A High Resolution Near-Detector for Neutrino Factory: $\mu \rightarrow \nu_e \nu_\mu$

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ॐ Measurement of the PMNS Matrix Elements

- Θ_{13}
- δ_{CP}
- ν-Mass Hierarchy
- Resolving degeneracies

⇒ *Need Syst.Precision*

ॐ Beyond PMNS

- Θ_{23} = 45^0 ?
- CPT Violation ?
- High Δm^2 Oscillation ?

⇒ *Phenomenon that defies the Zeitgeist*

ॐ The familiar, beautiful neighborhood

- X-secs, Sin**2(Θ_w): precision comparable to Colliders?
- Sum rules, Isospin Physics (Nu -vs- NuBar ⇐ δ_{CP})
- Heavy neutrinos
- ....
- Rewriting the ν text-book

Reinventing the Near Detector

- *Use of "identical" small detector at the near site is insufficient for future $\mathcal{LBL}$ experiments:*
  - $\Phi^{\nu,\bar{\nu}}(E_\nu, \theta_\nu)$ *different at Near & Far sites;*
  - *Impossible to have "identical" detectors, for $\mathcal{O}(100kt)$, at the projected luminosities;*
  - *Different compositions of event samples ($\nu_\mu, \bar{\nu}_\mu, \nu_e$, NC, CC)*

  $\Longrightarrow$ *Coarse resolution dictated by $\mathcal{O}(100kt)$ and different flux at Near-vs-Far tell us that the Identical Near Detector concept is insufficient*

- *Need a high resolution detector at the Near-Site to measure systematics affecting the Far-detector:*
  - $\nu_\mu, \bar{\nu}$, $\boxed{\nu_e}$, $\boxed{\bar{\nu}_e}$ *content vs. E_ν and θ_ν;*
  - *ν-induced $\pi^\pm/K^\pm/p/\pi^0$ in CC and NC interactions;*
  - *Quantitative determination of E_ν absolute energy scale;*
  - *Measurement of detailed event topologies in CC & NC.*

  $\Longrightarrow$ *Provide an 'Event-Generator' measurement for $\mathcal{LBL}\nu$*

> Measure over the full range of FD
>
> Background to the ν(Bar)e/μ-Appearance
>
> ν -vs0 ν(Bar) Interactions

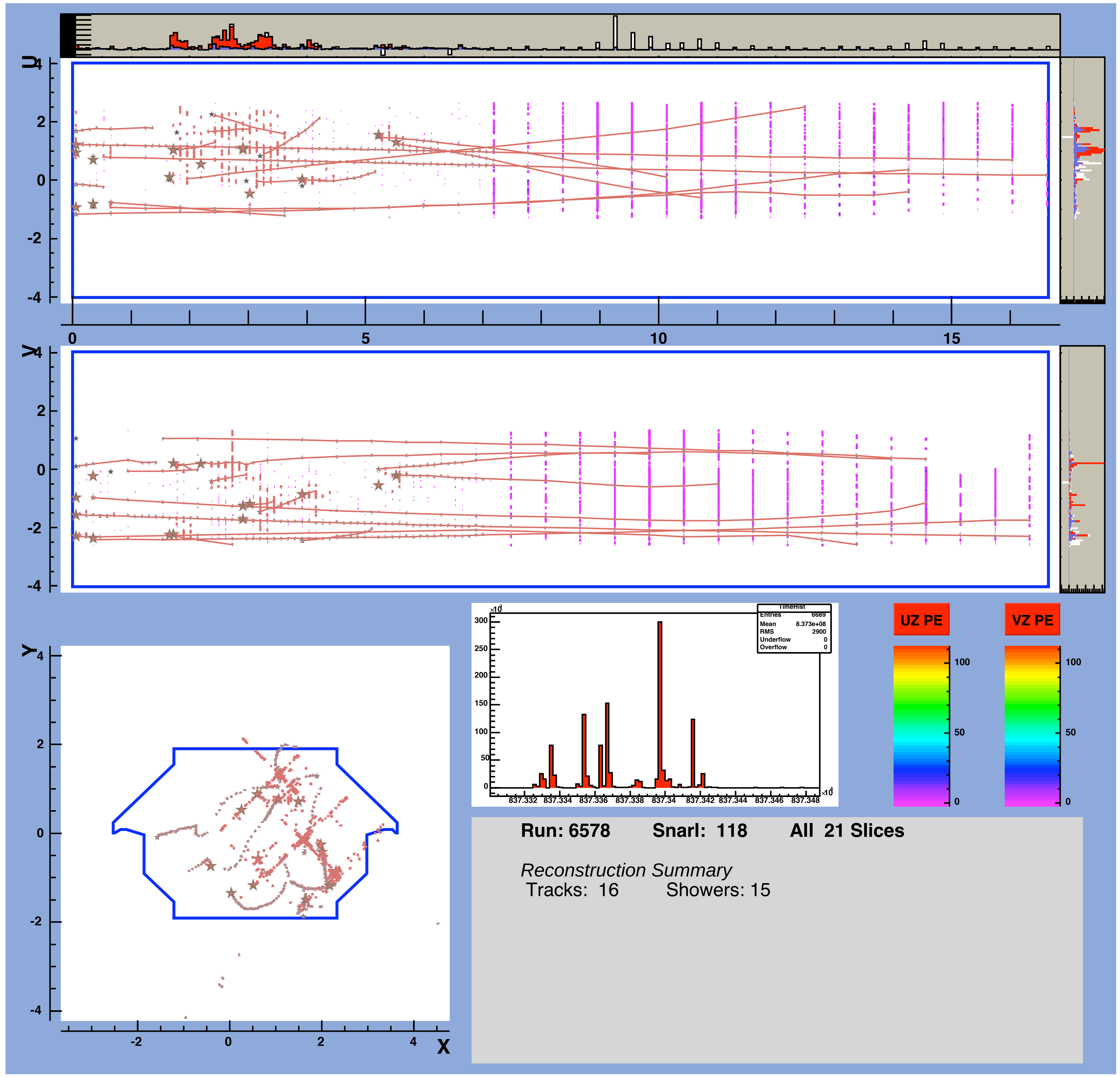
- *High Resolution near detectors at future $\mathcal{LBL}$ facilities are natural heirs to the precision neutrino scattering programme*

  Can they achieve sufficient precision to complement the Colliders?

Events/Spill in MINOS-ND

≃2e13 PoT/Spill in MINOS(NuMI)

(Juxtapose against that expected from 3e14 PoT/Spill in ProjectX)



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

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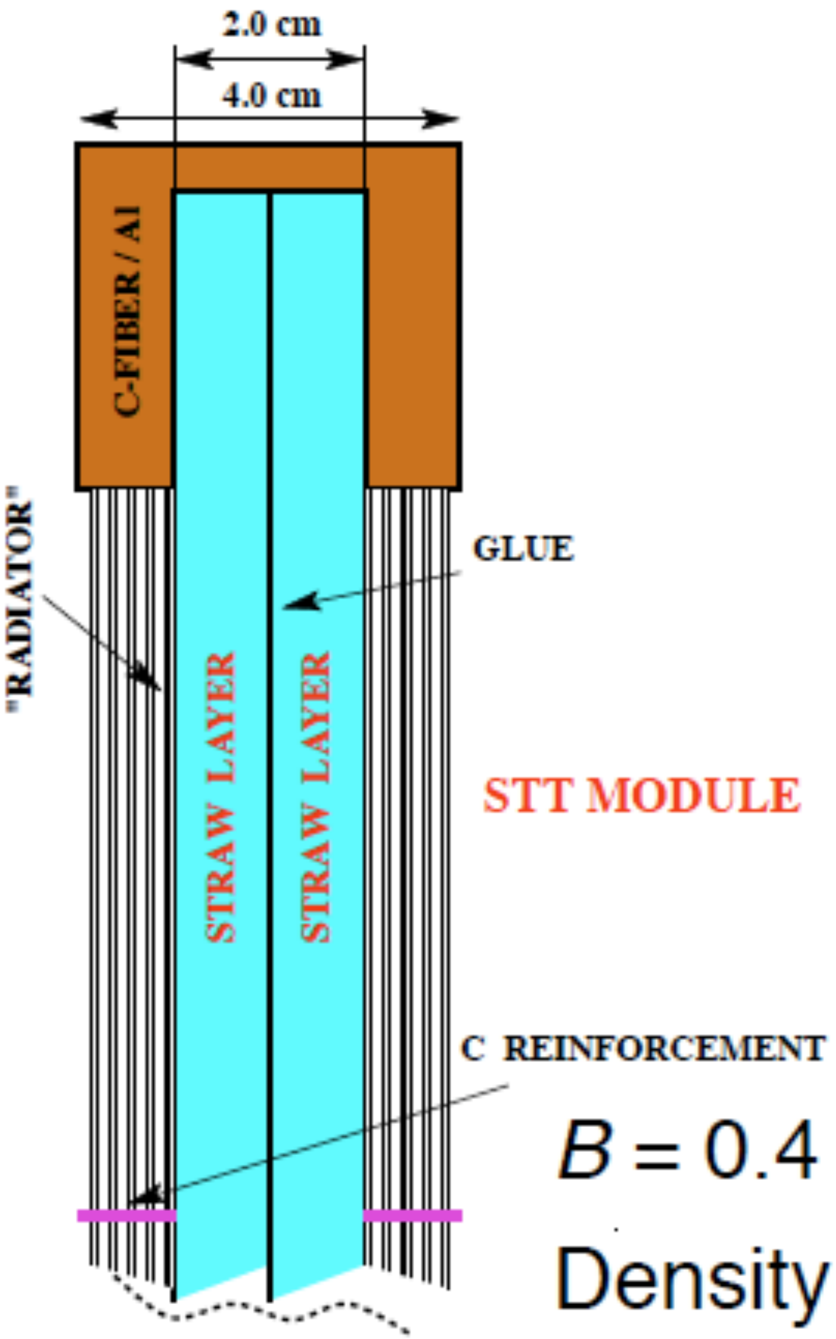
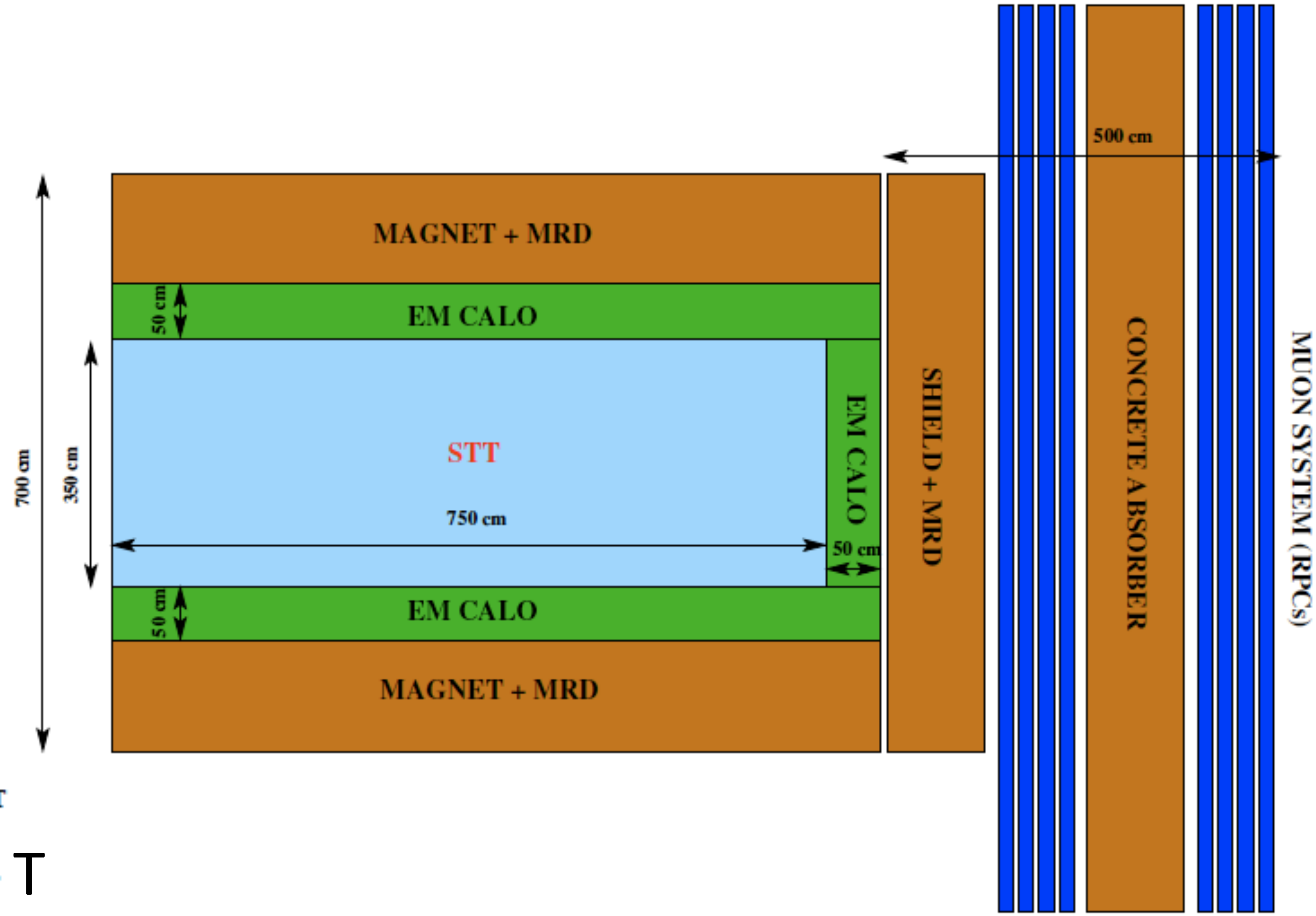
University of South Carolina

HiResMν

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





$B = 0.4$ T

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

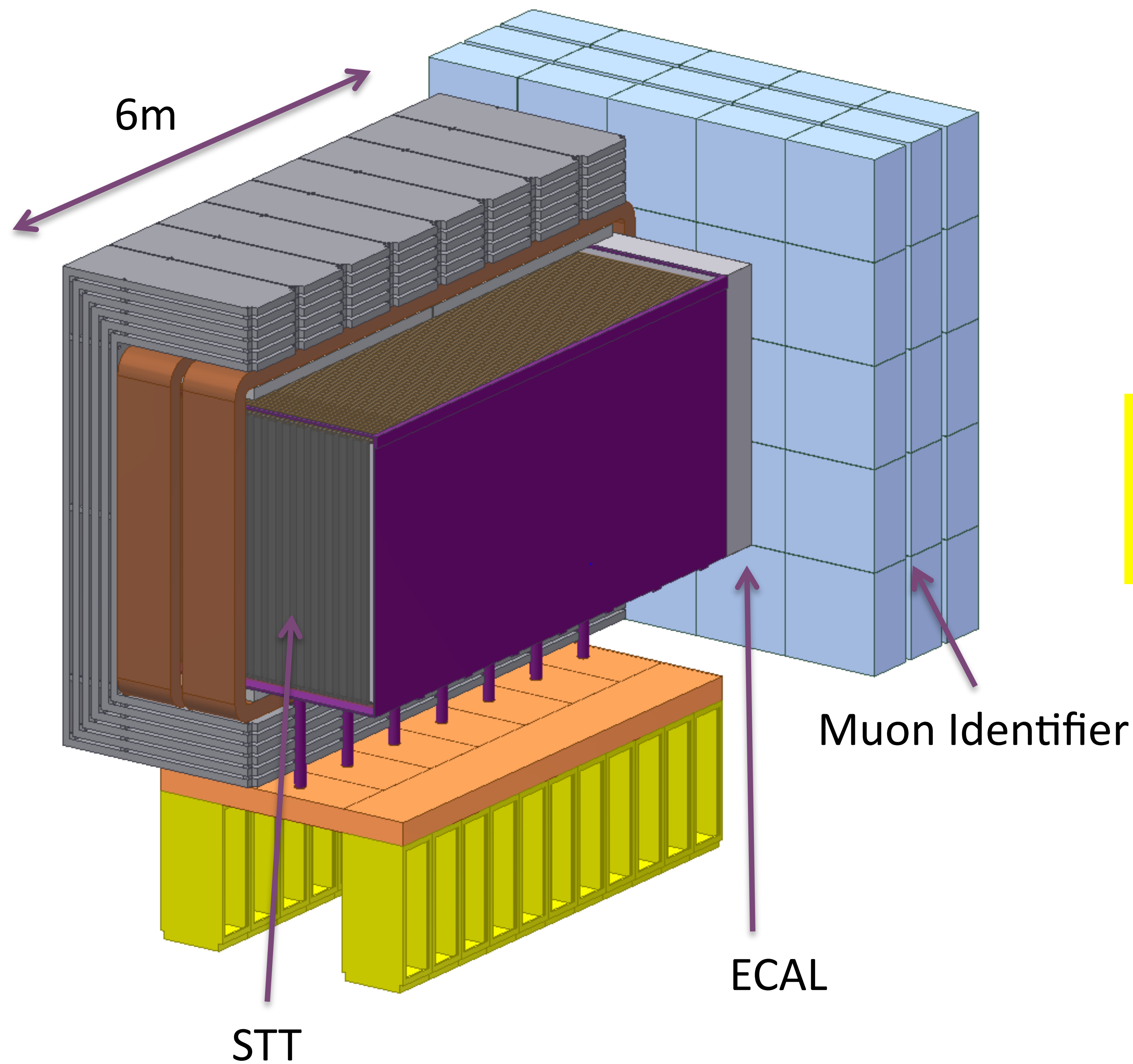
Transition Radiation ⤀ e-/e+ ID ⇒ γ (w. Kinematics)

dE/dx ⤀ Proton, π+/-, K+/- ID

Magnet/Muon Detector ⤀ μ+/-

⇒ *HiResMNu idea being developed within the LBNE collaboration*

Straw Tube Tracker (STT)



- Best performance of the 4-options at LBNE
- 3.5m x 3.5m x 7m STT (7 tons; ρ≃0.1gm/cm^3)

  4π-ECAL
  Dipole-Field (0.4T)
  μ-Detector (RPC) in Dipole and Downstream

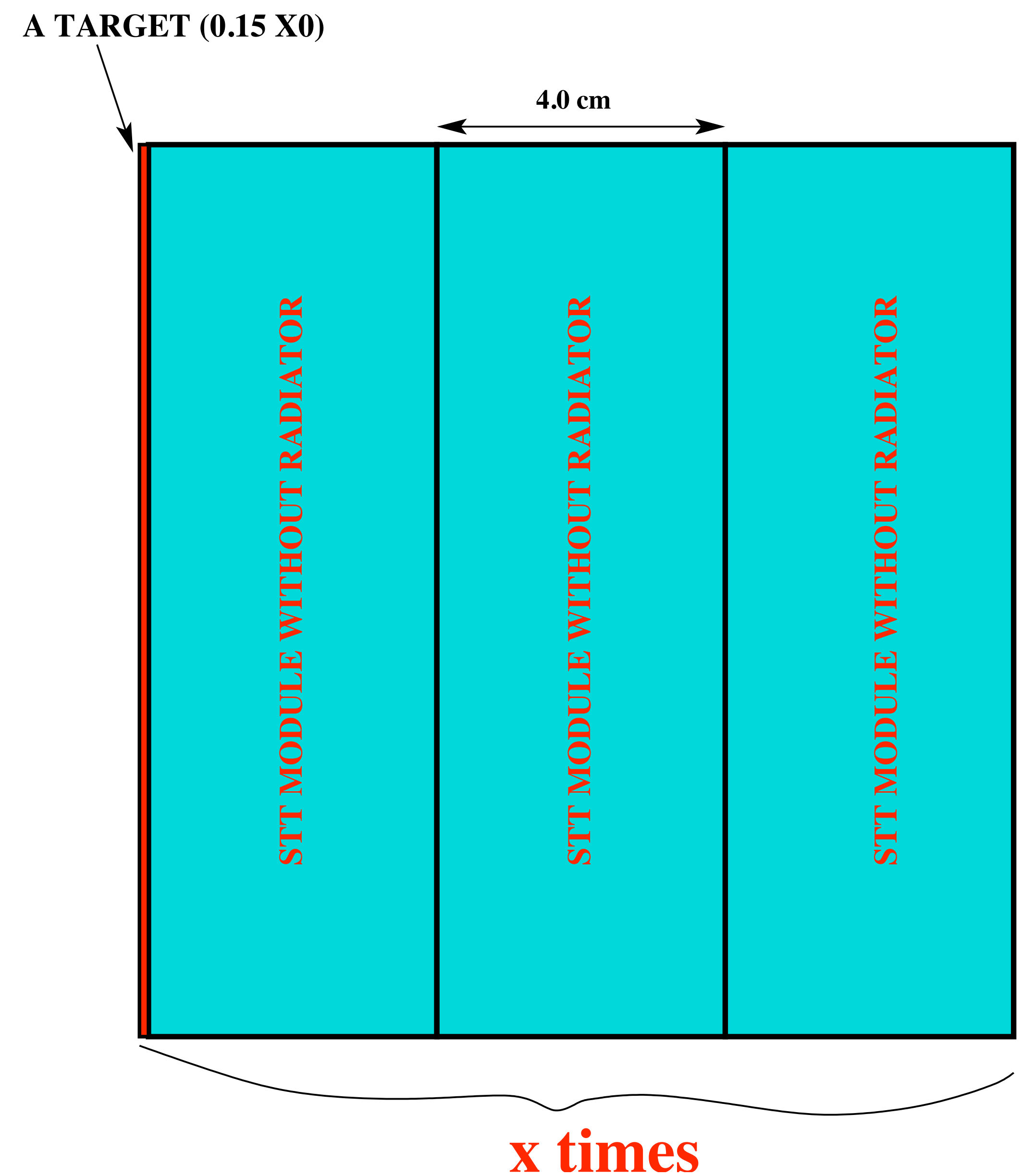
Transition Radiation ⤀ e-/e+ ID ⇒ γ
dE/dx ⤀ Proton, π+/-, K+/-
Magnet/Muon Detector ⤀ μ+/-

- Fe/`A' Targets (≃x10 FD-Stat) ⇛ *FD*
- Pressurized Ar-target (≃x5 FD-Stat) ⇛ *LAr-FD*

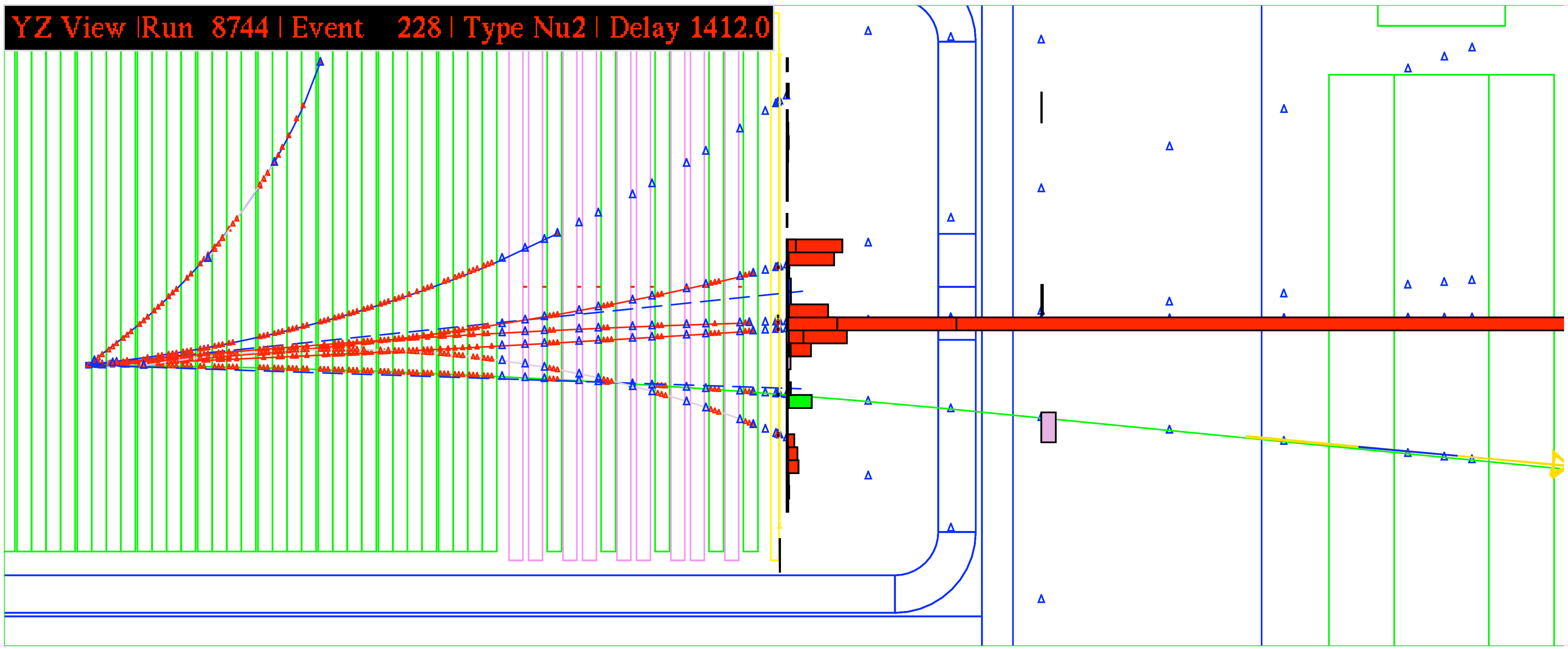
MEASURING NUCLEAR EFFECTS *(Fe, Water, Ar, ..)*

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

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



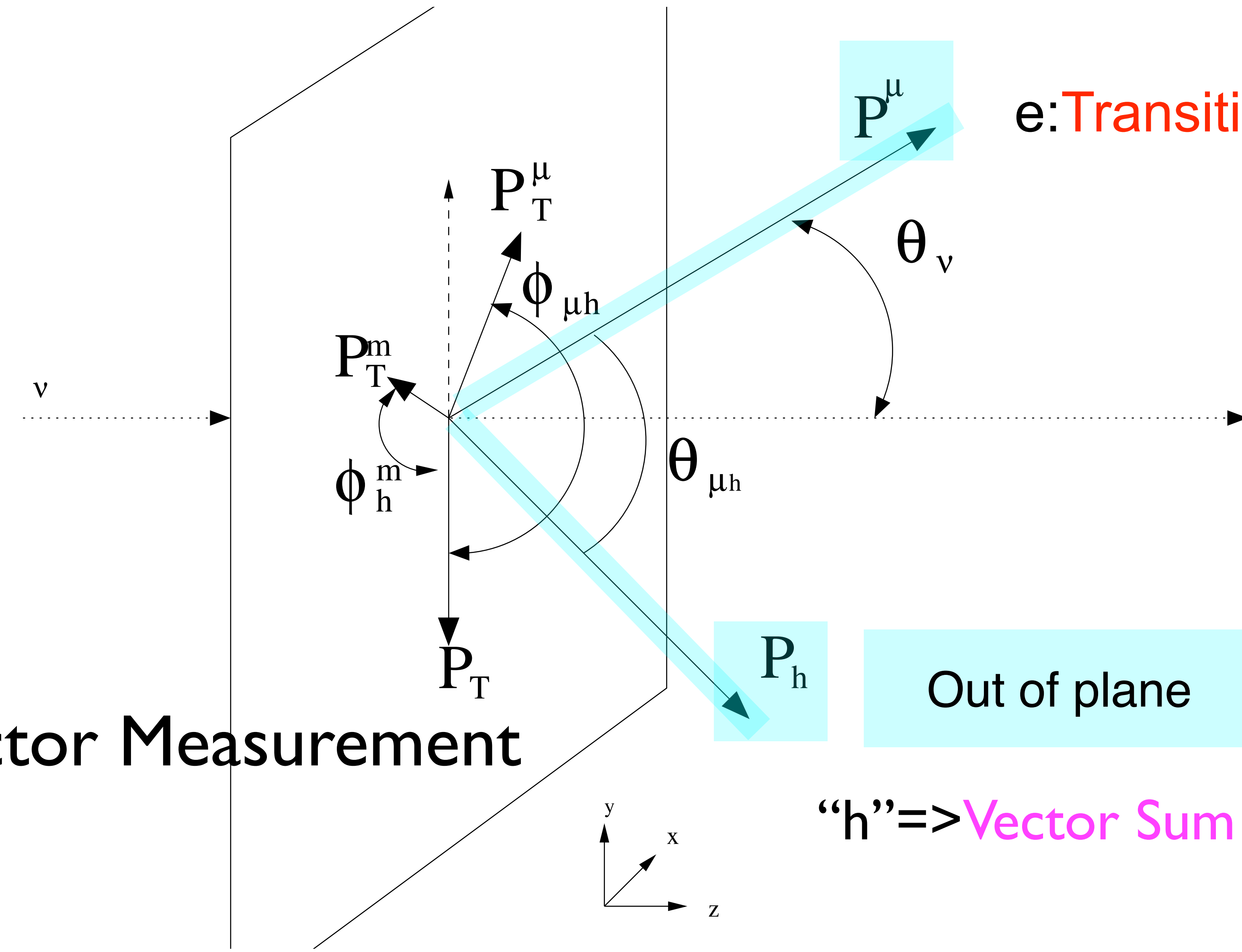
A ν_μ CC candidate in NOMAD



- x12 higher sampling in HiResMnu
- x4π calorimetric and μ converage

USC HEP
University of South Carolina
High Energy Physics

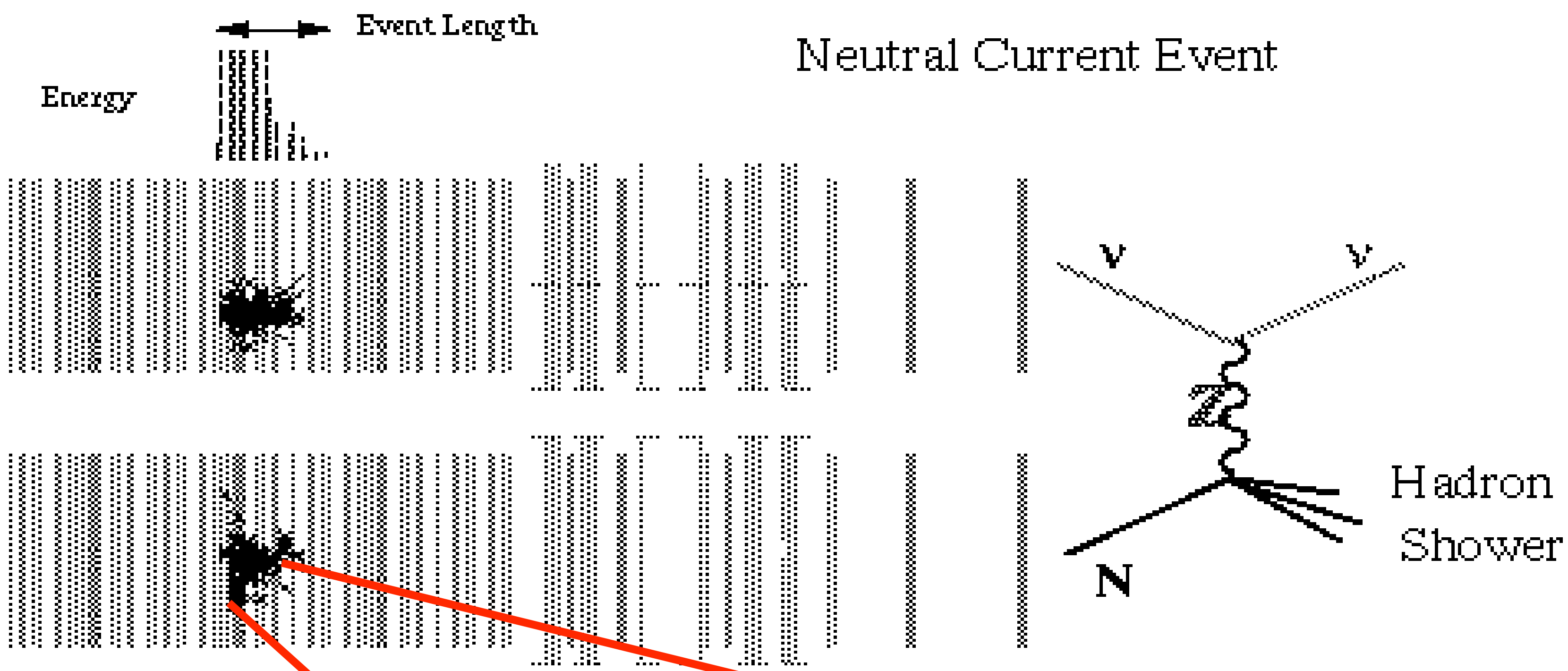
Kinematics in HiResMnu



e:Transition Radiation

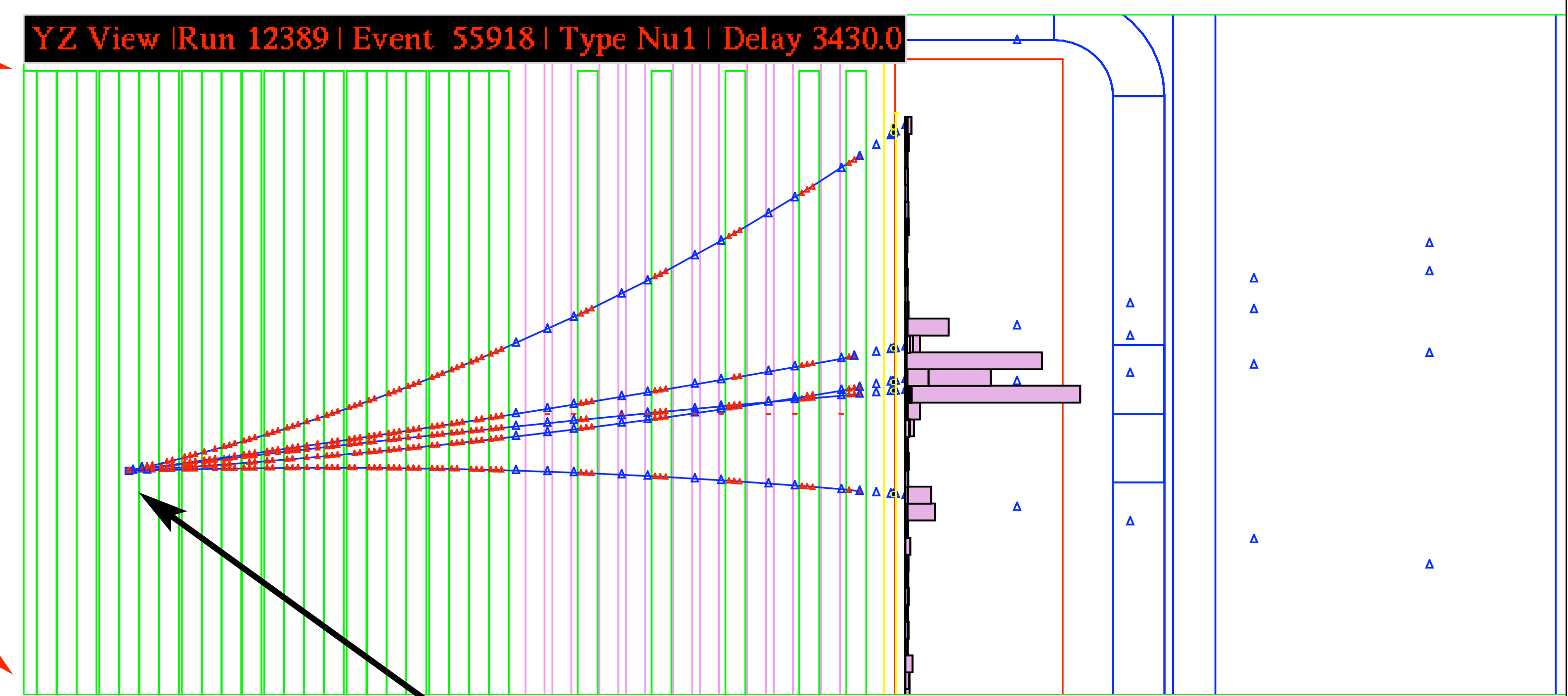
Pt-Vector Measurement

“h”=>Vector Sum of Tracks



MASSIVE CALO
(NuTeV)

PRECISE TRACKER
(NOMAD)



Missing transverse momentum

HiResMν : order of mag. higher segmentation

e- Sample

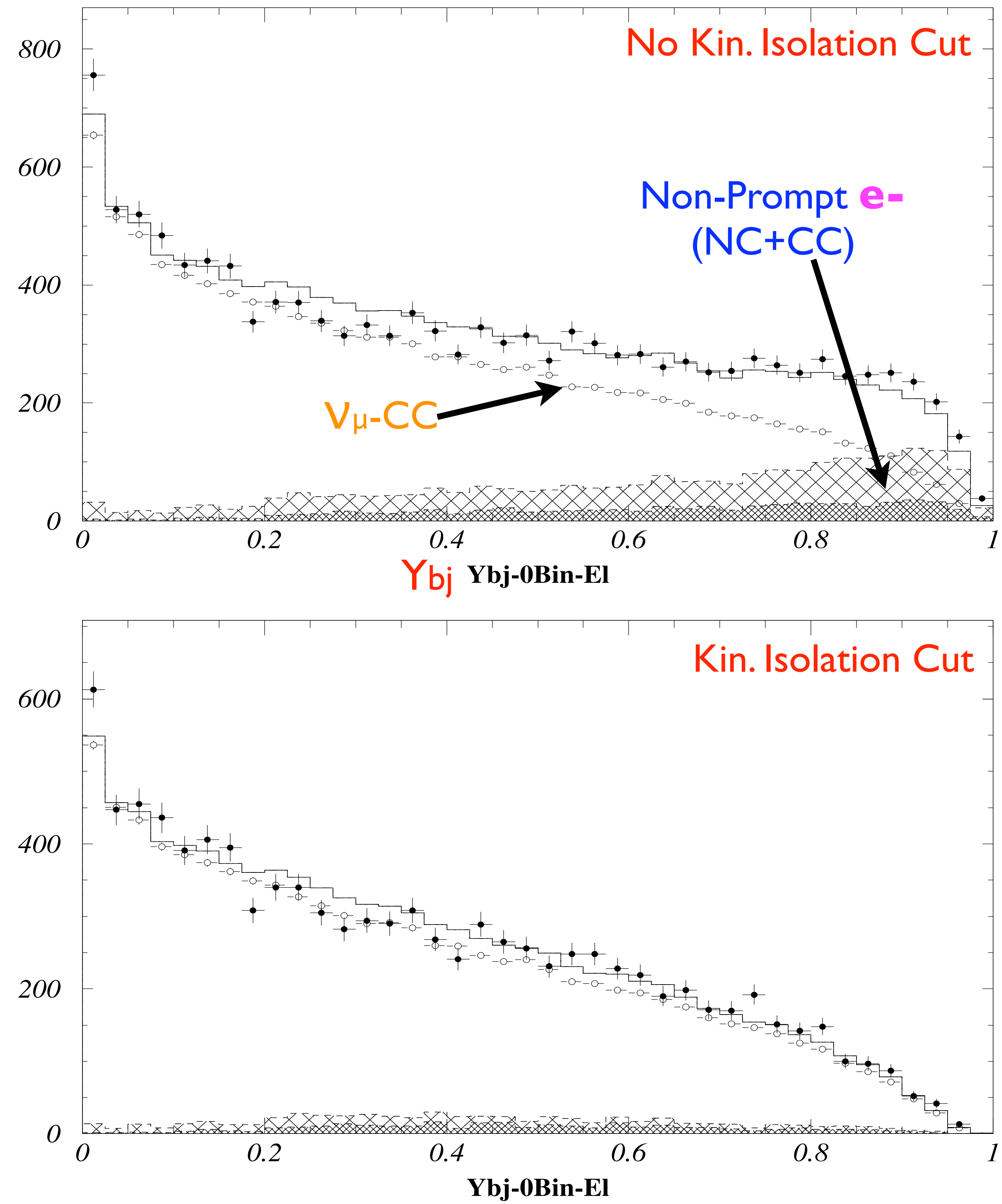


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Figure 20: Distribution of y_{bj} for e$^-$ (solid dots), μ^- (open dots), ν_μNC (big hatch) and CC (small hatch) background after scaling. The combined (histo) μ^- plus background agrees with the distribution of e$^-$ data. The bottom plot is the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

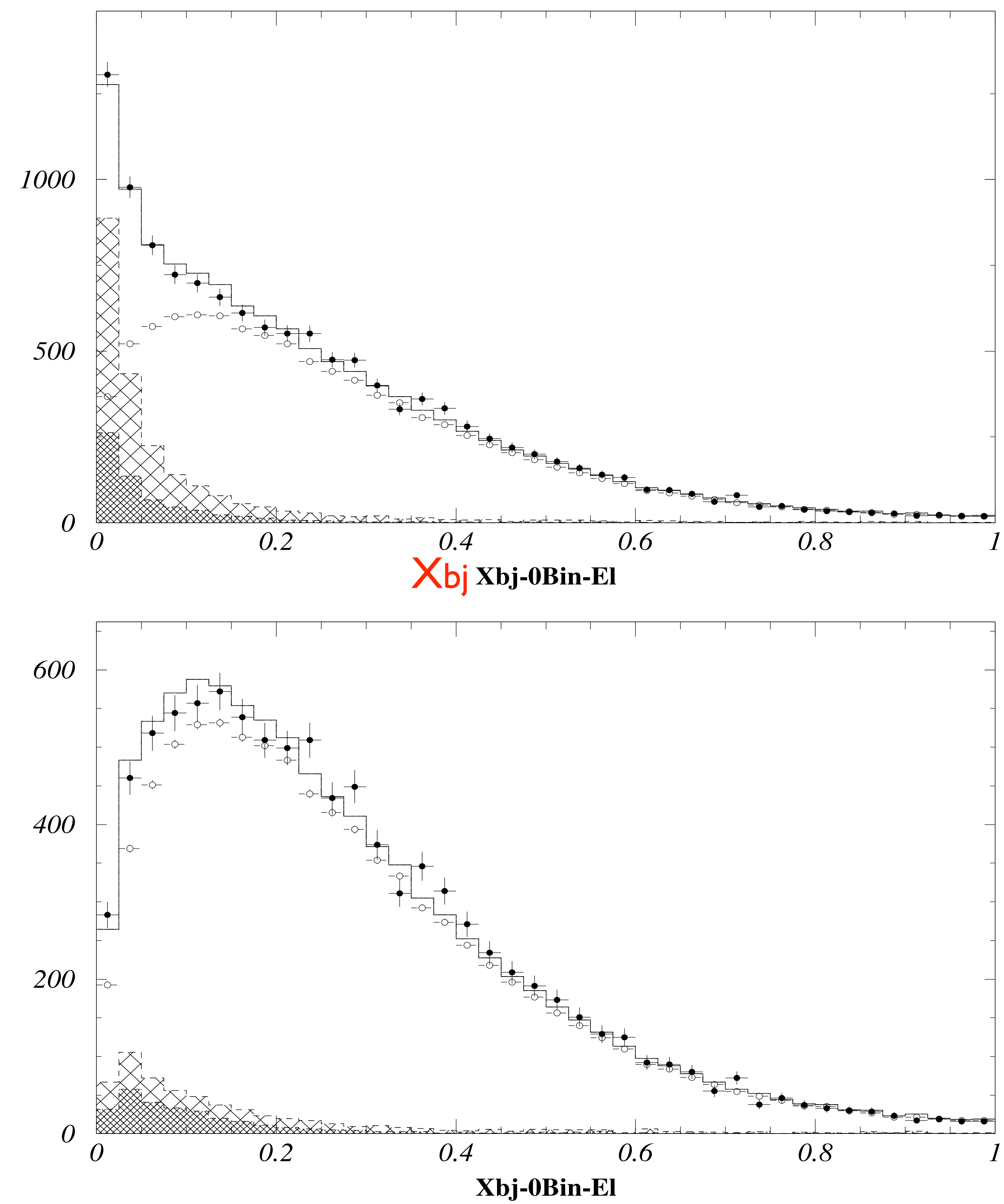

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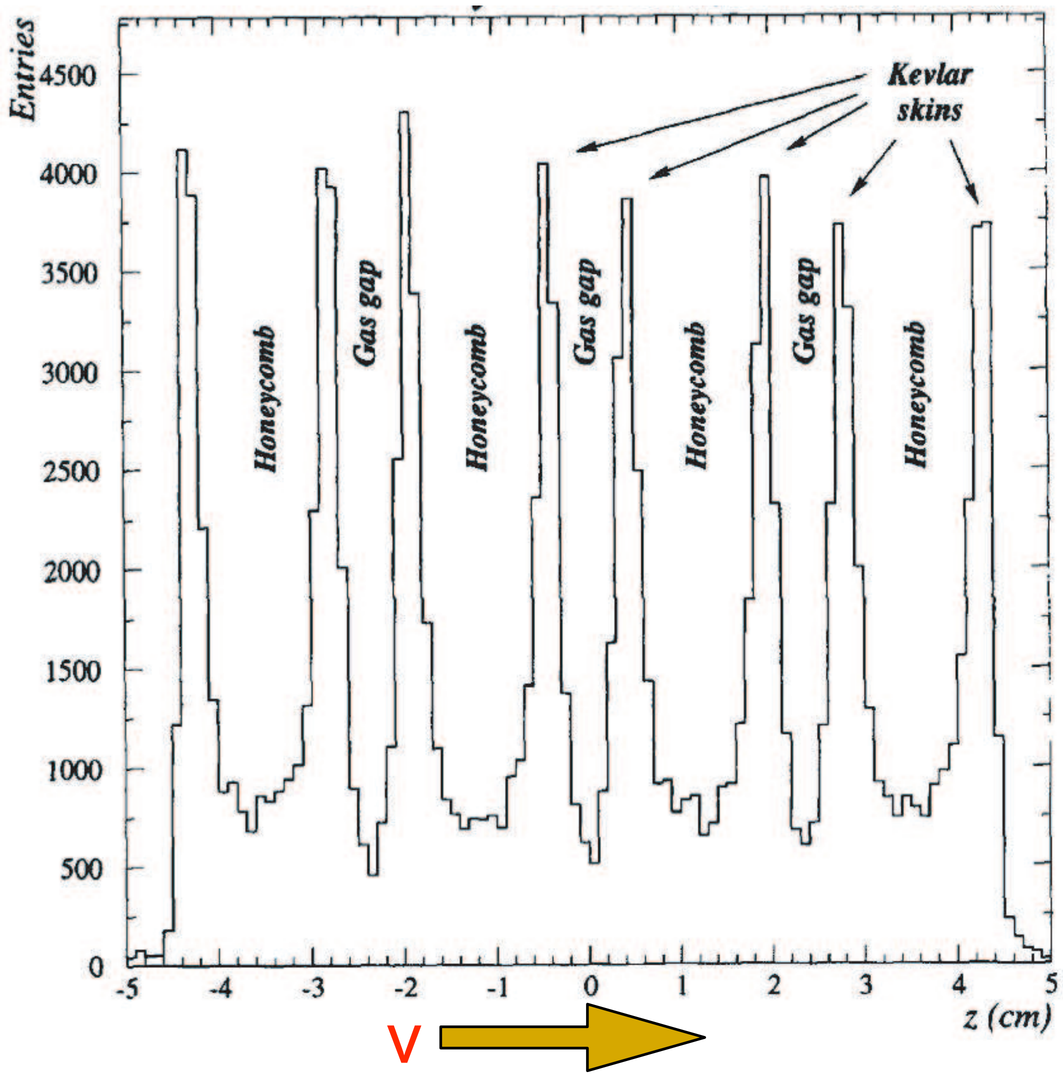
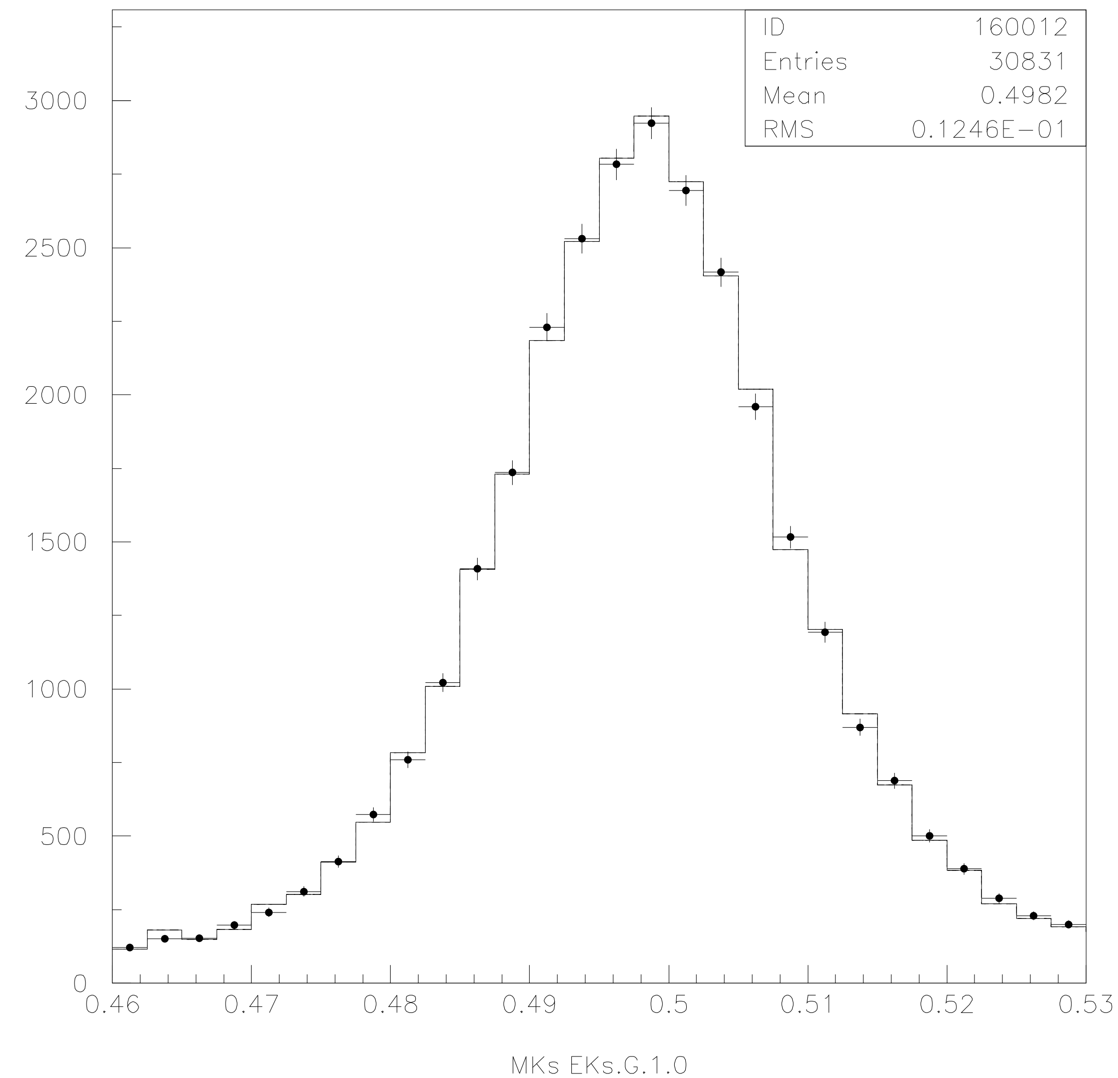
Figure 19: Distribution of x_{bj} for e$^-$ (solid dots), μ^- (open dots), ν_μNC (big hatch) and CC (small hatch) background after scaling. The combined (histo) μ^- plus background agrees with the distribution of e$^-$ data. The bottom plot is the same as the top but includes kinematic cuts

What we build on: NOMAD DATA



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:* 200 $\times$ *more statistics and* 12 $\times$ *higher segmentation*

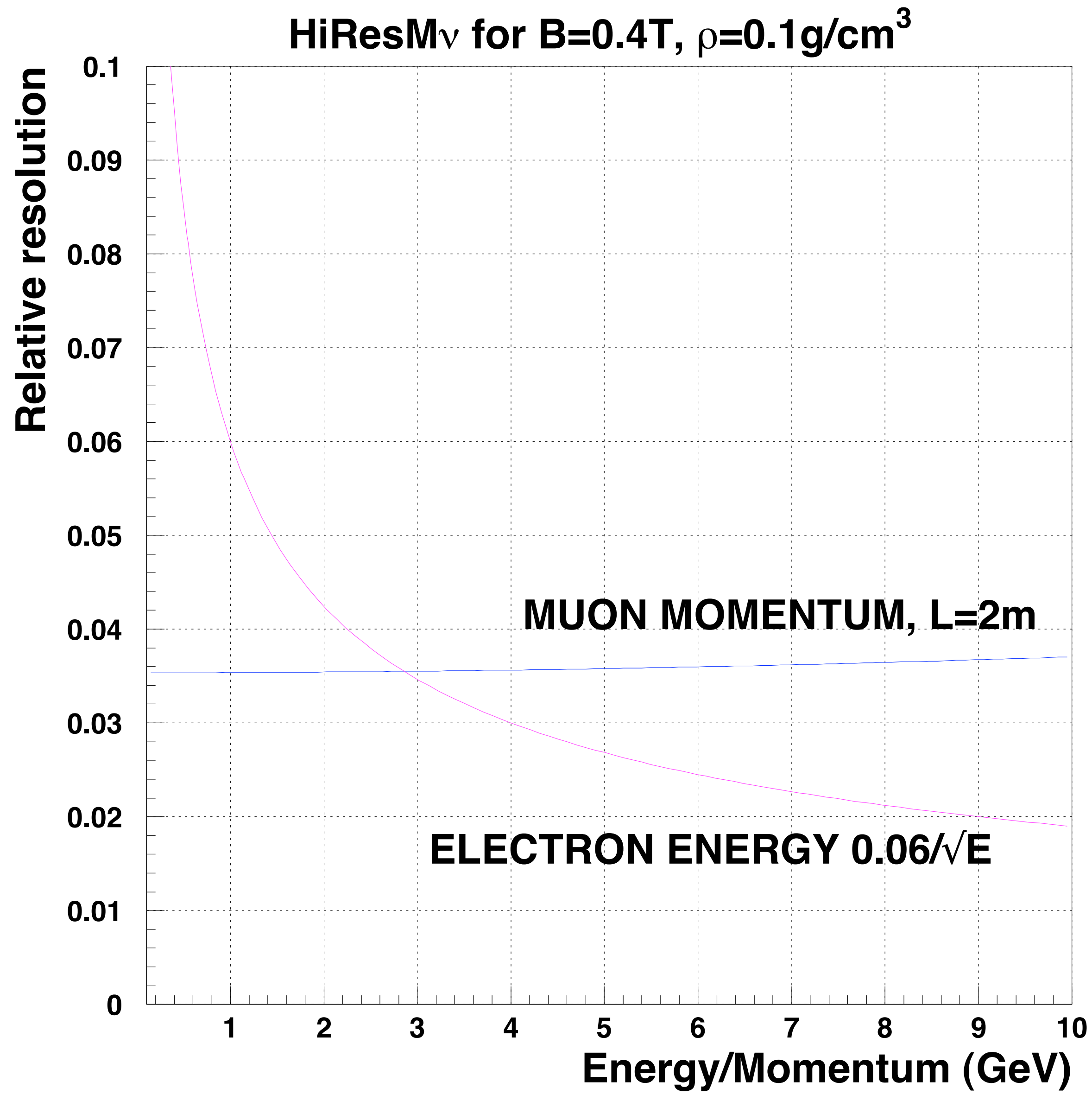
4π-ECAL & μ Coverage

<u>*Resolutions in HiResMν*</u>

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

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

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



Sensitivity Calculations:

- We have used LBNE Flux: Flux from μ ➢ ν_e ν_μ will be cleaner/simpler
- Parametrized calculation
- Repeat with NOMAD configuration and checked against the Data and Geant-MC (Agree within 15%)

Statistics

Assumptions:

25 GeV Emu; 1e20 Muon-decays/year; 3-year Mu- and 3-year Mu+ Runs

(Many thanks to Rosen, Yordan, and Roumen!)

μ- Decay

	CC-Events	NC-Events
ν_μ	1400M	500M
Anti-ν_e	600M	230M

μ+ Decay

	CC-Events	NC-Events
Anti- ν_μ	700M	250M
ν_e	1240M	420M

Expected IMD $\simeq$ 210k; ν-e NC $\simeq$ O(300k)

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 Measurement

- *An 'Event-Generator Measurement' for the LBLν 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.*

Why Tracker (ECAL/*μ-Detector)* within a B-Field?

- Constrain Eν-scale
- ND must measure the full range of Eν & θν else the sensitivity of FD will be compromized
- *Measure differences in* ν & Anti-ν *interactions which might fake a* " δ_{CP} "
- STT will be able to distinguish *μ-/μ+* down 0 ~0.3 GeV

⇛ *ND must measure and ID leptons (e & μ) emerging at large angles;*

Why track Protons & π(K)+/-?

- Precision determination of ν_μ-QE requires proton-tracking.

⇒ Key to QE measurement

⇒ (μ^-, p) provide an *in situ* constraint on the Fermi-motion and hence on the E_ν-scale

⇒ QE interactions dominant in Low-E_ν: Need accurate parametrization of QE *[see σ(QE) Fig.]*

⇒ dE/dx to ID-proton

- HIRESMNU option will have a large proton sample from $\Lambda \rightarrow p\pi$

- ND must measure the π^- & π^+ ($K^{+/-}$) in NC and CC:

⇒ *the largest source of background: wrong-sign Muon*

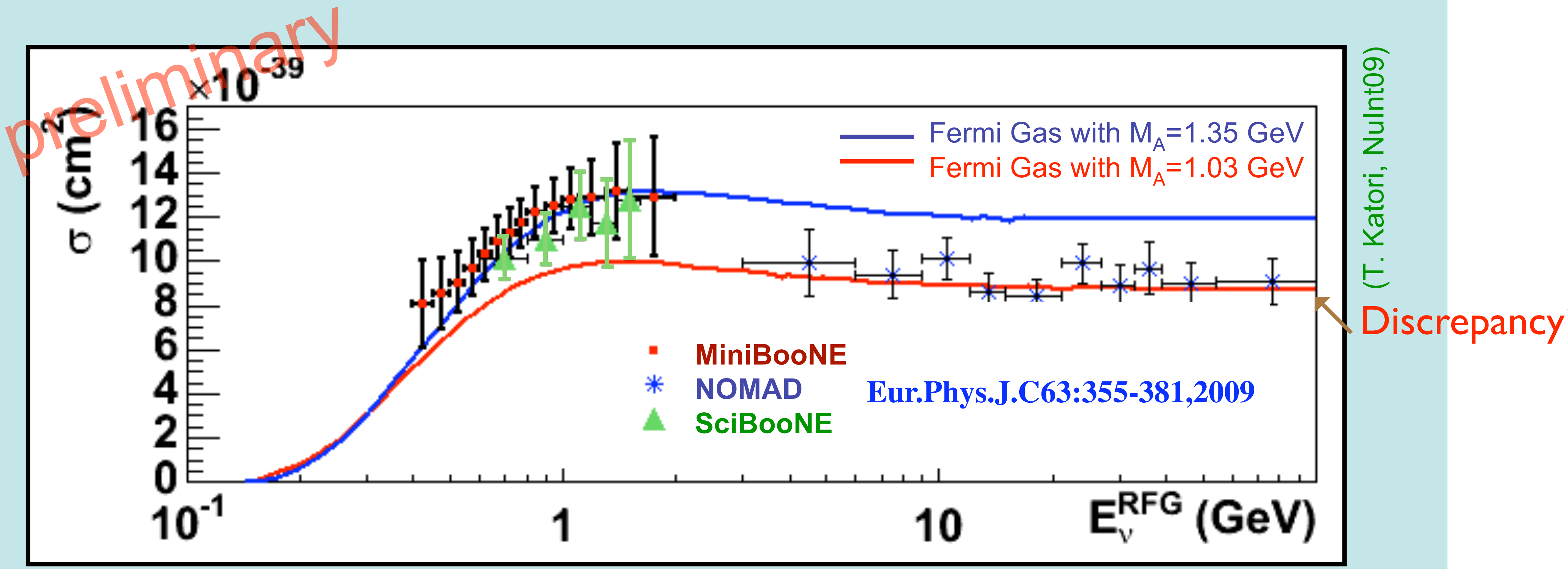
⇒ *the largest source of background to the* ν_μ & *Anti-*ν_μ *disappearance*

⇛ *ND must track & ID QE-protons & π(K)+/-*

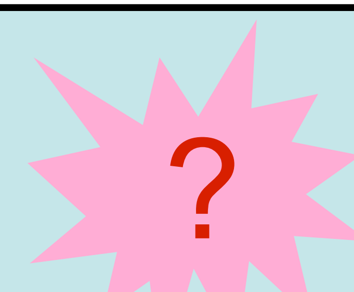
QE

Quasi-Elastic Scattering

- new, modern measurements of QE σ at these energies (on ^{12}C)



~ 30% difference between QE σ measured at low & high E on ^{12}C ?!



ν_μ-QE Sensitivity Calculation

- 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*)

- Use Nomad data/MC as calibration

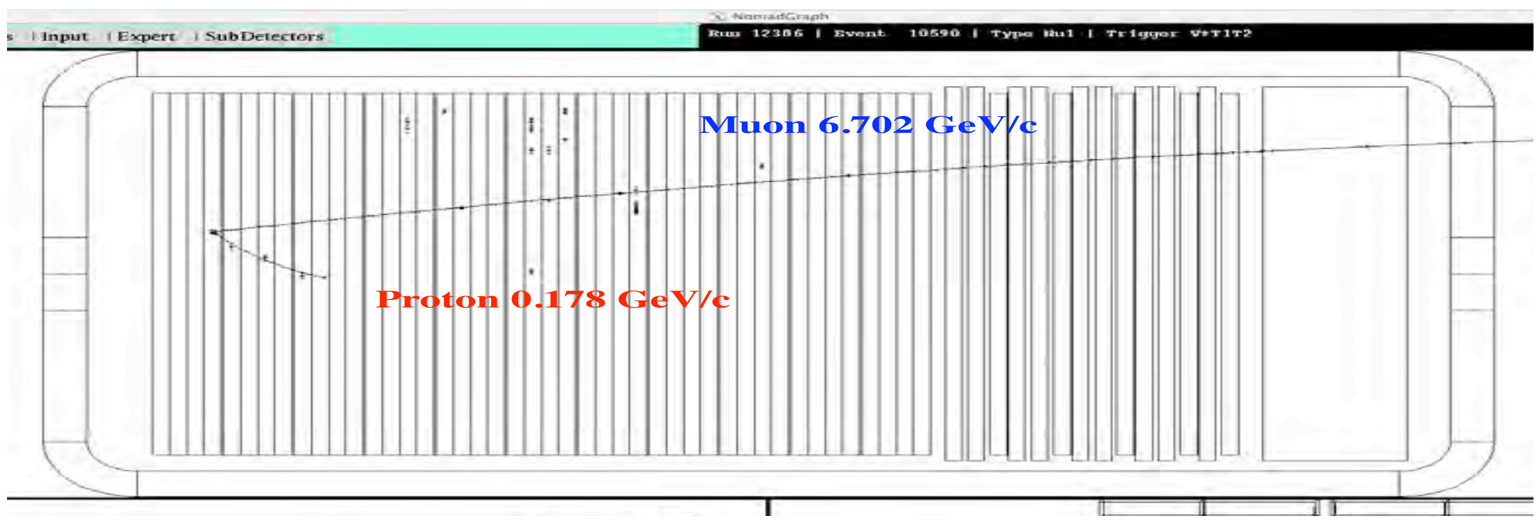


Figure 14: A ν_μ-QE candidate in NOMAD

QE Candidates in NOMAD: STT will have x6 more points for protons

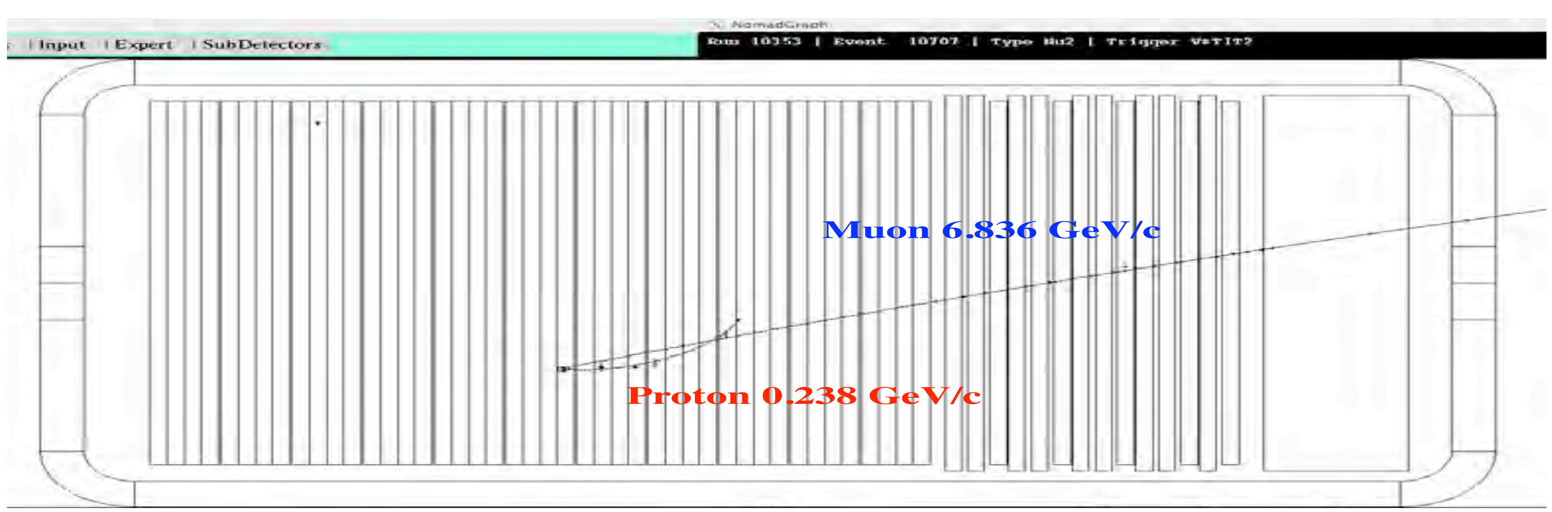
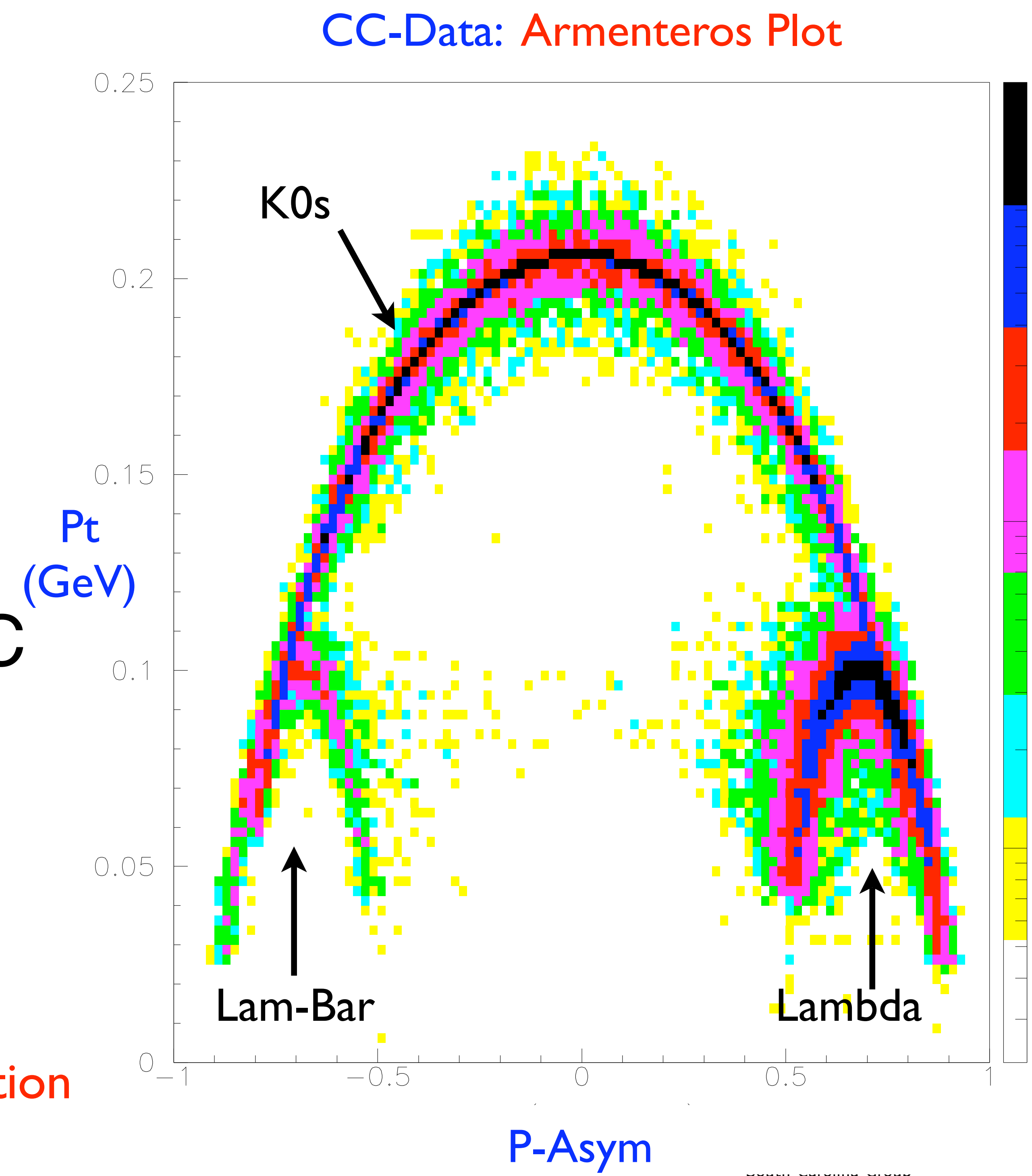


Figure 15: A ν_μ-QE candidate in NOMAD

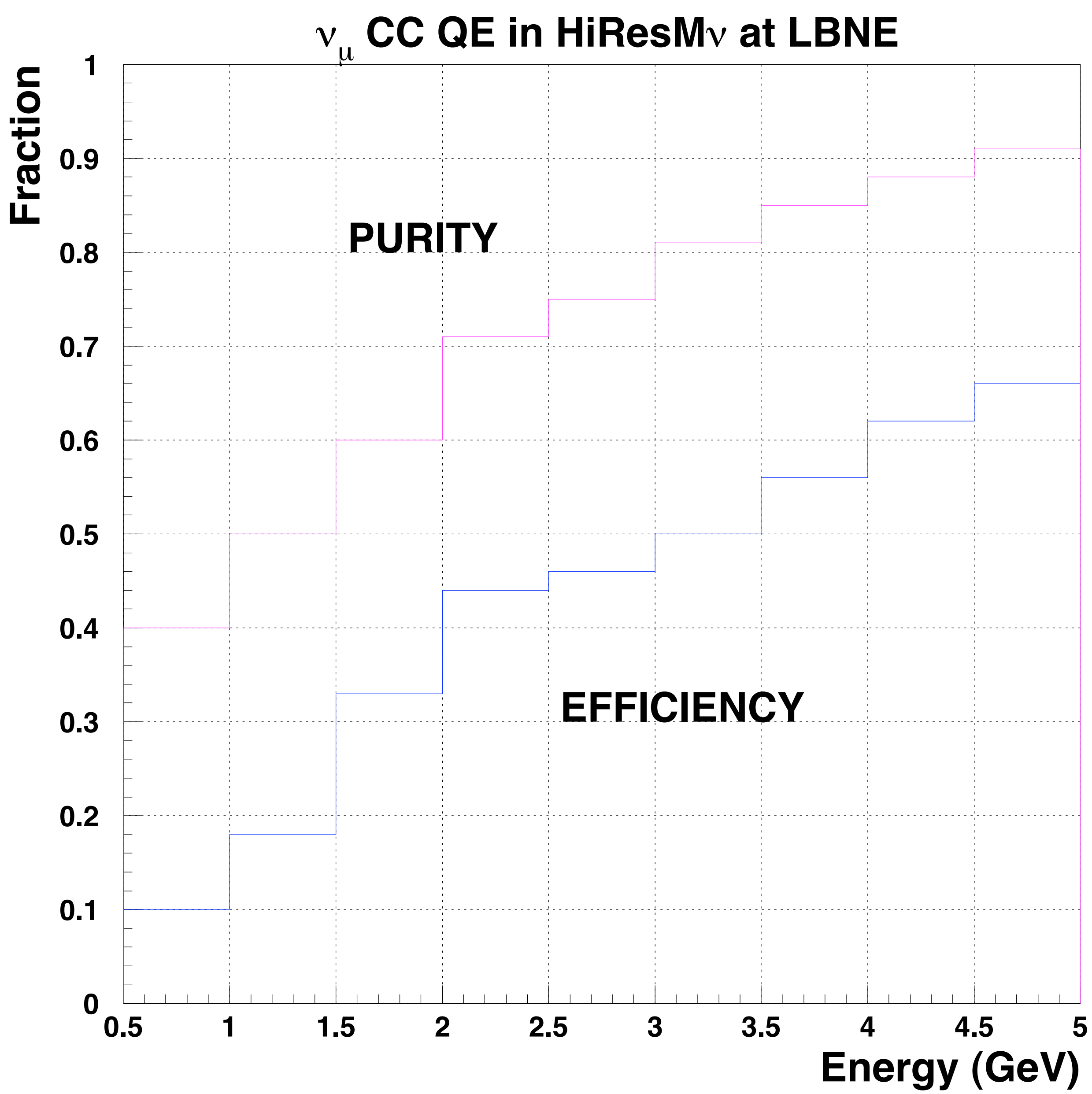
Measurement of exclusive topologies

- ✦ 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 $\Delta \rightarrow N\gamma$



ॐ Λ ⤀ Calibration of Proton Reconstruction

RECONSTRUCTION OF CC QUASI-ELASTIC INTERACTIONS



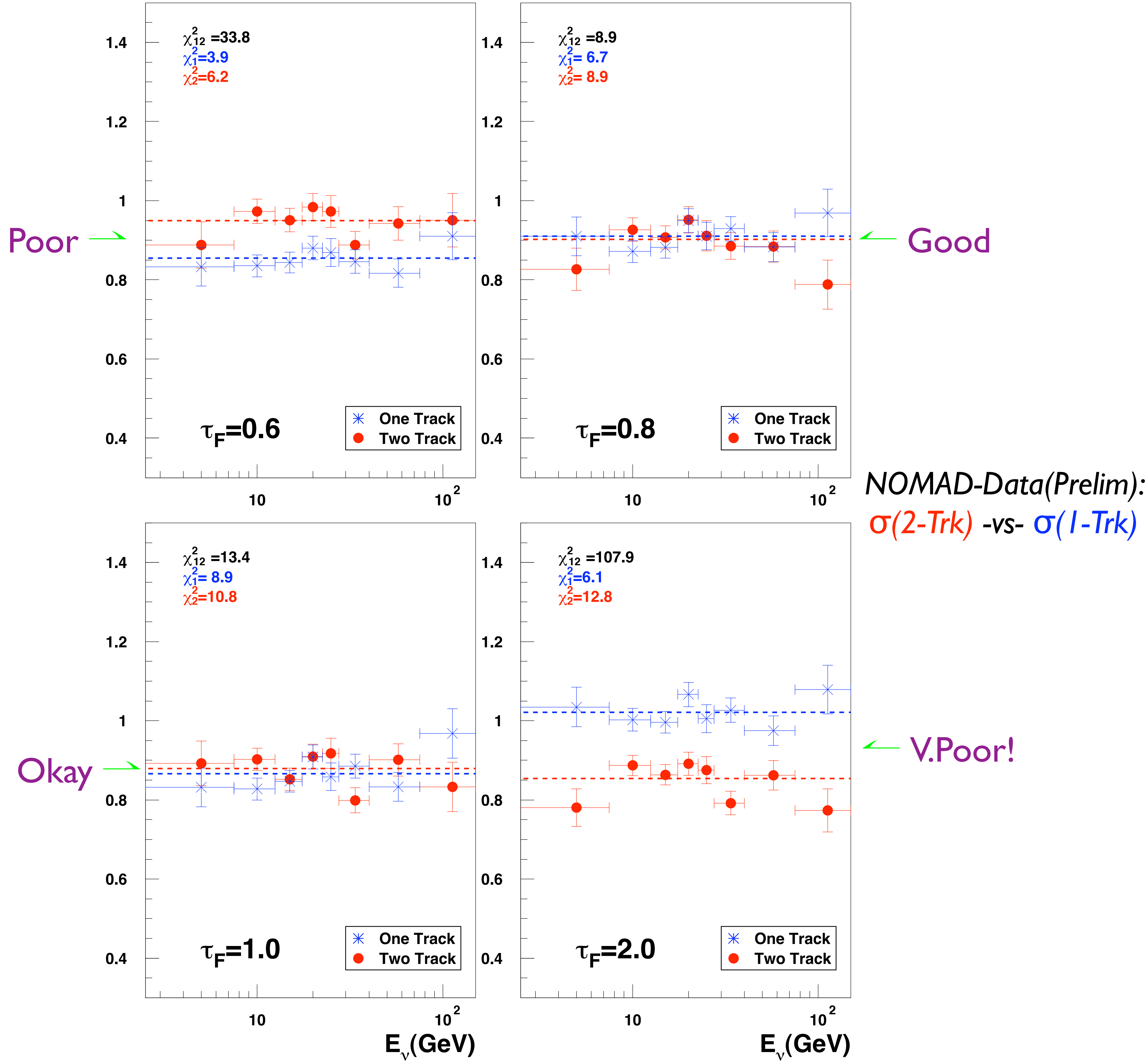
- *Protons easily identified by the large dE/dx in STT & range*

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

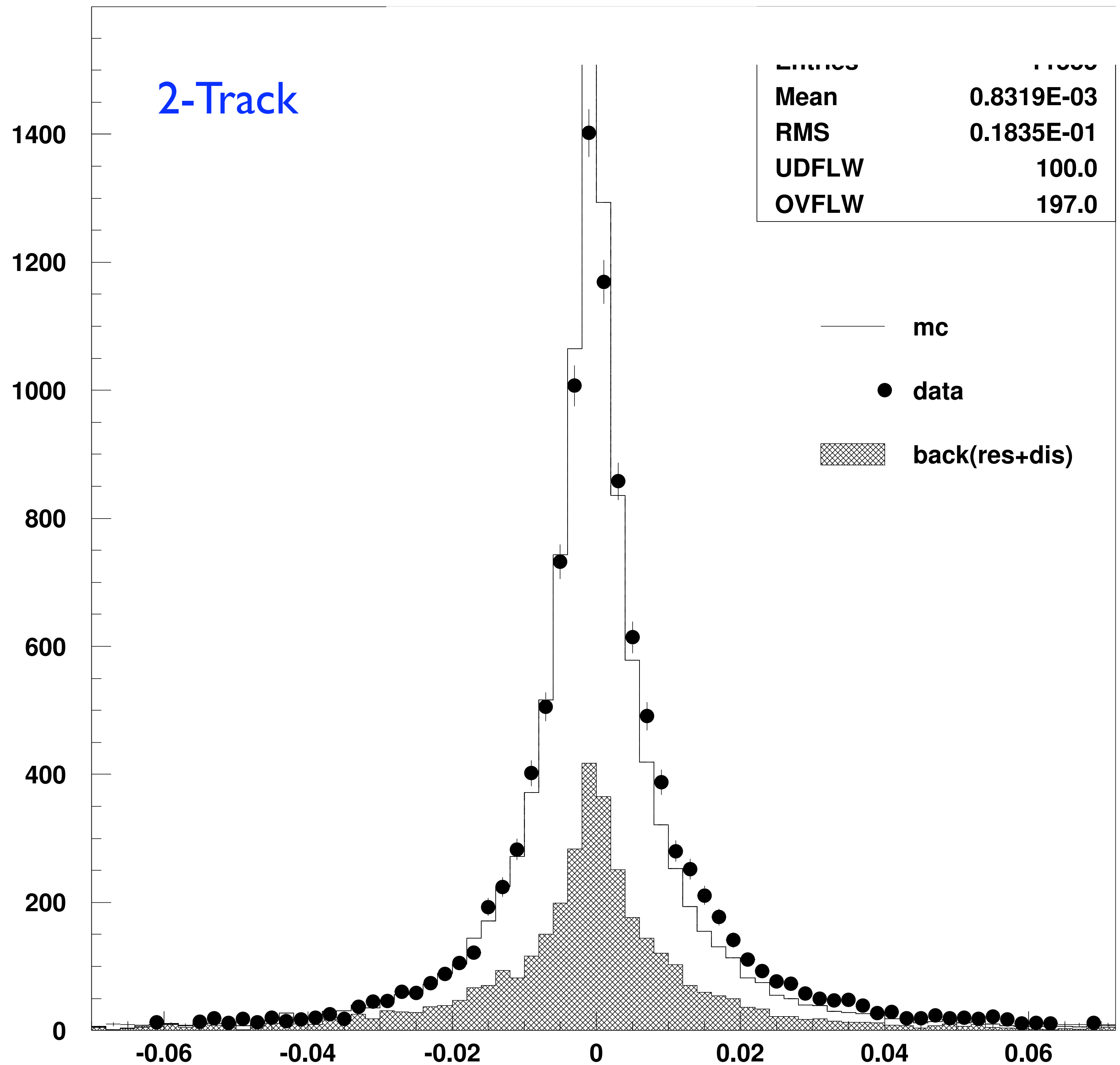
- *Analize BOTH 2-track and 1-track events to constrain FSI, Fermi motion and nuclear effects*

- *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*



χ²12 =33.8
χ²1=3.9
χ²2=6.2
τF=0.6
One Track
Two Track
χ²12 =8.9
χ²1= 6.7
χ²2= 8.9
τF=0.8
One Track
Two Track
χ²12 =13.4
χ²1= 8.9
χ²2=10.8
τF=1.0
One Track
Two Track
χ²12 =107.9
χ²1=6.1
χ²2=12.8
τF=2.0
One Track
Two Track
Eν(GeV)
Eν(GeV)
Poor
Good
Okay
V.Poor!
NOMAD-Data(Prelim):
σ(2-Trk) -vs- σ(1-Trk)



Evis(2-Trak) - Enu(1-Trk w. PFermi=0) (GeV)

⇒*Measure of Fermi Motion*

Why measure and ID *e*- & *e*+?

- Measurement of π^0 in NC and CC via $\gamma \rightarrow e^- e^+$ measured in the tracker

{π^0 is the largest background to (anti)ν_e-appearance}

- Measure beam ν_e and Anti-ν_e

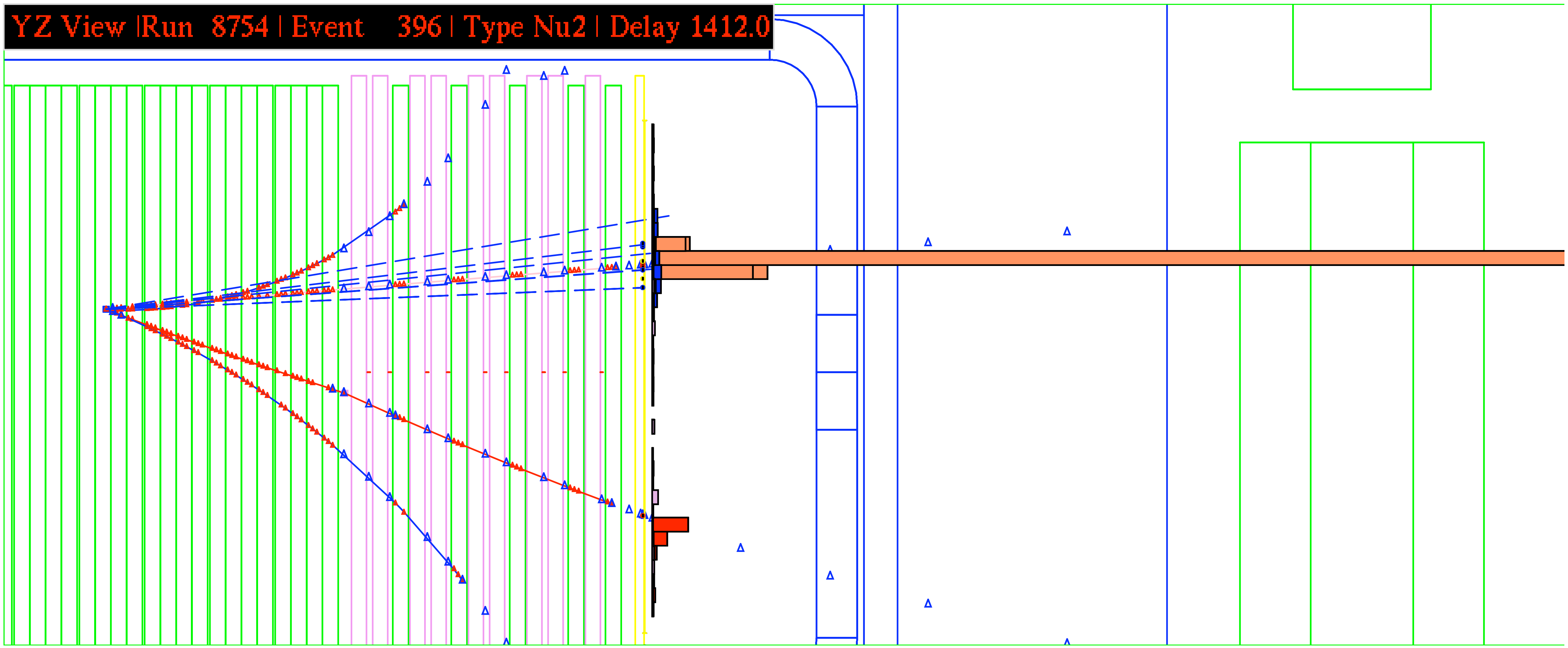
⇒ A must if there are large-Δm^2 oscillations

- Measurement of absolute flux

- To discover δ_{CP} we ought to ensure that ν_e & anti-ν_e events are as expected

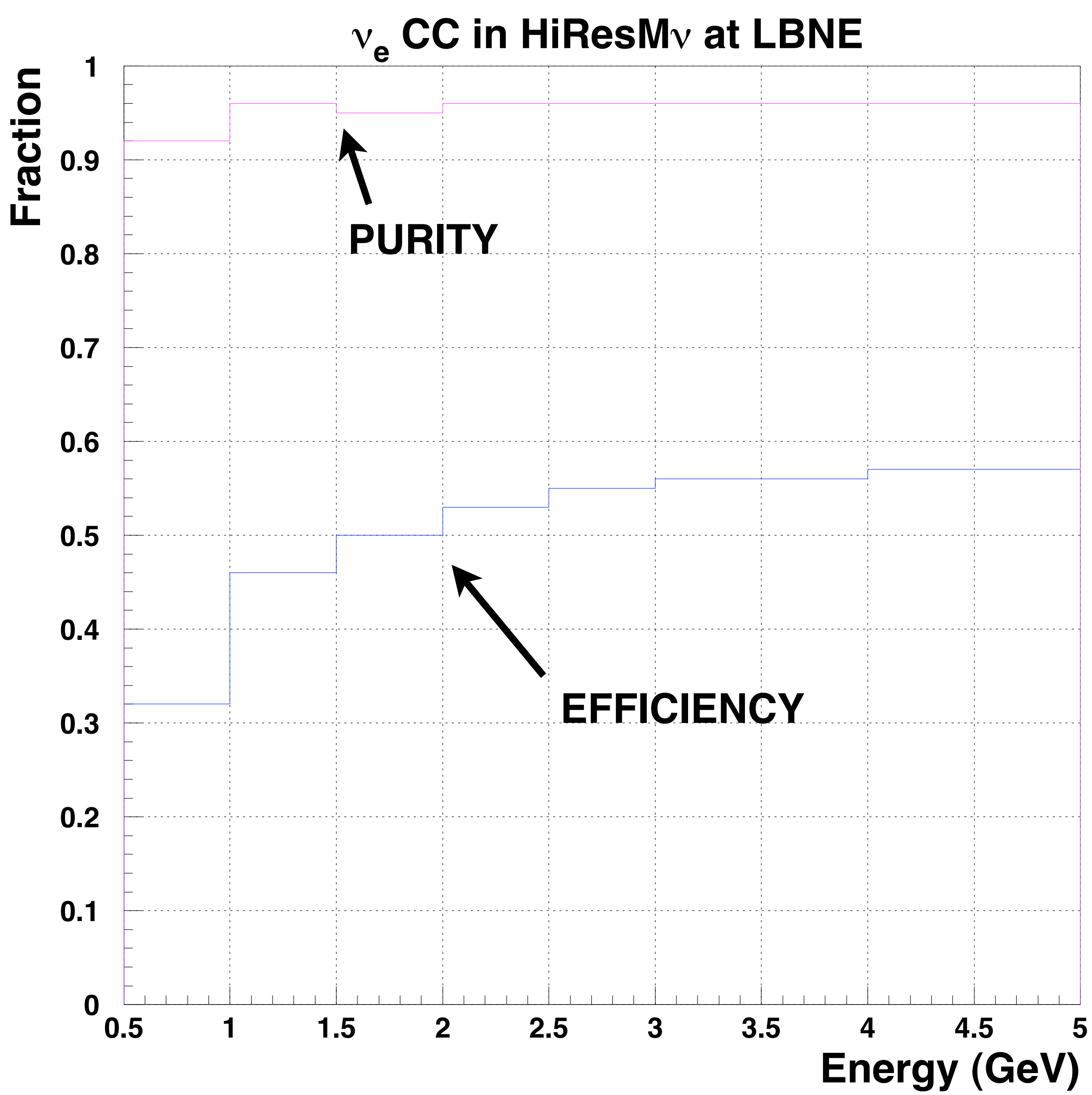
⇛ *ND must measure* π^0 *and* ν_e & *anti*-ν_e ➧ *e- -vs- e+*

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



- x12 higher sampling in HiResMnu
- x4π calorimetric and μ converage

IDENTIFICATION OF ν_e CC INTERACTIONS



- *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:

If we keep the signal efficiency at ~55%, then purity is about 95%

Flux: … Always the Flux

ॐ *Inverse Muon Decay*: $\nu_x + e^- \twoheadrightarrow \nu_x + \mu^-$ {Single, forward μ^-}

- ν_μ (t-channel) or Anti-ν_e (s-channel)
- Elegant, Simple but steep, though calculable, threshold, $E_\nu \geq 11$ GeV
- Systematic Advantage of HiResMnu lies in avoiding the systematic error incurred by CCFR or CHARM-II in extrapolating the background to the signal $\zeta = P_e(1-\cos\Theta_e) \leq$ Cut

ॐ *ν-Electron Elastic NC Events*: $\nu_x + e^- \twoheadrightarrow \nu_x + e^-$ {Single, forward e^-}

- Different processes: $\nu_e e$-CC, Anti-$\nu_e e$-CC, & all flavor $\nu_x e$-NC
- Different E_e spectrum
- Focus on $\nu_\mu e$-NC: Experimentally the most challenging

✺ The Weak Mixing Angle (0.238) at Q~0.1 GeV is known to ≤1% precision

$\Rightarrow \sigma(\nu_x e\text{-NC})$ known $\Rightarrow$ Absolute-$\phi(\nu_x)$

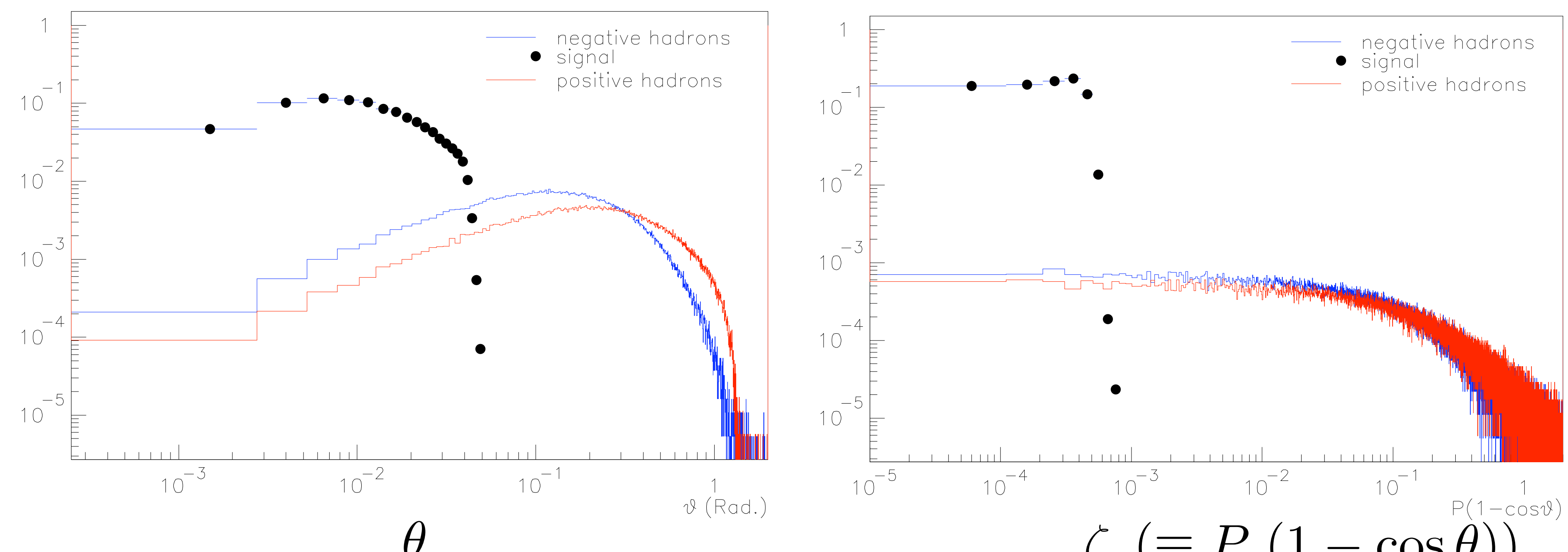
Absolute Flux using ν-e Elastic NC Scattering

ν-e ➽ Signal: Single, forward e-

Background: NC induced Pi0 ➽ γ ➽ e- (e+ invisible): charge-symmetric

Two-step Analysis: ✳ Electron-ID: TR ✳ Kinematic cut: ζ=Pe(1-cosΘe)

Simulation of charged hadron background. (use LBNE Flux)



Background charge symmetric & benign

Eff ➢ 64%

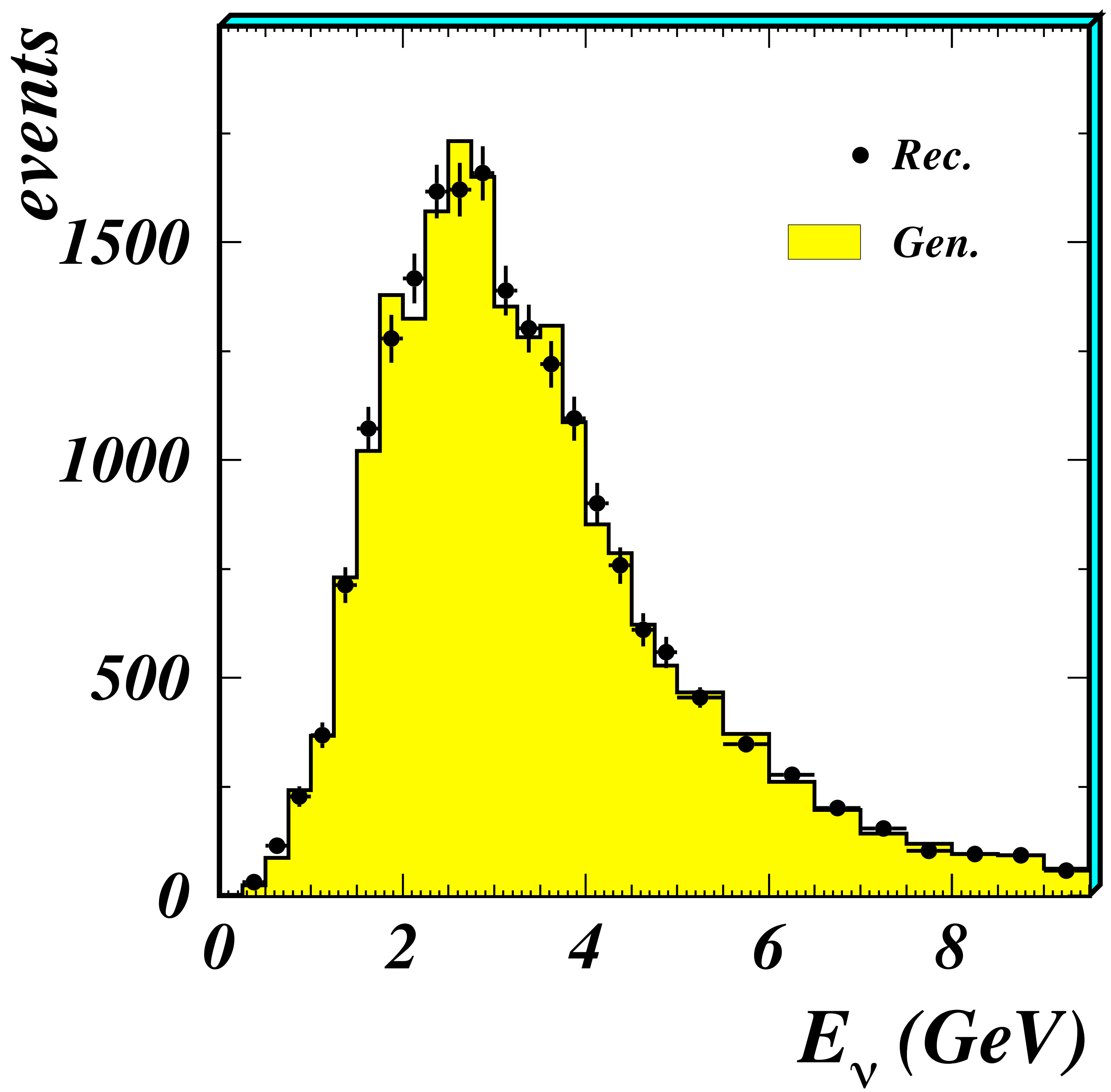
Bkg ➢ ≤10**(-6) ⇚ Measured

⇚ Conclusion

- Using (P_e, Θ_e), we can deduce E_ν-Rec Compare with Generated-E_ν

- Use 25,000 NC ν-e Events in Fid.Volume

- The precision on relative ν-flux (shape) is worse than in that determined using Low-ν0 technique



Conclusion ⇒

Measure

Absolute low-E_ν flux & Shape

ν_e-CC Sensitivity Study

ॐ ν_e-CC ➺ Signal: NC and CC(without Mu-ID) ➺ Background

ॐ Two Steps to Analysis:

✺ Electron-ID: TR

✺ Kinematic Isolation of NuE-induced e- from the Hadron-Vector

ॐ NOMAD data as a benchmark

ॐ HiResMnu	NuE	NuMu-CC	Nu-NC
Fiducial Volume	1,500	100,000	34,000
$p_\mu < 0.5$GeV	1,500	8,273	34,000
Electron-Sel against -ve Hadrons			
≥20-Mod(-Ve)	1,228	1,738	11,213
P-ve>0.5 GeV	1,192	1,319	8,662
TR-Cut	911	1.3	8.7
Pi0-Backgound			
Phton➢e-(e+)		5.5	24.1
TR-Cut		5.0	21.7
e- Sample	911	6.3	30.4

HiResMnu:

⇚NuE-Eff ➺ 60.8%

NuE-Purity ➺ 96.1%

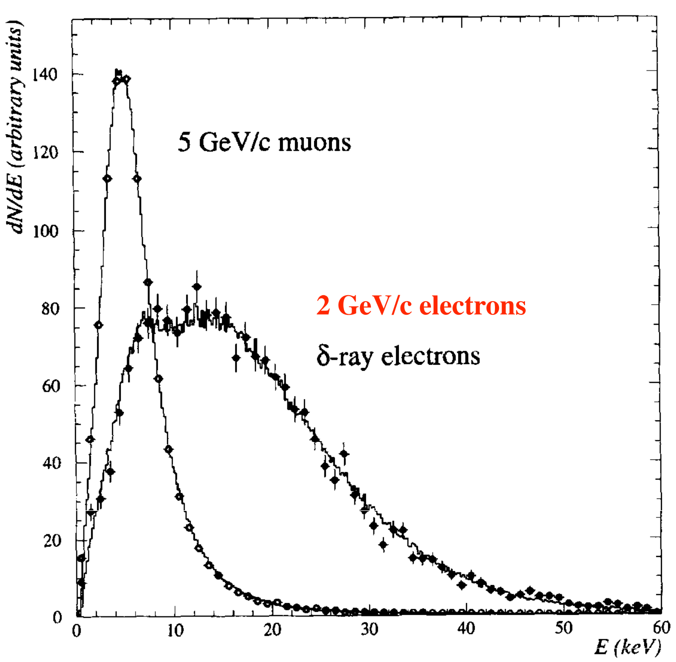
Check: For Nomad

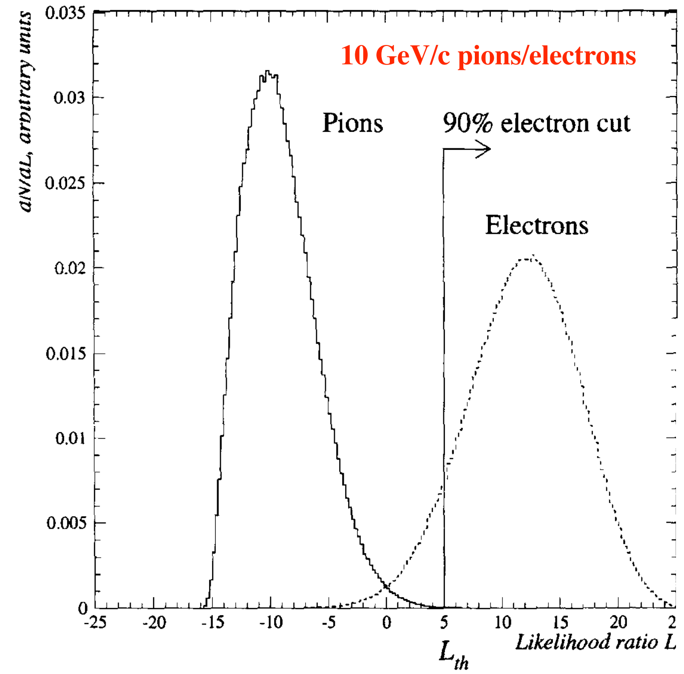
NuE-Eff ➺ 48.8%

Actual: Eff ➺ 45.0%

Pur ➺ 80.0%

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

- Atlas-TRT's Geant4 simulation conducted for the HiResMnu-config. verifies the e/π separation assumed for the STT ➢ (See P.Nevski DocDB#432-V1)

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

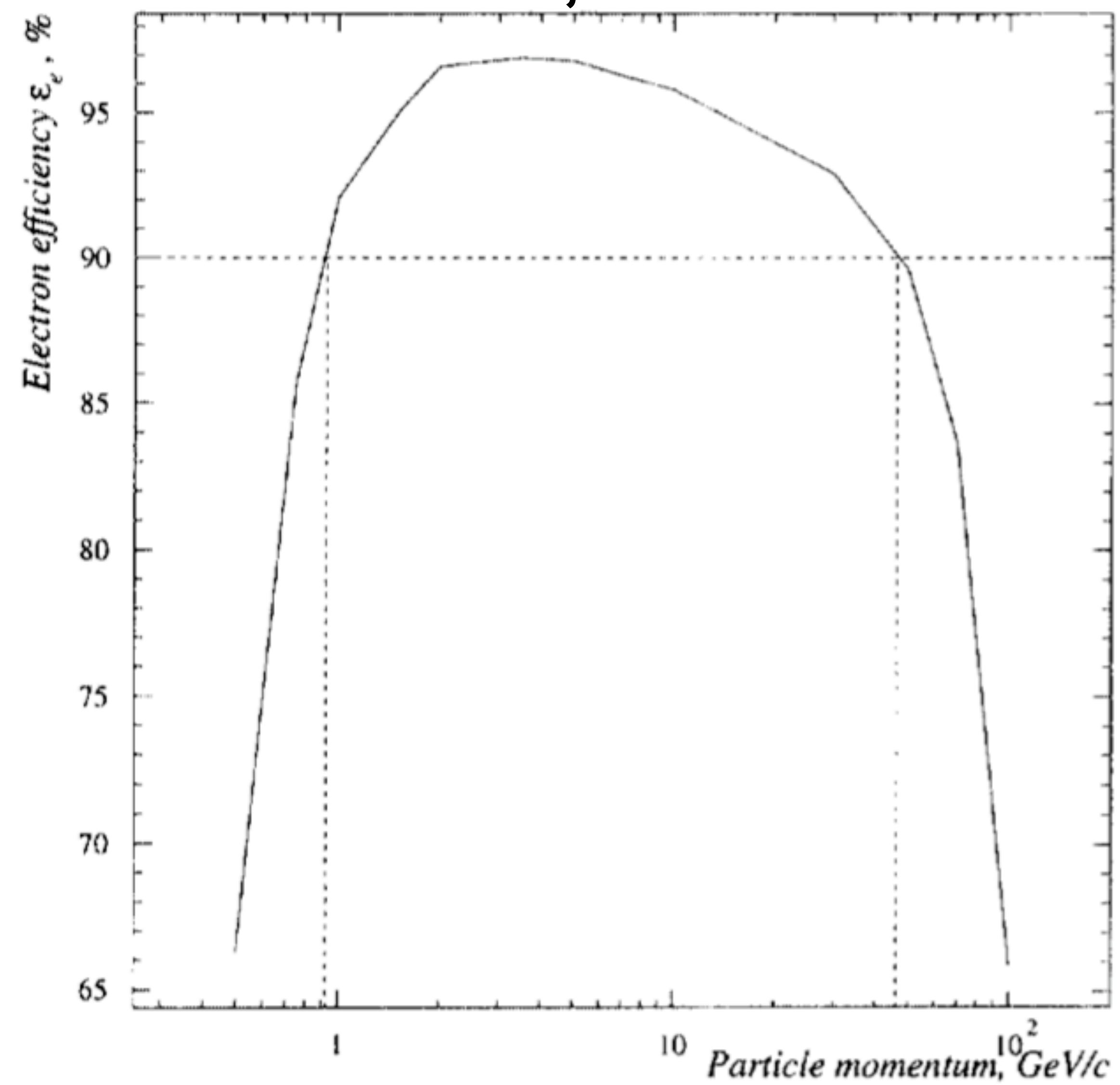
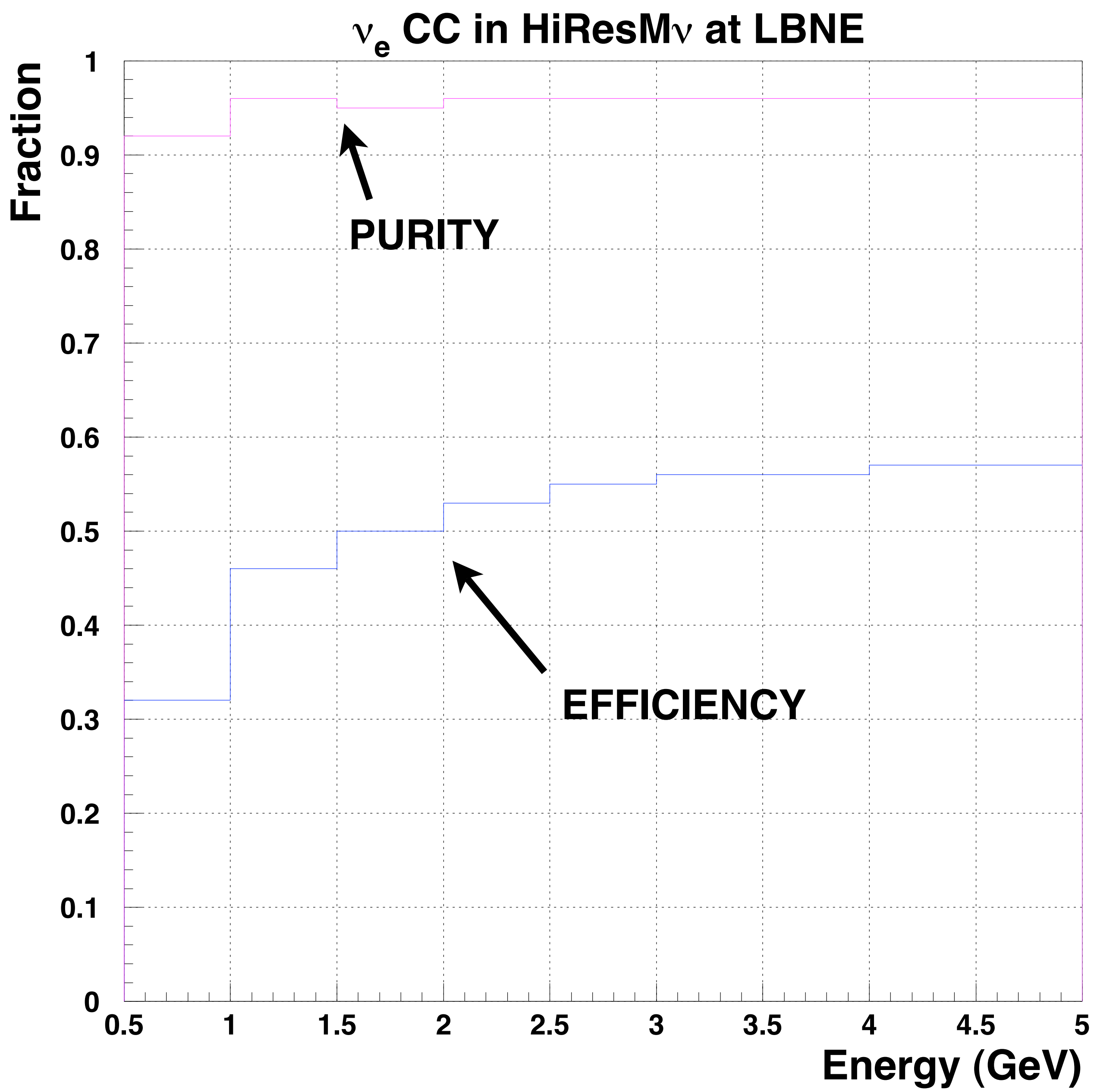


Fig. 8. Monte Carlo predicted electron efficiency ε_e corresponding to $\varepsilon_\pi = 10^{-3}$ as a function of the momentum of the particle for 9 associated hits.

IDENTIFICATION OF ν_e CC INTERACTIONS



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  $\Longrightarrow$ 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:*

If we keep the signal efficiency at ~55%, then purity is about 95%

LOW-ν_0 METHOD ⇐Shape of νμ or Anti-νμ Flux

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

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

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*

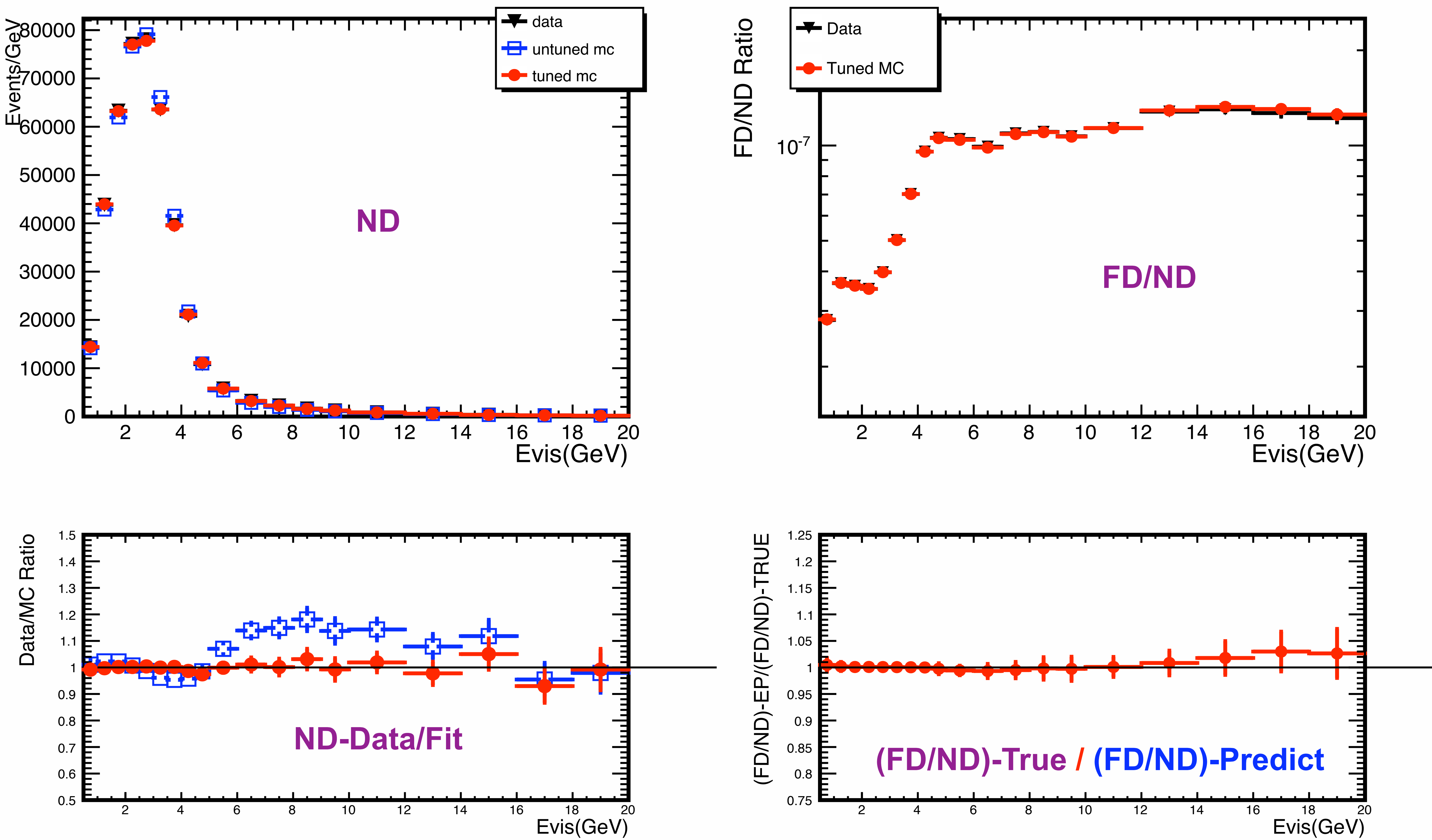
$$\frac{d^2\sigma}{dx_F dP_T^2} = f(x_F)g(P_T)h(x_F, P_T)$$

  - *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*

Shape of ν_μ or Anti-ν_μ Flux using Low-ν_0 Method

ν_μ, **Low-Nu0 Fit, ND at 500m** Relative ν_μ-Flux Measurement using Low-ν_0 @ LBNE



Conclusion ⇒

Predict FD/ND flux-ratio with high precision

Systematic-Errors in Low-ν_0 Relative Flux: ν_μ & Anti-ν_μ

- Variation in ν_0-cut
- Variation in ν_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 (ND at 1000m)

Includes:

*Alignment (1.0mm)
*Horn Current (0.5%)
*Inert material (0.25λ)
*Proton spot size

$\Rightarrow$ Revisit these (?) & Investigate ND @ 500m

π0-Reconstruction

ॐ Clean Π0- and γ-signatures in HiResMnu

ॐ 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

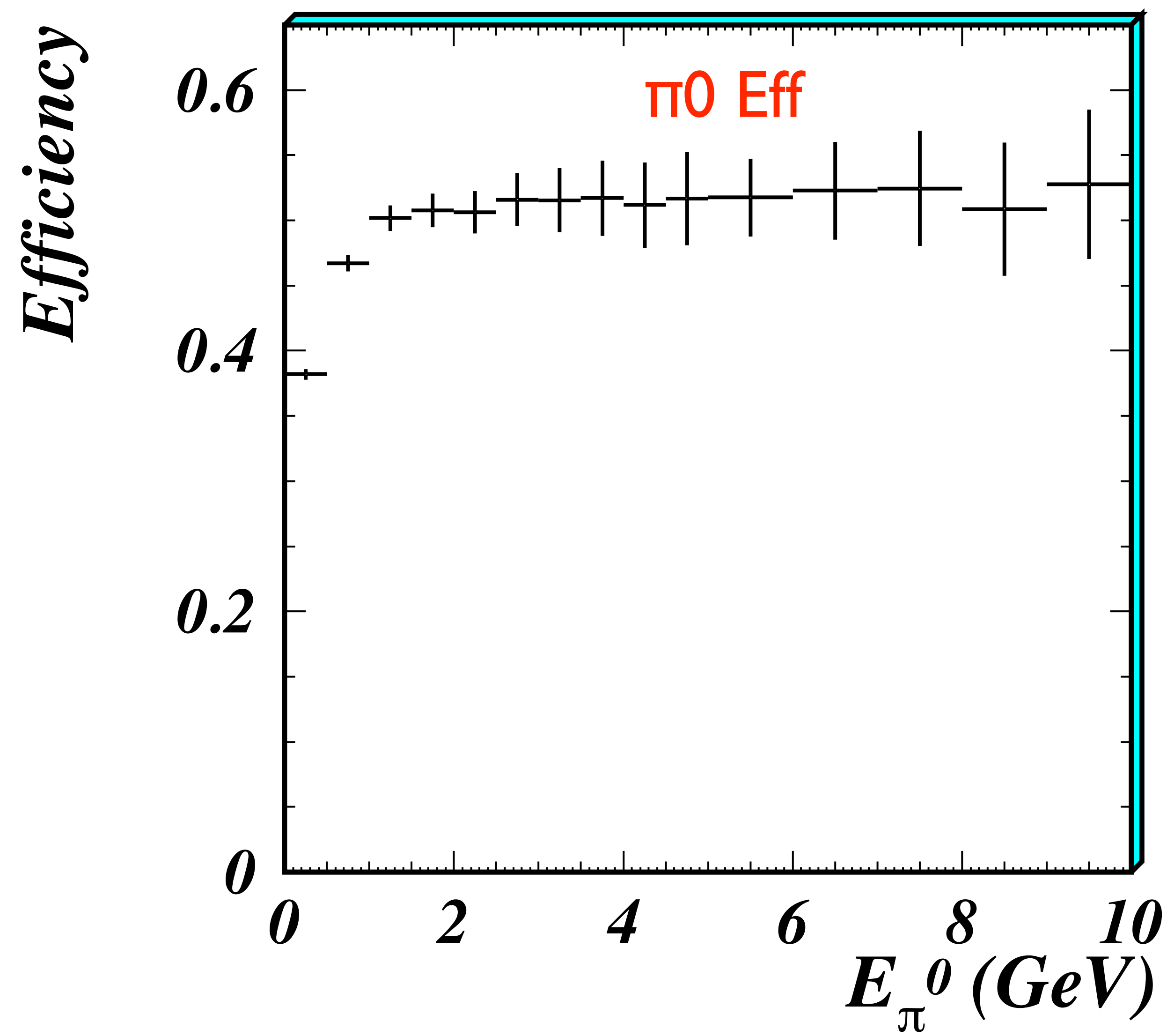
ॐ γ-Identification:

✺ 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)

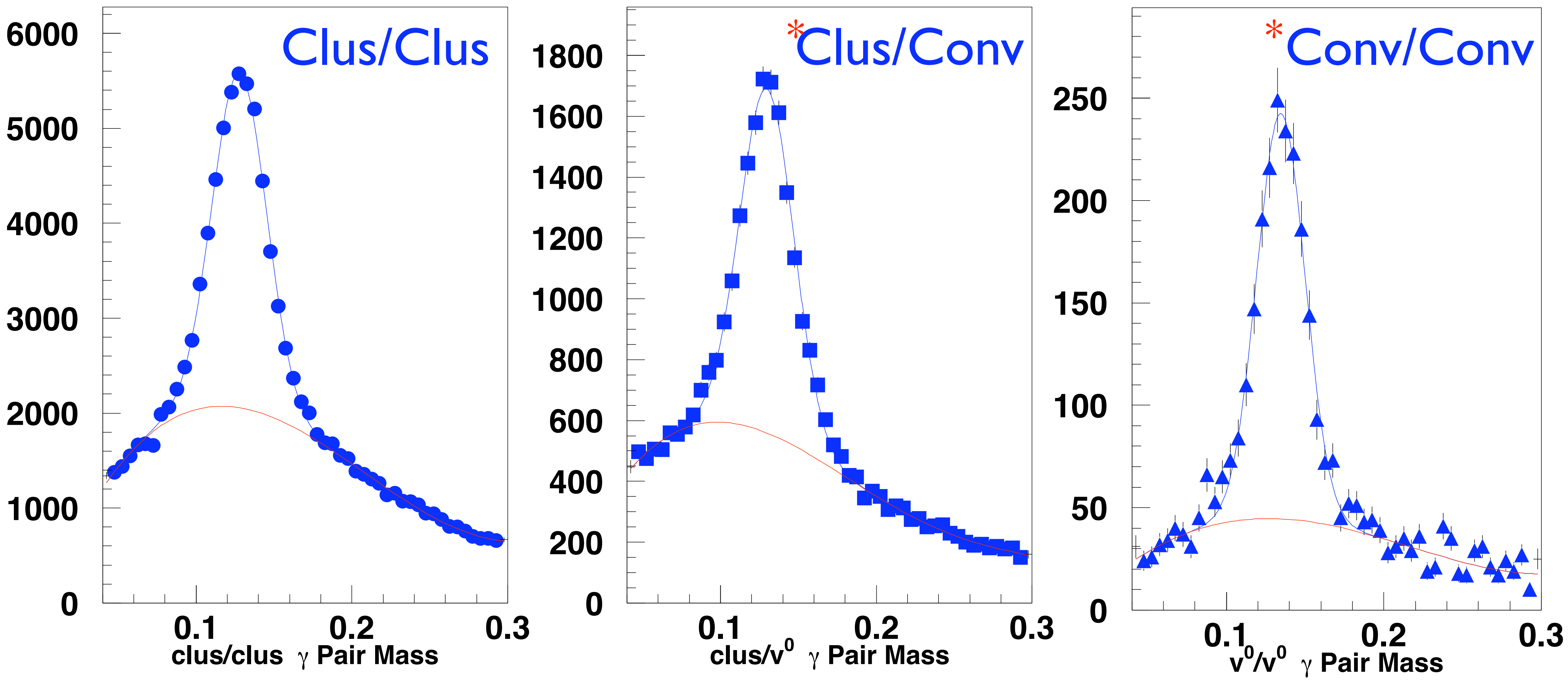
➢Another γ in the
Downstream & Side ECAL



Conclusion ⇒

π0's Very well constrained in CC and NC

Reconstructed π^0 in NC interactions in NOMAD



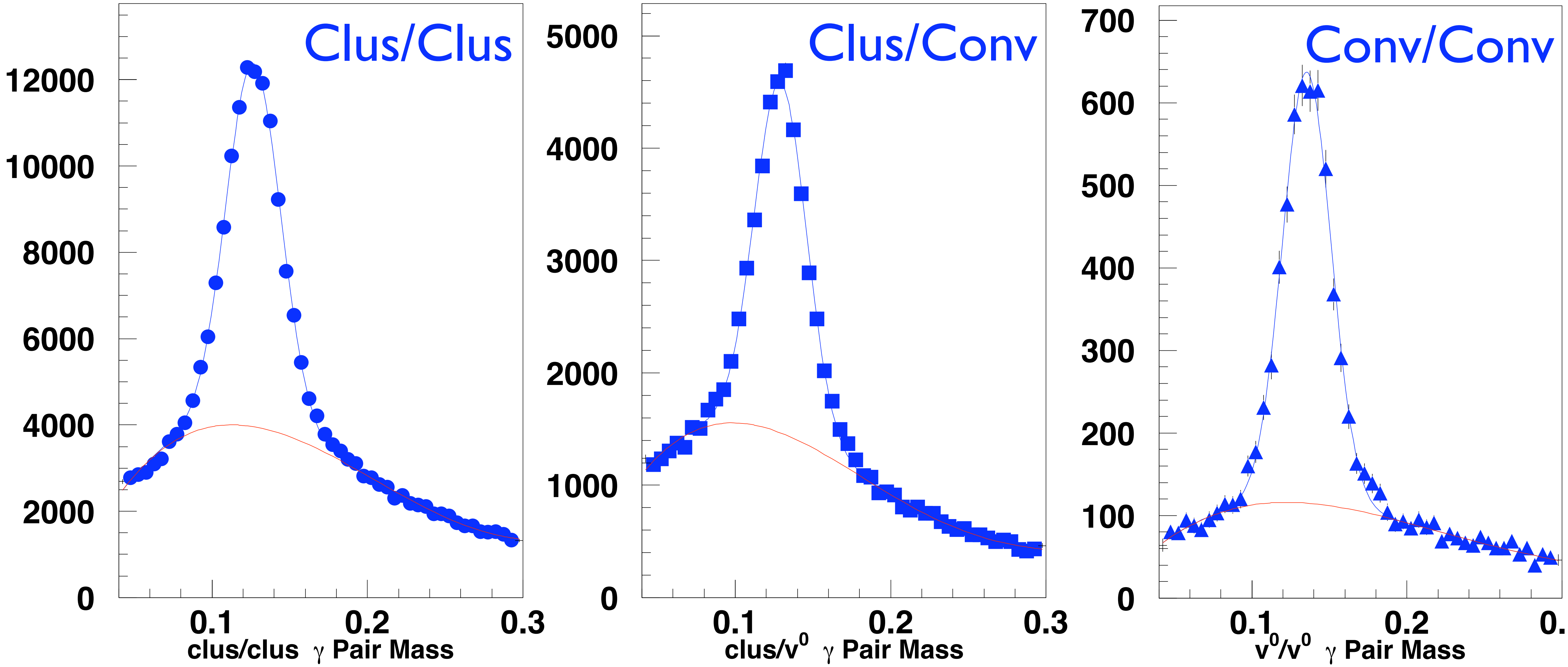
Overall more than 33k reconstructed events. Three topologies:

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

[STT: expect similar resolution but much lower combinatorics]

South Carolina Group

Reconstructed π^0 in CC interactions in NOMAD



Overall more than 100k reconstructed events. Three topologies:

- *Cluster/Cluster 72k events*
- *Cluster/Conversion 22k events*
- *Conversion/Conversion 7k events*

MEASUREMENT OF THE RATIO $\mathcal{R}_{e\mu}$ ⇐*Search/Impact of Large-Δm**2 Oscillation*

- *Independent analysis of neutrino data and anti-neutrino data due to possible differences following MiniBooNE/LSND results*

  $\Longrightarrow$ *Need a near detector which can identify e^+ from e^-*

- *Measure the ratio between the observed $\nu_e(\bar{\nu}_e)$ CC events and the observed $\nu_\mu(\bar{\nu}_\mu)$ CC events as a function of L/E_ν:*

$$\mathcal{R}_{e\mu}(L/(E\nu)) \equiv \frac{\#\ of\ \nu_e N \to e^- X}{\#\ of\ \nu_\mu N \to \mu^- X}(L/(E\nu))$$

$$\bar{\mathcal{R}}_{e\mu}(L/(E\nu)) \equiv \frac{\#\ of\ \bar{\nu}_e N \to e^+ X}{\#\ of\ \bar{\nu}_\mu N \to \mu^+ X}(L/(E\nu))$$

- *Compare the measured ratios $\mathcal{R}_{e\mu}(L/$ Eν and $\bar{\mathcal{R}}_{e\mu}(L/$ Eν with the predictions from the low-ν_0 flux determination assuming no oscillations*

- *Same analysis technique used in NOMAD to search for $\nu_\mu \to \nu_e$ oscillations.*

Particle Multiplicity: ν-induced Hardon-jet

ॐ ν_μ-CC identified by μ^- in the FD

However in ν-NC interactions:

⇒ π-/K-/D-hadron ➽ μ- form an *almost* irreducible background

⇒ -ve hadron punchthrough form additional, reducible background

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

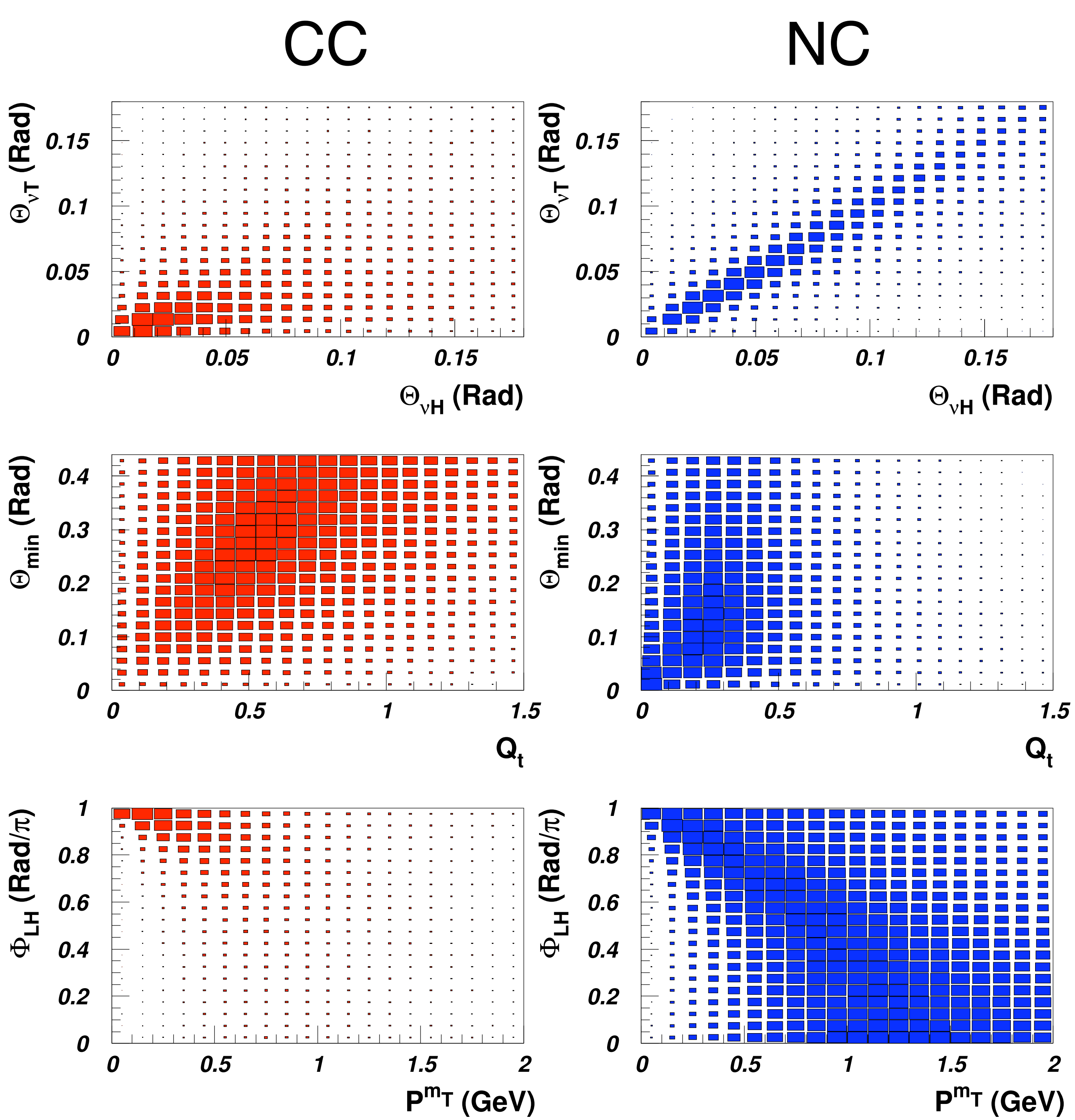
ॐ π^0's in NC ⇒ Largest backgrounds to (Anti)ν_e-appearance

ॐ ≃30% of the Non-Prompt background ($\pi^{0+-}/K^{0+-}/D$ ⇒ μ, EM-shower)

arise from "short" ν_μ-CC

➢➢ **Measure ($\pi^{0+-}/K^{0+-}/D$ ⇒ μ, EM-shower) in NC & in CC**

Identification of NC interactions in NOMAD



✦ Difficult to measure NC cross-section in conventional detectors

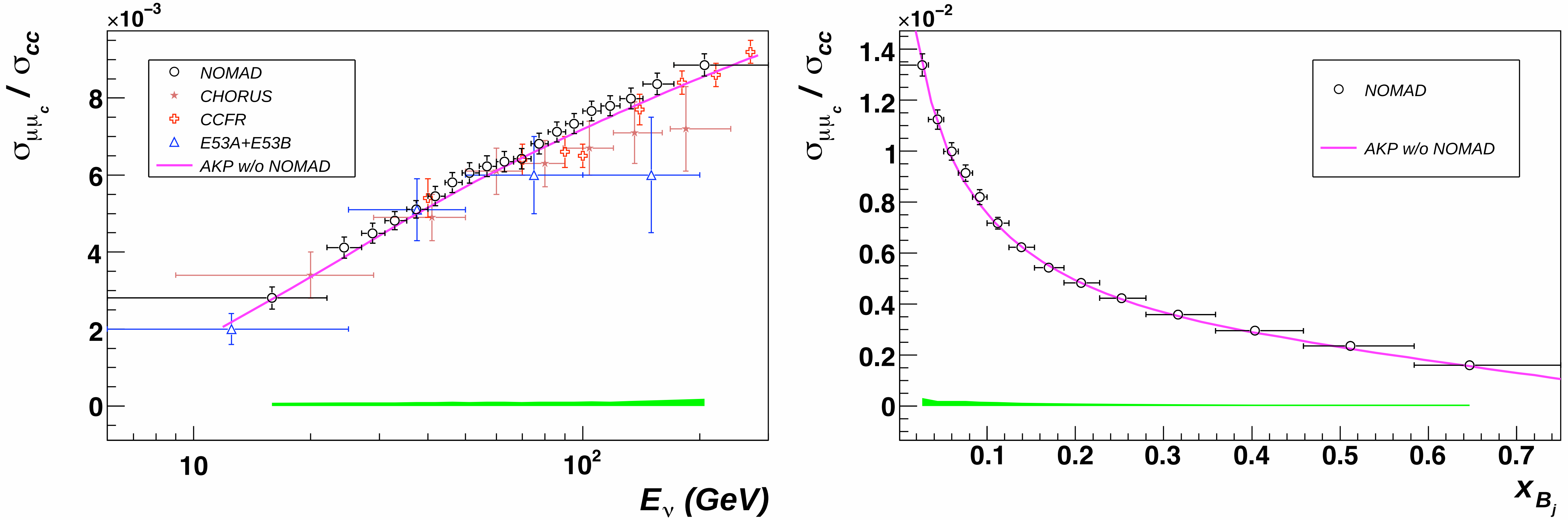
✦ NOMAD can identify NC events from kinematics with a purity of 90%

✦ Plots show NC/CC separation for events failing the muon identification

⇐Non-μID Events

CHARM DIMUON PRODUCTION FROM NOMAD

DIS-2011 by Petti



- *Measure* **RATIO** *of cross-sections to reduce systematics:*

$$\mathcal{R}_{\mu\mu} \equiv \sigma_{\mu\mu_c}/\sigma_{cc} \simeq N_{\mu\mu_c}/N_{cc}(x); \quad x = E_\nu, x_{B_j}, \sqrt{\hat{s}}$$

- *Require leading* μ^- *and* $Q^2 \geq 1$ *GeV*^{2}

$$\int \sigma_{\mu\mu_c} \phi \, dx \, dy \, dE_\nu \quad = \quad 5.15 \pm 0.05 \times 10^{-3} \; \nu_\mu \mathrm{CC}$$

- *Total systematic uncertainty (17 different sources)* $\sim 2\%$
- *Agreement with model calculation based upon global fits with NuTeV+CCFR only*

⇛ *Precise empirical constraints on* **π+/-** *in NC and CC*

ॐ Summary of Sensitivity Studies with HiResMnu-Idea

- Determination of Absolute Flux:

ν_μ + e- ⇻ ν_μ + e- & Inverse Muon Decay

- Relative Flux:

ν_μ-Flux Shape: Far-Detector/Near-Detector (E_ν)

ν_μBar-Flux Shape: Far-Detector/Near-Detector (E_ν)

ν_μBar/ν_μ Flux (E_ν)

- Efficiency of ν_μ-QE CC and Background as a function of E_ν

- Efficiency of ν_e-CC and Background (π^0) from NC and CC as a function of E_ν [Ditto for ν_eBar-CC]

- π^0-detection efficiency and background as a function of E_{π^0}

ॐ Precision Physics Studies with HiResMnu

- Sin**2(Θ_W)
- ν_μ-Nucleon Elastic Scattering ⇻ Del-S
- ν_μ-Energy scale: QE + Missing-Pt
- Search for Sterile ν
- Search for High Del-m**2 Oscillation
- .....

Synergy between the ND-Design for LBNE and Nu-Factory

- A group actively working on the ND-design for the LBNE & the Nu-Factory
- Although the Nu-Factory beam ($\mu \rightarrow \nu_e \, \nu_\mu$) simpler than LBNE, the requirements on systematic precision are much higher
- The LBNE-STT (HIRESMNU) is the reference candidate for LBNE

⇛ *Joint effort will benefit all*

Plans for the Future:

- Begun work with the Mu-decay flux files
- Studies/simulation of ν-interactions toward goals of a Nu-factory
- Formulate some ND-Metrics pertinent of Nu-Factory:
  (What sensitivity studies should be undertaken?)
- Abosolute & Relative (Shape) flux of (Anti)ν_μ/ν_e
- Estimation of backgrounds (Wrong-sign) to

$$\nu_e \rightarrow \nu_\mu$$

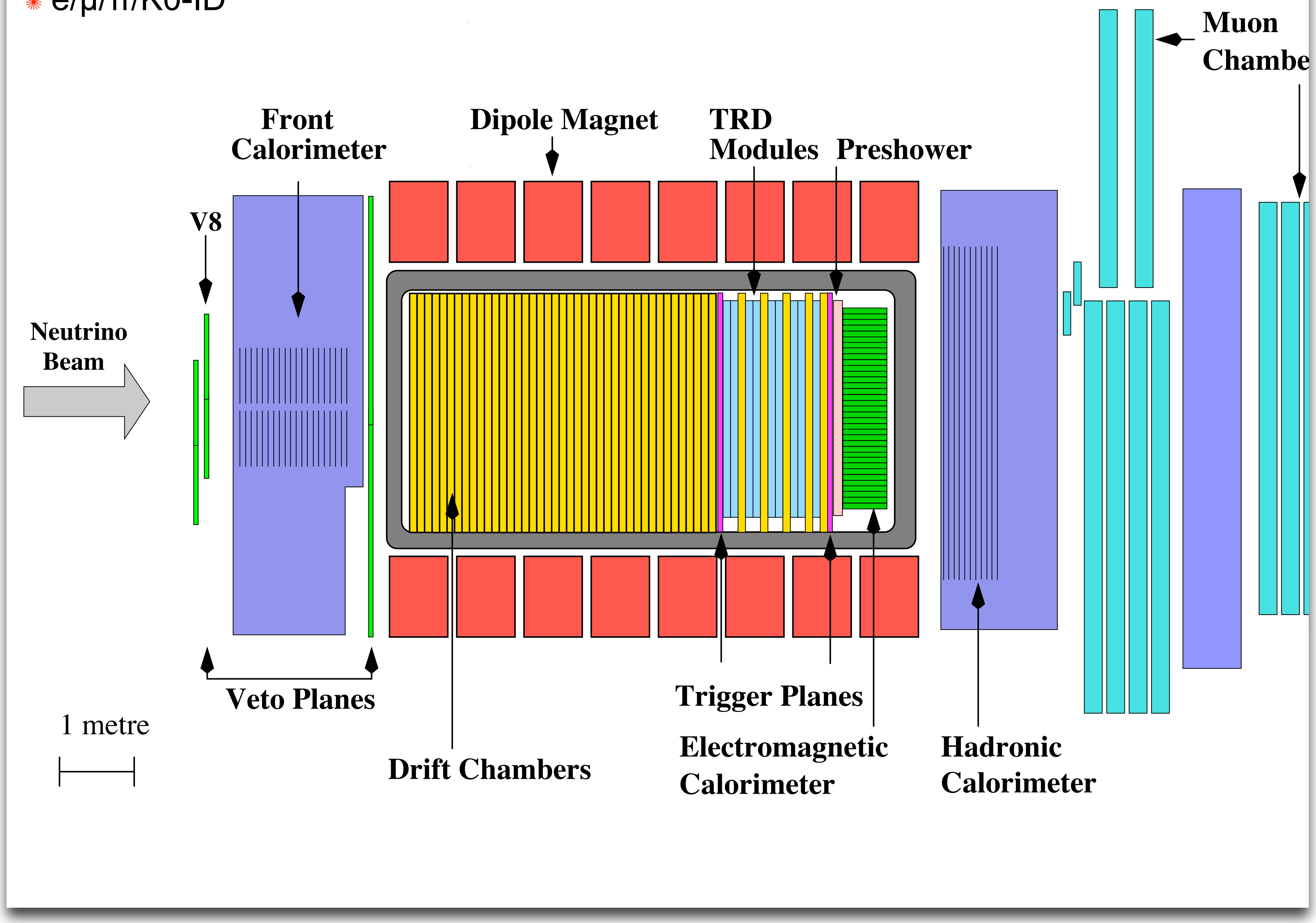
$$\nu_e \rightarrow \nu_\tau$$

- Deep synergy between the LBNE and Nu-Factory ND Efforts

Backup Slides

We build on the NOMAD experience:

- B=0.4T
- ρ~0.1gm/cm^3
- e/μ/π/K0-ID



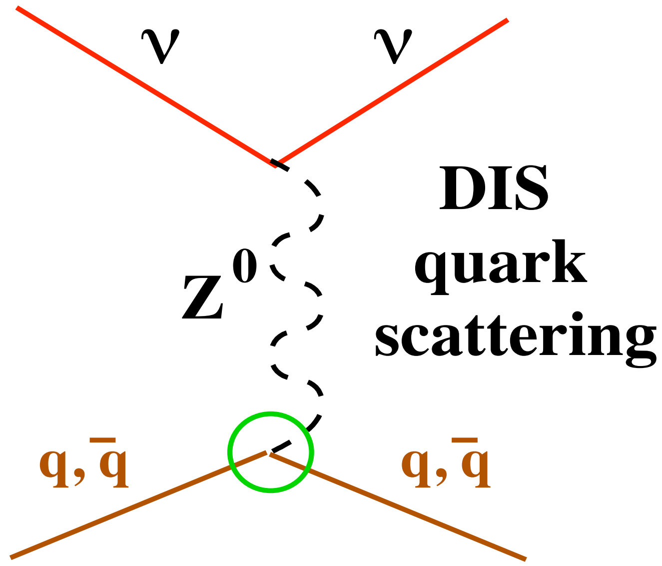
PRECISION MEASUREMENTS

✦ *Ratio of NC and CC in both ν-N and $\bar{\nu}$-N Deep Inelastic Scattering. Paschos-Wolfenstein relation allows a reduction of systematic uncertainties:*

$$R^{-} \stackrel{\text{def}}{\equiv} \frac{\sigma^{\nu}_{\text{NC}} - \sigma^{\bar{\nu}}_{\text{NC}}}{\sigma^{\nu}_{\text{CC}} - \sigma^{\bar{\nu}}_{\text{CC}}}$$

- $\delta sin^2\theta_W / sin^2\theta_W = \boxed{2.0 \times 10^{-3}}$
- *19(6)*$\times 10^6$ *NC selected events in* $\nu(\bar{\nu})$ *mode*

$\Longrightarrow$ *Dominated by systematics*

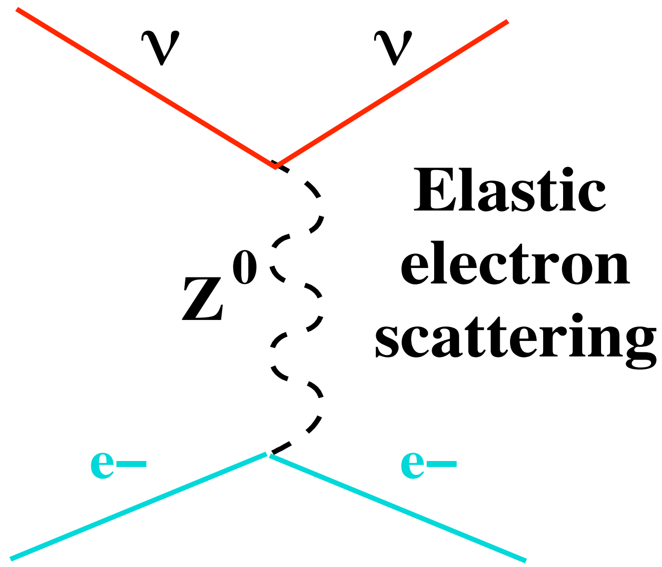


✦ *Ratio of $\nu e \rightarrow \nu e$ and $\bar{\nu} e \rightarrow \bar{\nu} e$ NC elastic scattering, which is free from hadronic uncertainties:*

$$R_{\nu e} \stackrel{\text{def}}{\equiv} \frac{\sigma(\bar{\nu} - e^-)}{\sigma(\nu - e^-)}$$

- $\delta sin^2\theta_W / sin^2\theta_W = \boxed{5.6 \times 10^{-3}}$
- *31(17)* $\times 10^3$ *NC selected events in* $\nu(\bar{\nu})$ *mode*

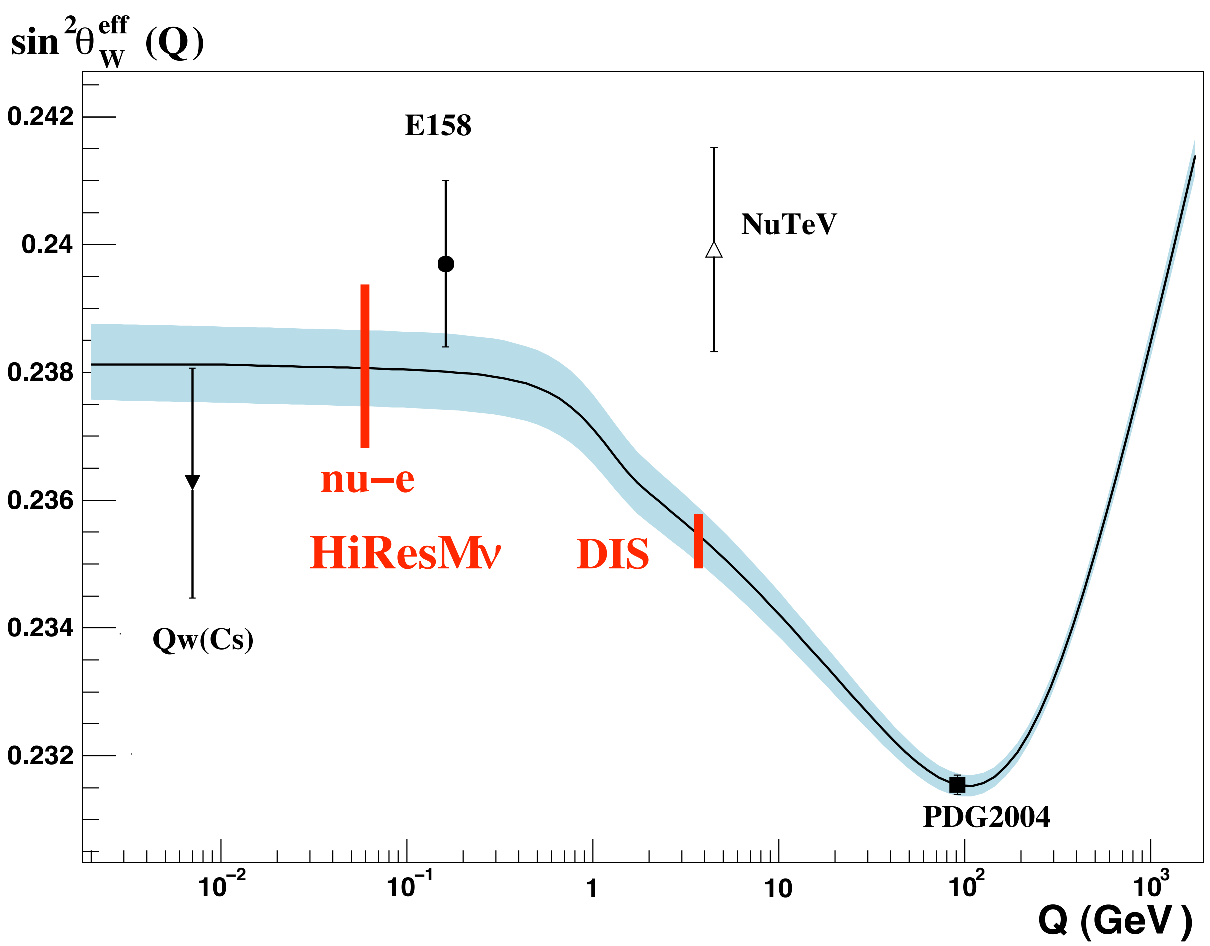
$\Longrightarrow$ *Dominated by statistics*



RELEVANCE OF THE $\sin^2\theta_W$ MEASUREMENT

✦ *Sensitivity expected from ν scattering in HiResMν comparable to the Collider precision:*

- *FIRST single experiment to directly check the running of $\sin^2\theta_W$:*
  elastic ν-e scattering and νN DIS have different scales
- *different scale of momentum transfer with respect to LEP/SLD (off Z^0 pole)*
- *direct measurement of neutrino couplings to Z^0*
  $\Longrightarrow$ *Only other measurement LEP $\Gamma_{\nu\nu}$*



✦ *Independent cross-check of the NuTeV $\sin^2\theta_W$ anomaly in a similar Q^2 range*

$\Longrightarrow$ *A discrepancy of 3σ with respect to SM in the NEUTRINO data*

MEASUREMENT OF Δs

✦ NC ELASTIC SCATTERING *neutrino-nucleus is sensitive to the strange quark contribution to nucleon spin, Δs, through axial-vector form factor G_1:*

$$G_1 = \left[-\frac{G_A}{2}\tau_z + \frac{G_A^s}{2} \right]$$

At $Q^2 \to 0$ we have $d\sigma/dQ^2 \propto G_1^2$ and the strange axial form factor $G_A^s \to \Delta s$.

✦ *Measure* NC/CC RATIOS *as a function of Q^2 to reduce systematics ($\sin^2\theta_W$ as well):*

$$R_\nu = \frac{\sigma(\nu p \to \nu p)}{\sigma(\nu n \to \mu^- p)}; \qquad R_{\bar\nu} = \frac{\sigma(\bar\nu p \to \bar\nu p)}{\sigma(\bar\nu p \to \mu^+ n)}$$

- *Statistical precison in HiResMν will be at the 10^{-3} level: $\sim$ 1.5 $\times 10^6$ ν NC and $\sim$ 800k $\bar\nu$ NC events*
- *High resolution tracking for protons down to momenta of 250 MeV/c in HiResMν allows to access low Q^2 values and reduce backgrounds;*
- *A precision measurement over an extended Q^2 range reduces systematic uncertainties from the Q^2 dependence of vector ($F_{1,2}^s$) and axial (G_A^s) strange form factors;*
- *Nuclear effects are expected to largely cancel in the ratios R_ν and $R_{\bar\nu}$;*
- *Need to check neutron background.*

Source of uncertainty	$\delta\mathcal{X}/\mathcal{X}$	$\delta R^{\nu}/R^{\nu}$	$\delta R^{\bar{\nu}}/R^{\bar{\nu}}$		$\delta\mathcal{X}/\mathcal{X}$
Data statistics	0.00593	0.00176	0.00393		
Monte Carlo statistics	0.00044	0.00015	0.00025		
Total Statistics	**0.00593**	**0.00176**	**0.00393**		**0.0008**
$\nu_e, \bar{\nu}_e$ flux ($\sim 1.7\%$)	0.00171	0.00064	0.00109		0.0001
Energy measurement	0.00079	0.00038	0.00059		0.0004
Shower length model	0.00119	0.00054	0.00049		n.a.
Counter efficiency, noise	0.00101	0.00036	0.00015		n.a.
Interaction vertex	0.00132	0.00056	0.00042		n.a.
Other					0.0008
Experimental systematics	**0.00277**	**0.00112**	**0.00141**		**0.0010**
d,s→c, s-sea	0.00206	0.00227	0.00454		0.0011
Charm sea	0.00044	0.00013	0.00010		n.a.
$r = \sigma^{\bar{\nu}}/\sigma^{\nu}$	0.00097	0.00018	0.00064		0.0005
Radiative corrections	0.00048	0.00013	0.00015		0.0001
Non-isoscalar target	0.00022	0.00010	0.00010		N.A.
Higher twists	0.00061	0.00031	0.00032		0.0003
R_L	0.00141	0.00115	0.00249	(F_2, F_T, xF_3)	0.0005
Model systematics	**0.00281**	**0.00258**	**0.00523**		**0.0014**
TOTAL	**0.00711**	**0.00332**	**0.00672**		**0.0019**

Table 4: Summary of uncertainties on the extraction of the weak mixing angle ($\mathcal{X} = \sin^2\theta_W$) based upon the Pascos-Wolfenstein relation. The first three columns refer to the published NuTeV errors [12] while the last column indicates the corresponding projection for our experiment.