The Very-Low Energy Neutrino Factory

ν physics with a μ storage ring

Alan Bross

VLENF

Experimental Motivation

- We have a collection of hints of something…
  - LSND: $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{\mathrm{e}}$
  - MiniBooNE: $\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{\mathrm{e}}$
  - MiniBooNE: $\nu_{\mu} \not\rightarrow \nu_{\mathrm{e}}$
    - Low E_{ν} excess
  - Reactor flux anomaly
  - MINOS: ν_{μ} vs. $\bar{\nu}_{\mu}$
- Cross-section measurements
  - μ storage ring presents only way to measure ν_{μ} & ν_{e} (ν and $\bar{\nu}$) x-sections in same experiment

SBNW11

Short-Baseline Neutrino Workshop

- From Richard Van de Water's SBNW summary
  - There are a smorgasbord of experimental hints that point to possible new physics.
    - "Not a single piece of evidence that directly contradicts LSND/MiniBooNE".
    - Much circumstantial experimental evidence that supports LSND/MB from MeV to GeV range. Karmen and ν_μ disappearance provides some restriction.
  - **Need to make smoking gun measurement.**
    - Need to make a >5 σ measurement at L/E ~1 to convince the community.
    - Need to measure neutrino properties to the ~ 1 percent level.
    - Need sufficient **Rate** = Flux x Cross Section x detector response
- Can an experiment utilizing ν from a μ storage ring provide this "Smoking Gun?"

Possibilities with μ storage ring

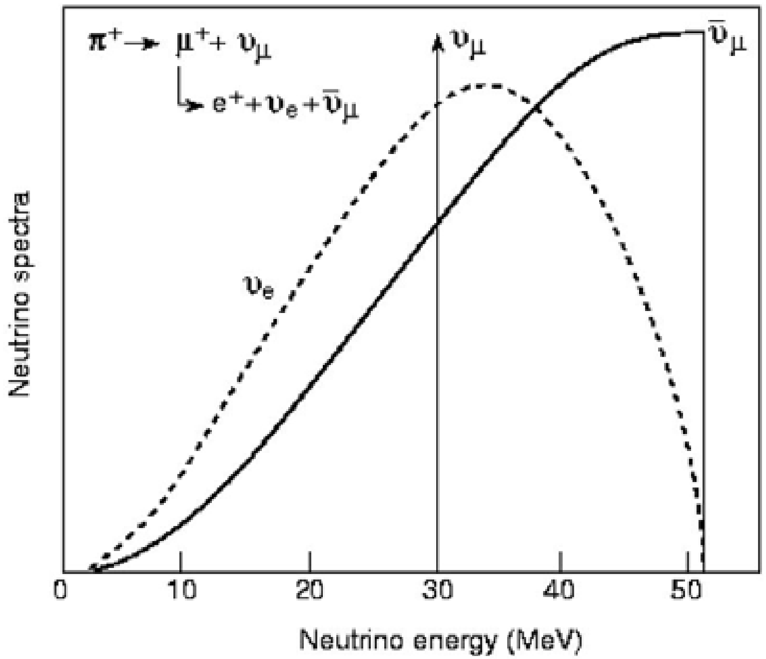
- Oscillation Physics @ L/E = 1
  - Appearance experiment with low background
    - A different approach to explore the LSND/MiniBooNE result
- ν disappearance experiment with 1% precision (10^4 events)
  - An experiment that uses a ν_e beam from a muon storage ring can go a long way in ruling out sterile ν_s
  - ν_μ disappearance (@ short baseline) also
- In addition, the beam opens up opportunities for
  - Detailed study of ν interactions
    - Known ν beam flux and flavor composition
    - **Only way** to get large sample of ν_e interactions at large E_ν

ν_s from muon decay

- Running with μ^-

$$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$$

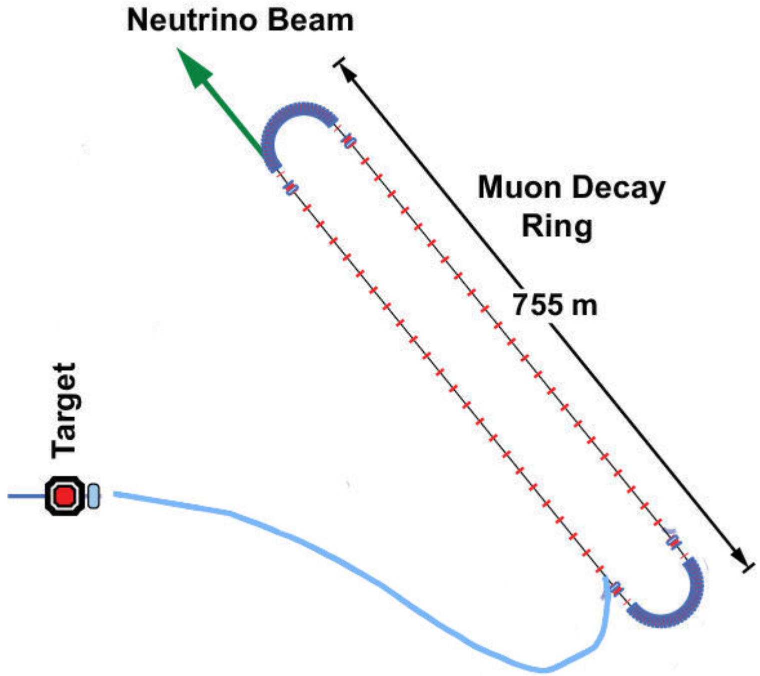
- Well defined flavor composition & energy



What the NF is
and what the VLENF is

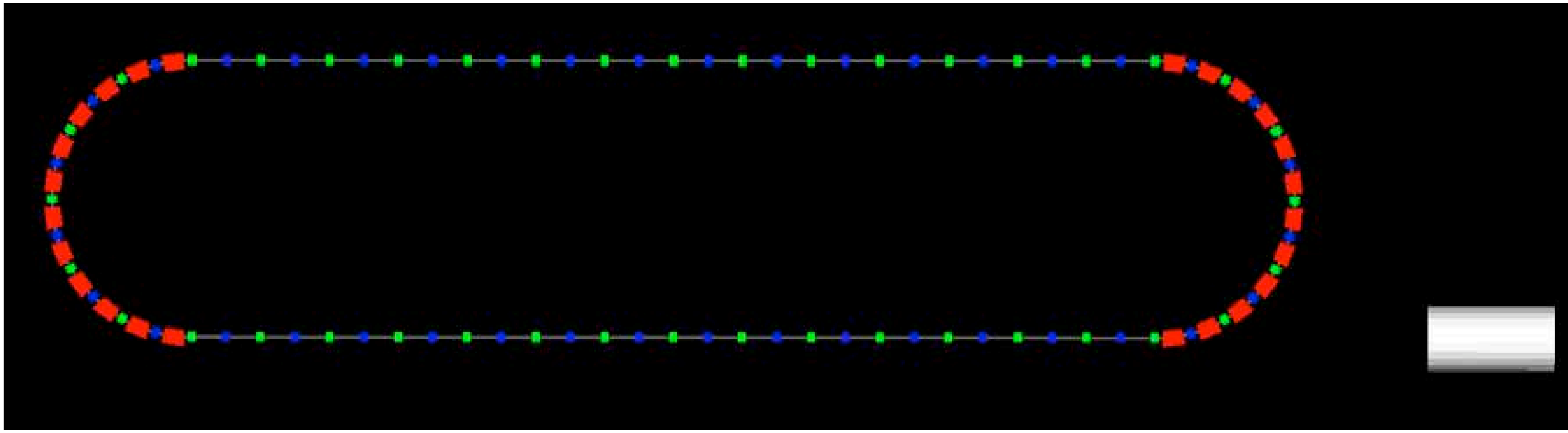
BASELINE

VLENF

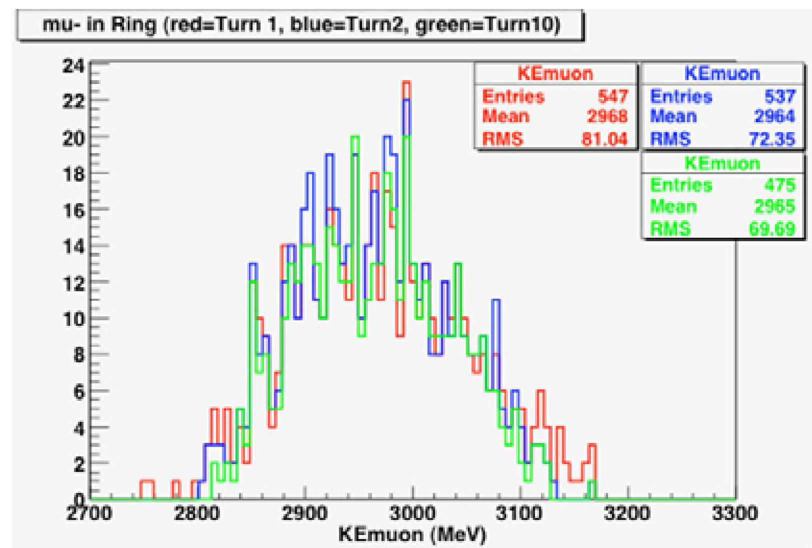


Status of the concept
G4Beamline Simulation

Tom Roberts
Muons Inc.



- 8 GeV protons on 2 λ_I Be target
- 3 GeV Racetrack ring (M. Popovic)
  - For now, injection is perfect
    - Not defined
- Tuned for μ^- with KE = 3.000 GeV
  - 3 GeV chosen primarily for x-section meas.
  - $\delta p/p \approx 2\%$
- Detectors (scintillator)
  - Near: 200T @ 20 m
  - Far: 800T @ 600 - 1000 m



Circulating μ^- beam flux

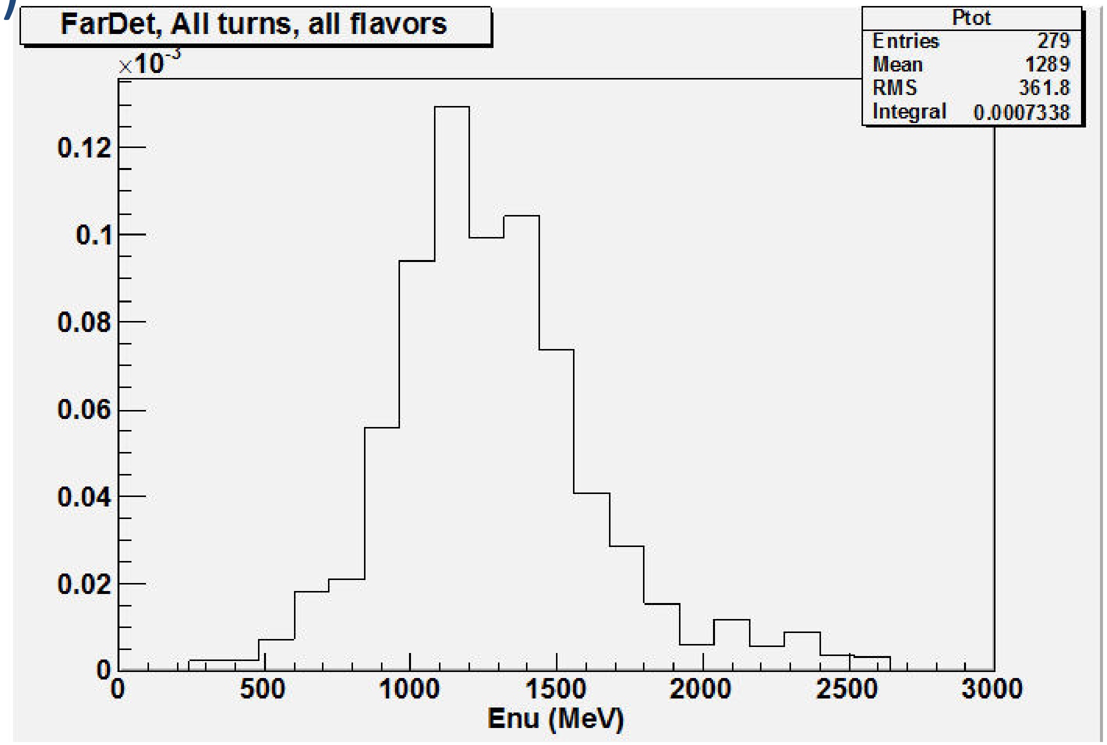
	Turn					
Particle	**1**	**2**	**3**	**4**	**10**	**100**
pi-	8.7E+07	1.9E+07	5.4E+06	1.4E+06	0	0
mu-	1.3E+08	1.3E+08	1.2E+08	1.2E+08	1.1E+08	3.6E+07
e-	5.8E+07	5.6E+07	5.6E+07	5.5E+07	5.2E+07	4.8E+07

- Particle count scaled to 10^{12} POT
- Figure of Merit: $\approx$ 1.1 X 10^{-4} stored μ/POT
  - After all π gone
- *Note: Based on experience at proton machines, this beam (flux and beam size) can be monitored with 0.1% precision with existing technology BCTs (according to the experts).*

Estimated event rates

Far Detector

- ν_μ Events per 10^{21} POT (turns 10 & up)
  - Near: 1.3 X 10^5 (200T)
  - Far: 0.7 X 10^4 (800T)



Note: Still having some "issues" with E_ν flux shape

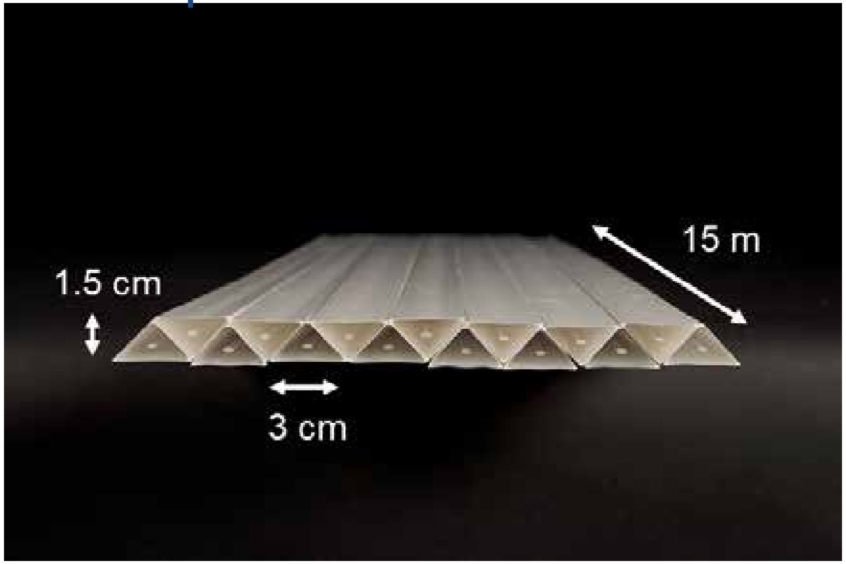
Detector Considerations

- Far detector *(Large Δm^2 oscillation physics)*
  - Magnetized totally active scintillator detector - ideal
  - Magnetized Fe (MIND) possible?
    - Depends on performance for $P_\mu < 1$ GeV/c
  - LAr also possible
    - But magnetization raises fundamental problem: PMTs used for trigger (Ar scintillation)
    - Some R&D on alternate approaches to the scintillation light readout being explored
      - WLS bars (might allow for PMTs outside field region?)
      - WLS fiber + SiPM readout
  - Near detector
    - More options, but must be totally active
      - TASD (need not be magnetized, but is an advantage)
        - » Could also mean *"Totally Active Straw Detector"*
      - LAr (μBooNE, already has made case for X-section meas. in MB line)

Far Detector

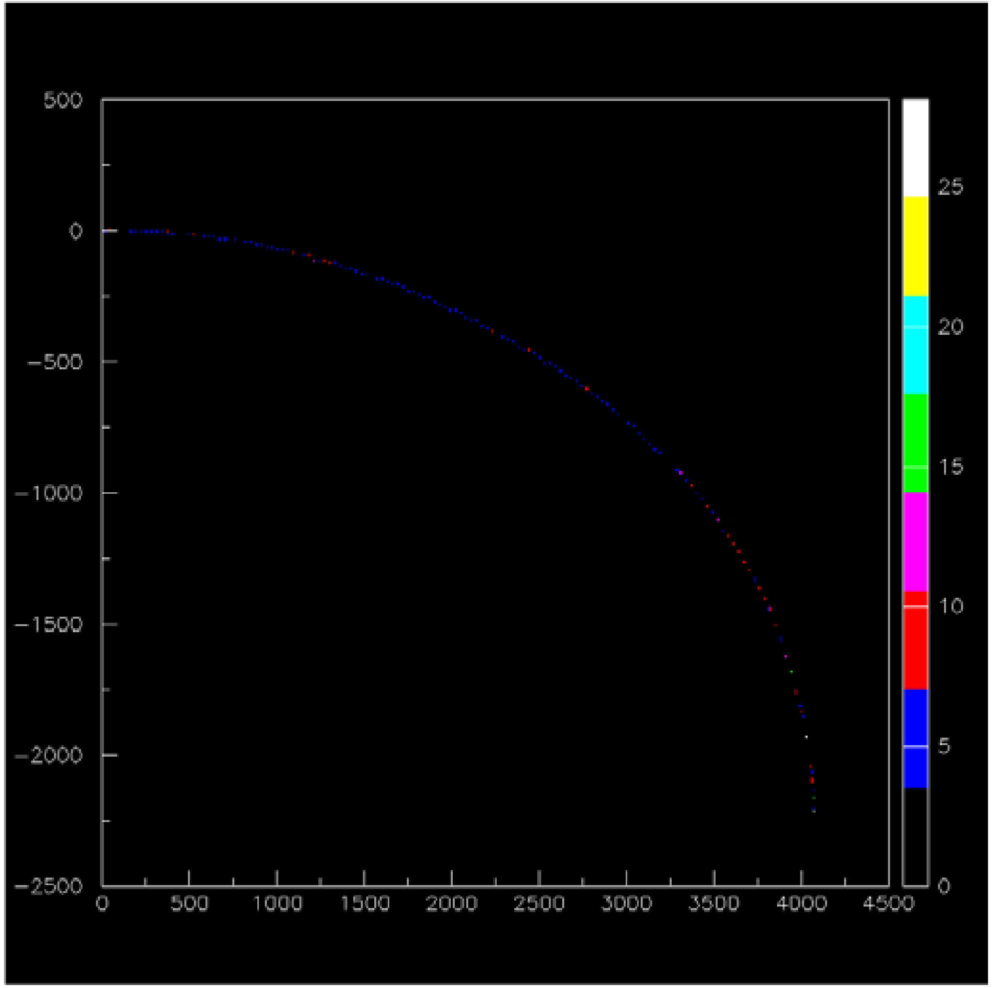
Magnetized Totally Active Scintillator Detector

- Simulation of a Totally Active Scintillating Detector (TASD) using Nova and Minerva concepts with Geant4 has been completed
  - Momenta between 100 MeV/c to 15 GeV/c
  - Magnetic field considered: **0.5 T**
  - Reconstructed position resolution ~ 4.5 mm



1 GeV μ track in TASD

Y(mm)

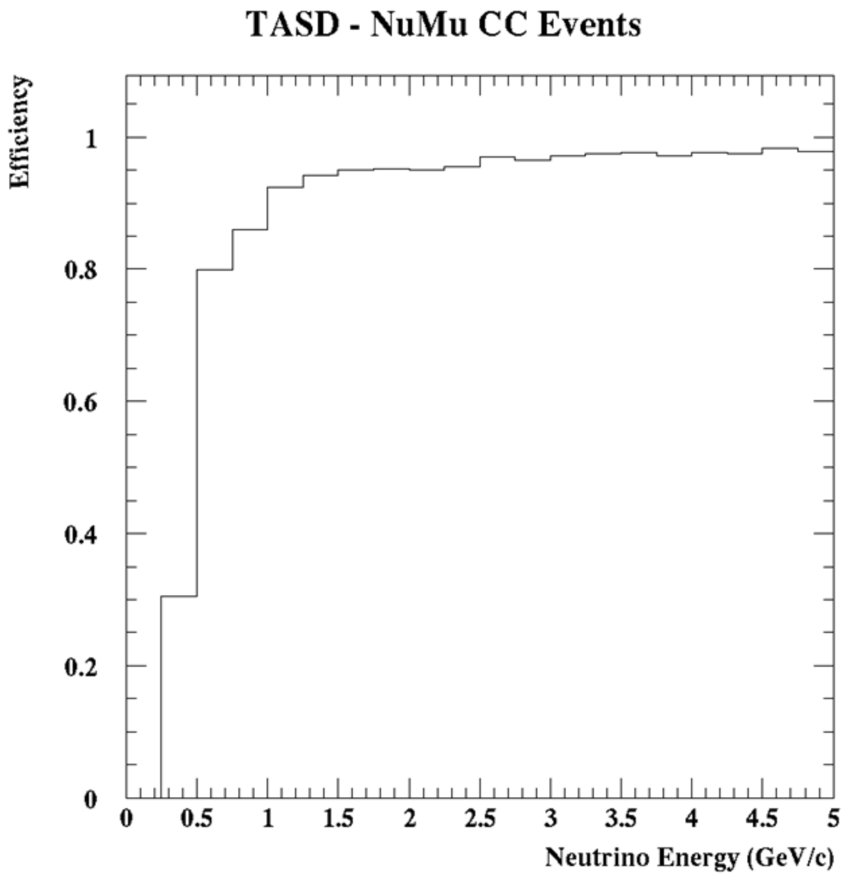


Z(mm)

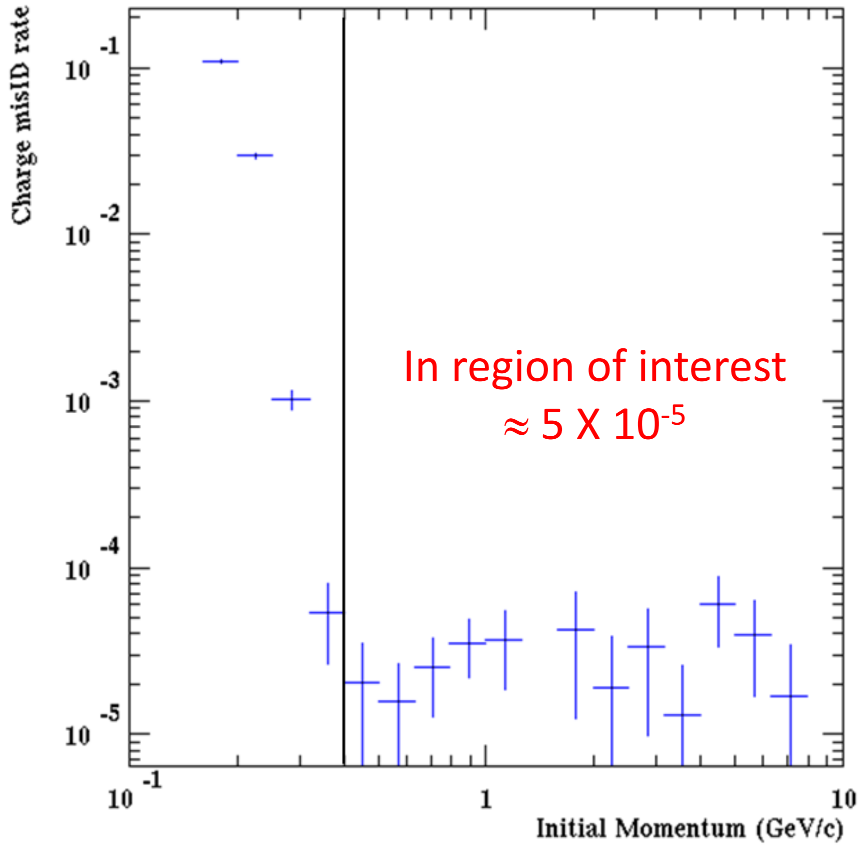
Y (bend plane) vs Z
B=0.5T

TASD Performance

It works



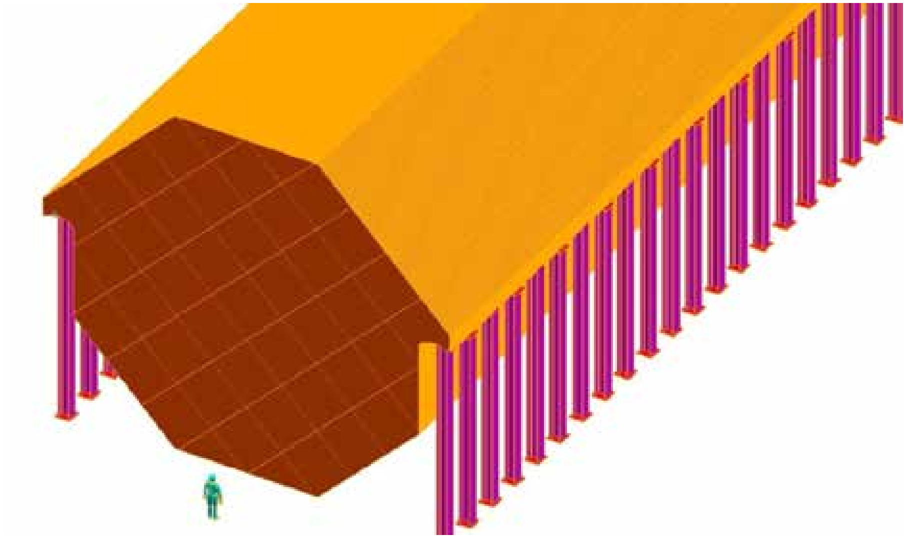
ν Event Reconstruction Efficiency

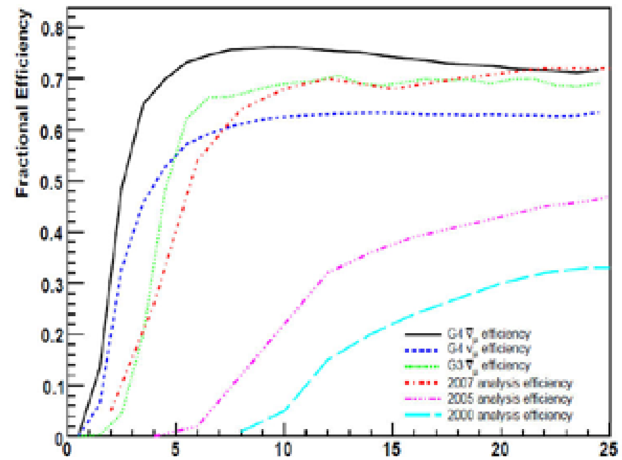


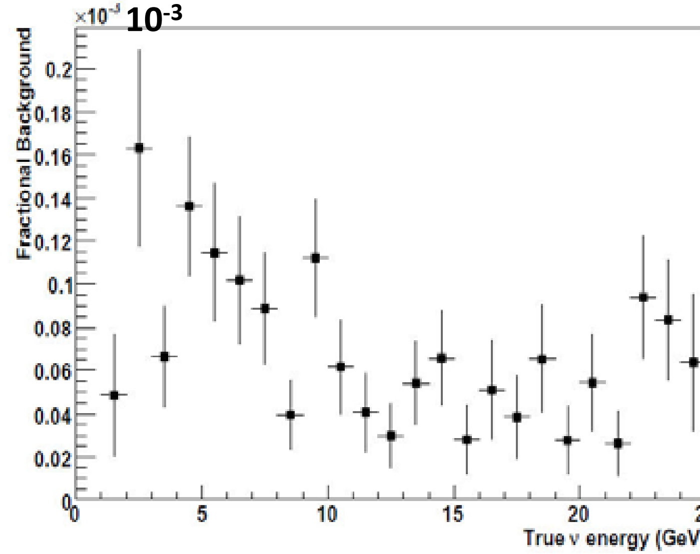
Muon charge mis-ID rate

Magnetized Iron Neutrino Detector (MIND)

Re-Optimize for lower energy?







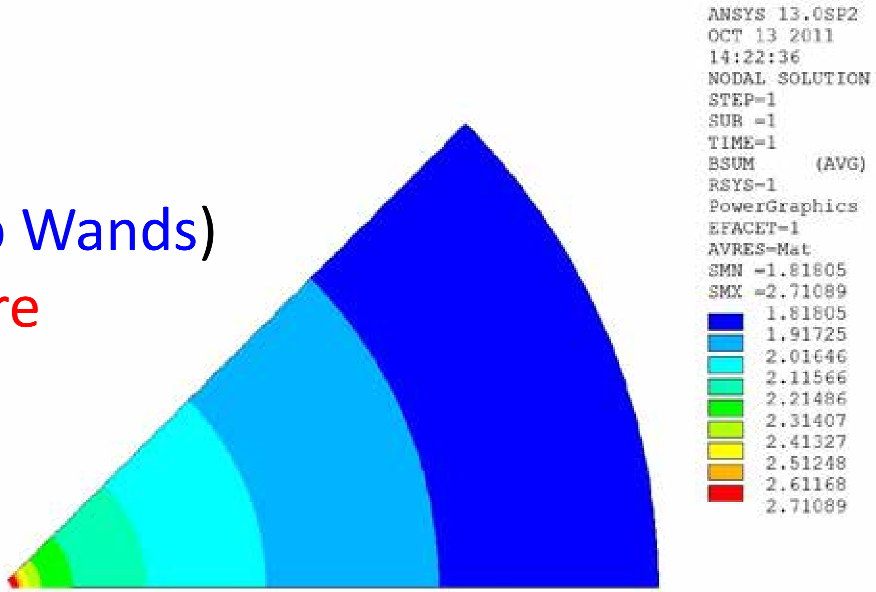
- MIND was optimized for the "Golden" channel at the NF (25 GeV μ storage ring)
- Optimization for FD for L/E ≈ 1
  - Essentially Minos ND with upgrades
    - Reduce plate thickness
    - 100-300kA-turn excitation (SCTL)
    - XY readout between planes

SuperBIND

- Reduce Plate thickness to 1cm
- Increase excitation to 270kA-turn
- XY scintillator strip readout between each plate as in MIND

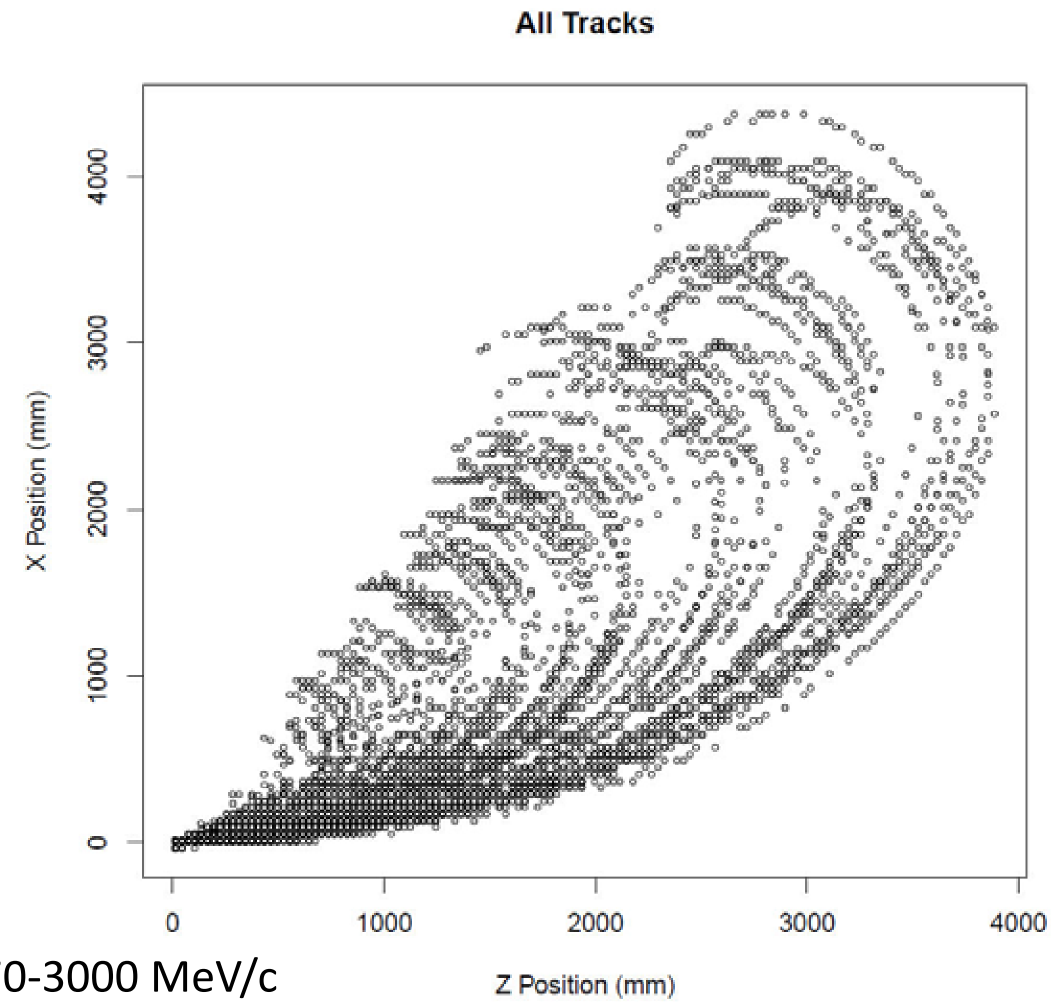
Quick first pass at B (Bob Wands)

B>1.8T everywhere



6m

SuperBIND
First Sim from down under



170-3000 MeV/c

Malcolm Ellis
HEP

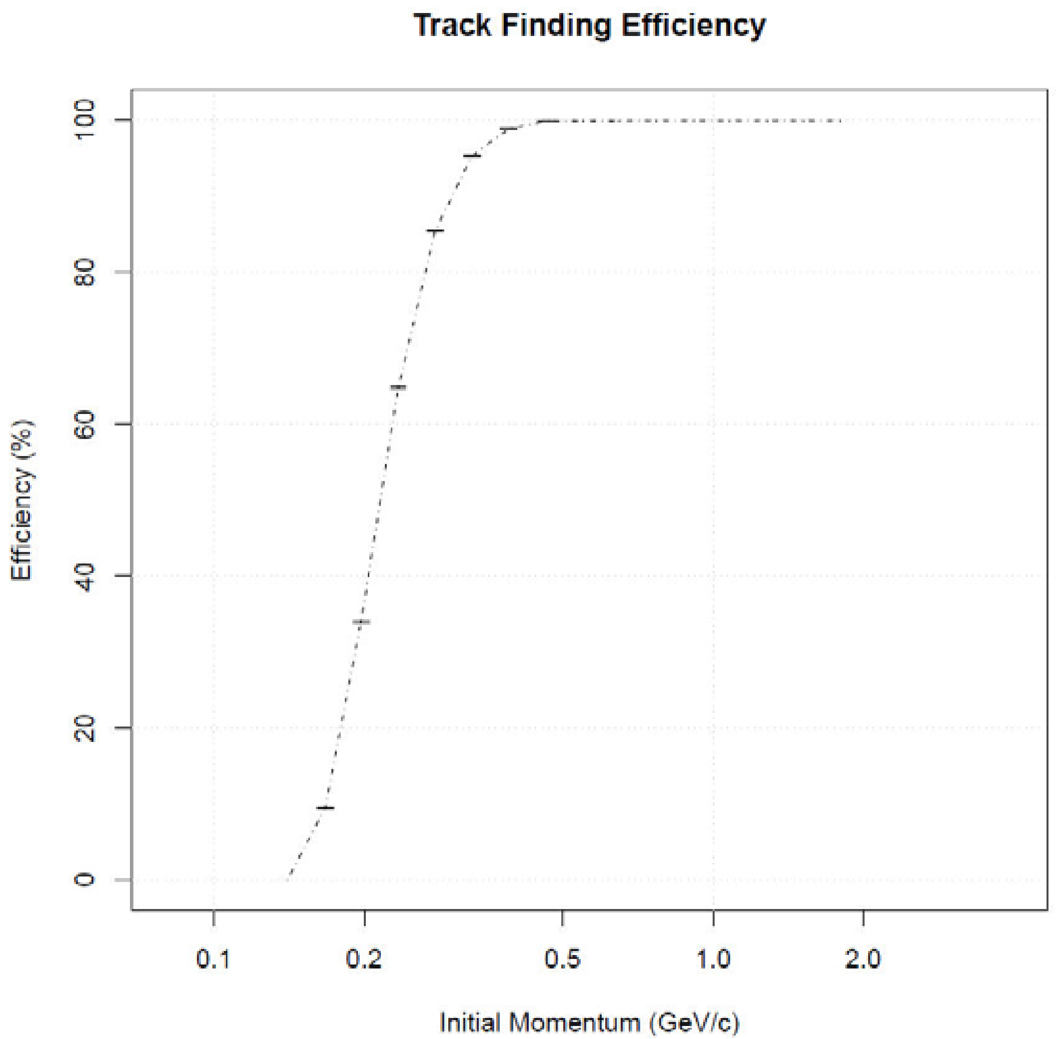
For p_{μ} > 250 MeV/c
there is no confusion with
respect to bending up or
down

But the devil is in the details
This is uniform 1.8T dipole field
Not realistic
Work in progress
Also see Ryan Bayes talk
on MIND
In the Physic/Detector parallel

That said….

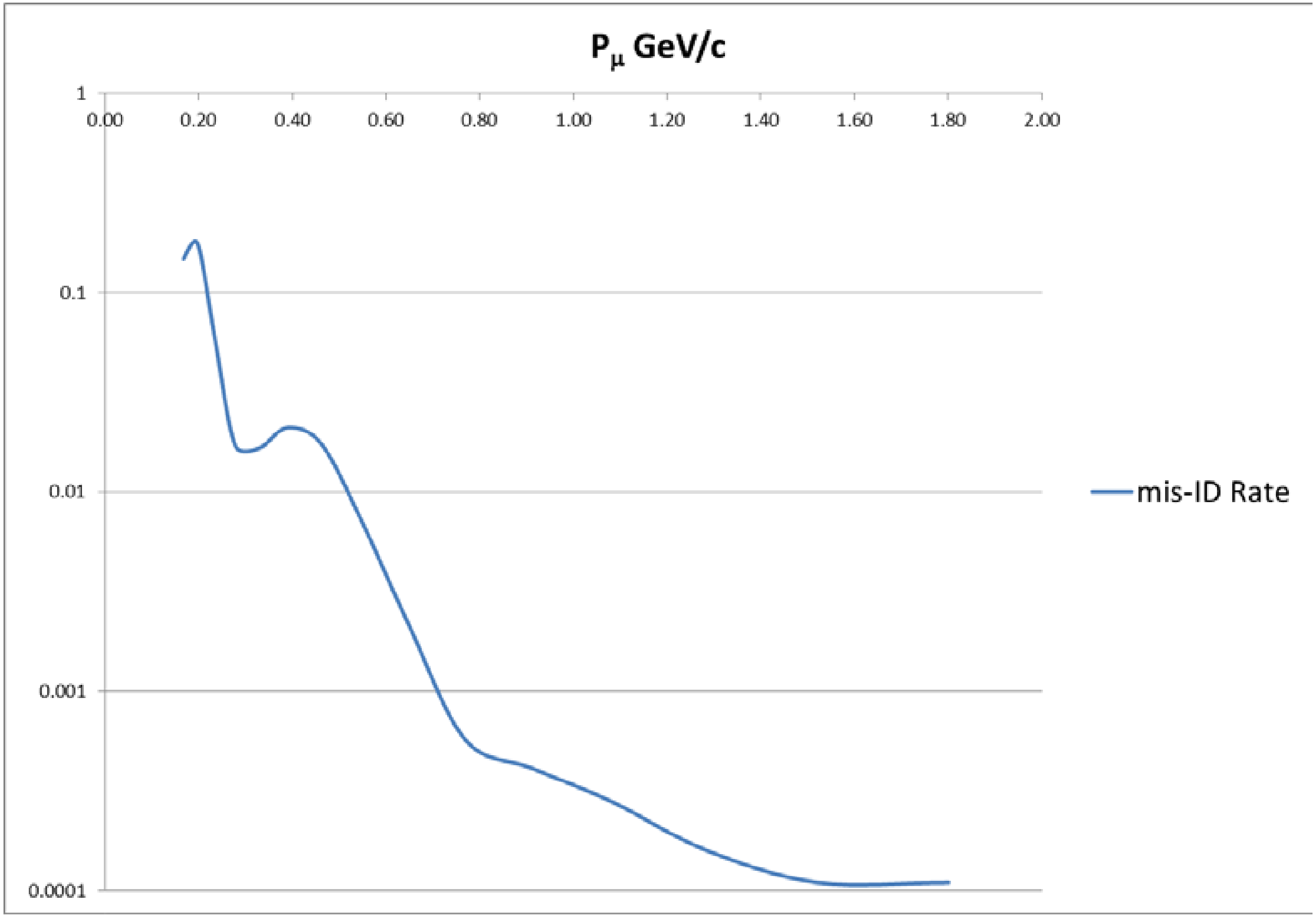
Very "Fresh" simulation data, 10^5 events/bin

Momentum (GeV/c)	Events with a Track	Events with a track of the correct charge	Tracking Efficiency	Charge ID Effic	mis-ID Rate
0.14	0	0	0.00%		
0.17	9492	8090	9.49%	85.23%	14.77%
0.20	34012	28014	34.01%	82.37%	17.63%
0.23	64756	60929	64.76%	94.09%	5.91%
0.28	85412	83946	85.41%	98.28%	1.72%
0.33	95339	93757	95.34%	98.34%	1.66%
0.39	98924	96841	98.92%	97.89%	2.11%
0.46	99861	98123	99.86%	98.26%	1.74%
0.55	99949	99234	99.95%	99.28%	0.72%
0.65	99957	99744	99.96%	99.79%	0.21%
0.77	99990	99933	99.99%	99.94%	0.06%
0.91	99994	99953	99.99%	99.96%	0.04%
1.08	99992	99964	99.99%	99.97%	0.03%
1.28	99995	99979	100.00%	99.98%	0.02%
1.52	99993	99982	99.99%	99.99%	0.01%
1.80	99994	99983	99.99%	99.99%	0.01%


Track Finding Efficiency
Efficiency (%)
0
20
40
60
80
100
0.1
0.2
0.5
1.0
2.0
Initial Momentum (GeV/c)

μ charge mis-ID rate

SuperBIND (preliminary)



$L/E \approx 1$ Oscillation reach

- Oscillation signal:

$$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$$

$$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$$

  - μ^+ in detector "NF *Golden Channel*"
- Why is this potentially so Powerful?
  - μ charge mis-ID rate 5 X 10^{-5} (TASD)
  - Res, DIS and NC background very small
  - CR bkg eliminated with μ veto
    - 2nd and 3rd need detailed simulation

$L/E \approx 1$ Oscillation reach

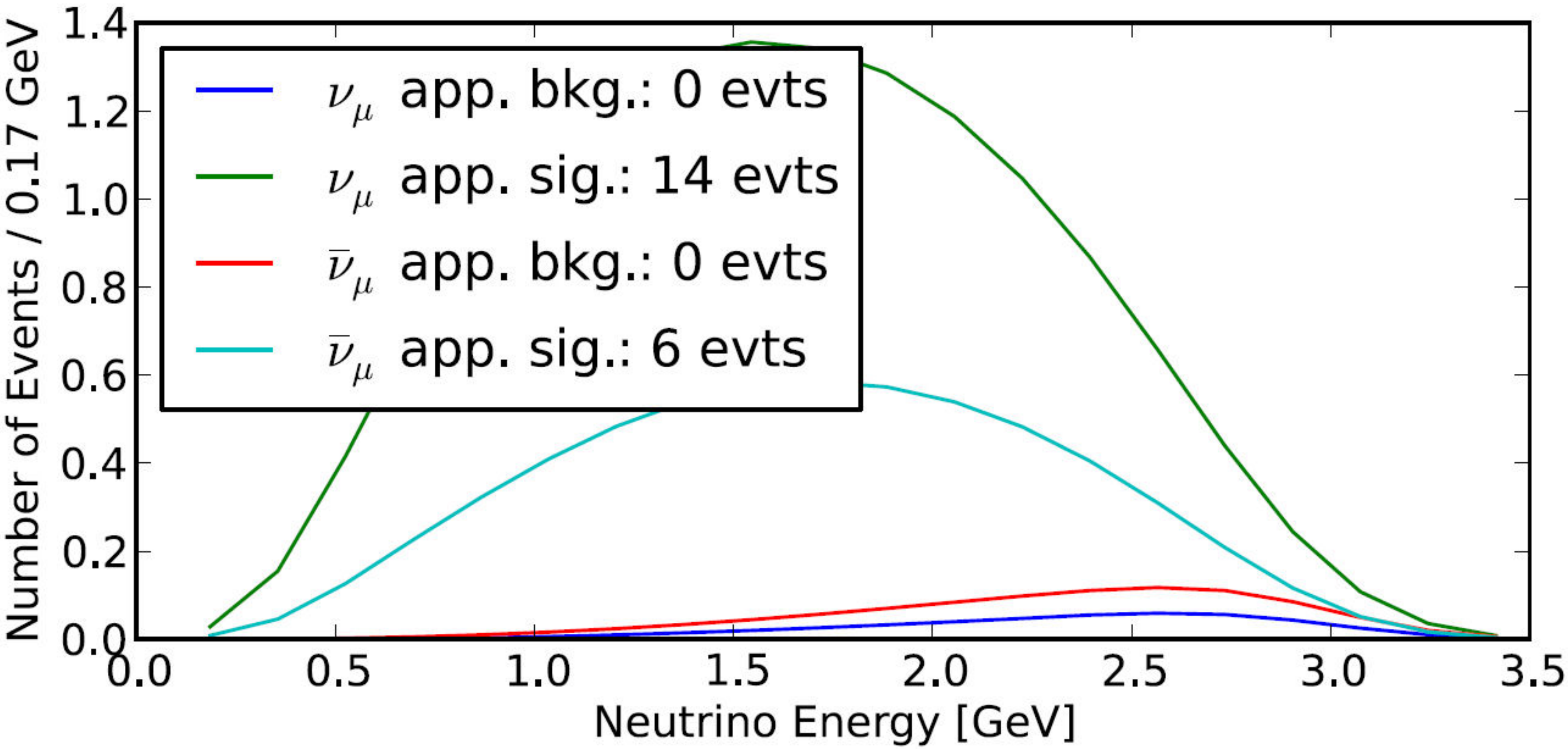
Numerology

- *Note: this calc. takes mean values*
- Signal vs. Background
  - N_{sig} (assuming 0.3% oscillation P)=$3X10^{-3}X4X10^{3}X0.9$ = **11**
  - $N_{Bkg} = 7X10^{3}X5X10^{-5} = 0.35$ (μ charge mis-ID) (TASD)
    + 0.1 evt (estimate of NC background) = **0.5**
- E_{μ}^{stored} optimized for oscillation search will improve on these values
- Obviously requires full MC simulation, but so far, the indication is that this is a >> 5σ measurement @ the MiniBooNE best-fit value

3+1 Globes Analysis

Chris Tunnel

Guinti **arXiv:1109.4033**



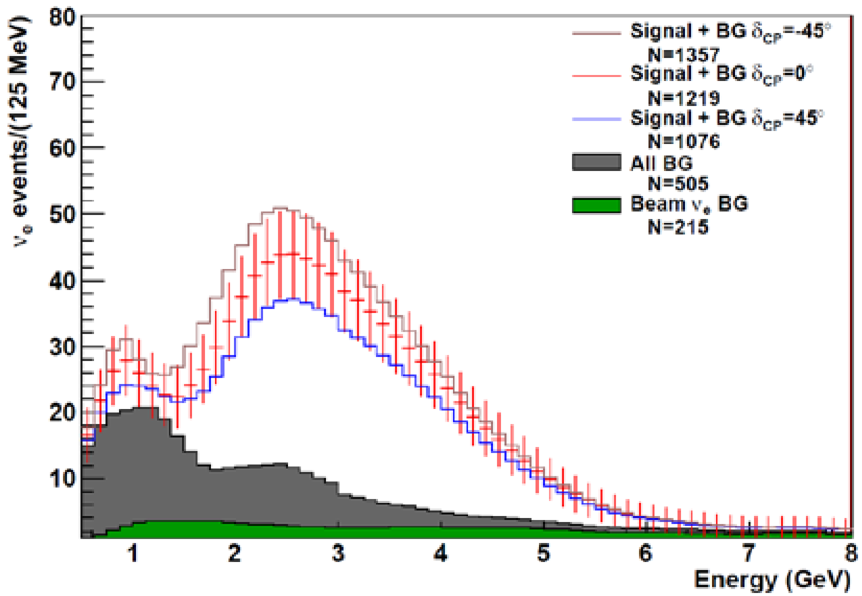
Much more from Chris in the Physics/Detector parallel

ν_e, ν_μ disappearance

- Again, 1kT of detector
  - 200T Near
  - 800T Far
- 10^{21} POT exposure (μ^+)
  - Number of ν_e events (CC):
    - $N_{evts\text{-}near} \approx 200{,}000$
    - $N_{evts\text{-}far} \approx 11{,}000$
  - Number of $\bar{\nu}_\mu$ events (CC):
    - Nevts-near ≈ 100,000
    - Nevts-far ≈ 5,500
- Near benchmark of 10^4 events in Far detector
- *"NC disappearance provides very strong case for new physics"*
    - Also possible with correct detector choices

Cross-section measurements

- Gaining a better understanding of x-sections beneficial to future LB expts.
  - The energy range of interest is roughly 1-3 GeV
    - Some tension here w/r to ideal E_{μ}^{stored} for oscillation experiment
- μ storage ring provides only way to get large sample of ν_e and $\bar{\nu}_e$ interactions
- Nuclear effects are important (Short-range correlations, Final-state interactions).
  - Important detector implications
- Measurements on nuclear targets important
  - H_2, C, D_2, Ar, Fe?



LBNE

of ν_e signal evts

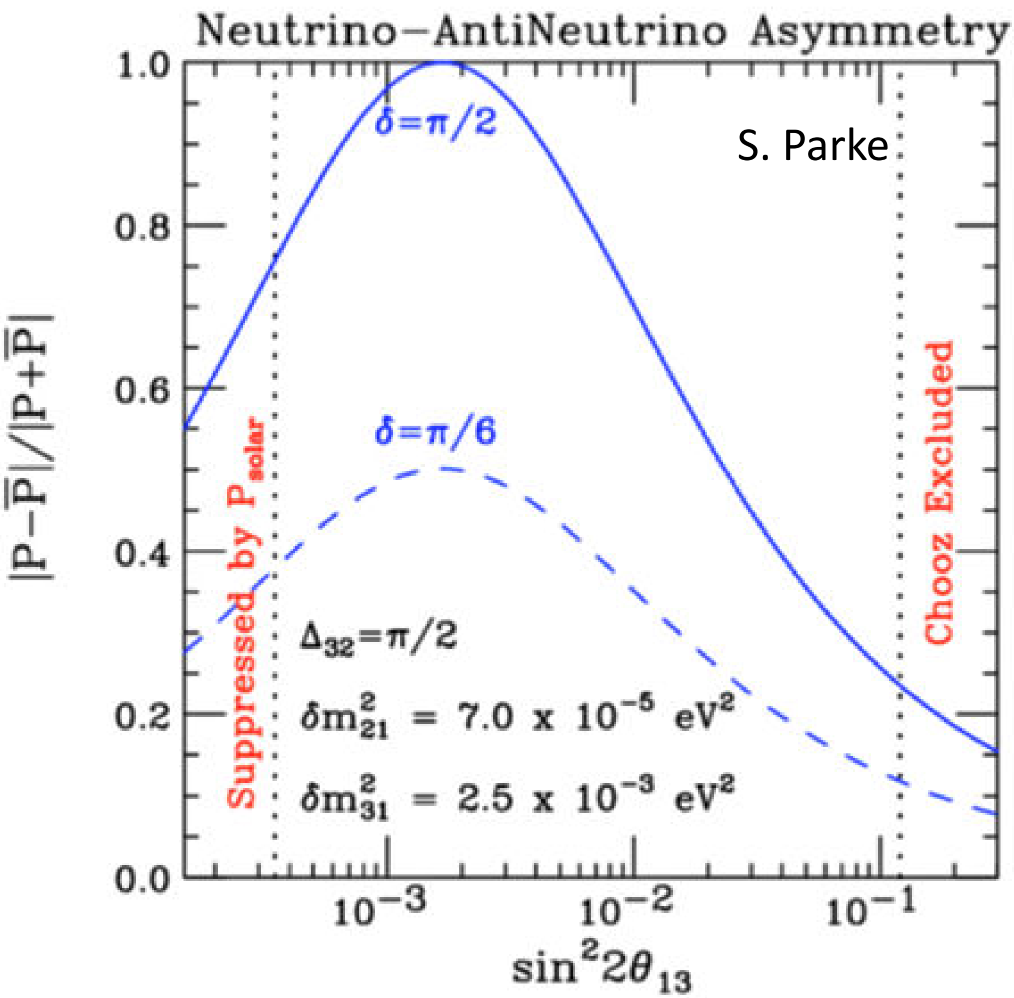
$Sin^2 2\theta_{13}$=0.06, NH, δ=0

200 kTon WC, 5 yrs, 700 kW

(M. Bass and B. Wilson)

Cross-section measurements II

ν_e & $\cancel{CP}$



$$\frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}$$

- Important to note that if θ_{13} is large, the asymmetry you're trying to measure is small, so:
  - Need to know underlying ν/νbar flux & σ more precisely
  - Bkg content & uncertainties start to become more important

Better data on ν_e and $\bar{\nu}_e$ important (?) for $\cancel{CP}$ δ_{CP} measurements

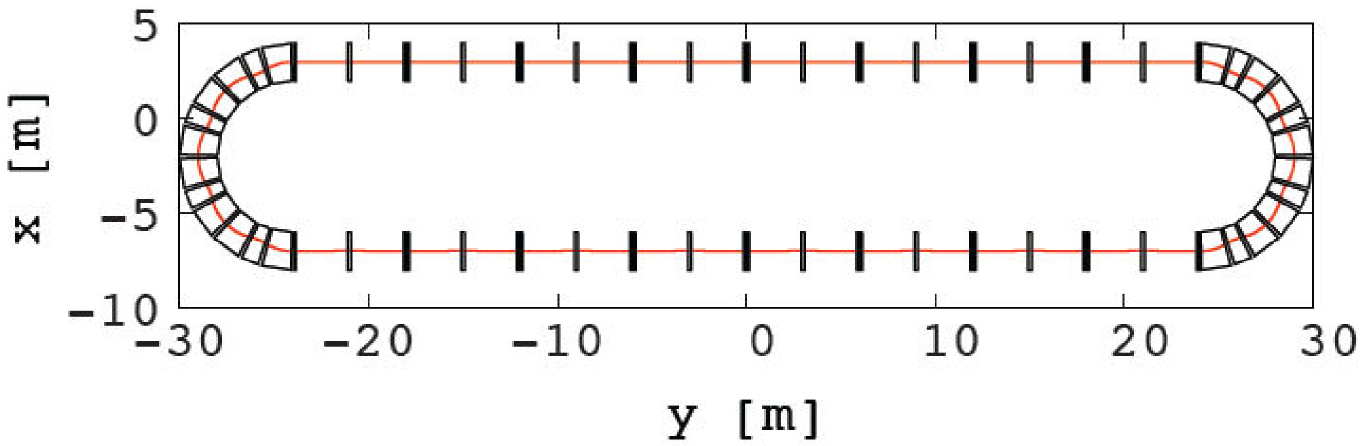
Optimization of E_μ

- There is some tension between optimizing for the L/E =1 oscillation physics and for the cross-section coverage
  - For L/E =1, $E_\nu^{mean} \approx$ .7-1.0 GeV is probably optimal
  - For the cross-section measurements, we want to cover $0.5 < E_\nu < 3$.
    - Maybe this is actually OK – See Chris Tunnel's talk
  - Also length of straight (s) vs. baseline (L)
    - Nominal s= 50m, L=1000

Outlook

- Much more work to be done
  - Detector simulation
    - For oscillation studies much more detailed MC study of backgrounds & systematics
    - For cross-section measurements need detector baseline design
      - And then detailed MC as above
  - Beamline
    - Injection
      - Need detailed design and simulation for targeting & injection
        - » Have first iteration on component layout
      - Proton removal for + running
    - Decay Ring optimization
      - Continue study of existing design
      - Alex Bogacz has preliminary design for ring with $\delta p/p$=5%
      - Yoshi Mori & JB Lagrange considering FFAG racetrack
      - ….?

Racetrack FFAG



1 GeV

6D acceptance > 100 times bigger than what is in the current G4 Beamline simulation

More from 森さん in a few minutes

Outlook II

- Start of staged program?
  - With NF/MC front-end, could get ≈ a X1500 increase in flux
    - 0.15 μ/POT vs. 1.1×10^{-4}
    - Does require acceleration, however: linac + RLA
      - Cooling possibly not needed (Factor of 2-3 reduction in μ/POT)
      - RLA could be operated in “scanning” mode (dual-purpose: acceleration + decay ring)
        - » Variable ν energy (scan L/E without moving far detector)
        - » [First mentioned by Geer & Ankenbrandt in 1997 *(Workshop on Physics at the First Muon Collider and at the Front End of the Muon Collider (AIP Conf Proc. 435)*]
- For 10^{21} POT, # ν_e events (low-power, 10-100kW):
    - $N_{evts\text{-}near} \approx 2 \times 10^9$
    - $N_{evts\text{-}far} \approx 2 \times 10^7$
- And ProjX would open up the opportunity for much higher power on the target, however

Conclusions

- Initial simulation work indicates that a $L/E \approx 1$ oscillation experiment using a muon storage ring can "easily" reach a $5\sigma+$ benchmark, *it is just the "Golden Channel" after all*
- ν_e and ν_μ disappearance experiments delivering at the 1% level look to be doable
  - Systematics need careful analysis
- Cross section measurements with near detector(s) offer a **unique** experimental opportunity
  - The detector design is crucial (need not be magnetized)
    - TASD (both types)
    - LAr
  - Ideally, build near-detector hall to accommodate multiple detectors (all of the above plus H_2O, MIND, etc.)

Conclusions II

- Doing measurements with a ν beam derived from a μ storage ring is both complementary to ongoing experiments and can be supportive to the next (next-to-next) round of experiments
- The technology needed to produce this type of ν beam exists and has for some time
  - David Neuffer was the first to describe (in detail) this type of experiment at the Telmark Wisconsin Neutrino Physics conference in 1980, and the technology needed to do it (beam) existed even then to a large degree
    - First mention – CERN 1974: Kashkarev
- *Finally, can be the first, very small step, on a path leading to even more exciting possibilities in the NOT to Far-future.*

Acknowledgements

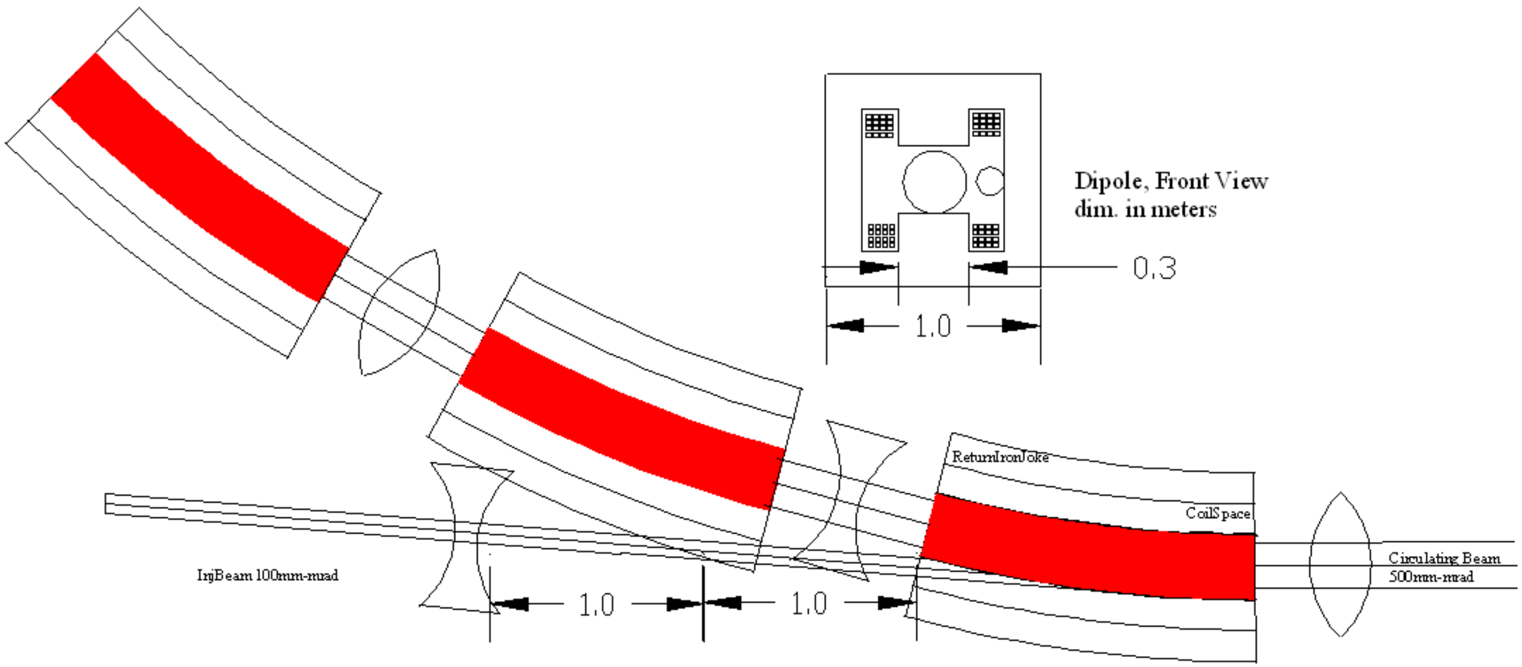
The *"Usual Suspects"*

Chuck Ankenbrandt, Andrea Palounek, Alex Bogacz, Chris Tunnell, André de Gouvêa, Malcolm Ellis, Joachim Kopp, Ken Long, Kirk McDonald, Nikolai Mokhov, David Neuffer, Patrick Huber, Milorad Popovic, Stephen Brice, Steve Geer, Sergei Striganov, Tom Roberts

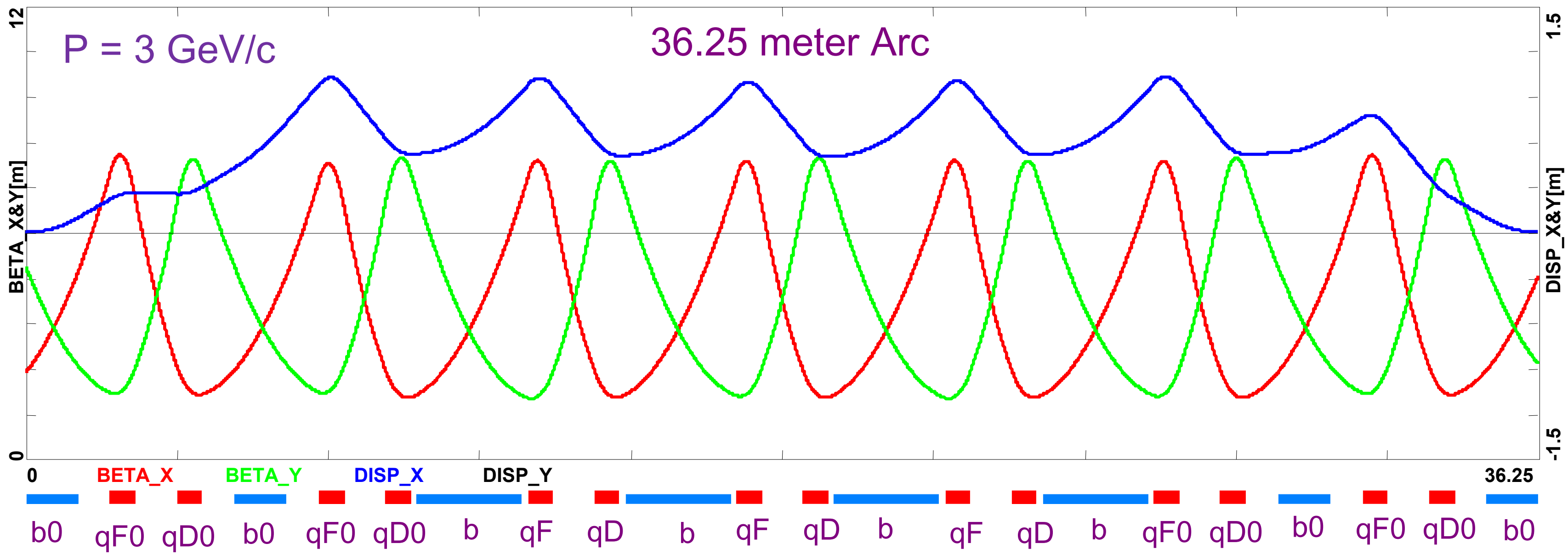
https://indico.fnal.gov/categoryDisplay.py?categId=185

Back up Slides

Injection Schematic
M. Popovic



Arc Optics (90^0 doublets)



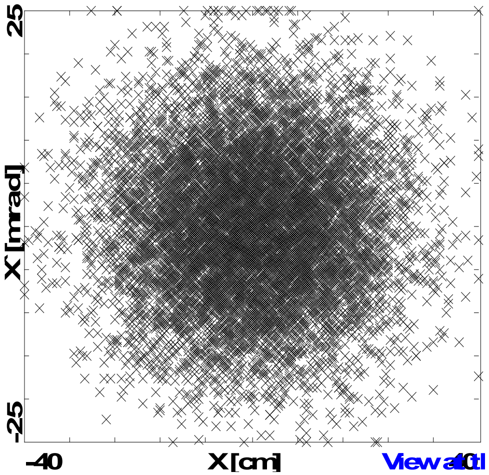
qF0	L[cm]=60	G[kG/cm]=1.100
qD0	L[cm]=60	G[kG/cm]=-1.075
qF	L[cm]=60	G[kG/cm]=1.124
qD	L[cm]=60	G[kG/cm]=-1.089
drift between quads in a doublet		L[cm]=100
drift between a quad and a bend		L[cm]=15

b0	L[cm]=125	B[kG]=12.575
b	L[cm]=250	B[kG]=12.575

Magnet aperture radius L[cm]=15

Dynamic Aperture – 90 turns

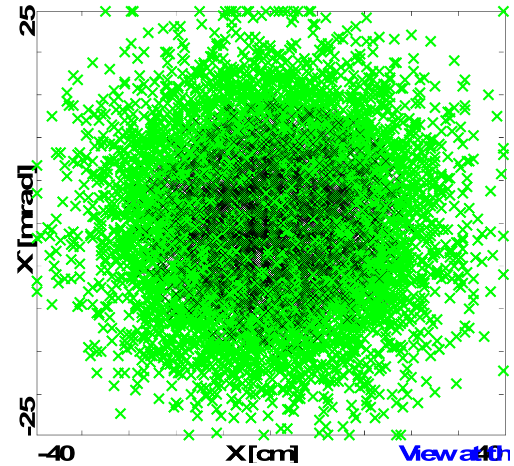
initial 1.000000



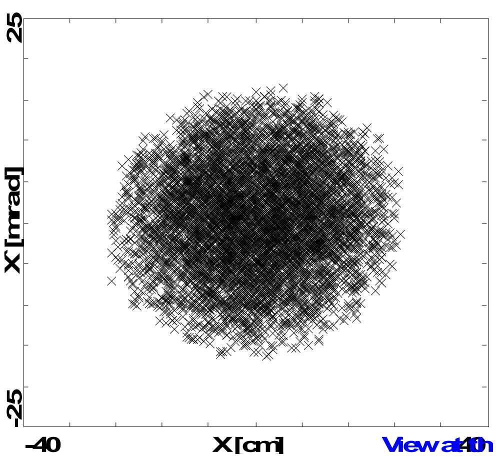

```
$MuDecay=2.2e-6;  =>     2.2e-06
$C=10150*2;  =>       20300
 $NTurn=$gamma*$MuDecay*$beta*$c/$C;  =>   92.249966
```

ε_N = 30 mm rad $\sqrt{\beta\varepsilon}$

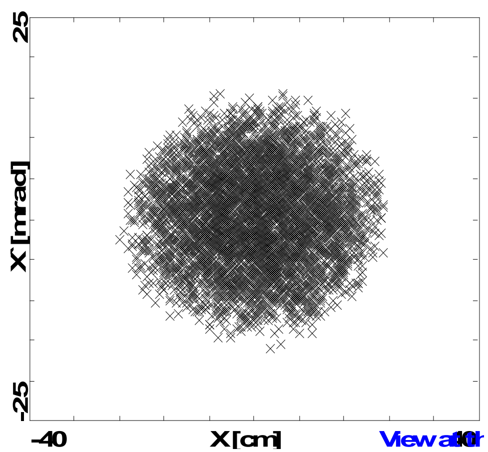
$\sigma_{\Delta p/p}$ = 0.05 $D_x\sigma_{\Delta p/p}$



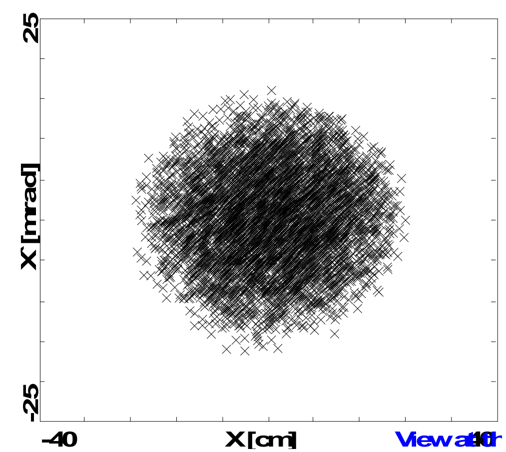
turn 1 0.720300



turn 30 0.569300



turn 90 0.540900



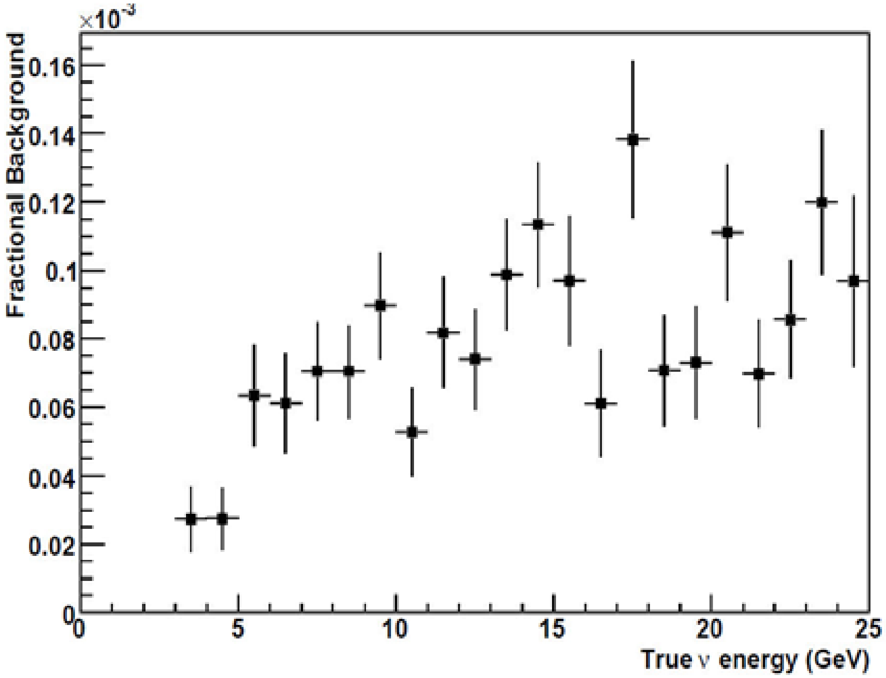
Summary

- Decay Ring (3 GeV Racetrack of 203 meter circumference)
  - 8 m betas, 90 cm hor. dispersion in the Arcs
  - 15 m betas in the Straight
- Acceptance - Dynamic Aperture Study
  - transverse: ε_N = 30 mm rad
  - momentum: $\sigma_{\Delta p/p}$ = 0.05
  - Physical aperture: r = 20 cm (Arc) and r = 25 cm (Straight)
  - 46% dynamic lost after 90 turns
- Compact Ring Optics – Linear lattice
  - Dipole bends (2.5 m long, 12.6 kGauss) $\times$ 20
  - Doublet focusing - Quads (0.6 m long, 1.1 kGaus/cm) $\times$ 36
  - FODO focusing - Quads (1 m long, 0.2 kGaus/cm) $\times$ 38

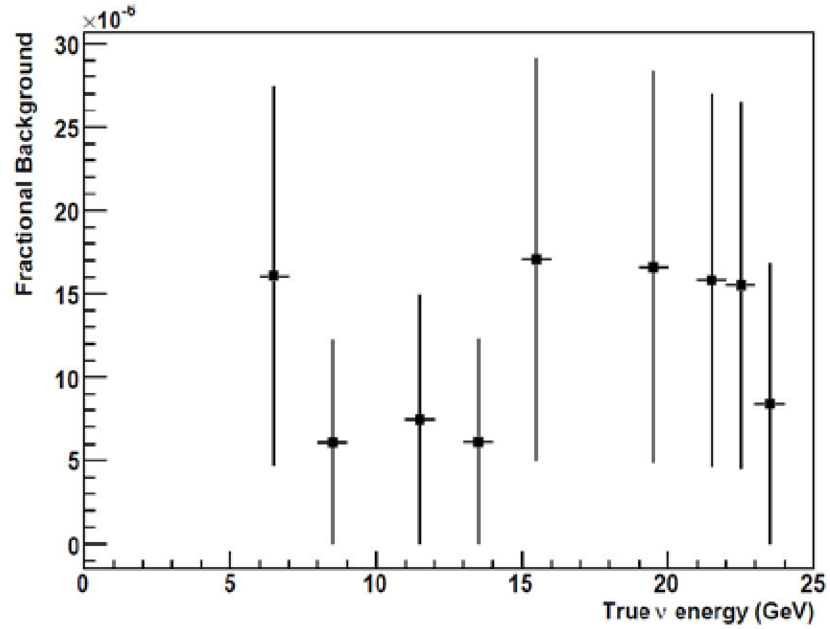
MIND analysis
IDS-NF IDR

Andrew Laing
Glasgow

10^-3



10^-6



NC background rate

ν_e background rate

If we can reach this Level of performance