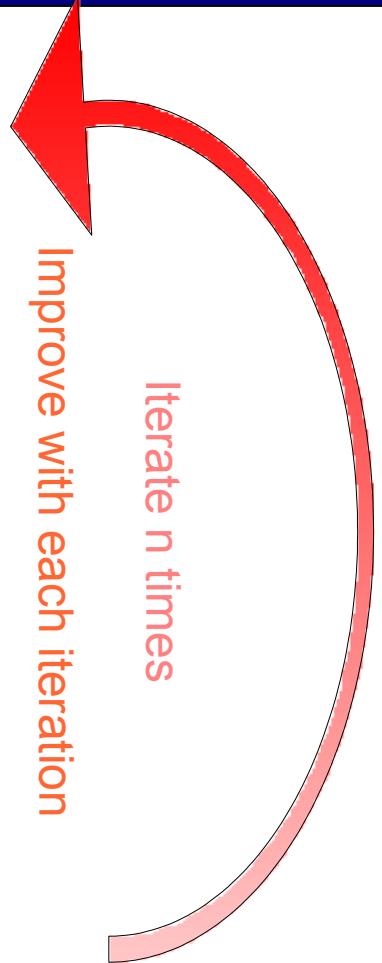


Calibration, alignment and tracking performance of the CMS Silicon Strip Tracker

M. Weber, Hamburg University
on behalf of the CMS collaboration

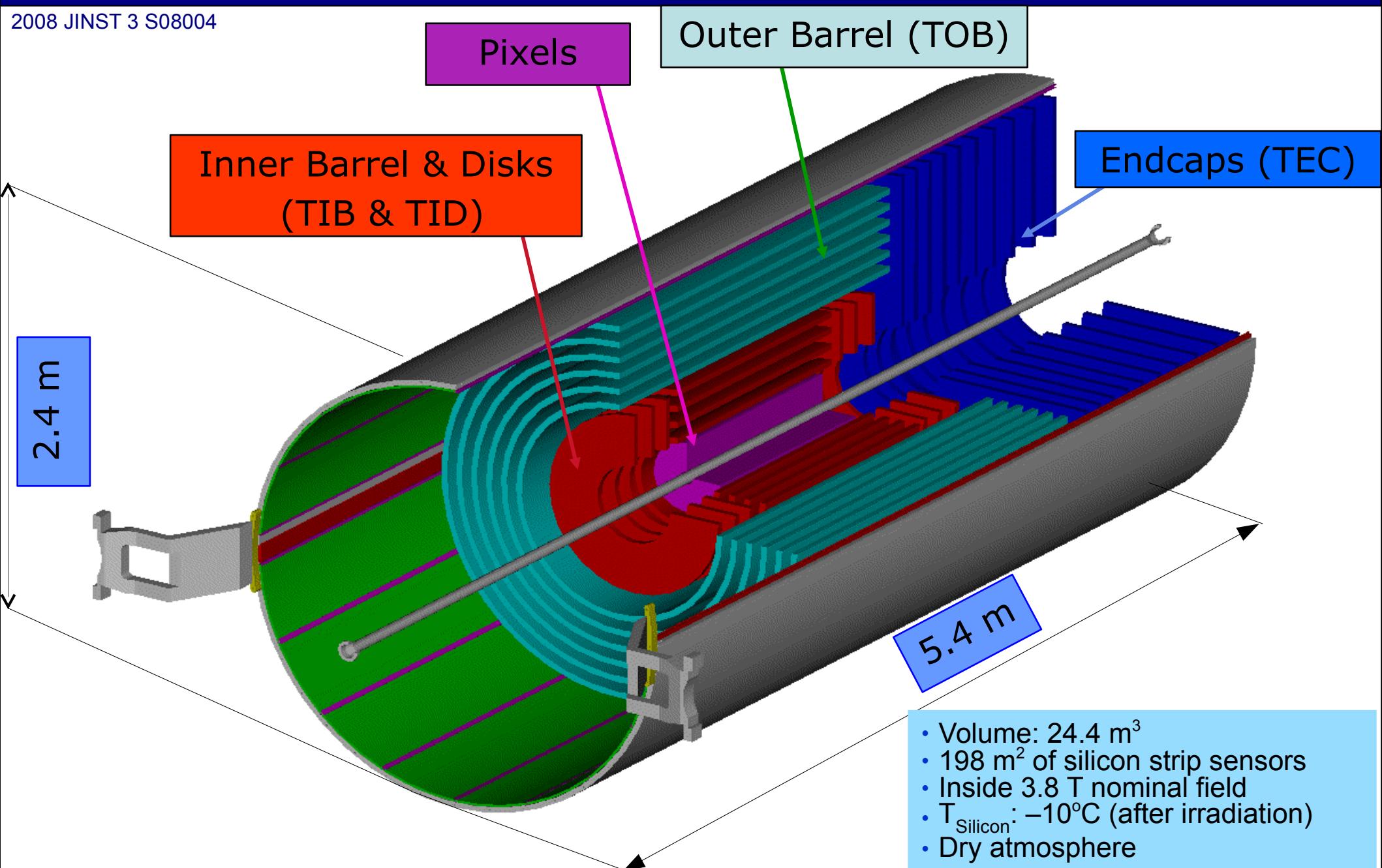
Vienna Conference on Instrumentation
15 – 20 February 2010

Strip tracker commissioning procedure

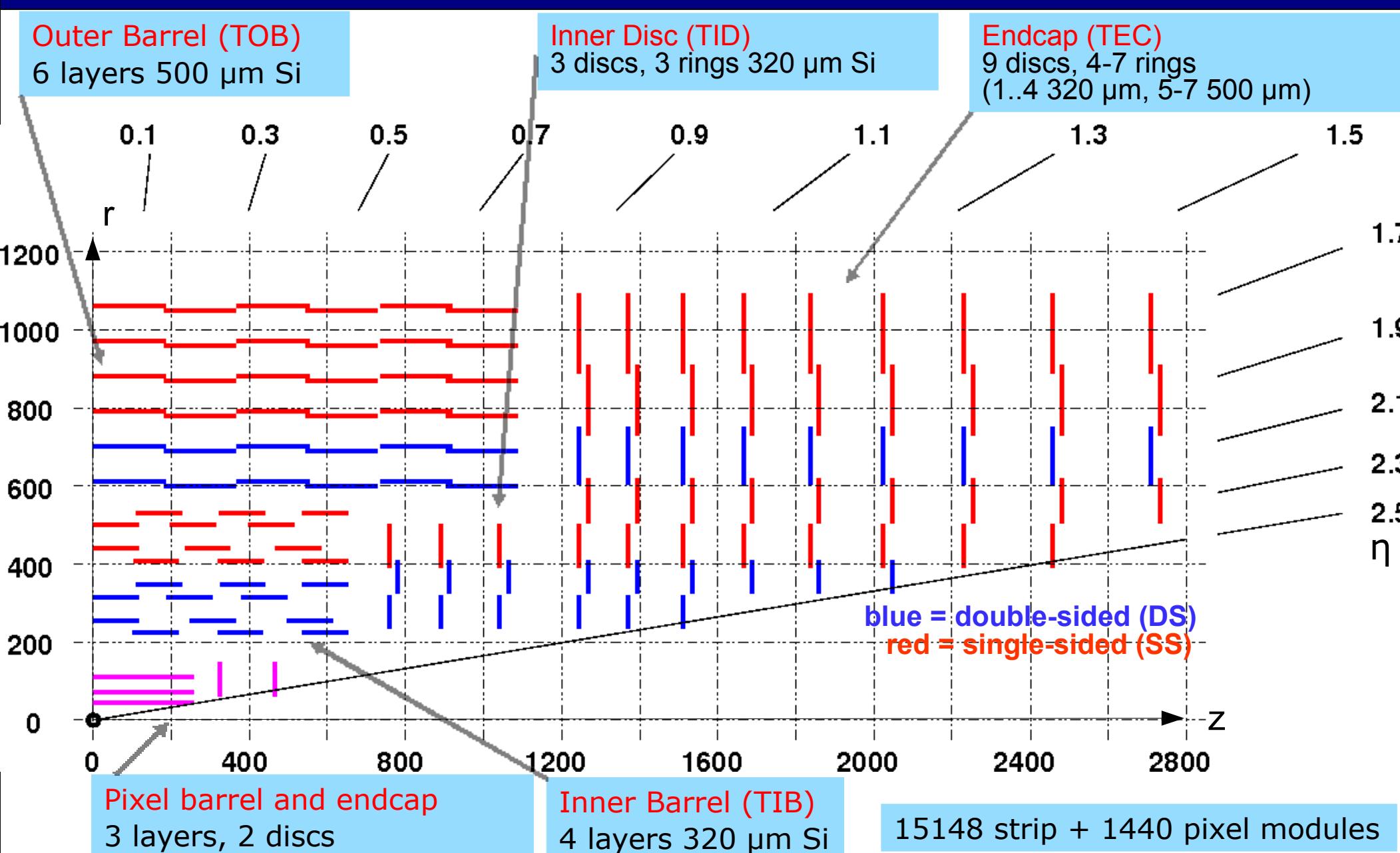
- Commission front-end electronics
 - Find responsive devices, cable map, front-end settings, timing
 - Calibrate sensors
 - Signal-to-noise ratio
 - Lorentz angle
 - dE/dx
 - Track reconstruction
 - Efficiency
 - Track parameter resolution
 - Alignment
 - Find actual module positions
 - Validation
 - Systematics
 - Shown results are after several iterations
 - Results from cosmic data taking (2008/2009), collision data (Dec 2009)
- 
- Iterate n times
Improve with each iteration

Tracker sub-detectors

2008 JINST 3 S08004



CMS Silicon Tracker Overview

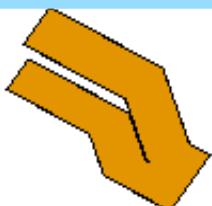


Silicon strip tracker Modules and structures

Hybrid conn.

Readout hybrid: APV

- 4 or 6 APV à 128 channel
- 192x25ns analog pipel.
- 0,25 µm CMOS technol.
- captow flex circuit
- ceramic stabiliser



pitch adapter (PA)

Kapton bias

TEC

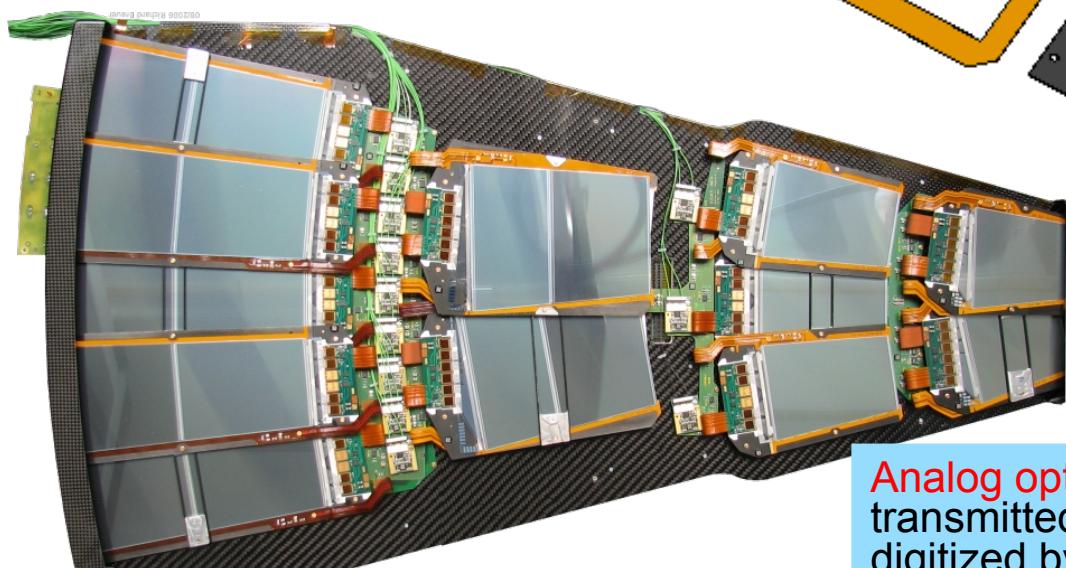
TOB

TIB



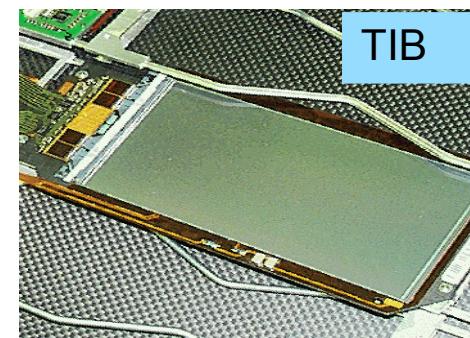
TEC petal

Carbon fibre or graphite frame



Analog optical signal transmitted O(100)m digitized by FED

76 000 APVs
36 000 fibres
440 FED

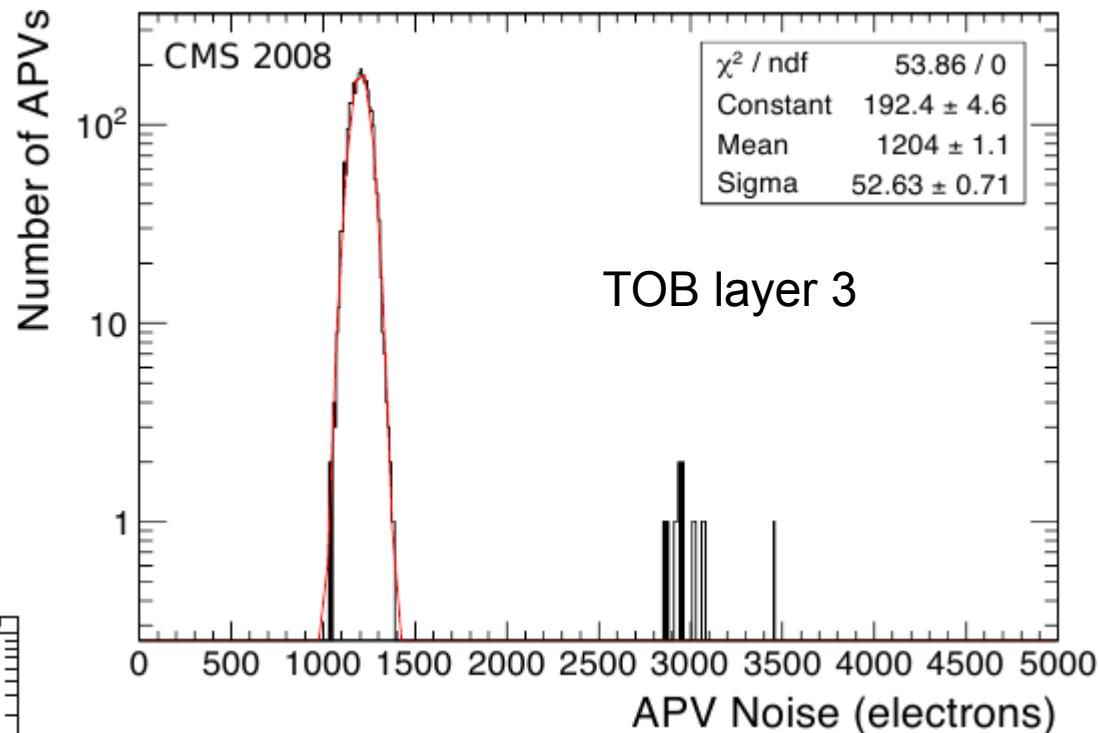
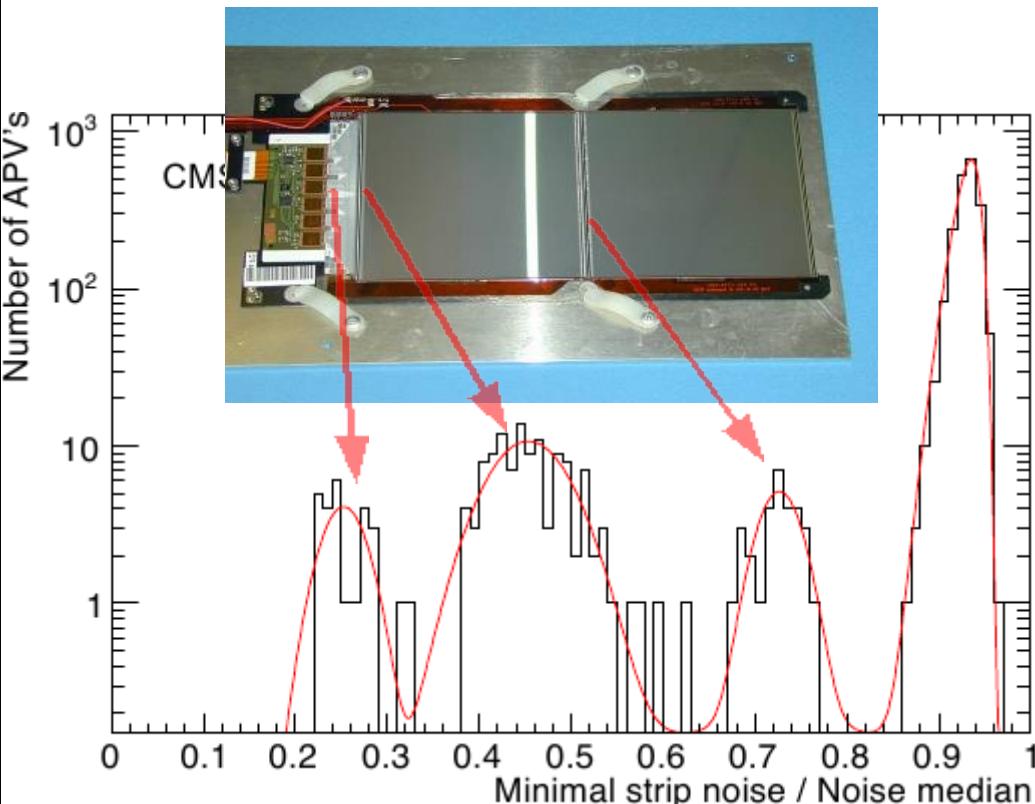


- Sensor
- 6" wafer size
- p⁺ on n
- 80..205 µm pitch
- 512 or 768 strips
- STM / HPK

- Random trigger (no physics)
- Strip noise in tracker

$$\text{noise}(e^-) = (427 \pm 39) + (38.7 \pm 3) \times \text{length(cm)}$$

- Strip length → capacitance → noise

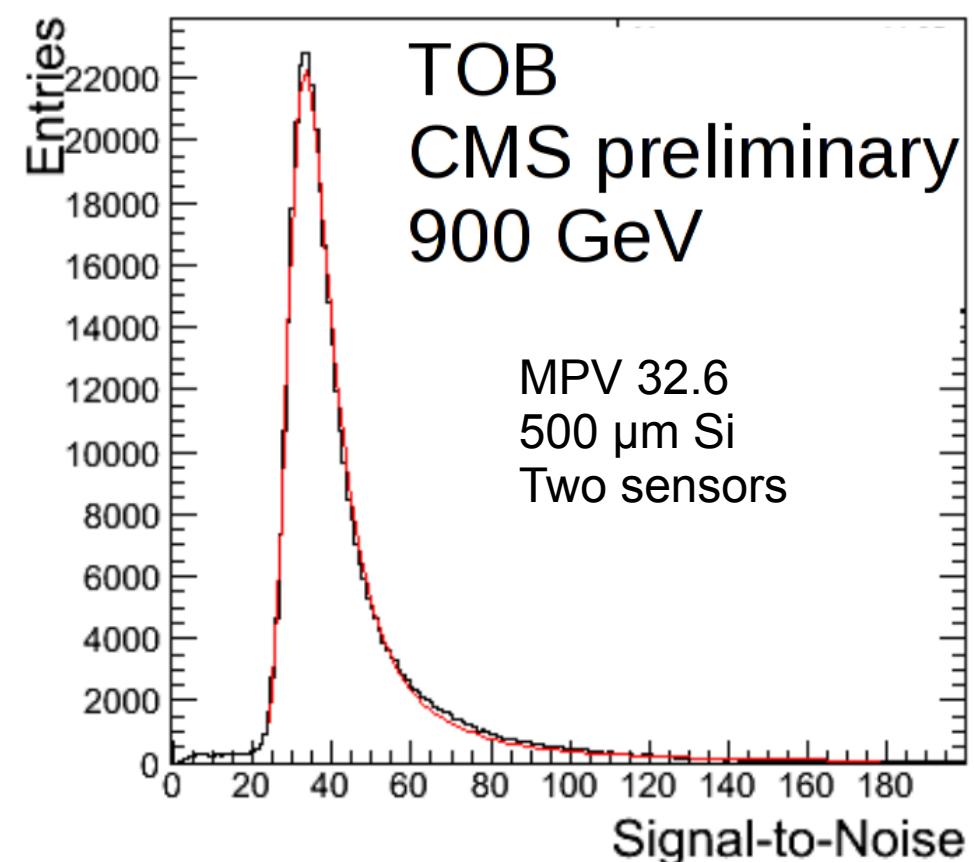
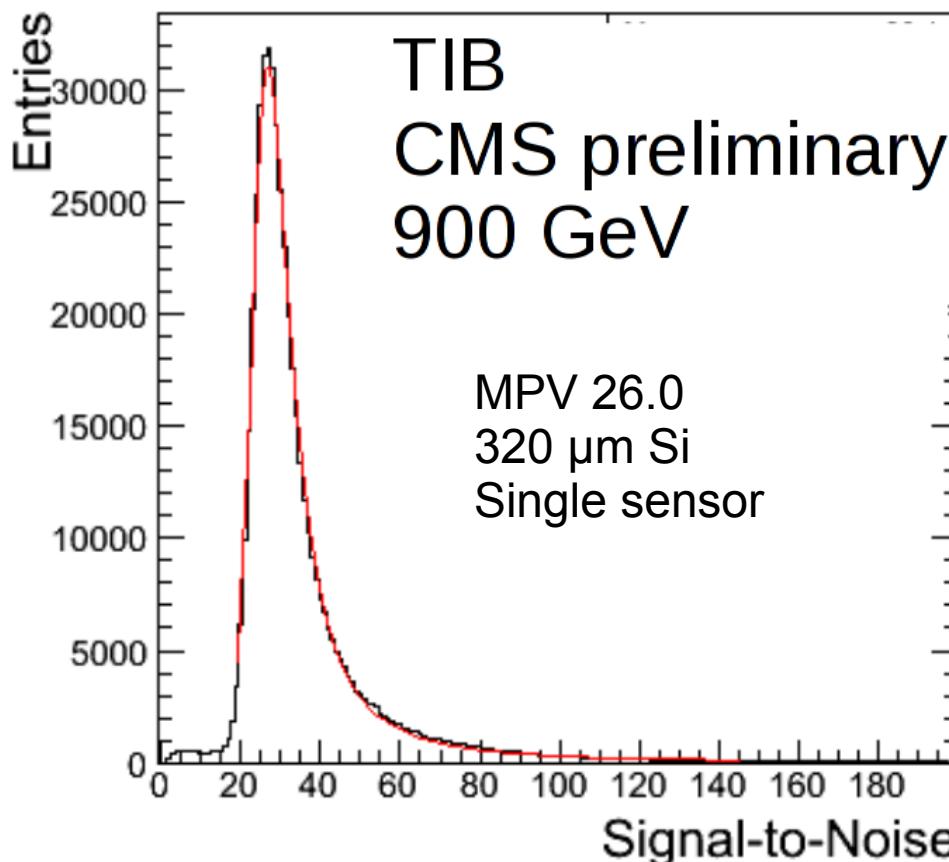


- Identify noise sources due to changes in capacitance:
 - Missing APV-PA bonds
 - Missing PA-sensor bonds
 - Missing sensor-sensor bonds
- E.g. bonding / sensor problem

<http://arxiv.org/abs/0911.4996>, submitted to JINST

Signal-to-noise ratio with collision tracks

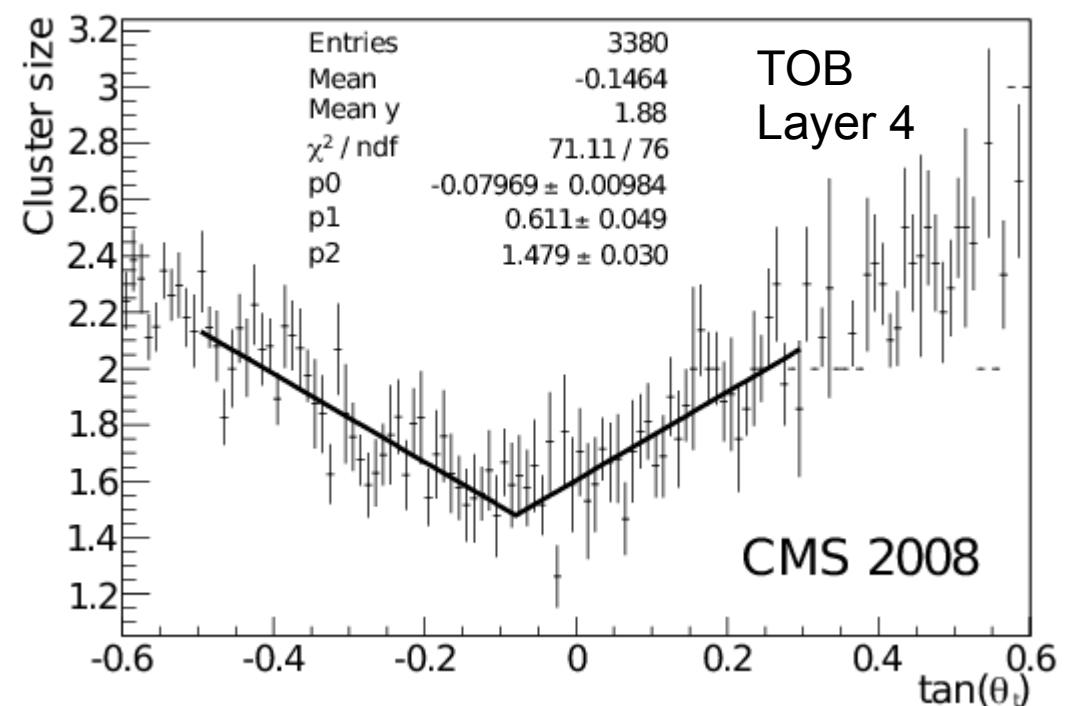
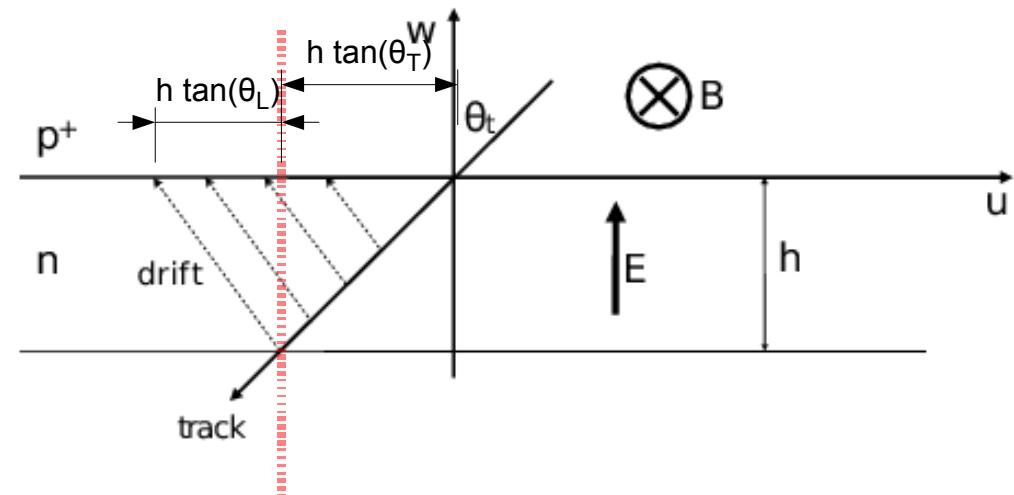
- Path length corrected signal-to-noise ratio



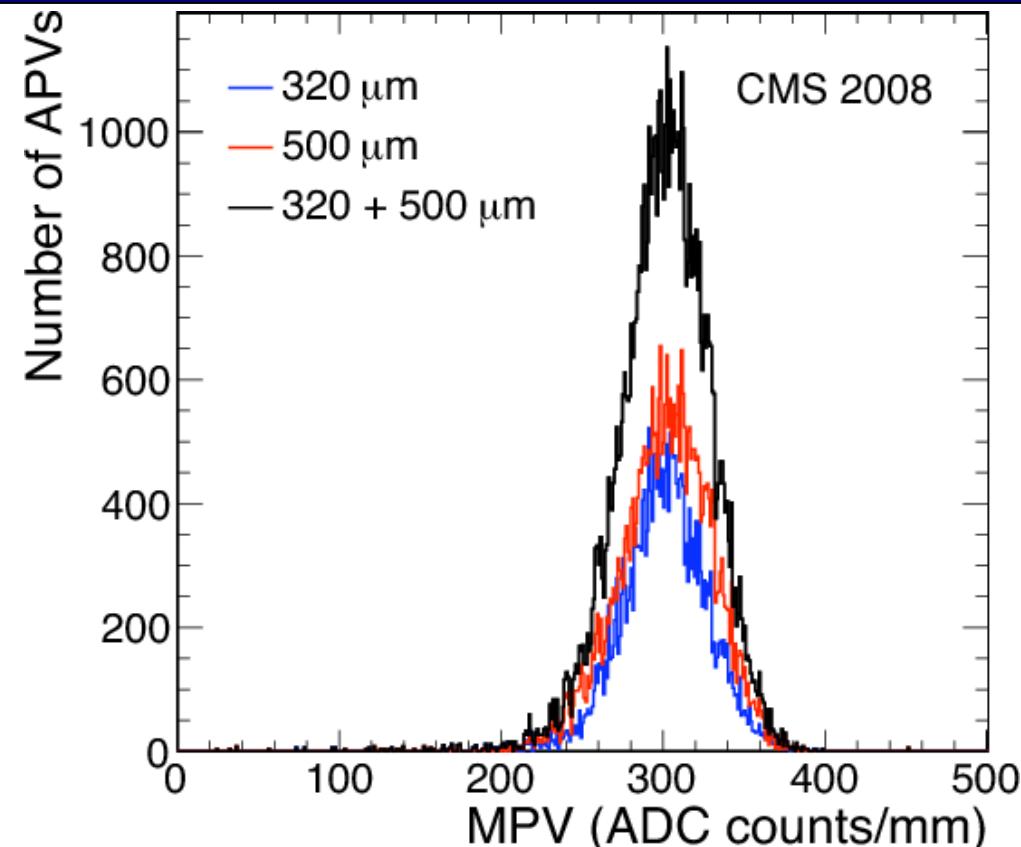
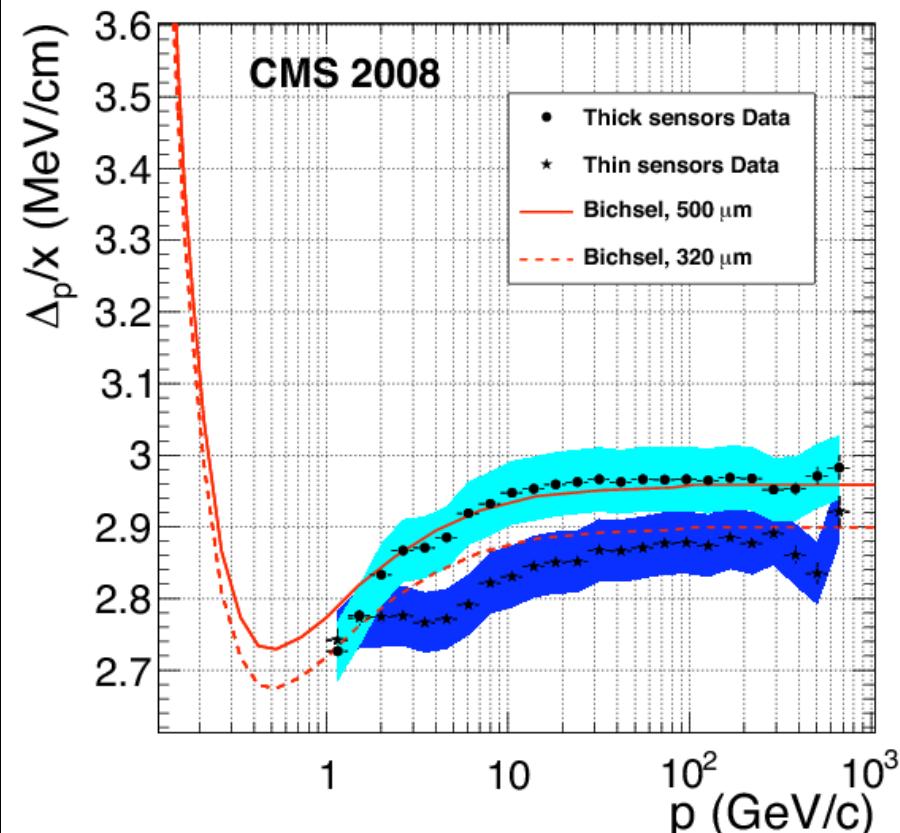
- More signal with increasing silicon sensor thickness (typical MIP: 25000 e⁻/320 μm)
- More noise with increasing capacitance (strip length)

Lorentz angle from cosmic muons

- In Barrel, E and B perpendicular
 - Lorentz drift, angle θ_L
 - Track angle θ_T
- Measure cluster size as $f(\theta_T)$
 - Fit function
$$f(\theta_T) = \frac{h}{pitch} p_1 |\tan(\theta_T) - \tan(\theta_L)| + p_2$$
- TIB: $\tan(\theta_L) = 0.07 \pm 0.02$
- TOB: $\tan(\theta_L) = 0.09 \pm 0.01$

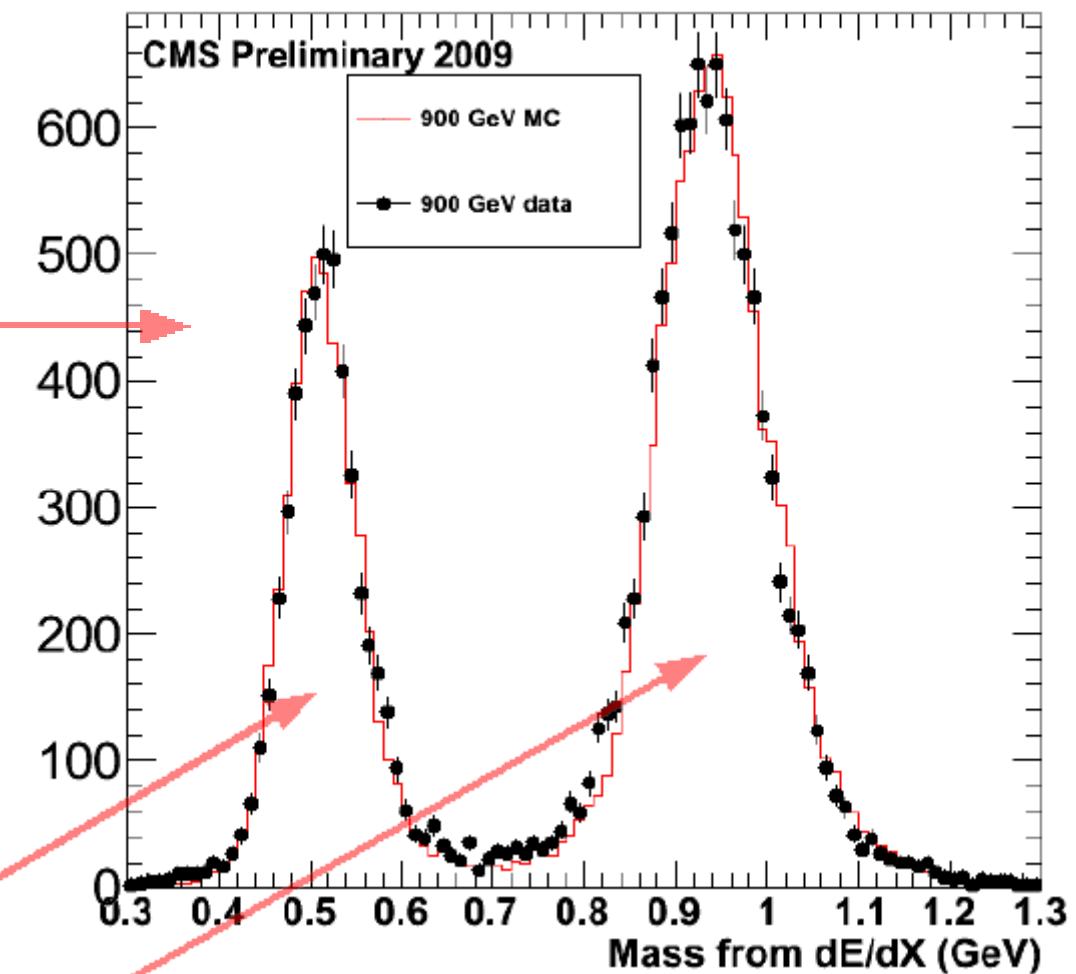
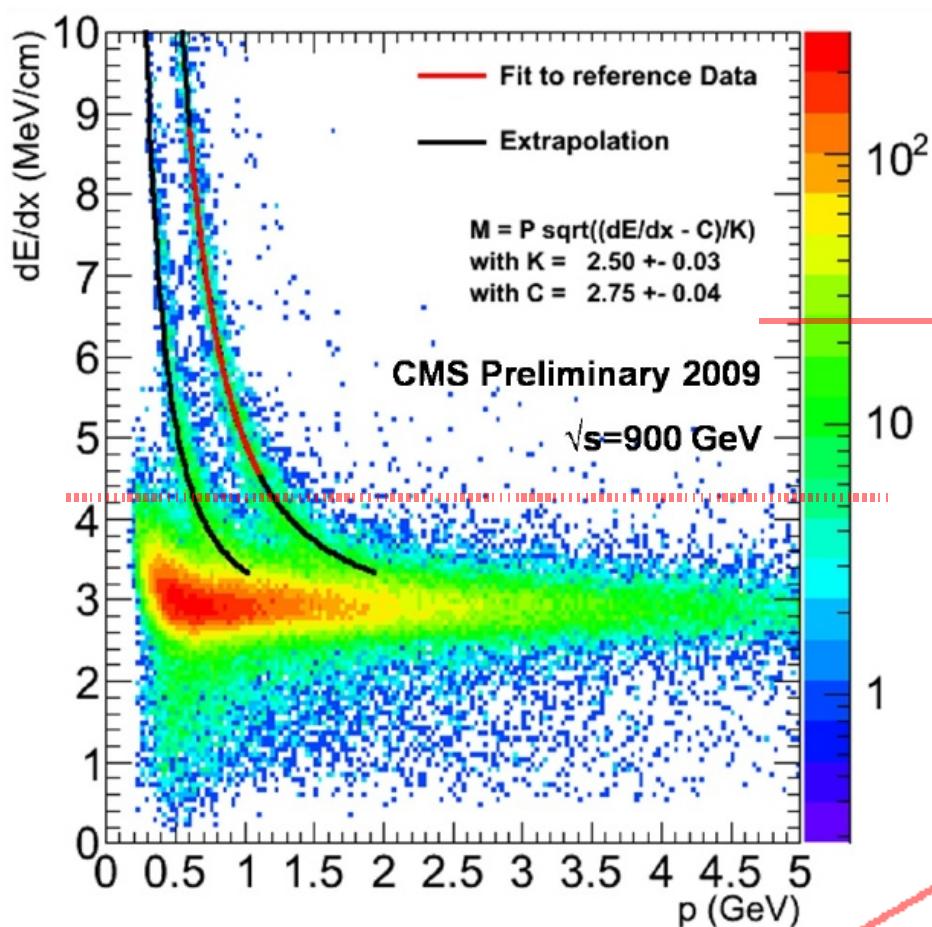


- For dE/dx , need to know conversion ratio electrons/ADC count
- Use cosmic muons (MIP) to calibrate all APVs → uniformity
- Path length corrected MPV of S



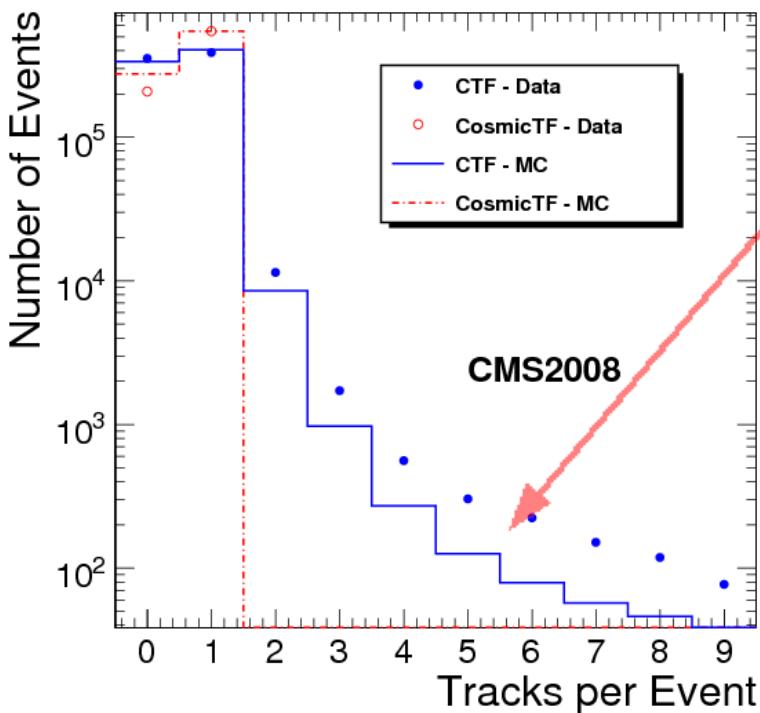
- Most probable energy loss/unit length
 - Use Landau-Vavilov-Bichsel theory
 - Fit as function of track momentum
 - Extract calibration constant for each sensor type

- After calibration, measure dE/dx during collisions

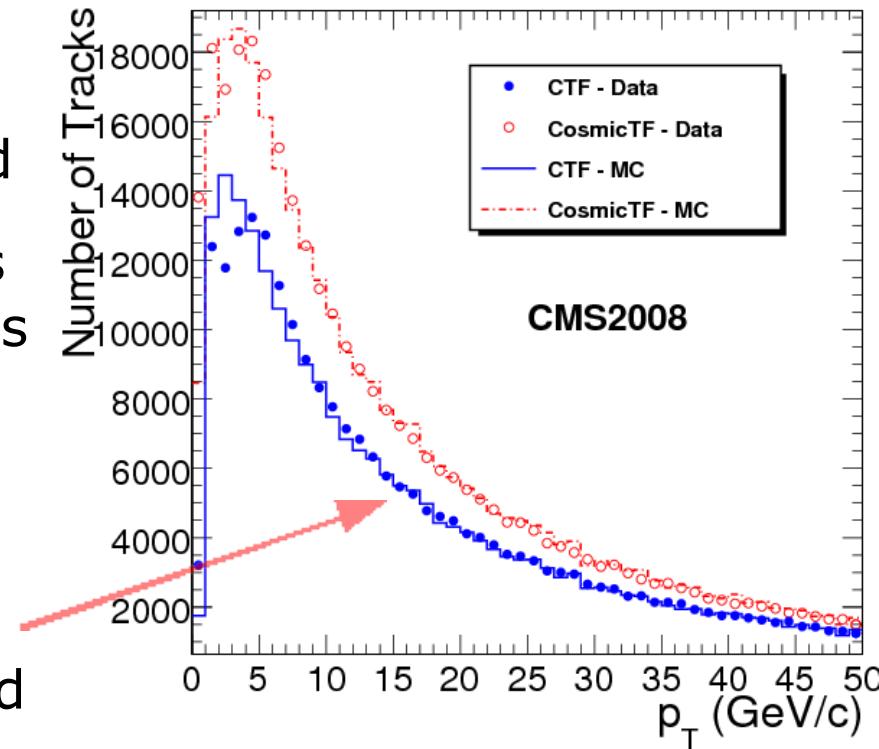


- Clear separation of kaons and protons, nice agreement with MC
 - Cut $dE/dx > 4.15 \text{ MeV}/\text{cm}$

- Hit efficiency > 90% in all layers, > 98.7% if known problems excluded
- Two tracking methods developed for cosmic muon reconstruction
 - Combinatorial Track Finder (CTF), Efficiency on cosmics 99.8%
 - default for collisions, efficiency 99% in collision-like cosmic event reconstruction
 - Cosmic Track Finder (CosmicTF), Efficiency on cosmics 99.5%
 - dedicated for cosmics, important cross-check of CTF

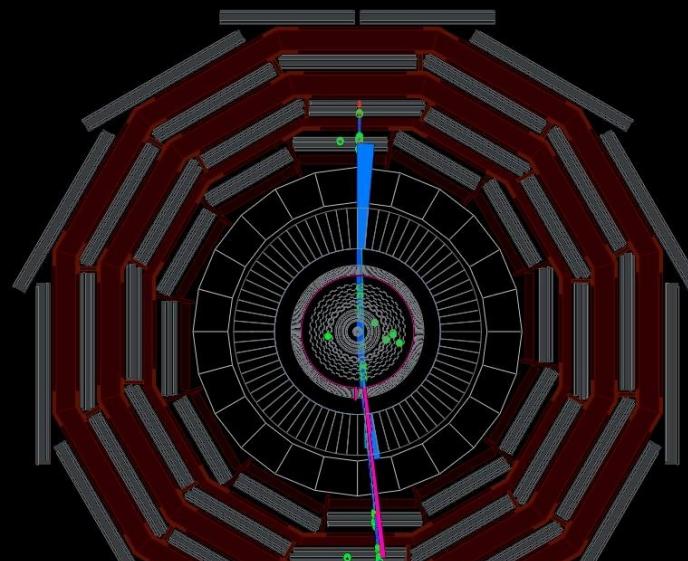


- Showers not well modelled
- Most analysis rely on events with exactly one track
- Transverse momentum well described

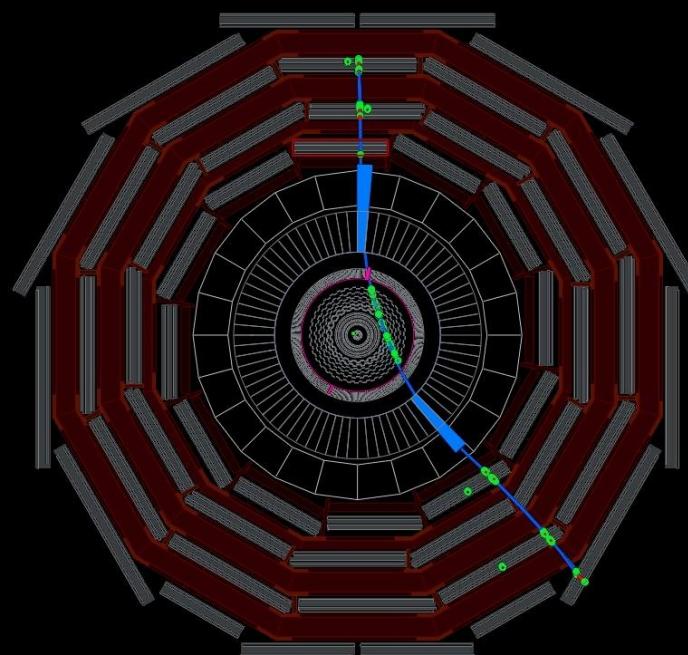


Cosmic muon tracks in late 2008

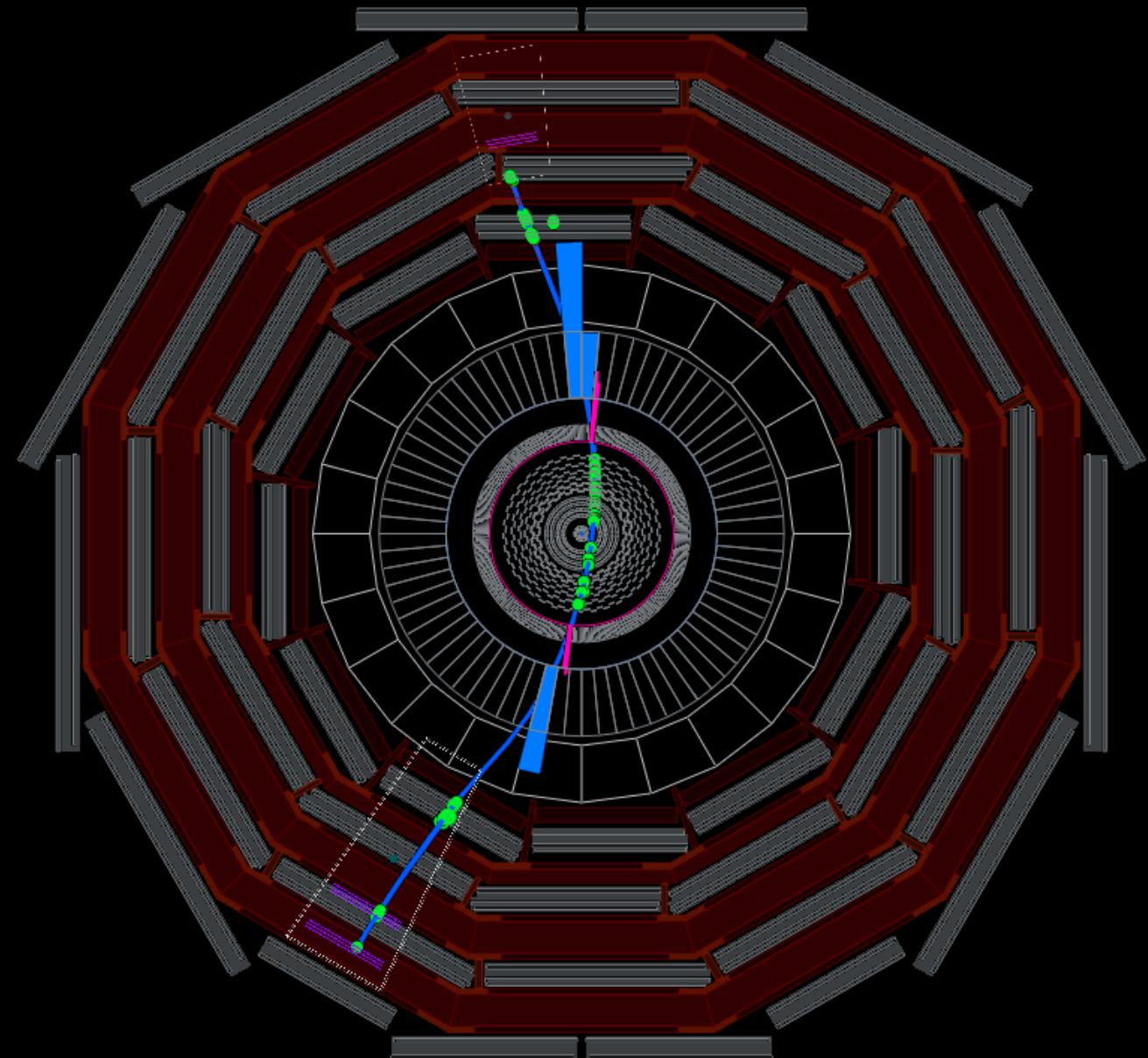
Run 66748, Event 8860756, LS 160, Orbit 166741956, BX 1921

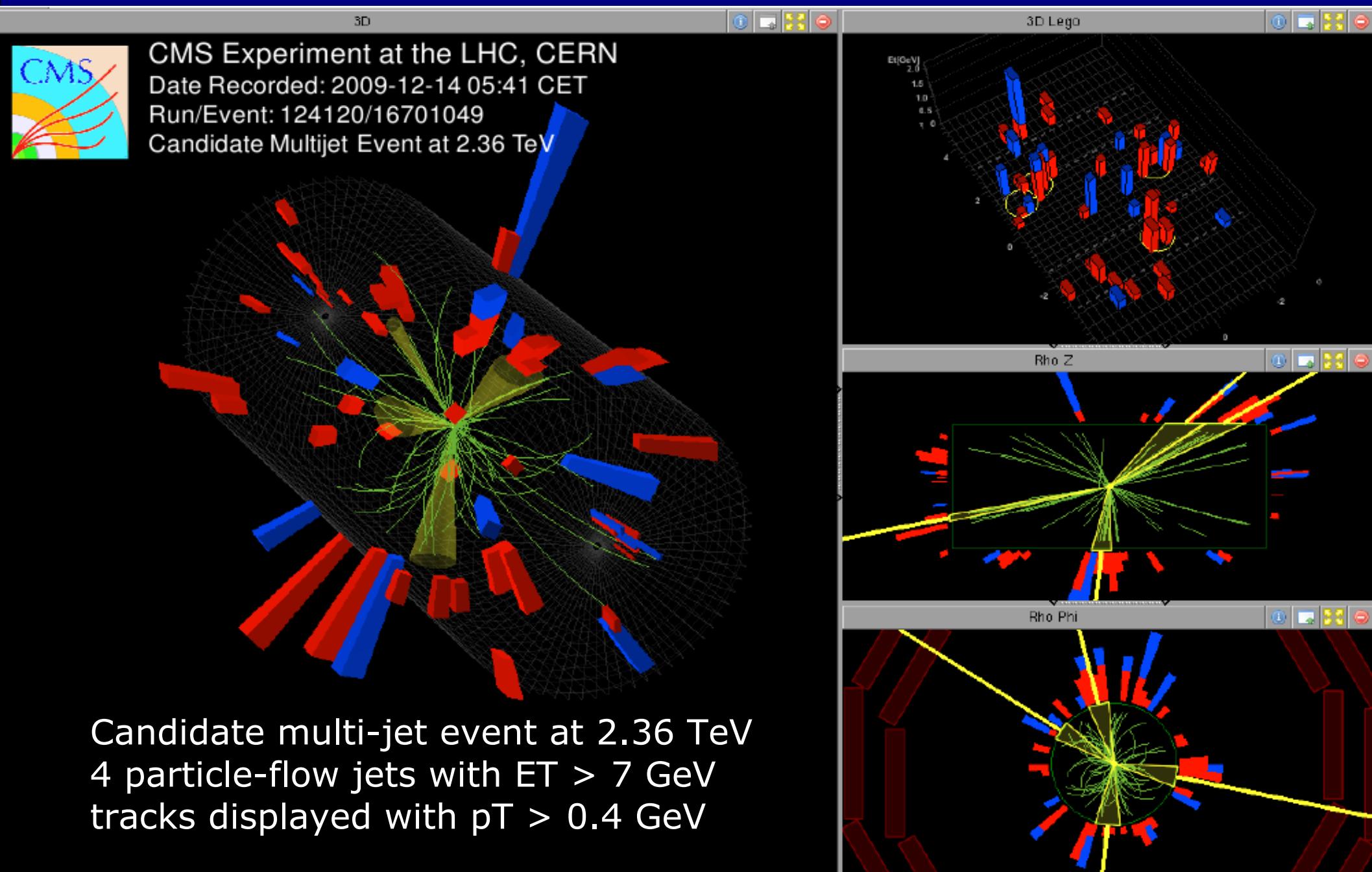


Run 66748, Event 8866986, LS 160, Orbit 166836178, BX 1956



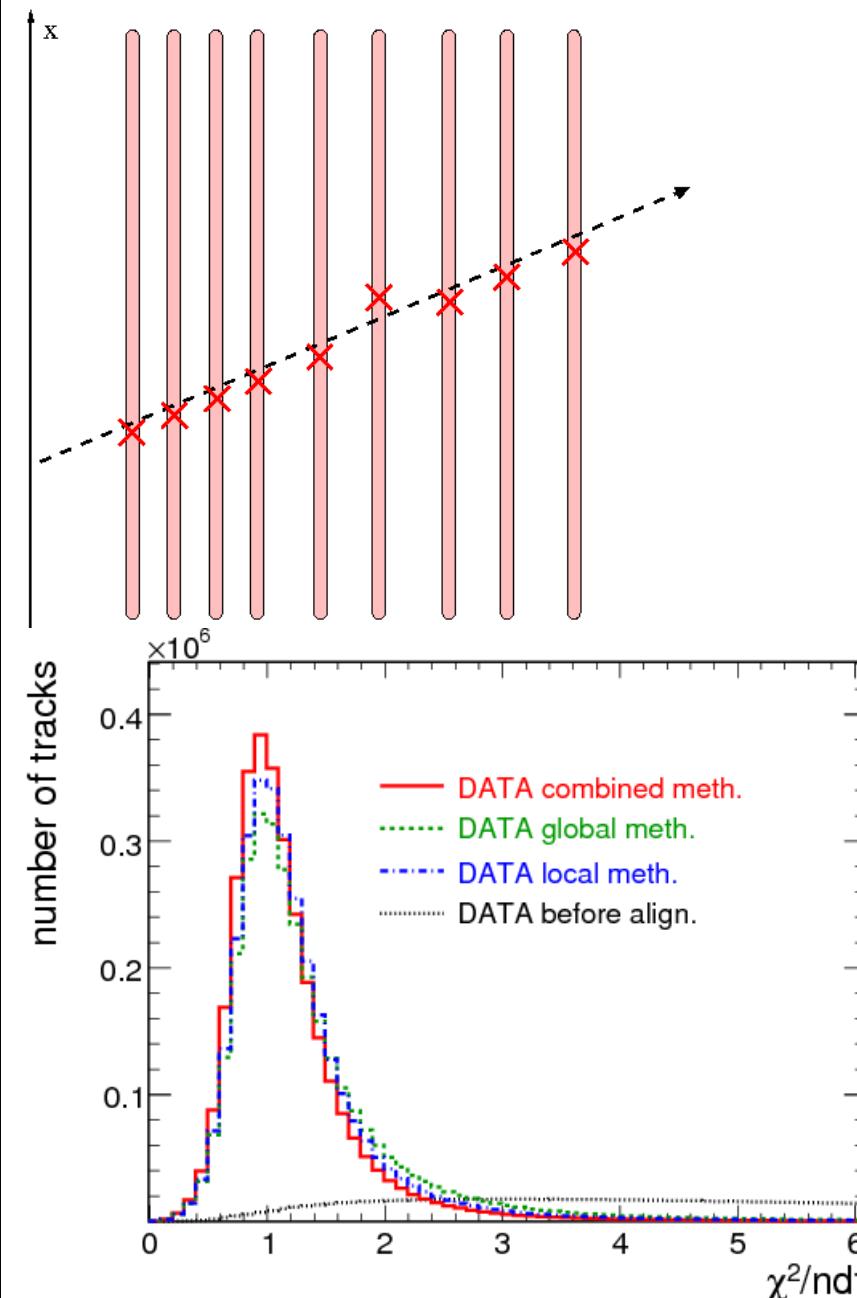
Run 66748, Event 8900172, LS 160, Orbit 167345832, BX 2011





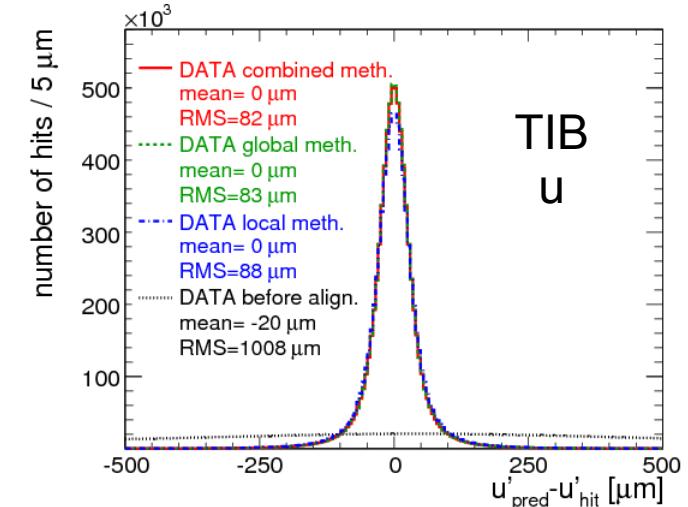
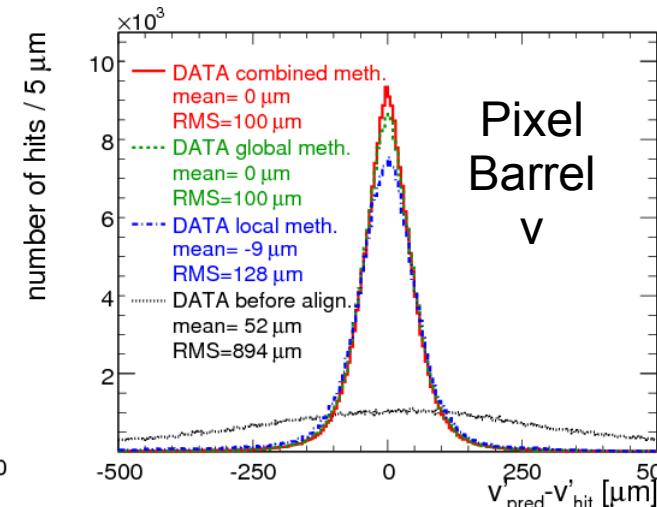
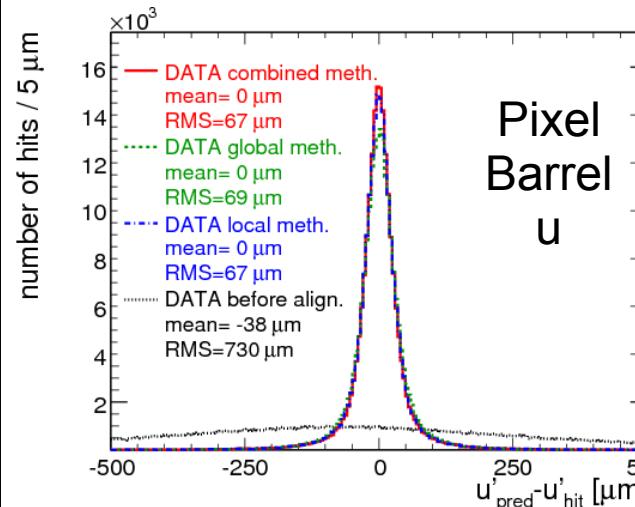
Alignment of pixel and strips:

Find position & orientation of sensor



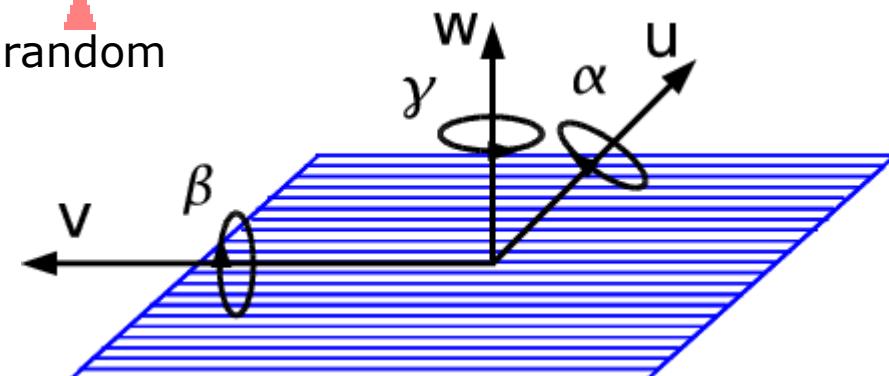
- Principle: minimize residuals ($x_{\text{hit}} - x_{\text{track}}$)
 - Practice: Minimize objective function
- $$\chi^2(\mathbf{p}, \mathbf{q}) = \sum_j^{\text{tracks}} \sum_i^{\text{hits}} \mathbf{r}_{ij}^T(\mathbf{p}, \mathbf{q}_j) \mathbf{V}_{ij}^{-1} \mathbf{r}_{ij}(\mathbf{p}, \mathbf{q}_j)$$
- \mathbf{r}_{ij} : residual
 - \mathbf{p} : alignment parameters
 - \mathbf{q}_j : track parameters
 - \mathbf{V}_{ij} : covariance matrix
 - Two algorithms employed
 - Global method aka Millepede II (V. Blobel)
 - Local method aka 'Hits and Impact Point' (HIP)
 - Combined method
 - Sequentially run global followed by local method, combine strengths of both algorithms
 - Data: 3.2M cosmic muon tracks @ 3.8T

- Clear improvement of residual width with alignment



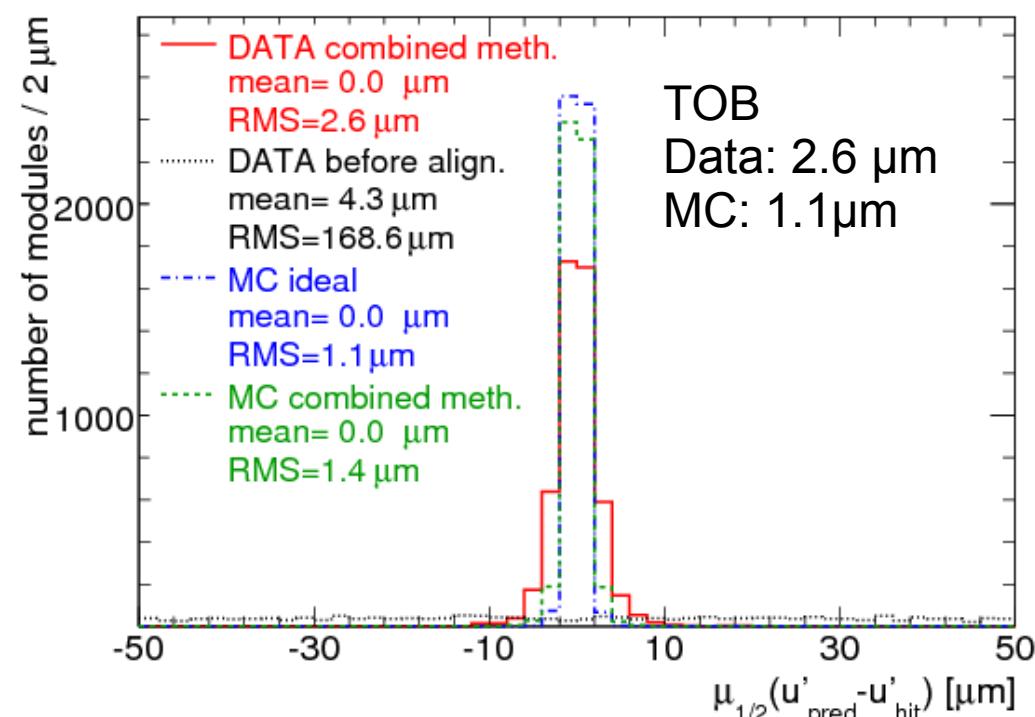
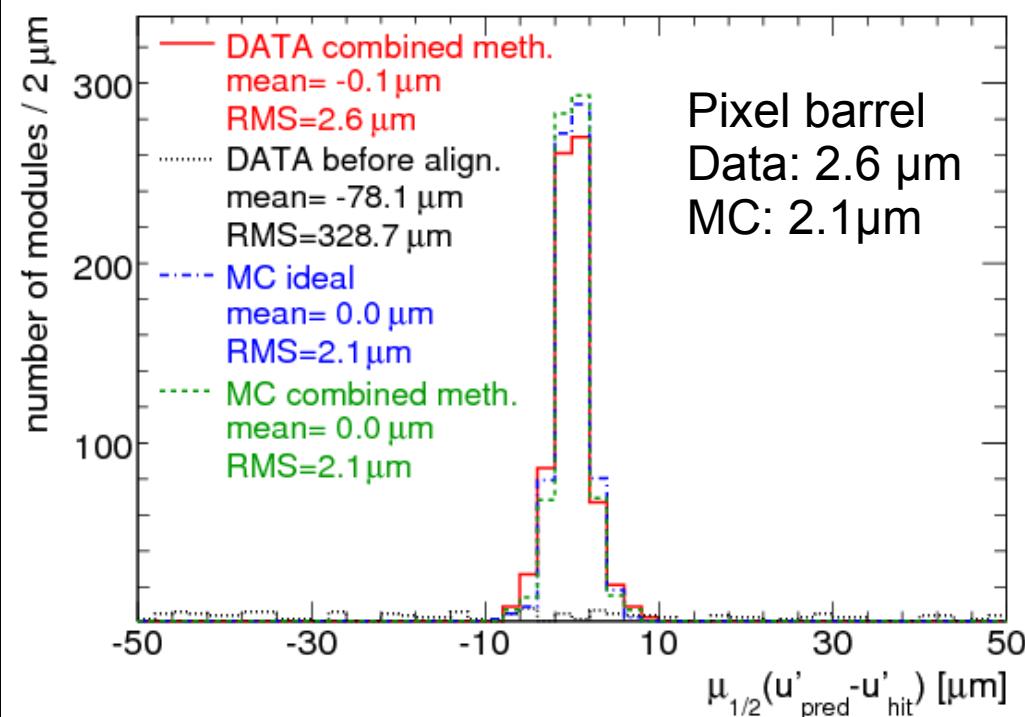
- Residuals contain multiple contributions:

- Alignment, track extrapolation, hit and multiple scattering uncertainties
 - systematic
 - random
 - random
 - random
- Random contributions dominating residual width → use better estimator for alignment quality
→ Distribution of the Median of the Residuals (DMR)



<http://arxiv.org/abs/0910.2505>, accepted by JINST

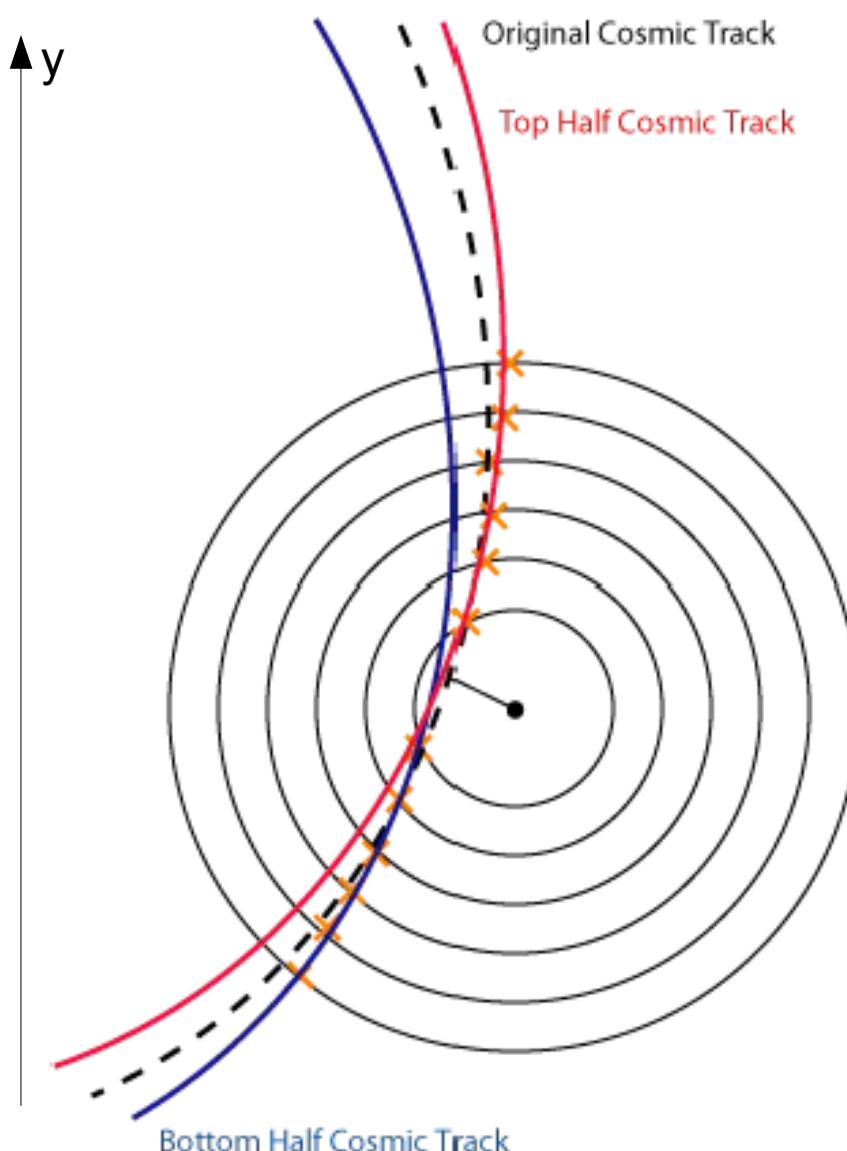
Distribution of the Median of the Residuals (DMR)



	before [μm]	global [μm]	local [μm]	combined [μm]	combined MC [μm]	ideal MC [μm]	modules >30 hits
BPIX (u')	328.7	7.5	3.0	2.6	2.1	2.1	757/768
BPIX (v')	274.1	6.9	13.4	4.0	2.5	2.4	
FPIX (u')	389.0	23.5	26.5	13.1	12.0	9.4	393/672
FPIX (v')	385.8	20.0	23.9	13.9	11.6	9.3	
TIB (u')	712.2	4.9	7.1	2.5	1.2	1.1	2623/2724
TOB (u')	168.6	5.7	3.5	2.6	1.4	1.1	5129/5208
TID (u')	295.0	7.0	6.9	3.3	2.4	1.6	807/816
TEC (u')	216.9	25.0	10.4	7.4	4.6	2.5	6318/6400

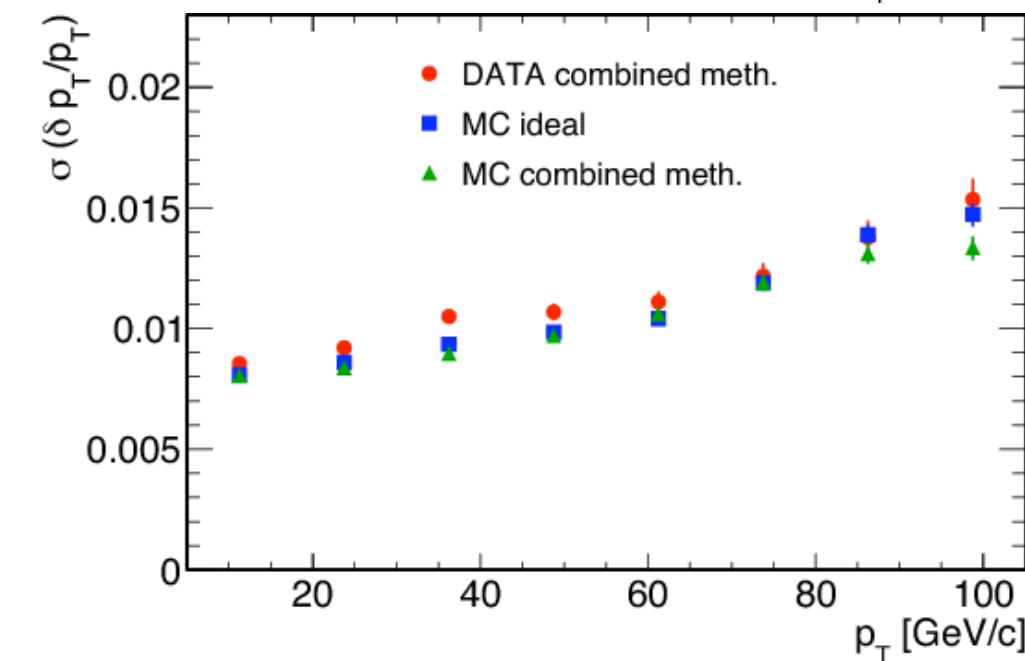
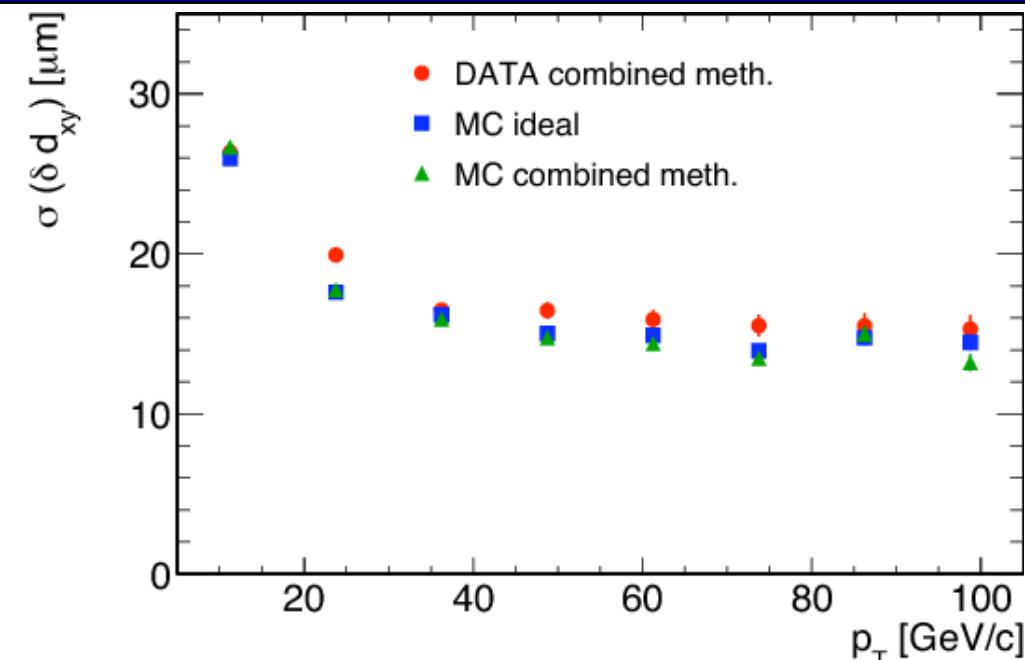
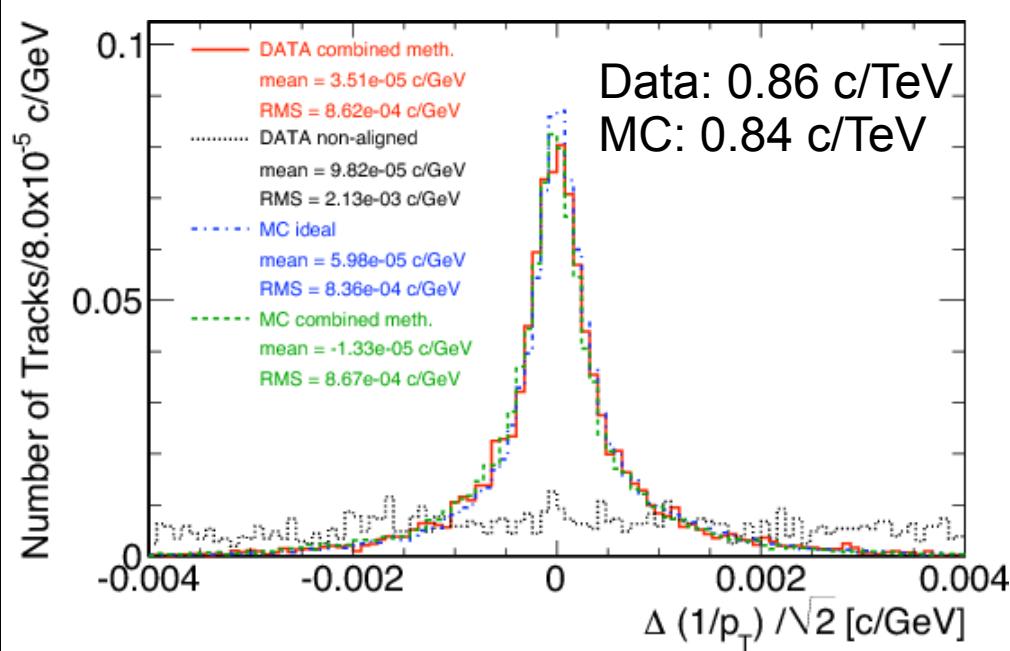
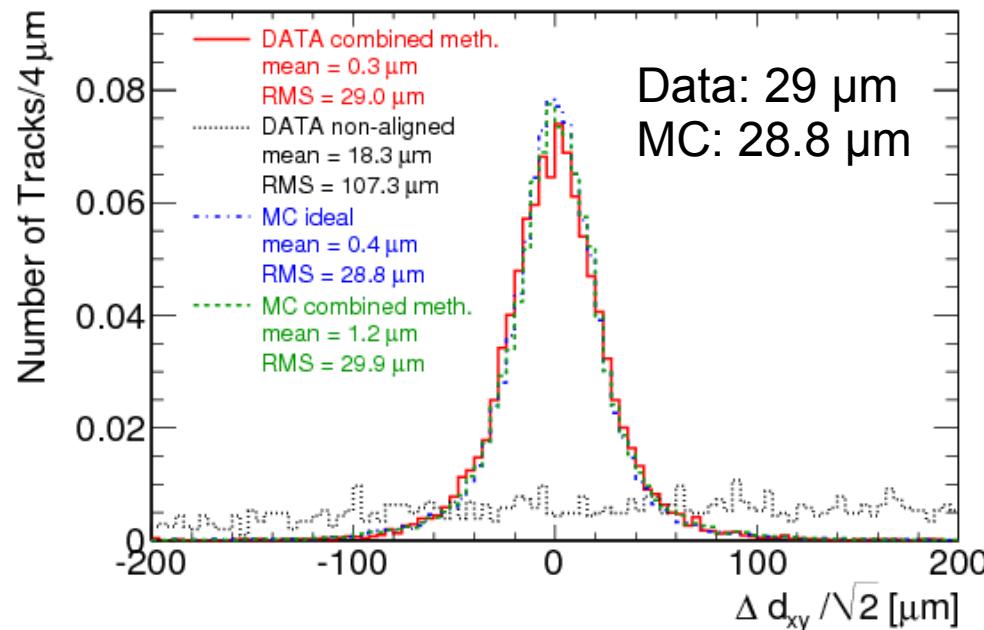
- Fantastic improvement
- Good agreement with MC
- Close to ideal

Validation with track splitting

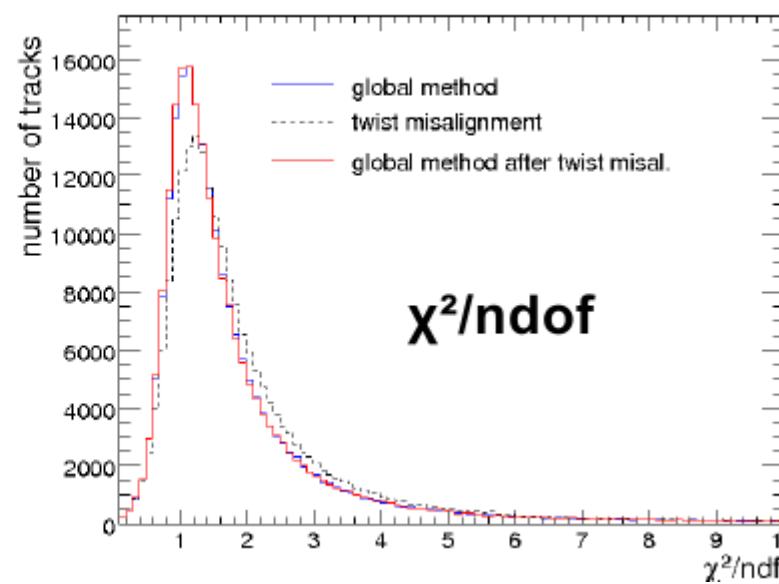
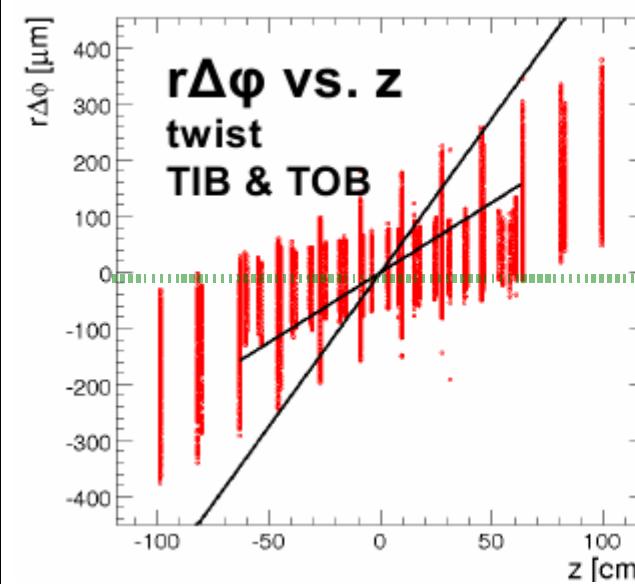
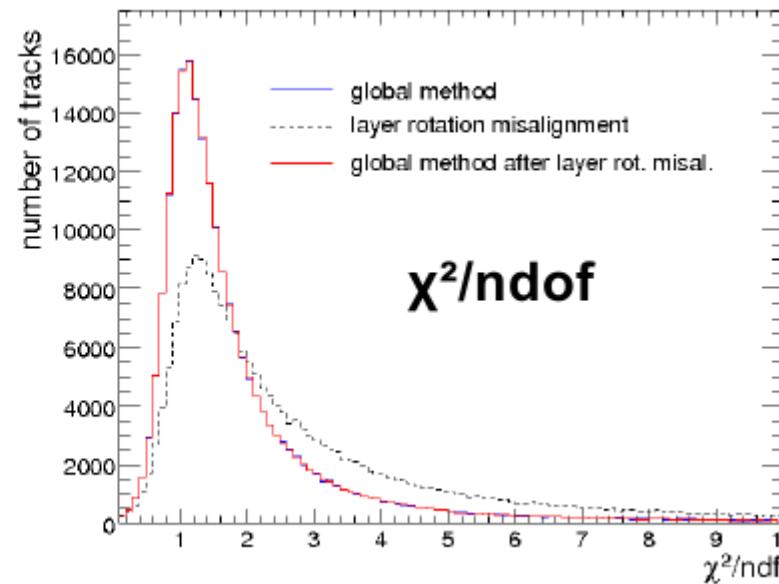
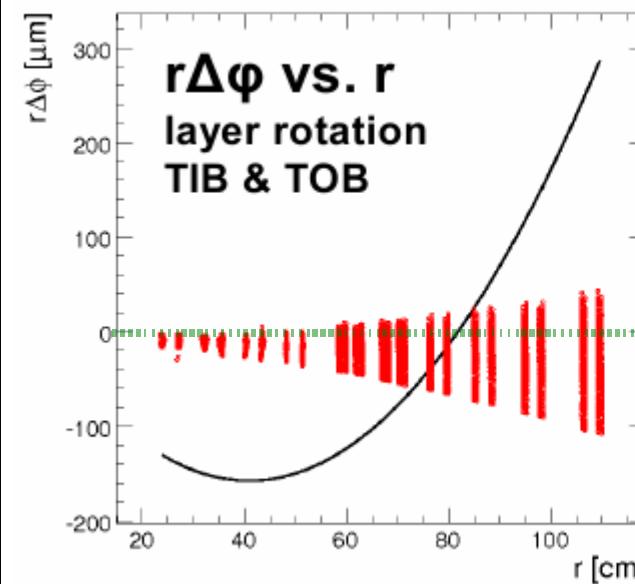


- Select tracks passing pixel detector
- Split tracks at distance of closest approach to the beam line
- Reconstruct top ($y>0$) and bottom ($y<0$) tracks separately
 - Collision-like tracks!
- Compare track parameters

Track splitting results



Systematic tracker deformation studies



- Start from aligned geometry
- Add systematic deformation
- Align → recover χ^2
- Discover remaining misalignment
- Solution:
Need complementary data / constraints for studies
(collision tracks, beam halo, vertex, ...)

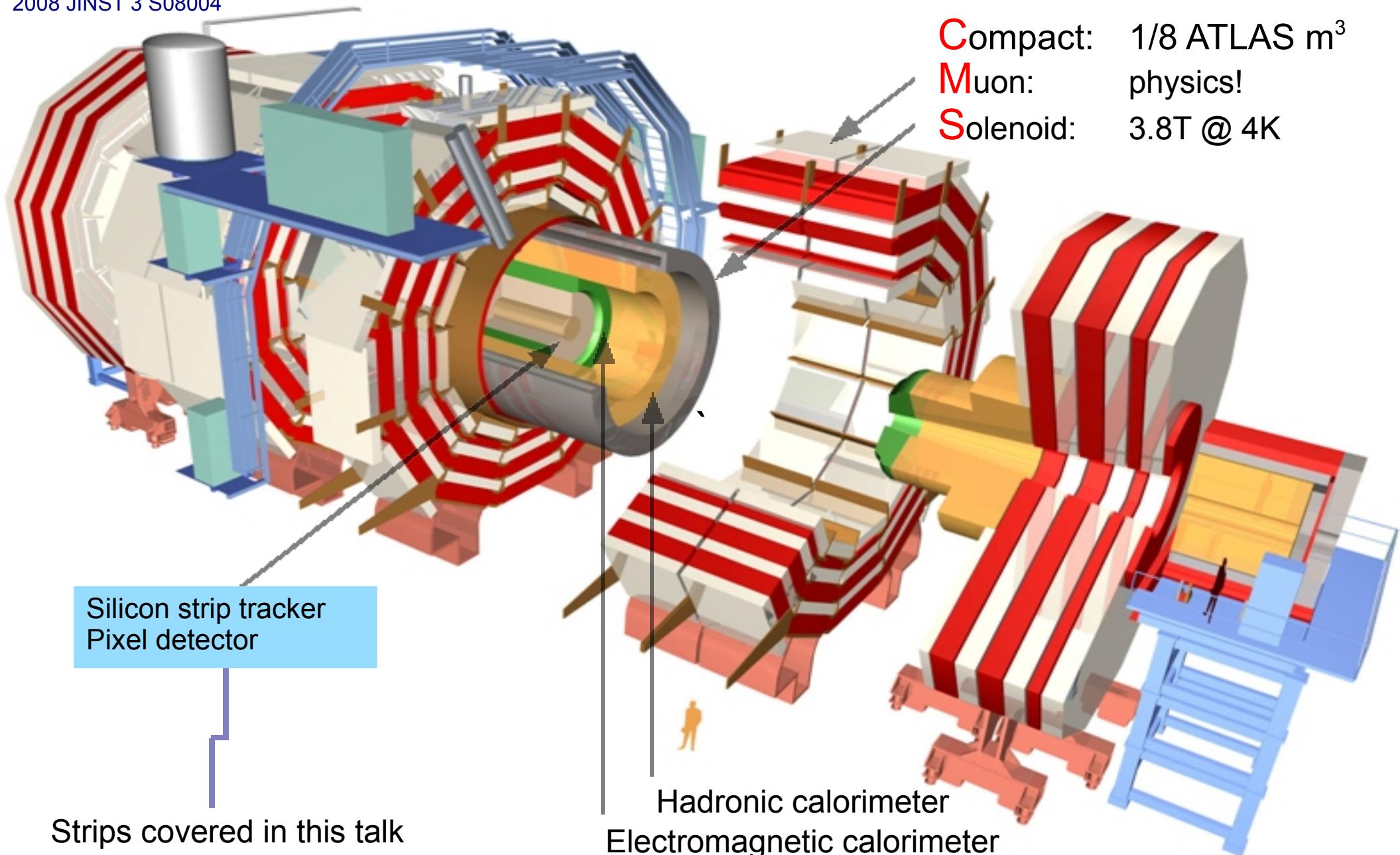
- CMS Strip Tracker has been fully commissioned
- High signal-to-noise ratio
 - TIB MPV S/N 26, TOB MPV S/N 32
- Lorentz angle measurement
 - TIB: $\tan(\theta_L) = 0.07 \pm 0.02$, TOB: $\tan(\theta_L) = 0.09 \pm 0.01$
- dE/dX measurement well working, separating kaons from protons
- Track reconstruction well tested, $\geq 99\%$ efficiency
- CMS Pixel and Strip Tracker well aligned
 - Systematic effects expected and to be understood
- Almost ideal tracking performance
 - Track parameter resolution
- CMS Silicon (Strip) Tracker is a unique scientific device
 - Well prepared for coming physics analysis



BACKUP

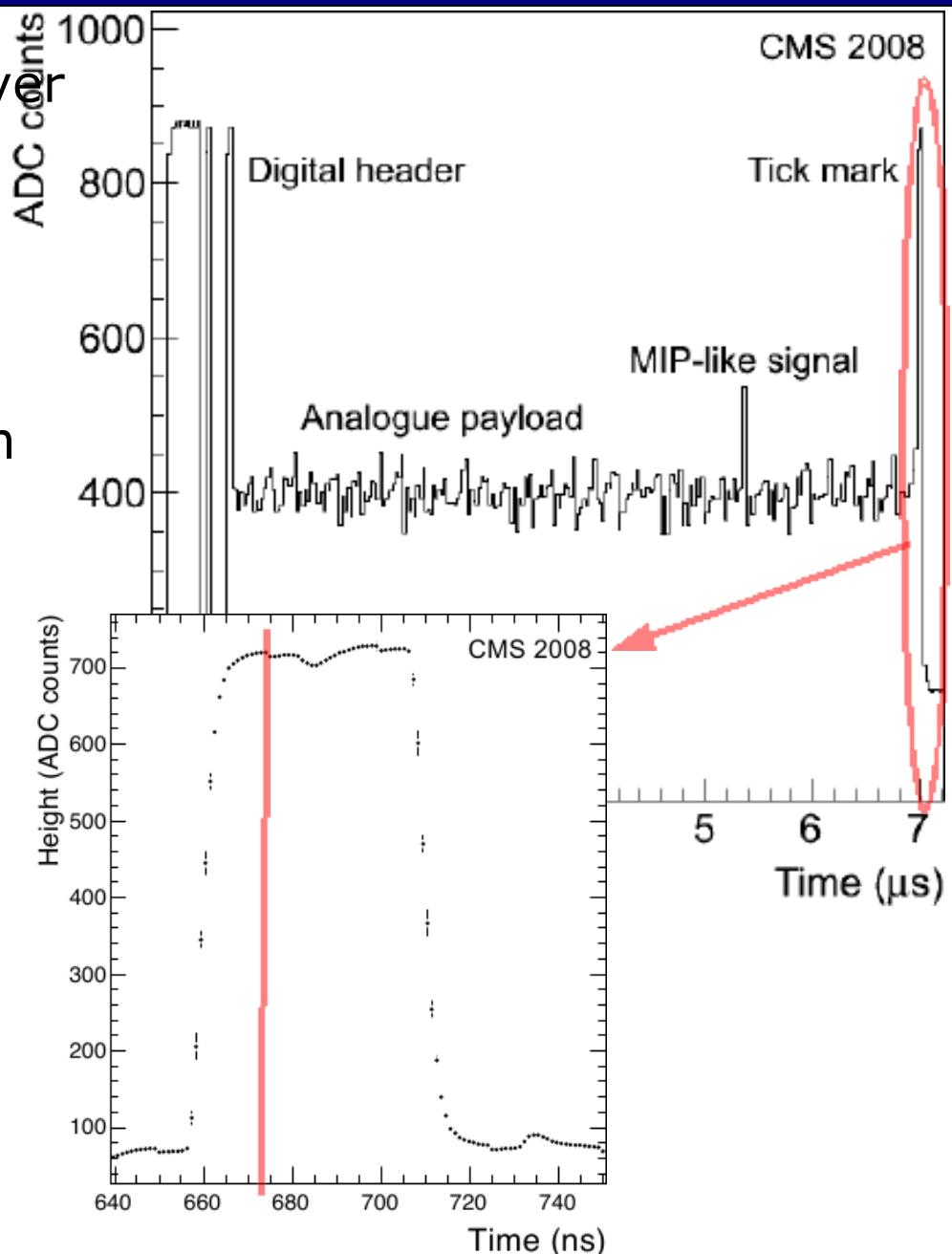
The tracker in CMS

2008 JINST 3 S08004

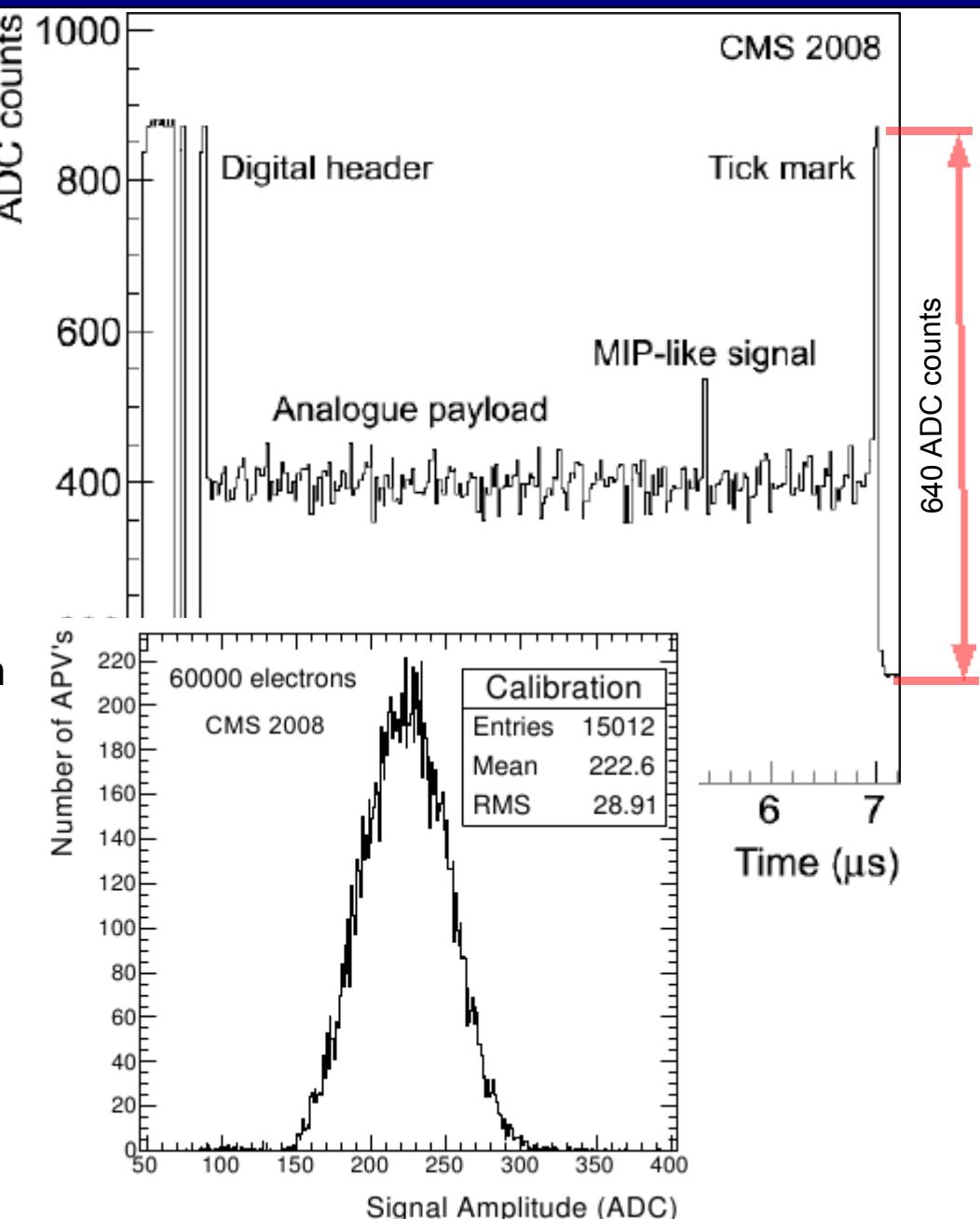


Commissioning of front-end electronics

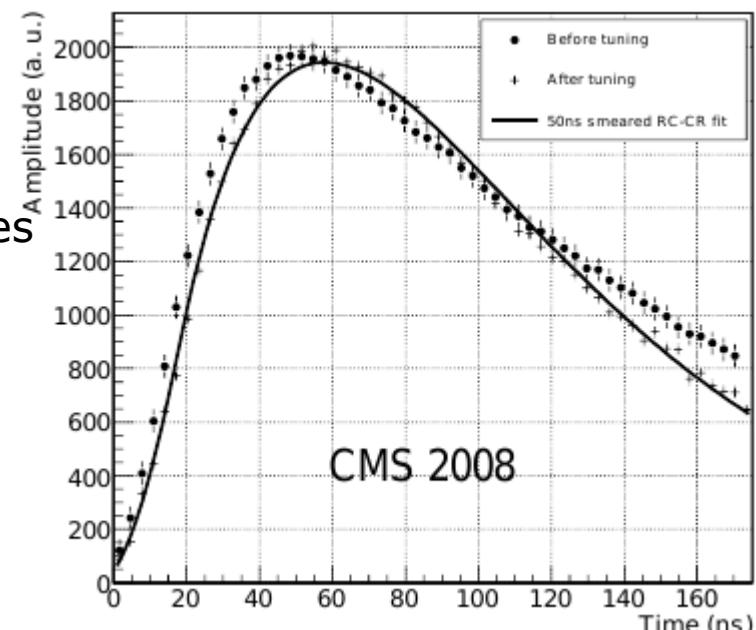
- Frame digitized by Front-End Driver (FED)
- Multiplexed data from two APVs
- Digital header: Address, State
- Analogue payload: Raw data from APV
- 1st step: Checkout
 - Find responsive devices
 - Establish cable map
- 2nd step: adjust timing
 - Compensate for signal travelling time
 - Scan tick mark with 1.04ns precision
- Last step: synchronize to particles (scan pulse shape)



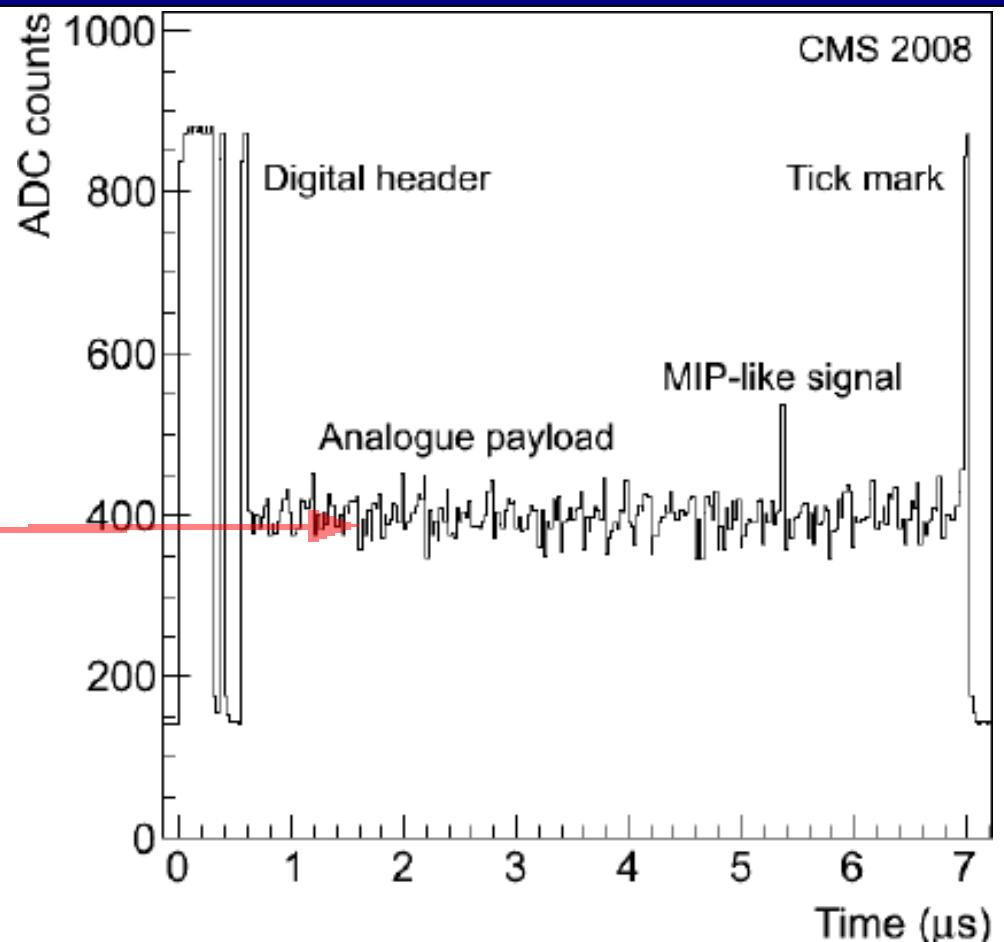
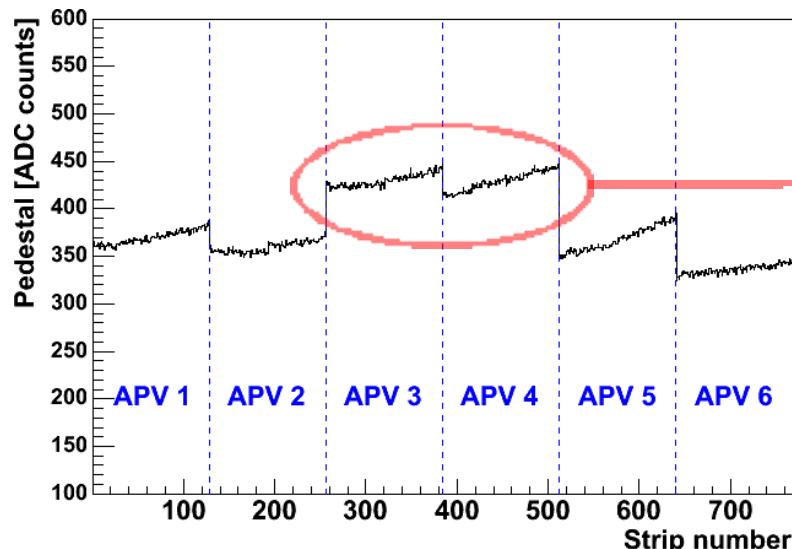
- Varying laser diode signal
 - Laser/fibre mounting precision during fabrication
 - Connections at patch panel
- Adjust tick mark height (175k e-)
 - Optimal value 640 ADC counts
 - Corresponds to design gain 0.8
 - Achieve 20% spread (granularity of laser driver settings), offline correction
 - Calibration factor 274 ± 14 e-/ADC, 5% systematic uncertainty
- Calibration charge (60k e-)
 - Internal circuit 60k e- injection
 - Calibration factor 269 ± 13 e-/ADC, 5% systematic uncertainty
 - After pulse-shape tuning (next slide)



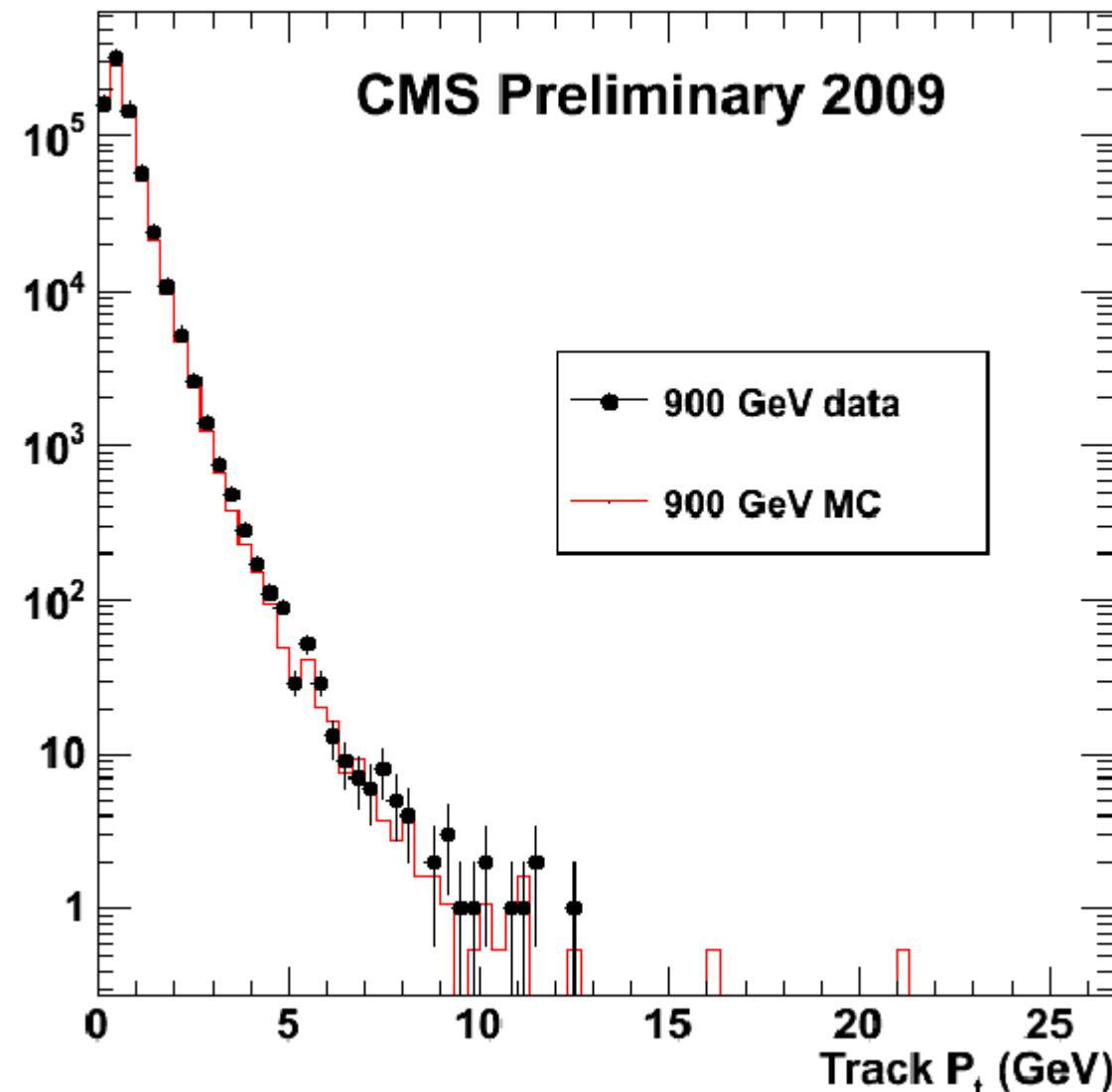
- Tuning shape for deconvolution mode
 - Standard collision mode: Deconvolution
 - Produce short pulse from three consecutive samples
 - Depends on CR-RC pre-amplifier shape
 - Tuning necessary due to small process variations
- Pulse shape adjustment
 - CR-RC time constant 50ns
 - Signal amplitude at $t_{max}+125\text{ns}$ tuned to 36% of maximum



- Pedestal, Noise, Common Mode
- FED frame: 2 multiplexed APV
- Pedestal

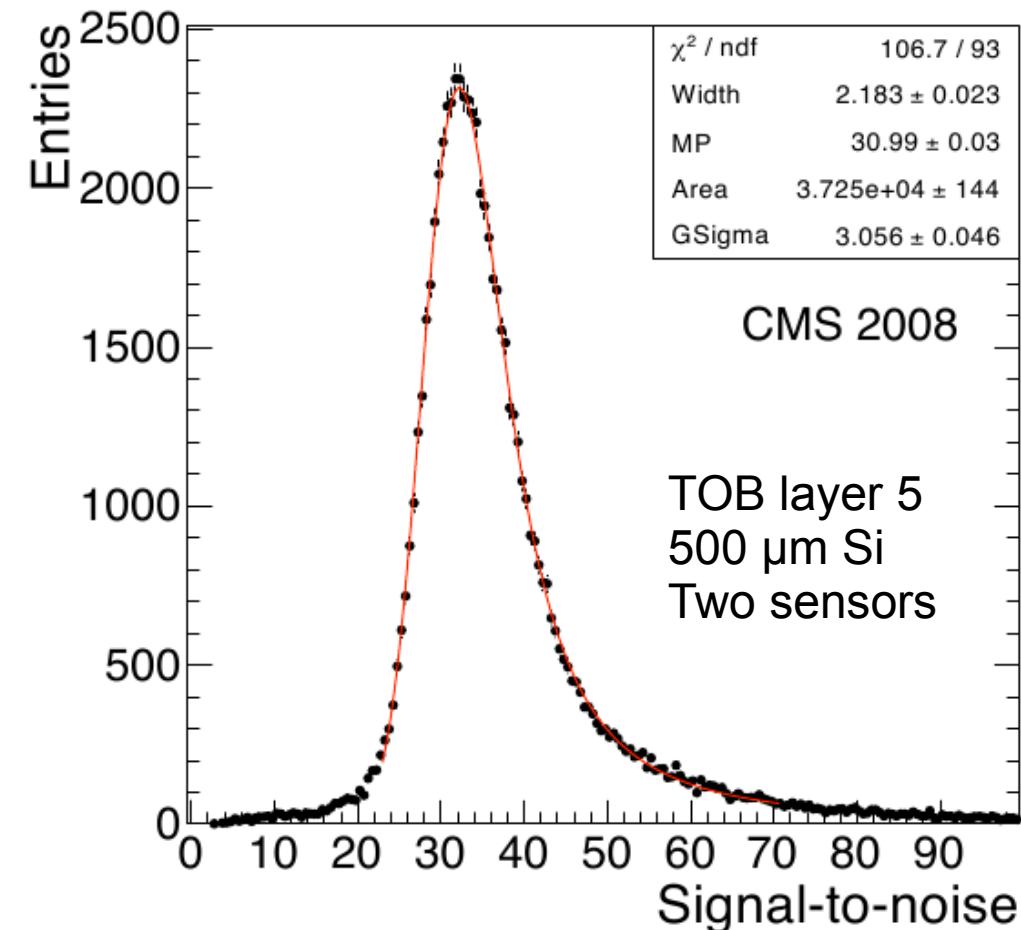
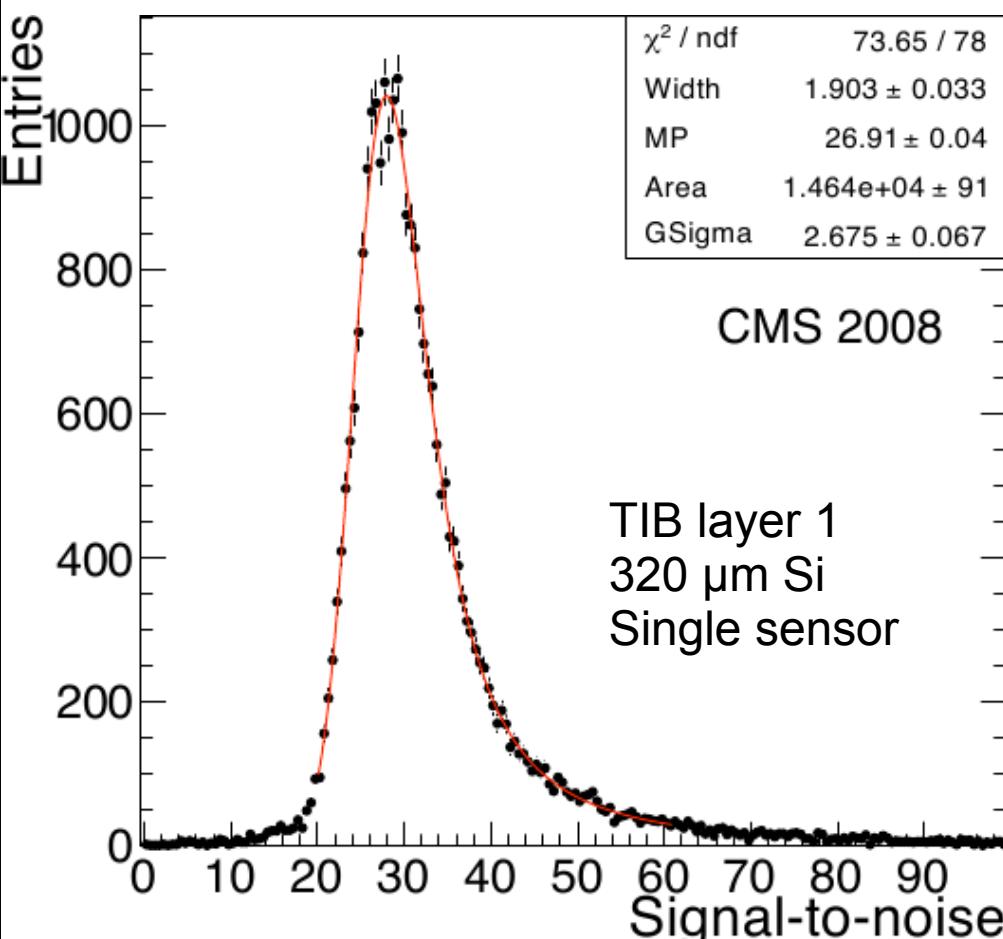


- Common mode: Subtract common movement of baseline per APV



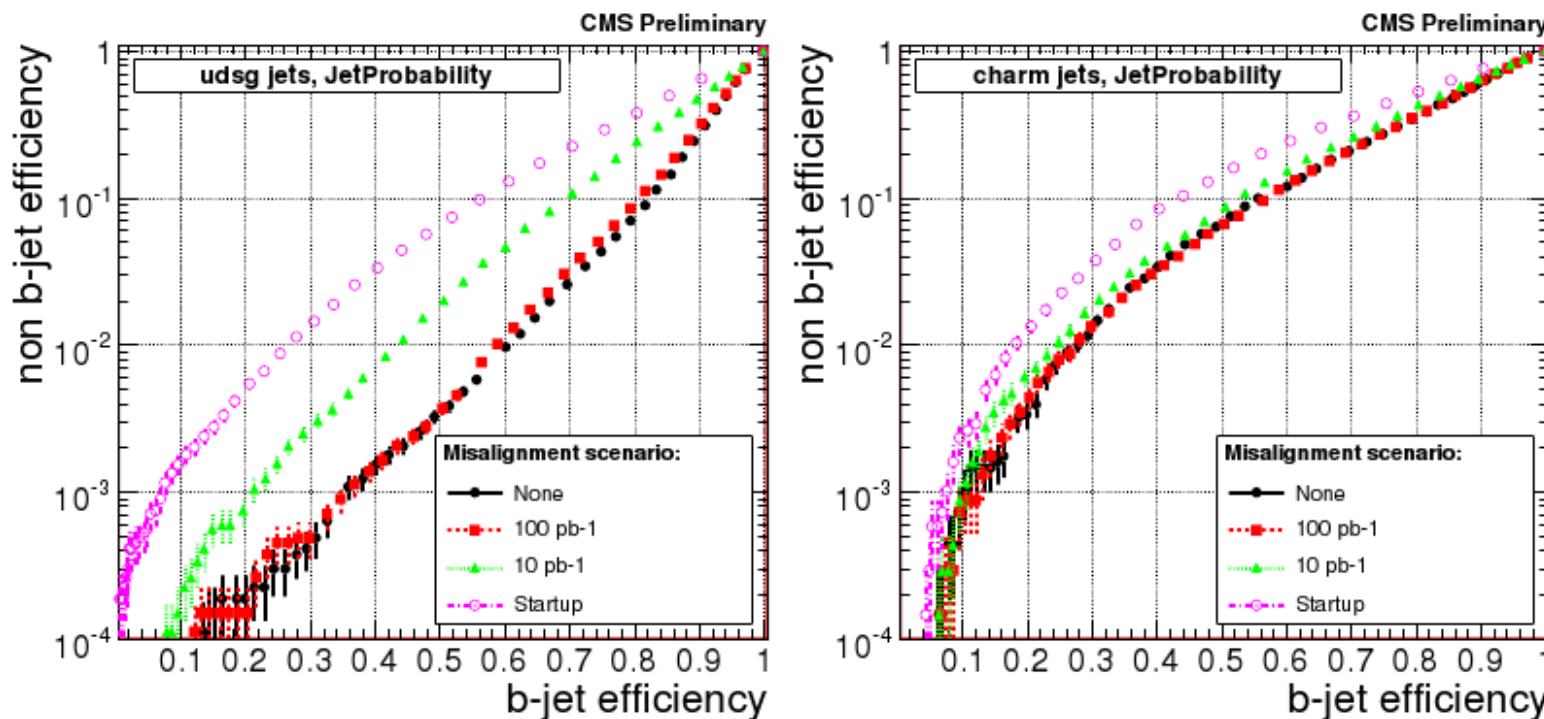
- Path-length corrected Signal-to-noise ratio
 - Cluster Noise:

$$\sigma_{Cluster} = \sqrt{\sum_{i=1}^{N_{Strips}} \sigma_i^2 / N_{Strips}}$$



B-tagging with misalignment

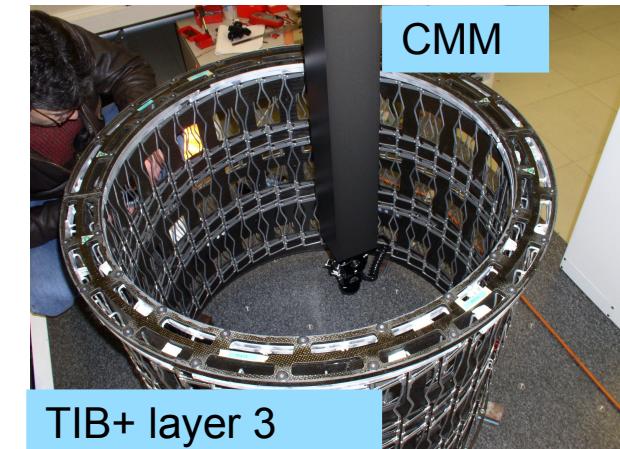
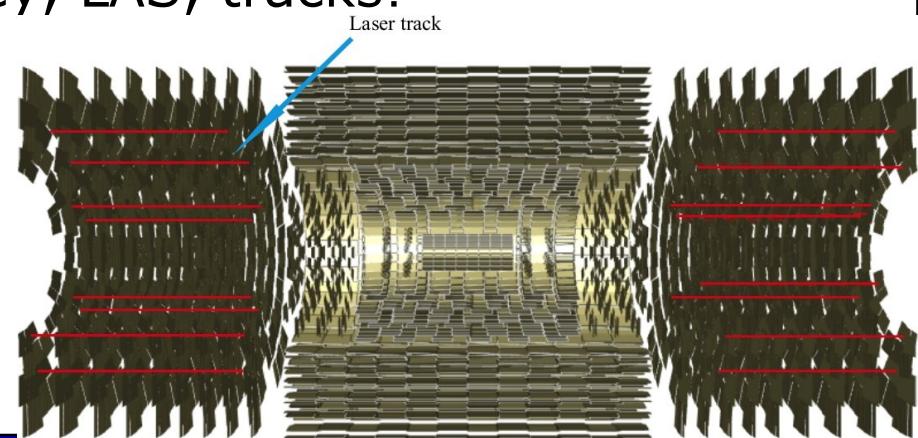
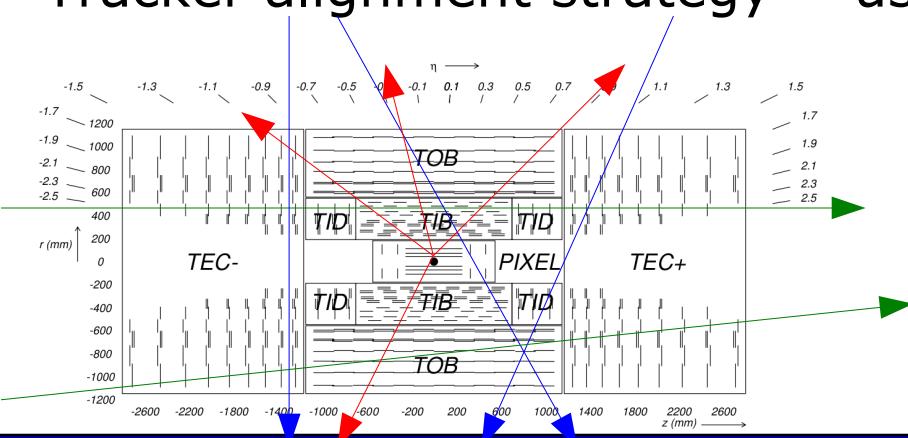
- Detailed study of misalignment effects on b-tagging CMS AN 2007/047
 - Several algorithms studied, all show worse performance in case of misalignment

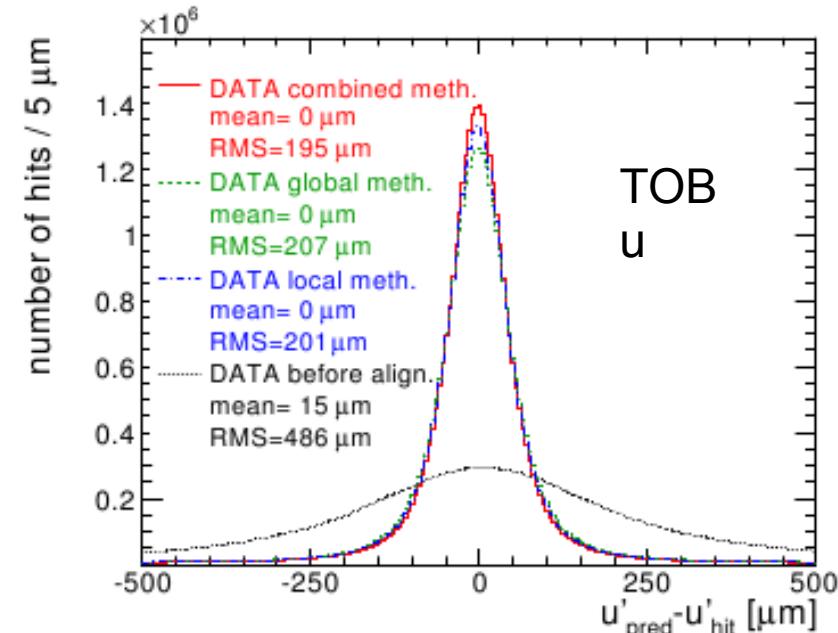
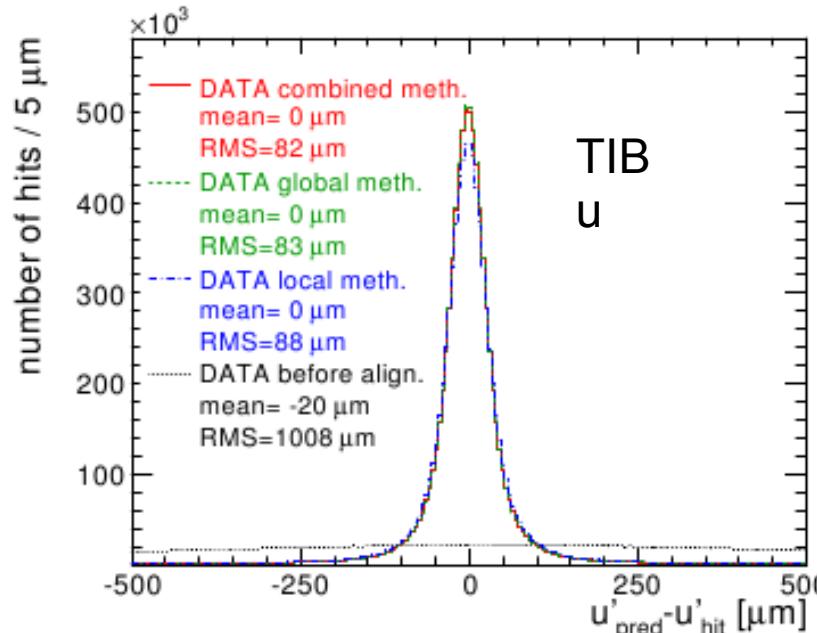
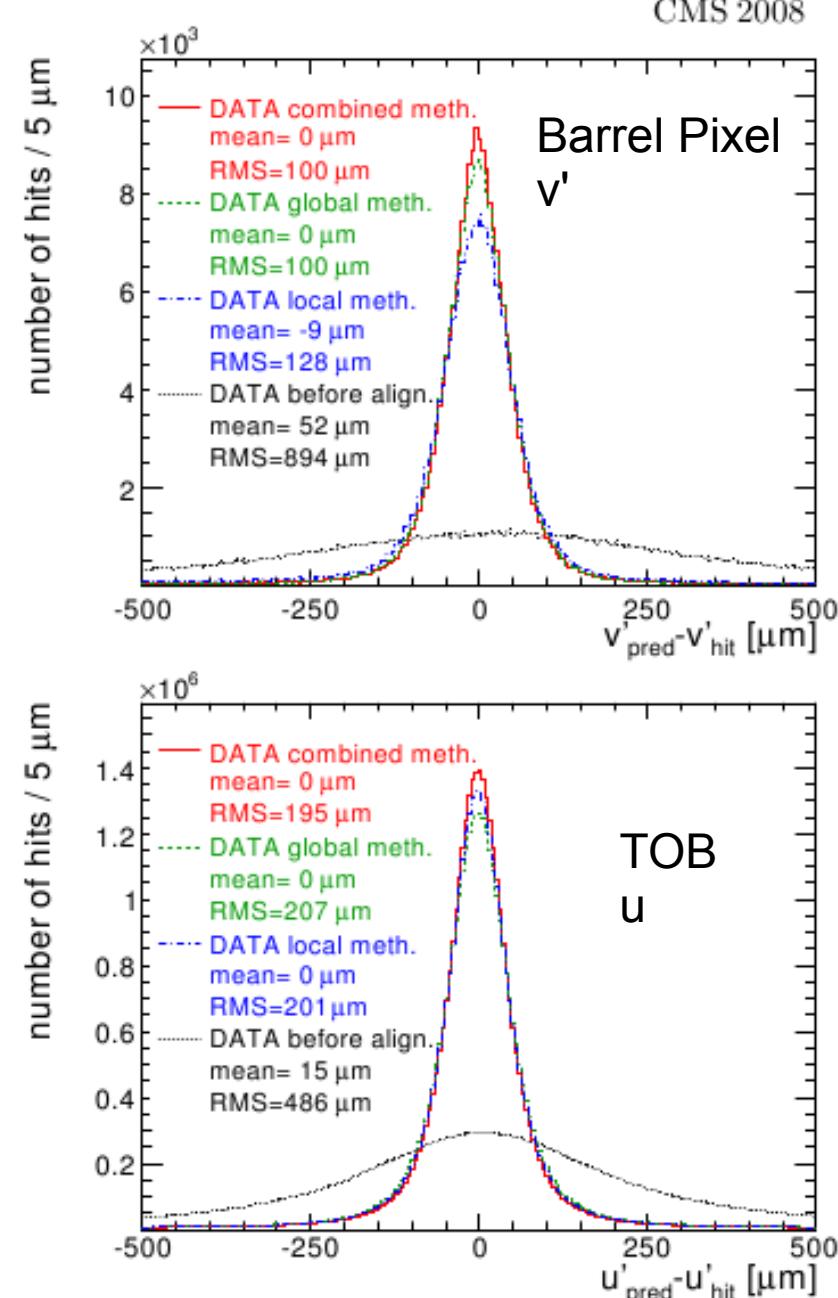
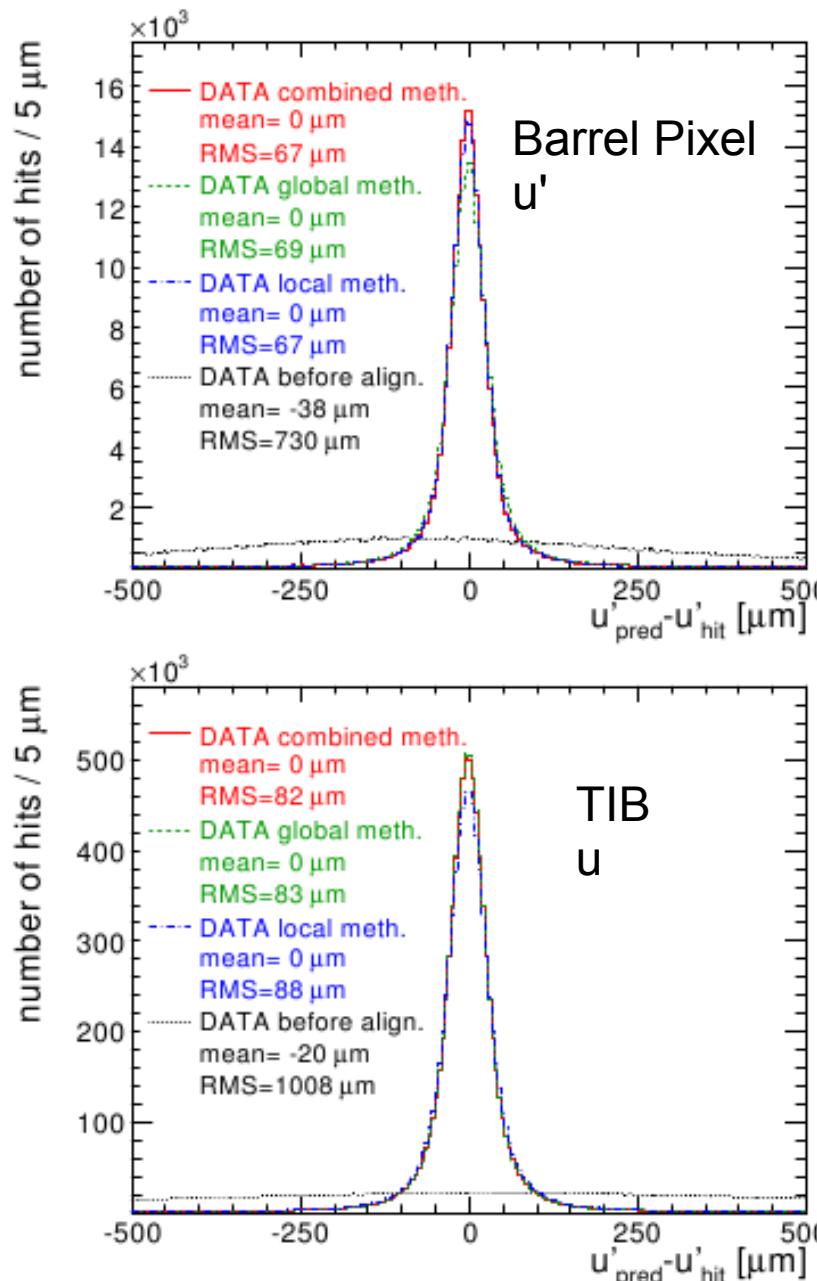


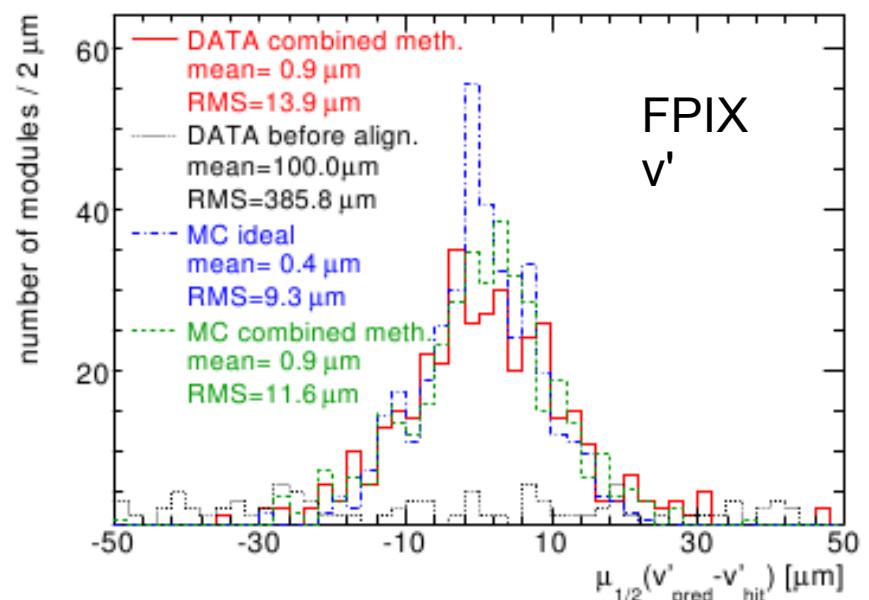
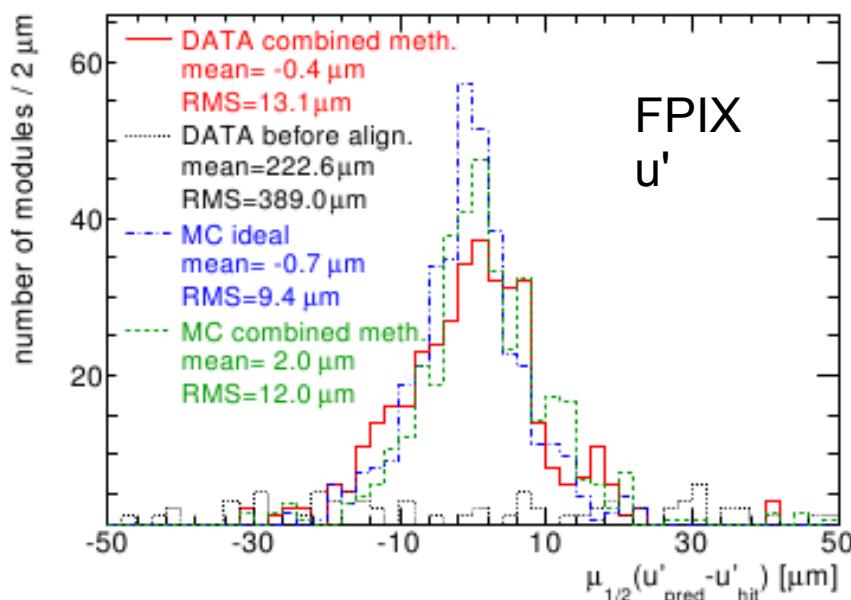
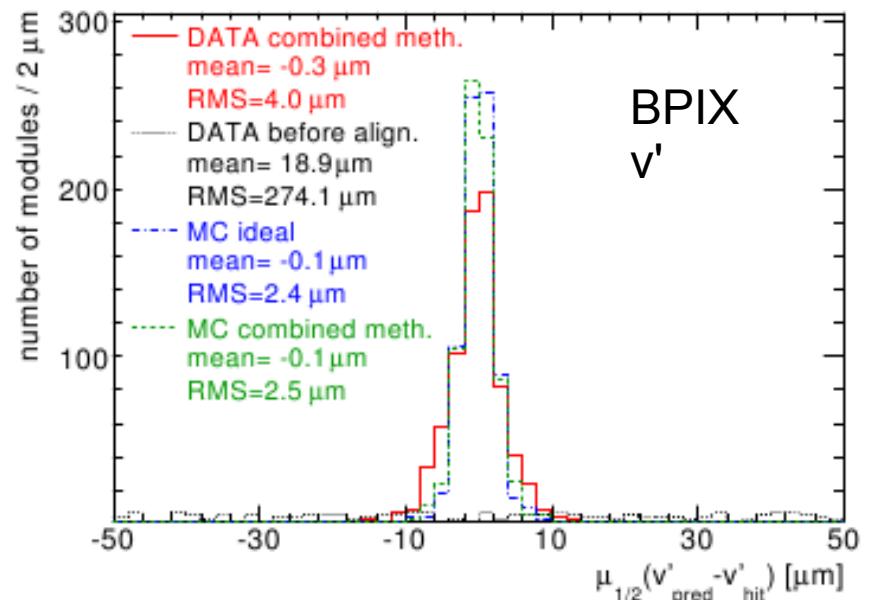
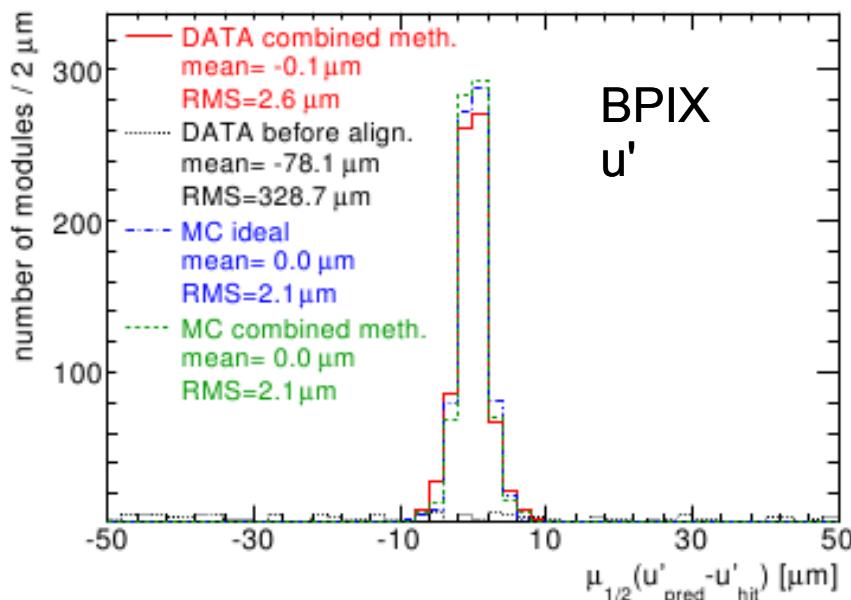
- Mistagging rate increases by more than a magnitude for initial detector!
 - Developed "robust" algorithm showing less sensitivity
- Need to have not only alignment but also good estimate of remaining misalignment
- Conclusion: Many physics measurements rely on tracker alignment!

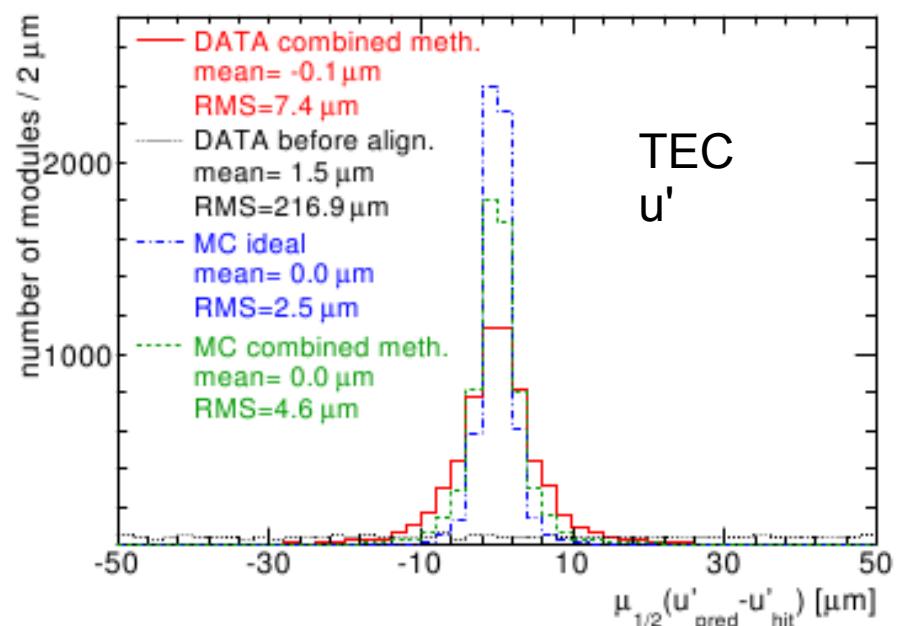
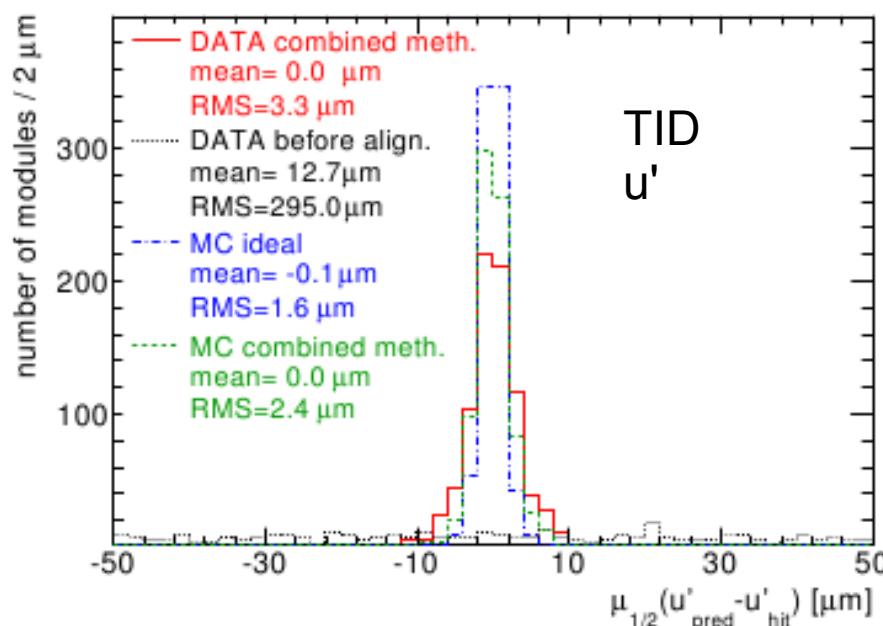
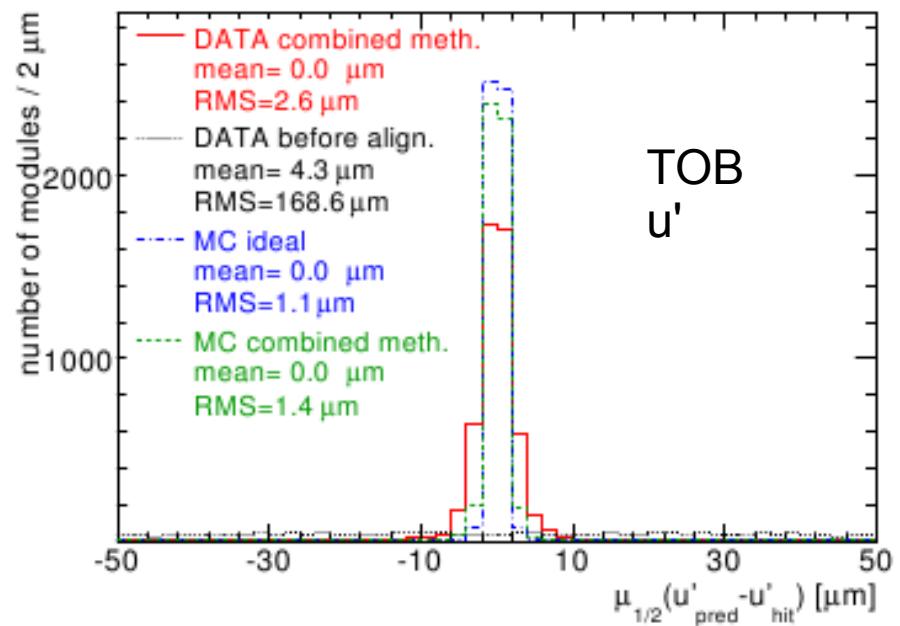
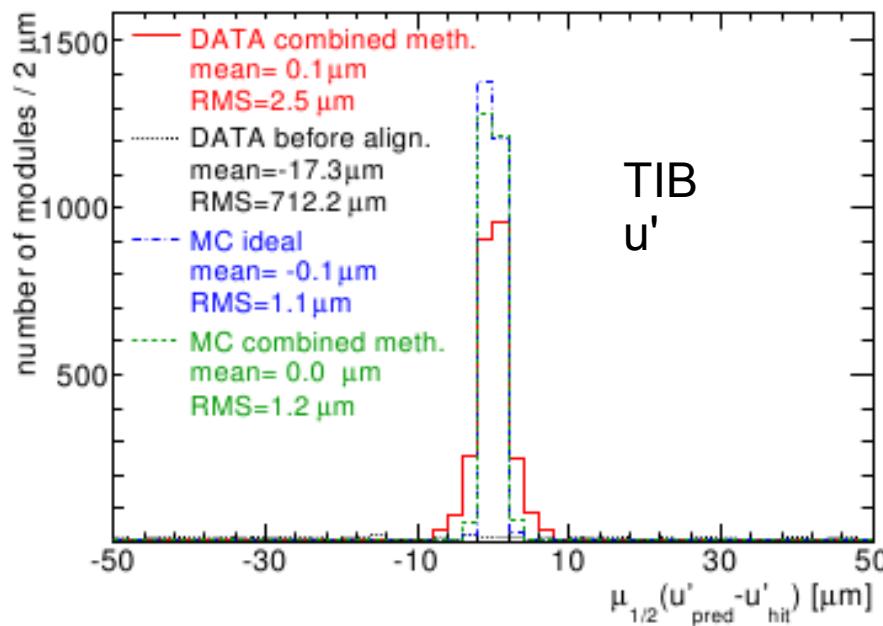
How can we determine module positions?

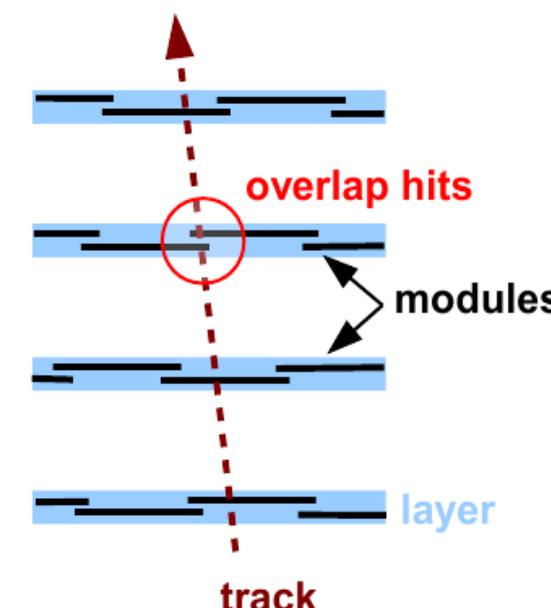
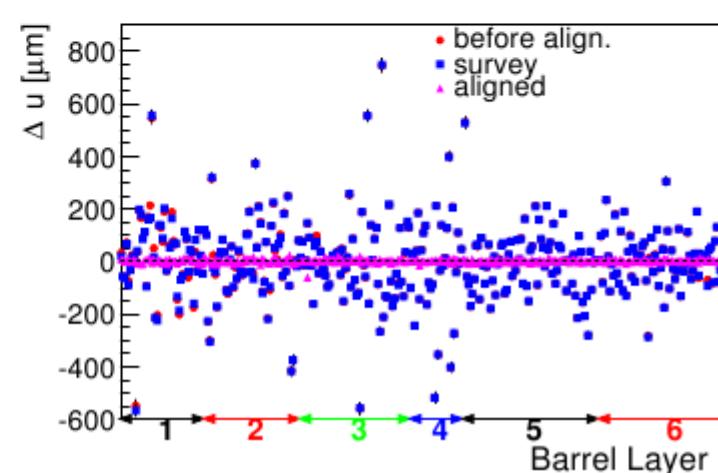
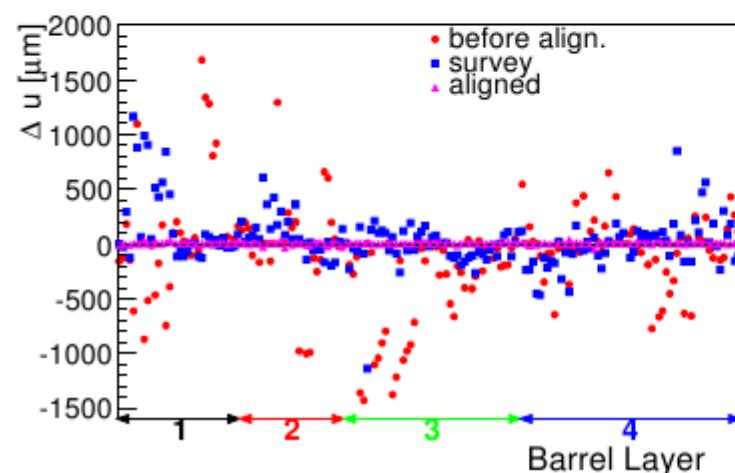
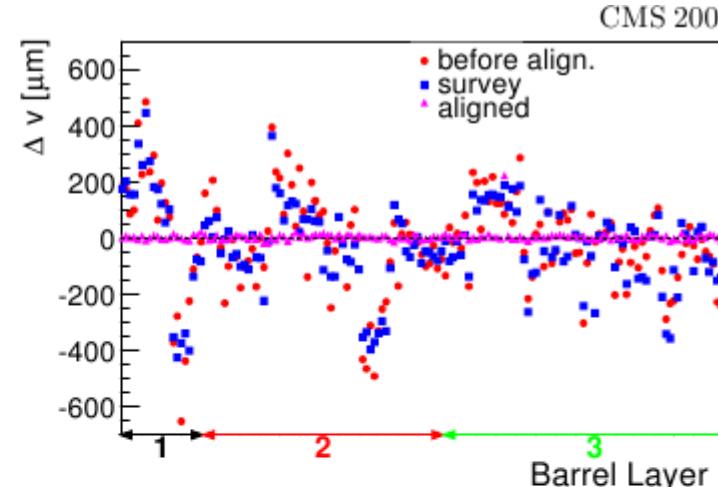
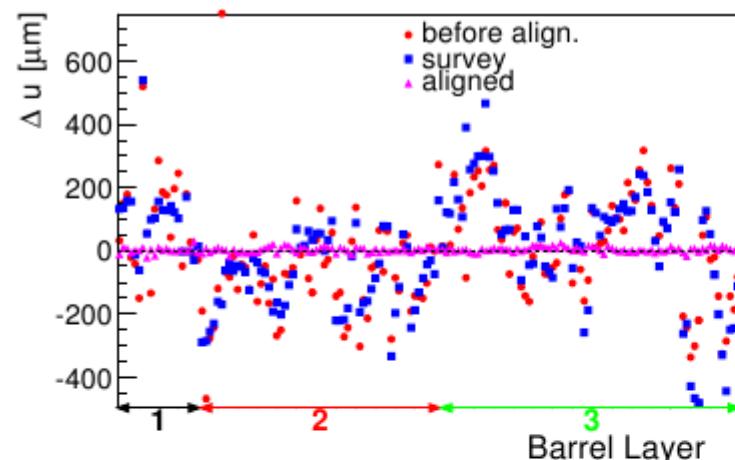
- Survey (e.g. photogrammetry, coordinate measurement machines)
 - Only during tracker integration, not in final position possible
 - Precision depending on size & accessibility of object
- Laser alignment system
 - Laser induced signals on 434 tracker modules
- Track based alignment
 - Signals from charged particle tracks in situ
 - Partial alignment with **cosmic muons**, **beam halo muons**
 - Combination with **collision tracks** yields most precise alignment
- Tracker alignment strategy = use survey, LAS, tracks!





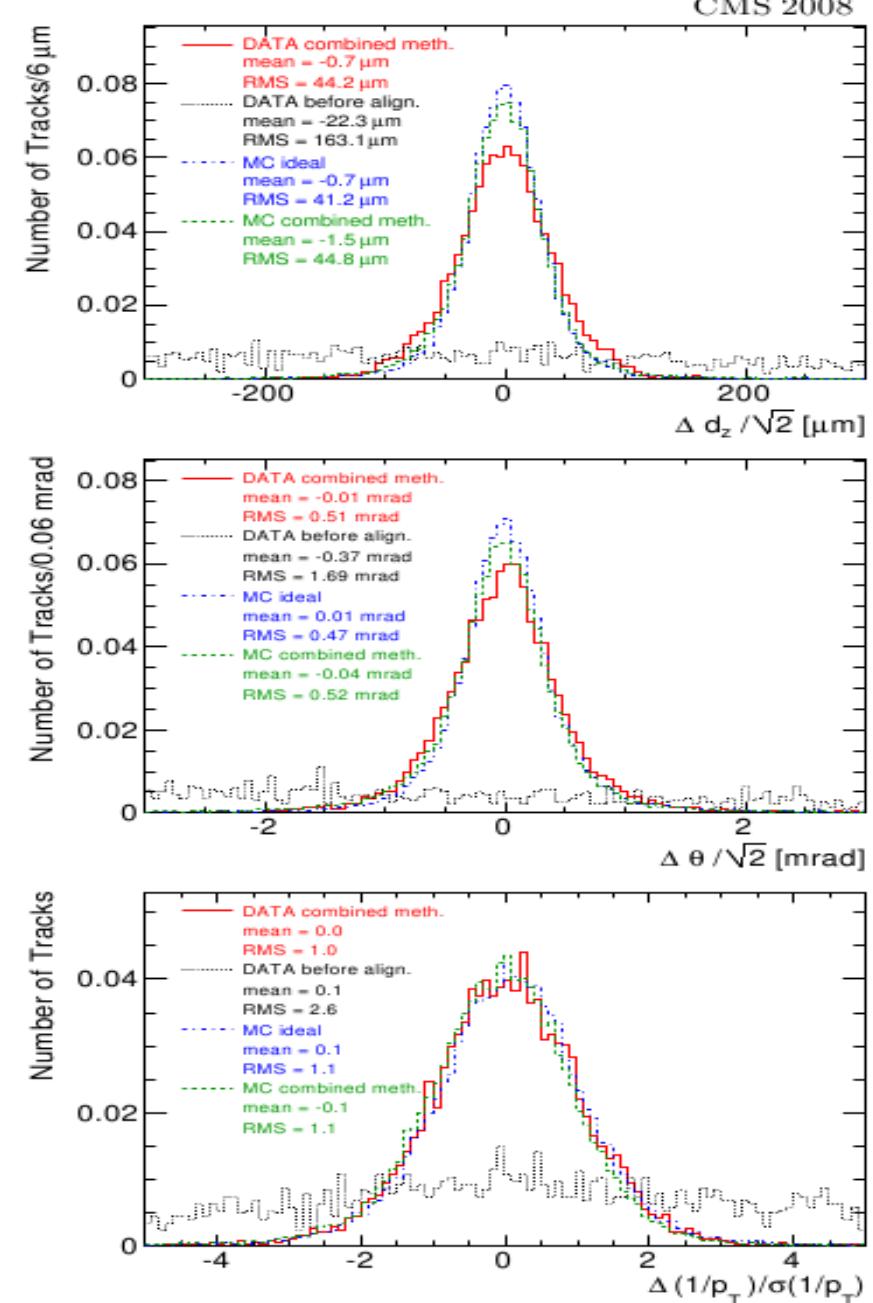
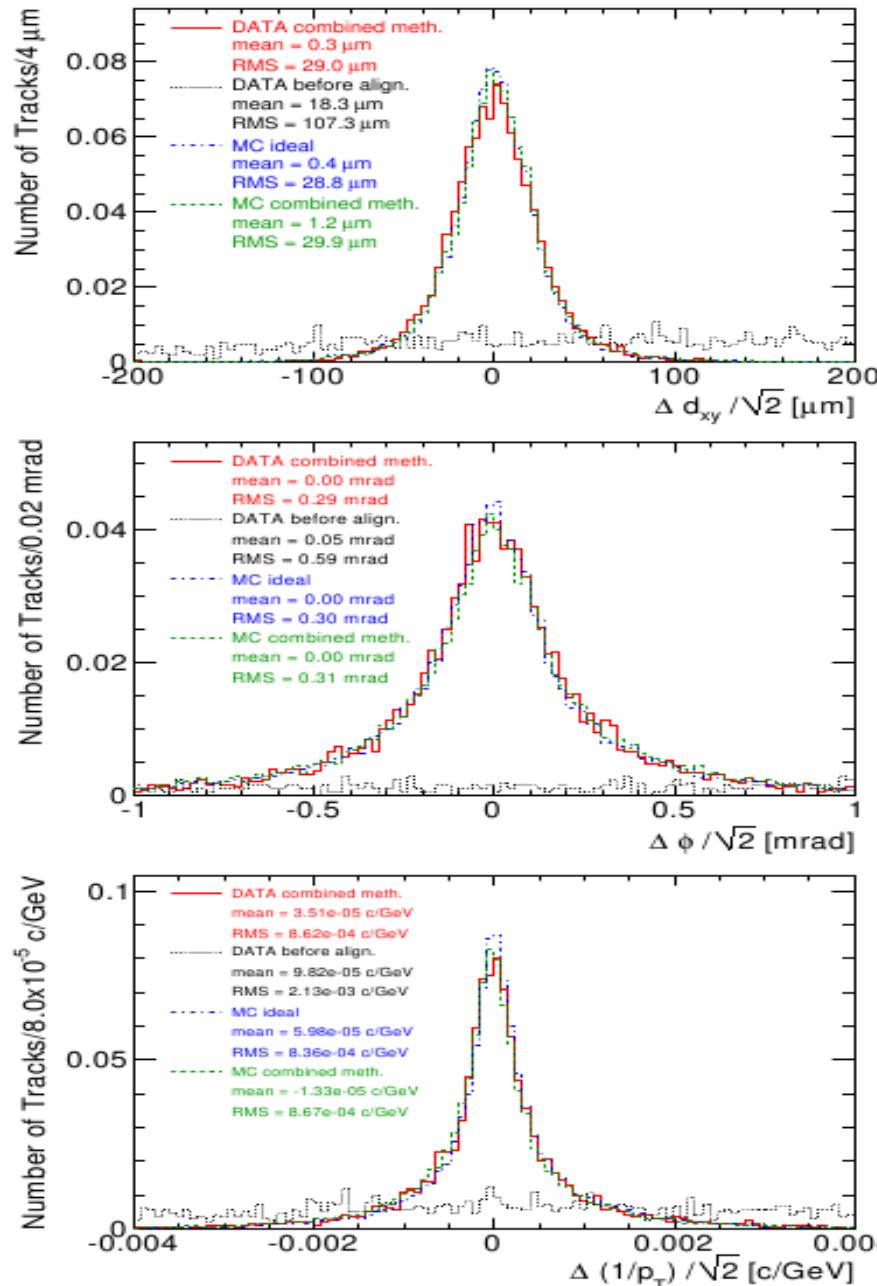


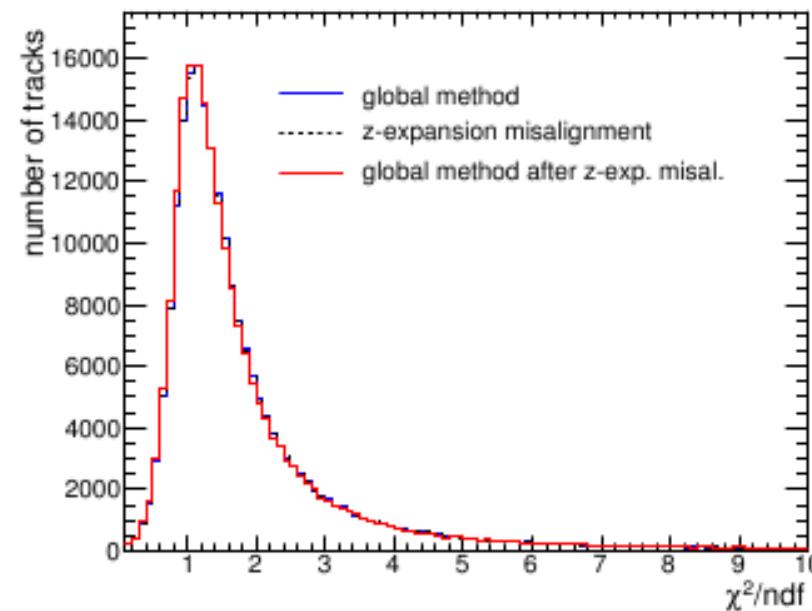
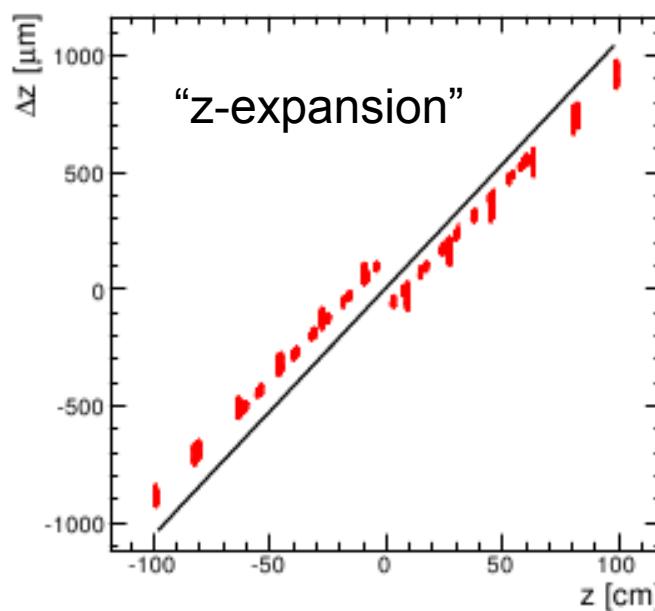
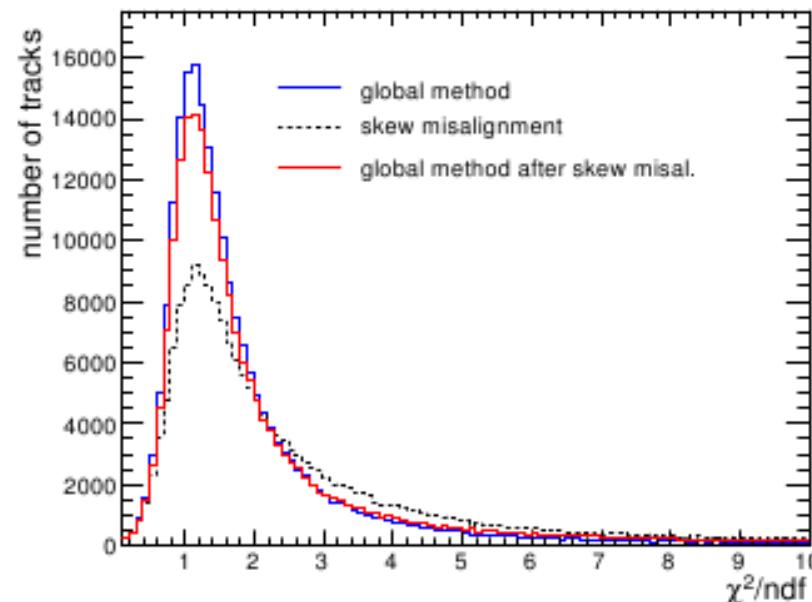
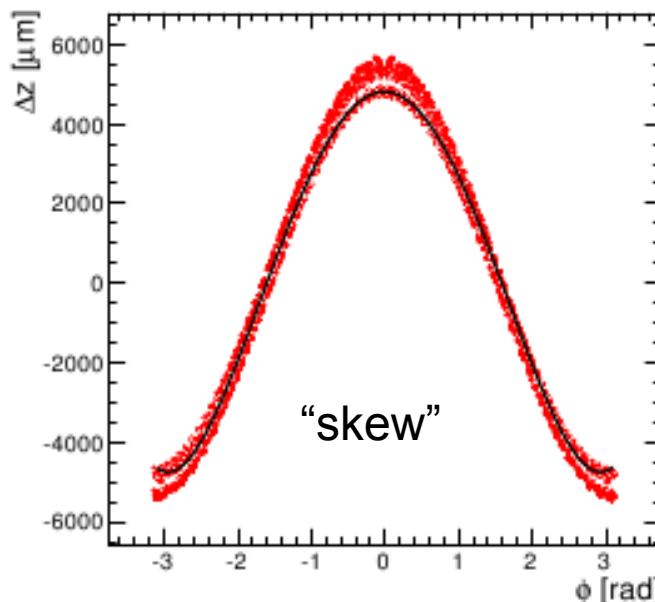




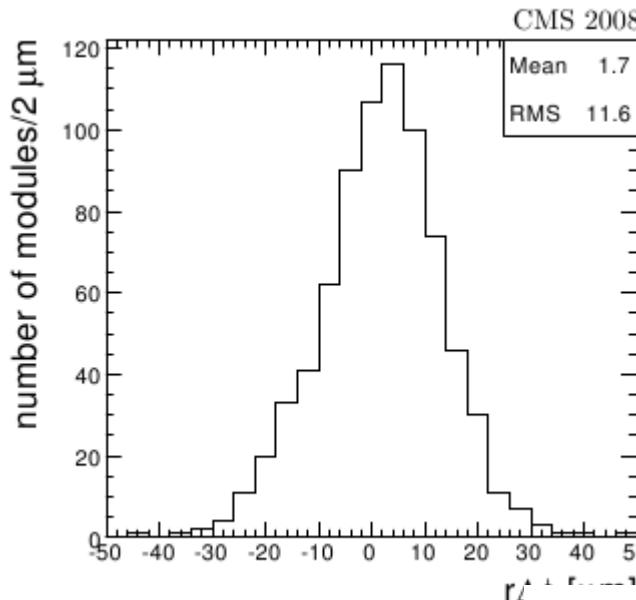
- Double-difference: $\Delta(x_{\text{hit},1} - x_{\text{hit},2}) - \Delta(x_{\text{track},1} - x_{\text{track},2})$
- Improvement with survey
- Large improvement with alignment

Track parameter resolution



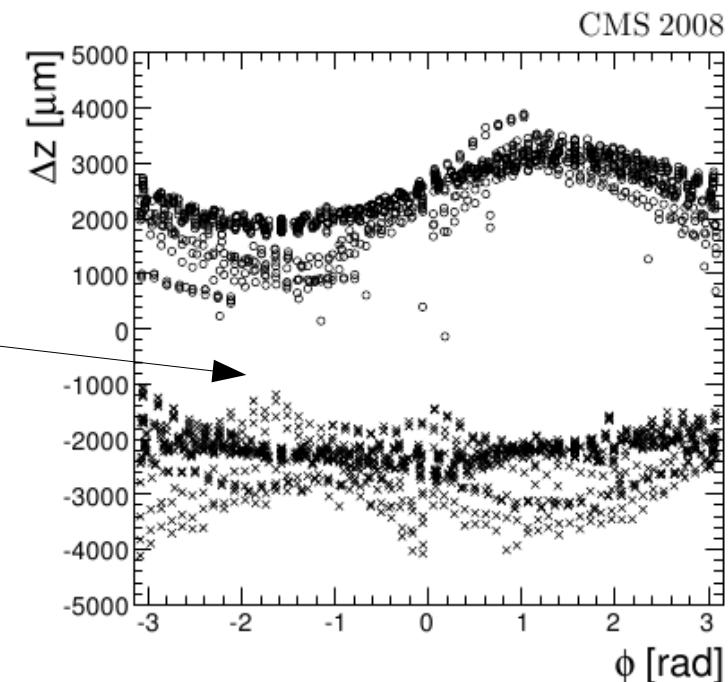
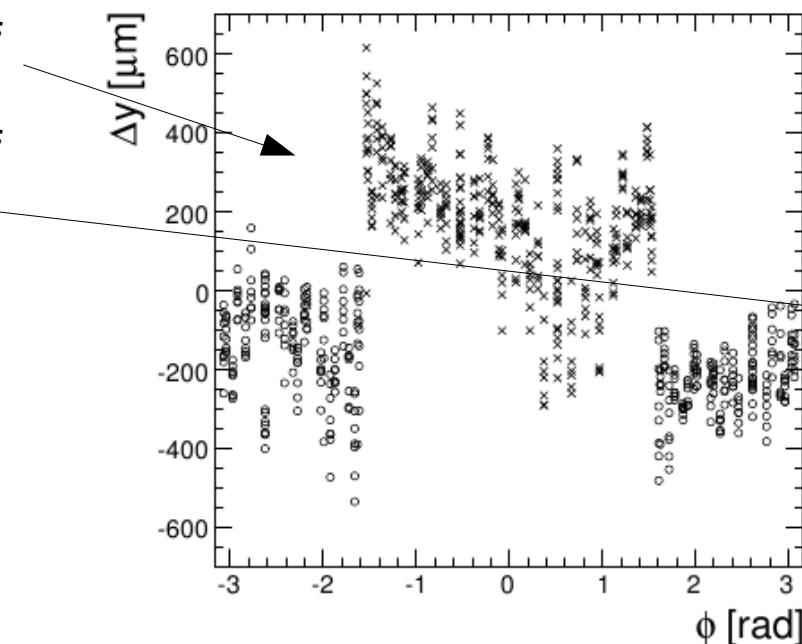


Estimate of global precision

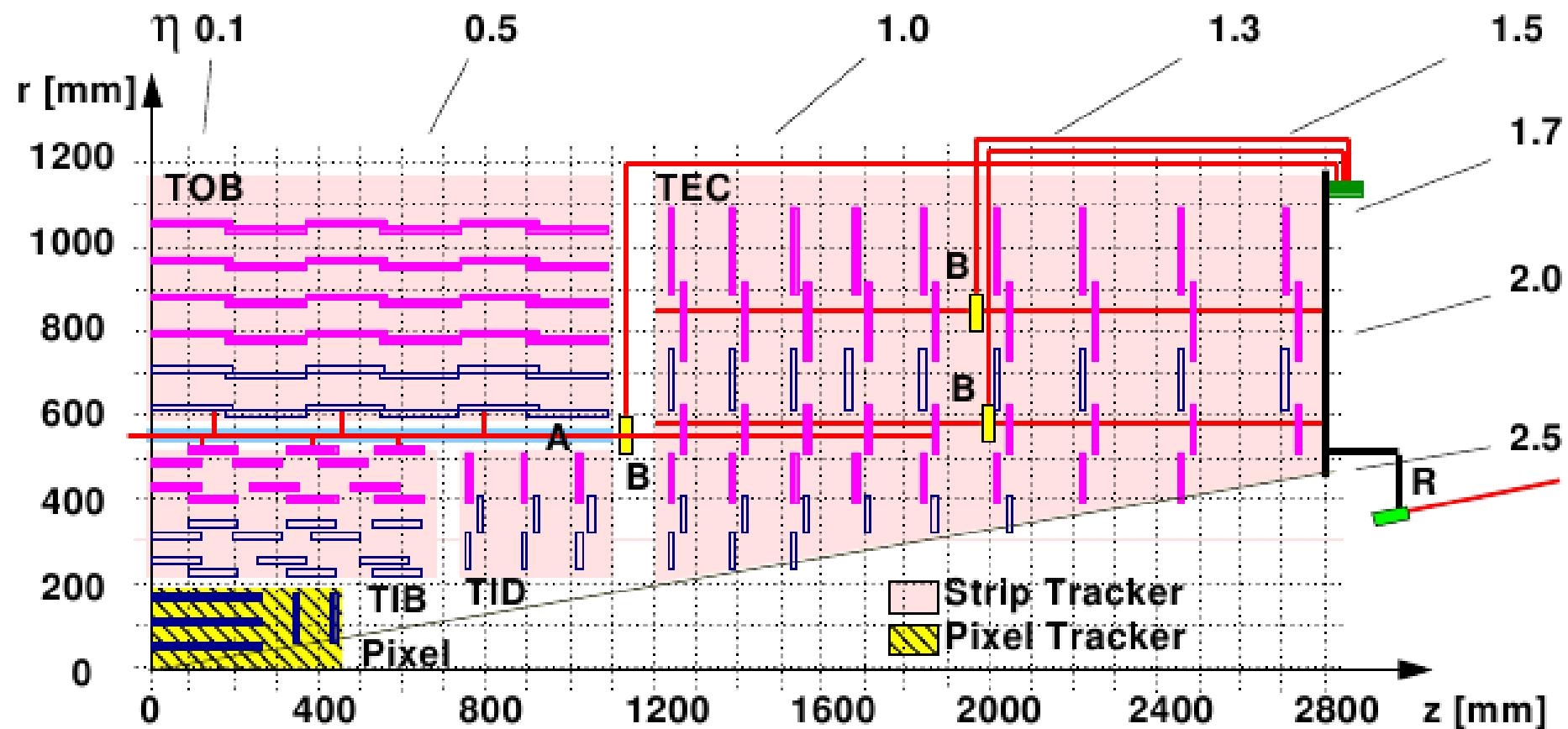


- Difference of $r^*\Delta(\phi)$ of global and local method
- Barrel pixel modules shown
- RMS $11\mu\text{m}$

- Separation in y of Pixel half barrels
- Separation in z of TIB half barrels

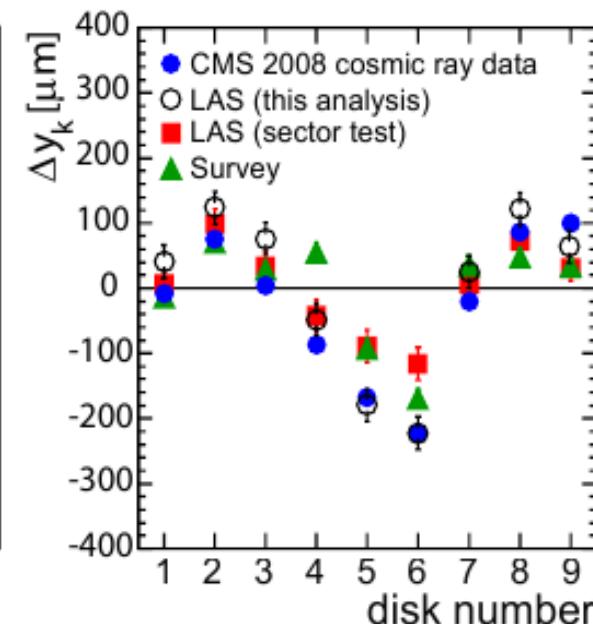
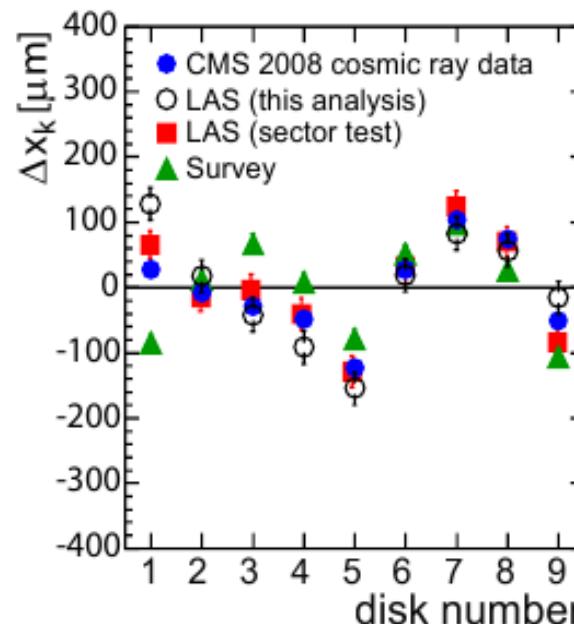
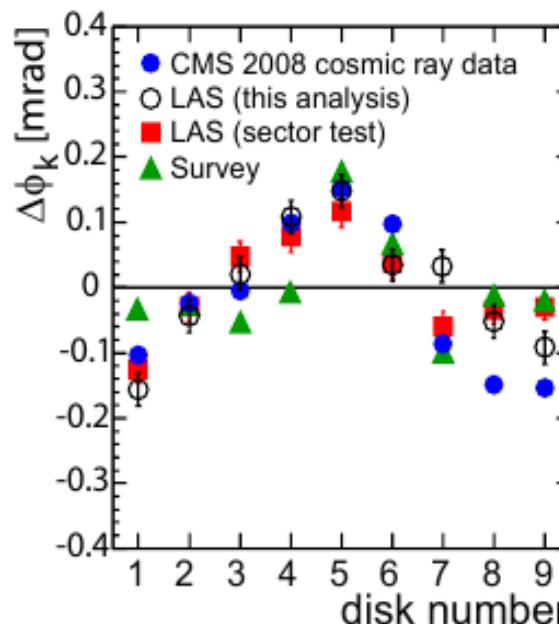


- Laser alignment system layout (positive z side)



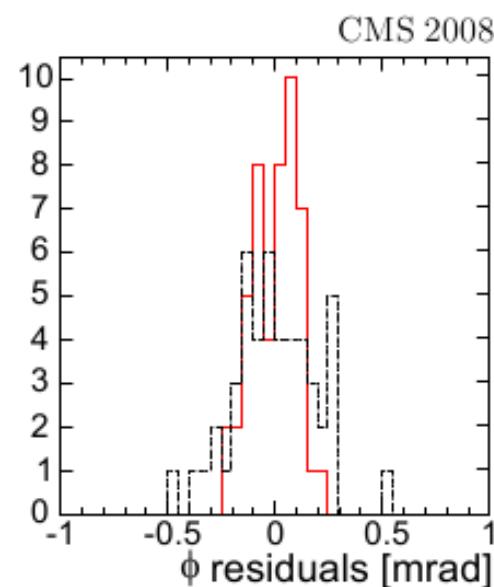
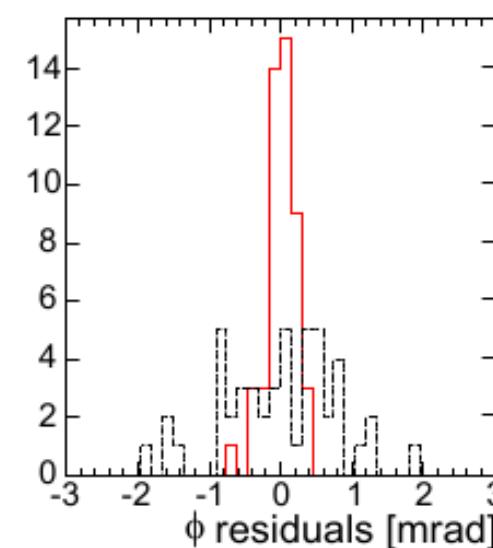
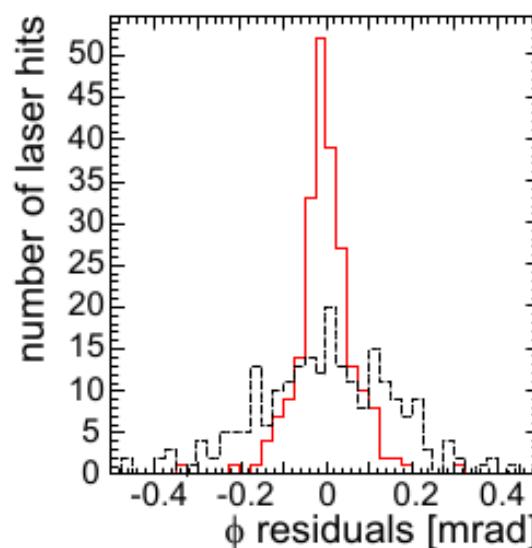
Validation with Laser Alignment System

- TEC+ laser alignment parameters: Disk parameters



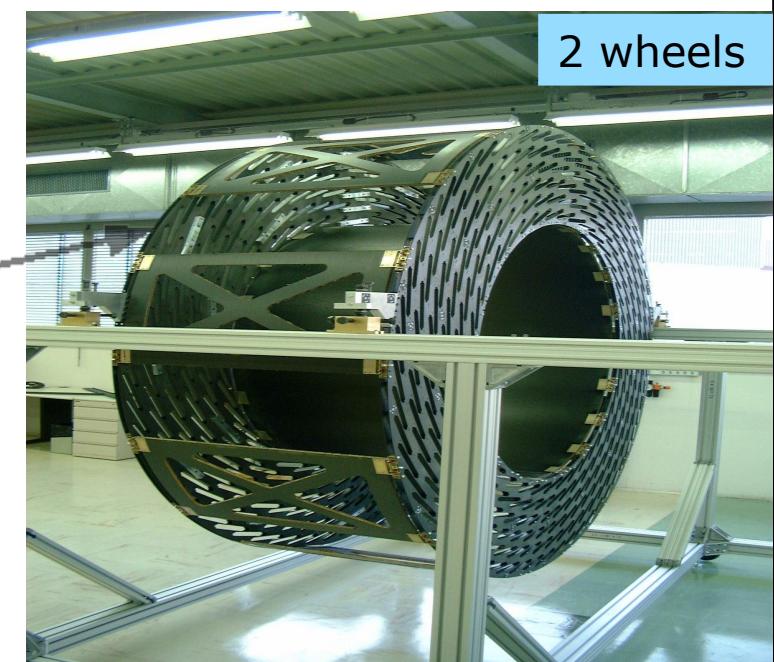
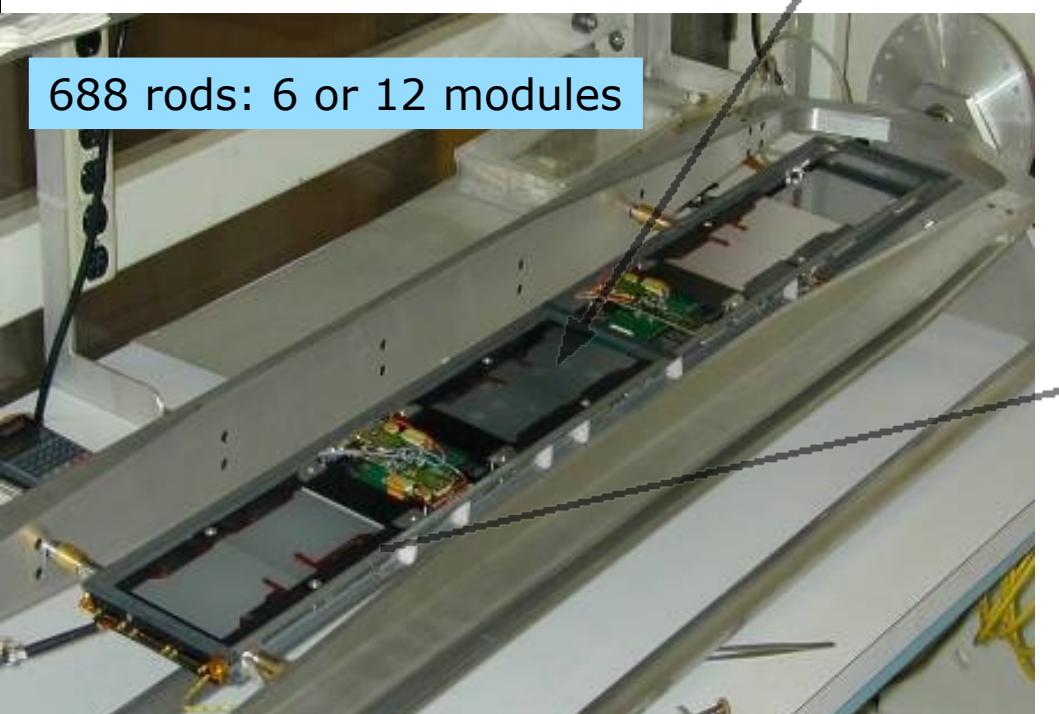
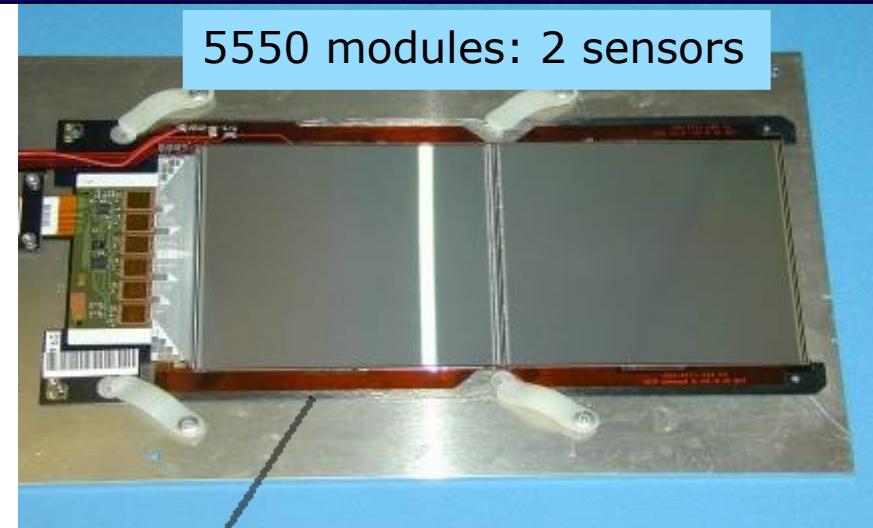
- Laser hit residuals before and after track based alignment (combined meth.)

	TIB [μrad]	TOB [μrad]	TEC [μrad]
before align.	790	200	160
aligned	200	110	70

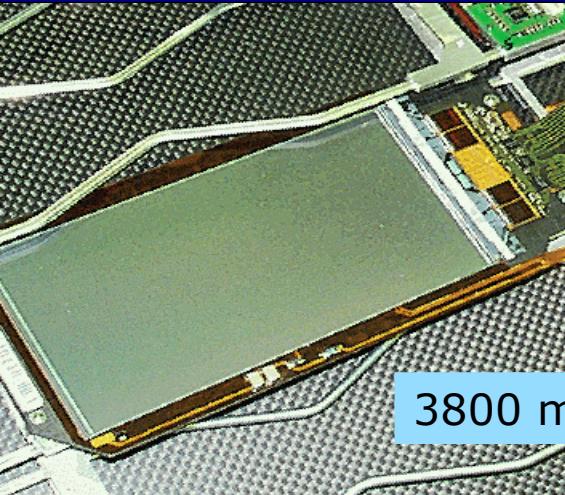


- Comparison of alignment algorithms
 - Each algorithm had its own advantages (steady development), for this analysis:
- Global method “Millepede II”
 - Includes correlations between modules
 - Few iterations (for outlier rejection)
 - Had simplified track model, no correlations due to multiple scattering
 - Had limited number of parameters
- Local Method “HIP”
 - Information from survey included
 - Kalman Filter CMS track model
 - Correlations between modules by iterations → many iterations
- Combine strength of both algorithms: “Combined method”
 - Sequentially run global method followed by local method
 - Best obtained results

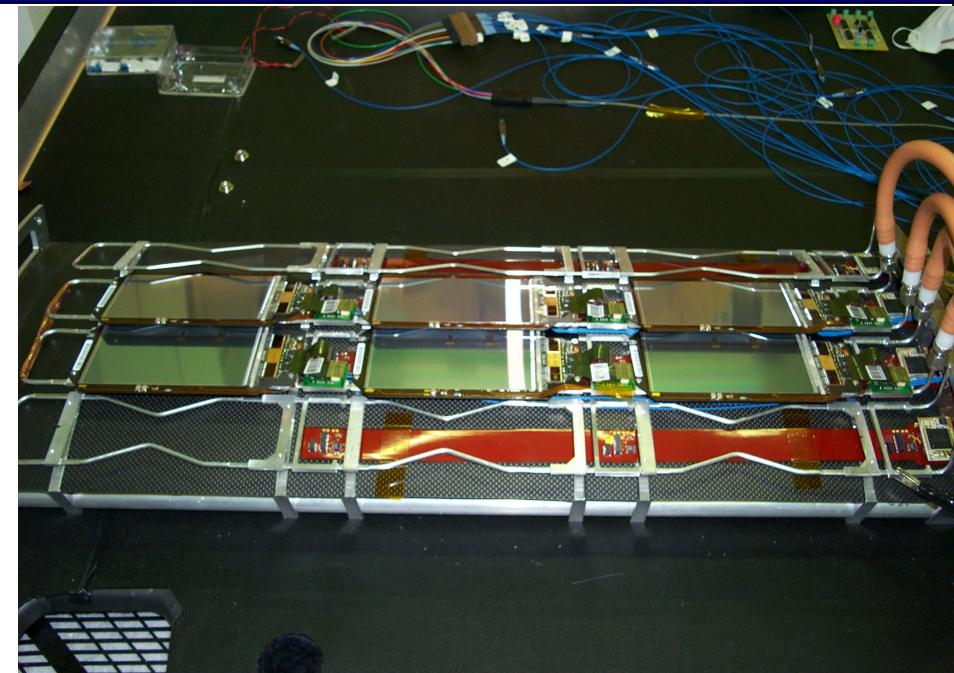
Modules and Superstructures: Outer Barrel



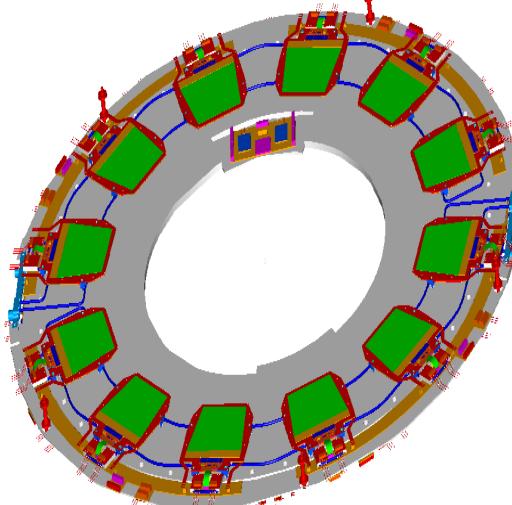
Modules and Superstructures: Inner Barrel



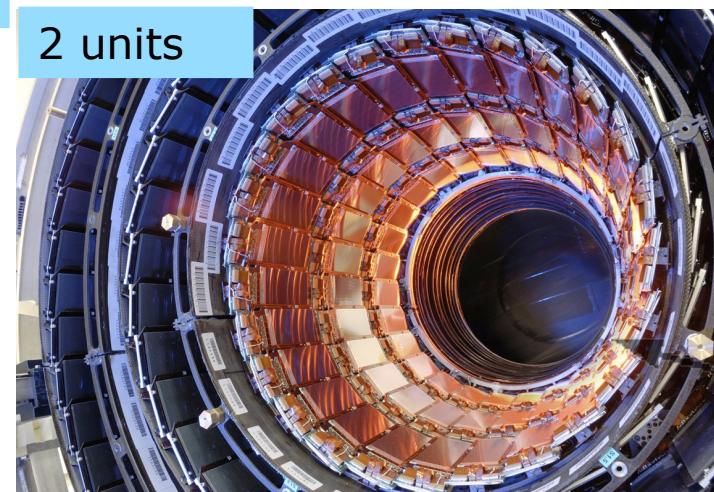
3800 modules: 1 sensor



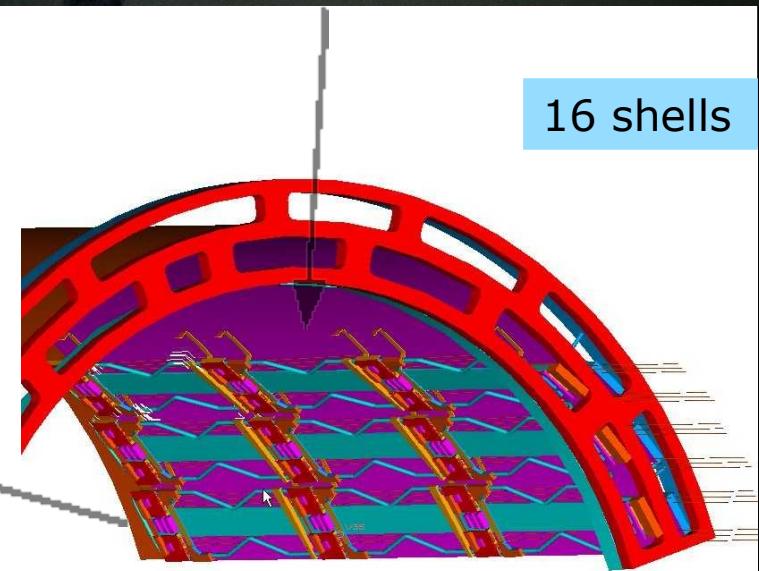
6 Tracker Inner Disk



2 units

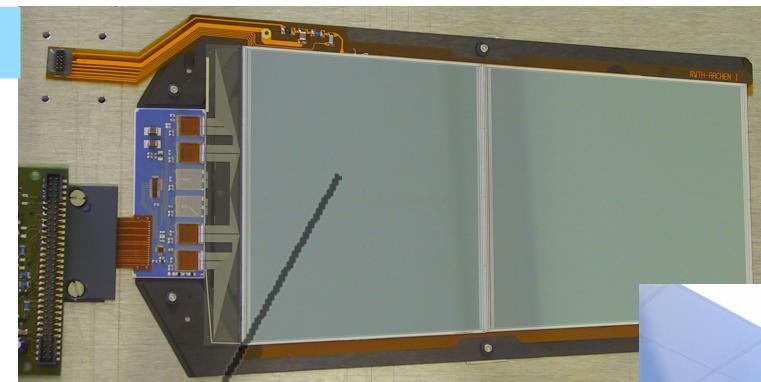


16 shells

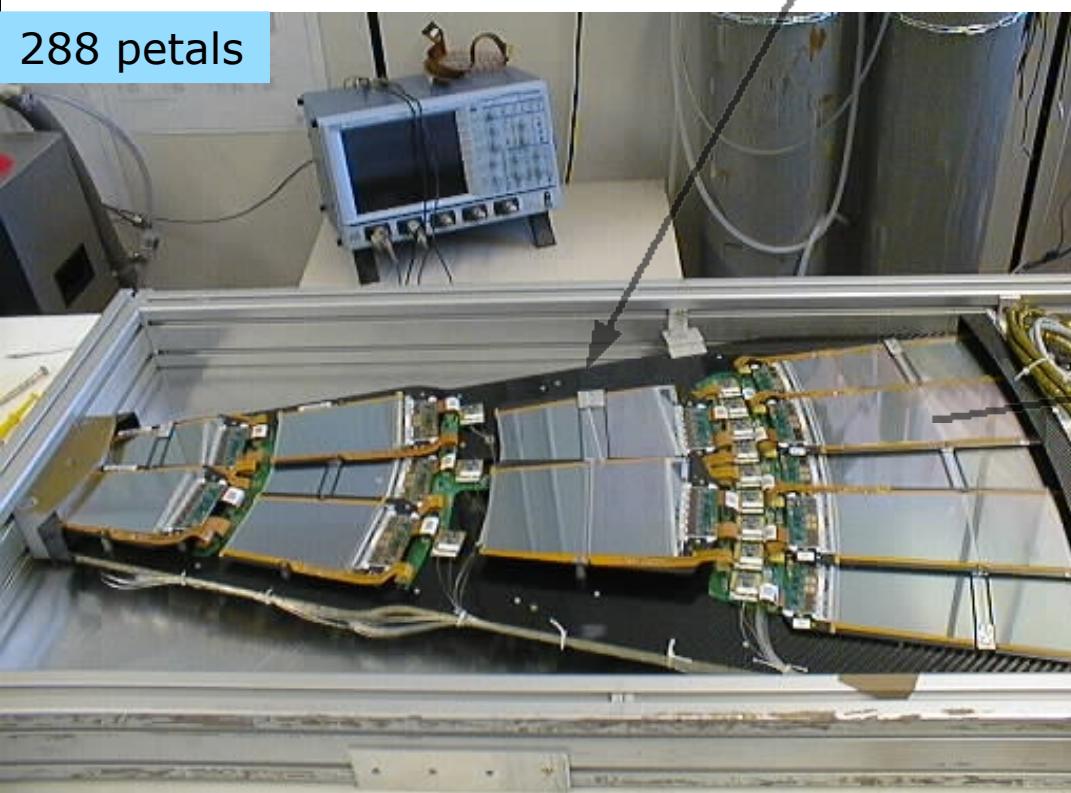


Modules and Superstructures: Endcap

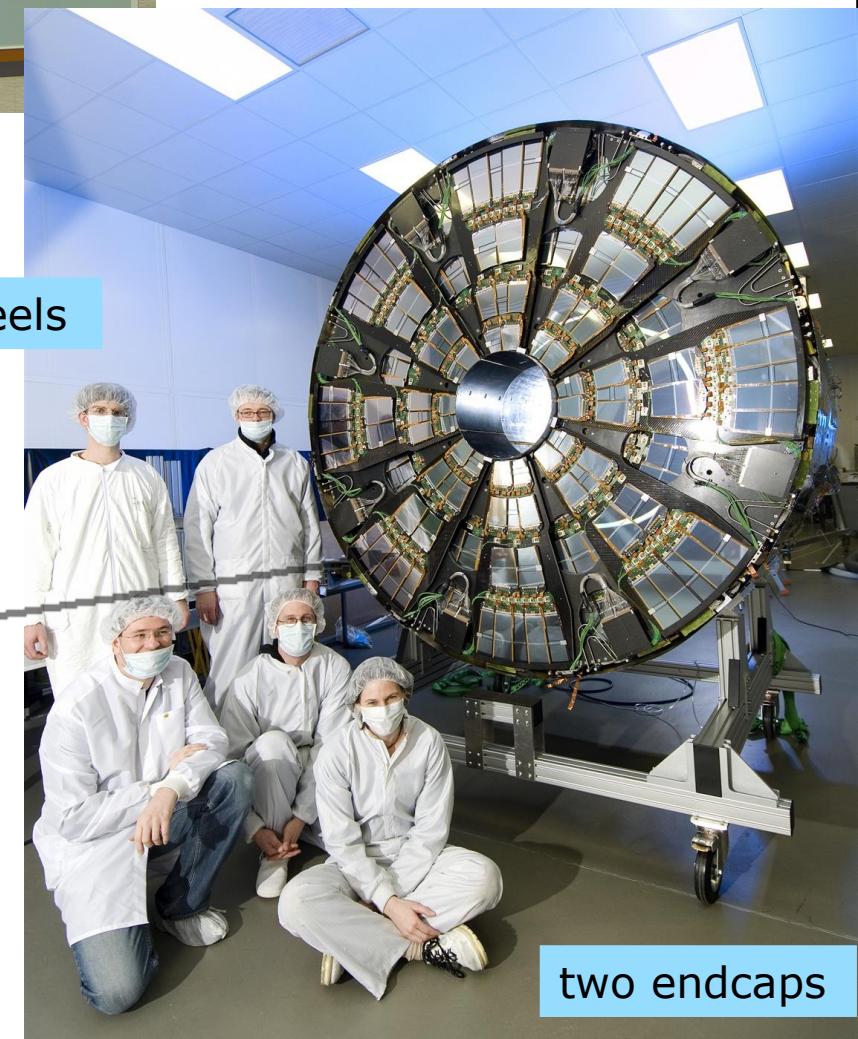
3800 modules: 1..2 sensor



288 petals



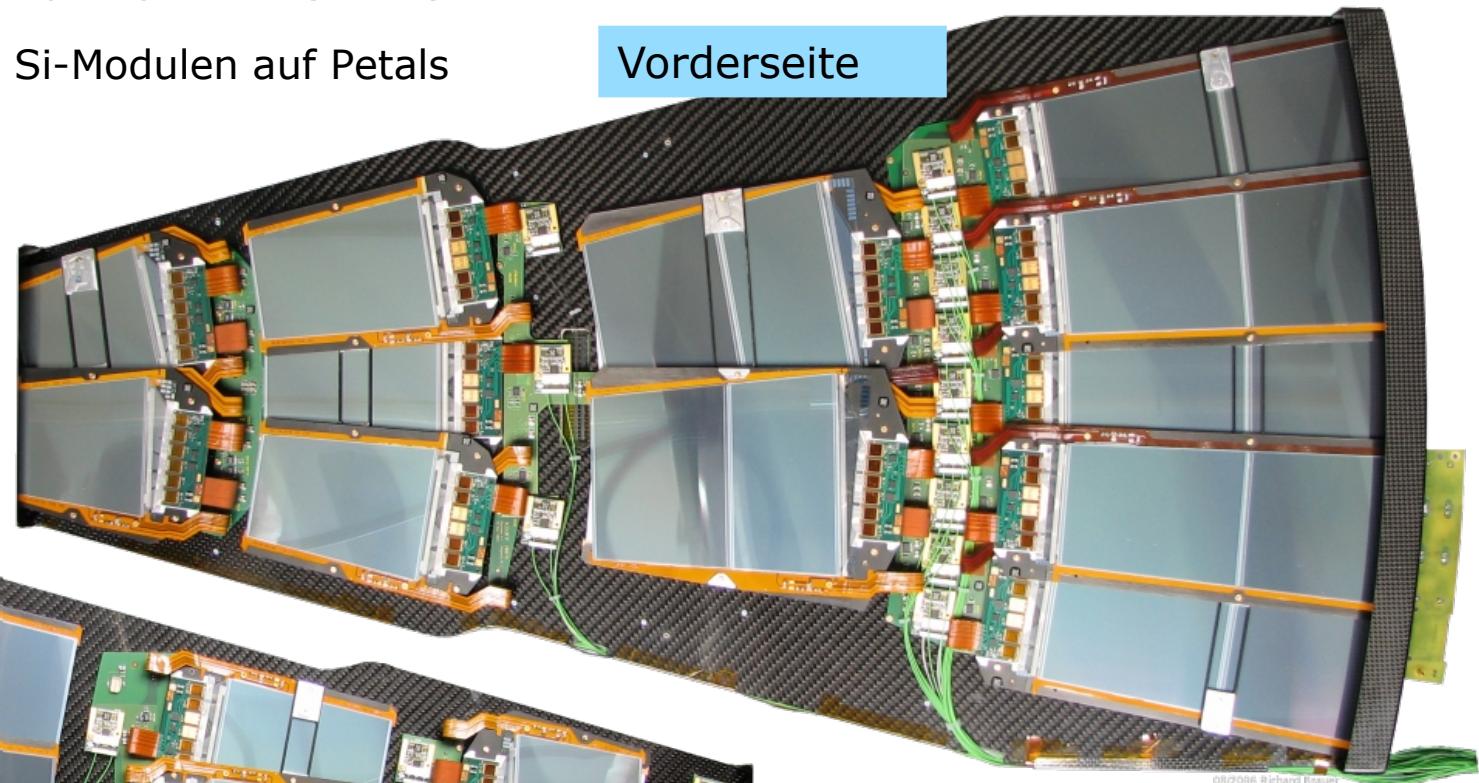
18 wheels



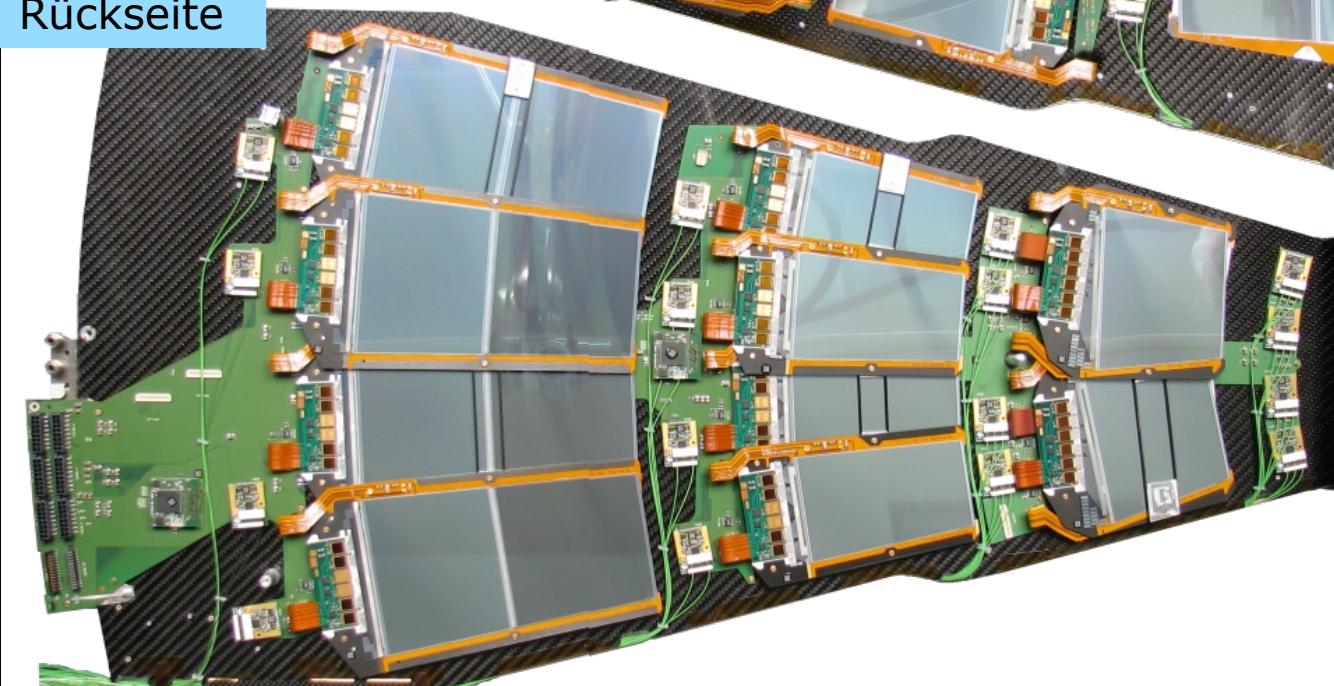
two endcaps

- Montage und Test von Optohybriden (AOHs) und Lichtleitern auf allen 288 CMS Petal
- Montage und Test von Si-Modulen auf Petals

Vorderseite



Rückseite



October & November 2008: Cosmic Run with full CMS detector

296 million cosmic tracks with muon system, strip tracker and full 3.8T field recorded,

4.77 million tracks in tracker after rough quality cuts, 4.2M with $p_T > 4$ GeV

Summer 2009: Similar numbers (deconvolution & peak mode)

Run 66748, Event 8900172, LS 160, Orbit 167345832, BX 2011

