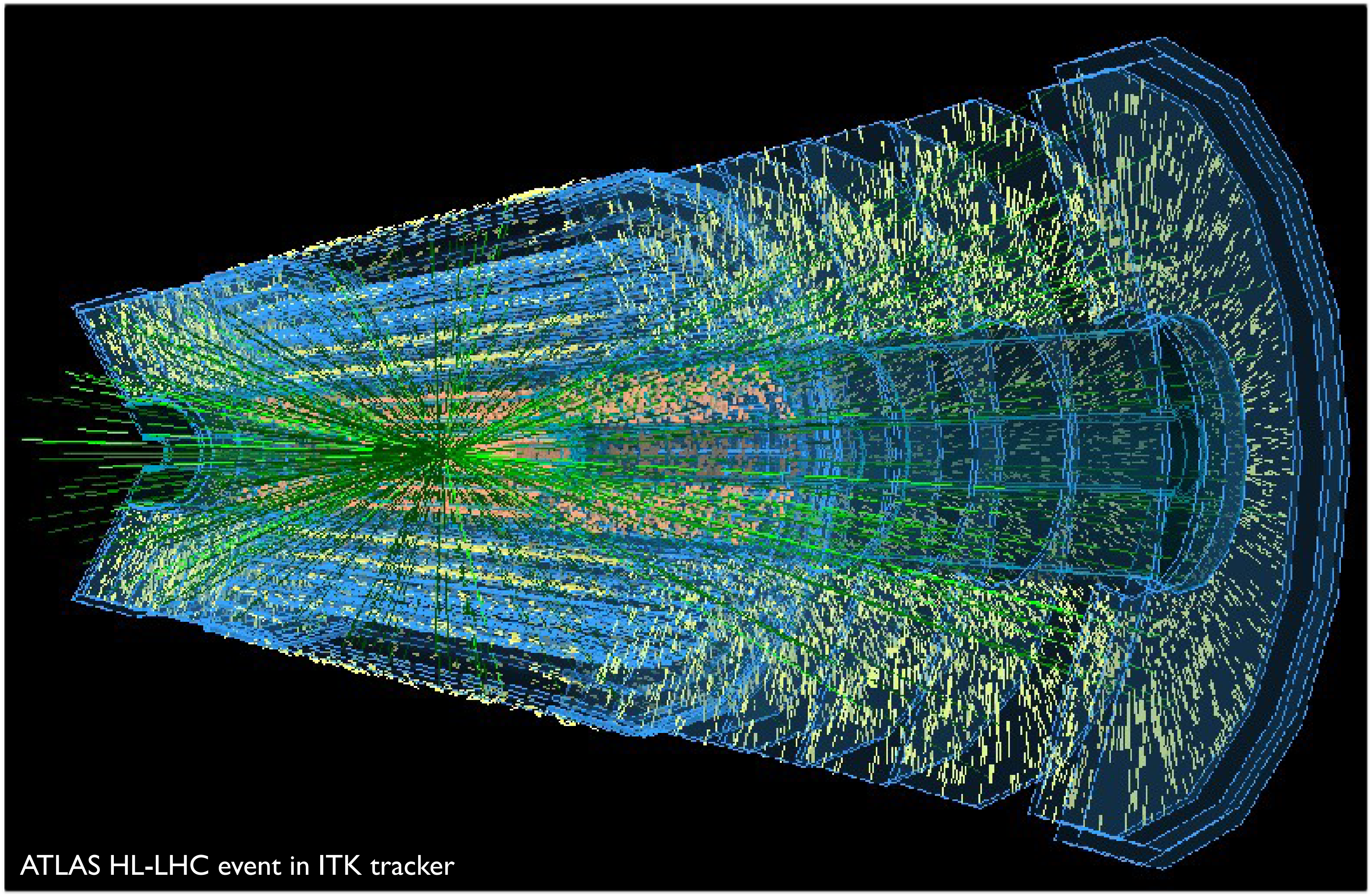
Markus Elsing

Tracking at the LHC (Part 5)

Lessons from early Data Taking



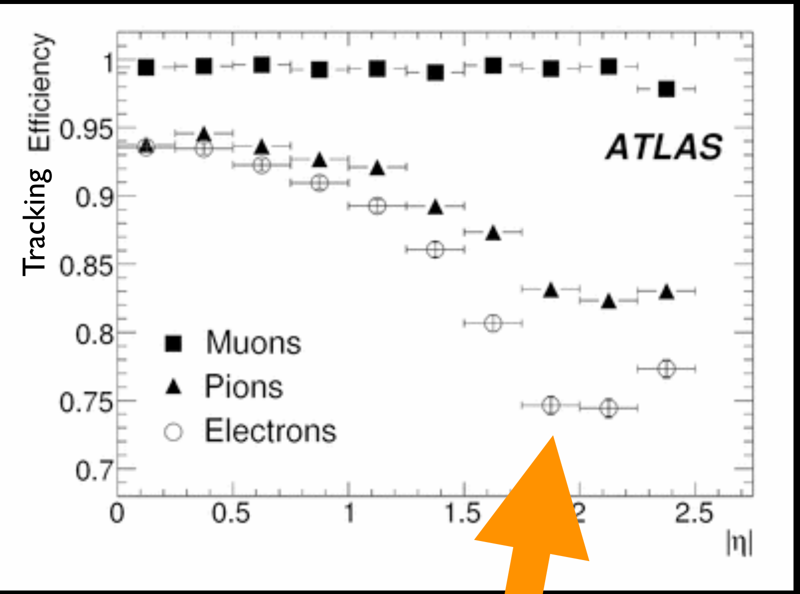
ATLAS HL-LHC event in ITK tracker

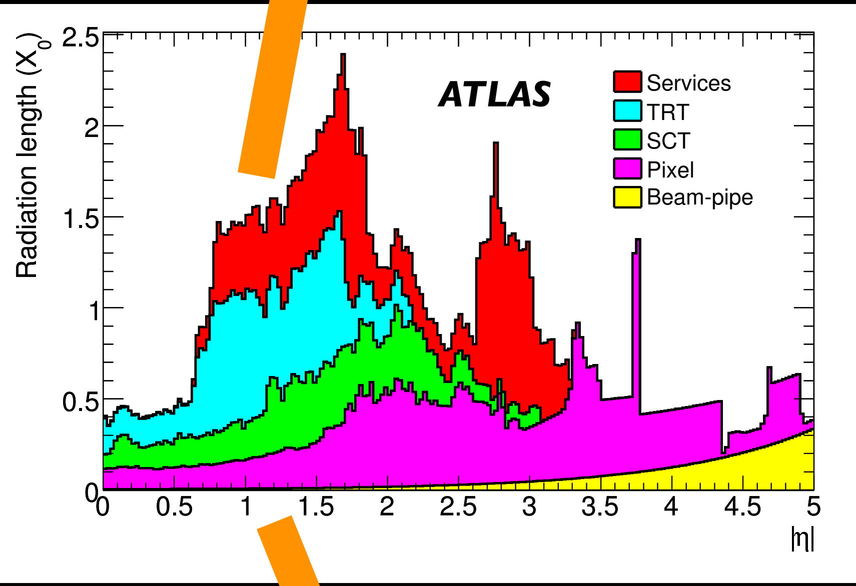
Outline of Part 5

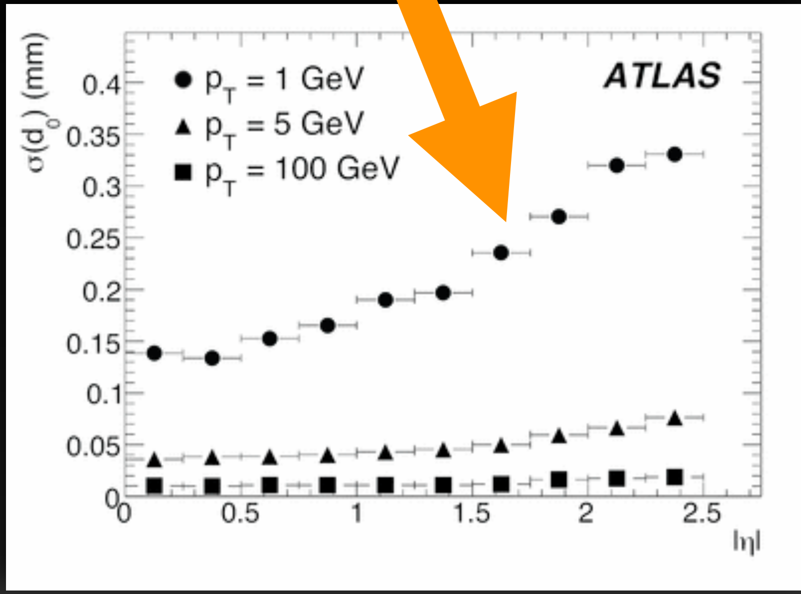
- recap expectations on tracking performance
- commissioning of detector and tracking
  - ➡ material studies, alignment
- short outlook on future of tracking in ATLAS

Expected Performance

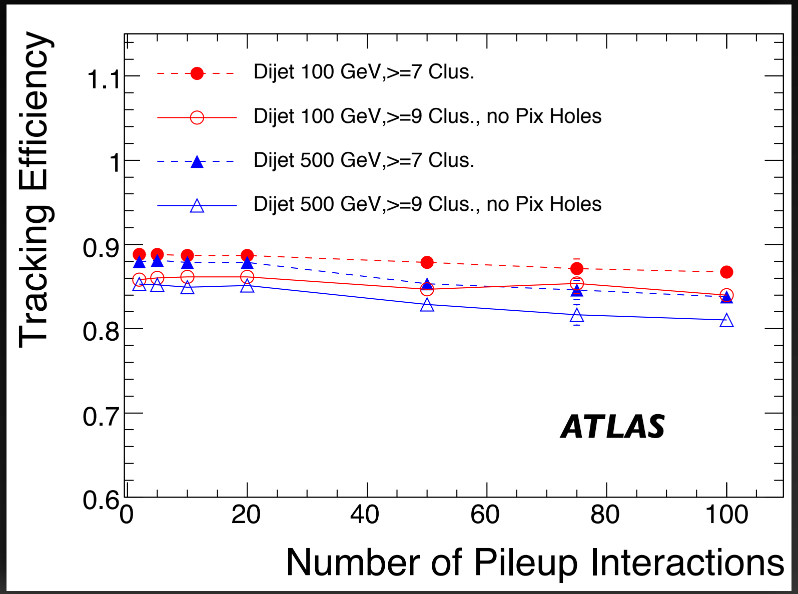
- excellent preparation before startup
  - ➡ more than 10 years of simulation and test beam
  - ➡ cosmics data taking in 2008 and 2009
  - ➡ payed off at startup year !
- detailed simulation studies
  - ➡ document expected performance in TDRs
  - ➡ few of the known critical items:
    - material effects 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





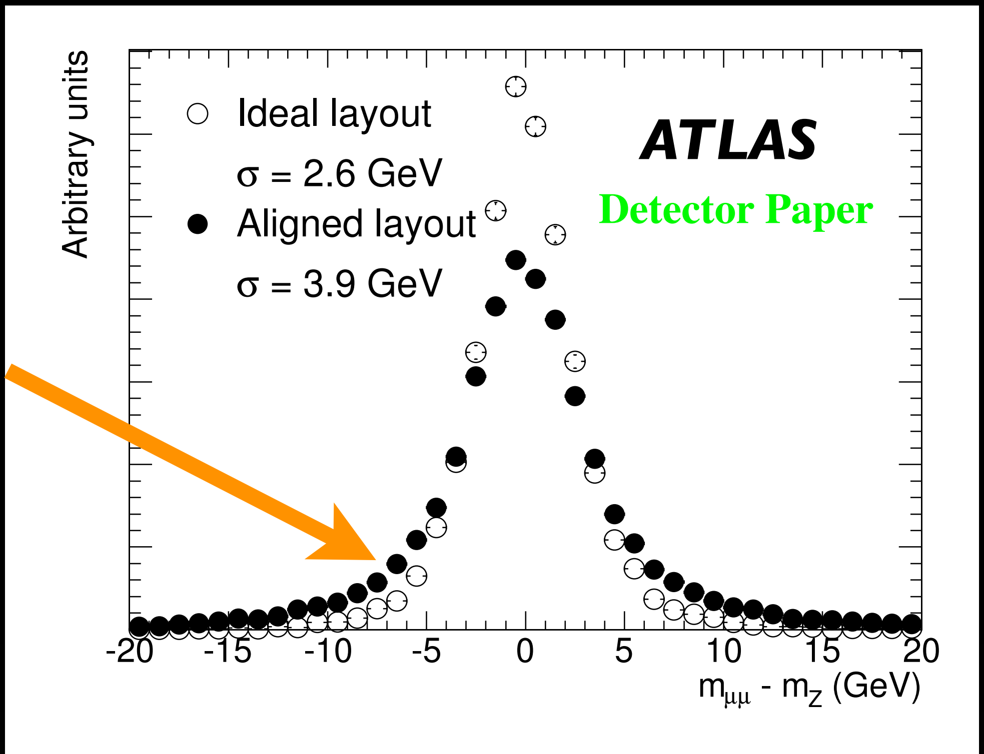


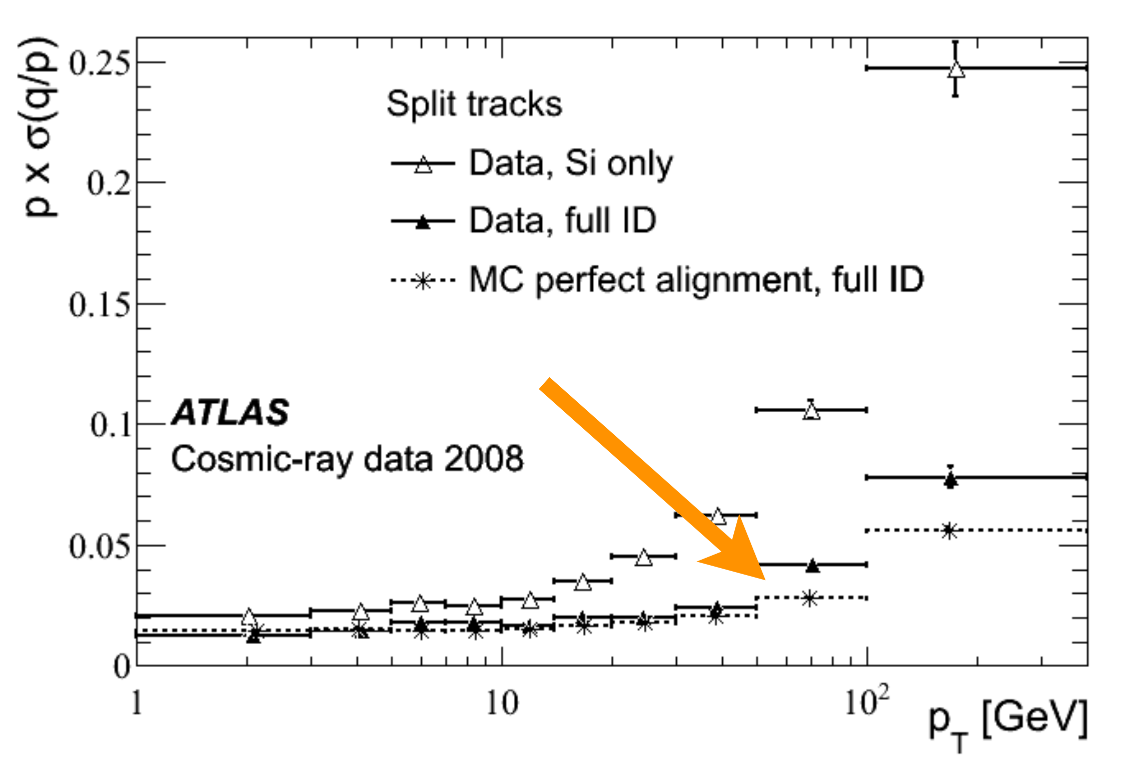
performance with
event pileup



Expected Difficulties ? - Yes

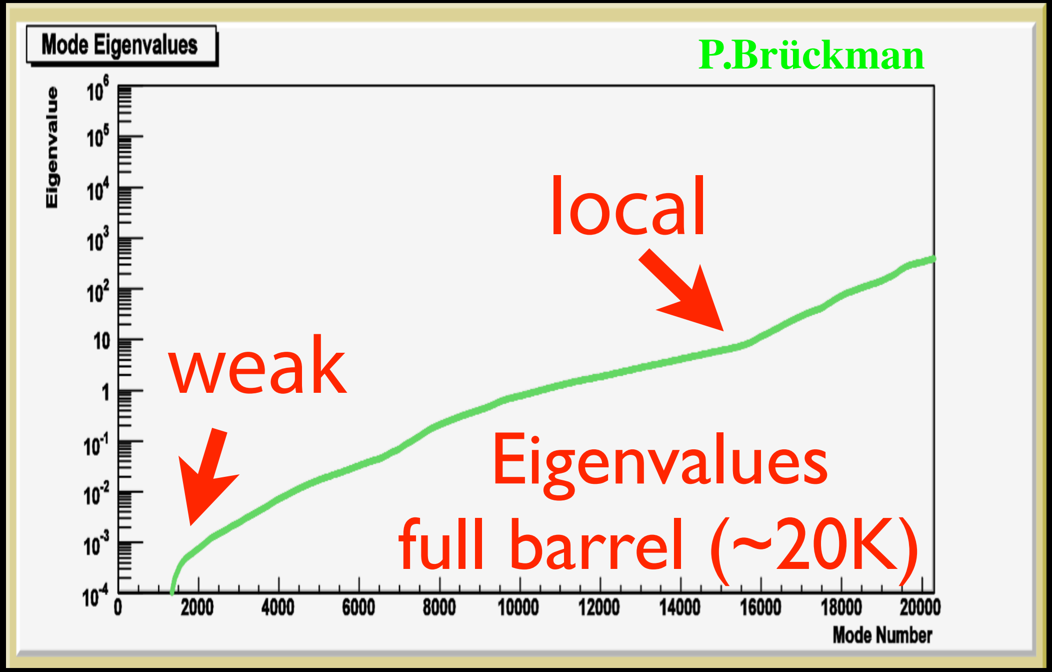
- ATLAS detector paper MC study:
  - ➡ ideal Z mass resolution 2.6 GeV
  - ➡ misalign MC by 100 µm, re-align using:
    - high-p_T muons and cosmics
  - ➡ Z mass resolution degraded to 3.9 GeV (!)
    - need to use external constraints to improve
- cosmics study using split tracks
  - ➡ good performance 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 ?



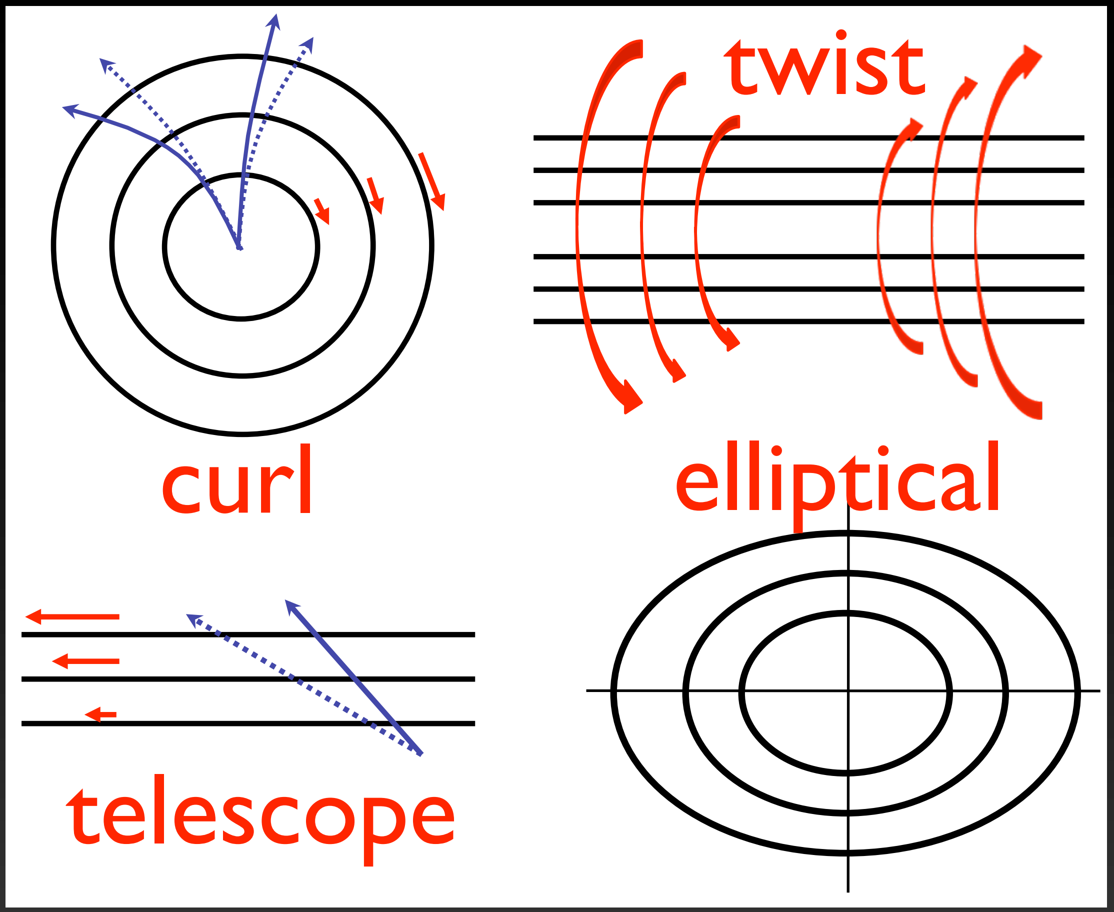


Alignment and Weak Modes

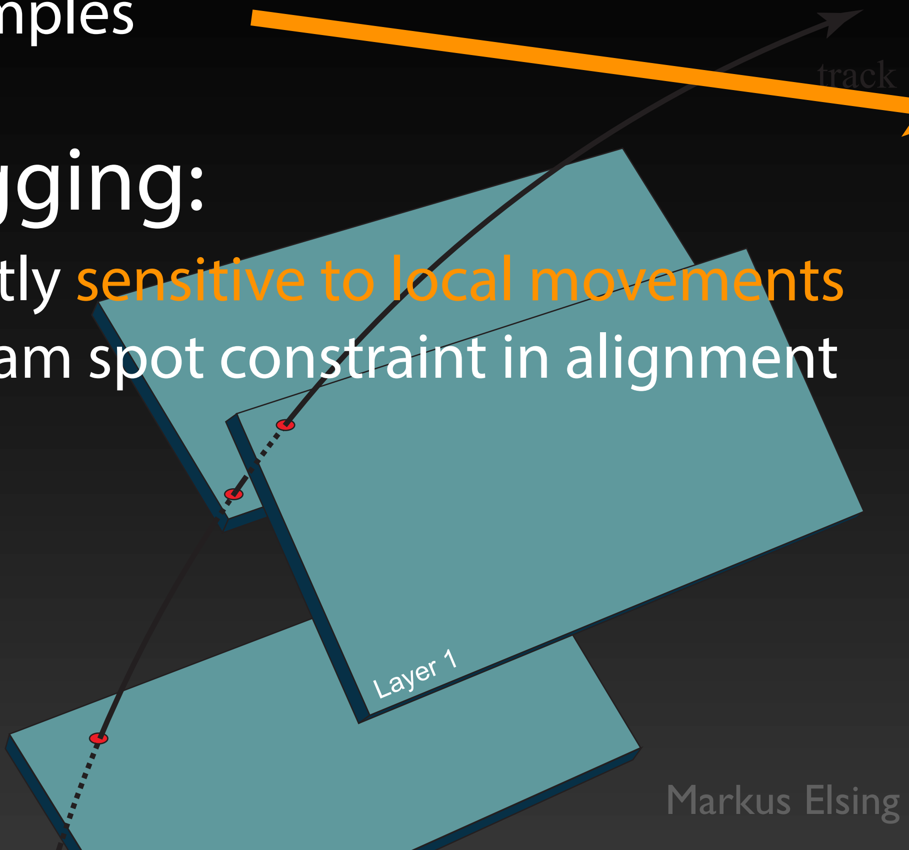
- global-χ^2 alignment
  - ➡ diagonalize alignment matrix (36k x 36k)
  - ➡ enables studies of Eigenvalue spectrum
    - well constraint : local movements
    - less well constaint : overall deformations
    - not constraint : global transform



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



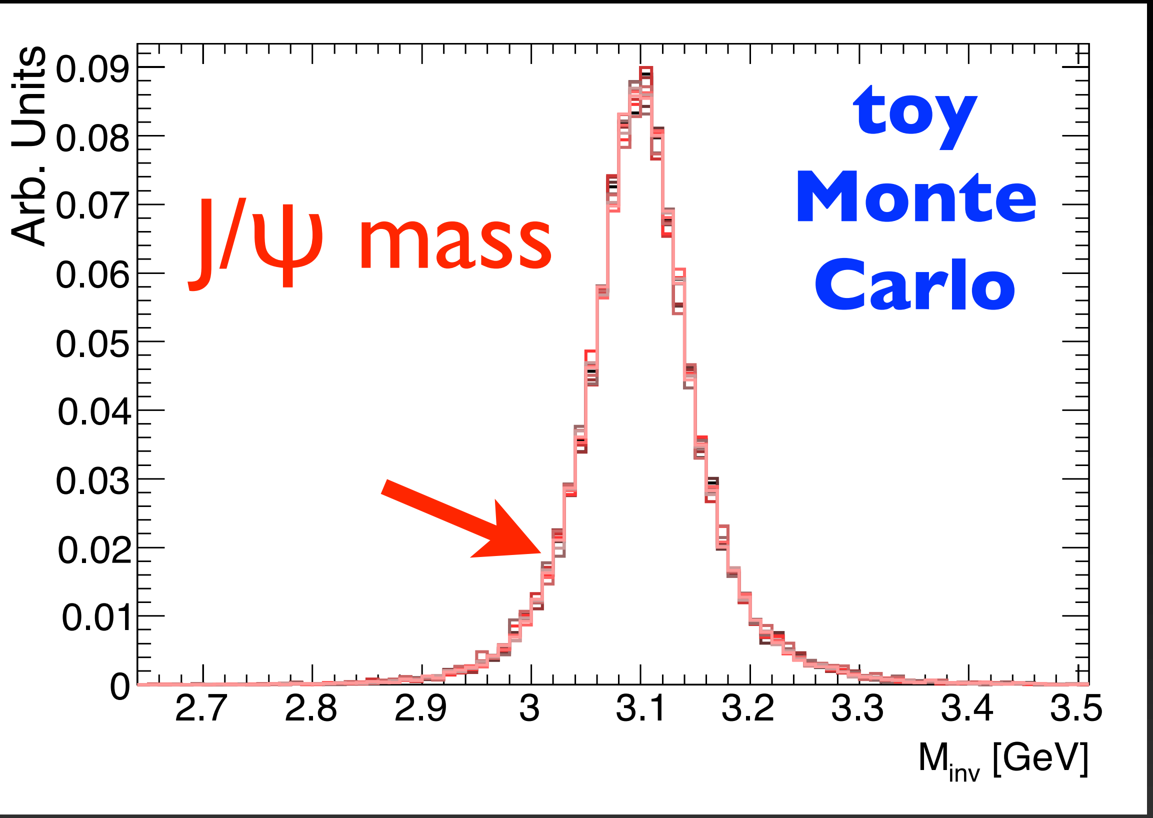
- b-tagging:
  - ➡ mostly sensitive to local movements
    - beam spot constraint in alignment

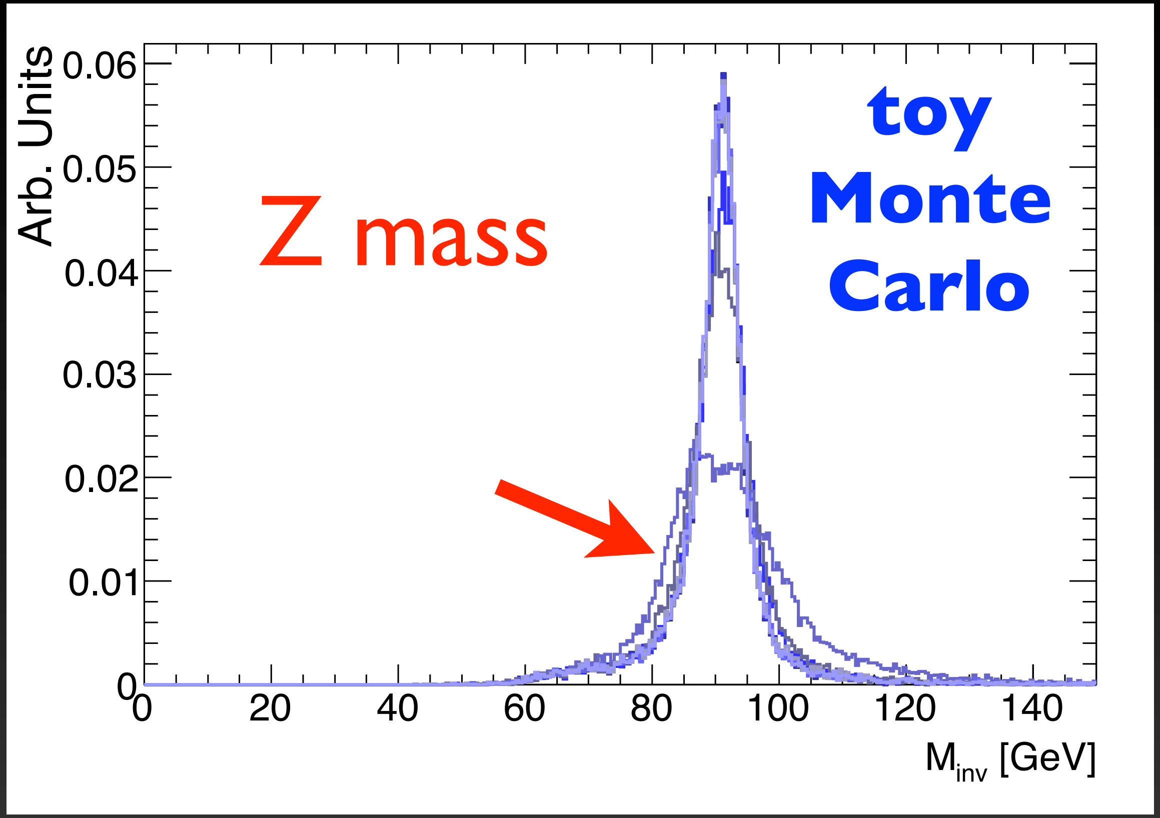


A.Salzburger

Toy Monte Carlo Study of Weak Modes

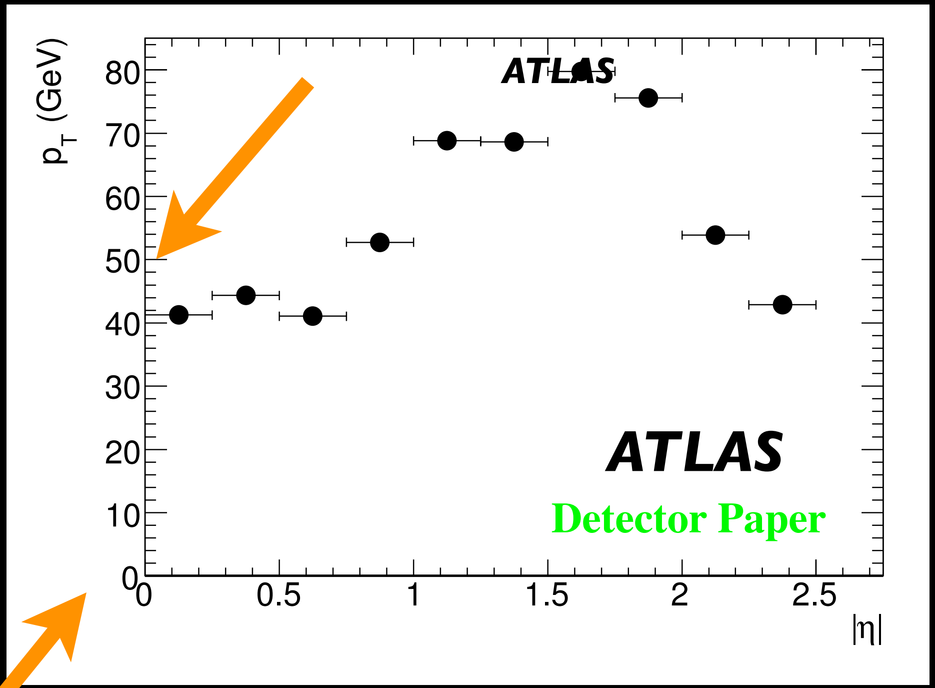
- used ad-hoc alignment sets with weak modes (2006)
  - ➡ 9 'easy' modes introduced by hand
  - ➡ rerun reconstruction to study effect on Z and J/ψ mass
  - ➡ compare against nominal Monte Carlo
- qualitatively one sees clear effects...
  - ➡ some modes affect the mass resolution
  - ➡ relative effect on J/ψ much smaller, much larger effect on Z

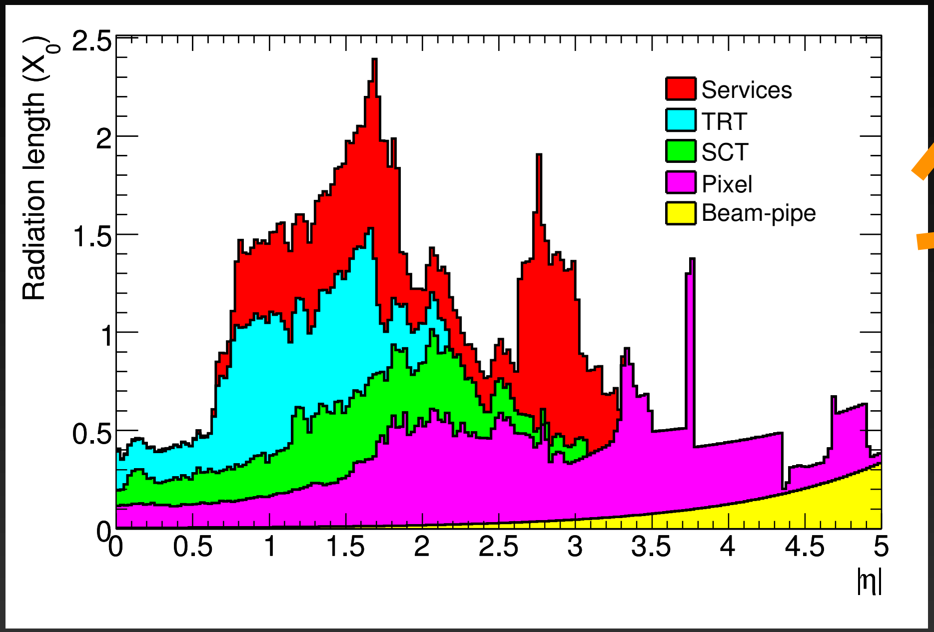


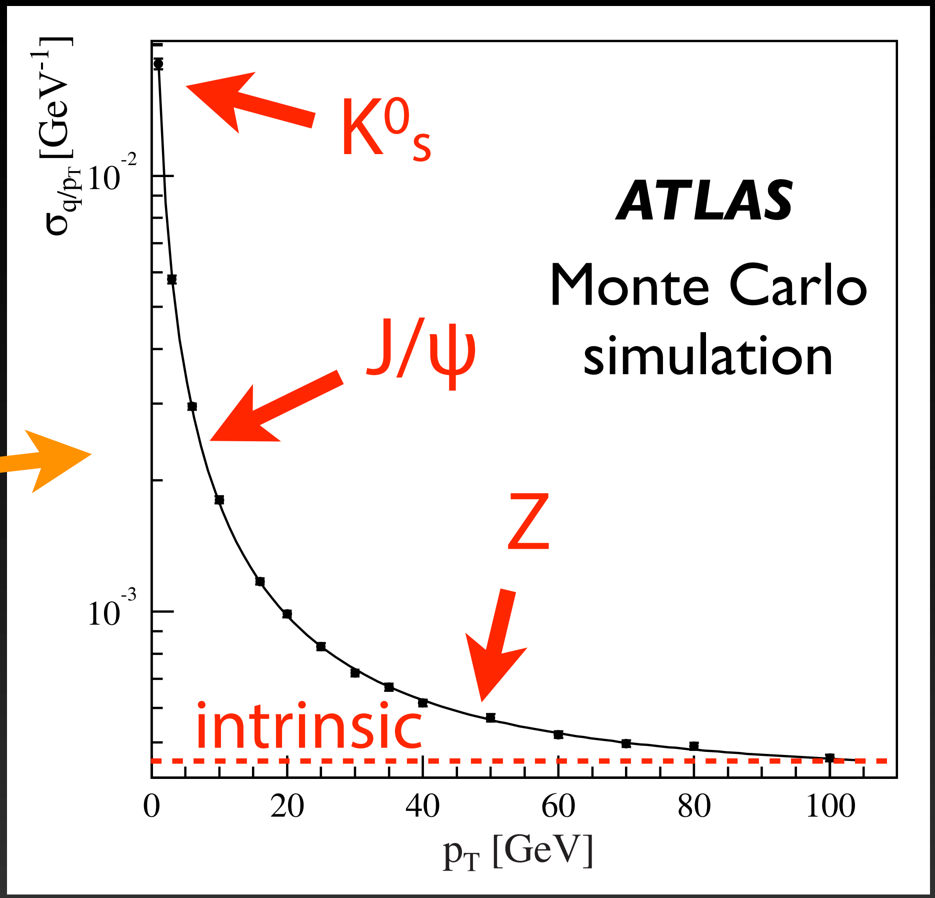


Material vs Momentum Resolution

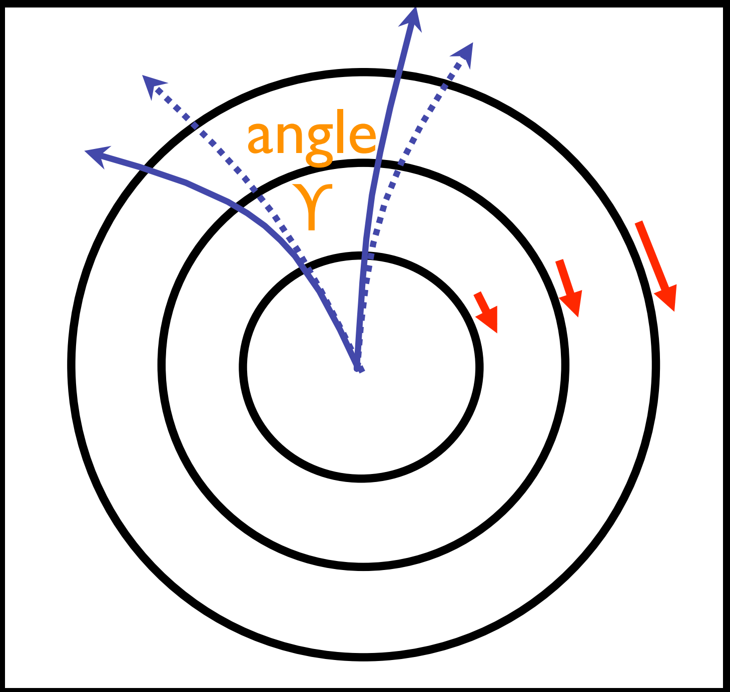
- let's remind ourselves:
  - ➡ resolution model: **$\sigma(q/p_T) = a \oplus b/p_T$**
    - **a** describes intrinsic resolution
    - huge multiple scattering term **b**
  - ➡ at ~50 GeV the intrinsic resolution equals the multiple scattering term
    - similar effects for CMS, but 4T B-field helps
  - ➡ in practice J/ψ is material dominated !







Weak Modes and Momentum Scale



- let's try to understand the toy MC results
  - ➡ why is the Z mass so much more sensitive ?
- weak modes biases the curvature (q/p_T)

$$q/p_T \Rightarrow q/p_T + \Delta$$

  - ➡ this means, the curvature bias scales with momentum

$$\delta(p)/p \ \ \alpha \ \ p$$

- invariant mass of a 2 body decay
  - ➡ scales with momentum and opening angle

$$m \sim p \sqrt{2 - 2 \cos \gamma}$$

  - ➡ neglecting the momentum difference between the 2 decay products

Interpretation of J/ψ and Z in Toy MC

- let's put in some numbers for J/ψ and Z:
  - ➡ for simplicity assume p ~ 50 GeV and $\gamma \sim 180^o$ for $Z \to \mu\mu$
  - ➡ let's assume average P ~ 5 GeV for the muons from J/ψ
    - factor **10** in curvature compared to muon from $Z \to \mu\mu$
  - ➡ using J/ψ mass and P ~ 5 GeV one gets
    - typical opening angle $\gamma = 35^o$
    - hence, a factor **3** smaller √(...) term than for $Z \to \mu\mu$
- therefore, effect on m(J/ψ) is inflated by factor **30** for m_Z
  - ➡ J/ψ mass scale shift by **0.2%** translates into **6%** on m_Z

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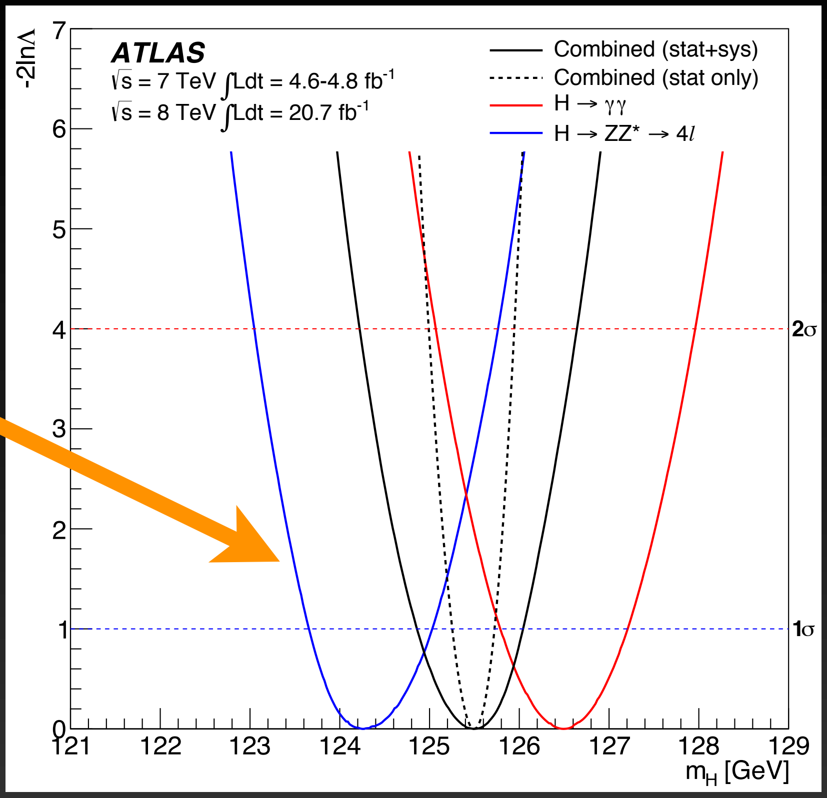
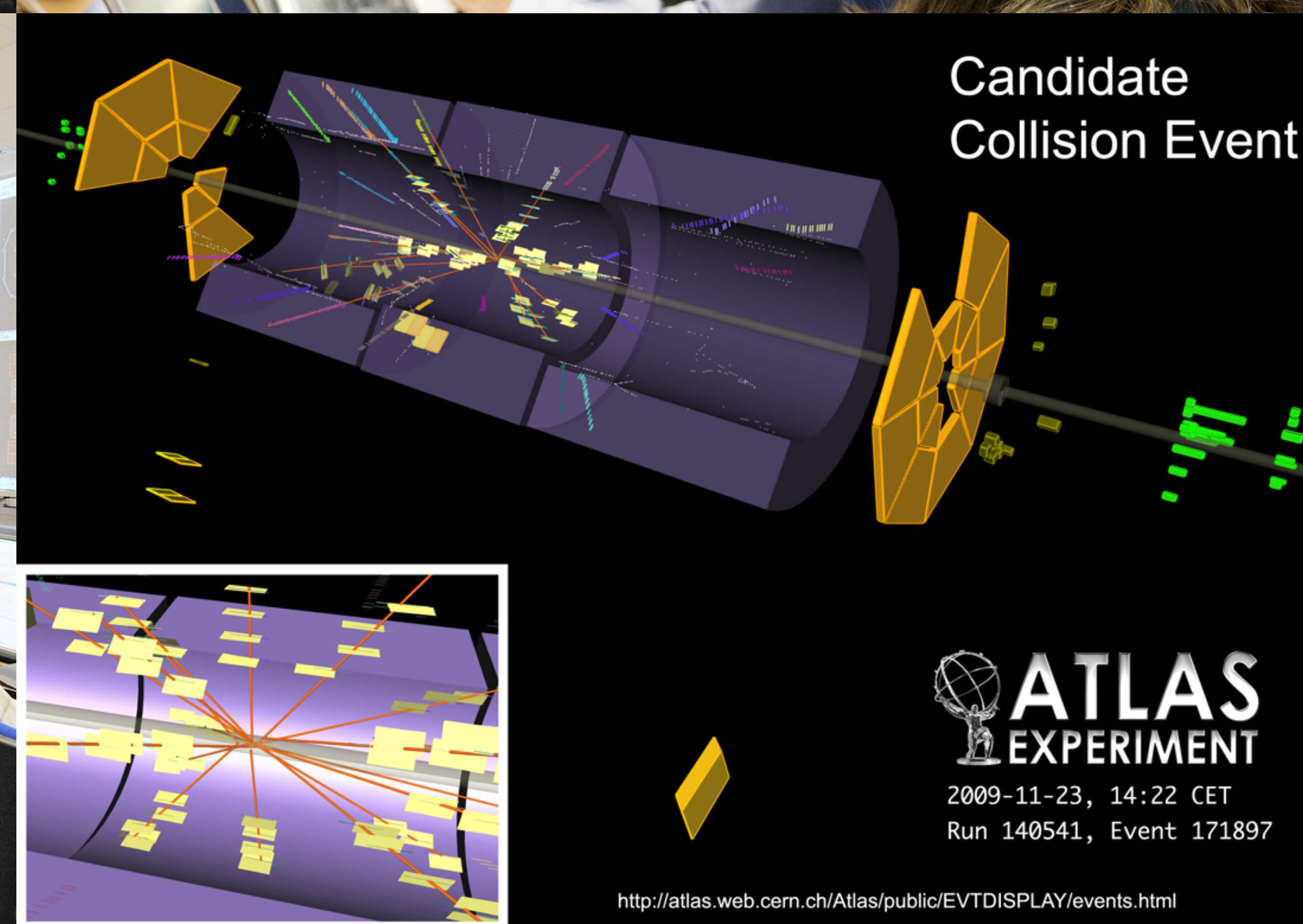
- ATLAS 2012: H→4l mass scale ?
  - ➡ H→ZZ*→4μ has a high and a low mass μμ-pair
  - ➡ H→4μ mass scale uncertainty:
    - low mass μμ pair doesn't contribute much
    - dominated by Z→μμ, which we do control well
  - ➡ illustrates importance to control weak modes !

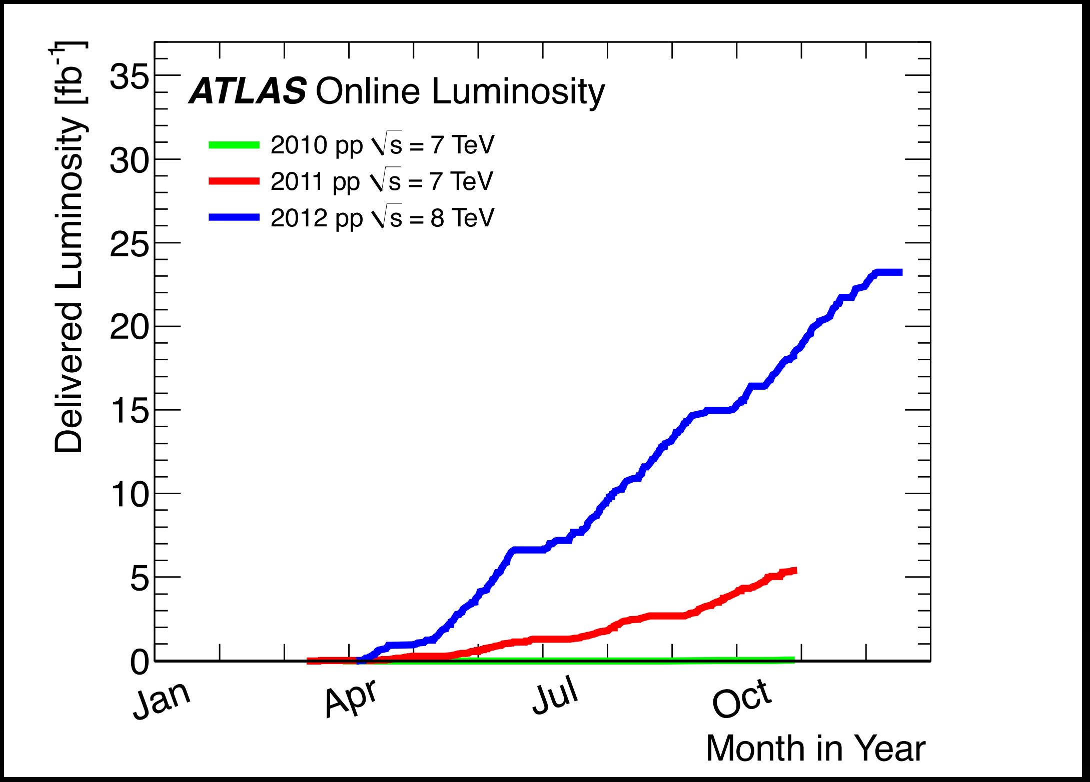


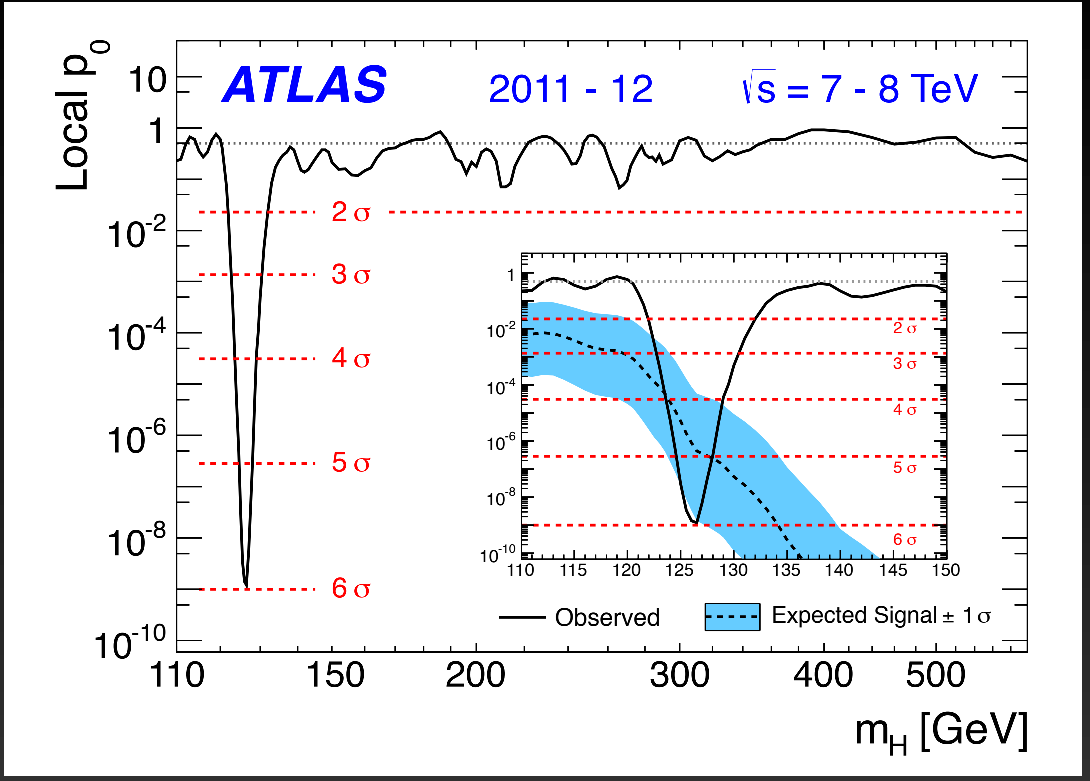
DAY ONE: Excitement with first beams...



Commissioning

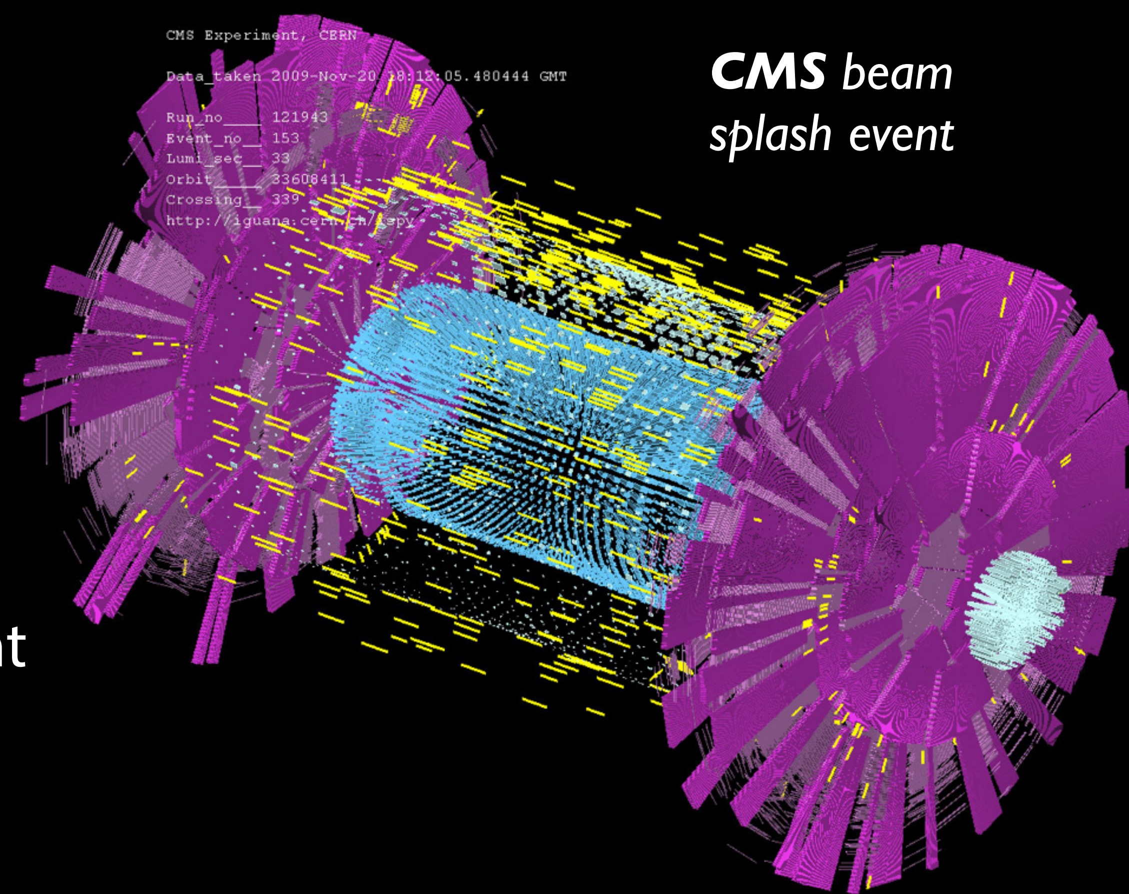
- LHC has done fantastic since !
  - ➡ pileup in 2012 exceeding LHC design (at 50 nsec)
- a long way from first collisions to physics
  - ➡ commission full readout chain (detector, trigger, DAQ)
  - ➡ calibrate and align the detector
  - ➡ optimize the tracking performance, allow for changing levels of pileup
  - ➡ ...
- basis of commissioning the tracking is excellent work done on the detector !
  - ➡ let's briefly discuss a few examples...



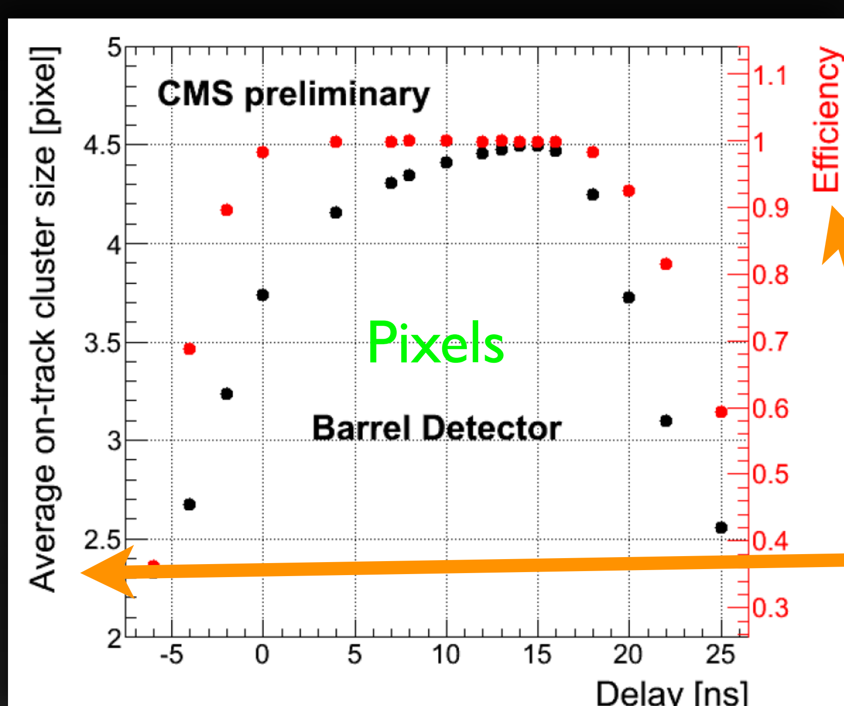


Timing of the Detector

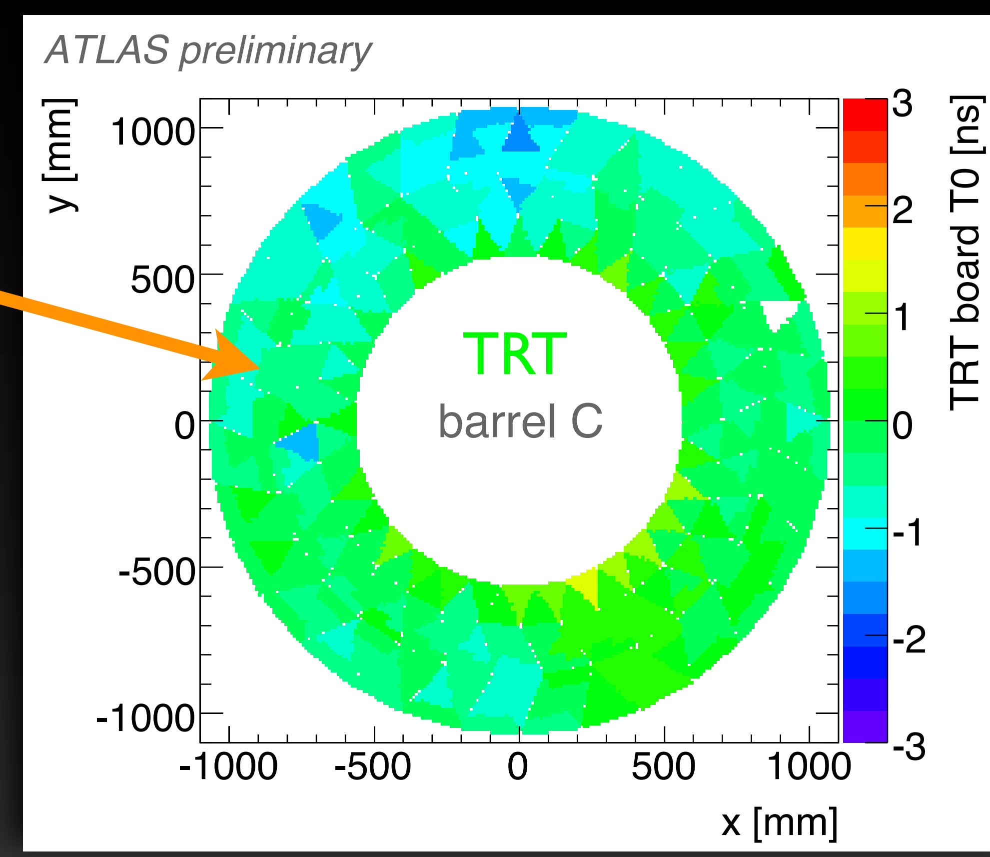
- timing in the detector is crucial
  - ➡ to be ready for 50/25 nsec operation
  - ➡ time of flight is large compared to LHC event rate
  - ➡ precise timing required to be fully efficient (time walk in silicon detectors, etc.)
- work started before collisions
  - ➡ cosmics and beam splash events were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



***CMS** beam splash event*



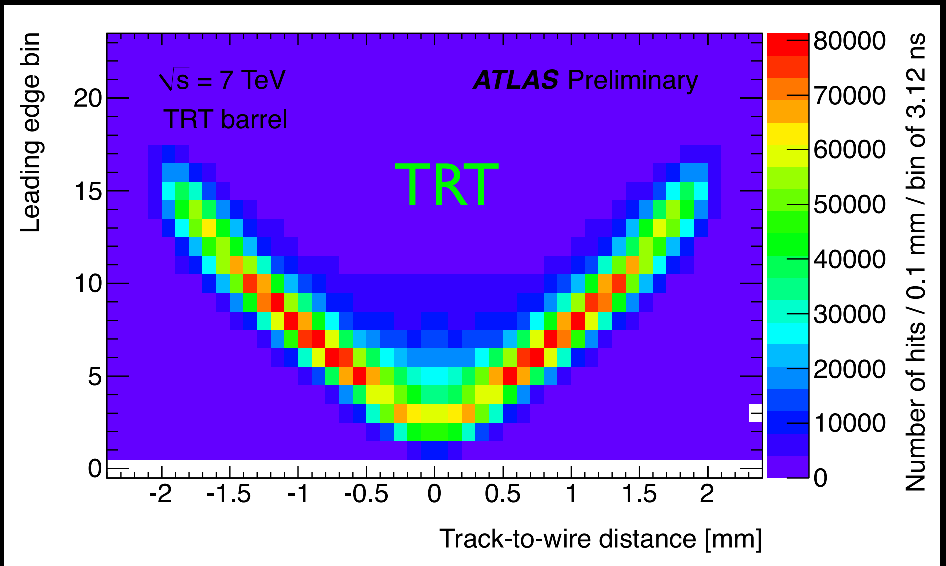
timing scan CMS Pixels

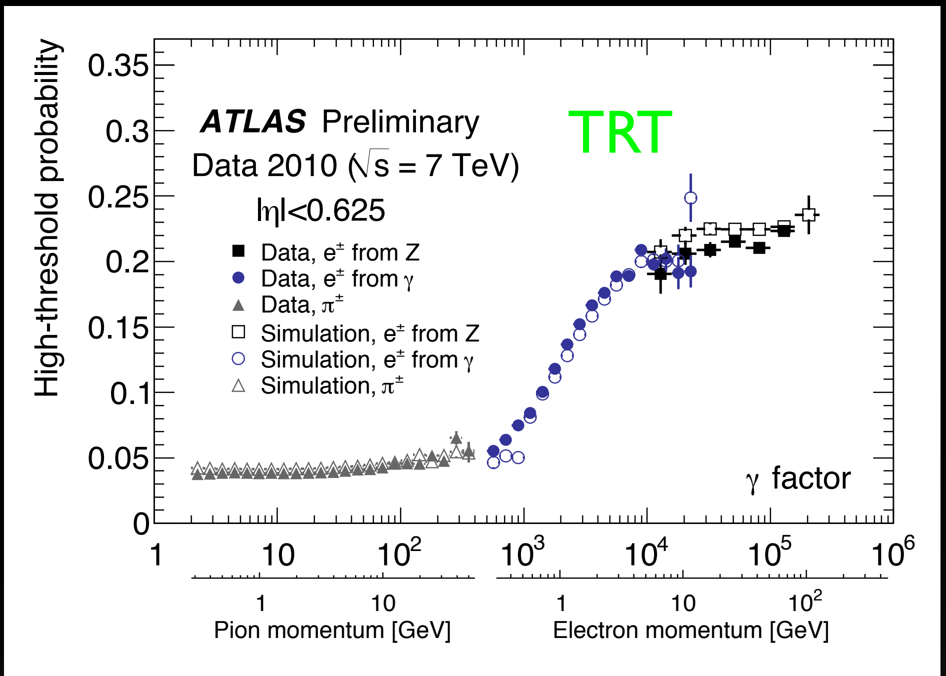


timing of ATLAS TRT

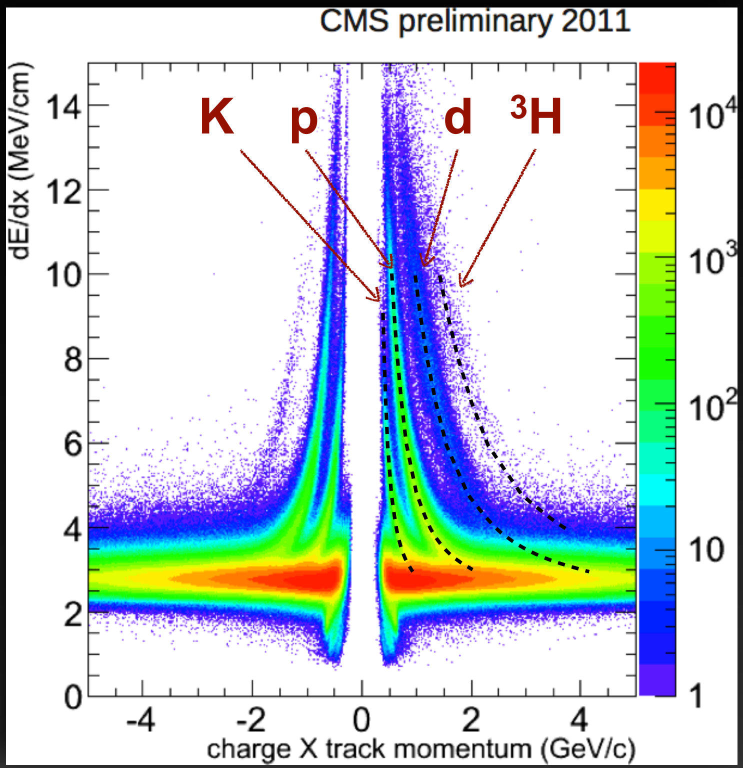
Detector Calibration

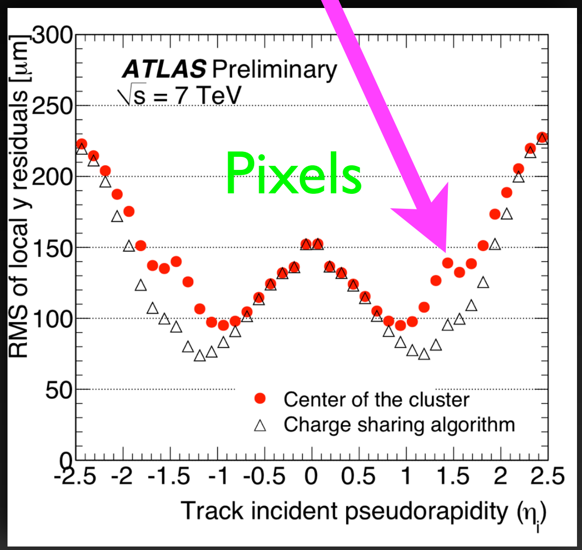
- careful calibration of detectors
  - ➡ required to reach design performance
  - ➡ online (thresholds,...) and offline
  - ➡ monitoring of variations with time
- examples:
  - ➡ TRT: R-t relation and high threshold probability
  - ➡ analog information from silicon detectors
    - allows to measure dE/dx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

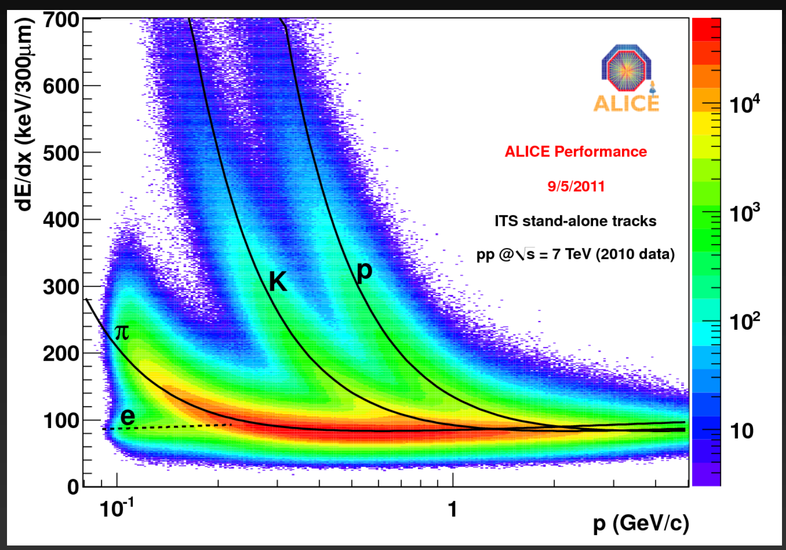




CMS:
10 layers
~0.5cm
of silicon

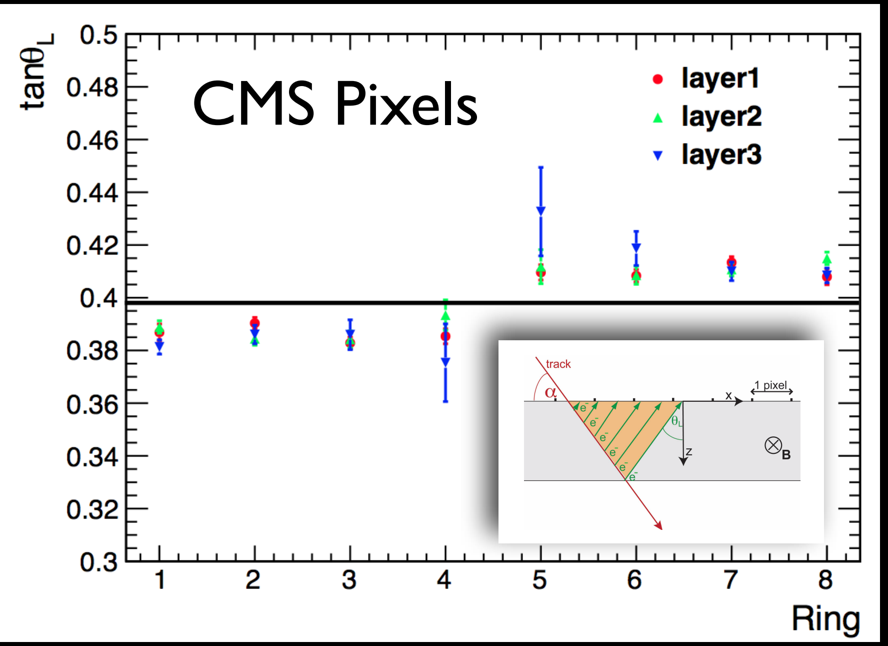


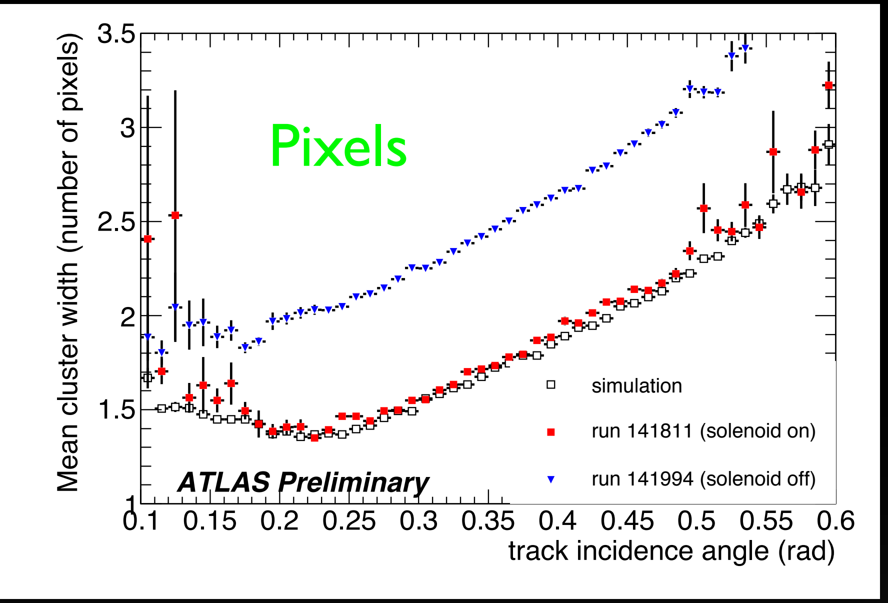


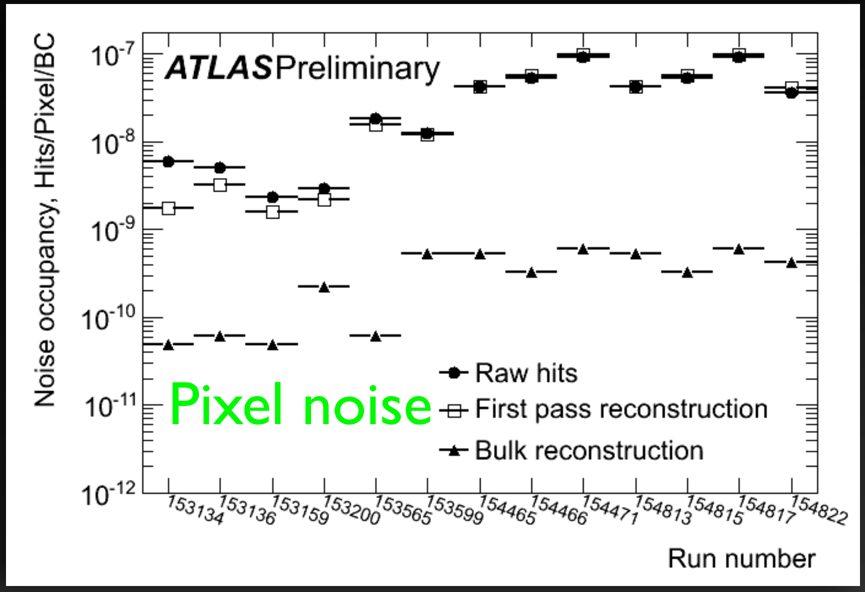


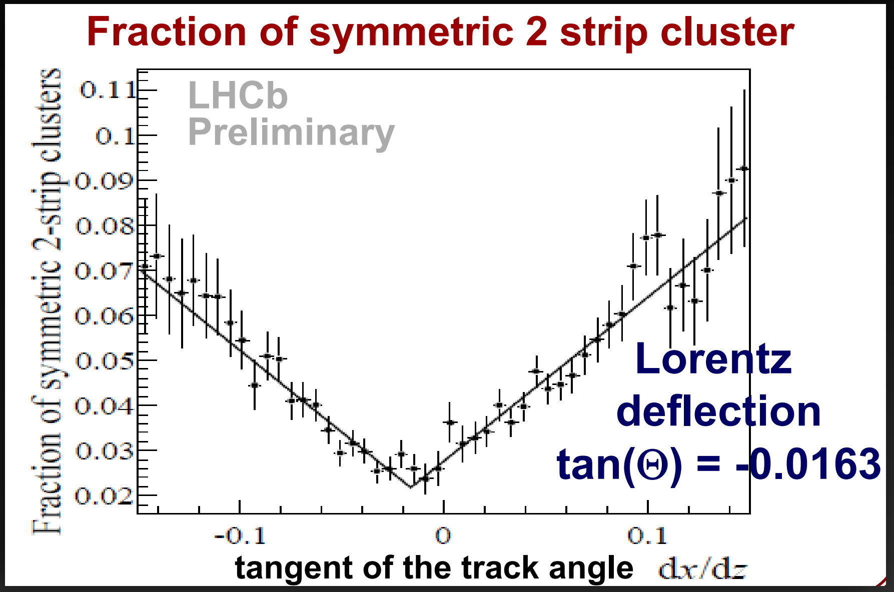
Detector Calibration

- 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



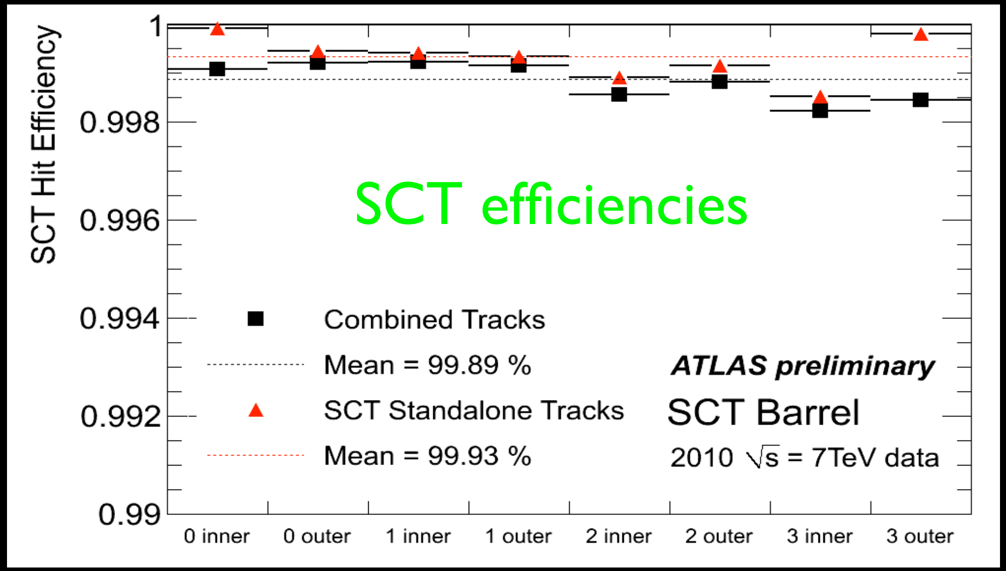


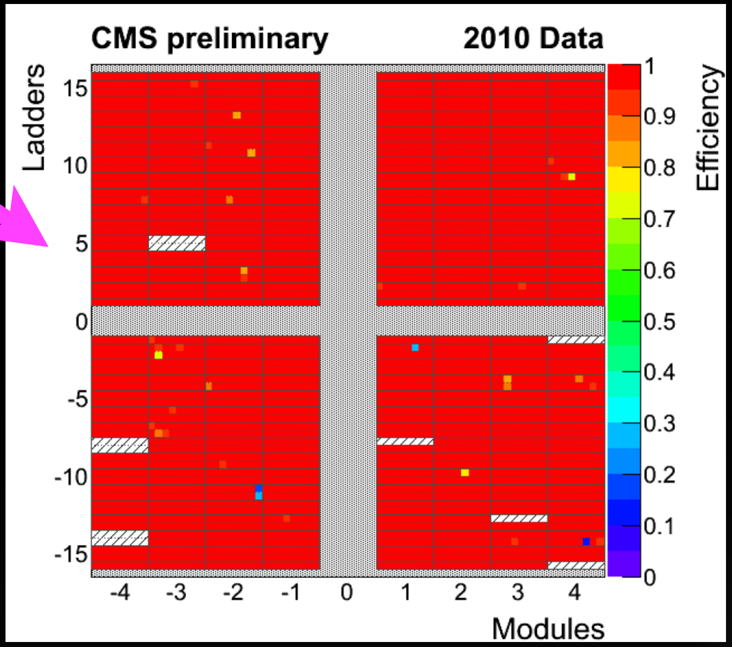


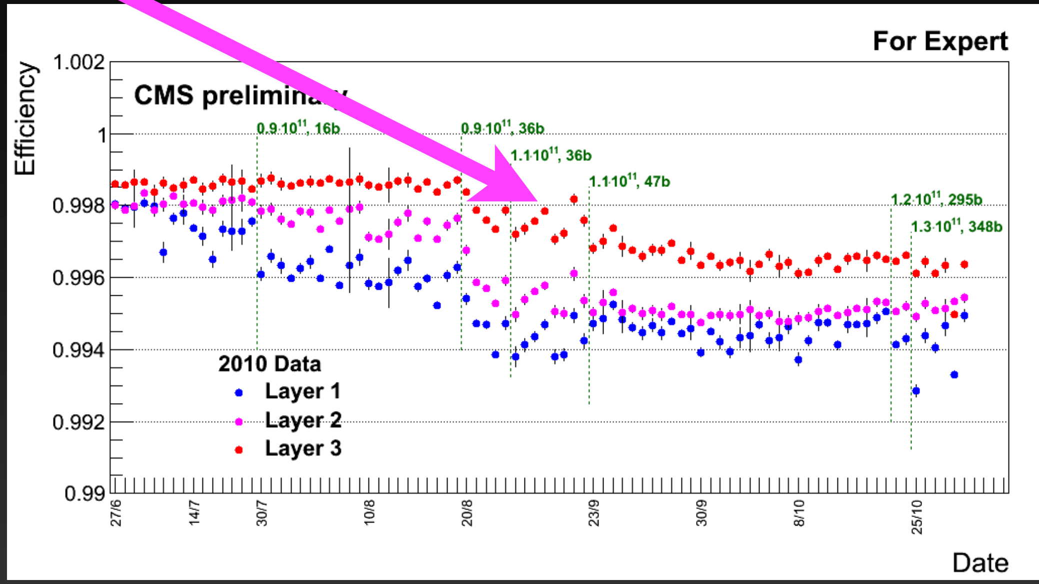


Detector Calibration

- 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 saw small efficiency loss (0.2-0.4%) with increasing luminosity already in 2010
    - occupancy increase effecting readout
    - ATLAS replaces readout cards this shutdown
- not limiting tracking performance
  - ➡ correct simulation to reproduce calibrated detector performance
  - ➡ allow for known defects and inefficiencies in reconstruction

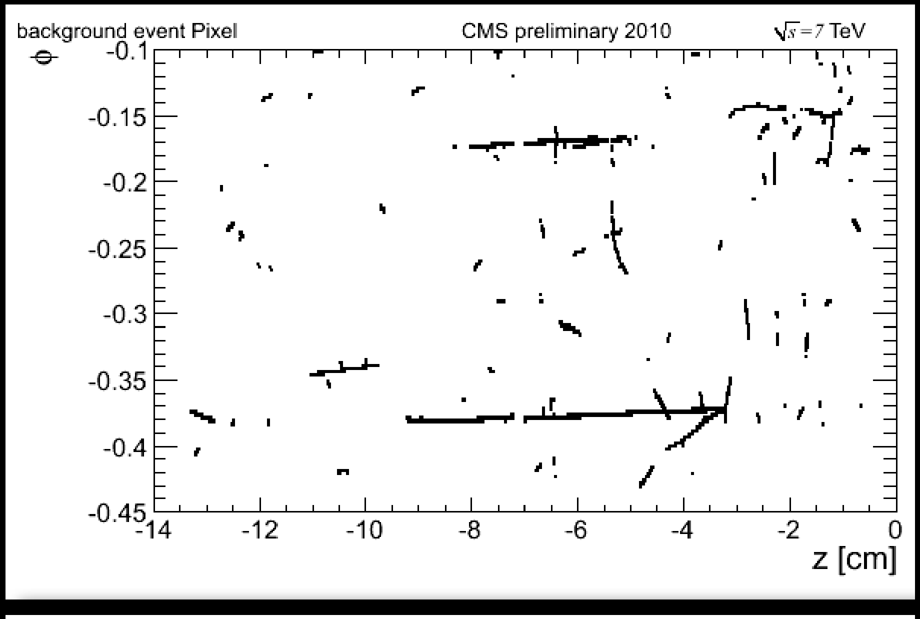


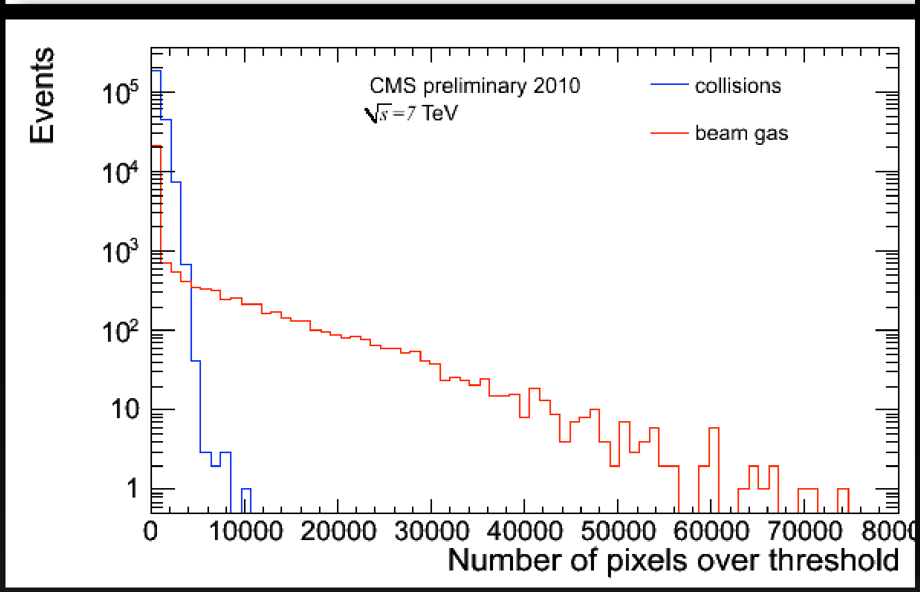


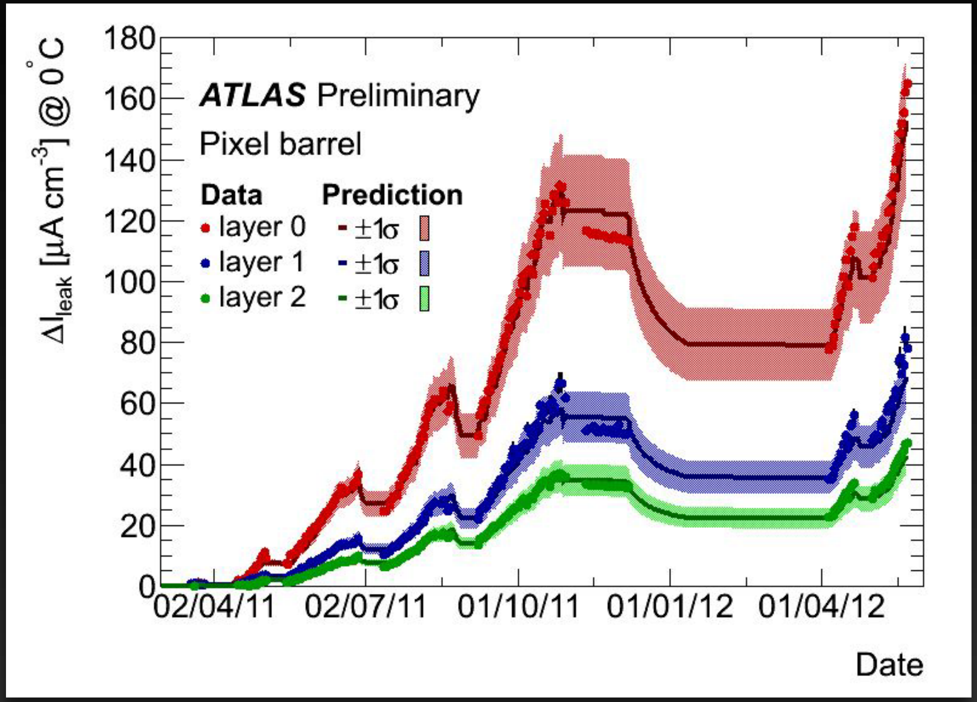


Beam Backgrounds and Radiation Effects

- CMS saw 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
    - type inversion at ~10 fb^{-1}

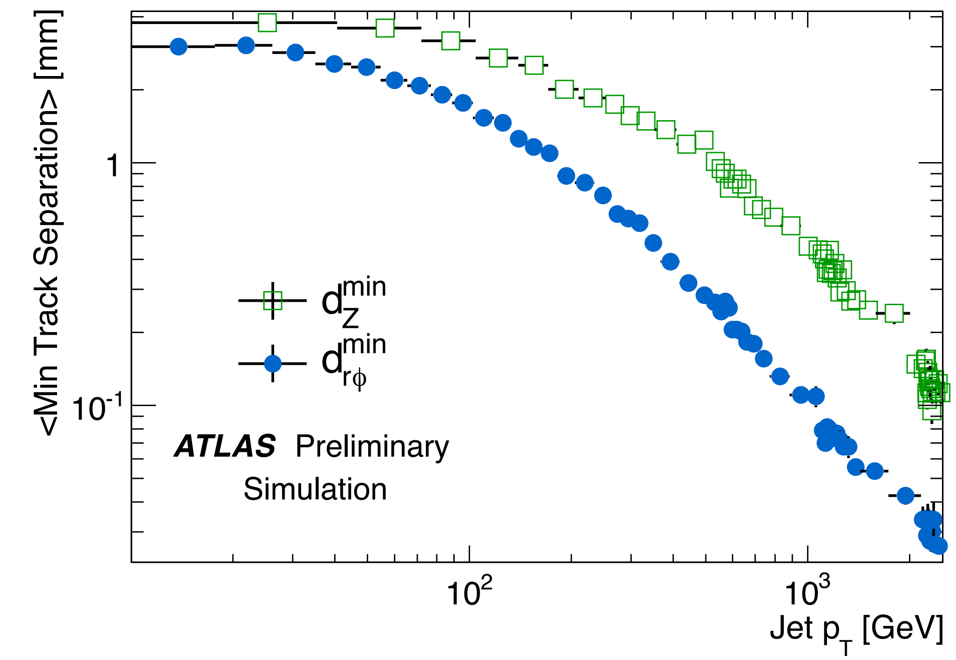


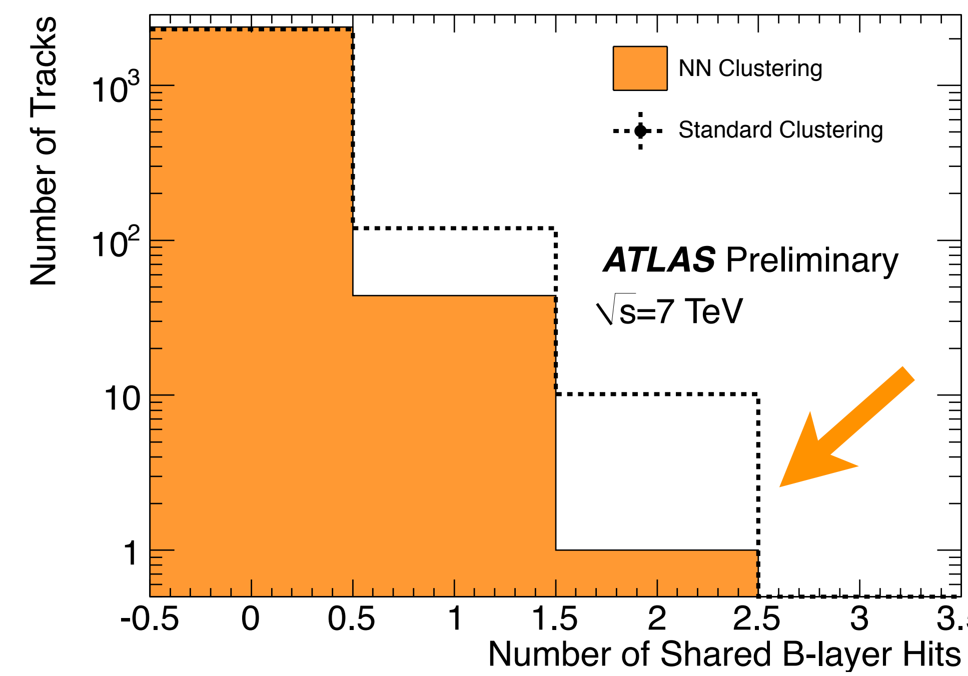


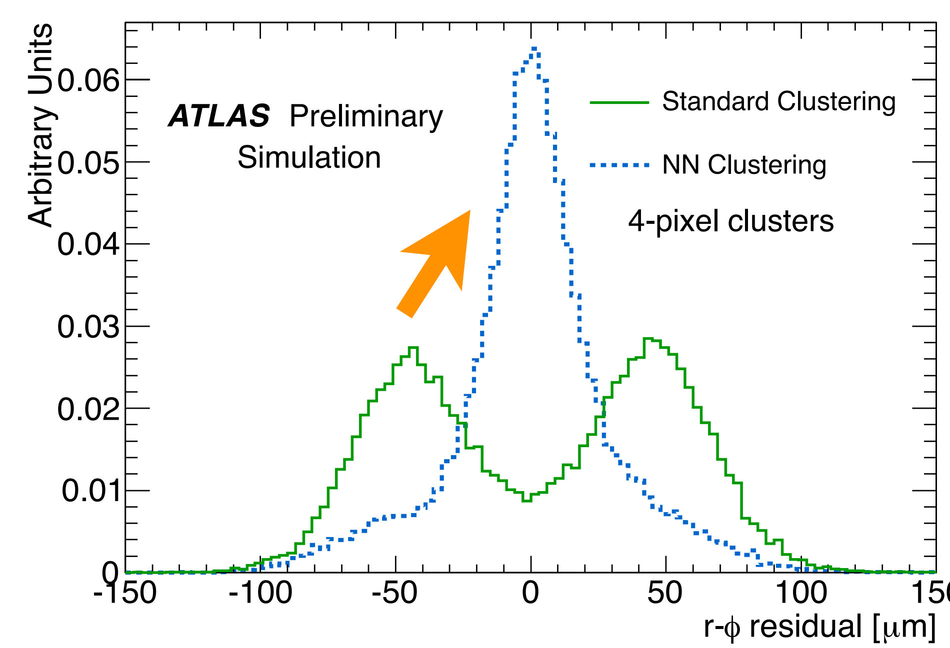


Neural Net Pixel Clustering

- novel technique, motivation:
  - ➡ high track density in jets leads to cluster merging
  - ➡ limits tracking in jets and b-tagging performance
- algorithm to split merge clusters
  - ➡ neural network (NN) based technique
    - explores analog Pixel information
  - ➡ run 5 networks:
    - NN1: probability a cluster is 1/2/>2 tracks
    - NN2: best position for each (sub)cluster
    - NN3: error estimate for cluster
    - NN4+5: redo NN2+3 using track prediction
  - ➡ adapt pattern recognition
- performance improvements (17.0.0)
  - ➡ improved cluster resolution
  - ➡ dramatic reduction in rate of shared B-layer hits and therefore improved tracking in core of jets

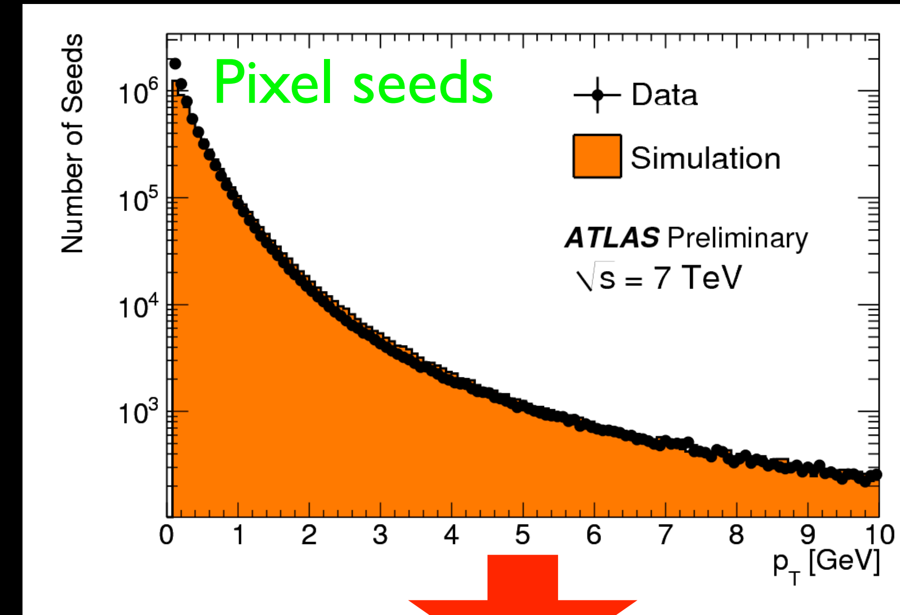


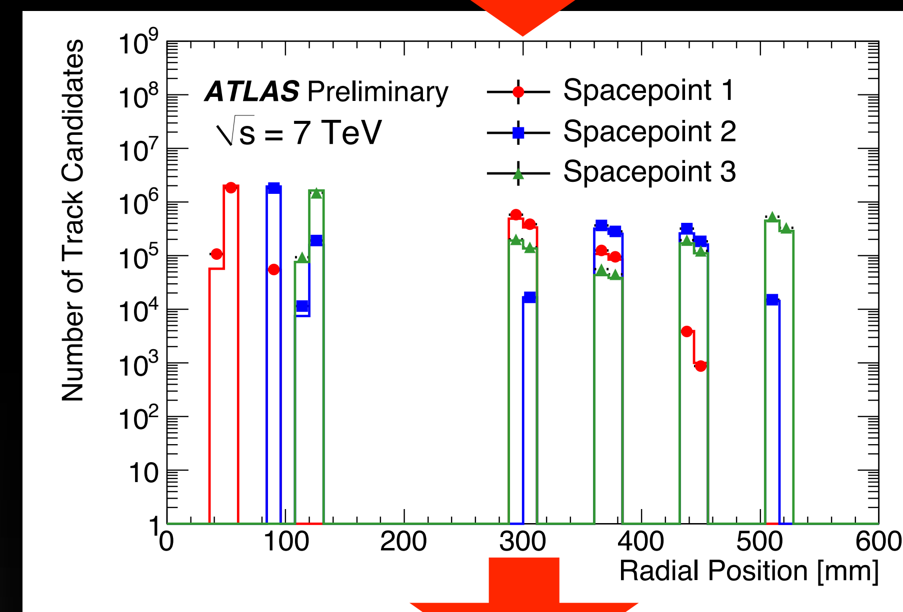


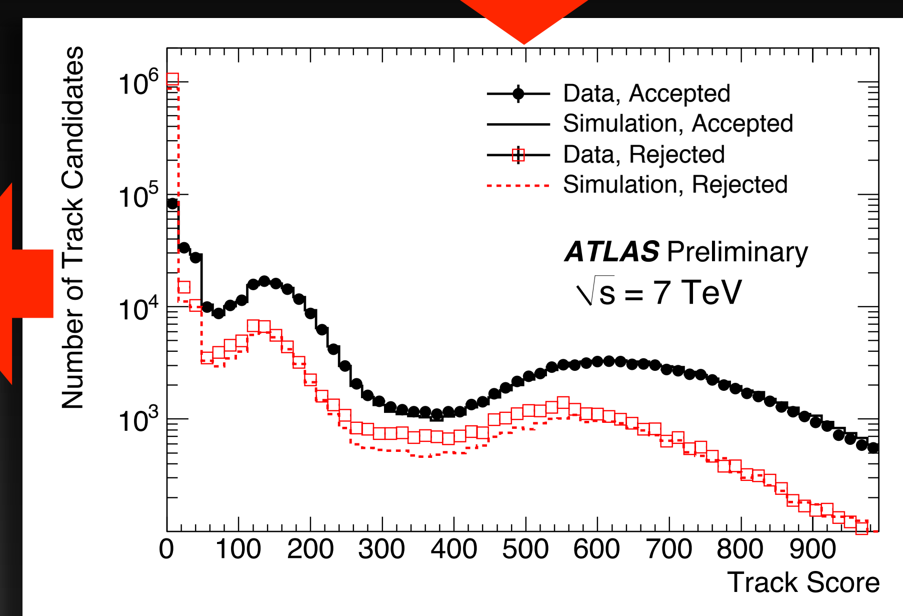


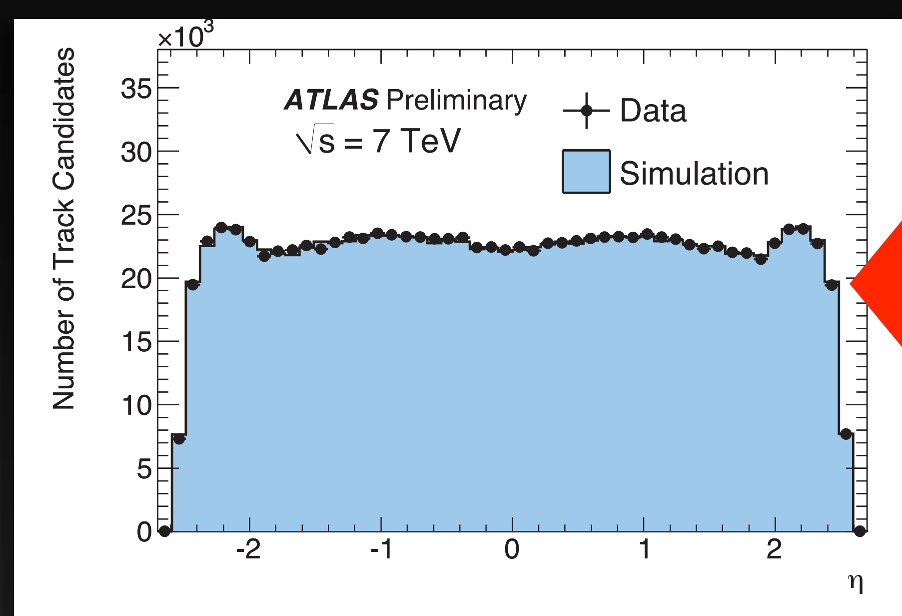
Tracking Commissioning

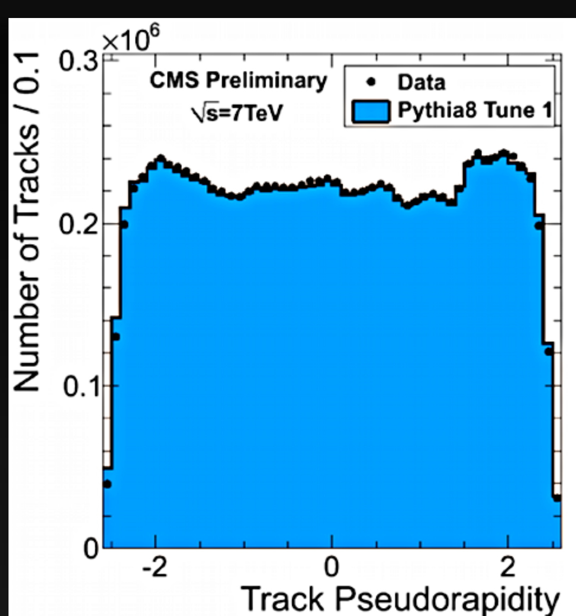
- at startup (same after LS1 for new IBL)
  - ➡ use commissioning settings
    - ensure “robustness”
    - allow for dead/noise modules
    - error scaling to reflect calibration + alignment
  - ➡ first physics was minimum bias
    - tracking with very low p_T thresholds, no pileup
- study behavior of reconstruction
  - ➡ seeding / candidate fitting / ambiguity / etc.
  - ➡ compare simulation to data





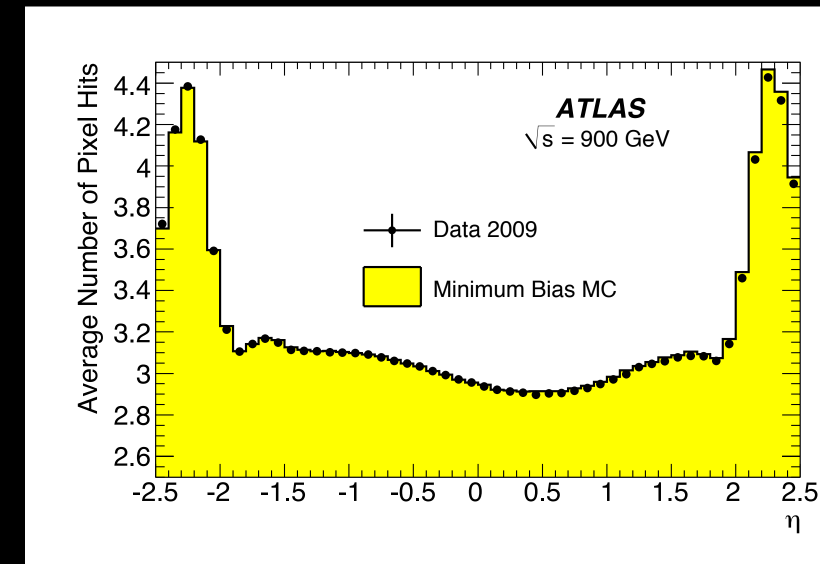


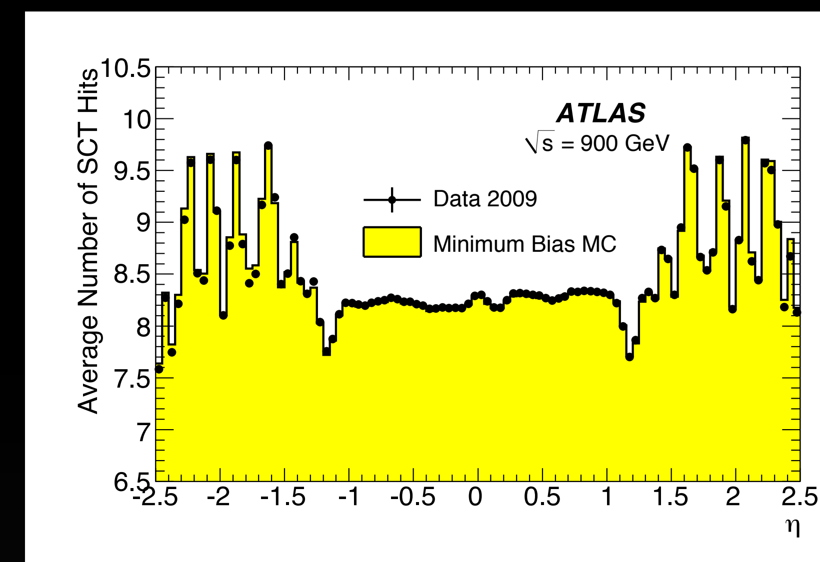




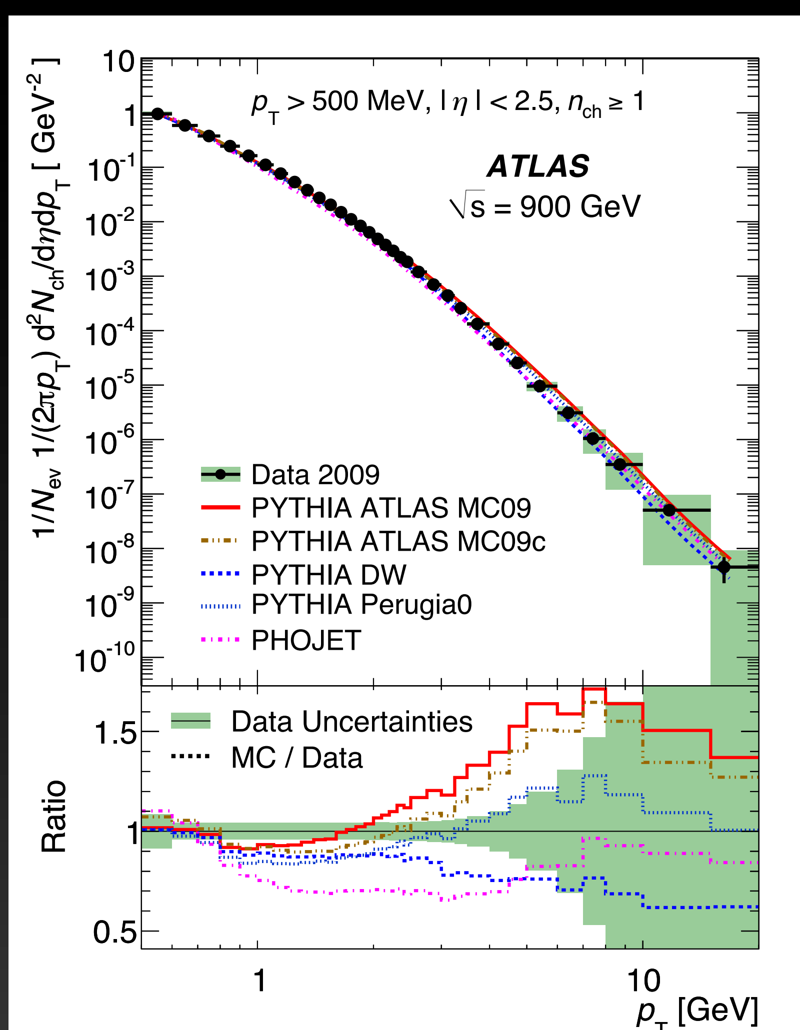
Tracking Commissioning

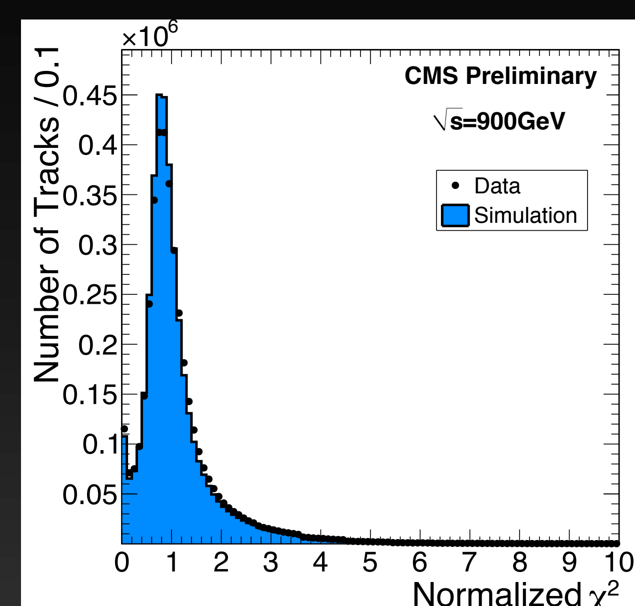
- detailed studies of properties of reconstructed tracks
  - ➡ hit associations, fit quality, etc.
  - ➡ leading towards first publications
    - tracking systematics driven by material uncertainties

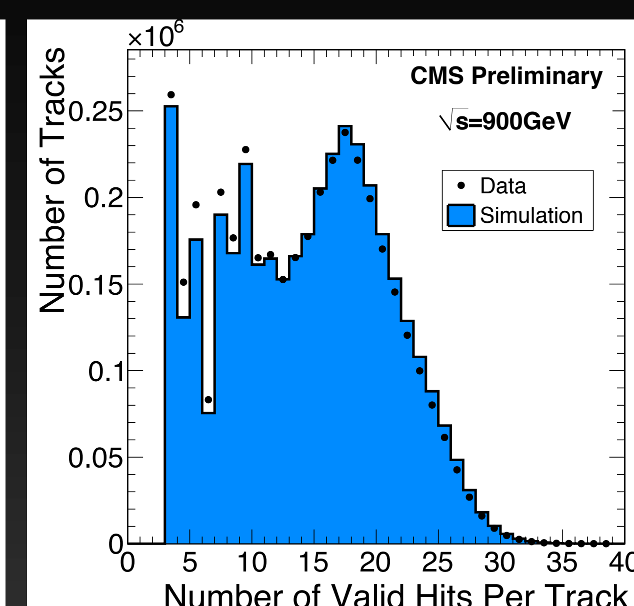




min.bias charged particle spectra

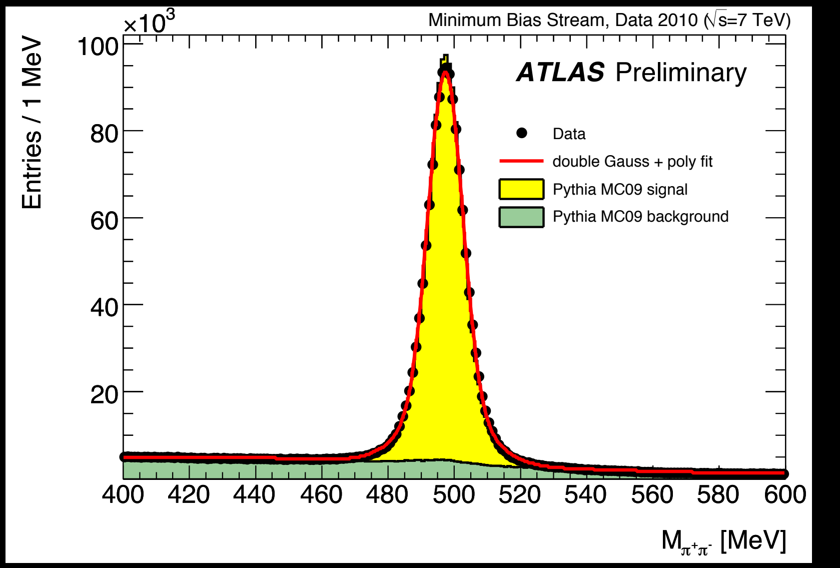


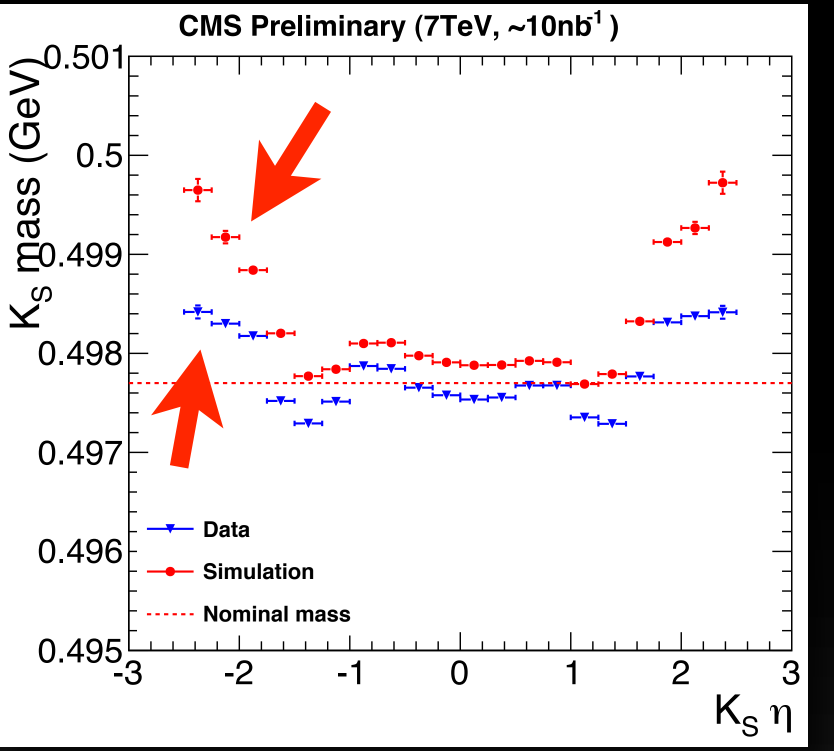


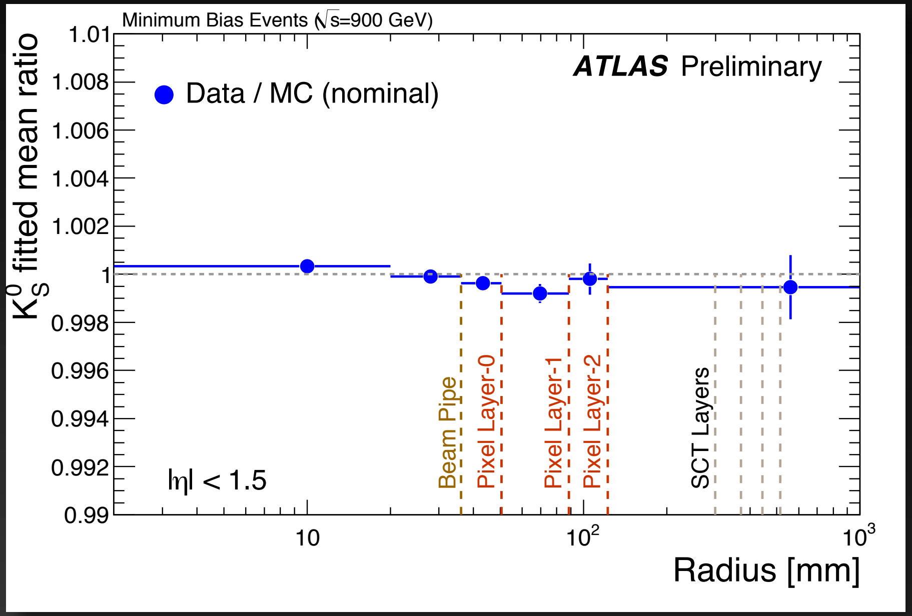


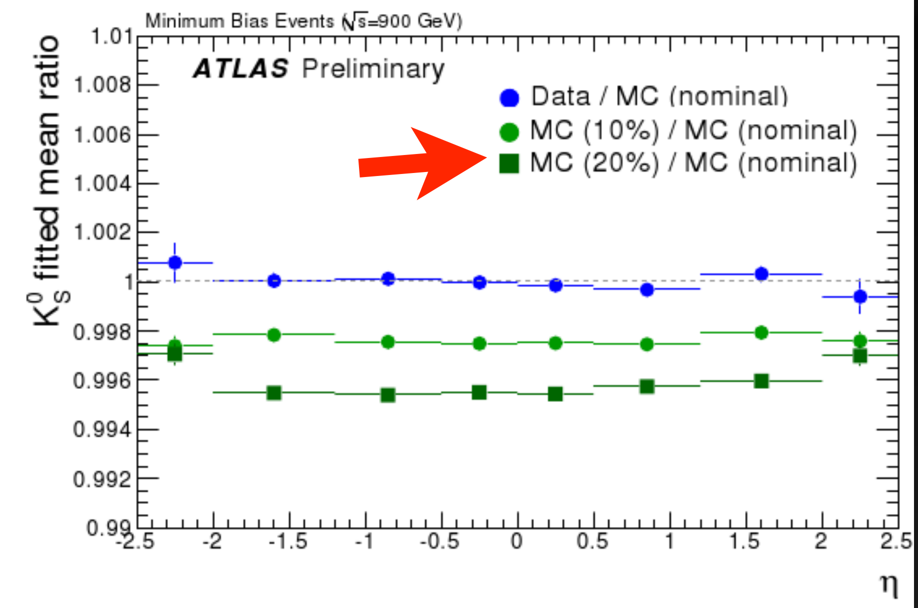
Material Studies using K^0_s

- 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%)



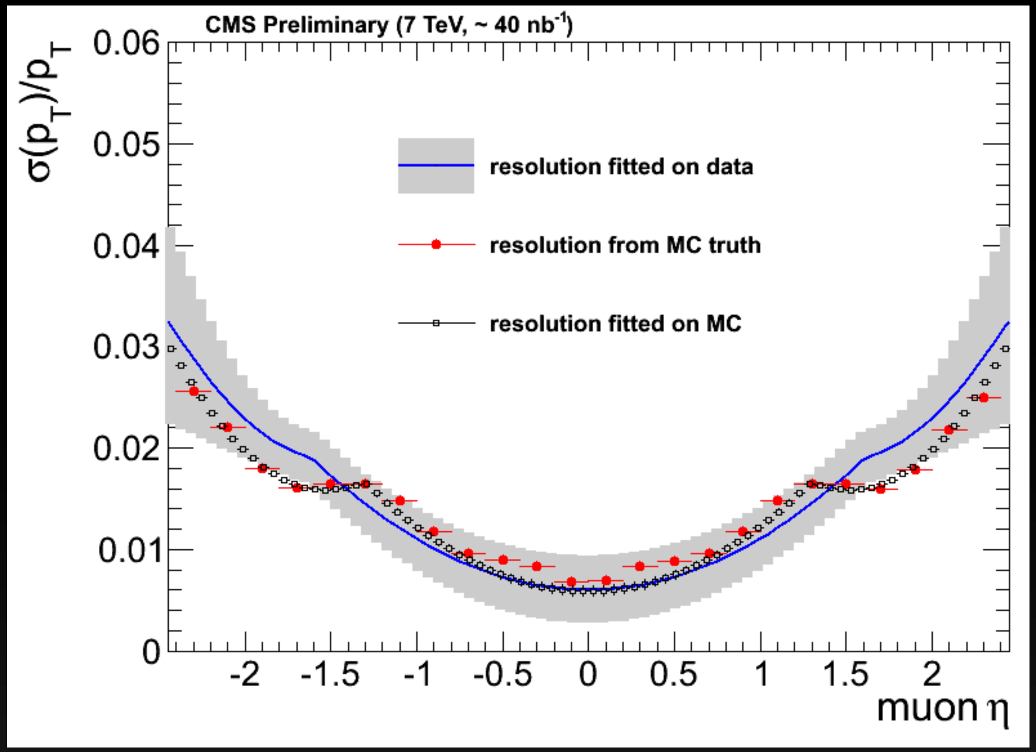


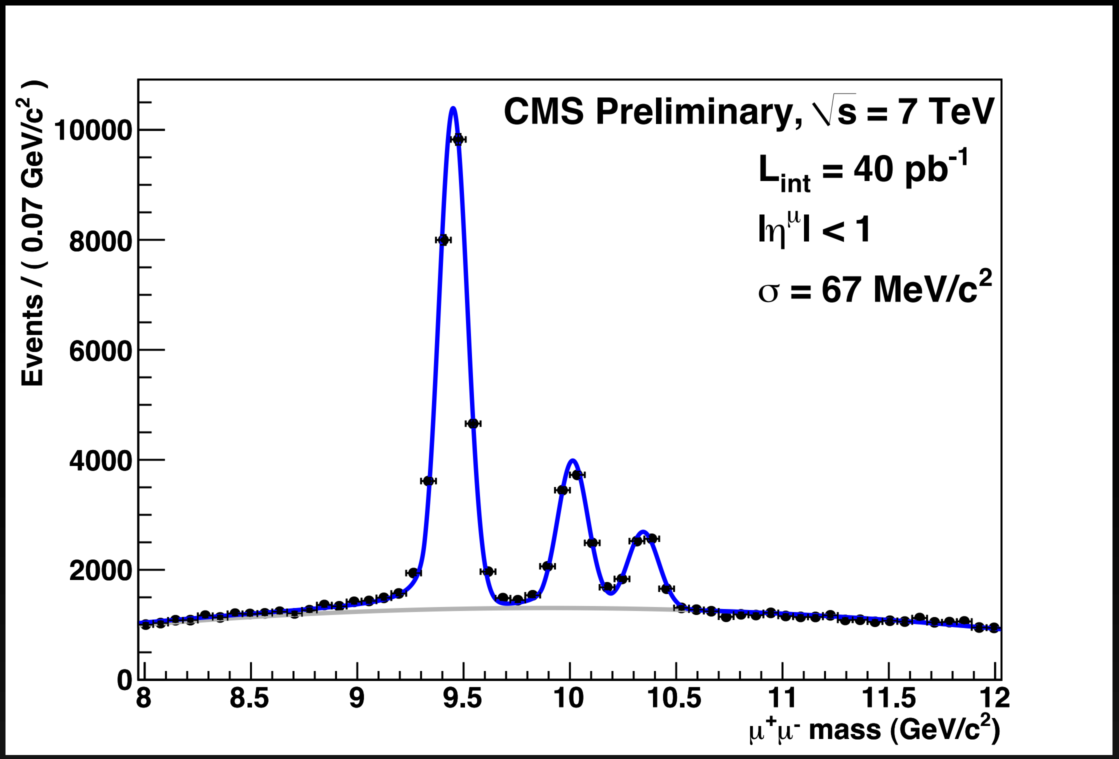




Material Studies using J/ψ

- 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

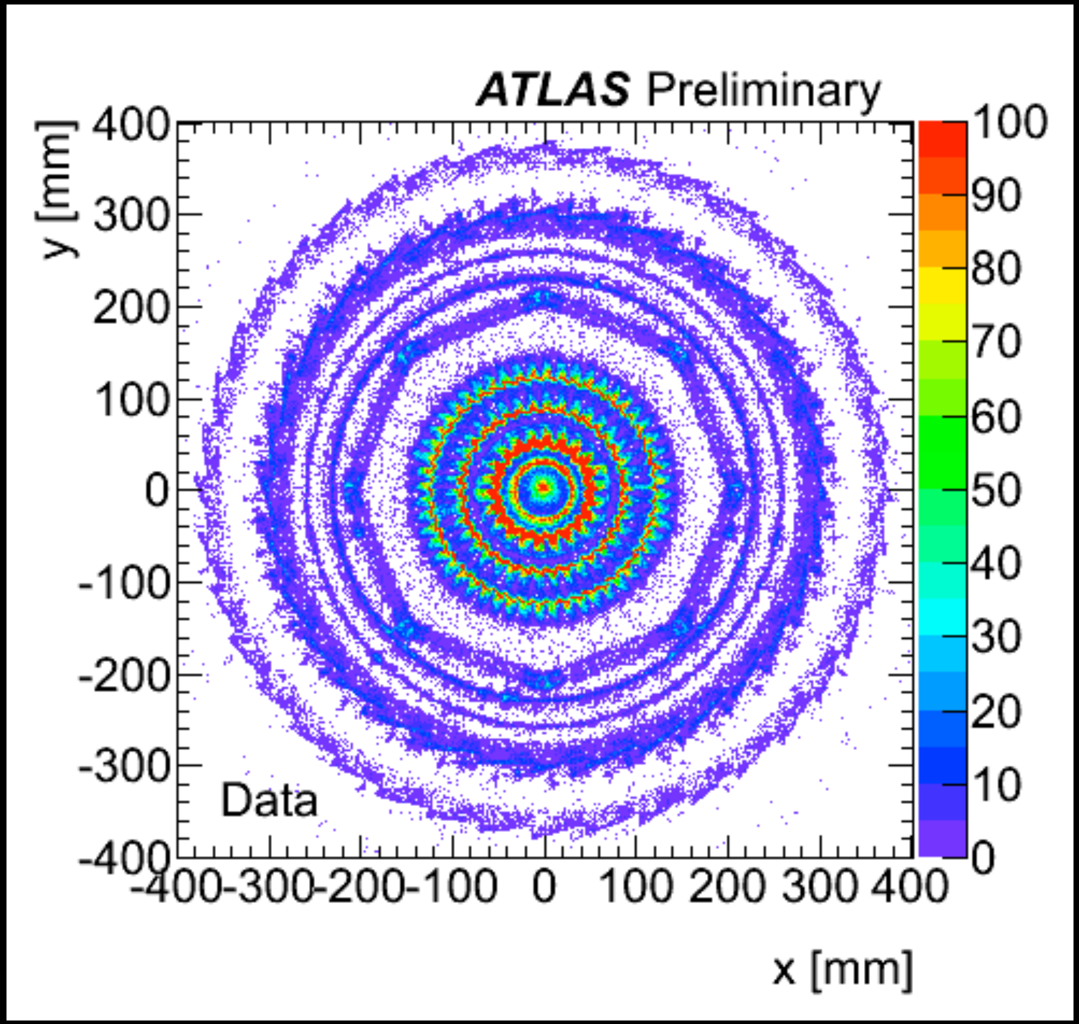


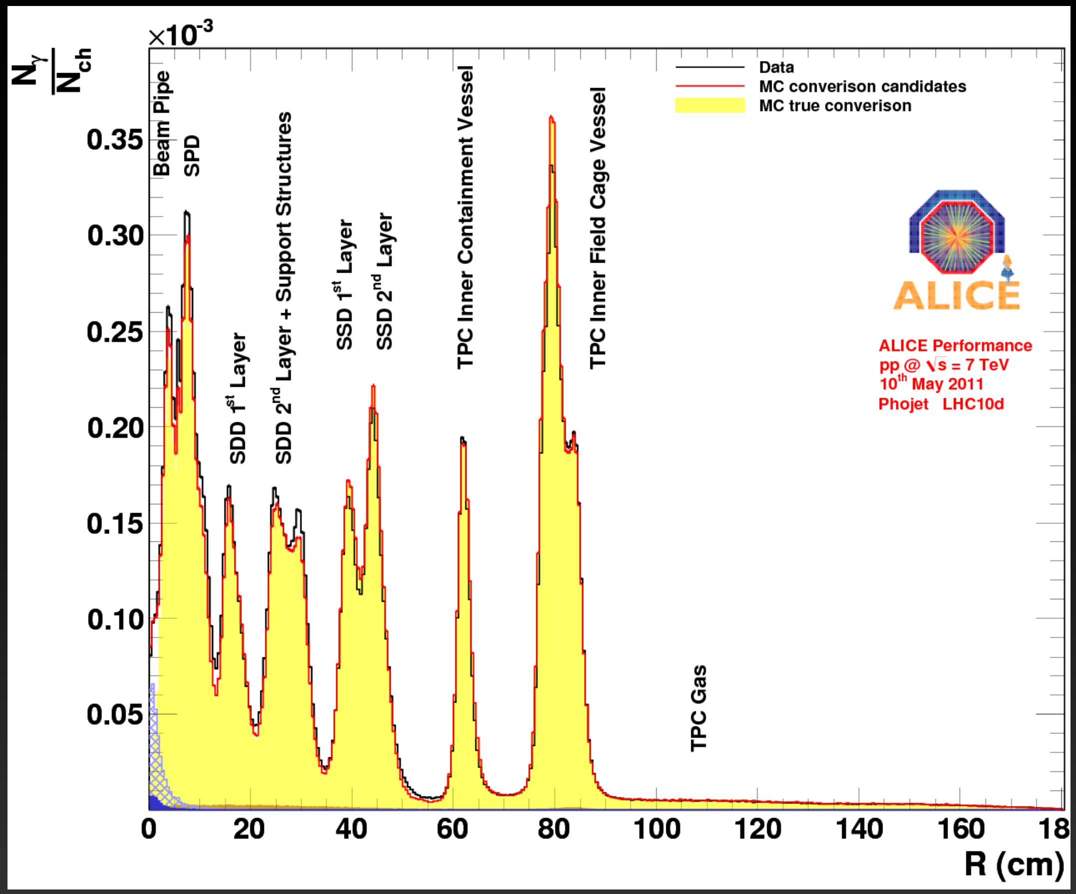


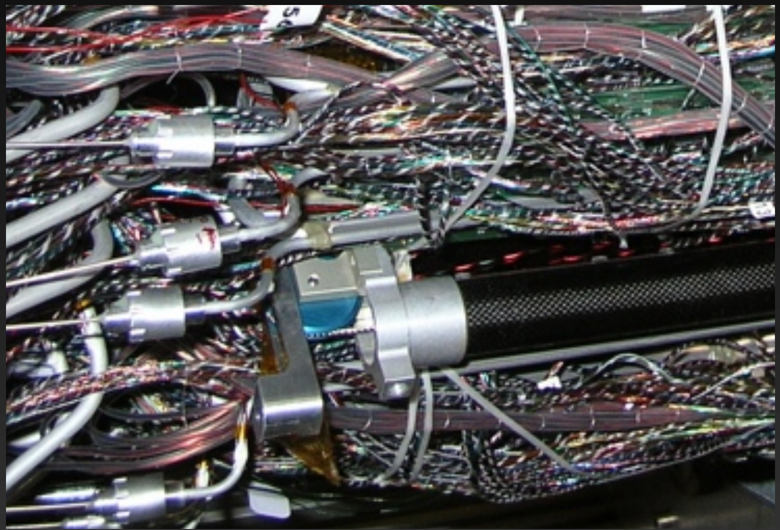
  - ➡ excellent CMS mass resolution seen as well in resonances near Υ
    (thanks to 4 T field)

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





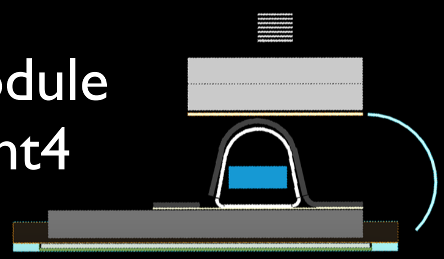


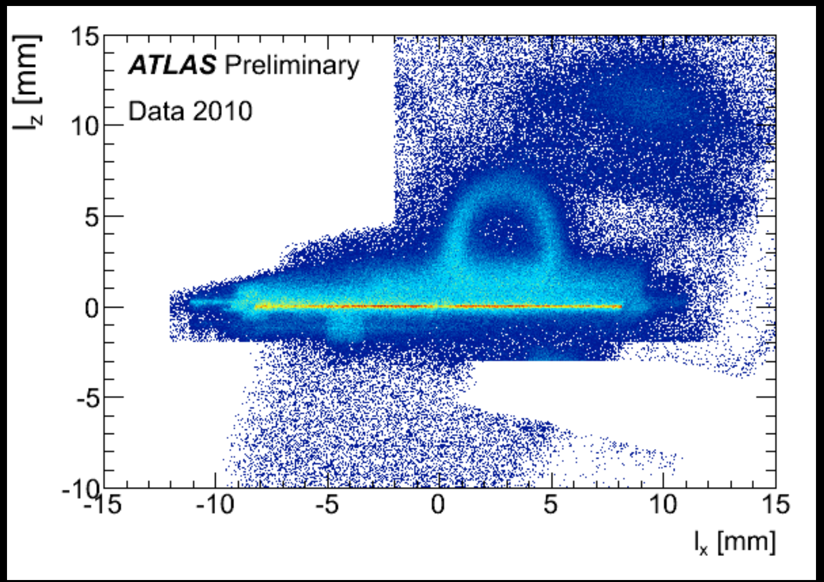
ATLAS Pixel PP0 region

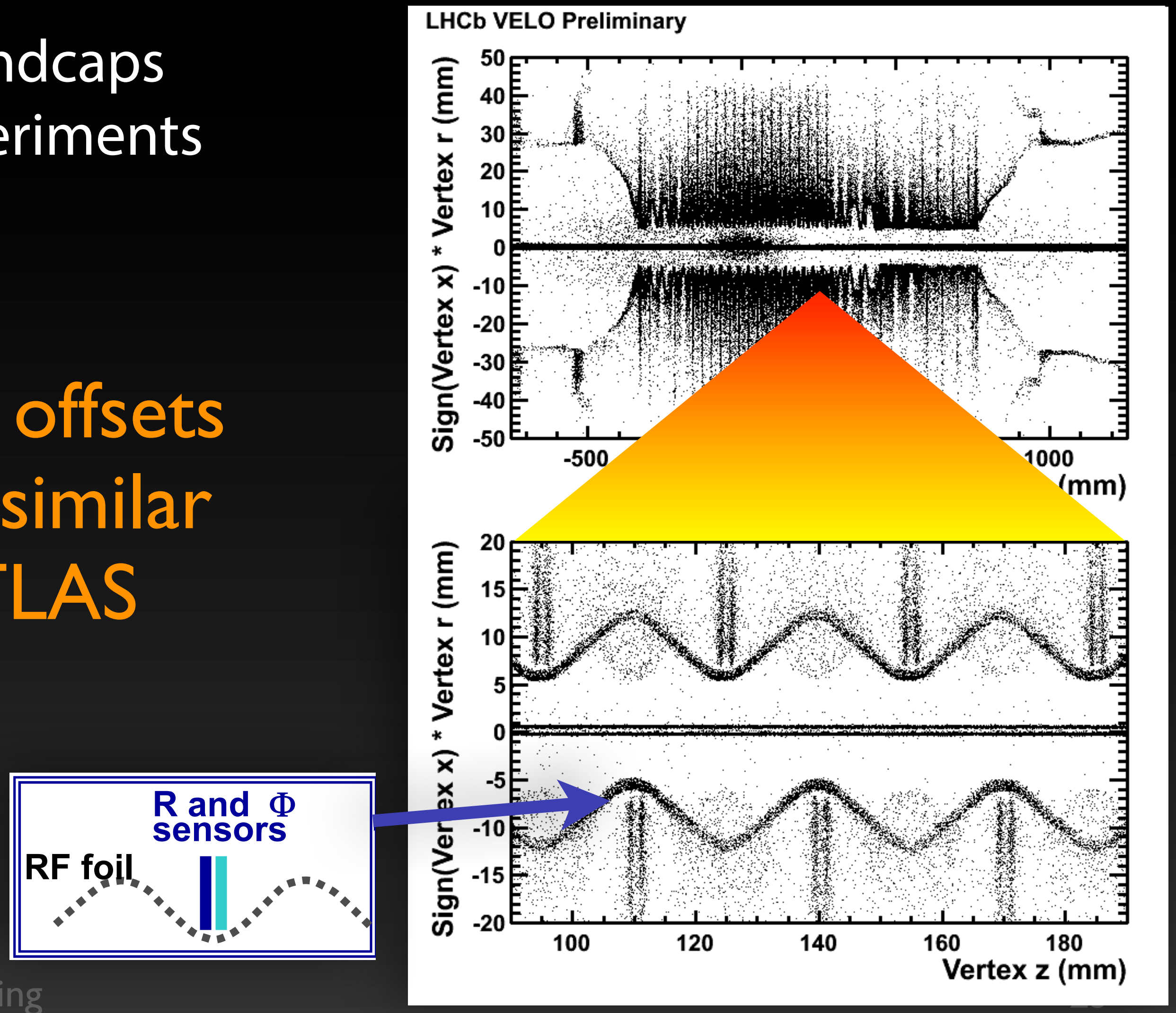
Hadronic Interactions

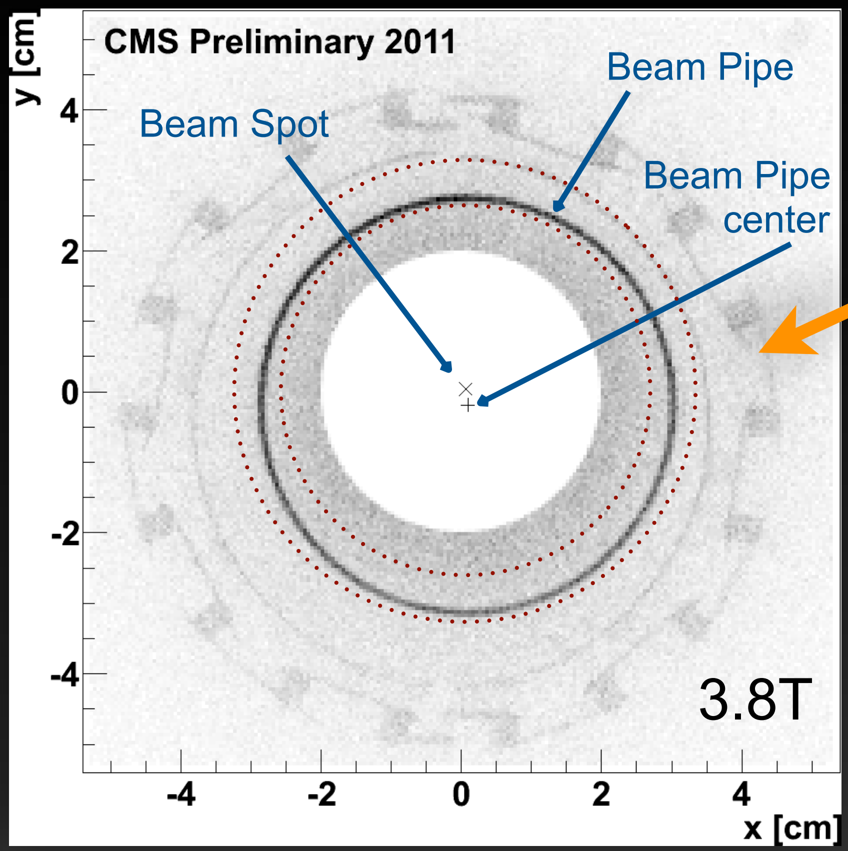
- 2nd method for a precise tomography of detector material
  - ➡ good vertex resolution allows to study fine details
- material uncertainty in simulation
  - ➡ better than ~5% in central region
  - ➡ at the level of ~10% in most of the endcaps
  - ➡ study of systematics ongoing in experiments

Pixel Module in Geant4



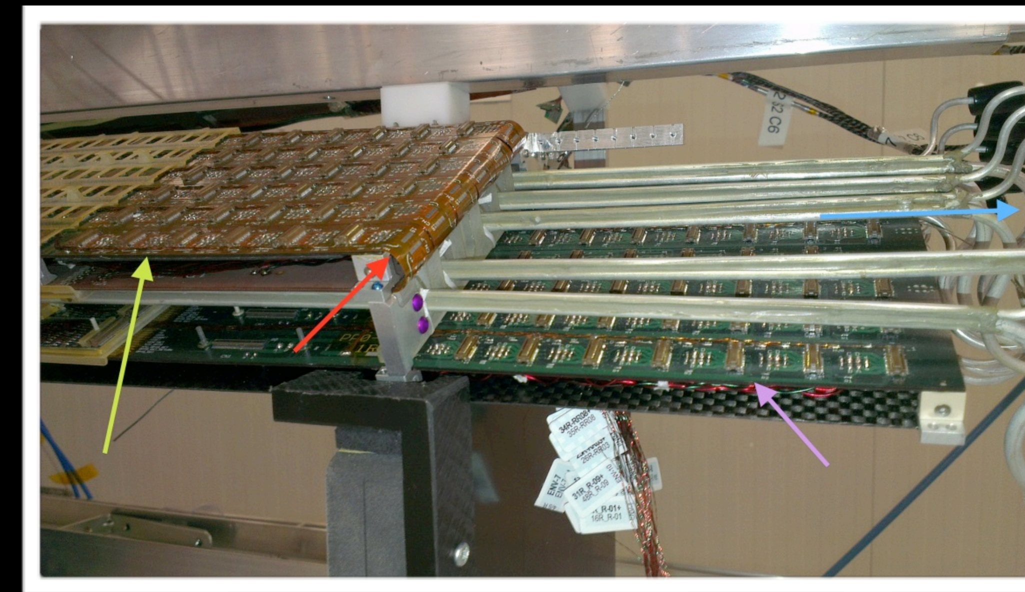




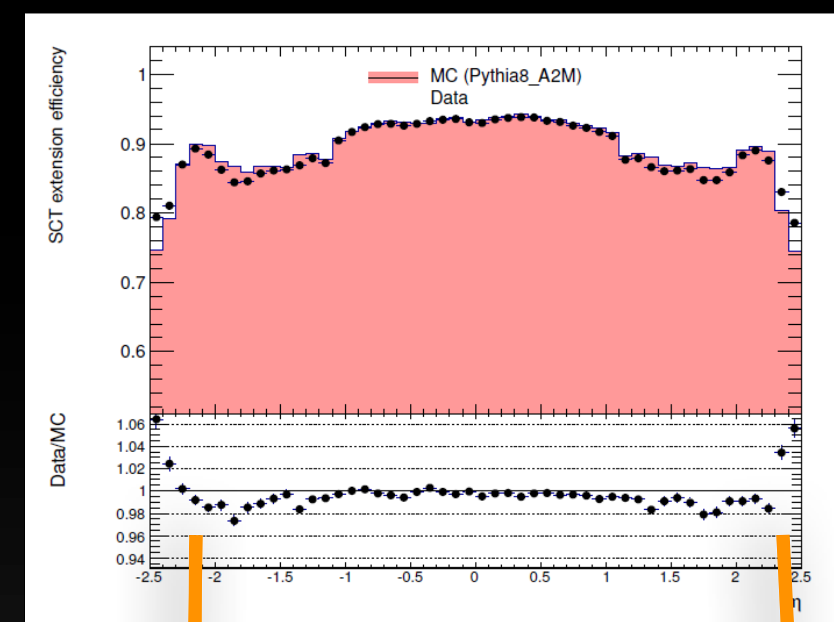


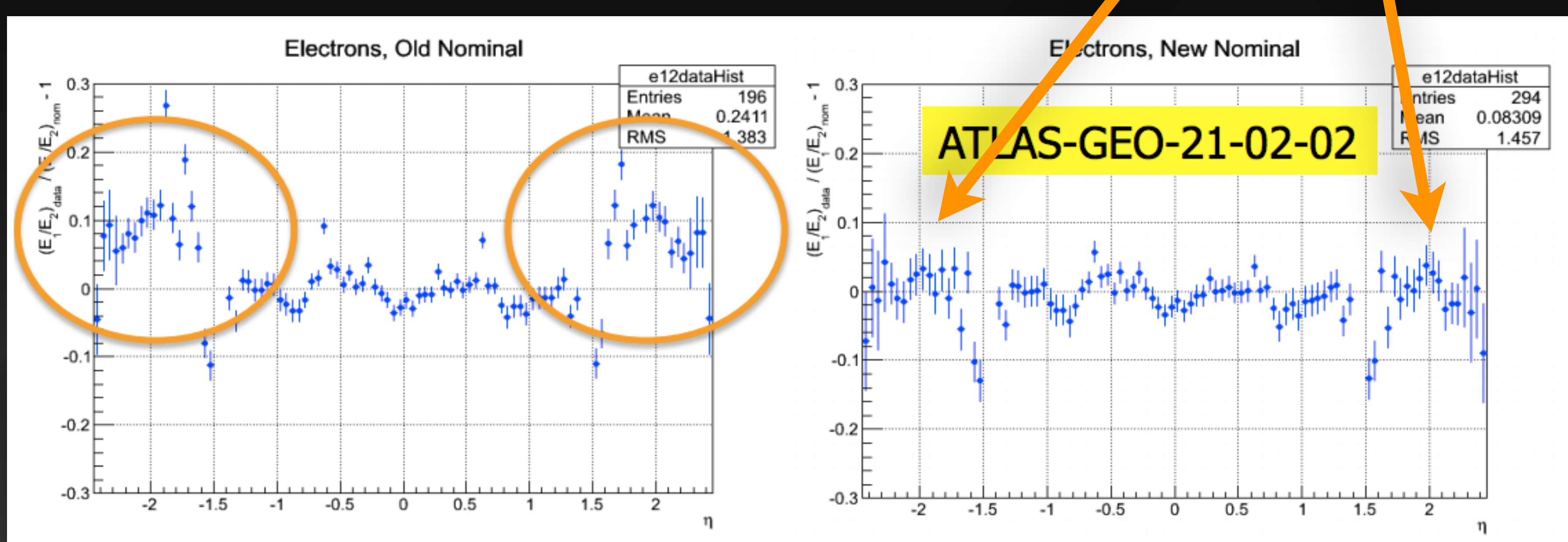
relative offsets visible, similar in ATLAS

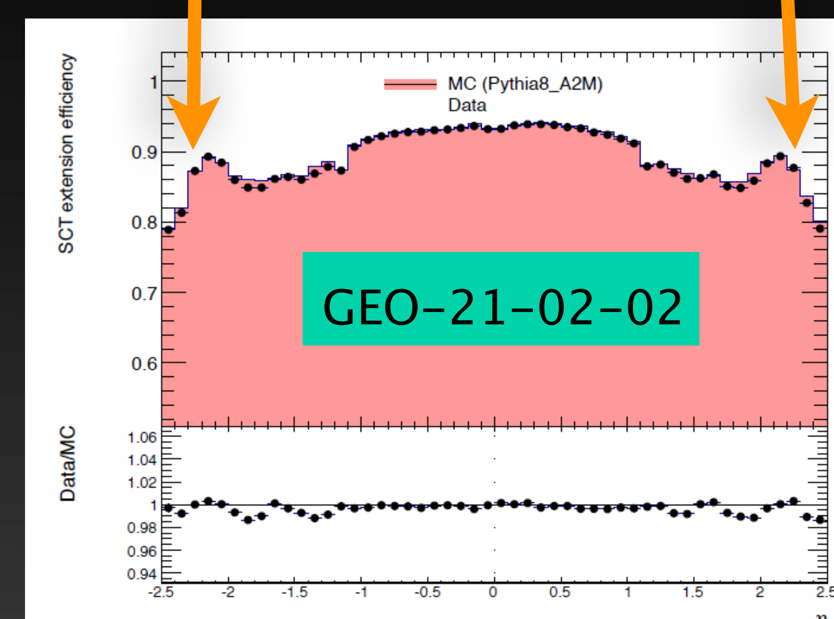
Status of Material studies



- working group to study material
  - ➡ biggest issue in Pixel PP0 region
  - ➡ SCT extension efficiency not well modeled so far
- SQP are being replaced in LS1
  - ➡ go back to the old ones and corrected geometry !
  - ➡ corrected beam pipe, SCT cooling loops, services
- much better description for MC14 (7.5-10%)!
  - ➡ affects as well the electron shower description in LAr







Track-based alignment

- alignment is based on the minimization of track-hit residuals $\boldsymbol{r}$

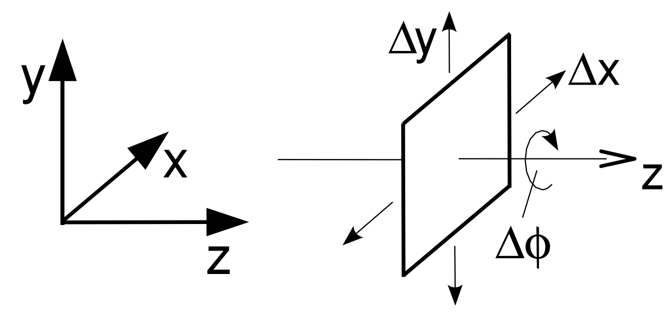
  $\chi^2 = \sum_{\text{tracks}} r^T V^{-1} r$ where $r = r(\pi, \alpha)$

  V - track covariance matrix

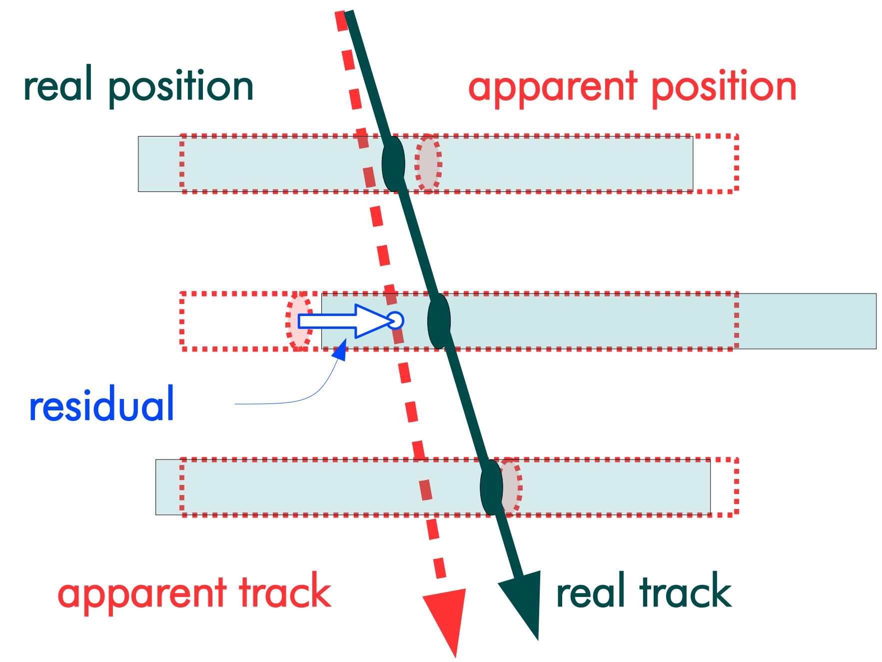
  π - track parameters

  α - alignment parameters

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



6 parameters per module



Global χ^2

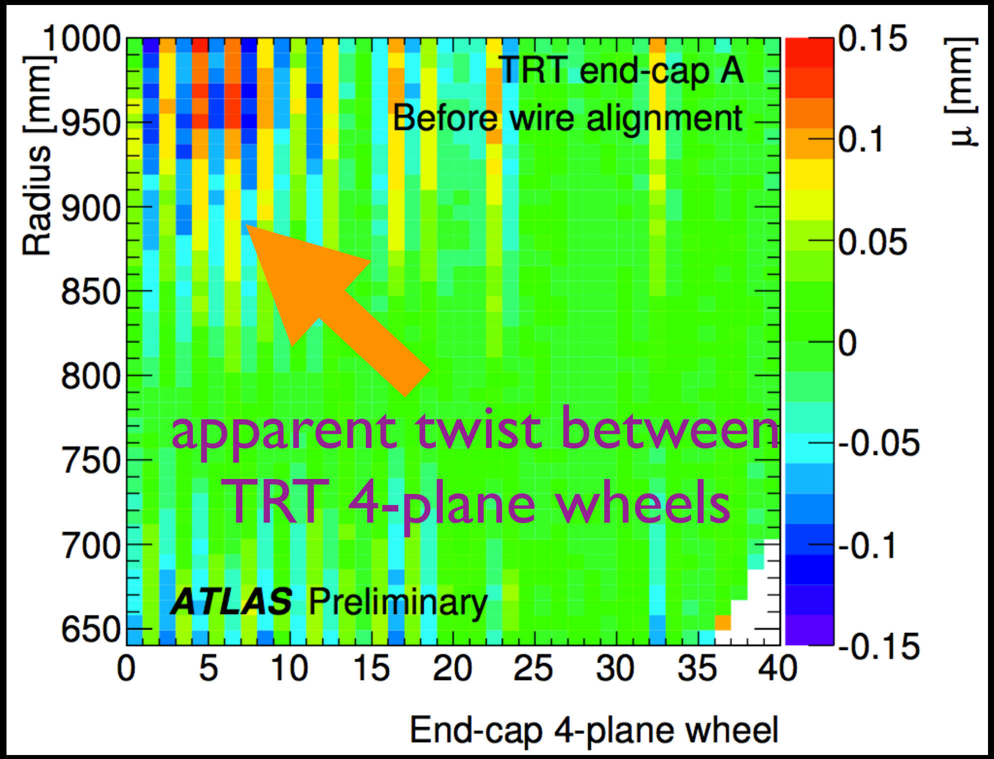
- single large matrix including all the correlations
  - huge number of DoF for the ATLAS Inner Detector **(and in for CMS !)**
- requires usage of fast solving techniques
- convergence within few iterations

Local χ^2

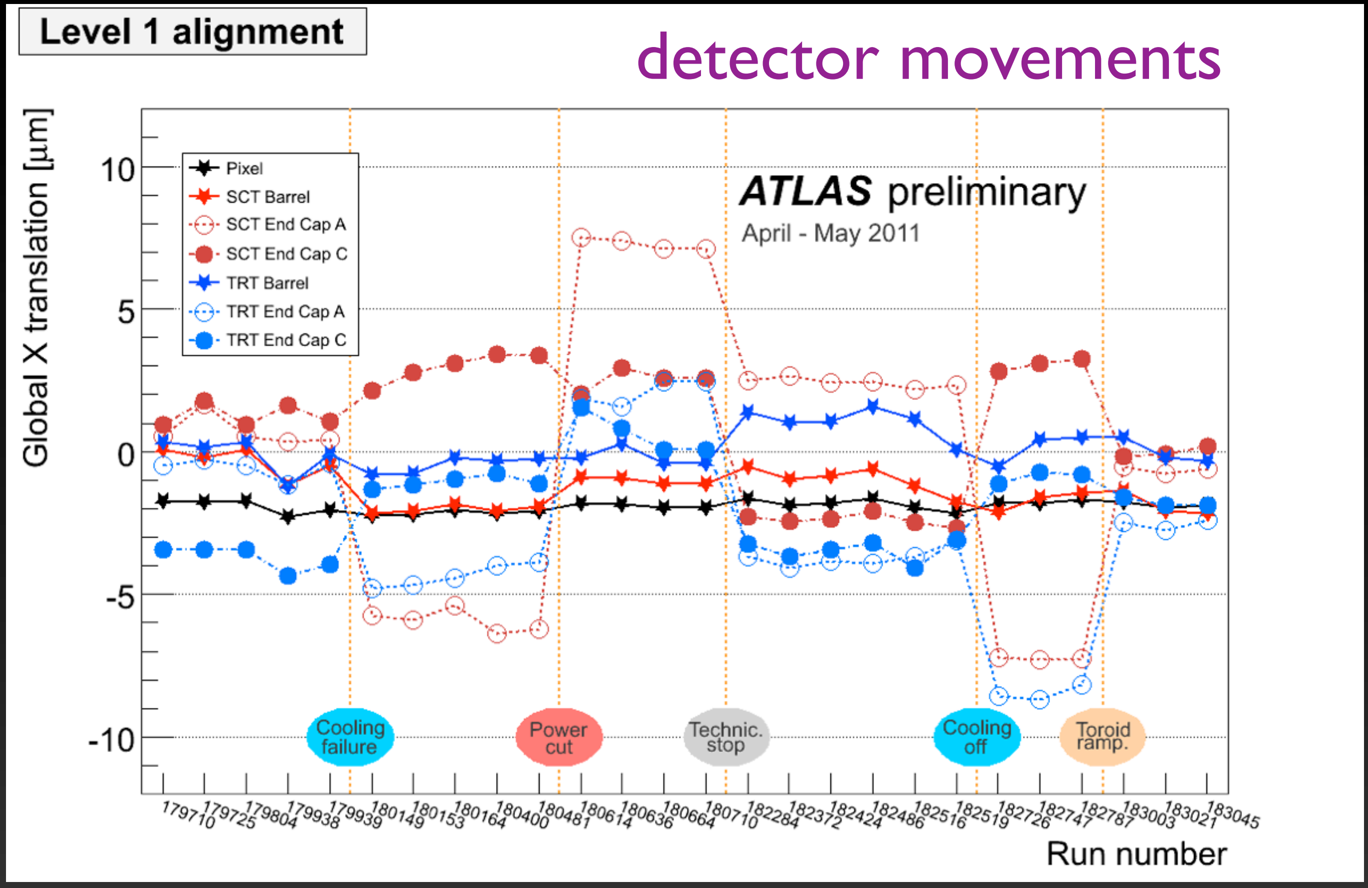
- solving of a small linear system independently for every aligned structure, ignoring explicit correlations between structures
- correlations are restored via iterations
- many iterations needed

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

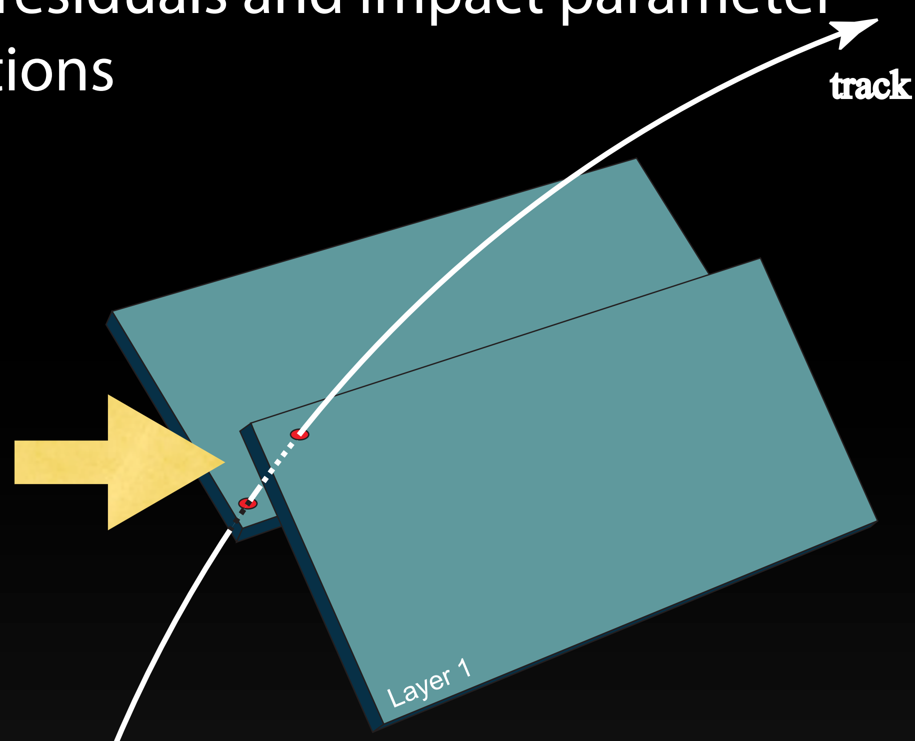


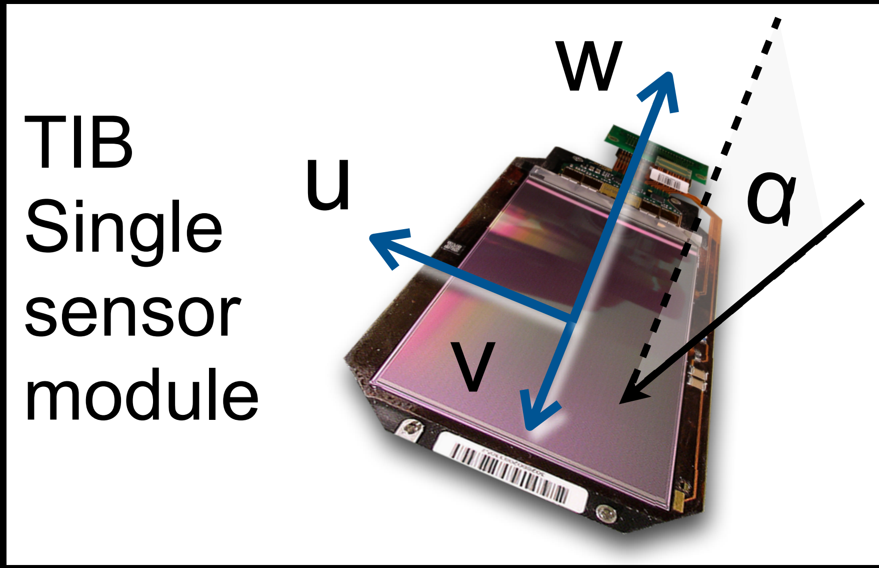
- also allow for
  - ➡ Pixel model deformations
    - survey data or fit
  - ➡ Pixel stave bowing
  - ➡ TRT wire alignment
  - ➡ movements of the detector
  - ➡ ...

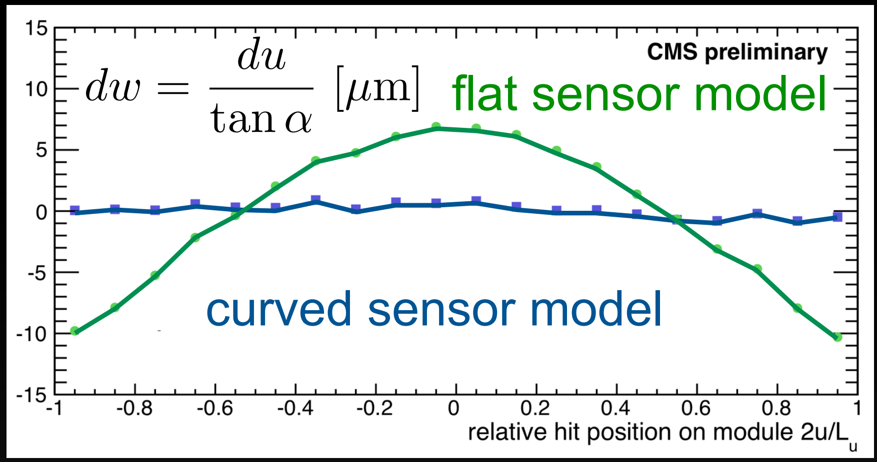


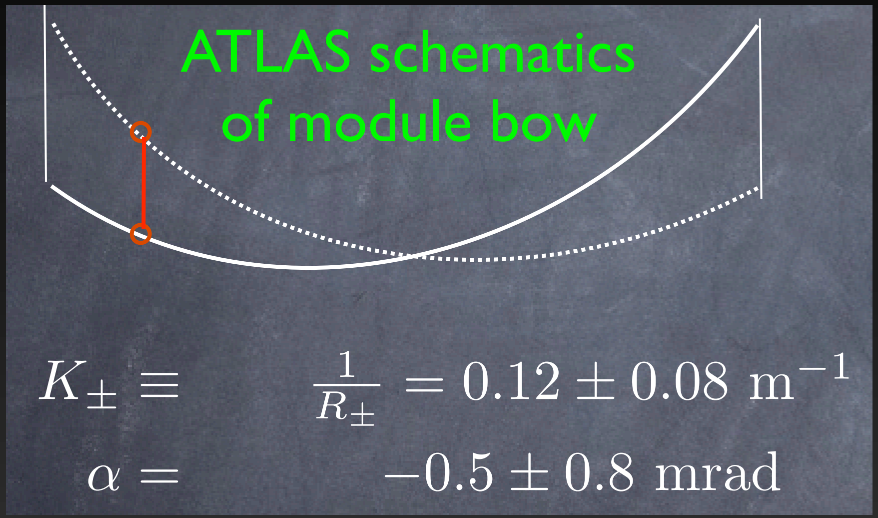
Local Misalignments

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





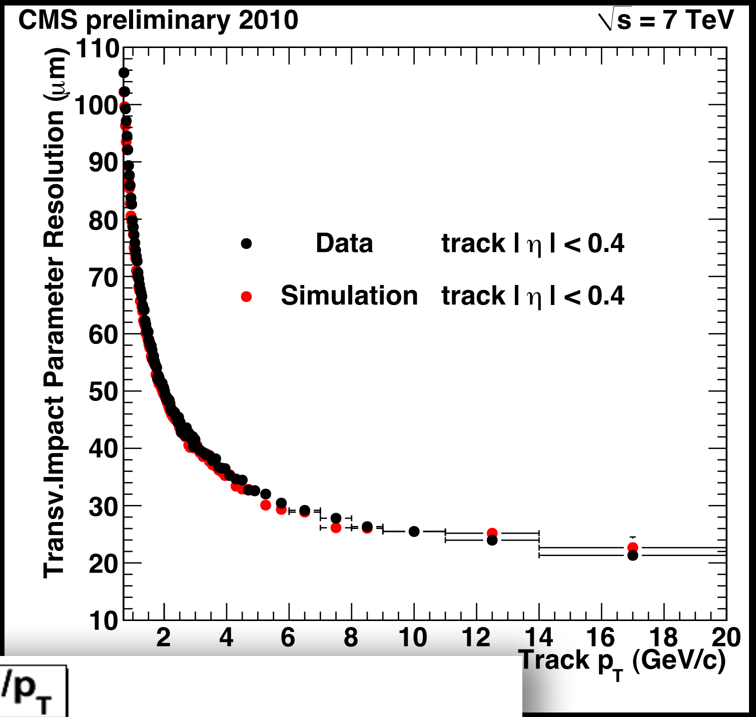


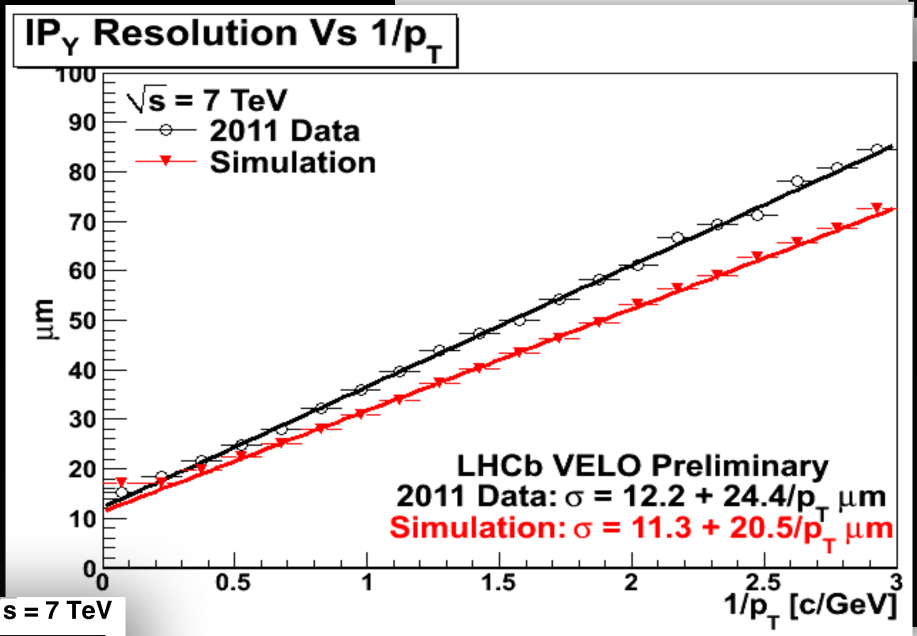


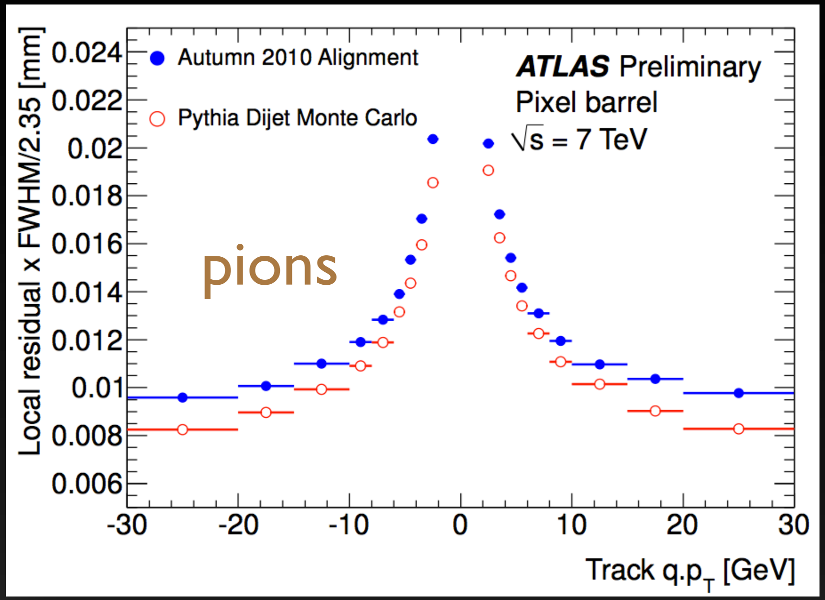
- alignment is sensitive to module distortions (not a flat shape)
  - ➡ ATLAS is using survey data for Pixels
  - ➡ CMS will allow for module bowing soon

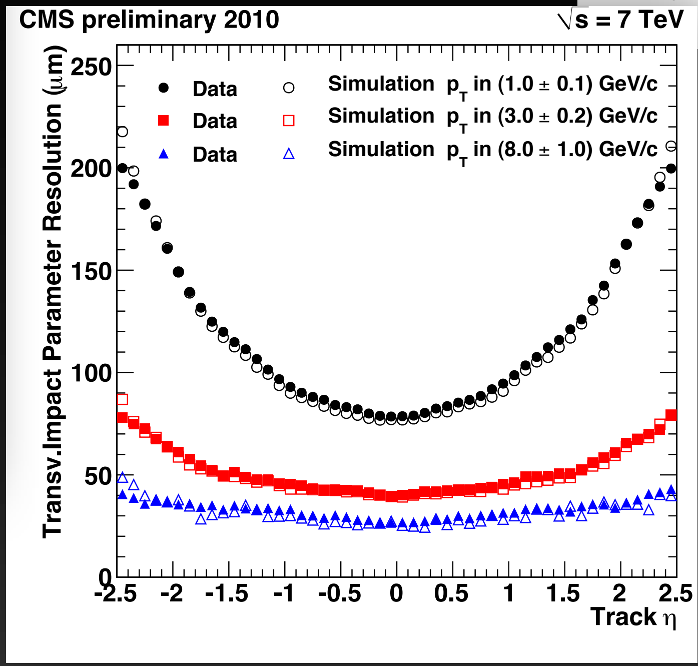
Impact Parameter Resolution

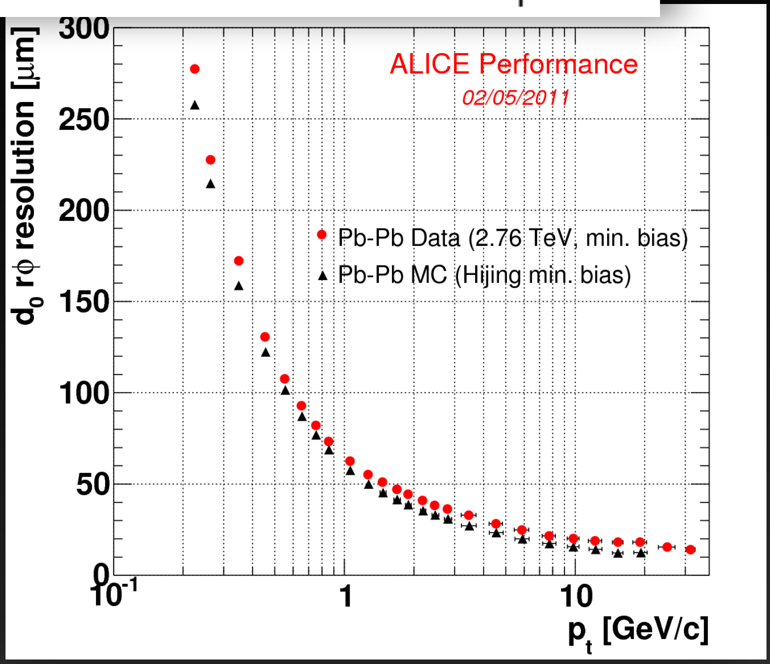
- driven by local misalignments
  - ➡ quickly approaching design resolutions
  - ➡ some small problems still visible
    - hence apply some error scaling in fit
- vertexing and b-tagging
  - ➡ fast commissioning helped by well constraint local alignment





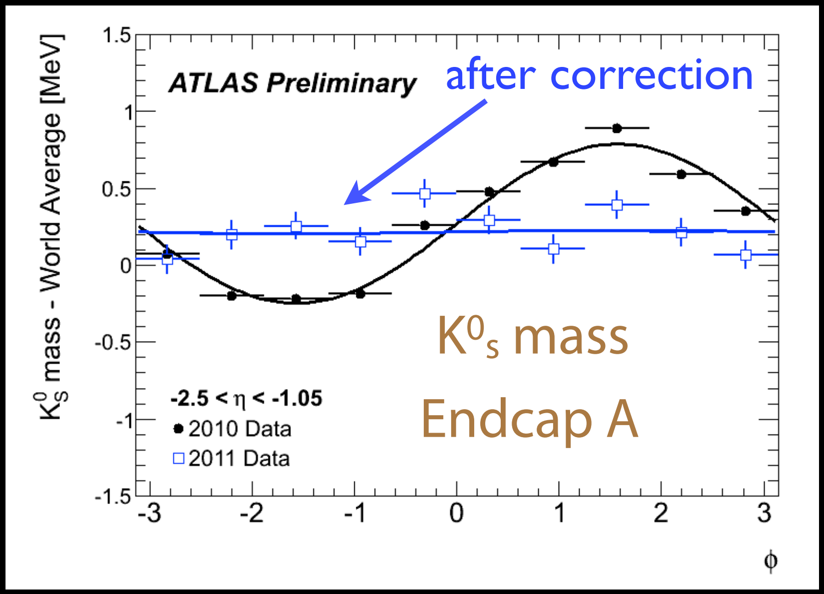


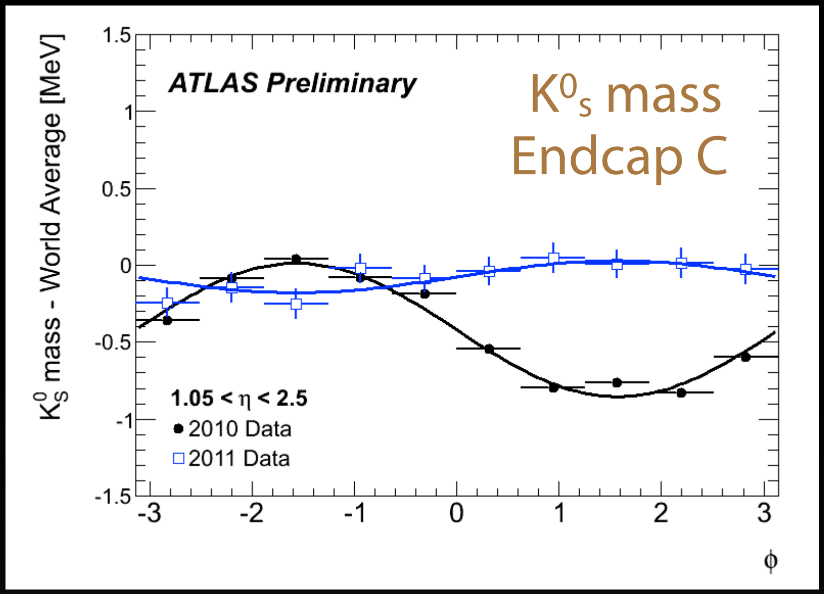


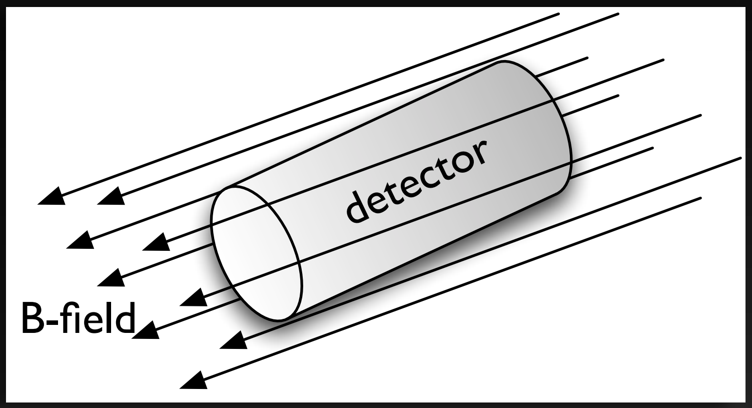


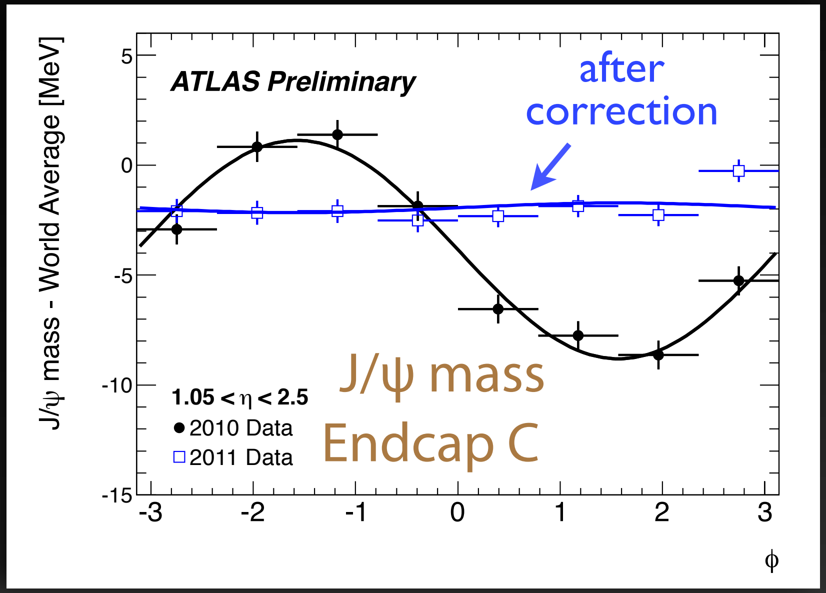
B-Field Tilt vs Nominal ?

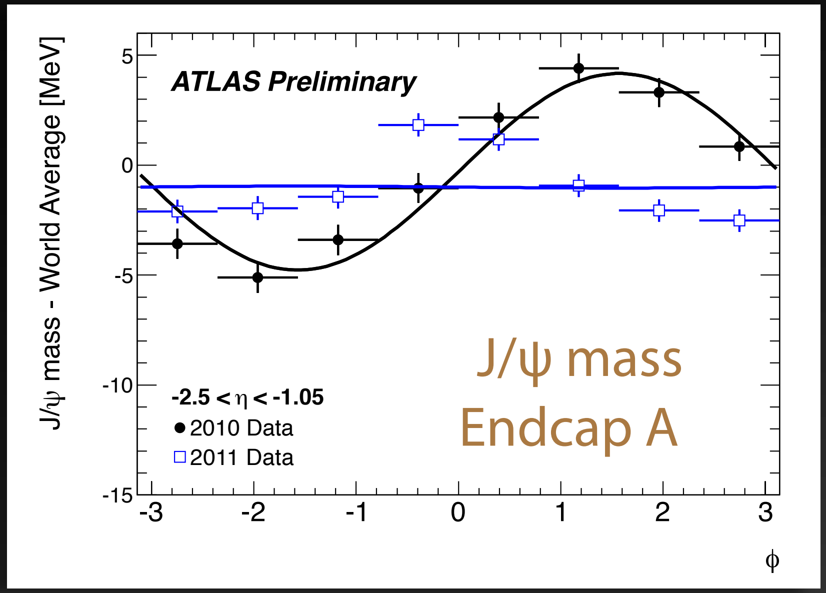
- field tilt in ATLAS visible in K^0_s + J/ψ mass bias vs ϕ
  - ➡ results in a sine modulation in mass in opposite directions in both endcaps
  - ➡ corrected by 0.55 *mrad* field rotation around y axis
  - ➡ consistent with survey constraints





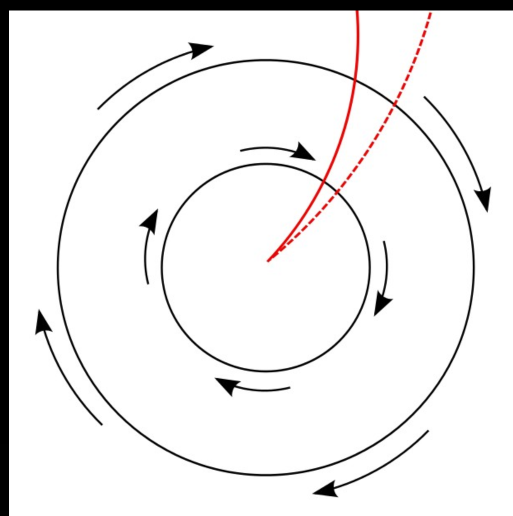




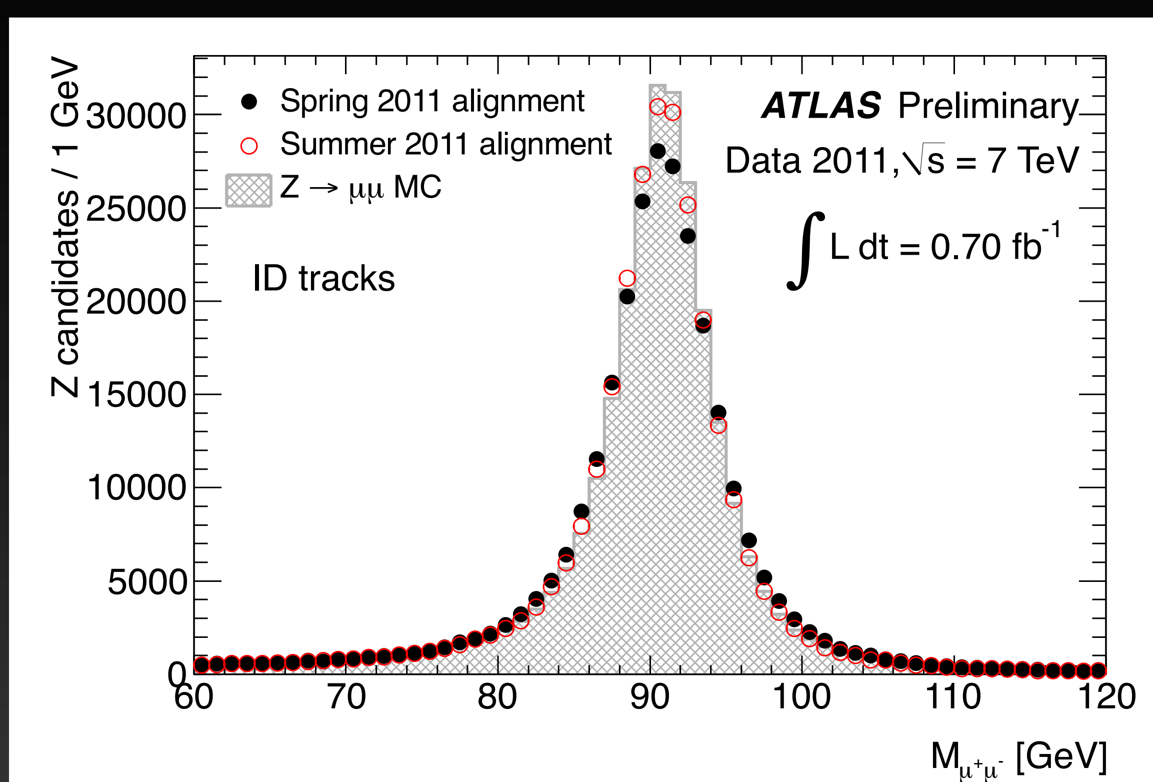


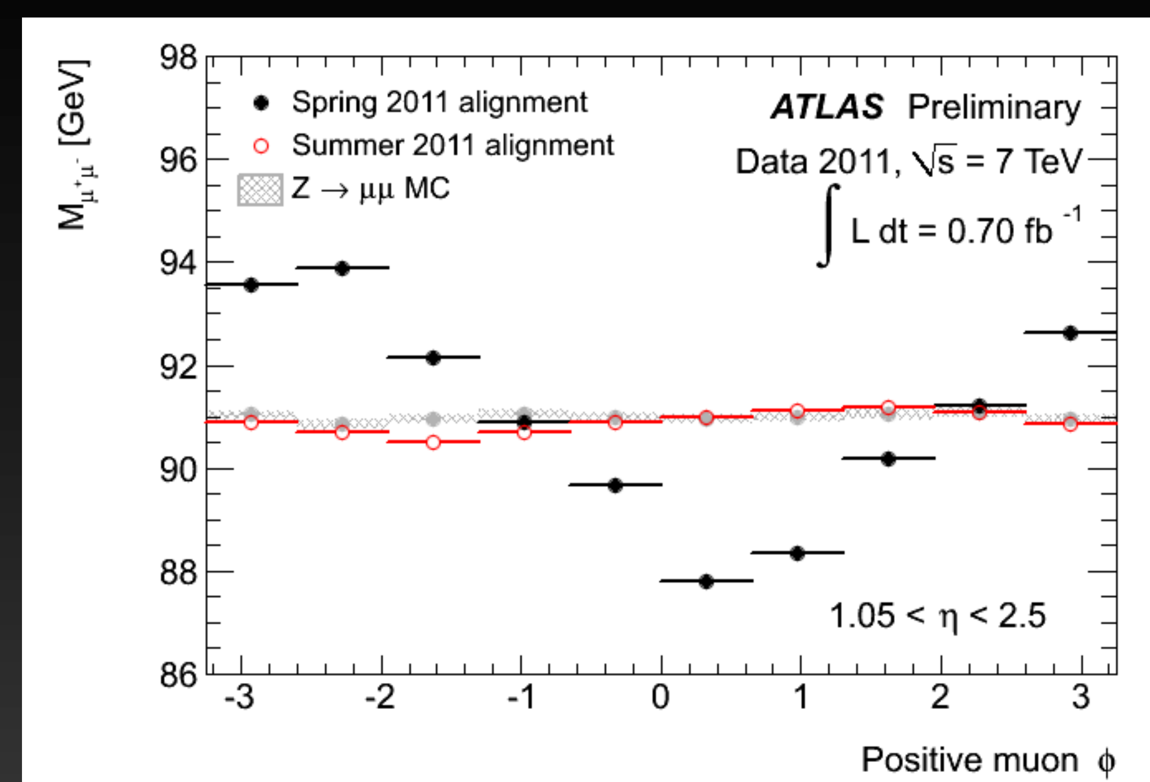
Evidence for Weak Modes ?

example:
curl weak mode



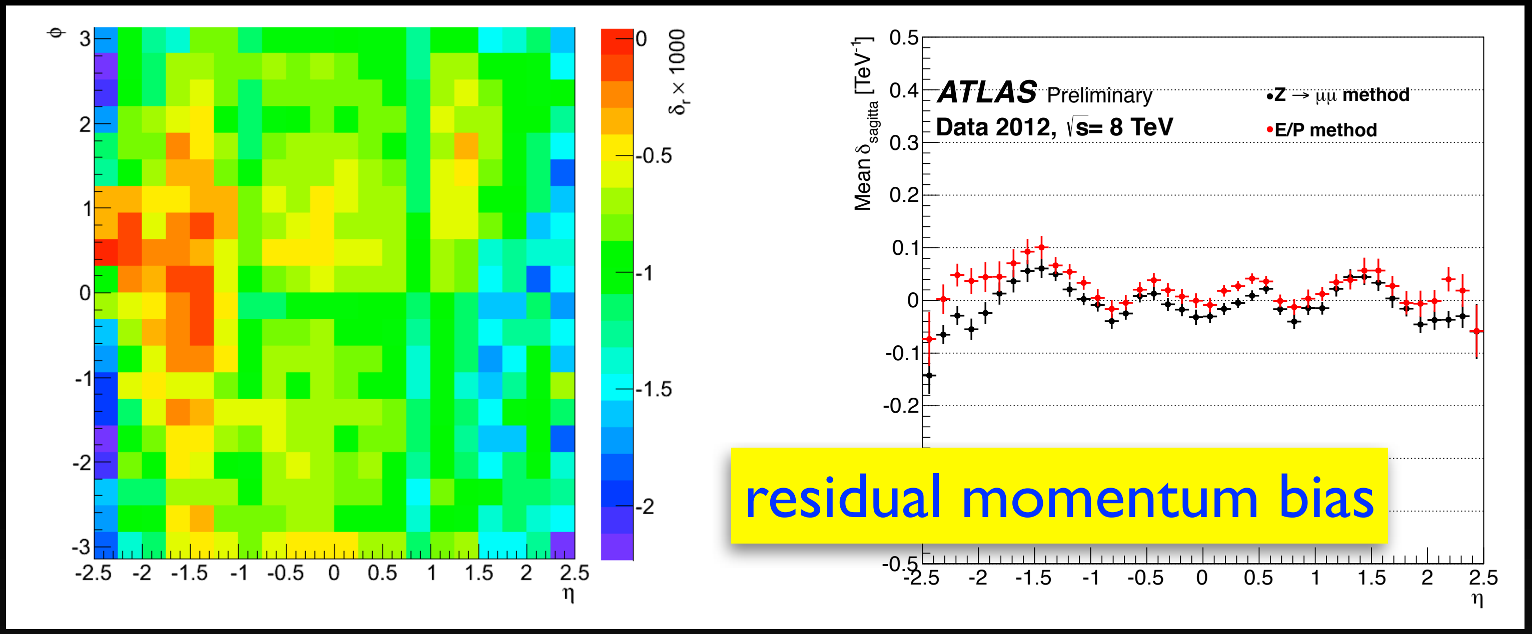
- “weak modes” are global deformations
  - ➡ leave fit-χ^2 nearly unchanged
  - ➡ affect momentum scale, e.g. Z-mass resolution
  - ➡ several techniques to control weak modes
    - electron E/p using calorimeter
    - muon momentum in tracker vs muon spectrometer
    - TRT to constrain Silicon alignment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





Todays Alignment Systematics ?

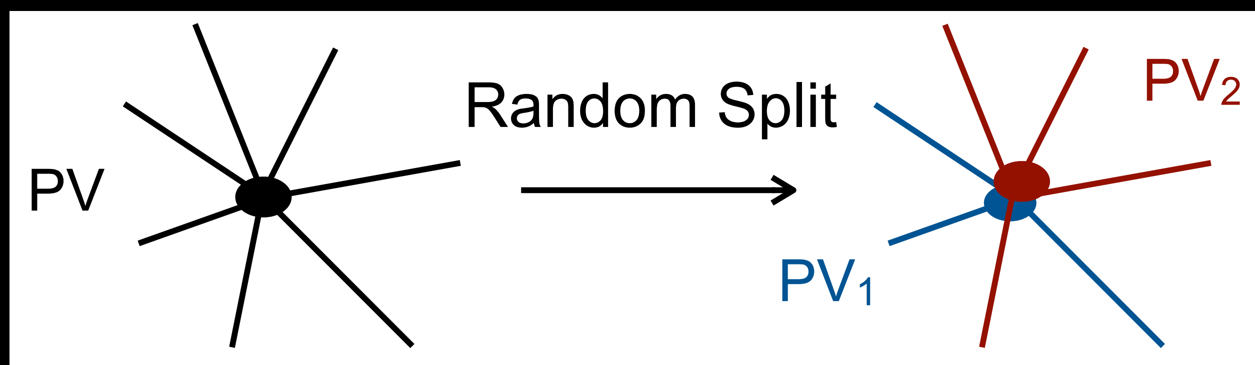
- momentum bias is very small !
  - ➡ less than 0.1 TeV^{-1} , much better than muon spectrometer systematics !
  - ➡ source for double sin structure not understood yet...

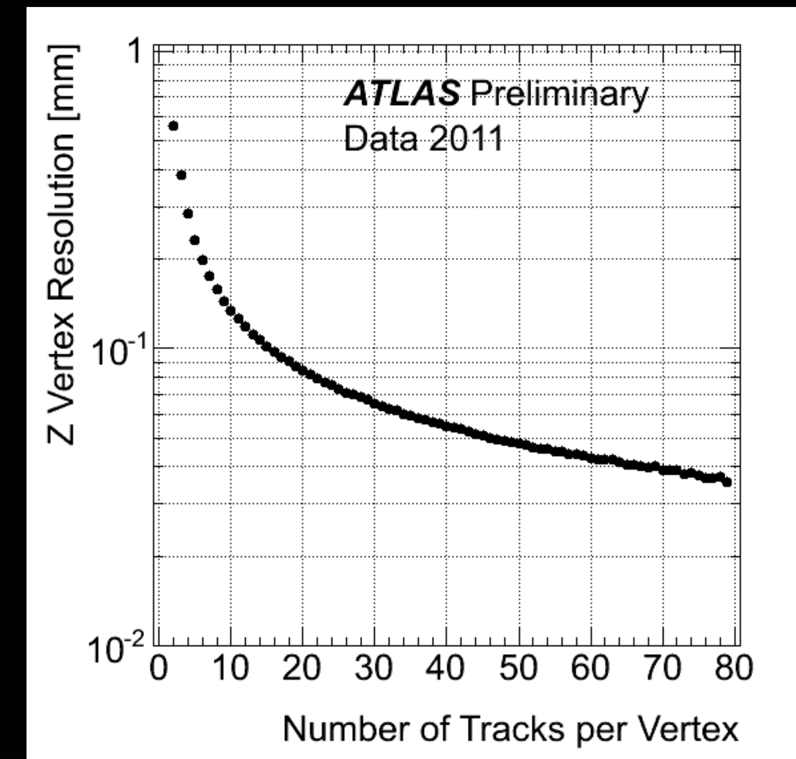


- still a lot to be improved...
  - ➡ additional TRT deformations in the endcaps
  - ➡ evidence for SCT module deformation effects, not yet corrected for
  - ➡ Pixel digitization does not describe data shapes, cluster z calibration is crap
  - ➡ evidence for Pixel endcap deformation

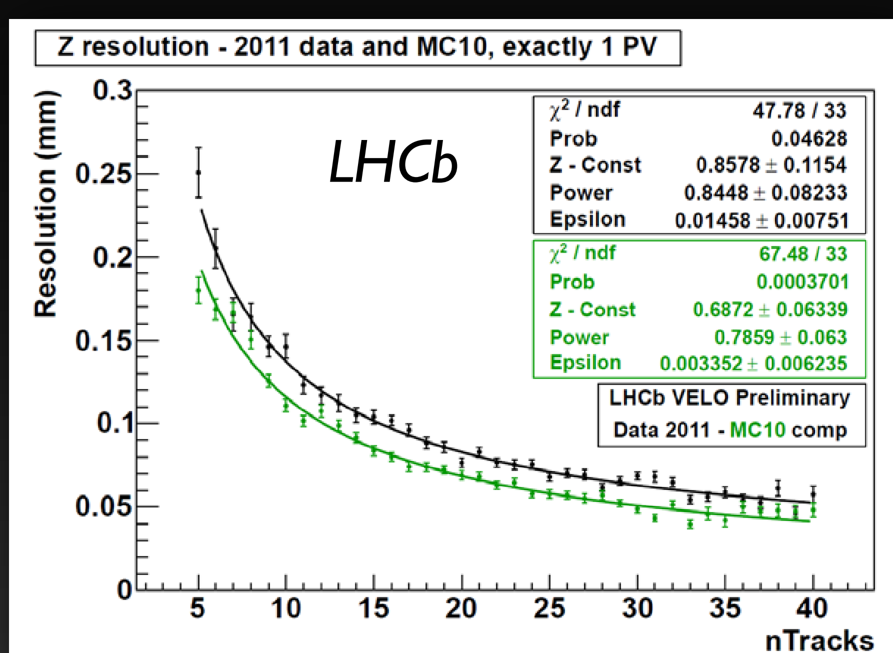
Primary Vertex Resolution from Data

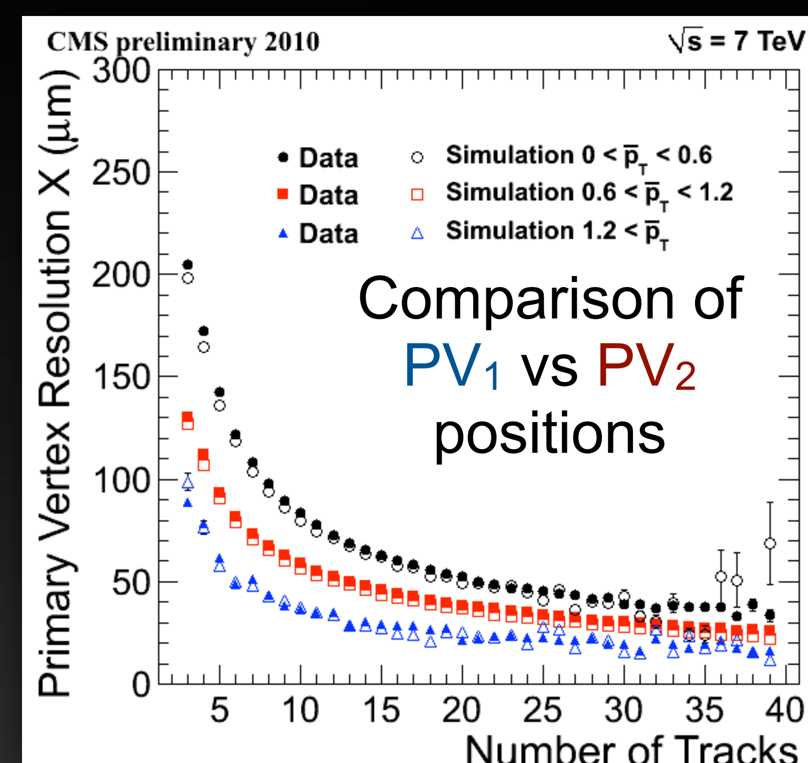
- primary vertex is input to b-tagging, etc.
  - ➡ need to understand precisely the resolution in data





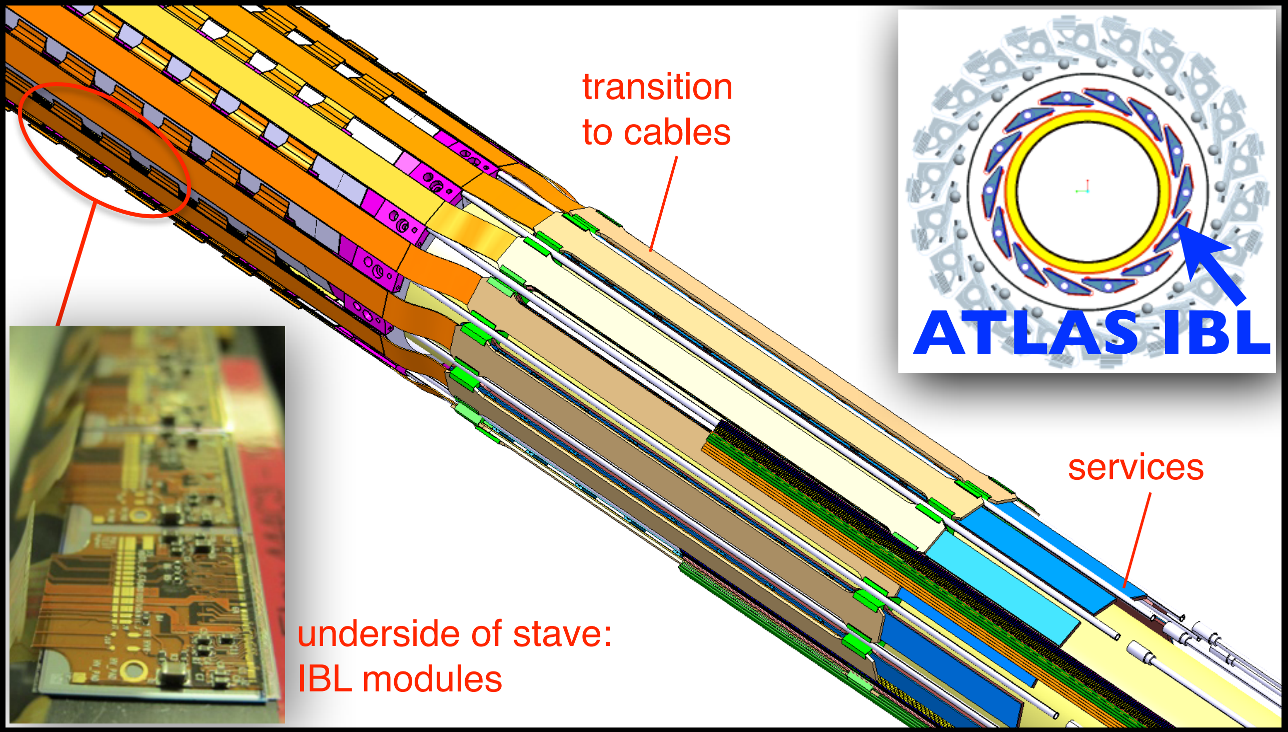
- split vertex technique
  - ➡ data driven method
  - ➡ split vertex in 2 and study difference in the 2 fitted positions as function of n tracks



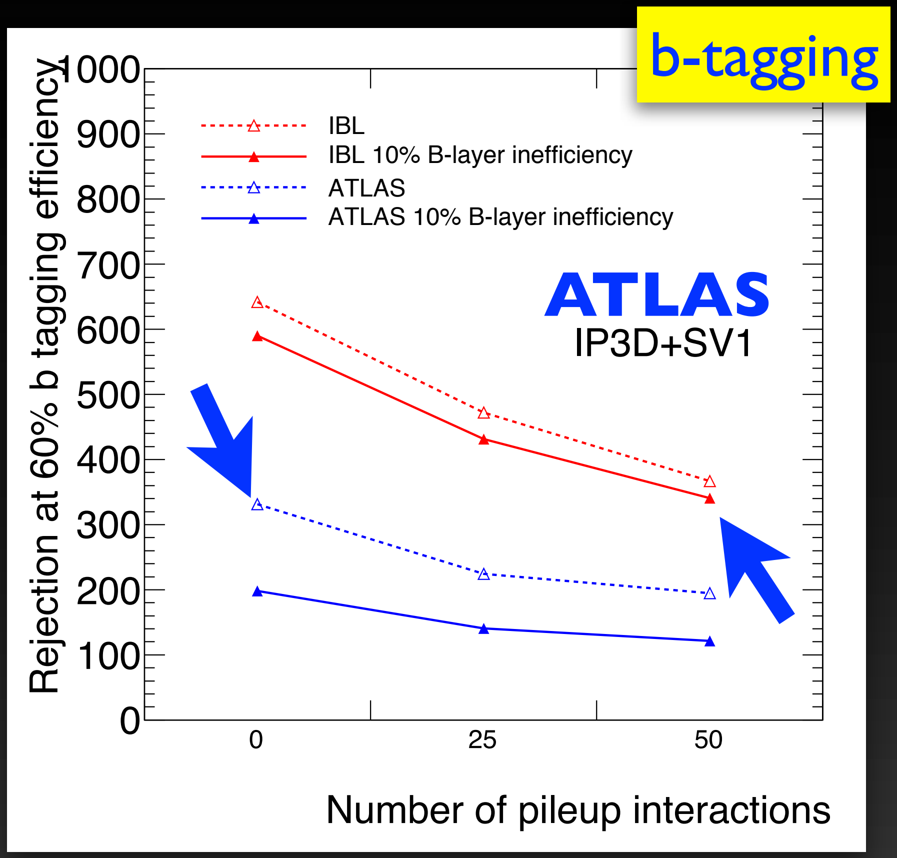


Insertable B Layer (IBL)

- 4th pixel layer for Phase-0
  - ➡ add low mass layer closer to beam, with smaller pixel size
    - improve tracking, vertexing, b-tagging and reconstruction
  - ➡ recovers from defects, especially in present b-layer
  - ➡ FE-I4b overcomes bandwidth limitations of present FE-I3
  - ➡ improves tracking, vertexing, b-tagging and τ-reconstruction at high pileup

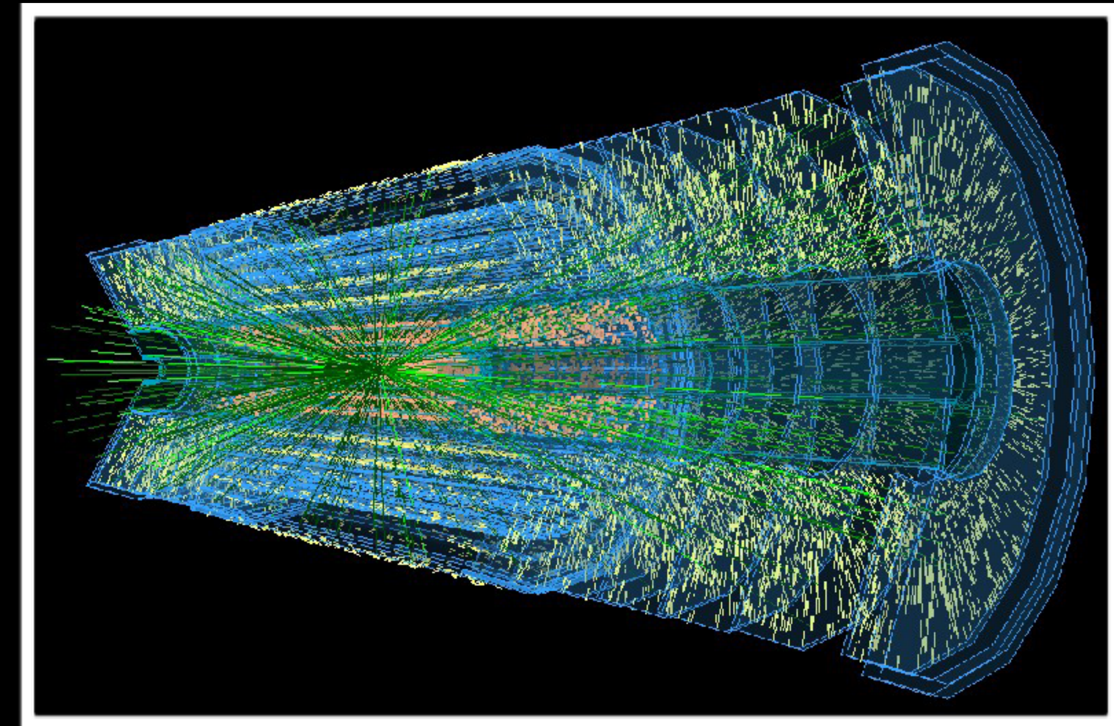


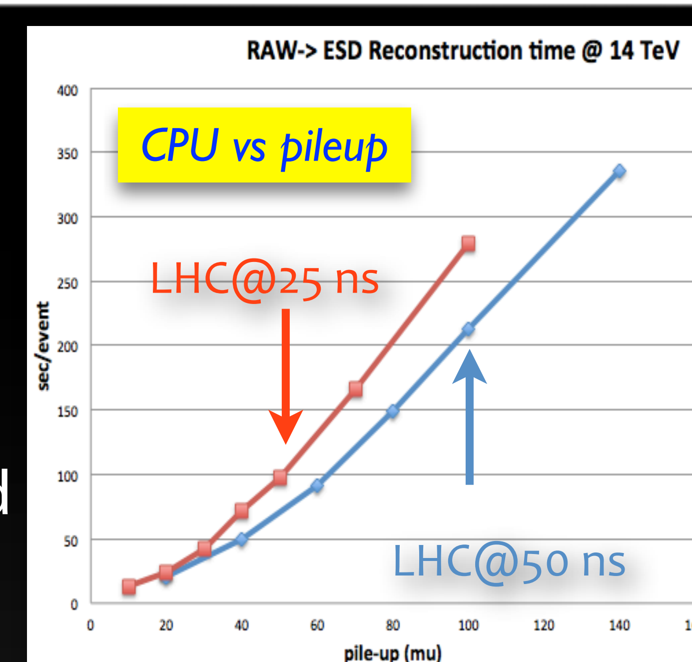
- commissioning and optimization
  - ➡ detector commissioning work similar to 2009
    - timing, calibration, alignment needs to be done
  - ➡ adapt Neural Network clustering
    - we have planar and 3D sensors !
  - ➡ modify tracking to take benefit from 4th Pixel layer

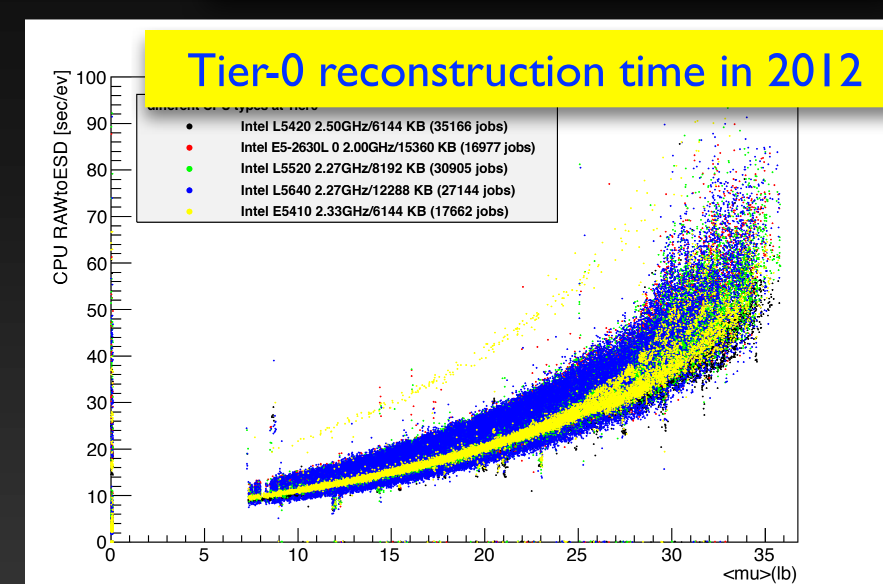


Future ATLAS Tracking ?

- track reconstruction
  - ➡ combinatorics grows with pileup
  - ➡ naturally resource driver (CPU/memory)
- million dollar question:
  - ➡ how to reconstruct ITK within resources ?
- this is not a new question !
  - ➡ we knew that tracking at the LHC is going to be a problem
    - we aim at improving over something that is highly optimized
  - ➡ but processor technologies are changing
    - need to rethink some of the design decisions we did
    - will require vectorization and multi-threading
    - improve data locality (avoid cache misses)

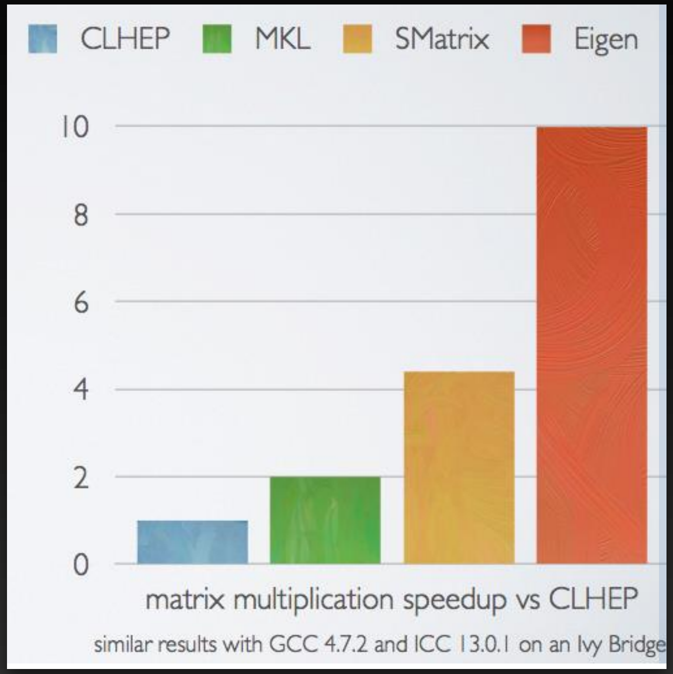






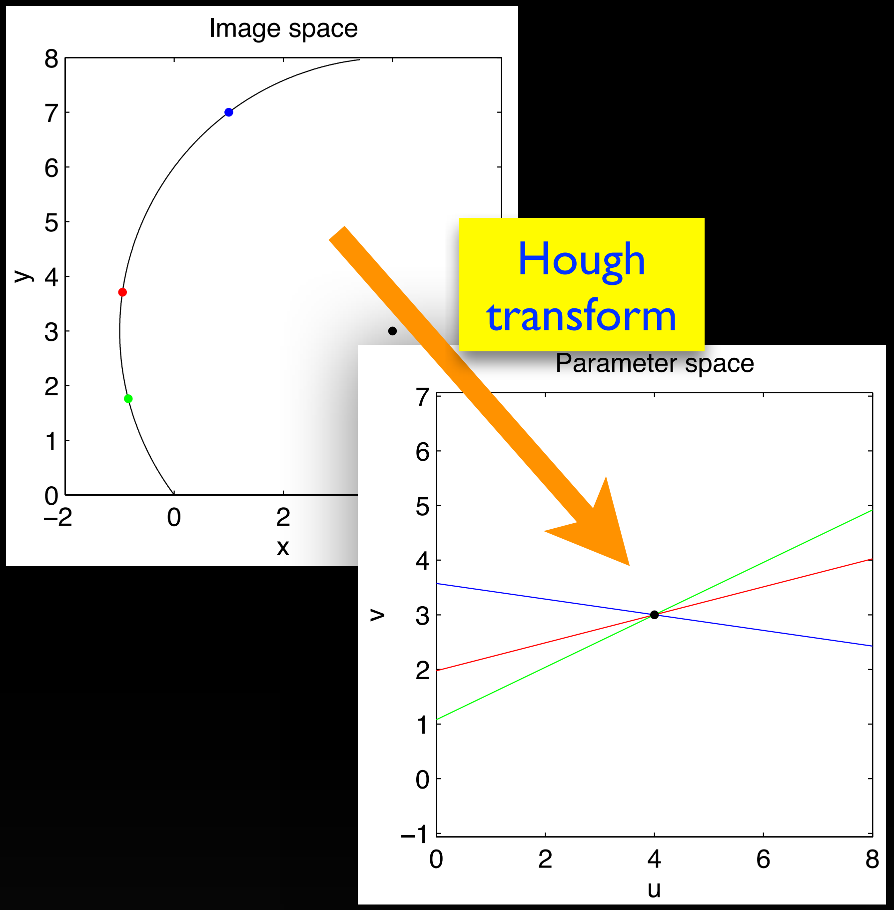
LS1 Developments

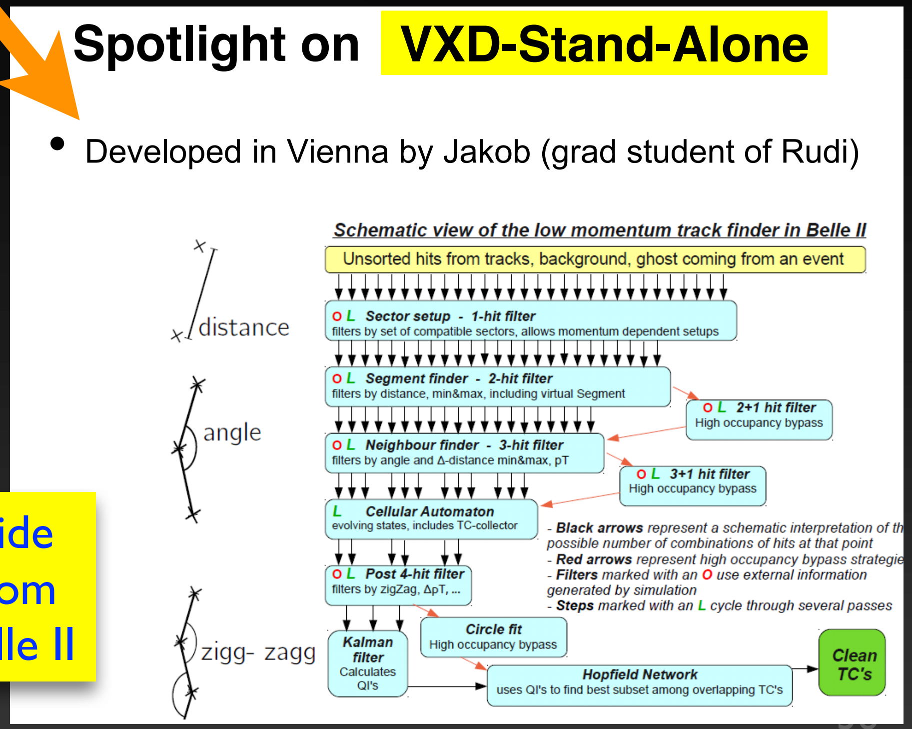
- work on technology to improve CURRENT algorithms
  - ➡ modified track seeding to explore 4th Pixel layer
  - ➡ Eigen migration - faster vector+matrix algebra
  - ➡ use vectorized trigonometric functions (VDT, intel math lib)
  - ➡ F90 to C++ for the b-field
  - ➡ simplify EDM design to be less OO (was the "hip" thing 10 years ago)
  - ➡ xAOD: a new analysis EDM, maybe more... (may allow for data locality)
- work will continue beyond this, examples:
  - ➡ (auto-)vectorize Runge-Kutta, fitter, etc. and take full benefit from Eigen
  - ➡ use only curvilinear frame inside extrapolator
  - ➡ faster tools like reference Kalman filter...
- hence, mix of SIMD and algorithm tuning
- may give us a factor 2 (maybe more...)
  - ➡ further speedups probably requires "new" thinking



Alternative Tracking Algorithms

- examples for algorithms in literature
  - ➡ conformal transforms: e.g. Hough transforms
    - scale ~ linear with pileup, need memory
    - used in track seeded and TRT segment finding
    - no successful application for full Pixels+SCT
  - ➡ still transforms: V-trees
    - scale ~ linear with pileup
    - used in IDSCAN for Level-2 tracking
    - intrinsically pointing, need primary vertex
  - ➡ cellular automaton
    - used by some experiments, example Belle II (not their default tracking code !)
    - idea is to evolve 3 hit combinations into tracks
    - it's a combinatorial algorithm that could be parallelized
    - Belle II example uses things like "high occupancy bypasses" in their algorithm flow ?





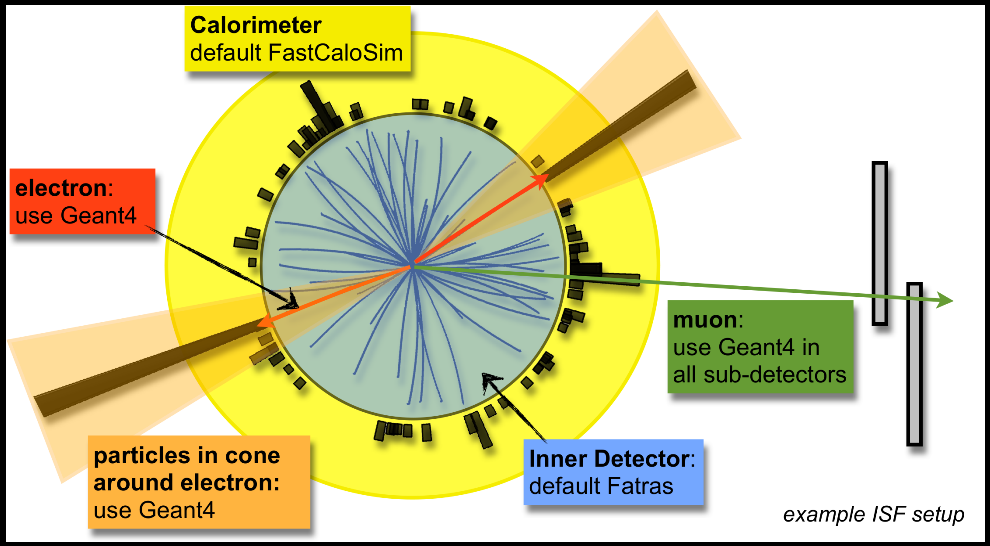
slide from Belle II

- we probably need new ideas !

The ISF Idea for Tracking ?

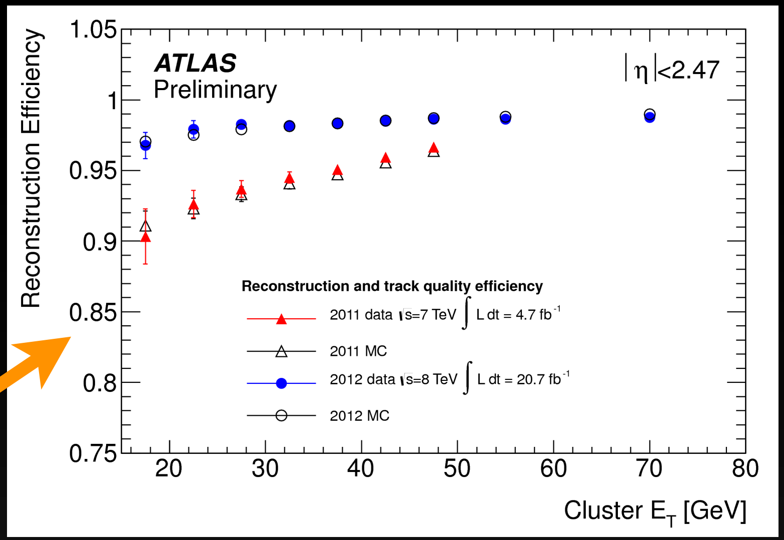
A.Salzburger

- ISF mixes different simulations
  - ➡ spend more times on important event aspects
  - ➡ dramatically reduces effects of pileup

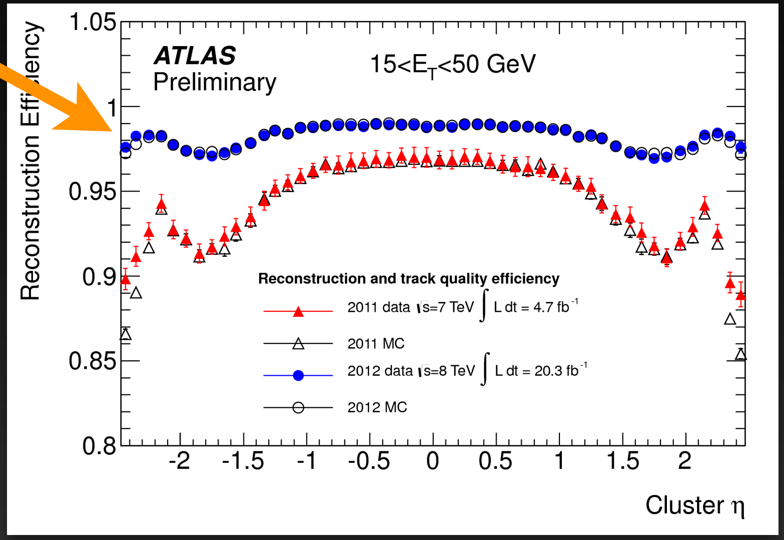


E.Ritsch, A.Salzburger

- this idea is to do the same for tracking !
  - ➡ hence elaborate tracking for regions of interest (RoI)
    - best performance for physics objects costs CPU
  - ➡ fast tracking for underlying event and pileup
    - good enough for primary vertexing and for particle flow / jet corrections



- we do this successfully since 2012 (!)
  - ➡ calorimeter seeded brem. recovery for electrons
  - ➡ GSF later in e/gamma reconstruction

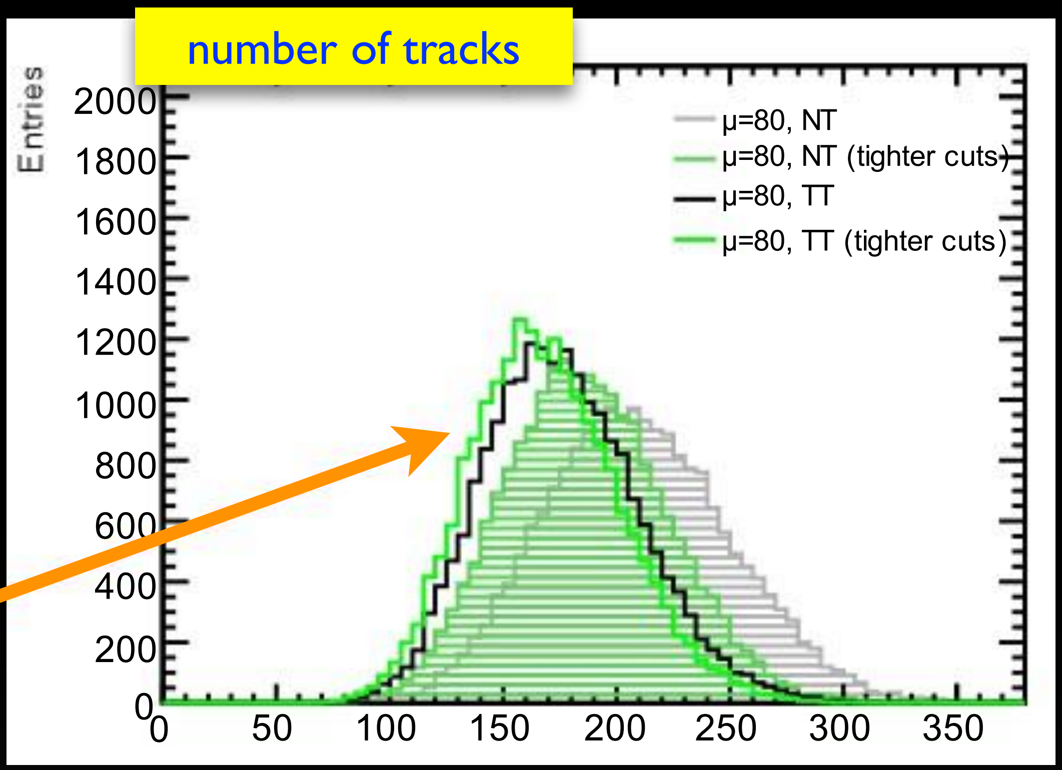


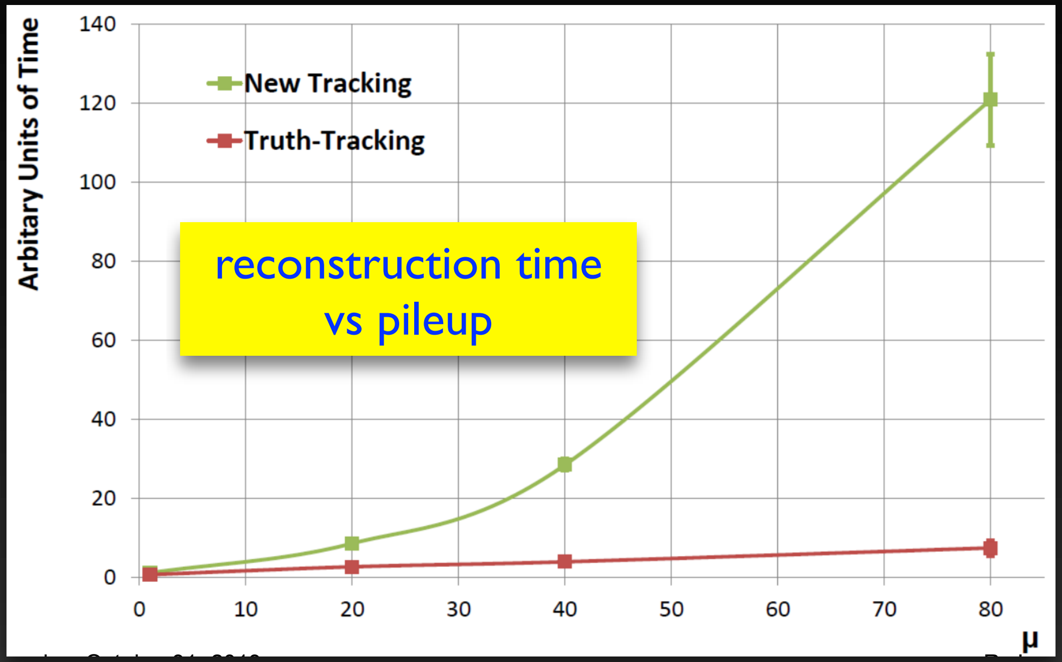
- we are discussing TRT back tracking
  - ➡ only for EM RoIs is logical option for pileup >> design

R.Jansky et al.

Truth Tracking from MC

- invented for fast simulation (ISF)
  - ➡ MC truth based hit filter to find tracks
  - ➡ replace pattern recognition
- good results achieved
  - ➡ real pattern is very efficient and very pure
    - modeling of hit association mostly ok
  - ➡ models main source of inefficiencies well
    - this is hadronic interactions in material (G4)
  - ➡ uses full fit, so resolution come out right
  - ➡ and it is fast (trivial) !
- still, corrections are needed
  - ➡ especially double track resolution
    - affects jet cores, taus, maybe 140 pileup (?)
  - ➡ corrections may be topology dependent
- clearly a tool for fast sim, more ?

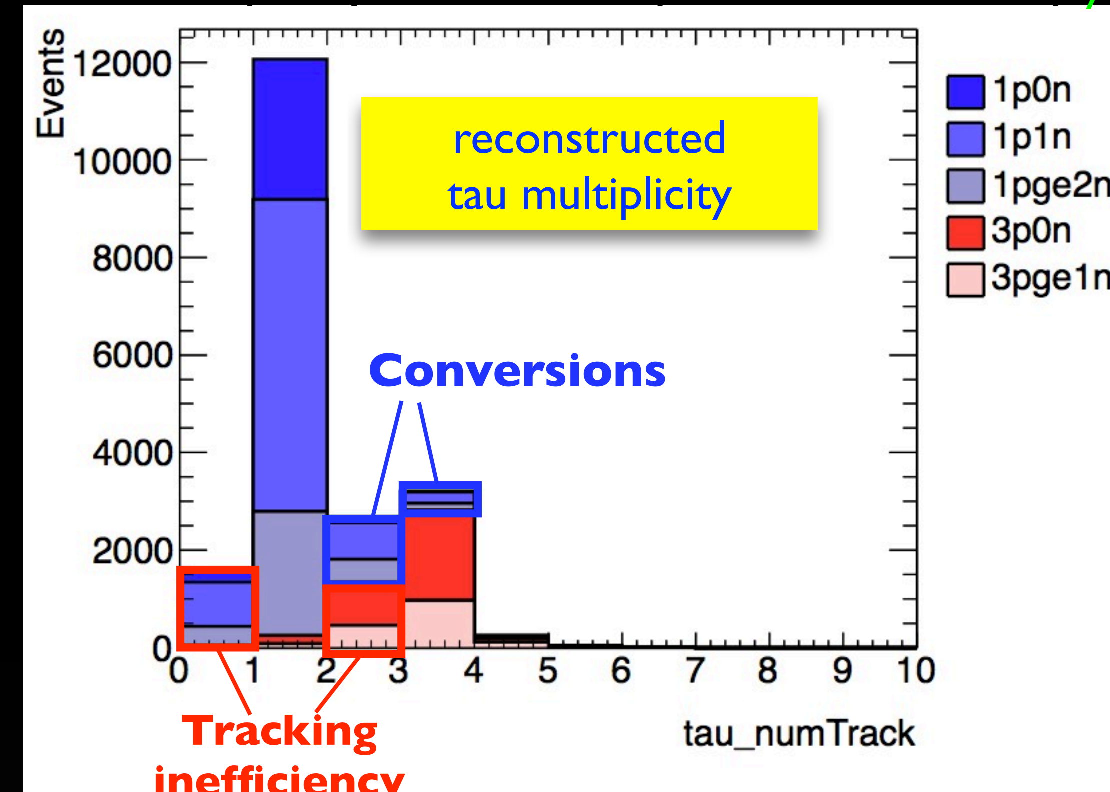


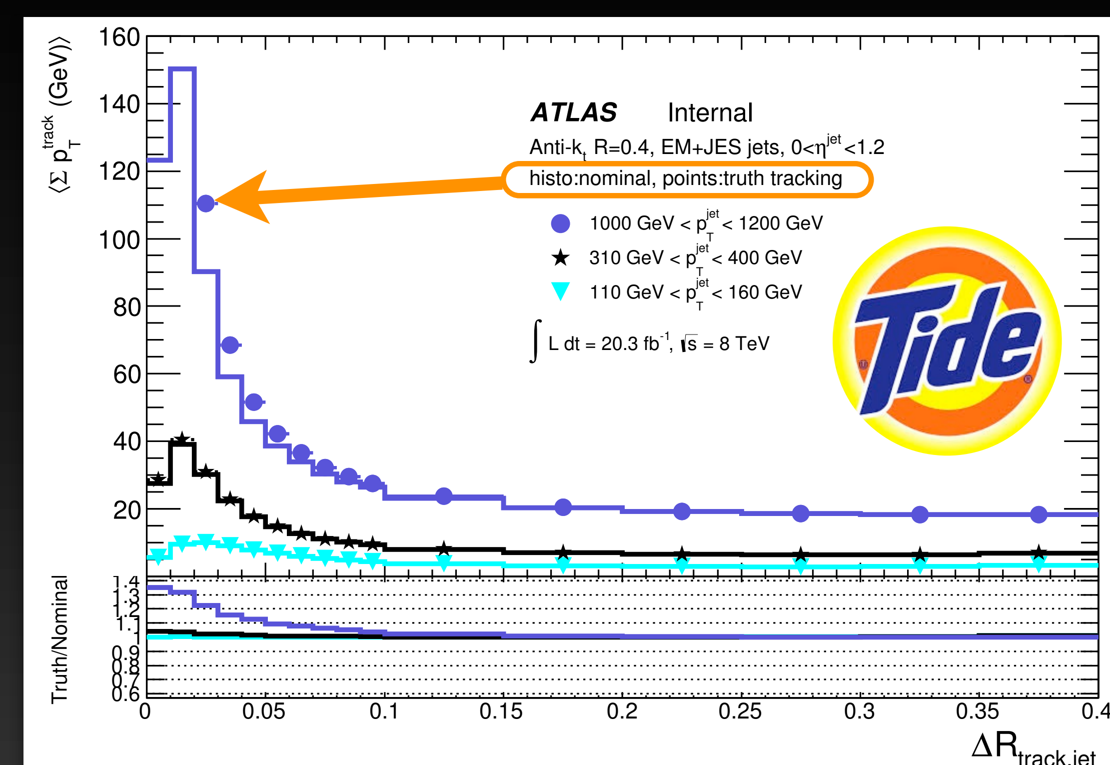


Opportunities to improve Performance

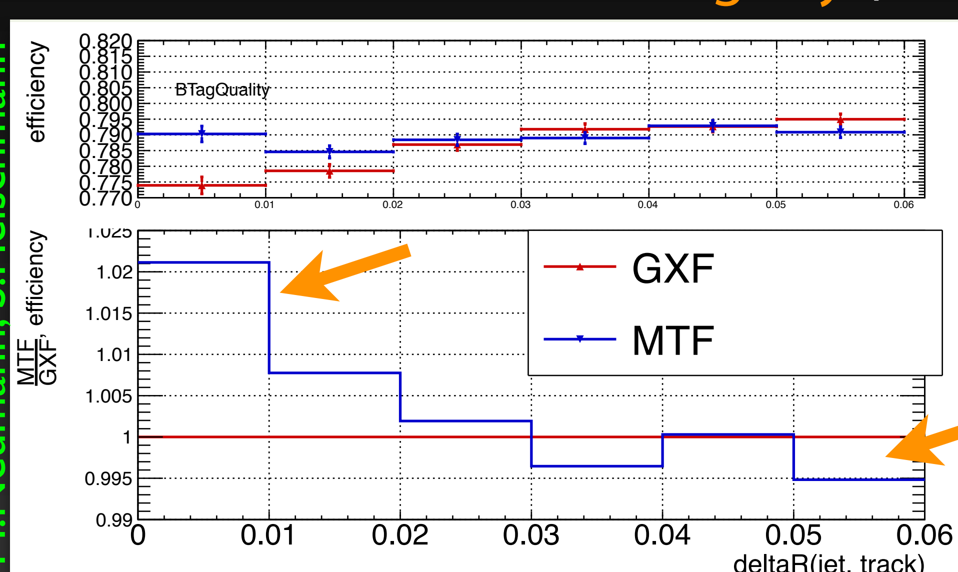
- tau RoI reconstruction
  - ➡ use e.g. Multi Track Fitter to resolve 1 prong and 3 prong taus, including conversions
- try to improve in high-p_T jet RoI
  - ➡ see work of TIDE working group
    - more elaborate tracking to recover tracks
    - especially relevant for p_T > 500 GeV
- work on candidate algorithms
  - ➡ example is MTF (robust fitting, slow)
  - ➡ alternative is full ambiguity (slow !)

Will Davey





M.Neumann, S.Fleischmann



Let's Summarize...

- gave overview of lessons with early data
  - ➡ how to reach design performance for calibration, tracking, alignment, vertexing
- some outlook on future tracking developments
- that's it - hope you found the lectures to be useful