The IDS Neutrino Factory Detectors: Baselines and Plans

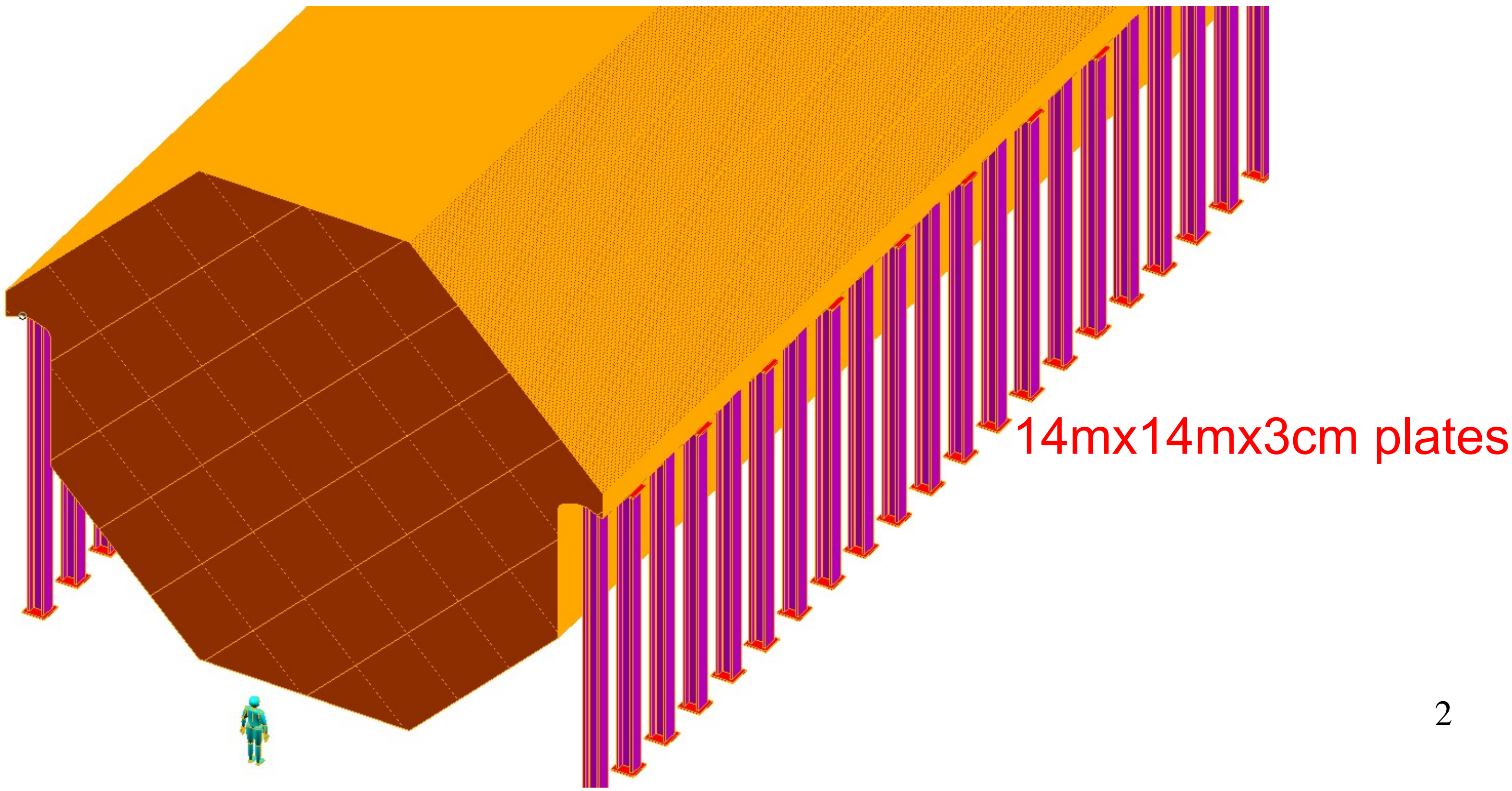
7th Neutrino Factory International Design Study Meeting
Virginia Tech - October, 2011

Jorge G. Morfín, Fermilab

Magnetised Iron Neutrino Detector (MIND)

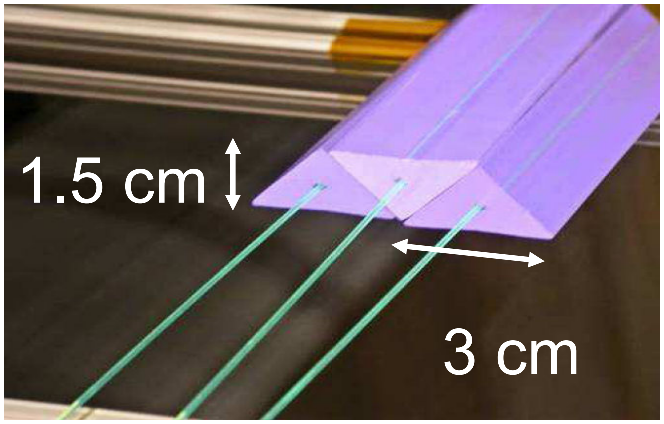
IDS-NF Far Detector baseline for 25 GeV NuFact:

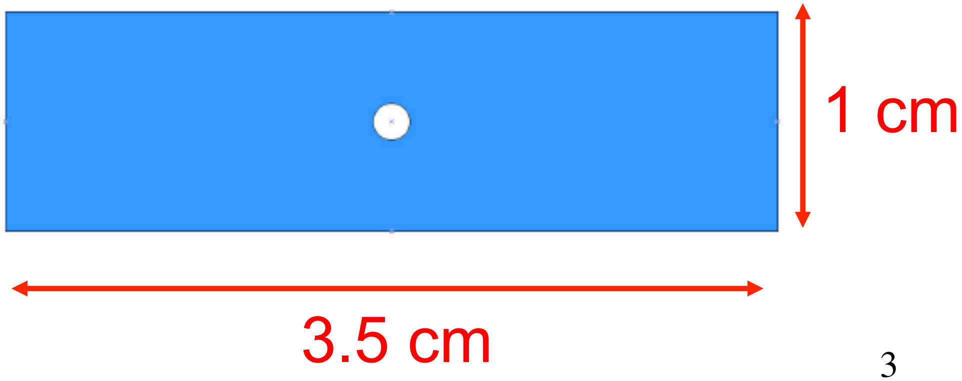
- Far detector: 100 kton at 2500-5000 km
- Magic detector: 50 kton at 7000-8000 km
- Appearance of “wrong-sign” muons
- Toroidal magnetic field > 1 T
- Segmentation: 3 cm Fe + 2 cm scintillator
- 50-100 m long
- Octagonal shape



MIND scintillator

- Scintillator: x-view and y-view planes 1 cm thick each plane
  - Baseline: rectangular scintillator strips (3.5 cm wide, $\sigma \sim 1$ cm)
  - Alternative: triangular strips ($\sigma \sim 5$ 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)

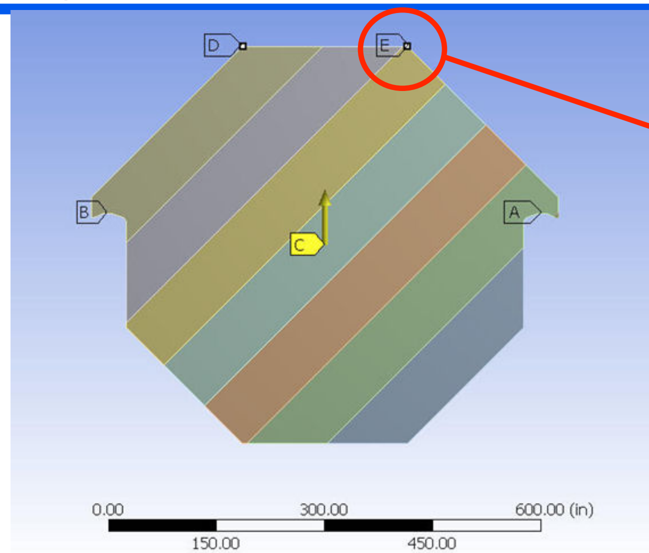


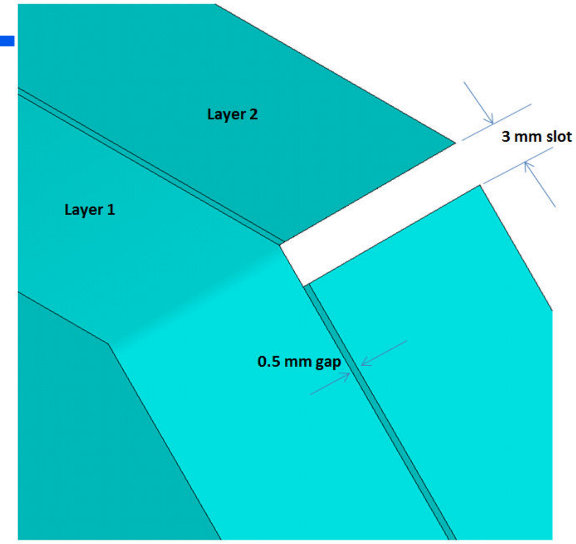


MIND engineering

- Plate engineering: A. Bross, B. Wands

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

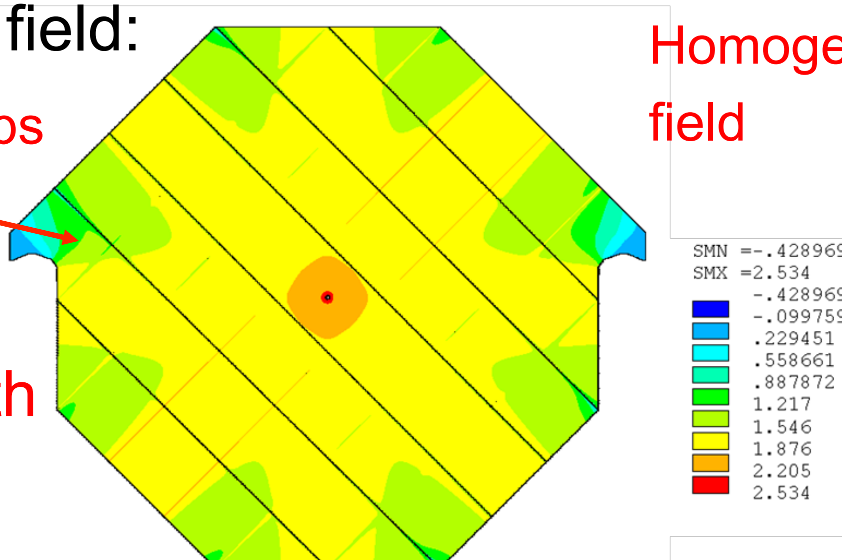




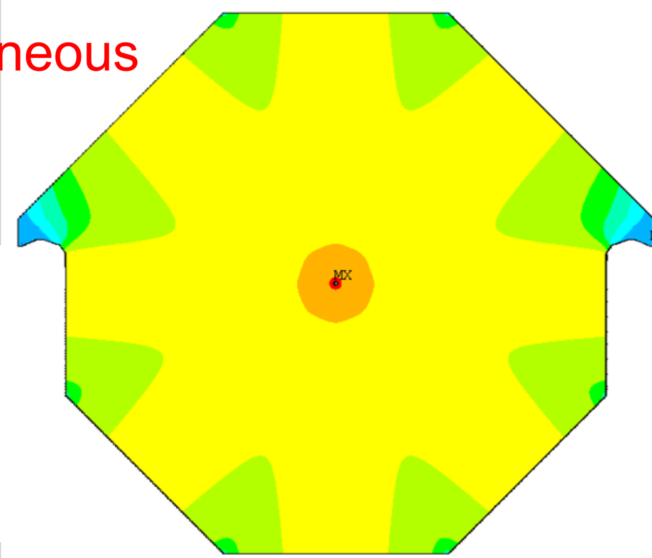
- Toroidal field:

Small field gaps and jumps

1.2-2.2 T with 100 kA turn

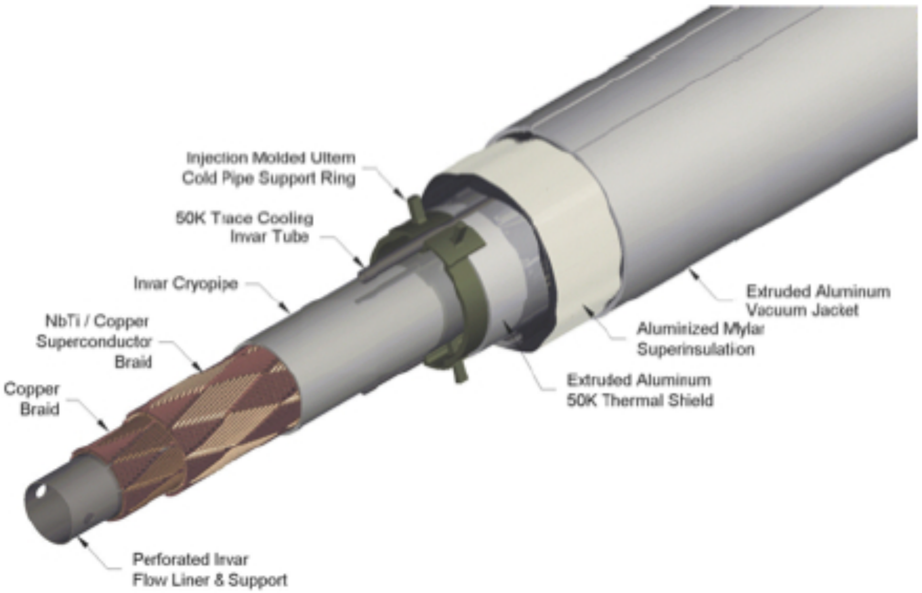


Homogeneous field



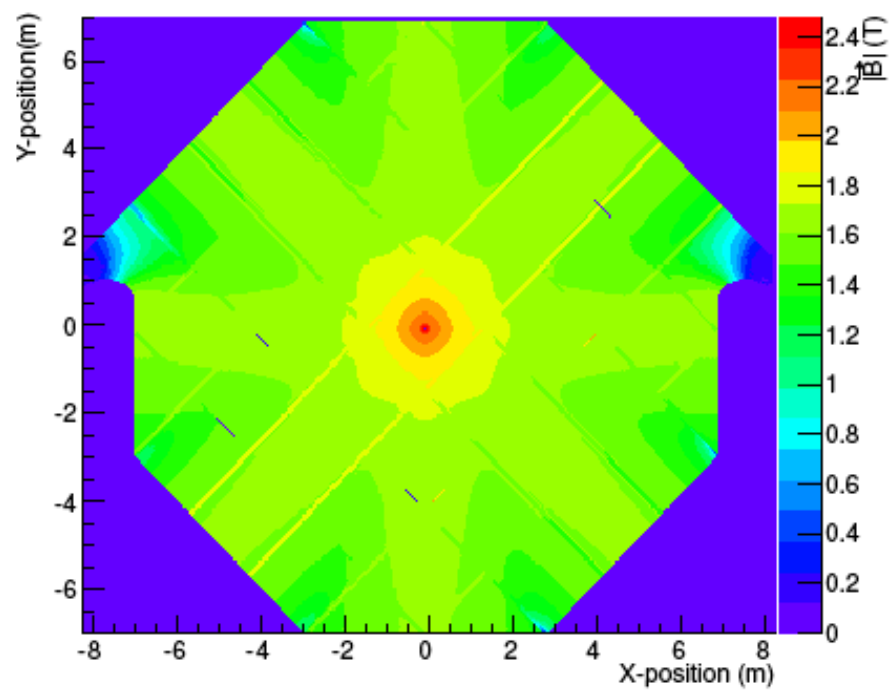
MIND Magnetic Field

- 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

Optimization of the MIND Simulation

R. Bayes[1], A. Bross[3], A. Cervera-Villanueva[2] , M. Ellis[4,5], A. Laing[1] , F.J.P. Soler[1] , and R. Wands[3]

[1]University of Glasgow, [2]IFIC and Universidad de Valencia, [3]Fermilab, [4]Brunell University, [5]Westpac Institutional Bank, Australia,
on behalf of the IDS-NF collaboration

IDS Meeting
18, October 2011

Changes Made to MIND Simulation

with respect to the Interim Design Report

Simulation

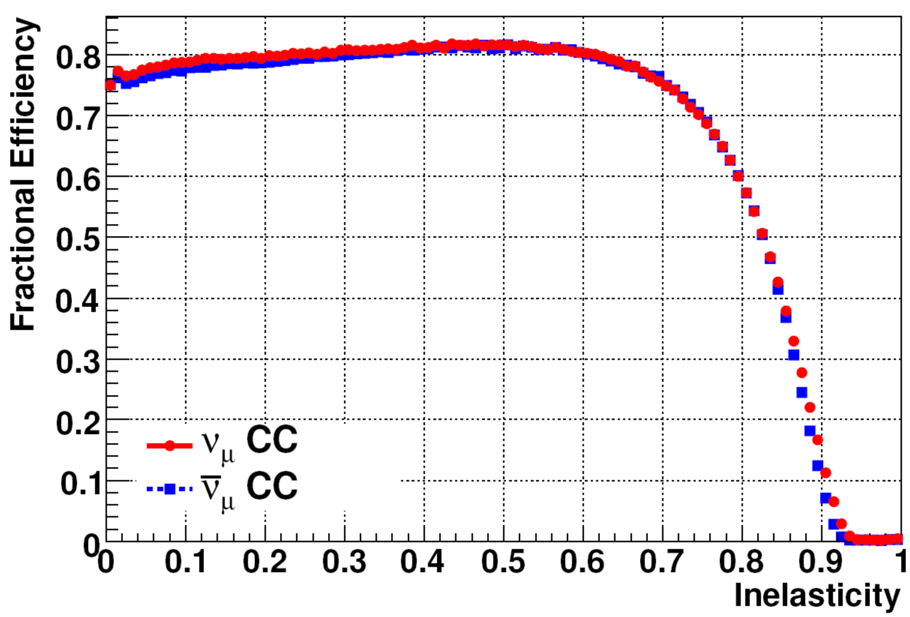
- Added GENIE capability
- Introduced octagonal geometry
- Added ability to read magnetic field map (as supplied by Bob Wands and Alan Bross)

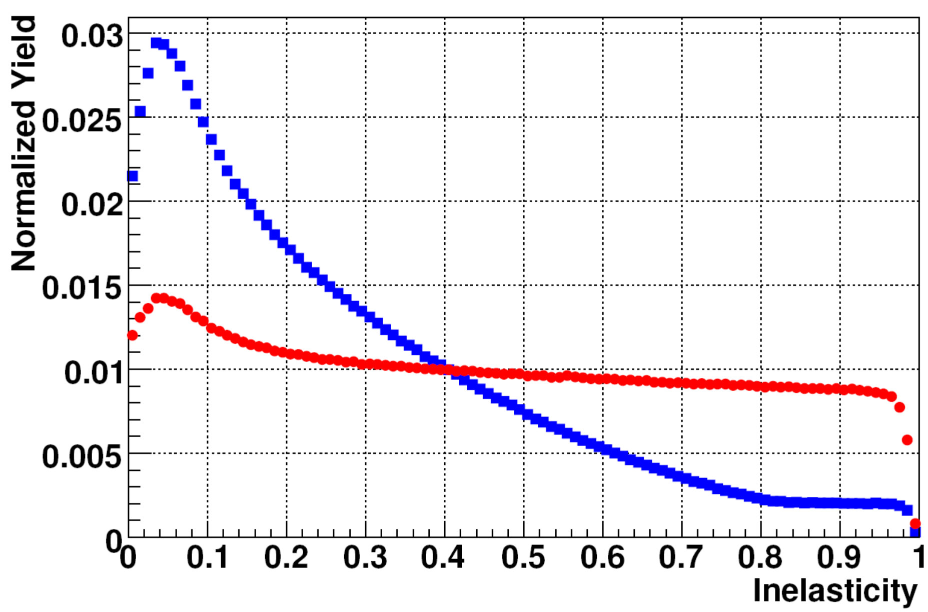
Reconstruction

- Added octagonal geometry/magnetic field map.
- Removed dipole field specific artifacts.
- Used a momentum range calculation to determine seed for track fitting.

MIND: progress in 2011

- Analysis redone using full GENIE simulation Ryan Bayes
  - Importance of Parton Distribution Functions and event generator

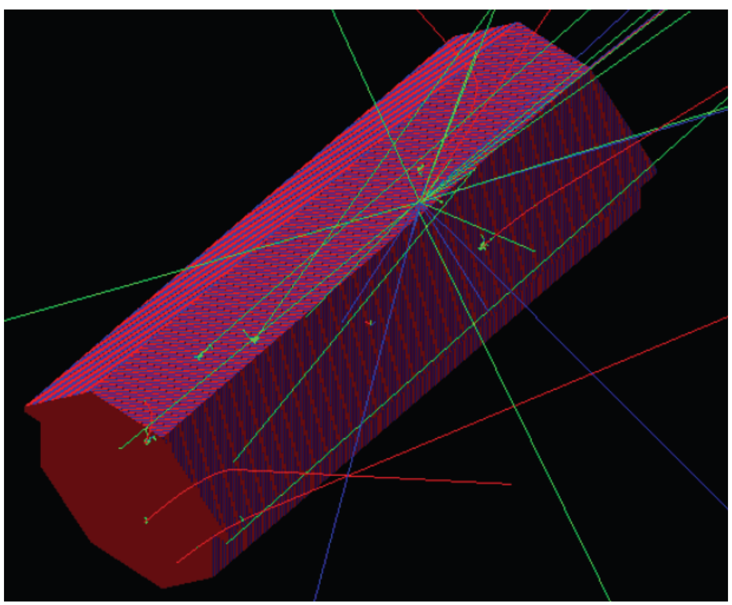


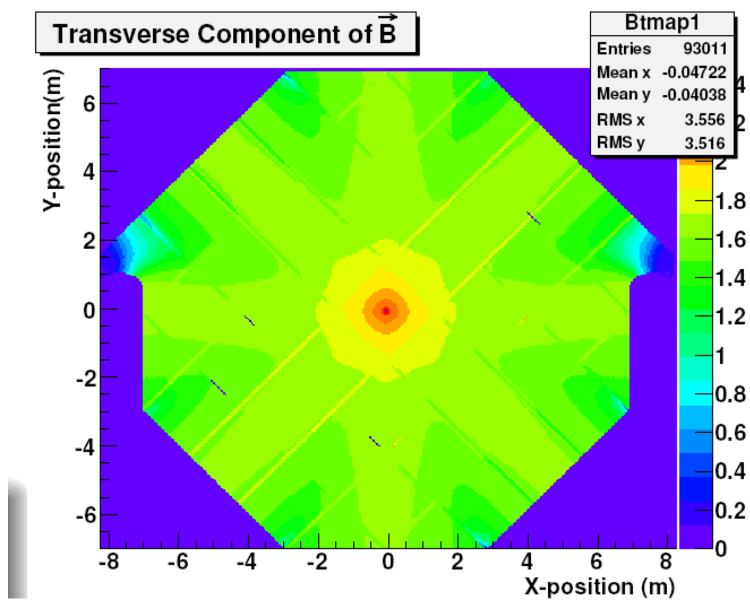


MIND: progress in 2011

- Octagonal geometry in GEANT4:
  - Implemented geometry
  - **Implemented realistic, toroidal B-field map**
  - Reconstruction and analysis need to be re-optimised for new geometry
  - Hadronic reconstruction
  - Complementary muon measurement of momentum by range

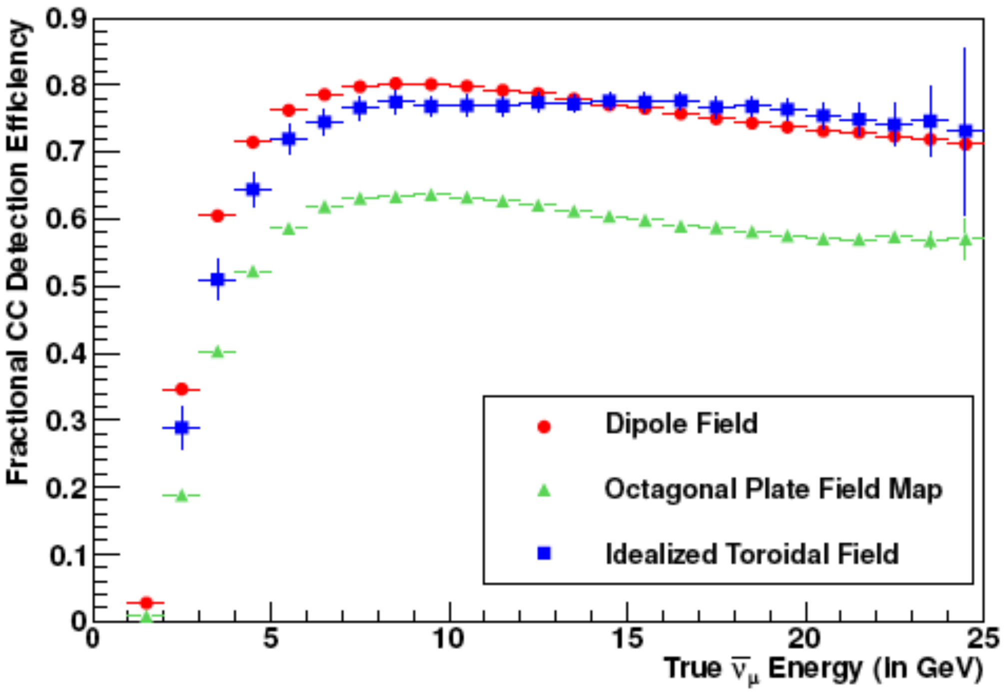
Ryan Bayes





Detector Response From Idealized Field

Reconstruction is capable of reproducing efficiencies observed in cuboid geometry.



- Optimization still not complete
- Is the problem due to slot fields or edge distortions?

Need intermediate case of realistic homogeneous field to answer question.

Conclusions

- Great progress has been made with MIND simulation
  - Implemented GENIE neutrino generator.
  - Introduced realistic geometry.
  - Added capability to read/use magnetic field map.
- Optimization of advanced simulation still in progress.
  - Changes made to Kalman filter.
  - Treatment of magnetic field to be evaluated.
  - Beginning re-evaluation of golden analysis.
- Missing pieces of analysis still needed
  - true reconstruction of hadronization still to be written.

MIND: Future directions

- Analysis and simulations:
  - Add ν_τ signal to wrong-sign muon signal – important for sensitivities ✔
  - Move to GENIE for neutrino interactions ✔
  - Improve digitisation, optimise geometry and add toroidal field ✔
  - Hadronic reconstruction: energy and angular resolution
  - New multivariate analysis: sensitivity plots
  - Cosmic backgrounds

Reconstruction being optimised for new geometry

- 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

- WBS and Costing (first pass) accomplished: Order \$500 M

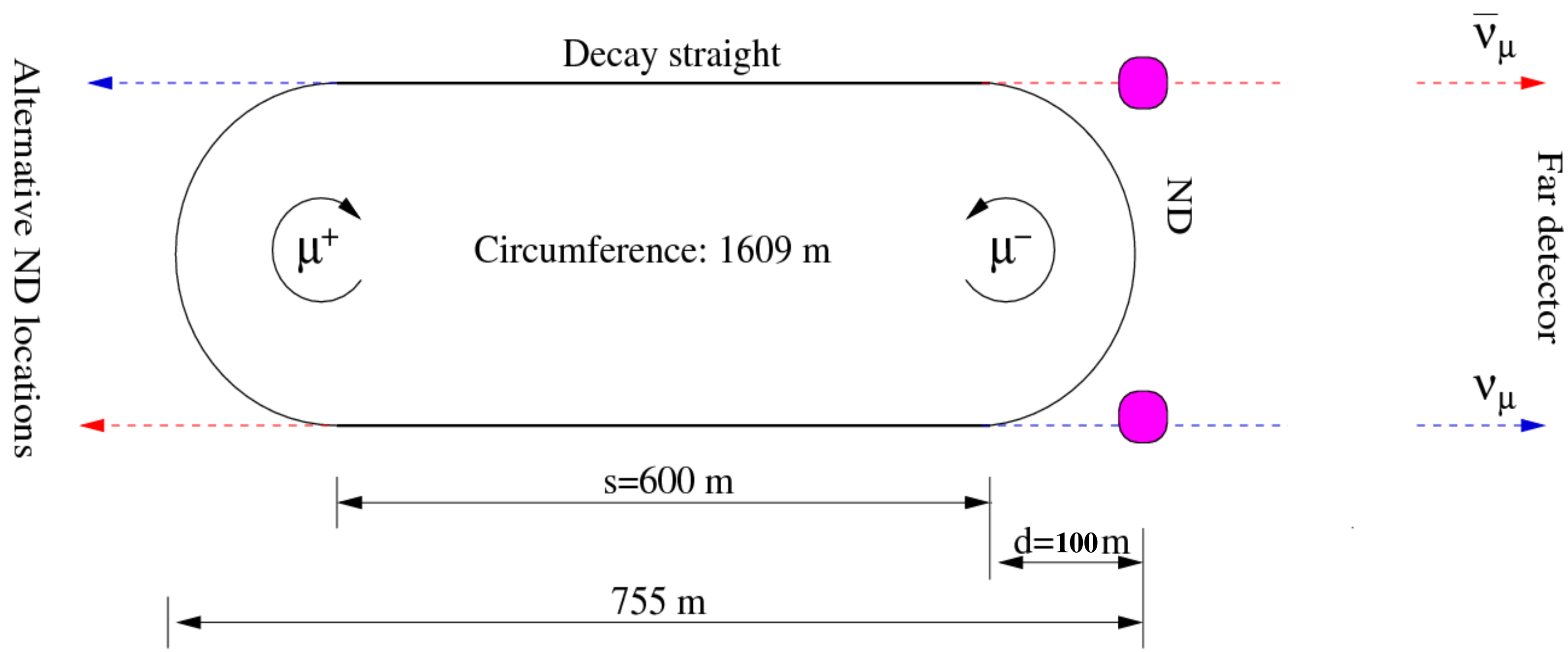
Neutrino Factory Near Detector(ss)

E_μ = 25 GeV ±80 MeV

Straight section length = 600 m

Muon angular spread 0.5 mrad

Decay straight dip angles of the two racetracks are 18° and 36°→ Near detectors will be at depths of 264 and 502 m, respectively.



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).

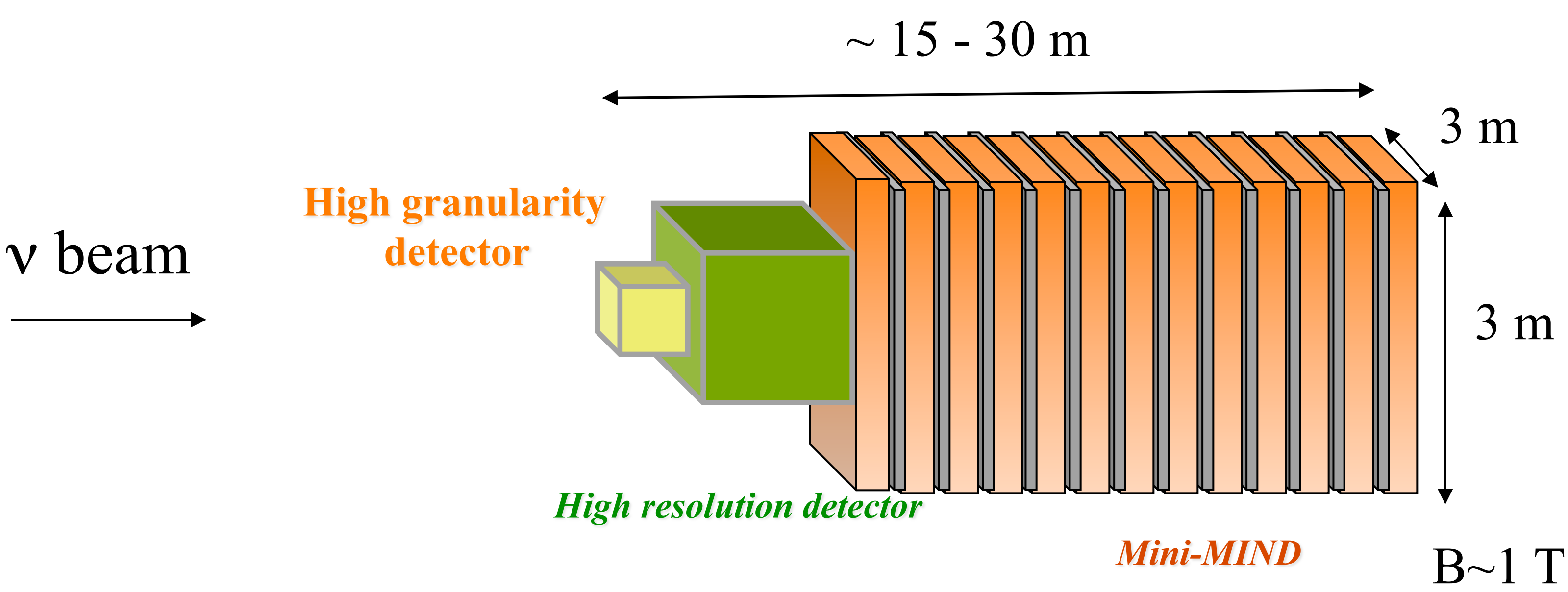
Near Detector Design Requirements

- 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:

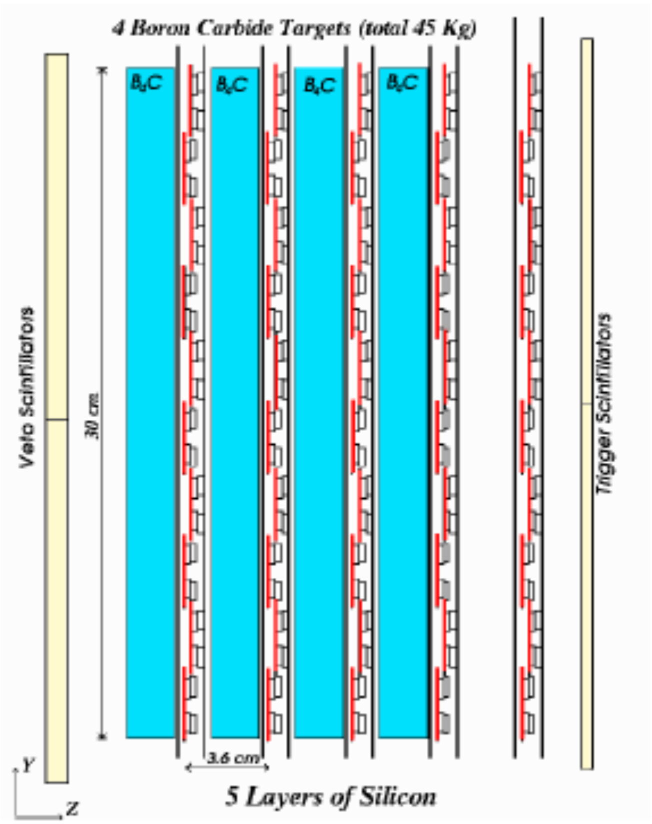
- High granularity detector for charm/tau measurement;
- High resolution detector (**Scintillating Fibres tracker** or **Straw Tube tracker**) for precise measurement of the event close to the vertex;
- Mini-MIND detector for higher energy muon measurement



High granularity vertex detector

Discussed at Near Detector Workshop 8/11

- **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 ~5×10^5 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.



NOMAD-STAR

Objectives for this Meeting: Updates on High-Resolution Near Detector Alternatives

- Update from Rosen and Roumen on the evolved design of SciFi tracker
- Presentation by Sanjib on the straw-tube tracker performance in the NF energy spectrum and with NF intensity.
- Get status of how well both designs can determine the NF flux.
- Discuss how well both can measure other neutrino cross sections, nuclear effects and “new physics”.
- Refine the list of procedures to compare the two designs in order to come to a decision on which one to use as baseline in RDR.
- Determine the steps necessary to cost both detector designs.
- **Begin to consider how systematics of near detector measurements propagate to the far detector.**

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**

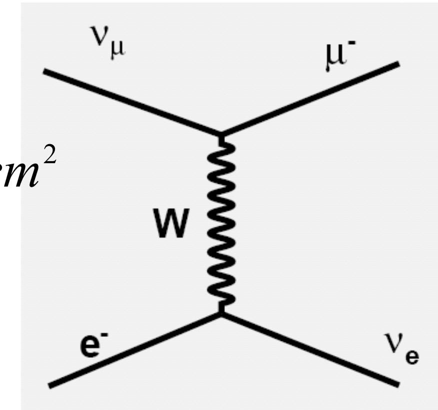
Inverse Muon Decay (IMD)

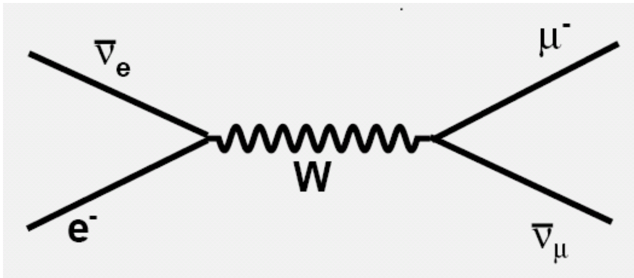
$$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_\mu + \mu^-$$

$$\sigma = \frac{G_F^2}{\pi}\frac{\left(s - m_\mu^2\right)^2}{s} = 4\times 10^{-41}\, cm^2$$

for 15 GeV ν_μ;

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





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

v-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.

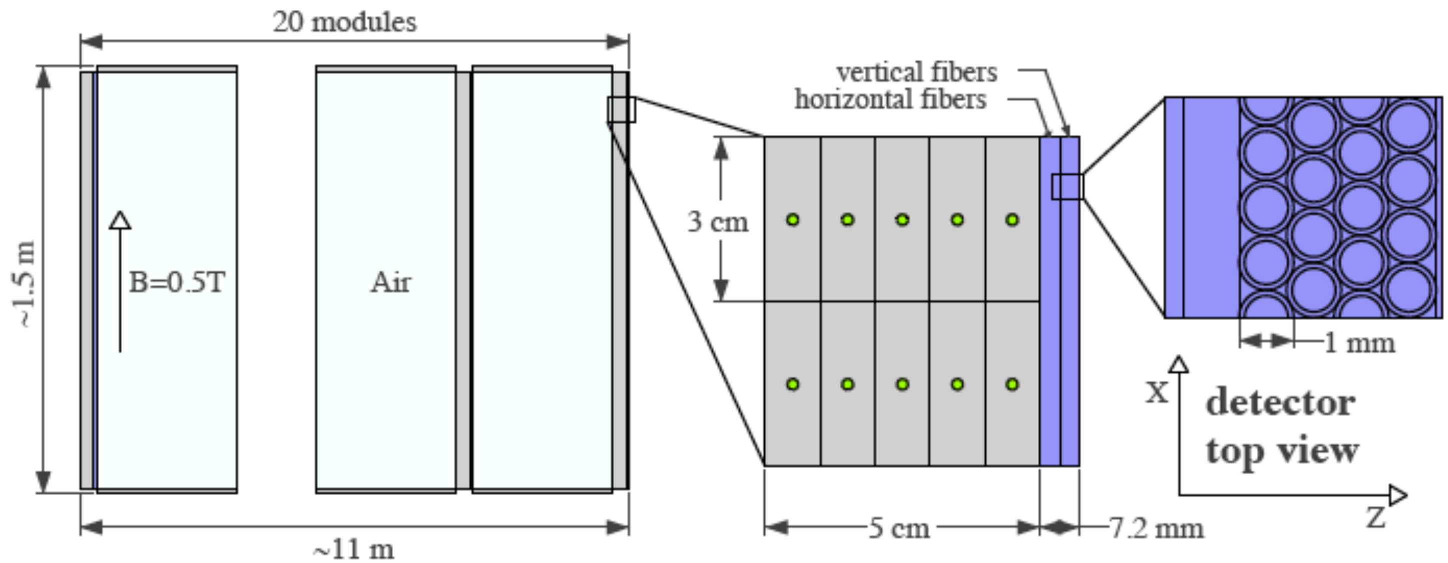
Status of Scintillating Fibre tracker near detector simulations

Maryan Bogomilov, Yordan Karadzhov,
Rosen Matev, Roumen Tsenov

University of Sofia

October 18, 2011

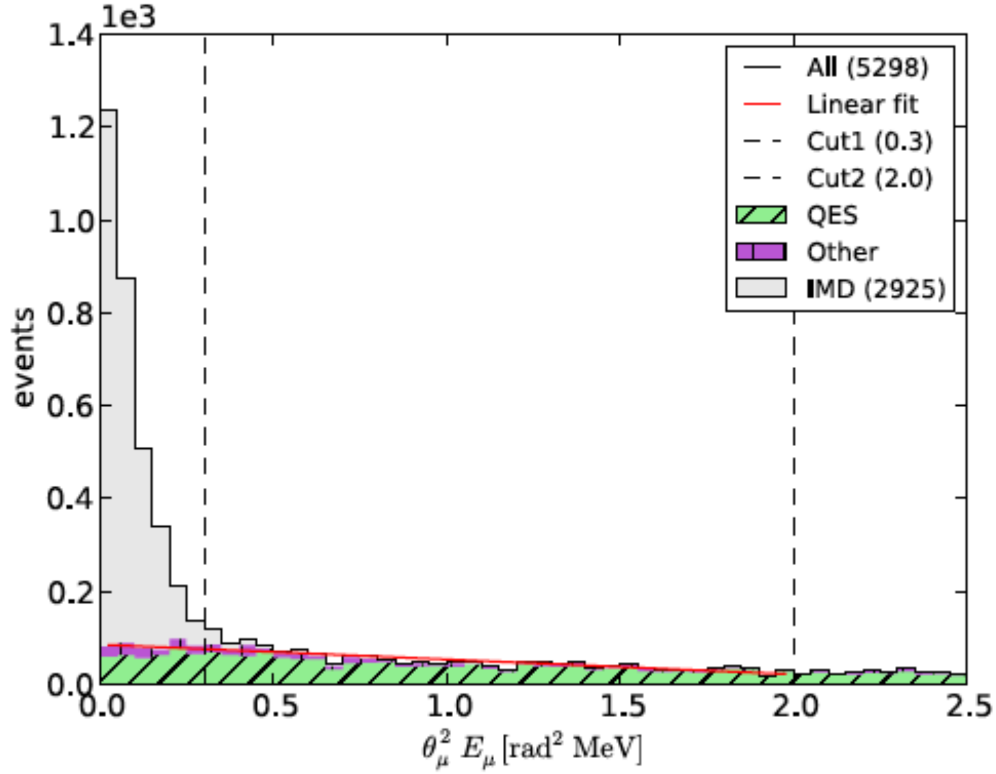
Scintillating fiber tracker



- 0.5 T dipole magnetic field;
- 20 modules with $\sim$ 50 cm air gaps in between;
- 5 layers of scintillating bars ($3 \times 1 \ \ \mathrm{cm}^2$) 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)

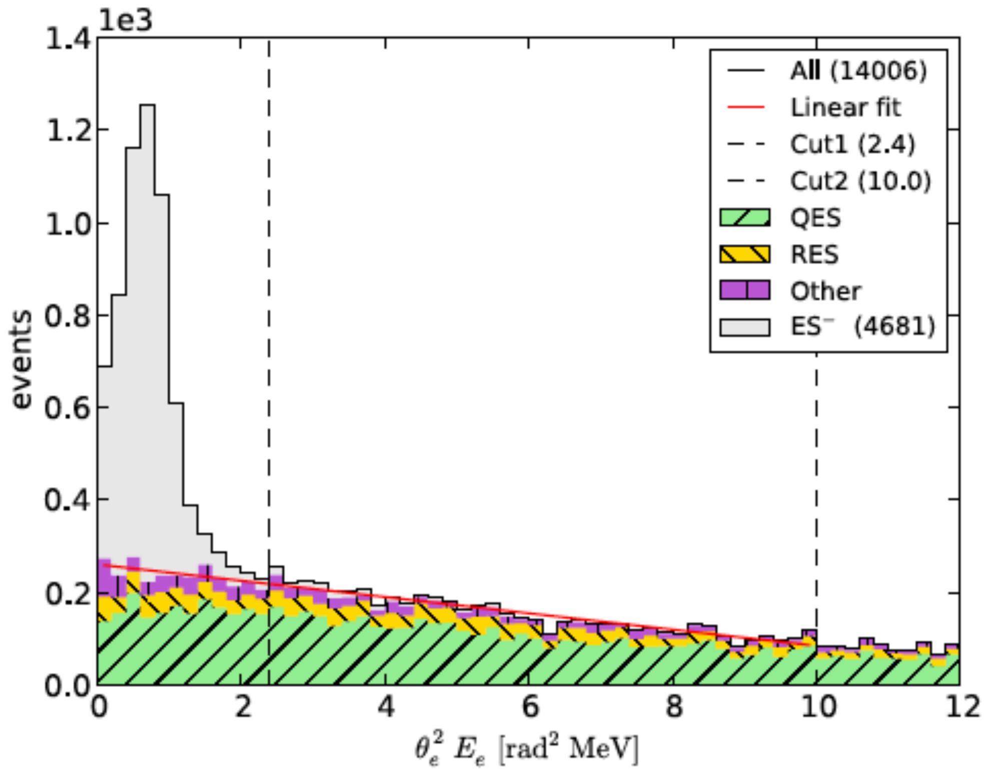
Use linear extrapolation of event rates in region between cut1 and cut2 to estimate background under the signal peak.



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}

Signal extraction summary

Estimated number of signal events for the three event samples. The result in the last row was obtained using the μ^+ background subtraction method, while the other three results were obtained using linear fit background subtraction method. Statistics correspond to 2.3×10^{19} μ^- decays and 2.3×10^{19} μ^+ decays, which is approximately a tenth of the nominal year.

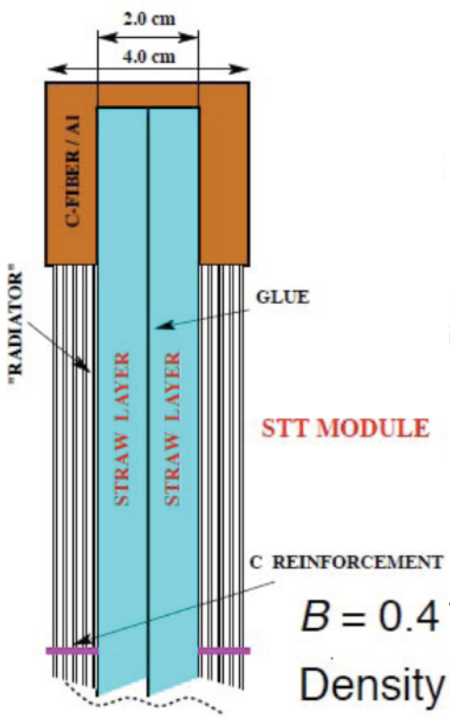
Event sample	Selection eff.	Overall eff.	Purity	All events	Signal events	Signal events from fit
IMD	85 %	45 %	85 %	3312	2801	2828 ± 58
ES^-	70 %	32 %	61 %	7355	4491	4479 ± 86
ES^+	83 %	37 %	63 %	16964	10607	10512 ± 131
IMD	86 %	46 %	81 %	3520	2850	2831 ± 61

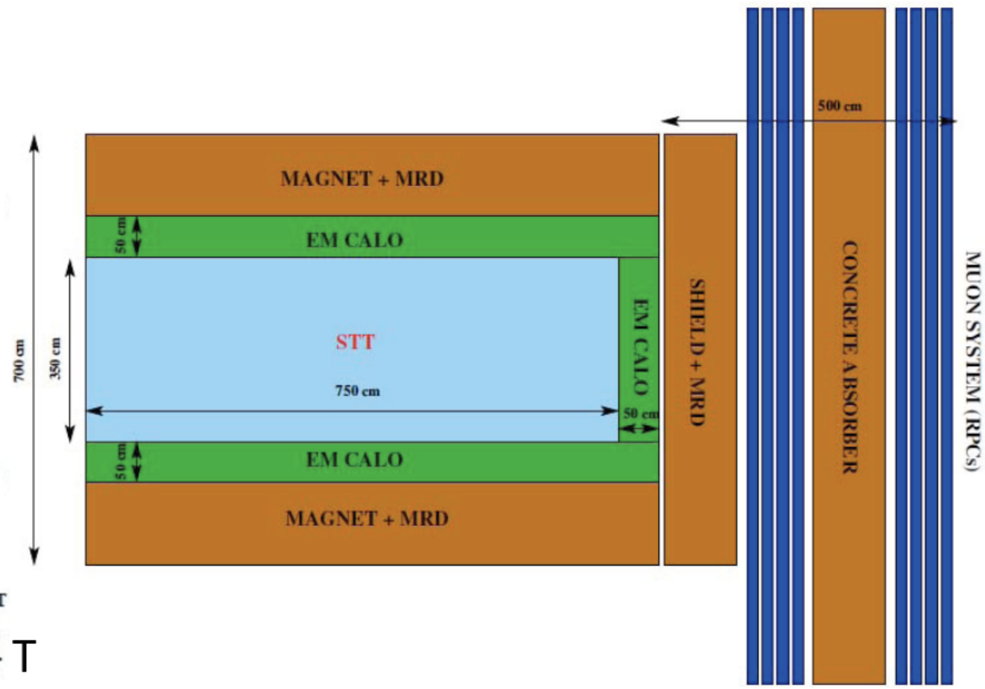
Outlook

- fix the Near detector baseline design and perform full simulation;
- systematic errors coming from near-to-far extrapolation (migration matrices);
- expectation on cross-section measurement precision;
- potential 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.).

Straw tube tracker design

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





Builds on NOMAD experience and 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+/-

S. Mishra

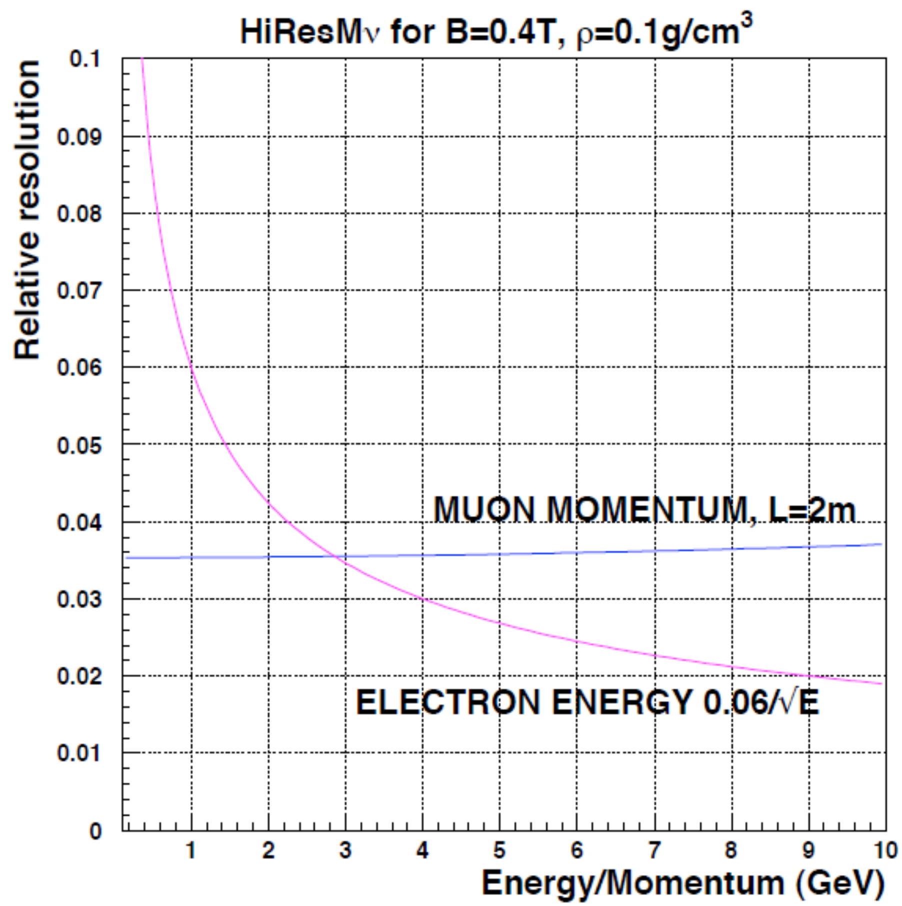
HiResMν design parameters

<u>*Resolutions in HiResMν*</u>

- ρ ≃ 0.1gm/cm^3
- Space point position ≃ 200μ
- Time resolution ≃ 1ns

- CC-Events Vertex: Δ(X,Y,Z) ≃ O(100μ)
- Energy in Downstream-ECAL ≃ 6%/√E
- μ-Angle resolution (~5 GeV) ≃ O(1 mrad)

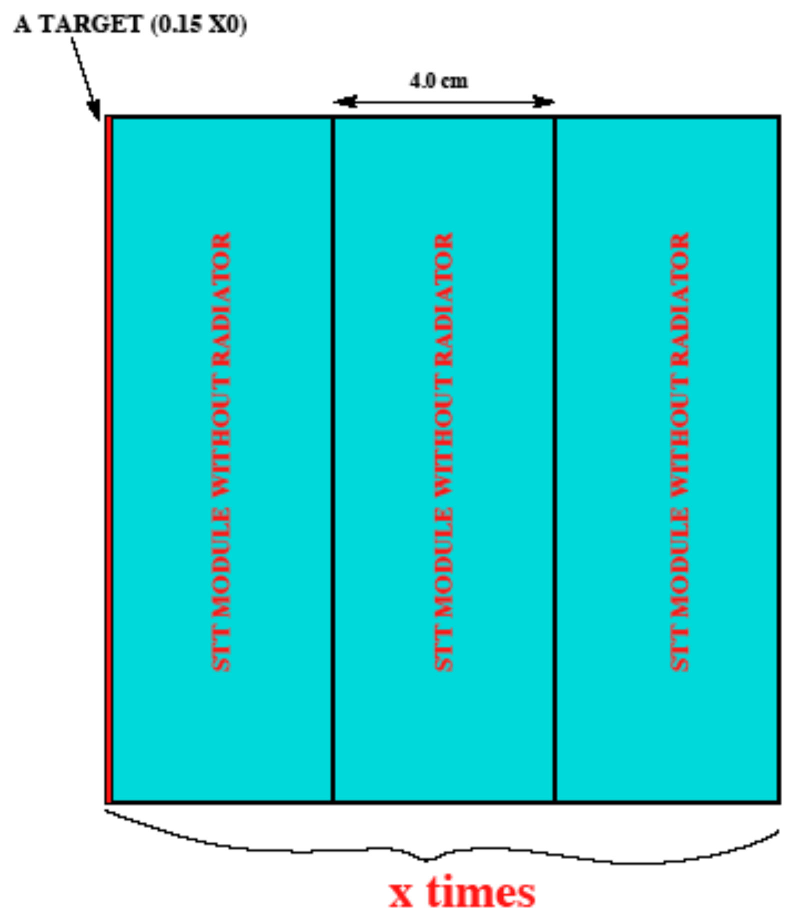
- μ-Energy resolution (~3 GeV) ~ 3.5%
- e-Energy resolution (~3 GeV) ~ 3.5%



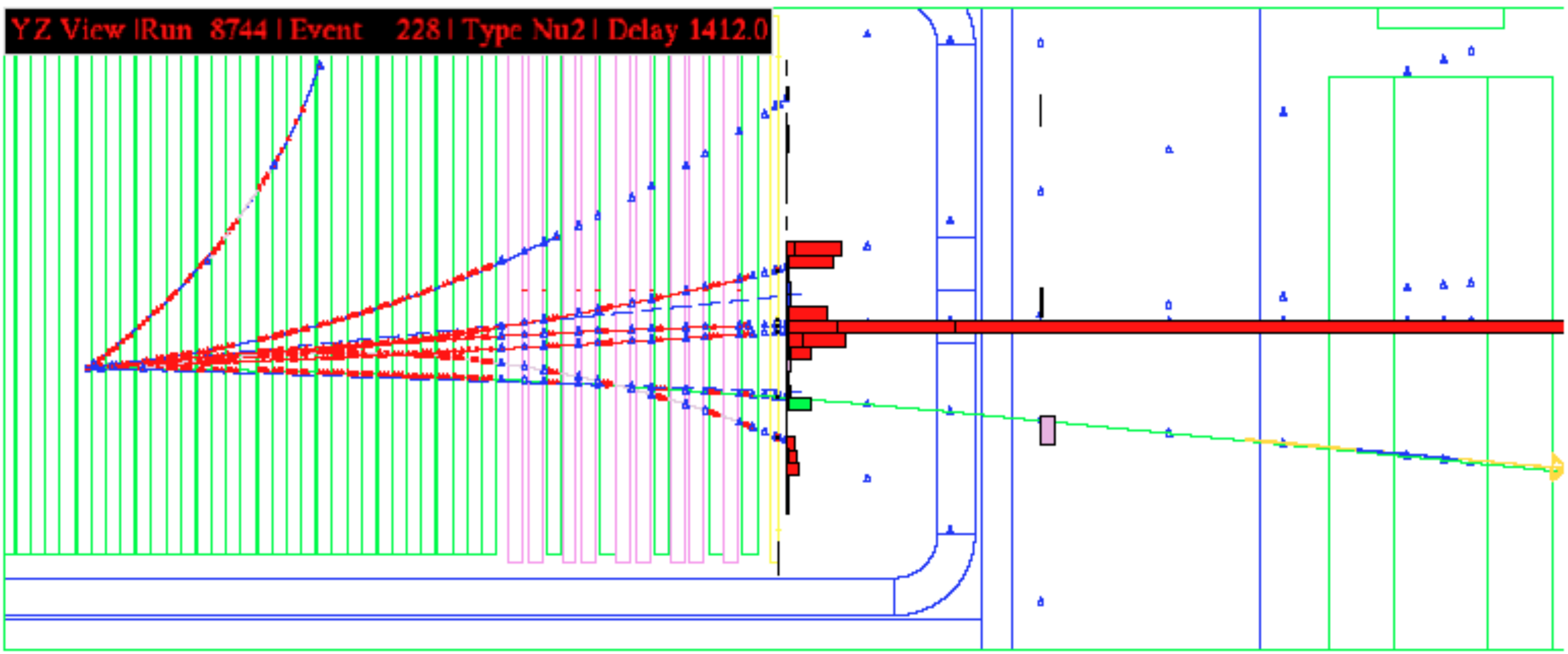
MEASURING NUCLEAR EFFECTS *(Fe, Water, Ar, ..)*

- *Measure the A dependence (Ca, Cu, H_2O, etc.) in addition to the main C target in STT:*
  - *Ratios of F_2 AND xF_3 on different nuclei;*
  - *Comparisons with charged leptons.*

- *Use $0.15X_0$ thick target plates in front of three straw modules (providing 6 space points) without radiators. Nuclear targets upstream.*
  - *For Ca target consider $CaCO_3$ or other compounds;*
  - $\boxed{\text{OPTION}}$: *possible to install other materials (Pb, etc.).*



A ν_μ CC candidate in NOMAD

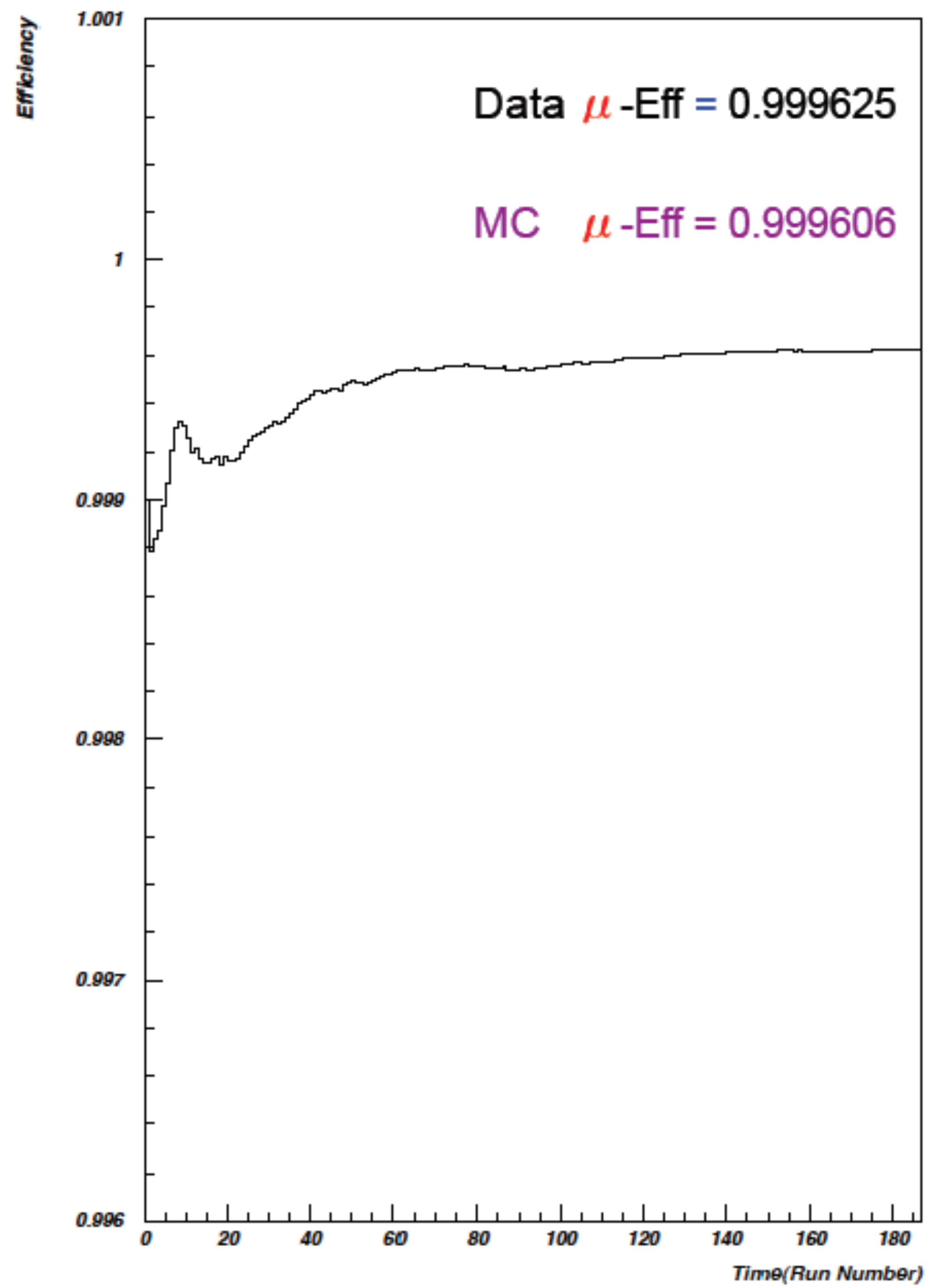


μ -Reconstruction:

* Track in the Tracker (P-measurement) matched to the track in μ -Detector

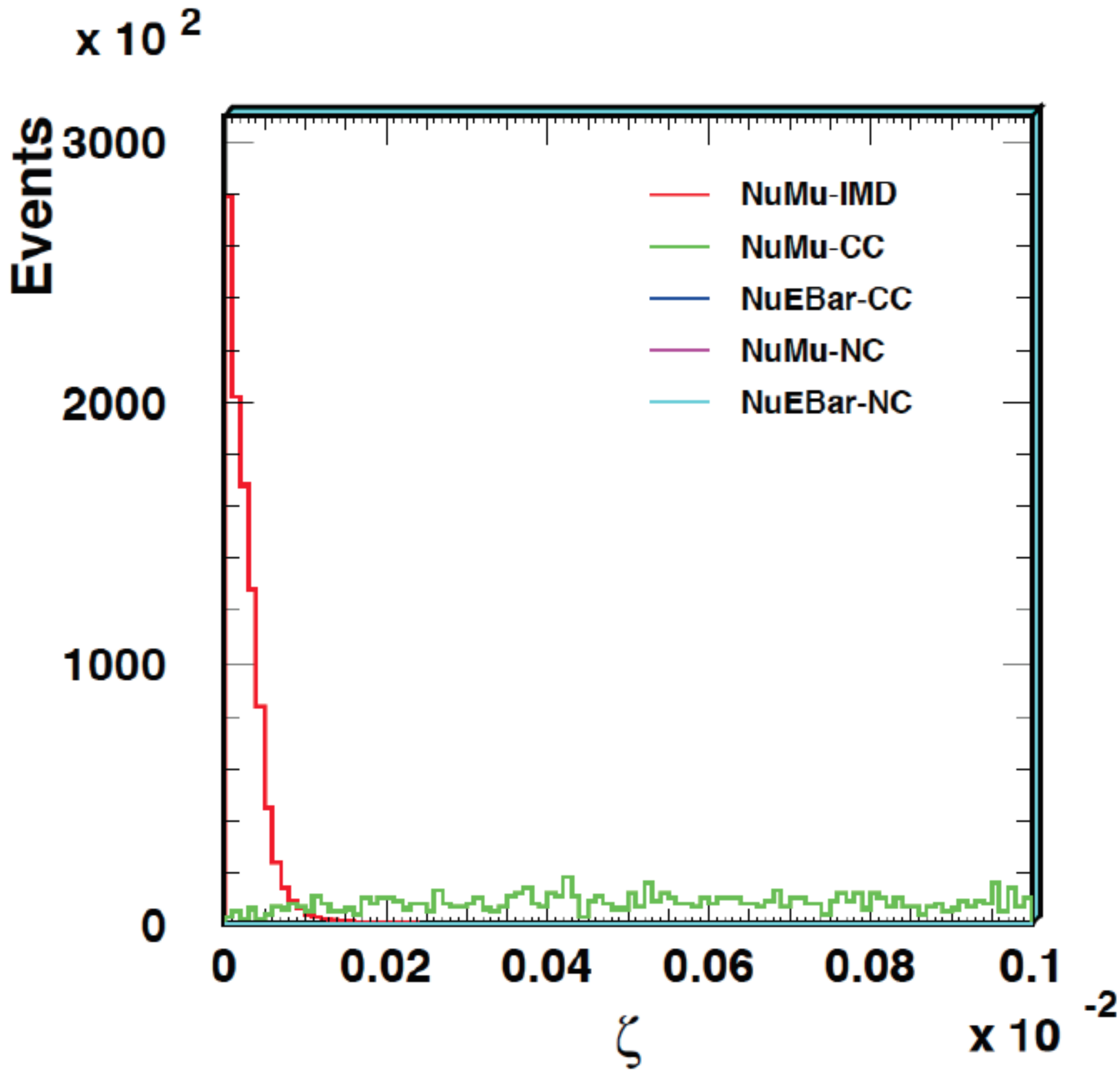
Ratio, Data/MC, Flattop μ -Eff $\Rightarrow$

(NOMAD Data)



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


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*

Sensitivity Analysis **νEl:** $\nu_\mu(ebar) + e^- \to e^- + \nu_e$ (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*

Observation on Measurement of ν_μ and ν_{ebar} Flux($E\nu$) using Leptonic-Channels

- We have presented a frame-work --- method holds promise. Need, first, to fix `fitting' artifacts.
- Only used $E\mu$/el. Must try calculated-$E\nu$ ($E\mu/e$, $\vartheta\ \mu/e$) on an event-by-event basis
- Need to make an assessment on the error on FD/ND-($E\nu$)
- Relative flux ($\nu_\mu : \nu_{ebar} : \nu_{\mu bar} : \nu_e$) using Quasi-Elastic and Coherent- π^{+-} :

Fully costed for LBNE - $ 70 M and will be fully "prototyped" since chosen as LBNE high-resolution near detector

Summary and Outlook

- 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

1. Determine procedure for deciding between two alternative high-resolution detectors for baseline.

SYSTEMATICS

2. Work with Patrick to determine elements in the overall covariant (systematic) error matrix.

3. Get best estimates of the size of these errors to get better understanding of errors involved in determining CP-violation.

4. Work with LBNE that is at a similar stage in study of systematics?

Backups

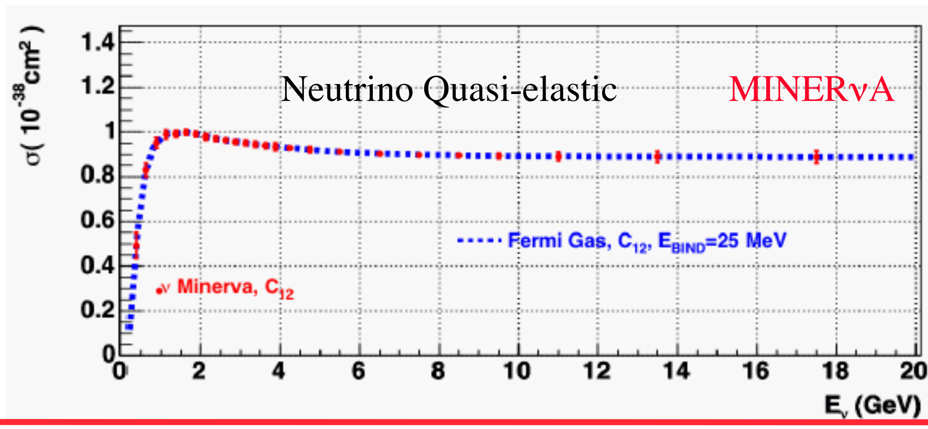
“Other” Near Detector Physics

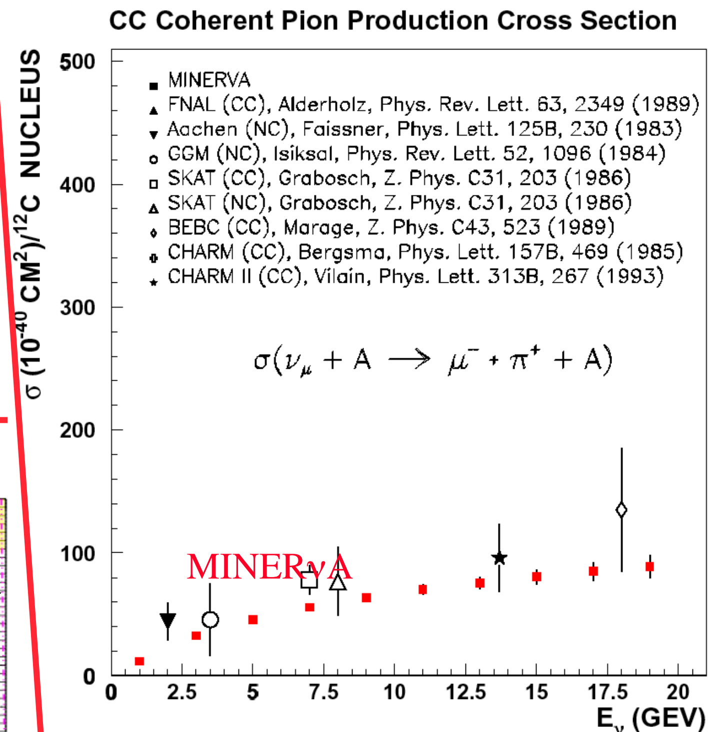
- To achieve the kind of accuracy we want on the neutrino flux measurement, we will have constructed a detector ideally suited for advanced studies of neutrino-nucleus interactions – the “other” physics.
- This in turn can be grouped into standard processes:
  - **Quasi-elastic**
  - **Resonance Production**
  - **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

Where will we be at the time of NF – ND

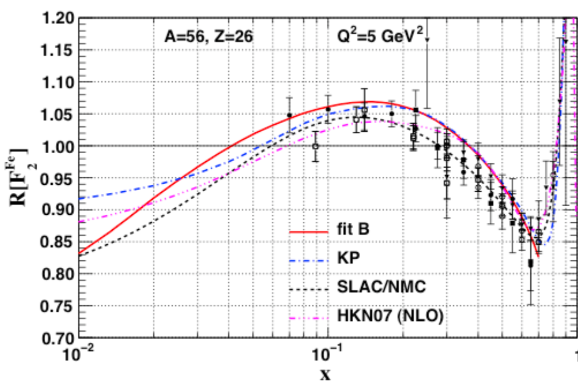
Dominated by systematics: Mainly Flux Errors

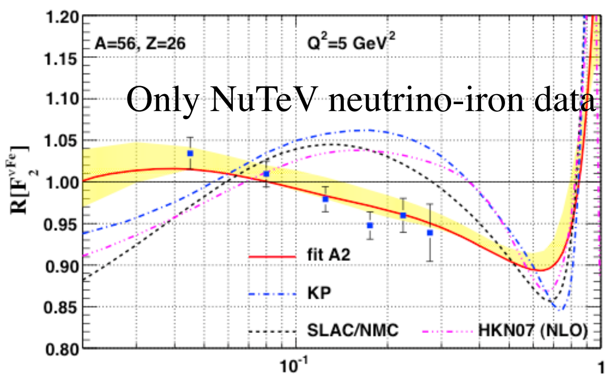
- The neutrino factory experiments will occur after MINERνA and LBNE will have taken and analyzed their data. Examples:





Neutrino Nuclear Effects





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

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…

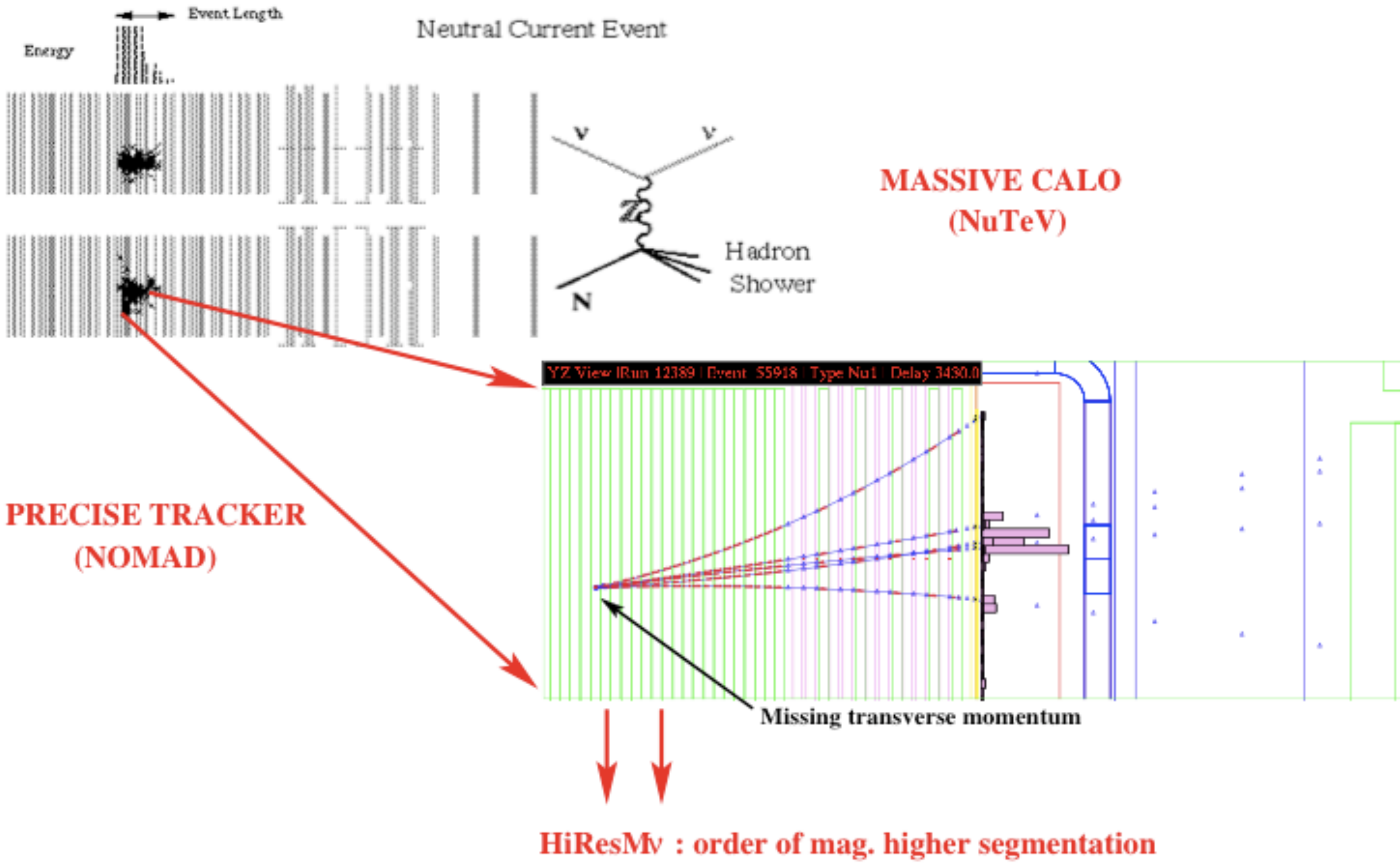
Requirements for the NF - Near Detector

- Need high resolution (low-Z) target for accurate measurement of angles of muons for flux determination and resolution of hadronic final states for cross section measurements.
- Need good identification and accurate momentum measurement of the muon – a magnetic field with muon identification.
- Very good hadron energy determination for flux and cross section measurements.
- Need excellent vertex resolution for charm production and ν_τ detection for indications of NSI.

- … somehow this sounds vaguely familiar

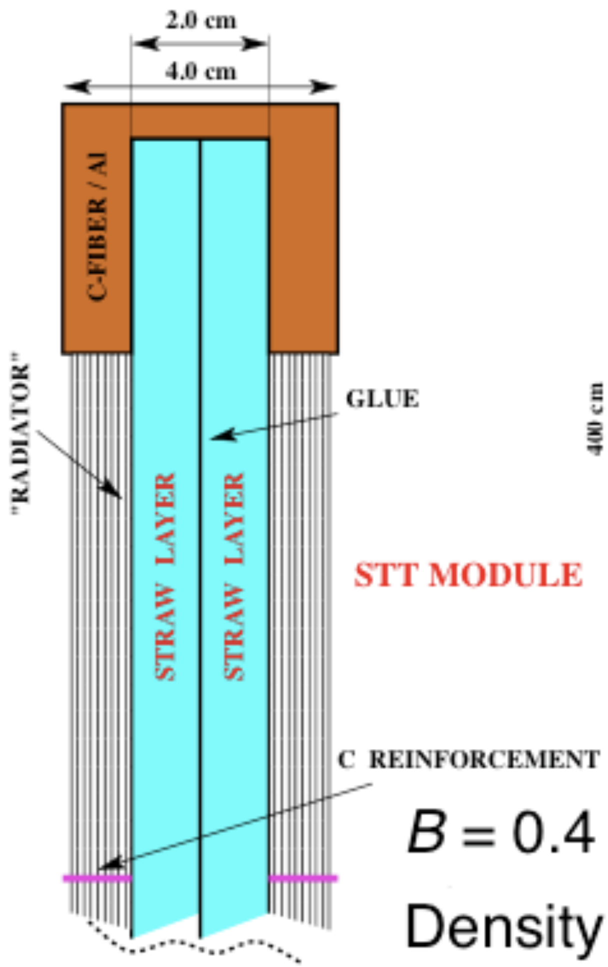
  (enter stage right….. **LBNE**)

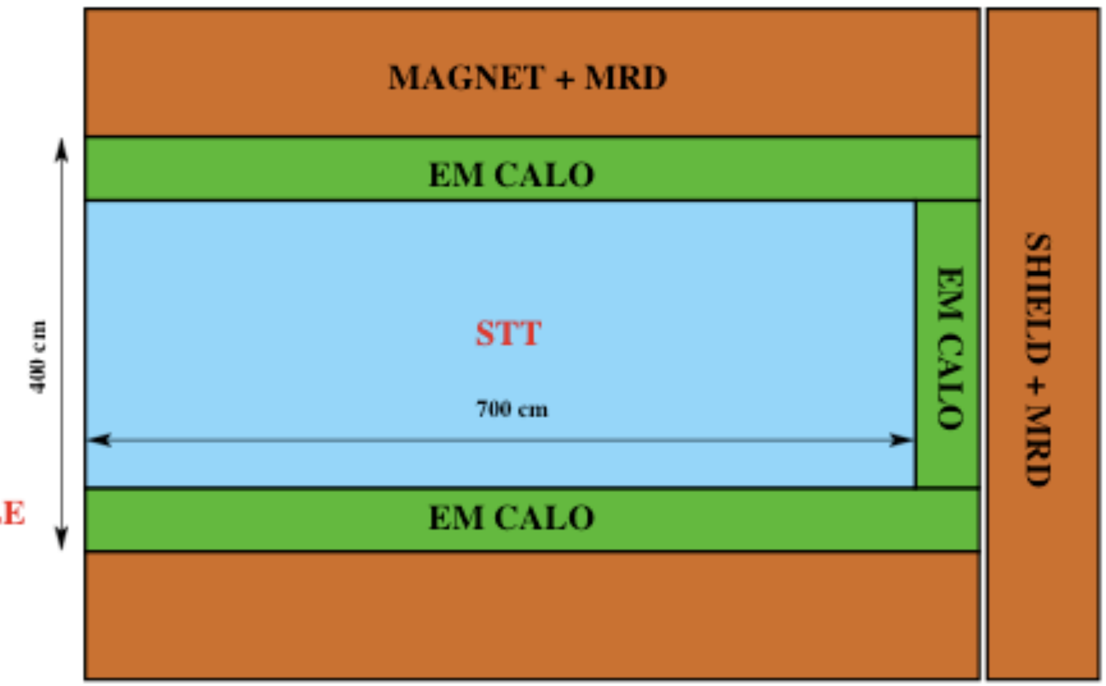
LBNE ND2: High Resolution STT Concepts



Overall Design and STT Concept

Sanjib Mishra (U South Carolina) – Detector session PS3 tomorrow AM





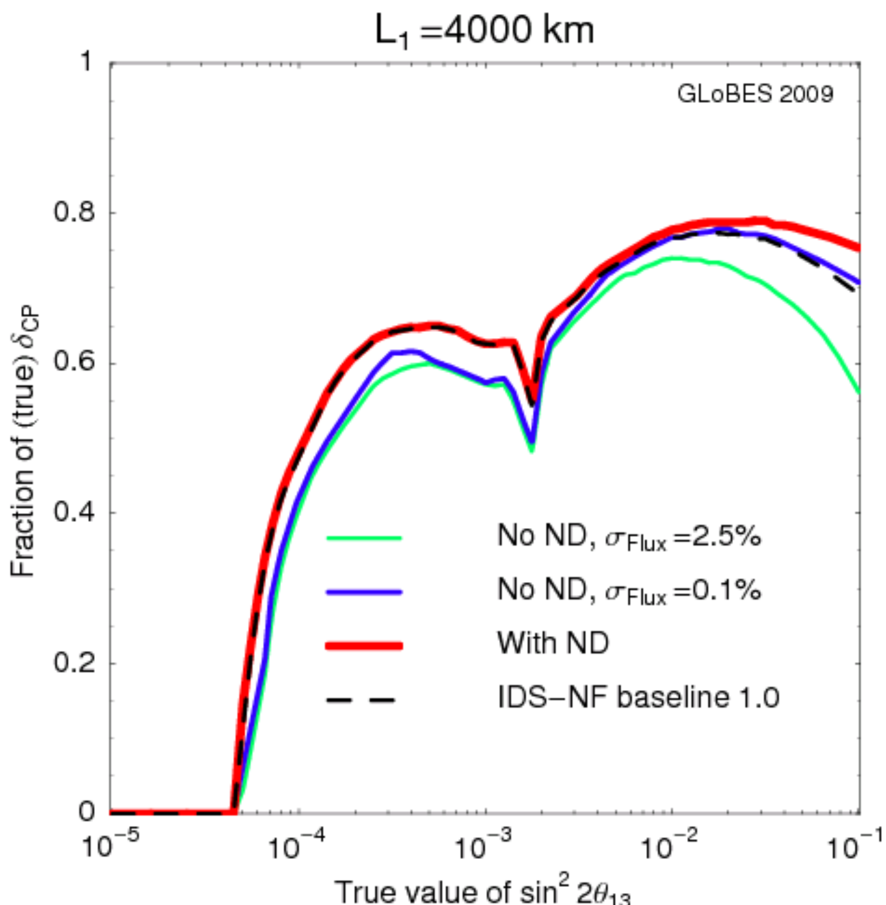
$B = 0.4$ T.

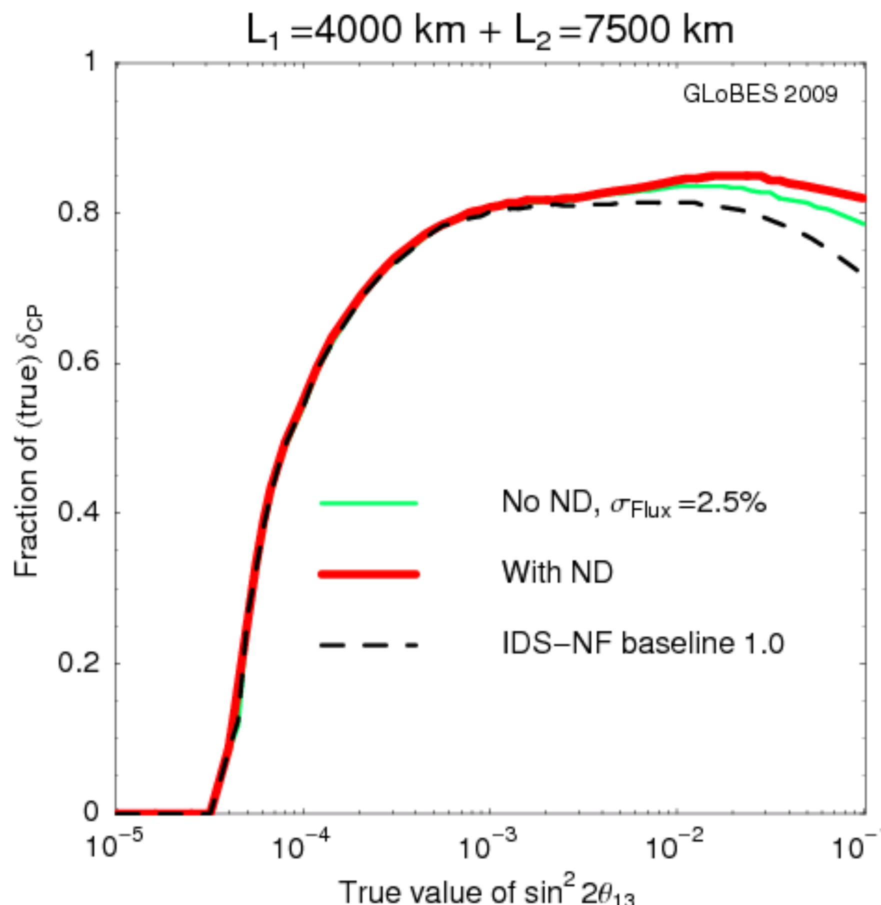
Density = 0.1 g/cm3, 85% in the radiator foils.

dE/dx for π, K ID, transition radiation for $e^{\pm}$ ID.

Importance of flux knowledge for systematics

2.5% error on flux makes big difference in CP coverage



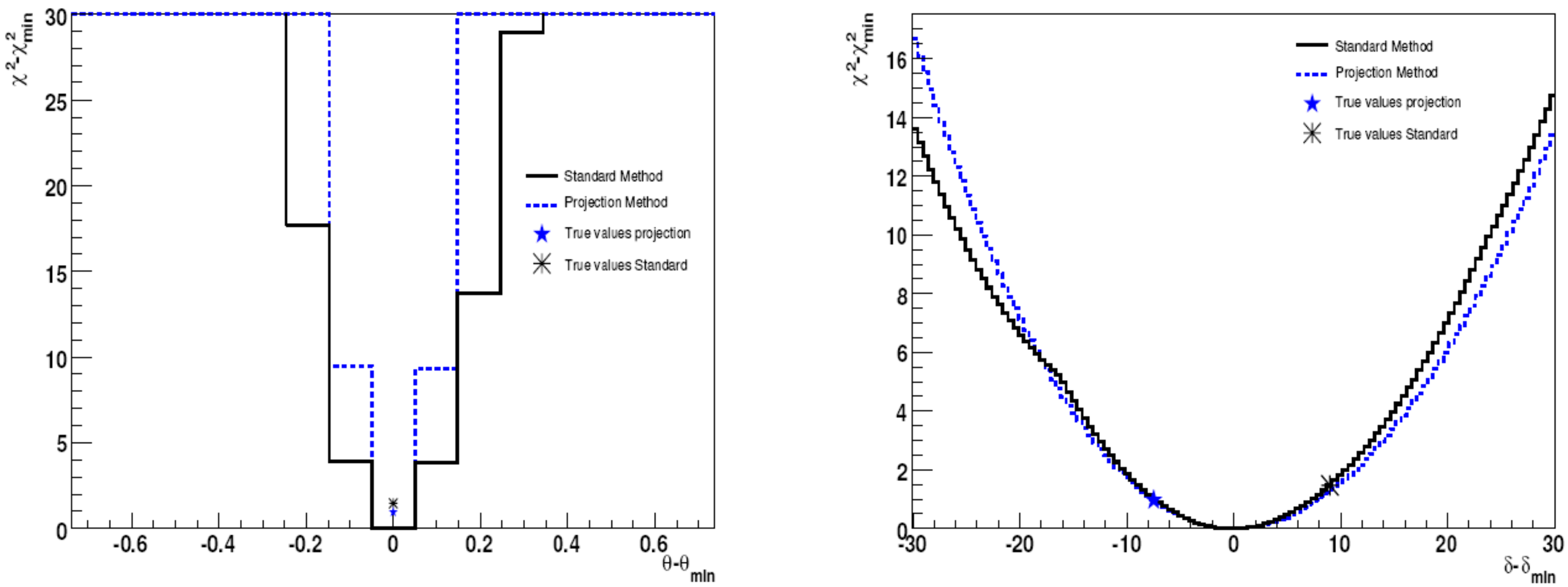


Winter, Tang

Projection method to the Far detector

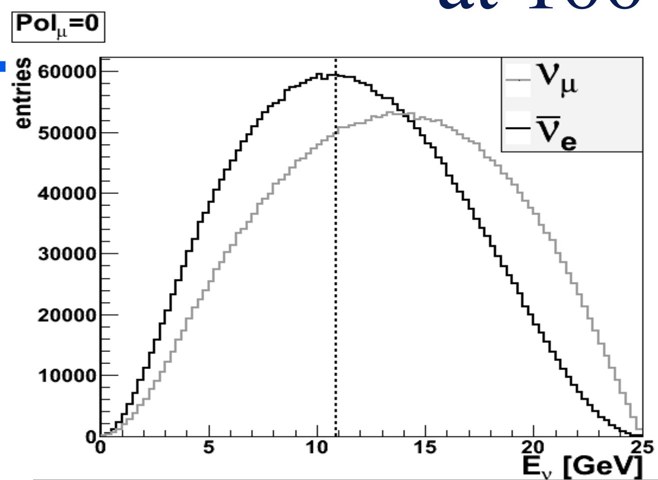
- Effect of fit accuracy from χ^2 for θ_{13} and δ between fitted value and true value
- Standard method: calculated flux with floating normalistion
- Projection method: fit using near detector flux to predict far detector

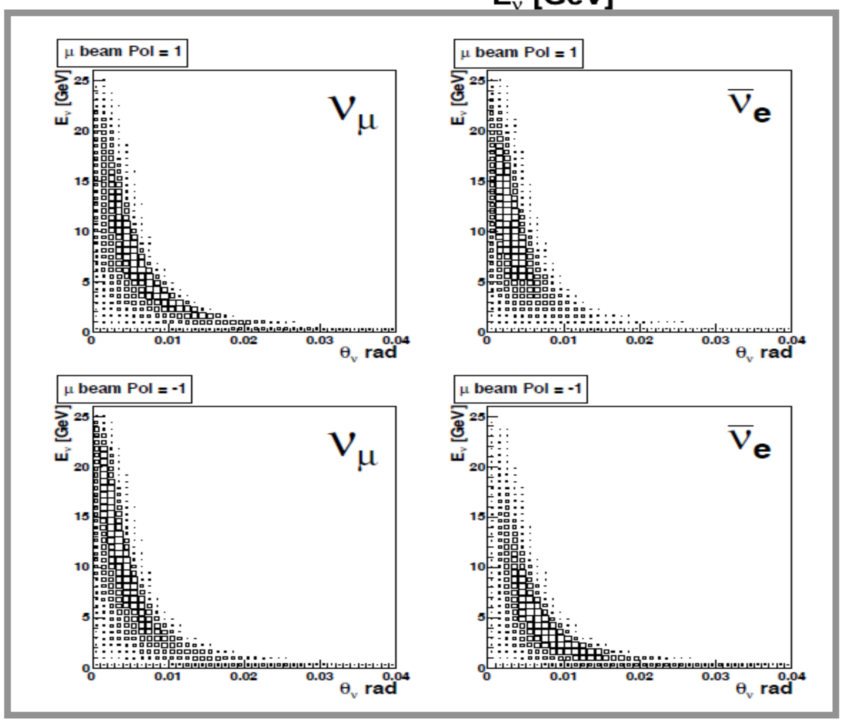
Normal hierarchy: $\theta_{13}=1^o$, $\delta=45^o$



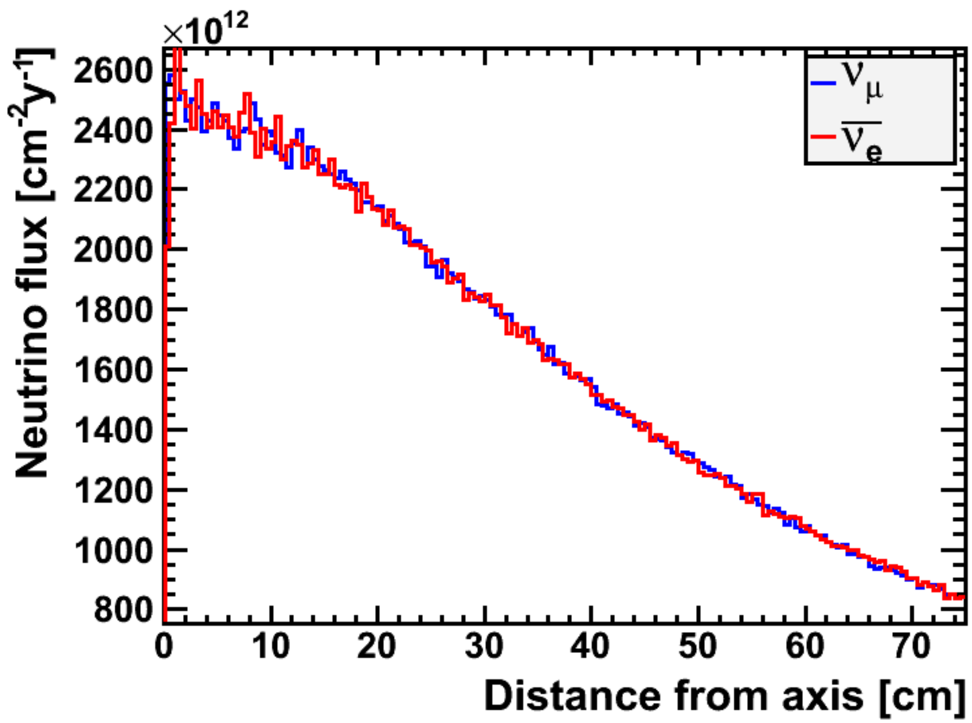
Slightly better fits using near detector projection: average residuals ~0.6σ compared to ~0.9σ with the standard one

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





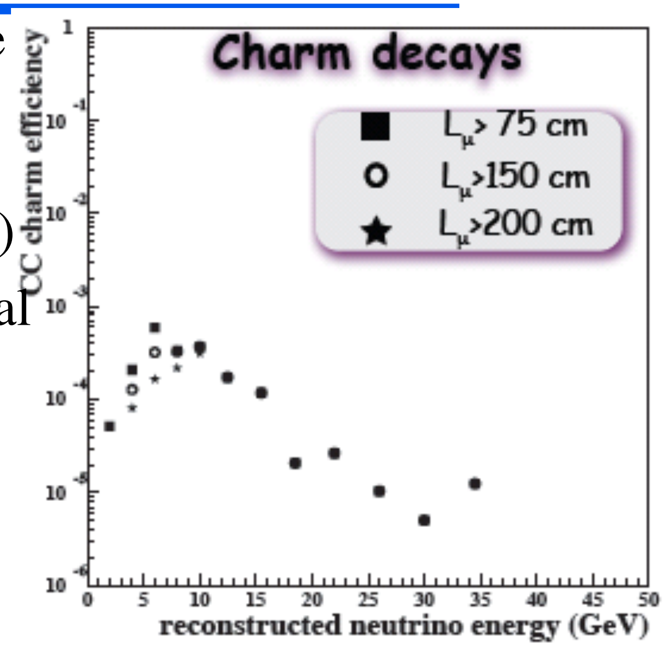
$1\mathrm{x}10^{20}$ μ - decays/year

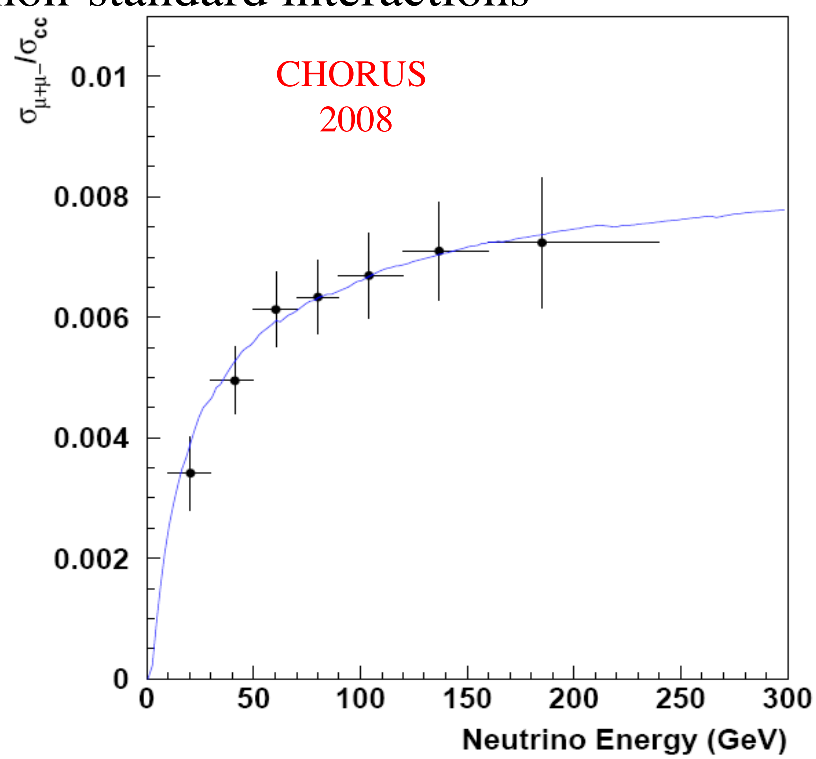


Charm production and τ measurement (NSI)

Discussed at Near Detector Workshop 8/11

- **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



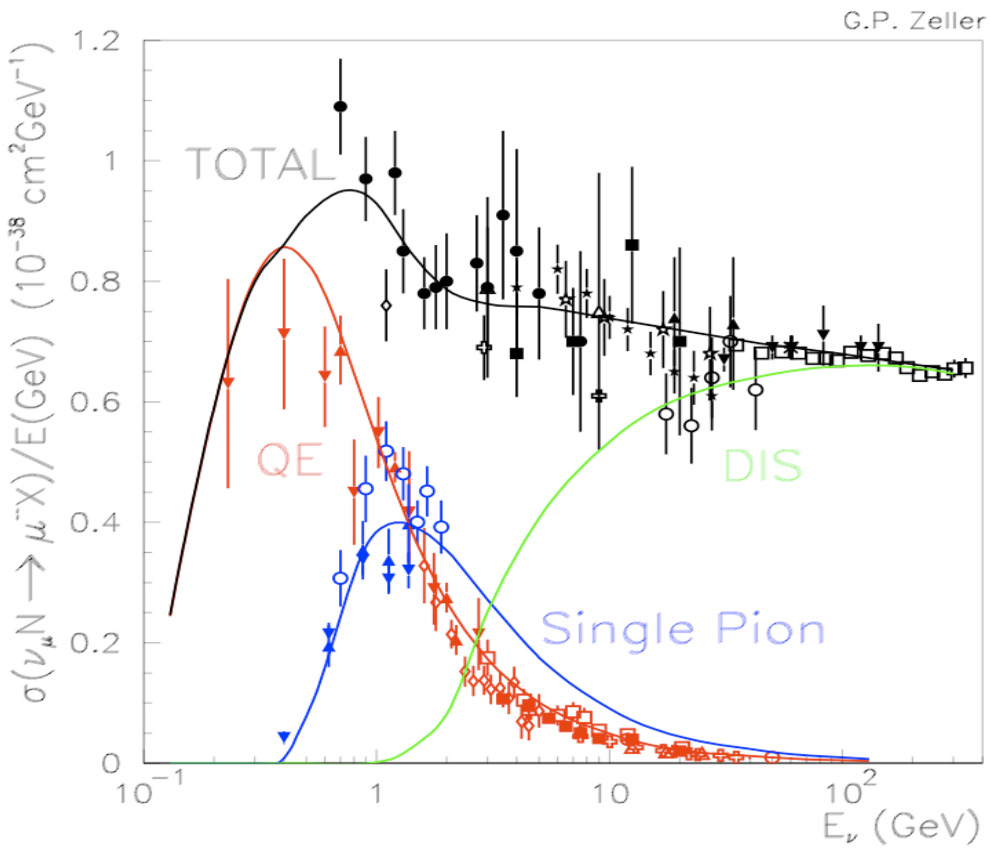


Vertex detector of high granularity is needed.

Silicon strips or emulsion sheets?

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?

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 → we can rely on MC;
- **Independent measurement of the neutrino flux in the Near detector – very important cross-check**