Scattering of 240 MeV/c muons with gaseous xenon in MICE

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Ionisation Cooling & Multiple Coulomb Scattering

Cooling Formula

$$\frac{d\varepsilon_N}{dX} \approx -\frac{\varepsilon_N}{\beta^2 E_\mu}\left\langle \frac{dE}{dX} \right\rangle + \frac{\beta_t (0.014\ \text{GeV})^2}{2\beta^3 E_\mu m_\mu X_0} \tag{1}$$

- Heating term due to Multiple Coulomb Scattering (MCS), derived using PDG expression:

PDG Scattering Formula

$$\theta_0 \approx \frac{(0.014\ \text{GeV})}{\beta p_\mu}\sqrt{\frac{\Delta z}{X_0}}\left[1 + 0.0038 \ln\left(\frac{\Delta z}{X_0}\right)\right] \tag{2}$$

- Most models use `GEANT4`, model works well for high-Z materials but overestimates scattering for low-Z materials - see `MUSCAT` `http://arxiv.org/pdf/hep-ex/0512005.pdf`

Multiple Scattering with Field Off

- Particles follow straight tracks through the spectrometers, scattering off absorber material in AFC
- Use TOFs to measure momentum, EMR & CKOVs for PID
- Measure multiple scattering as a function of momentum

Outline of Paper

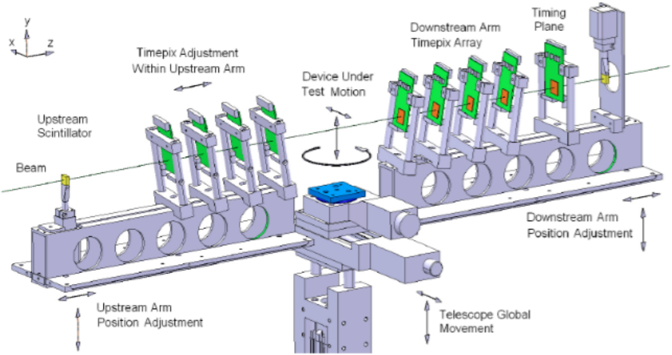
1. Introduce MICE and the issues relating to MCS measurement
2. MICE apparatus and beam conditions
3. Alignment of the MICE trackers
4. Analysis of xenon scattering data
    1. Unfolding geometric acceptance & detector response
    2. Bayesian deconvolution of scattering due to absorber from scattering due to interstitial material
5. Multiple scattering results and systematic errors

Shift Block 13/12/2015 - 17/12/2015

- MOM: Paolo Franchini, Shifters: Durga Rajaram, Chris Heidt, Francois Drielsma, Pierrick Hanlet
- Report from elog and Ops meetings - few ISIS trips, occasional crash from DATA or Online Monitoring
- Output from the physics devil looks good - plots populated, CDB entries for all but 2 runs
- Due to the low rate at TOF2 chose one beam line setting and collected data across shift block
  - (3,240) π beam collected $\sim$ 20k good muons
- Running with gaseous Xenon which is approximately 2% of X_0 in MICE

Tracker Alignment

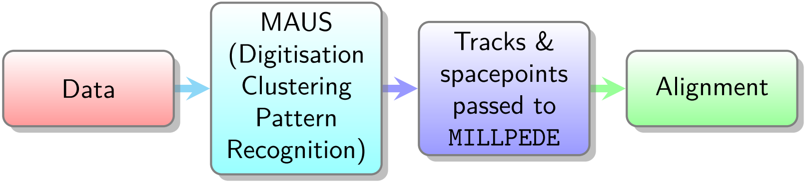
- Bach - common software-tool to align telescope-like detectors. Employs the `MILLEPEDE` alignment algorithm
- `MILLEPEDE` - solves a linear least squares problem with a simultaneous fit of all global and local parameters



https://svnsrv.desy.de/viewvc/aidasoft/AIDAAlign/

Tracker Internal Alignment

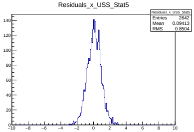
- Tracker frames were surveyed at Imperial - position of stations known accurately
- First do internal alignment of tracker stations with `MILLEPEDE`
- Alignment done with data taken in (3,200) μ mode in June 2015. Run 7157 & 7158 $\rightarrow$ 104254 TOF2 triggers

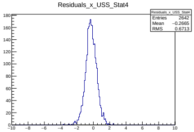


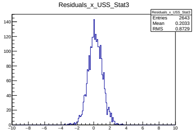
Data Used for Alignment

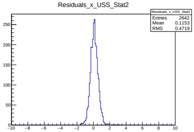
- All reconstruction done with MAUS-v2.0.0
  - Geometry ID 738
- CMM surveys made with respect to tracker stations 1 & 5
  - `MILLEPEDE` alignment made with respect to tracker station 1 & 5
- Cuts implemented
  - tracks must have 5 sp,
  - each sp must have 3 clusters
  - $>$ 12 pe
  - TOF2 sp
  - track projected from USS must be contained within DSS

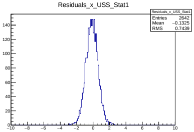
Before Alignment Residuals Upstream Data

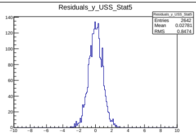


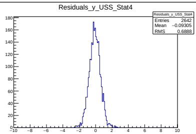


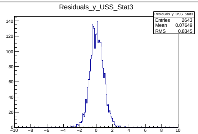


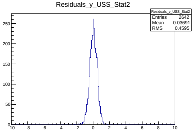


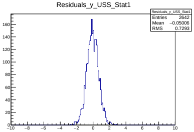




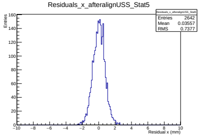


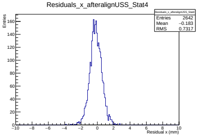


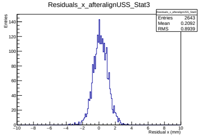


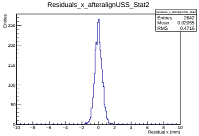


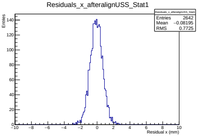
After Alignment Residuals Upstream Data

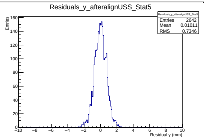


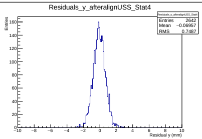


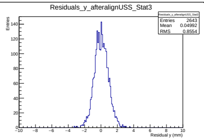


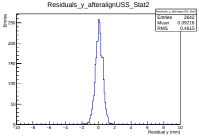


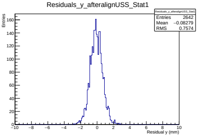












Alignment Offsets Upstream Data

Station	Position Before Alignment (CMM)			Position After Alignment		
	x (mm)	y (mm)	θ_z (mrad)	x (mm)	y (mm)	θ_z (mrad)
5	0	0	0	0	0	0
4	0.1722	-0.2912	0	0.1127	0.0453	-1.00
3	-0.6717	-0.1759	0	0	0	0
2	-0.4698	0.0052	0	-0.1209	0.0856	-1.10
1	0	0	0	0	0	0

Positions are taken from CMM measurements done at Imperial

Alignment done with 18948 tracks

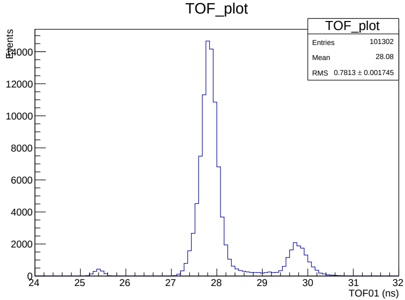
Tracker to Tracker Alignment

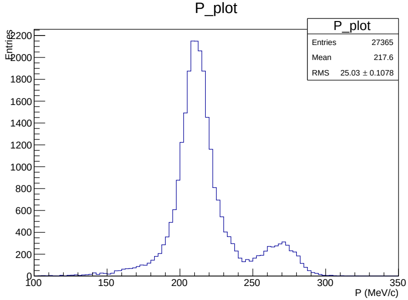
Procedure

1. Create single track for all spacepoints from both trackers - fitting done with Minuit as packaged in ROOT
2. Using all ten stations do tracker to tracker alignment.
3. USS stations 1 & 5 fixed all other stations float
4. Tracker to tracker alignment on-going and need further work

TOF Distributions & Beam Selection

- Three particle species seperated in TOF as expected for pion beam
- Momentum for muons centred just above 210 MeV/c

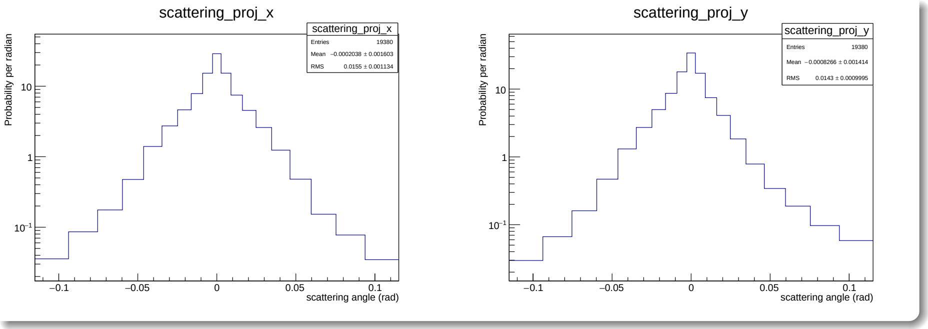




Cut	No. of events
Inital	984670
TOF 0 + 1 + 2 sp	105980
> 8 trk sp	101302
TOF cut (27 - 28.4 ns)	82617
track proj. cut	22721

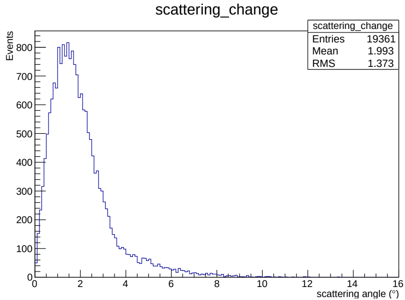
Scattering Distribution

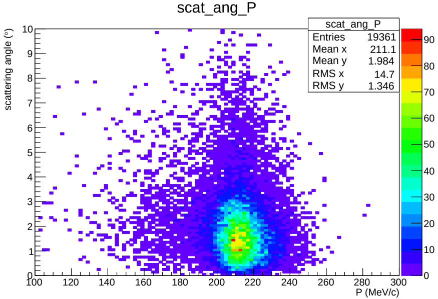
Data is official recostruction data $\rightarrow$ MAUS-v2.0.0 geometry 121



- Pattern recognition provides straight tracks & angles in each tracker
- $\theta_x = \text{atan}(\frac{dy}{dz})_{US} - \text{atan}(\frac{dy}{dz})_{DS}$
- $\theta_y = \text{atan}(\frac{dx}{dz})_{US} - \text{atan}(\frac{dx}{dz})_{DS}$

Scattering Distribution





- Top plot:

$$\theta = \left(\frac{\mathbf{p}_u \cdot \mathbf{p}_d}{|\mathbf{p}_u| p_d|} \right) \qquad (3)$$

- Bottom plot: P against scattering angle

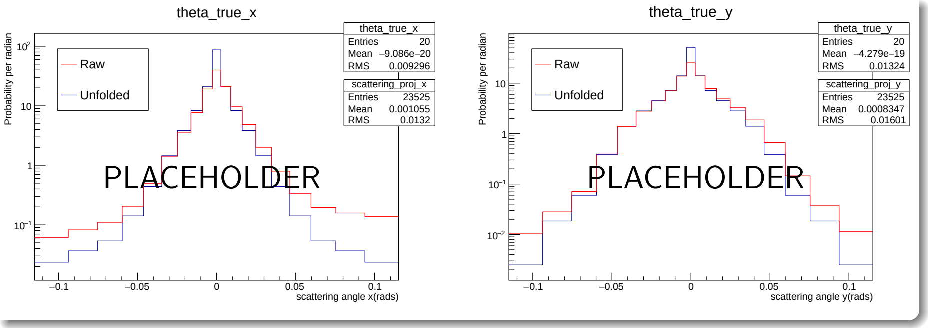
Tracker Unpacking

- MuScat unpacking uses expression : $D_j = B_j + R_{ij}\epsilon_{ii}\theta_i$
- $D_j \rightarrow$ data vector of no. of counts per position bin
- $B_j \rightarrow$ background vector of no. of counts per position bin PID != 13, primarily electron contamination
- $R_{ij} \rightarrow$ matrix of no. of counts per position bin j for angular bin i normalised by row
- $\epsilon_{ii} \rightarrow$ matrix is
  - $\frac{\text{No. of counts angular bin recon}}{\text{No. of counts angular bin truth}}$
- $\theta_i \rightarrow$ vector of no. of counts per angular bin of true scattering angle

Tracker Unpacking

- Use Minuit to minimise χ^2 expression
- Migrad tool varies θ_i entries for each iteration tests the gradient at each point until maximum is found
- $\chi^2 = \sum \frac{(D_{measured} - D_{calculated})^2}{D_{measured}}$
- χ^2 calculated for every D_{true} entry and minimised globally

Scattering Distribution



- Histograms are placeholders, waiting for MC to match data for Xenon runs
- Raw scattering distributions plotted over distributions from unfolding
- Unfolded distros are symmetric around 0 - required by Minuit for fit to converge
- As expected unfolded distributions are narrower than raw

Bayesian Deconvolution [1]

Bayes Theorem

$$P(C_i|E_j) = \frac{P(E_j|C_i)P_0(C_i)}{\sum_{l=1}^{n_c} P(E_j|C_l)P_0(C_l)}$$

The number of events for process

$$n(C_i) = \sum_{j=1}^{n_E} n(E_j)P(C_i|E_j)$$

- We want $C_i = \Delta\theta_Y^{abs}$ the deflection angle in the absorber material.
- We measure $E_j = \Delta\theta_Y^{tracker}$ the deflection angle measured at the first tracker plane.
- Depend on the simulation for
  - A conditional probability of observing an angle in the trackers given a scattering angle at the absorber. $P(E_j|C_i)$
  - A prior distribution for the scattering angle at the absorber. $P_0(C_i)$
- Virtual planes added to the absorber to provide $P(E_j|C_i)$.
- Use RooUnfold package (see `http://arxiv.org/abs/1105.1160`)
- Iterates P_0 based on $n(C_i)$ until $n(C_i)$ converges.

[1] NIM A 362 (1995) 487-498

Summary

- Data taking effort was a success
- First scattering plots with data from MICE
- Tracker alignment with MILLEPEDE
- Unfolding of scattering angle

Next Steps

- MC analysis coming now we have a new MAUS release
- Systematic errors
- Bayesian deconvolution
- Draft 0 of paper available on analysis issue tracker as issue #1827