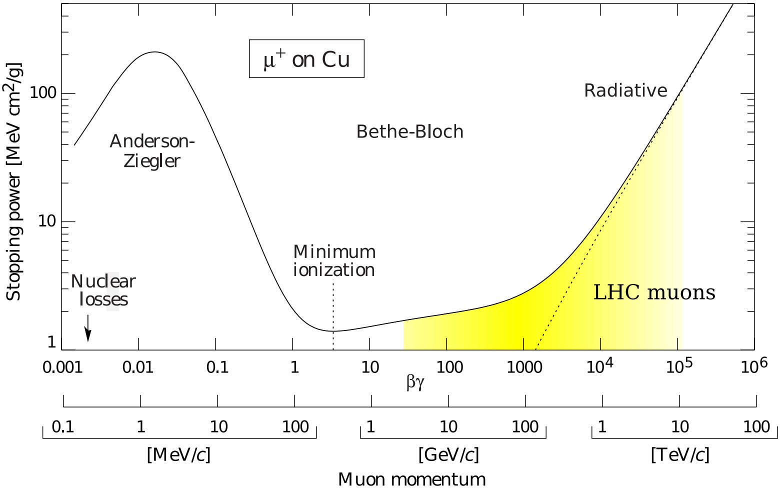
Magnetic field

(early TOSCA simulation from Magnetic Field Task Force)



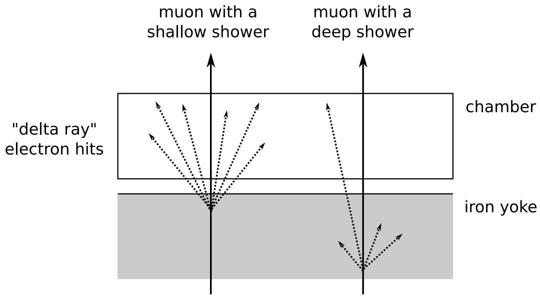
- Field lines try to follow iron return yoke: $\vec{B}(\vec{x}) \approx 0$ in most chambers

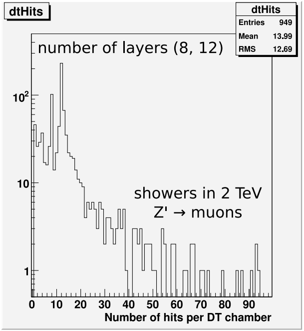
Average energy loss: $\langle dE/dx \rangle$

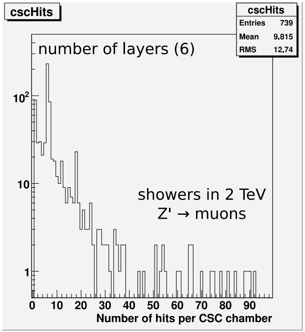


- Highest-energy muons from LHC collisions will have qualitatively different behavior in material: TeV muon showers

TeV muon showers

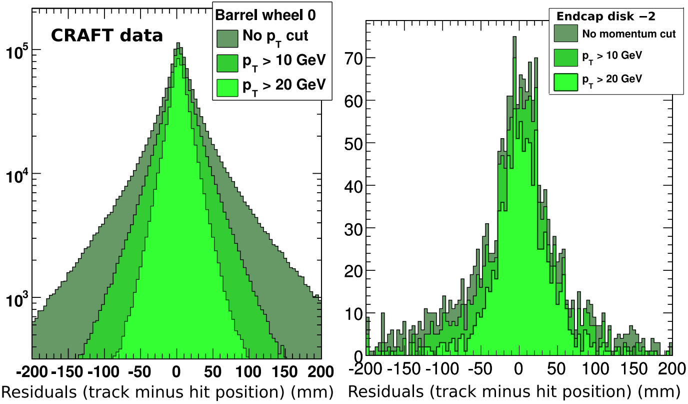




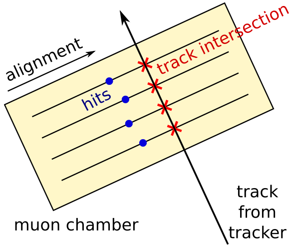


Low-p_T scattering

- In the minimum-ionizing regime, track-by-track energy loss can be non-negligible compared to energy
- Limit of many soft interactions ("multiple scattering") → Gaussian
- Single hard scattering has power-law tails
- Real distribution is a convolution of both, highly dependent on energy



1. Select globalMuons
2. Re-fit them to the tracker only
3. Propagate to the muon system
4. Convert peak of residuals distribution (track intersections minus hit positions) into alignment corrections



Matches muon chamber positions to tracks given by the tracker

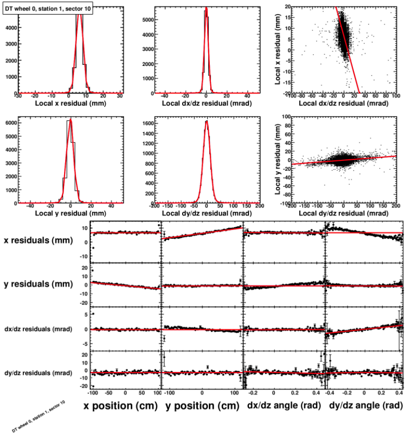
Motivation

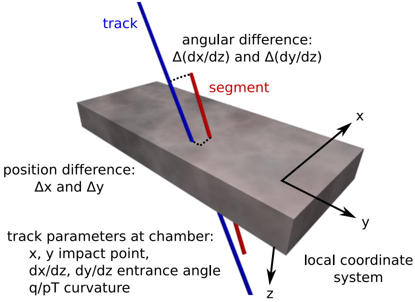
- Decouples track-fitting from alignment
- Tracker dominates resolution for most ($p_T \ll 200$ GeV) tracks anyway
- Peak of residuals distribution is where minimally scattered tracks agree on chamber position; highly-scattered tracks disagree in different ways (possibly asymmetric tails)

Sample alignment fits

- Model misalignment effects and propagation effects in a single ansatz, fit with Minuit
- 4-D residuals (position and angle) $\rightarrow$ 6 rigid body degrees of freedom

MC before alignment





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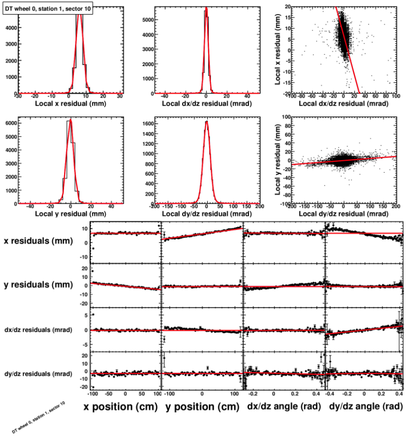
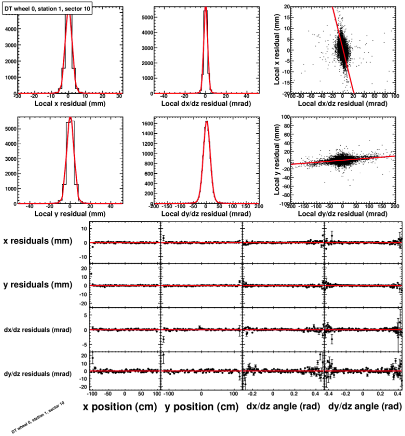


MC after alignment



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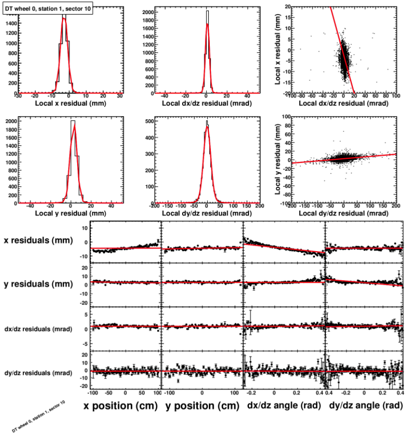
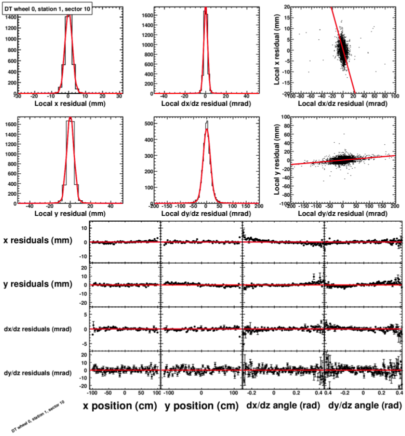
CRAFT data before alignment



CRAFT data after alignment

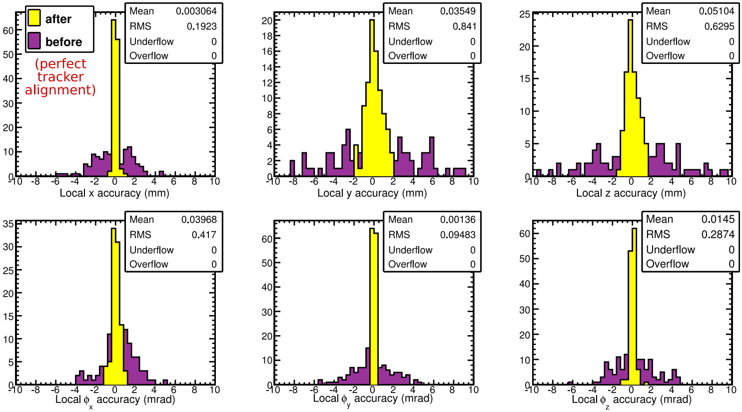


MC alignment results

- MC simulation of CRAFT alignment (DT wheels -1, 0, $+1$)
- Everything is the same as real-data alignment except
  - perfect tracker alignment, magnetic field, internal DT alignment

(to test chamber alignment procedure only)

- Final x misalignment is $\mathcal{O}(100\text{–}300\ \mu\text{m})$, like hit resolution

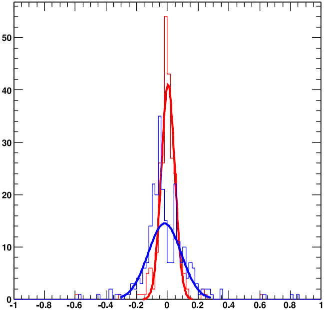


CRAFT data alignment results

- High-level test: split each cosmic ray into two LHC-like halves, fit top and bottom independently
  - any mismatch in $1/p_T$ is purely instrumental
  - select $p_T \gtrsim 200$ GeV to emphasize contribution of the muon alignment (long lever arm for resolution of small sagitta)

Before muon alignment

	mean	sigma
Tracker-only:	0.0040	0.044
With first muon station:	−0.0180	0.108

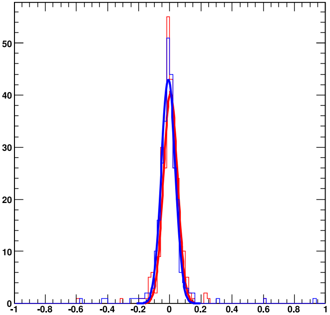


$$\frac{(1/p_T)_{\text{upper}} - (1/p_T)_{\text{lower}}}{\sqrt{2}\,(1/p_T)_{\text{lower}}}$$

J. Tucker

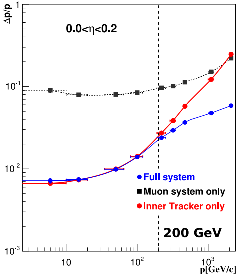
After muon alignment

	mean	sigma
Tracker-only:	0.0042	0.045
With first muon station:	−0.0097	0.045



$$\frac{(1/p_T)_{\text{upper}} - (1/p_T)_{\text{lower}}}{\sqrt{2}\,(1/p_T)_{\text{lower}}}$$

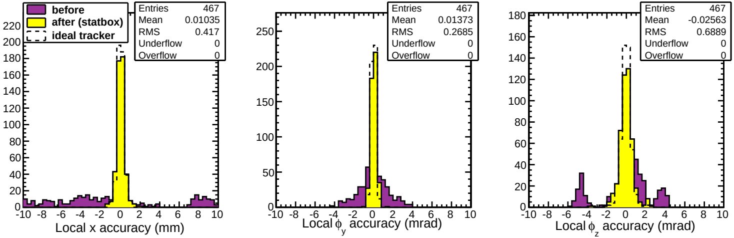
Plot from Technical Design Report (no misalignment)



sigma ∼ 0.025 at 200 GeV for a perfect detector

What about the endcaps?

- Cosmic rays for alignment and diagnostics are mostly vertical: incomplete coverage in endcaps from cosmic rays (many chambers have zero hits)
- No such problem with collisions muons
  Simulated alignment using 50 pb^{-1} $pp \to \mu X$, same technique:

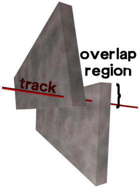


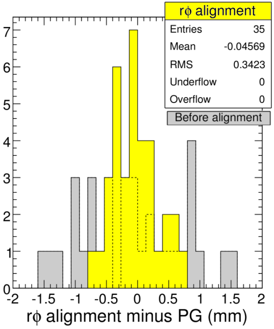
- M. Schmitt and J. Pivarski are working on methods to align endcap chambers with cosmic rays
- Beam-halo results (next page) demonstrate understanding of detector issues in real data

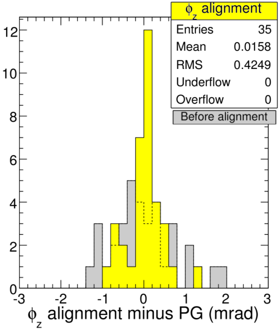
Beam-halo alignment

Using a different method:

1. Extrapolate segments between pairs of overlapping chambers
2. Solve system of local alignment corrections
3. Compare with independent photogrammetry (PG) (which has 210 μm, 0.23 mrad resolution)



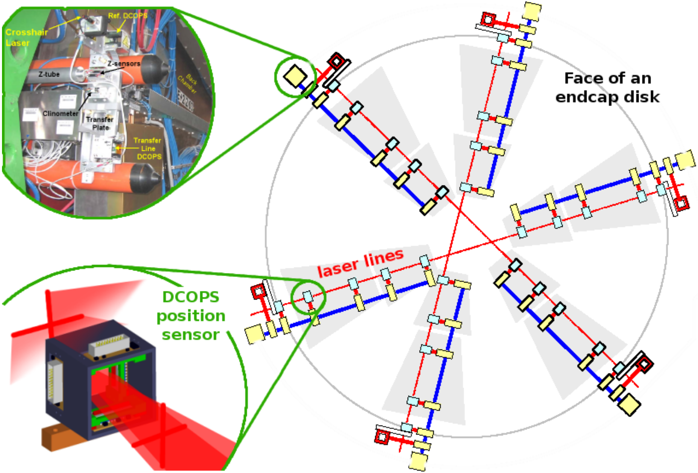




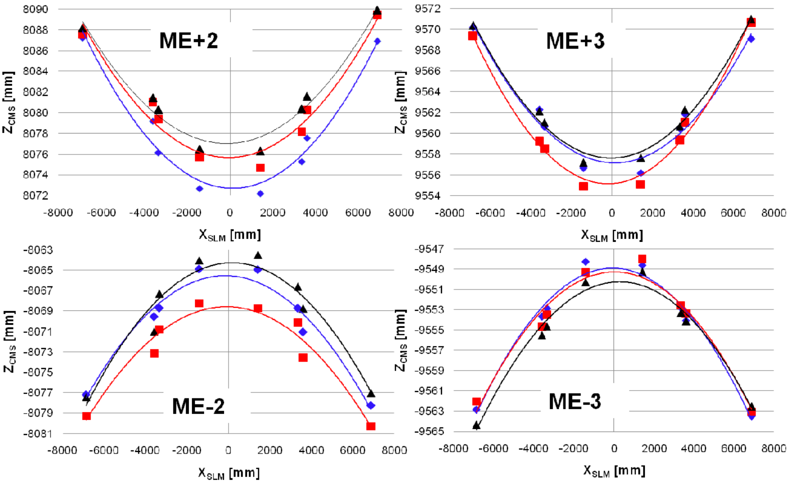
9 minutes of LHC beam-halo data!

- Muon system is instrumented with physical position detectors
- Complimentary to track-based alignment

Only showing laser monitors on an endcap disk:



- Bending of the endcap disks due to CMS $\vec{B}$-field
- About 14 mm in the center (huge!), parallel to beamline (z)
  (tracks are not very sensitive to CSC z positions, but the displacement is large)

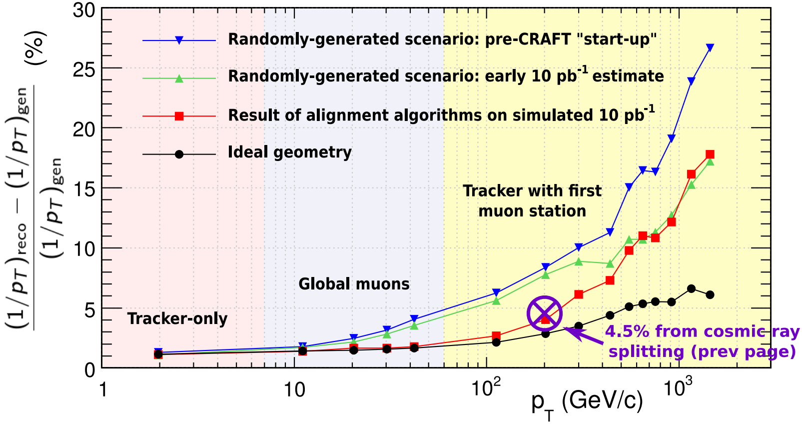


S. Guragain, M. Hohlmann

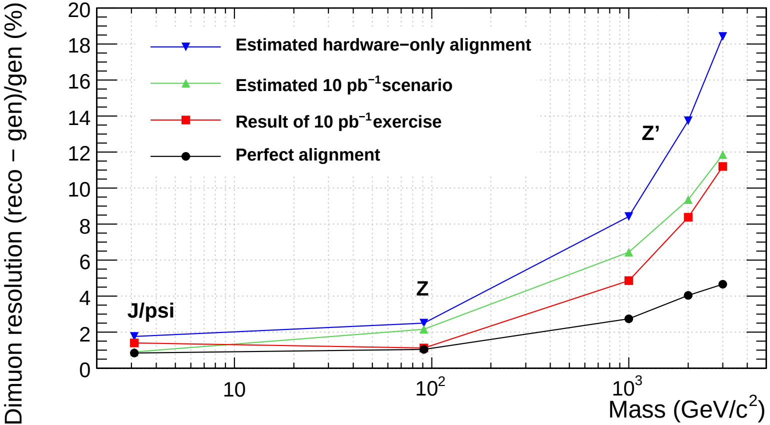
Concluding remarks

- Muons are key to many signatures of new physics
- CMS muon system has excellent signal-to-background due to its many layers in modular chambers
- Long "lever arm" of muon system also helps to resolve p_T of highest-momentum muons
- Alignment is an important correction for p_T resolution; cosmic rays and beam-halo data allow us to test our alignment procedures now
- Alignment exercises revealed biases in muon tracking, other than muon misalignment (not shown here, for time)
  - if you're looking for ways to help, I can point you to unresolved problems offline

Backup



- Important caveat: MC resolution studies include the whole muon system, cosmic ray splitting (purple point) is only central DT barrel



- Important caveat: not signed-off by J/ψ and Z groups