Alignment of the ATLAS Inner Detector – Run I Experience

(a quick journey to the world of geometry and linear algebra)

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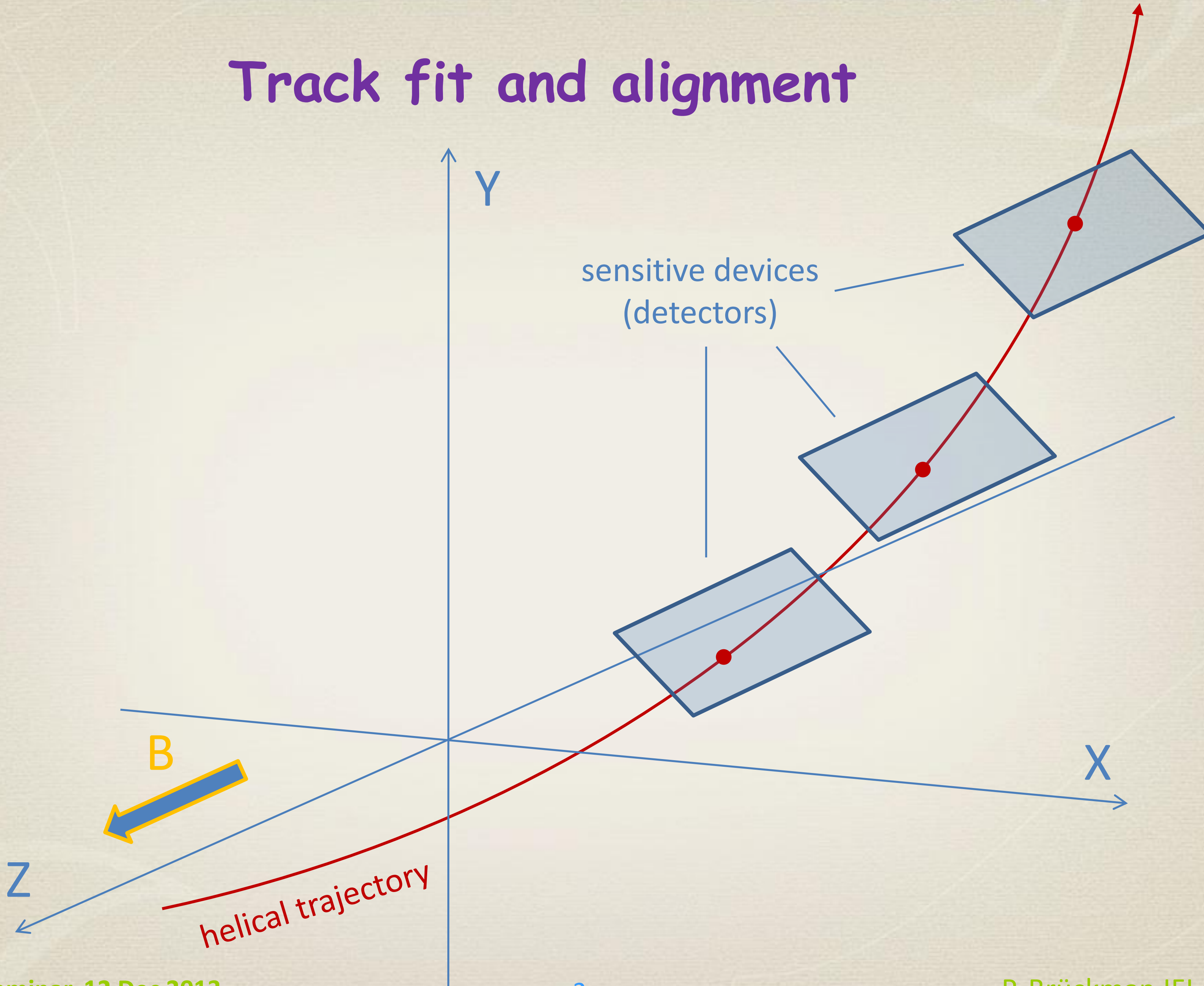
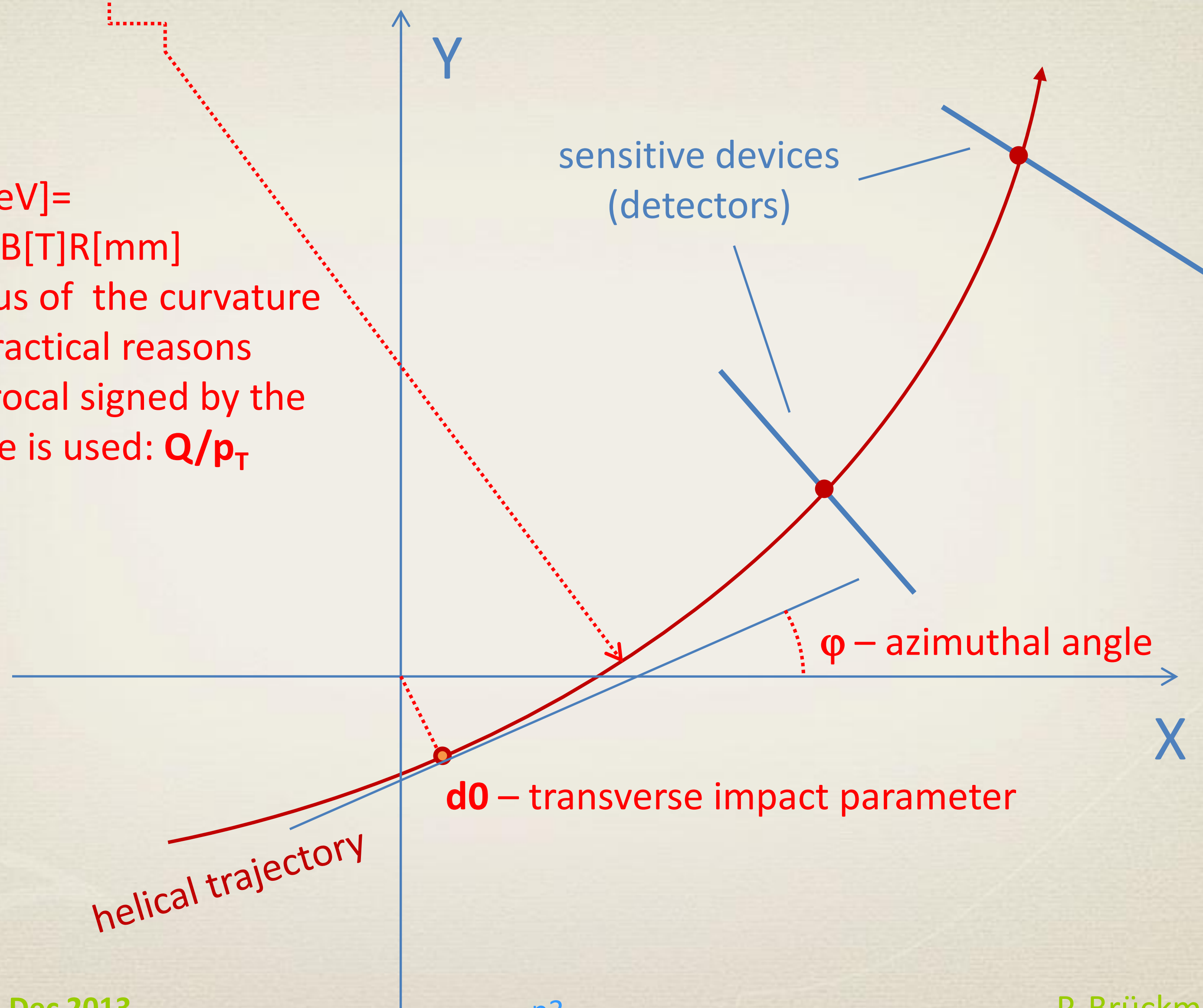
Track fit and alignment

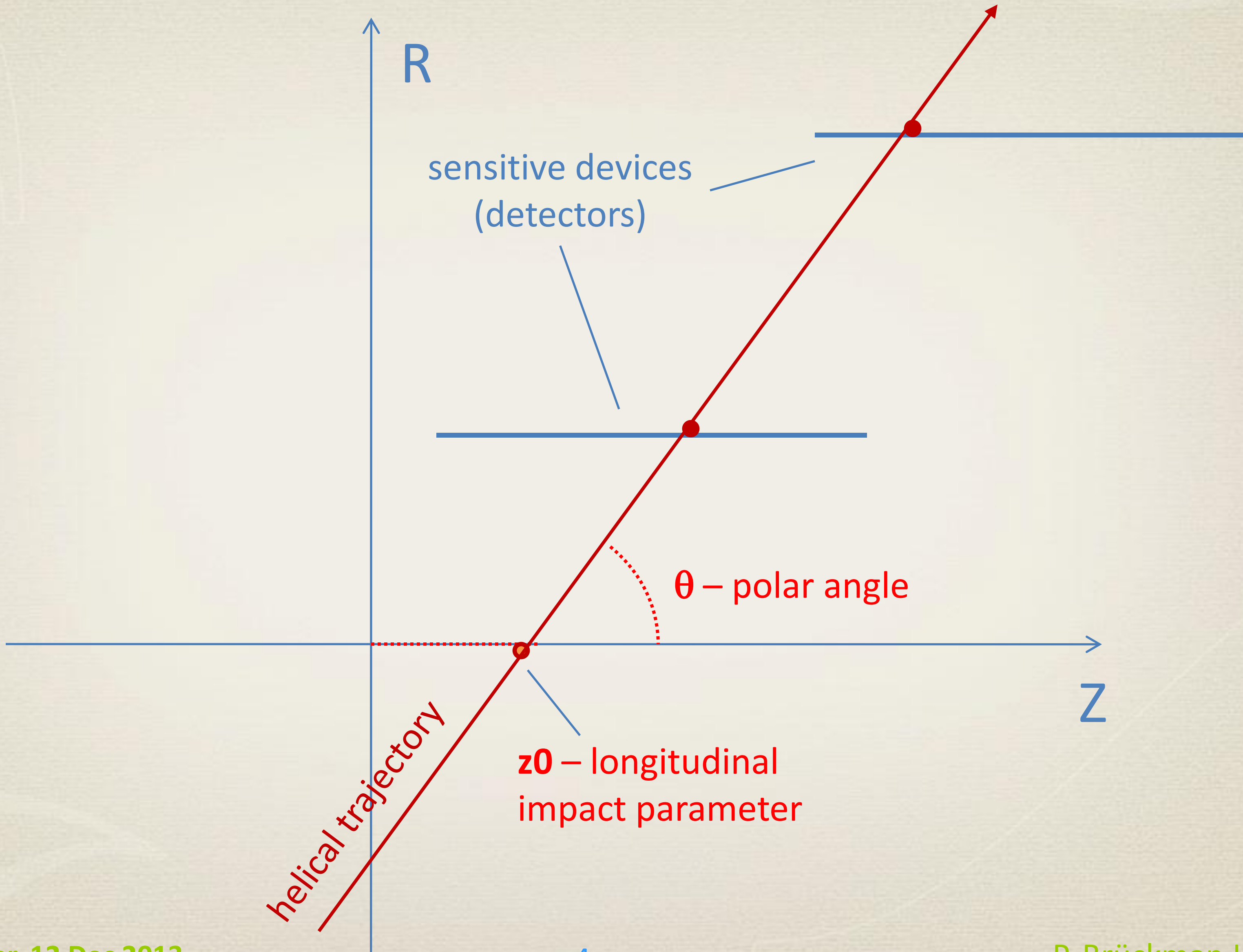


Track reconstruction - parameters

p_T [MeV]=
=0.3qB[T]R[mm]
- radius of the curvature
For practical reasons reciprocal signed by the charge is used: **Q/p_T**

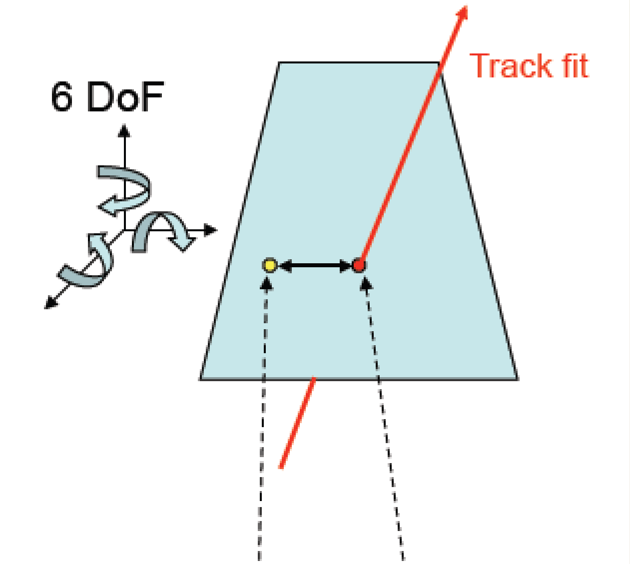


Track reconstruction - parameters



Basic track fit (linearization)

$$\pi = (d, z, \varphi, \vartheta, Q/p_T), \qquad \vec{e} \equiv \vec{e}(\pi)$$



$$\vec{r}_i \equiv \vec{m}_i - \vec{e}_i(\pi, a)$$

$$\chi^2 = \mathbf{r}^T \mathbf{V}^{-1} \mathbf{r}, \qquad r_i \equiv (\vec{e} - \vec{m}) \bullet \hat{k}$$

$$\mathbf{r}(\pi) = \mathbf{r_0} + \frac{\partial \mathbf{r}}{\partial \pi}(\pi - \pi_0)$$

linear exp. aro. seed

$$\frac{d\chi^2}{d\pi} = 0$$

minimization condition

$$\boxed{\pi - \pi_0 = \left(\frac{\partial \mathbf{r}}{\partial \pi}^T \mathbf{V}^{-1} \frac{\partial \mathbf{r}}{\partial \pi} \right)^{-1} \frac{\partial \mathbf{r}}{\partial \pi}^T \mathbf{V}^{-1} \mathbf{r}_0}$$

Basic track fit

$$\pi = (d, z, \varphi, \vartheta, Q / p_T)$$

CAUTION:

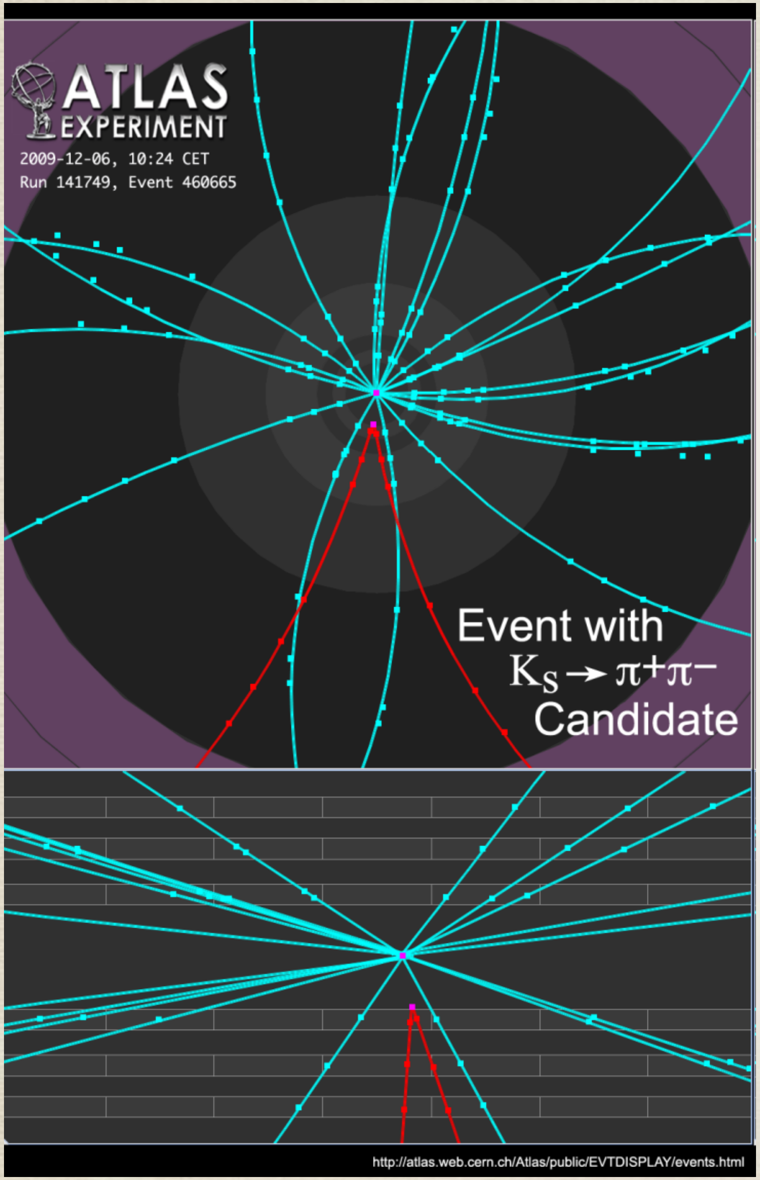
Lots of simplifications in the above. In reality at least two more effects need to be accounted for:

A) Multiple Coulomb Scattering (track deflects at every intersected material)

B) Energy Loss (particle losses energy for ionisation – changes momentum)

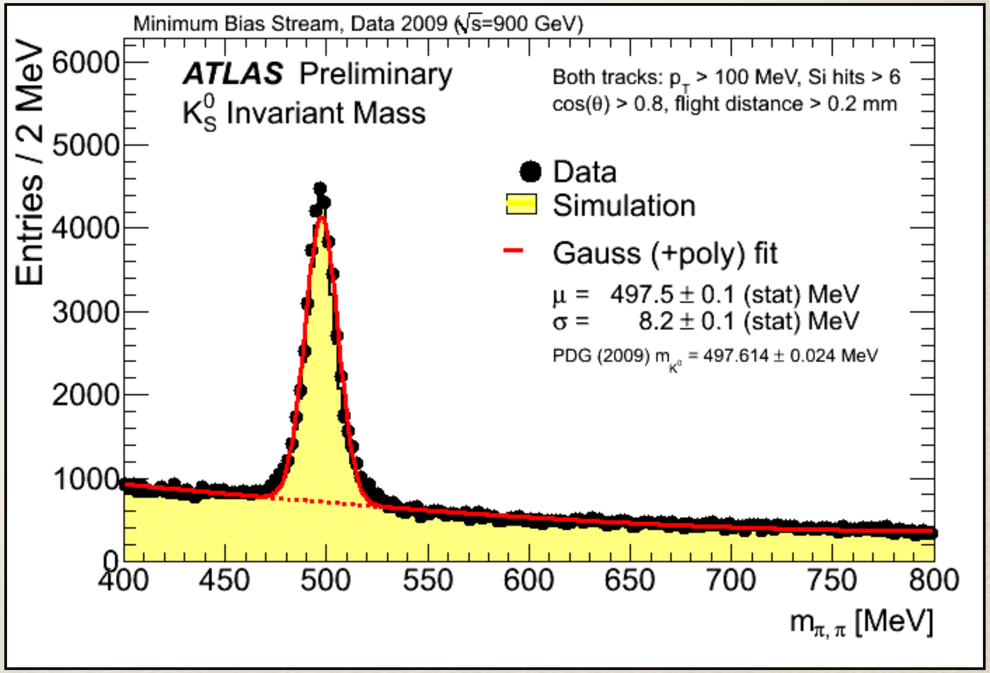
$$\boxed{\pi - \pi_0 = \left(\frac{\partial \mathbf{r}}{\partial \pi}^T \mathbf{V}^{-1} \frac{\partial \mathbf{r}}{\partial \pi} \right)^{-1} \frac{\partial \mathbf{r}}{\partial \pi}^T \mathbf{V}^{-1} \mathbf{r}_0}$$

What do we need it for?

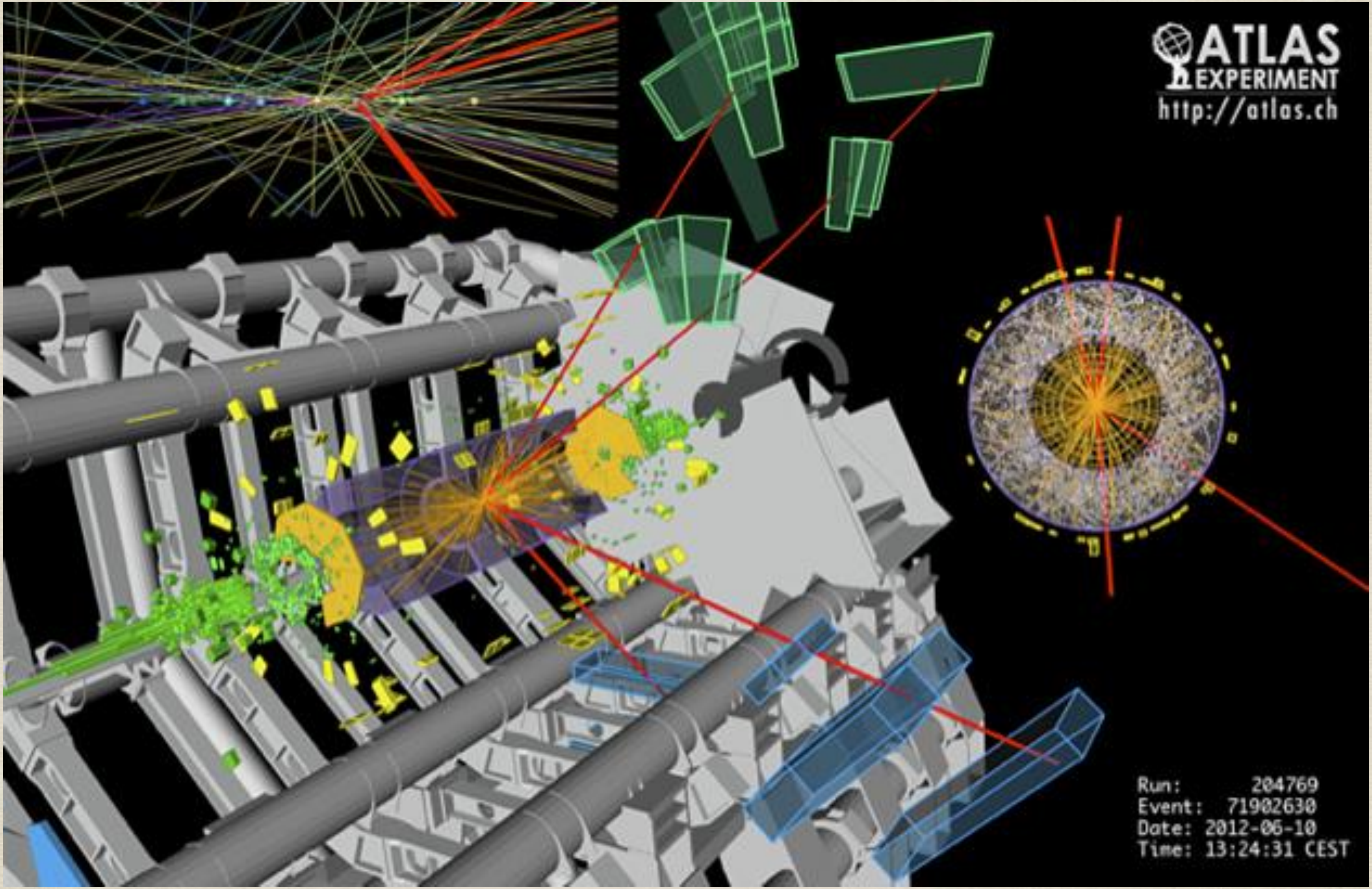


Example of one of the first measurements issue of ATLAS tracking:

- invariant mass,
- primary event vertex.
- K_s^0 decay vertex,



$H \rightarrow ZZ^* \rightarrow 4l$ candidate



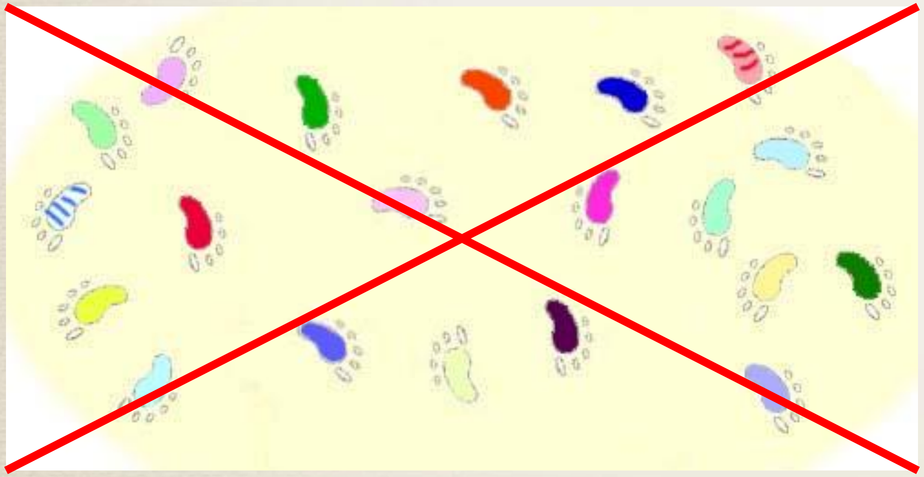
How does it work?

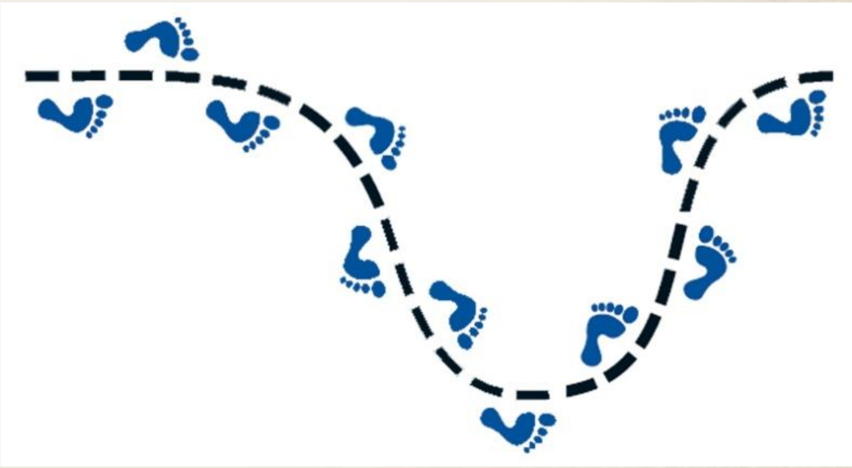
- We cannot see trajectories, only their „footmarks".
- Must „reconstruct" what happened.

How does it work?

❖We cannot see trajectories, only their „footmarks".
❖Must „reconstruct" what happened.

❖Each „footmark" gets „captured" independently.
❖In order to reconstruct a track one must complete the puzzle:

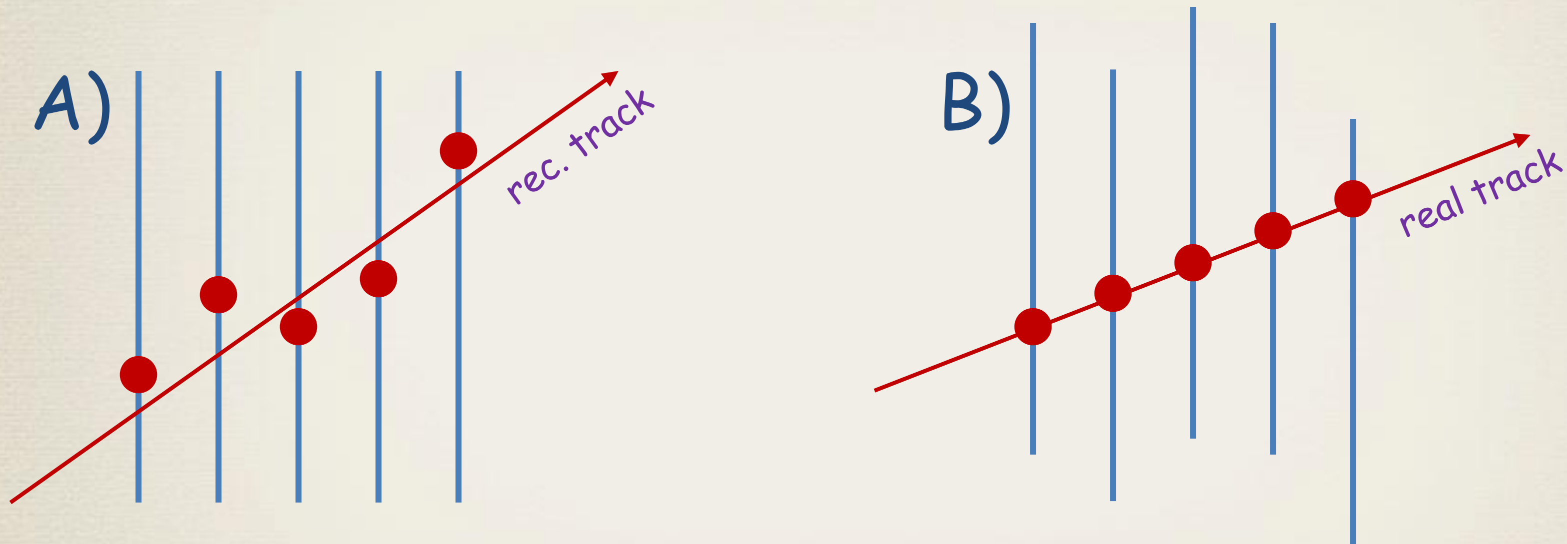




❖Only one hipothesis is correct!

Alignment – what is it all about?

- Parameters of charged particles reconstructed from space-point measurements:



assumed geometry
compromised resolution (fit quality),
biasd parameters

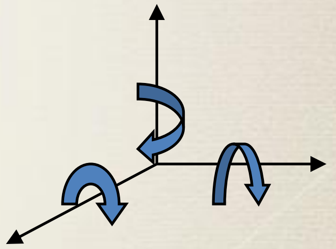
real geometry
optimal resolution,
unbiased parameters

- Alignment is supposed to bring us from A to B!

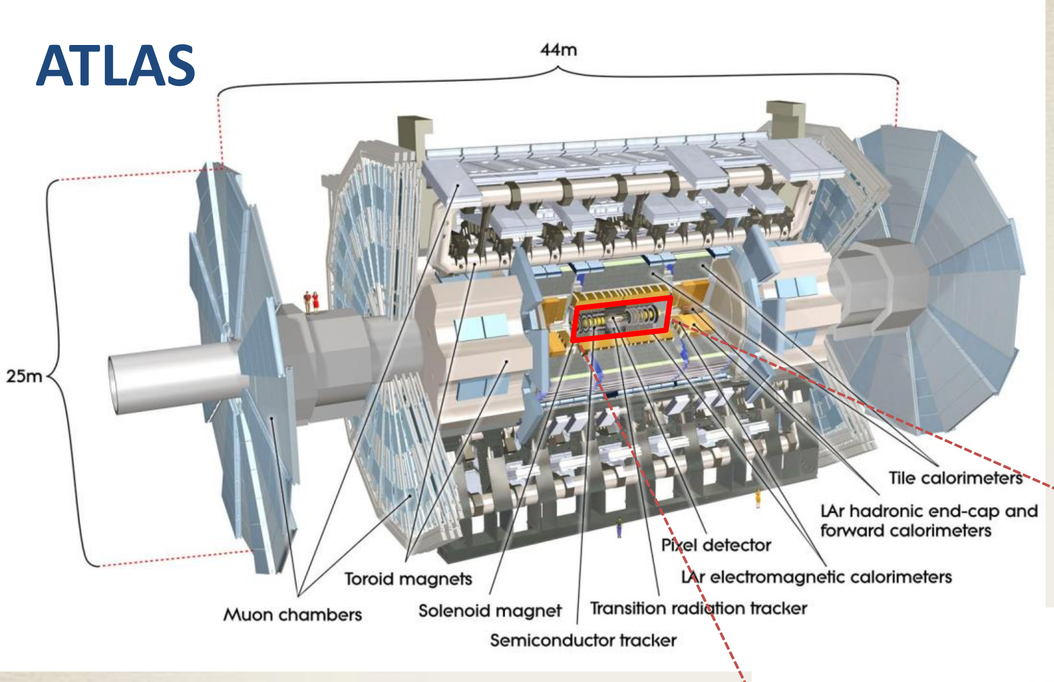
When did alignment became relevant?

1. Detector is composed of more than one sensitive element,
2. Intrinsic resolution is better than the assembly precisision and mechanical stability.

Ad1: The Inner Detector of ATLAS consists of ~360,000 elements.

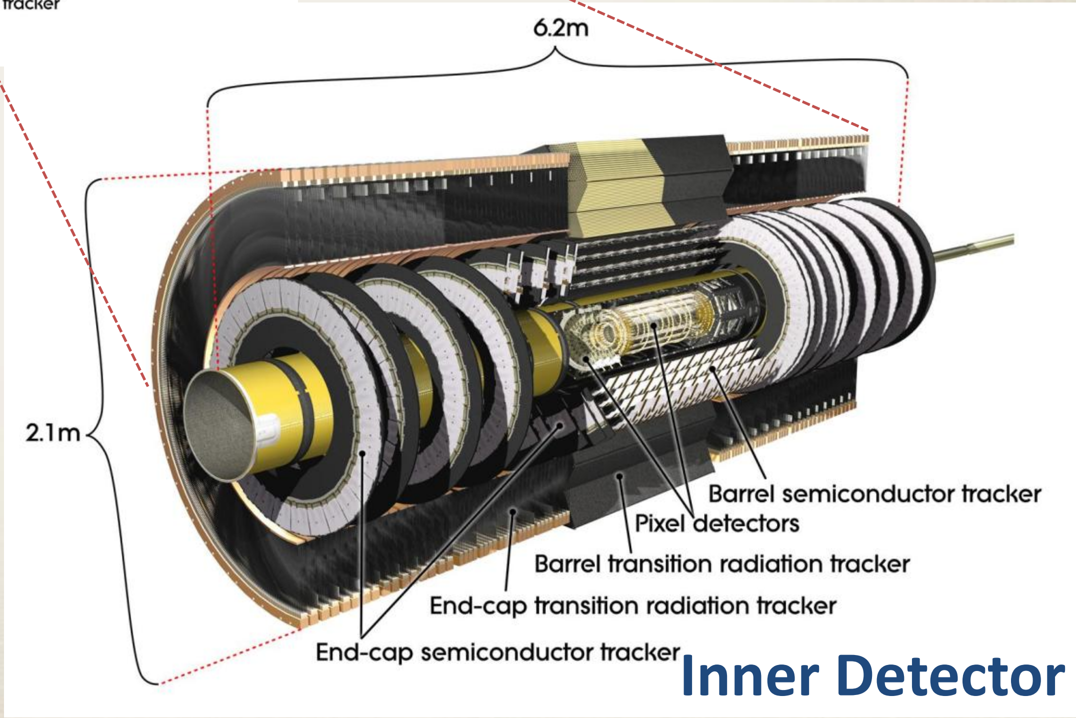


Ad2: Initial knowledge of their positions is one to two orders of magnitude worse than the resolution.

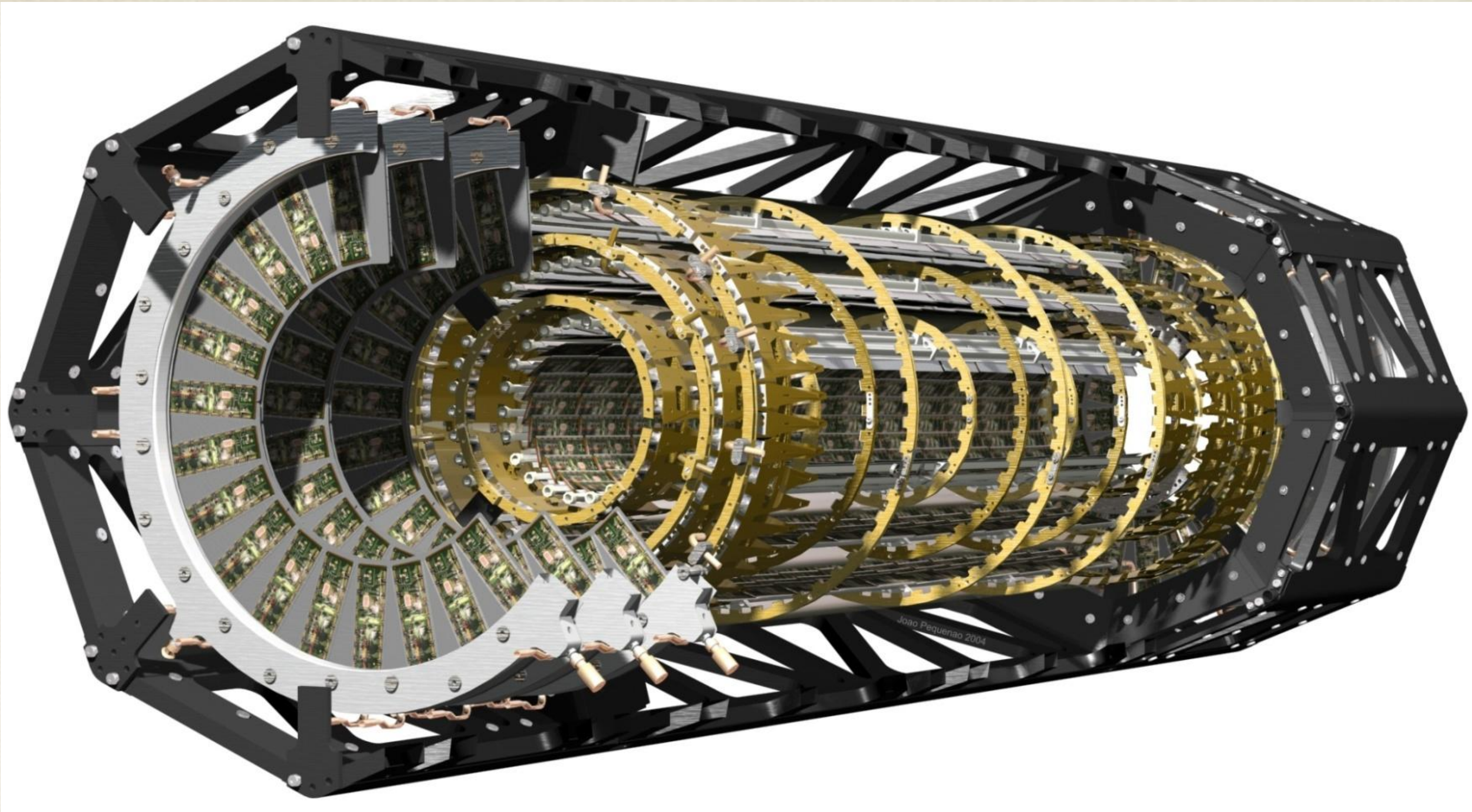


The tracking system of quite macroscopic size…

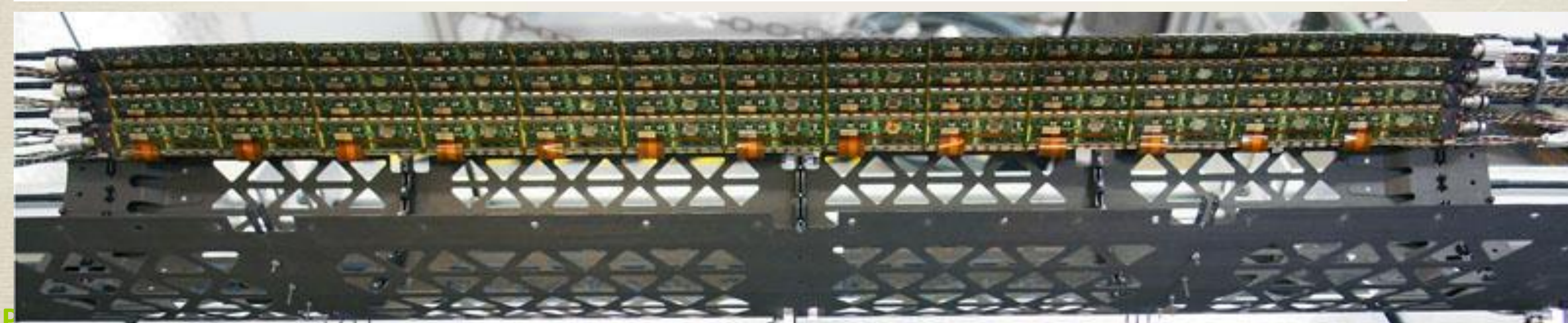
…in placed in the very heart of the detector.

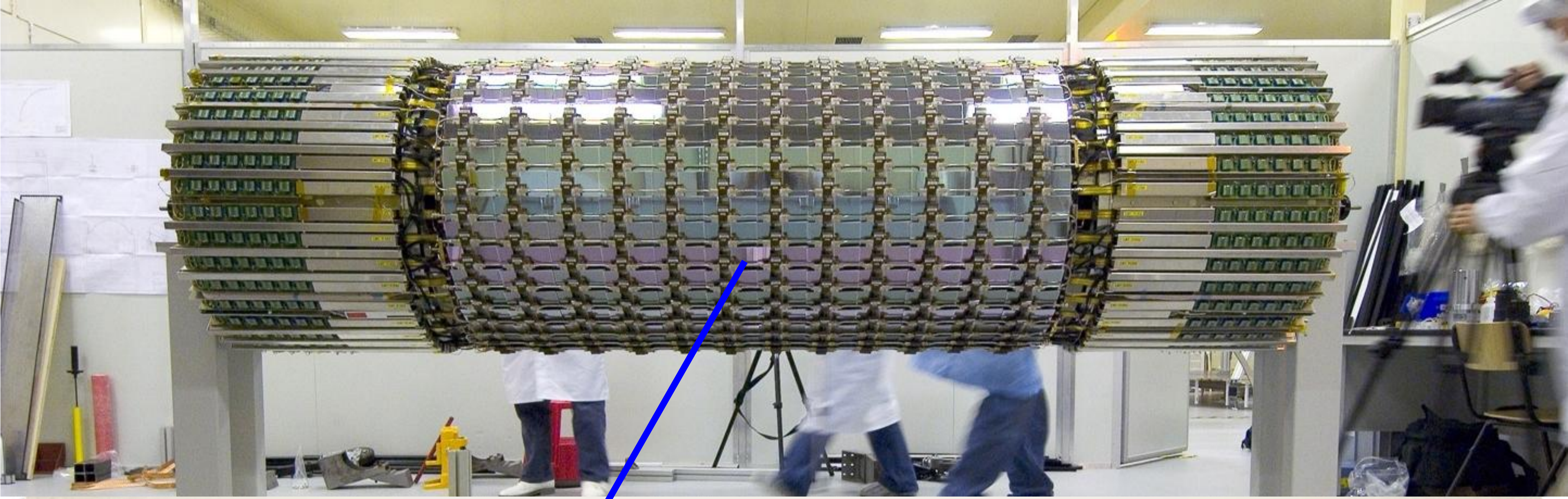


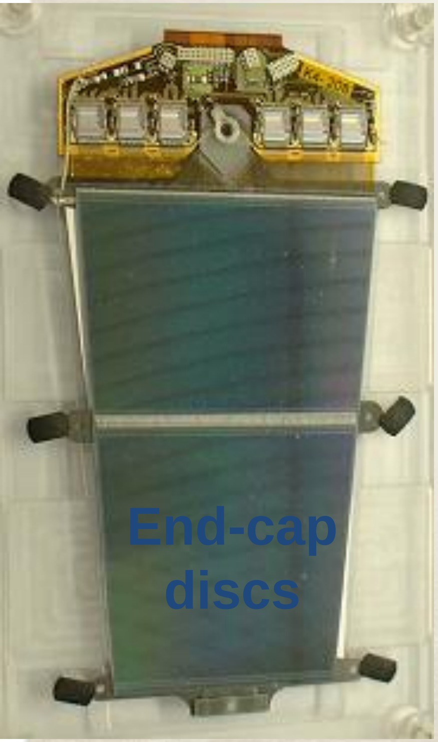
ATLAS Pixel detector

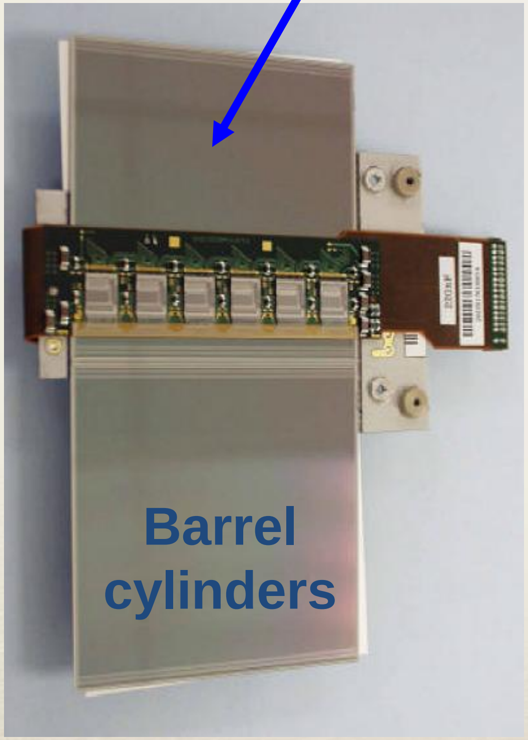


- 3 concentric cylinders
- 2x3 discs in the forward region





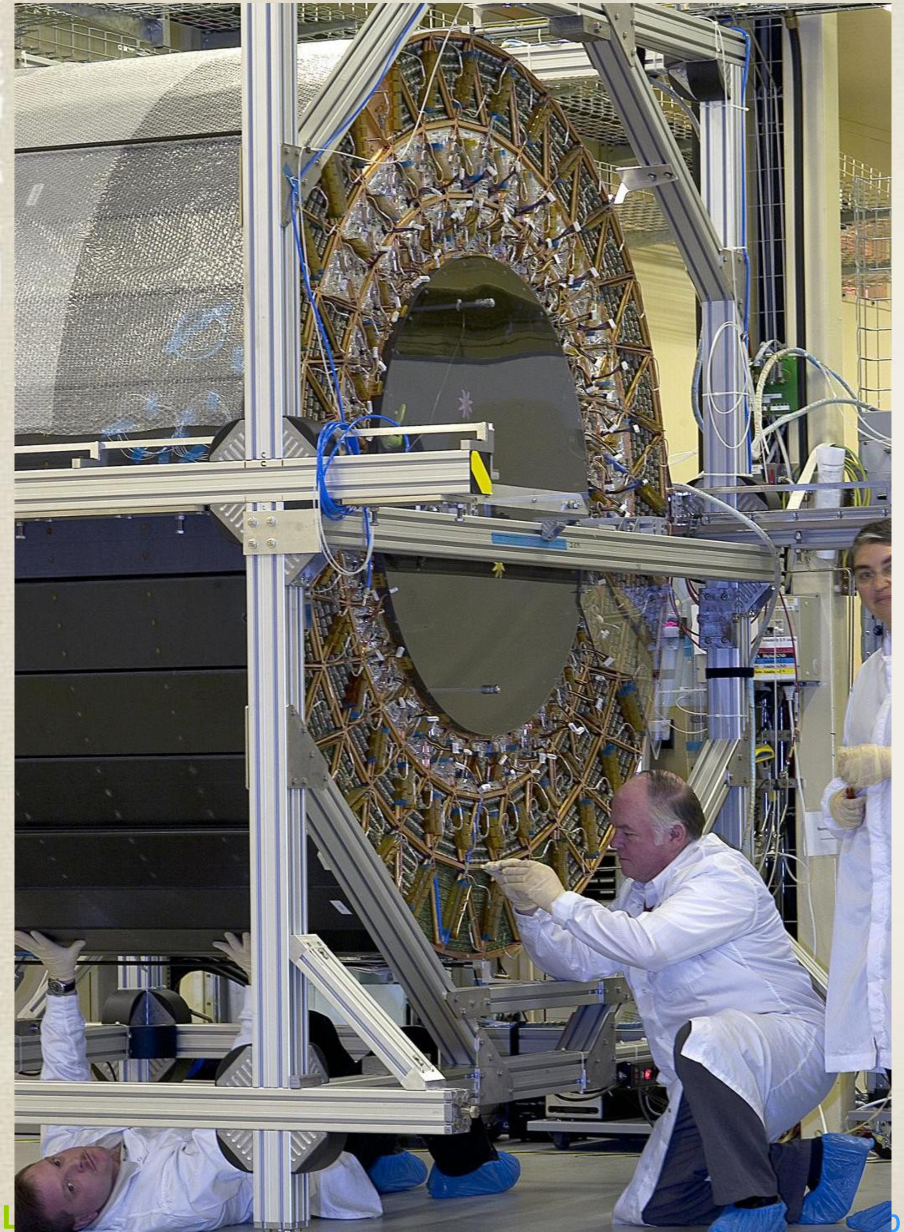




ATLAS Semiconductor Tracker (SCT)

- ❖ 4 concentric cylinders
- ❖ 2x9 discs in the forward region

ATLAS Transition Radiation Tracker (TRT)

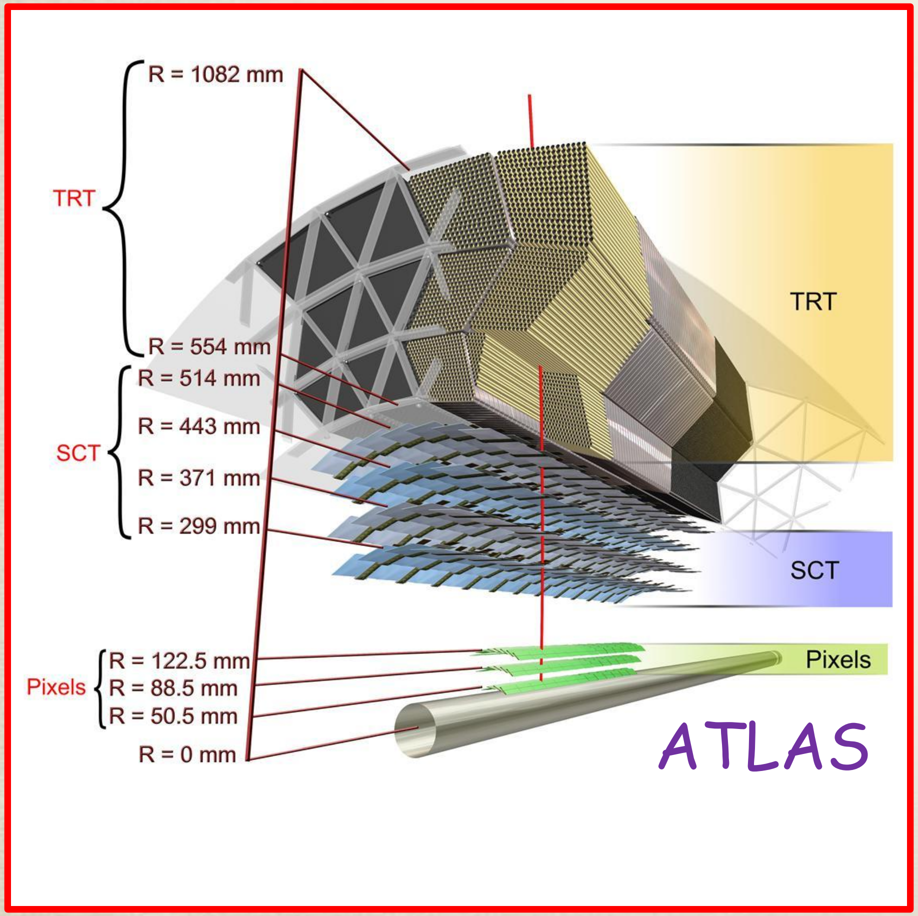


Straws:

- 350,000 proportional drift tubes, 4mm in diameter, arranged in
  - ❖ 96 barrel sectors
  - ❖ 2x20 end-cap wheels

ATLAS tracking system (ID)

silicon + gaseous devices



Pixels (Si pads):

- 1744 modules (10,464 par's)
- Pixel size: 50 μm × 400 μm
- Resolution : 10 μm × 115 μm

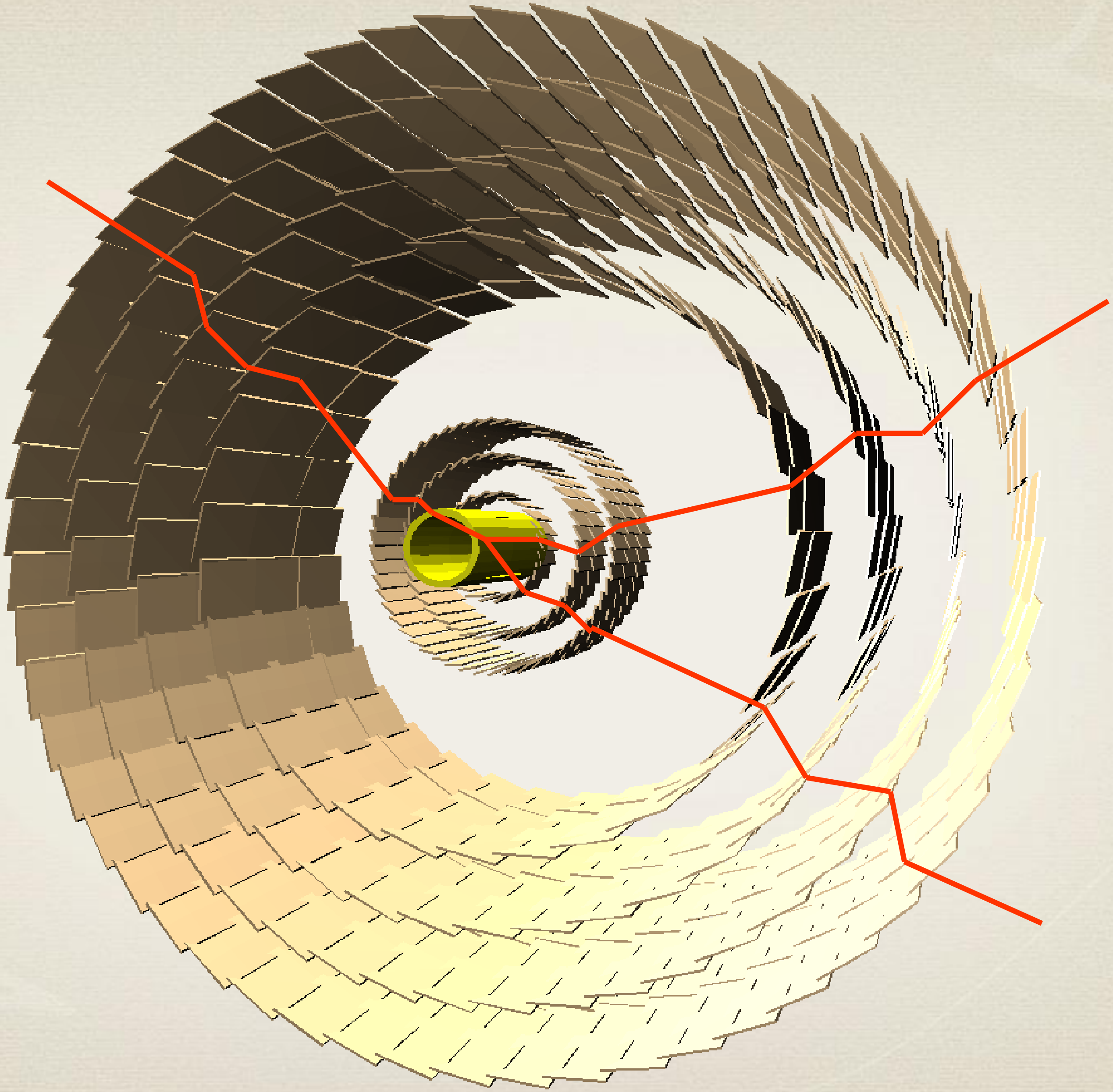
SCT (Si ministrip):

- 4088 modules (24,528 par's)
- Strip size: 80 μm × 12 cm
- Resolution: 17 μm × 580 μm

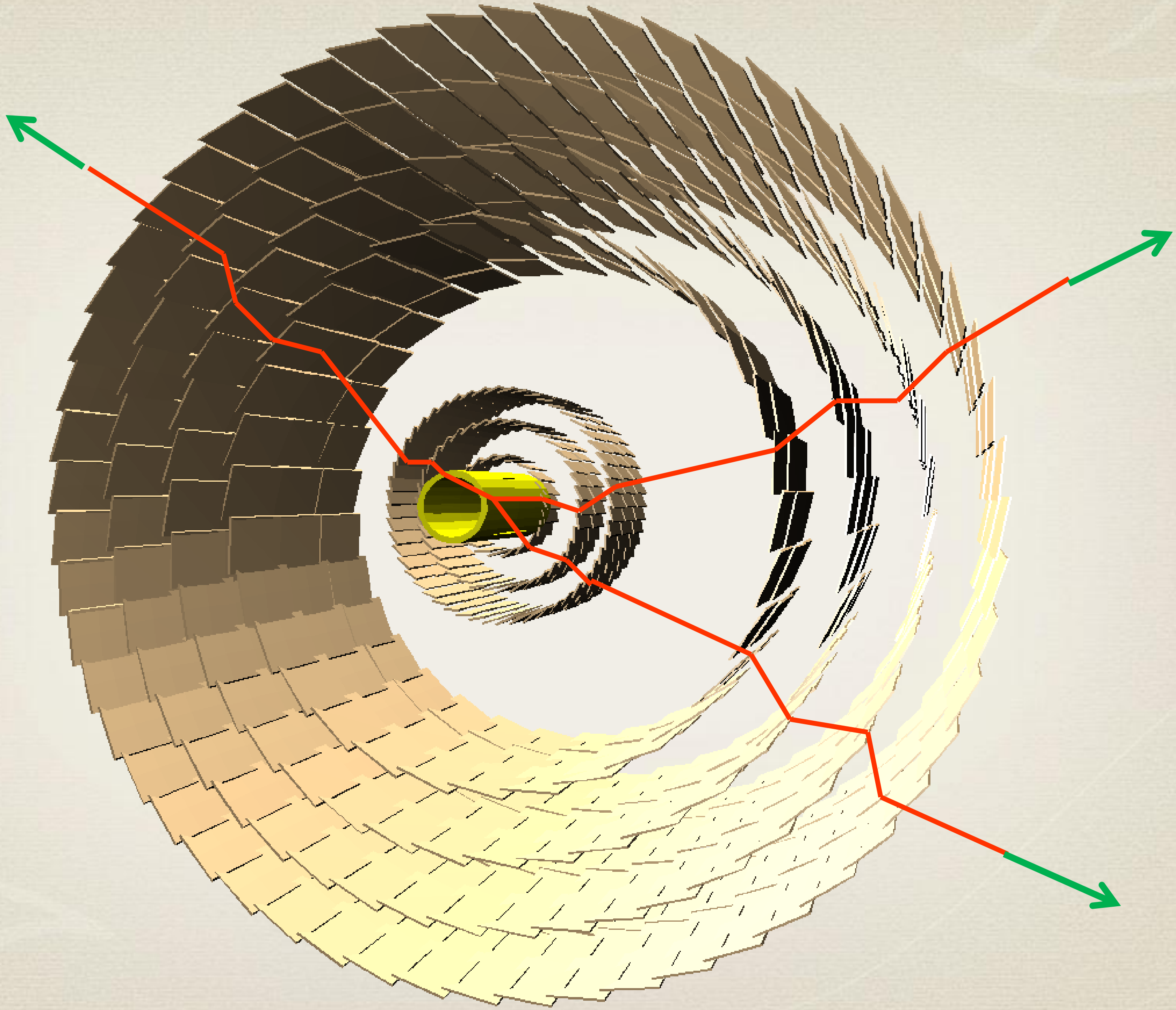
TRT (gas proportional):

- 350,048 straws (701,696 par's)
- Size: 4 mm × 71/39 cm
- Resolution: 130 μm

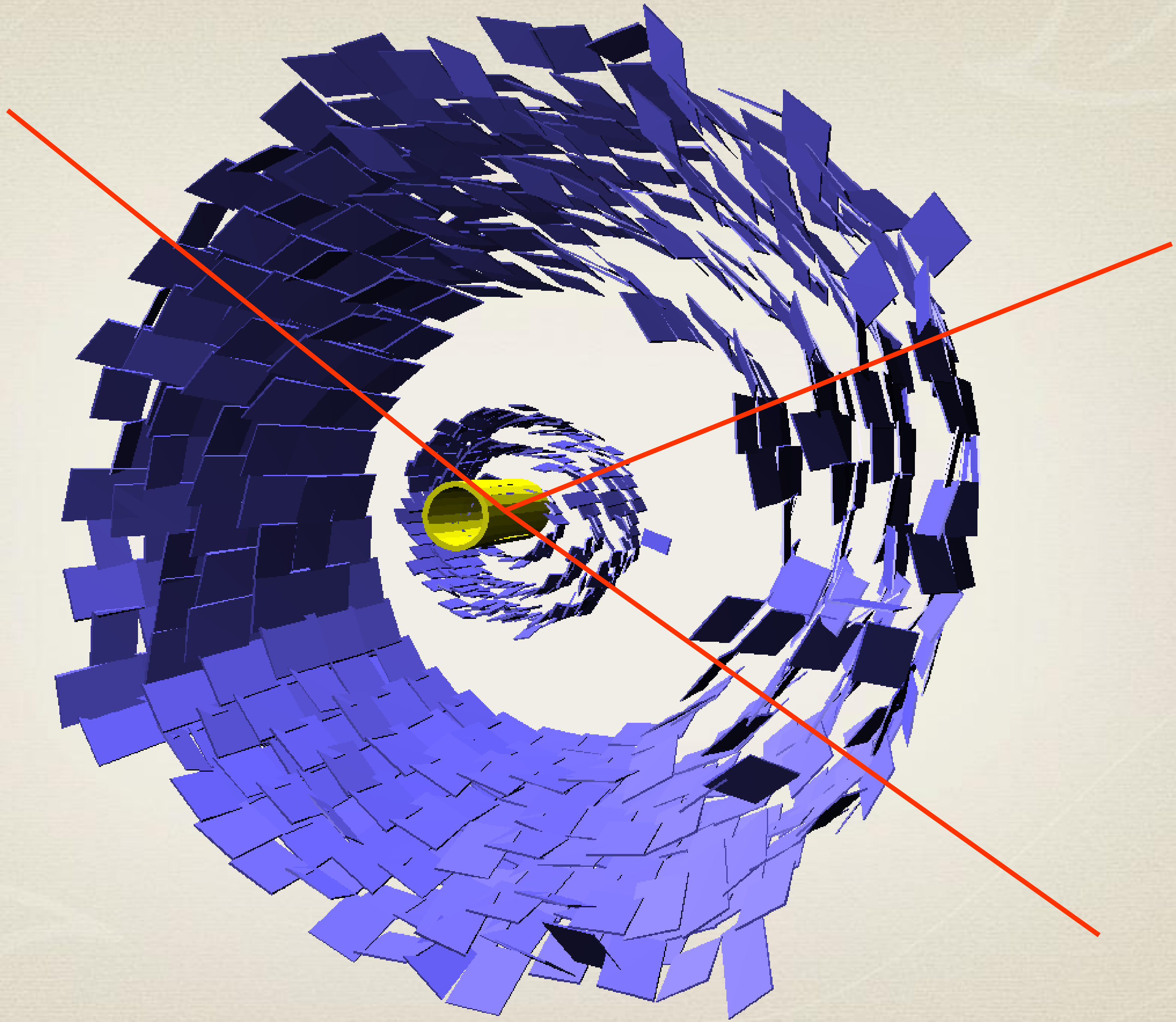
Track based alignment - the principle



Track based alignment - the principle



Track based alignment - the principle

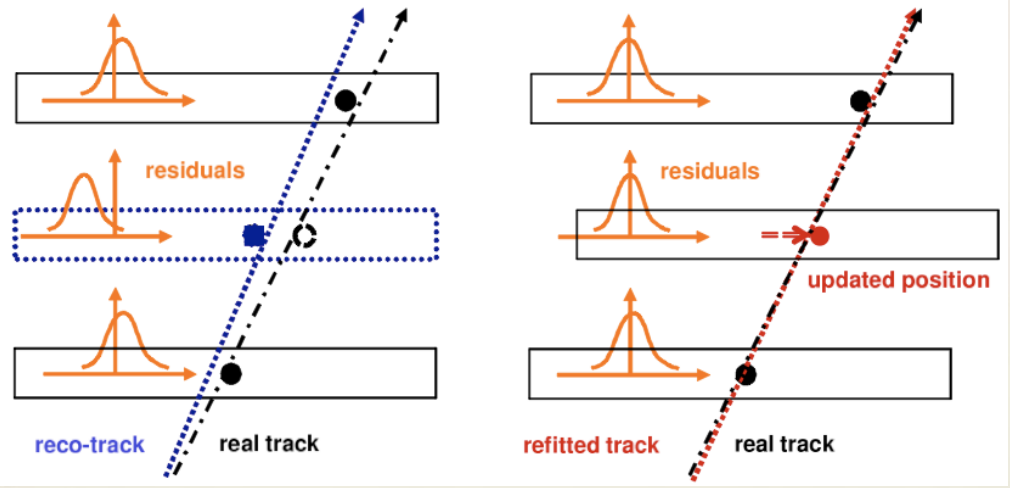


Track-based alignment a closer look

Track fit and alignment

How to get from fitted tracks to alignment corrections?Two basic philosophies:

1. Local: after fitting tacks attempt is made to match detector positions accordingly (inherently iterative)



1. Global: a simultaneous optimization (fit) of both track parameters and detector element positions is performed

Idea of the Global χ^2 approach

$$\mathbf{r}(\pi) = \mathbf{r_0} + \frac{\partial \mathbf{r}}{\partial \pi}(\pi - \pi_0) + \frac{\partial \mathbf{r}}{\partial a}(a - a_0) \qquad \frac{d\chi^2}{d\pi} = \frac{d\chi^2}{da} 0$$

simultaneous fit of all tracks and alignment parameters   N+n*k pars!

Impossible to solve !!! ☹

Way out!:

Fold the track fit in. Solve for the alignment only:

$$\mathbf{r}(\pi) = \mathbf{r_0} + \underbrace{\left(\frac{\partial \mathbf{r}}{\partial \pi} \frac{d\pi}{da} + \frac{\partial \mathbf{r}}{\partial a} \right)}_{\frac{d\mathbf{r}}{da}} (a - a_0)$$

$$\boxed{a - a_0 = \left(\sum_{\text{tracks}} \frac{d\mathbf{r}}{da}^T \mathbf{V}^{-1} \frac{d\mathbf{r}}{da} \right)^{-1} \sum_{\text{tracks}} \frac{d\mathbf{r}}{da}^T \mathbf{V}^{-1} \mathbf{r}_0}$$

„Locality ansatz" in the Global χ^2 approach

Having fitted the track, one satisfies:

$$\boxed{0 \equiv \left(\frac{\partial \mathbf{r}}{\partial \pi}^T \mathbf{V}^{-1} \frac{\partial \mathbf{r}}{\partial \pi} \right)^{-1} \frac{\partial \mathbf{r}}{\partial \pi}^T \mathbf{V}^{-1} \mathbf{r}_0} \qquad \frac{d\chi^2}{d\pi} = \frac{d\chi^2}{da} 0$$

Most importantly, residuals not explicitly dependent on alignment parameters drop out. Only „actual" residuals survive:

$$\boxed{a - a_0 = \left(\sum_{\text{tracks}} \frac{d\mathbf{r}}{da}^T \mathbf{V}^{-1} \frac{d\mathbf{r}}{da} \right)^{-1} \sum_{\text{tracks}} \frac{\partial \mathbf{r}}{\partial a}^T \mathbf{V}^{-1} \mathbf{r}_0}$$

Idea of the Global χ^2 approach

$$a - a_0 = \left(\sum_{\text{tracks}} \frac{d\mathbf{r}}{da}^T \mathbf{V}^{-1} \frac{d\mathbf{r}}{da} \right)^{-1} \sum_{\text{tracks}} \frac{d\mathbf{r}}{da}^T \mathbf{V}^{-1} \mathbf{r}_0$$

vector of size N

$$\begin{pmatrix} \delta a \end{pmatrix} = \begin{bmatrix} \mathbf{M} \end{bmatrix}^{-1} \begin{pmatrix} \mathbf{V} \end{pmatrix}$$

vector of size N

NxN
matrix

N = number of DoF's (align pars.)

Idea of the Local χ^2 approach

$$\mathbf{r}(\pi) = \mathbf{r_0} + \cancel{\frac{\partial \mathbf{r}}{\partial \pi}(\pi - \pi_0)} + \frac{\partial \mathbf{r}}{\partial a}(a - a_0) \qquad \frac{d\chi^2}{da} 0$$

Fit of alignment parameters ignoring the correlations via tracks. Numerically a lot easier. Problem breaks down to local (n=6) equations . Requires multiple iterations over the full reconstruction !

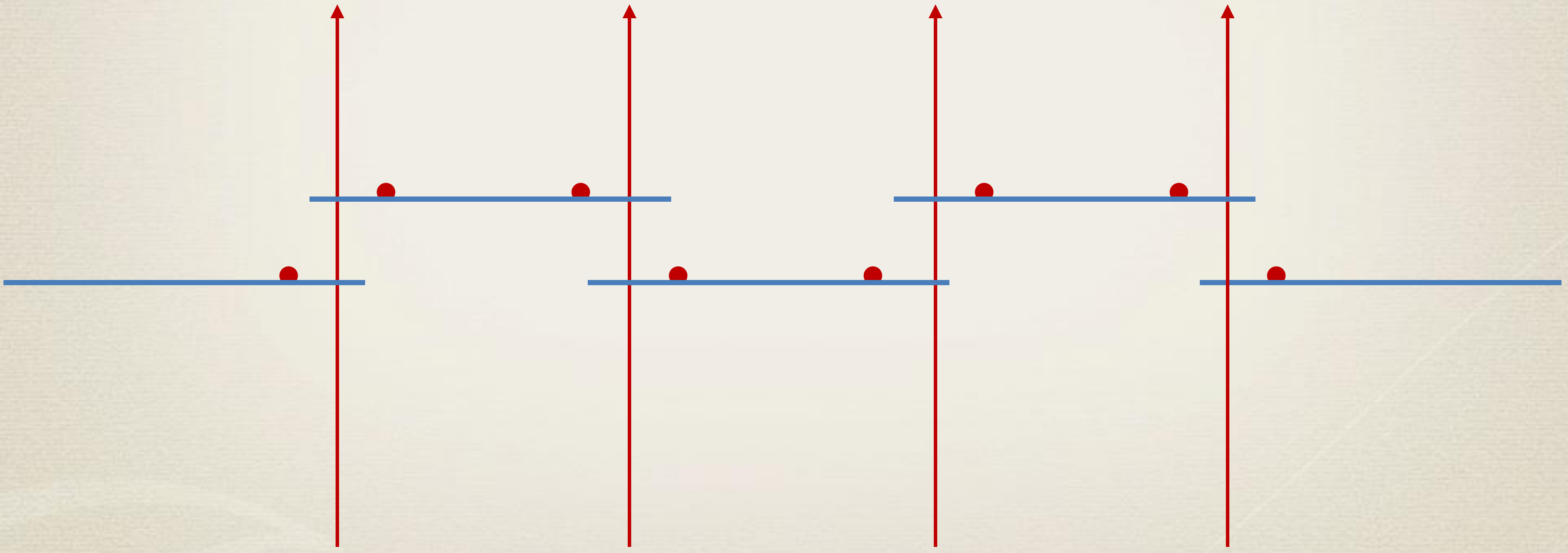
$$\mathbf{r}(\pi) = \mathbf{r_0} + \left(\cancel{\frac{\partial \mathbf{r}}{\partial \pi} \frac{d\pi}{da}} + \frac{\partial \mathbf{r}}{\partial a} \right)(a - a_0)$$

$$\boxed{a - a_0 = \left(\sum_{\text{tracks}} \frac{\partial \mathbf{r}}{\partial a}^T \mathbf{V}^{-1} \frac{\partial \mathbf{r}}{\partial a} \right)^{-1} \sum_{\text{tracks}} \frac{\partial \mathbf{r}}{\partial a}^T \mathbf{V}^{-1} \mathbf{r}_0}$$

Global vs local approach
(a simple 1D cartoon)

Example: uniform expansion

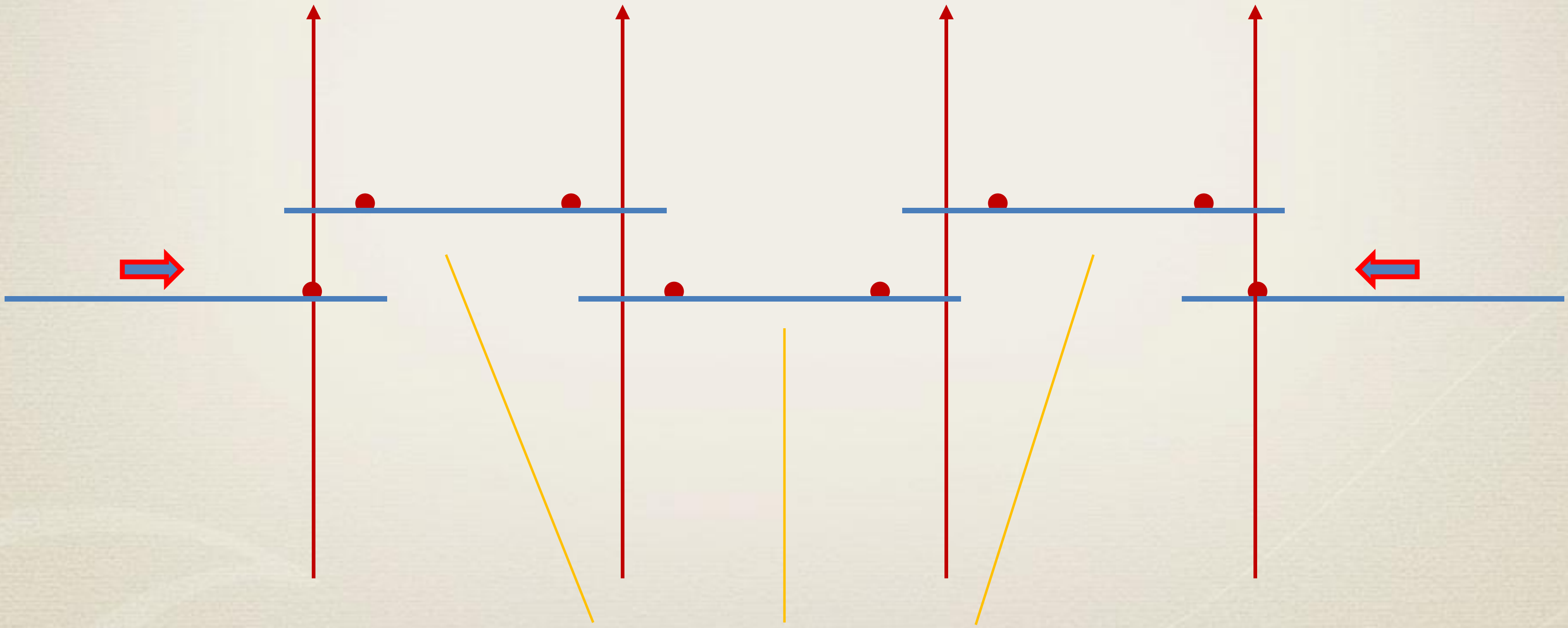
Let's try applying the two alignment philosophies…



Global vs local approach
(a simple 1D cartoon)

Local approach (tracks are frozen within one alignment pass)

Iteration 1:

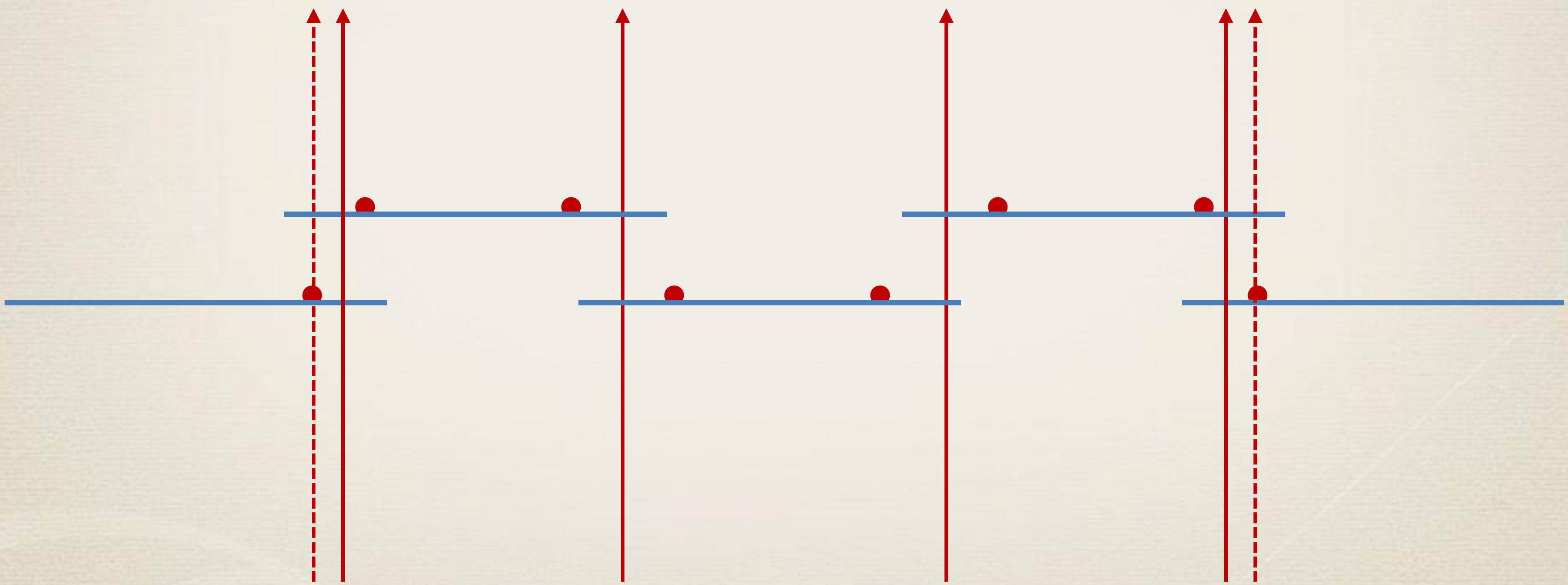


No net movement!

Global vs local approach
(a simple 1D cartoon)

Local approach (tracks are frozen within one alignment pass)

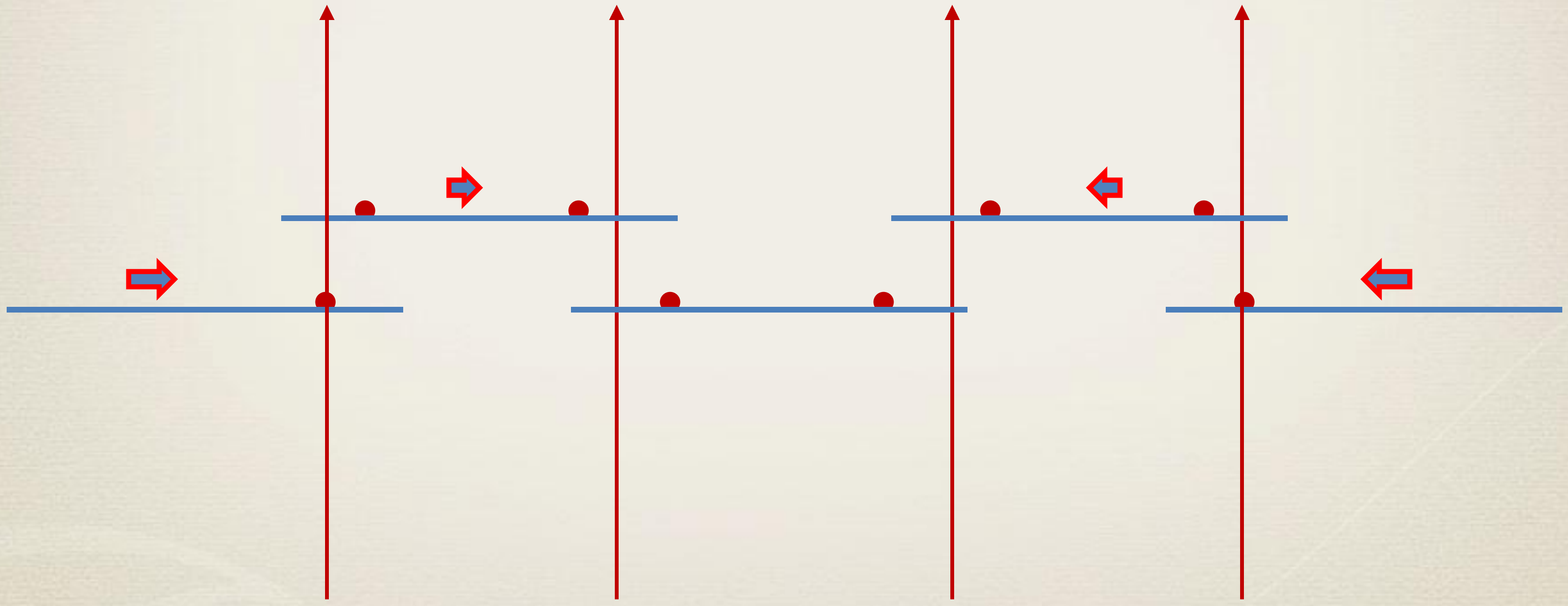
Iteration 2:



Global vs local approach
(a simple 1D cartoon)

Local approach (tracks are frozen within one alignment pass)

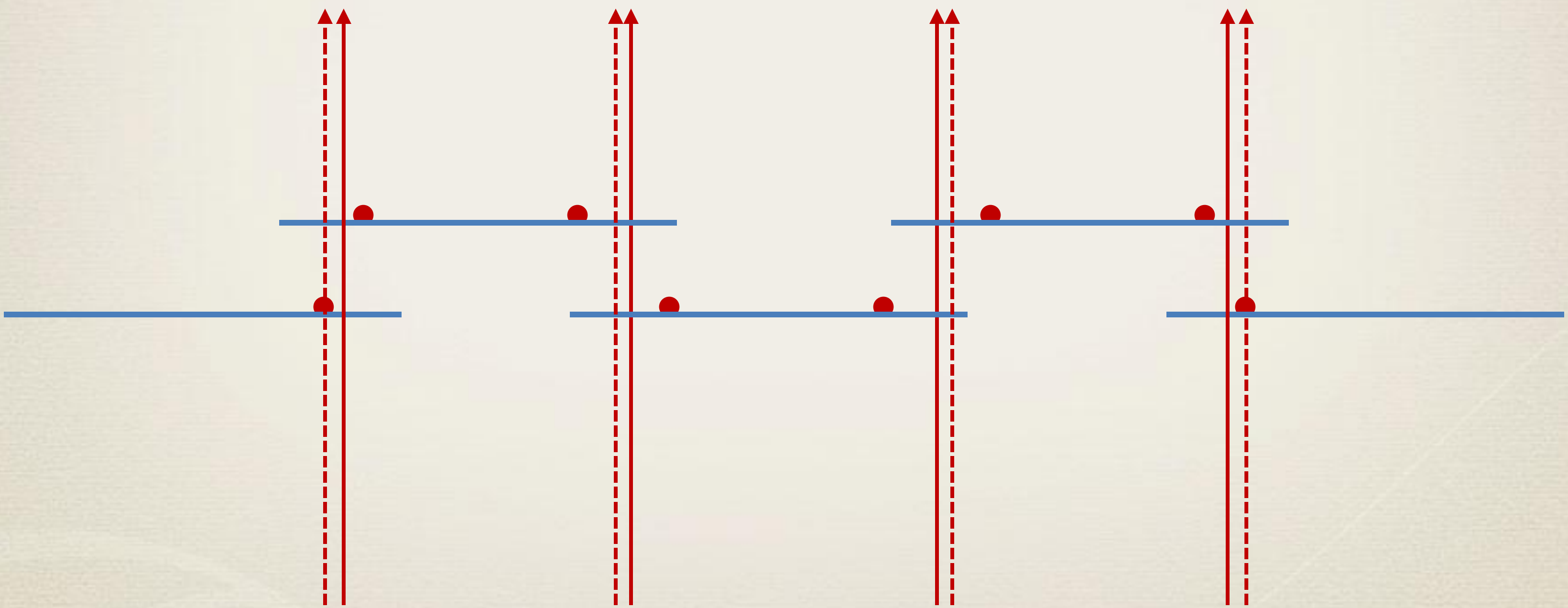
Iteration 2:



Global vs local approach
(a simple 1D cartoon)

Local approach (tracks are frozen within one alignment pass)

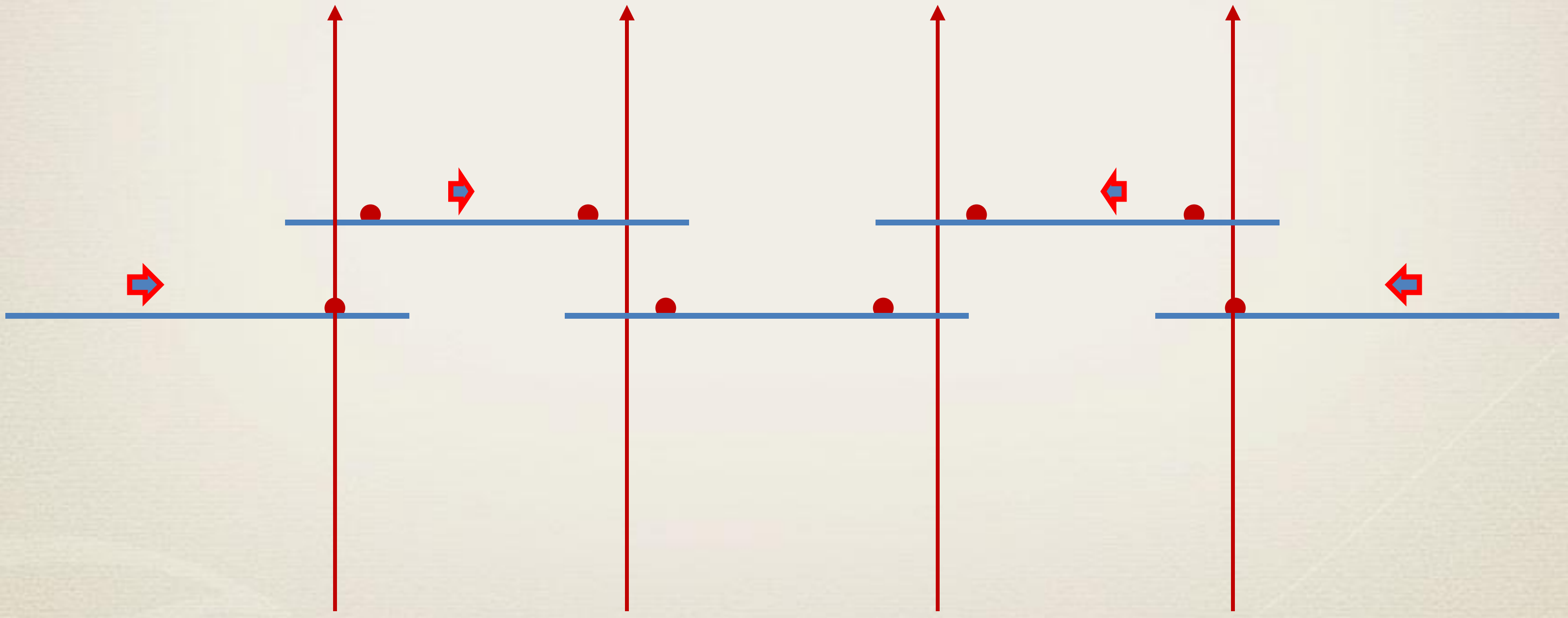
Iteration 3:



Global vs local approach
(a simple 1D cartoon)

Local approach (tracks are frozen within one alignment pass)

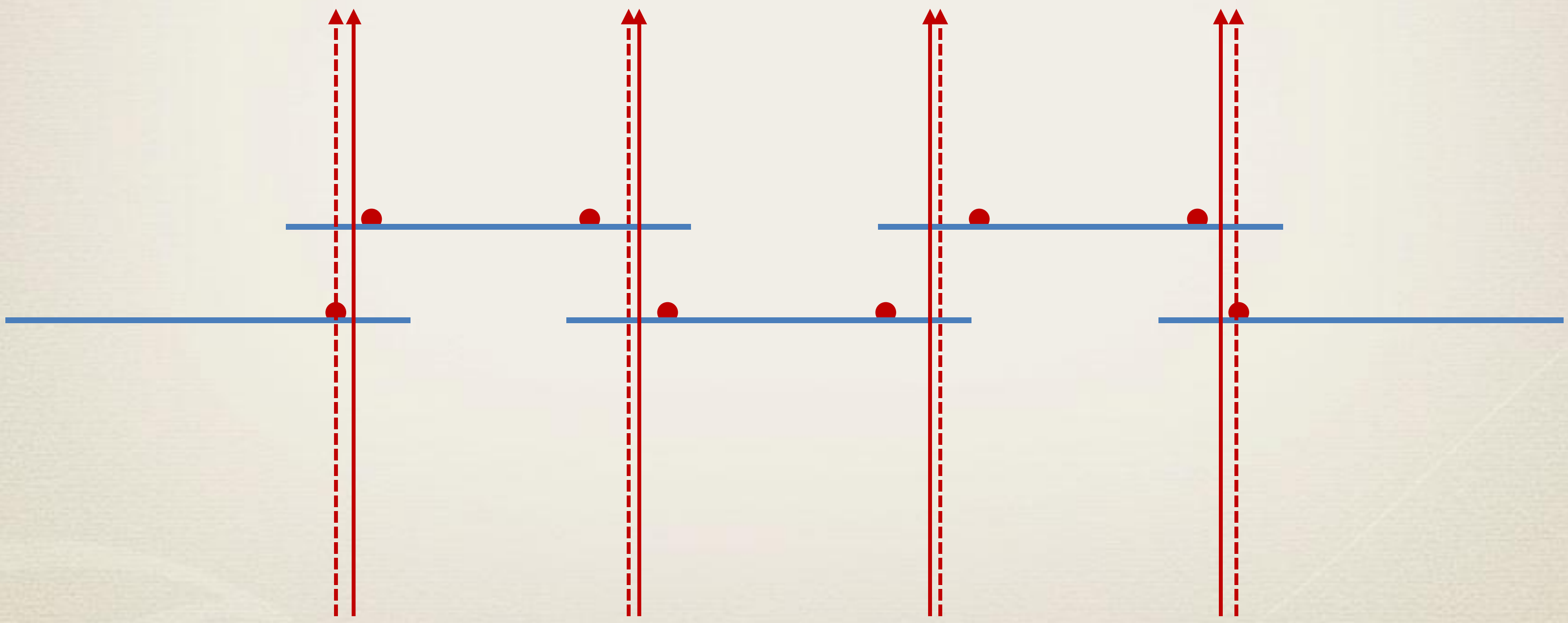
Iteration 3:



Global vs local approach
(a simple 1D cartoon)

Local approach (tracks are frozen within one alignment pass)

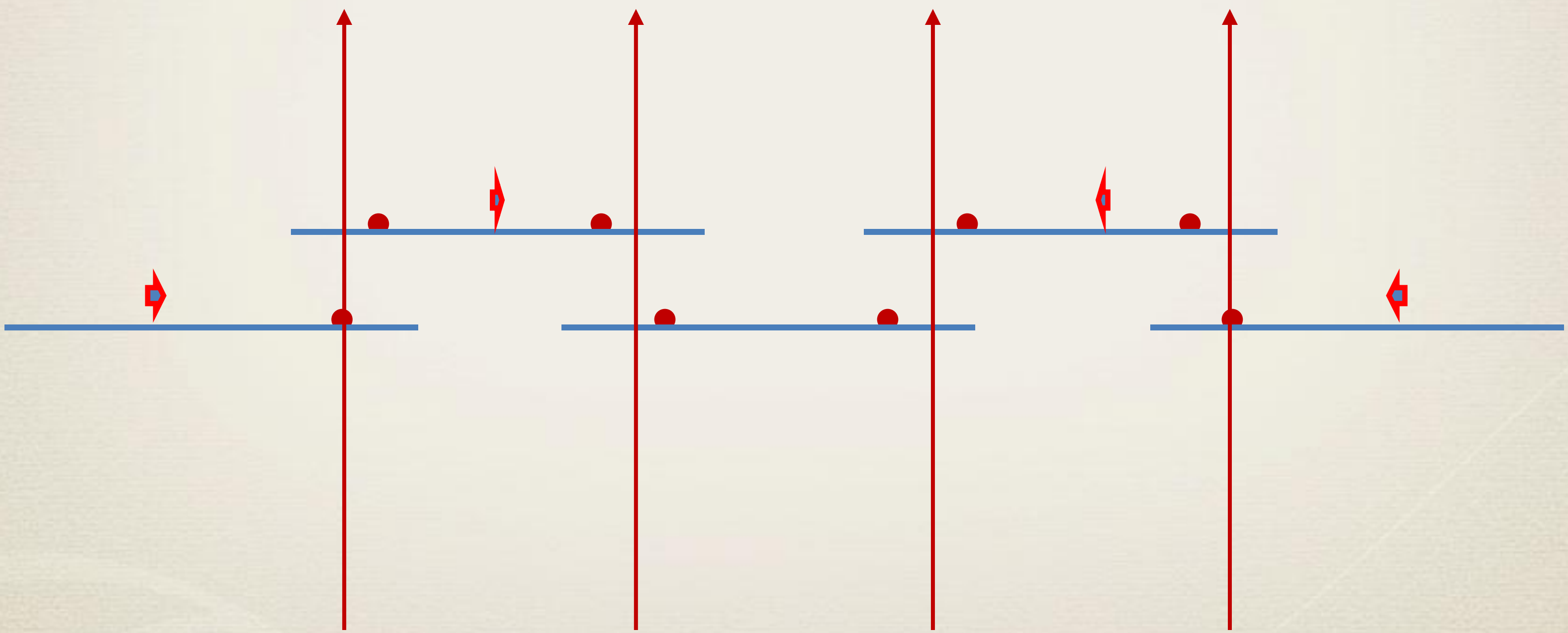
Iteration 4:



Global vs local approach
(a simple 1D cartoon)

Local approach (tracks are frozen within one alignment pass)

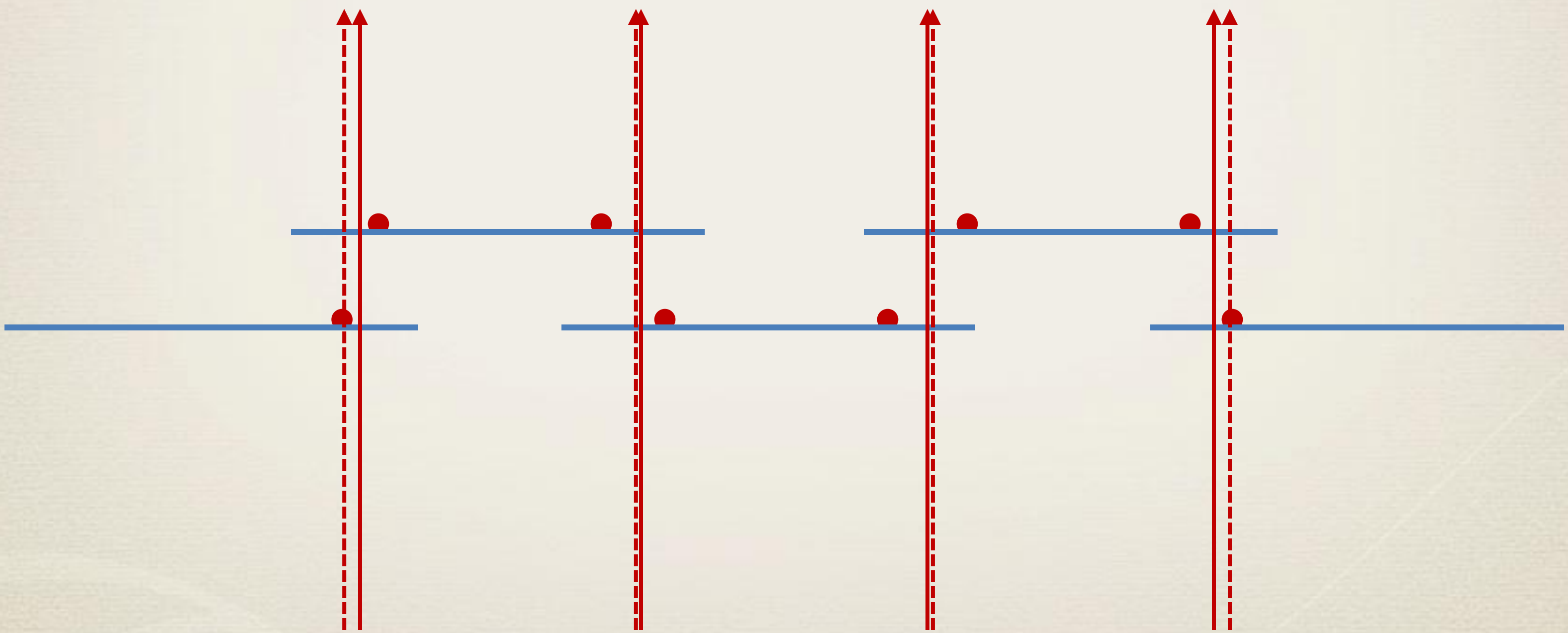
Iteration 4:



Global vs local approach
(a simple 1D cartoon)

Local approach (tracks are frozen within one alignment pass)

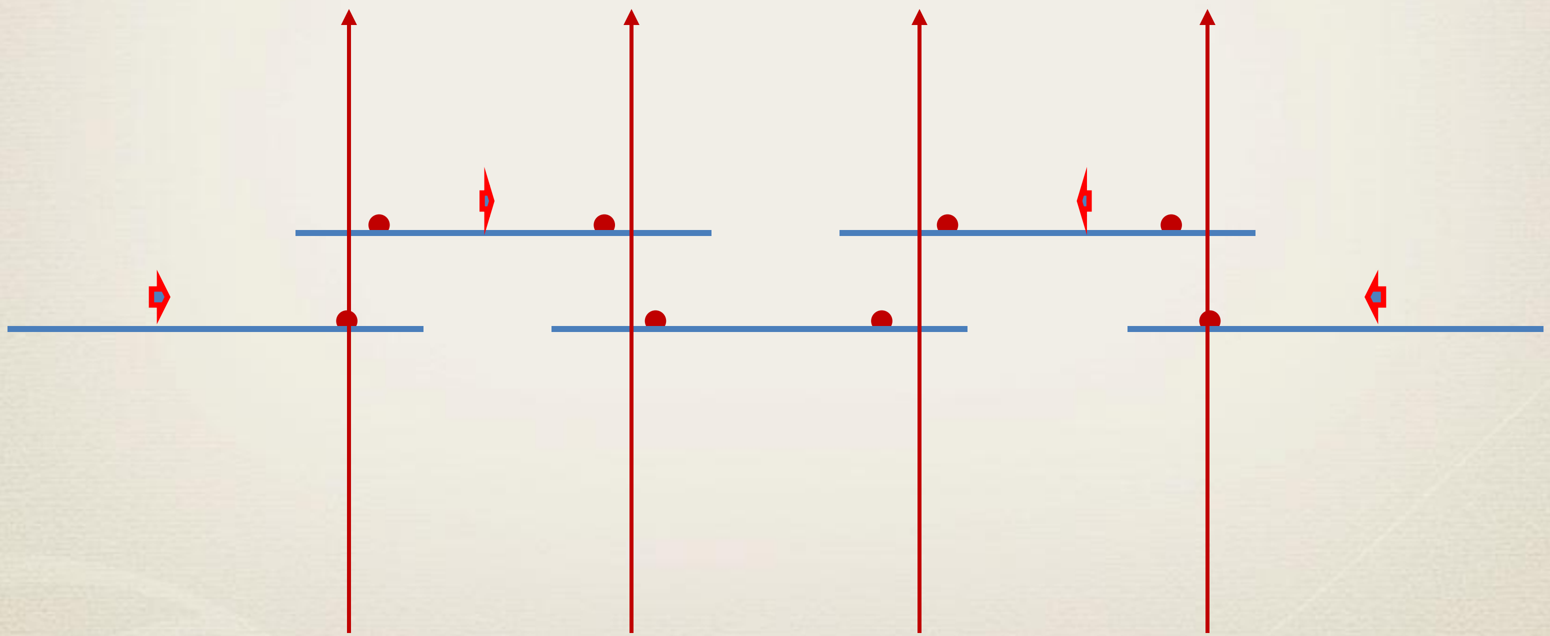
Iteration 5:



Global vs local approach
(a simple 1D cartoon)

Local approach (tracks are frozen within one alignment pass)

Iteration 5:

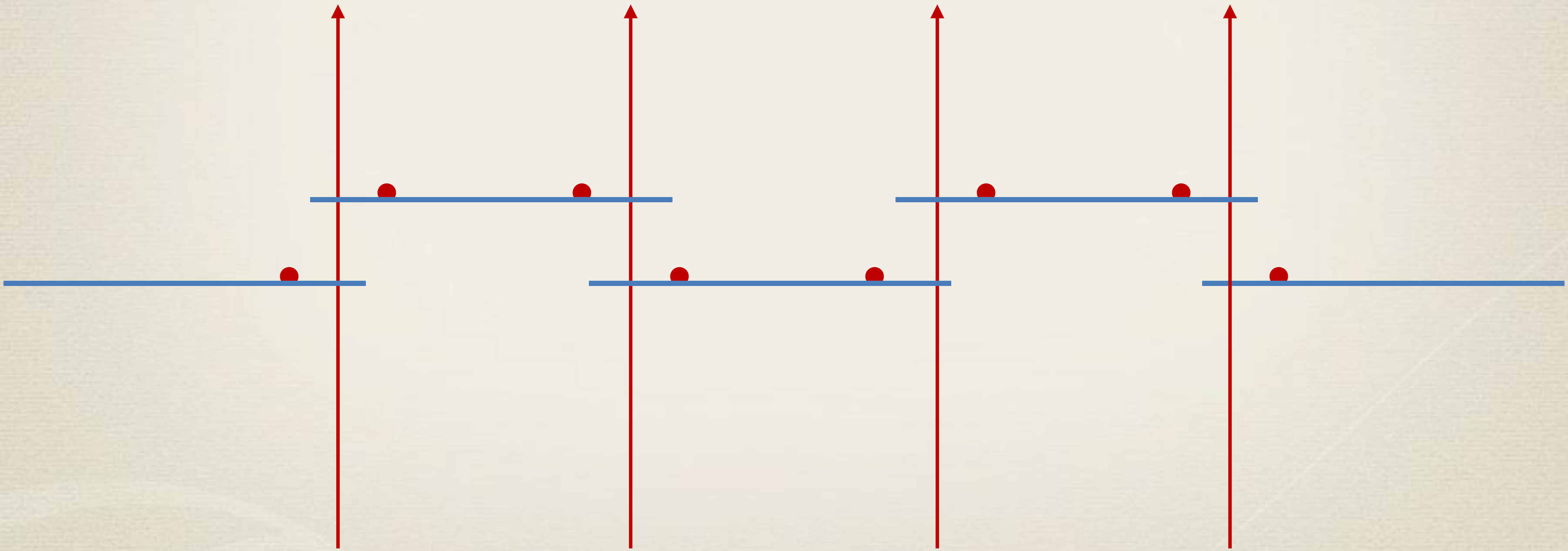


The process is converging but takes ∞ number of iterations!

Global vs local approach
(a simple 1D cartoon)

Example: uniform expansion

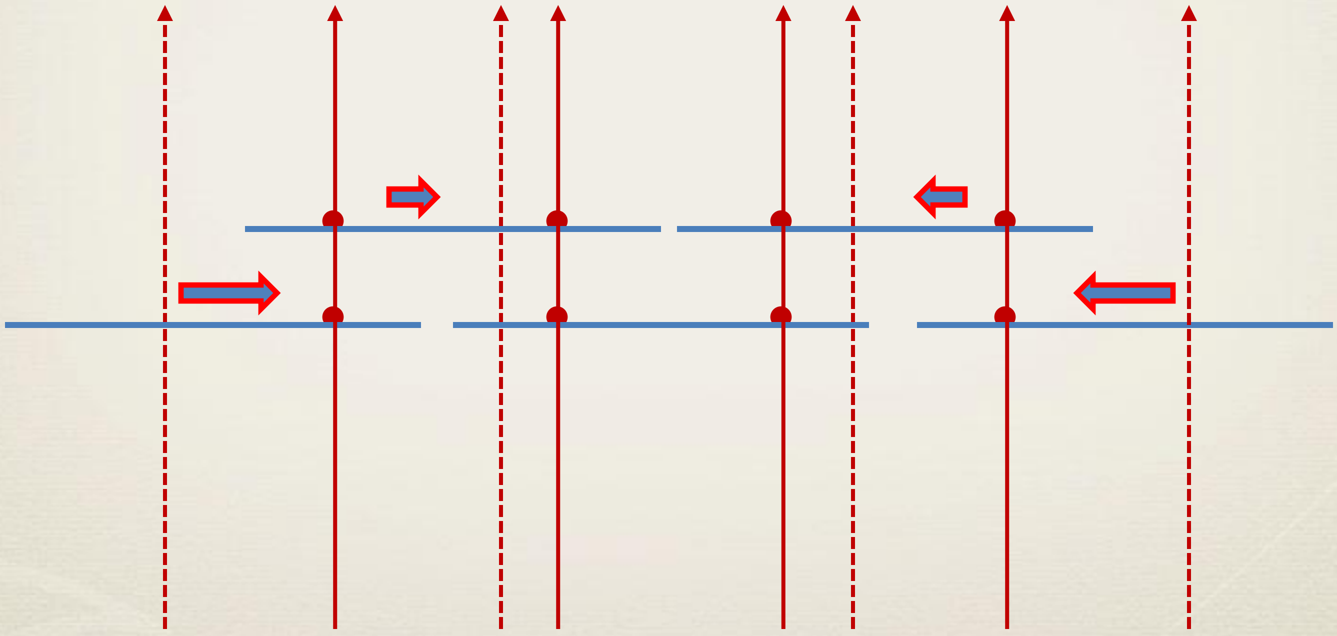
Now let's see what the global approach does…



Global vs local approach
(a simple 1D cartoon)

Global approach (tracks allowed to refit within one alignment pass – all correlations retained!)

Iteration 1:



Global vs local approach
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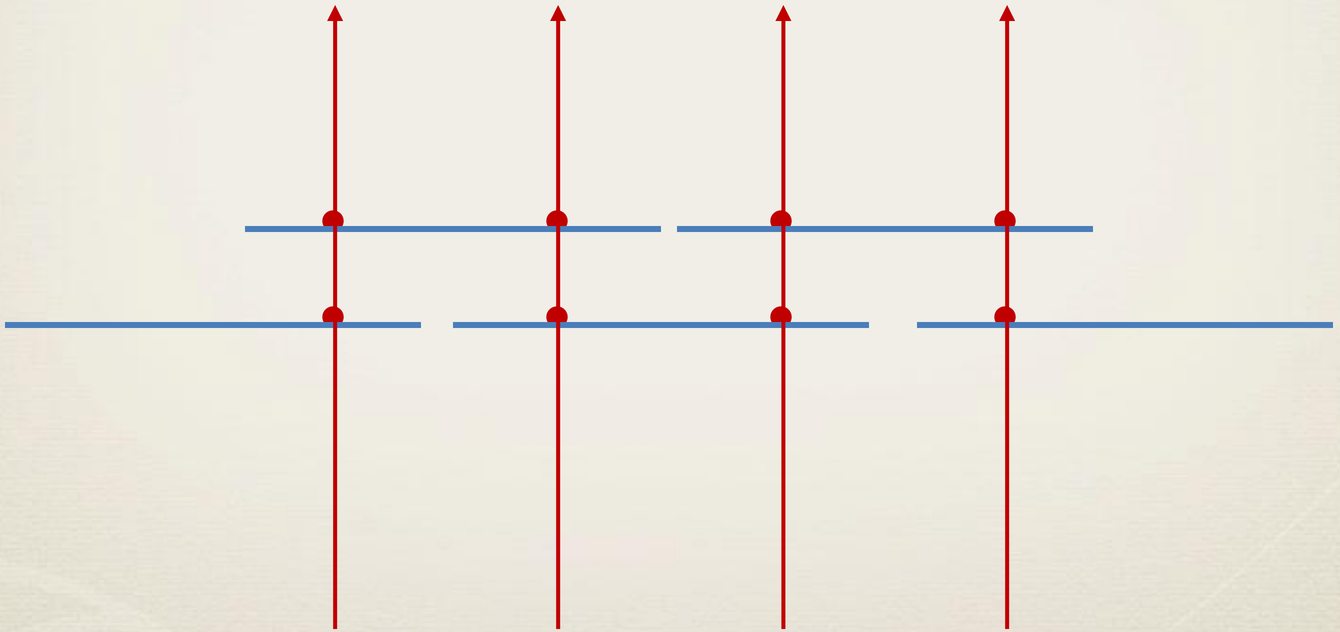
Global approach (tracks allowed to refit within one alignment pass – all correlations retained!)

Iteration 1:



Convrgence reached in a single iteration!

Things to remember:

- Local and Global approaches should asymptotically give the same result.

- Local methods are not numerically demanding. It may take them a lot of iterations to converge, though.

- Larger the system is more beneficial it is to use the global approach (potentially slower convergence of local methods for large systems) but become numerically challenging.

Where is the difficulty?

Two very different aspects of the same alignment task:

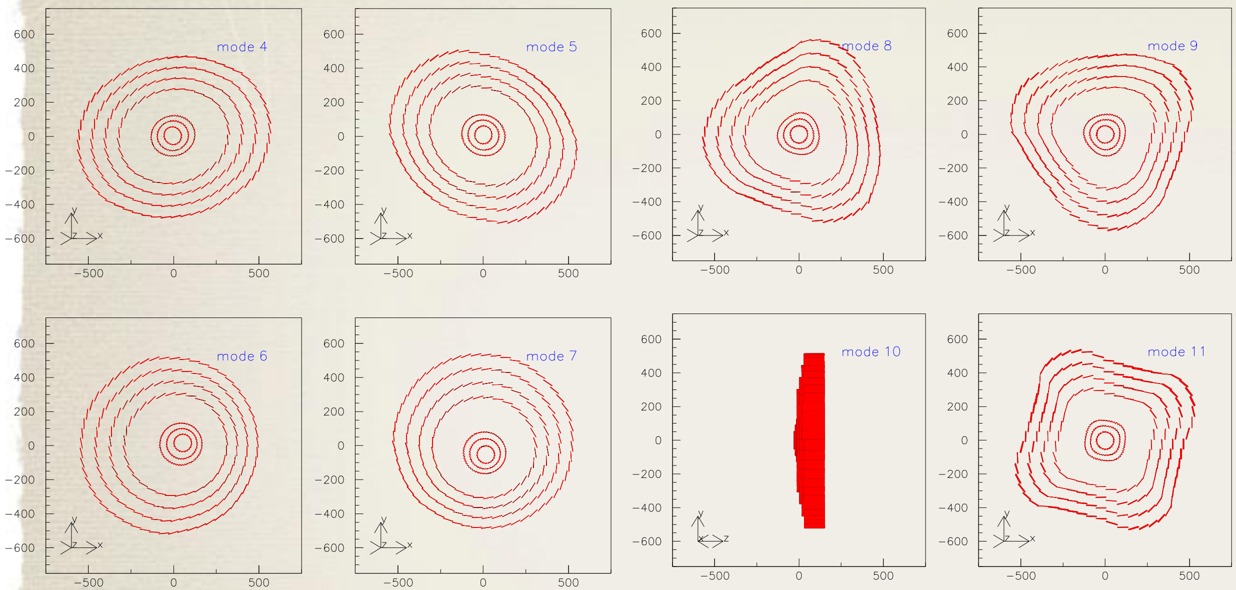
Efficiency of track reconstruction
Good track fit

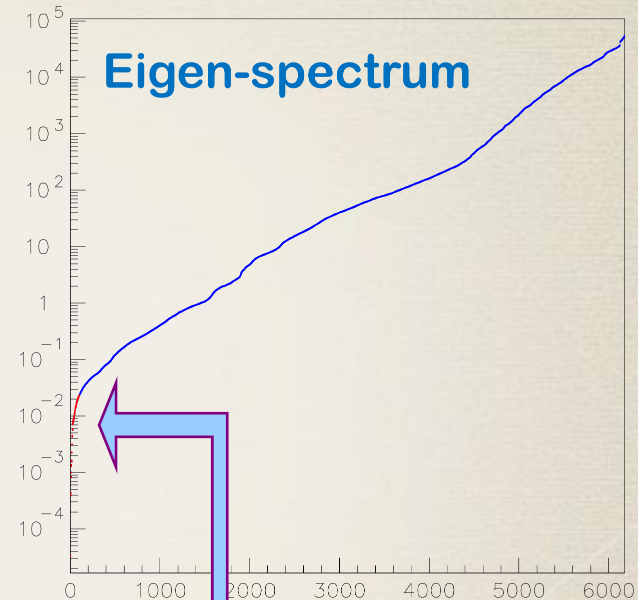
"easy"

Track reconstruction free from systematics
Fine track parameter resolution
Quality vertexing

highly nontrivial !!!

Matrix M generally singular (at least ill-conditioned). Needs special treatment. Formally, the most elegant – diagonalization.



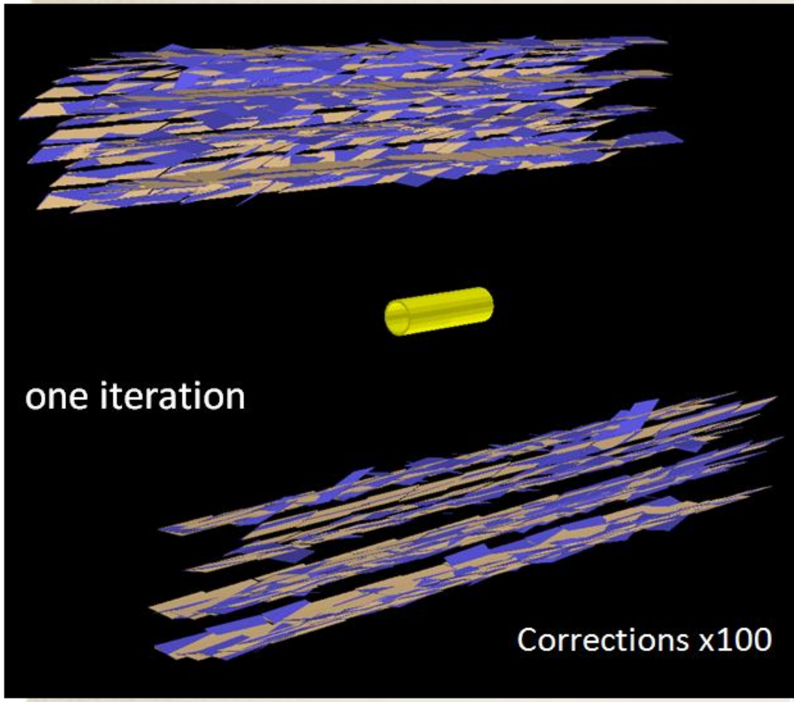


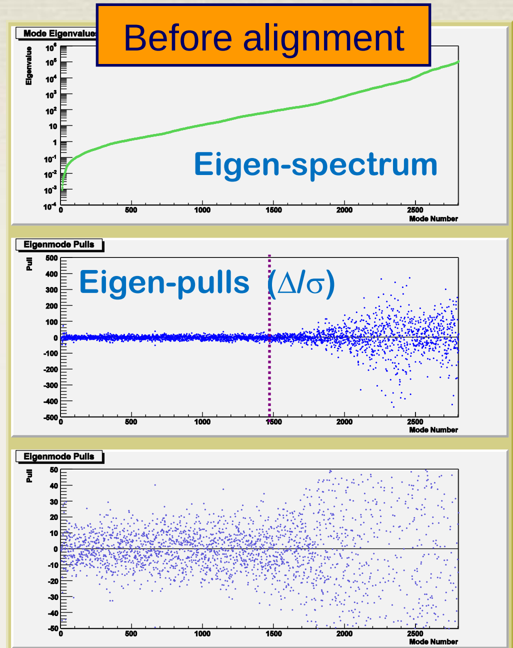
- The above "weak modes" contribute to the lowest part of the eigen-spectrum. Consequently they dominate the overall error on the alignment parameters.
- More importantly, these deformations may directly lead to biases on physics (systematic effects).

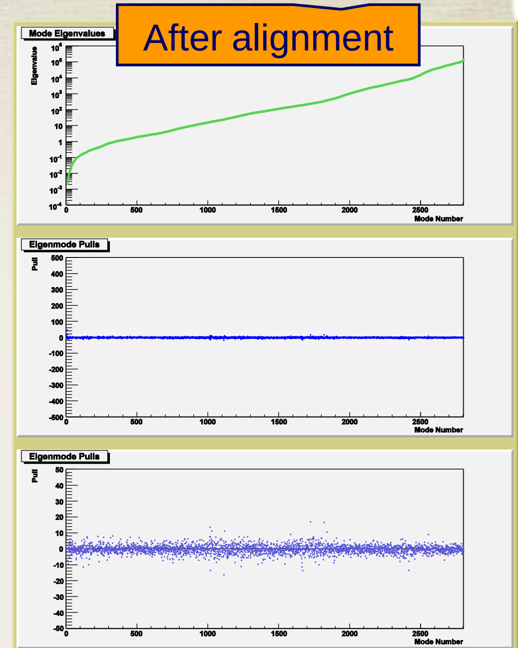
Example: cosmic alignment with Global χ^2

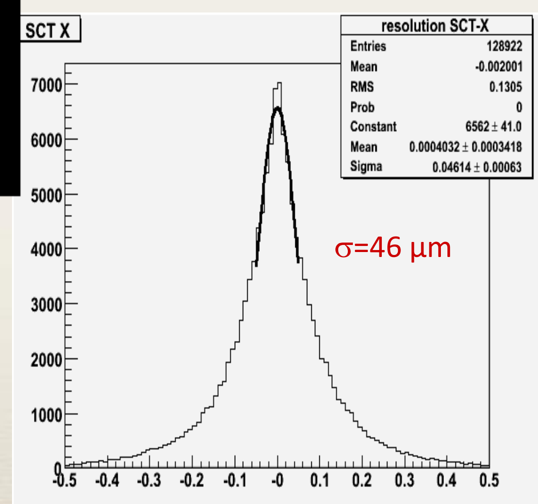
2808 DoF's

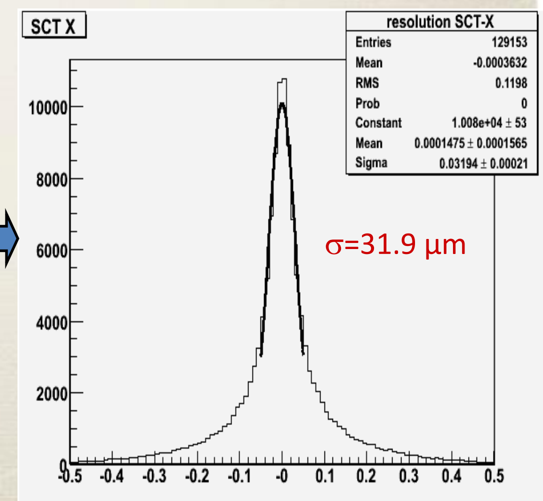
Corrections due to modes >1500





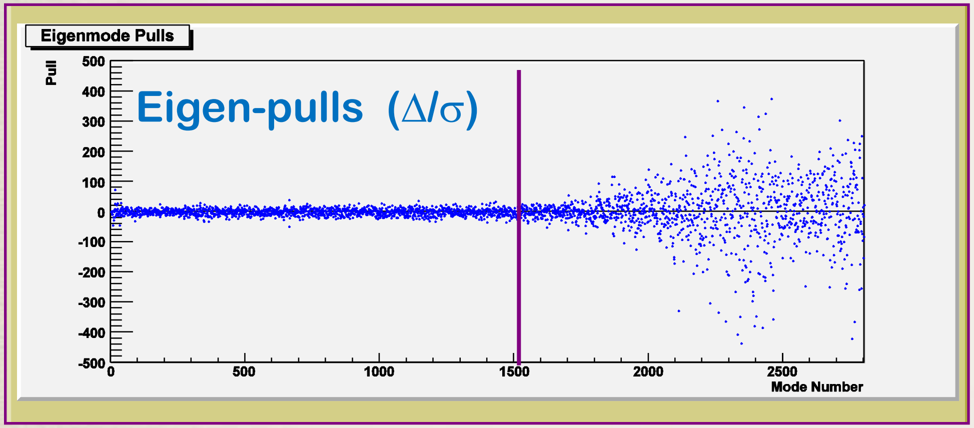




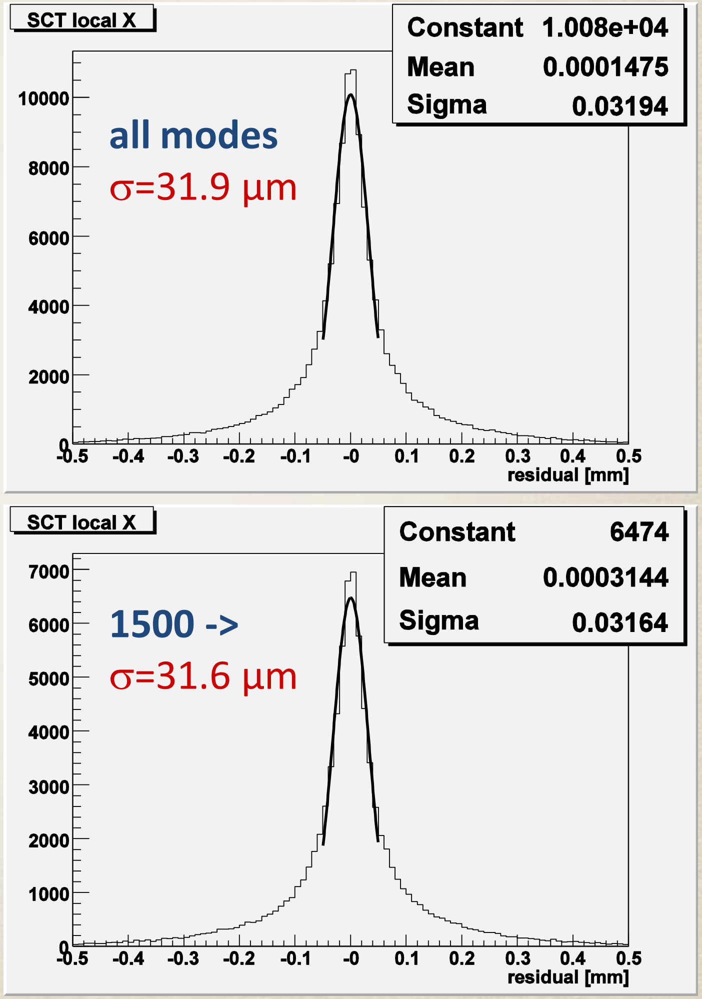


Example: cosmic alignment with Global χ^2

- Possible trap: Do not try to exploit all apparent information:



Residual distribution

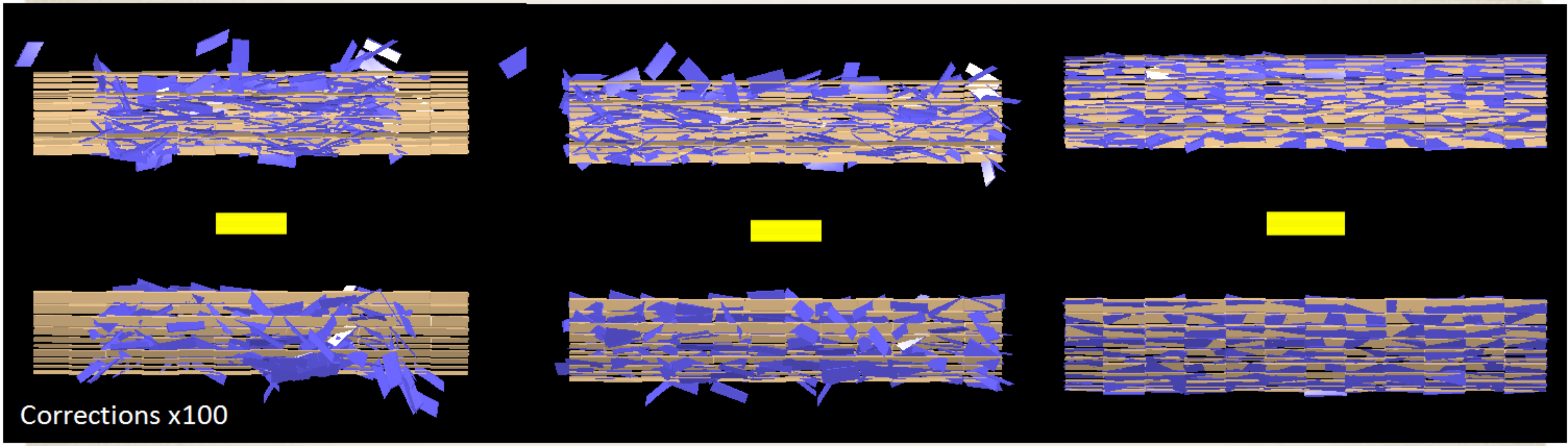


- Alignment quality the same for -1500!!!

Example: cosmic alignment with Global χ^2

...but the resulting geometry is dramatically different!

-10 modes -100 modes -1500 modes



I claim this one is physically justified!

Singular (and weak) modes need to be removed from the solution.

What can we do for very large systems?

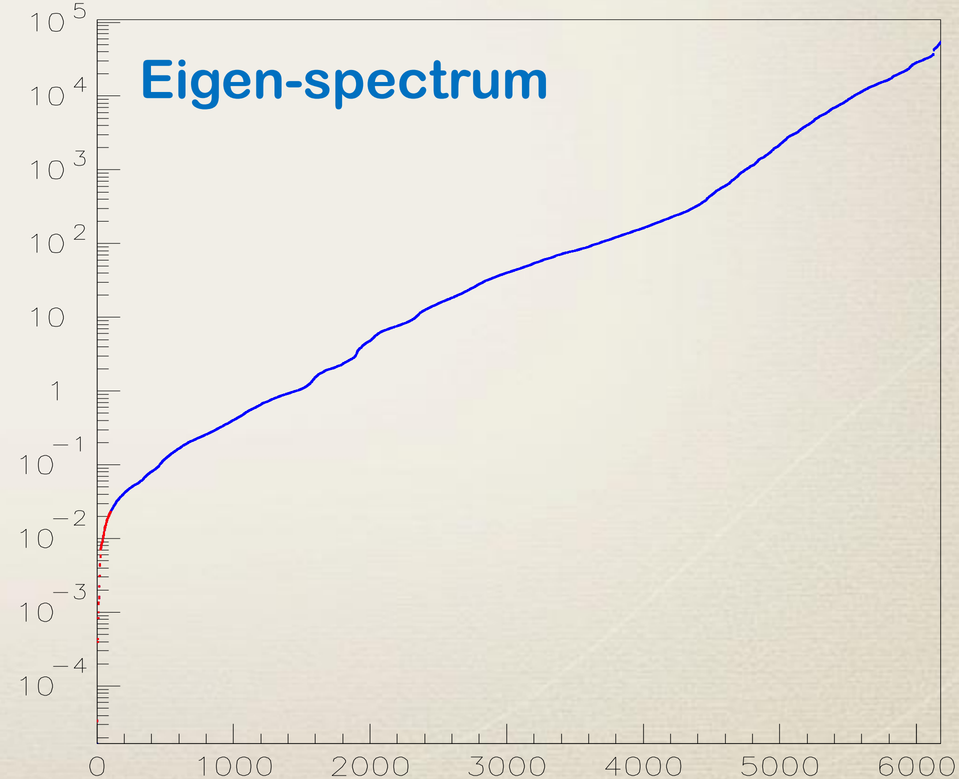
soft-mode-cut

(...and use fast solvers)

$$\mathbf{M}X = Y, \quad \mathbf{UMU}^{\mathrm{T}}\mathbf{U}X = \mathbf{U}Y \Rightarrow \mathbf{D}X_D = Y_D$$

$$X = \sum_i E_i \frac{1}{\lambda_i} Y_D$$

$$\boxed{\mathbf{M} \to \mathbf{M} + \kappa 1, \quad \mathbf{D} \to \mathbf{D} + \kappa 1, \quad \lambda_i \to \lambda_i + \kappa}$$



Singular (and weak) modes need to be removed from the solution.

What can we do for very large systems?

soft-mode-cut

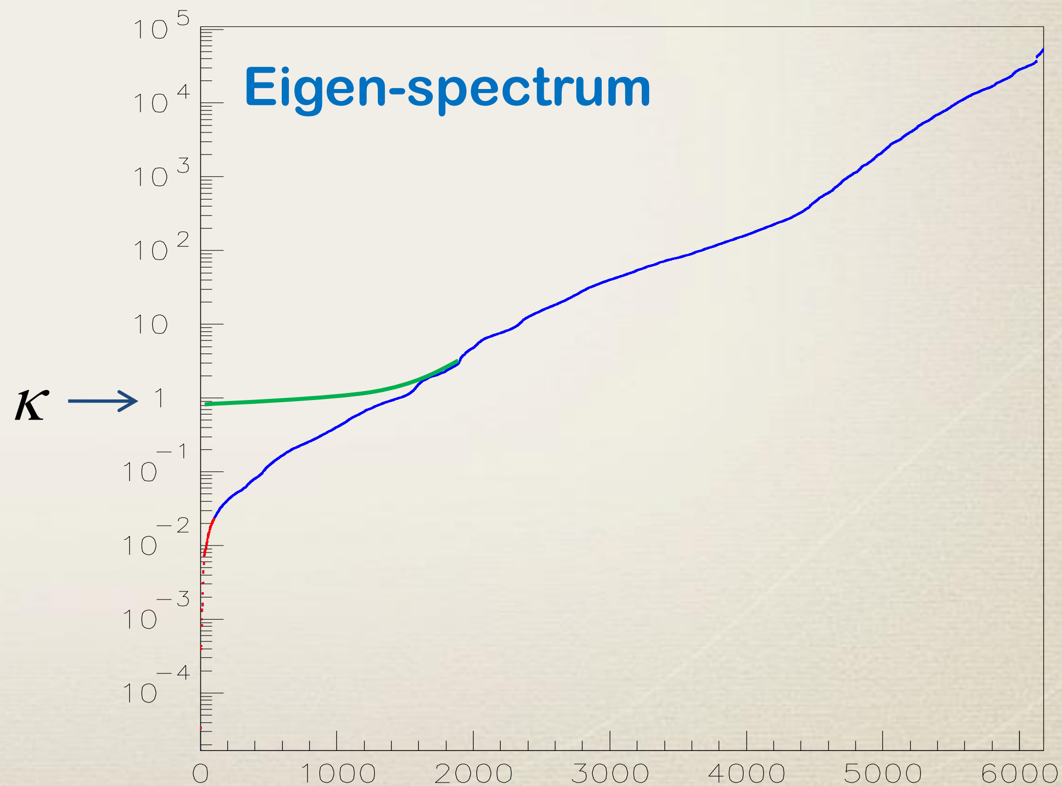
(...and use fast solvers)

$$\mathbf{M}X = Y, \quad \mathbf{U}\mathbf{M}\mathbf{U}^{\mathrm{T}}\mathbf{U}X = \mathbf{U}Y \Rightarrow \mathbf{D}X_D = Y_D$$

$$X = \sum_i E_i \frac{1}{\lambda_i} Y_D$$

$$\boxed{\mathbf{M} \to \mathbf{M} + \kappa 1, \quad \mathbf{D} \to \mathbf{D} + \kappa 1, \quad \lambda_i \to \lambda_i + \kappa}$$

$$\begin{bmatrix} +\kappa & & & & \\ & +\kappa & & & \\ & & +\kappa & & \\ & & & \ddots & \\ & & & & +\kappa \end{bmatrix}$$



Singular (and weak) modes need to be removed from the solution.
What can we do for very large systems?

soft-mode-cut
(...and use fast solvers)

In practice, it is useful to normalize the soft-cuts to the expected uncertainty. The cut-off can be tuned to each DoF individually. This is actually used in ATLAS.

$$\mathcal{M}_{ij} = \frac{d\chi^2}{d\frac{\alpha}{\sigma}_i d\frac{\alpha}{\sigma}_j}, \qquad \mathcal{M}_{ij} \longrightarrow \sigma(\alpha_i)\sigma(\alpha_j)\mathcal{M}_{ij}$$

$$(\sigma(\alpha_i)\sigma(\alpha_j)\mathcal{M}_{ij} + 1)\frac{X_j}{\sigma(\alpha_j)} = \sigma(\alpha_i)Y_i \quad \Longrightarrow \quad (\mathcal{M}_{ij} + \mathcal{D}(\frac{1}{\sigma(\alpha_i)^2}))X_j = Y_i$$

Here, $\mathcal{D}(\frac{1}{\sigma(\alpha_i)^2})$ denotes a diagonal matrix with $\frac{1}{\sigma(\alpha_i)^2}$ elements on the diagonal. In summary, the scaled soft mode cut is realized by adding the diagonal matrix $\mathcal{D}$ to the original matrix $\mathcal{M}$.

Solving the alignment problem

In the most general case diagonalisation is the approach:

- Allows to control statistical significance of individual modes
- Full covariance matrix readily available
- Memory-demanding
- Time consuming ($\sim N^3$)
- Can be used for problems < O(10,000)

Sparse problems (usually the case) can be tackled using fast solvers (Gaussian elimination - *MA27*, Numerical norm minimization GMRES)):

- Much faster ($\leq N^2$) and less memory-demanding
- Require preconditioning to remove weak modes
- No direct error control – indirectly using soft-cuts

Local method does not present any numerical challenge (except for large number of iterations).

To remember:

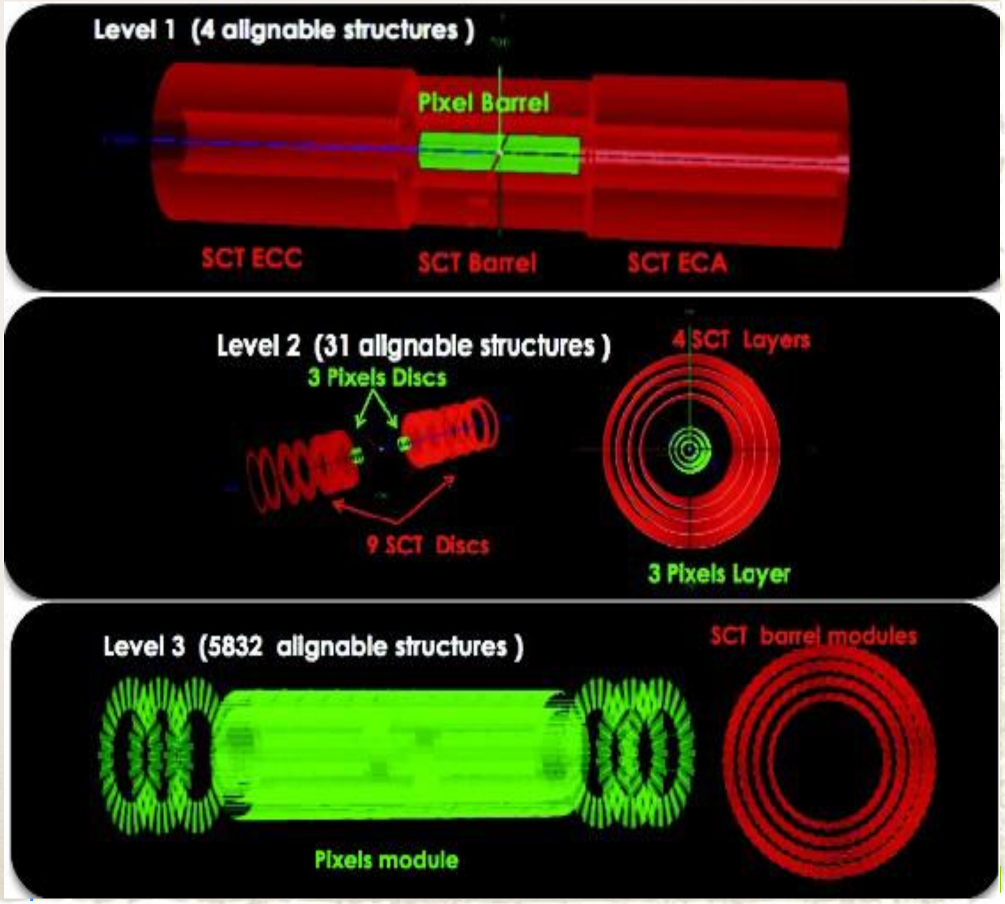
- Global approach results in a large system of linear equations which (usually) correlates all DoF's of the system.

- It is challenging to solve but provides the optimal answer in (quasi) single go.

- One must take special care not to introduce artificial deformations due to wrong statistical treatment!

Strategy adopted by ATLAS:

- The procedure consists of alignment at different levels of granularity – baginning with large structures and getting down to individual sensitive elements.
- Heavily rely on the Beam Spot constraint.
- The Global method is used for systems not exceeding the size of Pixel +SCT+TRT@L2 ~35,000 DoF's (diagonalization or „fast solver")
- TRT straw-level alignment (currently 2 DoF's per straw => ~700,000 parametes) uses the Local method.



Distortions considered so far

- Charge-antisymmetric momentum bias (sagitta):

$$q/p_{\mathrm{T}} \longrightarrow q/p_{\mathrm{T}} + \delta_{\mathrm{sagitta}} \quad \text{or} \quad p_{\mathrm{T}} \longrightarrow p_{\mathrm{T}}(1 + q p_{\mathrm{T}}\, \delta_{\mathrm{sagitta}})^{-1}.$$

$$p \longrightarrow p(1 + q p_{\mathrm{T}}\, \delta_{\mathrm{sagitta}})^{-1}.$$

- Charge-symmetric momentum bias (radial):

$$r \longrightarrow (1 + \epsilon_{\mathrm{radial}}(\phi, \eta))r.$$

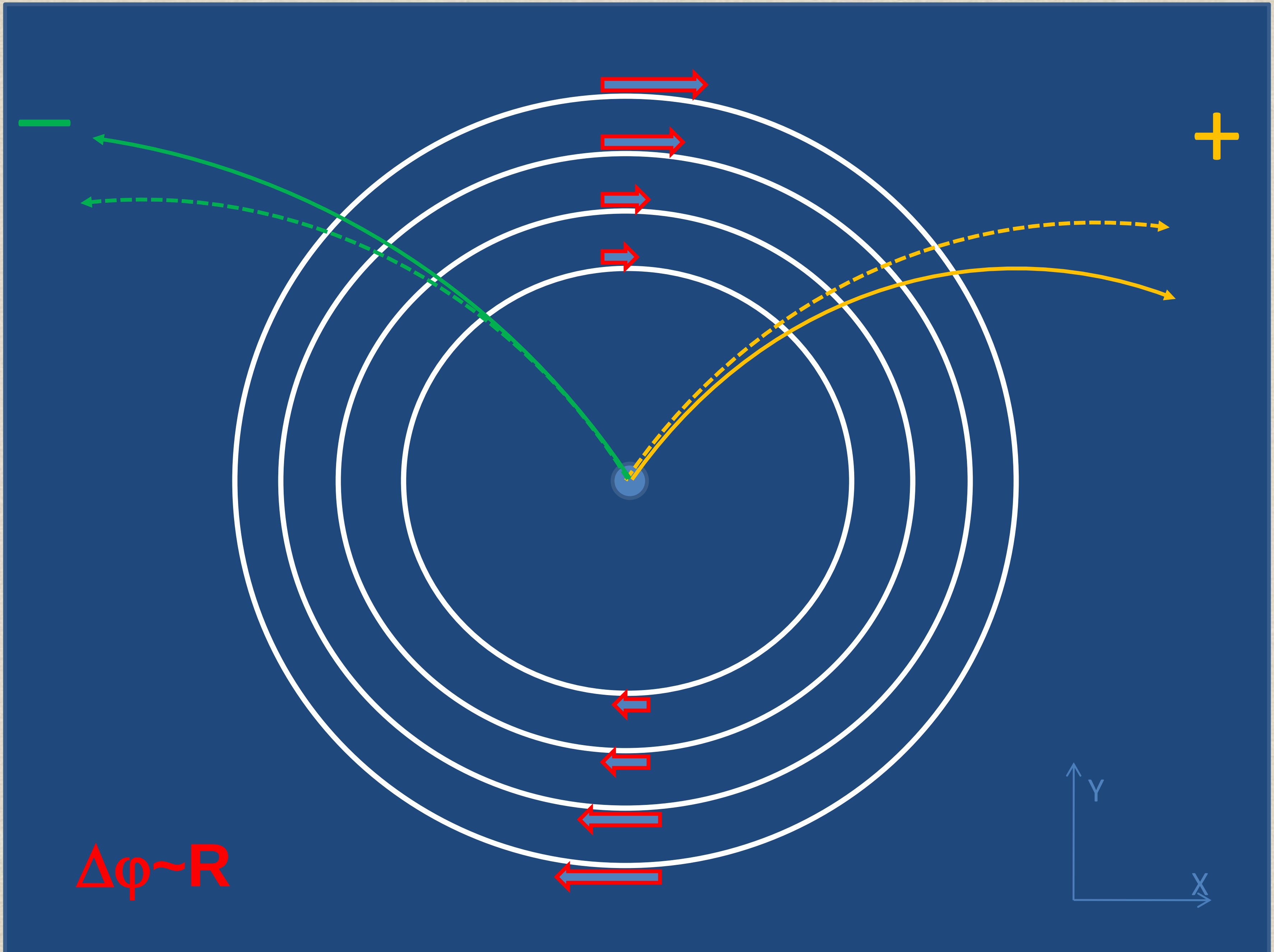
$$p_{\mathrm{T}} \longrightarrow p_{\mathrm{T}}(1 + 2\epsilon_{\mathrm{radial}}) \qquad \text{for small } \epsilon_{\mathrm{radial}}.$$

$$p_{\mathrm{z}} \longrightarrow p_{\mathrm{z}}(1 + \epsilon_{\mathrm{radial}}).$$

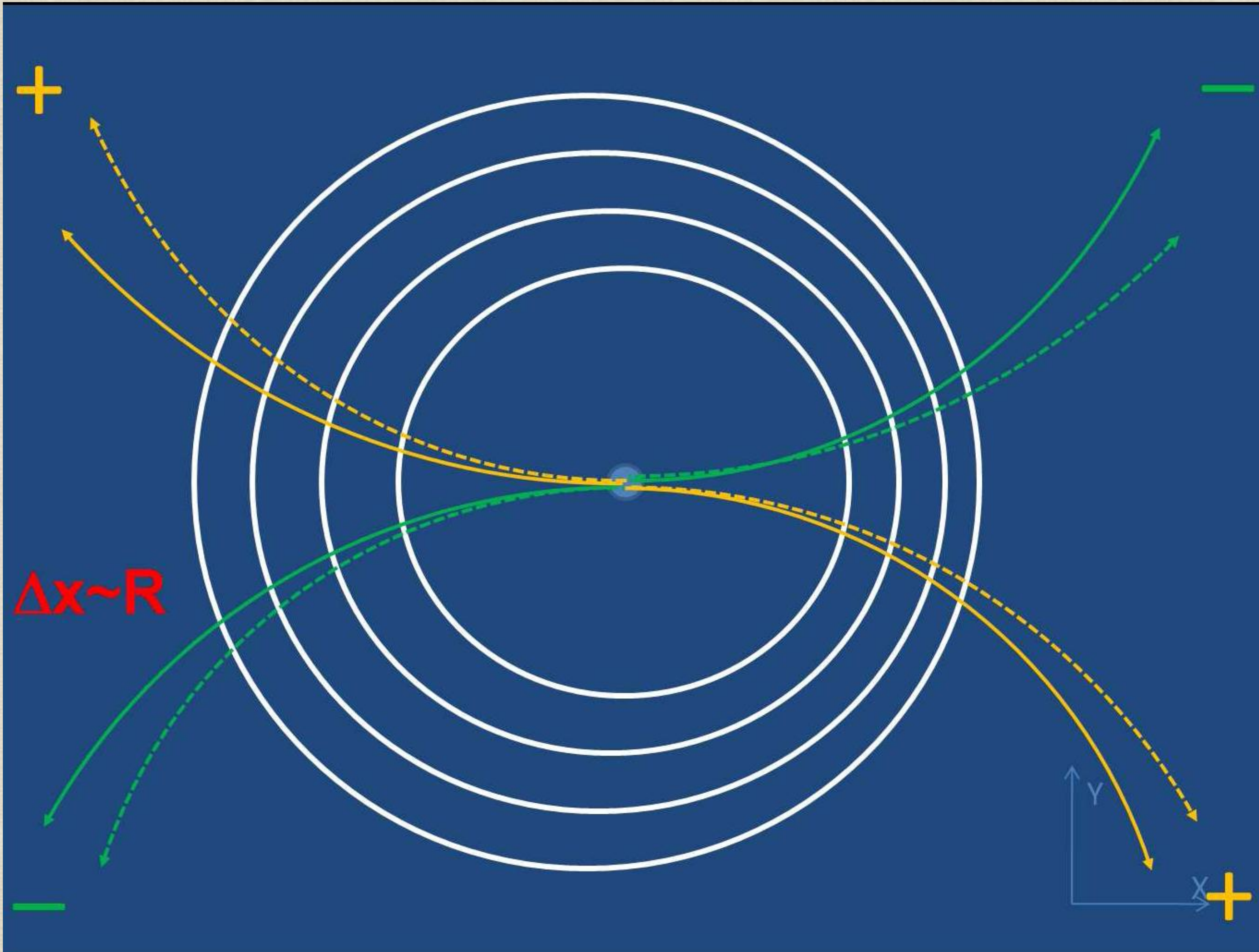
- Bias on the Impact Parameter (XY or Z)

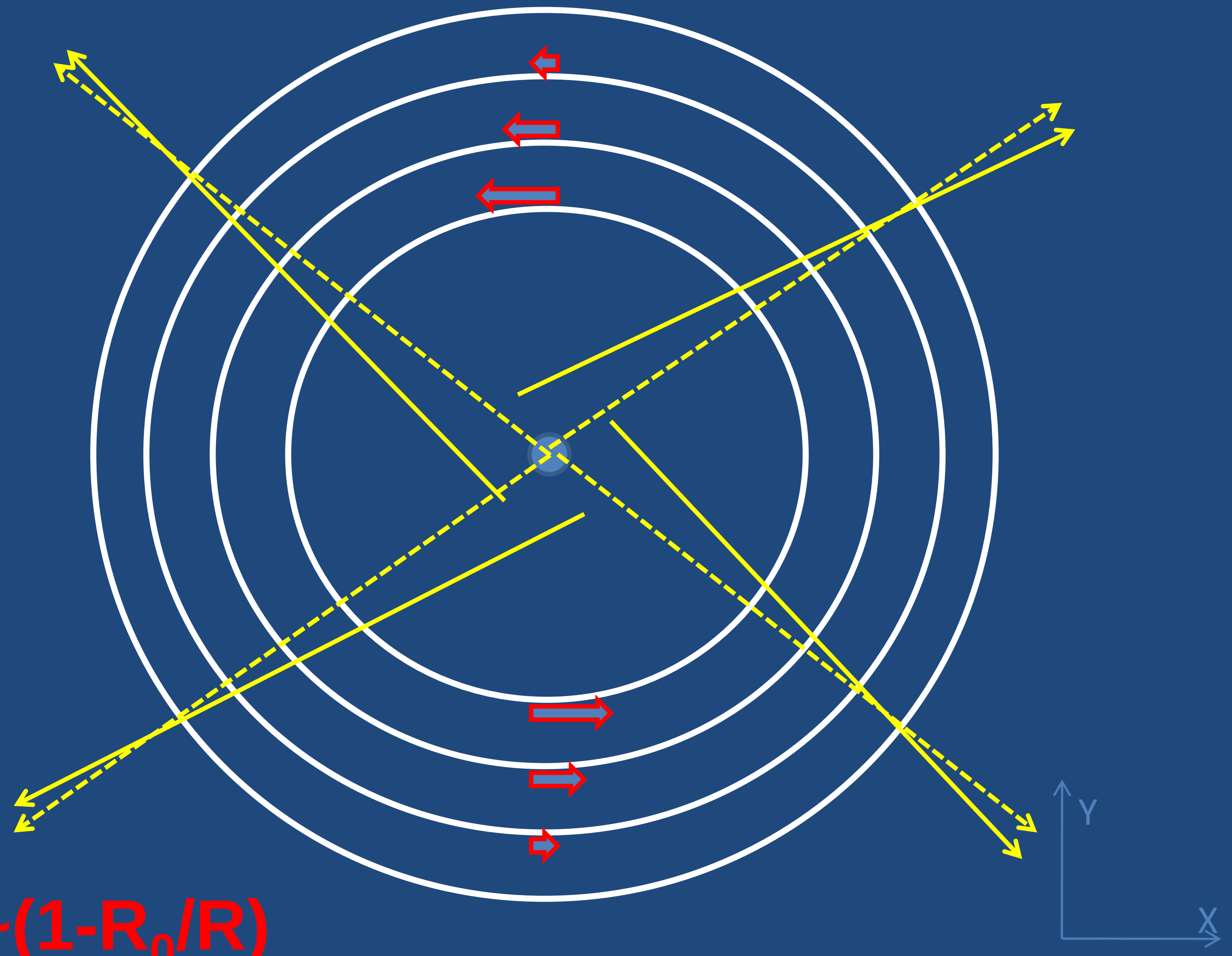
$$t \longrightarrow t + \delta d_0,$$

$$\Delta\phi[\mathrm{rad}] = \frac{\delta d_0}{r},$$



−
+
Δφ~R
Y
X


+
−
Δx~R
Y
X
−
+



$\Delta\varphi \sim (1 - R_0/R)$

Track parameter constraints in GX

* The generic expression for an arbitrary constraint on fitted track parameters takes the form:

track fit:

$$\delta\pi = -J^{-1}\left(\mathrm{E}^T V^{-1} r(\pi_0, a) + S^{-1}(\pi_0 - x)\right)$$
$$J \equiv \mathrm{E}^T V^{-1}\mathrm{E} + S^{-1}$$

alignment fit:

$$\delta a = -\mathcal{M}^{-1}$$
$$\sum_{tracks}\left(\frac{\partial r^T}{\partial a_0} W r_0 - \frac{\partial r^T}{\partial a_0} V^{-1}\mathrm{E}J^{-1}S^{-1}(\pi_0 - x)\right)$$

1. M is the second derivative matrix constructed in the standard way but using the constrained covariance matrix of tracks (J).
2. The „locality ansatz" preserves the constraint because:

$$0 = J^{-1}\left[EV^{-1}r + S^{-1}(\pi_0 - x)\right]$$

$$\delta a = -\mathbf{M}^{-1}\sum\frac{\partial r}{\partial a}\left[(V^{-1} - V^{-1}E\underline{J^{-1}EV^{-1})r} - V^{-1}E\underline{J^{-1}S^{-1}(\pi_0 - x)}\right]$$

* „Full" vertex constraint.

The idea of the vertex constraint in the GX sense is to leave its position fully free in the fit:

$$\frac{dr}{da} = \frac{\partial r}{\partial a} + \mathrm{E}\frac{d\pi}{da} + \mathrm{F}\frac{db}{da}$$

$$\frac{d\pi}{da} = -J^{-1}\mathrm{E}^T V^{-1}\left(\frac{\partial r}{\partial a} + \mathrm{F}\frac{db}{da}\right)$$

$$\frac{db}{da} = -\underbrace{\left(\sum_{tracks}^{ev} \mathrm{F}^T W \mathrm{F}\right)}_{M_b}^{-1}\left(\sum_{tracks}^{ev} \mathrm{F}^T W \frac{\partial r}{\partial a}\right)$$

vertex refit

- Track parameters are re-parameterrised!
- The final expression is analogous to the „baseline one" but the covariance matrix of the measurements takes a new (more complex) form:

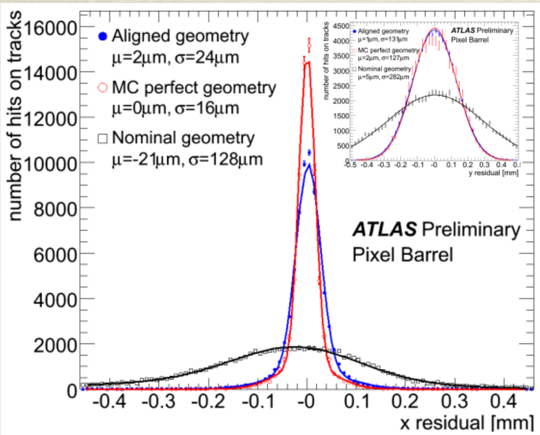
$$\delta a = -\underbrace{\left(\sum_{tracks} \frac{\partial r^T}{\partial a_0} X \frac{\partial r}{\partial a_0}\right)}_{\mathcal{M}}^{-1} \underbrace{\sum_{tracks} \frac{\partial r^T}{\partial a_0} X r(\pi_0, b_0, a_0)}_{\mathcal{V}} \quad X \equiv W - W\mathrm{F}M_b^{-1}\left(\sum_{tracks}^{ev} \mathrm{F}^T W\right)$$

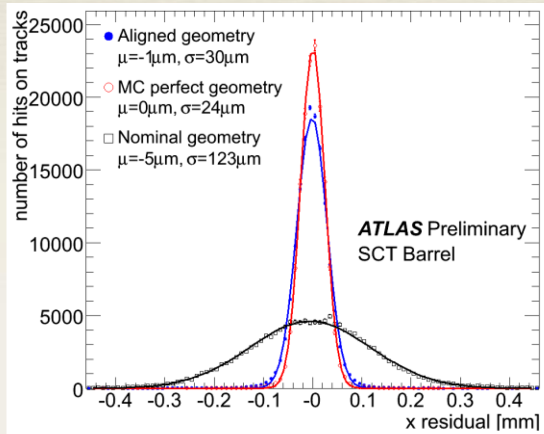
p57

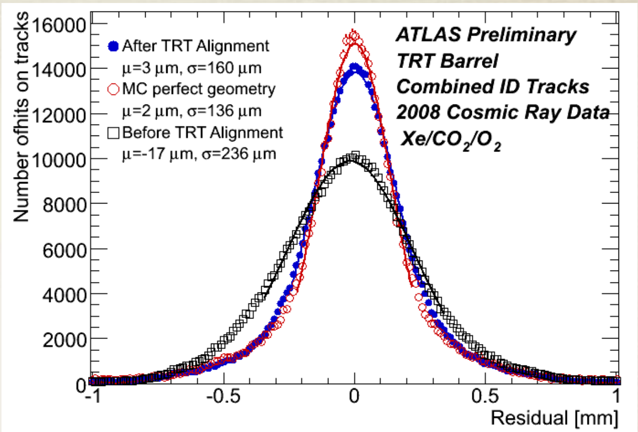
Run I timeline

- ➔ 2009:
  - ➔ Alignment infrastructure validation
  - ➔ Alignment with cosmics & 900GeV run
- ➔ 2010 (~50pb^{-1}):
  - ➔ Dedicated „ID calibration" stream and new alignment code
  - ➔ Alignment with 7TeV collision data
  - ➔ Wire to wire TRT alignment
  - ➔ Use of pixel module deformations
- ➔ 2011(~5fb^{-1}):
  - ➔ Implementation of alignment at Tier-0 calibration loop
  - ➔ ID to B-field alignment
  - ➔ Detected time dependent movements. Run-by-run alignment monitoring.
  - ➔ Use of E/P constraint, $Z \rightarrow \mu\mu$ as cross check
  - ➔ New Pixel clustering (NN) introduced
- ➔ 2012 (~20fb^{-1}):
  - ➔ Use of $Z \rightarrow \mu\mu$ constraint, E/P as cross check
  - ➔ Use of Impact Parameters biases as constraints
  - ➔ Advanced alignment split in periods
  - ➔ Detailed studies of momentum scale
  - ➔ Update the alignment constants (if needed) for the first T0 reprocessing

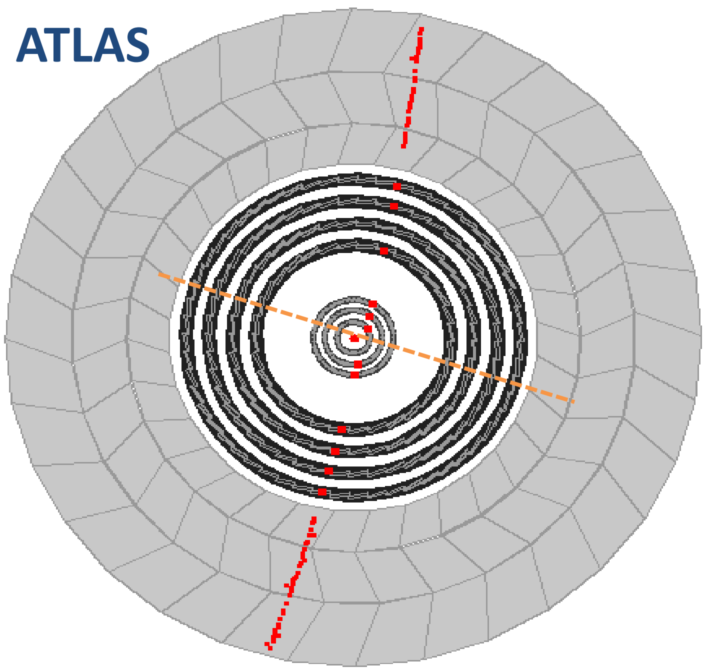
The first alignment using the cosmic-ray muons (2009)



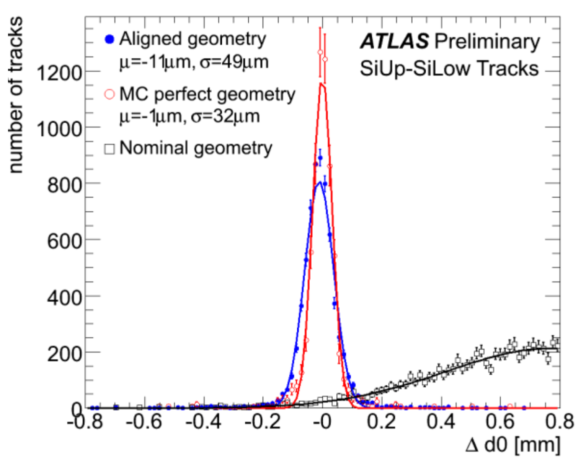


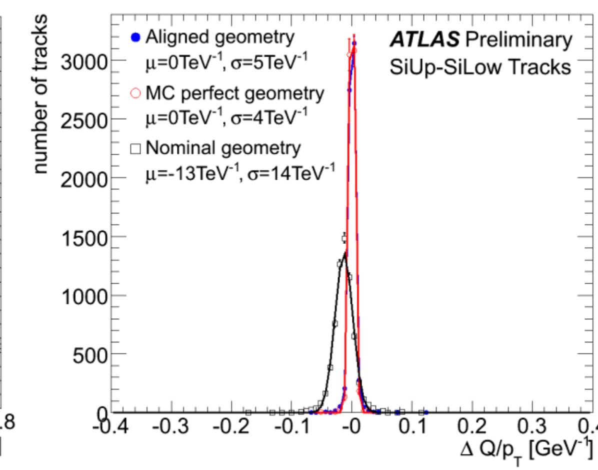


ATLAS

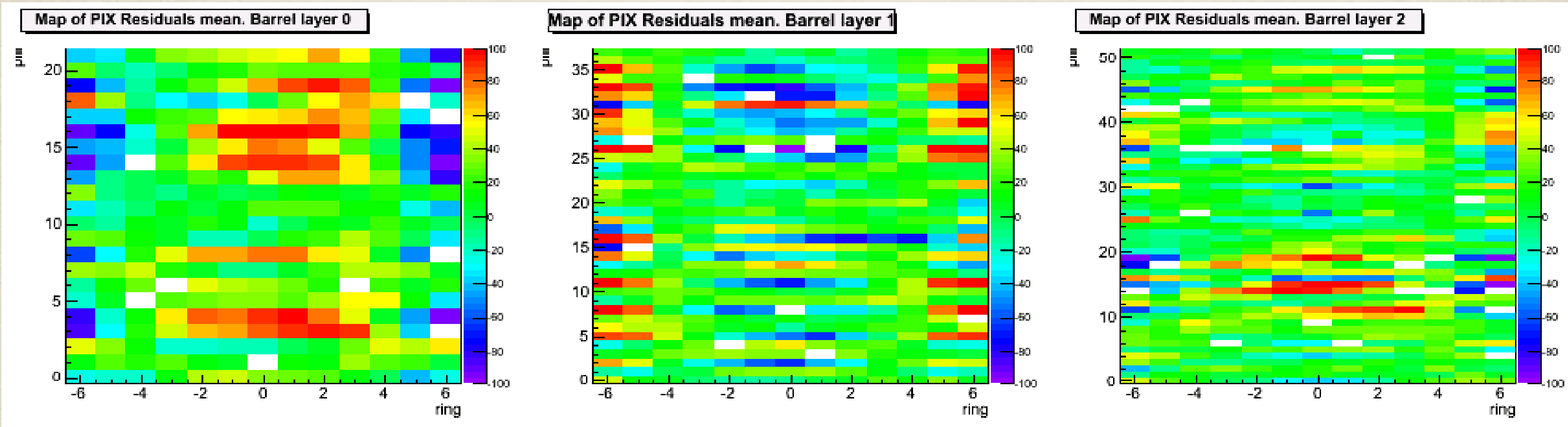


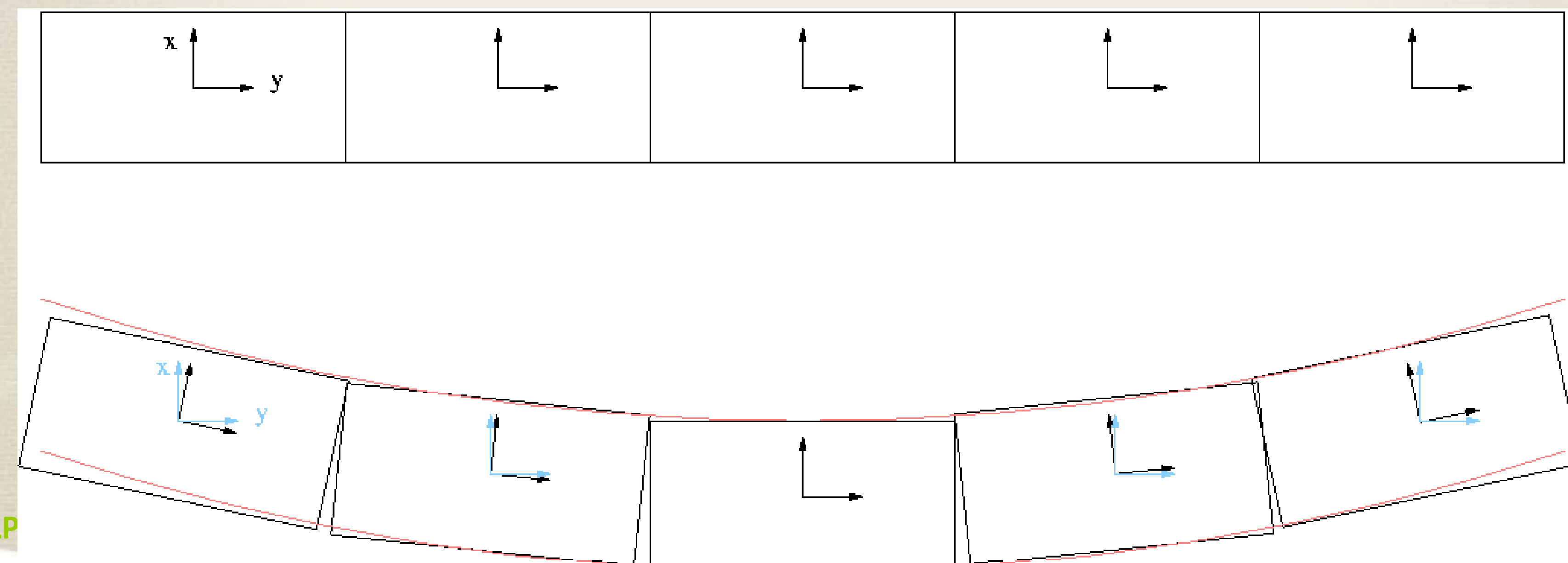
Reconstruction of kinematic parameters





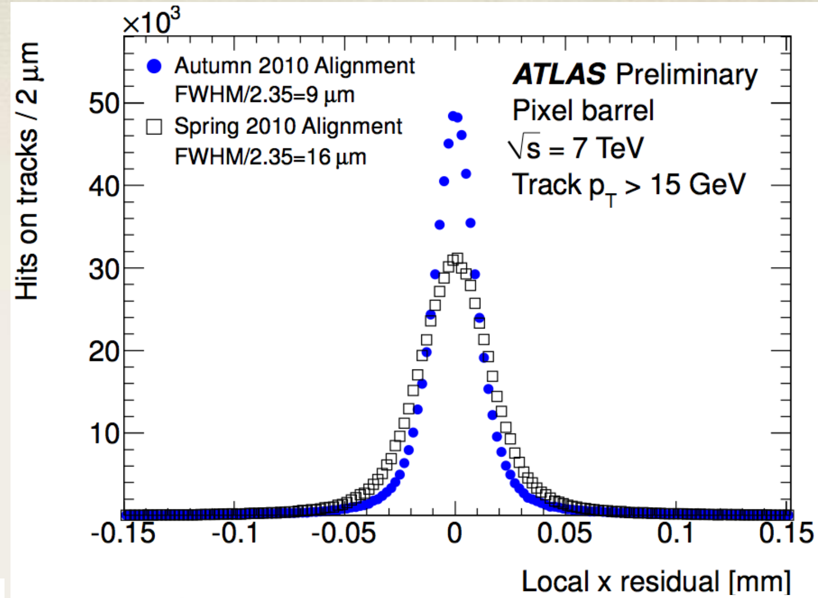
Observation of clear side bowing of pixel staves (collision data 2009)

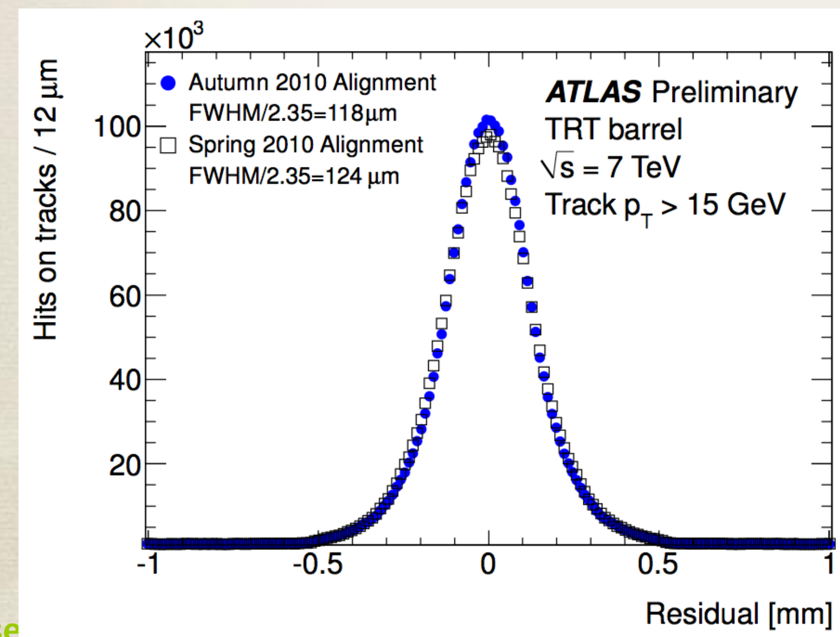


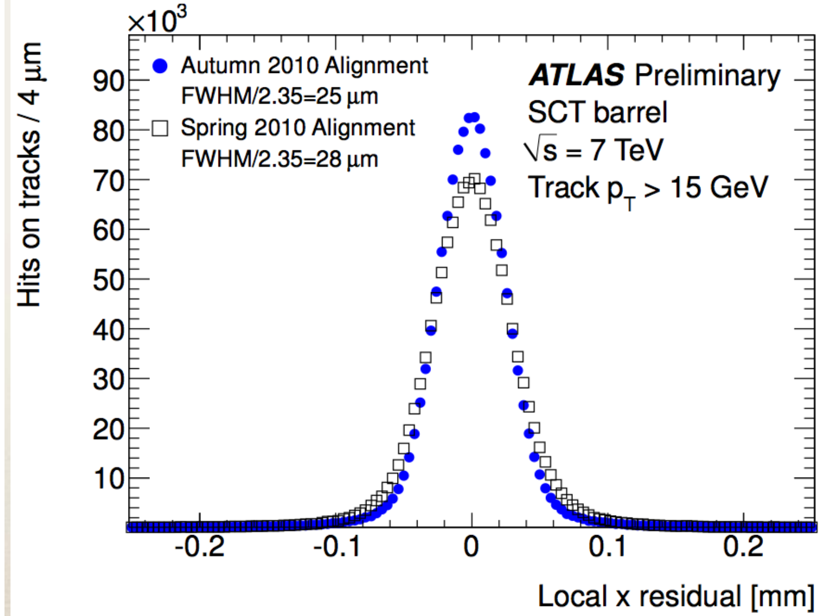


2010 ($\sqrt{s}$=7 TeV)

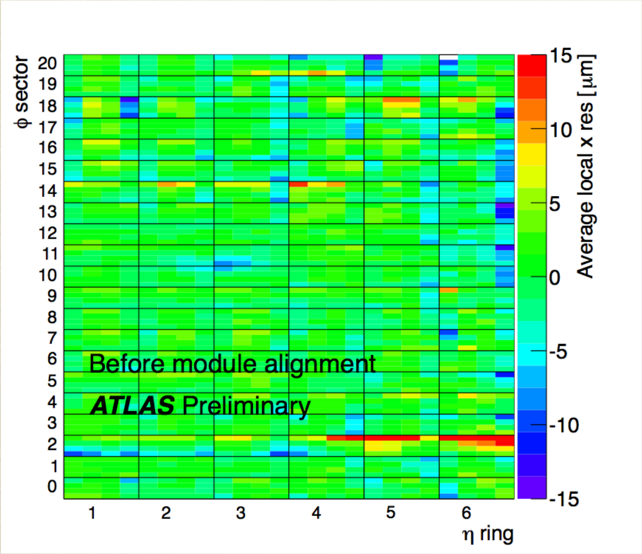
- 2010 was the first year of performing the alignment under 'real' working conditions
- Careful understanding of detector behaviour!



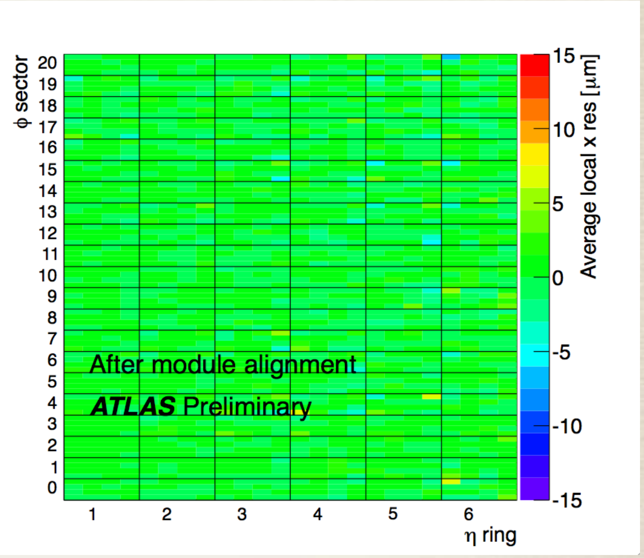


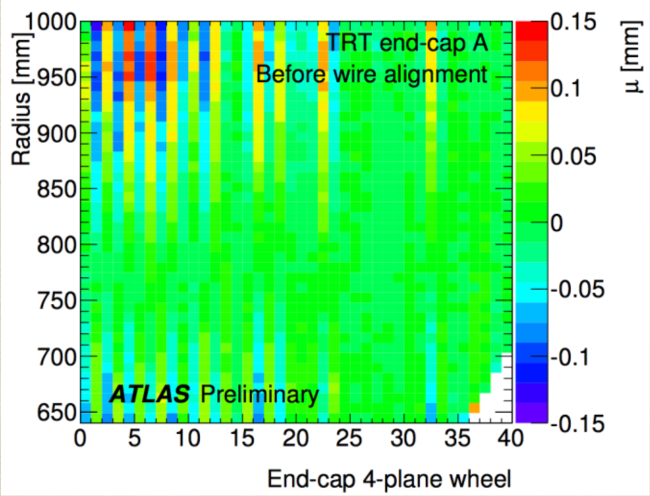


2010 ($\sqrt{s}$=7 TeV)

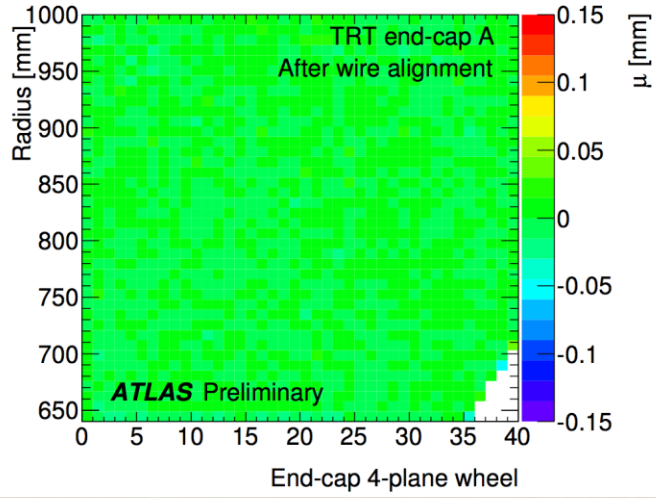


Out of the plane deformations of Pixel modules



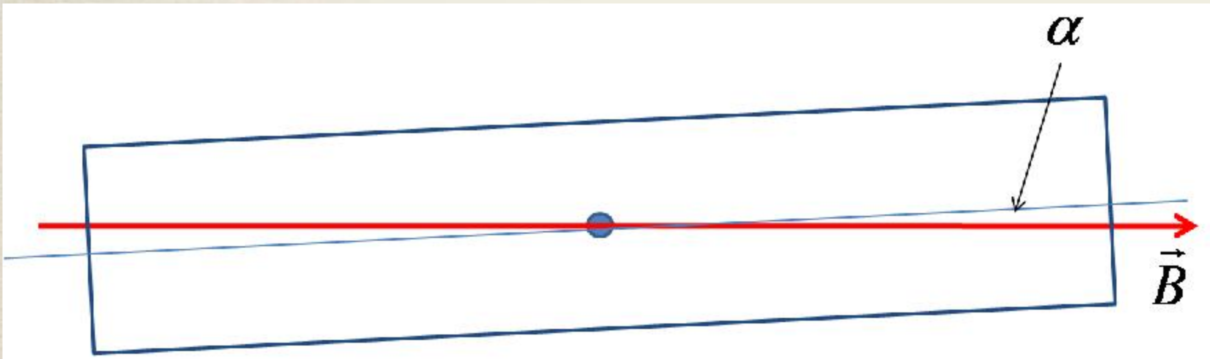


TRT straw alignment (2 DoF/straw)



ID-BF tilt: what to expect?

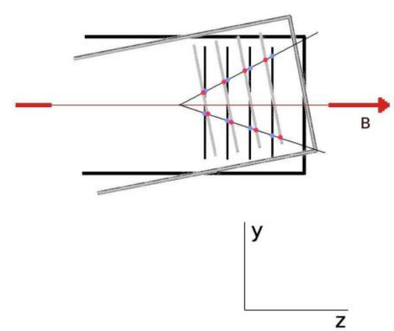
- Radial distortions give: $p_T \to p_T(1+\delta)$ – charge symmetric
  $\Delta m/m \sim \delta\, [p_T^2\,(1-\cos(\Delta\varphi))]/m^2 \sim \delta$

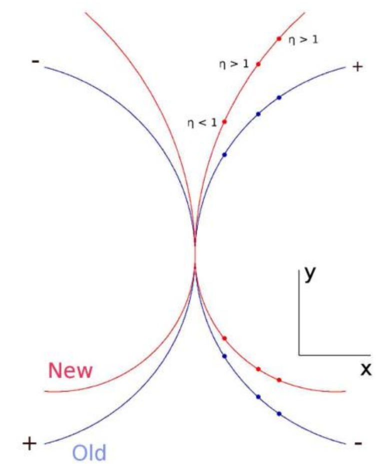


$$R = R_0 + \sin\varphi * \alpha * z, \qquad z = R_0 * \cot\theta$$

$$R = R_0(1 + \sin\varphi * \alpha * \cot\theta)$$

Which mimicks exactly the „radial“ deformation proportional to $\cot(\theta)$.

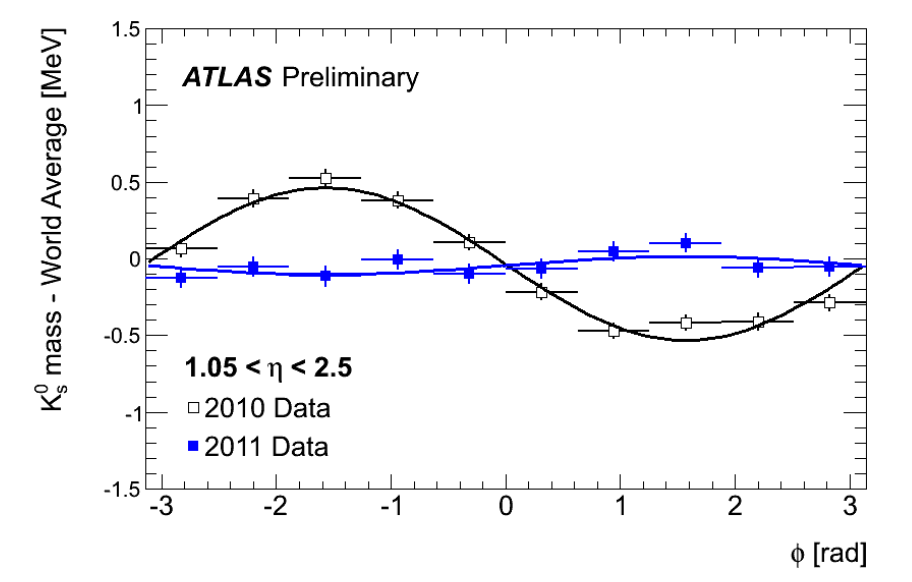


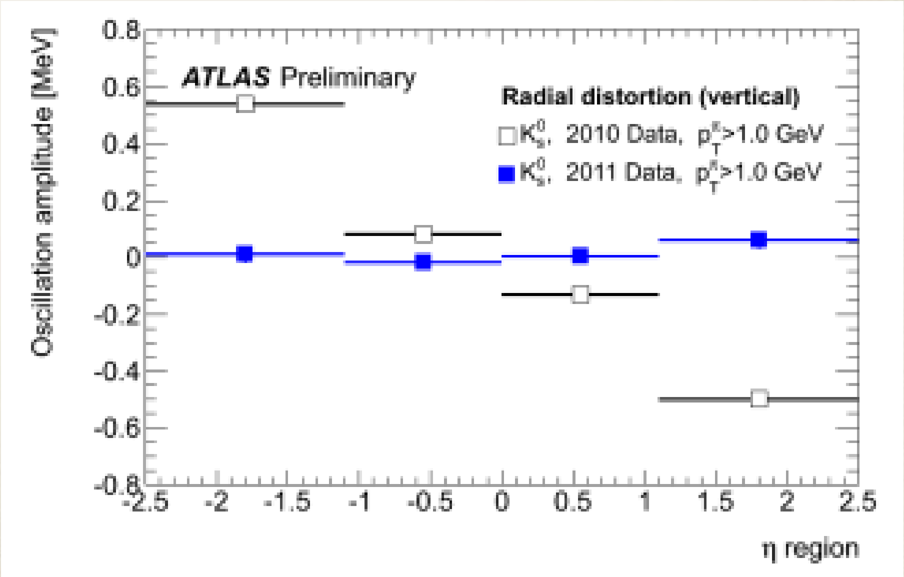


B-field rotation fit

	ECC	ECA
K_s	0.67 +/- 0.02	0.53 +/- 0.02
J/Psi (cal. data)	0.48 +/- 0.04	0.52 +/- 0.04
J/Psi (cal. MC)	0.52 +/- 0.03	0.58 +/- 0.03

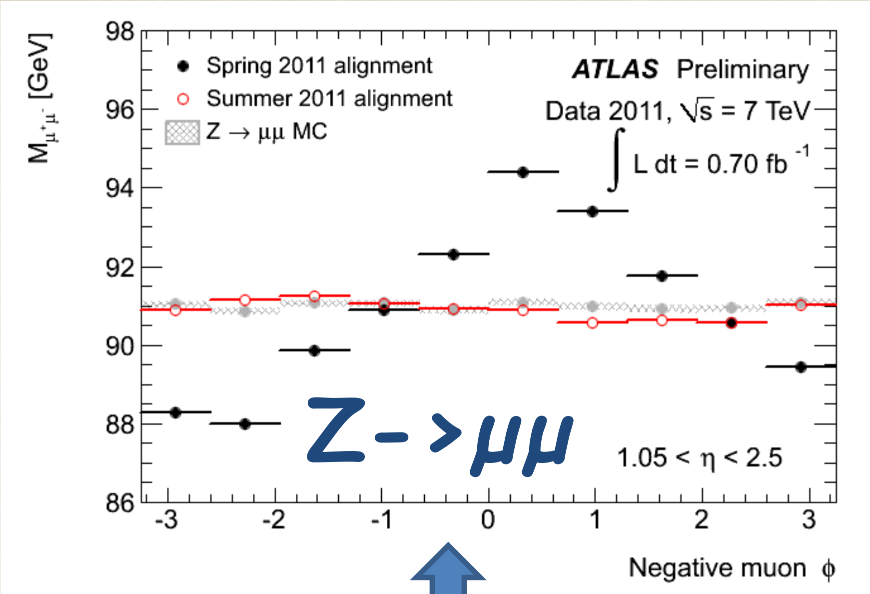
Rotate the B-field by +0.55 mrad around X

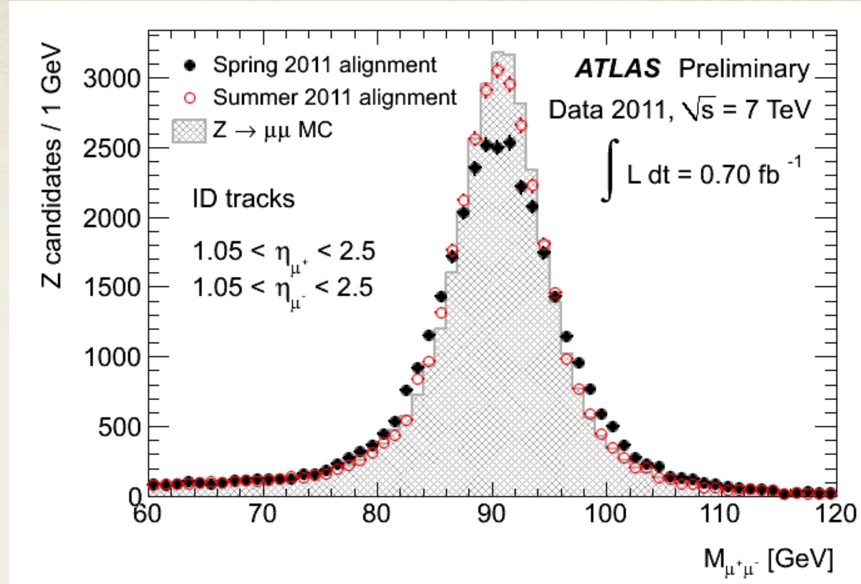


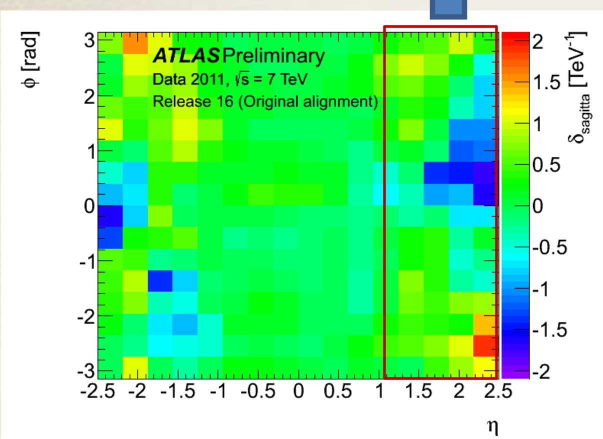


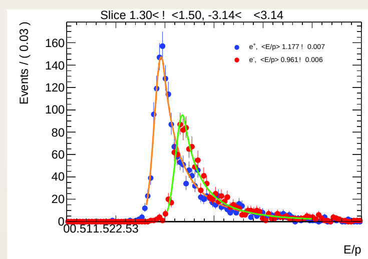
p64

2011 ($\sqrt{s}$=7 TeV)



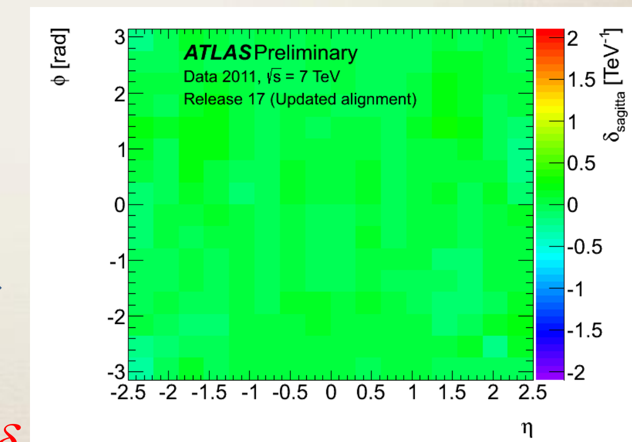






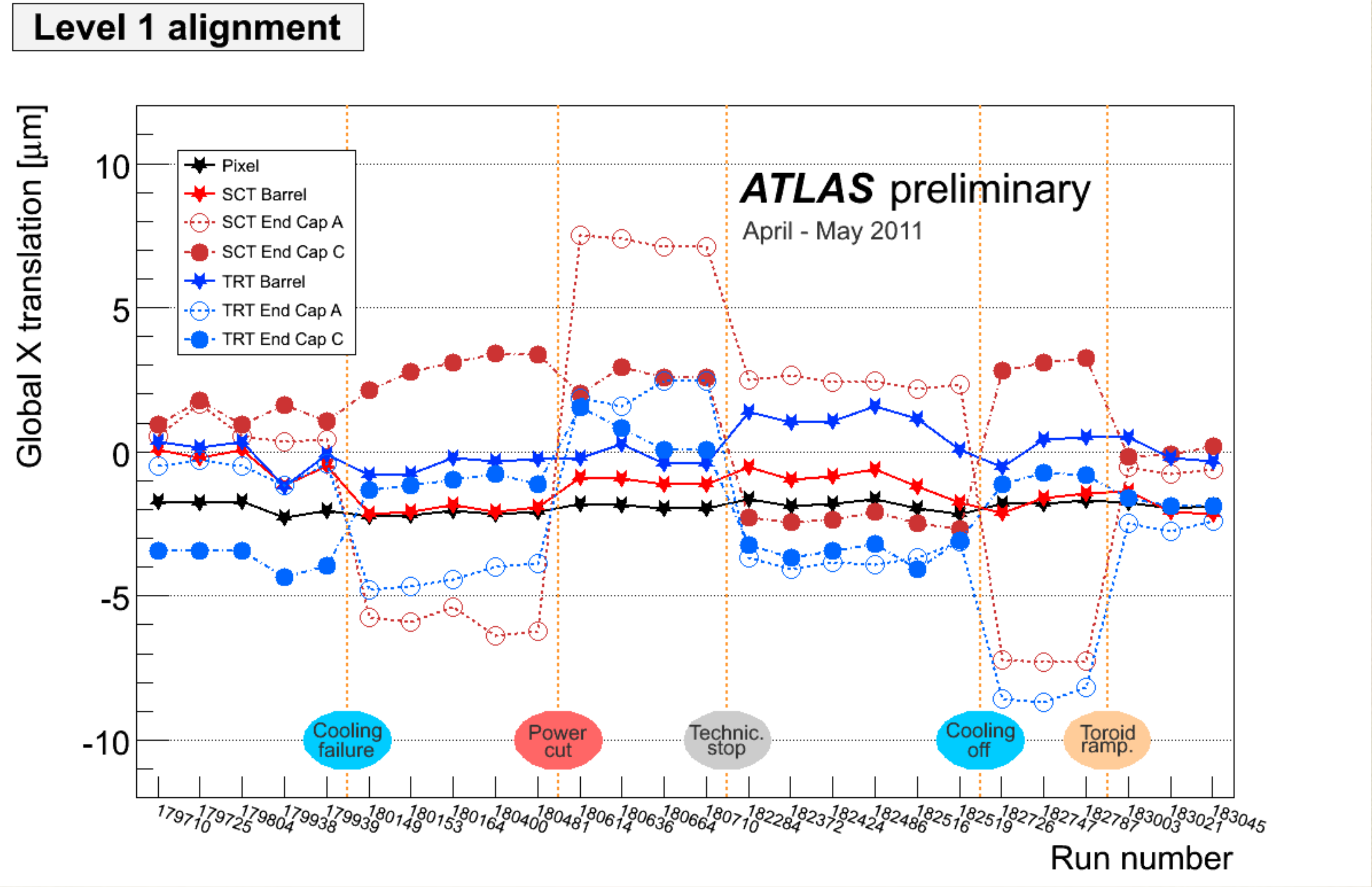
E/p for e⁺ i e⁻

$$\left\langle \frac{E}{p} \right\rangle^{+} - \left\langle \frac{E}{p} \right\rangle^{-} = 2 < E_T > \delta$$



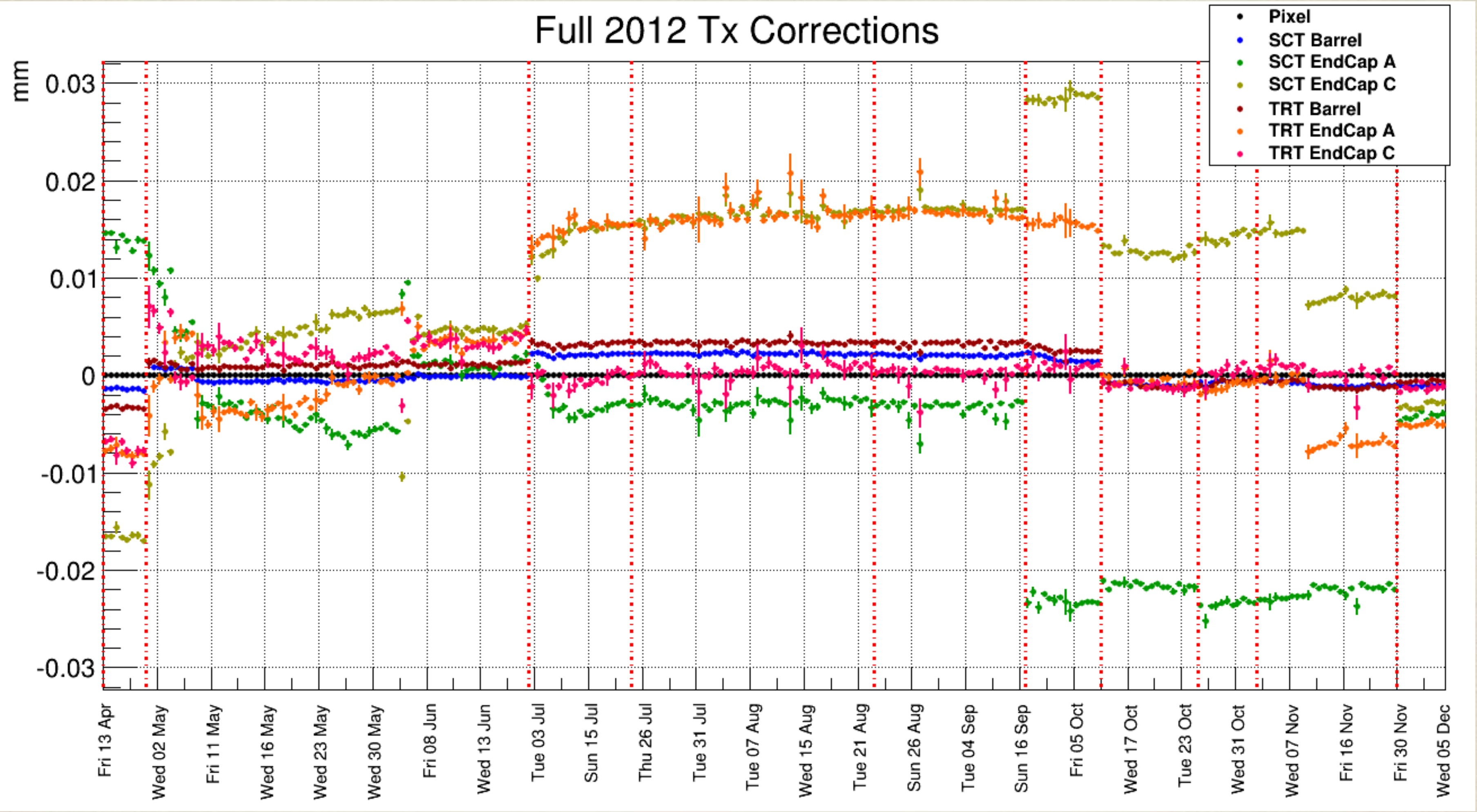
Global χ^2 with constraints

2011 ($\sqrt{s}$=7 TeV)



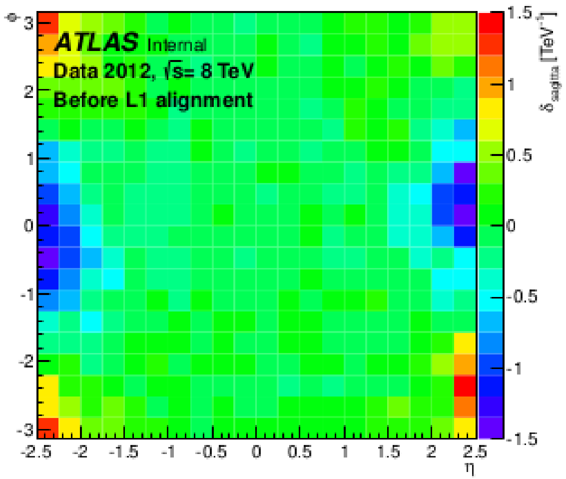
Run-by-run L1 alignment done at Tier 0 allows to monitor any gross movemets of ID structures.

2012 ($\sqrt{s}$=8 TeV)

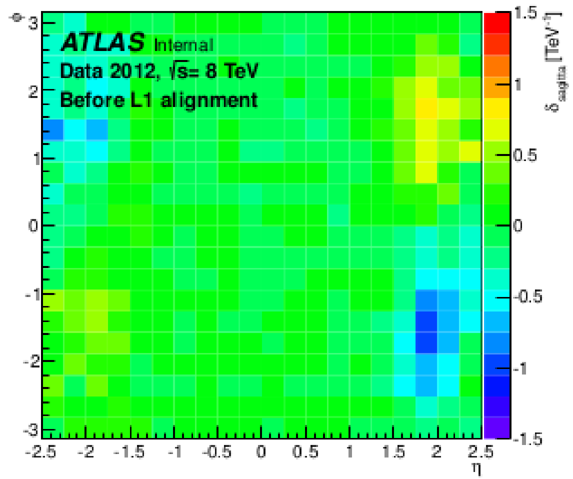


Run-by-run L1 alignment can trigger quasi real-time geometry update for the Tier0 bulk reconstruction.

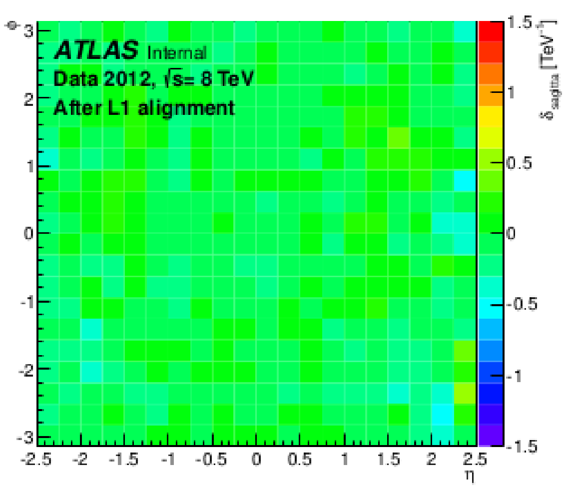
2012 ($\sqrt{s}$=8 TeV)



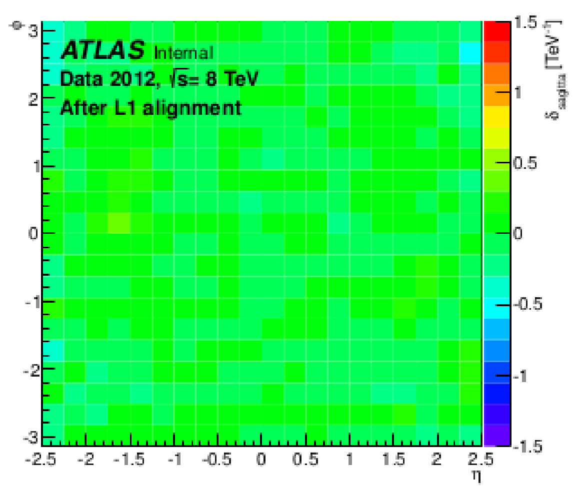
(a) Period A befor d-cap alignment



(b) Period H bef end-cap alignment



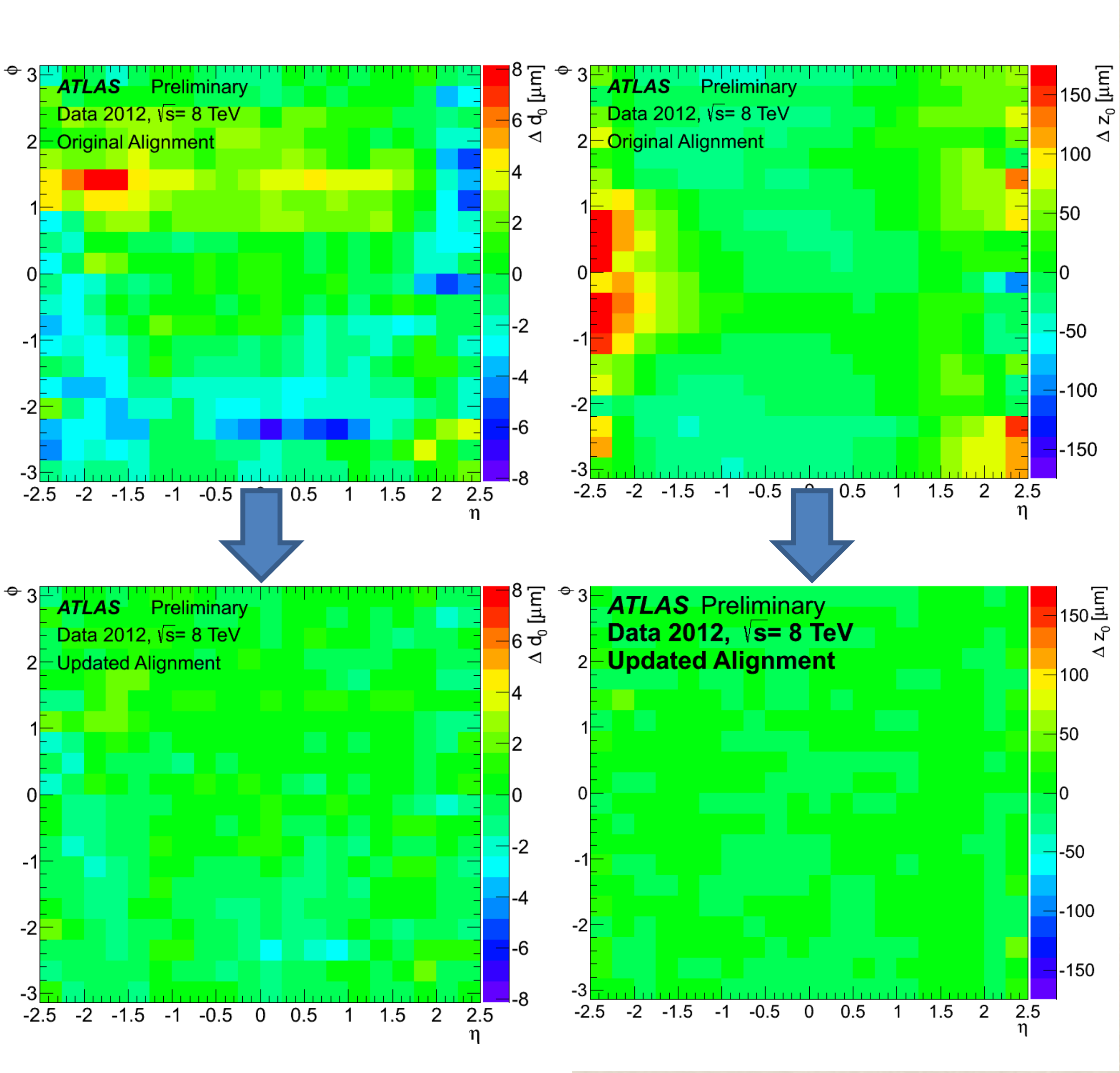
(c) Period A after end-cap alignment



(d) Period H after end-capalignment

Impact of Level 1 re-alignment on sagitta distortions

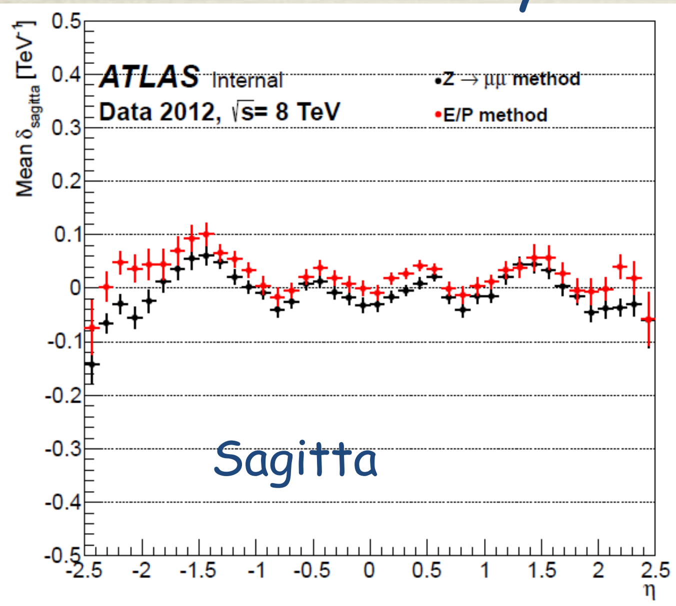
2012 (√s=8 TeV)

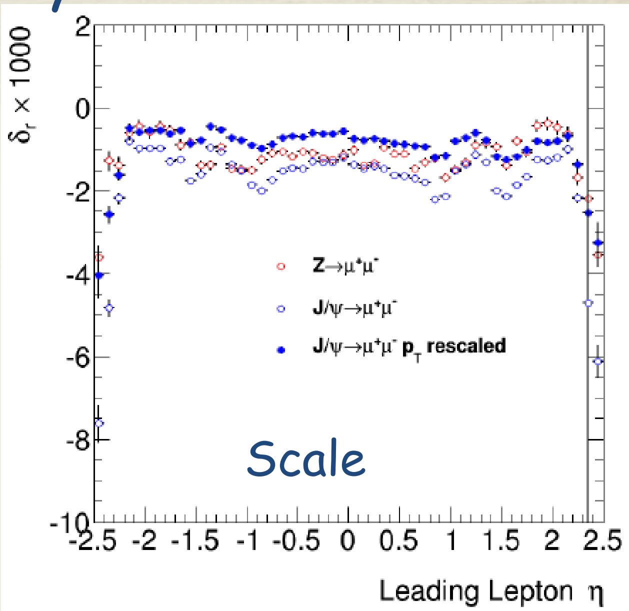


Correcting the Impact Parameter biases using constrained alignment.

2012 ($\sqrt{s}$=8 TeV)

Summary of observed systematics





Summary of the residual misalignment (with any outstanding detector effects entangled)

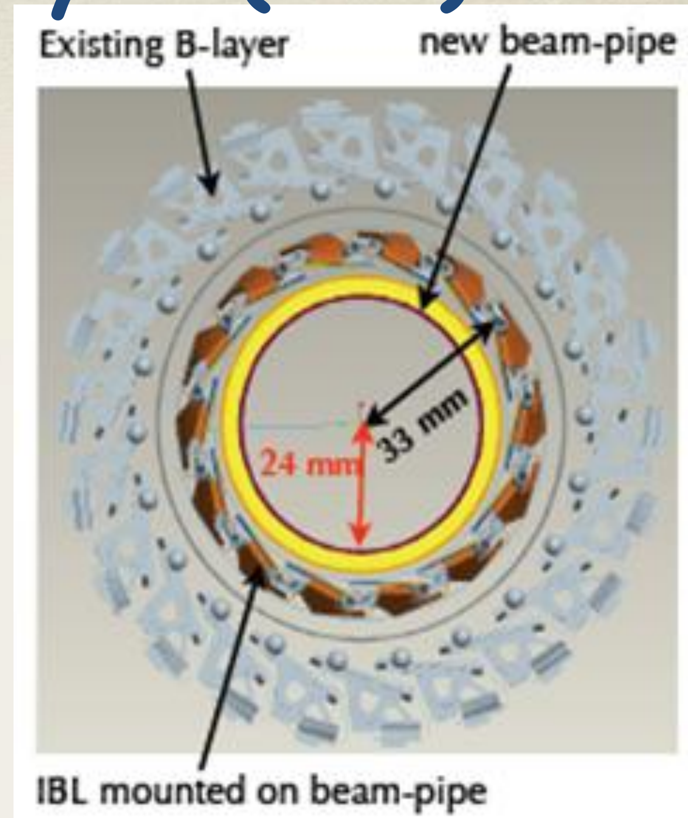
Detector	Pull σ before	Pull σ after	C (μm)
Pixel Barrel X	1.18	1.00	4.5
Pixel Barrel Y	1.13	1.00	33.5
Pixel End-cap X	1.06	1.00	3.6
Pixel End-cap Y	1.00	0.99	0
SCT Barrel	1.08	1.00	8.1
SCT End-cap	1.06	1.00	8.7
TRT Barrel	0.96	0.96	0.0
TRT End-cap	0.96	0.96	0.0

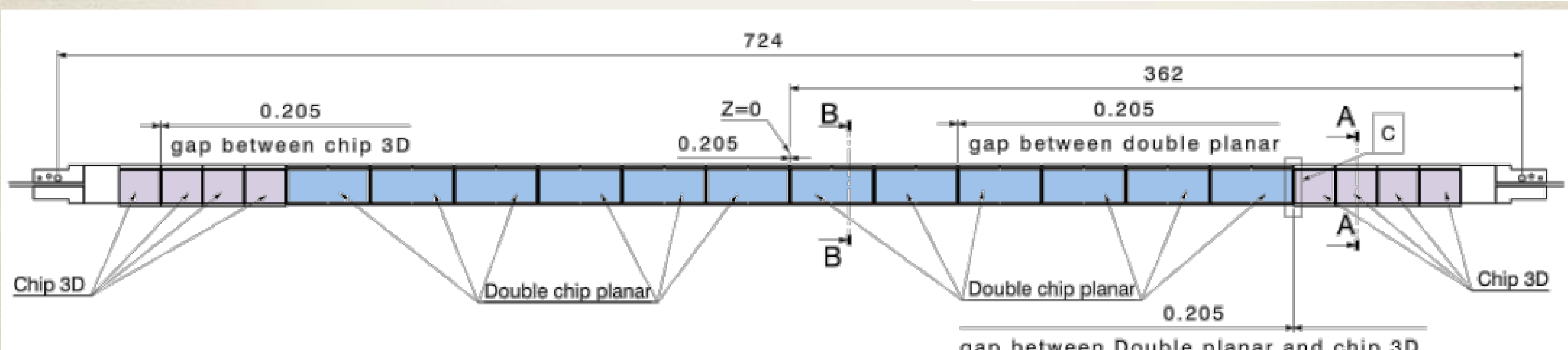
2015 - the Outlook

- Integration of the IBL – will be decisive for Beam Spot, vertexing, etc.
- Improve on run-by-run procedure. Possibly extend to Level 2 alignment.
- Understand better the remaining sagitta and overall momentum scale bias - finetune.
- Out-of-the-plane deformations may be included in the alignment procedure.

The Isertable B Layer (IBL)

- 14 staves of mixed technology will be installed directly on the reduced beam pipe.
- Average radius 3.3 cm, 64 cm long.
- Each stave consists of 12 planar pixel modules and 8 3D sensors.
- CO_2 – cooling system
- low radiation lenth ~1.9% X_0 together with carbon-fibre support.
- Will have to be aligned as a separate entity, due to mechanical independence – time dependence important!





Conclusions

- Alignment is an indispensable element of modern experiments but potentially hazardous.
- LHC Run I allowed to gather vast experience with the detector and achieve final performance exceeding original requirements.
- Good quality track fit was the easy part of the game (although involved solving linear systems with O(10-100)k parameters.
- Most of the effort was spent on understanding and eliminating systematic deformations.
- Run II will see integration of another subsystem (IBL), and further finetuning.

Thank you!

Documentation

ATL-INDET-PUB-2005-002, ATL-INDET-PUB-2007-009
ATLAS-CONF-2011-012, ATLAS-CONF-2012-141,
ATL-COM-SOFT-2012-006 (going public imminently)
ATL-COM-INDET-2013-033 (going public imminently)

ATLAS NOTE

July 27, 2012

Common Framework Implementation for the Track-Based Alignment of the ATLAS Detector

P. Brückman de Renstrom[1], R. Harrington[2] S-C. Hsu[3], S. Kaiser[4], D. Kóllar[5],
V. Lacuesta Miquel[6], S. Martí i García[7], A. Morley[8], J. Schieck[9], J. Wang[10]