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IDS-NF

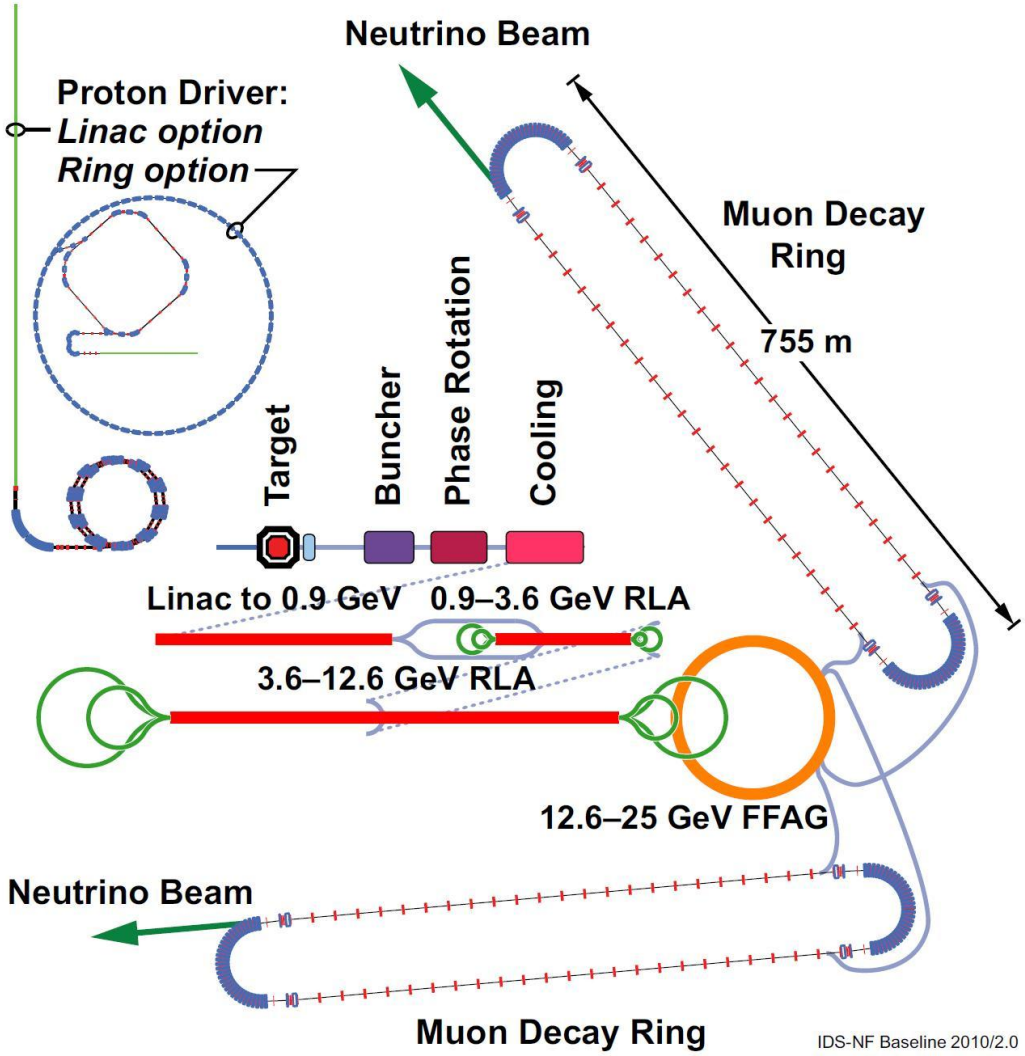
Beam monitoring and Near detector requirements for a Neutrino factory or long baseline beams

Dedicated workshop took place at CERN 30-31 July 2011, http://indico.cern.ch/event/ndws1

EUROν

R. Tsenov, 4 August, 2011

Neutrino factory baseline design



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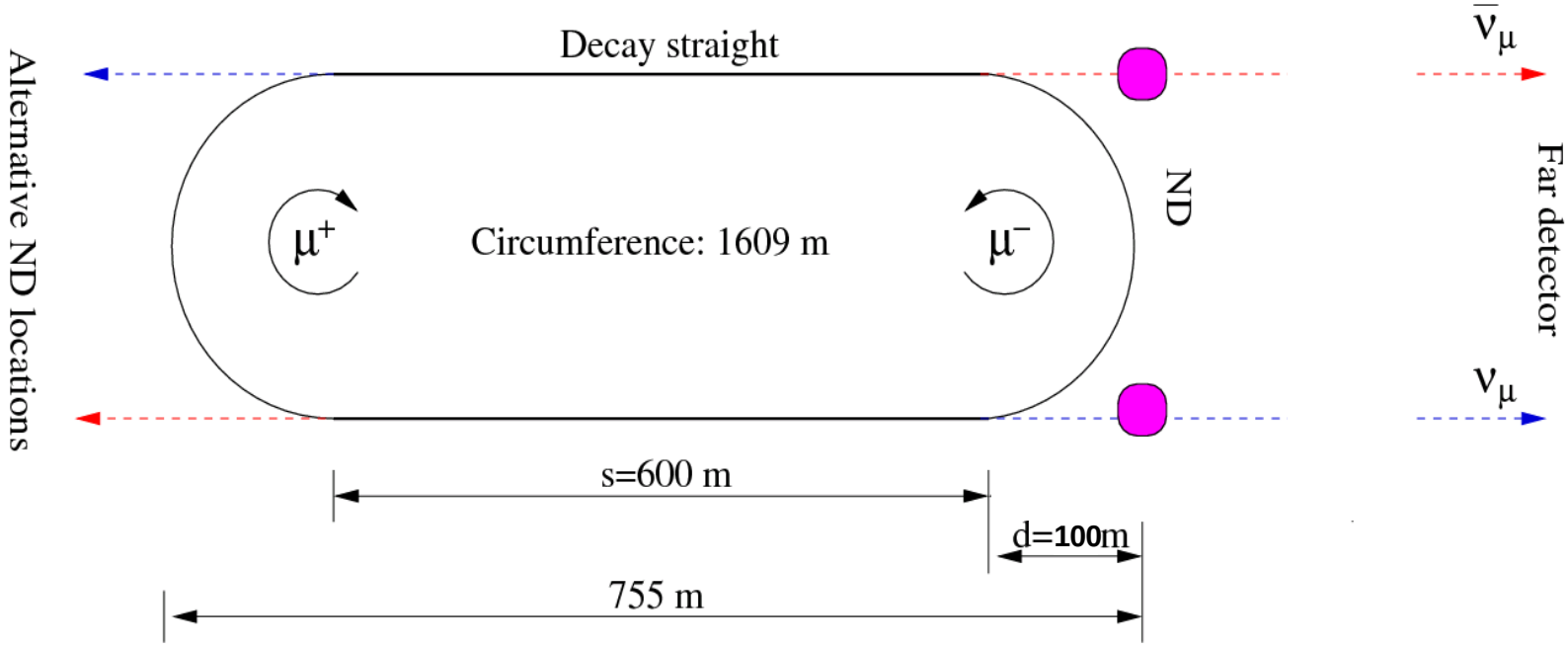
Neutrino Factory Near Detector(s)

E_μ = 25 GeV ±80 MeV

Straight section length = 600 m

Muon angular spread 0.5 mrad

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



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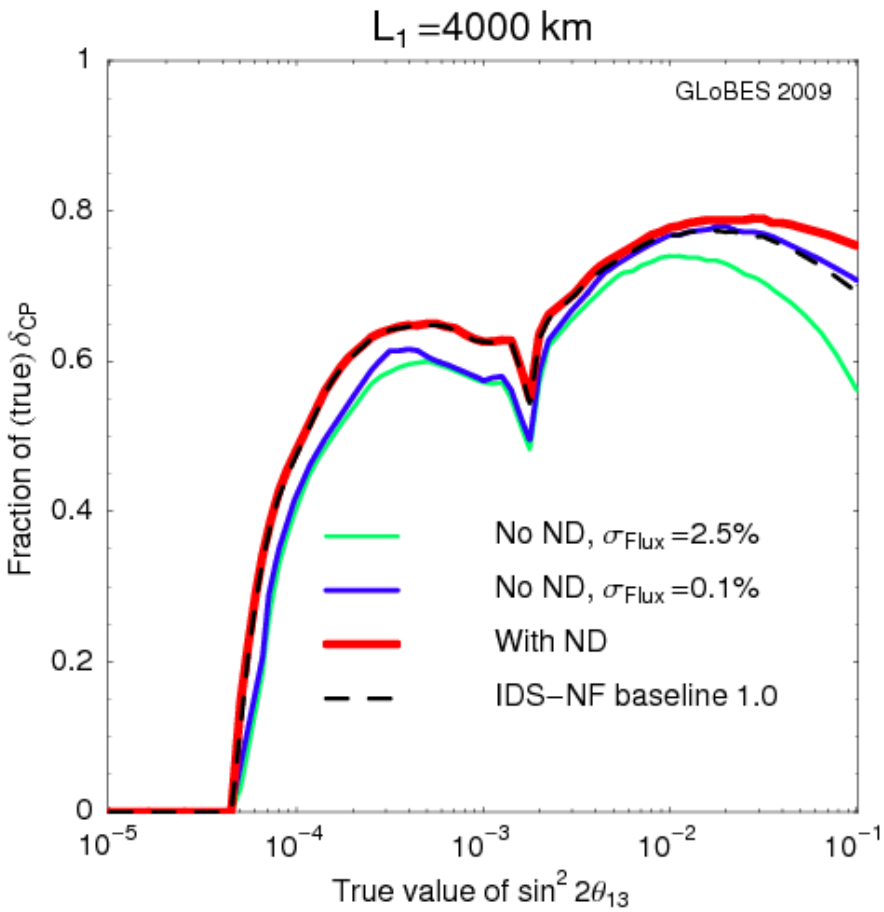
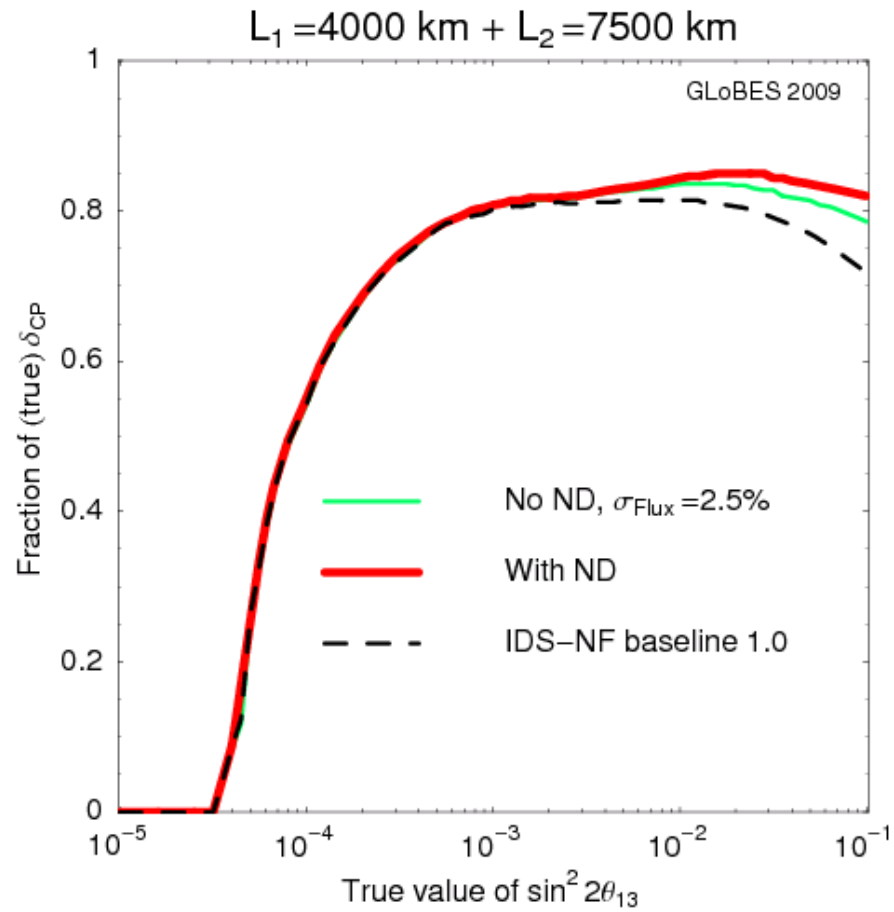
What do we want to measure with the Near detector(s)?

- neutrino flux (through the measurement of neutrino-electron scattering);
- neutrino-beam properties that are required for the flux to be extrapolated with accuracy to the far detectors;
- charm production cross sections over neutrino beam energy range (at least wrong sign muon production rate);
- $\nu_\mu N$ and $\nu_e N$ CC total cross-section and separately (?) deep inelastic, quasi-elastic, and resonant-scattering cross sections;
- fundamental electroweak and QCD physics (ie PDFs, $sin^2\theta_W$);
- non-standard interactions (NSI) via τ-lepton production;
- sterile neutrino search.

Importance of flux knowledge for systematics

2.5% error on flux makes big difference in CP coverage





CP violation discovery reach (3σ CL)

J.Tang, W.Winter, Phys.Rev.D80:053001,2009

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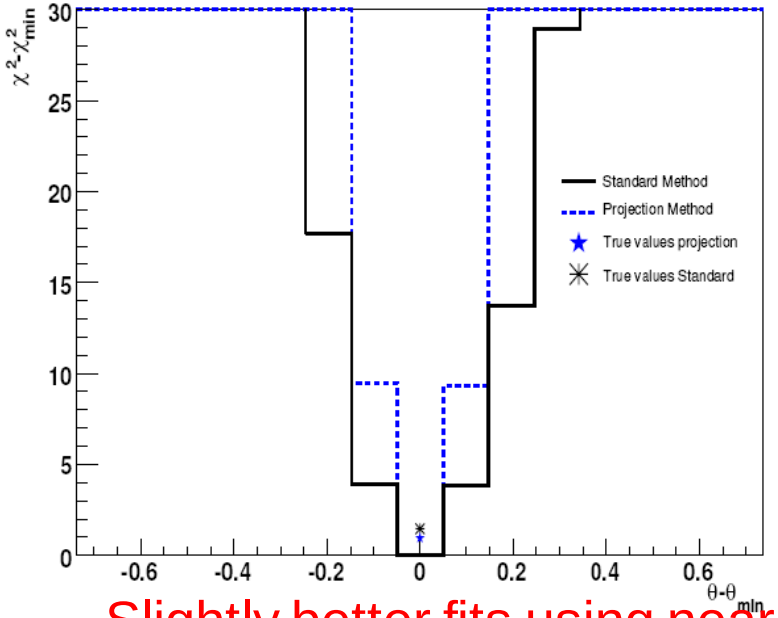
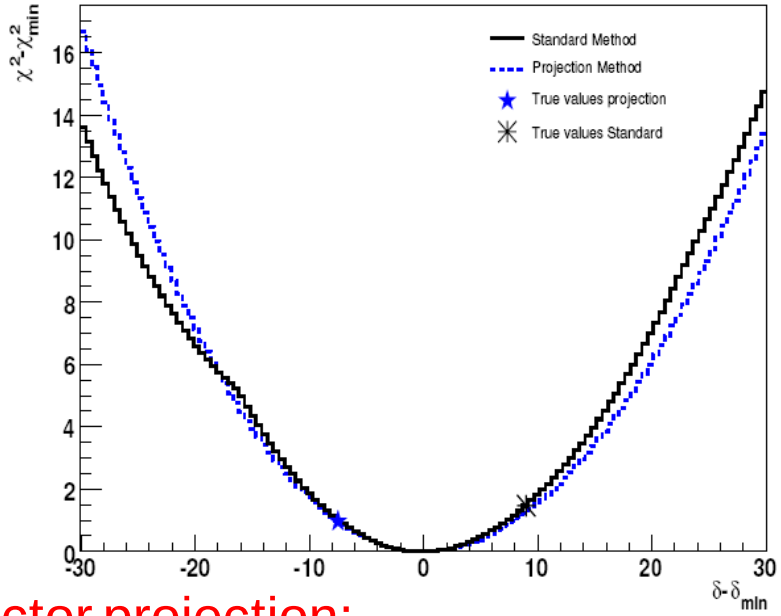
Projection method to the Far detector

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

Normal hierarchy: θ_{13}=1°, δ=45°,
5% error on rate ratio

A. Laing's Thesis,
http://theses.gla.ac.uk/2216/





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

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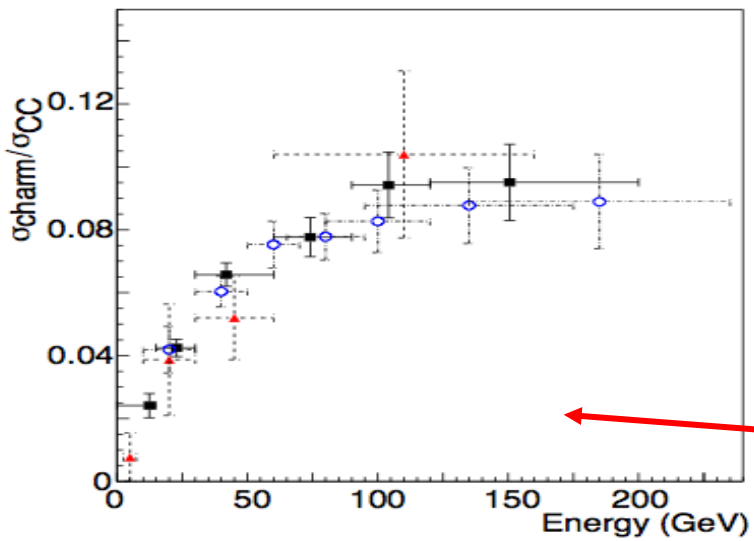
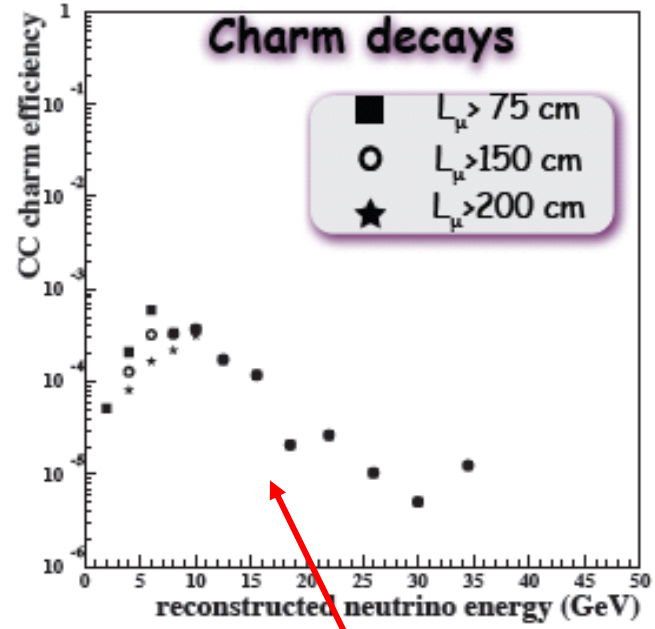
Charm and τ production measurement

- **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.





Emulsion sheets or silicon strips?

$\sigma(Charm)/\sigma(CC)=(5.75\pm0.32\pm0.30)\%$

Vertex detector of high granularity is needed.

Measurement of charm production in neutrino charged-current interactions.
CHORUS Collaboration, CERN-PH-EP-2011-109. Jul 2011, arXiv:1107.0613

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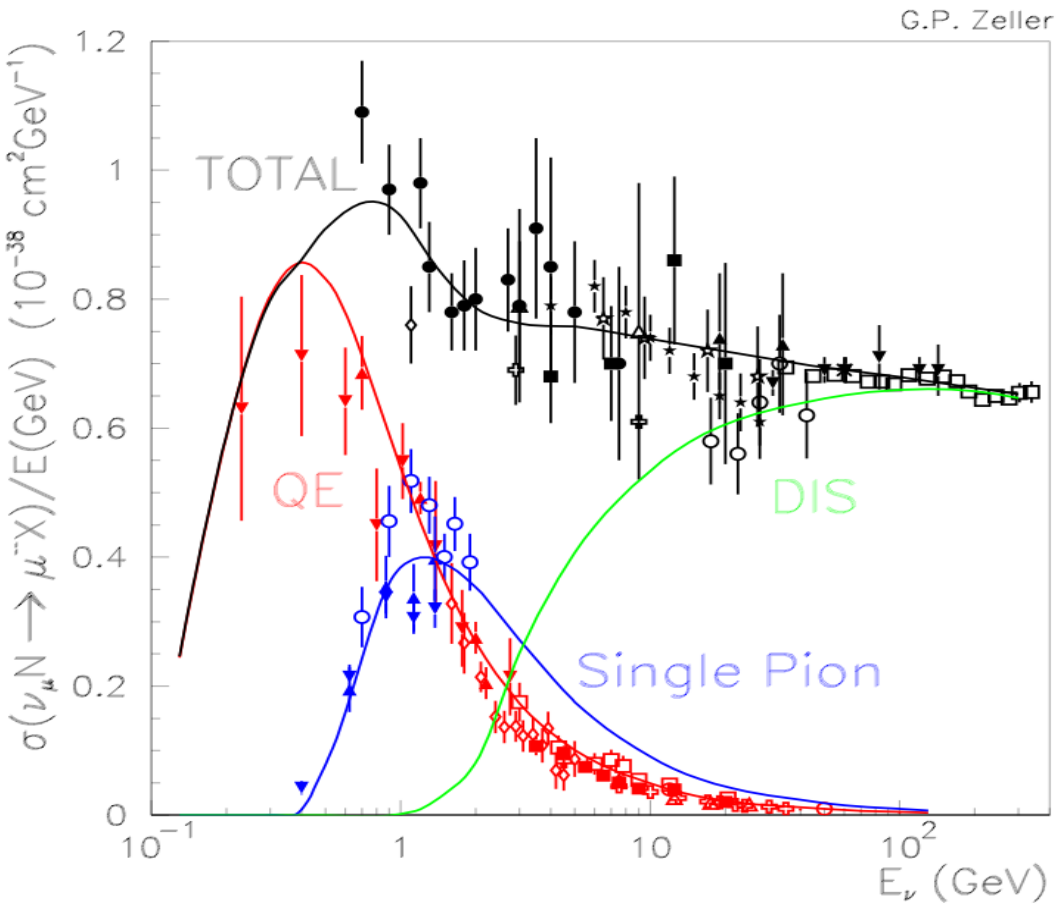
Cross section measurements



Expected cross-section errors from T2K and Minerva are dominated by absolute flux error before Neutrino Factory.

At Neutrino fsctory, with modest size targets one can obtain very large statistics.
What precision do we need?

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Determination of the neutrino flux

- measure the muon beam in the straight sections

(see Alain Blondel's talk at this workshop: http://indico.cern.ch/materialDisplay.py?contribId=9&sessionId=3&materialId=slides&confId=114816

  - 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 specialised 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.

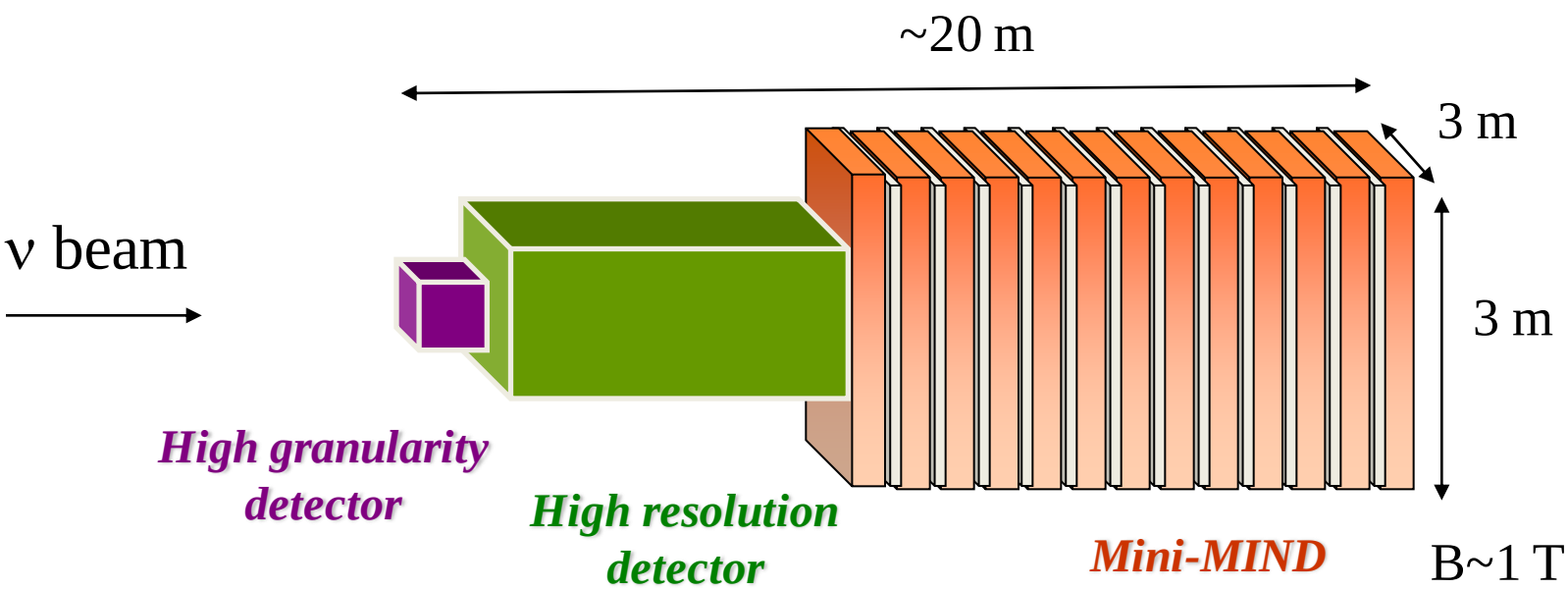
Near detector design requirements

- Vertex detector for charm and τ production (NSI+sterile neutrinos)
- Low Z high resolution tracker for flux and cross-section measurement (ν_μ and ν_e)
- Magnetic field for better than in MIND muon momentum measurement
- Muon catcher and capability for and e^+/e^- identification
- Good resolution on neutrino energy (much better than in Far Detector) for flux extrapolation – how much better?

Block diagram design

Near Detector design will have three sections:

- High granularity detector for charm/τ 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 muon measurement.



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

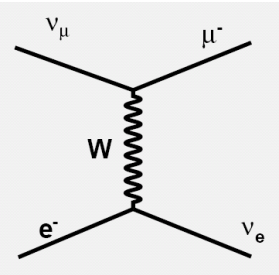
ν-e CC quasi-elastic scattering with *single muon in the final state*:

Absolute cross-section can be calculated theoretically with enough confidence.

Two processes of interest (available only for neutrinos from ***μ⁻ decays***):

Inverse Muon Decay (IMD)

$$\nu_\mu + e^- \rightarrow \nu_e + \mu^-$$



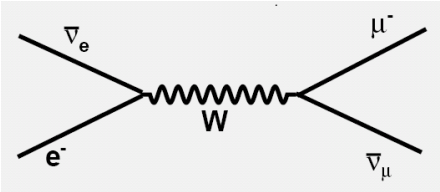
$$\sigma = \frac{G_F^2}{\pi}\frac{\left(s-m_\mu^2\right)^2}{s} = 1.7\times10^{-41} cm^2$$

for 15 GeV ν_μ;

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

Production via annihilation

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



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

ν-e NC elastic scattering with *single electron in the final state*:

$$\sigma(\nu_l e \rightarrow \nu_l e) = \frac{G_\mu^2 m_e E_\nu}{2\pi}\left[1 - 4\sin^2\theta_W + \frac{16}{3}\sin^4\theta_W\right] \sim 10^{-42}(E_\nu/\,\mathrm{GeV})\, cm^2$$

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

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

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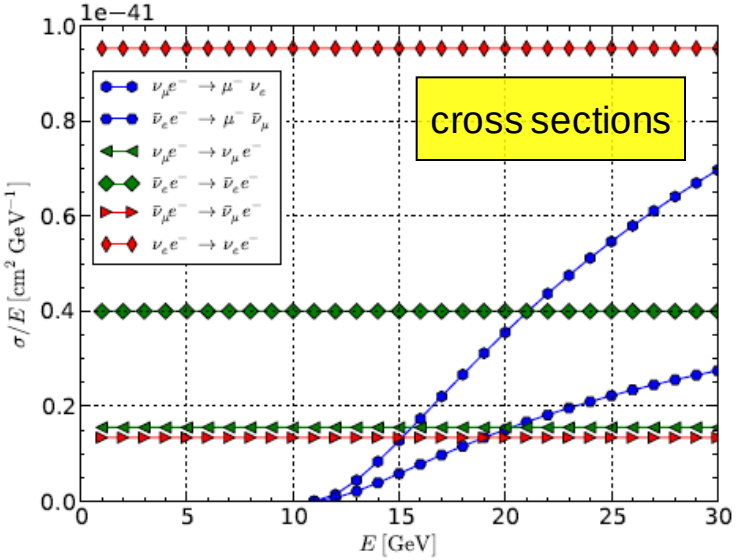
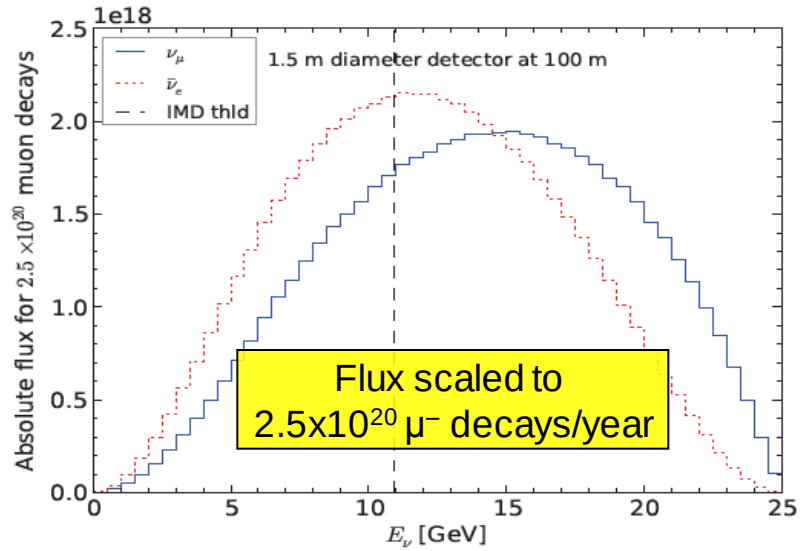
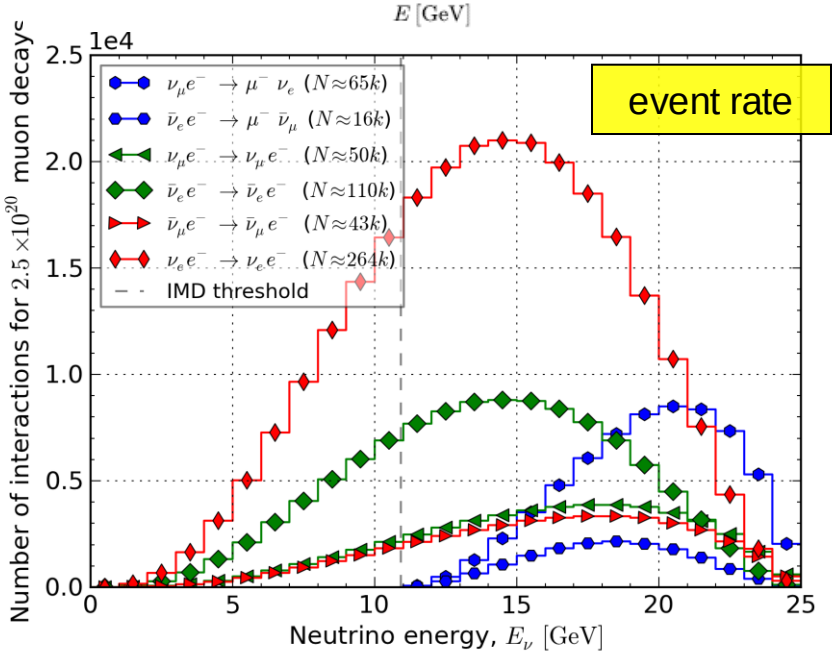
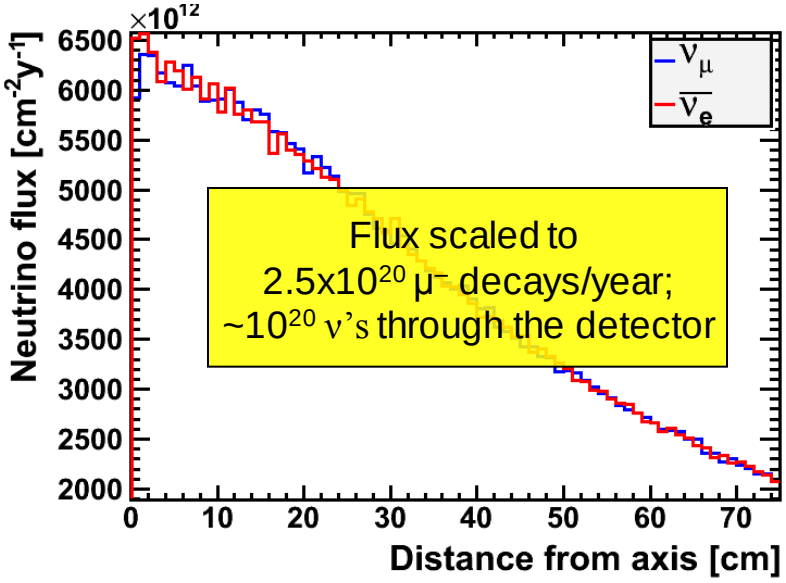
Neutrino flux from μ⁻ decays through the detector at 100 m from the straight end



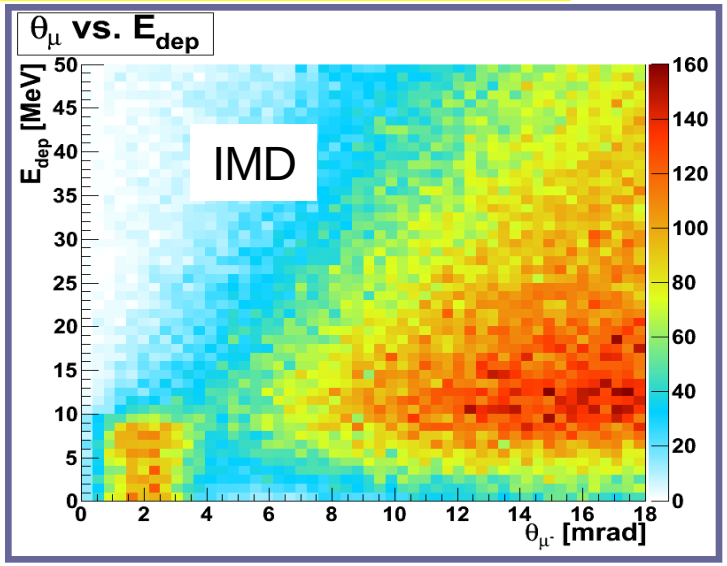






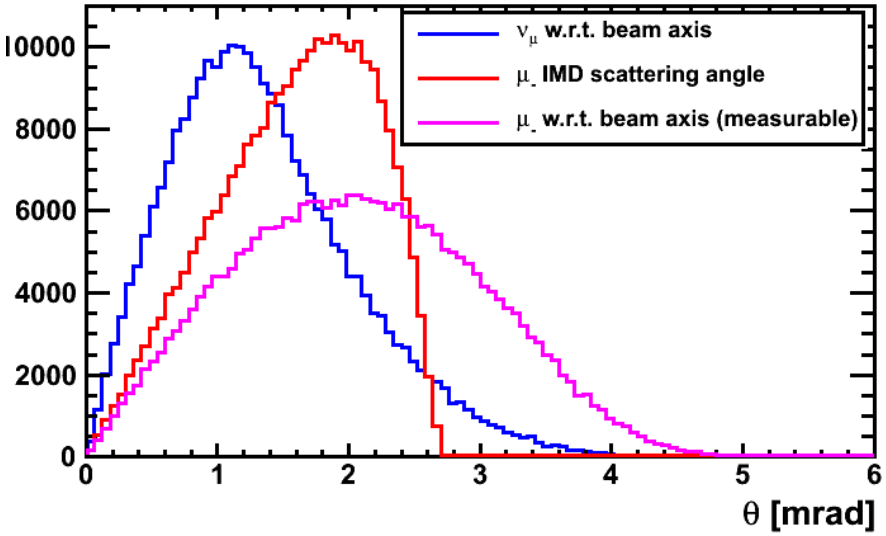
ν-e CC signal extraction *(only a μ^- in the final state)* → discriminating variables

- deposited energy around the vertex *and*
- muon scattering angle θ_μ, *or*
- $E_\mu \theta_\mu^2 \sim (1 - E_\mu / E_\nu) = y$ (inelasticity) *or*
- muon p_T^2



Tracker requirements:

- must provide sufficient interaction rates → **solid detector;**
- must be able to reconstruct the polar angle of the scattered muon with 0.5 mrad precision or better → **low Z tracker;**
- must be able to measure the hadron recoil energy down to values of several MeV → **precise calorimeter**.



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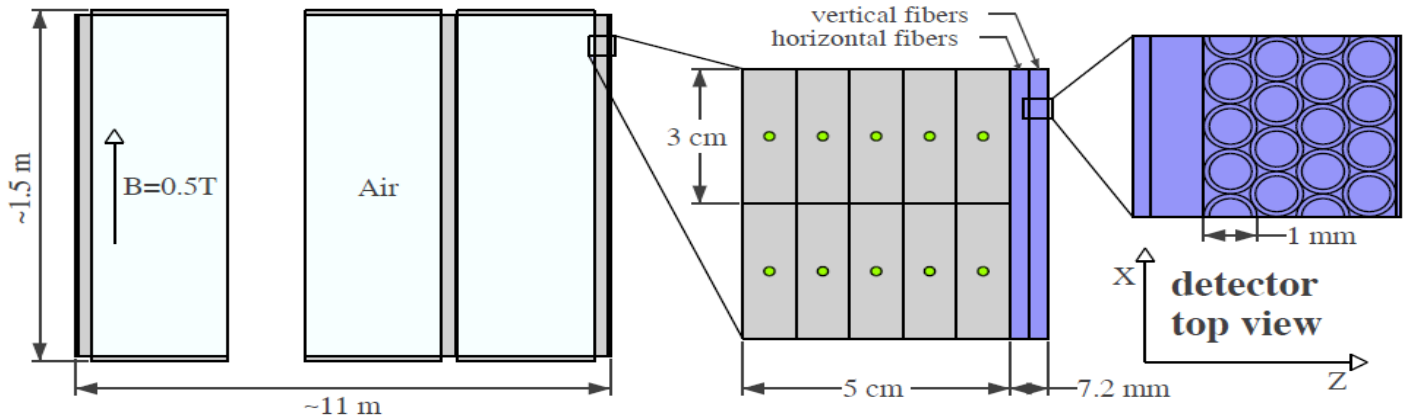
SciFi tracker design



- **20 tracker stations each consists of 4 horizontal and 4 vertical layers of 1 mm diameter scintillating fibres shifted with respect to each other + 5 cm thick active absorber, divided into 5 slabs to allow for more precise measurement of recoil energy near the event vertex;**
- **12 000 fibres per station (240 000 in total);**
- **air gaps are closed by a layer of scintillating bars;**
- **overall detector dimensions: 1.5 x 1.5 x 11 m^3 (2.7 tons of polystirene);**

- Ultimately, with perfect space alignment of fibers, a position resolution of ~70 μm per station is achievable and angular resolution of ~ 0.5 mrad (obtained by GEANT4 simulations and Kalman filter reconstruction).

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Detector characteristics

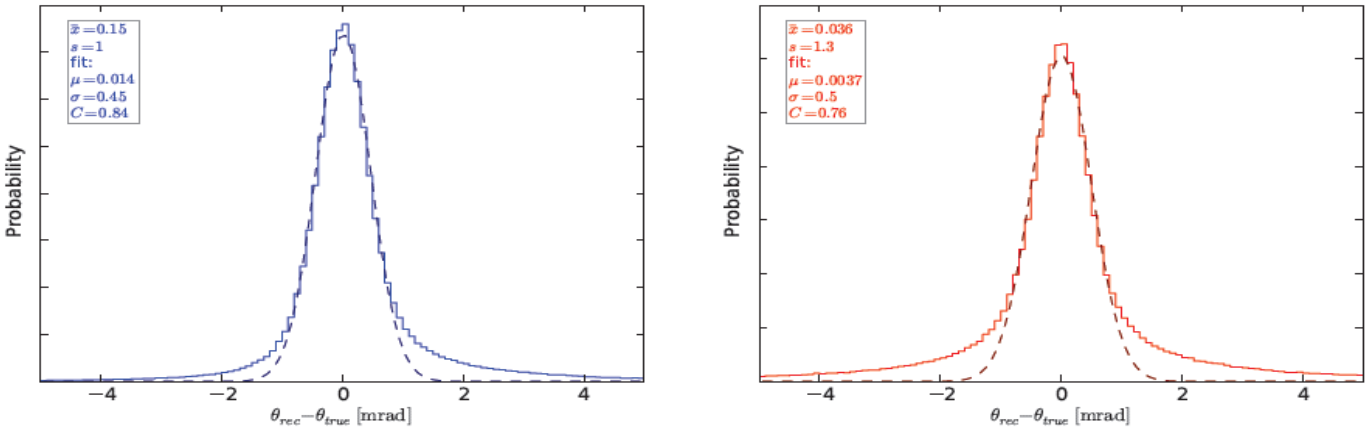

Figure: Obtained angular resolution for muons (left) and electrons (right).

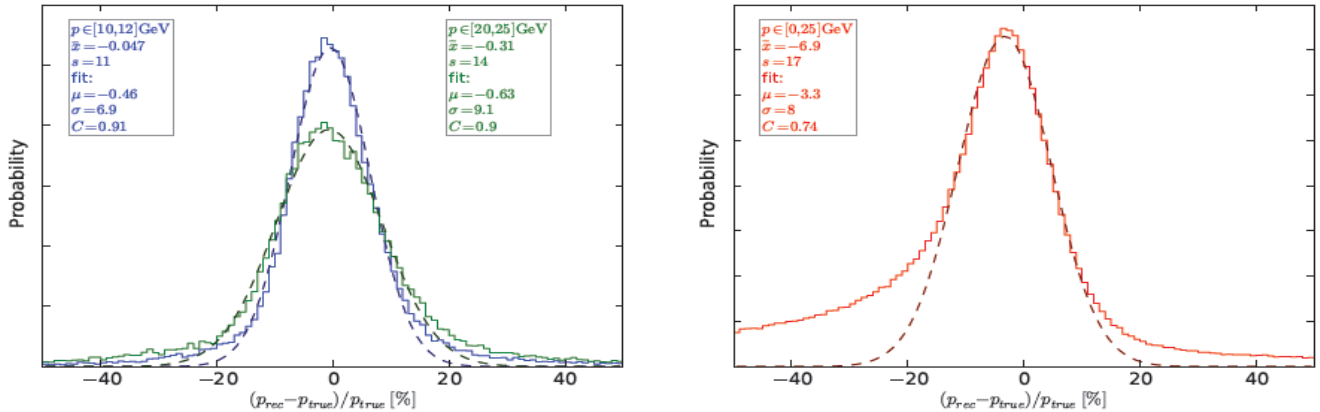

Figure: Obtained momentum resolution for muons (left) and electrons (right).

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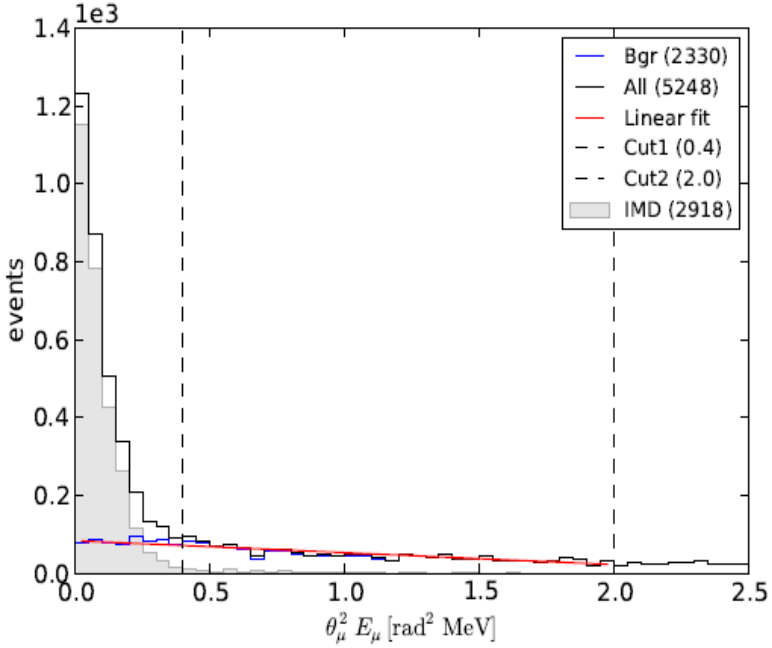
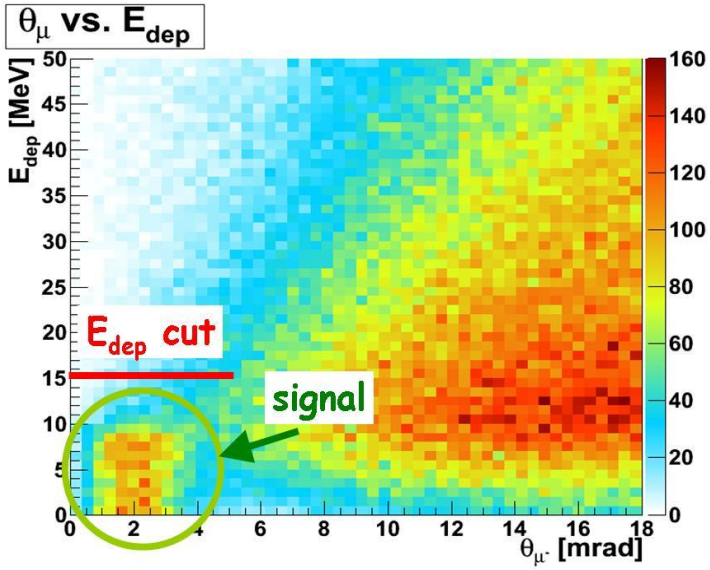
Signal extraction

IMD signal extraction

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





bgrrej&cut eff	overall eff	purity	all events	signal events	signal events from fit	μ decays
86 %	46 %	81 %	3498	2844	2880 ± 59	2.3×10^{19}

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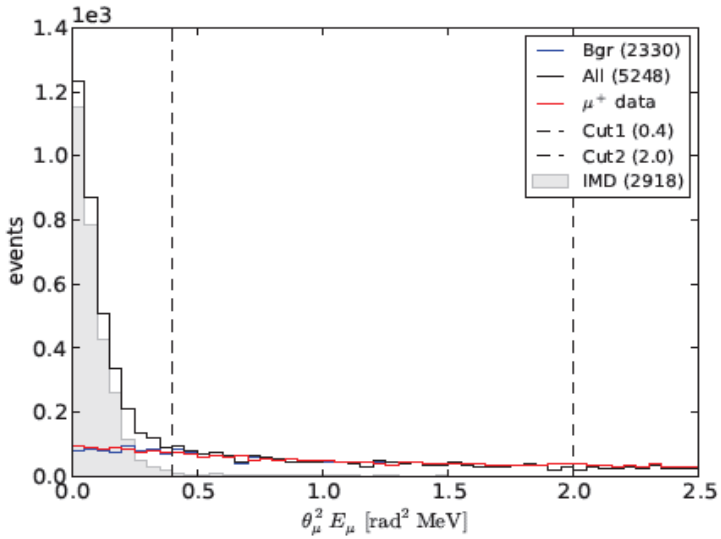
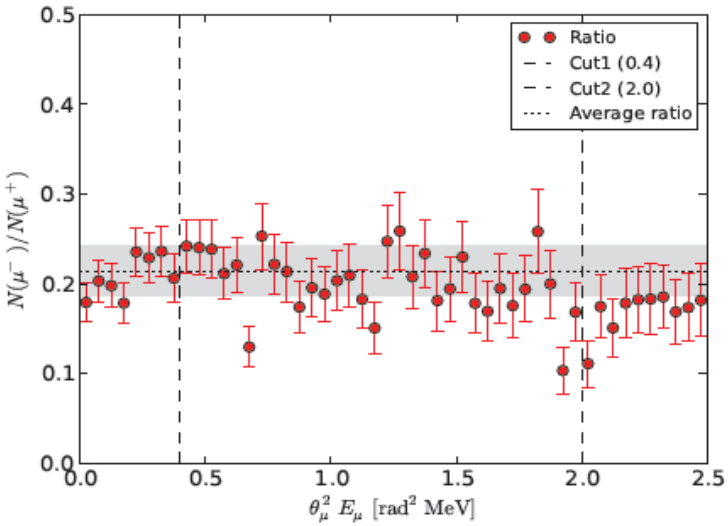
Background subtraction to IMD exploiting anti-ν_μ interactions

Use μ^+ events to estimate background under the IMD peak. Number of μ^+ events is normalized to μ^- events by the average ratio between cut1 and cut2.





bgrrej&cut eff	overall eff	purity	all events	signal events	signal events from fit	μ decays
86 %	46 %	81 %	3498	2844	2820 ± 60	2.3×10^{19}

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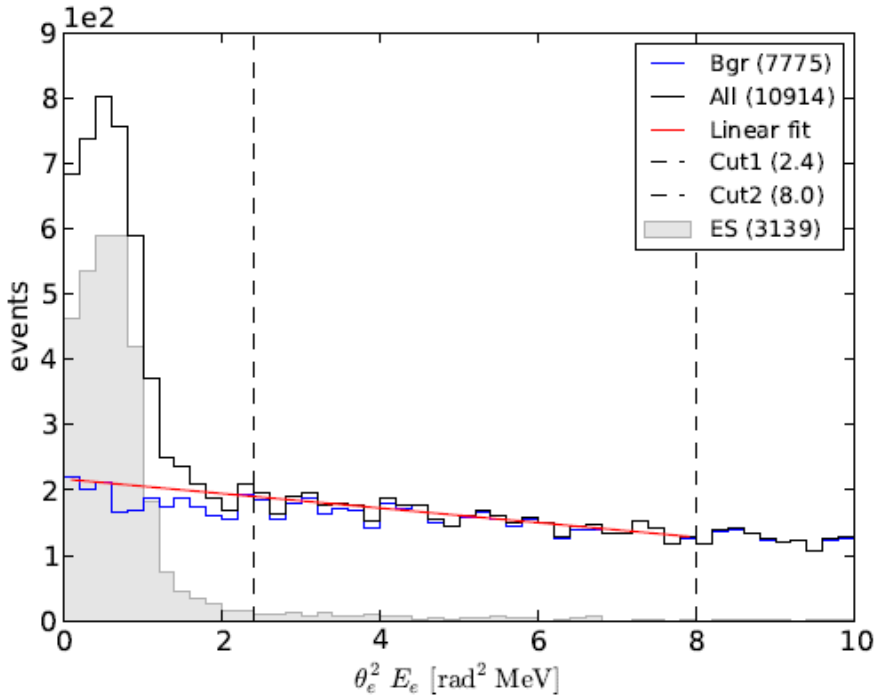
ν-e NC elastic scattering

ES signal extraction in μ^- beam

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



bgrrej&cut eff	overall eff	purity	all events	signal events	signal events from fit	μ decays
47 %	21 %	58 %	5202	2992	2760 ± 72	2.3×10^{19}

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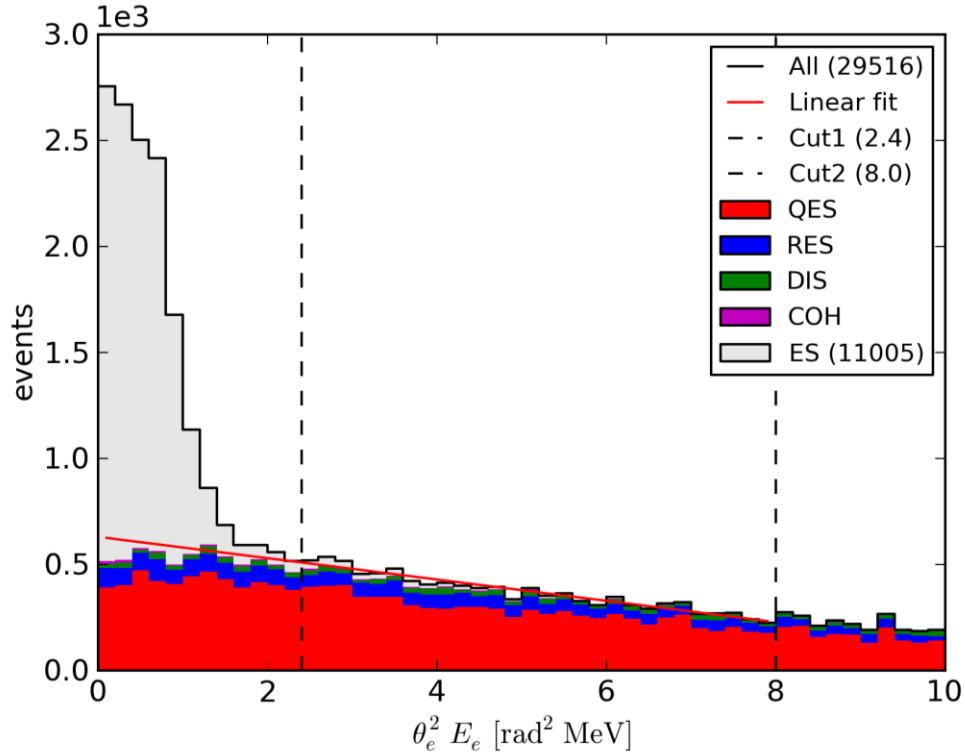
ν-e NC elastic scattering

ES signal extraction in μ^+ beam

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



bgrrej&cut eff	overall eff	purity	all events	signal events	signal events from fit	μ decays
83 %	37 %	63 %	16964	10607	10124 ± 131	2.3×10^{19}

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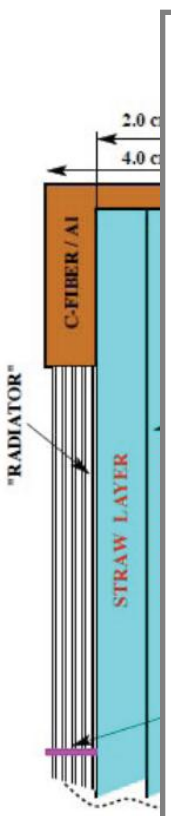
Result

With the SciFi tracker we can achieve ~1% uncertainty on the flux normalisation by exploring IMD or ν-e NC elastic scattering.

Straw tube tracker design

High resolution magnetised detector (*HiResM*ν) – proposed for LBNE Near detector



Proposal for A High Resolution Neutrino Experiment in a B-Field for Project-X

S.R. Mishra, R. Petti, C. Rosenfeld

University of South Carolina

HiResMν

Document on HiResMNu available at:
http://www.fnal.gov/directorate/Longrange/Steering_Public/community_letters.html
(To be submitted to NIM)

ECAL

STT

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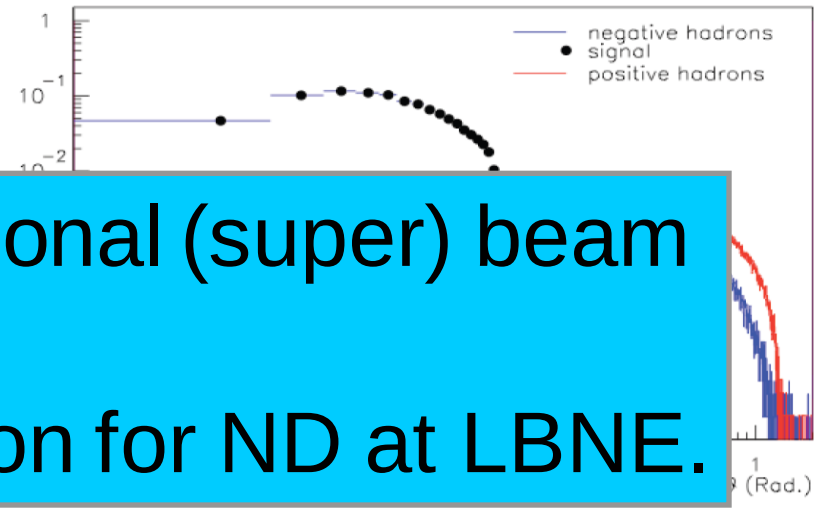
HiResMν absolute flux measurement via **ν-e NC elastic scattering**

S. Mishra

Resolutions in HiResMν

ρ ≈ 0.1gm/cm^3
Space point position ≈ 200μm
Time resolution ≈ 1ns
CC-eve
Energy
μ-Angl
μ-Ener
e-Ener

Signal and **charged hadrons background**
LBNE flux!



Optimised for conventional (super) beam flux monitoring.
Reference design option for ND at LBNE.

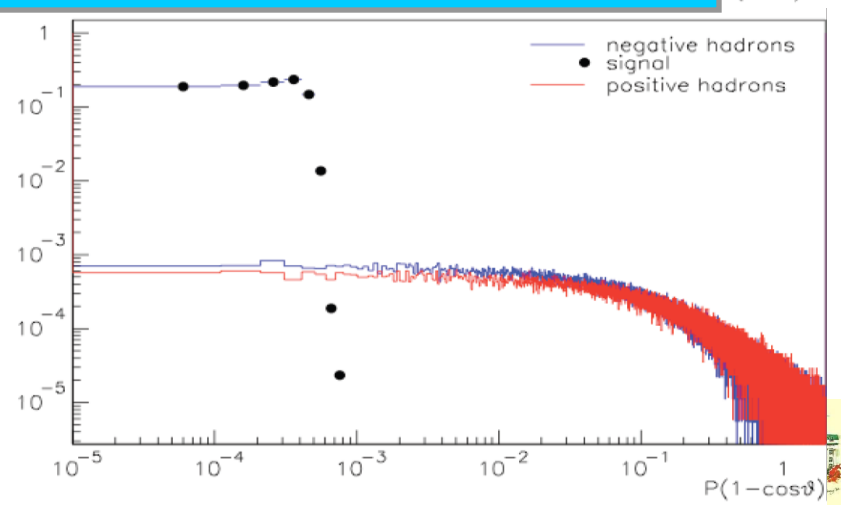
ν-e NC signal: single forward e⁻

Background: charged hadrons and
NC induced $\pi^\circ \rightarrow \gamma \rightarrow e^-$ (e^+ invisible)

Two-step Analysis:

- Electron-ID by transition radiation detection
- Kinematical cut on $y \sim P_e(1-\cos\Theta_e)$

It seems the background is benign *($\leq 10^{-6}$)*.

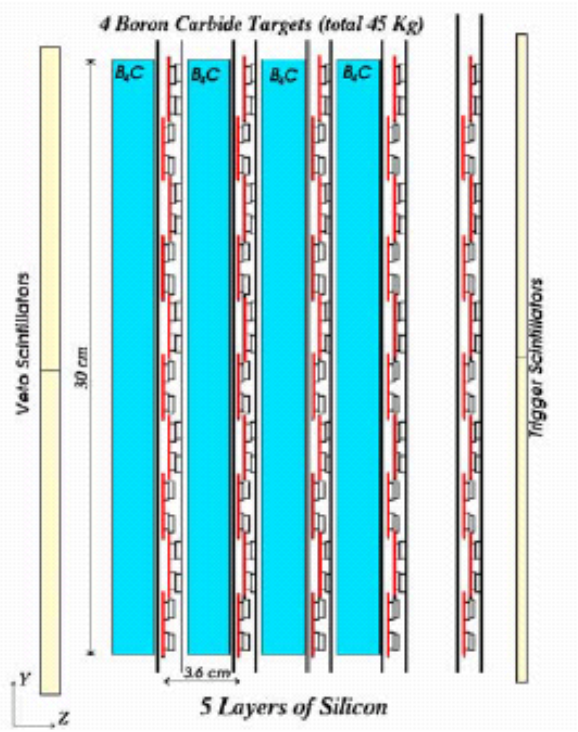


High granularity vertex detector

- 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 (NIMA 413 (1998), 17; NIMA 419 (1998), 1; NIMA 486 (2002), 639; NIMA 506 (2003), 217.)

Silicon TARget - STAR



1.14 m^2 silicon area

Total mass: 45 kg of B_4C target (largest density 2.49 g cm^{-3} for lowest X_0=21.7 cm.)

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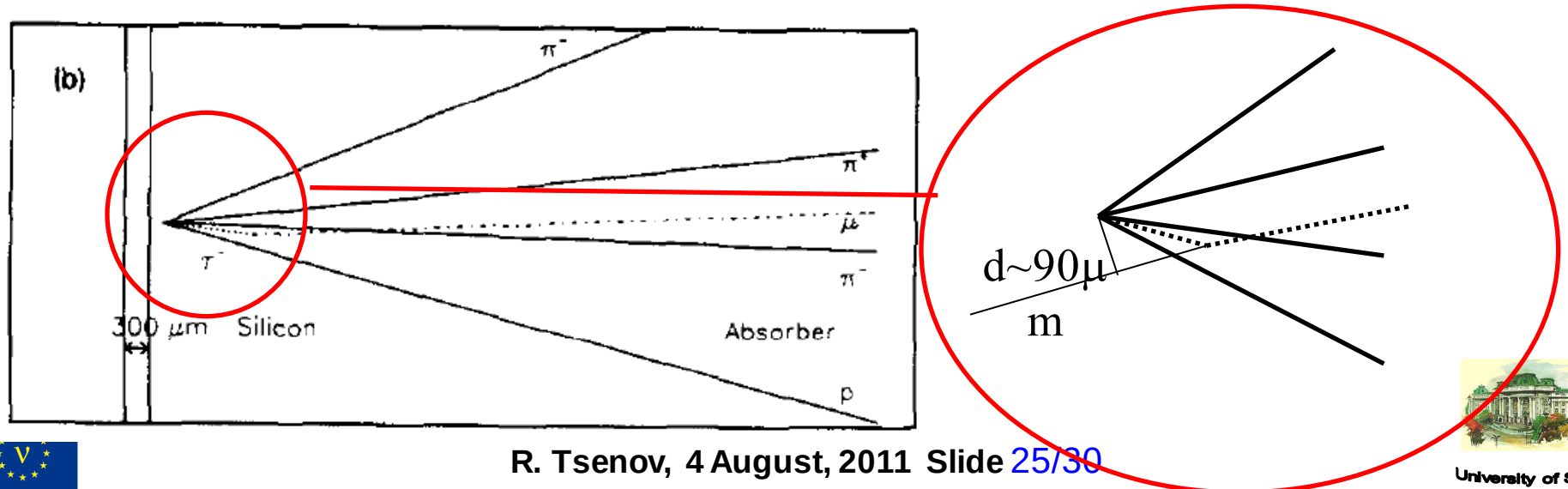
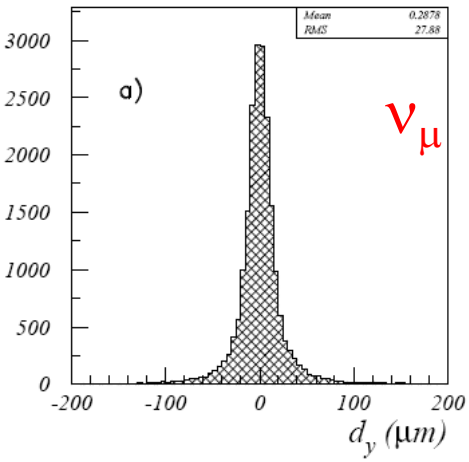
Impact parameter detection of τ

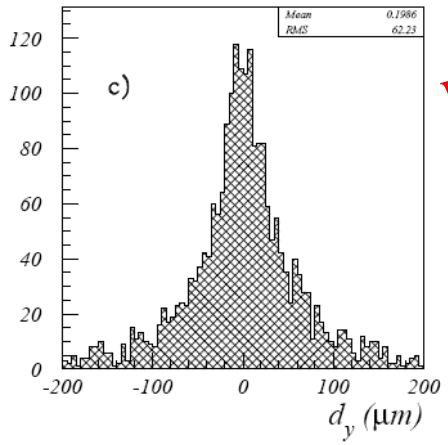
- This was invented by Gomez Cadenas et al.
  - NAUSICAA: (Si vertex detector): NIM A 378 (1996), 196-220
  - ESTAR (Emulsion-Silicon Target): NIM A 381 (1996), 223-235
- Identify tau by impact parameter (for one prong decay of τ) and double vertex (for 3 prong decays)

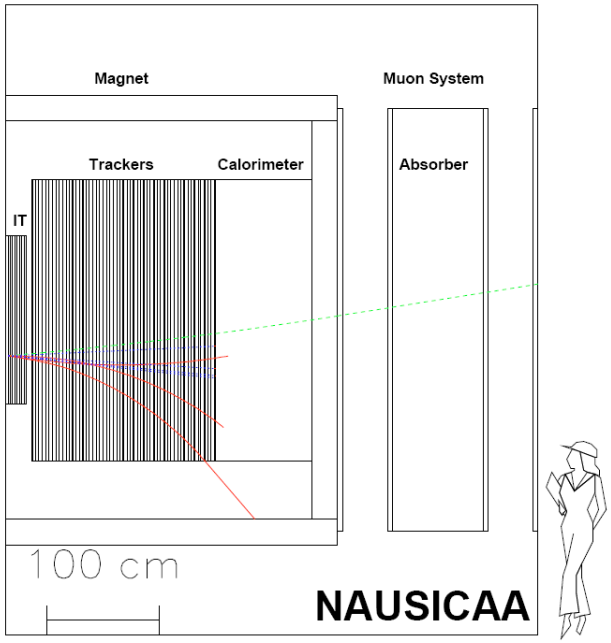


NAUSICAA PRD 55, (1997),1297. NIMA 385 (1997), 91.

- NAUSICAA proposal:
  - Impact parameter resolution ν_μ-CC=28μm
  - Impact parameter resolution ν_τ-CC=62μm







  - $\tau \rightarrow \mu$: ε=10%
  - $\tau \rightarrow \pi(n\pi^0)$: ε=10%
  - $\tau \rightarrow \pi\pi\pi(n\pi^0)$: ε=23%
  - Total eff:

ε=0.85x10%+0.15x23%=12%

  - σ_τ/σ_μ=0.29

- Sensitivity at Main Injector with 2×10^7 ν_μ CC interactions (MINSIS):

$$P_{osc}(\nu_\mu \rightarrow \nu_\tau) < \frac{2.48}{2\times10^7 \times 0.12 \times 0.29} = 3.6\times10^{-6}$$

- Intrinsic limit tau production $D_s \rightarrow \tau\nu_\tau$:
  - 3.5×10^{-6} at 450 GeV
  - 1.3×10^{-6} at 350 GeV
  - 9.6×10^{-8} at 120 GeV

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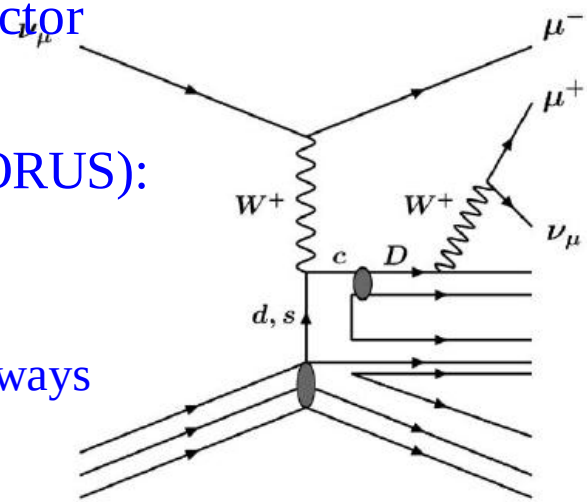
Vertex detector dimensions

- 150x150x2cm^3 per layer of B_4C (2.49 g/cm^3) and 18 layers: total mass = 2.02 tonnes
- 20 layers of silicon: 45 m^2 of silicon
- silicon strip detectors but could be pixels
- about 64,000 channels per layer: 1.28 million channels

Charm and τ measurements

- Rates: approx 3×10^7 ν_μ CC events/year in 2 tons detector
- Assume 12% eff from NAUSICAA
- Inclusive charm production at <27 GeV> (from CHORUS): (5.75±0.32±0.30)%
  - From 0-30 GeV: ~3% → 10^6 charm events!
  - Charm produced in CC reaction with d or s quark so always have lepton
  - Associated charm in NC interaction (see charm review De Lellis et al. Phys Rep 399 (2004), 227-320)



- For τ measurement the impact parameter analysis could be used:
  - search for $\nu_\mu \rightarrow \nu_\tau$ and search for τ^-
  - anti-ν_e background that can create D^- which looks like signal, → need to identify e^+ to reject background.

$$P(\nu_\mu \rightarrow \nu_\tau) < \frac{2.48}{3\times10^7 \times 0.12 \times 0.29} = 2.4\times10^{-6}$$

Very tough: probably overestimate in efficiency since background rejection will affect it

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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;
- **Silicon vertex detector+SciFi tracker+mini-MIND** set-up is most advanced with respect to simulations with NF beam. ν flux can be measured with ~1% error;
- Second option exsits for the tracker – HiResMν. Simulations with NF beam needed.
- Further tasks:
  - **fix the Near detector baseline design and perform full simulation;**
  - systematic errors coming from near-to-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.).

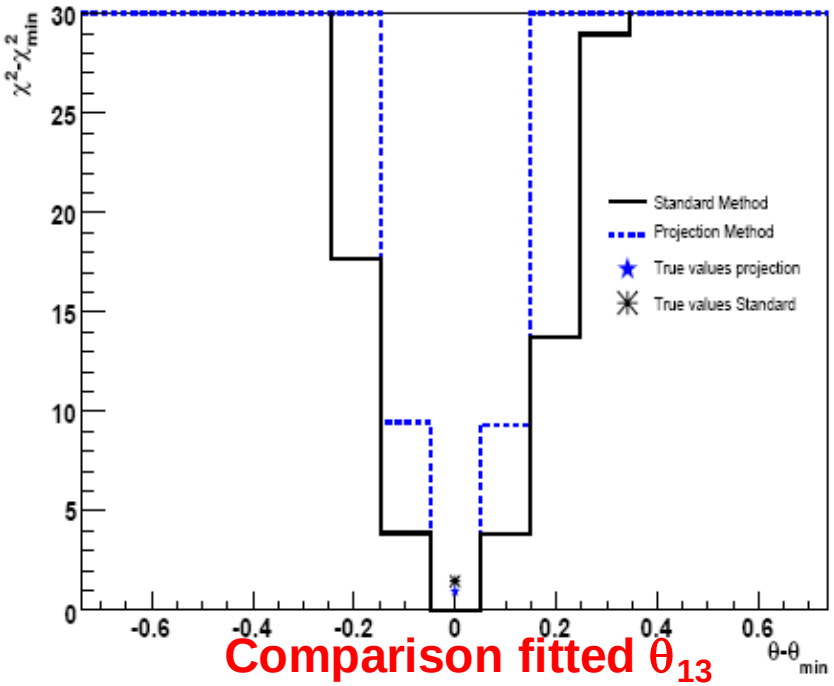
Thanks for your attention!

Back-up slides

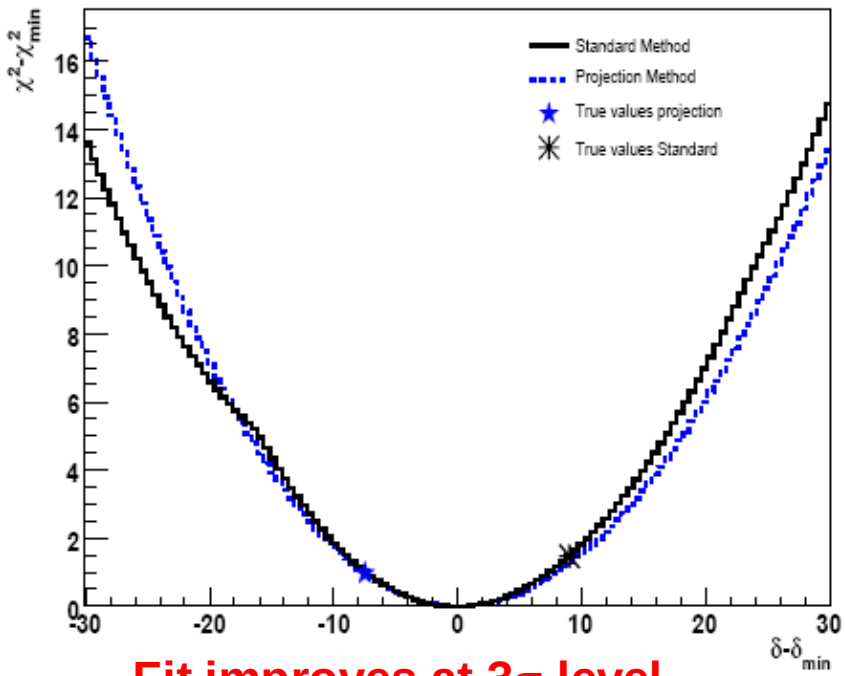
Flux extrapolation results

- Extrapolation near-to-far at Neutrino Factory:
  - Using the FD spectrum formula: $N_{FD} = M_{FD} P_{osc}(\theta_{13}, \delta_{CP}) M_{nOsc} M_{ND}^{-1} N_{ND}$
  - Fit FD spectrum to predicted spectrum from ND:

$$\chi^2 = \sum_i \sum_j (N_{ij} - n_{ij}) V_{ij}^{-1} (N_{ij} - n_{ij})^T$$



Comparison fitted θ_{13} and δ with true values



Fit improves at 3σ level

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Simulation

Near detector flux simulation

flux driver

GENIE

http://www.genie-mc.org
arXiv:0905.2517

ROOT file

GEANT4

ROOT file

(Simple) digitization

Reconstruction

Processes included in GENIE

Quasi-elastic scattering $\nu_\mu + n \rightarrow \mu^- + p$

Elastic NC scattering

Baryon resonance production in CC and NC

Coherent neutrino-nucleus scattering $\nu_\mu + A \rightarrow \nu_\mu + \pi^0 + A$ $\nu_\mu + A \rightarrow \nu_\mu + \pi^0 + A$

Non-resonant inelastic scattering (DIS)

Quasi-elastic charm production

Deep-inelastic charm production

Neutrino-electron elastic scattering and inverse muon decay **(IMD)** $\nu_\mu + e^- \rightarrow \nu_e + \mu^-$

C. Andreopoulos et al., *The GENIE Neutrino Monte Carlo Generator*, **arXiv:0905.2517**

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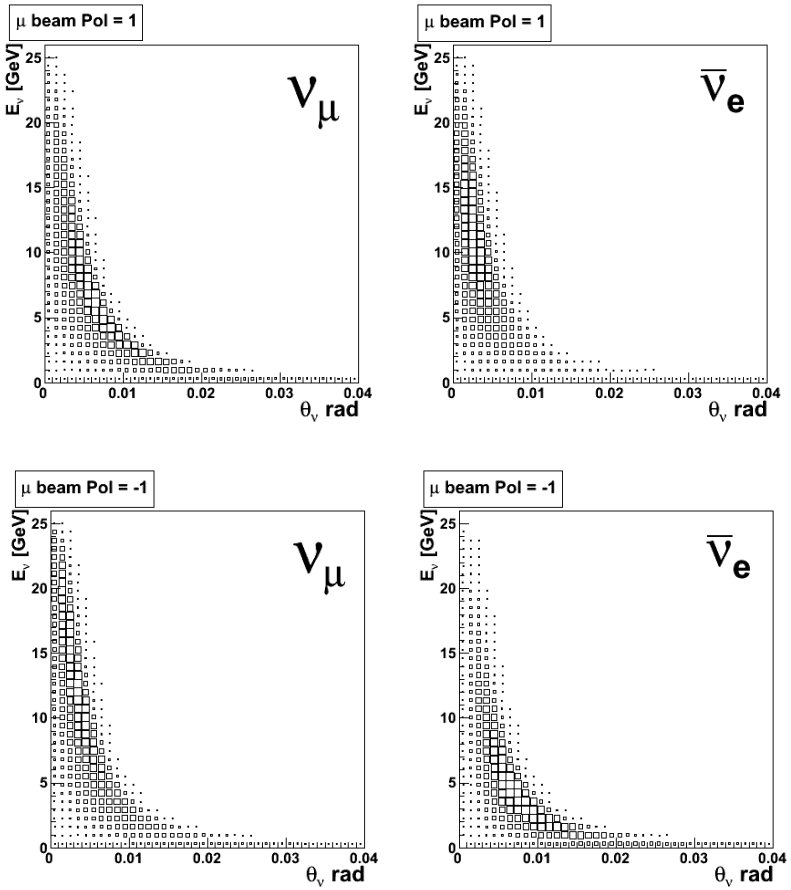
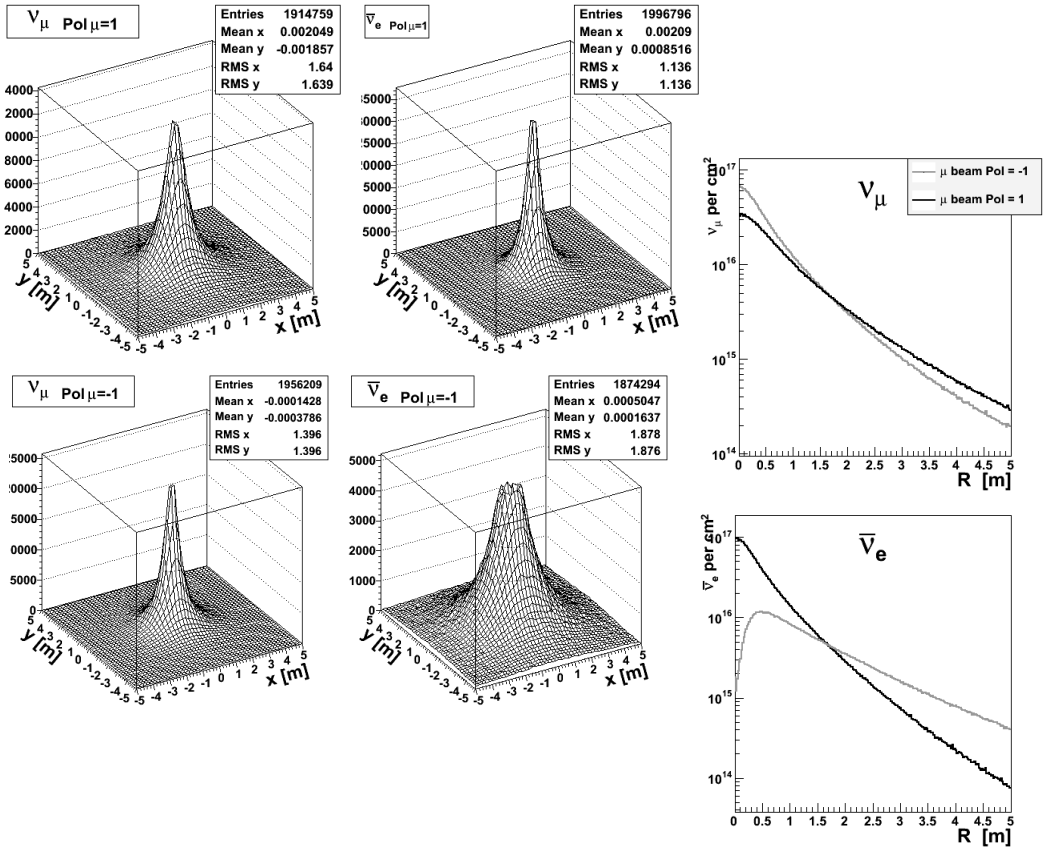
Simulation of the neutrino beam



Properties of the neutrino beam



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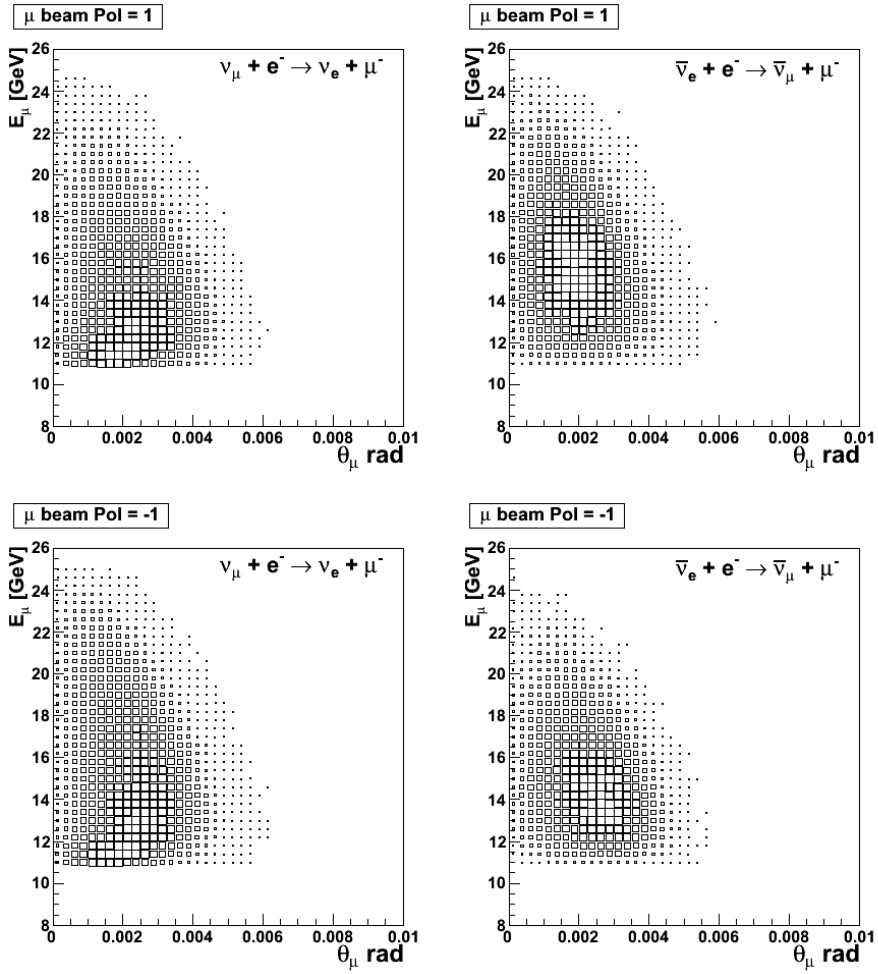
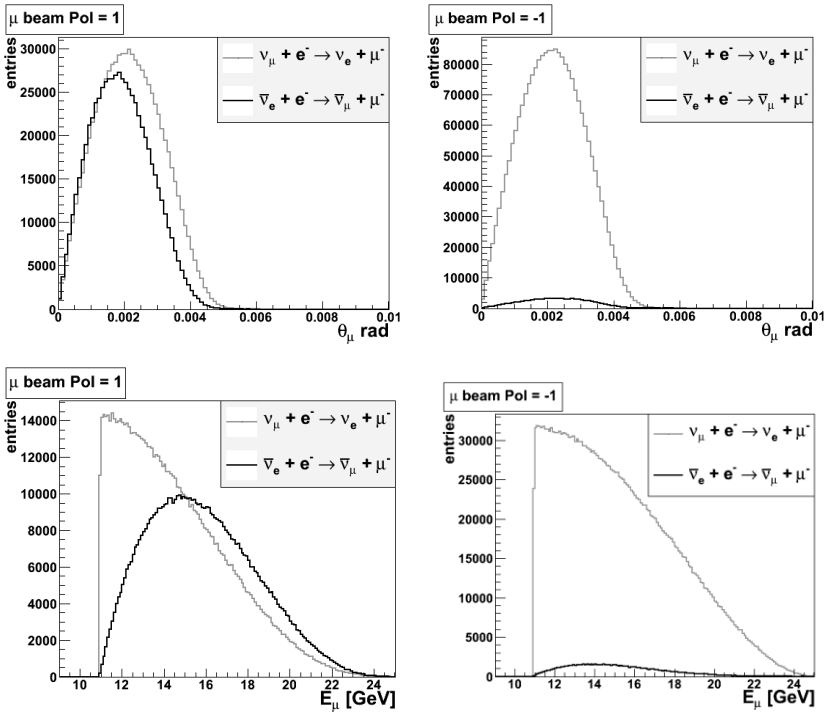
Quasielastic scattering off electrons





Distributions of the neutrinos over their energy and polar angle at the position of the near detector for the two polarizations of the decaying muons.

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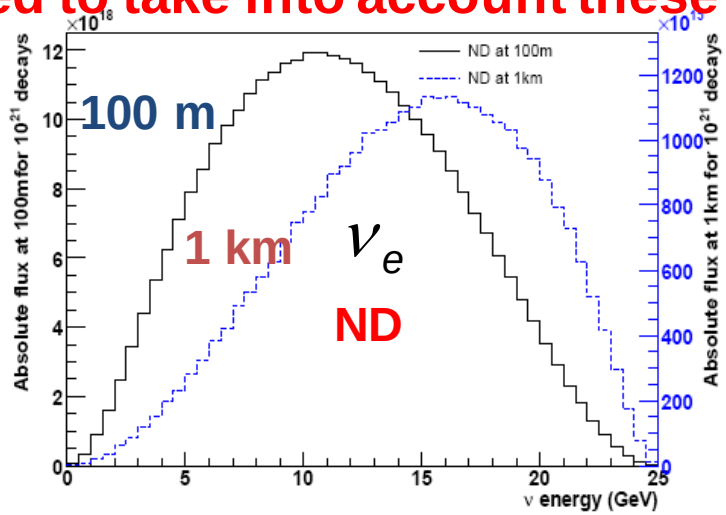
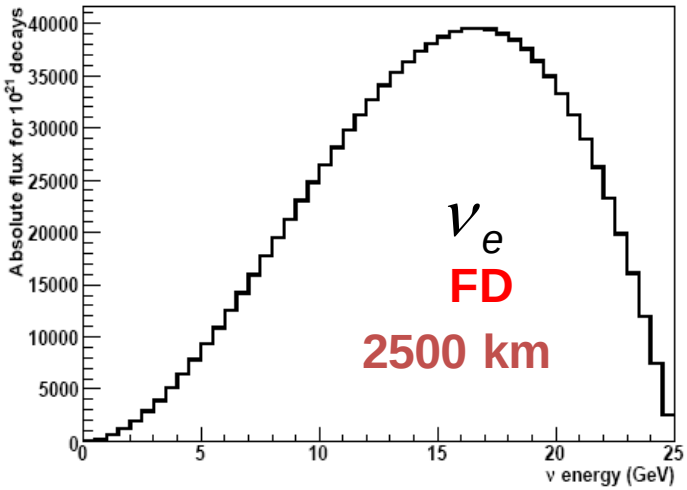
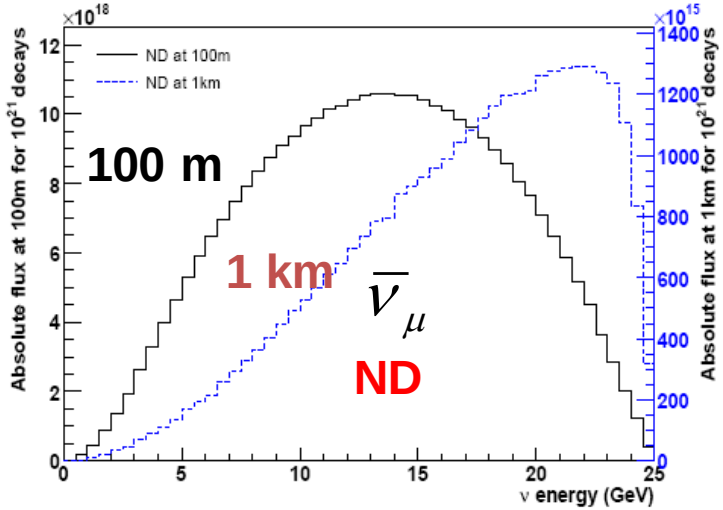
Spectra at Near Detector

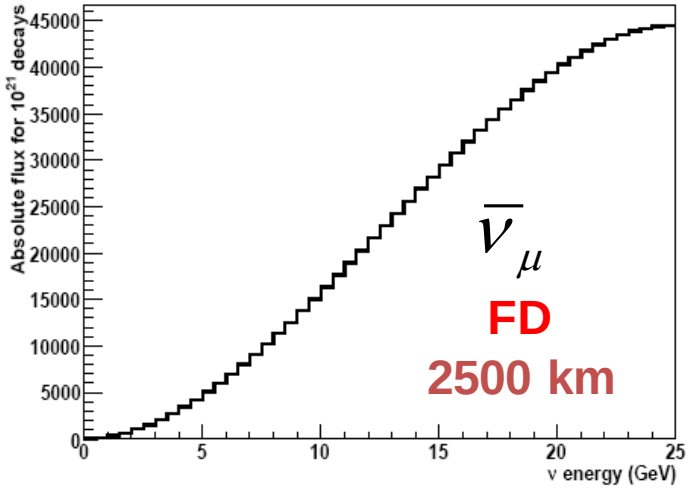
- Near Detector sees a line source (600 m long decay straight)
- Far Detector sees a point source

Need to take into account these differences for flux measurement









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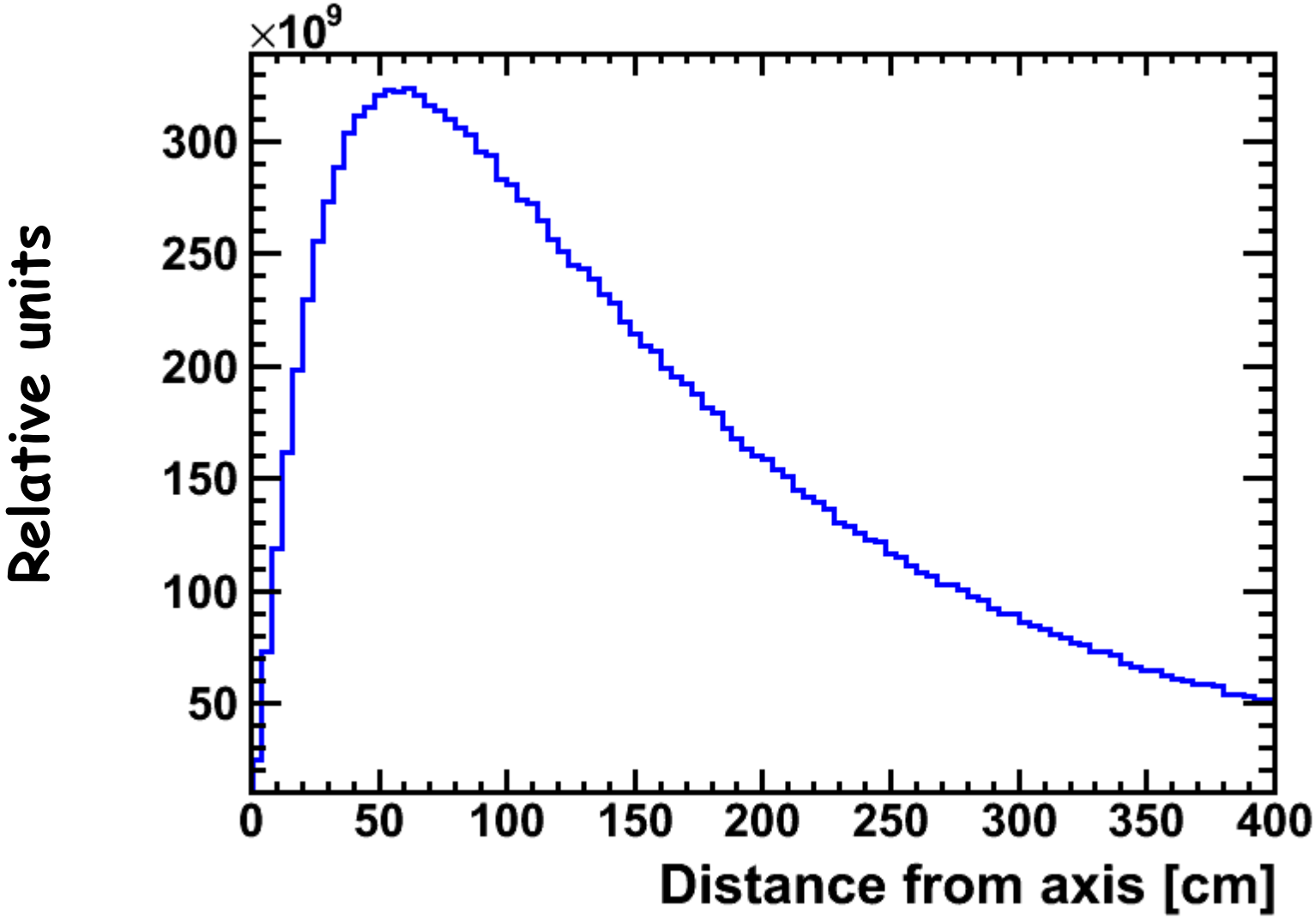
Neutrino flux per unit radius



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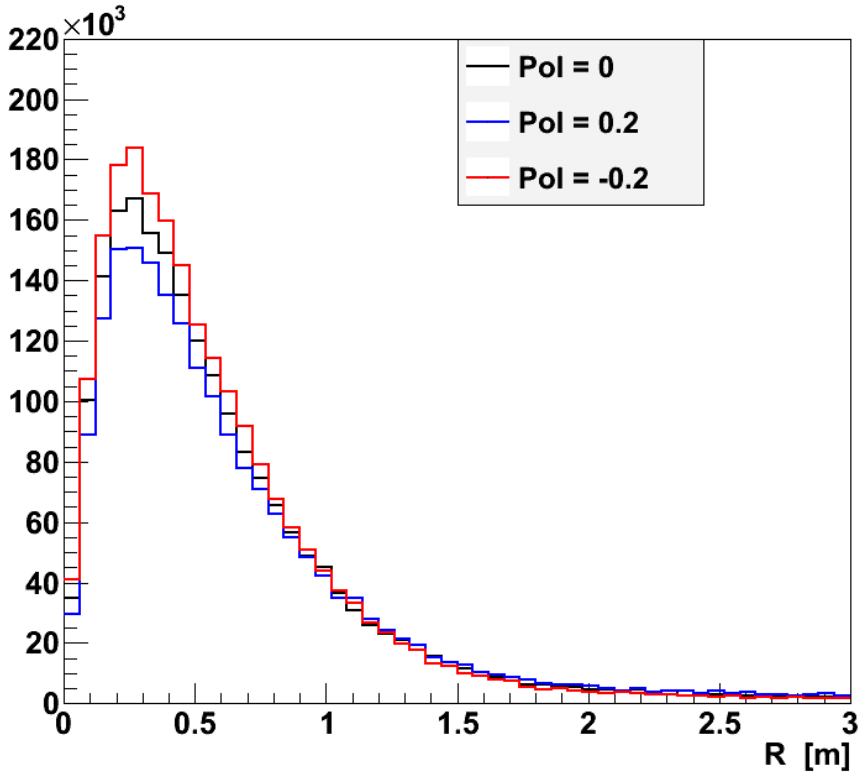
Monitoring of the muon beam polarization



The leptonoc interactions of the neutrinos can be used to monitor the polarization of the muon beam in the storage ring. The plot shows the number of leptonic events in 5 m long polystyrene detector as a function of the distance from the neutrino beam axis for three different polarizations of the muon beam in the storage ring and for 10^{21} muon decays (1 year). It is clear that the variation of the distribution of the events because of the different polarization of the muon beam is much bigger than the statistical errors.

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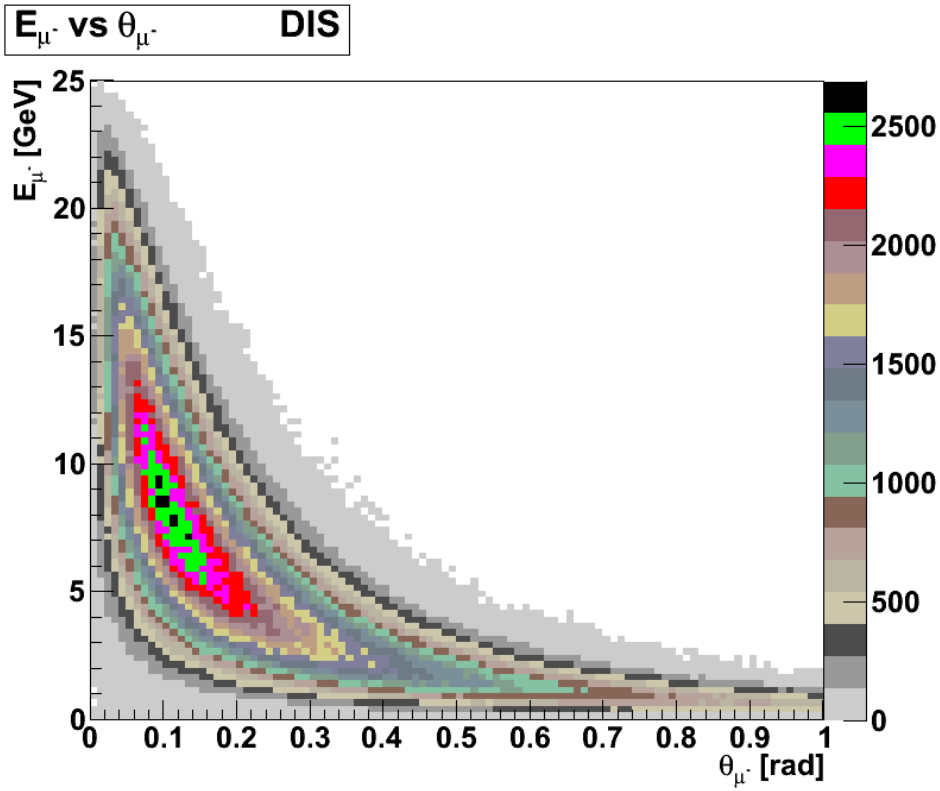

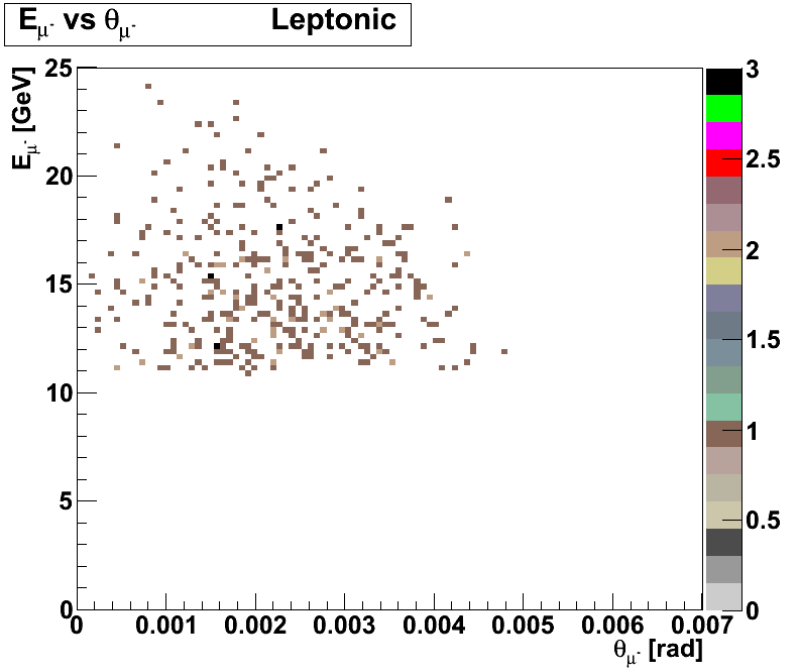

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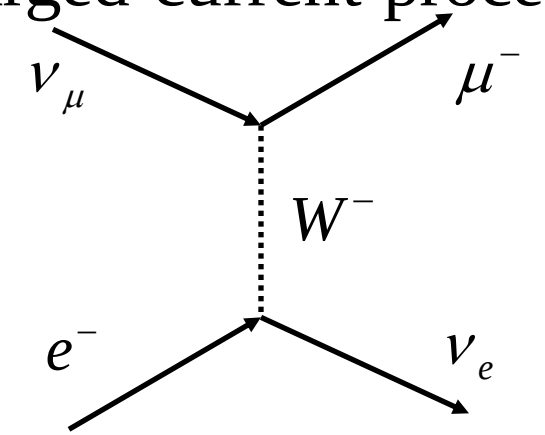
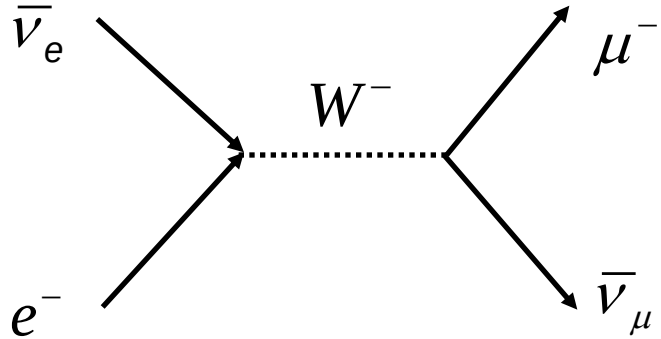
Inverse Muon Decay

- Charged current processes:





$$\nu_\mu + e^- \rightarrow \nu_e + \mu^-$$

$$\sigma^{CC}_{\nu_\mu e^-}(E) = \frac{G_F{}^2}{\pi}\frac{(s-m_\mu^2)^2}{s}$$

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

$$\sigma^{CC}_{\bar{\nu}_e e^-}(E) = \frac{G_F{}^2}{\pi}\frac{(s-m_\mu^2)^2}{s}\left(E_e E_\mu + \frac{1}{3}E_{\nu_1}E_{\nu_2}\right)$$

- Cross-section ~1.7x10^{-41} E(GeV) cm^2, threshold = 11 GeV
- We cannot distinguish between the two channels so we measure $N_1(E) + N_2(E)$:

$$N_1(E) = \phi_{\nu_\mu e^-}(E)\sigma^{CC}_{\nu_\mu e^-}(E) \qquad N_2(E) = \phi_{\bar{\nu}_e e^-}(E)\sigma^{CC}_{\bar{\nu}_e e^-}(E)$$

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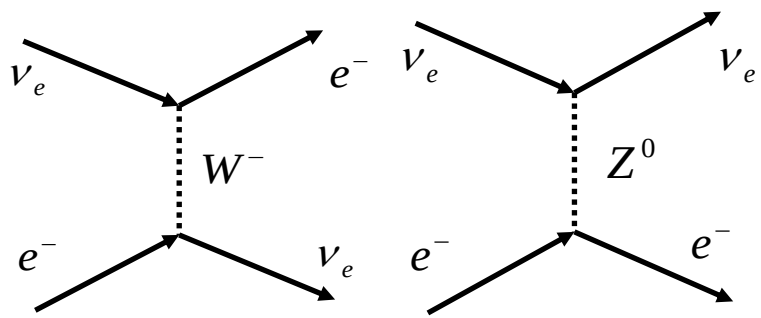
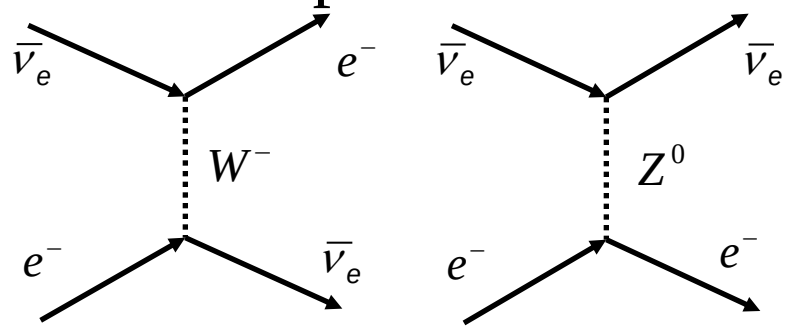
Electron-neutrino electron scattering

- Interference neutral and charged current processes:



$$\nu_e + e^- \rightarrow \nu_e + e^-$$



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

$$\sigma^{CC+NC}_{\nu_e e^-}(E) = \frac{G_F{}^2 s}{\pi}\left[\left(\frac{1}{2} + \sin^2\theta_W\right)^2 + \frac{1}{3}\sin^4\theta_W\right]$$

$$\sigma^{CC+NC}_{\bar{\nu}_e e^-}(E) = \frac{G_F{}^2 s}{\pi}\left[\frac{1}{3}\left(\frac{1}{2} + \sin^2\theta_W\right)^2 + \sin^4\theta_W\right]$$

- Cross-section $0.96\text{x}10^{-41}$ E(GeV) and $0.40\text{x}10^{-41}$ E(GeV) cm^2
- We can only distinguish between the two channels since each come from a different muon decay:

$$N_5(E) = \phi_{\nu_e e^-}(E)\sigma^{CC+NC}_{\nu_e e^-}(E) \qquad N_6(E) = \phi_{\bar{\nu}_e e^-}(E)\sigma^{CC+NC}_{\bar{\nu}_e e^-}(E)$$

Accuracy of cross-section depends on $sin^2\theta_W$

Combination of all channels

- So, if we consider the IMD and neutrino elastic scattering channels together we obtain:
  - For the NF decay: $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$

$$N_1(E) + N_2(E) = \phi_{\nu_\mu e^-}(E)\sigma^{CC}_{\nu_\mu e^-}(E) + \phi_{\bar{\nu}_e e^-}(E)\sigma^{CC}_{\bar{\nu}_e e^-}(E)$$

$$N_3(E) + N_6(E) = \phi_{\nu_\mu e^-}(E)\sigma^{NC}_{\nu_\mu e^-}(E) + \phi_{\bar{\nu}_e e^-}(E)\sigma^{CC+NC}_{\bar{\nu}_e e^-}(E)$$

  - We can extract the fluxes when we have IMD and elastic scattering:

$$\phi_{\nu_\mu e^-}(E) = \frac{\sigma^{CC+NC}_{\bar{\nu}_e e^-}(N_1 + N_2) - \sigma^{CC}_{\bar{\nu}_e e^-}(N_3 + N_6)}{\sigma^{CC+NC}_{\bar{\nu}_e e^-}\sigma^{CC}_{\nu_\mu e^-} - \sigma^{CC}_{\bar{\nu}_e e^-}\sigma^{NC}_{\nu_\mu e^-}}$$

$$\phi_{\bar{\nu}_e e^-}(E) = \frac{\sigma^{NC}_{\nu_\mu e^-}(N_1 + N_2) - \sigma^{CC}_{\nu_\mu e^-}(N_3 + N_6)}{\sigma^{CC+NC}_{\bar{\nu}_e e^-}\sigma^{CC}_{\nu_\mu e^-} - \sigma^{CC}_{\bar{\nu}_e e^-}\sigma^{NC}_{\nu_\mu e^-}}$$

Combination of all channels

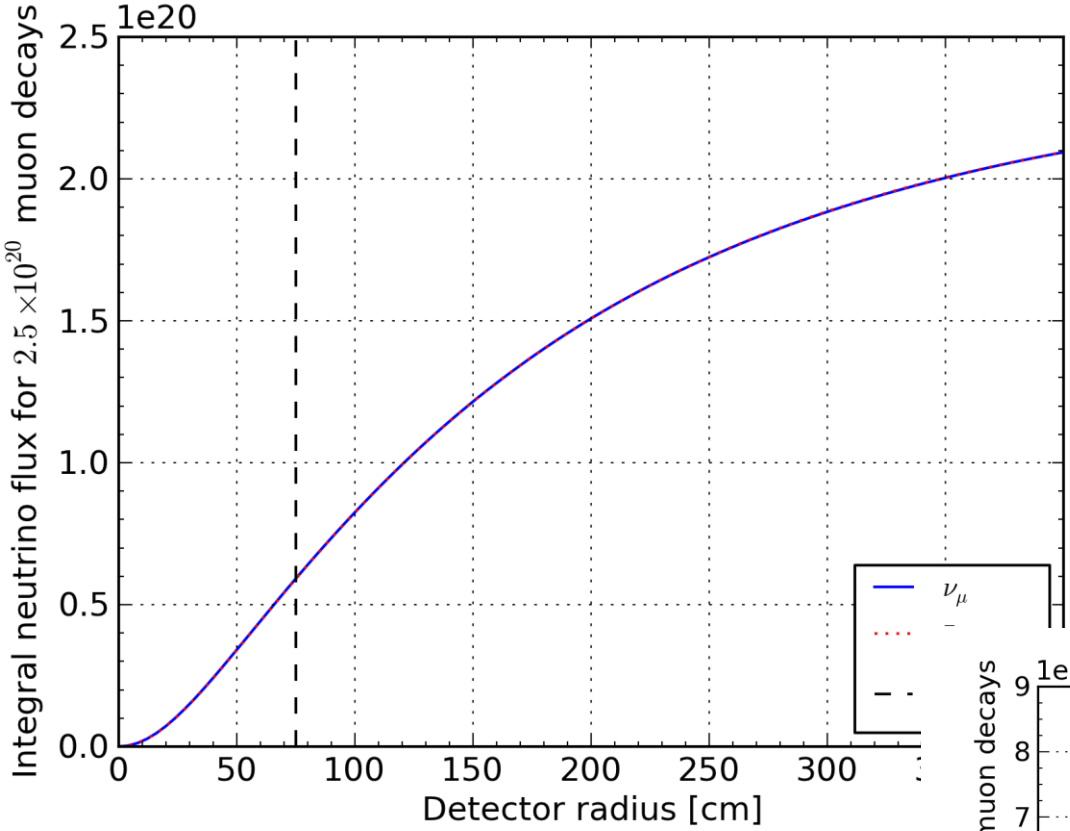
- So, if we consider the IMD and neutrino elastic scattering channels together we obtain:
  - For the NF decay: $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$
  - We cannot resolve the two fluxes because they are together:

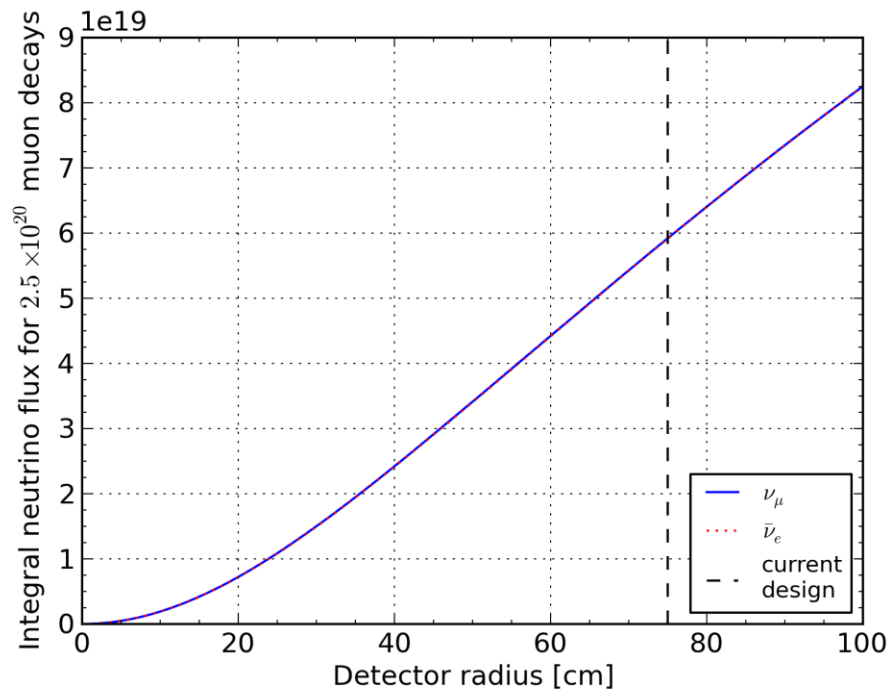
$$N_5(E) + N_4(E) = \phi_{\nu_e e^-}(E)\sigma^{CC+NC}_{\nu_e e^-}(E) + \phi_{\bar{\nu}_\mu e^-}(E)\sigma^{NC}_{\bar{\nu}_\mu e^-}(E)$$

- So, we can only resolve the fluxes when we are in an energy bin in which we have both IMD and elastic scattering for μ^- decay. For μ^+ decay, we cannot resolve fluxes with this method – maybe we can do ratio of μ^+/μ^- or fit shapes
- Are there any other neutrino processes that we can use?
- We need to look at these possibilities to extract final fluxes

Conclusions

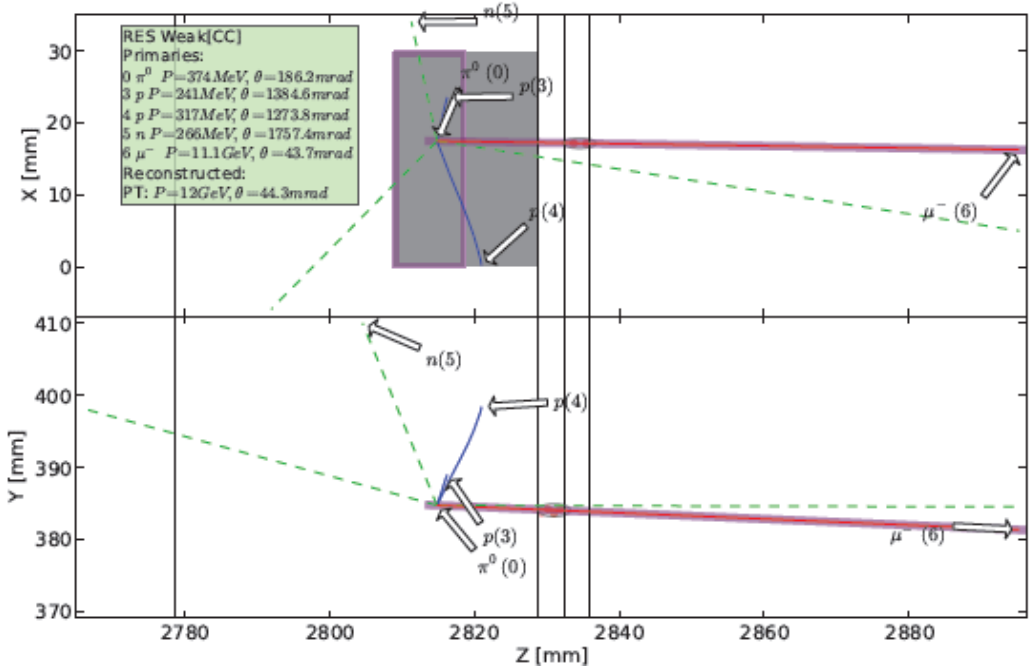
- Method for extracting neutrino fluxes at NF relies on using channels in which cross-sections are known very well theoretically
- Channels identified include:
  - Inverse Muon Decay
  - Muon-neutrino electron elastic scattering
  - Electron-neutrino electron elastic scattering
- Combination of IMD+neutrino elastic scattering works very well for μ^- decay above IMD threshold (11 GeV)
- For μ^+ decay cannot resolve two fluxes
- Might have to rely on fitting shapes or other processes (quasi-elastic scattering?)


1e20
Integral neutrino flux for 2.5×10^{20} muon decays
Detector radius [cm]
ν_μ


1e19
Integral neutrino flux for 2.5×10^{20} muon decays
Detector radius [cm]
ν_μ
$\bar{\nu}_e$
current design

Simulation chain

1. Neutrino flux simulation
2. Genie event generation
3. Geant4 transport
4. Digitization
5. Reconstruction
6. Background rejection and signal extraction



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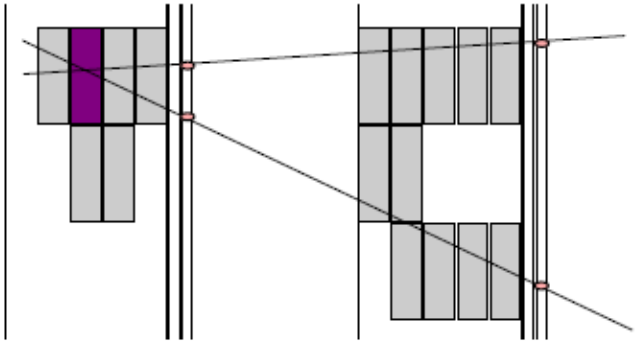
Vertex reconstruction

- **Clustering.** Fired neighboring fibers are grouped into clusters.
- **Vertex position reconstruction.** The volume containing the vertex is found. The two most upstream stations with clusters are considered. The most upstream fired bar consistent with clusters is labeled as vertex bar.

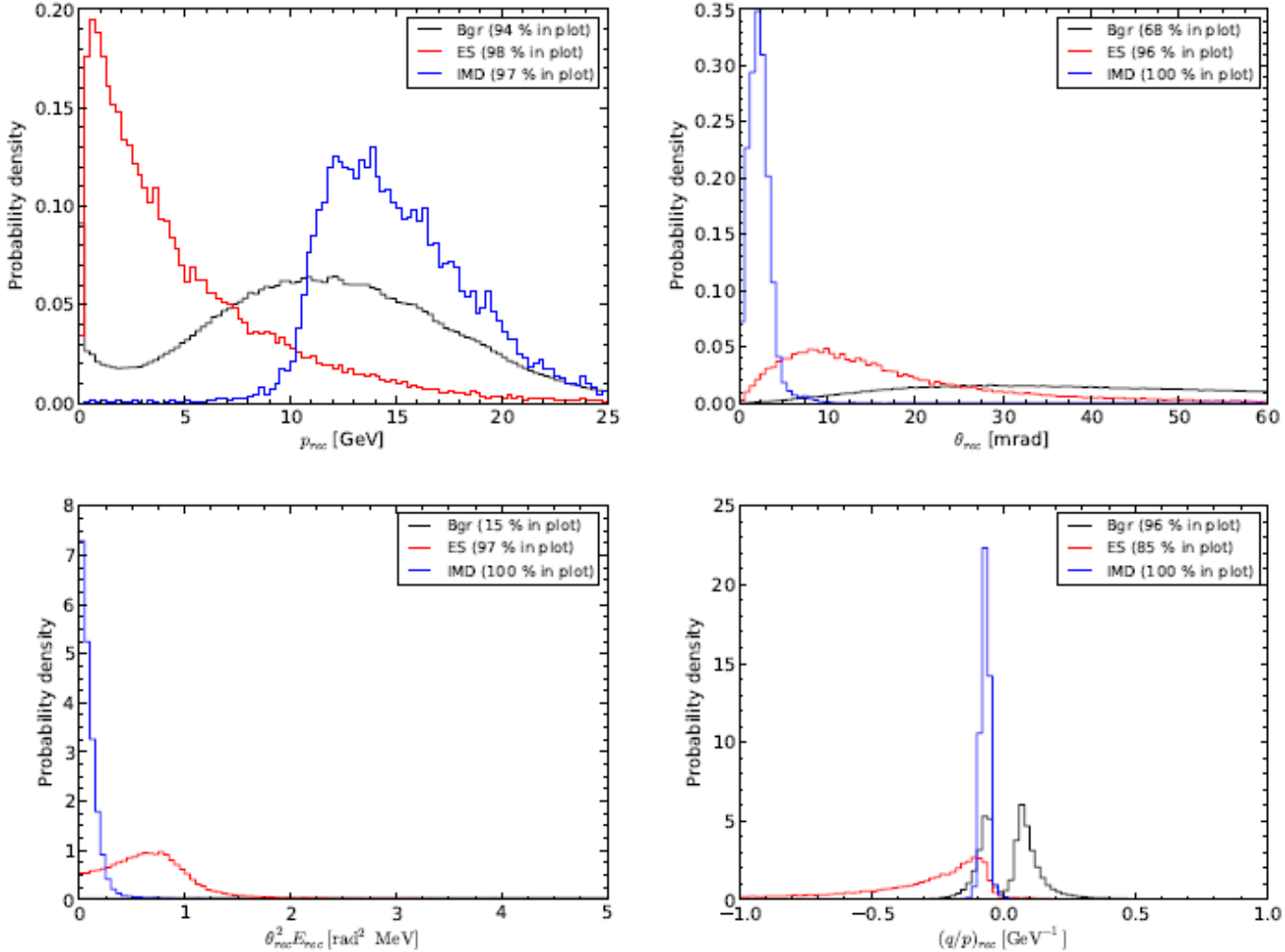


86 % of the signal events (IMD and ES) have their vertex volume reconstructed.

Background rejection

- No activity in bars covering air gaps adjacent to the vertex.
- Vertex activity - if vertex is in bar, require that energy deposit in the bar is no more than 4 MeV.
- Charge sign - only events with negative q/p of the primary track are selected.
- IMD specific cuts
  - mean of all slab deposits is less than 3 MeV;
  - maximum deposit in a slab is less than 12 MeV;
  - momentum of primary track is more than 10 $\mathrm{GeV/c}$;
  - transverse spread of calorimetric energy deposits relative to the primary track is less than 25 mm.
- ES specific cuts
  - transverse spread of calorimetric energy deposits relative to the primary track is less than 150 mm.

Background rejection - kinematic variables



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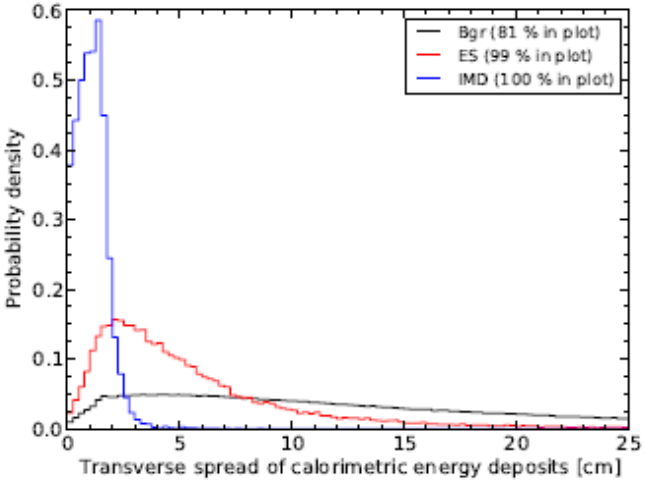
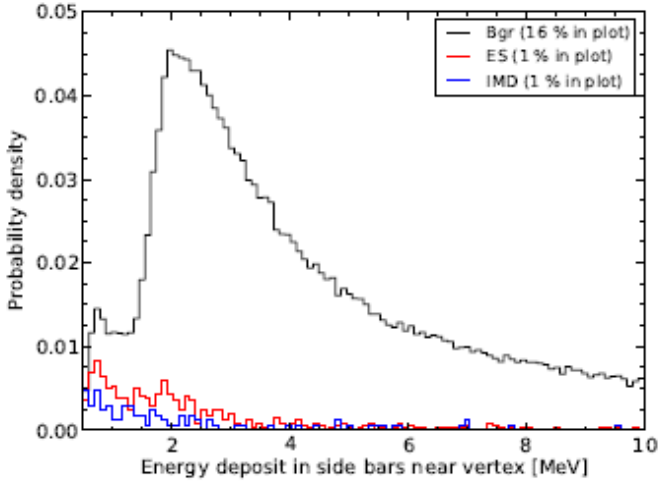
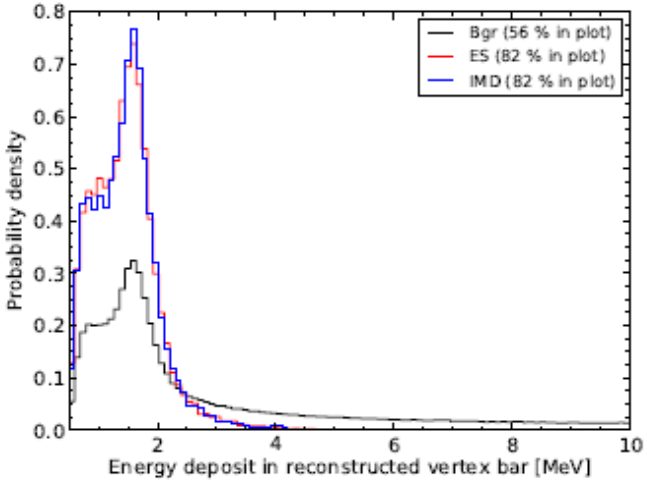
Background rejection - calorimetric variables







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