The LBNE Near-Detector Complex: a Status

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on behalf of the
LBNE Collaboration

Physics of LBNE

Questions regarding the PMNS Matrix Elements

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

Talk by Brajesh Choudhary

Beyond PMNS

- Θ_{23} = 45^0 ?
- CPT Violation ?
- High Δm**2 Oscillation ?
- Phenomenon that defies the Zeitghist

The familiar, beautiful neighborhood

- Sin**2(Θw): precision commensurate with Colliders
- Sum rules
- Isospin Physics
- 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;* $\Leftarrow \leftharpoonup \leftharpoonup$ ν(Bar)e/μ-Appearance
  - *Quantitative determination of* E_ν *absolute energy scale;*
  - *Measurement of detailed event topologies in CC & NC.*

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

- *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?

Four Near-Detector Choices

ༀ Liquid Argon (LAr) Detectors:

(a) 70-ton Unmagnetized LAr {MicroBOONE}
(b) 20-ton Magnetized LAr {UCLA-Gr}

ༀ Fine Grain Trackers:

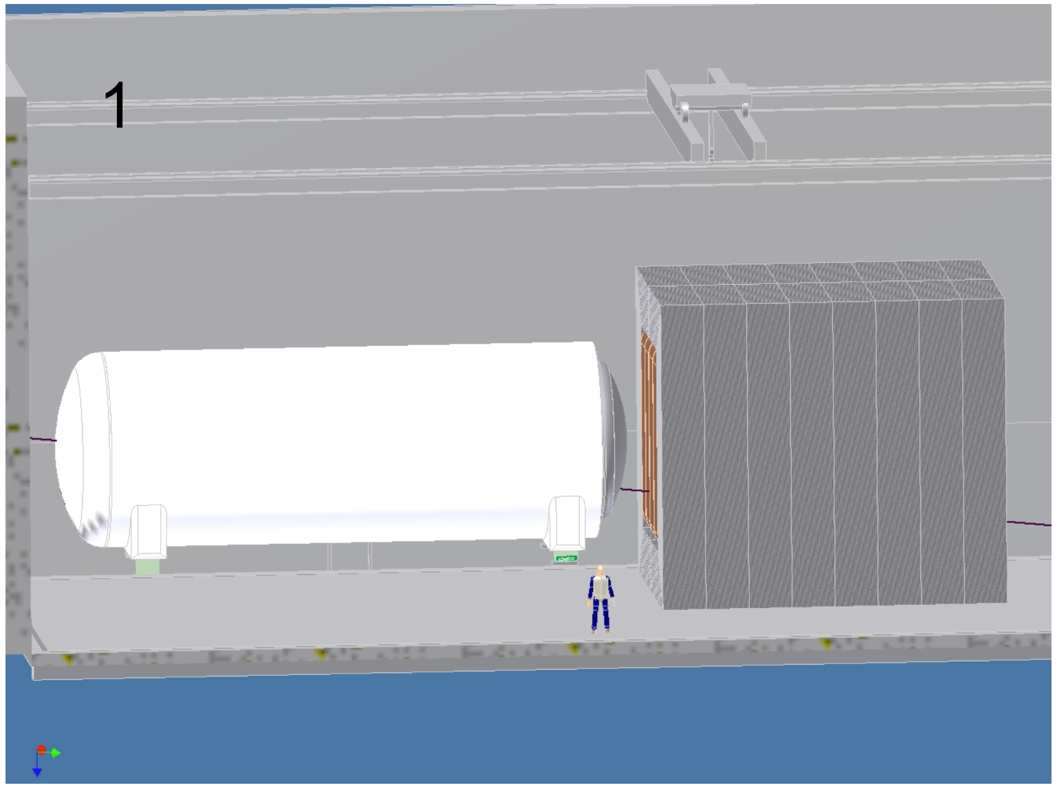
(i) Straw Tube Tracker {HiResMnu}
(ii) Scintillator Tracker {MINERvA}

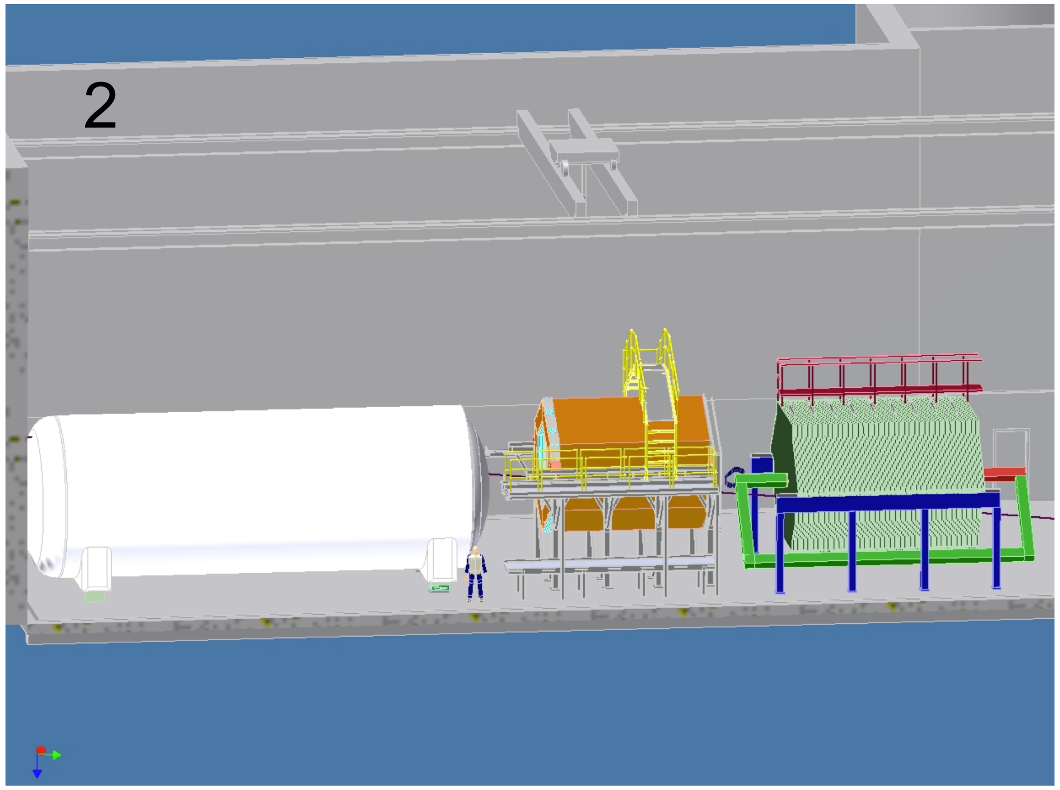
with H_2O
⇐ Target

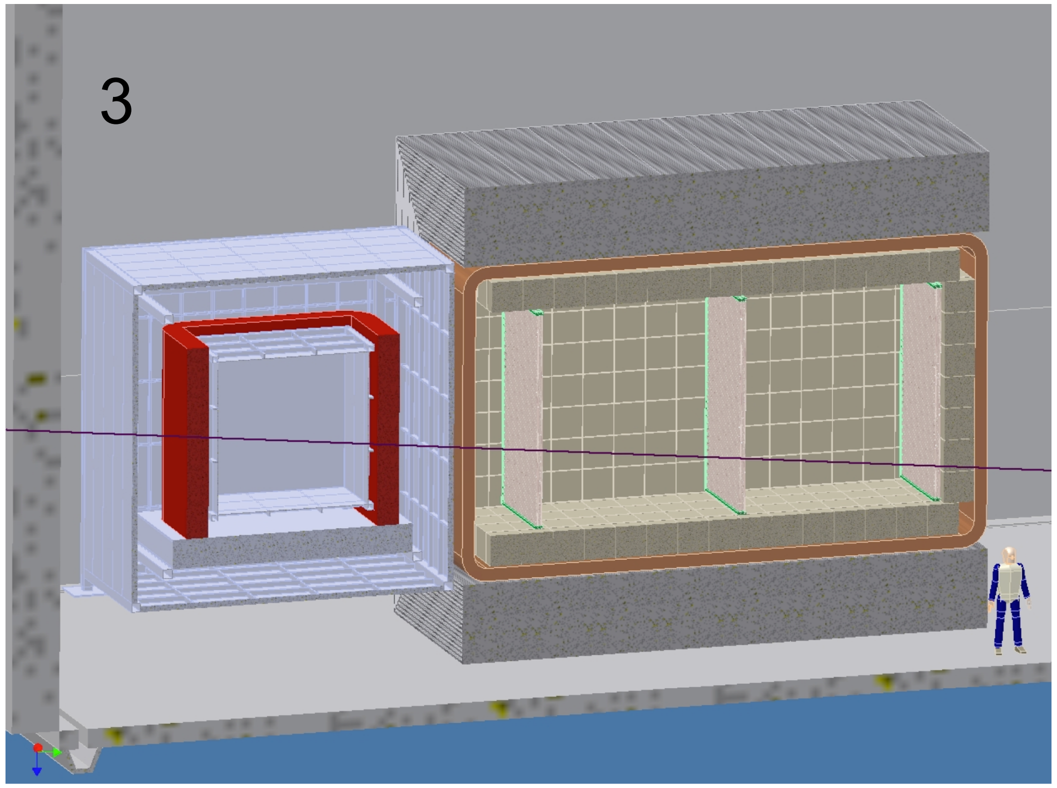
ༀ *Reference Design:*

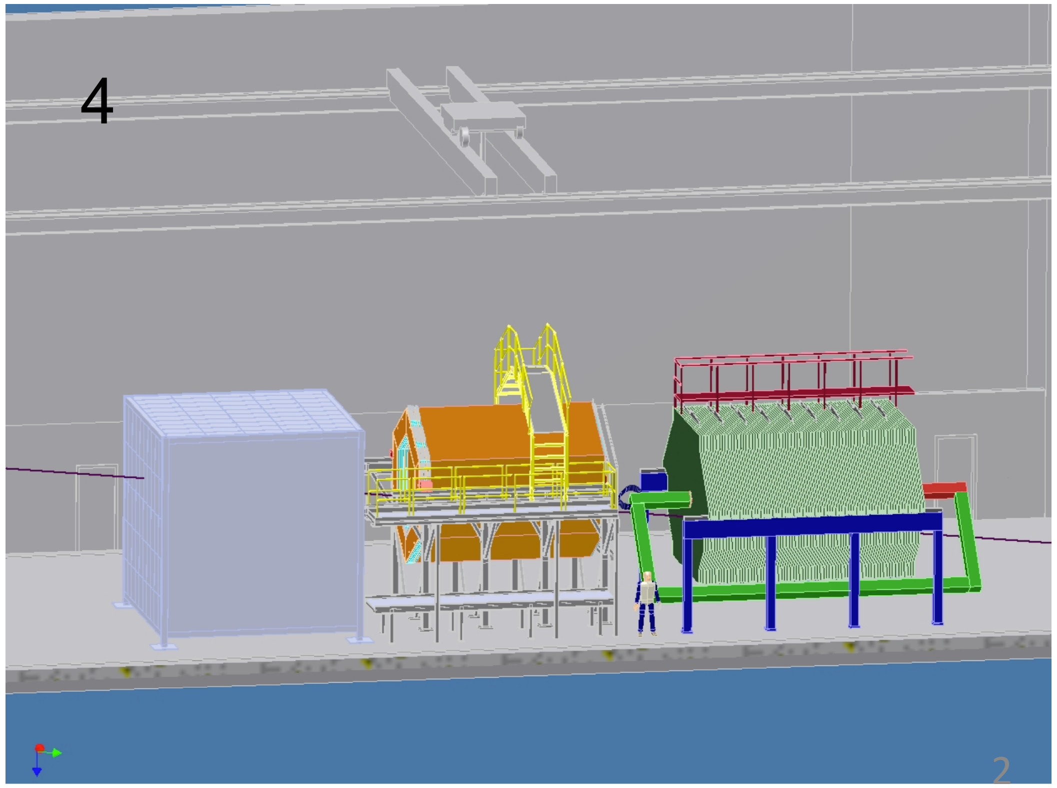
(a) 70-ton Unmagnetized LAr, followed by
(i) Straw Tube Tracker {HiResMnu}

The Four Detector Options









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.* ⇚Background to ν_e/ν_μ

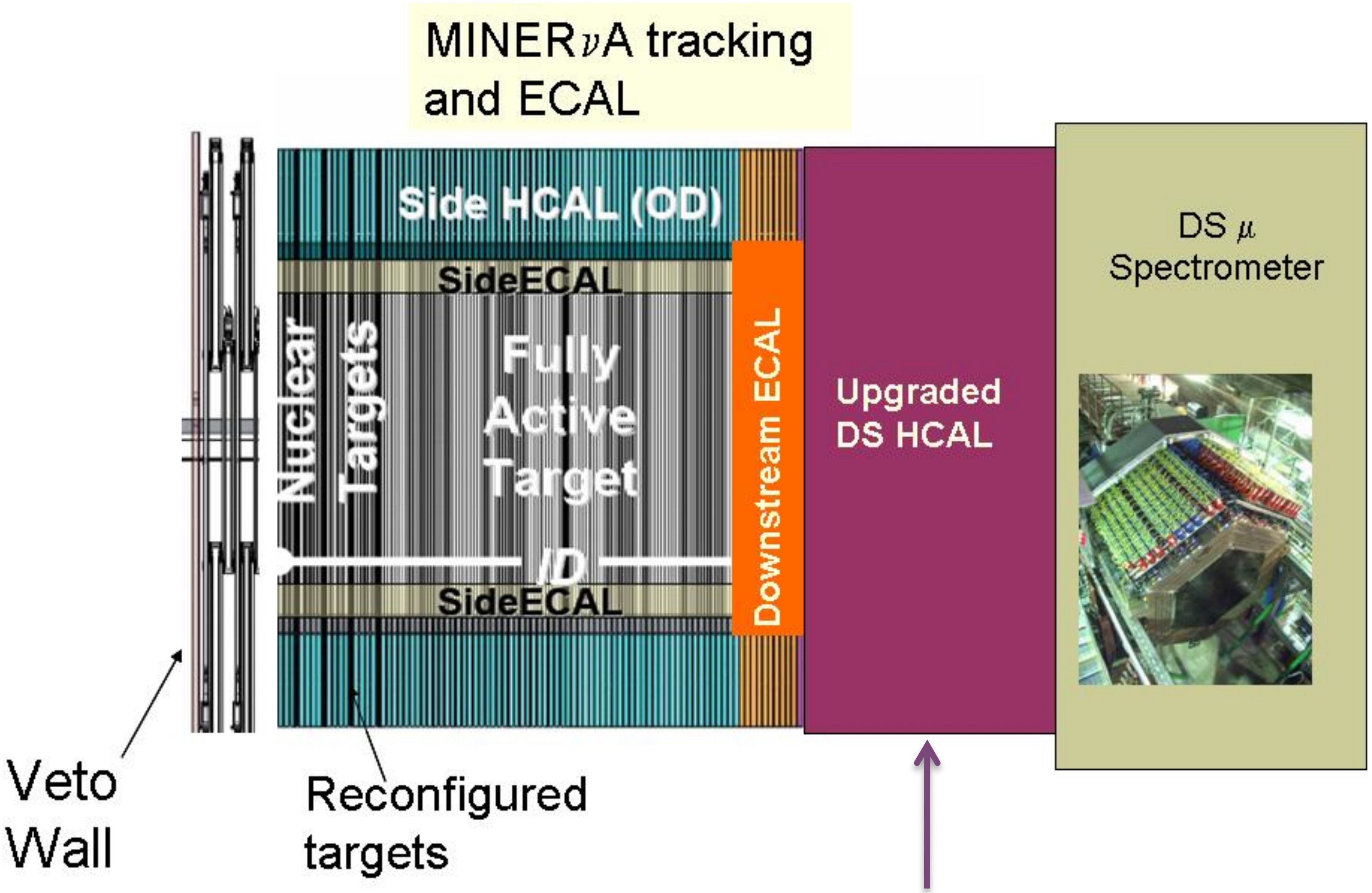
- *Measurement of the weak-mixing angle, sin$^2\theta_W$, with a precision of about 0.2%, using independent measurements:*
  - *$\nu(\overline{\nu})$-q (DIS);*
  - *$\nu(\overline{\nu})$-e$^-$ (NC).*

  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.*

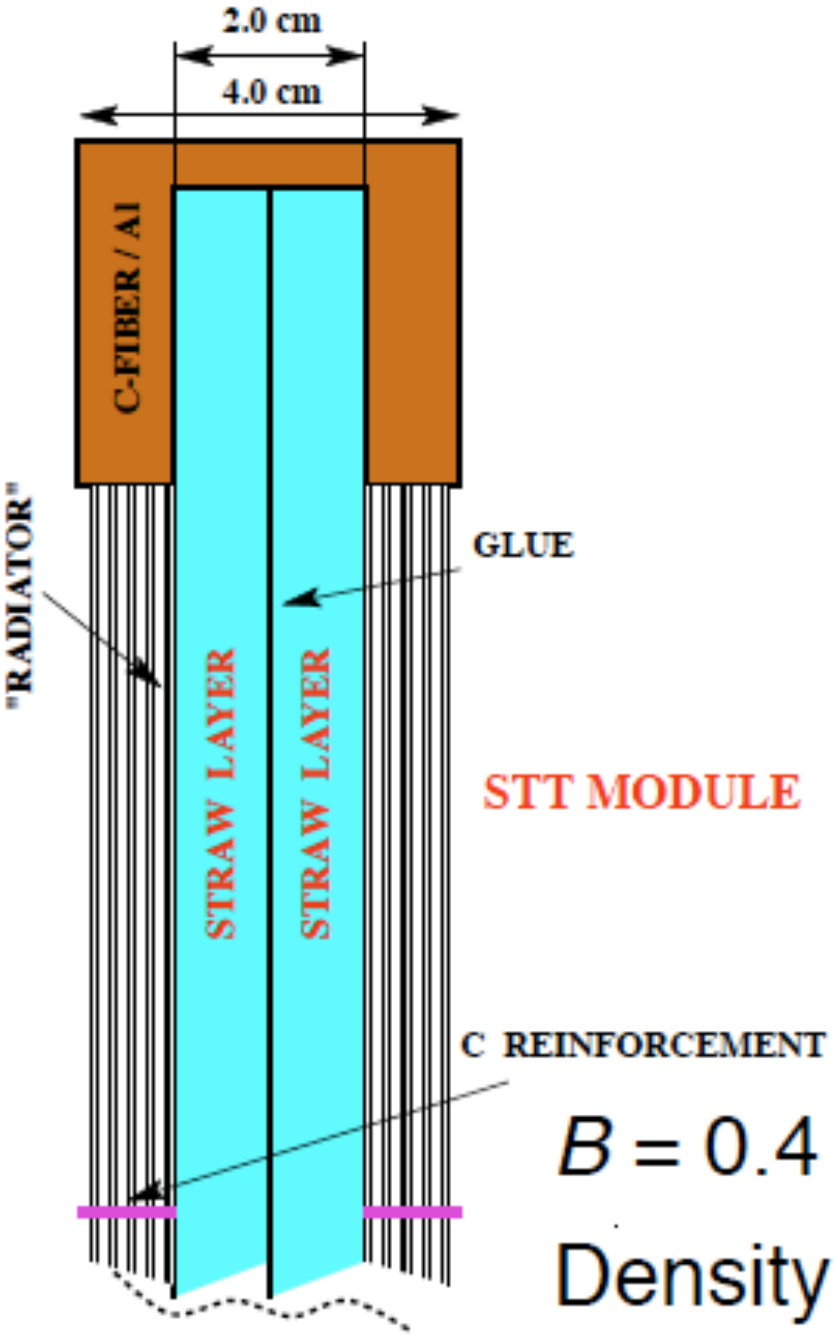
- *Search for weakly interacting massive particles with electronic, muonic, and hadronic decay modes with unprecedented sensitivity.*

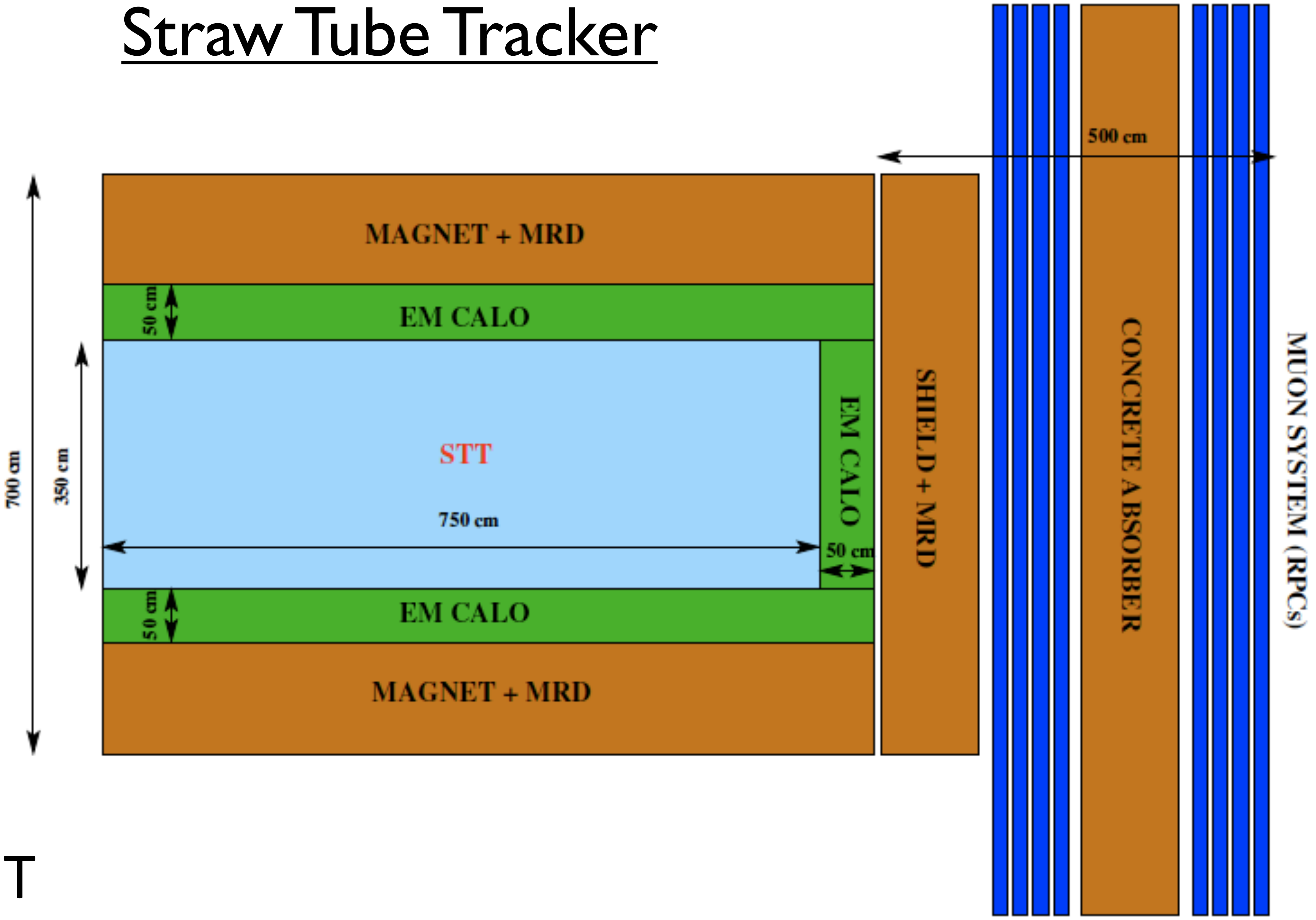
Scintillator Tracker



Upstream Muon Catcher

Straw Tube Tracker





$B = 0.4$ T

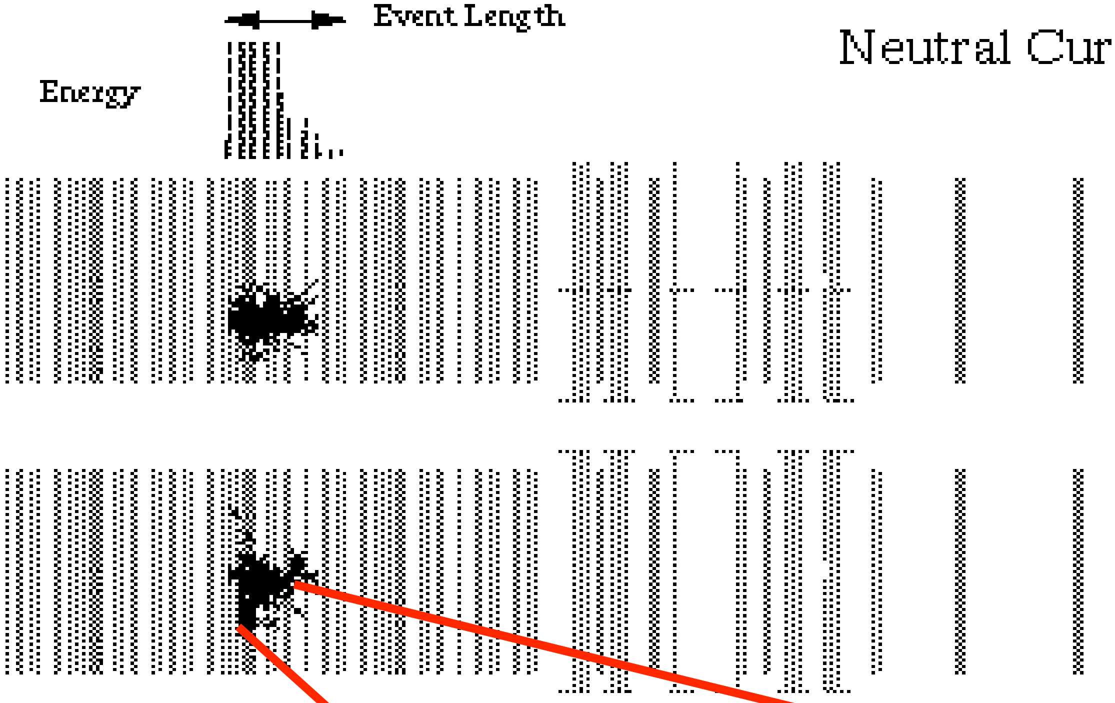
Density = 0.1 g/cm3, 85% in the radiator foils.

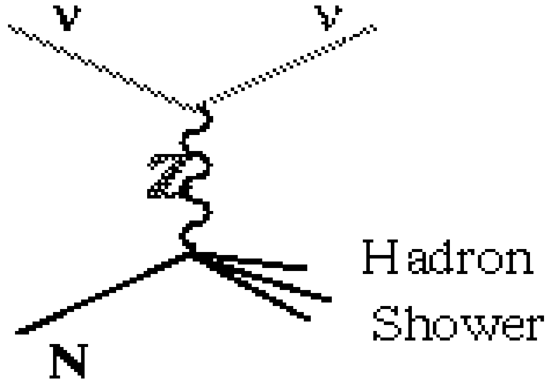
Transition Radiation ➼ Electron ID ⇒ γ (w. Kinematics)

dE/dx ➼ Proton, π, K ID

Magnet/Muon Detector ➼ μ

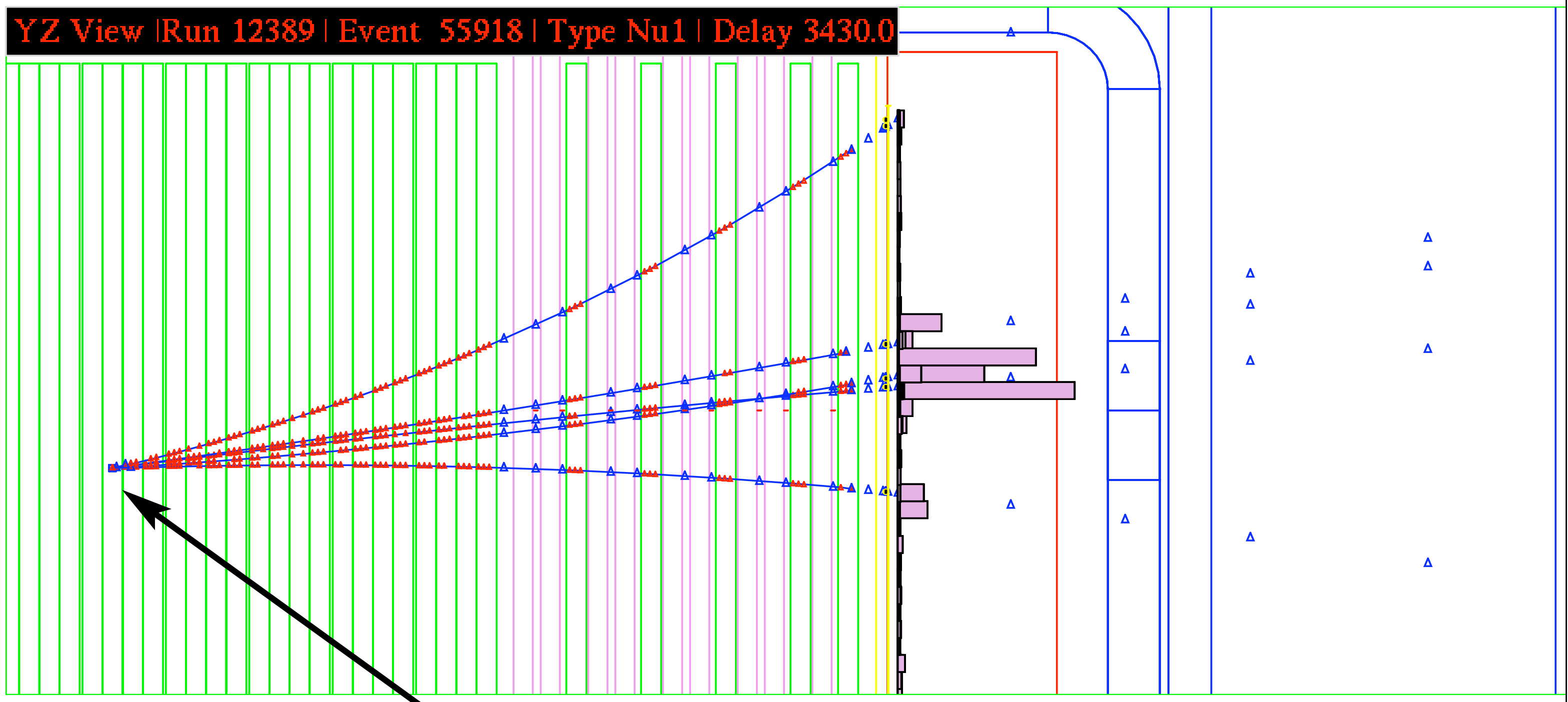
Neutral Current Event





MASSIVE CALO
(NuTeV)

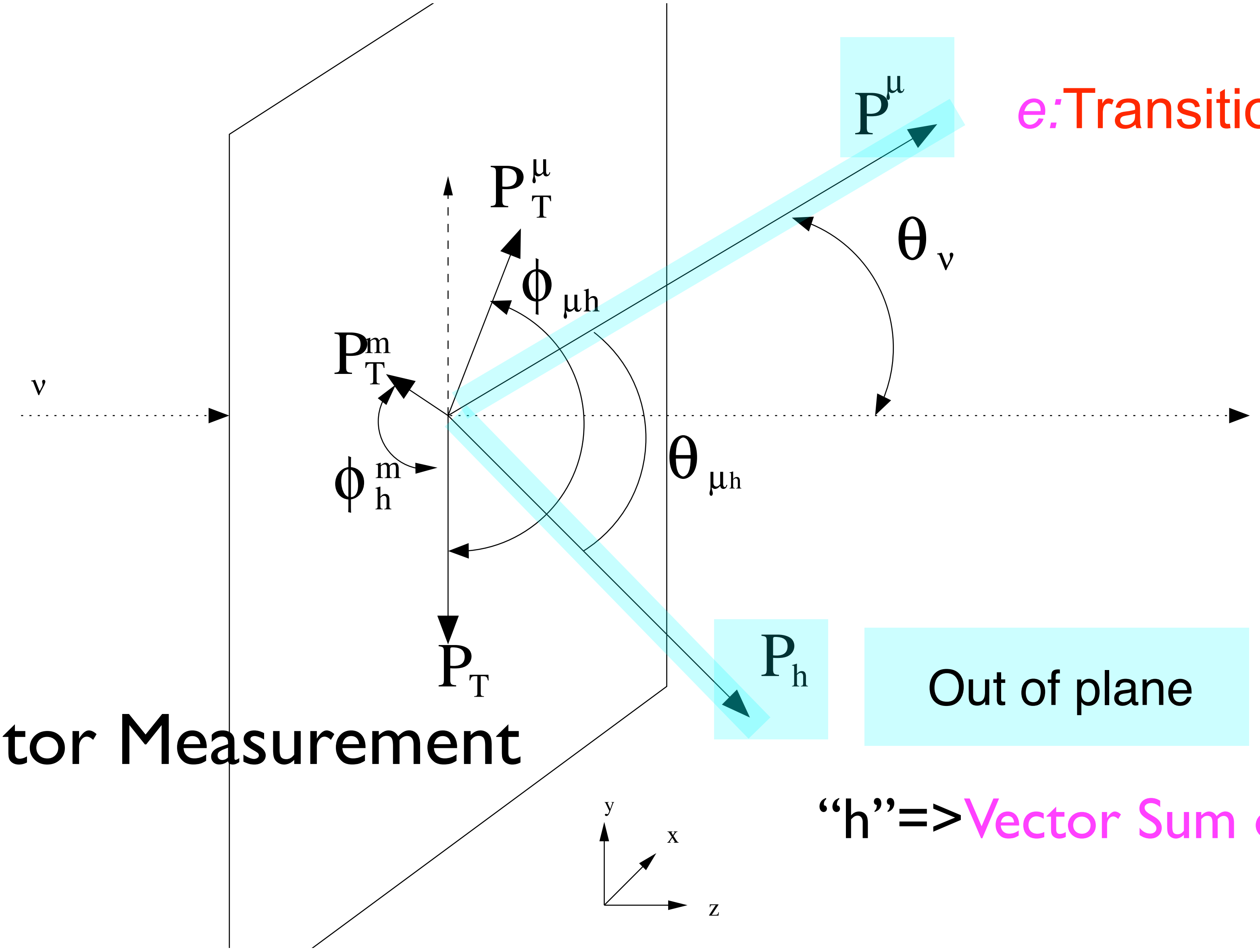
PRECISE TRACKER
(NOMAD)



Missing transverse momentum

HiResMν : order of mag. higher segmentation

Kinematics in HiResMnu



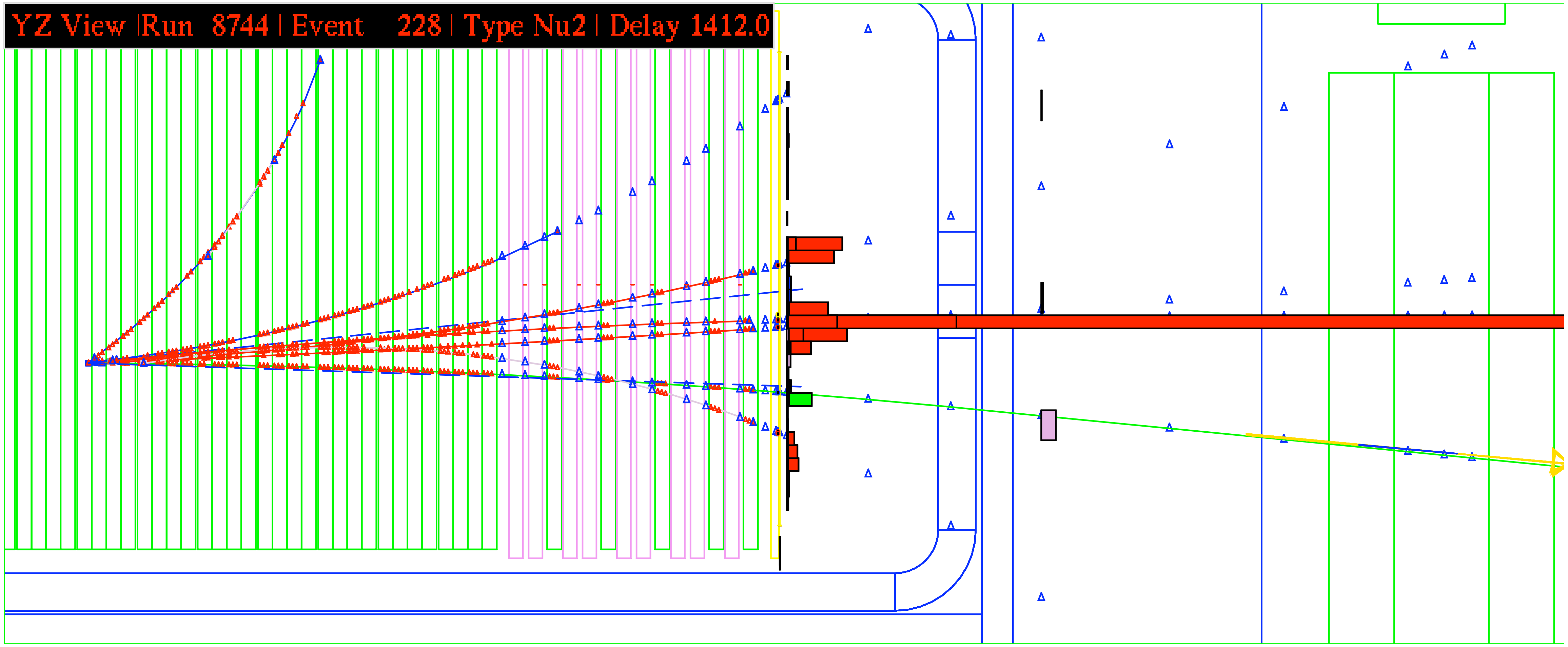
*e:*Transition Radiation

Out of plane

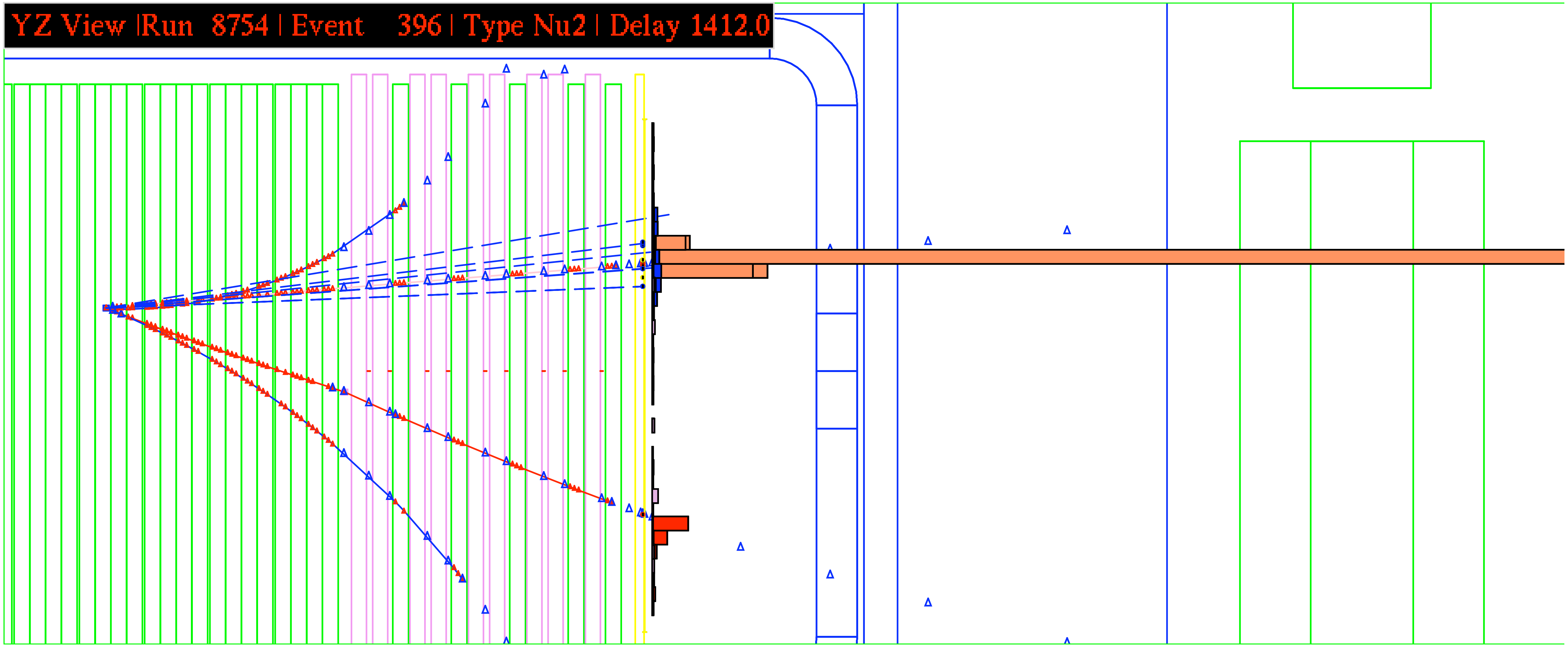
Pt-Vector Measurement

“h”=>Vector Sum of Tracks

A ν_μ CC candidate in NOMAD



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



NOMAD e- Sample

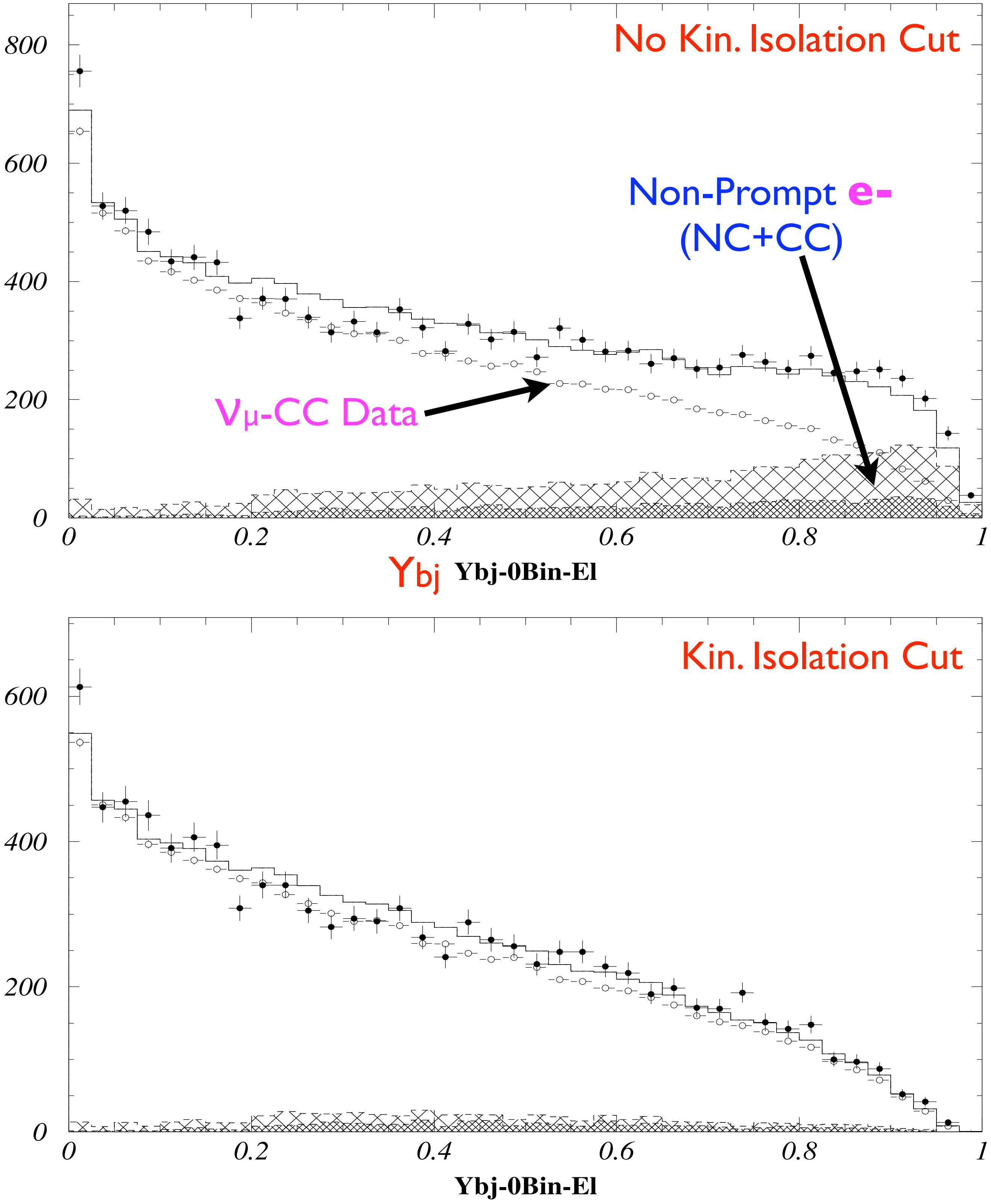


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Figure 20: Distribution of y_{bj} for e$^-$ (solid dots), μ^- (open dots), ν_μNC (big hatch) and CC (small hatch) background after scaling. The combined (histo) μ^- plus background agrees with the distribution of e$^-$ data. The bottom plot is the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

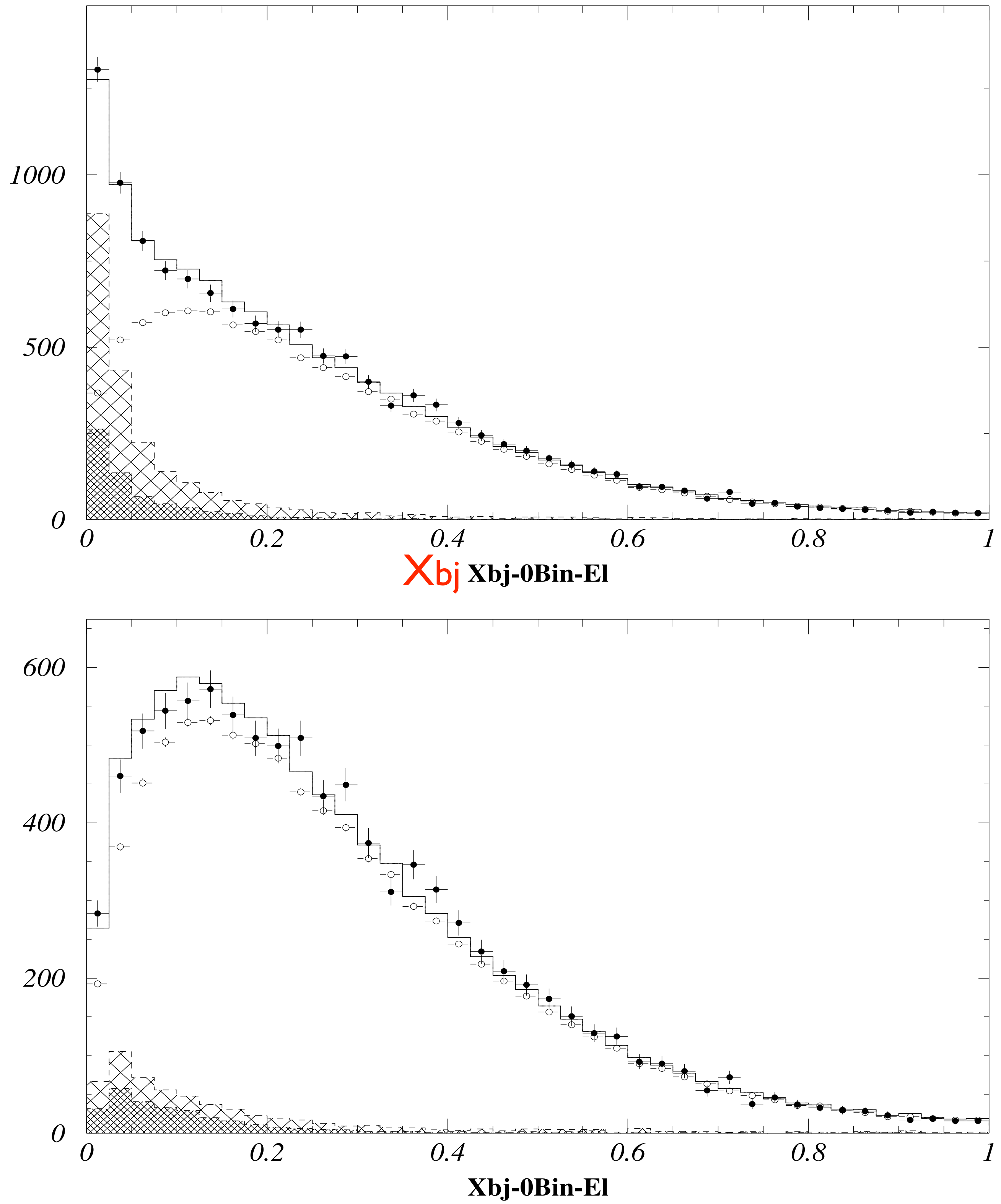

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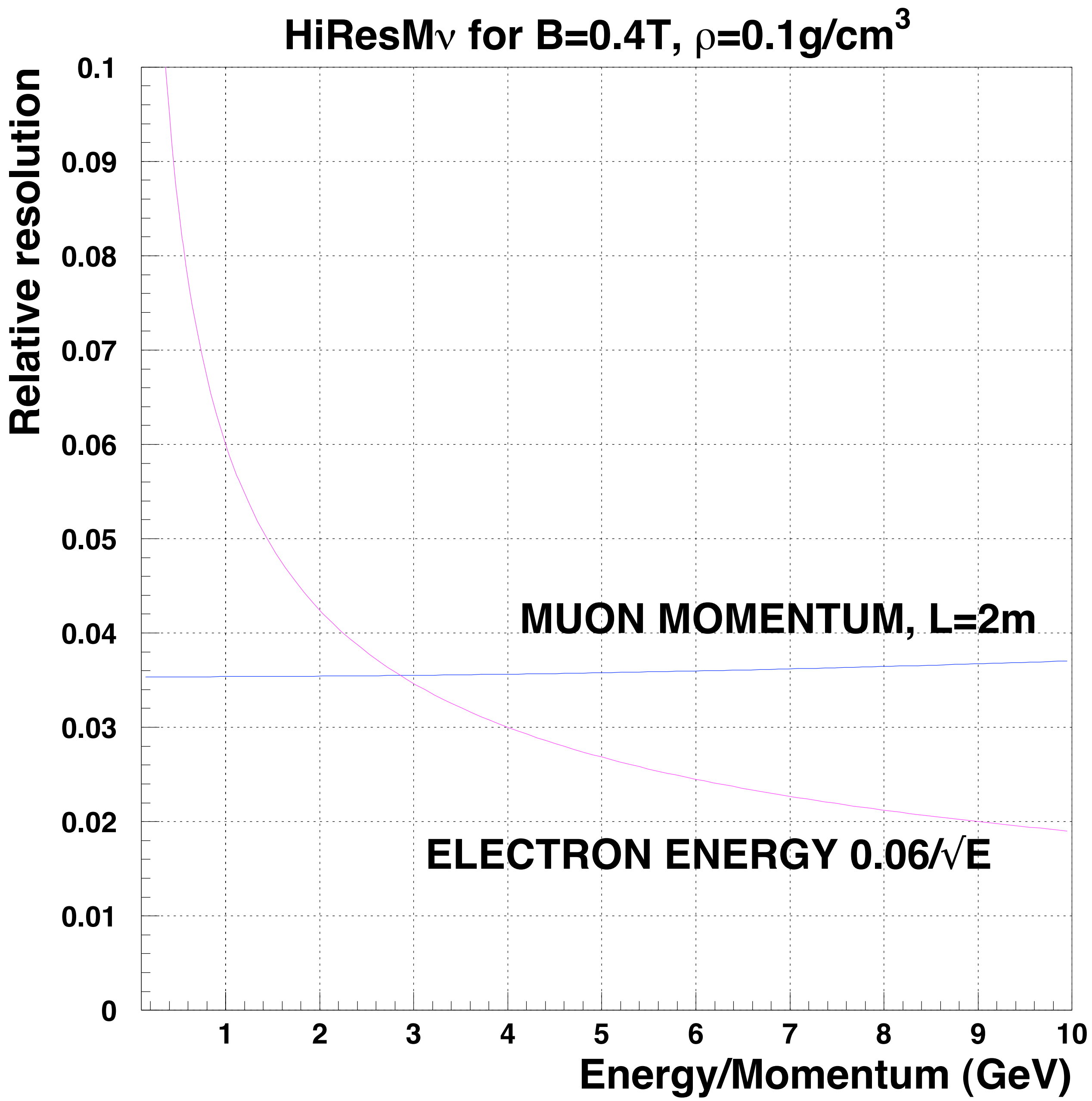
Figure 19: Distribution of x_{bj} for e$^-$ (solid dots), μ^- (open dots), ν_μNC (big hatch) and CC (small hatch) background after scaling. The combined (histo) μ^- plus background agrees with the distribution of e$^-$ data. The bottom plot is the same as the top but includes kinematic

Resolutions in HiResMν

- $\rho \simeq$ 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%



Requirements for the LBNE Fine-Grained Tracker

- Measure ν_μ- & ν_e-induced CC & NC interactions in $0.5 \le E_\nu \le 20$ GeV

- π_0 : Reconstruct with high purity & efficiency in ν-induced CC & NC
  (Largest background to ν_e-appearance)

- $\pi_{+/-}$: Measure precisely in ν-induced CC & NC
  (Largest background to ν_μ-disappearance)

- γ: Reconstruct with high purity & efficiency in ν-induced CC & NC ➢ `Dirt'-Events
  (background to ν_e-appearance)

- QE: Reconstruct with high purity & efficiency: Proton-reconstruction is the key
  ➢ A constraint on Flux & E_ν-Scale

- Distinguish ν from Anti-ν_μ

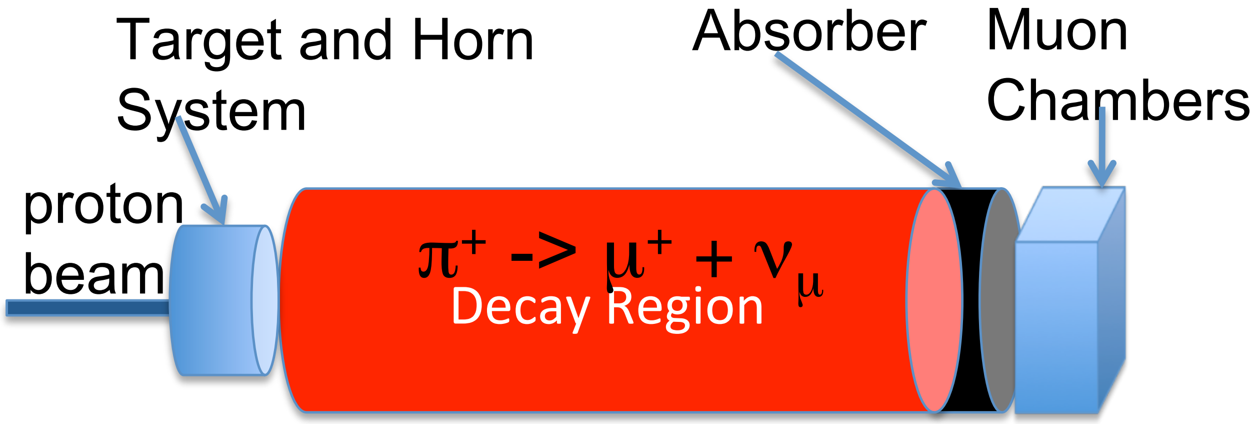
Requirements for $\nu_e/\bar{\nu}_e$ Appearance Background Rejection

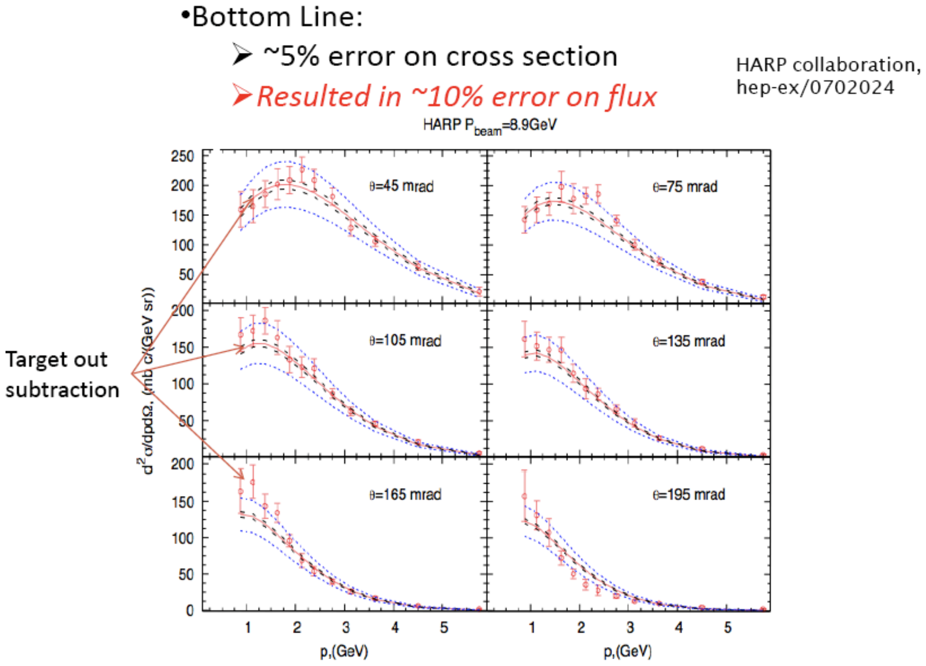
Main Backgrounds:

1. Intrinsic $\nu_e/\bar{\nu}_e$ from muon & kaon decay
2. NC π^0
3. NC γ
4. CC $\nu_\mu/\bar{\nu}_\mu$
5. NC DIS
6. External Events ("Dirt" Events)

We must be able to both measure & reject these backgrounds! (The neutrino flux is not the same at the near and far locations.)

Beamline Measurements: Neutrino fluxes, neutrino beam monitoring





- Bottom Line:
  - ~5% error on cross section
  - *Resulted in ~10% error on flux*

HARP collaboration, hep-ex/0702024

Measurements to constrain the ν fluxes

- In-situ measurement
  - Particle fluxes extreme: > 10^8/cm^2-spill
  - High precision unlikely
  - Currently, in-situ hadron measurements not being pursued
- External measurements ⇐ WG4
  - HARP (above π^+ production for MiniBooNE), MIPP, NA-61
  - Used by K2K, MiniBooNE, T2K
  - Make precise hadron production measurements of target and horn materials
  - Input to simulations
- Muon measurements
  - Threshold Cherenkov Detector
  - Michel Decay Detector

Measurements to monitor the ν beam

- Muon Ionization Chambers
- Solid State Detectors

Flux: … Always the Flux

insitu Absolute Flux

- **Inverse Muon Decay:** $\nu_\mu + e^- \twoheadrightarrow \nu_e + \mu^-$ {Single, forward μ^-}
  - Elegant, Simple: but steep, though calculable, threshold $E_\nu \geq 11$ GeV, Avg.$E_\nu \simeq 25$ GeV
  - Systematic Advantage of HiResMnu lies in avoiding the error that the CCFR or CHARM-II incurred in extrapolating the background to the signal $\zeta = P_e(1-\cos\Theta_e) \leq \mathrm{Cut}$

- **ν-Electron Elastic Events:** $\nu_x + e^- \twoheadrightarrow \nu_x + e^-$ {Single, forward e^-}
  - Focus on $\nu_x e$-NC: Experimentally the most challenging
    - Using Collider measurements, the Weak Mixing Angle (0.238) at Q~0.1 GeV, known to ≤1% precision

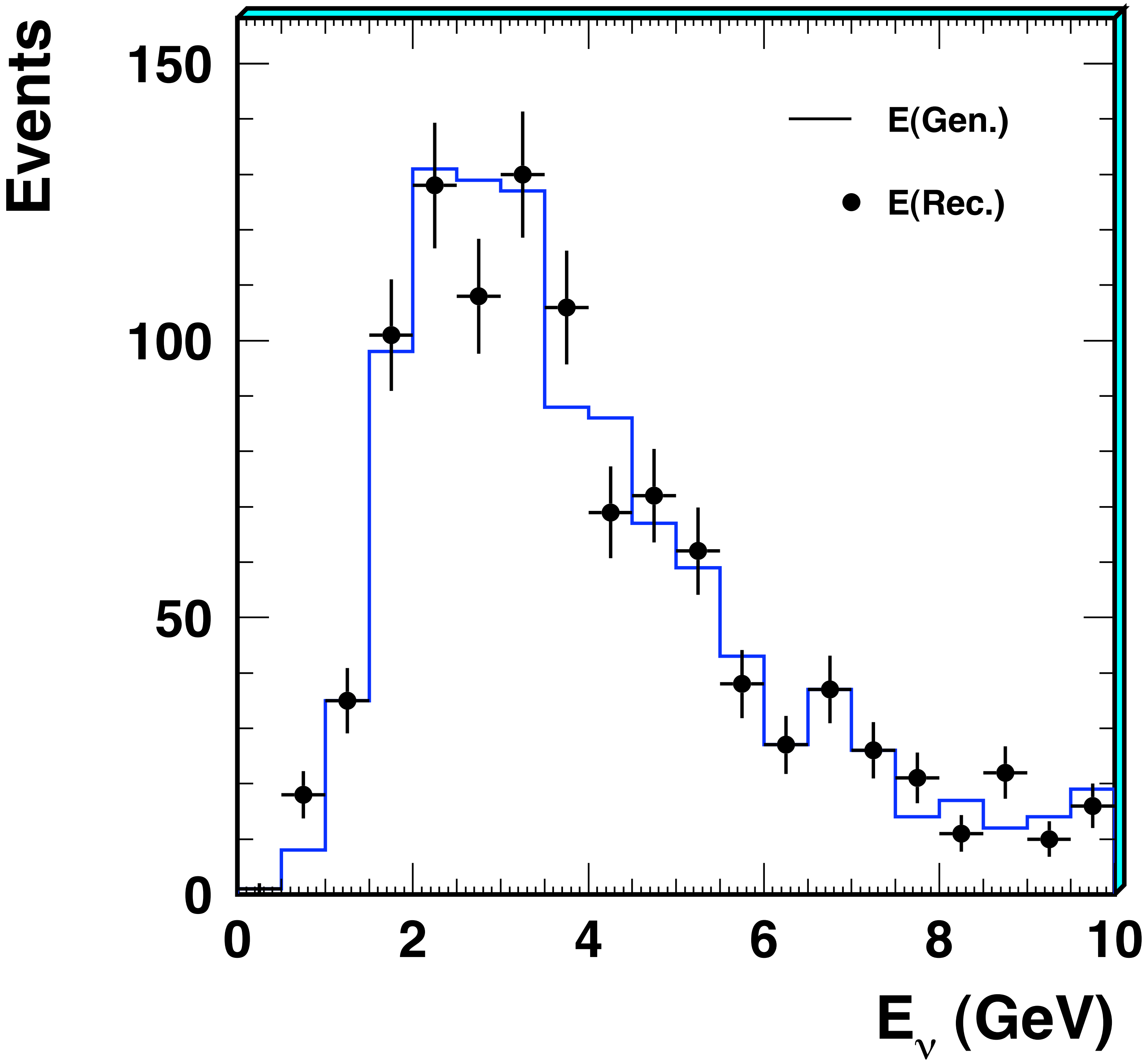
$\Rightarrow \sigma(\nu_x e\text{-NC})$ known $\Rightarrow$ ***Absolute-ϕ***$(\nu_\mu + \nu_\mu\text{-Bar} + \nu_e + \nu_e\text{-Bar})$-Flux

Note: ≥90% is ν_μ

- **Intercept of $d\sigma/dQ^{**}2$ of ν_μ-QE in D:** $\nu_\mu + n \twoheadrightarrow \mu^- + p$ {Gerry Garvey}

Absolute Flux using ν-e Elastic Scattering

- Shape of Enu using (Ee, θe):
- The precision on relative ν-flux (shape) is worse than in that determined using Low-ν0 technique



1<Enu<4 => 1000 events
700kW; 3Yr Nu-Run

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 $f(\nu^0/E_\nu) \rightarrow 1$ *for* $\nu^0 \rightarrow 0$.

$\Longrightarrow$ *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*

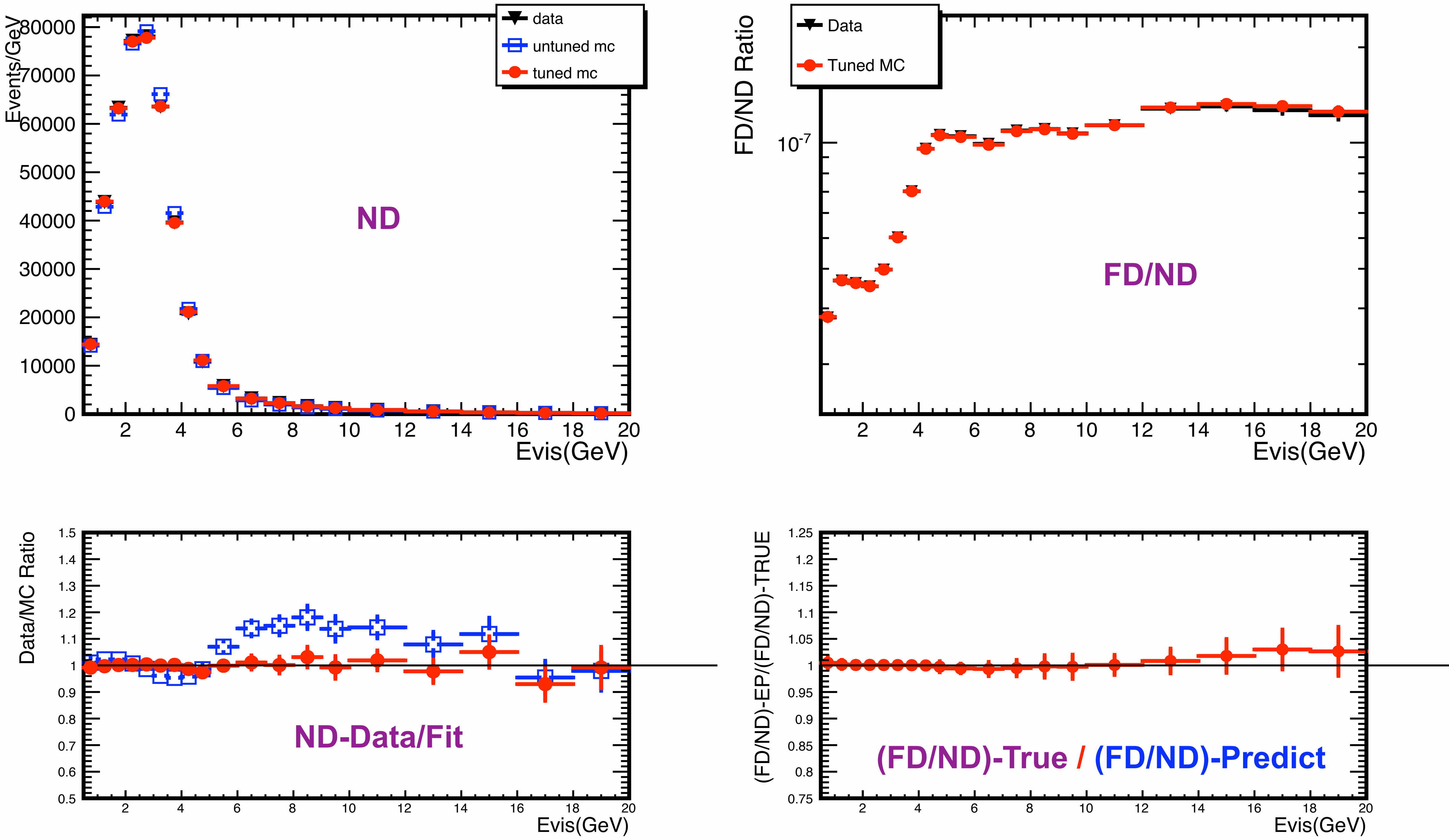
$$\frac{d^2\sigma}{dx_F dP_T^2} = f(x_F) g(P_T) h(x_F, P_T)$$

- *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*

ν_μ, **Low-Nu0 Fit, ND at 500m**

Relative $\nu\mu$-Flux Measurement using Low-ν0 @ LBNE



Systematic-Errors in Low-ν0 Relative Flux: νμ & Anti-νμ

- Variation in ν0-cut
- Variation in ν0-correction
- Systematic shift in Ehad-scale
- Vary σ(QE) ±10%
- Vary σ(Res) ±10%
- Vary σ(DIS) ±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

⇒ Revisit these (?) & Investigate ND @ 500m

REDUNDANCY: ν_e & $\bar{\nu}_e$

- *Direct measurement of* $\boxed{\nu_e \text{ AND } \bar{\nu}_e}$ *spectra in the Near Detector provides a powerful cross-check of the flux predictions:*

$$\nu_e \equiv \mu^+(\pi^+ \rightarrow \nu_\mu) \oplus K^+(\rightarrow \nu_\mu) \oplus K_L^0$$

$$\bar{\nu}_e \equiv \mu^-(\pi^- \rightarrow \bar{\nu}_\mu) \oplus K^-(\rightarrow \bar{\nu}_\mu) \oplus K_L^0$$

- *In the NuMI beam ν_e and $\bar{\nu}_e$ independent flux predictions:*

$$\begin{aligned} \mu &\Longrightarrow Well\ \ constrained \\ K^\pm &\Longrightarrow Need\ \frac{K^+}{\pi^+}\&\frac{K^-}{\pi^-}\ \ MIPP \\ K_L^0 &\Longrightarrow MIPP\ \ (NOMAD,\ \ HiResM\nu) \end{aligned}$$

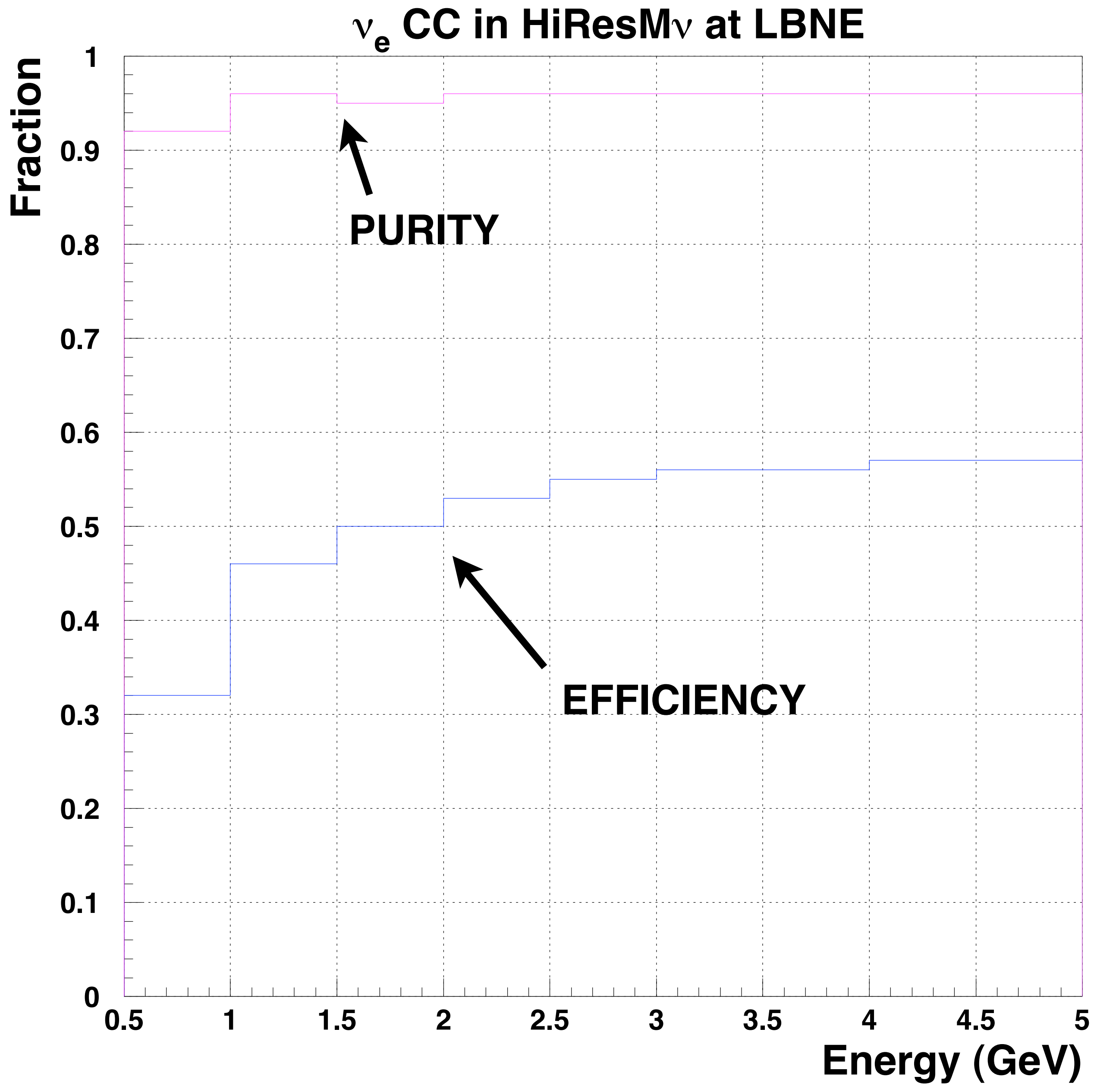
STT: Ok, LAr NO, Scint. NO

REQUIREMENTS FROM EXTERNAL MEASUREMENTS

- *We need the following external measurements from p-production experiments (e.g. MIPP at Fermilab):*
  - K^+/π^+ *as a function of* $P(2 \leq P \leq 20\ GeV)$ *&* $P_T(\leq 0.4\ GeV)$ *of* K^+ *and* π^+
  - K^-/π^- *as a function of* $P(2 \leq P \leq 20\ GeV)$ *&* $P_T(\leq 0.4\ GeV)$ *of* K^- *and* π^-
  - K^0/K^+ *ratio*

- *We need these measurements off:*
  - *LBNE neutrino target;*
  - *Thin/Thick Al, Cu, etc. targets that compose horn/beam-elements;*
  - *Air (N)*

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

νe-CC Sensitivity *HiResMν*

- Leading Lepton Identification (e-ID):

Eff(**ν**e-CC) = 61%

Purity = 96% (⟹ 4% of selected events are non-**ν**e-CC: π0-induced)

νμ-CC reduced by 6*10**(-5)

NC reduced by 10**(-3)

- Kinematic Isolation ➢ reduce non-prompt (NC) background

νμ-CC & NC reduced by an additional factor of 4

Eff(**ν**e-CC) ≃ 55%

Purity ≃99% (⟹ 1% of selected events are non-**ν**e-CC)

- ***VeBar-CC Sensitivity:***

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

MEASUREMENT OF THE RATIO $\mathcal{R}_{e\mu}$ ⇐Search/Impact of High-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*:*

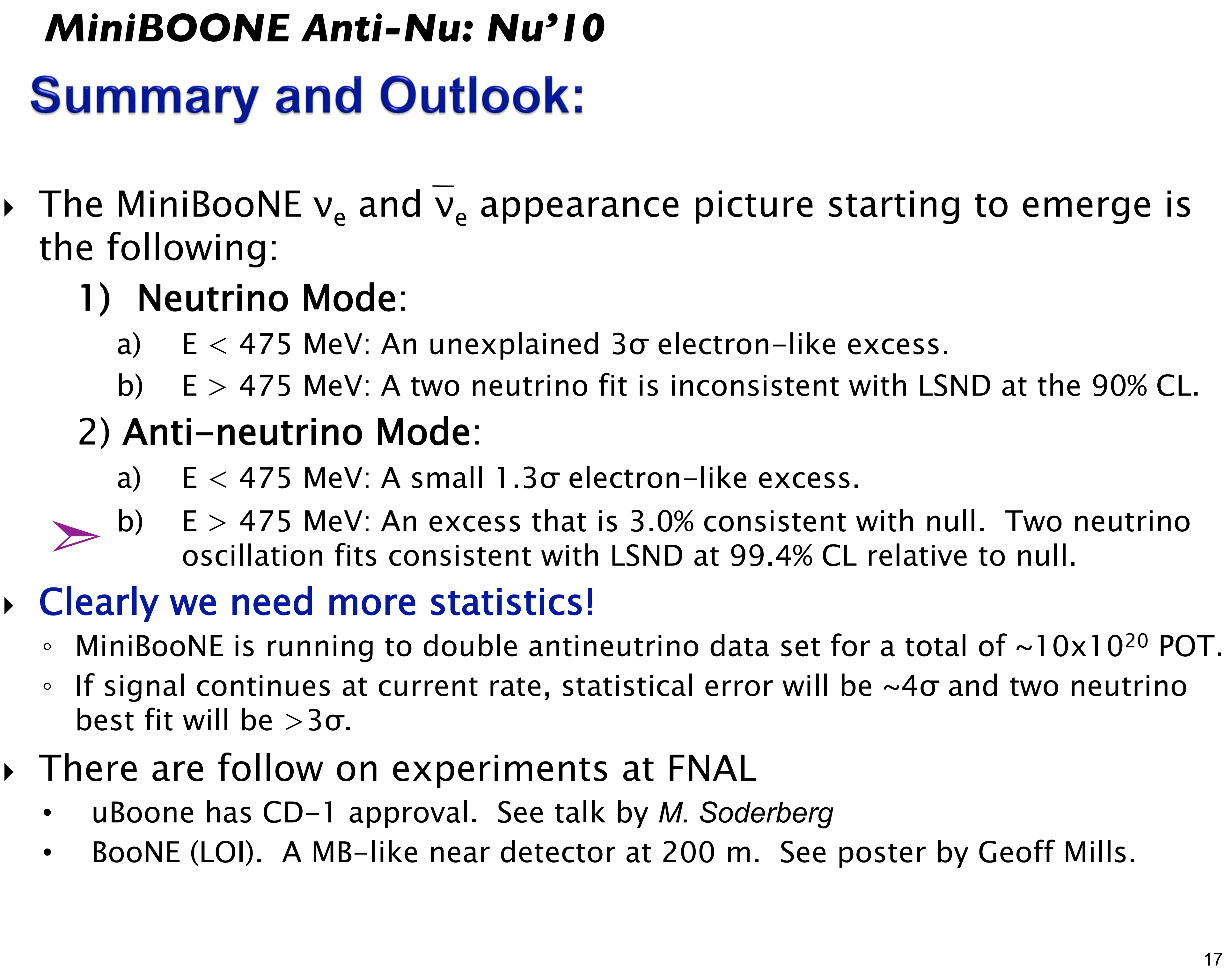
$$\mathcal{R}_{e\mu}(E\nu) \equiv \frac{\#\ of\ \nu_e N \rightarrow e^- X}{\#\ of\ \nu_\mu N \rightarrow \mu^- X}(E\nu)$$

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

- *Compare the measured ratios* $\mathcal{R}_{e\mu}($ Eν $)$ *and* $\bar{\mathcal{R}}_{e\mu}($ Eν $)$ *with the predictions from the low-*ν_0 *flux determination assuming no oscillations* ⇐ Need External K+/π+, K-/π0-, K0L/K+

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

At yesterday's discussion:...



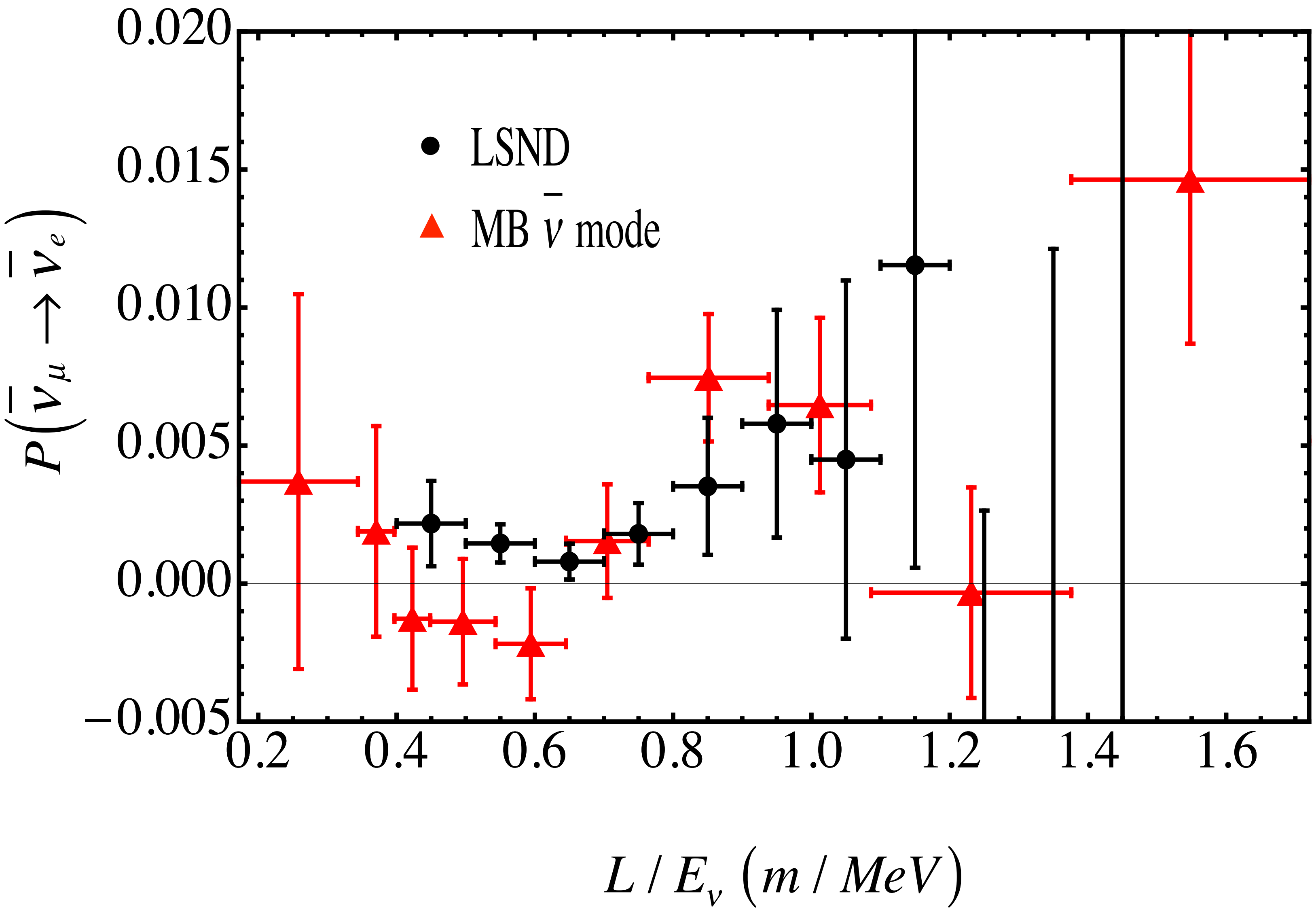
MiniBOONE Anti-Nu: Nu'10

Summary and Outlook:

- The MiniBooNE ν_e and $\bar{\nu}_e$ appearance picture starting to emerge is the following:
  1) **Neutrino Mode**:
     a) E < 475 MeV: An unexplained 3σ electron-like excess.
     b) E > 475 MeV: A two neutrino fit is inconsistent with LSND at the 90% CL.
  2) **Anti-neutrino Mode**:
     a) E < 475 MeV: A small 1.3σ electron-like excess.
     b) E > 475 MeV: An excess that is 3.0% consistent with null. Two neutrino oscillation fits consistent with LSND at 99.4% CL relative to null.
- Clearly we need more statistics!
  - MiniBooNE is running to double antineutrino data set for a total of $\sim 10\times10^{20}$ POT.
  - If signal continues at current rate, statistical error will be $\sim 4\sigma$ and two neutrino best fit will be $>3\sigma$.
- There are follow on experiments at FNAL
  - uBoone has CD-1 approval. See talk by *M. Soderberg*
  - BooNE (LOI). A MB-like near detector at 200 m. See poster by Geoff Mills.

At yesterday's discussion...

MiniBOONE Anti-Nu: Nu'10



ν_μ-QE Sensitivity

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

- Key is 2-Track (μ, p) signature

- Parametrized Calculation: Nomad data as Calibration
  - Proton reconstruction: the critical issue
  - dE/dx in but not used in the analysis

QE Candidates in NOMAD

Figure 14: A ν_μ-QE candidate in NOMAD

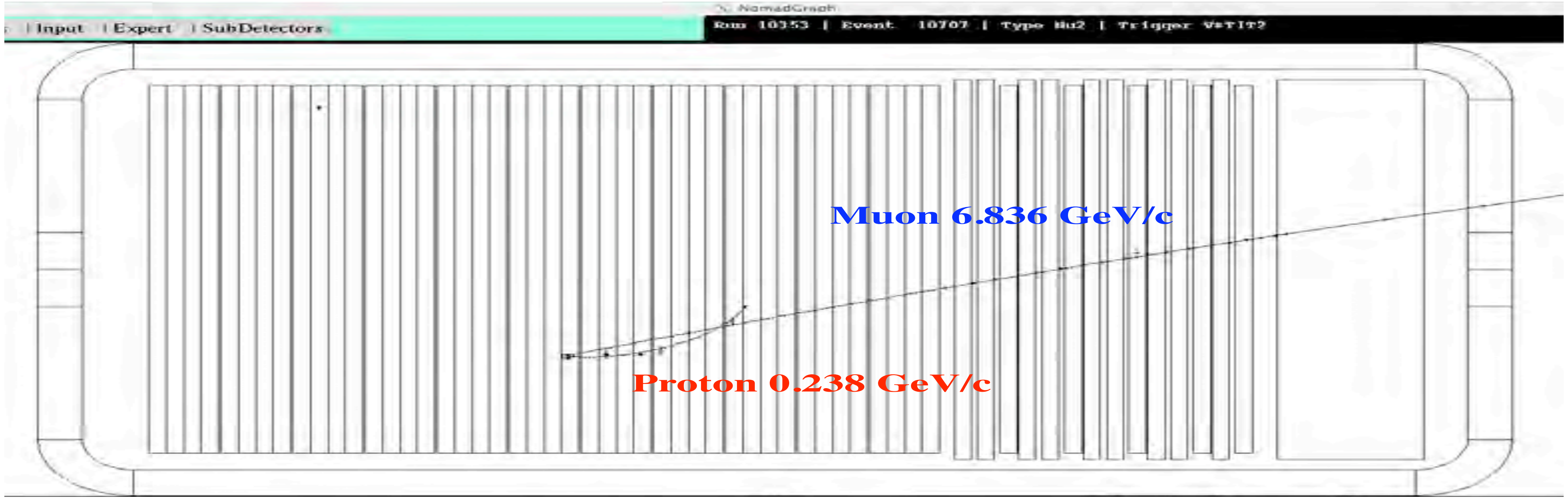
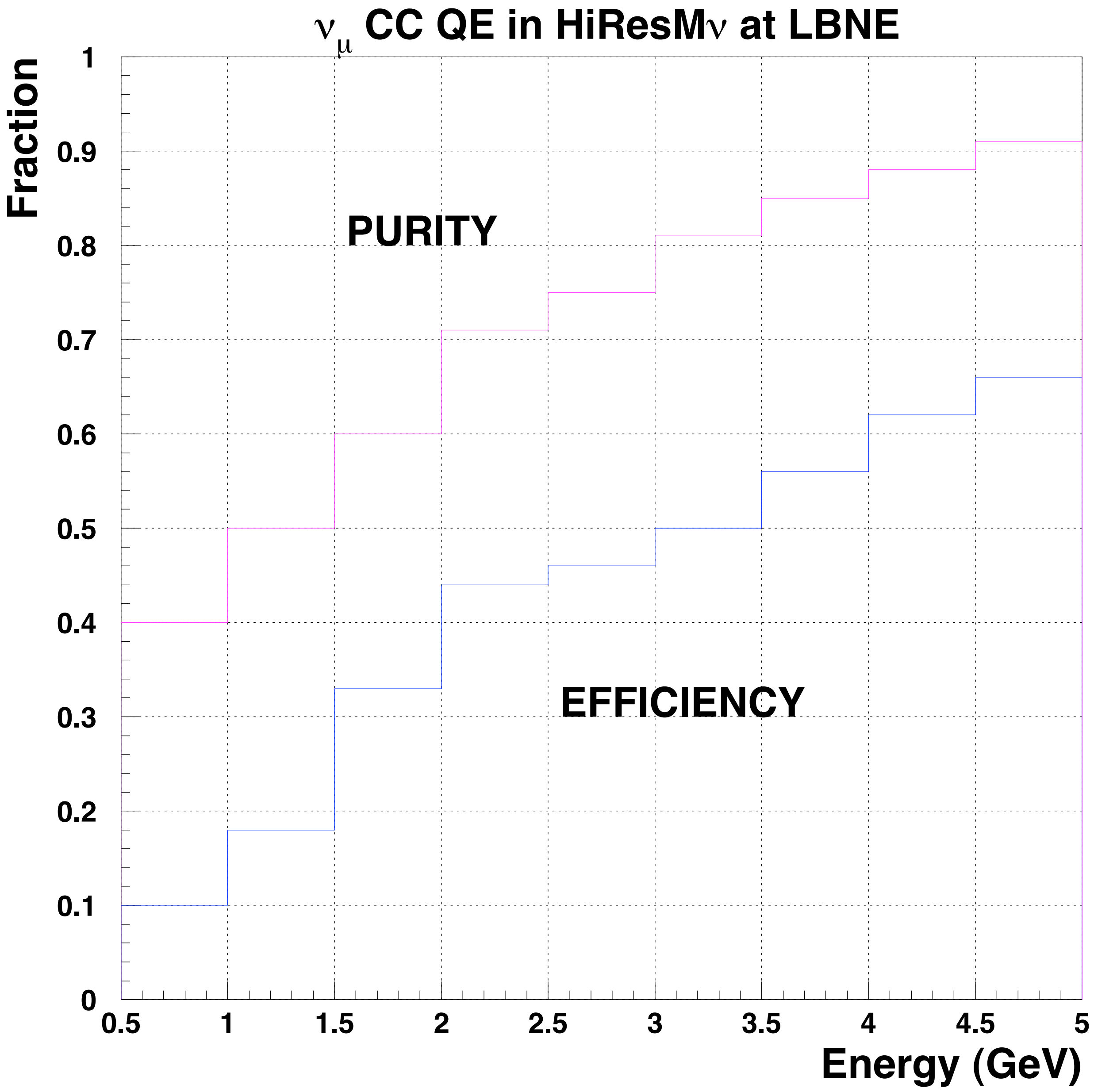


Figure 15: A ν_μ-QE candidate in NOMAD

RECONSTRUCTION OF CC QUASI-ELASTIC INTERACTIONS



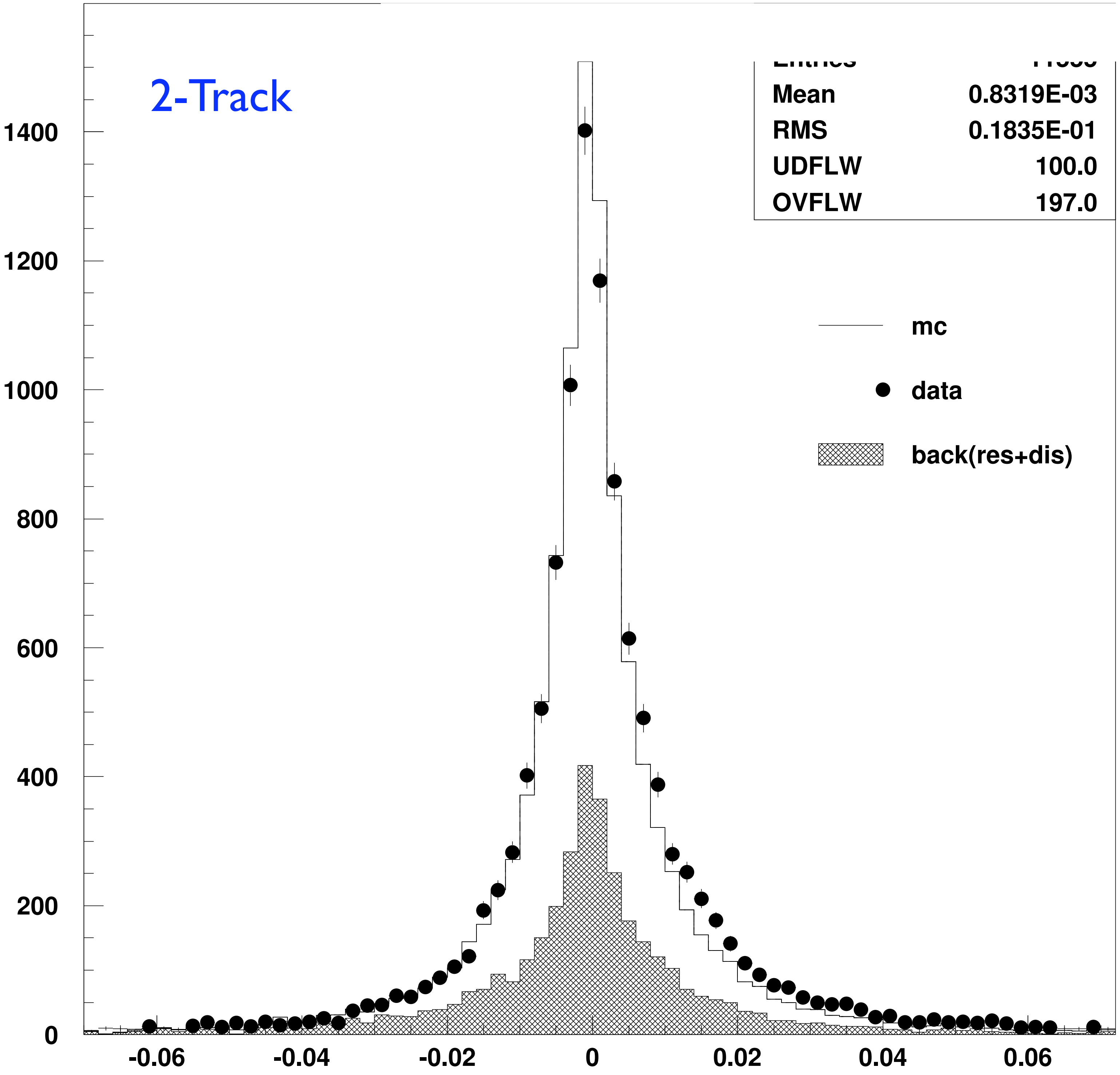
- ✦ *Protons easily identified by the large dE/dx in STT & range*

  ⟹ *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*

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



{Evis(2-Trak) - Enu(1-Trk w. PFermi=0)} / [Evis(2-Trak)]

⇒ *constraint on* *Eν Scale*

Particle Multiplicity: ν-induced Hardon-jet

- 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

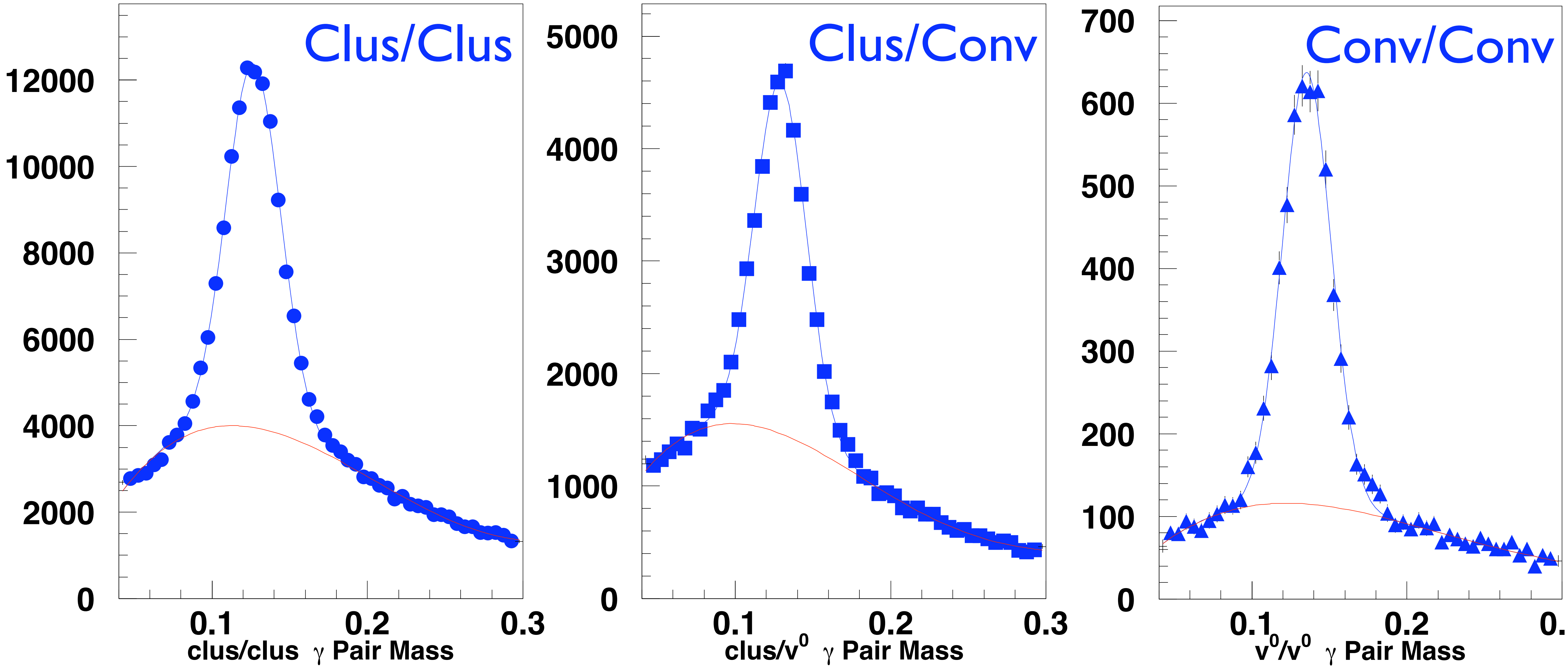
- π0's in NC ⇒ Largest backgrounds to (Anti)ν_e-appearance

- ≃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**

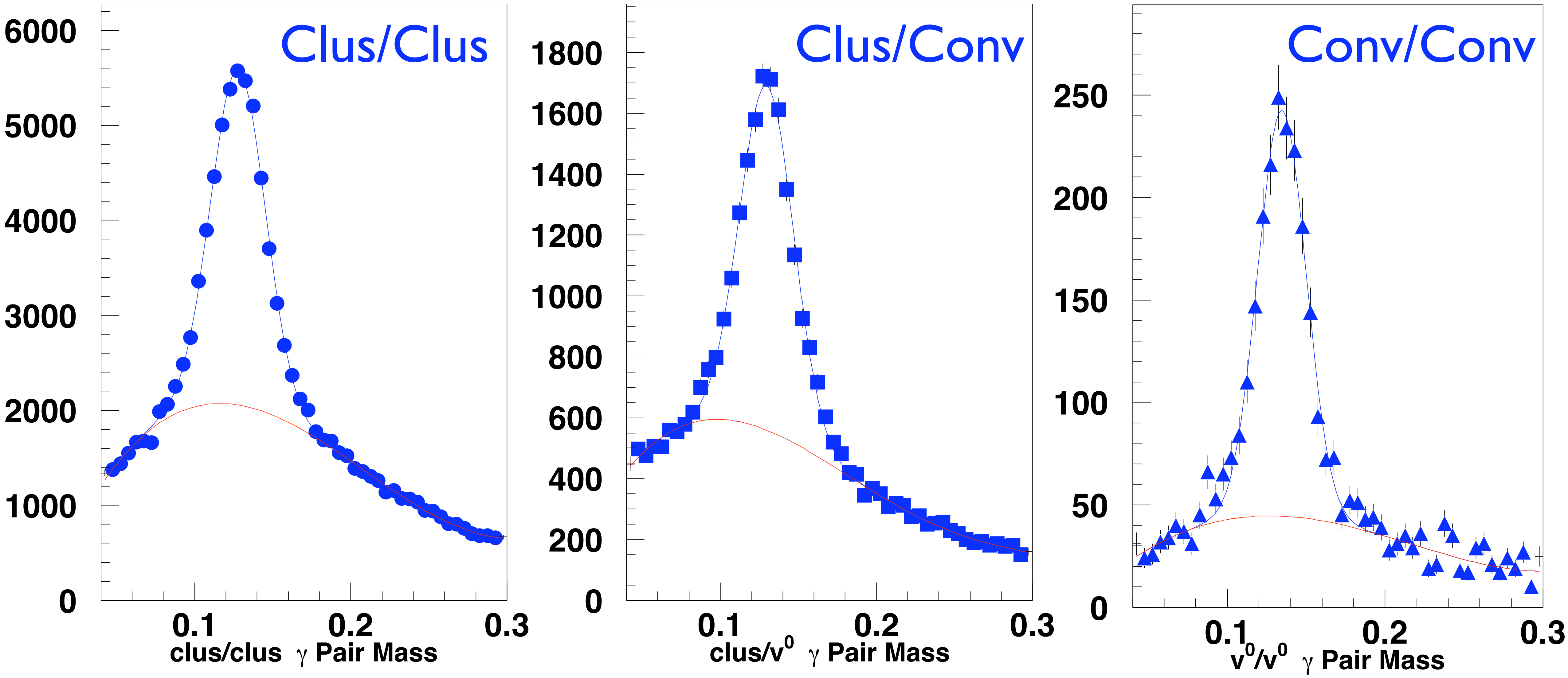
Reconstructed π^0 in CC interactions in NOMAD



Overall more than 100k reconstructed events. Three topologies:

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

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*

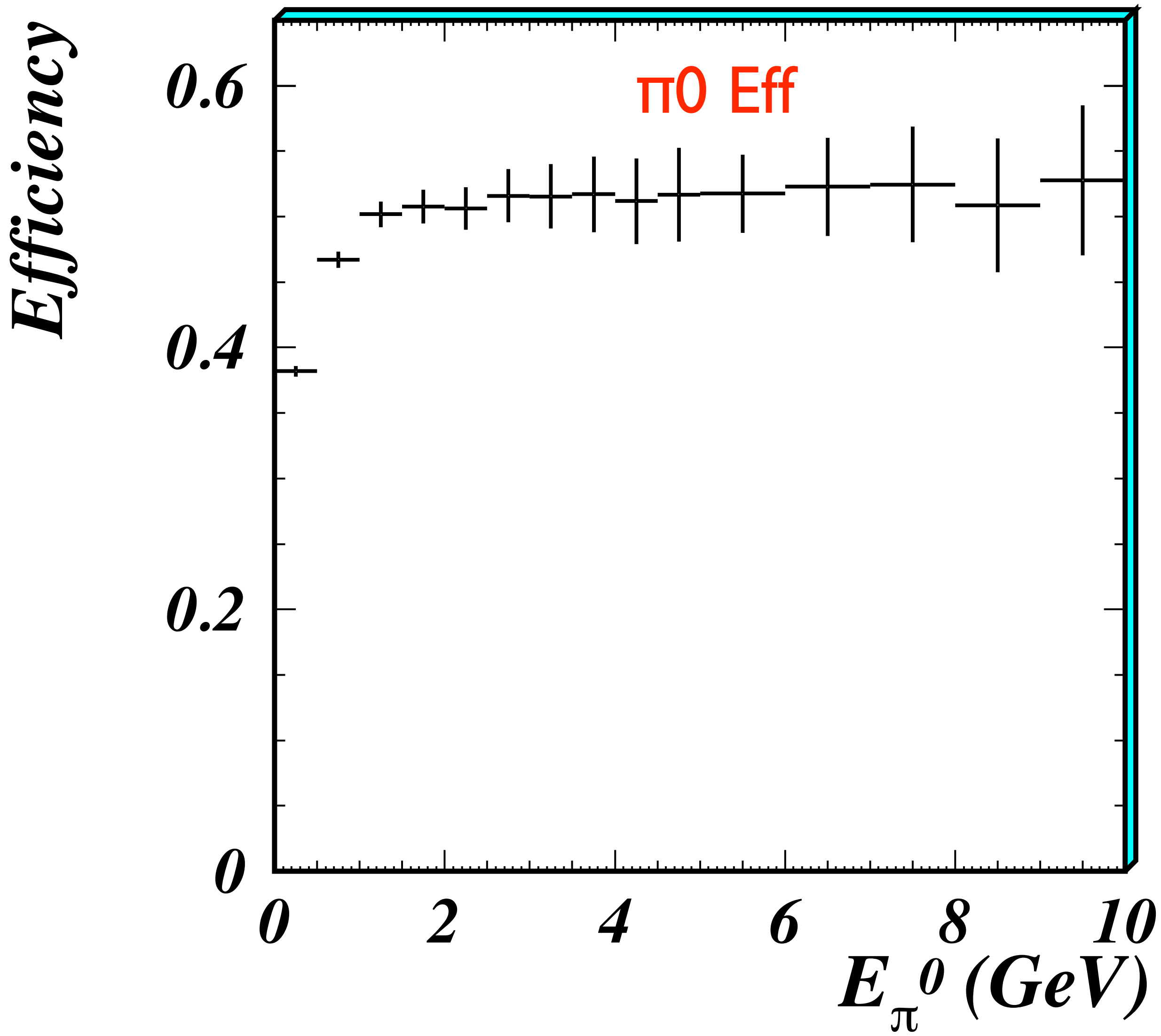
π0-Reconstruction

ཨོྃ Clean π0- and γ-signatures in STT

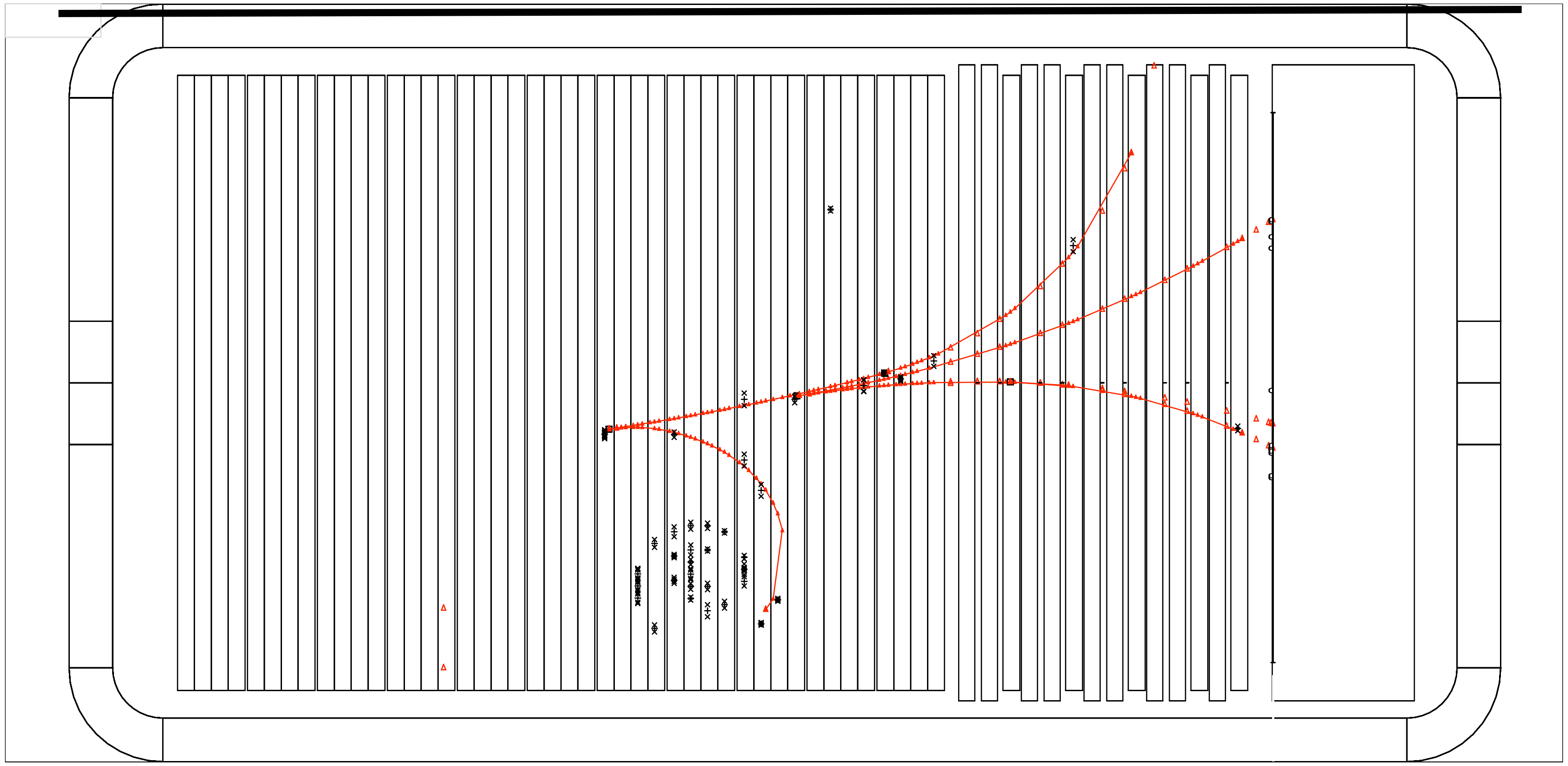
ཨོྃ ν-NC & CC ➽ π0 ➽ γγ
~50% of the γ ➽ e+e- will convert in the STT, away from the primary vertex.
We focus on these

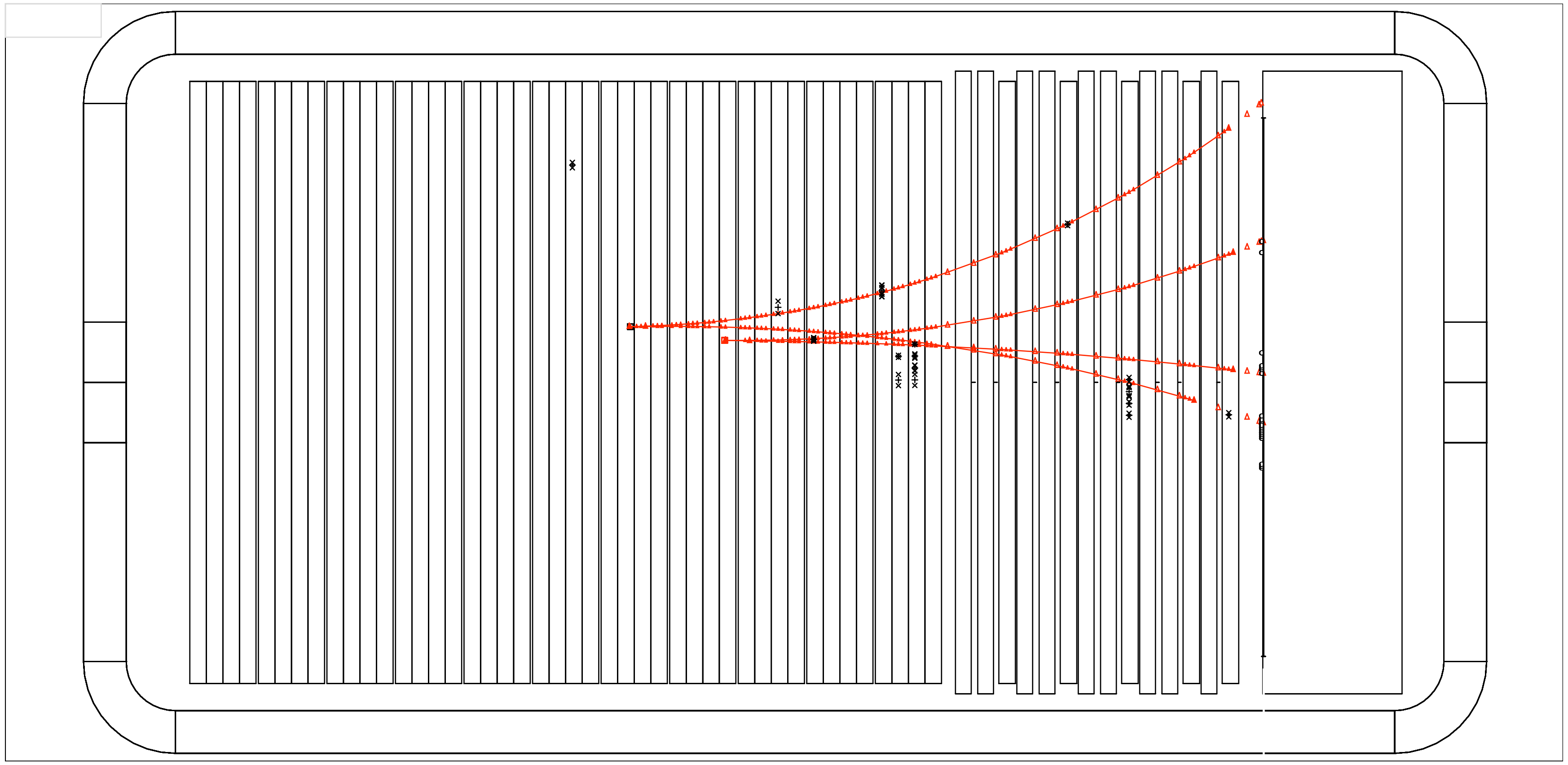
ཨོྃ γ-Identification:
✺ e-/e+ ID: TR
✺ Kinematic cut: Mass, Opening angle

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

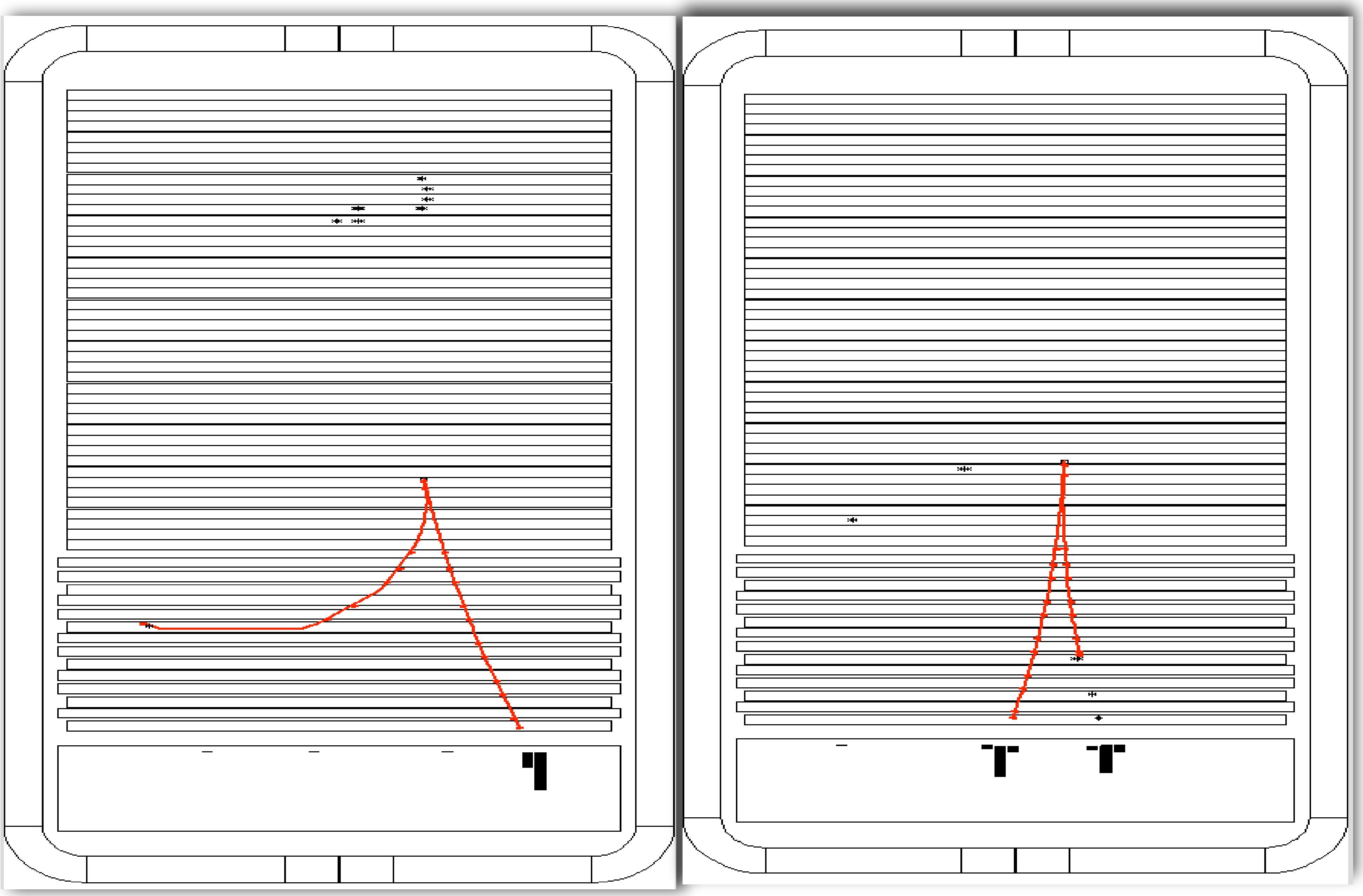


Coherent-π0 Candidates in NOMAD





Exclusive, single γ-Events in NOMAD

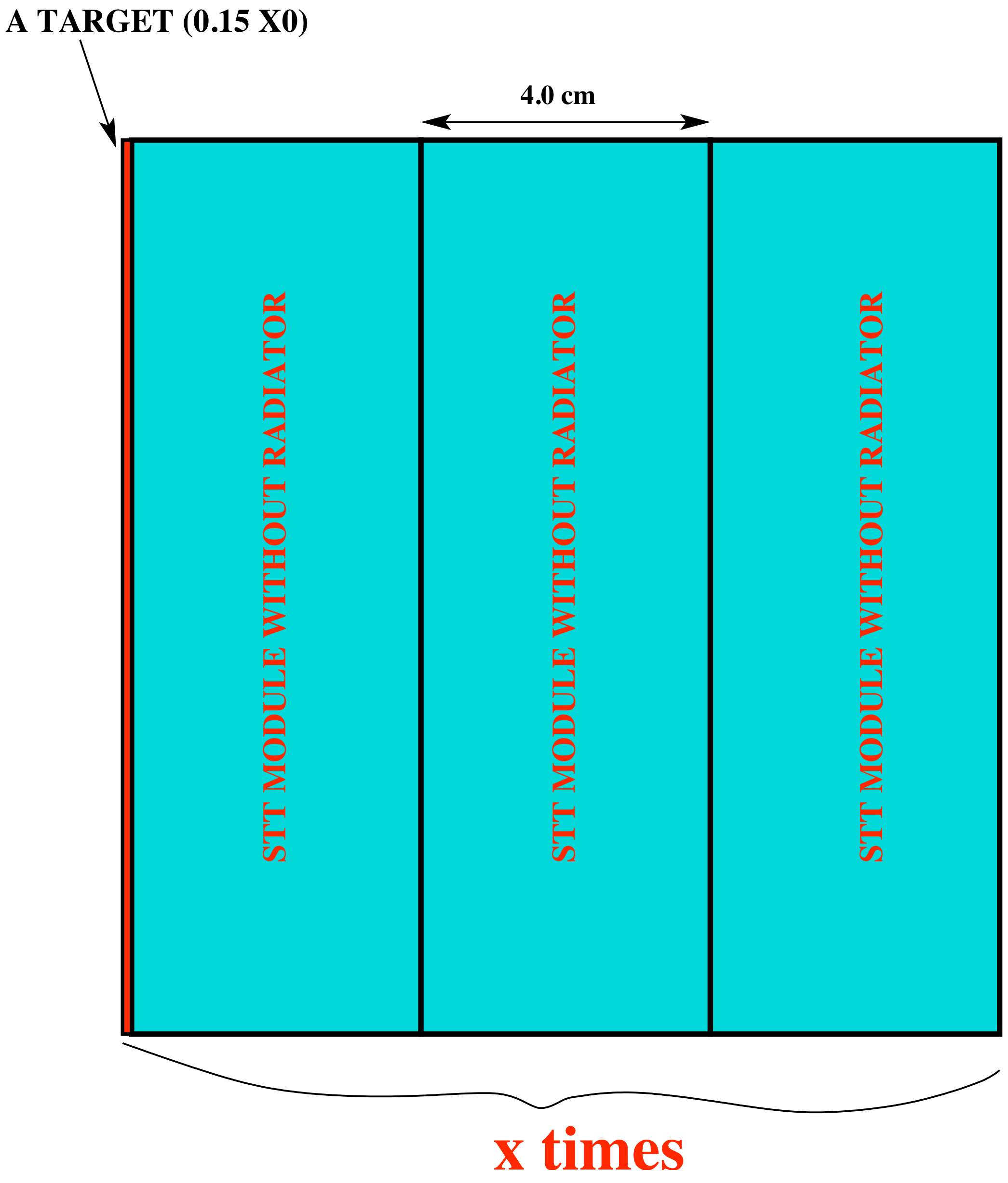


- ➢γ-Rec. in HiResMnu similar but much more efficient
- ➢Hermeticity of HiResMnu offers a powerful-veto against `Dirt'-events

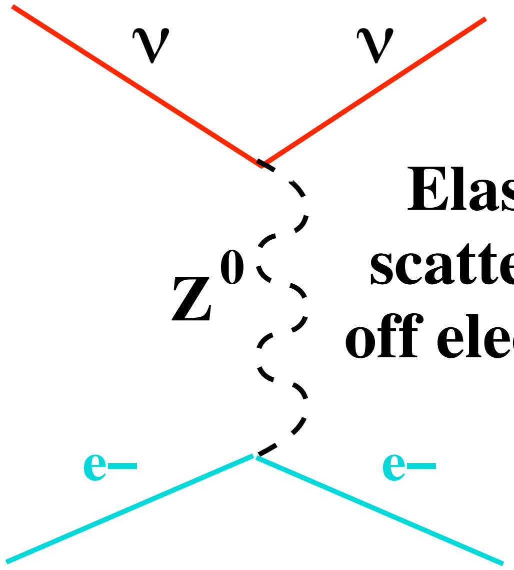
MEASURING NUCLEAR EFFECTS

H20 Target // D20 Target

- *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.).*



MEASUREMENT OF $\sin^2\theta_W$ FROM ν-e



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

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

Statistics available at LBNE with Project-X:

- 8×10^3 *NC events in ν mode;*
- 5×10^3 *NC events in $\bar{\nu}$ mode.*

- ✦ *Expected statistical uncertainty $\sim 1.0\%$. Systematic uncertainties related to the signal extraction reduced by $\nu/\bar{\nu}$ ratio and detector design:*
  - *High resolution e tracking and charge measurement avoid background extrapolation (CHARM II);*
  - *Electron energy measurement cancel in the ratio.*

- ✦ *Use the LAr detector present in the ND complex in front of the fine-grained tracker. The fiducial mass foreseen for the LAr is* ~ 100 *tons:*
  - *Total of* $\sim$ **80** $\times 10^3$ *NC events in* ν *mode;*
  - *Total of* $\sim$ **50** $\times 10^3$ *NC events in* $\bar{\nu}$ *mode.*

- ✦ *The optimal analysis uses a combination of* TWO DETECTORS *:*
  - *HiResM*ν *provides a precise measurement of backgrounds (charge symmetric) and an overall calibration for LAr;*
  - *LAr provides the actual statistics for* $\sin^2\theta_W$ *and a good electron identification.*

- ✦ *Statistical uncertainty which can be reached on the ratio at the level of 0.3%*

- ✦ *Evaluated the uncertainty on the* $\bar{\nu}/\nu$ *flux ratio using the low-*ν_0 *method in the neutrino beam mode (positive focusing)*
  - *With current understanding of* $p/\pi/K$ *nuclear collisions and beam elements systematic uncertainty on theflux ratio of about 1%*
  - *Overall improvement on the* $\sin^2\theta_W$ *only a factor* ~ 1.4 *for a total uncertainty of* $\sim 0.56\%$

STT: Ok, LAr Ok high bkg, Scint. Ok?

ainment of the events so reducing the usable statistics.

Measurement	STT	Sci+μDet	LAr	LArB	LArB+Sci+μDet	LAr+STT
In Situ Flux Measurements for LBL:						
$\nu e^- \to \nu e^-$	Yes	No	Yes	No	No	Yes
$\nu_\mu e^- \to \mu^- \nu_e$	Yes	Yes	No	Yes	Yes	Yes
$\nu_\mu n \to \mu^- p$ at $Q^2 = 0$	Yes	Yes	No	No	Yes	Yes
Low-ν_0 method	Yes	Yes	No	Yes	Yes	Yes
ν_e and $\bar{\nu}_e$ CC	Yes	No	No	Yes	Yes	Yes
Background Measurements for LBL:						
NC cross sections	Yes	Yes	No	Yes	Yes	Yes
π^0/γ in NC and CC	Yes	Yes	Yes	Yes	Yes	Yes
μ decays of $\pi^\pm, K^\pm$	Yes	No	No	Yes	Yes	Yes
(Semi)-Exclusive processes	Yes	Yes	Yes	Yes	Yes	Yes
Precision Measurements of Neutrino Interactions:						
$\sin^2\theta_W$ ν N DIS	Yes	No	No	No	No	Yes
$\sin^2\theta_W$ νe	Yes	No	Yes	No	No	Yes
Δs	Yes	Yes	Yes	Yes	Yes	Yes
νMSM neutral leptons	Yes	Yes	Yes	Yes	Yes	Yes
High Δm^2 oscillations	Yes	No	No	Yes	Yes	Yes
Adler sum rule	Yes	No	No	No	No	Yes
$D/(p+n)$	Yes	No	No	No	No	Yes
Nucleon structure	Yes	Yes	Yes	Yes	Yes	Yes
Nuclear effects	Yes	Yes	Yes	Yes	Yes	Yes

TABLE XXVIII: Summary of measurements that can be performed by different ND reference configurations.

Summary page from the Short-Baseline Physics Report: Roberto Petti

Summary of Sensitivity Studies with LBNE-ND (HiResMnu, LAr, ..-Idea)

- ***Determination of Absolute Flux:***

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

- ***Relative Flux:***

  νμ-Flux Shape: Far-Detector/Near-Detector (Ev)

  νμBar-Flux Shape: Far-Detector/Near-Detector (Ev)

  νμBar/νμ Flux (Ev)

- Efficiency of **νμ-*QE* *CC*** and Background as a function of Ev

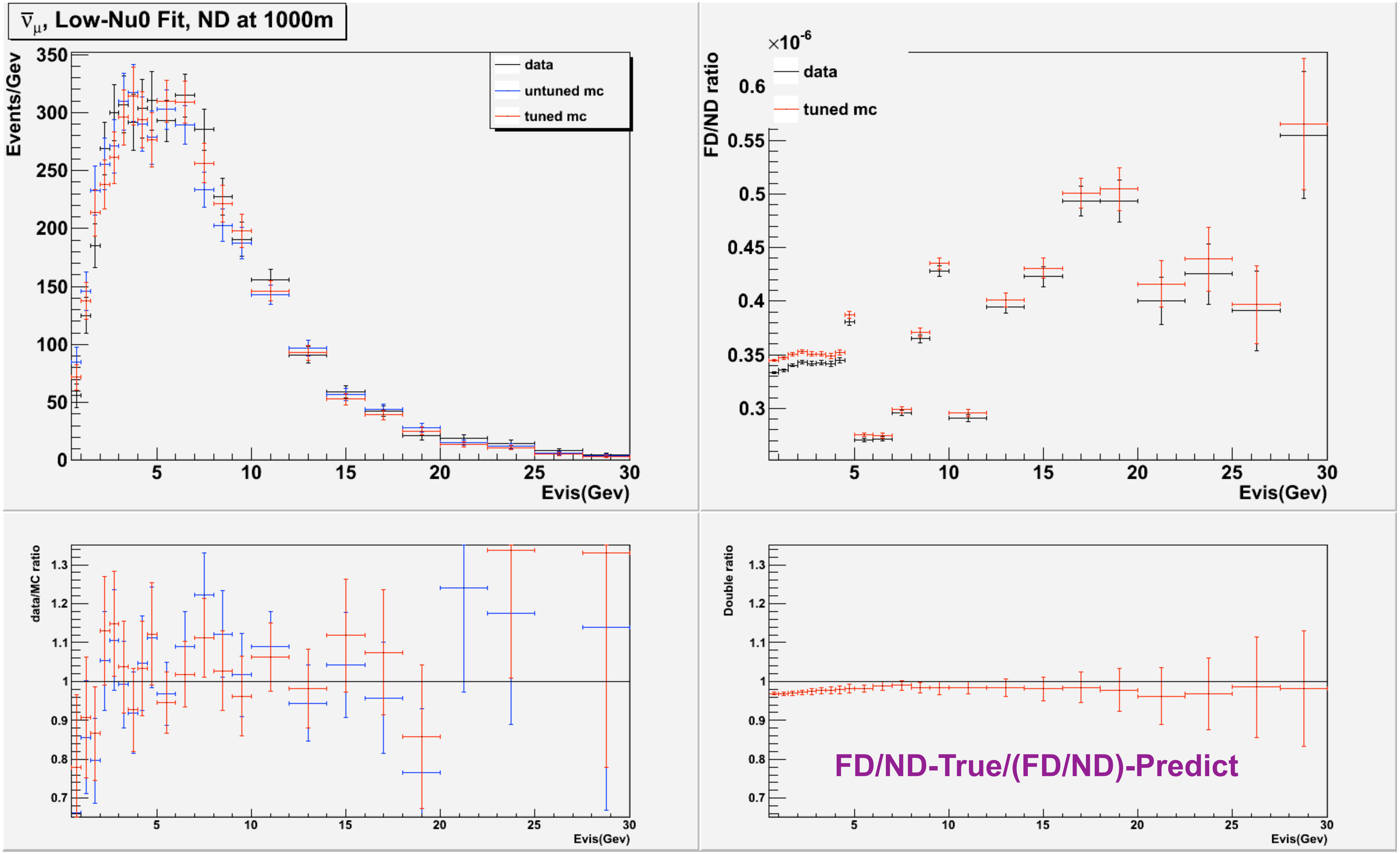
- Efficiency of **νe-*CC*** and Background (π0) from NC and CC as a function of Ev [Ditto for **νeBar-**CC]

- π***0-detection*** efficiency and background as a function of Eπ0

Precision Studies with LBNE-ND (SBP Gr.: Roberto Petti)

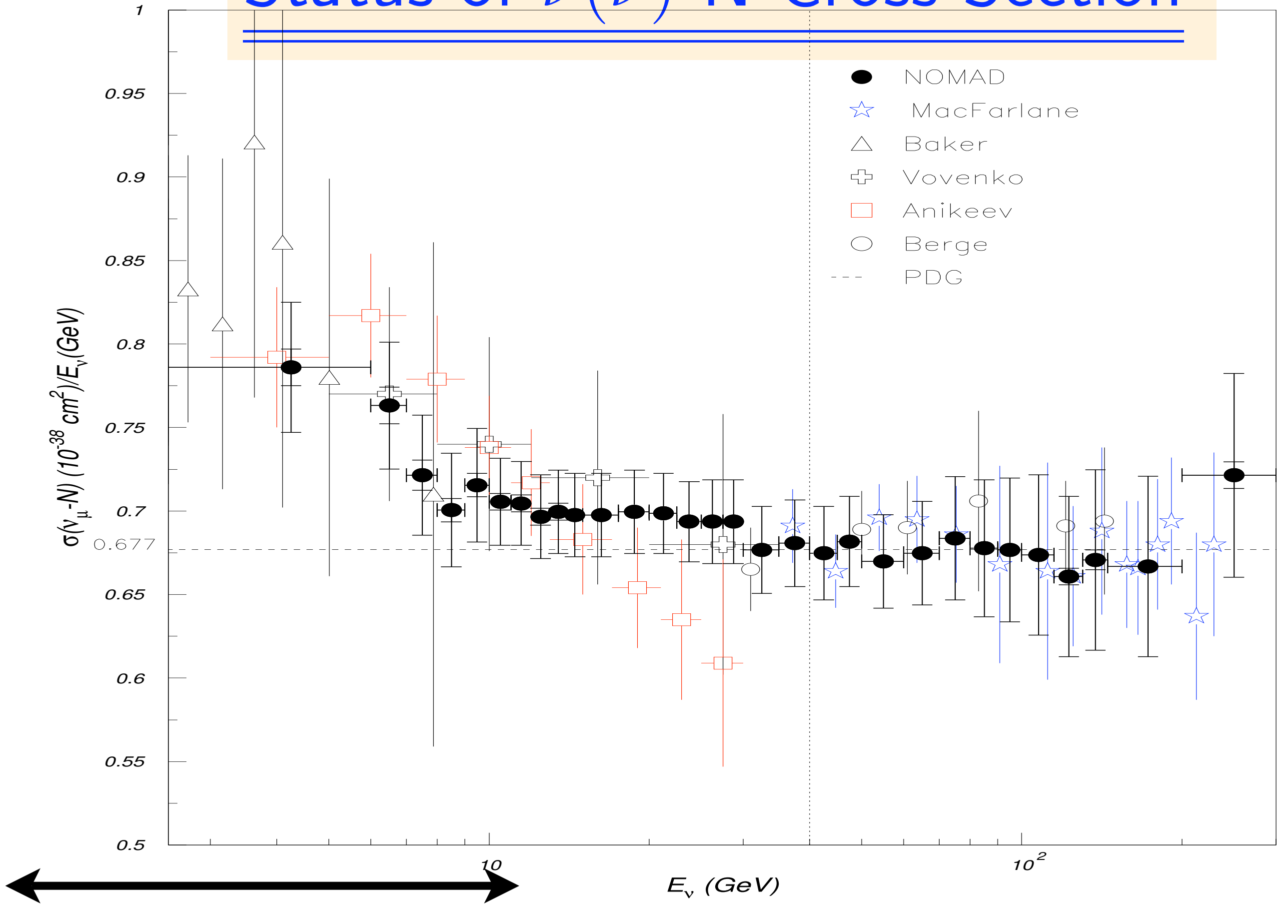
- ***Sin**2(Θw)***
- νμ-Nucleon Elastic Scattering ⇻ Del-S
- νμ-Energy scale: QE + Missing-Pt
- Search for Sterile ν
- Search for High Del-m**2 Oscillation
- •••••

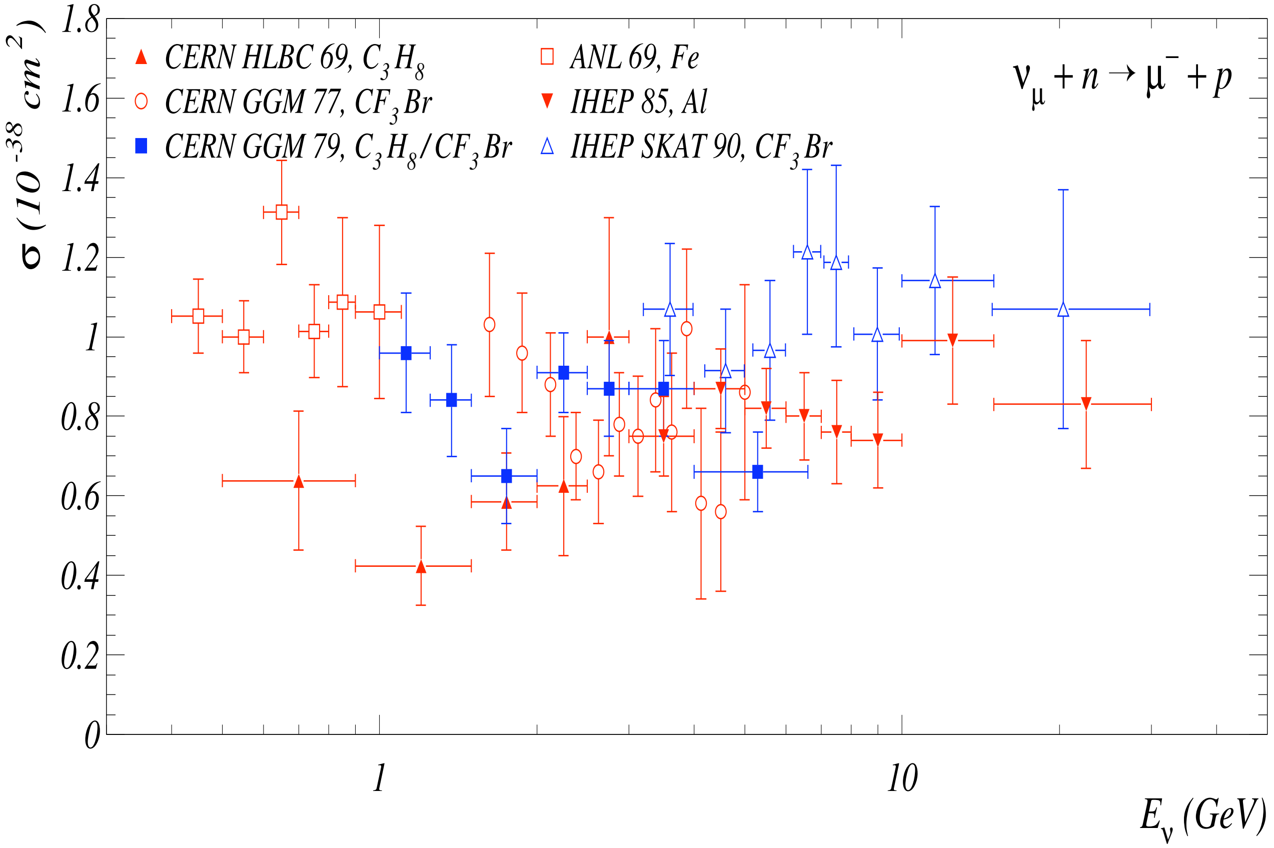
Backup Slides



FD/ND-True/(FD/ND)-Predict

Status of $\nu(\bar{\nu})$-N Cross-Section





- ✦ *Inclusive ν-N cross-section known to 2.6% for $E_\nu \geq 10$ GeV, and to 4% for $E_\nu > 2.5$ GeV*

  $\Longrightarrow$ *Need precision data for $E_\nu < 5.0$ GeV (oscillation region)*

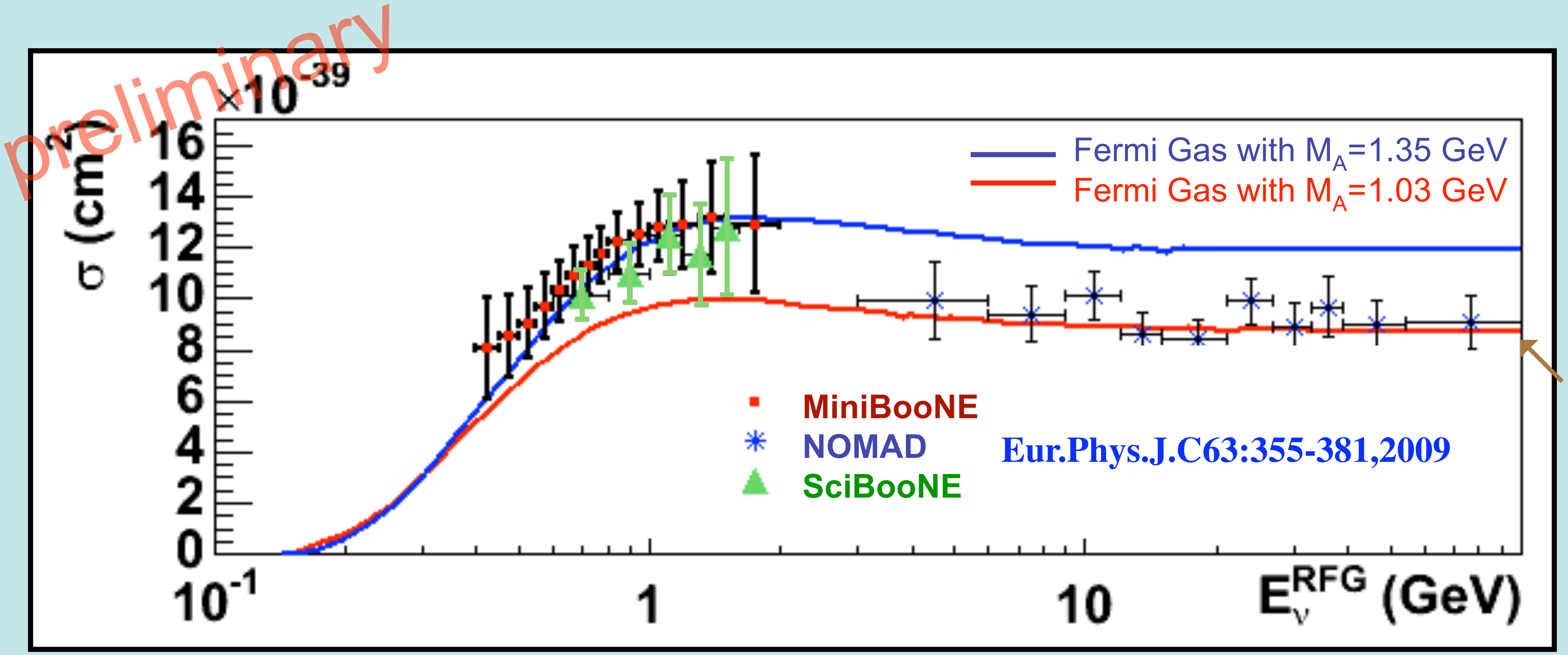
- ✦ *Large uncertainties on exclusive processes: quasi-elastic (20%), resonance (40%) and coherent production in CC and NC (50%)*

- ✦ *Poorly known $\bar{\nu}$ cross-sections and $\bar{\nu}$-induced processes*

- ✦ *In HiResMν: Absolute flux mesurement ($E_\nu \simeq 20$ GeV) at 1% using Inverse Muon Decay; Use QE and Low-ν^0 method to determine relative ν_μ and $\bar{\nu}_\mu$ flux*

Quasi-Elastic Scattering

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



Eur.Phys.J.C63:355-381,2009

(T. Katori, NuInt09)

Discrepancy?

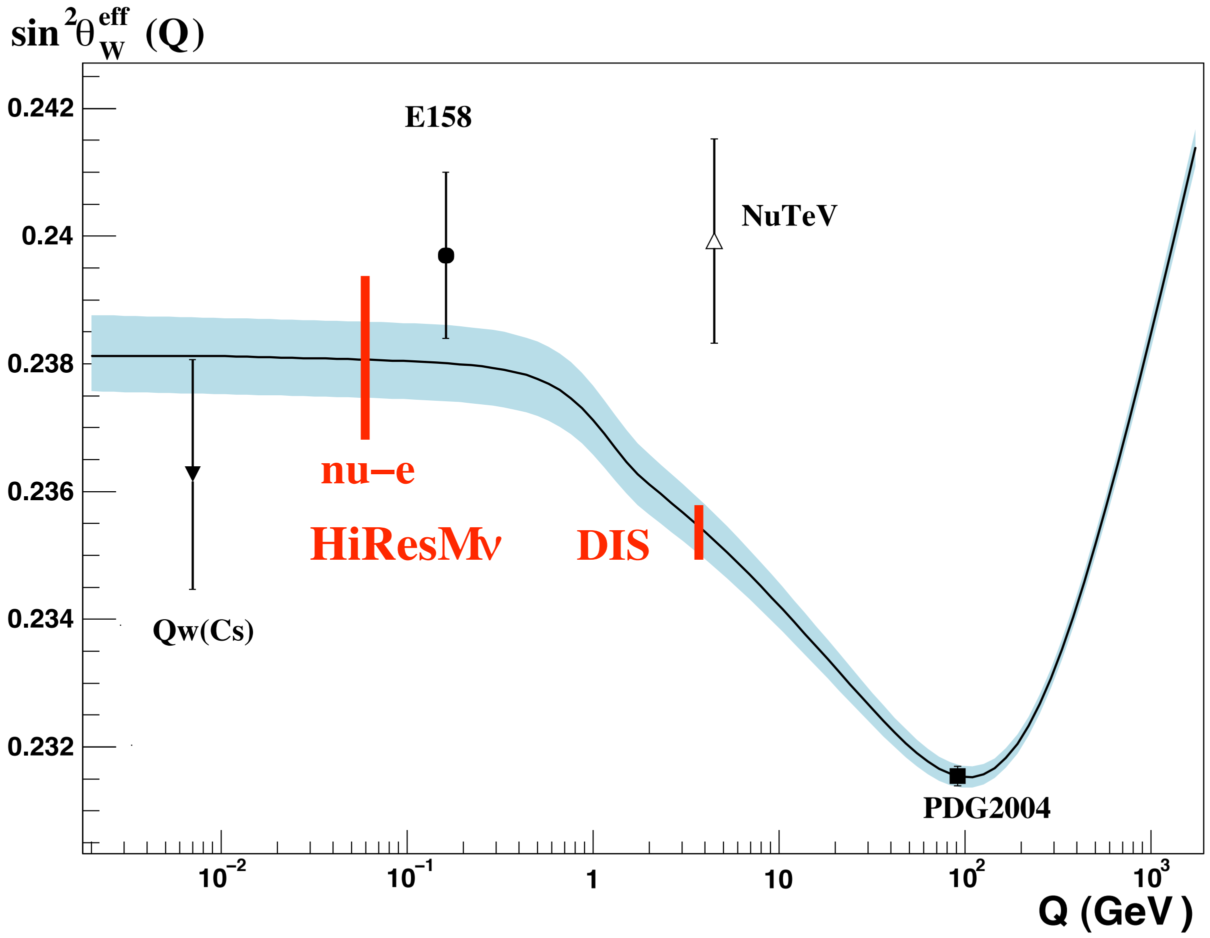
~ 30% difference between QE σ measured at low & high E on ^{12}C ?!

?

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 $\Gamma_{\nu\nu}$*



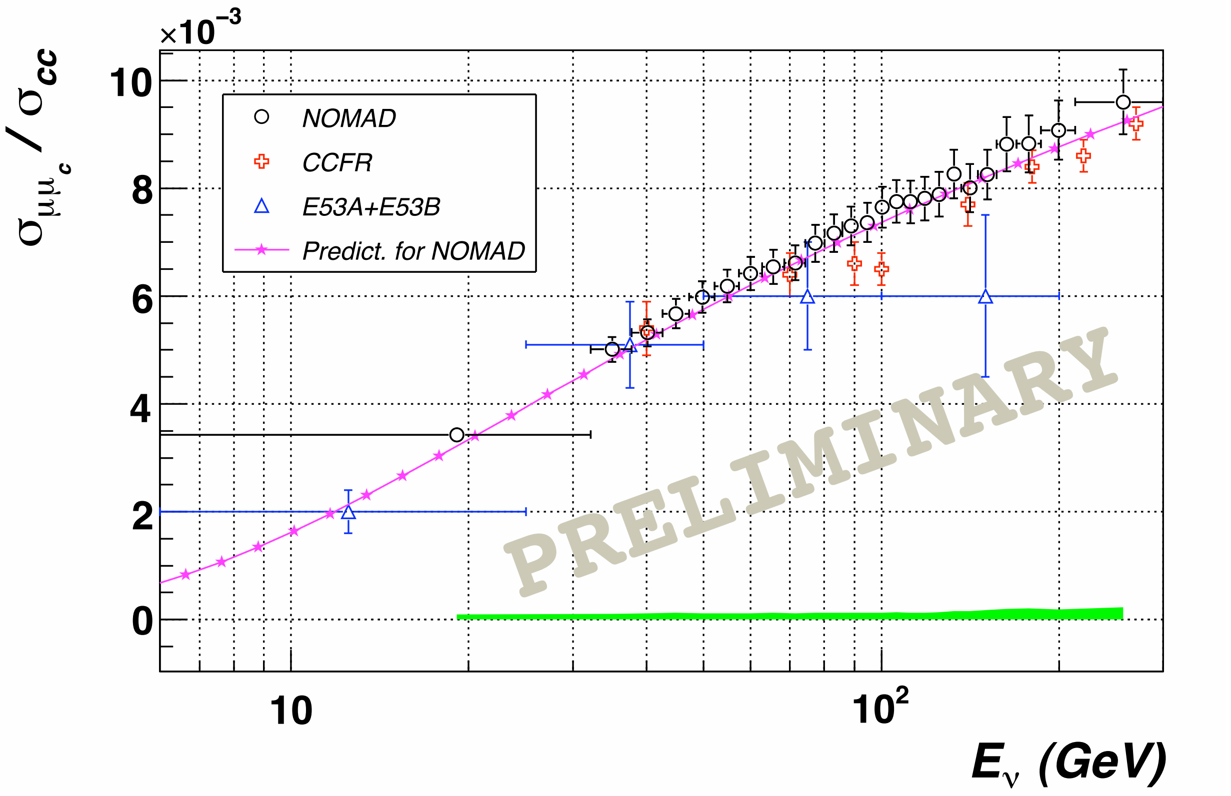
✦ *Independent cross-check of the NuTeV $\sin^2\theta_W$ anomaly in a similar Q^2 range*

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

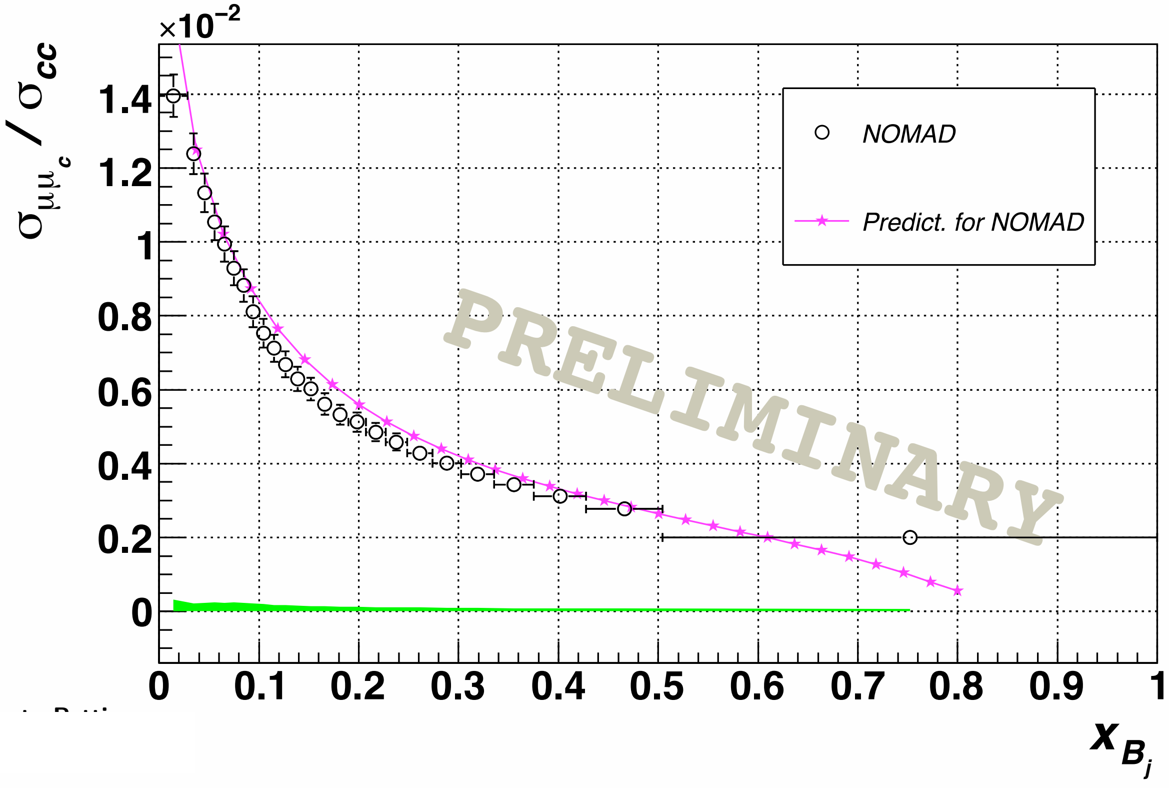
Source of uncertainty	$\boldsymbol{\delta\mathcal{X}/\mathcal{X}}$	$\boldsymbol{\delta R^{\nu}/R^{\nu}}$	$\boldsymbol{\delta R^{\bar{\nu}}/R^{\bar{\nu}}}$	$\boldsymbol{\delta\mathcal{X}/\mathcal{X}}$
Data statistics	0.00593	0.00176	0.00393	
Monte Carlo statistics	0.00044	0.00015	0.00025	
Total Statistics	**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**

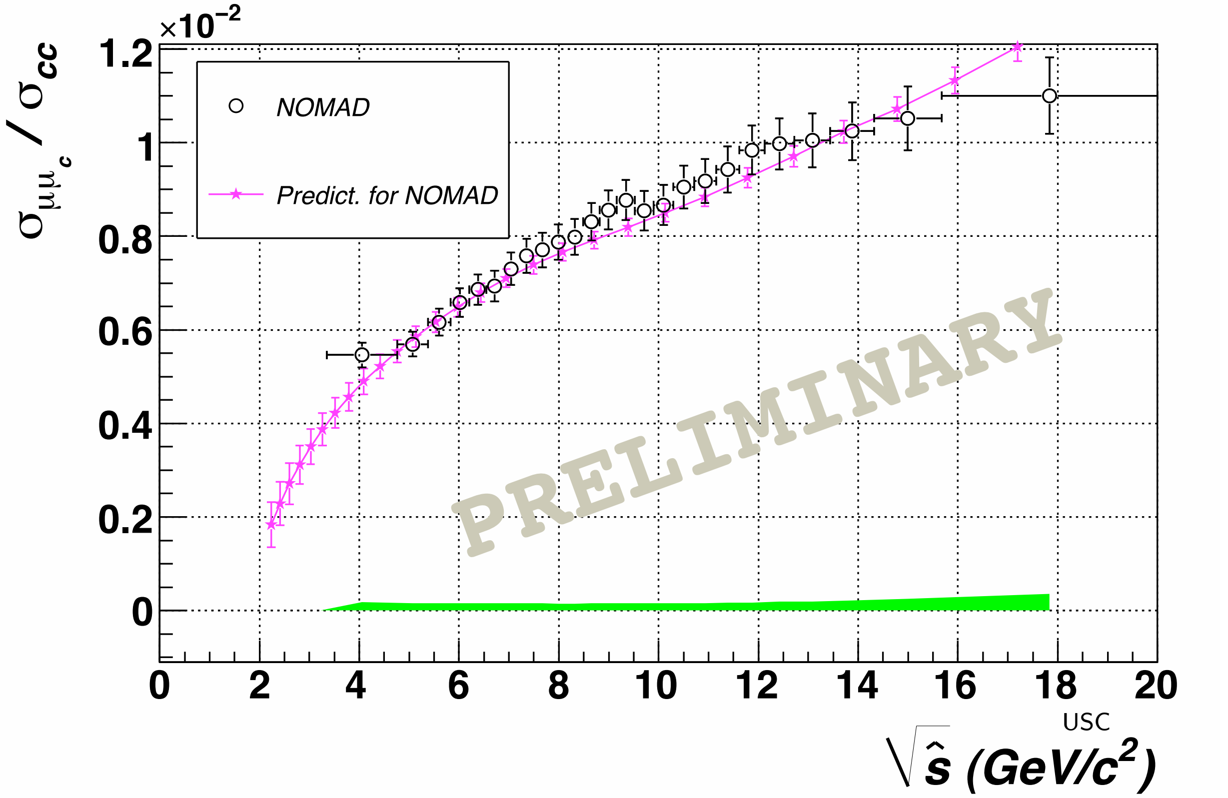
Table 4: Summary of uncertainties on the extraction of the weak mixing angle ($\mathcal{X} = \sin^2\theta_W$) based upon the Pascos-Wolfenstein relation. The first three columns refer to the published NuTeV errors [12] while the last column indicates the corresponding projection for our experiment.

PRESENTED AT DIS 2010



Statistical and
systematic uncertainties ($\leq 2.5\%$)





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.