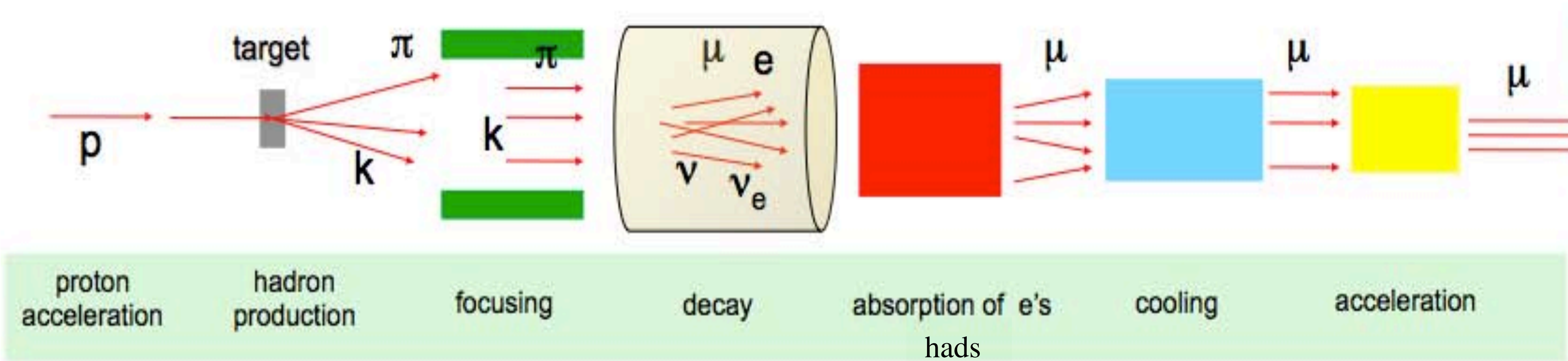
The IDS Neutrino Factory Detectors

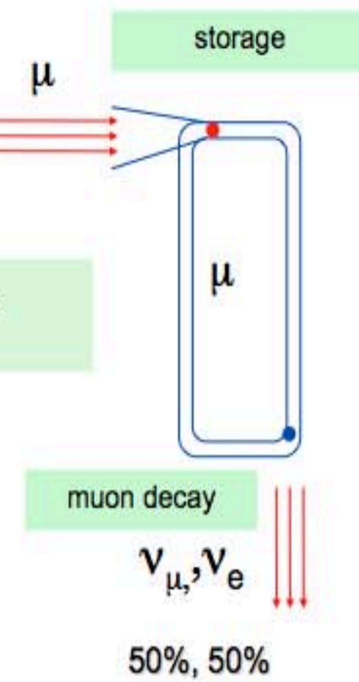
Muon Accelerator Program Collaboration Meeting

March 2012

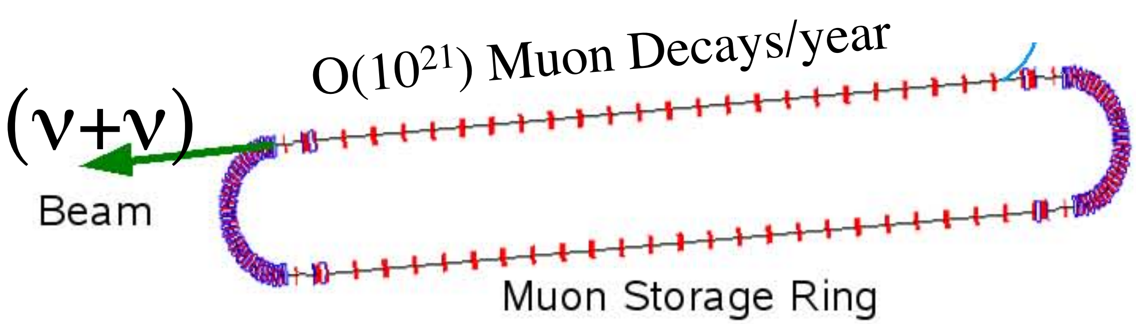
Jorge G. Morfín, Fermilab

The Neutrino Factory Concept



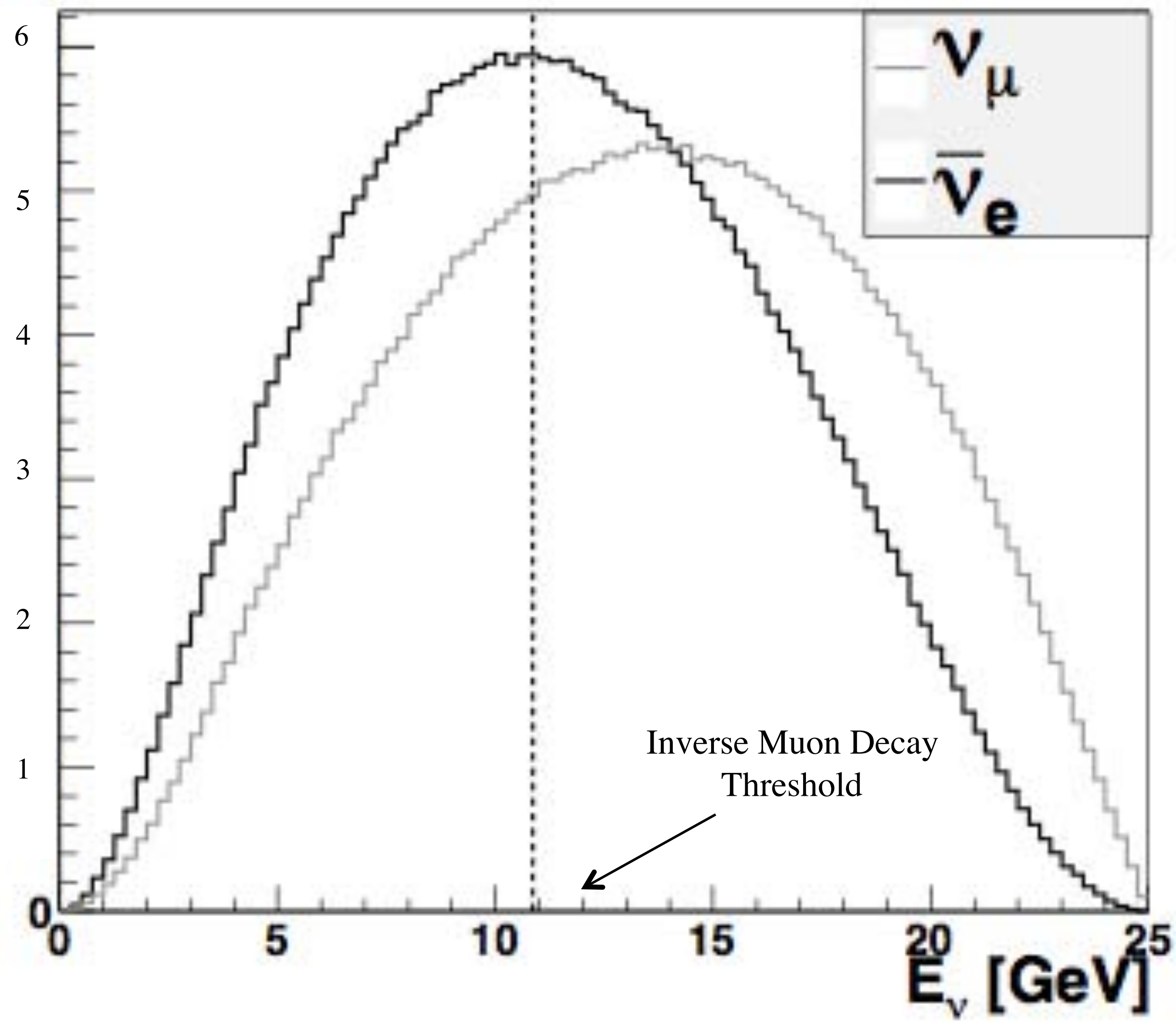


$$\mu^+ \rightarrow \overline{\nu}_\mu + \nu_e + e^+ \qquad \mu^- \rightarrow \nu_\mu + \overline{\nu}_e + e^-$$

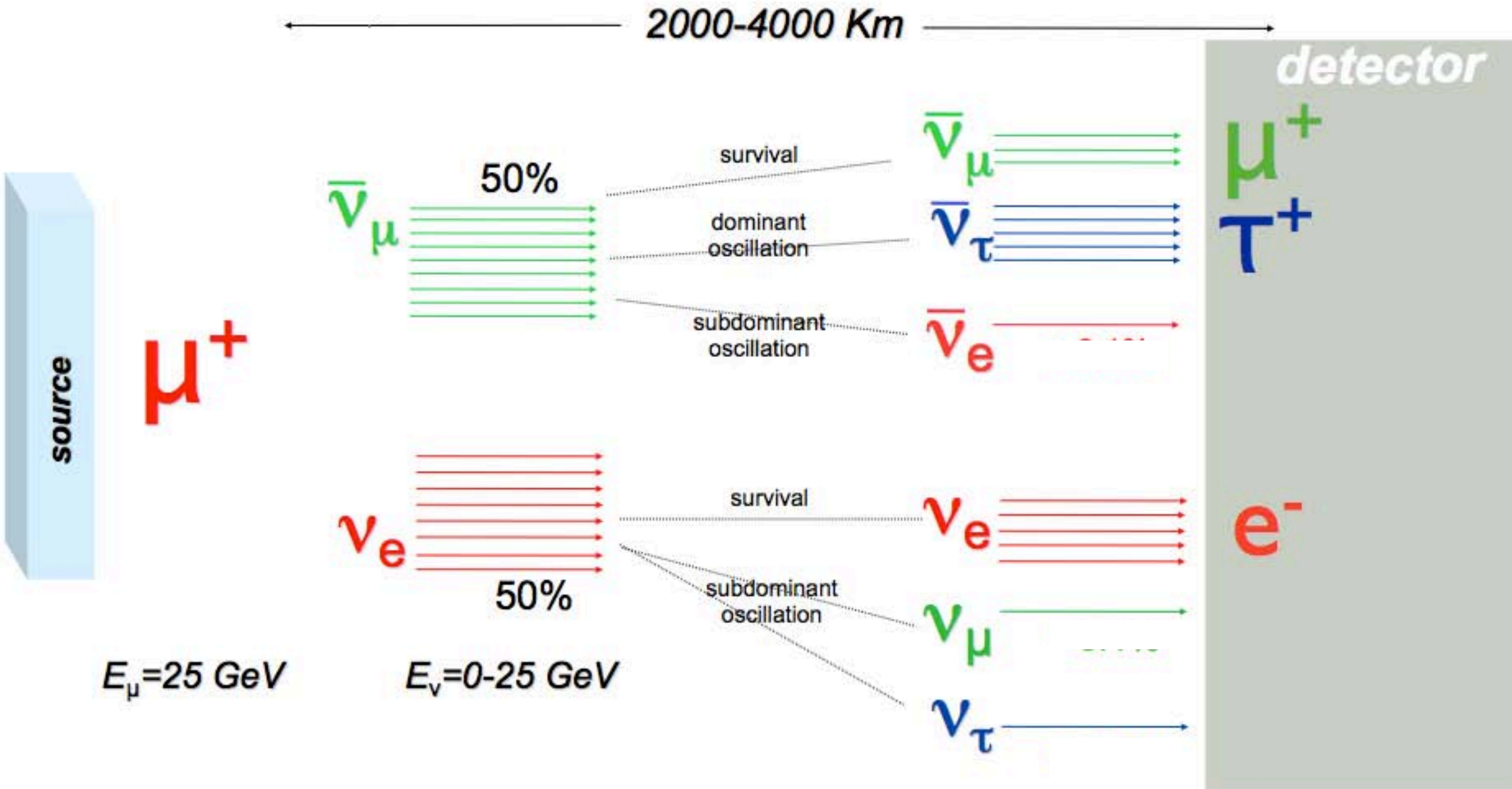


Example Event Rate Energy Distribution

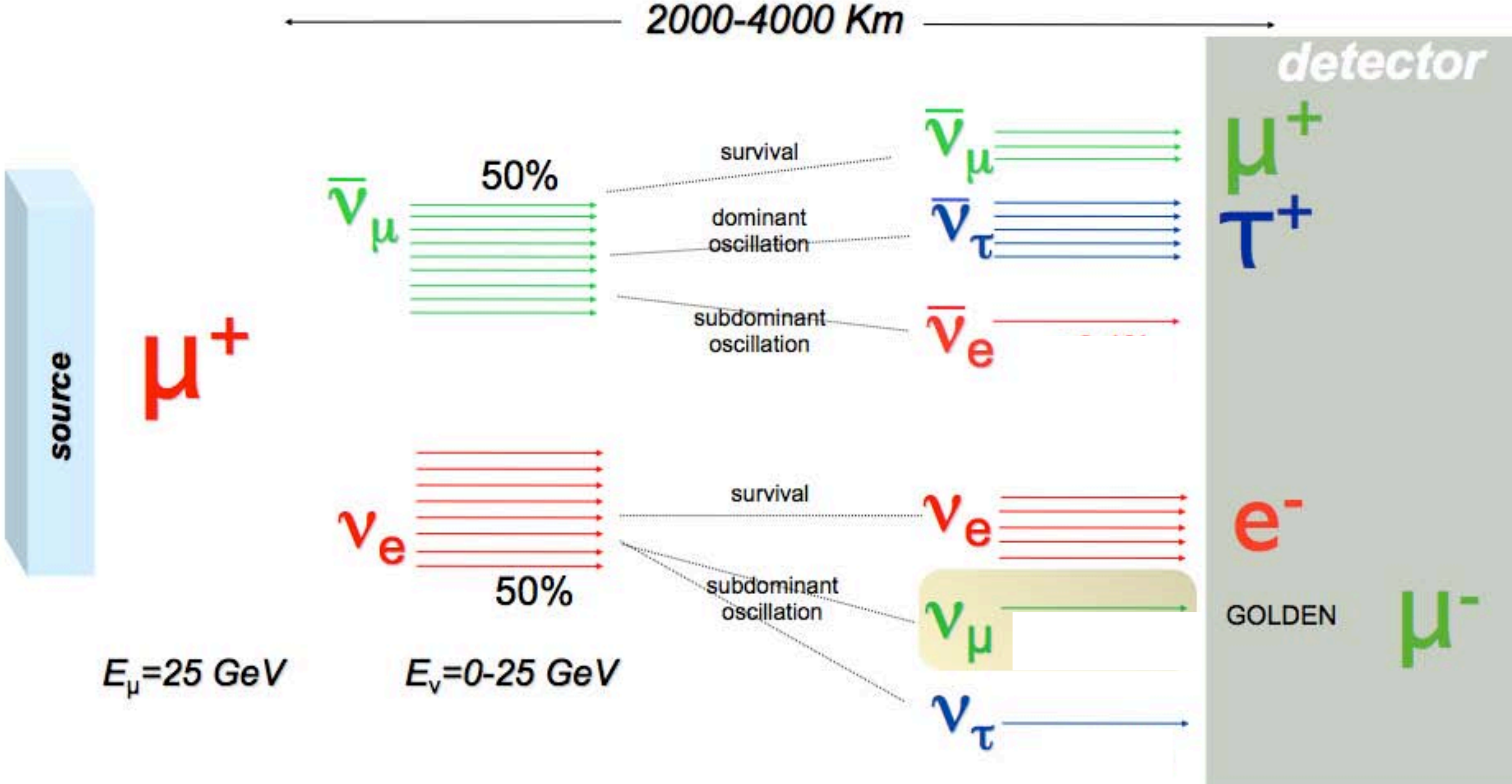
25 GeV μ^-



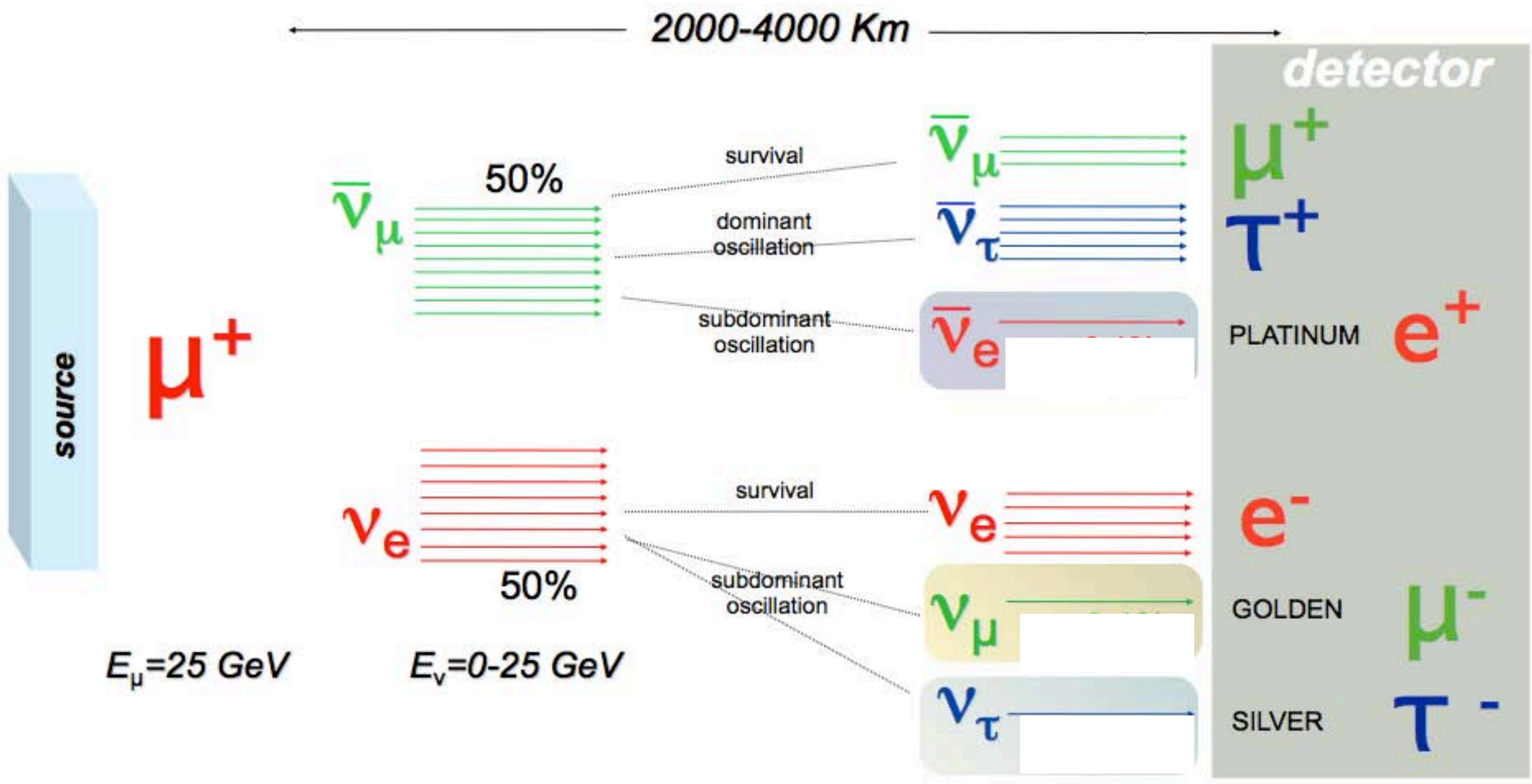
Motivation for the Neutrino Factory Oscillation Channel Studies



Oscillation Channels



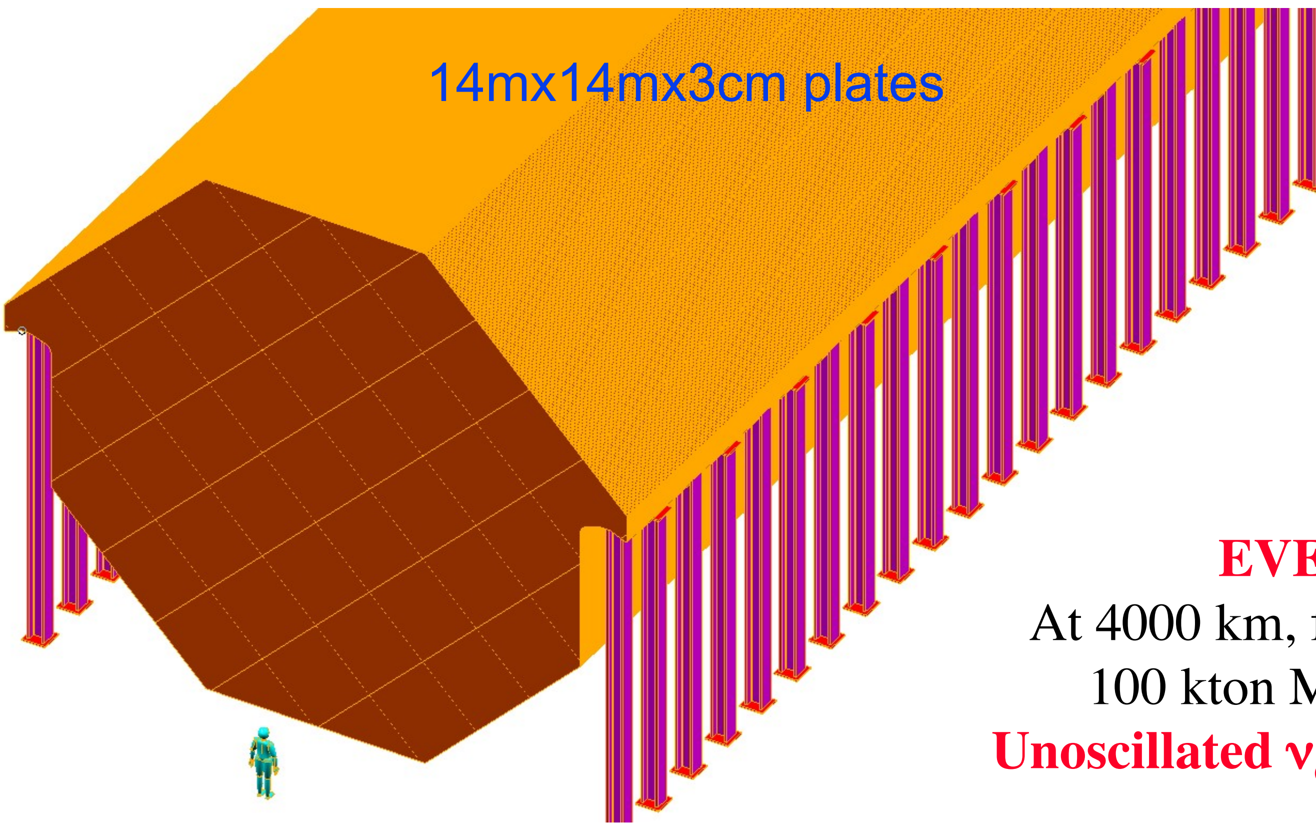
Oscillation Channels



Far Detectors: Magnetised Iron Neutrino Detector (MIND)

R. Bayes, A. Bross, A. Laing, P. Soler….

- Far detector: 100 kton at 2500-5000 km
- 2^{nd} detector: 50 kton at 7500 km - "magic"
- Appearance of "wrong-sign" muons
- Toroidal magnetic field > 1 T
- Segmentation: 3 cm Fe + 2 cm scintillator
- 50-100 m long
- Octagonal shape



EVENT RATES

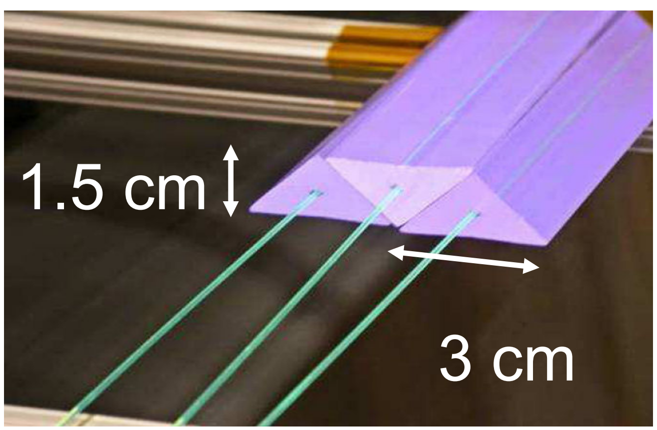
At 4000 km, for 10^{21} μ decays/year

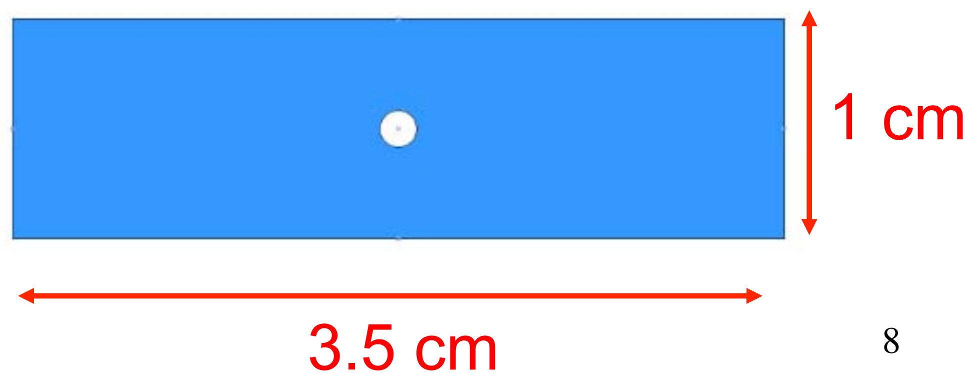
100 kton MIND for μ^+ decay:

Unoscillated ν_e CC would be $7.1 x 10^5$

MIND Scintillator

- Scintillator: x-view and y-view planes 1 cm thick each plane
  - Baseline: rectangular scintillator strips (3.5 cm wide, σ ~ 1 cm)
  - Alternative: triangular strips (σ ~ 5 mm) - 2.3 times more channels
  - Co-extrusion fibre-scintillator (makes project ~20% more expensive)
- Wavelength shifting fibres
  - Kuraray currently is the only manufacturer in the world that can deliver WLS fibres of consistently good performance
- Numbers: 788 scint./module x 2800 modules = 2.2 M bars
  - 25,000 km of WLS fibre (~€1/m)

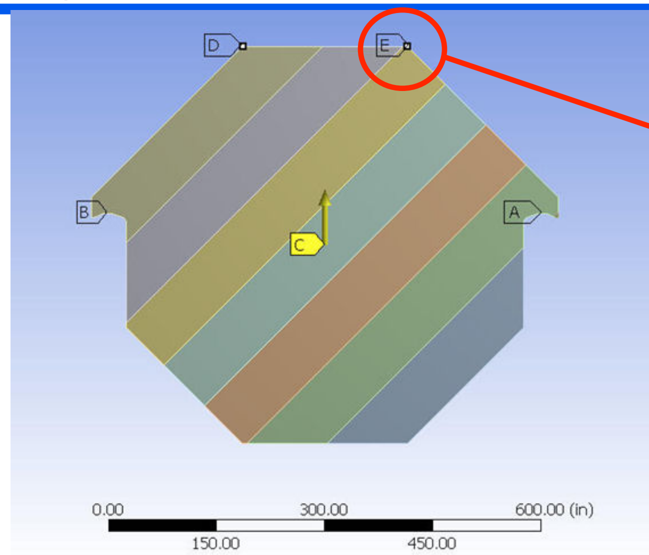


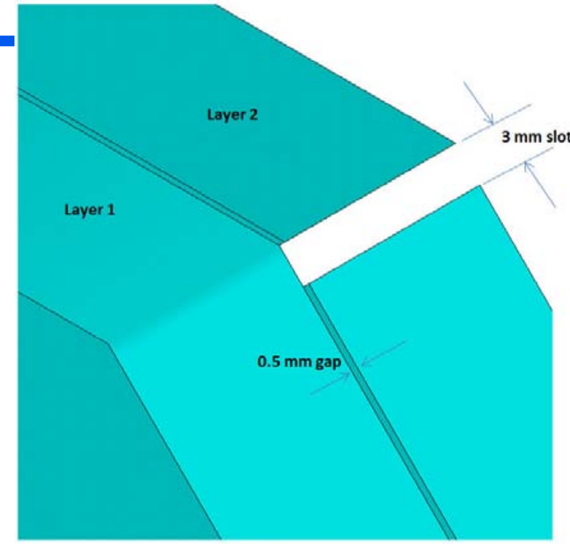


MIND engineering

- Plate engineering: A. Bross, B. Wands

Plates: two welded layers (0.5mm gaps) 3 mm slots between Plates (2 m wide)

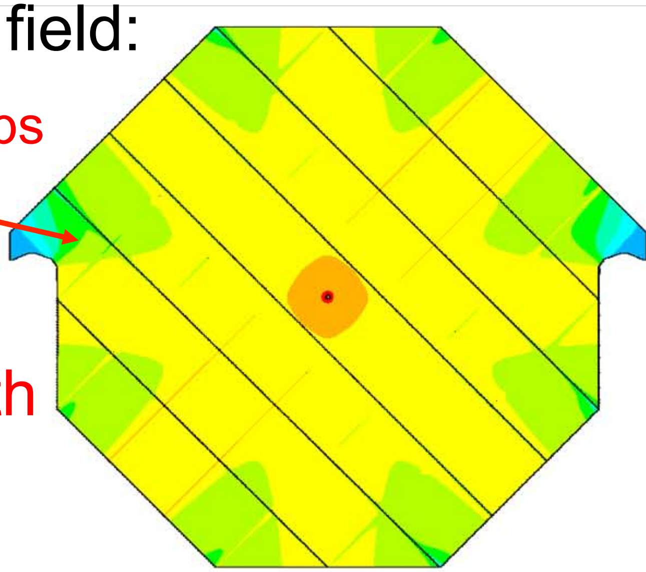




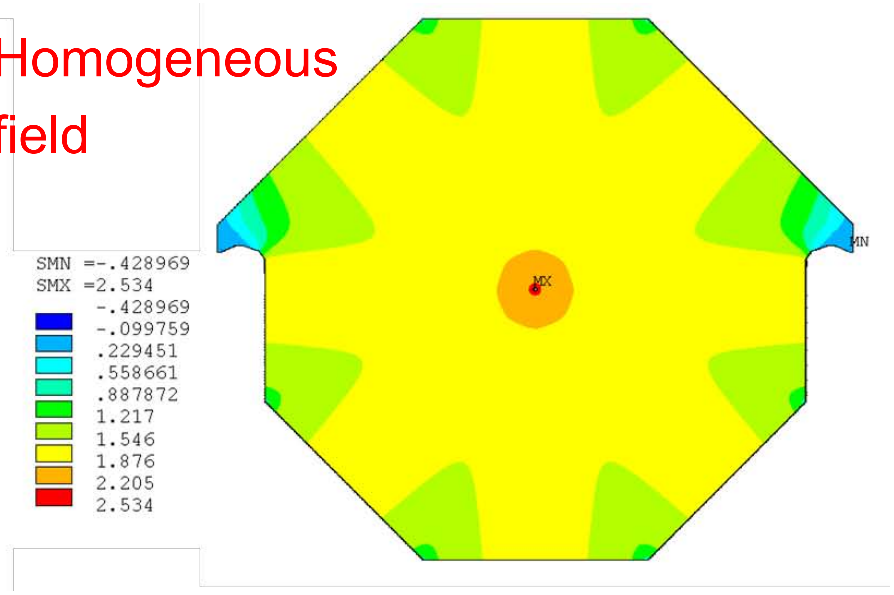
- Toroidal field:

Small field gaps and jumps

1.2-2.2 T with 100 kA turn

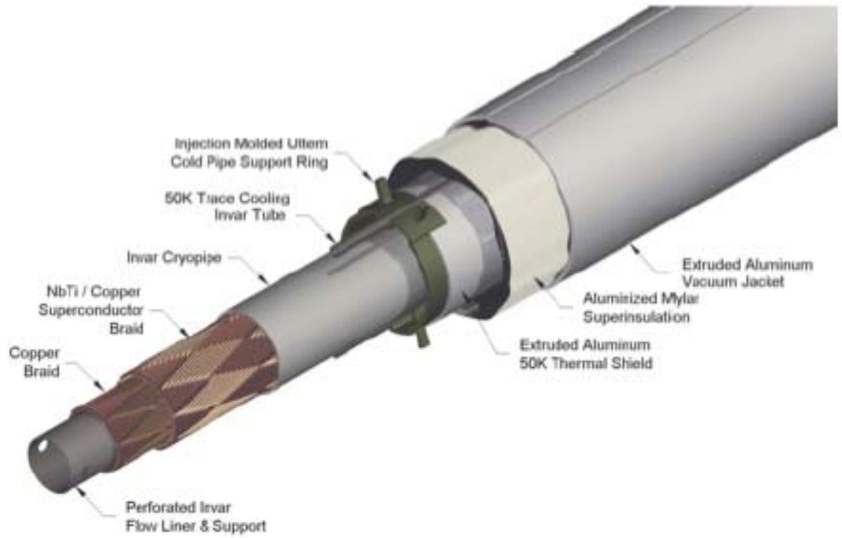


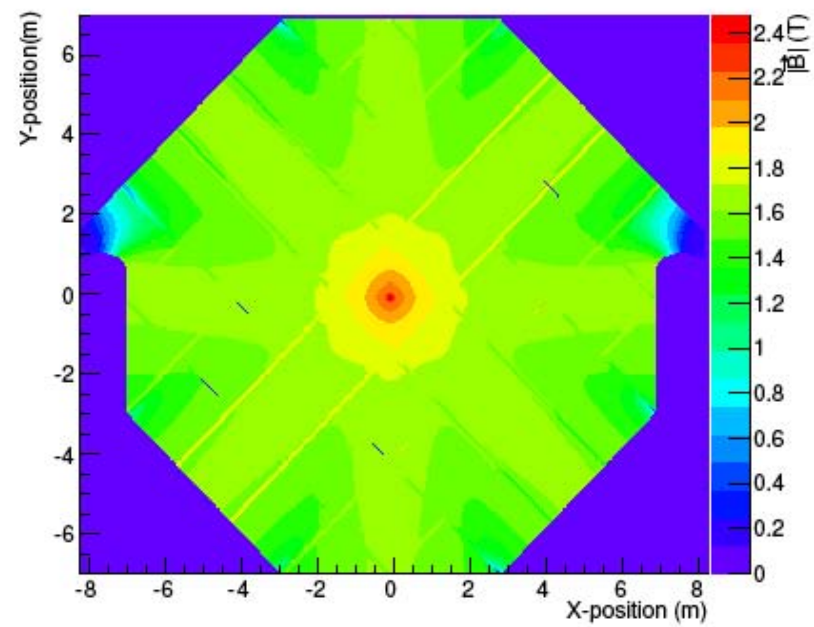
Homogeneous field



MIND Magnetic Field

- Required for identification of wrong sign muons.





Magnetic field to be induced by superconducting transmission line

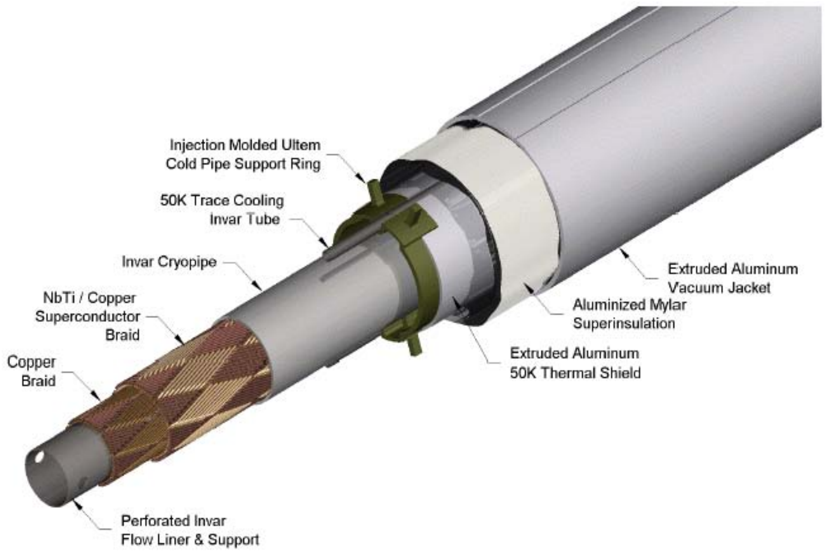
- Transmission line 7.8 cm in diameter.
- Contained in a 10 cm hole in the iron.

Small distortions caused by slots between strips

- Simulated using a 100 kA excitation current

Magnetic Field Excitation

Superconducting Transmission Line



The test apparatus used at MW-9 for developing the transmission line.

- **SCTL not simply a "concept" – prototyped, tested and costed for the VLHC Project at Fermilab**

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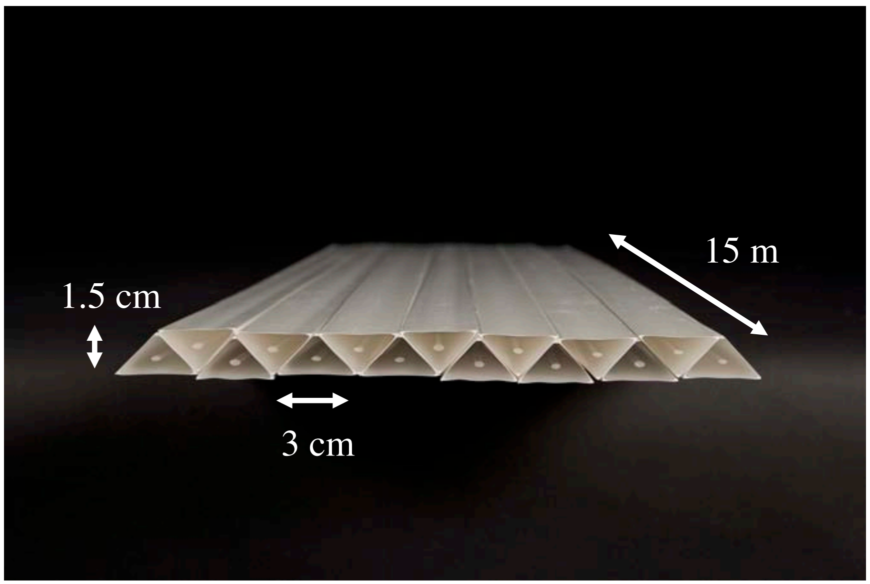
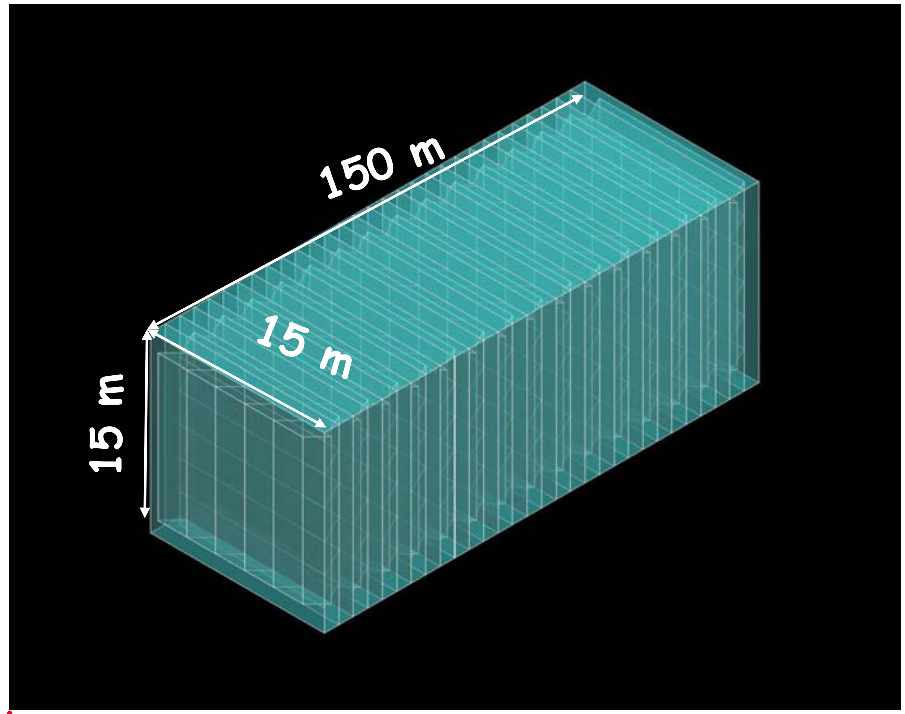
Alternative: Fine-Resolution Totally Active Far Detector (Low-E Neutrino Factory)

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



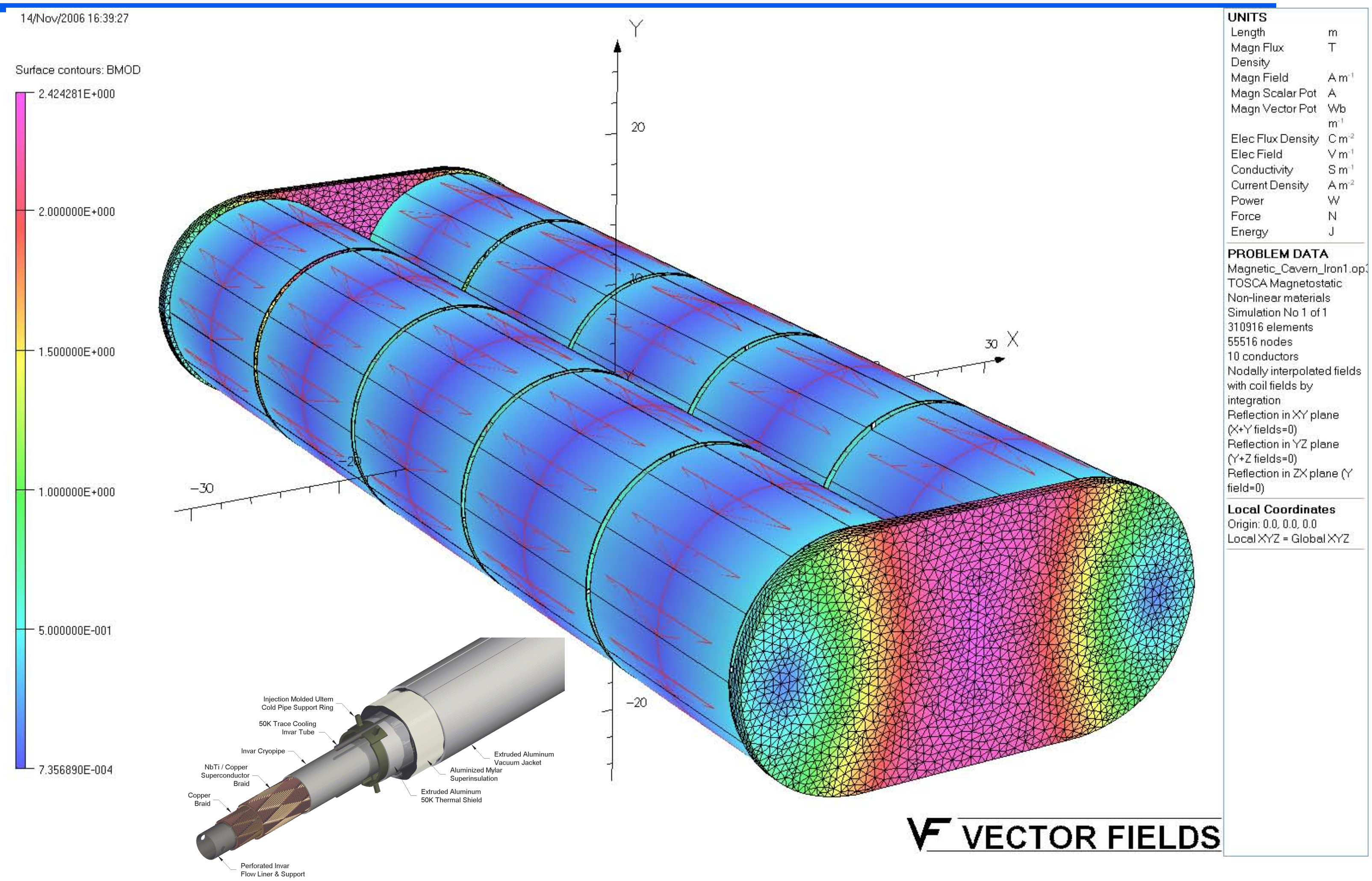


- Momenta between 100 MeV/c to 15 GeV/c
- Magnetic field considered: 0.5 T
- Reconstructed position resolution ~ 4.5 mm

B = 0.5T

Active Detector Has to be Magnetized

Super Conducting Transmission Line



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Neutrino Factory Near Detector(s)

E_μ = 25 GeV ±80 MeV

Straight section length = 600 m

Muon angular spread 0.5 mrad

Event Rates

2.5e20 μ-decays/year

3 Years of μ^+ and μ–)

Fid.Mass 3.5 Tons

μ^+:

ν_u-CC: 1.8e9 Events

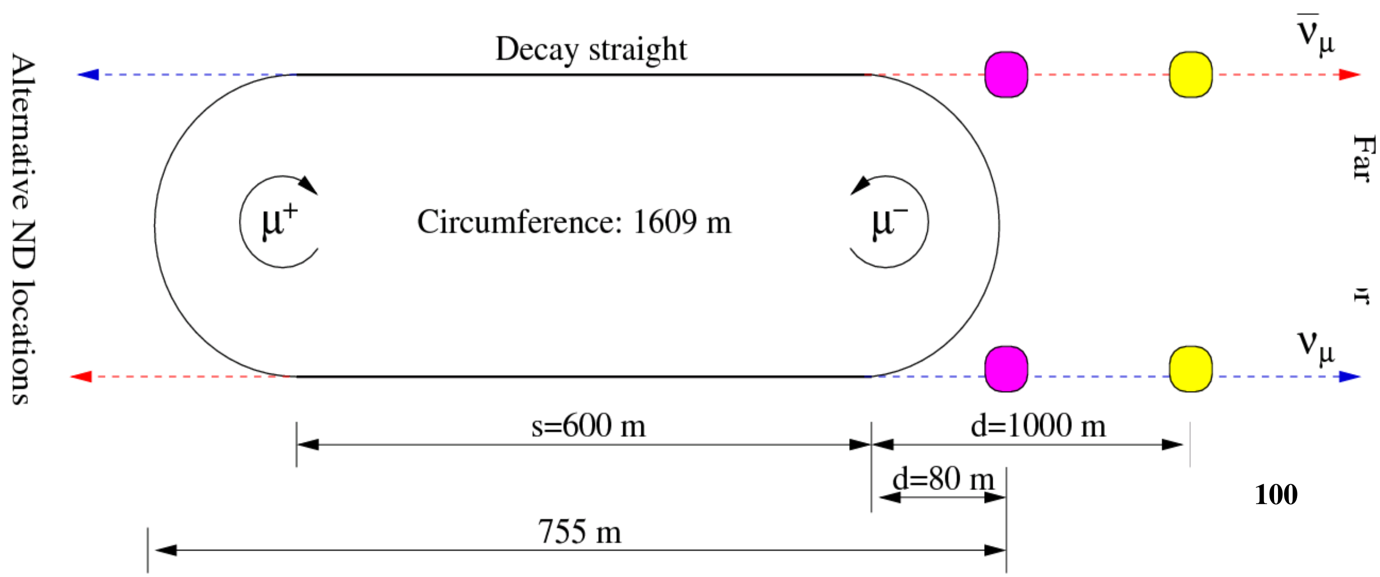
IMD: 1.3e6 Events

ν_ue Elas:1.1e6 Events

μ^--:

ν_uBar-CC: 0.9e9 Event

ν_ue Elas : 1.5e6 Event



Near Detector Physics Tasks

- **Determination of the neutrino flux (through the measurement of neutrino-electron scattering)**

- Measurement of the neutrino-beam properties that are required for the flux to be extrapolated with accuracy to the far detectors;

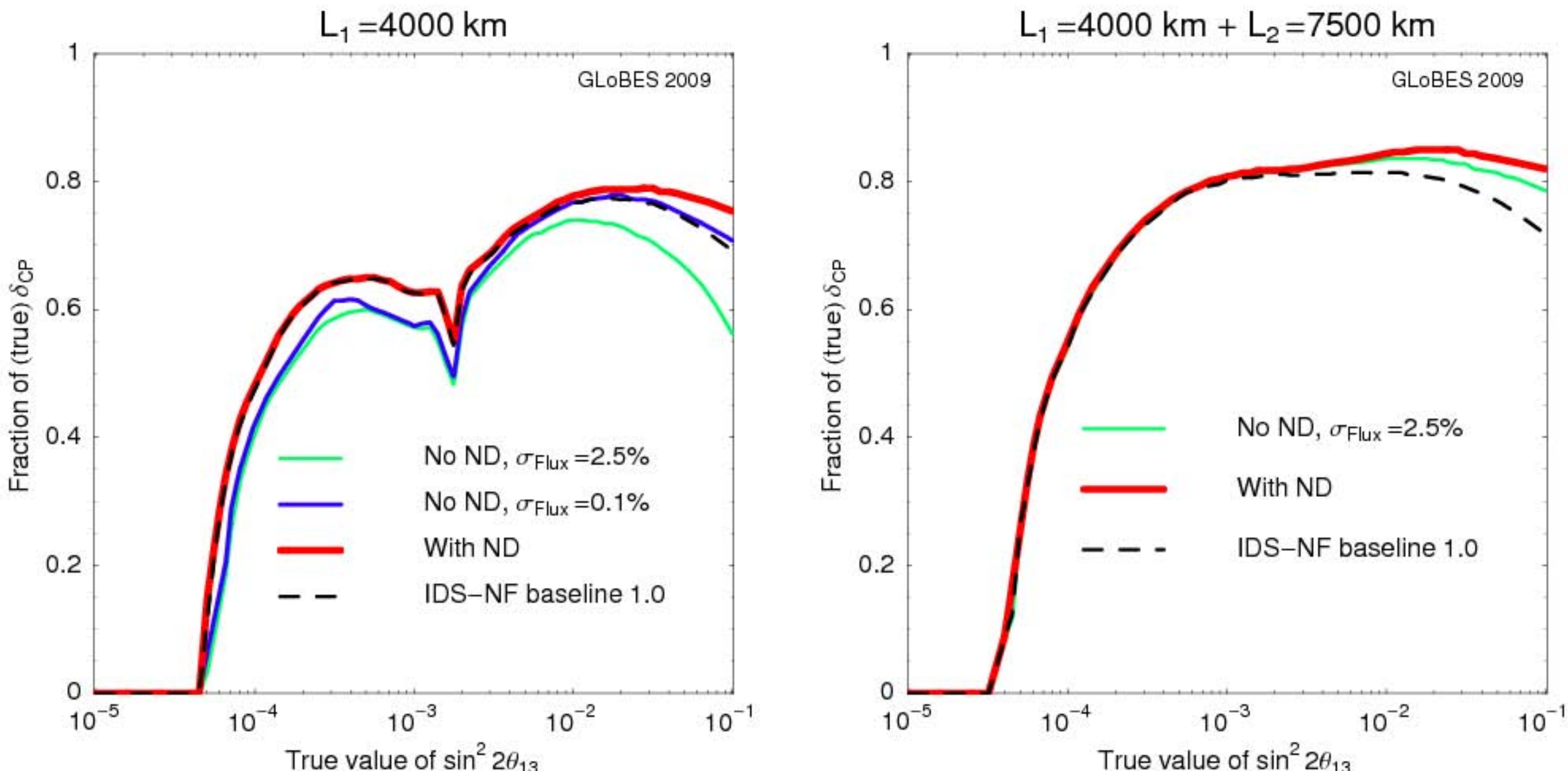
- Measurement of the charm production cross sections;
- Measurement of the νN deep inelastic, quasi-elastic, and resonant-scattering cross sections;
- Search for Non Standard Interactions (NSI).

Determination of the neutrino flux

- Measure the muon beam in the straight sections:
  - beam intensity by Beam Current Transformer like device – "good" confidence that relative precision of few 10^{-3} can be reached (task on its own);
  - beam divergence by specialized device inside or around the beam pipe;
  - muon polarisation – averages out to zero;
- Calculate the neutrino flux:
  - muon decay properties incl. radiative corrections are extremely well known → can we rely on MC?
- **Independent measurement of the neutrino flux in the near detector – crucial cross-check to experimentally confirm calculations.**

Importance of flux knowledge for systematics

2.5% error on flux makes big difference in CP coverage



Winter, Tang

"Other" Near Detector Physics

- To achieve the kind of accuracy we want on the neutrino flux measurement, we will have constructed a detector ideally suited for advanced studies of neutrino-nucleus interactions – the "other" physics.
- This in turn can be grouped into standard processes:
  - **Quasi-elastic**
  - **Resonance Production**
  - **Transition: Resonance to DIS**
  - **DIS, Structure Functions. and high-x PDFs**
  - **Coherent Pion Production**
  - **Strange and Charm Particle Production**
  - **Generalized Parton Distributions**
  - **Nuclear Effects**
- and more exotic…
  - NSI such as the measurement of ν_τ in the near detector

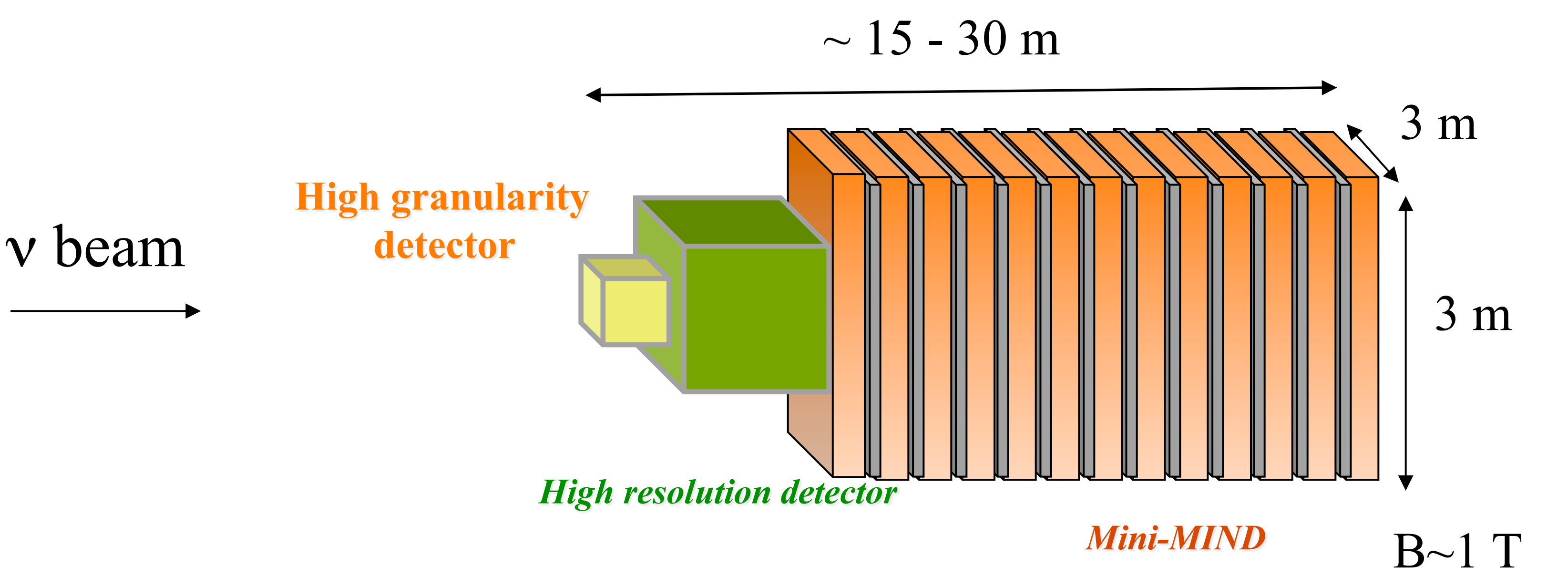
Near Detector Design Requirements

- Vertex detector for charm and τ production (NSI)
- Low Z high resolution target for flux and cross-section measurement (ν_μ and ν_e)
- Magnetic field for muon momentum ($\delta p/p \sim 1\%$)?
- Muon catcher and capability for and e^+/e^- identification
- Good resolution on neutrino energy for flux extrapolation (much better than Far Detector) – goal $\delta E/E \sim 1\%$

Block-diagram design

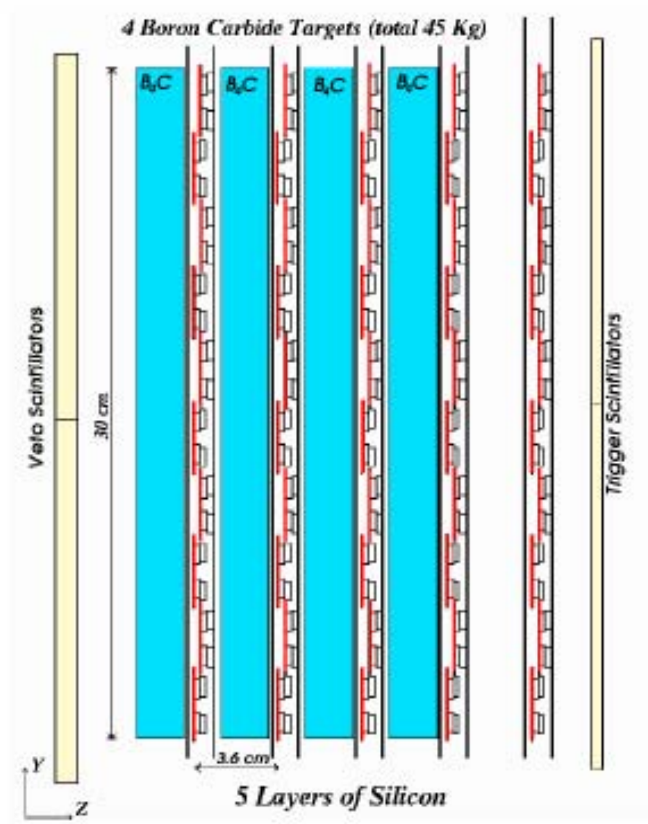
Near Detector design will have three sections:

– High granularity detector for charm/tau measurement;
– High resolution detector (**Scintillating Fibres tracker** or **Straw Tube tracker**) for precise measurement of the event close to the vertex;
– Mini-MIND detector for higher energy muon measurement



High-granularity Vertex Detector

- **Stack of OPERA-like emulsion sheets**: 150 sheets, overall volume ~500 cm^3, mass ~ 1 kg, thickness - 4.6 cm (0.2 X_0), capacity ~ 5000 neutrino events out of ~5x10^5 ν_μ CC interactions per year for this mass;
- **Silicon vertex detector like NOMAD-STAR detector**: ~50 kg, ~7×10^5 charm events reconstructed per year, sensitivity for $P_{\mu\tau} < 3 \times 10^{-6}$ at 90% C.L.



Measurement of the neutrino flux by *ν-e* scattering

ν - e CC quasi-elastic scattering:

- absolute cross-section can be calculated theoretically with enough confidence;
- two processes of interest for neutrinos from ***μ⁻ decays***. **11 GeV Threshold**

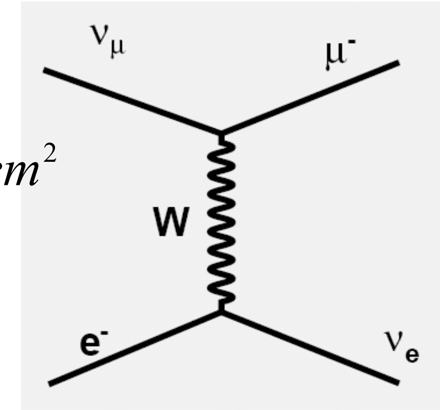
Inverse Muon Decay (IMD)

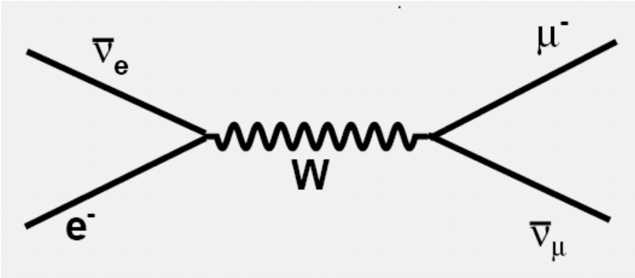
$$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_\mu + \mu^-$$

$$\sigma = \frac{G_F^2}{\pi}\frac{\left(s - m_\mu^2\right)^2}{s} = 4\times10^{-41}\,cm^2$$

for 15 GeV ν_μ:

it is ~10^{-3} of $\sigma_{total}(\nu N)$





$$\sigma = \frac{2G_F^2}{\pi}\frac{\left(s - m_\mu^2\right)^2 (E_e E_\mu + \frac{1}{3}E_{\nu 1}E_{\nu 2})}{s^2}$$

ν-e NC elastic scattering

$$\sigma(\nu_l e \to \nu_l e) = \frac{G_\mu^2 m_e E_\nu}{2\pi}\left[1 - 4\sin^2\theta_W + \frac{16}{3}\sin^4\theta_W\right]$$

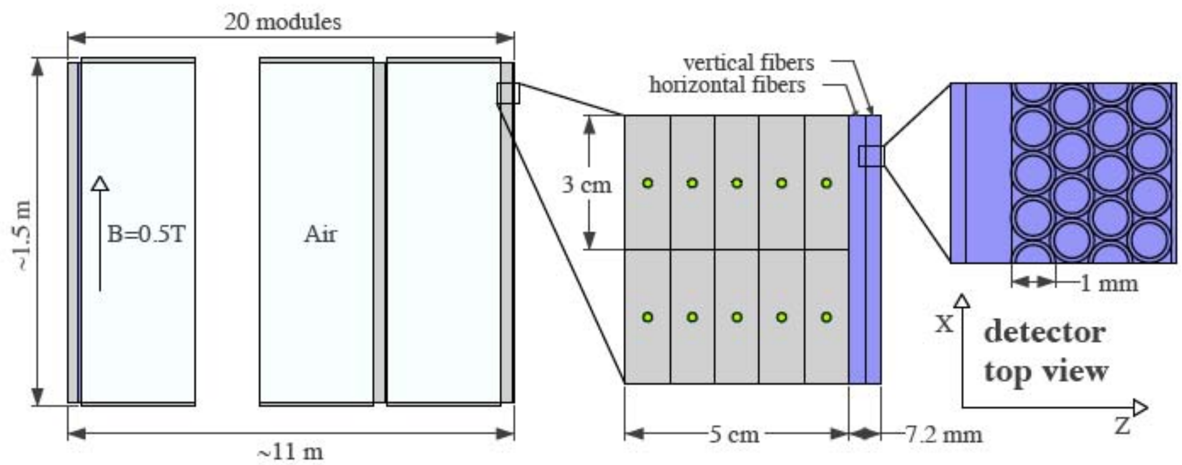
$$\sigma(\bar{\nu}_l e \to \bar{\nu}_l e) = \frac{G_\mu^2 m_e E_\nu}{2\pi}\left[\frac{1}{3} - \frac{4}{3}\sin^2\theta_W + \frac{16}{3}\sin^4\theta_W\right]$$

$$\sim 10^{-42}(E_\nu/\,\mathrm{GeV})\; cm^2$$

$sin^2\theta_W$ is known to better than 1% for this Q^2 domain.

Two Options, First: Scintillating Fiber Tracker

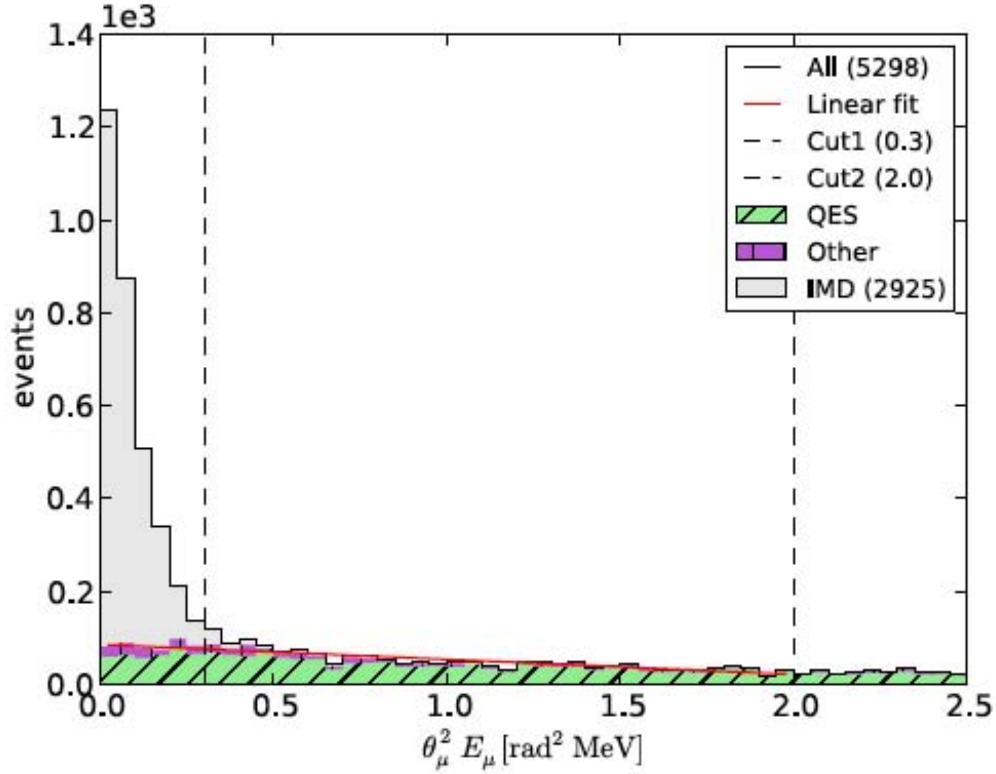
M. Bogomilov, Y. Khradzov, R. Matev, R. Tzenov – Univ. Sofia



- 0.5 T dipole magnetic field;
- 20 modules with $\sim$ 50 cm air gaps in between;
- 5 layers of scintillating bars ($3 \times 1\ \ cm^2$) in absorber section;
- 4+4 layers of cylindrical ($\varnothing$1 mm) scintillating fibers in tracker station;
- air gaps are covered by one layer of scintillating bars;
- silicon photomultipliers (SiPM) detect photons from all fibers;
- overall detector dimensions are $\sim 1.5 \times 1.5 \times 11\ \mathrm{m}^3$;
- $\sim$ 2.7 tons of polystyrene ($[\mathrm{C_6H_5CHCH_2}]_\mathrm{n}$).

IMD signal extraction (linear fit)

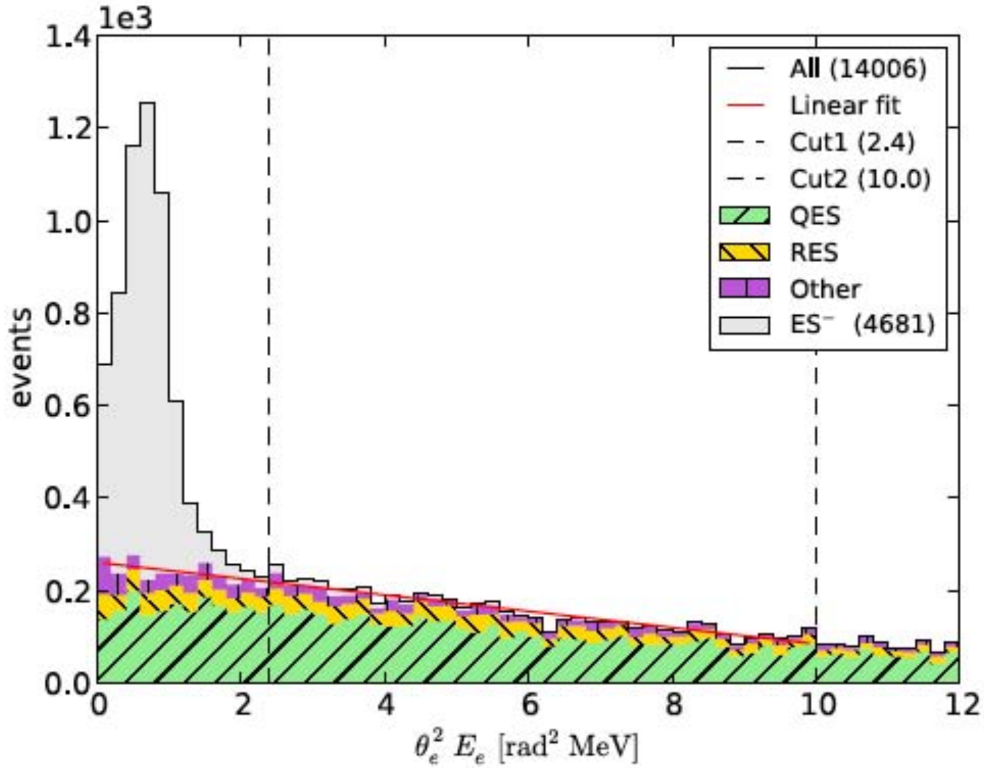
Use linear extrapolation of event rates in region between cut1 and cut2 to estimate background under the signal peak.



Selection eff.	Overall eff.	Purity	All events	Signal events	Signal events from fit	μ decays
85 %	45 %	85 %	3312	2801	2828 ± 58	2.3×10^{19}

ES^- signal extraction (μ^- decay mode)

Use linear extrapolation of event rates in region between cut1 and cut2 to estimate background under the signal peak.



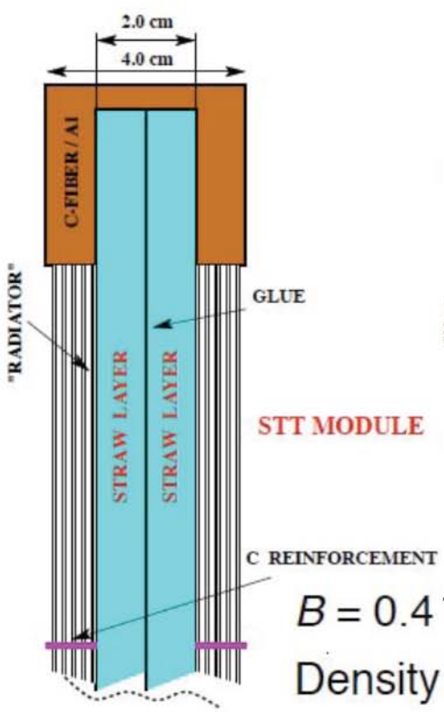
Selection eff.	Overall eff.	Purity	All events	Signal events	Signal events from fit	μ decays
70 %	32 %	61 %	7355	4491	4479 ± 86	2.3×10^{19}

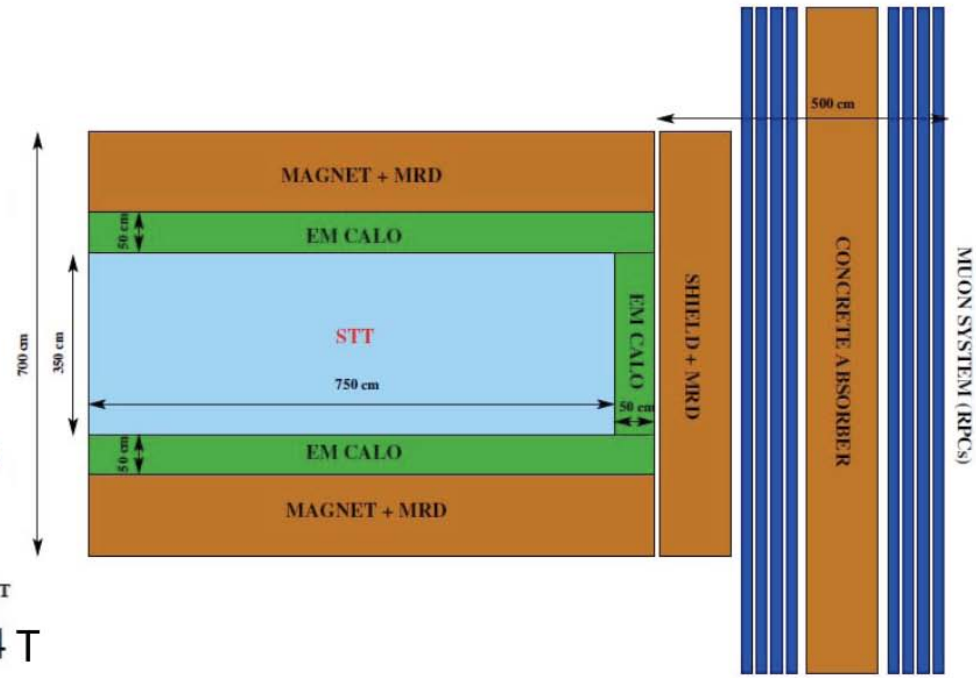
Second Alternative: Straw-tube Tracker Design

S. Mishra – Univ. S. Carolina

High resolution magnetised detector (*HiResMν*) – LBNE Standard Near detector

Builds on NOMAD experience, ATLAS TRT and COMPASS detector designs





$B = 0.4$ T

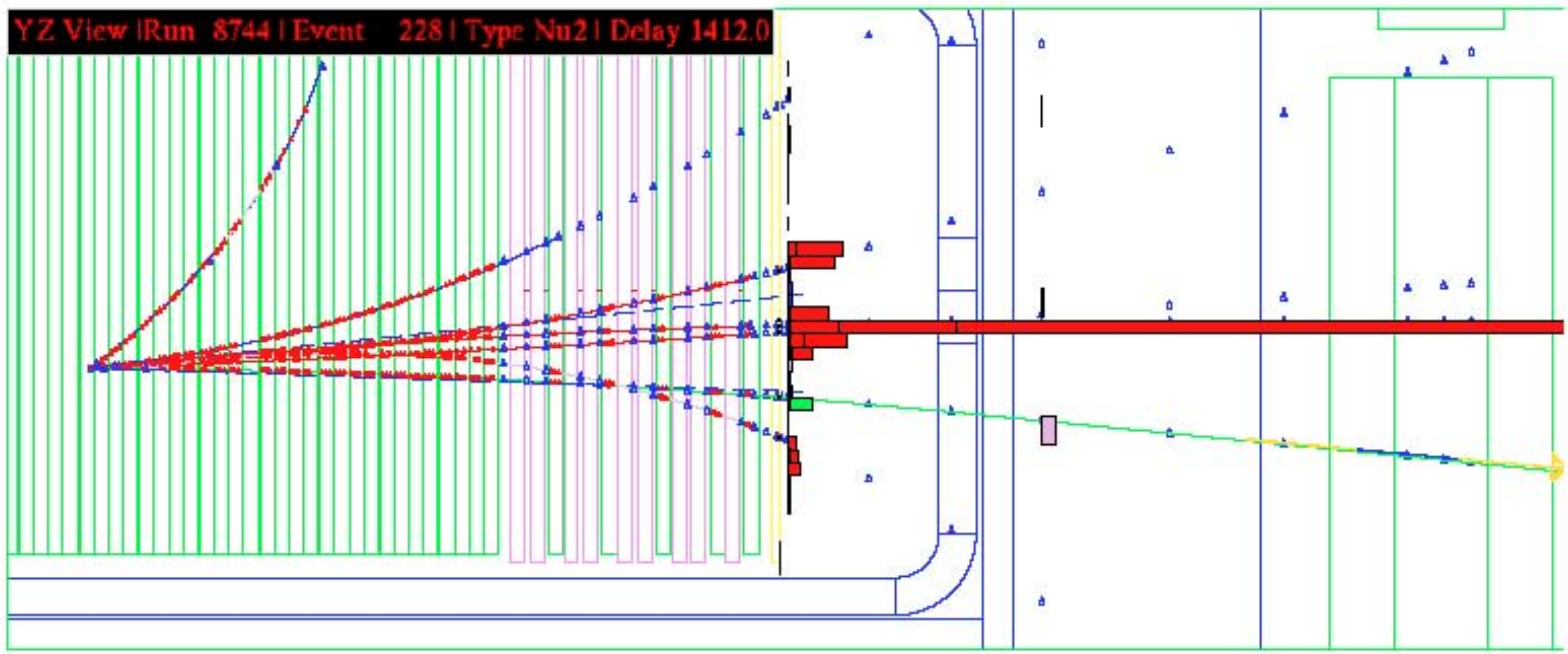
Density = 0.1 g/cm3, 85% in the radiator foils.

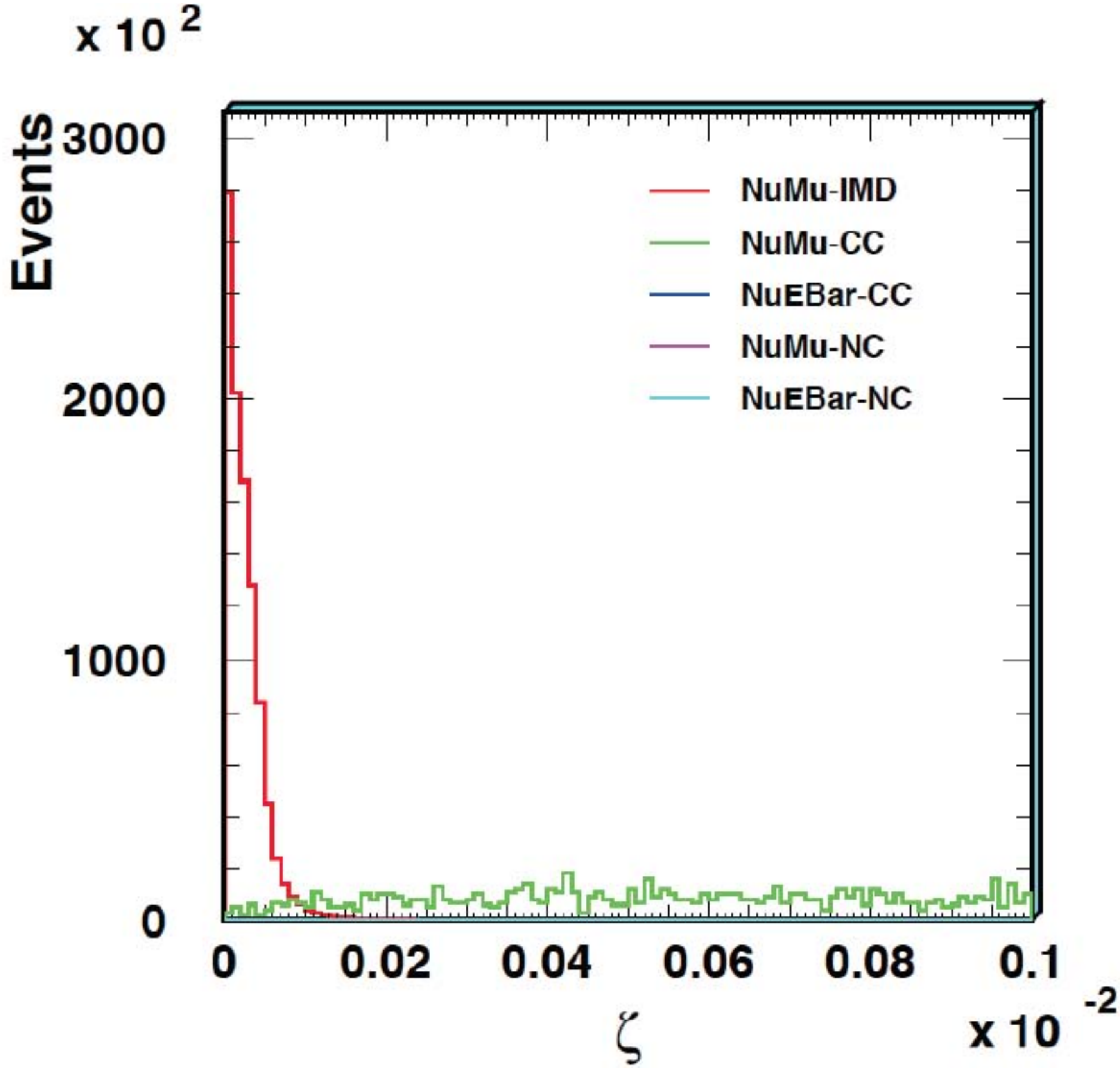
Transition Radiation ↠ e-/e+ ID ⇒ γ (w. Kinematics)

dE/dx ↠ Proton, π+/-, K+/- ID

Magnet/Muon Detector ↠ μ+/-

A ν_μ CC candidate in NOMAD




x 10 2
Events
3000
2000
1000
0
NuMu-IMD
NuMu-CC
NuEBar-CC
NuMu-NC
NuEBar-NC
0
0.02
0.04
0.06
0.08
0.1
ζ
x 10 -2

Salient steps of the IMD-Analysis

	ν_μ-IMD	ν_μ-CC	ν_μ-CCQE	$\bar{\nu}_e$-CC	ν_μ-NC	$\bar{\nu}_e$-NC
	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
1 negative Track	1,000,000	67,851	414,856	102,961	14,219	14,679
Neutral Veto ($E_\gamma \gtrsim 0.1$ GeV)	1,000,000	34,660	411,019	57,765	4,722	5,891
Neutral Veto ($E_{neutron} \gtrless 0.5$ GeV)	1,000,000	20,703	375,027	33,536	2,454	3,348
Neutral Veto ($E_{K_S,K_L} \gtrless 0.5$ GeV)	1,000,000	20,266	375,027	32,759	2,111	2,972
$E > 11$ GeV	983,355	13,544	257,736	661	341	419
$\varsigma\, \mu < 0.001$ GeV	979,403	831	16,614	49	2	3
$\varsigma\, \mu < 0.0001$ GeV	959,227	50	829	8	0	2

Efficiency $\Rightarrow$ *95%* *5e-05*

Summary and Outlook
Near Detectors

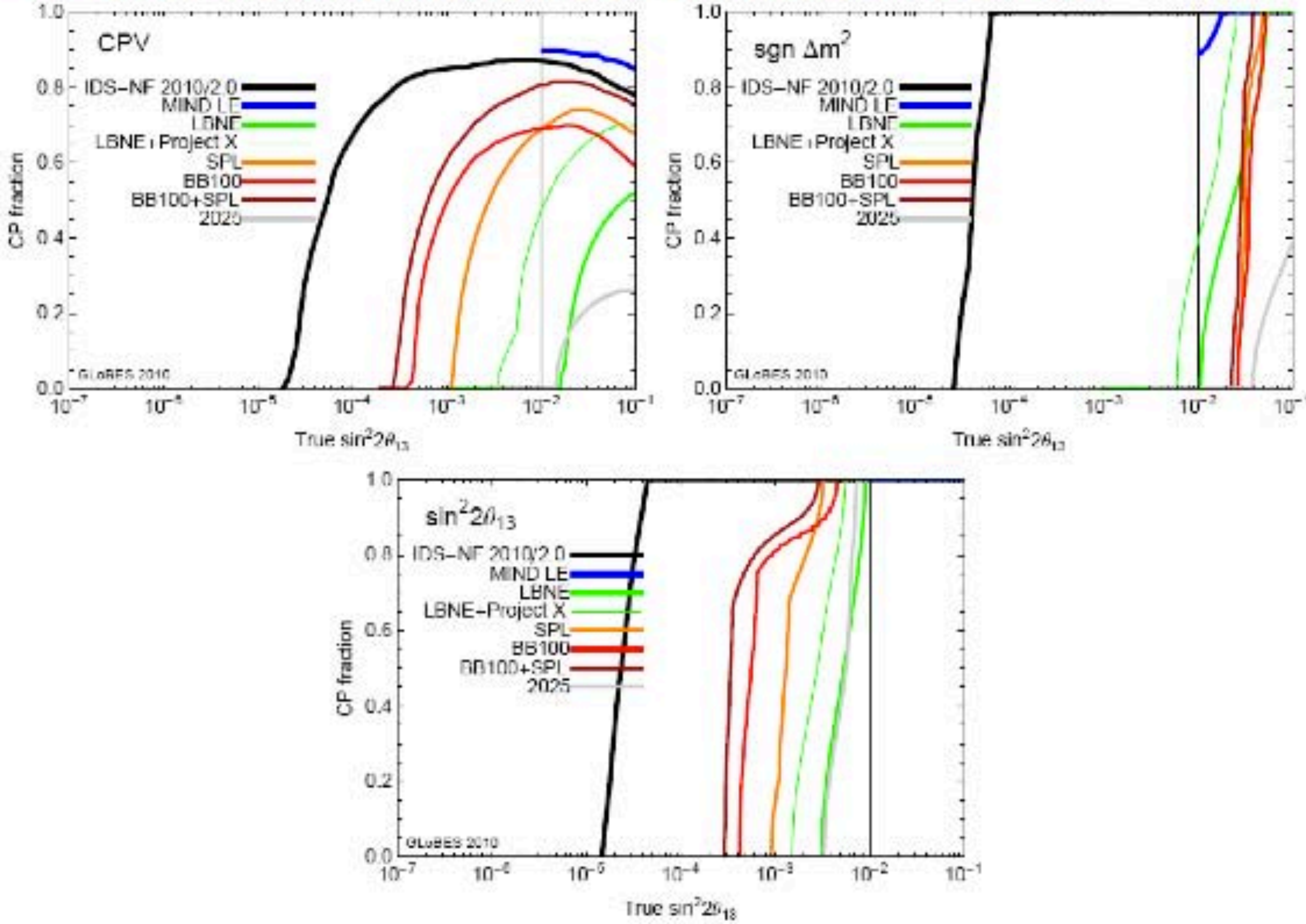
- Near detector(s) at the Neutrino factory is a valuable tool for neutrino flux measurement and standard and non-standard neutrino interactions study;
- Set-up: high granularity vertex detector, high resolution tracker, muon catcher – the design is dictated mostly by requirements for flux measurement;
- Two options considered for the high-resolution sub-detector: **SciFi OR Straw-tube tracker**. To join silicon vertex detector + mini-MIND.
- Further tasks:
  - **determination of the Near detector baseline design via full simulation;**
  - determination of systematic errors from near/far extrapolation (migration matrices);
  - expectation on cross-section measurements;
  - other physics studies: electroweak parameters, PDFs, etc.;
  - sensitivity to non-standard interactions (τ -lepton production);
  - R&D efforts to validate technology (e.g. vertex detectors, tracking detectors, etc.)

NEXT STEPS: Detector Design

- MIND R&D Effort
  - Prototype detectors with SiPM and extruded scintillator
  - Measure charge mis-ID rate
  - Develop CERN test beam for neutrino detector R&D – European AIDA proposal to make H8 into low E beam
- Near Detectors
  - Determine procedure for deciding between two alternative high-resolution near detectors for baseline
- Systematics
  - Determine elements in the overall covariant error matrix (systematic).
  - Get best understanding of how the size of these errors are involved in determining CP-violation.
  - Work with LBNE that is at a similar stage in study of systematics?

Neutrino Factory Performance

- Comparison Neutrino Factory and other facilities
  - **Neutrino Factory outperforms all other facilities**



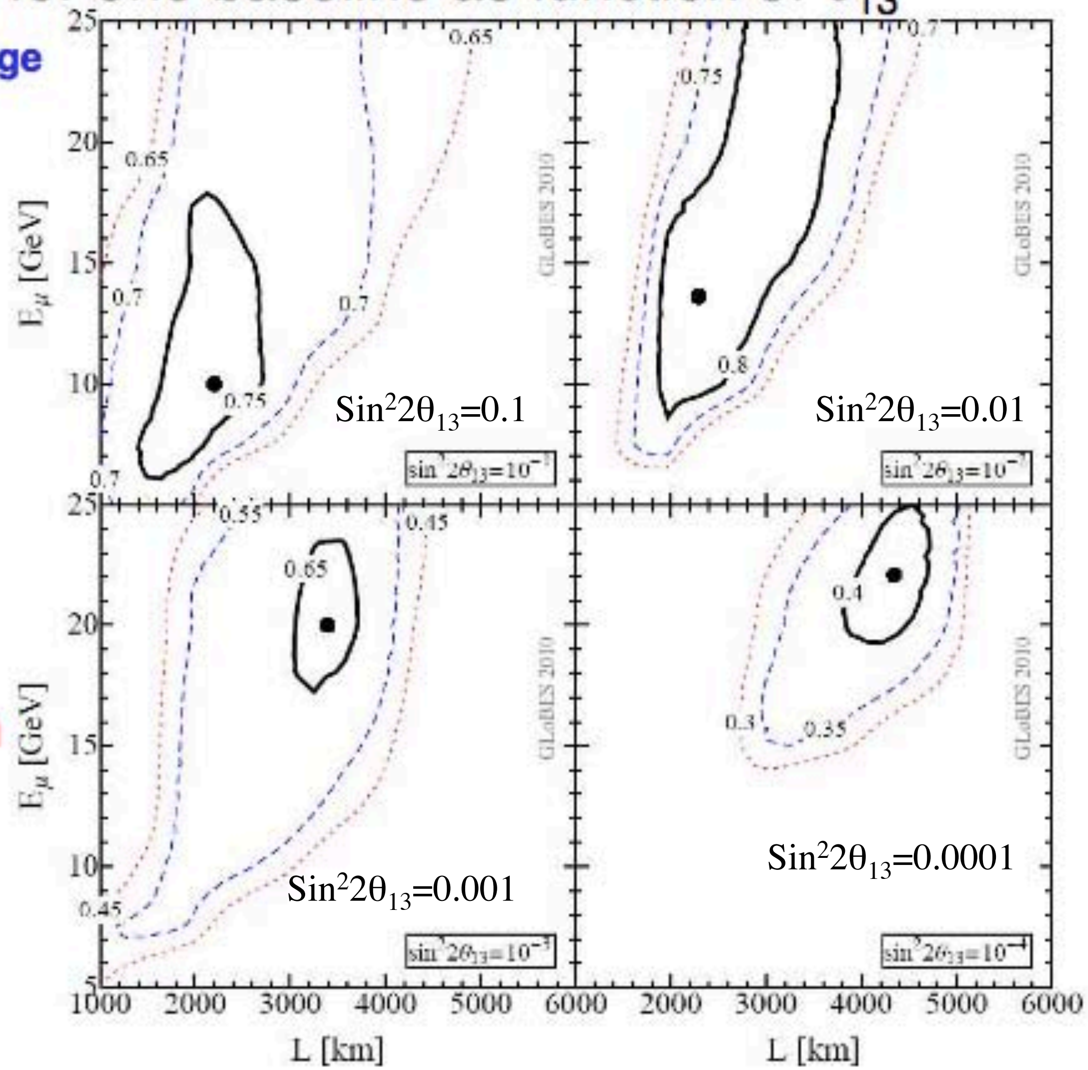
Flexible design of Neutrino Factory

- Optimisation for one baseline as function of θ_{13}

Contours of CP coverage

For large θ_{13}:
Energy 10 GeV
Baseline 2000 km
100 kton MIND

For small θ_{13}:
Energy ~25 GeV
Baseline ~4000 km
100 kton MIND



Overall Conclusions

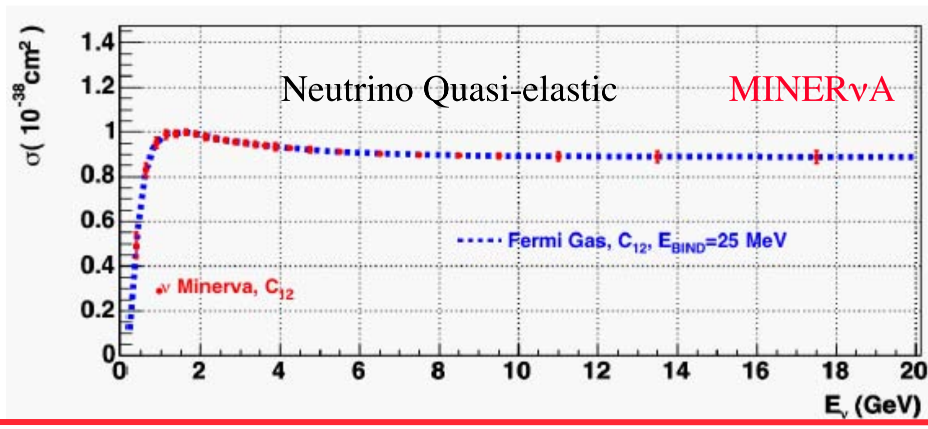
- International Design Study is progressing on course
  - Interim Design Report delivered March 2011
  - We had successful ECFA review May 2011 (final report due soon)
  - On target to produce Reference Design Report, including performance and costs by 2013
- Main concepts for accelerator systems have been defined
  - Main areas of work are at interfaces between components
- Two Magnetised Iron Neutrino Detectors (MIND) at standard Neutrino Factory (25 GeV) is small θ_{13} baseline:
  - 2500-5000 km with100 kton mass
  - 7000-8000 km (magic baseline) with 50 kton
- 10 GeV Neutrino Factory with one 100 kton MIND shows best performance for large θ_{13} ($\sin^2 \theta_{13} > 10^{-2}$)
- Conceptual design for near detector being established

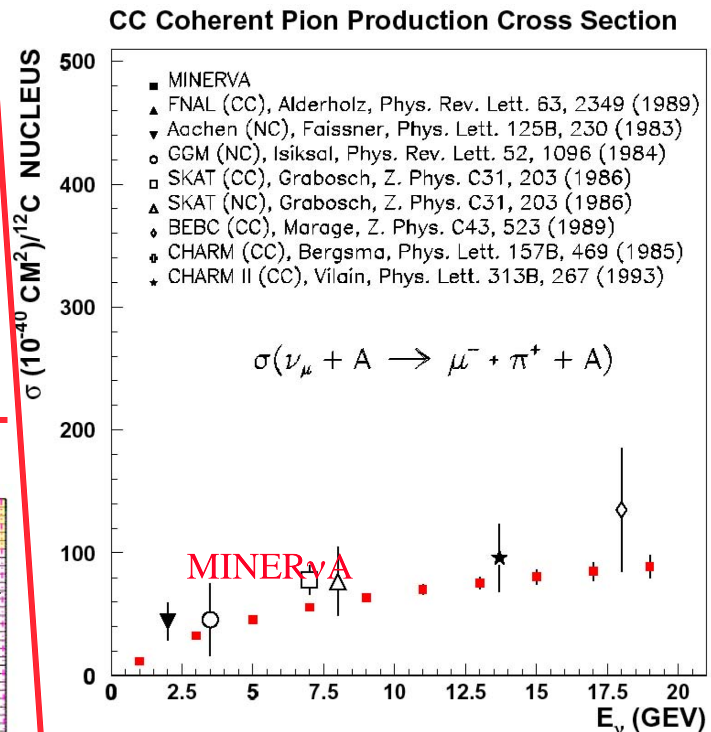
Backups

Where will we be at the time of NF – ND

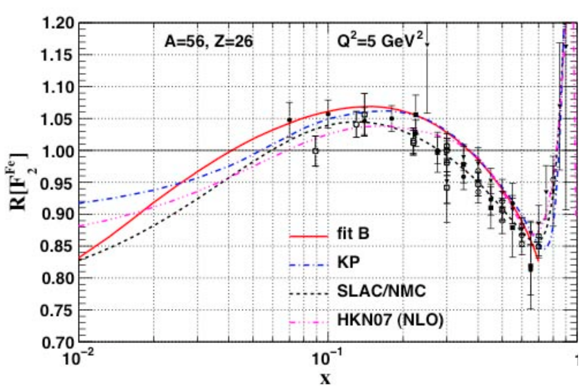
Dominated by systematics: Mainly Flux Errors

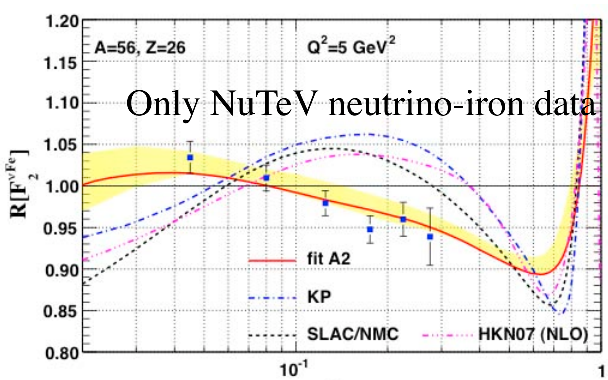
- The neutrino factory experiments will occur after MINERνA and LBNE will have taken and analyzed their data. Examples:





Neutrino Nuclear Effects





- Combined many charged lepton data sets on many different nuclei
- MINERνA provides **He, C, Fe, Pb**

Neutrino-nucleus Scattering Physics at NF-ND

post MINERνA and LBNE

- Take advantage of much-increased knowledge of the flux:
  - absolute cross-sections
- Take advantage of much-increased event rate:
  - use of H_2 and D_2 targets as well as higher A,
  - study of rare topologies,
  - high-x phenomena …..
- Take advantage of extended kinematic coverage:
  - study lower-x phenomena at reasonable Q^2,
  - extended reach in Q^2
- Certainly to be other benefits…

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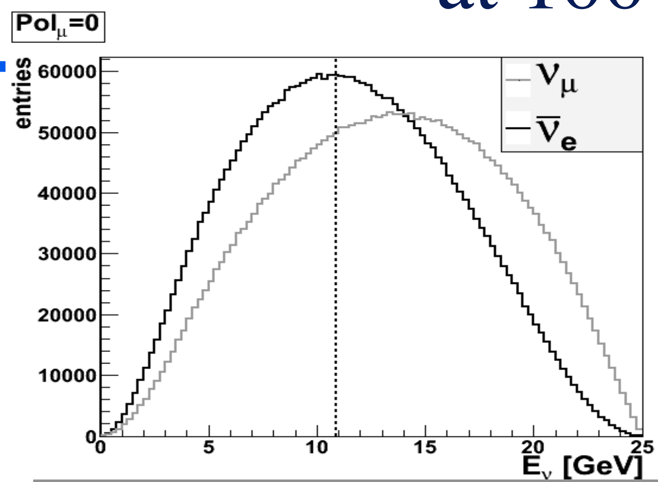
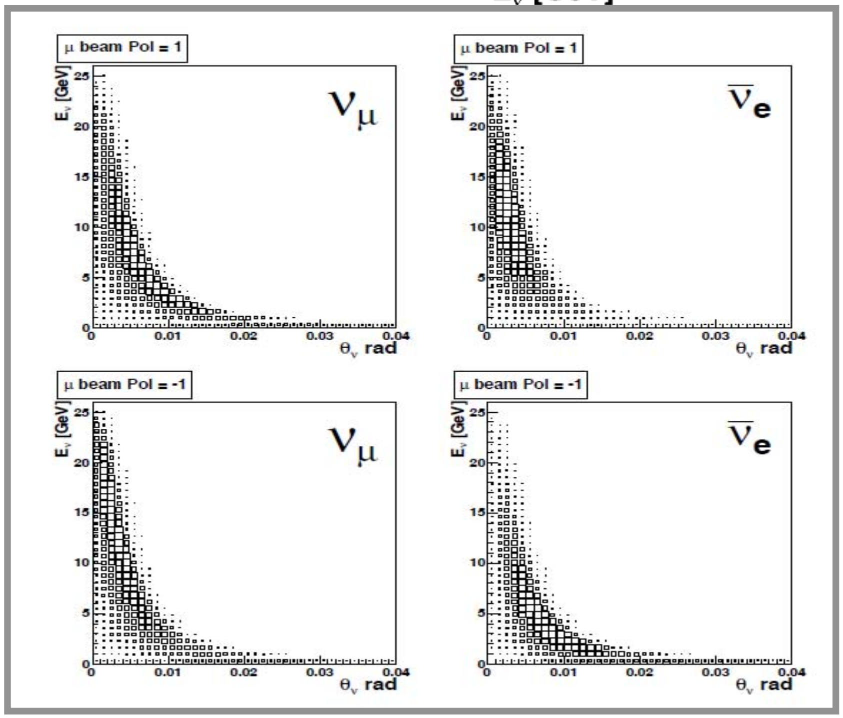
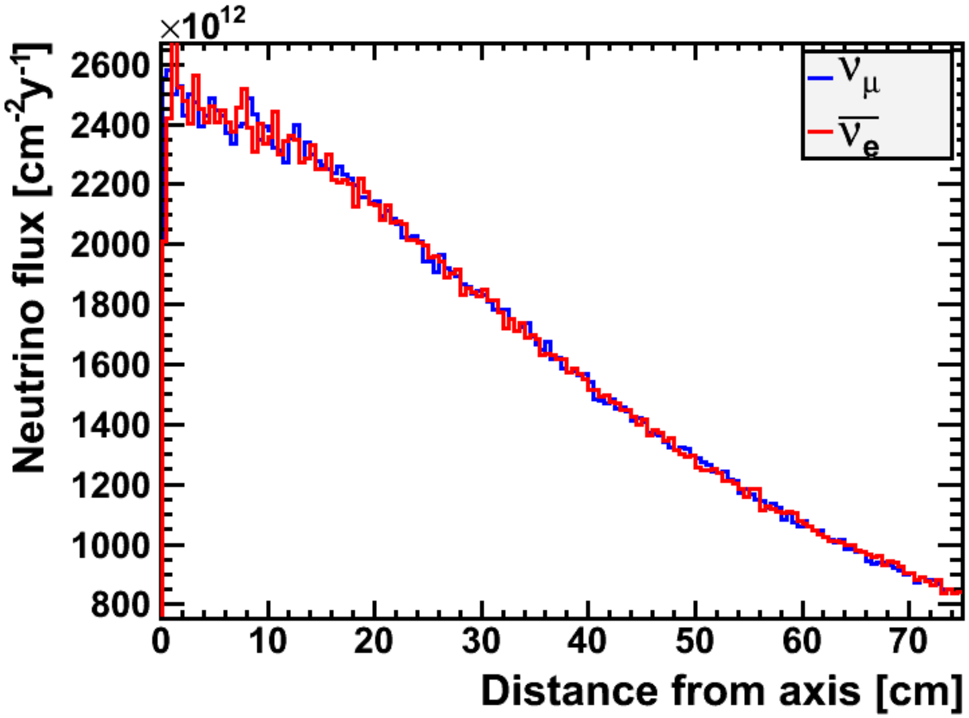
Neutrino flux through the detector at 100 m from the straight end

1x10^{20} μ - decays/year

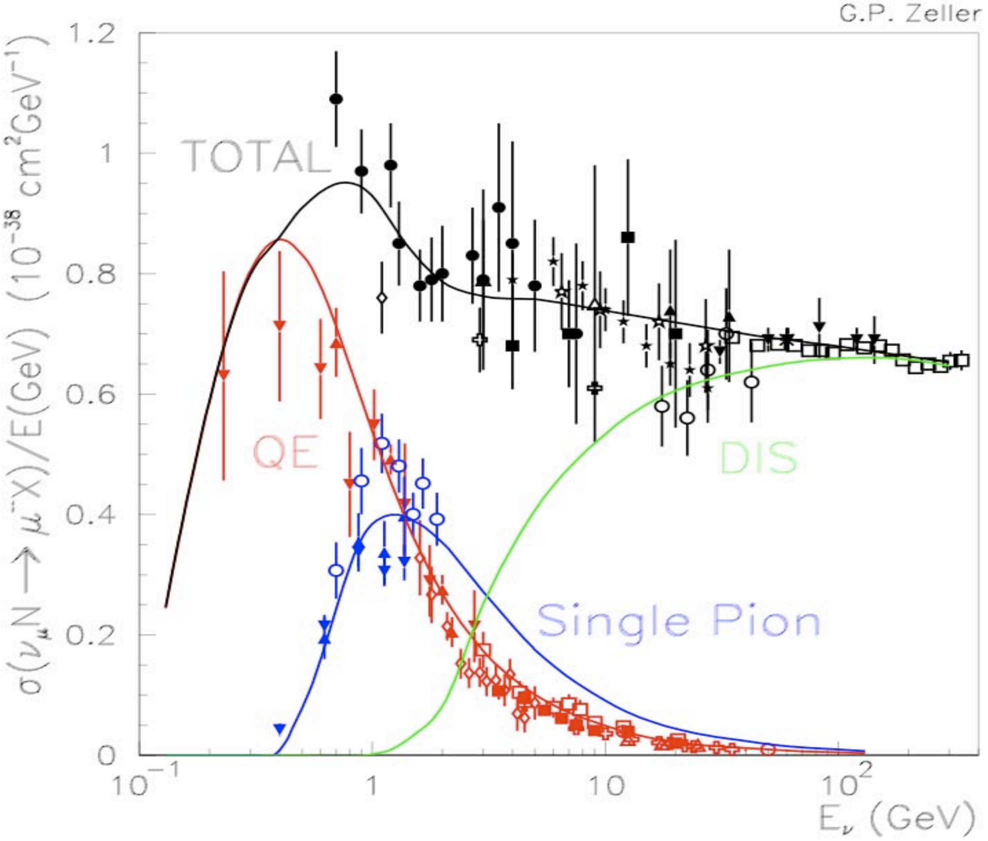






Cross section measurements

- Measurement of cross sections in DIS, QEL and RES.
- Coherent and diffractive π, ρ, ...
- Different nuclear targets: H_2, D_2
- Nuclear effects, nuclear shadowing, reinteractions



Expected cross-section errors from T2K, Minerva and LBNE dominated by absolute flux error before compared to Neutrino Factory.

At NF, with modest size targets one can obtain very large statistics, but is <1% error achievable?

Improvements over the NOMAD: HiResMnu-Concept

- Tracking Charged Particles
  - x6 more hits in the Transverse-Plane (X-Y)
  - x2 more hits along Z-axis
- Electron/Positron ID
  - Continuous TR providing e+/e- ID
- Calorimetry: 4π-Coverage
  - Downstream ECAL: fine Longitudinal & Transverse segmentation
  - Barrel & Upstream ECAL
- μ-ID
  - 4π-Coverage: min-P_μ ⤃ 0.3 GeV

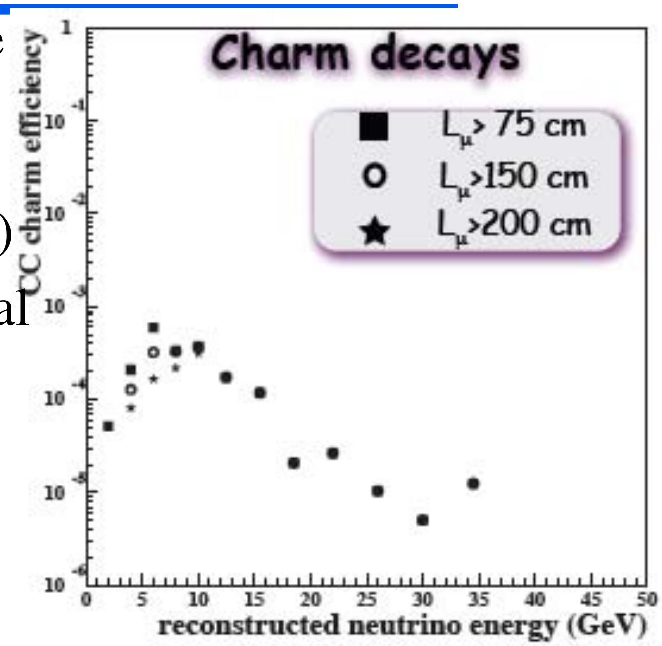
Sensitivity Analysis **νEI:** ν_μ(ebar) + e- → e- + ν_e (*Single, forward e-*)

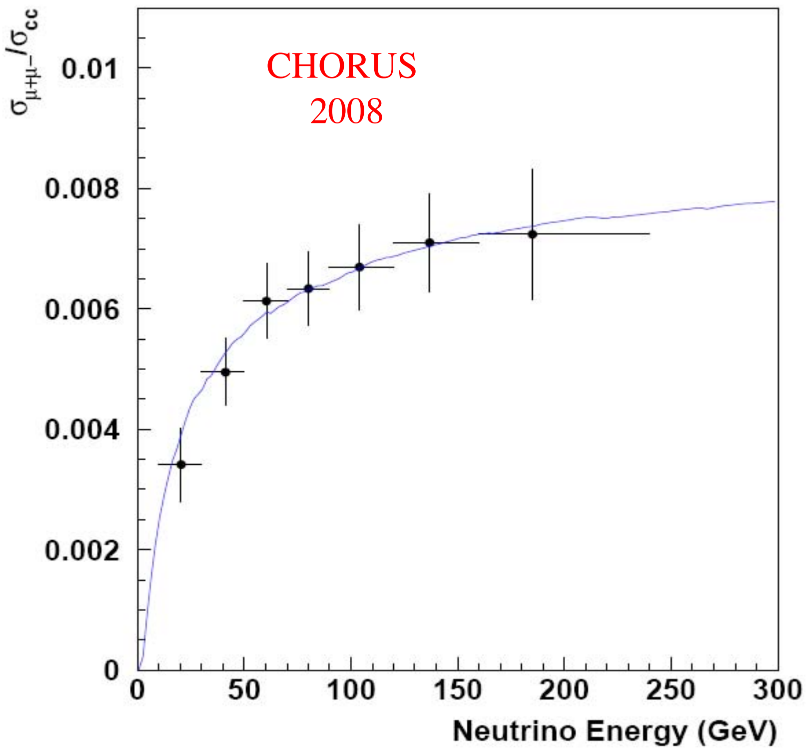
* $\nu_{\mu(ebar)}$-N NC background due to single, asymmetric $\gamma \to e^- e^+$ and π^-/μ^-

$\gamma \to e^- e^+ \Rightarrow$	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_e$-CC	ν_μ-CC	$\bar{\nu}_e$-NC	ν_μ-NC
	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
Positron/muon veto	1,000,000	1,000,000	40,168	50,219	1,000,000	1,000,000
Hadron Veto	1,000,000	1,000,000	32,028	30,570	209,171	147,826
Photon Conversion & $E_{e^+} < 0.05$ GeV	1,000,000	1,000,000	81	79	460	340
20 planes	833,179	836,172	1	1	0	0
$E_e > 0.5$ GeV	748,786	794,086	0	0	0	0
$z < 0.001$ GeV	733,723	785,240	0	0	0	0
Efficiency ⇒	*66%*	*71%*			*~10^-6*	

Charm production and τ measurement (NSI)

- **Motivation:** measure charm cross-section to validate size of charm background in wrong-sign muon signature (charm cross-section and branching fractions poorly known, especially close to threshold)
- **Motivation**: tau production in near detector is a signal for non-standard interactions





Vertex detector of high granularity is needed.

Silicon strips or emulsion sheets?

HiResMν design parameters

Resolutions in HiResMν

- $\rho \simeq 0.1 gm/cm^3$
- Space point position $\simeq 200\mu$
- Time resolution $\simeq 1ns$

- CC-Events Vertex: $\Delta(X,Y,Z) \simeq O(100\mu)$
- Energy in Downstream-ECAL $\simeq 6\%/\sqrt{E}$
- μ-Angle resolution (~5 GeV) $\simeq O(1\ mrad)$

- μ-Energy resolution (~3 GeV) ~ 3.5%
- e-Energy resolution (~3 GeV) ~ 3.5%