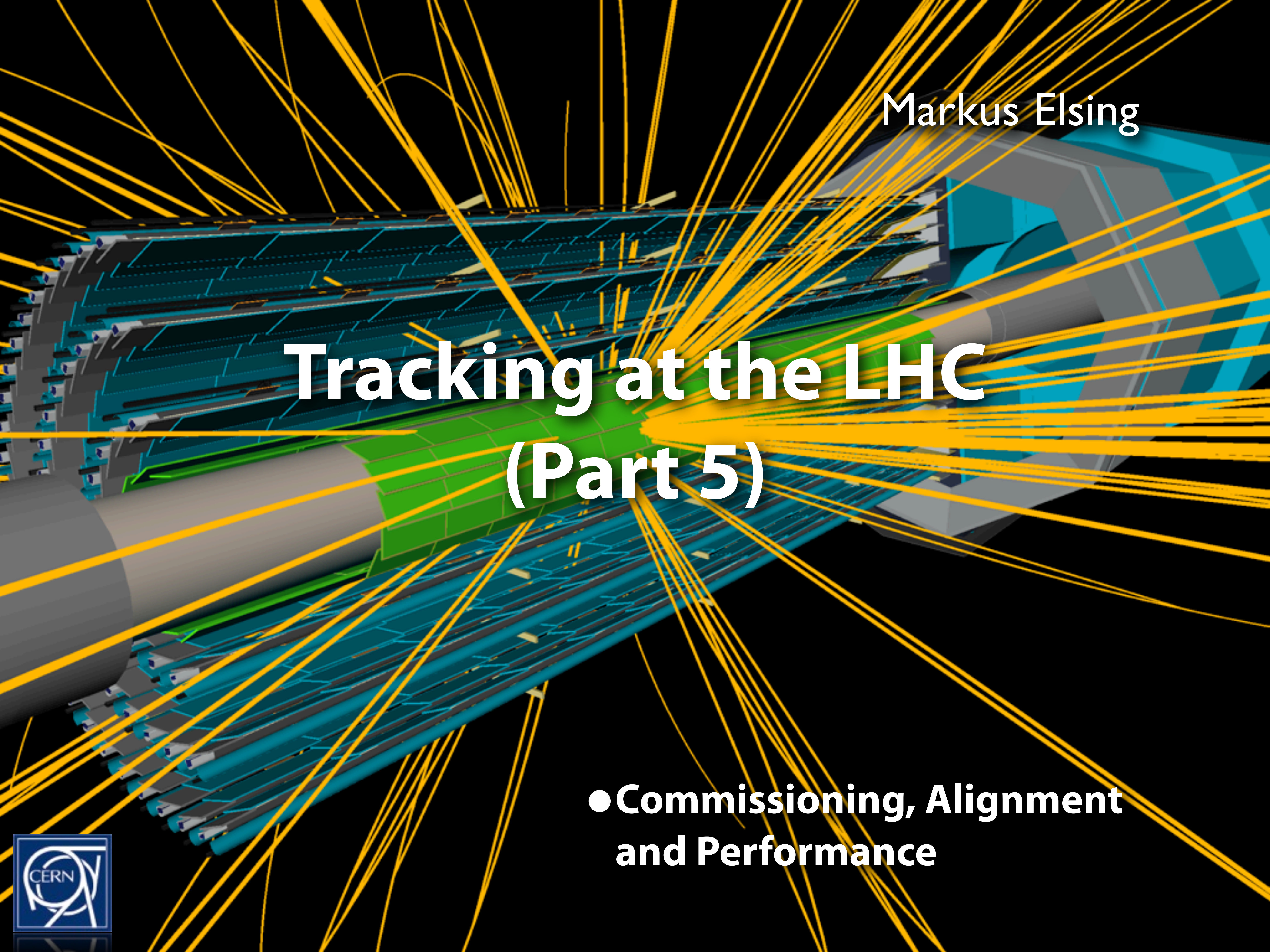


Markus Elsing

Tracking at the LHC (Part 5)

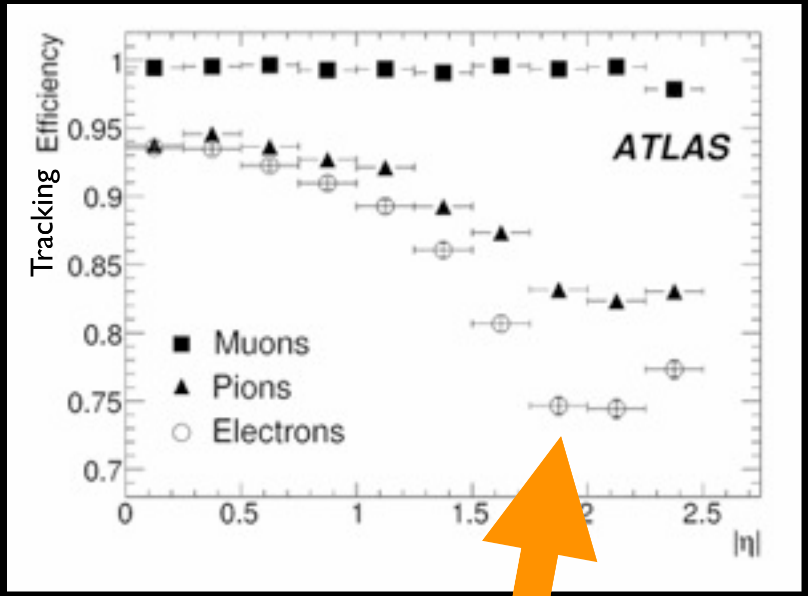
- Commissioning, Alignment and Performance

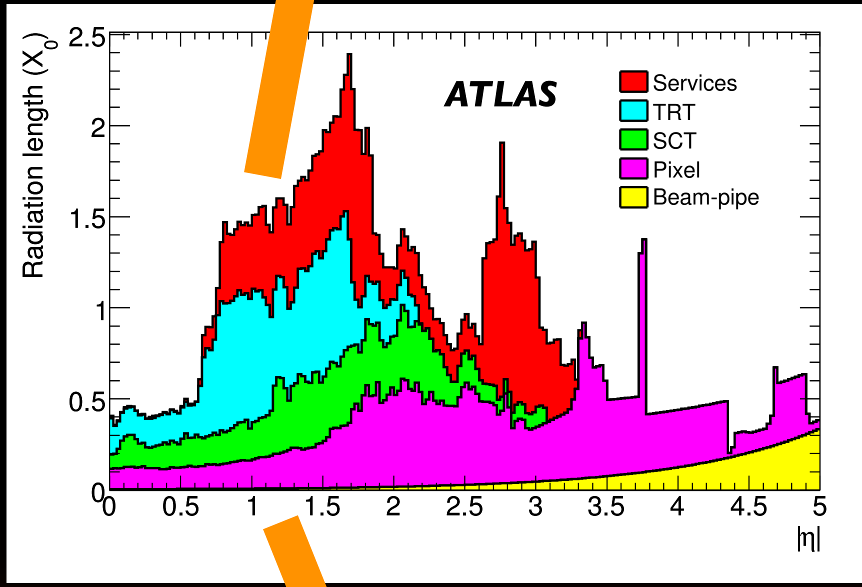
Outline of Part 5

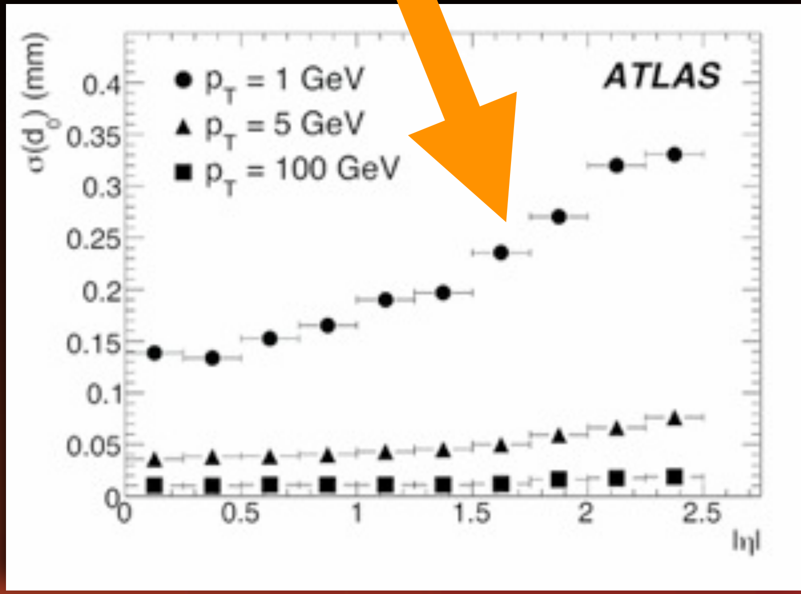
- recap expectations on tracking performance
- commissioning of detector and tracking
  - ➡ material studies, alignment
  - ➡ vertexing and b-tagging performance

Expected Performance

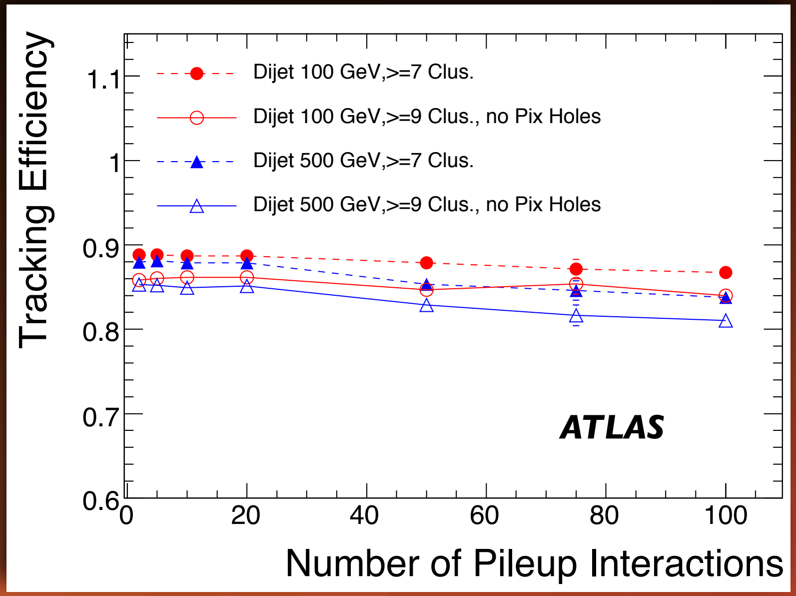
- excellent preparation before startup
  - ➡ more than 10 years of simulation and test beam
  - ➡ cosmics data taking in 2008 and 2009
  - ➡ payed off last year !
- detailed simulation studies
  - ➡ document expected performance in TDRs
  - ➡ few of the known critical items:
    - material effects limit efficiency and resolution at low p_t
    - good (local) alignment for b-tagging
    - momentum scale and alignment "weak modes"
  - ➡ focus for commissioning of tracking and vertexing





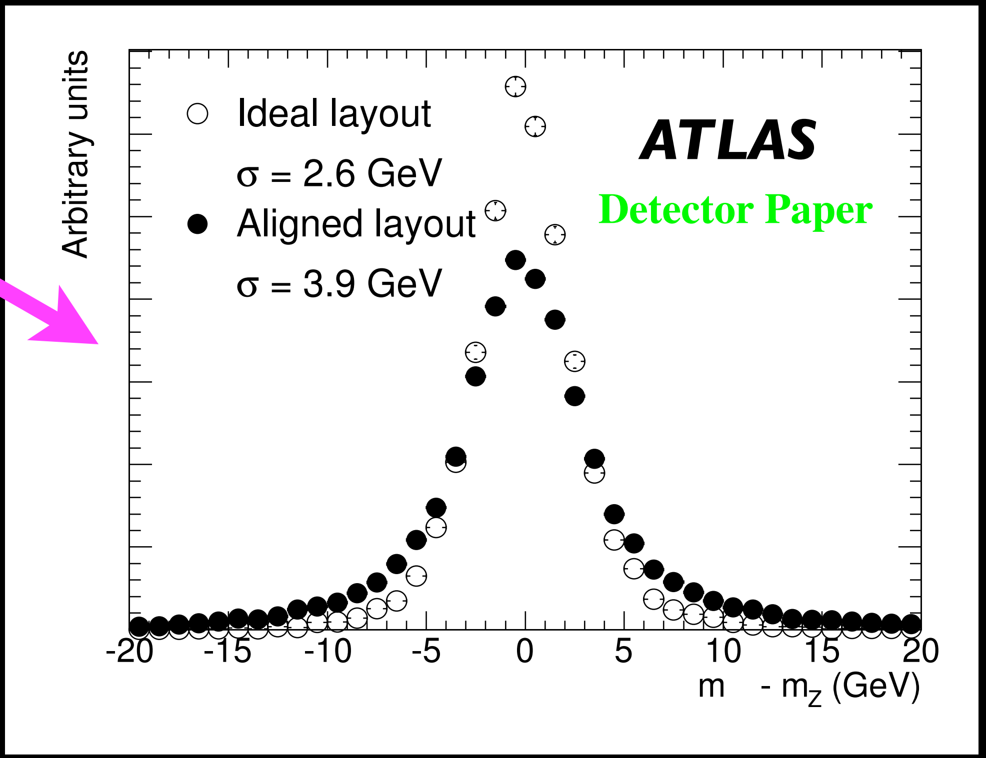


performance with event pileup

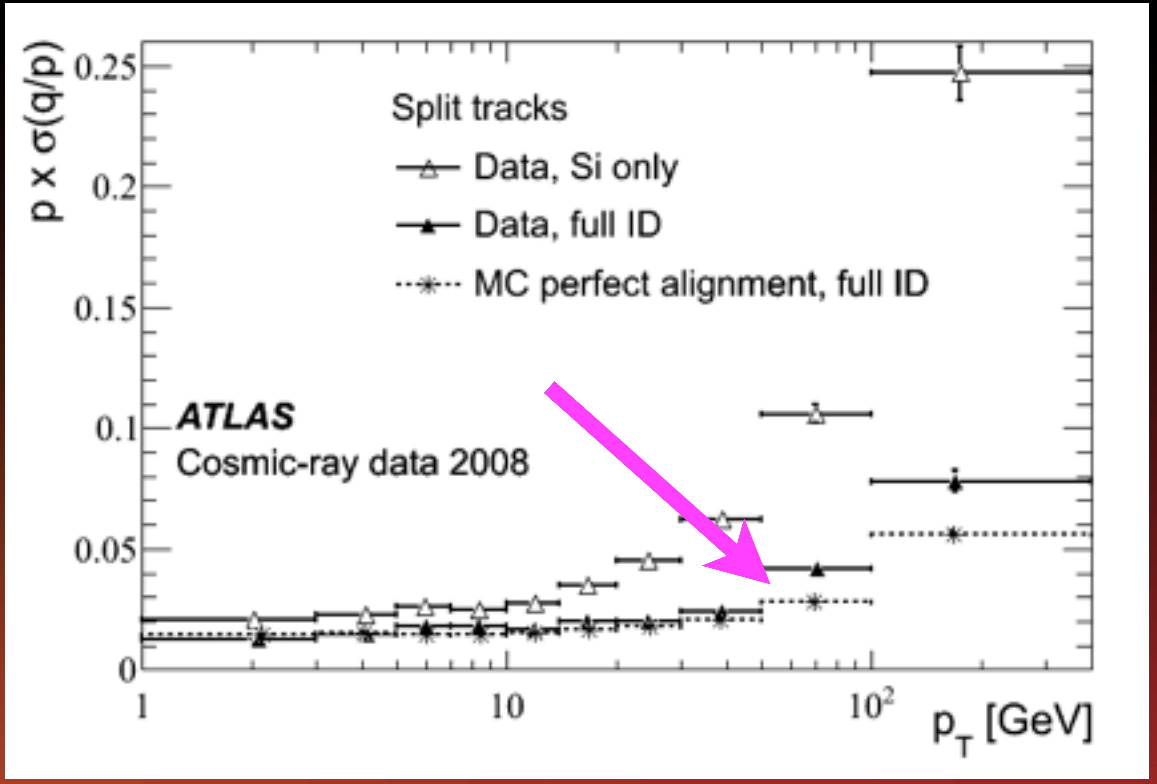


Expected Difficulties ?

- Detector Paper MC study:
  - ➡ ideal Z mass resolution 2.6 GeV
  - ➡ misalign MC by 100 µm, re-align using:
    - high-p_T muons and cosmics
  - ➡ Z mass resolution degraded to 3.9 GeV (!)
    - need to use external constraints to improve



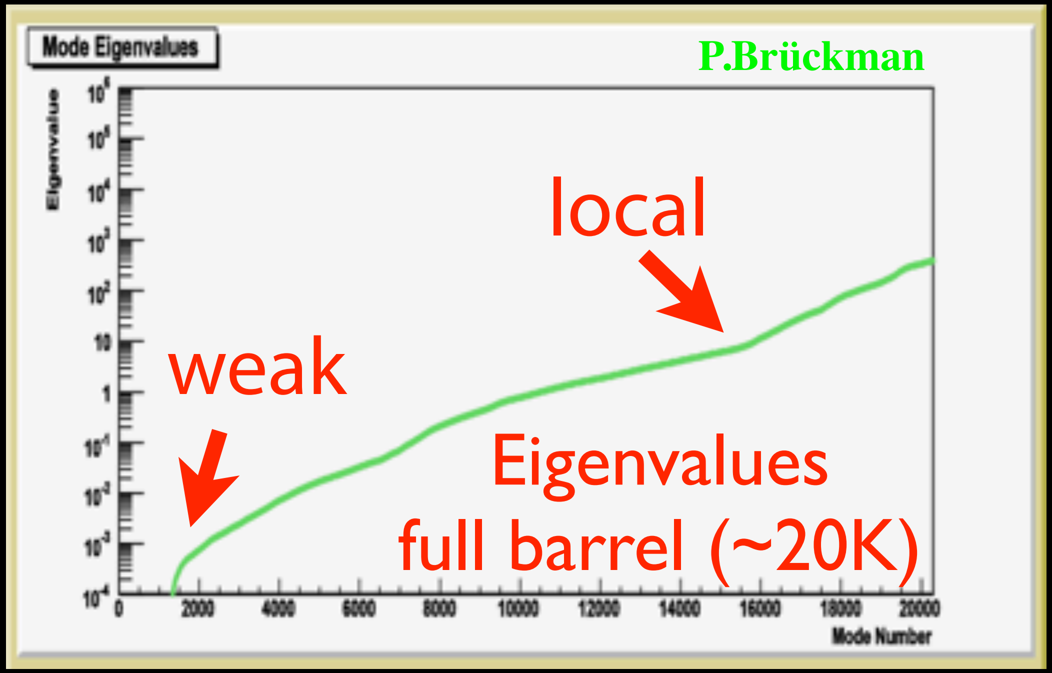
- cosmics study using split tracks
  - ➡ good performance overall
    - cosmics are mostly in the barrel (!)
    - done with the alignment at the time...
  - ➡ but: at higher p_T the data starts to diverge from MC



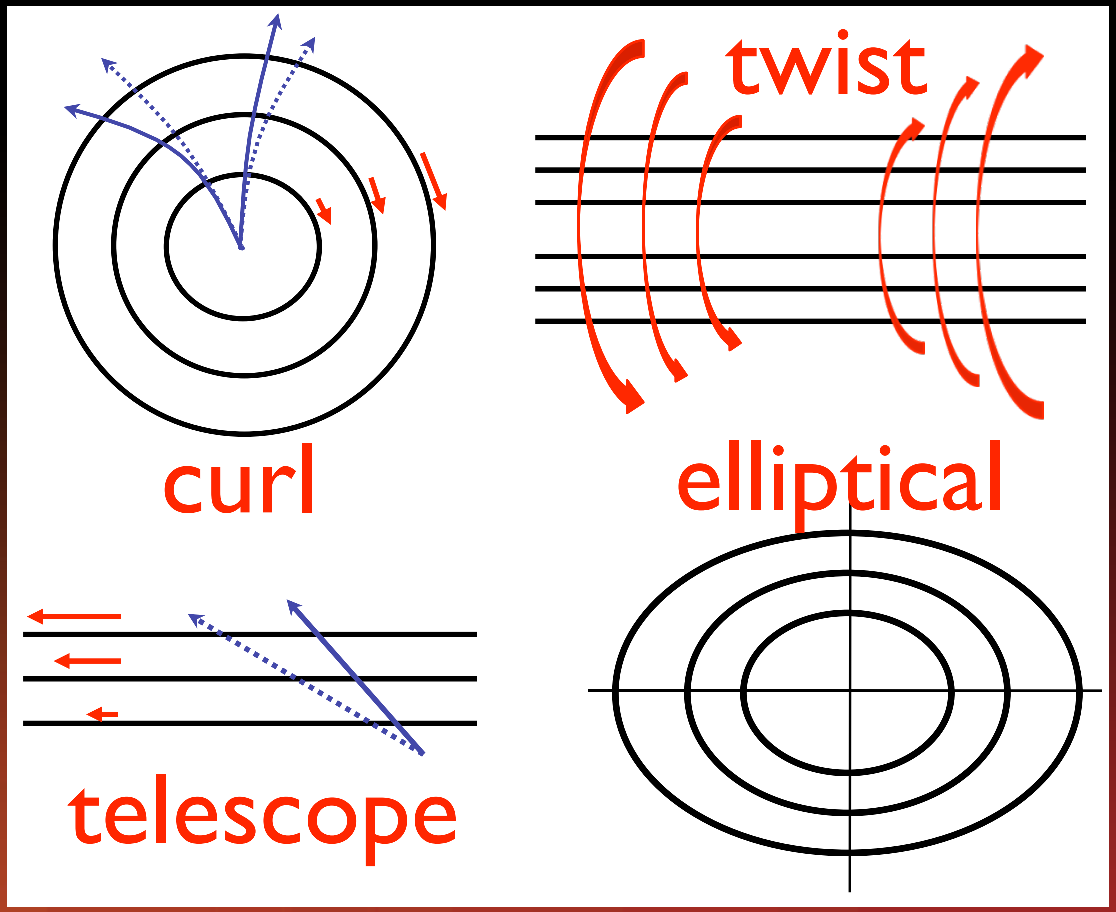
- what was the reason ?

Alignment and Weak Modes

- global-χ^2 alignment
  - ➡ diagonalize alignment matrix (36k x 36k)
  - ➡ enables studies of Eigenvalue spectrum
    - well constraint : local movements
    - less well constaint : overall deformations
    - not constraint : global transform



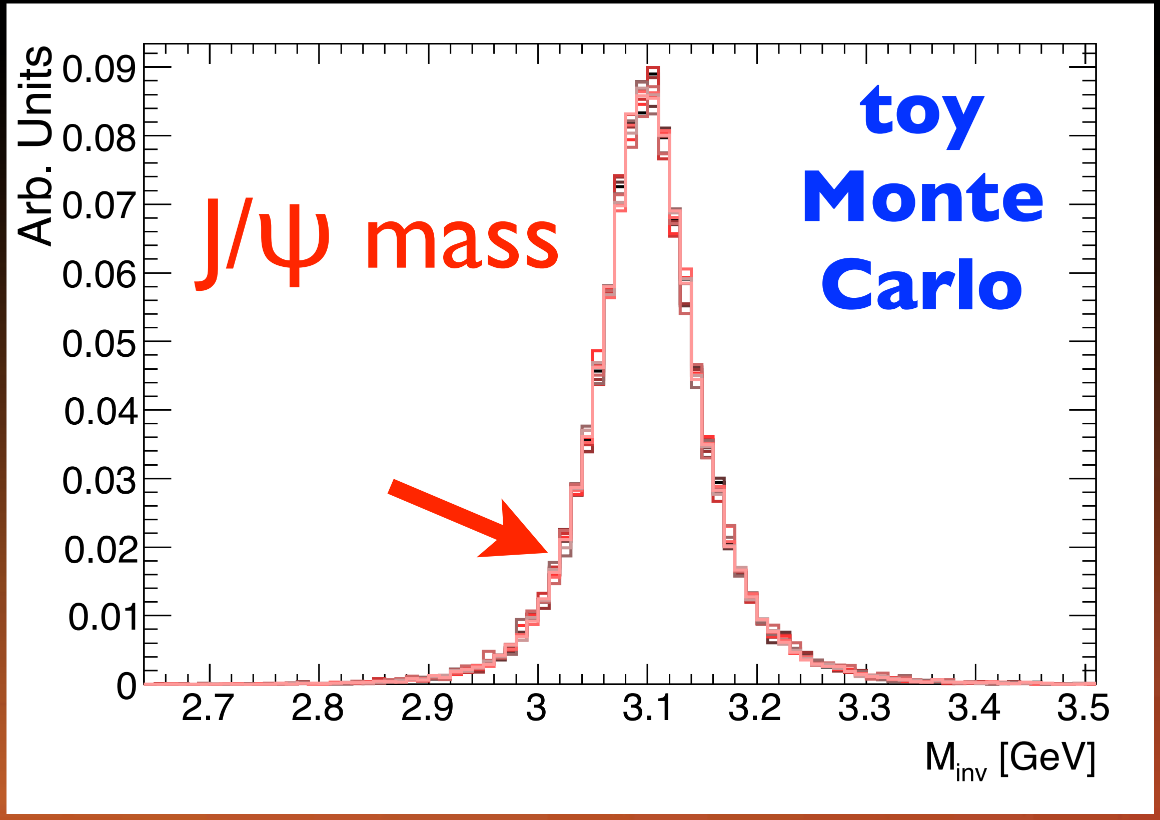
- weak modes affect p_T-scale:
  - ➡ overall deformations that leave $\Delta\chi^2 \sim 0$
  - ➡ examples

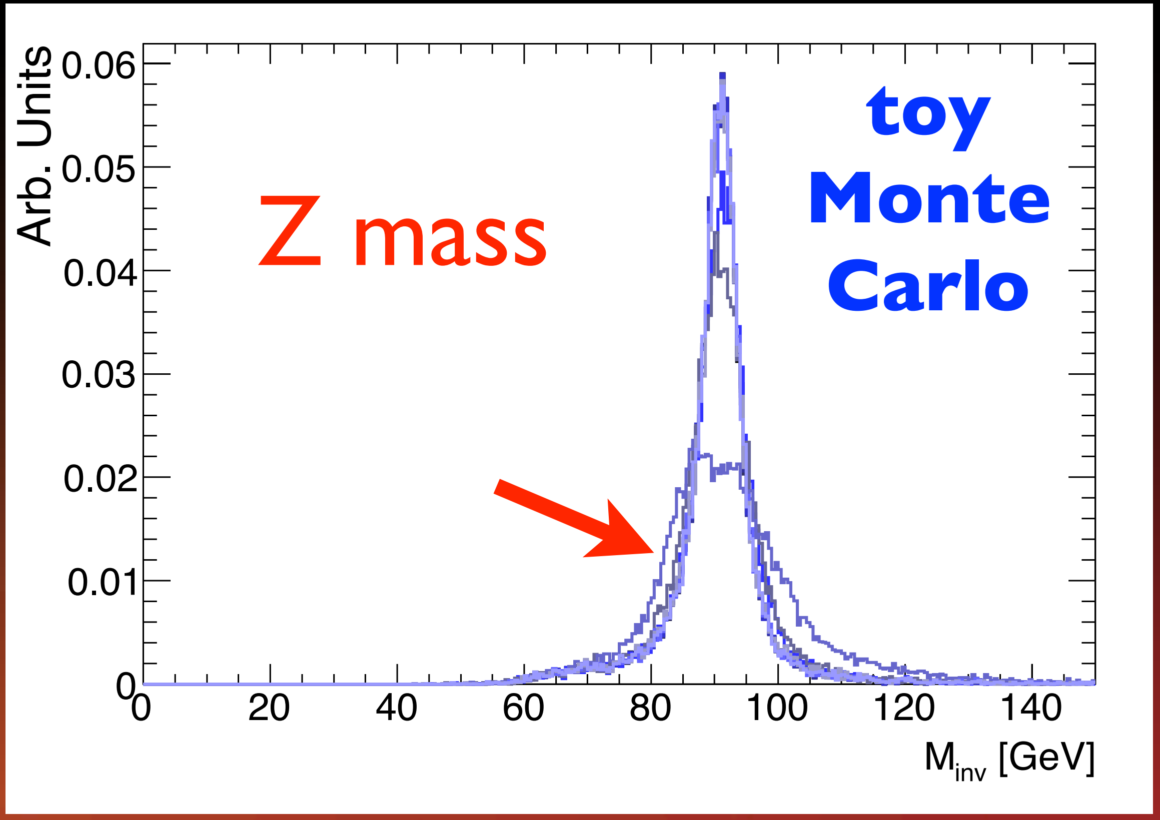


- b-tagging:
  - ➡ mostly sensitive to local movements
  - ✓ beam spot constraint in alignment

Monte Carlo Study of Weak Modes

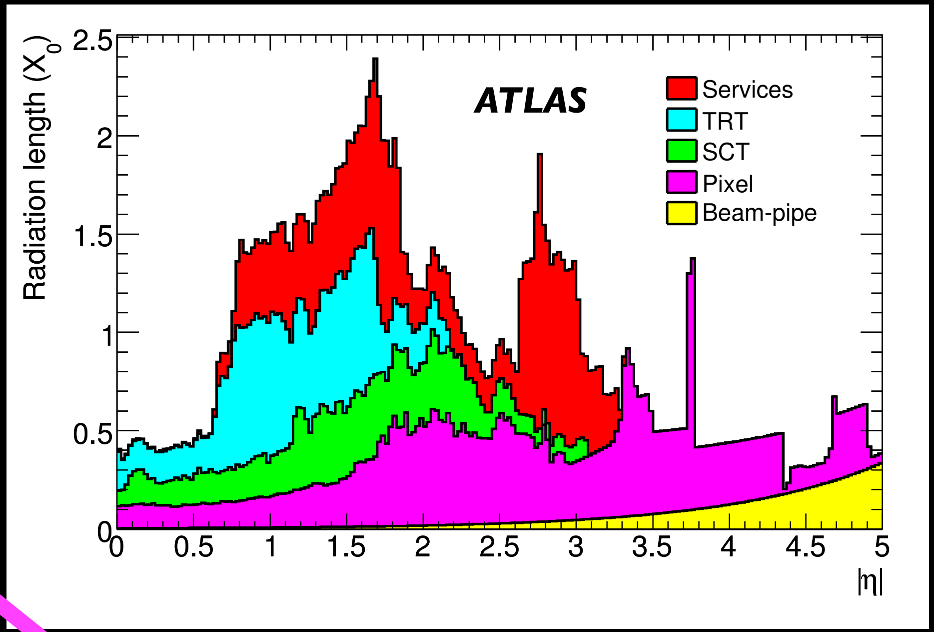
- use ad-hoc alignment sets with weak modes
  - ➡ 9 'easy' modes introduced by hand
  - ➡ rerun reconstruction to study effect on Z and J/ψ mass
  - ➡ compare against nominal Monte Carlo
- qualitatively one sees clear effects...
  - ➡ some modes affect the mass resolution
  - ➡ relative effect on J/ψ much smaller, much larger effect on Z

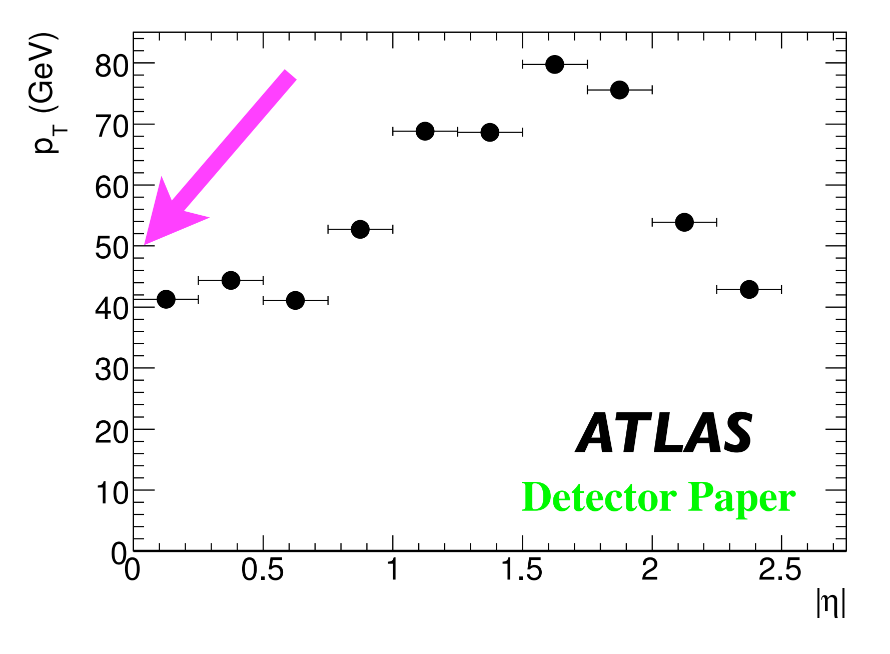


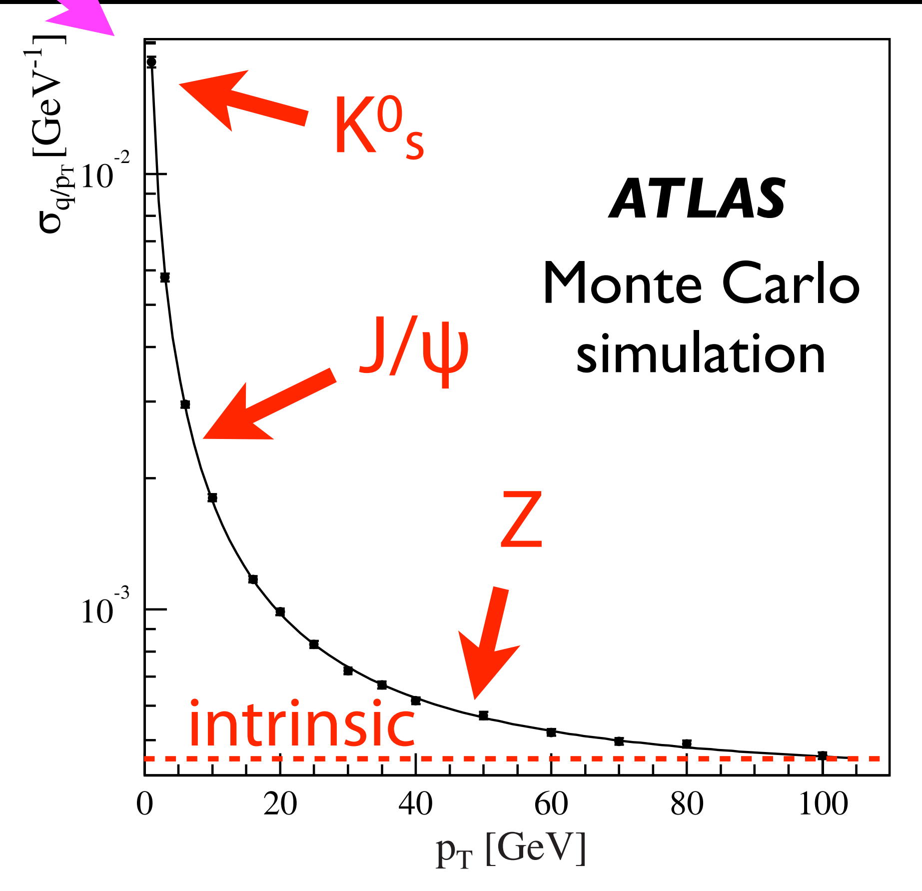


Material vs Momentum Resolution

- resolution model: **$\sigma(q/p_T) = a \oplus b/p_T$**
  - ➡ **a** describes intrinsic resolution
  - ➡ material dominated
    - huge multiple scattering term **b**
- at ~50 GeV the intrinsic resolution equals the multiple scattering term
  - ➡ similar effects for CMS, but 4T B-field helps
  - ➡ important to understand tracking performance



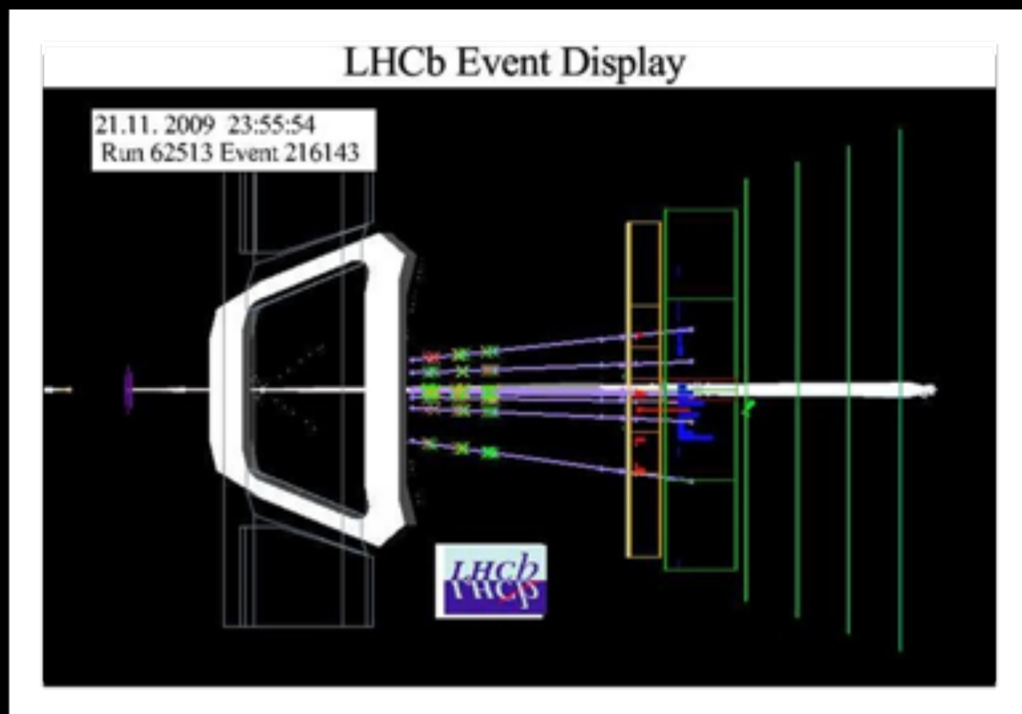


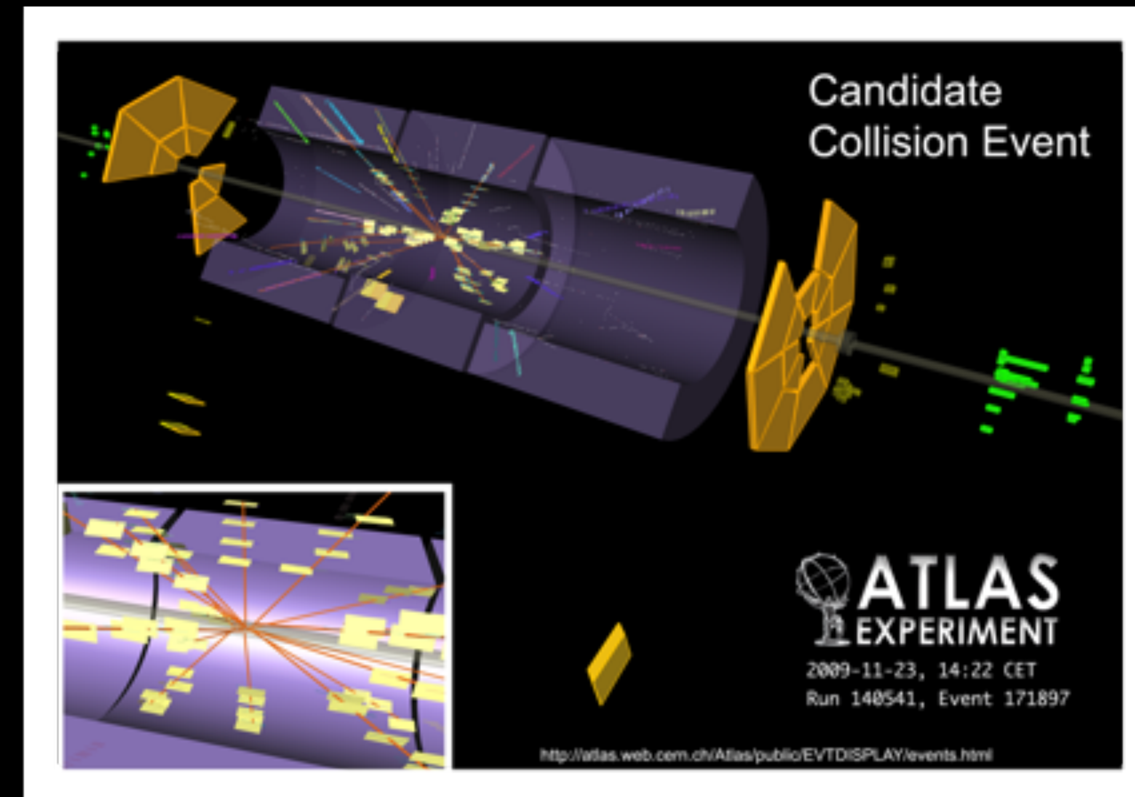


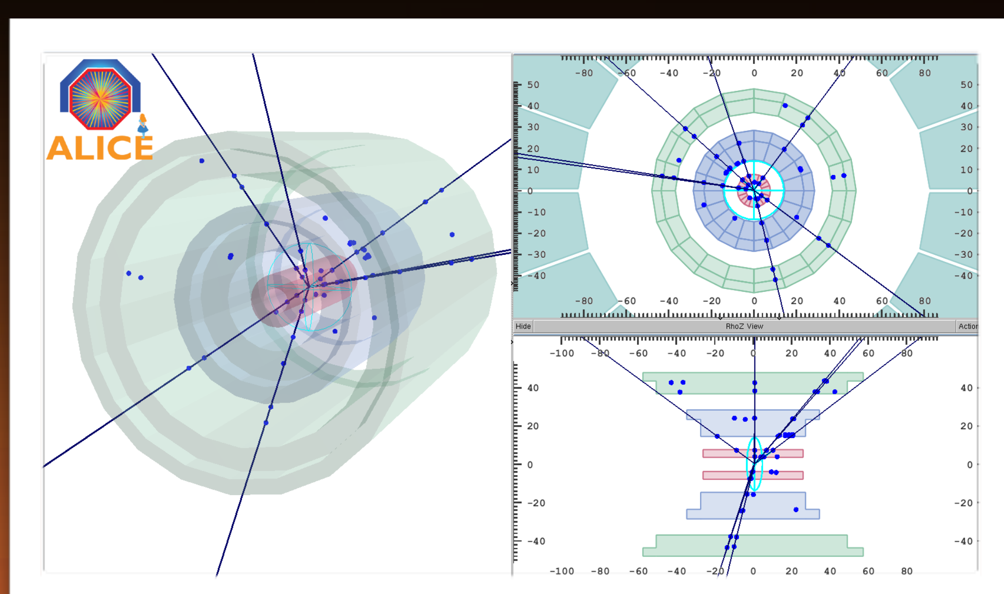
Excitement with first beams...

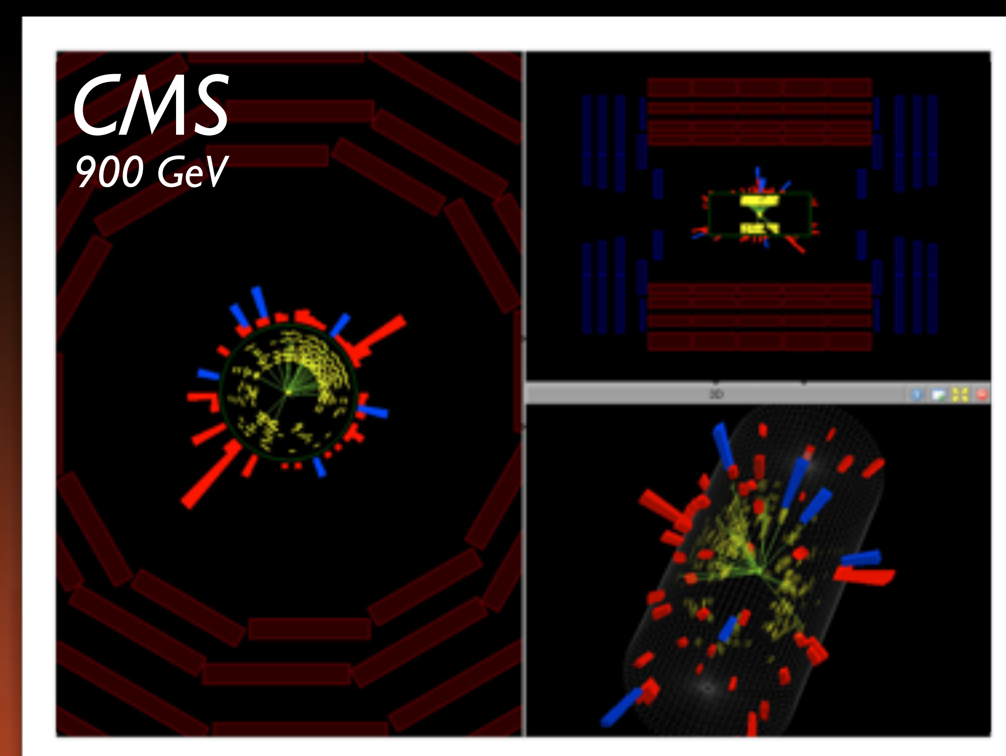



... and first Collisions



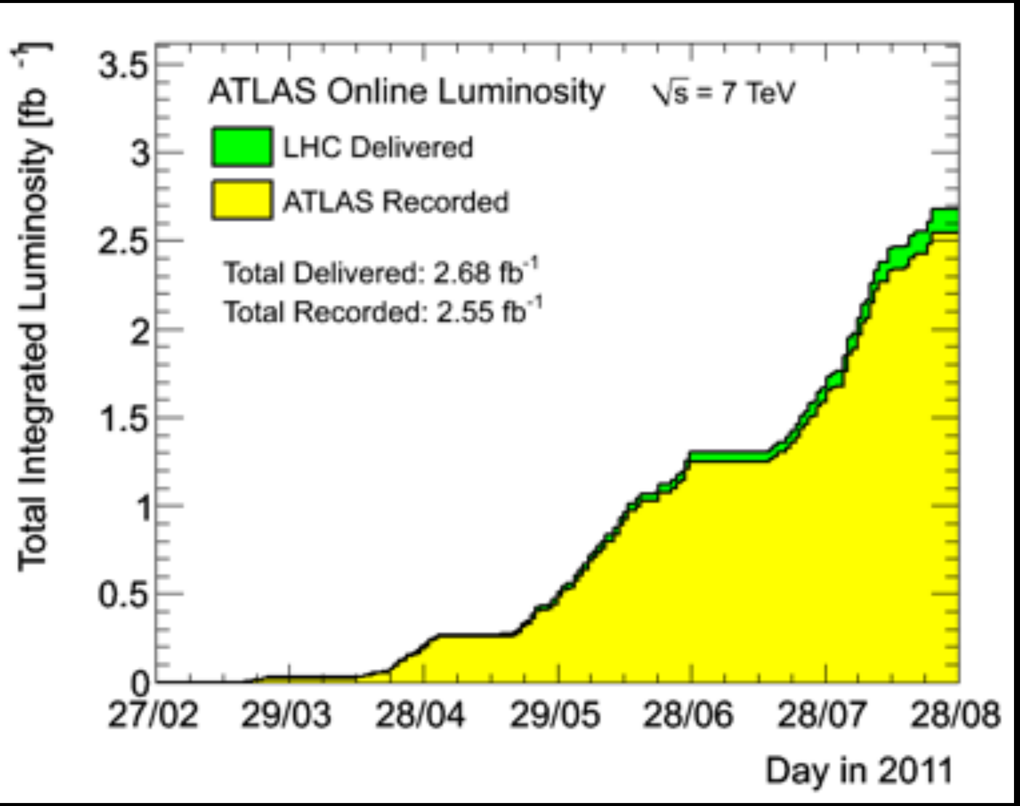


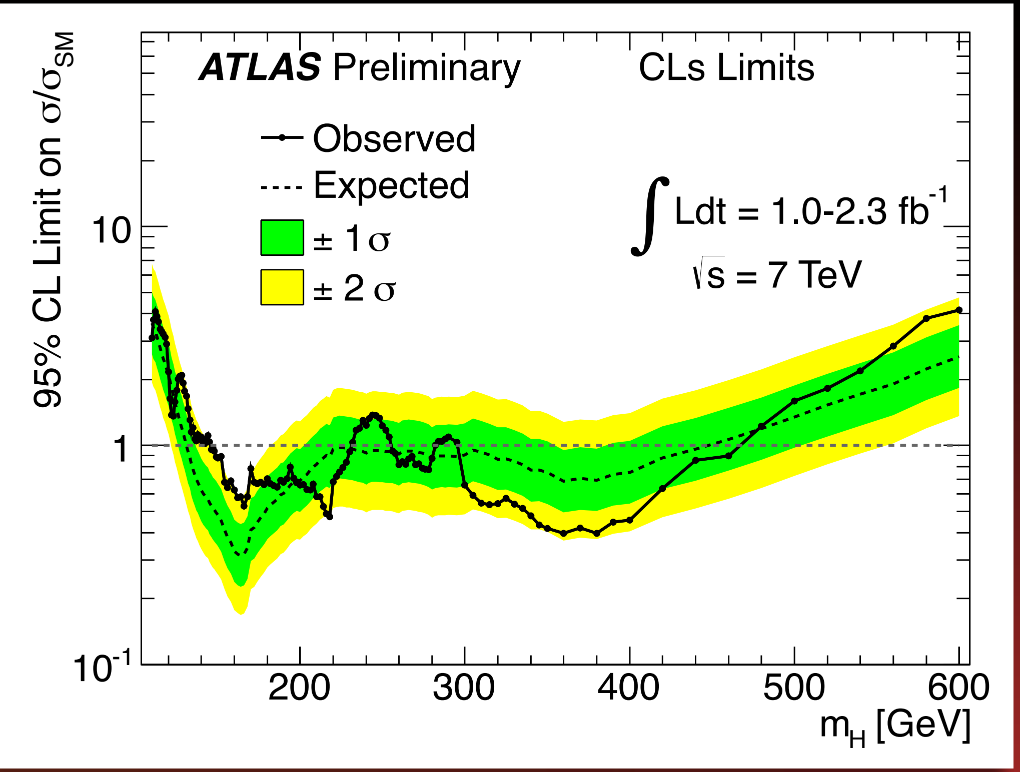




Commissioning with Collision Data

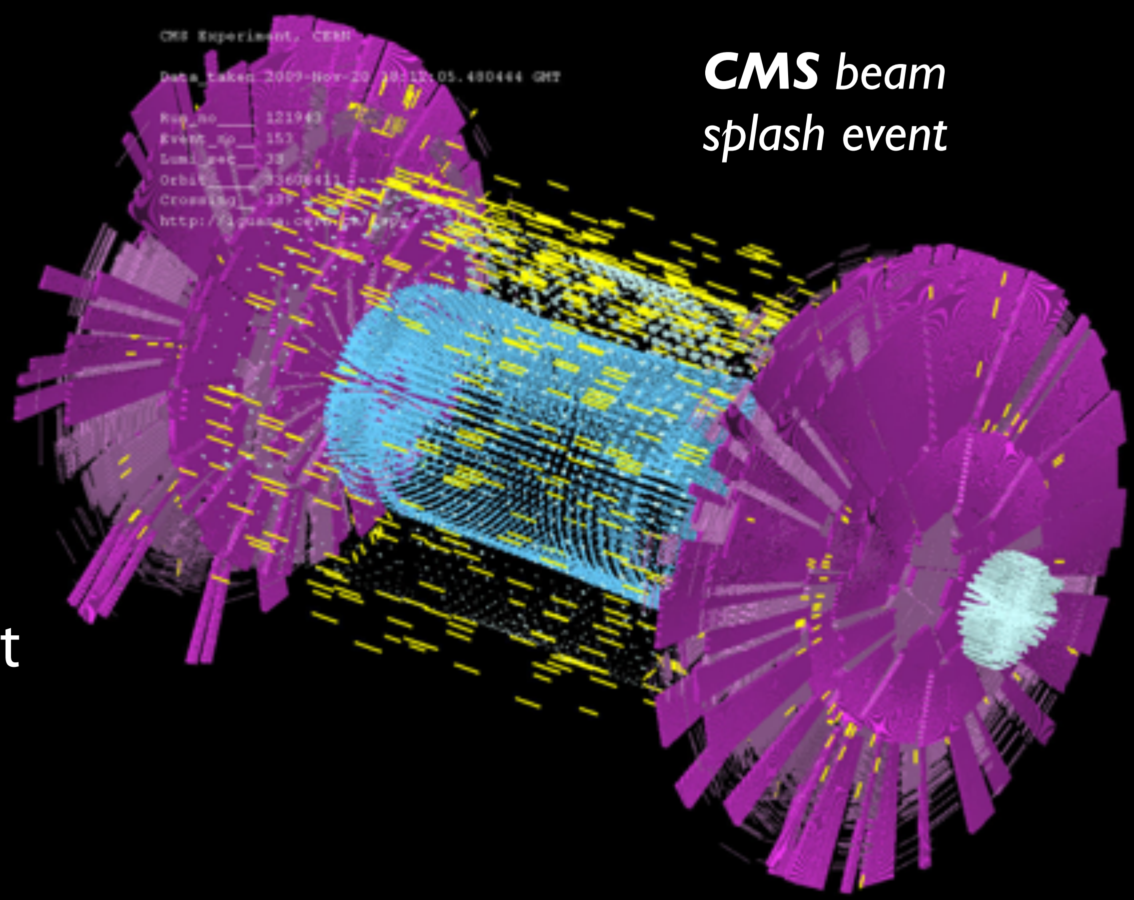
- LHC has done fantastic since !
  - ➡ luminosity increase almost exponential
- a long way from first collisions to physics
  - ➡ commission full readout chain (detector, trigger, DAQ)
  - ➡ calibrate and align the detector
  - ➡ optimize the tracking performance, allow for changing levels of pileup
  - ➡ ...
- basis of commissioning the tracking is excellent work done on the detector !
  - ➡ let's briefly discuss a few examples...

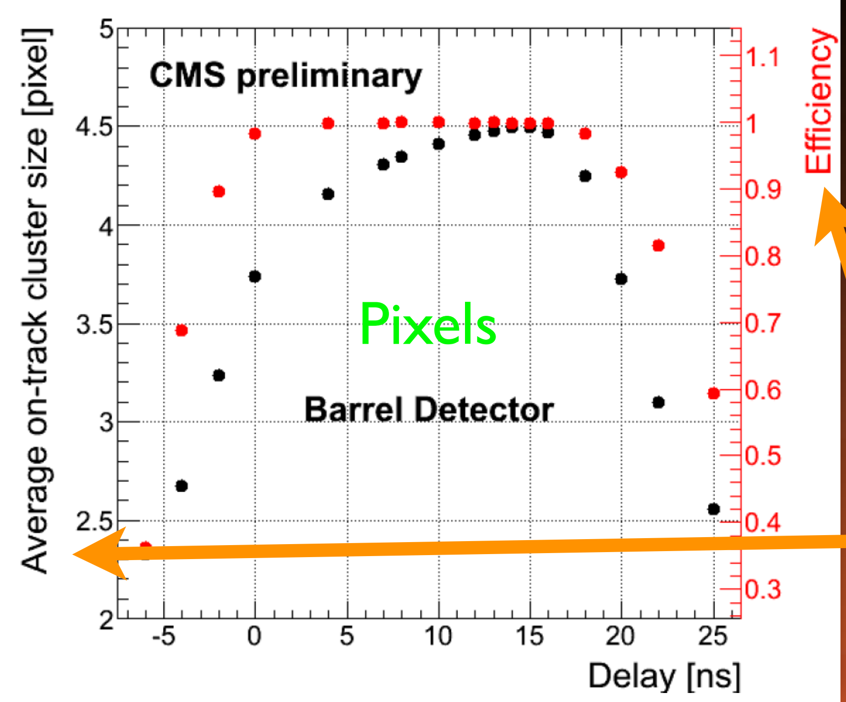




Timing in the Detector

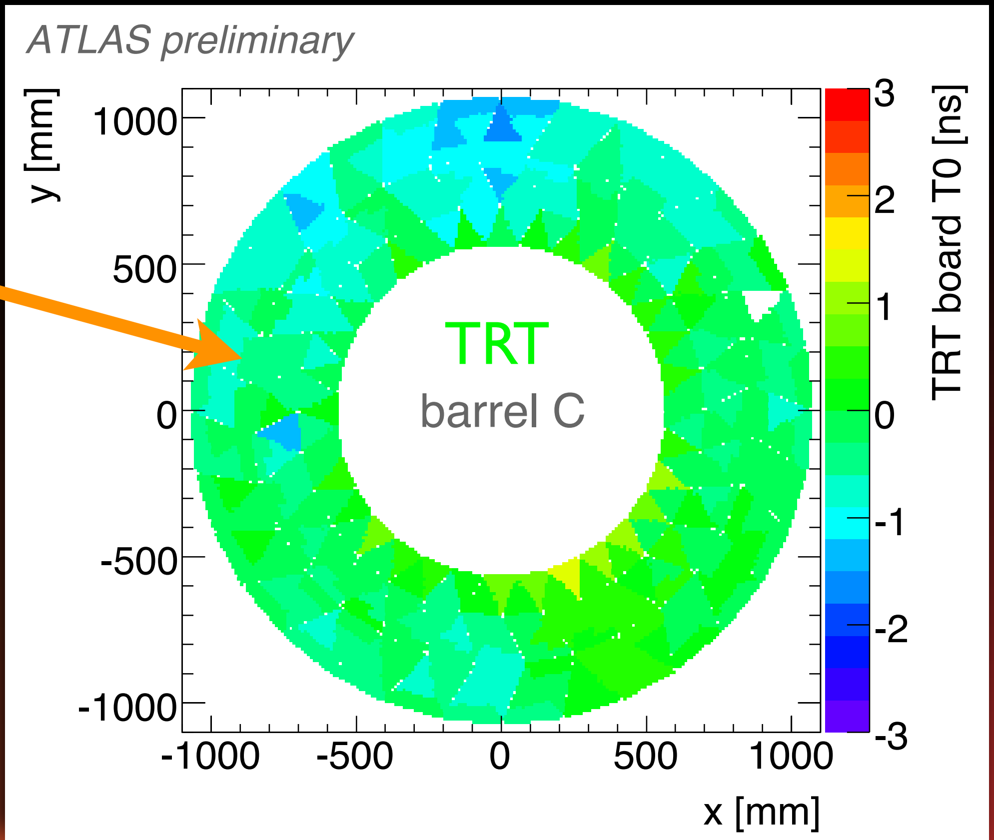
- timing in the detector is crucial
  - ➡ to be ready for 50/25 nsec operation
  - ➡ time of flight is large compared to LHC event rate
  - ➡ precise timing required to be fully efficient (time walk in silicon detectors, etc.)
- work started before collisions
  - ➡ cosmics and beam splash events were extremely useful
  - ➡ fine tuning with collision events





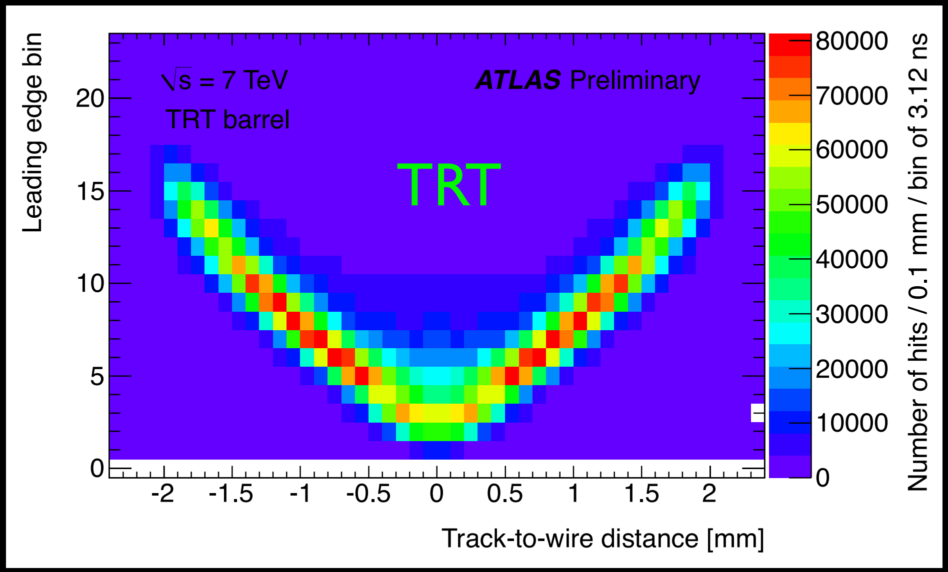
timing scan CMS Pixels

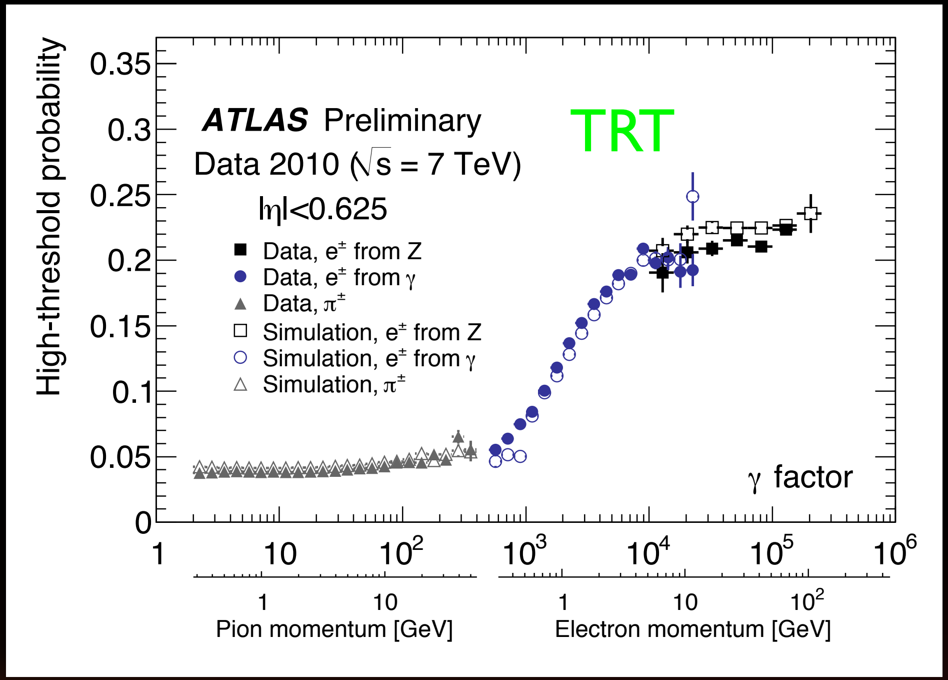
timing of ATLAS TRT



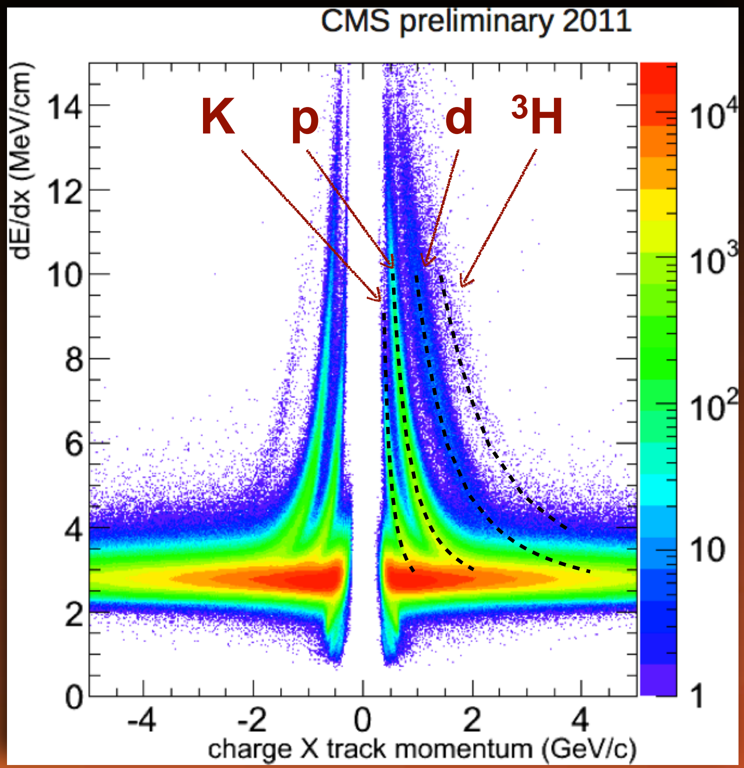
Detector Calibration

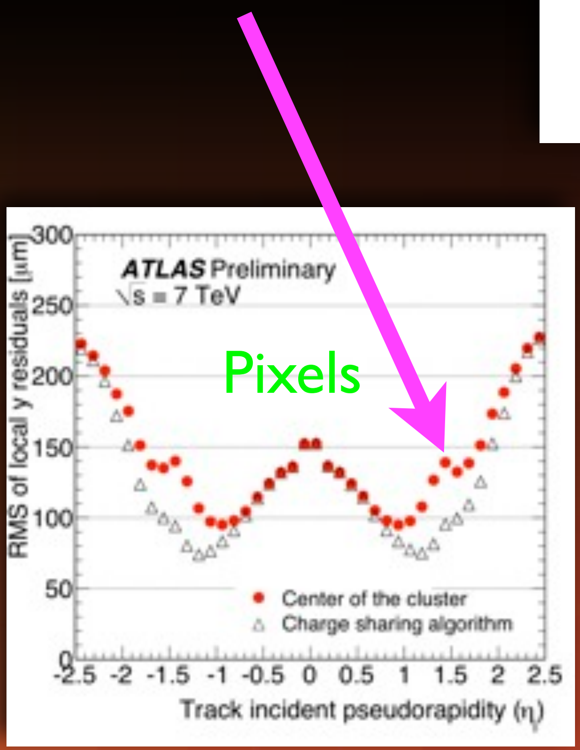
- careful calibration of detectors
  - ➡ required to reach design performance
  - ➡ online (thresholds,...) and offline
  - ➡ monitoring of variations with time
- examples:
  - ➡ TRT: R-t relation and high threshold probability
  - ➡ analog information from silicon detectors
    - allows to measure dE/dx
    - required to explore power of analog clustering

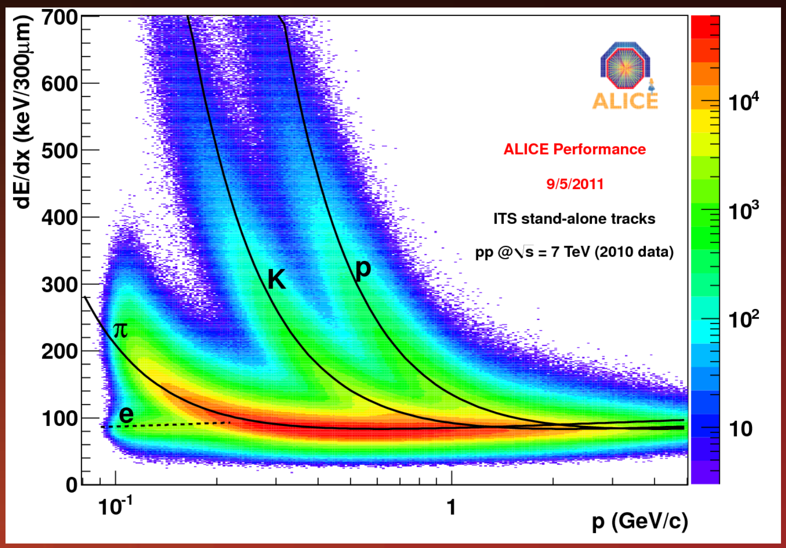




CMS:
10 layers
~0.5cm
of silicon

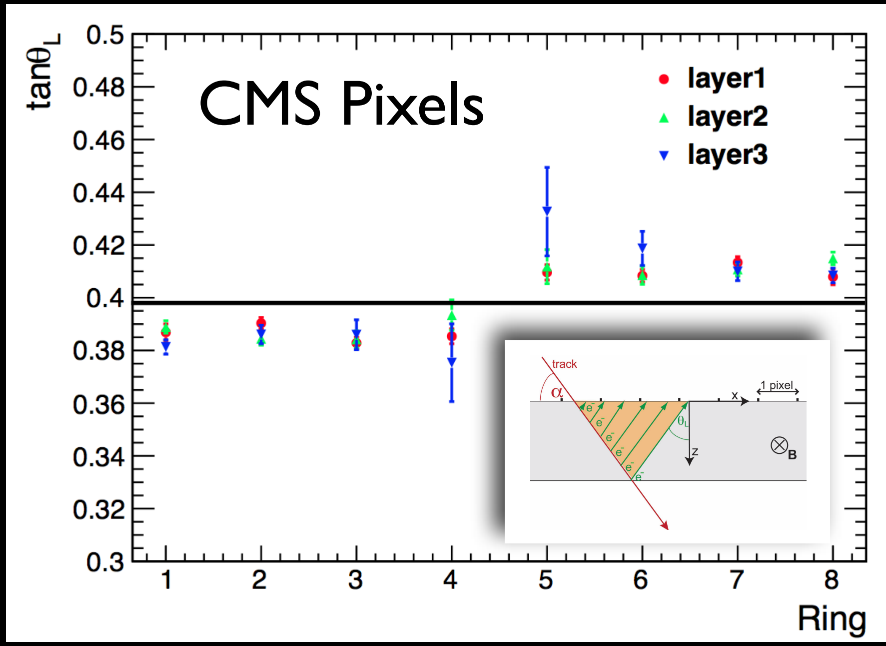


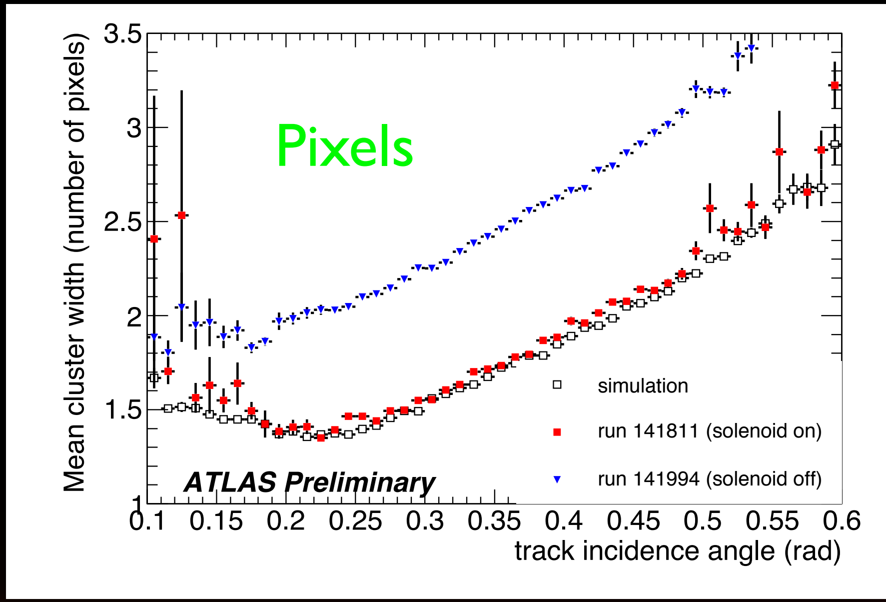


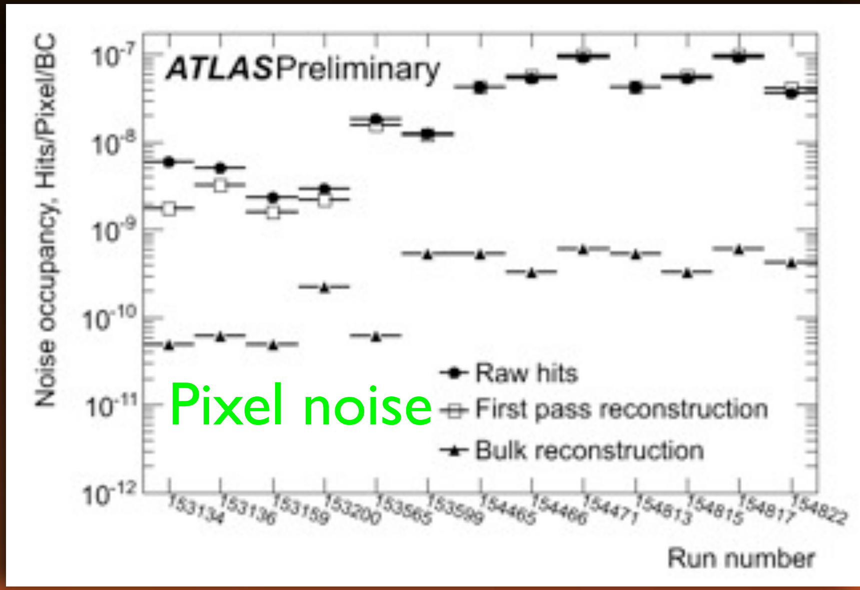


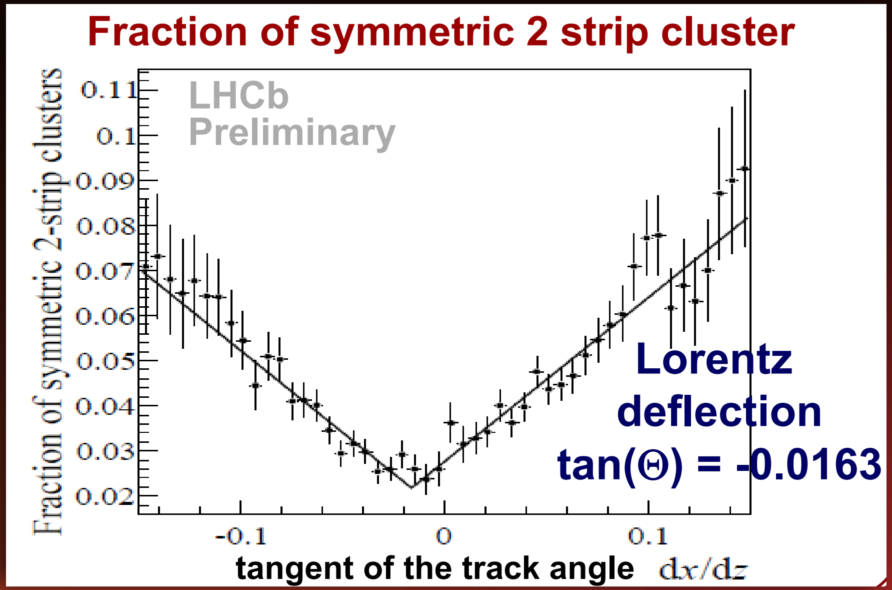
Detector Calibration

- measure Lorentz angle
  - ➡ cluster sizes vs track incident angle
- study cluster properties
  - ➡ resolutions
  - ➡ charge sharing...
- study dead and noisy channels
  - ➡ excellent performance after masking known noisy channel

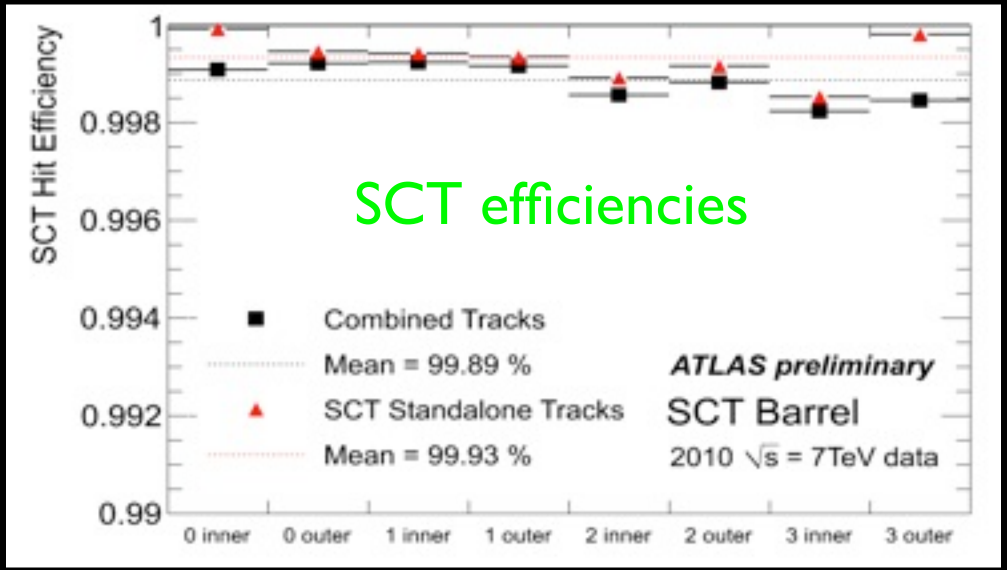




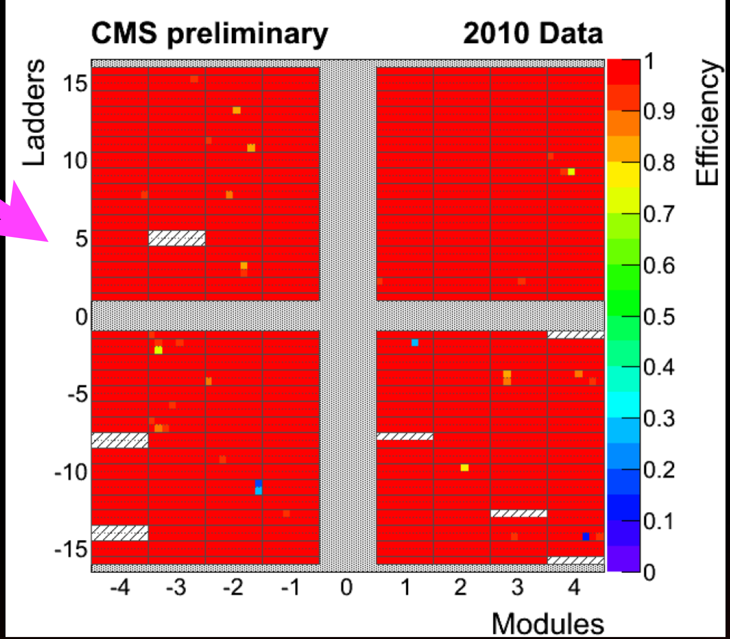




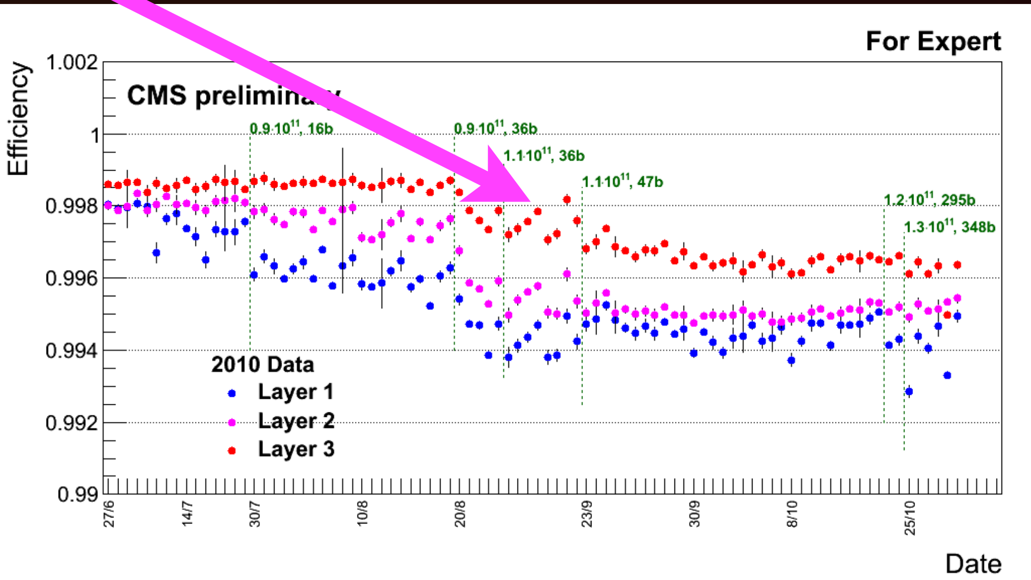
Detector Calibration



- study detector efficiencies
  - ➡ identify dead channels, chips, modules
  - ➡ typically > 95% of detectors are operational



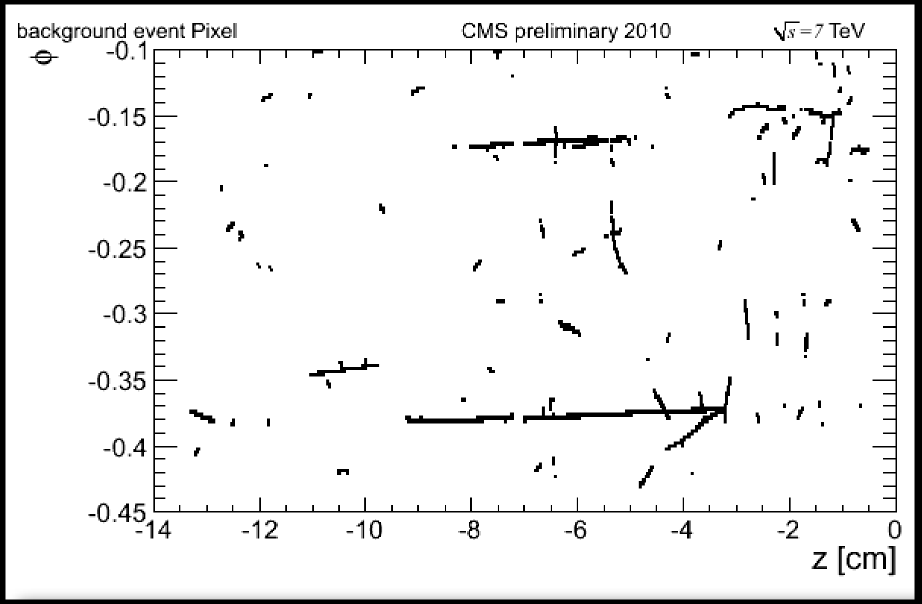
- in general, detectors are behaving excellent
  - ➡ very high efficiencies of the sensors (>98%) and very low noise
  - ➡ CMS sees small efficiency loss (0.2-0.4%) with increasing luminosity
    - occupancy increase effecting readout

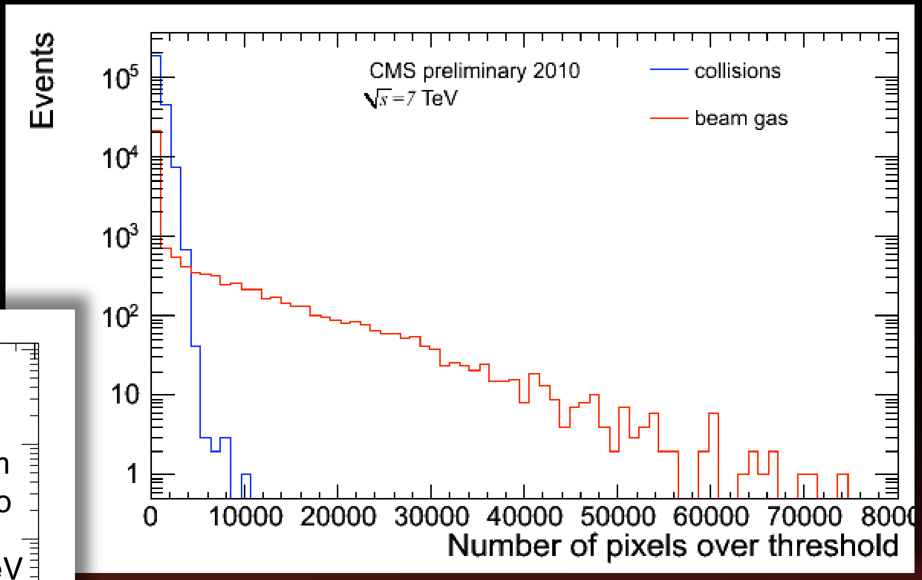


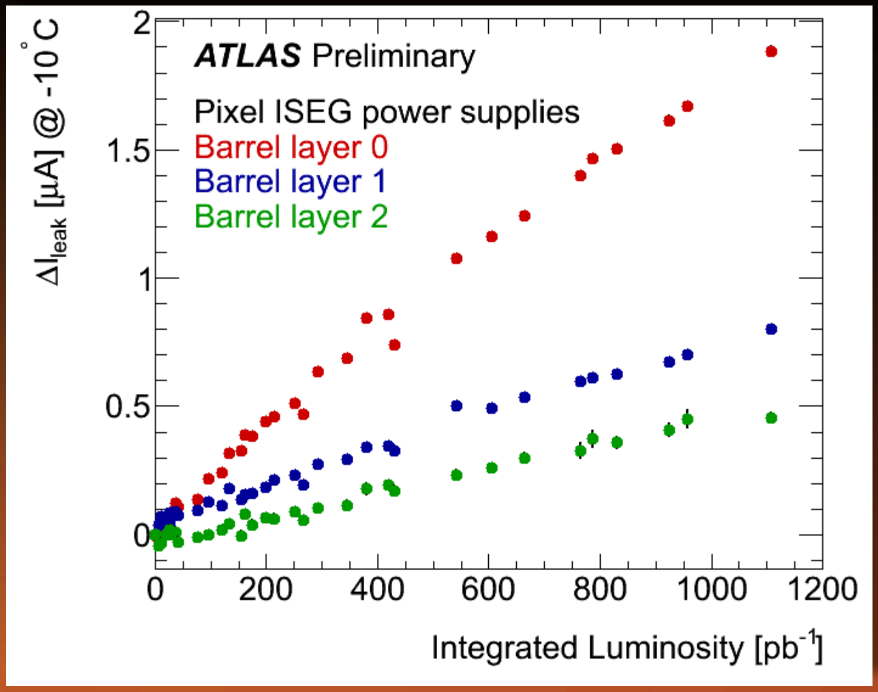
- not limiting tracking performance
  - ➡ correct simulation to reproduce calibrated detector performance
  - ➡ allow for known defects and inefficiencies in reconstruction

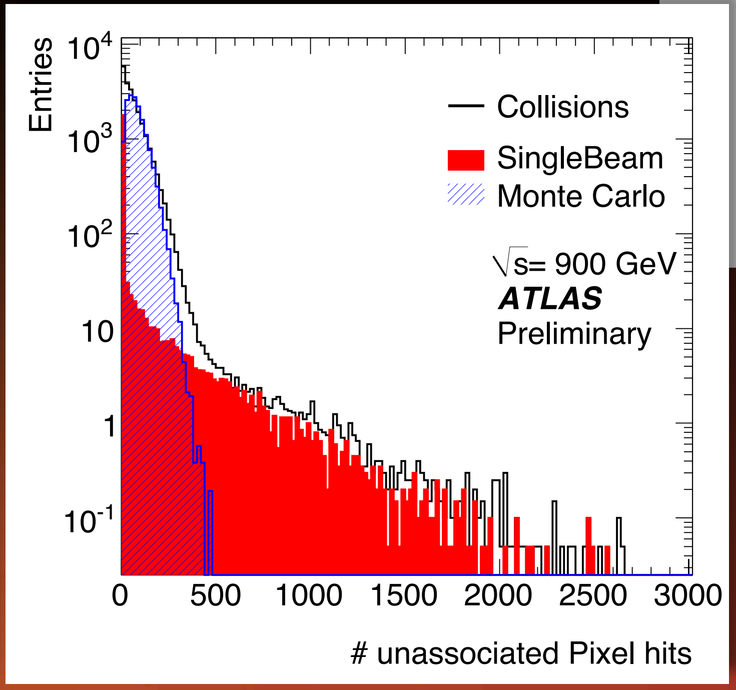
Beam Backgrounds and Radiation Effects

- CMS sees backgrounds in Pixels
  - ➡ induced by low level beam loss into detector
    - consistent with beam-gas interactions
  - ➡ risk for desynchronization of readout
- radiation effects on silicon
  - ➡ monitor leakage current and cross talk
  - ➡ example: ATLAS
    - $\varphi = 2.43 \cdot 10^{12} \cdot$ (1 MeV neq)/fb-1 at b- Layer
    - expect type inversion at ~10 fb^{-1}



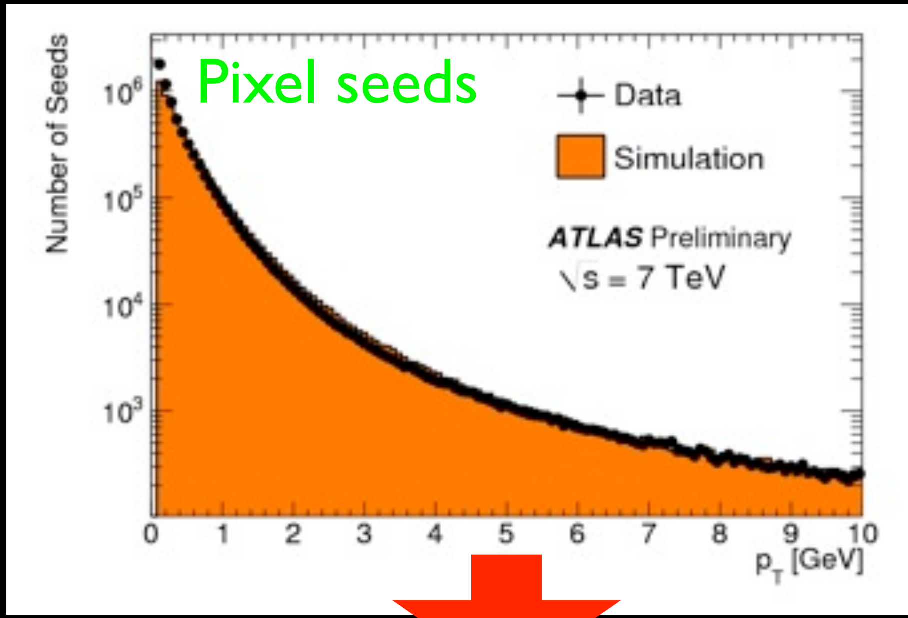


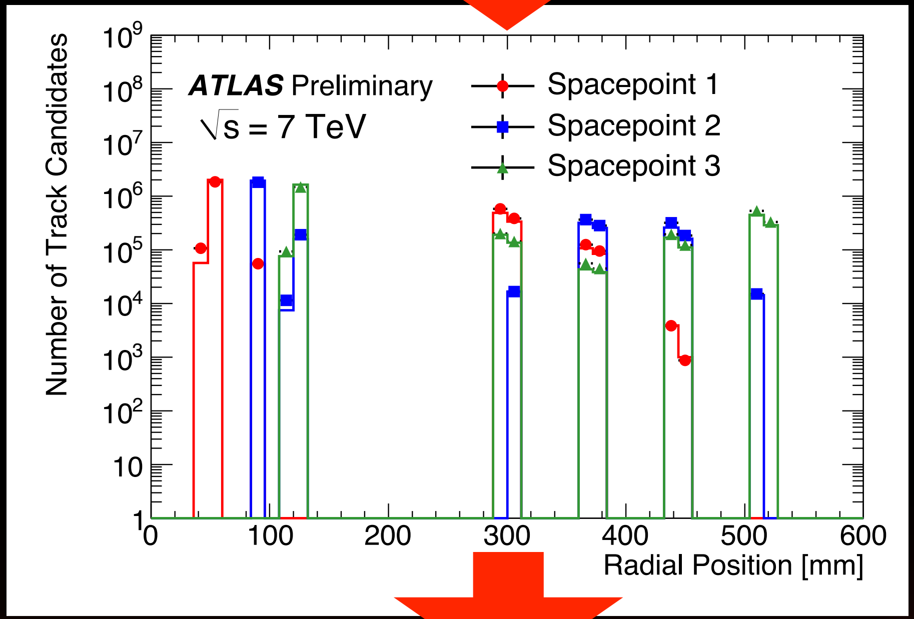


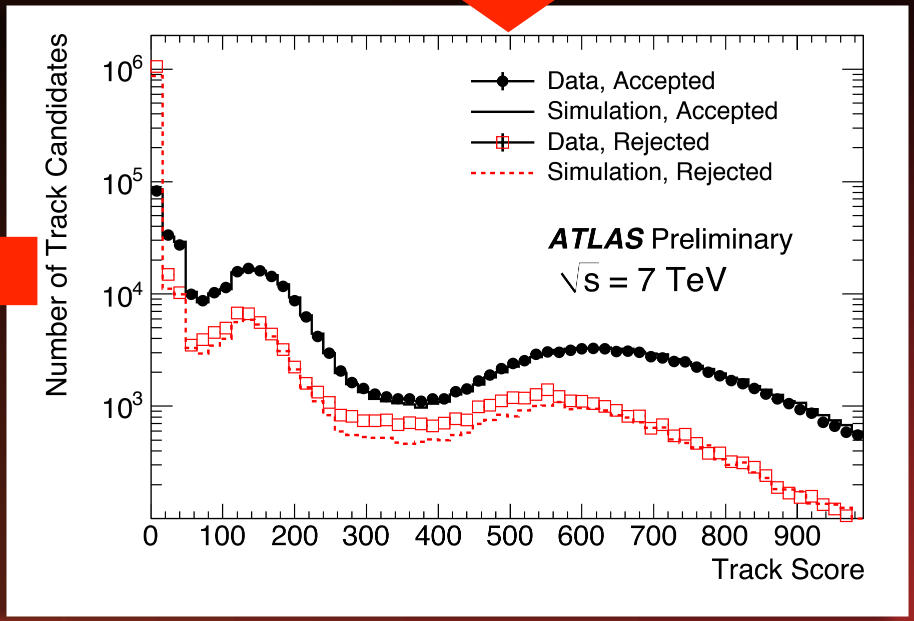


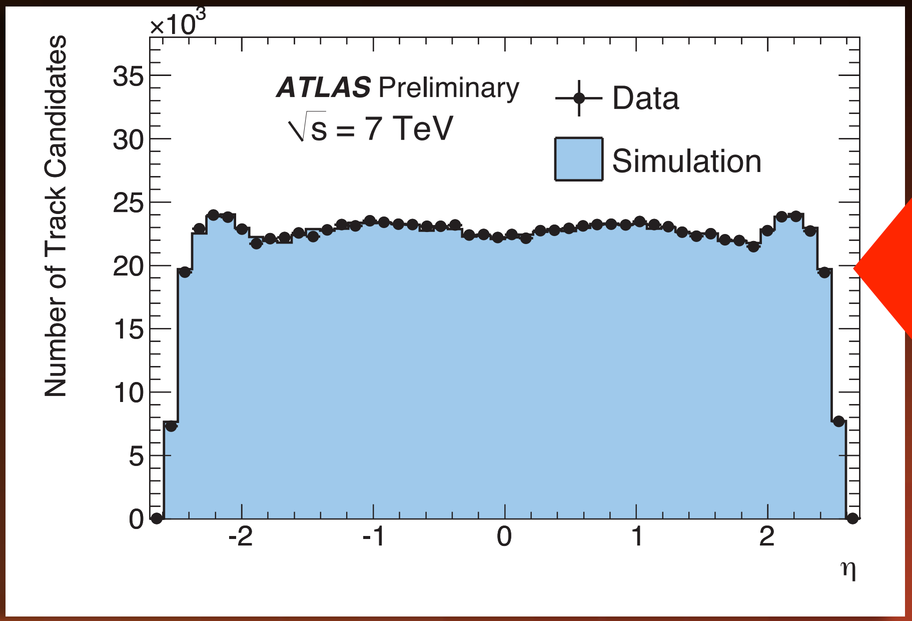
Tracking Commissioning

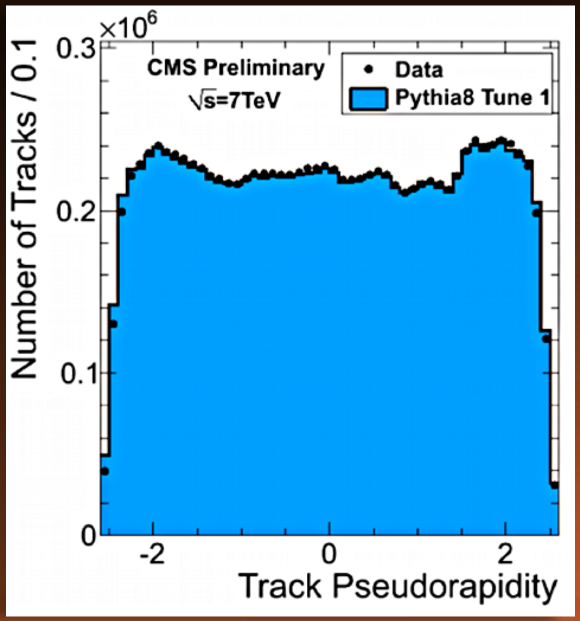
- at startup
  - ➡ use commissioning settings
    - ensure "robustness"
    - allow for dead/noise modules
    - error scaling to reflect calibration + alignment
  - ➡ first physics was minimum bias
    - tracking with very low p_T thresholds, no pileup
- study behavior of reconstruction
  - ➡ seeding / candidate fitting / ambiguity / etc.
  - ➡ compare simulation to data





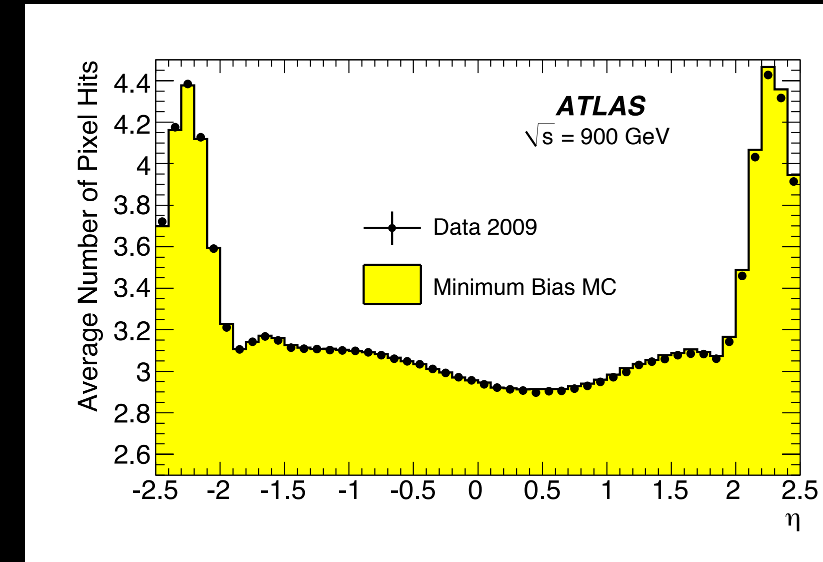


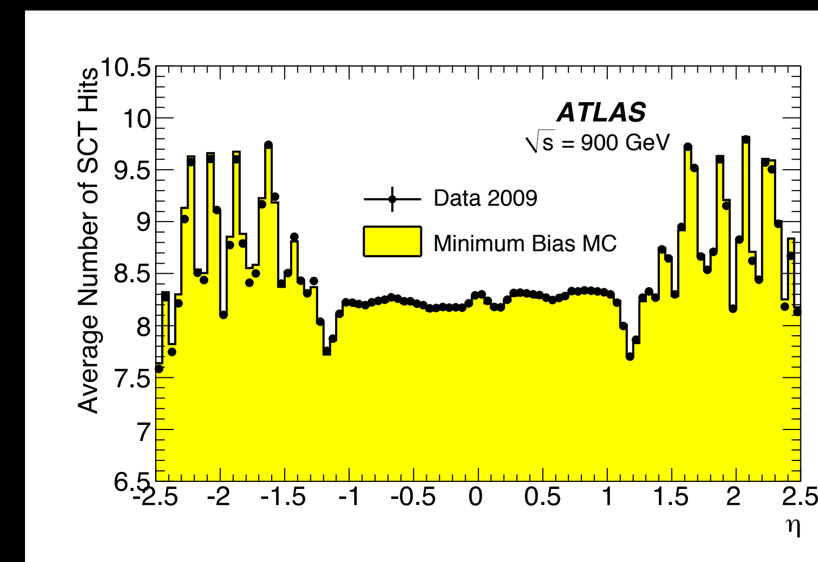




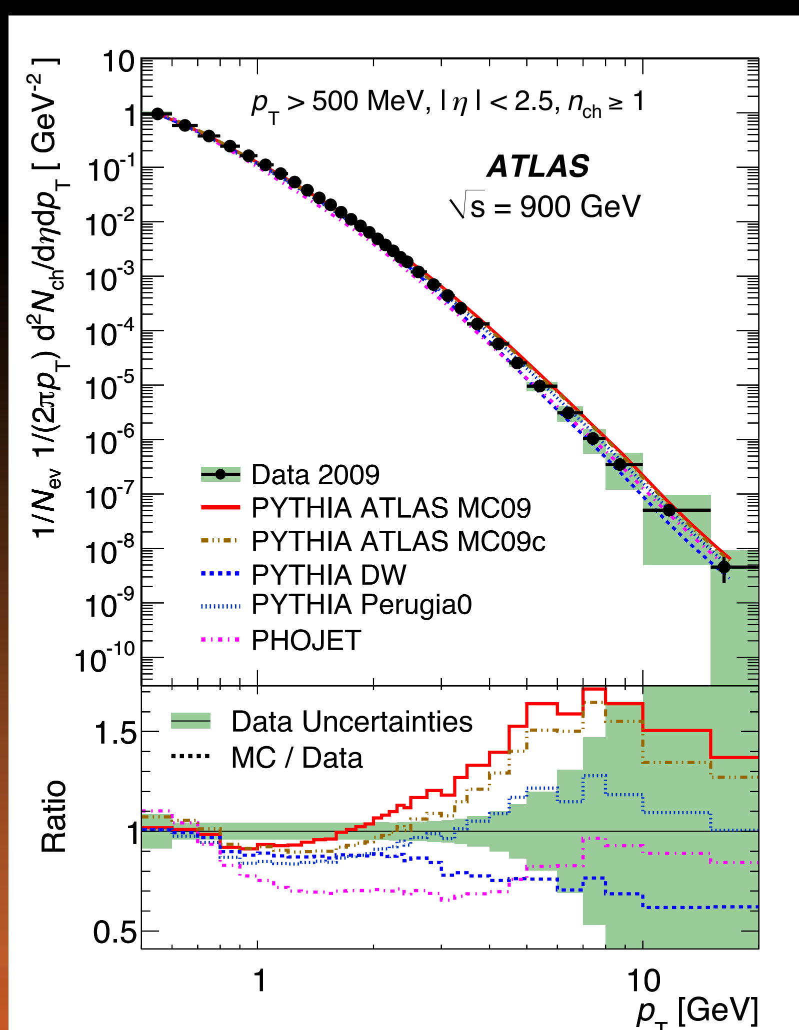
Tracking Commissioning

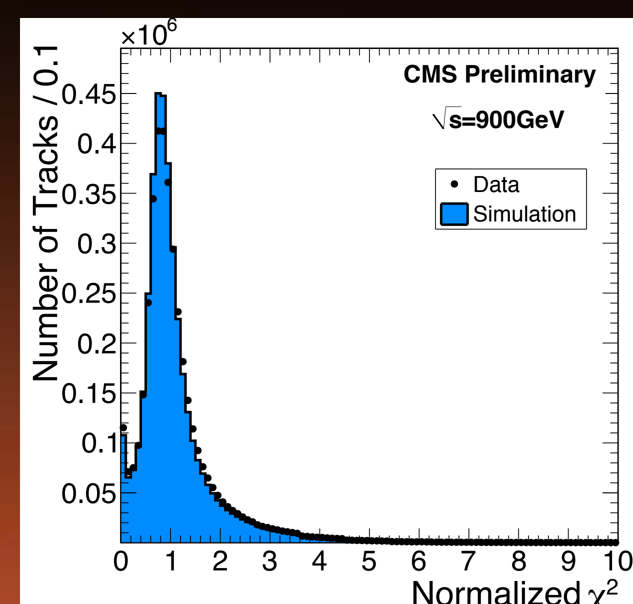
- detailed studies of properties of reconstructed tracks
  - ➡ hit associations, fit quality, etc.
  - ➡ leading towards first publications
    - tracking systematics driven by material uncertainties

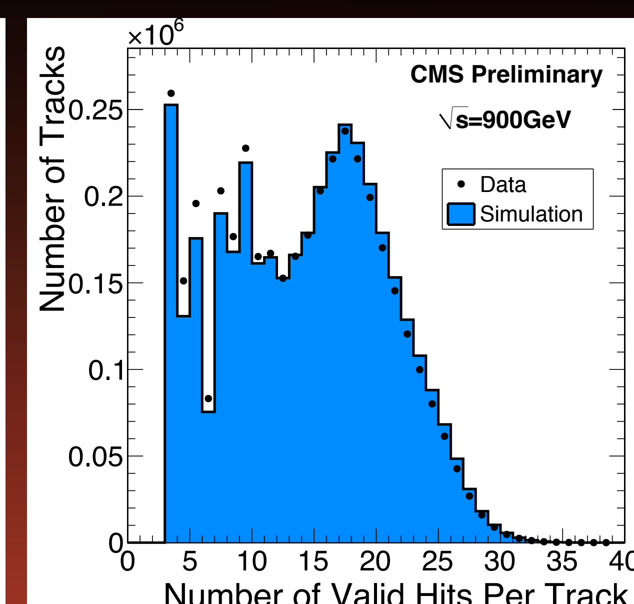




min.bias charged particle spectra



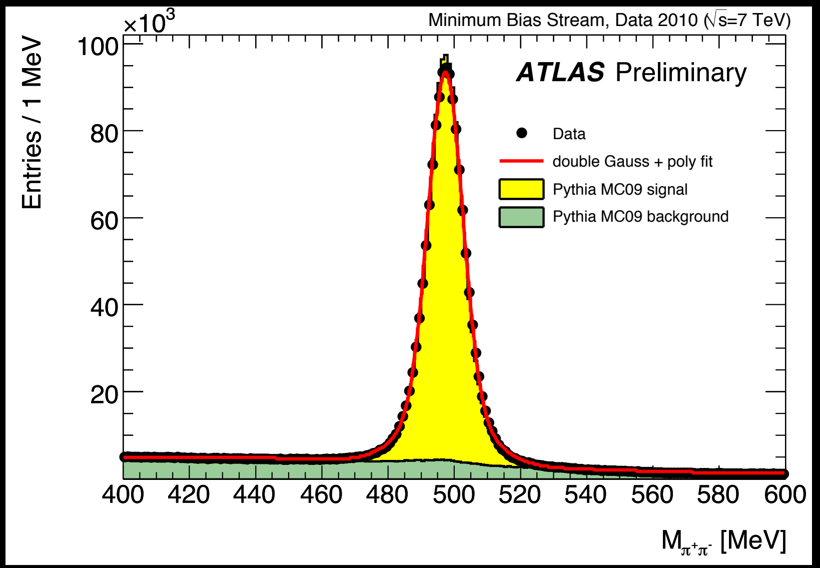


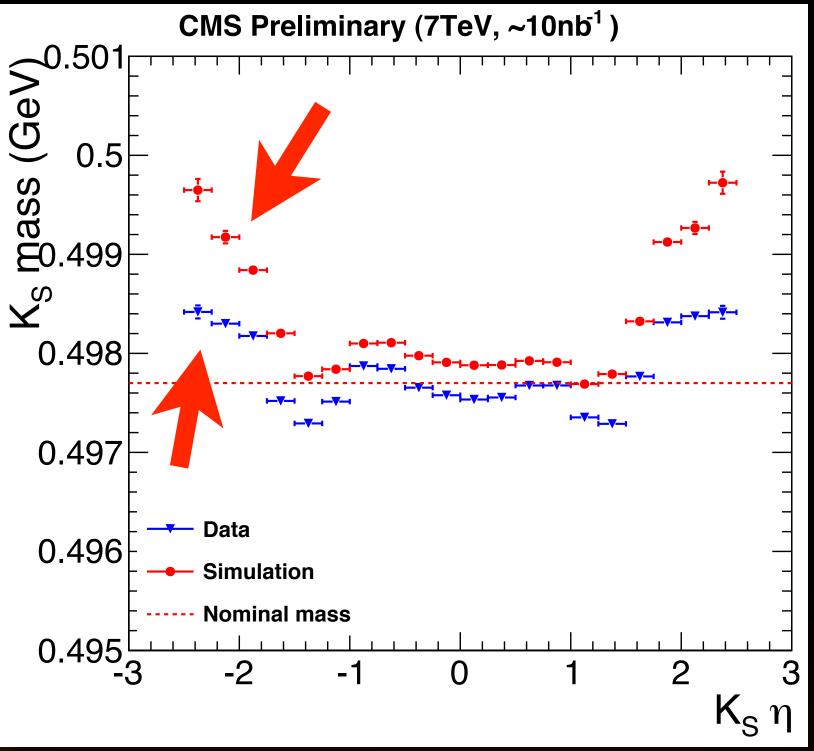


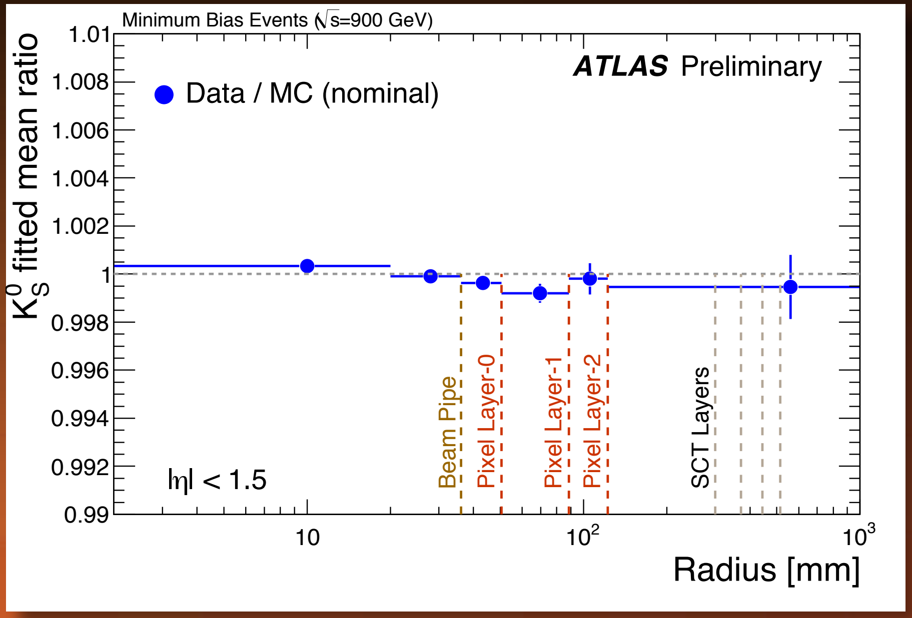
Material Studies using K^0_s

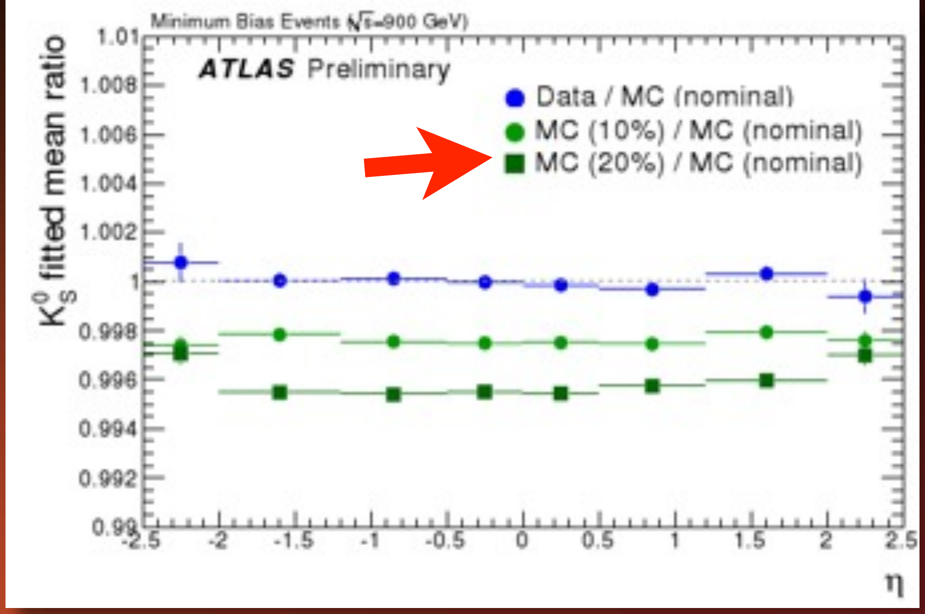
- crucial to understand tracking performance

- mass and width of K^0_s is sensitive to material description
  - ➡ one of the first signals people looked at
  - ➡ can study effects vs η,ϕ,p_T and decay radius
  - ➡ sensitive to integrated effects in data/MC
  - ➡ can simulate effect of wrong material in MC (10%/20%)



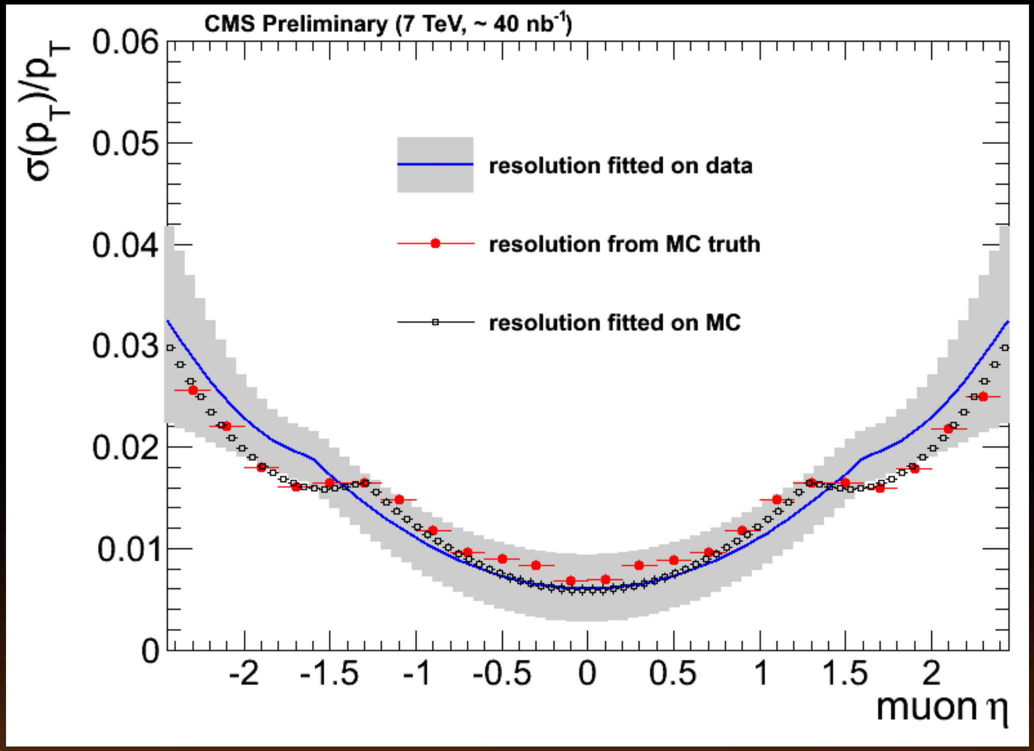


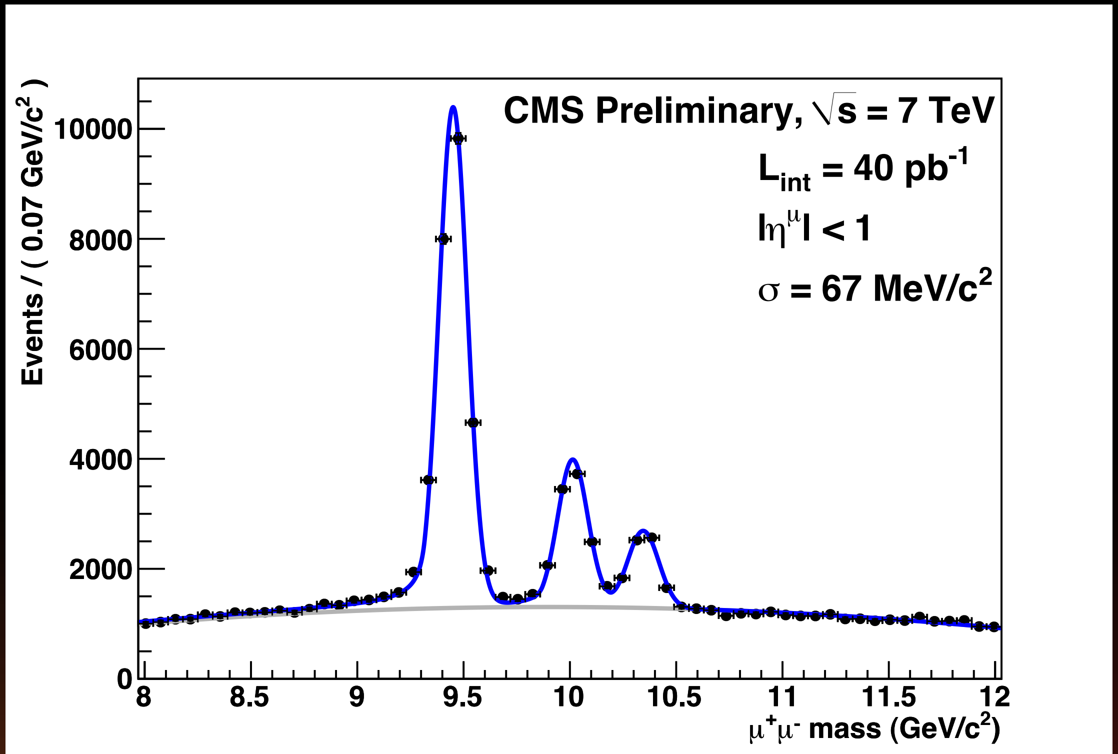




Material Studies using J/ψ

- J/ψ still mostly sensitive to material
  - ➡ similar studies as with K^0_s possible
  - ➡ example: CMS study of momentum resolution from fit to J/ψ→μμ signal

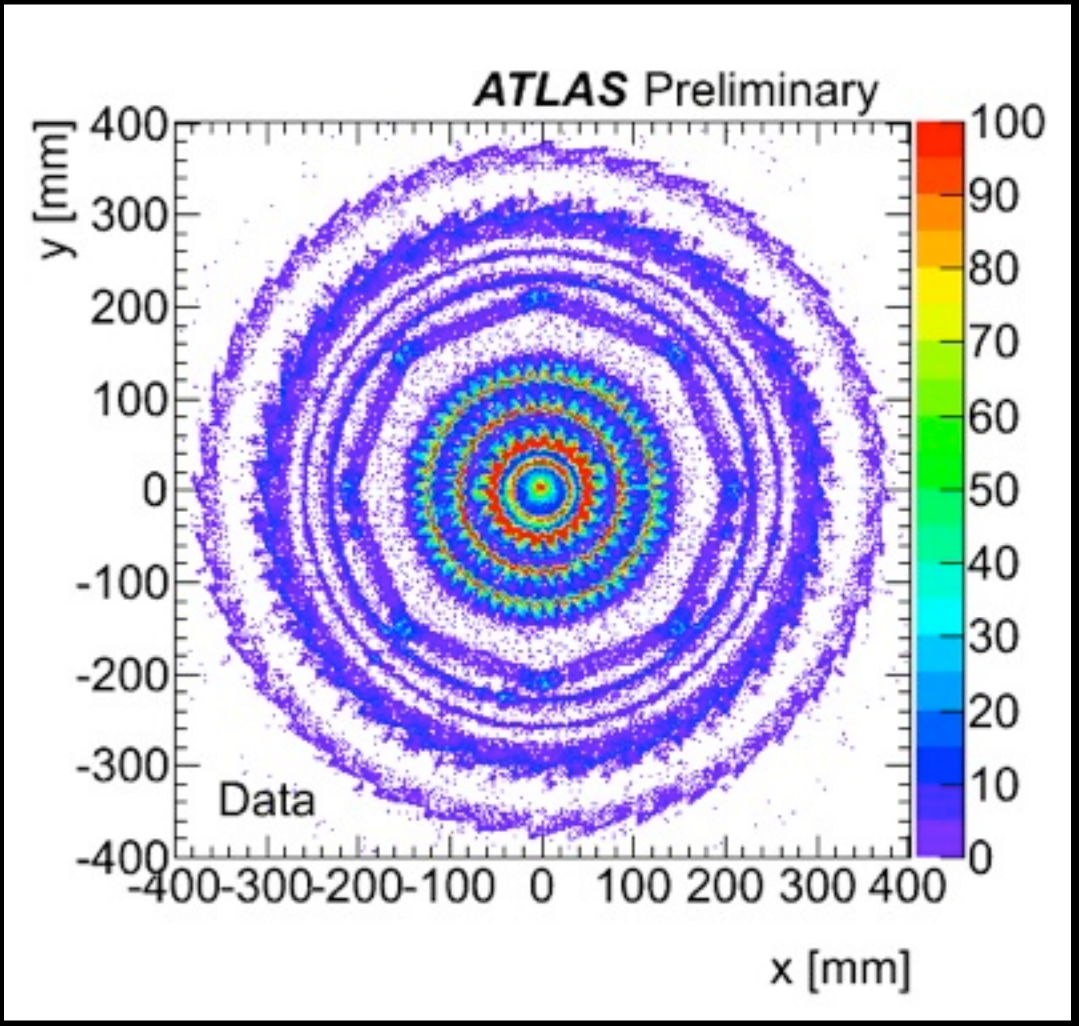


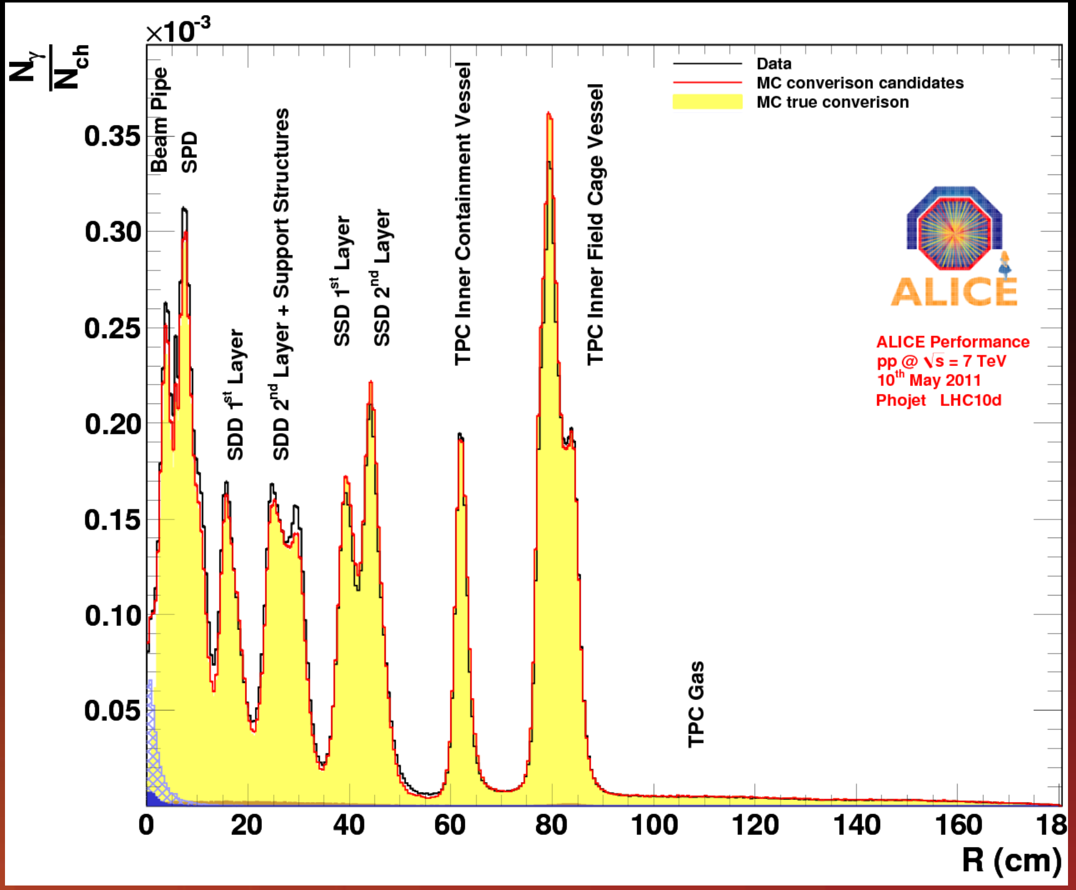


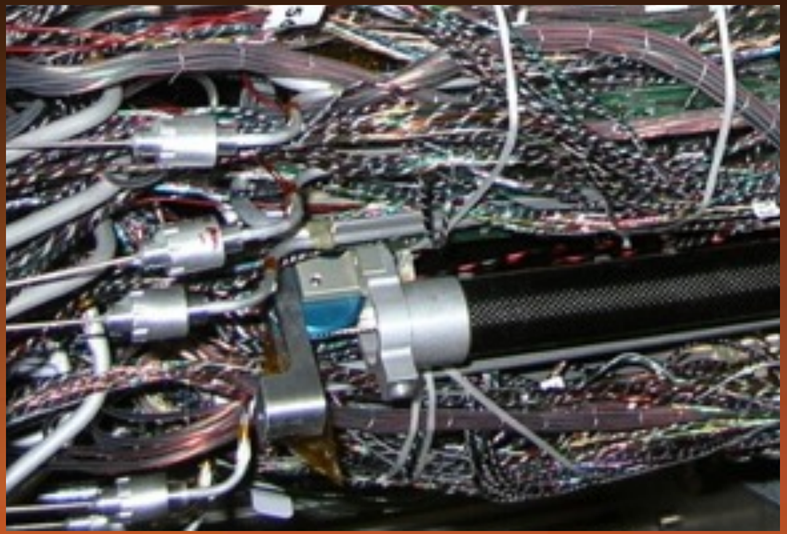
- ➡ excellent CMS mass resolution seen as well in resonances near Υ (thanks to 4 T field)

Conversions

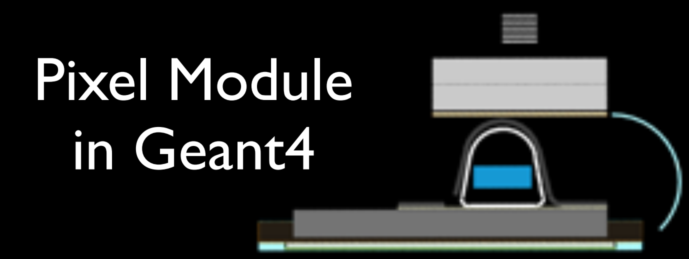
- detailed tomography of material with γ conversions
  - ➡ able to map details in material distribution
    - measure difference in data/MC, e.g. PP0
  - ➡ ultimately should result in a very precise estimate of material
    - need to control reconstruction efficiency
    - calibrate measurement e.g. on “known” beam pipe
    - needs huge statistics





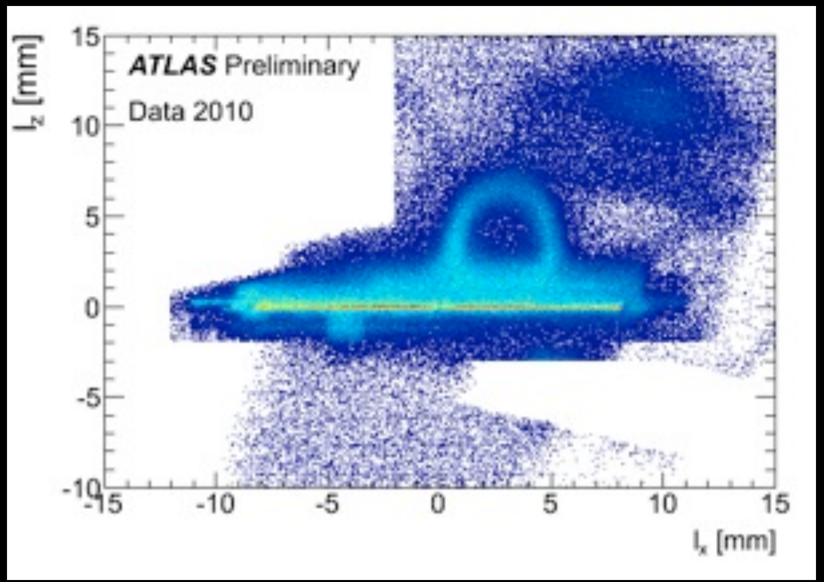


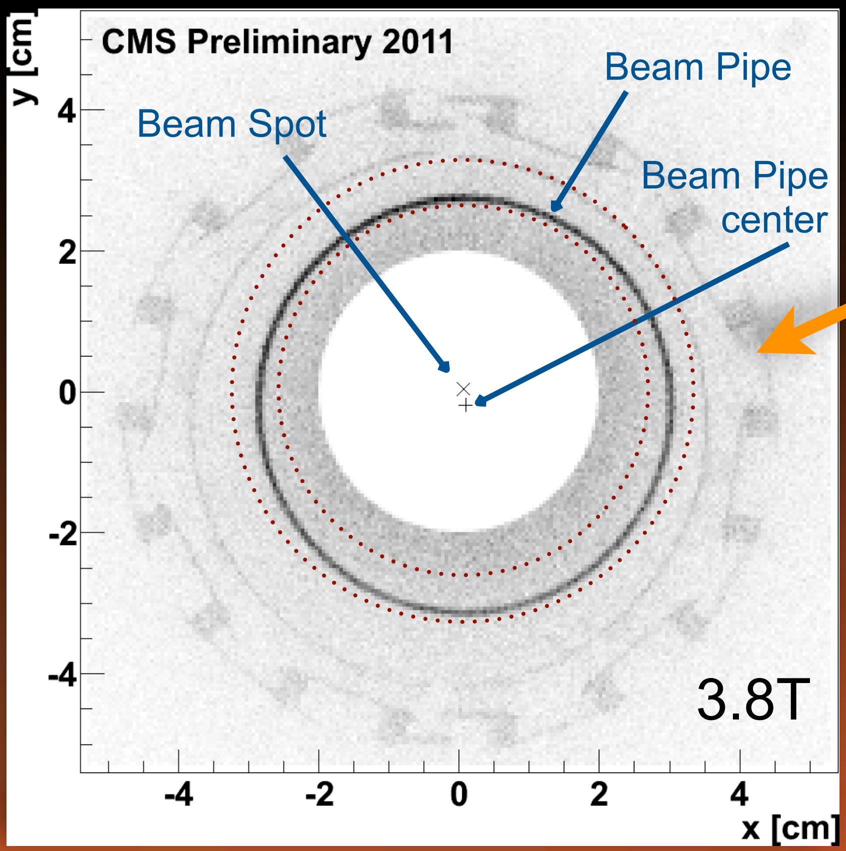
ATLAS Pixel PP0 region



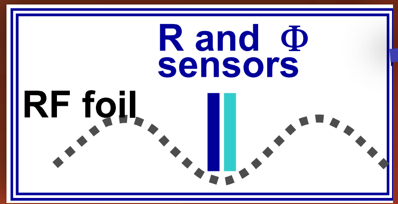
Hadronic Interactions

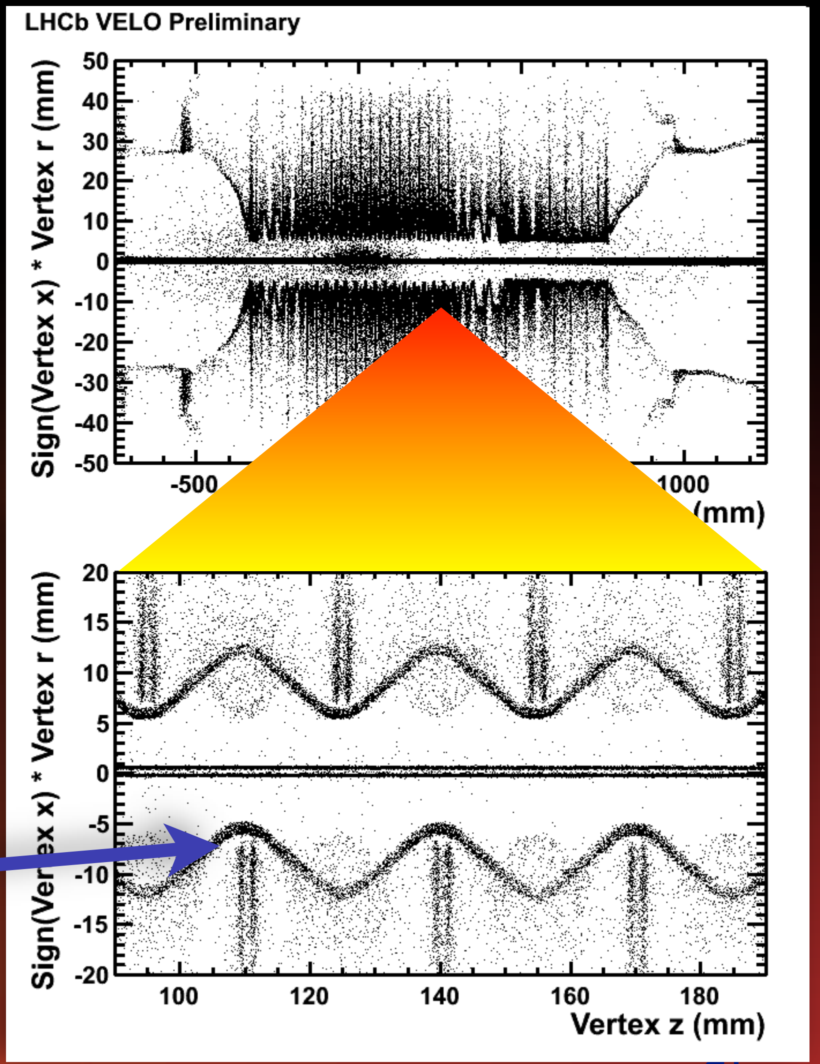
- 2nd method for a precise tomography of detector material
  - ➡ good vertex resolution allows to study fine details
- material uncertainty in simulation
  - ➡ better than ~5% in central region
  - ➡ at the level of ~10% in most of the endcaps
  - ➡ study of systematics ongoing in experiments





relative offsets visible, similar in ATLAS





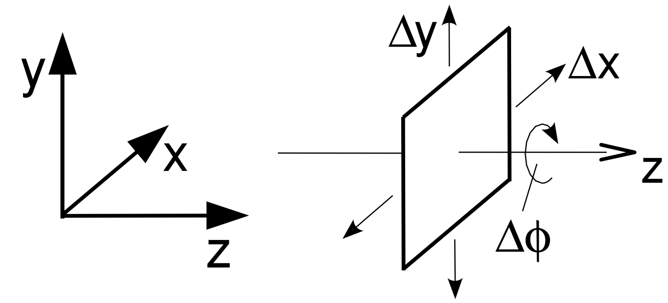
Track-based alignment

- alignment is based on the minimization of track-hit residuals ***r***

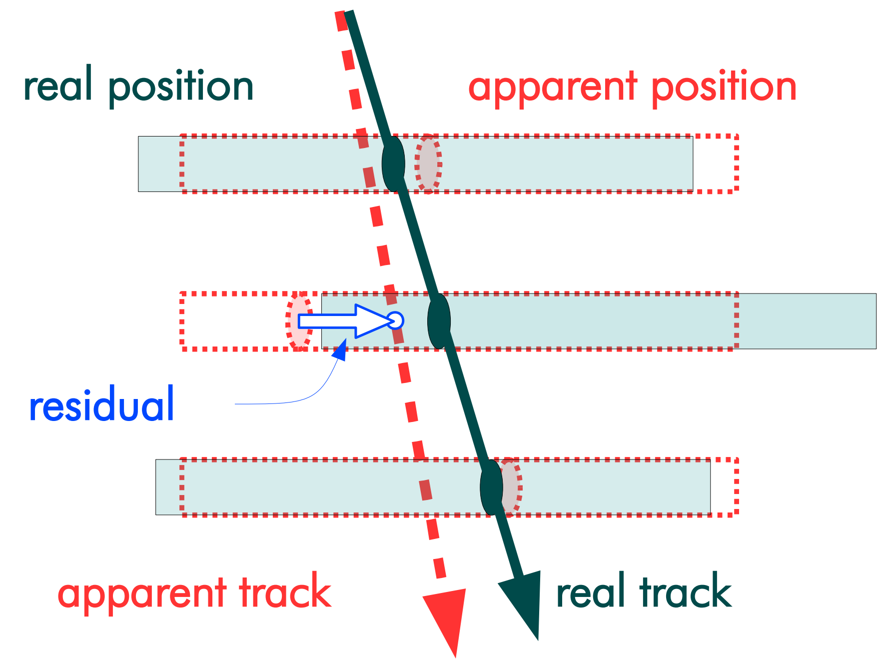
$$\chi^2 = \sum_{\text{tracks}} r^T V^{-1} r \quad \text{where} \quad r = r(\pi, \alpha)$$

V - track covariance matrix
π - track parameters
α - alignment parameters

- solution $\frac{d\chi^2}{d\alpha} = 0$



6 parameters per module



Global χ^2

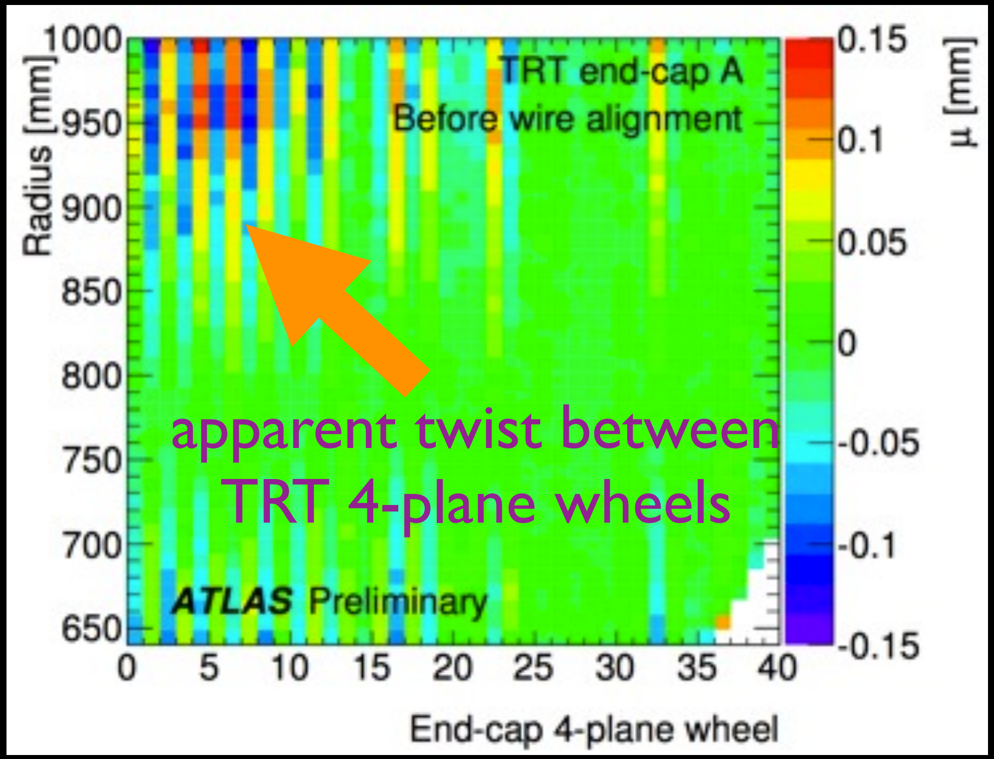
- single large matrix including all the correlations
  - huge number of DoF for the ATLAS Inner Detector (and in for CMS !)
- requires usage of fast solving techniques
- convergence within few iterations

Local χ^2

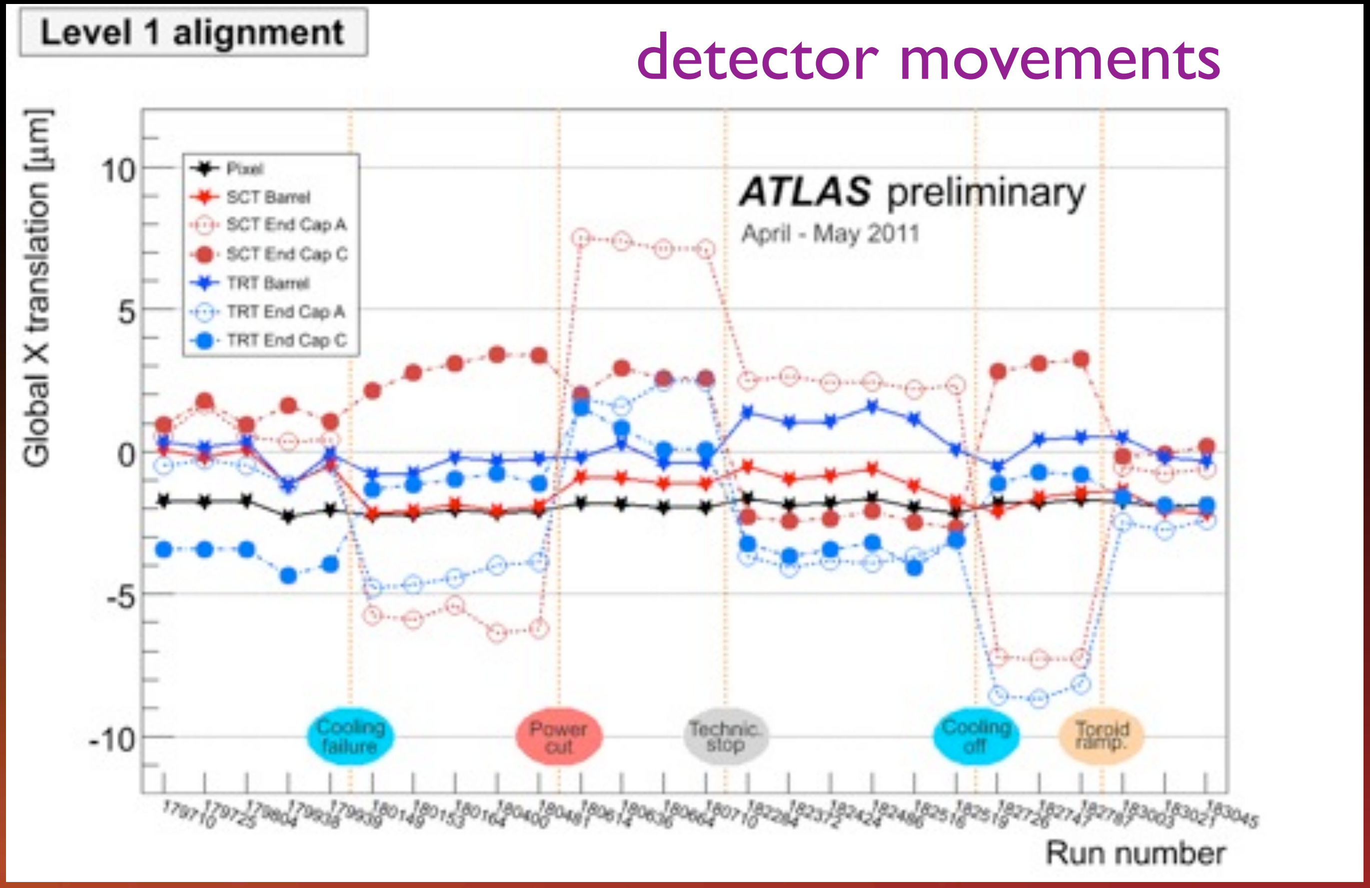
- solving of a small linear system independently for every aligned structure, ignoring explicit correlations between structures
- correlations are restored via iterations
- many iterations needed

Detector Alignment

- alignment strategy
  - ➡ starting point is detailed survey
  - ➡ hardware alignment systems
    - e.g. CMS tracker, ALTAS muons
  - ➡ alignment stream with high-p_t tracks
  - ➡ define different levels of granularity
    level 1 (e.g.SCT barrel) to level 3 (module)
  - ➡ global-χ^2 and local alignment

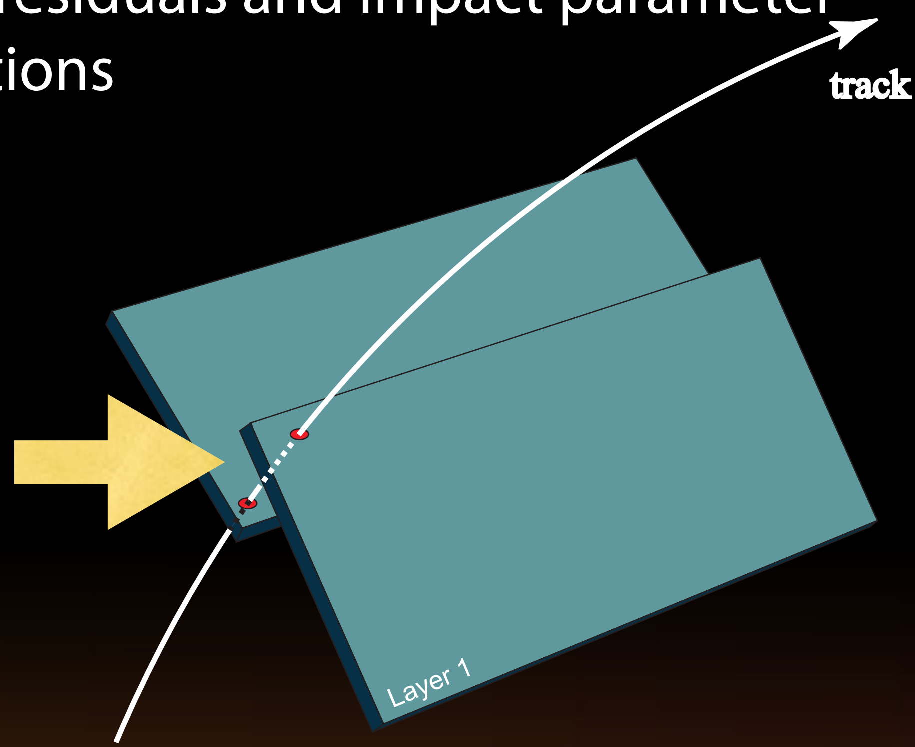


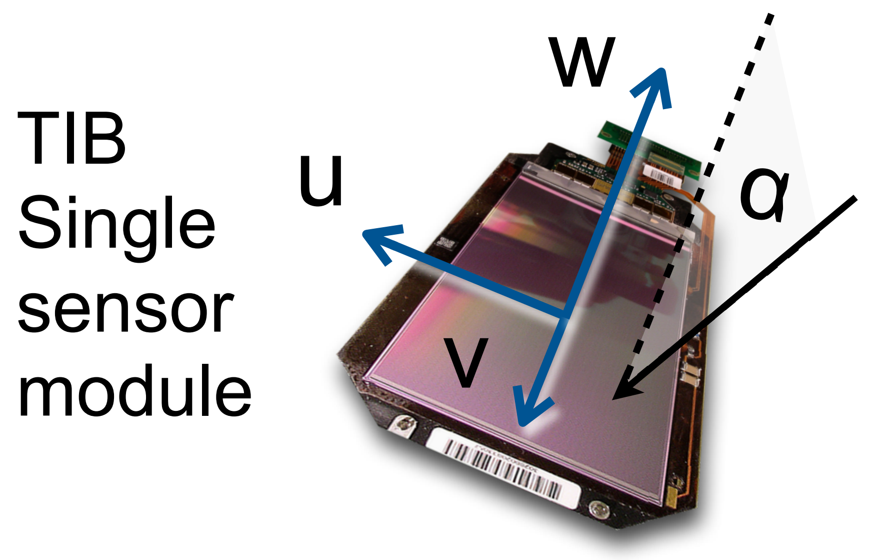
- also allow for
  - ➡ Pixel model deformations
    - survey data or fit
  - ➡ Pixel stave bowing
  - ➡ TRT wire alignment
  - ➡ movements of the detector
  - ➡ ...

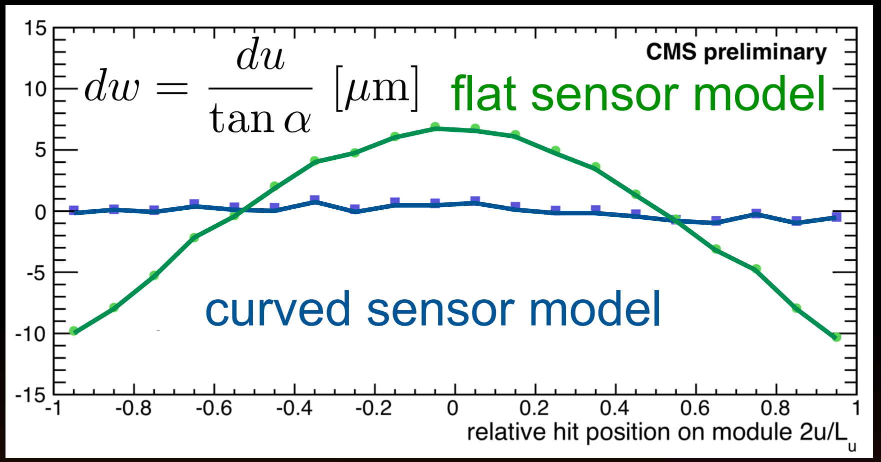


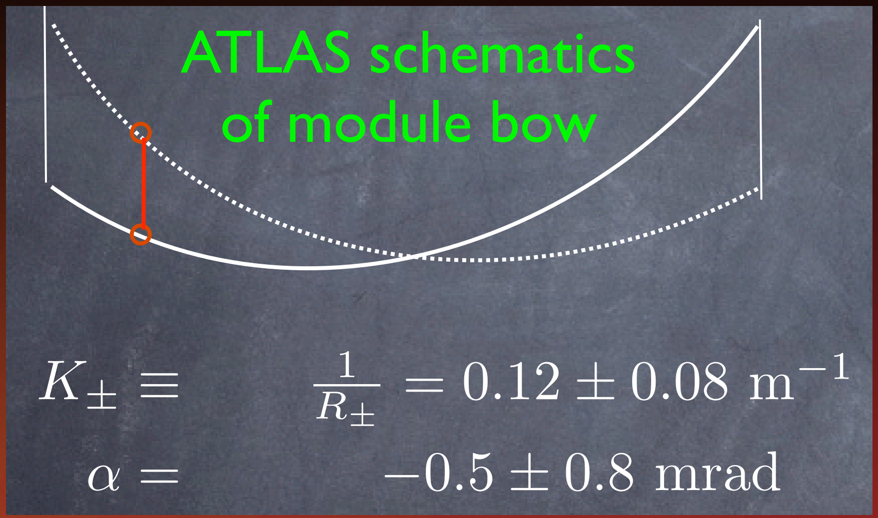
Local Misalignments

- module to module misalignments
  - ➡ very good constraint from overlapping modules
  - ➡ drives residuals and impact parameter resolutions





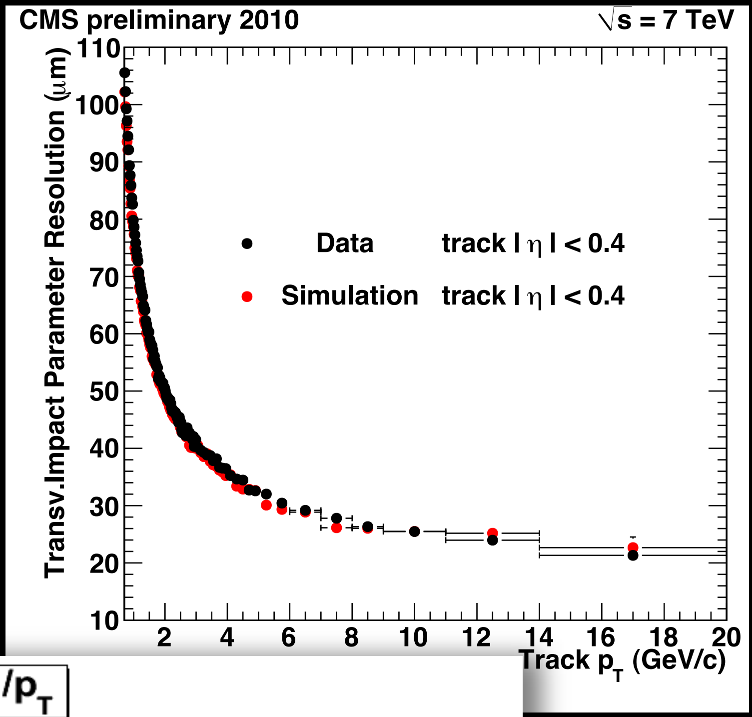


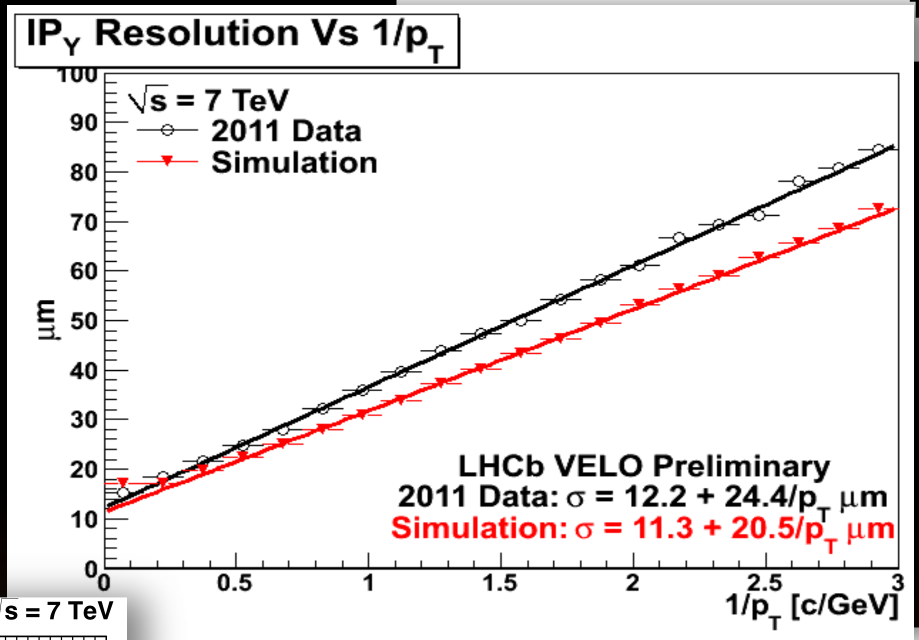


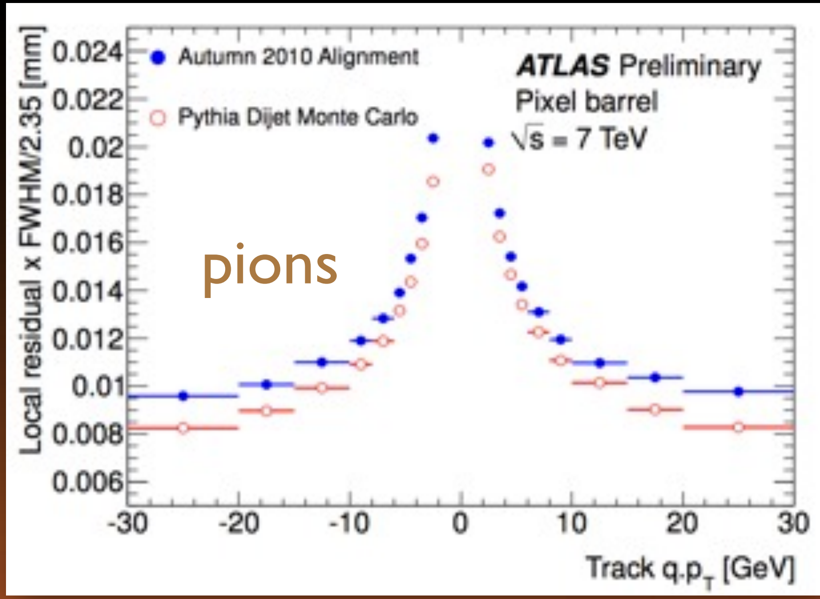
- alignment is sensitive to module distortions (not a flat shape)
  - ➡ ATLAS is using survey data for Pixels
  - ➡ CMS will allow for module bowing soon

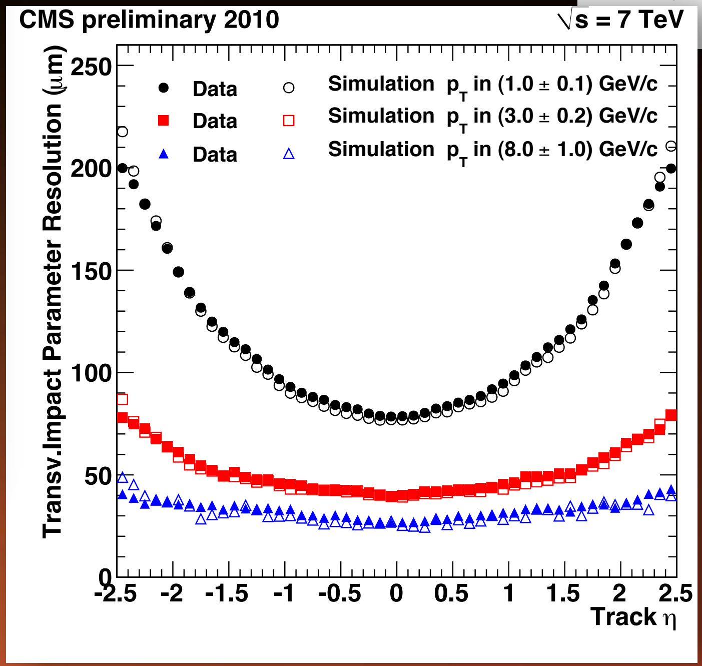
Impact Parameter Resolution

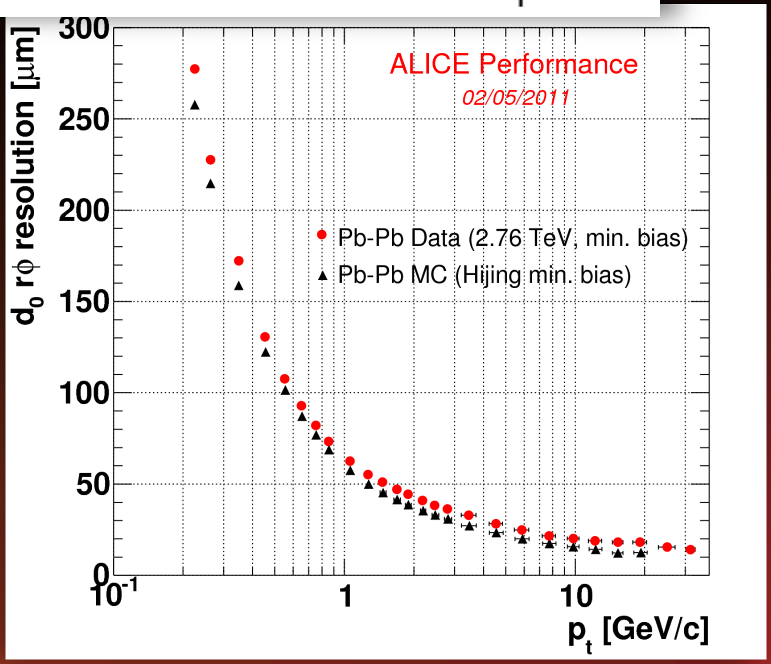
- driven by local misalignments
  - ➡ quickly approaching design resolutions
  - ➡ some small problems still visible
    - hence apply some error scaling in fit
- vertexing and b-tagging
  - ➡ fast commissioning helped by well constraint local alignment





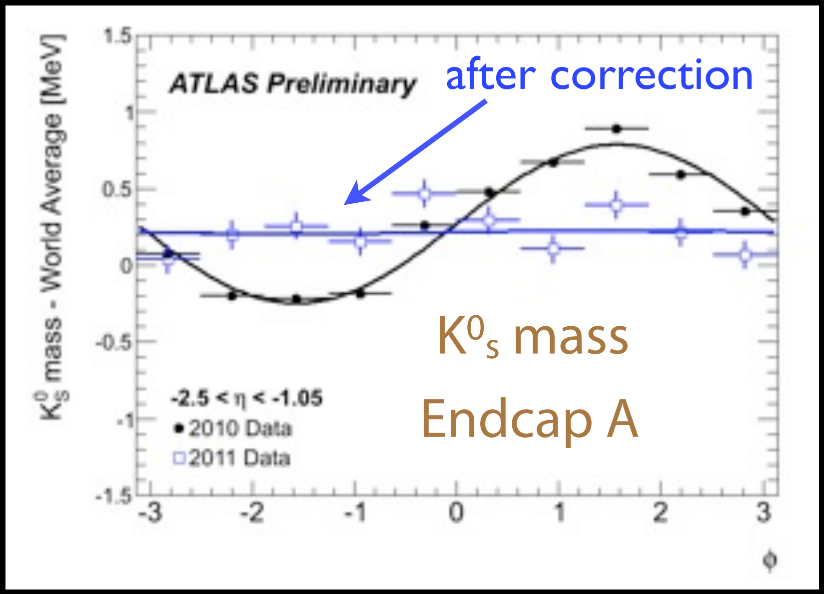


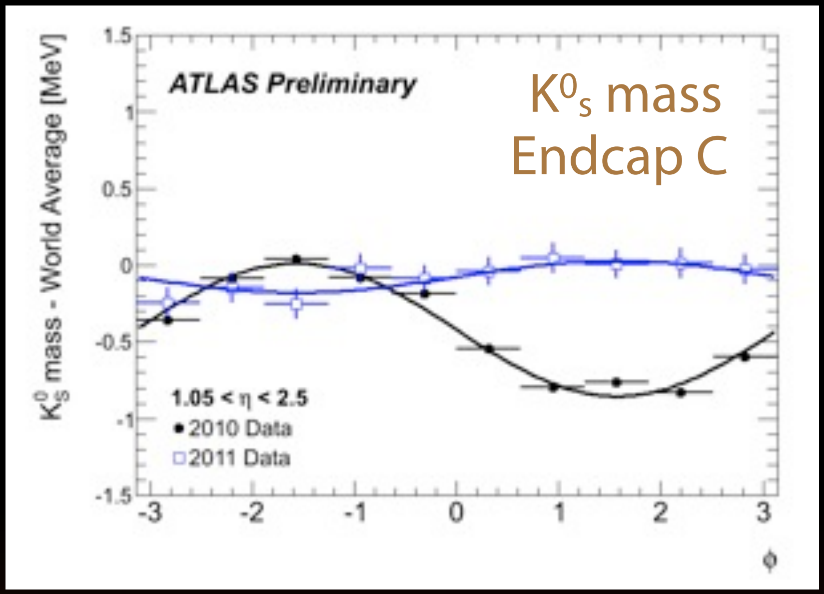


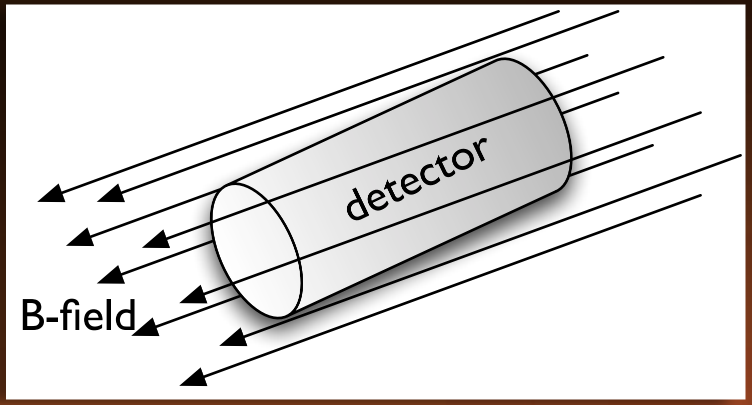


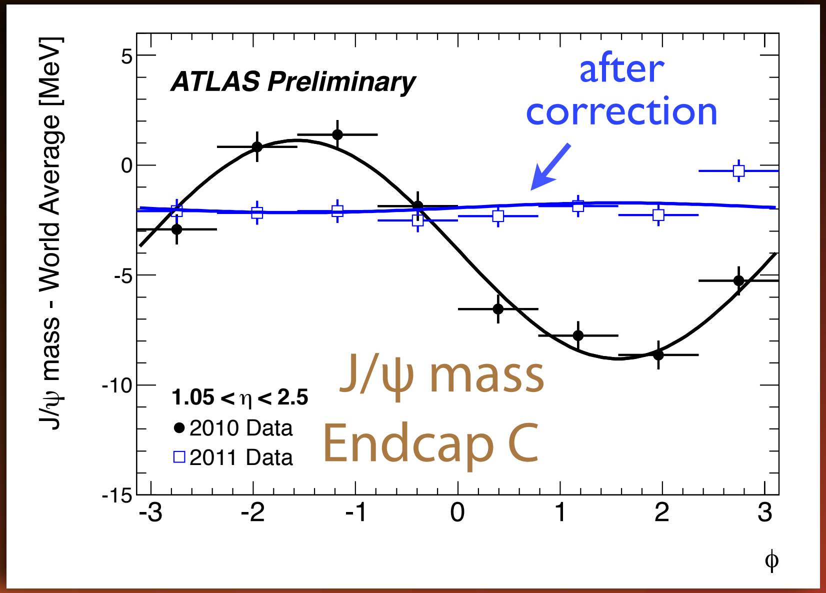
B-Field Tilt vs Nominal ?

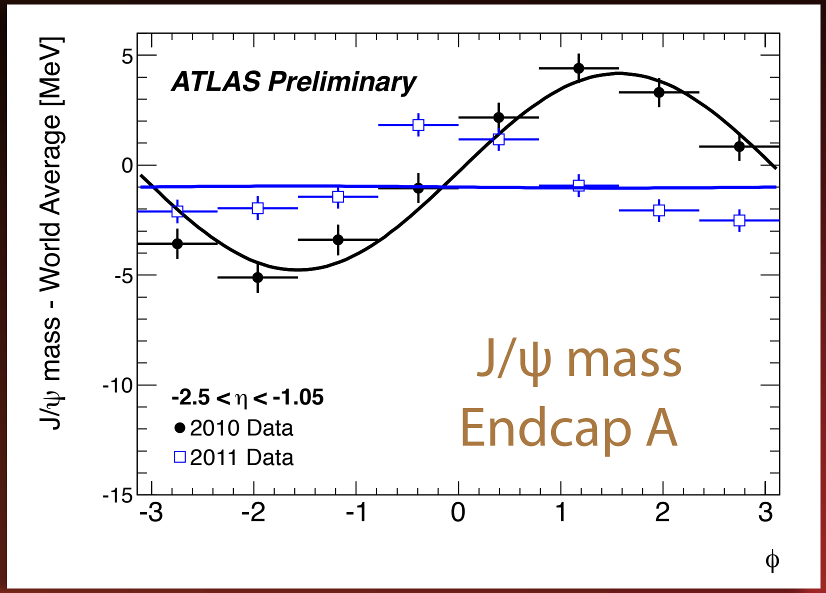
- field tilt in ATLAS visible in K^0_s + J/ψ mass bias vs ϕ
  - ➡ results in a sine modulation in mass in opposite directions in both endcaps
  - ➡ corrected by 0.55 *mrad* field rotation around y axis
  - ➡ consistent with survey constraints





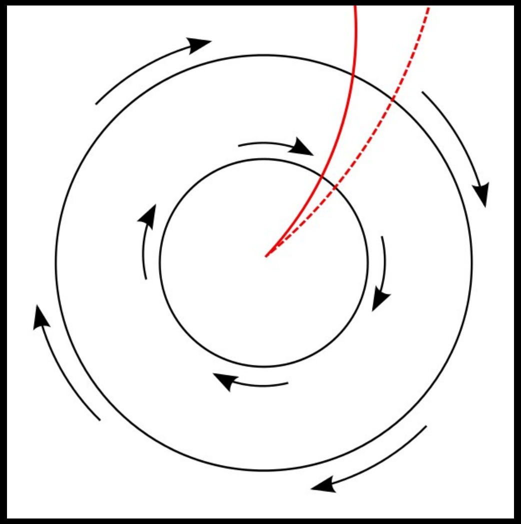




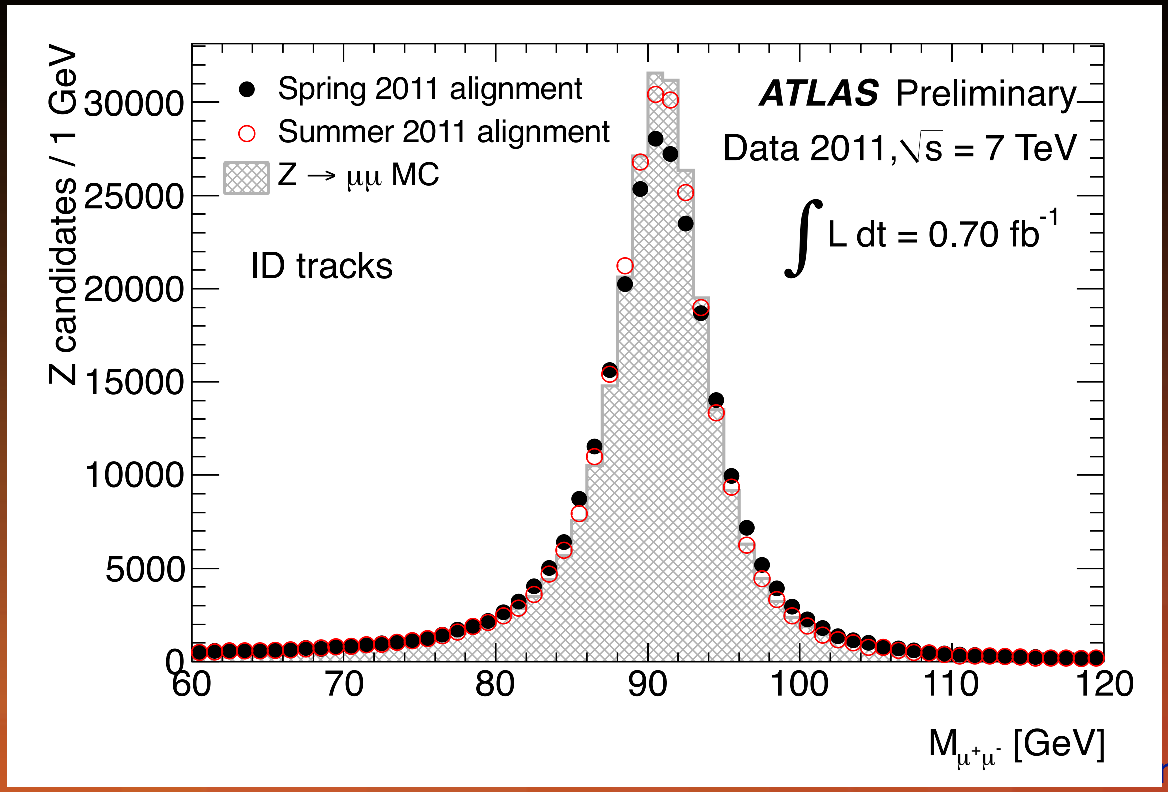


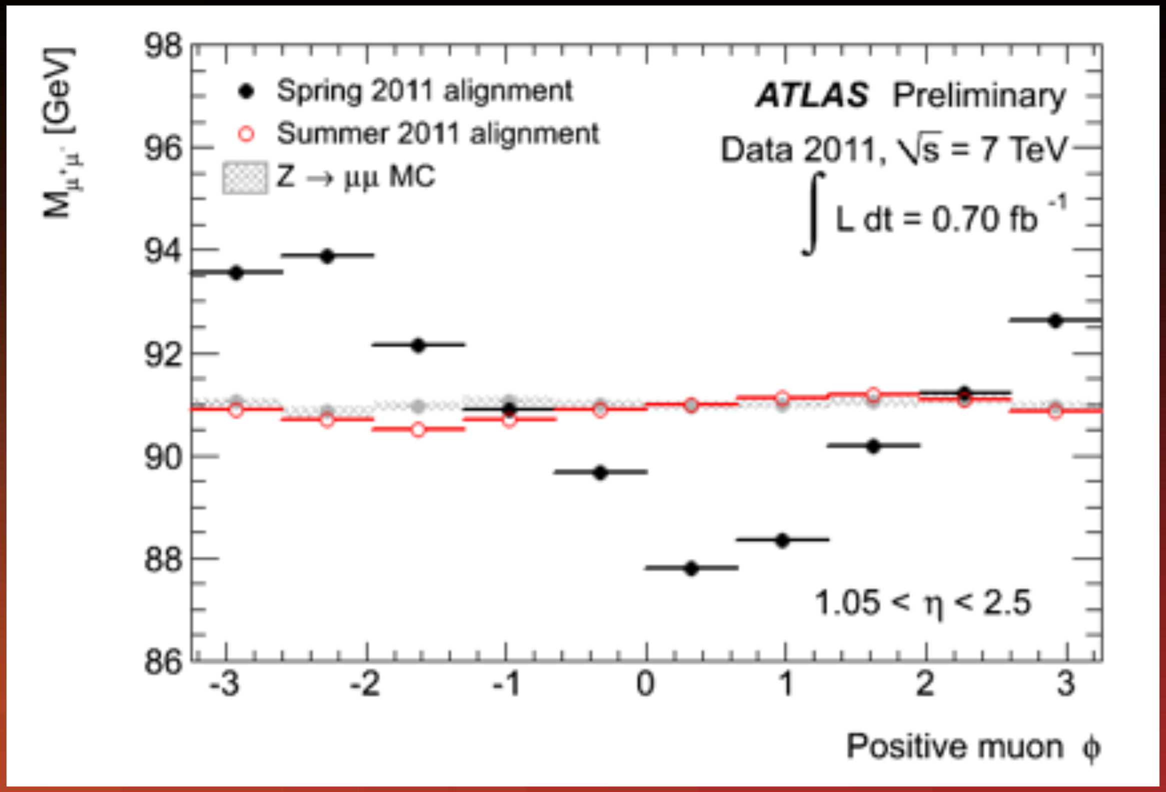
Evidence for Weak Modes ?

example:
curl weak mode



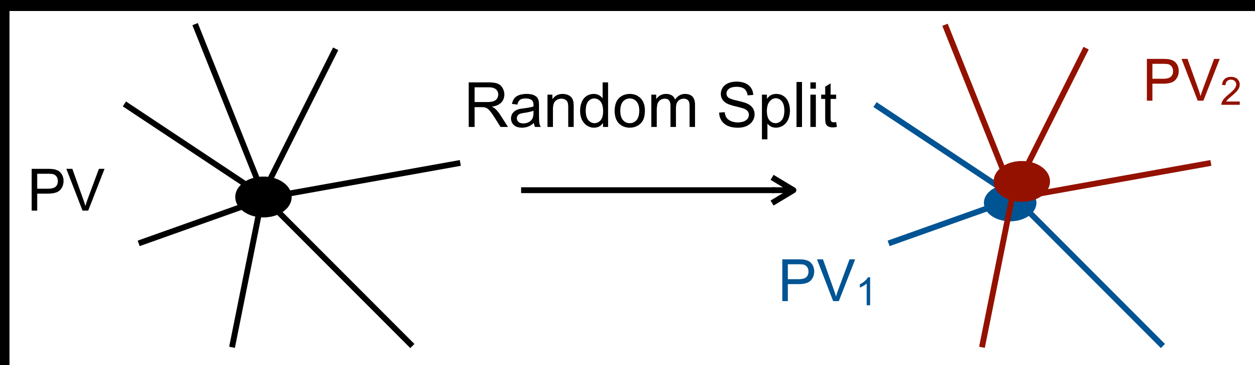
- "weak modes" are global deformations
  - ➡ leave fit-χ^2 nearly unchanged
  - ➡ affect momentum scale, e.g. Z-mass resolution
  - ➡ several techniques to control weak modes
    - electron E/p using calorimeter
    - muon momentum in tracker vs muon spectrometer
    - TRT to constrain Silicon alignment (ATLAS)
- limiting performance in data
  - ➡ ATLAS saw modulation in Z mass vs $\phi(\mu^+)$ in endcaps

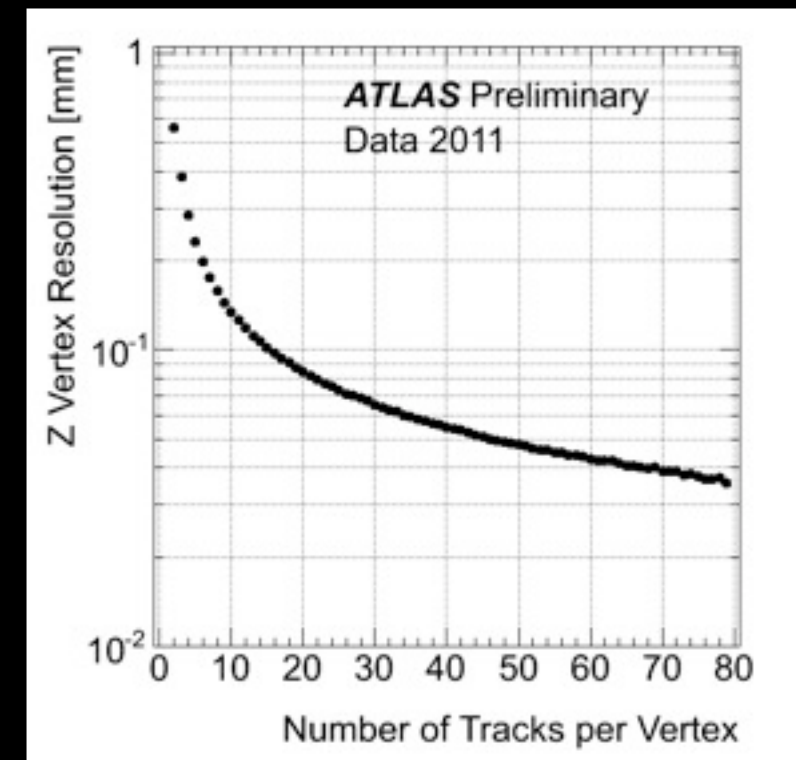




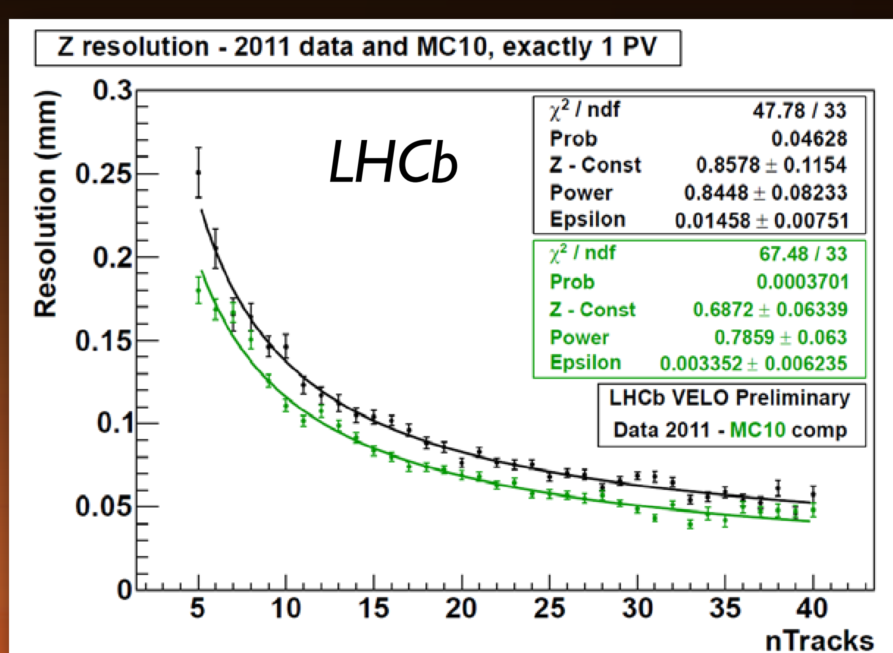
Primary Vertex Resolution from Data

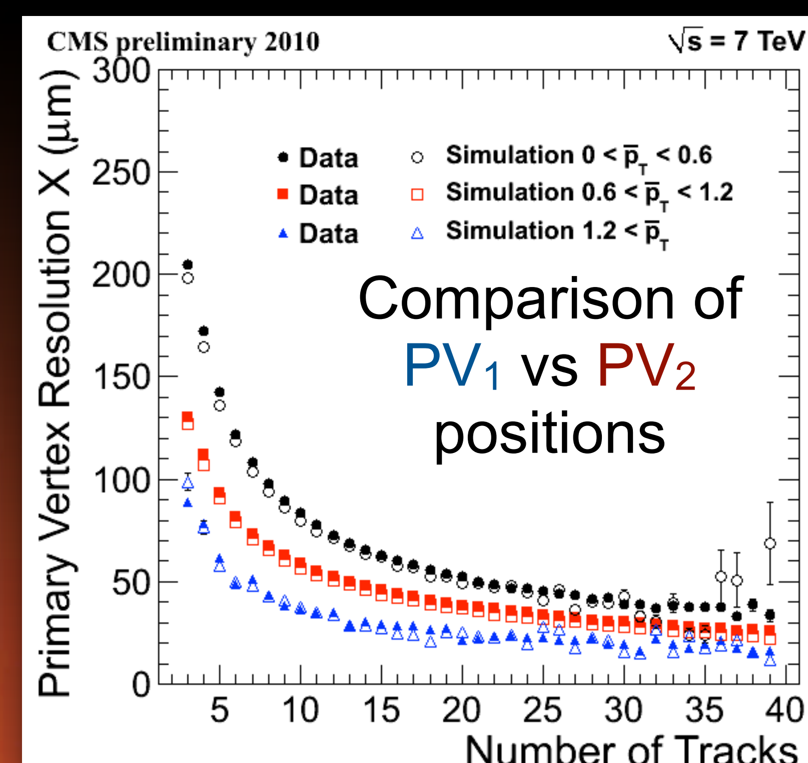
- primary vertex is input to b-tagging, etc.
  - ➡ need to understand precisely the resolution in data





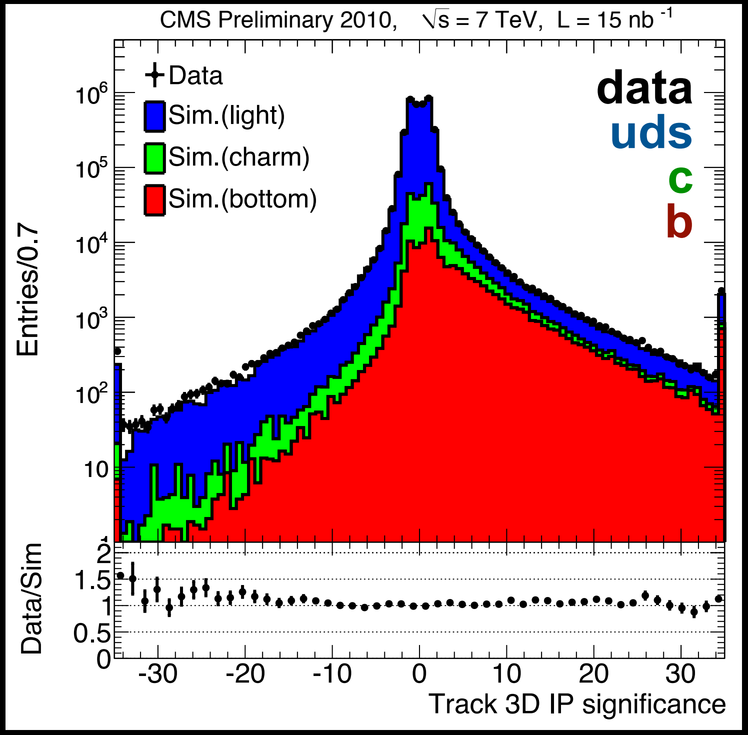
- split vertex technique
  - ➡ data driven method
  - ➡ split vertex in 2 and study difference in the 2 fitted positions as function of n tracks

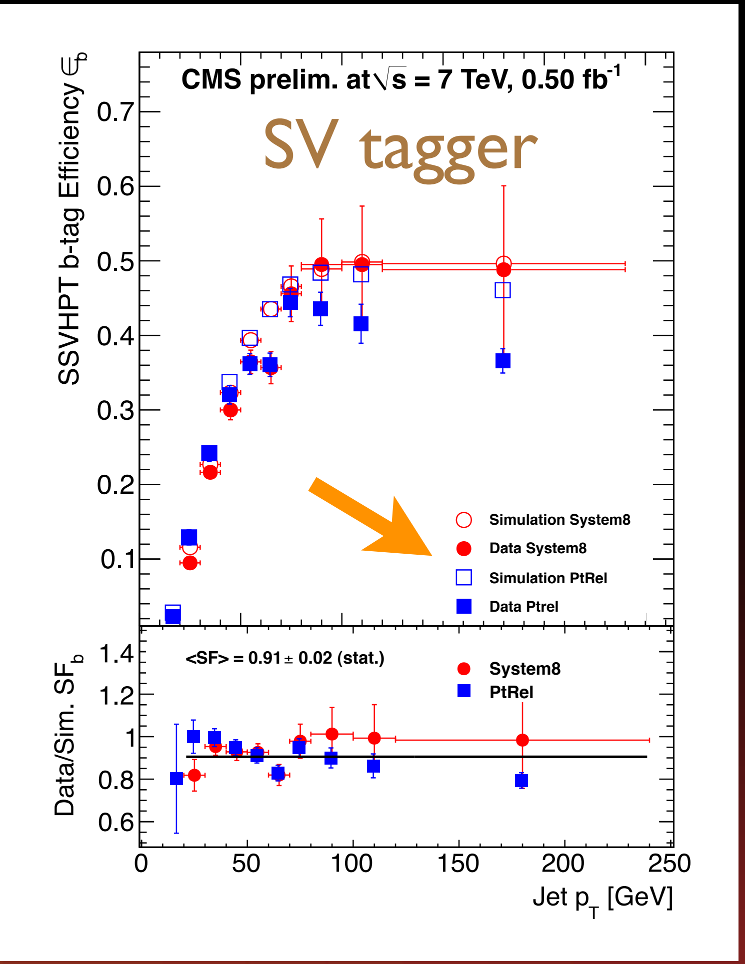


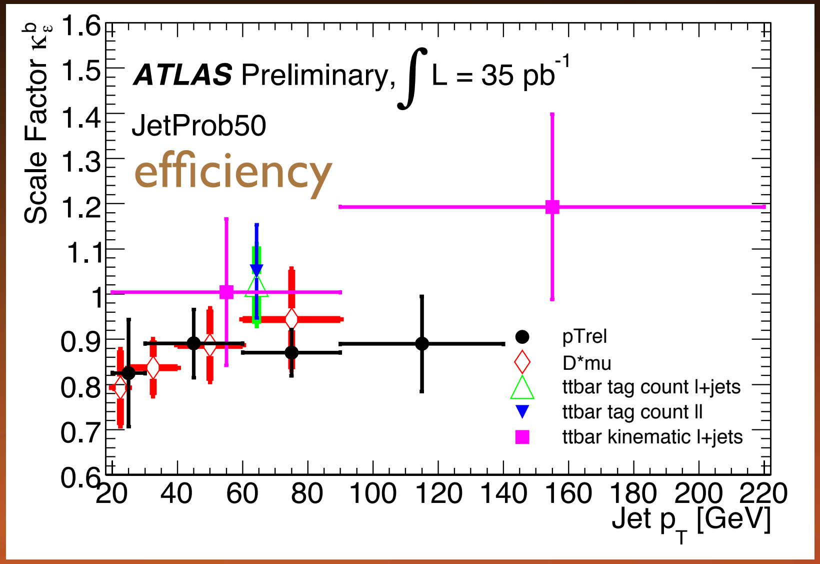


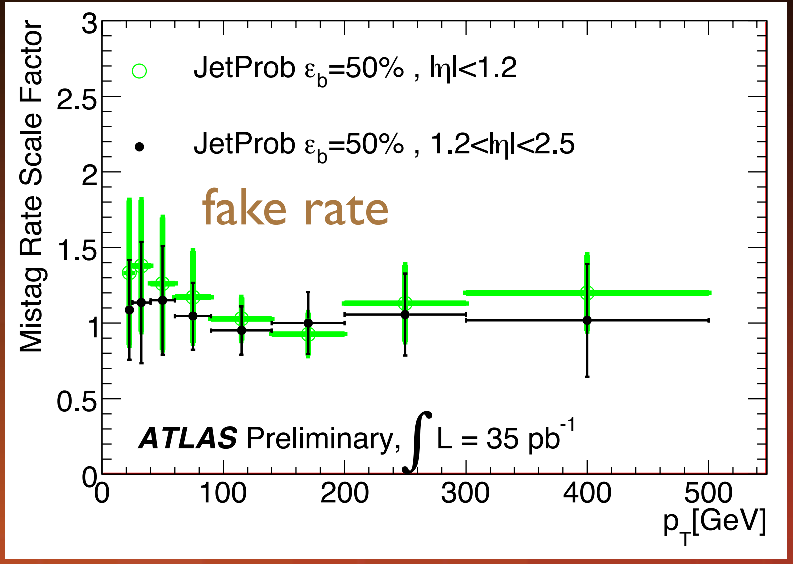
b-Jet Tagging

- commissioning of b-tagging
  - ➡ helped by good local alignment
- initially used robust taggers
  - ➡ impact parameter (IP) significance (JetProb)
  - ➡ inclusive secondary vertex tagger (SV)
- data driven performance calibration
  - ➡ efficiency using independent tagger, e.g. muon p_T-rel
  - ➡ b-jet tagging in tt events
  - ➡ 'system8' in lepton tagged di-jet events
  - ➡ mis-tags using 'vtx mass' template fits or 'neg. tags'



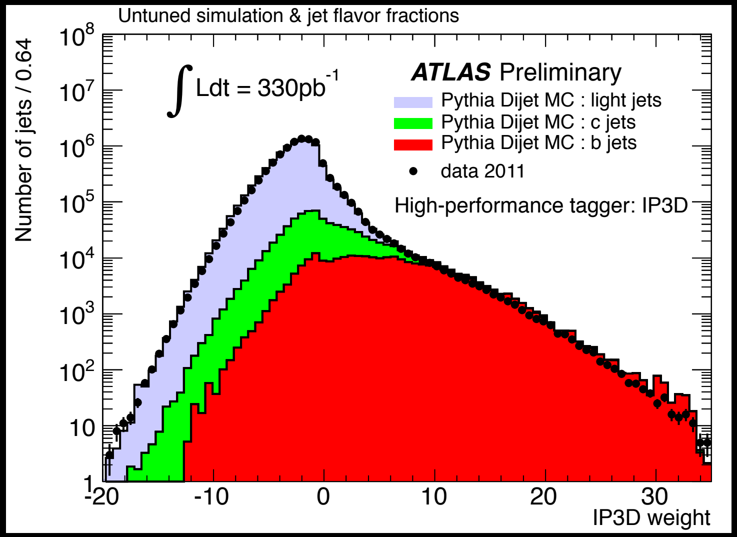


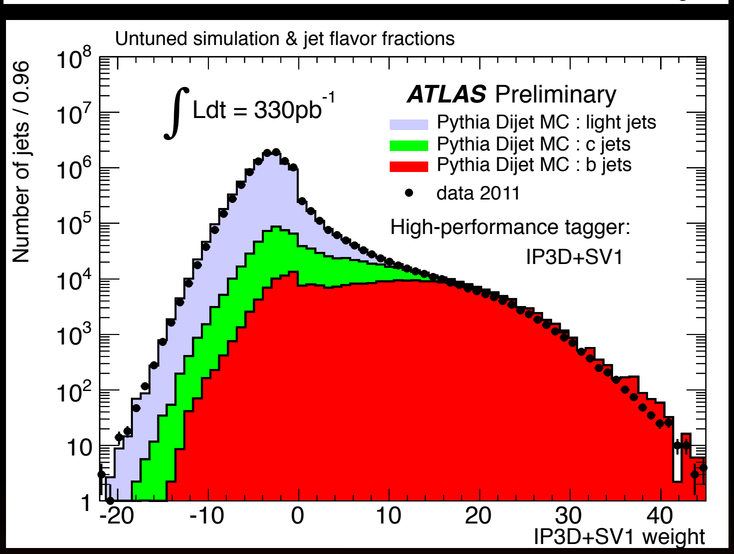


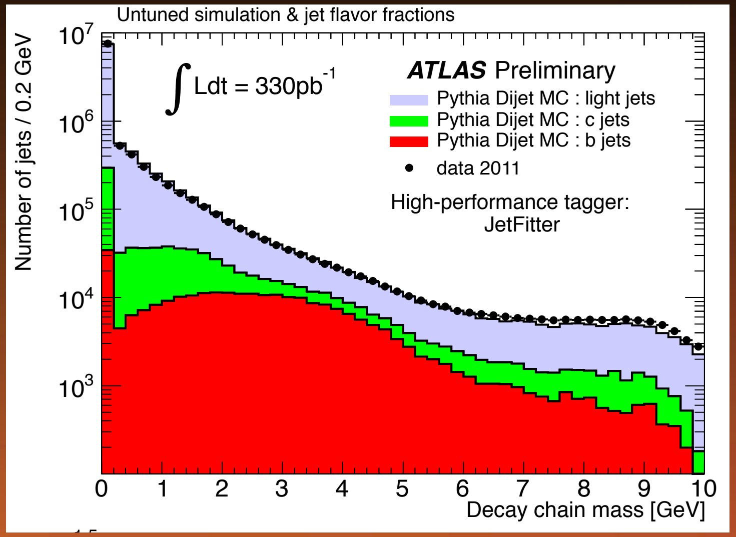


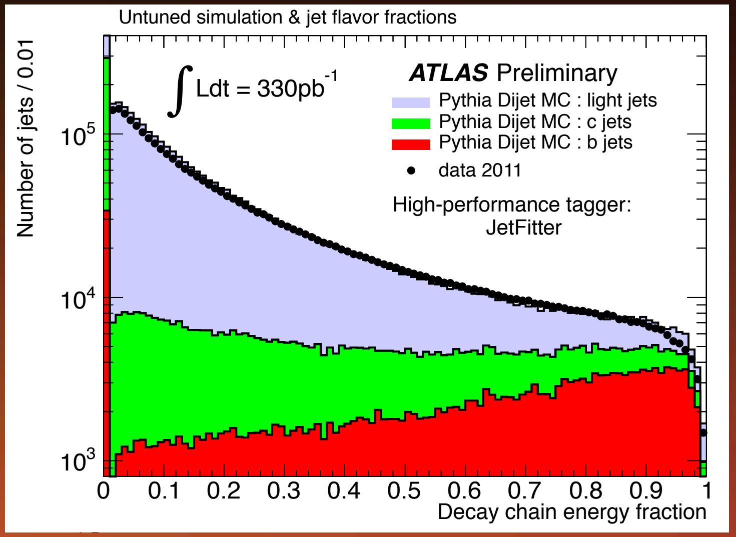
b-Jet Tagging

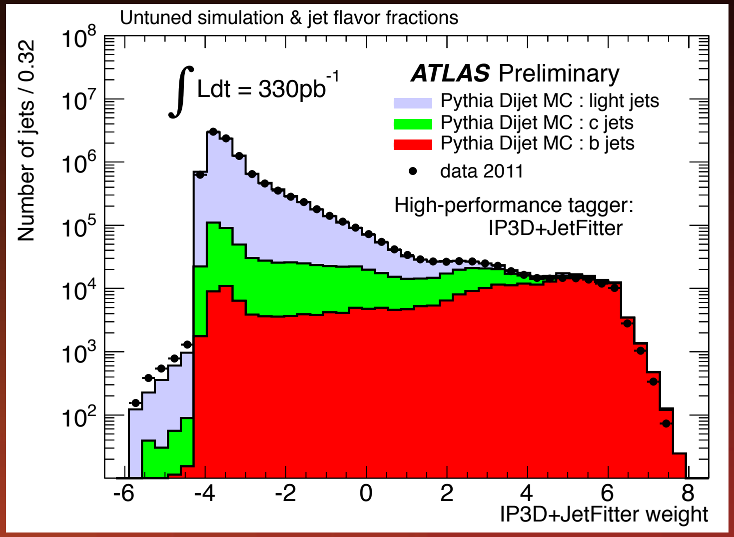
- towards more sophisticated taggers
  - ➡ optimal combination of IP and vertex information
  - ➡ require excellent control on tracking performance
  - ➡ interplay with properties of jets and fragmentation in different event topologies
  - ➡ been used for recent physics results (summer 2011)











Let’s Summarize...

- gave overview of tracking and vertexing commissioning
  - ➡ how to reach design performance for calibration, tracking, alignment, vertexing
  - ➡ commissioning of b-tagging
- next is pileup tracking and upgrade