A High Resolution ν Near-Detector for Neutrino Factory $\mu \succ \nu_e\, \nu_\mu$

✴ *The PMNS Matrix Elements*

❧ δ Sensitivity

❧ ν-Mass Hierarchy

❧ Resolving degeneracies

✴ *Beyond PMNS*

❧ Θ_{23} = 45^0 ?

❧ Θ_{13} vs $\bar{\Theta}_{13}$

❧ CPT Violation ?

⇒ *Need systematic precision*

❧ High Δm**2 Oscillation ?

❧ Phenomenon that defies the Zeitgeist

✴ *The Familiar, Beautiful Neighborhood*

❧ Cross-section

❧ Sin**2(Θ_W): precision commensurate with Colliders

❧ Sum rules

❧ Isospin Physics

❧ Heavy neutrinos

❧ ……..

❧ Rewriting the ν-text-book

$\mathcal{ND}$ PHYSICS GOALS

- *Determination of the relative abundance, the energy spectrum, and the detailed topology (complete hadronic multiplicity) of the four neutrino species in NuMI:* ν_μ, $\bar{\nu}_\mu$, $\boxed{\nu_e}$, *and* $\boxed{\bar{\nu}_e}$ *CC-interactions.* ⇐Absolute ν-Flux & Eν-scale; Cross-Sections

- *An 'Event-Generator Measurement' for the LBL*ν *experiments including single and coherent* π^0 (π^+) *production,* $\pi^\pm/K^\pm/p$ *for the* ν_e*-appearance experiment, and a quantitative determination of the neutrino-energy scale.* ⇐Backgrounds to Oscillation

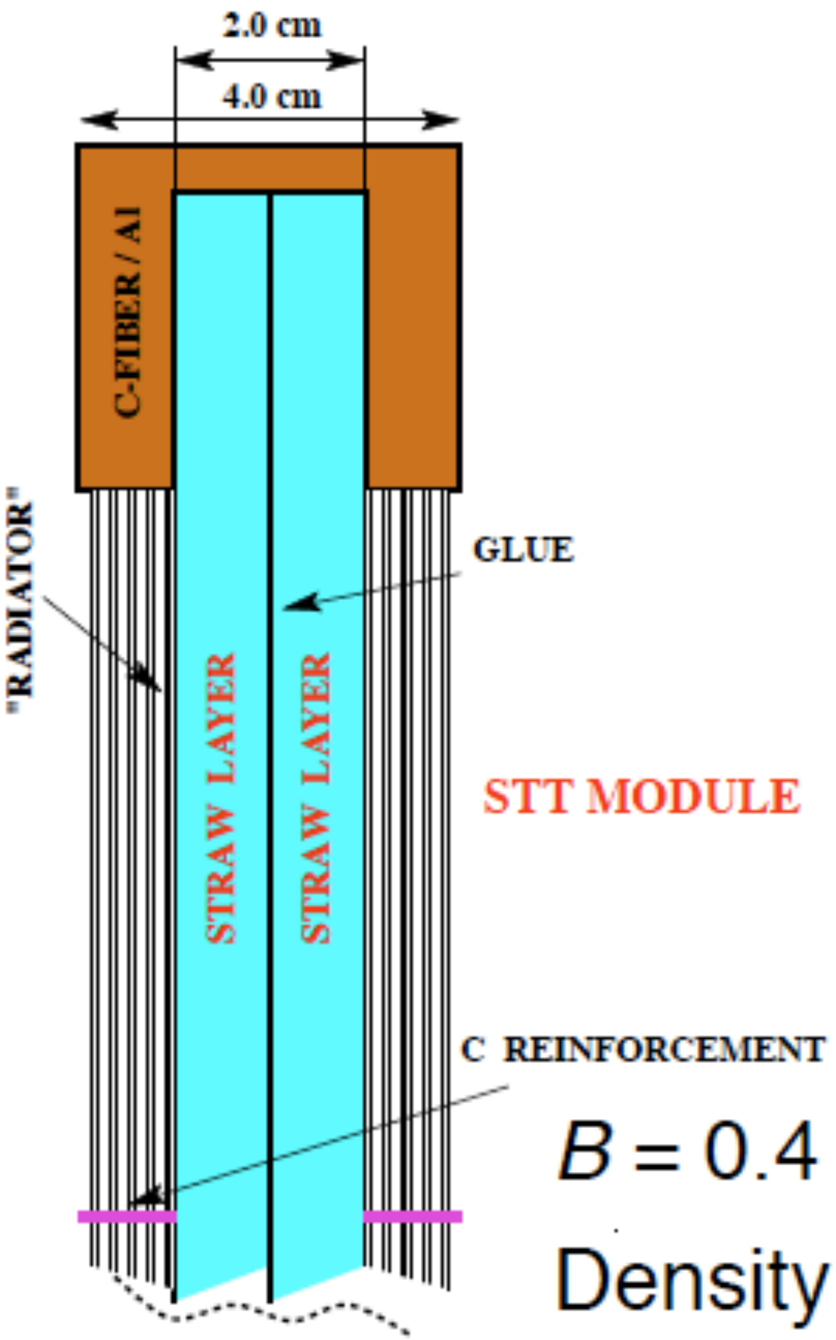
- *Measurement of the weak-mixing angle,* $\sin^2\theta_W$, *with a precision of about 0.2%, using independent measurements:*
  - $\nu(\overline{\nu})$*-q (DIS);*
  - $\nu(\overline{\nu})$*-e*$^-$ *(NC).*

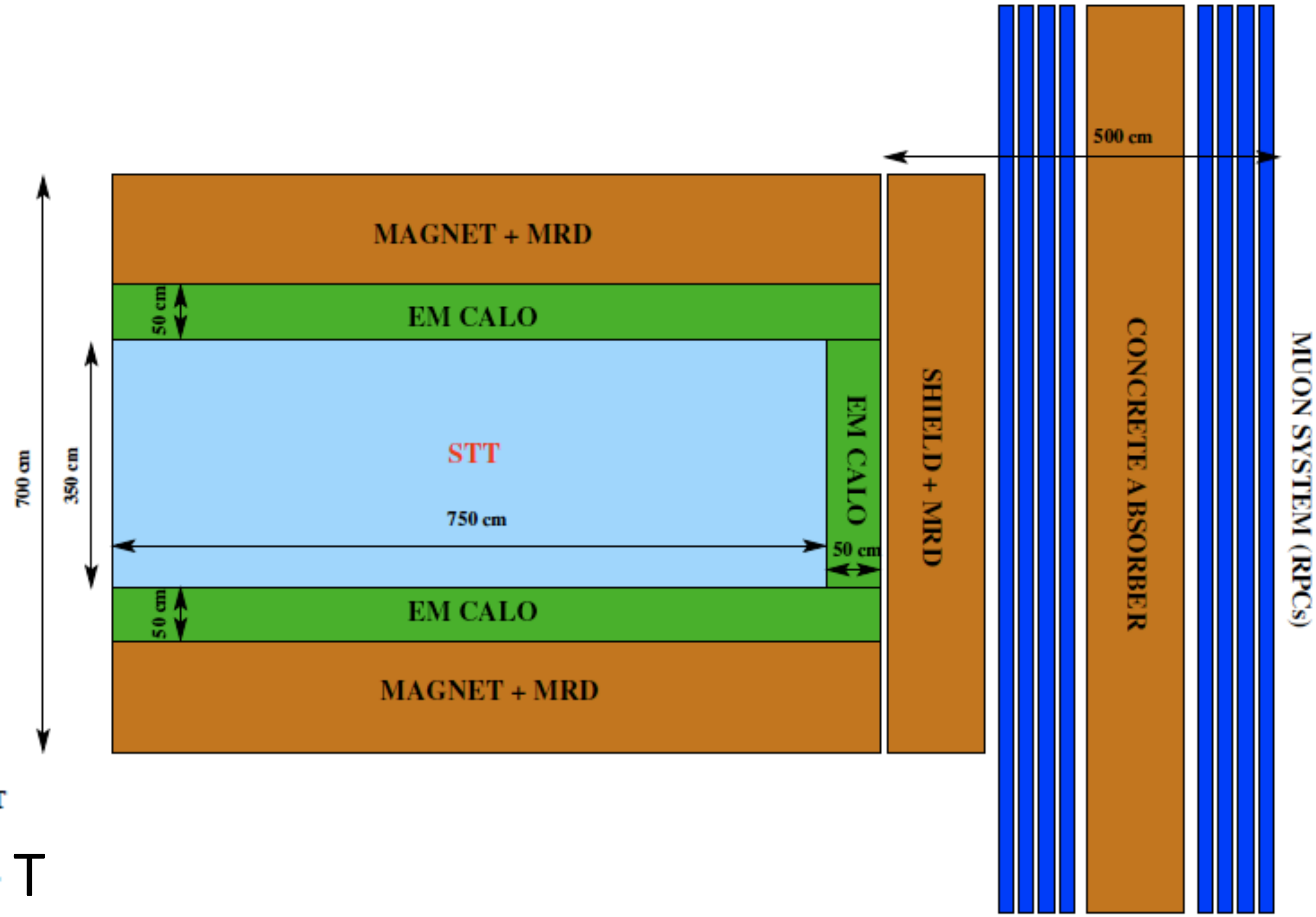
  ⇐Example of Precision Measurement

  Direct probe of the running of $\sin^2\theta_W$ *within a single experiment.*

- *Precise determination of the exclusive processes such as* ν *quasi-elastic, resonance,* $K^0/\Lambda/D$ *production, and of the nucleon structure functions.*

- *Search for weakly interacting massive particles with electronic, muonic, and hadronic decay modes with unprecedented sensitivity.*





$B = 0.4\ \mathrm{T}$

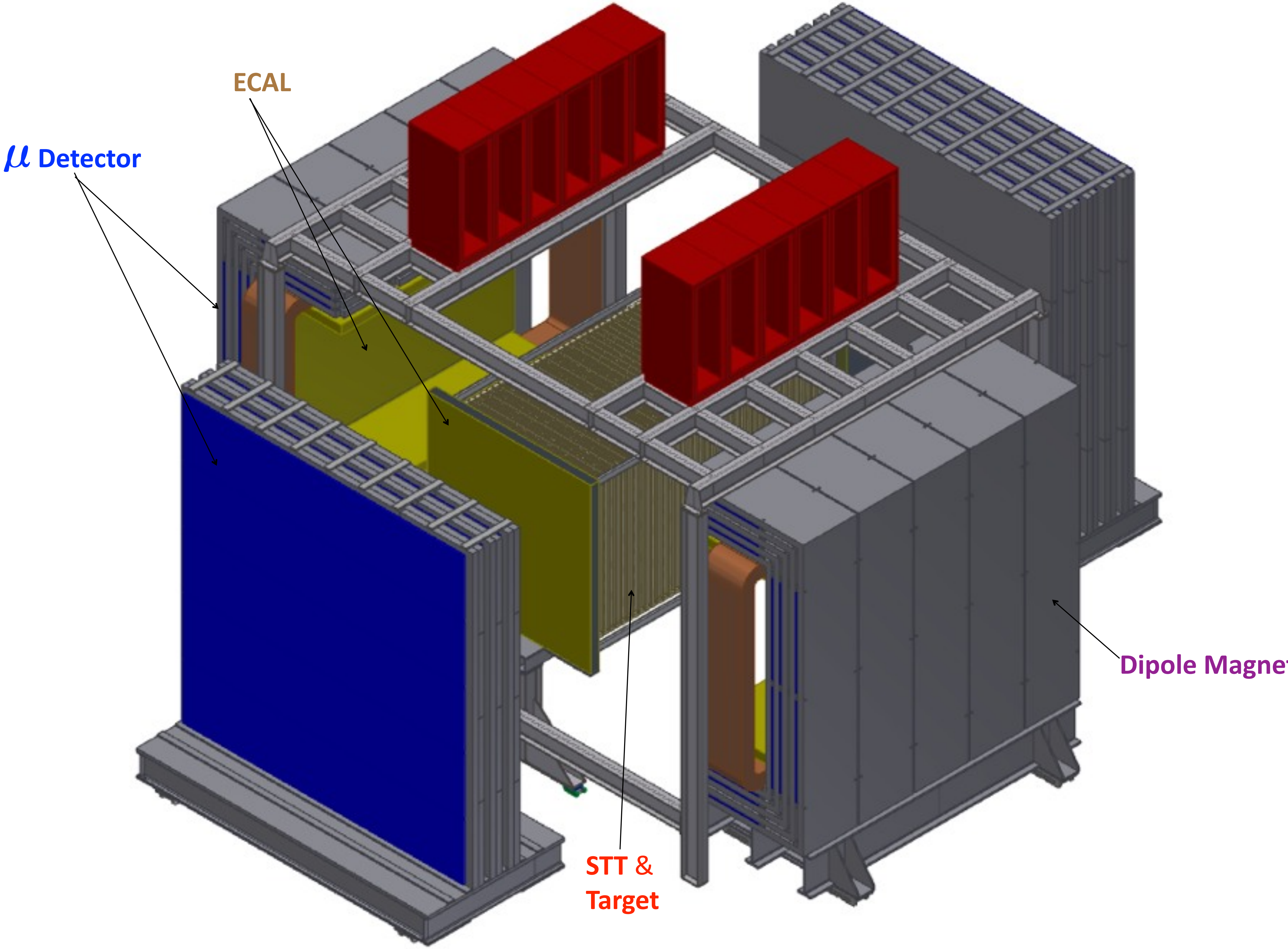
Density = 0.1 g/cm3, 85% in the radiator foils.

Transition Radiation ↠ Electron ID ⇒ γ (w. Kinematics)

dE/dx ↠ Proton, π, K ID

Magnet/Muon Detector ↠ μ

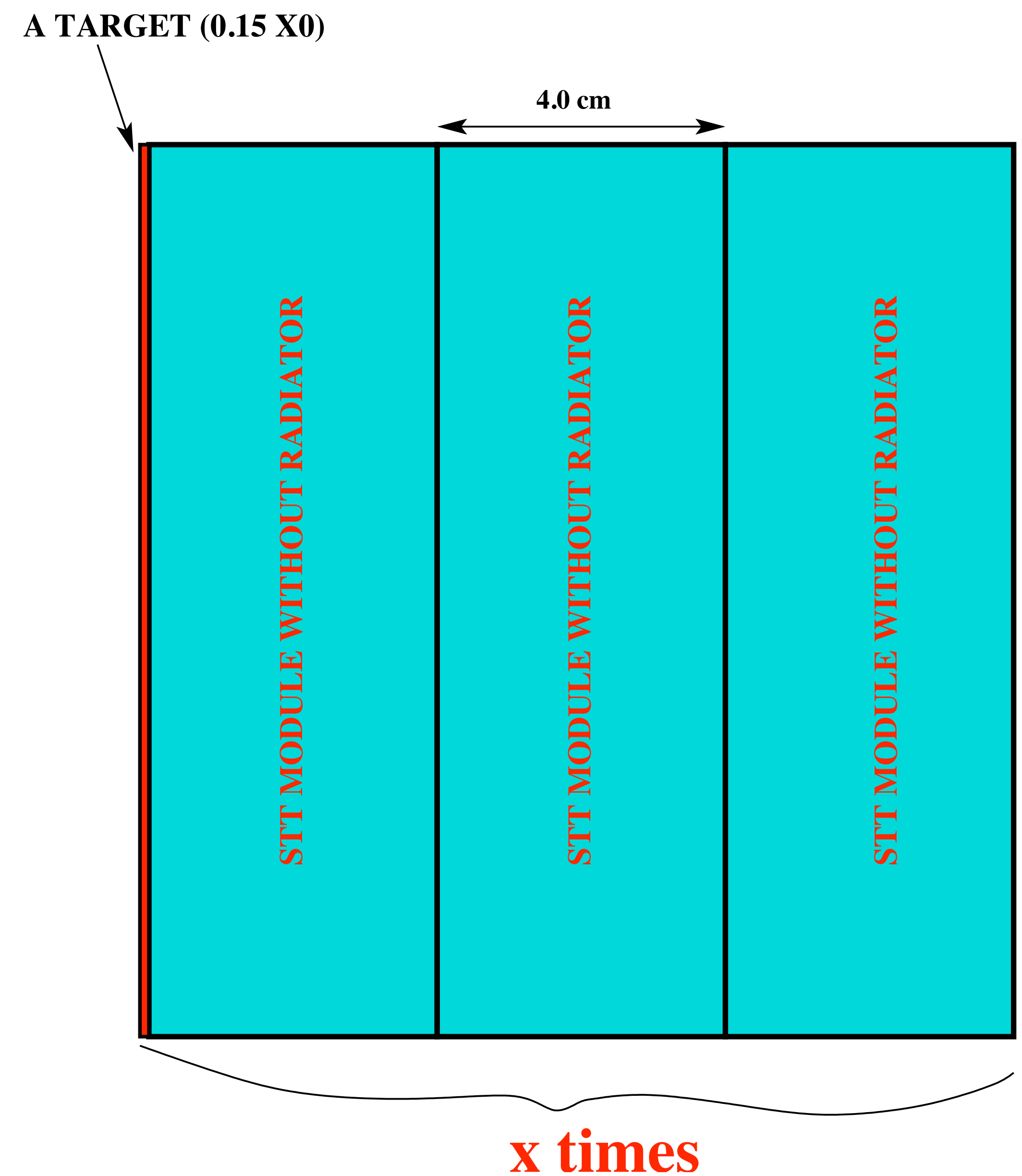
HIRESMNU: *N*ear *D*etector for *LBNE*



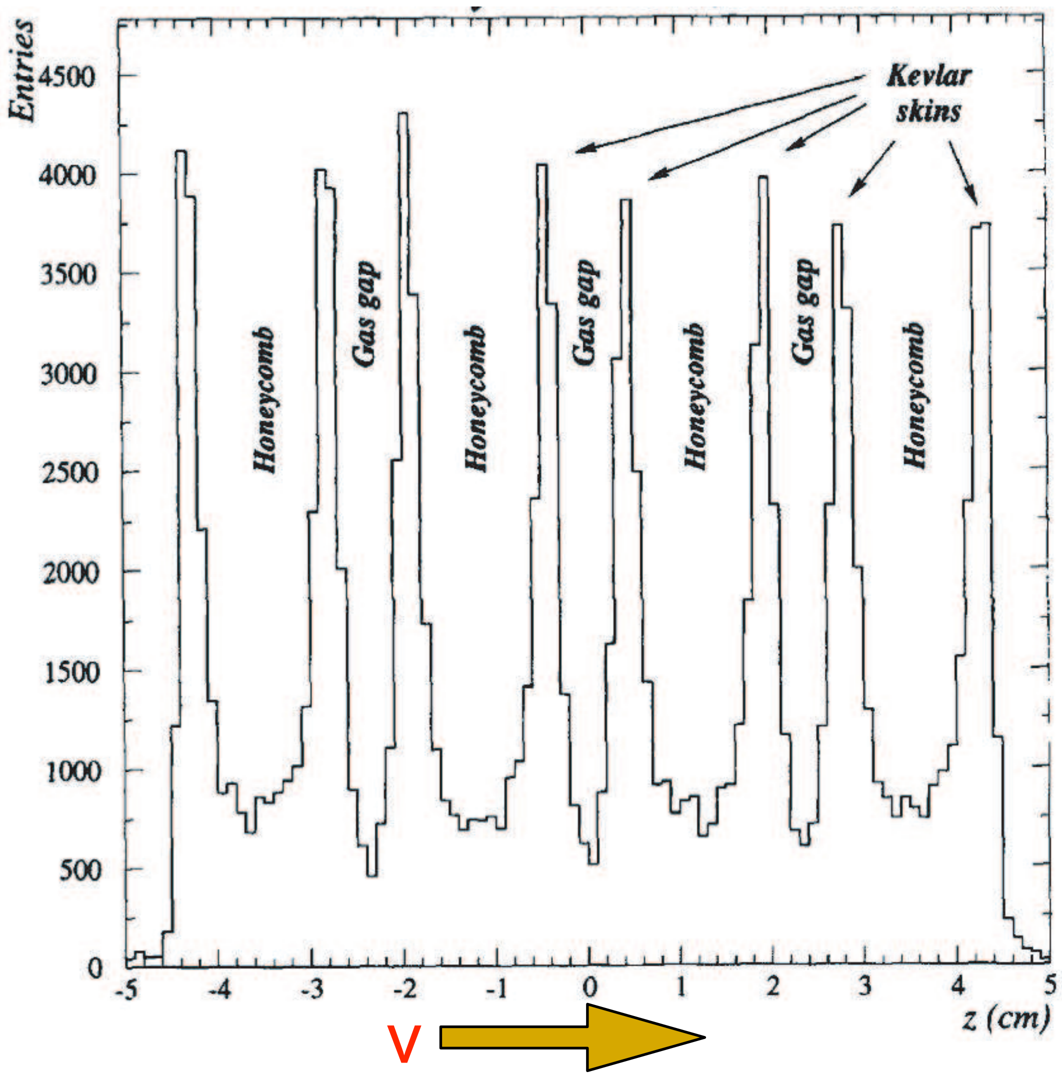
MEASURING NUCLEAR EFFECTS *(Fe, Ar, ..)*

- *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.*

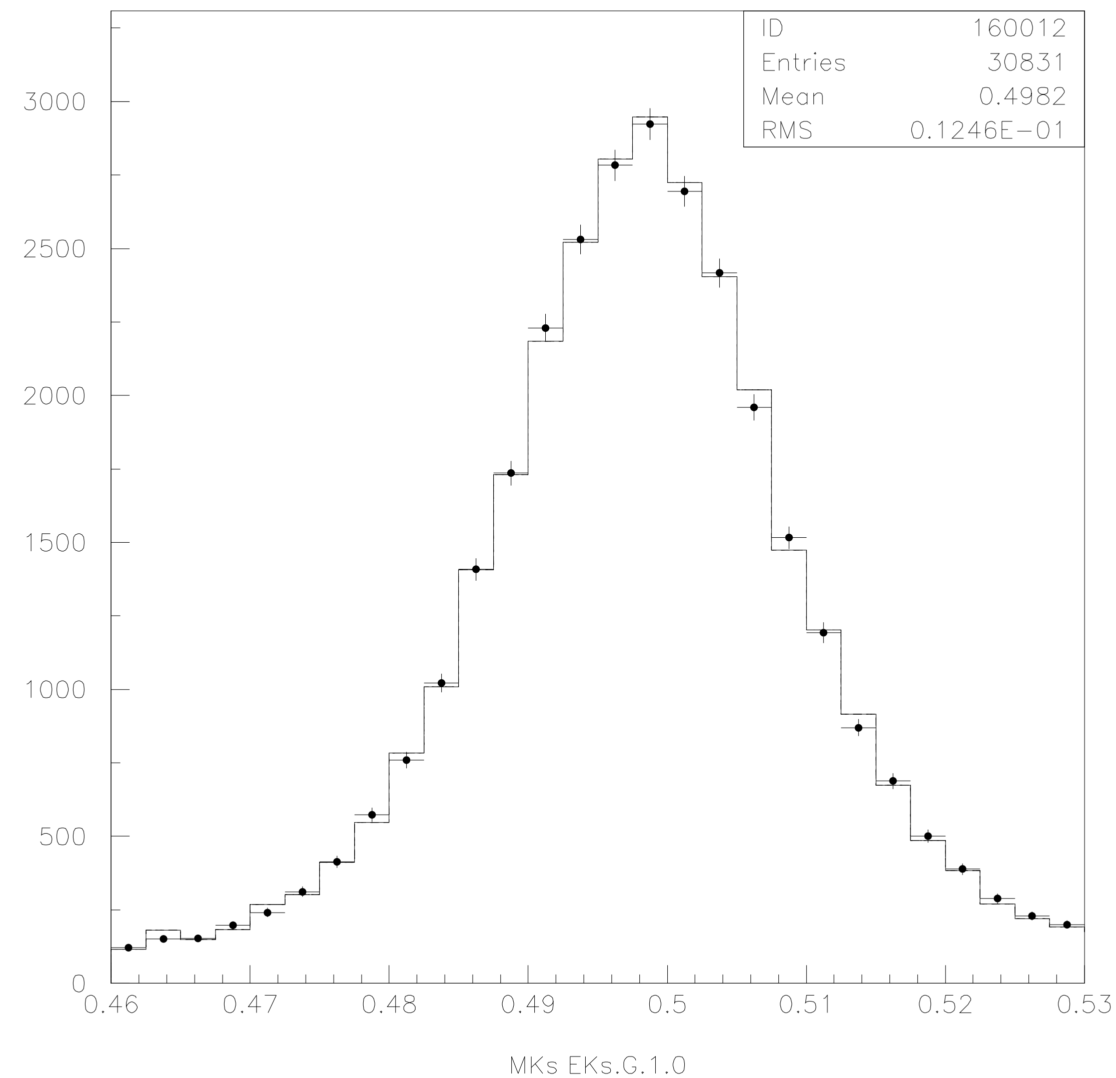
- *Use 0.15X_0 thick target plates in front of three straw modules (providing 6 space points) without radiators. Nuclear targets upstream.*
  - *For Ca target consider CaCO_3 or other compounds;*
  - $\boxed{\text{OPTION}}$*: possible to install other materials (Pb, etc.).*



What we build on: NOMAD DATA



Momentum Scale of μ



Neutrino radiography of one drift chamber

Reconstructed K^0 mass

- ✦ *NOMAD: charged track momentum scale known to* $< 0.2\%$
  hardonic energy scale known to $< 0.5\%$
- ✦ *HiResMν:* $\boxed{200\times}$ *more statistics and* $\boxed{12\times}$ *higher segmentation*

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

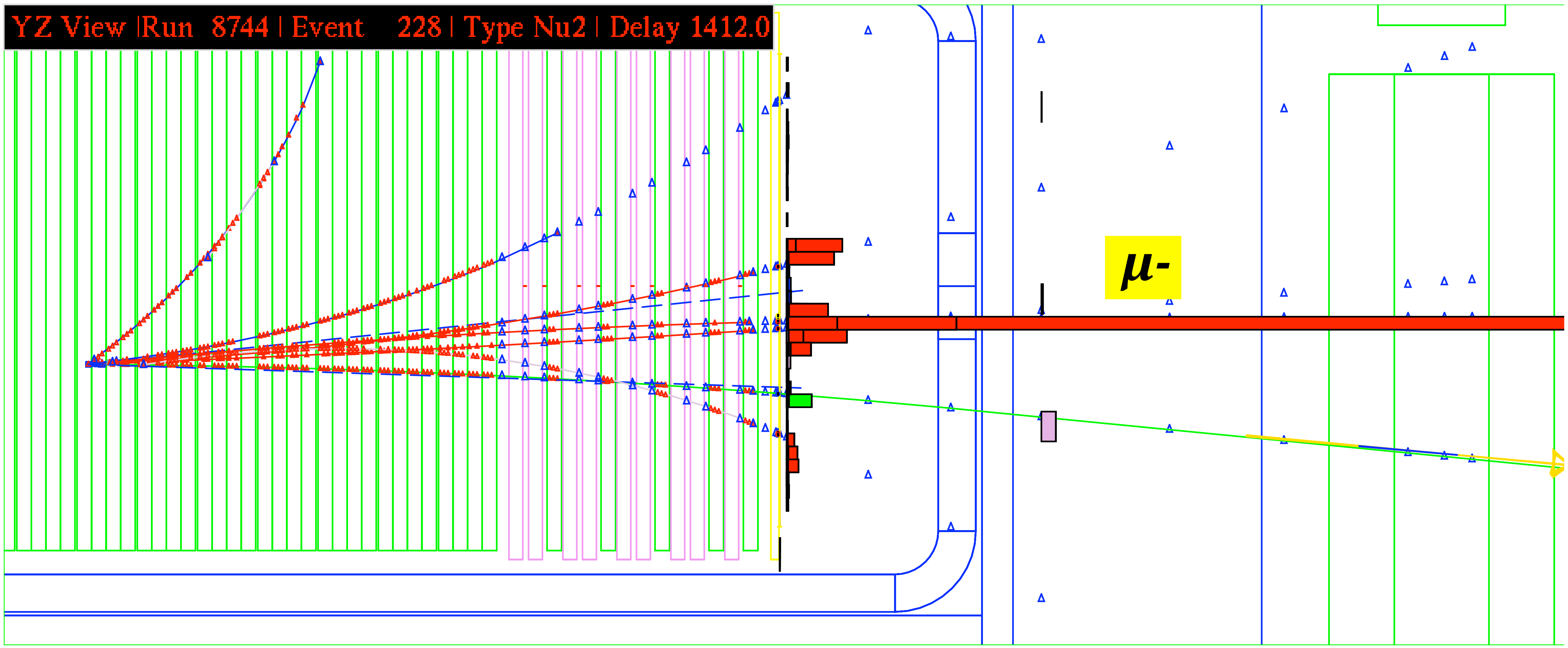
NOMAD -vs- HIRESMNU

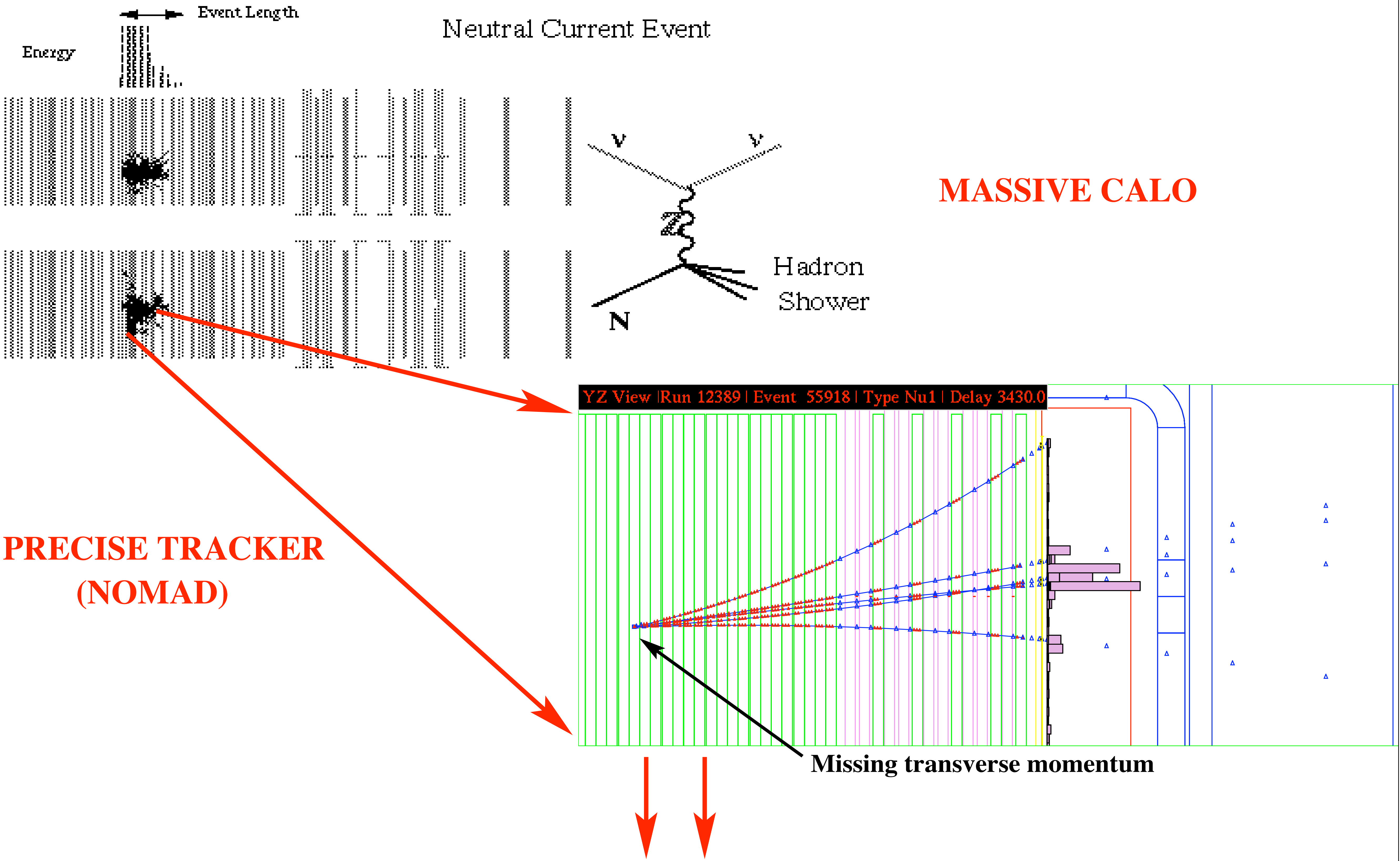
- Tracking Charged Particles ⇒
- Electron/Positron ID ⇒
- Calorimetry ⇒
- μ-ID ⇒
- Trigger ⇒

Sub-Detector	NOMAD	HiResMnu	Improvement
Tracking		$\times 6$ more hits in X-Y $\times 2$ more hits along Z	$\times 2$ higher QE-Proton Eff. $e^{\pm}$ down to 80 MeV γ-Conv. Reconstruction
TR: Electron-ID	Downstream	Continuous	$\simeq \times 3$ $e^{\pm}$-Eff
Calorimetry Segmentation	Downstream No Longitudinal Transverse	4π Coverage Fine Longitudinal Finer Transverse	Much better converage $e^{\pm}/\pi$ Separation Better miss-P_T Powerful 'Dirt'-Veto
E-shower Resolution	$3\%/\sqrt{E}$	$6\%/\sqrt{E}$	Poorer resolution
μ-ID	Downstream $P_\mu \geq 2.5$ GeV	4π Coverage	P_μ down to 0.3 GeV
Trigger	Downstream No Cal.Trigger	Continuous in STT Calorimetric Trigger	P down to 0.1 GeV $E \simeq 0.3$ GeV

NOMAD versus HiResMnu

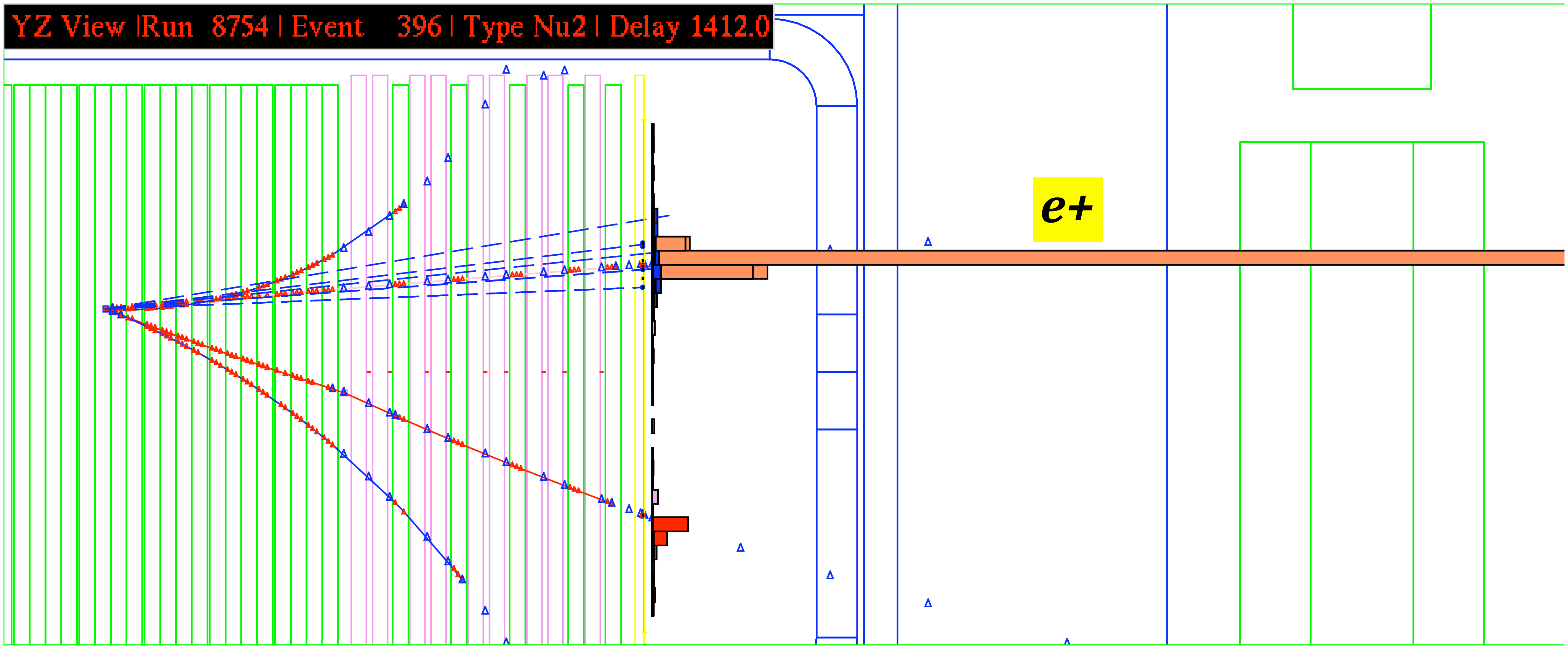
A ν_μ CC candidate in NOMAD





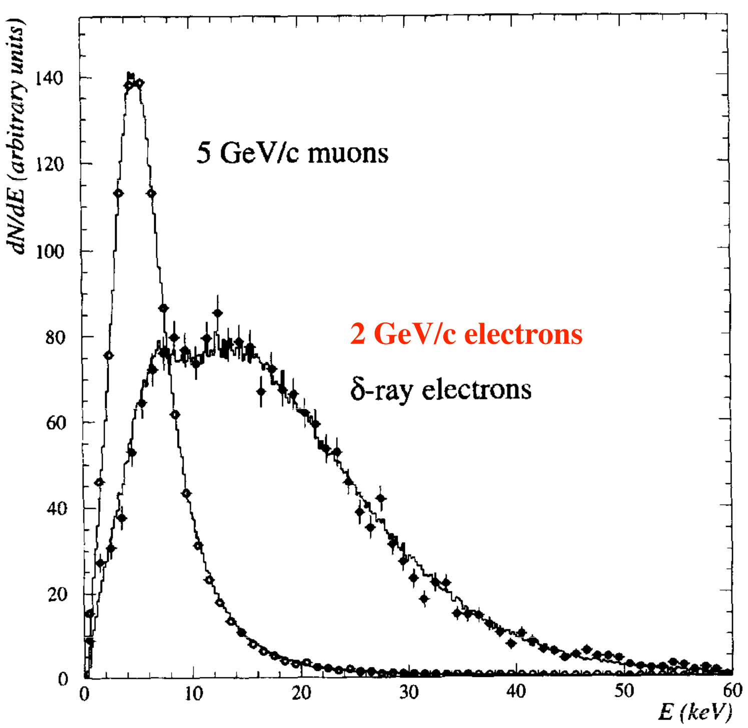
HiResMν : order of mag. higher segmentation

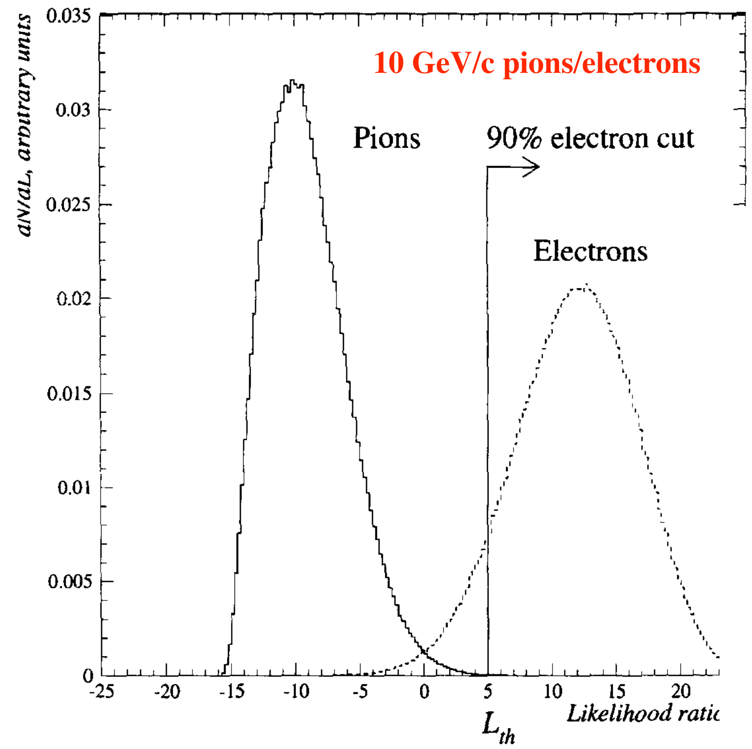
A $\bar{\nu}_e$ CC candidate in NOMAD



Electron ID

Analog readout: pulse height





NOMAD TRD reaches a 0.1% pion contamination for isolated tracks of momenta 1-50 GeV/c with 90% electron efficiency

Electron TR-Eff as a function of Pe for 10**-3 rejection of μ-π

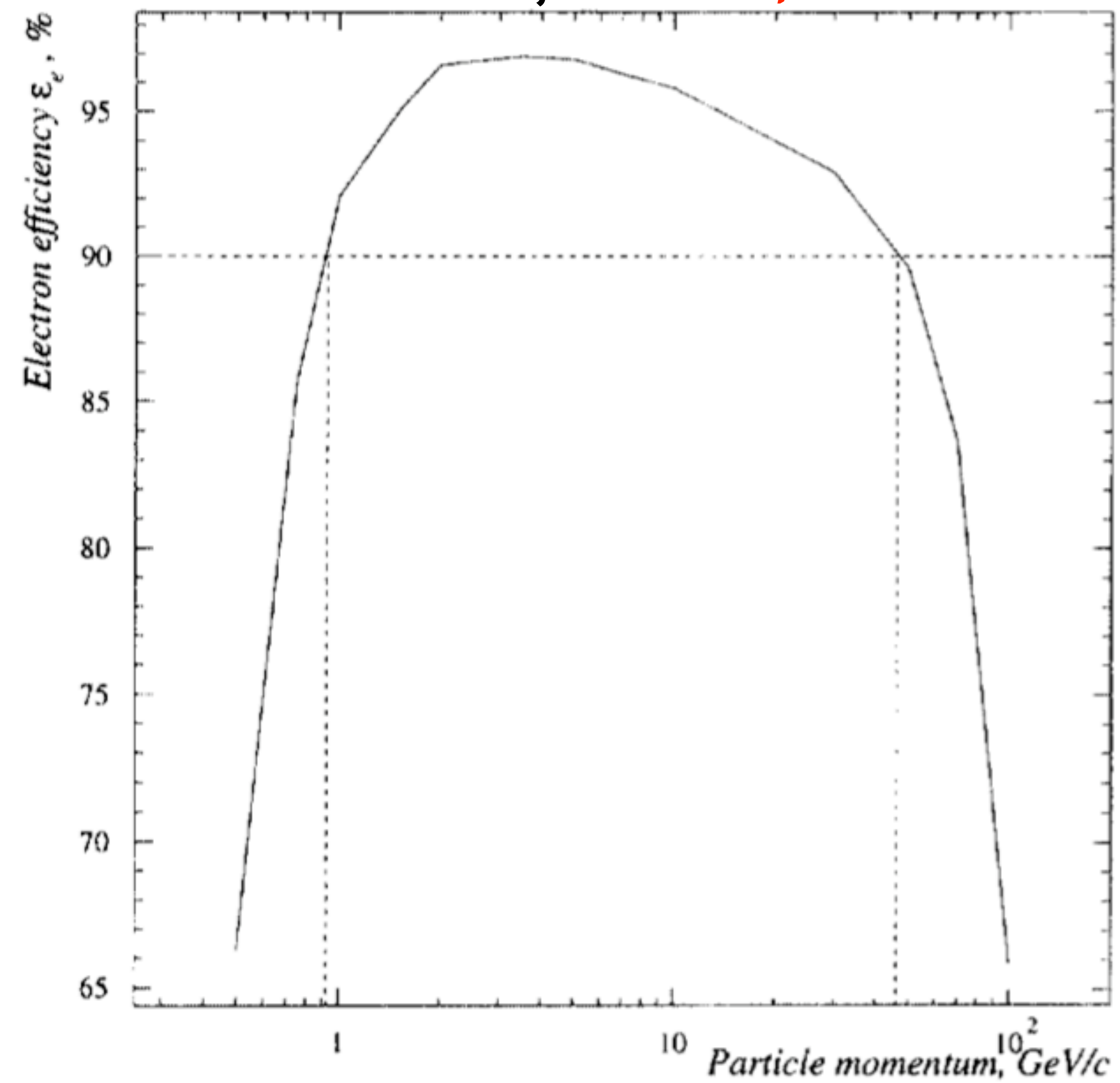


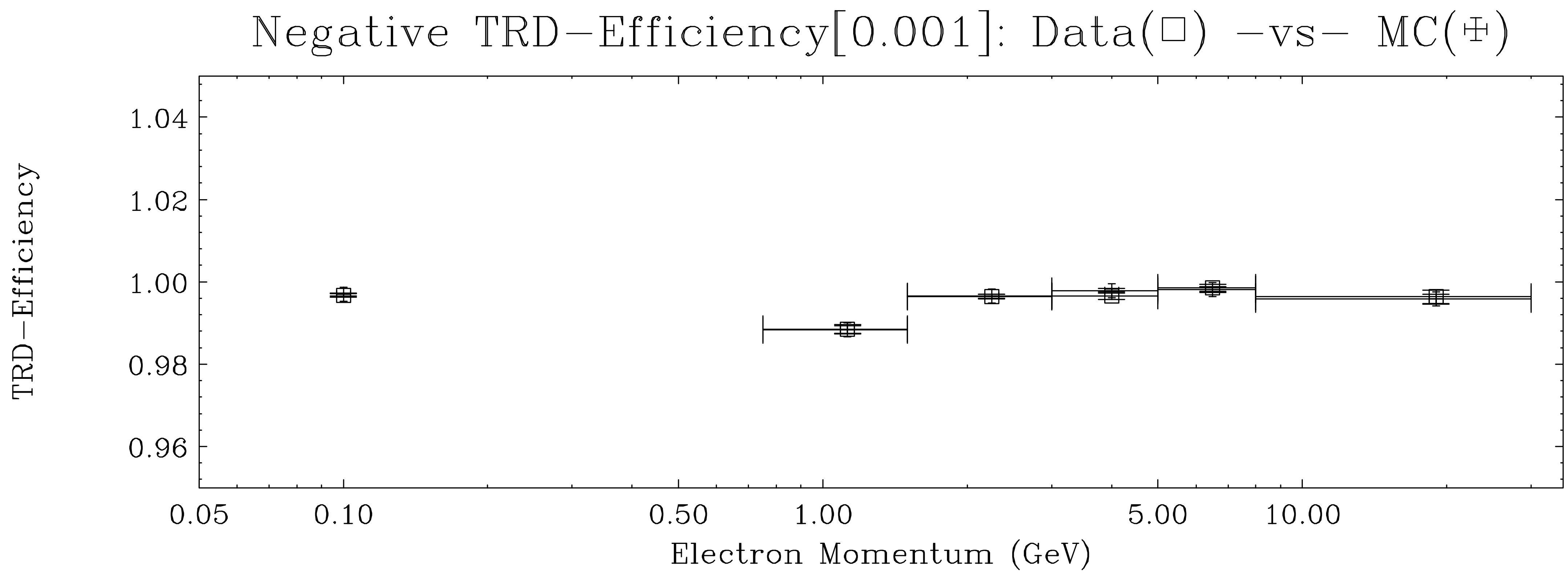
Fig. 8. Monte Carlo predicted electron efficiency ε_e correspond-ing to $\varepsilon_\pi = 10^{-3}$ as a function of the momentum of the particle for 9 associated hits.

✷Atlas-TRT's Geant4 simulation conducted for the HiResMnu-config. verifies the e/μ-π separation assumed for the STT ➢

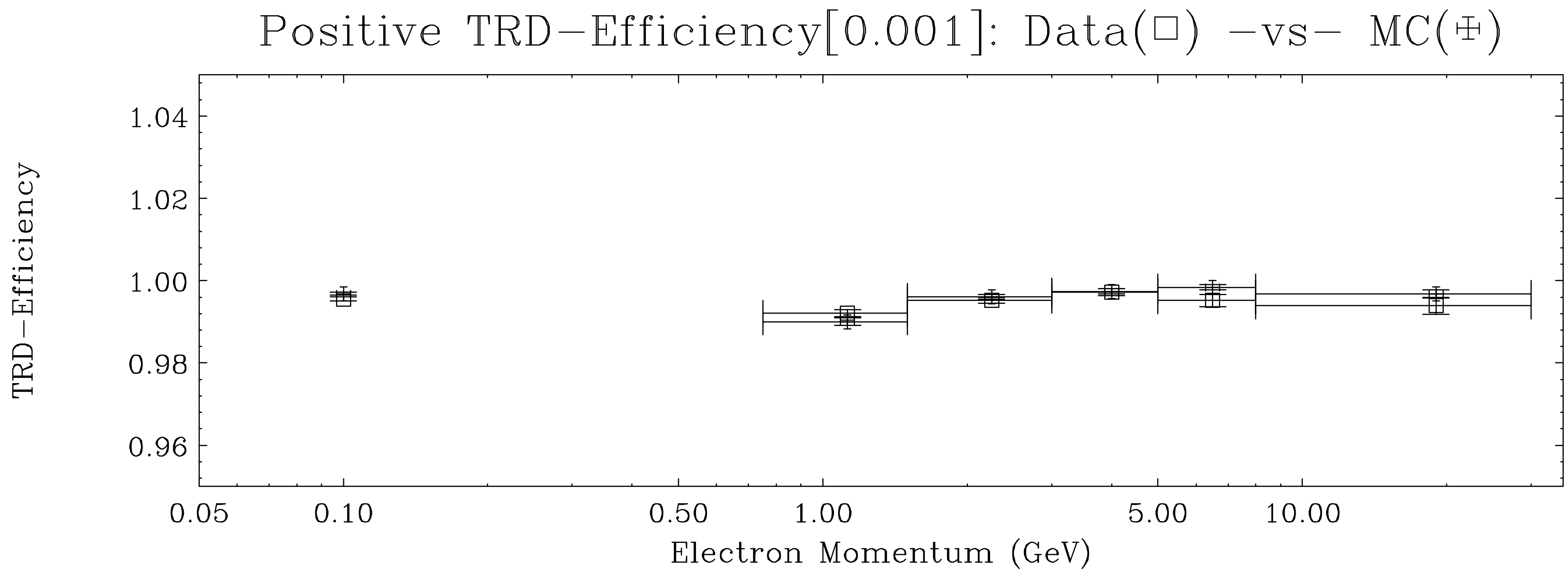
(See P.Nevski DocDB#432-V1)

e-/e+ TR-Efficiency in Data and MC

Use $\gamma \rightarrow e^- e^+$ sample (γ's come from $\pi^0 \twoheadrightarrow \gamma\gamma$)



Conclusion ⇛ Data-Eff−el = MC-Eff−el at << 1%



e- Sample

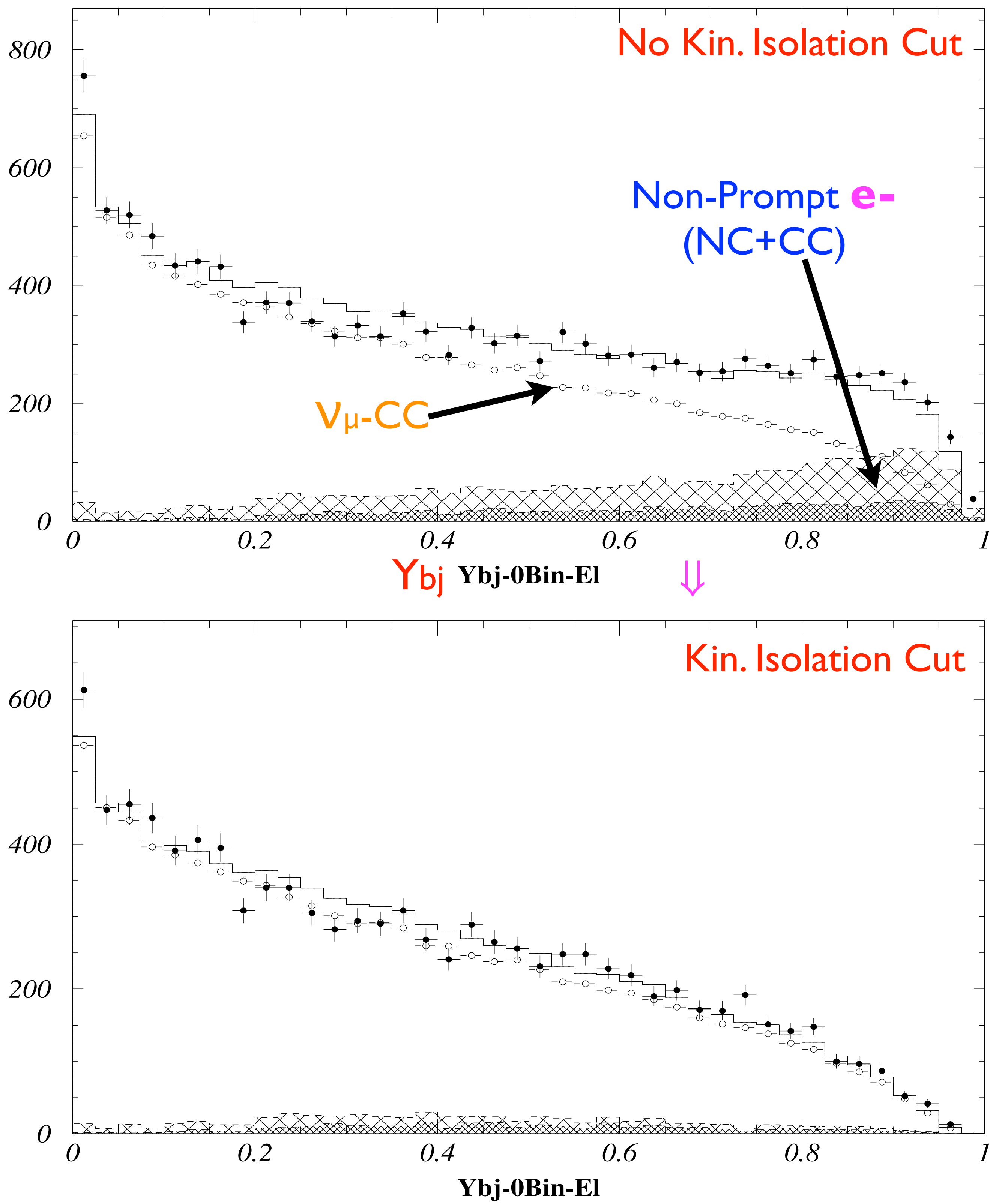


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Figure 20: Distribution of y_{bj} for e$^-$ (solid dots), μ^- (open dots), ν_μNC (big hatch) and CC (small hatch) background after scaling. The combined (histo) μ^- plus background agrees with the distribution of e$^-$ data. The bottom plot is the same as the top but includes kinematic

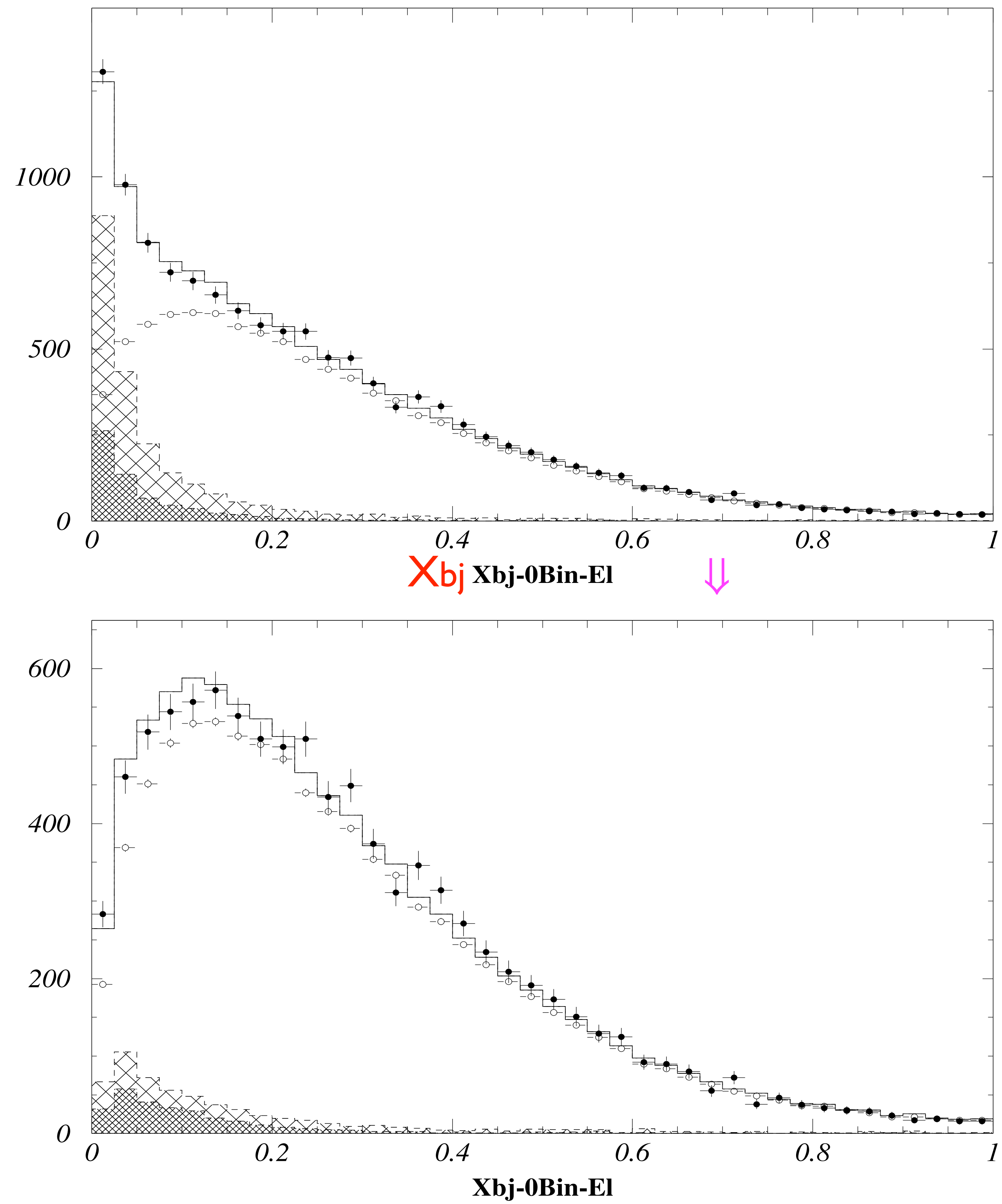

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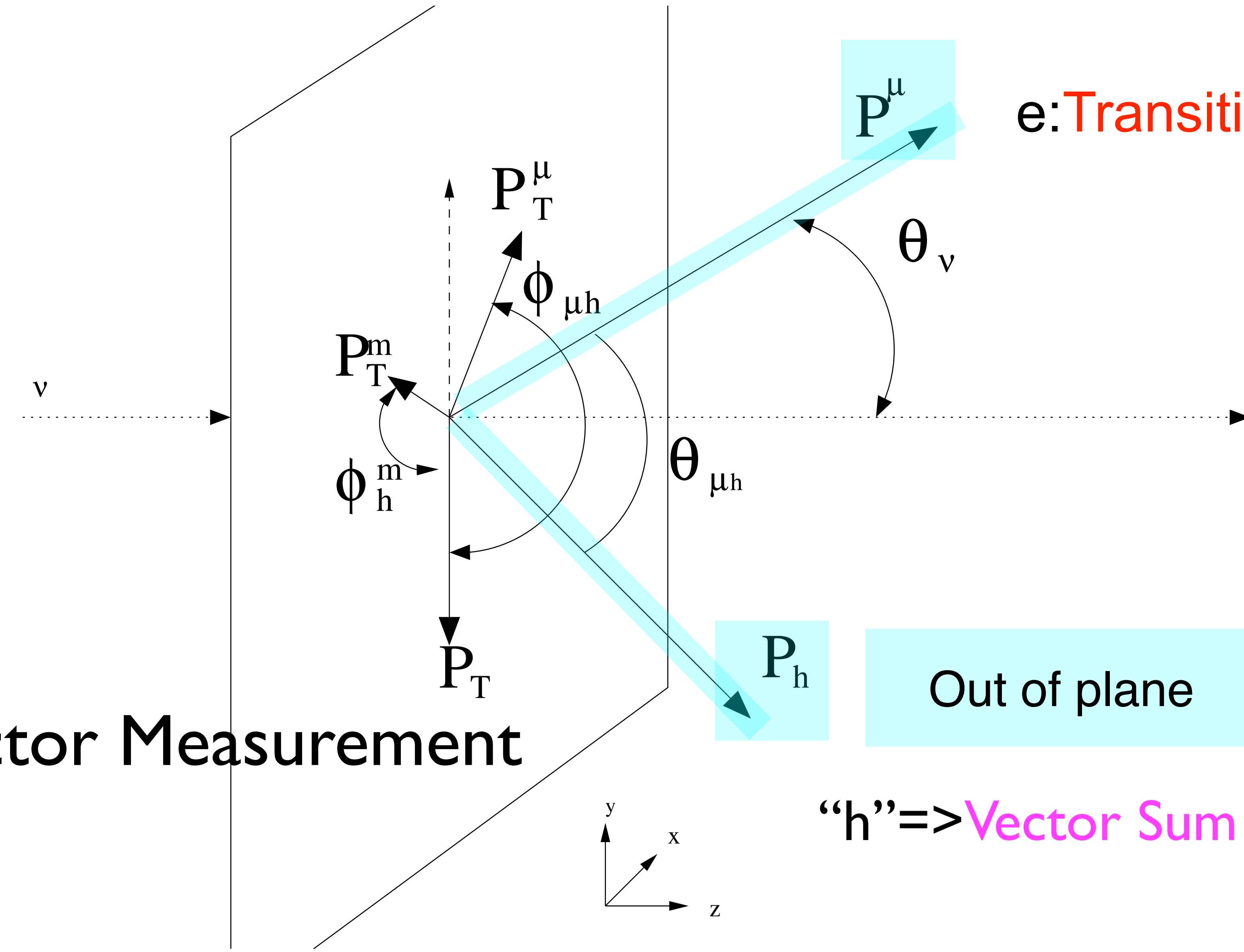
Figure 19: Distribution of x_{bj} for e$^-$ (solid dots), μ^- (open dots), ν_μNC (big hatch) and CC (small hatch) background after scaling. The combined (histo) μ^- plus background agrees with the distribution of e$^-$ data. The bottom plot is the same as the top but includes kinematic

Kinematics in HiResMnu



e:Transition Radiation

Out of plane

Pt-Vector Measurement

"h"=>Vector Sum of Tracks

Kinematic Isolation $\nu\hat{}=(P_TL-mP_T)/P_TH$: $\not{P}_T$-Plane

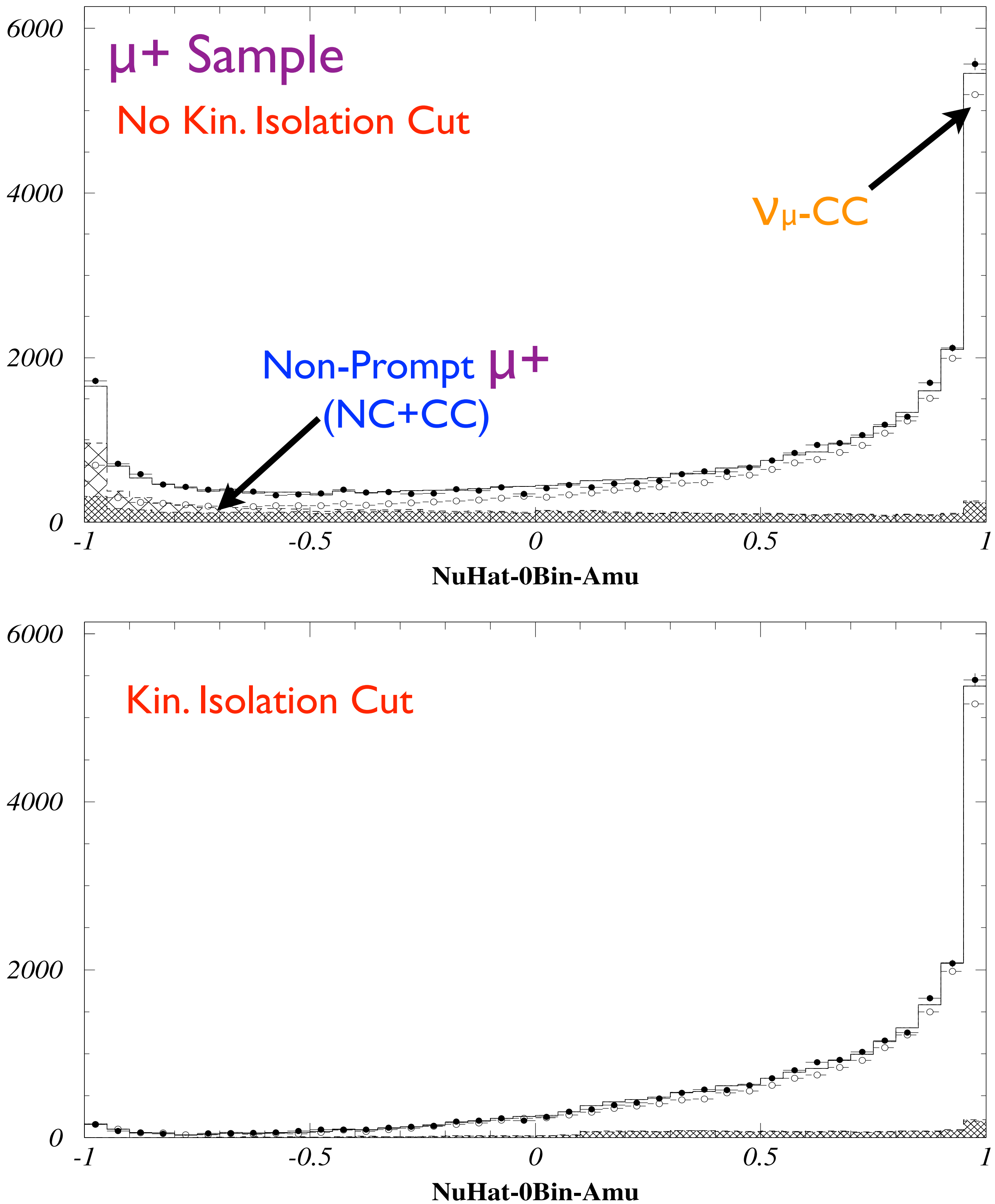


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Figure 11: Distribution of $\hat{\nu}$ for μ^+ (solid dots), μ^- (open dots), ν_μNC (big hatch) and CC (small hatch) background after scaling. The combined (histo) μ^- plus background agrees with the distribution of μ^+ data. The bottom plot is the same as the top but includes kinematic cuts.

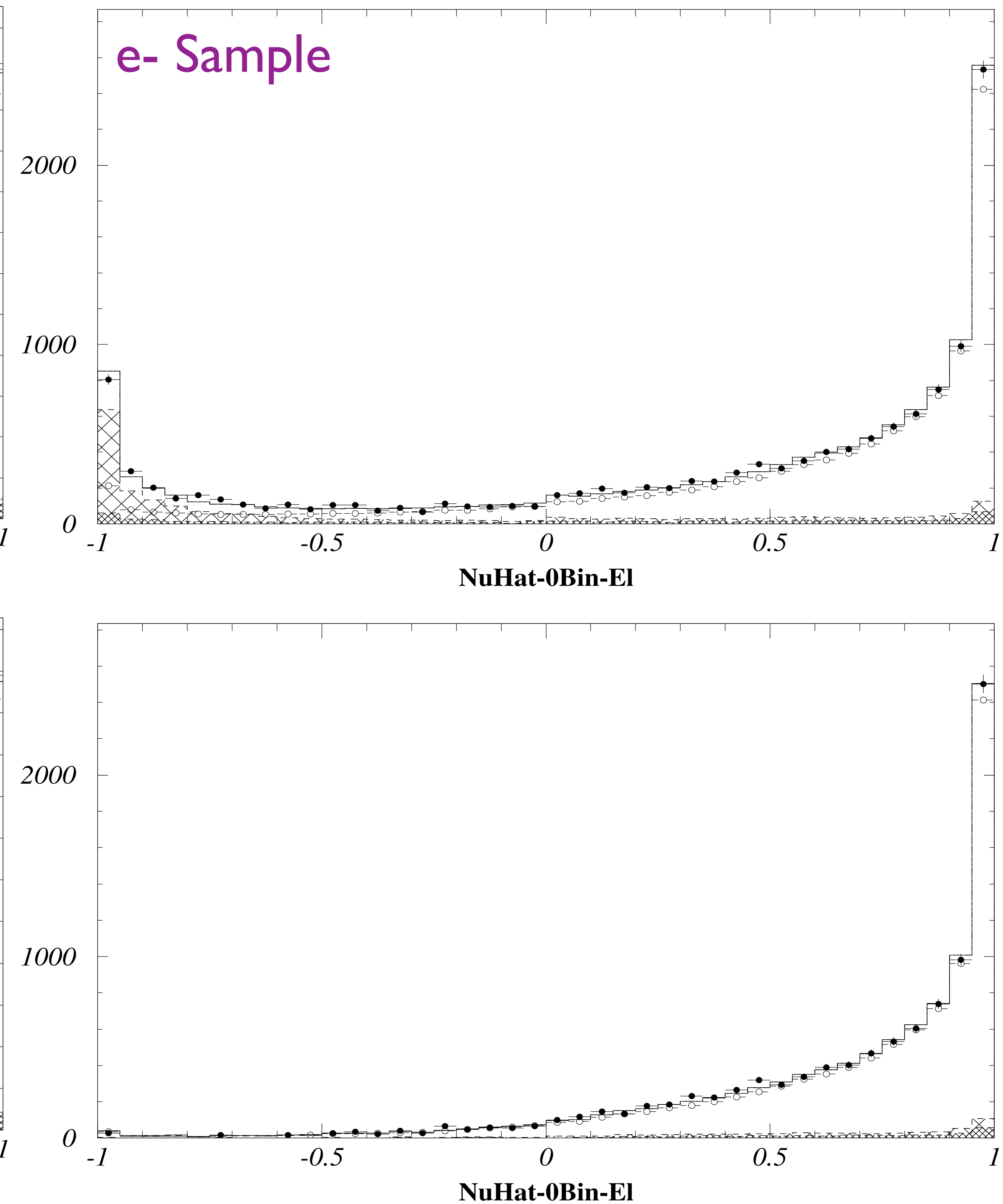

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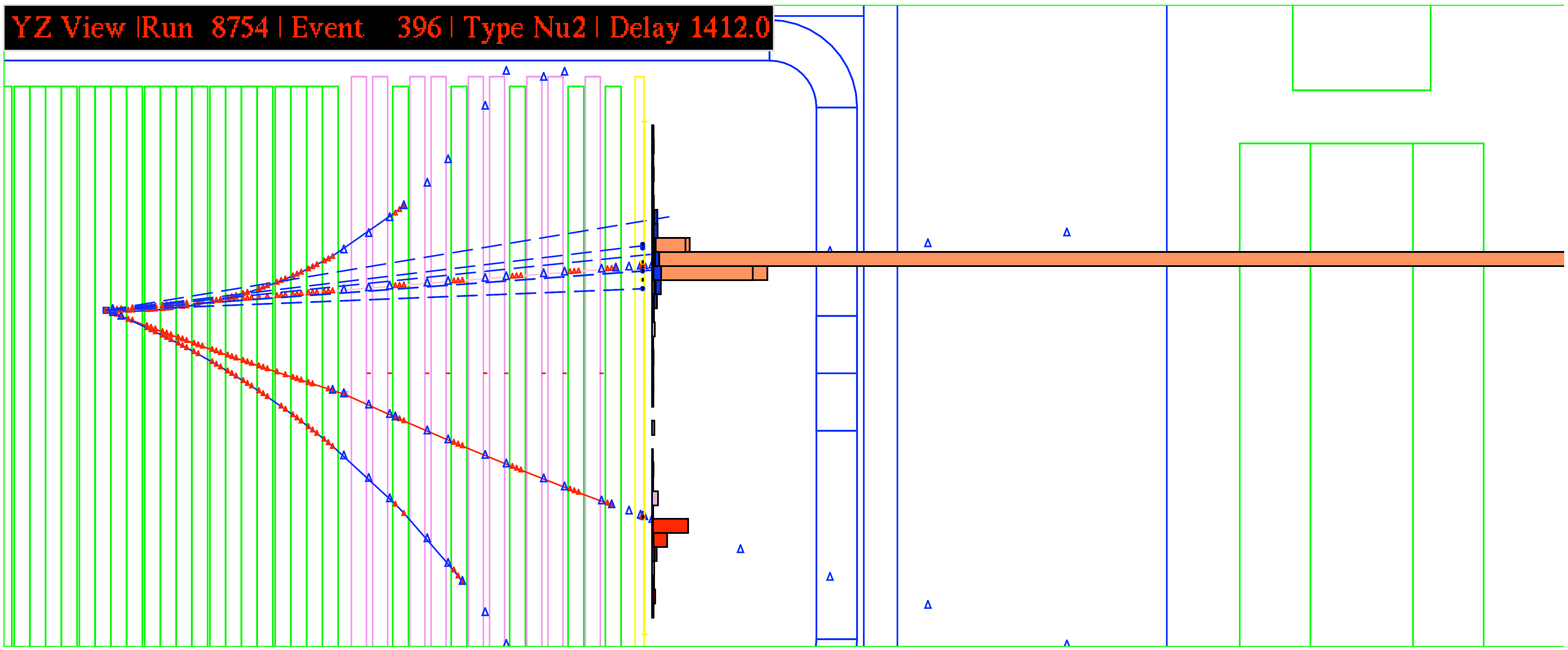
Figure 15: Distribution of $\hat{\nu}$ for e$^-$ (solid dots), μ^- (open dots), ν_μNC (big hatch) and CC (small hatch) background after scaling. The combined (histo) μ^- plus background agrees with the distribution of e$^-$ data. The bottom plot is the same as the top but includes kinematic cuts.

A $\bar{\nu}_e$ CC candidate in NOMAD

e-/e+ ID *using* TRD, ECAL



Conclusion ⇛

(1) μ *from* ν_μ *and* e *from* ν_e *are Tracks: Determined with very high precision*

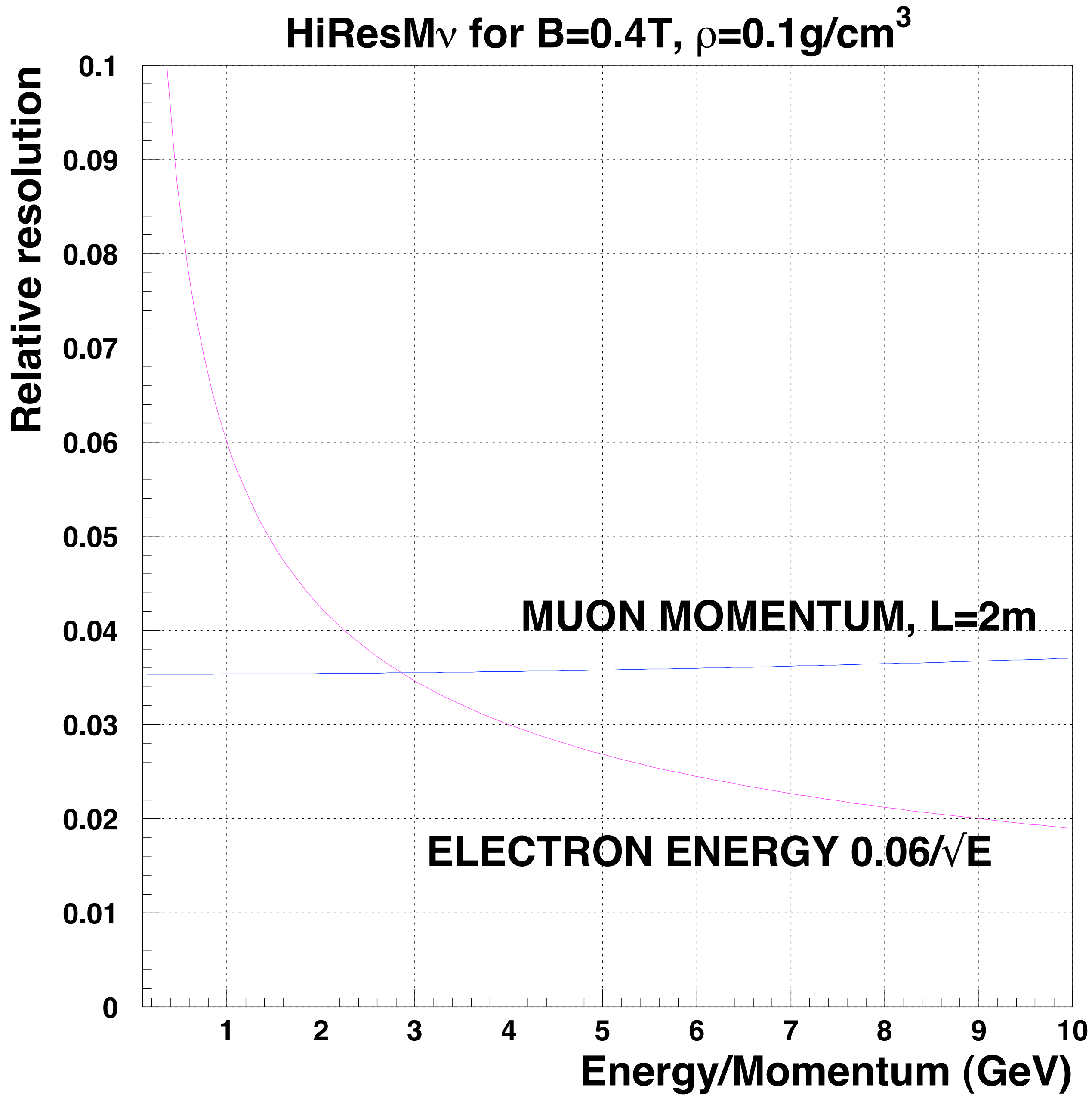
(2) Universality equivalence: μ -ν_μ ↔ e -ν_e

Resolutions in HiResMν

- 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%



Near Detector Sensitivity Studies for Neutrino Factory $\mu \rightarrow \nu_e \, \nu_\mu$

✴ *Flux*

- Inverse Muon Decay $\nu_x + e^- \rightarrow \nu_x + \mu^-$ *(Single, forward μ^-)*

  ν_μ (t-channel) or Anti-ν_e (s-channel)

- ν-Elas $\nu_x + e^- \rightarrow \nu_x + e^-$ *(Single, forward e^-)*

  ν_e-CC, Anti-ν_e-CC, & all flavor $\nu_x e$-NC

- E_ν-Dependence

  Fixed-ν_0 Method

  Combined fit of Single, forward μ^- & Single, forward μ^-

  $E\nu$-Scale

✴ *Interactions*

- ν_μ-QE Analysis:
  - ⇛ *For ν-Factory, Eff ~ 60% with 90%-purity*
- ν_e-CC *(inclusive)* Analysis:
  - ⇛ *For ν-Factory, ν_e-CC: Eff ~ 55% with 99%-purity*
  - ⇛ *For ν-Factory, ν_eBar-CC: Eff ~ 55% with 99%-purity*
- π^0-Reconstruction:
  - ⇛ *with one $\gamma \rightarrow e^+e^-$, Eff ~ 55% from 0.5--20 GeV*
- Event by Event Separation of NC -vs- CC: $1.0 \leq E_{HAD} \leq 20$ *GeV*
- Precision Measurement of the *Weak Mixing Angle:* $\delta(\sin^2\theta_W) \rightarrow 0.0003$

To Do:

Determination of Beam-Divergence using ν-Data

ν_μ-QE Analysis

✳ Example of a ν-interaction in a high-resolution ND as a calibration of FD

✳ Key is 2-Track (μ, p) signature ✳*Proton reconstruction: the critical issue*
(✳*dE/dx in but not used in the analysis*)

✳ Parametrized Calculation: Nomad data as *calibration*

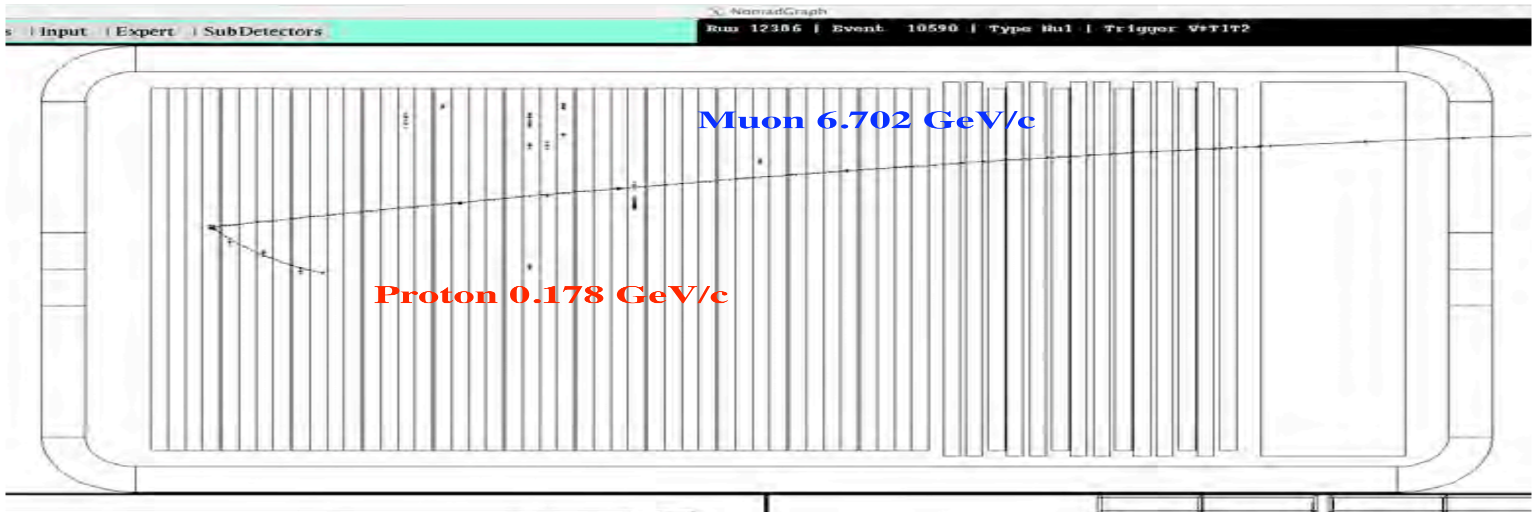


Figure 14: A ν_μ-QE candidate in NOMAD

QE Candidates in NOMAD

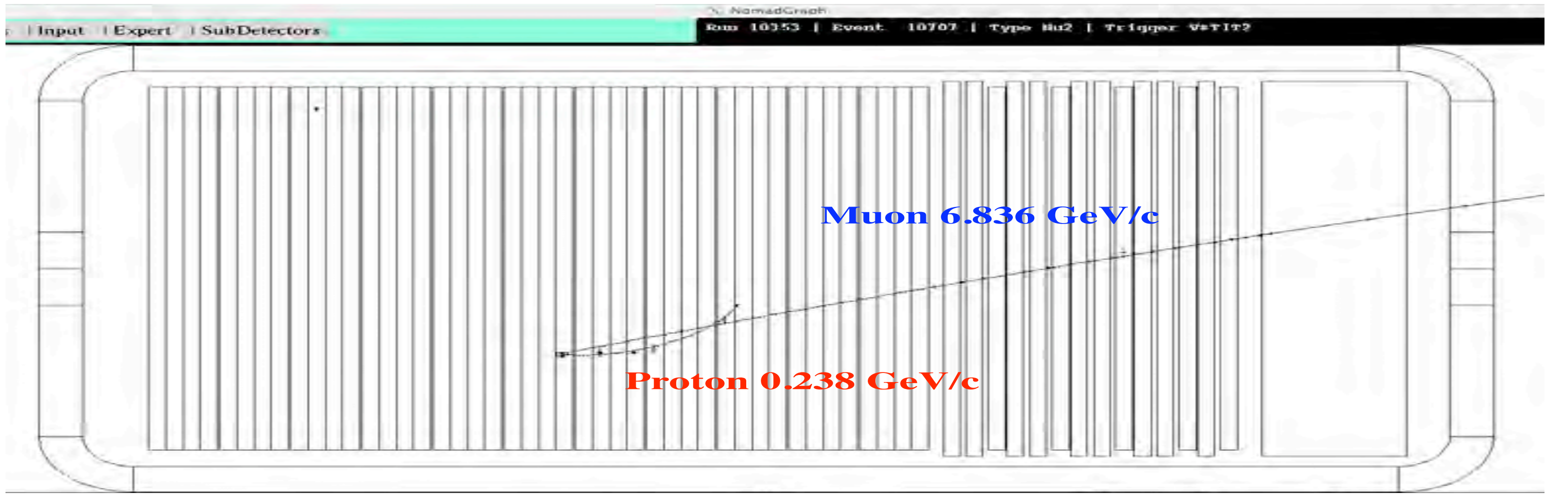
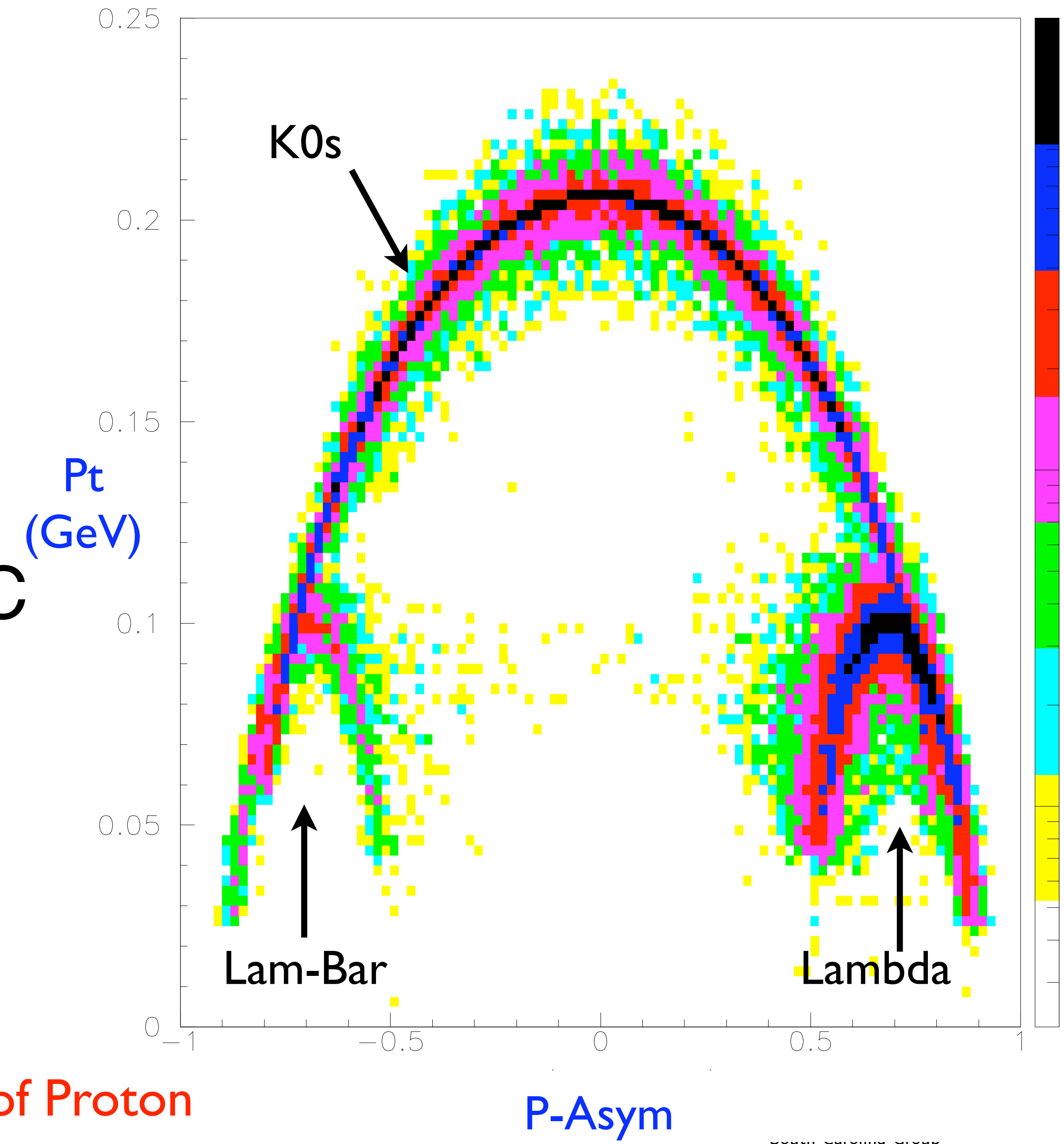


Figure 15: A ν_μ-QE candidate in NOMAD

Measurement of exclusive topologies

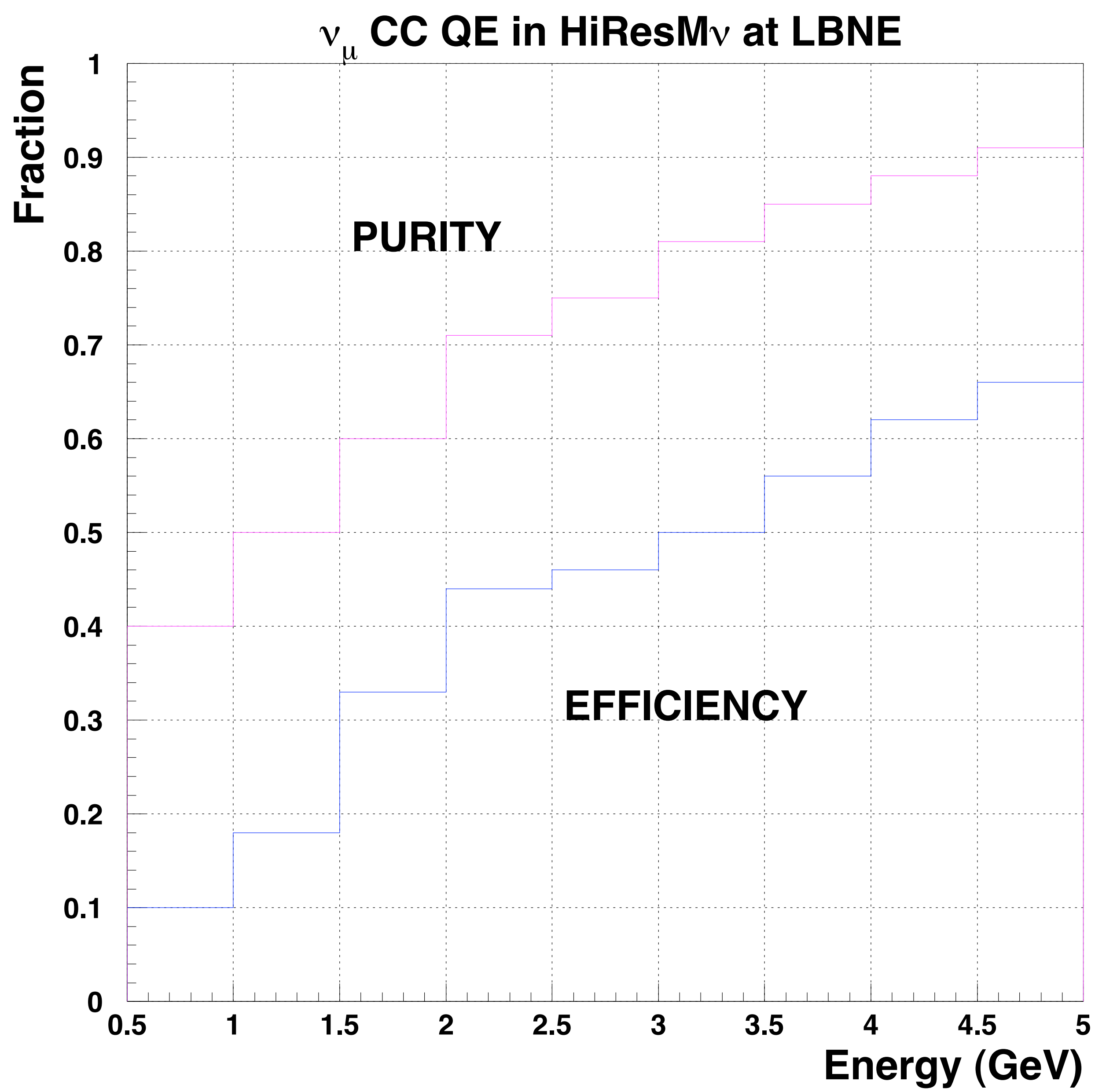
- ✦ High resolution allows excellent reconstruction of exclusive decay modes
- ✦ NOMAD performed detailed analysis of strange particle production: $\Lambda, \bar{\Lambda}$
- ✦ Δ resonances in CC & NC are easier to reconstruct
- ✦ Constraints on NC decay mode $\Delta \rightarrow N\gamma$

CC-Data: Armenteros Plot



✴ Λ ↠ Calibration of Proton Reconstruction

RECONSTRUCTION OF CC QUASI-ELASTIC INTERACTIONS



- *Protons easily identified by the large dE/dx in STT & range*

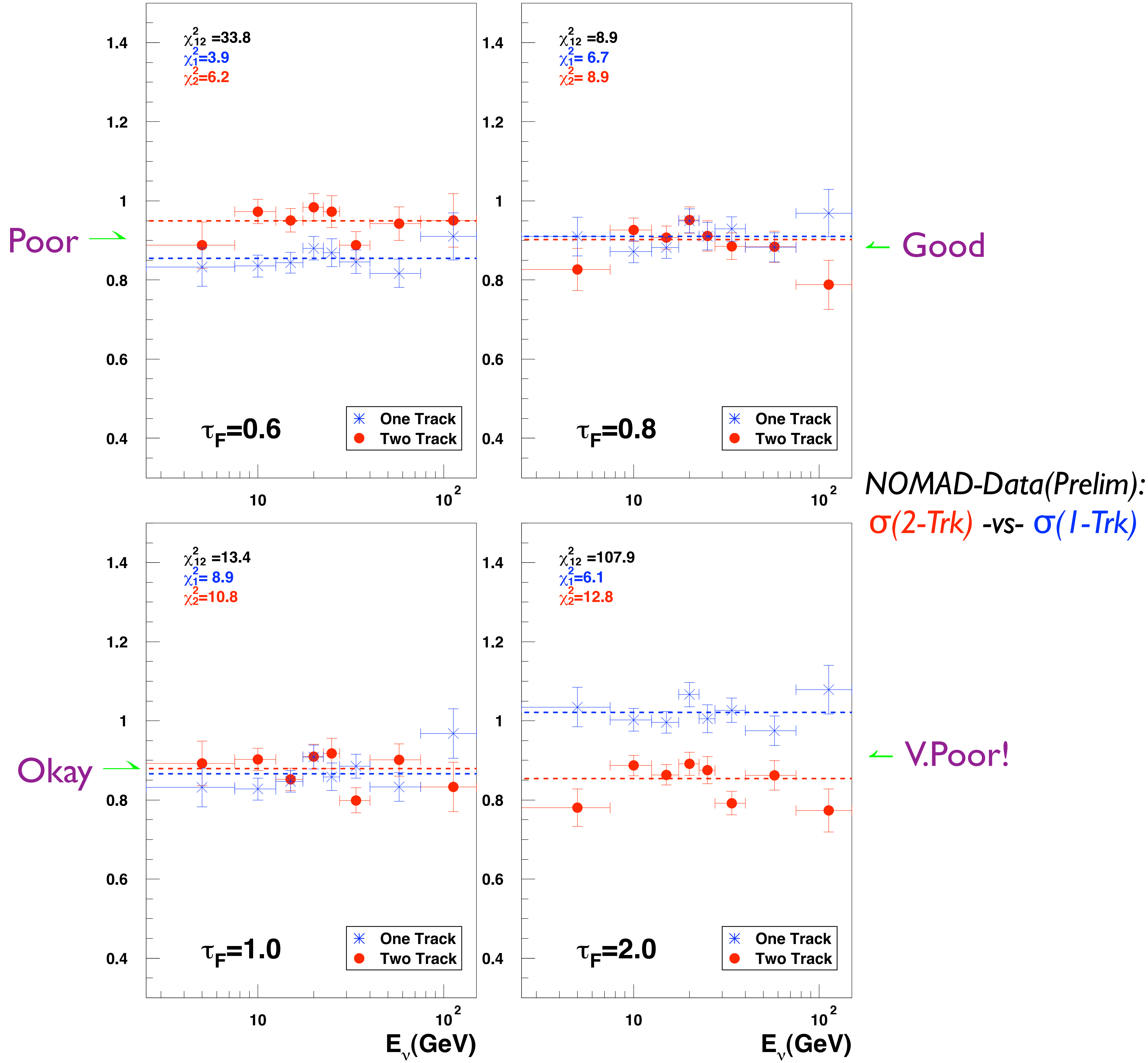
  $\Longrightarrow$ *Minimal range to reconstruct p track parameters 12cm* $\Rightarrow 250\ MeV$

- *Analize BOTH 2-track and 1-track events to constrain FSI, Fermi motion and nuclear effects* ⇒ Fig.

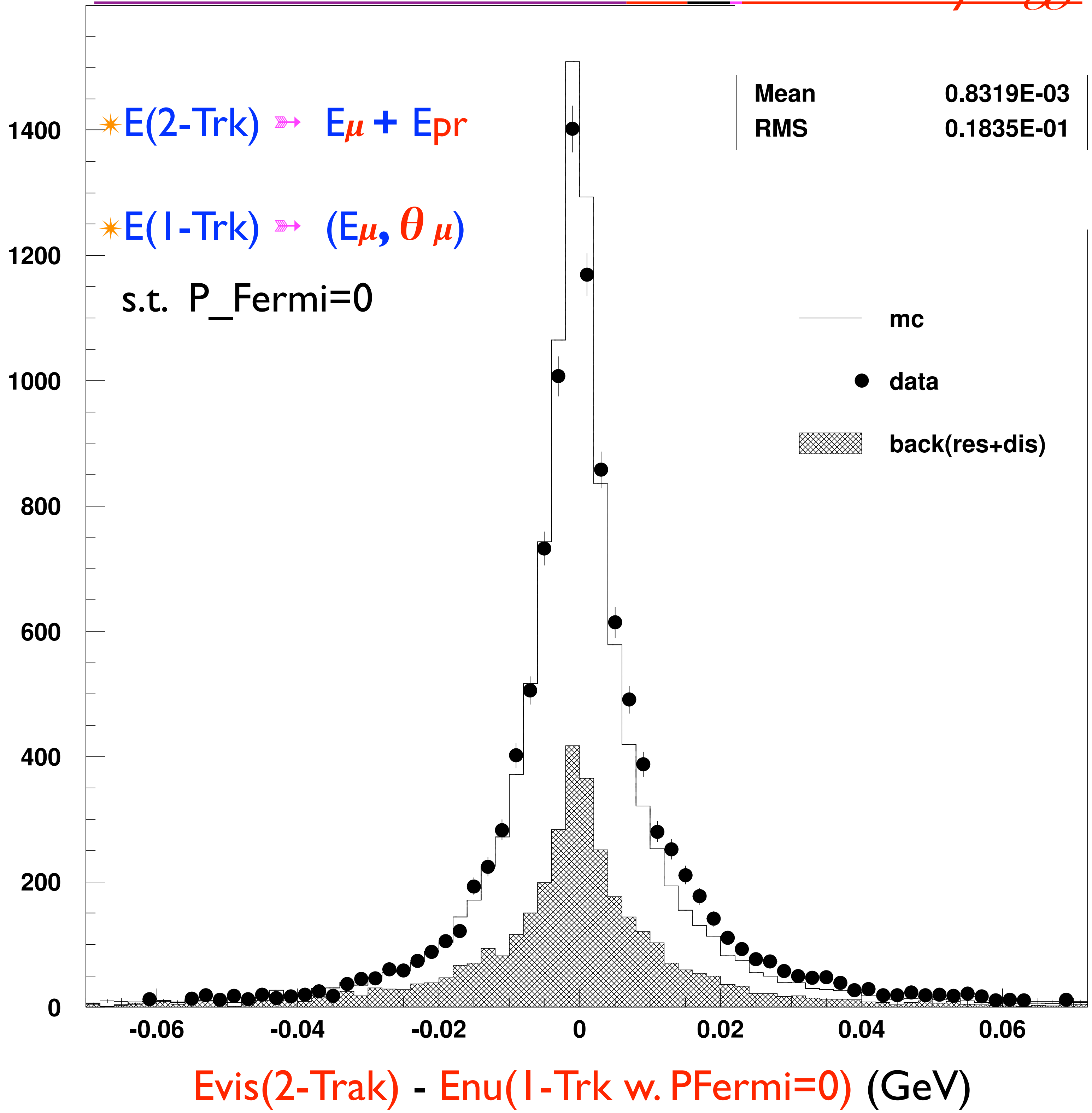
- *Use multi-dimensional likelihood functions incorporating the full event kinematics to reject DIS & Res backgrounds*

  $\Longrightarrow$ *On average* $\varepsilon = 52\%$ *and* $\eta = 82\%$ *for CC QE at LBNE*

Expect ⇛ *For ν-Factory, Eff ~ 60% with 90%-purity*


Poor
Good
Okay
V.Poor!
NOMAD-Data(Prelim):
σ(2-Trk) -vs- σ(1-Trk)
χ^2_{12} =33.8
χ^2_1=3.9
χ^2_2=6.2
τ_F=0.6
χ^2_{12} =8.9
χ^2_1= 6.7
χ^2_2= 8.9
τ_F=0.8
χ^2_{12} =13.4
χ^2_1= 8.9
χ^2_2=10.8
τ_F=1.0
χ^2_{12} =107.9
χ^2_1=6.1
χ^2_2=12.8
τ_F=2.0
One Track
Two Track
E_ν(GeV)

NOMAD Data: $\mathcal{QE} \Rightarrow$ 2-Track Topology



⇒Experimental check on Fermi Motion

ν_μ- & ν_μBar- (semi)Exclusive Charged Current Interactions ⇛

(1) QE Interaction

(i) n reconstruction

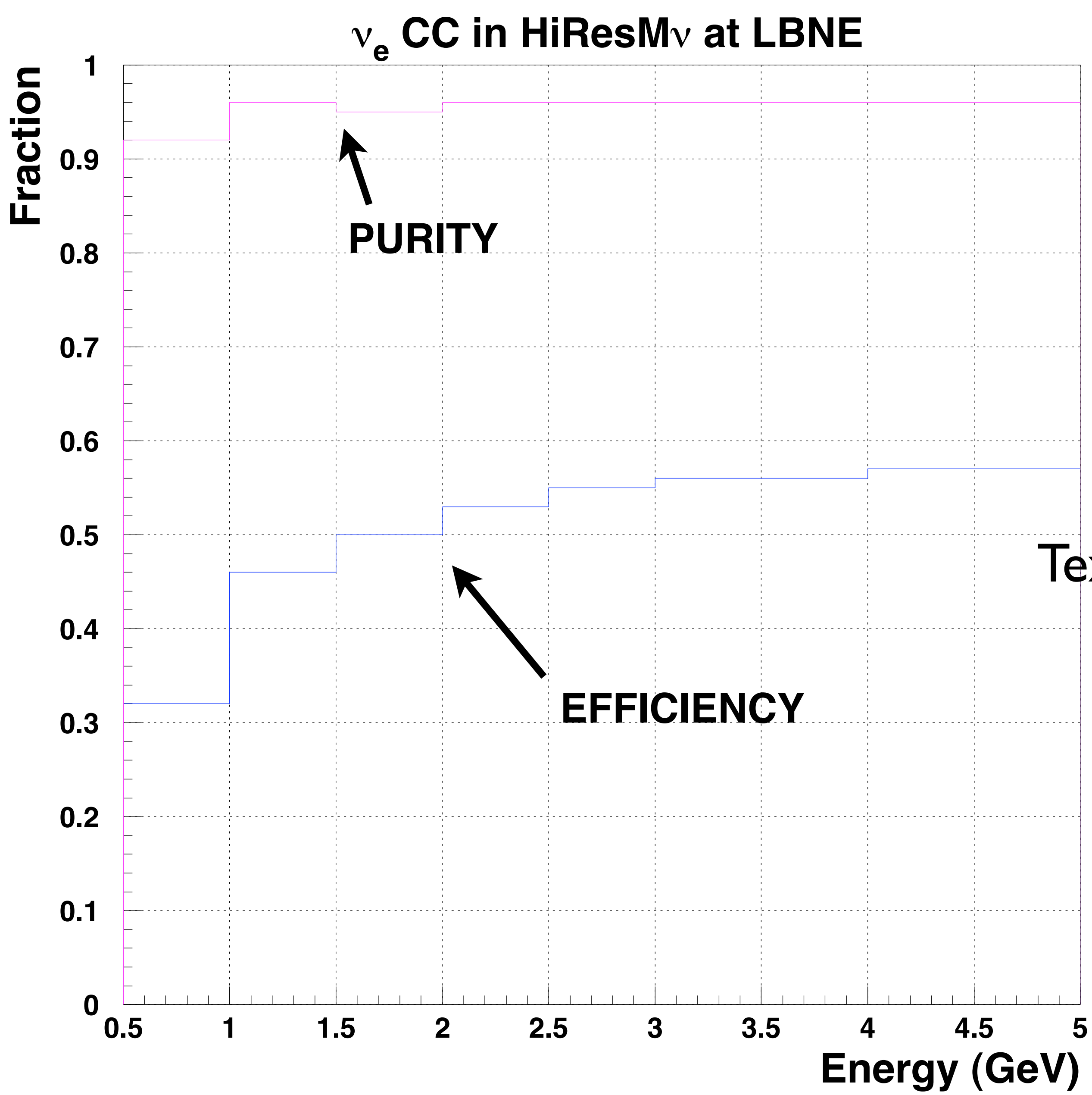
(2) Resonance Interactions (to do) reconstruction

(i) Δ^{++} and Δ^{+} ⇒ $p\pi^+$, $p\pi^0$, & $n\pi^+$ reconstruction

(3) Coherent Pion Interactions

IDENTIFICATION OF ν_e CC INTERACTIONS

Inclusive ν_e-CC



Text

- *The HiResMν detector can distinguish electrons from positrons in STT*
  $\Longrightarrow$ *Reconstruction of the e's as bending tracks NOT showers*
- *Electron identification against charged hadrons from both TR and dE/dx*
  $\Longrightarrow$ *TR π rejection of 10^{-3} for $\varepsilon \sim 90\%$*
- *Use multi-dimensional likelihood functions incorporating the full event kinematics to reject non-prompt backgrounds (π^0 in ν_μ CC and NC)*
  $\Longrightarrow$ *On average $\varepsilon =$ 55% and $\eta =$ 99% for ν_e CC at LBNE*

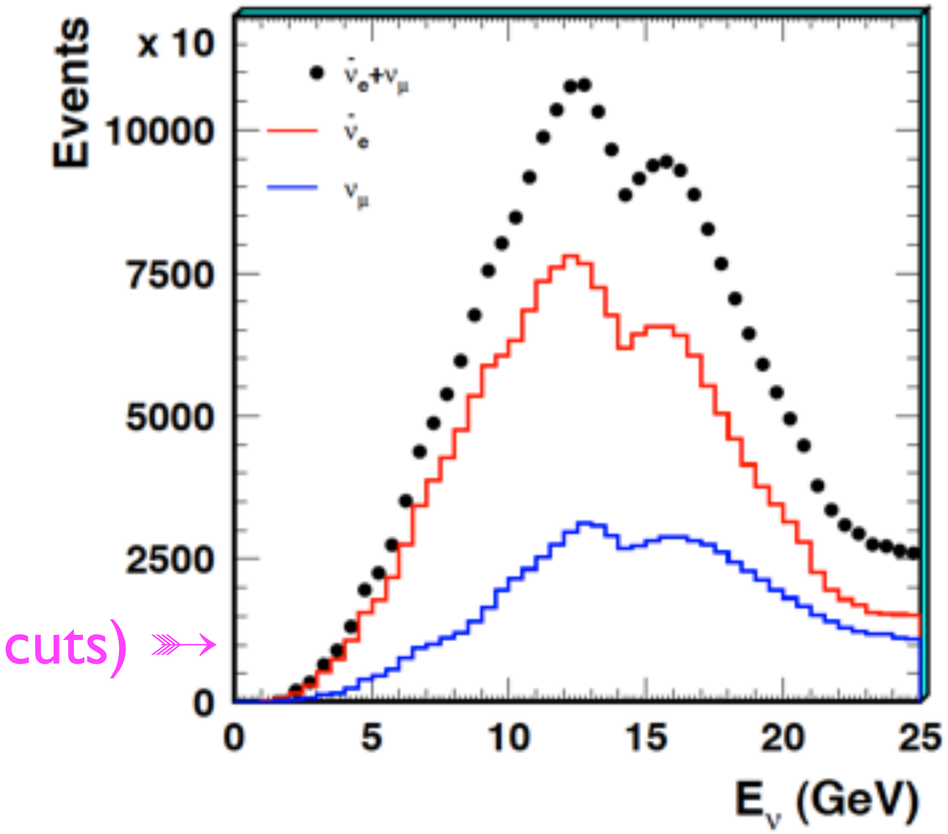
VeBar-CC Sensitivity: Eff ~55% and Purity ~ 99%

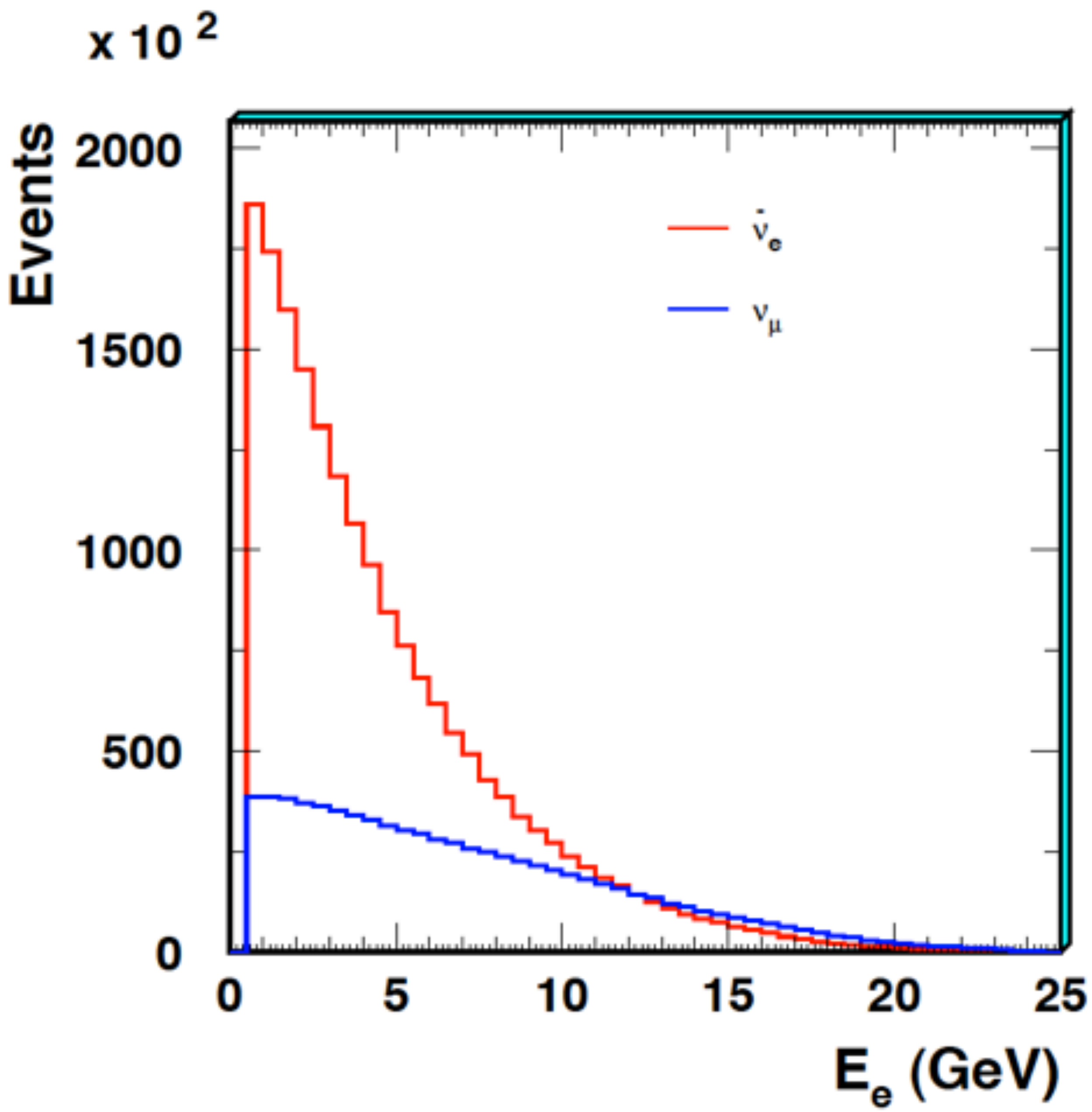
ν-e *Elastic Scattering* ⇛

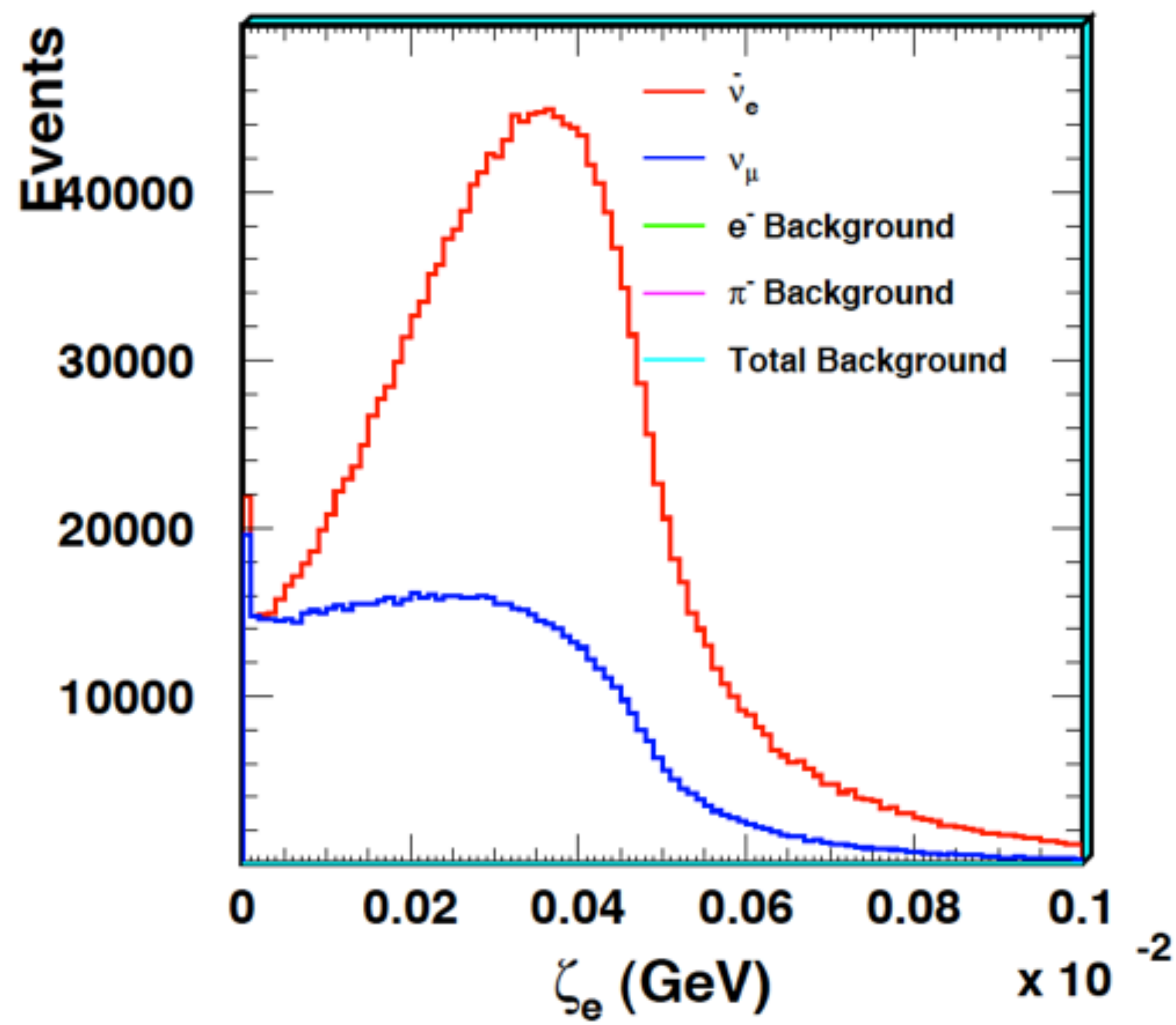
$\nu_x + e^- \twoheadrightarrow \nu_x + e^-$ (Single, forward e-)

Distribution of Kinematic Quantities ⇛

E_ν (passing cuts) ⤜







Sensitivity Analysis **νEl:** 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

TR sel. ⤜→

Efficiency ⇛ *66%* *71%* *~10^-6*

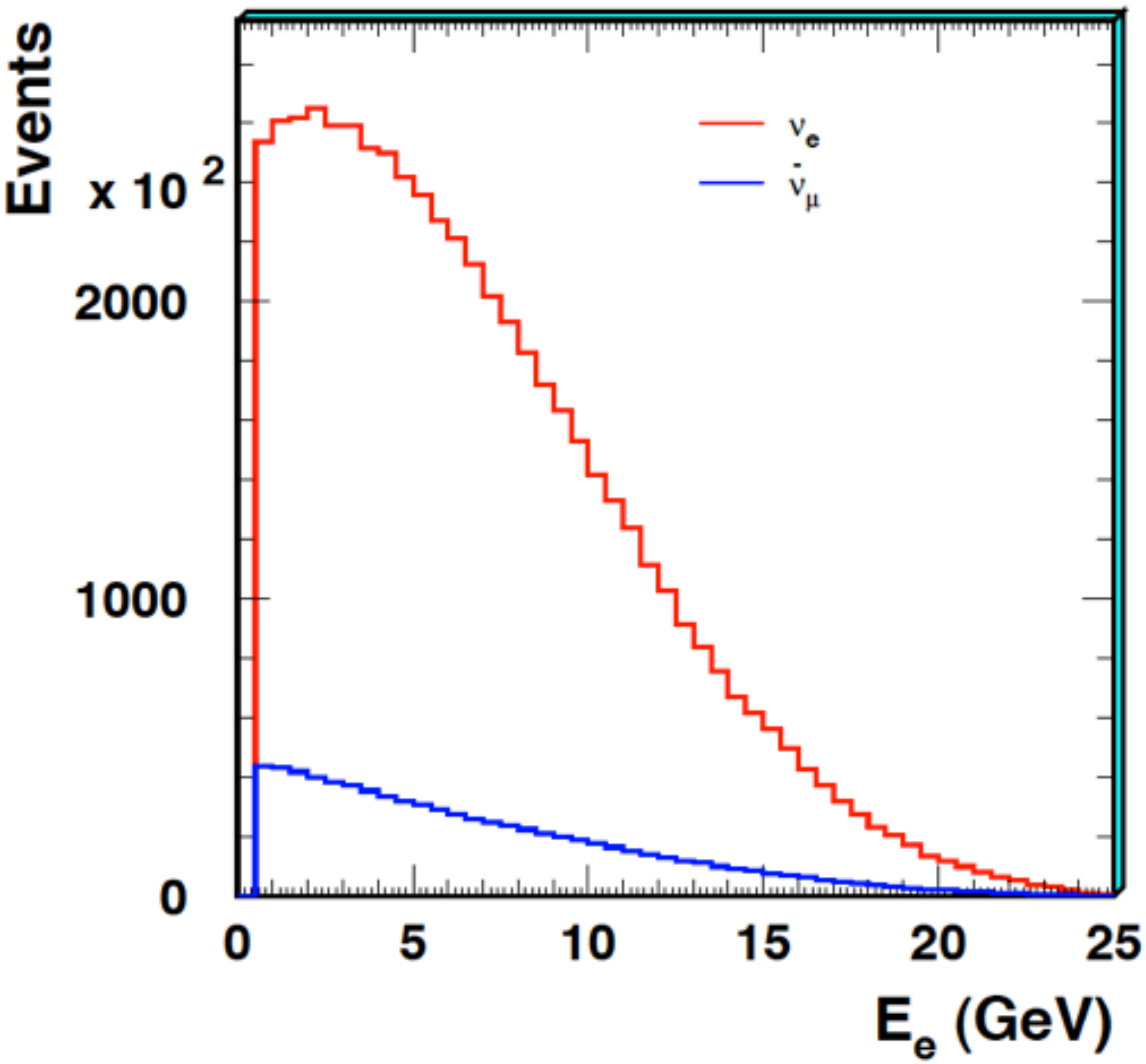
$\pi^- \Rightarrow$	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_e$-CC	ν_μ-CC	$\bar{\nu}_e$-NC	ν_μ-NC
	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000	1,000,000
Positron veto	1,000,000	1,000,000	40,168	50,219	1,000,000	1,000,000
One negative track	1,000,000	1,000,000	1,154	110	13,393	12,151
20 planes	833,179	836,172	700	34	4,416	4,500
$E_e > 0.5$ GeV	748,786	794,086	587	33	3,531	3,909
$z < 0.001$ GeV	733,723	785,240	26	1	50	55

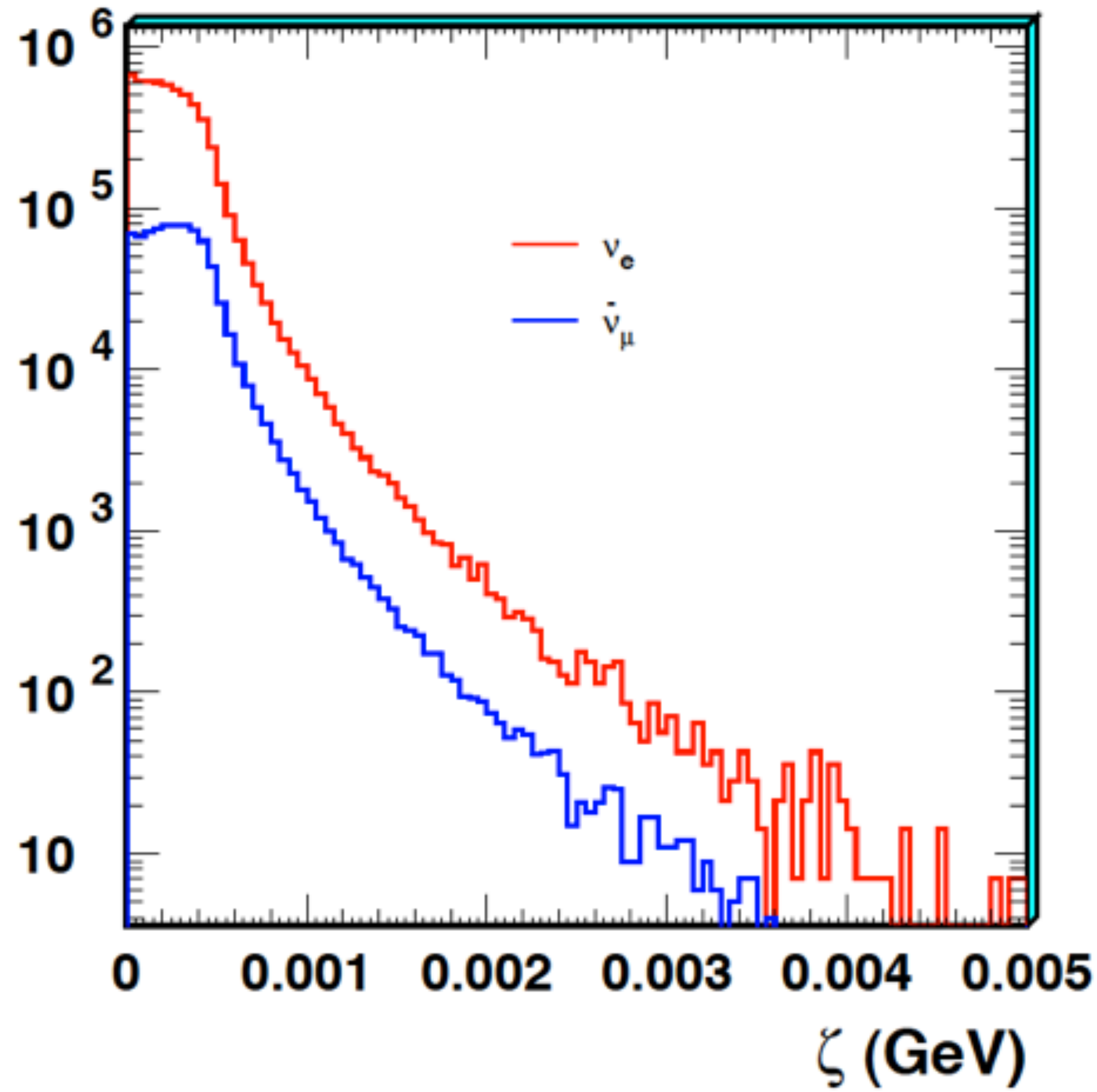
TR sel. ⤜→

Efficiency ⇛ *66%* *71%* *<10^-6*

Sensitivity Analysis νEl: μ^+ **Beam** $\nu_{e(\mu bar)}$ + e- ⇻ e- + ν_e (*Single, forward e-*)

✶ $\nu_{e(\mu bar)}$-N NC background dominated by single, asymmetric $\gamma \rightarrow e^- e^+$ and $\pi^- / \mu^- \Rightarrow$





Conclusion ⇛ *The cleanest separation of* ν_e−e *interaction among all* --- ν_μ−e, ν_{eBar}−e, $\nu_{\mu bar}$−e --- *the leptonic channels*

Measurement of $\nu_{\mu/e}$ *and* $\nu_{\mu/ebar}$ *Flux*
and of the $E\nu$*-Scale*

(1) Low-ν0 Method

(2) Neutrino-Electron Scattering: ***e***-sample

(3) Quasi-Elastic and Coherent-π^{+-} :

For Relative flux determination

Fitting ν_μ and ν_eBar flux as a function of E_ν

- ✴ *(i)* Mock Data: simulate a signal/back --- Low-ν_0 CC (ν_e/μ-CC) or νe (e-sample)
- ✴ *(ii)* Reconstruct (parametric smearing)
- ✴ *(iii)* Subject it to analysis
  - ✴ *(a)* Start with a Trial Flux
  - ✴ *(b)* Fold in Cross-section
  - ✴ *(c)* Fold in Acceptance (Efficiency-Smearing); add background
- ✴ *(1)* Compare samples *(iii)* with *(c)* : From χ^2
- ✴ *(2)* Vary Flux parameter; Go to *(a)*; arrive at *(c)*; go to *(1)*
- ✴ *(3)* Minimize χ^2: $\Rightarrow$ Fitted Flux

LOW-ν_0 METHOD $\Leftarrow$Shape of ν_μ or Anti-ν_μ Flux

✦ *Relative flux vs. energy from low-ν_0 method:*

$$N(E_\nu : E_{\text{HAD}} < \nu^0) = C\Phi(E_\nu) f(\frac{\nu^0}{E_\nu})$$

$\Leftarrow$*SRM(1990): Used by CCFR, NOMAD, NuTeV, MINOS..*

the correction factor $f(\nu^0/E_\nu) \to 1$ *for* $\nu^0 \to 0$.

$\Longrightarrow$ *Need precise determination of the muon energy scale and good resolution at low ν values*

✦ *Fit Near Detector $\nu_\mu, \bar{\nu}_\mu$ spectra:*

- *Trace secondaries through beam-elements, decay;*
- *Predict $\nu_\mu, \bar{\nu}_\mu$ flux by folding experiental acceptance;*
- *Compare predicted to measured spectra $\Longrightarrow \chi^2$ minimization*

$$\frac{d^2\sigma}{dx_F dP_T^2} = f(x_F)g(P_T)h(x_F, P_T)$$

- *Functional form constraint allows flux prediction close to $E_\nu \sim \nu^0$.*

✦ *Add measurements of $\pi^\pm/K^\pm$ ratios from hadro-production experiments to the empirical fit of the neutrino spectra in the Near Detector*

Low-Nu0 Idea (1989 @ FNAL)

Wold.Sci. 84(1990), Ed.Geesman

$$\frac{d\sigma^{\nu(\bar{\nu})}}{dxdy} = \frac{G_F^2 ME}{\pi} \times \left[\left(1 - y - \frac{Mxy}{2E}\right) F_2^{\nu(\bar{\nu})} + \frac{y^2}{2} 2xF_1^{\nu(\bar{\nu})} \pm y\left(1 - \frac{y}{2}\right) xF_3^{\nu(\bar{\nu})}\right]$$

=> Number of events < Nu0

$$\mathcal{N}(\nu < \nu_0) = \Phi(E_\nu) \cdot \int_0^{\nu_0} \int_0^1 \frac{d\sigma}{dxd\nu} dxd\nu$$
$$= C \cdot \Phi(E_\nu) \cdot \left[\left(\nu_0 - \nu_0^2/2E_\nu\right) \mathcal{F}_2 + \frac{\nu_0^3}{6E_\nu^2} \mathcal{F}_1 \pm \left(\frac{\nu^2}{2E_\nu} - \frac{\nu^3}{6E_\nu^2}\right) \mathcal{F}_3\right]$$

Rearrange terms:

$$\mathcal{N}(\nu < \nu_0) = C \cdot \Phi(E_\nu) \cdot \nu_0 \cdot \left[\mathcal{F}_2 - \frac{\nu_0}{2E_\nu}\left(\mathcal{F}_2 \mp \mathcal{F}_3\right) + \frac{\nu_0^2}{6E_\nu^2}\left(\mathcal{F}_2 \mp \mathcal{F}_3\right)\right]$$
$$= C \cdot \Phi(E_\nu) \cdot \nu_0 \cdot \left[\mathcal{A} + \left(\frac{\nu_0}{E_\nu}\right) \mathcal{B} + \left(\frac{\nu_0}{E_\nu}\right)^2 \mathcal{C} + \mathcal{O}\left(\frac{\nu_0}{E_\nu}\right)^3\right]$$

N(nu<nu0) is prop. Phi(Enu) up to..

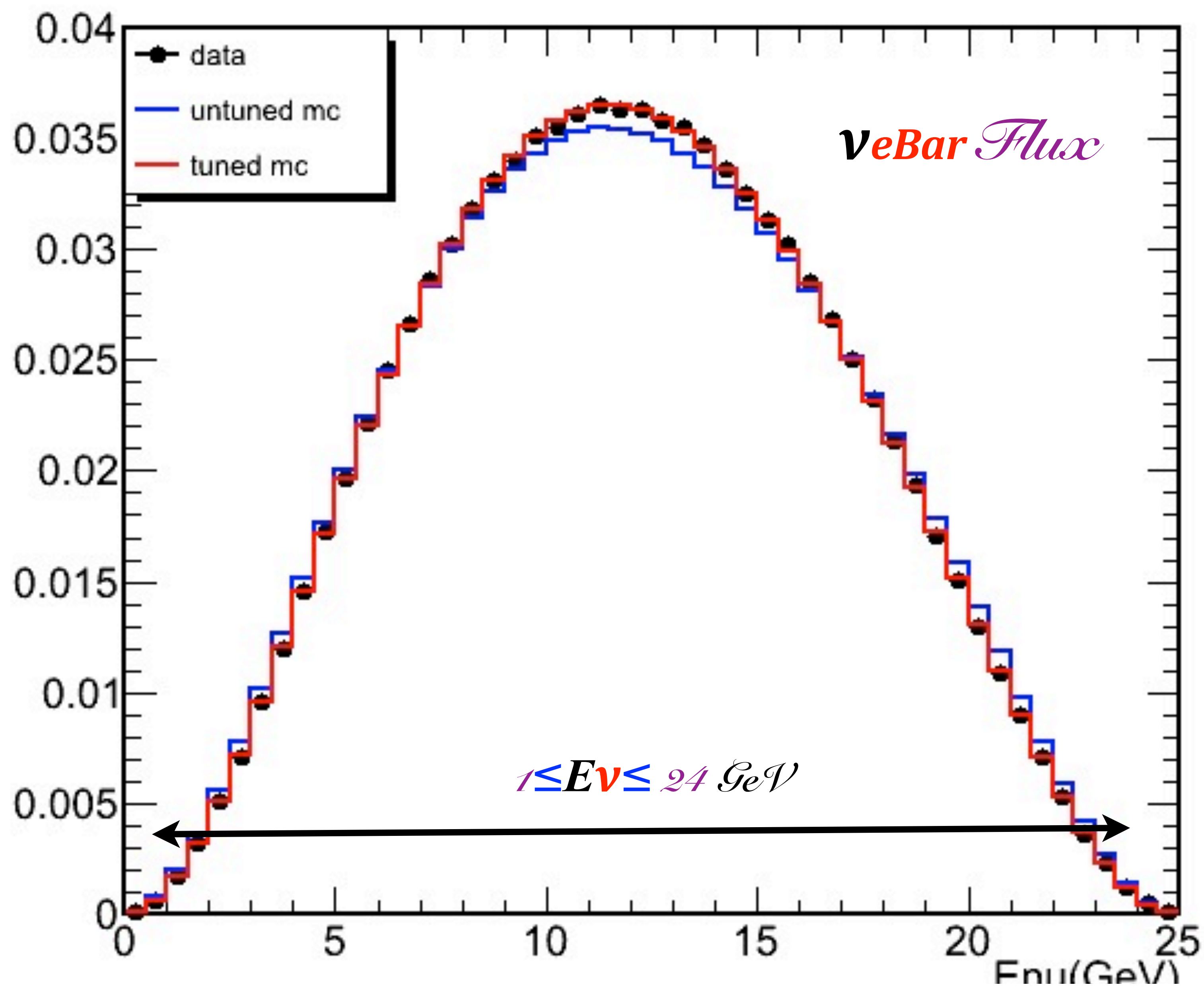
Low-ν0:

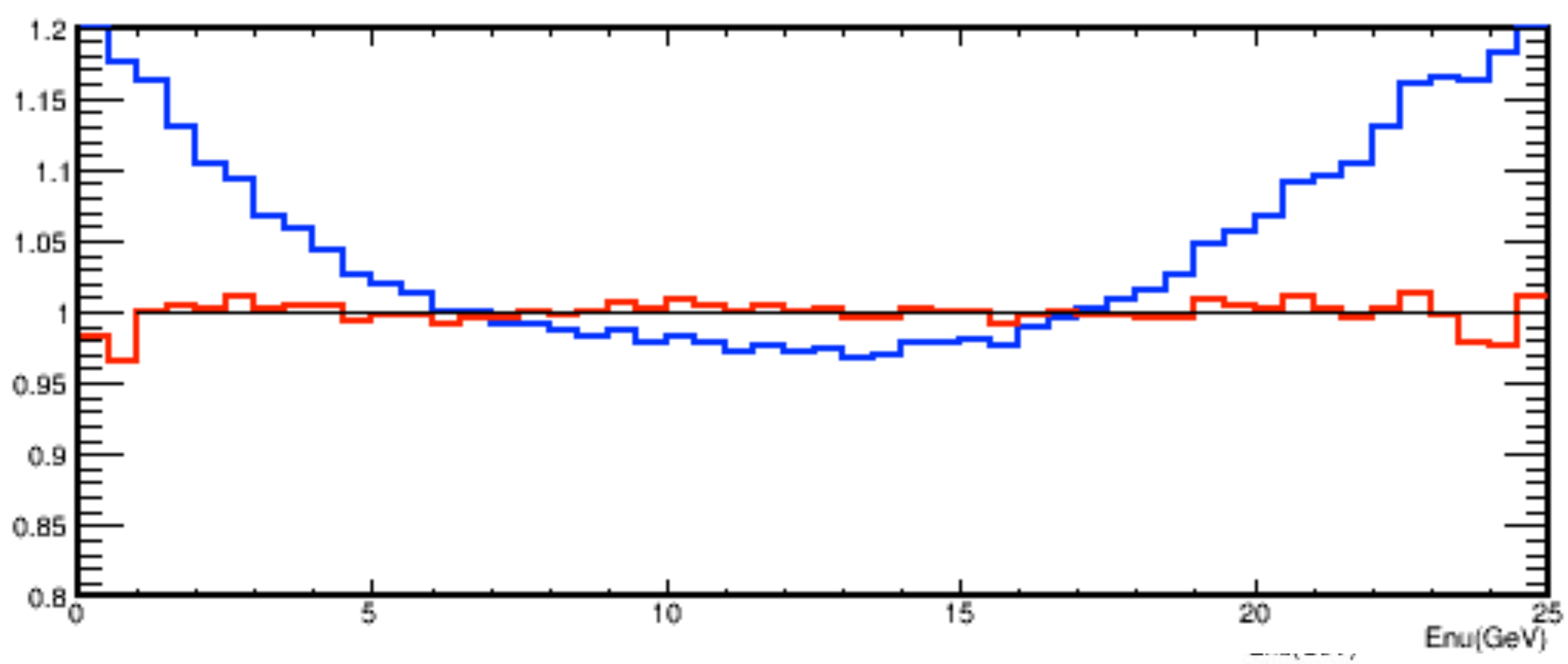
ν*eBar* + N ⇛ **e**$^+$ + **x** ***(Ex<0.5 GeV)***

Observation ⇛ The Low-ν0 method should permit flux determination of νμ and νeBar within ± ~1-% at ND;

Ditto for (νe and νμBar).

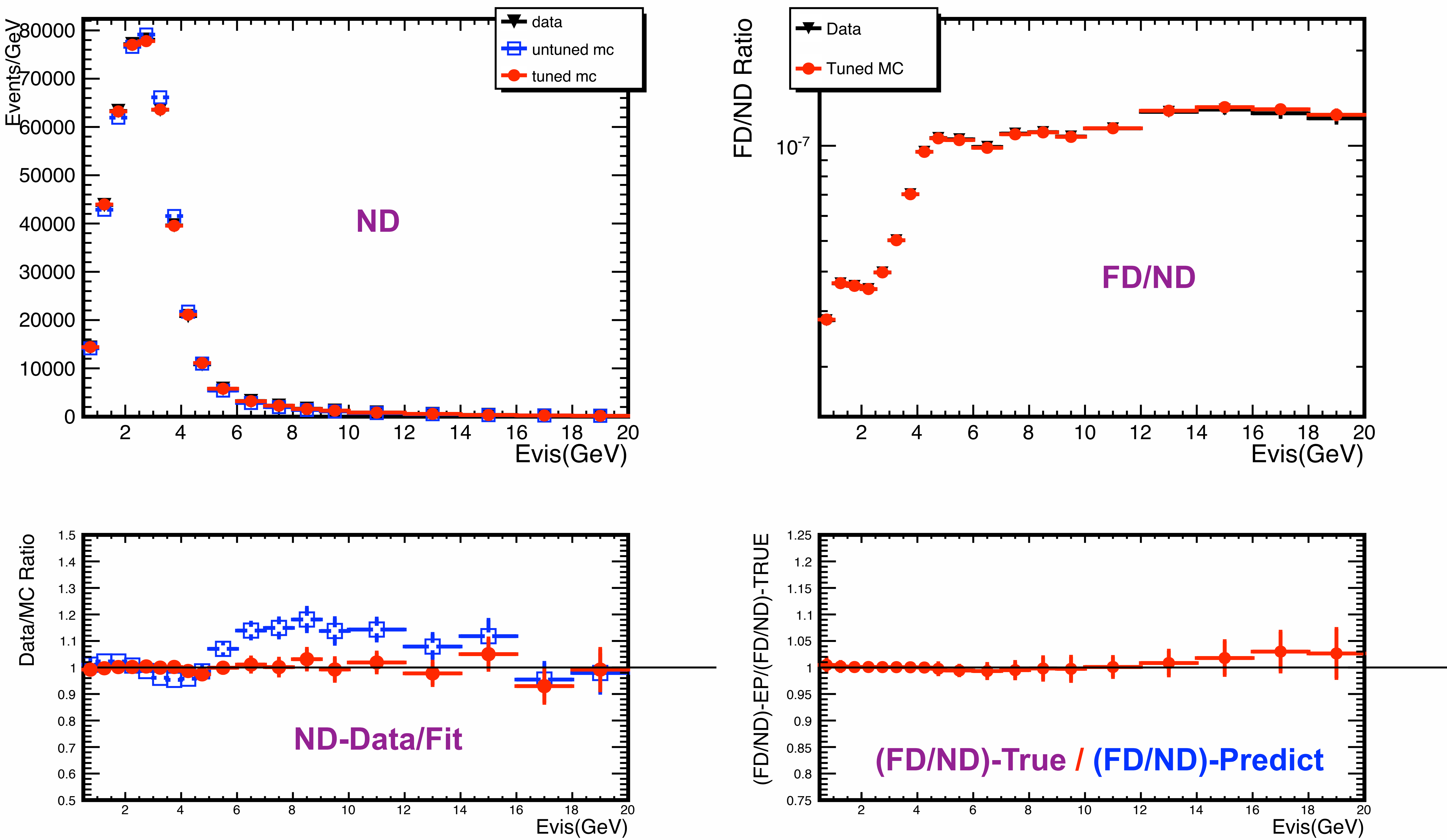
⇛ FD/ND will be more precise





Shape of ν_μ Flux using Low-ν_0 Method @ LBNE

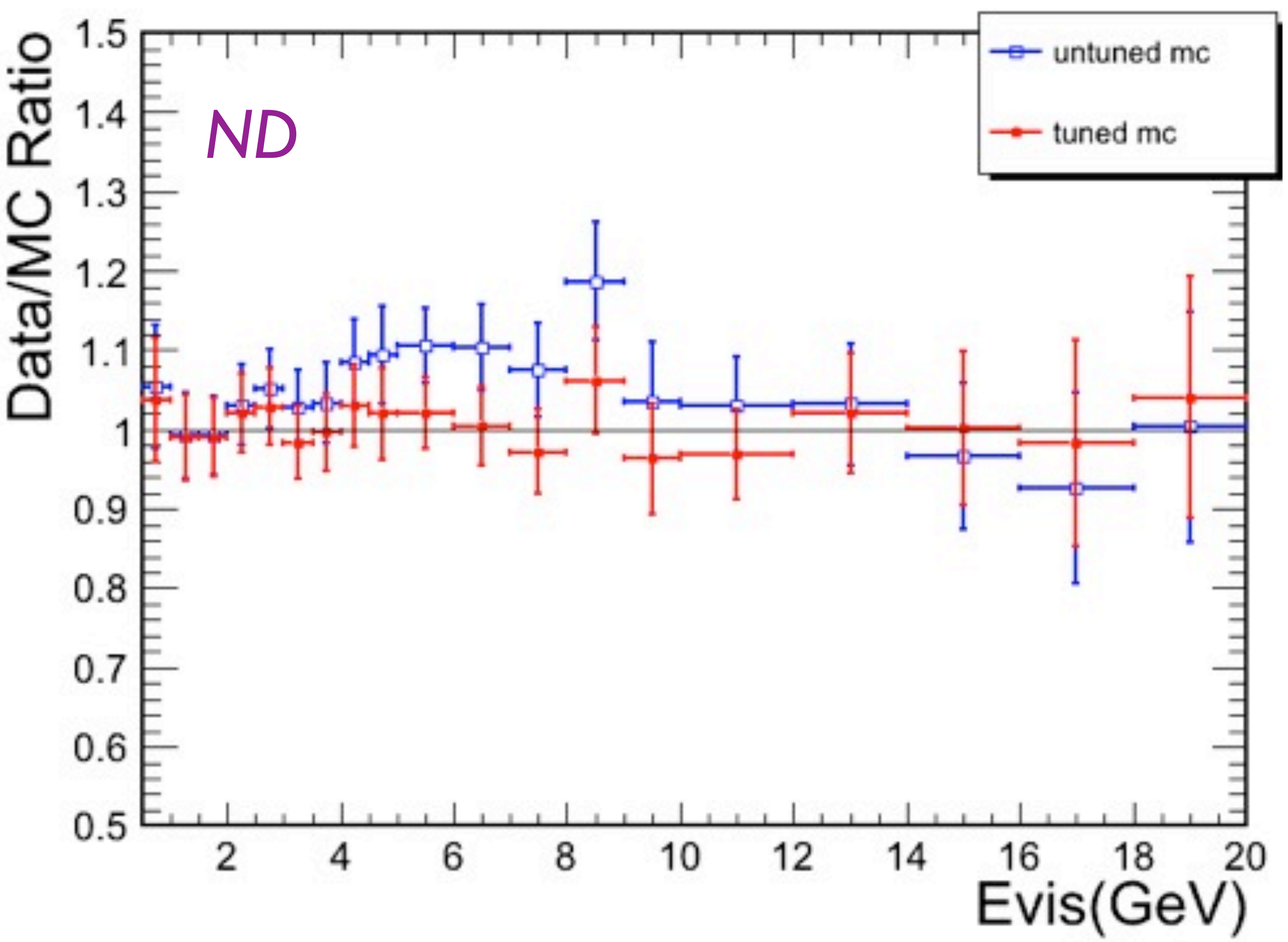
ν_μ, **Low-Nu0 Fit, ND at 500m**

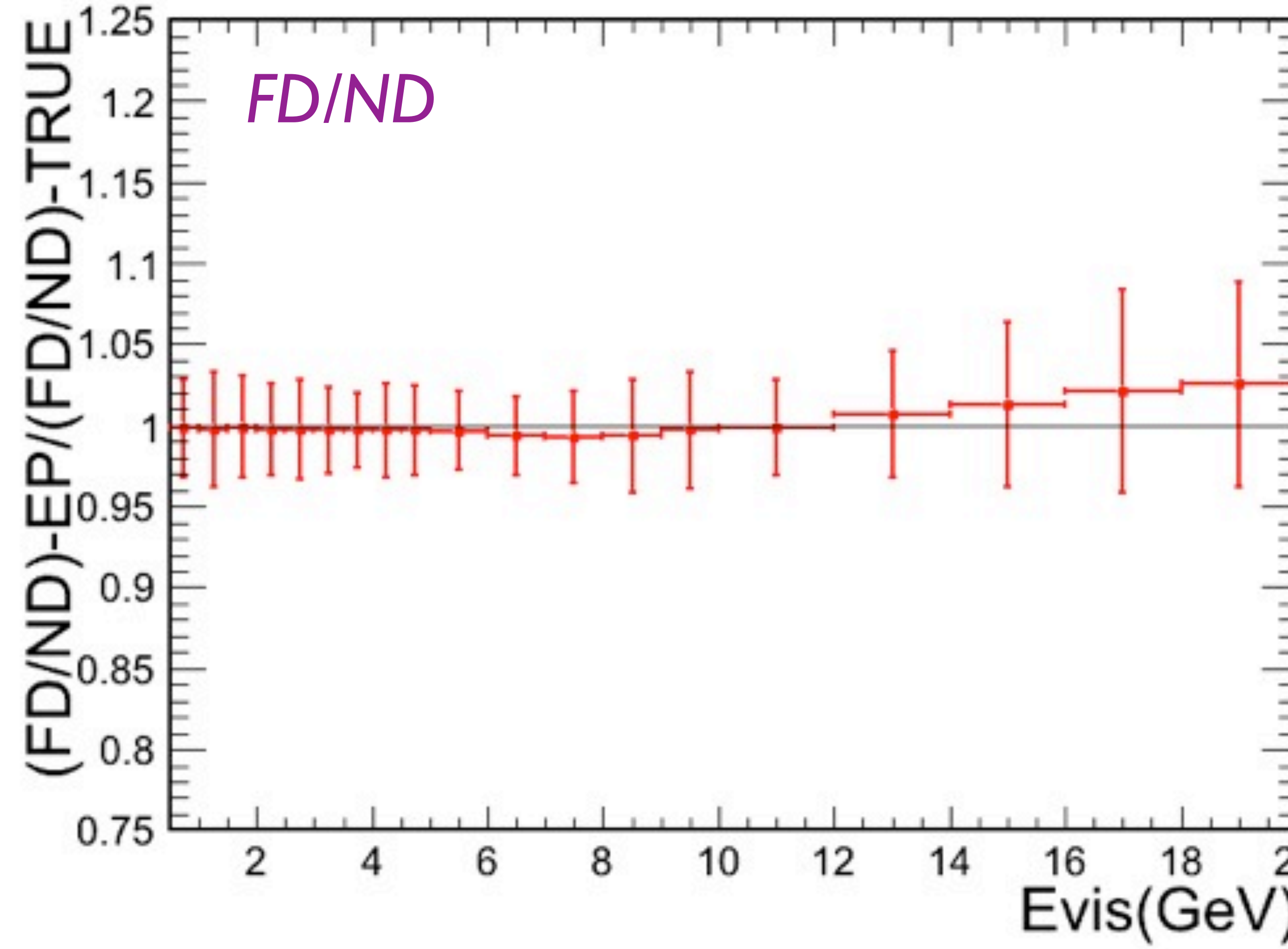


Conclusion ⇒

Predict FD/ND flux-ratio with high precision

Shape of Anti-ν_μ Flux using Low-ν_0 Method @ LBNE

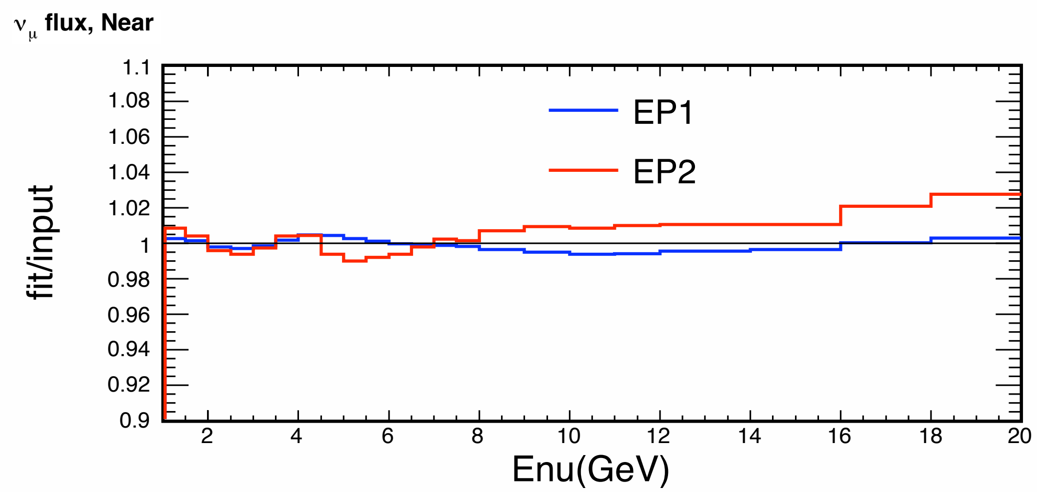




Conclusion ⇒

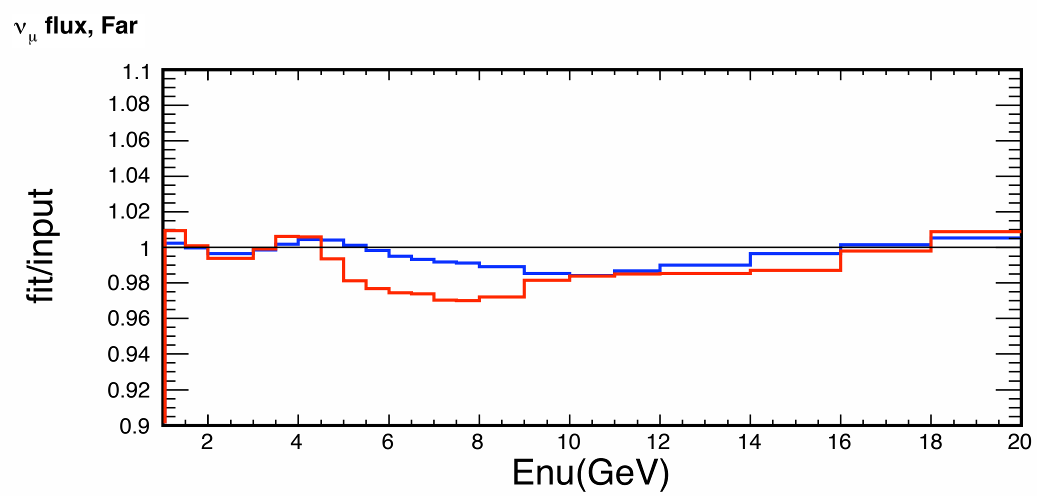
Predict FD/ND flux-ratio with high precision

Functional Form: NuMu

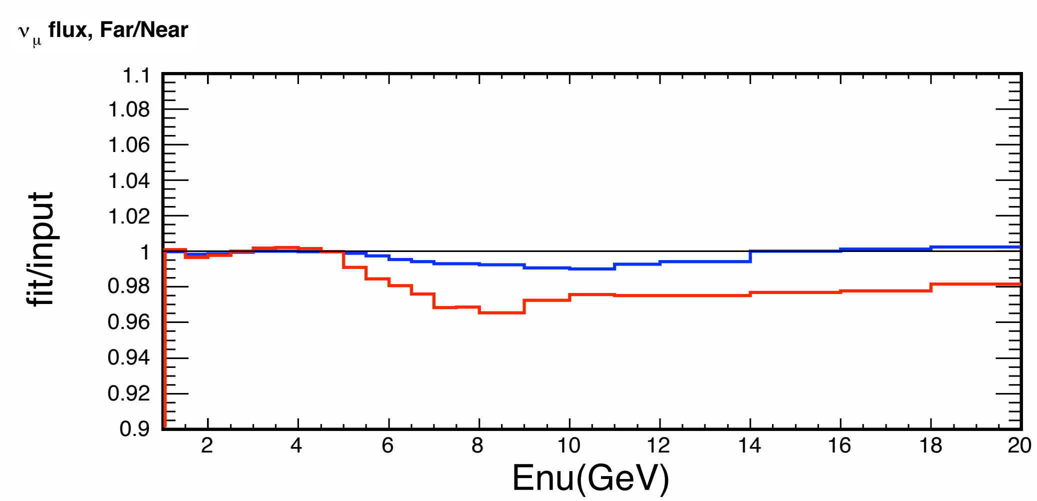


ND

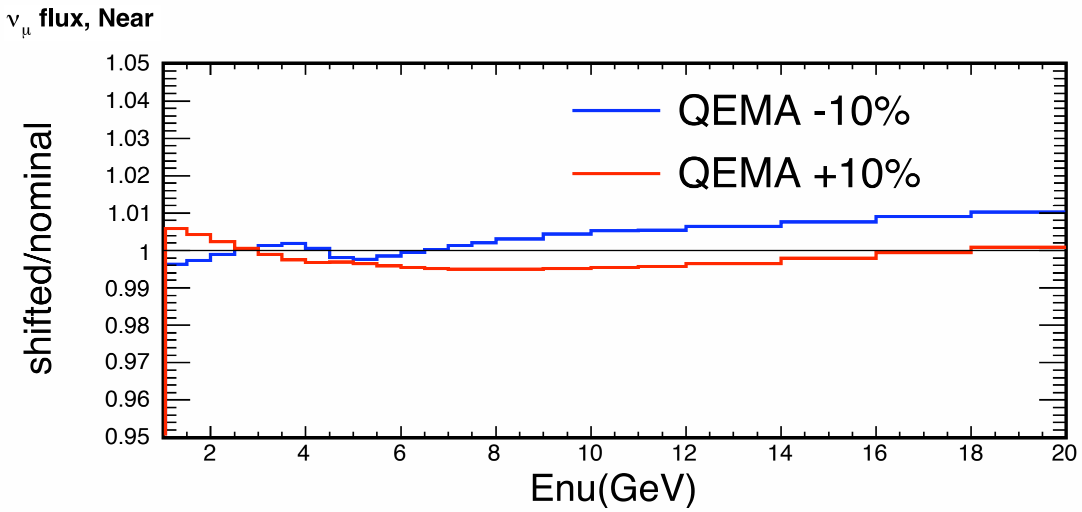
Poor fit !

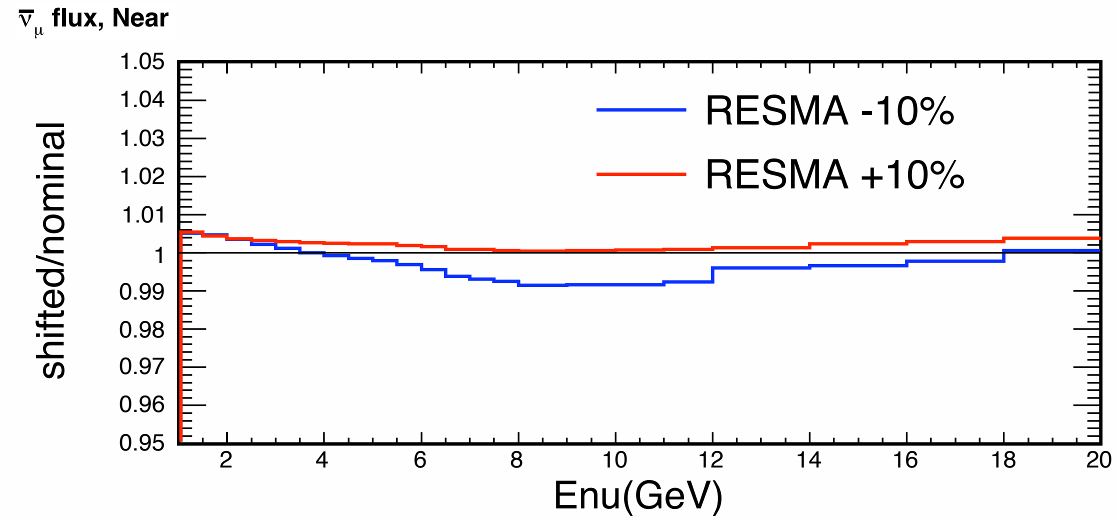


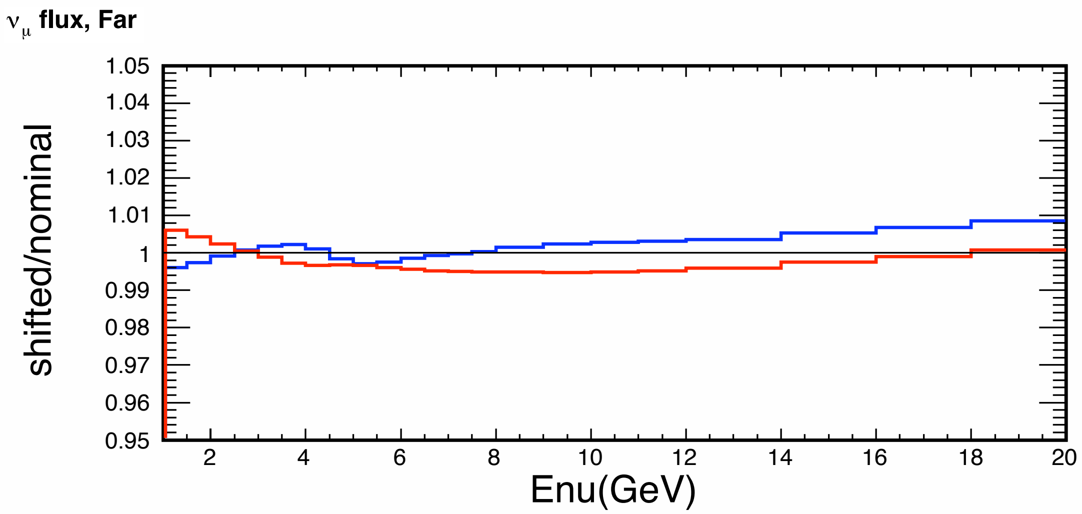
FD

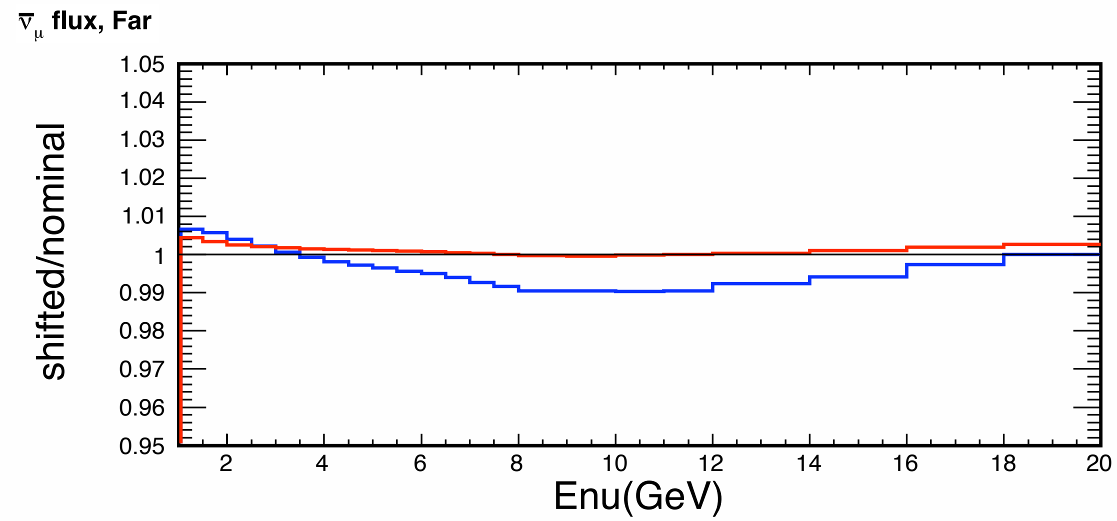


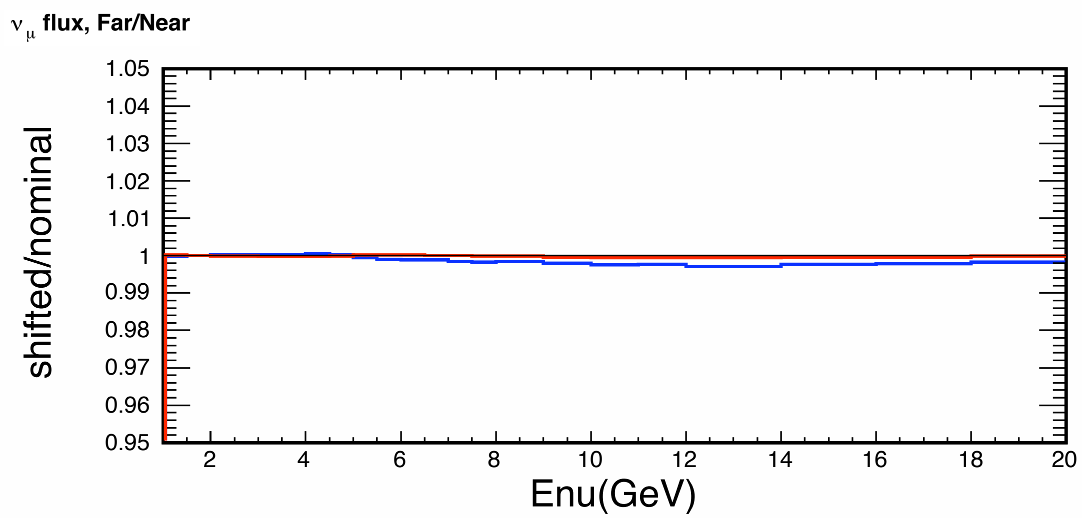
FD/ND

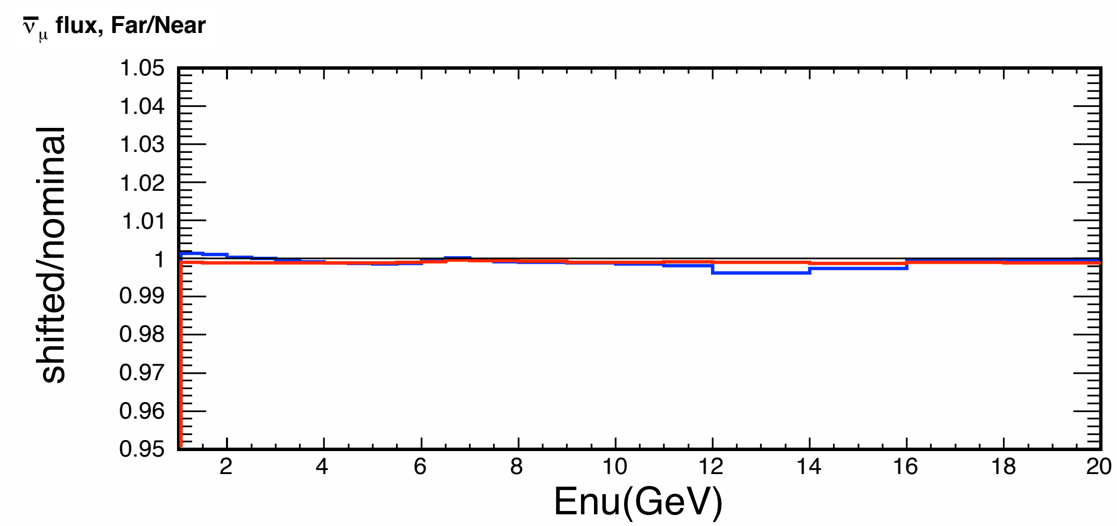

ν_μ flux, Near
QEMA -10%
QEMA +10%
shifted/nominal
Enu(GeV)


$\bar{\nu}_\mu$ flux, Near
RESMA -10%
RESMA +10%
shifted/nominal
Enu(GeV)


ν_μ flux, Far
shifted/nominal
Enu(GeV)


$\bar{\nu}_\mu$ flux, Far
shifted/nominal
Enu(GeV)


ν_μ flux, Far/Near
shifted/nominal
Enu(GeV)

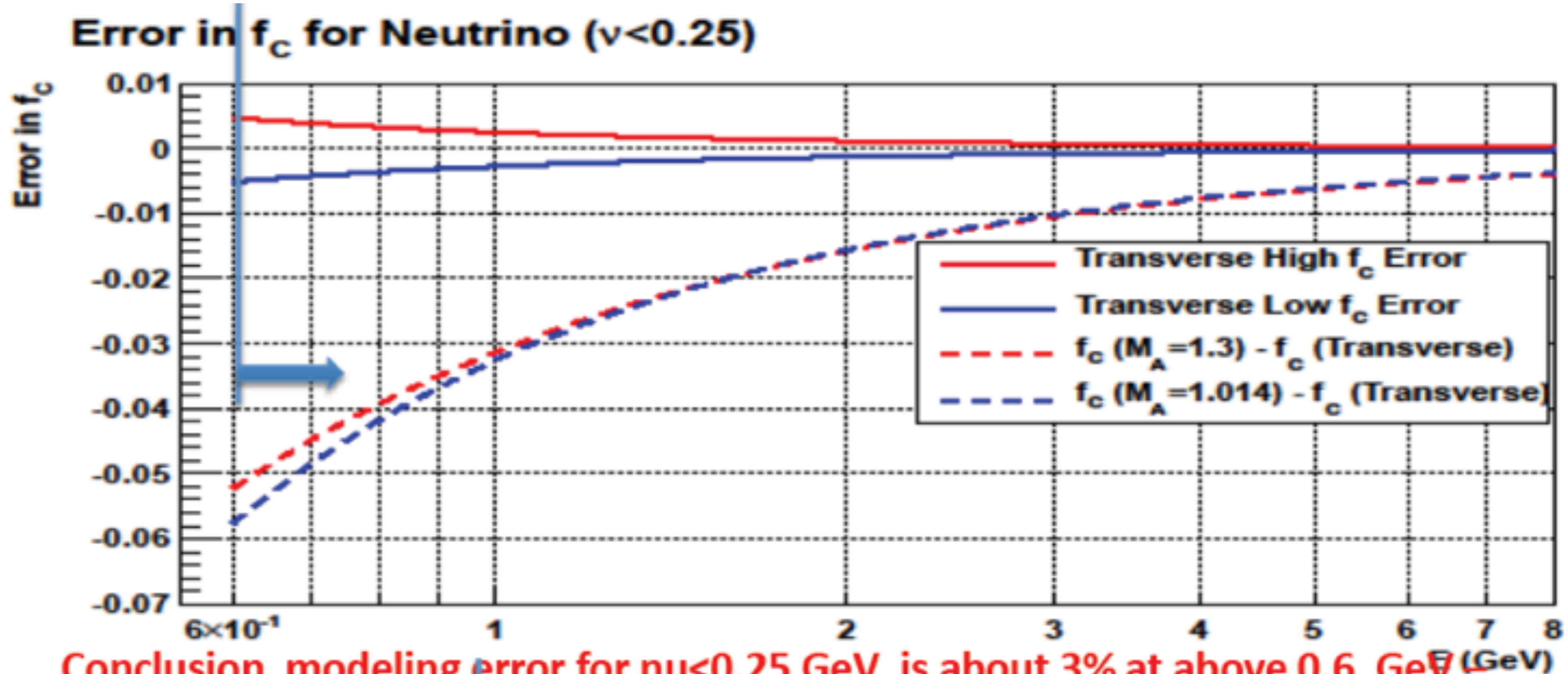

$\bar{\nu}_\mu$ flux, Far/Near
shifted/nominal
Enu(GeV)

Systematic-Errors in Low-$\nu 0$ Relative Flux: ν_μ & Anti-ν_μ

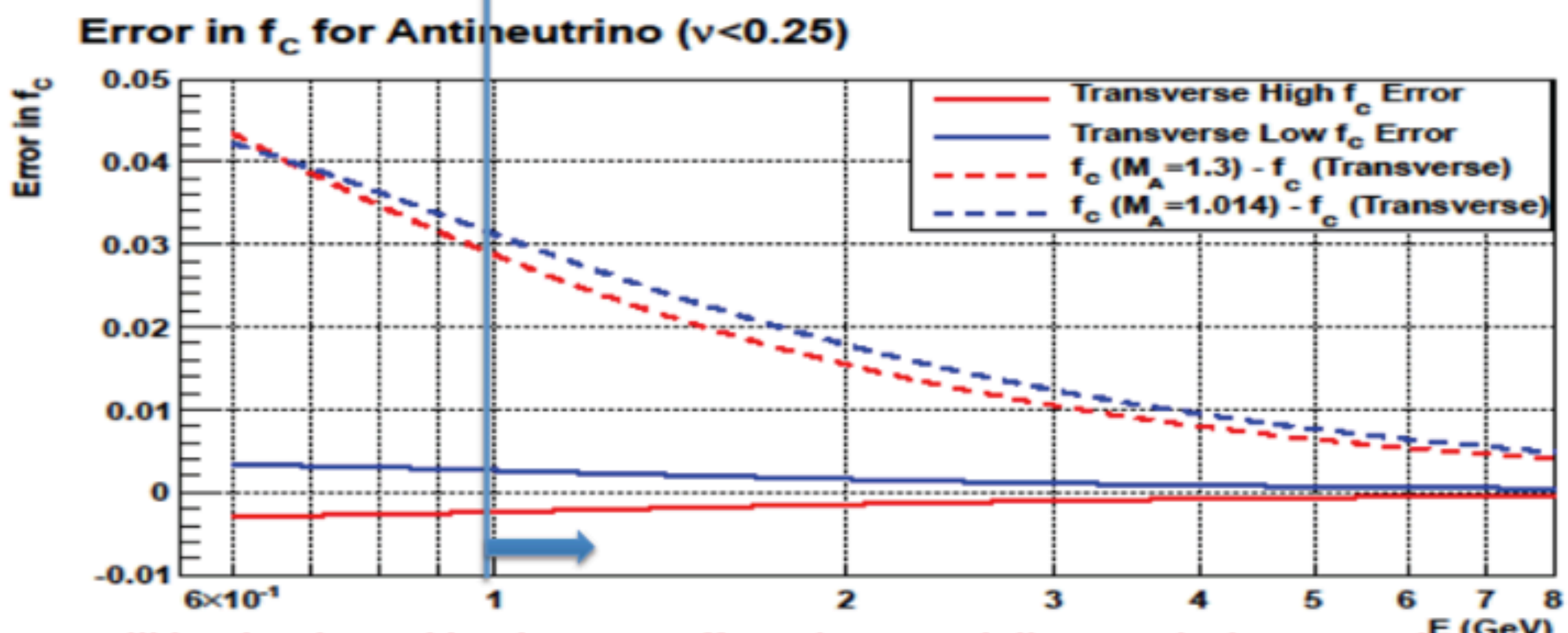
- Variation in Emu-Reconstruction
- Variation in Ehad-correction

- Variation in $\nu 0$-cut
- Variation in $\nu 0$-correction
- Systematic shift in Ehad-scale
- Vary σ(QE) $\pm 10\%$
- Vary σ(Res) $\pm 10\%$
- Vary σ(DIS) $\pm 10\%$
- Vary functional-forms
- Systematic shift in Emu-scale

- Beam-Transport $\Leftarrow$ Different



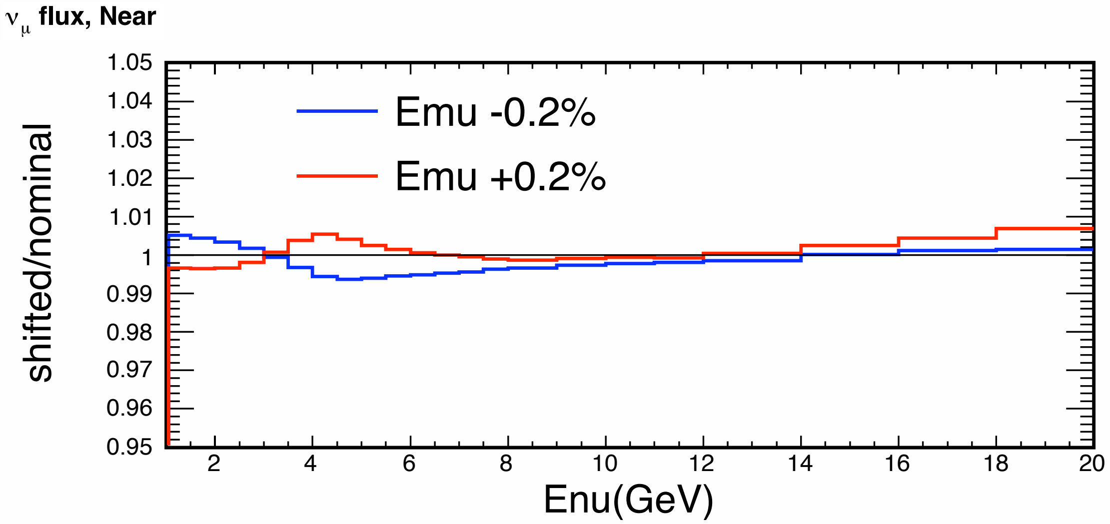
Conclusion modeling error for nu<0.25 GeV is about 3% at above 0.6 GeV

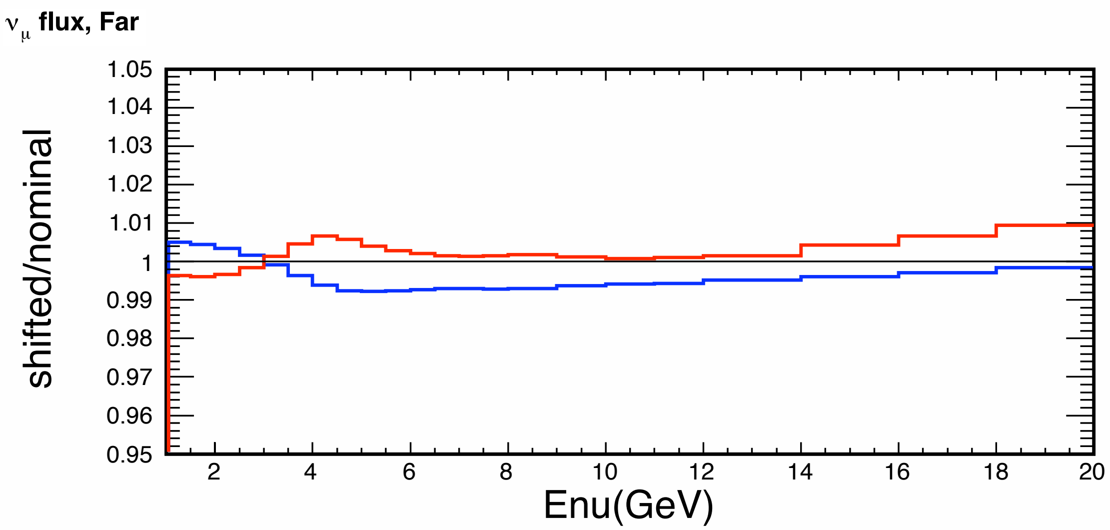


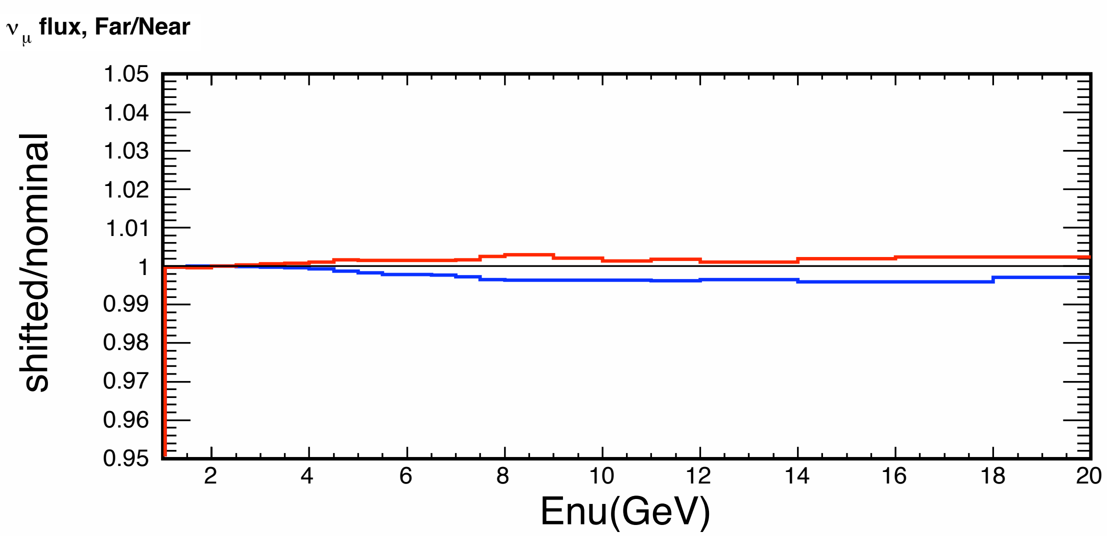
Error will be dominated by detector effects (e.g. modeling resolution smearing)

Bodek et al., arXiv: 1201.3025 (EPJ,C)

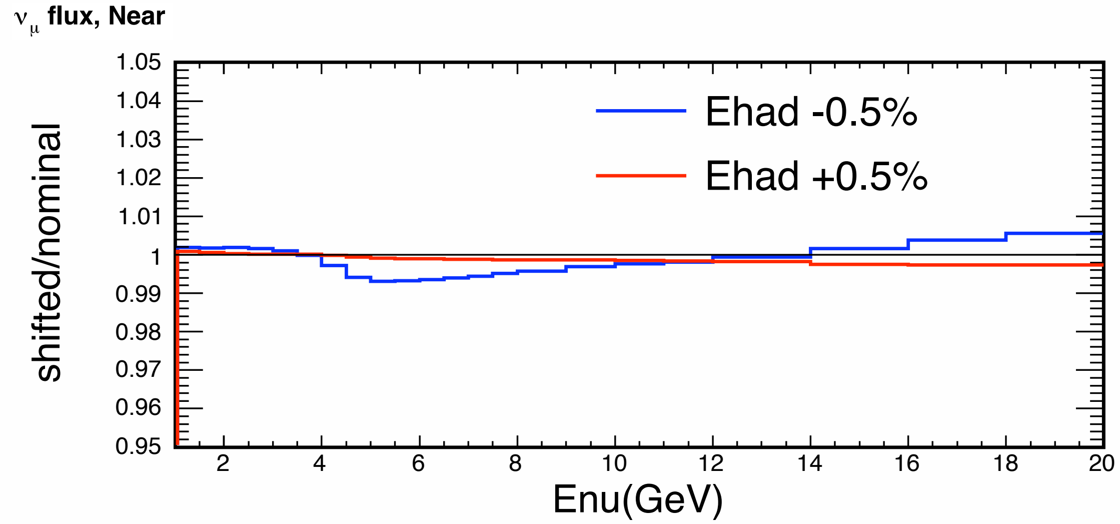
NuMu: Emu-Scale

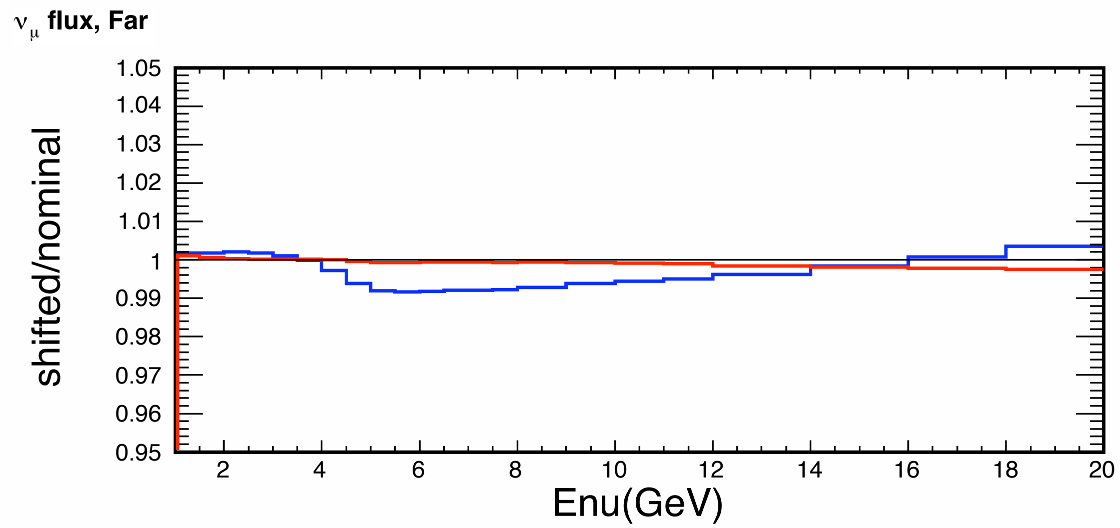


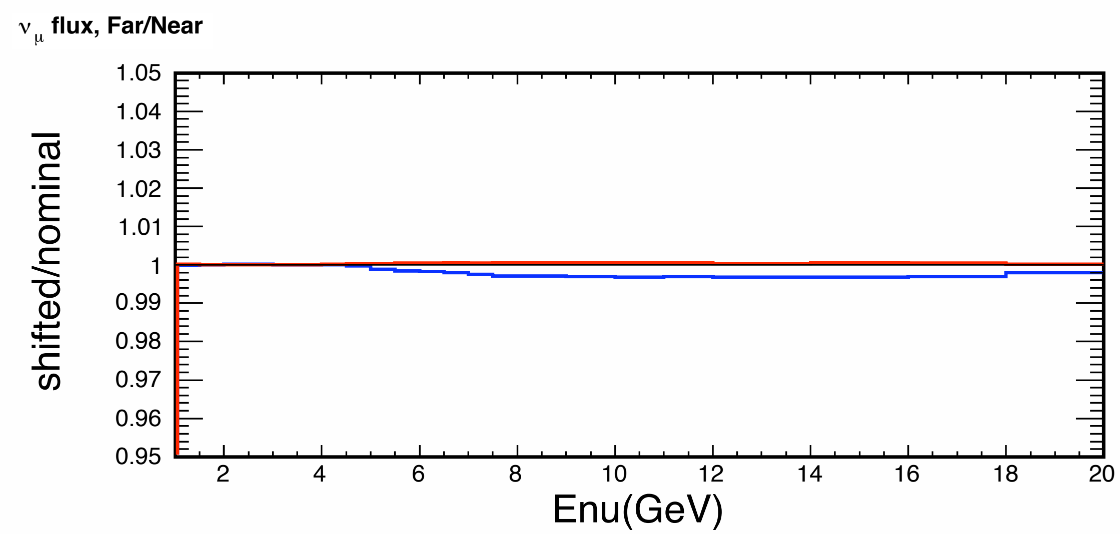




Ehad-Scale

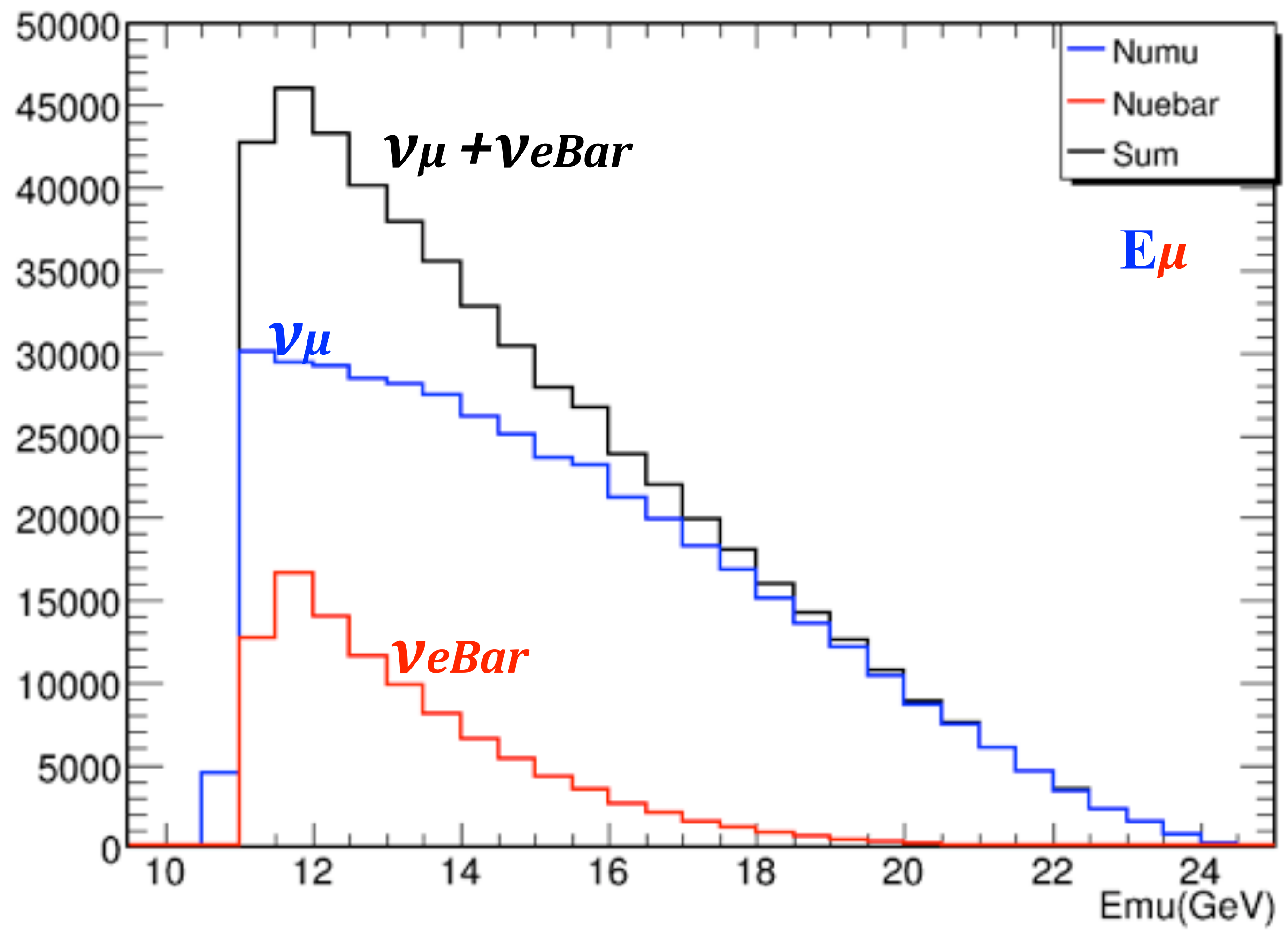


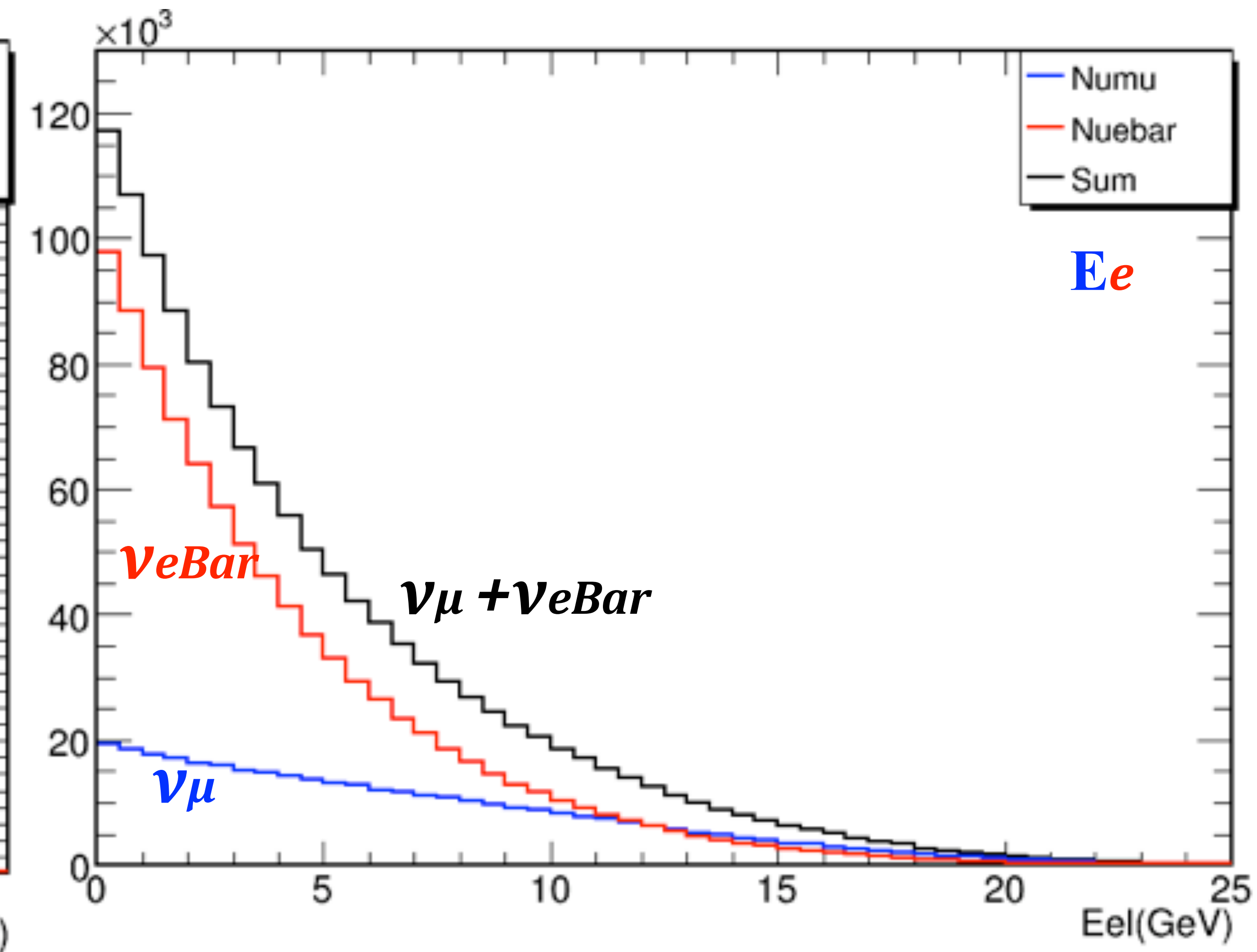




Fitting $\nu\mu$ *and* $\nu eBar$ *using Elastic* ν*-Electron Scattering*

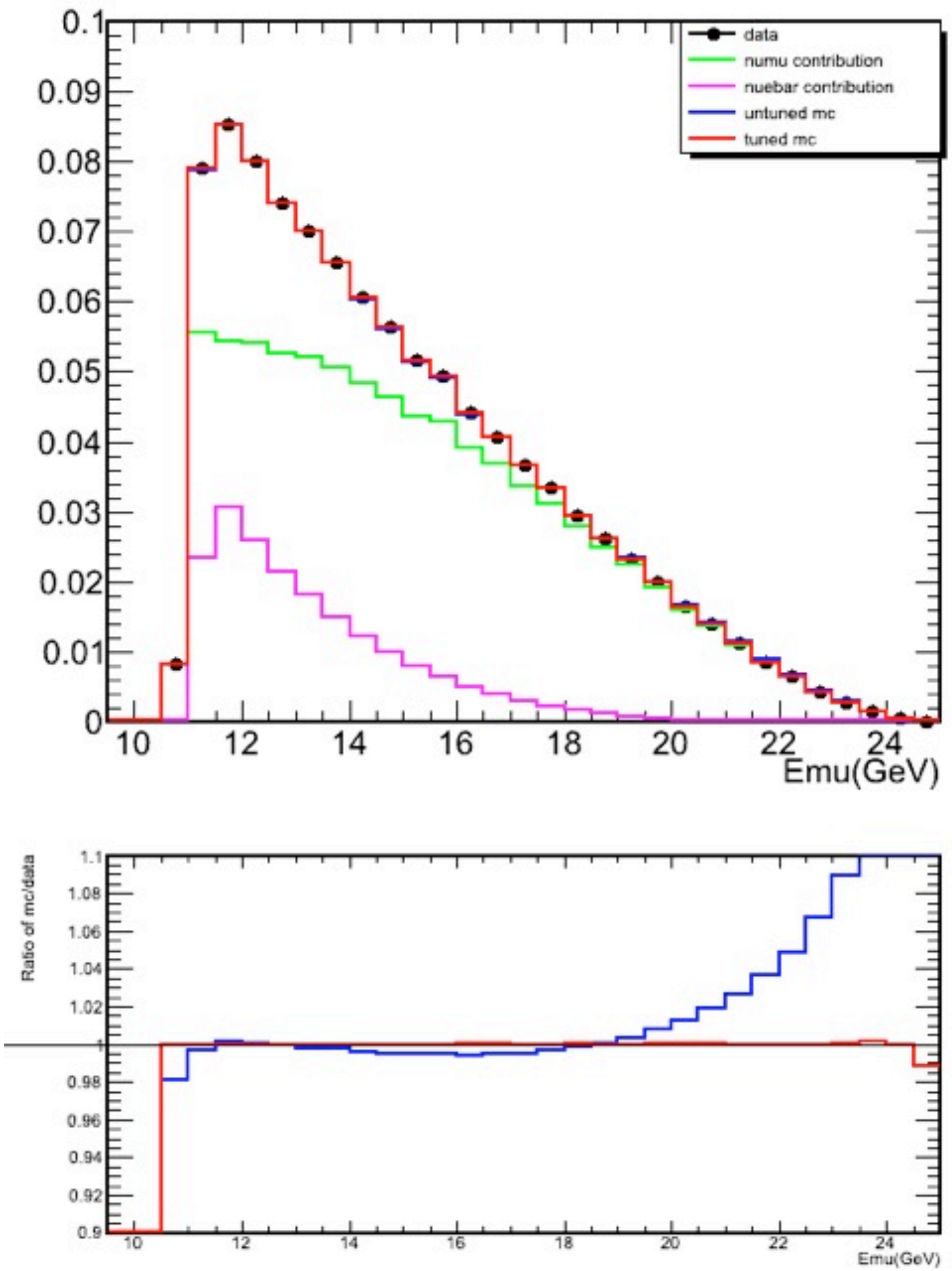
- *(iii)* Mock Data: IMD (μ-sample) and νe (e-sample); 10^6 $\nu\mu$-IMD-events
  For now, ignore background
  - *(a)* Start with a Trial $\nu\mu$ & $\nu eBar$ Flux
  - *(b)* Simulate IMD and El-samples
  - *(c)* Reconstruct Eμ *and* Ee
- *(1)* Compare samples *(iii)* with *(c)* : From χ^2
- *(2)* Vary Flux parameter; Go to *(a)*; arrive at *(b)*; go to *(1)*
- *(3)* Minimize χ^2: $\Rightarrow$ Fitted $\nu\mu$ *and* $\nu eBar$ Flux



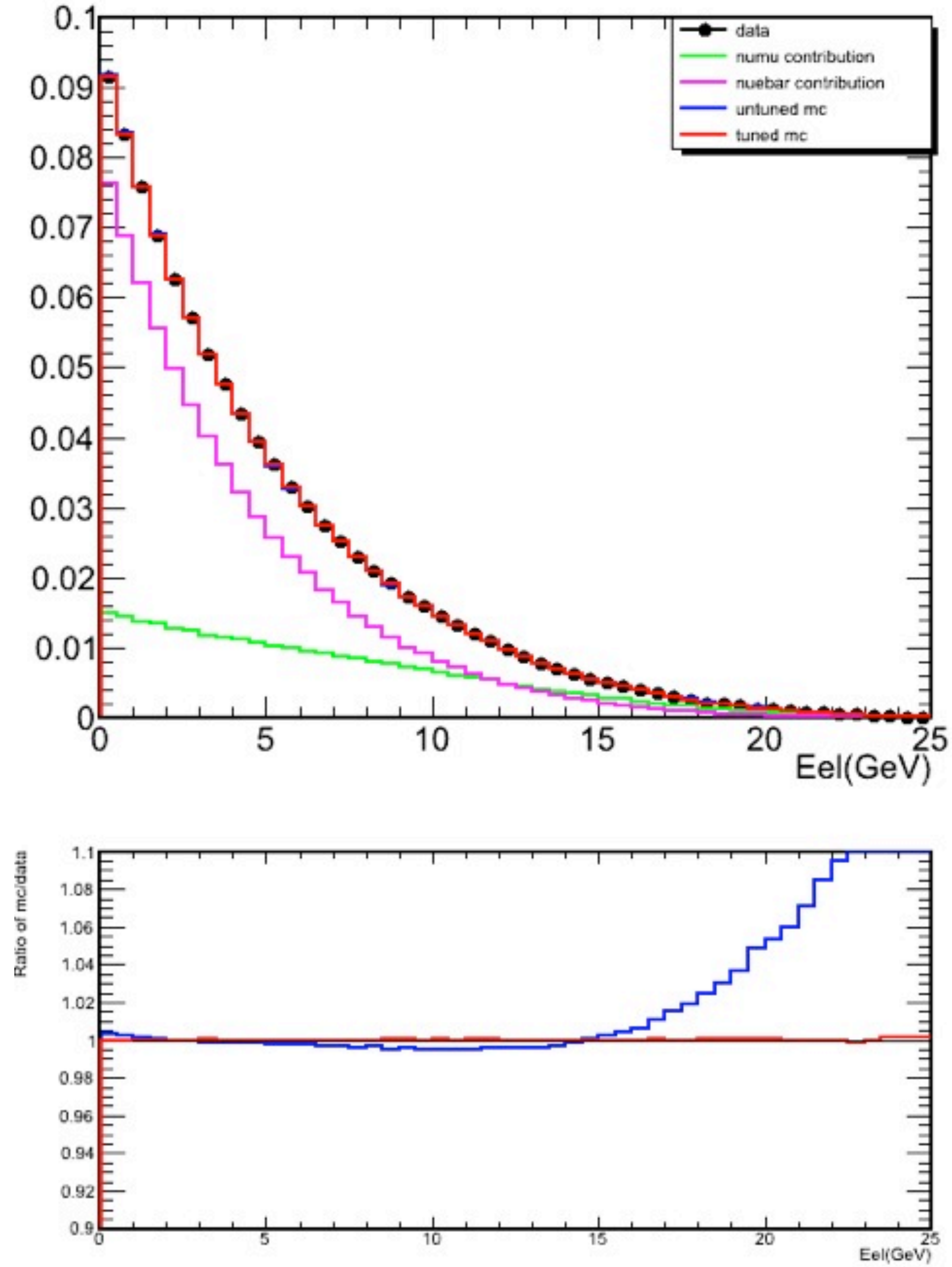


$\mathscr{Both}$ IMD (μ-sample) and νe (e-sample)

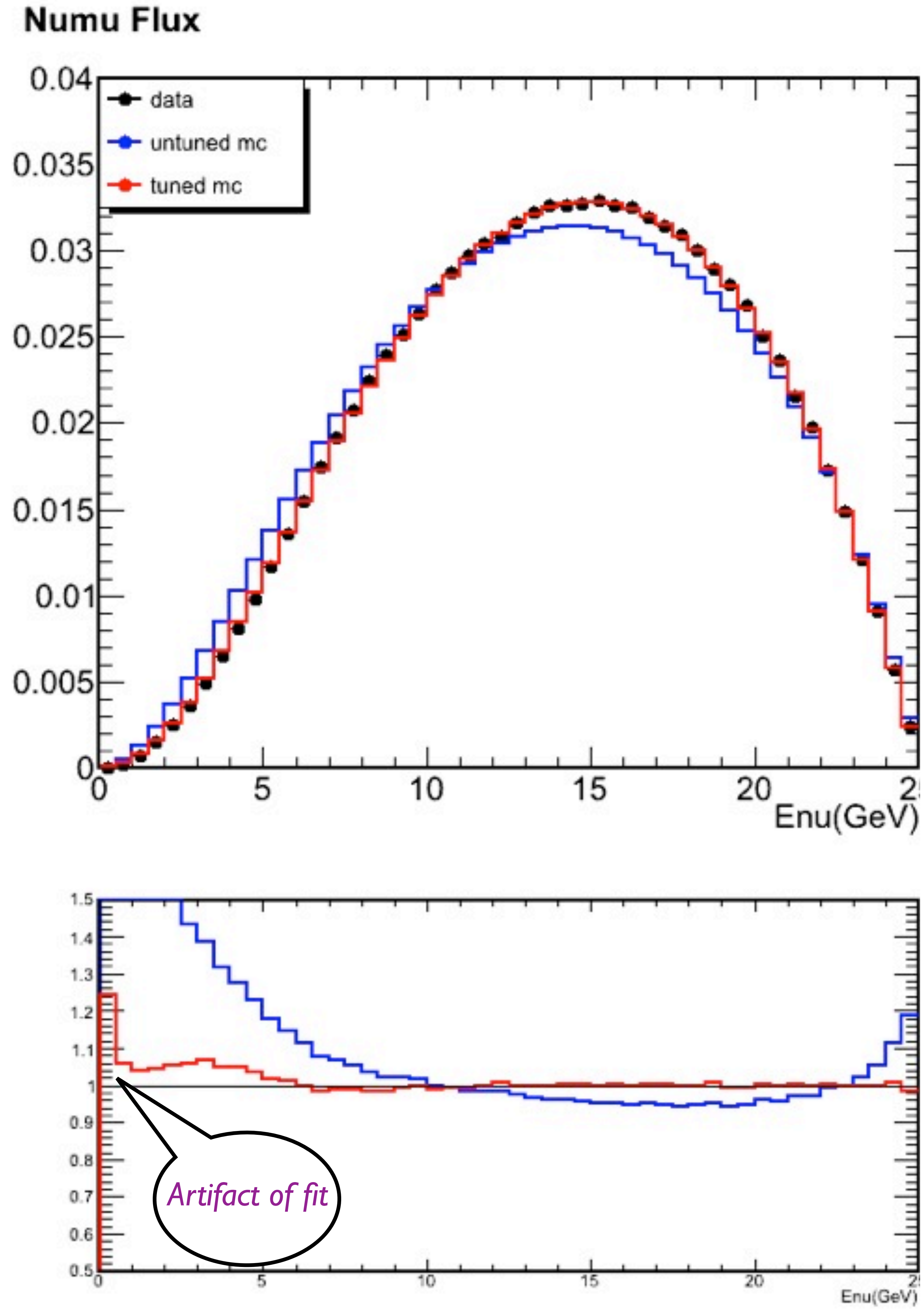
Muon Spectrum

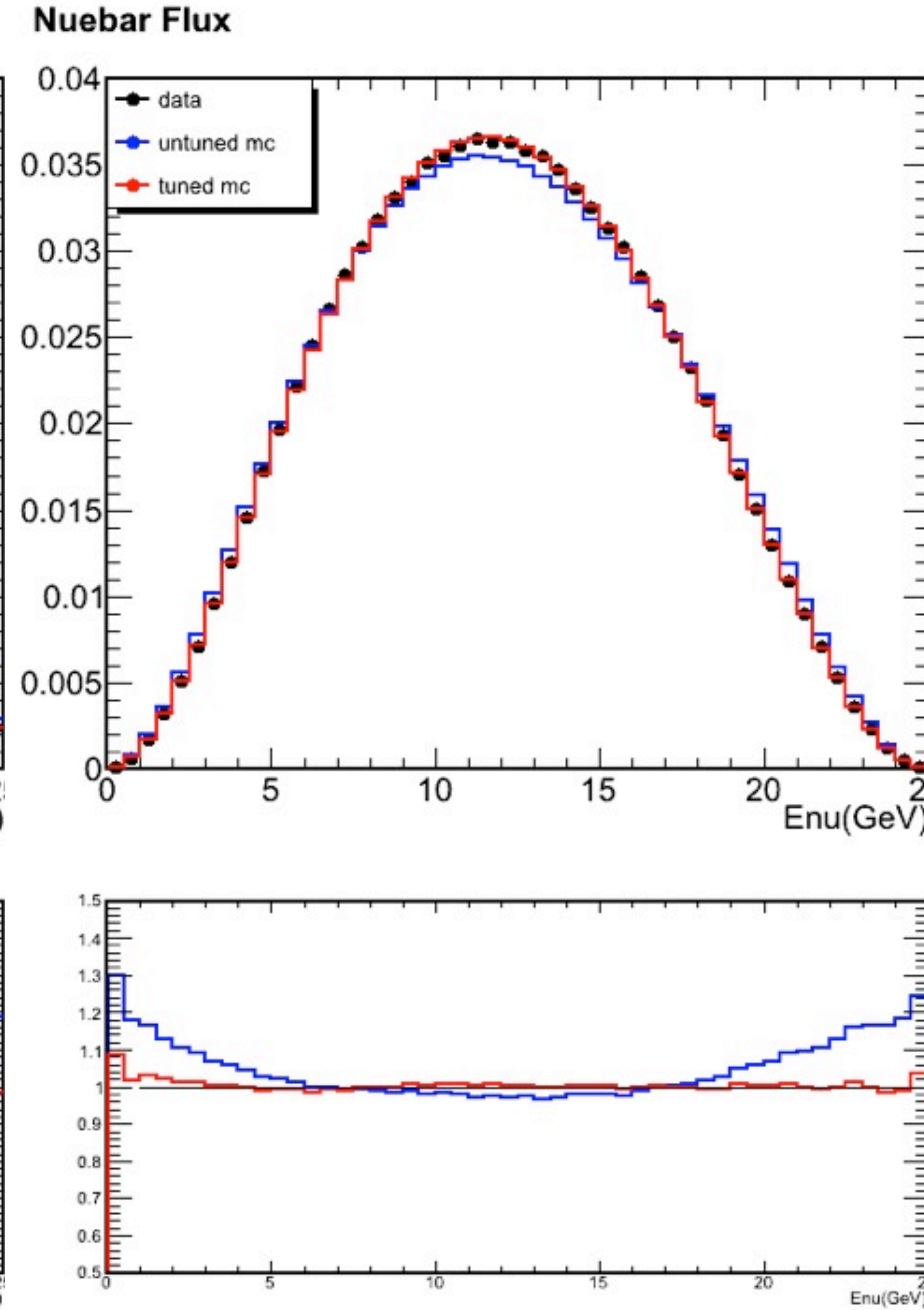


Electron Spectrum

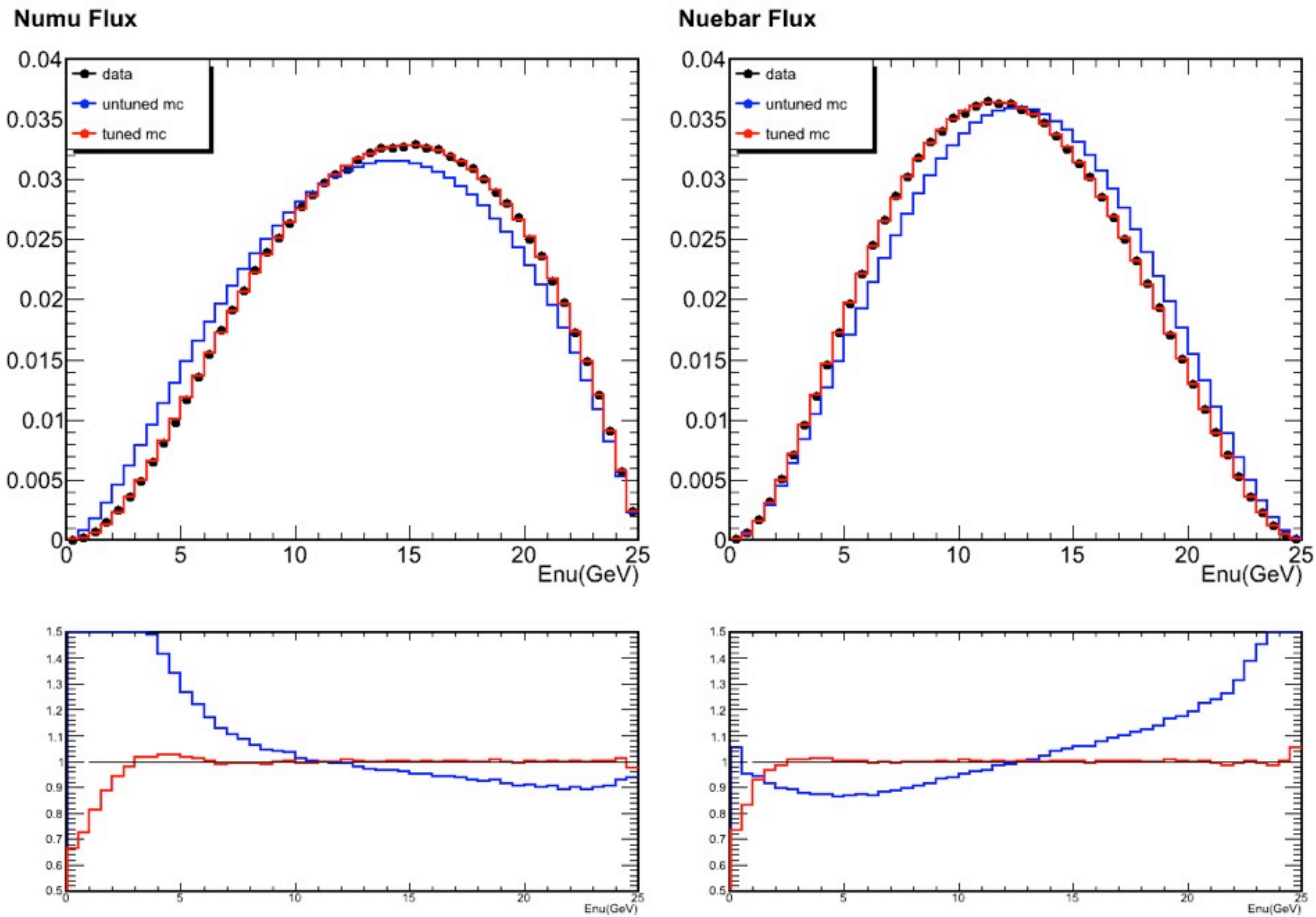


Both IMD (μ-sample) and νe (e-sample)



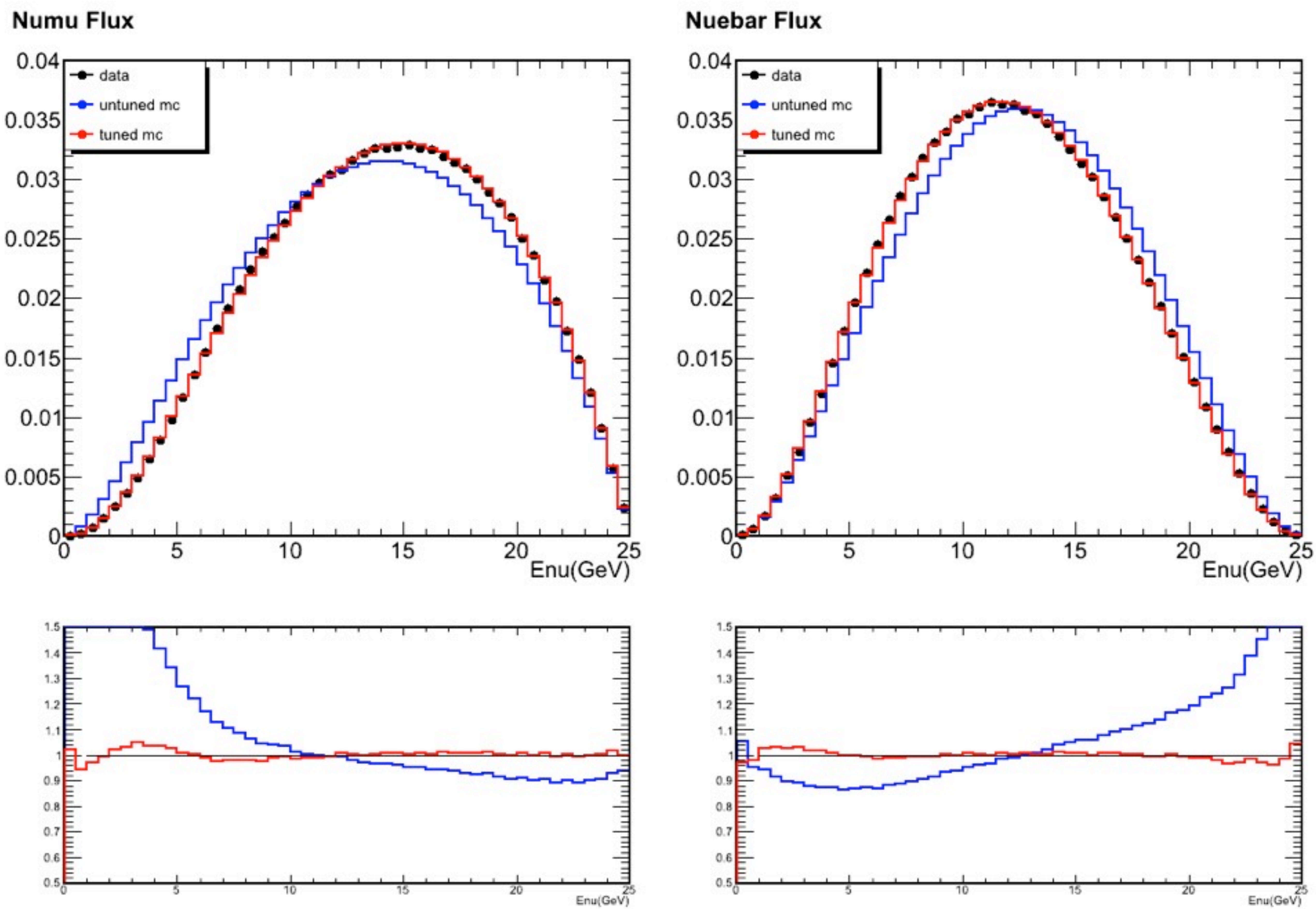


slightly Different Functional Form: *Both* IMD (**μ**-sample) and **νe** (**e**-sample)



slightly Different Functional Form: *Both* IMD (**μ**-sample) and ***νe*** (***e***-sample)

and constraining ***νμ*** -flux ±5% & *and* ***νeBar***-flux ±7.5% ⇐ *Low-νo*



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

- We have presented a promising frame-work to determine ν-flux.
- Only used $E\mu$/el.
- Need to make an assessment on the error on FD/ND-($E\nu$)
- Relative flux ($\nu\mu$: νebar : $\nu\mu bar$: νe) using Quasi-Elastic and Coherent- π^{+-} :

Particle Multiplicity: <u>ν-induced Hardon-jet</u>

✴ ν_μ-CC identified by μ^- in the FD

However in ν-NC interactions:

⇒ π-/K-/D-hadron ⤀ μ- form an irreducible background

⇒ -ve hadron punchthrough form additional, reducible background

✴ Anti-ν_μ CC identified by μ+ in the FD: Still higher backgrounds

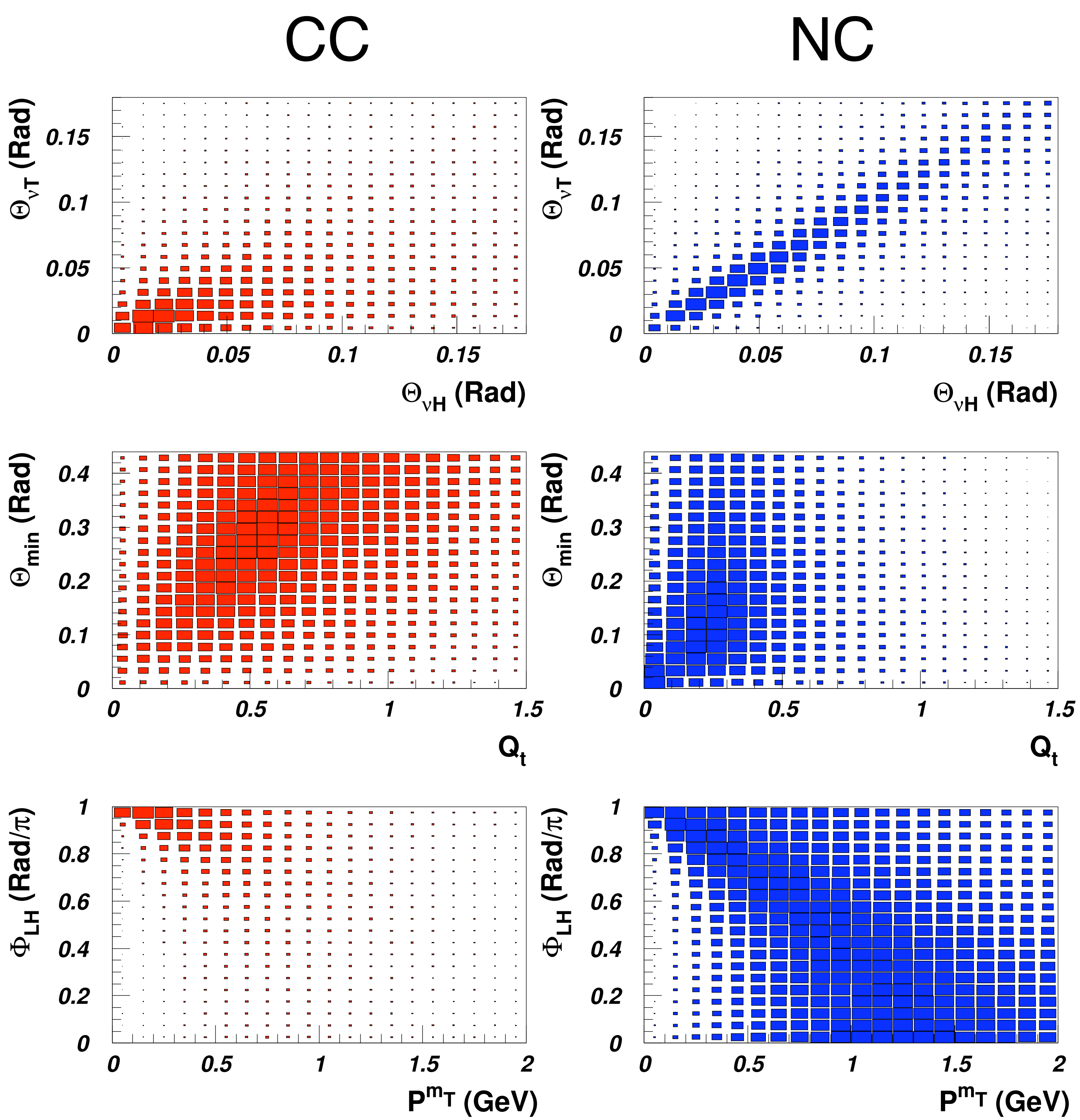
✴ π^0's in NC ⇒ Largest backgrounds to (Anti)ν_{e^-}-appearance

✴ ≃30% of the Non-Prompt background (π0+-/K0+-/D ⇒ μ, EM-shower)

arise from "short" ν_μ-CC

➢➢ *Measure (π0+-/K0+-/D ⇒ μ, EM-shower) in NC & in CC*

Identification of NC interactions in NOMAD

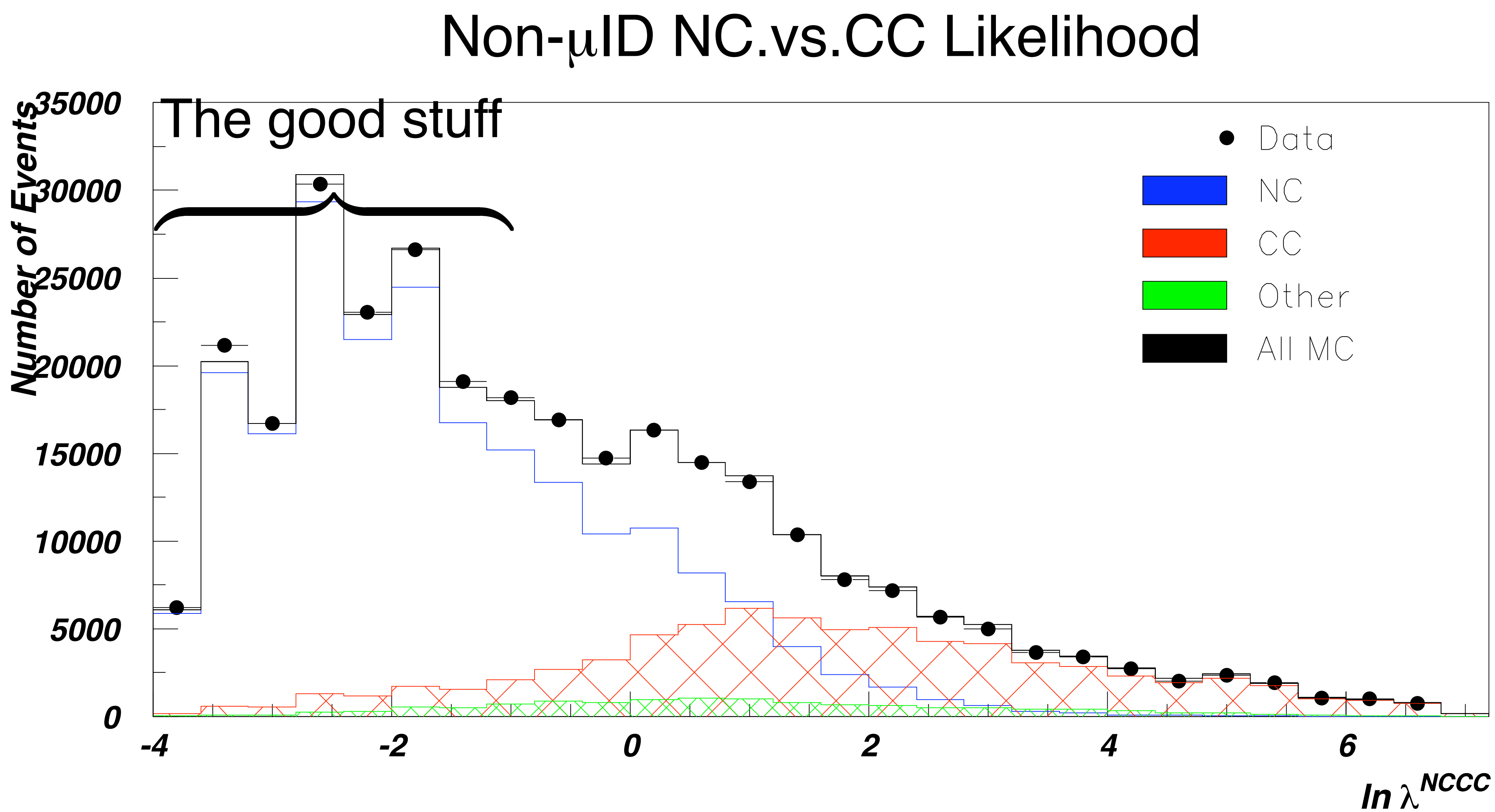


- ✦ Difficult to measure NC cross-section in conventional detectors
- ✦ NOMAD can identify NC events from kinematics with a purity of 90%
- ✦ Plots show NC/CC separation for events failing the muon identification

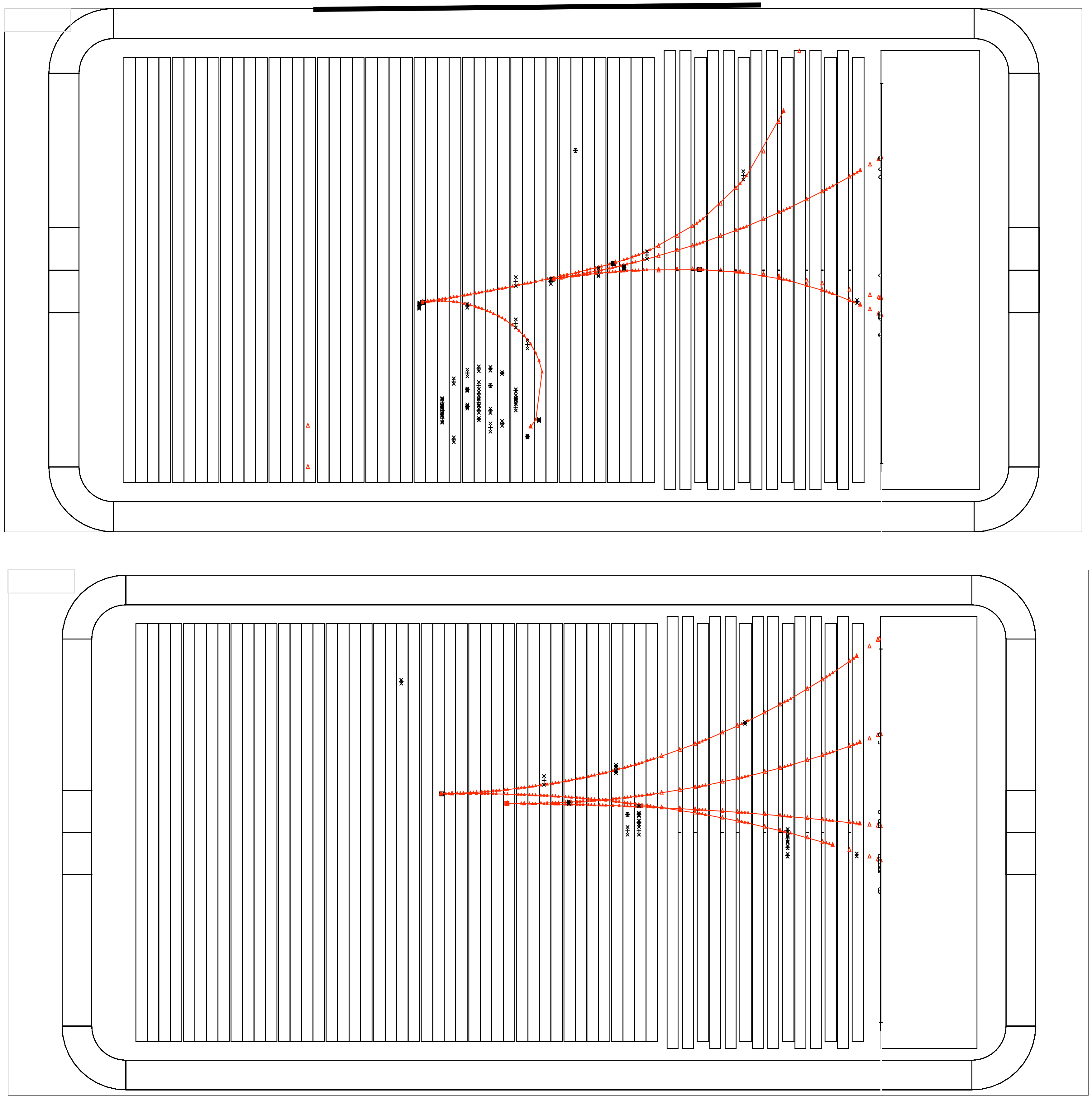
⇐Non-μID Events

NC *vs* CC

Kinematic separation of NC events in NOMAD. The abscissa variable is a likelihood.



π0 Candidates in NOMAD



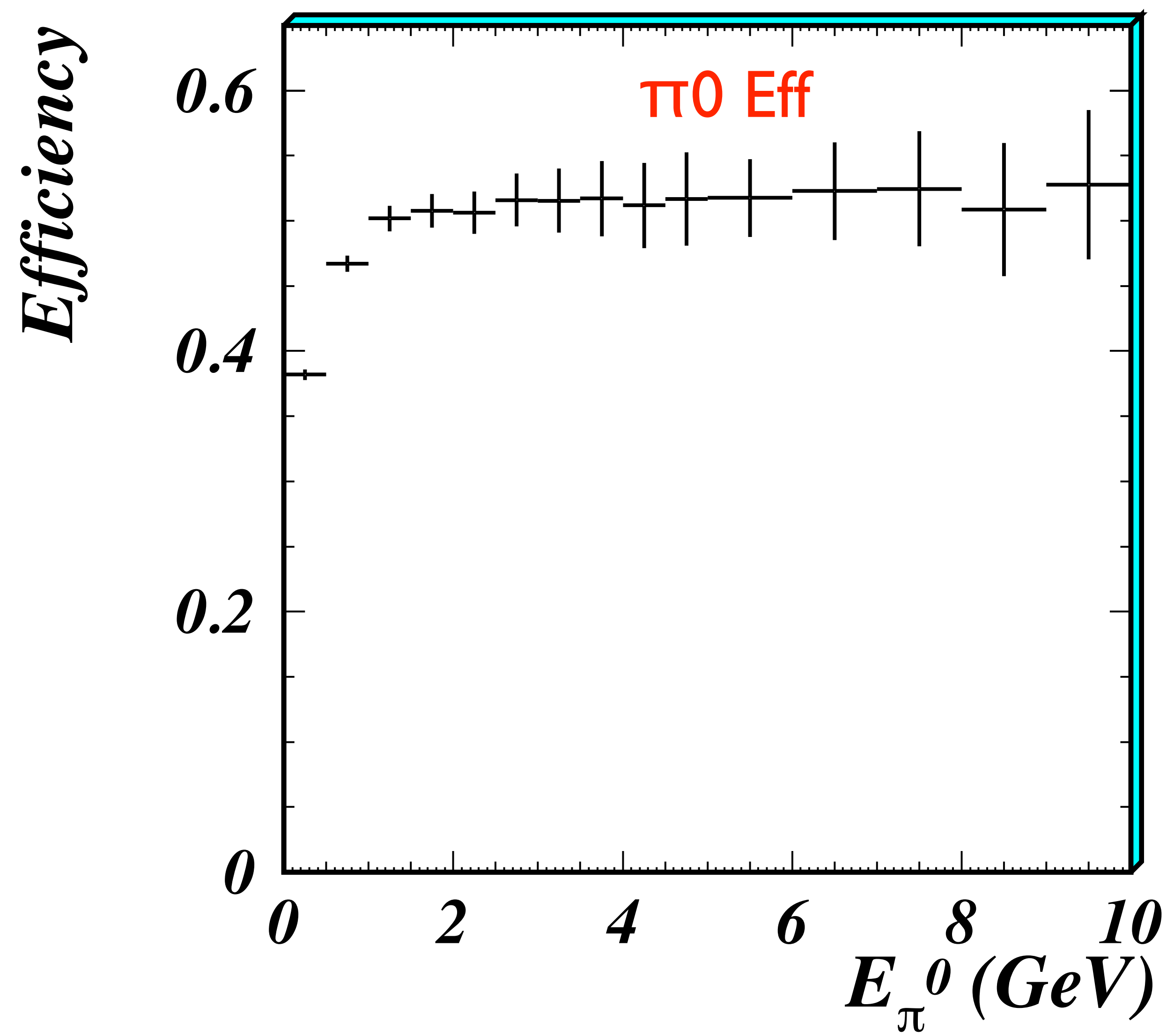
π0-Reconstruction

✴ Clean Π0- and γ-signatures in STT

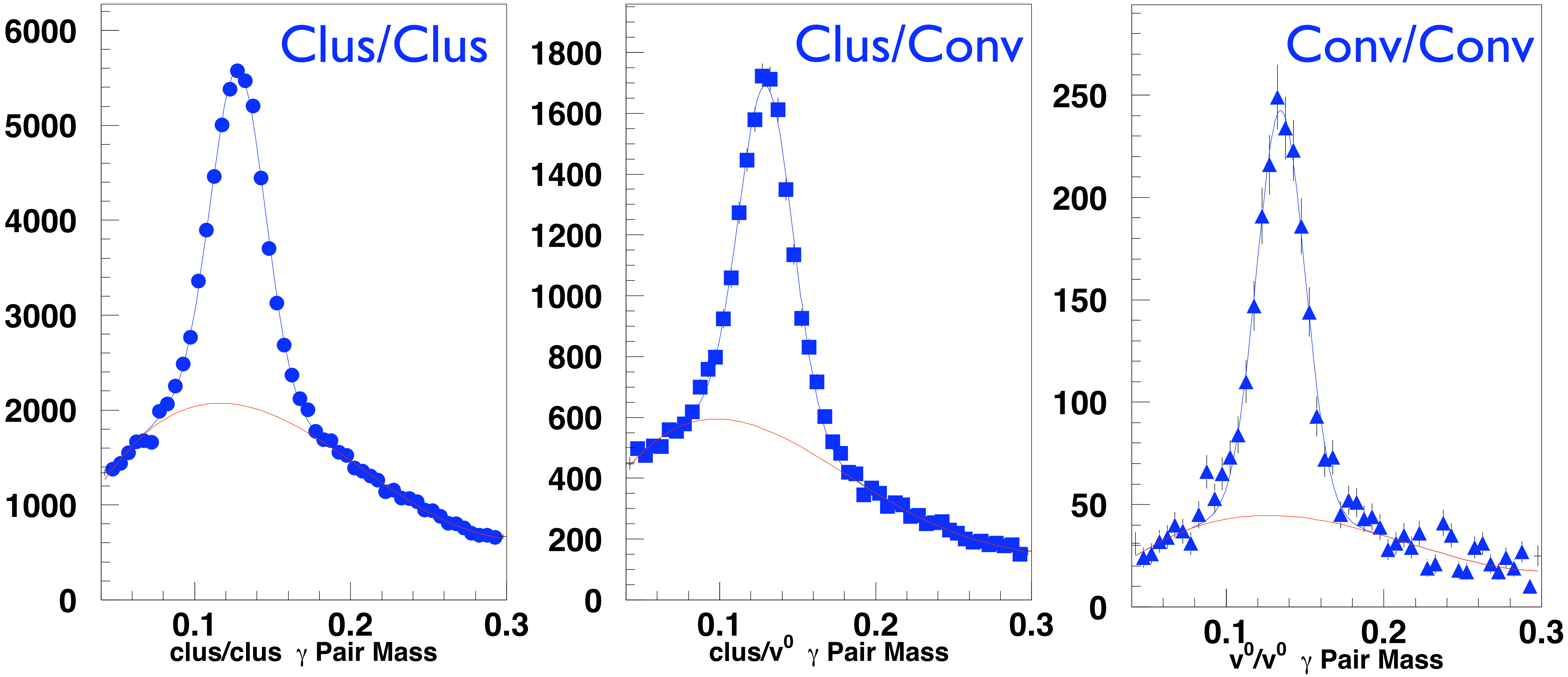
✴ ν-NC & CC ➽ π0 ➽ γγ
~50% of the γ ➽ e+e- will convert in the STT, away from the primary vertex.
We focus on these

✴ γ-Identification:
✺ e-/e+ ID: TR
✺ Kinematic cut: Mass, Opening angle

➢ At least one converted γ in STT
(Reconstructed e- & e+;
e- or e+ traverse ≥6 Mods)
➢ Another γ in the
Downstream & Side ECAL



Reconstructed π^0 in NC interactions in NOMAD



Overall more than 33k reconstructed events. Three topologies:

- *Cluster/Cluster 24k events*
- *Cluster/Conversion 7k events*
- *Conversion/Conversion 2k events*

South Carolina Group

Coherent Processes:

- ✴ Coherent π^0 ❧
- ✴ Coherent π^+ ❧
- ✴ Coherent π^-
- ✴ Coherent ρ^0 ❧
- ✴ Coherent ρ^+ ❧
- ✴ Coherent ρ^-

(❧ ➳ Different Analyses)

⇛ *Structure of Weak-Current and its Hadronic-Content*

Partially conserved axial current (PCAC) & Adler's theorem
Conserved vector current (CVC) & Vector meson dominance (VMD)

⇛ ✴ Cohπ^-/Cohπ^+ ⇒ Identical signatures ($\mu\,\pi$)

Constraint on the Anti-Nu/Nu flux

✴ Coh ρ^0 ⇒ If/Since CVC and VMD are at work, using γ-induced Coh ρ^0

get an independent measure of the Absolute-Neutrino Flux;
Coh ρ^+ and Coh ρ^- provide additional redundancies.

A matrix of measurements leading to a better modeling of Low-Q**2 processes and provide independent constraints on Flux.

APPENDIX A: Physics Potential of HiResMν

Below we enumerate some physics topics which can be studied with the proposed experiment and can be the subject of PhD theses. The list is not complete. It is intended to illustrate the outstanding physics potential of HiResMν; the many theses it will engender.

About NuMI and Service to LBLν

1: The energy scale and relative flux of ν_μ Flux in NuMI

2: The $\overline{\nu}_\mu$ relative to ν_μ as a function of E_ν in NuMI

3: Relative abundance of ν_e and $\overline{\nu}_e$ -vs- ν_μ and $\overline{\nu}_\mu$ in NuMI

4: An empirical parametrization of K^0_L yield in NuMI using the $\overline{\nu}_e$ data

5: Redundancy check on the MIPP π^+, K^+, π^-, K^-, and K^0_L yields in NuMI using the ν_μ , $\overline{\nu}_\mu$, ν_e , and $\overline{\nu}_e$ induced charged current interactions

Neutral-Pion Production in ν-Interactions

6: Coherent and single π^0 production in ν-induced neutral current interactions

7: Multiplicity and energy distribution π^0 production in neutral current and charged current processes as a function of hadronic energy

8: The cross section of π^0 production as a function of X_F and P_T in the ν-CC interactions

Charged-Pion & Kaon and Proton & Neutron Production in ν-Interactions

9: Coherent and single π^+ production in ν-induced charged current interactions

10: Coherent and single π^- production in $\overline{\nu}$-induced charged current interactions

11: Charged π/K/Proton production in the the neutral current and chaged current interactions as a function of hadronic energy

12: The cross section of $\pi^\pm$/K$^\pm$/proton production as a function of X_F and P_T in the ν-CC interactions

13: Measurement of neutron production via charge-exchange process in the CC and NC interactions

Neutrino-Electron Scattering

14: Measurement of inverse muon decay and absolute normalization of the NuMI flux above $E_\nu > 11$ GeV with $\leq 1\%$ precision

15: Search for the lepton violating $\overline{\nu}_\mu - e^-$ CC interaction

16: The ν_μ-e^- and $\overline{\nu}_\mu$-e^- neutral current interaction and determination of $\sin^2\theta_W$

17: Measurement of the chiral couplings, g_L and g_R using the ν_μ-e^- and $\overline{\nu}_\mu$-e^- neutral current interactions

ν-Nucleon Neutral Current Scattering

18: Measurement of neutral current to charged current ratio, R^ν, as a function of hadronic energy in the range $0.25 \leq E_{Had} \leq 20$ GeV

19: Measurement of neutral current to charged current ratio, R^ν and $R^{\overline{\nu}}$, for $E_{Had} \geq 3$ GeV and determination of the electroweak parameters $\sin^2\theta_W$ and ρ.

Non-Scaling Charged and Neutral Current Processes

20: Measurement of ν_μ quasi-elastic CC interaction

21: Measurement of $\overline{\nu}_\mu$ quasi-elastic CC interaction

22: Determination of M_A from the QE cross section and the shape of the kinematic variables (Q^2, Y_{bj}, etc.)

23: Measurement of the axial form-factor of the nucleon from quasi-elastic interactions

24: Measurement of ν_μ induced resonance processes

25: Measurement of $\overline{\nu}_\mu$ induced resonance processes

26: Measurement of resonant form-factors and structure functions

27: Study of the transition between scaling and non-scaling processes

28: Constraints on the Fermi-motion of the nucleons using the 2-track topology of neutrino quasi-elastic interactions

29: Coherent $\rho^\pm$ production in ν-induced charged current interactions

30: Neutral Current elastic scattering on proton $\nu(\overline{\nu}_\mu)p \to \nu(\overline{\nu}_\mu)p$

31: Measurement of the strange quark contribution to the nucleon spin ΔS

32: Determination of the weak mixing angle from NC elastic scattering off protons

Inclusive Charged Current Processes

33: Measurement of the inclusive ν_μ charged current cross-section in the range $0.5 \leq E_\nu \leq 40$ GeV

34: Measurement of the inclusive $\overline{\nu}_\mu$ charged current cross-section in the range $0.5 \leq E_\nu \leq 40$ GeV

35: Measurement of the inclusive ν_e and $\overline{\nu}_e$ charged current cross-section in the range $0.5 \leq E_\nu \leq 40$ GeV

36: Measurement of the differential ν_μ charged current cross-section as a function of x_{bj}, y_{bj} and E_ν.

37: Measurement of the differential $\overline{\nu}_\mu$ charged current cross-section as a function of x_{bj}, y_{bj} and E_ν.

38: Determination of xF_3 and F_2 structure functions in ν_μ charged current interactions and the QCD evolution

39: Determination of xF_3 and F_2 structure functions in $\overline{\nu}_\mu$ charged current interactions and the QCD evolution

40: Measurement of the longitudinal structure function, F_L, in ν_μ and $\overline{\nu}_\mu$ charged current interactions and test of QCD

41: Determination of the gluon structure function, bound-state and higher twist effects

42: Precise tests of sum-rules in QPM/QCD

43: Measurement of ν_μ and $\overline{\nu}_\mu$ charged current differential cross-section at large-x_{bj} and -y_{bj}

44: Measurement of scaled momentum, rapidity, sphericity and thrust in (anti)neutrino charged current interactions

45: Search for rapidity gap in neutrino charged current interactions.

46: Verification of quark-hadron duality in (anti)neutrino interactions

47: Verification of the PCAC hypothesis at low momentum transfer

48: Determination of the behavior of $R = \sigma_L/\sigma_T$ at low momentum transfer

Nuclear Effects

49: Measurement of nuclear effects on F_2 in (anti)neutrino scattering from ratios of Pb,Fe and C targets

50: Measurement of nuclear effects on xF_3 in (anti)neutrino scattering from ratios of Pb,Fe and C targets

51: Study of (anti)shadowing in neutrino and antineutrino interactions and impact of axial-vector current

52: Measurement of axial form-factors for the bound nucleons from quasi-elastic interactions on Pb, Fe and C

53: Measurement of hadron multiplicities and kinematics as a function of the atomic number

Semi-Exclusive and Exclusive Processes

54: Measurement of charmed hadron production via dilepton ($\mu^-\mu^+$, and μ^-e^+) processes

55: Determination of the nucleon strange sea using the (anti)neutrino charm production and QCD evolution

56: Measurement of J/ψ production in neutral current interactions

57: Measurement of K^0_S, Λ and $\overline{\Lambda}$ production in neutrino CC processes

58: Measurement of K^0_S, Λ and $\overline{\Lambda}$ production in antineutrino CC processes

59: Measurement of K^0_S, Λ and $\overline{\Lambda}$ production in (anti)neutrino NC processes

60: Measurement of exclusive strange hadron and hyperon production in (anti)neutrino charged and neutral current

61: Measurement of the Λ and $\overline{\Lambda}$ polarization in neutrino charged current interactions

62: Measurement of the Λ and $\overline{\Lambda}$ polarization in antineutrino charged current interactions

63: Measurement of the Λ and $\overline{\Lambda}$ polarization in (anti)neutrino neutral current interactions

64: Inclusive production of rho0(770), f0(980) and f2(1270) mesons in (anti)neutrino charged current interactions

65: Measurement of backward going protons and pions in neutrino CC interactions and constraints on nuclear processes

66: D*+ production in neutrino charged current interactions

67: Determination of the D^0, D^+, D_s, Λ_c production fractions in (anti)neutrino interactions

68: Production of K*(892)+- vector mesons and their spin alignment in neutrino interactions

Search for New Physics and Exotic Phenomena

69: Search for heavy neutrinos using electronic, muonic and hadronic decays

70: Search for eV (pseudo)scalar penetrating particles

71: Search for the exotic Theta+ resonance in the neutrino charged current interactions

72: Search for heavy neutrinos mixing with tau neutrinos

73: Search for an anomalous gauge boson in pi0 decays at the 120 GeV p-NuMI target

74: Search for anomaly mediated neutrino induced photons

75: Search for the magnetic moment of neutrinos

76: A test of ν_μ-ν_e universality down to 10^{-4} level

77: A test of ν_μ-ν_τ coupling down to 10^{-5} level

- *>80 HiResMnu Topics listed*
- *Many topics are pertinent to oscillation physics*
- *Some non-oscillation topics might lead to discovery*

South Carolina Group

HIRESMNU: A Cost Estimate

HIRESMNU-idea comprises 4 sub-detectors.

Cost: Prototype+Material+Labor [+Contigency]

✴ *Straw Tube Ttracker* (inside the B-Field): $23.5M [Contigency(40%)]

- Based on ATLAS, COMPASS, and the NOMAD-TRD designs
- A critical part ⇒ compromises, need detailed studies

✴ *ECalorimeter* (inside the B-Field): $18.6M [Contigency(43%)]

- Motivated by the T2K ECAL
- Downstream (DS ⇒ $4.9M), Barrel-Up (Side), Barrel-Dw (Side), & Upstream (UP) calorimeters

✴ *Muon Detector:* $8.6M [Contigency(45%)]

- RPC's and Absorbers
- Instrumenting the dipole & two muon stations, outside the magnet, at the downstream end

✴ *Dipole Magnet:* ≃$22.5M [Contigency(26%)]

- Based on UA1 (& LHCb) designs (but no beam-tube!)
- Design linked to the STT and ECal

Total (Prototype + Material + Labour + Contingency) ⇒ $74.15 M

Detailed Cost & Schedule Doument (RLS)

WBS	BOE File	Task Name	Cost		TPC	Duration	Start
1.03.04.02.02.02	**HR**	**Strawtube tracker(STT)**	**$16,914,991.20**	**0**	**$23,533,539.68**	**2216 days?**	**Fri 4/1/**
1.03.04.02.02.02.01	**HR**	**Factories(4)**	**$534,600.00**	**0**	**$748,440.00**	**1193 days?**	**Fri 4/1/**
1.03.04.02.02.02.01.01	HR	Design	$46,600.00	0.4	$65,240.00	10 wks	Fri 4/1/
1.03.04.02.02.02.01.02	HR	Manufacture jigs	$100,000.00	0.4	$140,000.00	8 mons	Wed 10/1/
1.03.04.02.02.02.01.03	HR	procure flat tables	$100,000.00	0.4	$140,000.00	1 day?	Wed 10/1/
1.03.04.02.02.02.01.04	HR	assemble	$288,000.00	0.4	$403,200.00	6 mons	Wed 5/13/
1.03.04.02.02.02.02	**HR**	**Prototyping & R&D**	**$1,288,080.00**	**0**	**$1,674,504.00**	**860 days**	**Mon 1/2/**
1.03.04.02.02.06	**HR**	**ECAL**	**$13,261,295.00**	**0**	**$18,569,727.40**	**1480 days?**	**Wed 10/1**
1.03.04.02.02.06.01	**HR**	**downstream ECAL**	**$5,115,270.00**	**0**	**$7,165,292.40**	**1480 days?**	**Wed 10/1**
1.03.04.02.02.06.01.01	**HR**	**Factory**	**$318,600.00**	**0**	**$446,040.00**	**280 days?**	**Mon 1/25**
1.03.04.02.02.06.01.01.01	HR	design	$46,600.00	0.4	$65,240.00	50 days?	Mon 1/25
1.03.04.02.02.06.01.01.02	HR	Manufacture jigs	$100,000.00	0.4	$140,000.00	8 mons	Mon 1/25
1.03.04.02.02.06.01.01.03	HR	Procure assembly station	$100,000.00	0.4	$140,000.00	6 mons	Mon 1/25
1.03.04.02.02.06.01.01.04	HR	Setup factory	$72,000.00	0.4	$100,800.00	6 mons	Mon 9/5
1.03.04.02.02.06.01.02	**HR**	**Prototyping**	**$552,480.00**	**0**	**$777,386.40**	**300 days**	**Wed 10/1**

Future Plans

✴ Error in FD/ND

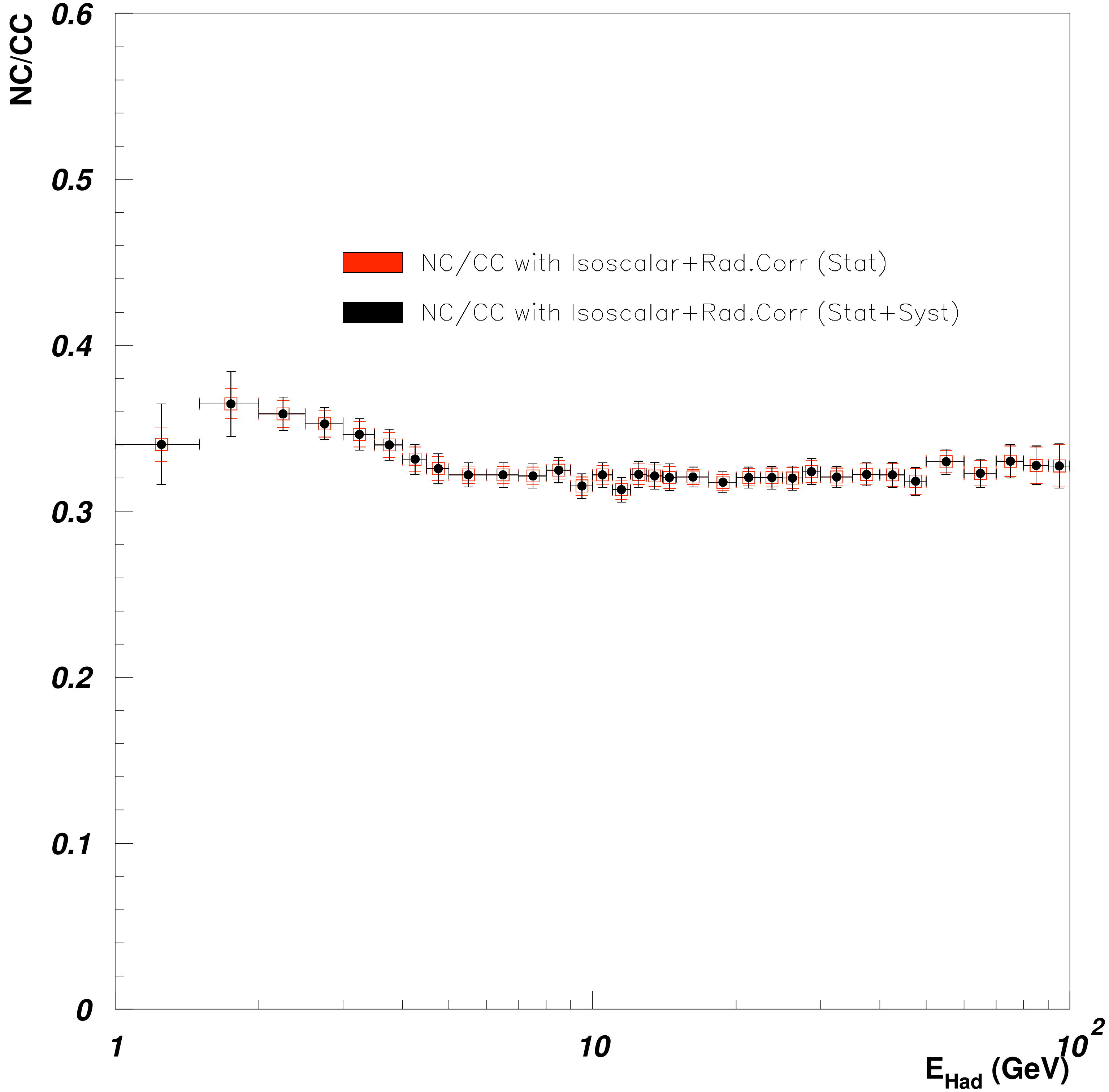
✴ Estimation of backgrounds to

$\nu_e \twoheadrightarrow \nu_\mu$

$\nu_e \twoheadrightarrow \nu_\tau$

✴ ND synergy between the LBNE and Nu-Factory // support ?? ⇐ *Biggest hurdle*

Backup Slides



First Measurement of the Rate of NC/CC(Ehad):
1<Ehad<100 GeV (NOMAD)