Tracking at LHC

(Calibration and Alignment)

4th School on the Physics of LHC

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Lecture 2

Tracking: an increasing challenge

- Tracking at LHC is a very complex procedure due to the high track density. It needs specific implementation adapted to the detector type and geometry
- Precise and efficient detector modules are required to measure where the particle crossed the module
- Fast and radiation hard detectors and electronics are needed
- Track reconstruction requires specific software implementation:
  - track finding (pattern recognition)
  - estimation of track parameters (fitting)
- Precise alignment of detector modules is a prerequisite for efficient tracking

Pattern Recognition

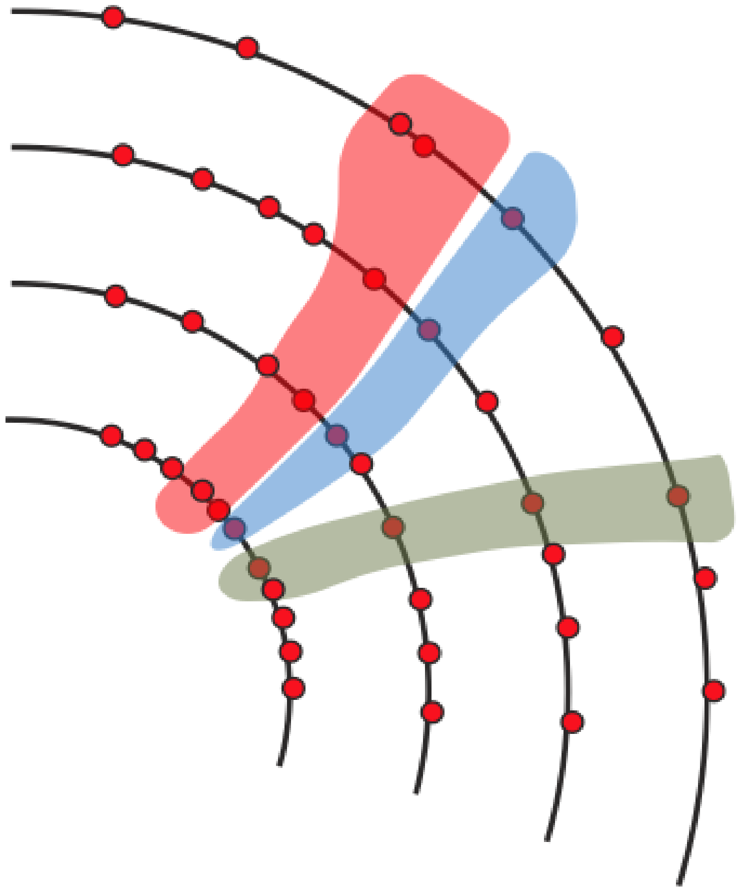
- The **main** goal of the pattern recognition is to **associate hits to tracks** (particle trajectories). It should be efficient (use of all hits) and robust (no noise or hits from other tracks)

Two approaches:
Global and **Local** pattern recognition

- **Global methods:**
  Template matching, neural network techniques, Hough space transform, …..
  (Simultaneous consideration of all hits)

- **Local methods (also called track following):**

  Combinatorial Kalman filter updates the information (track parameters and error matrix) of candidates tracks along the track finding process and gives a precise prediction of the next point to be found. It is a progressive methods (boundary pattern recognition/track fitting vanished). Track fit became part of the track finding approach.



Track fitting

Process to estimate the kinematical parameters, such as position (or impact parameter), direction of flight and momentum of a particle starting from the measured hits which have been correctly identified in the pattern recognition step.

- ✓ **Multiple scattering effects and energy loss are taken into account in the track fitting procedure**
- ✓ **In general the fitting methods assume Gaussian errors**

Two approaches:

- ❑ **Least squares estimation**: requires the global availability of all measurements at fitting time

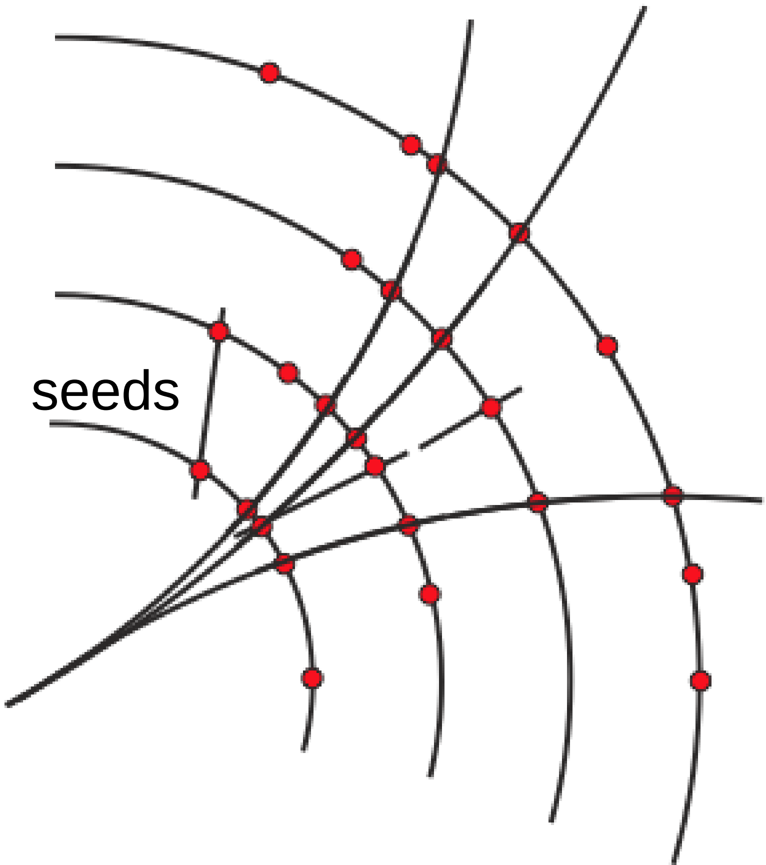
- ❑ The **Kalman filter technique**: proceeds progressively from one measurement to the next, improving the knowledge of the trajectory with each new measurement (**boundary pattern recognition/track fitting vanishes)**

Track finding / track fitting:
the combinatorial Kalman filter

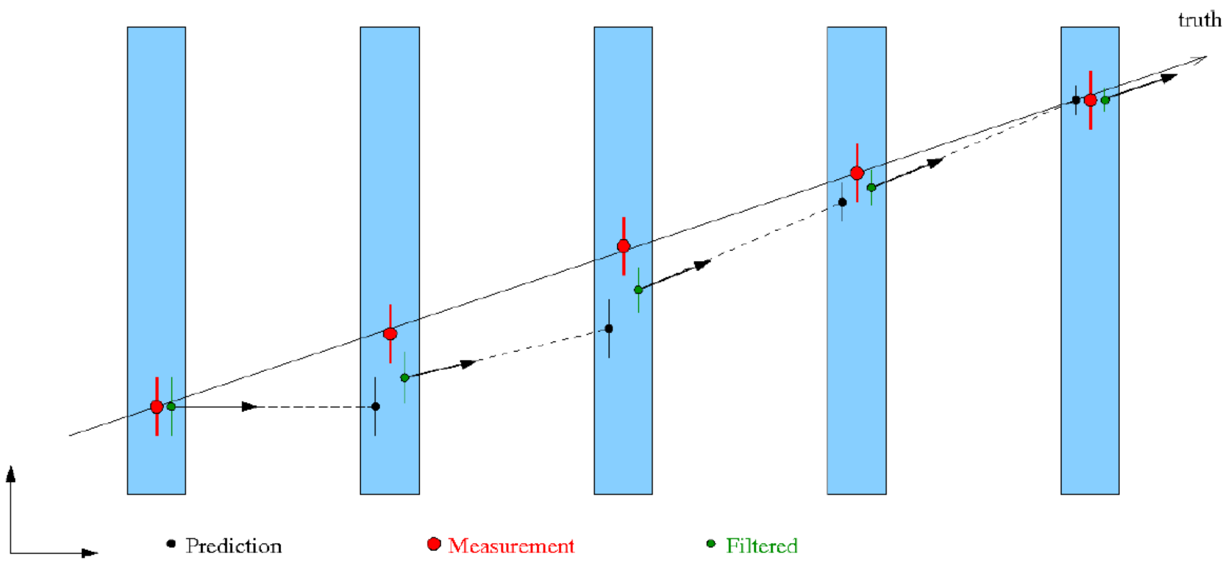
Progressive method: track fitting works simultaneously with track finding.

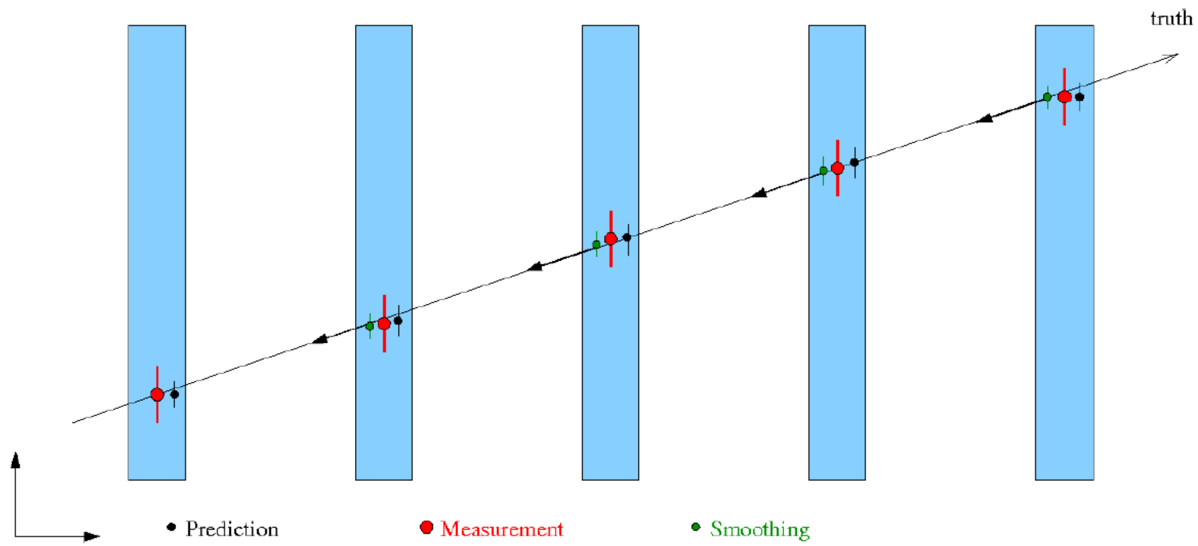
The Kalman Filter consists of a succession of alternating *prediction and filter steps:*

- ✓ As one example, in CMS track reconstruction is initiated by a *seeding* in the innermost tracker layers: both pixel and silicon strip hits.
- ✓ The system equation propagates the track state in one surface to the next.
- ✓ Accuracy on the track state estimate increases after each new measurement is added



Filtering and Smoothing





Is the Kalman Filter the last word?

- The Kalman filter is an optimal estimator of track parameters in case of
  - Unbiased measurements with Gaussian errors
  - Gaussian process noise (multiple scattering etc.)
  - No outliers (hits that don't belong to the track)

- Reaches its limits when underlying statistics are far from Gaussian. This problem is enhanced in electron fitting with plenty of material.

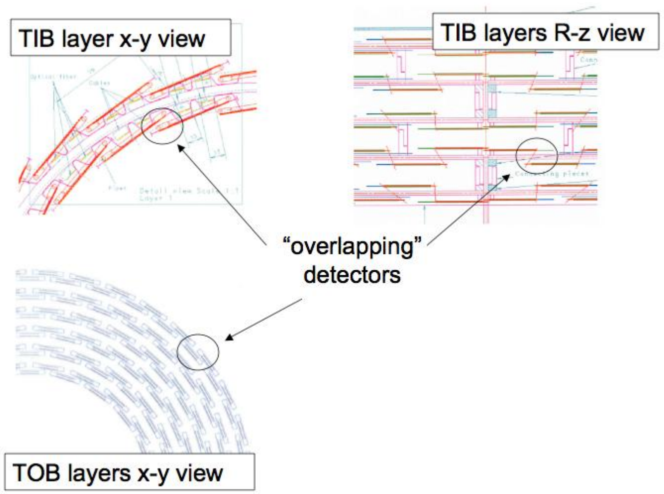
  Dense environment will also be a challenge for LHC reconstruction at full luminosity

- Non-Gaussian generalisations based on adaptive algorithms exist and are used:
  - Gaussian Sum Filter (GSF) Non-gaussian noise (energy loss) can degrade the fit seriously
  - Deterministic Annealing Filter (DAF) Ambiguous situation require more advanced treatment
  -
  -

Tracking

Each experiment needs specific software implementation adapted to the detector type and geometry to improve tracking efficiency.

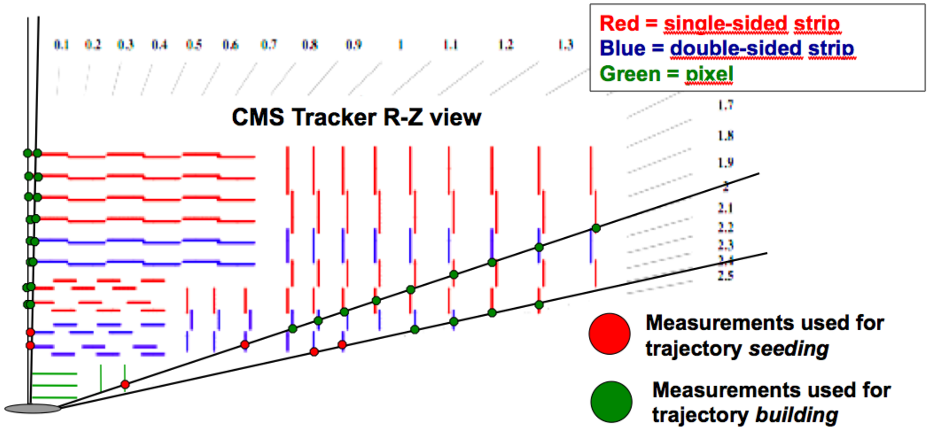
A couple of examples from CMS:



Overlapping modules in the same layer

Implementation obstacles:

- Because of the different design, each of the 6 Tracker sub-detectors involves different types of "overlaps".
- Sorting of hits along the trajectory is not trivial.
- Track parameters are "updated" on each layer with the information provided by a track segment (instead of a point).



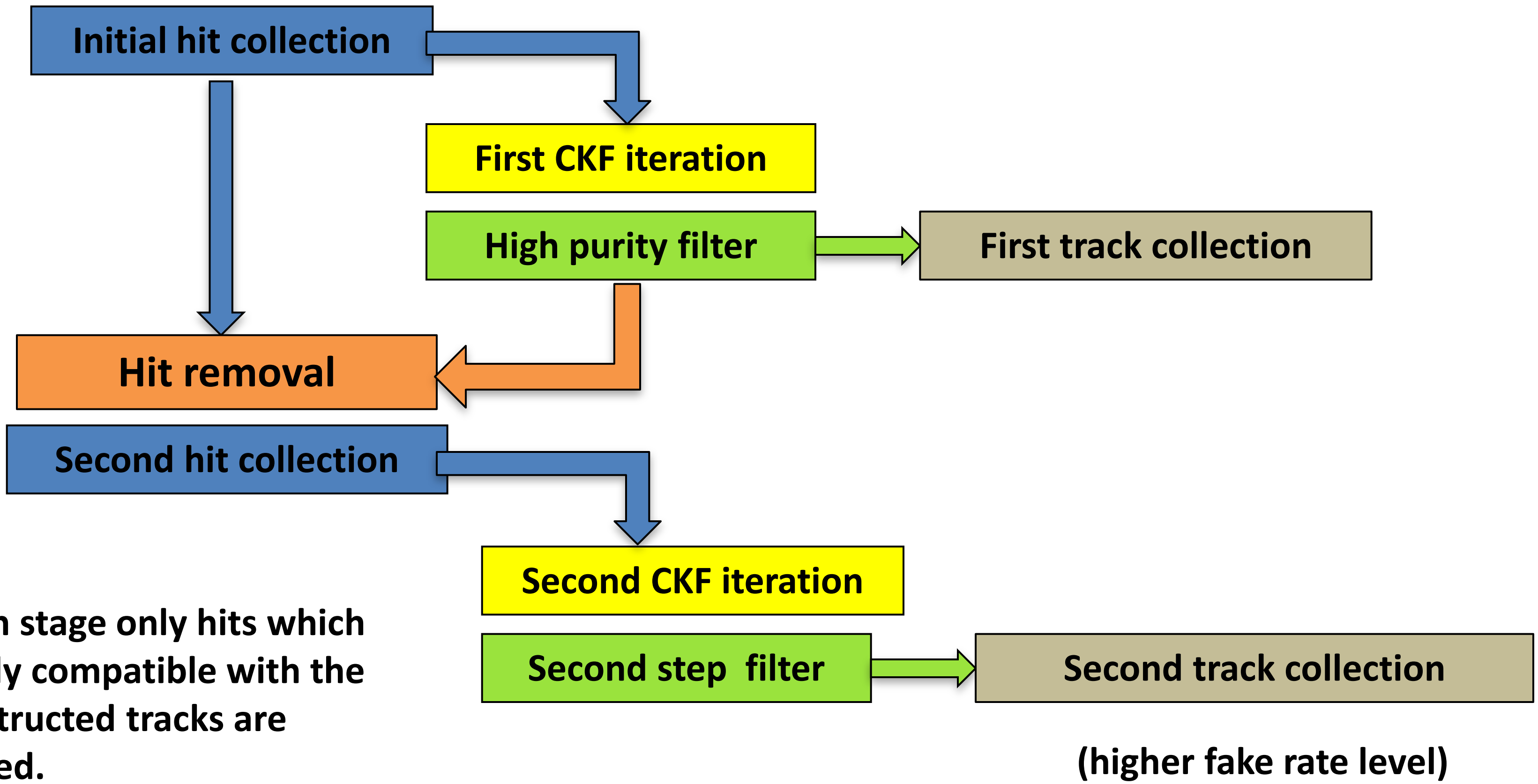
Inefficiency due to pixel-based seeding

Compared to the pixel-only seeder, the new implementation had to cope with:

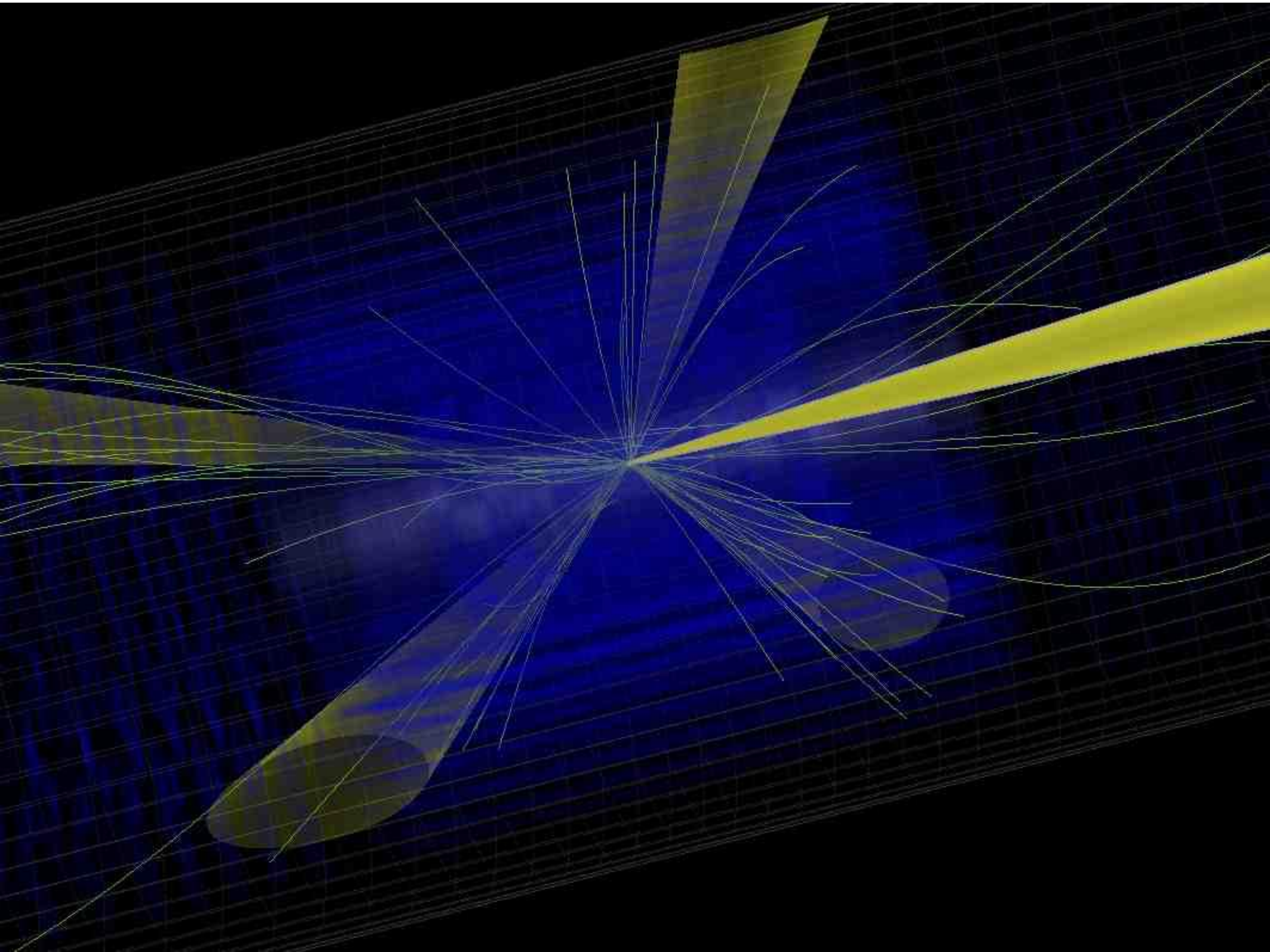
- position measurements with uncertainties spanning more than order of magnitude.
- sensors with 4 different topologies arranged on 4 different types of "layers".
- material budget in between Tracker sub-detectors had to be optimally parameterized.

Iterative tracking

An *iterative procedure* performs the track reconstruction in stages, **running different times the CKF reconstruction**



At each stage only hits which are fully compatible with the reconstructed tracks are removed.



Tracking: an increasing challenge

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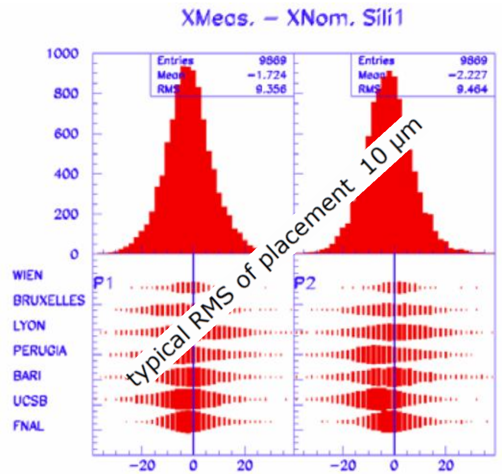
- Precise alignment of detector modules is a prerequisite for efficient tracking

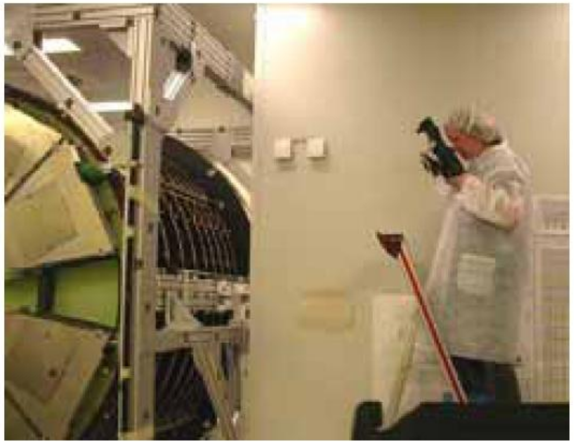
Alignment

- Precise alignment of detector modules is a prerequisite for efficient tracking.
- must be well monitored during the construction process from single module assembly to final operation of the full tracking system

automated module assembly

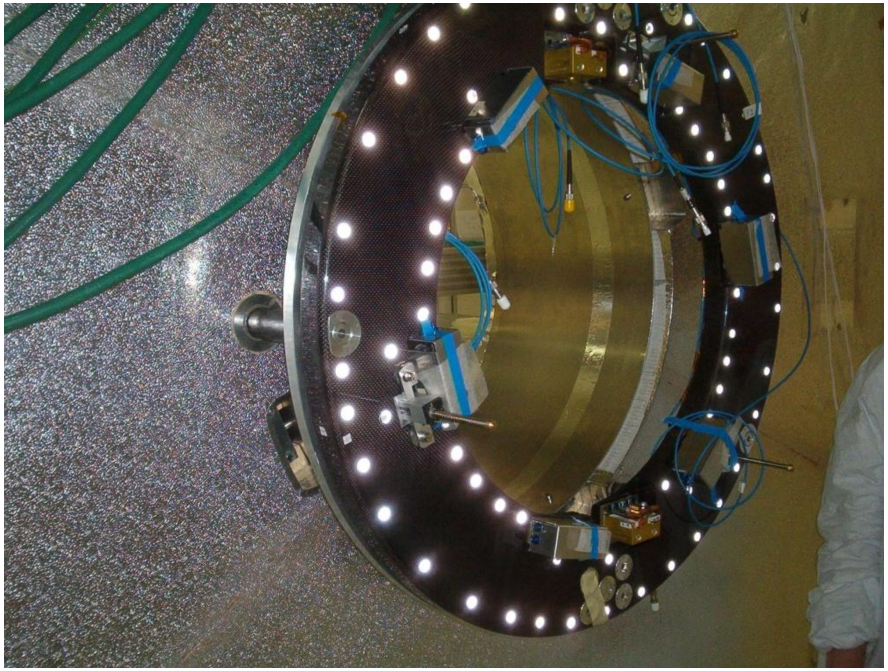


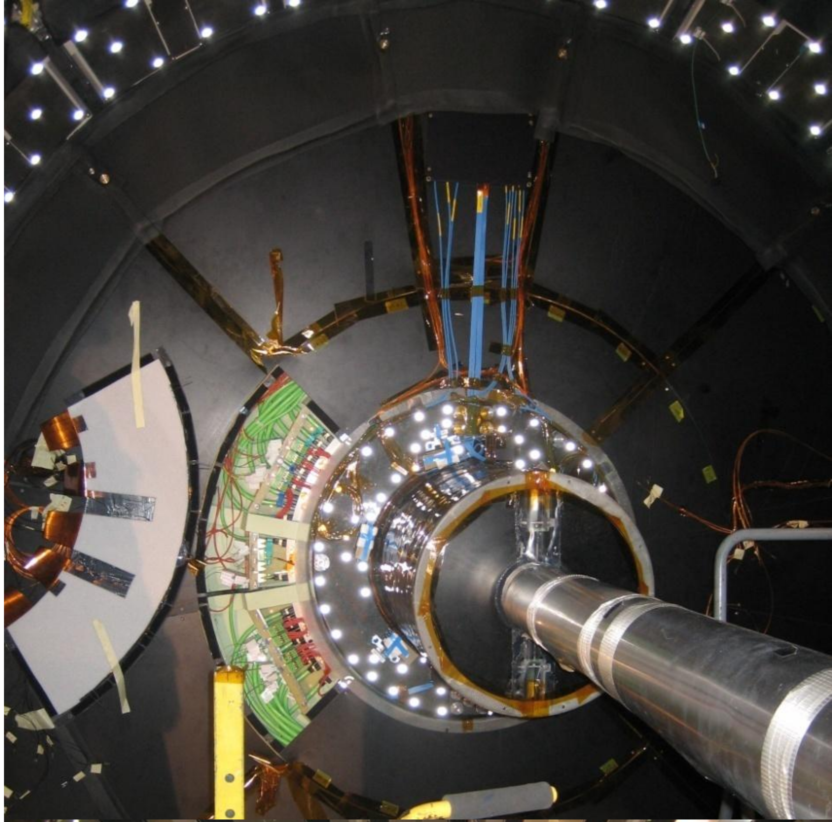
precise tooling and quality control measurements

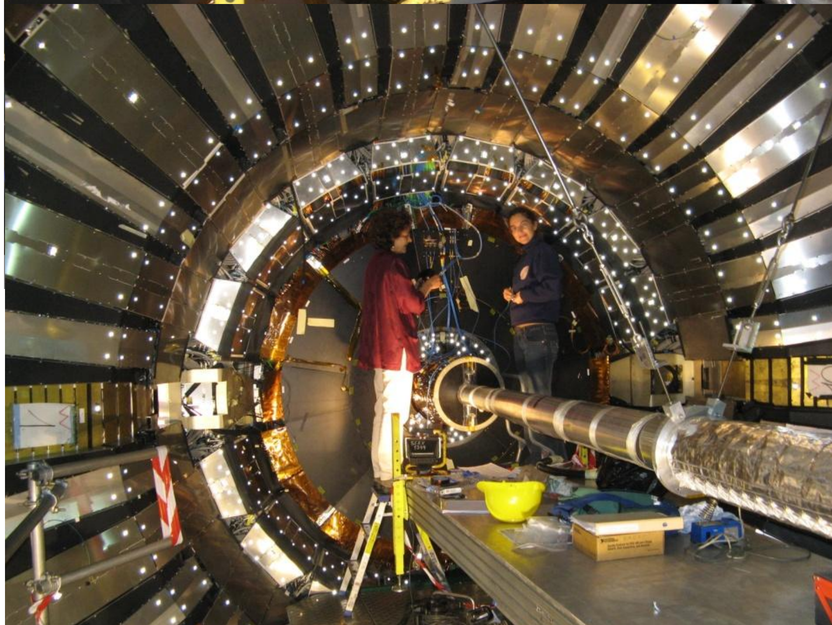


Survey and optical measurements

CMS Alignment rings



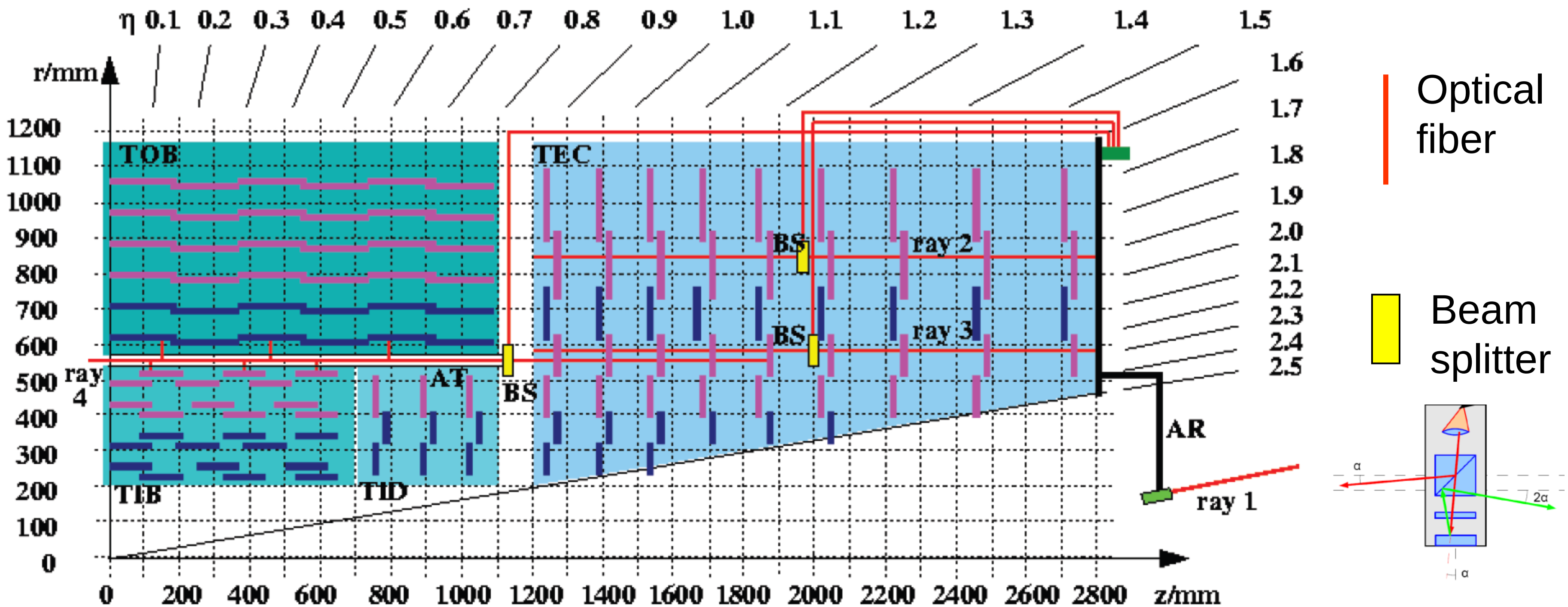




Installed in Endcap Tracker
end plates (precise mechanical mounts)

Optical alignment / monitoring

CMS Si Tracker: Laser Alignment System



2 x 8 beams for internal alignment of each Endcap
8 beams to align subdetectors (Inner/Outer Barrel and Endcaps)

- **LAS operates globally on tracker substructures: TIB, TOB and TEC discs. It does not attempt to determine the position of individual modules**
- **Laser measurements can be performed during physics data-taking**
- **Relative position monitoring of global tracker structures with a precision of ~100 μm (needed to start track reconstruction)**

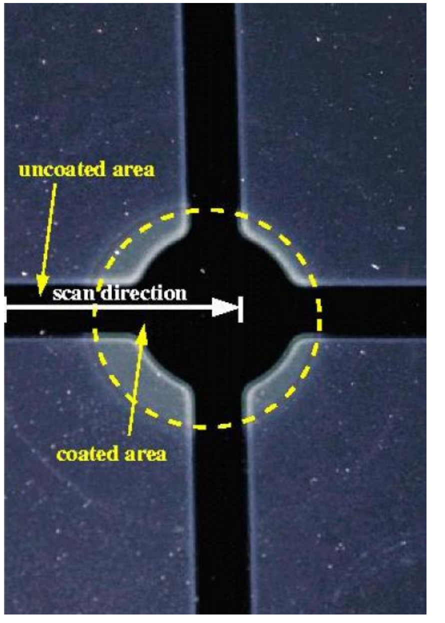
CMS Silicon Tracker

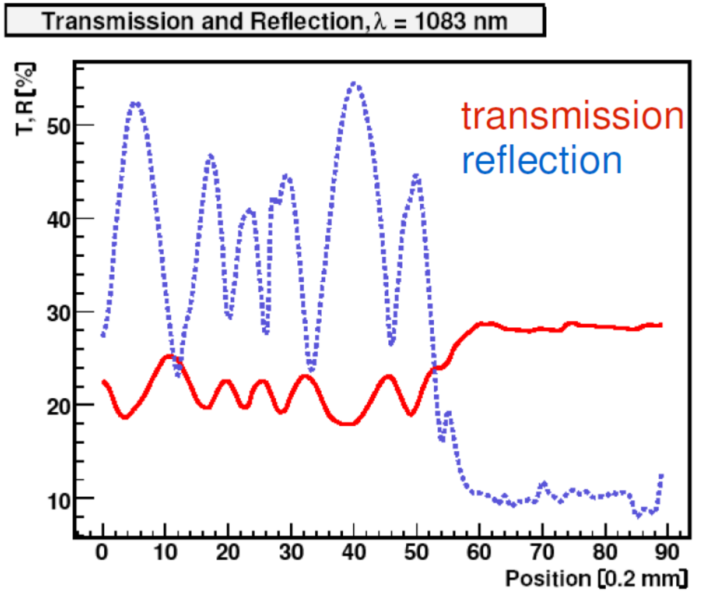
Silicon is semitransparent to infrared light (laser pulses λ ~1080 nm)

Sensor treatment:

- Silicon sensors polished on both sides
- ~ 10 μm hole in backplane metallization
- Antireflective coating on backside: improves transmission and reduces

  multiple reflections, interference, and distortions of the beam profiles
  No antireflective coating on strips due to effects on interstrip capacitance



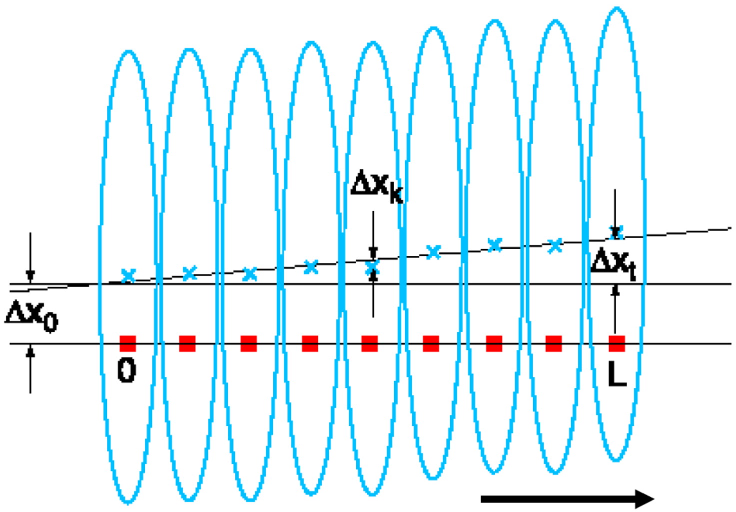


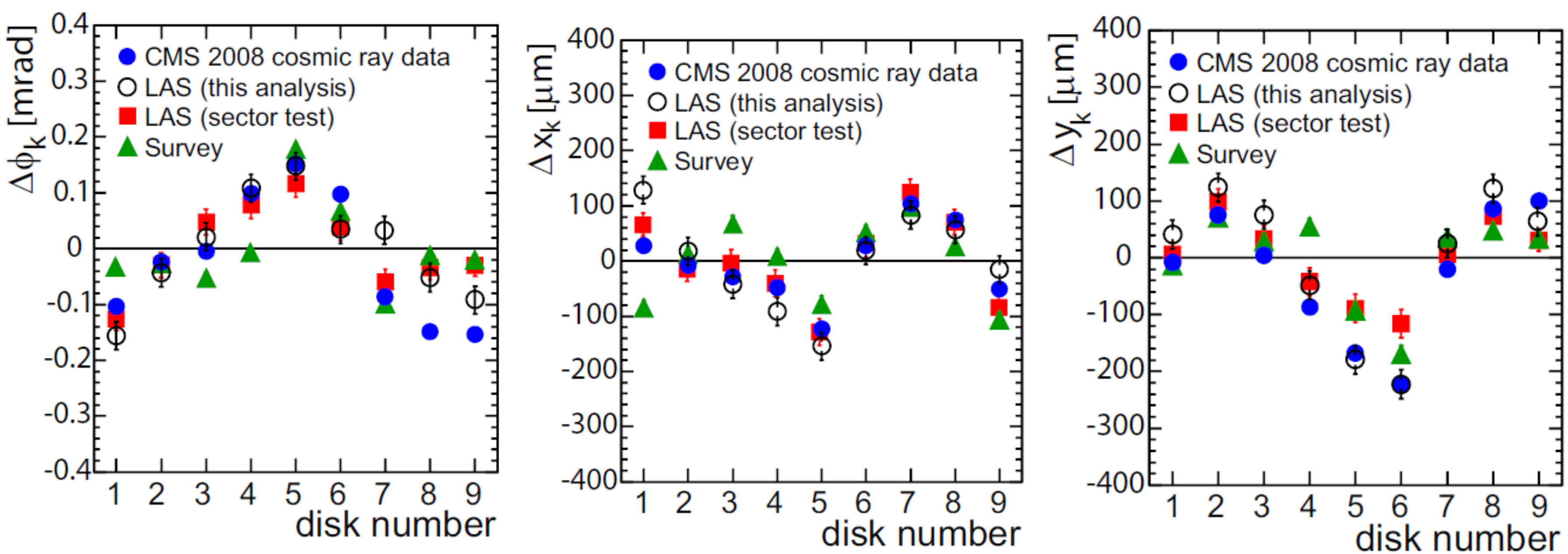
Laser intensity adjusted for each layer to obtain an optimal signal-over-noise ratio. Accumulate several “laser events”

CMS Tracker Endcap Alignment

Separate collective movements
from individual disc movements

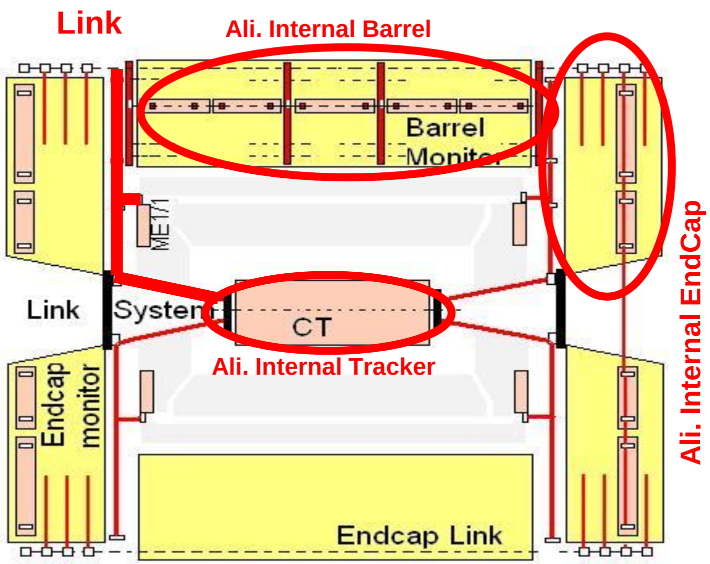
Overall TEC movement Δx_0
Overall TEC skew Δx_t



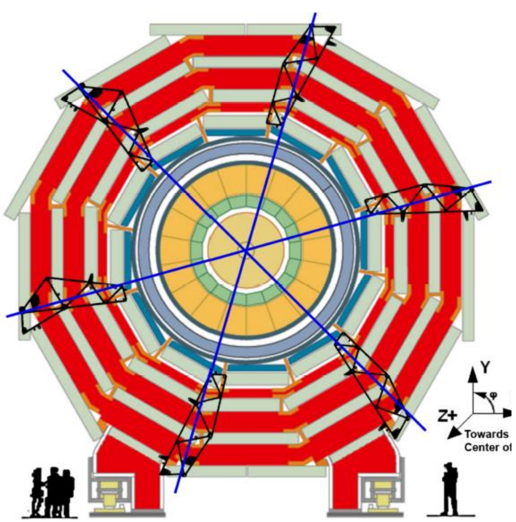


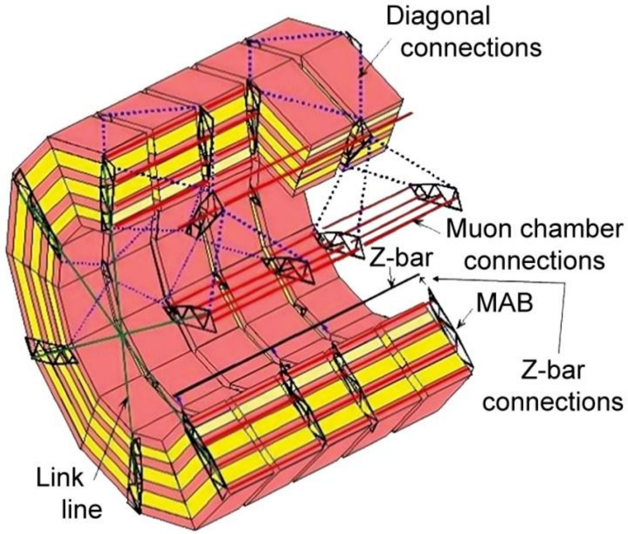
CMS Alignment System

Tracker internal alignment and monitoring the muon chambers relative positions (barrel and endcap) with respect to the tracker.



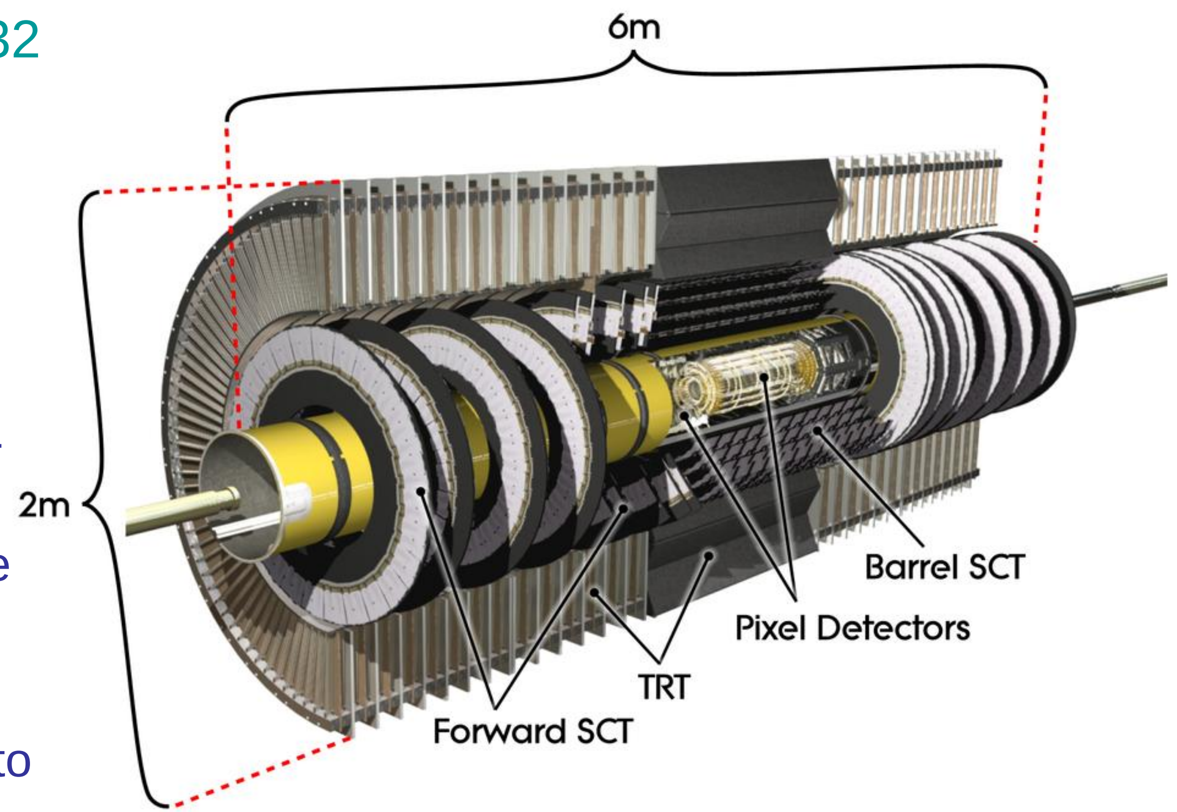
Muon align components:
Light sources: 10000 LEDs + 150 lasers.
~900 Photosensors + ~ 600 analog sensors (position, tilt sensors)
Temperature, humidity and Magnetic probes
→ ~ 30000 parameters in the geometrical reco.



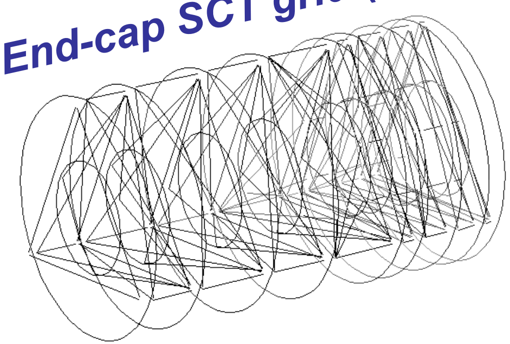


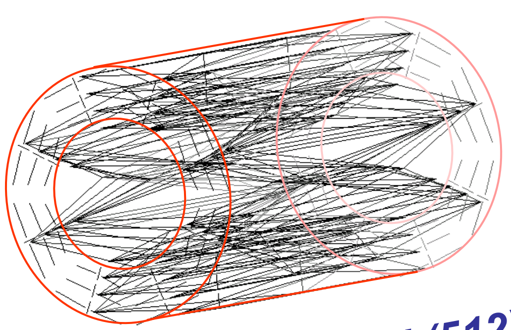
ATLAS Tracker Detector

- ATLAS Silicon detector: 5832 modules (80M pixels, 6.3M strips)
- 3D monitoring through Frequency Scanning Interferometry
  - A geodetic grid of length measurements between nodes attached to the SCT support structure.
  - All 842 grid line lengths are measured simultaneously using FSI to a precision of <1micron.
  - Repeat every ten minutes to measure time varying distortions

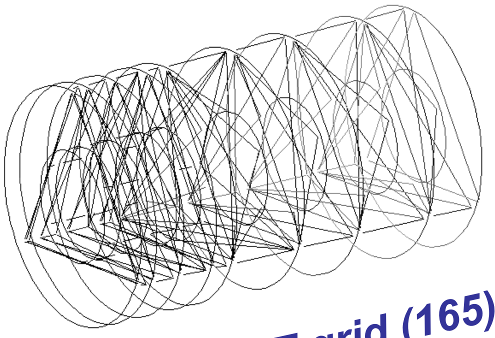


End-cap SCT grid (165)



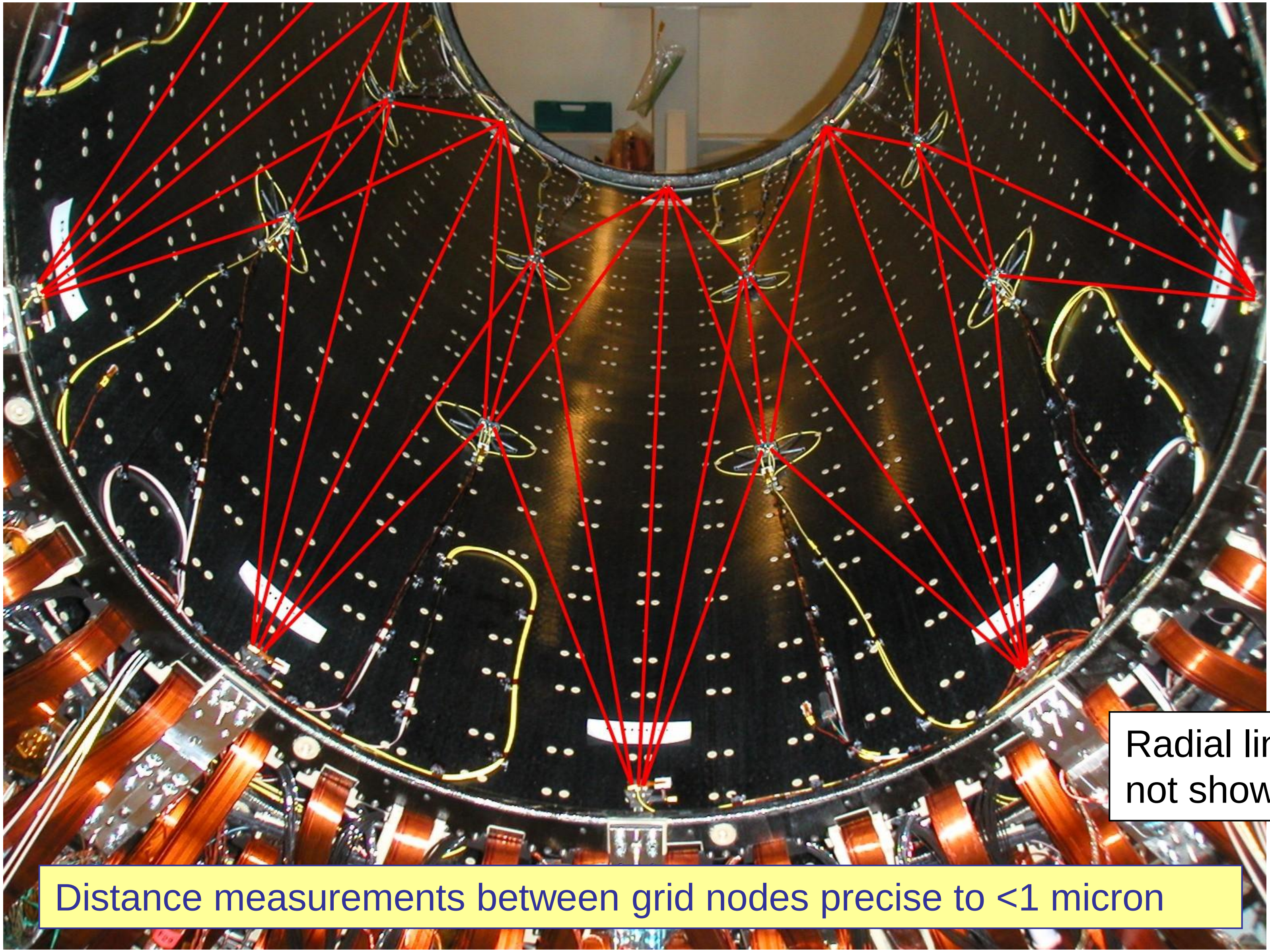


Barrel SCT grid (512)



End-cap SCT grid (165)

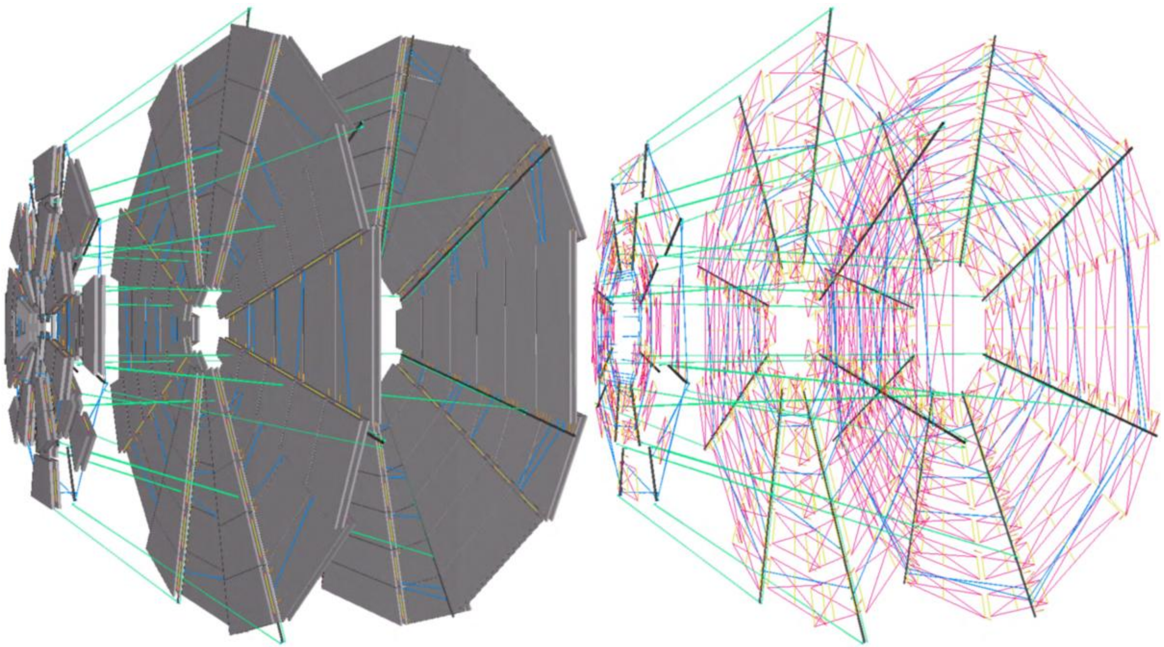
ATLAS: on-detector FSI System

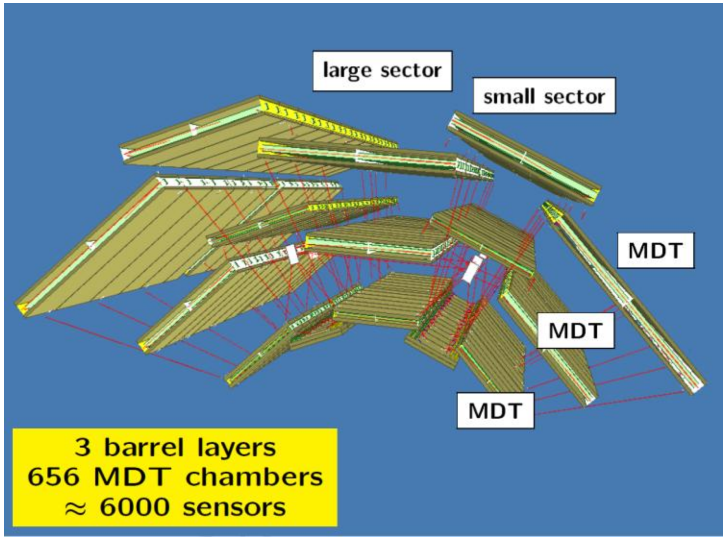


Radial lines not shown

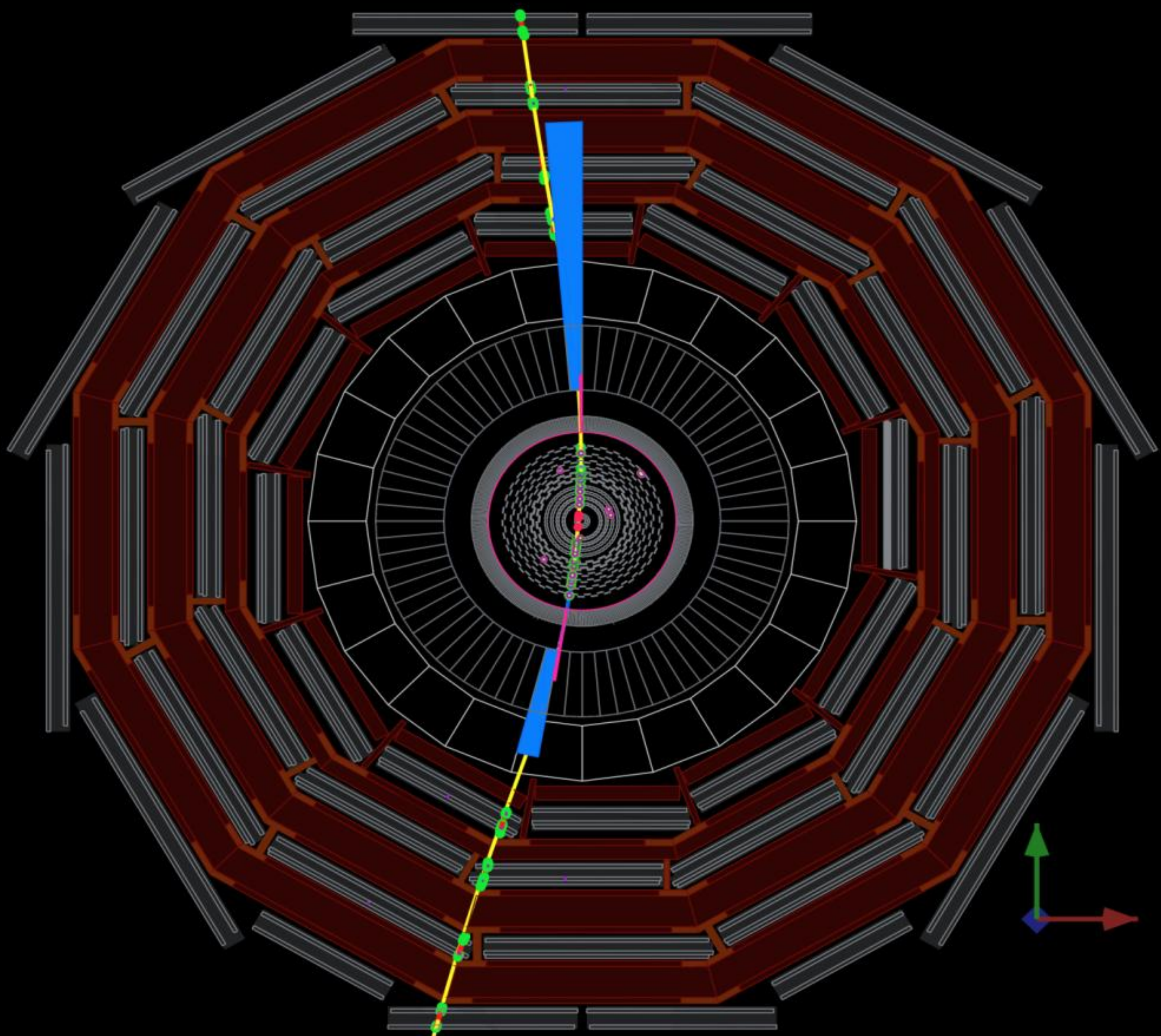
Distance measurements between grid nodes precise to <1 micron

Optical alignment / monitoring

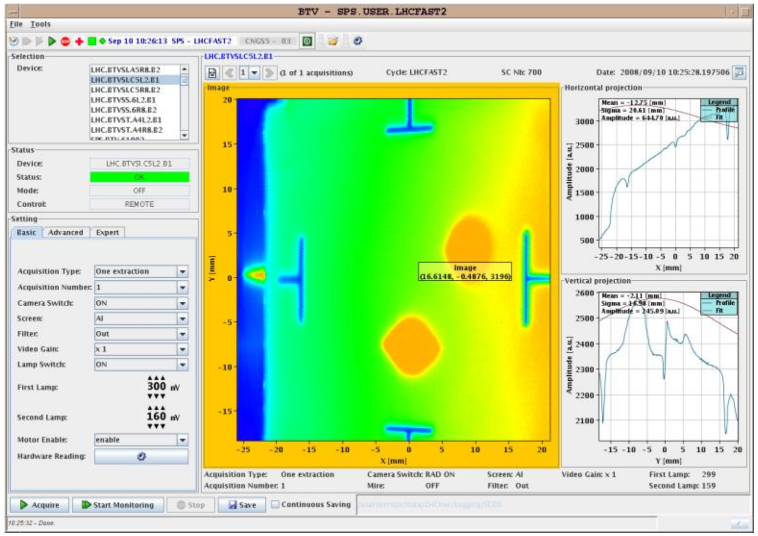




After installation in 2008 precise alignments were done by all experiments with millions of cosmic muons

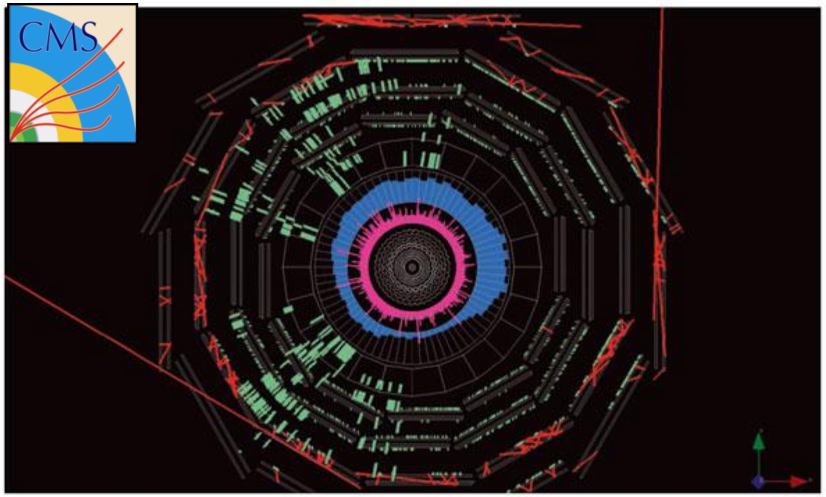


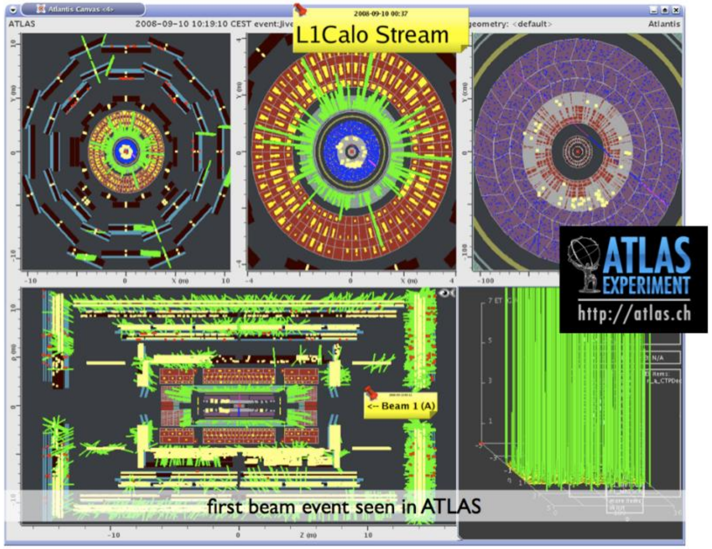
10 September 2008:



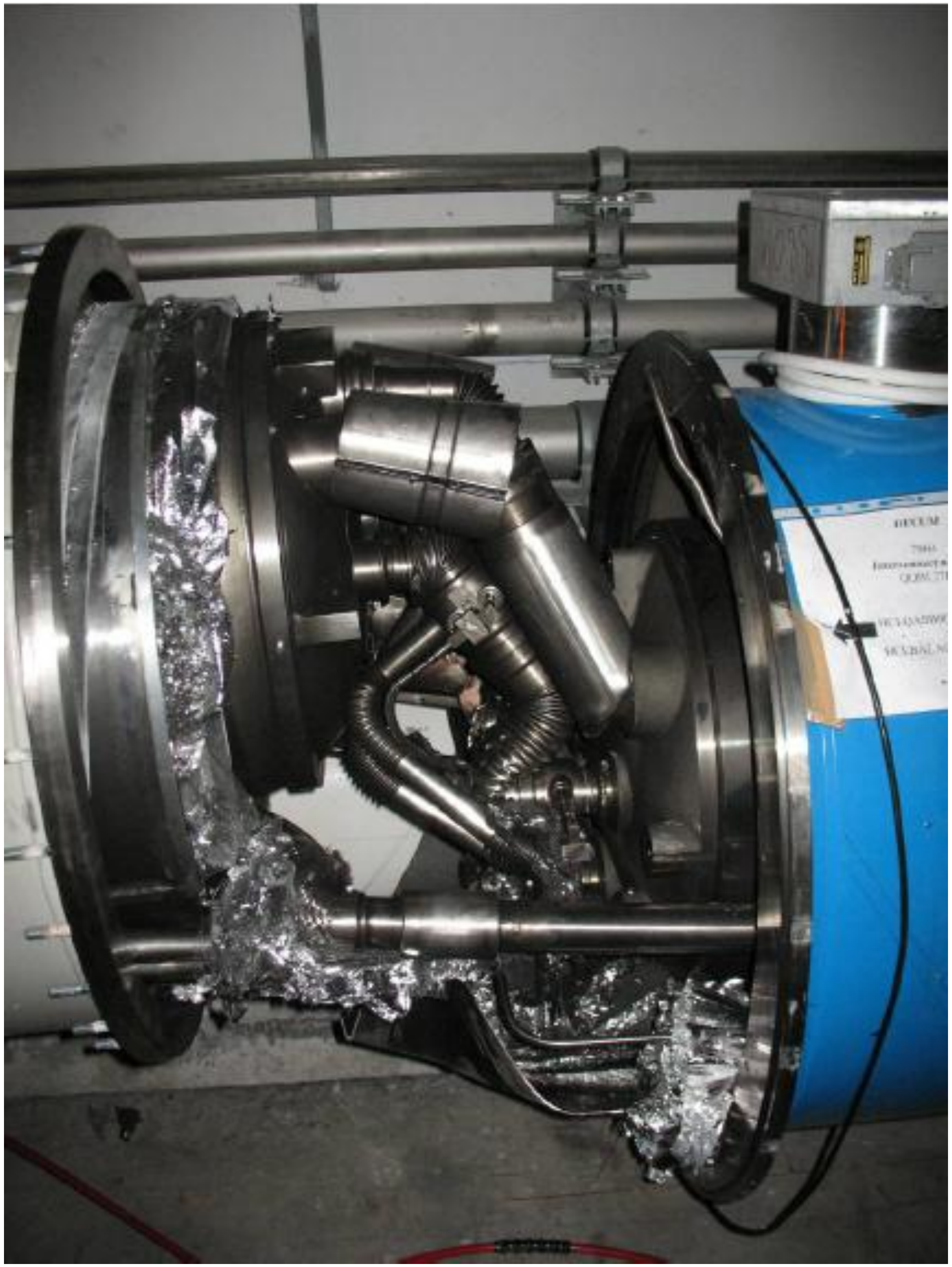
The first LHC beam !

First splash events seen by the experiments

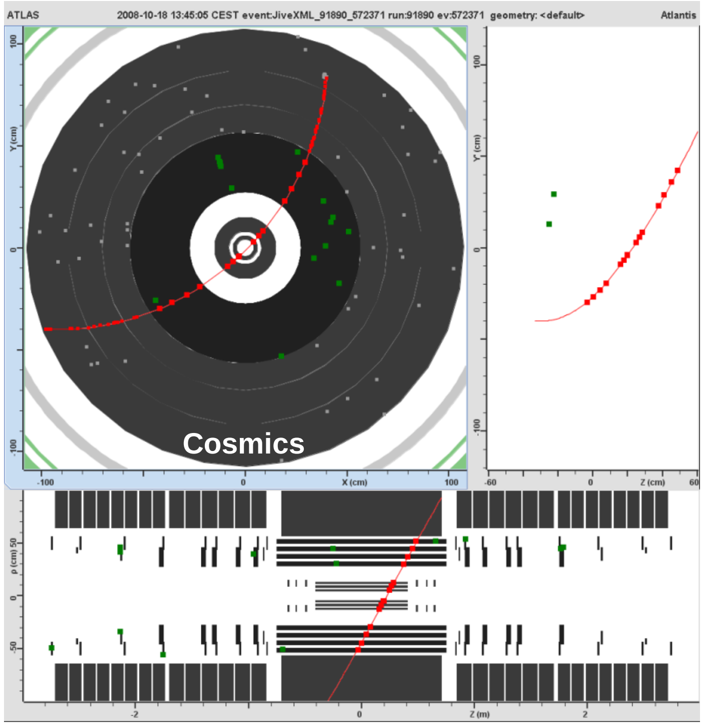




19 September 2008 ….

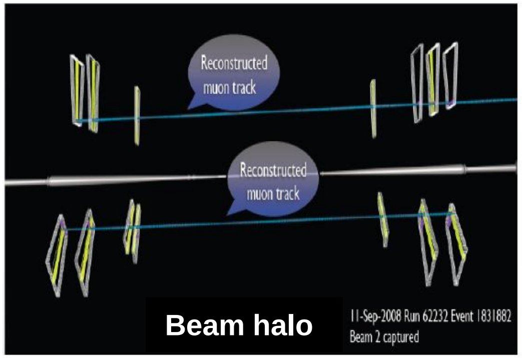


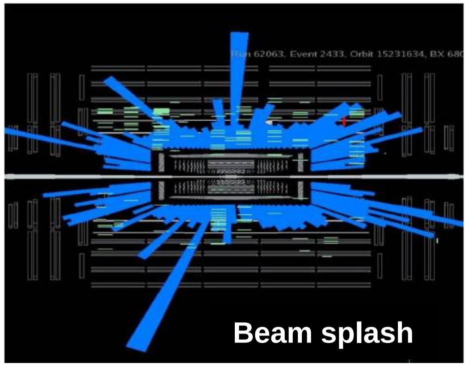
Another full year (2008+2009) for commissioning with Cosmics



- ✓ Alignements
- ✓ Calibrations
- ✓ Timing
- ✓ Studies of magnetic field

+

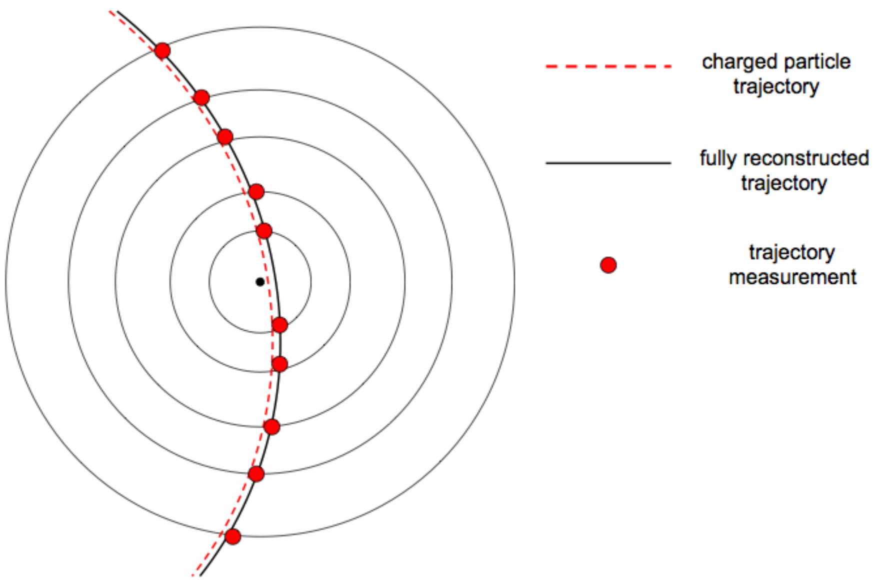


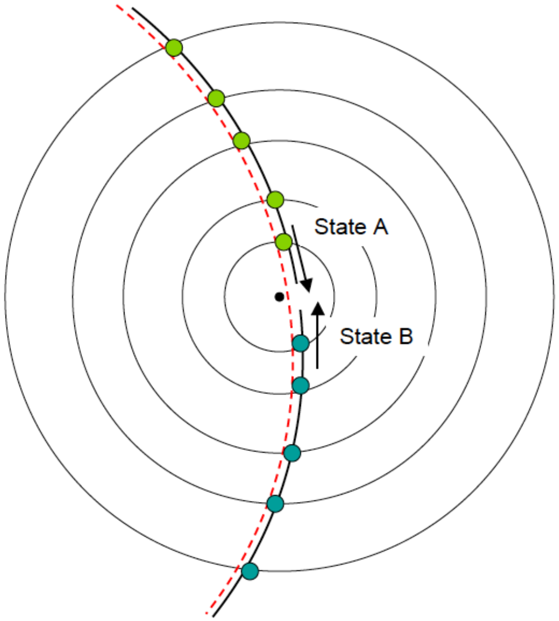


Reconstruction of Cosmic ray data

Cosmic rays data have been very useful to align the tracking detectors before the LHC start-up.

Data with magnet on can also be used to evaluate the resolution of the momentum measurement.

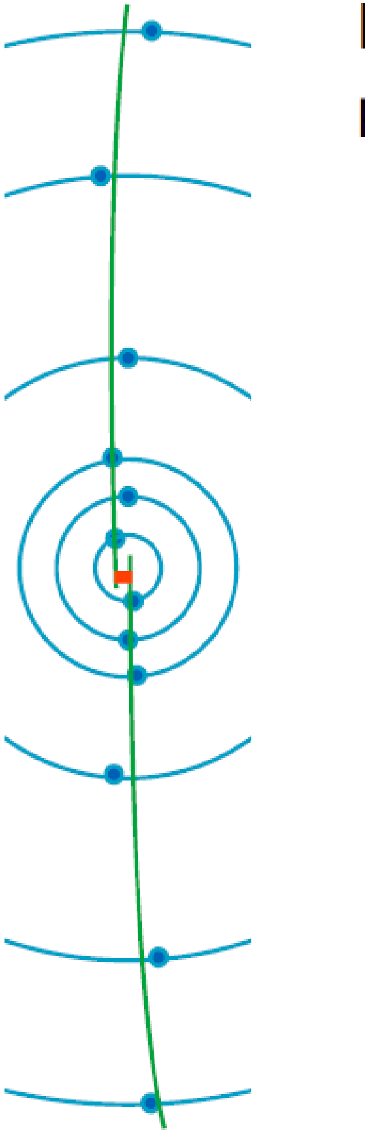


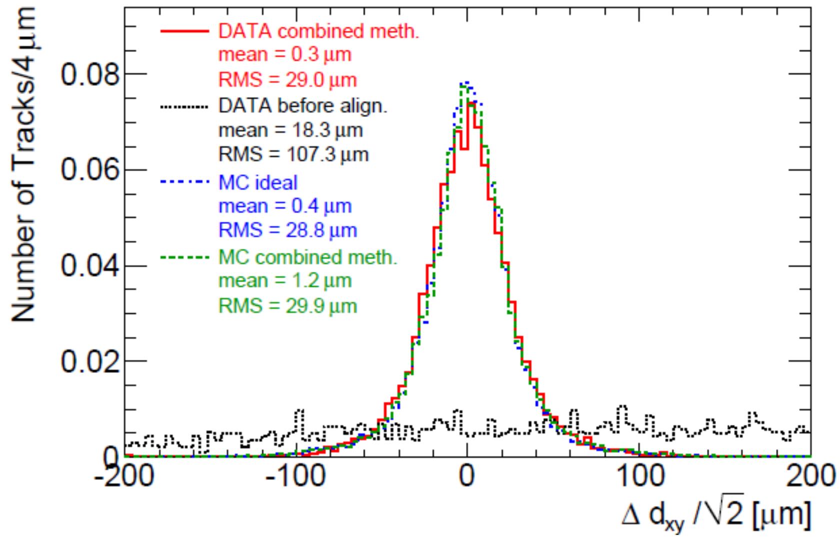


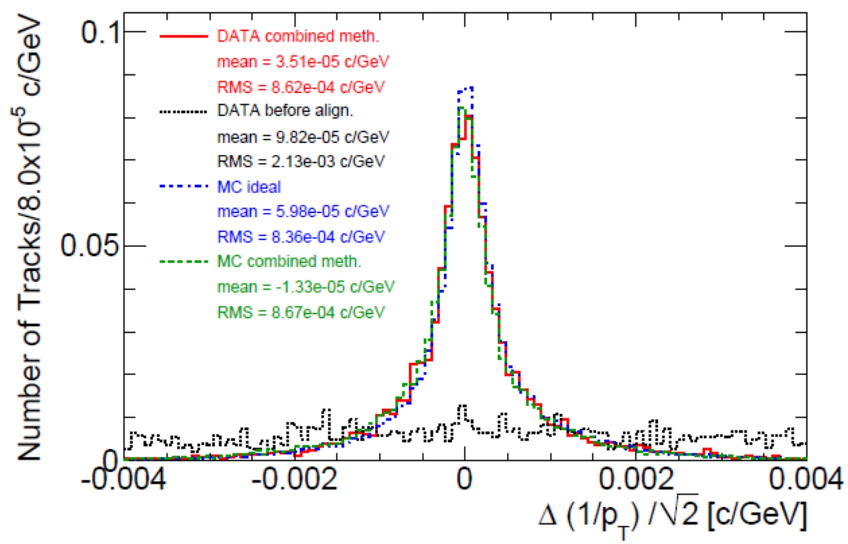
Cosmic rays have the special feature of crossing the Tracker volume on both hemispheres: The same particle is *reconstructed twice.*

The distribution of the difference of the momenta of the 2 tracks is an estimation of the resolution of the momentum measurement itself.

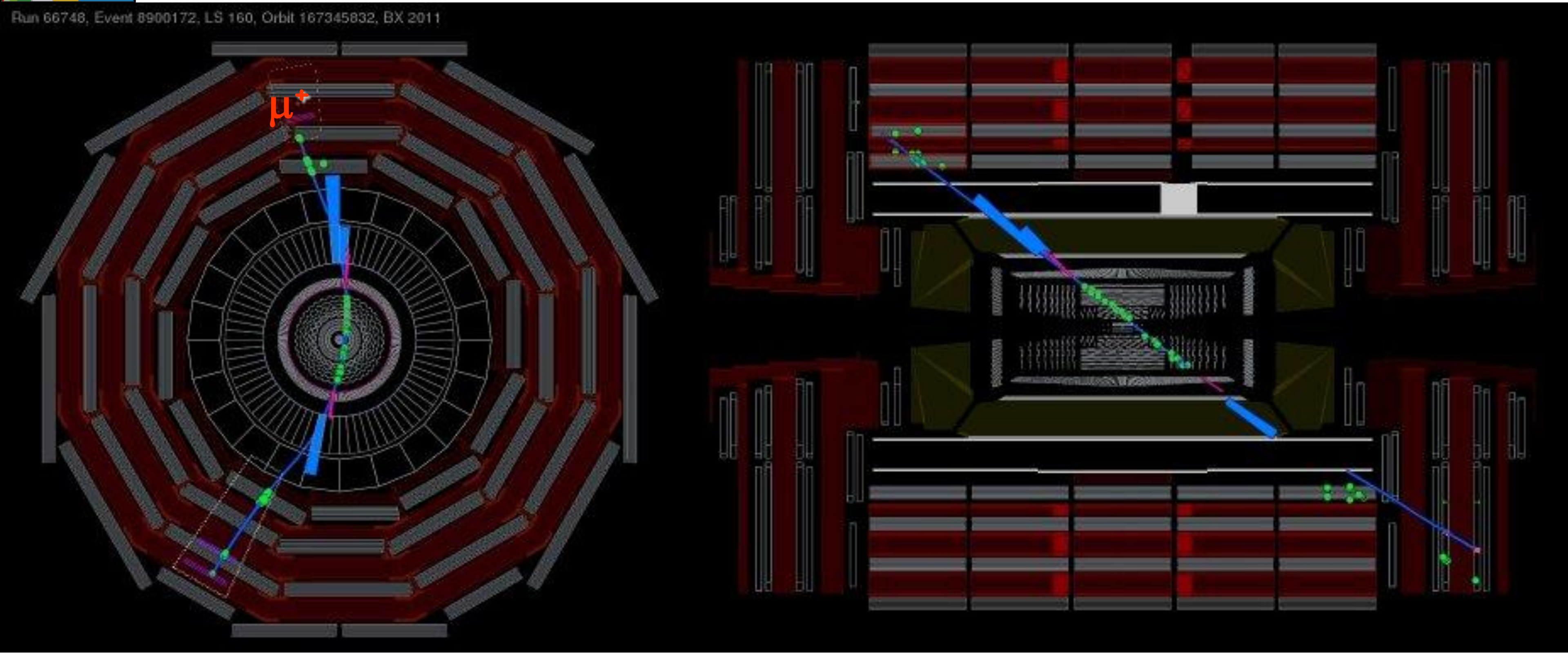
Results with Cosmics (CMS as example)

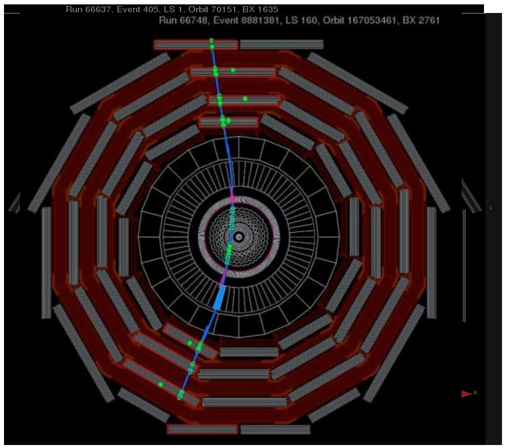


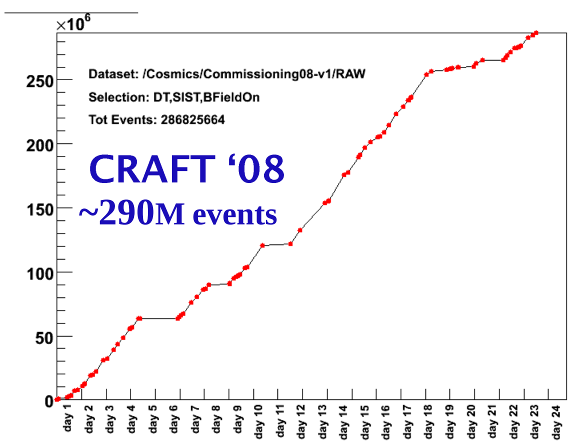


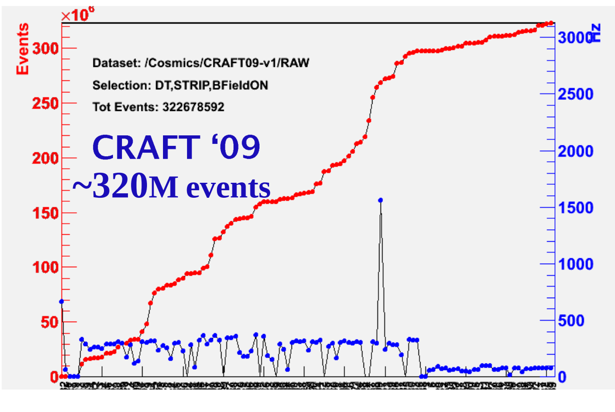


CMS: Cosmic Runs At Four Tesla



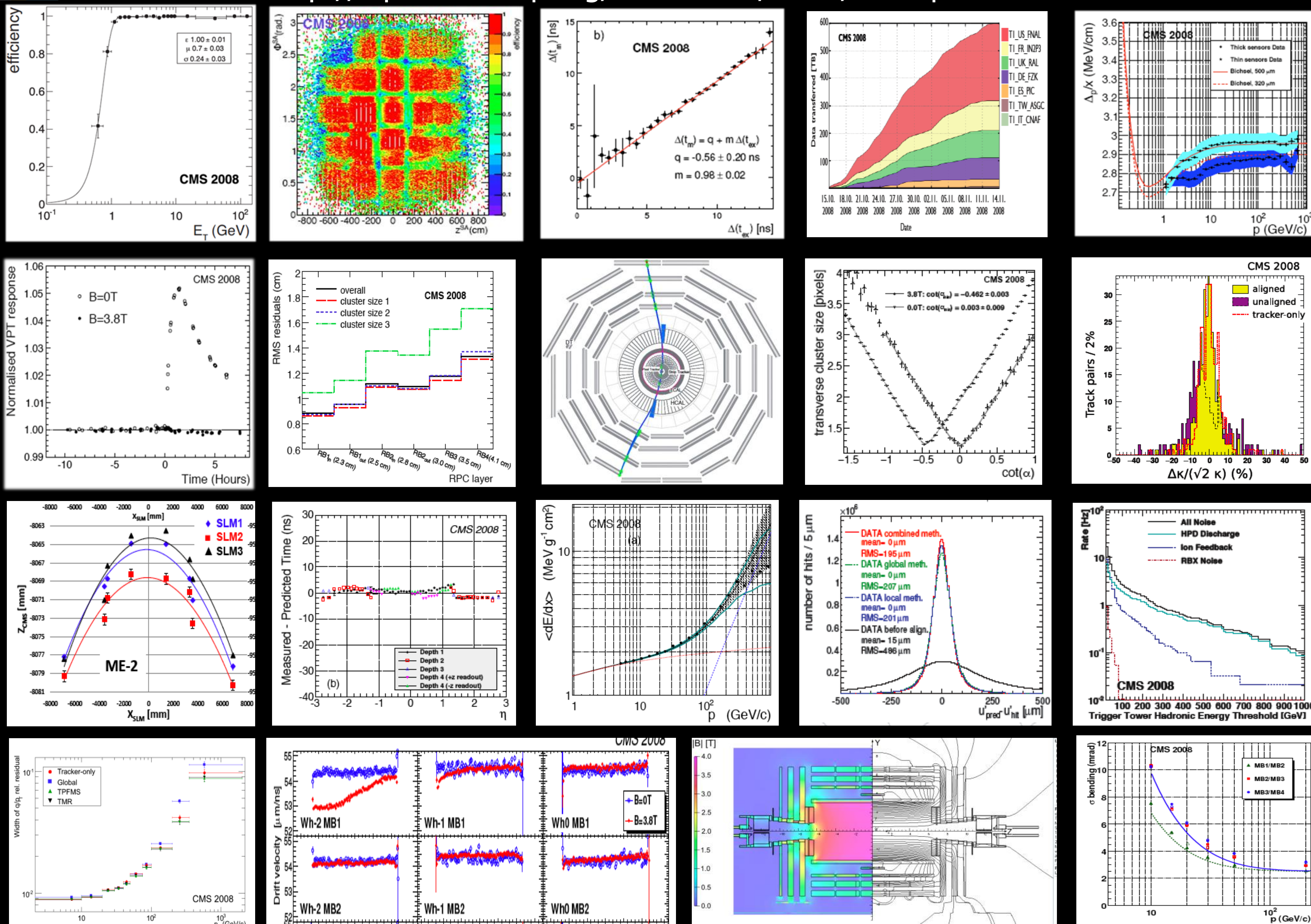






23 “CRAFT” Papers Published in JINST

http://iopscience.iop.org/1748-0221/focus/extra.proc6



CRAFT:Solenoid Field MAP

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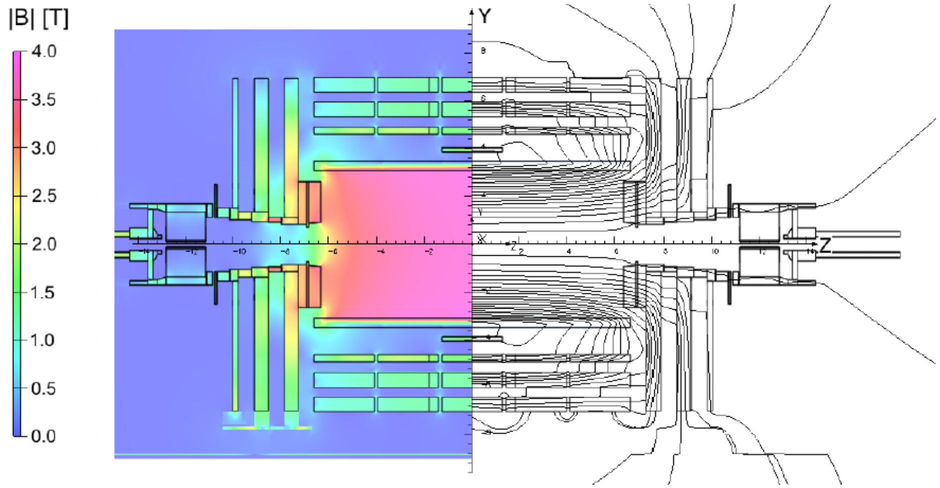
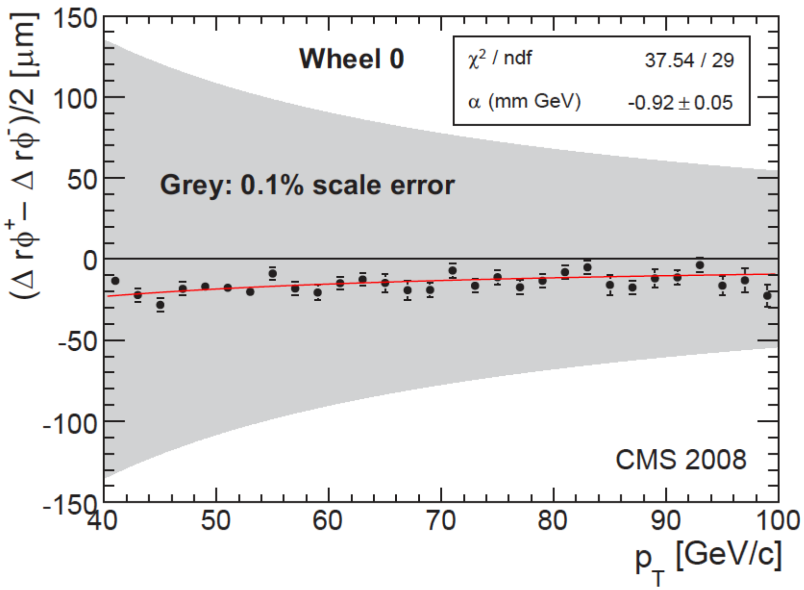


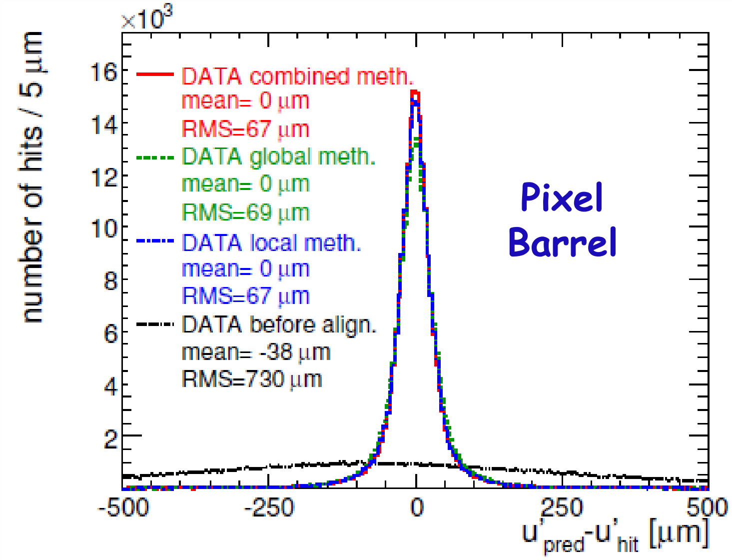
Precision modelling and measurement of the B field
- ➢ implemented in MC model



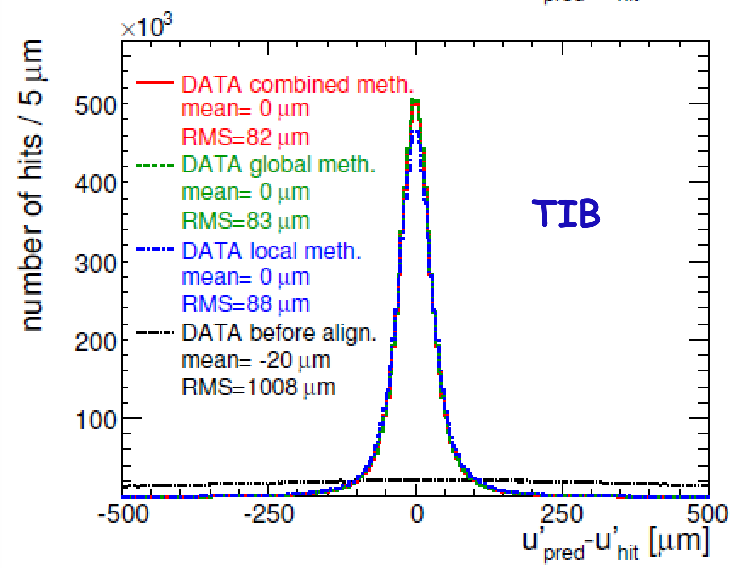
Extrapolation of track from inner tracker to first layer of barrel muon chamber
- ➢ verity that B field inside solenoid known to < 1‰

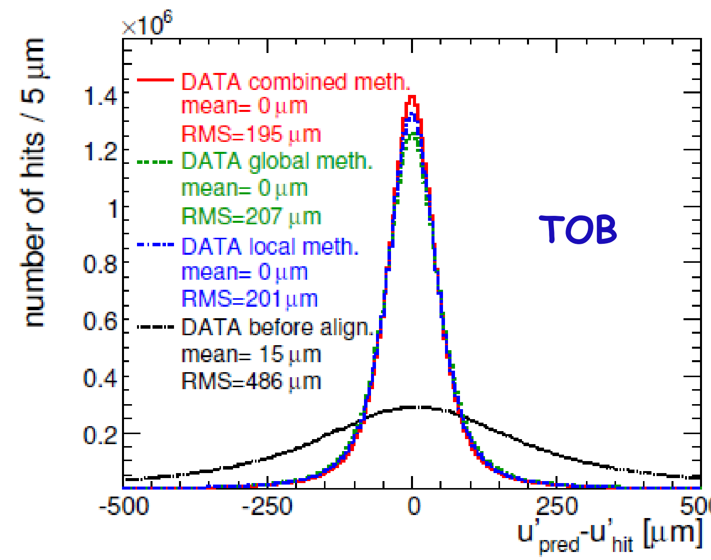
CRAFT: Tracker alignment

2010 *J. Inst.* 5 T03009



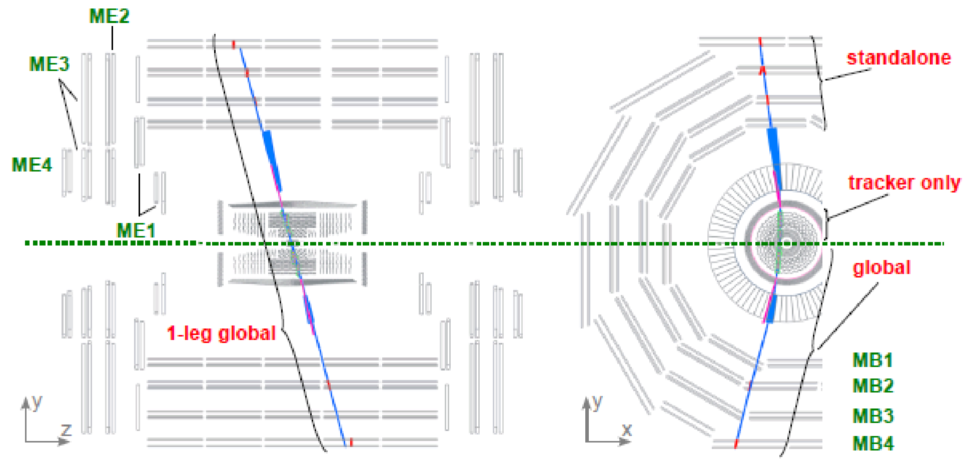
DMR RMS (µm)	CRAFT 2008	2009 prelim.	MC alignment	Ideal alignment	Modules >30 Hits
BPIX (x)	2.6	2.5	2.1	2.1	757/768
BPIX (y)	4.0	4.0	2.5	2.4	757/768
FPIX (x)	13.1	13	12.0	9.4	391/672
FPIX (y)	13.9	13	11.6	9.3	391/672
TIB (x)	2.5	3	1.2	1.1	2623/2724
TOB (x)	2.6	3	1.4	1.1	5129/5208
TID (x)	3.3	4	2.4	1.6	807/816
TEC (x)	7.4	8	4.6	2.5	6318/6400

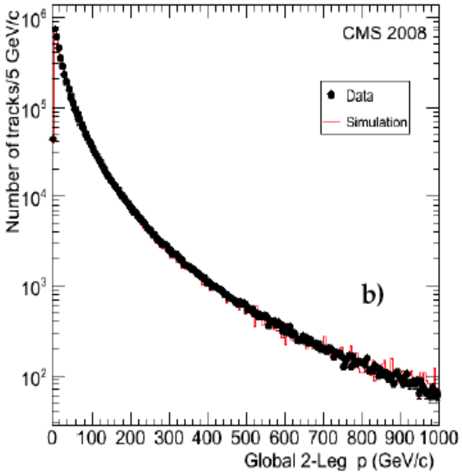




Black lines are before alignment

CRAFT: Muon/Tracker commissioning





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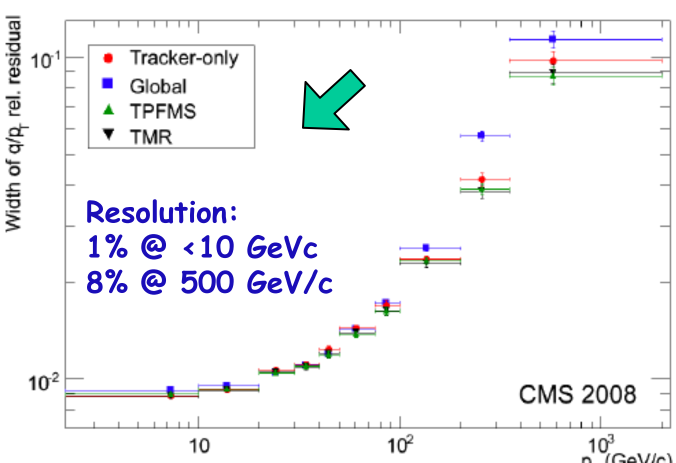
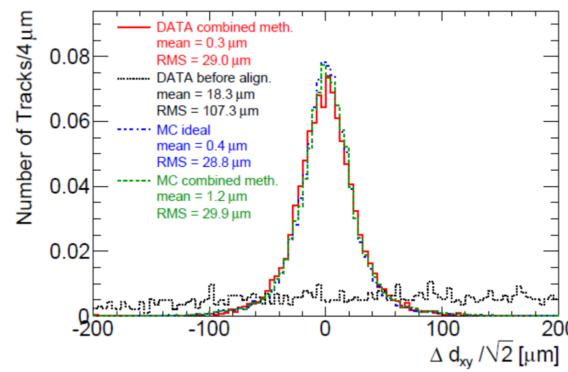
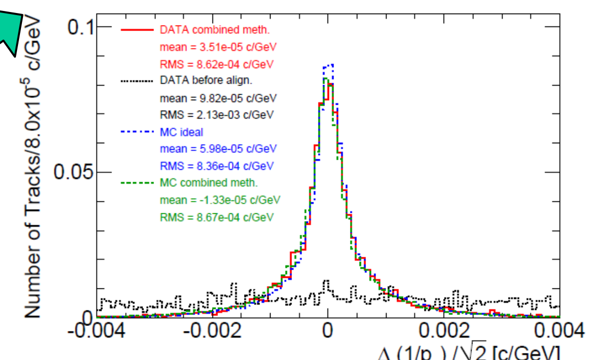
Good understanding of muon reconstruction and resolution

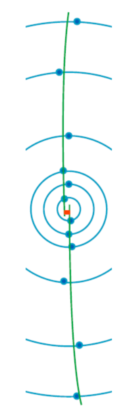


Resolution:
1% @ <10 GeVc
8% @ 500 GeV/c

Alignment already as good as can be obtained with several pb^{-1} of LHC data



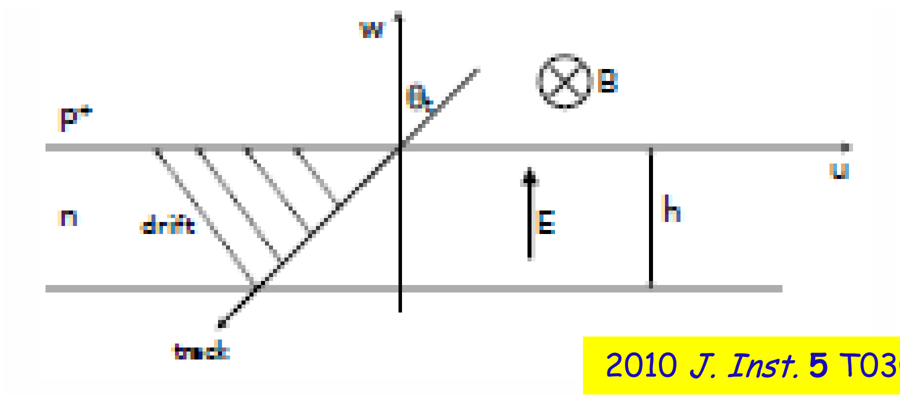




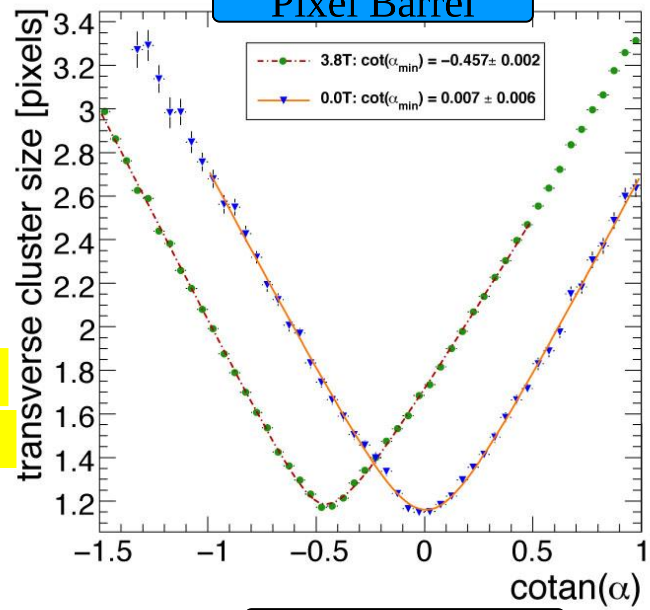
2010 *J. Inst.* 5 T03009

Lorentz angle determination

- Charge carriers are affected by the Lorentz force (deflected at Lorentz Angle)



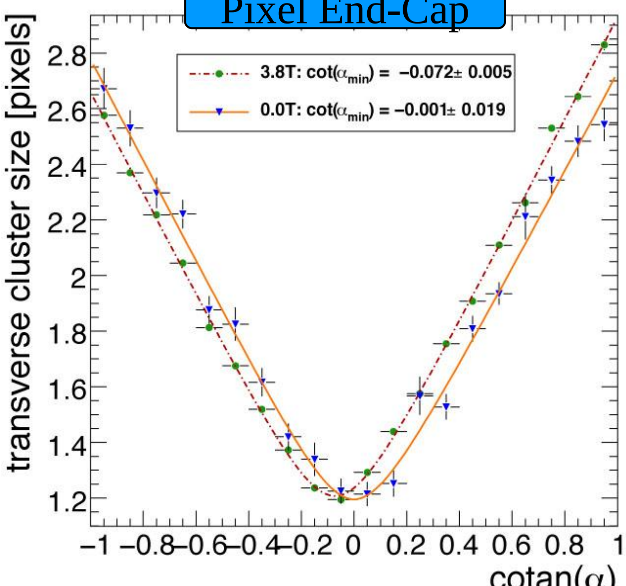
Pixel Barrel



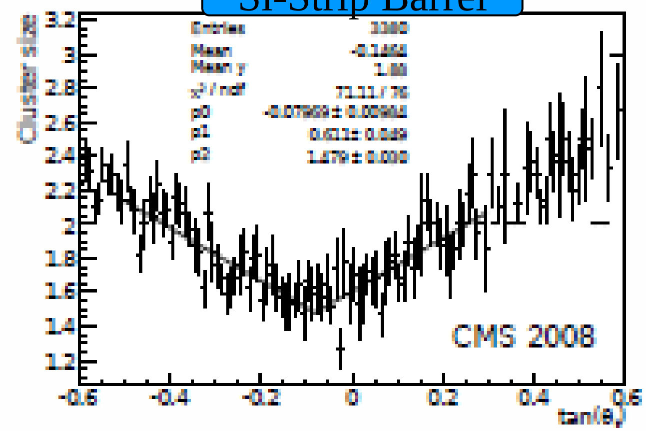
2010 *J. Inst.* **5** T03007

2010 *J. Inst.* **5** T03008

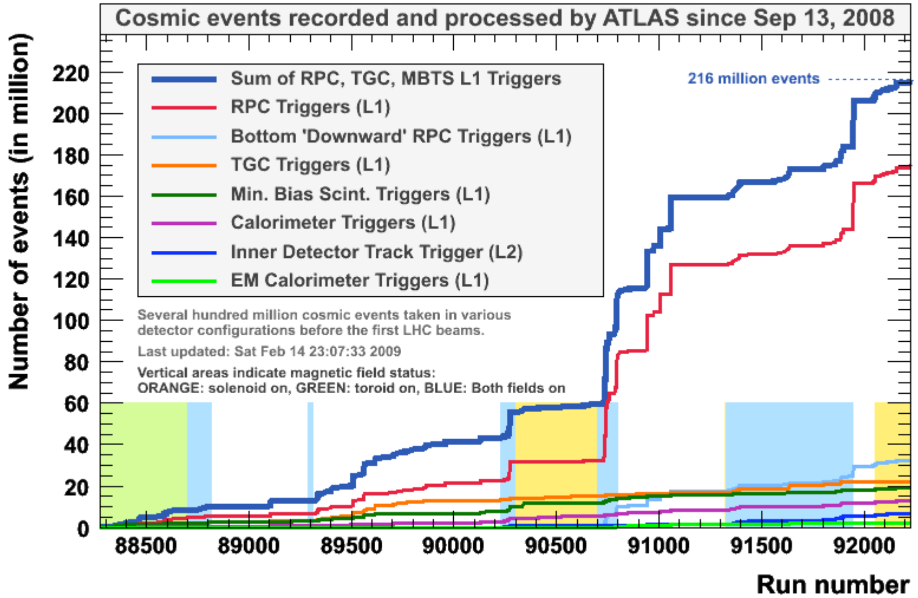
Pixel End-Cap



Si-Strip Barrel

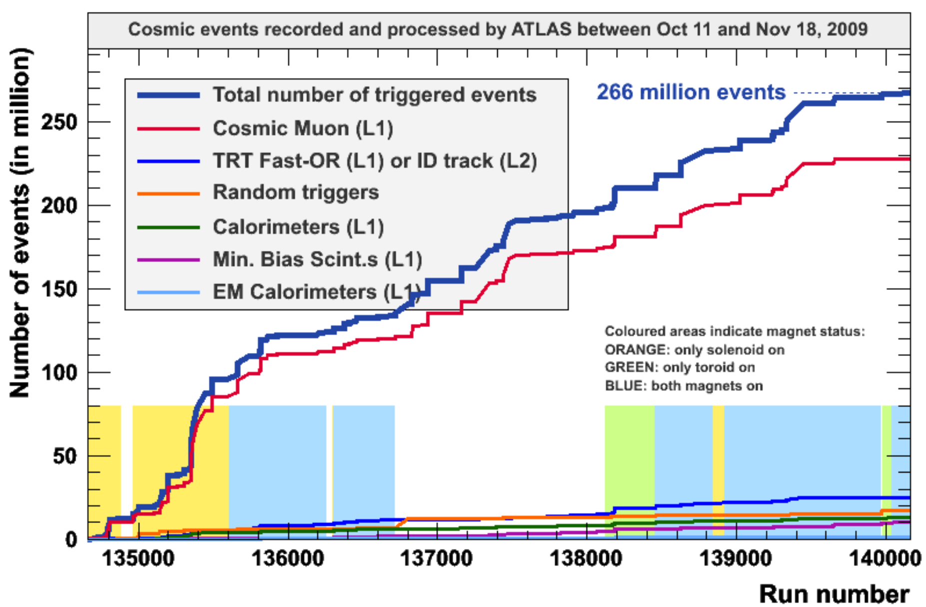


ATLAS: Cosmic data-taking



2008

216 million events

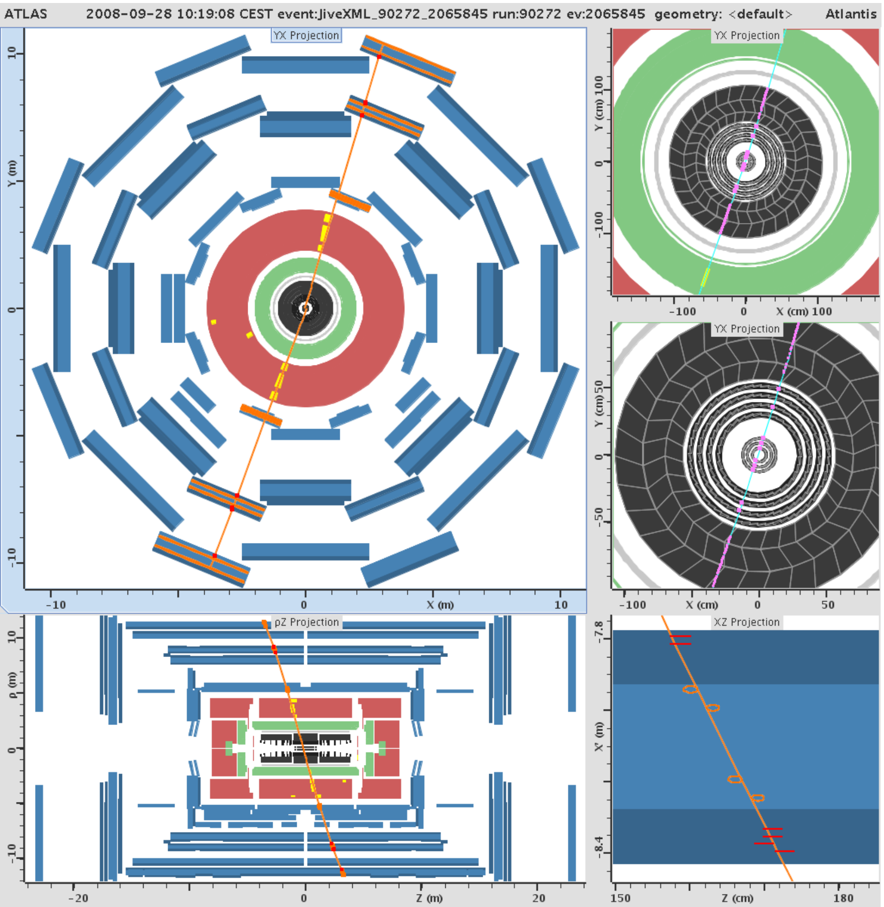


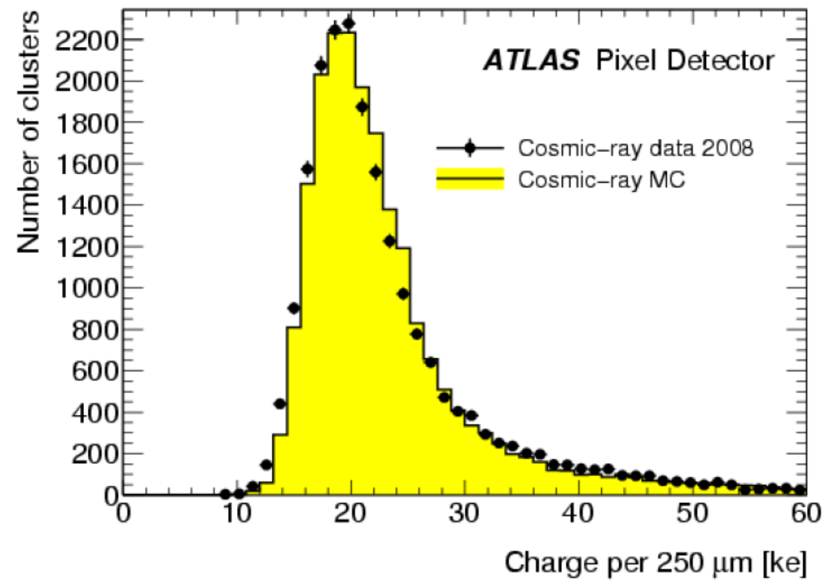
2009

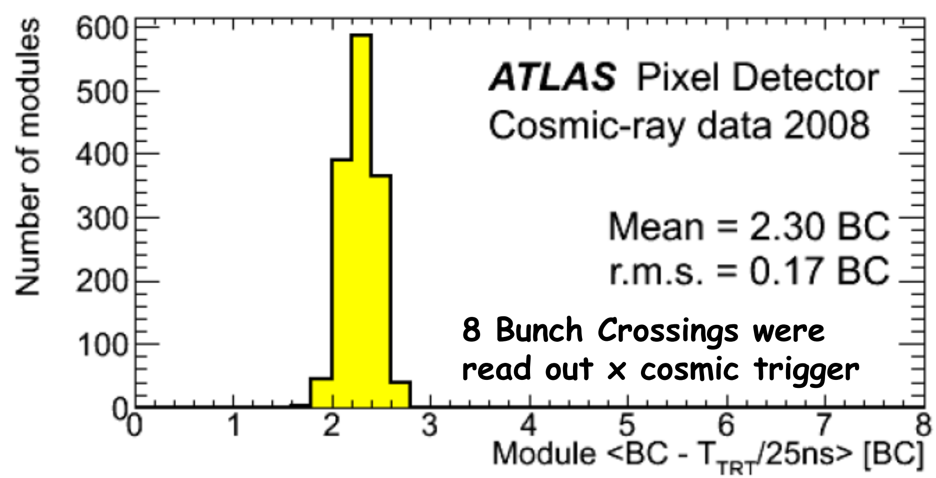
266 million events

ATLAS: pixel commissioning with cosmics

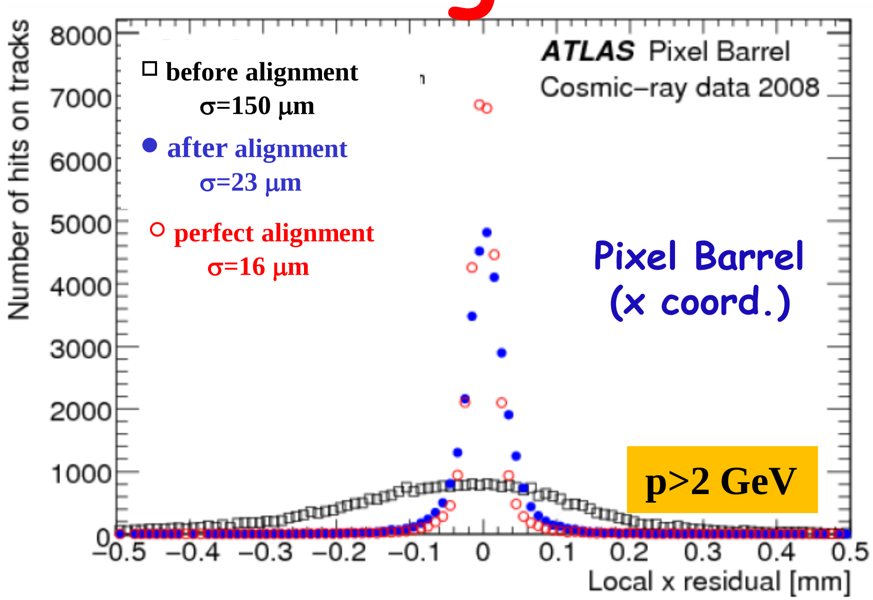
arXiv:1004.5293v1

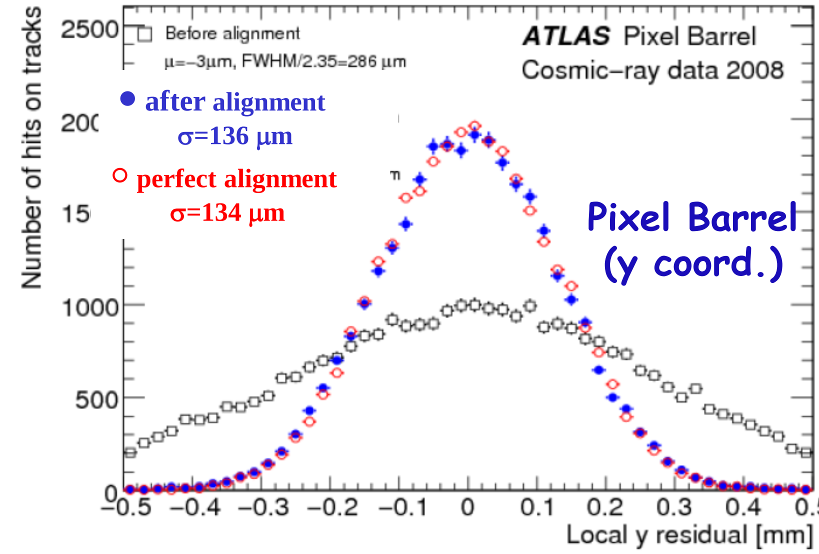


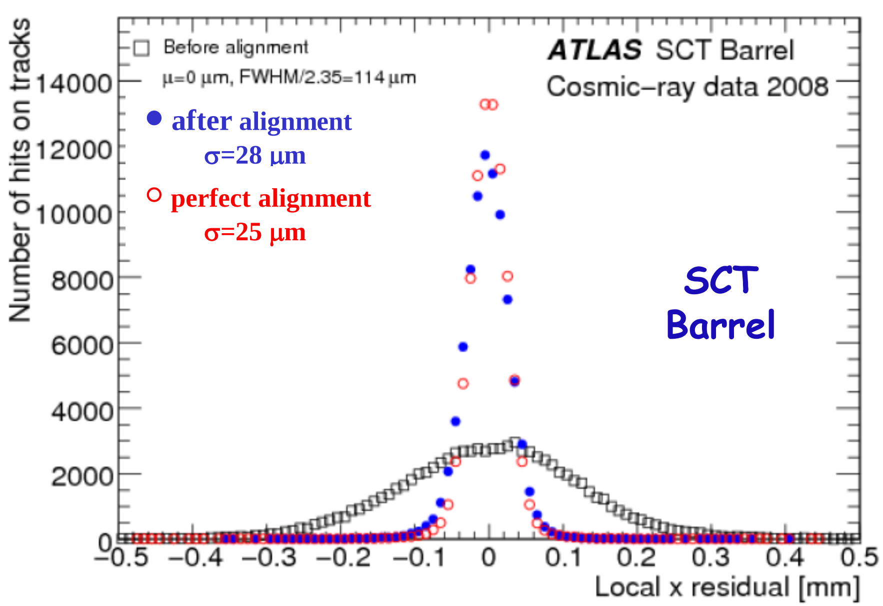


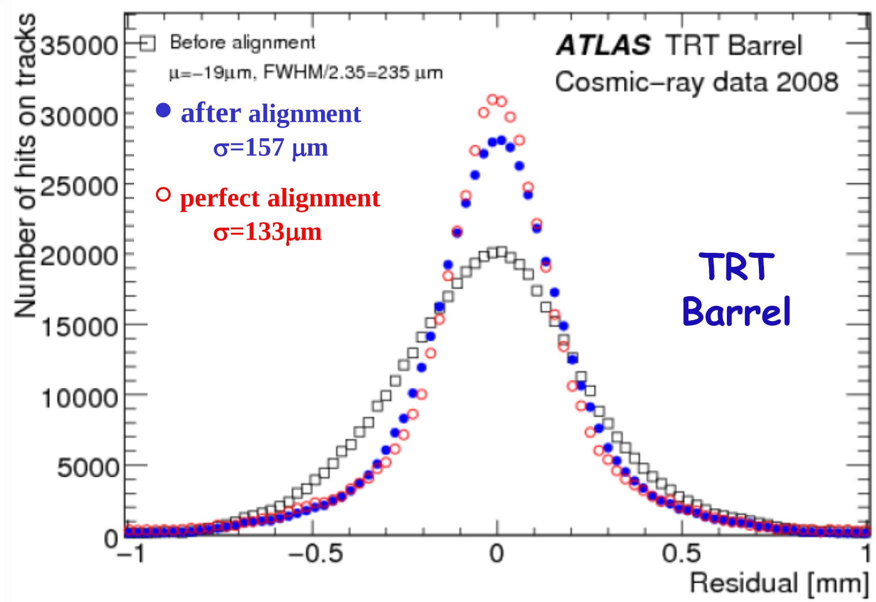


Tracking: residuals distributions







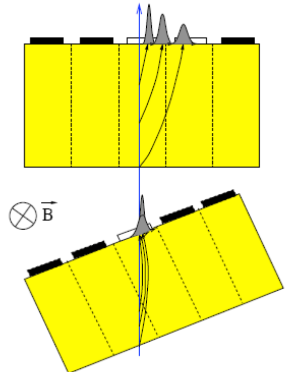


arXiv:1004.5293v1

Lorentz angle determination

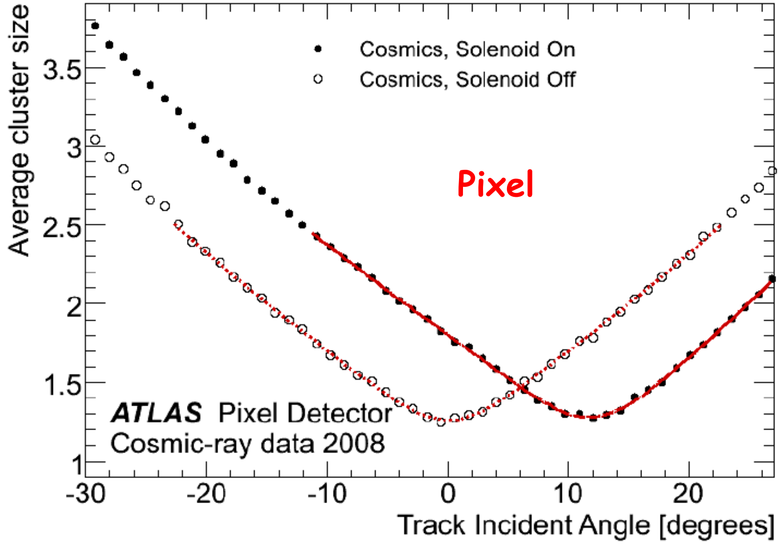
- **Drift in silicon is affected by E×B effect**
- **Charge is (de)focused along the Lorentz angle direction:**

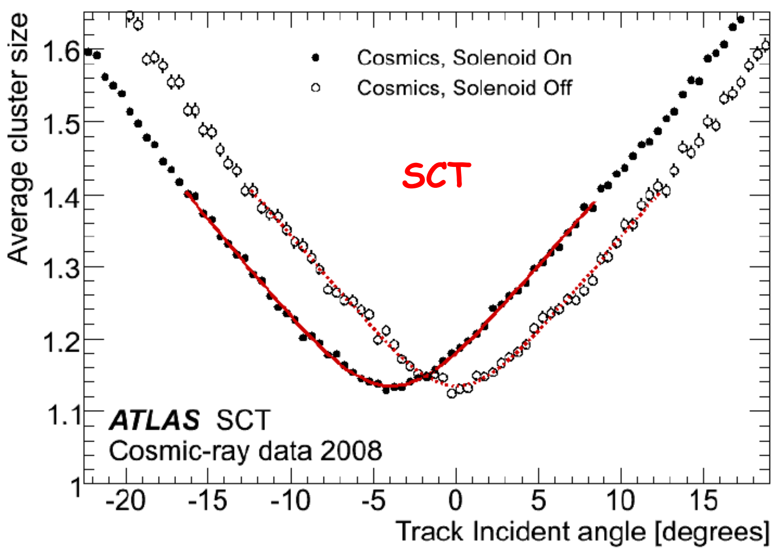
$$\tan\alpha_L = \mu_H B$$



- **Point displacement: thickness×tan(α_L)/2**
  - **≈ 30 μm for pixels**
  - **≈ 10 μm for SCT**
- **measurement using cluster size vs. incidence angle α:**

$$\text{cluster size} = a\left(\tan\alpha - \tan\alpha_L\right) + b/\sqrt{\cos\alpha}$$

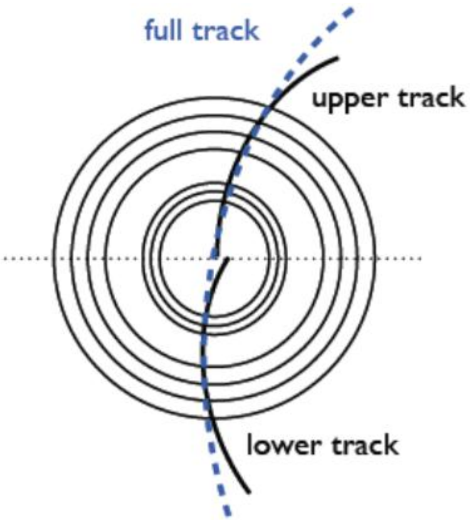




arXiv:1004.5293v1

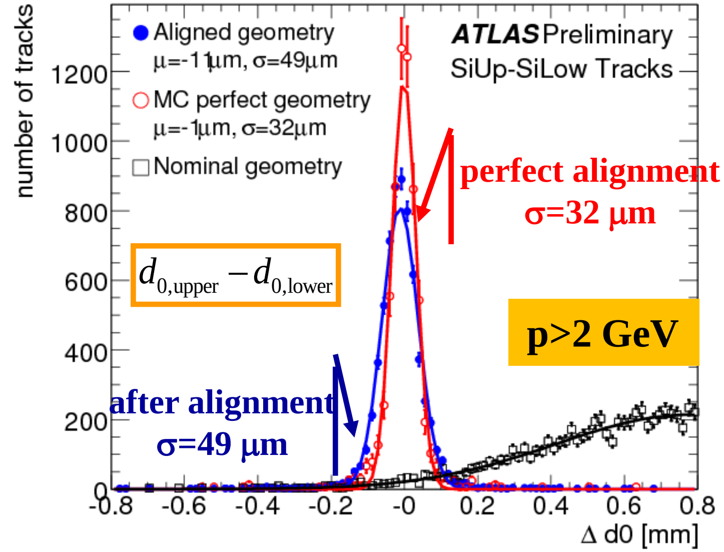
Track parameter resolution

- Resolution of track parameters can be obtained:
  - splitting the track in two segments
  - compare extrapolation at the interaction point of the segments.

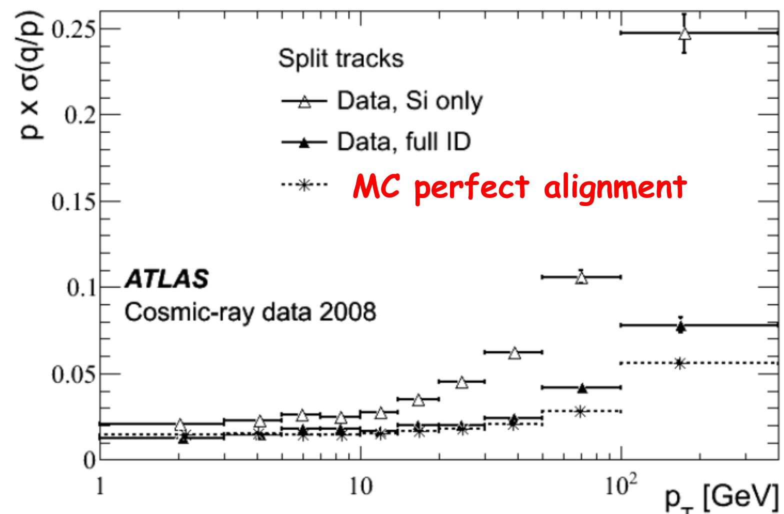


$$\text{resolution} = \frac{\sigma_{\text{upper}-\text{lower}}}{\sqrt{2}}$$

N.B.:
- plots before correcting for √2
- integrated over full momentum spectrum



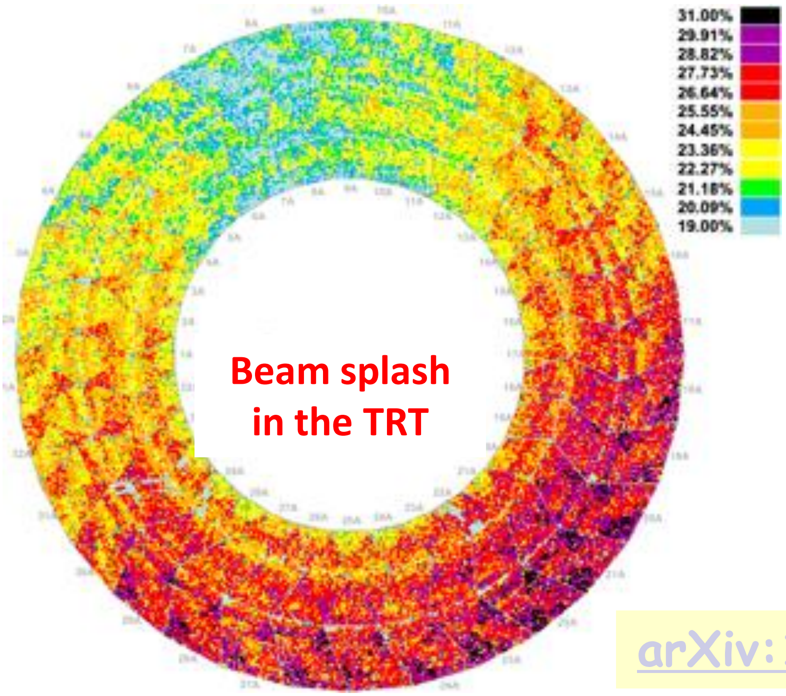
Impact parameter resolution

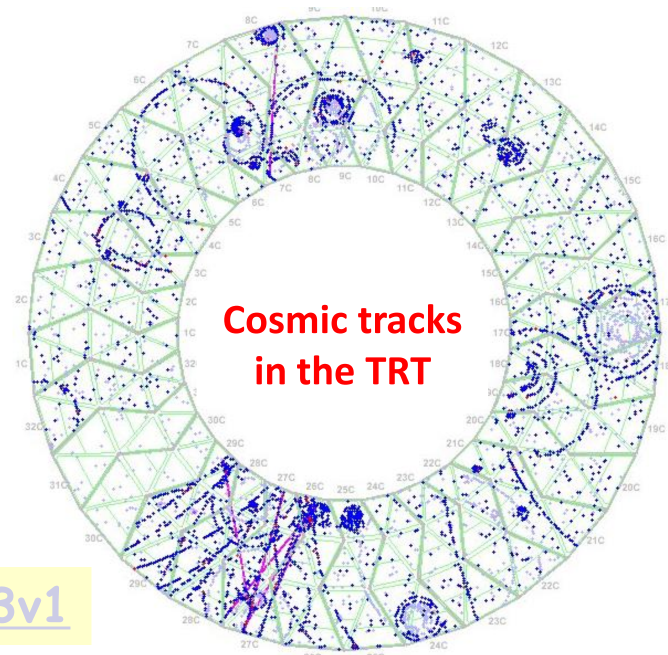


Momentum resolution

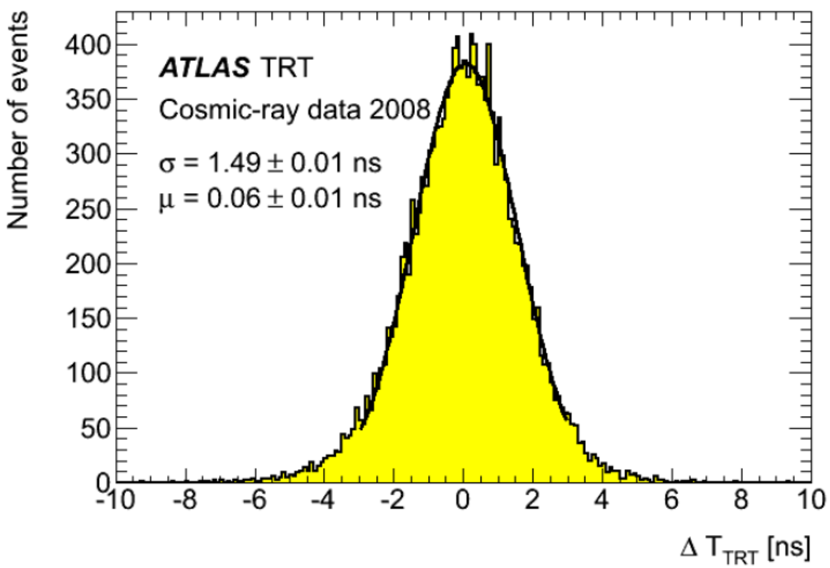
Resolution not far from perfect alignment, already before LHC startup!

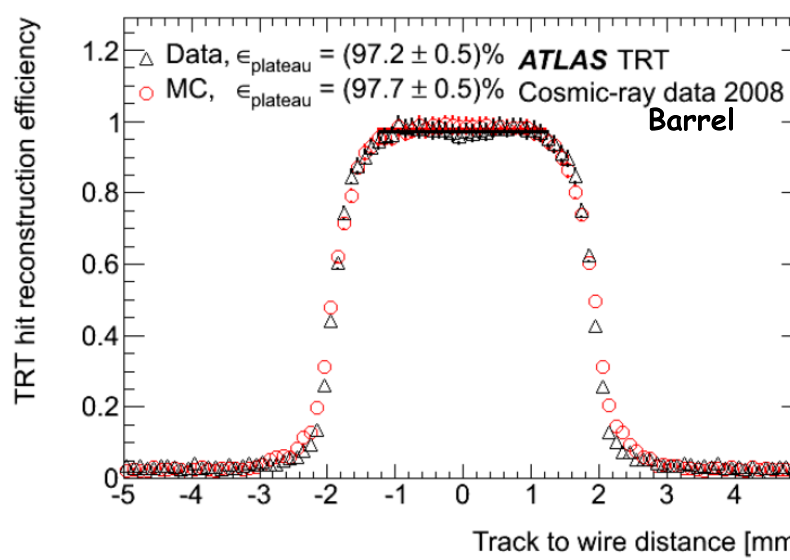
TRT Timing and Efficiency



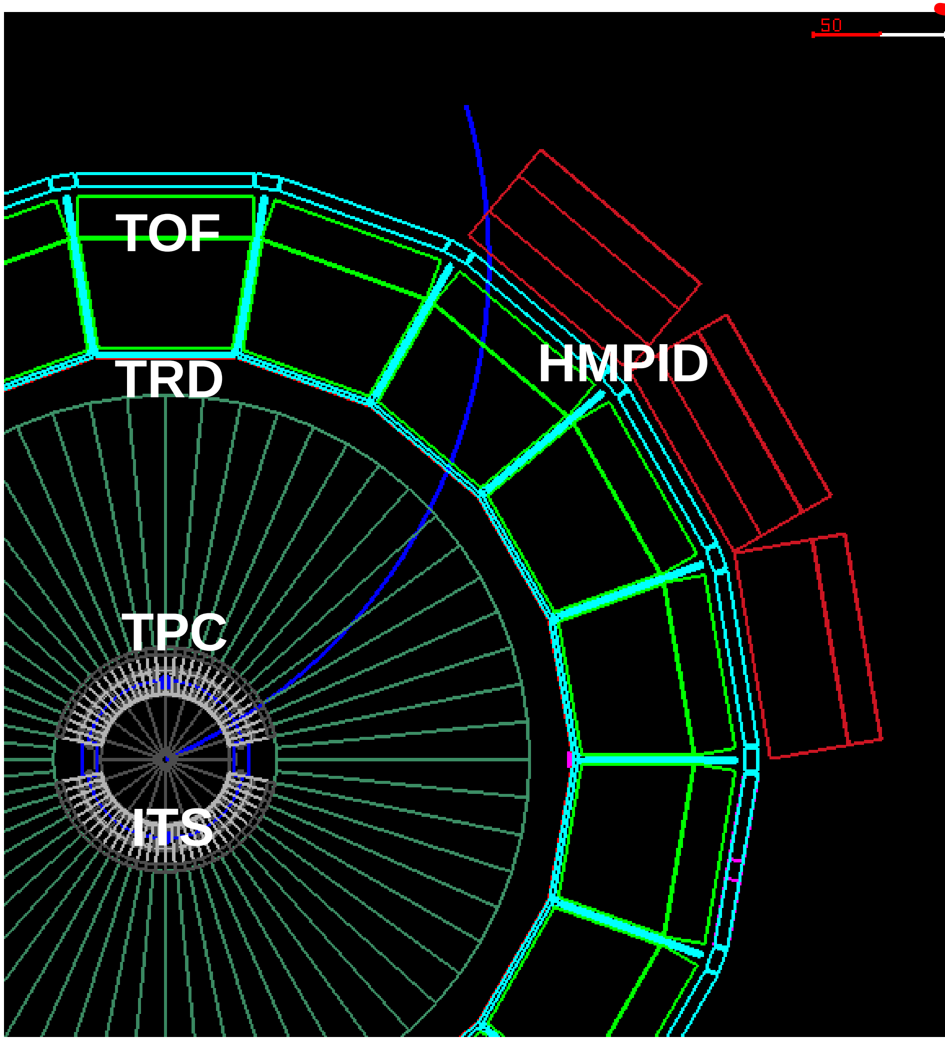


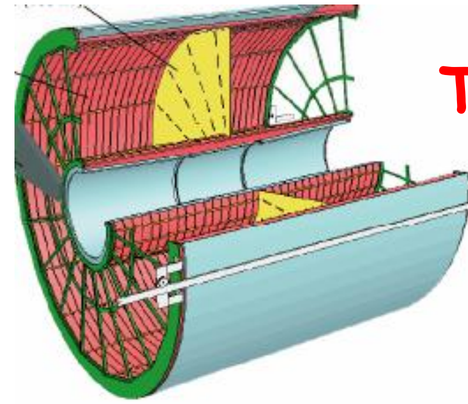
arXiv:1004.5293v1

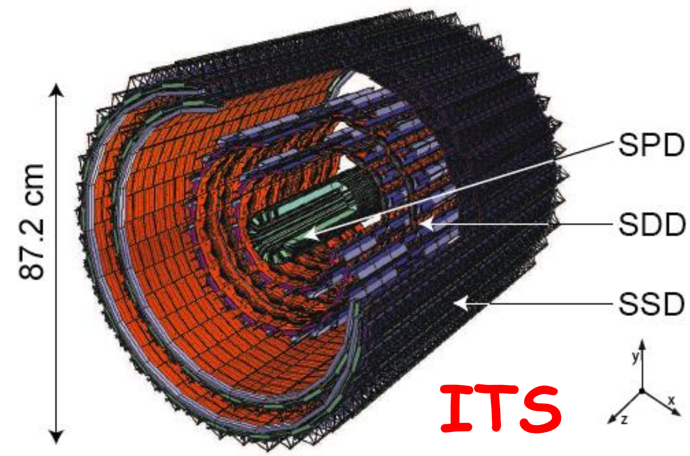




ALICE Commissioning with Cosmics







3 Tracking detectors (|h|<0.9):

- Inner Tracking System (4<R<43 cm)
- Time Projection Chamber (90<R<250cm)
- Transition Radiation Det

Inner Tracking System: Alignment with Cosmics

Silicon Pixel Detector (SPD):
- **~10M channels**
- **240 sensitive vol. (60 ladders)**

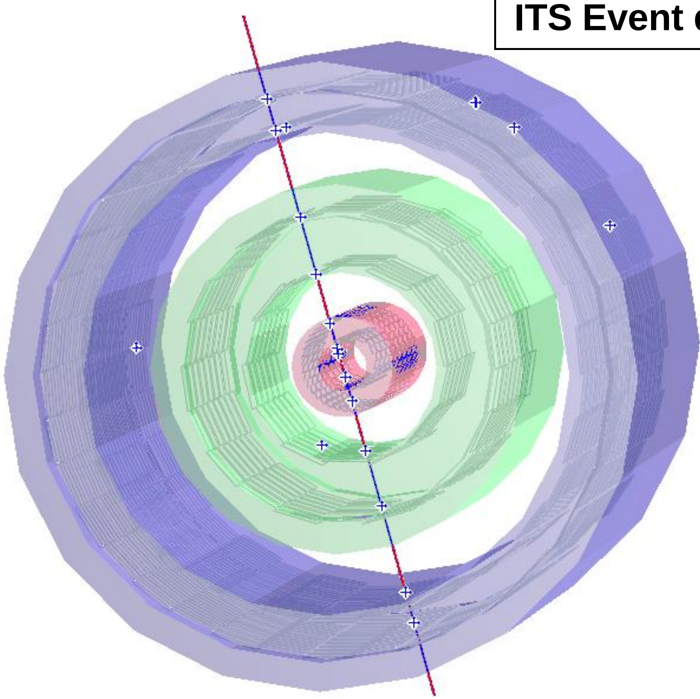
Silicon Drift Detector (SDD):
- **~133k channels**
- **260 sensitive vol. (36 ladders)**

Silicon Strip Detector (SSD):
- **~2.6M channels**
- **1698 sensitive vol. (72 ladders)**

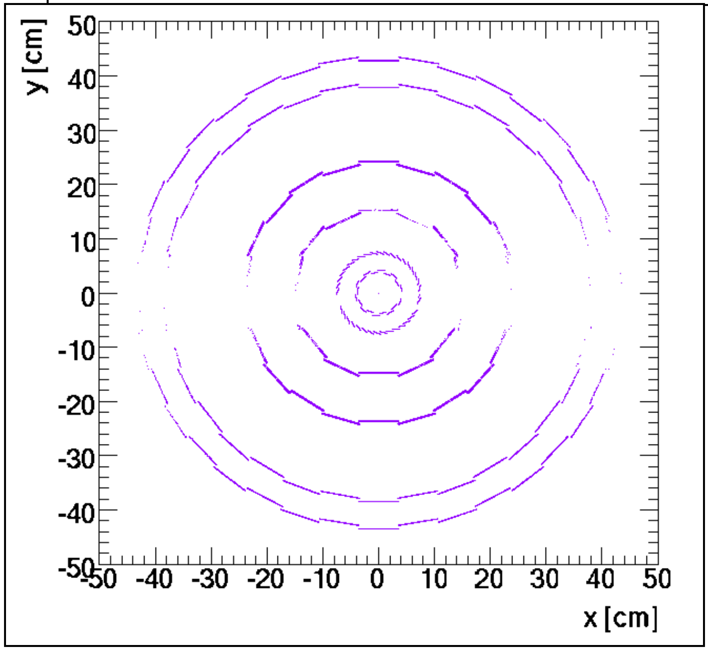
ITS total: 2.2k alignable sensitive volumes → 13k degrees of freedom

- Alignment using tracks and Millepede program in a hierarchical approach
  - Transiton from Millepede1 to Milledepe2 (faster, less memory); Iterative local method as a cross-check
- ~100k cosmic □ for alignment collected Jun-Oct 08, using Pixel trigger

ITS Event display

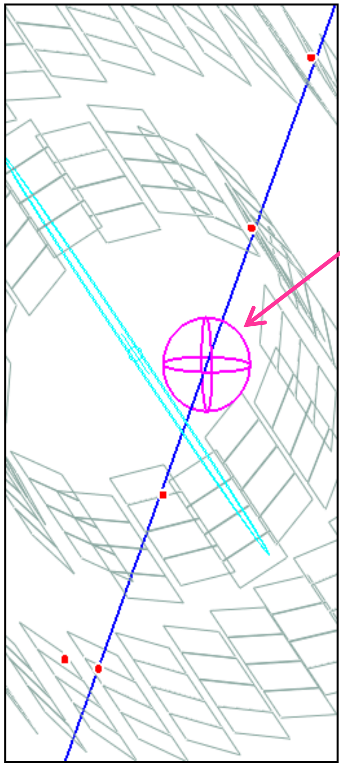


Distribution of clusters in the 6 layers

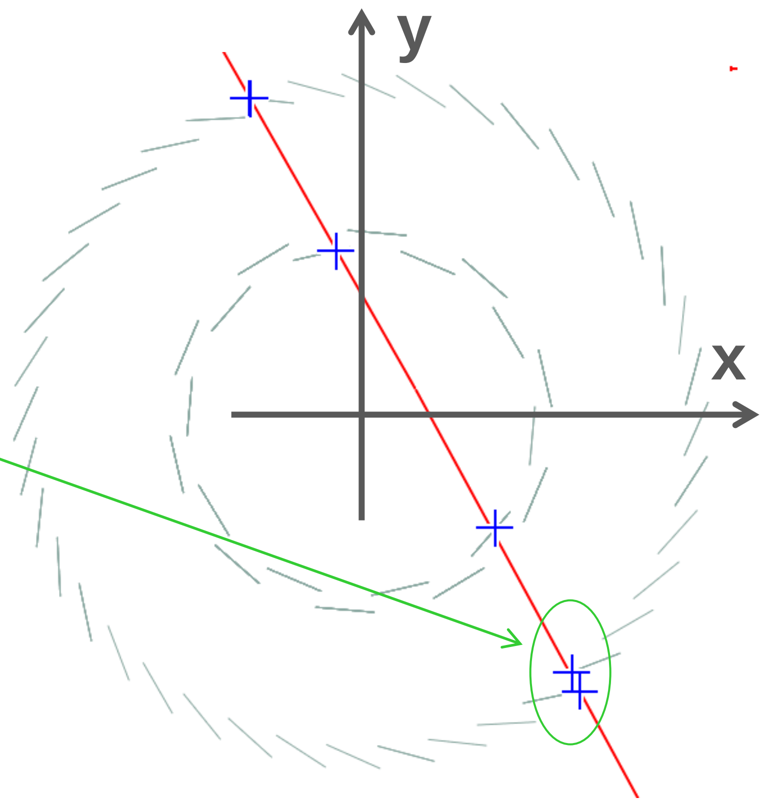


Checking the quality of realignment

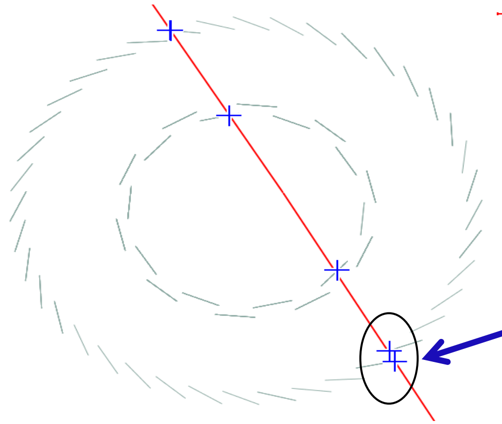
Select muons with DCA to (0,0) < 1 cm



- **Cosmics track-to-track Δxy at y=0**
- **Acceptance overlaps → "extra" clusters**
- **Track-to-point residuals**



SPD "extra" clusters



Track-to-"extra clusters" distance
in transv. plane (SPD overlap)

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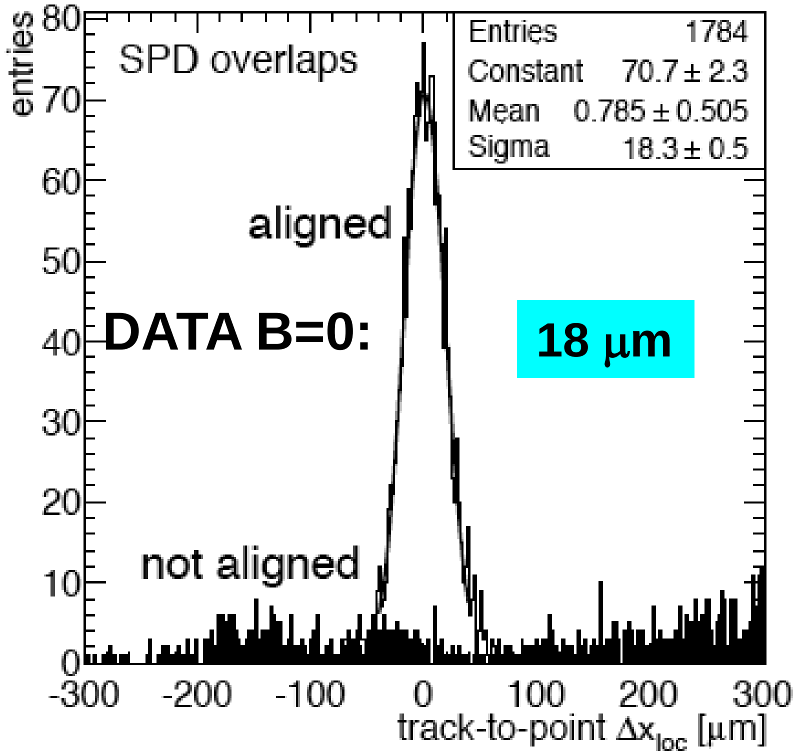
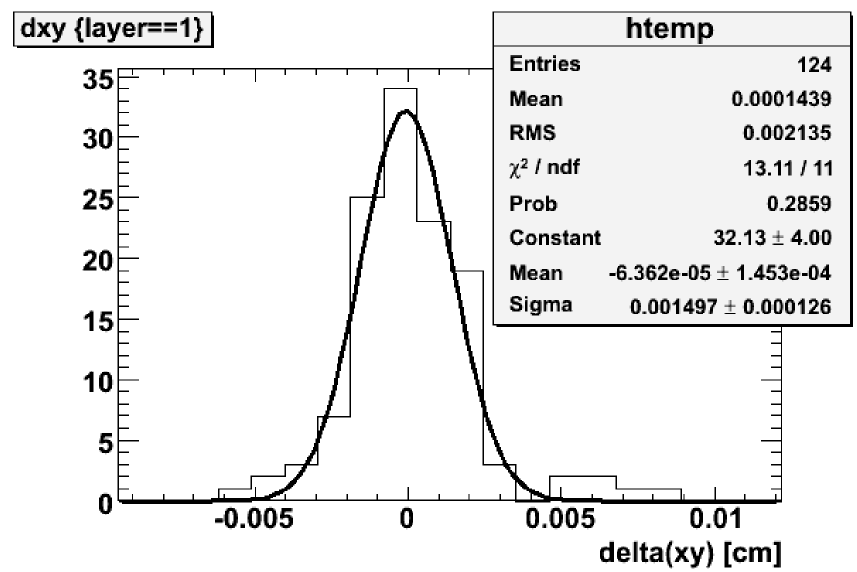


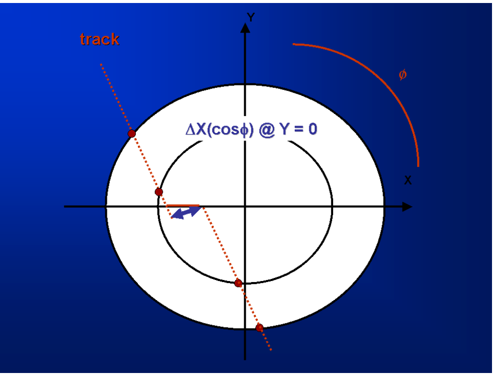
$$\sigma^2_{\Delta xy} \approx 2 \cdot \sigma^2_{spatia}$$

→ $\sigma_{spatial} \approx 18 / \sqrt{2} = 13$ μm

MC, ideal geom: 15 μm



→ $\sigma_{spatial}$=11 μm (Sim)



Millepede SPD realignment: Δxy at y=0

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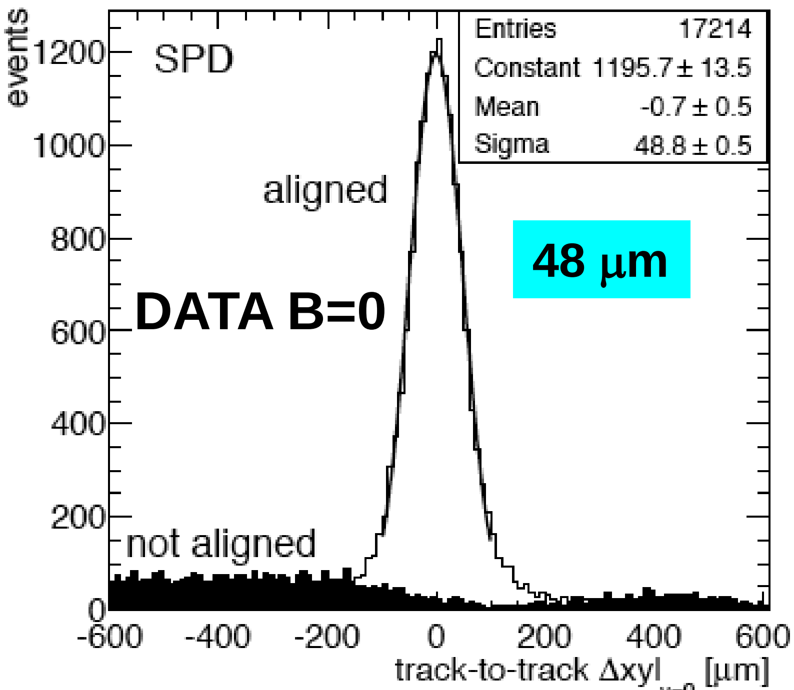
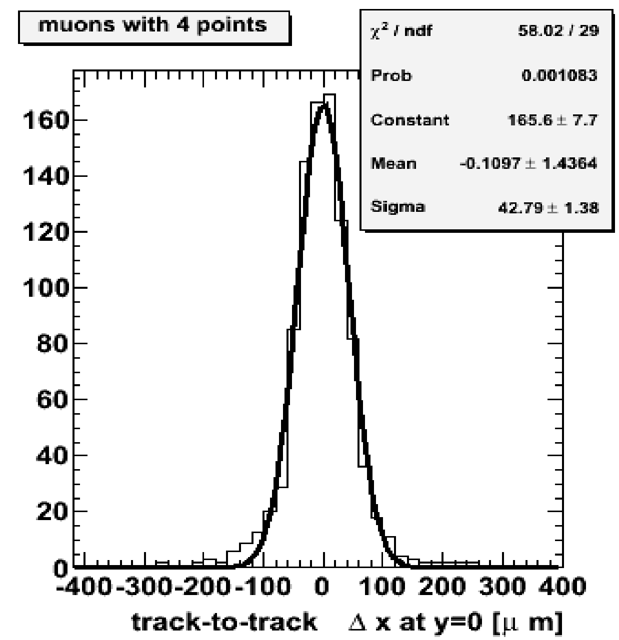
- Track-to-track matching (2 points per track in the pixels)



MC, ideal geom: 43 μm



Expected spread

$$\sigma^2_{\Delta x} = 2*(r^2_{SPD2}+r^2_{SPD1})/(r_{SPD2}-r_{SPD1})^2*\sigma^2_{spatial}$$

→ $\sigma_{spatial}$≈13 μm → σ_{misal}~7 μm

→ $\sigma_{spatial}$=11 μm (Sim)

Validation of SSD survey with cosmics

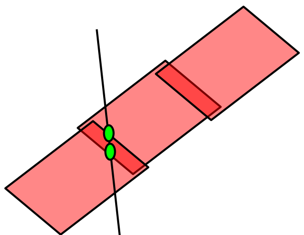
✓ SSD survey measurement collected during detector assembly

Modules on ladders (critical: small stat on single modules with cosmics) precision ~5 μm

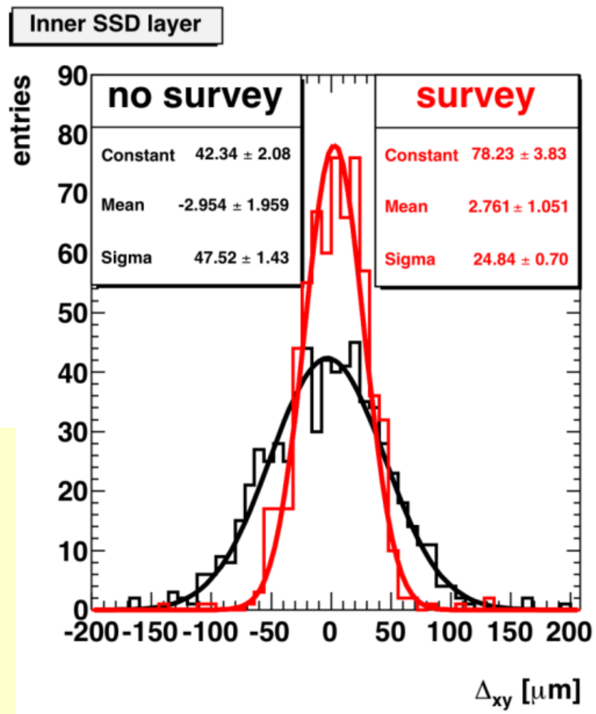
Ladders on support cones (important starting point for alignment) precision ~15 μm

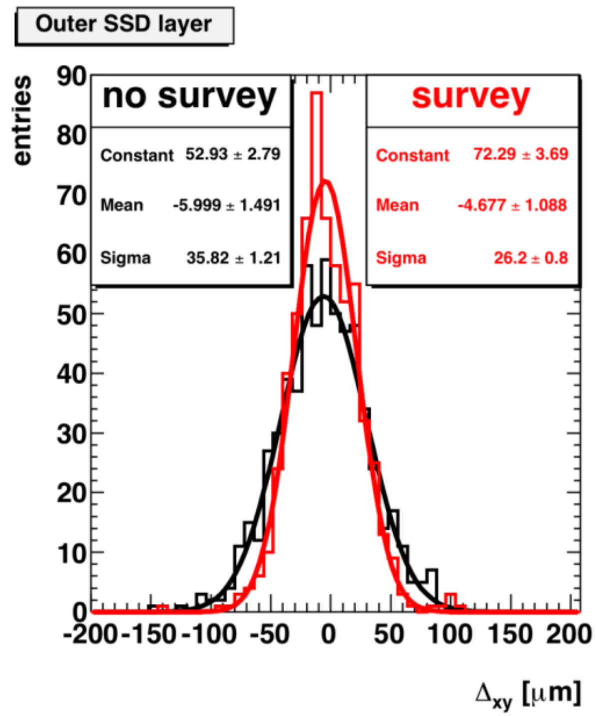
✓ **Validation with cosmics:**

Extra clusters from acceptance overlaps → distance between two clusters from same track on contiguous (overlapping) modules on same ladder



Module on ladder misalignment





Cosmic validation with two additional methods:
2) Track-to-track residuals: fit one track on outer layer, one on inner layer → distance and angles between the two tracks
3) Track-to-point residuals: fit track on one SSD layer (2 points) → residuals on other SSD layer

σ(Δxy)=25 μm (48)
⇒σ(point)=25/√2=18 μm
⇒σ(misal)<5 μm (27)

σ(Δxy)=26 μm (36)
⇒σ(point)=26/√2=18 μm
⇒σ(misal)<5 μm (15)

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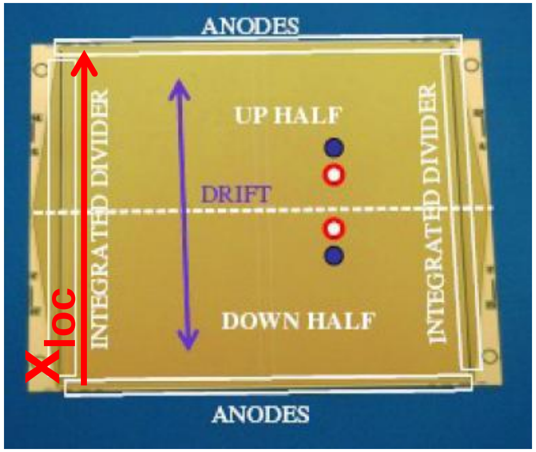
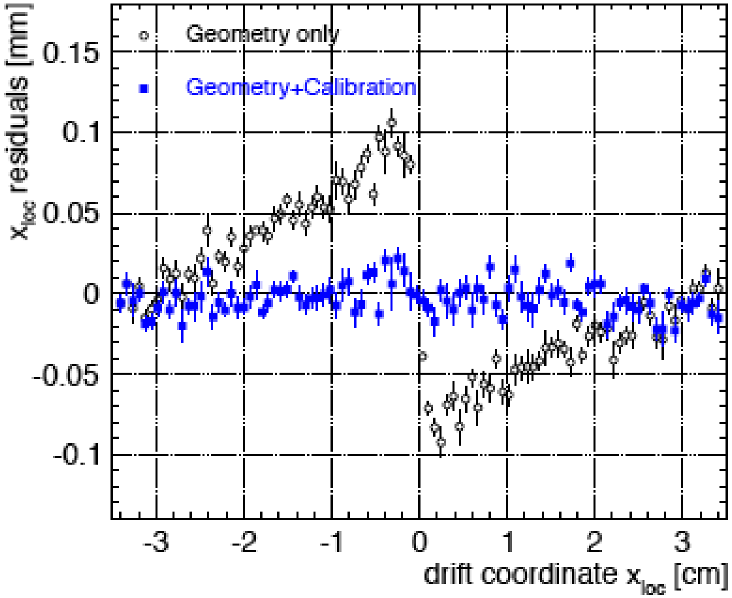
Silicon Drift Detectors: calibration & alignment in progress

- The two intermediate layers of the ITS
- In SDD, local x determined from drift time:

  $x_{loc} = (t - t_0) \times v_{drift}$
  - two calibration parameters: t_0 and v_{drift}
- Interplay between alignment and calibration
- t_0 and v_{drift} (the latter also obtained from injectors) as additional parameters in Millepede



residuals at SDD vs local x:



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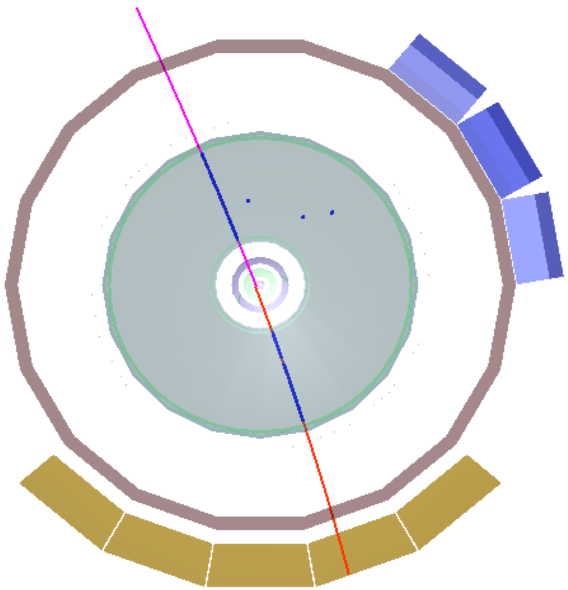
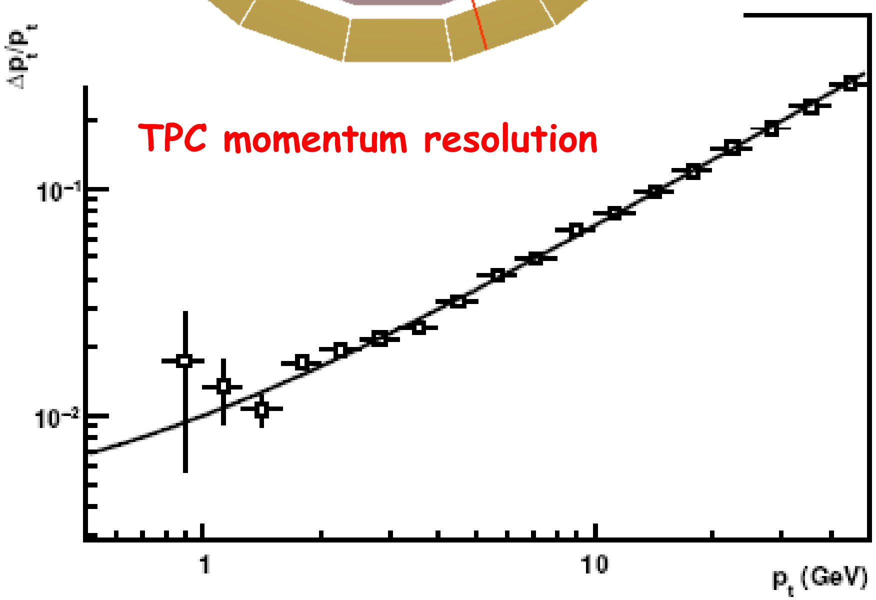
TPC: tracking performance

Results from cosmics (7 million events)

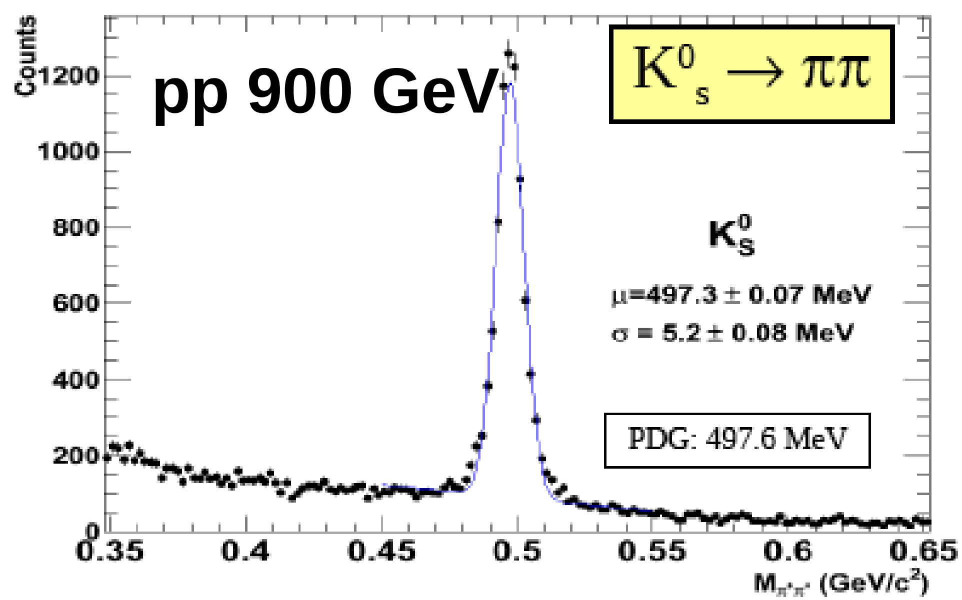
Comparison of the pt for the two halves (top / bottom) of the same cosmic muon:

→ p_t resolution TPC only (design goal: 5% @10 GeV/c)
measured ~ 6.5% @ 10 GeV/c (~ 1% below 1 GeV/c)
expected to improve by factor 10 with ITS and TRD



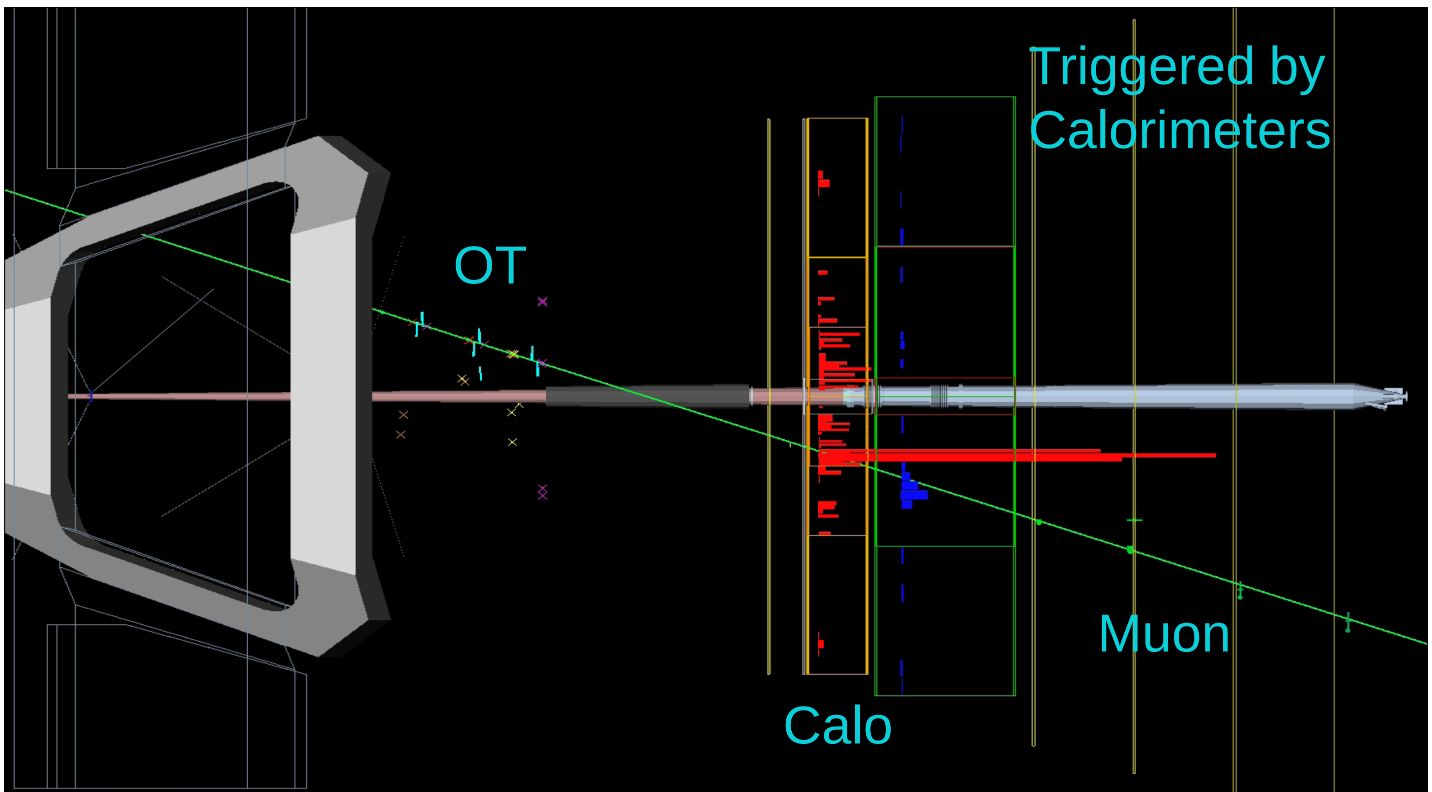


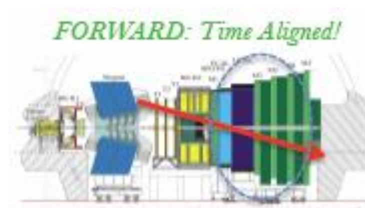
Confirmed by width of K^0_S



LHCb Commissioning: Cosmics

- LHCb geometry NOT well suited for cosmics…
- Rate of 'horizontal' cosmics well below 1 Hz, still very useful for Outer Tracker Calorimeters and Muons. Inner Tracker too small. Vertex Detector and Trigger Tracker too far.
- Collected a total of ~ 4 Million triggers to perform initial synchronization (few nsec) and space alignment (~1 mm)

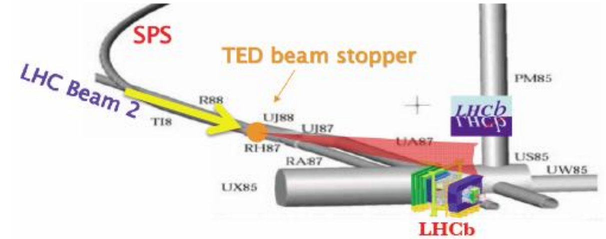




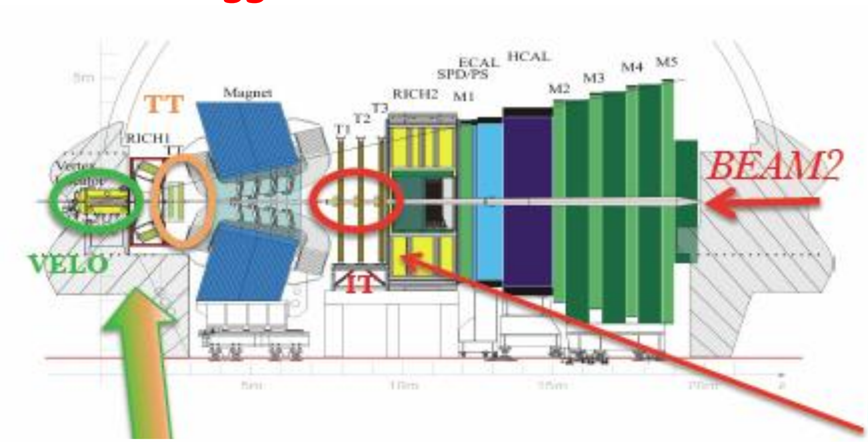
Commissioning: LHC injection test

TED Runs (Transfer line External beam Dump)

Beam2 dumped on the injection line beam stopper
350 m downstream LHCb

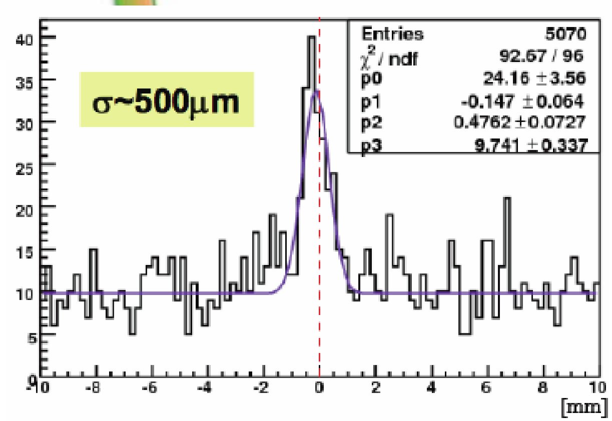


VELO, Trigger Tracker, Inner Tracker detectors: start of spatial alignment

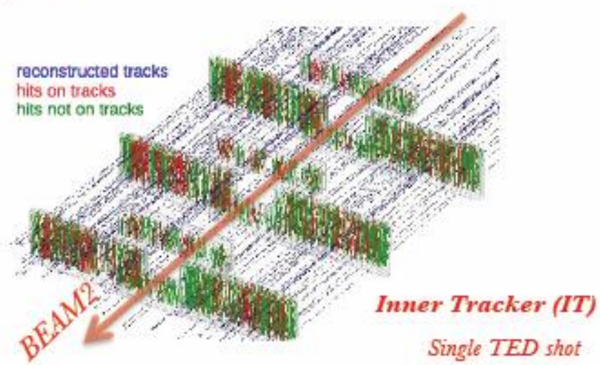


Shots every 48 seconds
- several 10^3 events acquired

Inner Tracker (IT) alignment ~ 15 μ m

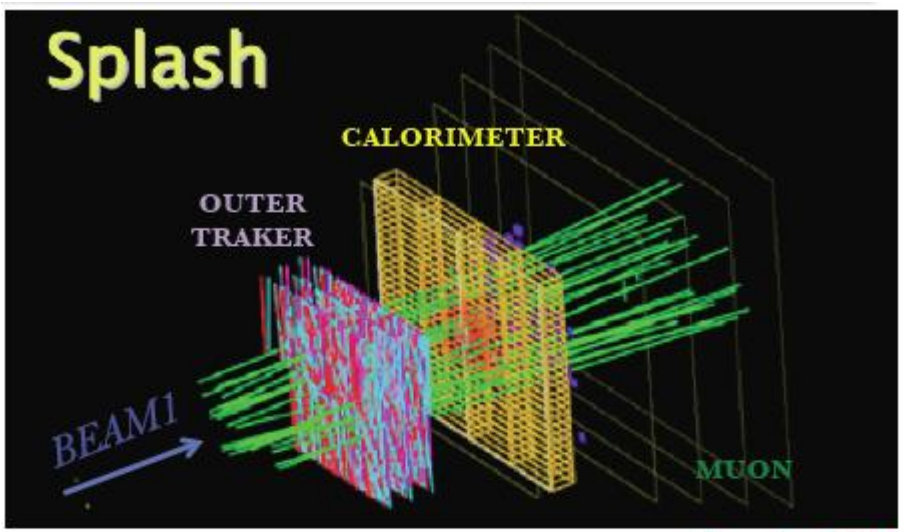


Residual for relative Alignment VELO -Trigger Tracker (TT)



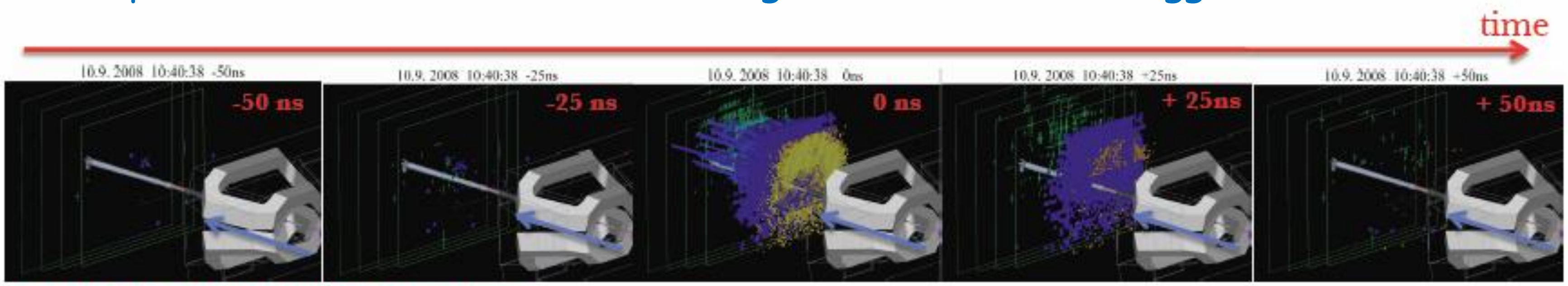
Commissioning: Splash from Beam1

Beam1 on the Target Collimator



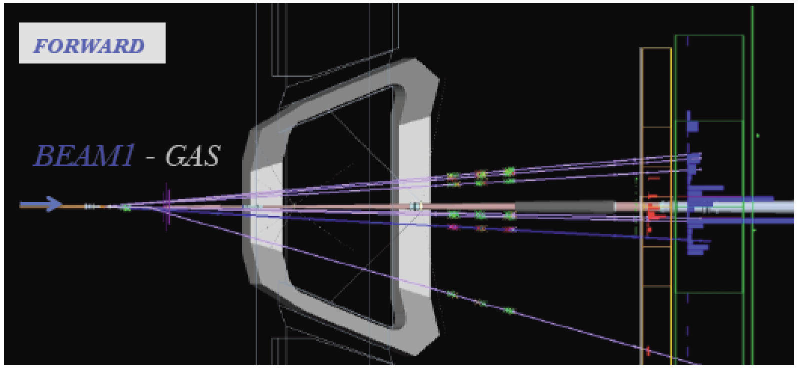
September 2008

Acquired **5 consecutive bunch crossing centered on the trigger event**

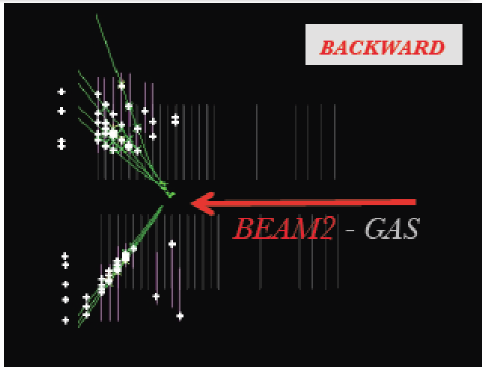


Readout of 5 bunch crossing centered on the trigger event

Commissioning: Beam-Gas interaction



Beam1-Gas 11/2009: Triggered by Calorimeters OR Muon (rate ~ 5Hz)

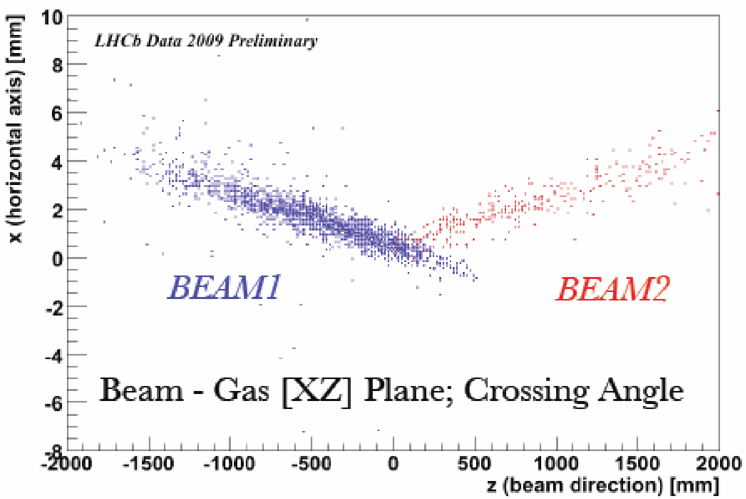


Beam2-Gas 11/2009: Triggered by VErtex LOcator: backward silicon stations

VErtex LOcator (VELO) reconstructs the interaction beam – gas

❖ Retractable detector halves
- open during injection (30 mm per side)
- closed in stable beam condition
- open @ 15 mm beam-gas and beam-beam 2009 runs

VErtex LOcator
21 stations of Silicon strip detector



❖ VELO reconstructs the beams crossing angle using beam-gas interactions

❖ Impact of LHCb dipole magnet
beams cross at 2 mrad angle in [xz] plane as expected at the full magnetic field @ 450 GeV

Commissioning with Collisions

Pilot Runs:

- ❑ **23/11/2009**

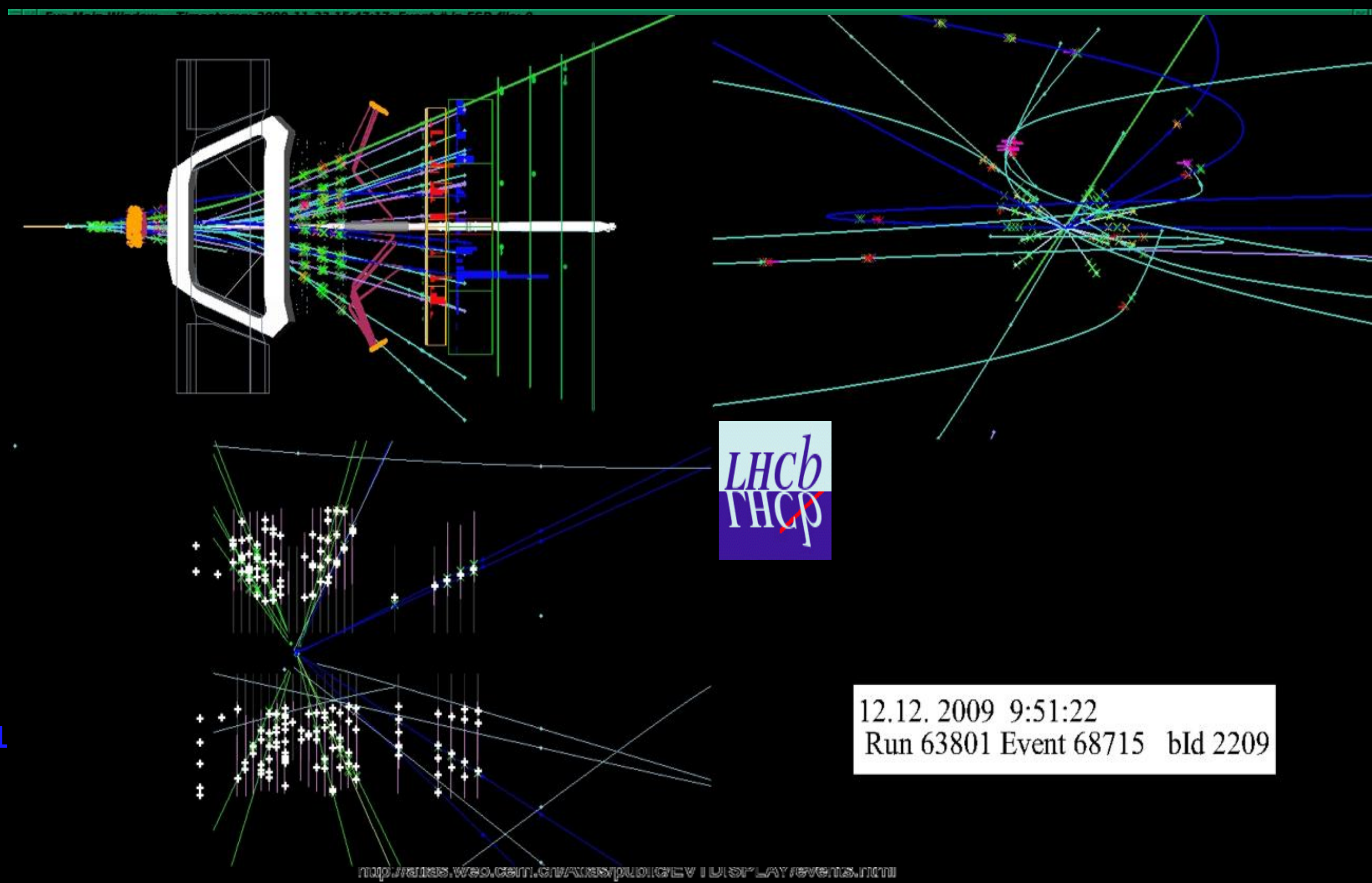
  $\sqrt{s}$ = 0.9 TeV

  (CMS: $\mathcal{L}$ = 10μb^{-1}
  3.9x10^5 events)

- ❑ **14/12/2009**

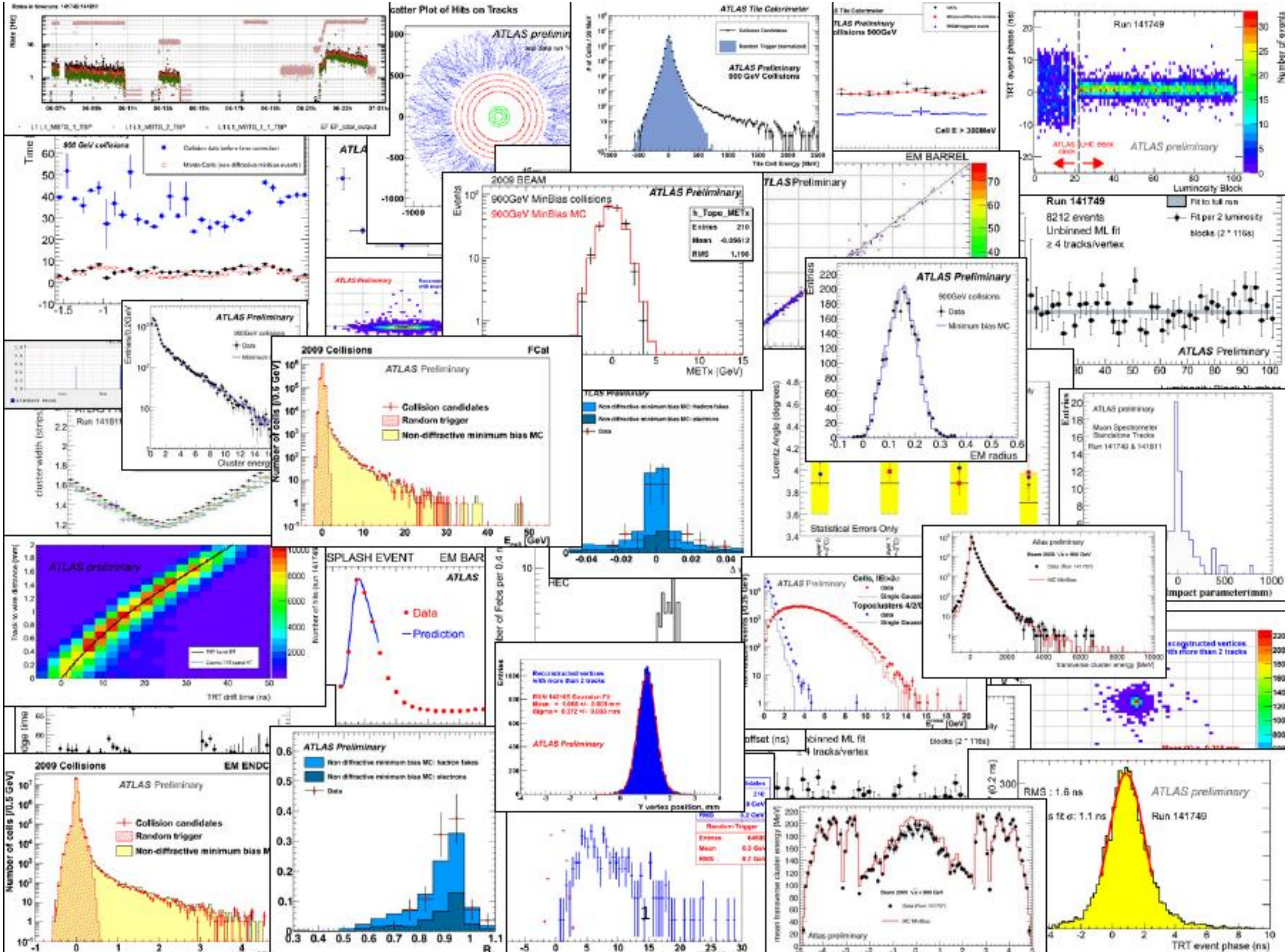
  $\sqrt{s}$ = 2.36 TeV

  (CMS: $\mathcal{L}$ = 0.4 μb^{-1}
  2.0x10^4 events)



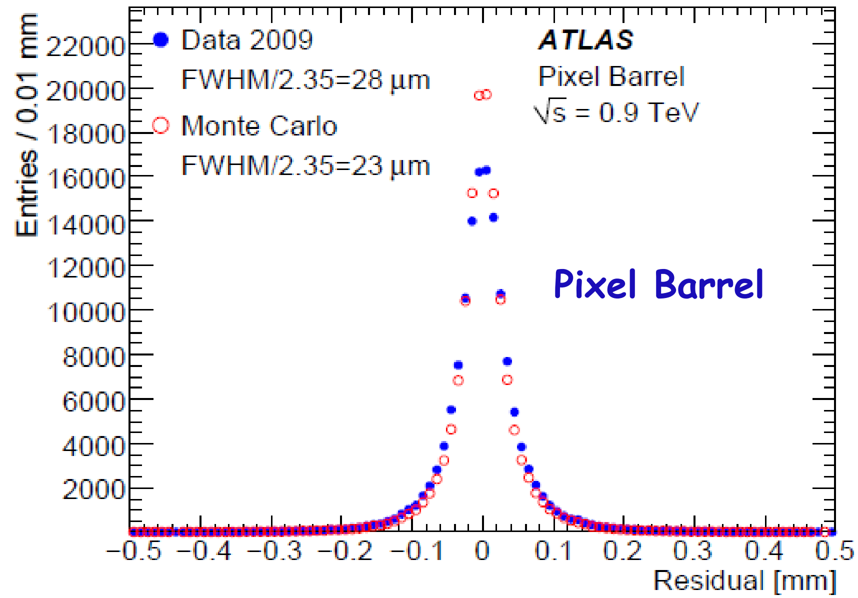
23/11/2009 : first collision at √s = 900 GeV

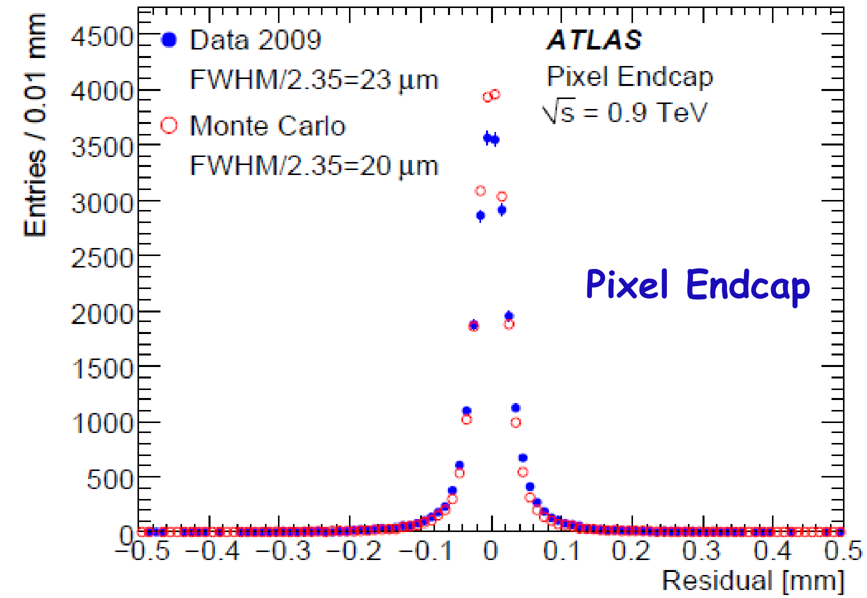
ATLAS: Commissioning with 2009 beams

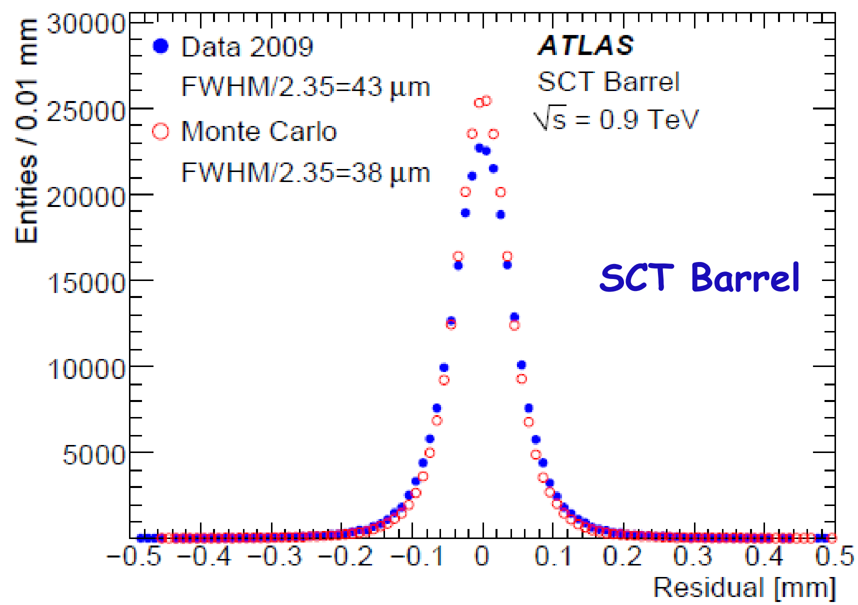


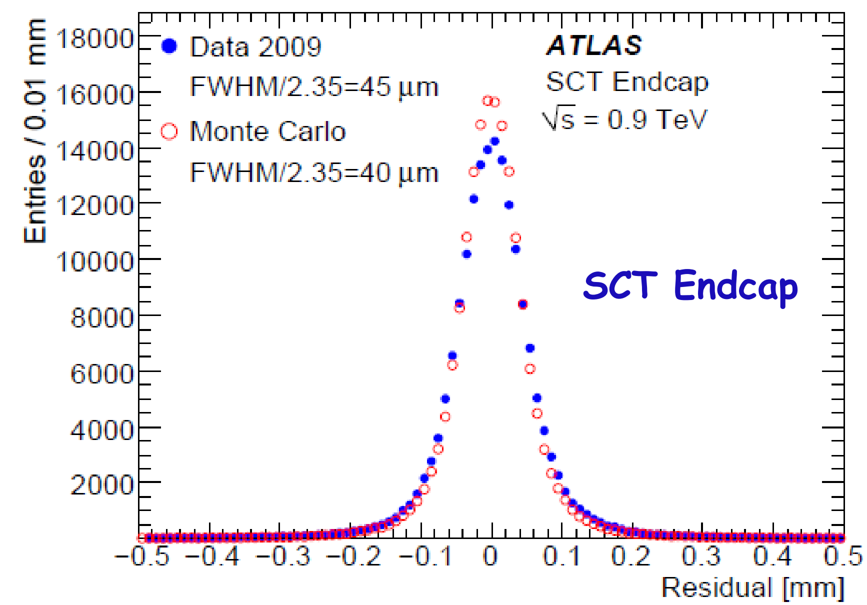
ATLAS Inner Tracking: residuals distributions (with 2009 beams)

arXiv:1005.5254v1



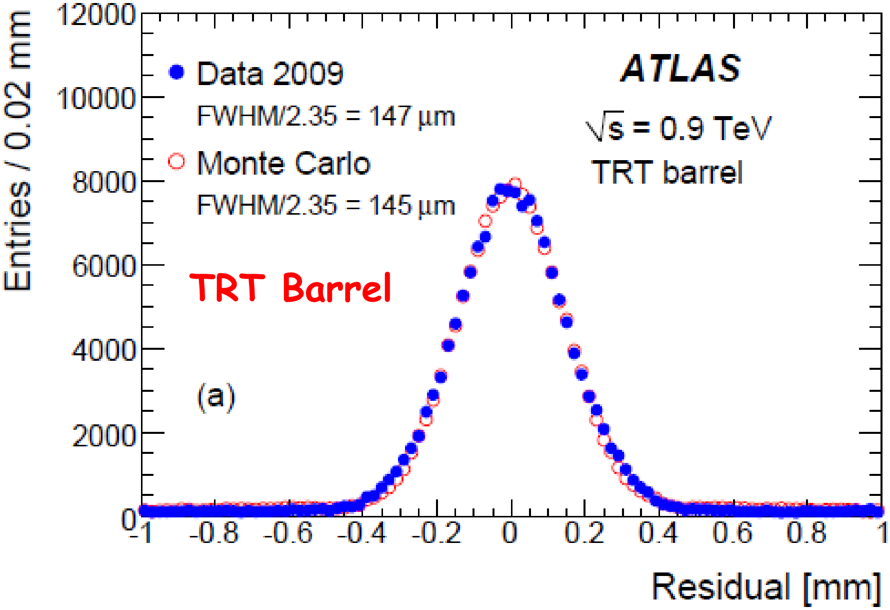


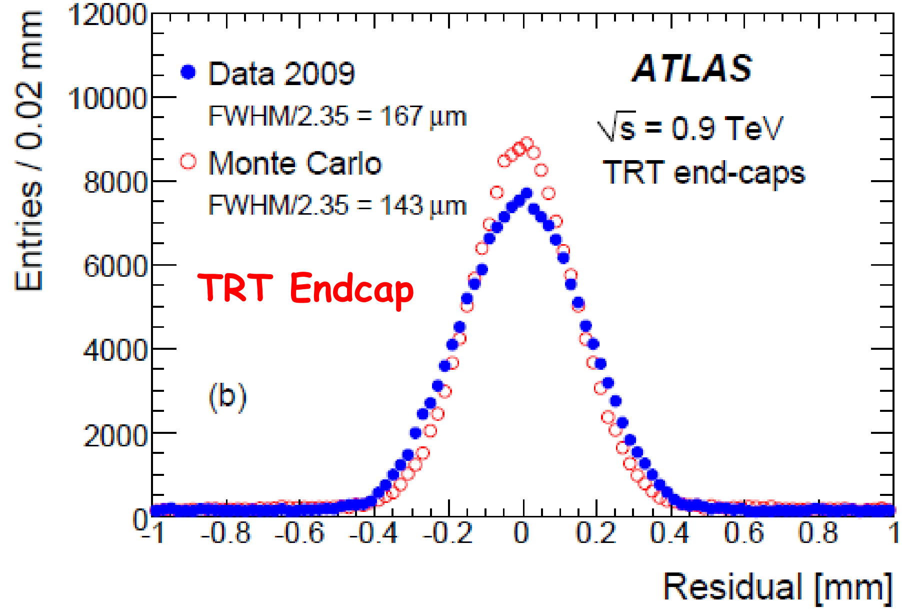


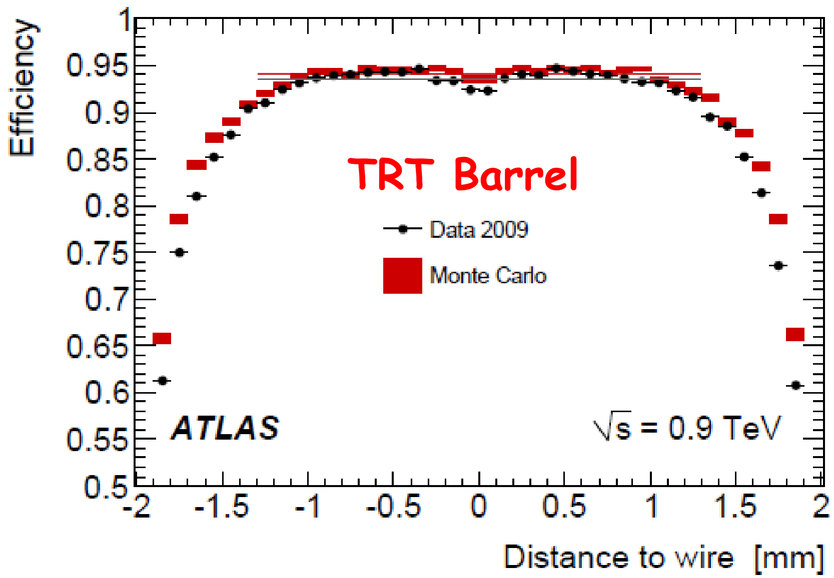


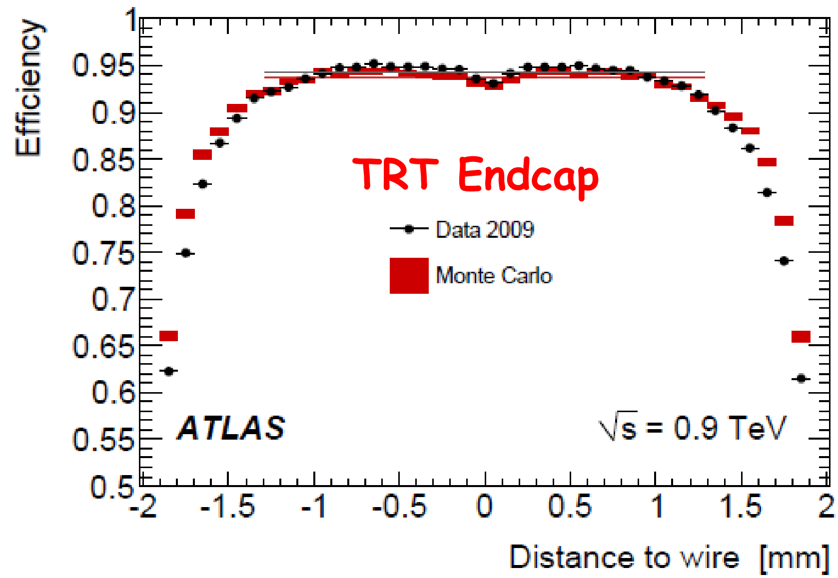
TRT: residuals distributions and efficiencies (with 2009 beams)

arXiv:1005.5254v1

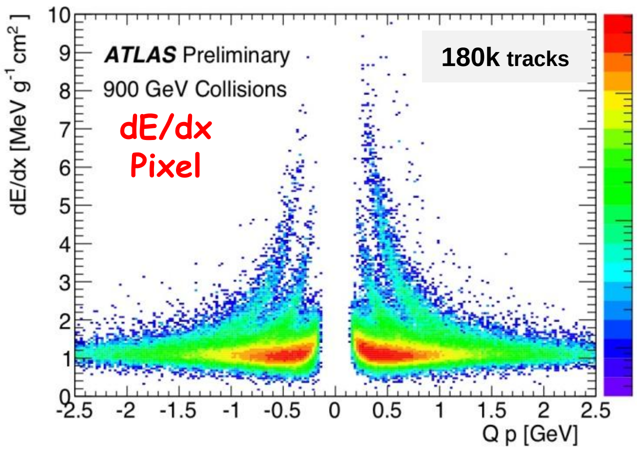


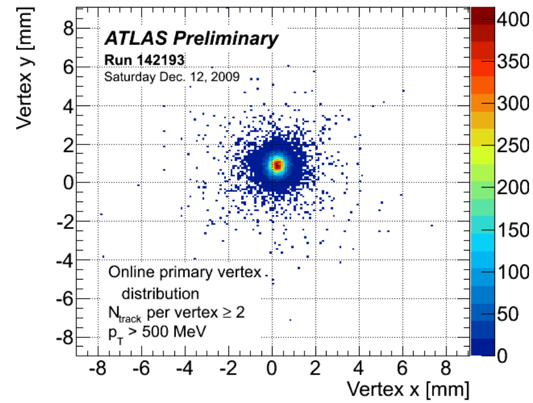






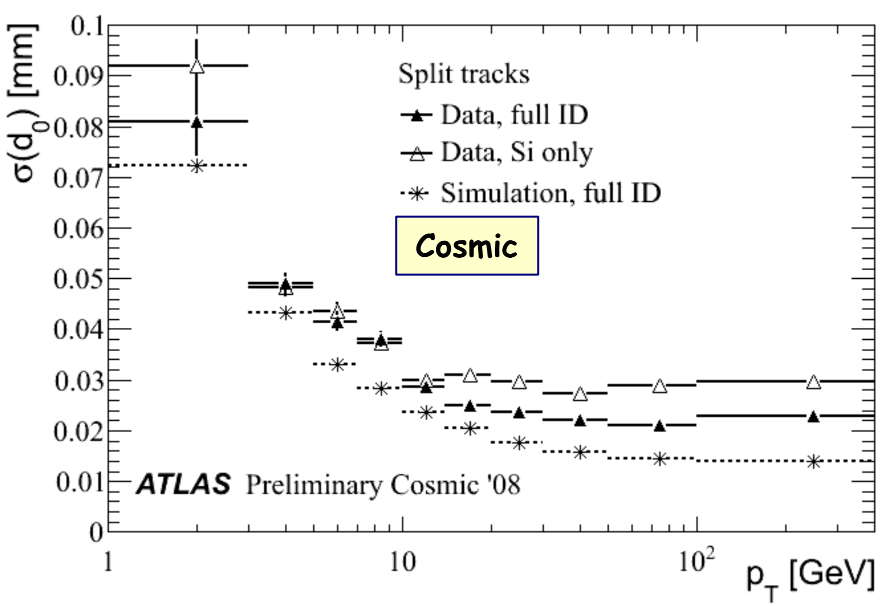
ATLAS: Inner Tracking Performance

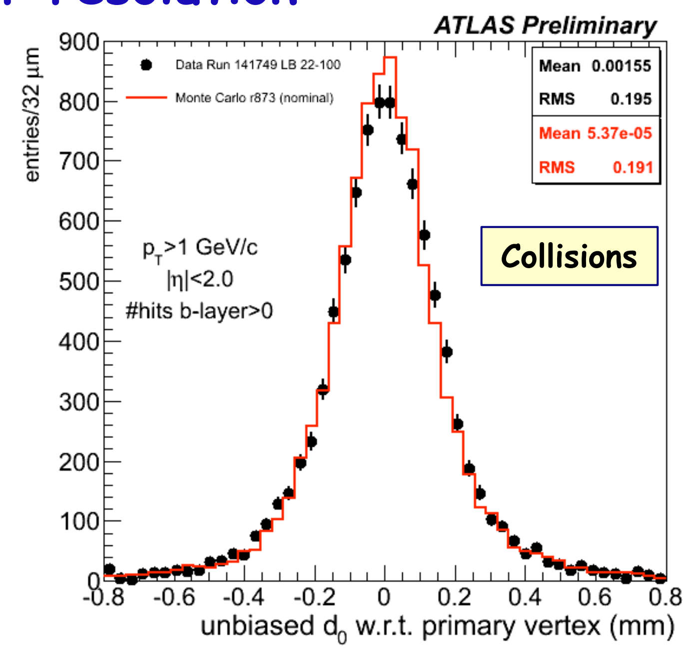




Online primary vertex reconstruction -> Luminosity meas.

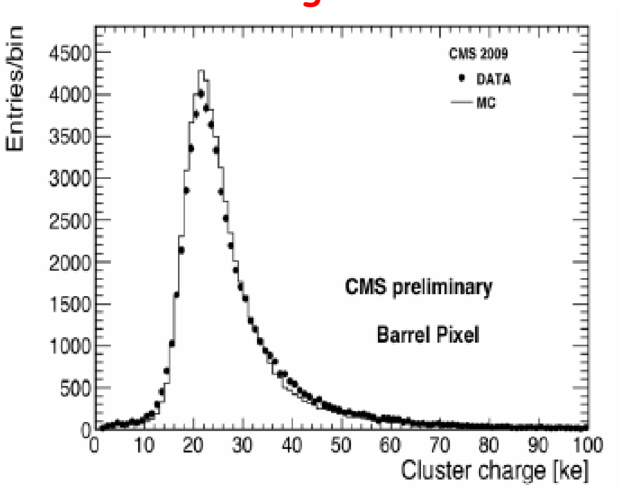
Impact parameter resolution

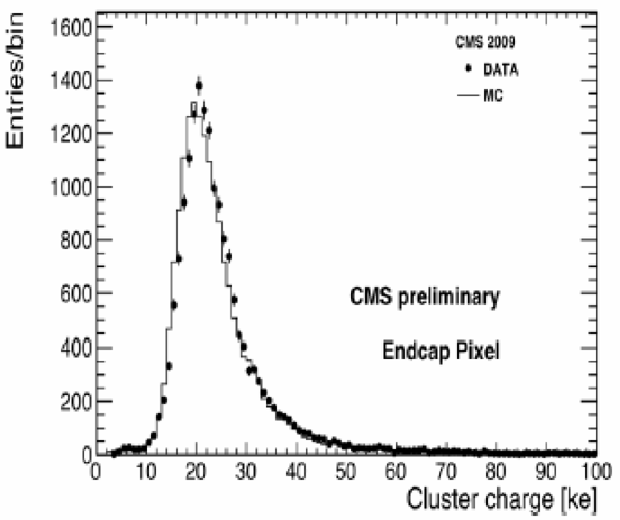




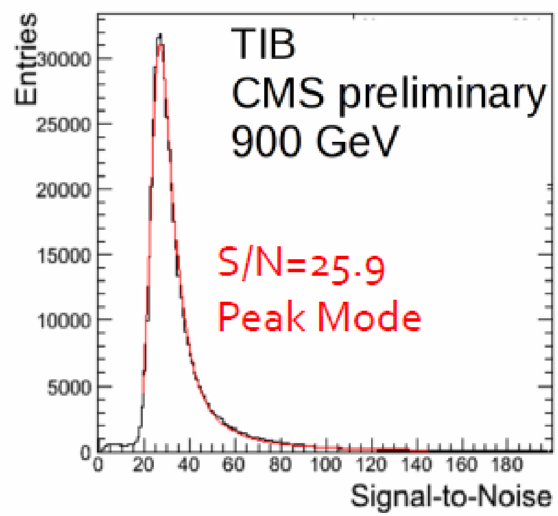
CMS: Tracker Performance at $\sqrt{s}$ = 900 GeV

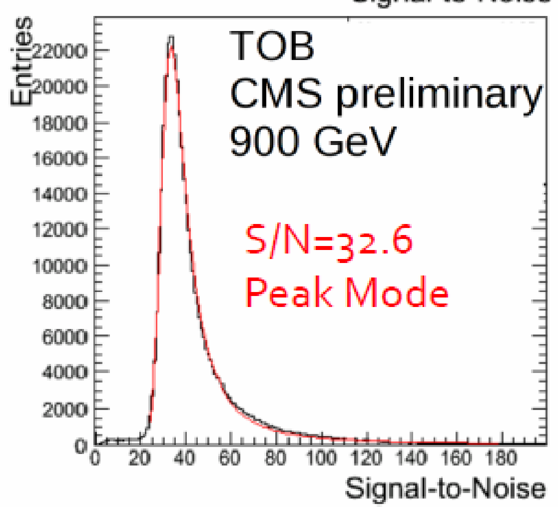
Pixel: Charge Distribution



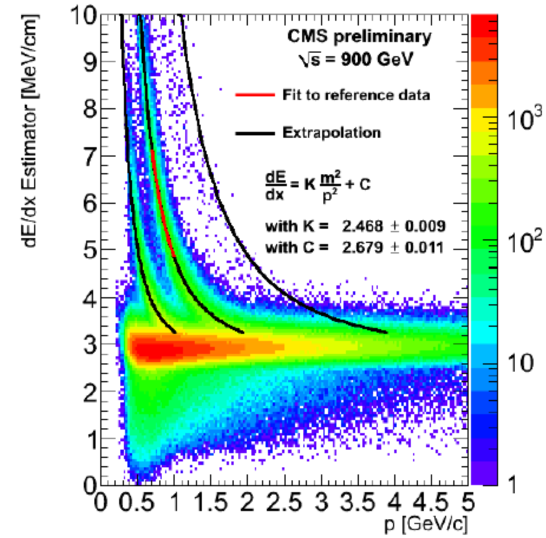


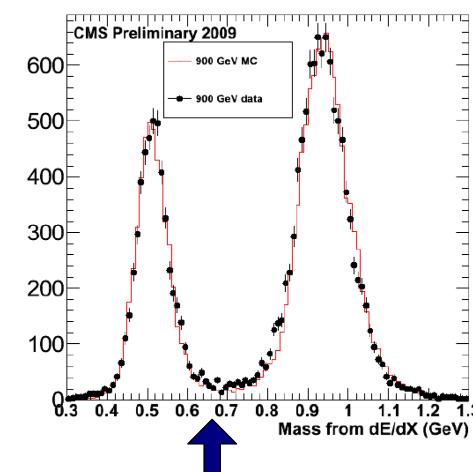
Si-Strip: Charge Distribution





dE/dx

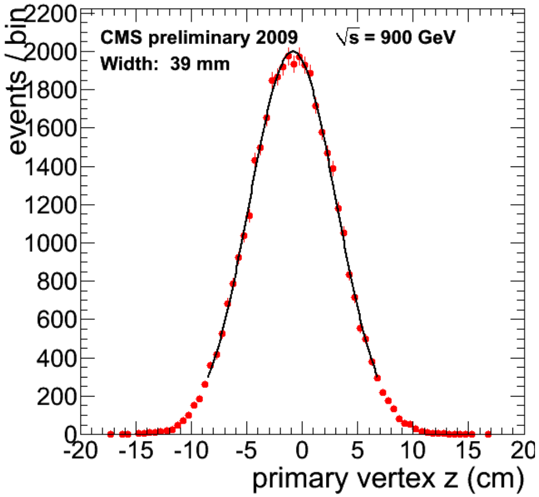




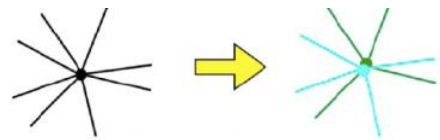
p < 2 GeV
dE/dX > 4.15 MeV/cm

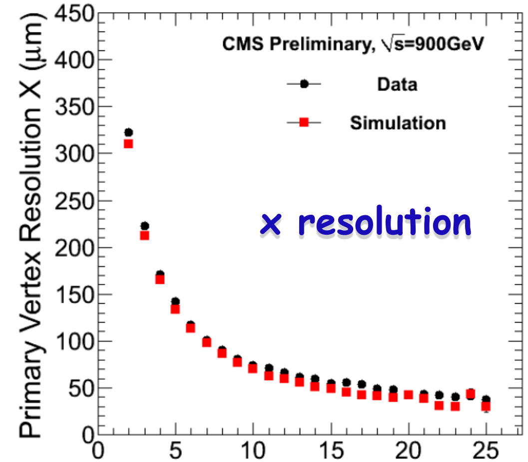
CMS: Tracker Performance at √s = 900 GeV

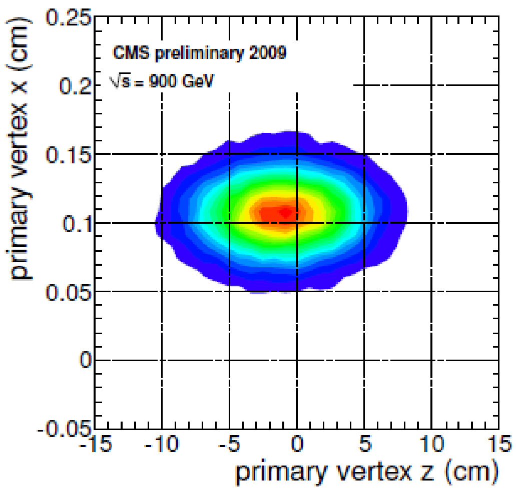
Primary Vertex

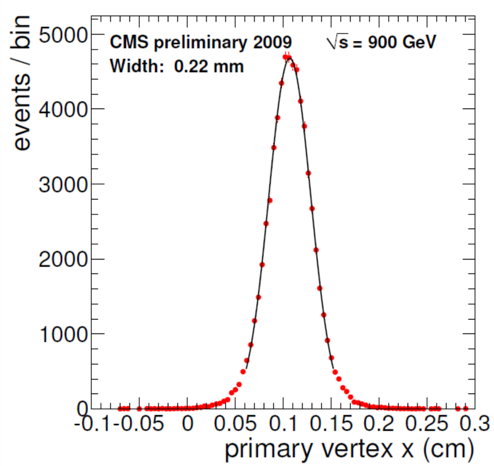


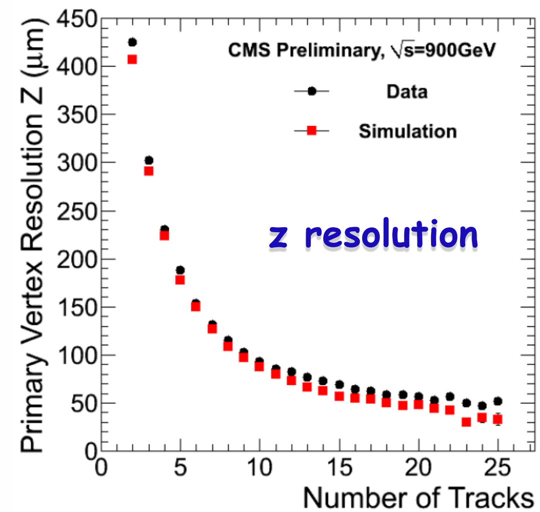
Primary vertex resolution obtained splitting tracks and comparing fits



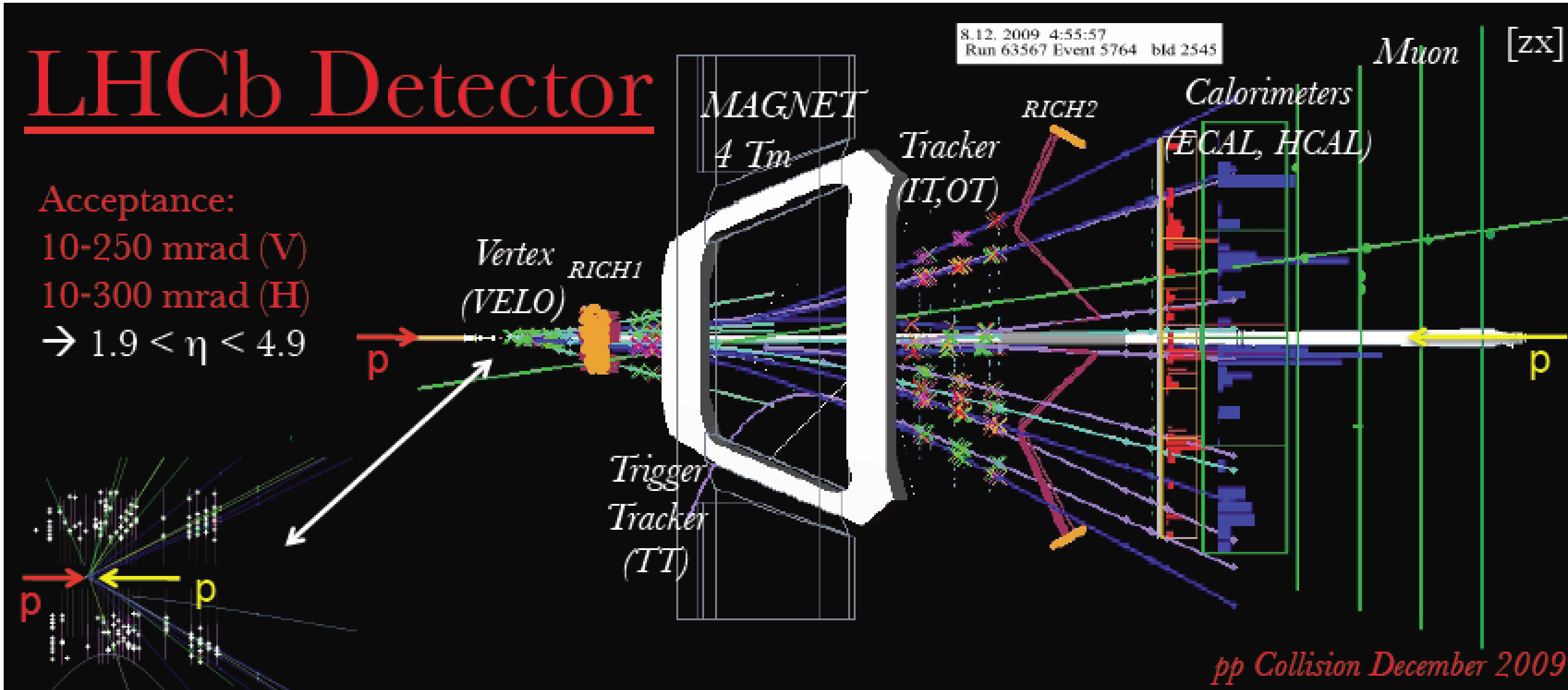


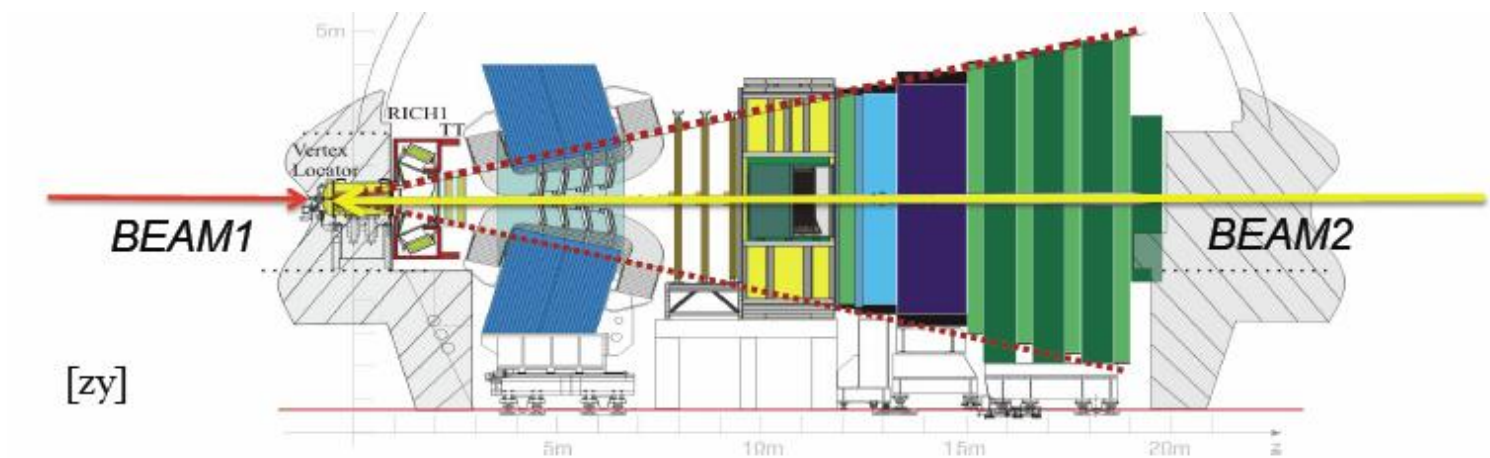




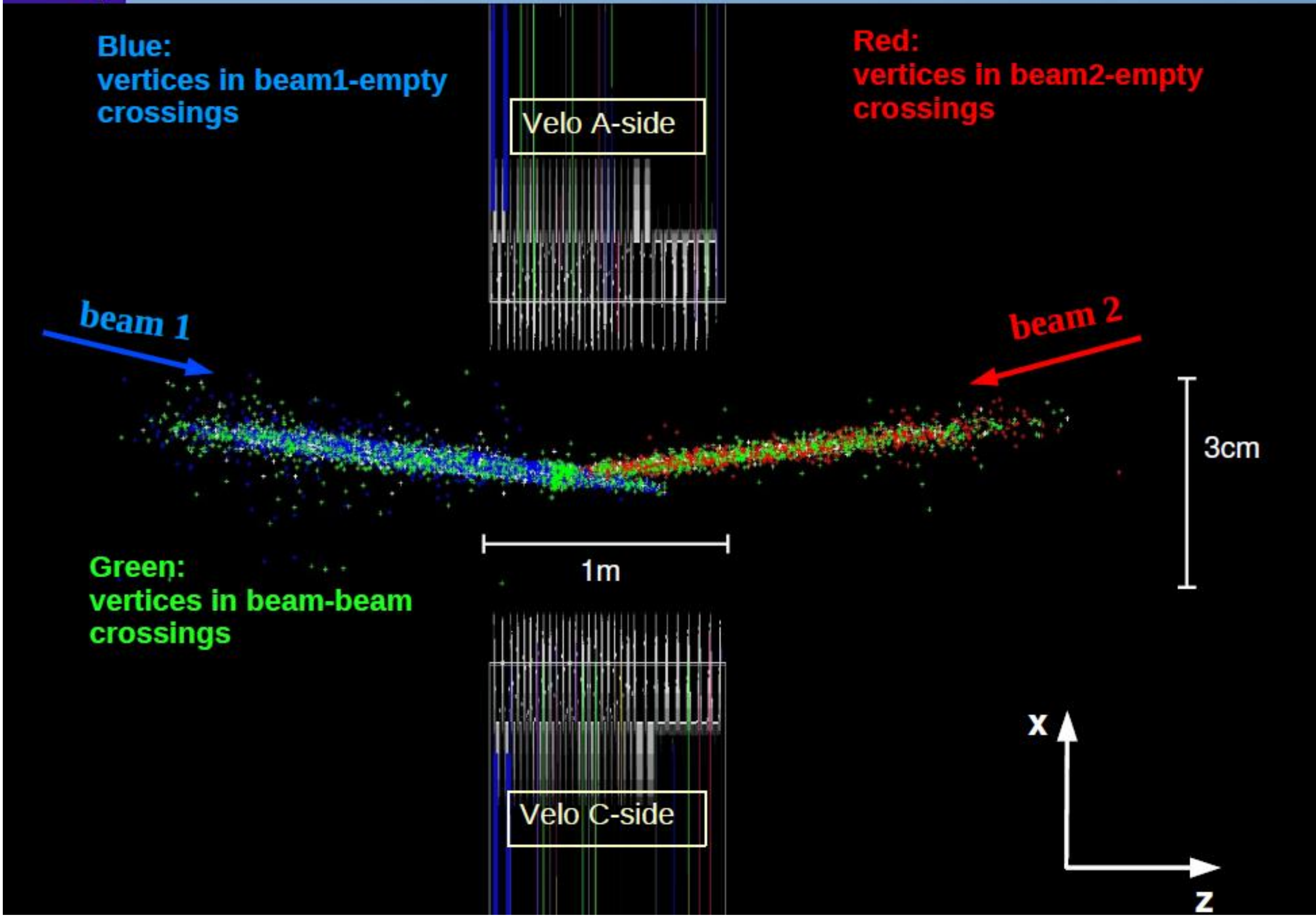


LHCb Commissioning

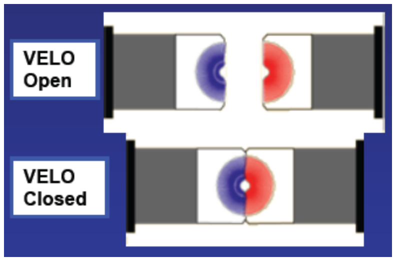


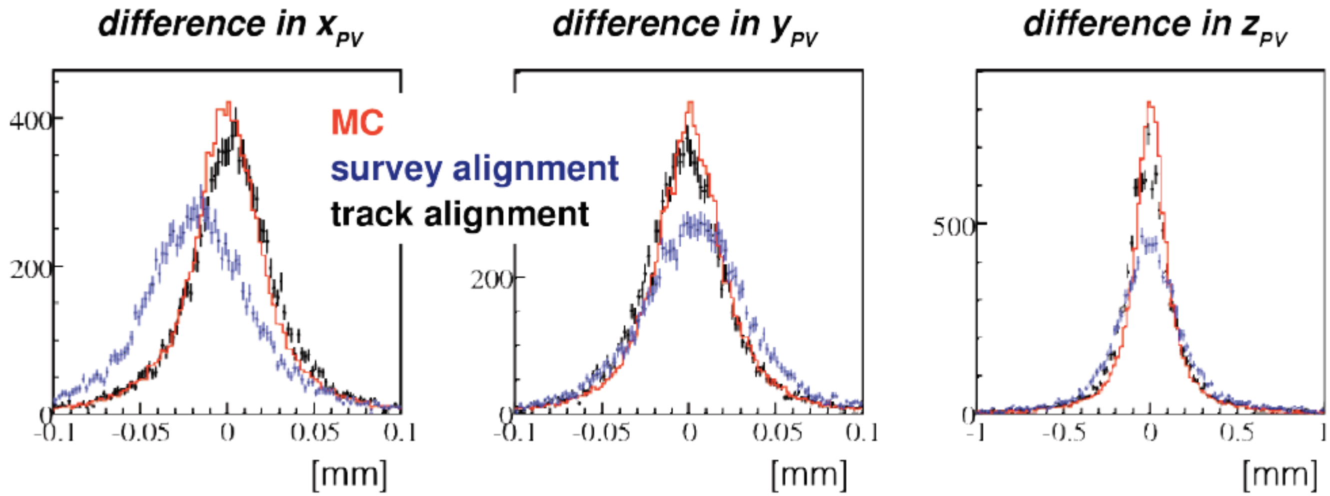


primary vertices for beam-beam and beam-gas collisions

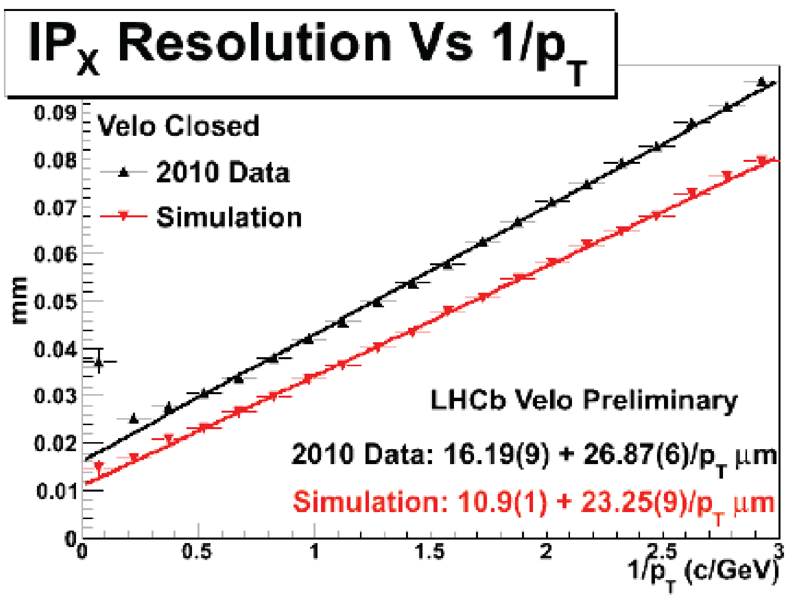


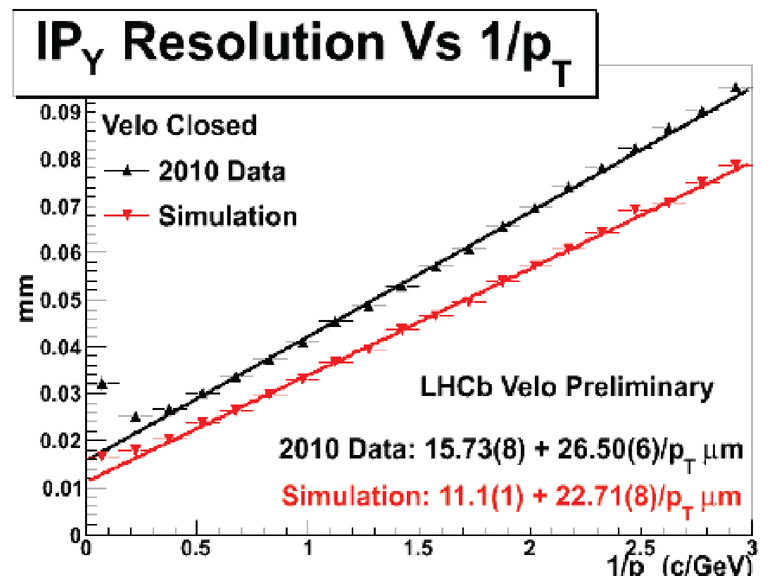
VErtex LOcator Performance





Align VELO halves using Primary Vertex from each side



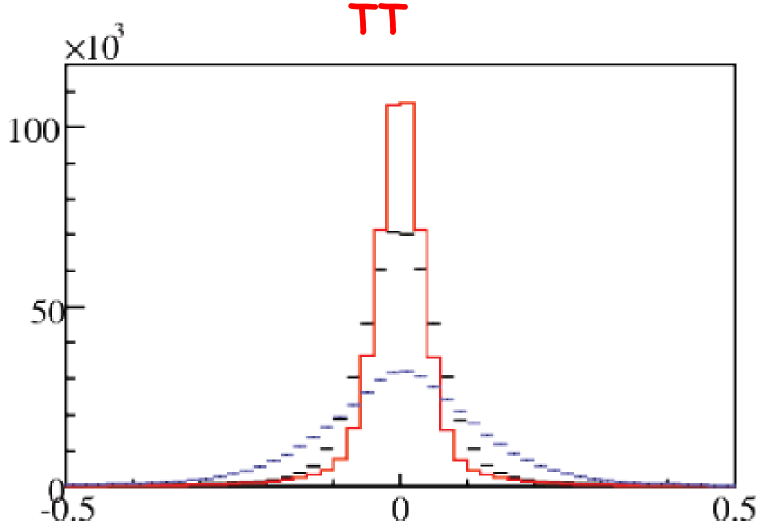


Impact parameter resolution $\propto 1/p_T$

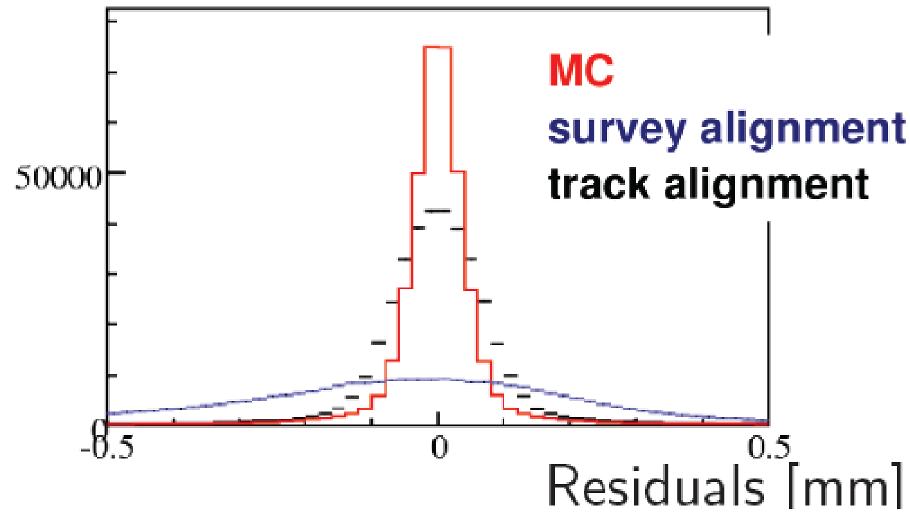
Silicon Trackers and Outer Tracker alignement

Still something to gain:residual width is 65 µm. MC expectation is 50 µm

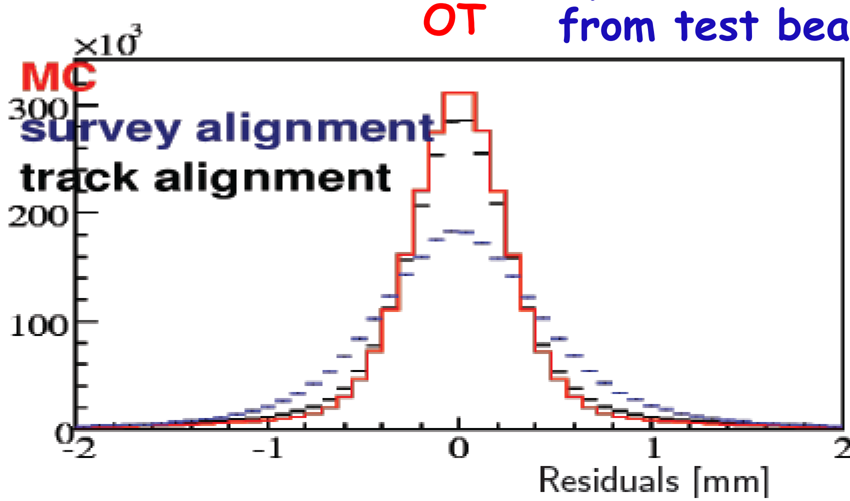
TT



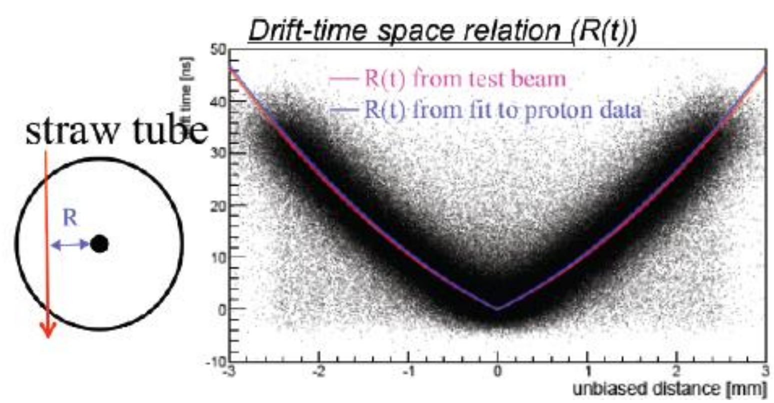
IT



OT

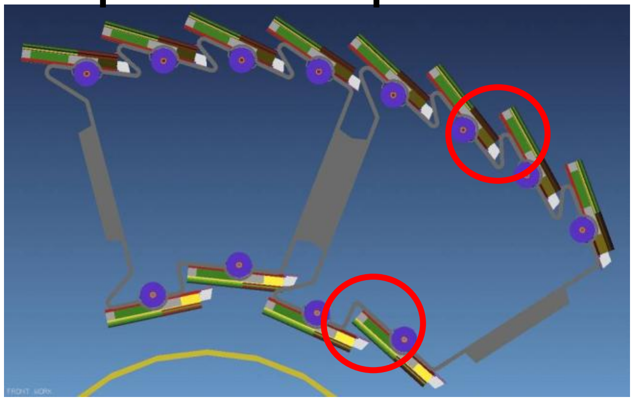


Space vs drift-time relations expectation from test beam validated on proton data



Alignment quality: SPD double hits in overlaps

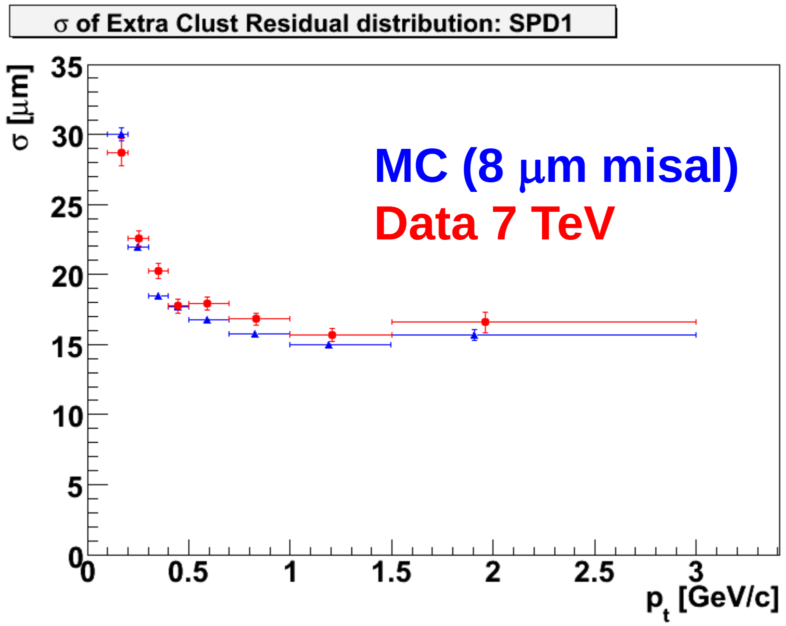
examples of overlaps in the SPD

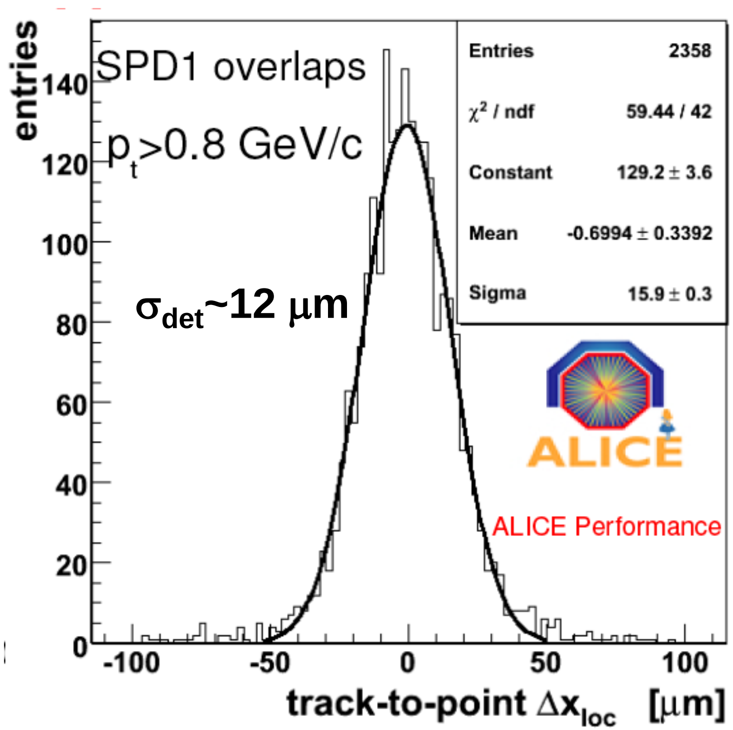


→ Residual between the two hits is sensitive to alignment quality & intrinsic resolution

$$\sigma_{residual} \sim \sigma_{det} \sqrt{2}$$

pp 7 TeV B=0.5T



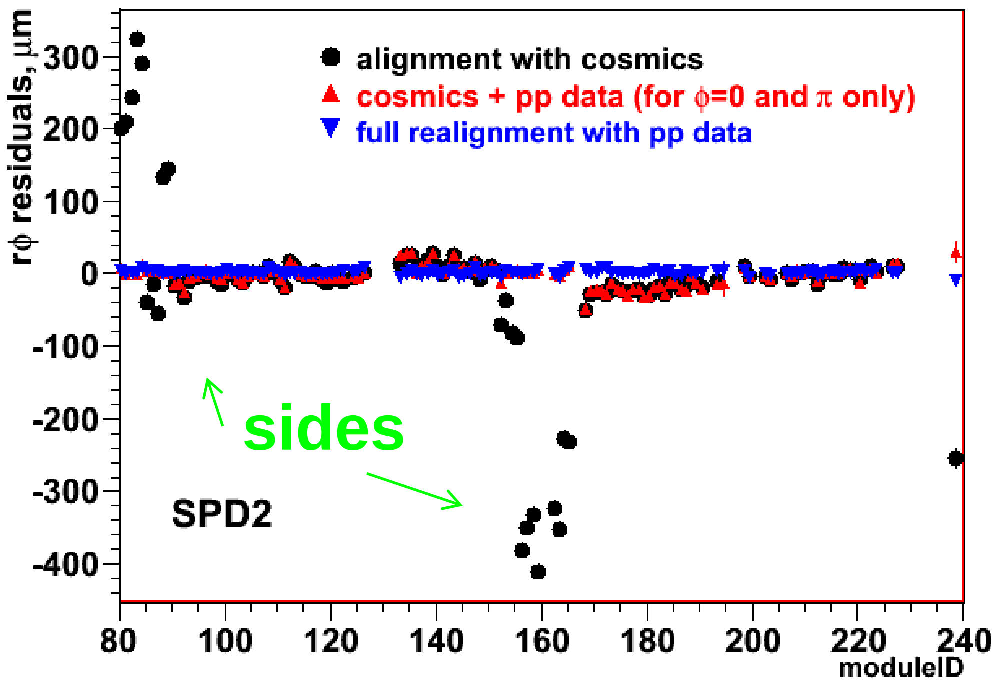


~8 μm misalignment

SPD alignment with pp

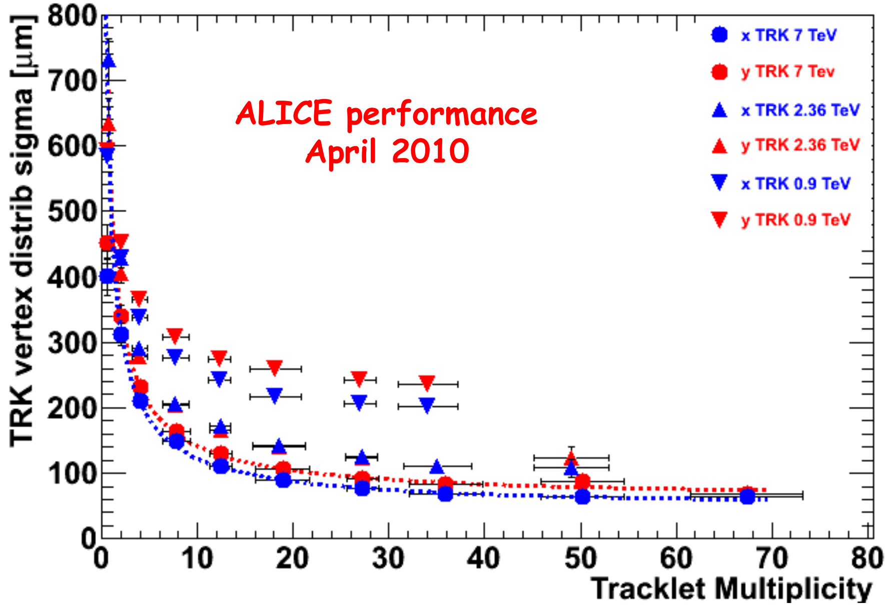
- From cosmics-only, coverage-limited, alignment to full alignment with pp

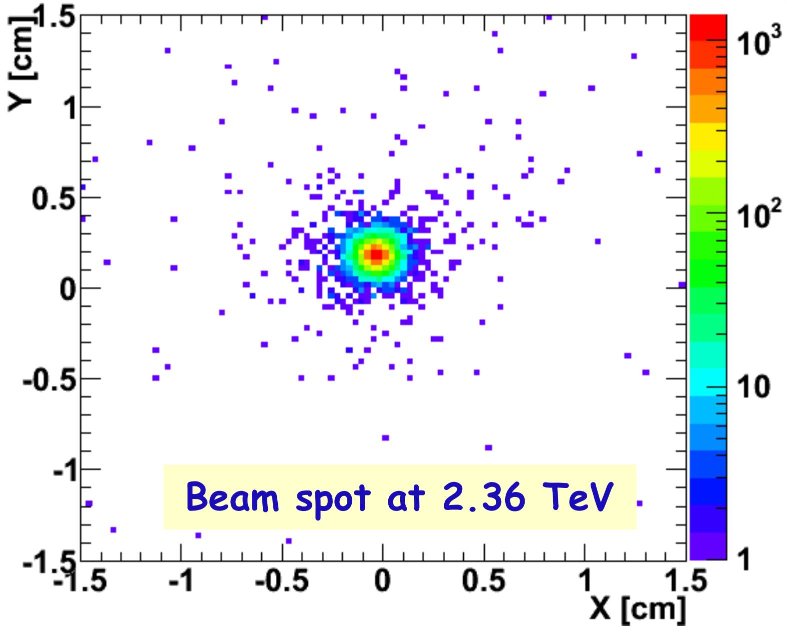
mean of residuals at outer SPD layer (r=7cm)

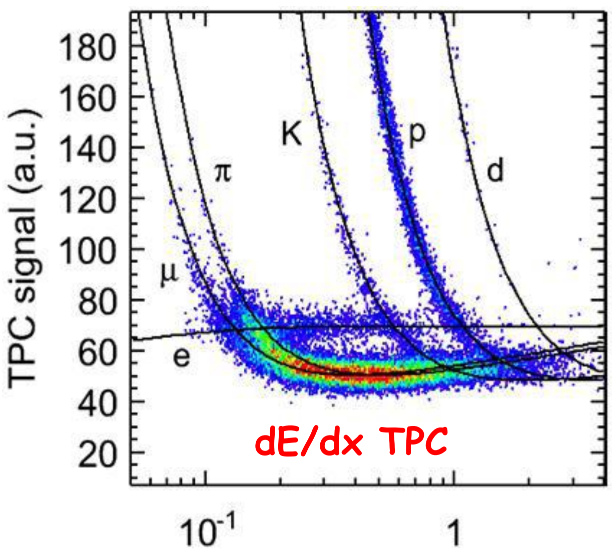


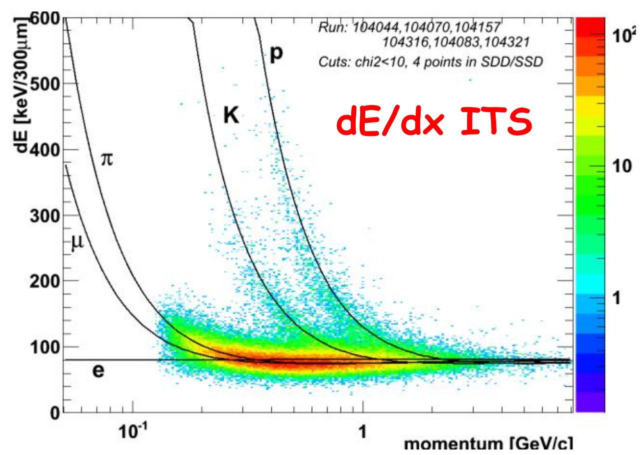
ALICE: Trackers performance

Vertex resolution versus # tracks



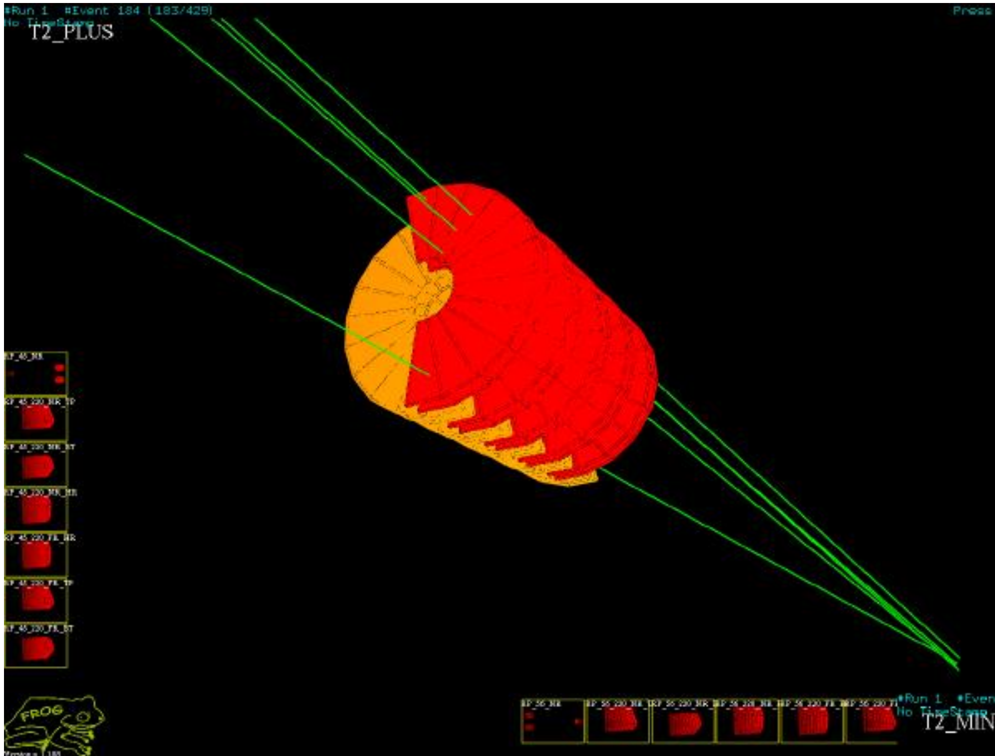


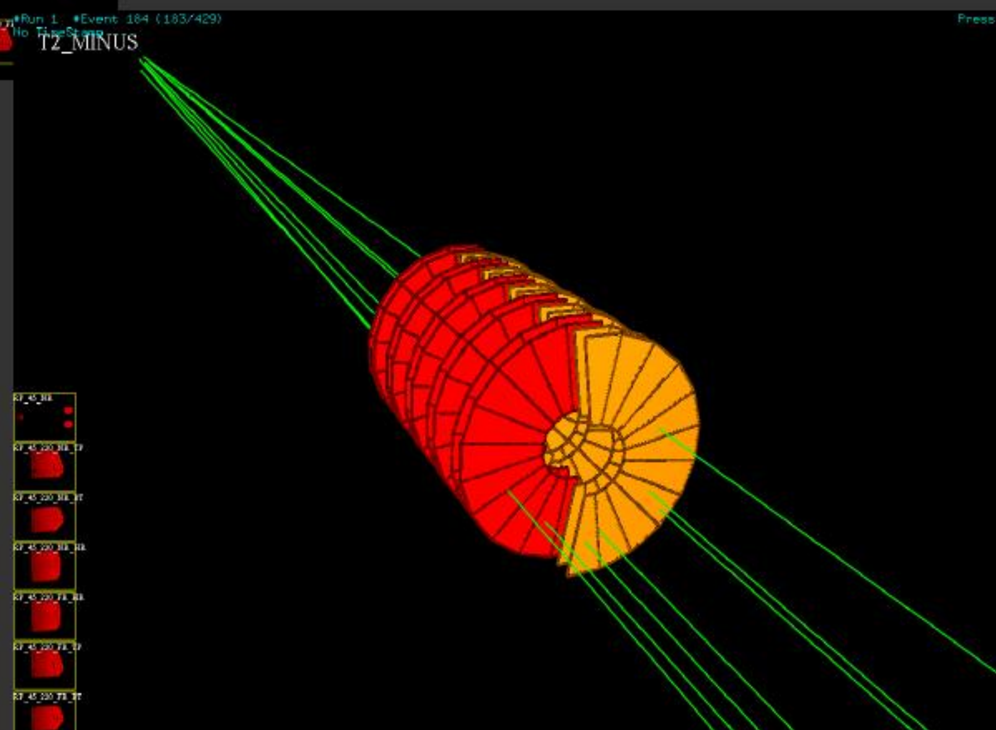




Event in T2

Collisions at 7 TeV

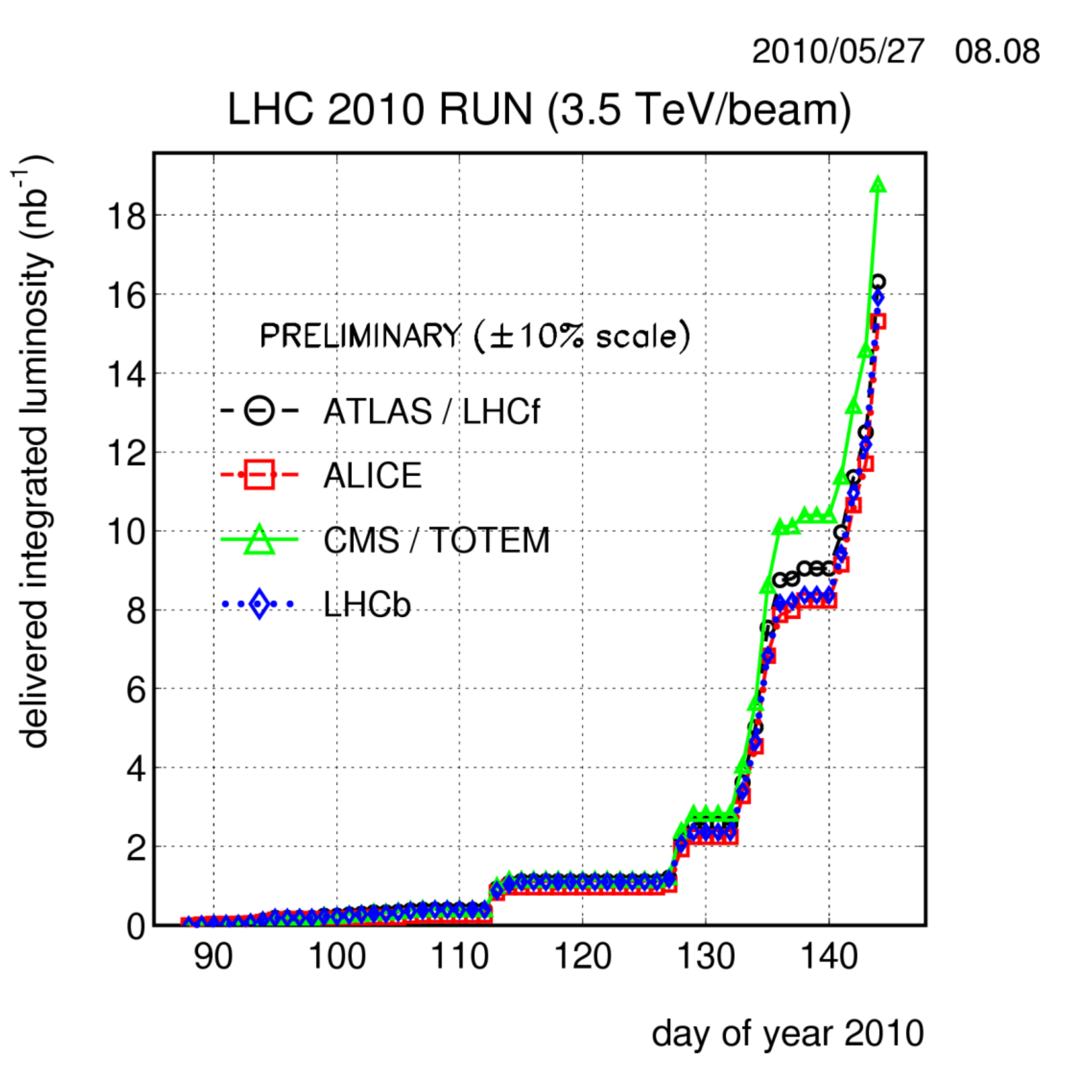


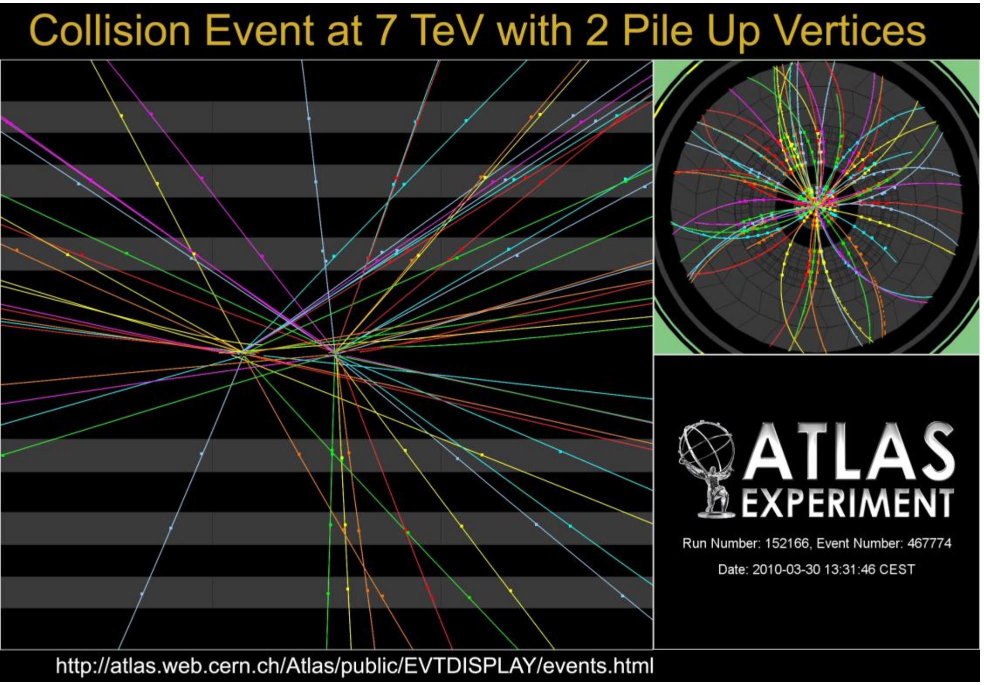


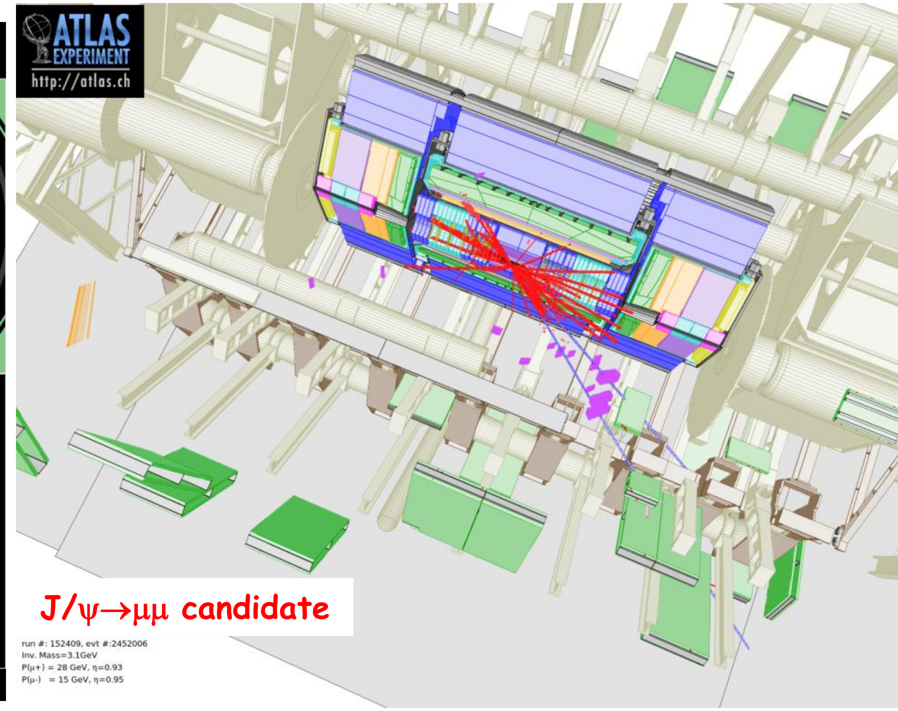
Physics Run @ $\sqrt{s}$ = 7 TeV

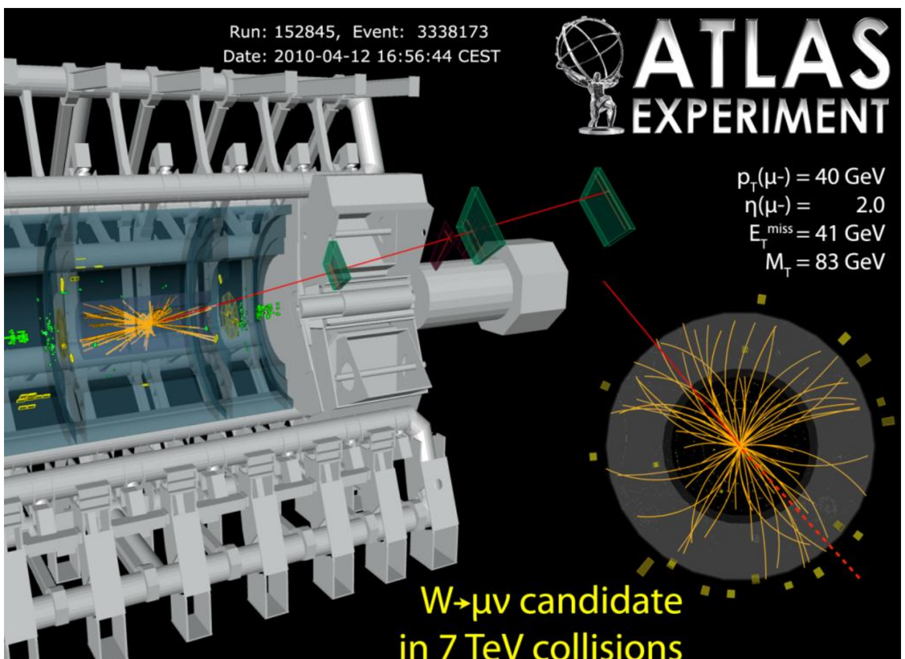
Start-up: March the 30th 2010

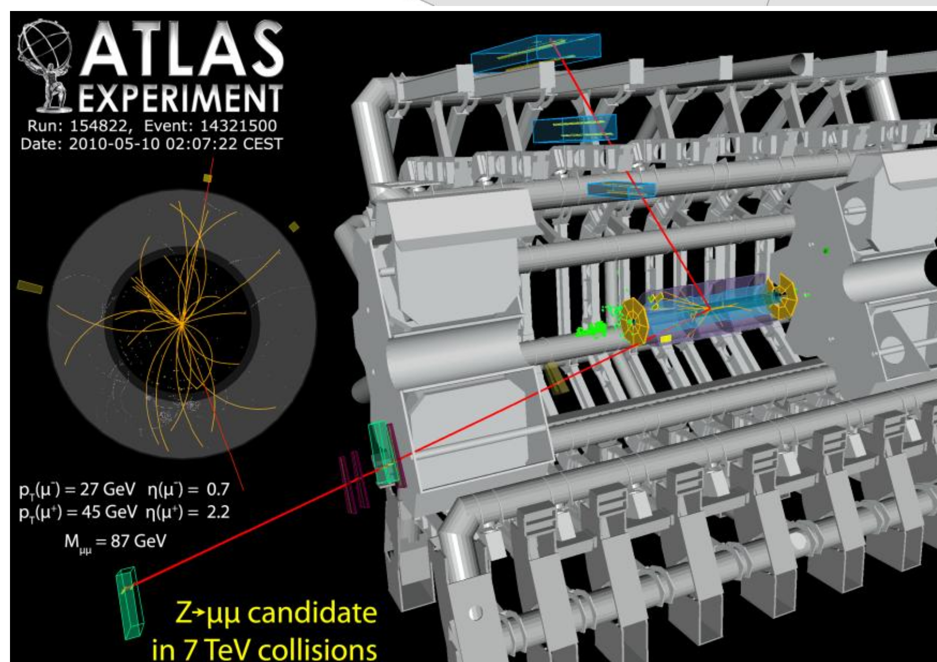
- All tracking systems of all LHC experiments are well aligned and commissioned ready for taking data for physics.
- Delivered luminosity is still very low, but LHC is improving fast….
- A few event displays in the next slides are worth than a thousand words to show how well all the LHC tracking systems are working.

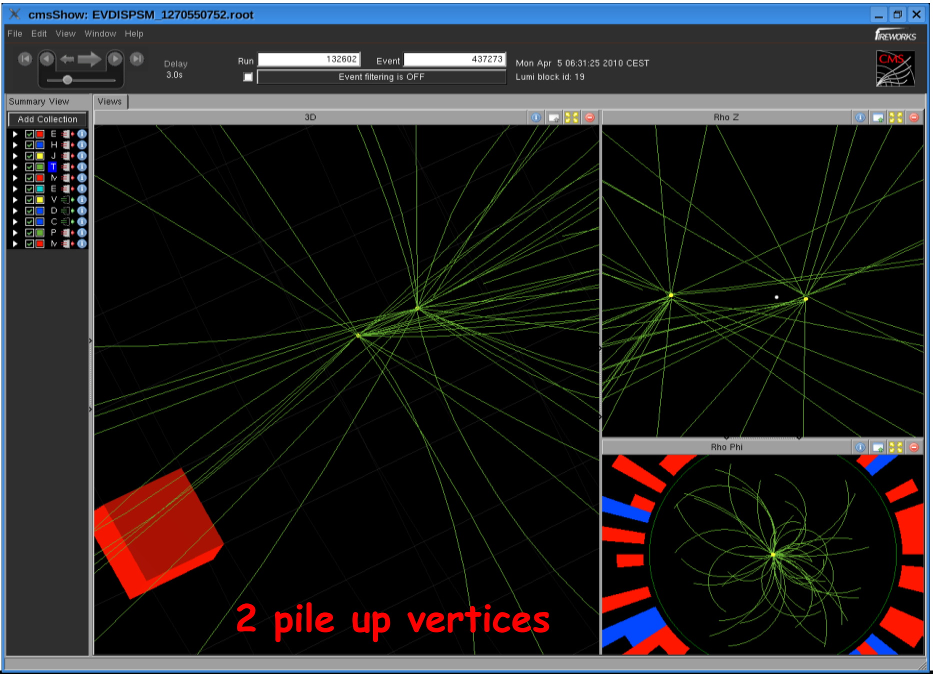


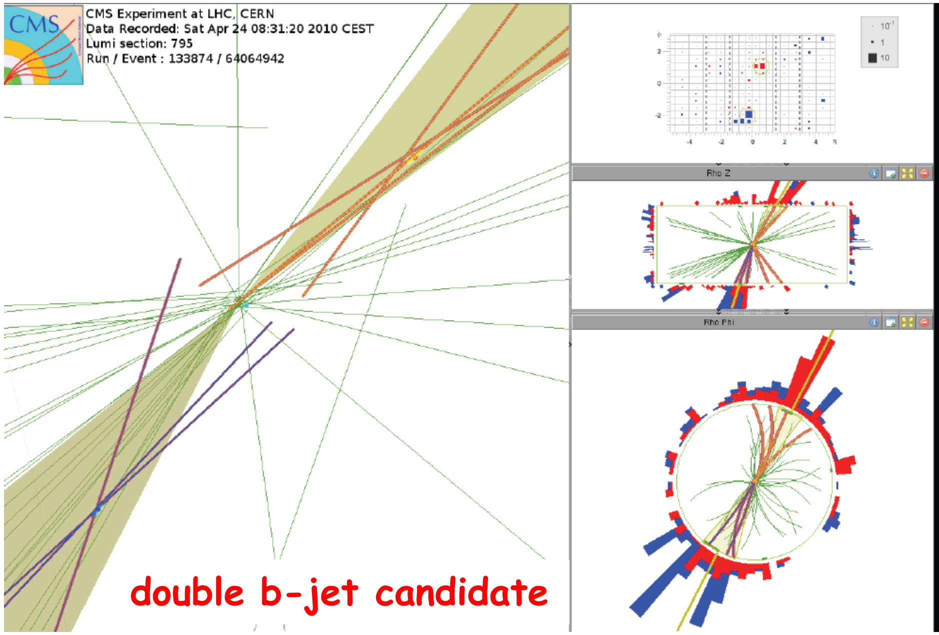

Collision Event at 7 TeV with 2 Pile Up Vertices
ATLAS
EXPERIMENT
Run Number: 152166, Event Number: 467774
Date: 2010-03-30 13:31:46 CEST
http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

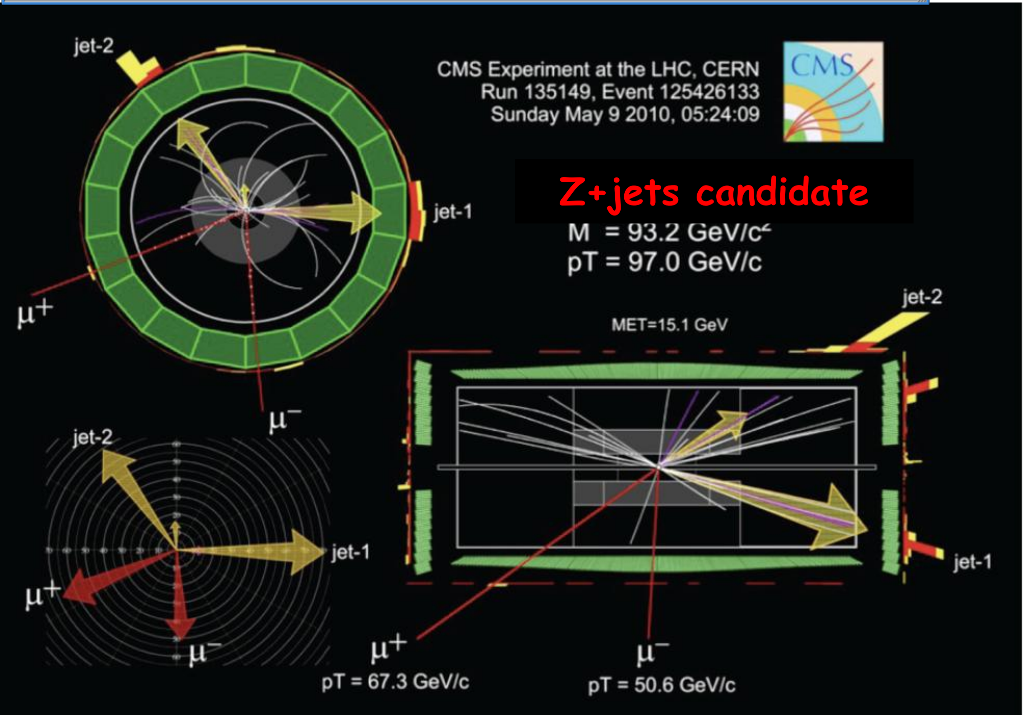

ATLAS
EXPERIMENT
http://atlas.ch
J/ψ→μμ candidate
run #: 152409, evt #:2452006
Inv. Mass=3.1GeV
P(μ+) = 28 GeV, η=0.93
P(μ-) = 15 GeV, η=0.95


Run: 152845, Event: 3338173
Date: 2010-04-12 16:56:44 CEST
ATLAS
EXPERIMENT
$p_T(\mu-) = 40$ GeV
$\eta(\mu-) = 2.0$
$E_T^{miss} = 41$ GeV
$M_T = 83$ GeV
W→μν candidate
in 7 TeV collisions

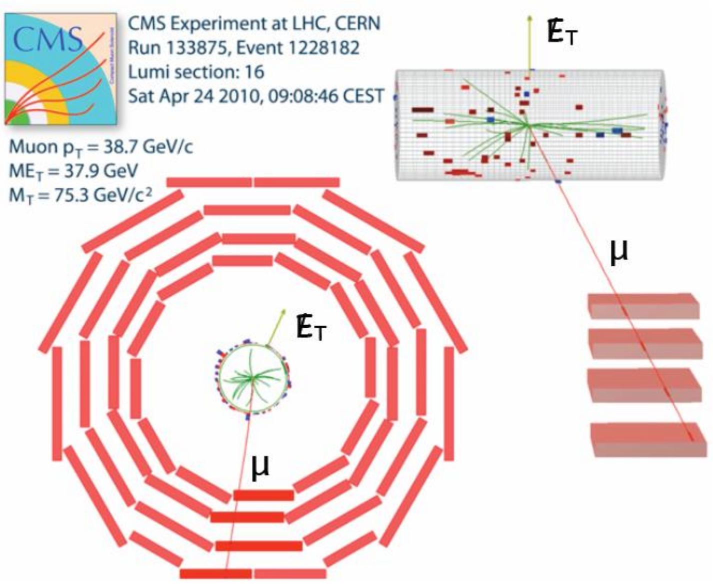

ATLAS
EXPERIMENT
Run: 154822, Event: 14321500
Date: 2010-05-10 02:07:22 CEST
$p_T(\mu^-) = 27$ GeV $\eta(\mu^-) = 0.7$
$p_T(\mu^+) = 45$ GeV $\eta(\mu^+) = 2.2$
$M_{\mu\mu} = 87$ GeV
Z→μμ candidate
in 7 TeV collisions





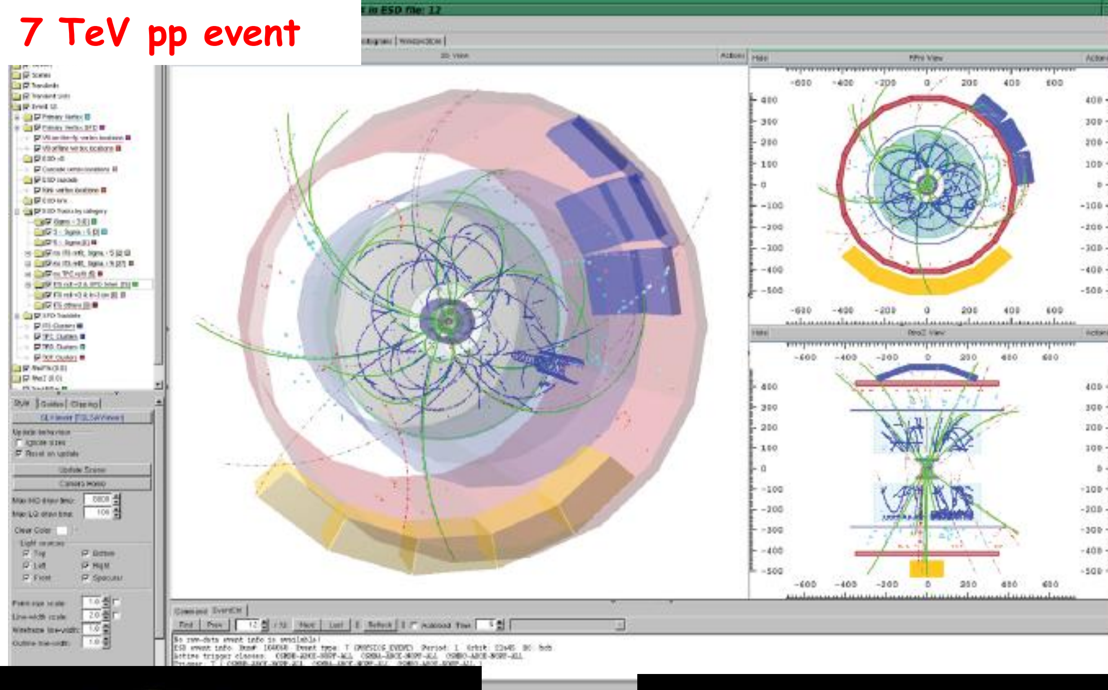


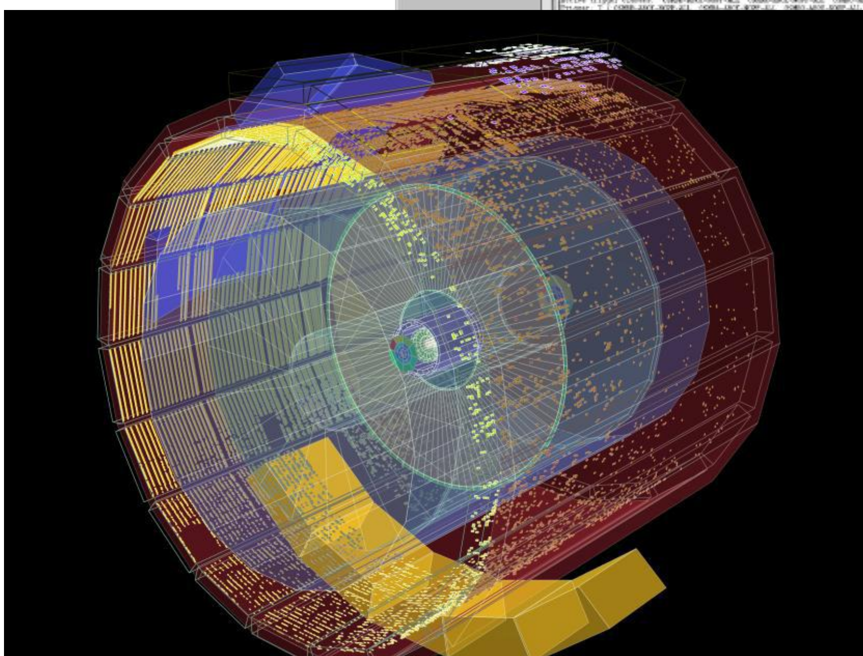
W→μν candidate



ALICE

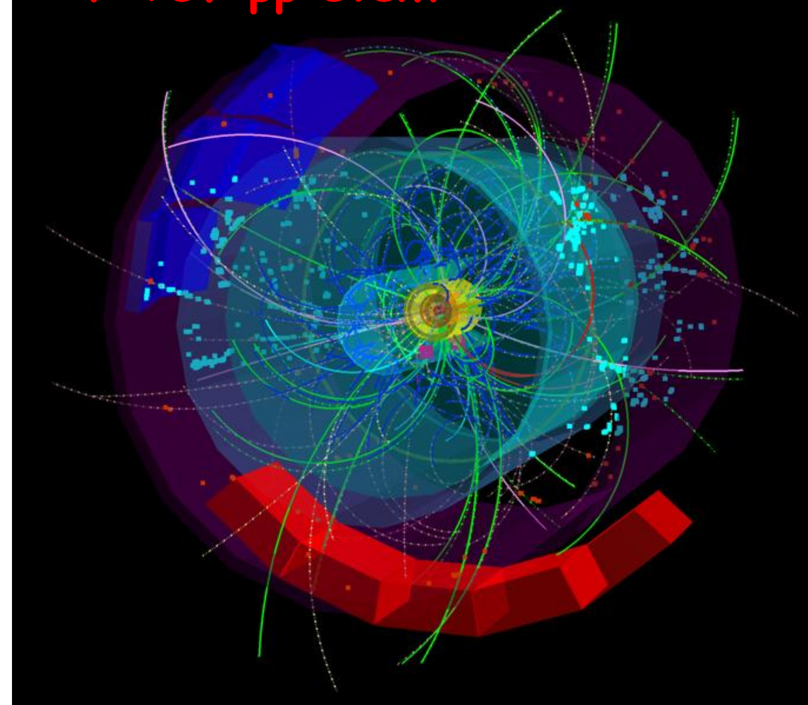
7 TeV pp event

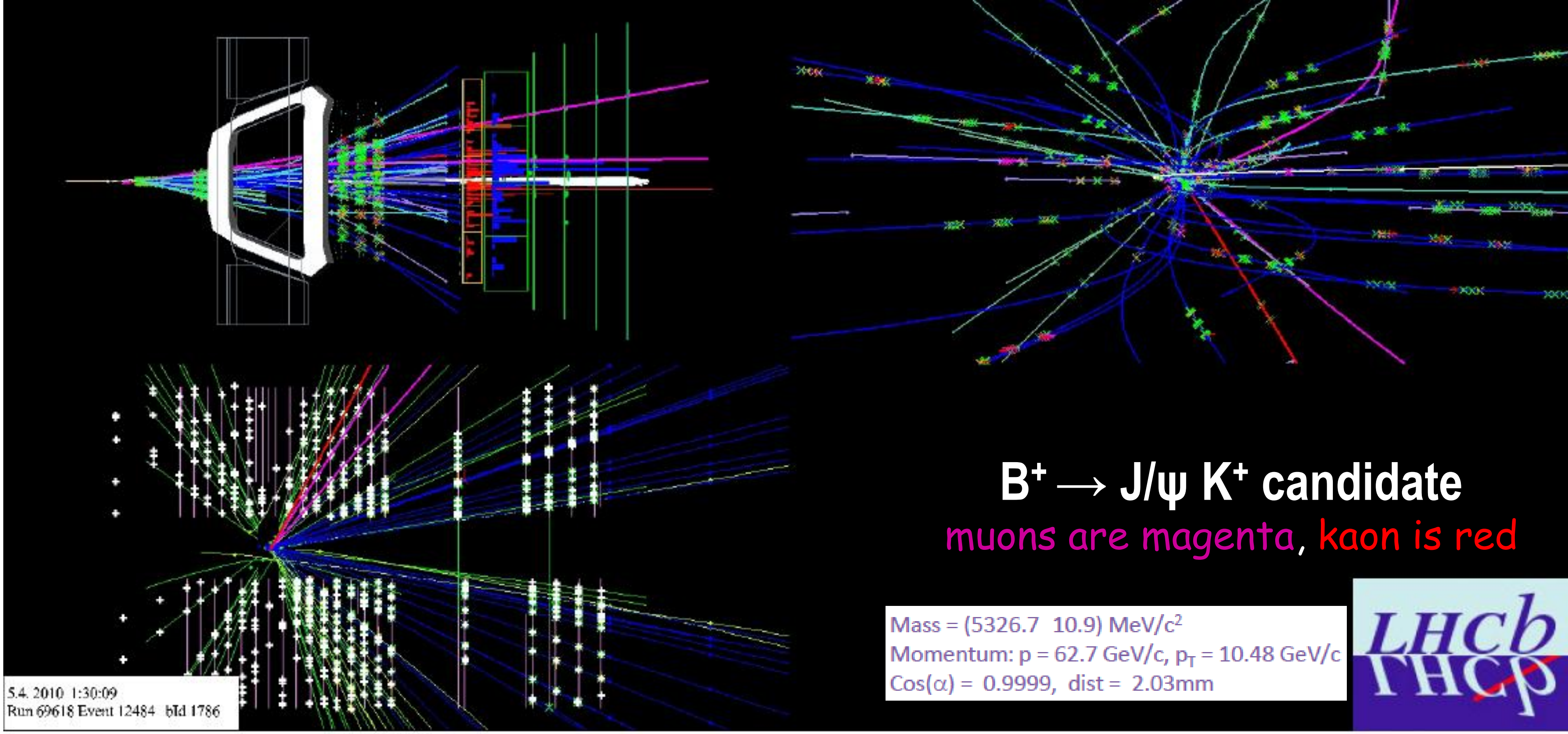


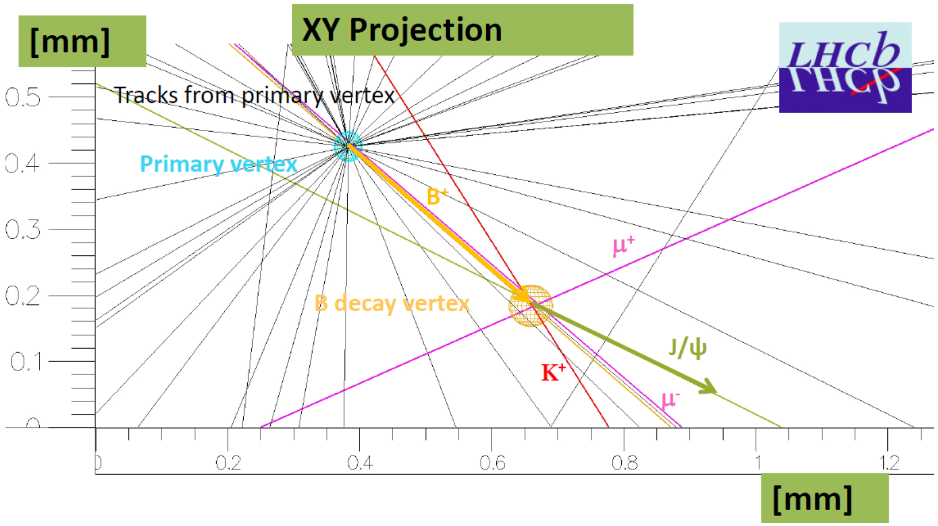


First lead ions to ALICE !!! (dumped on TED, about 300m upstream of ALICE)

7 TeV pp event




5.4. 2010 1:30:09
Run 69618 Event 12484 bId 1786
$B^+ \rightarrow J/\psi\ K^+$ candidate
muons are magenta, kaon is red
Mass = (5326.7 10.9) MeV/c^2
Momentum: p = 62.7 GeV/c, p_T = 10.48 GeV/c
Cos(α) = 0.9999, dist = 2.03mm
LHCb


[mm]
XY Projection
LHCb
Tracks from primary vertex
Primary vertex
B^+
μ^+
B decay vertex
J/ψ
K^+
μ^-
0.5
0.4
0.3
0.2
0.1
0
0.2
0.4
0.6
0.8
1
1.2
[mm]

Conclusions

- The LHC Physics Run I @ $\sqrt{s}$ = 7 TeV is ongoing

- All the tracking systems of the LHC experiments are performing very well and I expect that they will play an essential role for new physics discoveries....
...stay tuned!

Special thanks to:
Paolo Azzurri, Andrea Dainese, Simone Gennai and Boris Mangano for providing me some very useful slides.
Many thanks also to:
Leonardo Rossi, Giovanni Carboni and Paolo Giubellino

for useful information on data of Atlas, LHCb and Alice.

Backup slides

Track reconstruction:

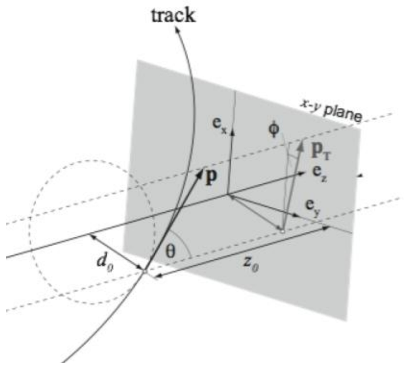
- Track finding, or "pattern recognition":
  the attribution of hits to tracks

- Track fitting, or the determination of
  the track parameters from a given set of hits

Track model and parameters

The **track model** depends on:

- Detector geometry
- Measurement type (2D, 3D)
- Straight tracks or **Helix** (depending on magnetic field)



Forward geometry

Assuming the *z* coordinate points down the spectrometer axis and *x, y* are the transverse coordinates:

Cylindrical geometry

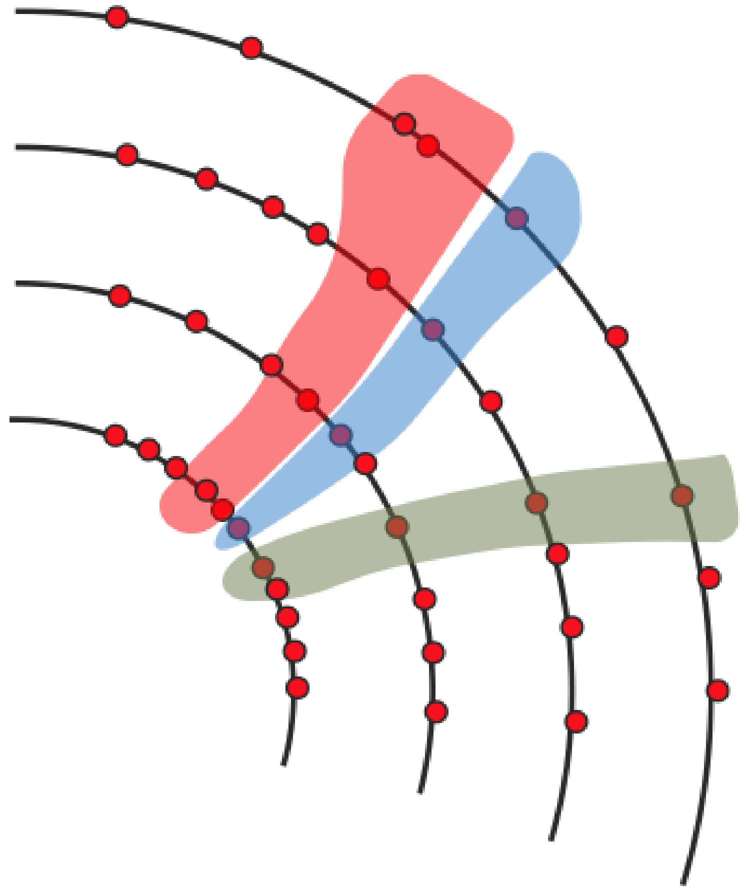
In a homogenous axial solenoid field with the *z* coordinate oriented along the detector axis: helix parameters

Track State Parametrization:

A track state can be represented as a point in 5D linear space (usually 2 positions, 2 angles and a curvature) and 5x5 symmetric error matrix.

Pattern Recognition

- The **main** goal of the pattern recognition is to **associate hits to tracks** (particle trajectories). It should be efficient (use of all hits) and robust (no noise or hits from other tracks)



Two approaches:
Global and **Local** pattern recognition

- **Global methods:**
  Template matching, neural network techniques, Hough space transform, …..
  (Simultaneous consideration of all hits: can be very inefficient in terms of speed)

- **Local methods (also called track following):**

  Combinatorial Kalman filter updates the information (track parameters and error matrix) of candidates tracks along the track finding process and gives a precise prediction of the next point to be found. It is a progressive methods (boundary pattern recognition/track fitting vanished). Track fit became part of the track finding approach.

Track fitting

Process to estimate the kinematical parameters, such as position (or impact parameter), direction of flight and momentum of a particle starting from the measured hits which have been correctly identified in the pattern recognition step.

- ✓ **Multiple scattering effects and energy loss are taken into account in the track fitting procedure**
- ✓ **In general the fitting methods assume Gaussian errors**

Two approaches:

- ❑ **Least squares estimation**: requires the global availability of all measurements at fitting time

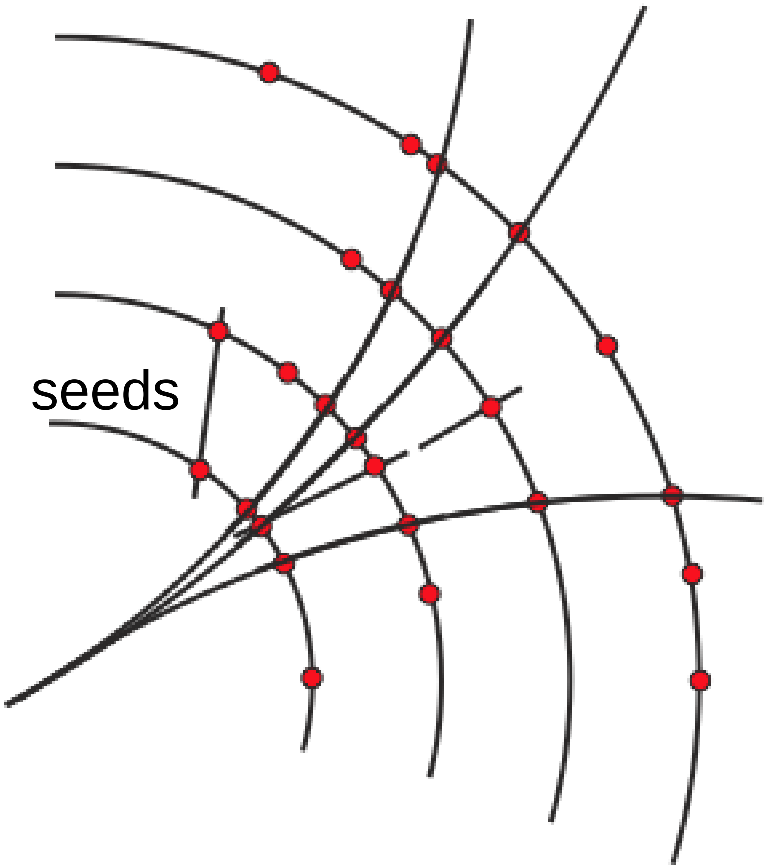
- ❑ The **Kalman filter technique**: proceeds progressively from one measurement to the next, improving the knowledge of the trajectory with each new measurement (**boundary pattern recognition/track fitting vanishes)**

Track finding / track fitting:
the combinatorial Kalman filter

Progressive method: track fitting works simultaneously with track finding.

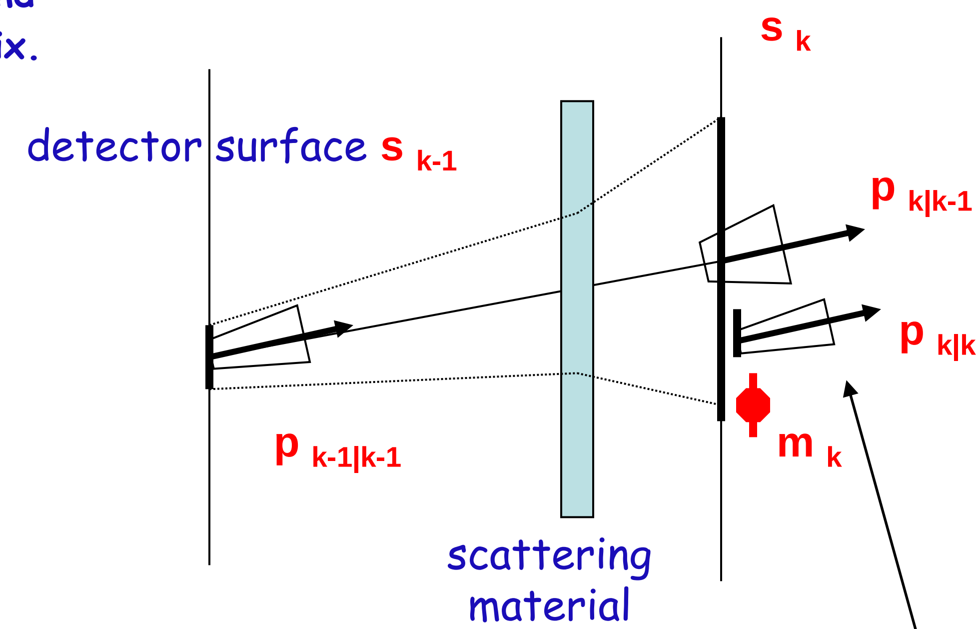
The Kalman Filter consists of a succession of alternating *prediction and filter steps:*

- ✓ As one example, in CMS track reconstruction is initiated by a *seeding* in the innermost tracker layers: both pixel and silicon strip hits.
- ✓ The system equation propagates the track state in one surface to the next.
- ✓ Accuracy on the track state estimate increases after each new measurement is added



Kalman filter formalism for track fitting

Consider a track state $p_{n|n}$ as known on a surface n and represented as a point in 5D linear space (usually 2 positions, 2 angles and a curvature) and 5x5 symmetric error matrix.



Extrapolation on surface k of the state known on surface k-1:

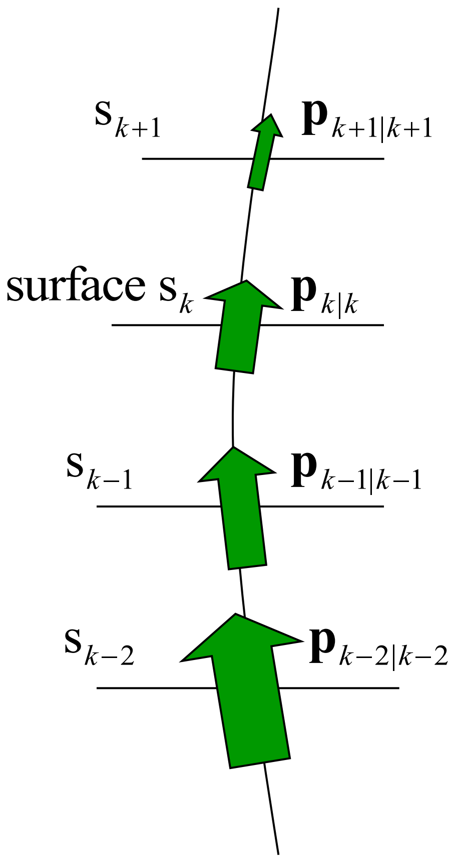
$$\mathbf{p}_{k|k-1} = \underbrace{\mathbf{F}_k}_{\text{Equations of motion}} \cdot \mathbf{p}_{k-1|k-1}$$

Covariance matrix of the extrapolated state:

$$\mathbf{C}_{k|k-1} \equiv \mathbf{C}(\mathbf{p}_{k|k-1}) = \underbrace{\mathbf{F}_k \cdot \mathbf{C}_{k-1|k-1} \cdot \mathbf{F}_k^{-1}}_{\text{propagation of errors}} + \underbrace{\mathbf{P}_k \cdot \mathbf{Q}_k \cdot \mathbf{P}_k^{-1}}_{\text{effect of material}}$$

$p_{k|k}$ is the result of the combination of the extrapolated state and the information provided by the measured hit position

Kalman filter formalism for track fitting



Accuracy on the track state estimate increases after each new measurement is added.

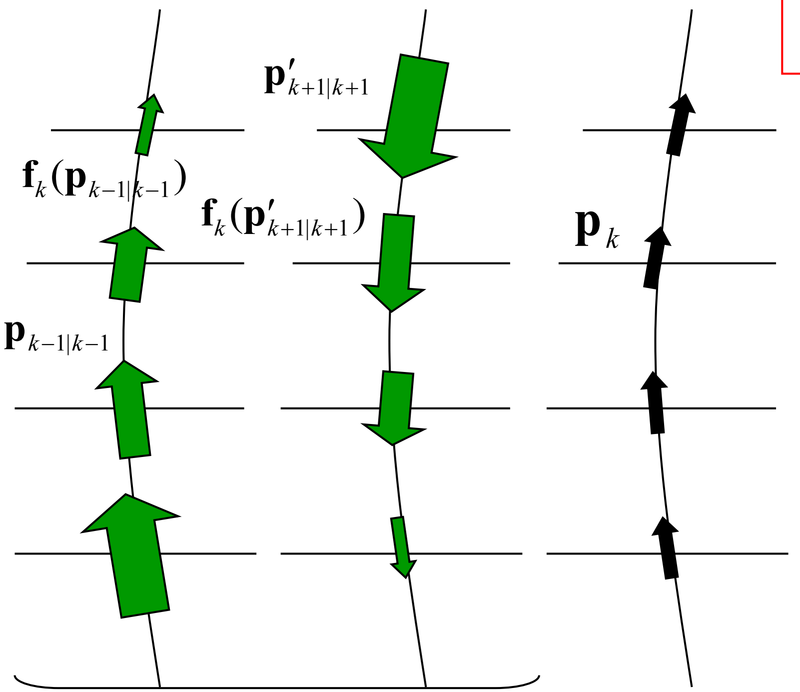
The last track state $\mathbf{p}_{n|n}$ is determined with the best precision: it is the only one which **is estimated using the full information provided by the detector**, i.e. all the *n* measurements.

An increasing accuracy is adequate for trajectory building. Nevertheless is often desirable to have the best estimate of track's parameters on all the detector surface.

In particular **the track has to be know with the best precision at the point of max approach** to the primary vertex of interaction.

Kalman *smoothing* for track fitting

- At the end of the "forward in-out fit", the track parameters are known precisely at the exit of the tracker, but completely unknown at the origin
- We can perform a "backward out-in fit", using only the hits from the forward fit (no pattern recognition) to find the parameters at origin
  - But we lose them at the other end
- A procedure, called *smoothing*, allows to combine the forward and backward fits in such a way that the parameters are optimally known at every measurement



Both in-out filter and out-in one are run

$$\boxed{\mathbf{p}_k = \mathbf{p}_{k|k} \oplus \mathbf{f}_k(\mathbf{p}'_{k+1|k+1})}$$

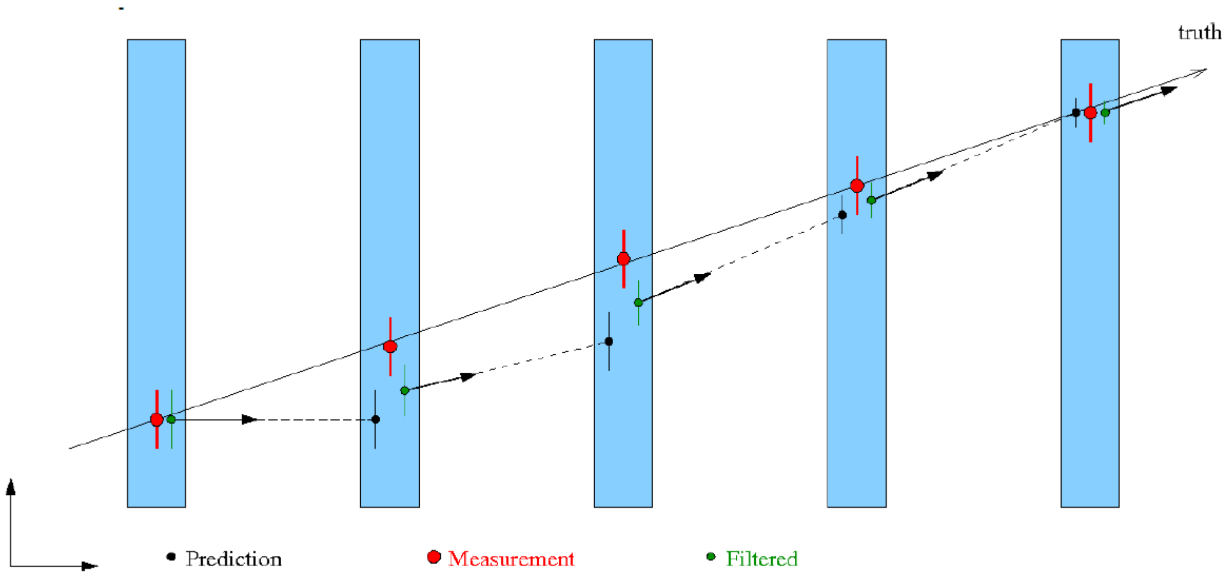
A statistically correct *weighted mean:* **Kalman *smoother***

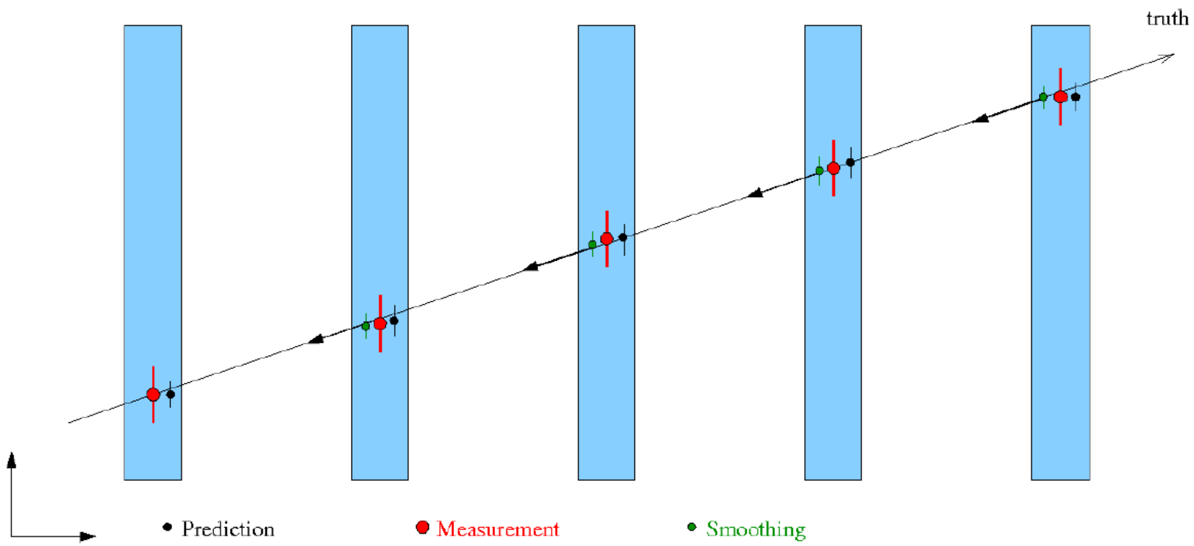
$\mathbf{p}_{k|k}$ **Contains information from measurements: 1,2,..,k**

$\mathbf{p}'_{k+1|k+1}$ **Contains information from measurements: n,n-1,…,k+1**

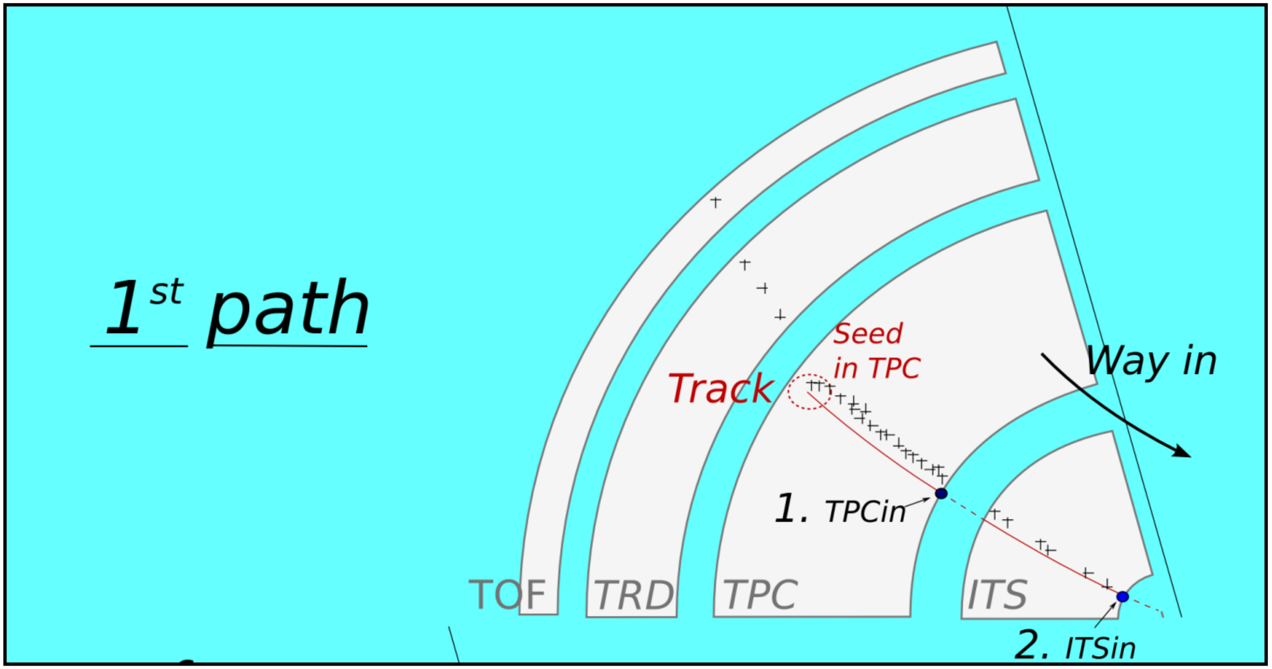
$\mathbf{p}_k$ **Contain the full information. All measurement from 1 to n are used.**

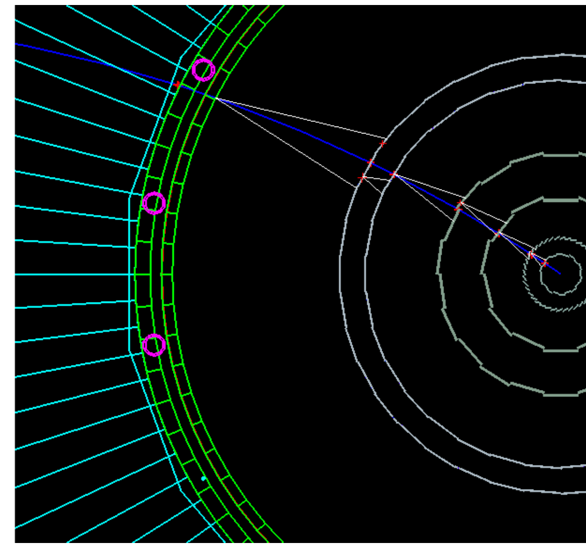
Filtering and Smoothing





The three paths of the combined tracking

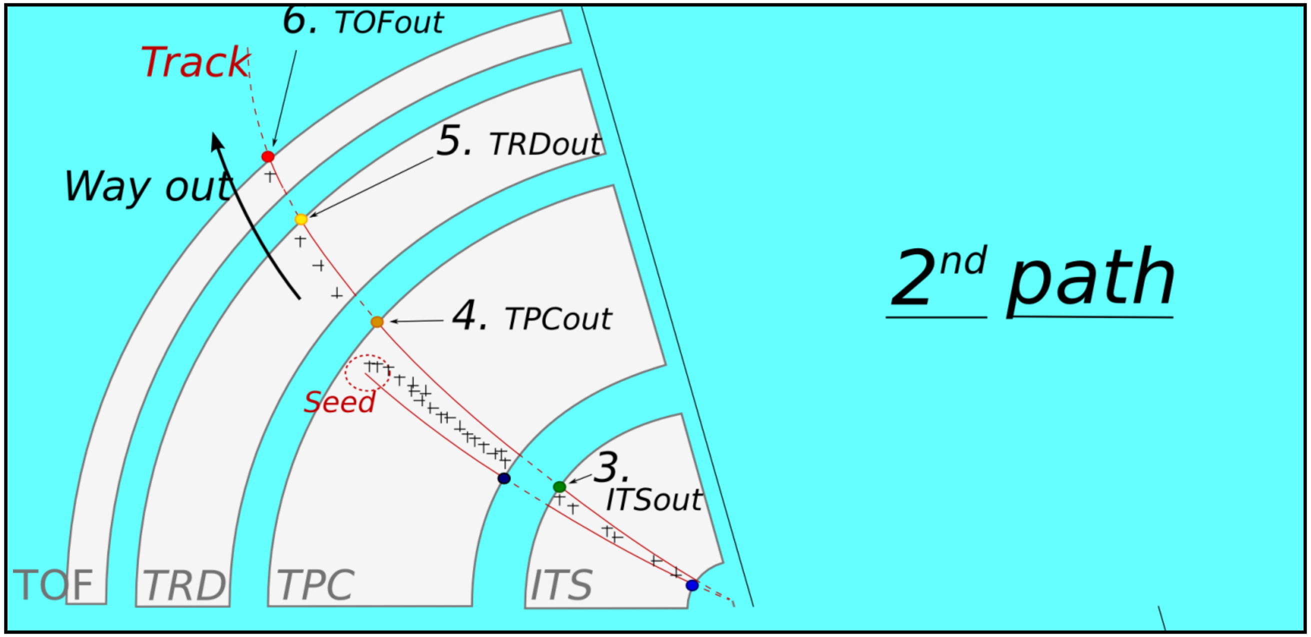




1. "Seeds" in outer part of TPC (lowest track density per unit area). Kalman-filter based tracking from the outer to the inner wall of TPC. The same in ITS.
   - Track parameters are OK
   - PID is not yet OK

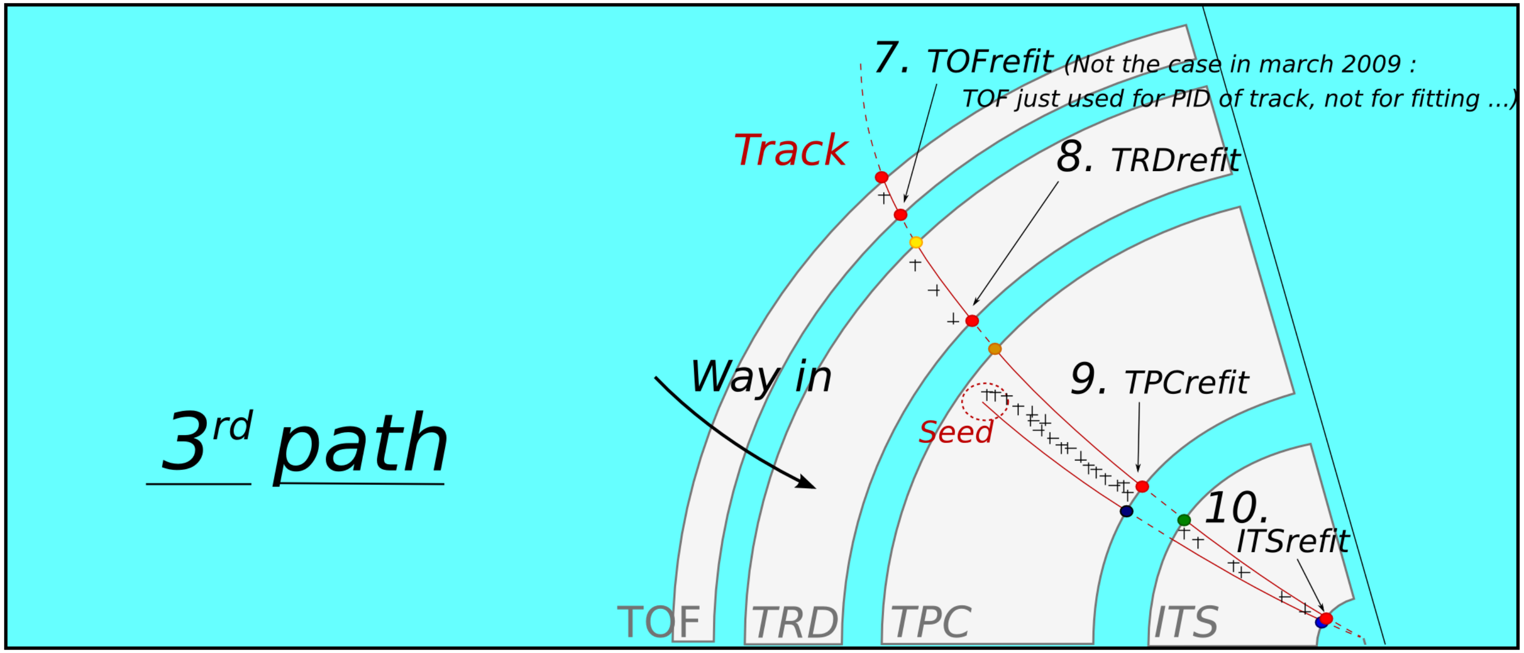
Kalman-filter:
a. track extrapolation to next layer
b. track-cluster χ^2 prediction
c. track parameters and errors update with cluster info

The three paths of the combined tracking



1. Tracking from the inner to outer layer of ITS. The same in TPC. The same in TRD. Matching with TOF, HMPID, PHOS/EMCAL
   - PID is OK
   - Track parameters are not OK

The three paths of the combined tracking



1. Tracking from the outer to inner TRD wall. The same in TPC. The same in ITS.
    - PID is OK
    - Track parameters are also OK