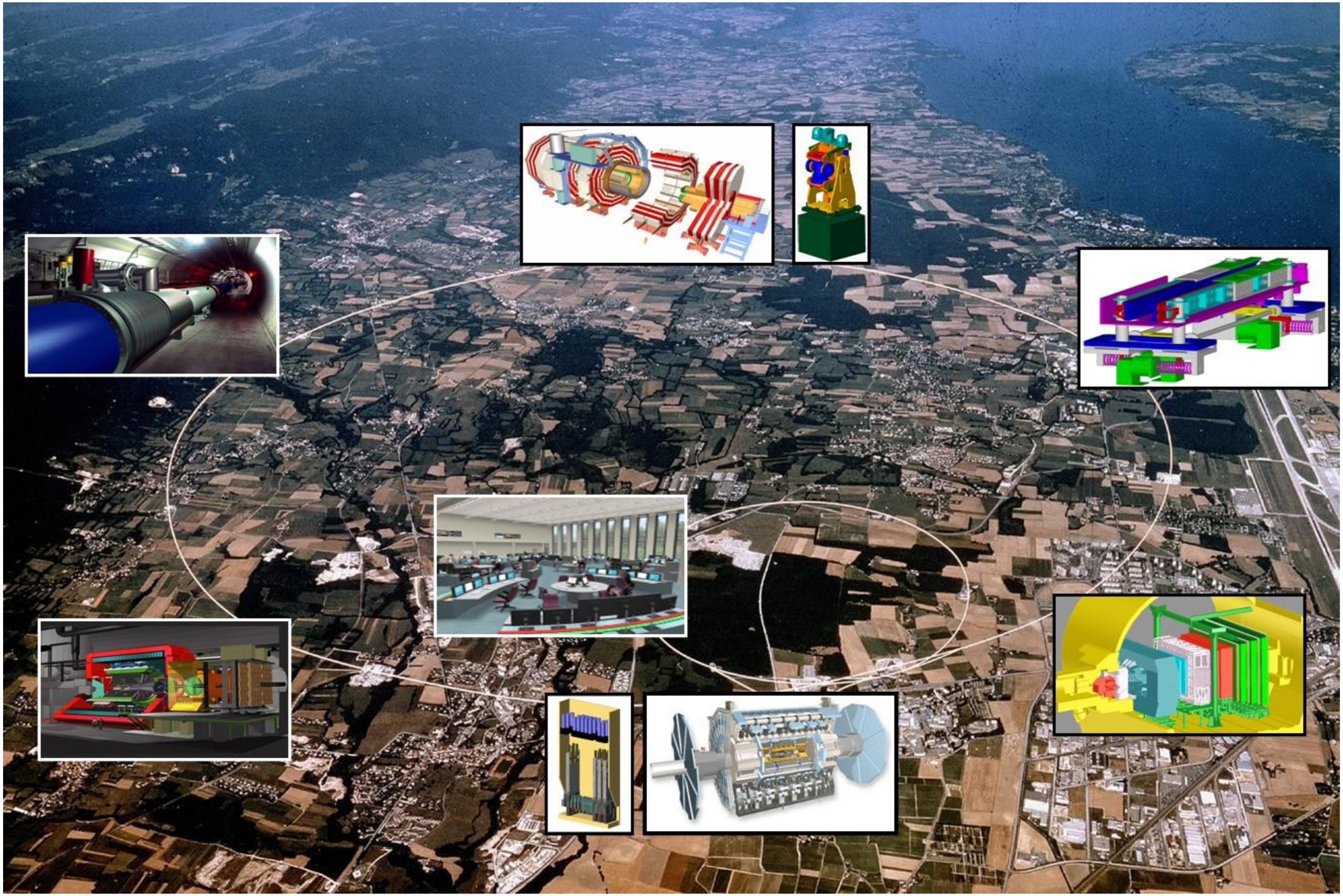
Tracking at the LHC

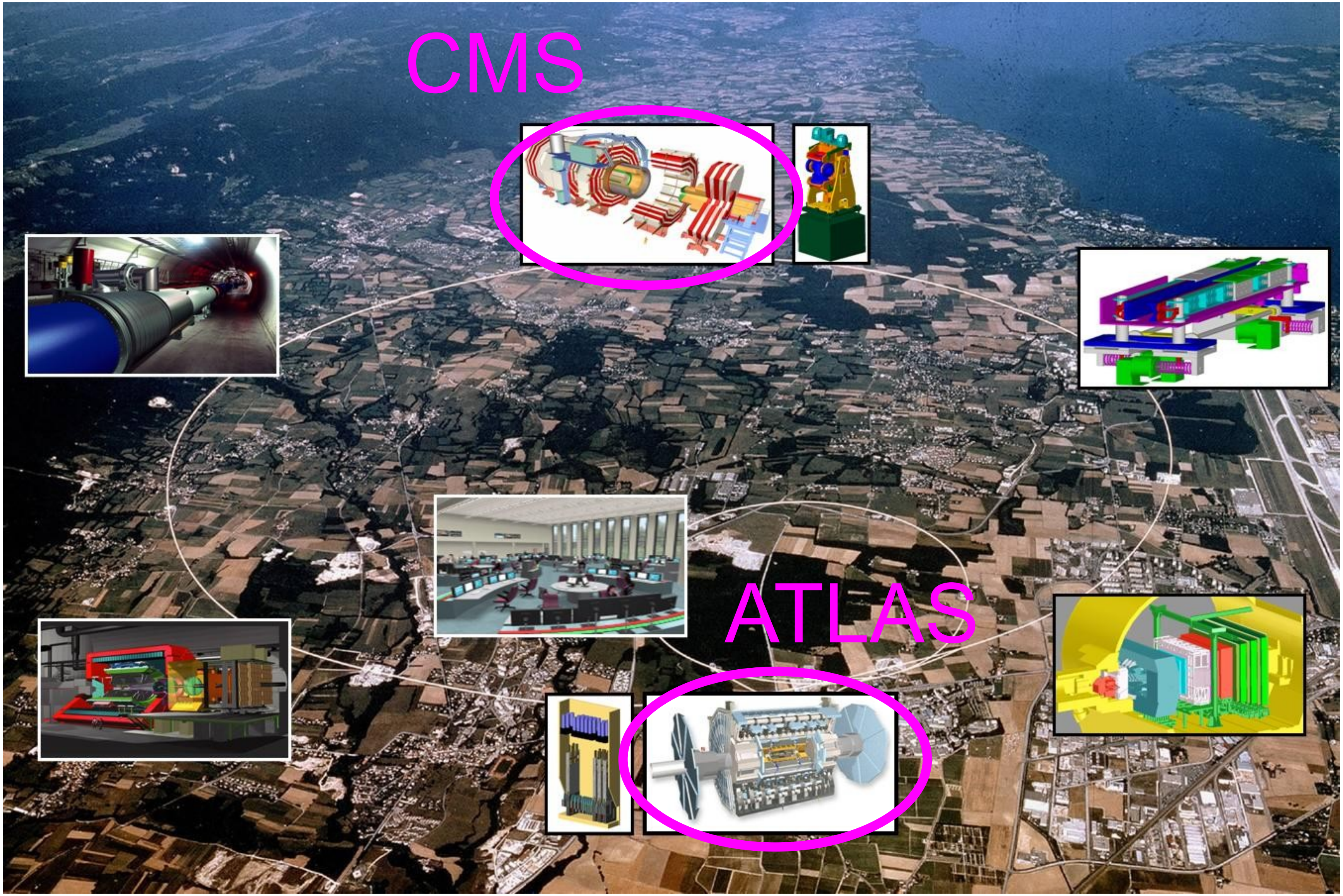
- Aims of central tracking at LHC
- Some basics influencing detector design
- Consequences for LHC tracker layout
- Measuring material before, during and after construction

Pippa Wells, CERN

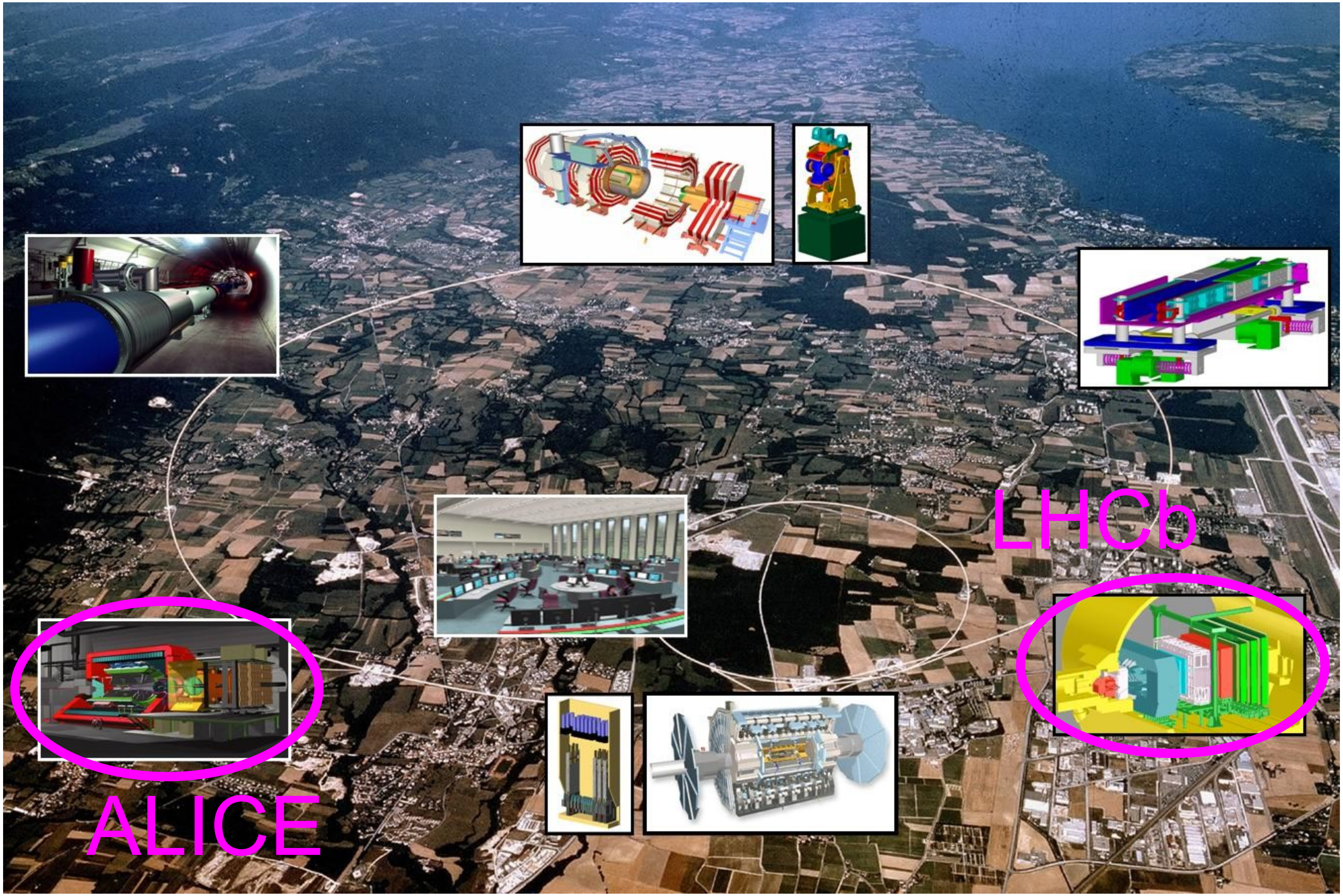
The LHC



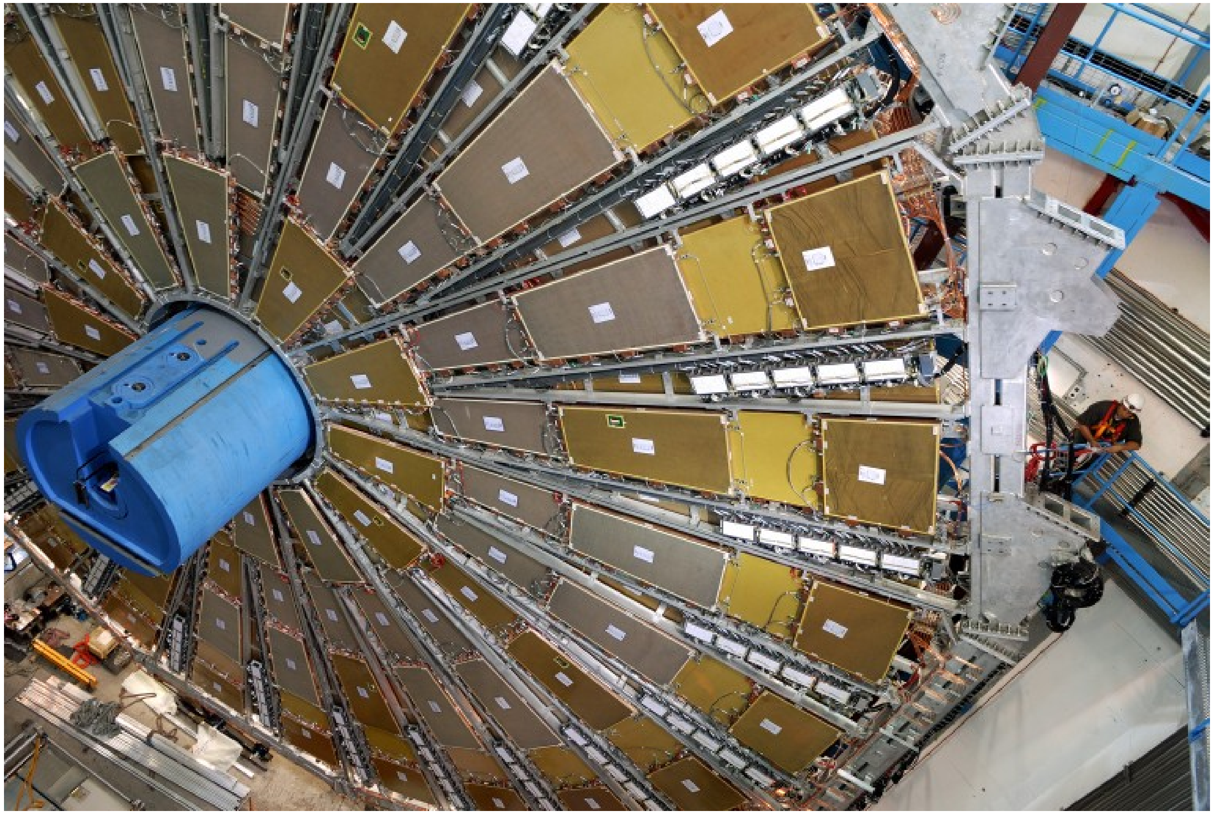
Two General Purpose Detectors



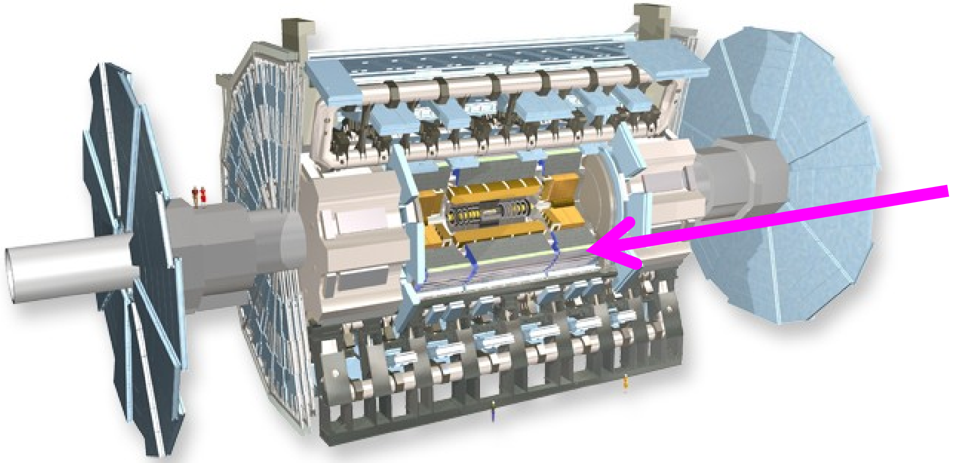
Two more specialised, large detectors



ATLAS



From the outside, all you see is muon chambers. These are trackers too…

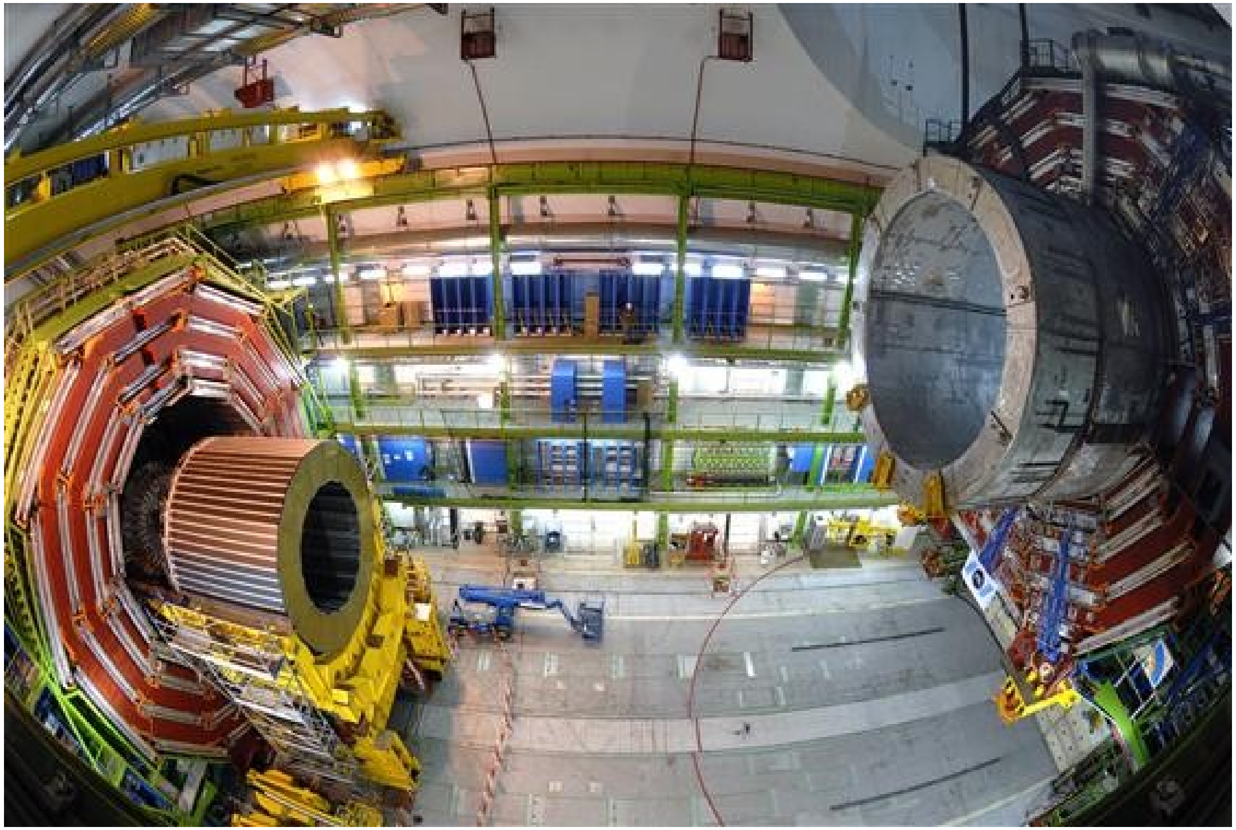


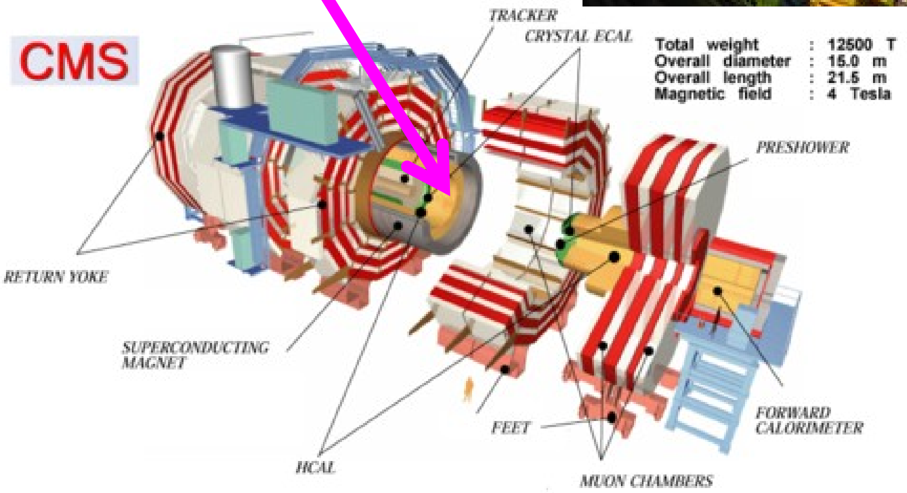
Most particles are absorbed in the calorimeters, which measure their energy.

Muons (& neutrinos) escape.

CMS

This lecture concentrates on central trackers.

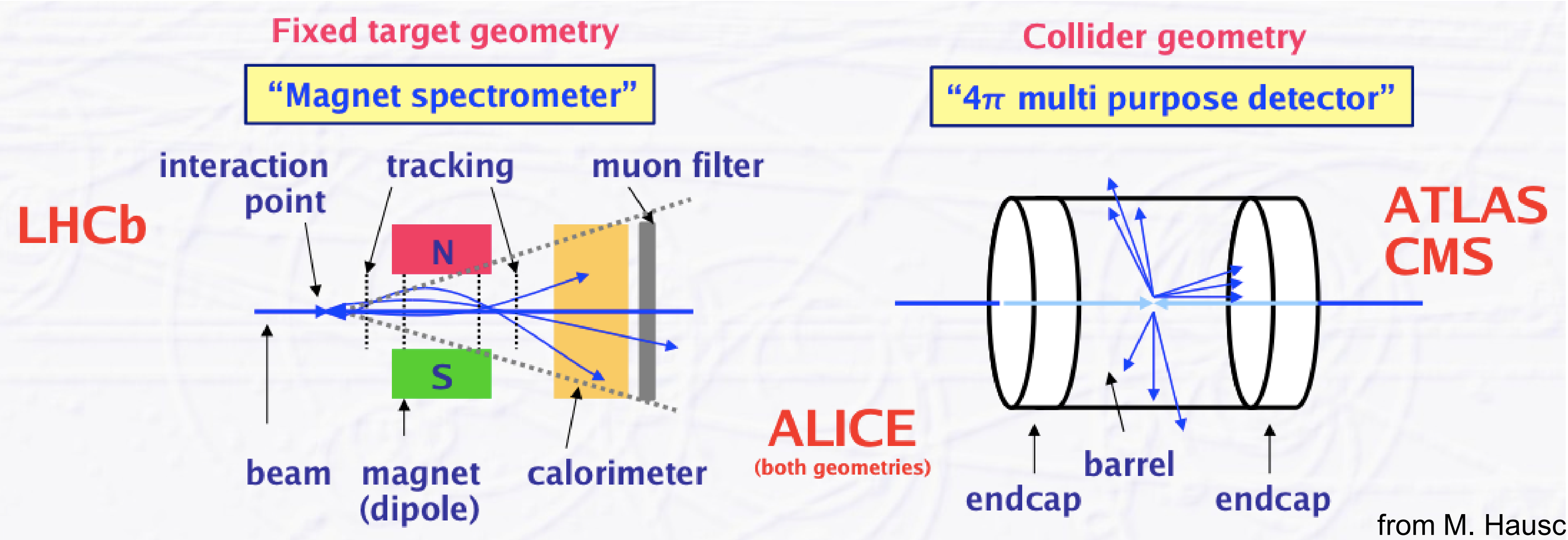




Measure charged particles as they emerge from the interaction point, disturbing them as little as possible.

Role of trackers at LHC

- ATLAS and CMS 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
- LHCb – beauty-hadron production in forward direction



from M. Hauschild

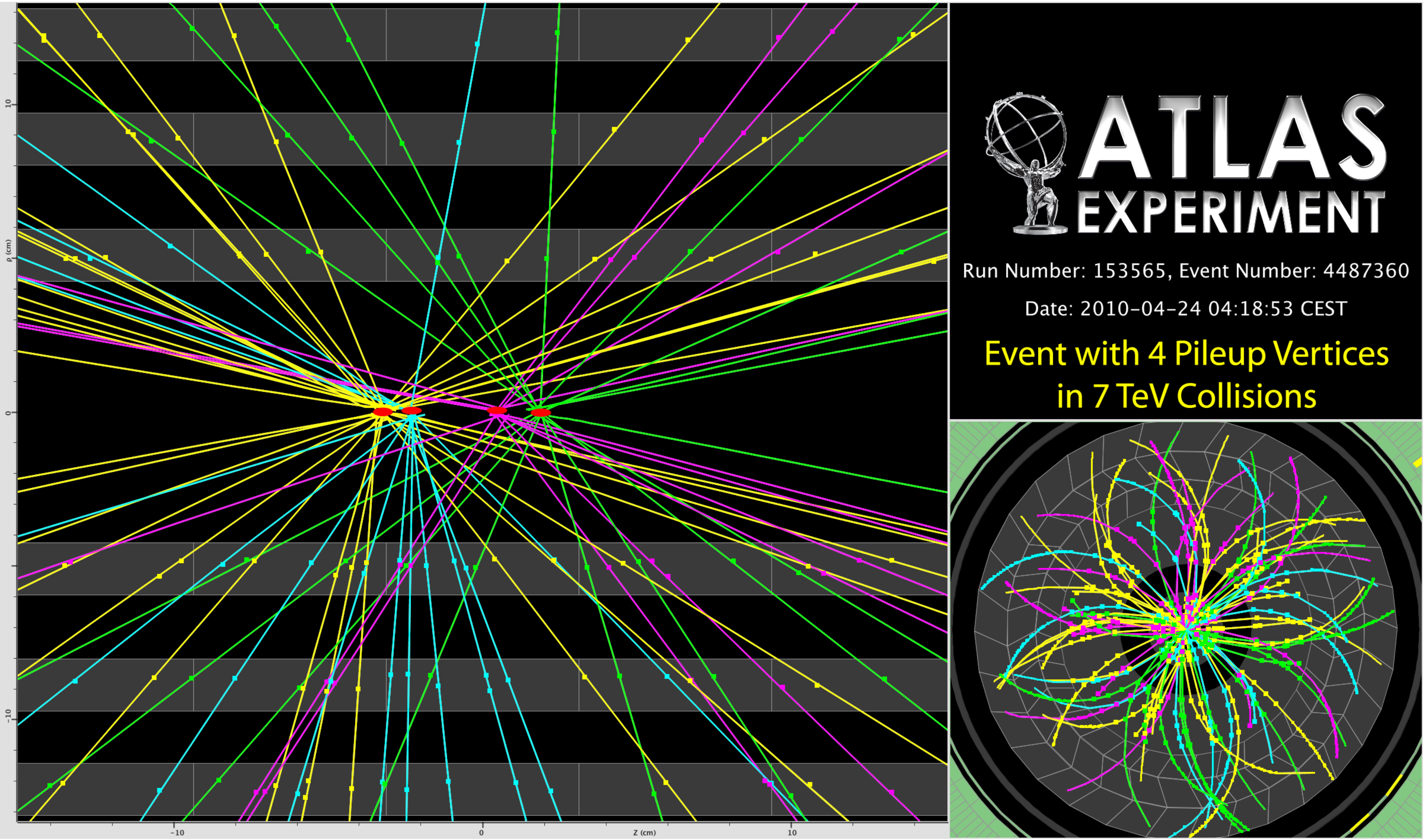
Role of trackers at LHC

- Measure the trajectory of charged particles
  - Measure several points ("hits") along the track.
  - Fit curves to the hits (helix, straight line)
  - → measure the momentum of charged particles from their curvature in a magnetic field.
- High occupancy, radiation dose and data rates
  - 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
  - Increasing sensor granularity to reduce occupancy increases the number of electronics channels, increasing material and heat load.
- Minimise material so as to minimise interactions of charged (and neutral) particles before the calorimeter

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, nuclear interactions

Primary vertices



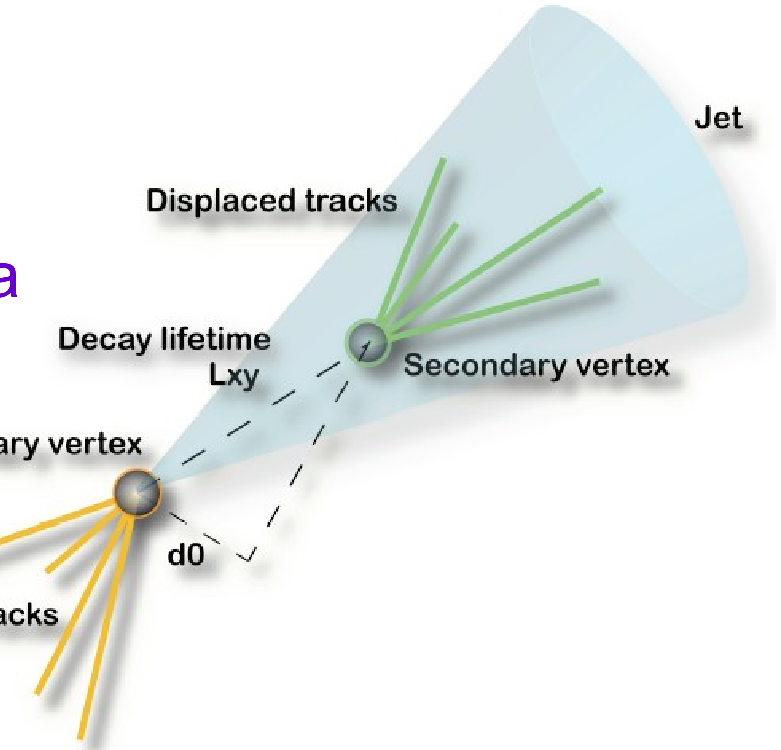
Run Number: 153565, Event Number: 4487360

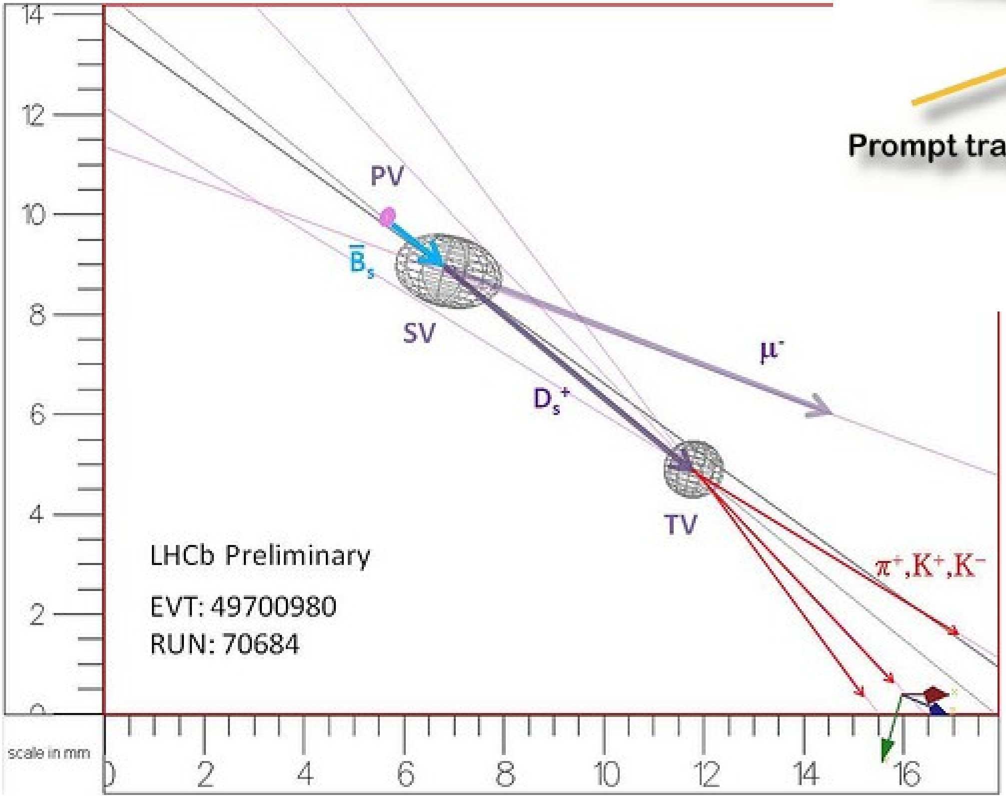
Date: 2010-04-24 04:18:53 CEST

Event with 4 Pileup Vertices in 7 TeV Collisions

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.

Role 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

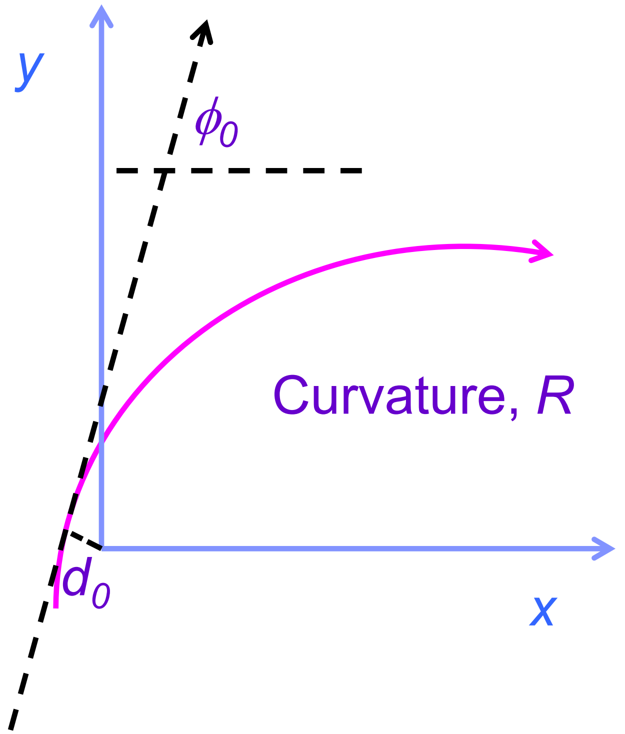
- Focus today on vertexing, tracking and measuring material…

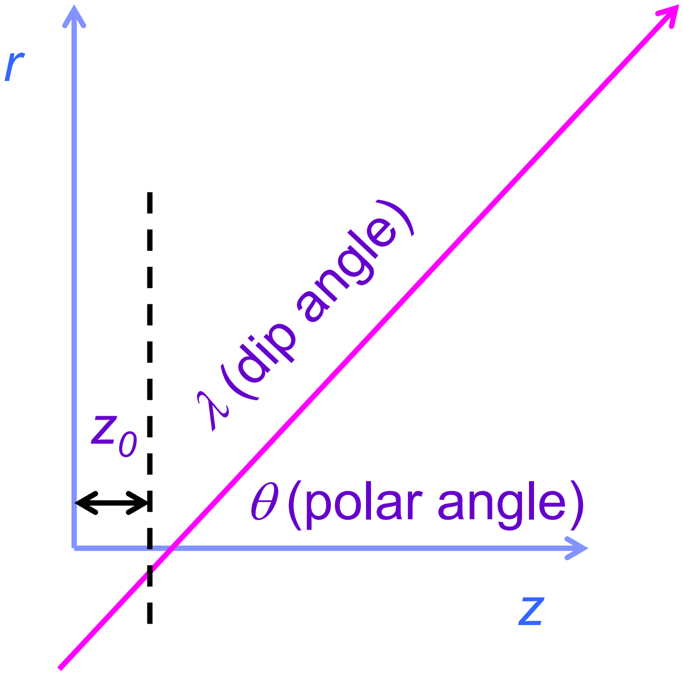
Track coordinates

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

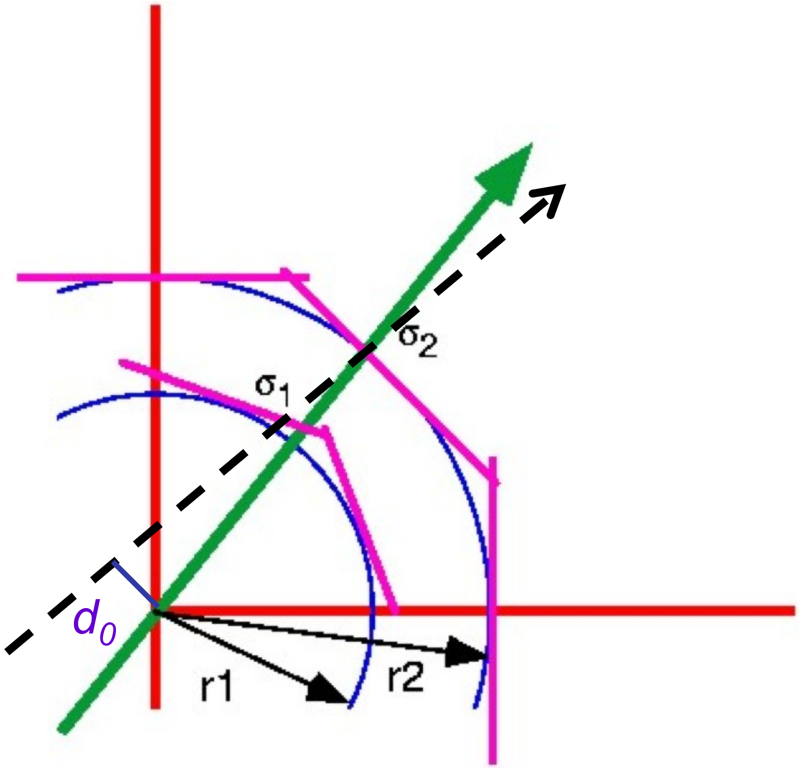




Impact parameter resolution

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

Simplified formula for just two layers:



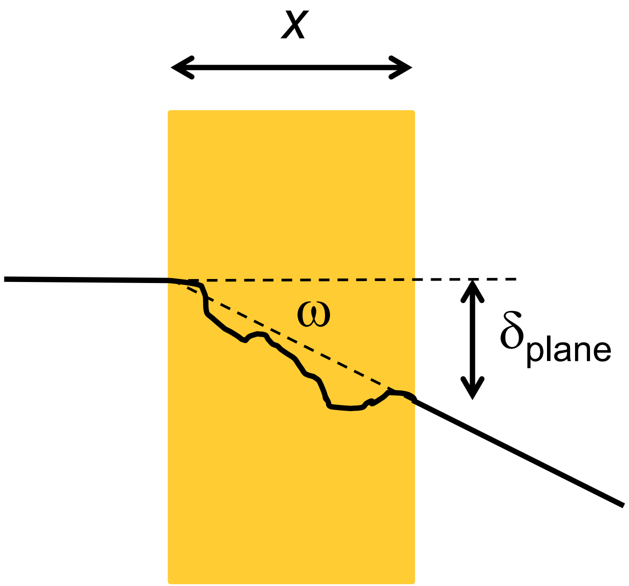
$$\sigma_{d_0}^2 = \frac{r_2^2\sigma_1^2 + r_1^2\sigma_2^2}{(r_2 - r_1)^2}$$

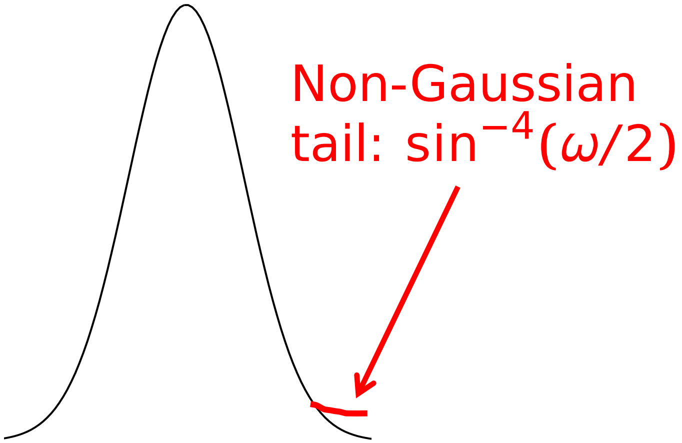
Suggests small r_1, large r_2, small σ_1, σ_2

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)

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

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

Transverse IP resolution

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

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

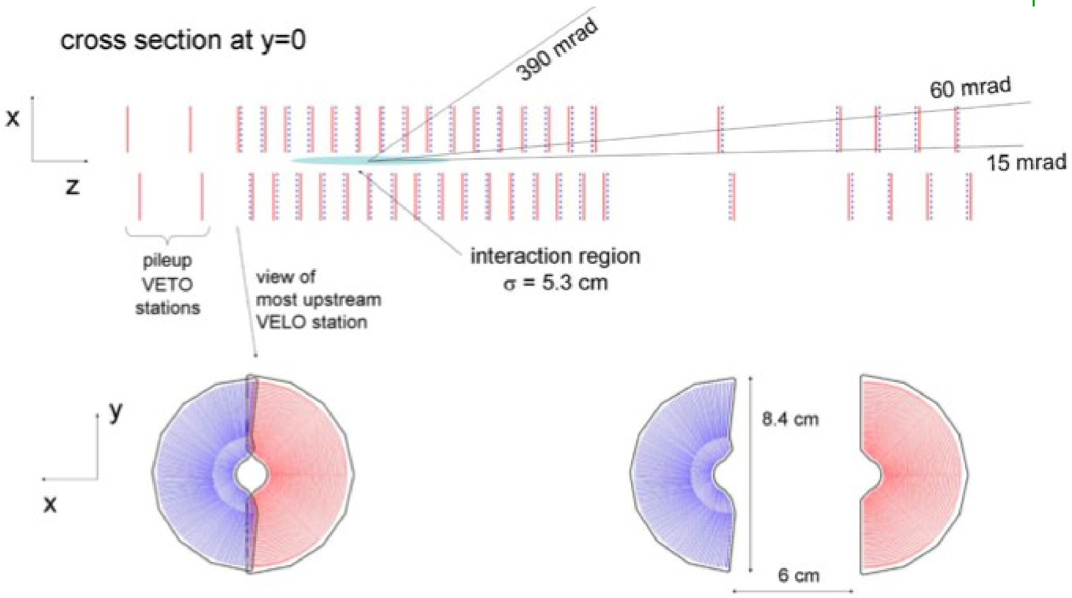
and term depending on material, decreasing with p_T

Summary of pixel layouts

	ALICE	ATLAS	CMS
Radii (mm)	39 – 76	50.5 – 88.5 – 122.5	44 – 73 – 102
Pixel size $r\phi$ x z (μm^2)	50 x 425	40 x 400	100 x 150
Thickness (μm)	200	250	285
Resolution $r\phi$ / z	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 it is stable.

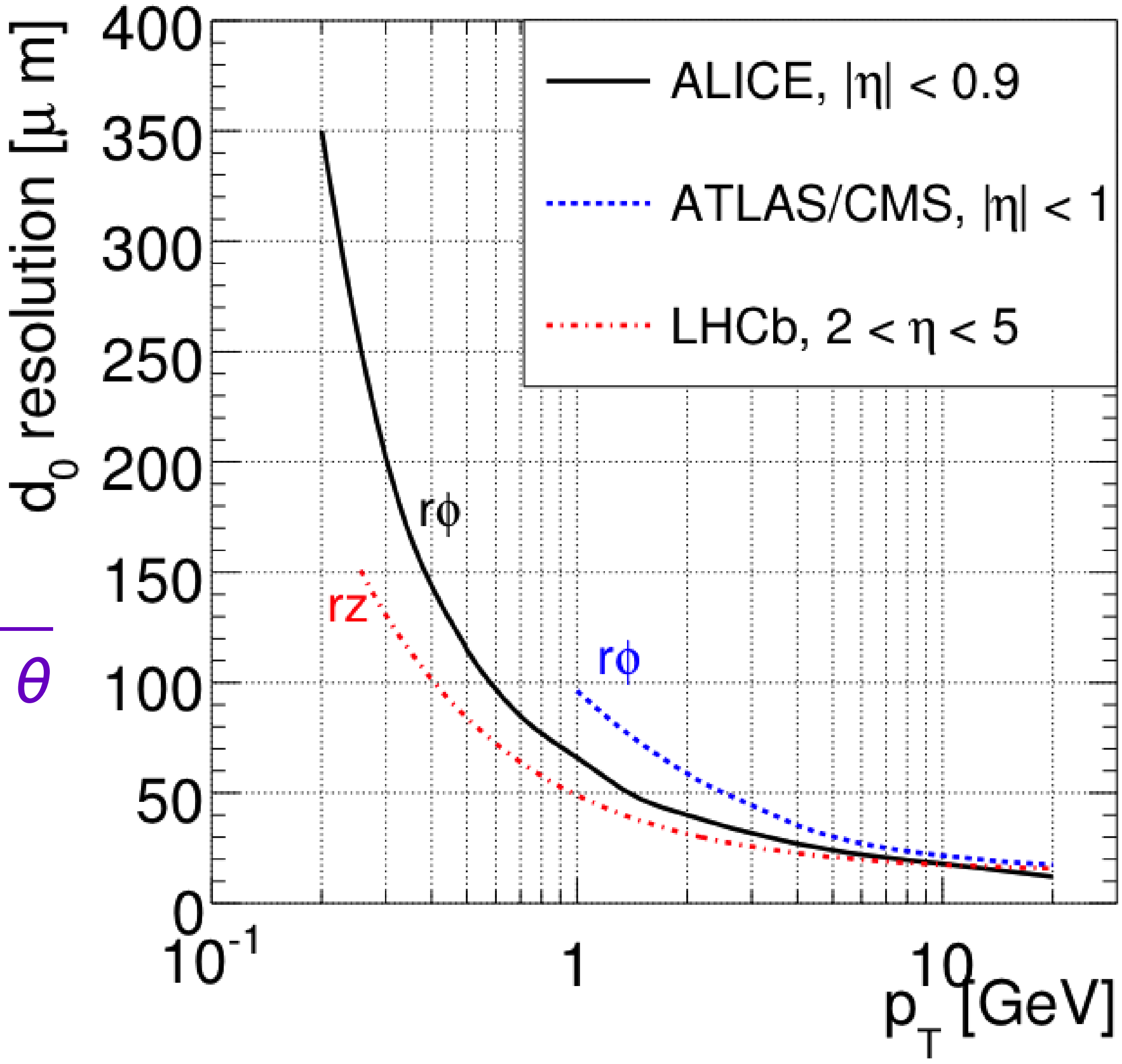


VELO fully closed
(stable beam)

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:

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

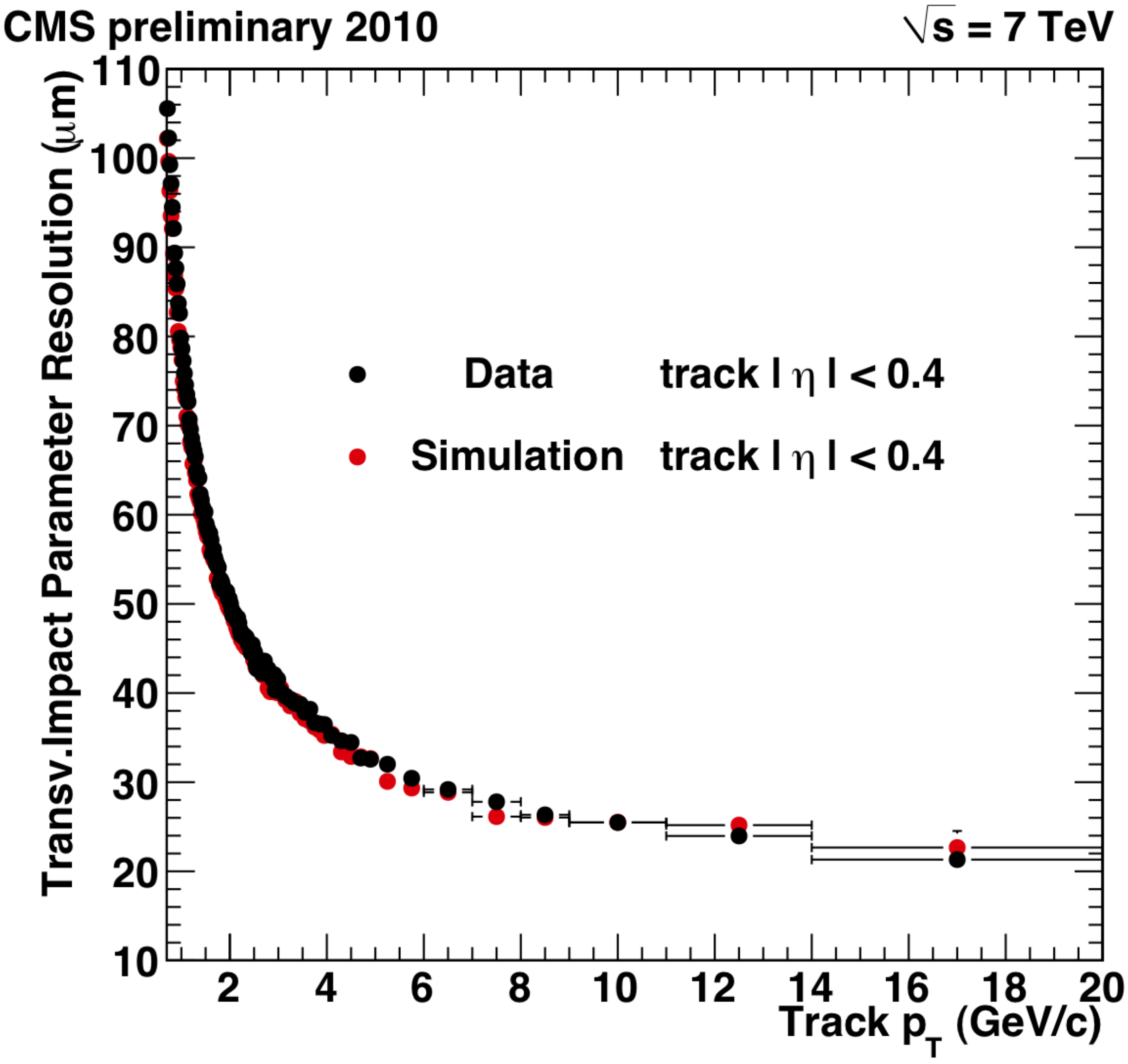
ATLAS/CMS expect:

100 μm @ 1 GeV,

20 μm @ 20 GeV

CMS-PAS-TRK-10-005

IP resolutions



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

Observed:

100 μm @ 1 GeV,

20 μm @ 20 GeV

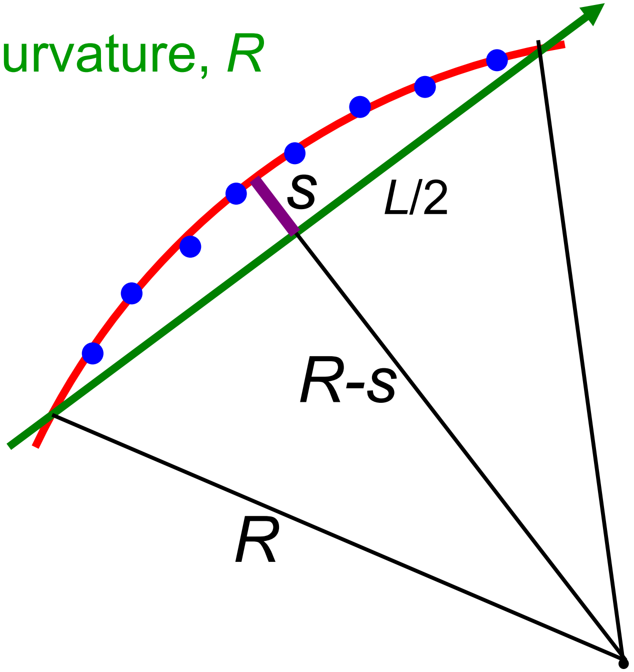
Measuring momentum

- 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

Precision in 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, so for σ_s:

Multiple scattering contribution:
(L is in the transverse plane)

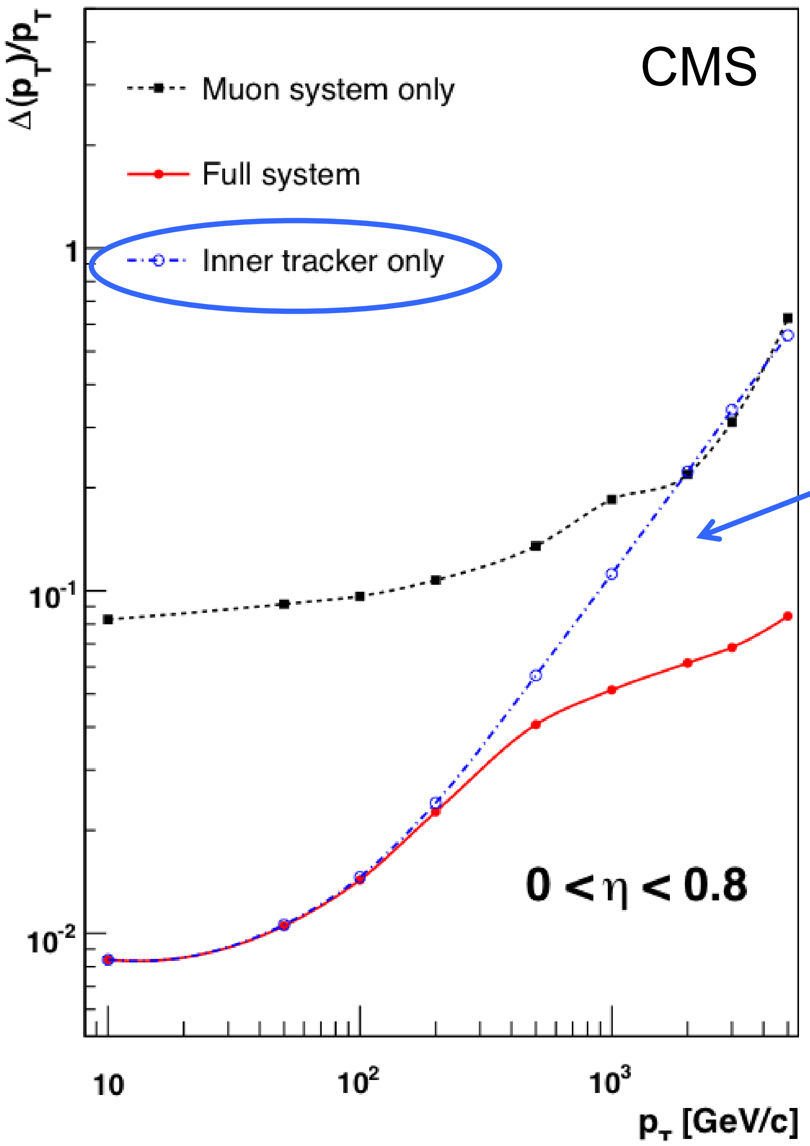
$$\sigma_s \propto \frac{L}{p_T \sin^{1/2}\theta}\sqrt{\frac{L}{X_0}}$$

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

Momentum resolution

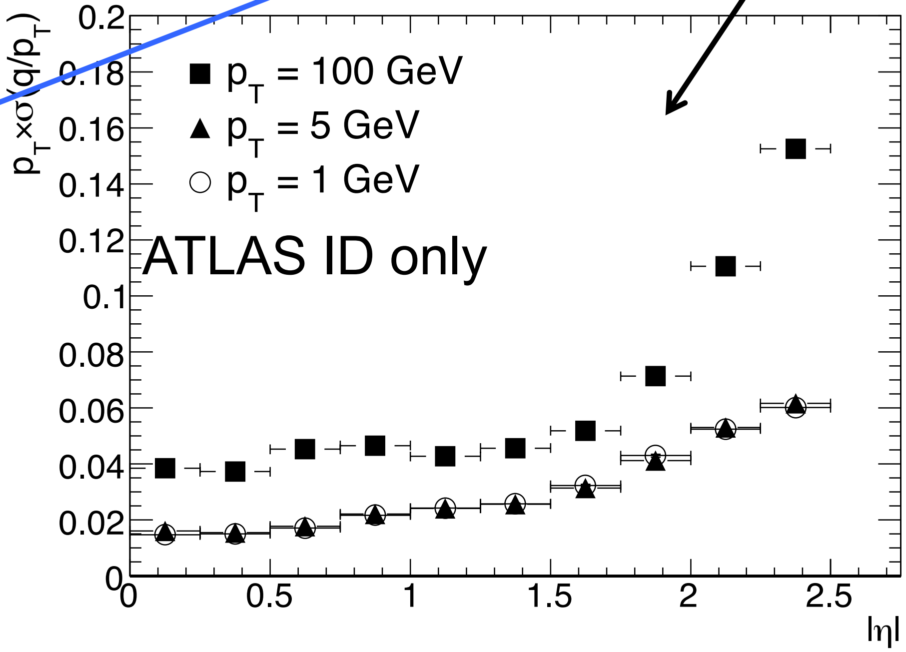
2008 JINST 3 S08004 CMS Experiment

2008 JINST 3 S08003 ATLAS Experiment



Expected relative p_T resolution for muons vs |η| and p_T.

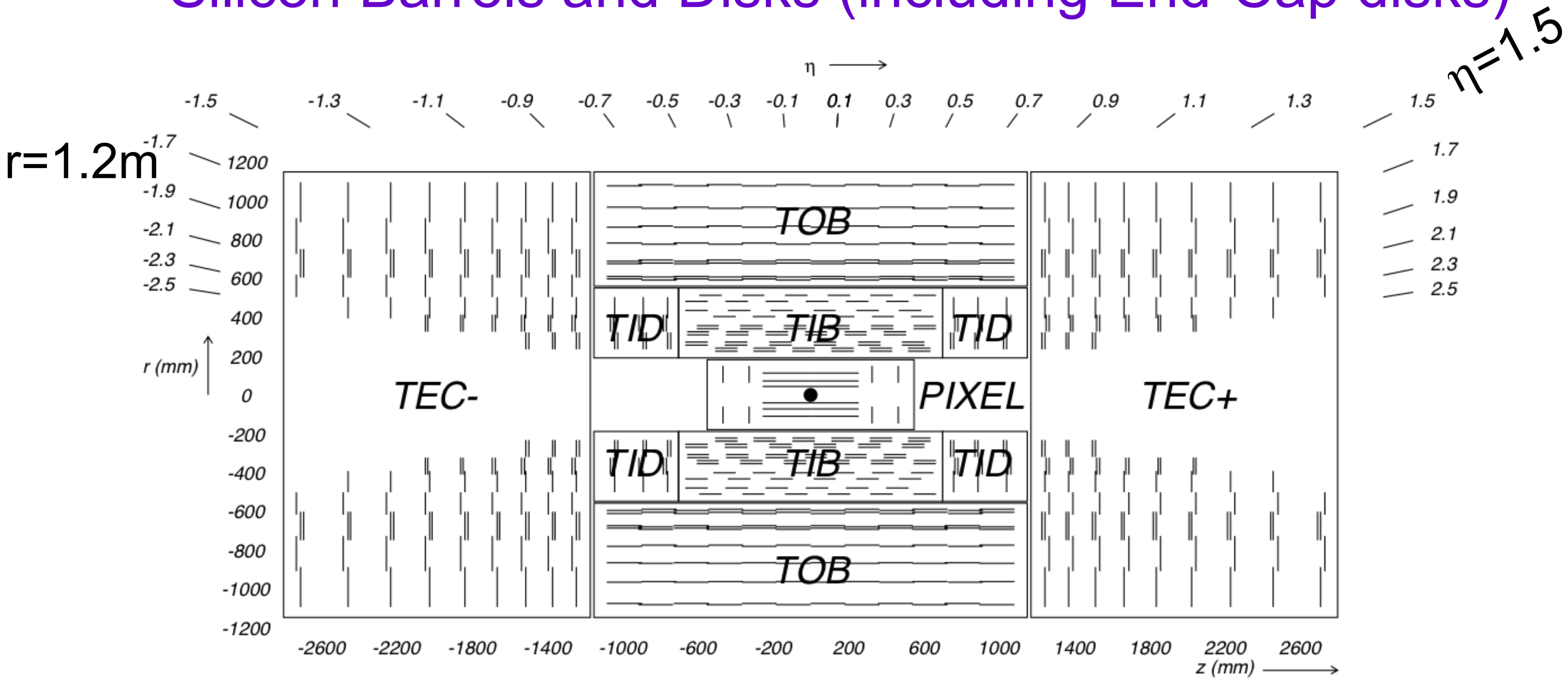
$$\frac{\sigma_{p_T}}{p_T} \approx a \cdot p_T \oplus \frac{b}{\sin^{1/2}\theta}$$



(More material) →

CMS tracker layout

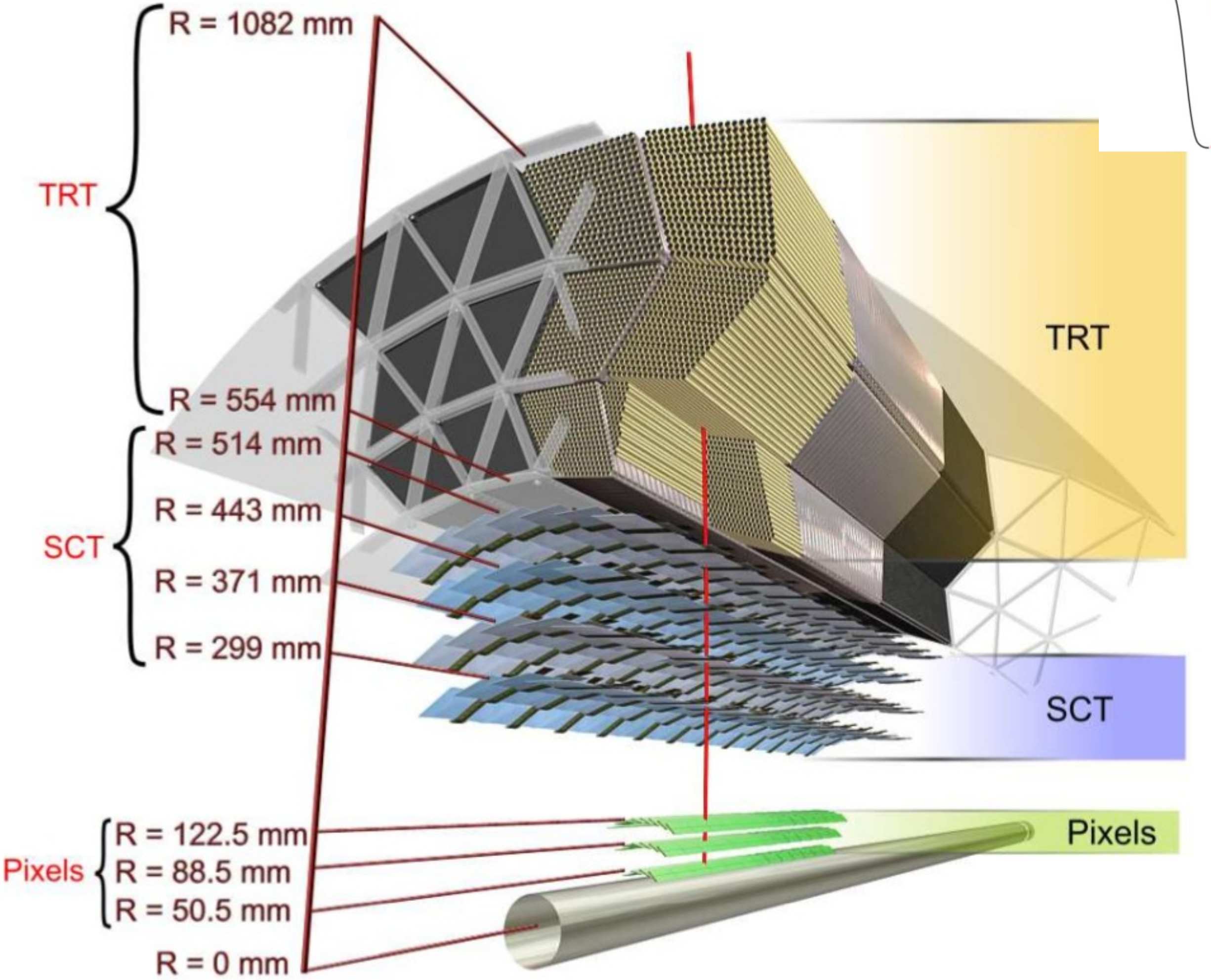
- Silicon Barrels and Disks (including End-Cap disks)

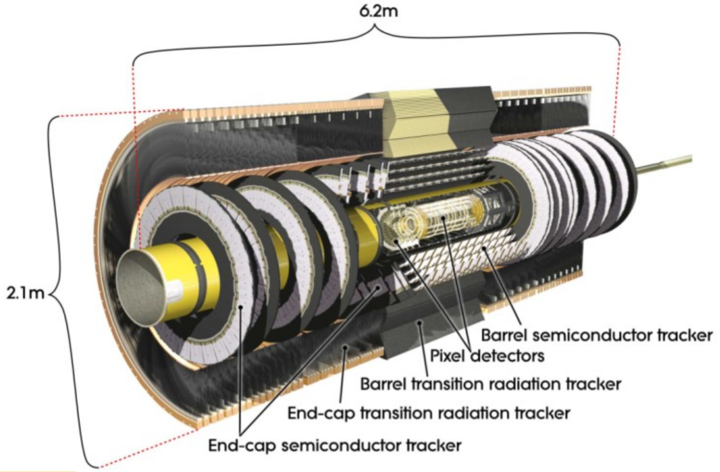


- Barrels have 3 pixel layers and 10 microstrip layers
    - Inner strips 10cm x 80 to 120 μm (320 μm thick)
    - Outer strips 25cm x 180 to 120 μm (500 μm thick for S/N)
    - 4 strip layers have additional stereo module for z coordinate

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

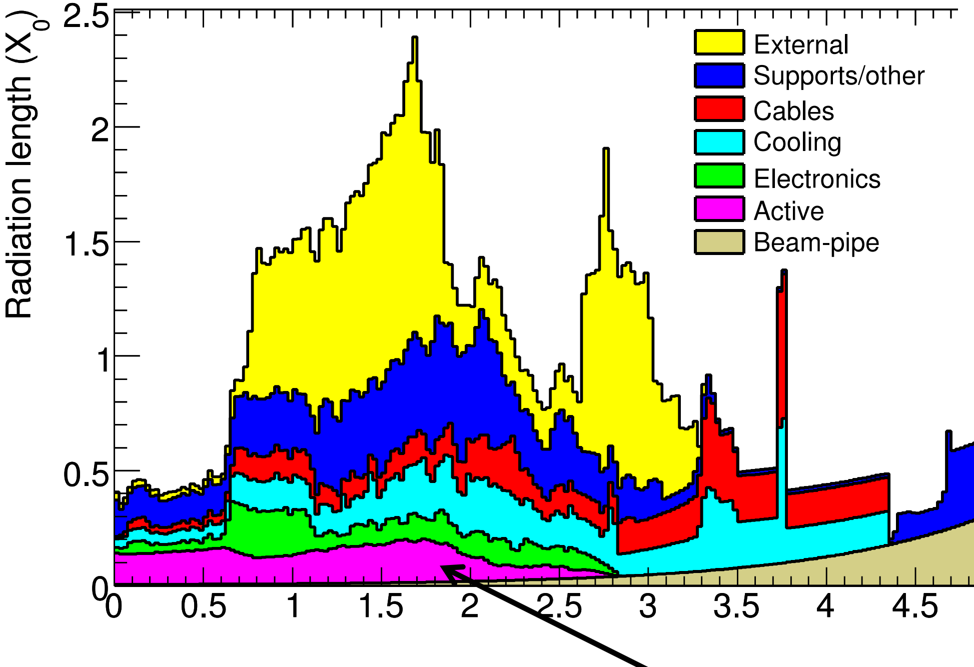
3 pixel layers, 250μm thick

Material

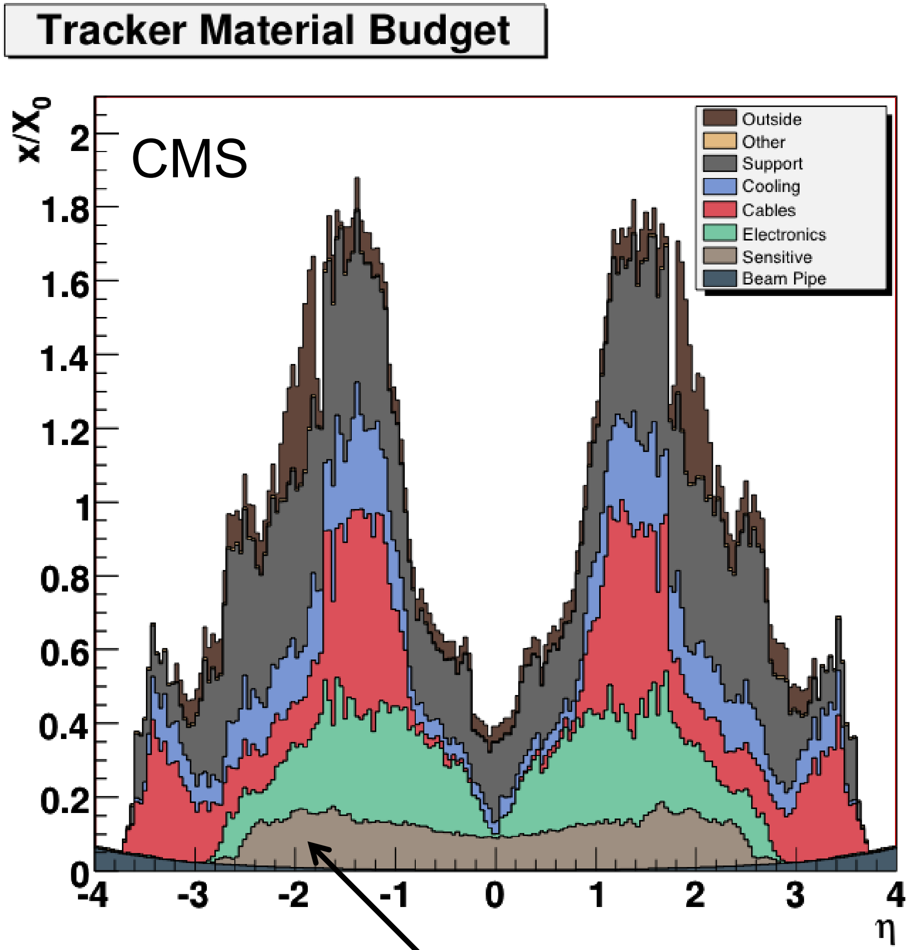
Big contributions from

supports, cables,

cooling, electronics…


ATLAS Inner Detector

Sensitive material

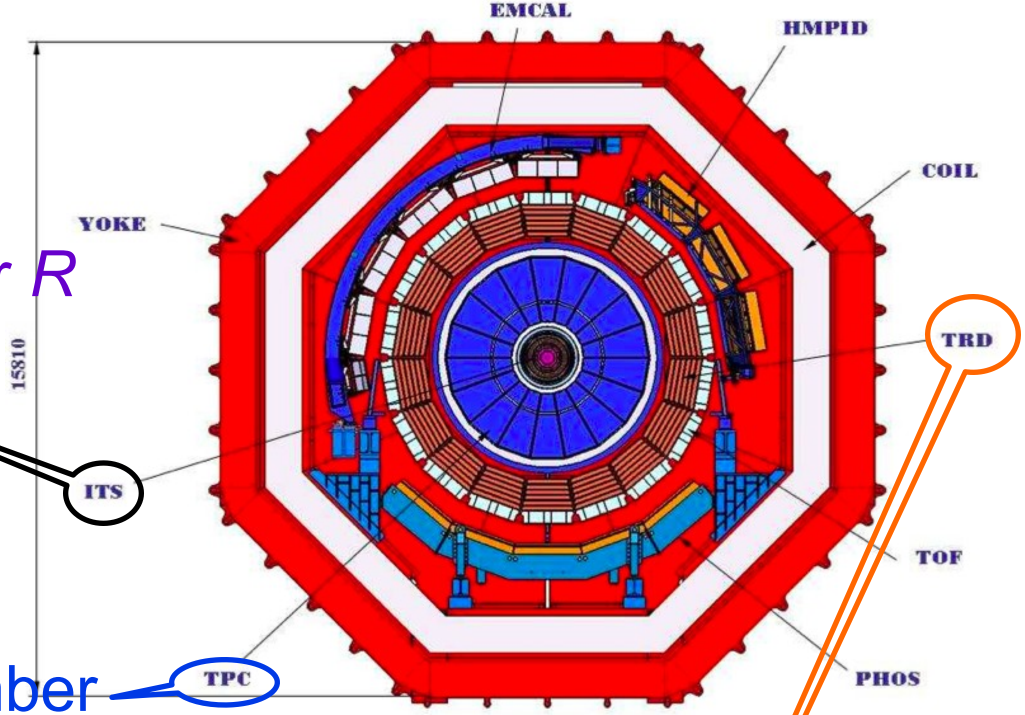

Tracker Material Budget

Sensitive material

2008 JINST 3 S08004 CMS Experiment

2008 JINST 3 S08003 ATLAS Experiment

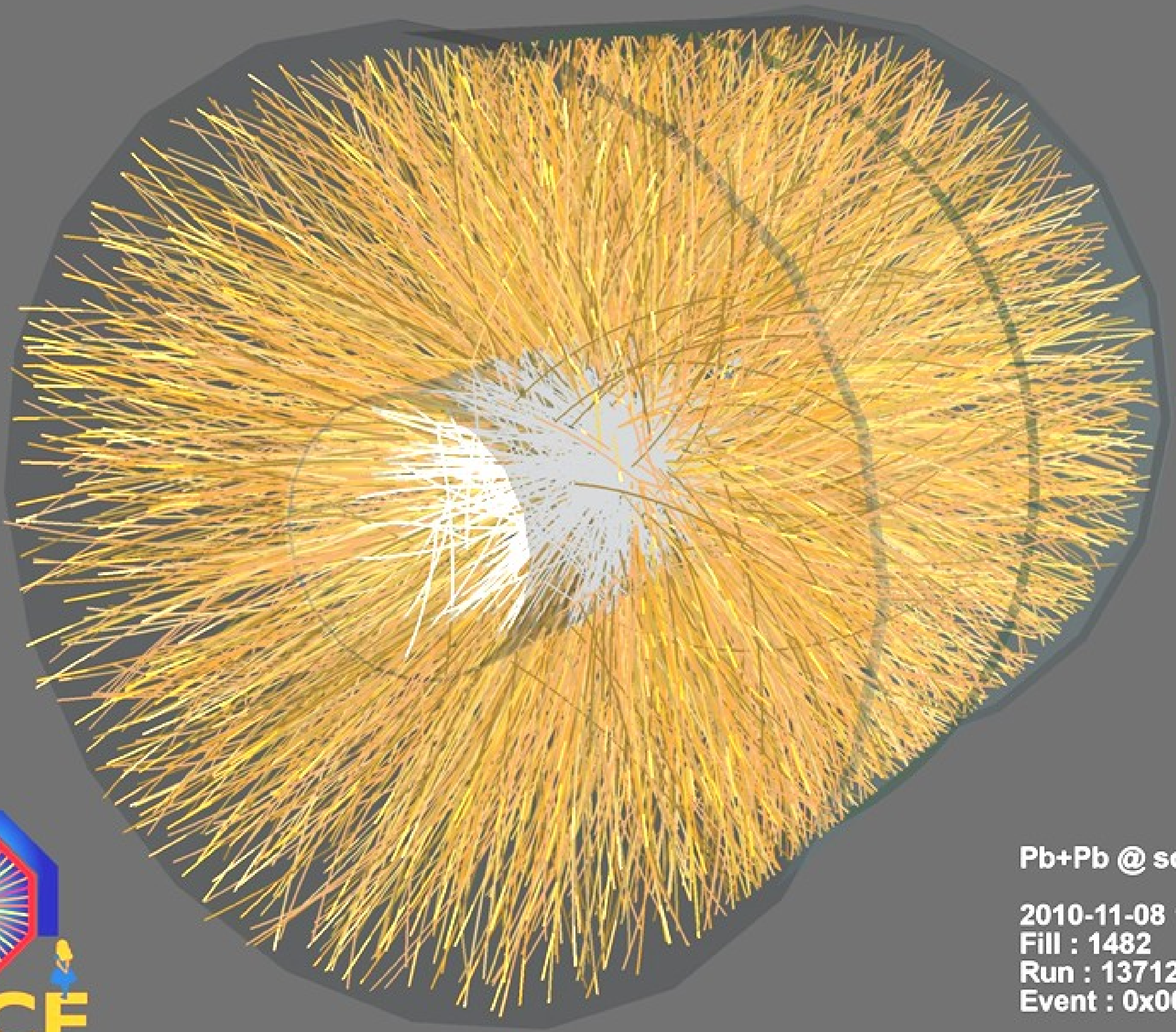
ALICE



- 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

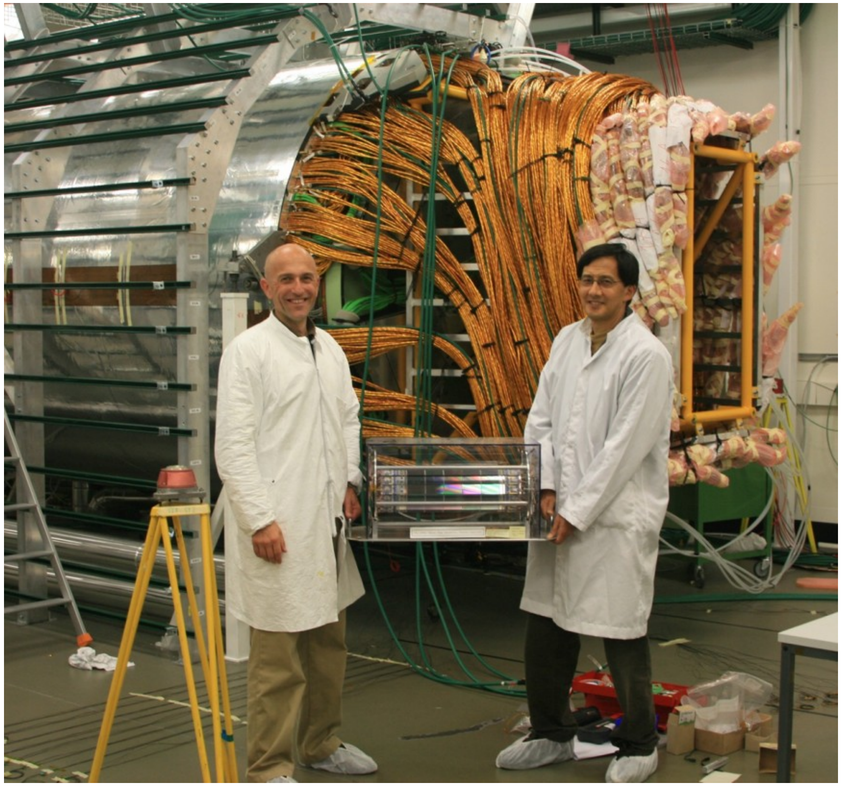
ALICE heavy ion event display



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!)

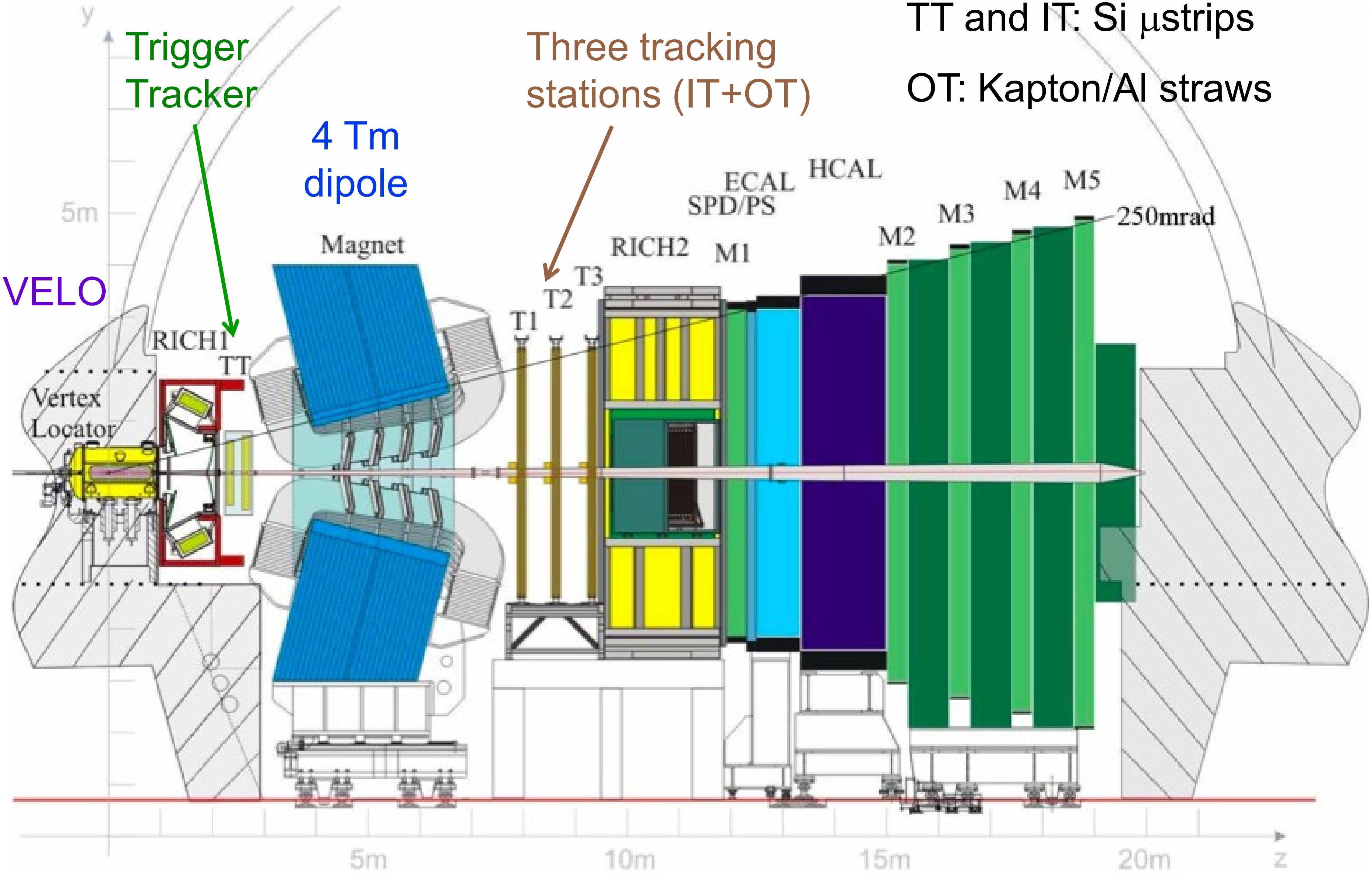
2008 JINST 3 S08005 LHCb Detector

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
$\|\eta\|$ 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

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 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

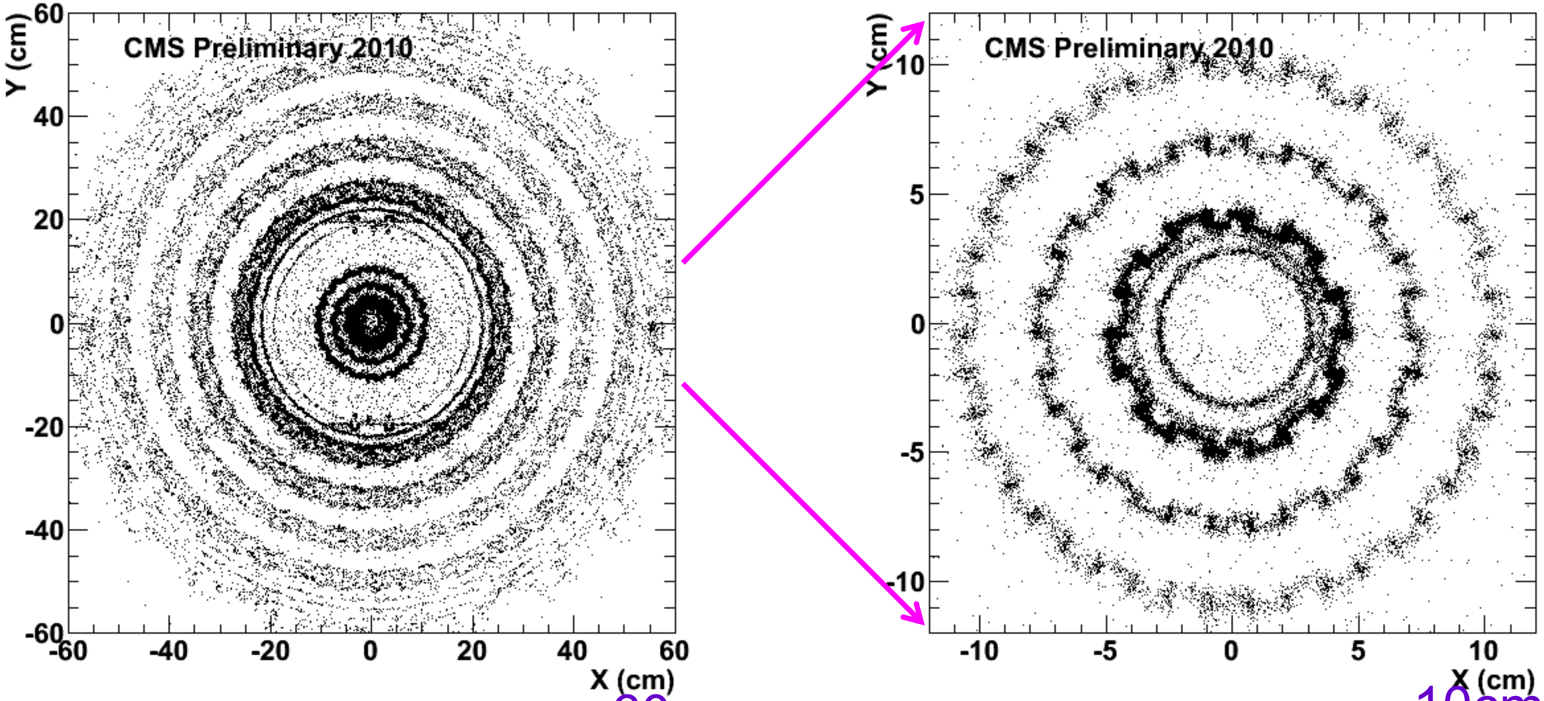
Weighing detectors after construction

- 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

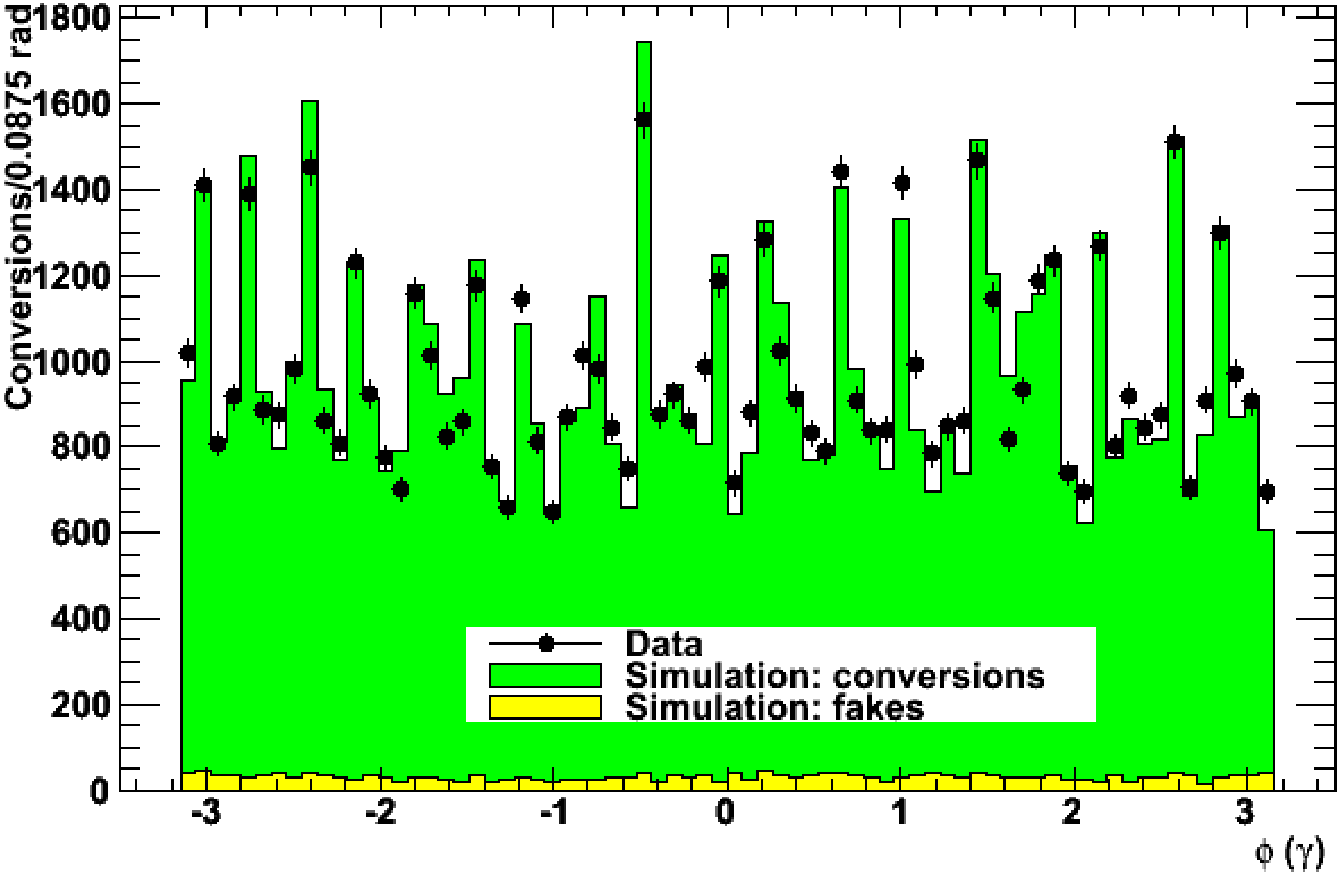


60cm

10cm

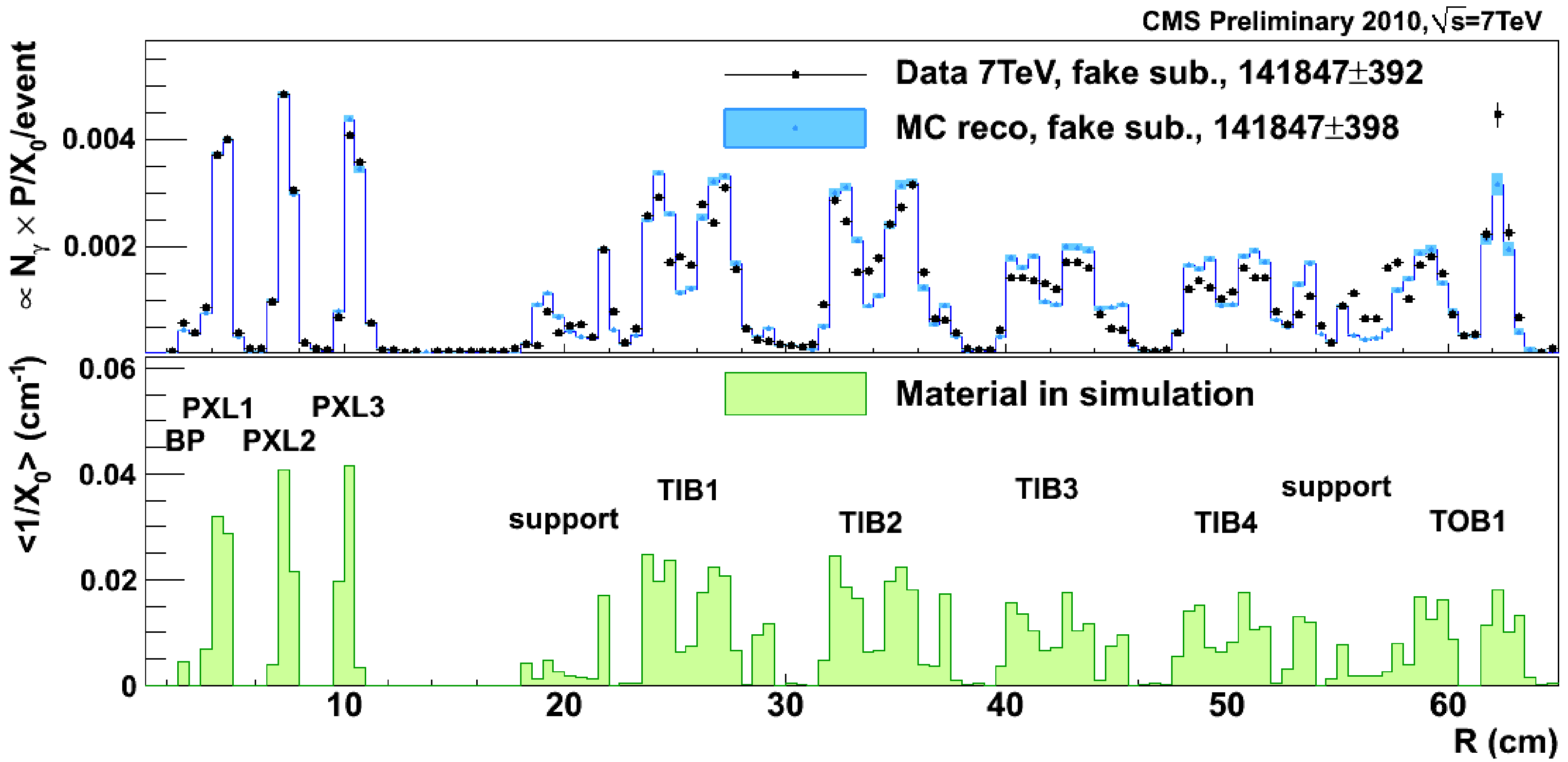
CMS conversions in pixel barrel

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



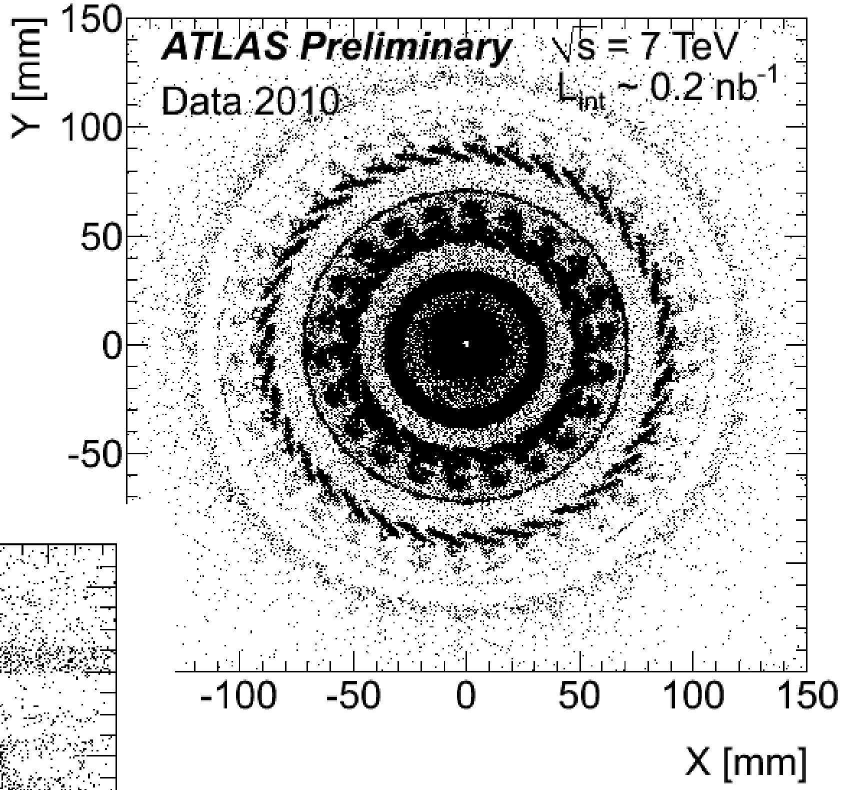
CMS conversions

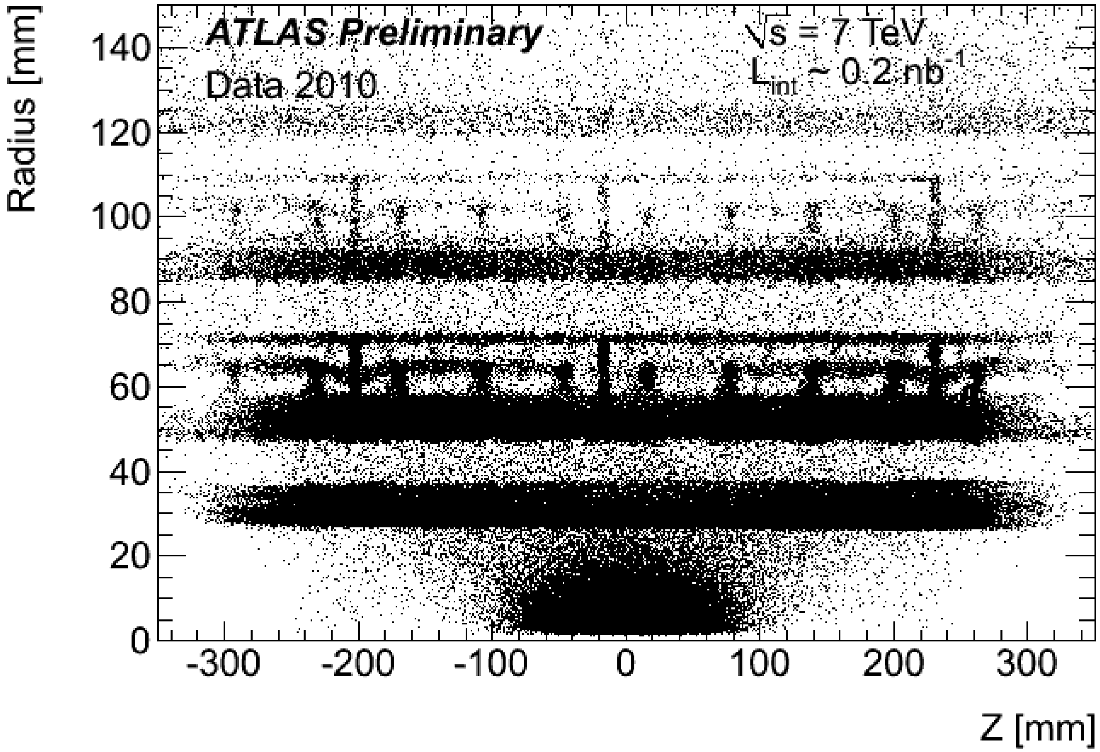
- Correct for identification efficiency to make a quantitative measurement of pixel and inner tracker barrel material
- Relative agreement between data and simulation ~10%
- Local discrepancy for support between TIB and TOB



Nuclear interactions

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



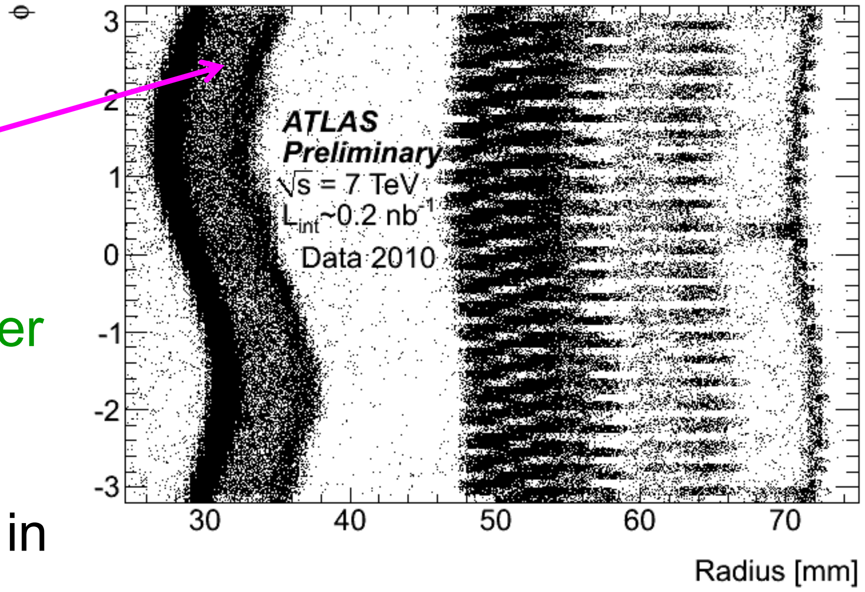


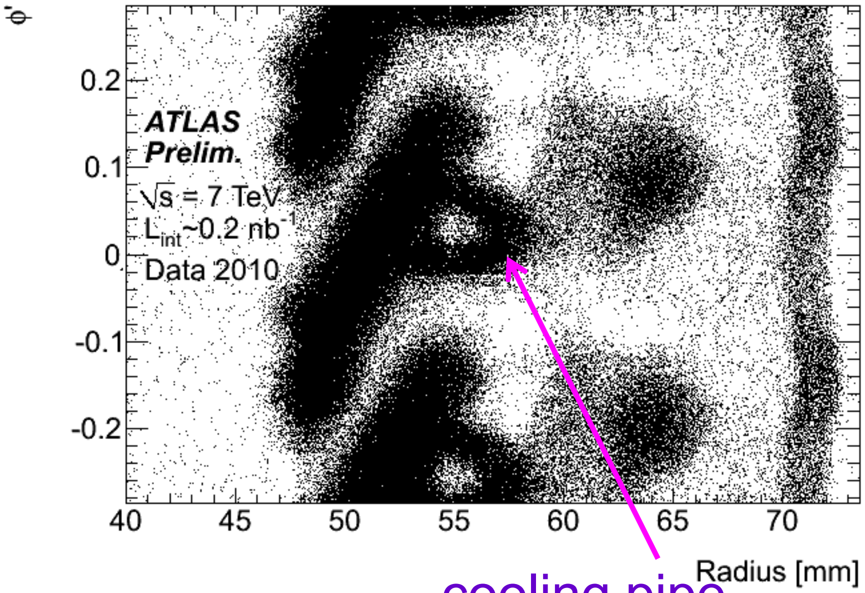
- x-y view for |z|< 300mm
- Sensitive to interaction lengths

ATLAS-CONF-2010-058

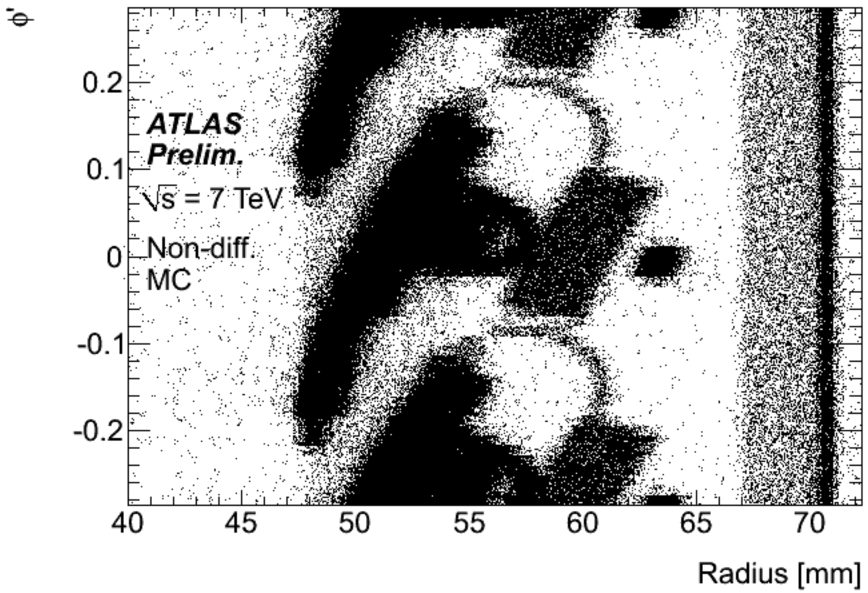
Interactions rϕ plots

- 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.



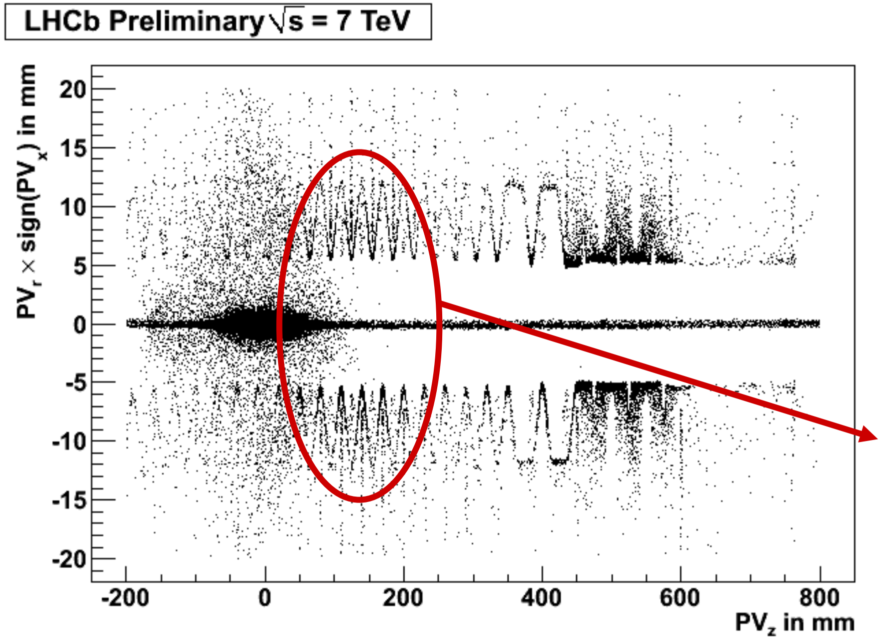


cooling pipe

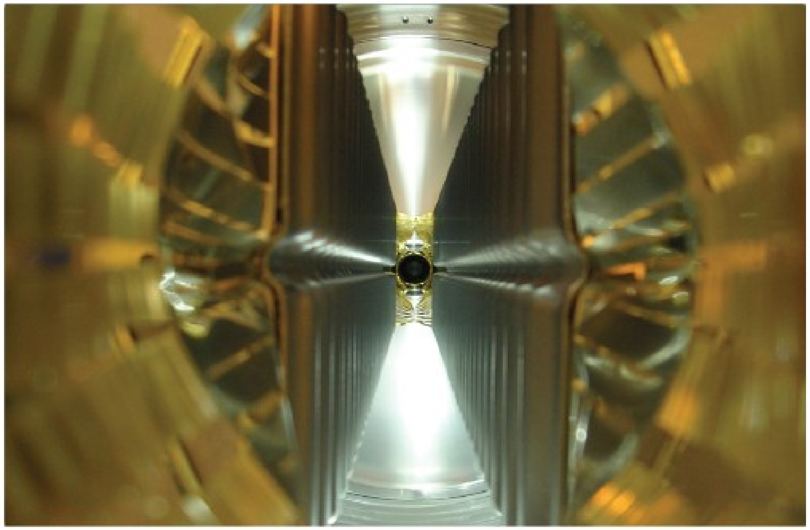


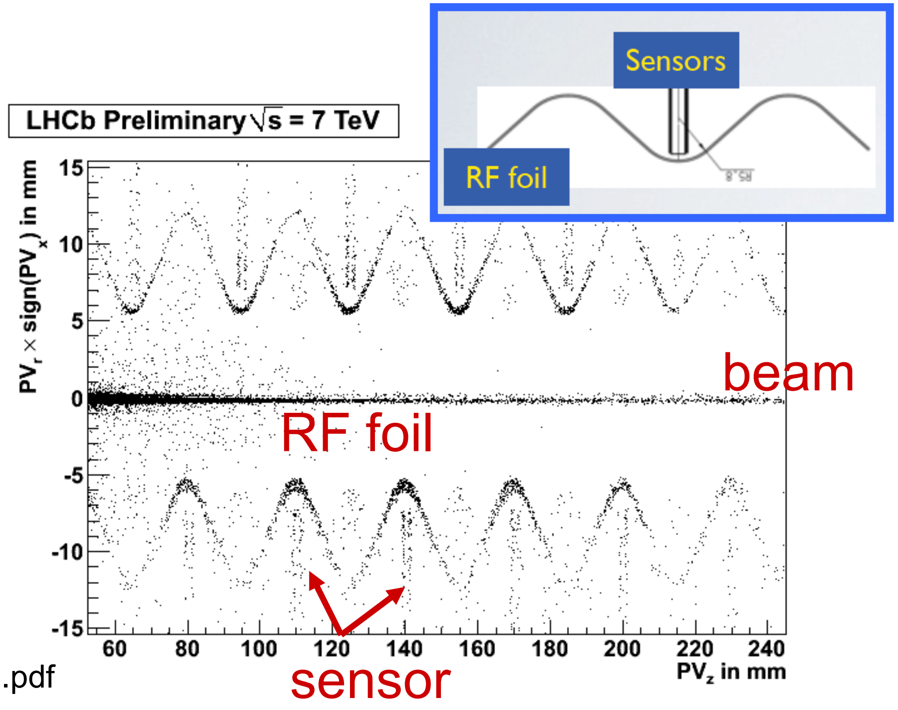
LHCb VELO material

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



RF foil photo with VELO open

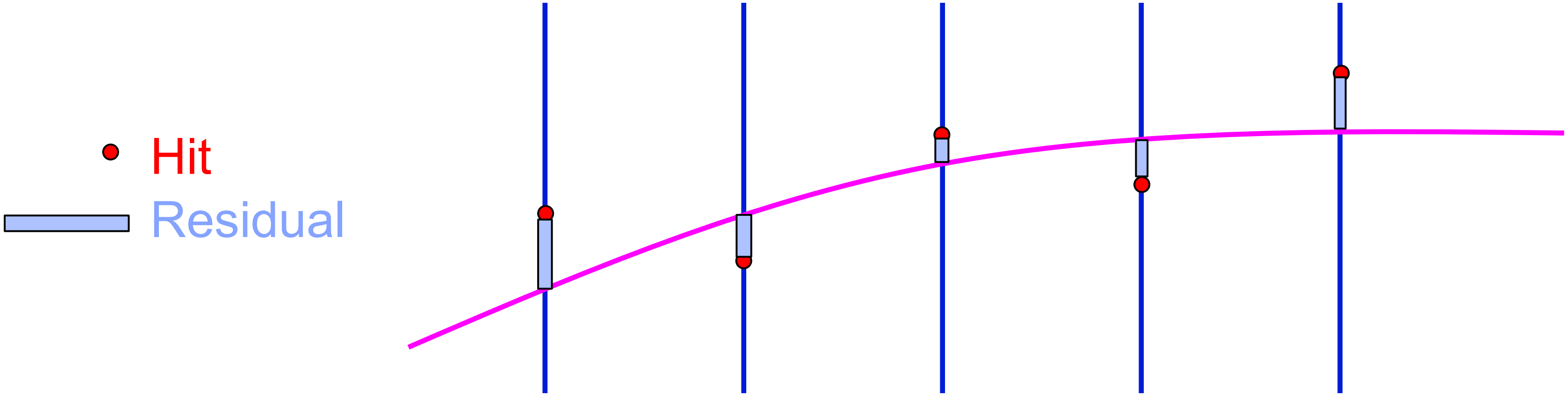




http://cdsweb.cern.ch/record/1271471/files/LHCb-TALK-2010-052.pdf

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.

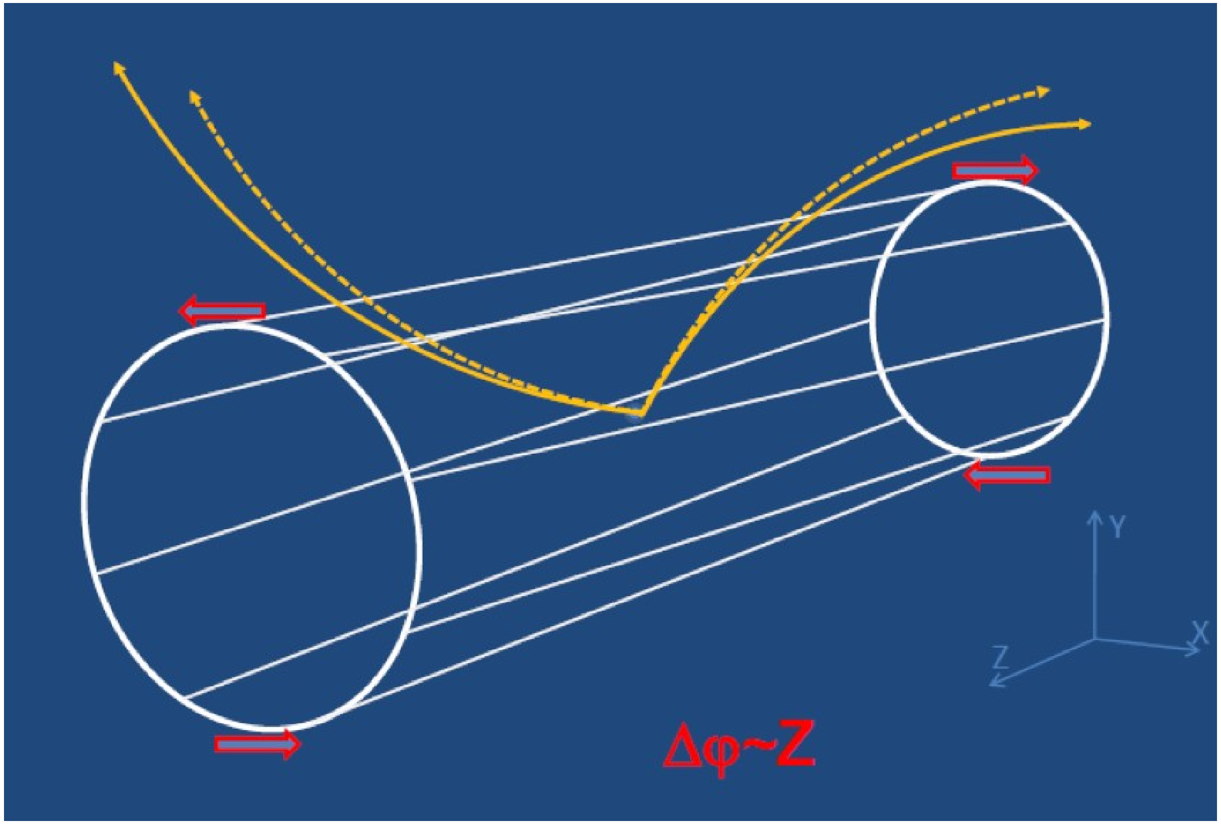


from F. Meier

Alignment performance

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

Track residuals can be minimised but p_T is biassed.

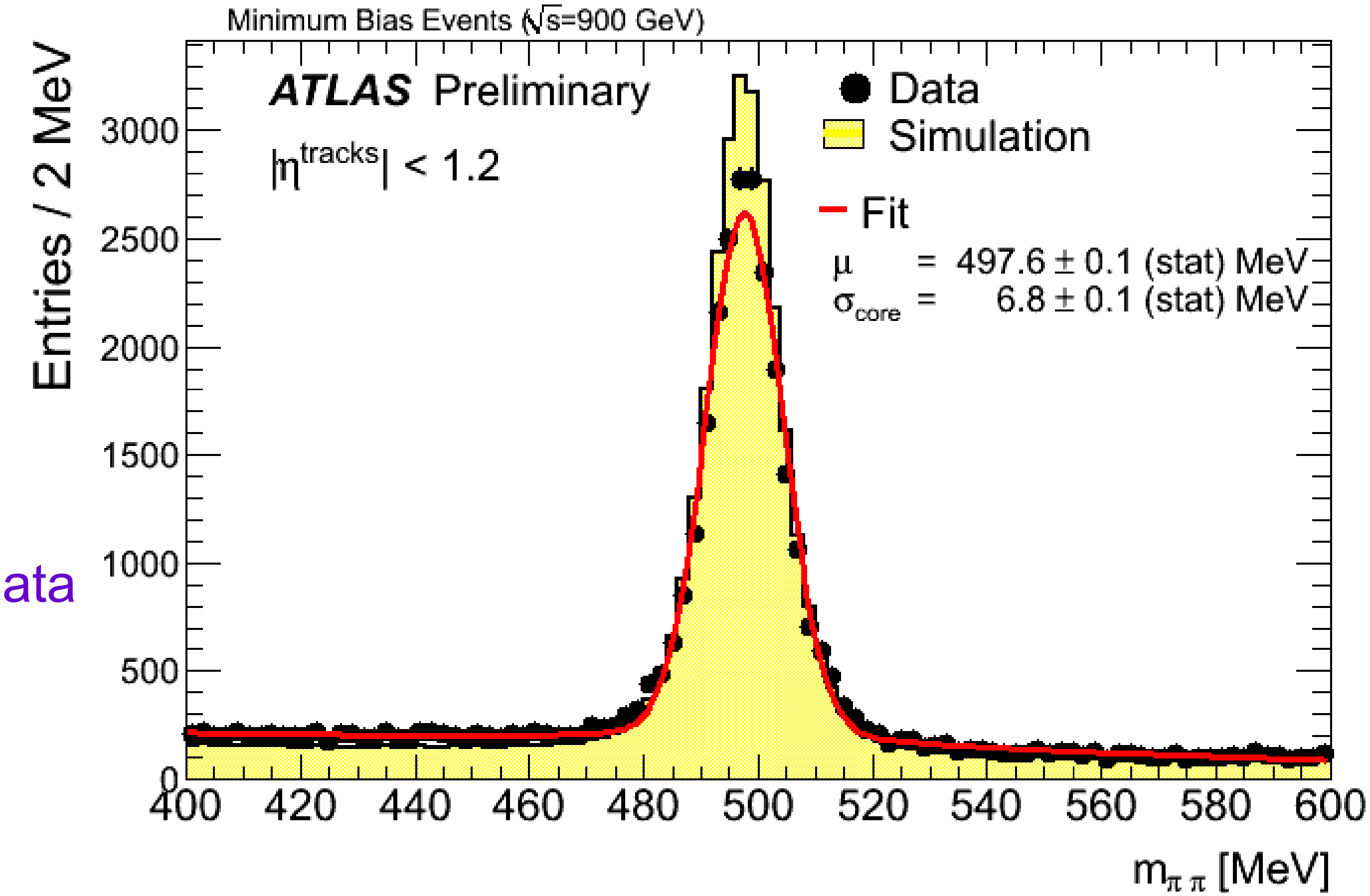


from P. Brückman de Renstrom

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

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

PDG value 497.614 ± 0.024 MeV

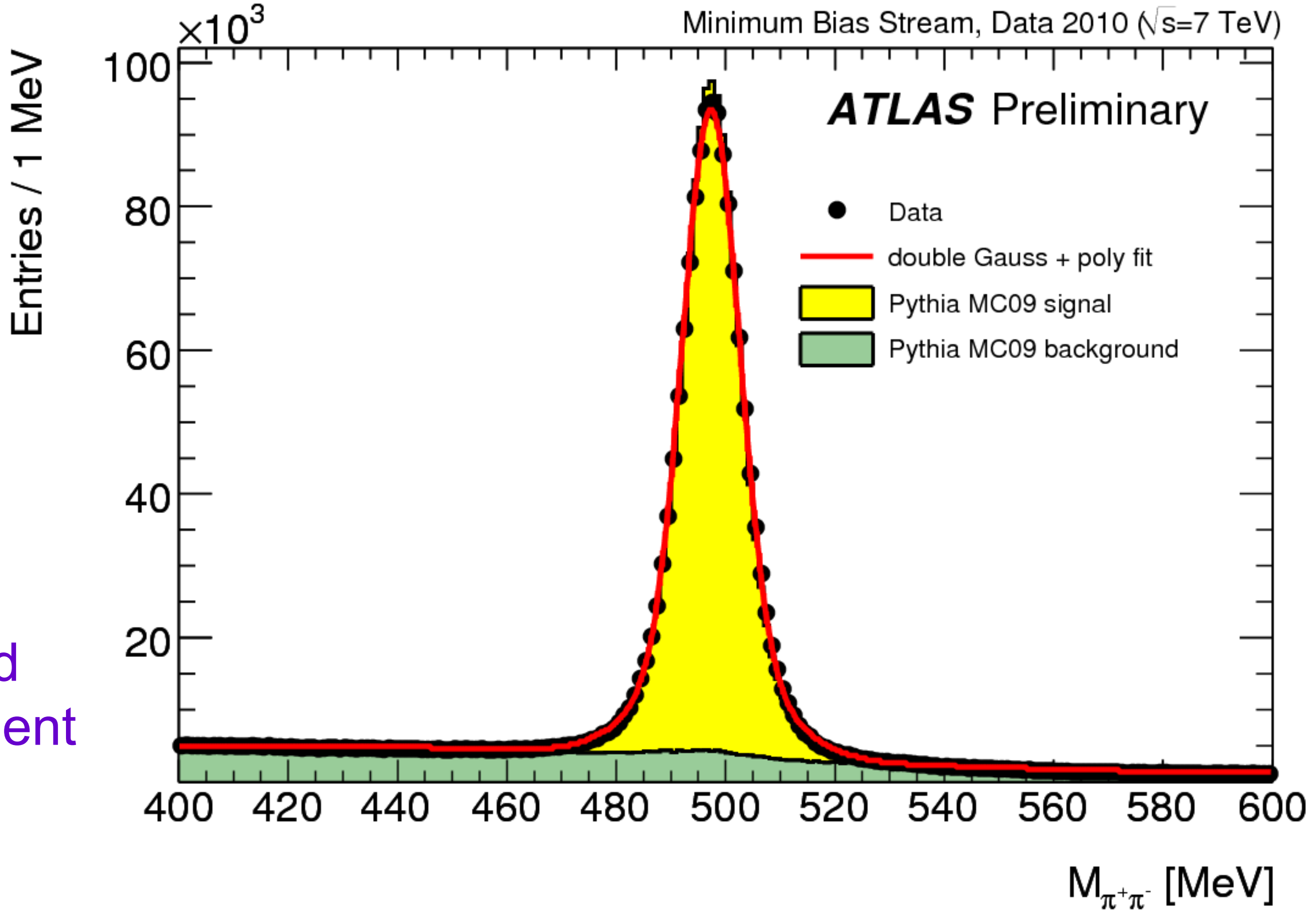


ATLAS example:2009 data slightly broader than simulation

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.
PDG value 497.614 ± 0.024 MeV

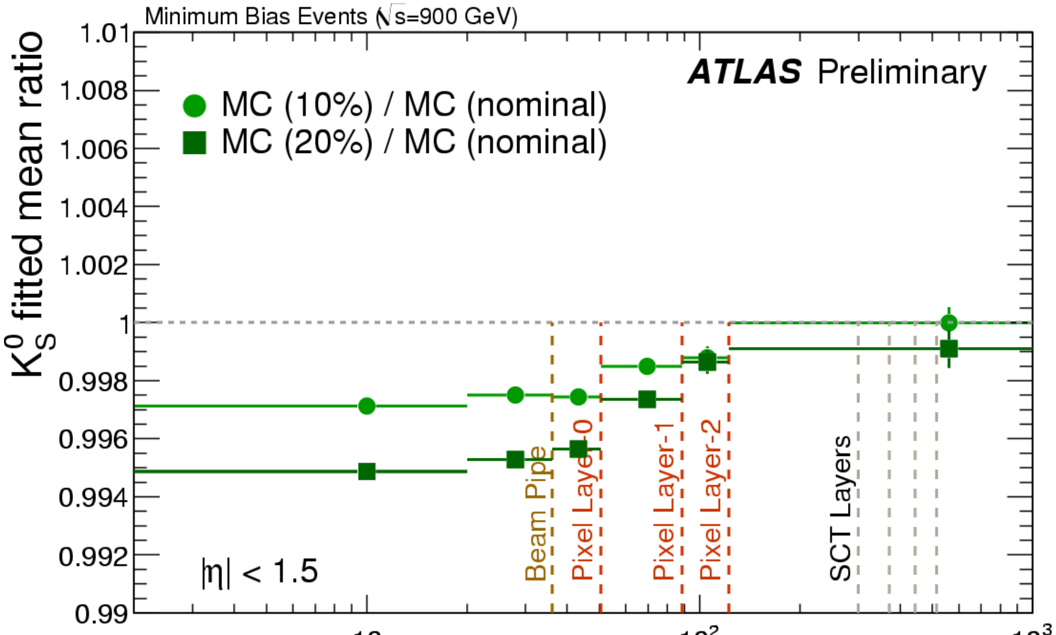


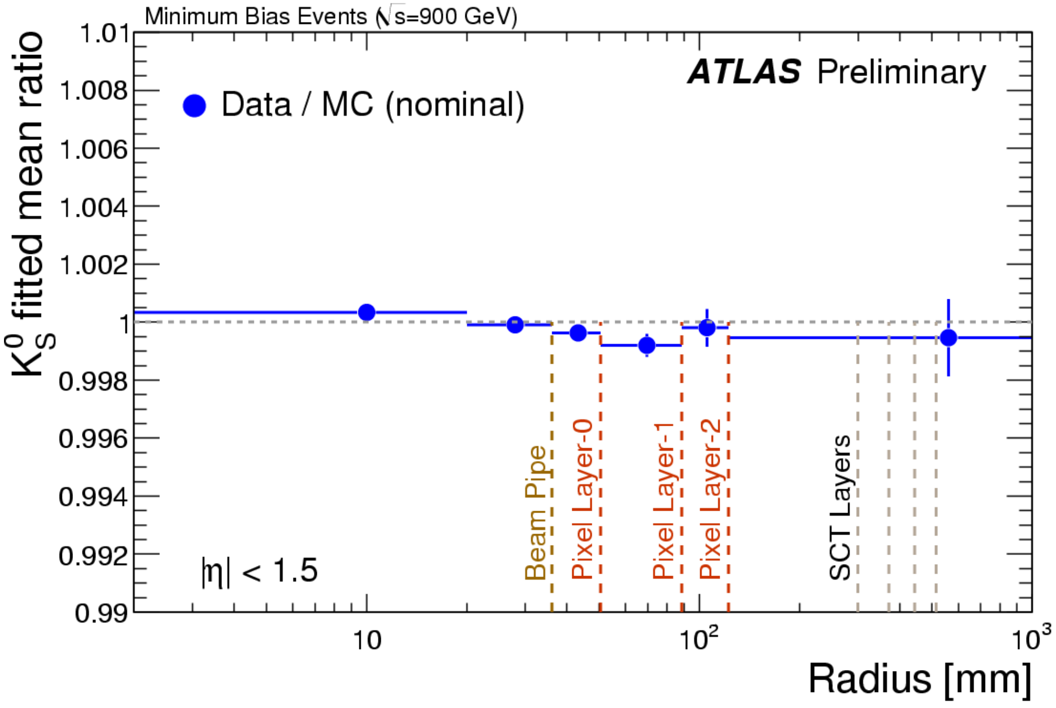
Much better agreement with 2010 sample and improved alignment

ATLAS-CONF-2010-033

K^0_s and material

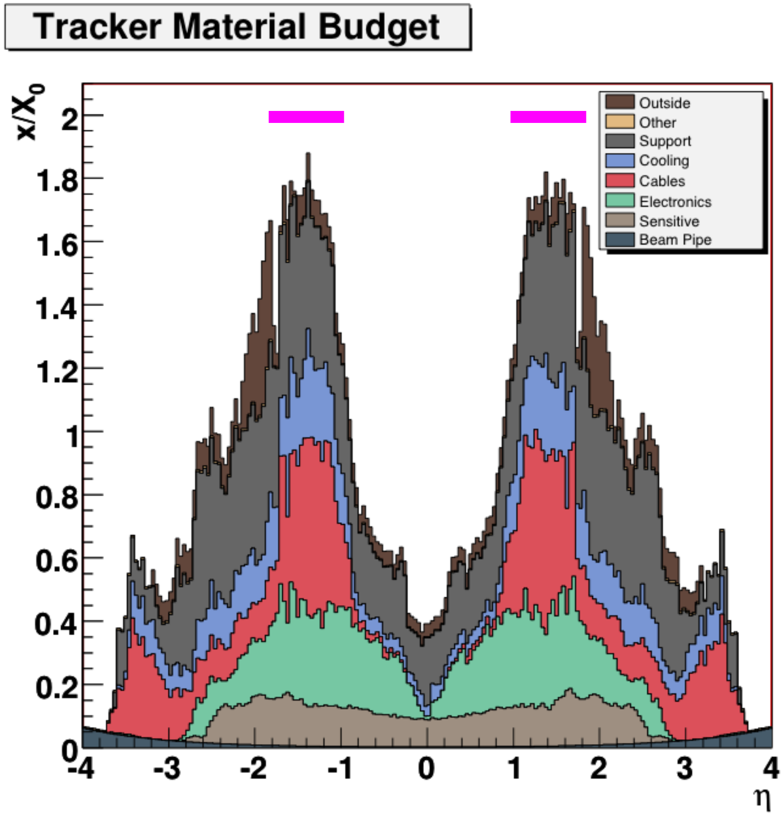
- Look at fitted mass as a function of decay radius
- Data consistent with nominal MC

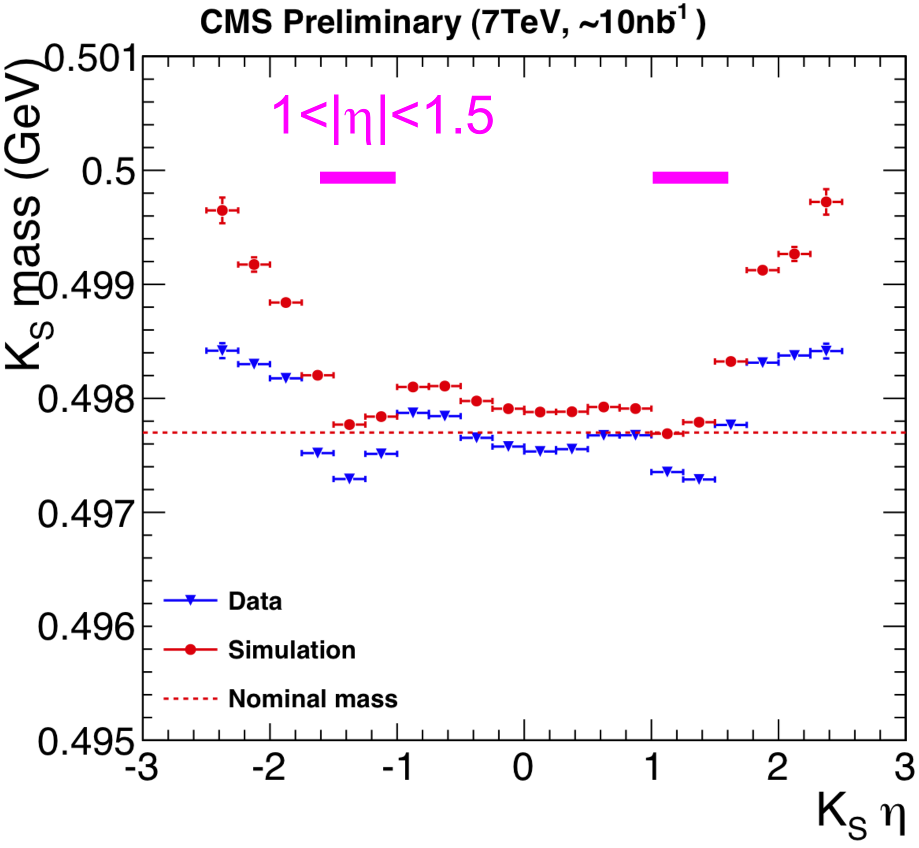




- MC with 10% or 20% extra material predicts much bigger deviations
- With larger data samples, make finer binned studies in future

K^0_s mass in CMS





CMS example: K^0_s mass vs η

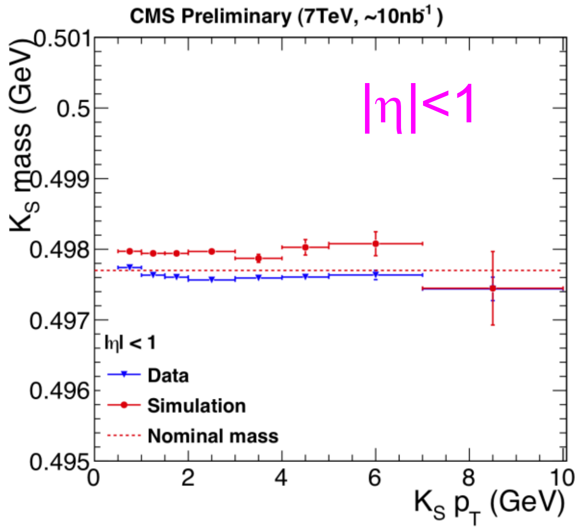
1<|η|<1.5 is most difficult to model

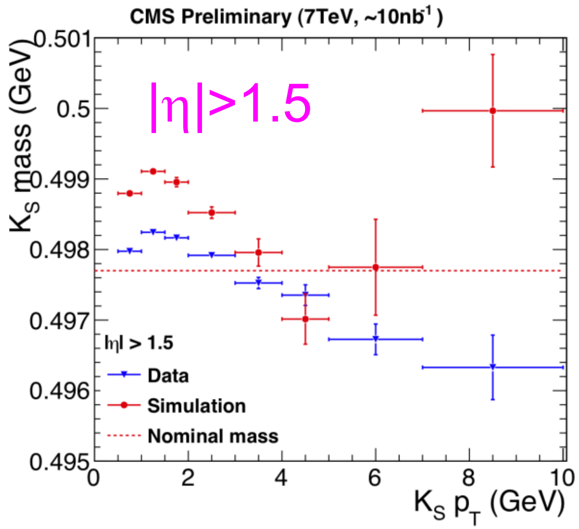
Mass shifted upwards in simulation

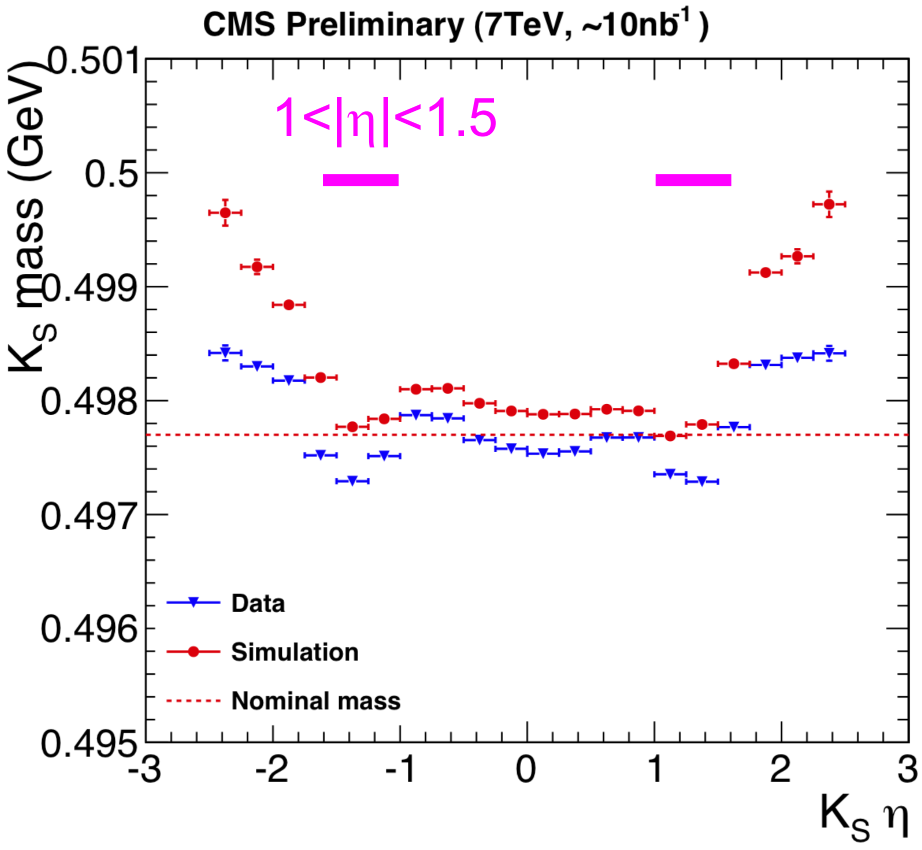
Same trend with η in data

CMS-PAS-TRK-10-004

K^0_s mass in CMS







CMS example: K^0_s mass vs η and p_T

1<|η|<1.5 is most difficult to model

Mass shifted upwards in simulation

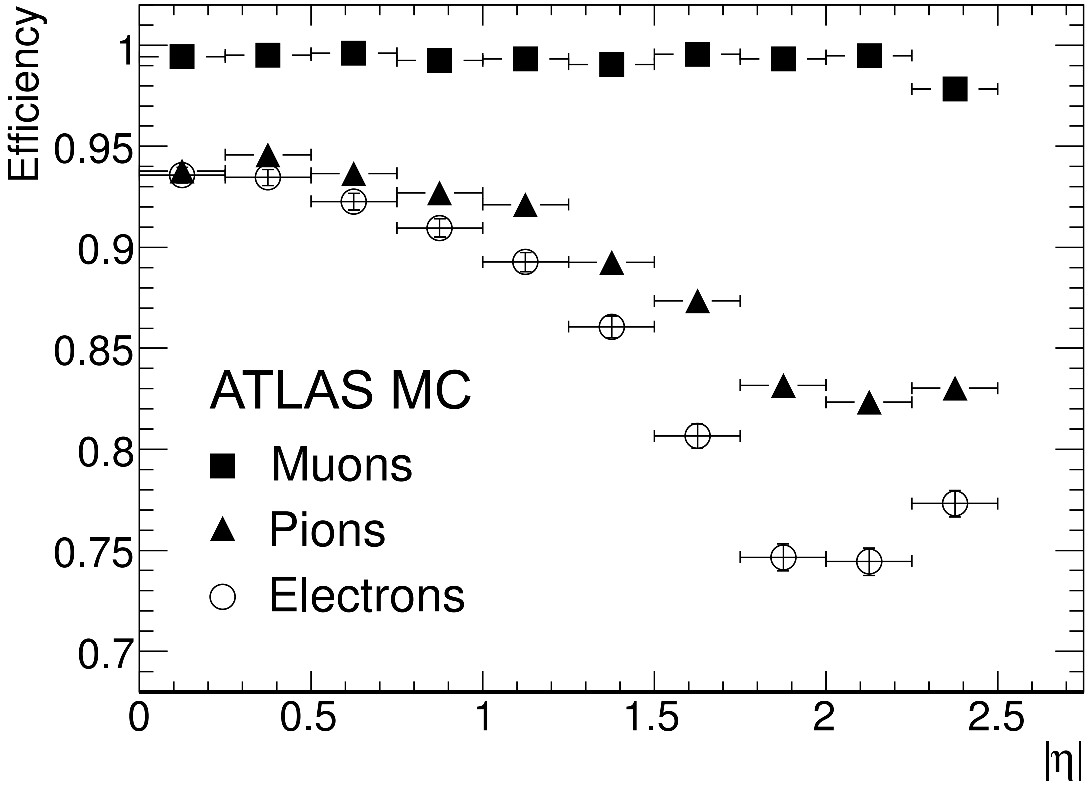
Same trends with η and p_T in data

CMS-PAS-TRK-10-004

Pions vs. muons

2008 JINST 3 S08003 ATLAS Experiment

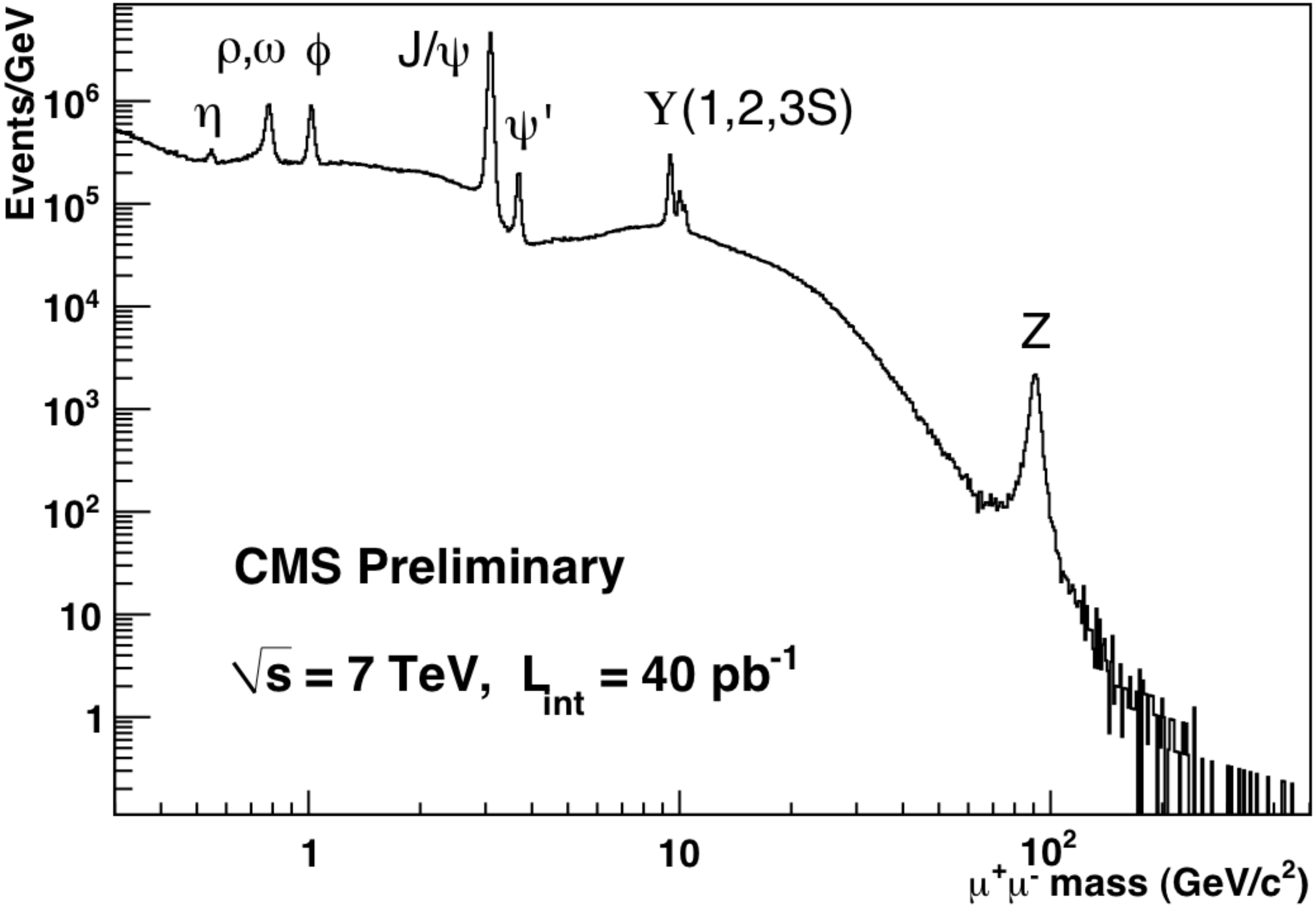
- Because of material interactions, track finding efficiency is lower for π and e than for μ



$\mu^+\mu^-$ 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 …

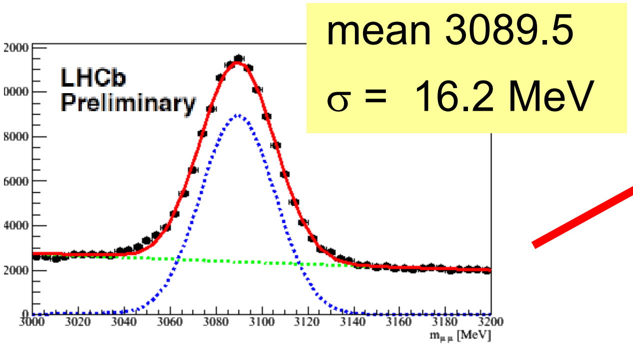


J/ψ and Υ → $\mu^+\mu^-$

J/ψ PDG mass 3096.916 ± 0.011 MeV

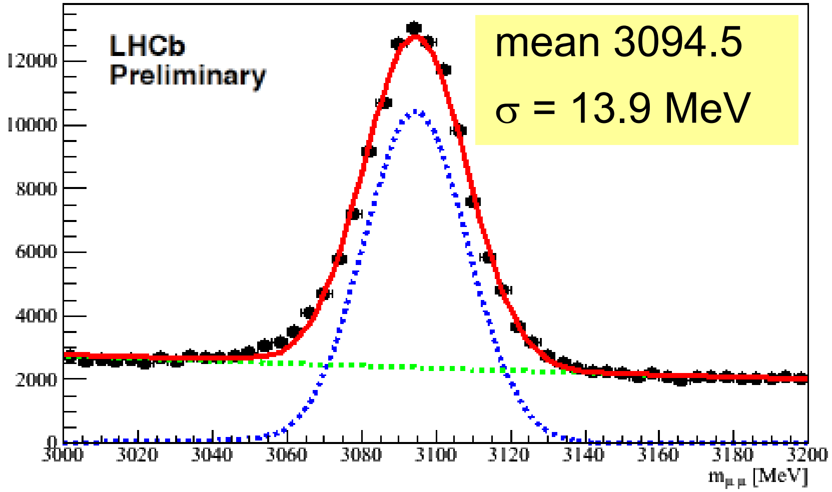
LHCb improved alignment

(LHCC meeting September 2010)



mean 3089.5

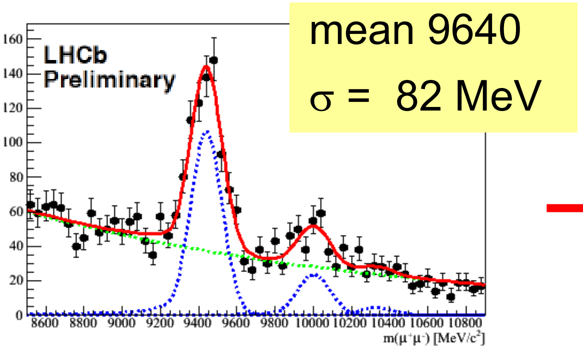
σ = 16.2 MeV



mean 3094.5

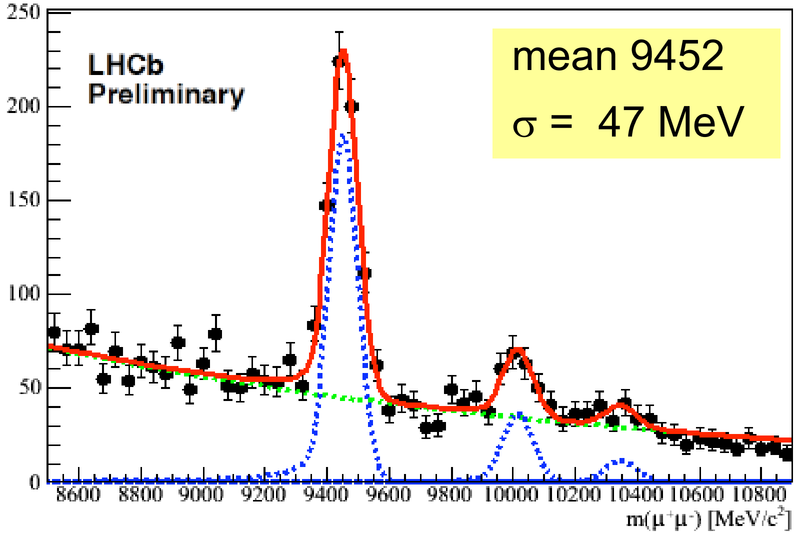
σ = 13.9 MeV

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



mean 9640

σ = 82 MeV

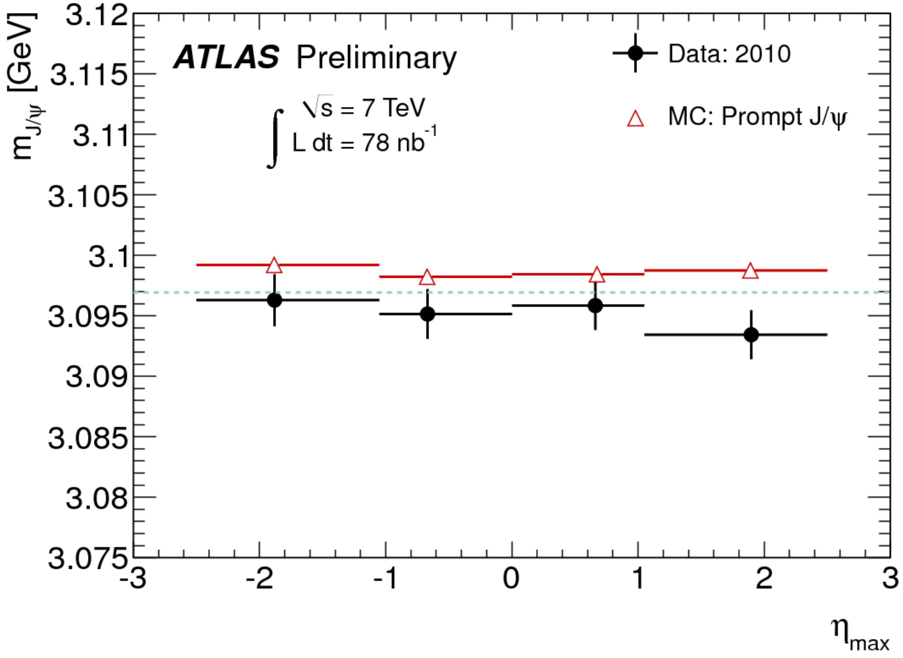


mean 9452

σ = 47 MeV

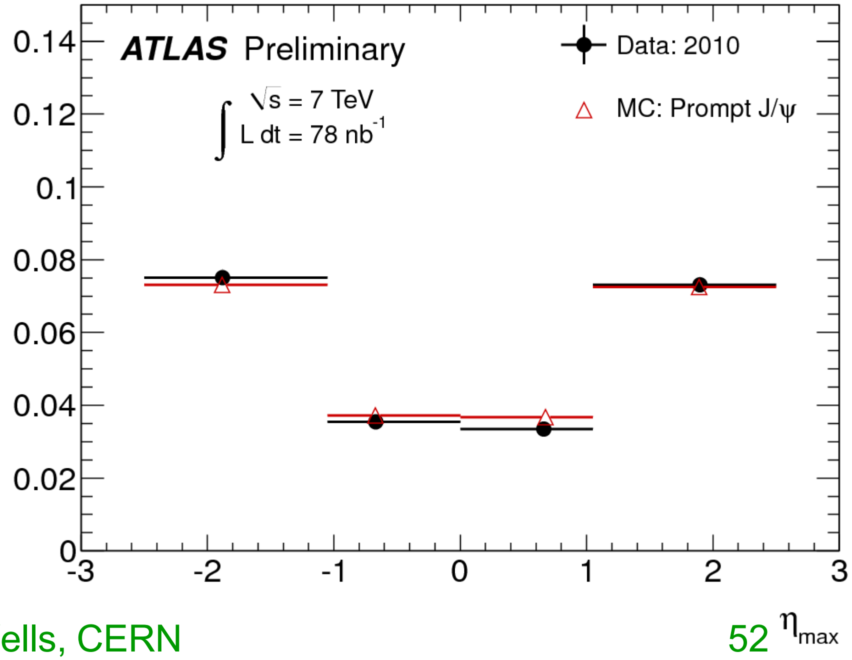
J/ψ → $\mu^+\mu^-$ mass and width

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



Offset between reconstructed mass and PDG value in simulation

Mass in data lower than in simulation (limited statistics)

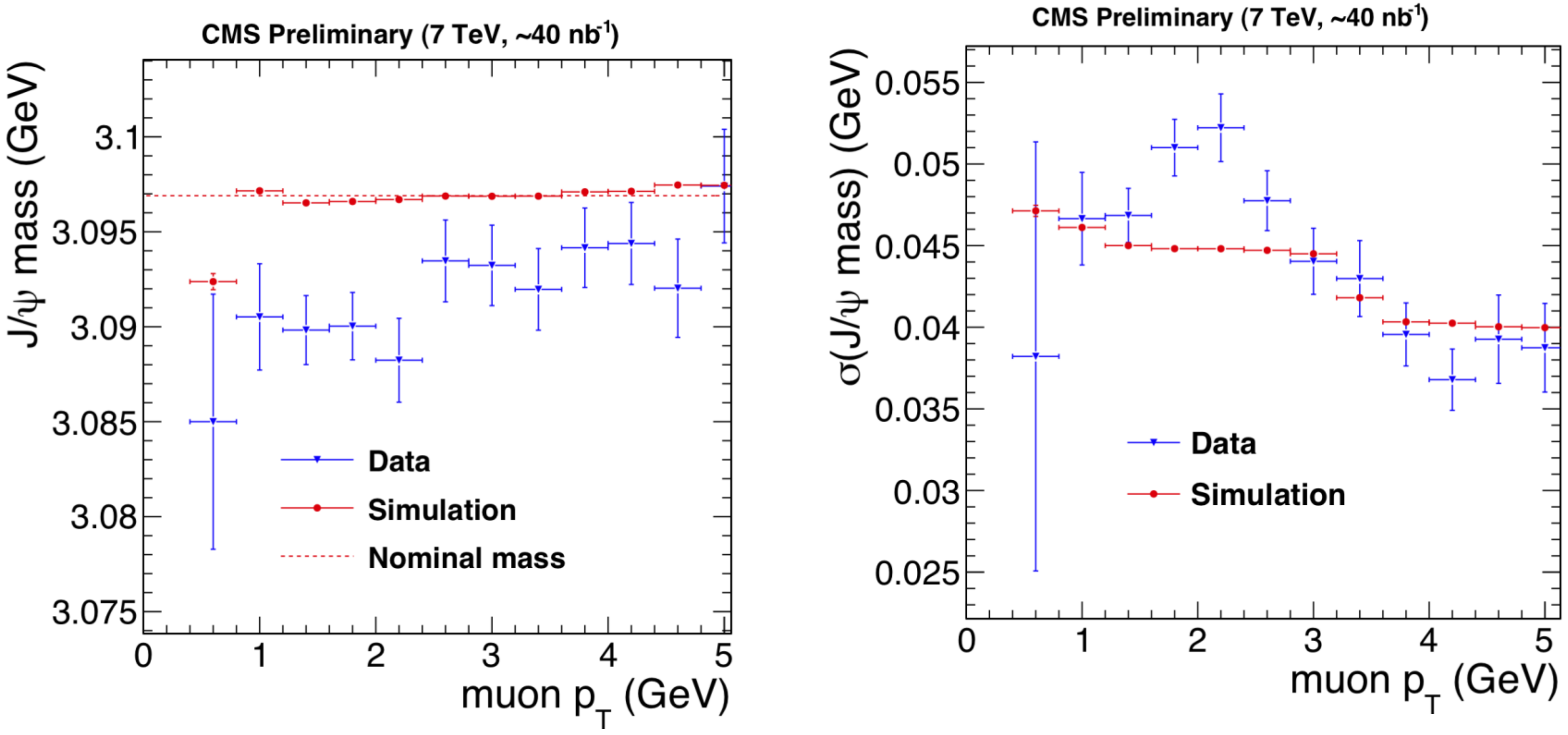


Widths agree well between data and simulation → momentum resolution reasonably modelled.

ATLAS-CONF-2010-078

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

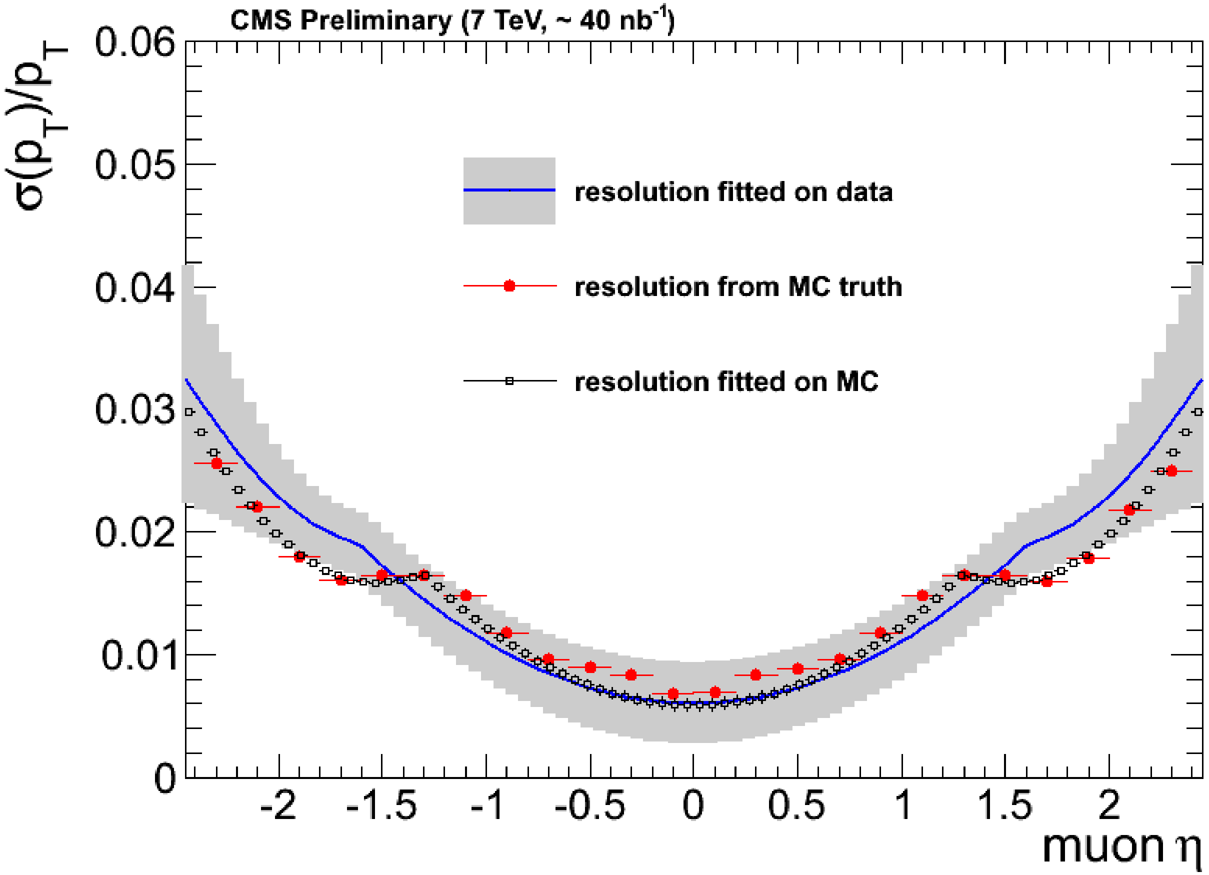
As a function of muon transverse momentum (CMS example)



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.

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

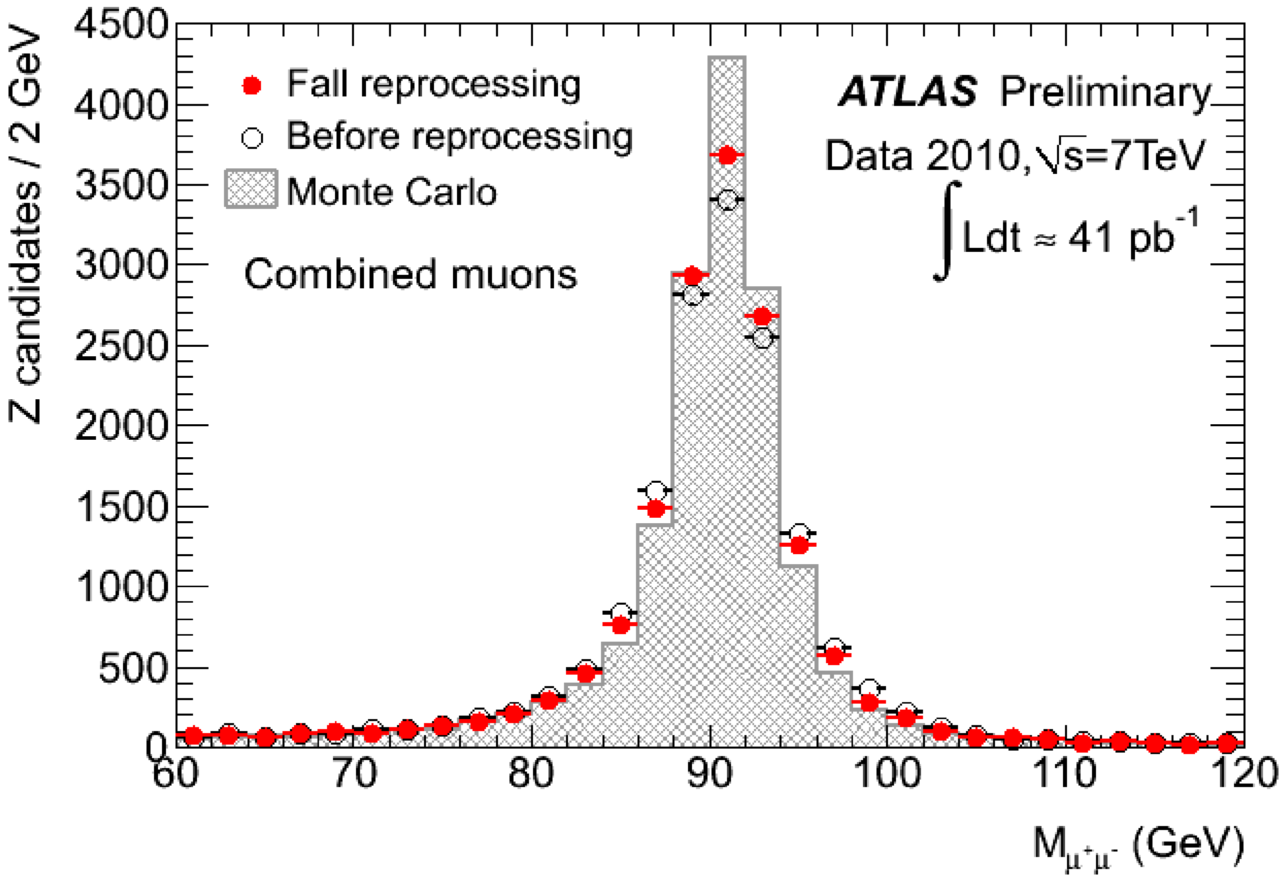
Momentum resolution measured using J/ψ



(This only uses a small sample from early 2010 run)

$Z \rightarrow \mu^+\mu^-$ the highest mass cross-check

- Example from ATLAS before/after improvements to Inner Detector (& Muon System) alignment and material description.
- Getting closer to resolution in perfectly aligned MC for higher p_T



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…
- Already seeing good agreement between simulated performance and measurements with data, and the tools are in place to make more improvements
  - Careful work to control material during construction
  - 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 to be made