Neutrinos from Stored Muons
nuSTORM

ν *physics with a* μ *storage ring*

Great things Big & Small

Outline

- Introduction
- Physics motivation
- Current facility design status
- Moving forward and Conclusions

Introduction

- For over 30 years physicists have been talking about doing ν experiments with νs from μ decay

Well-understood neutrino source:

μ Decay Ring:

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

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

- Flavor content fully known
- Energy spectrum known to a few parts in 10^4
- "*Near Absolute*" Flux Determination is possible in a storage ring
  - Beam current, polarization, beam divergence monitor, μ_p spectrometer
- Overall, there is tremendous control of systematic uncertainties with a well designed facility

νSTORM

ν physics with a μ storage ring – *Neutrino Factory*

$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$	$\mu^- \to e^- \overline{\nu}_e \nu_\mu$	
$\overline{\nu}_\mu \to \bar{\nu}_\mu$	$\nu_\mu \to \nu_\mu$	disappearance
$\overline{\nu}_\mu \to \bar{\nu}_e$	$\nu_\mu \to \nu_e$	appearance (challenging)
$\overline{\nu}_\mu \to \bar{\nu}_\tau$	$\nu_\mu \to \nu_\tau$	appearance (atm. oscillation)
$\nu_e \to \nu_e$	$\bar{\nu}_e \to \bar{\nu}_e$	disappearance
$\nu_e \to \nu_\mu$	$\bar{\nu}_e \to \bar{\nu}_\mu$	appearance: "golden" channel
$\nu_e \to \nu_\tau$	$\bar{\nu}_e \to \bar{\nu}_\tau$	appearance: "silver" channel

12 channels accessible
if E_ν is above the τ threshold

NuFact2013 - #15

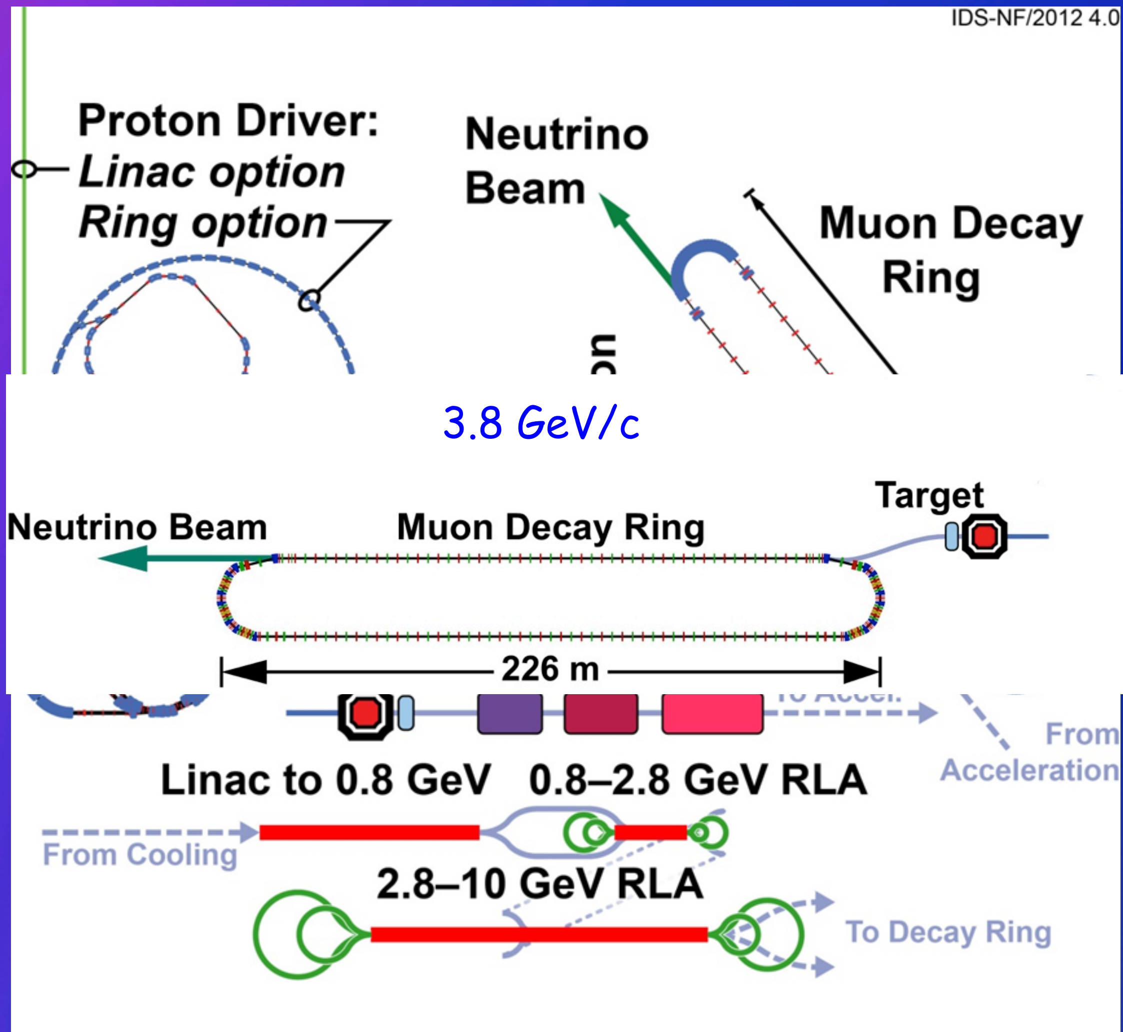
- Well, "*we*" have been taking about it within this venue for 15 years!
- This meeting has evolved over the last 1½ decades.
  - Some say it has lost focus (de-evolved?)
- What has been somewhat lost is the focus on "*A New Way to do Neutrino Physics*"
  - Although detector & accelerator technology has advanced, where we are headed relies on concepts that existed when NuFact started.
    - Now moving to more intensity & Bigger – much Bigger
  - To paraphrase James Carville – "*It is the beam stupid.*"
- Paul will give overview of our "*holy grail*" – the NF
  - But we now realize it is difficult and expensive
- What I will discuss (nuSTORM) is a real option to take the first step along this long journey and do great physics
  - We can do it now.

nuSTORM is an "*affordable*" μ-based ν beam "*First Step*"

- It is a NEAR-TERM FACILITY
  - Because, technically, we can do it now
- Addresses the SBL, large δm^2 ν-oscillation regime
  - *I will show it can convincingly resolve the question*
- Provides a beam for precision ν interaction physics
- Accelerator & Detector technology test bed
  - Potential for intense low energy muon beam
  - Provides for μ decay ring R&D (instrumentation) & technology demonstration platform
  - Provides a ν Detector Test Facility

This is what we mean by short term: Neutrinos from STORed Muons, nuSTORM

Status of the Neutrino Factory design: IDS-NF



This is the simplest implementation of the NF

And DOES NOT Require the Development of ANY New Technology

νSTORM

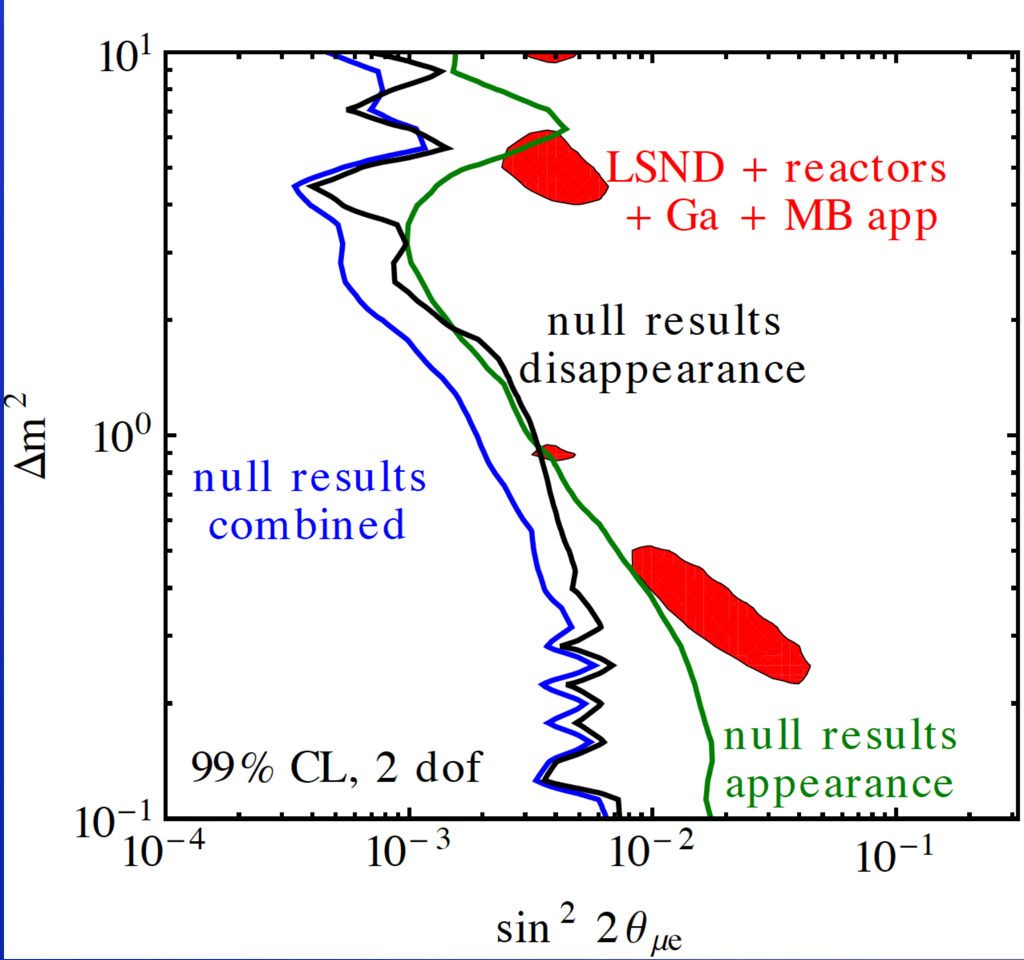
Physics motivation & Theoretical Considerations

Beyond the νSM

Fermilab

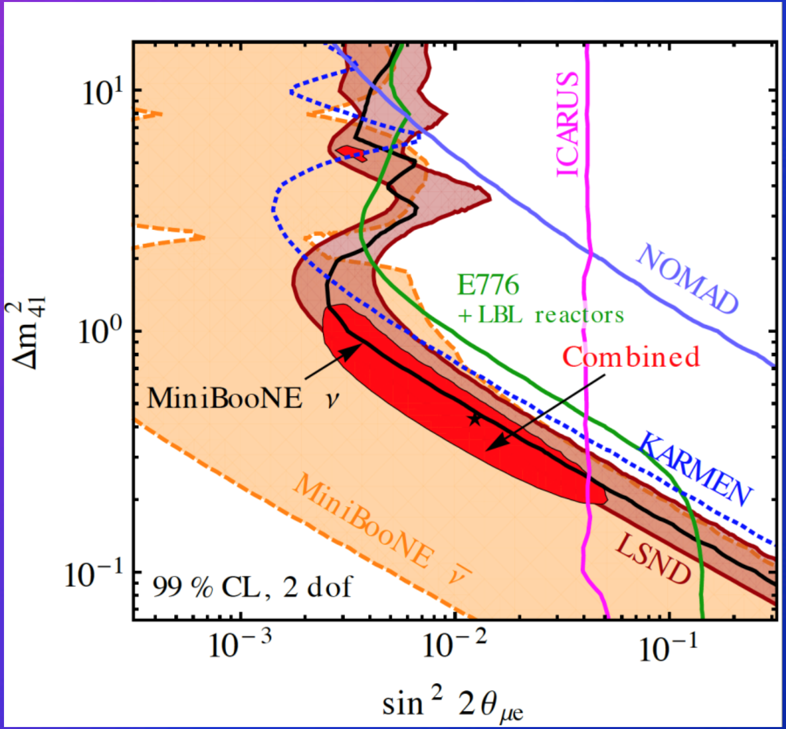
Short-baseline ν oscillation studies

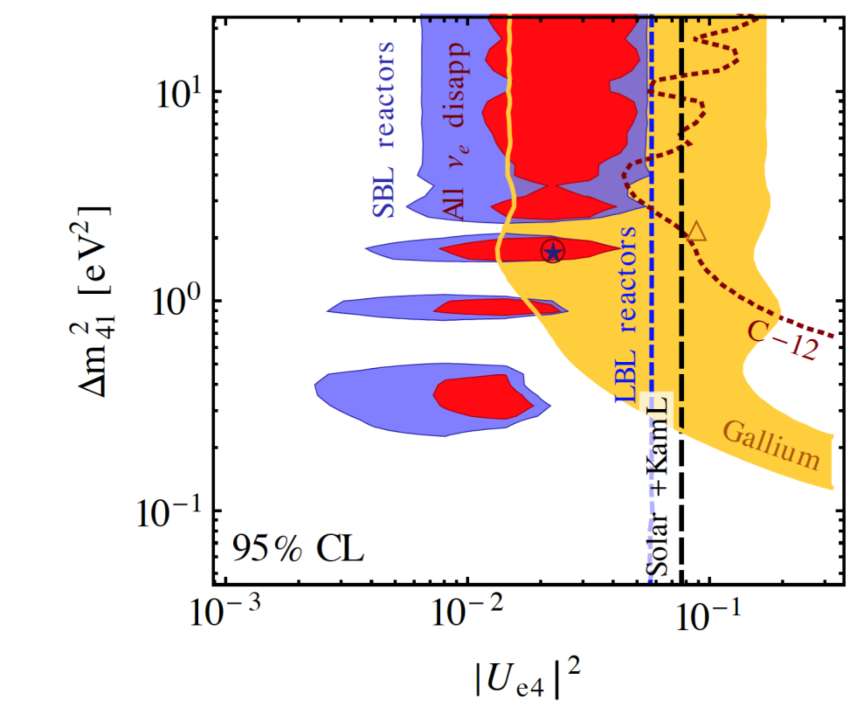
- Sterile neutrinos arise naturally in many extensions of the Standard Model.
  - GUT models
  - Seesaw mechanism for ν mass
  - "Dark" sector
- Usually heavy, but light not ruled out.
- Experimental hints
  - LSND
  - MiniBooNE
  - Ga
  - Reactor "anomaly"



Kopp, Machado, Maltoni & Schwetz: arXiv:1303.3011".

Appearance & disappearance





Subsets of appearance and disappearance data are found to be consistent, and it is only when they are combined and when, in addition, exclusion limits on ν_μ disappearance are included, that tension appears.

Steriles?

- We conclude that, given the current experimental situation:
  - It is impossible to draw firm conclusions regarding the existence of light sterile neutrinos.
  - An experiment searching for short-baseline neutrino oscillations with good sensitivity and well-controlled systematic uncertainties has great potential to clarify the situation.
  - But a truly definitive experiment for both the muon appearance and muon disappearance channels is required to reach a convincing conclusion on the existence of light, sterile neutrinos.

ν Interaction Physics

ν Interaction Physics
A partial sampling

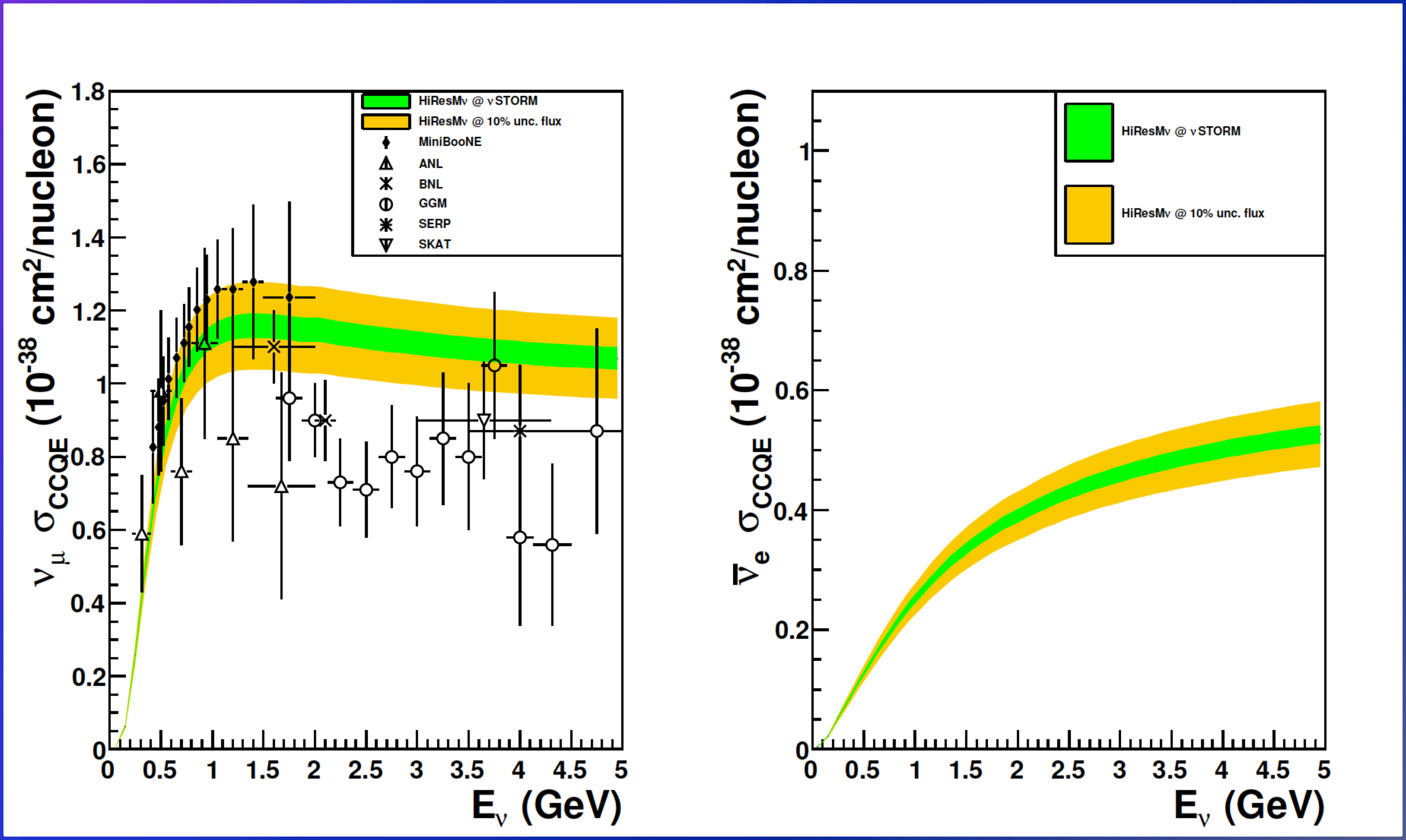
- ν_e and ν_e-bar x-section measurements
  - A UNIQUE contribution from nuSTORM
  - Essentially no existing data
- π^0 production in ν interactions
  - Coherent and quasi-exclusive single π^0 production
- Charged π & K production
  - Coherent and quasi-exclusive single π^+ production
- Multi-nucleon final states
- ν-e scattering
- ν-Nucleon neutral current scattering
  - Measurement of NC to CC ratio
- Charged and neutral current processes
  - Measurement of ν_e induced resonance production
- Nuclear effects
- Semi-exclusive & exclusive processes
  - Measurement of K_s^0, Λ & Λ-bar production
- New physics & exotic processes
  - Test of ν_μ - ν_e universality
  - Heavy ν
  - eV-scale pseudo-scalar penetrating particles

Over 60 topics (thesis) accessible at nuSTORM

Cross section measurements

Edward Santos
Imperial

μ^+



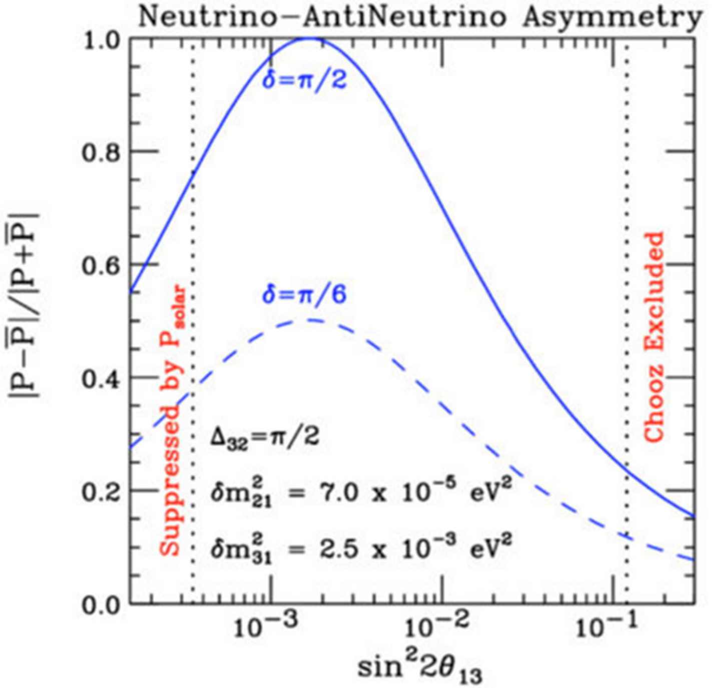
μ^-

HIRESMν – systematics only

ν Cross-section measurements

Cross-section measurements

- μ storage ring presents only way to measure ν_μ & ν_e & (nu and anti-nu) x-sections in same experiment
  - Supports future long-baseline experiments



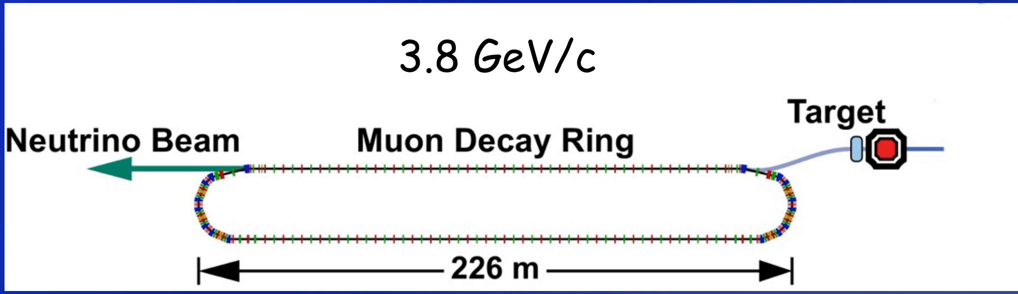
$$\frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}$$

- Important to note that with θ_{13} large, the asymmetry you're trying to measure is small, so:
  - Bkg content & uncertainties start to become more important
  - A "better" understanding of ν/vbar cross-sections beneficial

The Facility

Baseline

- ~ 100 kW Target Station (designed for 400kW)
  - Assume 120 GeV proton
    - Fermilab PIP era
  - Carbon target
    - Inconel
  - Horn collection after target
- Collection/transport channel
  - Stochastic injection of π
- Decay ring
  - Large aperture FODO
    - Also considering RFFAG
  - Instrumentation
    - BCTs, mag-Spec in arc, polarimeter



μ-base ν beam:
Oscillation channels

$\mu^+ \rightarrow e^+ \nu_e \overline{\nu}_\mu$	$\mu^- \rightarrow e^- \overline{\nu}_e \nu_\mu$	
$\overline{\nu}_\mu \rightarrow \bar{\nu}_\mu$	$\nu_\mu \rightarrow \nu_\mu$	disappearance
$\overline{\nu}_\mu \rightarrow \bar{\nu}_e$	$\nu_\mu \rightarrow \nu_e$	appearance (challenging)
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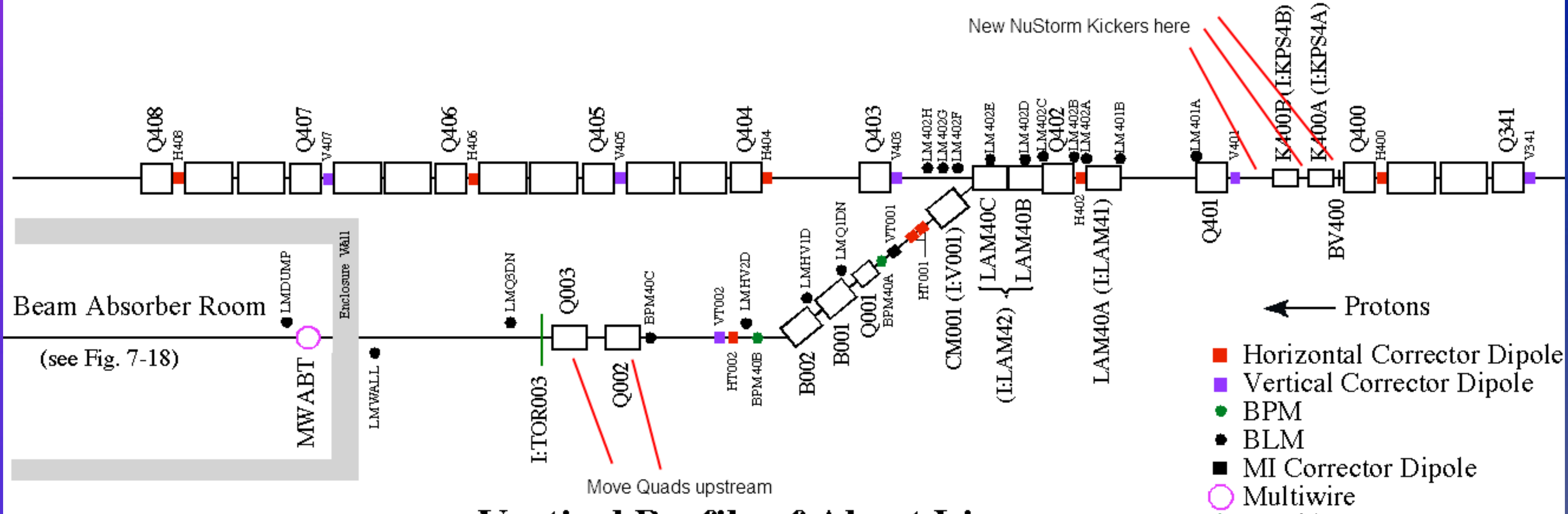
8 out of 12 channels potentially accessible

Extraction from MI

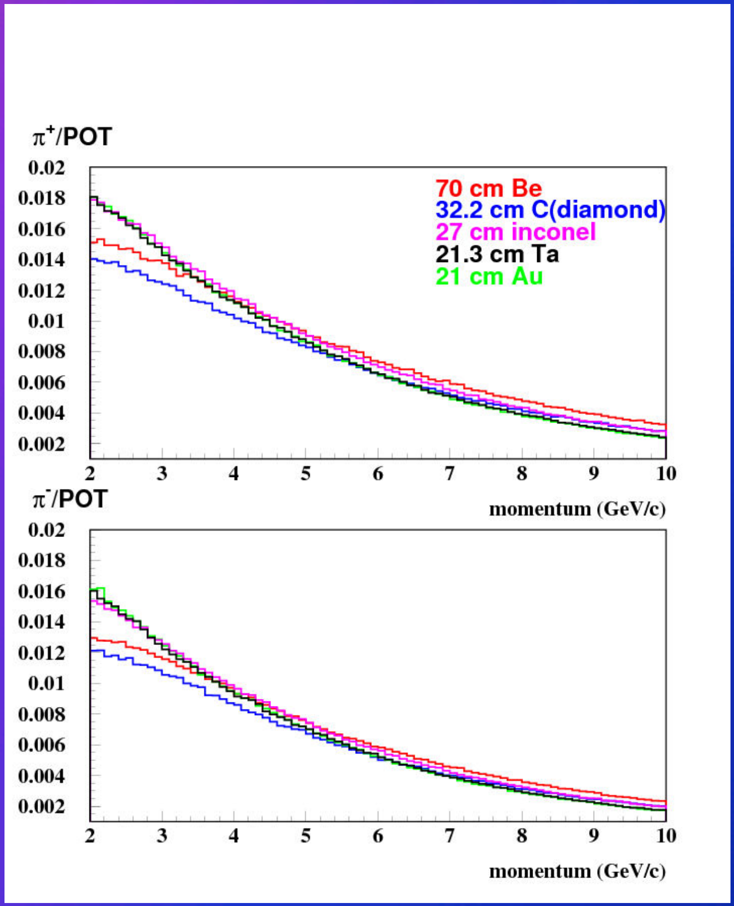
The devil in is the details



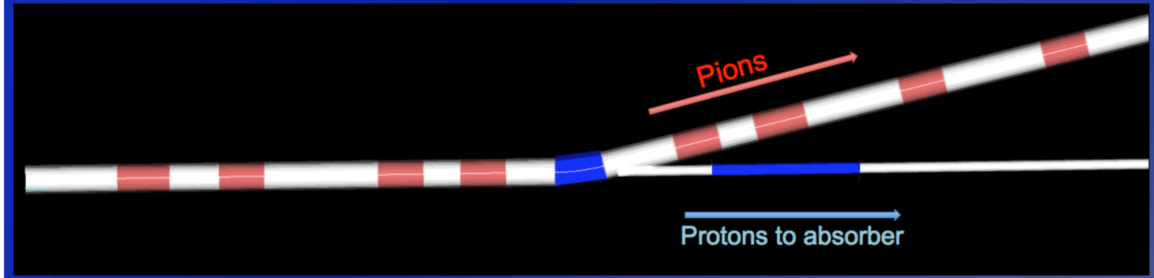
Vertical Profile of Abort Line

π Production, Capture & Transport

Sergei Striganov
Ao Liu
Fermilab

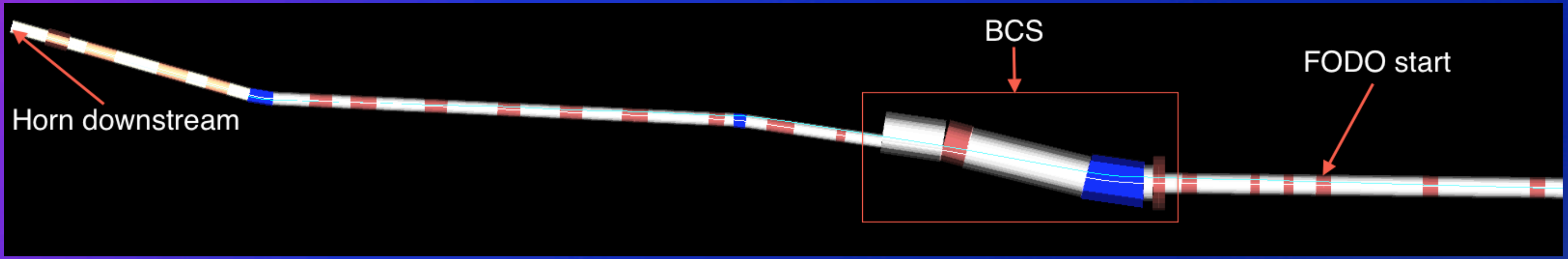


In momentum range
4.5 < 5.0 < 5.5
obtain ≈ 0.09 $\pi^{\pm}$/POT
within decay ring acceptance.
With 120 GeV p & NuMI-style horn 1
Carbon target



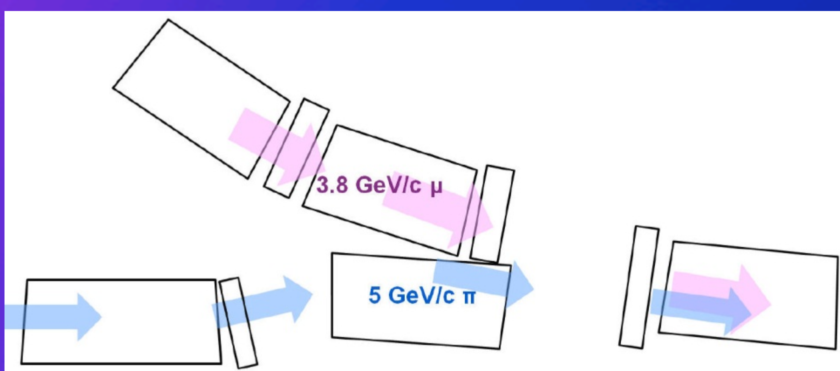
Target/capture optimization ongoing

π Transport & Decay ring

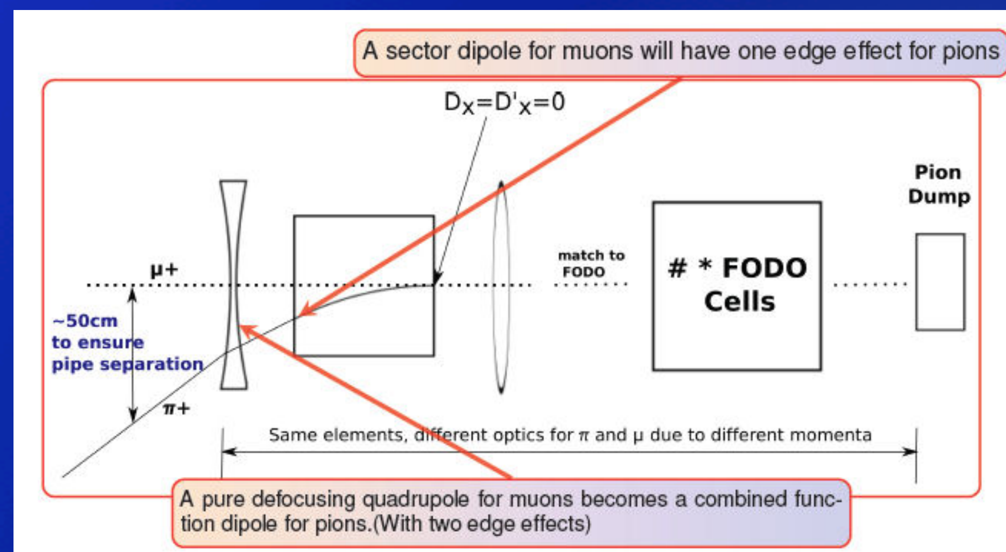


Injection scheme

- π's are on an injection orbit
  - separated by chicane
- μ's are in ring circulating orbit
  - lower p ~3.8 GeV/c
- ~30cm separation between
- Concept works for FODO lattice
  - Now detailed by Ao Liu
- Beam Combination Section (BCS)



David Neuffer's original concept from 1980

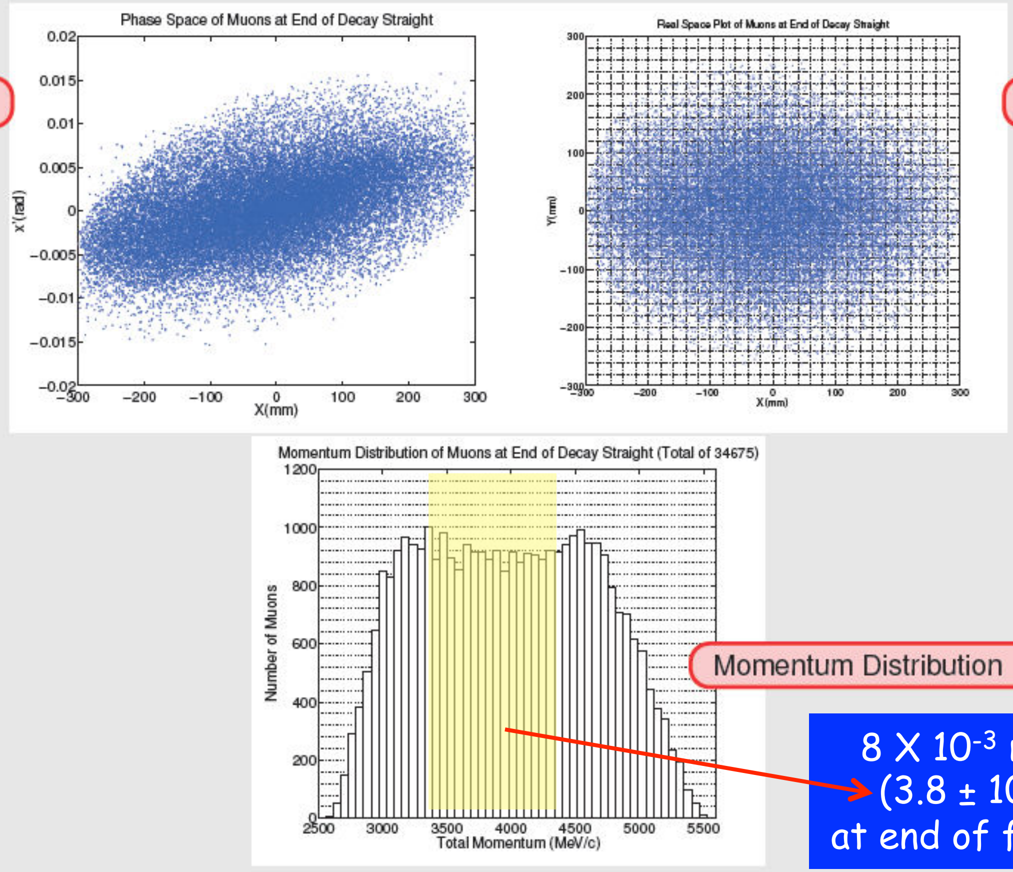


μs at end of first straight

Ao Liu
Fermilab

Phase space plot

Real space plot



Momentum Distribution

8 X 10^{-3} muons/POT
(3.8 ± 10%) GeV/c
at end of first straight

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%)

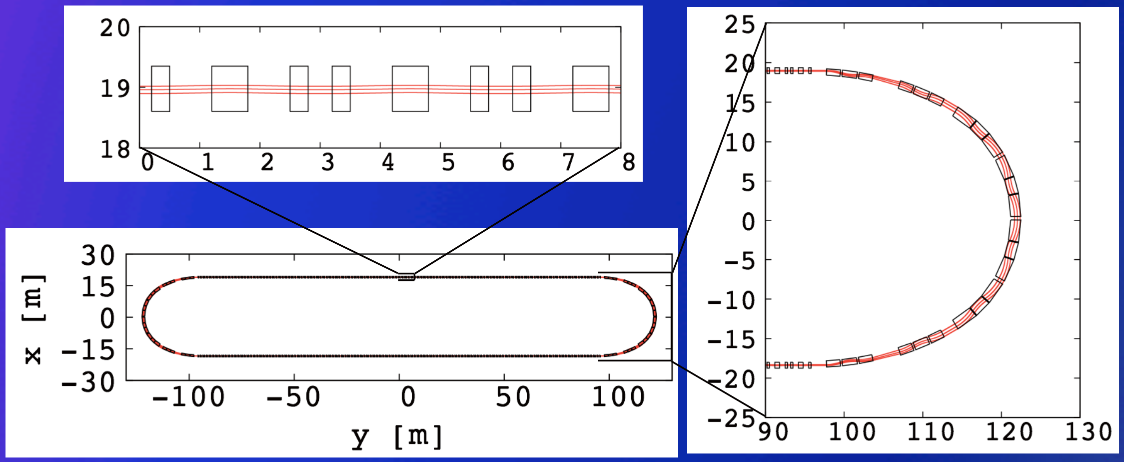
Racetrack FFAG Decay Ring

JB Lagrange & Y. Mori: Kyoto
J. Pasternak: Imperial
A. Sato: Osaka

- Scaling FFAGs have special properties, which makes them ideal for large momentum spread and large emittance beams
  - Tune chromaticity is automatically zero
    - Stable optics for very large momentum spread
    - Allows good working point with a large acceptance avoiding dangerous resonances
  - Beta chromaticity is negligible (strictly zero in the current racetrack)
    - Allows to remove the beta beat for off-momentum particles
  - This allows to design the ring with quasi-zero beam loss
    - Good performance for nuSTORM facility!
- Initial FFAG design
  - Confirmed the large acceptance
  - Assumed initially muon injection with a kicker (not preferred currently)
  - Assumed only normal conducting magnets
    - Large ring size
    - Tight space in the arc -> Difficult Stochastic Injection
- Recent FFAG design
  - Based on superferric magnets (up to 3T) in the arc and normal conducting ones in the straight
    - Reduction of the ring size and the cost!
  - Compact Arc (71m)
    - Allows to incorporate the dispersion matching
  - Stochastic injection is now possible
    - Thanks to a smooth dispersion transition and empty drifts in the compact arc.
  - Ring performance with respect to acceptance is very good!

Recent FFAG Decay Ring design

Parameter	FODO	FFAG with normal conducting arcs	FFAG with SC arcs
$L_{Straight}$ (m)	185	240	192
Circumference [m]	480	706	527
Dynamical acceptance A_{dyn}	0.6	0.95	0.95
Momentum acceptance	±10%	±16%	±16%
π/POT within momentum acceptance	0.094	0.171	0.171
Fraction of π decaying in the straight (F_S)	0.52	0.57	0.54
Ratio of $L_{Straight}$ to the ring Circ. (Ω)	0.39	0.34	0.36
$A_{dyn} \times \pi/POT \times F_S \times \Omega$	0.011	0.031	0.033



Layout of the FFAG Decay Ring with SC Arc

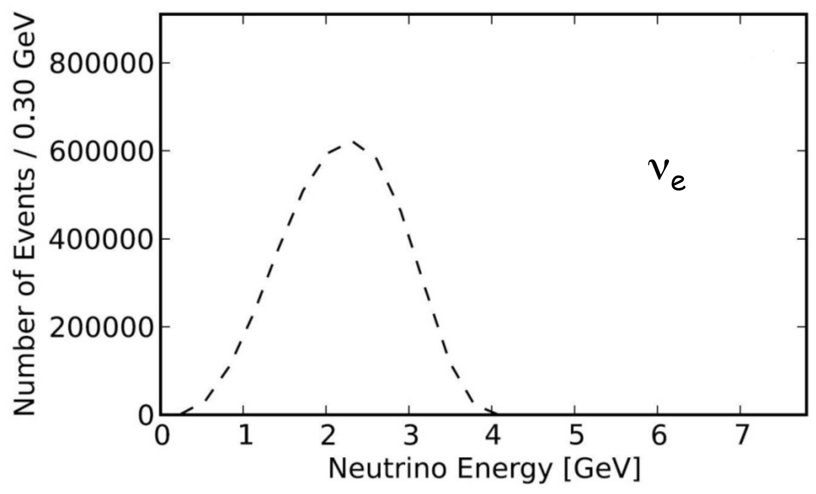
nuSTORM's Physics performance

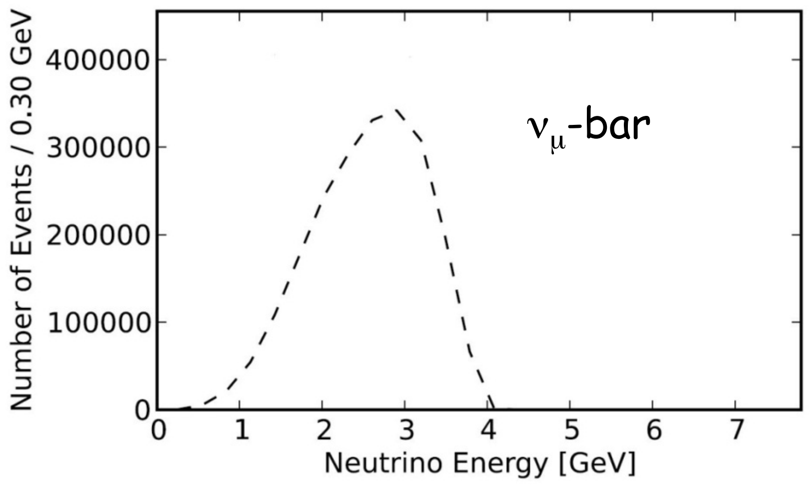
Assumptions

- N_μ = (POT) X (π/POT) X μ/π X $A_{dynamic}$ X Ω
  - 10^{21} POT @ 120 GeV integrated exposure
  - 0.1 π/POT
  - Muons/POT at end of first straight (8×10^{-3})
    - =(π/POT) X (μ/π) within the 3.8 ± 10% GeV/c momentum acceptance
  - $A_{dynamic}$ = 0.6 (FODO)
    - Fraction of muons surviving 100 turns
  - Ω = Straight/circumference ratio (0.39) (FODO)
- This yields ≈ 1.9×10^{18} useful μ decays

Note: nuSTORM will be limited to 10^{20} POT/yr

E_ν spectra (μ^+ stored)





Event rates/100T
at ND hall 50m
from straight with
μ^+ stored
for
10^{21} POT exposure

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

SBL oscillation searches

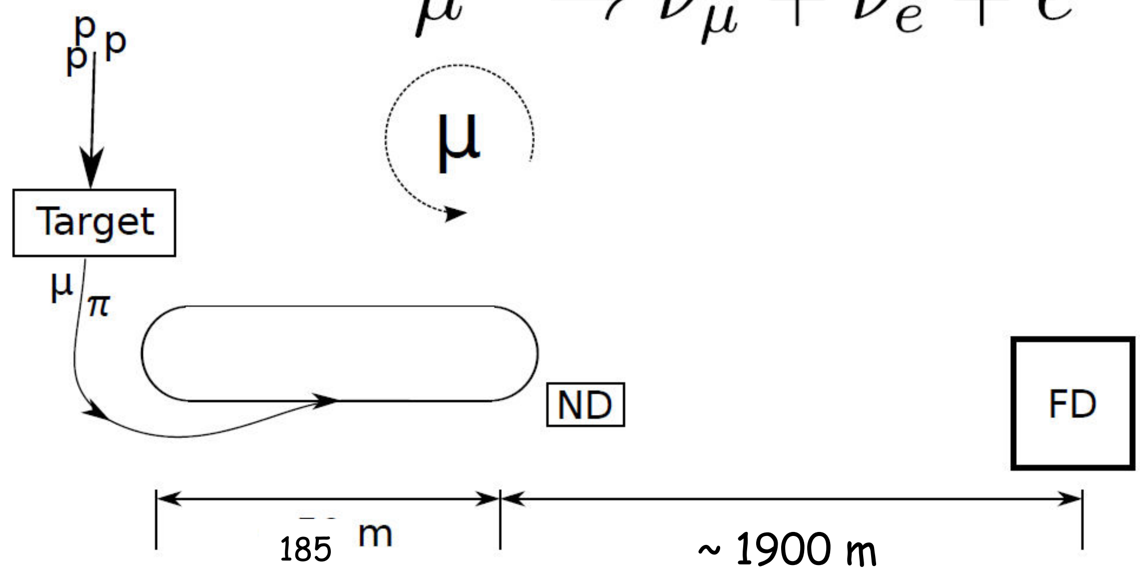
Appearance

The Golden channel

Experimental Layout

Chris Tunnell
Oxford*

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



Appearance-only (though disappearance good too!)

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

Appearance Channel:

$\nu_e \rightarrow \nu_\mu$

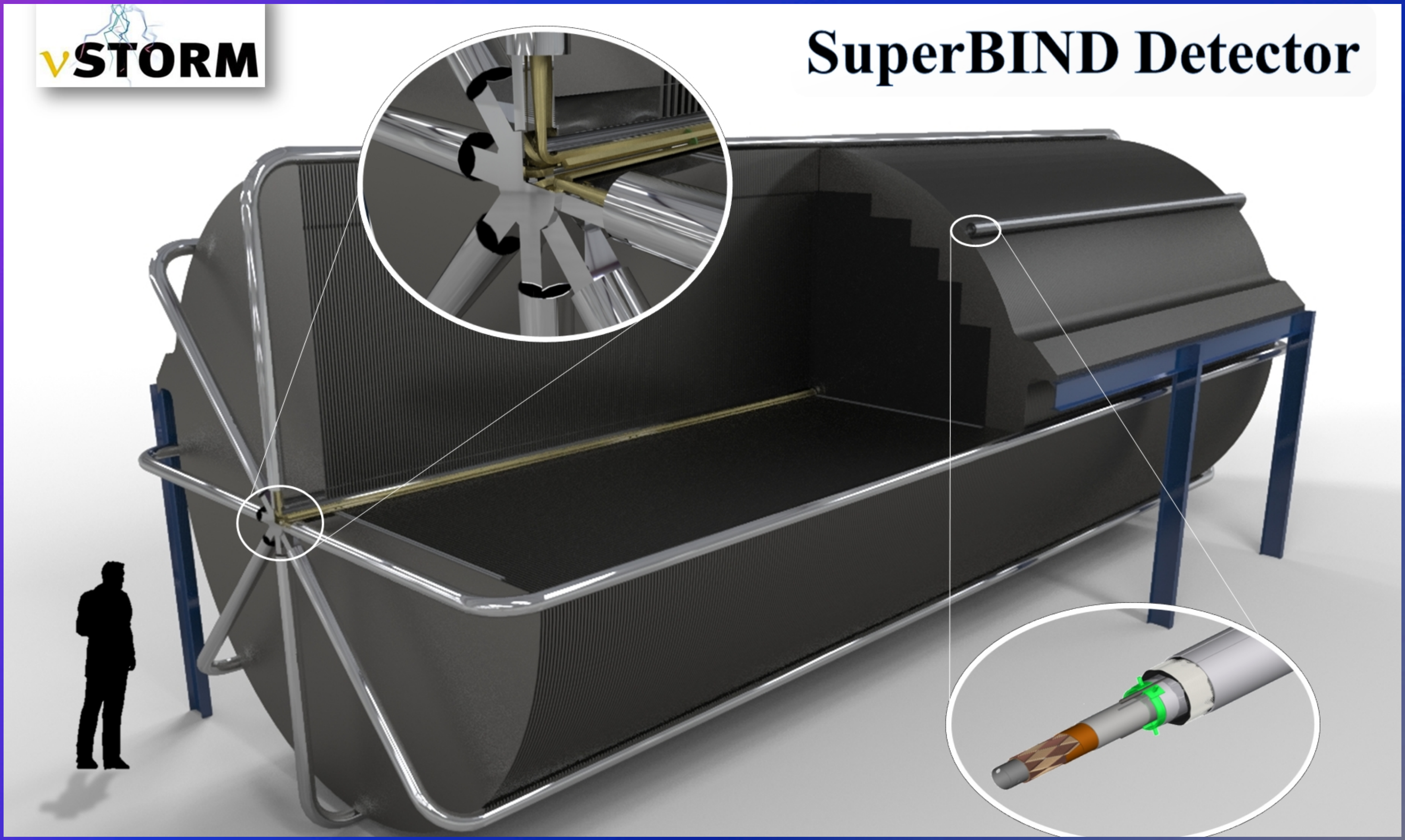
Golden Channel

Must reject the "wrong" sign μ with great efficiency

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

* Now at NIKHEF

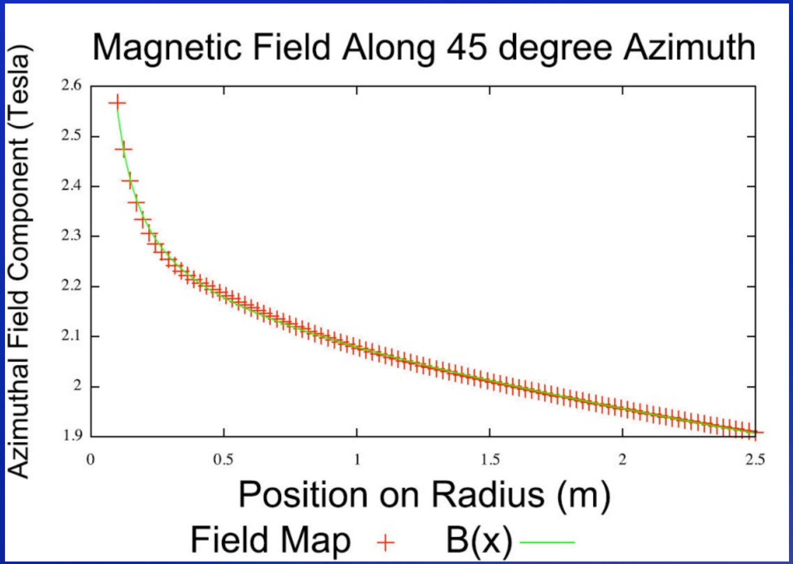
SuperBIND



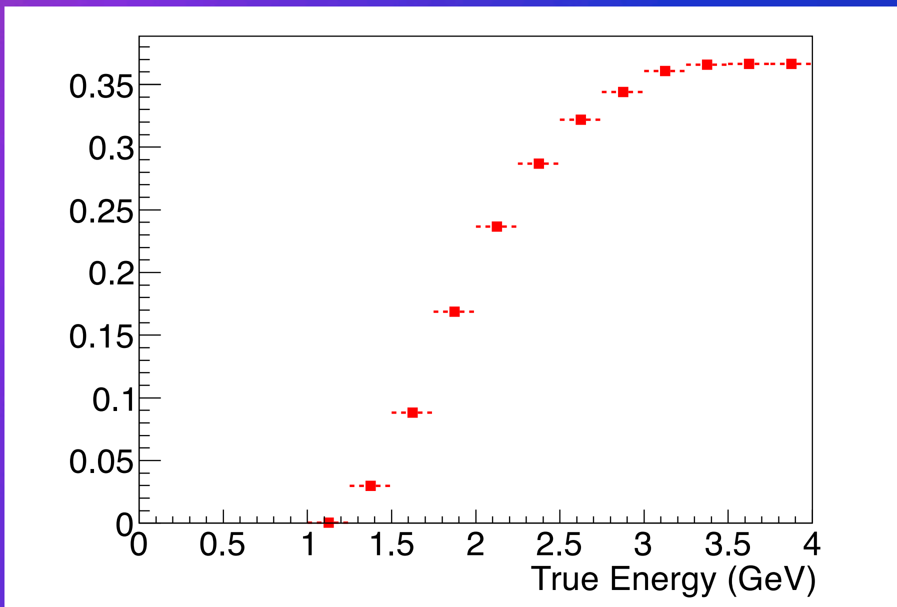
Ryan Bayes
Steve Bramsiepe
Glasgow

Simulation – ν_μ appearance

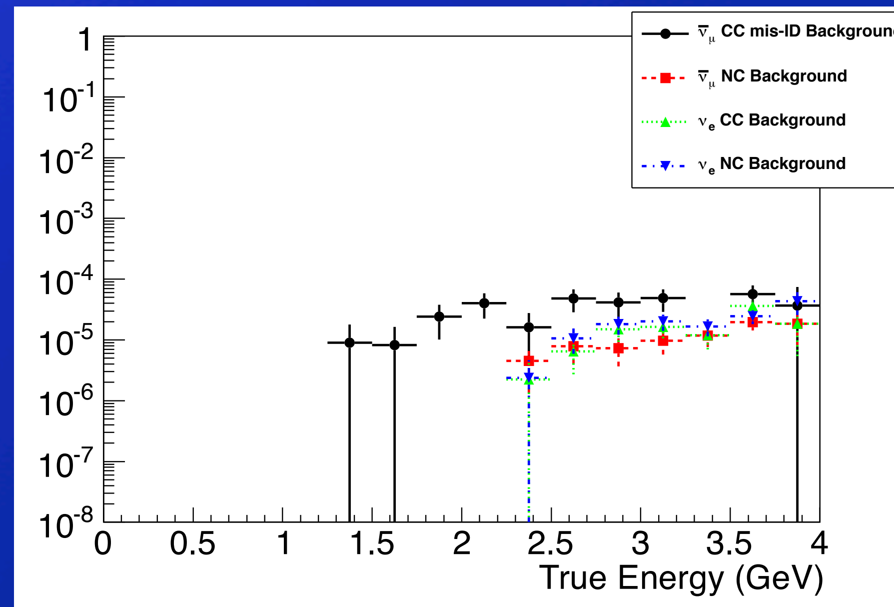
- Full GEANT4 Simulation
  - Extrapolation from ISS and IDS-NF studies for the MIND detector
  - Uses GENIE to generate the neutrino interactions.
  - Involves a flexible geometry that allows the dimensions of the detector to be altered easily (for optimization purposes, for example).
  - Have not used the detailed B field map, but parameterized fit is very good
  - Event selection/cuts
  - Multivariate analysis



Event reconstruction efficiency & Backgrounds



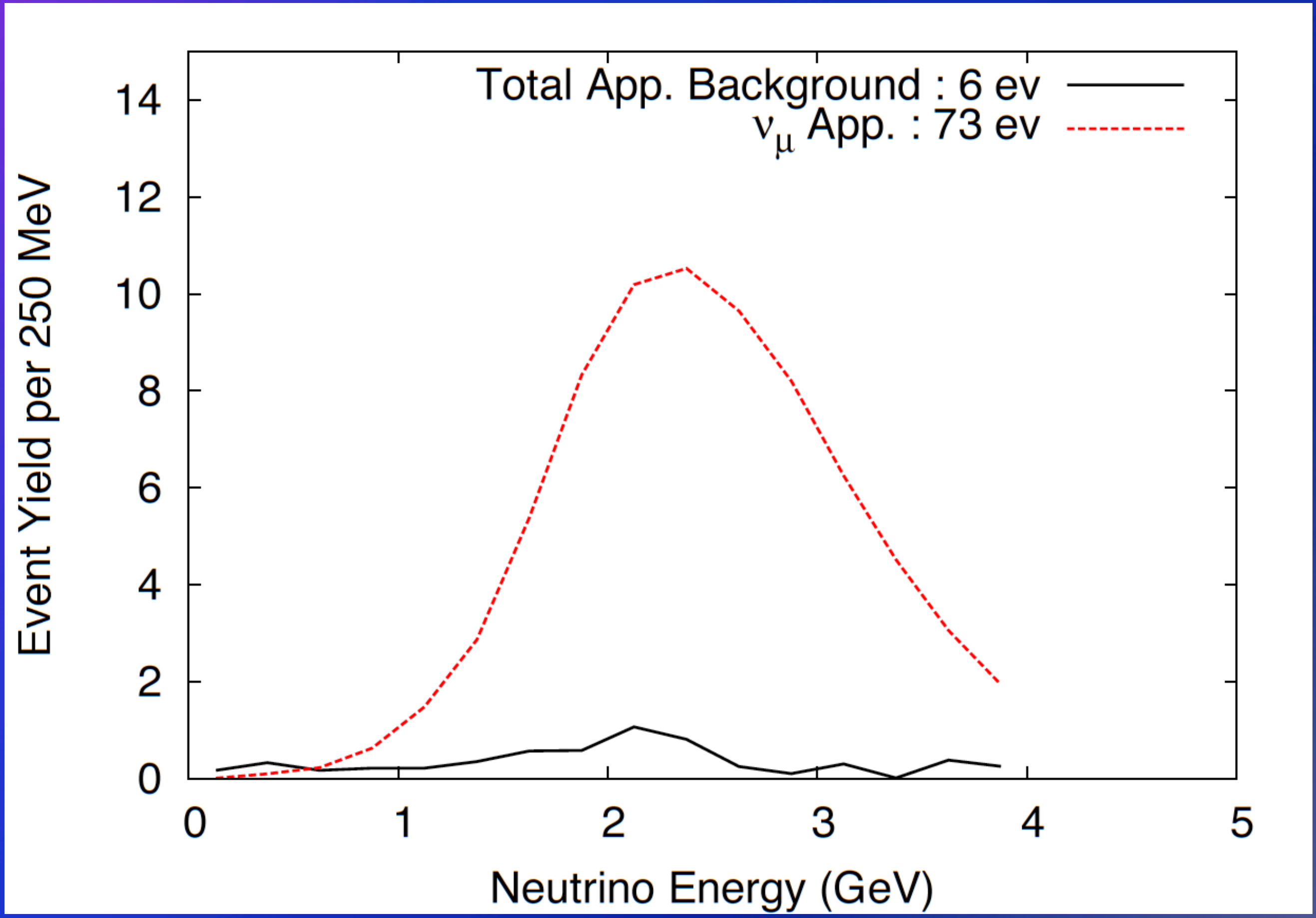
Signal efficiency



Background efficiency

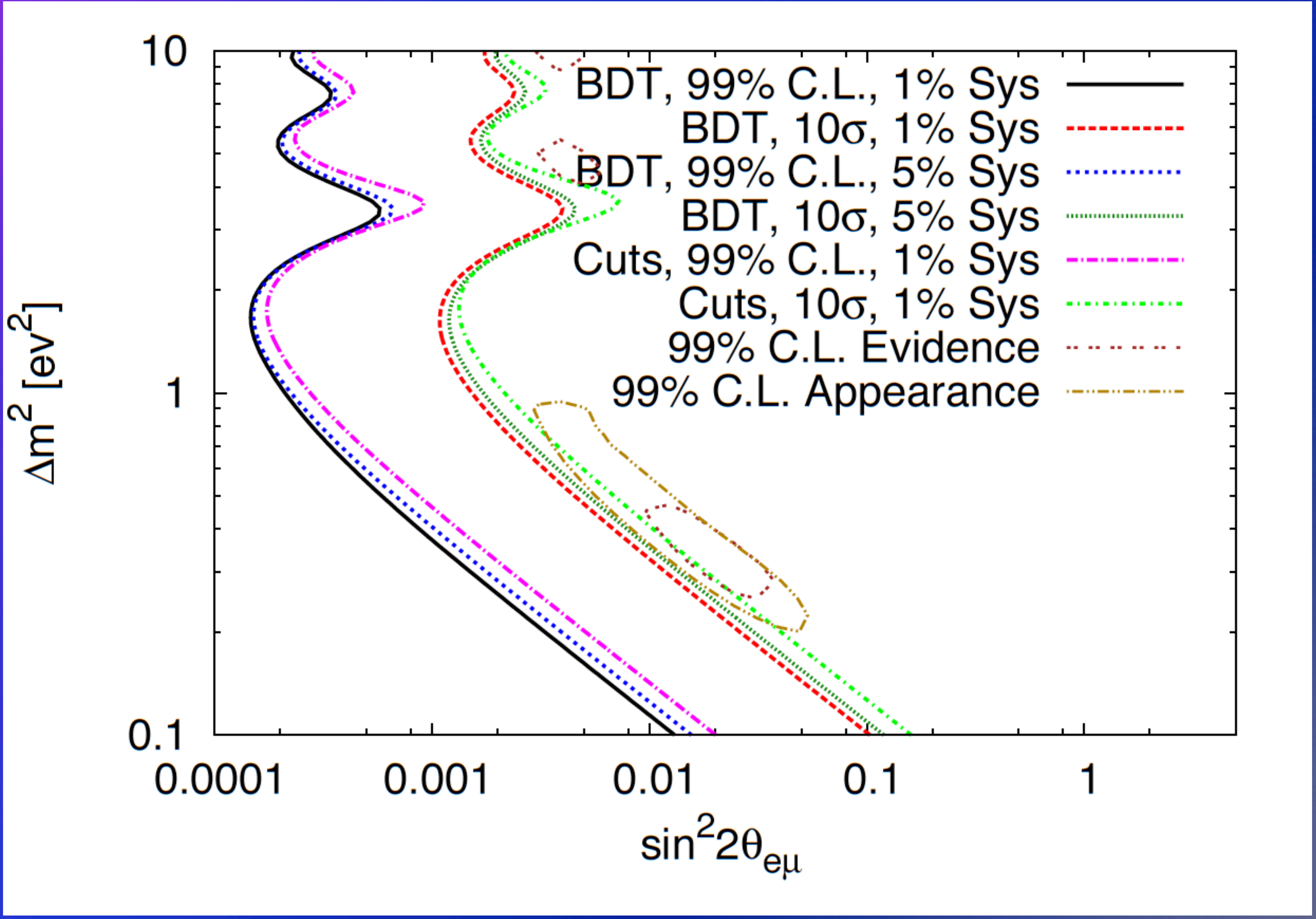
Boosted Decision Tree (BDT) analysis

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

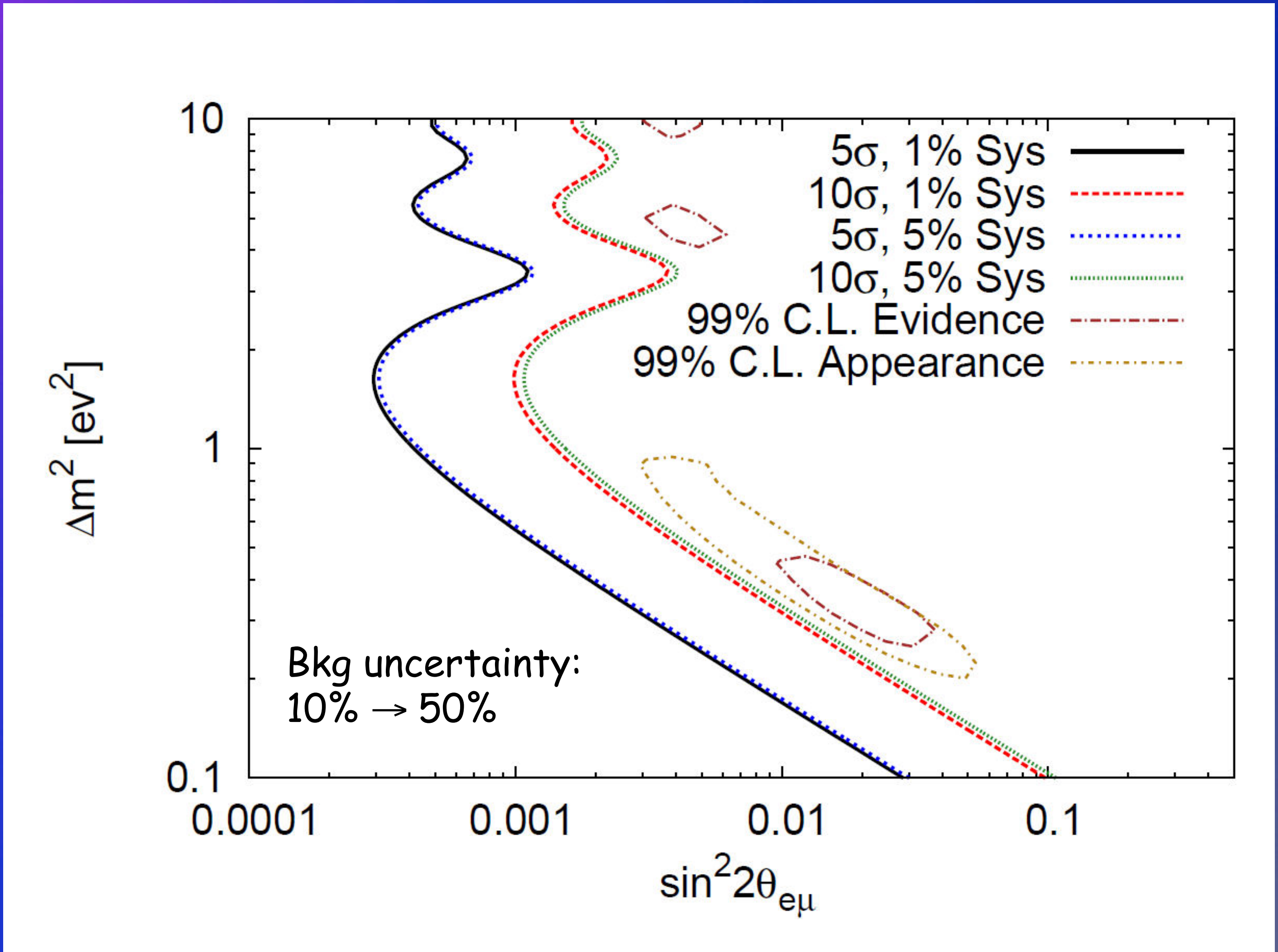


S:B = 12:1

Appearance
Exclusion contours



"Robustness" of appearance search



Disappearance searches

Raw Event Rates

Neutrino mode with stored μ^+.

Channel	$N_{osc.}$	N_{null}	Diff.	$(N_{osc.} - N_{null})/\sqrt{N_{null}}$
$\nu_e \to \nu_\mu$ CC	332	0	∞	∞
$\bar{\nu}_\mu \to \bar{\nu}_\mu$ NC	47679	50073	-4.8%	-10.7
$\nu_e \to \nu_e$ NC	73941	78805	-6.2%	-17.3
$\bar{\nu}_\mu \to \bar{\nu}_\mu$ CC	122322	128433	-4.8%	-17.1
$\nu_e \to \nu_e$ CC	216657	230766	-6.1%	-29.4

Anti-neutrino mode with stored μ^-.

Channel	$N_{osc.}$	N_{null}	Diff.	$(N_{osc.} - N_{null})/\sqrt{N_{null}}$
$\bar{\nu}_e \to \bar{\nu}_\mu$ CC	117	0	∞	∞
$\bar{\nu}_e \to \bar{\nu}_e$ NC	30511	32481	-6.1%	-10.9
$\nu_\mu \to \nu_\mu$ NC	66037	69420	-4.9%	-12.8
$\bar{\nu}_e \to \bar{\nu}_e$ CC	77600	82589	-6.0%	-17.4
$\nu_\mu \to \nu_\mu$ CC	197284	207274	-4.8%	-21.9

μ dis. channels follow naturally from μ appear.

ν_e channels will take more work

Tremendous Statistical Significance

3+1 Assumption

Appearance channels

Accelerator R&D

Looking Forward

νSTORM

Looking Forward: Beyond ν physics
Friends in High Places

Conclusions (cont)

- The recent discovery of the Higgs particle of 125 GeV at CERN has brought in also the additional requirement of a remarkably small longitudinal emittance.
- The unique feature of the direct production of a H° scalar in the s-state is that the mass, total width and all partial widths of the H° can be directly measured with remarkable accuracy.
- The main innovative component could be the practical and experimental realization of a *full scale cooling demonstrator*, a relatively modest and low cost system but capable to conclusively demonstrate "ionization cooling" at the level required for a Higgs factory and eventually as premise for a subsequent multi-TeV collider and/or a long distance ν factory
- The additional but conventional facilities necessary to realize the facility with the appropriate luminosity should be constructed *only after the success of this "initial cooling experiment" has been conclusively demonstrated*.

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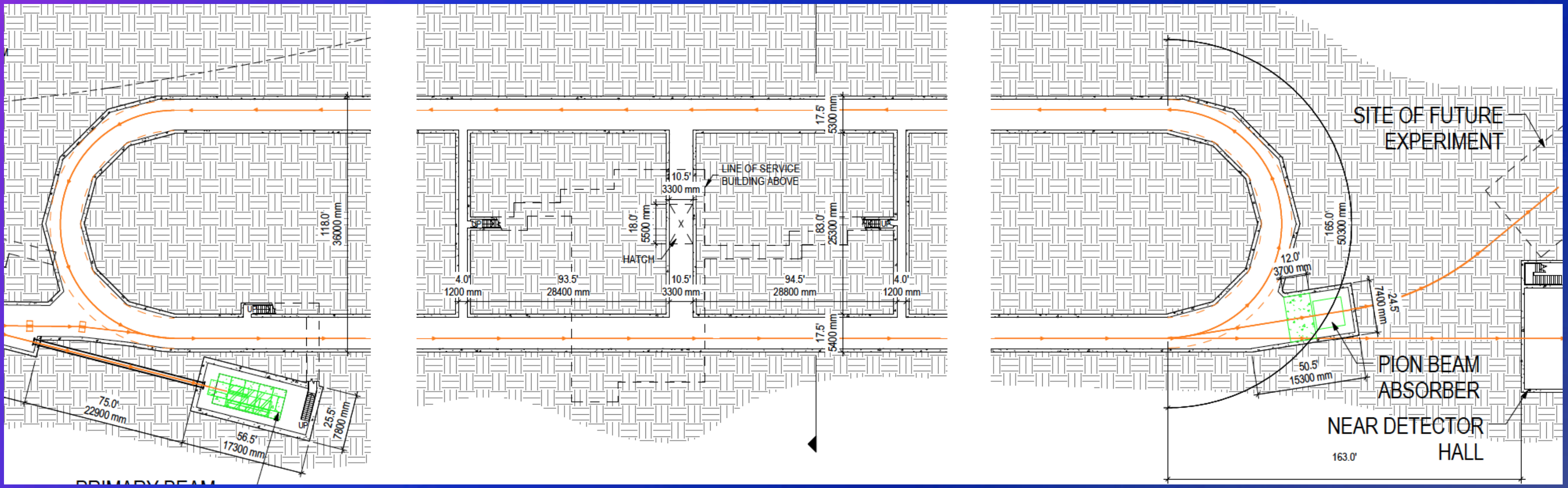
C. Rubbia, Neutrino Telescopes 2013

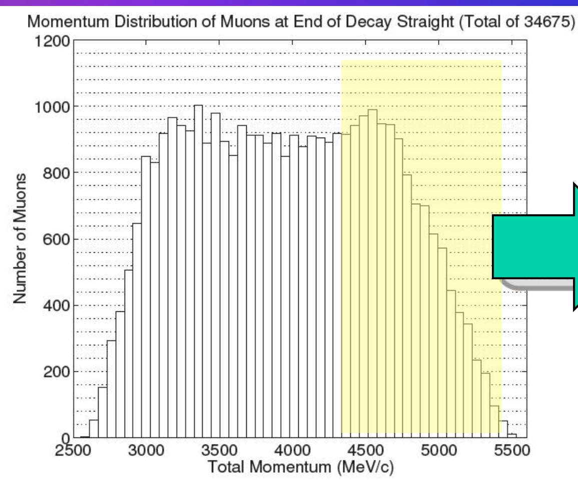
nuSTORM

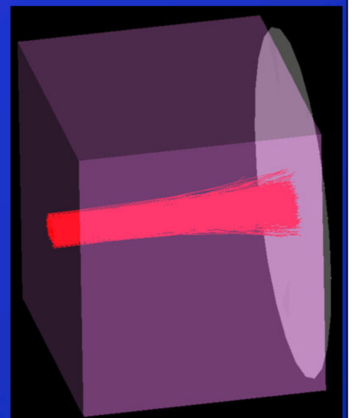
Setting the stage for the next step

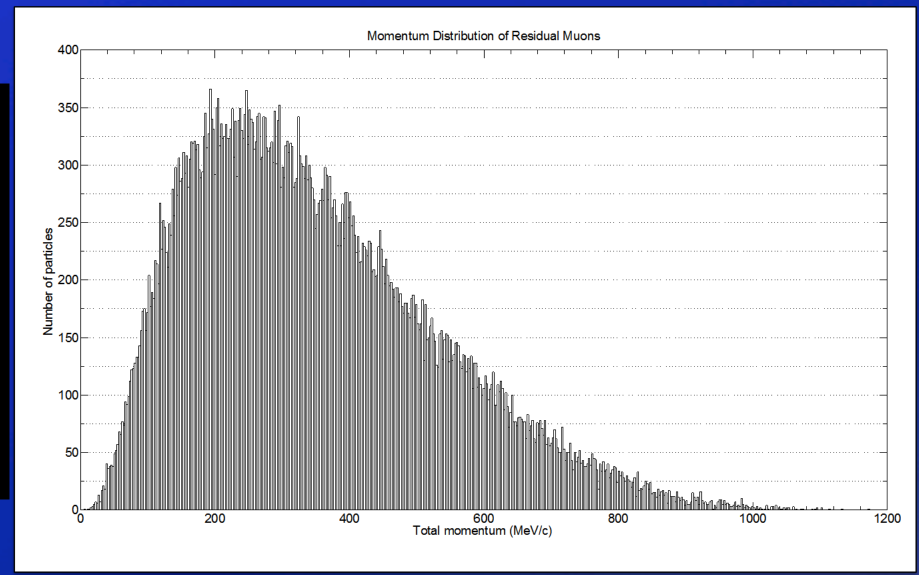


Only ~50% of πs decay in straight
Need π absorber

Low Energy μ beam

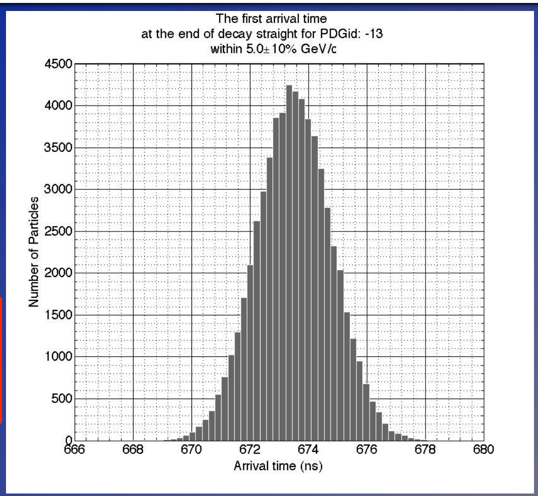






At end of straight we have a lot of πs, but also a lot of μs with 4.5 < P(GeV/c) < 5.5

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



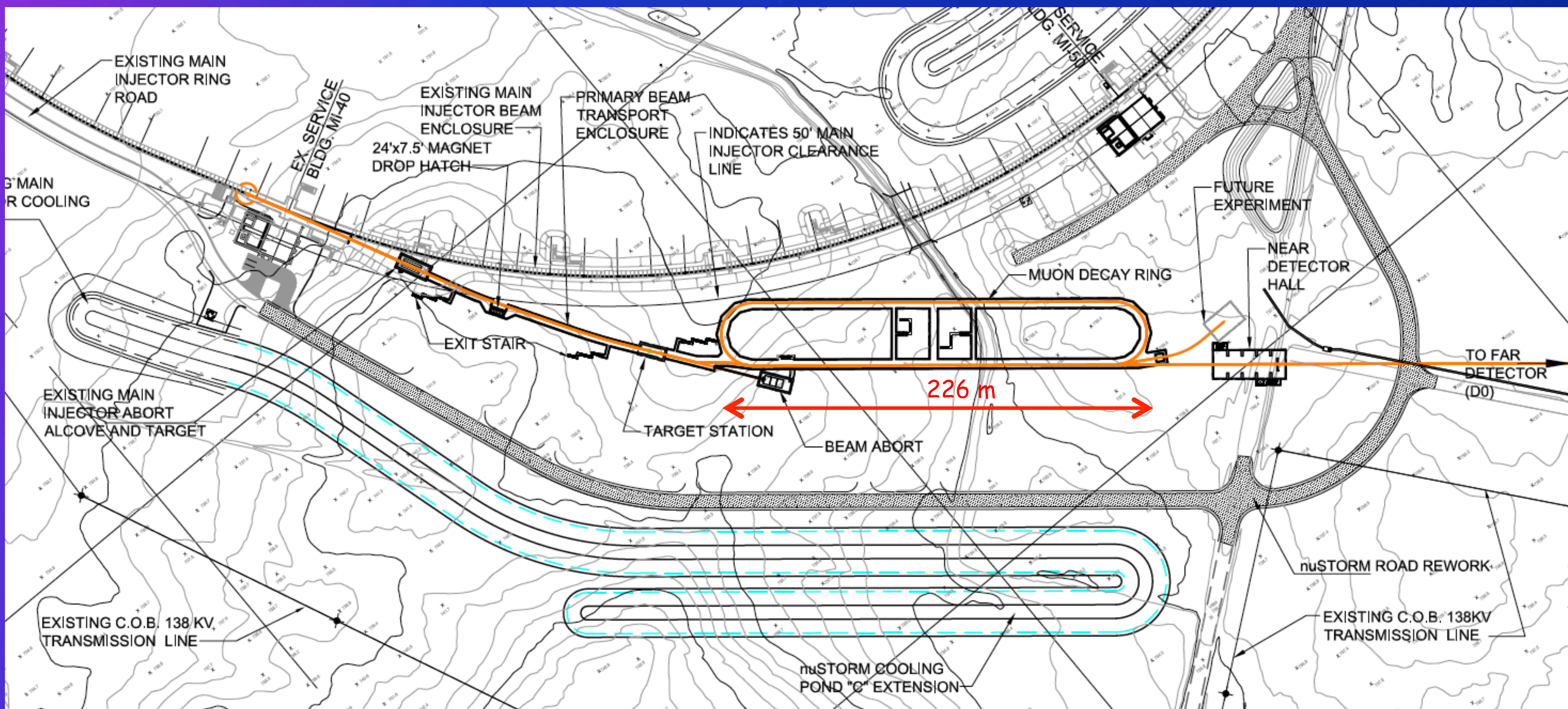
≈ 1.5 ns FWHM (preliminary)

Siting at Fermilab

Siting Plan

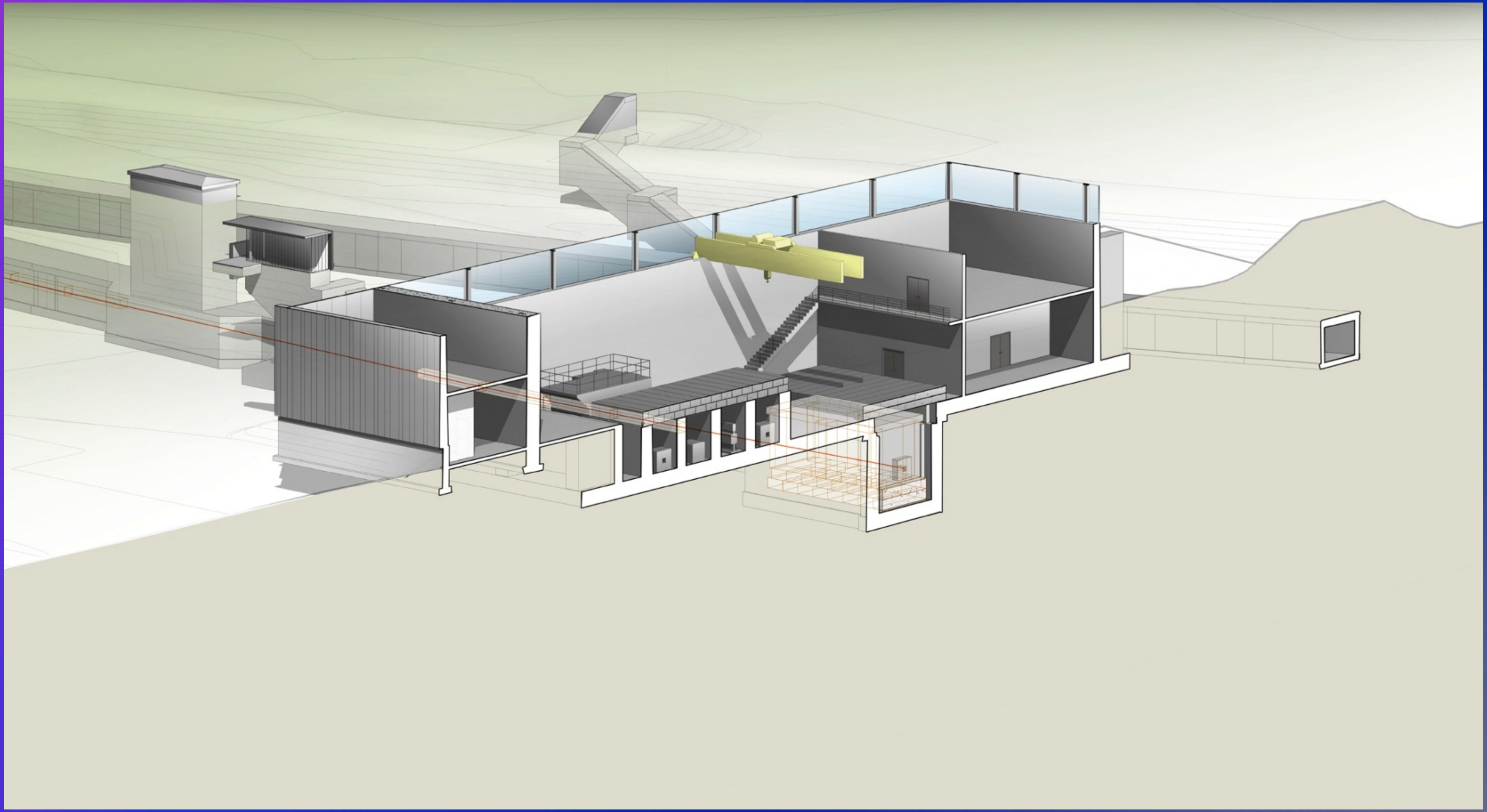
Steve Dixon
Fermilab FESS

Site schematic

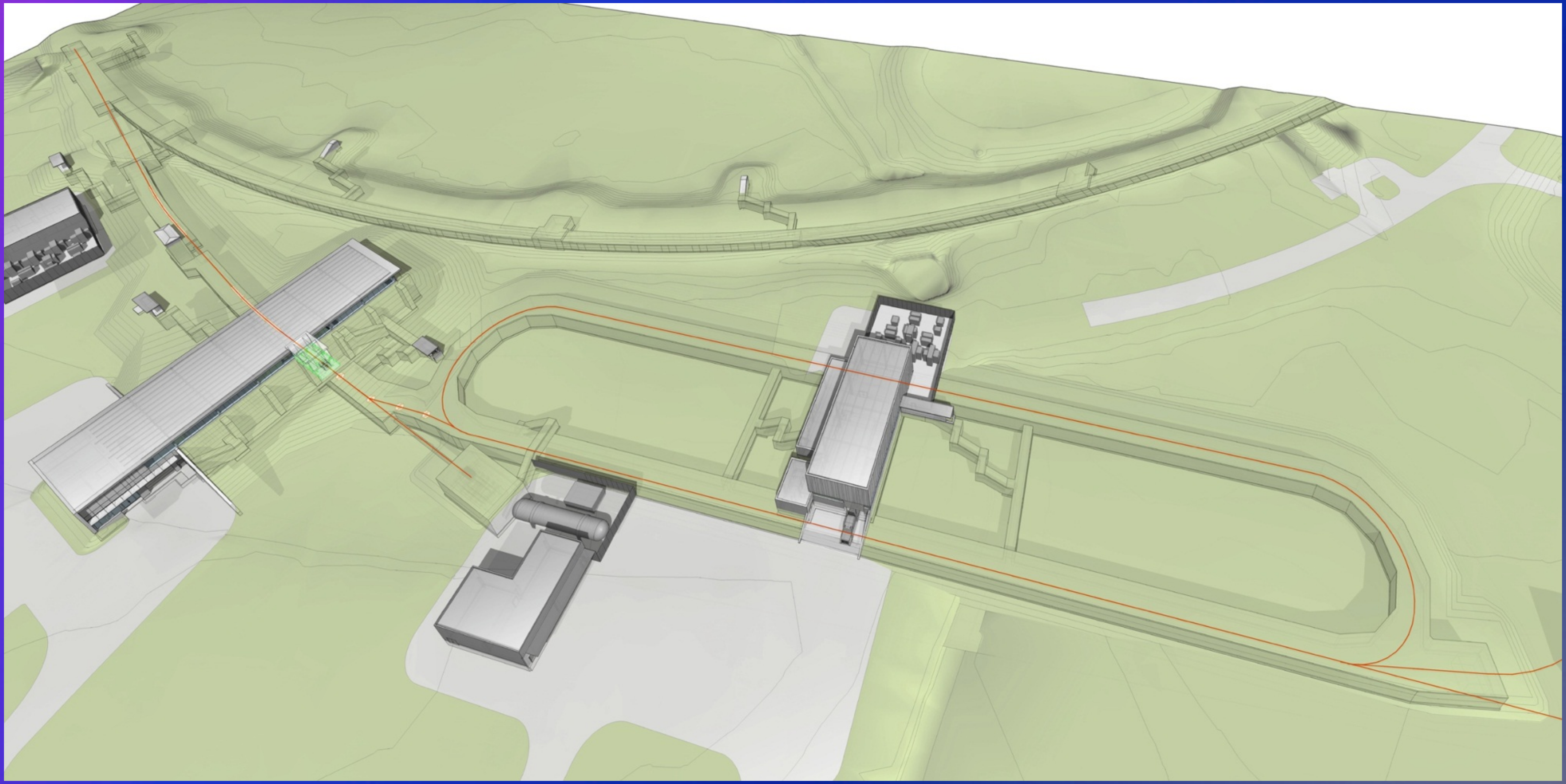


Target Station

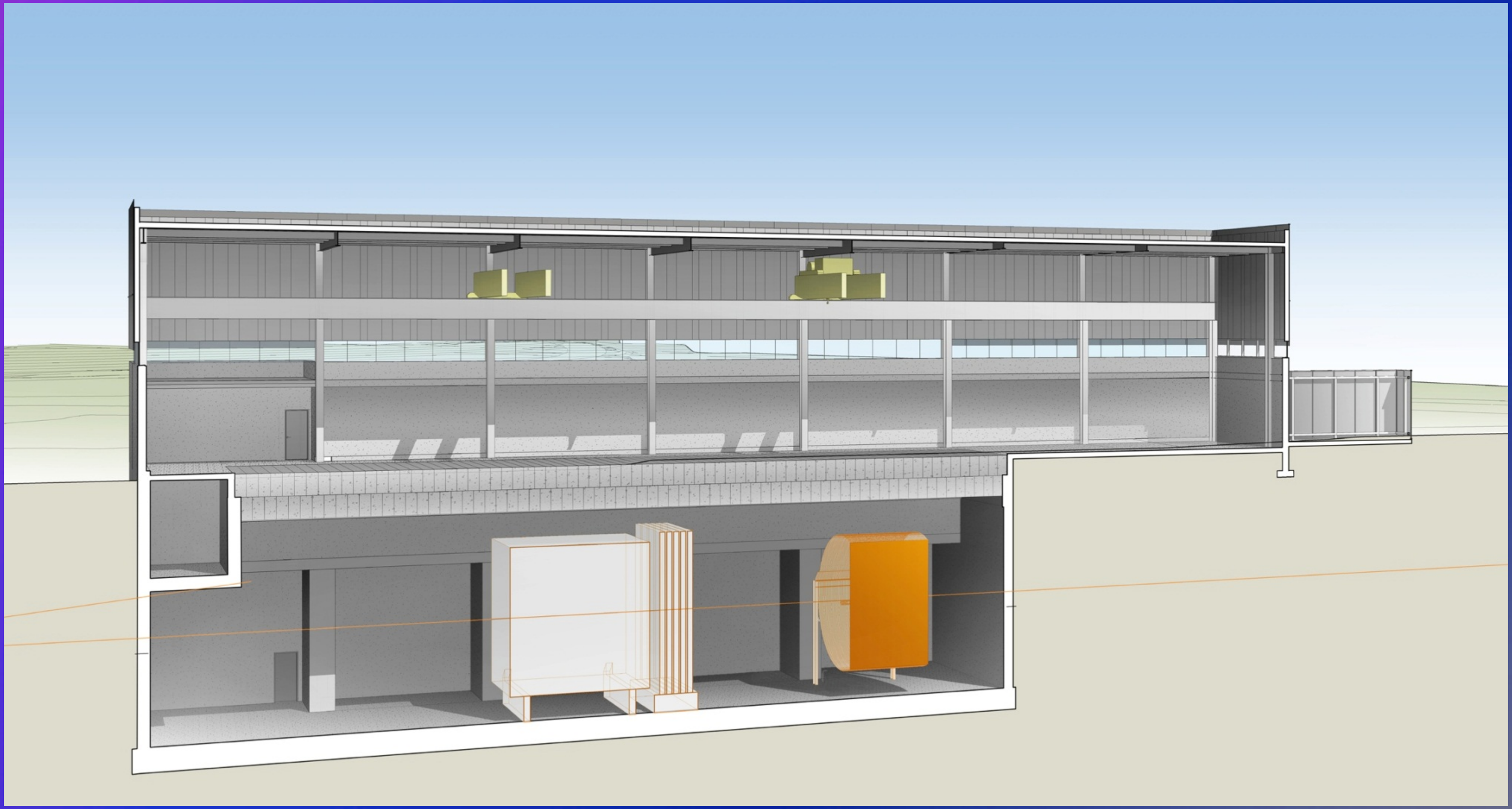
TS section



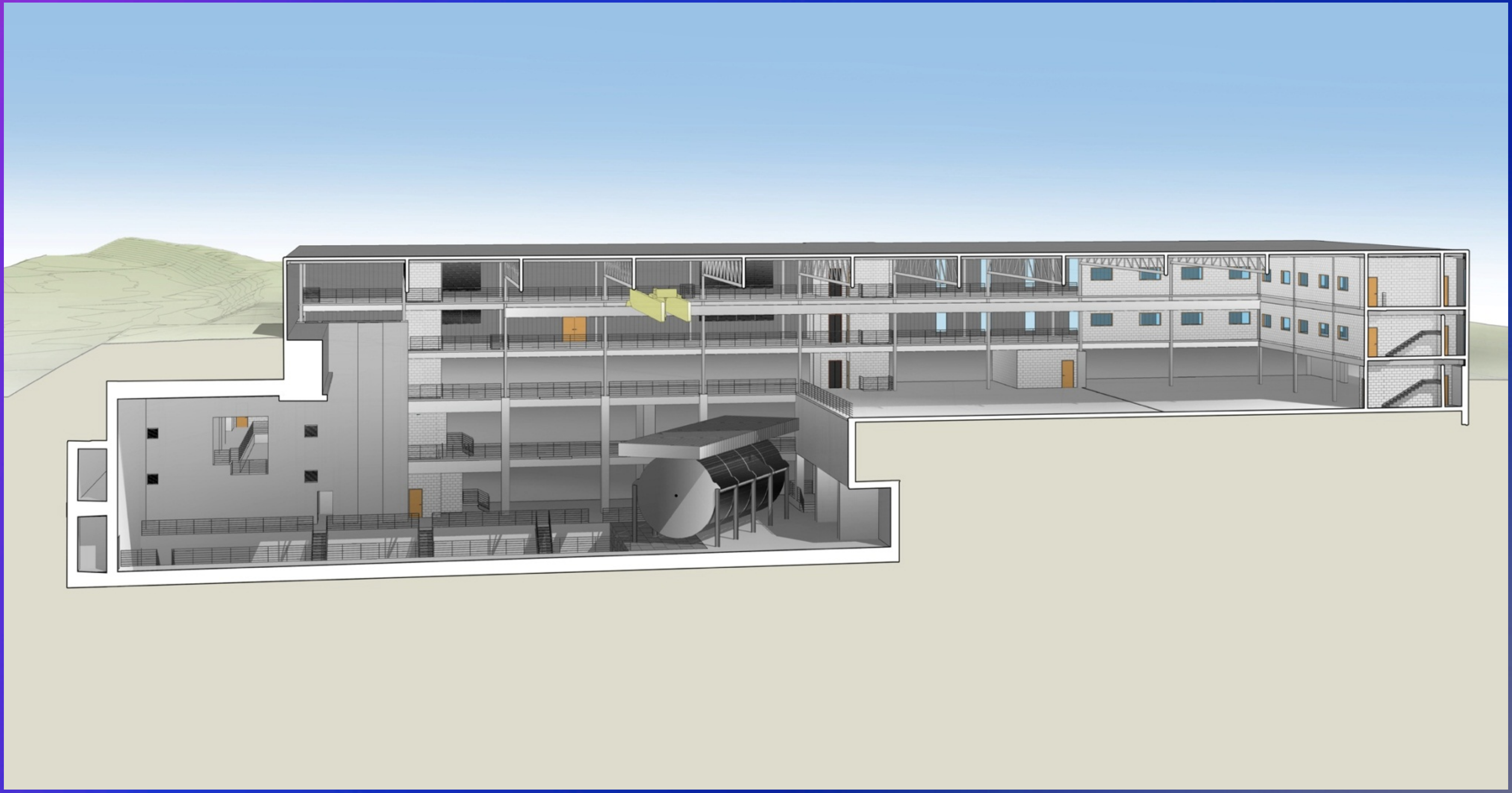
Decay ring



Near detector hall



Far Detector Hall
D0 Assembly Building



Cost:
Sorry Sir, we don't take American Express

nuSTORM Costing

Sub System	Cost M$
Primary Beam Line	28.5
Target Station	37.9
Transport Line	16.5
Decay Ring	135.2
Near Hall	23.5[1]
SuperBIND	27.1[2]
Site work	27
Other	2.5
Sub Total	**298.2**
Management	37.1[3]
Total	**335.3**

Total contingency – 45%

[1]Near Hall sized for multiple experiments & ND for SBL oscillation physics
[2]1.3kT Far + .2kT Near & include DAB work
[3]Assumes LBNE estimates: Proj. Office (10%), L2 (9.4%), L3 (4%)

Moving Forward

nuSTORM

- Twin-Track Approach
  - Develop International support at the Laboratory level for the concept
    - Already Bottom-up (grass roots), now add Top-down
  - LOI to Fermilab (June 2012), EOI to CERN (April 2013), Proposal to Fermilab (June 2013)
- Has produced significant increase in the size of the collaboration
  - From 38 at time of Fermilab LOI to 110 now (single collaboration)
- Full Proposal submitted to Fermilab PAC in June
  - **nuSTORM has been given Stage I Approval**
- EOI to CERN presented at June SPSC meeting. Requested support to:
  - Investigate in detail how nuSTORM could be implemented at CERN; and
  - Develop options for decisive European contributions to the nuSTORM facility and experimental program wherever the facility is sited
- It defines a roughly two-year program which culminates in the delivery of a Technical Design Report.

νSTORM

nuSTORM: Conclusions

The Physics case:

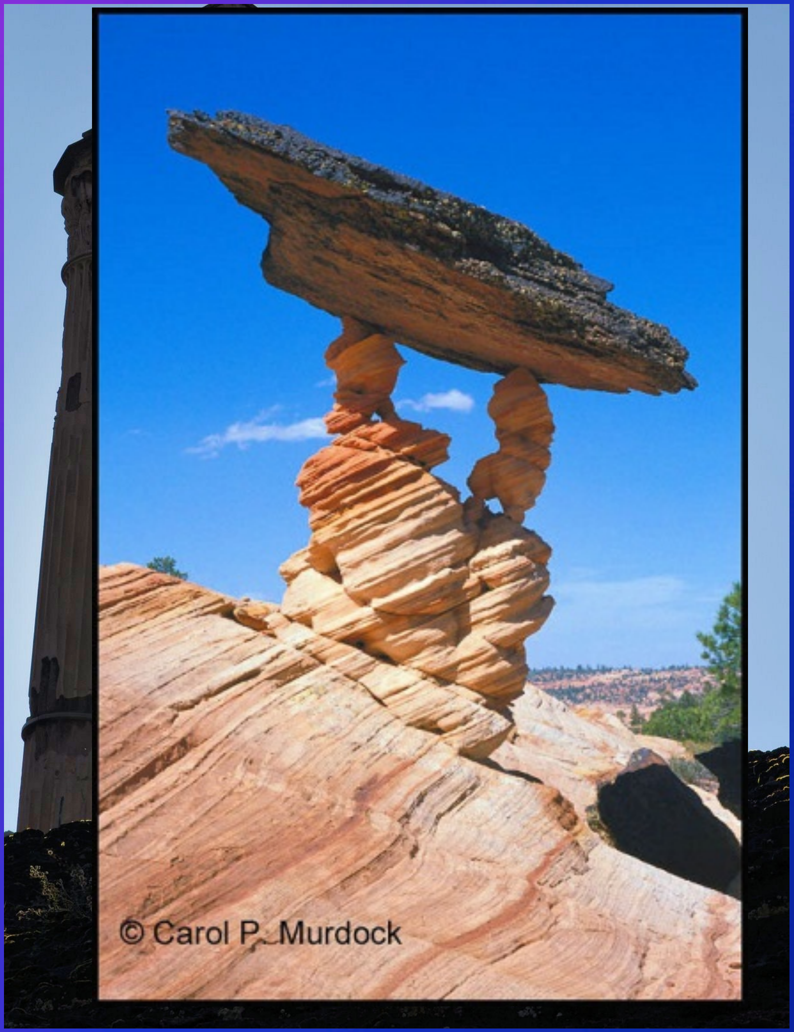
- Simulation work indicates we can confirm/exclude at 10σ (CPT invariant channel) the LSND/MiniBooNE result
  - ν_μ and (ν_e) disappearance experiments delivering at the <1% level look to be doable
    - Systematics need careful analysis
    - Detailed simulation work on these channels has not yet started
- 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
  - First step to the NF and potentially is stagable.
    - Parts of nuSTORM reused
  - Provides μ beam for advanced 6D cooling studies
    - Key element with regard to a return to the EF via $\mu^+\mu^-$
  - *nuSTORM connects the Intensity & Energy Frontiers*
- Has considerable flexibility in its implementation that allows siting at either Fermilab or CERN
  - Just need the protons

Three Pillars of nuSTORM

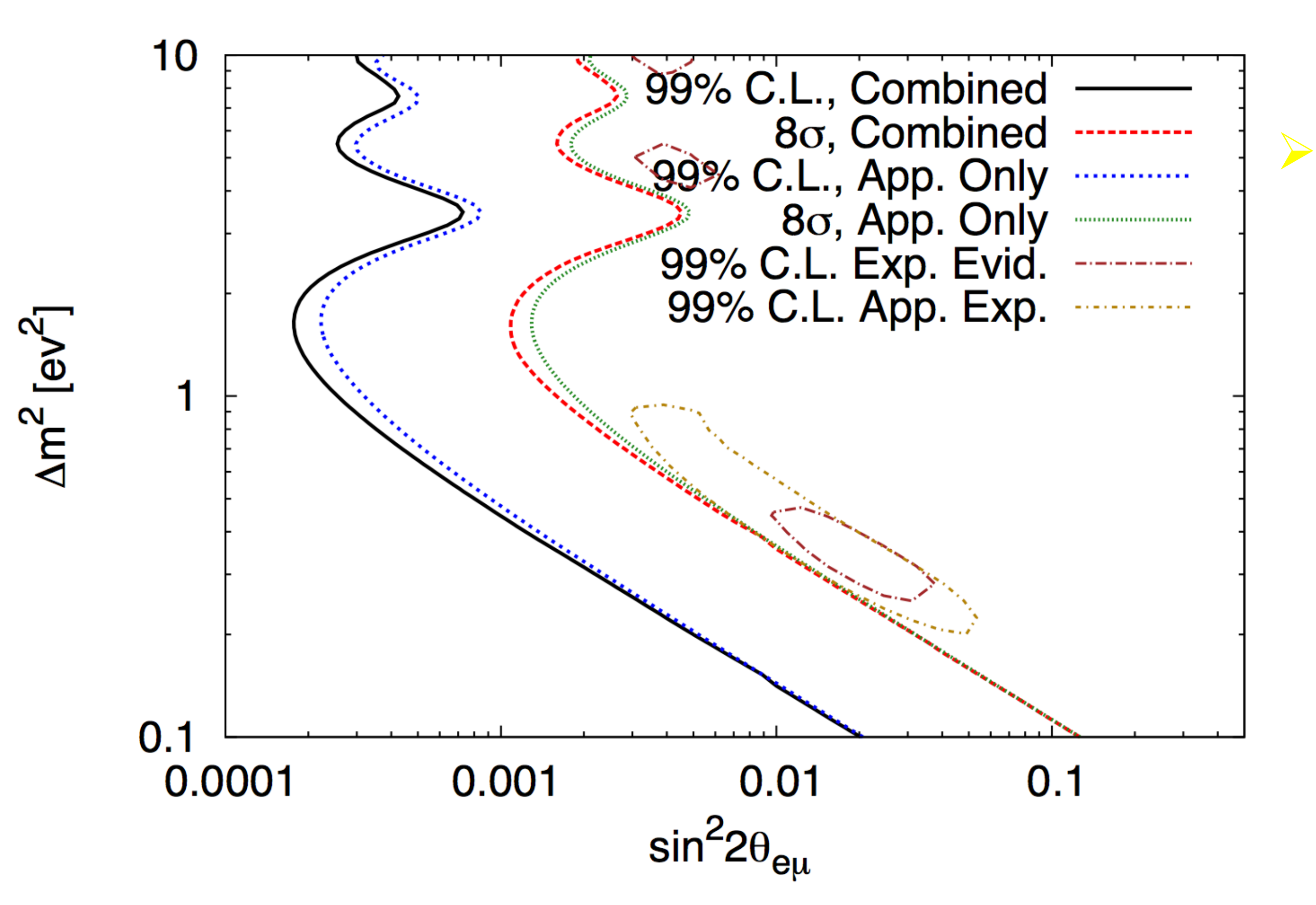


- Deli[illegible]rs o[illegible] the physics fo[illegible] of sterile ν
  - O[illegible]a new approach to th[illegible]tion of ν beams [illegible]σ benchmark t[illegible]make [illegible]finitive statement w/r LSND/ MiniBooNE
- Can add significantly to our knowledge of ν interactions, particularly for ν_e
  - ν *"Light Source"*
- Provides an accelerator & detector technology test bed
  - First step towards full NF

Thank you

Back Ups

"Robustness" of appearance search II

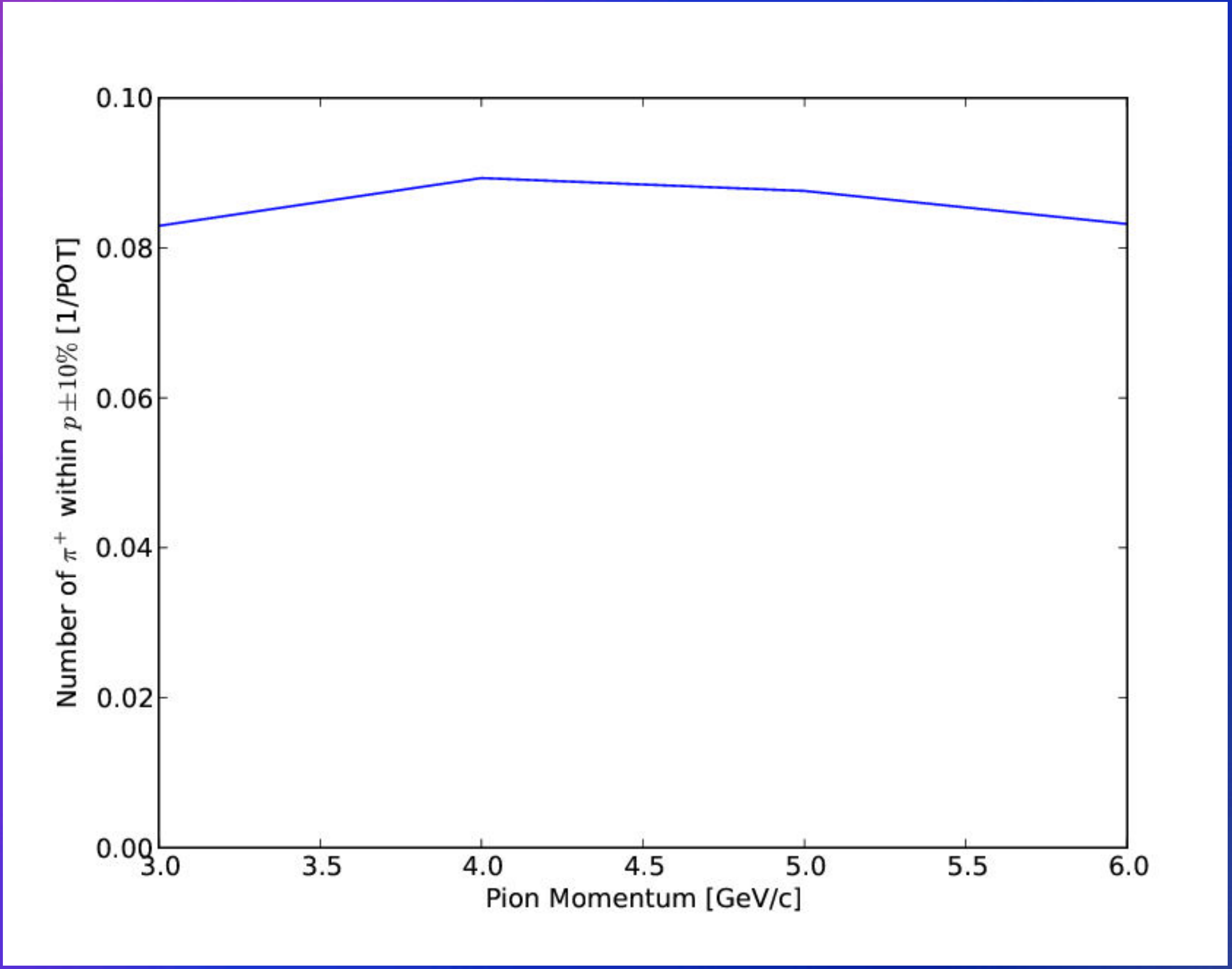


- Approach to recover:
  - DR higher-order correction
    - $A_{dynamic}$ .6 -> .9 [1.5]
  - Target optimization
    - Medium-Z [1.5]

X2.25

Assuming 10^{20} POT/yr. for 5 years, 10σ contour becomes 8σ

π collection
 # within p ± 10%

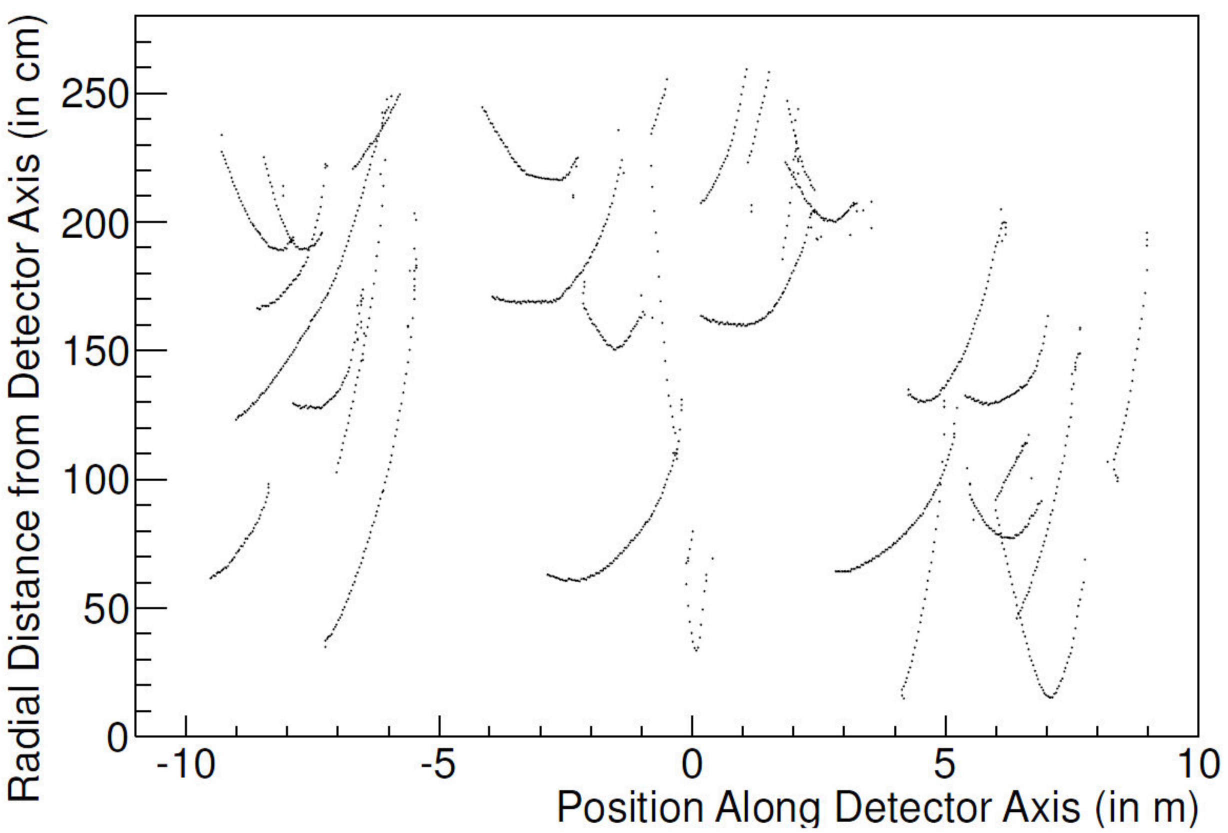


Retune line
(with some loss in efficiency)
to cover $0.3<E_\nu<4$ GeV
&
Resultant extension in L/E
X2-2.5 from lattice
considerations

Detector Issues

Event Candidates in SuperBIND

ν_μ CC Events

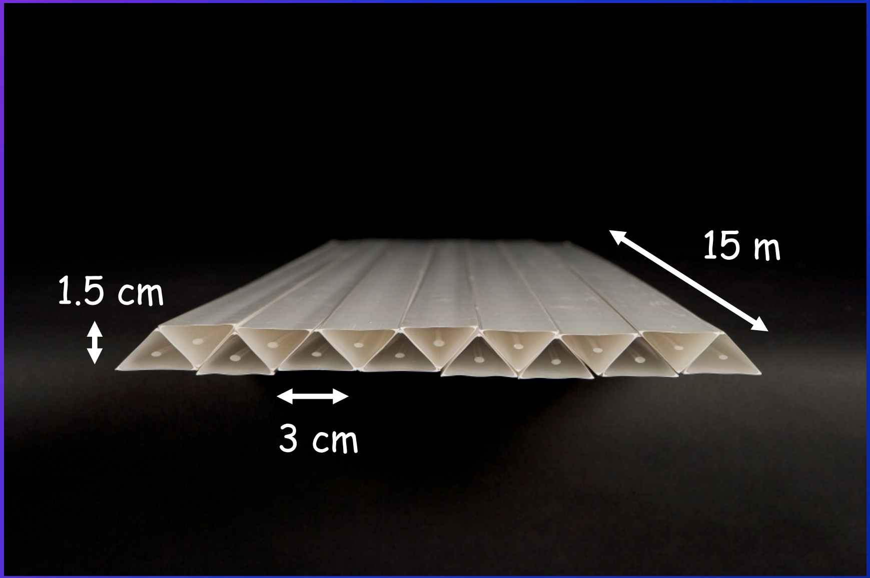


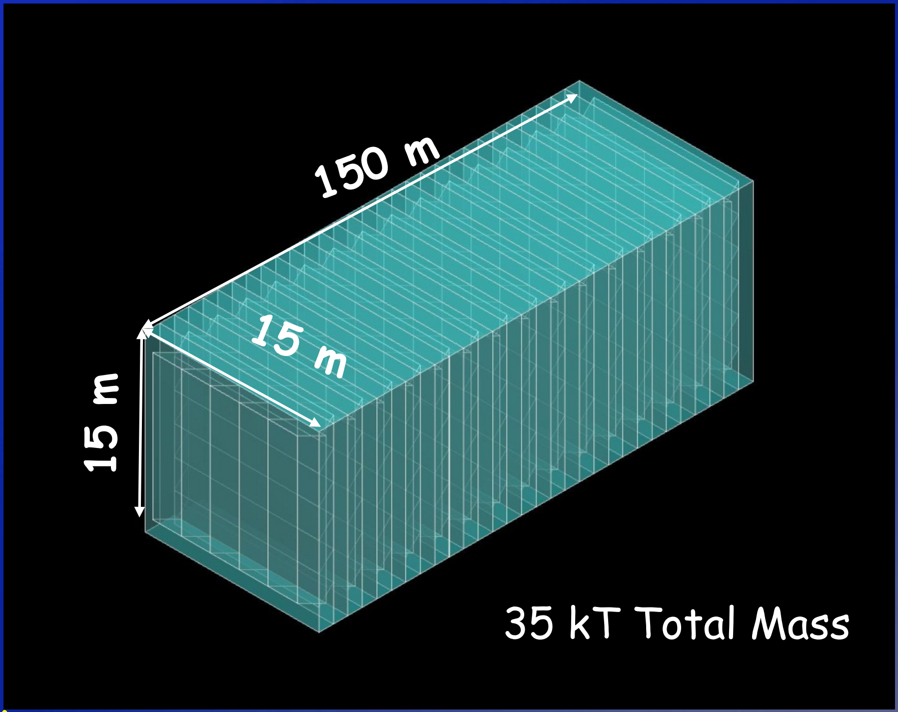
Hits
R vs. Z

Fine-Resolution Totally Active Segmented Detector (IDS-NF)

Simulation of a Totally Active Scintillating Detector (TASD) using Nova and Minerva concepts with Geant4

- 3333 Modules (X and Y plane)
- Each plane contains 1000 slabs
- Total: 6.7M channels



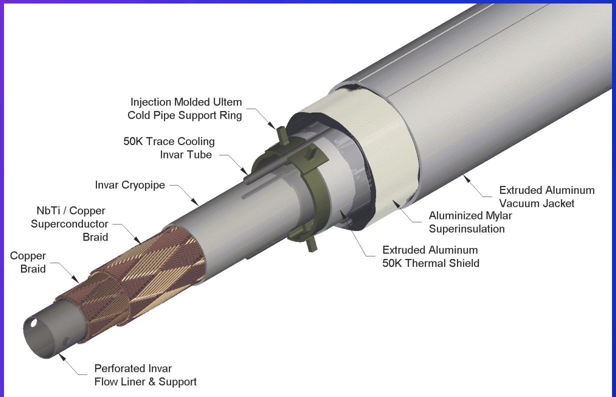


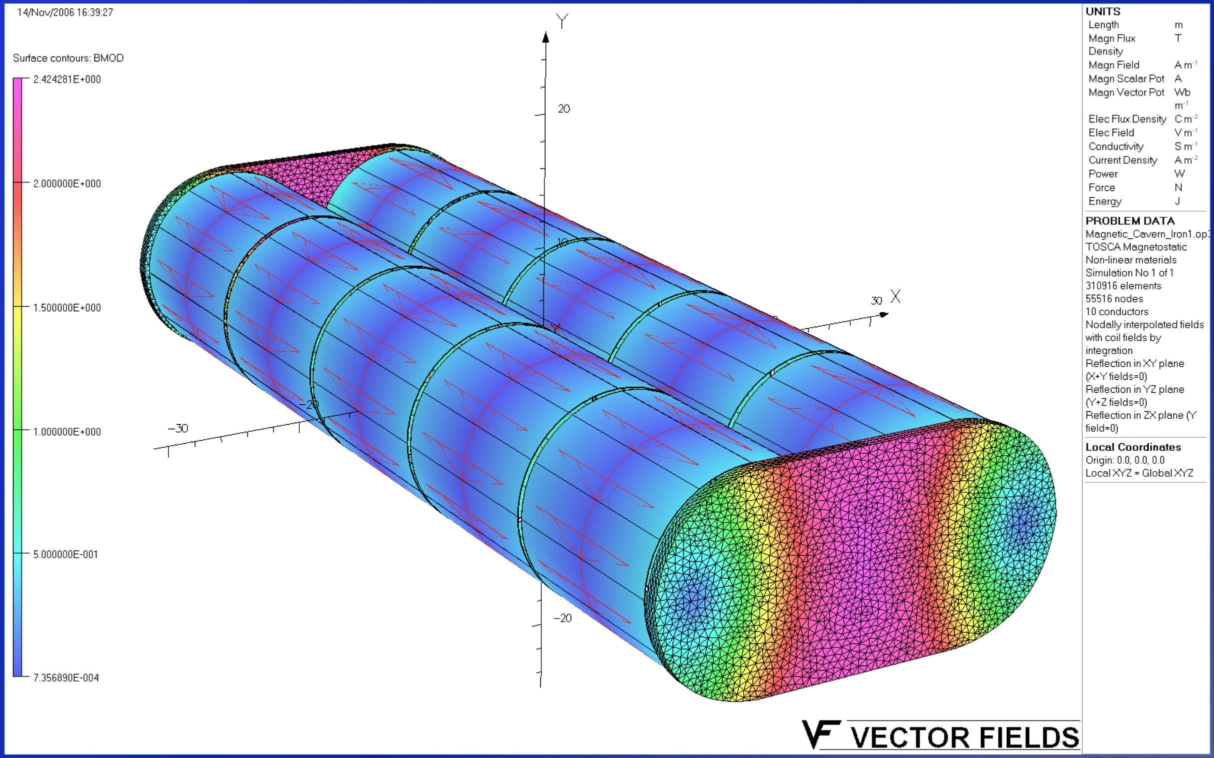
- Momenta between 100 MeV/c to 15 GeV/c
- Magnetic field considered: 0.5 T
- Reconstructed position resolution ~ 4.5 mm

B = 0.5T

Magnet- Concept for IDS-NF

- VLHC SC Transmission Line
  - Technically proven
  - Affordable



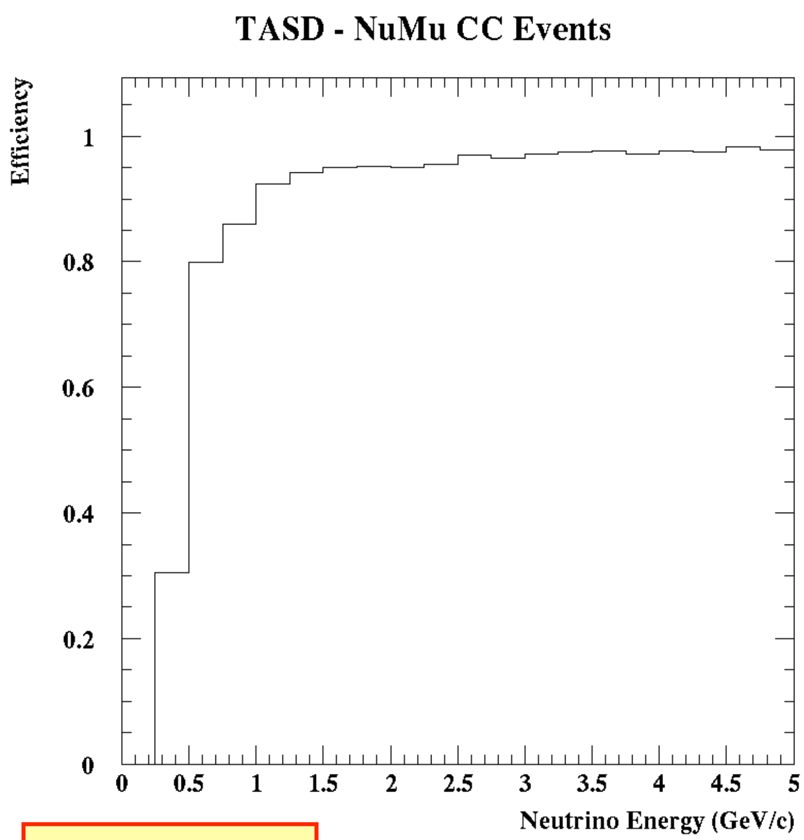


R&D to support concept
Has not been funded

1 m iron wall thickness.
~2.4 T peak field in the iron.
Good field uniformity

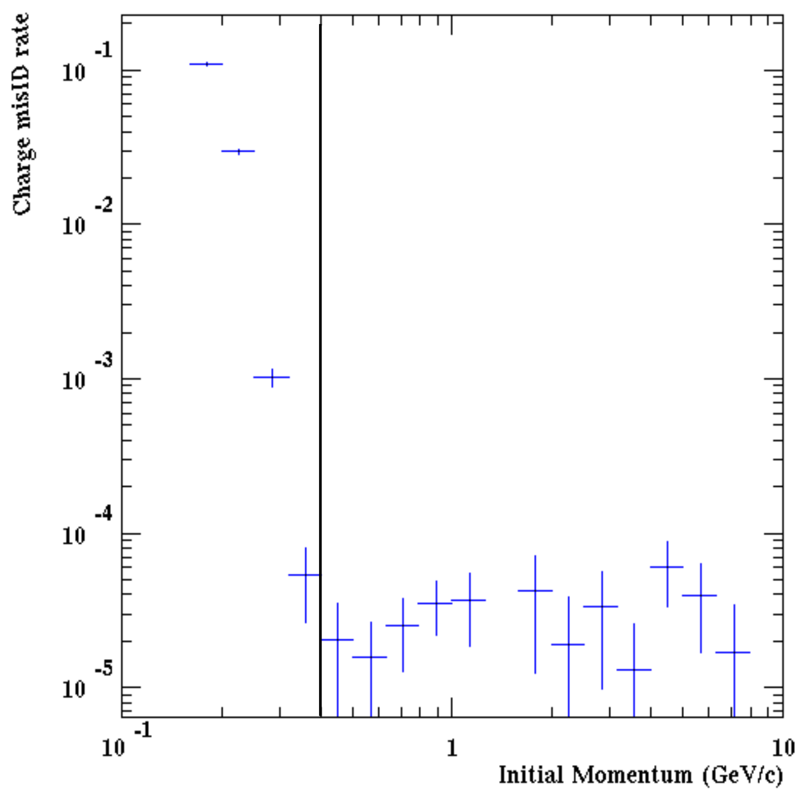
TASD Performance

ν Event Reconstruction ε



Excellent σ_E

Muon charge mis-ID rate



NF Physics & 3+n Models

3 + 3 Model

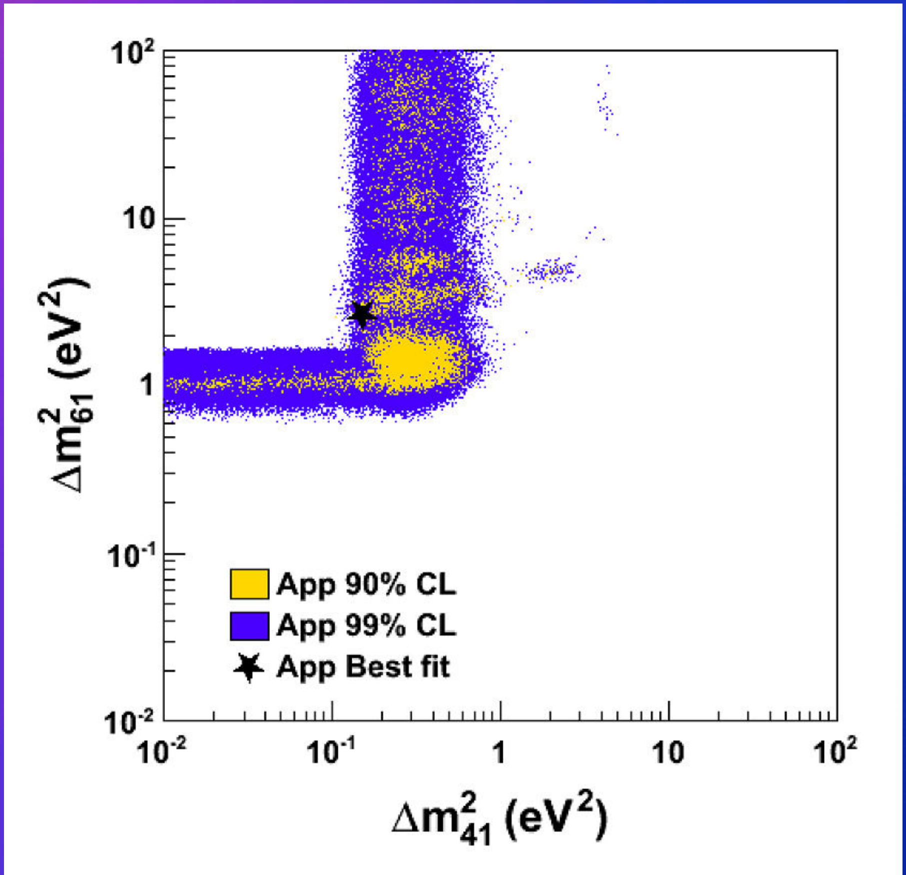
	χ^2_{min} (dof)	χ^2_{null} (dof)	P_{best}	P_{null}	χ^2_{PG} (dof)	PG (%)
3+1						
All	233.9 (237)	286.5 (240)	55%	2.1%	54.0 (24)	0.043%
App	87.8 (87)	147.3 (90)	46%	0.013%	14.1 (9)	12%
Dis	128.2 (147)	139.3 (150)	87%	72%	22.1 (19)	28%
ν	123.5 (120)	133.4 (123)	39%	25%	26.6 (14)	2.2%
$\bar{\nu}$	94.8 (114)	153.1 (117)	90%	1.4%	11.8 (7)	11%
App vs. Dis	-	-	-	-	17.8 (2)	0.013%
ν vs. $\bar{\nu}$	-	-	-	-	15.6 (3)	0.14%
3+2						
All	221.5 (233)	286.5 (240)	69%	2.1%	63.8 (52)	13%
App	75.0 (85)	147.3 (90)	77%	0.013%	16.3 (25)	90%
Dis	122.6 (144)	139.3 (150)	90%	72%	23.6 (23)	43%
ν	116.8 (116)	133.4 (123)	77%	25%	35.0 (29)	21%
$\bar{\nu}$	90.8 (110)	153.1 (117)	90%	1.4%	15.0 (16)	53%
App vs. Dis	-	-	-	-	23.9 (4)	0.0082%
ν vs. $\bar{\nu}$	-	-	-	-	13.9 (7)	5.3%
3+3						
All	218.2 (228)	286.5 (240)	67%	2.1%	68.9 (85)	90%
App	70.8 (81)	147.3 (90)	78%	0.013%	17.6 (45)	100%
Dis	120.3 (141)	139.3 (150)	90%	72%	24.1 (34)	90%
ν	116.7 (111)	133.4 (123)	34%	25%	39.5 (46)	74%
$\bar{\nu}$	90.6 (105)	153 (117)	84%	1.4%	18.5 (27)	89%
App vs. Dis	-	-	-	-	28.3 (6)	0.0081%
ν vs. $\bar{\nu}$	-	-	-	-	110.9 (12)	53%

- *A 3+3 model has recently been shown to better fit all available data*

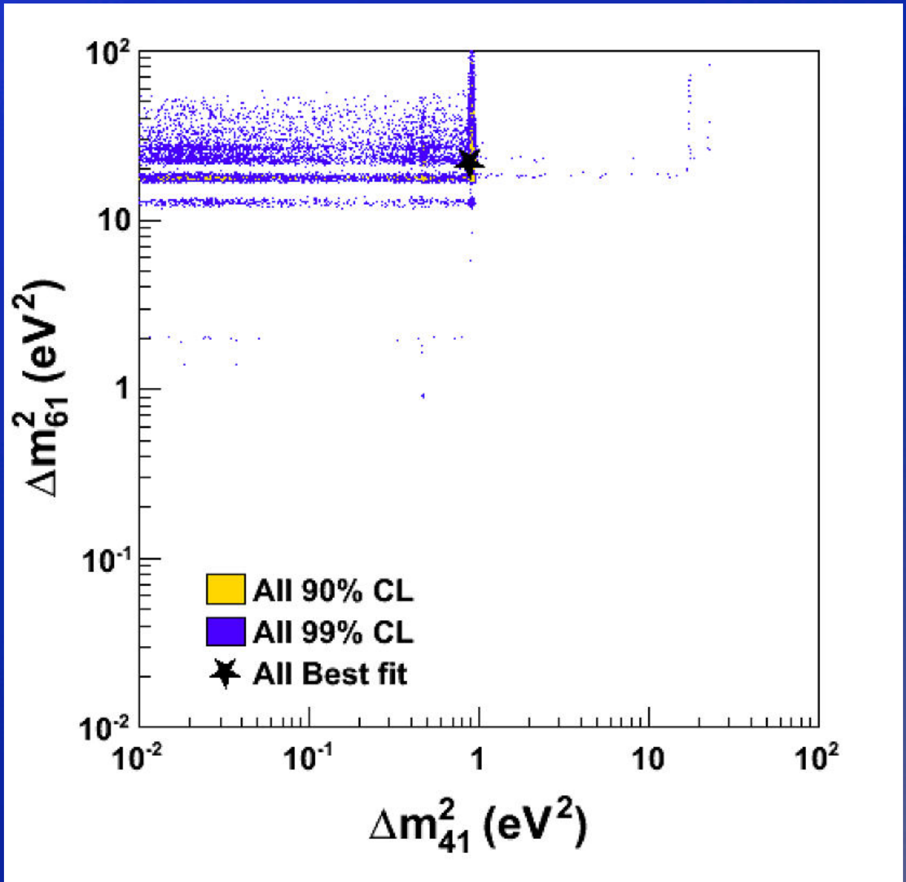
Tag	Section	Process	ν vs. $\bar{\nu}$	App vs. Dis
LSND	3.2.1	$\bar{\nu}_\mu \to \bar{\nu}_e$	$\bar{\nu}$	App
KARMEN	3.2.1	$\bar{\nu}_\mu \to \bar{\nu}_e$	$\bar{\nu}$	App
KARMEN/LSND(xsec)	3.2.1	$\nu_e \to \nu_e$	ν	Dis
BNB-MB(νapp)	3.2.2	$\nu_\mu \to \nu_e$	ν	App
BNB-MB($\bar{\nu}$app)	3.2.2	$\bar{\nu}_\mu \to \bar{\nu}_e$	$\bar{\nu}$	App
NuMI-MB(νapp)	3.2.2	$\nu_\mu \to \nu_e$	ν	App
BNB-MB(νdis)	3.2.2	$\nu_\mu \to \nu_\mu$	ν	Dis
NOMAD	3.2.3	$\nu_\mu \to \nu_e$	ν	App
CCFR84	3.2.3	$\nu_\mu \to \nu_\mu$	ν	Dis
CDHS	3.2.3	$\nu_\mu \to \nu_\mu$	ν	Dis
Bugey	3.2.4	$\bar{\nu}_e \to \bar{\nu}_e$	$\bar{\nu}$	Dis
Gallium	3.2.4	$\nu_e \to \nu_e$	ν	Dis
MINOS-CC	3.2.5	$\bar{\nu}_\mu \to \bar{\nu}_\mu$	$\bar{\nu}$	Dis
ATM	3.2.5	$\nu_\mu \to \nu_\mu$	ν	Dis

J.M. Conrad, C.M. Ignarra, G. Karagiorgi, M.H. Shaevitz, J. Spitz (arXiv:1207.4765v1)

3 + 3 Model II



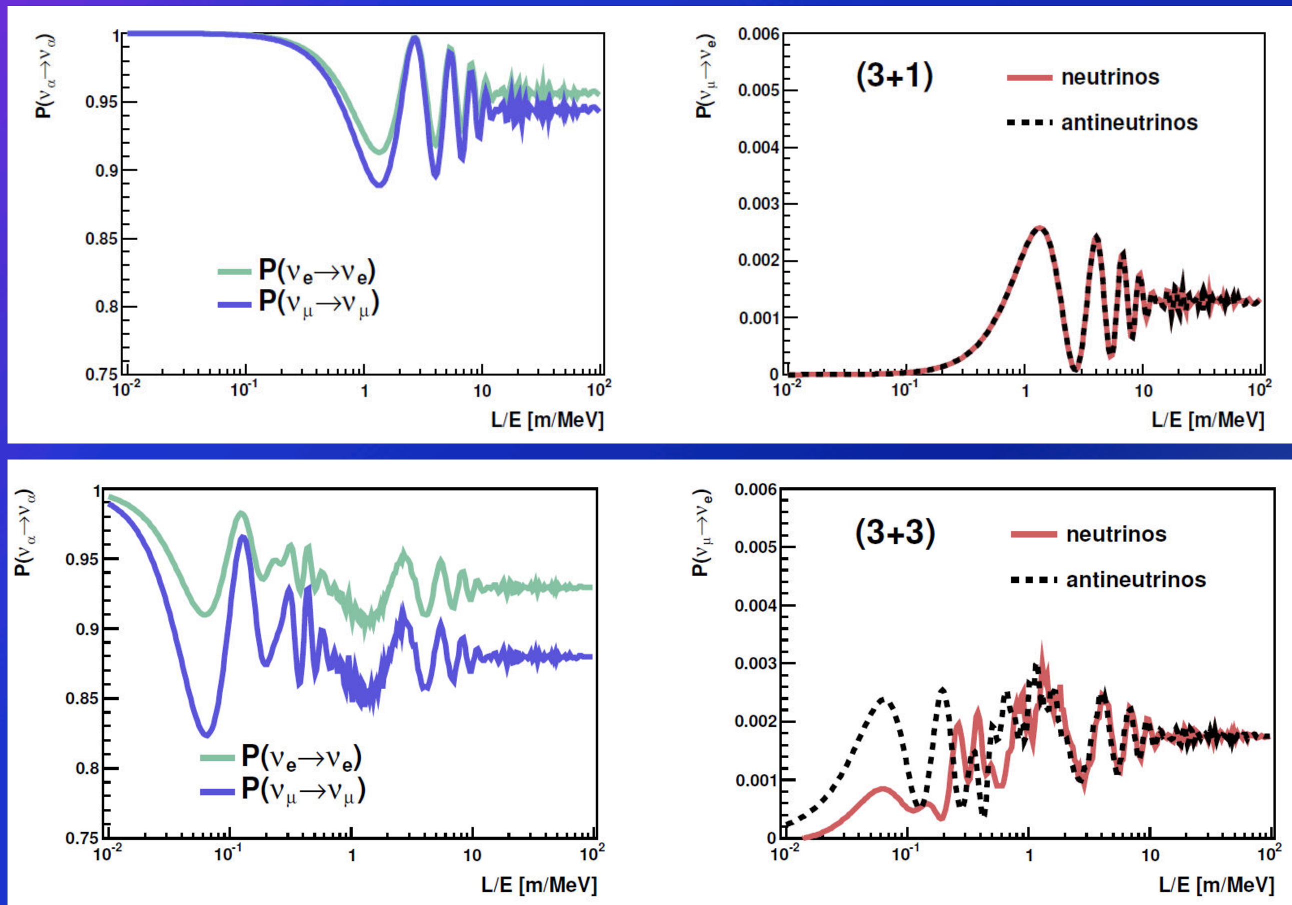
Appearance Data



All Data

Lesson: Have access to as many channels as possible and cover as much of the parameter space as possible

L/E dependence



Very different L/E dependencies for different models
Experiments covering a wide range of L/E regions are required.

Future sterile searches

S:B for Appearance Channel
Past and Future(?)

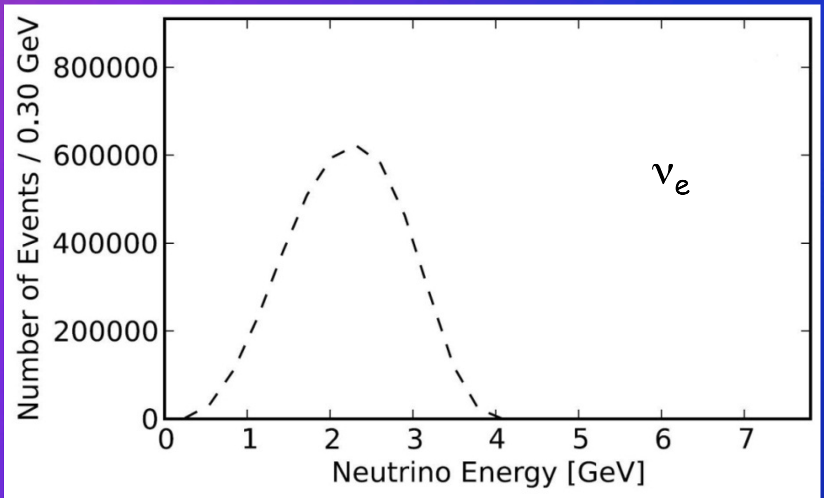
Experiment	S:B
LSND	2:1
MiniBooNE	1:1 → 1:2
ICARUS/NESSiE	≈1.5:1 / 1:4
LAr-LAr	1:4
K^+ DAR	≈4:1
LSND Reloaded	5:1
oscSNS	3:1
nuSTORM	11:1 → 20:1

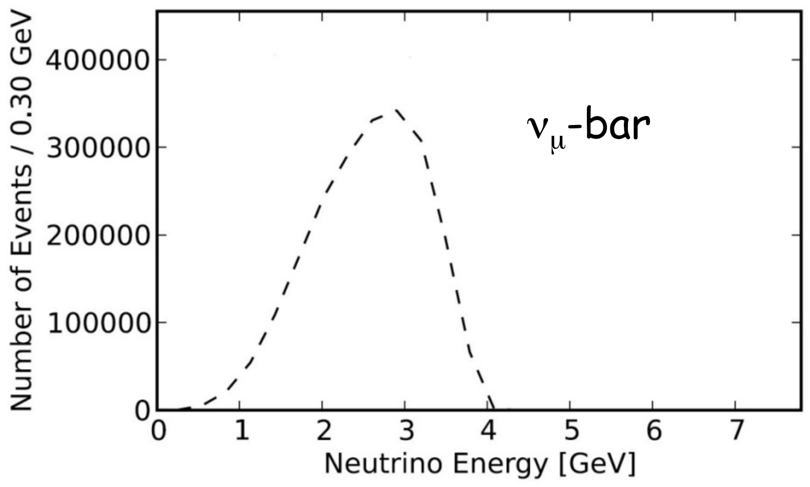
- Note: There are a number of experiments with megaCi to petaCi sources next to large detectors that have an exquisite signature of steriles (# evts/unit length displays oscillatory behavior in large detector) and have large effective S:B
  - SNO+Cr, Ce-Land, LENS, Borexino, Daya Bay
  - IsoDAR
  - A number of very-short baseline reactor experiments

ν Interaction Physics

Preliminary studies

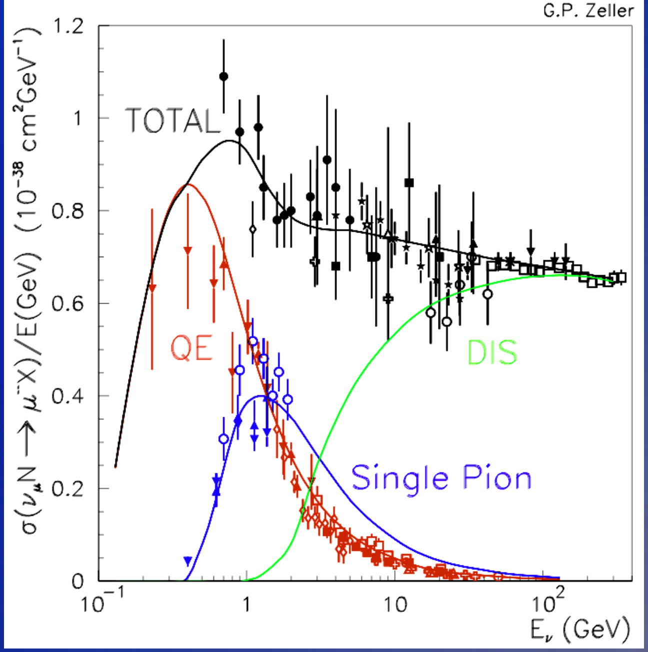
E_ν spectra (μ^+ stored)





Event rates/100T
at ND hall 50m
from straight with
μ^+ stored
for
10^{21} POT exposure

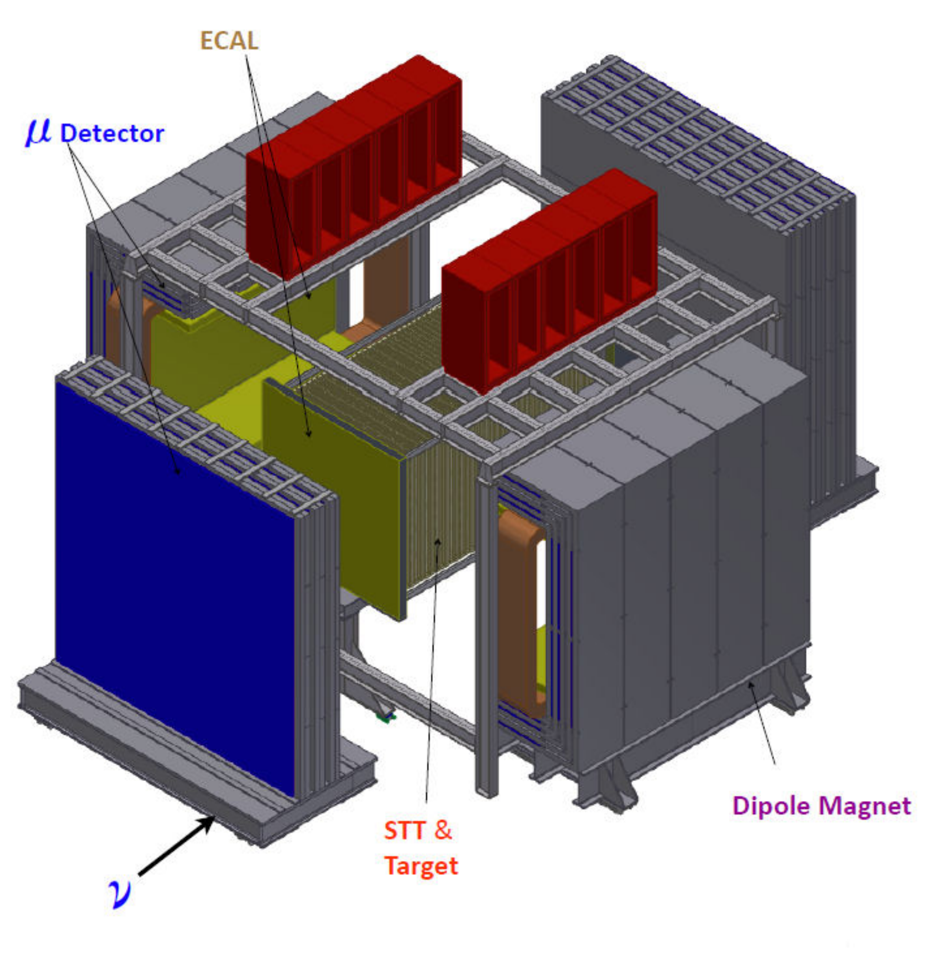
Channel	N_{evts}
$\bar{\nu}_\mu$ NC	844,793
ν_e NC	1,387,698
$\bar{\nu}_\mu$ CC	2,145,632
ν_e CC	3,960,421



A detector for ν interaction physics

One Example

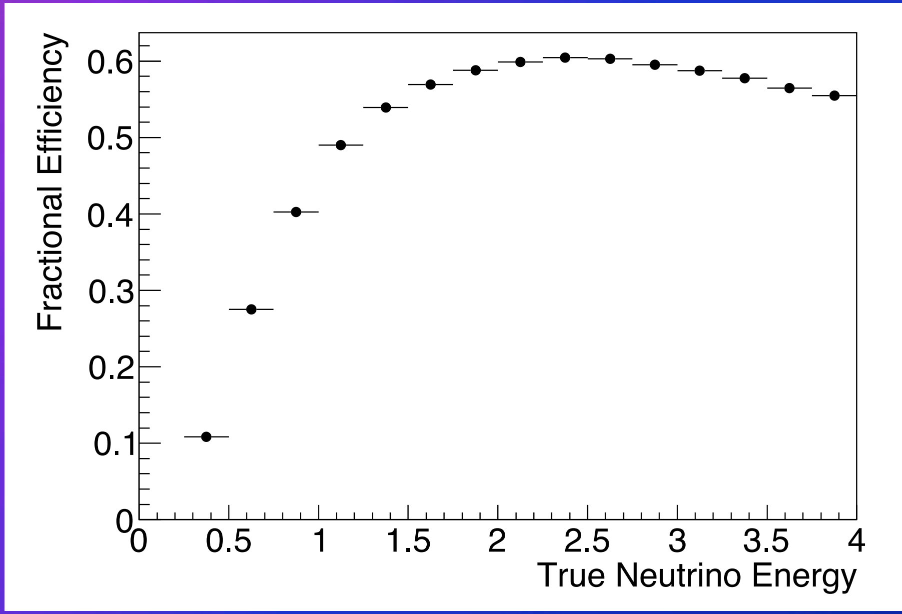
Sanjib Mishra



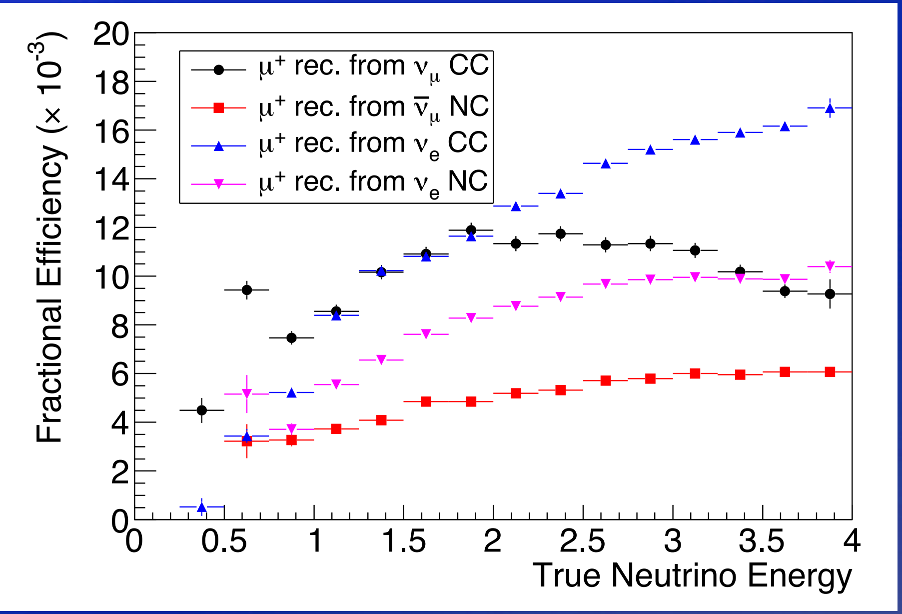
- HiResMν
  - Evolution of the NOMAD experiment
  - One of the concepts considered for ND for LBNE
  - Studied as ND for NF
- Capabilities
  - High resolution spectrometer
  - Low density
  - PID & tracking
  - Nuclear targets

Disappearance channels

ν_μ disappearance analysis

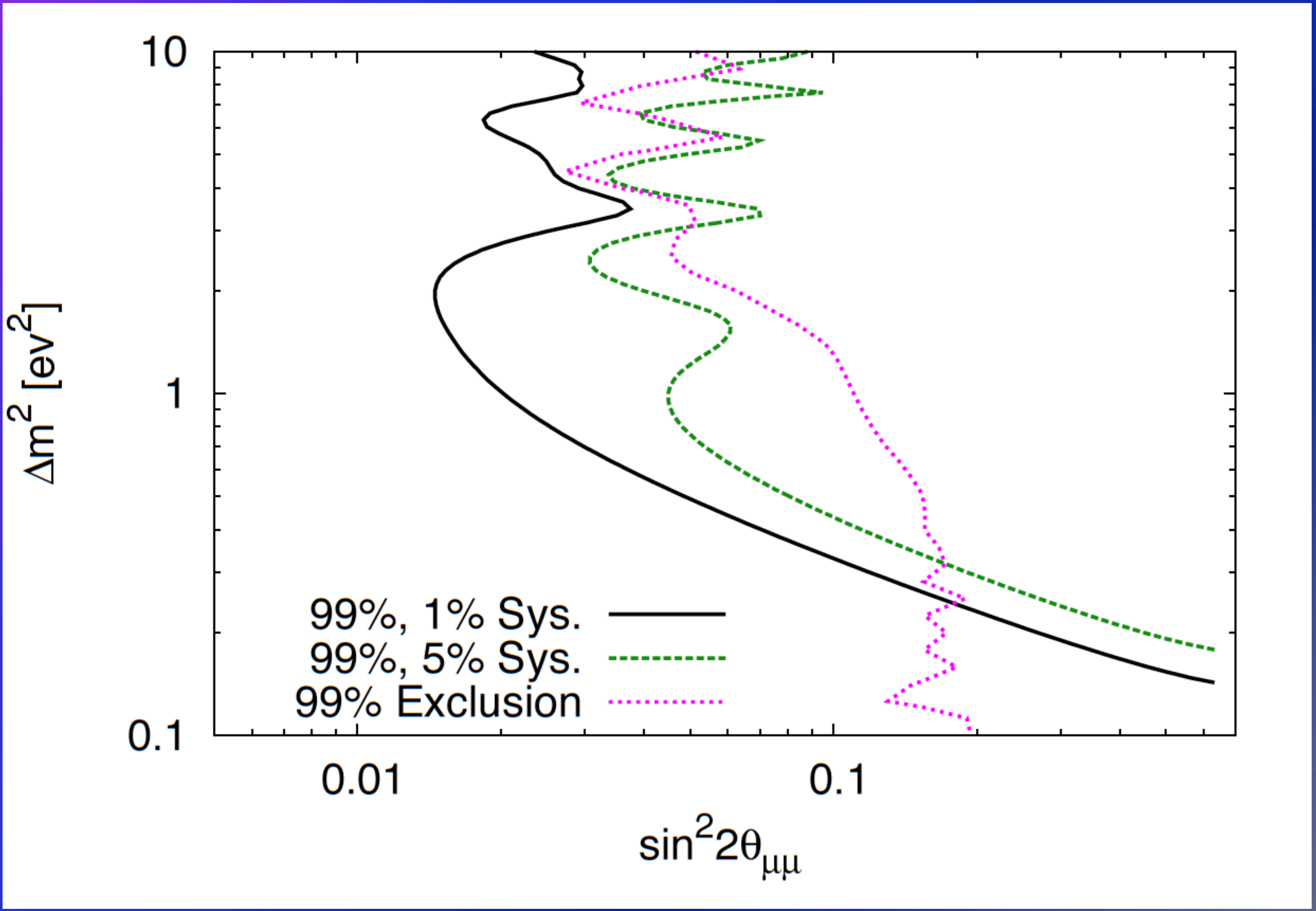


Efficiency



Background

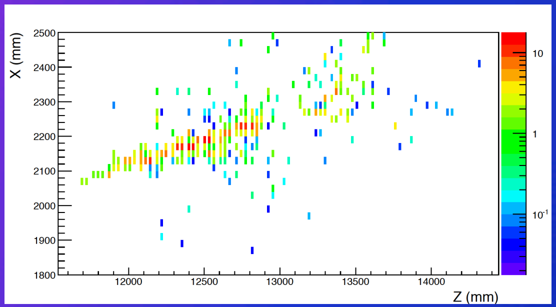
ν_μ disappearance



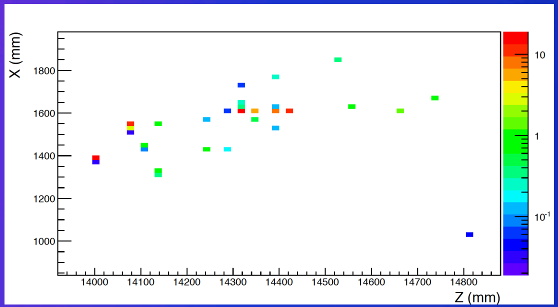
Preliminary ν_e work

David Adey
Fermilab

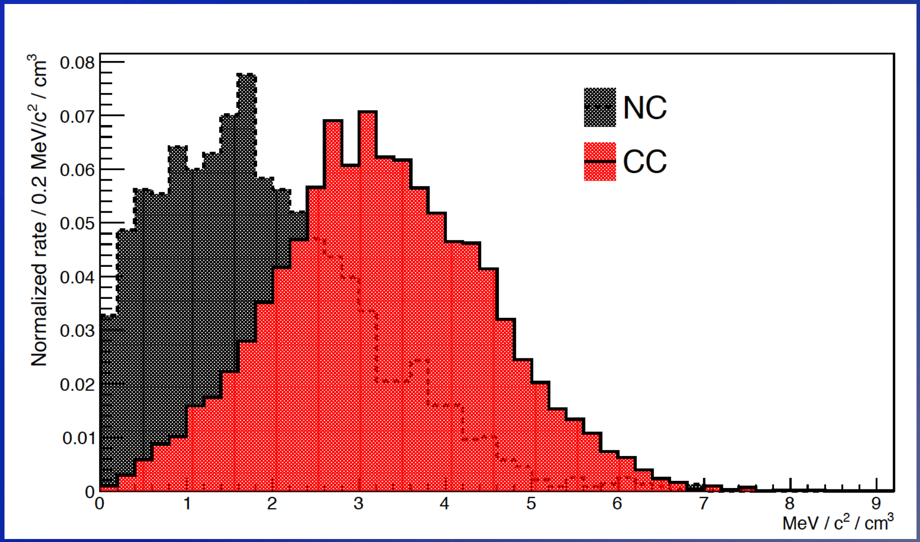
- SuperBIND is not the ideal detector for ν_e interaction physics or for the study of NC.
- However, SuperBIND's aggressive design does provide opportunity to study ν_e disappearance.
  - CC-NC distinction required for these types of events could also provide an option to study NC disappearance.



ν_e CC



NC



Cuts-based analysis lacks discrimination power. MVA approach needed