Neutrinos from Stored Muons
νSTORM

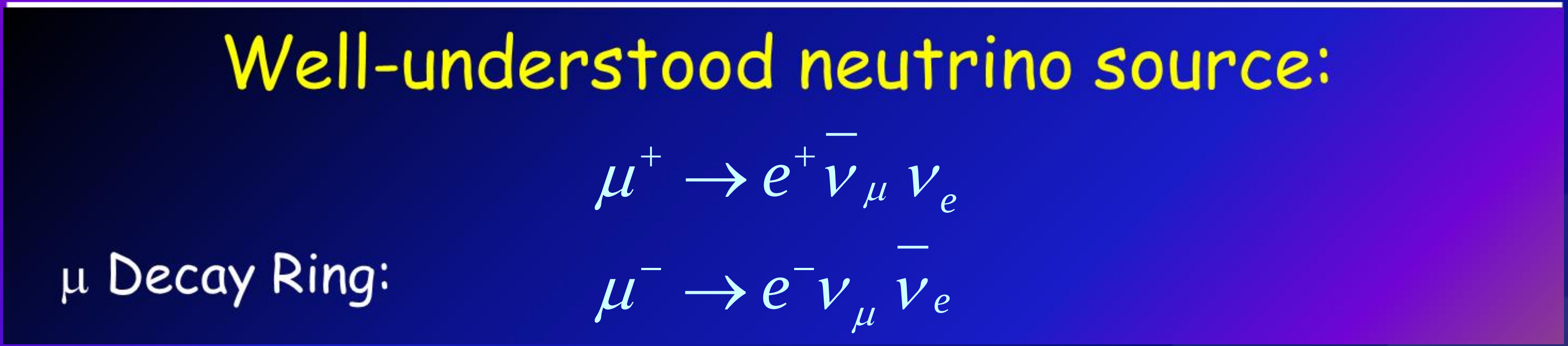
ν physics with a μ storage ring

Outline

- Introduction & Physics motivation
- Current facility design status
- International context
- 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:

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

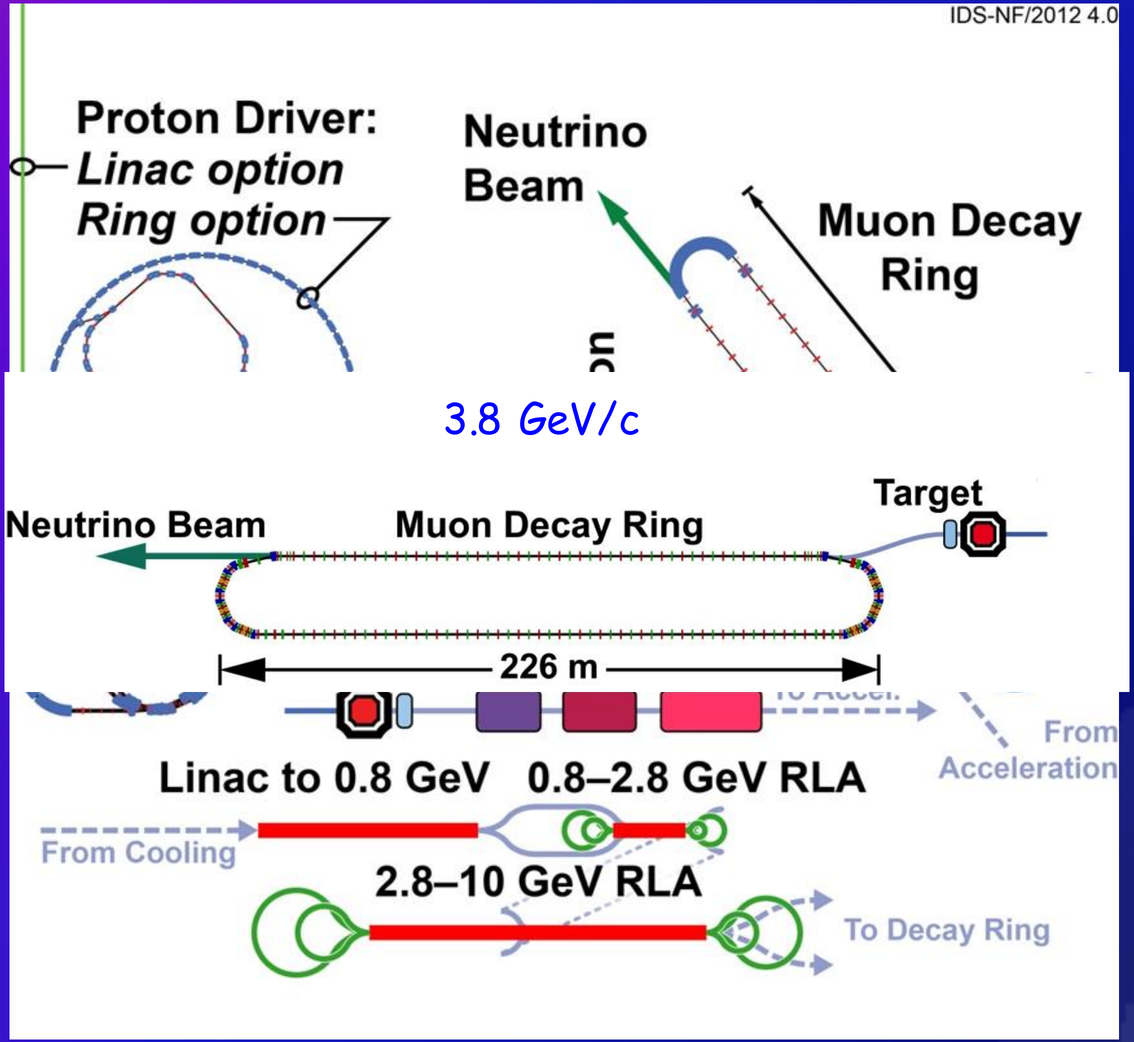
$$\mu^- \to e^- \nu_\mu \bar{\nu}_e$$

- Flavor content fully known
  - On the order of rare decay modes (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 system
- Initially the motivation was high-energy ν interaction physics.

- BUT, so far no experiment has ever been done!

This is what we want to do near term: Neutrinos from STORed Muons, νSTORM

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

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

- It is a NEAR-TERM FACILITY
  - Because, technically, we can do it now

Three Scientific Pillars or themes

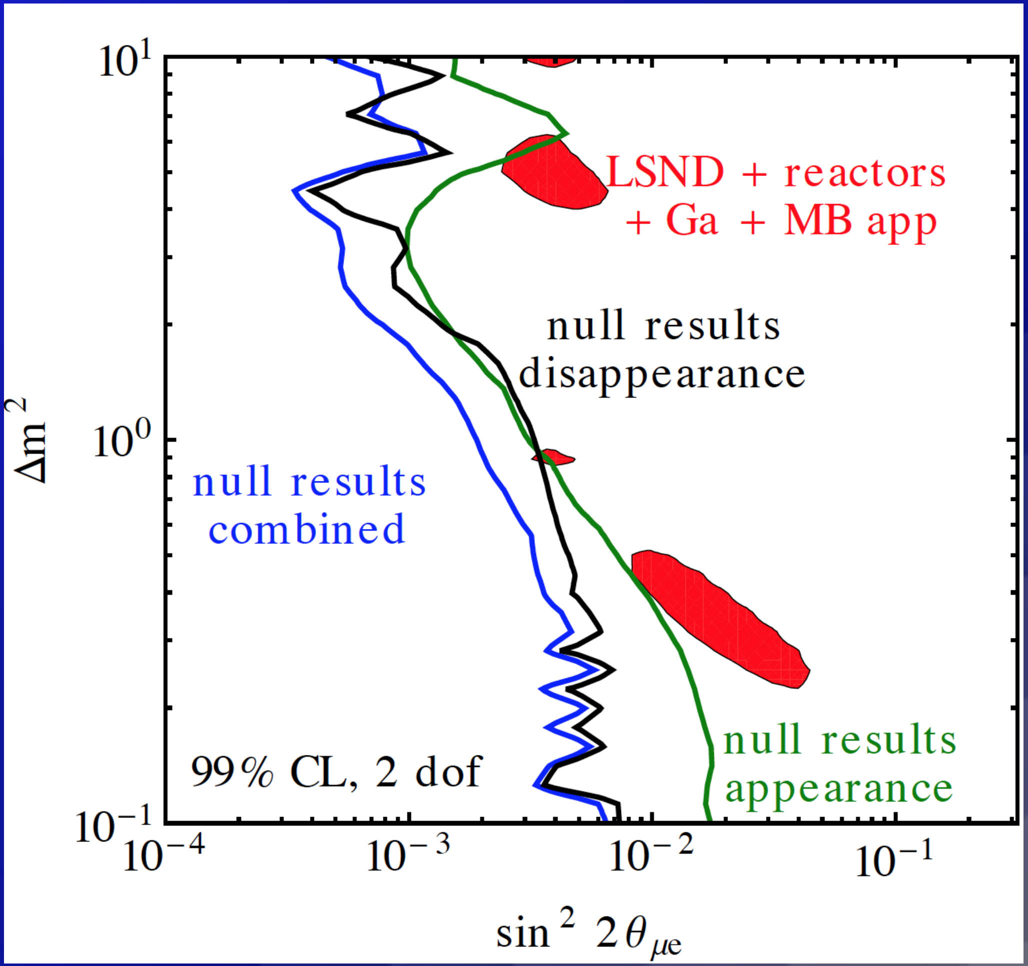
- Addresses the SBL, large δm^2 ν-oscillation regime
- Provides a beam for precision ν interaction physics
- Accelerator & Detector technology test bed
  - Potential for intense low energy muon beam
  - Provides for μ decay ring R&D (instrumentation) & technology demonstration platform
  - Provides a ν Detector Test Facility

Physics motivation & Theoretical Considerations

Beyond the νSM

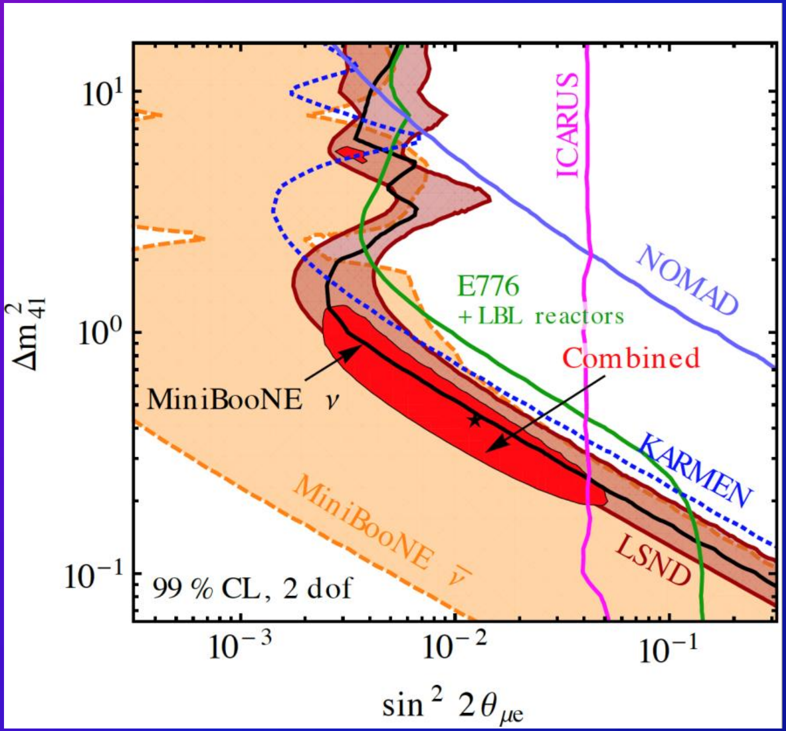
Short-baseline ν oscillation studies

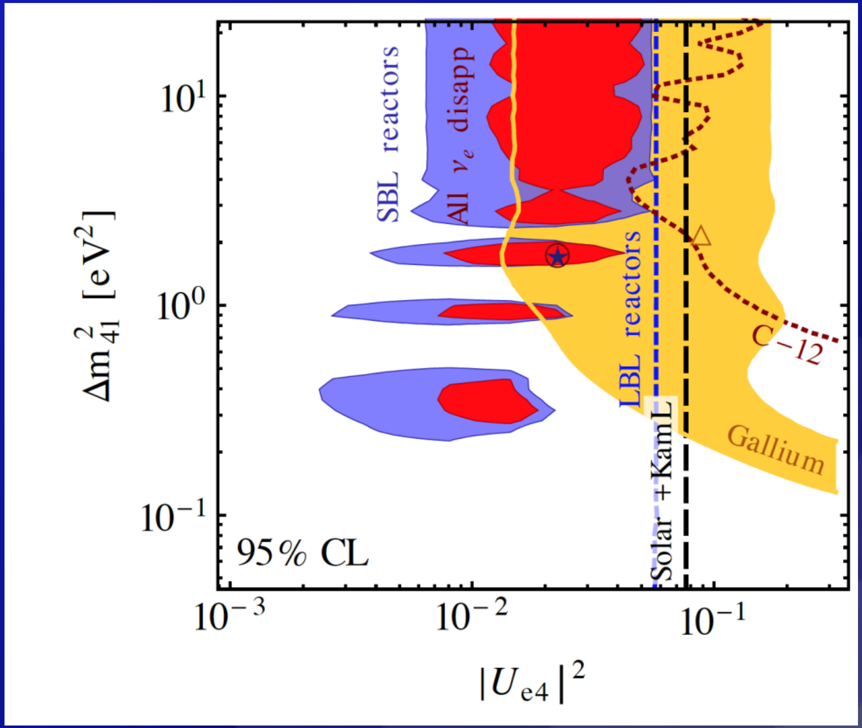
- Sterile neutrinos arise naturally in many extensions of the Standard Model.
  - GUT models
  - Seesaw mechanism for ν mass
  - "Dark" sector
- Usually heavy, but light not ruled out.
- Experimental hints
  - LSND
  - MiniBooNE
  - Ga
  - Reactor "anomaly"



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.

ν Interaction Physics

ν Interaction Physics

A partial sampling

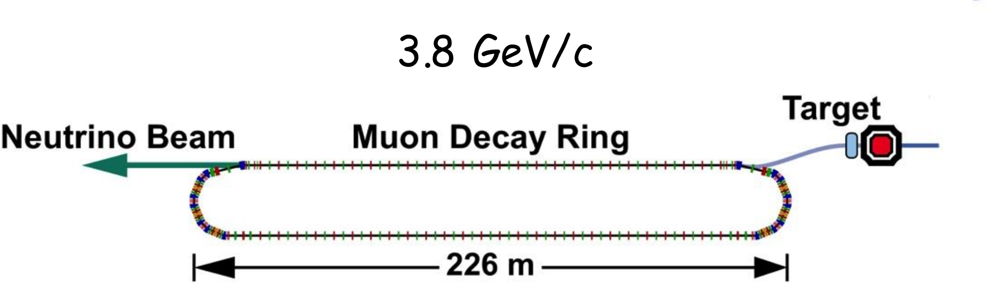
- ν_e and ν_e-bar x-section measurements
  - A UNIQUE contribution from nuSTORM
  - Essentially no existing data
- π^0 production in ν interactions
  - Coherent and quasi-exclusive single π^0 production
- Charged π & K production
  - Coherent and quasi-exclusive single π^+ production
- Multi-nucleon 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

The Facility

Baseline

- ~ 100 kW Target Station (designed for 400kW)
  - Assume 60-120 GeV proton
  - 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



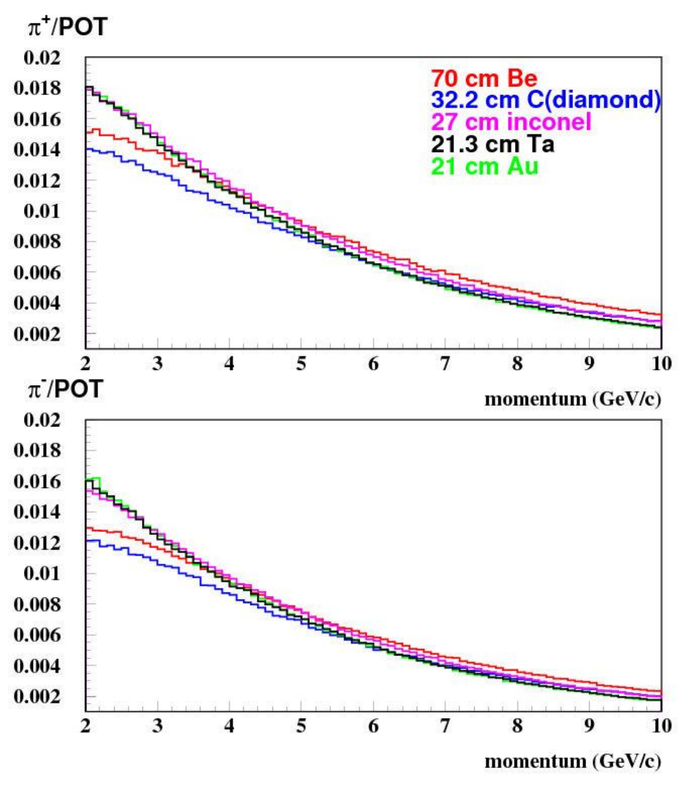
μ-base ν beam:
Oscillation channels

$\mu^+ \to e^+\nu_e\overline{\nu}_\mu$	$\mu^- \to e^-\overline{\nu}_e\nu_\mu$	
$\overline{\nu}_\mu \to \bar{\nu}_\mu$	$\nu_\mu \to \nu_\mu$	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

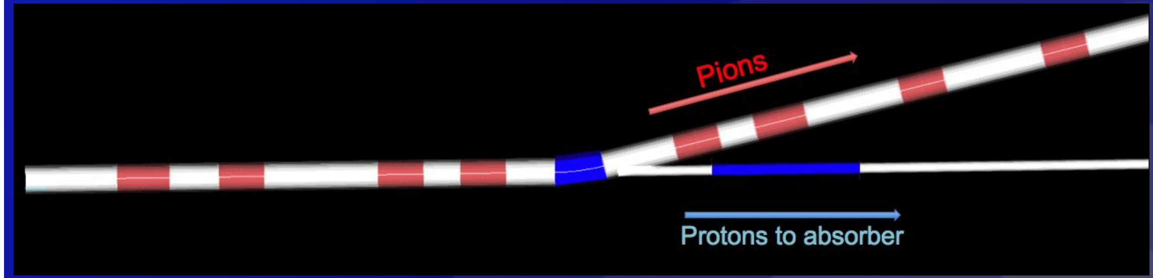
8 out of 12 channels potentially accessible

π Production, Capture & Transport

Sergei Striganov
Ao Liu
Fermilab

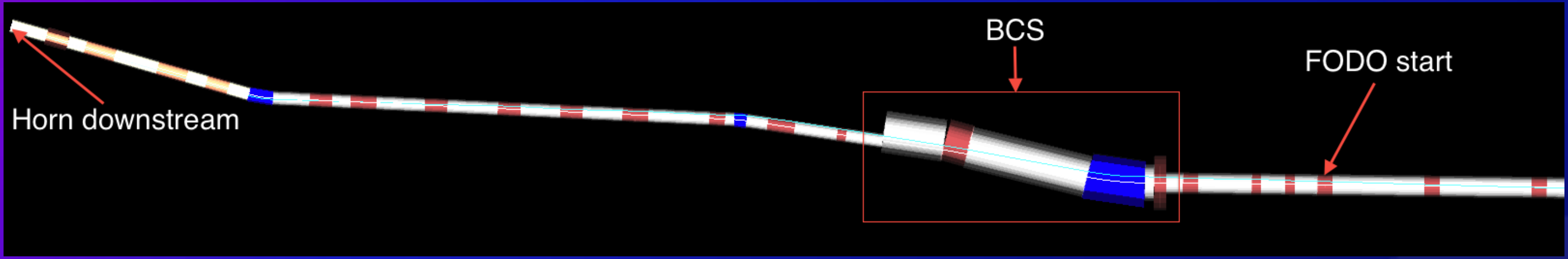


In momentum range
4.5 < 5.0 < 5.5
obtain ≈ 0.09 $\pi^\pm$/POT
within decay ring acceptance.
With 120 GeV p & NuMI-style horn 1
Carbon target



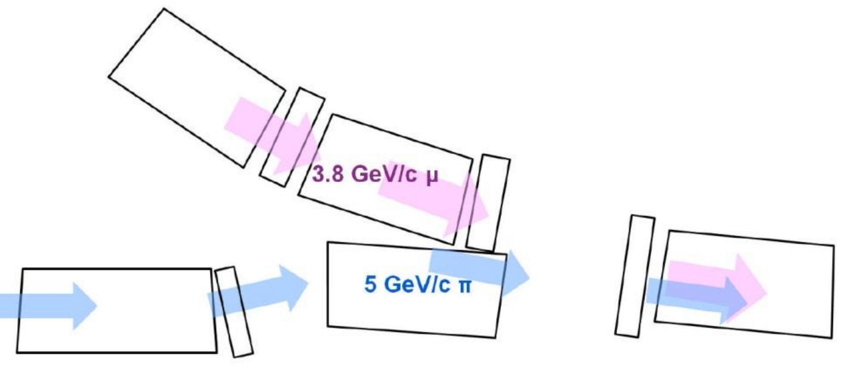
Target/capture optimization ongoing

π Transport & Decay ring

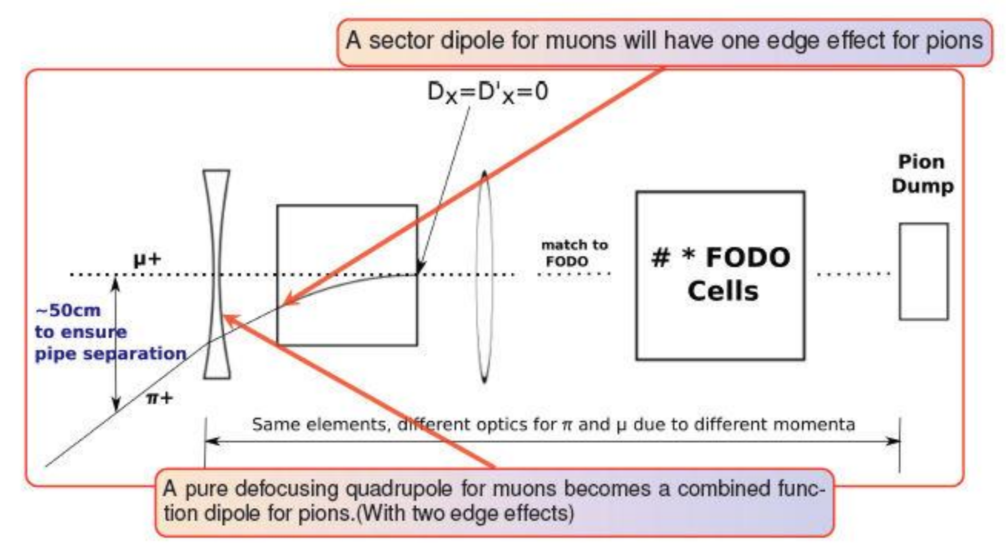


Injection scheme

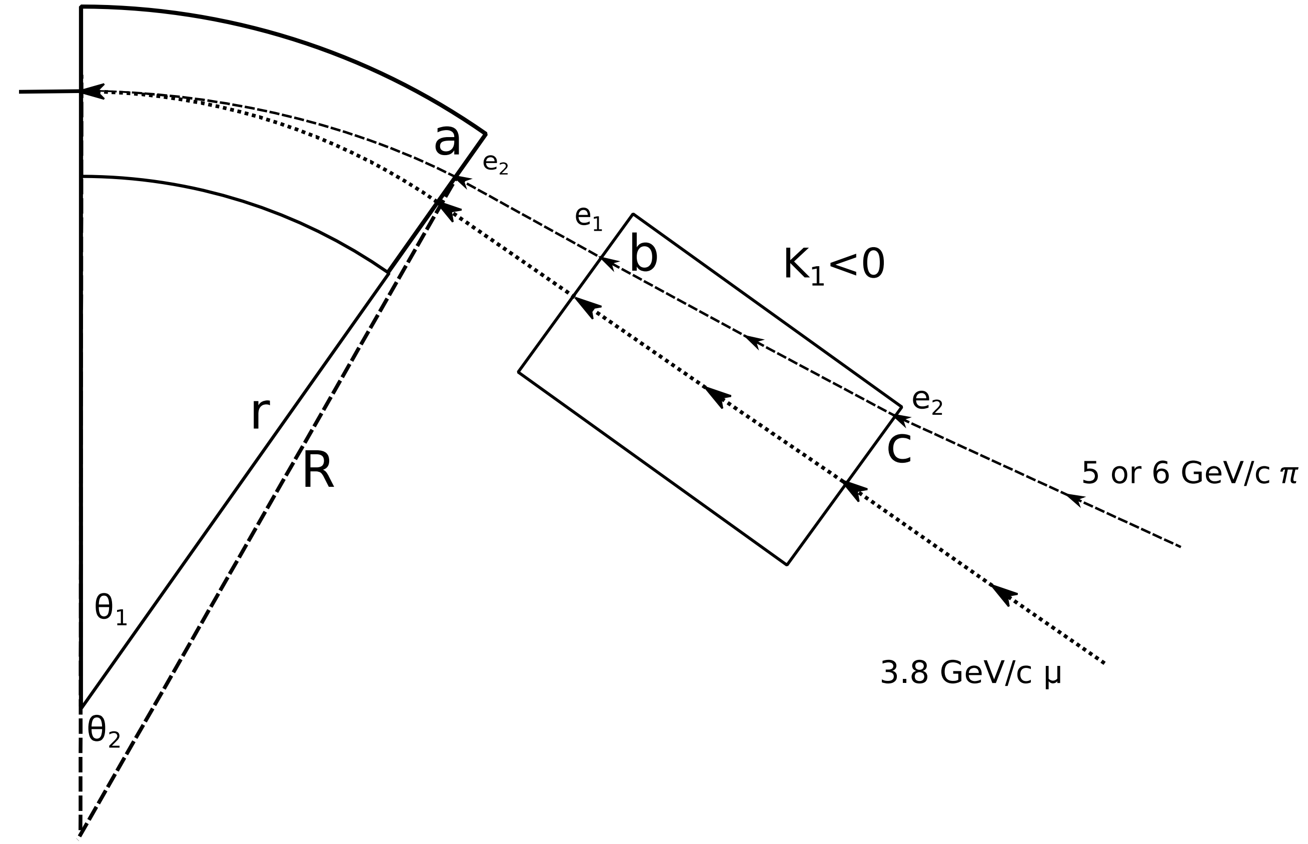
- π's are on an injection orbit
  - separated by chicane
- μ's are in ring circulating orbit
  - lower p ~3.8 GeV/c
- ~30cm separation between
- Concept works for FODO lattice
  - Now detailed by Ao Liu
- Beam Combination Section (BCS)



David Neuffer's original concept from 1980

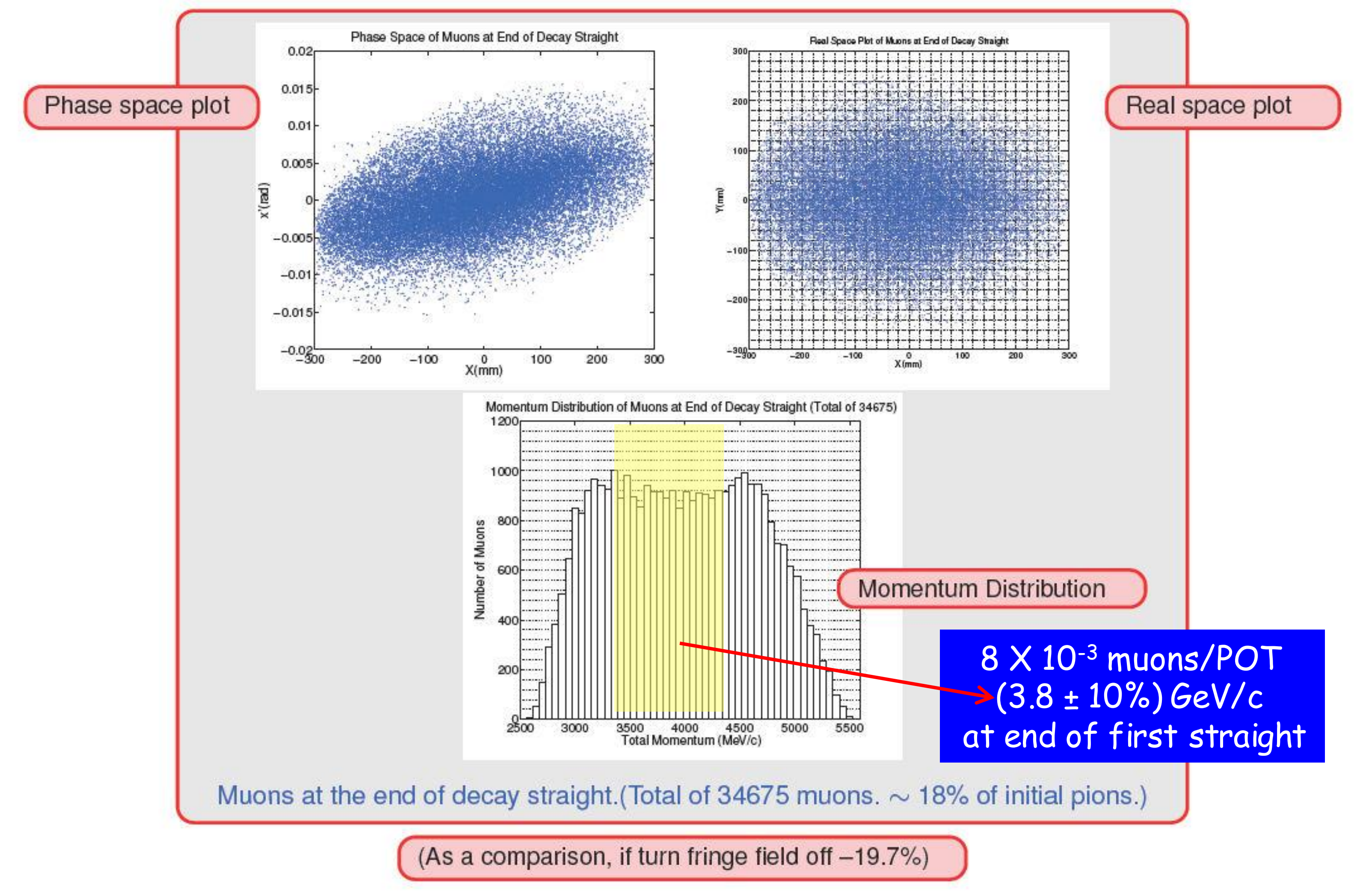


BCS



μs at end of first straight

Ao Liu
Fermilab



Phase space plot

Phase Space of Muons at End of Decay Straight

Real space plot

Real Space Plot of Muons at End of Decay Straight

Momentum Distribution

Momentum Distribution of Muons at End of Decay Straight (Total of 34675)

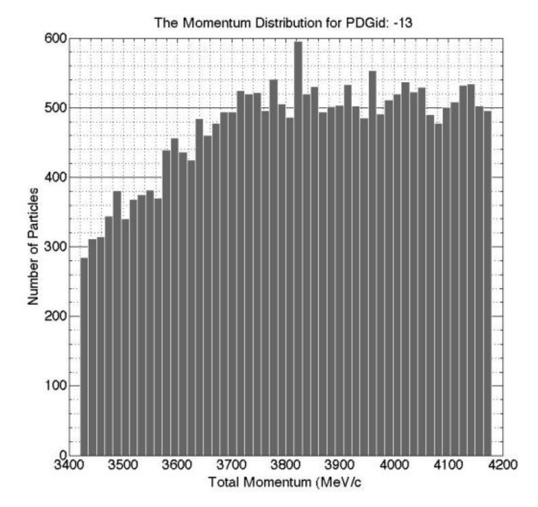
8 X 10^{-3} muons/POT
(3.8 ± 10%) GeV/c
at end of first straight

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%)

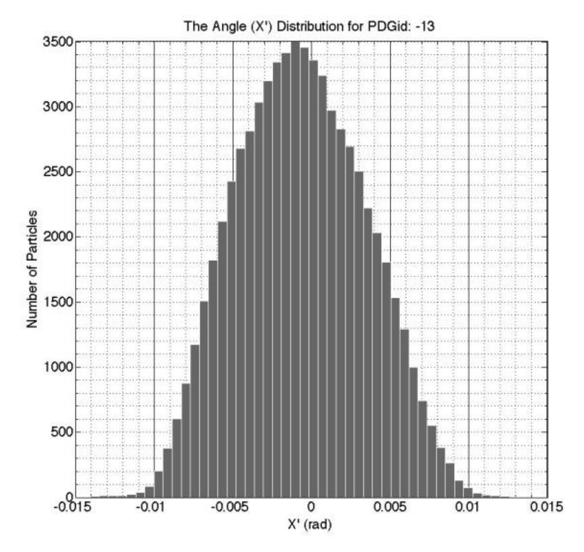
νSTORM

Injecting 6 GeV/c π

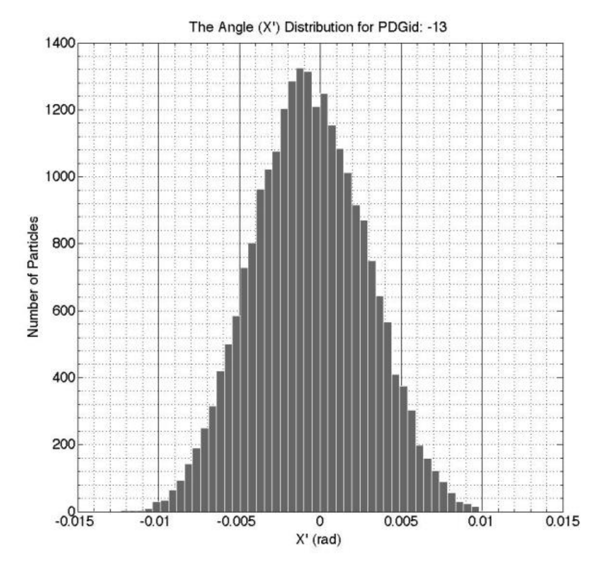


μ momentum distribution at end of first straight

x′: 5 GeV/c injection



x′: 6 GeV/c injection



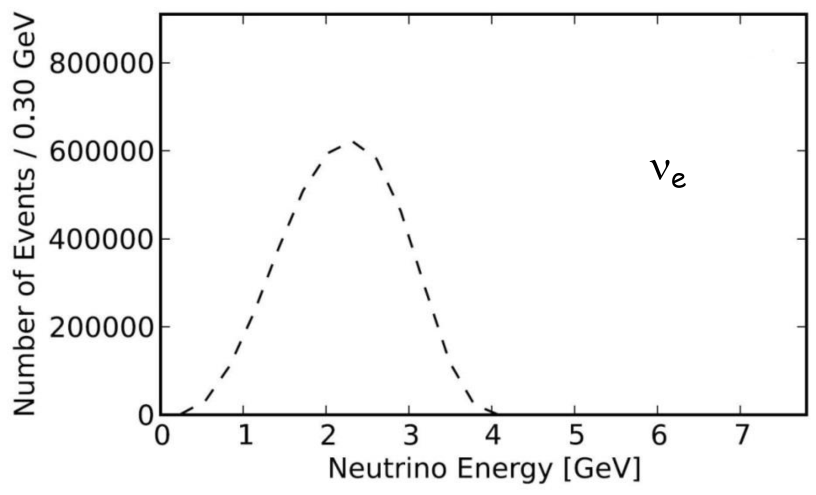
Fermilab

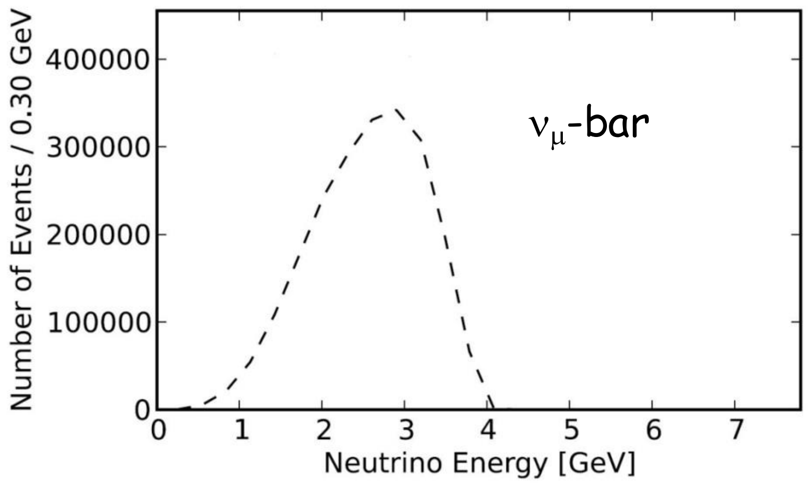
nuSTORM's Physics performance

Assumptions

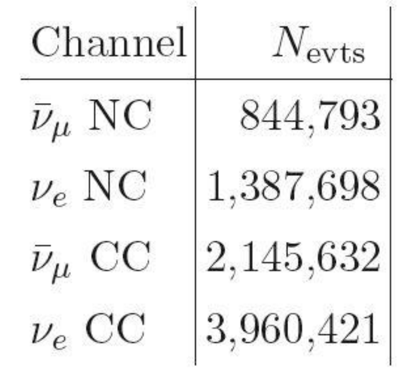
- N_μ = (POT) X (π/POT) X μ/π X $A_{dynamic}$ X Ω
  - 10^{21} POT @ 120 GeV integrated exposure
  - 0.1 π/POT
  - Muons/POT at end of first straight (8 X 10^{-3})
    - =(π/POT) X (μ/π) within the 3.8 ± 10% GeV/c momentum acceptance
  - $A_{dynamic}$ = 0.6 (FODO)
    - Fraction of muons surviving 100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

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

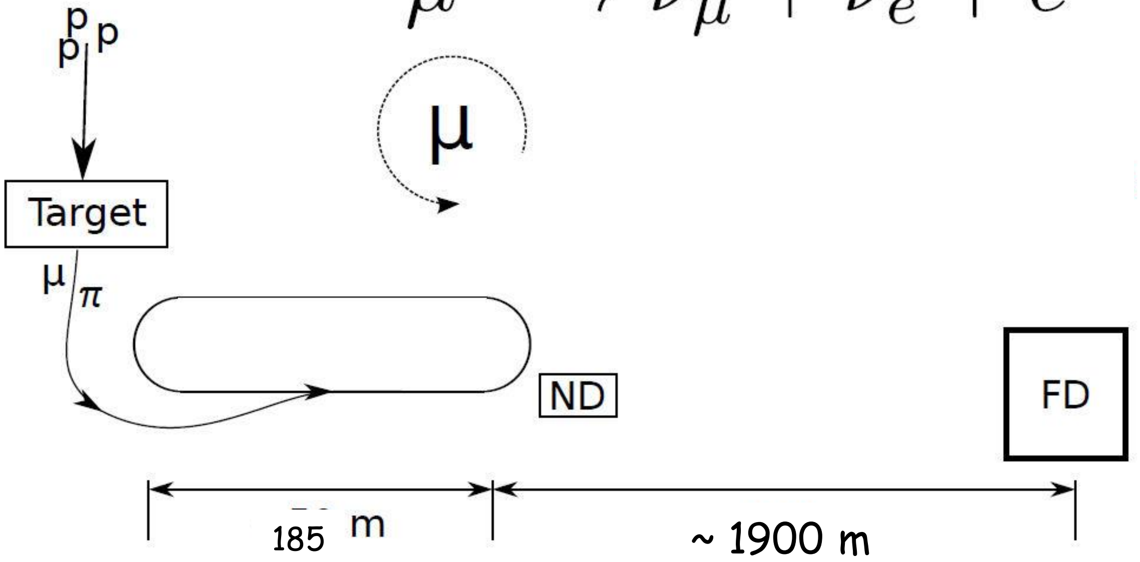
The Golden channel

νSTORM

Experimental Layout

Chris Tunnell
Oxford*

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



Appearance-only (though disappearance good too!)

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

Appearance Channel:

$\nu_e \rightarrow \nu_\mu$

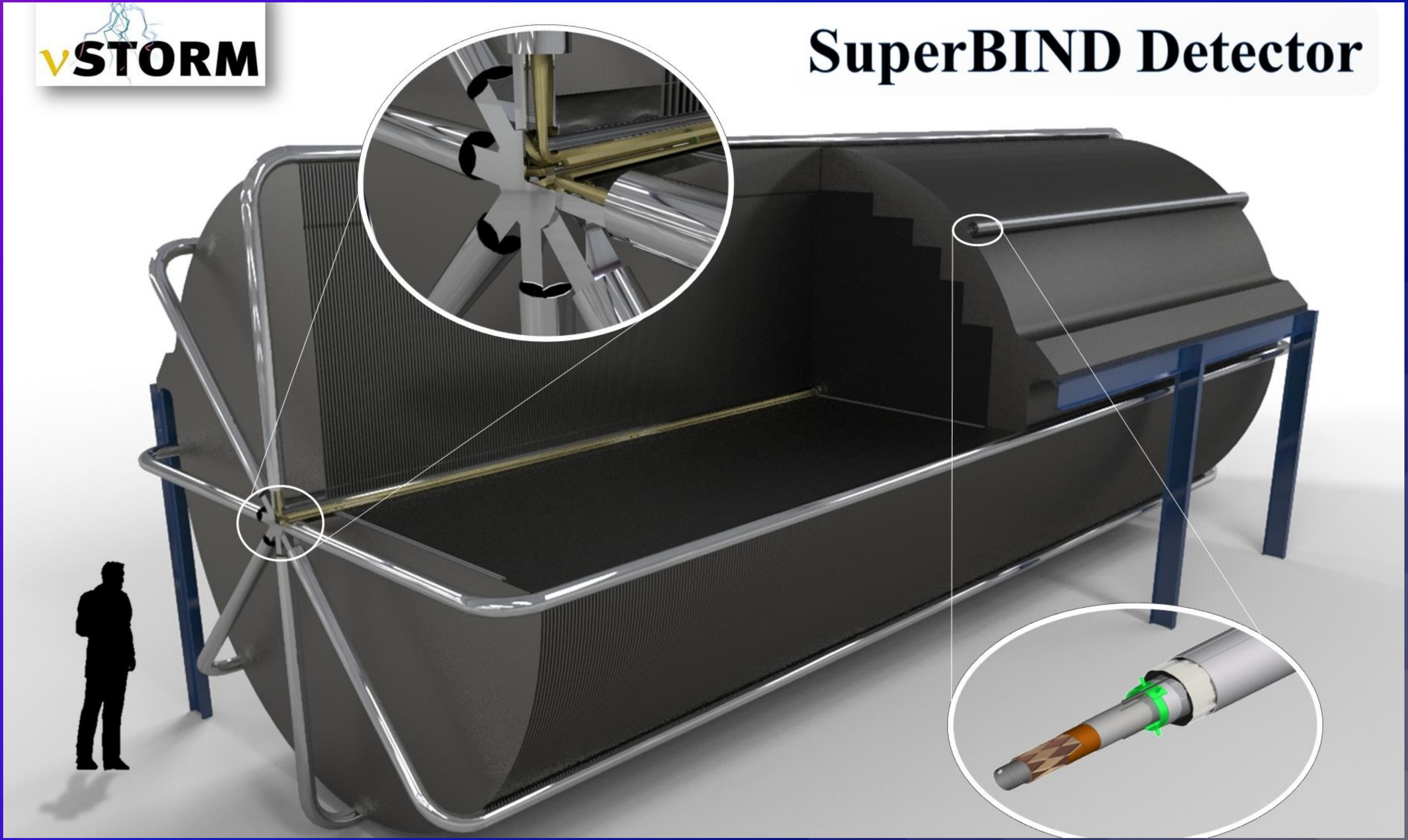
Golden Channel

Must reject the "wrong" sign μ with great efficiency

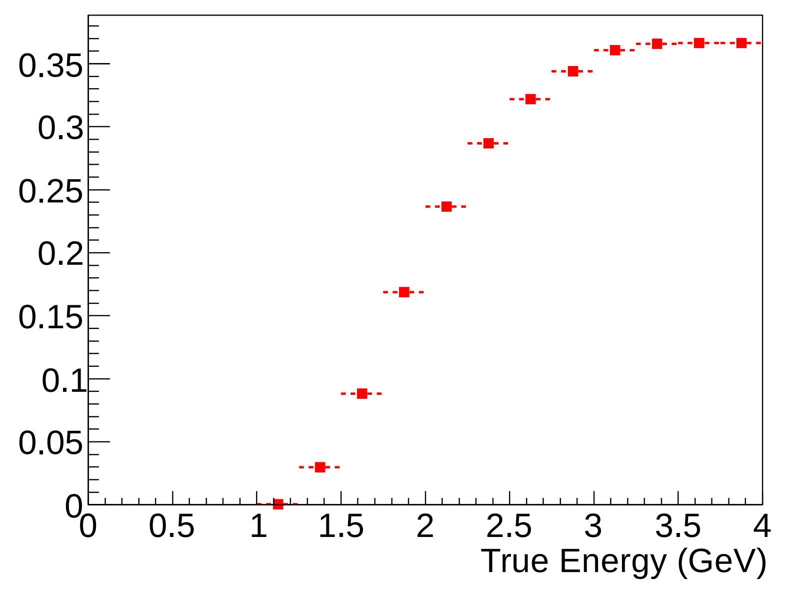
Why $\nu_\mu \rightarrow \nu_e$ Appearance Ch. not possible

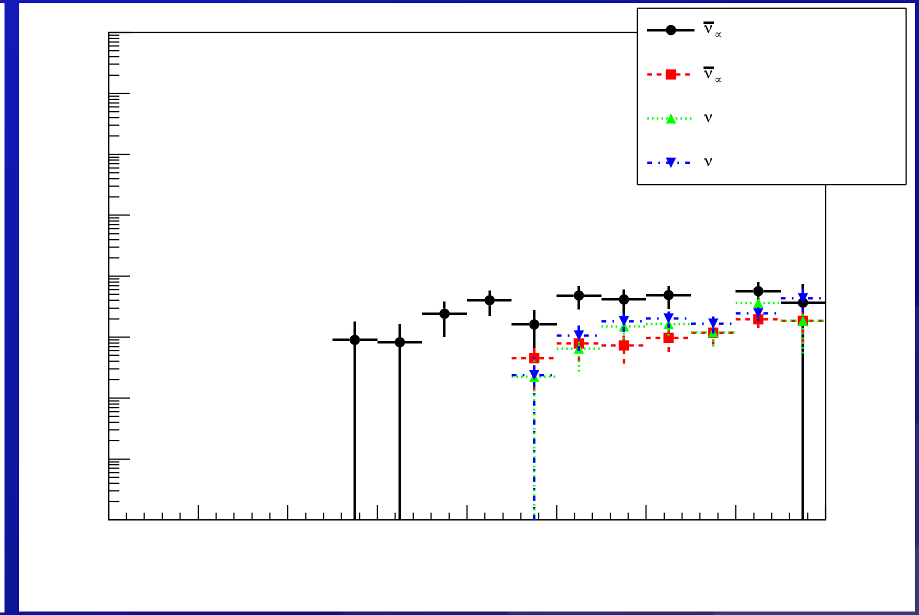
* Now at NIKHEF

SuperBIND



Event reconstruction efficiency & Backgrounds





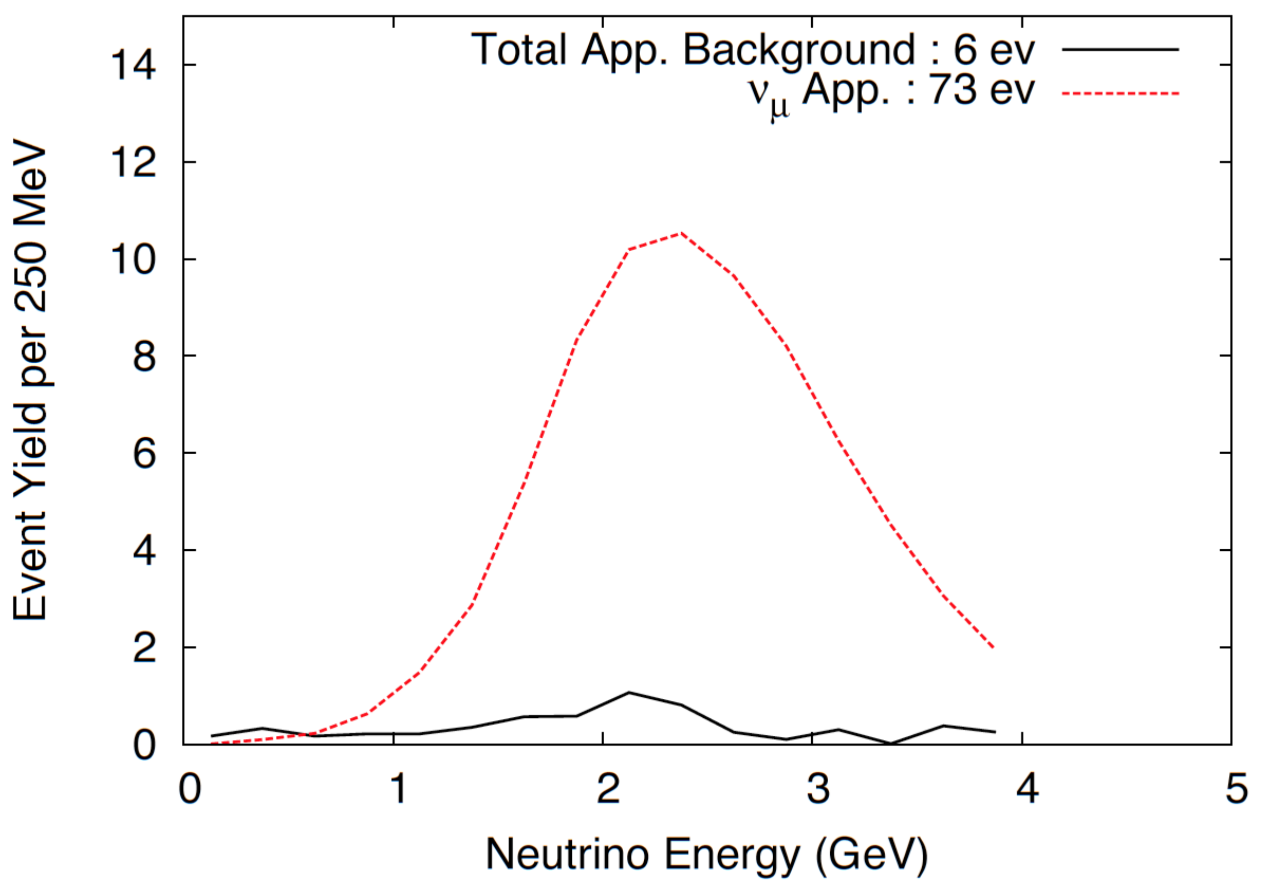
Signal efficiency

Background efficiency

Boosted Decision Tree (BDT) analysis

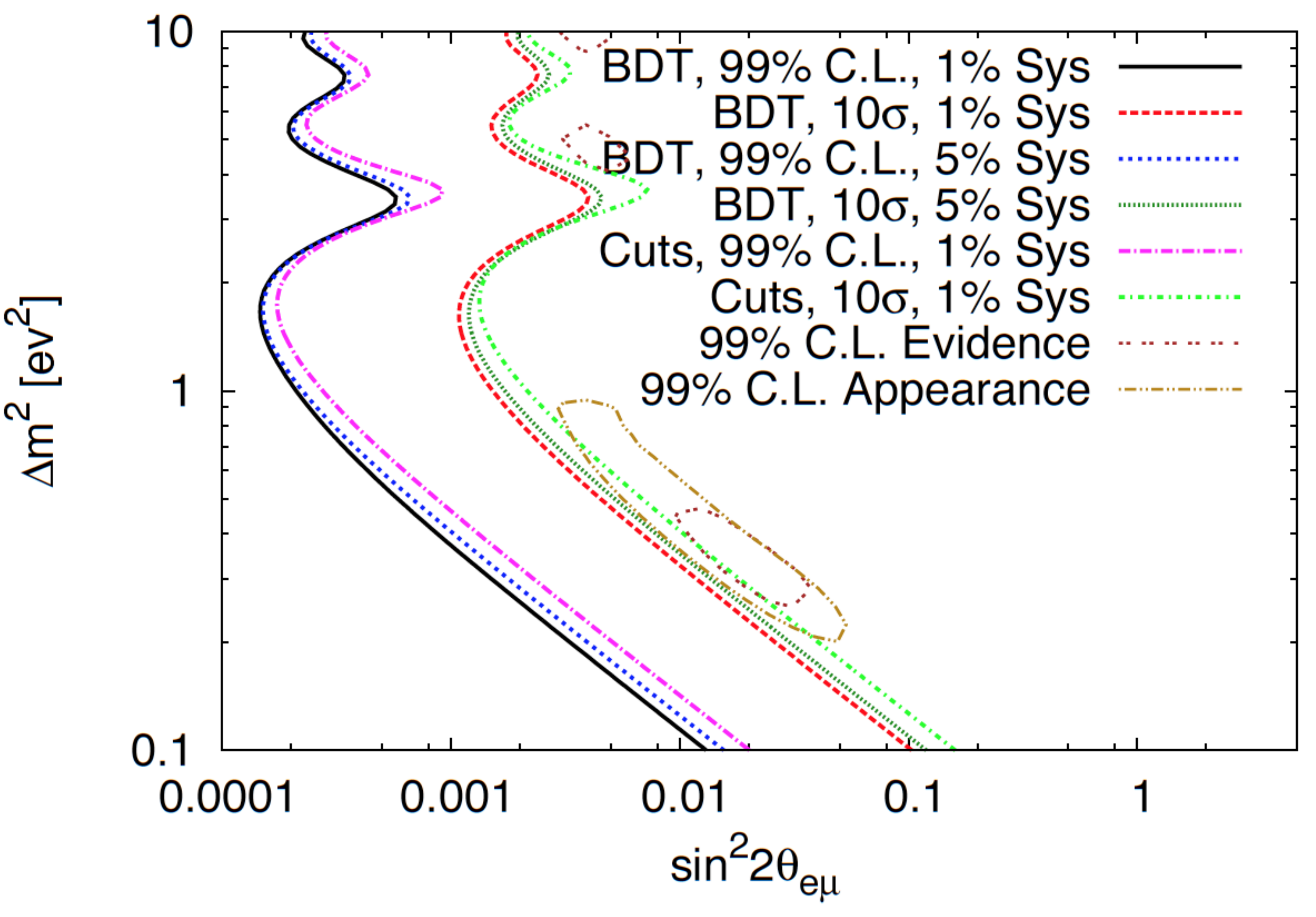
$\nu_e \to \nu_\mu$ appearance

CPT invariant channel to LSND/MiniBooNE



S:B = 12:1

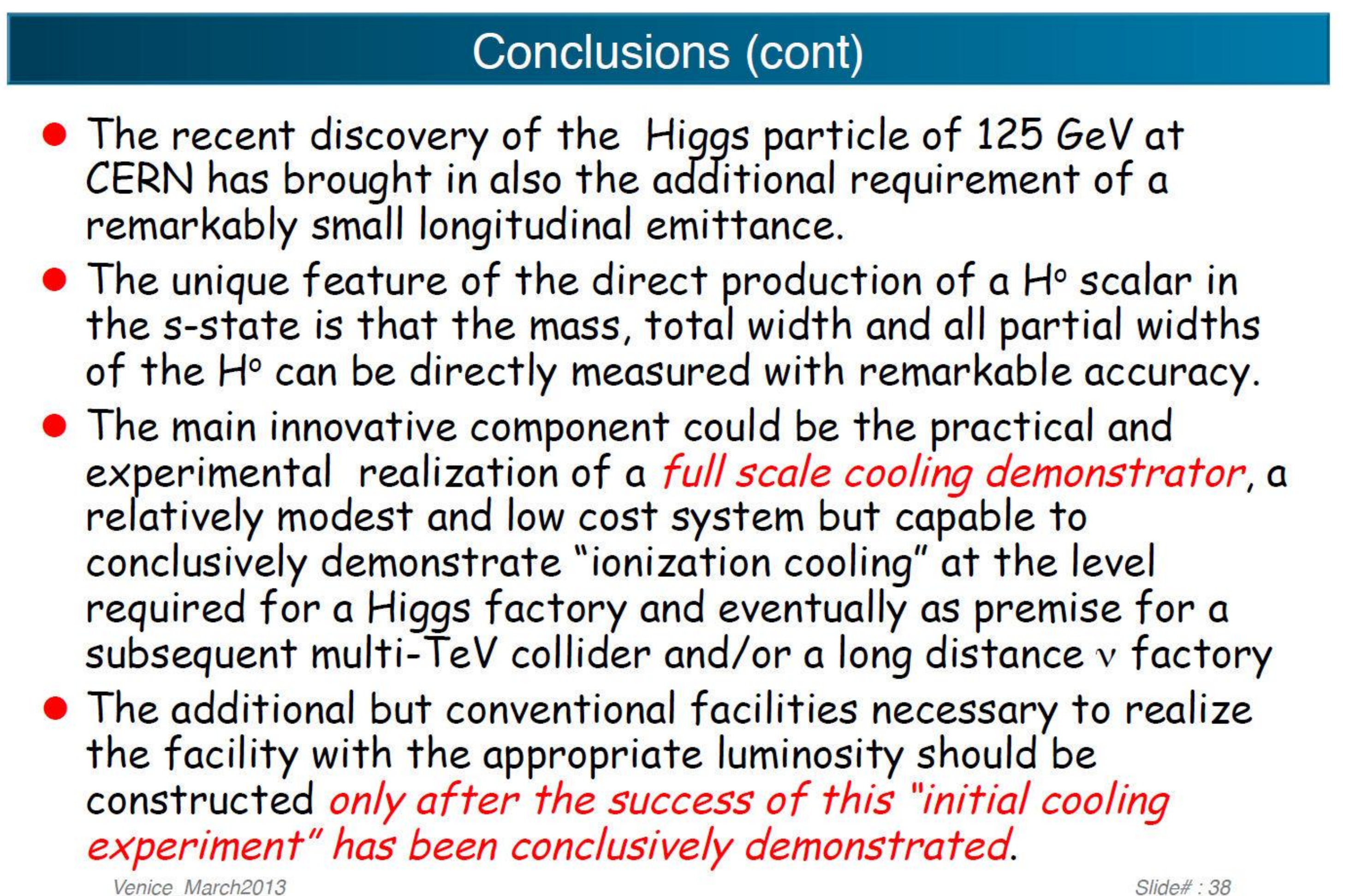
Appearance
Exclusion contours



Accelerator R&D

Looking Forward

Looking Forward: Beyond ν physics



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*.

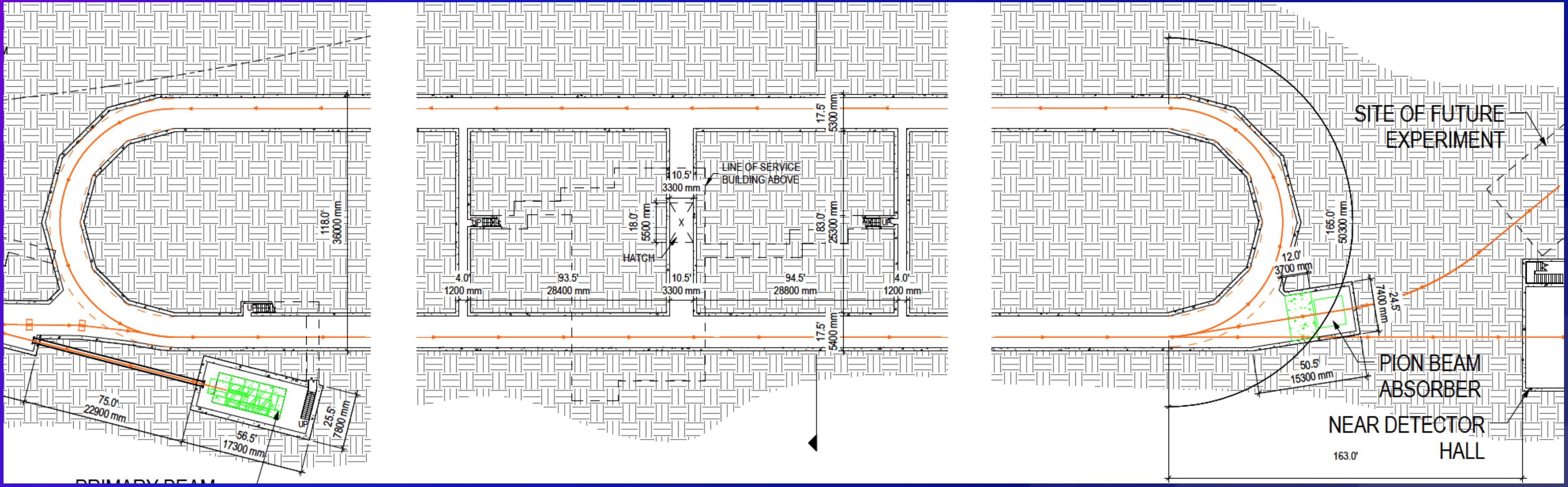
Venice_March2013

Slide# : 38

C. Rubbia, Neutrino Telescopes 2013

nuSTORM

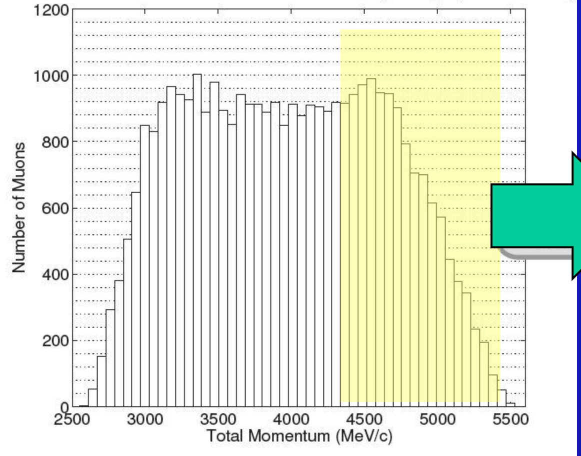
Setting the stage for the next step

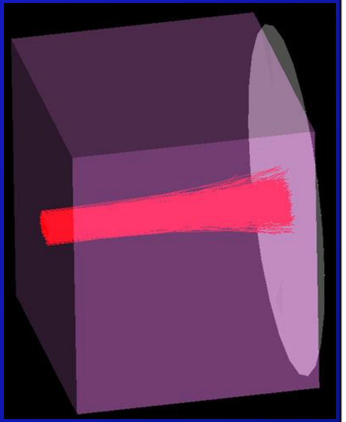


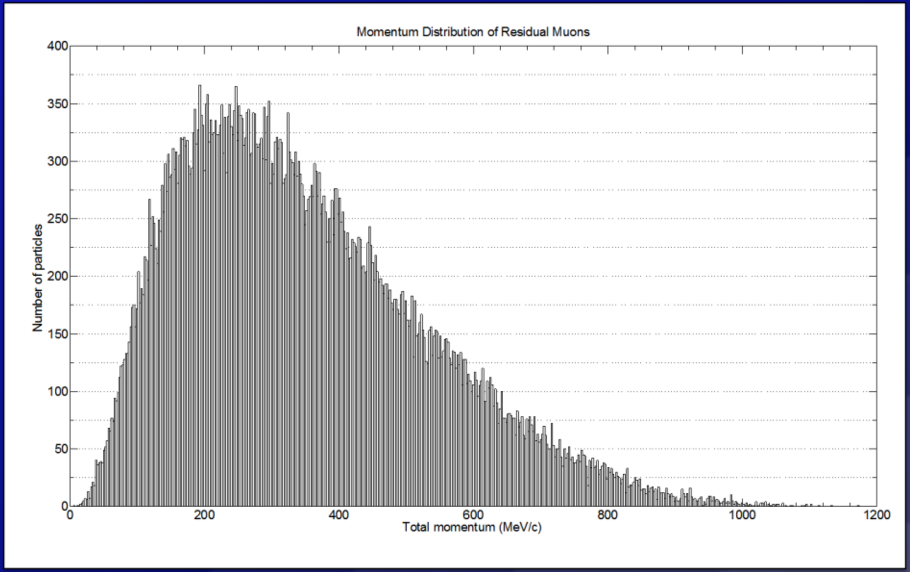
Only ~50% of πs decay in straight
Need π absorber

νSTORM

Low Energy μ beam


Momentum Distribution of Muons at End of Decay Straight (Total of 34675)




Momentum Distribution of Residual Muons

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

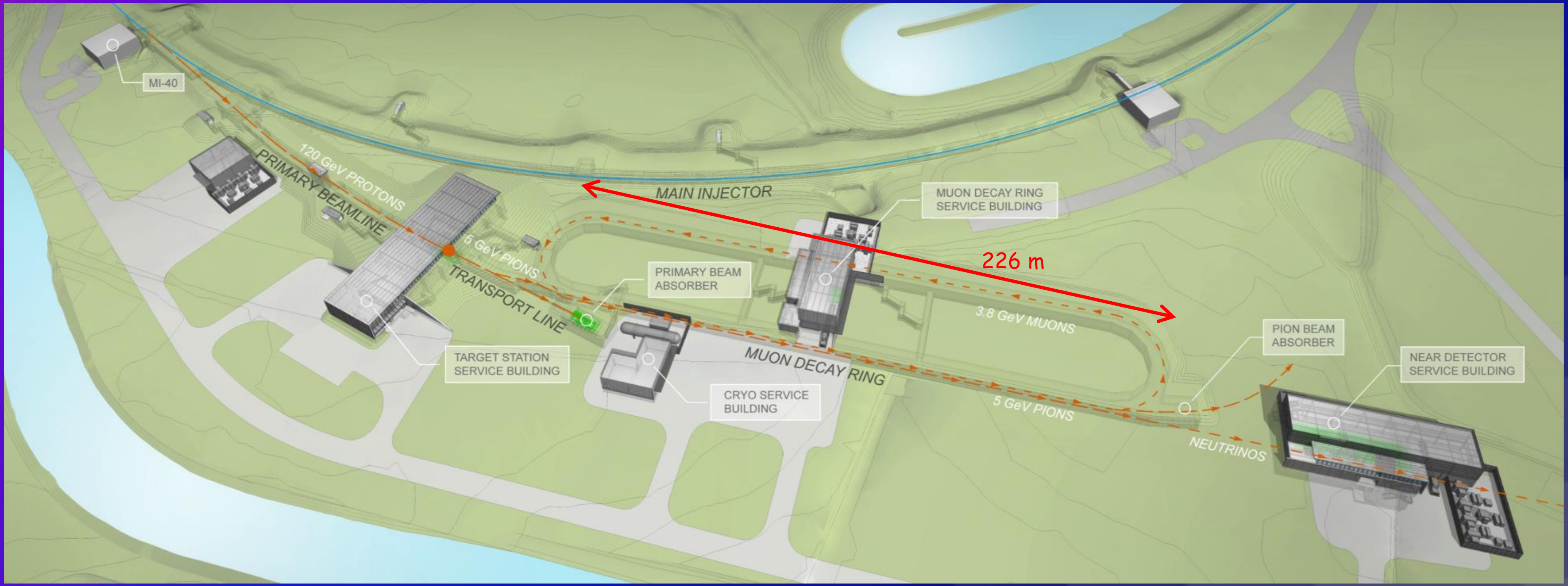
After 3.48m Fe, we have ≈ 10^{10} μ/pulse in $100 < P(MeV/c) < 300$

Project Siting

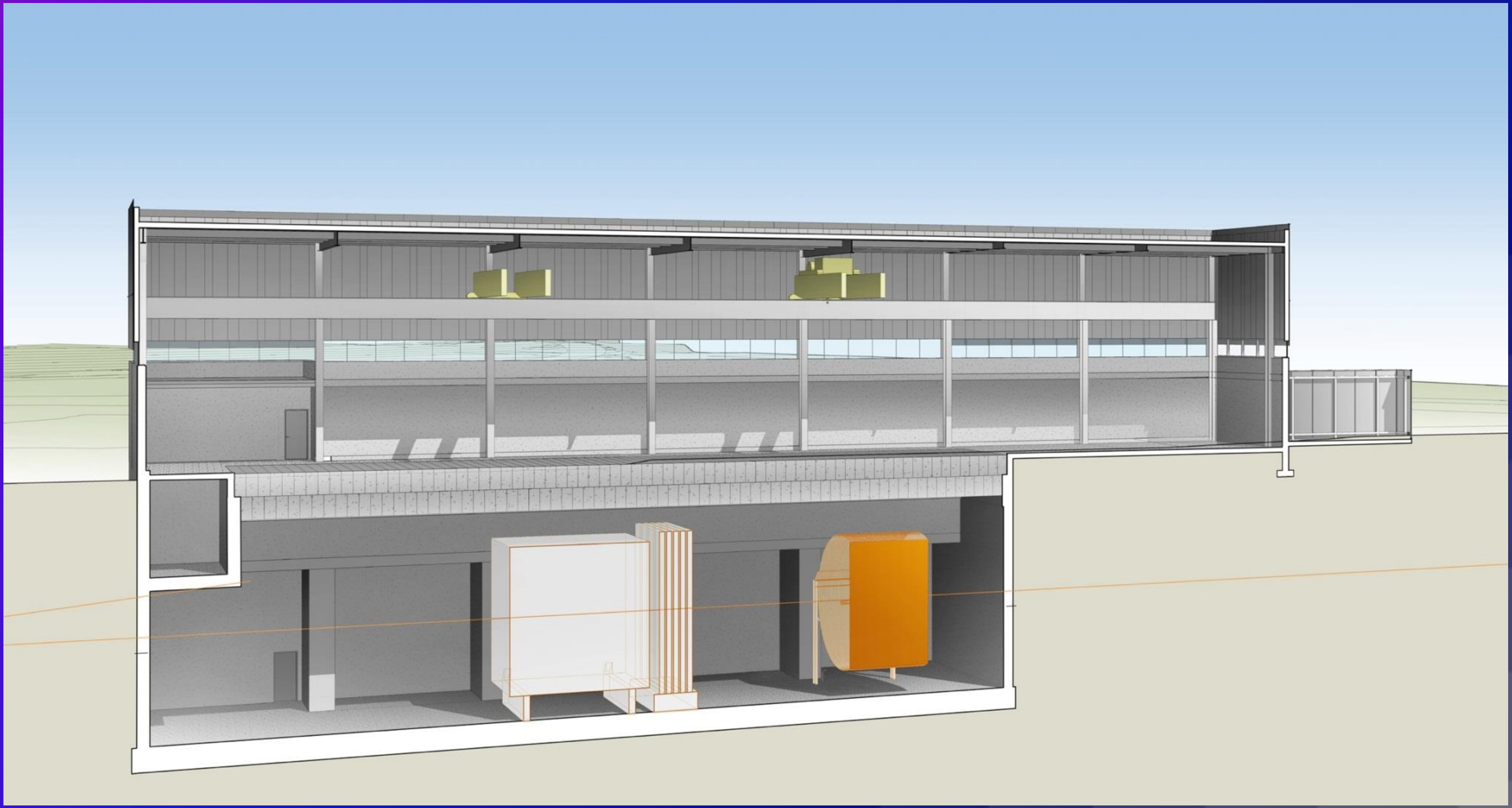
Siting Plan

Steve Dixon
Fermilab FESS

Site schematic

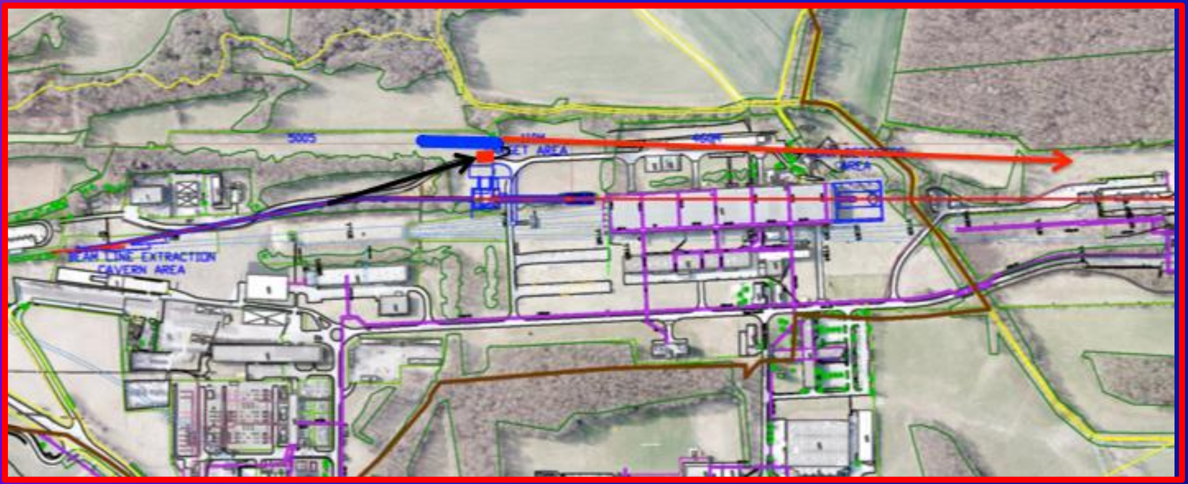


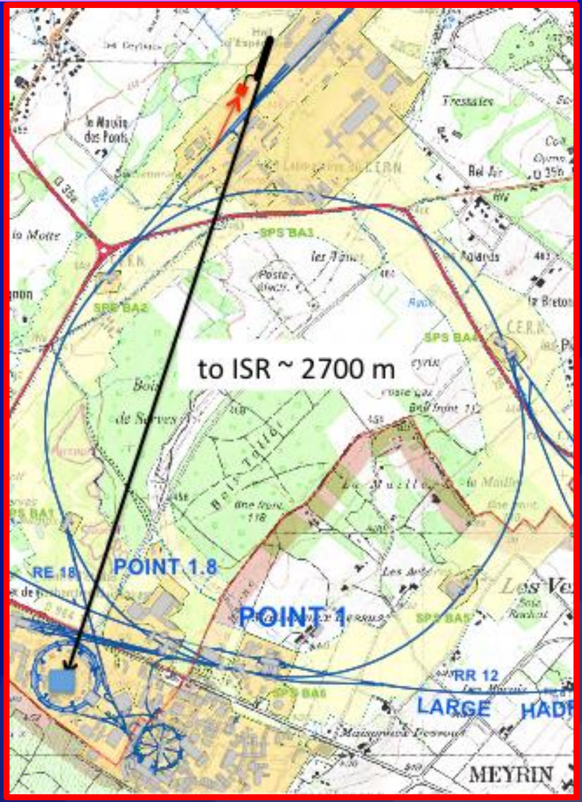
Near detector hall



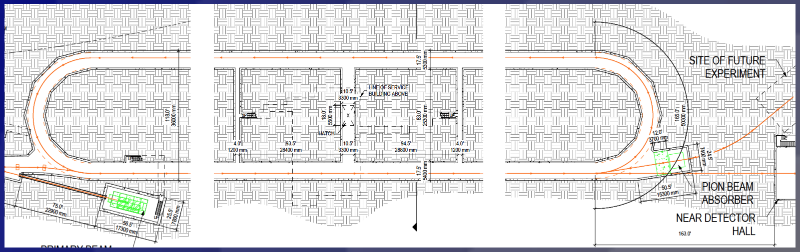
Far Detector Hall
D0 Assembly Building

Implementation, at CERN:




to ISR ~ 2700 m

- Principal issue:
  - SPS spill is 10 μs:
    - Implies bend for proton or pion beam
      - Or development of fast extraction
- Two options:
  - North Area implementation:
  - NA-to-WA implementation:
    - Advantage is proton/pion bend not required;
    - Longer baseline must be tuned to larger muon energy (possibly an advantage too)



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)
- 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.
- Full Proposal submitted to Fermilab PAC in June
  - Requested Stage I approval
- It defines a roughly two-year program which culminates in the delivery of a Technical Design Report.

Status

- nuSTORM has received Stage I approval from Fermilab
  - Opens up opportunity for R&D funds to further development towards TDR/CDR
- Response from SPSC:
  - The SPSC recognizes the nuSTORM project as an important step in the long-term development of a neutrino factory, presently considered as the ultimate facility to study CP violation in the neutrino sector. nuSTORM would also constitute a test bed for accelerator and beam physics R&D. The Committee appreciates that, in addition to these long term goals, nuSTORM could also provide the opportunity to settle important questions in the sector of sterile neutrinos, and to perform precise neutrino cross section measurements for the future neutrino programmes.
  - Currently, conventional long baseline LA-based programmes are being discussed in Europe (LBNO) and in the US (LBNE), aiming at the determination of CP violation in the neutrino sector on a shorter time scale than neutrino factories. The Committee **notes** that the nuSTORM collaboration is also exploring the possibility of being hosted by Fermilab and that there is a sizeable overlap with the LBNO community. All projects under discussion would involve a large amount of funding and resources, which calls for adequate cooperation and prioritisation within the neutrino community.
  - In this context, the SPSC considers that, in line with the recently updated European Strategy, an involvement in nuSTORM could be part of the CERN contributions to the development of future neutrino programmes. A further review of the project would require a more focused proposal identifying which tasks could be performed at CERN within a more general project defined in cooperation with Fermilab and other contributing institutes.

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
- Has considerable flexibility in its implementation that allows siting at either Fermilab or CERN
  - Just need the protons

Three Pillars of nuSTORM

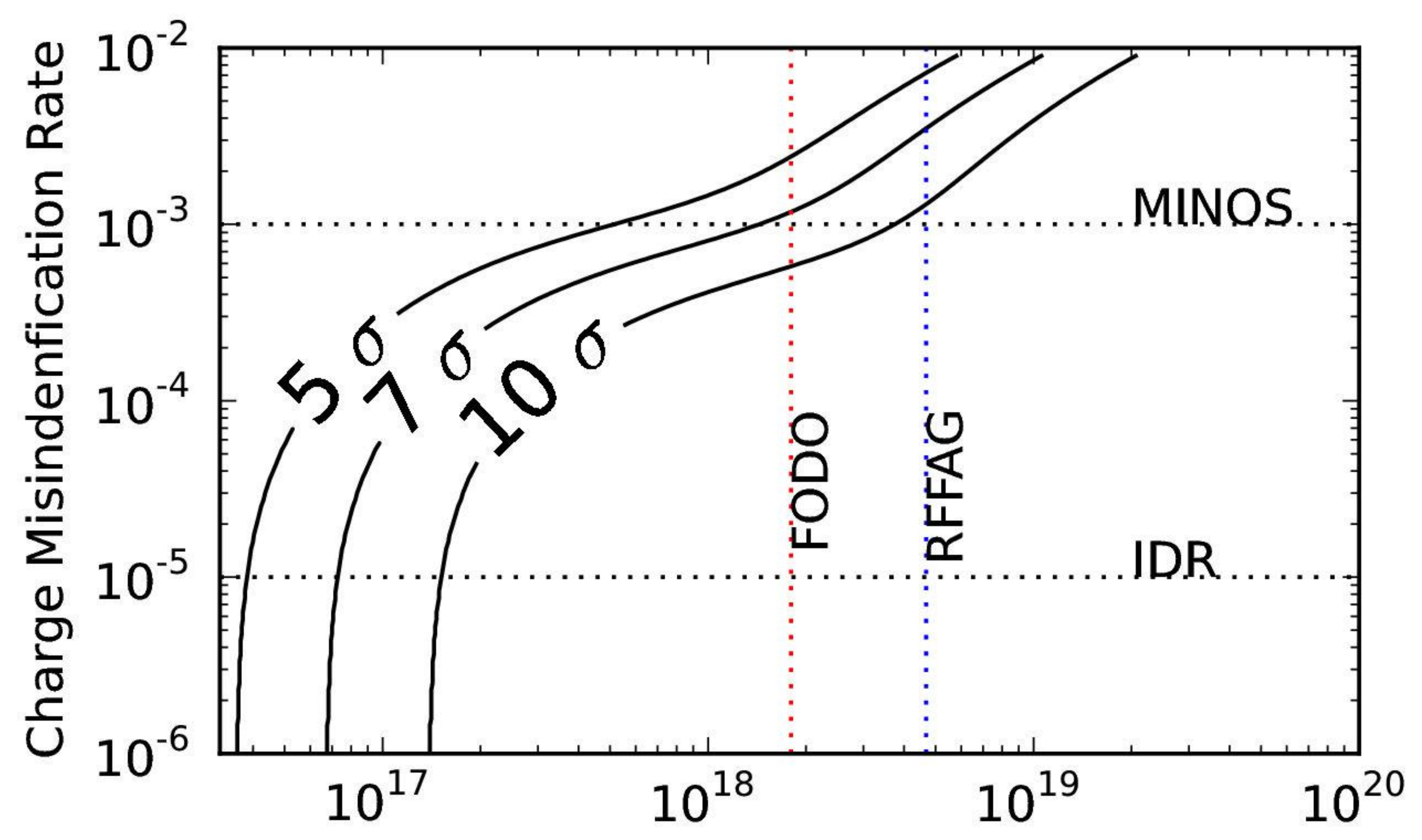
- Delivers on the physics for the study of sterile ν
  - Offering a new approach to the production of ν beams setting a 10 σ benchmark to make definitive statement w/r LSND/MiniBooNE
- Can add significantly to our knowledge of ν interactions, particularly for ν_e
  - ν *"Light Source"*
- Provides an accelerator & detector technology test bed

Thank you

Back Ups

Required μ charge mis-ID rate needed for given sensitivity

Chris Tunnell
Oxford

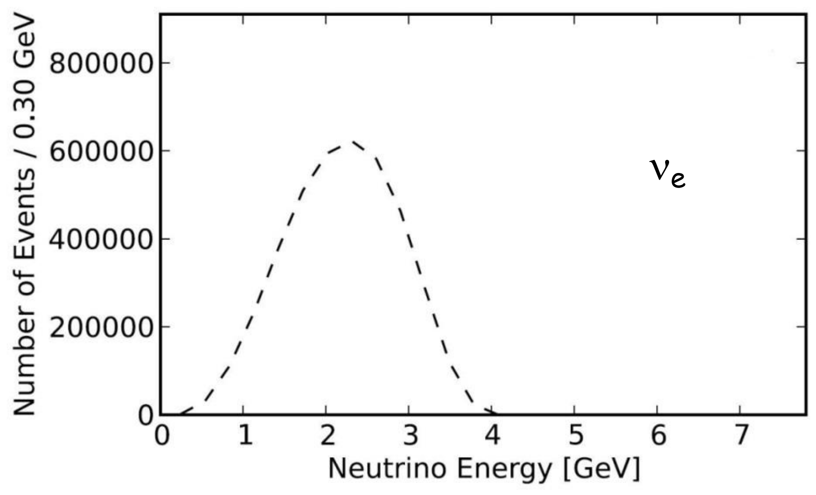


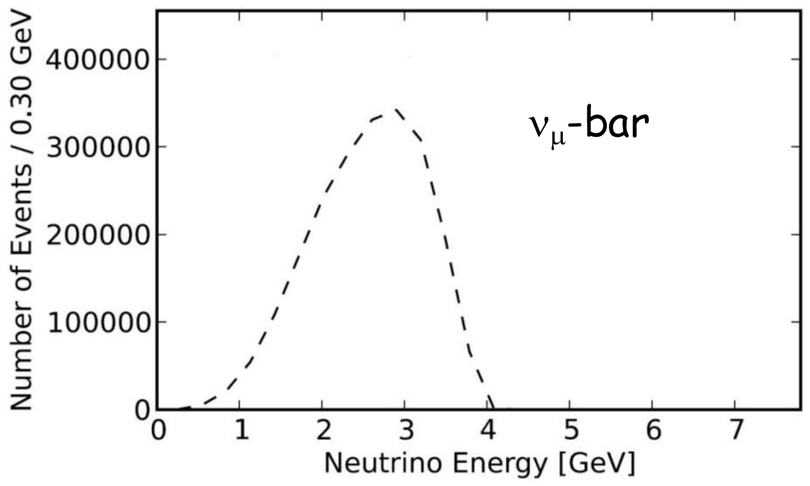
Number of useful muon decays

ν Interaction Physics

Preliminary studies

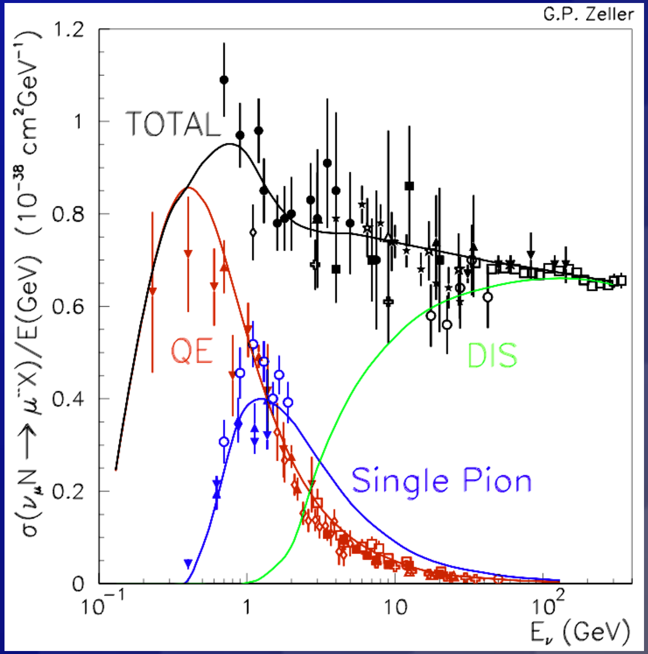
E_ν spectra (μ^+ stored)





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

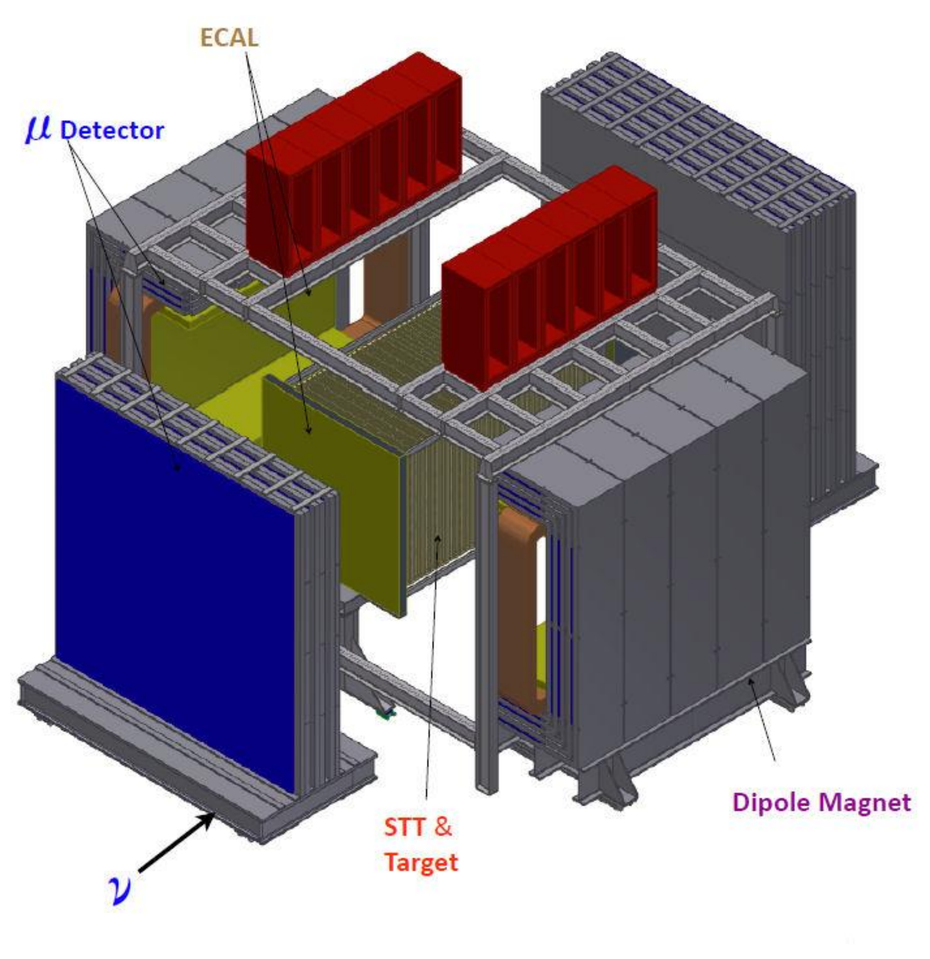
Channel	N_{evts}
$\bar{\nu}_\mu$ NC	844,793
ν_e NC	1,387,698
$\bar{\nu}_\mu$ CC	2,145,632
ν_e CC	3,960,421



A detector for ν interaction physics

One Example

Sanjib Mishra

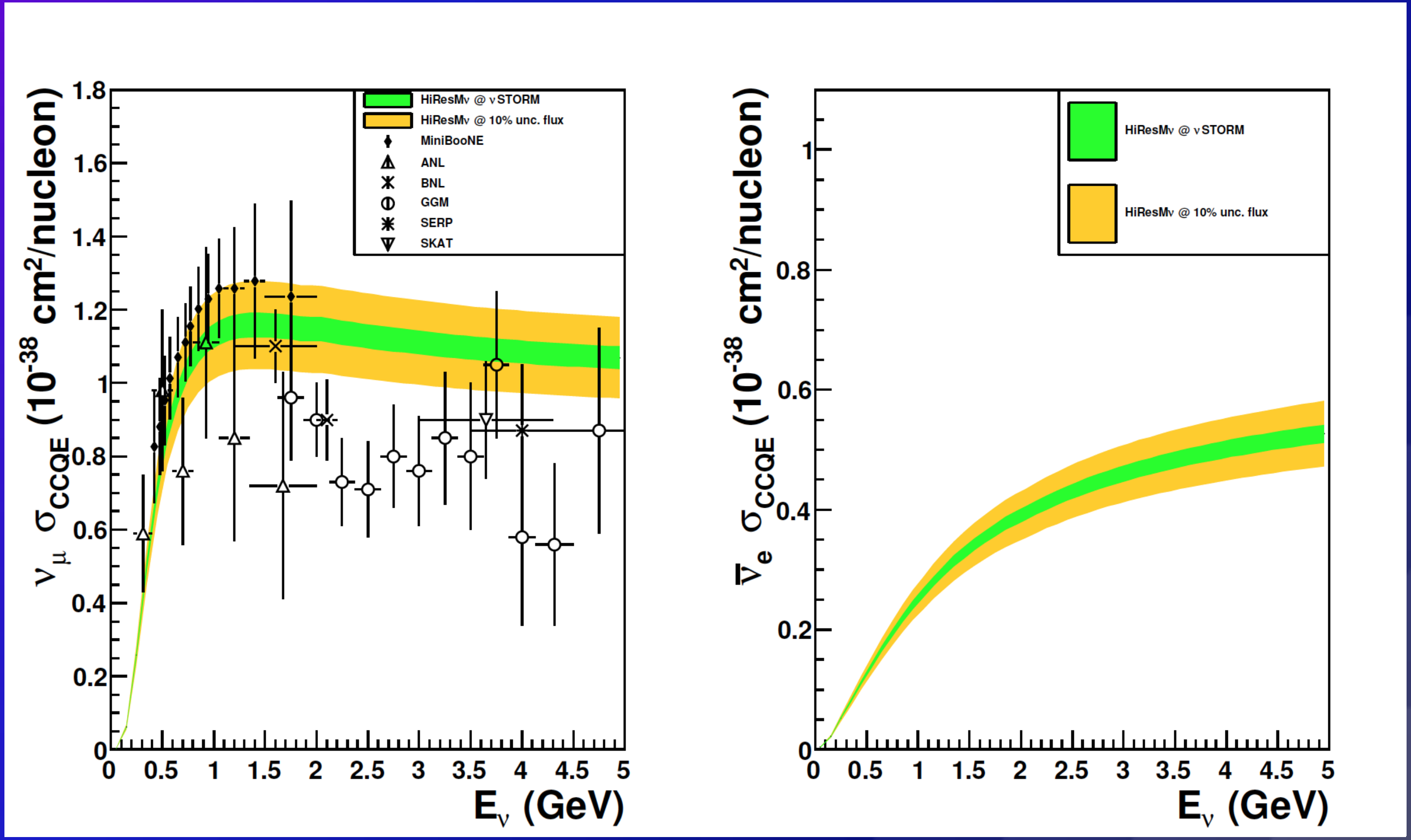


- HiResMν
  - Evolution of the NOMAD experiment
  - One of the concepts considered for ND for LBNE
  - Studied as ND for NF
- Capabilities
  - High resolution spectrometer
  - Low density
  - PID & tracking
  - Nuclear targets

Cross section measurements

Edward Santos
Imperial

μ^+

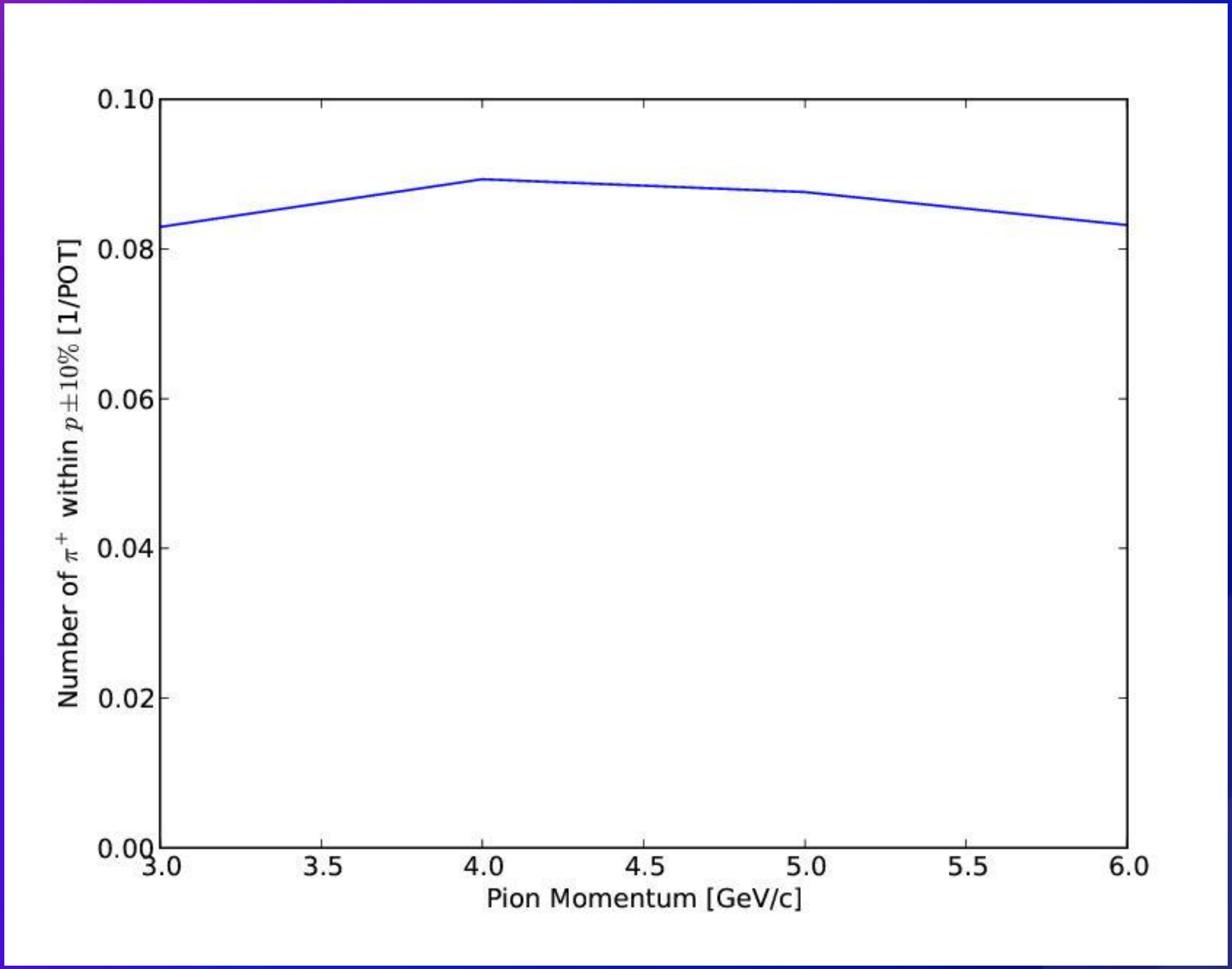


μ^-

HIRESMν □ systematics only

Accelerator

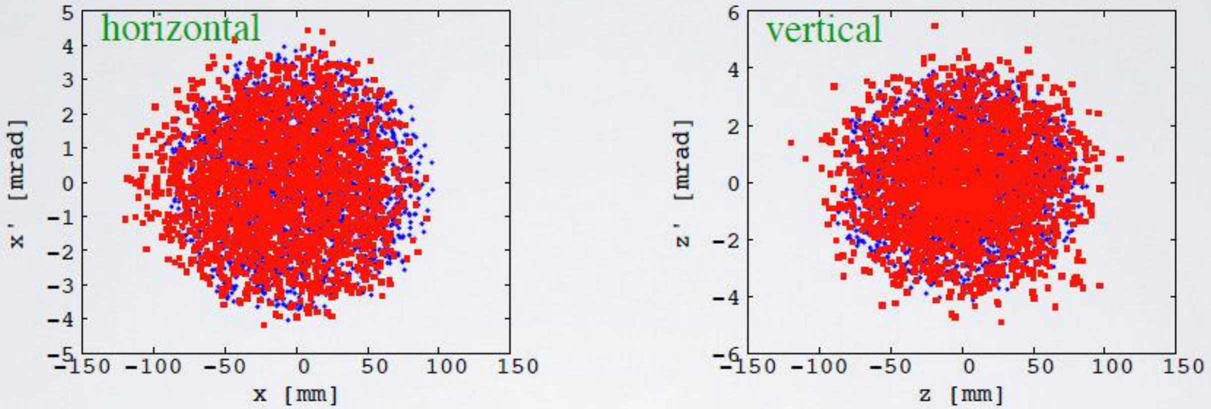
π collection
 # within p ± 10%



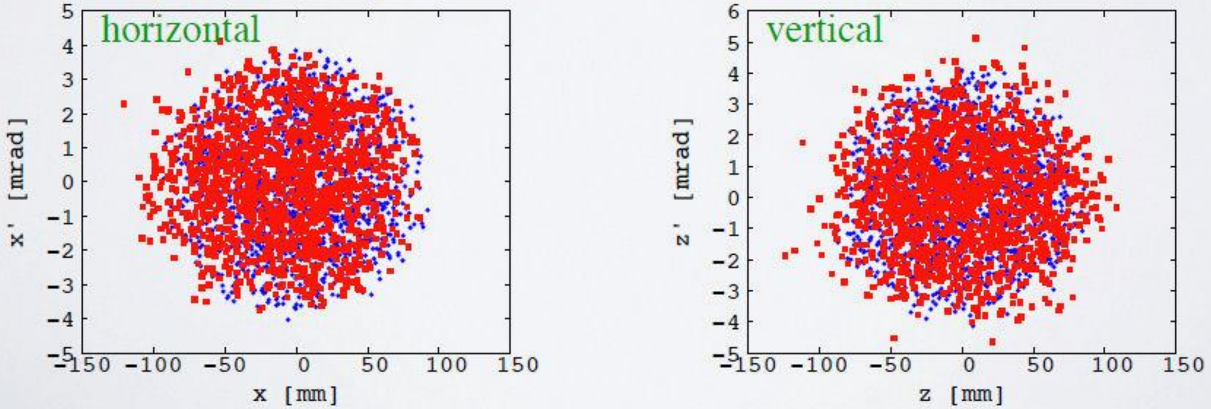
Retune line
(with some loss in efficiency)
to cover $0.3<E_\nu<4$ GeV
&
Resultant extension in L/E
X2-2.5 from lattice
considerations

RFFAG Dynamic Aperture

- Δp/p=+-20%; No particle loss after 60turns

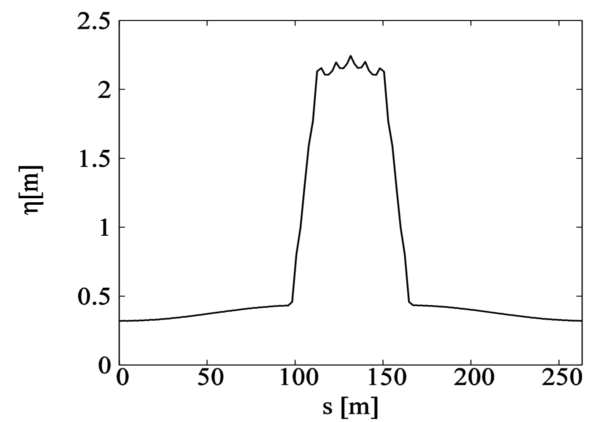


- Δp/p=+-26%; 0.7% particle loss after 60turns

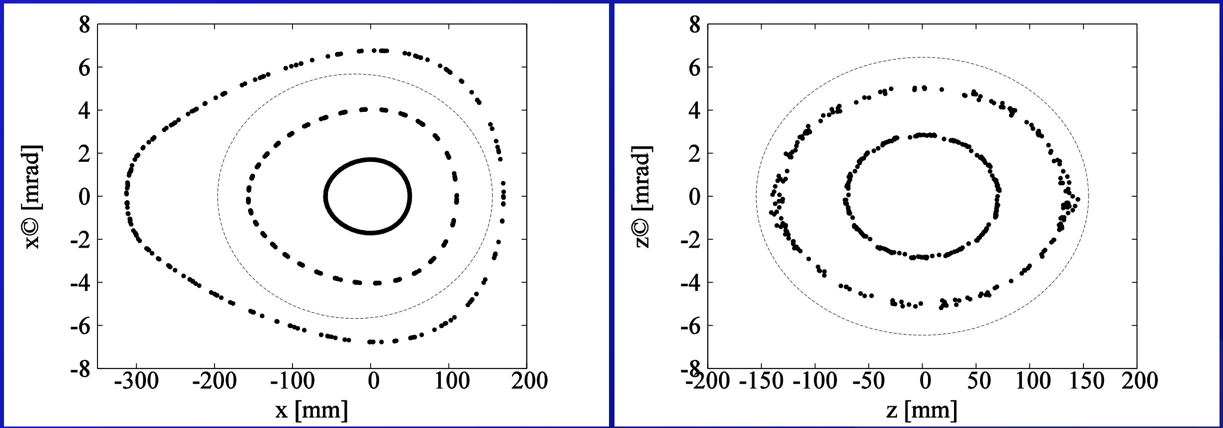


Recent FFAG Decay Ring design

JB Lagrange, Y Mori, J Pasternak, A Sato

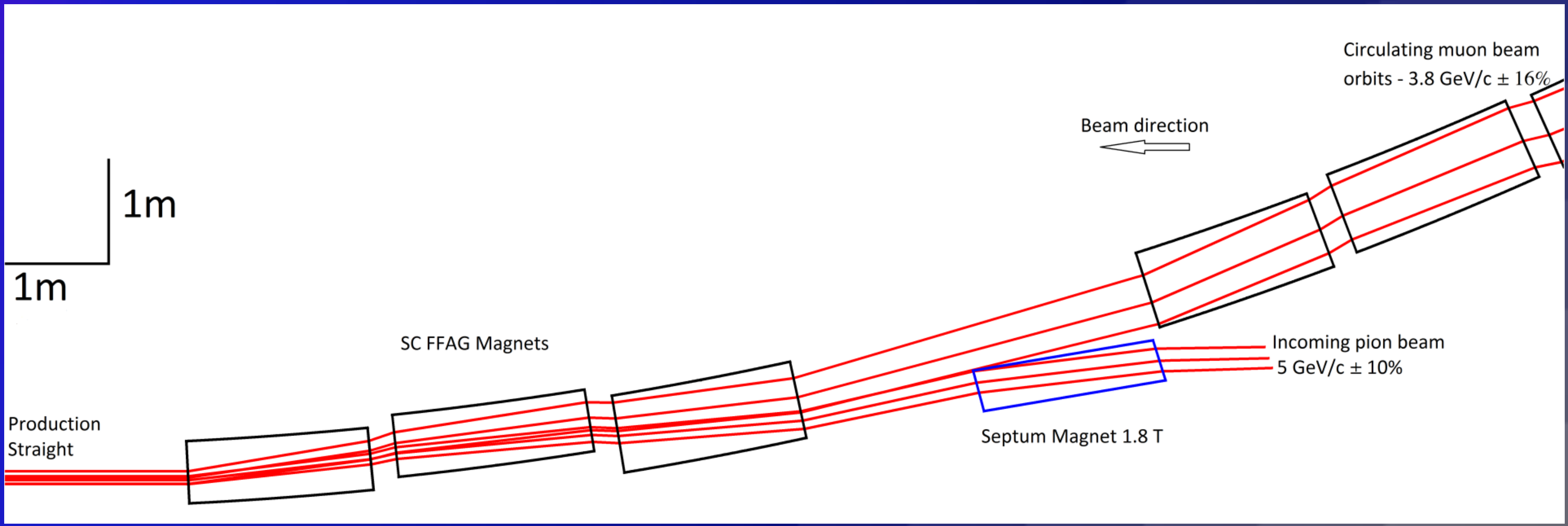


Good dispersion matching (new ring).



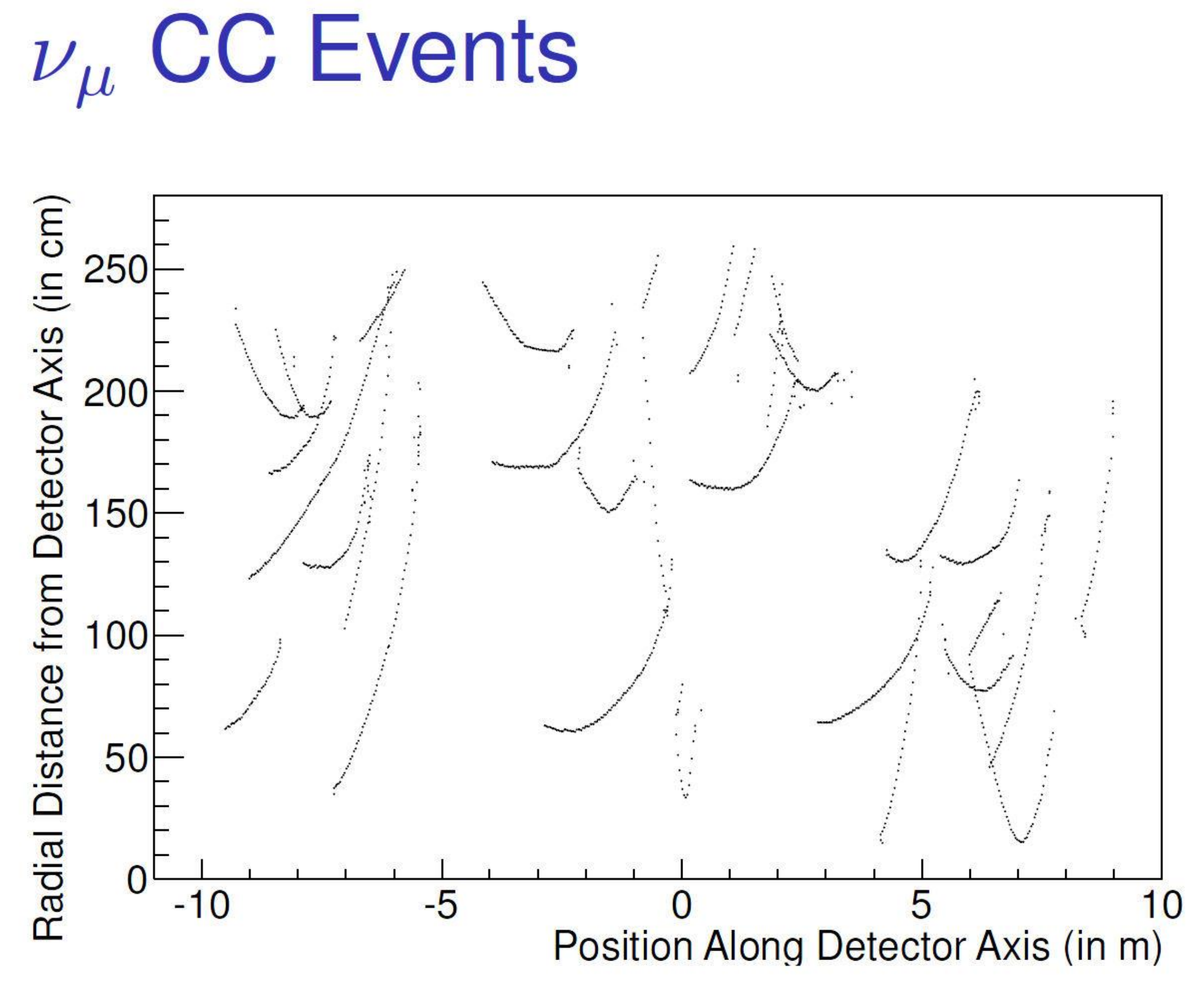
Horizontal (left) and vertical (right) DA (100 turns).

Preliminary stochastic injection geometry



Detector Issues

Event Candidates in SuperBIND

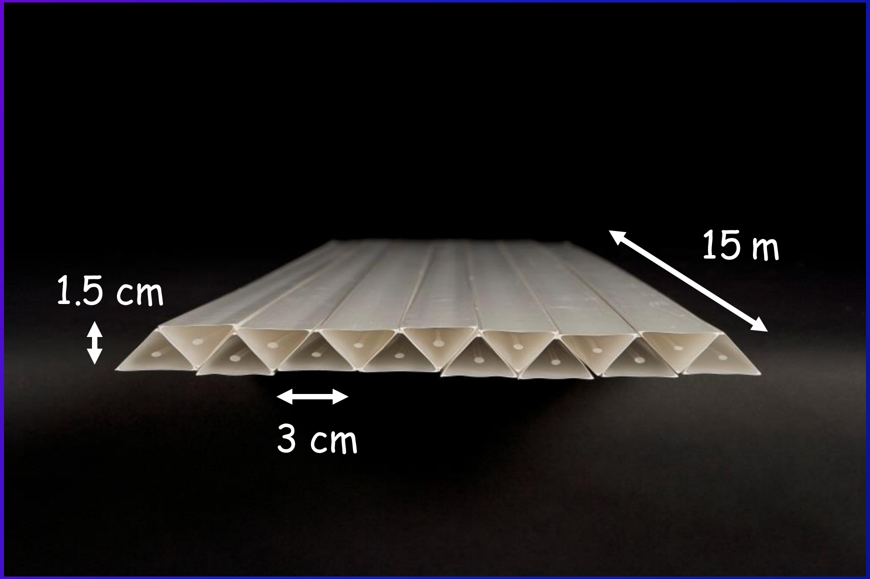


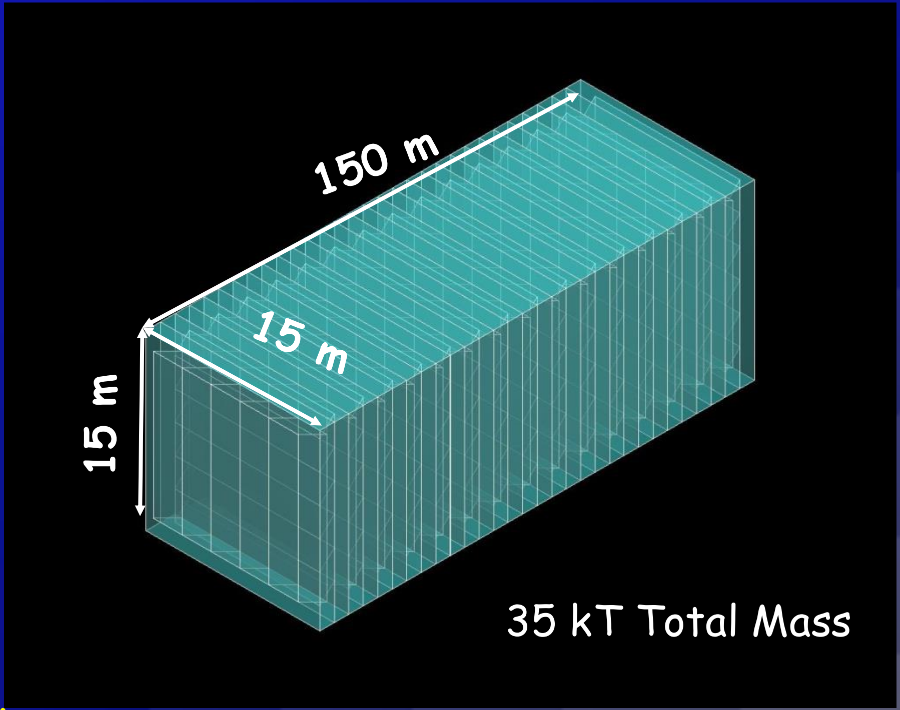
Hits
R vs. Z

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





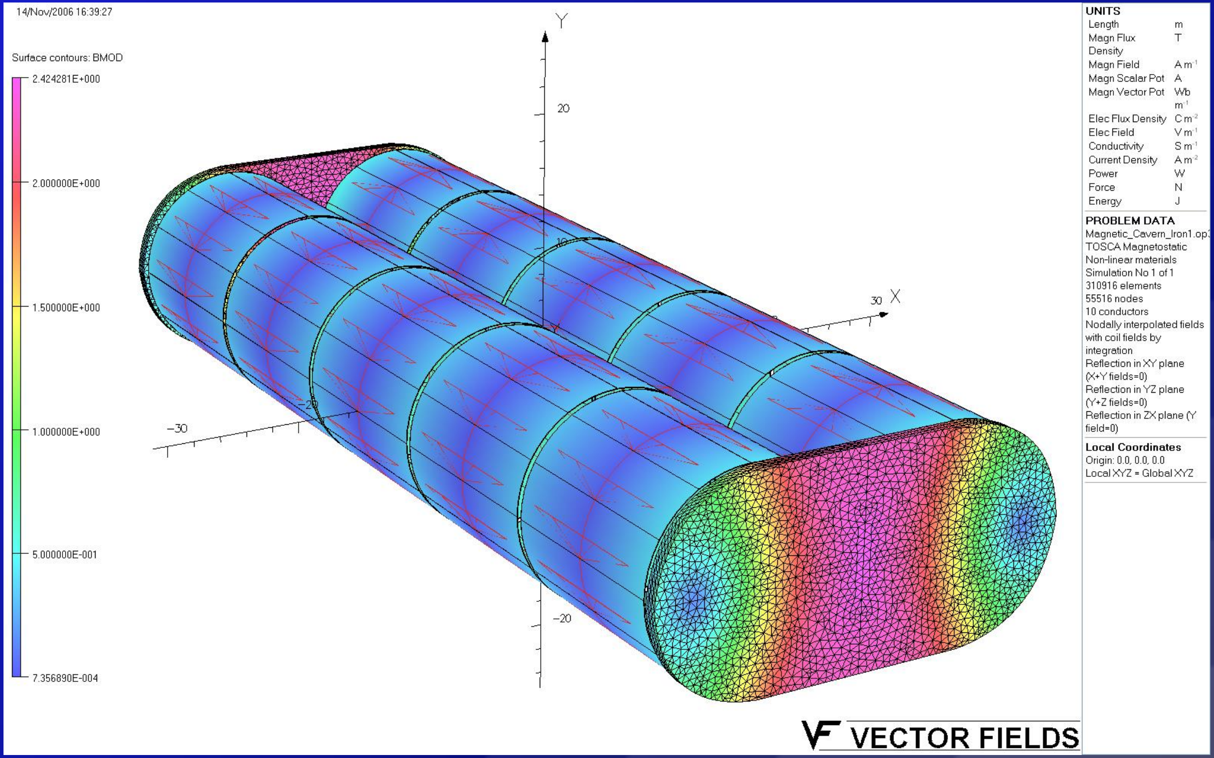
35 kT Total Mass

- 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



UNITS

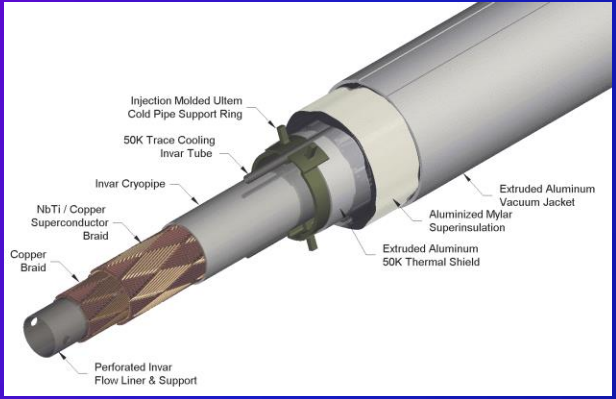
Length	m
Magn Flux Density	T
Magn Field	A m^{-1}
Magn Scalar Pot	A
Magn Vector Pot	Wb m^{-1}
Elec Flux Density	C m^{-2}
Elec Field	V m^{-1}
Conductivity	S m^{-1}
Current Density	A m^{-2}
Power	W
Force	N
Energy	J

PROBLEM DATA

Magnetic_Cavern_Iron1.op3
TOSCA Magnetostatic
Non-linear materials
Simulation No 1 of 1
310916 elements
55516 nodes
10 conductors
Nodally interpolated fields with coil fields by integration
Reflection in XY plane (X+Y fields=0)
Reflection in YZ plane (Y+Z fields=0)
Reflection in ZX plane (Y field=0)

Local Coordinates

Origin: 0.0, 0.0, 0.0
Local XYZ = Global XYZ

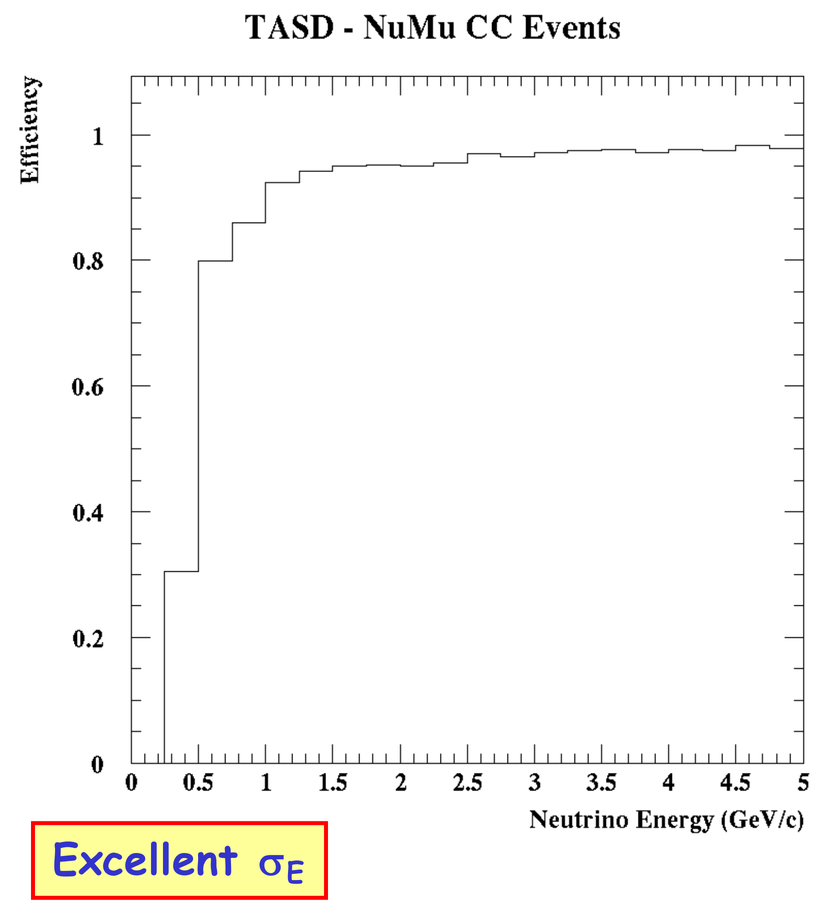


R&D to support concept
Has not been funded

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

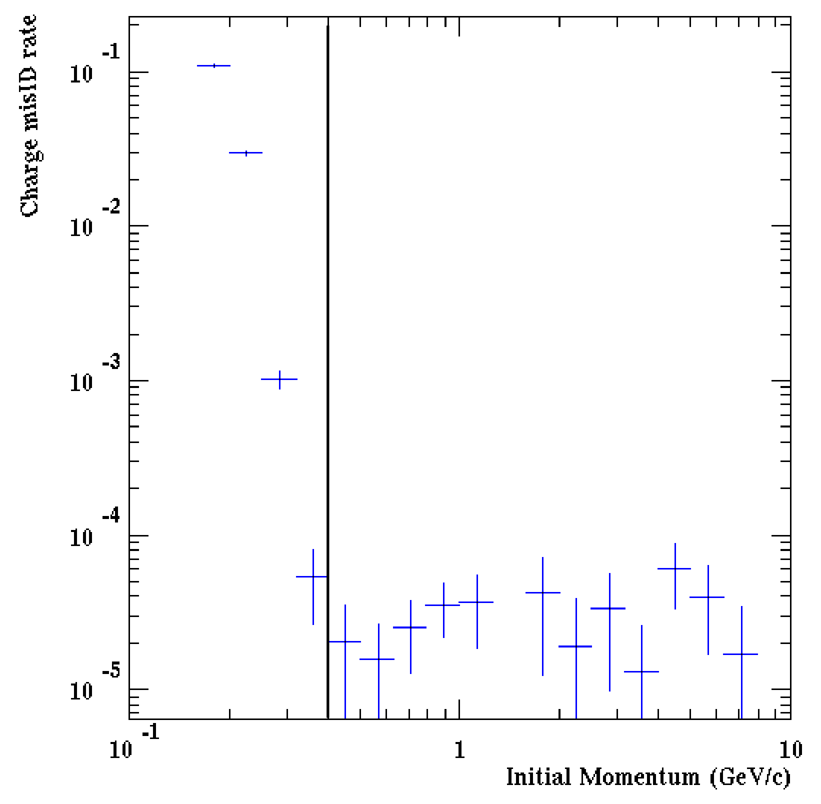
TASD Performance

ν Event Reconstruction ε



Excellent σ_E

Muon charge mis-ID rate



Detector Options

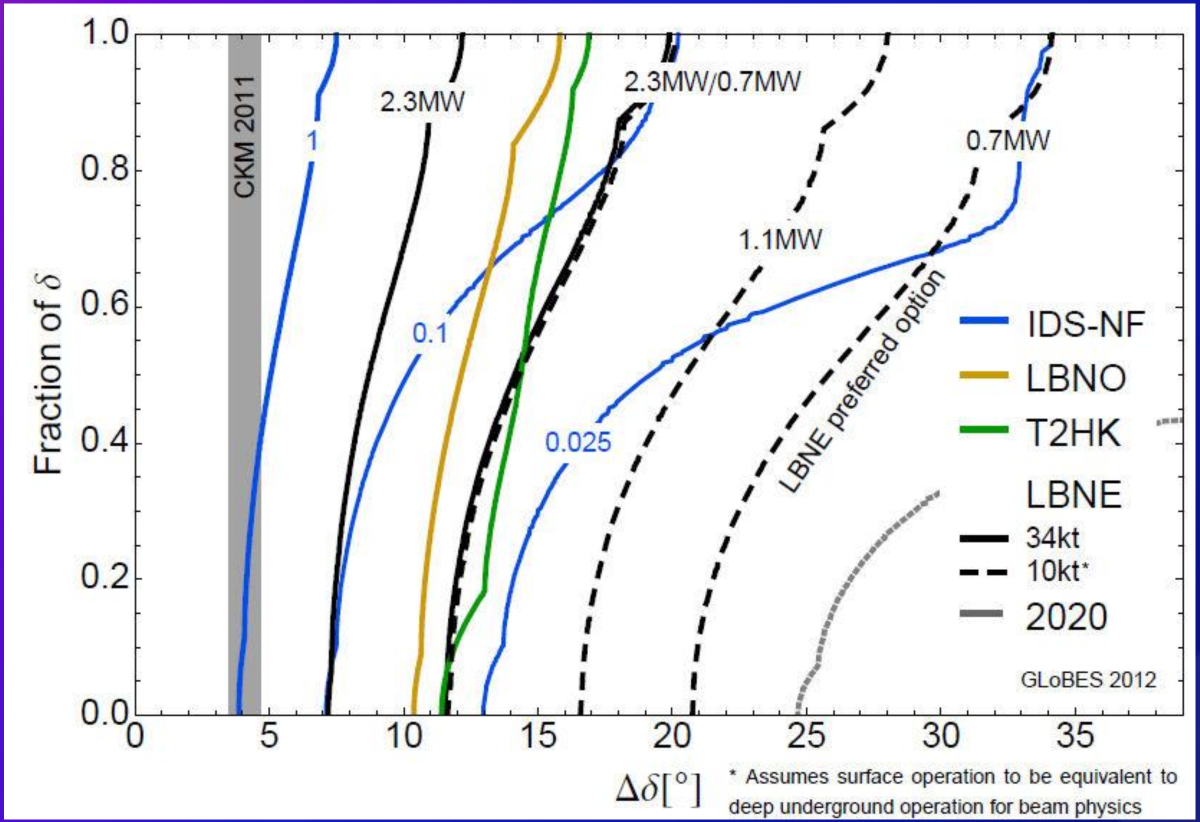
Technology check List

	Fid Volume	B	Recon	Costing Model
SuperBIND	🟦	🟦	🟦	🟦
Mag-TASD	🟦	🟥	🟦	⬛
Mag-LAr	⬛	🟥	⬛	🟥

🟦	Yes - OK
⬛	Maybe
🟥	Not Yet

NF Physics & 3+n Models

NF Upgrade path



* Assumes surface operation to be equivalent to deep underground operation for beam physics

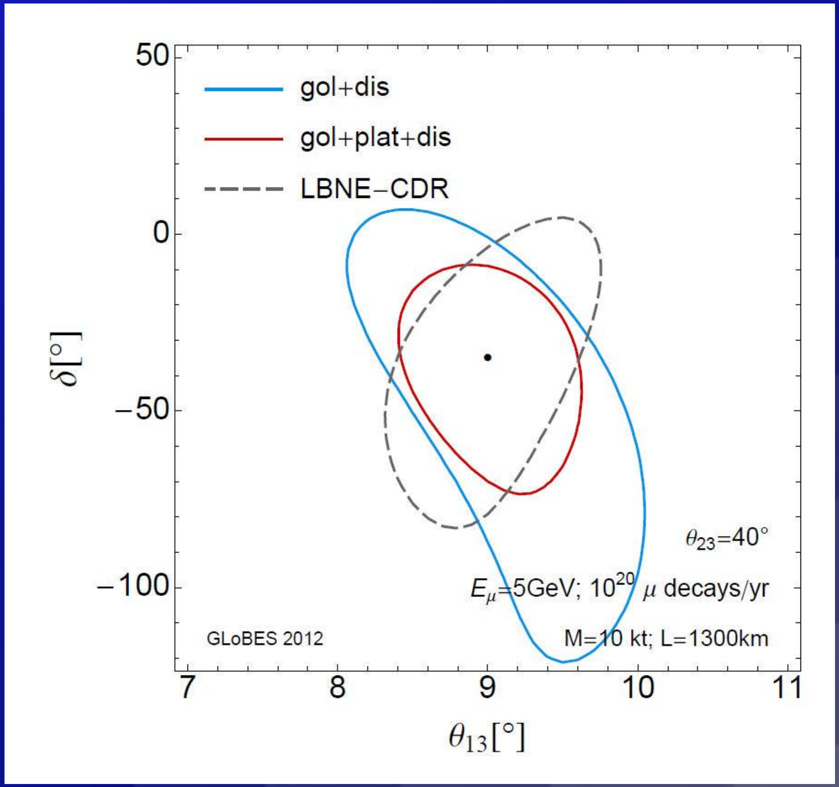
P. Coloma, P.Huber, J. Kopp, W. Winter, in preparation

- 2020 – T2K, NOνA and Daya Bay
- LBNE – 1300 km, 34 kt
  - 0.7MW, 2 × 10^8 s (10 yrs)
- LBNO – 2300 km, 100 kt
  - 0.8MW, 1 × 10^8 s (10 yrs)
- T2HK – 295 km, 560 kt
  - 0.7MW, 1.2×10^8 s (10 yrs)
- 0.025 IDS-NF
  - 700kW (5 yrs)
  - no cooling
  - 2 × 10^8 s running time
  - 10 kt detector
  - Still Very Expensive
    - LBNE (10kt, surface)

νSTORM

Think even smaller (cheaper)

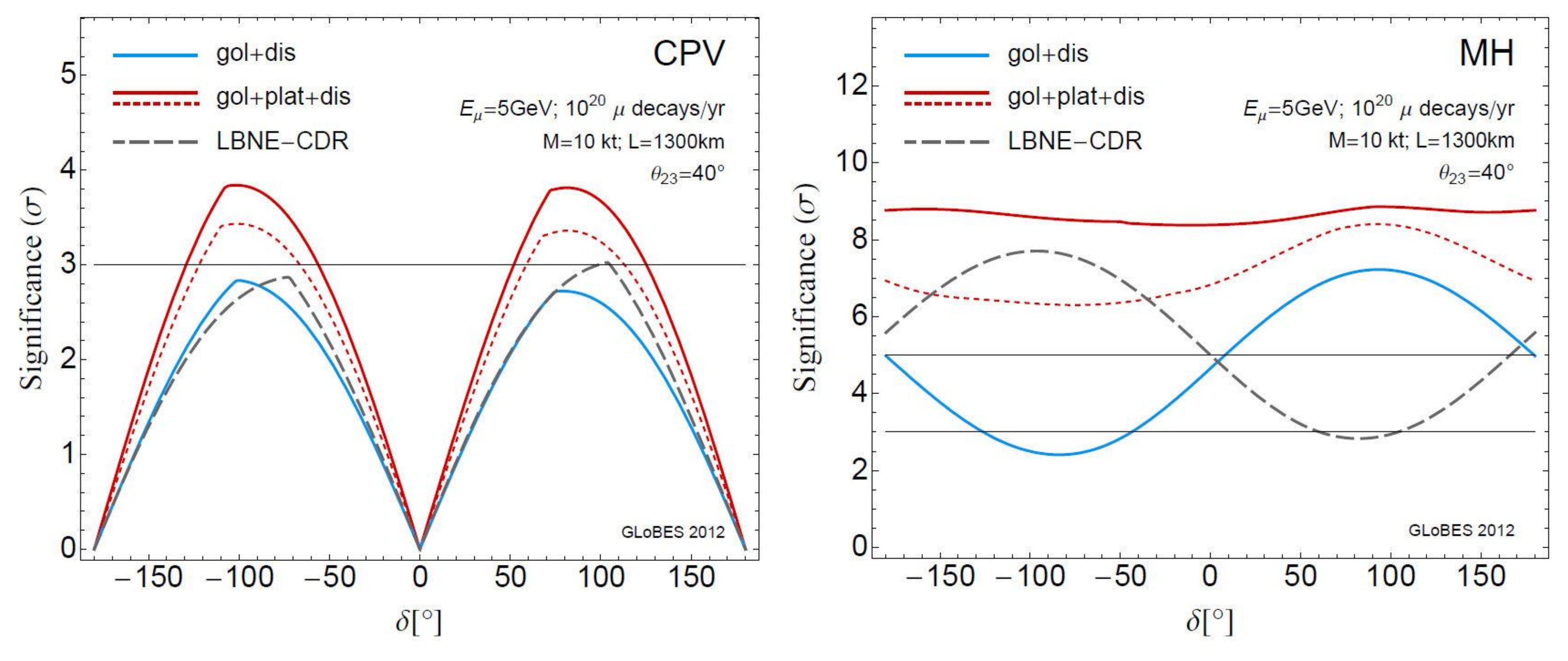
- Low energy Low luminosity NF (L3NF)
  - Add platinum channel (ν_e appearance)
    - Need excellent charge ID
  - E_μ of 5 Gev
  - L = 1300 km
- Specifics
  - 700 kW on target
  - 2 X 10^7 sec/yr.
  - No cooling
- 1% of baseline NF:
  - 10^{20} useful μ decays/yr.
  - 10 kT of Magnetized LAr
    - Underground



Christensen, Coloma and Huber
arXiv: 1301.7727

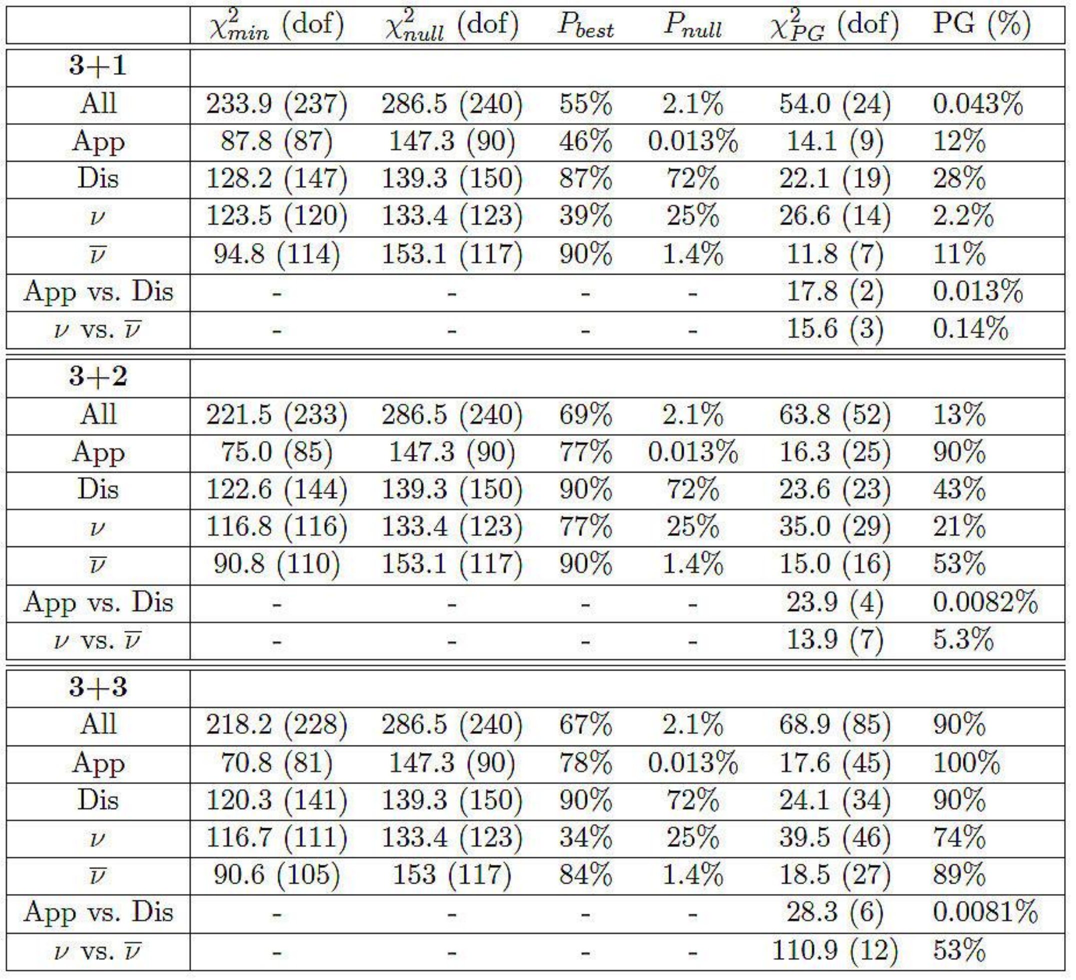
Confidence region in the $\theta_{13} - \delta$ plane for a particular point in the parameter space, at 1σ

L3NF: CPV and MH



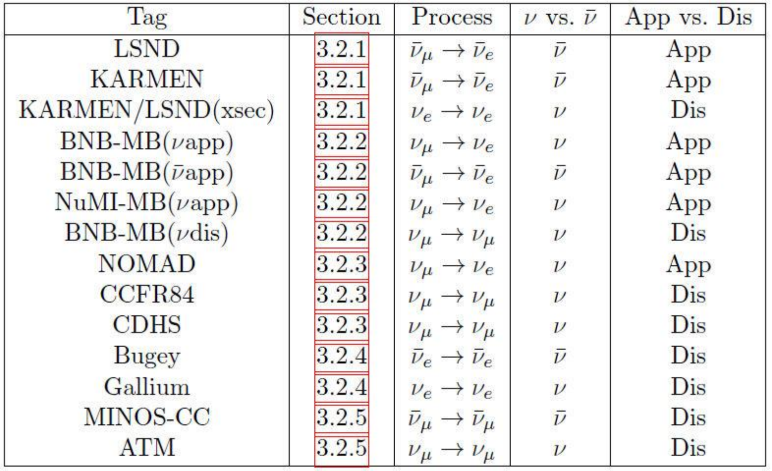
What is still so compelling about the NF is how robust its physics case is. Even at only 1% of the baseline Flux X (Fiducial Mass), it still can do world-class physics. It also presents a tenable upgrade path to explore with much greater precision the νSM and to look beyond, NSIs, heavy ν……?.

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%
$\overline{\nu}$	94.8 (114)	153.1 (117)	90%	1.4%	11.8 (7)	11%
App vs. Dis	-	-	-	-	17.8 (2)	0.013%
ν vs. $\overline{\nu}$	-	-	-	-	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%
$\overline{\nu}$	90.8 (110)	153.1 (117)	90%	1.4%	15.0 (16)	53%
App vs. Dis	-	-	-	-	23.9 (4)	0.0082%
ν vs. $\overline{\nu}$	-	-	-	-	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%
$\overline{\nu}$	90.6 (105)	153 (117)	84%	1.4%	18.5 (27)	89%
App vs. Dis	-	-	-	-	28.3 (6)	0.0081%
ν vs. $\overline{\nu}$	-	-	-	-	110.9 (12)	53%

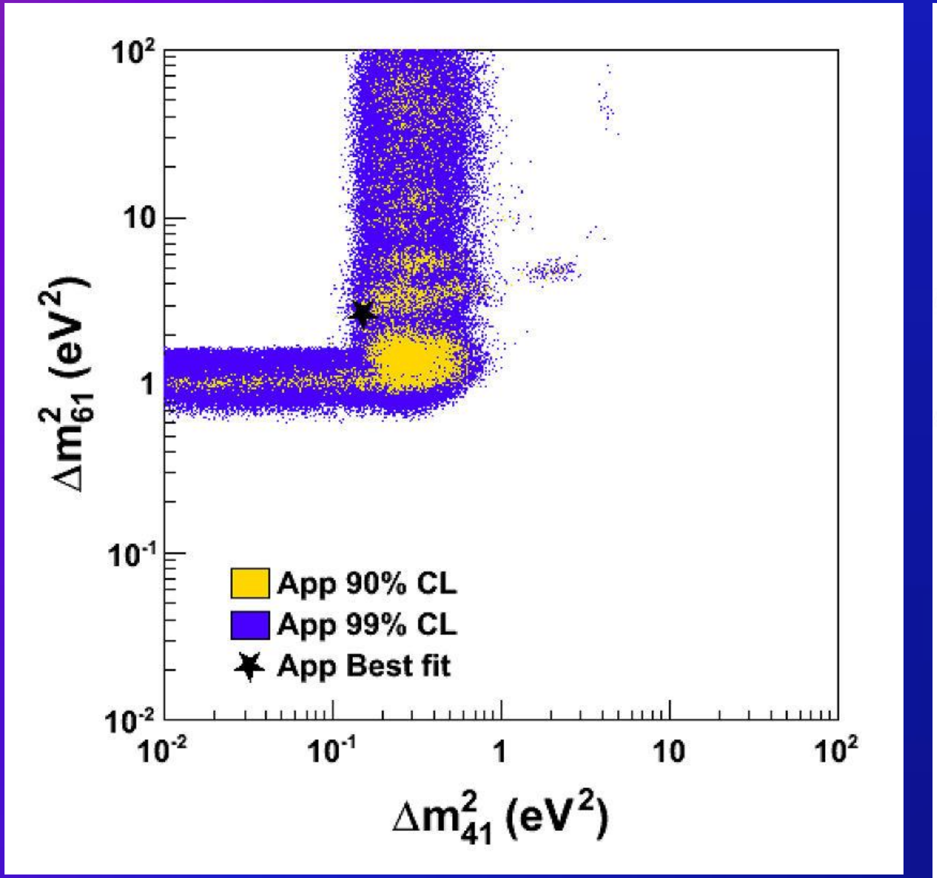
- *A 3+3 model has recently been shown to better fit all available data*



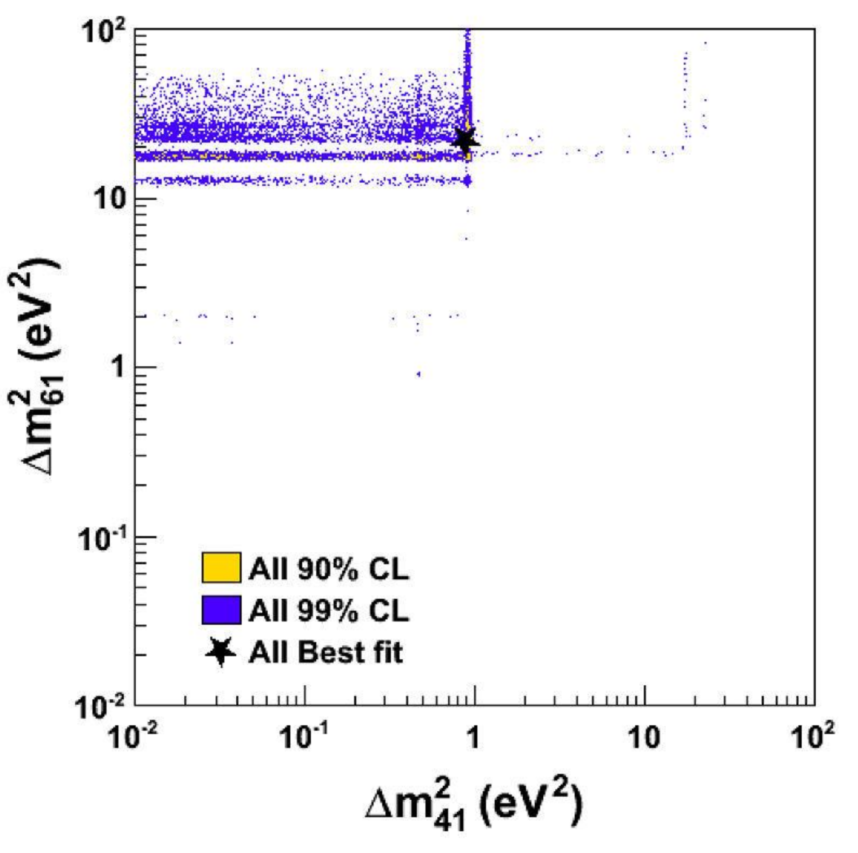
Tag	Section	Process	ν vs. $\bar{\nu}$	App vs. Dis
LSND	3.2.1	$\bar{\nu}_\mu \to \bar{\nu}_e$	$\bar{\nu}$	App
KARMEN	3.2.1	$\bar{\nu}_\mu \to \bar{\nu}_e$	$\bar{\nu}$	App
KARMEN/LSND(xsec)	3.2.1	$\nu_e \to \nu_e$	ν	Dis
BNB-MB(νapp)	3.2.2	$\nu_\mu \to \nu_e$	ν	App
BNB-MB($\bar{\nu}$app)	3.2.2	$\bar{\nu}_\mu \to \bar{\nu}_e$	$\bar{\nu}$	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



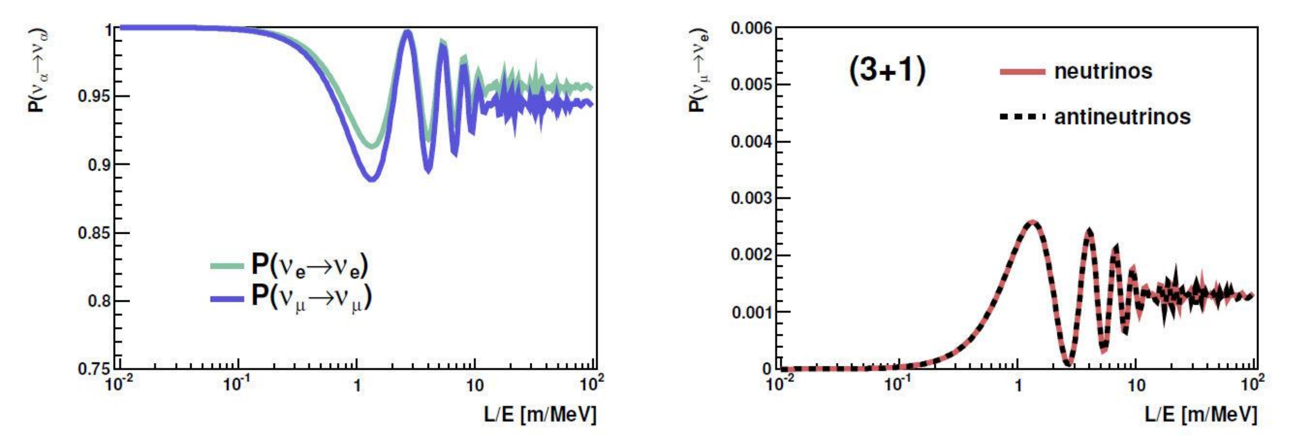
Appearance Data

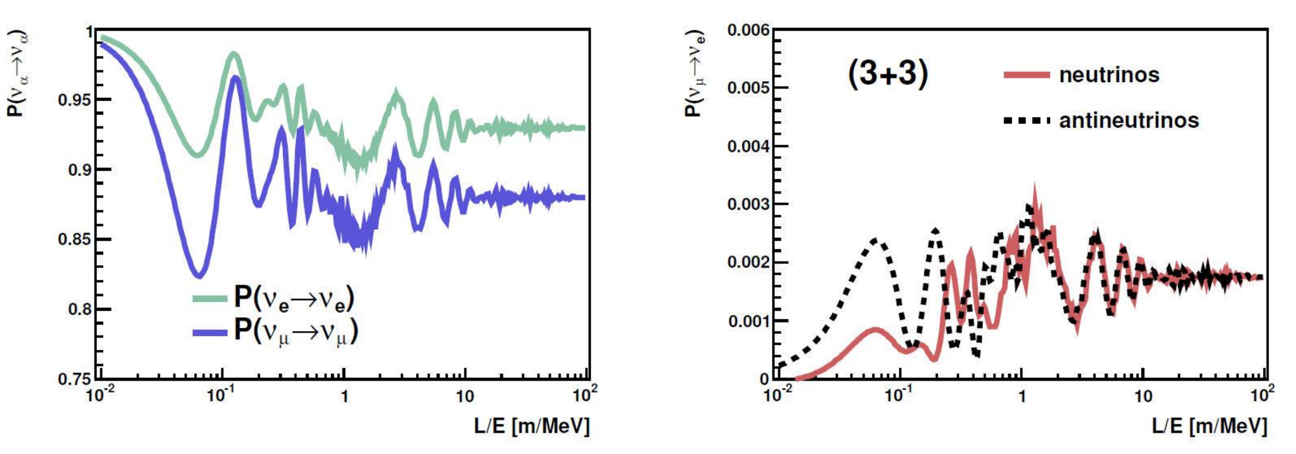


All Data

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

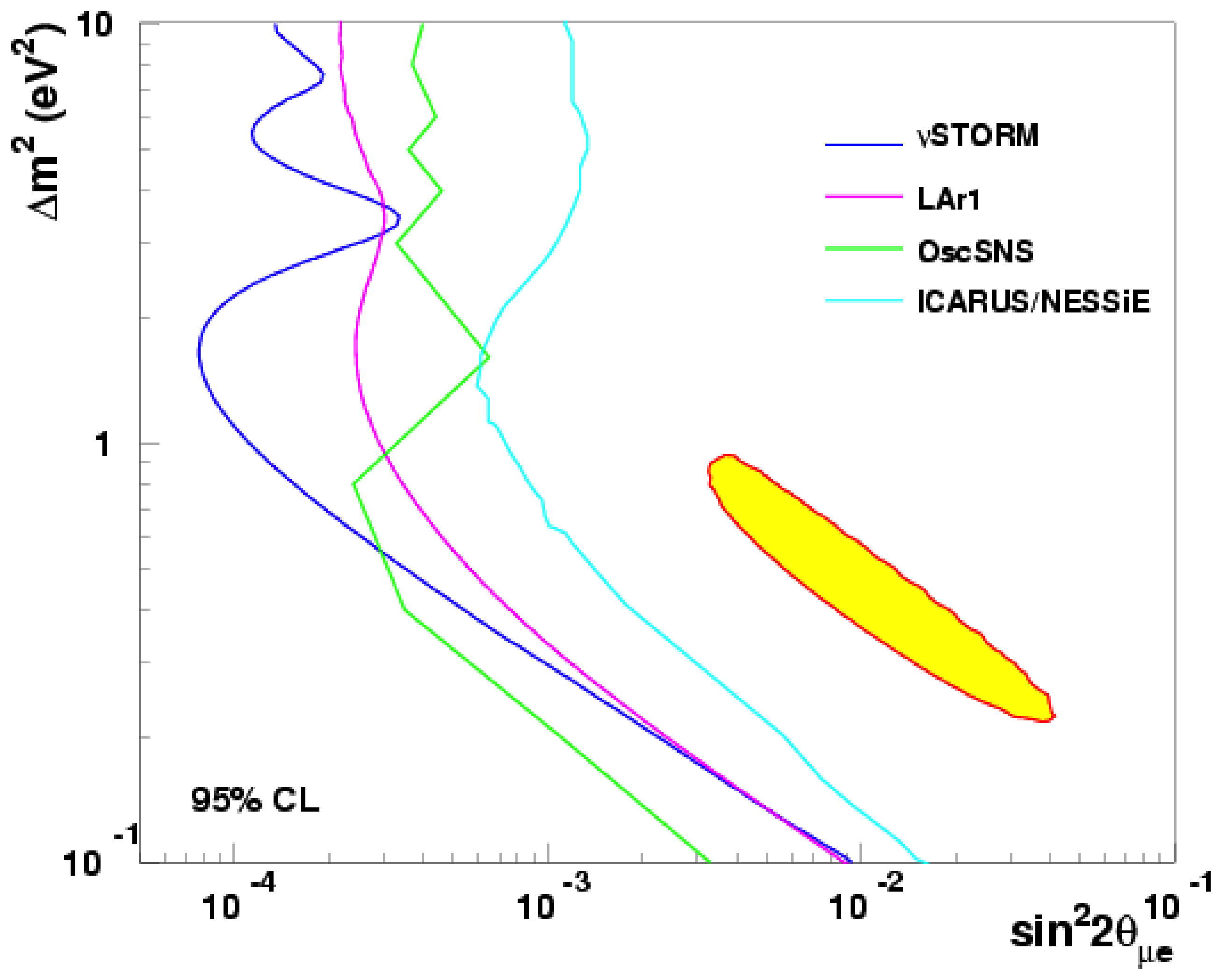
S:B for Appearance Channel

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

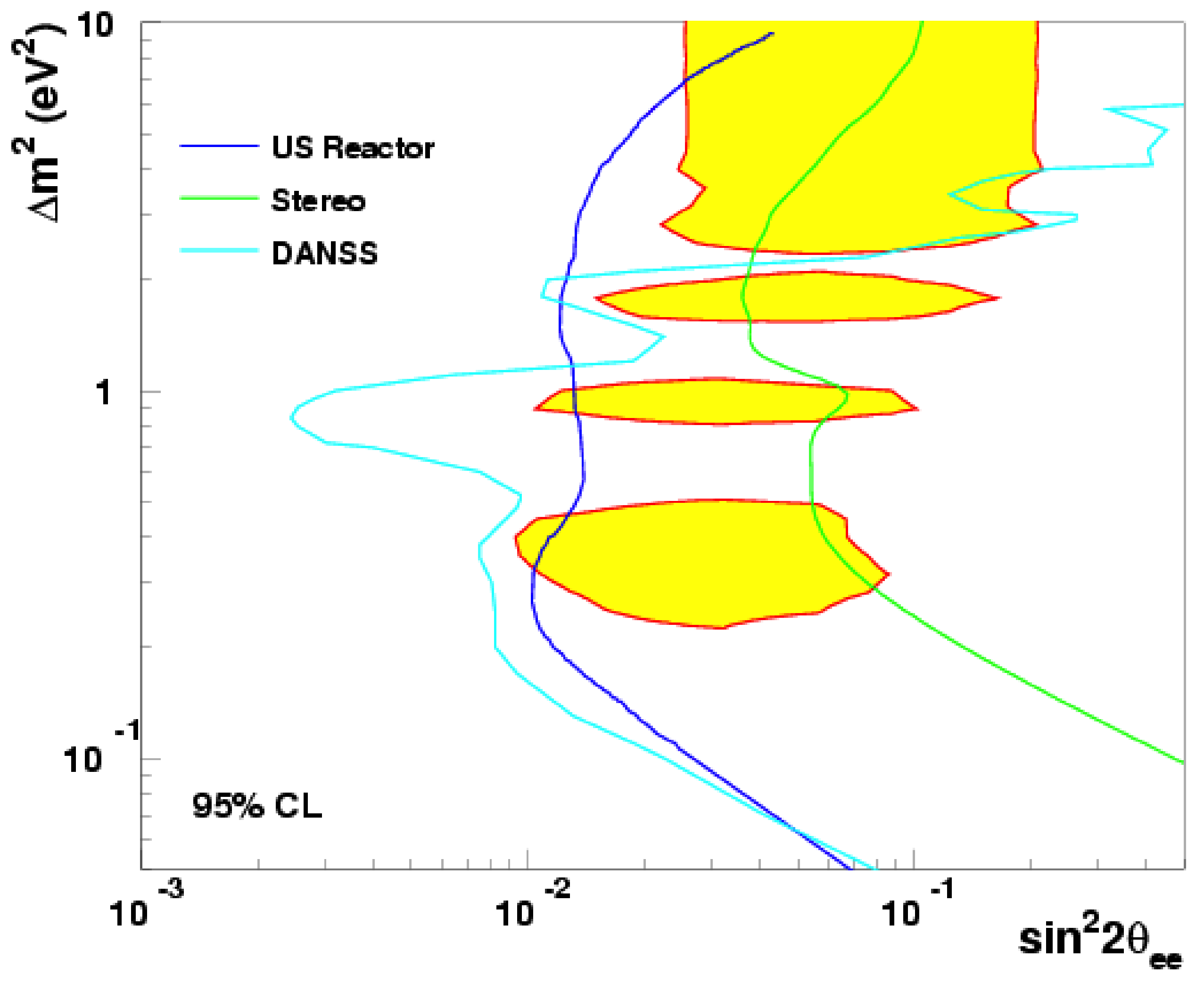
- Note: There are a number of experiments with megaCi to petaCi sources next to large detectors that have an exquisite signature of steriles (# evts/unit length displays oscillatory behavior in large detector) and have large effective S:B
  - SNO+Cr, Ce-Land, LENS, Borexino, Daya Bay
  - IsoDAR
  - *A*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

Appearance



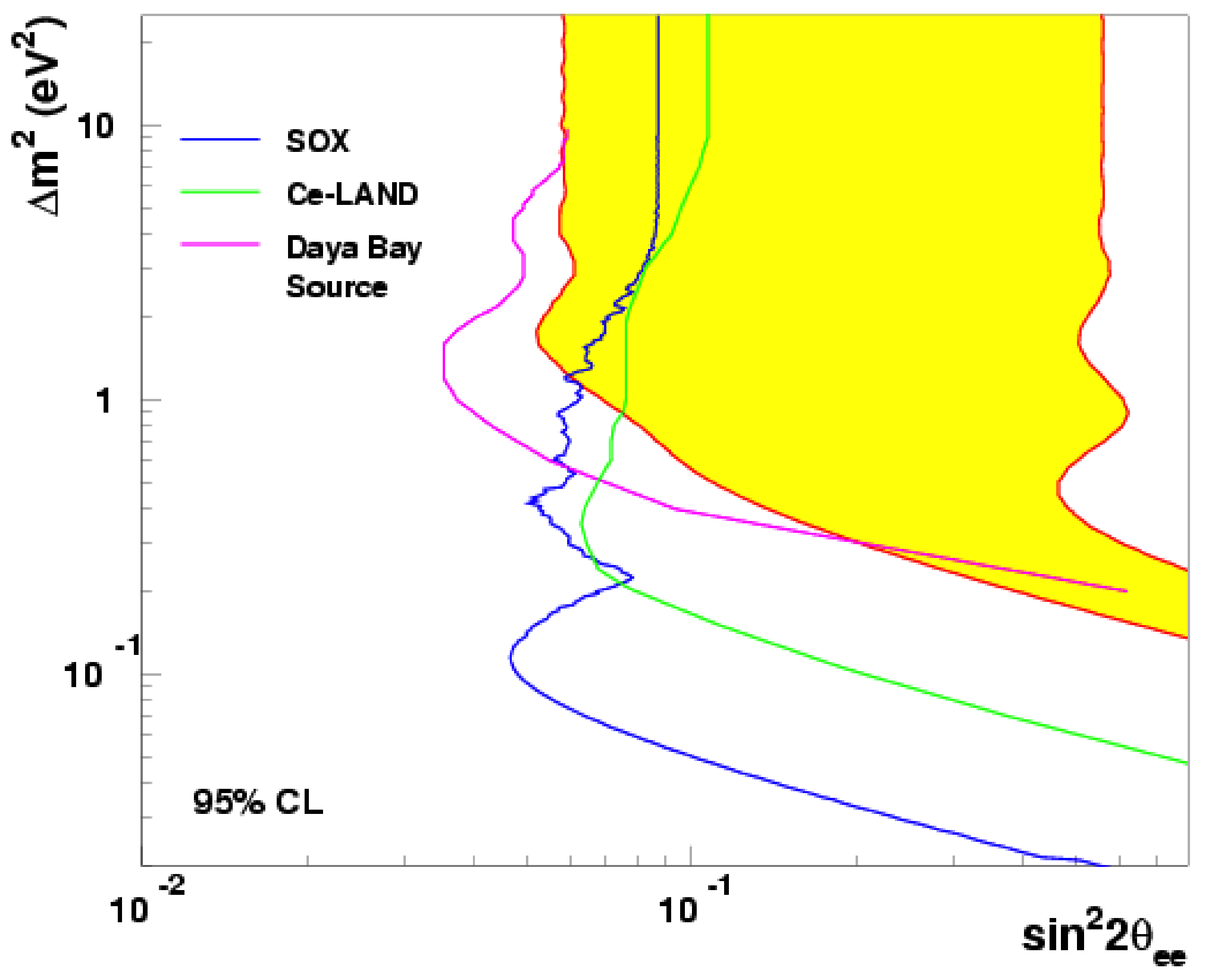
Δm^2 (eV^2)
10
1
10^{-1}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
$\sin^2 2\theta_{\mu e}$
νSTORM
LAr1
OscSNS
ICARUS/NESSiE
95% CL

Reactor



Δm^2 (eV^2)
10
1
10^{-1}
US Reactor
Stereo
DANSS
95% CL
10^{-3}
10^{-2}
10^{-1}
$\sin^2 2\theta_{ee}$

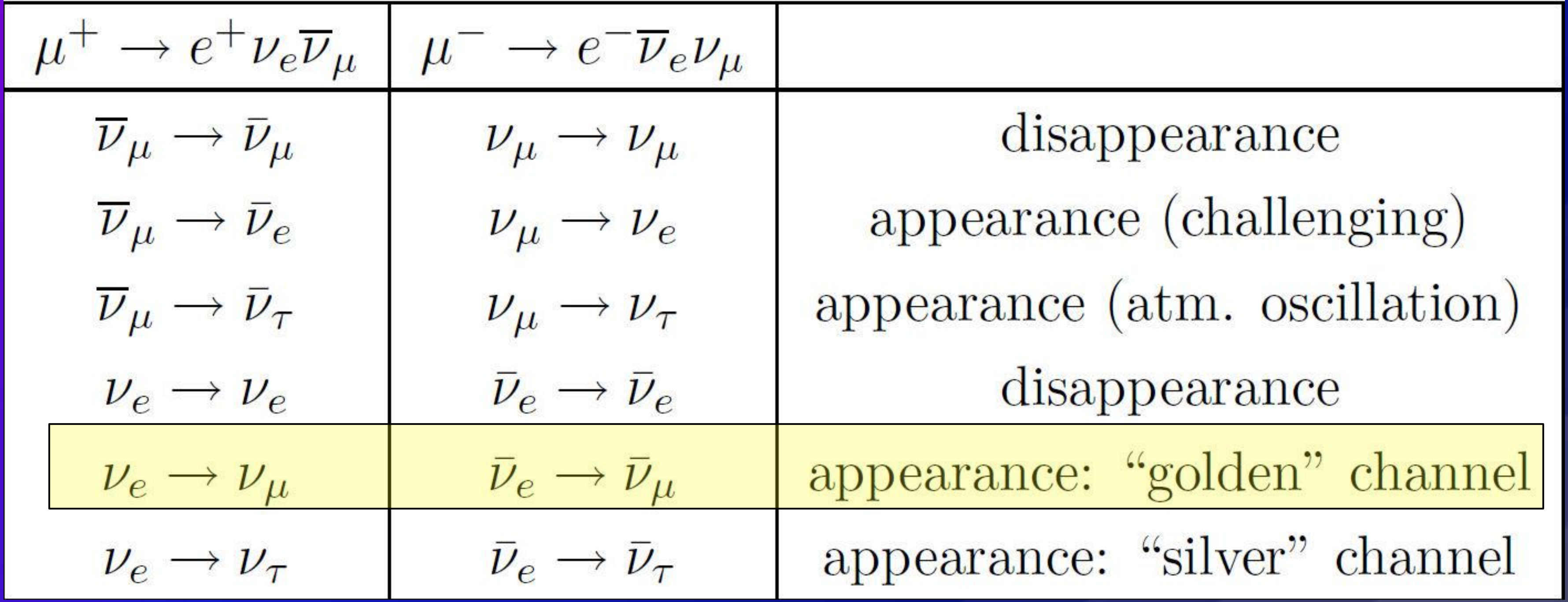
Radioactive source



νSTORM

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

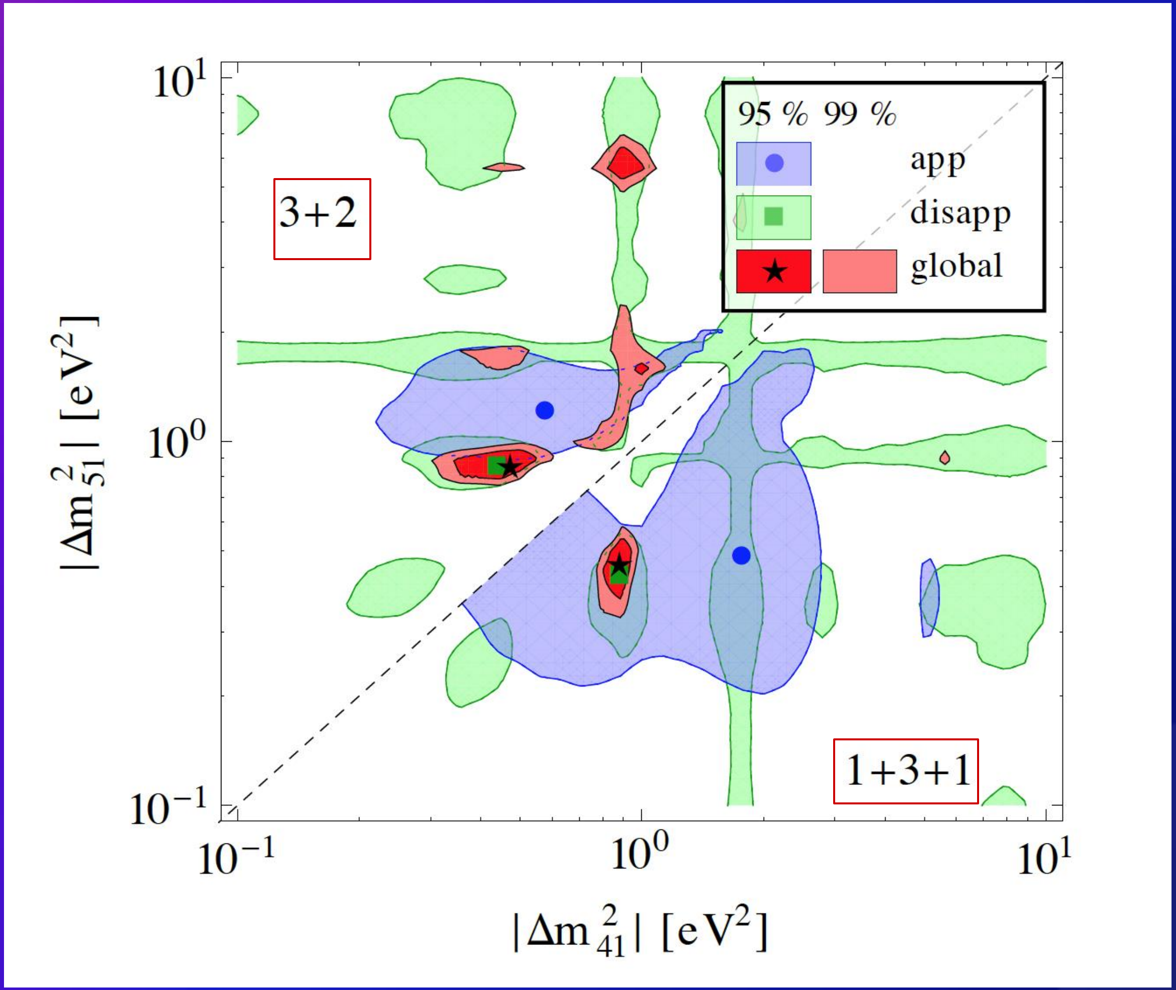
For the past decade+, the focus has been on LBL ν-oscillation physics



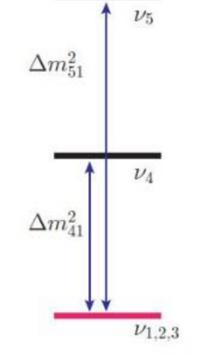
$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$	$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$	
$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$	$\nu_\mu \rightarrow \nu_\mu$	disappearance
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	$\nu_\mu \rightarrow \nu_e$	appearance (challenging)
$\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau$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

12 channels accessible
if E_ν is above the τ threshold

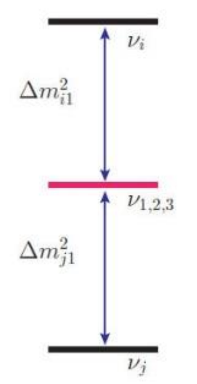
3 + 2 Models



- Fit in 1+3+1 improved over 3+1
- The compatibility of appearance and disappearance data is still low in 1+3+1, at the level of 0.2%.
- $\Sigma_\nu^{min} \approx 3.2$ eV



3+2



1+3+1

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

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.
  - 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.

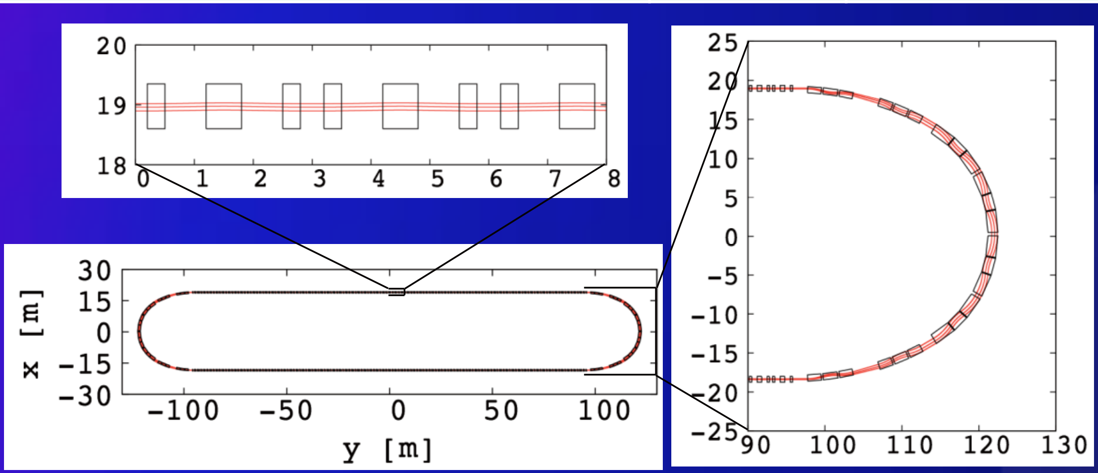
Racetrack FFAG Decay Ring

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%
□/POT within momentum acceptance	0.094	0.171	0.171
Fraction of □ decaying in the straight (F_S)	0.52	0.57	0.54
Ratio of $L_{Straight}$ to the ring Circ. (□)	0.39	0.34	0.36
A_{dyn} □ □/POT □ F_S □ □	0.011	0.031	0.033

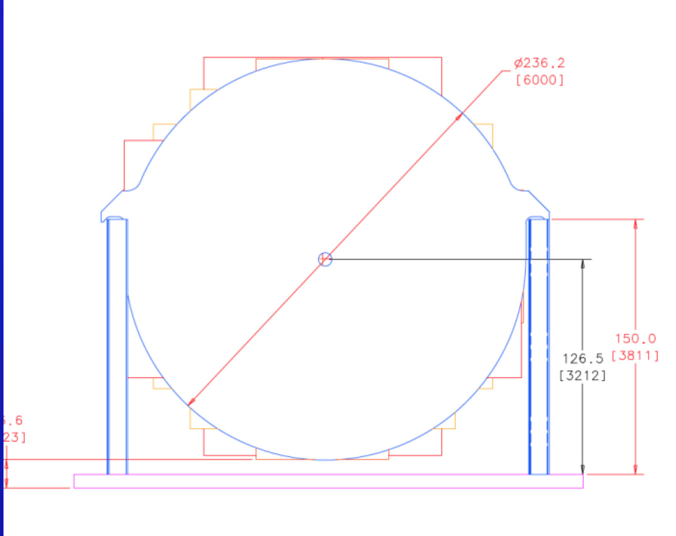


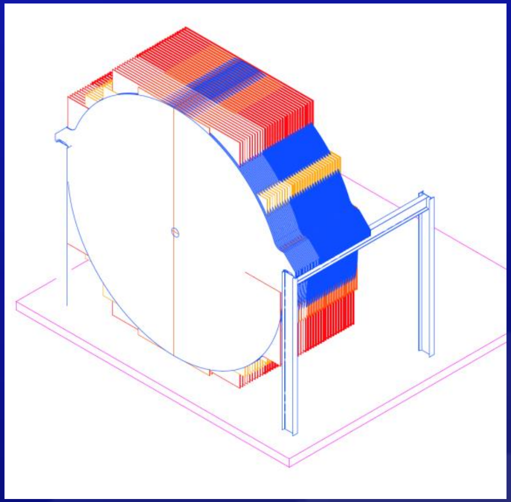
Layout of the FFAG Decay Ring with SC Arc

Baseline Detector

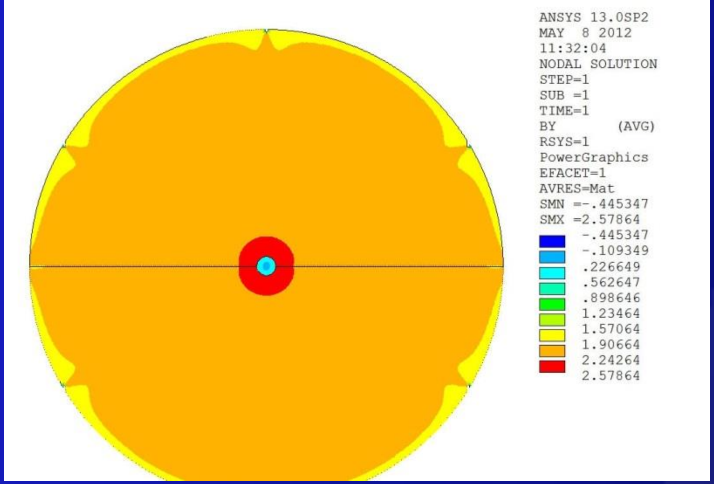
Super B Iron Neutrino Detector: SuperBIND

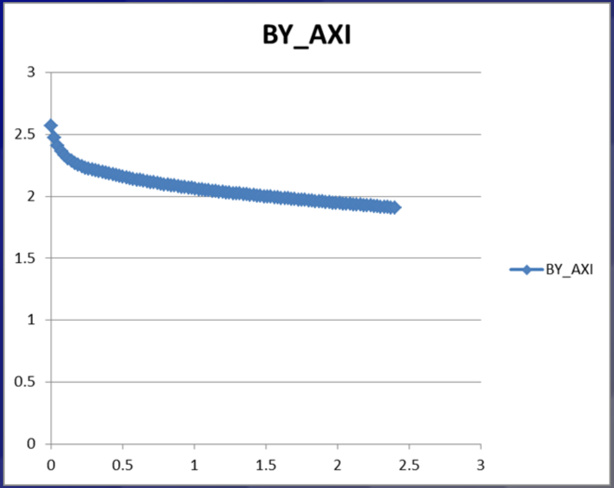
- Magnetized Iron
  - 1.3 kT
    - Following MINOS ND ME design
    - 1.5 cm Fe plate
    - 6 m diameter
  - Utilize superconducting transmission line concept for excitation
    - Developed 10 years ago for VLHC
    - ITER
  - Extruded scintillator +SiPM





20 cm hole for central cryostat

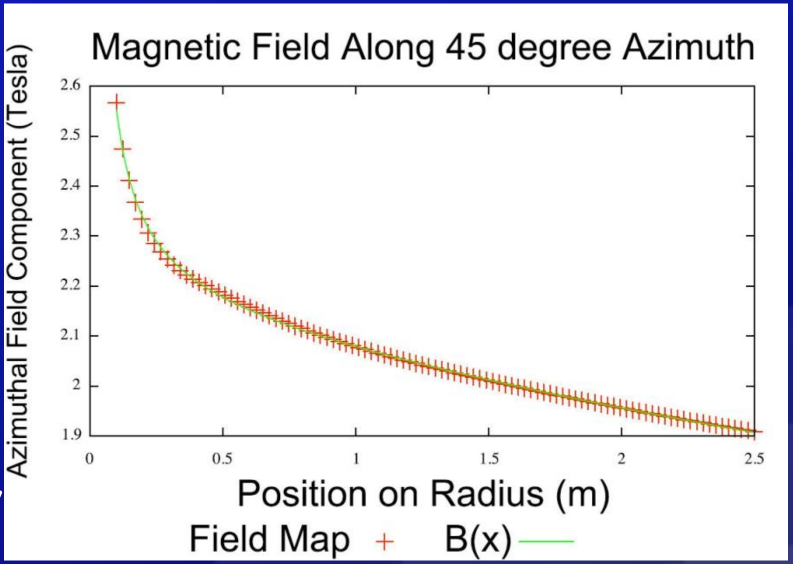




Simulation – ν_μ appearance

Ryan Bayes
Steve Bramsiepe
Glasgow

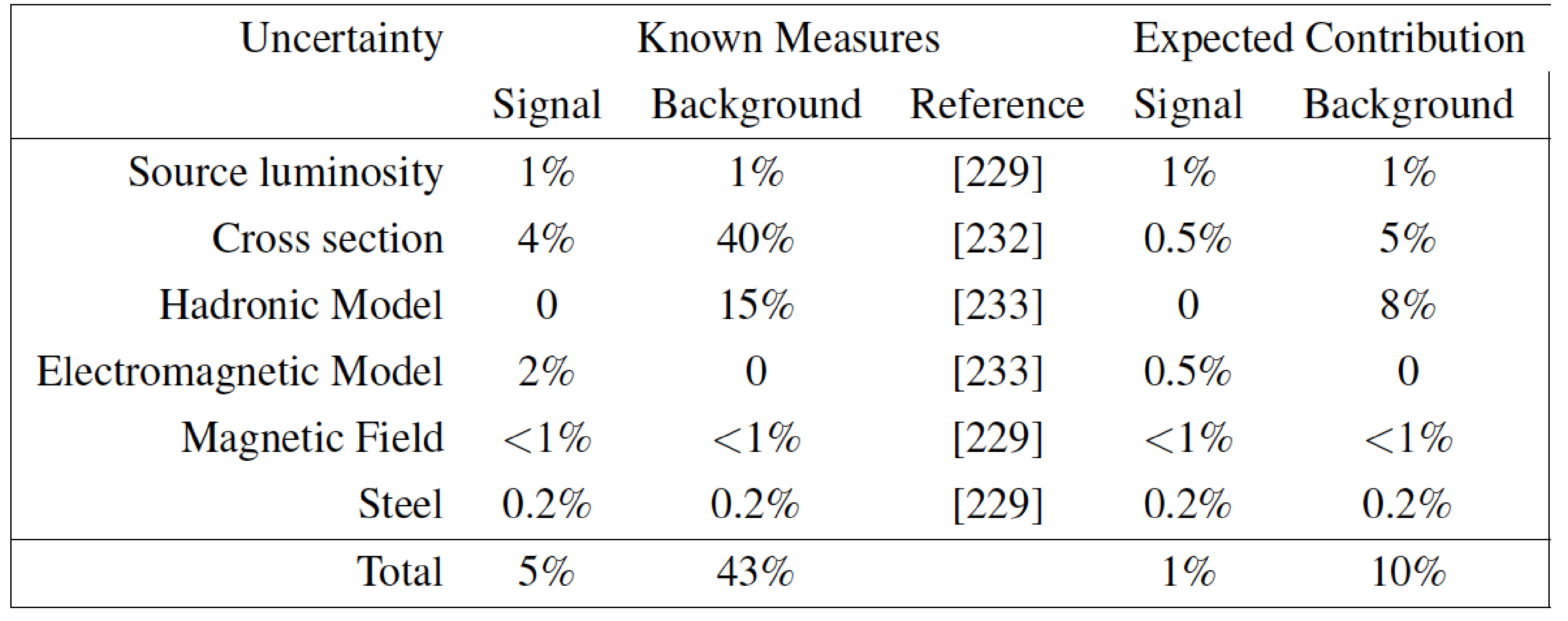
- Full GEANT4 Simulation
  - Extrapolation from ISS and IDS-NF studies for the MIND detector
  - Uses GENIE to generate the neutrino interactions.
  - Involves a flexible geometry that allows the dimensions of the detector to be altered easily (for optimization purposes, for example).
  - Have not used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



Systematics for Golden Channel in nuSTORM

- Magnetic field uncertainties
  - If we do as well as MINOS (3%), no impact
  - Need high field, however. STL must work
- Cross sections and nuclear effects
  - Needs some more work
    - ND for disappearance ch (100T of SuperBIND) should minimize contribution to the uncertainties
- Cosmic rays
  - Not an issue (we do need to distinguish between upward and downward going muons via timing).
- Detector modeling (EM & Hadronic showering)
  - Experience from MINOS indicates we are OK, but this needs more work for SuperBIND
- Atmospheric neutrinos
  - Negligible
- Beam and rock muons
  - Active veto – no problem

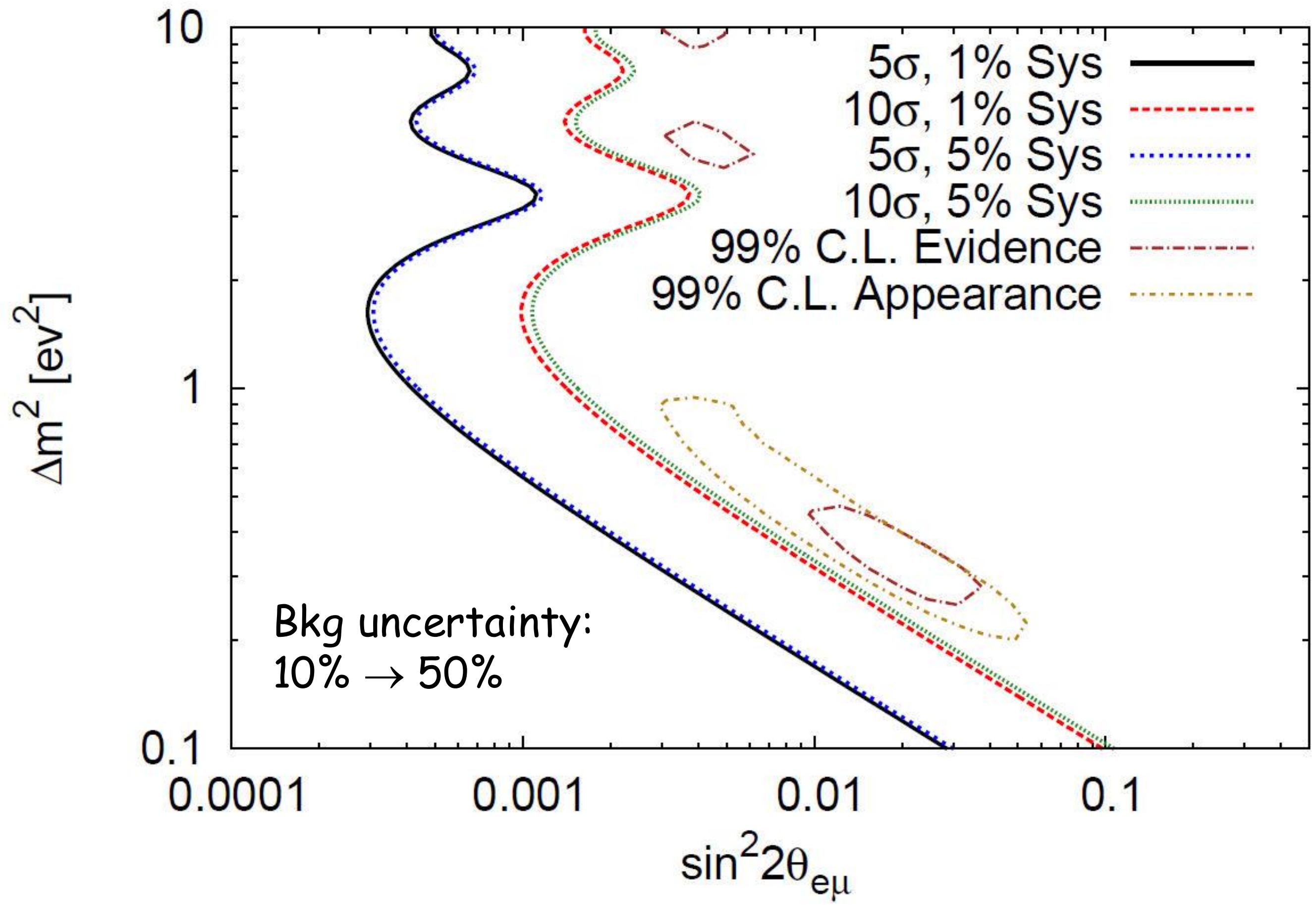
Systematics II



Uncertainty	Known Measures			Expected Contribution	
	Signal	Background	Reference	Signal	Background
Source luminosity	1%	1%	[229]	1%	1%
Cross section	4%	40%	[232]	0.5%	5%
Hadronic Model	0	15%	[233]	0	8%
Electromagnetic Model	2%	0	[233]	0.5%	0
Magnetic Field	$<1\%$	$<1\%$	[229]	$<1\%$	$<1\%$
Steel	0.2%	0.2%	[229]	0.2%	0.2%
Total	5%	43%		1%	10%

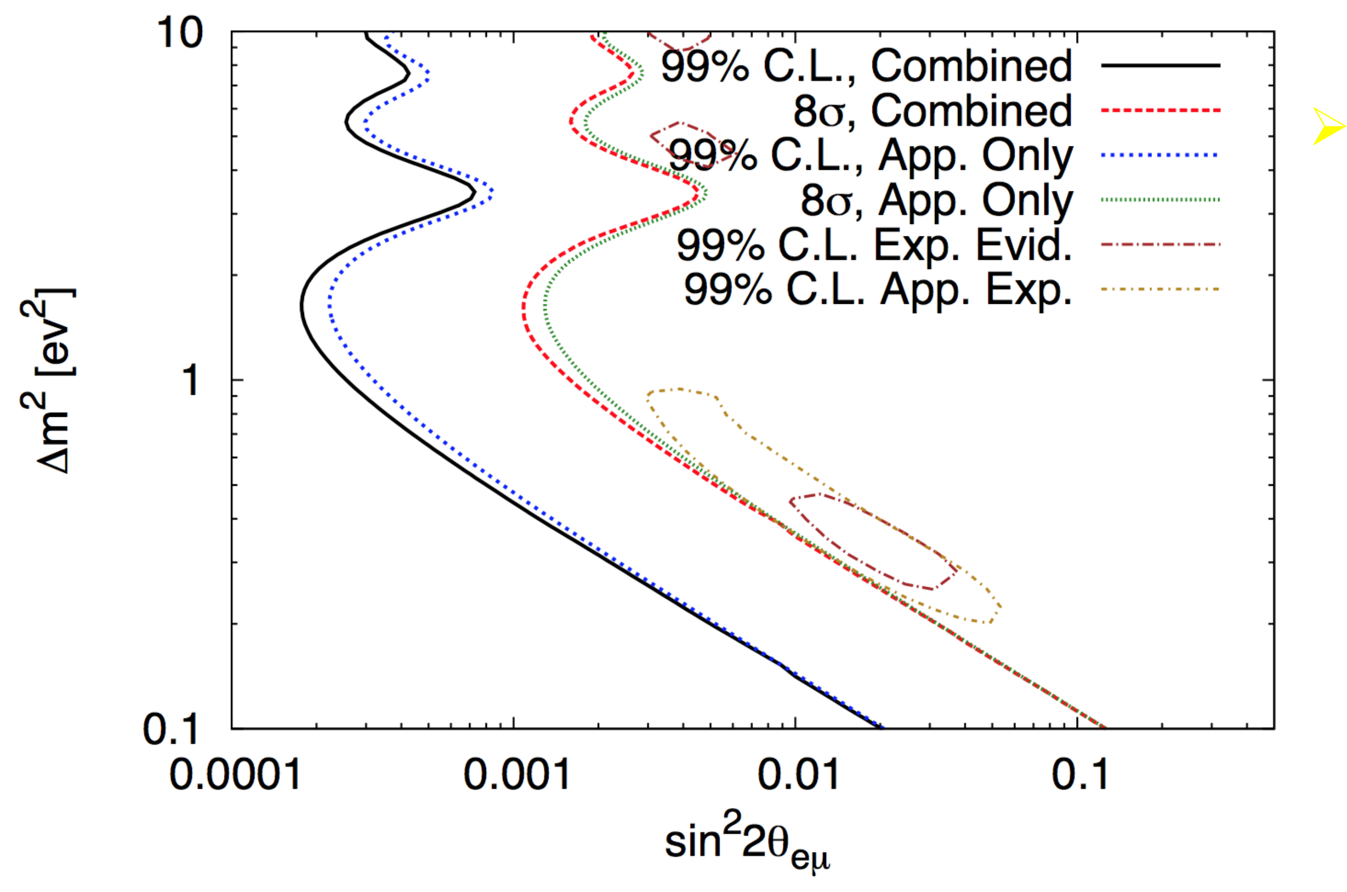
[232], [233] - MINOS

"Robustness" of appearance search



Bkg uncertainty:
10% → 50%

"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