Track based alignment of the ATLAS Silicon Tracker

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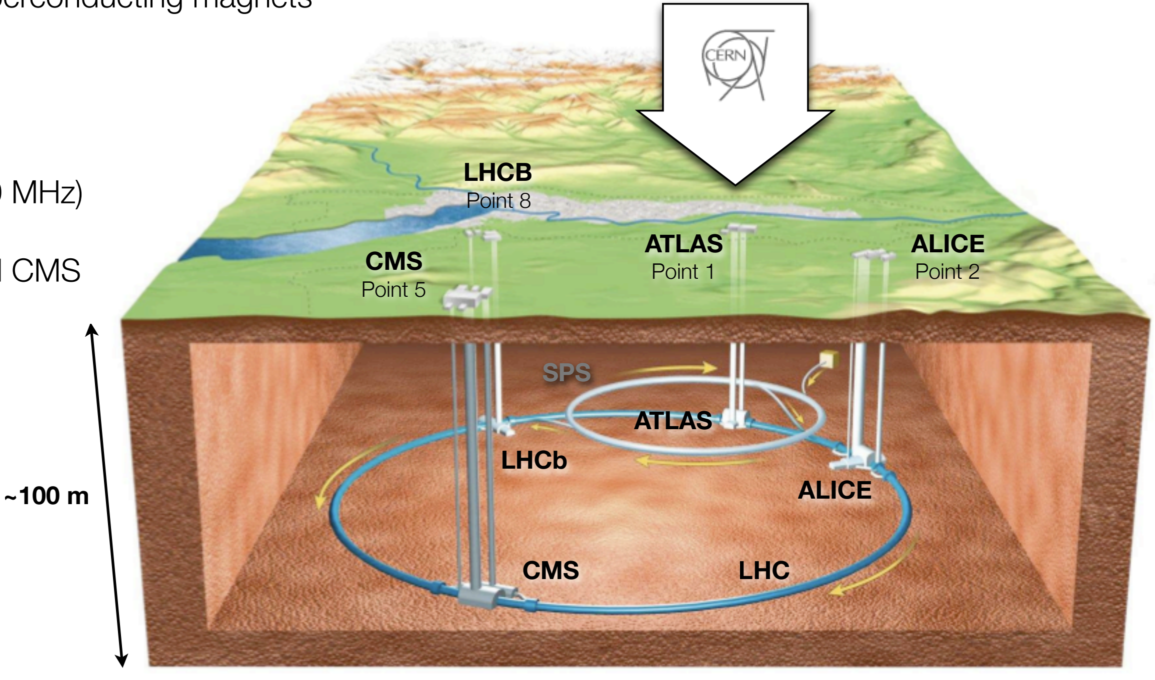
on behalf of the ATLAS ID Alignment group

LHC

Large Hadron Collider (LHC)

- **It is a *pp* accelerator:**
  - 7 TeV per beam
    - 5 TeV at start-up, 2008
  - 27 km of circumference with superconducting magnets
    - B field: 8.33 T
    - Temperature: 1.9 K
  - Design luminosity: 10^{34} cm^{-2} s^{-1}
    - In 2008, 10^{31} cm^{-2} s^{-1}
  - Bunch crossings every 25 ns (40 MHz)
  - 4 Experiments:
    - General purpose: ATLAS and CMS
    - B Physiscs: LHCb
    - Heavy ions: ALICE

- **Main Physics program:**
  - Precise Standard Model (SM)
    - Top quark measurements
  - Higgs Searches
  - SUSY Models
  - Extra Dimensions
  - Microscopic Black Holes

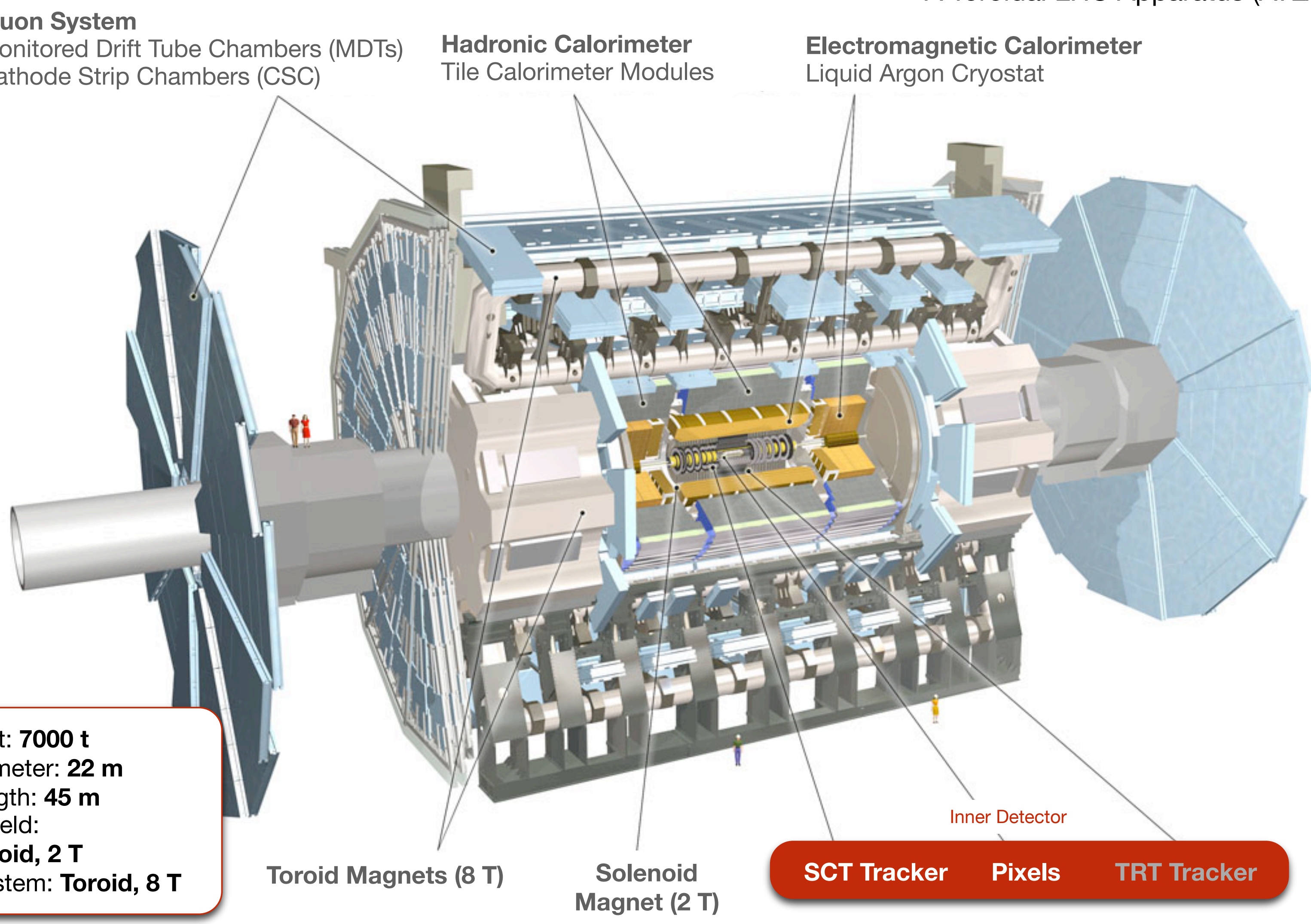


Expected start-up summer 2008!

Would happen one of the following days... ;-)

ATLAS Experiment

A Toroidal LHC Apparatus (ATLAS)

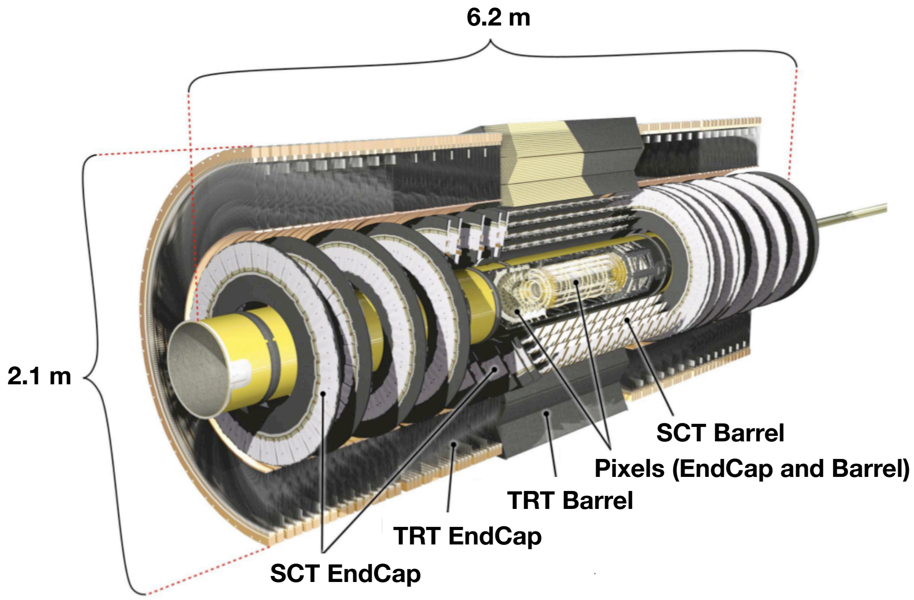


Total Weight: **7000 t**
Overall Diameter: **22 m**
Overall Length: **45 m**
Magnetic Field:
- ID: **Solenoid, 2 T**
- Muon System: **Toroid, 8 T**

ATLAS Inner Detector

Inner Detector (ID)
Efficient track reconstruction, precise momentum measurement and vertex determination (b-tagging).
Three technologies used, all mounted in Barrel/EndCaps layout:

- **Pixel detector**
  - Silicon pixels
  - Size: (50x400) μm^2
  - Single module design
  - Analogue readout
  - Intrinsic point resolution: (14x115) μm
  - 3 layers (Barrel) and 2x3 disks (EndCaps)
- **SemiConductor Tracker (SCT)**
  - Silicon microstrips
  - Strip pitch:
    - 80 μm (barrel)
    - 57-90 μm (endcap, fan-out structure)
  - Barrel and EndCap module design: 5 topologies
  - Binary readout
  - Intrinsic resolution: 23 μm
  - 3D spacepoint by stereo angle (resol. 580 μm in Z)
    - Barrel: 4 layers (Barrel) and 2x9 disks (EndCaps)
- **Transition Radiation Tracker (TRT)**
  - Gaseous drift tubes with gold wire
  - Straw tube diameter: 2 mm
  - Time dependece: Drift time
  - Straw resolution: 170 μm
  - 96 modules in 3 layers (Barrel)
  - 35 hits per track on average

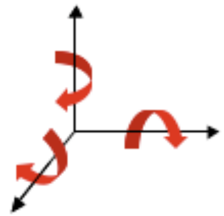


	Pixels	SCT	TRT
Technology	Silicon pixels	Silicon microstrips	Gaseous drift-tubes
Modules	1744	4088	988
Intrinsic resolution	~14 μm (rΦ) ~115 μm (z)	~23 μm (rΦ)	~130 μm (rΦ)

Silicon Alignment Challenge

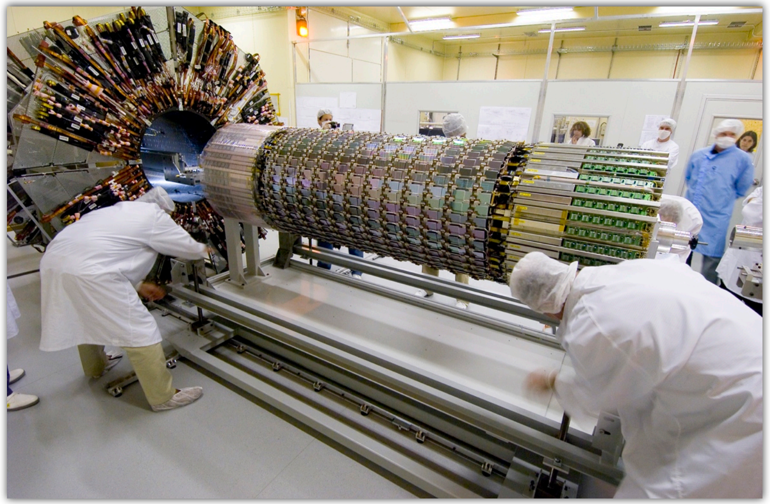
To achive the ATLAS physics goals, we need...

- Exploit the excellent intrinsic resolution of our precision tracking devices.
  - Mounting and survey precision O(100 μm), depending on subdetector.
- Requirements
  - Don't degrade resolution of track parameters > 20 %
  - Systematic error M(W) < 15 MeV/c^2
  - b-tagging efficiency drops by 10 % with a misalignment of O(10 μm), so...
- We need high accuracy alignment: precision in rΦ < 10 μm
- **Ultimate precision reached with track-based alignment algorithms!!!**



3 translations and 3 rotations per alignable structure

I will focus on just the Silicon Alignment....



	Barrel		EndCap	
Detector	Pixels	SCT	Pixels	SCT
Nbr. of Layer/Disks	3	4	2x3	2x9
Nbr. of modules	1456	2112	2x144	2x988
Subtotal	3568		2264	
Total	**5832**			

5832 modules → **34992 DoFs**

- 6 DoF per module (rigid body)
- Large number of DoFs to solve!

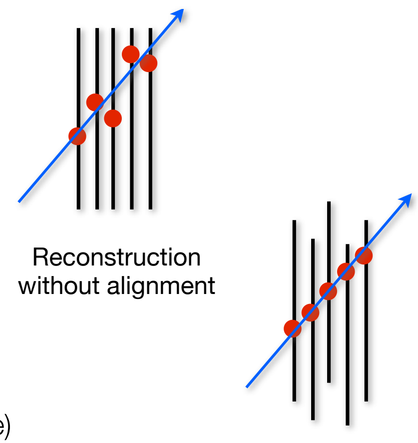
What's next? bows and bends

- Due to temperature, B fields and material load

Track-based alignment

Several approaches implemented within the ATLAS software framework (called Athena)

- Nowadays, we use independent alignment algs for silicon and for the TRT
  - Relative alignment of the TRT wrt the silicon by track extrapolation
  - Working on the unification



Reconstruction without alignment

Real situation

- Implemented methods for Silicon:
  - GlobalChi2:
    - In-plane residuals use to build the chi2 to minimise: 6 DoF per module
    - Correlations managed, therefore small number of iterations
    - Inherent challenge of large matrix handling and solving (35k x 35k): whole system in one step
  - LocalChi2:
    - Similar to GlobalChi2 (particular case, in theory), but inversion of small 6x6 matrix (one per module)
    - No inter-module nor MCS correlations (diagonal covariance matrix), but 6 DoF per module
    - Large number of iterations to get compensate the lack of correlations
  - Robust:
    - Centres residual and overlap distributions without minimisation (histograming method)
      - Use weighted residuals, z and r overlap residuals of neighboring modules
    - 2 or 3 DoF within plane (x, y, gamma)
    - Intrinsic iterative procedure (many iterations)

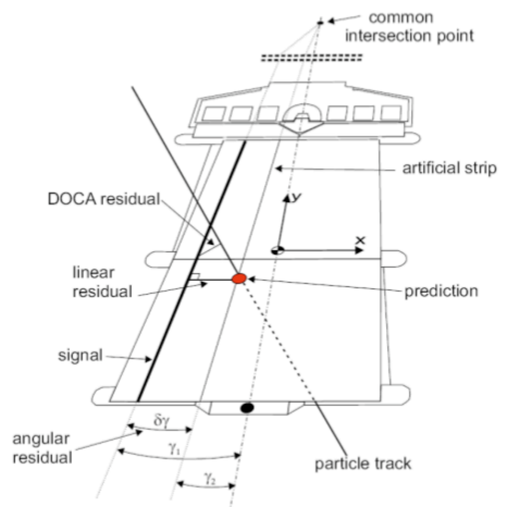
covariance matrix (V)

$$\chi^2 = \sum_{tracks} r^T V^{-1} r$$

vector residuals: r = r(π,a)
- **π: track parameters**
- **a: alignment parameters**

$$\frac{d\chi^2}{da} = -M^{-1}\nu$$

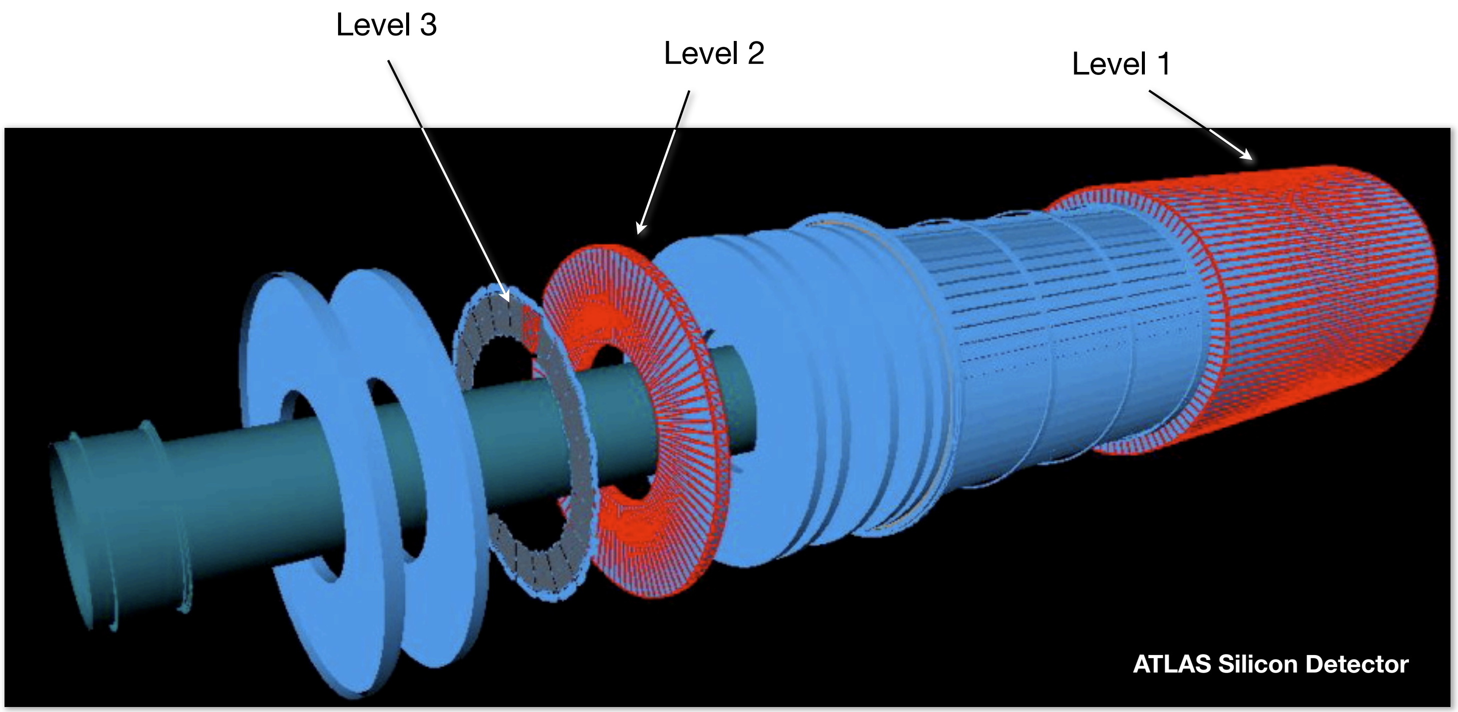
- **For the GlobalChi2, requires inversion of a symmetric 35k x 35k matrix**



Track-based alignment

Alignment Levels

- Detector description in terms of geometrical primitives (GeoModel)
  - Logical volumes grouped in hierarchical nodes
  - Alignment infrastructure based on alignable nodes
- Three different alignment levels:
  - Level 1: entire subdetectors (whole Pixel, SCT barrel and end-caps)
  - Level 2: silicon layers & disks
  - Level 3: silicon modules

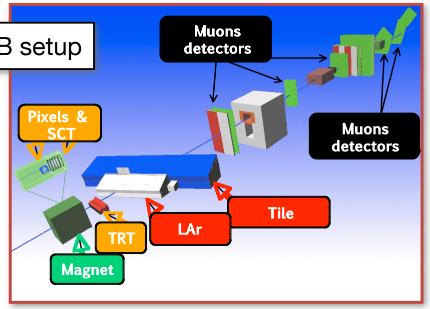


Earlier Alignment Tests: CTB and SR1 Cosmics

Combined TestBeam (2004)

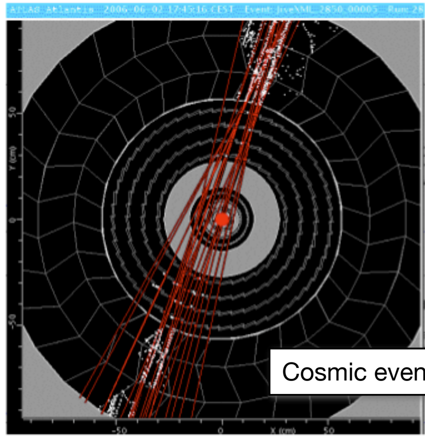
- First ever 'ATLAS data' from subsystems combined
  - Large statistics (~20M tracks) at different beam momenta (2-180 GeV/c^2)
  - e^+, e^- and π with (1.4 T) and without magnetic field
- Challenge: small setup, collimated beam through narrow tower of modules
  - (just an ATLAS barrel slice, so certain DoFs unconstrained)
- Achived resolution: 5 μm for Pixels and 10 μm for the SCT
- Results summited to JINST: arXiv:0805.3984v1 [phyisics.ins-det]

CTB setup



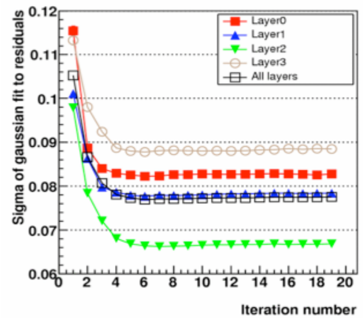
SR1 Cosmics (2006)

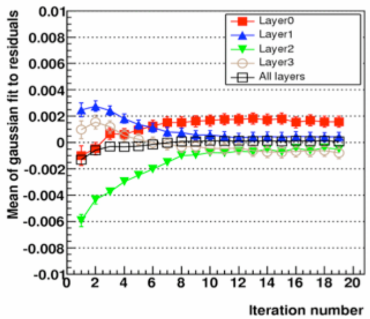
- First ever 'SCT+TRT cosmic data'
  - Data-taking at surface (SR1 clean room)
  - 22% of the SCT Barrel and 13% of the TRT Barrel
  - ~400k events recorded
  - No B field → No momentum estimation
    - MSC important for tracks with $p \leq 10$ GeV/c^2 (Spectrum dominant)
    - Larger residuals than CTB
- Challenge for alignment: small setup, collimated beam through narrow tower of modules (certain DoFs unconstrained)

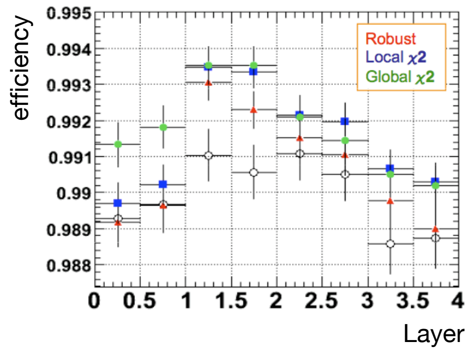


Cosmic event

Alignment convergence for SR1 Cosmic run alignment

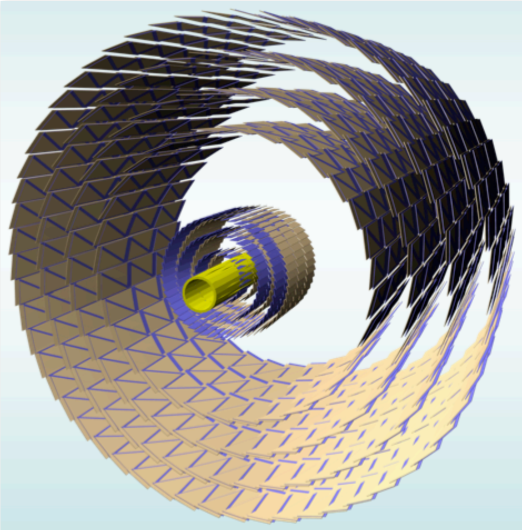




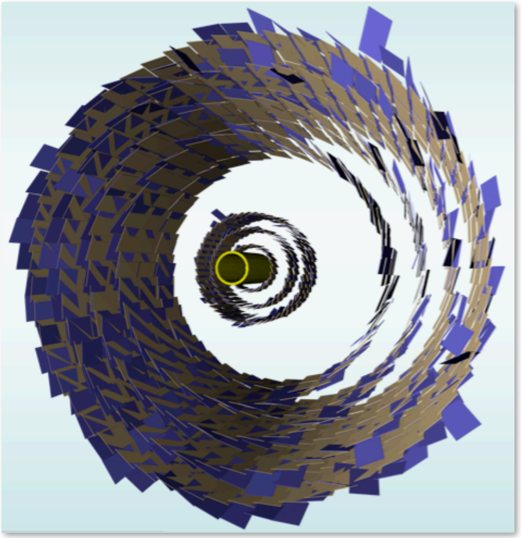


Computing System Commissioning (CSC)

- First ever simulations using realistic as-built geometry
- Testbed for the ID algorithms to test its performance and to get ready for real conditions
  - All physics productions performed with misaligned geometry
- Underlying hardware reflected in structure of alignment constants
  - CSC misalignments:
  - Shifted and rotated magnetic field
  - Misalignments at all levels:
    - Level 1: Translations O(1 mm), Rotations O(0.1 mrad) - Surveyed O(several mm)
    - Level 2: Translations O(100 μm), Rotations O(1 mrad) - Surveyed O(100 μm)
    - Level 3: Translations O(100 μm), Rotations O(1 mrad) - Surveyed O(30-100 μm)



Ideal ATLAS Silicon Barrel Detector



Misaligned ATLAS Silicon Barrel Detector
(Displacements exaggerated by a factor 100)

Computing System Commissioning (CSC)

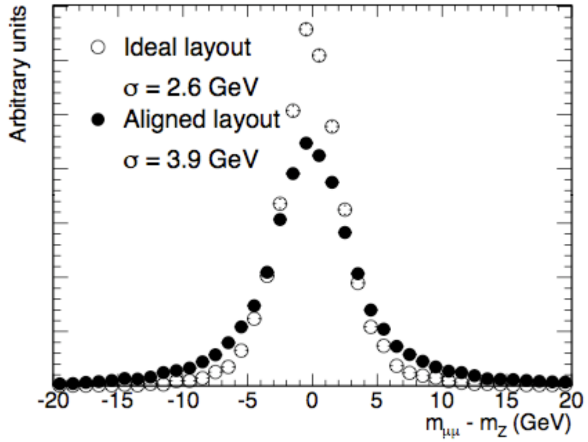
Alignment Performance

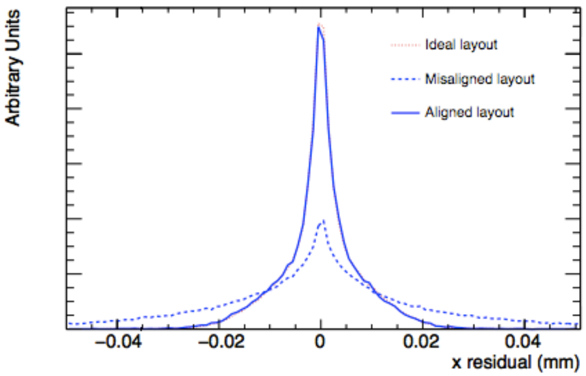
Algorithms converging (almost perfect residuals)

Using a multimuon sample

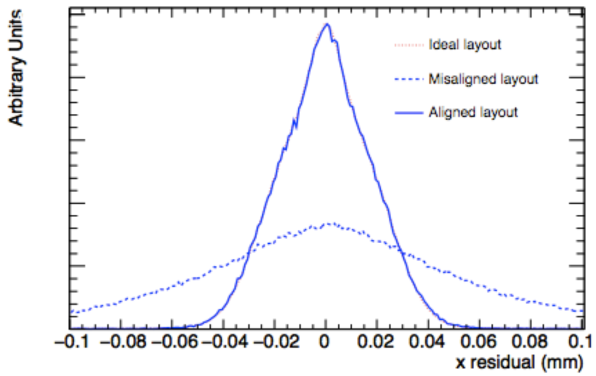
- 10 muons/event
- σ_{xy} = 15 µm ; σ_z = 56 mm
- p_T = [2, 50] GeV/c^2

- O(100) plots to validate the alignment results/convergence
- InDetAlignMonitor (athena package) and GlobalChi2 monitor (root macros)
  - Ideal layout means as-built geometry
  - Misaligned layout means nominal geometry
  - Aligned layout was after running our alignment algorithms
- What do we learn?
  - Improved residuals do not mean that the detector is correctly aligned
  - We discovered that our track parameters were biased because of the systematic effects (weak modes)
    - algs cannot fix them: need additional constrains and handles (more studies are required) → *off-axis events*





(a) Pixel barrel



(b) SCT barrel

CSC and Milestones

Cosmic tracks simulations

High momentum tracks (> 2 GeV/c^2)

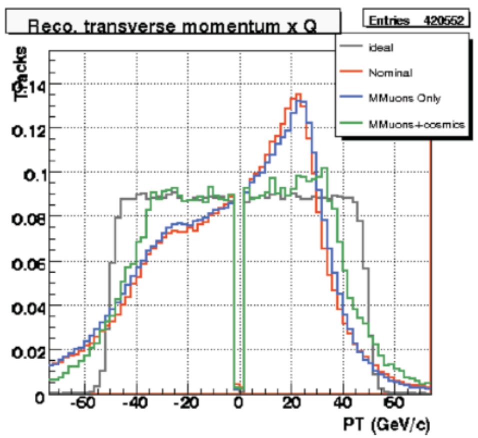
Simulations done and available with and without magnetic field

- No B-Field → constrains pT biasing modes

Introduce correlations between top and bottom hemisphere → constrains telescope mode

Off-axis → constrains twist, elliptical distortions

Low rate (MC simulation: 0.5 Hz through Pixel barrel), non-uniform illumination



Adding cosmics improved the momentum reconstruction

Real data taking in the pit: Milestone weeks (M6)

- Commissioning in the cavern using cosmic rays without B field
  - Very low statistics
- SCT barrel module misalignments were better than expected!

Beam Halo and Beam-gas events

Recently, beam halo events have been considered.

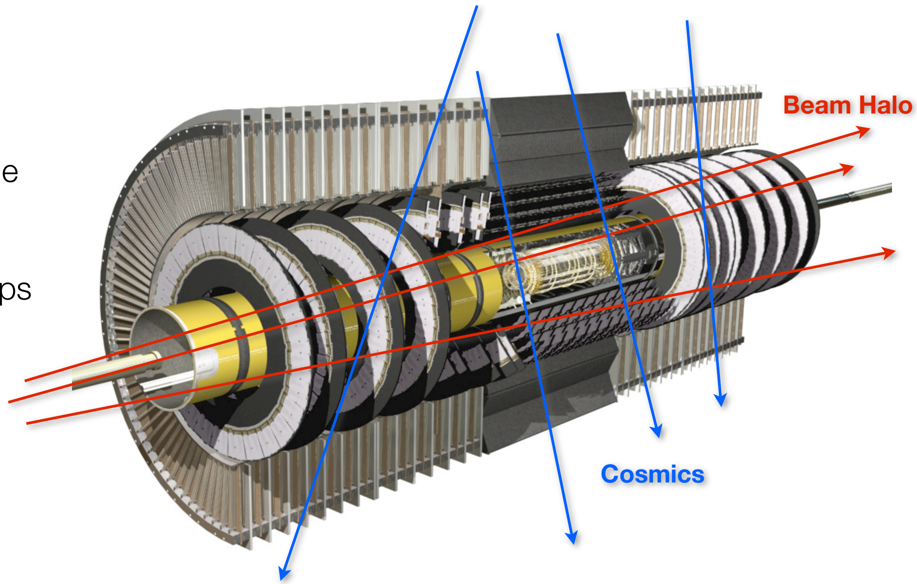
- Simulations with detector misalignments are available
- Need to be studied

Complementary events (in angle) to Cosmic rays

Cosmics good for Barrel and Beam Halo good for EndCaps

How to trigger?

- Using the Hadronic Calorimeter (TileCal)
- Expected rate: ~10 Hz



Full Dress Rehearsal (FDR)

The latest challenge where the alignment team has tested the alignment algorithms is the Full Dress Rehearsal (FDR). It is an exersice where the full data adquisition chain is tested, emulating a data sample roughly equivalent to one day or more of real data-taking

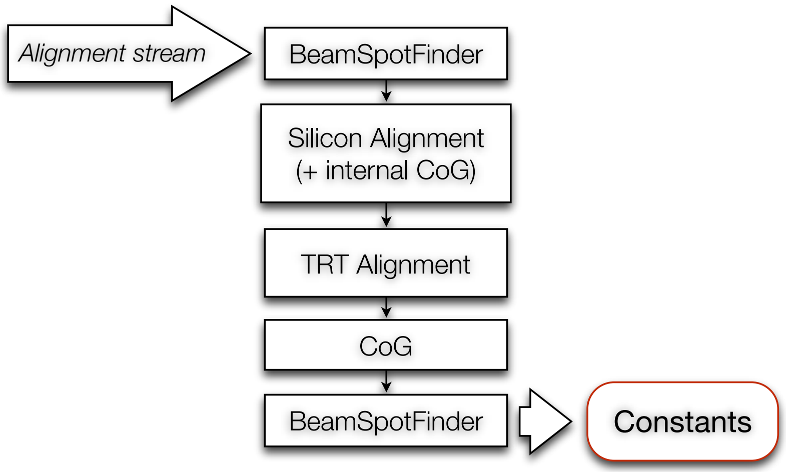
- **Goal:** Run the whole ATLAS computing system as for real data and try to find early the problems we'll have with data

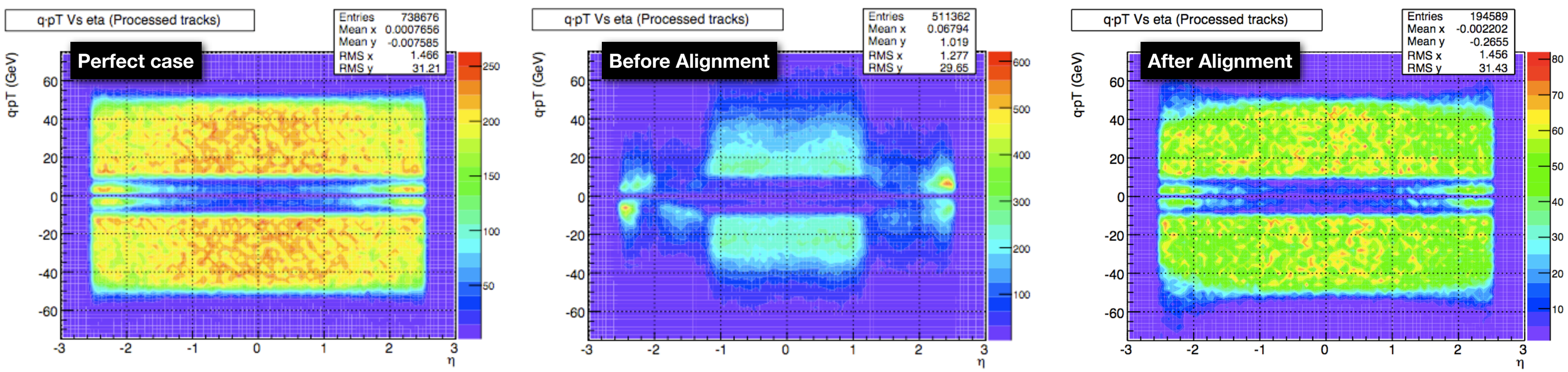
Phases:

- FDR1 run (1 week starting 4th February 2008)
- FDR2 run (1 week starting 2on June 2008)
- FDR2a run (1 week starting 22on July 2008)

FDR for alignment:

- Use the idcalibration stream:
  - 1M Single track events (single pions) with pT=[10, 50] GeV/c
  - 41k Cosmic events (~11k tracks) with B field
- Parallel environment: 80 CPUs





Weak Modes

Global Distortions, so-called Weak Modes

By definition the weak modes are such movements that the track-based residual minimisation (with collision tracks) cannot resolve, because they leave the Chi2 unchanged.

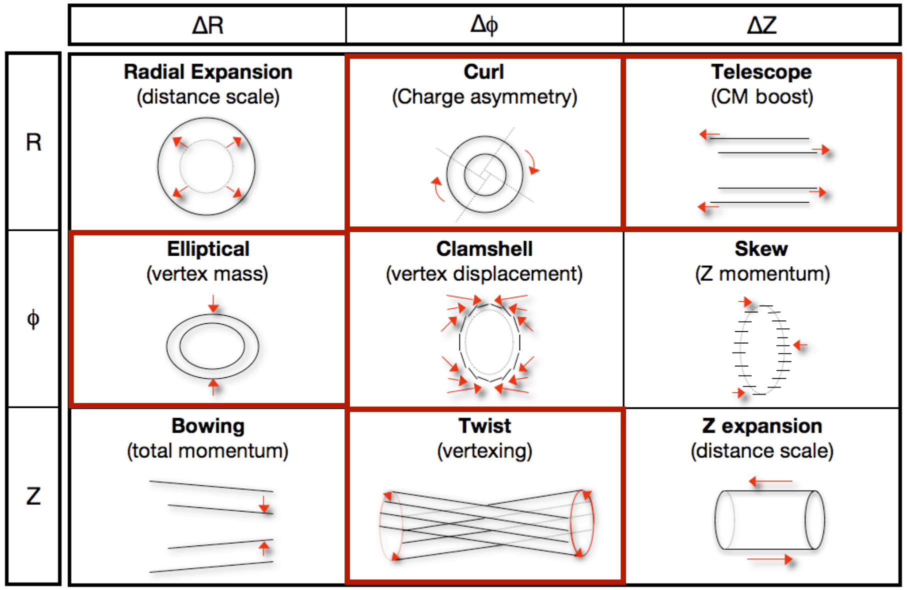
It is not question of maths, the only option is the use of ‘extra’ information, generally called ‘external constrains’

Candidates:

- Common vertex for a group of tracks
- Constrains on track parameters or vertex position (external tracking, resonant mass, etc...)
- Off-axis events: Cosmic rays, Beam Halo / Beam Gas tracks
- External constrains on alignment parameters: survey data, hardware systems (FSI), etc...

Weak Mode Study Strategy

- Simulations with global distortions on top of them
  - Some of them have been already produced and propagated to physics/performance groups.
  - We must evaluate systematic uncertainty on measurements originating from systematic deformations

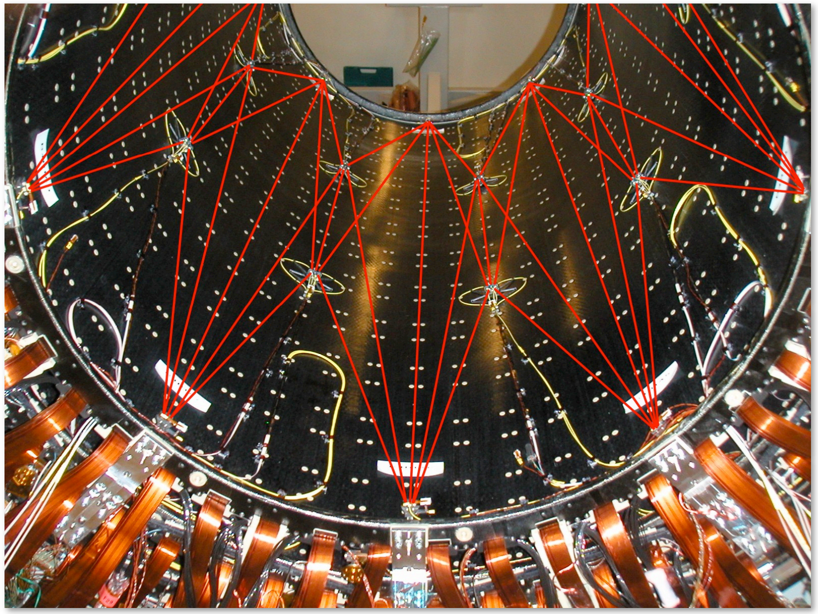


Hardware-based alignment

Frequency Scanning Interferometry (FSI)

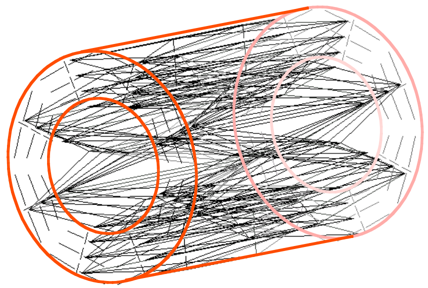
Geodetic grid of 842 simultaneous length measurements in between nodes on the SCT structure

- Distance measurements between grid nodes precise to ~1 μm
- 3D grid geometry can be reconstructed to a precision of < 5 μm in the critial direction
- Will be used intensively before and during the early runs
  - track-based alignment and FSI interplay has to be tested
- Already installed and tested in the ATLAS cavern
  - All grid lines have been illuminated and read out



Time + spatial frequency sensitivity of FSI complements track based alignment:

- Track alignment average over ~24 h
- FSI timescale: ~10 min



SCT Barrel Grid (512 measurements)

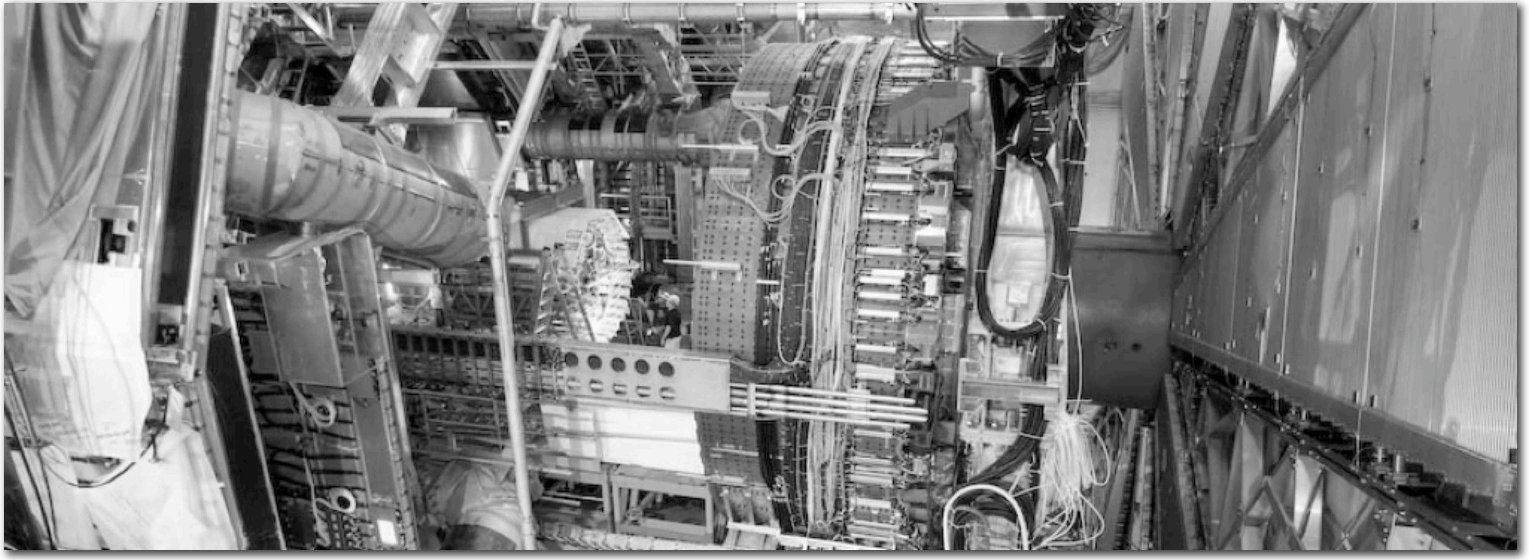
Summary

- Various alignment algorithms are adapted to optimally align the ATLAS Silicon Tracker
  - TRT uses similar algorithms

- All track-based approaches are ready and have been proved, tested and validated with simulation and real data
  - Real Data
    - Combined Testbeam, CERN SPS H8 beamline, 2004
    - SR1 Cosmic run, at the surface, 2006
    - Milestone 6, cosmics in the pit, 2008
  - Simulations
    - Simulations with as-built geometry (expected misalignments at three levels)
    - Computing System Commissioning (CSC)
      - Physics stream (collision samples) and alignment stream (multimuon sample)
      - Cosmics in the pit with/without magnetic field
      - Beam Halo events
    - Full Dress Rehearsal
      - Final tests before the LHC start-up
      - The full alignment chain is tested during these exersice
      - Run the whole ATLAS computing system as for real data and try to find early the problems we'll have with data

  - We realised that weak modes were very important issues, therefore...
    - Weak Modes are very important for the determination of alignment constants
    - Performing systematic studies from simulations to determine the effect on physics observables

  - Frequency Scanning Interferometry (FSI) is ready to play its role with early data
    - Track-based alignment and FSI interplay will be tested



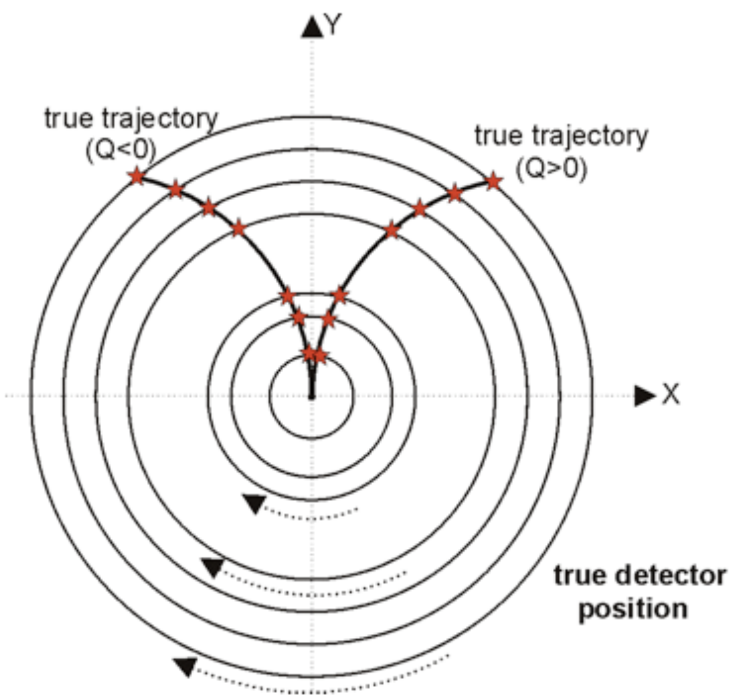
Thank you for your attention

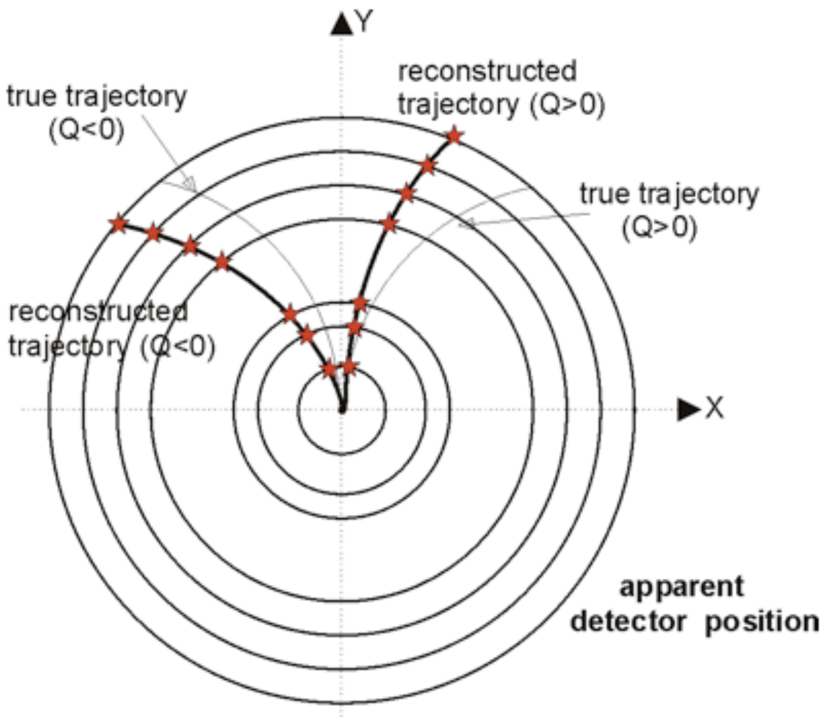
Backup slides

Weak Modes: example

Sagitta distortions

- Bias in track parameters → *but helical path mantained*
- Chi2 of the tracks blind to these global deformations
- Produce momentum asymmetries





The GlobalChi2 Approach

The method consists of minimizing the giant Chi2 resulting from a simultaneous fit of all particle trajectories and alignment parameters:

$$\chi^2 = \sum_{tracks} r^T V^{-1} r \quad \text{where} \quad r \equiv (\vec{e}(\pi, a) - \vec{m}).\hat{k}$$

Intrinsic measurement error + MCS

Let us consequently use the linear expansion (we assume all second order derivatives are negligible). The track fit is solved by:

$$\pi = \pi_0 + \delta\pi = \pi_0 - \left(\frac{\partial e^T}{\partial \pi_0} V^{-1} \frac{\partial e}{\partial \pi_0} \right)^{-1} \frac{\partial e^T}{\partial \pi_0} V^{-1} r(\pi_0, a)$$

while the alignment parameters are given by:

$$\frac{d\chi^2}{da} = 0 \quad \Longrightarrow \quad \sum_{tracks} \frac{dr^T}{da} V^{-1} r = 0$$

key relation

$$\frac{dr}{da} = \frac{\partial r}{\partial a} + \frac{\partial r}{\partial \pi}\frac{d\pi}{da}$$

$$\delta a = -\underbrace{\left(\sum_{tracks} \frac{\partial r^T}{\partial a_0} W \frac{\partial r}{\partial a_0} \right)^{-1}}_{\mathcal{M}} \underbrace{\sum_{tracks} \frac{\partial r^T}{\partial a_0} W r(\pi_0, a_0)}_{\mathcal{V}}$$

$$W \equiv V^{-1}\hat{W} \equiv V^{-1} - V^{-1}E(E^T V^{-1} E)^{-1} E^T V^{-1} \quad \mathrm{E} \equiv \frac{\partial e}{\partial \pi_0}$$