Implementation of a global fit method for the alignment of the Silicon Tracker in ATLAS Athena framework

Adlène Hicheur (RAL, UK), Sergio Gonzalez Sevilla (IFIC, Valencia)

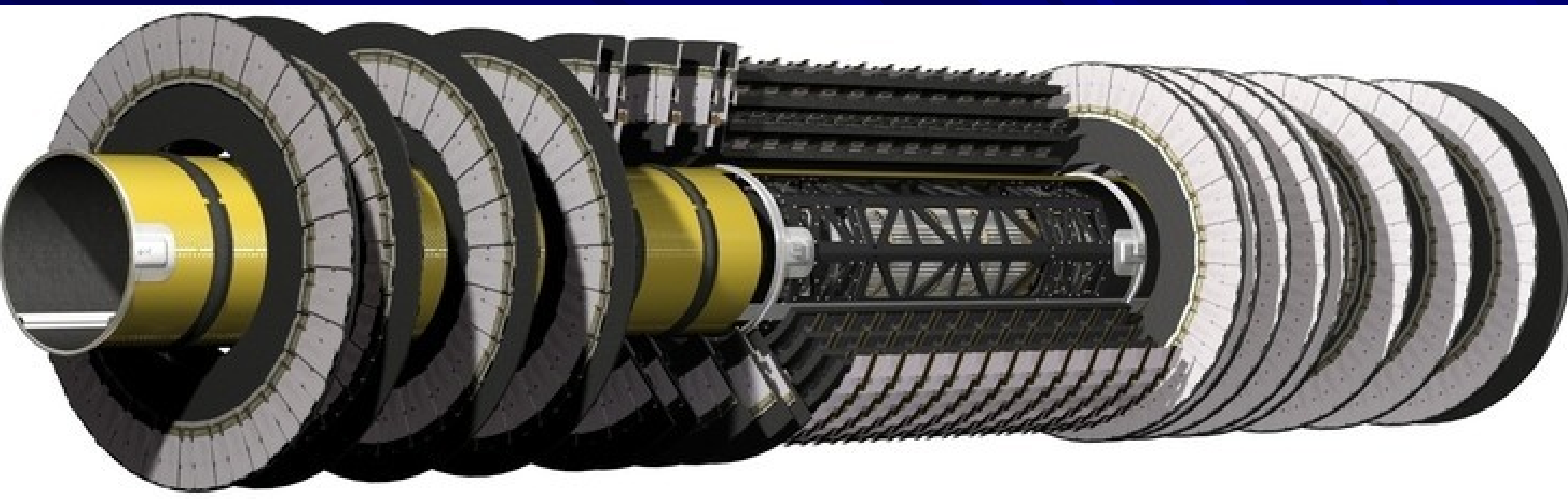
ATLAS Si SW Alignment group

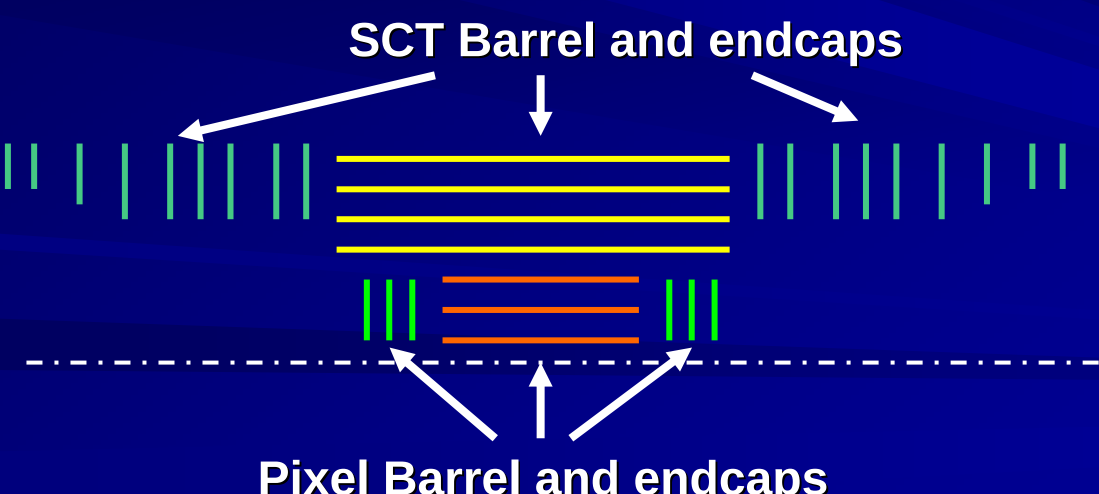
A.Hicheur, S.Haywood (RAL); J.Schieck, S.Kluth, R.Haertel, T.Goettfert (MPI Munich); C.Garcia, S.Marti, S.Gonzalez-Sevilla, C.Escobar (IFIC, Valencia); P.Bruckman, M.K.Unel, F.Heineman, D.Hindson (Oxford U.); A.Bonissent, K.Bernadet, D.Fouchez, A.Tilquin (CPPM, Marseille); R.Hawkings (CERN); G.Gorfine (Wuppertal U.); T.Golling (LBL)

Outline

- ATLAS Inner Silicon Tracker
- Alignment problematic
- Physics requirements
- Principle of the fit
- Code implementation and infrastructure
- Some results of tests
- Conclusion and outlook
- *Note: given the limited time, not possible to be exhaustive $\rightarrow$ go to the main points*

Inner Silicon Tracker





Silicon detector:

Barrel: 1456 Pixel (3 layers) + 2112 SCT (4 layers) = 3568 modules

End caps: 2x144 Pixel (2x3 discs) + 2x988 (2x9 discs) SCT = 2264 modules

Total: 5832 modules

Alignment problematic

- Monitor the motion of ~ 5.8k Si modules (!) using tracks
  - Huge number of DoF: solving? Correlations? Numerical stability? Which tracks?...
- Question: what kind of motion?
  - Local movements: module position “fluctuation”, typically O(10μm)
  - Global movements: Cylinders/discs deformations, typically O(100μm)
  - Foreseen: apply hierarchical alignment
- Several reason to monitor the movements with tracks
  - Day one alignment unknown
    - as opposed to running mode calibration where changes are expected to be small on a ~ 24h basis
    - Survey data useful only for module to module placement within a common structure (e.g.: disc or layer)
    - Transport between sites and down in the pit: loss of information on global shapes misplacements.
  - Shutdowns
  - Daily changing conditions (temperature effects, etc…)

Physics requirement

- Controlling the alignment to the ~ O(1 μm) level is important for physics analysis and performance, e.g.:
- Precise measurement of W mass requires stringent constraint on the pt resolution (and control of systematics)
  - Radiative corrections to m_W involve m_t and m_H: constrain m_H
- B physics and b jet tagging make extensive use of Si tracker
- From first estimations:
  - Expected # of tracks to achieve 0(1μm) precision: ~ 10^7
  - Understanding the systematics may take more time

Principle of the global fit (1)

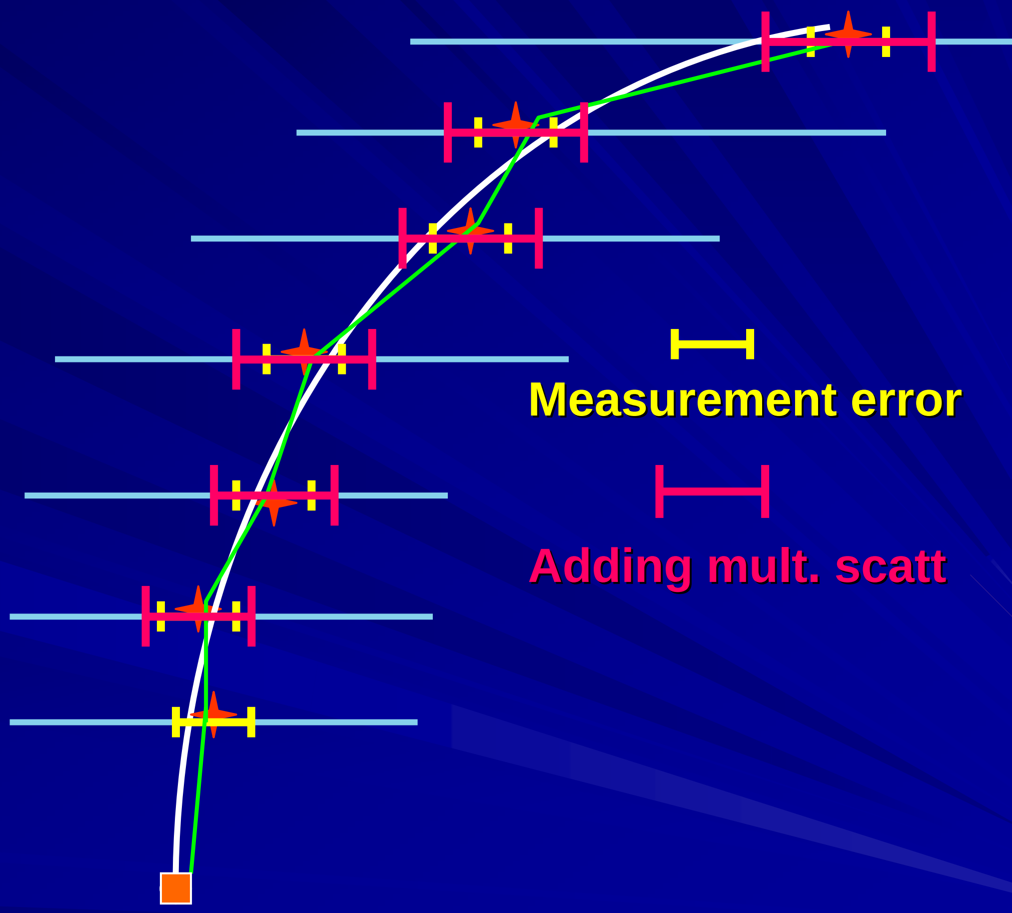
- Explained in detail in note CERN-ATL-INDET-2005-004
- Relies on a traditional χ^2 minimization
  - $\chi^2 = \Sigma_{tracks}\, r^T V^{-1} r$; r: residuals, V: res. error matrix, contains multiple scattering effects off-diagonal terms.
  - Global?: multi-parameter minimization
  - E.g. simultaneous minimization wrt a (align. param.), π (track param.): $(\partial\chi^2/\partial a)_m = 0$ & $(\partial\chi^2/\partial\pi)_m = 0$.
- How to solve analytically → linearization (of residuals) ⇔ parabolic approximation of the χ^2 , expand about the current state $(a_0,\pi_0,\ldots)$:
  - $\chi^2 \approx (\chi^2)_0 + (\partial\chi^2/\partial p^i)_0\, \delta p^i + ½\, (\delta p^i)^T\, (\partial^2\chi^2/\partial p^i\partial p^j)_0\, \delta p^j$
    - $p^1 = \pi$, $p^2 = a$; $p^3 = v$ (common vertex) for the three parameters case
  - This assumes we are “close enough” to the solution

Principle of the global fit (2)

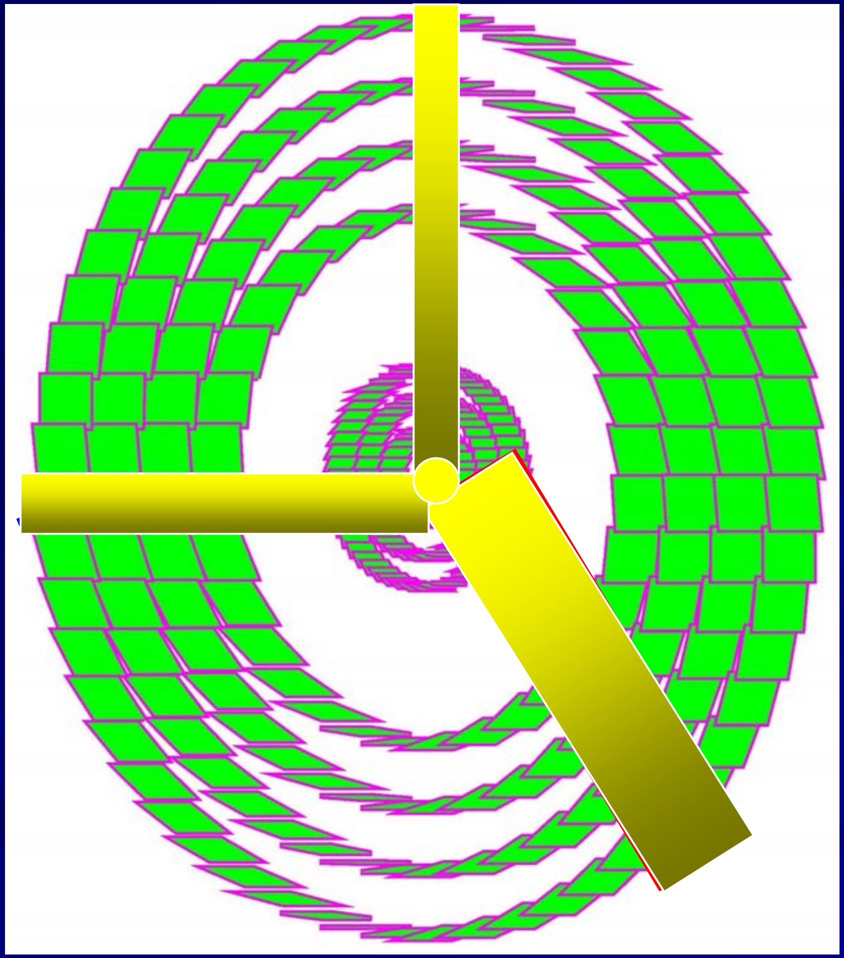
- Single param. alignment: $(\partial\chi^2/\partial a)_m = 0$ only
  - Solution: $\delta a_m = a_m - a_0 = -(\Sigma_{tracks}\ \partial r/\partial a^T\ V^{-1}\ \partial r/\partial a\ )\text{-}1\ (\Sigma_{tracks}\ \partial r/\partial a^T\ V^{-1}\ r_0)$
  - Local fit: “the module does not know about the others”.
  - $\rightarrow M = \Sigma_{tracks}\ \partial r/\partial a^T\ V^{-1}\ \partial r/\partial a$ is formed of 6x6 blocks on the diagonal
- Adding $(\partial\chi^2/\partial\pi)_m = 0 \rightarrow$ tracks will tie the modules they cross together
  - $\delta a_m = a_m - a_0 = -(\Sigma_{tracks}\ \partial r/\partial a^T\ W\ \partial r/\partial a\ )^{-1}\ (\Sigma_{tracks}\ \partial r/\partial a^T\ W\ r_0)$
  - W contains the effect of the tracking and connects different modules
    - $W = V^{-1} - V^{-1}\ \partial r/\partial\pi\ (\partial r/\partial\pi^T\ V^{-1}\ \partial r/\partial\pi)^{-1}\ \partial r/\partial\pi^T\ V^{-1}$
  - $M = \Sigma_{tracks}\ \partial r/\partial a^T\ W\ \partial r/\partial a$ is no more block diagonal, though not completely populated
- Adding primary vtx minimization $(\partial\chi^2/\partial v)_m = 0$
  - Impact trk param.$\rightarrow$ primary vtx position
  - Obviously more module “talk to each other” (all the modules fired by selected tracks in the event are now coupled)
  - $\delta a_m = -M^{-1}\ V$, where M is more populated
- Note: M is simply the alignment inverse covariance matrix
- Possible constraints can be added as an additive term in the χ^2
  - E.g.: constraint a_c on alignment param. from survey: $(a-a_c)^T.U.(a-a_c)$; U constraint weight matrix

How is track info used?

- Track treated as a whole
  - High sensitivity to correlations between measurement planes
- Track param taken at the perigee
  - Extrapolation: multiple scattering taken into account, χ^2 properly reweighted and effect on residuals taken into account



Common vertex fit: intuitive idea



- Different regions of the detector are connected through the common vertex (not just “radial connection” provided by single track)
- Obviously additional information that should be carefully used
- Helps controlling the global modes

Principle of the code implementation

GeoModel

Tracking

InDetAlign Algs and Tools

Pre-processing, extract/select relevant info from tracks and module geom

GlobAlign

Processing of track/geom info for alignment

Intermediate calculations

Residual derivatives, etc.

Accumulate, fill objects

Evt level

Finalize

- Check for “dead” modules (use hit map)

- Output M & V and/or

- ~~Solve~~

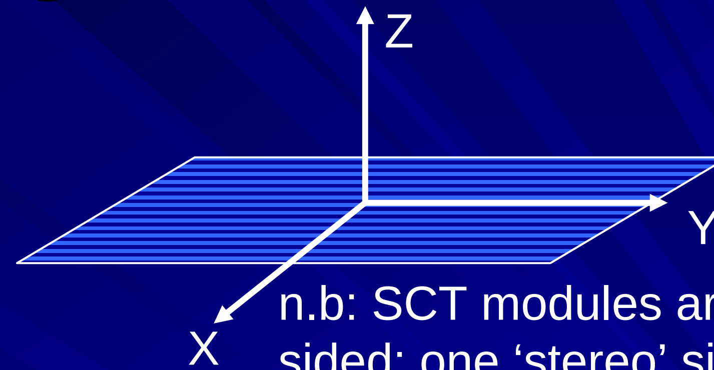
Update constants in DB

Beowulf cluster

See M.Karagoz-Unel presentation

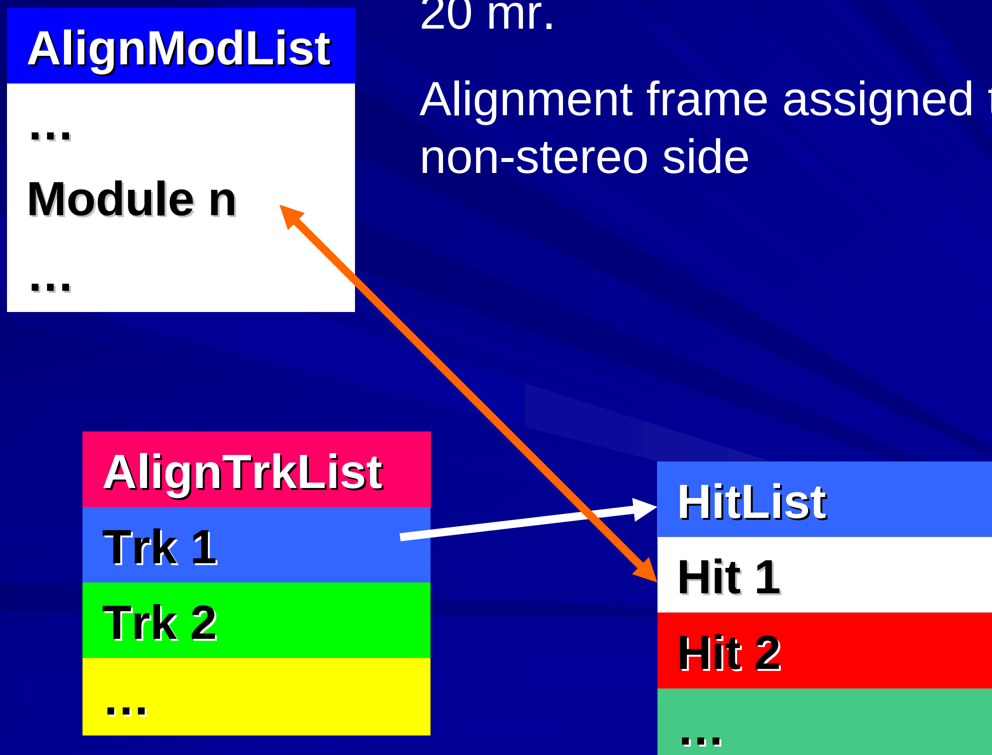
Pre-processing information

- Create Si Module objects, filled in a module list once at the beginning of the job
  - Module object contains basic info: geometry, identification bits (which detector, layer, ring, etc…), Position/orientation of local frame, mapping index to link with hit
- Create AlignTrk list, beginning of event
  - Trk object: hits list, trk param., etc..
    - Hit Object: residual, hitpos, scat. angles/errors, module ID, residual derivatives wrt trk param.,…

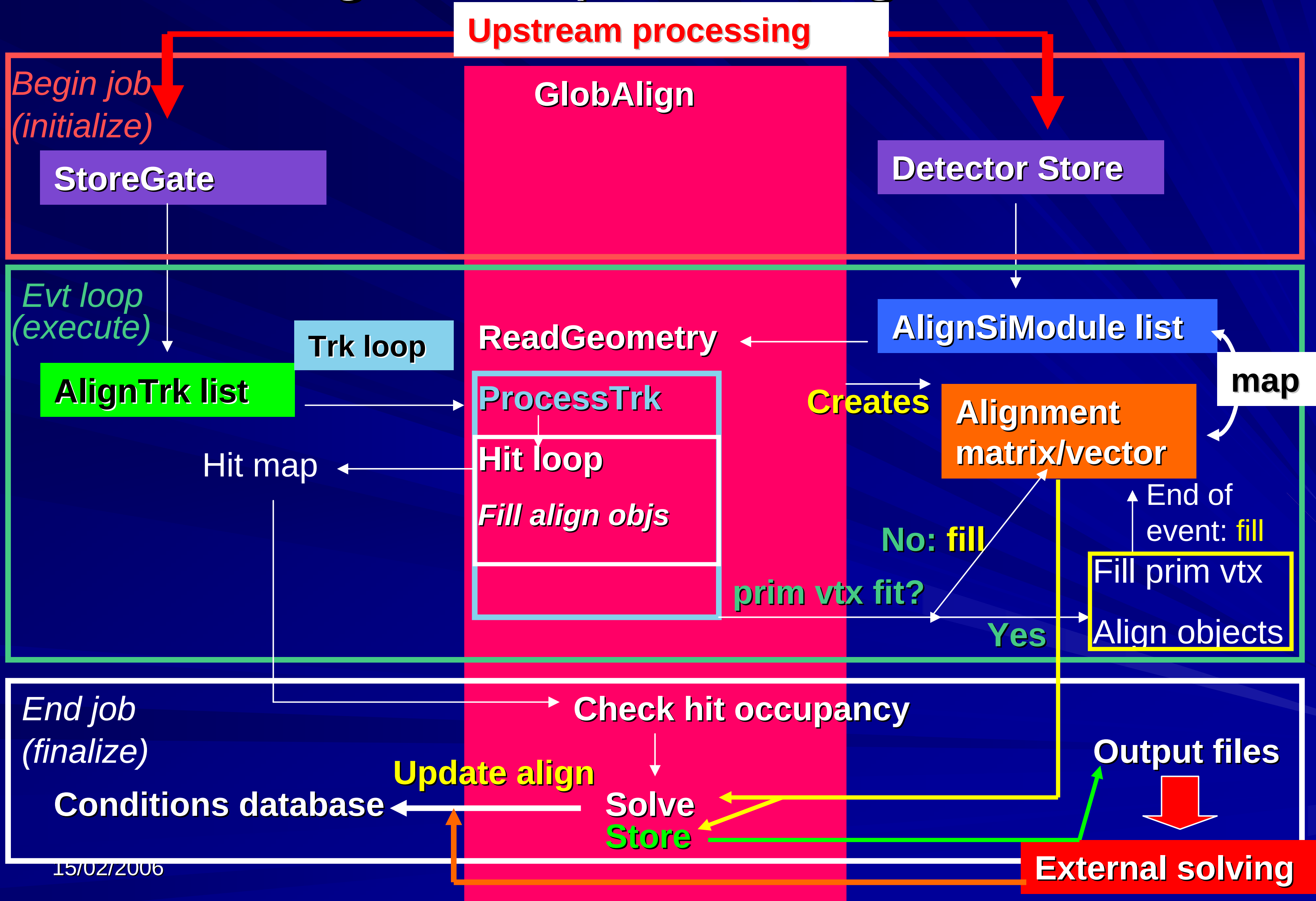


n.b: SCT modules are double sided: one ‘stereo’ side tilted ~ 20 mr.

Alignment frame assigned to non-stereo side



Alignment processing flow

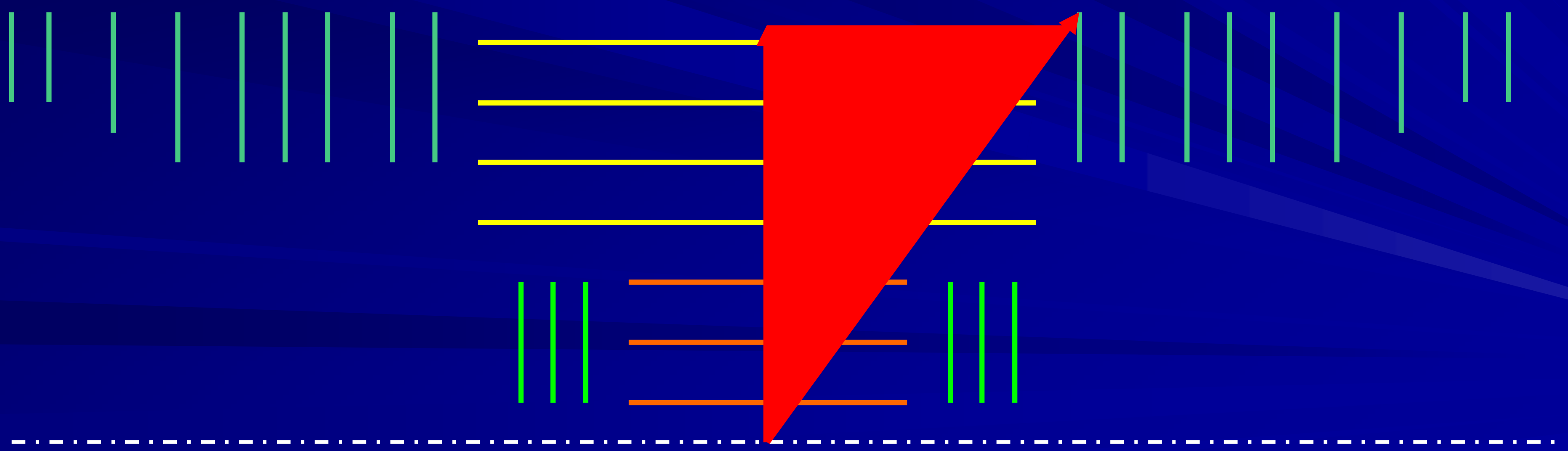


A word about solving

- Solving not done through direct inversion
- Use of diagonalization instead (LAPACK)
  - $\delta a_m = -M^{-1} V$
  - $M = U^T D U$; $V = U^T Vd$; $\delta a_m = - U^T D^{-1} Vd$
  - End up with δa_m = linear combination of eigen modes
- Analyze of eigenvalues spectrum to remove singularities
  - Ex: without any external constraint or reference, global (exact or approached) degeneracies give zero or very small eigenvalues
  - To build solution remove ill-defined modes from the combination
- Important: the influence of ill-defined and global modes is removed by more information/constraints fed in the alignment procedure
  - Could also be done by freezing artificially some of the (reference) modules
- For the full detector, number of DoF too big for one single processor
  - LAPACK $\rightarrow$ SCALAPACK (scalable LAPACK)
  - Single processor $\rightarrow$ parallel cluster
  - See M.Karagoz-Unel talk for details
- Solving still possible with single processor for sub-geometry
  - # DoF <10000, typically

Test sample

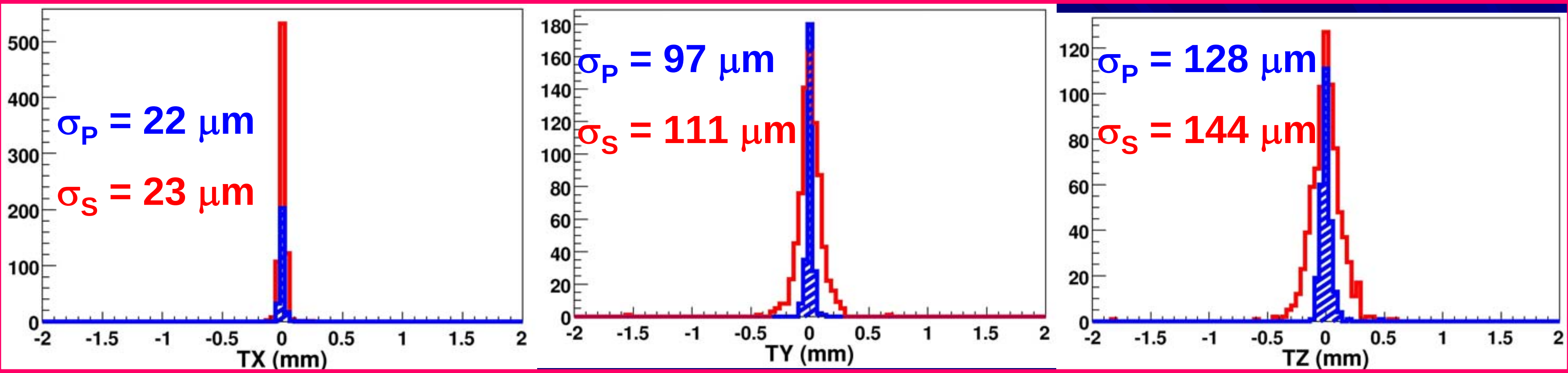
- Use 10k muon events, 10 trk/evt, pt $\in$ [2,20] GeV/c, $\eta \in$ [0,1]
- Primary vtx: <XY>=0mm,σ(xy) = 1mm - <Z>=6cm, σ(z) = 1cm
- Active region in the barrel: 1030 modules, 6180 DoF
  - Significative sample: more than 1/6 of the full geometry



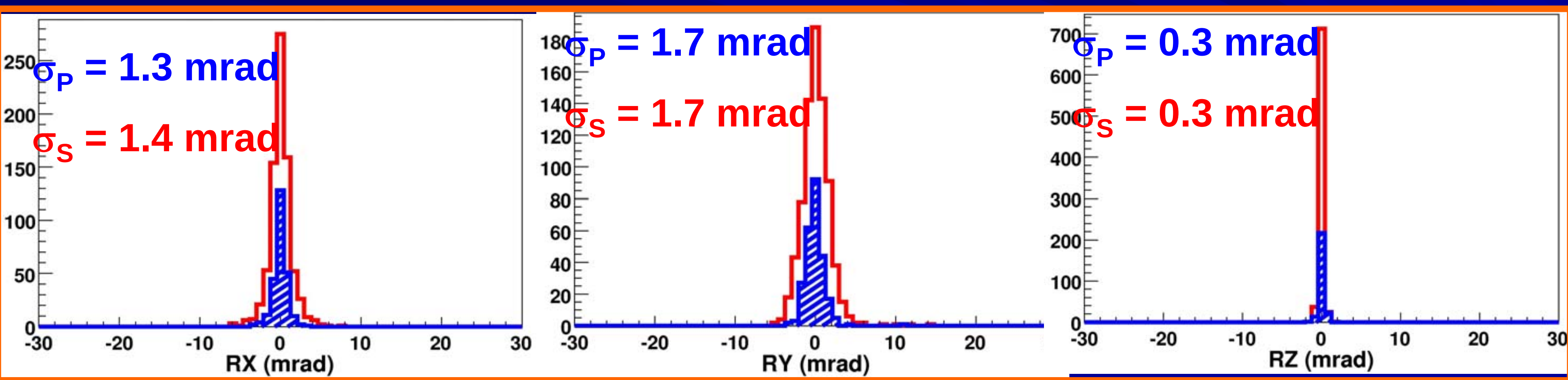
Results for alignment constants

PIXEL & SCT (vtx fit on)

Translations



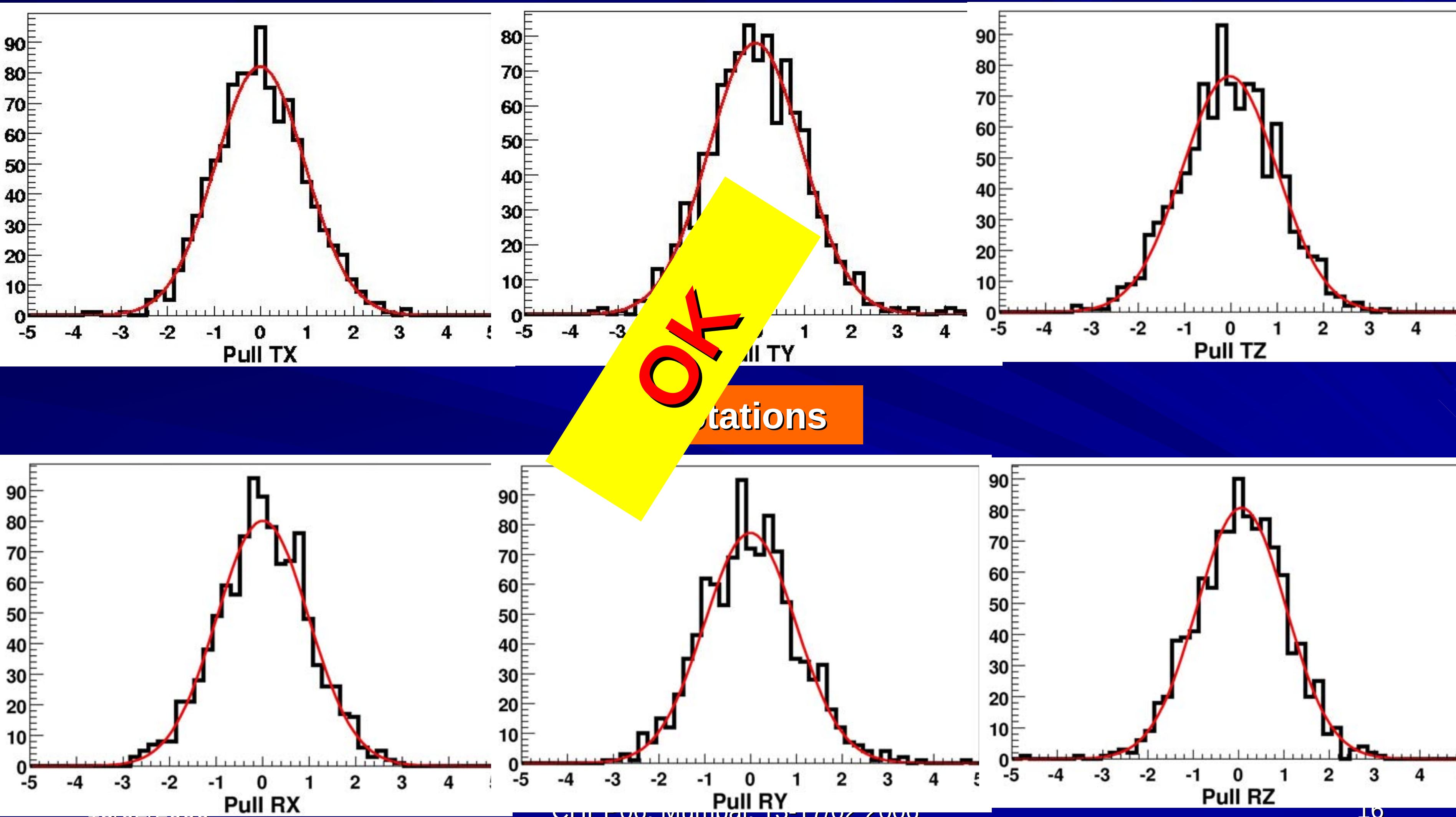
Rotations



Check of errors calculation: pulls of the parameters

PIXEL + SCT merged

Translations

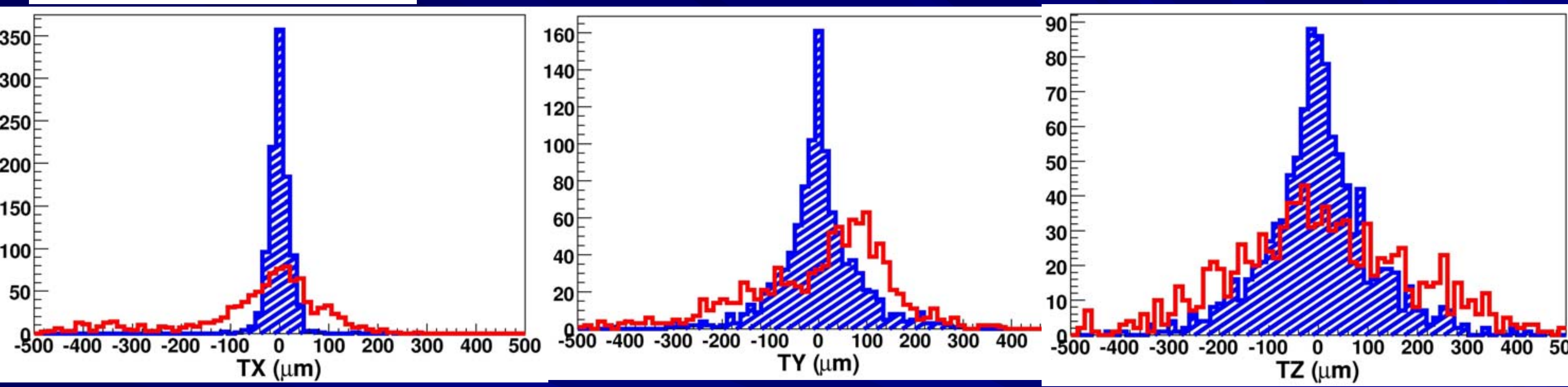


Benefit of including common vtx in the fit

With & without vtx fit

PIXEL + SCT merged

Translations



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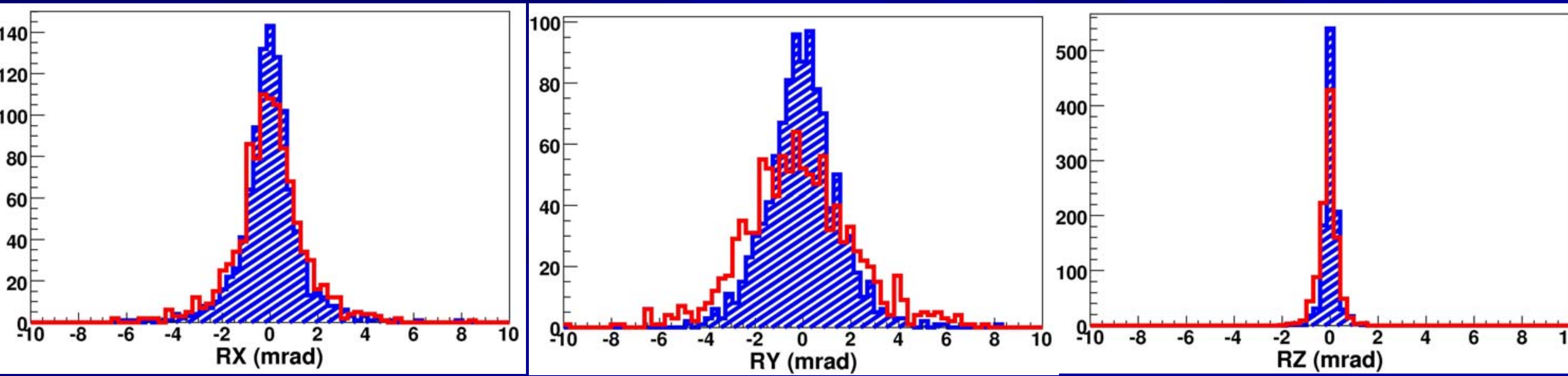


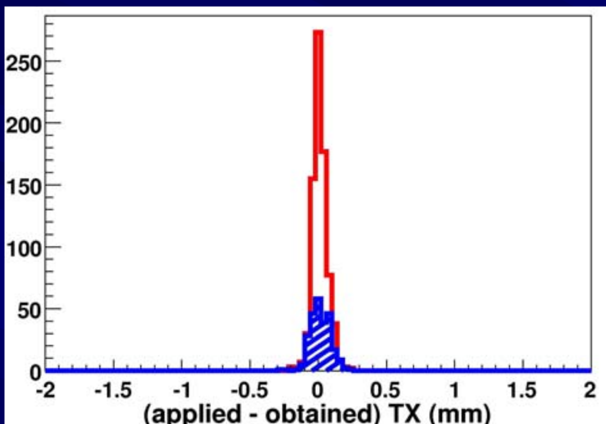
Simulating misalignments

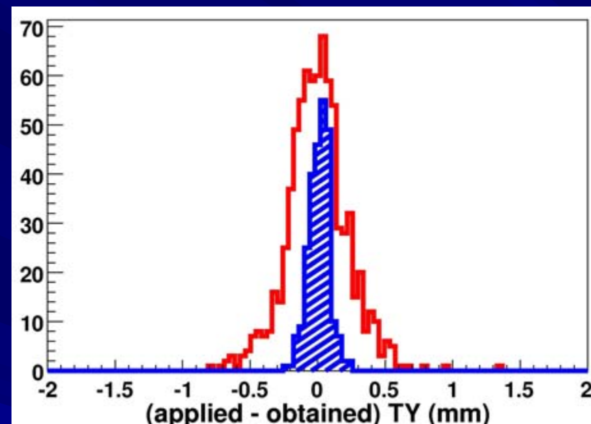
- Misalignments at the reco level, before pattern recognition
  - Move hits around for now
  - Ultimately, would like to move the detector volumes: tools will be ready soon (see V.Tsulaia talk))
- Tried three misalignment sets
  - P1: Pixel, local with RMS (rϕ:30,z: 20,r: 30 μm) + collective layer motion with RMS (rϕ:20,z: 20,r: 20 μm)
  - S1: SCT, local - RMS (rϕ:100,z: 100,r: 500 μm)
  - S1P1: combination of both
- Plot difference between applied and obtained numbers “out of the box”. Study first iteration for now.

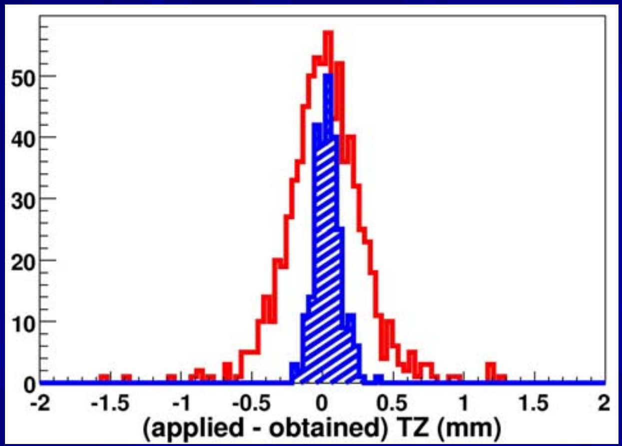
Results for P1

Pixel & SCT (vtx fit on)

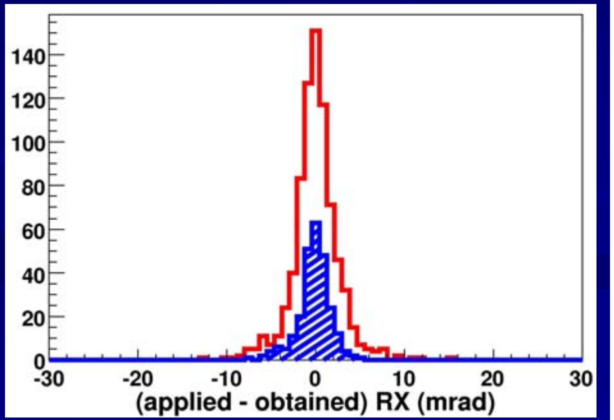
Translations

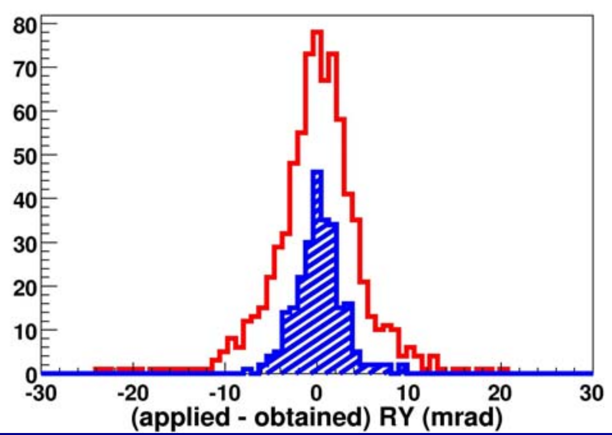


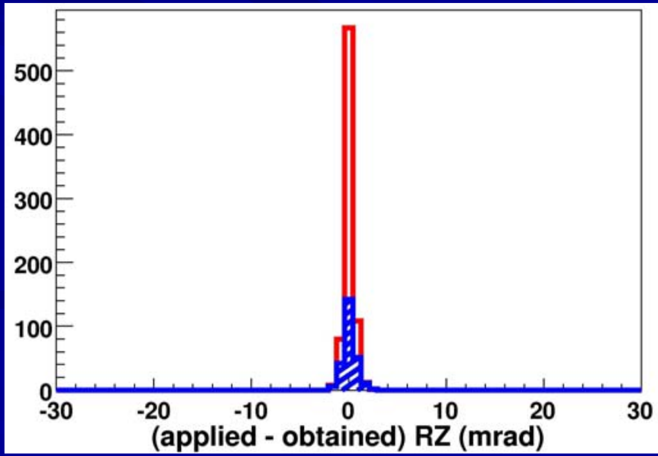




Rotations



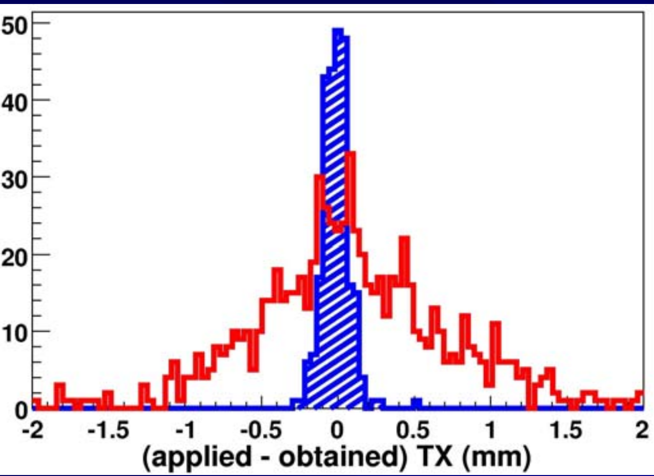


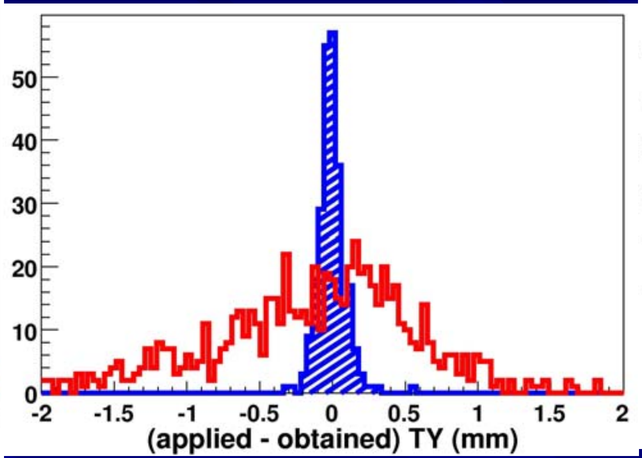


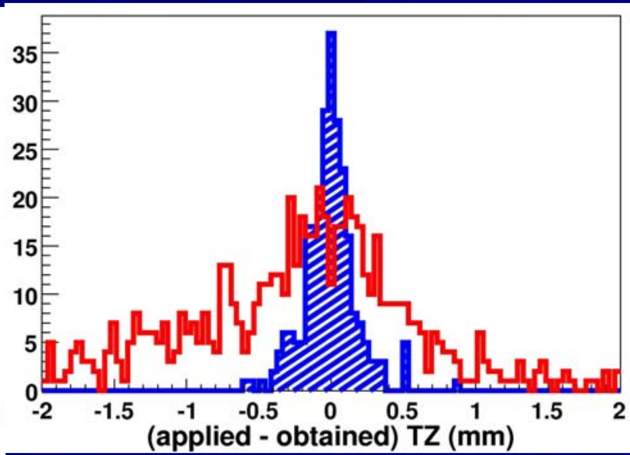
Results for S1P1

Pixel & SCT (vtx fit on)

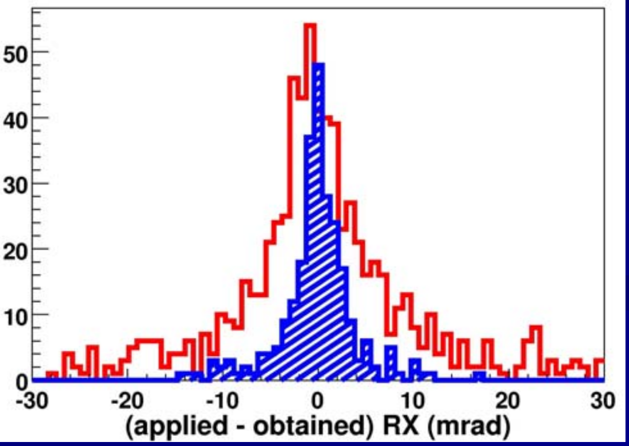
Translations

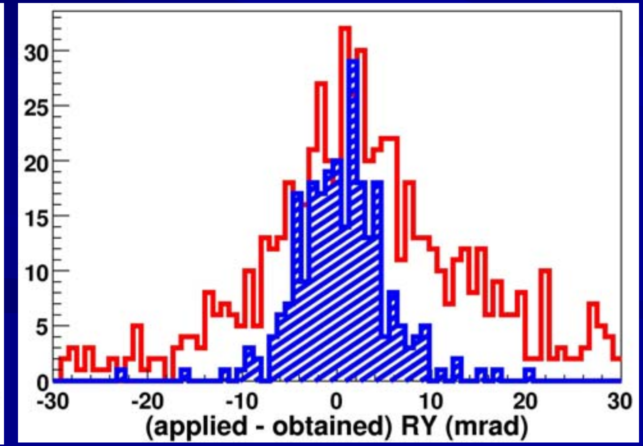


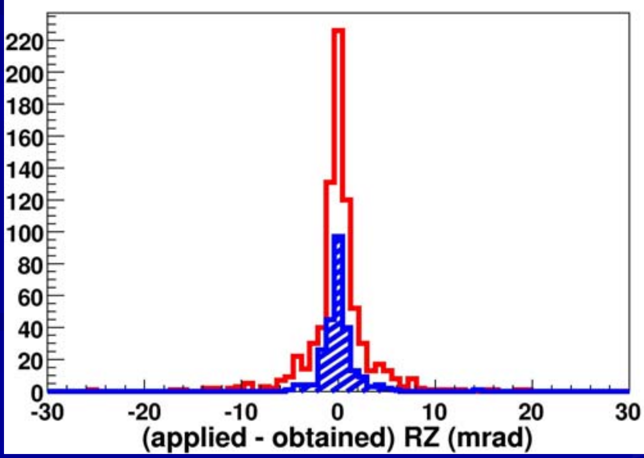




Rotations







What have we learnt?

- Used statistics ~ 100 times less than the target data sample
- Scaling the RMS of obtained results: final goal of O(1μm) stat precision in transverse plane achievable in principle
- Error calculation Ok
  - Pull distribution centred at zero, RMS ~ 1.
- Decisive role of common vtx!
- Preliminary test with misaligned datasets reinsuring
  - Although some of the misalignments are far from the linear approximation, alignment results still behave well for a first iteration, no serious bias observed (entries in asymmetric tails for S1P1 are also the ones with biggest errors).
  - Distributions of (applied – obtained) misalignments are centred near zero
    - Spread due to lack of statistics + linear approximation not always satisfied (e.g: O(100μm) misalignments for SCT!). Need for iteration at this stage expected anyway
    - Unfolding large structure (e.g layers) alignment and local alignment may help converging more efficiently (“hierarchical” alignment)

Summary

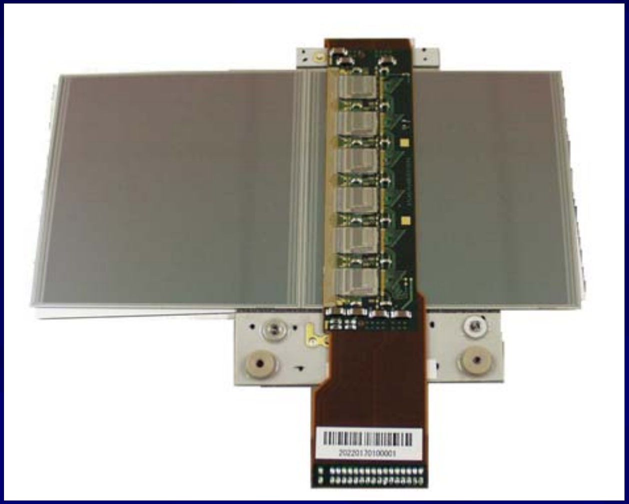
- Alignment software using global fit method has been implemented in ATLAS SW framework
  - Reasonable timing ~ 5ms/track
- First tests with this package have shown that aligning a system with big number of DoF (O(1000)) is quantitatively possible
  - Extension to full geometry still to be studied, though
  - More constraints to be considered, e.g.:
    - Survey constraint currently being studied
    - Planned: study of constraints from resonances (Z or $J/\psi \rightarrow \mu\mu$) or calorimeter energy measurement for electrons.
- First glimpse with misalignments promising
  - Look forward repeating it with more statistics and trying a couple of iterations for recovering large misalignments
  - New coming ATLAS simulated samples for further tests
- Coming months will be very busy but exciting!
  - Aligning huge number of Silicon modules to a high precision is meant to be a major achievement with big impact on physics performance

Summary – cont

- Alternative alignment methods developed in ATLAS
  - These are mainly iterative methods. No big system to solve but iterations required even for small misalignments
- New innovative method is being developed
  - Relies on Kalman filter approach, some common points with global χ^2
  - See CMS talk (E.Widl - R.Fruhwirth et al.) for the first tests
  - Plans in ATLAS to use a similar philosophy as an alternative
    - Avoids solving big system but allocation of big covariance still needed
- Acknowledgements: to our ATLAS collaborators in general and in particular to S.Haywood, P.Bruckman, A.Bonissent, K.Bernardet, D.Fouchez, A.Tilquin for their first thoughts on applying the global fit to ATLAS detector and for doing feasibility studies with standalone prototype code(s). Thanks also to R.Hawkings and G.Gorfine for providing tools for the crucial pre- and post-processing stages.

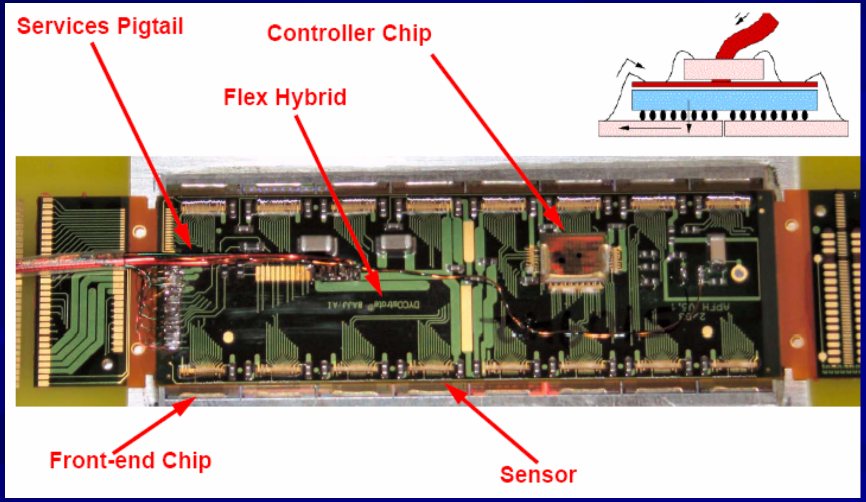
Back up slides

Pixel/SCT Modules



SCT Barrel module: double sided with a stereo angle (40 mr), pitch 80 μm

One dimension measurement for each side: rϕ residual, precision ~ 20 μm



Pixel module size: 16.4 mm x 60.8 mm; 46K channels per module; pixel size: 50 x 400 μm^2

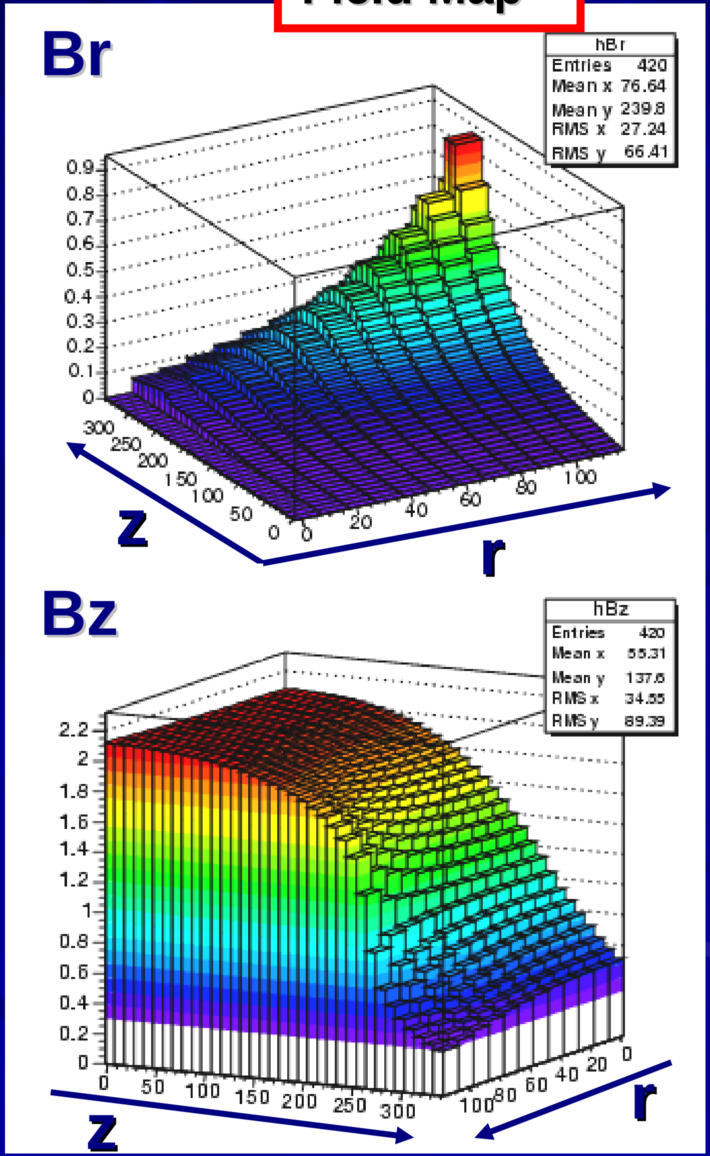
Two dimension measurement:

rϕ and z residuals precision ~ 10 and 90 μm

Numerical accuracy

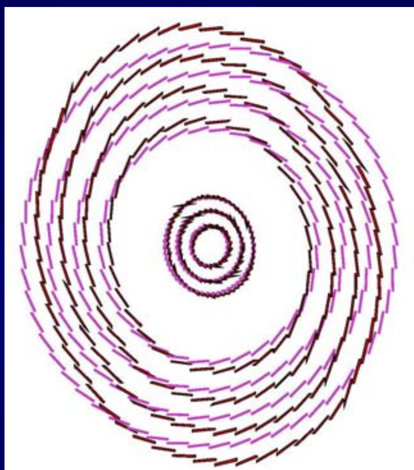
- Derivatives wrt track parameters
  - Extrapolation assumes analytical approximation in constant B(z) field
  - Assumption not valid in endcaps region. Use numerical integration (parabolic, Runge Kutta) of the trajectory to determine more accurate derivatives
    - To save computing time, do it only for most sensitive parameters, e.g, curvature.
- Alignment weight matrix W
  - Needs inversion of V^{-1} and track weight $\partial r/\partial \pi^T V^{-1} \partial r/\partial \pi$
  - Numerical caution already at this stage
    - V^{-1} size could be up to 19x19 (in overlap regions)
    - Order of magnitude of V elements becomes important
      - E.g if Vij ~ $0(10^{-q})$, determinant ~ 10^{-19q}. Low determinant = unstable/imprecise inversion $\rightarrow$ use of rescaling to avoid big $\mathbf{VV^{-1} - I}$ deviations
    - Determinant check done via quick LU decomposition, using Crout convention. Cholesky decomposition LL^T for symmetric positive definite matrices.

Field Map

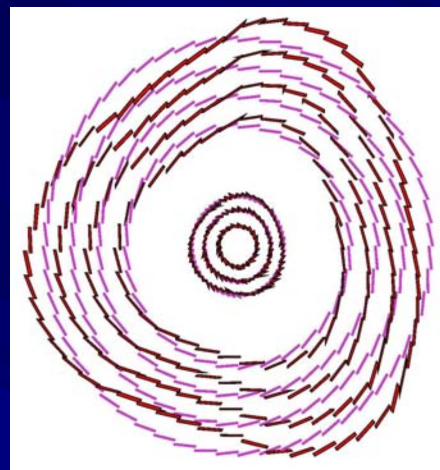


Vibrational global modes
N folds

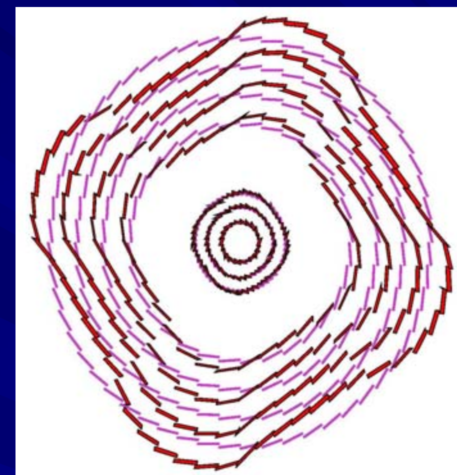
N=2



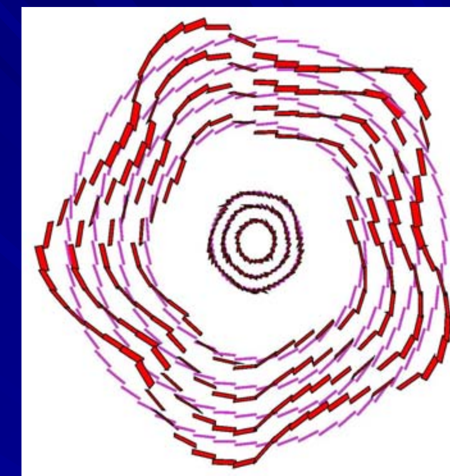
N=3



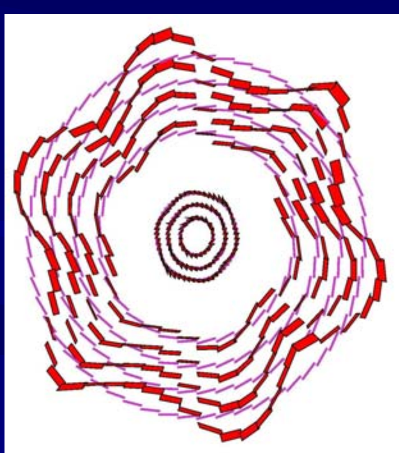
N=4



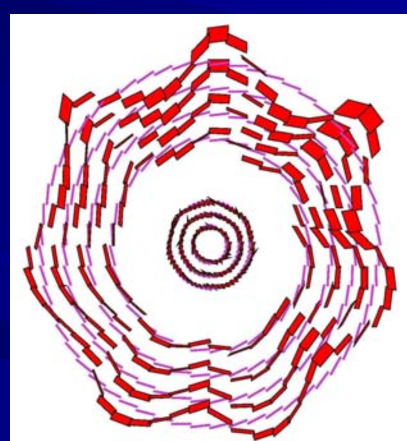
N=5



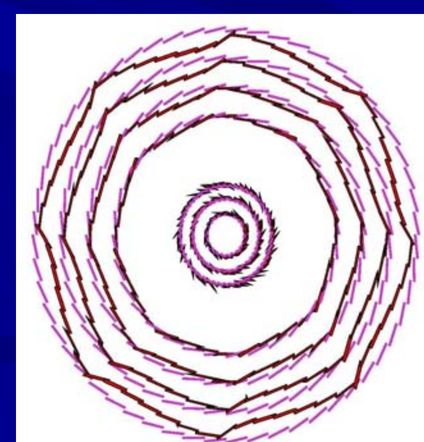
N=6



N=7



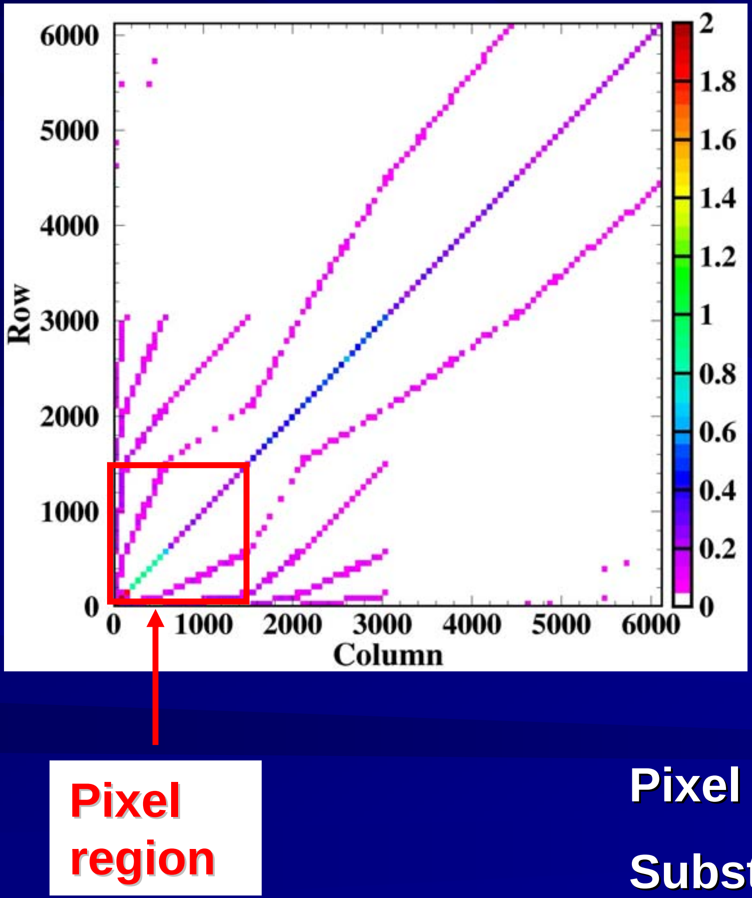
N=8

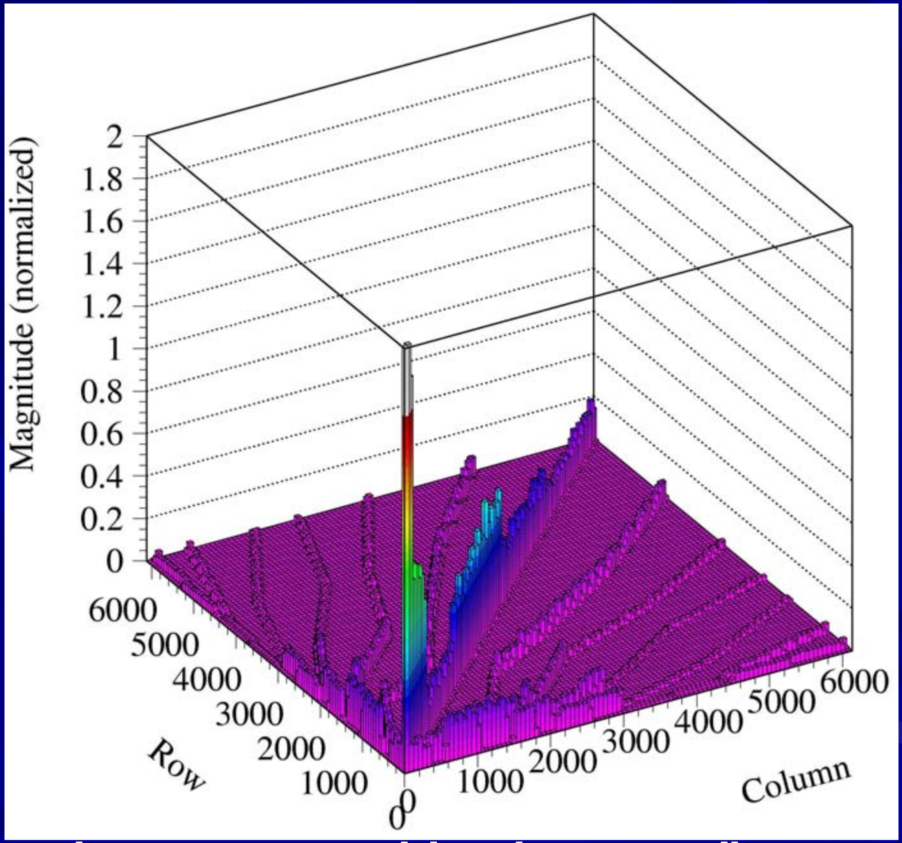


Plots of the eigen-displacements corresponding to some of the lowest eigenvalues

Normalized $|\Delta M_{ij}|$ (difference of matrix elements with and without primary vtx fit)

Note: modules are ordered by layer and increasing ring/pseudo-rapidity





Pixel region more sensitive (expected)

Substantial off-diagonal correlation terms