In-situ absolute flux constraints from FastMC studies

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Outline

ND Parametrized Simulation/Reconstruction (Fast MC)

$\nu e^- \rightarrow \nu e^-$

Inverse Muon Decay

Summary and Outlook

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$\nu e^- \to \nu e^-$

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Summary and Outlook

Fast MC Basics

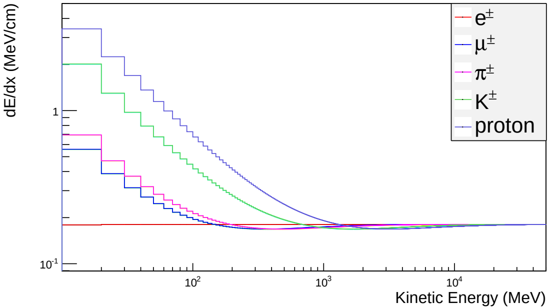
- Fast MC = Fast Detector Simulation + Fast Reconstruction
  - Originally developed by Daniel Cherdack and Rik Gran for LBNE FD. Re-use as much as possible the existing Fast MC codes. It is also a good cross check of the existing code
- The Chain: G4LBNE→GENIE→ND Fast MC→Analyzing the output ROOT files
  - G4LBNE produces the flux
  - GENIE produces the interactions with a homogeneous detector with approximately the same composition as the current design of HiResMν
  - ND Fast MC will mimic the detector simulation and recontruction to produce the "reconstructed" variables for downstream analysis
  - Analyzing the output "reconstructed" ROOT files for specific topics
- Use the exisiting NOMAD data to benchmark the whole chain

ND specs (FGT)

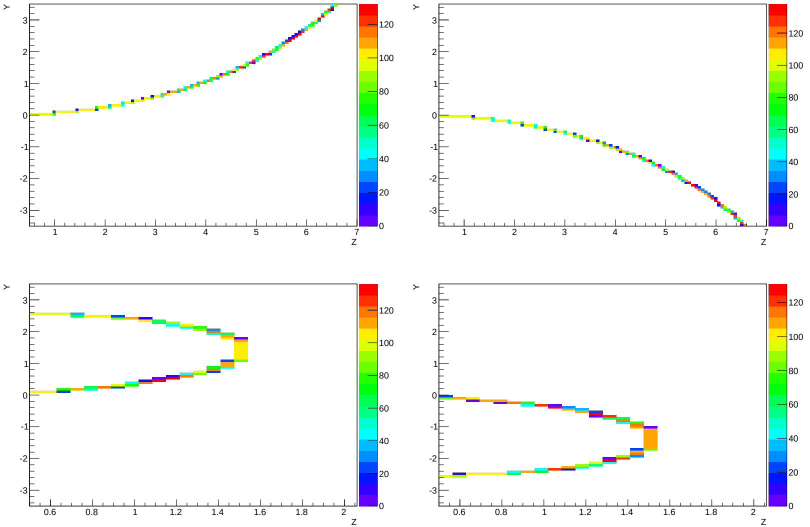
- These are defined in the configuration file: $FMC_CONFIG/FastMC_DetParams.xml within the block of <param_set name="STT_1">
- Internal Magnetic Volume: 4.0×4.0×8.1 m
- Tracker volume (STT): 3.5×3.5×7.04 m (6.40 m), density = 0.1 g/cm^3
- Fiducial volume: $|x, y| < 150$ cm, $25 < z < 550$ cm
- Radiation length: $X_0 \simeq 600$ cm
- hadronic interaction length: 1,200 cm
- Charged particle momentum resolution: $\sigma_p/p = \frac{0.05}{\sqrt{L}} + 0.008p/\sqrt{L^5}$, where L is the track length
- Angular resolution: $\theta_0 = \frac{13.6\,\mathrm{MeV}}{\beta cp} z\sqrt{x/X_0}[1 + 0.038\ln(x/X_0)]$
- EM shower energy resolution: $\sigma_E/E = 1\% + 0.06/\sqrt{E}$
- Hadronic shower energy resolution: $\sigma_E/E = 1\% + 0.50/\sqrt{E}$

dE/dx as a function of kinetic energy

- dE/dx as a function of kinetic energye determined by a standalone G4 simulation with a homogeneous HiResMν detector: same detector composition as in the GENIE phase.
  - Geant4 → Kinetic energy & dE/dx table → dE/dx as function of kinetic energy histograms



Magnetic field : 4^{th} order Runge-Kutta method, same method as used in Geant4



$\nu e^- \to \nu e^-$

ND Parametrized Simulation/Reconstruction (Fast MC)

$\nu e^- \to \nu e^-$

Inverse Muon Decay

Summary and Outlook

$\nu e^- \to \nu e^-$ [1]

- Cross section is extremely small
  - $\sigma(\nu_{\mu,\tau} e \to \nu_{\mu,\tau} e) = \frac{G_\mu^2 m_e E_\nu}{2\pi}[1 - 4\sin^2\theta_W + \frac{16}{3}\sin^4\theta_W]$
  - $\sigma(\bar{\nu}_{\mu,\tau} e \to \bar{\nu}_{\mu,\tau} e) = \frac{G_\mu^2 m_e E_\nu}{2\pi}[\frac{1}{3} - \frac{4}{3}\sin^2\theta_W + \frac{16}{3}\sin^4\theta_W]$
  - $\sigma(\nu_e e \to \nu_e e) = \frac{G_\mu^2 m_e E_\nu}{2\pi}[1 + 4\sin^2\theta_W + \frac{16}{3}\sin^4\theta_W]$
  - $\sigma(\bar{\nu}_e e \to \bar{\nu}_e e) = \frac{G_\mu^2 m_e E_\nu}{2\pi}[\frac{1}{3} + \frac{4}{3}\sin^2\theta_W + \frac{16}{3}\sin^4\theta_W]$
- $\sigma(\nu_{\mu,\tau} e \to \nu_{\mu,\tau} e)$:$\sigma(\bar{\nu}_{\mu,\tau} e \to \bar{\nu}_{\mu,\tau} e)$:$\sigma(\nu_e e \to \nu_e e)$:$\sigma(\bar{\nu}_e e \to \bar{\nu}_e e) =$ 1:0.854:6.077:2.547
- 10520 $\nu e^- \to \nu e^-$ events assuming 1.2 MW beam power, 5 tons ND fiducial mass, 5 years neutrino running
  - $\sigma(\nu_\mu e \to \nu_\mu e)$:$\sigma(\bar{\nu}_\mu e \to \bar{\nu}_\mu e)$:$\sigma(\nu_e e \to \nu_e e)$:$\sigma(\bar{\nu}_e e \to \bar{\nu}_e e) \simeq$ 7800: 1690: 845 : 184
- A clean determination of the neutrino flux
- A clean determination of the weak mixing angle $\sin^2\theta_W$

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[1] W. Marciano and Z. Parsa, arXiV: hep-ph/0403168

Selection Cuts

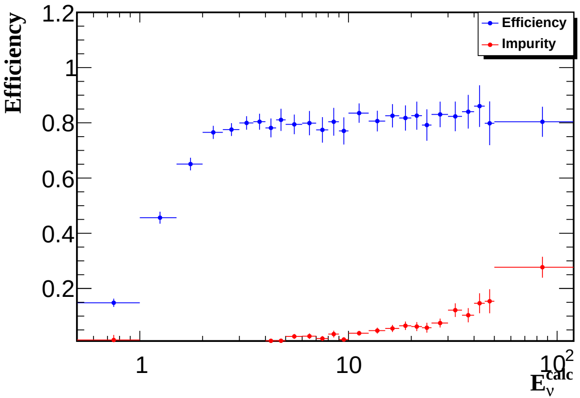
Cut	Sig.	Sig. Eff.	Back.	Back. Surv. Prob.
Fiducial	1.052e+04	1	9.747e+07	1
$p_e > 0.2$ GeV/c & $n_e^{\rm hits} \geq 4$	9784	0.9301	9.607e+07	0.9856
μ-veto	9784	0.9301	3.476e+07	0.3566
$\pi^0/n/K_0$ veto	9784	0.9301	1.69e+07	0.1734
no positive track	9784	0.9301	2.961e+06	0.03038
1 negative track	8724	0.8294	2.288e+04	0.0002347
$E_e > 0.5$ GeV & $n_e^{\rm hits} \geq 12$	7680	0.7301	331.5	3.401e-06
$p_e^T < 0.1$ GeV	7677	0.7298	324.9	3.333e-06
$\theta_e < 0.1$ Rad	7677	0.7298	324.9	3.333e-06

- $\mu_{\rm ID}$:
  $\mu_{\rm ID} = 60\%$ @ $p_\mu \in [0.2, 0.6]$ GeV/c,
  $\mu_{\rm ID} = 80\%$ @ $p_\mu \in [0.6, 1.0]$ GeV/c,
  $\mu_{\rm ID} = 95\%$ @ $p_\mu > 1.0$ GeV/c.
- π^0 veto: Require $p_\gamma < 0.08$ GeV,
- neutron veto: Require $T_n < 0.25$ GeV,
- K_0 veto: Require $T_{K_0} < 0.25$ GeV,
- TRD efficiency applied: 90% for electron, 10^{-3} for $\mu^\pm, \pi^\pm, K^\pm$, *etc.*

$\nu e^- \to \nu e^-$ efficiency as a function of $E_{\rm calc}$

- Average signal efficiency is 73% (7677 signal events passing the cuts) with 4% background

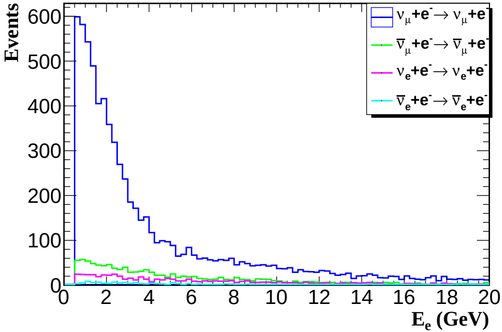
$$E_\nu^{\rm calc} = \frac{(M_e E_e - M_e^2)}{M_e - E_e + E_e \cos\theta_e} \tag{1}$$



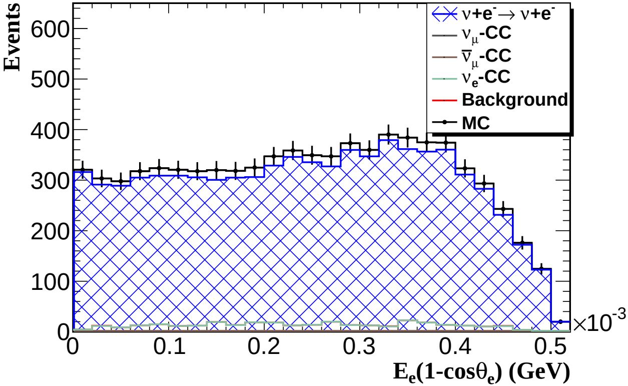
$\nu e \to \nu e$ composition

Energy Range	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$
0.5-5.0 GeV	0.907	0.085	0.006	0.001
5.0-10 GeV	0.624	0.345	0.022	0.009
$>$ 10 GeV	0.624	0.332	0.026	0.017

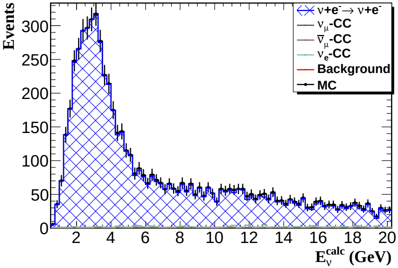
Table: Flux composition in different energy range.

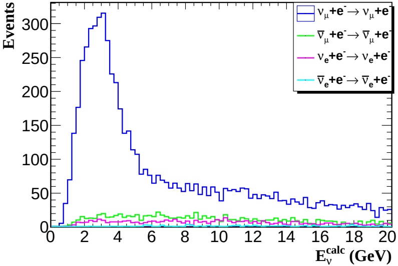


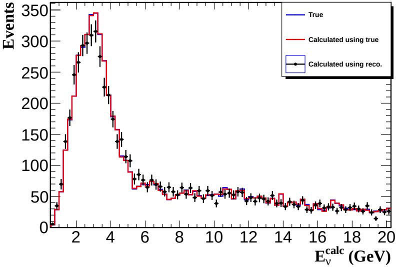
$\mathcal{Z}_e$ distribution



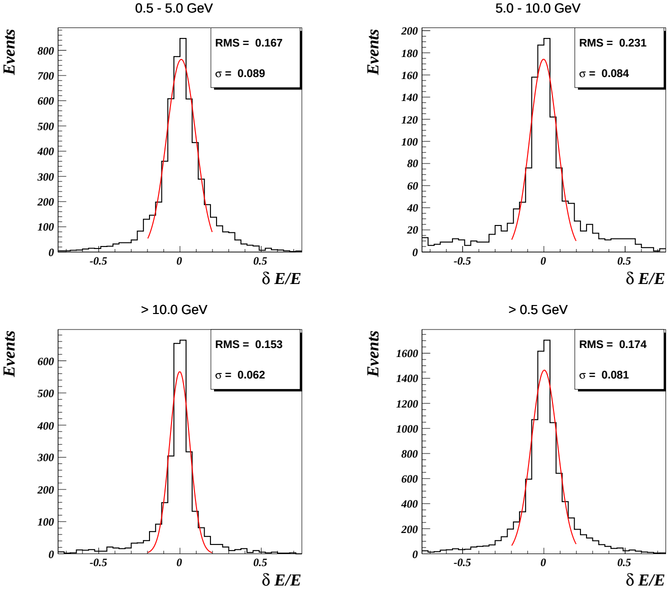
E_ν^{calc}



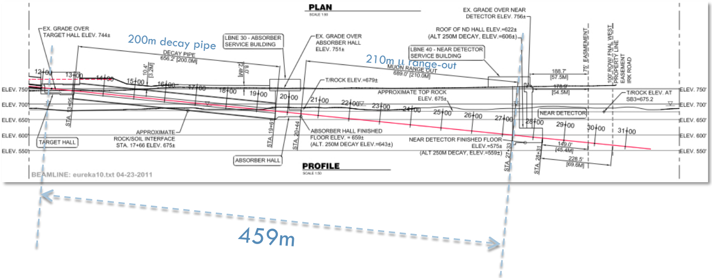




Energy resolution - nominal angular resolution



Effect of the beam divergence



- 459 m[2] = distance from upstream end of proton target to upstream end of ND hall
- Target is 9 m downstream of upstream end of target hall
- Target hall + 200 m decya pipe + absorber + 210 m of rock for muon range out

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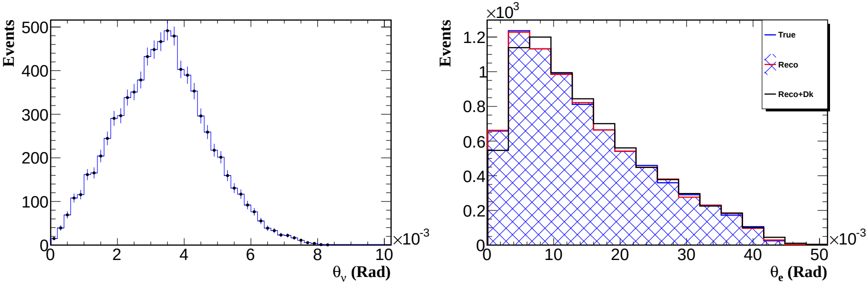
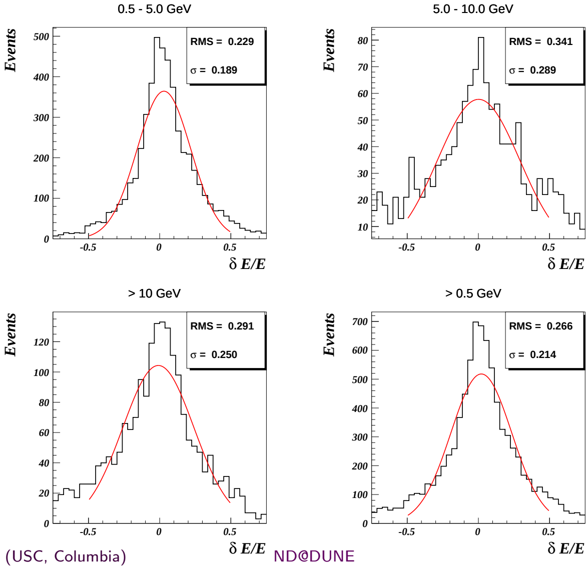
[2] 574 m in current engineering drawing

Neutrino's intrinsic p_T (θ_ν)

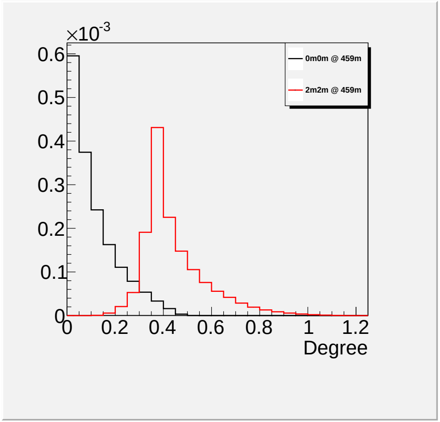


- The beam p_T can be measured precisely with coherent pion production

Energy resolution - nominal angular resolution + neutrino intrinsic angle

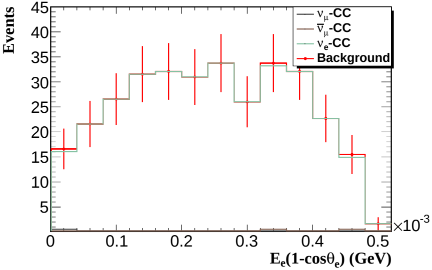


Neutrino's intrinsic p_T (θ_ν)



- We can reduce the effect of the beam divergence by considering the correlation between the electron angle and the vertex location (i.e. final uncertainty should be smaller).

e^- vs e^+ sample background



- e^+/e^- separation in B field allows to calibrate in-situ symmetric backgrounds (from data).

ND Requirements for $\nu e^- \to \nu e^-$ Scattering

- Low density medium to track $e^\pm$ - $\rho \sim 0.1$ g/cm^3
- Trasition Radiation : $e^\pm$
- dE/dx : $\pi^\pm$, $K^\pm$ and proton
- Magnet : $+$ .vs. -
- Large statistics to reach $\sim$ 3% statistical precision
- Excellent momentum and angular resolution

Inverse Muon Decay

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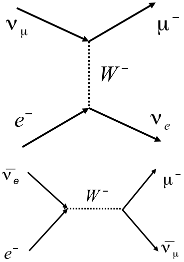
Inverse Muon Decay [3]

$$\frac{d\sigma(\nu_l e \rightarrow l \nu_e)}{dy} = \frac{G_\mu^2}{\pi}(2m_e E_\nu - (m_l^2 - m_e^2)) \qquad (2)$$

$$\frac{d\sigma(\bar{\nu}_e e \rightarrow l \bar{\nu}_l)}{dy} = \frac{G_\mu^2}{\pi}(2m_e E_\nu (1-y)^2 - (m_l^2 - m_e^2)(1-y)) \qquad (3)$$

$$y = \frac{E_l - \frac{m_l^2 + m_e^2}{2m_e}}{E_\nu} \qquad (4)$$

$$0 \leq y \leq y_{\max} = 1 - \frac{m_l^2}{2m_e E_\nu + m_e^2} \qquad (5)$$



- Cross section is extremely small
  - $\sigma(\nu_\mu e^- \rightarrow \mu^- \nu_e) \simeq 3\sigma(\bar{\nu}_\mu e^- \rightarrow \mu^- \bar{\nu}_\mu) \simeq \frac{2G_\mu^2 m_e E_\nu}{\pi} \simeq 1.5 \times 10^{-41}\ (E_\nu/\text{GeV})\ \text{cm}^2$
- Threshold $E_\nu \geq \frac{m_l^2 - m_e^2}{2m_e} \simeq 10.9$ GeV
- 5360 $\sigma(\nu_\mu e^- \rightarrow \mu^- \nu_e)$ events assuming 1.2 MW beam power, 5 tons ND fiducial mass, 5 years neutrino running
- A clean determination of the neutrino flux

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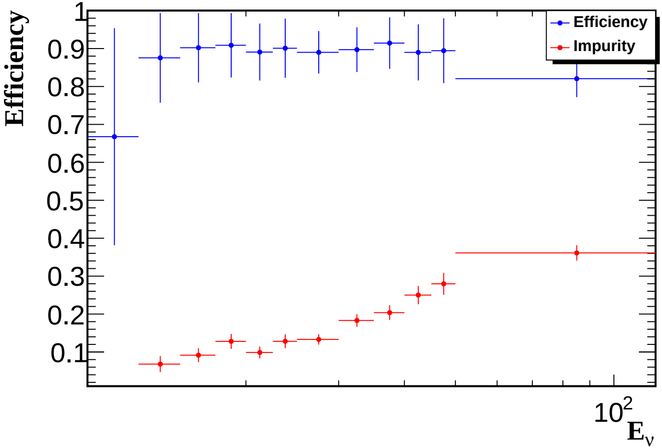
[3] W. Marciano and Z. Parsa, arXiV: hep-ph/0403168

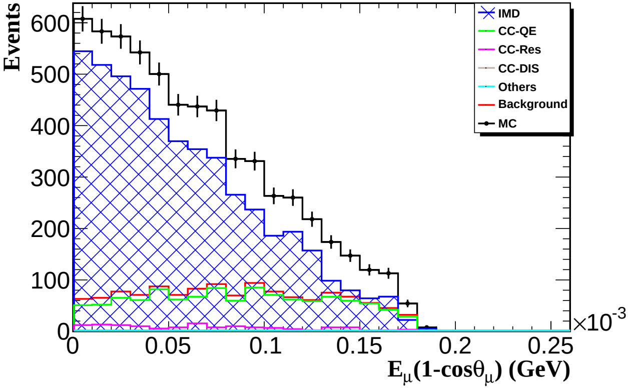
Cut Table

Cut	Sig.	Sig. Eff.	Back.	Back. Surv. Prob.
Fiducial	5357	1	6.505e+07	1
$p_\mu > 0.2$ GeV/c & $n_e^{\rm hits} \geq 12$	5357	1	6.281e+07	0.9655
μ-ID	5091	0.9502	5.648e+07	0.8683
$\pi^0/n/K_0$ veto	5091	0.9502	3.148e+07	0.484
no second track	5091	0.9502	2.02e+06	0.03106
$E_\mu > 10.9$	4960	0.9258	1709	2.627e-05
$p_\mu^T < 0.15$ GeV	4960	0.9258	1699	2.612e-05
$\theta_\mu < 0.005$ Rad	4960	0.9258	1699	2.612e-05
$\mathcal{Z}_\mu < 0.00025$	4960	0.9258	1699	2.612e-05
$\mathcal{NN} > 0.20$	4881	0.9112	1253	1.926e-05

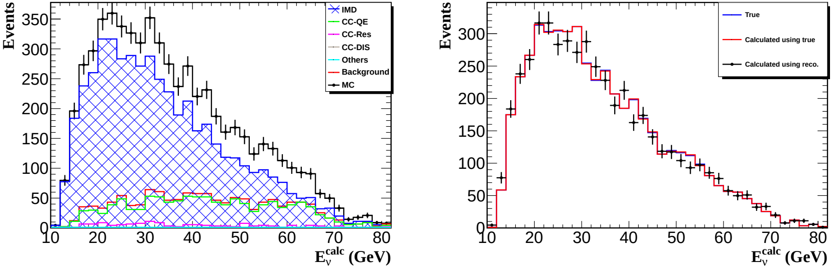
IMD efficiency as a function of E_ν W/ NN cut



$\mathcal{Z}_\mu$ distribution W/ NN cut

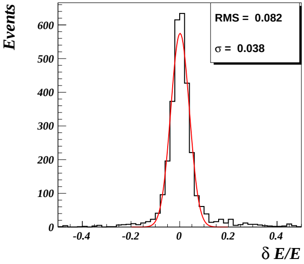


E_ν^{true} vs E_ν^{calc} w/ NN cut

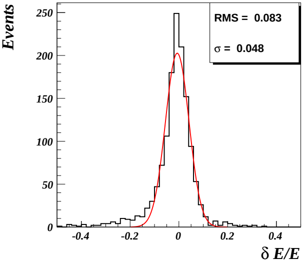


Energy resolution - nominal angular resolution

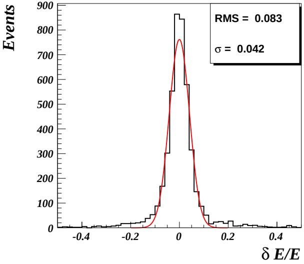
11.0 - 40.0 GeV



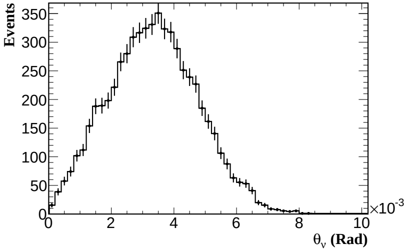
> 40.0 GeV

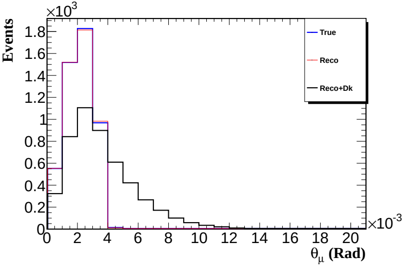


> 11.0 GeV

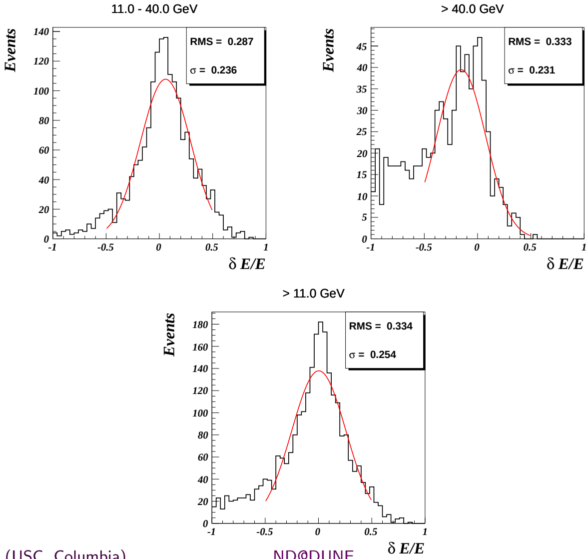


Neutrino Intrinsic p_T (θ_ν)

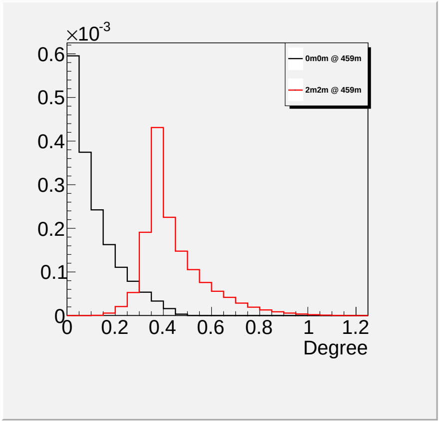




Energy resolution - nominal angular resolution + neutrino intrinsic angle



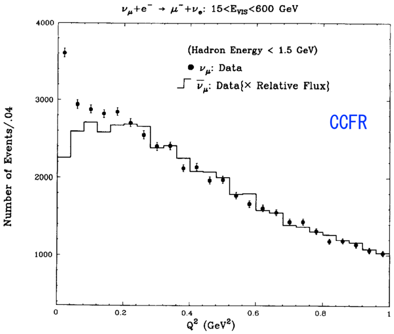
Neutrino's intrinsic p_T (θ_ν)

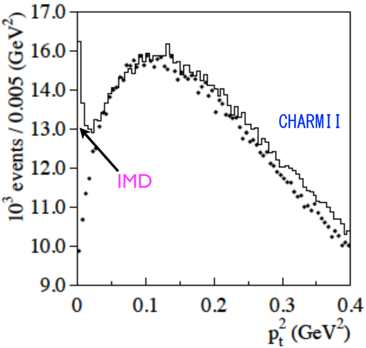


- We can reduce the effect of the beam divergence by considering the correlation between the electron angle and the vertex location (i.e. final uncertainty should be smaller).

$\nu_\mu N$-CC background to IMD

- $\nu_\mu N$-CC background to IMD dominated by low-y interactions, largely QE
  - The nuclear effects in CCQE, in particular the FSI which can dramatically increase the number of 1 track events
- A measure of this background is $\bar{\nu}_\mu N$-CC (No IMD in $\bar{\nu}_\mu$), but with $\sim 5\%$ precision
- CCFR (S. R. Mishra *et al.* Phys. Lett. B 252, 170 (1990)): $\pm 5.2\%$ with $|E_\nu| \cong 100$ GeV
- Charm II (P. Vilain *et al.* Phys. Lett B 364, 121 (1995)): $\pm 5.6\%$ with $|E_\nu| \cong 23$ GeV
- Measure 2-track $\nu_\mu N$-CC ($\mu^- + X$) to constrain the background when $E_x \sim 0 \Rightarrow (\mu^-, 0)$





$\nu_\mu N$-CC background to IMD - Constraints from μ^+ and $\mu^- + X$

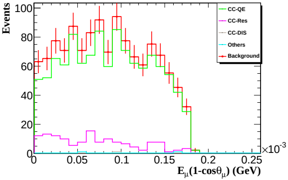


Figure: IMD background

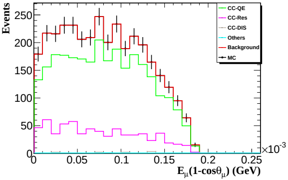


Figure: μ^+ IMD-like

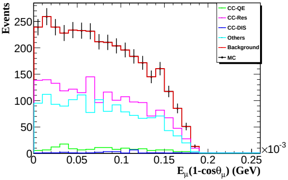
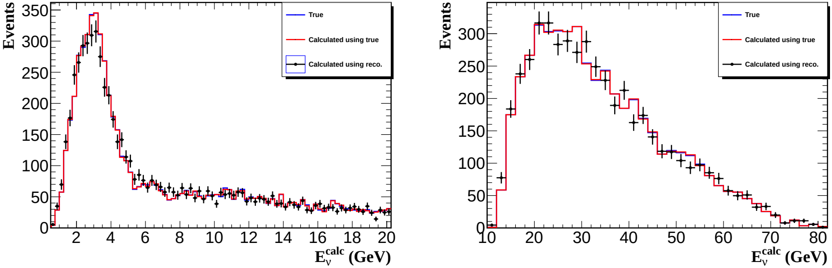


Figure: $\mu^- + X$ IMD-like

Neutrino Electron NC scattering + IMD



ND Requirements for IMD

- dE/dx : $\pi^{\pm}$, $K^{\pm}$ and proton
- Magnet : + .vs. -
- MuID : μ
- Large statistics
- Excellent momentum and angular resolution

Near Detector Options

Fine Grained Tracker

- Pros
  - Angular resolution ~2 mrad, $e^{\pm}$ID: transition radiation + dE/dx + ECAL, μID, Charge measurement: B field, e+ vs. e- separation: ρ ~0.1 g/cm^3
- Cons
  - Statistics

Liquid Argon TPC

- Pros
  - Large statistics, $e^{\pm}$ ID: dE/dx + e.m. shower (calorimetry), e/γ separation
- Cons
  - Containment .vs. pile-up, angular resolution, B field?

Gaseous Argon TPC

- Pros
  - Angular resolution ~mrad, $e^{\pm}$ID: dE/dx + ECAL, μID, Charge measurement: B field, e+ vs. e- separation: ρ ~0.04 g/cm^3
- Cons
  - VERY low statistics (fiducial mass ~0.5 t), pile-up vs. outside backgrounds

Summary and Outlook

ND Parametrized Simulation/Reconstruction (Fast MC)

$\nu e^- \rightarrow \nu e^-$

Inverse Muon Decay

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- Absolute neutrino flux determination
  - Neutrino electron NC scattering:
    - Signal efficiency is ∼73% with 4% background
    - Can measure the flux to 2% level
  - IMD:
    - Signal efficiency is ∼91% with 20% background
    - Can measure the absolute flux to 3% precision for $E_\nu > 11$ GeV
- Ongoing analysis
  - Coherent $\pi^{\pm}$
  - Beam dispersion