STAR Forward Tracker Alignment

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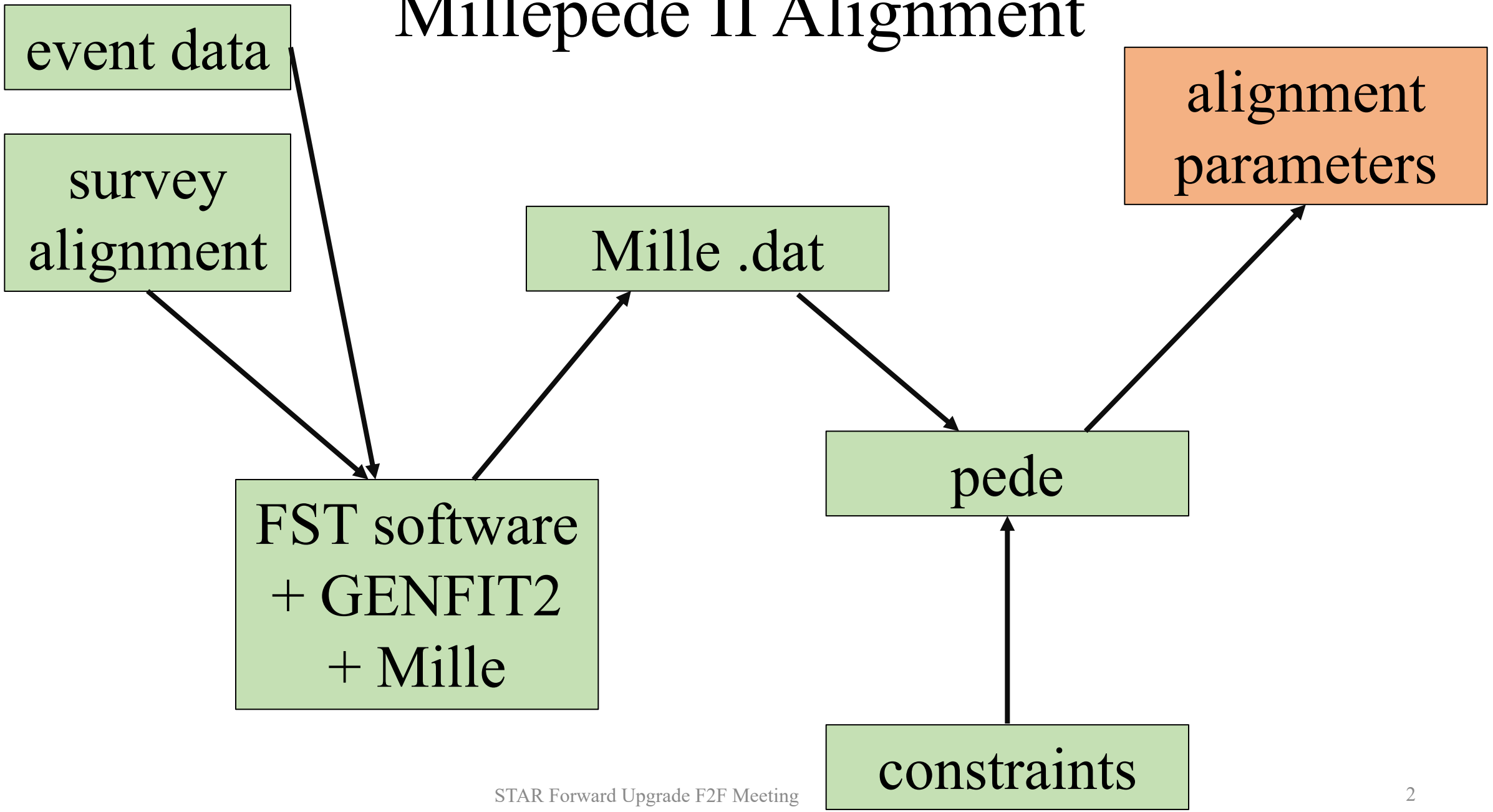
Millepede II Alignment



Millepede-II with GBL

- Track parameterized by $\boldsymbol{q} = (\boldsymbol{u_i}, \ldots, \boldsymbol{u_{\#planes}})$, where $\boldsymbol{u_i}$ vectors are offsets at FST or sTGC plane.
- Minimize the following function, where **p** are the alignment parameters and $\mathbf{q_j}$ are the track parameters.

$$\chi^2(\mathbf{p}, \mathbf{q}) = \sum_{j}^{\text{tracks}} \sum_{i}^{\text{measurements}} \left(\frac{m_{ij} - f_{ij}(\mathbf{p}, \mathbf{q}_j)}{\sigma_{ij}} \right)^2$$

- Data necessary to run Millepede-II:

# of local parameters	array: $\left(\frac{\partial f}{\partial q_j}\right)$
# of global parameters	array: $\left(\frac{\partial f}{\partial p_l}\right)$
residuals = $m_{ij} - f_{ij}(\boldsymbol{p}, \boldsymbol{q}_j)$	label array, l
σ = standard deviation of the measurement	

https://www.desy.de/~kleinwrt/MP2/doc/html/draftman_page.html

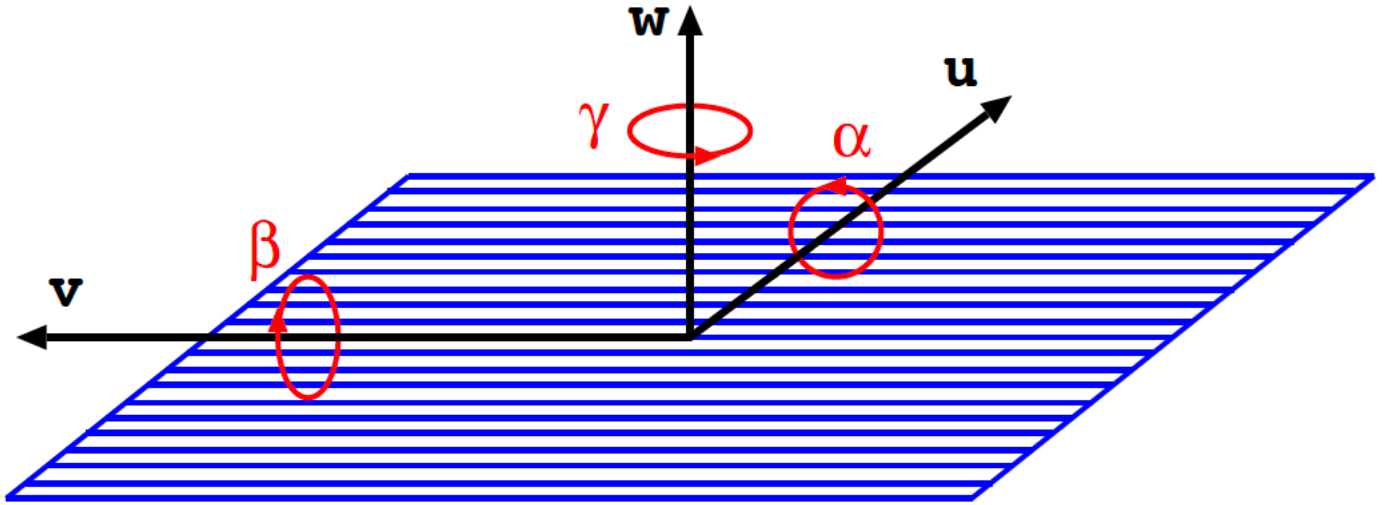
Alignment (global) Parameters

FST

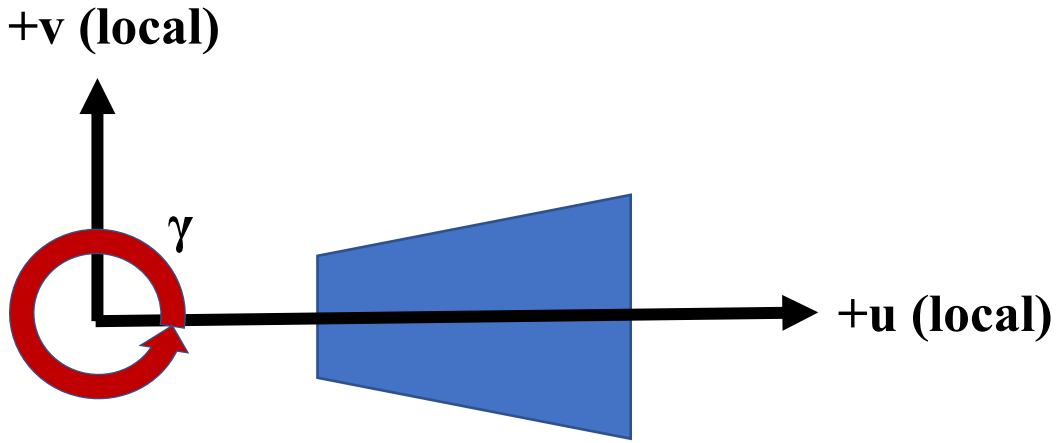
Translations: $\Delta u,\ \Delta v,\ \Delta w$

Rotations: $\Delta\alpha, \Delta\beta, \Delta\gamma$

- 3 alignment parameters for a sensor (108 sensors).
  - $\Delta w,\ \Delta\alpha, \Delta\beta\ = 0$, since we assume they lie flat on the wedge.
- 6 per wedge (36 wedges).
- 6 per FST half (2 halves).
- 6 for FST.
- 558 alignment parameters.



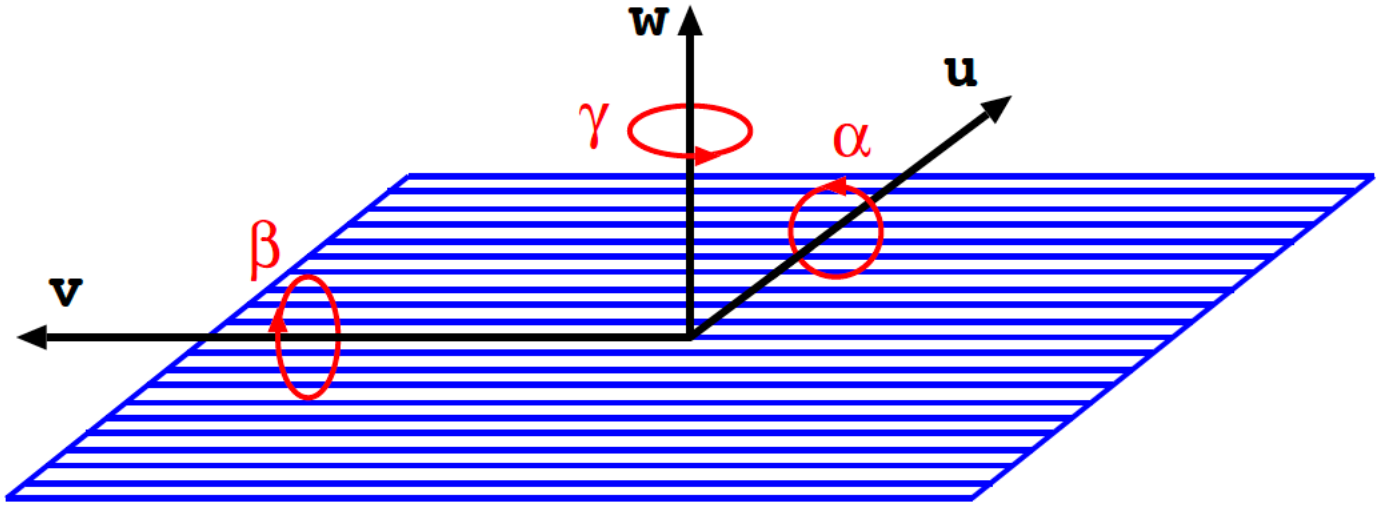
CMS, doi:10.1088/1748-0221/9/06/P06009.



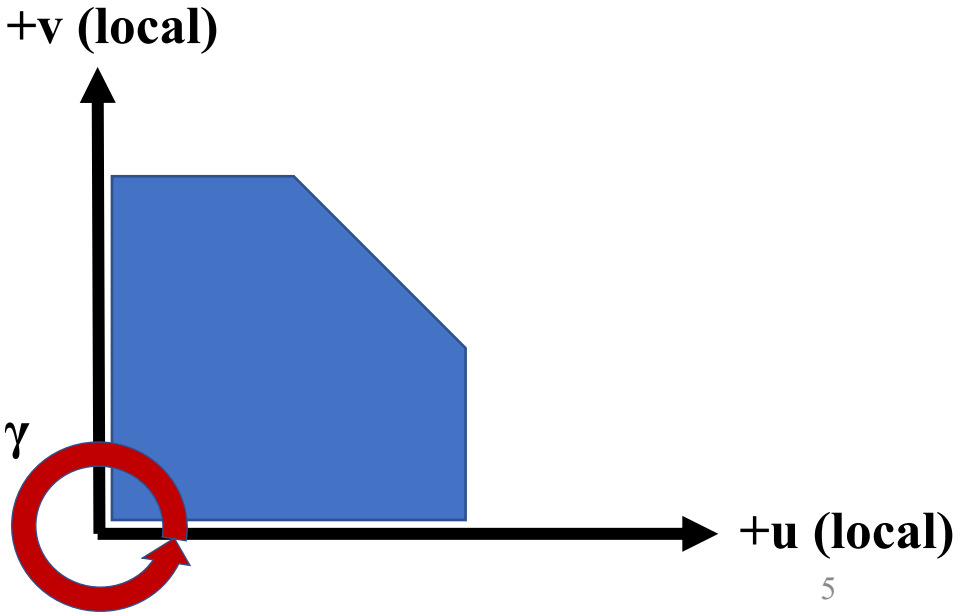
Alignment (global) Parameters

FTT (sTGC)

- 6 alignment parameters per pentagon (16 pentagons).
- 6 per plane (4 planes).
- 6 for sTGC.
- 126 alignment parameters.



CMS, doi:10.1088/1748-0221/9/06/P06009.



Hierarchy of Alignment Parameters

- Each track prediction for a sensor relies on the larger structures it is contained within.
  - Sensor on wedge, wedge on FST half, half on Full FST, full on TPC.
- We can calculate the all the global derivatives using chain rule

$$\frac{\mathrm{d}f_{u/v}}{\mathrm{d}\boldsymbol{\Delta p}_l} = \frac{\mathrm{d}\boldsymbol{\Delta p}_s}{\mathrm{d}\boldsymbol{\Delta p}_l} \cdot \frac{\mathrm{d}f_{u/v}}{\mathrm{d}\boldsymbol{\Delta p}_s},$$

$f_{u/v}$ = track prediction
$\mathrm{d}\boldsymbol{\Delta p}_s$ = change in sensor global parameter
$\mathrm{d}\boldsymbol{\Delta p}_l$ = change in containing structure global parameter

- The sum of all sensors global parameters pertaining to a larger substructure are constrained to zero to prevent shift of overall structure by the sub-components.
- Constraints added by .txt file input to pede.

CMS, doi:10.1088/1748-0221/9/06/P06009.

Multiple Scattering in GBL

- Multiple scattering covariance from the previous measurement plane accounted for at the current measurement plane in the GBL trajectory.
- The covariance matrix of scattering angle (w.r.t track direction) is calculated using:

$$\sigma_\theta = \frac{0.0136}{p}\sqrt{x/\chi_0}[1 + 0.038ln(x/\chi_0)].$$

$$V_k = \begin{pmatrix} \sigma_\theta^2 & 0 \\ 0 & \sigma_\theta^2 \end{pmatrix}.$$

- Where x is track length within the sensor, χ_0 is the radiation length of the material and p is the magnitude of momentum.
- Kalman filter can treat material as continuous, while GBL uses discrete scatters.

J. Beringer et al. (Particle Data Group), Phys. Rev. D86, 010001 (2012)

GENFIT2 Classes for GBL

GblPoint.h/cc: contains all data for 2D measurements (derivatives, residuals, covariance, etc.).

GblTrajectory.h/cc: holds all GblPoints, can be fit or used directly for Mille output.

MilleBinary.h/cc: Organizes the data from GblTrajectory into the exact format required for pede.

GFGbl.h/cc: GBL fitter class implementing Mille binary file output and data collection. Originally written for BELLE II alignment.

StFwdGbl.h/cc: Adapted version of GFGbl for use with the Forward Tracker Alignment.

Single Sensor Alignment

- Misalign 1 inner sensor (sensorIdx = 36) in FST simulated geometry.
- Throw mu+ with particle gun with following settings:
  - $0.2 < p_T < 2.0$ GeV/c
  - $2.8 < \eta < 4.5$
  - $0.9 < \varphi < 1.7$ rad
  - B = 0 T
- Require hits on sensors: 0, 36, 72 (3 inner sensors, 3 different disks, all in same φ position. Also, all 4 sTGC.
- Fit with GenFit Kalman filter and then refit with GenFit GBL.
- Output all necessary data to Mille.dat files.

Single Sensor Alignment

- Mille.dat files are then fed to pede.
- Can specify initial values of alignment parameters and their pre-sigma (helps stabilize a poorly defined parameter).

```
Parameter
label   initial_value   presigma
 ...
label   initial_value   presigma
```

Example of pede parameter entries.

- Fix rotations about u-axis and v-axis, in addition to w translation by setting pre-sigma < 0.0.
- Matrix inversion used to solve for alignment parameters.
- ~50k tracks used for each trial.

Single Sensor Alignment Results

No Misalignment

Parameter	Input	Output	Error
Δu (μm)	0.0	-0.3	2.9
Δv (μm)	0.0	0.0	1.5
Δγ (mrad)	0.0	4.3E-3	1.7E-2

w-axis rotation

Parameter	Input	Output	Error
Δu (μm)	0.0	-0.2	3.2
Δv (μm)	0.0	-2.1	1.7
Δγ (mrad)	2.00	1.91	0.02

u shift

Parameter	Input	Output	Error
Δu (μm)	50.0	46.4	2.9
Δv (μm)	0.0	-1.2	1.5
Δγ (mrad)	0.0	1.0E-2	1.7E-2

v shift

Parameter	Input	Output	Error
Δu (μm)	0.0	1.6	2.9
Δv (μm)	50.0	44.1	1.6
Δγ (mrad)	0.0	2.9E-2	1.8E-2

Single Sensor Alignment Results

u,v shift + w-axis rotation (~50k tracks)

Parameter	Input	Output	Error
Δu (μm)	50.0	46.1	3.2
Δv (μm)	50.0	43.2	1.7
Δγ (mrad)	2.0	1.92	0.02

u,v shift + w-axis rotation (~850k tracks)

Parameter	Input	Output	Error
Δu (μm)	50.0	49.3	0.9
Δv (μm)	50.0	41.5	0.5
Δγ (mrad)	2.0	1.938	0.006

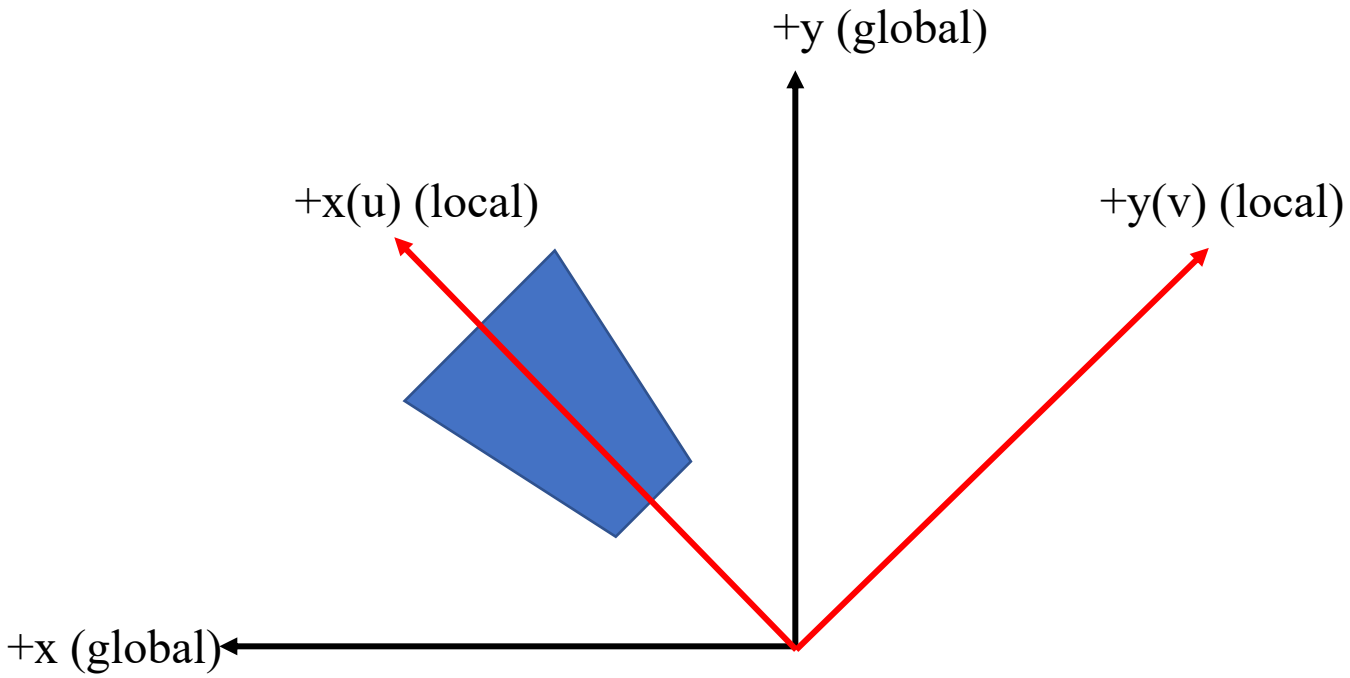
- Single FST inner sensor can be aligned to some degree with GenFit + Millepede II.
  - Slight discrepancy between input and output parameters.
  - Perhaps due to correlation between u and v coordinates?
    - Covariance is diagonalized for use in Millepede.

Summary and Outlook

- Single FST inner sensor has been somewhat successfully aligned using GenFit + Millepede II.
  - Discrepancy between input and output due to correlation between u and v coordinates?
- Attempt alignment of the following:
  - Outer silicon sensors
  - Multiple sensors simultaneously (just inner, just outer, and both)
  - Build up hierarchy (wedge and sensor simultaneously, etc.)
  - Single sTGC pentagon module
- Study effect of small misalignments on tracking performance and improvement after alignment.

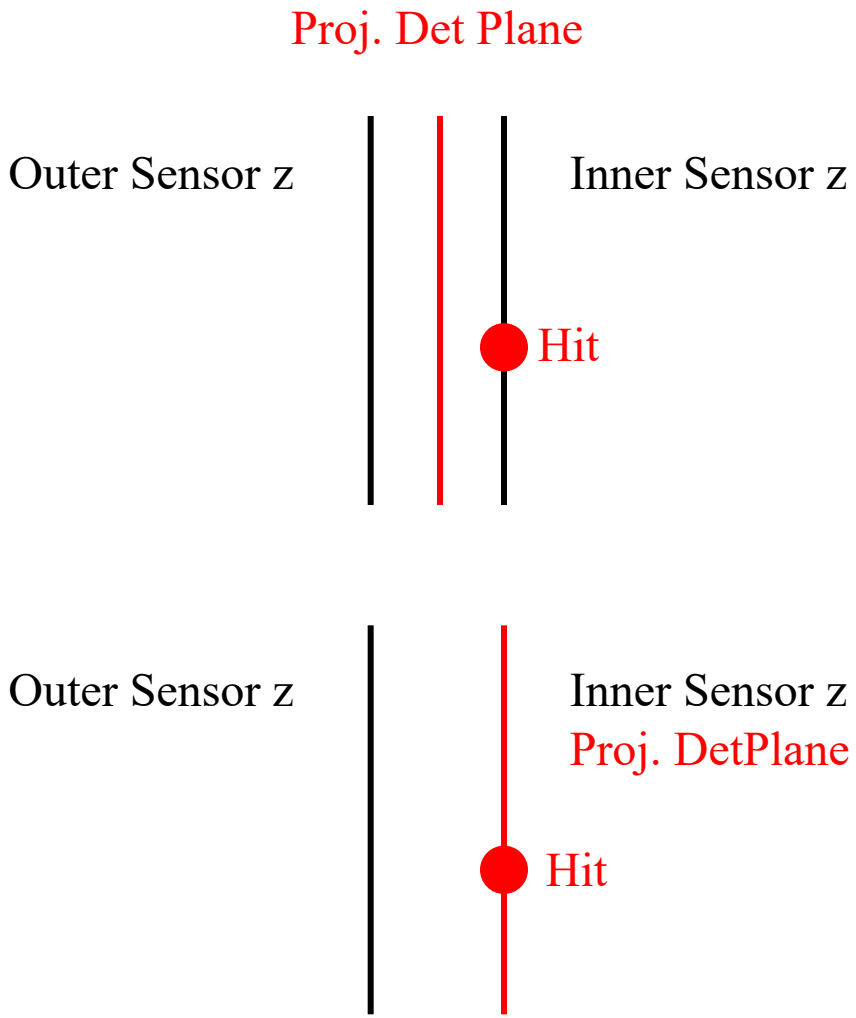
BACKUP

Changes to Tracking Code



- GenFit DetPlanes are placed with coordinate system (u,v,w) matching the sensor coordinate systems.
  - DetPlanes can be misaligned.
- Sensor hits are placed in local coordinate system.
  - When measurement is added to track, plane is specified. (Proper global placement)
- Sensor ID added to FwdHit object.

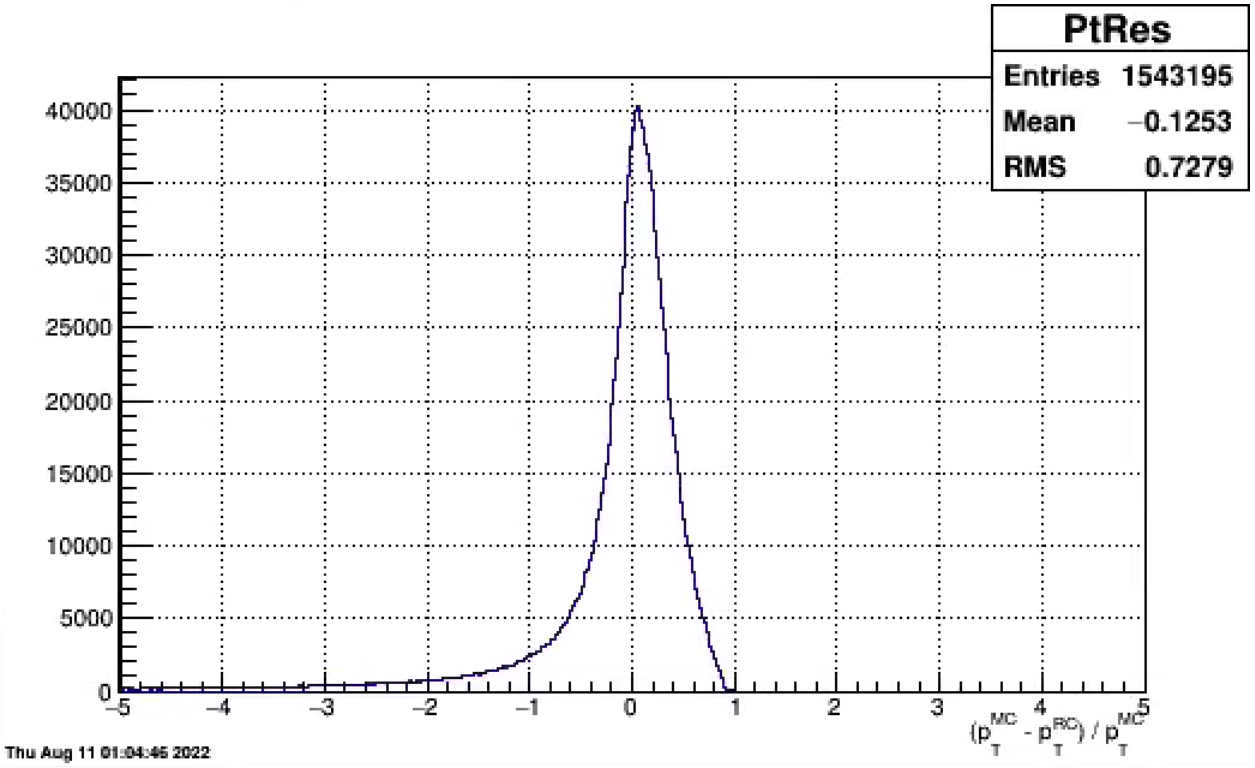
Changes to Tracking Code



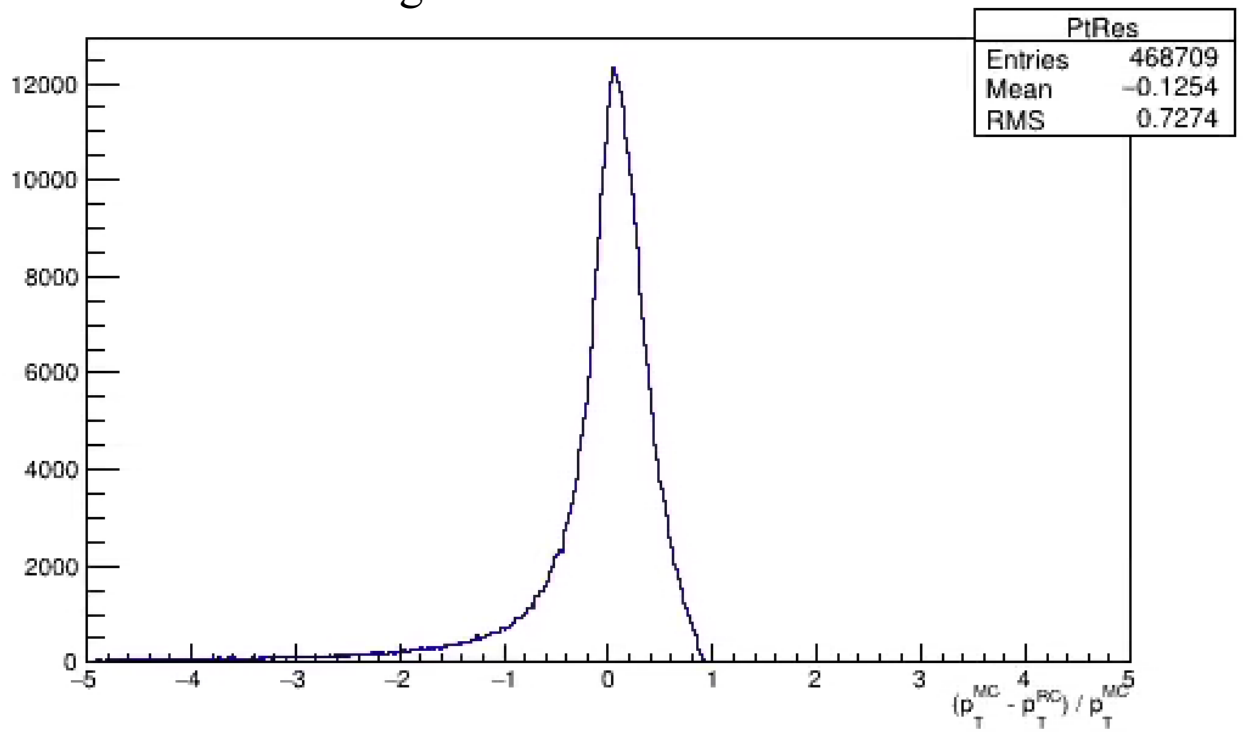
- Track is now projected to individual FST sensor GenFit::DetPlane.
- Previously projected to (x,y) position on midplane between sensors.
- Could be important if there are xz, yz rotations.
- Higher precision for alignment at cost of computation.

Tracking performance

Original Tracking

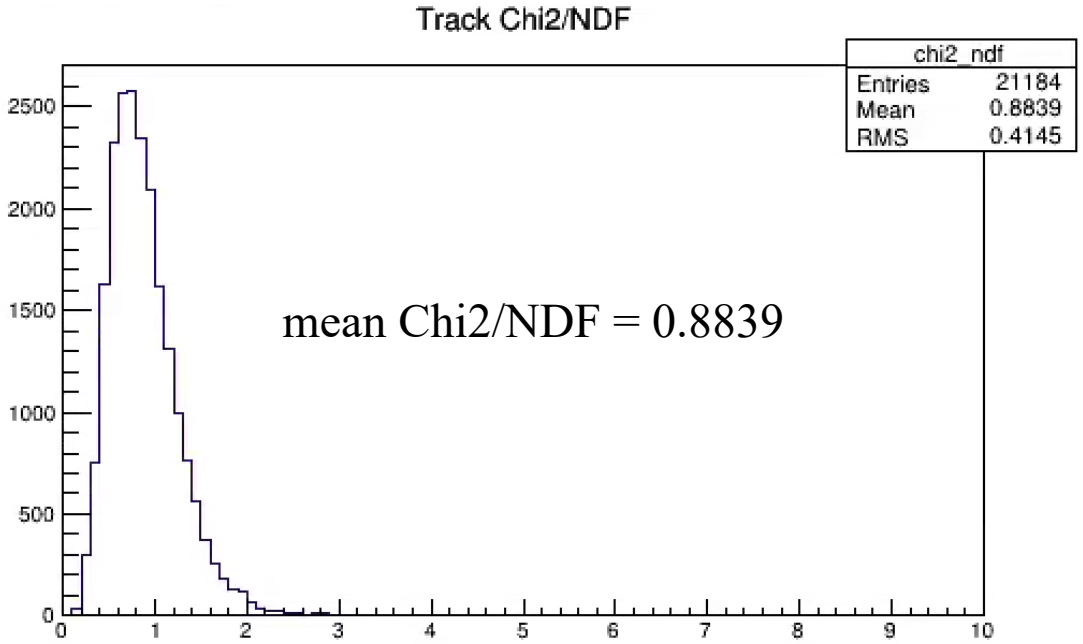


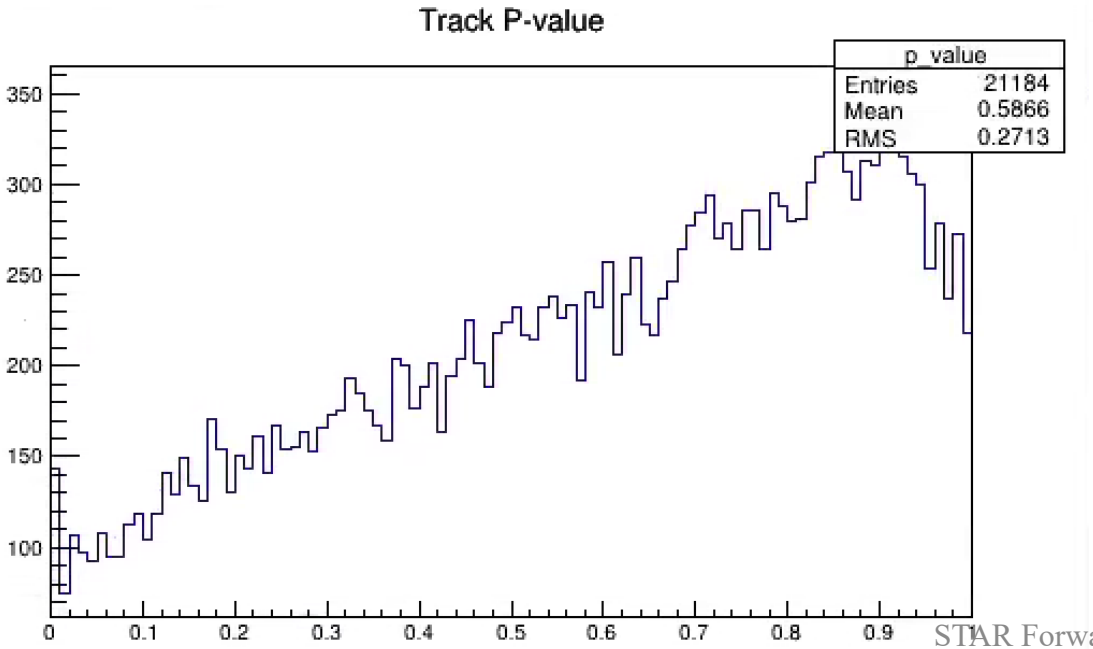
After tracking updates for alignment



- With ideal sensor placement, pT resolution is nearly identical.

Kalman Filter Fitted





GBL refitted