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

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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]**

### Measuring pz using the MICE TOFs

- **True pt [MeV/c]**
- **True pz [MeV/c]**

\[
\begin{align*}
\text{pt resolution} &= 1.3 \\
\text{pz resolution} &= 4.5
\end{align*}
\]
The MICE time of flight counters

- Designed, constructed and currently being tested in Milan by Maurizio Bonesini and others
- Expected $\sigma_t \sim 50$ ps

Momentum resolution?
- $\text{TOF}_0 \rightarrow \text{TOF}_1 \sigma_{\Delta t} \sim 70$ 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

\[
P_{\text{AIR}} = \frac{s m}{\sqrt{t^2 c^2 - s^2}}
\]

- Momentum losses from PDG \( dE/dx \) for minimum ionizing particles
  - Estimate \( p \) before TOF0 \( p_{\text{TOF0}} = p_{\text{AIR}} + \Delta p_{\text{AIR}} + \Delta p_{\text{CKOV}} + \Delta p_{\text{TOF0}} \)
  - Estimate \( p \) after TOF1 \( p_{\text{TOF1}} = p_{\text{AIR}} - \Delta p_{\text{TOF1}} \)
What is \( p_{\text{AIR}} = \frac{s m}{\sqrt{t^2 c^2 - s^2}} \) ?

- \( p_{\text{AIR}} \) using truth
  - true \( p_z \) before TOF0

- \( p_{\text{AIR}} \) using recon.
  - true \( p_z \) before TOF0

- \( p_{\text{AIR}} \) using truth
  - true \( p_z \) after TOF1

- \( p_{\text{AIR}} \) using recon.
  - true \( p_z \) after TOF1

\(~250 \text{ MeV/c realistic muon beam}\)
• 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 $\sigma_{pz} \sim$ intrinsic beam line $\sigma_{pz}$
- $\sigma_t < 500$ps would be desirable in the tracker reference plane
  - Chris got $\sim 125$ps using only the tracker $p_z$
  - A back of an envelope calculation suggests TOFs can achieve $\sim 60$ps using TOF reconstructed $p_z$
  - Try adding the TOF $(t, p_z)$ measurement to the tracking fit

- TOF $\sigma_{pz}$ may be complementary to tracker $\sigma_{pz} > 6$MeV/c when $p_t < 10$ MeV/c
  - 38% of muons when there is no diffuser, $E=200$MeV/c, $\epsilon_n=2$mm, $\beta=33.3$cm (John Cobb, CM19)

### Table

<table>
<thead>
<tr>
<th>$\sigma_{pz}$ [MeV/c]</th>
<th>Before TOF0</th>
<th>After TOF1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intrinsic to beam line</td>
<td>2.8</td>
<td>3.5</td>
</tr>
<tr>
<td>Due to $\sigma_{TOF}$</td>
<td>4.4</td>
<td>4.7</td>
</tr>
<tr>
<td>Total</td>
<td>5.2</td>
<td>5.8</td>
</tr>
</tbody>
</table>

Chris Rogers, Thesis

Resolution of the tracker

Smearing due to stochastic processes

Both + 50ps TOF timing resolution
Extra slides
Fringe fields TOF1 $\rightarrow$ Tracker 1

How much do $p_t$ and $p_z$ increase?

Busch’s theorem

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

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

Tracker Ref Plane 0

Transverse momentum [MeV/c]
Transverse phase space: horizontal

Before TOF0  After TOF0  After CKOV  Before Q789  After Q789  Before TOF1  After TOF1

-100 MeV – 100 MeV  px / MeV  x / cm  -40 cm – 40 cm
Transverse phase space: vertical

Before TOF0
After TOF0
After CKOV
Before Q789
After Q789
Before TOF1
After TOF1

y
py

-100 MeV – 100 MeV
py / MeV

y / cm
-40 cm – 40 cm

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Measuring pz using the MICE TOFs

Slide 15
Longitudinal phase space

- **hPostTof1_t**
  - Entries 389
  - Mean x 31.47
  - Mean y 240.1
  - RMS x 0.3105
  - RMS y 30.74

- **hPostCkov_tpz**
  - Entries 982
  - Mean x 5.092
  - Mean y 246.7
  - RMS x 0.3036
  - RMS y 29.21

- **hPostTof0_tpz**
  - Entries 985
  - Mean x 1.953
  - Mean y 258.3
  - RMS x 0.3035
  - RMS y 28.48

- **hPreTof0_tpz**
  - Entries 986
  - Mean x 1.445
  - Mean y 258.3
  - RMS x 0.3035
  - RMS y 28.48

- **hPreQ789_tpz**
  - Entries 881
  - Mean x 13.14
  - Mean y 239.7
  - RMS x 0.3683
  - RMS y 29.77

- **hPostQ789_tpz**
  - Entries 397
  - Mean x 25.94
  - Mean y 238.9
  - RMS x 0.542
  - RMS y 29.46

- **hPreTof1_tpz**
  - Entries 391
  - Mean x 30.44
  - Mean y 239.5
  - RMS x 0.6058
  - RMS y 28.07

- **hPostTof1_tpz**
  - Entries 389
  - Mean x 31.47
  - Mean y 227.2
  - RMS x 0.6261
  - RMS y 28.54

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Amplitude of muons surviving to TOF1

Before TOF0

- MC amplitude of survivors

- Just before TOF0

- Just after TOF1

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Measuring pz using the MICE TOFs
Measuring $p_z$ using the MICE TOFs

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

Only muons which get through TOF1
All muons

4d emittance [mm]

Transmittance [# muons]

Average muon energy [MeV]

-10.1 MeV (PDG)
-2.8 MeV
-1.6 MeV
-10.1 MeV

Scattering: ON, energy loss: ON
Scattering: OFF, energy loss: ON
Scattering: ON, energy loss: OFF
Scattering: OFF, energy loss: OFF
## PDG estimates

<table>
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<tr>
<th>detector</th>
<th>material</th>
<th>details</th>
<th>thickness</th>
<th>density</th>
<th>dE/dx (min I)</th>
<th>dE</th>
<th>mass</th>
<th>p</th>
<th>E</th>
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<tbody>
<tr>
<td>TOF0</td>
<td>scintillator</td>
<td>polyvinyltoluene</td>
<td>5.00</td>
<td>1.03</td>
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<td>10.12</td>
<td>105.00</td>
<td>250.00</td>
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<tr>
<td>Cherenkov</td>
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<tr>
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<td>dry, 1 atm</td>
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<td>0.00</td>
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<tr>
<td>TOF1</td>
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<td>polyvinyltoluene</td>
<td>5.00</td>
<td>1.03</td>
<td>1.97</td>
<td>10.12</td>
<td>105.00</td>
<td>234.19</td>
<td>256.65</td>
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</table>

<table>
<thead>
<tr>
<th>beta</th>
<th>dt</th>
<th>gamma</th>
<th>E - dE = E_{new}</th>
<th>p_{new}</th>
<th>dp</th>
<th>X0</th>
<th>X0</th>
<th>98% Δψ</th>
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<tbody>
<tr>
<td>ns</td>
<td>MeV</td>
<td>MeV c-1</td>
<td>MeV c-1</td>
<td>g cm-2</td>
<td>cm</td>
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<tr>
<td>0.92</td>
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<td>238.99</td>
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<td>43.90</td>
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<td>0.91</td>
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<td>246.53</td>
<td>223.06</td>
<td>11.14</td>
<td>43.90</td>
<td>42.62</td>
<td>1.15</td>
</tr>
</tbody>
</table>
Can measure $p_z$ only for $\mu$s 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 $\varepsilon_n \sim 2\text{mm}$, $\beta = 33.3 \text{ cm}$ has

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

$p_t$ distributed – in 4D Gaussian world – as

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

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

$\Rightarrow \sim 38\%$ of muons have $p_t < 10 \text{ MeV/c}$ and $p_z$ measured with $\sigma(p_z) > 6 \text{ MeV/c}$

Actually not quite so bad....

John Cobb, CM19