νSTORM Beamline Design

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Outline

• Introduction to $\nu$STORM ($\nu$ from STORed Muons)
• Design of $\nu$STORM Transport Line
• Low Energy Muons from $\nu$STORM
• $\nu$STORM Muon Decay Ring Design
• Summary
• For the past decade, a lot of effort has been spent on $\nu$ oscillation physics

<table>
<thead>
<tr>
<th>$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$</th>
<th>$\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$</th>
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<tbody>
<tr>
<td>$\bar{\nu}<em>\mu \rightarrow \bar{\nu}</em>\mu$</td>
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- disappearance
- appearance ("platinum" channel?)
- appearance (atmospheric oscillation)
- disappearance
- appearance: "golden" channel
- appearance: "silver" channel
For the past decade, a lot of effort has been spent on $\nu$ oscillation physics.

8 channels accessible by $\nu$STORM

\[
\begin{align*}
\mu^+ & \rightarrow e^+ \nu_e \bar{\nu}_\mu & \nu_e & \rightarrow \nu_e & \text{disappearance} \\
\bar{\nu}_\mu & \rightarrow \bar{\nu}_\mu & \nu_\mu & \rightarrow \nu_\mu & \text{disappearance} \\
\bar{\nu}_\mu & \rightarrow \bar{e} & \nu_\mu & \rightarrow e & \text{appearance ("platinum" channel?)} \\
\nu_e & \rightarrow \nu_e & \bar{\nu}_e & \rightarrow \bar{\nu}_e & \text{disappearance} \\
\nu_e & \rightarrow \nu_\mu & \bar{\nu}_e & \rightarrow \bar{\nu}_\mu & \text{appearance: "golden" channel} \\
\nu_\mu & \rightarrow \nu_\mu & \bar{\nu}_\mu & \rightarrow \bar{\nu}_\mu & \text{appearance: "silver" channel}
\end{align*}
\]
• 3.8 GeV/c muon decay ring (±10%) + near detector + far detector to study eV-scale $\nu$ oscillations and search for sterile $\nu$.
  
  - $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$, $\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$
  
  - Well understood neutrino flux + flavor

  – Provides short baseline neutrino oscillation study, cross section measurement, and works as a technology test bed (muon accelerator study, neutrino detector study, etc);

  – No new technology; Simple implementation; More affordable
Introduction-Motivation (Cont’d)

- 3.8 GeV/c muon decay ring (±10%) + near detector + far detector to study eV-scale $\nu$ oscillations and search for sterile $\nu$.

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Introduction-Facility

- **100 KW target station**
  - 60-120 GeV protons from Main injector;
  - Magnetic horn to collect π;
  - Target material: graphite;

- **A total run exposure of $10^{21}$ protons** over a period of 4-5 years

- **Stochastic injection scheme**
  - No full-aperture fast kicker or separate pion decay channel needed;
  - Initially proposed by David Neuffer (Fermilab, U.S.)

\[ \varepsilon = 2 \text{ mm: yield } = 0.064 \]
\[ r < 20 \text{ cm: yield } = 0.126 \]
Introduction-Facility

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Phase space of π at 1 cm after target, Courtesy of S. Striganov (Fermilab)

\[ \xi = 2 \text{ mm: yield} = 0.064 \]
\[ r < 20 \text{ cm: yield} = 0.126 \]
Use a NuMI-like magnetic horn, after which 0.1 pions per POT are collected in 20cm region, 0.056 pions per POT in 2000 μm acceptance
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Transport Line Design Strategy

• Design the optics to
  – Achieve a beam size as small as possible by constraining $\beta$ functions and dispersion;
  – Match Twiss parameters from the horn into the ring;
  – Use the smallest number of magnet families as possible.

• Optics + Simulation design tools
  – MADX(CERN), OptiM(V. Lebedev, Fermilab), apGA(myself)
  – G4Beamline(T. Roberts, Muons Inc.)
Transport Design - Stochastic Injection

- Right: Concept drawing; Bottom: Layout screenshot (White blocks-drift tubes, red-quads, blue-dipoles)
- Circled section is beam combination section for two beams
Transport Design – Details (Cont’d)

FODO cells for decay ring

Match Twiss of ring lattice to transport lattice, at the injection point

Check the pion flux delivered from horn to injection point

Initial Consideration

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• Questions:
  – π decay in the straight:
    • 5 GeV/c π and 3.8 GeV/c μ have very different optics;
  – Is there enough space for magnets along the ring and transport?
• Answers:
  – Upper: Periodic $\beta_{x,y}$ for 3.8 GeV/c μ in the FODO cell.
  – Lower: Same FODO cells(lengths, gradients), 5 GeV/c π.
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• Answers:
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  – Lower: Same FODO cells(lengths, gradients), 5 GeV/c π.
• Need 1:
  – As many $\pi$ as possible survive in the decay straight before decay;
• Action 1:
  – Design the FODO cell with 2 sets of periodic Twiss ($\mu$ and $\pi$).
  – Use $\pi$ parameters in transport optics matching.

Determine betas for FODO cell:
• Larger $\beta$:
  ➢ Smaller transverse angle acceptance, $\mu$ angles from $\pi$ decay w.r.t parent $\pi$ determined by energy;
  ➢ Larger beam size
• Smaller $\beta$ -> Larger divergence:
  ➢ $\nu$'s not well oriented;
  ➢ Lower divergence measurement accuracy;
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• Smaller $\beta$ -> Larger divergence:
  ➢ $\nu$’s not well oriented;
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Need 2:
- Ensure enough separation of the two beams

A pure defocusing quadrupole for \( \mu \) becomes a combined-function dipole with edge effects for \( \pi \);

A pure sector dipole for \( \mu \) has one edge effect on \( \pi \);

Same elements, different optics for \( \pi \) and \( \mu \) due to different momenta.
Action 2:
- Create large dispersion at the injection point to separate $\pi$ and $\mu$

A pure defocusing quadrupole for $\mu$ becomes a combined-function dipole with edge effects for $\pi$;

A pure sector dipole for $\mu$ has one edge effect on $\pi$;

Same elements, different optics for $\pi$ and $\mu$ due to different momenta;
Continued from section above, match to downstream end of horn.
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Injecting beam direction continued by ~150 meters long decay straight.
Continued from section above, match to downstream end of horn.

Continued by ~150 meters long decay straight.

~16 meters after 1st dipole to gain space for a proton absorber.

Injecting beam direction.

50 m ($\beta$)

5 m (D)

45 m
Pions at downstream side of the horn
Phase Space Plot of Initial Pions

Pions at downstream side of the horn

Target+Horn

Decay Straight

Degrader
Transport Design – Simulation (Cont’d)

Real Space Plot of Initial Pions

Pions at downstream side of the horn

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13-May-13

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Transport Design – Simulation (Cont’d)

Momentum Distribution of Initial Pions

Total Momentum (MeV/c)

Number of p (Total Number: 233362)

Pions at downstream side of the horn

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Decay ON, End of injection straight, 12% of the pions yield a muon.
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Momentum Distribution of Muons at End of Straight

- Decay ON, End of injection straight, 12% of the pions yield a muon

- Ring Momentum Acceptance (32.3%)

- Extract to Degrader (26%)
• Able to achieve 0.04 muon per pion at downstream side of the horn, within $3.8 \pm 10\%$ GeV/c band.
  – Roughly 2 times the number vSTORM proposed in LOI paper;
  – Injection scheme can also be used to extract, both $\pi$ and $\mu$
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• 3480 mm Iron
• Exponentially Modified Gaussian distribution or Log-normal distribution fit
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The injection scenario has been shown to work well. Next step – to design a ring which can accept the $\mu$ from $\pi$ decay.

- Large dispersion at injection; Require compact arcs;
- First FODO ring to pursue such a large momentum acceptance ($\pm 10\%$) and phase space acceptance (2 mm).
  - Higher order chromatic effects include high-order dispersion and tune shift, which increases requirements for the arcs (more higher-order magnets) to correct them.
- Relatively small number of turns required for $\mu$ decay (e.g. 450 meters circumference – 85% decay in 100 turns)

Racetrack FFAG is also under study;
- Y. Mori, J.B. Lagrange (Kyoto U); J. Pasternak (Imperial College)
Fractional tunes: $v_x = 0.61, v_y = 0.76$

Double-bend-achromat;
Smaller beam size but harder to place high-order magnets

Injection point
Fractional tunes: $\nu_x = 0.61$, $\nu_y = 0.76$

Double-bend-achromat; Smaller beam size but harder to place high-order magnets

Injection point
100 turns loss ~40% without chromatic correction; single turn loss by ~10%

Double-bend-achromat; Smaller beam size but harder to place high-order magnets

Injection point
• Study effects of tune chromaticity and beta beat;
• Consider longer arc lengths with more space for magnets;
• Non-achromat FODO cells to be considered;
• Apply G4beamline for simulations of neutrino flux at near + far detector.
Conclusions

• Injection scenario was proved to work by simulations from G4beamline; careful designs of decay straight, the BCS, and the transport line have been done.

• We expect the ring performance to be dramatically improved with further work.

• vSTORM is in progress – Proposal will be on Fermilab Physics Advisory Committee table soon.
Conclusions

• Injection scenario was proved to work by simulations from G4beamline; careful designs of decay straight, the BCS, and the transport line have been done.

• We expect the ring performance to be dramatically improved with further work.

• vSTORM is in progress – Proposal will be on Fermilab Physics Advisory Committee table soon.
• Backup
### Introduction - Target

Table I. $\pi^+$ yield/POT with 60 GeV/c protons, into 2 mm radian acceptance.

<table>
<thead>
<tr>
<th>material</th>
<th>momentum (GeV/c)</th>
<th>±15%</th>
<th>±10%</th>
<th>±5%</th>
<th>target length (cm)</th>
<th>density (g/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>3</td>
<td>0.085</td>
<td>0.056</td>
<td>0.028</td>
<td>27.3</td>
<td>3.52</td>
</tr>
<tr>
<td>Carbon</td>
<td>5</td>
<td>0.099</td>
<td>0.067</td>
<td>0.033</td>
<td>32.2</td>
<td>3.52</td>
</tr>
<tr>
<td>Inconel</td>
<td>3</td>
<td>0.131</td>
<td>0.087</td>
<td>0.044</td>
<td>19.2</td>
<td>8.43</td>
</tr>
<tr>
<td>Inconel</td>
<td>5</td>
<td>0.136</td>
<td>0.091</td>
<td>0.045</td>
<td>27.0</td>
<td>8.43</td>
</tr>
<tr>
<td>Tantalum</td>
<td>3</td>
<td>0.164</td>
<td>0.109</td>
<td>0.054</td>
<td>15.3</td>
<td>16.6</td>
</tr>
<tr>
<td>Tantalum</td>
<td>5</td>
<td>0.161</td>
<td>0.107</td>
<td>0.053</td>
<td>21.3</td>
<td>16.6</td>
</tr>
<tr>
<td>Gold</td>
<td>3</td>
<td>0.177</td>
<td>0.118</td>
<td>0.059</td>
<td>18.0</td>
<td>19.32</td>
</tr>
<tr>
<td>Gold</td>
<td>5</td>
<td>0.171</td>
<td>0.112</td>
<td>0.056</td>
<td>21.0</td>
<td>19.32</td>
</tr>
</tbody>
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- Able to achieve ~ 0.11 $\pi$ per POT in ± 10% bin;
- Medium/Heavy targets preferred;
- Courtesy of S. Striganov (Fermilab)
Introduction – \(\pi\) Production (Old)

- Pion phase space distribution at 1 cm after target
- Vertical: \(x'\) (rad)
- Horizontal: \(x\) (cm)

\[d\sigma/d\Omega\]

- Target: Au, 20 cm length, 0.45 mm radius
- 60 GeV proton, \(\sigma_x = \sigma_y = 0.15\) mm
- \(\pi^+ - \delta p/p = 0.1, \epsilon = 2\) mm rad, \(\beta = 47.5\) cm, \(\alpha = -3\)

\[\epsilon = 2\) mm: yield = 0.094\]
\[r < 20\) cm: yield = 0.118\]
3.8 GeV/c $\mu$: $\beta_{\text{max}} \sim 30.2$ m, $\beta_{\text{min}} \sim 23.3$ m
3.8 GeV/c μ: $\beta_{\text{max}} \sim 30.2$ m, $\beta_{\text{min}} \sim 23.3$ m

5 GeV/c π: $\beta_{\text{max}} \sim 38.5$ m, $\beta_{\text{min}} \sim 31.6$ m
Continued from decay straight FODO

3.8 GeV/c $\mu$

At the end of beam combination section, separation ~ 48 cm
Continued from decay straight FODO

At the end of beam combination section, separation ~ 48 cm

- Different from μ’s
- Match the transport to the end of this section
- Injecting beam direction reversed

5 GeV/c π
Continued from section above, match to downstream of horn.

Reversed Injecting beam direction.
Continued from section above, match to downstream of horn.

Injecting beam direction

Continued by 147 meters long decay straight FODO cells (Not shown all)

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Phase Space Plot of Pions at End of FODO Cell

Gold Target Decay OFF, End of injection straight, 54%
Transport Design – Simulation (Cont’d)

Real Space Plot of Pions at End of FODO Cell
Momentum Distribution of Pions at End of FODO Cell

Total Momentum (MeV/c) vs. Number of Pions (Total Number of 105507)

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Gold Target Decay ON, End of injection straight muons, 19%
Transport Design – Simulation (Cont’d)

Real Space Plot of Muons at End of FODO Cell
Momentum Distribution of Muons at End of FODO Cell

Number of Muons (Total Number of 38367)

Total Momentum (MeV/c)
Phase Space Plot of Pions at End of Decay Straight

Decay OFF, End of injection straight, 35.5%
Phase Space Plot of Pions at End of Decay Straight

Decay OFF, End of injection straight, 35.5%
Transport Design – Simulation (Cont’d)

Real Space Plot of Pions at End of Decay Straight

Decay OFF, End of injection straight, 35.5%
Transport Design – Simulation (Cont’d)

Pions at the end of decay straight

Decay OFF, End of injection straight, 35.5%
Assume $\mu$ within $5 \pm 0.5$ GeV/c bin can be extracted.
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- Exponentially Modified Gaussian fit or Log-normal distribution
Low Energy Muons

Assume \[ \mu \] within \[ 5 \pm 0.5 \, \text{GeV} / c \] bin can be extracted

- 3480 mm Iron
- Exponentially Modified Gaussian fit or Log-normal distribution

\[
f(x; \mu, \sigma, \lambda) = \frac{\lambda}{2} e^{\frac{1}{2} \lambda^2} \text{erfc}(\frac{\lambda^2 + \lambda^2 - \sigma}{\sqrt{2}\sigma})
\]

\[
f(x; \mu, \sigma) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}, \sigma > 0
\]
Higher-order Dispersion Correction

Phase Space of Particles with Different Initial Action and Momentum
Before Dispersion Correction

\[ \delta \in [\pm 1\%], x_0=0.01 \text{ m} \]
\[ \delta \in [\pm 1\%], x_0=0.1 \text{ m} \]
\[ \delta \in [\pm 10\%], x_0=0.1 \text{ m} \]
\[ \delta \in [\pm 10\%], x_0=0.01 \text{ m} \]

Phase Space of Particles with Different Initial Action and Momentum
After Dispersion Correction

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