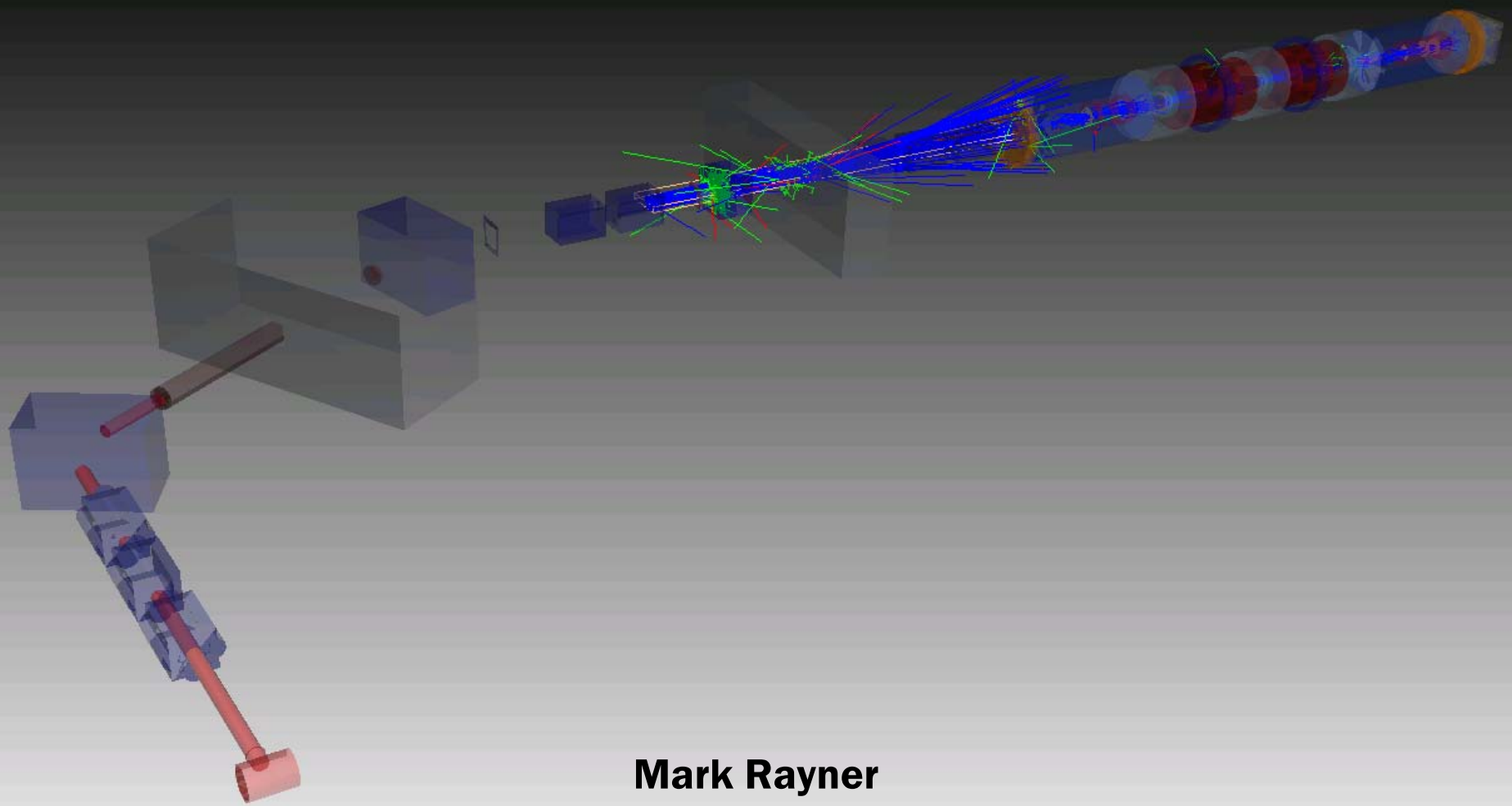
The MICE experiment: Momentum measurements using the time of flight counters



Mark Rayner

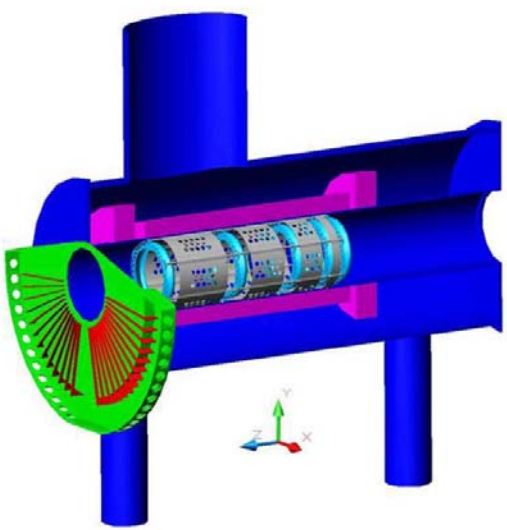
UKNF meeting, 4th April 2008

Motivation

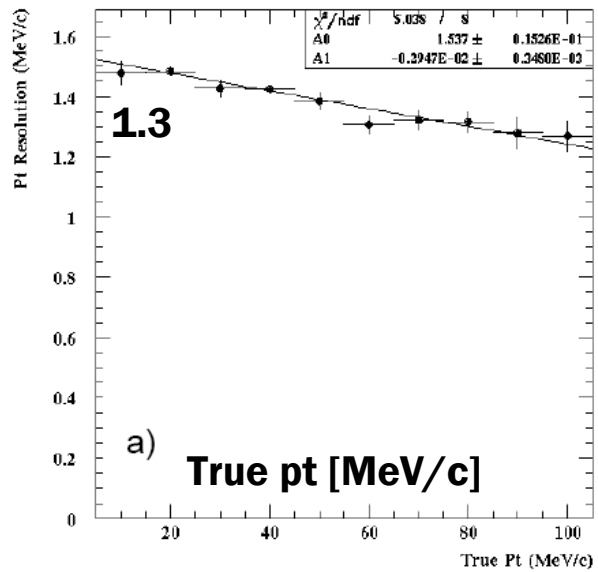
- **Analysis tasks requiring pz**
  - Understanding the ISIS beam
  - Measurement of longitudinal emittance
  - Selection of a neutrino factory beam
- **Methods using tracker measurements are well researched**
- **Can the TOFs help?**
  1. Quick overview of tracker, TOFs, and beam line
  2. Momentum reconstruction using TOF0 and TOF1
  3. Compare the numbers…

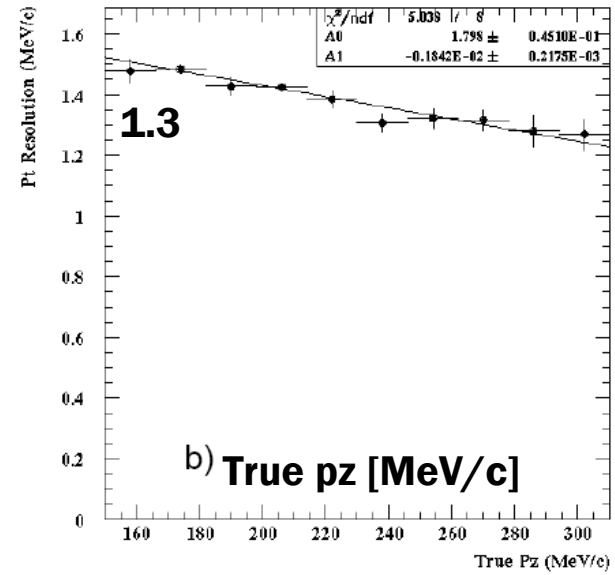
Tracker momentum resolution

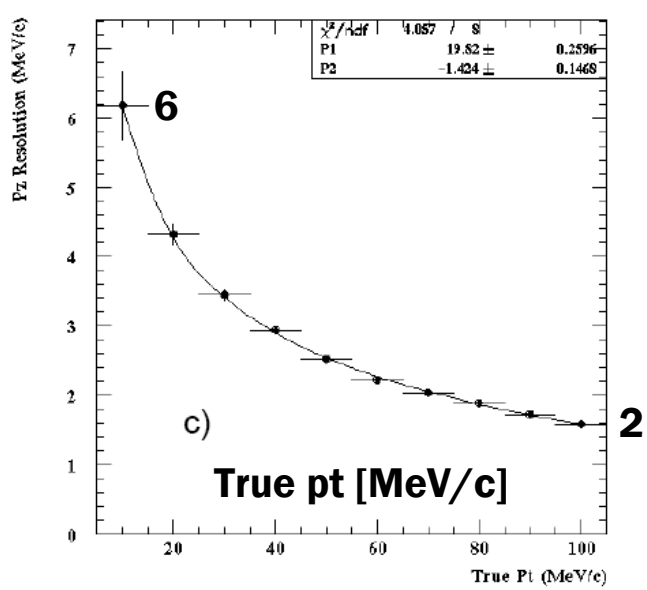
pt resolution [MeV/c]

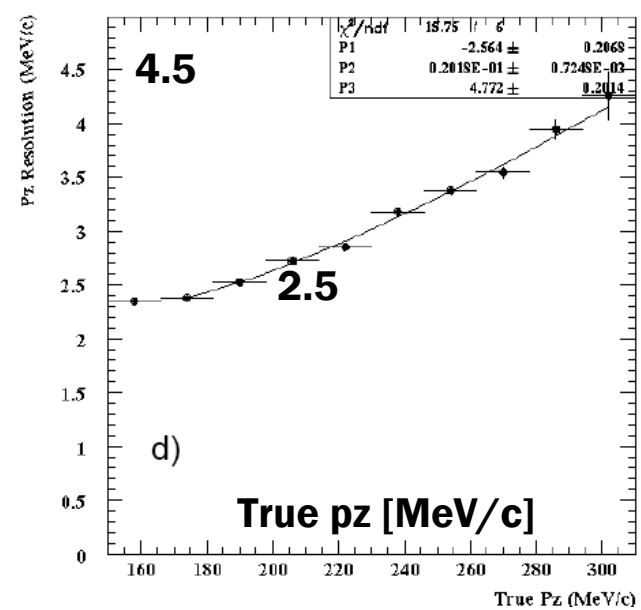


pz resolution [MeV/c]



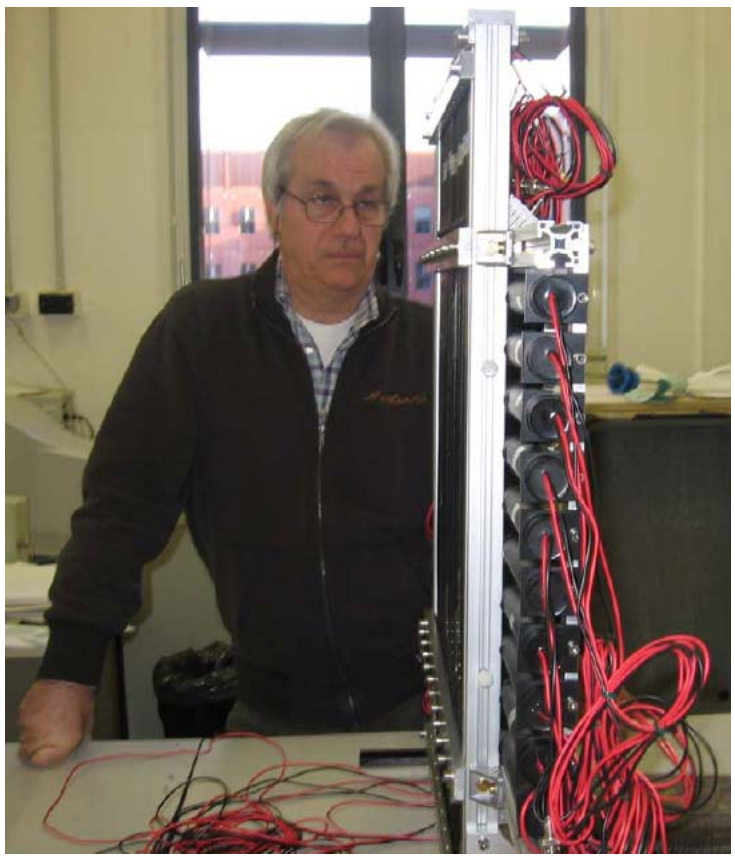




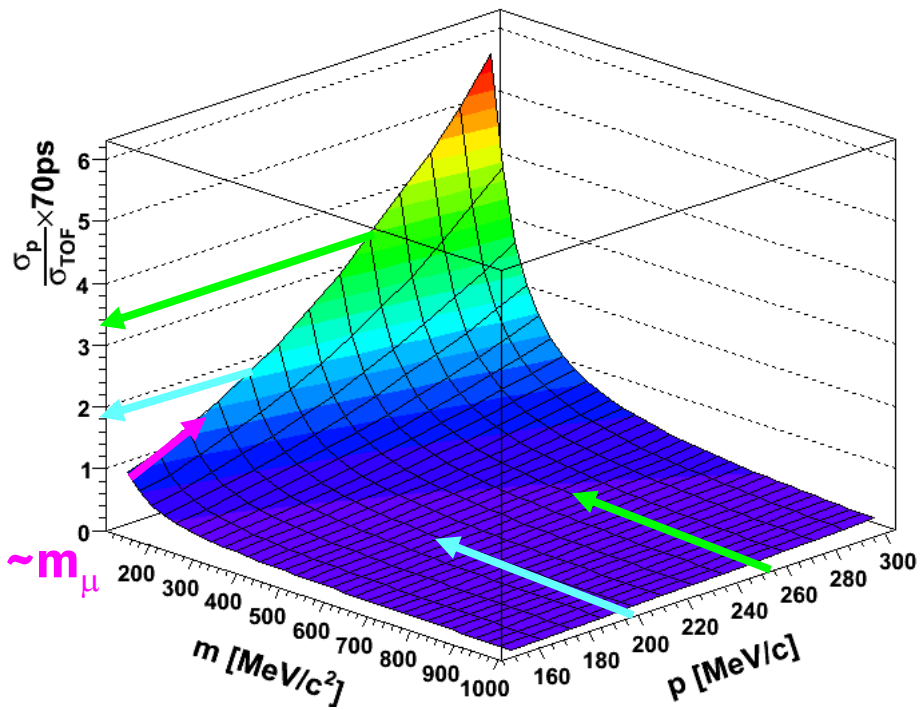


The MICE time of flight counters

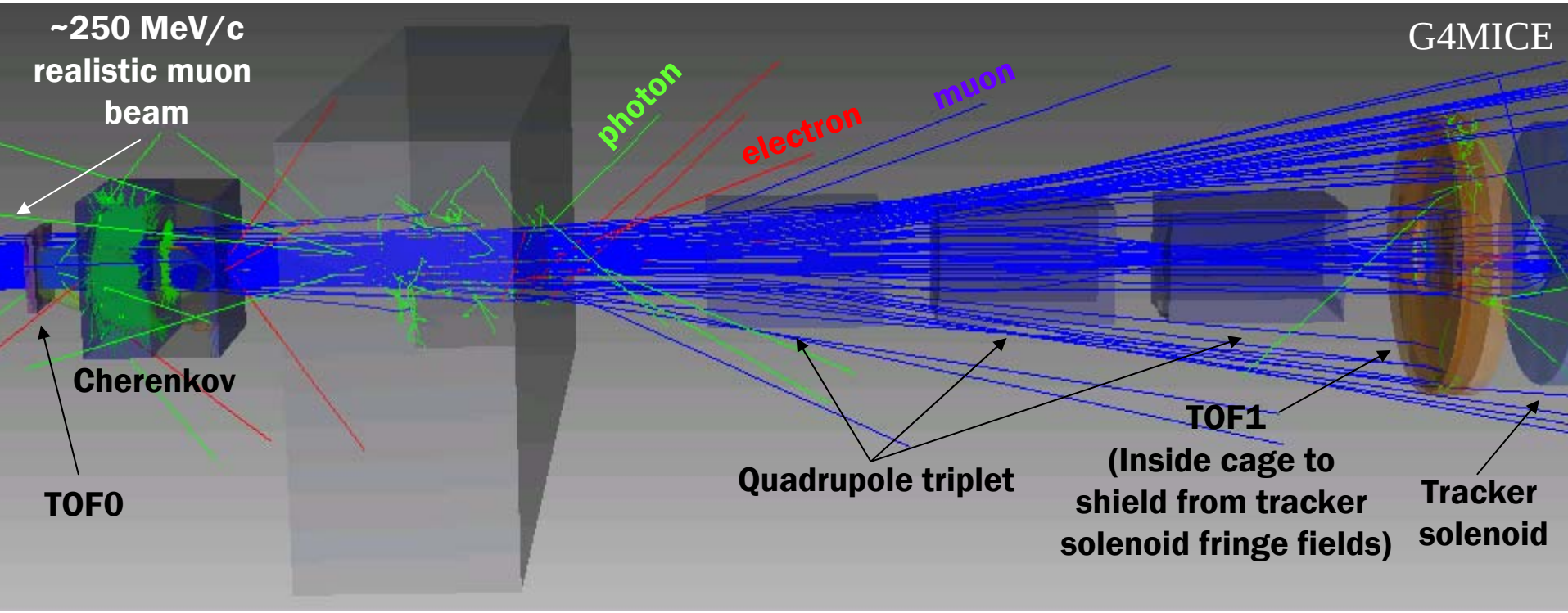
- Designed, constructed and currently being tested in Milan by Maurizio Bonesini and others
- Expected σ_t ~ 50 ps



- Momentum resolution?
  - TOF0 → TOF1 $\sigma_{\Delta t}$ ~ 70 ps
  - Assuming this is the main error…



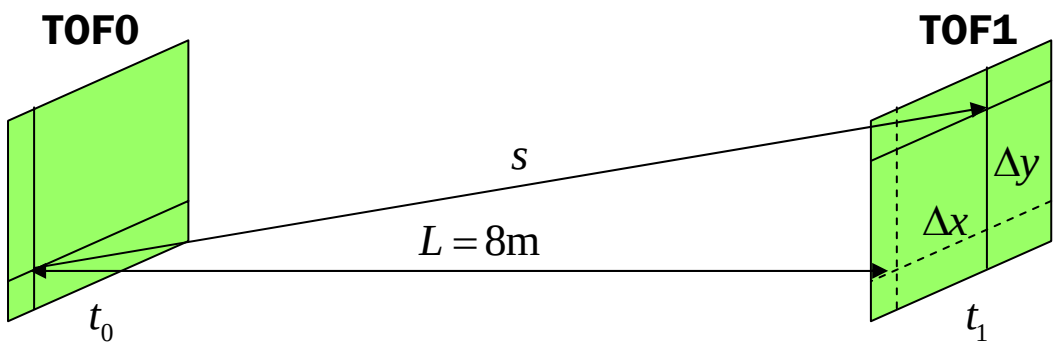
Reconstructing p_z before the 1st tracker

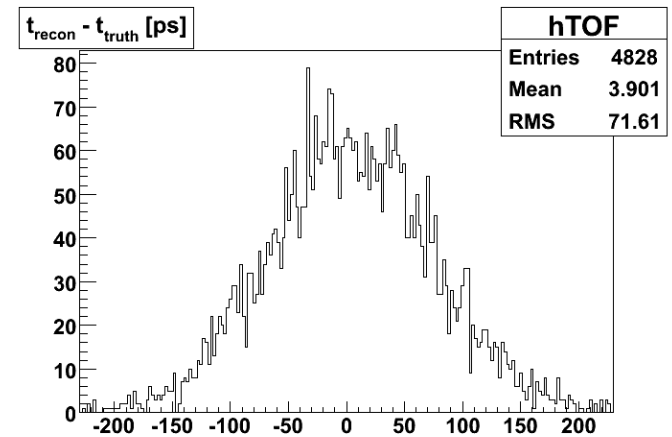


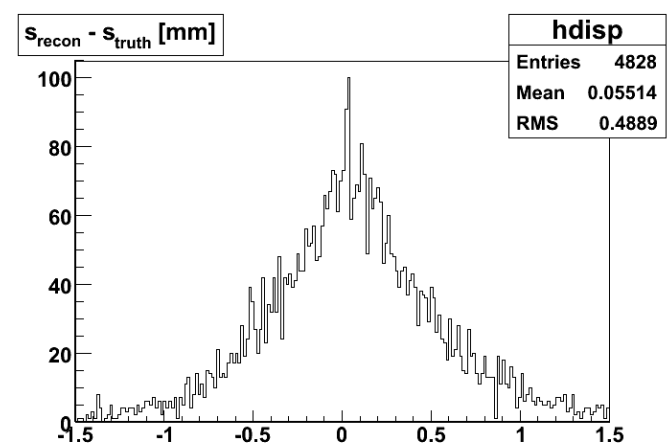
- **Energy loss**
  - 10.1 +/- 1.4 MeV per TOF station
  - 2.8 +/- 0.9 MeV in the Ckov
  - 1.8 MeV in the 8m of air
- **Scattering**
  - 1.8 +/- 1.1 degrees per TOF
  - 1.4 +/- 0.8 degrees per Ckov
- **Focussing**
  - 4.6 +/- 2.6 degrees in Q789

Simple momentum reconstruction

- **Data available from time of flight counters**
  - **Time of flight** $t = t_1 - t_0$
  - **Displacement** $s = \sqrt{L^2 + \Delta x^2 + \Delta y^2}$





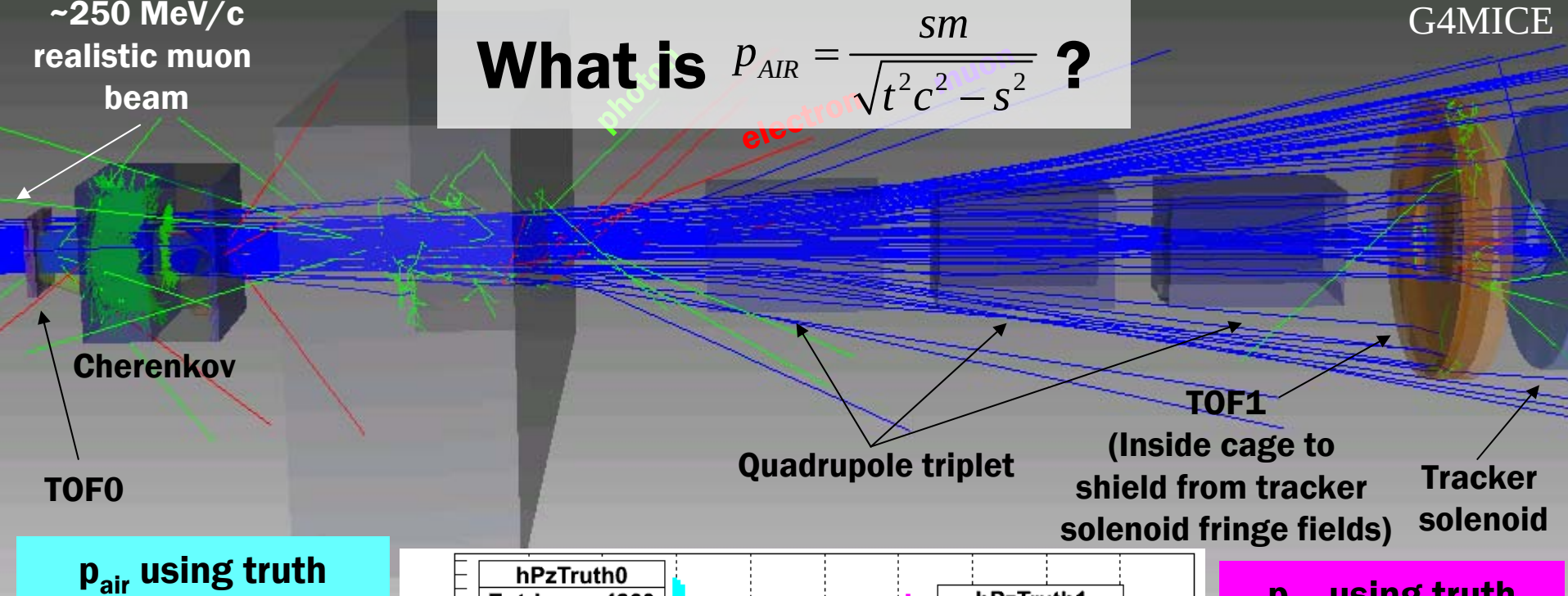


- **Estimate p in the air between TOF0 and TOF1**

$$p_{AIR} = \frac{sm}{\sqrt{t^2c^2 - s^2}}$$

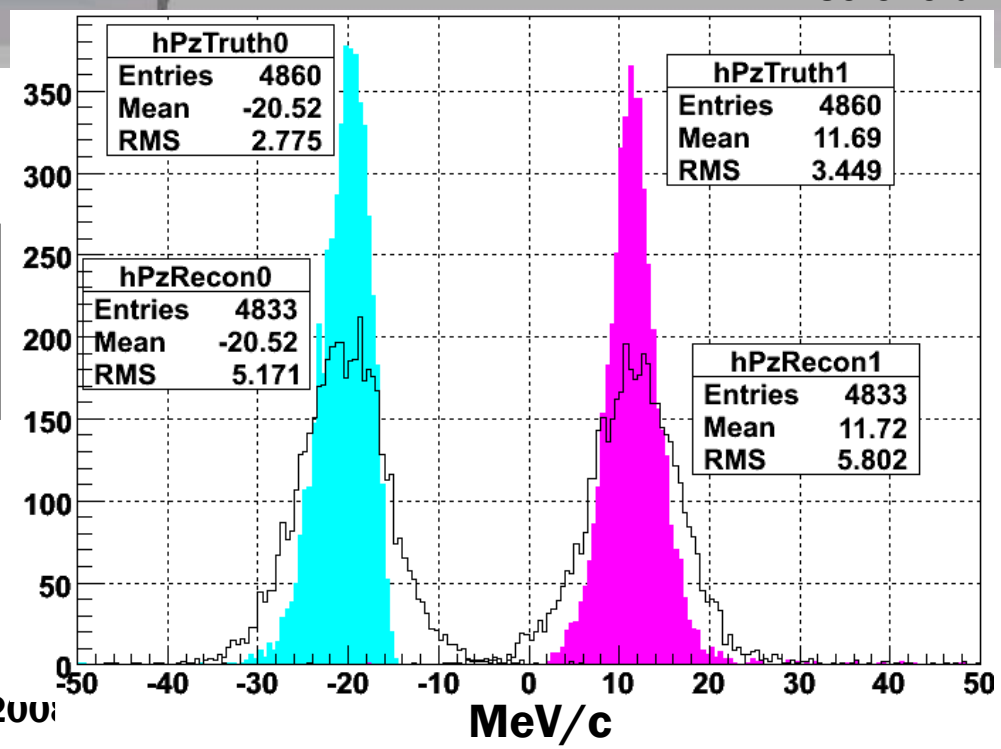
- **Momentum losses from PDG dE/dx for minimum ionizing particles**
  - **Estimate p before TOF0** $p_{TOF0} = p_{AIR} + \Delta p_{AIR} + \Delta p_{CKOV} + \Delta p_{TOF0}$
  - **Estimate p after TOF1** $p_{TOF1} = p_{AIR} - \Delta p_{TOF1}$

What is $p_{AIR} = \frac{sm}{\sqrt{t^2c^2 - s^2}}$?



p_{air} using truth – true p_z before TOF0

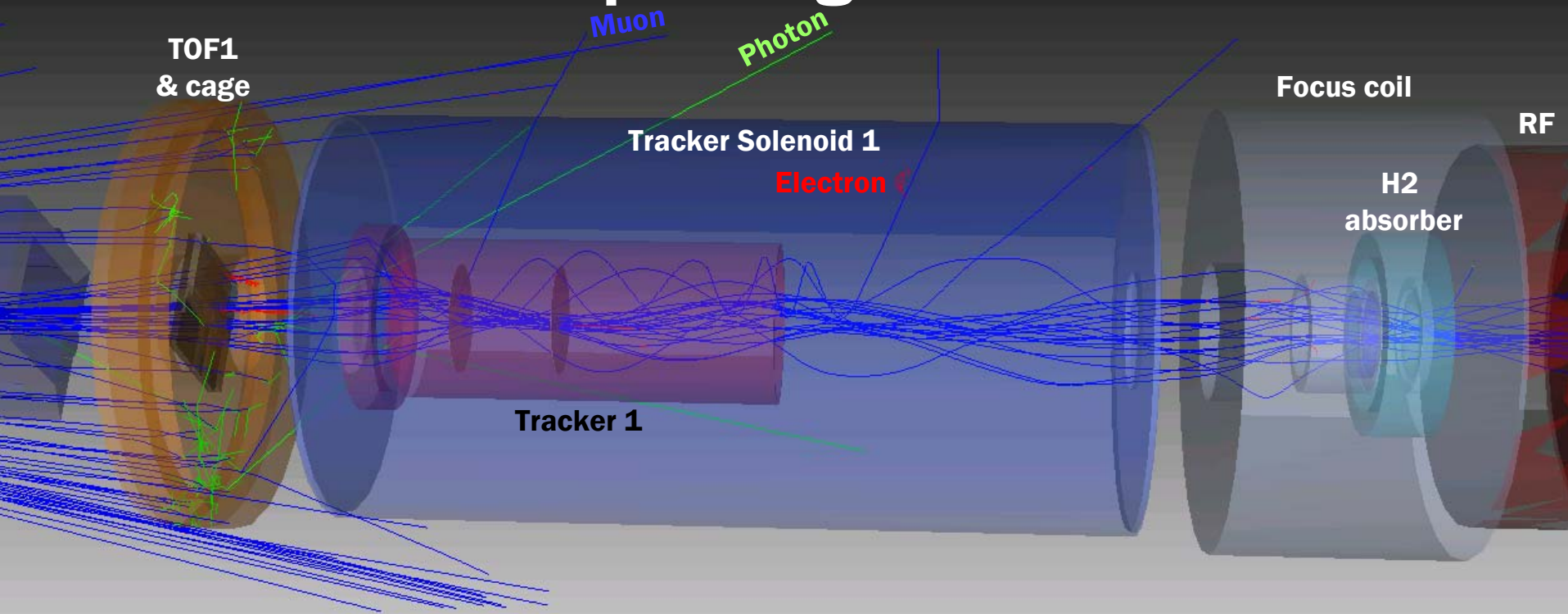
p_{air} using recon. – true p_z before TOF0



p_{air} using truth – true p_z after TOF1

p_{air} using recon. – true p_z after TOF1

Extrapolating the time



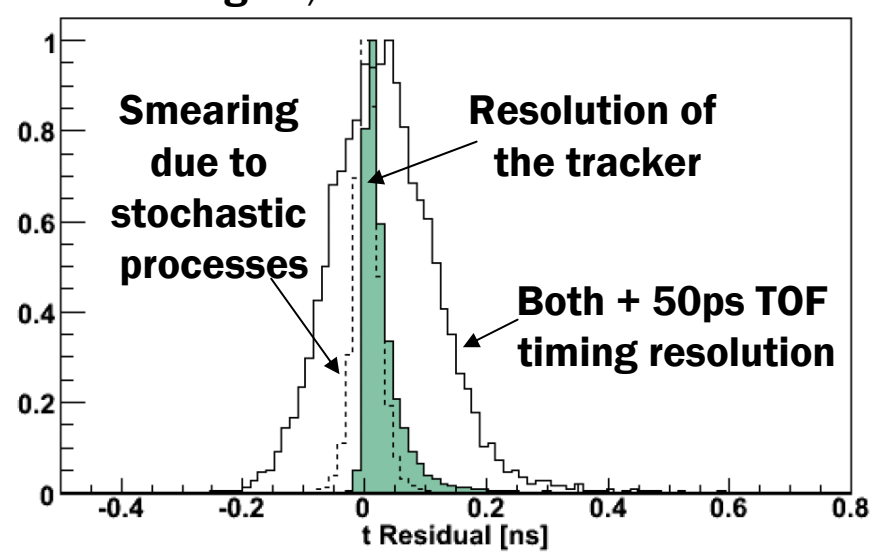
- Time extrapolation to tracker reference plane (or RF cavity) required for
  - Defining a neutrino factory like bunched, stable beam
  - Measuring longitudinal emittance
- Necessary to track each muon on the basis of
  - Tracker (and TOF?) x, p_x, y, p_y, t, p_z measurements
  - Magnetic (and electric) field maps
  - Energy loss models

Conclusion: a summary of the numbers

- Time of flight σ_{pz} ~ intrinsic beam line σ_{pz}
- σ_t<500ps would be desirable in the tracker reference plane
  - Chris got ~125ps using only the tracker pz
  - A back of an envelope calculation suggests TOFs can achieve ~60ps using TOF reconstructed p_z
  - Try adding the TOF (t,p_z) measurement to the tracking fit
- TOF σ_{pz} may be complementary to tracker σ_{pz}>6MeV/c when p_t<10 MeV/c
  - 38% of muons when there is no diffuser, E=200MeV/c, ε_n=2mm, β=33.3cm (John Cobb, CM19)

σ_{pz} [MeV/c]	Before TOF0	After TOF1
Intrinsic to beam line	2.8	3.5
Due to σ_{TOF}	4.4	4.7
Total	5.2	5.8

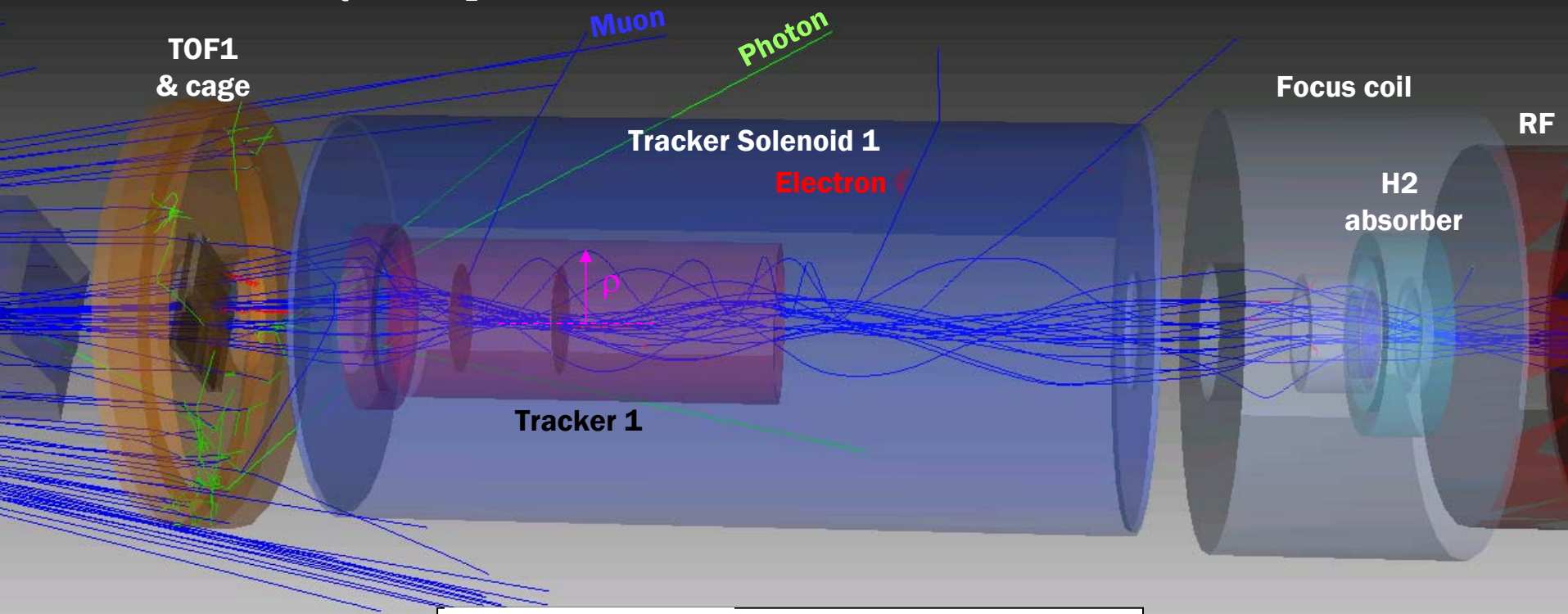
Chris Rogers, Thesis



Extra slides

Fringe fields TOF1 → Tracker 1

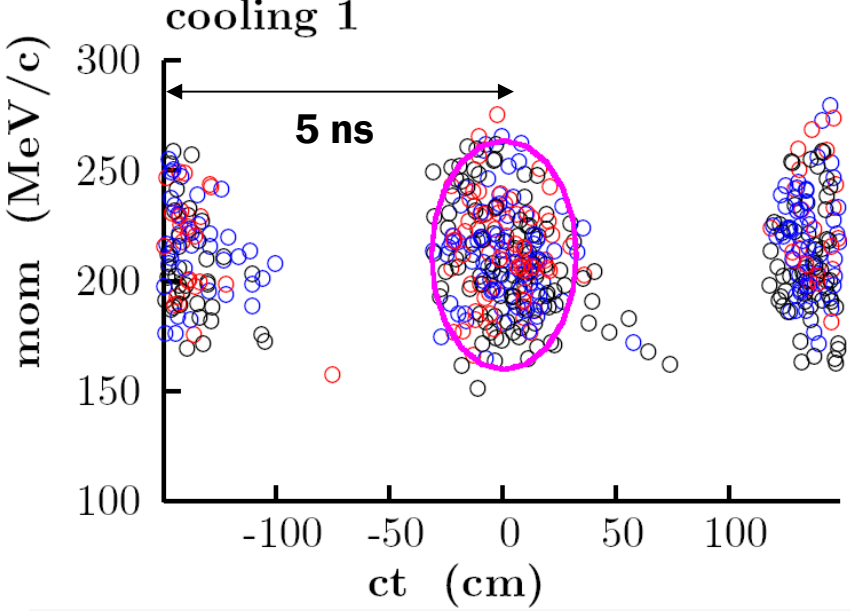
How much do p_t and p_z increase?



Busch's theorem

$$\Delta p_\phi \approx -q\frac{\rho_0}{2}B_0$$

$$\Delta p_\phi \approx -300\ \mathrm{MeV/c}\ \frac{\rho_0\ [\mathrm{m}]}{2}\ B_0\ [\mathrm{T}]$$



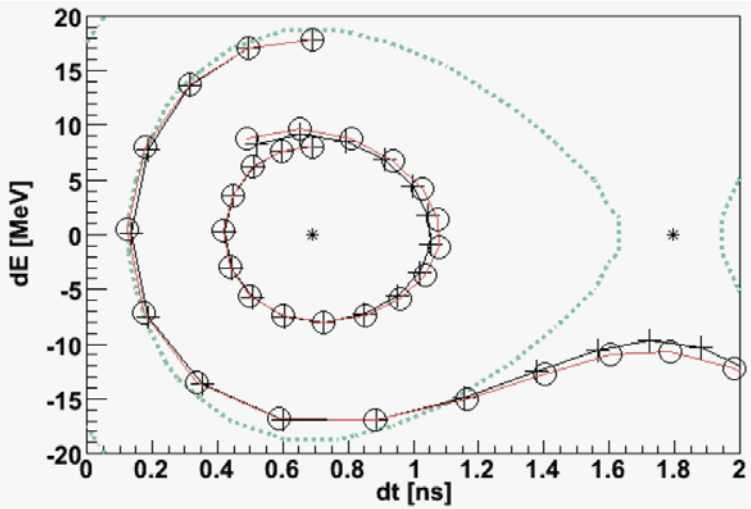
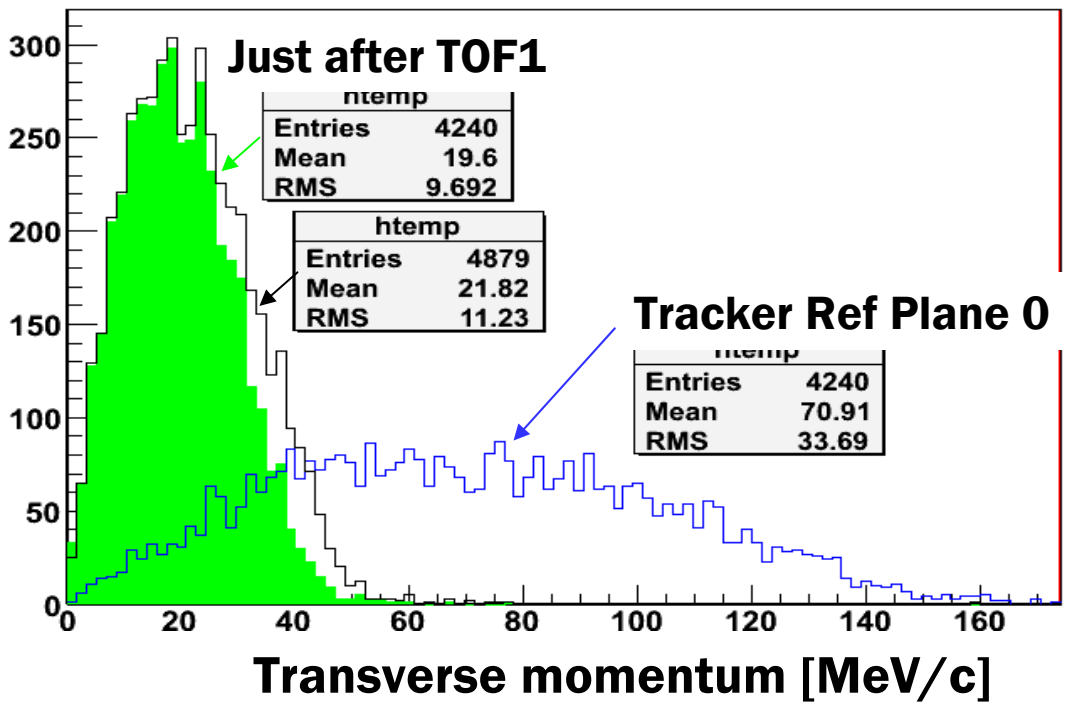
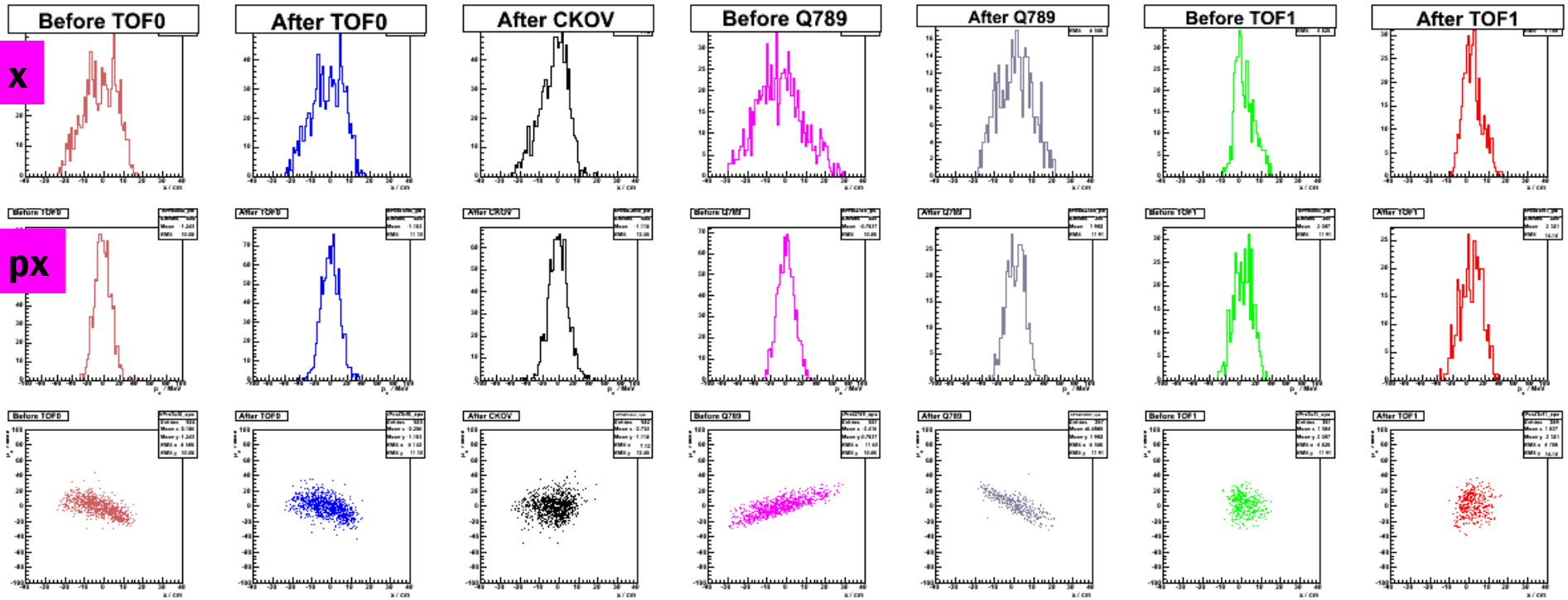


Figure 7.6: Muons tracked around the RF bucket with RF phased at 50° (o) using RF field maps (+) using the pillbox model. Contours in the Hamiltonian are shown in turquoise.


Just after TOF1
htemp
Entries 4240
Mean 19.6
RMS 9.692
htemp
Entries 4879
Mean 21.82
RMS 11.23
Tracker Ref Plane 0
htemp
Entries 4240
Mean 70.91
RMS 33.69
300
250
200
150
100
50
0
0
20
40
60
80
100
120
140
160
Transverse momentum [MeV/c]

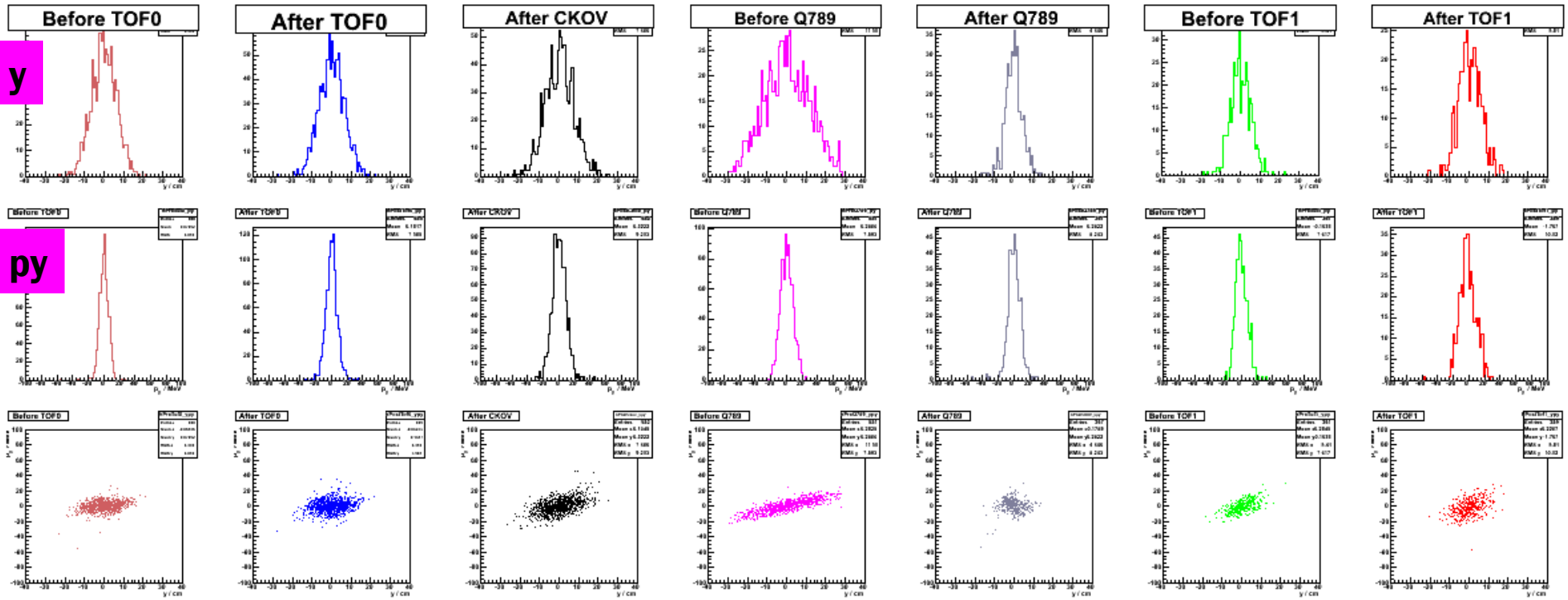
Transverse phase space: horizontal



-100 MeV – 100 MeV px / MeV

x / cm -40 cm – 40 cm

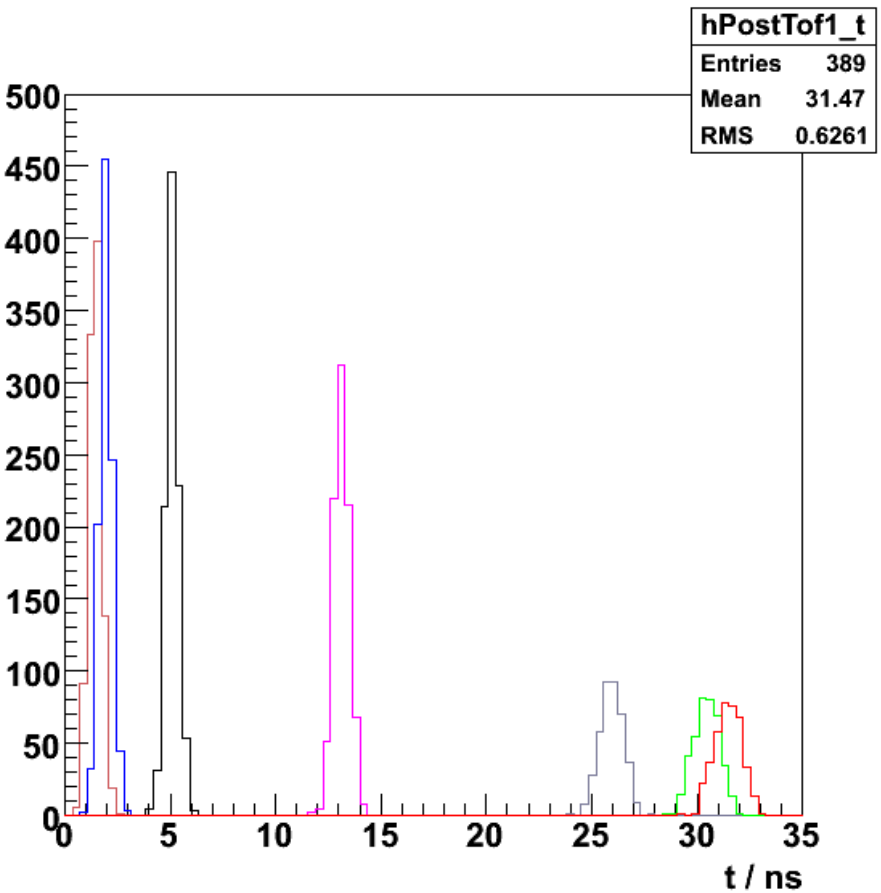
Transverse phase space: vertical

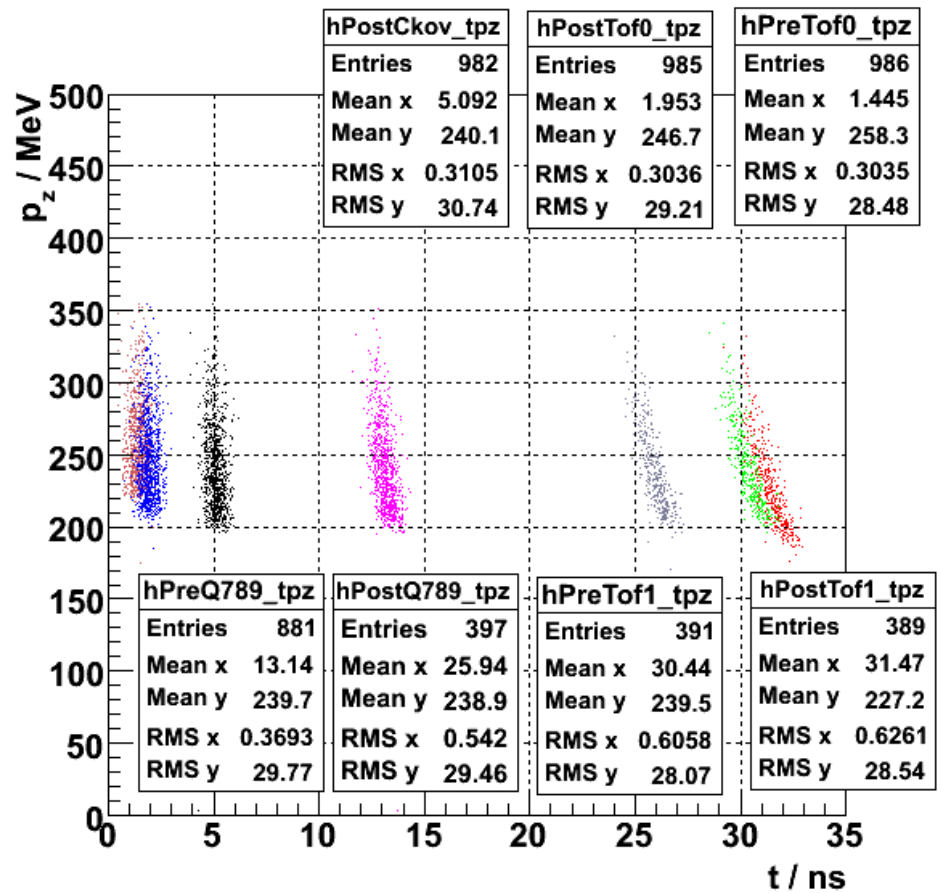


-100 MeV – 100 MeV py / MeV

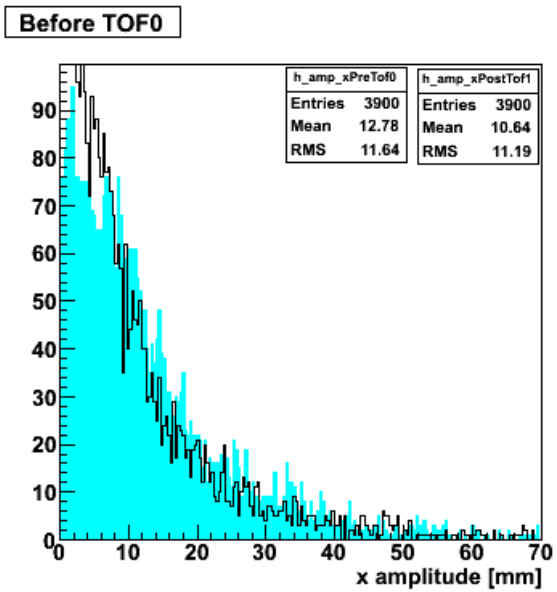
y / cm -40 cm – 40 cm

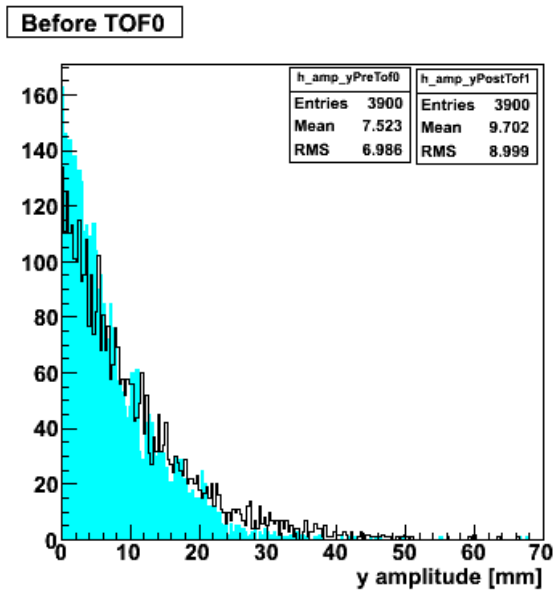
Longitudinal phase space

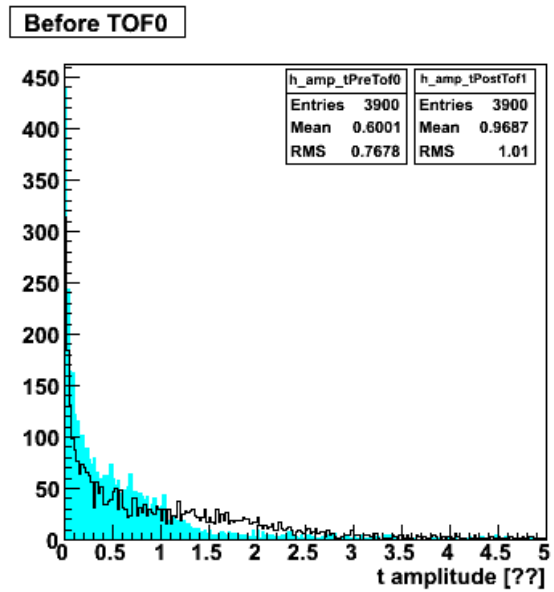




Amplitude of muons surviving to TOF1



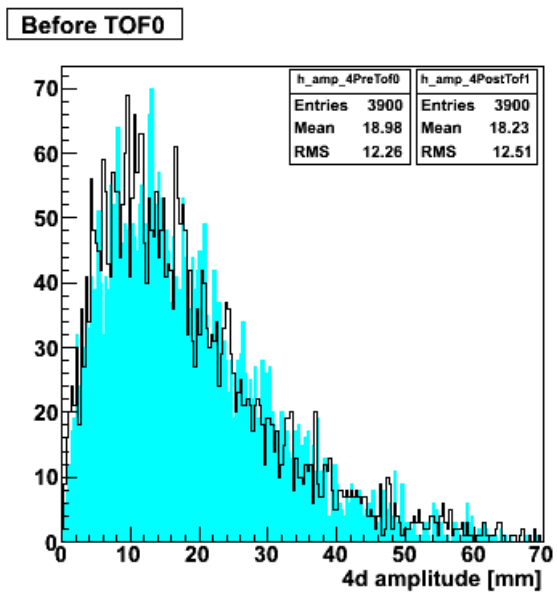


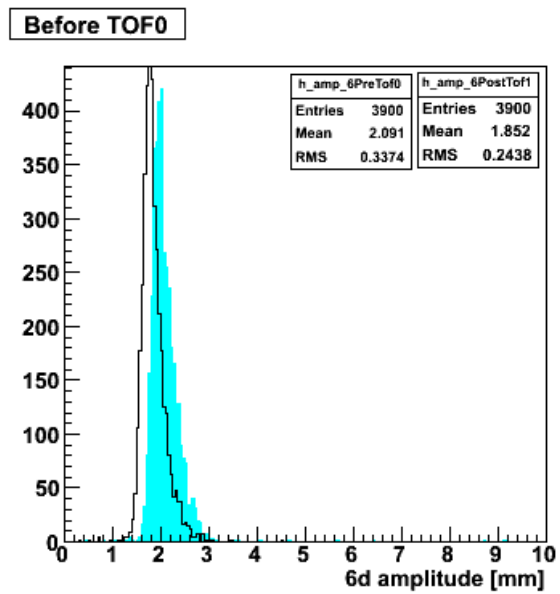


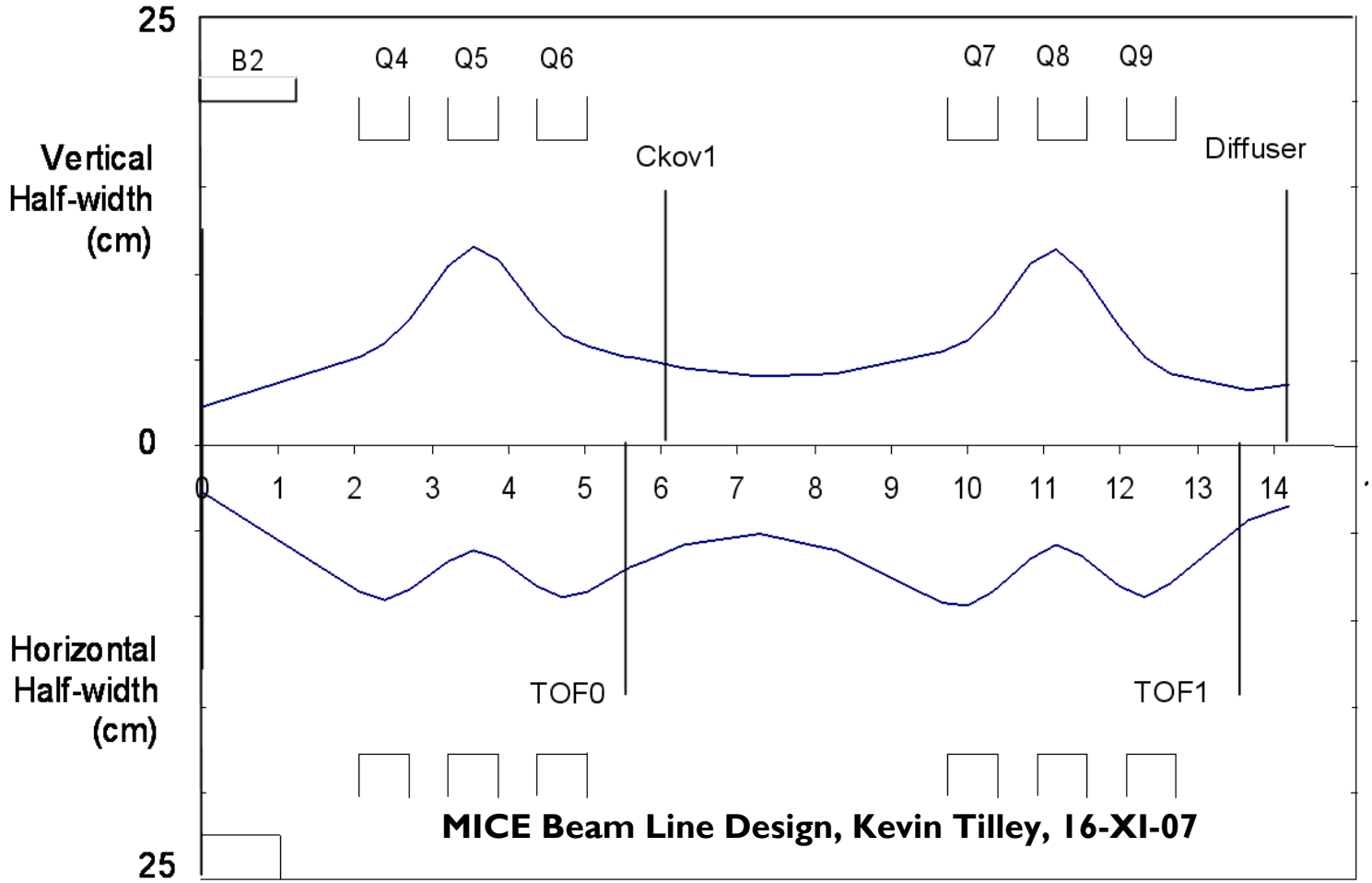
MC amplitude of survivors

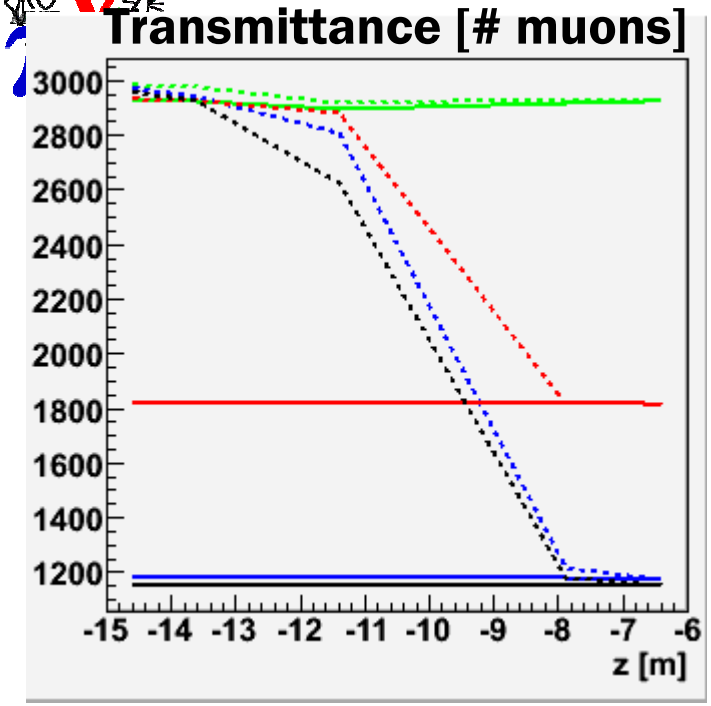
Just before TOF0

Just after TOF1



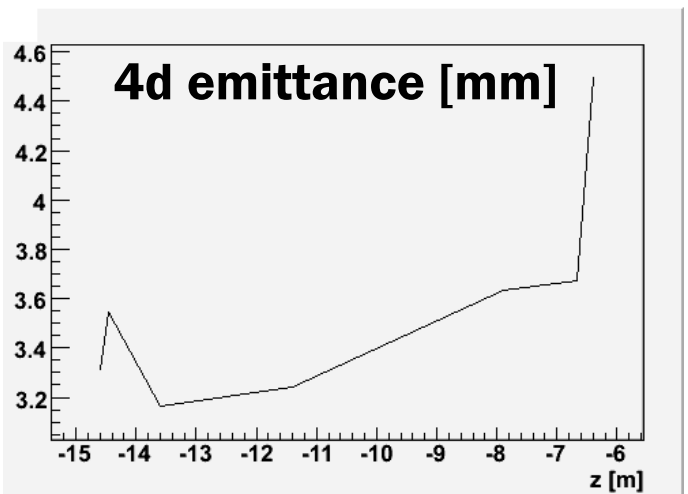


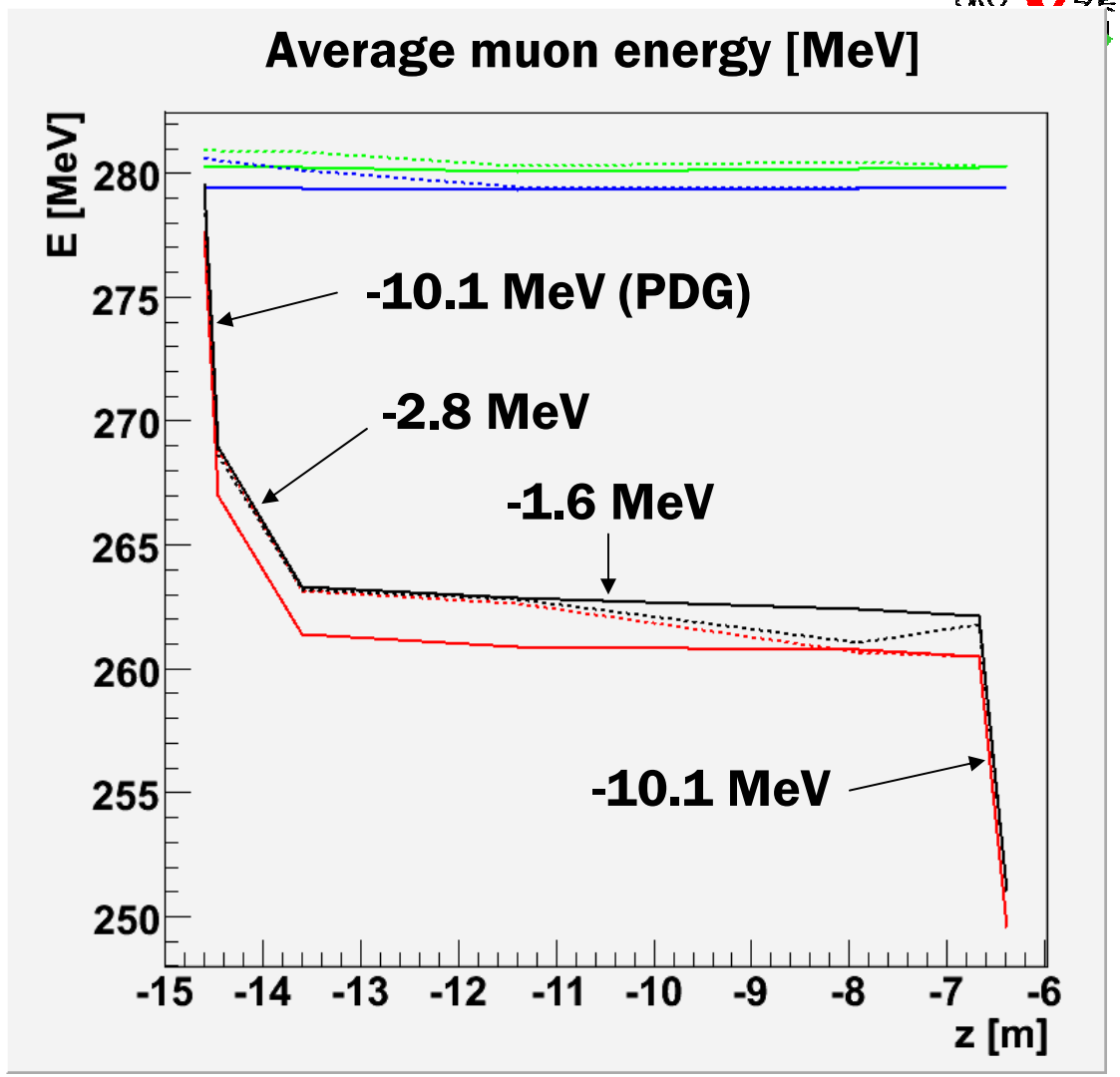

25
B2
Q4
Q5
Q6
Q7
Q8
Q9
Vertical
Half-width
(cm)
Ckov1
Diffuser
0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Horizontal
Half-width
(cm)
TOF0
TOF1
MICE Beam Line Design, Kevin Tilley, 16-XI-07
25



Only muons which get through TOF1

All muons





Scattering: ON, energy loss: ON	Scattering: OFF, energy loss: ON
Scattering: ON, energy loss: OFF	Scattering: OFF, energy loss: OFF

PDG estimates

detector	material	details	thickness	density	dE/dx (min I)	dE	mass	p	E
			cm	g cm-3	MeV g-1 cm2	MeV	MeV c-2	MeV c-1	MeV
TOF0	scintillator	polyvinyltoluene	5.00	1.03	1.97	10.12	105.00	250.00	271.15
Cherenkov	aerogel	silica aerogel	8.00	0.20	1.74	2.78	105.00	238.99	261.04
Air	air	dry, 1 atm	730.00	0.00	1.82	1.60	105.00	235.94	258.25
TOF1	scintillator	polyvinyltoluene	5.00	1.03	1.97	10.12	105.00	234.19	256.65

beta	**dt**	gamma	E - dE = Enew	pnew	**dp**	X0	X0	**98% dθ**
	ns		MeV	MeV c-1	**MeV c-1**	g cm-2	cm	**degrees**
0.92	**18.08**	2.58	261.04	238.99	**11.01**	43.90	42.62	**1.06**
0.92	**29.13**	2.49	258.25	235.94	**3.04**	27.25	136.25	**0.77**
0.91	**2663.41**	2.46	256.65	234.19	**1.75**	36.62	30390.04	**0.48**
0.91	**18.27**	2.44	246.53	223.06	**11.14**	43.90	42.62	**1.15**

p_z RESOLUTION

Can measure p_z only for μs with finite p_t in tracker

Cannot measure p_z for closely paraxial muons, i.e. close and parallel to axis

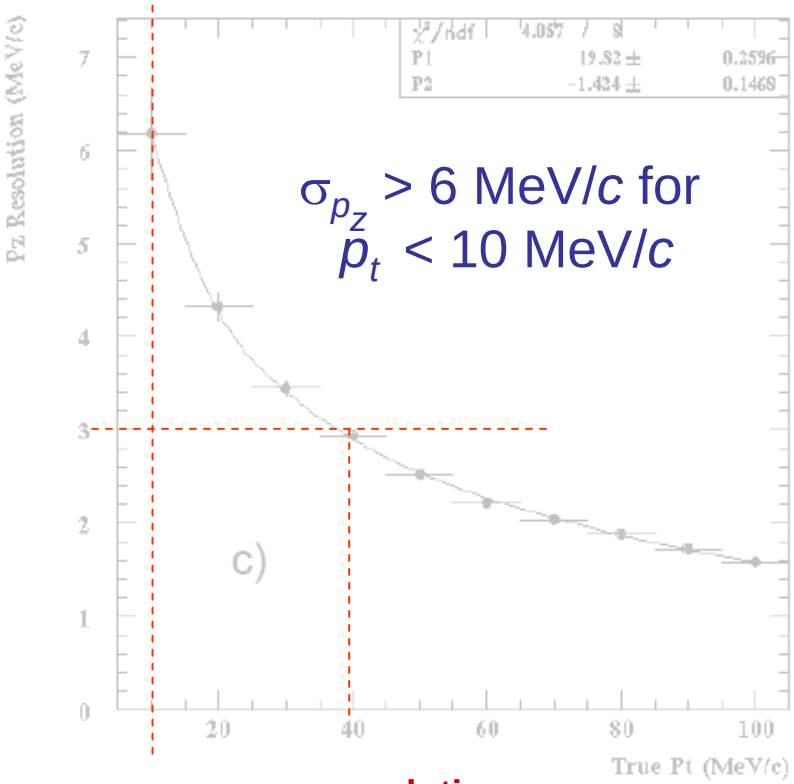
Smallest emittance beam (no diffuser, 200 MeV/*c*) with ε_n ~ 2mm, β = 33.3 cm has

$\sigma_{x,y}$ ~ 1.9 cm and $\sigma_{p_{x,y}} = \sigma_{p_t}$ ~ 11 MeV/*c*

p_t distributed – in 4D Gaussian world – as

$$\frac{dn}{dp_t^2} = \int f(x, y, p_x, p_y)dxdy$$

$$\frac{dn}{dp_t^2} = \frac{1}{2\sigma_{p_t}^2}\exp\left(-\frac{p_x^2 + p_y^2}{2\sigma_{p_t}^2}\right) = \frac{1}{2\sigma_{p_t}^2}\exp\left(-\frac{p_t^2}{2\sigma_{p_t}^2}\right)$$



p_z resolution versus p_t from MICE note 90 (note suppressed zero)

➔ ~ 38% of muons have p_t < 10 MeV/c and p_z measured with $\sigma(p_z)$ > 6 MeV/*c*

Actually not *quite* so bad....