# The Very-Low Energy Neutrino Factory

## $\nu$ physics with a $\mu$ storage ring

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# VLENF

## *Experimental Motivation*

- We have a collection of hints of something…
  - LSND: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
  - MiniBooNE: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
  - MiniBooNE: $\nu_\mu \not\rightarrow \nu_e$
    - Low $E_\nu$ excess
  - Reactor flux anomaly
  - MINOS: $\nu_\mu$ vs. $\bar{\nu}_\mu$
- Cross-section measurements
  - $\mu$ storage ring presents only way to measure $\nu_\mu$ & $\nu_e$ ( $\nu$ 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 $\nu_\mu$ disappearance provides some restriction.
  - **Need to make smoking gun measurement.**
    - Need to make a >5 $\sigma$ 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 $\nu$ from a $\mu$ storage ring provide this "Smoking Gun?"

# Possibilities with $\mu$ storage ring

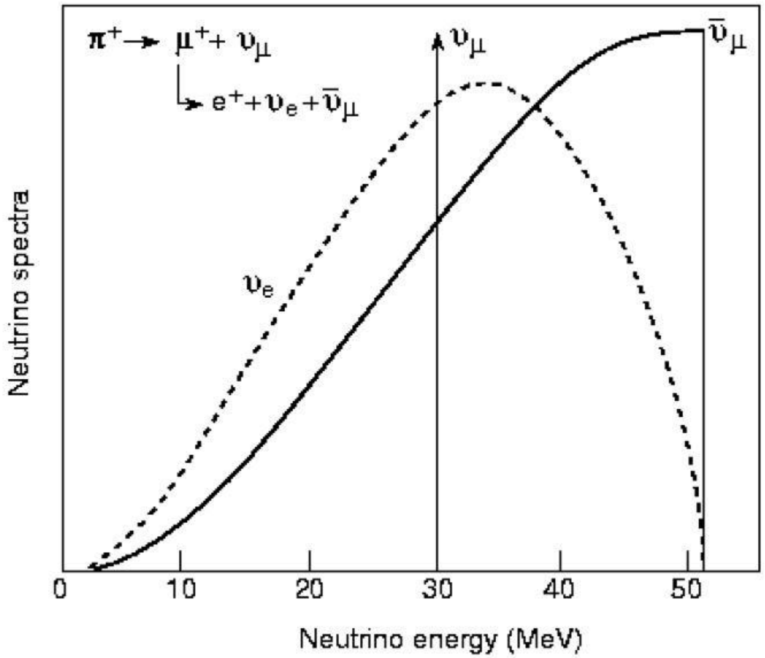
- Oscillation Physics @ L/E = 1
  - Appearance experiment with low background
    - A different approach to explore the LSND/MiniBooNE result
- $\nu$ disappearance experiment with 1% precision ($10^4$ events)
  - An experiment that uses a $\nu_e$ beam from a muon storage ring can go a long way in ruling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

# $\nu$s from muon decay

- Running with $\mu^-$

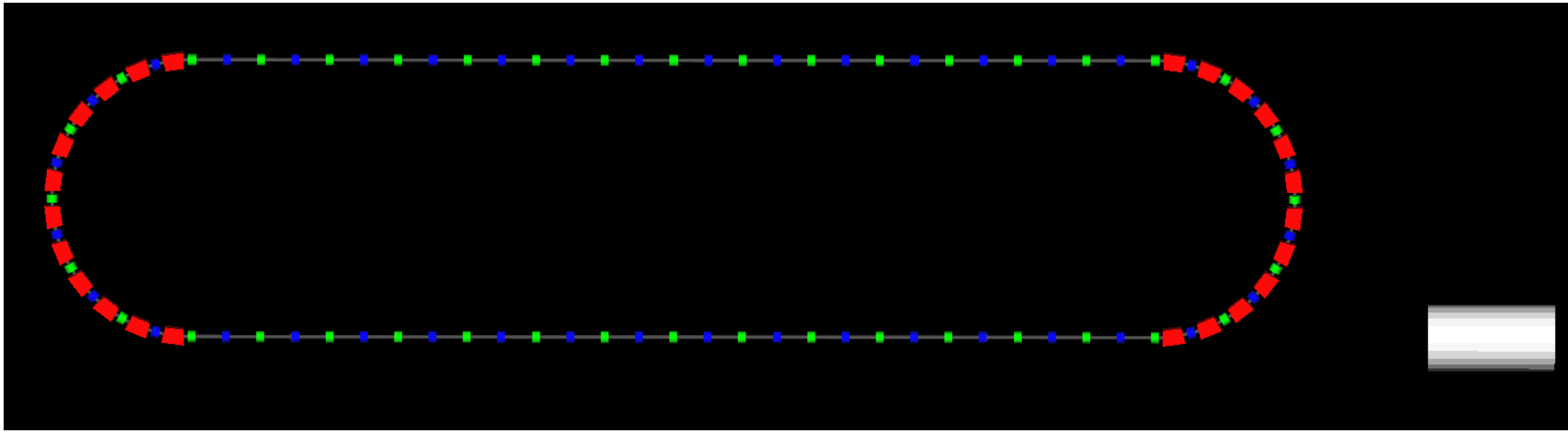
$$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$$

- Well defined flavor composition & energy

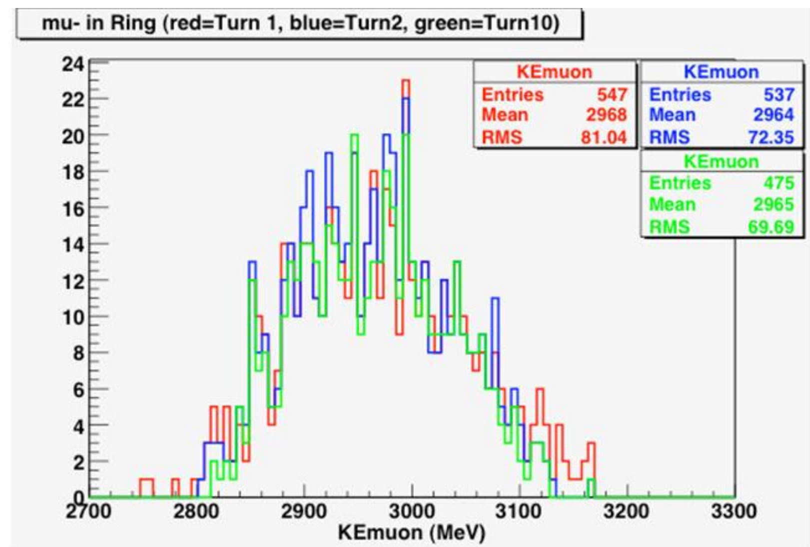


# Status of the concept
# *G4Beamline Simulation*

Tom Roberts
Muons Inc.



- 8 GeV protons on 2 $\lambda_I$ Be target
- 3 GeV Racetrack ring (M. Popovic)
  - For now, injection is perfect
    - Not defined
- Tuned for $\mu^-$ 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



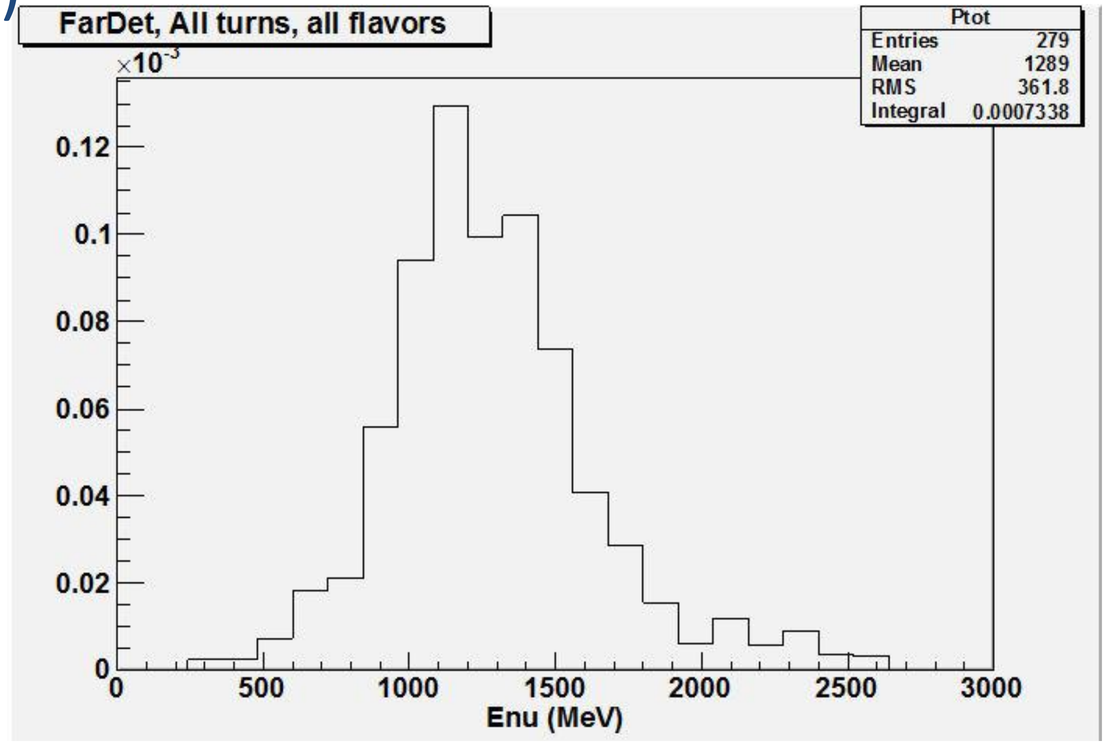
# Circulating $\mu^-$ beam flux

| | 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: $\approx 1.1 \times 10^{-4}$ stored $\mu$/POT
  - After all $\pi$ 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*

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



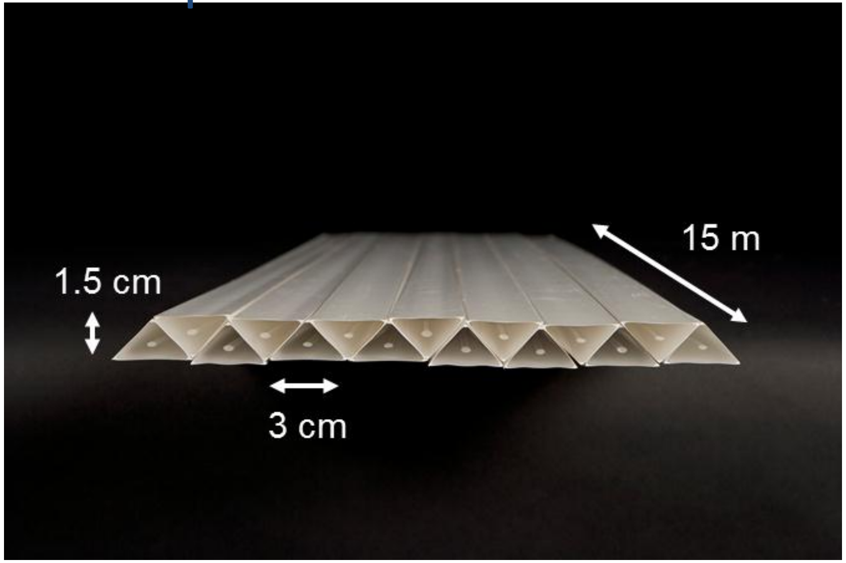

Note: Still having some “issues” with $E_\nu$ flux shape

# Detector Considerations

- Far detector *(Large $\Delta m^2$ 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)
      - LAr (μBooNE, already has made case for X-section meas. in MB line)

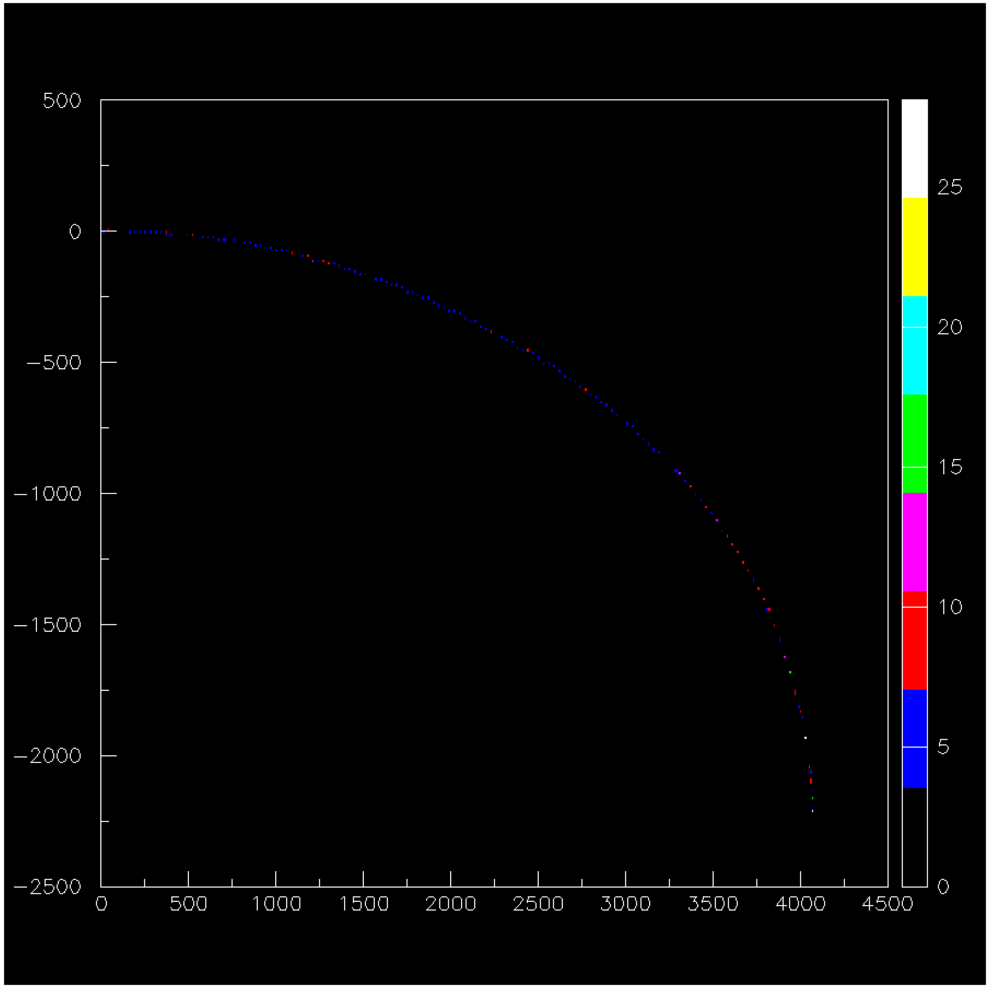
# Totally Active Scintillator Detector

- 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

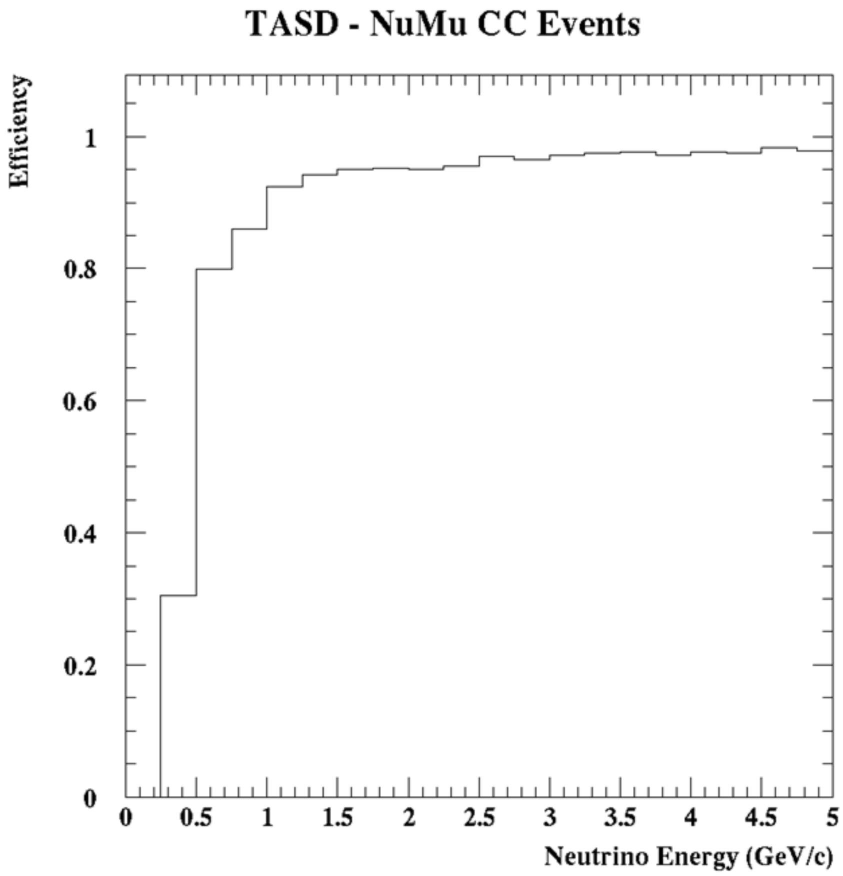
Y(mm)



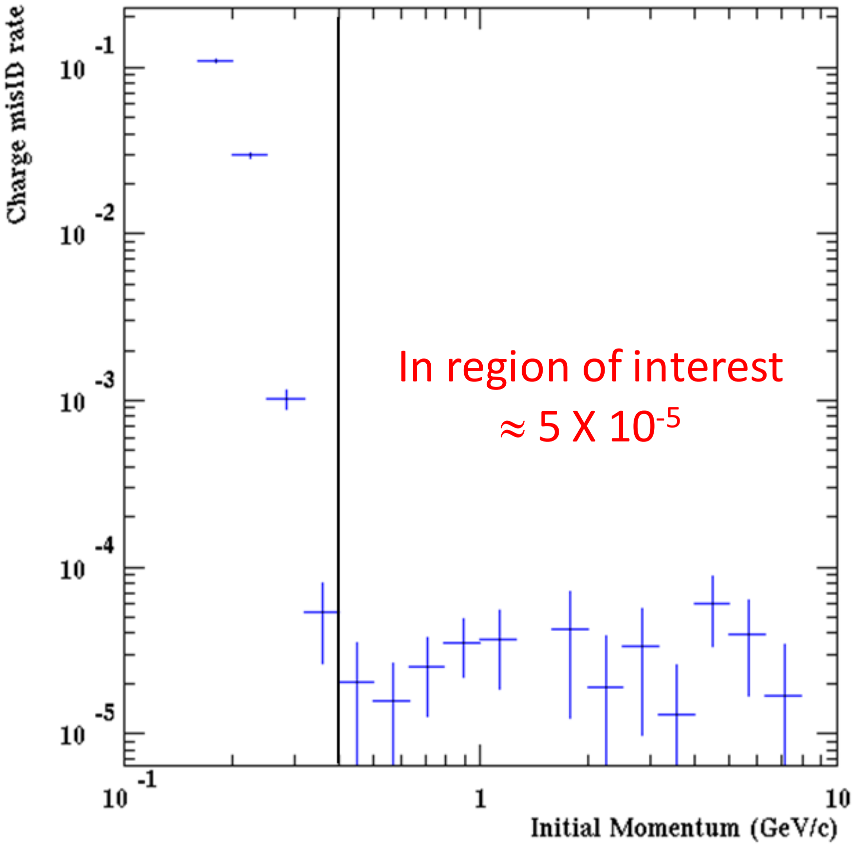

Z(mm)

Y (bend plane) vs Z
B=0.5T

# TASD Performance

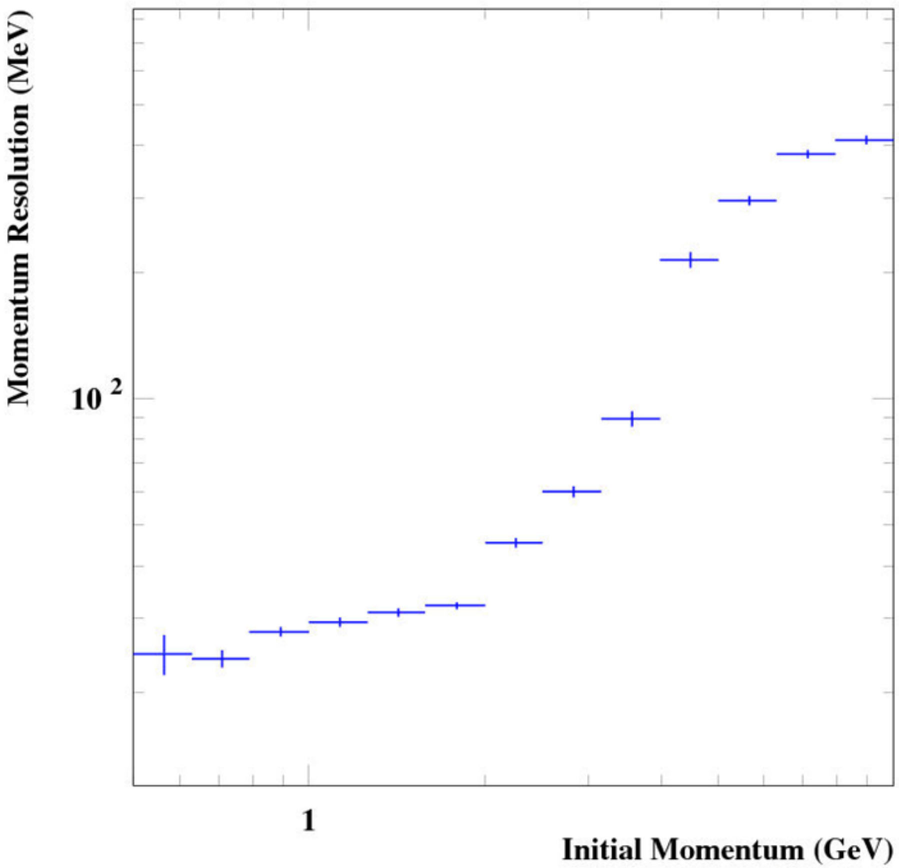



ν Event Reconstruction Efficiency




Muon charge mis-ID rate

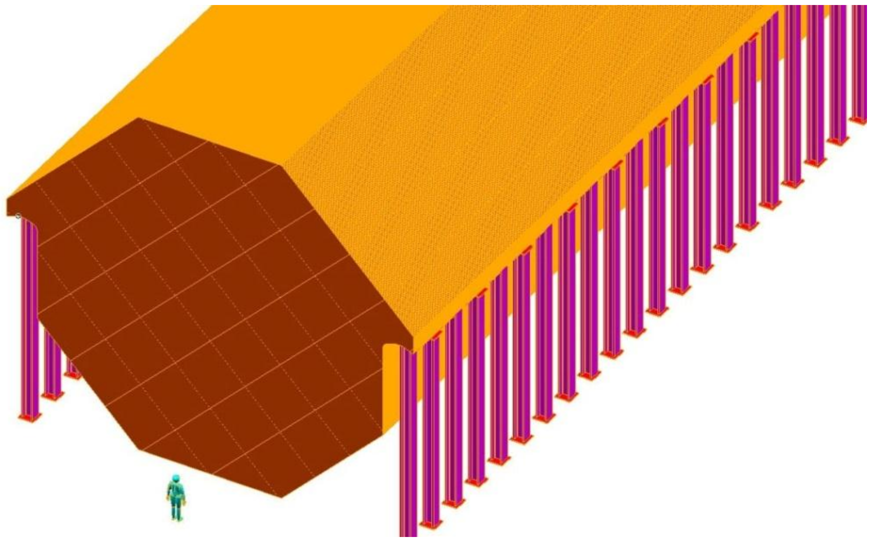
# TASD Performance II

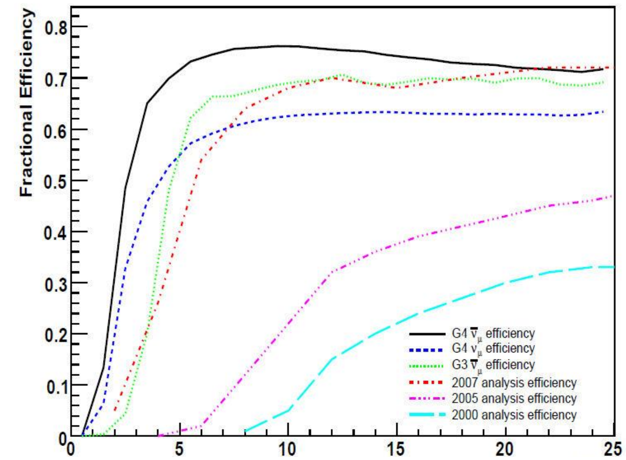


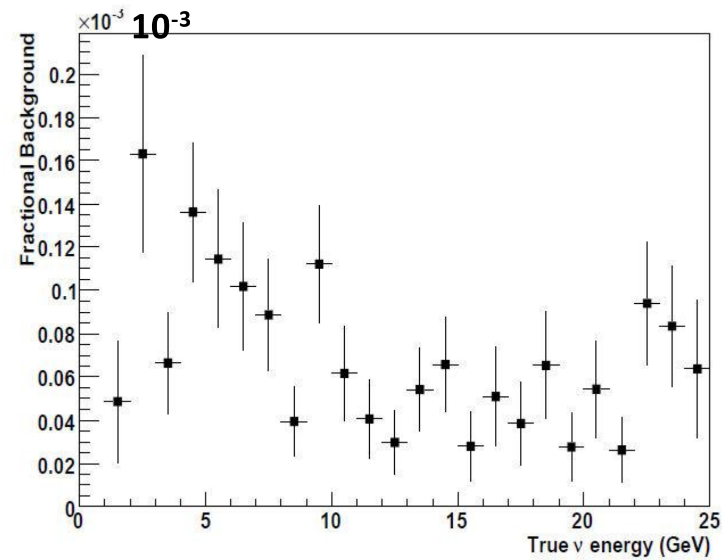

- Momentum resolution excellent
  - Neutrino Event energy reconstruction from tracking
  - EM component from hit counting – possibly
  - Expect ν event $E^{\nu}_{res}$ of ≈ 5%
    - From tracking resolution & calorimetry studies

# 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
    - 100kA-turn excitation (SCTL)
    - XY readout between planes

# $L/E \approx 1$ Oscillation reach

- Oscillation signal:

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

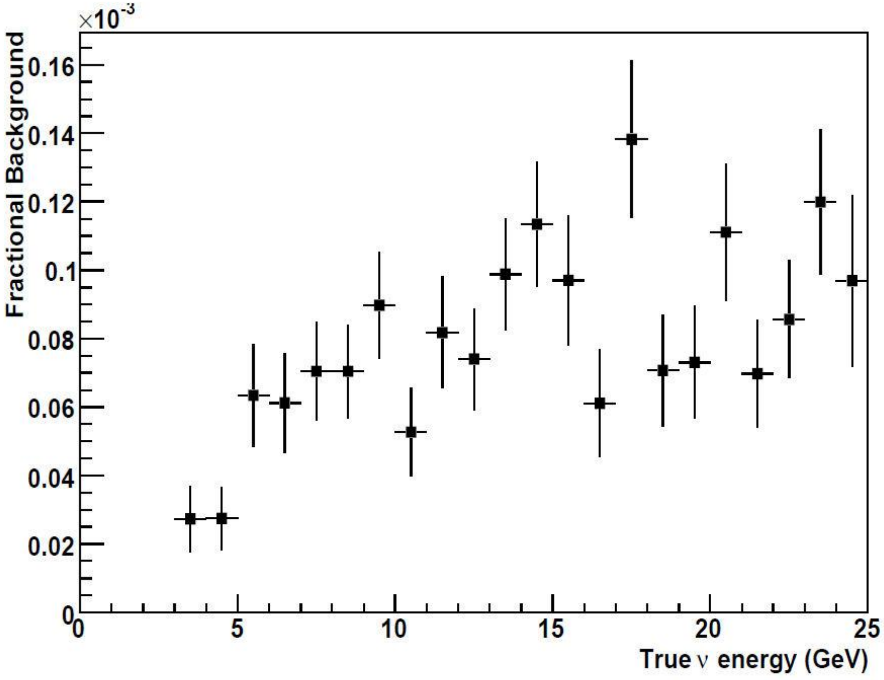
$$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$$

  - $\mu^+$ 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

# MIND analysis
## *IDS-NF IDR*

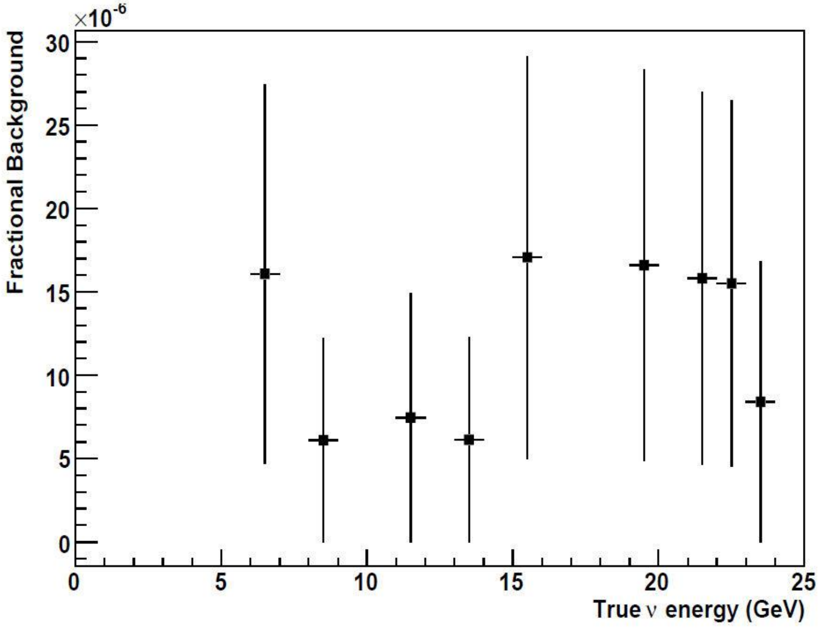
Andrew Laing
Glasgow

$10^{-3}$




NC background rate

$10^{-6}$




$\nu_e$ background rate

# $L/E \approx 1$ Oscillation reach

## *Numerology*

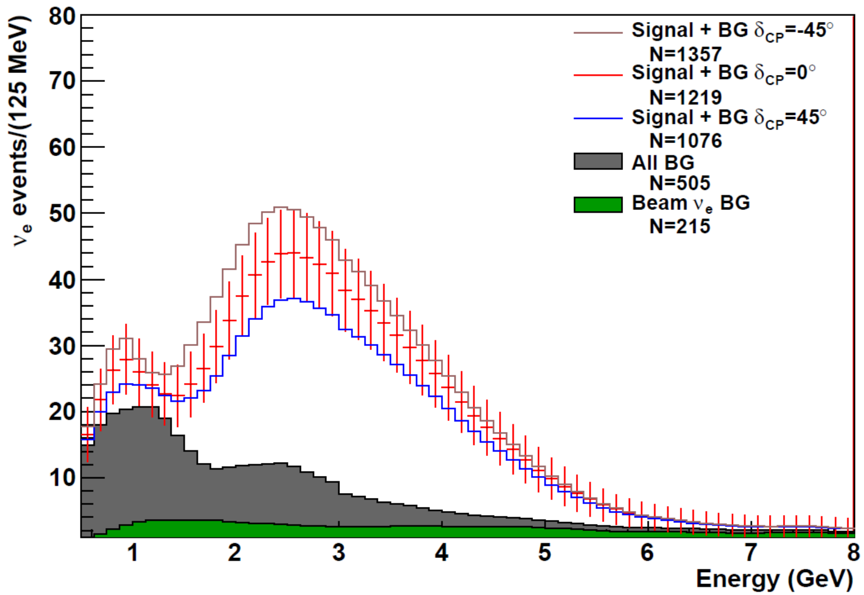
- *Note: this calc. takes mean values*
- Signal vs. Background
  - $N_{sig}$ (assuming 0.3% oscillation P)=$3X10^{-3}X4X10^{3}X0.9$ = **11**
  - $N_{Bkg}$ = $7X10^{3}X5X10^{-5}$ = 0.35 ($\mu$ charge mis-ID)
    + 0.1 evt (estimate of NC background) = **0.5**
- $E_{\mu}^{stored}$ optimized for oscillation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

# $\nu_{e,}\ \nu_{\mu}$ disappearance

- Again, 1kT of detector
  - 200T Near
  - 800T Far
- $10^{21}$ POT exposure ($\mu^{+}$)
  - Number of $\nu_e$ events (CC):
    - $N_{evts\text{-}near} \approx 200{,}000$
    - $N_{evts\text{-}far} \approx 11{,}000$
  - Number of $\overline{\nu}_{\mu}$ events (CC):
    - Nevts-near ≈ 100,000
    - Nevts-far ≈ 5,500
- Near benchmark of $10^4$ events in Far detector
- Following up on Bob Svoboda's comment this morning
  - *"NC disappearance provides very strong case for new physics"*
    - Also possible with correct detector choices

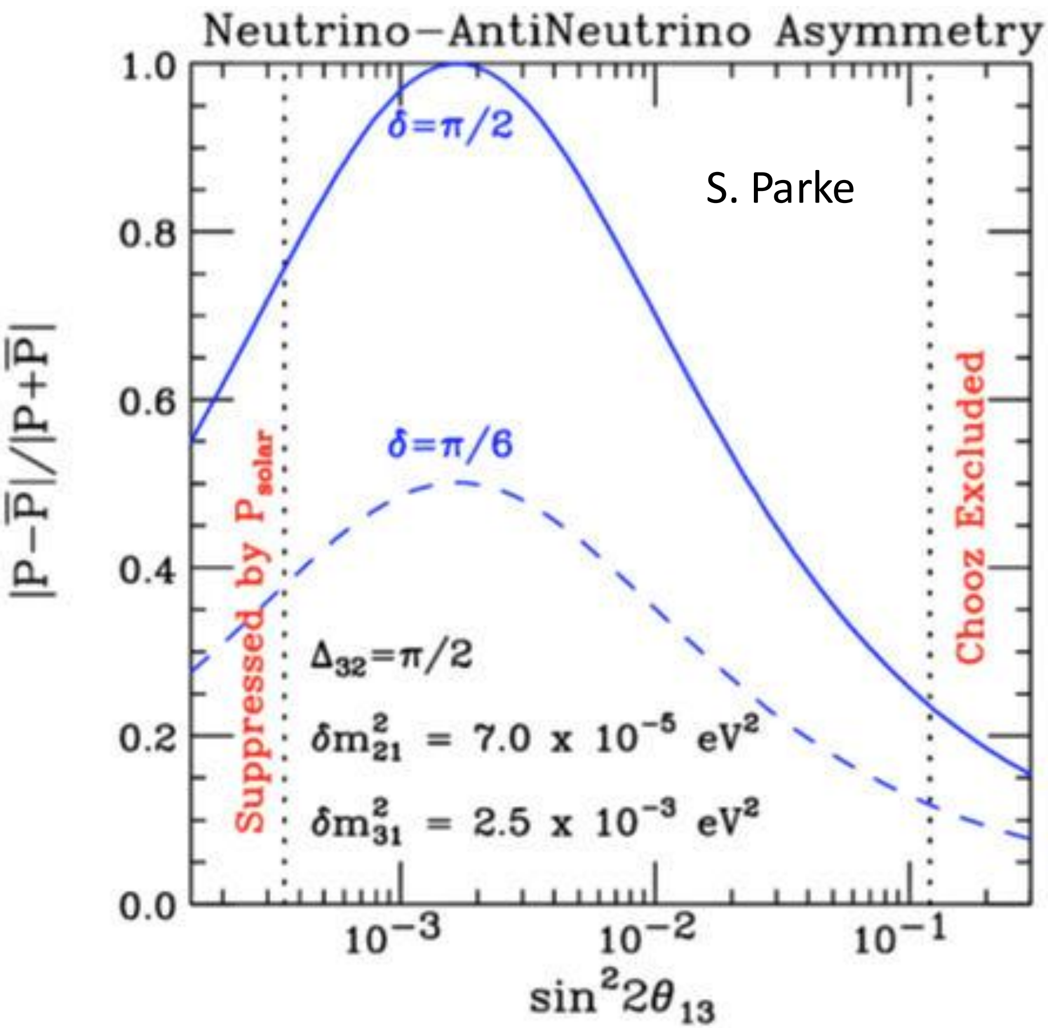
# Cross-section measurements

- 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 $E_{\mu}^{stored}$ for oscillation experiment
- $\mu$ storage ring provides only way to get large sample of $\nu_e$ 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 $\nu_e$ signal evts
$Sin^2 2\theta_{13}$=0.06, NH, $\delta$=0
200 kTon WC, 5 yrs, 700 kW
(M. Bass and B. Wilson)

# Cross-section measurements II
## $\nu_e$ & CP̸




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

Better data on $\nu_e$ and $\bar{\nu}_e$ Important (?) for CP̸ $\delta_{CP}$ measurements

# Optimization of $E_\mu$

- 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 $0.5 < E_\nu < 3$.

# Outlook

- Much more work to be done
  - 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 considering FFAG racetrack
      - ….?
  - 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

# Outlook II

- Start of staged program?
  - With NF/MC front-end, could get ≈ a X1500 increase in flux
    - 0.15 $\mu$/POT vs. 1.1 X $10^{-4}$
    - Does require acceleration, however: linac + RLA
      - Cooling possibly not needed (Factor of 2-3 reduction in $\mu$/POT)
      - RLA could be operated in "scanning" mode (dual-purpose: acceleration + decay ring)
        - » Variable $\nu$ 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, # $\nu_e$ 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*
- $\nu_e$ and $\nu_\mu$ disappearance experiments delivering at the 1% level look to be doable
- Cross section measurements at a 200T near detector offer a **unique** experimental opportunity
  - The detector design is crucial (need not be magnetized)
    - TASD
    - LAr

# Conclusions II

- Doing measurements with a $\nu$ beam derived from a $\mu$ 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 $\nu$ 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 1970's? *Anyone have the reference?*
- Finally, the general experimental program utilizing ultra-intense (cLFV, NF, MC) $\mu$ beams is compelling
  - This is the first, very small step, towards that goal.

# Acknowledgements

I want to thank all my colleagues who have been working on these concepts.

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

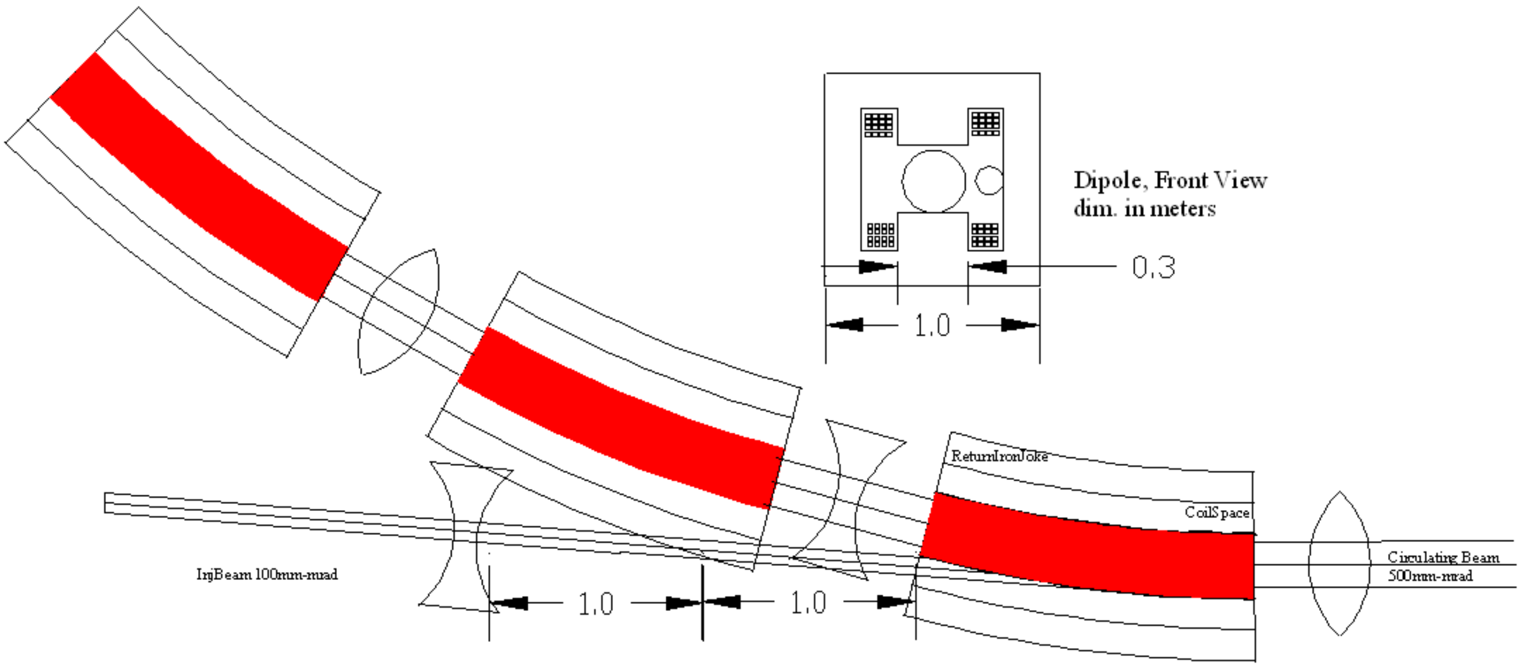
Please come join the Fun

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

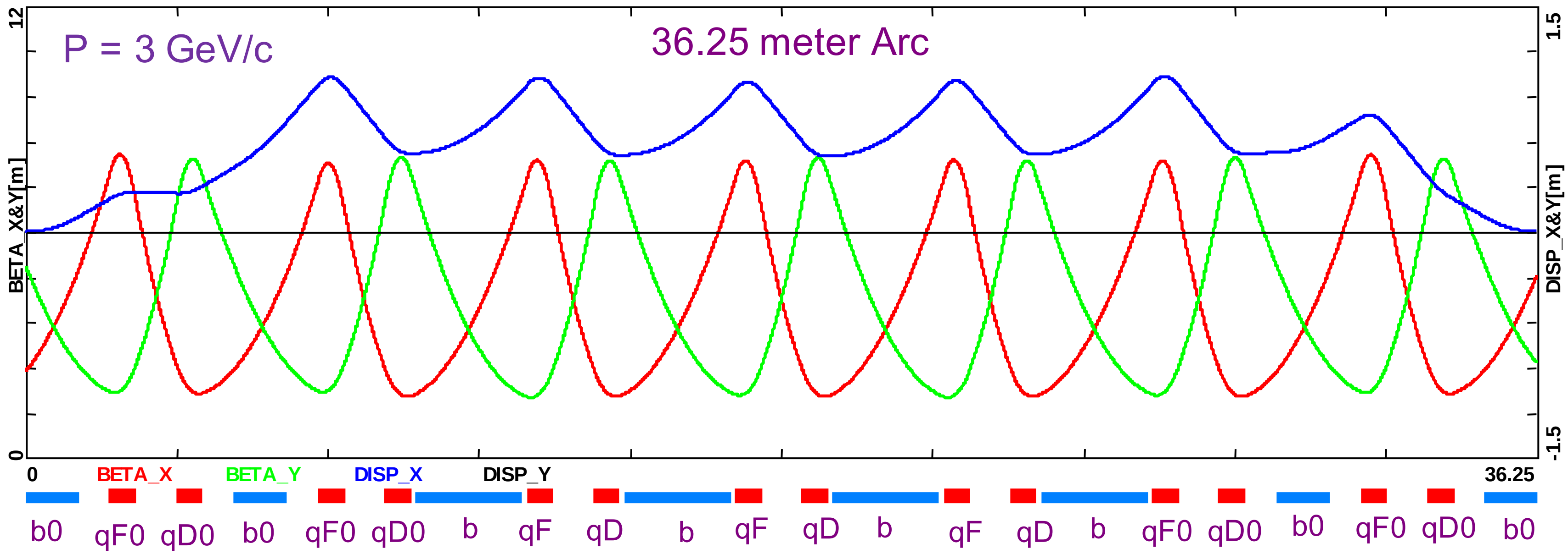
# THANK YOU

# Back up Slides

# Injection Schematic
## *M. Popovic*



# Arc Optics ($90^0$ doublets)



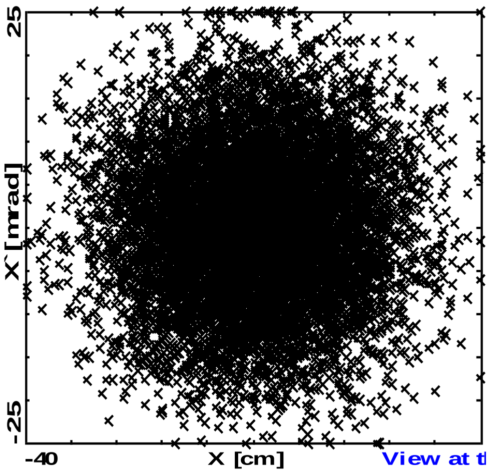

| | | |
|---|---|---|
| qF0 | L[cm]=60 | G[kG/cm]=1.100 |
| qD0 | L[cm]=60 | G[kG/cm]=-1.075 |
| qF | L[cm]=60 | G[kG/cm]=1.124 |
| qD | L[cm]=60 | G[kG/cm]=-1.089 |
| drift between quads in a doublet | L[cm]=100 | |
| drift between a quad and a bend | L[cm]=15 | |

| | | |
|---|---|---|
| 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

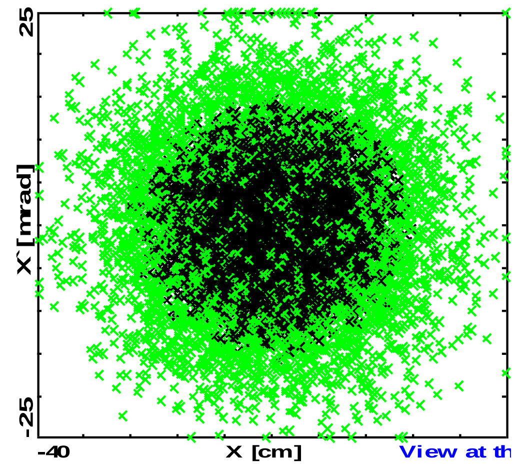
initial 1.000000



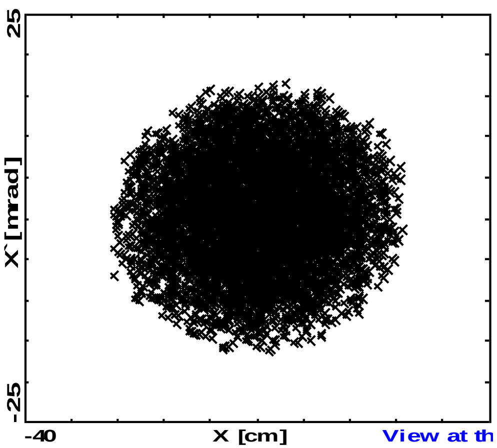

$MuDecay=2.2e-6; => 2.2e-06
$C=10150*2; => 20300
$NTurn=$gamma*$MuDecay*$beta*$c/$C; => 92.249966

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

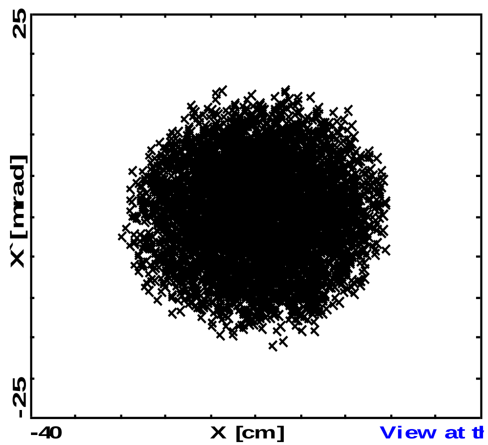
$\sigma_{\Delta p/p}$ = 0.05 $D_x \sigma_{\Delta p/p}$



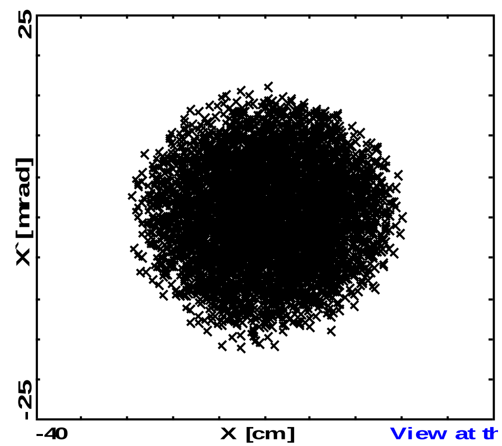

turn 1 0.720300




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: $\varepsilon_N = 30$ 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