nuSTORM Neutrino Flux Calculations and Uncertainties

Ryan Bayes
on behalf of the nuSTORM collaboration

School of Physics and Astronomy
University of Glasgow

NuInt Workshop
23 May, 2014

Overall Outline

Benefits of a Muon Storage Ring for Neutrino Physics

Produce multiple high quality beams of different flavours

- μ^+ decay produces ν_e and $\bar{\nu}_\mu$ in equal quantities
- ν_μ beam from π^+ decay (specific to nuSTORM and MOMENT)

Excellent energy range for interaction studies

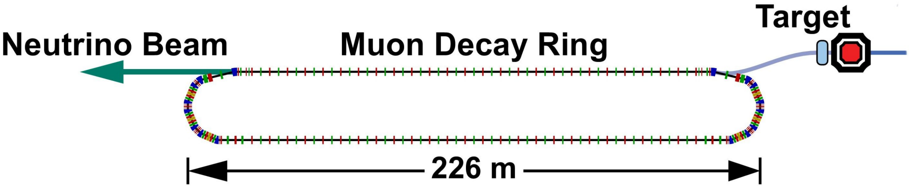
- All neutrino beam energies between 0 and 4 GeV.
- Equal shares of QES and DIS interactions in this region.

Strong control over systematic effects

- Muon-decay beam energy and content precisely known.
- Pion beam flux with low contamination.

The nuSTORM Facility

- 120 GeV proton beam incident on a graphite target produce pions.
- Pions are horn captured, transported, and injected into ring.
  - 52% of pions decay to muons before first turn
- Muons within momentum acceptance circulate in ring.
- Muon lifetime is 27 orbits of decay ring.



- Schematic representation of nuSTORM

Flux from Muon Decay in a Muon Storage Ring

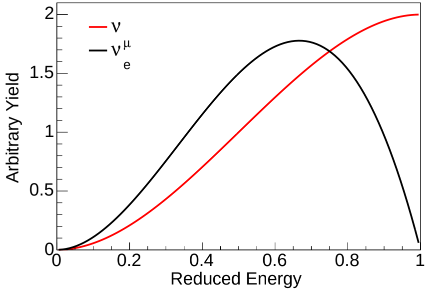
Neutrino distributions from unpolarized muon decays at rest

- In the SM ν_e appear in the distribution,

$$\frac{d\Gamma}{dy} = \frac{m_\mu^5 G_F^2}{16\pi^3} y^2(1-y)$$

- ν_μ appear in a distribution,

$$\frac{d\Gamma}{dy} = \frac{m_\mu^5 G_F^2}{192\pi^3} y^2(3-2y)$$



- The reduced energy $y = 2E_\nu/m_\mu$

- Muon decays are subject to a boost in the z-direction

$$\vec{p}'_\nu = \vec{p}_\nu + \frac{(\gamma-1)}{\beta^2}(\vec{p}_\nu \cdot \vec{\beta})\vec{\beta} + \gamma\vec{\beta}E_\nu$$

Angular Spread of ν Beam from a Muon Storage Ring

- For nuSTORM; E_μ=3.8 GeV
  - β = 0.99963
  - γ = 36.968
- From μ decay $0 < p_\nu < 52.828$ MeV/c
- Two extreme cases of interest:

$\vec{p}_\nu \parallel \vec{\beta}$

$$\theta_\nu \approx \sqrt{\frac{\vec{p}'_\nu \cdot \vec{p}'_\nu - (\vec{p}'_\nu \cdot \hat{k})(\vec{p}'_\nu \cdot \hat{k})}{(\vec{p}'_\nu \cdot \hat{k})(\vec{p}'_\nu \cdot \hat{k})}} \rightarrow \frac{\sqrt{(\vec{p}_\mu \cdot \hat{i})^2 + (\vec{p}_\mu \cdot \hat{j})^2}}{(\vec{p}_\mu \cdot \hat{k})}$$

$\vec{p}_\nu \perp \vec{\beta}$

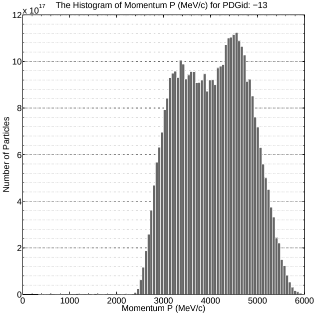
$$\theta_\nu \approx \frac{|\vec{p}_\nu|}{\gamma\beta E_\nu} \approx \frac{1}{\beta\gamma} = 0.028$$

- Fixed component from beam acceleration.
- Need simulation of muon beam to determine p_t and p_z.

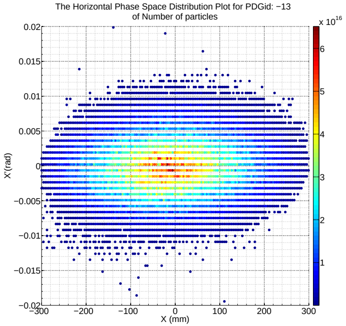
Muon Momentum from Full Simulation

- Full simulation of FODO run developed with G4beamline
- Tracks secondaries ($K^\pm$, $\pi^\pm$, $\mu^\pm$) and scales yield to 10^{21} POT.
- Precise profiles of momentum beam extracted.

μ^+ Distribution

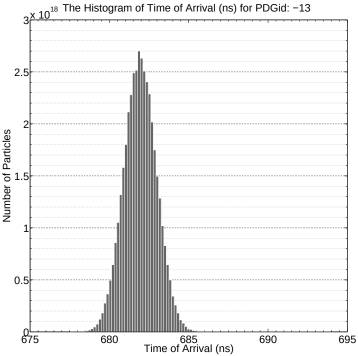


p_x/p_z versus x



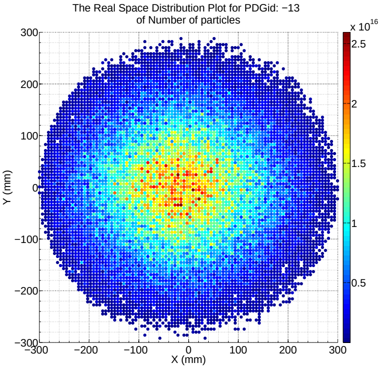
Beam structure from Full Simulation

Time distribution



- Beam structure well defined
- Time given from the target to the end of first straight.

Beam Profile



- Uniform decays in straight.
- Integrate over decay positions to produce ν beams.

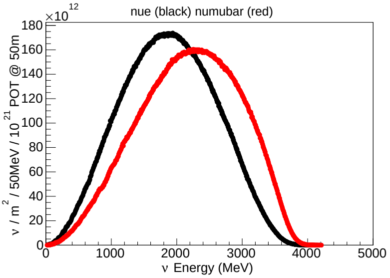
nuSTORM Rate Calculations from Muon Decay

- For 10^{20} POT we expect 2.6×10^{17} μ^+.
- Flux calculated from simulations and studies of ring performance, target capture, and particle transport (summarized below).

Relative μ yield for FODO ring

Parameter	Values
$L_{\rm straight}$ (m)	185
Circumference (m)	480
Dynamic aperture $A_{\rm dyn}$	0.6
Momentum acceptance	$\pm$ 20%
π/POT in momentum acc.	0.094
Fraction of π decays in straight (F_s)	0.52
Ratio of $L_{\rm straight}$ to circumference (Ω)	0.39
$A_{\rm dyn} \times \pi/{\rm POT} \times F_s \times \Omega$	0.011

μ^+ Decay Flux at Near Detector



- Assume a 3 m radius.
- 50 m distance from straight.

Beam Line Instrumentation[1]

- Rates and beam characteristics in the ring well known from instrumentation
- Should lead to precise knowledge of the integrated neutrino rate and average beam dispersion.

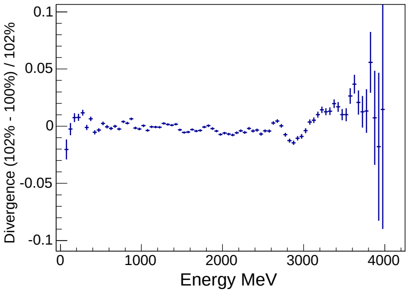
Quantity	Planned Detectors	Comment
Intensity	Beam Current Transformer	0.1% resolution realistic
Beam Position	Button BPM	1 cm resolution expected
Beam Profile	Scintillating screens	Destructive, 1 cm resolution
Energy	Polarimeter	
Energy Spread	Beam Profile measurement in Arcs	order of 0.1% resolution
Beam loss	Ionization or Diamond Detectors	

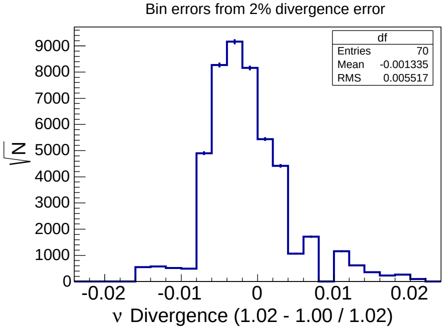
[1] adopted from presentation by Lars Soby, 26/03/2013

Beam Uncertainty Study

- Generated muon beam with dispersion inflated by 2%.
- μ beam uncertainty of 1%.

Rate Difference

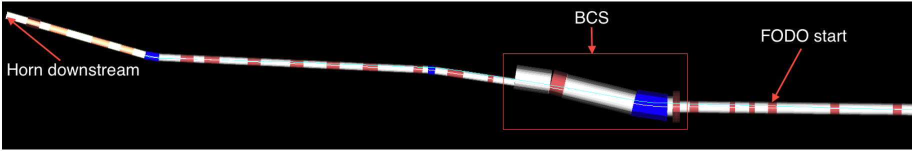




- RMS of bin-to-bin change less than 0.6%
- Expect less than 0.3% uncertainty

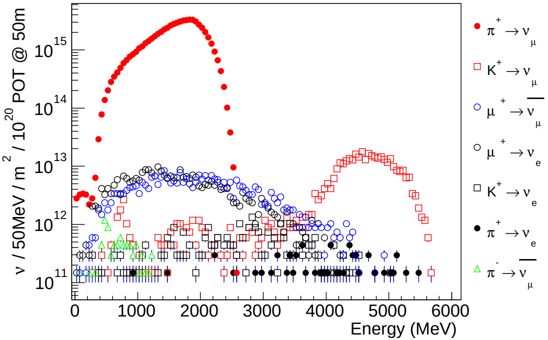
Pion Beams at nuSTORM

Pion Transport Line



- 50% of pions decay in straight.
- Injection produces a ν_μ flash of $\pi^+ \rightarrow \mu^+\nu_\mu$ decays.
- For 10^{20} POT we expect 8.6×10^{18} π^+ decays.
- Target not aligned with detectors; no neutral beam contamination.

Neutrino Flux from Pion Flash



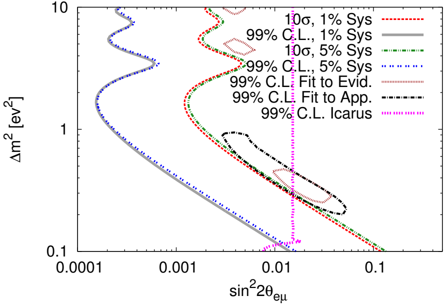
- All secondaries from production target tracked into decay straight
- Integrated flux from first pass through decay straight after injection.

- Pion ν flux much greater than muon ν flux.
  - $\pi^+ \to \nu_\mu$ flux is 6.27$\times 10^{16}$ ν/m^2 at 50 m
  - $\mu^+ \to \nu_e$ flux is 2.95$\times 10^{14}$ ν/m^2 at 50 m
  - $K^+ \to \nu_\mu$ flux is 3.78$\times 10^{14}$ ν/m^2 at 50 m
- Can be used for short baseline neutrino experiments.

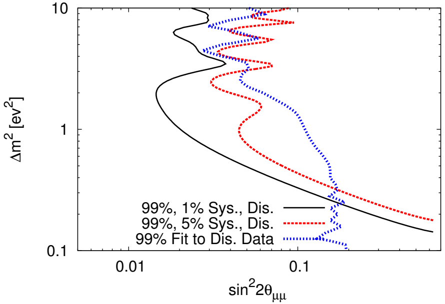
Sterile Neutrino Oscillation Sensitivity

- Studies of sterile neutrino discovery potential completed[2]
- Assume sample of 1×10^{18} useful μ^+ decays.
- 1.3 kTon iron-scinitillator calorimeter detector.
- Assume a 0.5% rate and 0.5% cross-sectional systematic.

$\nu_e \rightarrow \nu_\mu$ Appearance Search



$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ Disappearance Search



[2] D. Adey *et. al.* Phys. Rev. D 89, 071301(R)

Potential for Cross-Section Measurement

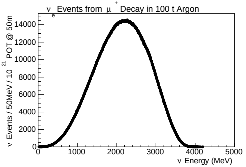
- Flux uncertainties a significant contribution to cross-sections

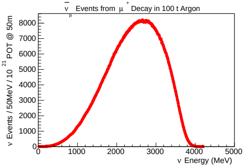
Experiment	Flux Error
MiniBooNE	6.7—10.5%
T2K	10.9%
Minerva	12%
nuSTORM	$<1\%$

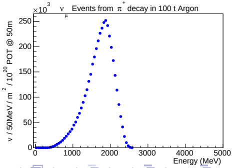
Event Rate per 10^{21} POT, 100 tonnes at 50 m

μ^+ Channel	μ^+ N_{evts}	μ^- Channel	μ^- N_{evts}
$\bar{\nu}_\mu$ NC	1,174,710	$\bar{\nu}_e$ NC	1,002,240
ν_e NC	1,817,810	ν_μ NC	2,074,930
$\bar{\nu}_\mu$ CC	3,030,510	$\bar{\nu}_e$ CC	2,519,840
ν_e CC	5,188,050	ν_μ CC	6,060,580
π^+		π^-	
ν_μ NC	14,384,192	$\bar{\nu}_\mu$ NC	6,986,343
ν_μ CC	41,053,300	$\bar{\nu}_\mu$ CC	19,939,704

- nuSTORM measurements limited by detector systematics.





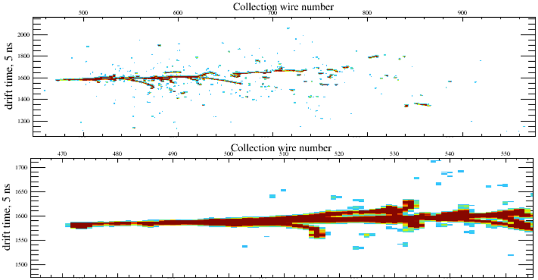


Example: Straw-man LAr detector[3]

- Considered a 100 t LAr detector in the CCQE channels.
- Clean event reconstruction wi/ good fiducial cuts.
- Assuming 10 million events/year and 10 ms window
    - Event rate: 1 mHz
    - Pile up of a few events per hour.

Assumed LAr simulation parameters

Effect	Value
Momentum resolution of contained tracks	3%
Angular resolution	3%
Minimum range for track finding	2 cm

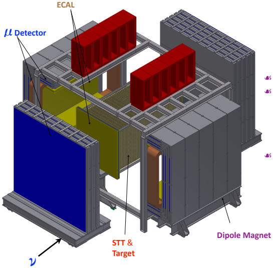


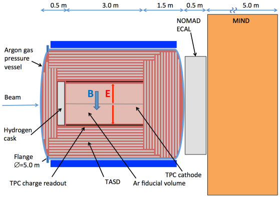
- Determined that a potential 6 fold increase in precision possible.

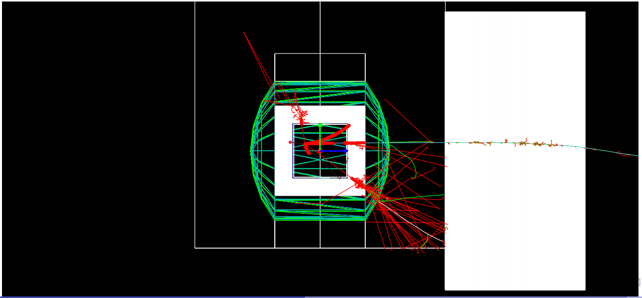
[3] arXiv:1308.6822v1

Possible Near Detectors

- LBNE Near Detector, HIRESMUNU
  - Straw tube tracker, (S. Mishra & R. Petti).
  - Builds on NOMAD experience
  - Foil layers for some nuclear targets
- LBNO / LAGUNA Near Detector
  - Install @ nuSTORM prior to LBNO.
  - Gas TPC, with fully active calorimeter.
  - Potential for hydrogen target.







Conclusions

nuSTORM facility offers great potential for future neutrino physics

- Short baseline neutrino oscillation measurements
- Neutrino interaction studies
- Offers neutrino beams from π and μ decay
- Three neutrino beam flavours available ν_μ, ν_e, and $\bar{\nu}_\mu$.

Simulations of μ and π beams in nuSTORM ring completed

- Neutrino spectra understood with precision of $< 1\%$.
- Neutrino backgrounds from π decay $< 10^{-3}$ of ν_μ spectra.

Early simulations show promising physics results

- LAr sim. suggests 6 fold increase in precision of $\bar{\nu}_\mu$ cross-section.
- Other detectors under consideration for placement in a near detector site.

Thank you

Material provided by:

- David Adey
- Ao Liu
- Lars Soby
- Ed Santos
- Ian Taylor
- Etam Noah

D. Adey,[1] S.K. Agarwalla,[2] C.M. Ankenbrandt,[3,*] R. Asfandiyarov,[4] J.J. Back,[5] G. Barker,[5] E. Baussan,[6] R. Bayes,[7,†] S. Bhadra,[8] V. Blackmore,[9] A. Blondel,[4] S.A. Bogacz,[10] C. Booth,[11] S.B. Boyd,[5] S.G. Bramsiepe,[7] A. Bravar,[4] S.J. Brice,[1] A.D. Bross,[1] F. Cadoux,[4] H. Cease,[1] A. Cervera,[12] J. Cobb,[9] D. Colling,[13] P. Coloma,[14] L. Coney,[15] A. Dobbs,[13] J. Dobson,[13] A. Donini,[12] P. Dornan,[13] M. Dracos,[6] F. Dufour,[4] R. Edgecock,[16] M. Geelhoed,[1] M.A. Uchida,[13] T. Ghosh,[12] J.J. Gómez-Cadenas,[12] A. de Gouvêa,[17] A. Haesler,[4] G. Hanson,[15] P.F. Harrison,[5] M. Hartz,[8,‡] P. Hernández,[12] J.A. Hernando Morata,[18] P. Hodgson,[11] P. Huber,[14] A. Izmaylov,[12] Y. Karadzhov,[4] T. Kobilarcik,[1] J. Kopp,[19] L. Kormos,[20] A. Korzenev,[4] Y. Kuno,[21] A. Kurup,[13] P. Kyberd,[22] J.B. Lagrange,[23] A. Laing,[12] A. Liu,[1] J.M. Link,[14] K. Long,[13] K. Mahn,[24] C. Mariani,[14] C. Martin,[4] J. Martin,[25] N. McCauley,[26] K.T. McDonald,[27] O. Mena,[12] S.R. Mishra,[28] N. Mokhov,[1] J. Morfín,[1] Y. Mori,[23] W. Murray,[16] D. Neuffer,[1] R. Nichol,[29] E. Noah,[4] M.A. Palmer,[1] S. Parke,[1] S. Pascoli,[30] J. Pasternak,[13] R. Plunkett,[1] M. Popovic,[1] P. Ratoff,[20] M. Ravonel,[4] M. Rayner,[4] S. Ricciardi,[16] C. Rogers,[16] P. Rubinov,[1] E. Santos,[13] A. Sato,[21] T. Sen,[1] E. Scantamburlo,[4] J.K. Sedgbeer,[13] D.R. Smith,[22] P.J. Smith,[11] J.T. Sobczyk,[31] L. Søby,[32] F.J.P. Soler,[7] M. Sorel,[12] P. Snopok,[33,§] P. Stamoulis,[12] L. Stanco,[34] S. Striganov,[1] H.A. Tanaka,[35] I.J. Taylor,[5] C. Touramanis,[26] C. D. Tunnell,[9,¶] Y. Uchida,[13] N. Vassilopoulos,[6] M.O. Wascko,[13] A. Weber,[9] M.J. Wilking,[24] E. Wildner,[32] and W. Winter[36]

(The nuSTORM Collaboration)

[1] *Fermi National Accelerator Laboratory, Box 500, Batavia, IL 60510-5011, USA*
[2] *Institute of Physics, Sachivalaya Marg, Sainik School Post, Bhubaneswar 751005, Orissa, India*
[3] *Muons Inc., 552 N. Batavia Avenue, Batavia, IL 60510, USA*
[4] *University de Geneve, 24, Quai Ernest-Ansermet, 1211 Geneva 4, Switzerland*
[5] *Department of Physics, University of Warwick, Coventry, CV4 7AL, UK*
[6] *IPHC, Université de Strasbourg, CNRS/IN2P3, F-67037 Strasbourg, France*
[7] *School of Physics and Astronomy, Kelvin Building, University of Glasgow, Glasgow G12 8QQ, Scotland, UK*
[8] *Department of Physics and Astronomy, York University, 4700 Keele Street, Toronto, Ontario, M3J 1P3, Canada*
[9] *Oxford University, Subdepartment of Particle Physics, Oxford, UK*
[10] *Thomas Jefferson National Accelerator Facility, Newport News, VA, USA*
[11] *University of Sheffield, Dept. of Physics and Astronomy, Hicks Bldg., Sheffield S3 7RH, UK*
[12] *Instituto de Física Corpuscular (IFIC), Centro Mixto CSIC-UVEG, Edificio Institutos Investigación, Paterna, Apartado 22085, 46071 Valencia, Spain*
[13] *Physics Department, Blackett Laboratory, Imperial College London, Exhibition Road, London, SW7 2AZ, UK*
[14] *Center for Neutrino Physics, Virginia Polytechnic Institute and State University. Blacksburg, VA 24061-0435*
[15] *University of California, Riverside, CA, USA*
[16] *STFC Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire, OX11 0QX, UK*
[17] *Northwestern University, Evanston, IL, USA*
[18] *Universidade de Santiago de Compostela (USC), Departamento de Fisica de Particulas, E-15706 Santiago de Compostela, Spain*
[19] *Max-Planck-Institut für Kernphysik, PO Box 103980, 69029 Heidelberg, Germany*
[20] *Physics Department, Lancaster University, Lancaster, LA1 4YB, UK*
[21] *Osaka University, Osaka, Japan*
[22] *Centre for Sensors and Instrumentation, School of Engineering and Design, Brunel University, Uxbridge, Middlesex, UB8 3PH, UK*
[23] *Kyoto University, Kyoto, Japan*
[24] *TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C., V6T 2A3, Canada*
[25] *Department of Physics, University of Toronto, 60 St. George Street, Toronto, Ontario, M5S 1A7, Canada*
[26] *Department of Physics, Oliver Lodge Laboratory, University of Liverpool, Liverpool, L69 7ZE, UK*
[27] *Princeton University, Princeton, NJ, 08544, USA*
[28] *Department of Physics and Astronomy, University of South Carolina, Columbia SC 29208, USA*
[29] *Department of Physics and Astronomy, University College London, Gower Street, London, WC1E 6BT, UK*
[30] *Institute for Particle Physics Phenomenology, Department of Physics, Durham University, Durham, DH1 3LE, UK*
[31] *Institute of Theoretical Physics, University of Wroclaw, pl. M. Borna 9,50-204, Wroclaw, Poland*
[32] *CERN,CH-1211, Geneva 23, Switzerland*
[33] *Illinois Institute of Technology, Chicago, IL 60616*
[34] *INFN, Sezione di Padova, 35131 Padova, Italy*

[35] *Department of Physics and Astronomy, Hennings Building, The University of British Columbia, 6224 Agricultural Road, Vancouver, B.C., V6T 1Z1, Canada*
[36] *Fakultät für Physik und Astronomie, Universität Würzburg Am Hubland, 97074 Würzburg, Germany*