Presentation of latest results

A first measurement of the emittance of the MICE muon beam

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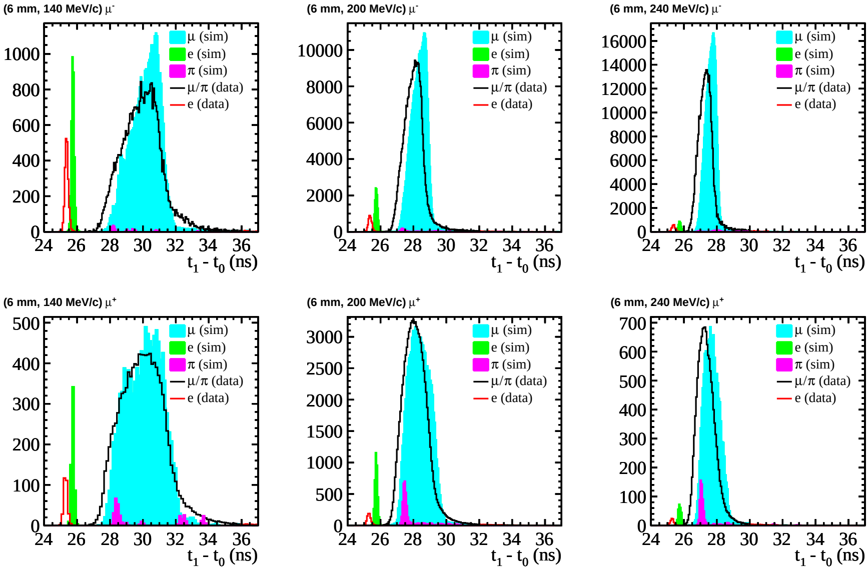
30th collaboration meeting of the MICE experiment
The University of Oxford
7/7/2011

AMDG – LDS

Raw 6 mm data (including 1000/1024 correction)



L between TOF centre planes

Corners A, B, C, D, centre planes $\hat{n} \cdot (\vec{r} - \vec{r}_0) = 0$

$\hat{n}$ is the normal, obtained from $\vec{AC} \times \vec{BD}$
$\vec{r}_0$ is the centre of the detector, deduced from $\vec{AC} + \vec{BD}$
Unrotated TOF would sit in $z = z_0$ where $\hat{n} = \hat{z}$

Tilt (dihedral angle) given by $\cos\alpha = \hat{n}_1 \cdot \hat{n}_2$

TOF0 normal $= (-0.467, -0.509, 99.998)$, $\alpha = 0.396\,\text{deg}$
TOF1 normal $= (-0.927, -1.423, 99.986)$, $\alpha = 0.974\,\text{deg}$
$(20\text{ cm})\sin 1^\circ = 3.5$ mm $\Rightarrow$ uncertainty on L

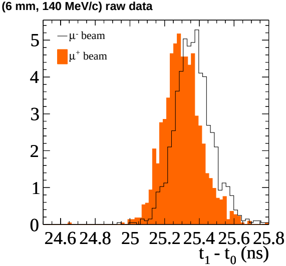
Middles of the detector (from the survey recon)

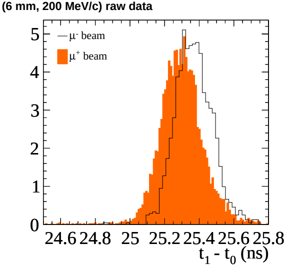
TOF0 $\vec{r}_0 = (1.8, 2.6, 5293.8)$ mm, TOF1 $\vec{r}_0 = (30.2, -17.6, 12999.0)$ mm

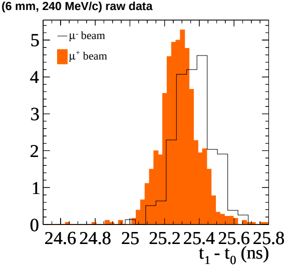
Intersection with design orbit at $z_{\text{design}} = \hat{n} \cdot \vec{r}_0 / \hat{n}_z$

TOF0 $z_{\text{design}} = 5293.7$ mm, TOF1 $z_{\text{design}} = 12999.0$ mm

Position of the $e^{\pm}$ peak in raw data



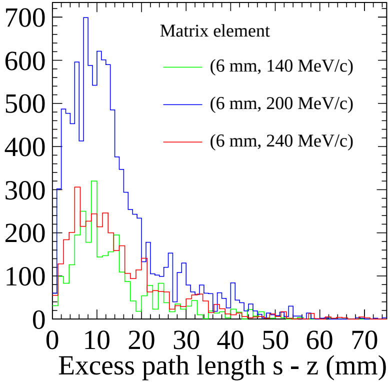




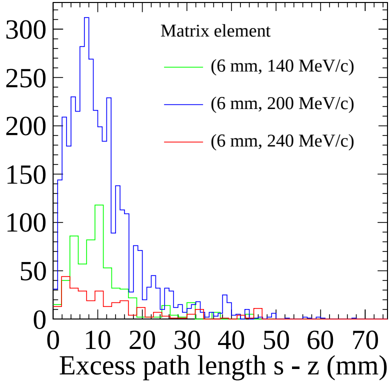
$\langle t_e^{\text{data}} \rangle$	Electrons	Positrons
(6 mm, 140 MeV/c)	25.366 ns ± 3 ps	25.303 ns ± 3 ps
(6 mm, 200 MeV/c)	25.369 ns ± 3 ps	25.298 ns ± 2 ps
(6 mm, 240 MeV/c)	25.370 ns ± 9 ps	25.289 ns ± 4 ps

$e^{\pm}$ path length is $> L$

Monte Carlo electrons

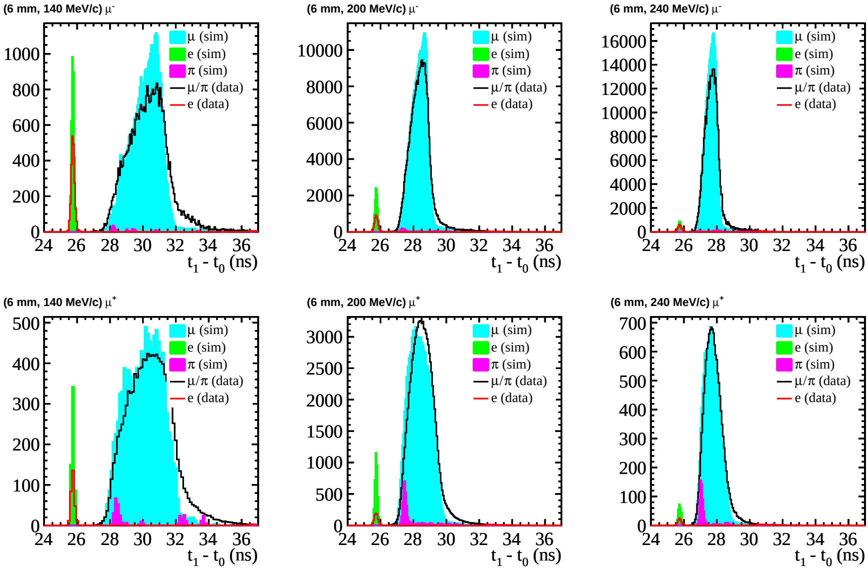


Monte Carlo positrons



$\langle \delta_e^{\mathrm{sim}} \rangle$	Electrons	Positrons
(6 mm, 140 MeV/c)	13.9 ± 0.2 mm	10.9 ± 0.3 mm
(6 mm, 200 MeV/c)	13.8 ± 0.1 mm	11.0 ± 0.1 mm
(6 mm, 240 MeV/c)	14.6 ± 0.2 mm	12.7 ± 0.7 mm

Corrected 6 mm data



Systematic uncertainty on p_z

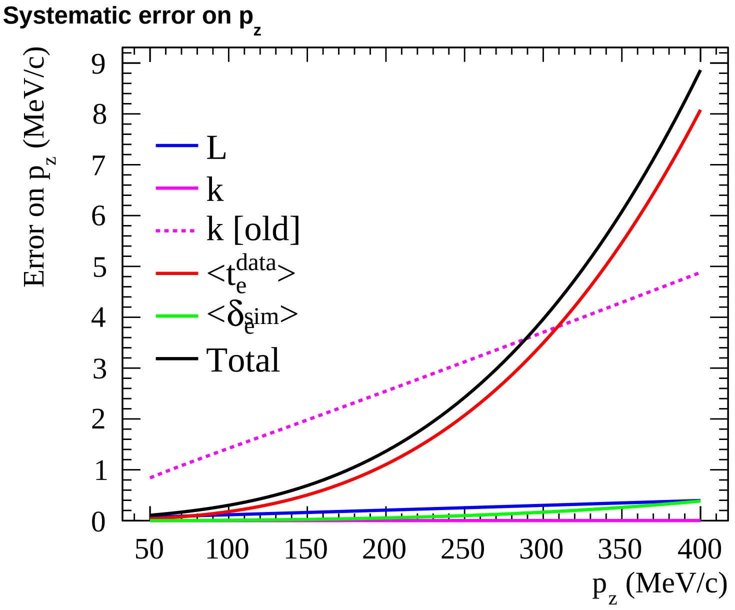
A precise measurement based on $p/E = L/t$

In units where $c = 1$,

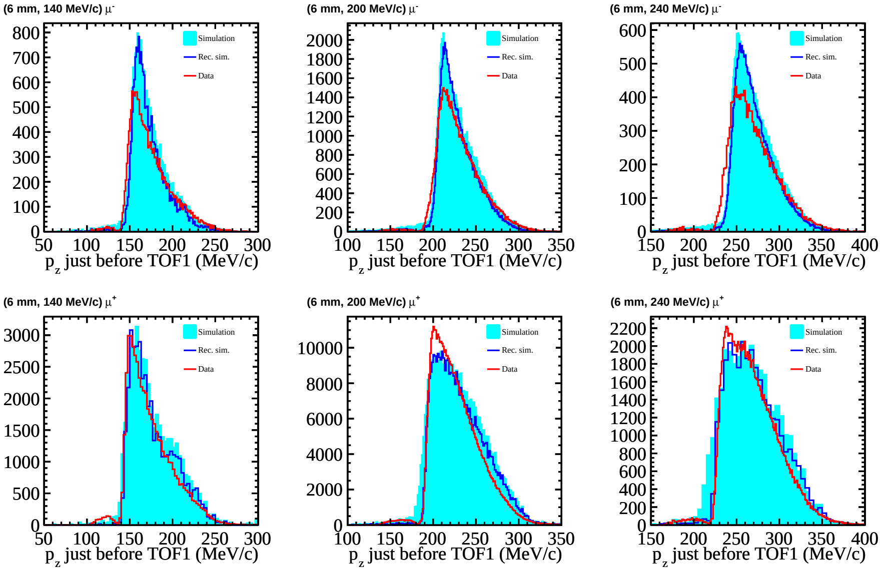
$$E_\mu/p_\mu\left(L + \delta_\mu^{\text{calc}}\right) = k\left(t_\mu - \left\langle t_e^{\text{data}}\right\rangle\right) + \left(L + \left\langle \delta_e^{\text{sim}}\right\rangle\right)$$

Variable	Resolution	Comment
L	3 mm ≡ 12 ps	Survey resolution plus tilt uncertainty
	1.5 cm ≡ 50 ps	Elbow uncertainty
	~~5 cm ≡ 170 ps~~	~~Survey misinterpreted~~
k	10^{-5} ≡ 0.3 ps	Previous analyses assumed 25 ps rather than 24.414 ps TDC bins ⇒ 0.6 ns error
$\left\langle t_e^{\text{data}}\right\rangle$	35 ps	∵ don't understand e^+/e^- discrepancy, apply separate +/− correction
$\left\langle \delta_e^{\text{sim}}\right\rangle$	0.5 mm ≡ 2 ps	Apply M.C. correction based on polarity and p_z of matrix element

Systematic uncertainty on p_z



p_z data/simulation comparison



p_z data/simulation comparison

Mean p_z	Rec. sim.	Data
(6 mm, 140 MeV/c) μ^-	174.80 ± 1.5	174.78 ± 1.5
(6 mm, 140 MeV/c) μ^+	178.66 ± 1.5	173.89 ± 1.5
(6 mm, 240 MeV/c) μ^-	273.01 ± 3.5	270.68 ± 3.5
(6 mm, 240 MeV/c) μ^+	272.44 ± 3.5	267.90 ± 3.5
(6 mm, 200 MeV/c) μ^-	230.95 ± 2.5	230.85 ± 2.5
(6 mm, 200 MeV/c) μ^+	233.03 ± 2.5	227.01 ± 2.5

Statistical errors only:

RMS p_z	Rec. sim.	Data
(6 mm, 140 MeV/c) μ^-	21.16 ± 0.15	24.51 ± 0.13
(6 mm, 140 MeV/c) μ^+	25.97 ± 0.32	26.12 ± 0.08
(6 mm, 200 MeV/c) μ^-	23.19 ± 0.05	25.38 ± 0.06
(6 mm, 200 MeV/c) μ^+	29.53 ± 0.11	27.60 ± 0.03
(6 mm, 240 MeV/c) μ^-	24.83 ± 0.05	28.04 ± 0.16
(6 mm, 240 MeV/c) μ^+	32.08 ± 0.30	30.65 ± 0.06

Step 1 G4MICE software suite

The applications:

`Step1Ensemble`

Applies Y.K.'s TOF calibration to data, obtains μ tracks

`XCalibration`

Extends Y.K.'s TOF calibration for timing based (x, y) measurements

`Step1Reconstruction`

Applies `common/Step1Tracking` to data

`TestStep1Reconstruction`

Applies resolutions and `common/Step1Tracking` to simulation

`Step1Optics`

Attempts to correct resolution bias on emittance (just for fun)

Step 1 G4MICE software suite

Reconstruction classes, common to data/simulation reconstruction:

`common/Step1Tracking`

Instantiates `common/Step1BeamLine`, and 10 `common/Step1Iterations`

`common/Step1BeamLine`

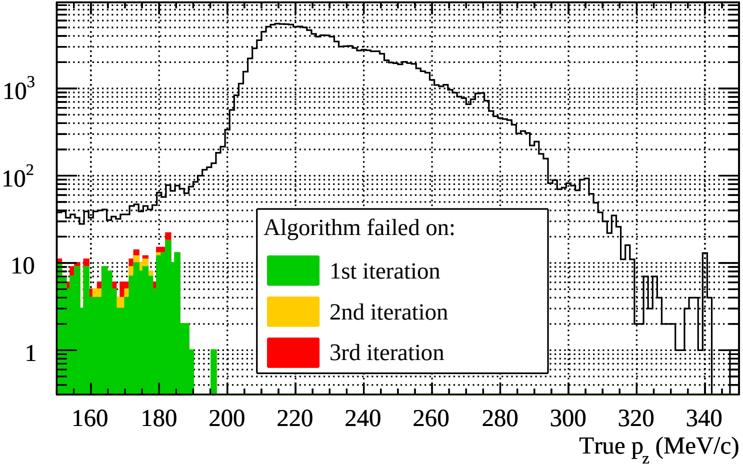
Holds info on geometry, provides $\mathbf{M}(p_z)$ and approximation of path length
User selects quad field model class (all inherit from `Quadrupole`):

- `ThinLens`
- `TopHat`
- `FastQuad` - default
- `SliceQuad`

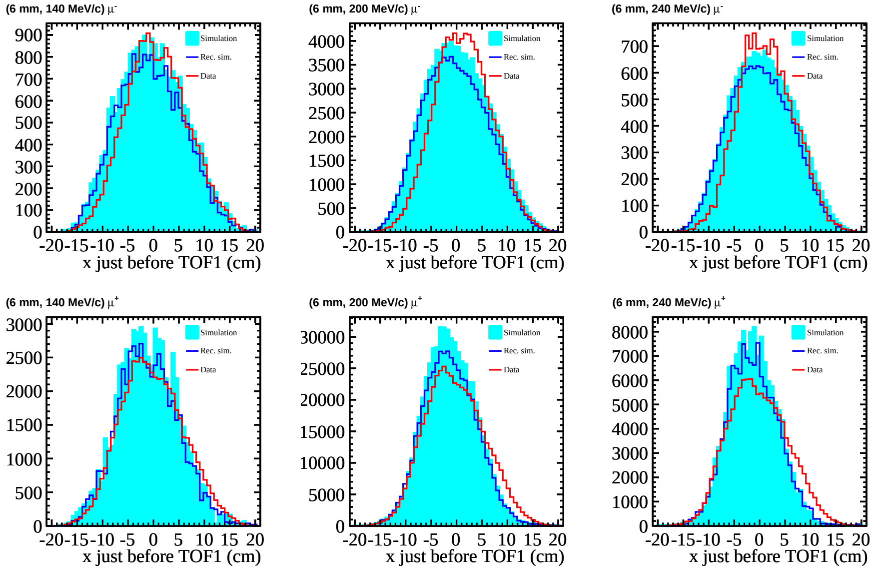
`common/Step1Iteration`

Improves estimates of s, p_z, x', and y'

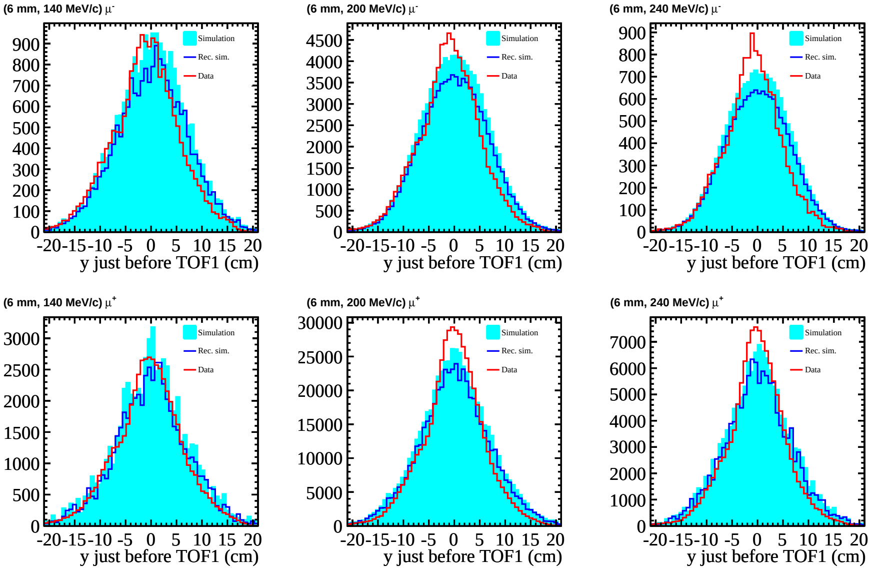
Reconstruction efficiency



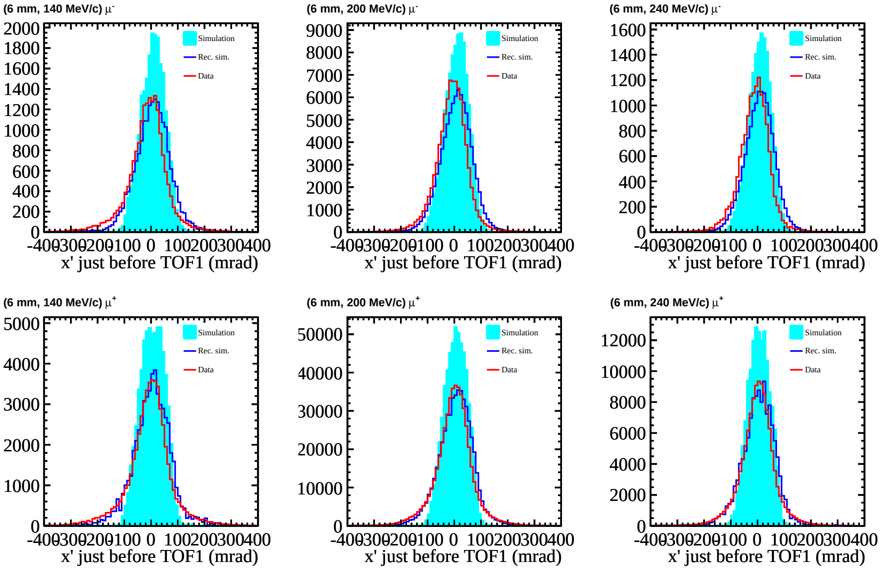
x data/simulation comparison



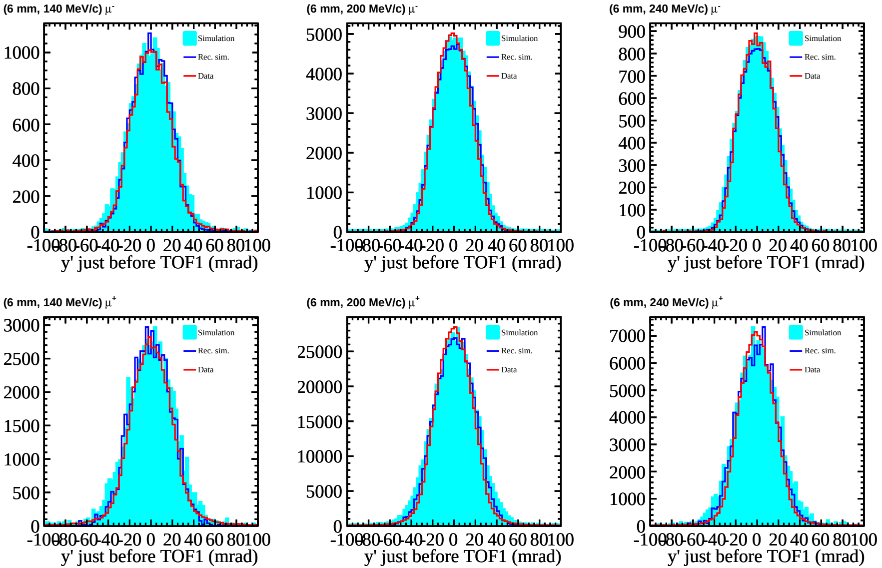
y data/simulation comparison



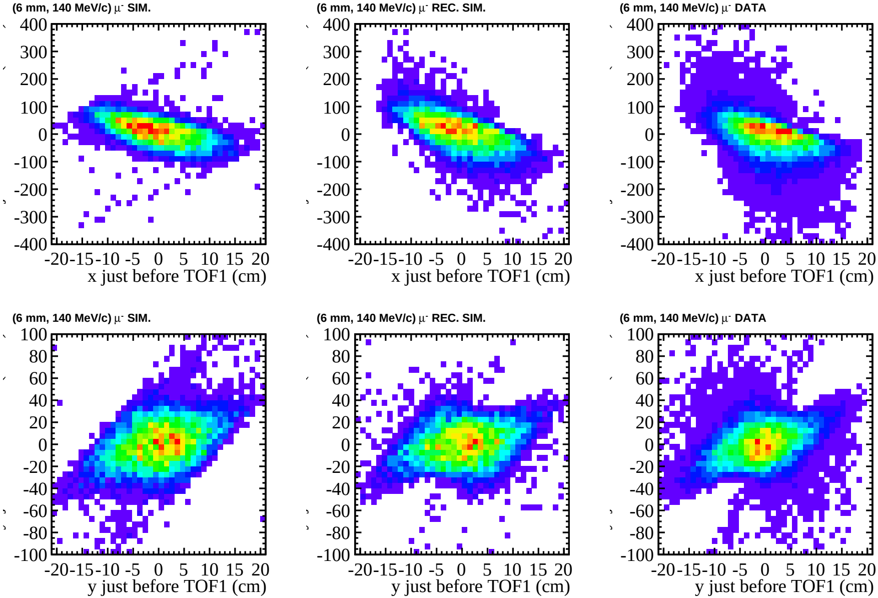
x' data/simulation comparison



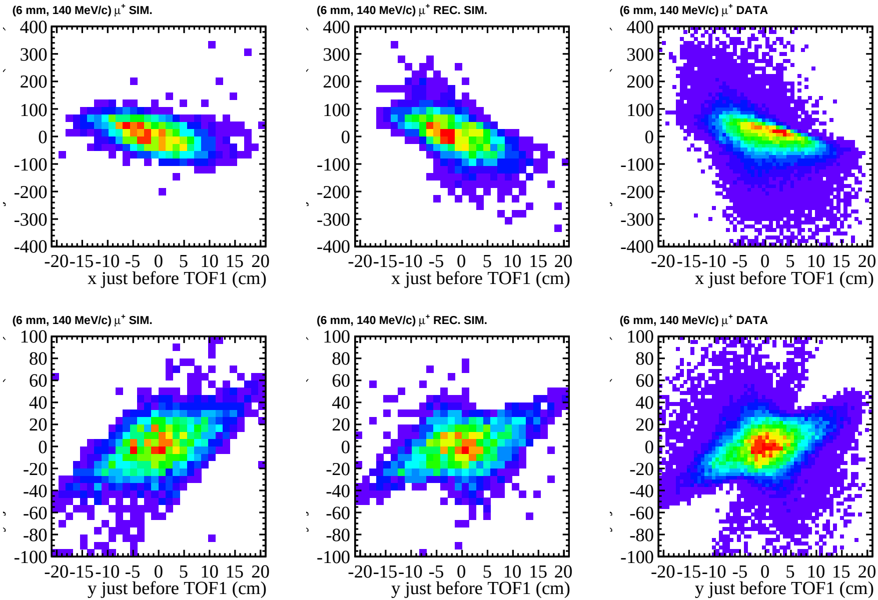
y' data/simulation comparison



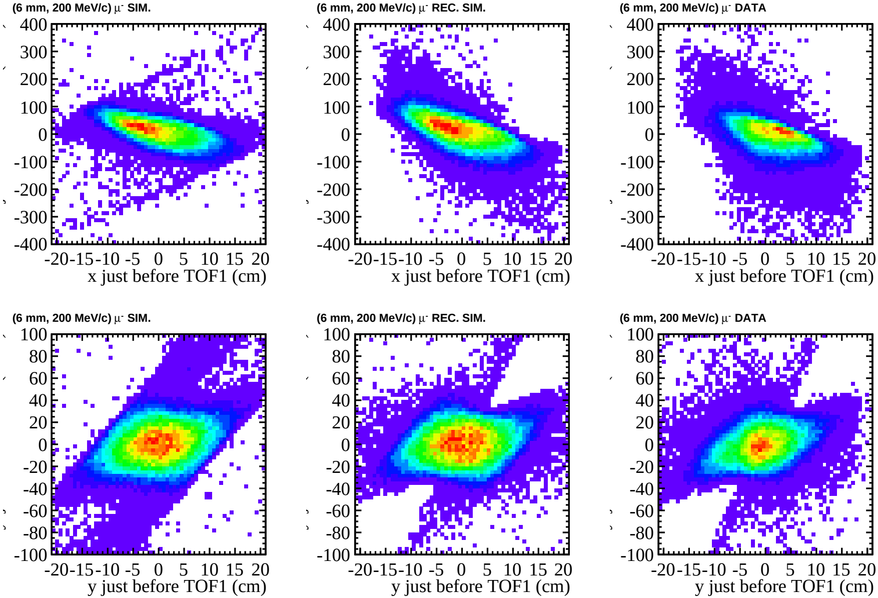
(6 mm, 140 MeV/c) μ^- trace space (mm,mrad)



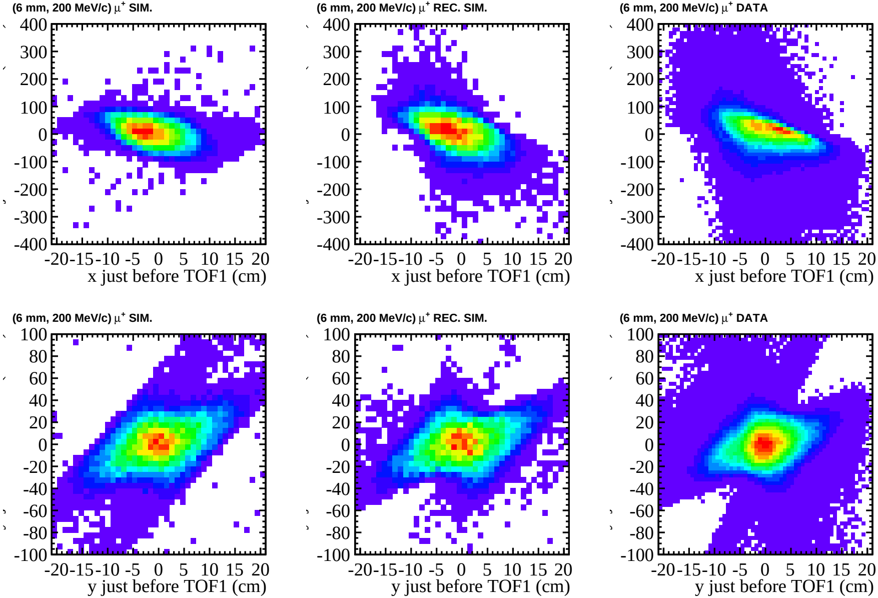
(6 mm, 140 MeV/c) μ^+ trace space (mm,mrad)



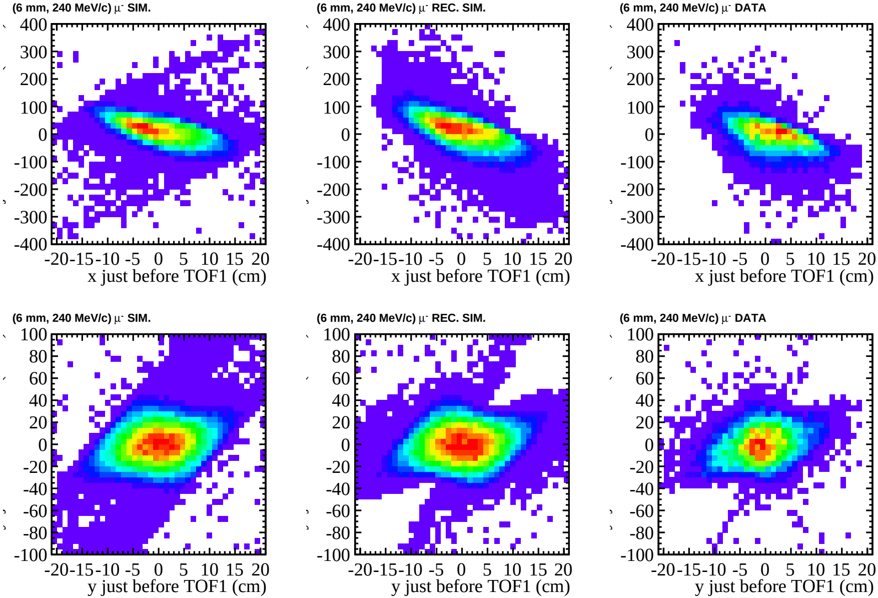
(6 mm, 200 MeV/c) μ^- trace space (mm,mrad)



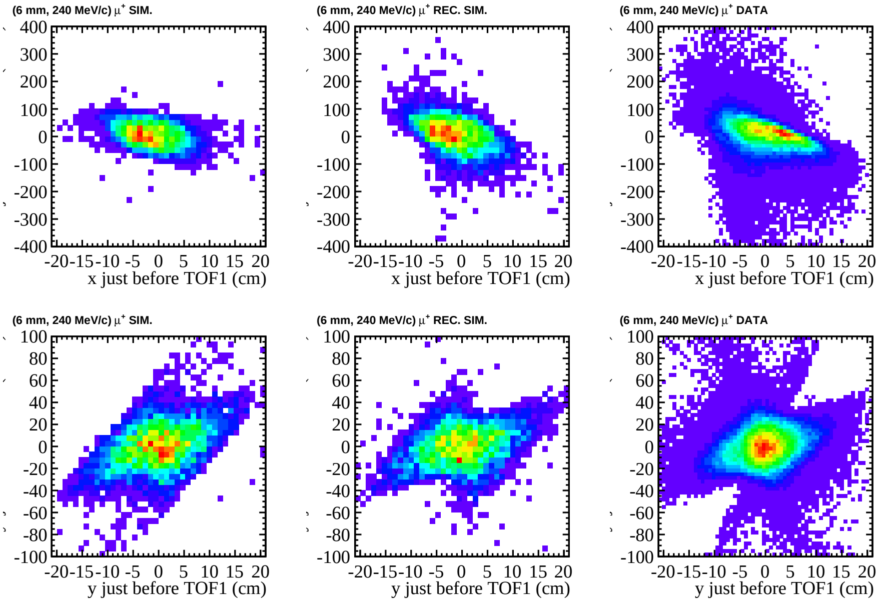
(6 mm, 200 MeV/c) μ^+ trace space (mm,mrad)



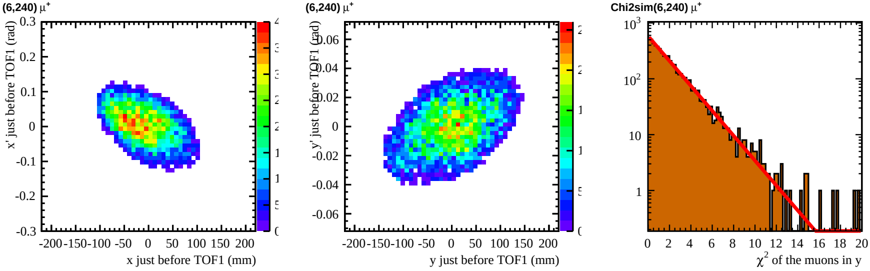
(6 mm, 240 MeV/c) μ^- trace space (mm,mrad)



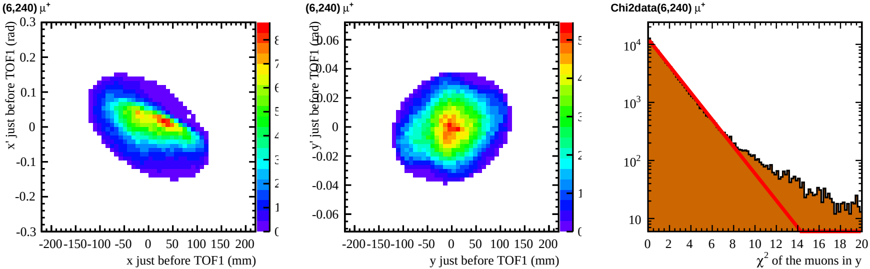
(6 mm, 240 MeV/c) μ^+ trace space (mm,mrad)

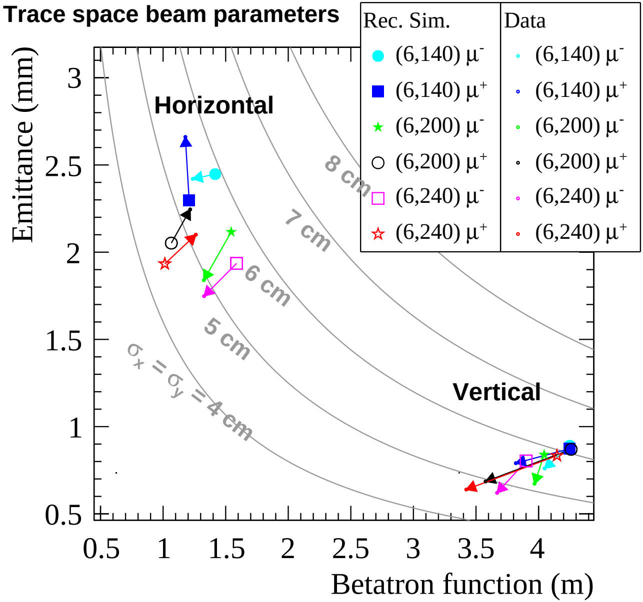


$\chi^2 \equiv A/\epsilon$ cut on rec. sim. and data (6 mm, 240 MeV/c) μ^+

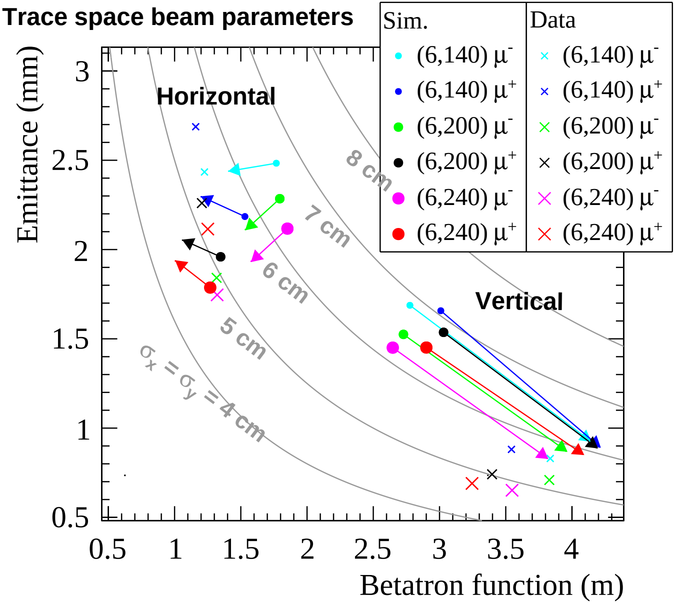


$\chi^2 < 4.61$ (90%) cut cleans up "high amplitude" noise in the data:




Trace space beam parameters
Rec. Sim.
(6,140) μ-
(6,140) μ+
(6,200) μ-
(6,200) μ+
(6,240) μ-
(6,240) μ+
Data
(6,140) μ-
(6,140) μ+
(6,200) μ-
(6,200) μ+
(6,240) μ-
(6,240) μ+
Horizontal
Vertical
8 cm
7 cm
6 cm
5 cm
σx = σy = 4 cm
Emittance (mm)
Betatron function (m)
0.5
1
1.5
2
2.5
3
3.5
4

The effect of resolution bias



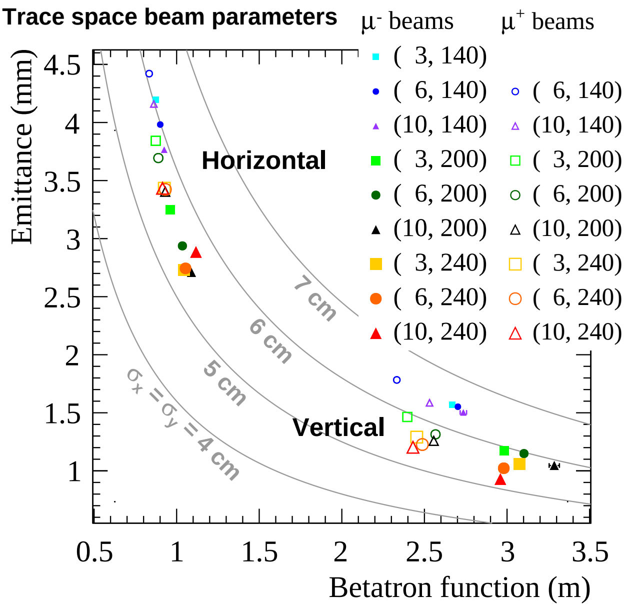
A summary table of the matrix element beam optics

The Step 1 data in a nutshell

	ϵ_n (mm)	p_z (MeV/c)	$\langle p_z \rangle$ (MeV/c)	σ_{pz} (MeV/c)	ϵ_x (mm)	β_x (m)	α_x	D_x (cm)	ϵ_y (mm)	β_y (m)	α_y
μ^- beams	3	140	168.0	24.4	4.20	0.87	0.55	14.5	1.57	2.67	-0.18
		200	219.0	25.6	3.25	0.96	0.56	16.3	1.18	2.98	-0.22
		240	256.5	27.2	2.73	1.04	0.60	16.3	1.06	3.08	-0.22
	6	140	172.8	24.6	3.98	0.90	0.57	13.8	1.55	2.70	-0.20
		200	228.2	25.5	2.94	1.03	0.64	14.1	1.15	3.10	-0.25
		240	267.6	28.3	2.74	1.05	0.59	17.5	1.02	2.98	-0.19
	10	140	179.9	24.7	3.77	0.92	0.59	14.2	1.50	2.74	-0.19
		200	243.1	26.6	2.71	1.09	0.63	16.0	1.05	3.29	-0.26
		240	279.2	29.3	2.88	1.12	0.65	15.1	0.93	2.96	-0.19
μ^+ beams	3	200	219.0	25.6	3.25	0.96	0.56	16.3	1.18	2.98	-0.22
		240	256.5	27.2	2.73	1.04	0.60	16.3	1.06	3.08	-0.22
	6	140	172.8	24.6	3.98	0.90	0.57	13.8	1.55	2.70	-0.20
		200	228.2	25.5	2.94	1.03	0.64	14.1	1.15	3.10	-0.25
		240	267.6	28.3	2.74	1.05	0.59	17.5	1.02	2.98	-0.19
	10	140	179.9	24.7	3.77	0.92	0.59	14.2	1.50	2.74	-0.19
		200	243.1	26.6	2.71	1.09	0.63	16.0	1.05	3.29	-0.26
		240	279.2	29.3	2.88	1.12	0.65	15.1	0.93	2.96	-0.19

Caveat: need to apply 1000/1024 correction and χ^2 cut and re-calculate

An original summary plot (1000/1024 and χ^2 caveats)



Observations

All the beams have approximately constant size

Due to beam selection by detectors and scraping (60% in quadrupole 6)

$\epsilon_x \approx 2\epsilon_y$

Despite decay solenoid mixing, due to FDF-FDF?

μ^+ have higher emittance than μ^-

Due to proton absorber?

Low-p_z have higher emittance

Despite scaling the magnet currents to try to preserve the same trace space distributions
χ^2cut will ameliorate the effect, not perfect scaling, and scraping dominant

Encouraging agreement with Monte Carlo!