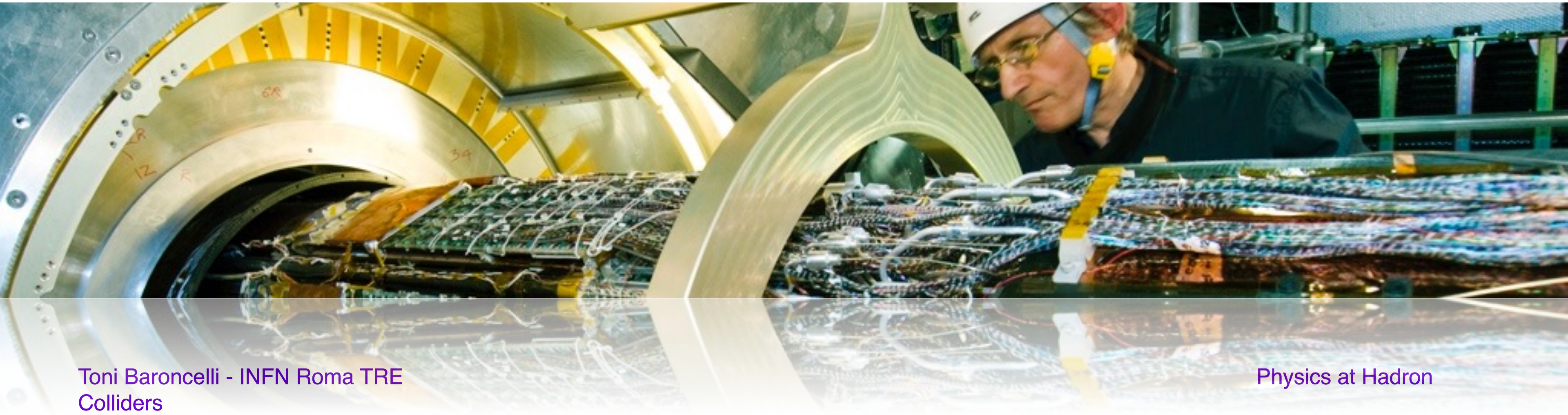
Advanced Topics in Particle Physics

Physics at Hadron Colliders:
the point of view of an experimentalist



Tracking at the LHC

- Role of inner tracking detectors
- Silicon pixel and microstrip detectors
- Impact parameter and vertex resolution
    - Layout of pixel detectors
- Momentum resolution
    - Overall tracker layout
- Tracking performance
    - Material and alignment
- Future detector developments

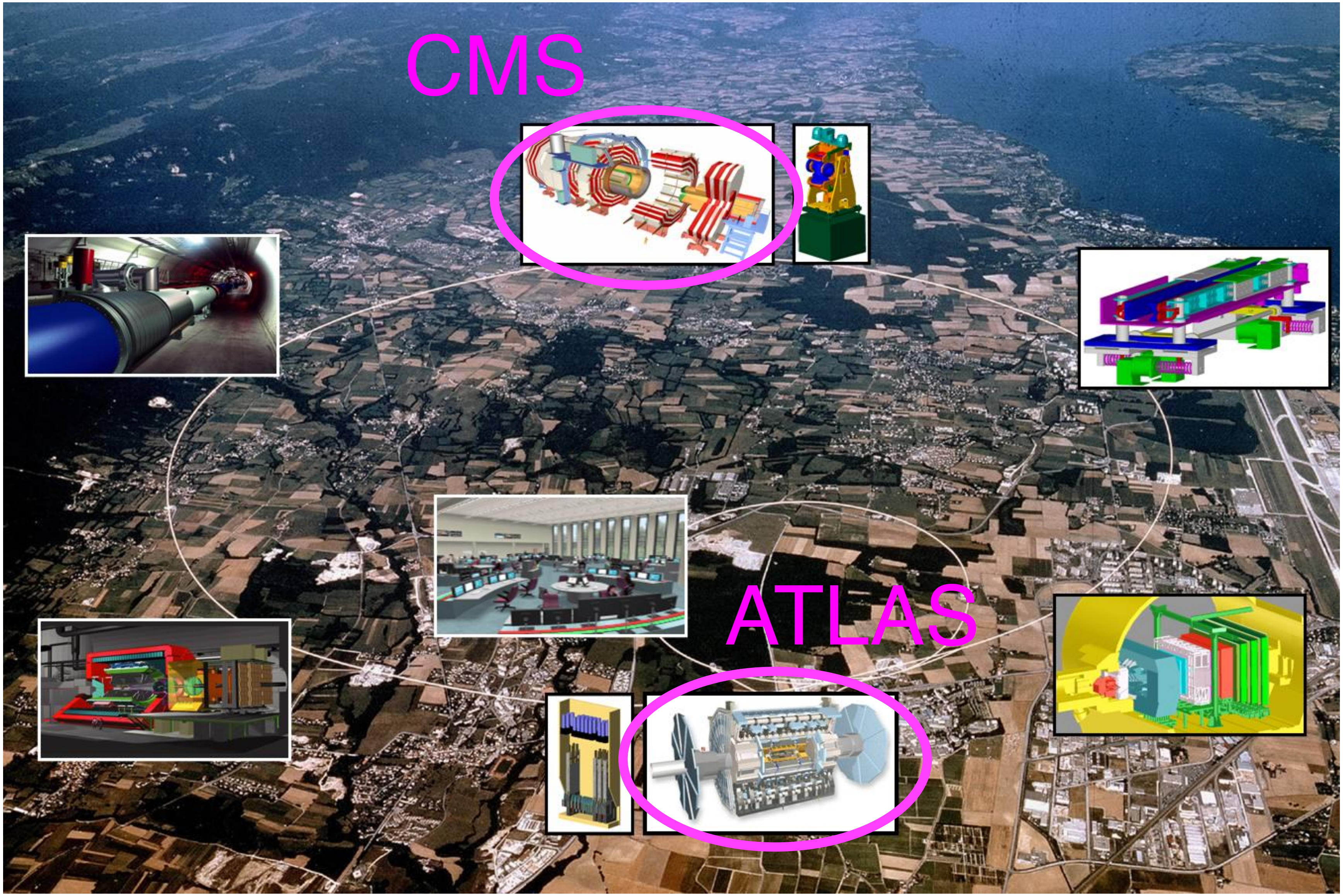
Pippa Wells, CERN

Acknowledgements

- Many thanks for their help in finding information to:
  - P. Allport, P. Collins, K. Gill, M. Hauschild, C. Parkes, H. Pernegger, P. Riedler, W. Trischuk

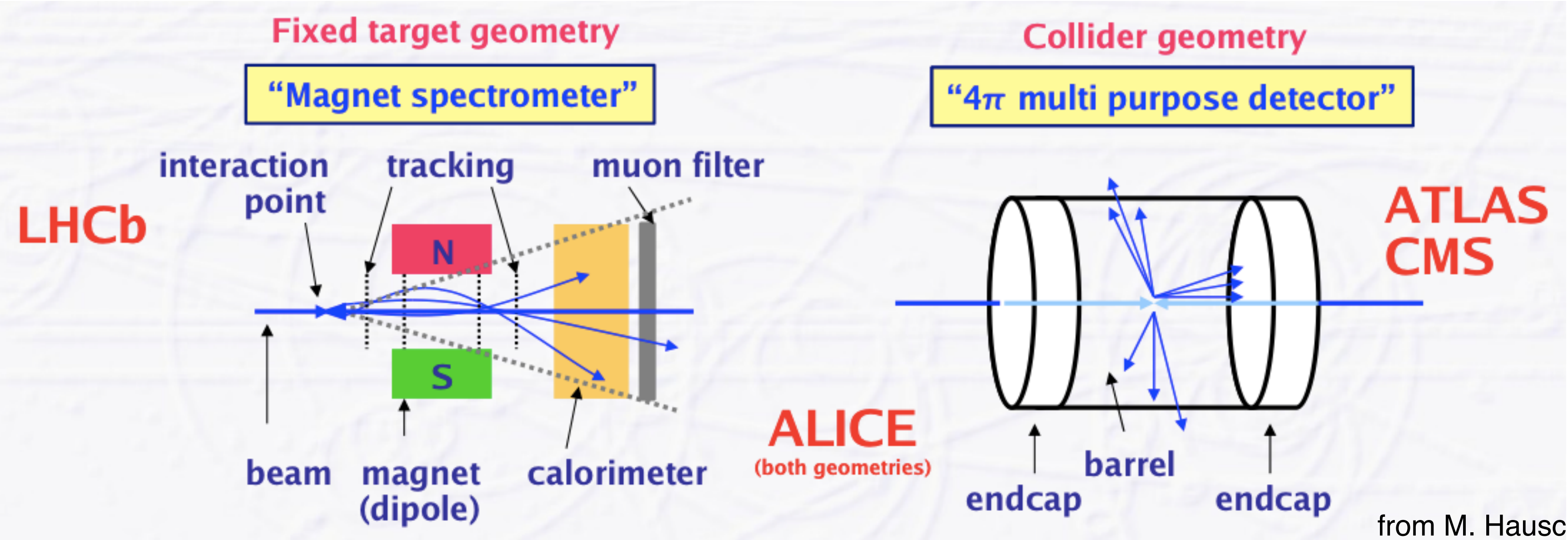
- Also note:
  - More information about tracking with gaseous detectors in the lecture on Muon systems by Kerstin Hoepfner
  - More information on Particle Identification in the lecture by Peter Krizan

Two General Purpose Detectors



Collider detectors

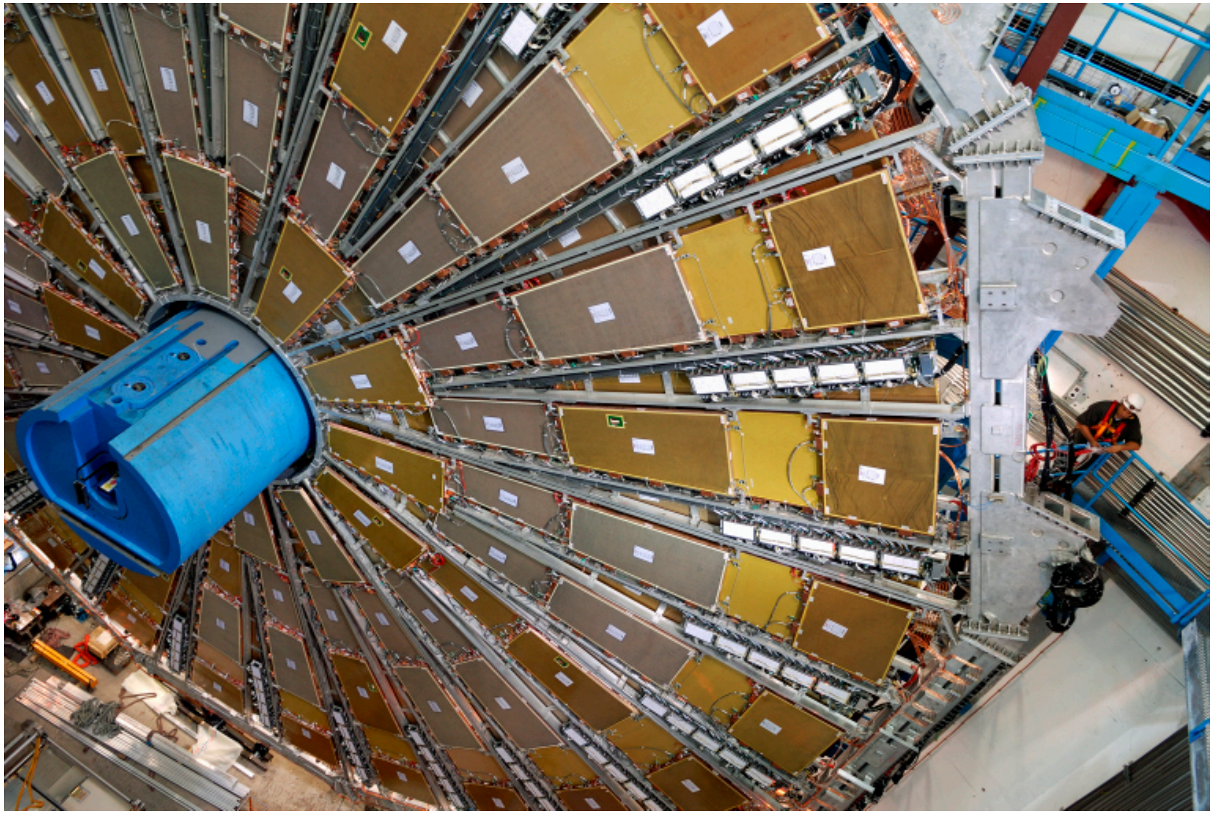
- Central tracker
  - Locate primary interactions and secondary vertices
  - Measure momentum of charged particles
- Calorimeters
  - Fully absorb most particles and measure their energy
- Muon spectrometer
  - Measure momentum of muons which pass through the calorimeter

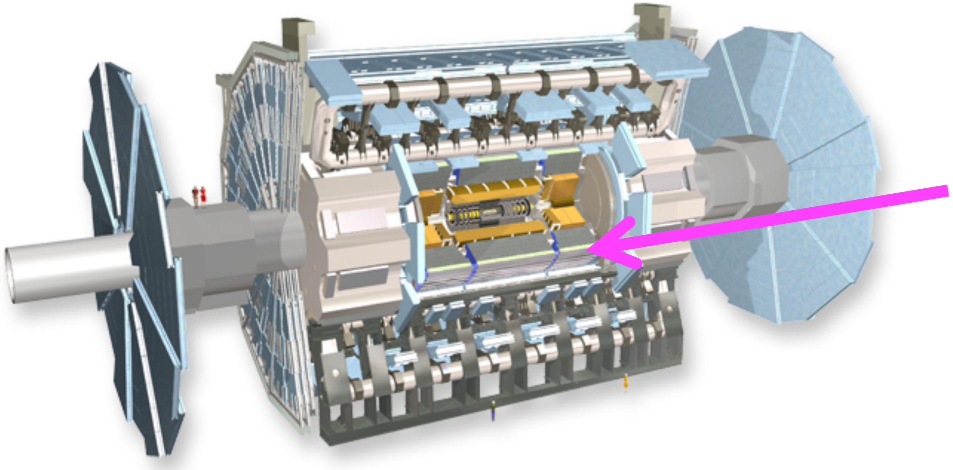


from M. Hauschild

ATLAS

From the outside, all you see is muon chambers: trackers, but not today's topic



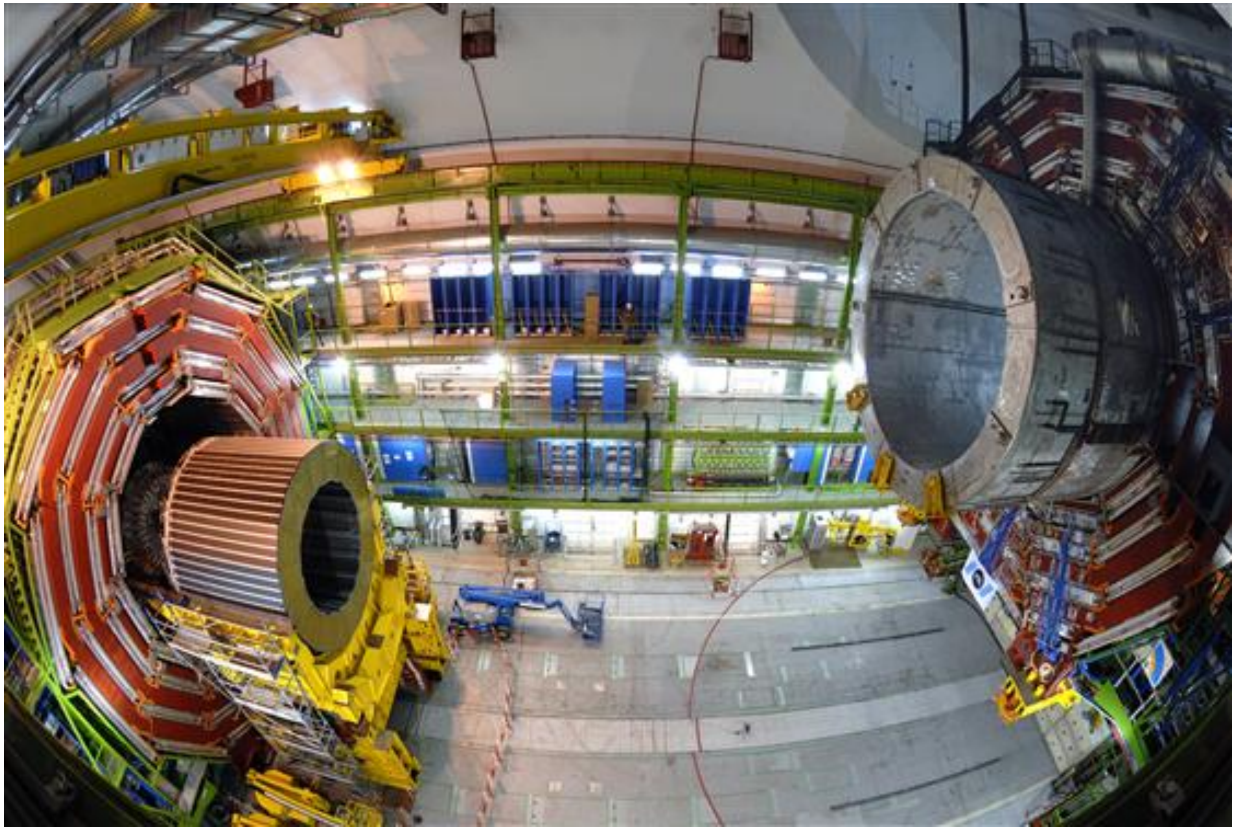


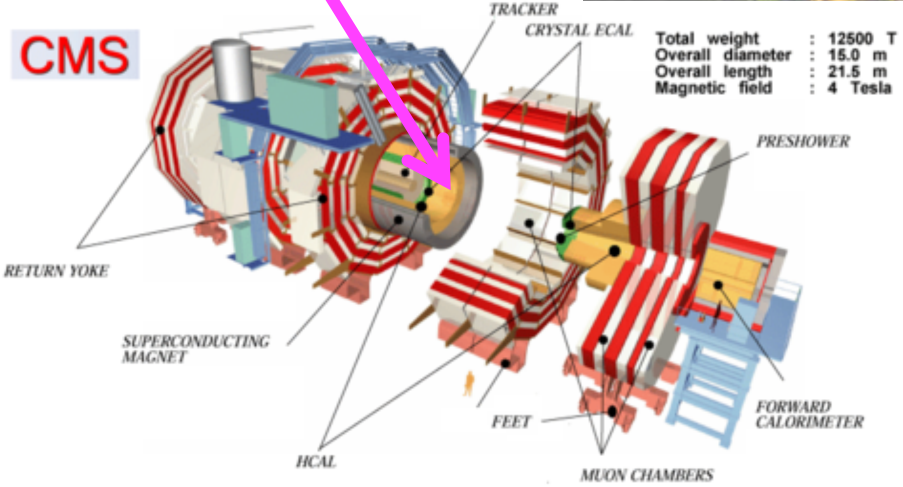
Most particles are absorbed in the calorimeters, which measure their energy.

Muons (& neutrinos) escape.

CMS

This lecture concentrates on central trackers.





Total weight : 12500 T
Overall diameter : 15.0 m
Overall length : 21.5 m
Magnetic field : 4 Tesla

Measure the tracks of charged particles emerging from the interaction point.

Role of trackers at the LHC

- Extrapolate back to the point of origin. Reconstruct:

- Primary vertices
  - → distinguish primary vertices and identify the vertex associated with the interesting "hard" interaction
- Secondary vertices
  - Identify tracks from tau-leptons, b and c-hadrons, which decay inside the beam pipe, by lifetime tagging
  - Reconstruct strange hadrons, which decay in the detector volume
  - Identify photon conversions and nuclear interactions

- Measure the trajectory of charged particles
  - Fit curve to several measured points ("hits") along the track.
  - → measure the momentum of charged particles from their curvature in a magnetic field.

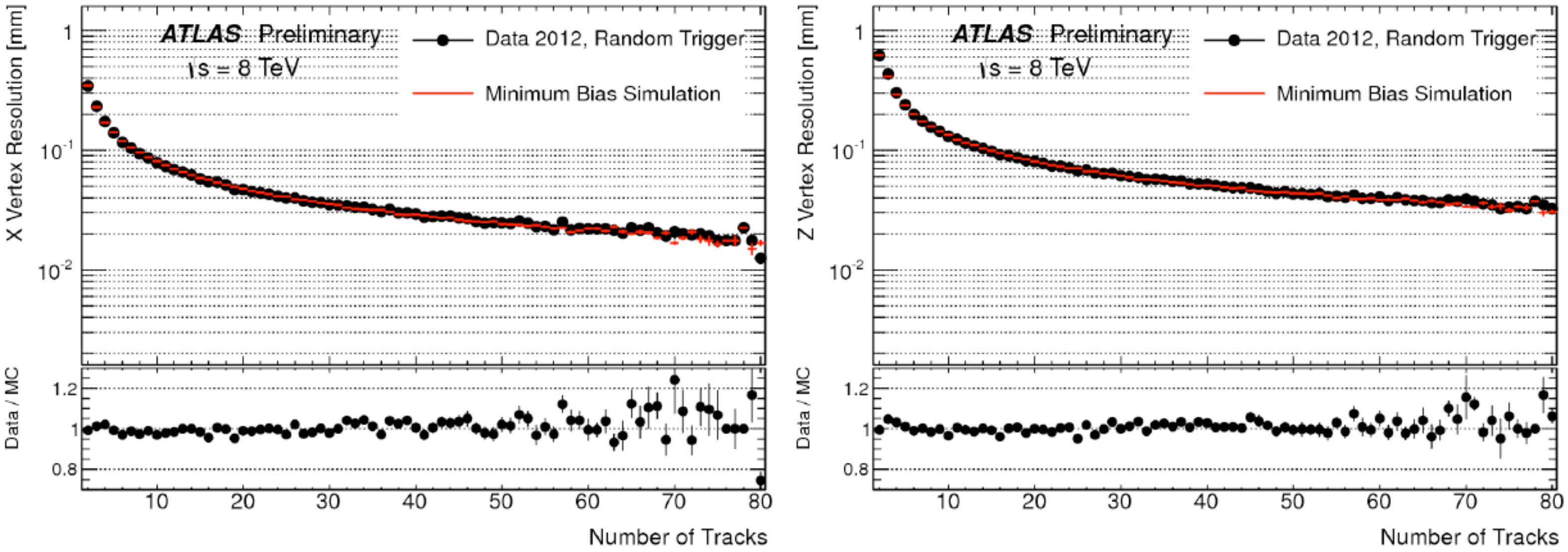
ATLAS vertexing

l takes z-position of track at beam-line as seed

l iterative Chi^2 fit of nearby tracks

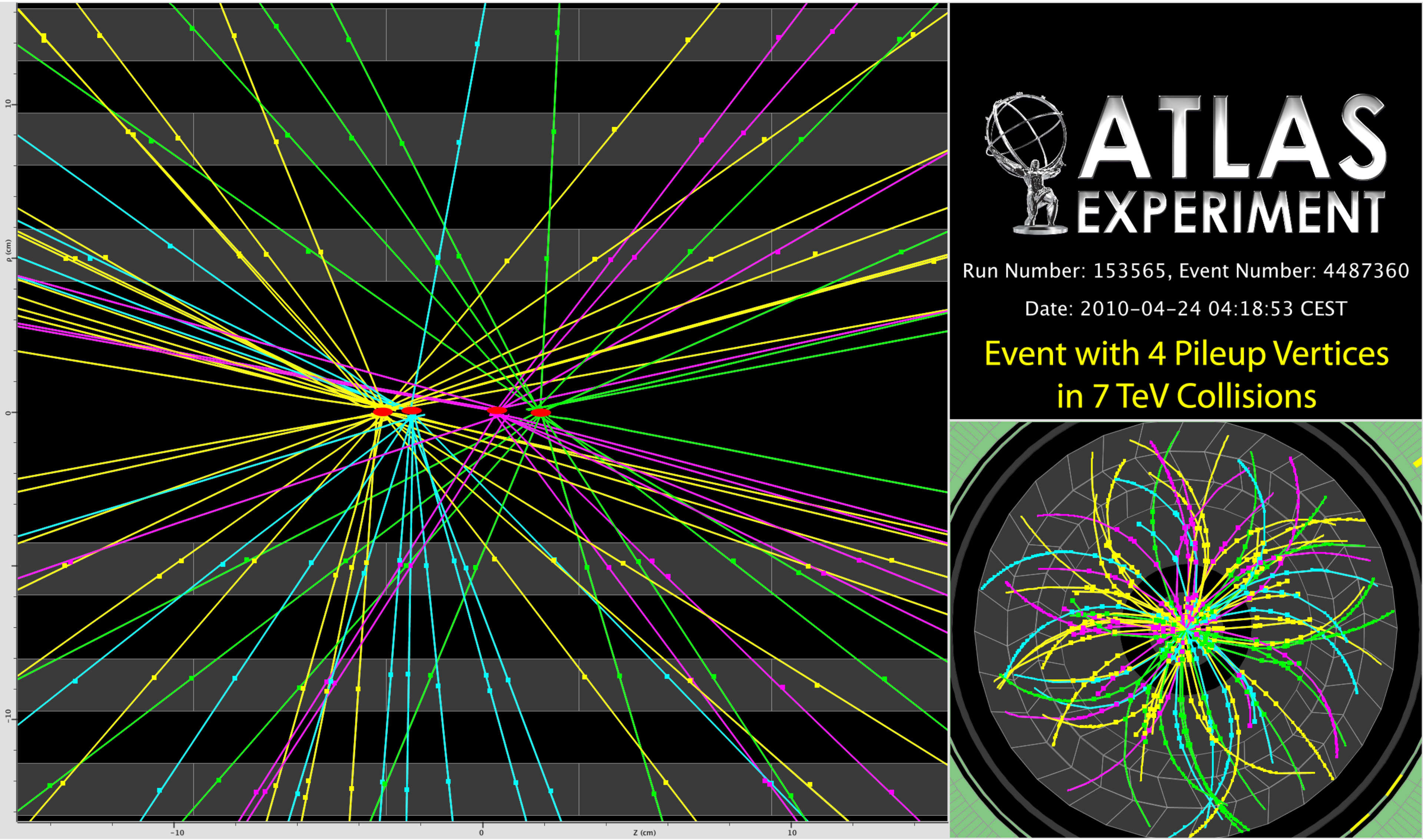
l new seed from tracks displaced by more than n-σ (n>5)

l beam-spot used as a constraint



Vertex position resolution in data and MC for the transverse (left) and longitudinal coordinate as a function of number of tracks in vertex [2].

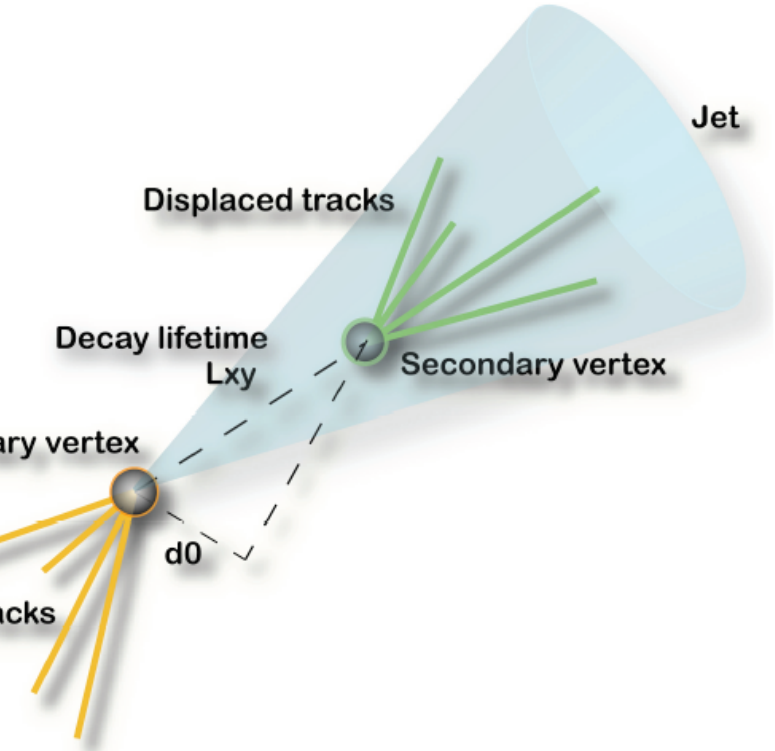
Primary vertices

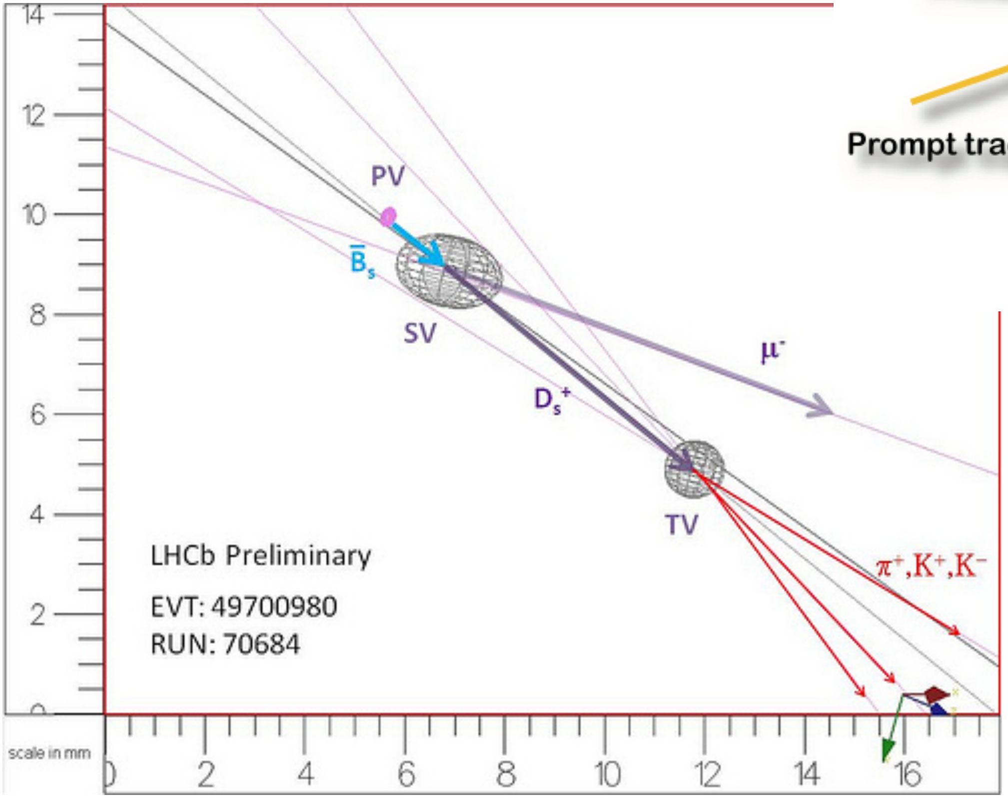


& curving tracks

Lifetime tagging

Tracks have significant impact parameter, d_0, and maybe form a reconstructed secondary vertex





Example of a fully reconstructed event from LHCb, with primary, secondary and tertiary vertex.

Constraints on trackers

- High occupancy, high radiation dose and high data rate
  - At full design luminosity, >20 interactions per pp bunch crossing → 1000 charged particles in tracker, every 25ns.
  - Even higher multiplicity in central (head-on) Pb-Pb collisions (ALICE speciality) with >10000 charged particles in trackers
  - Design for 10^{15} neq (neutron equivalent) for innermost layers (10 year lifetime)
- Minimise material for most precise measurements & to minimise interactions before the calorimeter
  - Increasing sensor granularity to reduce occupancy
→ increase number of electronics channels and heat load
→ more material
- Technology choice
  - Silicon detectors, usually pixels for vertexing, and strips for tracking
→ good spatial resolution, high granularity, fast signal response, & thin detector gives a large signal.
  - Usually complemented by gas detectors further away from vertex

Additional roles of trackers at LHC

- Trackers also contribute to particle identification (PID)
  - Measure rate of energy loss (dE/dx) in the tracker
  - Use dedicated detectors to distinguish different particle types
    - Transition Radiation Detectors also contribute to tracking
    - Time of Flight
    - Ring Imaging Cerenkov Detectors
  - Match tracks with showers in the calorimeter
    - Identify electrons from characteristic shower shape
  - Match central tracks with muon chamber track segments
    - Muon chamber information improves muon momentum measurement

- Focus today on the silicon detectors
  - Vertexing and impact parameter measurement
  - Pattern recognition and momentum measurement from full track

Overall design choices

- ATLAS and CMS General Purpose Detectors (GPDs)
  - Central tracker covers $|\eta|<2.5$.
    Polar angle expressed as pseudorapidity: $\eta = -\ln \tan (\theta/2)$
- ALICE – optimised for heavy ions, high occupancy
  - Tracker restricted to $|\eta|<0.9$, plus forward muons
- All three are symmetric about the interaction point
  - Solenoid magnet providing uniform magnetic field parallel to the beam direction

- LHCb – beauty-hadron production in forward direction
  - Despite the different geometry, design is driven by the same principles to give optimal performance
  - Tracker is not in a magnetic field. Tracks are measured before and after a dipole magnet

Kalman filters

Goal: compute X, observable using a sequence of measurements (k=1,2…
Indicates successive measurements/states)

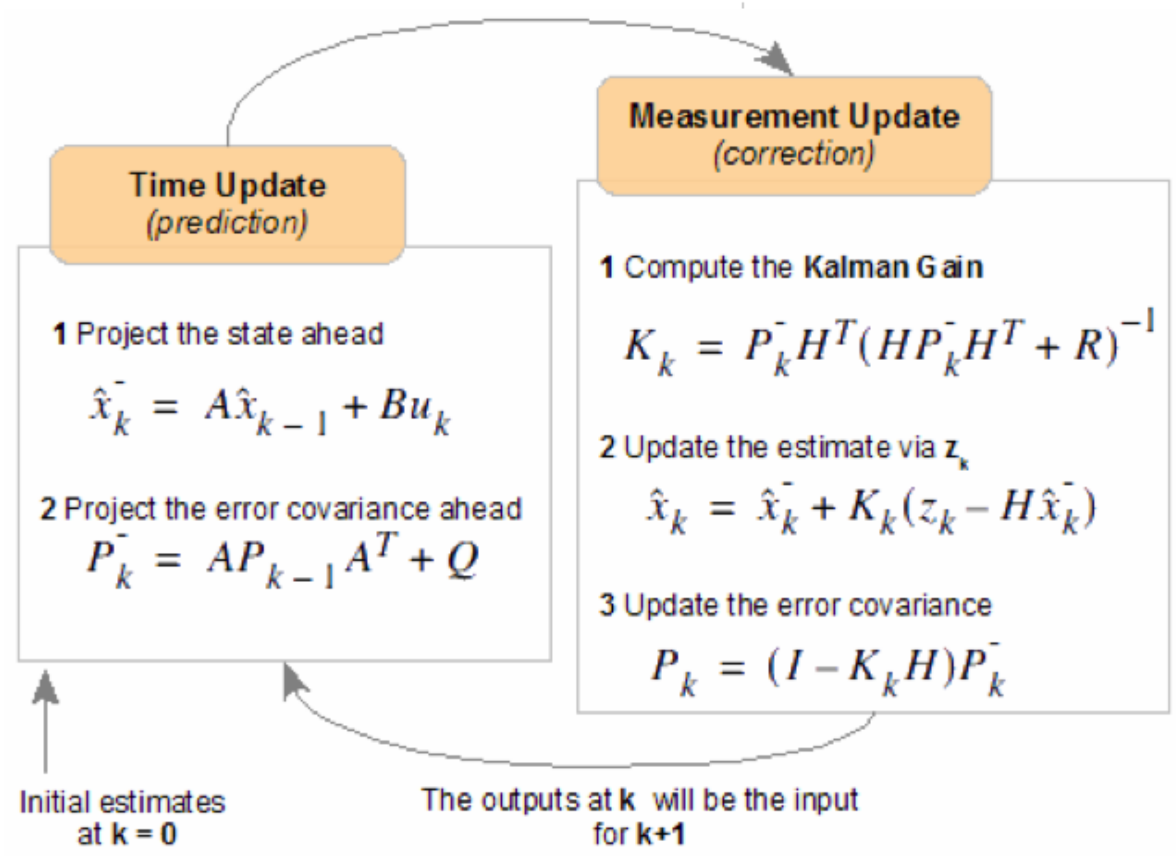
Current estimation of signal

Actual measurement

K_k = Kalman gain

$$\hat{X}_k = K_k \,.\, Z_k + (1 - K_k) \,.\, \hat{X}_{k-1}$$

Previous estimation of signal



Time Update
(prediction)

1 Project the state ahead

$$\hat{x}_k^- = A\hat{x}_{k-1} + Bu_k$$

2 Project the error covariance ahead

$$P_k^- = AP_{k-1}A^T + Q$$

Measurement Update
(correction)

1 Compute the **Kalman Gain**

$$K_k = P_k^- H^T (HP_k^- H^T + R)^{-1}$$

2 Update the estimate via $\mathbf{z_k}$

$$\hat{x}_k = \hat{x}_k^- + K_k(z_k - H\hat{x}_k^-)$$

3 Update the error covariance

$$P_k = (I - K_k H)P_k^-$$

Initial estimates at **k = 0**

The outputs at **k** will be the input for **k+1**

ATLAS track reconstruction

"Primary tracks", first stage

1. Start from 3-point seed in silicon detectors
2. Add hits moving away from IP using Kalman filters
3. Tracks extended to TRT
4. Tracks required to have p_T>400 MeV

Refine tracks, second stage

1. Go back inward and add silicon hits

Mitigate effect of pile up.
Robust algorithm

1. Increase of pile up induces more combinatorial fake tracks
2. Tighten track quality: 9 hits, no hole. Less fakes, less efficiency

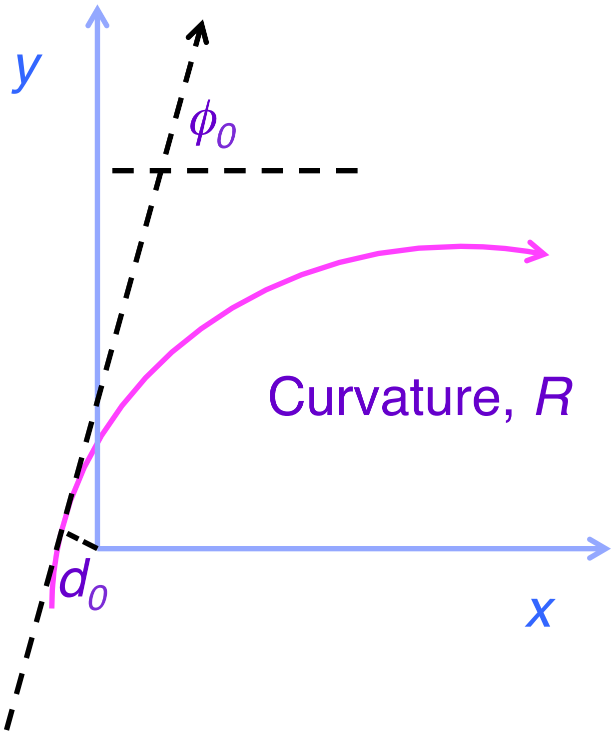
Vertex precision & pixel detectors

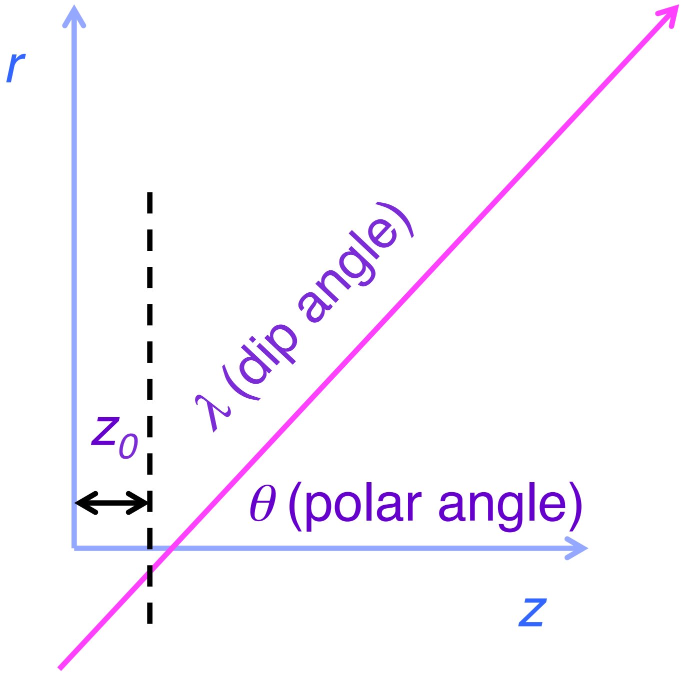
Track coordinates

With a uniform B field along the z-axis (= beam line), track path is a helix (i.e. for ALICE, ATLAS or CMS central trackers)

Pseudorapidity, $\eta = -\ln \tan(\theta/2)$. Transverse momentum, $p_T = p \sin\theta$

Transverse (*xy*) and Longitudinal (*rz*) projections. Define impact parameter w.r.t. point of closest approach to origin or PV

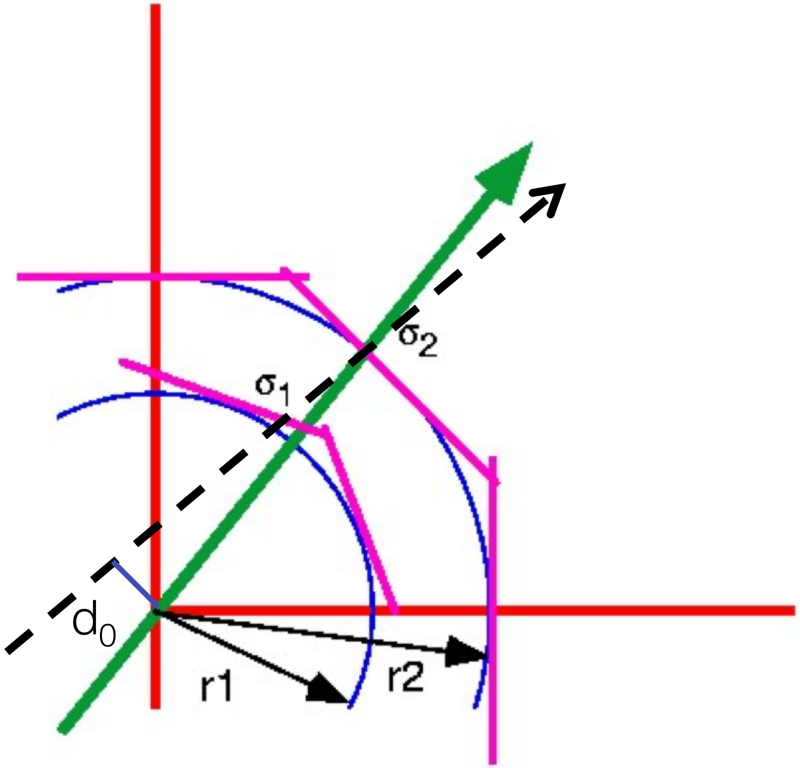




Impact parameter resolution

Uncertainty on the transverse impact parameter, d_0, depends on the radii and space point precision.

Simplified formula for just two layers:



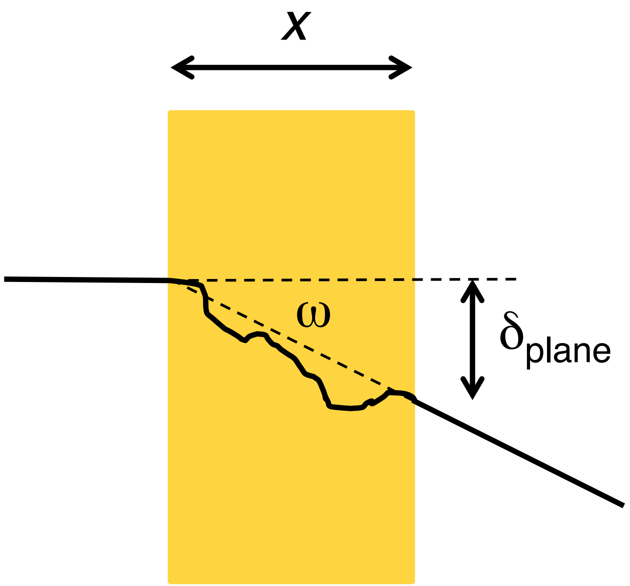
$$\sigma_{d_0}^2 = \frac{r_2^2\sigma_1^2 + r_1^2\sigma_2^2}{(r_2 - r_1)^2}$$

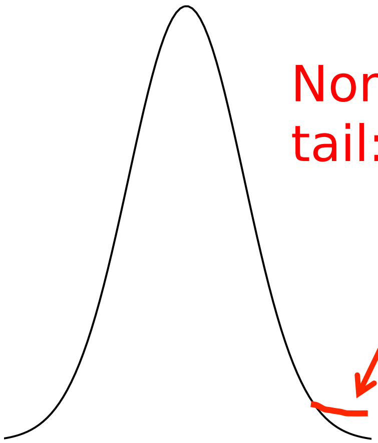
Suggests small r_1, large r_2, small σ_1, σ_2

But precision is degraded by multiple scattering…

Multiple Scattering

- Particle incident on a thin layer, fraction x/X_0 of a radiation length thick, is bent by angle ω





Non-Gaussian tail: $\sin^{-4}(\omega/2)$

- Distribution of ω is nearly Gaussian (central 98%)
- $d_0 = r \tan\omega \approx r\omega$

K. Nakamura et al. (PDG), J. Phys. G 37, 075021 (2010)

$$\sigma_{d_0} = \frac{r}{\beta c p} 13.6\,\mathrm{MeV} \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \log\left(\frac{x}{X_0}\right) \right]$$

- Higher momentum, p → less scattering
- Best precision with small radius, r, and minimum thickness x

Transverse IP resolution

For a track with $\theta \neq 90°$ $r \rightarrow \frac{r}{sin\theta}, \; x \rightarrow \frac{x}{sin\theta}$

Resulting in:

$$\sigma_{d_0} \approx \sqrt{\frac{r_2^2\sigma_1^2 + r_1^2\sigma_2^2}{(r_2 - r_1)^2}} \oplus \frac{r}{p \sin^{3/2}\theta} 13.6\mathrm{MeV} \sqrt{\frac{x}{X_0}}$$

$$\sigma_{d_0} \approx a \oplus \frac{b}{p_T \sin^{1/2}\theta}$$

Constant term depending only on geometry

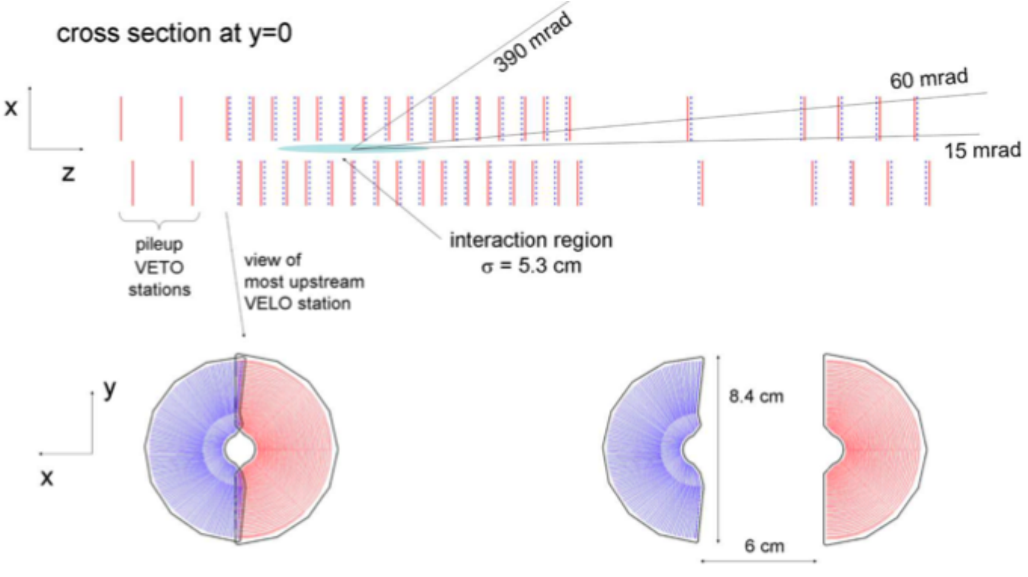
and term depending on material, decreasing with p_T

Summary of pixel barrel layouts

	ALICE	**ATLAS**	**CMS**
Radii (mm)	39 – 76	50.5 – 88.5 – 122.5	44 – 73 – 102
Pixel size *r*ϕ x *z* (μm^2)	50 x 425	40 x 400	100 x 150
Thickness (μm)	200	250	285
Resolution *r*ϕ / *z* (μm)	12 / 100	10 / 115	~15-20
Channels (million)	9.8	80.4	66
Area (m^2)	0.2	1.8	1

The LHCb VELO: forward geometry strip detector with 42 stations along, inner radius of 7 mm.

Moves close to beam when conditions are stable.

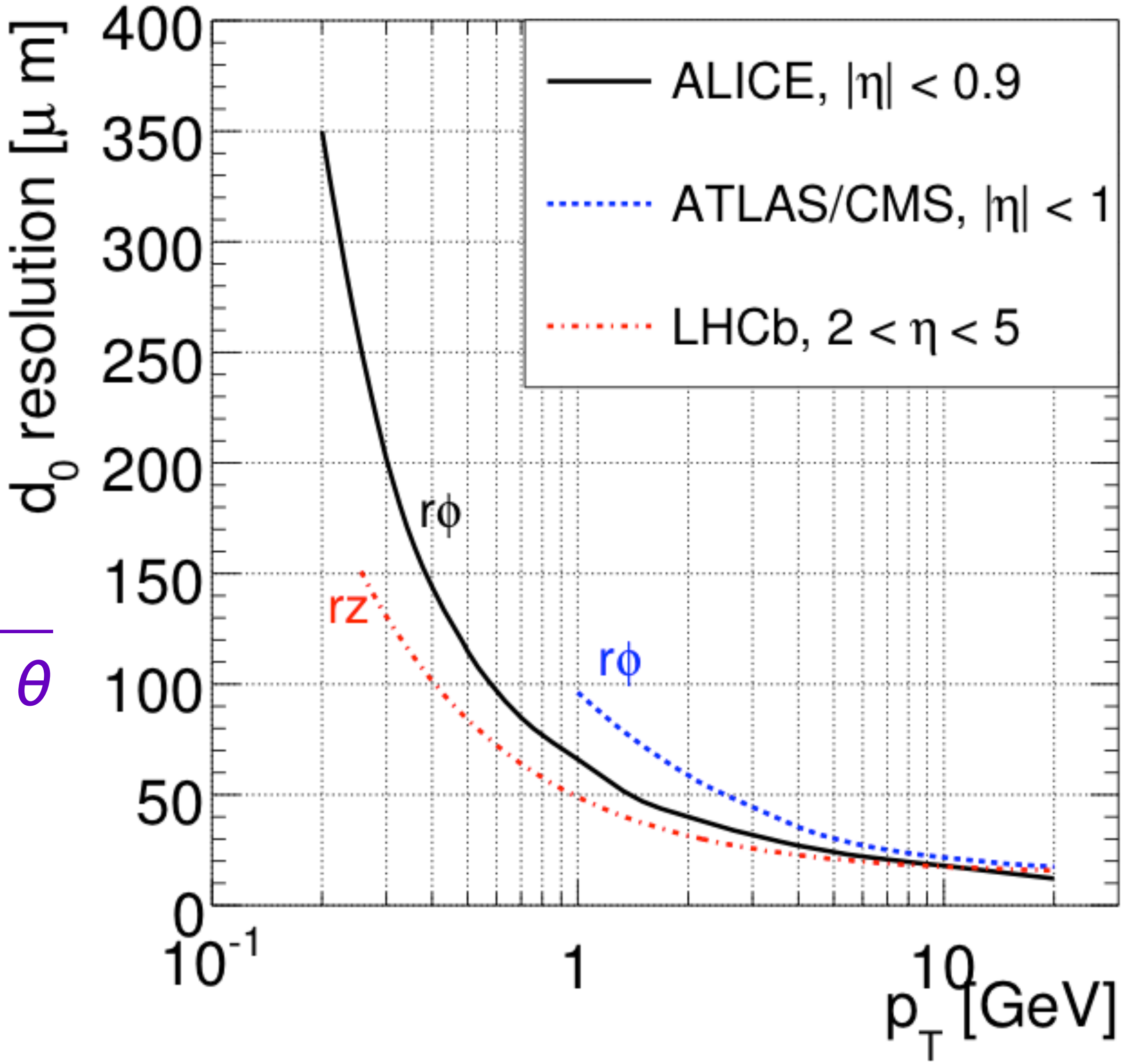


VELO fully closed
(stable beam)

VELO fully open

IP resolutions

S.Alekhin et al. HERA and the LHC - A workshop on the implications of HERA for LHC physics:Proceedings Part B, arXiv:hep-ph/0601013.



LHCb in rz

For the rest:

$$\sigma_{d_0} \approx a \oplus \frac{b}{p_T \sin^{1/2}\theta}$$

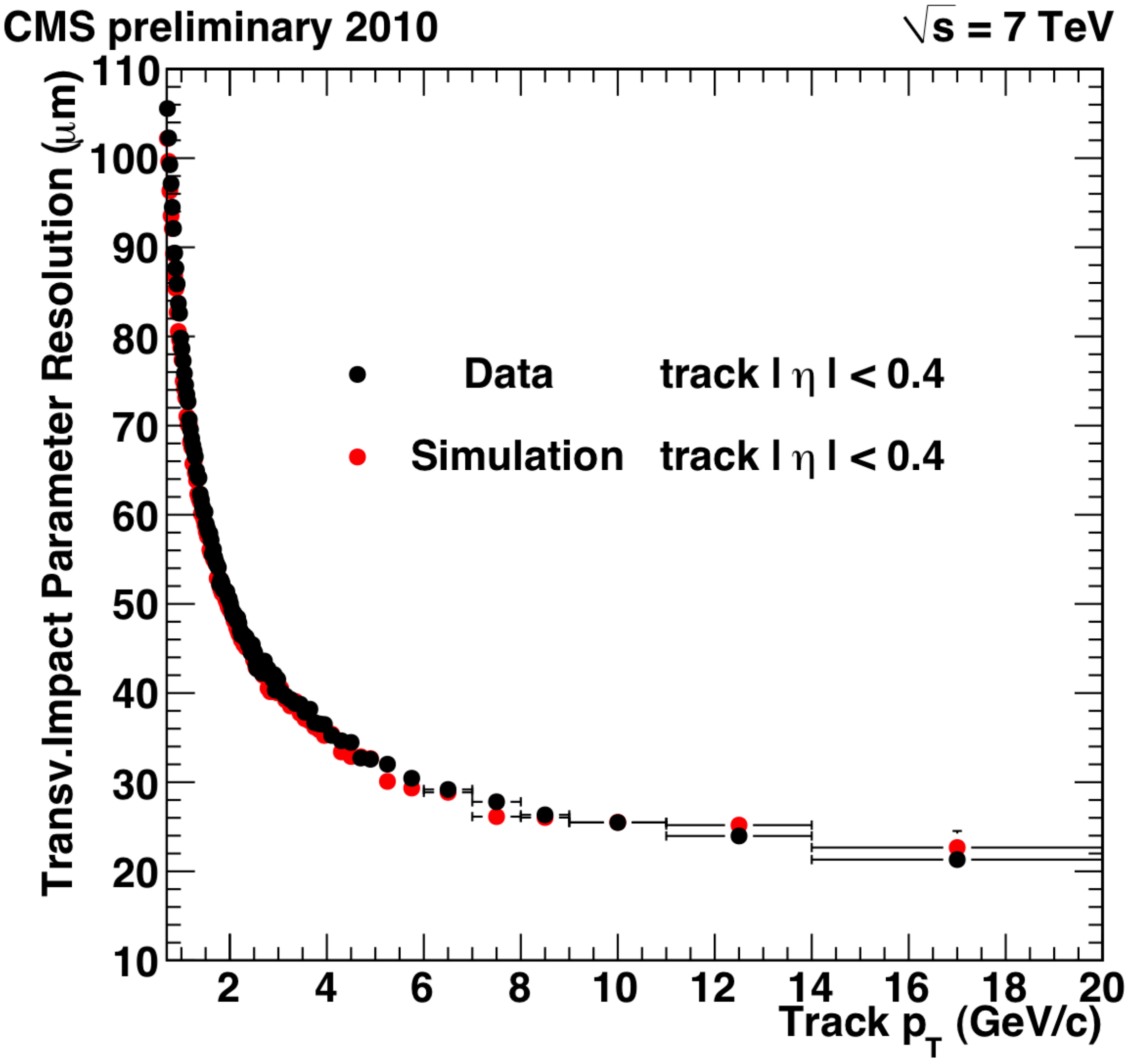
ATLAS/CMS expect:

100 μm @ 1 GeV,

20 μm @ 20 GeV

IP resolutions

CMS-PAS-TRK-10-005



$$\sigma_{d_0} \approx a \oplus \frac{b}{p_T \sin^{1/2}\theta}$$

Observed:

100 μm @ 1 GeV,

20 μm @ 20 GeV

Momentum measurement & tracker layout

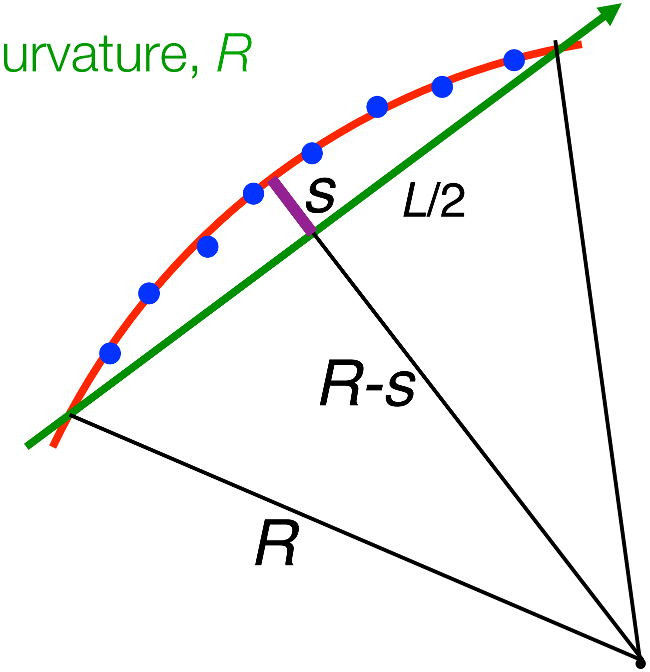
Measuring momentum

- Circular motion transverse to uniform B field:

$$p_T[\mathrm{GeV/c}] = 0.3 \cdot B[\mathrm{T}] \cdot R[\mathrm{m}]$$

- Measure sagitta, *s*, from track arc → curvature, *R*

$$R = \frac{L^2}{2s} + \frac{s}{2} \approx \frac{L^2}{2s}$$



- $$\frac{\sigma_{p_T}}{p_T} = \frac{8p_T}{0.3BL^2}\sigma_s$$

- Relative momentum uncertainty is proportional to p_T times sagitta uncertainty, σ_s. Also want strong B field and long path length, *L*

Measuring momentum

Sagitta uncertainty, σ_s, from N points, each with resolution $\sigma_{r\phi}$ is:

$$\sigma_s = \sqrt{\frac{A_N}{N+4}}\frac{\sigma_{r\phi}}{8}$$

Statistical factor $A_N = 720$:

(Gluckstern)

The point error, $\sigma_{r\phi}$, has a constant part from intrinsic precision, and a multiple scattering part.

Multiple scattering contribution:

(*L* is in the transverse plane)

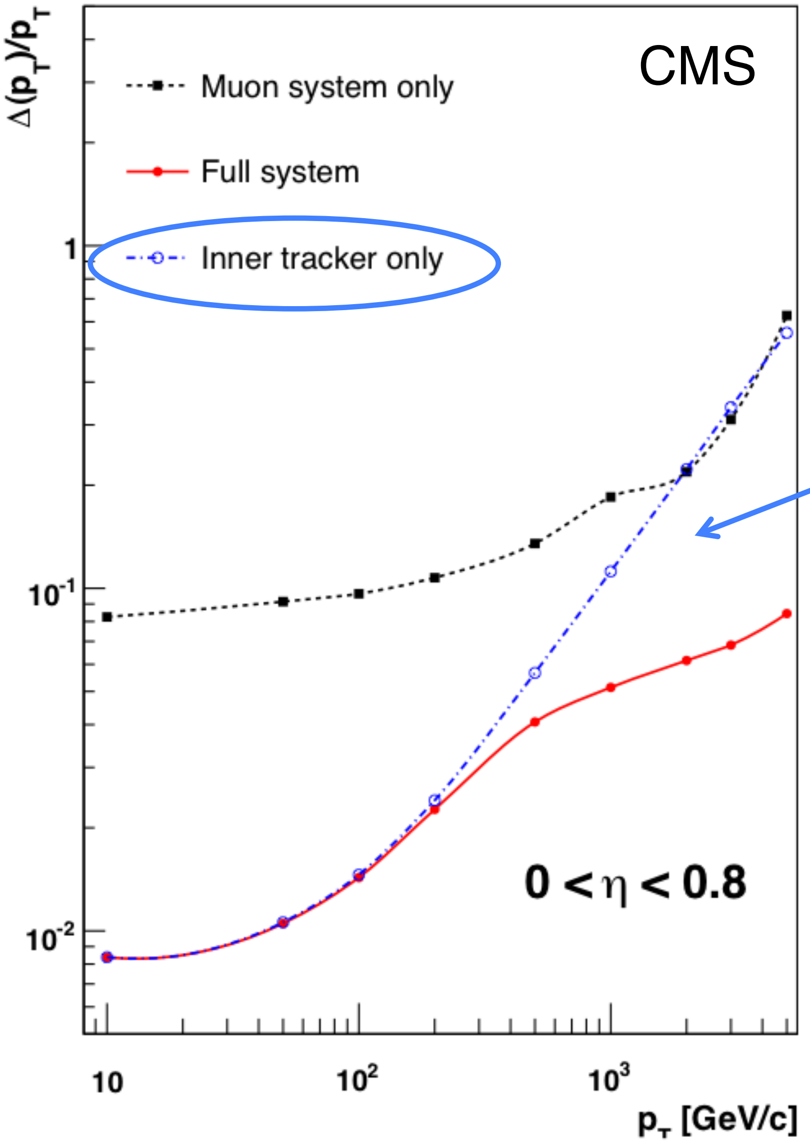
$$\sigma_s \propto \frac{L}{p_T \sin^{1/2}\theta}\sqrt{\frac{L}{X_0}}$$

$$\frac{\sigma_{p_T}}{p_T} = \frac{8p_T \cdot \sigma_s}{0.3BL^2} \approx a \cdot p_T \oplus \frac{b}{\sin^{1/2}\theta}$$

Momentum resolution

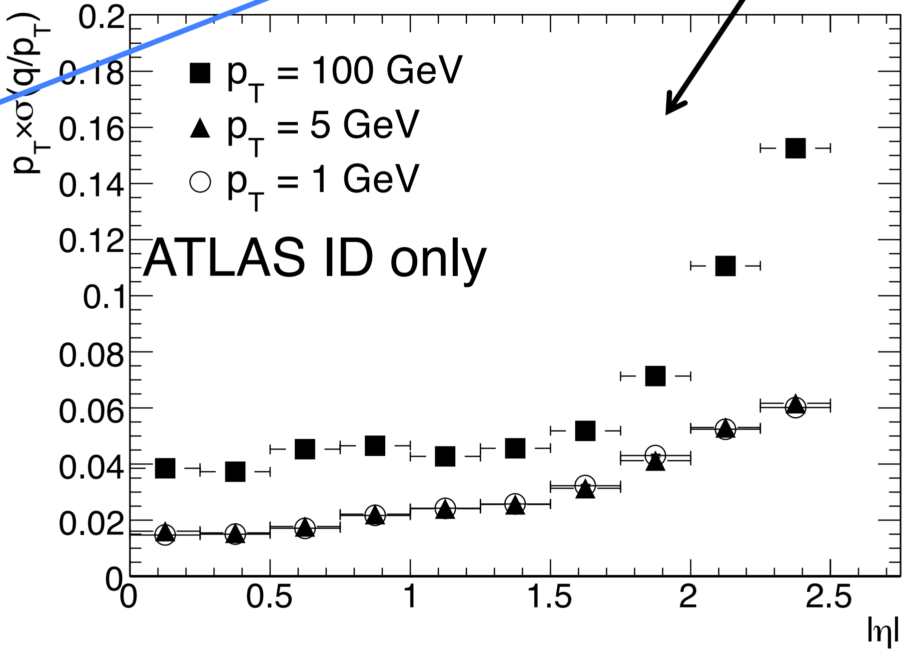
2008 JINST 3 S08004 CMS Experiment

2008 JINST 3 S08003 ATLAS Experiment



Expected relative p_T resolution for muons vs $|\eta|$ and p_T.

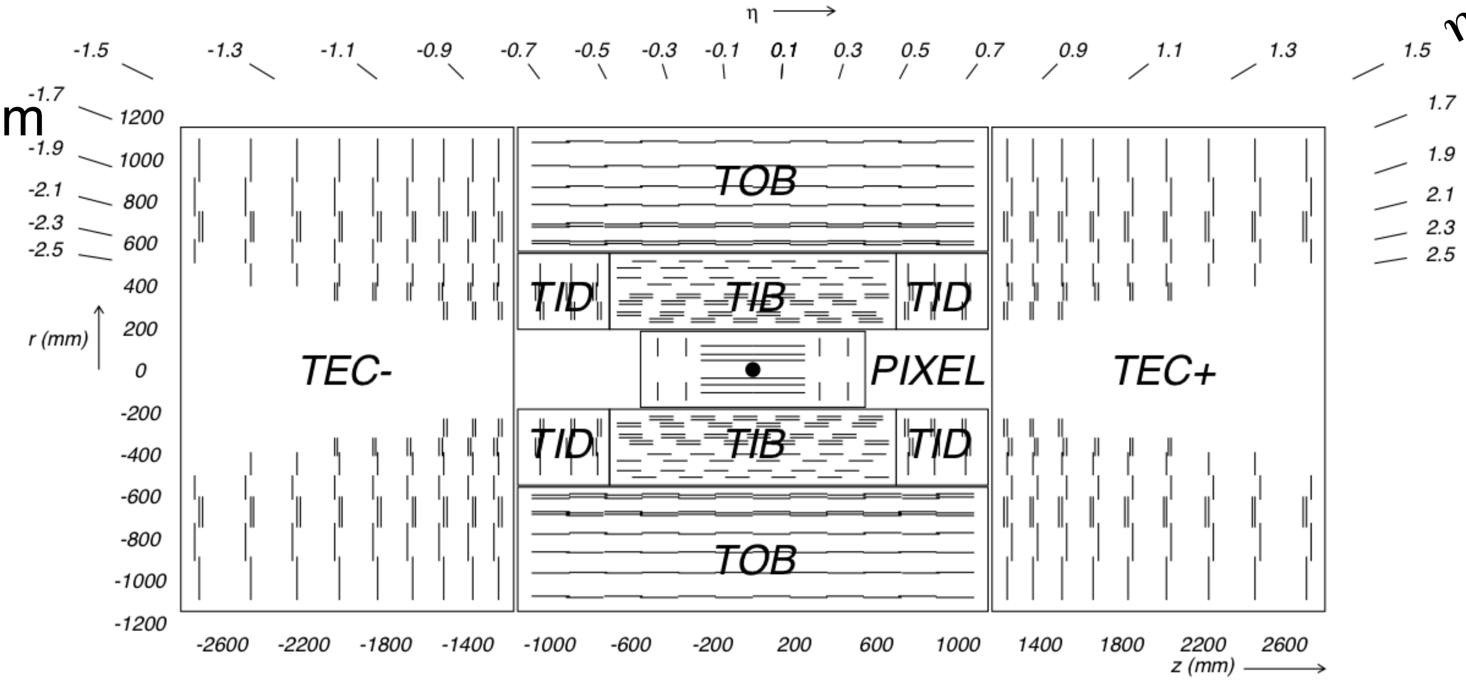
$$\frac{\sigma_{p_T}}{p_T} \approx a \cdot p_T \oplus \frac{b}{\sin^{1/2}\theta}$$



(More material) →

CMS tracker layout

- Silicon Barrels and Disks (including End-Cap disks)

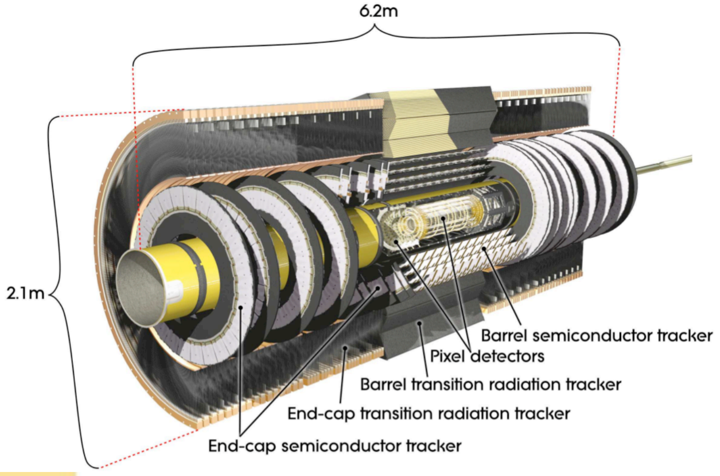


η=1.5

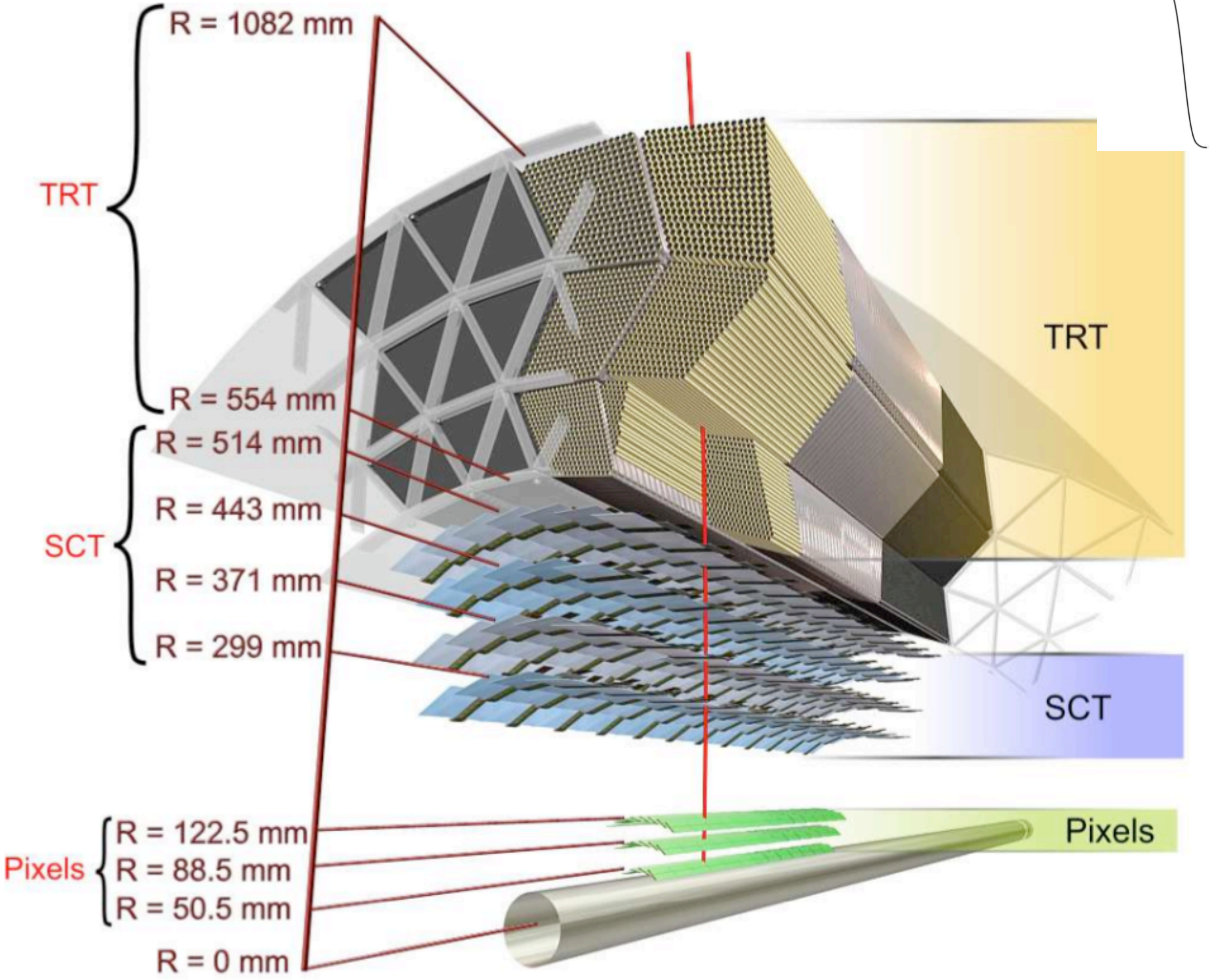
r=1.2m

- Barrels have 3 pixel layers and 10 microstrip layers
  - Inner strips 10cm x 80 to 120 μm (320 μm thick)
  - Outer strips 25cm x 180 to 120 μm (500 μm thick for S/N)
  - 4 strip layers have additional stereo module for z coordinate

ATLAS ID



Expanded view of barrel



Barrel track passes:

~36 TRT 4mm straws (Transition Radiation Tracker – gas detector)

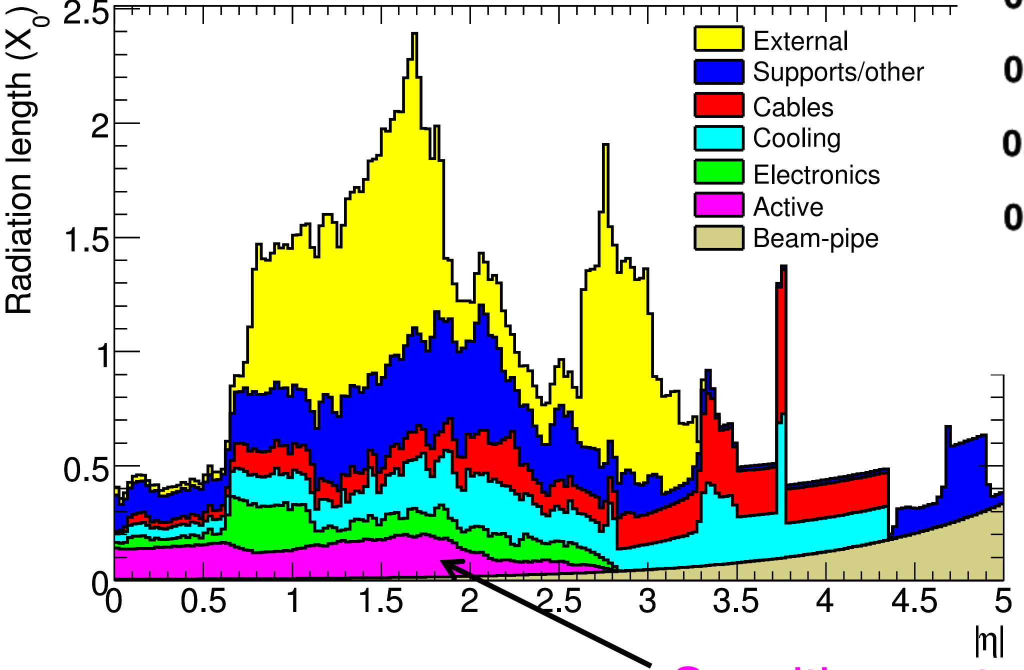
4x2 Si strips on stereo modules12cm x 80 μm, 285μm thick

3 pixel layers, 250μm thick

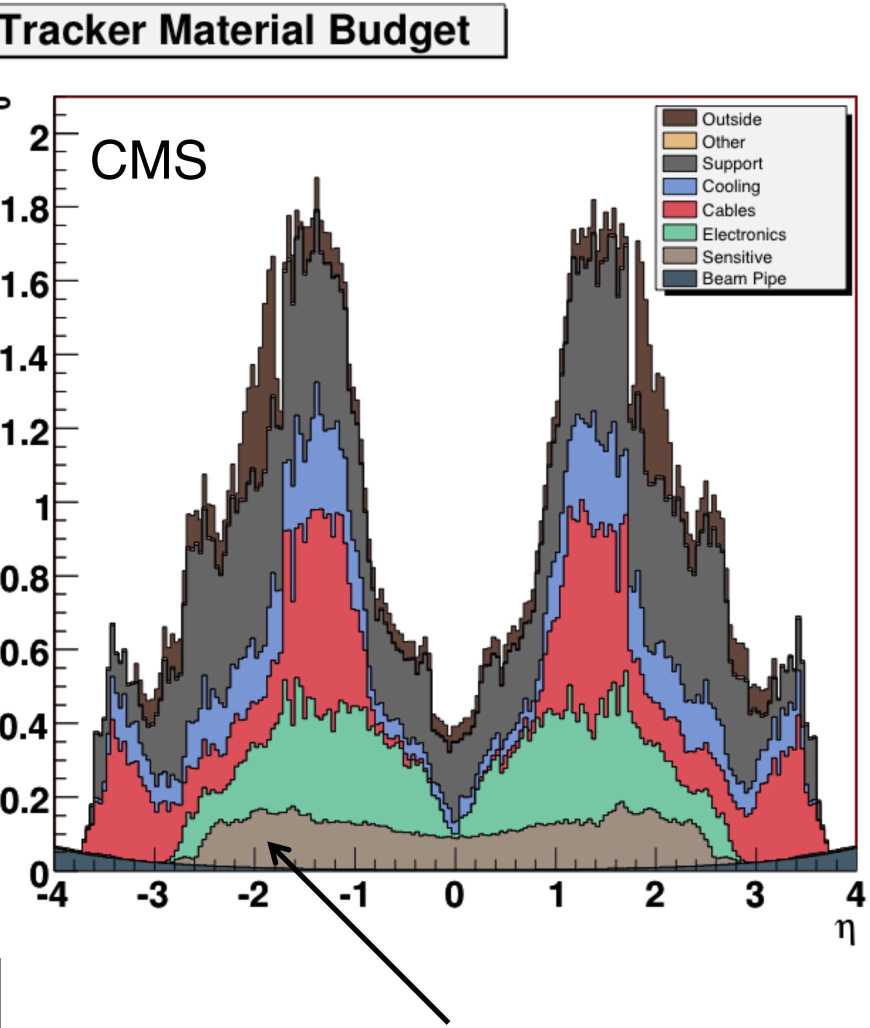
Material

Big contributions from supports, cables, cooling, electronics…

ATLAS Inner Detector



Sensitive material



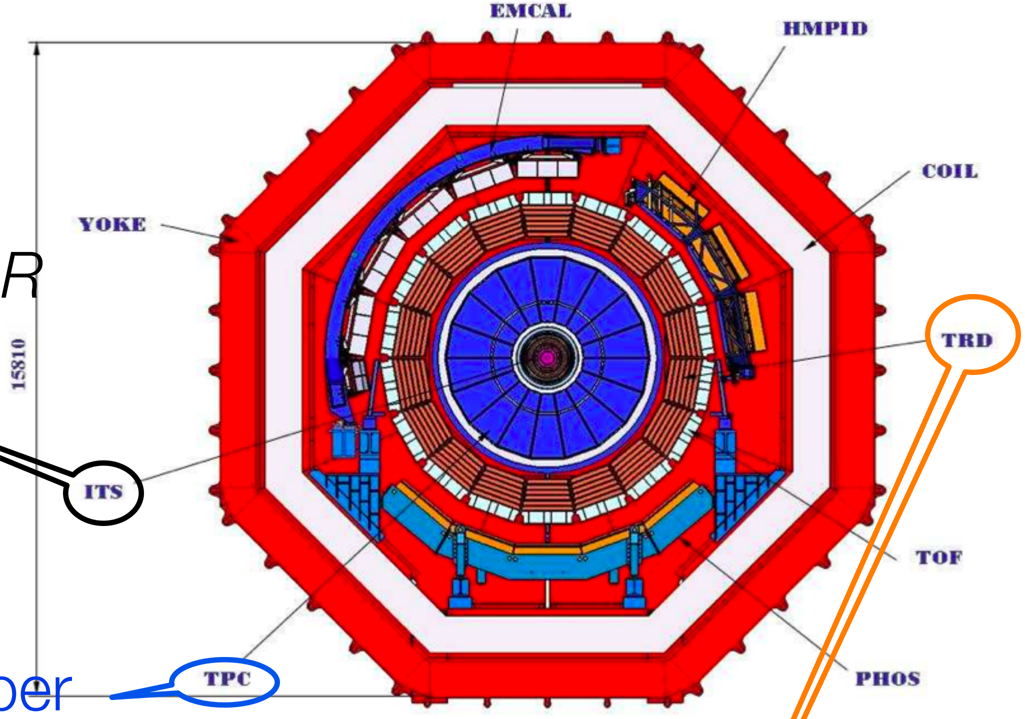
Sensitive material

2008 JINST 3 S08004 CMS Experiment

2008 JINST 3 S08003 ATLAS Experiment

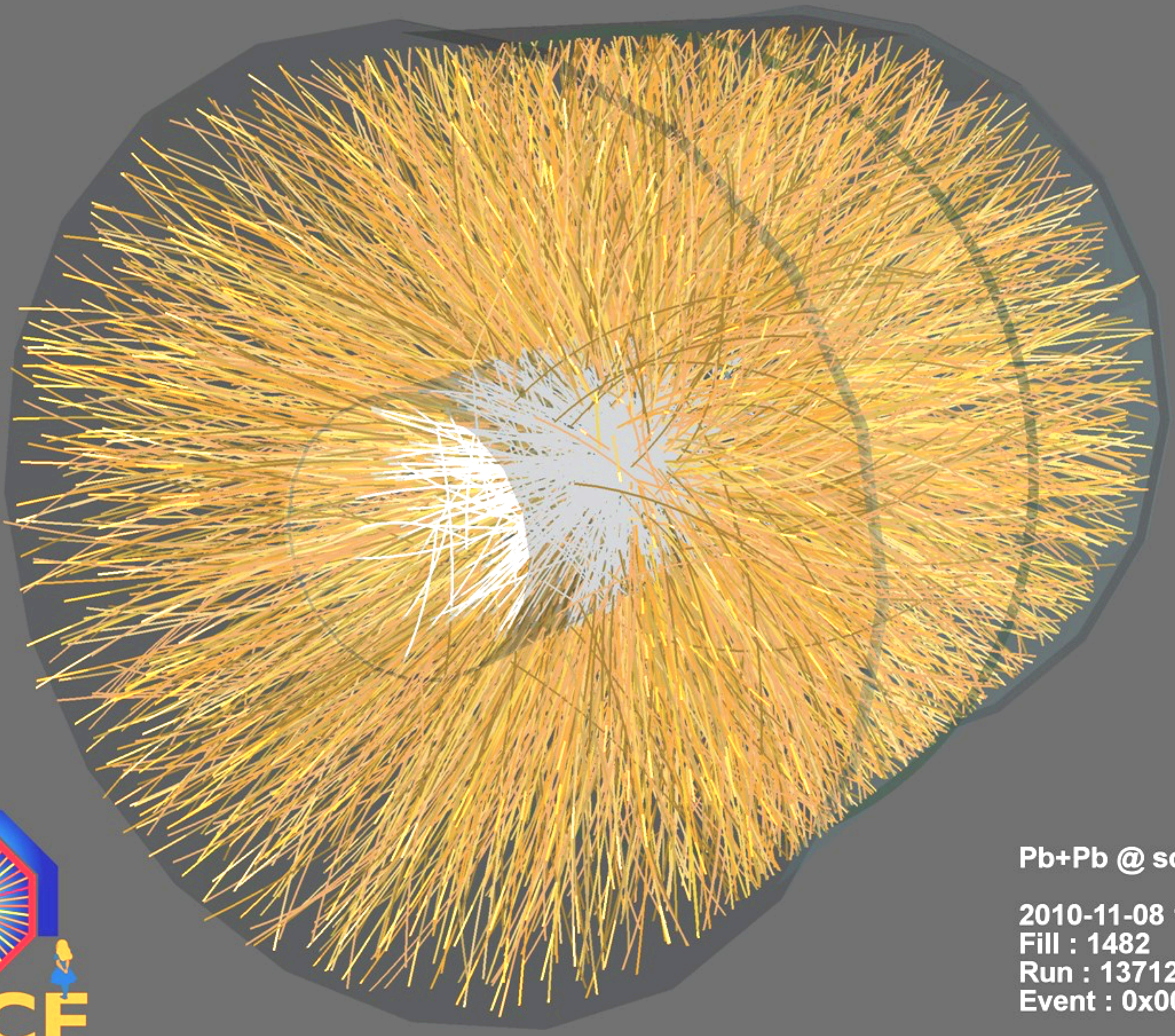
ALICE

- Lower *B* (0.5 T), larger *R*
- ITS – 6 layers
  - 2 pixels
  - 2 silicon drift
  - 2 double sided strips
- Time Projection Chamber
  - Large volume gas detector with central electrode
  - MWPC with cathode pad readout in end plates
  - Very good two-track resolution
  - Very low material in active region
- Transition Radiation Detector
  - Electron ID, and improves momentum resolution
  - Outer radius 3.7m



2008 JINST 3 S08002 ALICE Experiment

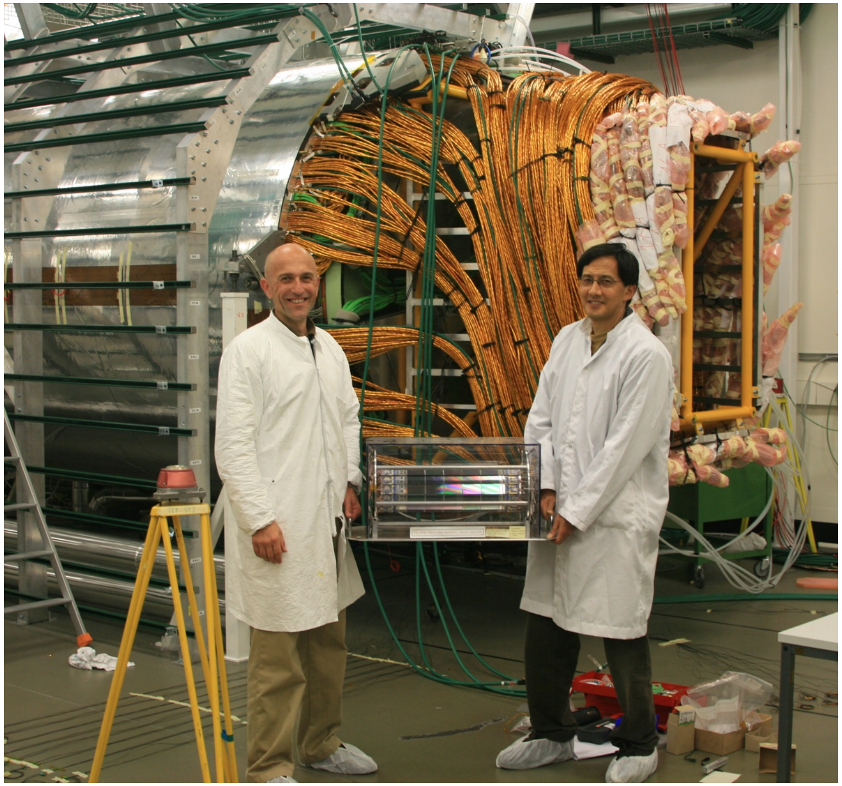
ALICE heavy ion event display



Pb+Pb @ sqrt(s) = 2.76 ATeV

2010-11-08 11:30:46
Fill : 1482
Run : 137124
Event : 0x00000000D3BBE693

CMS Tracker & ALICE TPC



(plus a LEP silicon detector!)

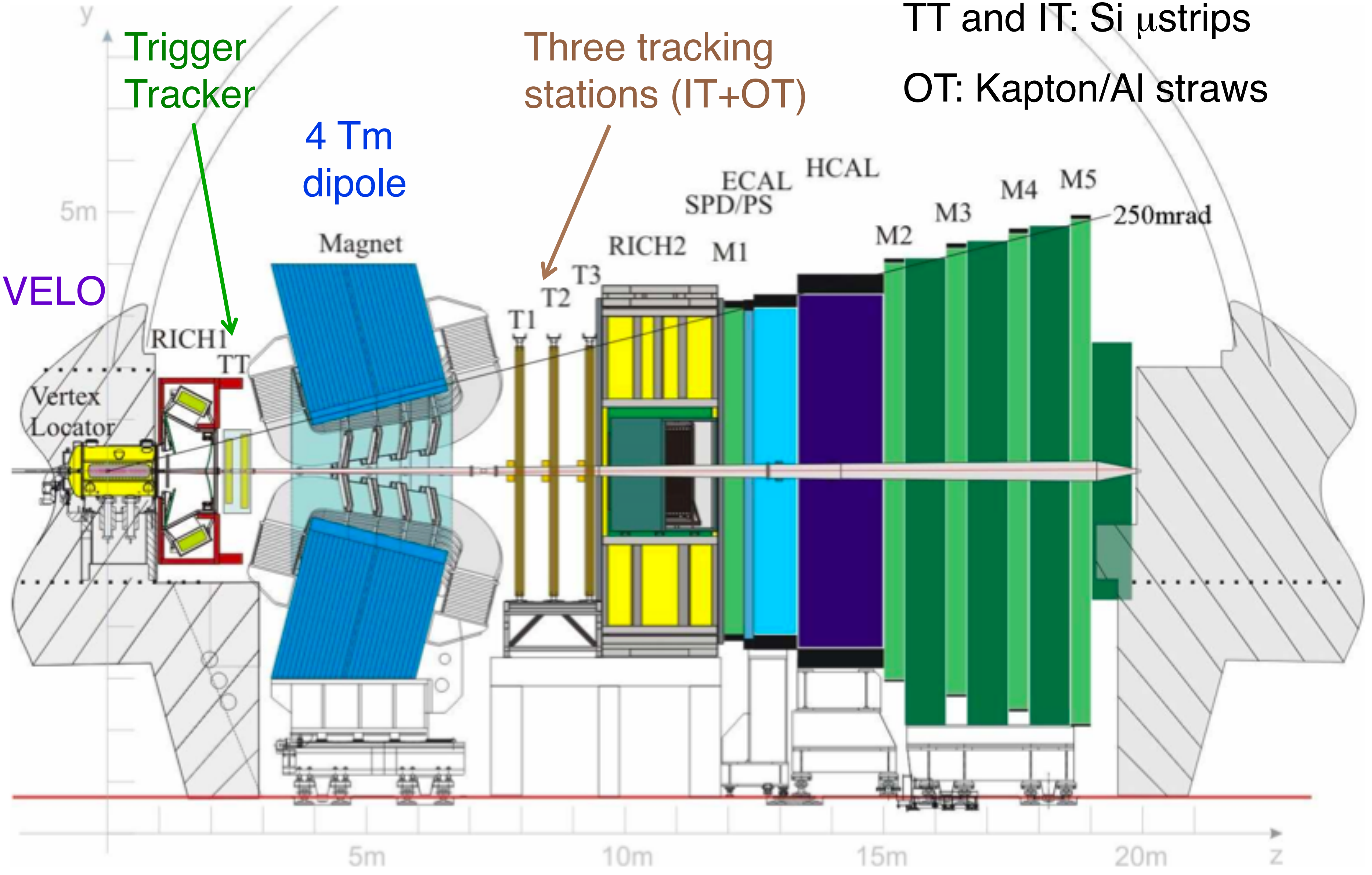
2008 JINST 3 S08005 LHCb Detector

LHCb tracking

VELO: rφ Si strips

TT and IT: Si μstrips

OT: Kapton/Al straws



Comparison of (barrel) tracker layouts

	ALICE	**ATLAS**	**CMS**
R inner	3.9 cm	5.0 cm	4.4 cm
R outer	3.7 m	1.1 m	1.1 m
Length	5 m	5.4 m	5.8 m
$\vert\eta\vert$ range	0.9	2.5	2.5
B field	0.5 T	2 T	4 T
Total X_0 near $\eta=0$	0.08 (ITS) + 0.035 (TPC) + 0.234 (TRD)	0.3	0.4
Power	6 kW (ITS)	70 kW	60 kW
$r\phi$ resolution near outer radius	~ 800 μm TPC ~ 500 μm TRD	130 μm per TRT straw	35 μm per strip layer
p_T resolution at 1GeV and at 100 GeV	0.7% 3% (in pp)	1.3% 3.8%	0.7% 1.5%

Summary - Precision of trackers

- Intrinsic space point resolution
  - Sensor design (pixels, strips, gas detectors…)
- Magnetic field
  - Strength, and precise knowledge of value
- Alignment
  - Assembly precision, survey, stability
  - Measure the positions of detector elements with the tracks themselves
  - Control systematic effects
- Multiple scattering and other interactions
  - Minimise the material
  - Measure the amount of material in order to simulate the detector and reconstruct tracks correctly
  - Also affects energy measurement in calorimeter

Material and alignment

Weighing detectors before construction

Keep track of all the parts, big and small.

Weigh them, and know what material they are made of.

ATLAS SCT end cap PEEK harness clips:

weight 0.125 g

length ~1cm

2101 used per end cap

Weighing detectors during construction

Weigh assembled parts where possible, to cross check.

eg. Measured ATLAS TRT, and TRT+SCT after insertion.

Compare the weighing methods…

- Measured weight (from weighing complete detector)
- Estimated weight from adding up all the parts
- Simulated weight – as implemented in Monte Carlo description

Detector	Measured weight (kg)	Estimated weight (kg)	Simulated weight (kg)
SCT barrel	201± 20	222 ± 6	222
TRT barrel	707± 20	703 ± 3	700
SCT+TRT barrel	883 ± 20	925 ± 7	922
SCT end-cap A	207 ± 10	225 ± 10	225
SCT end-cap C	172 ± 10	225 ± 10	225
TRT end-cap A	1118 ± 12	1129 ± 10	1131
TRT end-cap C	1120 ± 12	1129 ± 10	1131
Pixel barrel		20.1	18.3
Pixel package	193.5 ± 5	201	197

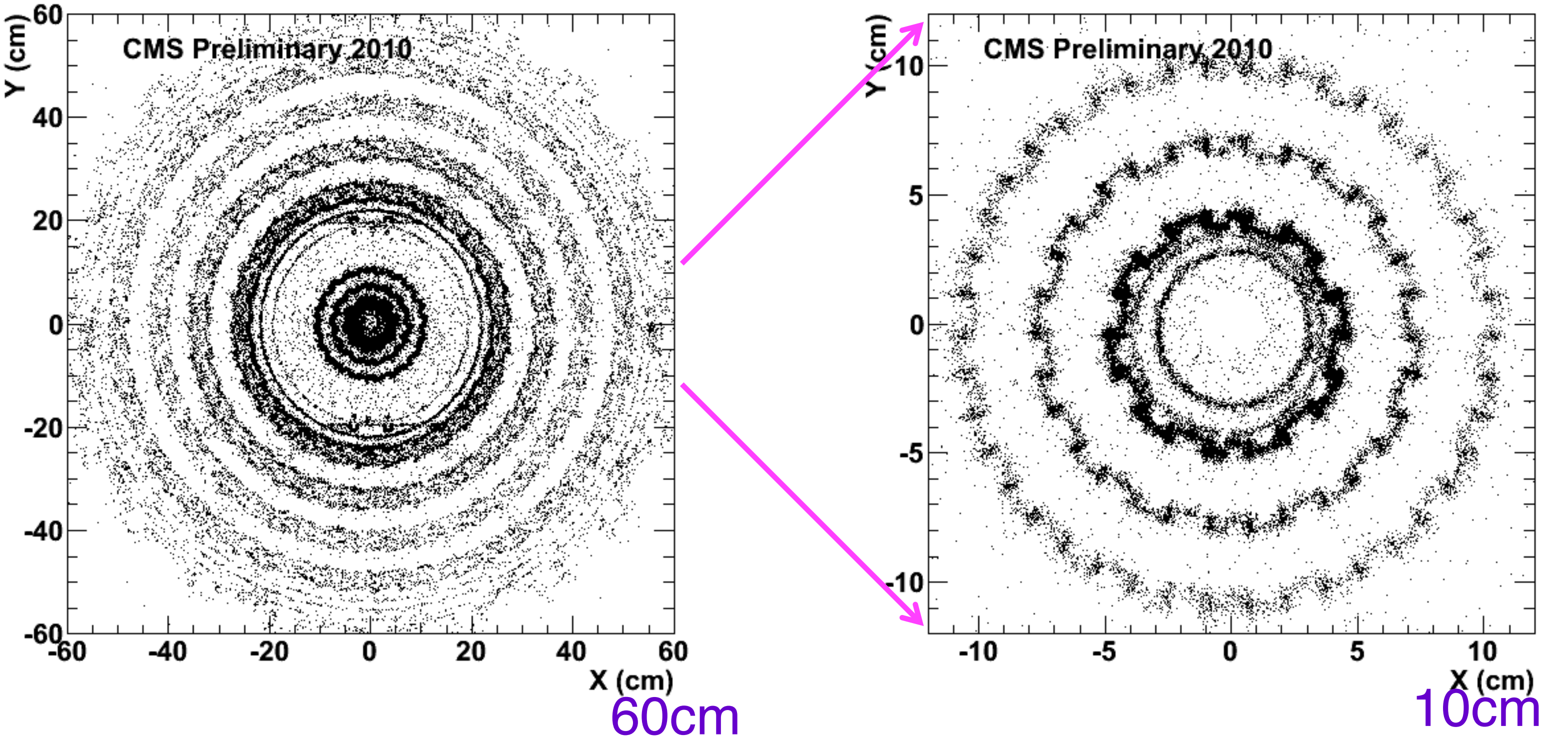
Weighing detectors after construction

- Central trackers are buried inside the experiments
- Identify material interactions to assess material, eg.
  - Photon conversions
  - Nuclear interactions
  - Stopping tracks (track ends when particle interacts)
- Have to disentangle effects of
  - Material
  - Alignment
  - Magnetic field map
  - → Effects on momentum measurements which distort the measured masses and width of particles, (K^0_s, J/ψ, Z…) or give systematic +/- charge differences
- In general, compare real data with detailed GEANT 4 simulation based on design, and gradually refined

CMS-PAS-TRK-10-003

Photon conversions

- Conversions, $\gamma \rightarrow e^+e^-$, example from CMS
  - Two oppositely charged tracks
  - Consistent with coming from the same point
  - Consistent with fit to a common vertex, imposing zero mass

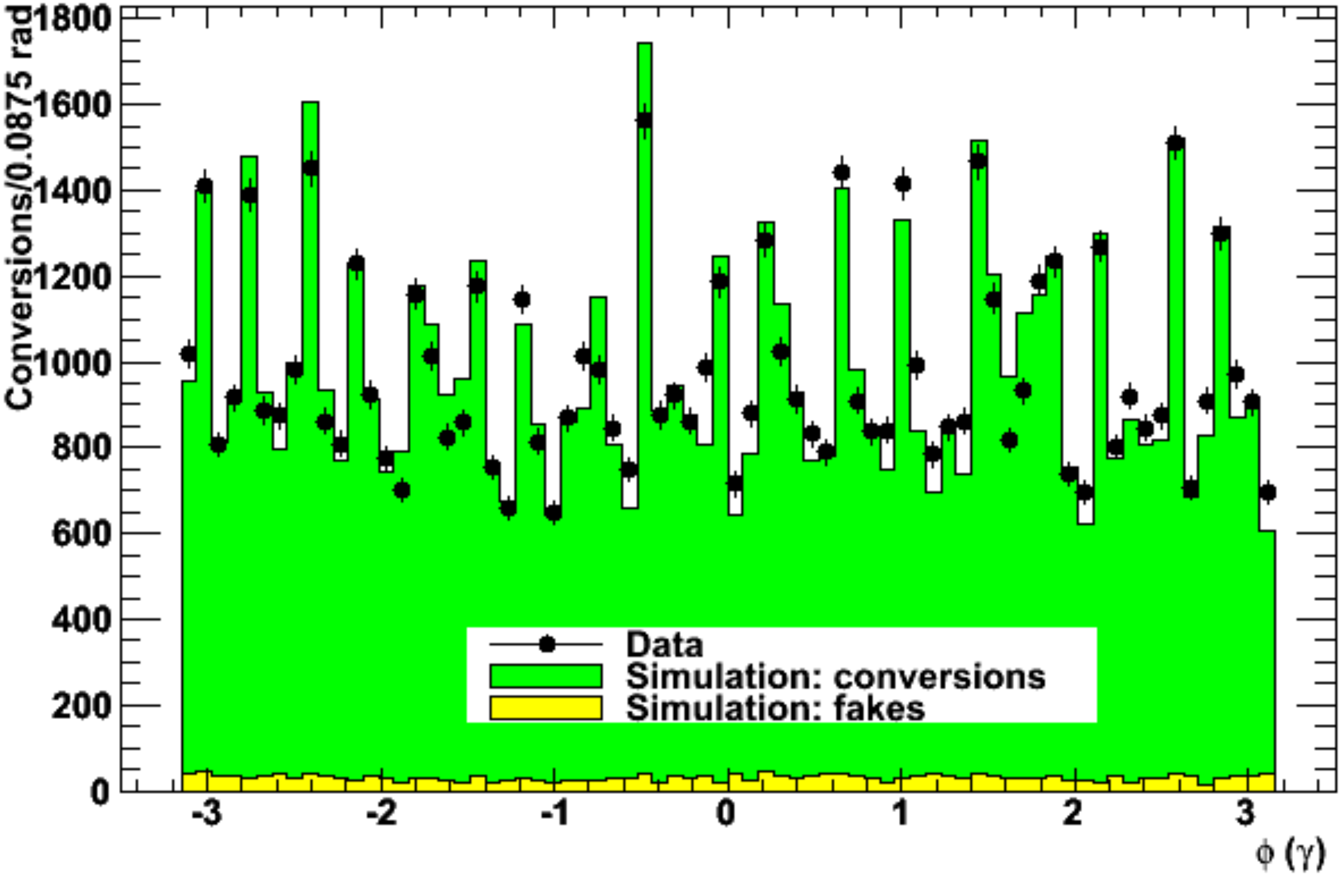


60cm

10cm

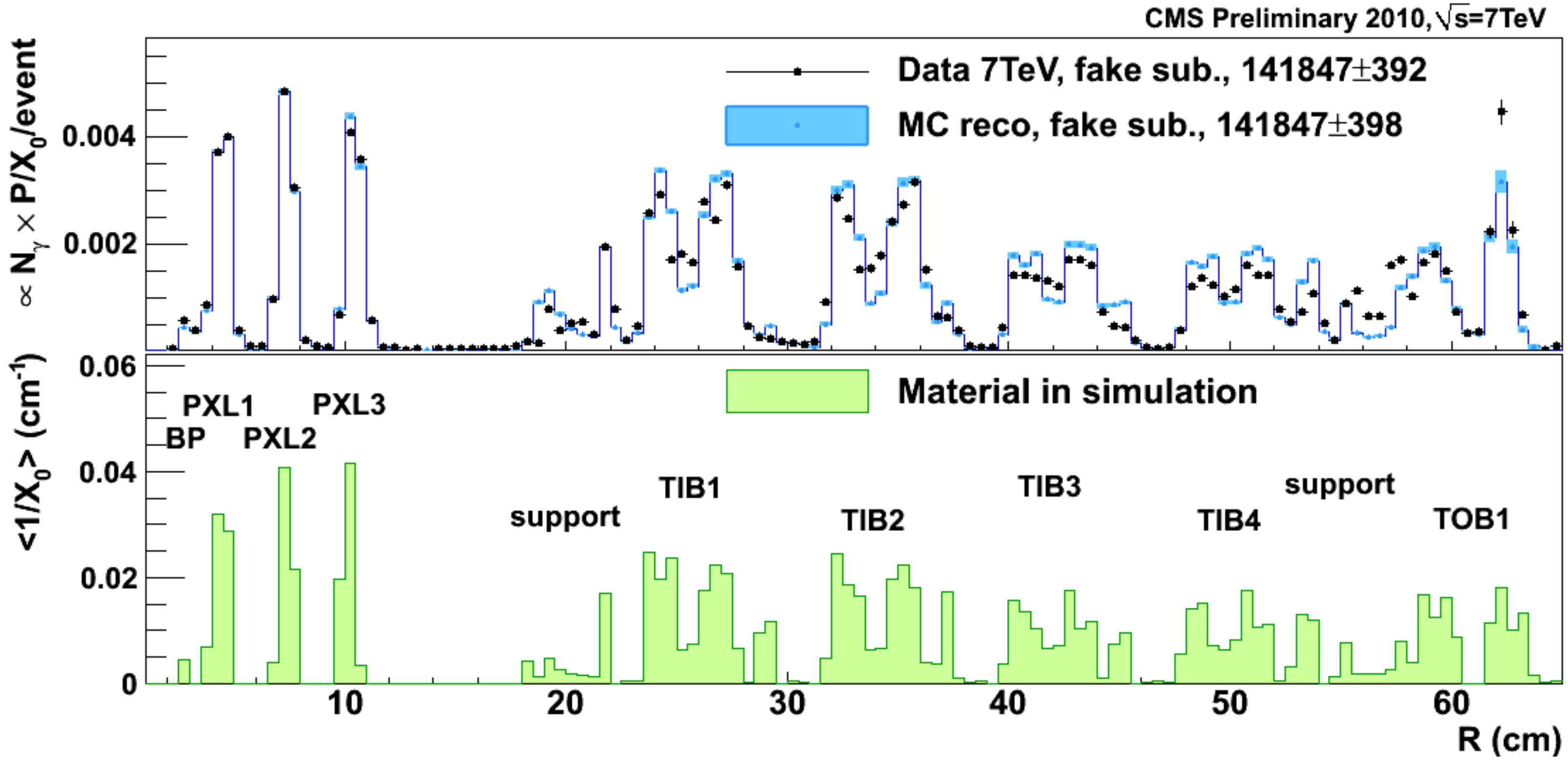
CMS conversions in pixel barrel

- ϕ distribution for conversions with $|z| < 26$cm, $R < 19$cm
- → Compare pixel barrel structure in data and simulation
- Spikes due to cooling pipes



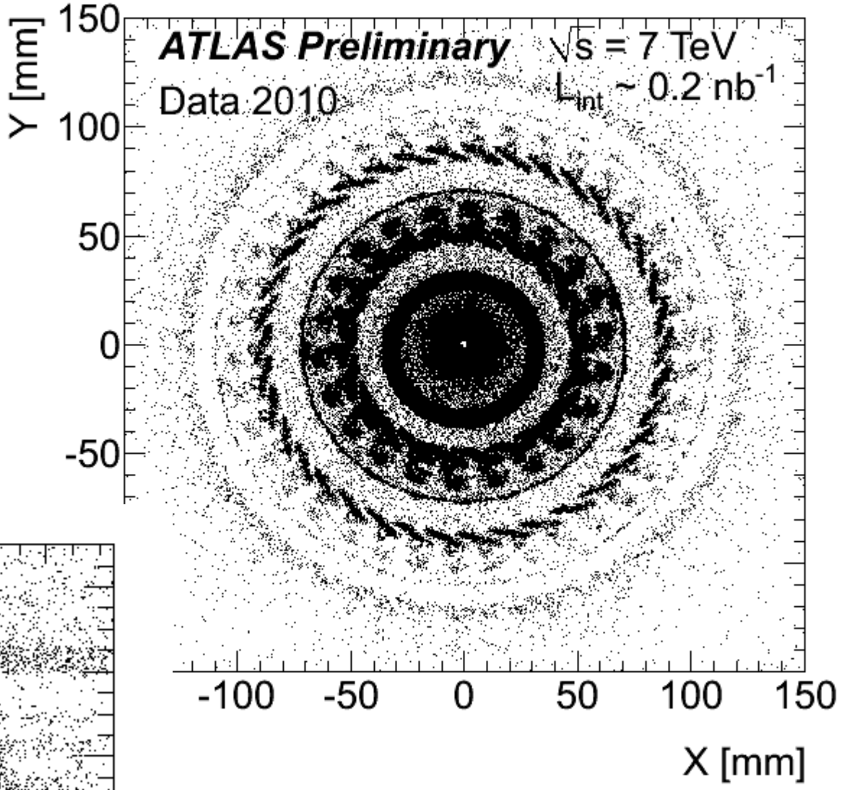
CMS conversions

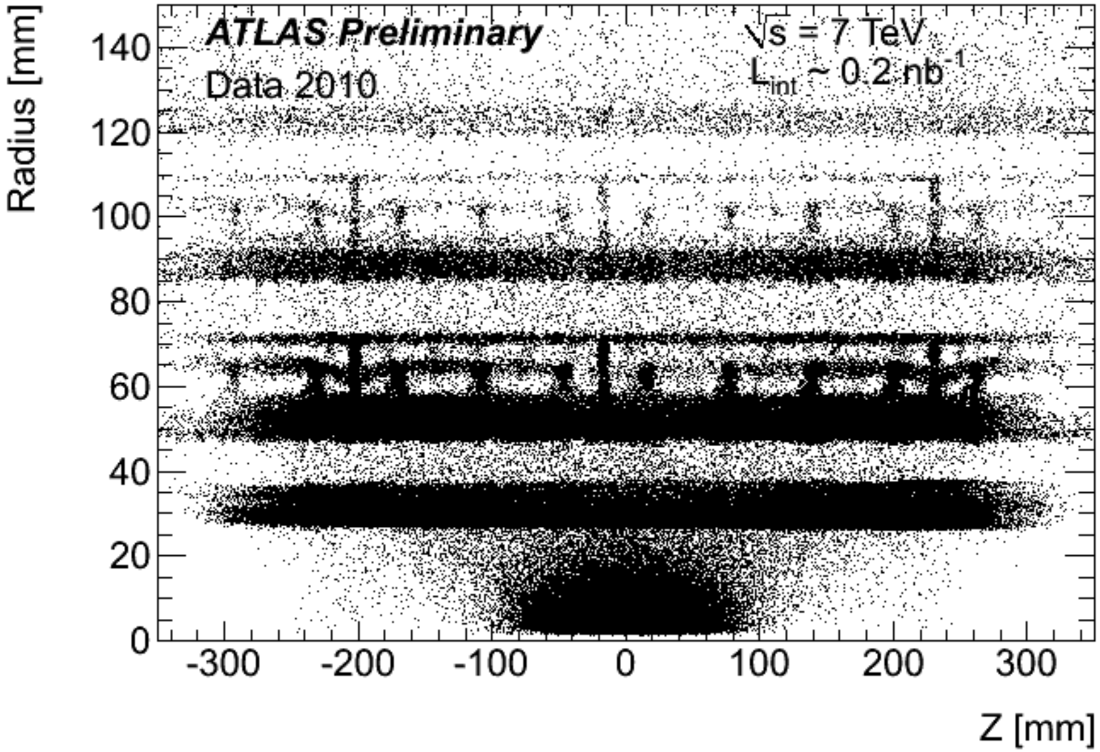
- Correct for identification efficiency to make a quantitative measurement of pixel and inner tracker barrel material
- Relative agreement between data and simulation ~10%
- Local discrepancy for support between TIB and TOB



Nuclear interactions

- ATLAS example
  - Tracks with d_0>2mm w.r.t PV
  - Form secondary vertices
  - Mass veto for γ, K^0_s, Λ



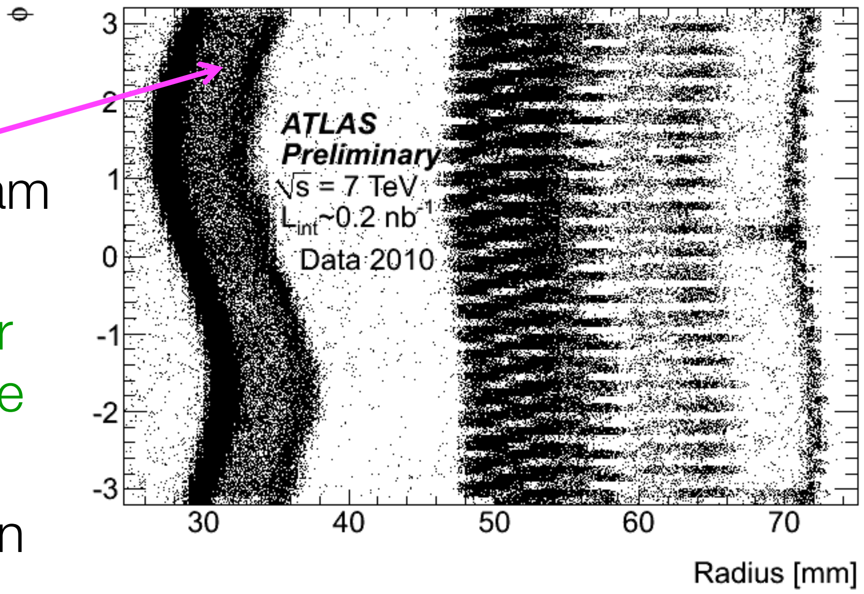


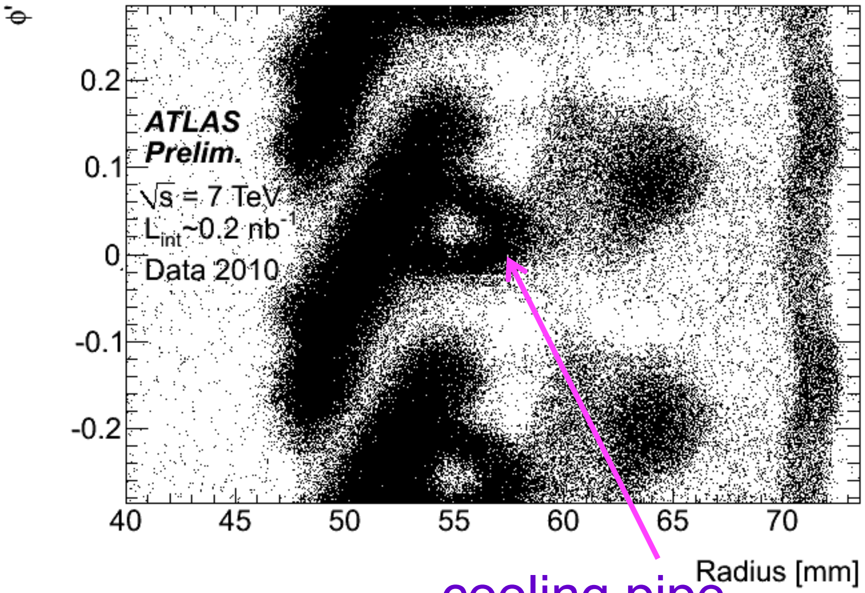
- x-y view for |z|< 300mm
- Sensitive to interaction lengths instead of radiation lengths

ATLAS-CONF-2010-058

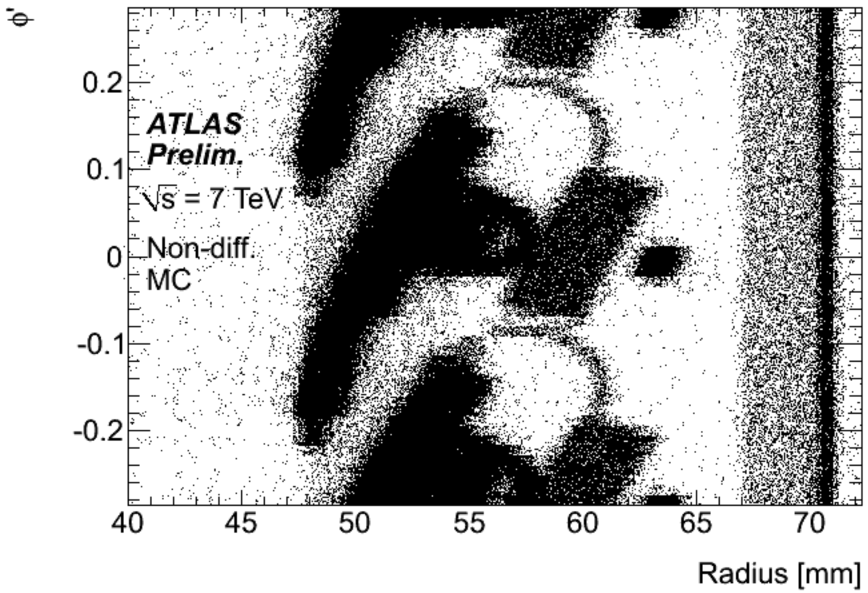
Interactions rϕ plots

- Full ϕ range shows displaced beam pipe(i.e. r varies with ϕ)
- Zoom in, and plot pixel inner layer local ϕ (i.e. pile all modules on one picture)
- Some features more spread out in data than MC.





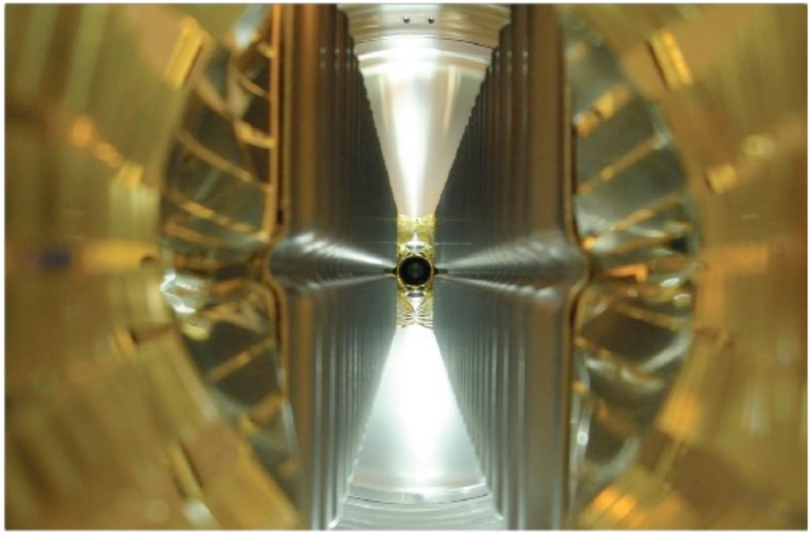
cooling pipe

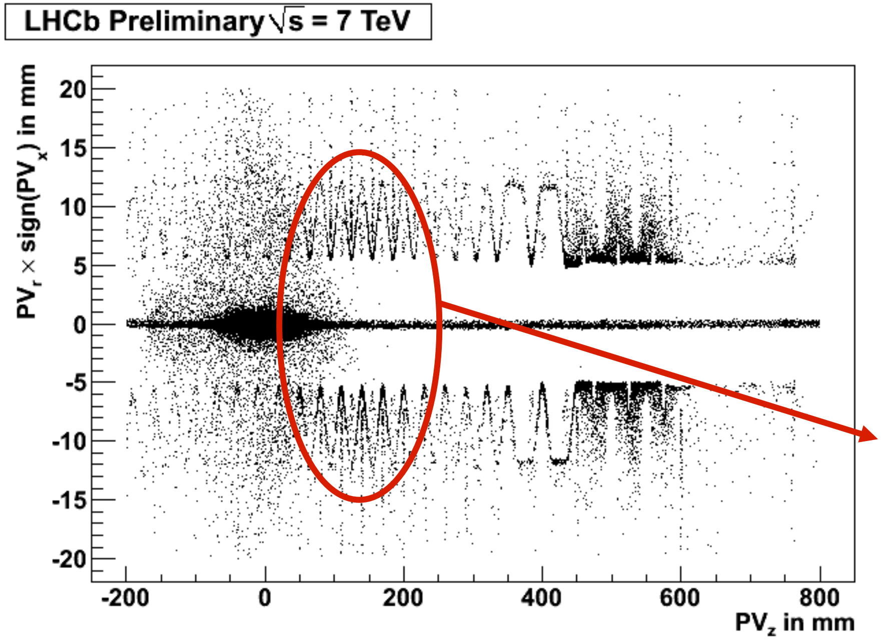


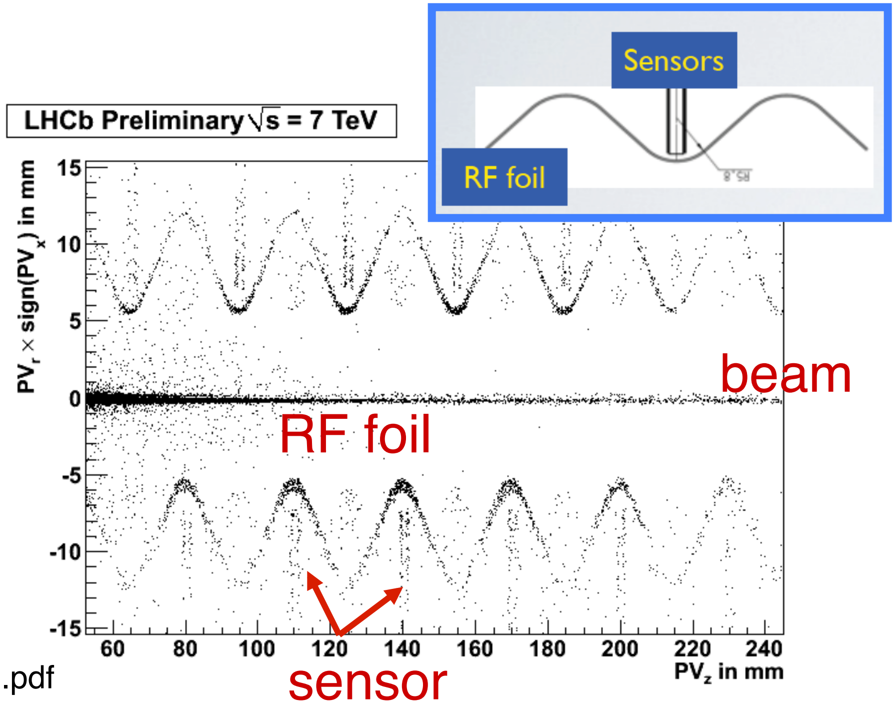
LHCb VELO material

- 2.4M vertices in plot
- ~20k from material interactions
- Require ≥3 tracks per vertex

RF foil photo with VELO open



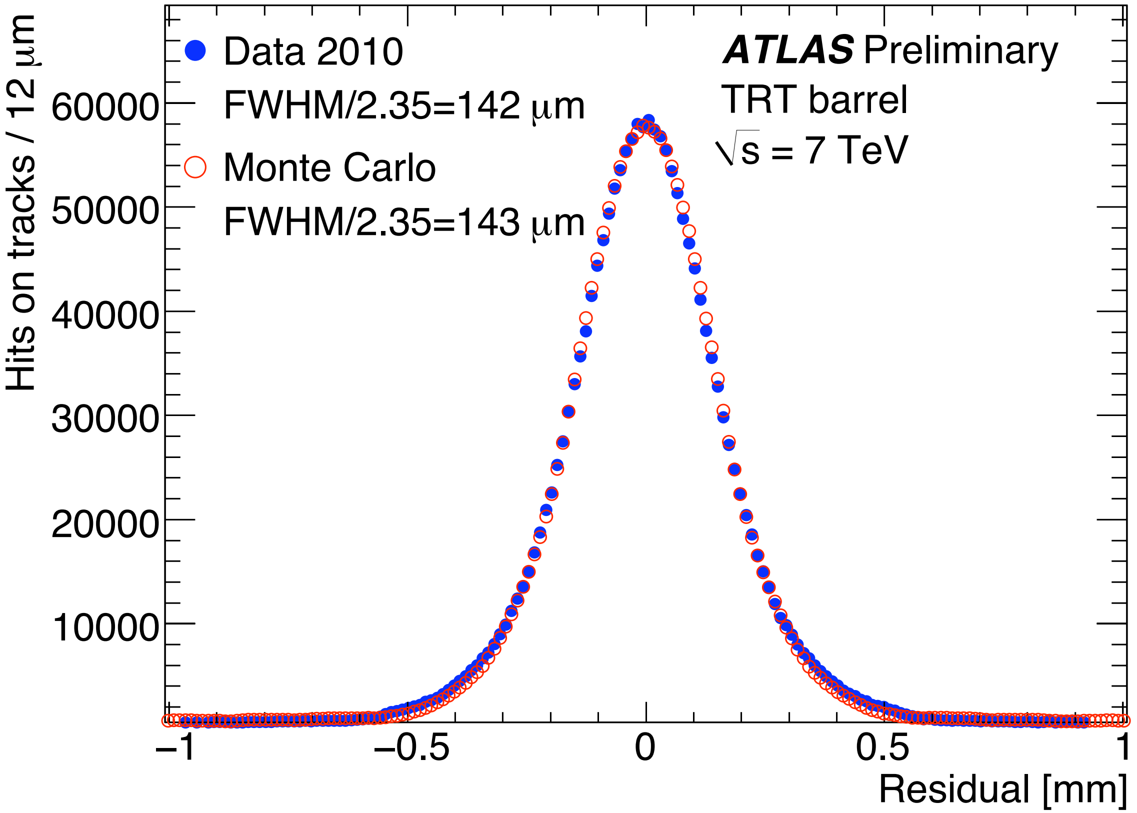


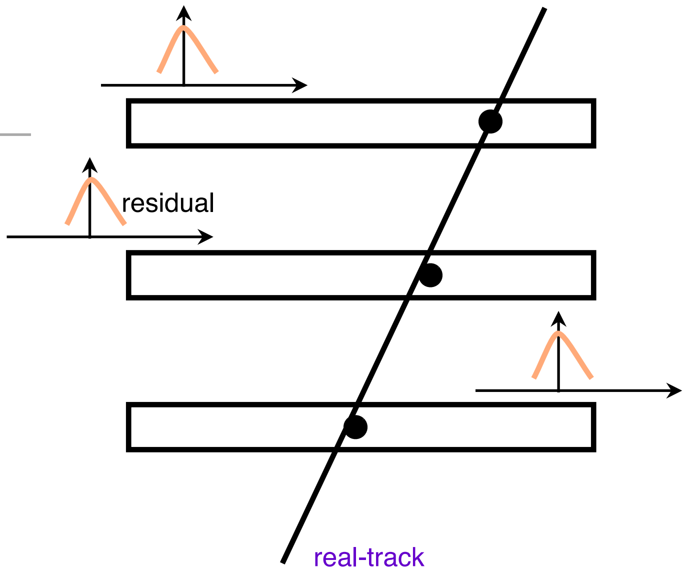


http://cdsweb.cern.ch/record/1271471/files/LHCb-TALK-2010-052.pdf

Spatial Resolution and Alignment

TRT Track Residuals



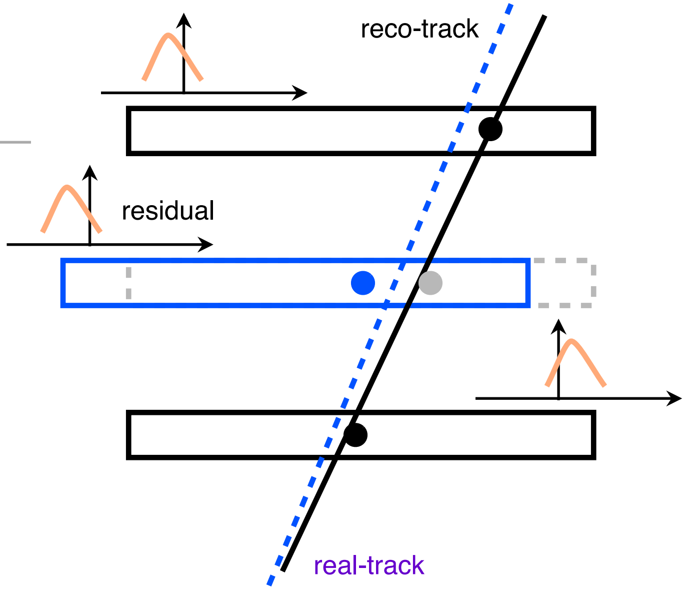


Residual distribution in TRT barrel

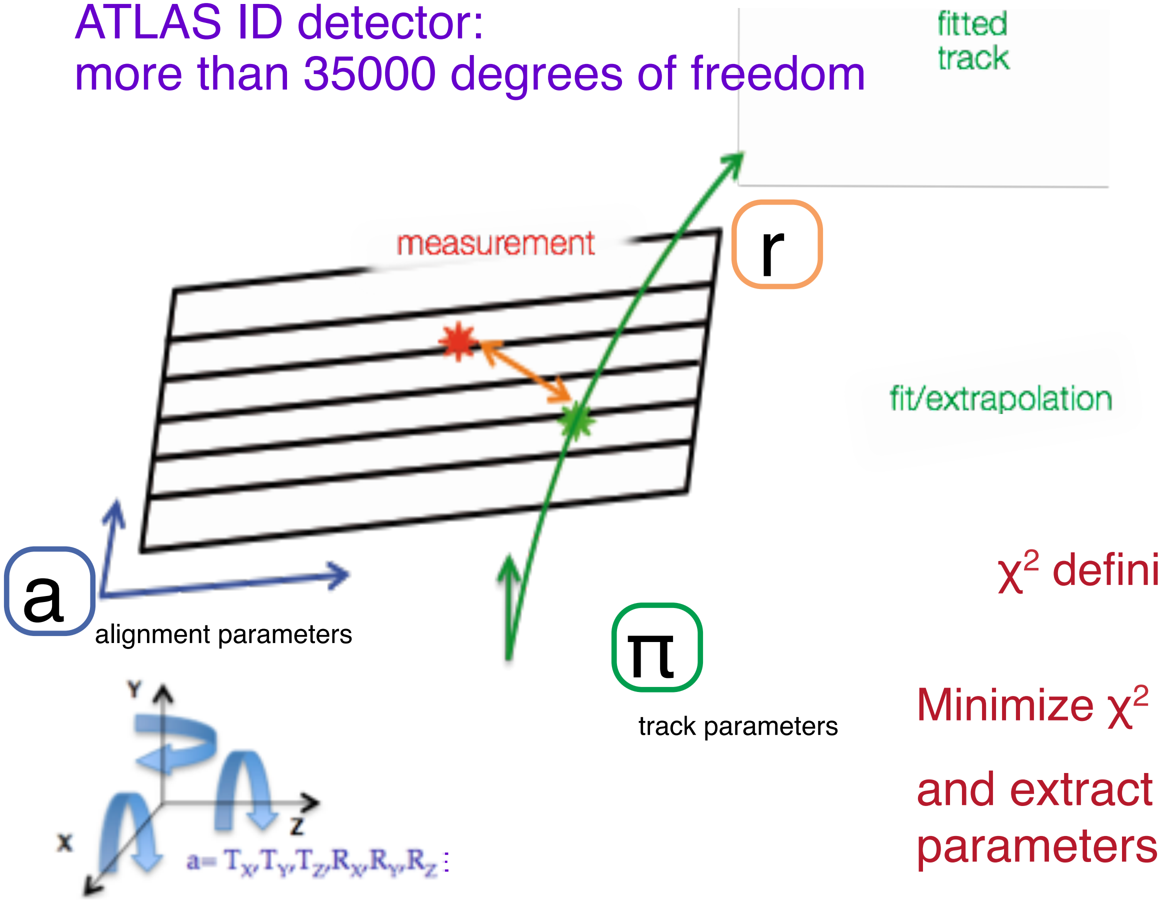
[TRT: Transition Radiation Tracker]

Spatial Resolution and Alignment

Alignment done
using residual information



ATLAS ID detector:
more than 35000 degrees of freedom



Residual:

$$r = \mathrm{hit}_{\mathrm{meas.}} - \mathrm{hit}(\pi, a)_{\mathrm{fit}}$$

χ^2 definition:

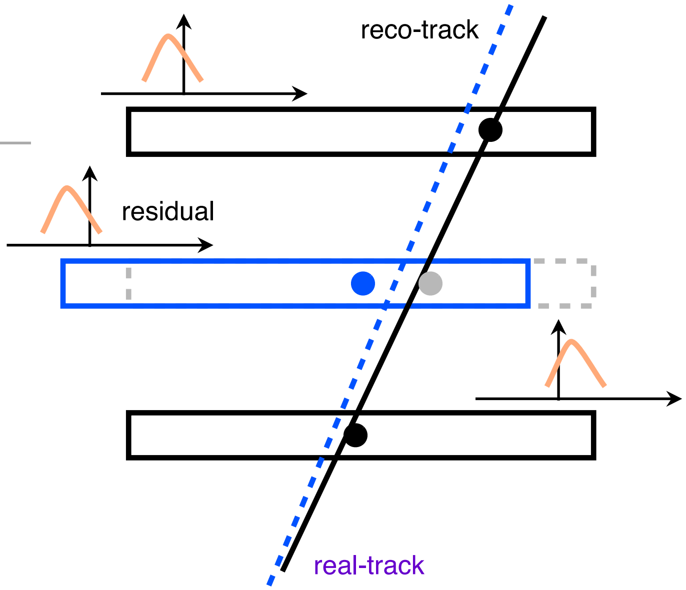
$$\chi^2 = \sum_{\mathrm{tracks}} r^T(\pi, a) V^{-1} r(\pi, a)$$

Minimize χ^2

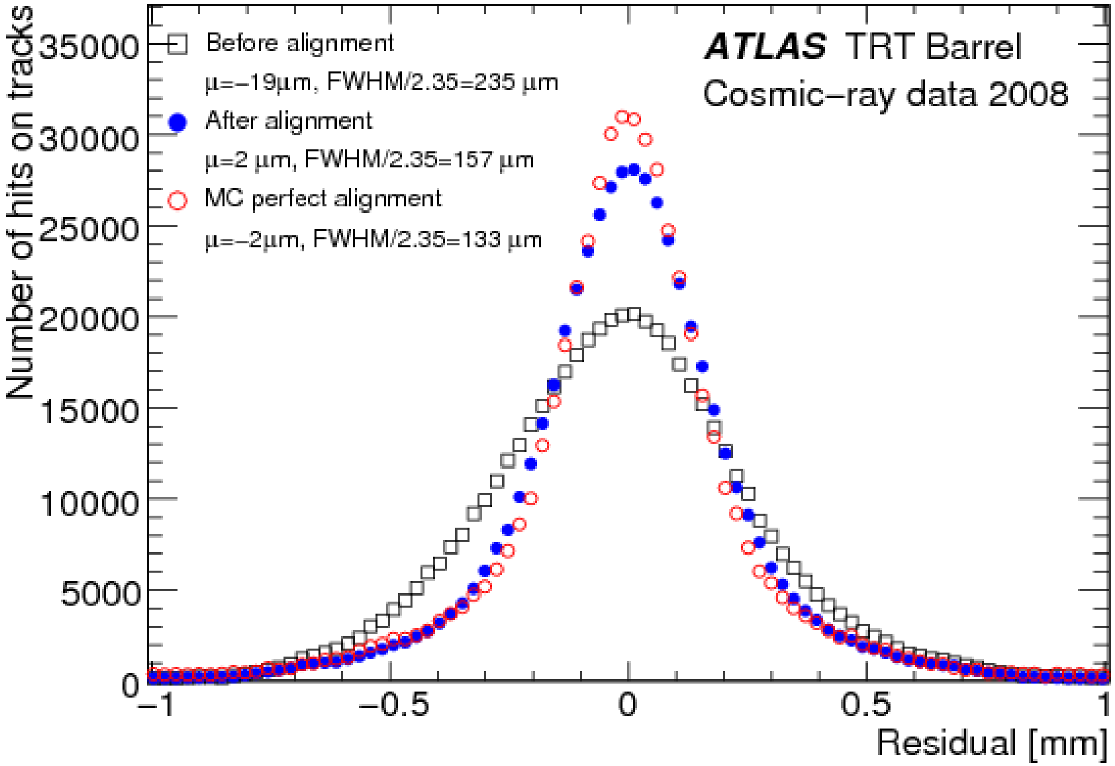
and extract alignment parameters ...

a: alignment parameters
π: track parameters
V: covariance matrix of hit measurements ...

Spatial Resolution and Alignment



TRT Track Residuals



Residual distribution

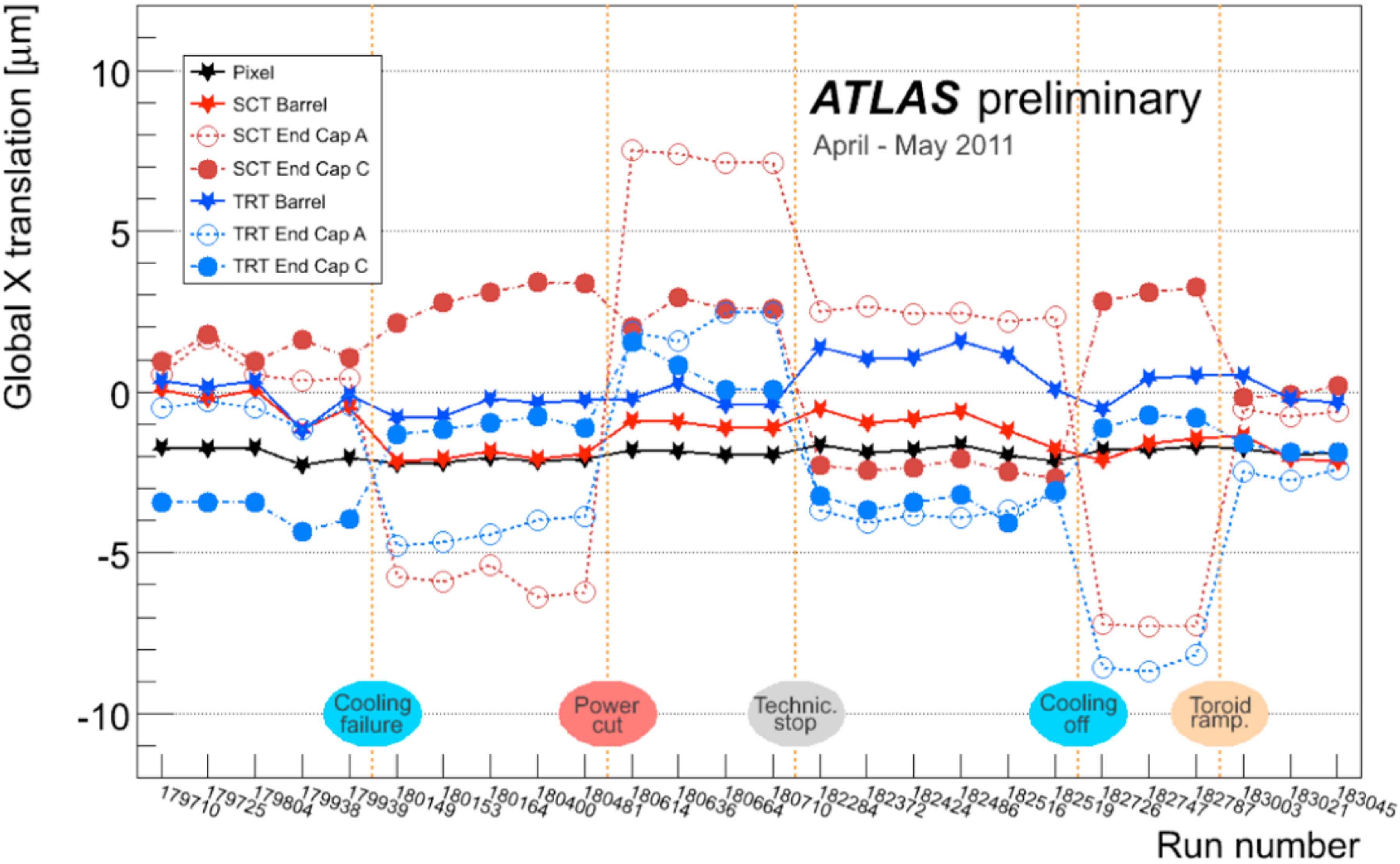
in TRT barrel ...

… before and

after alignment

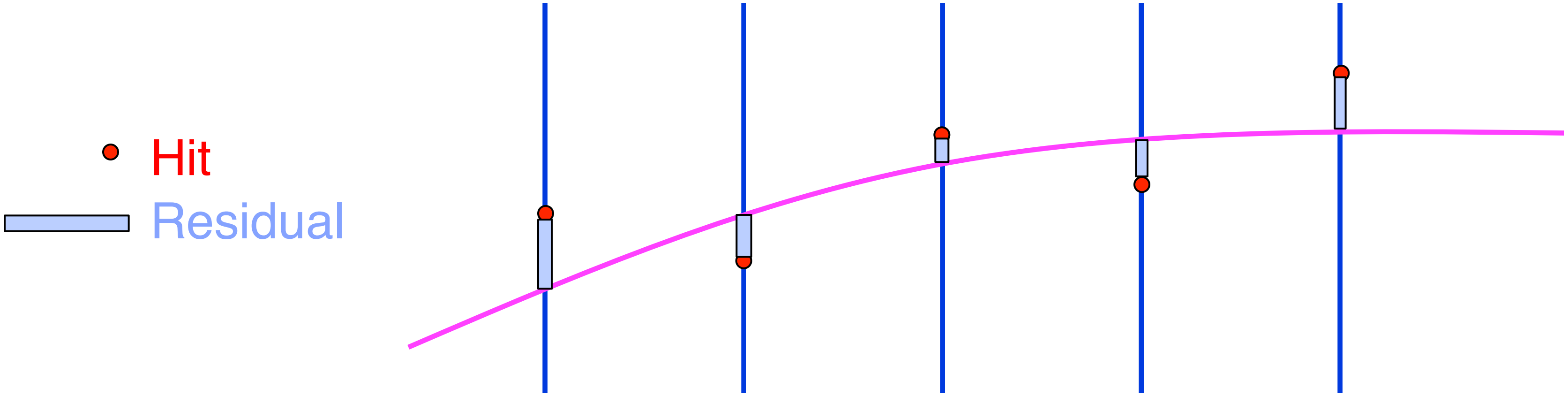
[TRT: Transition Radiation Tracker]

ATLAS alignment



Alignment performance

- Track based alignment minimises residuals for a sample of tracks, by adjusting position of sensitive elements.
- Position and width of known mass objects allows momentum resolution measurement.

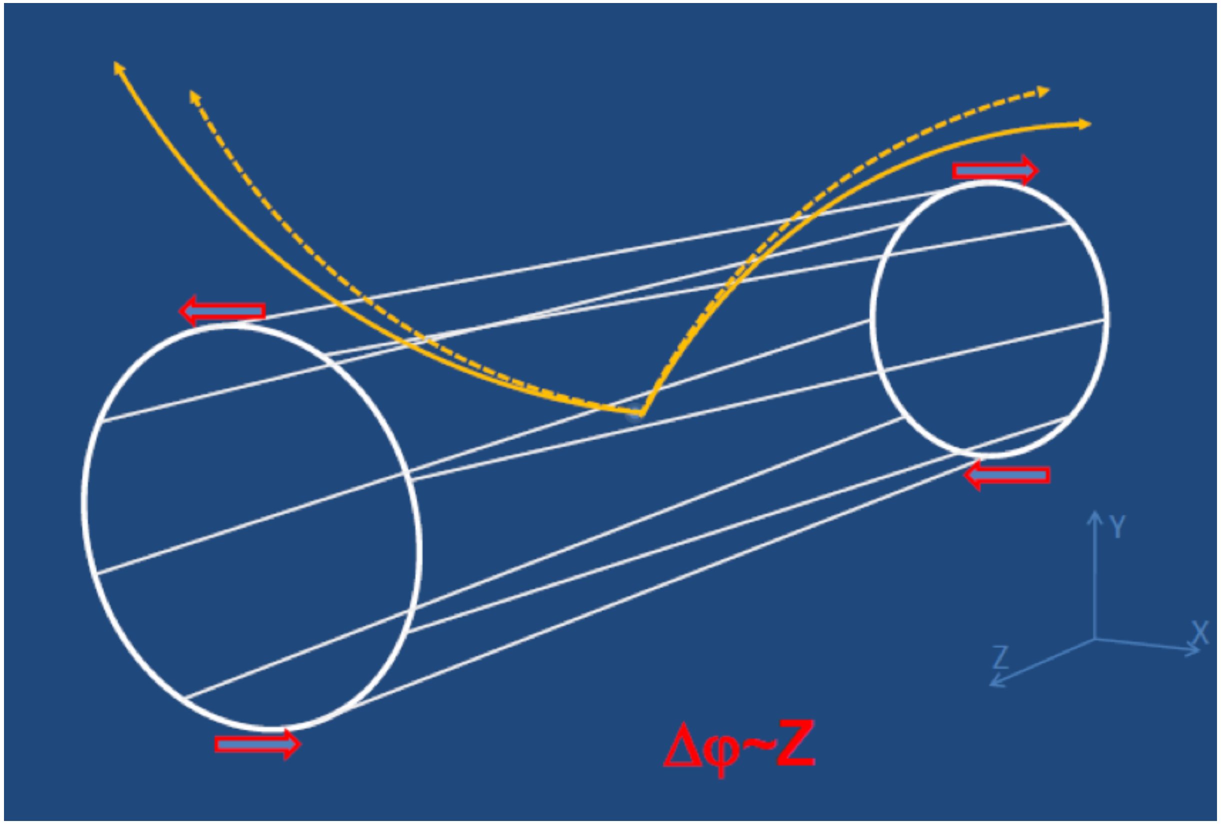


from F. Meier

Alignment performance

Systematic distortions, example a twist, are hard to detect.

Track residuals can be minimised but p_T is biassed.

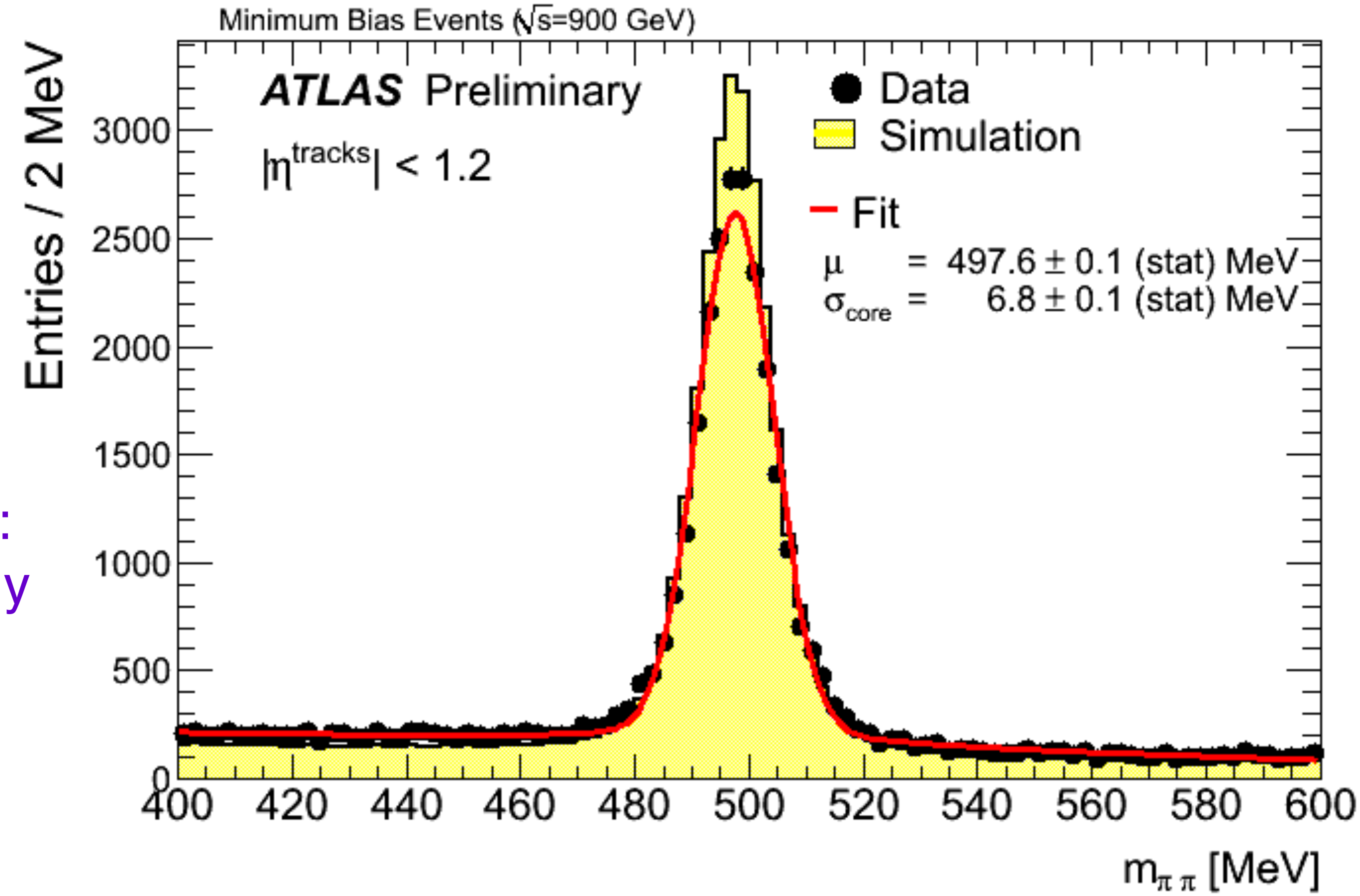


from P. Brückman de Renstrom

$K^0_s \rightarrow \pi^+\pi^-$

Two oppositely charged tracks, consistent with the same vertex.
Assume the tracks are pions. Reconstruct the pair invariant mass.

World Average PDG value 497.614 ± 0.024 MeV



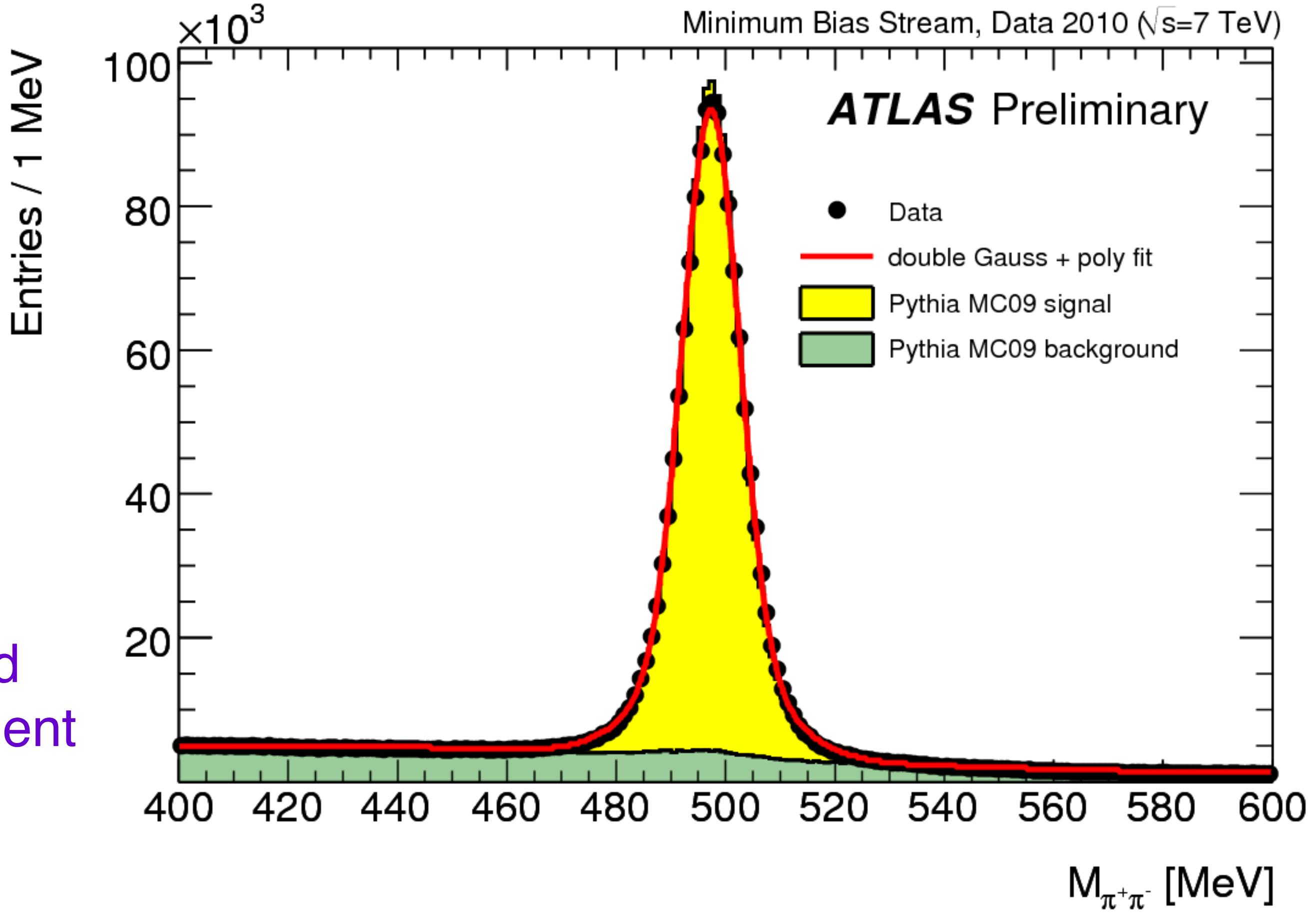
ATLAS example: 2009 data slightly broader than simulation

ATLAS-CONF-2010-019

$K^0_s \rightarrow \pi^+\pi^-$

Two oppositely charged tracks, consistent with the same vertex. Assume the tracks are pions. Reconstruct the pair invariant mass.

World Average PDG value 497.614 ± 0.024 MeV

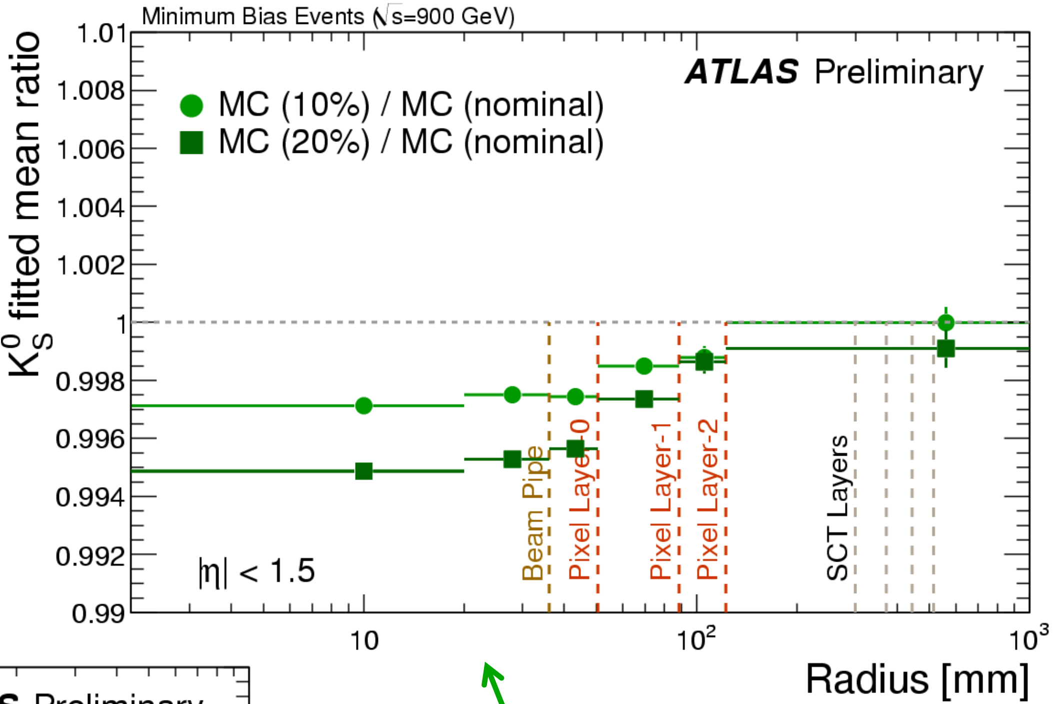


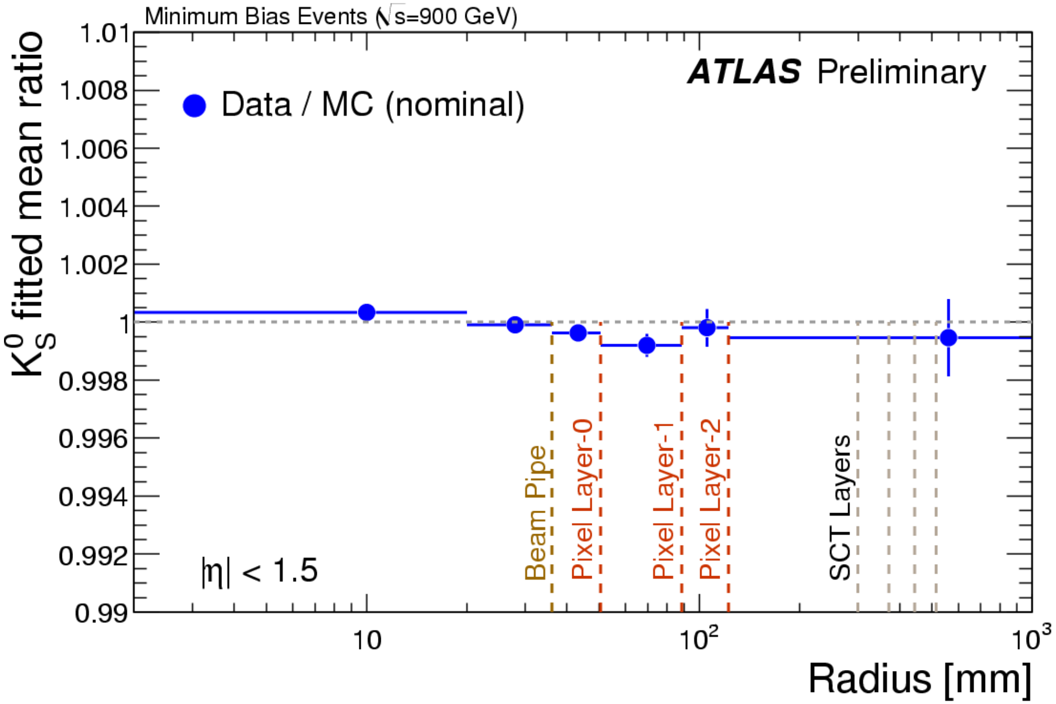
Much better agreement with 2010 sample and improved alignment

ATLAS-CONF-2010-033

K^0_s and material

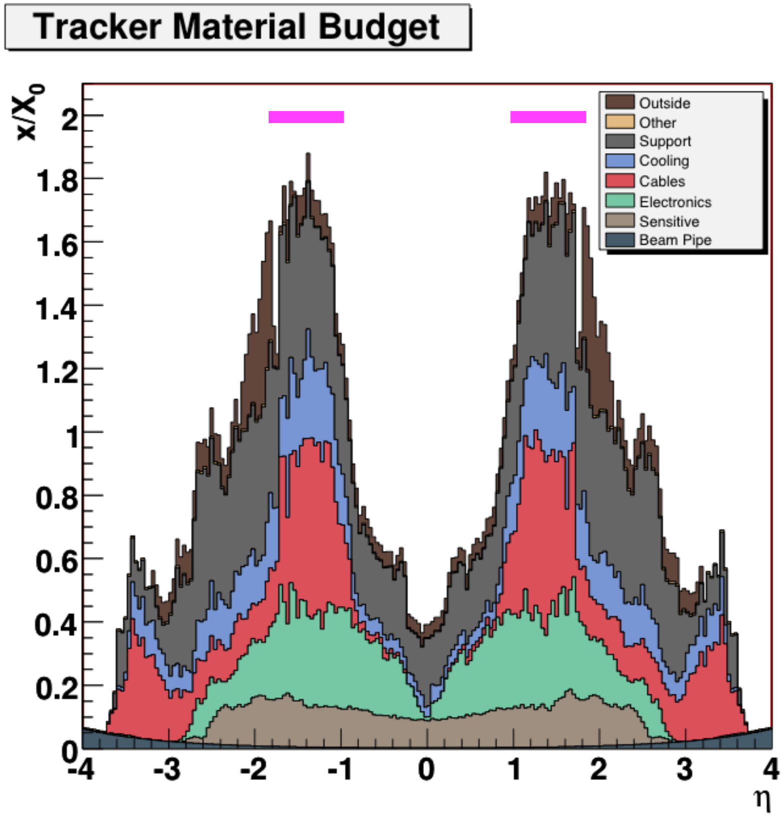
- Look at fitted mass as a function of decay radius
- Data consistent with nominal MC

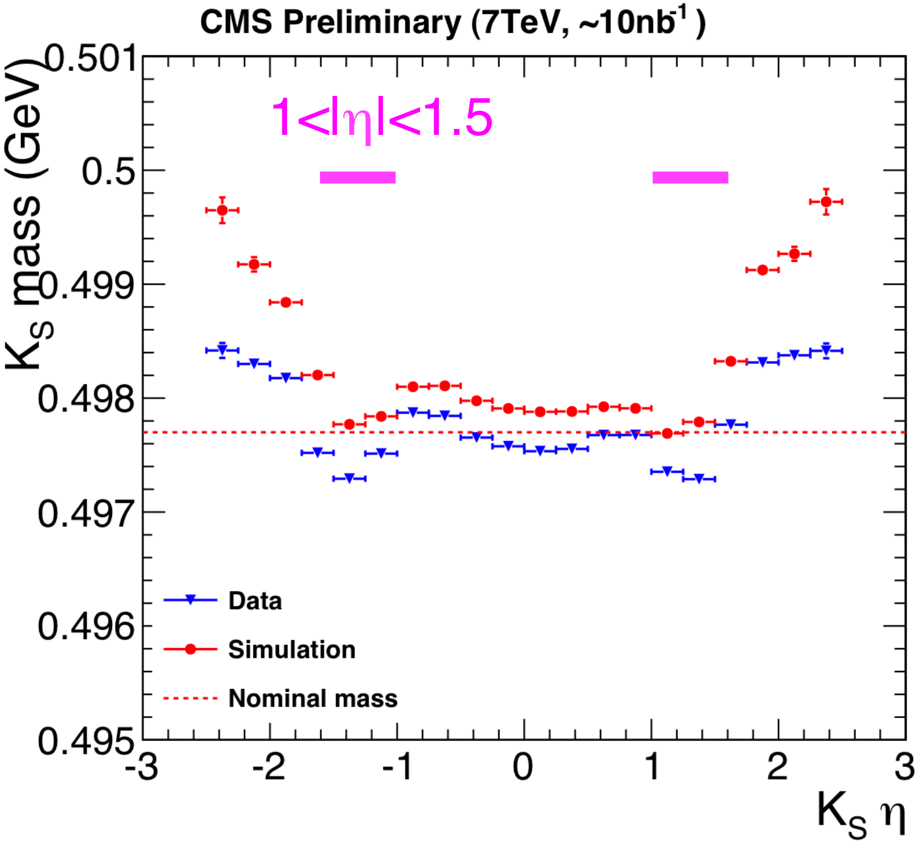




- MC with 10% or 20% extra material predicts much bigger deviations
- With larger data samples, make finer binned studies in future

K^0_s mass in CMS





CMS example: K^0_s mass vs η

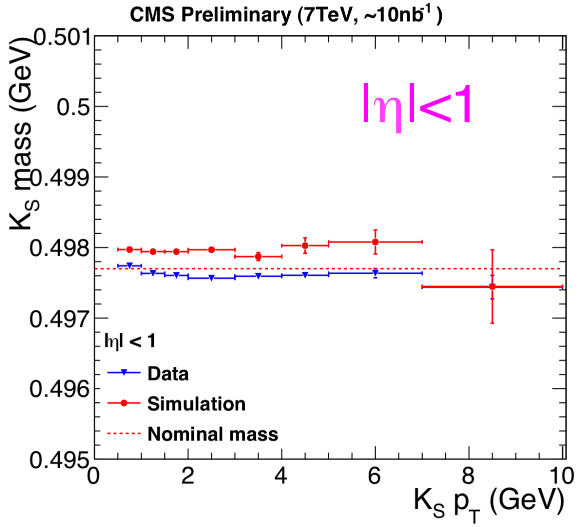
1<|η|<1.5 is most difficult to model

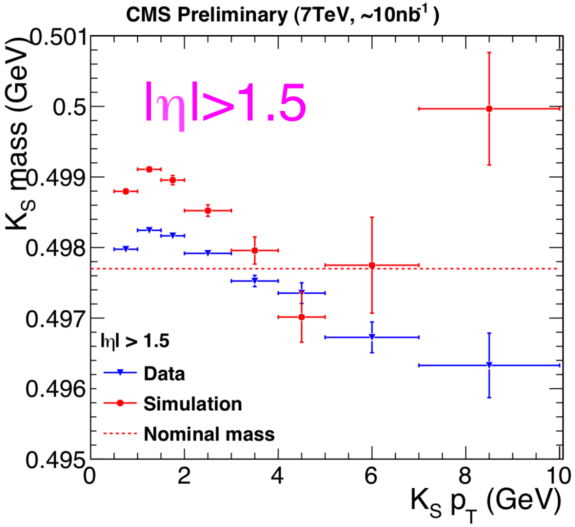
Mass shifted upwards in simulation

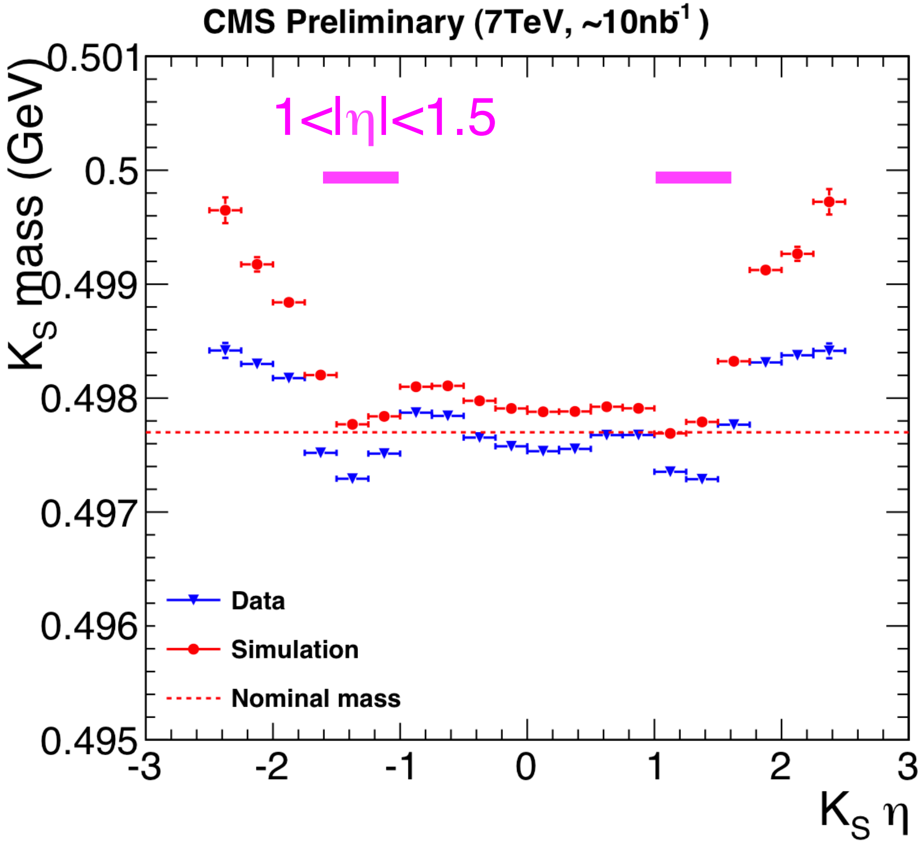
Same trend with η in data

CMS-PAS-TRK-10-004

K^0_s mass in CMS







CMS example: K^0_s mass vs η and p_T

$1<|\eta|<1.5$ is most difficult to model

Mass shifted upwards in simulation

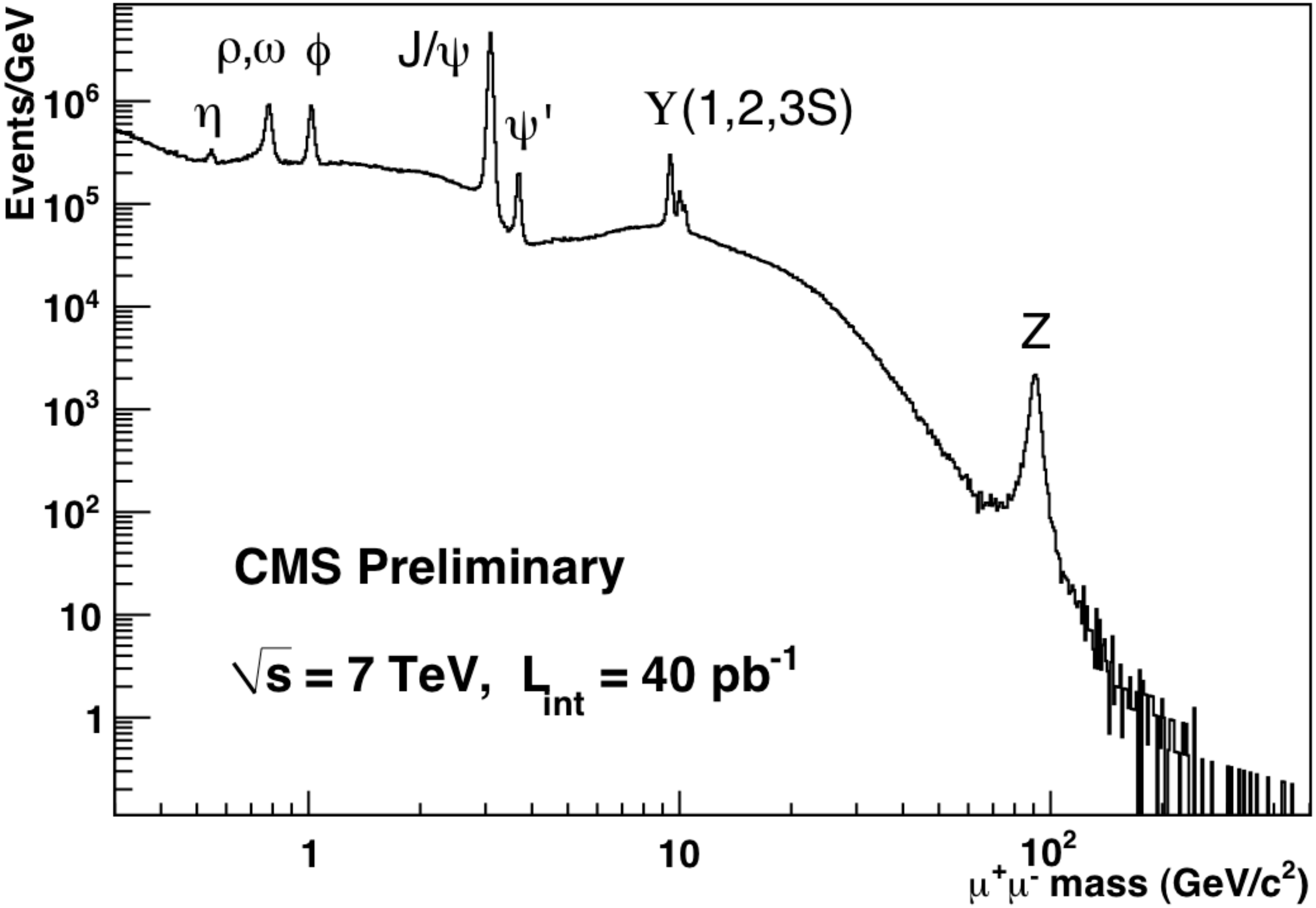
Same trends with η and p_T in data

CMS-PAS-TRK-10-004

$\mu^+\mu^-$ mass spectrum

Well known resonances. Observed widths depend on p_T resolution.

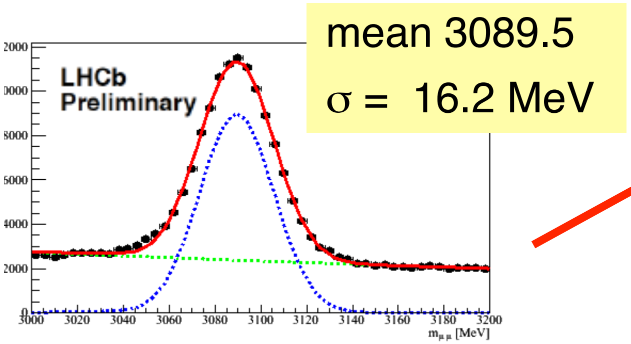
Again, check for biases in mass value as a function of η, ϕ, p_T …



J/ψ and $\Upsilon \to \mu^+\mu^-$

LHCb improved alignment

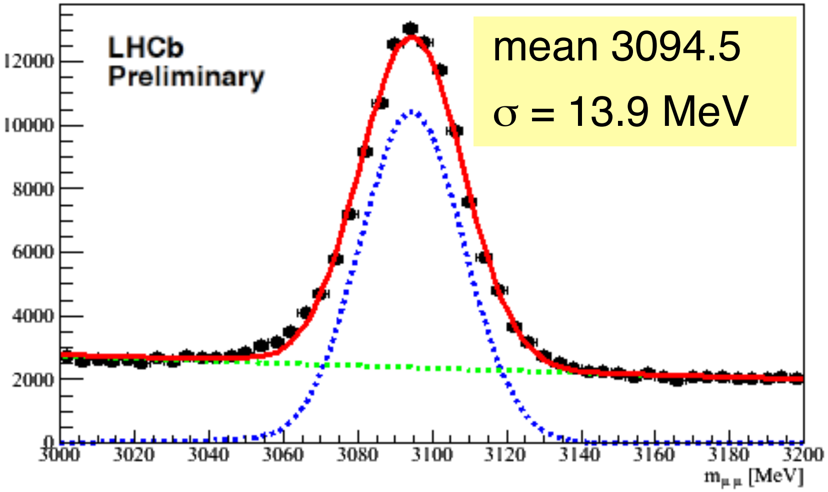
(LHCC meeting September 2010)



mean 3089.5

σ = 16.2 MeV

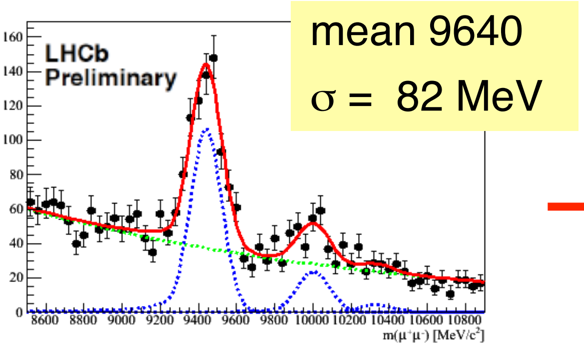
J/ψ PDG mass 3096.916 ± 0.011 MeV



mean 3094.5

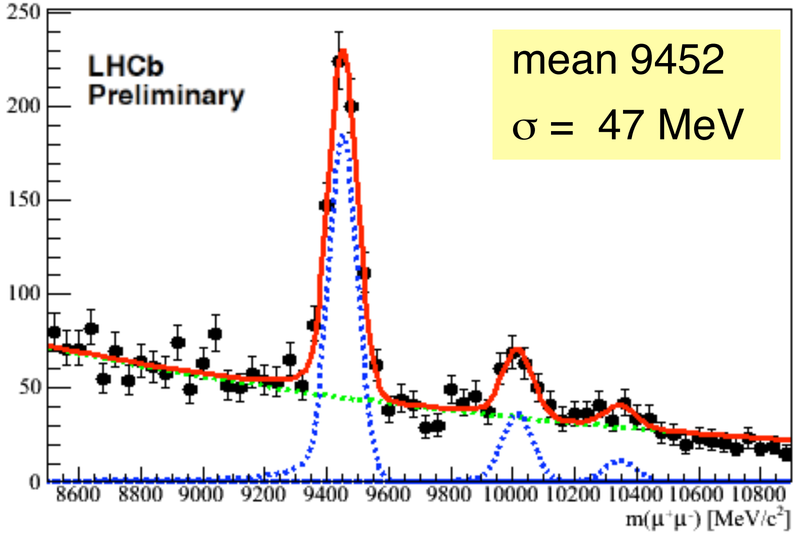
σ = 13.9 MeV

Υ(1S) m = 9460.30 ± 0.26 MeV, (2S) and (3S) states resolved



mean 9640

σ = 82 MeV

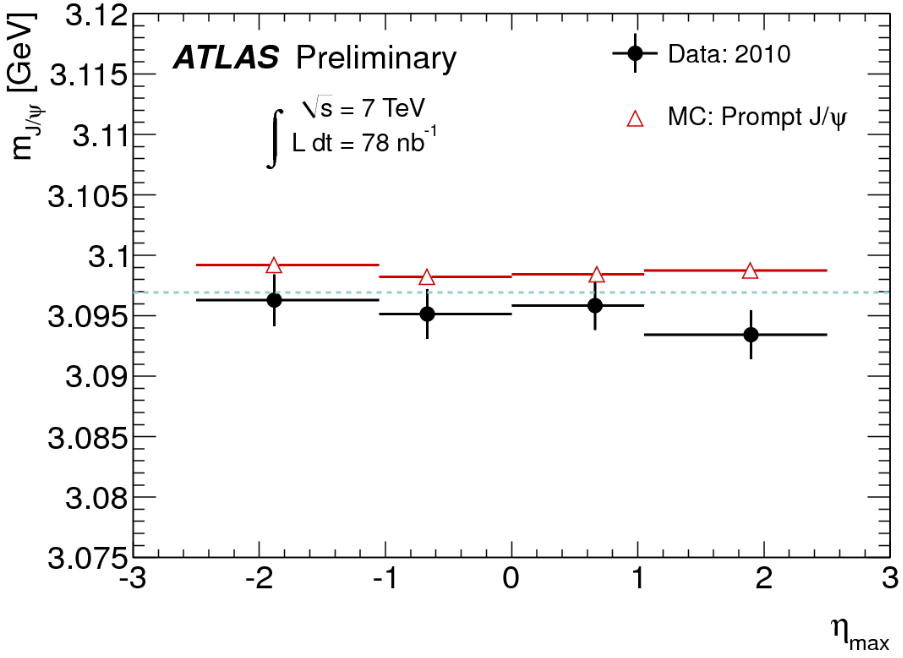


mean 9452

σ = 47 MeV

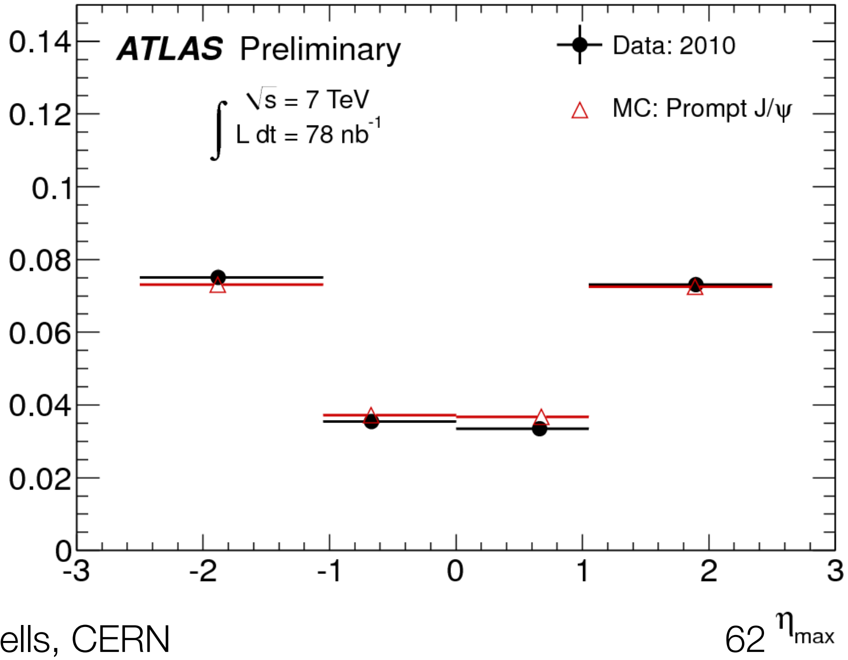
$J/\psi \rightarrow \mu^+\mu^-$ mass and width

As a function of the η of the more forward muon.



Offset between reconstructed mass and WA PDG value in simulation

Mass in data lower than in simulation (limited statistics)

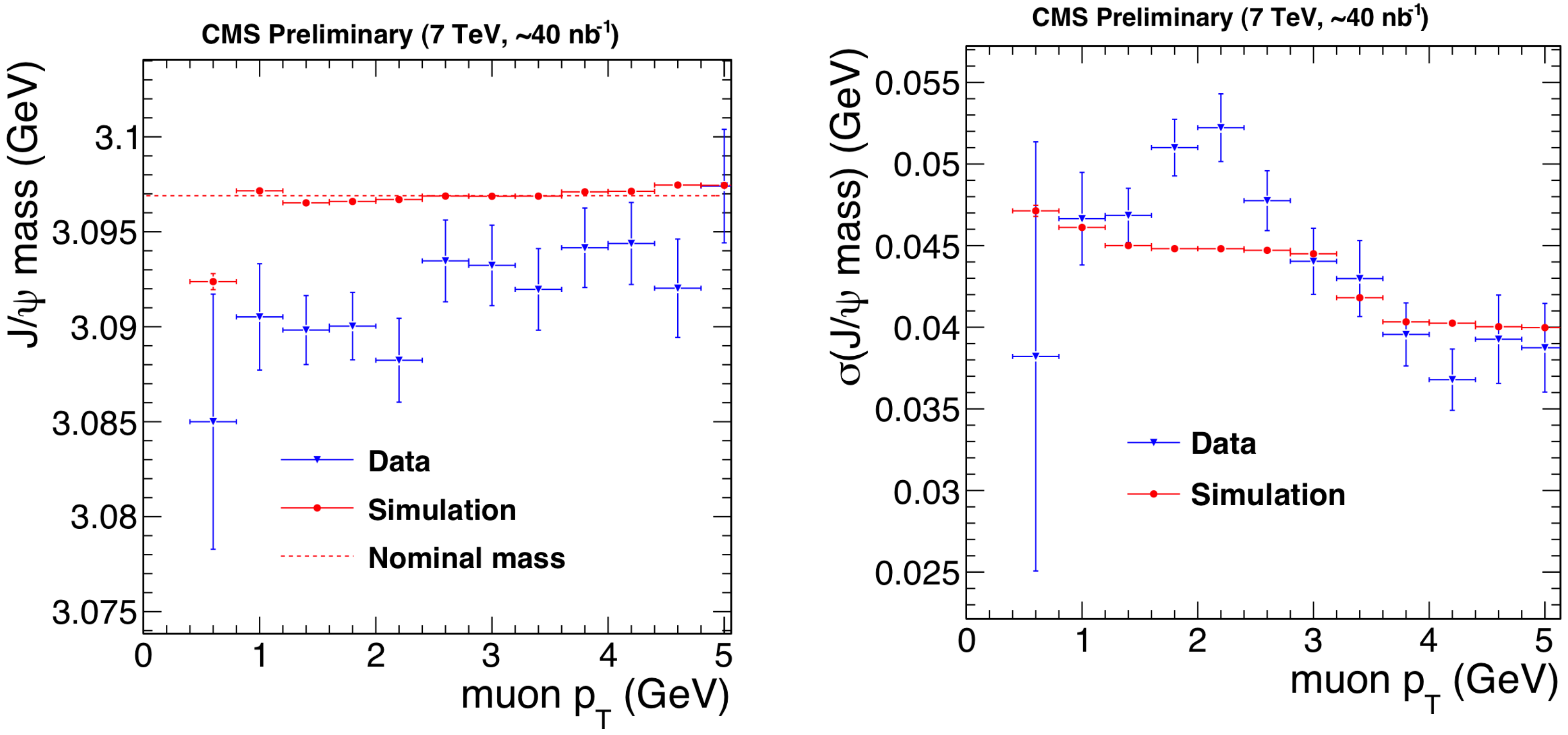


Widths agree well between data and simulation → momentum resolution reasonably modelled.

ATLAS-CONF-2010-078

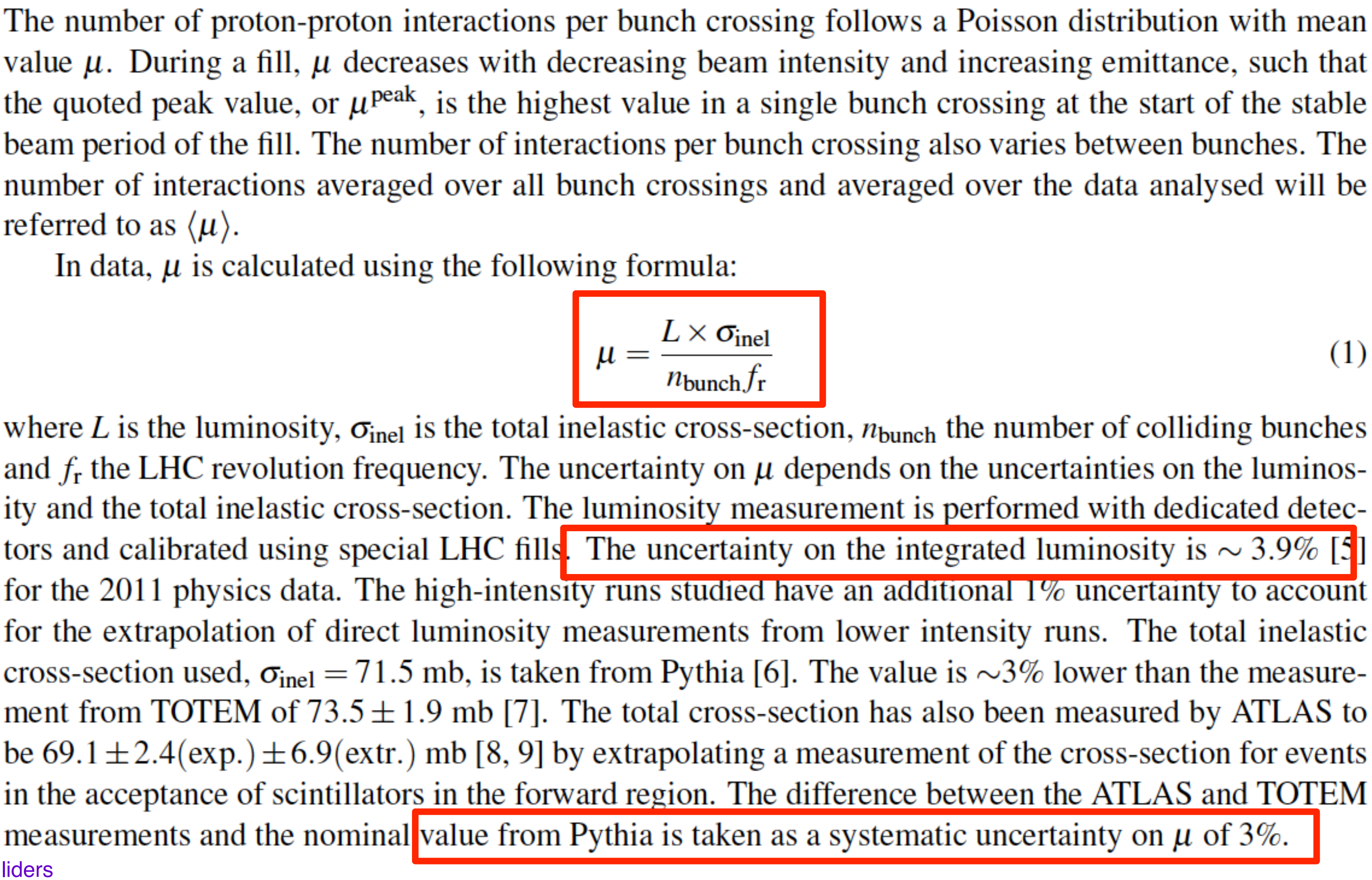
$J/\psi \rightarrow \mu^+\mu^-$ mass and width

As a function of muon transverse momentum (CMS example)



Reconstructed mass in data tends to be too low at low momentum, and p_T resolution is up to 10% worse (from width). These distributions can then be used to make corrections.

High pile-up events: μ and N_{PV}



The number of proton-proton interactions per bunch crossing follows a Poisson distribution with mean value μ. During a fill, μ decreases with decreasing beam intensity and increasing emittance, such that the quoted peak value, or μ^{peak}, is the highest value in a single bunch crossing at the start of the stable beam period of the fill. The number of interactions per bunch crossing also varies between bunches. The number of interactions averaged over all bunch crossings and averaged over the data analysed will be referred to as $\langle\mu\rangle$.

In data, μ is calculated using the following formula:

$$\boxed{\mu = \frac{L \times \sigma_{\text{inel}}}{n_{\text{bunch}} f_{\text{r}}}} \tag{1}$$

where L is the luminosity, σ_{inel} is the total inelastic cross-section, n_{bunch} the number of colliding bunches and f_{r} the LHC revolution frequency. The uncertainty on μ depends on the uncertainties on the luminosity and the total inelastic cross-section. The luminosity measurement is performed with dedicated detectors and calibrated using special LHC fills. The uncertainty on the integrated luminosity is $\sim 3.9\%$ [5] for the 2011 physics data. The high-intensity runs studied have an additional 1% uncertainty to account for the extrapolation of direct luminosity measurements from lower intensity runs. The total inelastic cross-section used, $\sigma_{\text{inel}} = 71.5$ mb, is taken from Pythia [6]. The value is $\sim$3% lower than the measurement from TOTEM of 73.5 ± 1.9 mb [7]. The total cross-section has also been measured by ATLAS to be $69.1 \pm 2.4(\text{exp.}) \pm 6.9(\text{extr.})$ mb [8, 9] by extrapolating a measurement of the cross-section for events in the acceptance of scintillators in the forward region. The difference between the ATLAS and TOTEM measurements and the nominal value from Pythia is taken as a systematic uncertainty on μ of 3%.

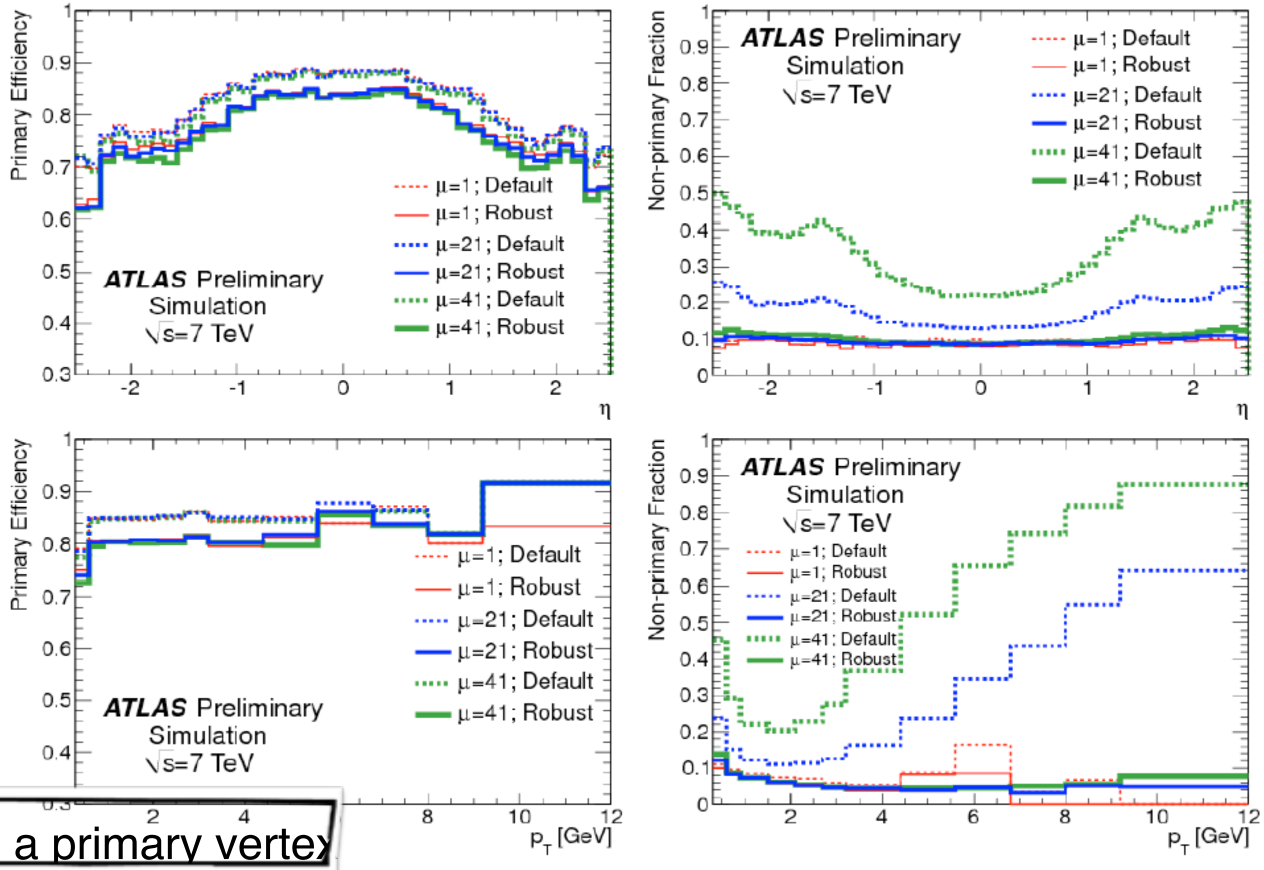
High pile-up events

μ=number of primary interactions

A special track selection allows

the reconstruction of tracks with pT>400 MeV in events with many superimposed vertices

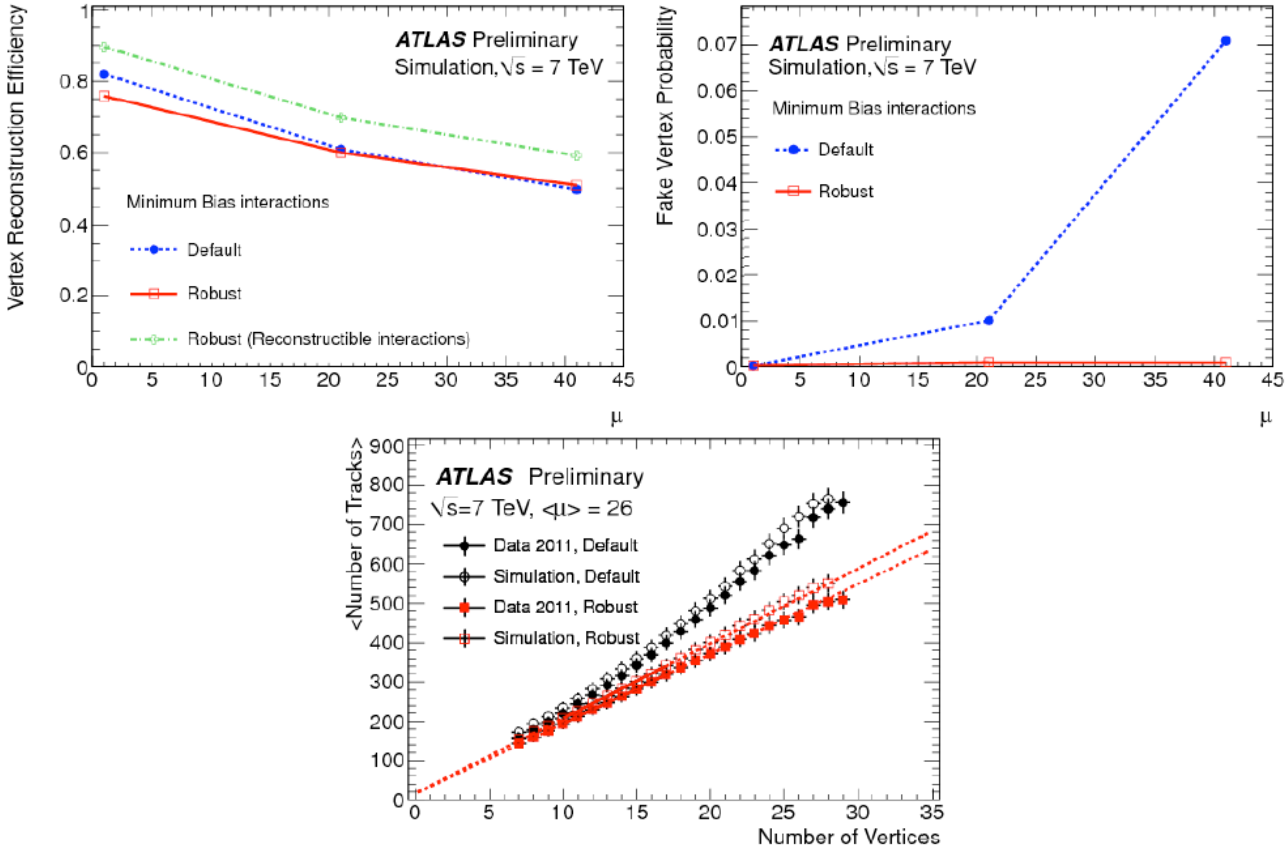
Robust reconstruction



non-primary = not pointing to a primary vertex

Primary track reconstruction efficiency (left) and the non-primary fraction (i.e. secondary and fake tracks, right) as a function of pseudorapidity (top) and transverse momentum (down) in minimum bias MC samples containing one or on average 21 or 41 interactions [4].

Vertices in high pile-up events



Vertex reconstruction efficiency (top left) and fake probability (top right) as a function of the average number of interactions in minimum bias MC and the average number of tracks per event as a function of the number of vertices for data and simulation (bottom) [4].

Conclusions

- LHC tracker layouts were optimised for the physics goals:
  - Distinguish primary vertices
  - Measure impact parameters and secondary vertices
  - Measure the track momentum
- Trade-off between precision and material
  - Most of the material budget is not in the sensitive elements, but support structures, cables, cooling…
  - Careful work to control material during construction
  - Very little radiation damage so far – to be monitored carefully
- Good agreement between simulated performance and measurements with data. Further improvements in progress.
  - Alignment of detectors using tracks is already high quality
  - Photon conversions, material interactions, and masses of known particles allow material to be measured and systematic checks of alignment distortions to be made.
- R&D for upgrades is underway