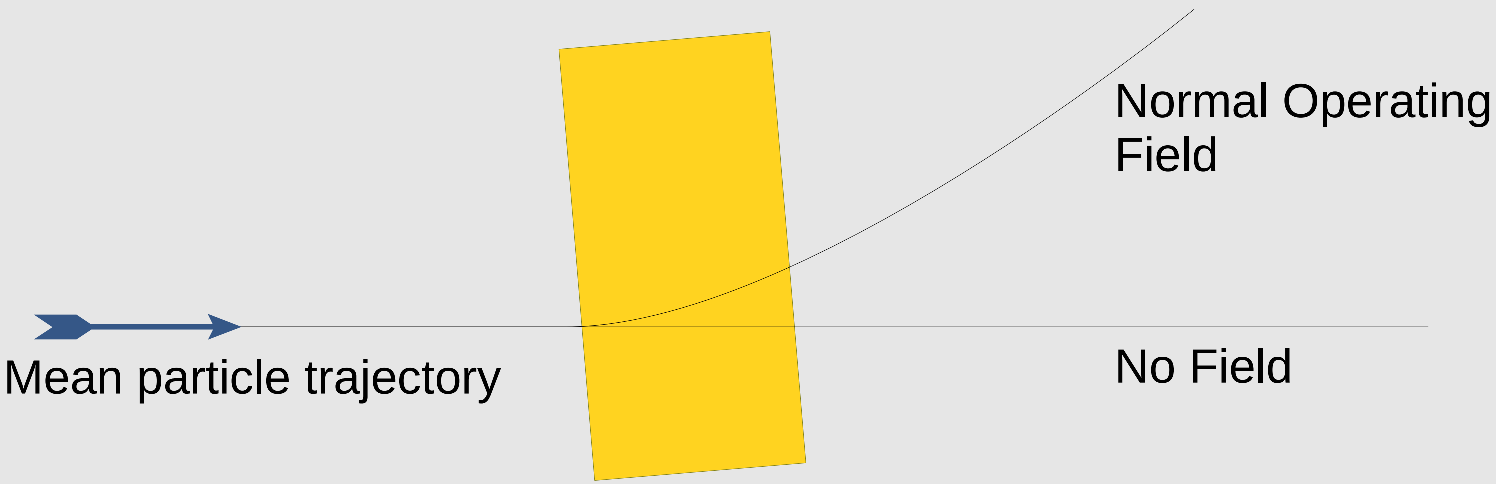
TOF/Quad Alignment Study

Outline:

- Quadrupole scan method to determine magnet misalignments
- Linear beam optics of the quadrupole scan
  - Momentum calculation
  - Position Calculation & Parametrisation
  - Fitting the misalignment scan data
- 2 for 1: A covariance study
  - Fitting the covariance data
- Conclusions

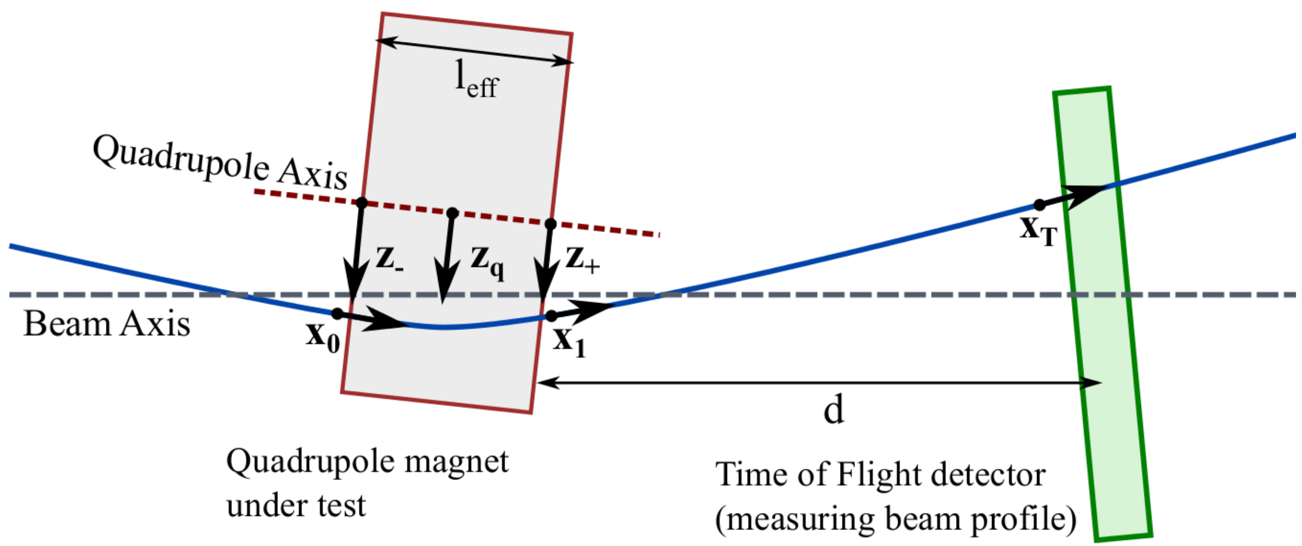
Quadrupole Scan Method



- By increasing the quadrupole current from 0A, the deflection caused by a misalignment is increased from nothing to something.
- Next, by measuring the deflection in a downstream detector it should be possible to observe the deflection and determine the misalignment of the quadrupole.
- Without particle tracking before/after the quadrupole it is not possible to use each particle individually and a mean of the beam must be taken.
- Thanks to Chris Rogers for the idea

Optics of the Alignment Study (1/3)

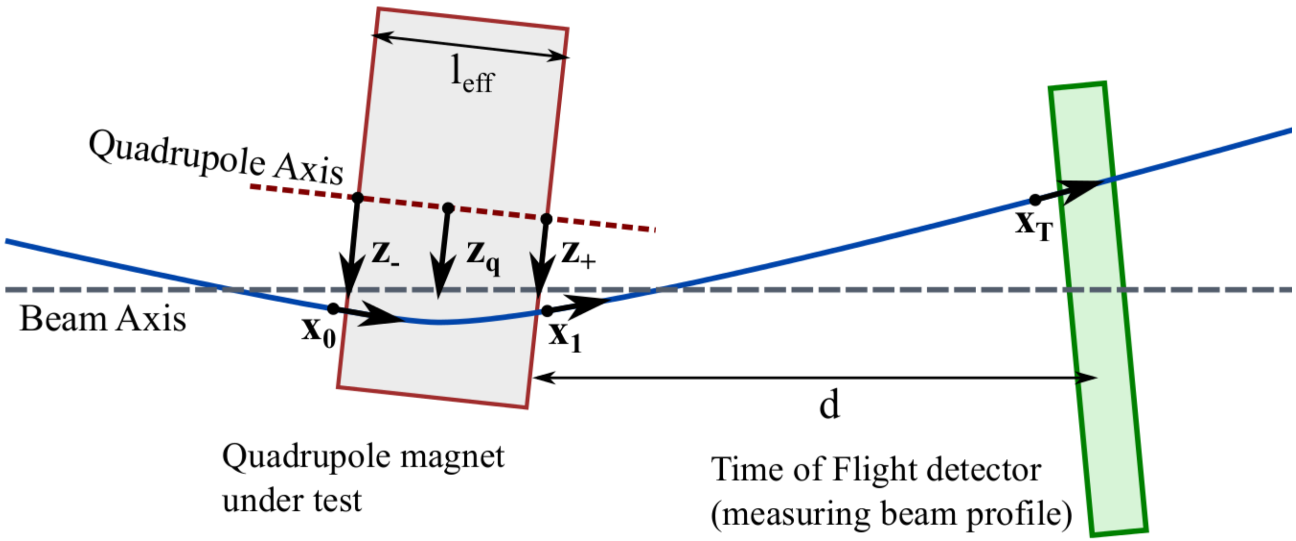
- In order to calculate a misalignment the scan needs describing mathematically. I took an approach using 2D linear beam optics. A single particle can be traced through the misaligned quadrupole as follows:



$$\boldsymbol{x_1} = \hat{F}(k)(\boldsymbol{x_0} + \boldsymbol{z_-}) - \boldsymbol{z_+}$$

Apply offset (z-) before propagation through the magnet to translate the particle to the quadrupole axis. A second offset (z+) reunites the particle with the beam axis after the quadrupole.

Optics of the Alignment Study (2/3)



The two offsets can be calculated from a single misalignment (zq), which is chosen to be at the centre of the quadrupole, where O is the drift matrix:

$$\boldsymbol{z_\pm} = \hat{O}(\pm l_{eff}/2)\boldsymbol{z_q}$$

The track can be transported from the end of the quadrupole to the TOF detector using:

$$\boldsymbol{x_T} = \hat{O}(d)\boldsymbol{x_1}$$

Optics of the Alignment Study (2/3)

The mean **position** of the particle at the TOF can then be written as a sum over all particles, (++ the previous equations):

$$< m(k) >= \frac{1}{n}\sum_{i=1}^{n}\left(\hat{O}(d)\left(\hat{F}(k)\left(\boldsymbol{x_{0,i}} + \hat{O}(-l_{eff}/2)\boldsymbol{z_q}\right) - \hat{O}(+l_{eff}/2)\boldsymbol{z_q}\right)\right)_1 - z_T$$

z_T Accounts for an additional offset of the detector

The first moments of an on axis particle beam evaluate to zero, ie:

$$\frac{1}{n}\sum_{i=1}^{n}\boldsymbol{x_{0,i}} = \begin{pmatrix}0\\0\end{pmatrix}$$

and since the equation is linear, the sum and x can be removed. Leaving us with: (note: z_q has been split into individual components):

$$< m(k) >= T_{11}(k)z_q + T_{12}(k)z'_q - z_T$$

Use measured mean position to fit this equation

Where T11, T12 are elements of the matrix:

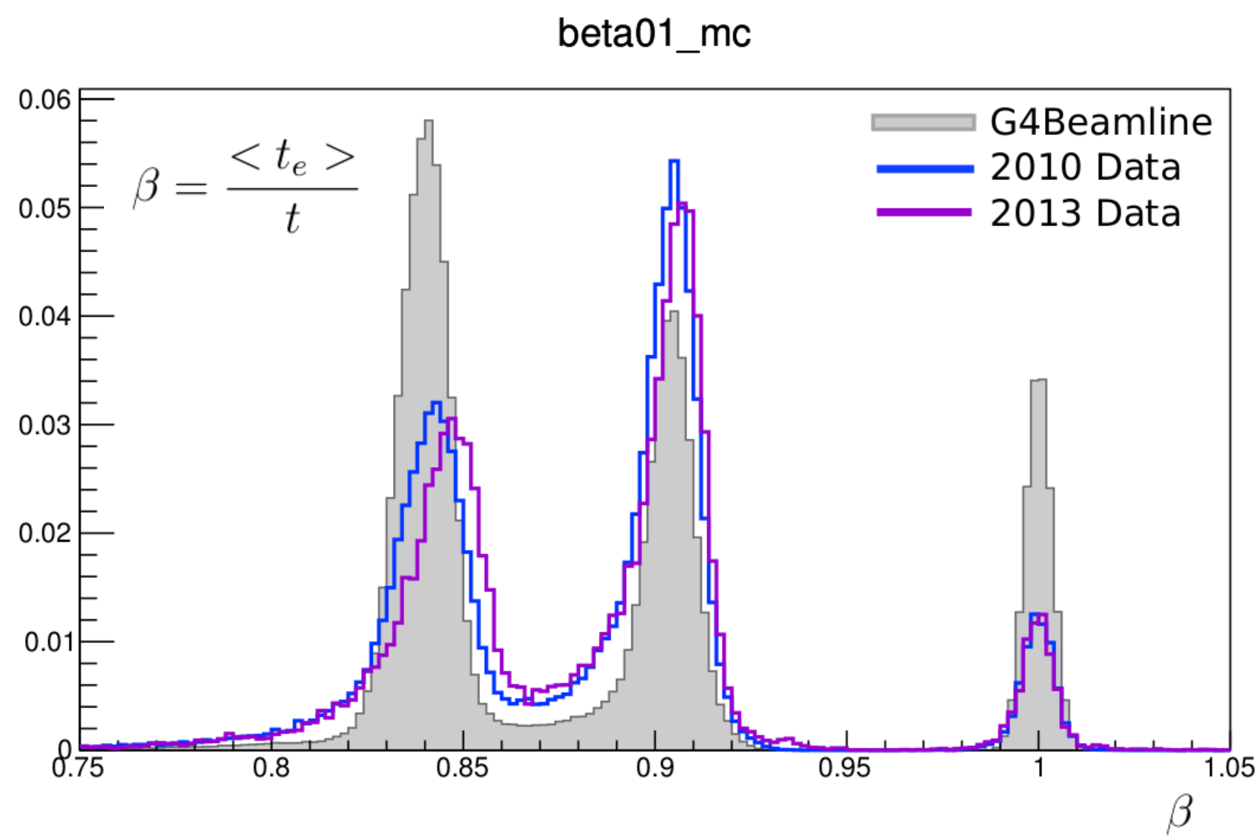
$$\hat{T}(k) = \hat{O}(d)\left(\hat{F}(k)\hat{O}(-l_{eff}/2) - \hat{O}(+l_{eff}/2)\right)$$

Use beam line settings and momentum to evaluate this

We want to determine the misalignments (z_q, z_q' and z_T for each quadrupole)

Momentum Calculation (1/2)

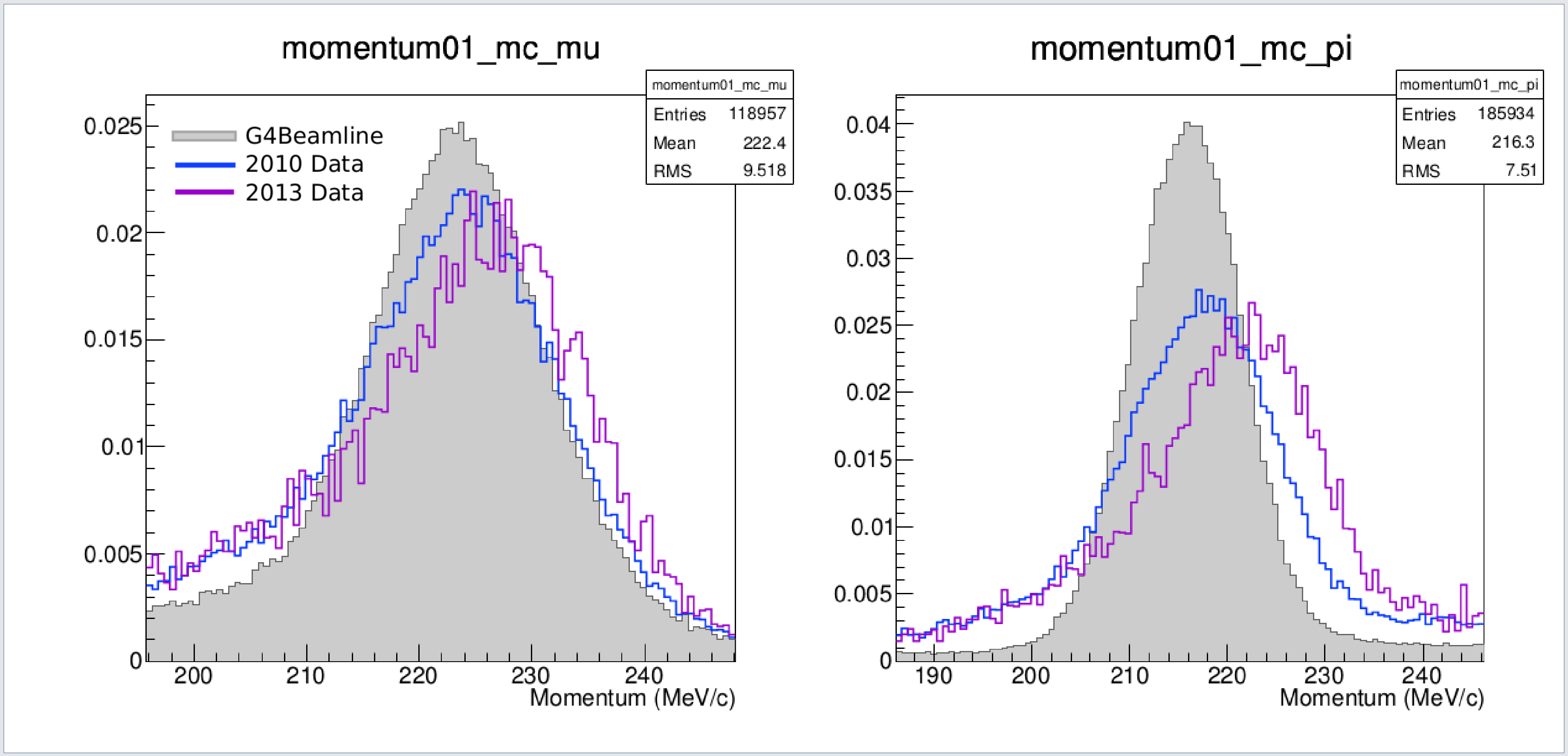
- In order to calculate the bending strength of the quadrupole (k), the momentum must be known. This data can be obtained using Beta from the TOF system.
- The electron peak is used as a reference point to ensure compatibility.



G4BL from Hansen's Deck

Momentum Calculation (2/2)

- From cuts on Beta, the momentum of the beam is obtained.
- To minimise the fraction of misidentified particles only 205->235 MeV/c particles are used in this study



Position Calculation & Parametrisation (1/2)

- Next the mean position of the beam must be obtained. This is complicated by the following:

1. Finite detector size:
   Use central 380mm of detector, cut central to detector location.

2. Losses downstream of the Quadrupole being scanned:
   Use central 240mm of the beam.

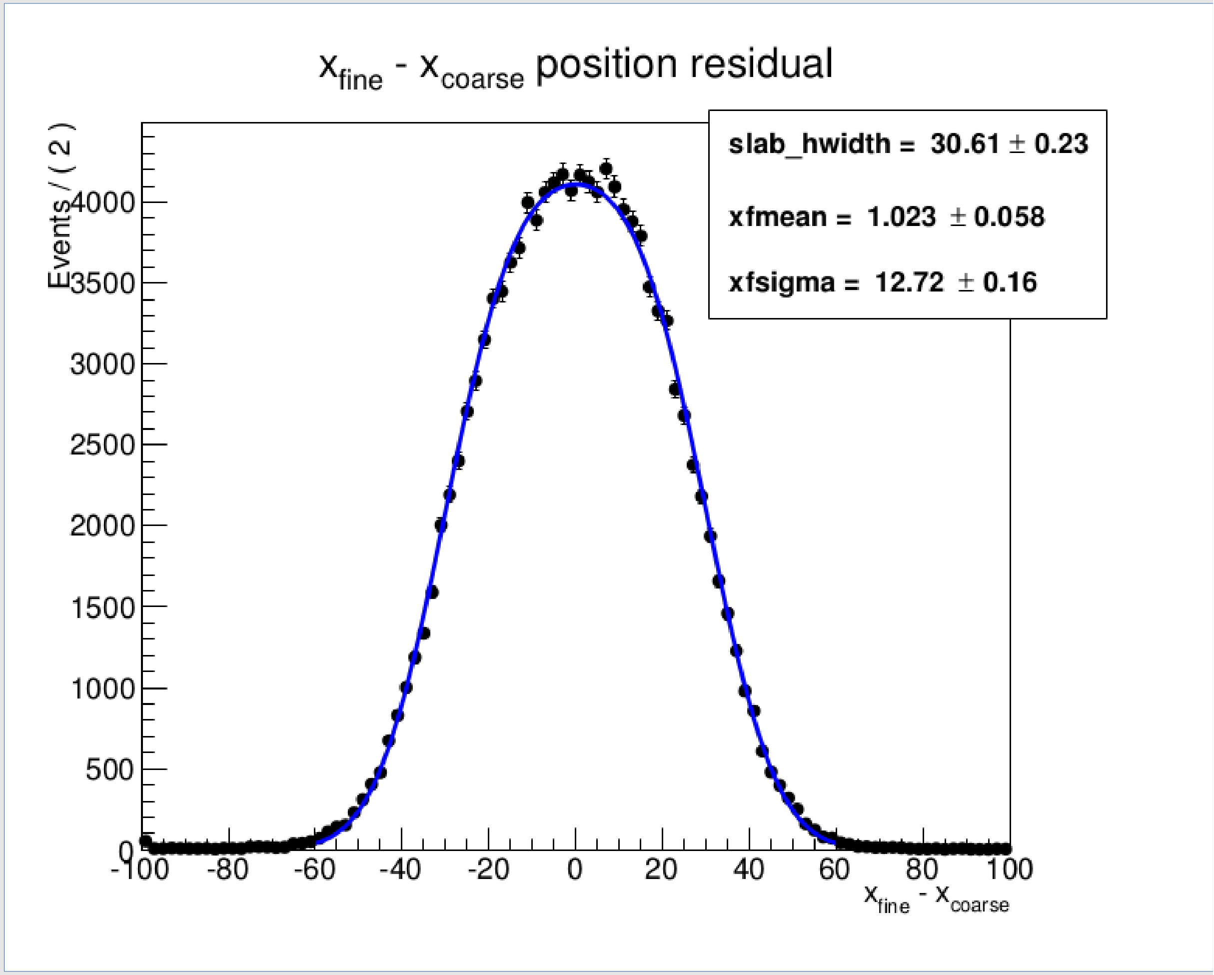
3. Losses up to and including the scanned quadrupole:
   Use central fraction of the beam depending on width (Q7:1.3σ, Q8:0.96σ,Q9:0.74σ)

After placing these cuts, it was necessary to fit a Gaussian to the beam, since evaluation of the raw moments would be problematic.

- Finally, it would be nice to avoid the 'pixel' effects of the slabs:
  Need to use a differential time measurement across the slab, like used in the Step I reconstruction..

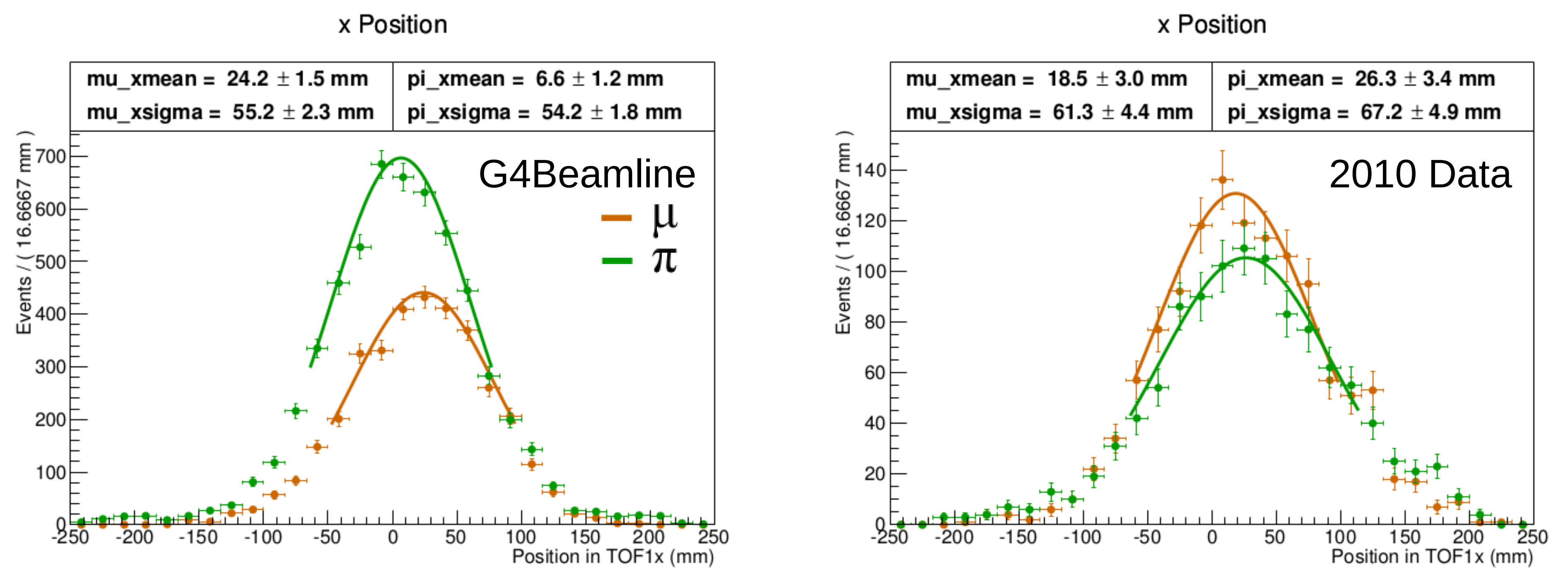
Detour to the *“fine”* position measurement

- Using the same technique as adopted in Step I, a 'fine' position measurement was made from the differential time of the PMT slabs.
- Following instructions in M.Rayner thesis, it was also easy to generate the needed calibrations for the 2010 and 2013 datasets under study.
- Plot to the right shows the difference between the “coarse” pixel measurement and the “fine” measurement. It is fitted with a convolution of a Gaussian with a uniform distribution.



Position Calculation (2/2)

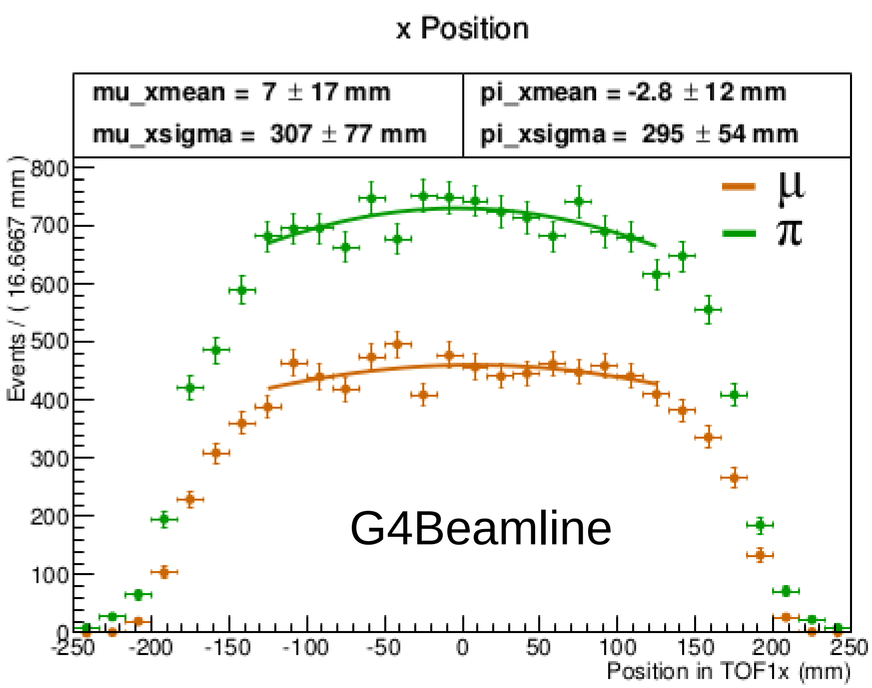
- Beam profile parametrisation was completed by fitting a Gaussian to each of the X and Y distributions.
- To avoid the need to neatly bin the data, an unbinned maximum liklihood fit was conducted with the Roofit libraries in PyROOT...

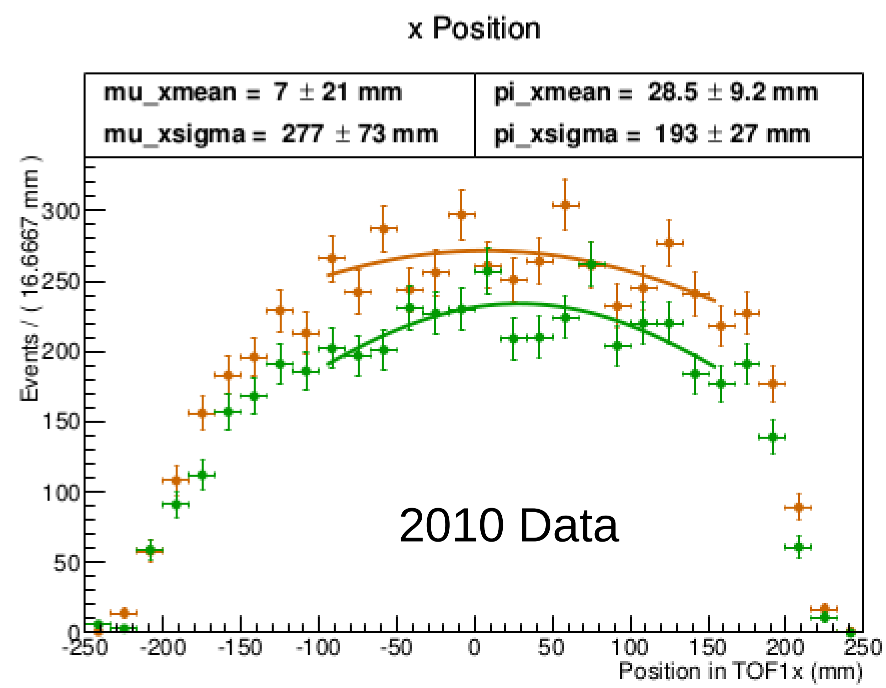


Focusing Q7 (120A), Just enough focusing to make a nice Gaussian on TOF1..

Position Calculation (2/2)

- Many of the scan points were not where the quadrupole neatly focuses the beam...
- Below is the beam profile with Q7=Q8=Q9=0A. Note that Q7 **defocuses** y, so the y axis fit only deteriorates with increasing current.



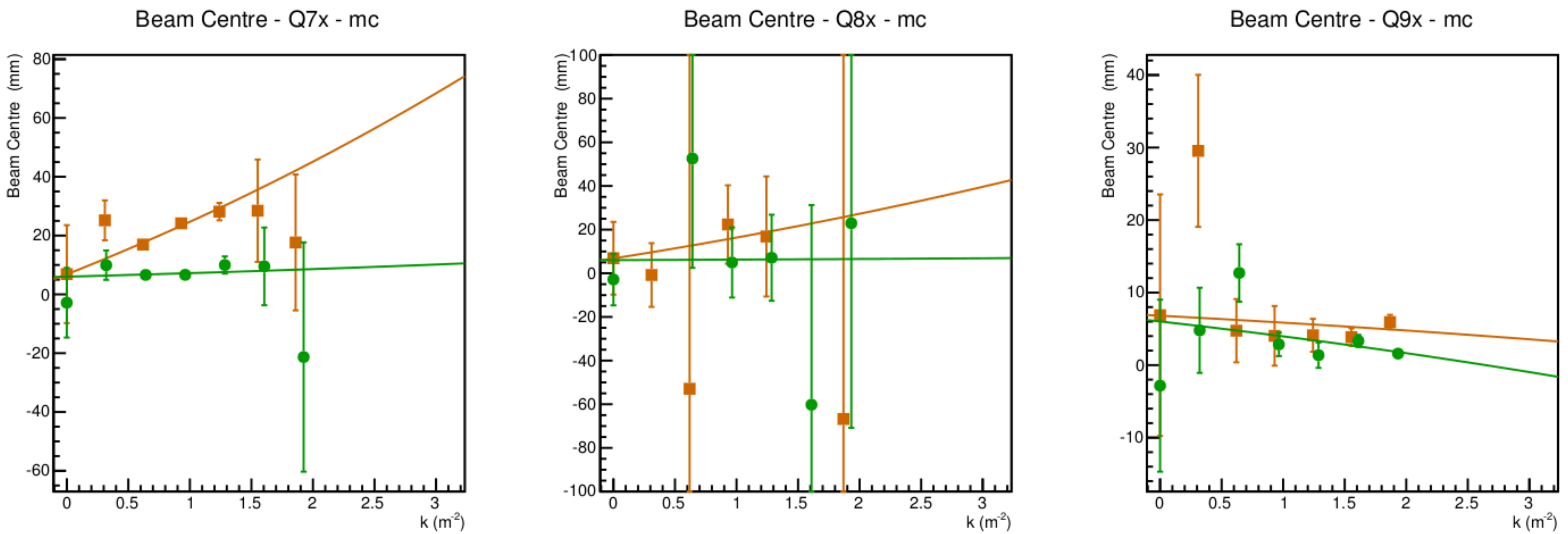


Not so nice, but demonstrates the need to limit the fit range...

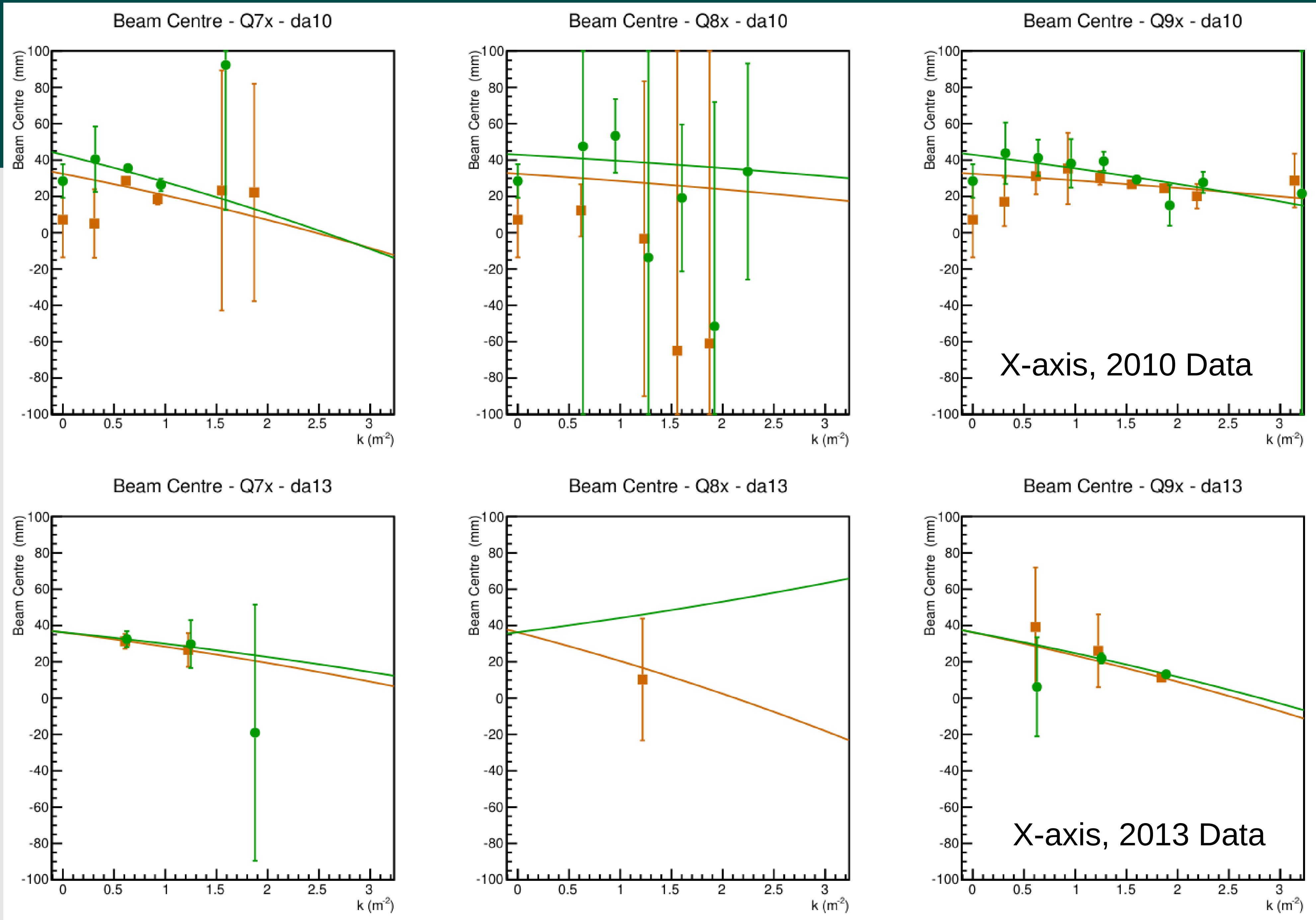
Fitting <m(k)>

- With the mean position, momentum and quadrupole current, we fit <m(k)>.
- The misalignment of the TOF (zt) is common to all scans. For this reason a simultaneous fit of Q7, Q8, Q9 is run, with zt as a common parameter.
- Large uncertainty from the mean position resulted and a limited number of data points resulted in a large correlation between angular and position offsets. The result of this correlation was the fit parameters wandering off to non-physical values.
  - The solution to this was to fix the angular offset (zq') to zero. Note a 5 degree angular offset would result in less than a 1mm change in position at the TOF.
- Good fits were obtained for Q7, Q9 in x and Q8 in y, since these were the focusing quads.

Fitting <m(k)>



X-axis, G4Beamline


Beam Centre - Q7x - da10
Beam Centre - Q8x - da10
Beam Centre - Q9x - da10
X-axis, 2010 Data
Beam Centre - Q7x - da13
Beam Centre - Q8x - da13
Beam Centre - Q9x - da13
X-axis, 2013 Data
Beam Centre (mm)
k (m^{-2})

Results..

- The fit results from the previous 9 plots and an additional 9 plots for y are below:
- The truth data is derived from virtual detector planes placed just upstream from each quad.

X axis results

Parameter		Monte-Carlo Truth	Monte-Carlo Fit	Data 2010	Data 2013
z_t (mm)	μ	-	6.8 ± 2.6	32.5 ± 4.6	36 ± 11
	π	-	6.0 ± 1.8	43.0 ± 5.0	36.3 ± 7.2
z_7 (mm)	μ	-4.1 ± 0.9	-7.0 ± 1.2	4.6 ± 2.5	3.0 ± 5.8
	π	-2.0 ± 0.7	-0.4 ± 0.8	5.9 ± 2.7	2.5 ± 4.4
z_8 (mm)	μ	0.9 ± 2.0	-5.4 ± 8.2	2.3 ± 9.3	9 ± 16
	π	3.0 ± 1.7	-0.1 ± 6.3	2.0 ± 7.8	-5 ± 75
z_9 (mm)	μ	5.4 ± 2.9	1.1 ± 1.8	4.2 ± 3.1	14.9 ± 6.7
	π	2.0 ± 2.1	2.4 ± 1.3	8.8 ± 3.6	13.5 ± 4.9
ChiSq/NDF	μ	-	15/14	12/17	2.9/7
	π	-	11/14	10/17	3.6/7

Y axis results

Parameter		Monte-Carlo Truth	Monte-Carlo Fit	Data 2010	Data 2013
z_t (mm)	μ	-	-2.1 ± 2.5	14.6 ± 6.8	23 ± 11
	π	-	-2.6 ± 2.0	-3.1 ± 8.2	-15 ± 10
z_7 (mm)	μ	-0.2 ± 1.0	3.1 ± 5.1	20 ± 70	15 ± 13
	π	-4.1 ± 0.7	-1.1 ± 6.9	-1.3 ± 7.1	-6.1 ± 5.7
z_8 (mm)	μ	-2.4 ± 2.0	-1.1 ± 1.4	0.4 ± 3.9	12 ± 5.7
	π	-1.8 ± 1.4	-1.6 ± 1.1	-10.6 ± 4.7	-6.7 ± 6.5
z_9 (mm)	μ	-1.4 ± 2.8	-8 ± 11	12 ± 12	43 ± 26
	π	-2.5 ± 2.0	1.1 ± 6.9	8 ± 29	21 ± 64
ChiSq/NDF	μ	-	8.5/14	14/17	2.4/7
	π	-	8.1/14	13/17	2.5/7

- No glaring signs of misalignment, but was only able to achieve ~4mm resolution!

2 for 1: A covariance study

- Thanks goes to Victoria for this idea/paper*.
- One of many techniques for calculation of emittance is to vary the quadrupole field and study how this changes the beam width. From the following equations it is possible to determine the covariance matrix just upstream of the scanned quad:

$$\Sigma_T(k) = \hat{R}(k)\Sigma_Q\hat{R}^T(k)$$

Covariance matrix at the TOF. The first element is the variance of particle position. A normal distribution was fitted, so:

$$\sigma_m^2(k) = \Sigma_{T,11}(k) + \sigma_R^2$$

Combines the previous fit result, with the first covariance matrix element and accounts for detector resolution.

Transfer Matrix:

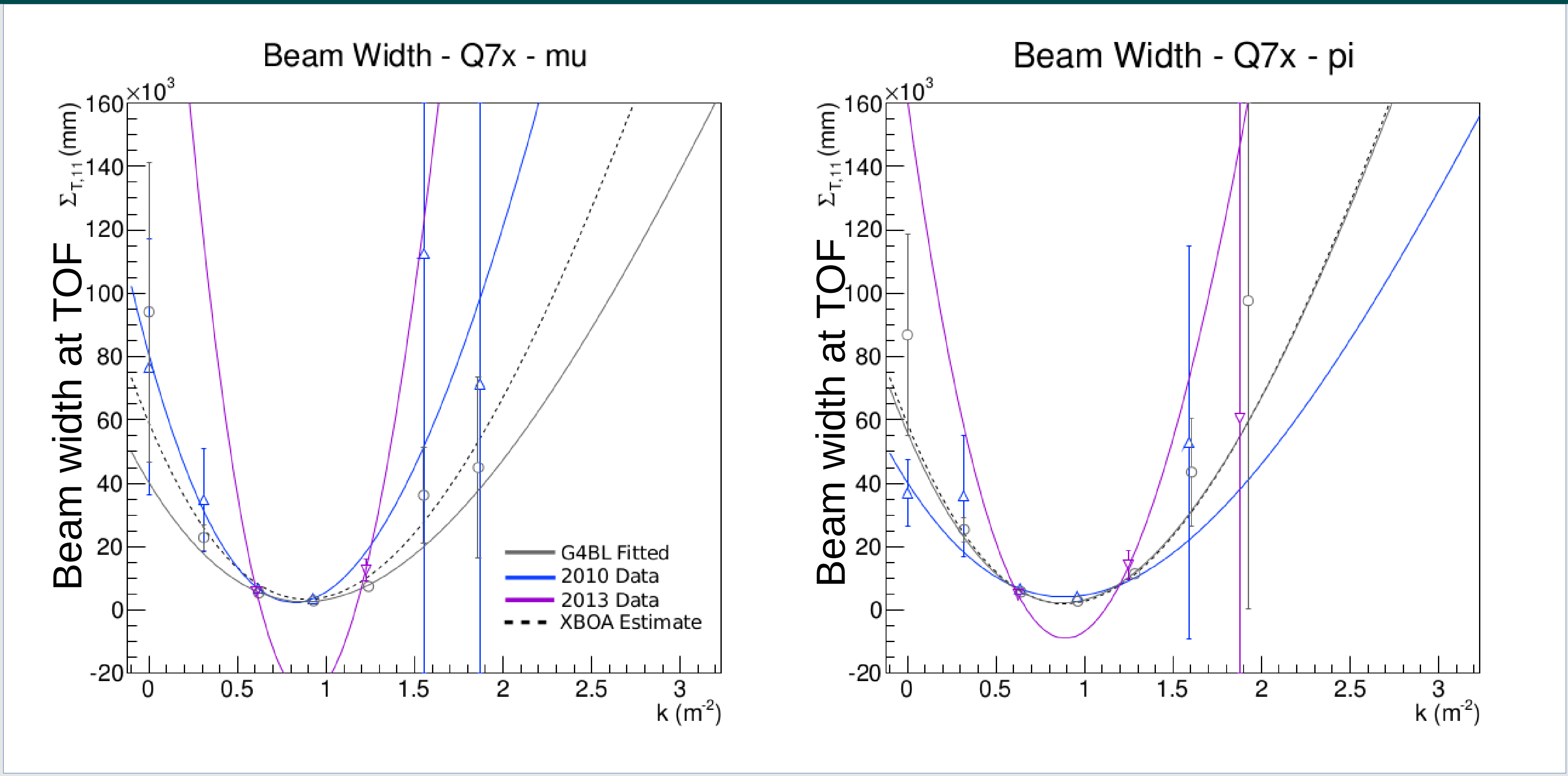
$$\hat{R}(k) = \hat{O}(d)\hat{F}(k)$$

Covariance matrix upstream of the quad. Variation of k will help reveal the elements..

- Onwards, to the fit..

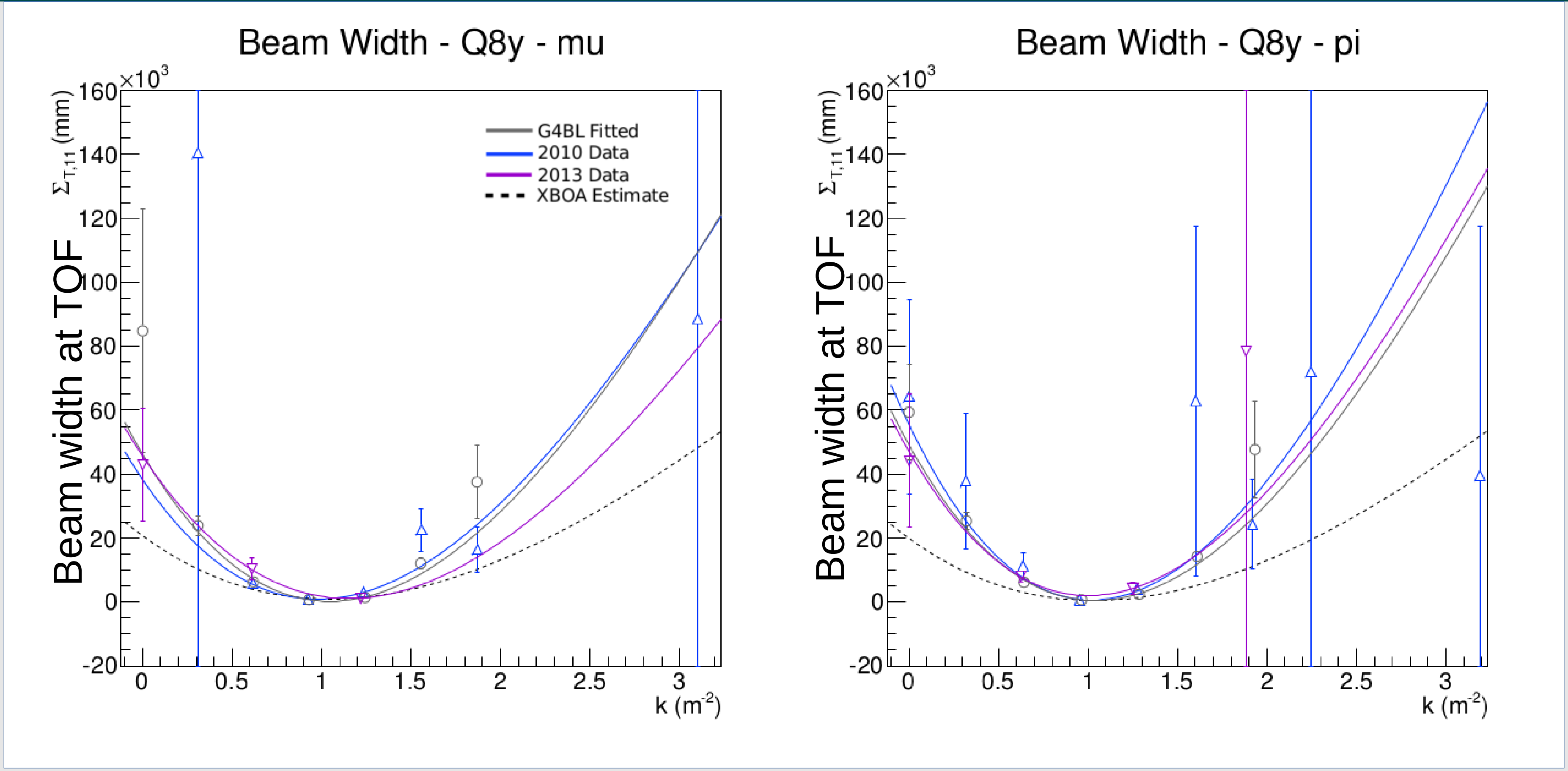
* From this paper: Methods of emittance measurement. K. T. McDonald and D. P. Russell, Frontiers of Particle Beams; Observation, Diagnosis and Correction.

covariance fits



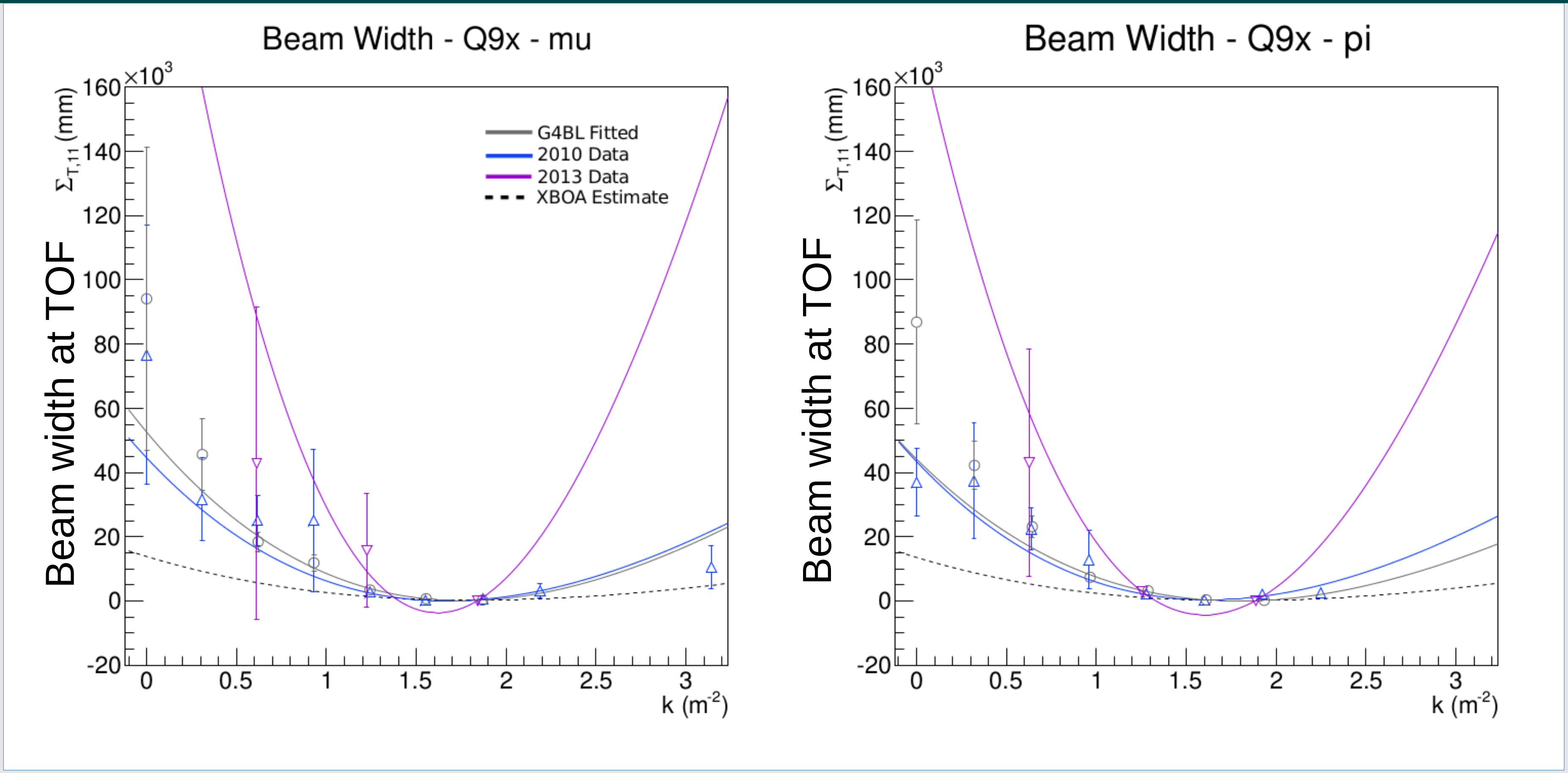
- … Q7(x): G4BL, 2010 data and an estimate from xboa all come pretty close.
- The 2013 dataset had no data point at the ~ k=1 and the fit headed out towards the non-physical as a result.

covariance fits



- … Q8(y): G4BL, 2010 data, 2013 data also come pretty close.
- The xboa prediction begins to differ because it evaluates the beam moments, which scrape in the quadsand care was taken to avoid in the alignment scan.

covariance fits



- … Q9(x): G4BL, 2010 data, come close. The 2013 suffers the same fate as Q7 data.
- The xboa prediction begins to differs further due to more clipped beam in the quads.

2 for 1: Results

- The fit results show substantial uncertainty in each term of the covariance matrix.
- The large uncertainty combined in the calculation of emittance, ultimately making the calculation pointless.
- The first element Σ_{11} increases in the fit result for increasing z, which is to be expected considering the lack of focusing.

Parameter			Monte-Carlo XBOA	Monte-Carlo Scan Fit	Data 2010	Data 2013
Q7x	Σ_{11}	μ	13181	9100 ± 1100	21800 ± 9800	80000 ± 25000
		π	13454	13100 ± 1100	8500 ± 3300	39000 ± 22000
	Σ_{12}	μ	3556	2390 ± 280	5000 ± 2000	23600 ± 7900
		π	3671	3460 ± 280	2240 ± 700	11300 ± 7200
	Σ_{22}	μ	1294	887 ± 73	1380 ± 310	4290 ± 120
		π	1199	1138 ± 69	990 ± 130	680 ± 130
	ϵ_N	μ	4.4	3.2 ± 1.9	5 ± 18	*
		π	2.6	2.6 ± 1.8	2.8 ± 3.0	*
	χ^2/n.d.f.	μ		5.0/3	0.2/2	0.3/1
		π		2.3/3	2.6/2	1.1/1
Q8y	Σ_{11}	μ	8123	20000 ± 1100	17400 ± 3300	14000 ± 11000
		π	8162	20000 ± 1100	23300 ± 5500	20000 ± 12000
	Σ_{12}	μ	1660	2310 ± 130	2990 ± 720	4000 ± 1500
		π	1646	4200 ± 270	4600 ± 1500	3700 ± 1900
	Σ_{22}	μ	542	581 ± 37	690 ± 160	1380 ± 600
		π	434	979 ± 61	1050 ± 350	1090 ± 360
	ϵ_N	μ	2.7	2.5 ± 1.1	4 ± 5	4 ± 13
		π	1.4	2.1 ± 2.4	3 ± 12	5 ± 7
	χ^2/n.d.f	μ		9.5/3	5.4/5	1.5/1
		π		9.8/3	4.7/5	0.6/1
Q9x	Σ_{11}	μ	8259	34200 ± 4800	31400 ± 5700	-7000 ± 10000
		π	8374	27600 ± 2200	32300 ± 5300	143000 ± 72000
	Σ_{12}	μ	1520	5460 ± 580	3970 ± 940	7700 ± 2100
		π	1475	4930 ± 300	3200 ± 1000	13900 ± 5800
	Σ_{22}	μ	485	960 ± 150	530 ± 140	4270 ± 160
		π	357	865 ± 89	600 ± 250	-1840 ± 160
	ϵ_N	μ	2.7	4 ± 7	2 ± 14	*
		π	1.4	*	5 ± 4	*
	χ^2/n.d.f	μ		3/3	6/5	0.4/1
		π		11/3	7.1/5	0.4/1

Conclusions

- The TOF detectors have been used for an interesting study of our Step I beam line.
- Neither the beam line or detectors were designed to undertake this study and resulted in large uncertainty in parametrisation of the x,y distributions of the beam.
- Nevertheless, data has been fitted:
  - Q789 in 2010 and 2013 have been scanned for signs of misalignment.
  - The misalignment study was able to achieve ~5mm resolution (for focusing magnets)
  - No substantial sign of misalignment has been observed.
  - The covariance matrix just upstream of Q7, Q8, Q9 has been determined for the scan.
  - The scan shows a good agreement to the G4Beamline data.

Thank you for your attention and patience!