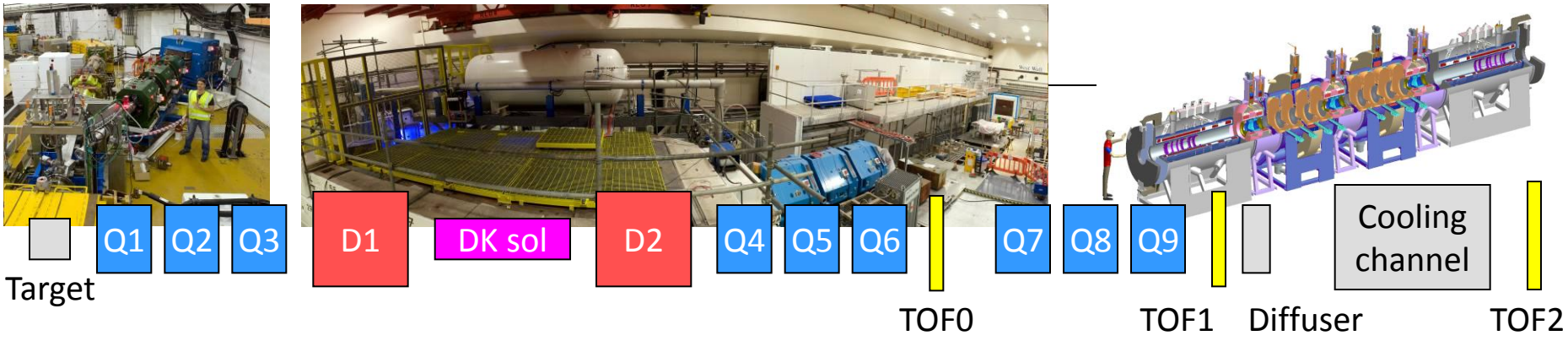


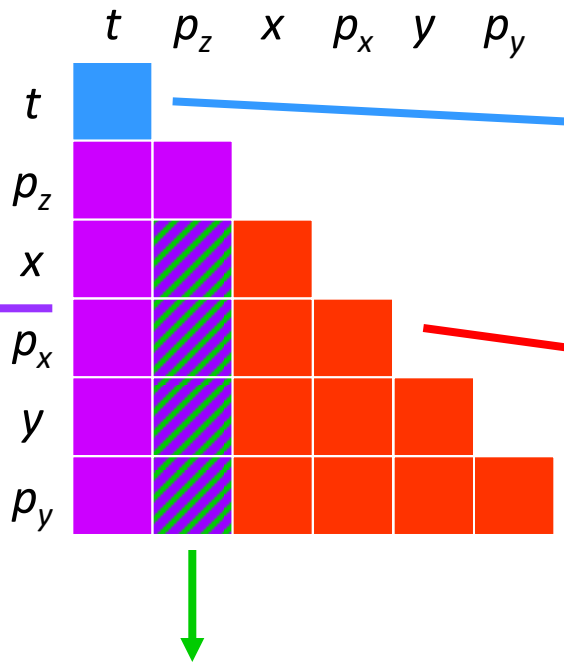
Demonstrating the momentum-emittance matrix with TOF0 and TOF1

Analysis of runs since Q3 was fixed,
and re-analysis of the December 2010 runs

Mark Rayner, The University of Oxford

CM27 – 7/7/2010 – Rutherford Appleton Laboratory

6D phase space upstream of the cooling channel



Longitudinal-transverse coupling
Matches the beam in the RF

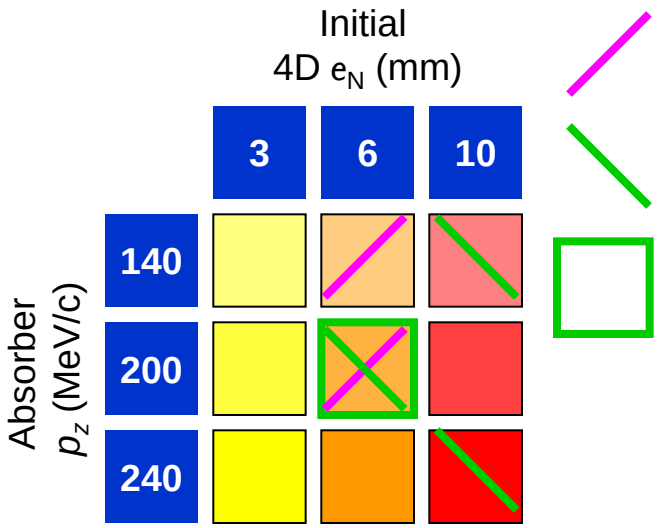
Spread in time
Defined by TOF measurements of extrapolated RF phase

Transverse phase space
Must be matched into the spectrometer solenoids

Dispersion
Relevant for future 6D cooling investigations
LiH wedge absorbers etc…

Introduction

- Purpose of the beam line:
  - Generate the emittance-momentum matrix elements in pion → muon decay beam lines



Recorded December 2009
Calibration: December 2009

June/July 2010
Calibration: February 2010

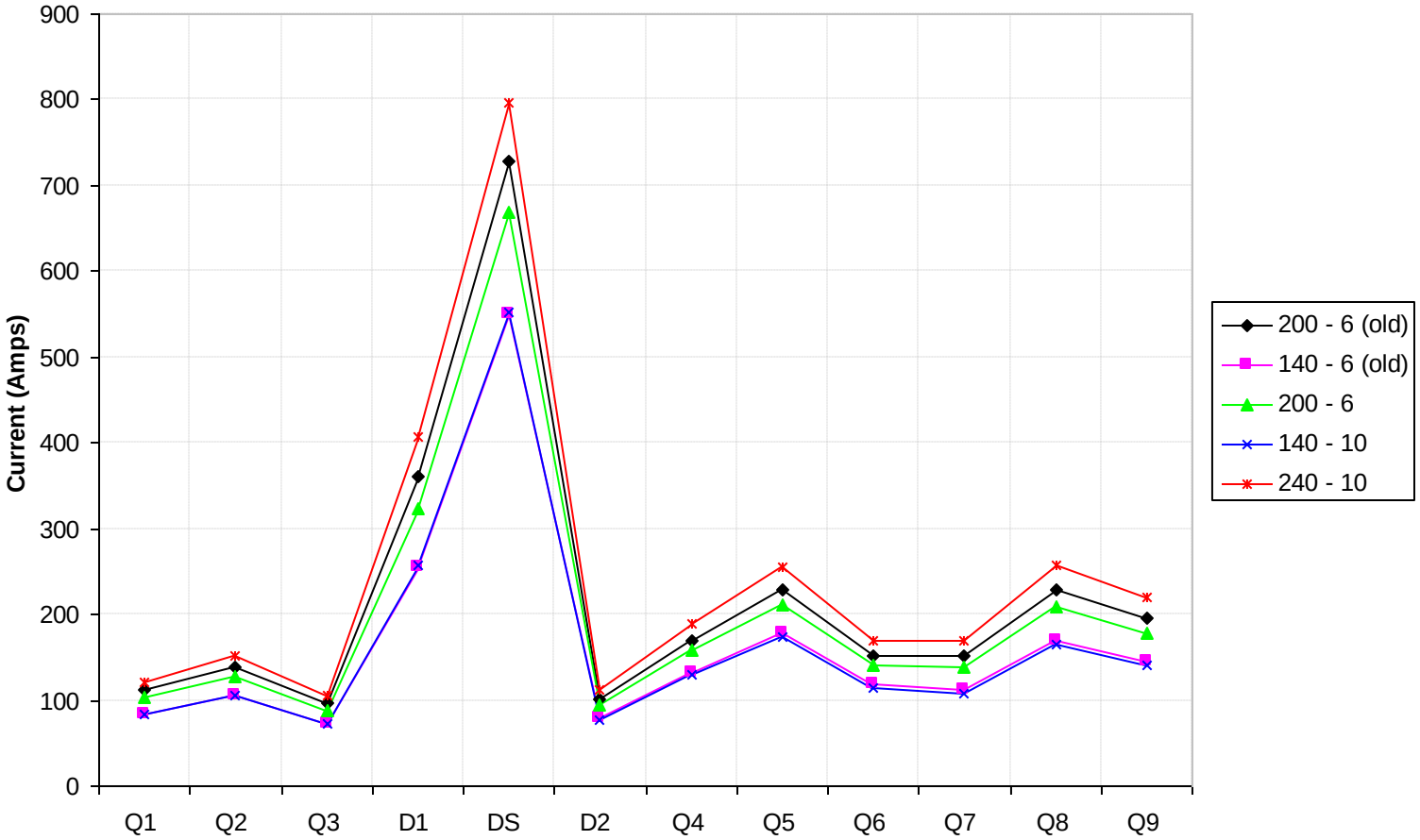
Also:
- Q123 scan
- Decay Sol scan
- Q456 scan
- Q789 scan

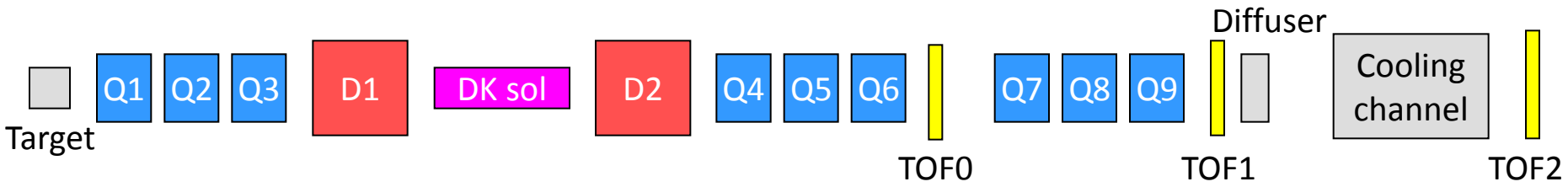
ϵ_{4D} (mm·rad)	P_μ (MeV/c)	140	200	240
3		t=0.0 mm	t=0.0 mm	t=0.0 mm
		P_{dif}=151	P_{dif}=207	P_{dif}=245
		α=0.2	α=0.1	α=0.1
		β=56 cm	β=36 cm	β=42 cm
6		t=5.0 mm	t=7.5 mm	t=7.5 mm
		P_{dif}=148	P_{dif}=215	P_{dif}=256
		α=0.3	α=0.2	α=0.2
		β=113 cm	β=78 cm	β=80 cm
10		t=10.0 mm	t=15.5 mm	t=15.5 mm
		P_{dif}=164	P_{dif}=229	P_{dif}=267
		α=0.6	α=0.4	α=0.3
		β=198 cm	β=131 cm	β=129 cm

Design optics at the upstream diffuser face

- Phase space reconstruction by TOF0 and TOF1
  - Longitudinal momentum resolution O(5 MeV/c)
  - Transverse position resolution O(2 cm)
  - Transverse momentum resolution O(p_x^{max}/70)
    - Dependent on p_x^{max}, the maximum un-scraped momentum of the optics in question
- (Take advantage of the unique mapping of points in phase space)
  - (Apart from stochastic effects like scattering)

Reference magnet currents for the elements studied here

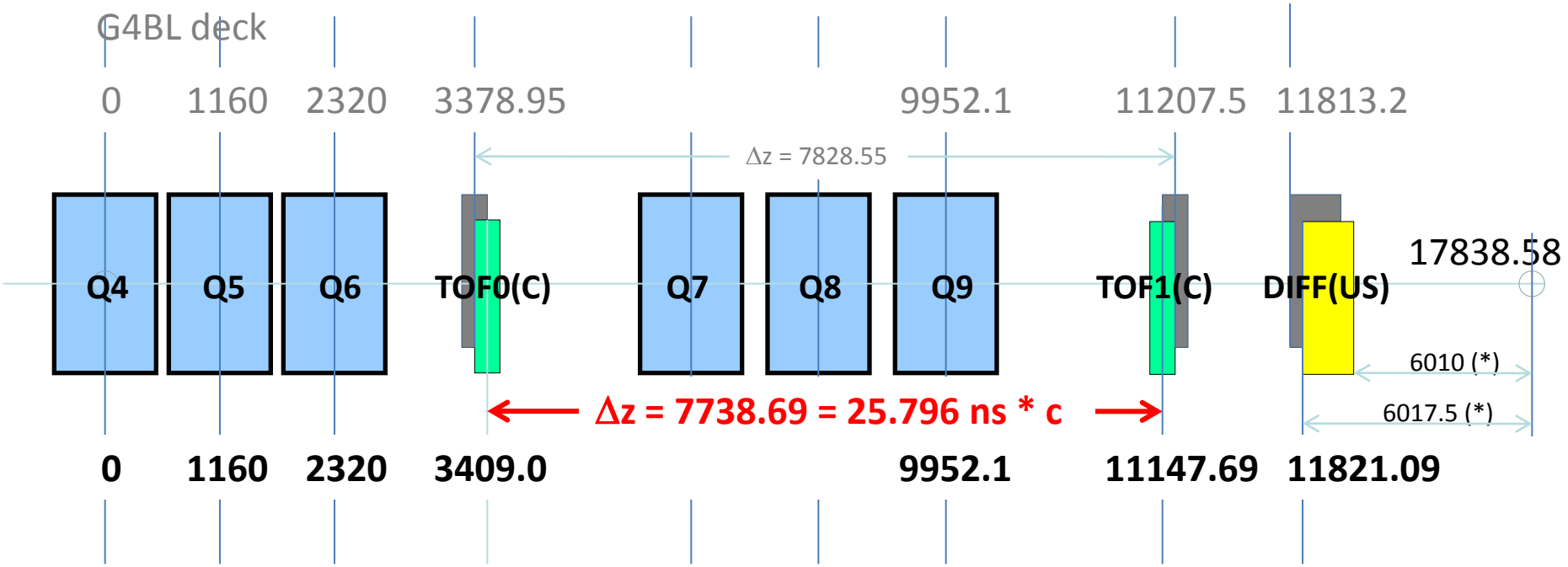




Compendium of DS-BL key locations

Marco's sterling investigative work ➔ our best understanding of the beam line geometry yet:

(Positions refer to the centre of Q4)

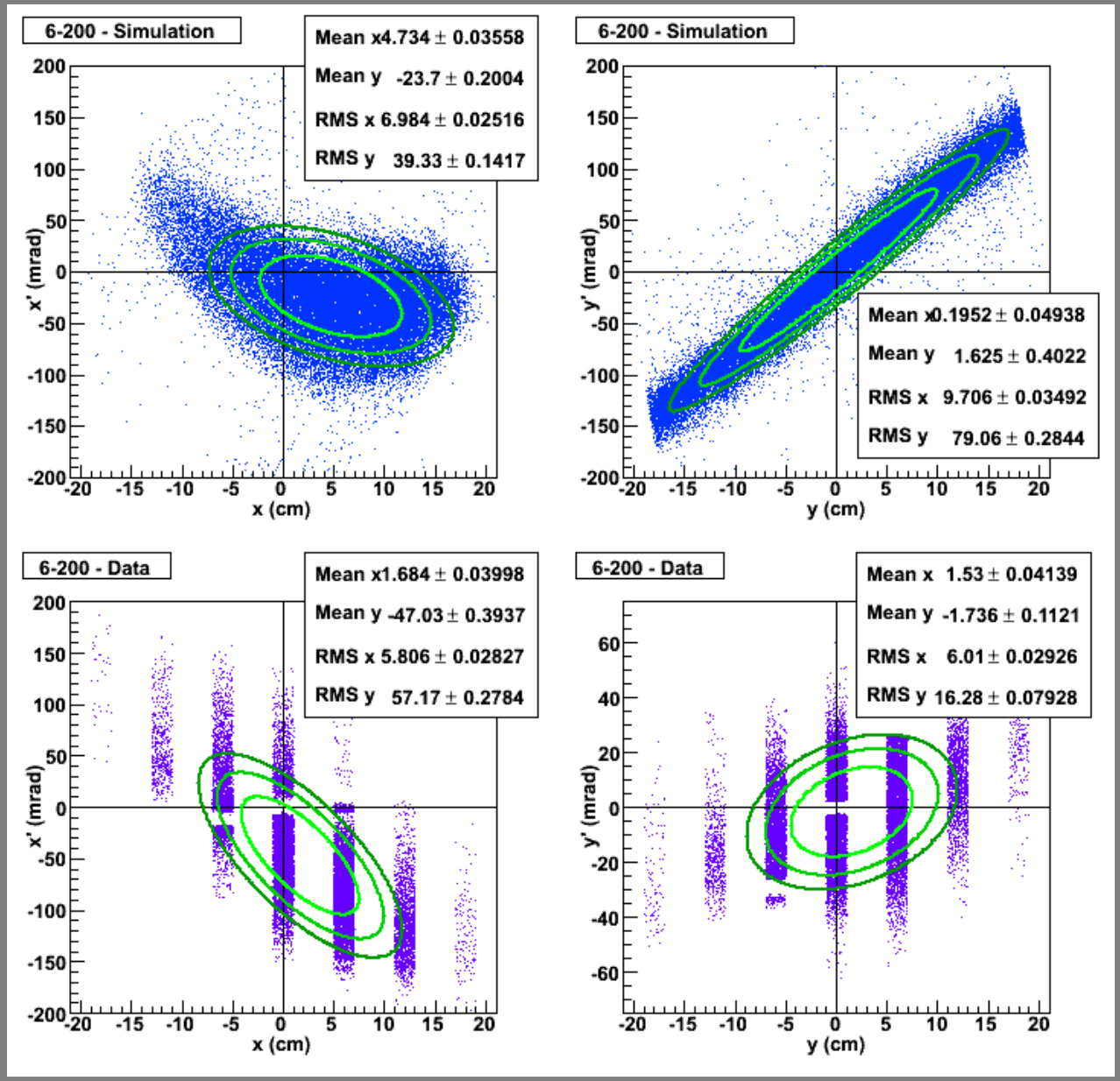


SURVEY + addendum Jan 2010 (should be the latest take)

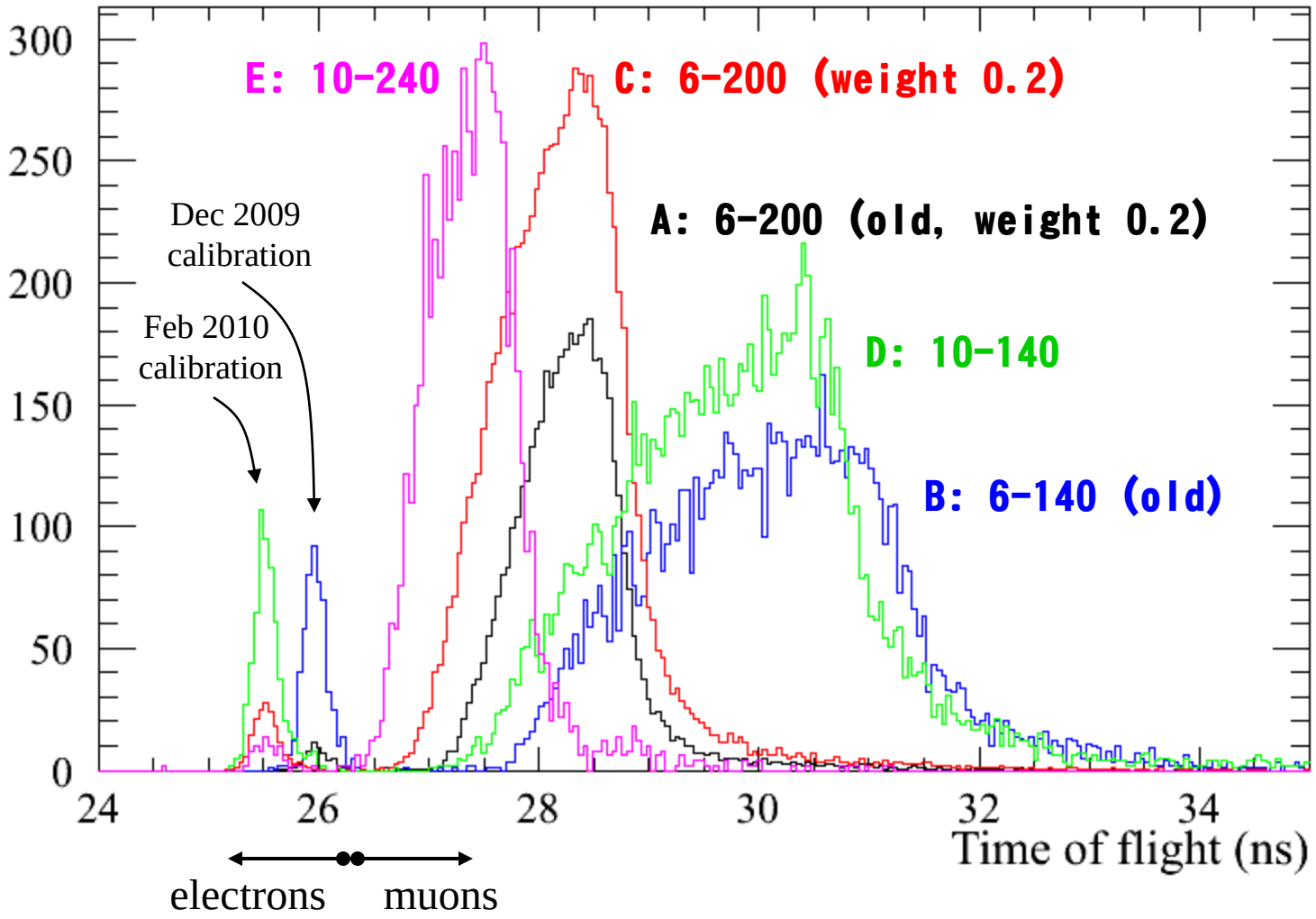
(*) Relative distances from NOTE 176 wrt to MICE CENTRE. DS face is fixed to 6010, US face assumes thickness=7.5 mm

Trace space comparison with Monte Carlo at TOF1

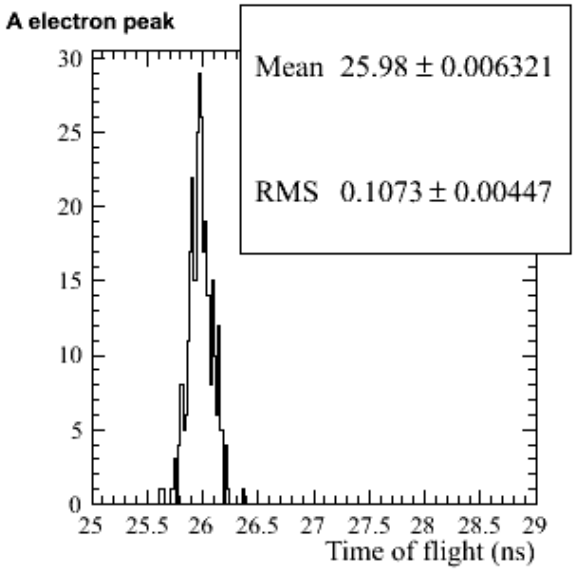
HISTORICAL ASIDE

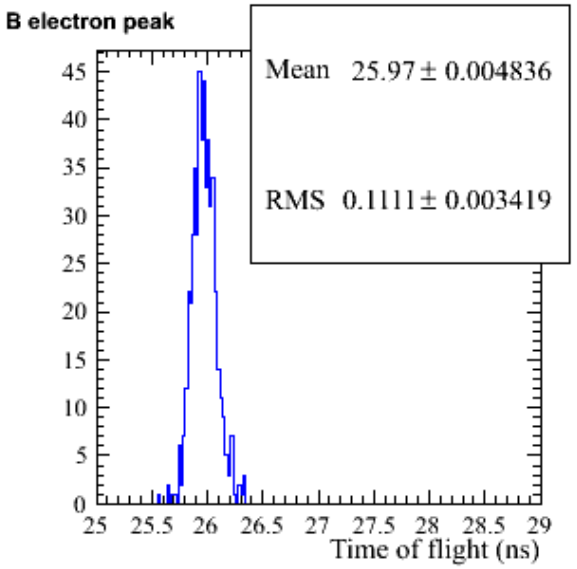


Time of flight

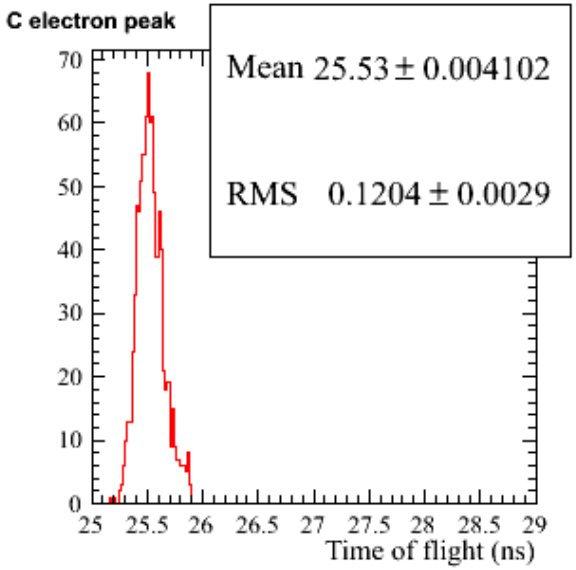


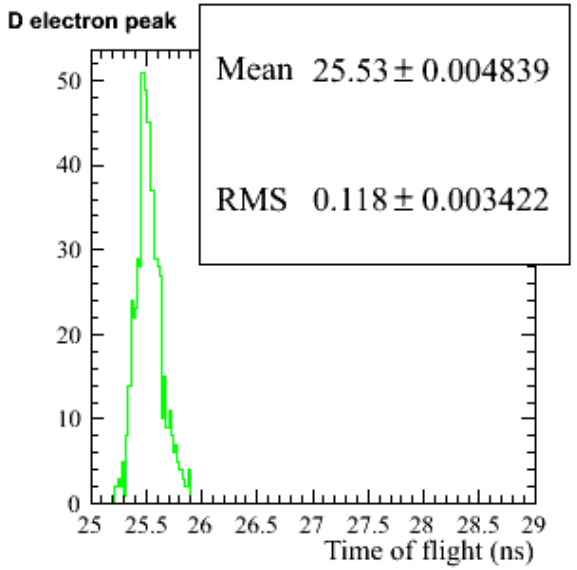
The electron peaks

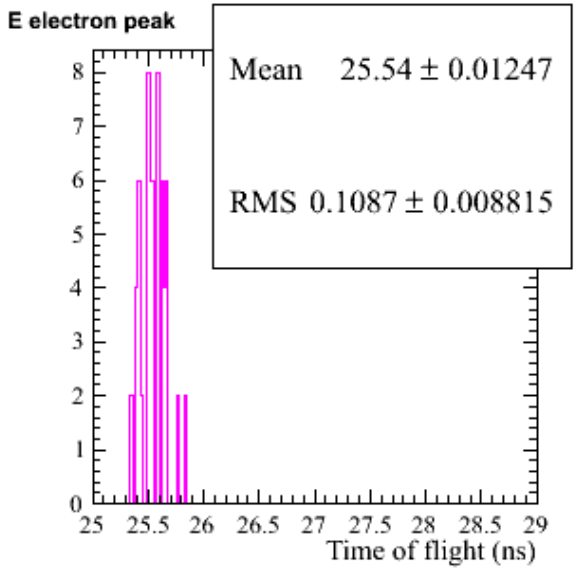




Yordan, CM26:
TOF0 resolution = 51 ps
TOF1 resolution = 62 ps
Therefore:
T.o.F. resolution = 80 ps
From this data:
Measured electron width ~ 120 ps
> 80 ps
Therefore:
Natural electron width ~ 89 ps
RMS path length deviation ~ 2.7 cm

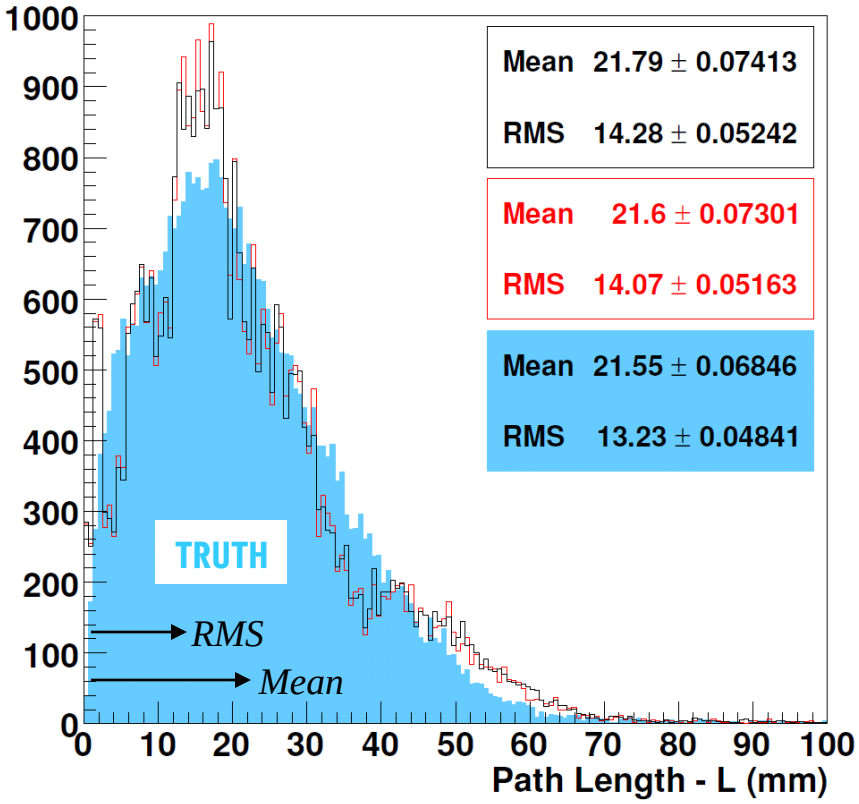






Estimating the true absolute time of flight

Muon path length TOF0 – TOF1 for a G4BeamLine muon beam from Marco



Bias on the measurement of a muon's p:

$$\frac{\Delta p}{p} = \frac{E^2}{m_0^2}\left(\frac{\Delta s}{s} - \frac{\Delta t}{t}\right)$$

? True electron path length = L + 4 cm ?

If so, by normalizing $(t_1 - t_0)|_{\text{electron peak}} = L/c$ we bias time of flight by $\Delta t = -133$ ps

And we reconstruct with a bias
$\Delta p \sim +2.2$ MeV when $p_{\text{abs}} = 140$ MeV/c
$\Delta p \sim +5.5$ MeV when $p_{\text{abs}} = 200$ MeV/c
$\Delta p \sim +8.8$ MeV when $p_{\text{abs}} = 240$ MeV/c

➔An electron path length calibration is important

To the best of my knowledge, note 242 is correct December 2009 – July 2010, and refers to TOF centres
Therefore calibrate $(t_1 - t_0)|_{\text{electron peak}}$ = (796.6 cm + 4 cm) / c = 26.7 ns

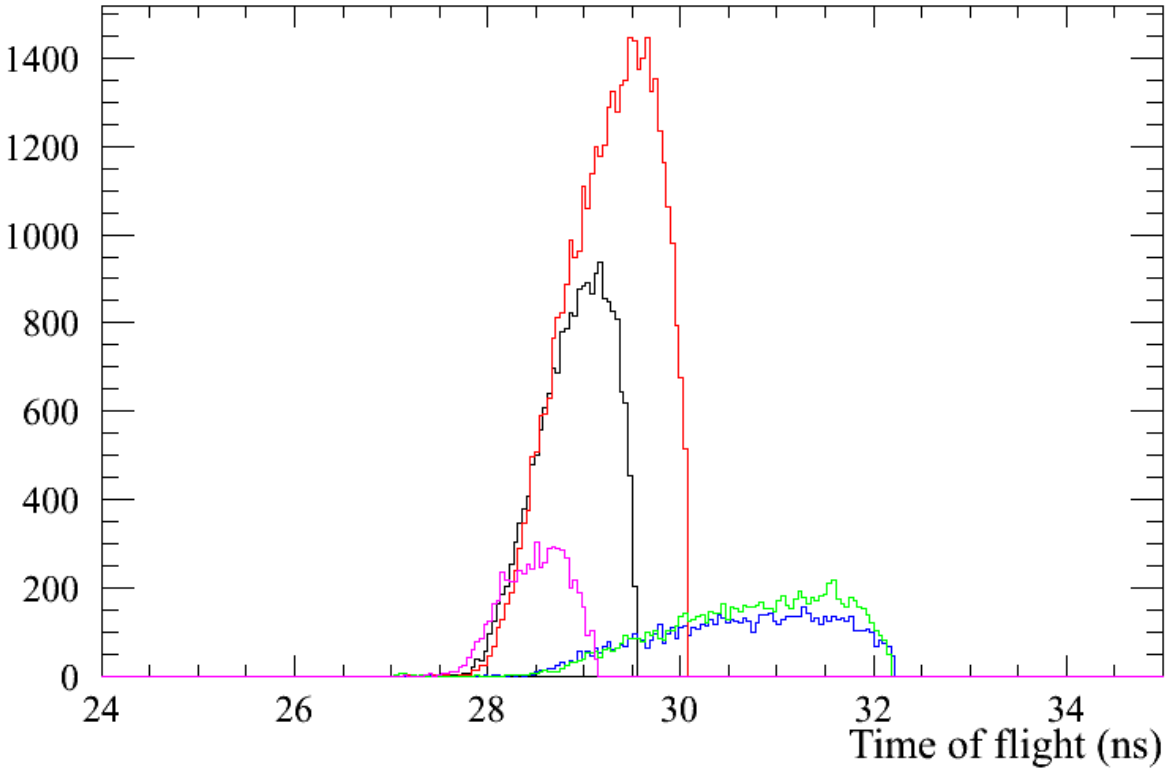
PID cuts and reconstructed momentum

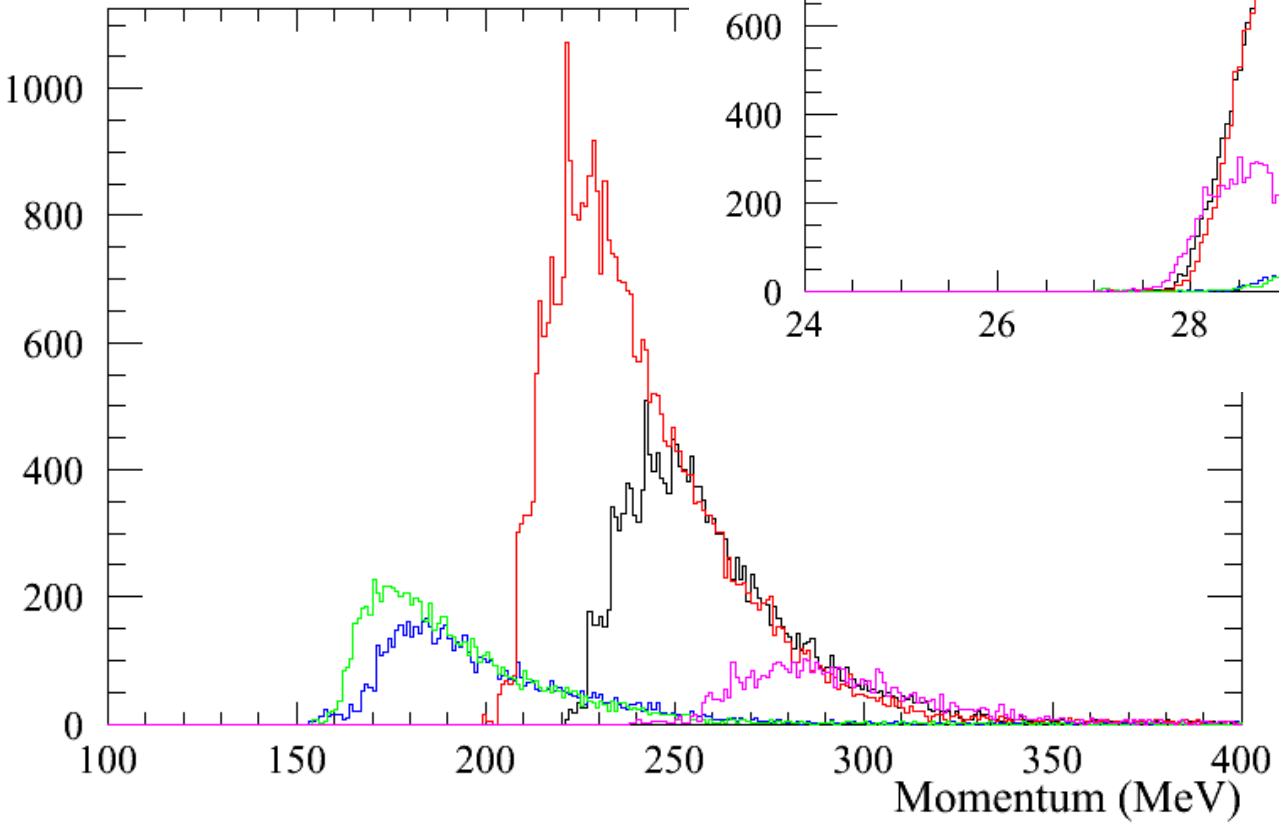
Lower cut (electron/muon)

- Cut at the local minimum

Higher cut (muon/pion)

- Minimize pion contamination
- Cut at half maximum

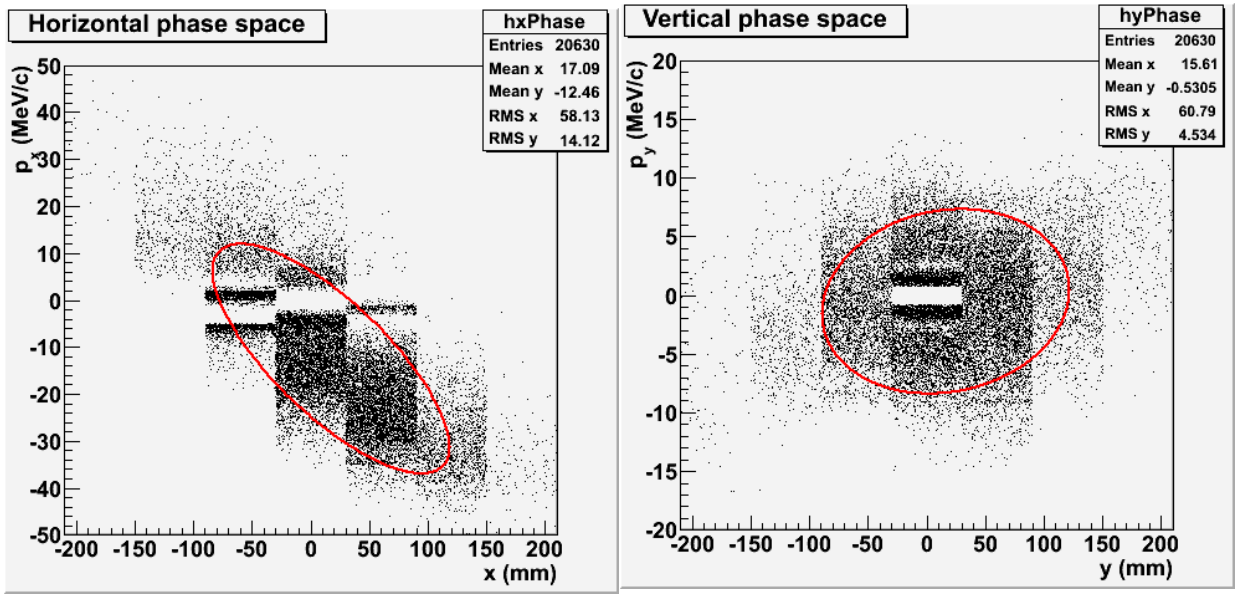




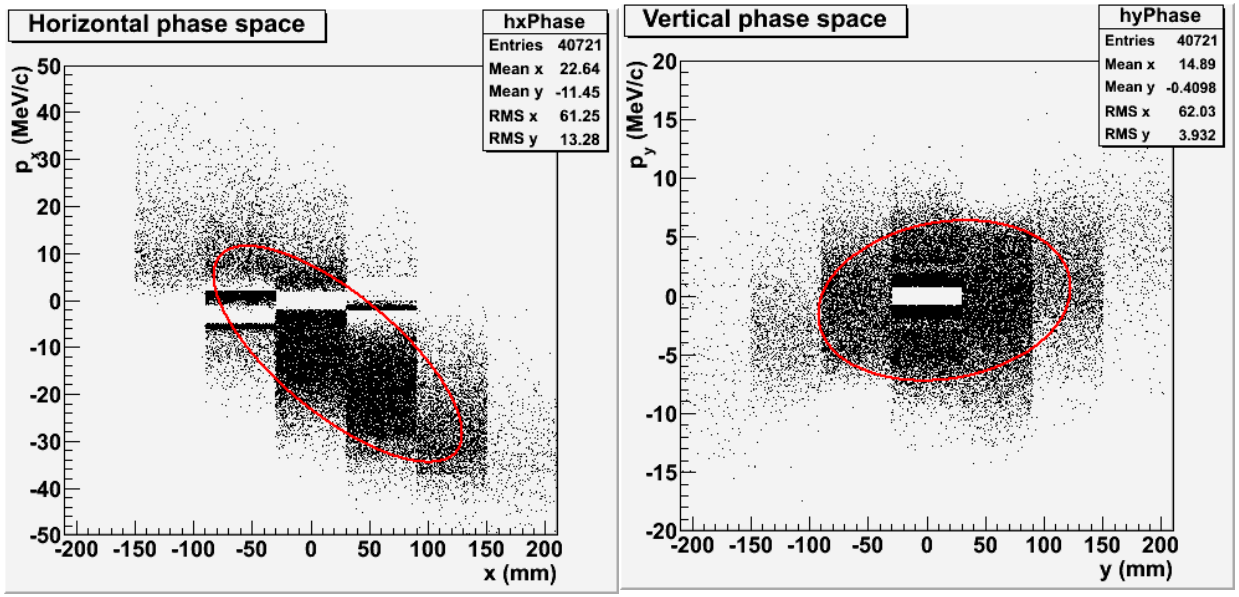
$\langle p_z \rangle$	Meas. Bef. TOF1	Required Bef. diff.
6-200(old)	250.1	215
6-140(old)	191.0	148
6-200	231.7	215
10-140	184.1	164
10-240	281.9	267

6-200, old and new optics

A: 6-200 (old)



C: 6-200

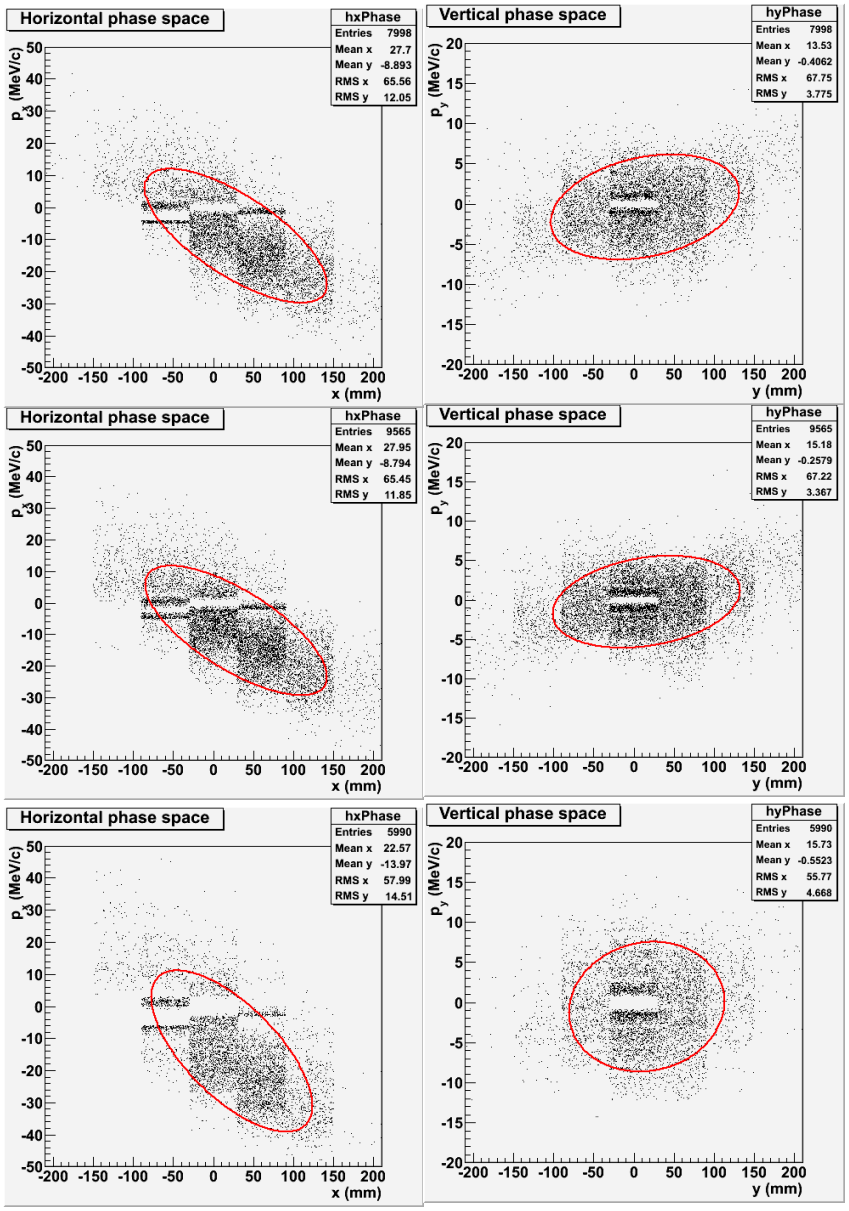


The other three elements

B: 6-140 (old)

D: 10-140

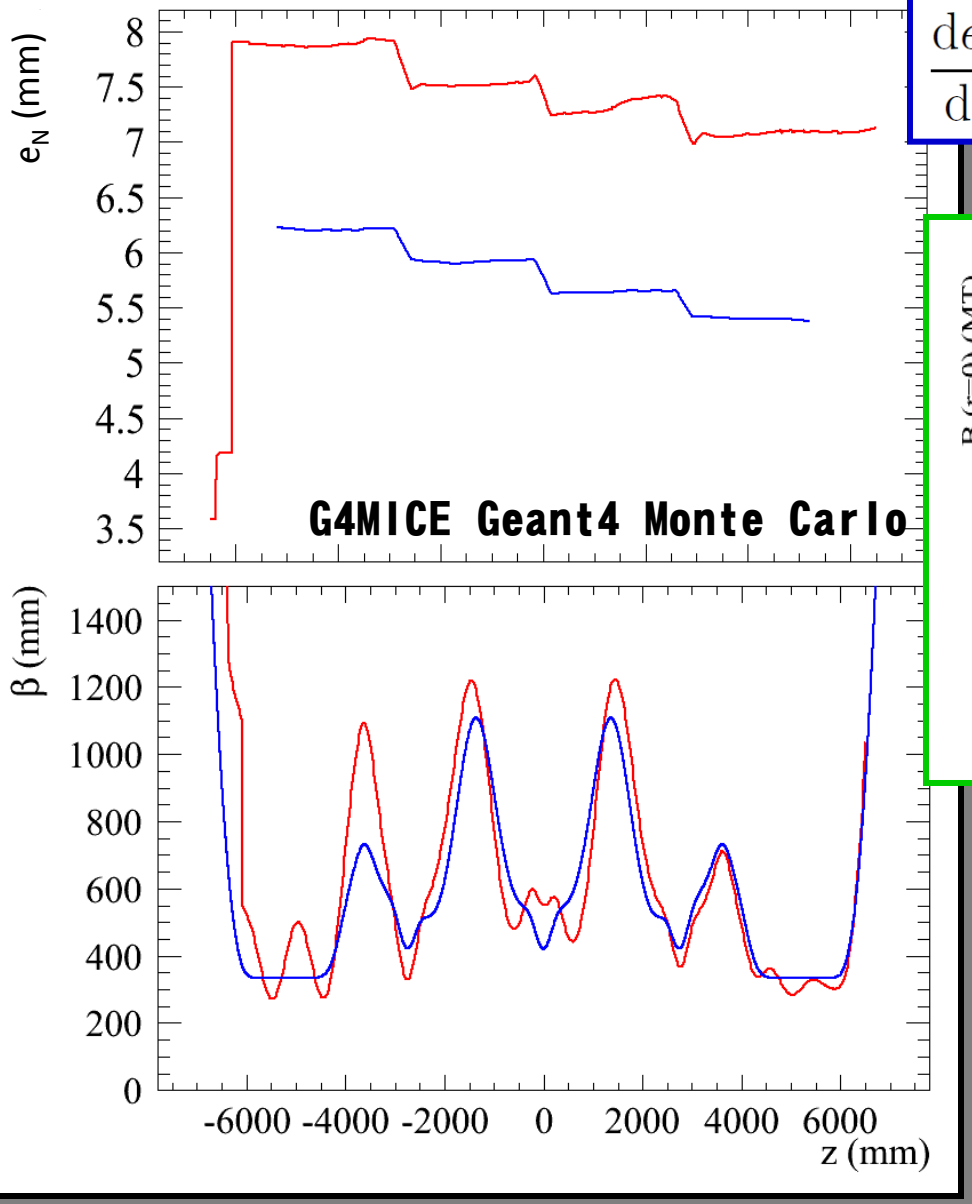
E: 10-240



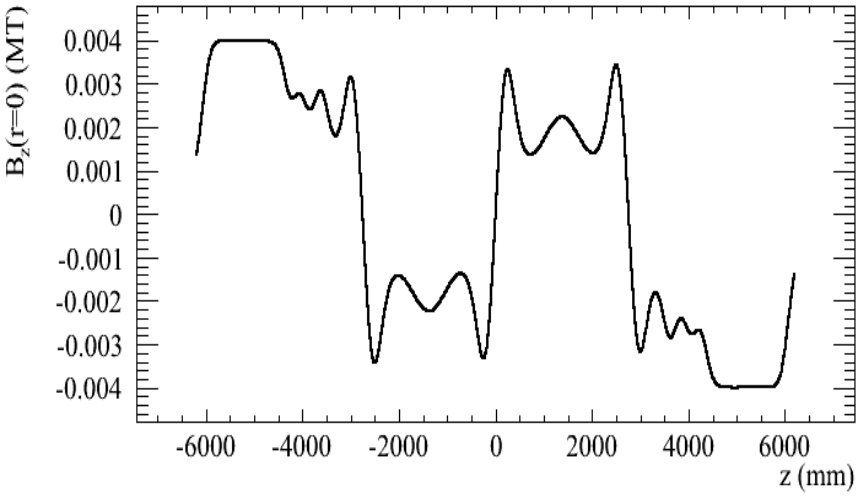
Conclusion

- Momentum bias #1 – Assuming the wrong geometry
  - Overestimated muon momentum
    - Fixed, to the best of our knowledge
    - Precise survey information is essential for TOFs
- Momentum bias #2 – Neglect electron path length > L
  - Calibrate electron ToF to be too quick
  - Reconstruct muon ToF to be too quick
  - Overestimate muon momentum
    - Corrected approximately, but Monte Carlo required (controversial)
- Momentum bias #3 – Neglect muon path length > L
  - Path length S in $p/E = S/\Delta t$ is too small
  - Underestimate muon momentum
    - Fixed – see IPAC paper, and a plethora of previous talks
- In the last few days progress has been made in demonstrating the ε-P momentum matrix
  - The *OnlineReconstruction* application now reconstructs phase space in real time from the socket
    - See talk on Friday
- Analysis steps in progress:
  - Swim the beam to the diffuser face:
    - What fraction of muons fall within the acceptance?
    - How do the measured and design optics compare?
  - Are x-y asymmetries problematic for matching?
  - What are the transverse optics of the subset of muons which may be continuously accelerated by peak RF in the MICE cavities?
  - Analyze data from the magnet current scan data, and optimize the matrix element optics

Comparison of matched and measured simulated input beams



$$\frac{\mathrm{d}\epsilon_\perp}{\mathrm{d}z} = \frac{(14\ \mathrm{MeV})\beta_\perp}{2(v/c)^3 E m_\mu X_0} - \left\langle \frac{dE}{dX} \right\rangle \frac{\epsilon_\perp}{(v/c)^2 E}$$

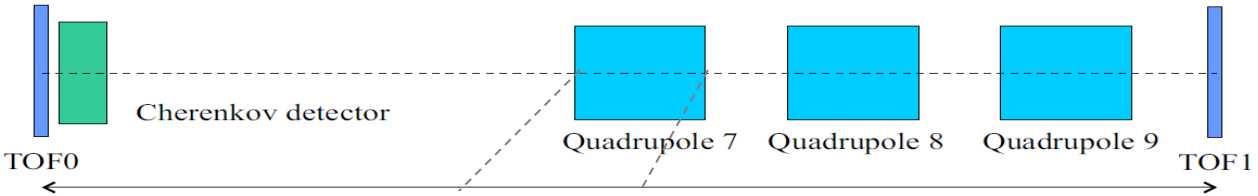


$$k[\mathrm{m}^{-1}] = \frac{150B[\mathrm{T}]}{p[\mathrm{MeV/c}]}$$

$$2\beta\beta'' - (\beta')^2 + 4\beta^2 k^2 - 4 = 0$$

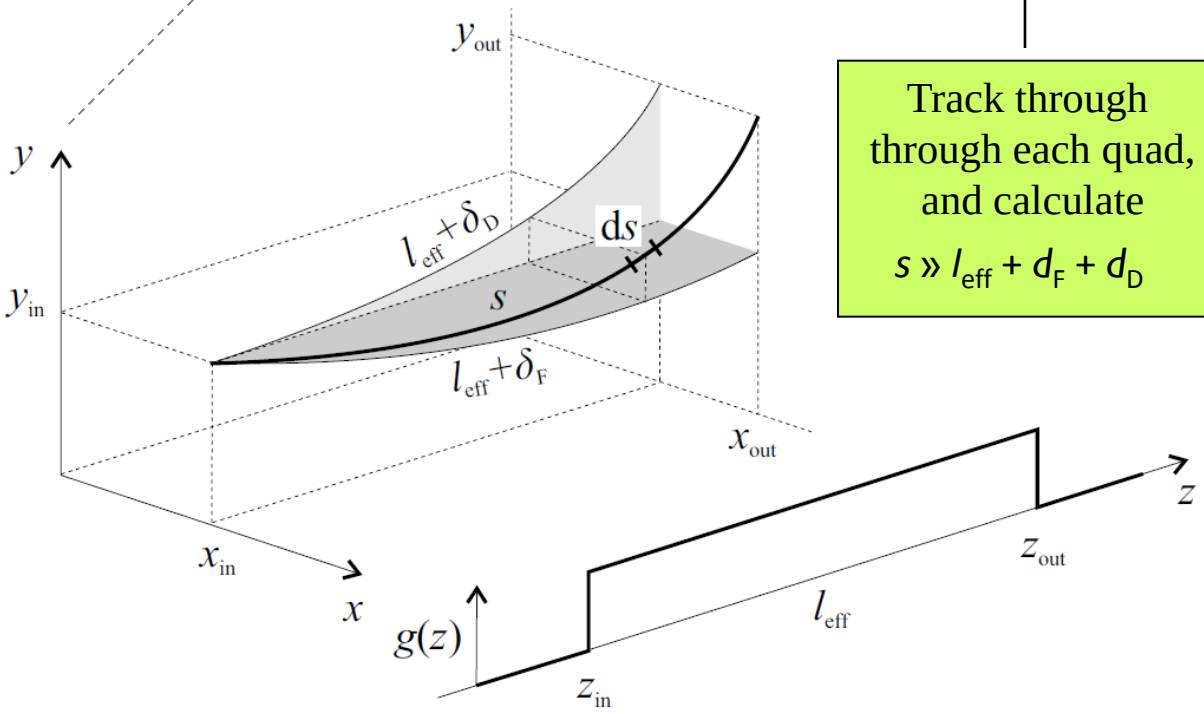
Extra slides

Reconstruction procedure



$z_{TOF1} - z_{TOF0} = 8$ m

$$\begin{pmatrix} x_0' \\ x_1' \end{pmatrix} = \frac{1}{M_{12}} \begin{pmatrix} -M_{11} & 1 \\ -1 & M_{22} \end{pmatrix} \begin{pmatrix} x_0 \\ x_1 \end{pmatrix}$$



Assume the path length
$S \approx z_{TOF1} - z_{TOF0}$

Estimate the momentum
$p/E = S/Dt$

Add up the total path
$S = s_7 + s_8 + s_9 +$ drifts

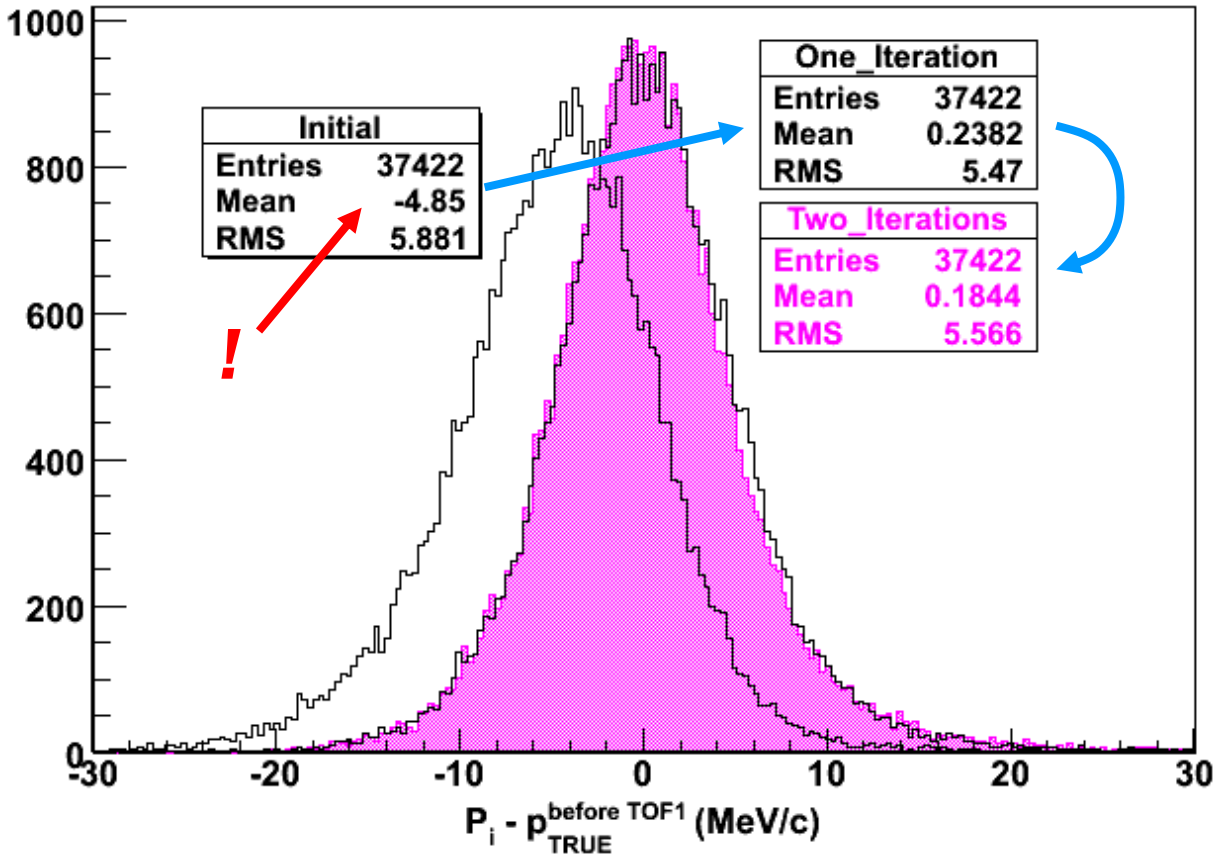
Track through through each quad, and calculate
$s \approx l_{eff} + d_F + d_D$

Calculate the transfer matrix

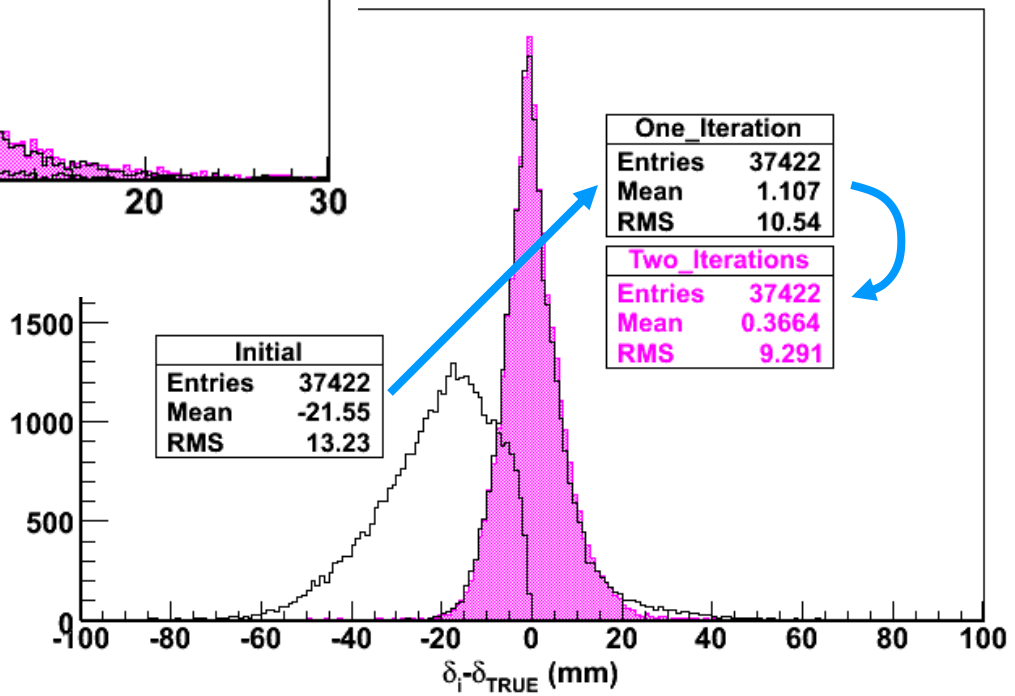
Deduce (x', y') at TOF0 from (x, y) at TOF1

Deduce (x', y') at TOF1 from (x, y) at TOF0

Momentum reconstruction: 6-200 simulation

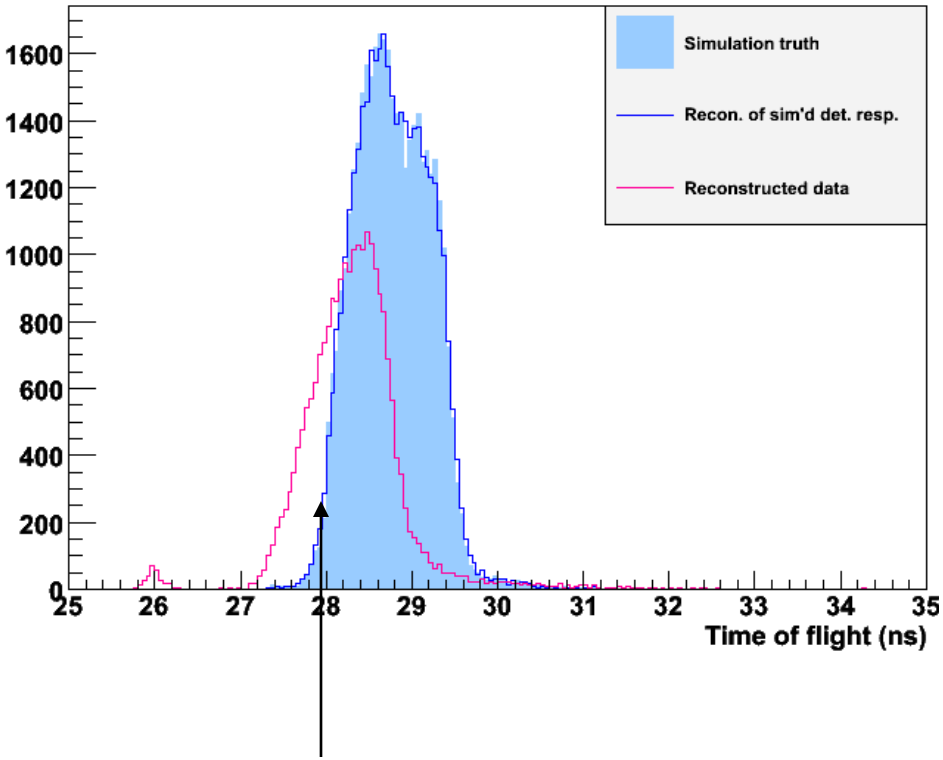


Measuring path length removes the bias on the momentum measurement

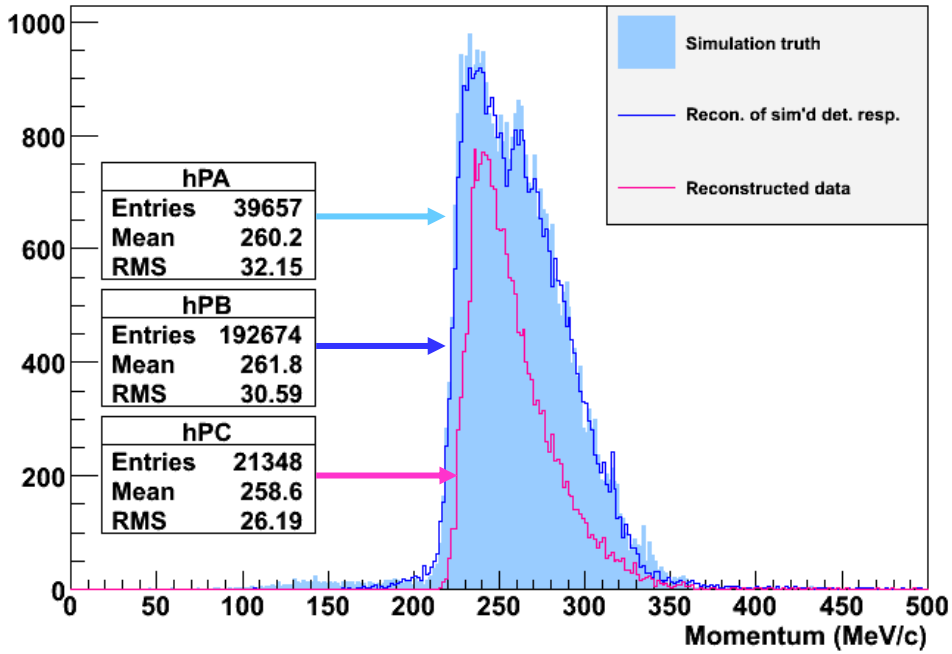


Simulation/data comparison at TOF1 (6-200 matrix element)

Muon time of flight



Muon momentum



This simulation uses the geometry from before TOF1 was moved

$\Delta z = -16.7$ cm $= -0.56$ ns / c

MICE note 242 – the old, incorrect understanding