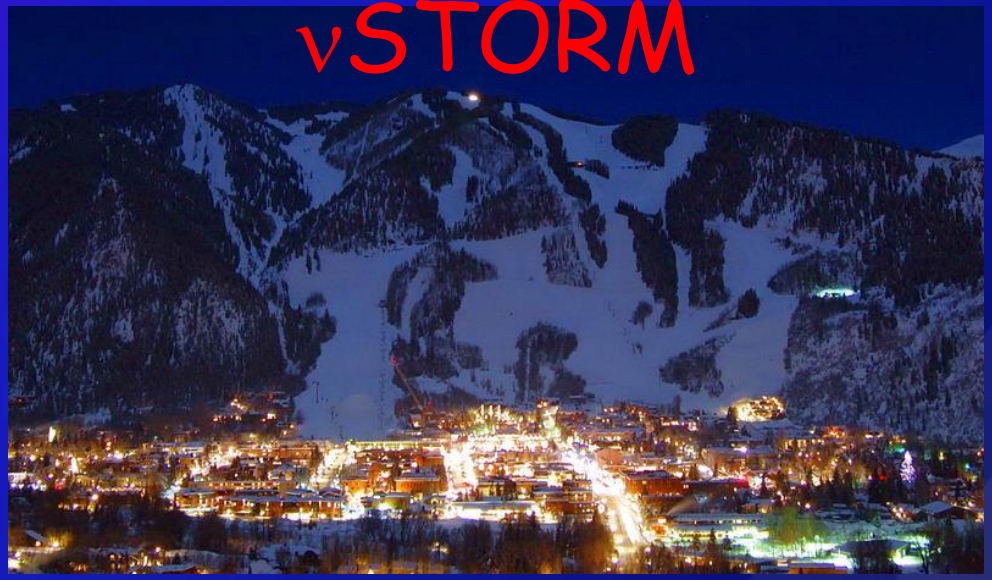
Neutrinos from Stored Muons
νSTORM



A new paradigm for neutrino physics?

Fermilab

Motivation

- 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
- However, no implementation has been done to date[1]
- nuSTORM does use a μ storage/decay ring and can:
  - Address the large δm^2 ν oscillation regime
  - Provide beam for precision ν interaction physics
  - Provide an accelerator technology test bed
    - potential for intense low E muon beam
  - Provides a μ decay ring R&D (instrumentation) & technology demonstration platform
  - Provides a ν Detector Test Facility

[1]Fermilab Debuncher operated as one for 20 years, but ν beam never exploited

μ-based ν beams

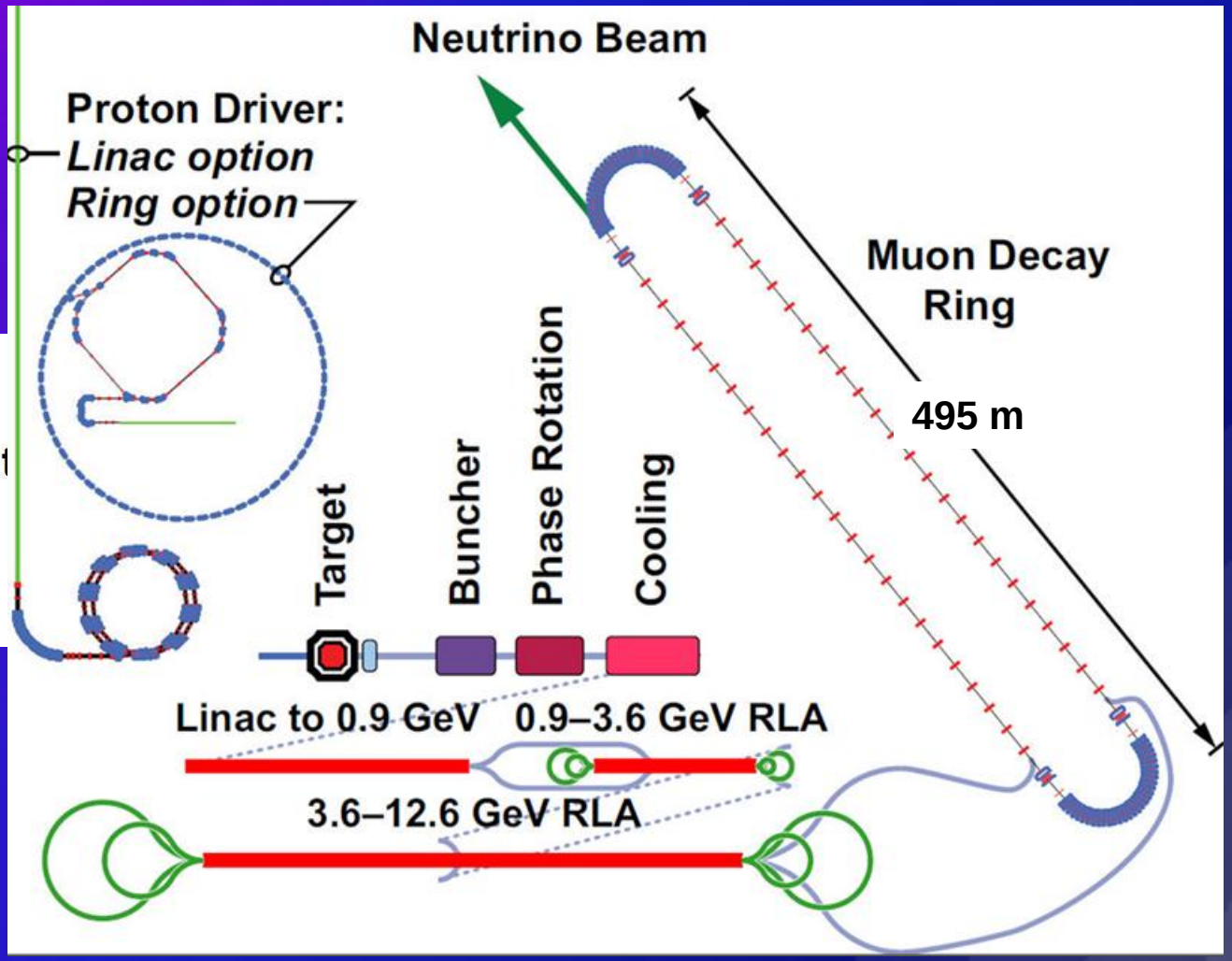
Well-understood neutrino source:

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

μ Decay Ring: $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$

- Flavor content fully known
- "*Near Absolute*" Flux Determination is possible in a storage ring
  - Beam current, beam divergence monitor, μ_p spectrometer
- Overall, there is tremendous control of systematic uncertainties with a well designed system

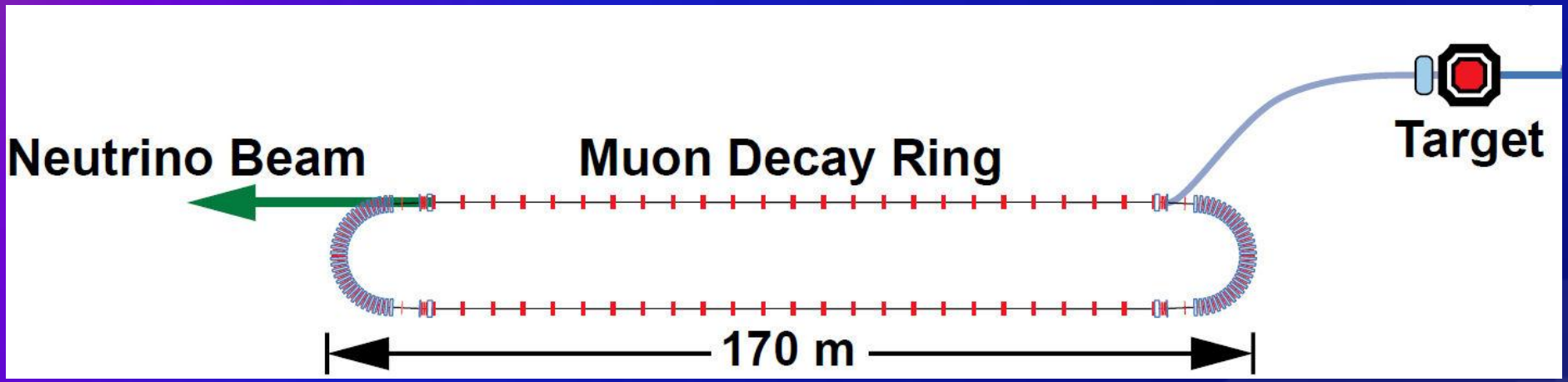
IDS-NF
Neutrinos from STORed Muons
Single baseline, Lower E



This is the simplest implementation of the NF

And DOES NOT Require the Development of ANY New Technology

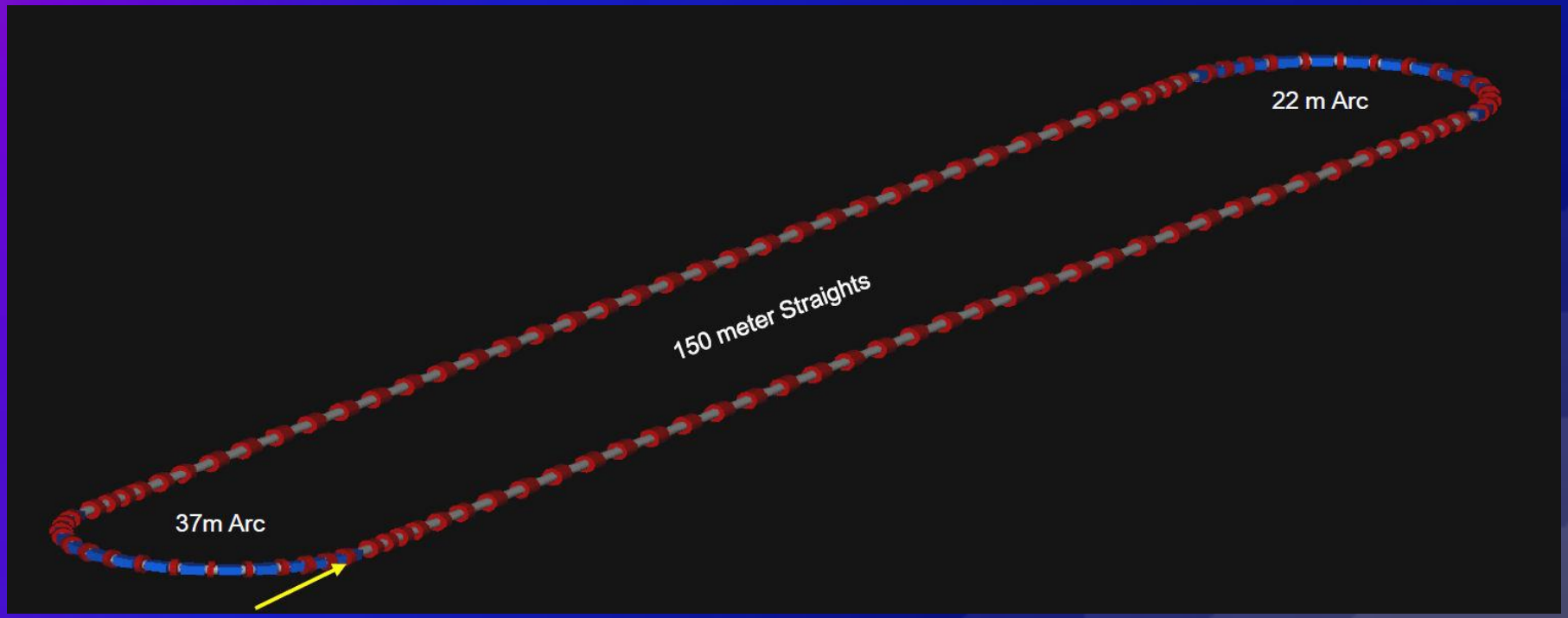
Baseline



- 100 kW Target Station
  - Assume 60-120 GeV protons (Fermilab PIP)
  - Graphite target
    - Optimization on-going
  - Horn collection after target
- π collection/transport channel π injected into decay ring
- Decay ring
  - Large aperture FODO
  - Instrumentation: BCTs, mag-Spec in arc, polarimeter

FODO Decay ring

Alex Bogacz JLAB
Ao Liu Fermilab

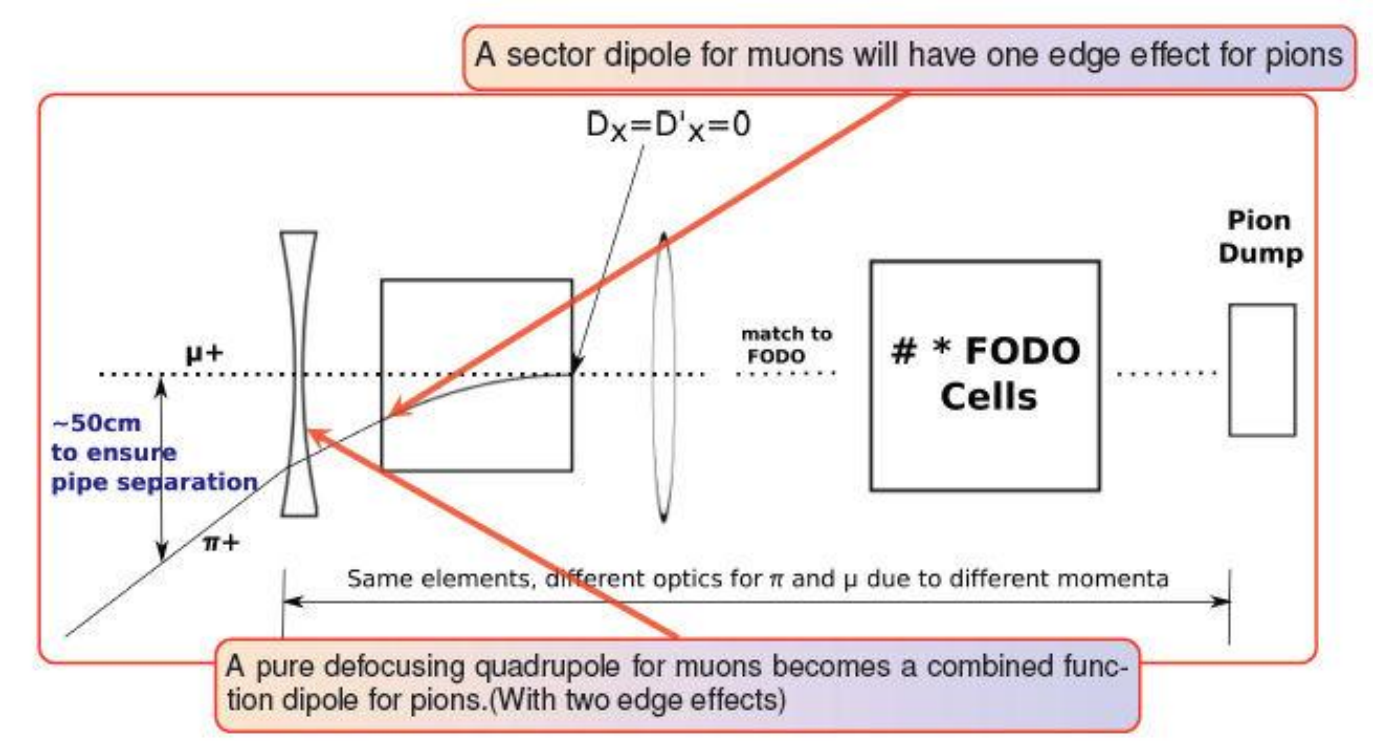


3.8 GeV/c ± 10% momentum acceptance, circumference = 350 m

Injection

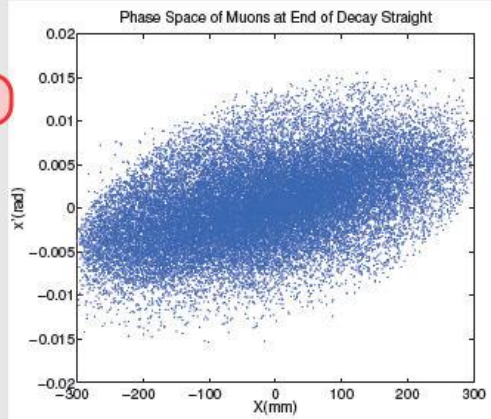
Ao Liu
Fermilab

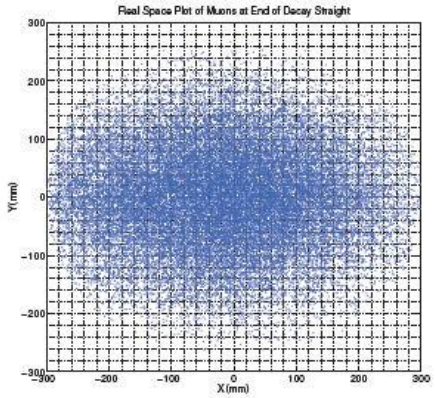
- π's are on an injection orbit
  - separated by chicane
- μ's are in ring circulating orbit
  - lower p = 3.8 GeV/c



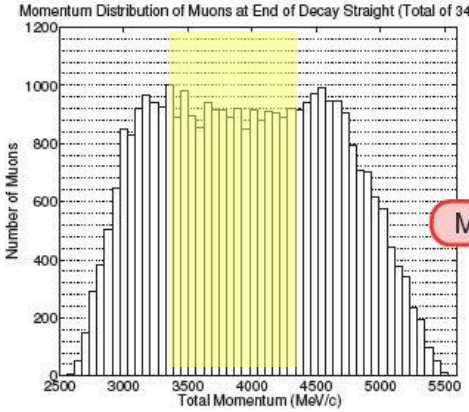
μs at end of first straight

Phase space plot





Real space plot

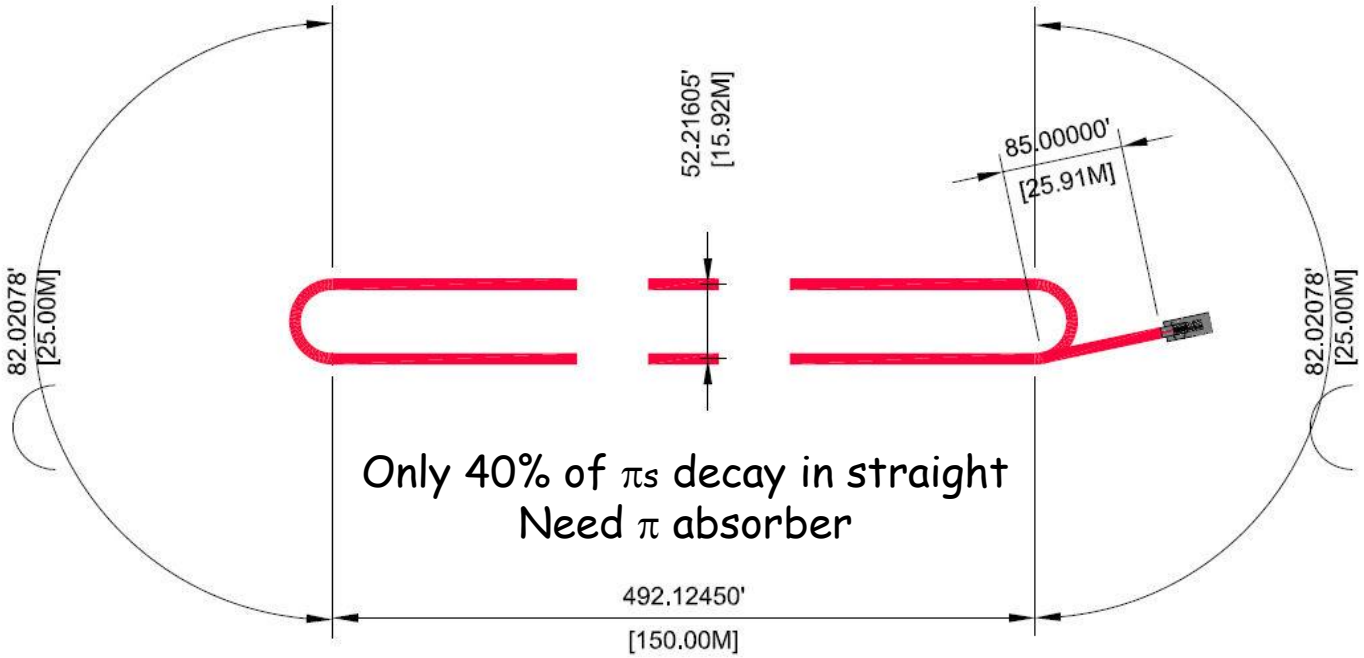


Momentum Distribution

Muons at the end of decay straight.(Total of 34675 muons. ~ 18% of initial pions.)

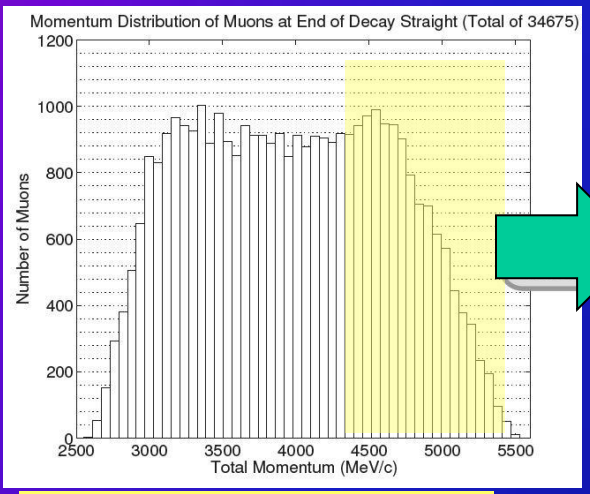
(As a comparison, if turn fringe field off –19.7%)

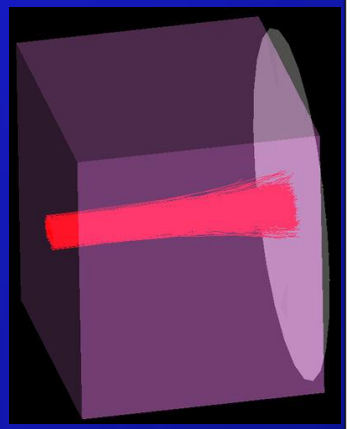
Looking to the Energy Frontier
Not on topic here, but is Neat

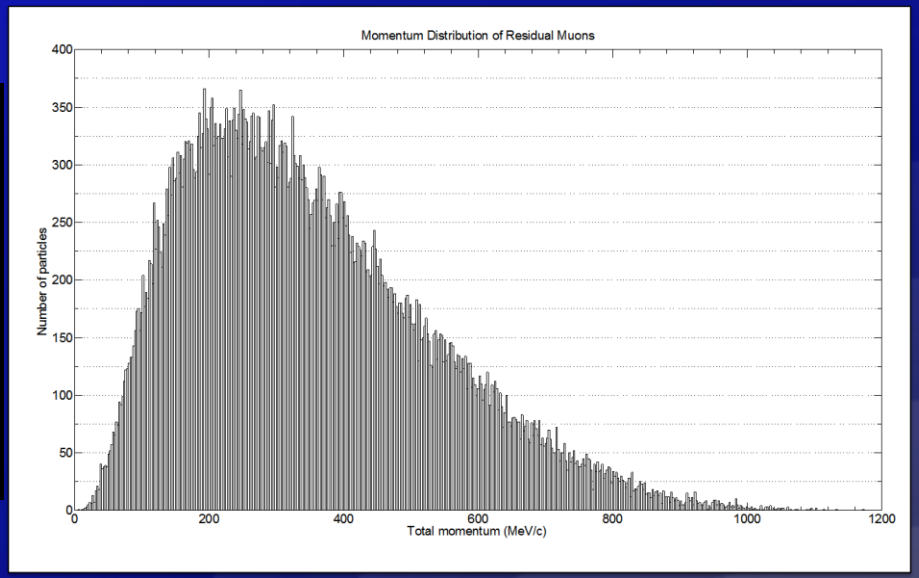


DECAY RING - PLAN

Low Energy μ beam







At end of straight we have a lot of πs, but also a lot of μs with 4.5 < P(GeV/c) < 5.5

After 3.48m Fe, we have ≈ 10^{10} μ/pulse in 100 < P(MeV/c) < 300

The Physics Reach

μ appearance channel

NF "Golden" channel

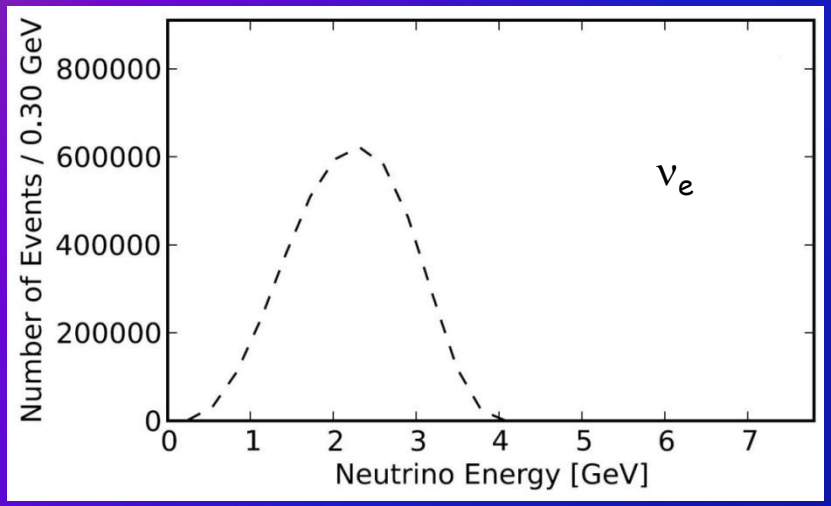
Assumptions

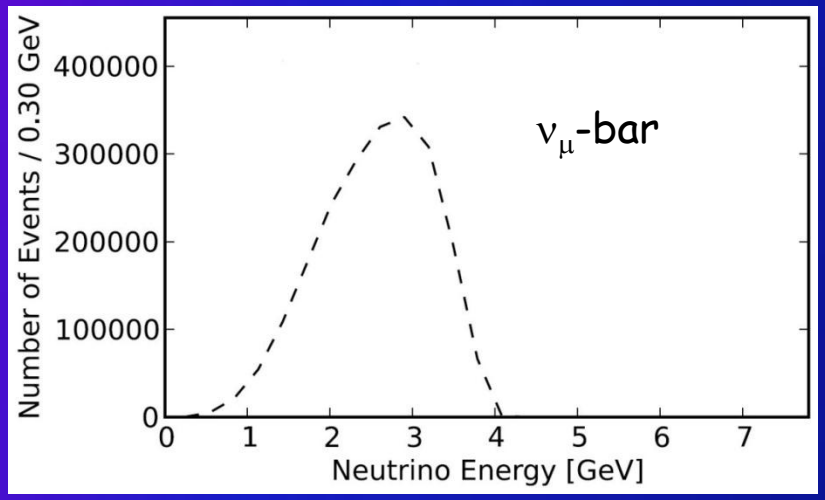
- N_μ = (POT) X (π/POT) X $\varepsilon_{collection}$ X ε_{inj} X (μ/π) X $A_{dynamic}$ X Ω
  - 10^{21} POT in 5 years of running @ 60 GeV in Fermilab PIP era
  - 0.1 π/POT (FODO)
  - $\varepsilon_{collection}$ = 0.8 ☑
  - ε_{inj} = 0.8 ☑
  - μ/π = 0.08 (γct X μ capture in $\pi \rightarrow \mu$ decay) [π decay in straight]
  - $A_{dynamic}$ = 0.75 (FODO)
  - Ω = Straight/circumference ratio (0.43) (FODO)
- This yields ≈ 1.7 X 10^{18} useful μ decays

Ao Liu
Fermilab/UI

E_ν spectra (μ^+ stored)

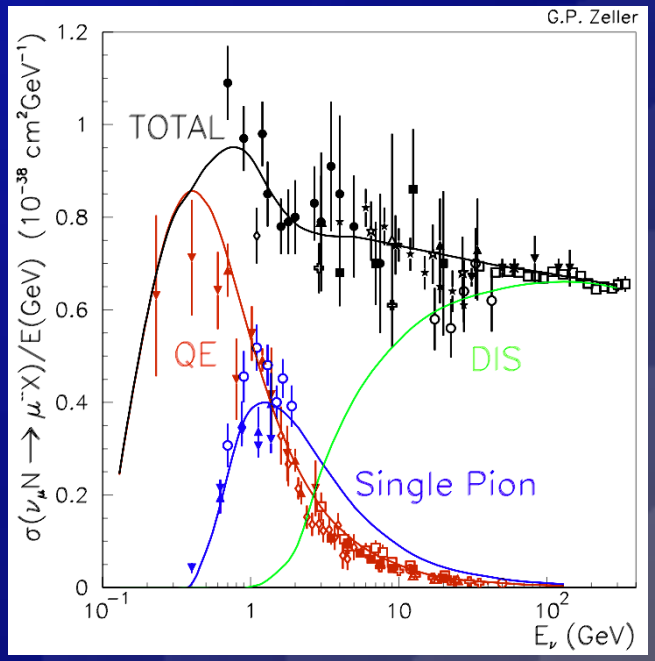
Chris Tunnell
Oxford



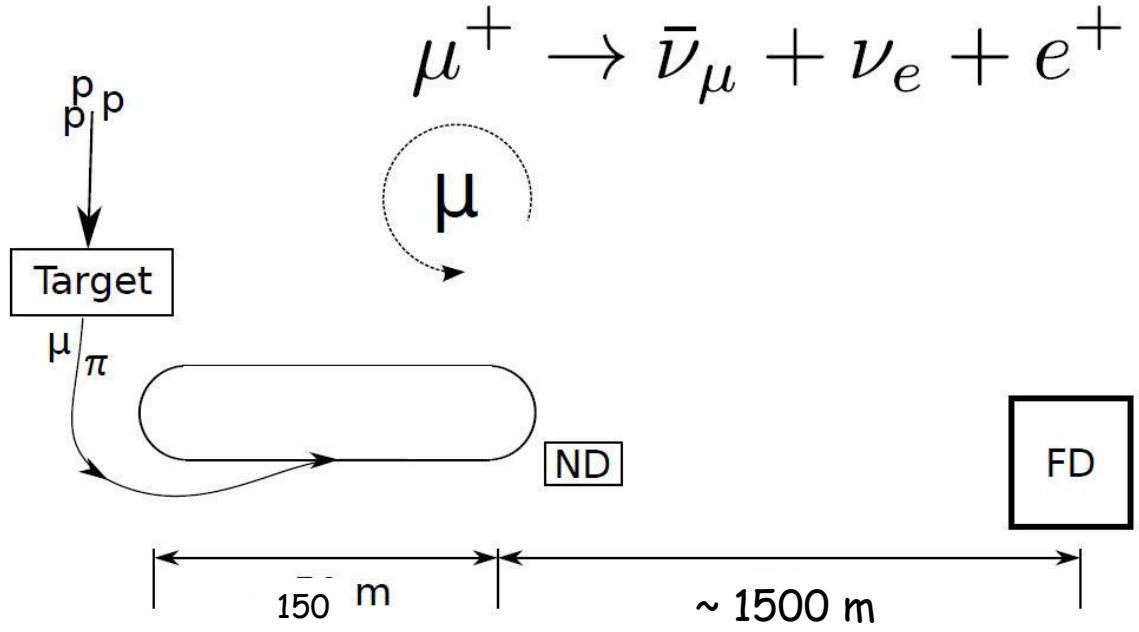


Event rates/100T at ND hall 50m from straight with μ^+ stored

Channel	N_{evts}
$\bar{\nu}_\mu$ NC	844,793
ν_e NC	1,387,698
$\bar{\nu}_\mu$ CC	2,145,632
ν_e CC	3,960,421



Experimental Layout



Appearance-only (though disappearance good too!)

$$Pr[e \rightarrow \mu] = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2(\frac{\Delta m^2_{41} L}{4E})$$

Appearance Channel:

$\nu_e \rightarrow \nu_\mu$

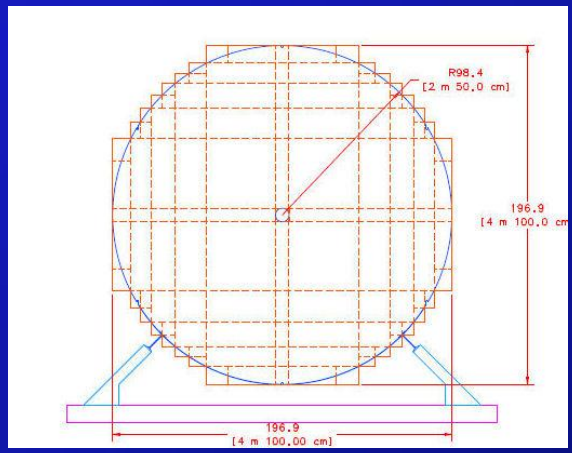
Golden Channel

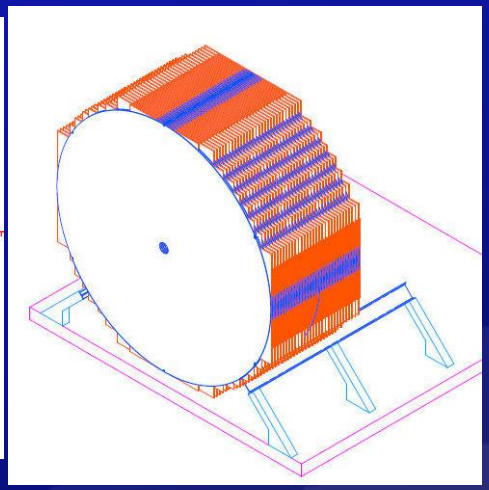
Must reject the "wrong" sign μ with great efficiency

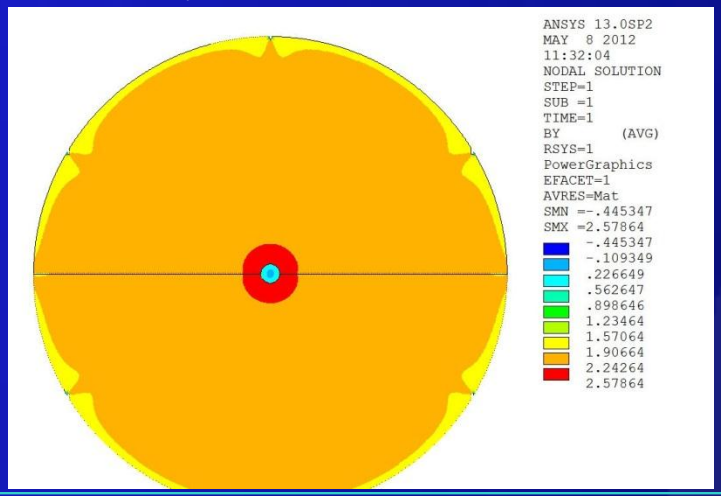
Why $\nu_\mu \rightarrow \nu_e$ Appearance Ch. *"not"* possible

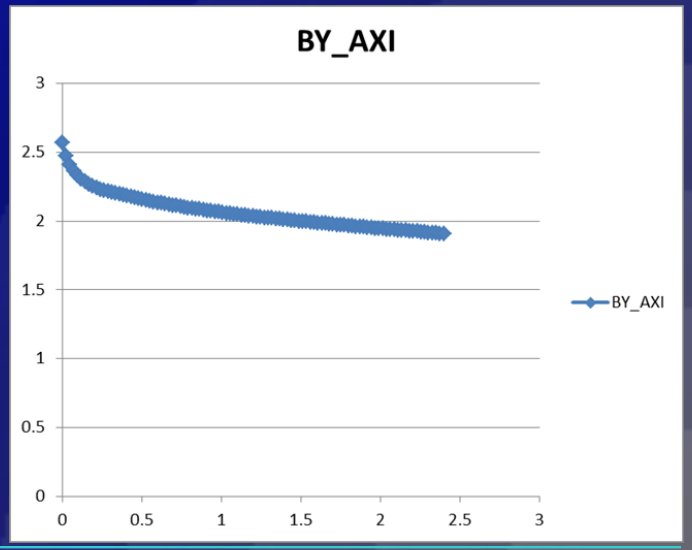
Baseline Detector
Super B Iron Neutrino Detector: SuperBIND

- 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
  - X&Y readout between plates







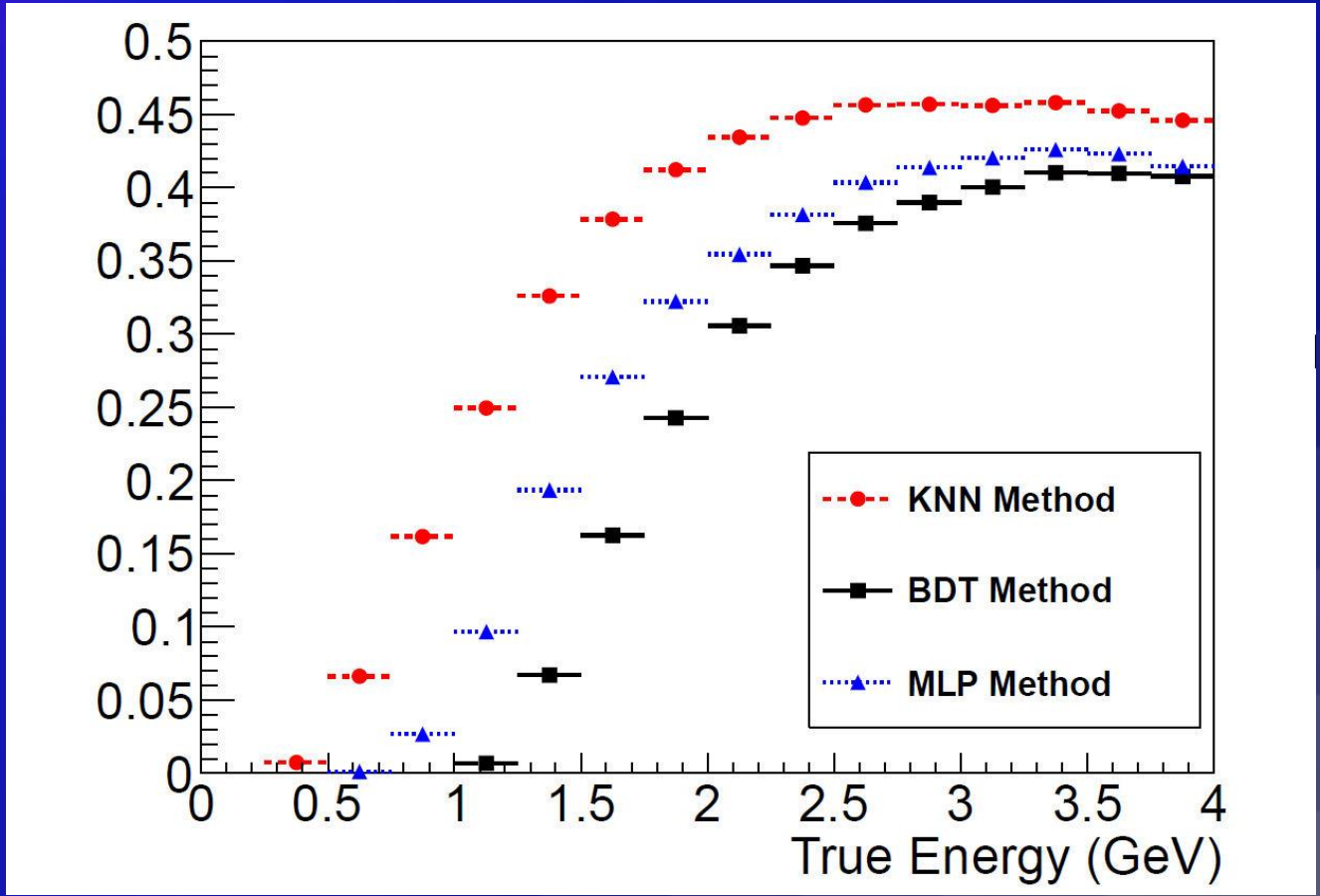


20 cm hole
For 6-8 turns
of STL

Multivariate Analysis
CC-NC discrimination

Ryan Bayes
Steve Bramsiepe
Glasgow

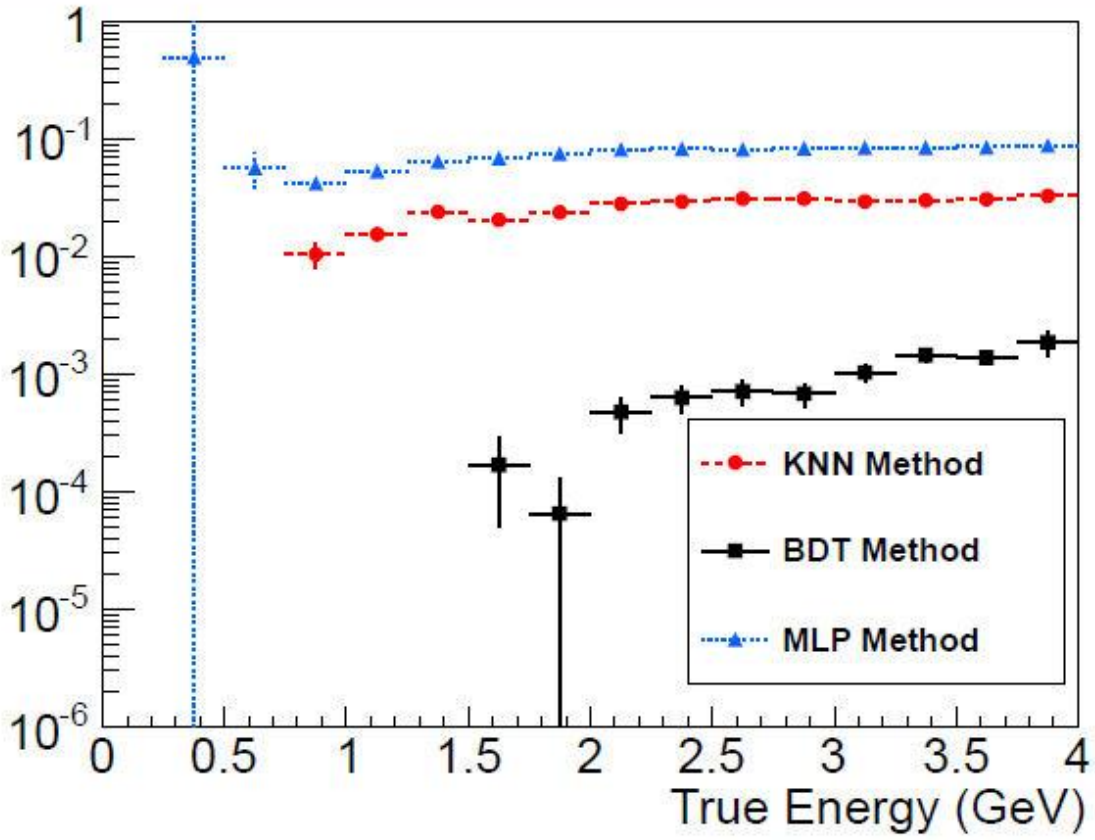
- 2 cm plates
- Updated reconstruction
- Tested 3 multi-variate methods
  - KNN
  - BDT
  - MLP
- Goal to reduce threshold & increase eff.



Clearly, raising our peak E_ν by .5 to 1 GeV would help

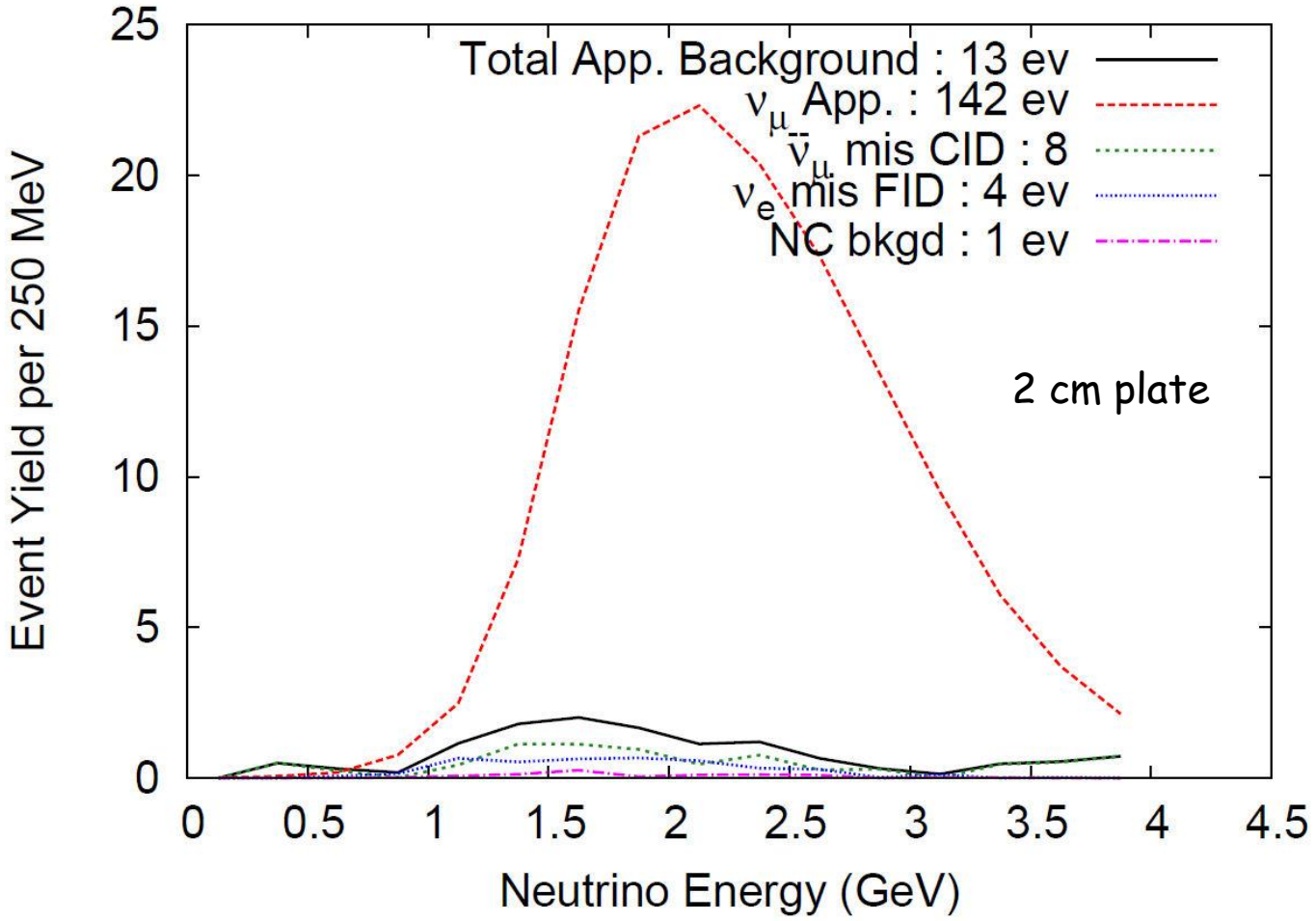
Background rates

$\bar{\nu}_\mu$ NC Mis-ID

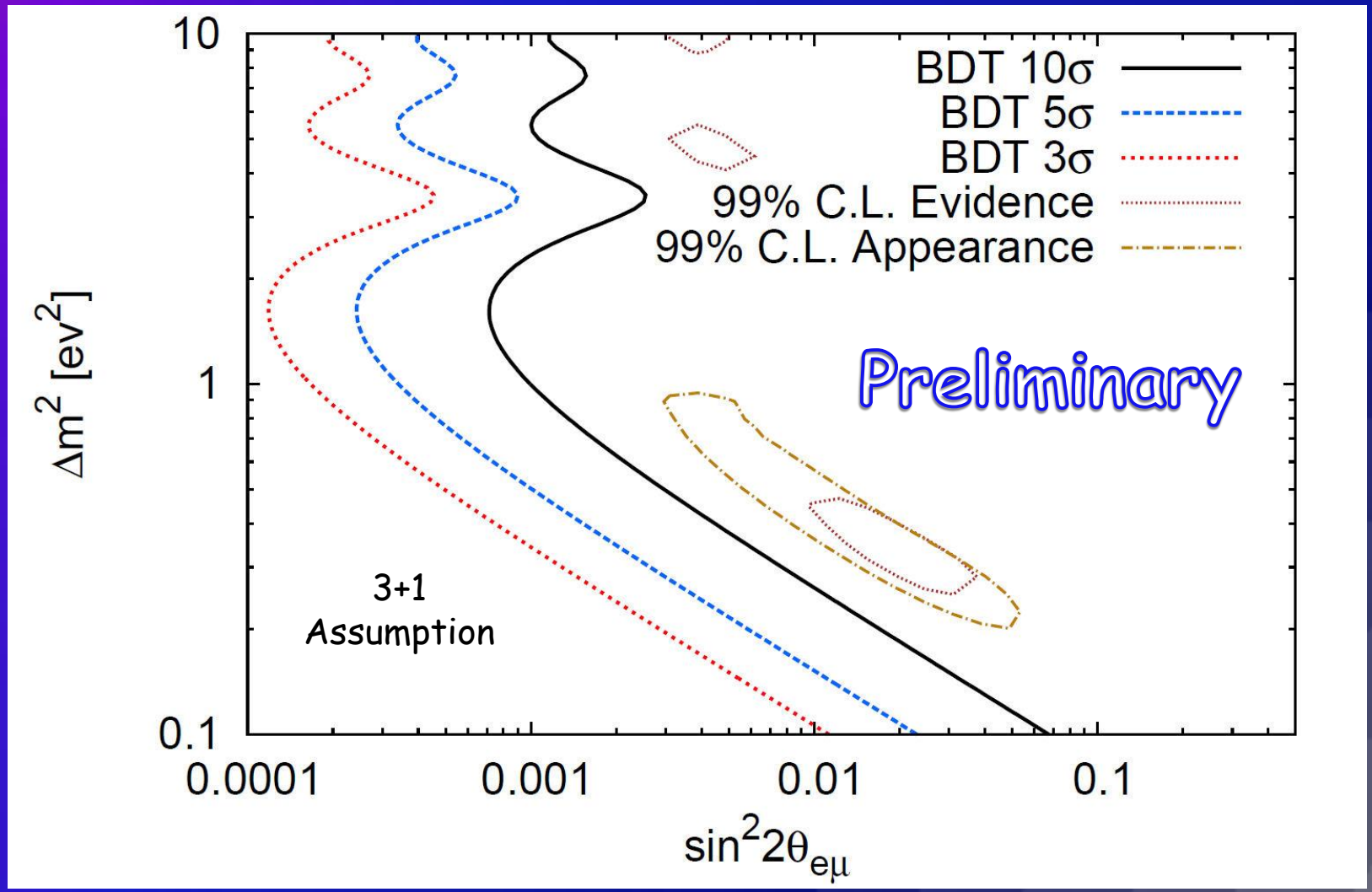


On-going work to understand

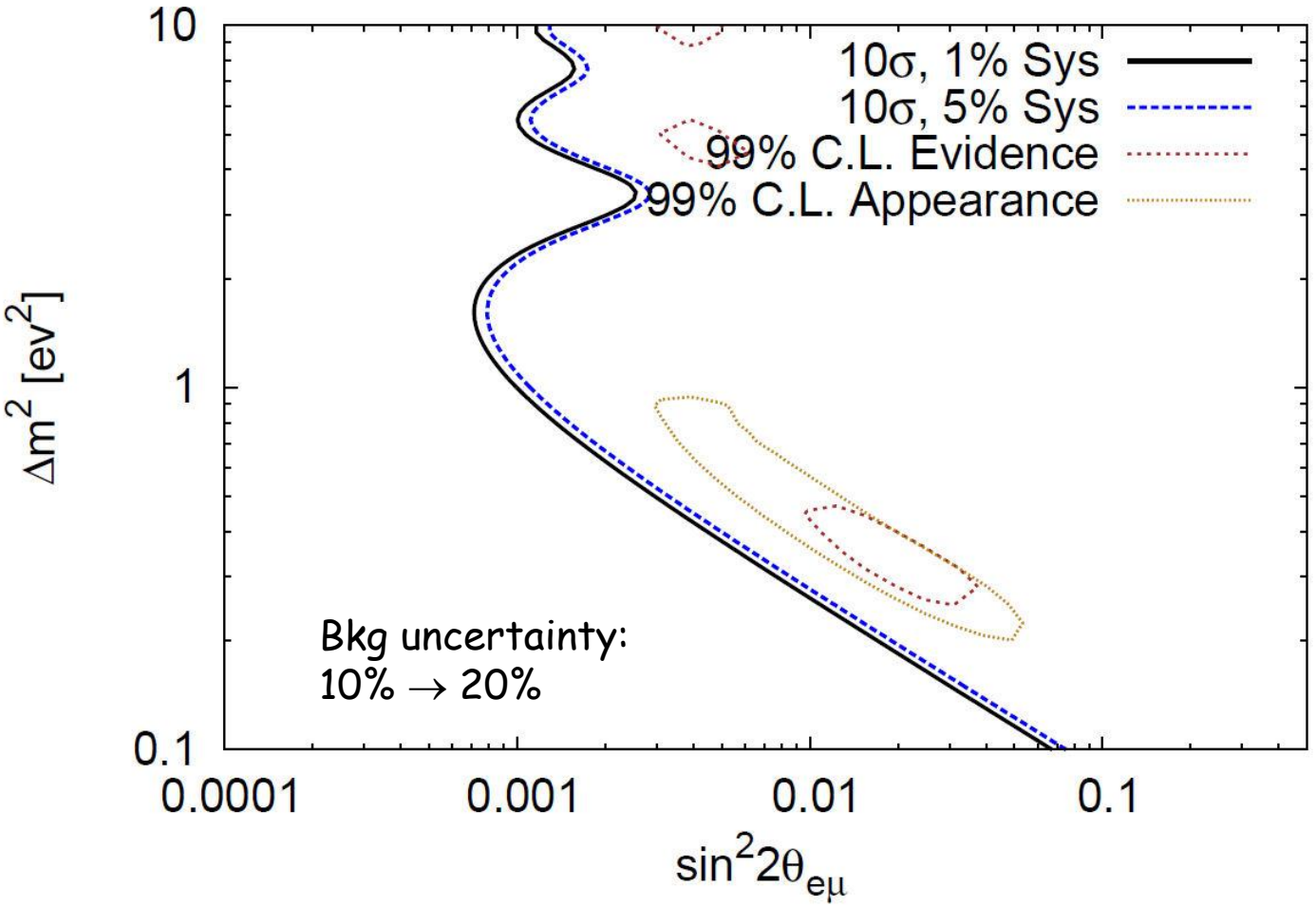
$\nu_e \rightarrow \nu_\mu$ appearance
CPT invariant channel to MiniBooNE



$\nu_e \rightarrow \nu_\mu$ appearance



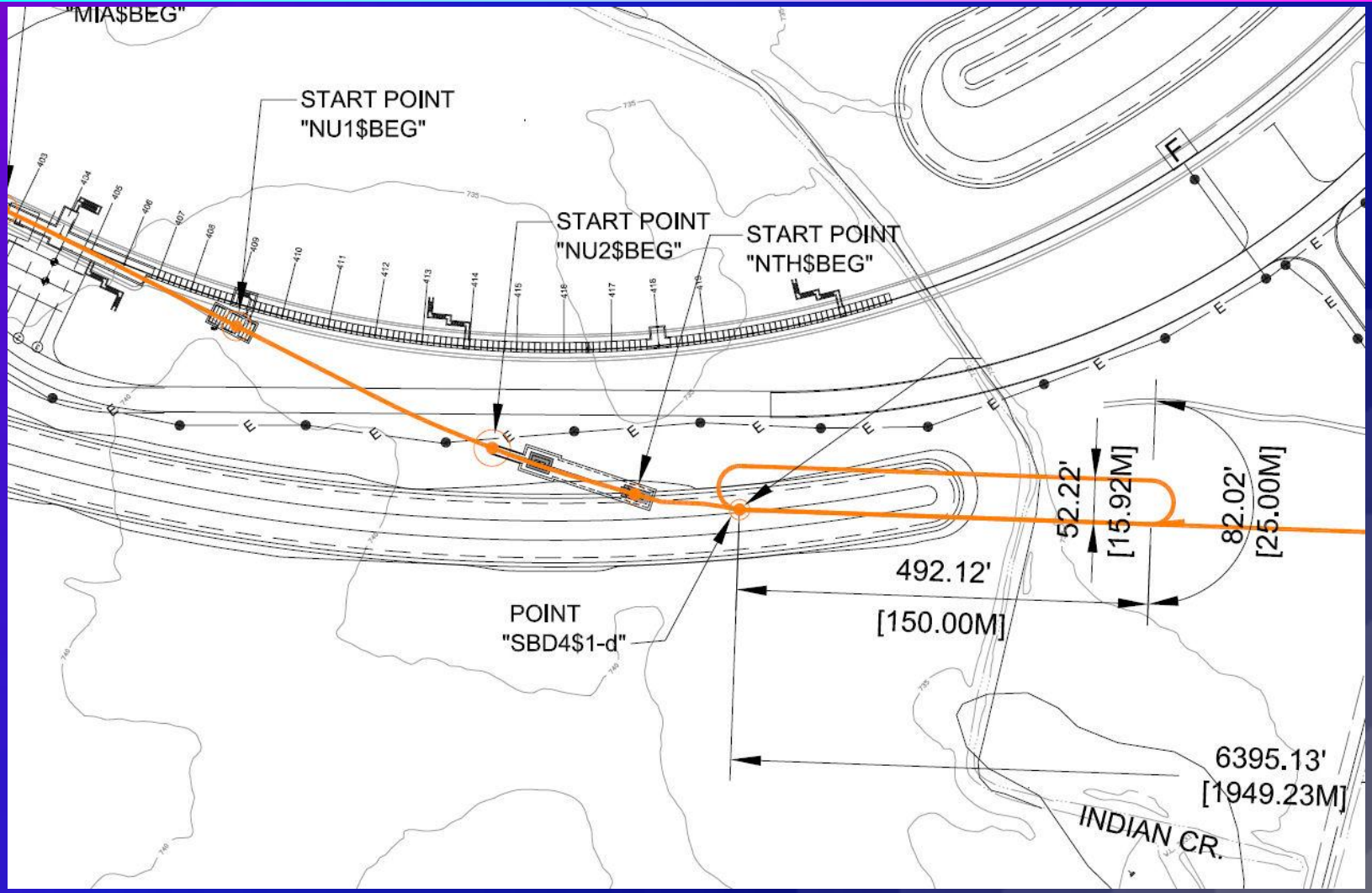
"Golden Channel" Robustness



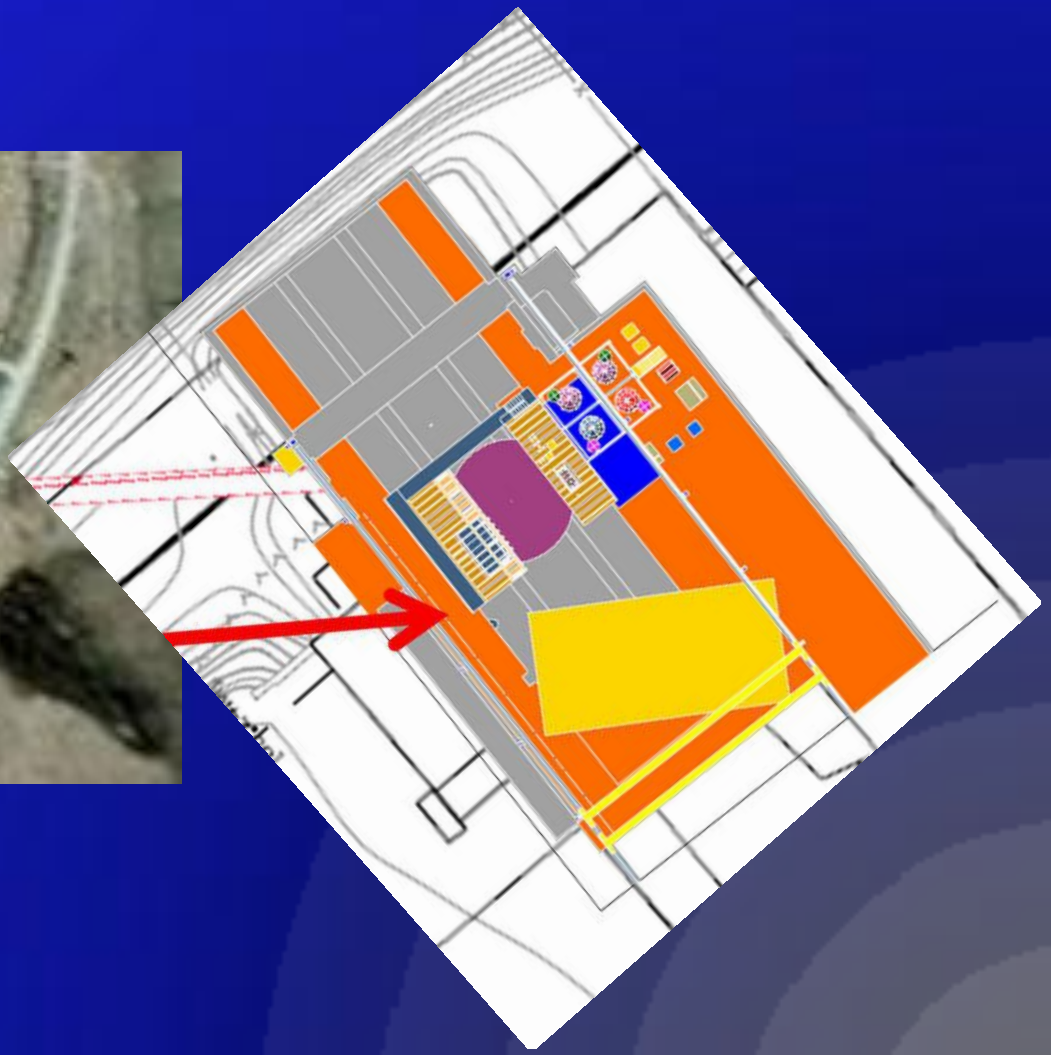
Project Considerations

Siting Concept

MI-40 Beam Absorber



Far Detector Hall and Detector(s)



Moving Forward

Ongoing & future work

- Facility
  - Targeting, capture/transport & Injection
    - Need to complete detailed design and simulation
  - Decay Ring optimization
    - Continued study of both FODO & RFFAG decay rings
  - Decay Ring Instrumentation
    - Define and simulate performance of BCT, polarimeter, Magnetic-spectrometer, etc.
  - Produce full G4Beamline simulation of all of the above to define ν flux (Fermilab PhD student - thesis)
    - And verify the precision to which it can be determined.

Ongoing & future work II

- Detector simulation
  - For oscillation studies, continue MC study of backgrounds & systematics
    - Start study of disappearance channels
    - Look in detail at all sources of backgrounds: CR, atmospheric ν, etc.
      - First pass done & with timing to remove CR, small compared to charge mis-ID
    - Will lead to detector (FAR) optimization
  - Move to Multivariate techniques. [Begun]
  - For cross-section (& general ν interaction physics) measurements need detector baseline design
    - Learn much from work for LBNE & IDS-NF (both detector & physics)
      - Increased emphasis on ν_e interactions, however

Important steps to move forward

- Two workshops are planned
  - CERN: March 26-27 (contact: Elena Wildner)
  - Virginia Tech: April 12-13 (contact: Jon Link
  - Aim:
    - Consolidate technical options
    - Define work-packages
    - Identify possible collaborative topics
    - Discussion on the collaborative EOI to CERN SPC (to be ready by April '13)
      - Ken Long, Elena Wildner
  - Production of Full Proposal to Fermilab (June 2013 PAC & Snowmass)

nuSTORM: Conclusions

The Physics case:

- Initial simulation work indicates we can confirm/exclude at 10σ (CPT invariant channel) the LSND/MiniBooNE result
  - ν_μ and (ν_e) disappearance experiments delivering at the <1% level look to be doable
    - Simulation work on these channels has not yet started
- ν interaction physics studies with near detector(s) offer a unique opportunity & can be extended to cover 0.2<GeV< E_ν< 4 GeV
  - Could be *"transformational"* w/r to ν interaction physics
  - For this physics, nuSTORM should really be thought of as a facility: *A ν "light-source"* is a good analogy
    - nuSTORM provides the beam & users will bring their detector to the near hall

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
- Move P_μ to 5 Gev/c & set stage for LBL program?
- And, presents a new direction in ν physics

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