Neutrinos from Stored Muons

vSTORM

ν physics with a μ storage ring
Outline

Introduction/Motivation

Facility

SBL oscillation physics

Neutrino interaction physics possibilities

Jorge covered this very nicely on Wednesday, so I will be brief

Project Considerations
The idea of using a muon storage ring to produce neutrino beams for experiments is not new:
- 50 GeV beam - Koshkarev @ CERN in 1974
- 1 GeV - Neuffer in 1980

nuSTORM can:
- Address the large $\Delta m^2$ oscillation regime and make a major contribution to the study of sterile neutrinos
  - Either allow for precision study (in many channels), if they exist in this regime
  - Or greatly expand the dis-allowed region
- Make precision $\nu_e$ and $\bar{\nu}_e$ cross-section measurements
  - In general, possibly offer a paradigm shift in the study of neutrino interactions
- Provide a technology test demonstration (muon decay ring) and $\mu$ beam diagnostics test bed for future facilities (NF and/or MC)
- Provide a precisely understood $\nu$ beam for detector studies
**μ-based ν beams**

**Well-understood neutrino source:**

\[ \mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e \]

\[ \mu^- \rightarrow e^- \bar{\nu}_\mu \bar{\nu}_e \]

- Flavor content fully known
- “Near Absolute” (1% ± 0.1%) Flux Determination is possible in a storage ring
  - Beam current, $\mu_p$ spectrometer & beam divergence monitor,
  - Overall, there is tremendous control of systematic uncertainties with a well designed system
IDS-NF
Neutrinos from STOREd Muons
Single baseline, Lower E

This is the simplest implementation of the NF
And DOES NOT Require the Development of ANY New Technology
Baseline(s)

- 100 kW Target Station
  - Assume 60 GeV proton
    - Fermilab PIP era
  - Ta target (Heavy metal)
    - Optimization on-going
  - Horn (NuMI) collection
    - Li lens has also been explored

- Collection/transport channel
  - Stochastic injection of $\pi$
  - At present NOT considering simultaneous collection of both signs

- Decay ring
  - Large aperture FODO
  - Racetrack FFAG
  - Instrumentation
    - BCTs, mag-Spec in arc, polarimeter
In momentum range $4.5 < 5.0 < 5.5$

Obtain

$\approx 0.11 \pi^\pm/$pot

with 60 GeV p

Target/capture optimization ongoing
3.8 GeV/c ± 10% momentum acceptance, circumference = 350 m
FFAG Racetrack

Y. Mori, JB Lagrange
Kyoto

\[ \delta p/p \approx 15\text{-}20\% \]
Low dispersion in straight

3.8 GeV/c
The Physics Reach

*Short-baseline oscillation physics*
Assumptions

\[ N_\mu = (\text{POT}) \times (\pi/\text{POT}) \times \varepsilon_{\text{collection}} \times \varepsilon_{\text{inj}} \times (\mu/\pi) \times A_{\text{dynamic}} \times \Omega \]

\[ \times 10^{21} \text{ POT in 5 years of running @ 60 GeV in Fermilab PIP era} \]

\[ \times 0.1 \pi/\text{POT (FODO)} \]

\[ \times \varepsilon_{\text{collection}} = 0.8 \]

\[ \times \varepsilon_{\text{inj}} = 0.8 \]

\[ \times \mu/\pi = 0.08 \] \( (\gamma c t \times \mu \text{ capture in } \pi \rightarrow \mu \text{ decay}) \) \( [\pi \text{ decay in straight}] \)

\[ \times A_{\text{dynamic}} = 0.75 \text{ (FODO)} \]

\[ \times \Omega = \text{Straight/circumference ratio (0.43) (FODO)} \]

\[ \text{This yields } \approx 1.7 \times 10^{18} \text{ useful } \mu \text{ decays} \]
Integrated over the 150 m straight at a position 50m from the end of the straight with 3m diameter detector

NOTE: The transport line and ring could be re-tuned for 2 GeV/c $\mu$ and move these spectra lower by a factor of two with some drop in $\mu$ production efficiency.
Experimental Layout

\[ \mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+ \]

Appearance Channel:
\[ \nu_e \rightarrow \nu_\mu \]
Golden Channel

Must reject the “wrong” sign \( \mu \) with great efficiency

Why \( \nu_\mu \rightarrow \nu_e \) Appearance Ch. “not” possible

Appearance-only (though disappearance good too!)

\[ Pr[\nu \rightarrow \mu] = 4|U_{e4}|^2|U_{\mu4}|^2 \sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right) \]
Baseline Detector
Super B Iron Neutrino Detector: SuperBIND

- **Magnetized Iron**
  - 1.3 kT
    - Following MINOS ND ME design
    - 1-2 cm Fe plate
    - 5 m diameter
  - Utilize superconducting transmission line for excitation
    - Developed 10 years ago for VLHC
- Extruded scintillator + SiPM

20 cm hole
For 6-8 turns of STL
Backgrounds

Left: 1 cm plates

Right: 2 cm plates
Event reconstruction efficiency

Left: 1 cm plates,
Right: 2 cm plates
Raw Event Rates

Neutrino mode with stored $\mu^+$.  

<table>
<thead>
<tr>
<th>Channel</th>
<th>$N_{osc.}$</th>
<th>$N_{null}$</th>
<th>Diff.</th>
<th>$(N_{osc.} - N_{null})/\sqrt{N_{null}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e \rightarrow \nu_\mu$ CC</td>
<td>332</td>
<td>0</td>
<td>$\infty$</td>
<td>$\infty$</td>
</tr>
<tr>
<td>$\bar{\nu}<em>\mu \rightarrow \bar{\nu}</em>\mu$ NC</td>
<td>47679</td>
<td>50073</td>
<td>-4.8%</td>
<td>-10.7</td>
</tr>
<tr>
<td>$\nu_e \rightarrow \nu_e$ NC</td>
<td>73941</td>
<td>78805</td>
<td>-6.2%</td>
<td>-17.3</td>
</tr>
<tr>
<td>$\bar{\nu}<em>\mu \rightarrow \bar{\nu}</em>\mu$ CC</td>
<td>122322</td>
<td>128433</td>
<td>-4.8%</td>
<td>-17.1</td>
</tr>
<tr>
<td>$\nu_e \rightarrow \nu_e$ CC</td>
<td>216657</td>
<td>230766</td>
<td>-6.1%</td>
<td>-29.4</td>
</tr>
</tbody>
</table>

Anti-neutrino mode with stored $\mu^-$.  

<table>
<thead>
<tr>
<th>Channel</th>
<th>$N_{osc.}$</th>
<th>$N_{null}$</th>
<th>Diff.</th>
<th>$(N_{osc.} - N_{null})/\sqrt{N_{null}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{\nu}<em>e \rightarrow \bar{\nu}</em>\mu$ CC</td>
<td>117</td>
<td>0</td>
<td>$\infty$</td>
<td>$\infty$</td>
</tr>
<tr>
<td>$\bar{\nu}_e \rightarrow \bar{\nu}_e$ NC</td>
<td>30511</td>
<td>32481</td>
<td>-6.1%</td>
<td>-10.9</td>
</tr>
<tr>
<td>$\nu_\mu \rightarrow \nu_\mu$ NC</td>
<td>66037</td>
<td>69420</td>
<td>-4.9%</td>
<td>-12.8</td>
</tr>
<tr>
<td>$\bar{\nu}_e \rightarrow \bar{\nu}_e$ CC</td>
<td>77600</td>
<td>82589</td>
<td>-6.0%</td>
<td>-17.4</td>
</tr>
<tr>
<td>$\nu_\mu \rightarrow \nu_\mu$ CC</td>
<td>197284</td>
<td>207274</td>
<td>-4.8%</td>
<td>-21.9</td>
</tr>
</tbody>
</table>

3+1 Assumption

Appearance channels
$\nu_e \rightarrow \nu_\mu$ appearance

CPT invariant channel to MiniBooNE

![Graph showing neutrino energy distribution with a peak at approximately 61.2 eV with a 2 cm plate.](image)
$\nu_e \rightarrow \nu_\mu$ appearance

CPT invariant channel to LSND/MiniBooNE

3+1 Assumption

99% MB$\bar{\nu}$/LSND

arXiv:1205.6338

Wrong-sign $\mu^-$

$10^{21}$ POT

$\chi^2_{stats}$
Required $\mu$ charge mis-ID rate needed for given sensitivity

- Charge Misidentication Rate
- $10^{-2}$
- $10^{-3}$
- $10^{-4}$
- $10^{-5}$
- $10^{-6}$

- $10^{17}$
- $10^{18}$
- $10^{19}$
- $10^{20}$

- MINOS
- FODO
- RFFAG
- IDR

5 $\sigma$, 7 $\sigma$, 10 $\sigma$
Comments on $\nu$ beam

$\checkmark$ Although the primary beam is from $\mu$ decay, at the beginning of $\pi$ injection into the first straight, $\pi \rightarrow \mu \nu_\mu$ may offer the opportunity to study $\nu_\mu \rightarrow \nu_e$ appearance

$\checkmark$ Capture transport line reduces $\nu_e$ background from $K$ decay by factor of roughly 100

$\checkmark$ Left only with $\nu_e$ from $\mu$ decay
ν Interaction Physics

Possibilities at a Near Detector Hall
$E_{\nu}$ spectra ($\mu^+$ stored)

Event rates/100T at ND hall 50m from straight with $\mu^+$ stored

<table>
<thead>
<tr>
<th>Channel</th>
<th>$N_{evts}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{\nu}_\mu$ NC</td>
<td>844,793</td>
</tr>
<tr>
<td>$\nu_e$ NC</td>
<td>1,387,698</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$ CC</td>
<td>2,145,632</td>
</tr>
<tr>
<td>$\nu_e$ CC</td>
<td>3,960,421</td>
</tr>
</tbody>
</table>

Alan Bross  
NuInt12  
October 26, 2012
nuSTORM can deliver a ν beam with unprecedented control over systematics.

The strength of the physics will depend on the detector(s) and their design.

Near detector studies for the IDS-NF and LBNE already point to some very powerful options:
- LAr
- HighRes

Detailed simulation studies are just beginning.
Project Considerations
Steve Dixon (Fermilab FESS) will discuss tomorrow
Preliminary Cost Estimate

Major Components

- Beamline, Target Station & Horn: $30M
- Transport line: 9
- Decay ring: 54
- Detectors (Far & Near): 18
- Project Office: 15

Total: $126M

Basis of Estimation (BOE)

- Took existing facilities (MiniBooNE beam line and target station, NuMI target station, MINOS detector, vetted magnet costing models, μ2e civil construction costs, EuroNu detector costing, have added all cost loading factors and have escalated to 2012 $ when necessary.

Alan Bross  NuInt12  October 26, 2012
Moving Forward
Moving Forward

ý Optimize the Facility:

ý Targeting, capture/transport & Injection
  ý Need to complete detailed design and simulation

ý Decay Ring optimization
  ý Continued study of both RFFAG & FODO decay rings

ý Decay Ring Instrumentation
  ý Define and simulate performance of BCT, Magnetic-spectrometer, etc.

ý Produce full G4Beamline simulation of all of the above to define $\nu$ flux
  ý And verify the precision to which it can be determined.
Detector simulation

- For oscillation studies, continue MC study of backgrounds & systematics
  - Start study of disappearance channels
- In particular the event classification in the reconstruction needs optimization.
  - Currently assumes "longest track" is interaction muon.
  - Plan to assign hits to and fit multiple tracks.
  - Vertex definition must also be improved.
  - Multivariate analysis.

- $\nu$ interaction physics need detector baseline design
  - Learn much from detector work for LBNE & IDS-NF
- Increased emphasis on $\nu_e$ interactions, however

- Produce Full Proposal for June 2013 PAC Mtg.
The Physics case:

- Initial simulation work indicates that a L/E ≈ 1 oscillation experiment using a muon storage ring can confirm/exclude at 10σ (CPT invariant channel) the LSND/MiniBooNE result.
- $\nu_\mu$ and ($\nu_e$) disappearance experiments delivering at the <1% level look to be doable.
  - Systematics need careful analysis.
  - Detailed simulation work on these channels has not yet started.
- $\nu$ physics studies with near detector(s) offer a **unique** opportunity & can be extended to cover 0.2<GeV< $E_\nu$< 4 GeV.
- Could be "transformational" w/r to $\nu$ interaction physics.
Conclusions II

The Facility:

- Presents very manageable extrapolations from existing technology
  - But can explore new ideas regarding beam optics and instrumentation
- Offers opportunities for extensions
  - Add RF for bunching/acceleration/phase space manipulation
  - Provide μ source for 6D cooling experiment with intense pulsed beam
Interested \AE subscribe to NUSTORM mailing list on listserv.fnal.gov

In the end, nuSTORM will only succeed if there is a large non-US component to the collaboration with commensurate resources

\[ \frac{1}{2} \] the names on the LOI are from non-US institutions: A Good Start!
Obrigado
Back Ups
Injection Concept

- π's are in injection orbit
  - separated by chicane
- μ's are in ring circulating orbit
  - lower energy - ~3.8 GeV/c
- ~30cm separation between

Concept works for FODO lattice
Work in progress for RFFAG
FFAG Tracking

Max amplitude 100 turns for \( p_0 \)

Initial phase: Red
\( \epsilon_{\text{unnormalized}} \sim 400 \pi \text{ mm mrad} \)

After 100 turns: Blue

\( \pm 0.075 \text{m}, \pm 0.005 \text{rad} \)

\( \pm 0.090 \text{m}, \pm 0.035 \text{rad} \)

from JB. Lagrange, [acc-kerri-1119-01-2011]

>90% dynamic aperture
A Perfect vSTORM?

- SuperBIND & a large LAr detector can fit in D0 pit
  - kT-scale each

- $\nu_\mu$ beam (fr. $\pi$ decay, Turn 1)

- $\mu$ decay $\nu$ beam

- With 40k evts/ton add small LAr detector at near hall in addition to the 1-200T of SuperBIND

- $\nu_\mu$ appearance in SuperBIND
- $\nu_\mu$ and $\nu_e$ disappearance in both SuperBIND & LAr
- $\nu_e$ appearance in LAr from $\nu_\mu$ from $\pi$ decay
- Upgrade - magnetize the LAr
- $\nu_\mu$ appearance LAr
- $\nu_e$ appearance (from $\nu_\mu$ $\Rightarrow$ $\nu_e$) in LAr?
π collection