# A High Resolution ν Near-Detector for Neutrino Factory    μ ➢ $\nu_e$ $\nu_\mu$

✴ *The PMNS Matrix Elements*

❧ δ Sensitivity

❧ ν-Mass Hierarchy

❧ Resolving degeneracies

✴ *Beyond PMNS*

❧ $\Theta_{23}$ = 45^0 ?

❧ $\Theta_{13}$ Precision

❧ CPT Violation ?

⇒ *Need systematic precision*

❧ High Δm**2 Oscillation ?

❧ Phenomenon that defies the Zeitgeist

✴ *The Familiar, Beautiful Neighborhood*

❧ Cross-section

❧ Sin**2($\Theta_W$): precision commensurate with Colliders

❧ Sum rules

❧ Isospin Physics

❧ Heavy neutrinos

❧ ........

❧ Rewriting the ν-text-book

## 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:* $\nu_\mu$, $\bar{\nu}_\mu$, $\boxed{\nu_e}$, *and* $\boxed{\bar{\nu}_e}$ *CC-interactions.* ⇐Absolute ν-Flux & Eν-scale; Cross-Sections

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

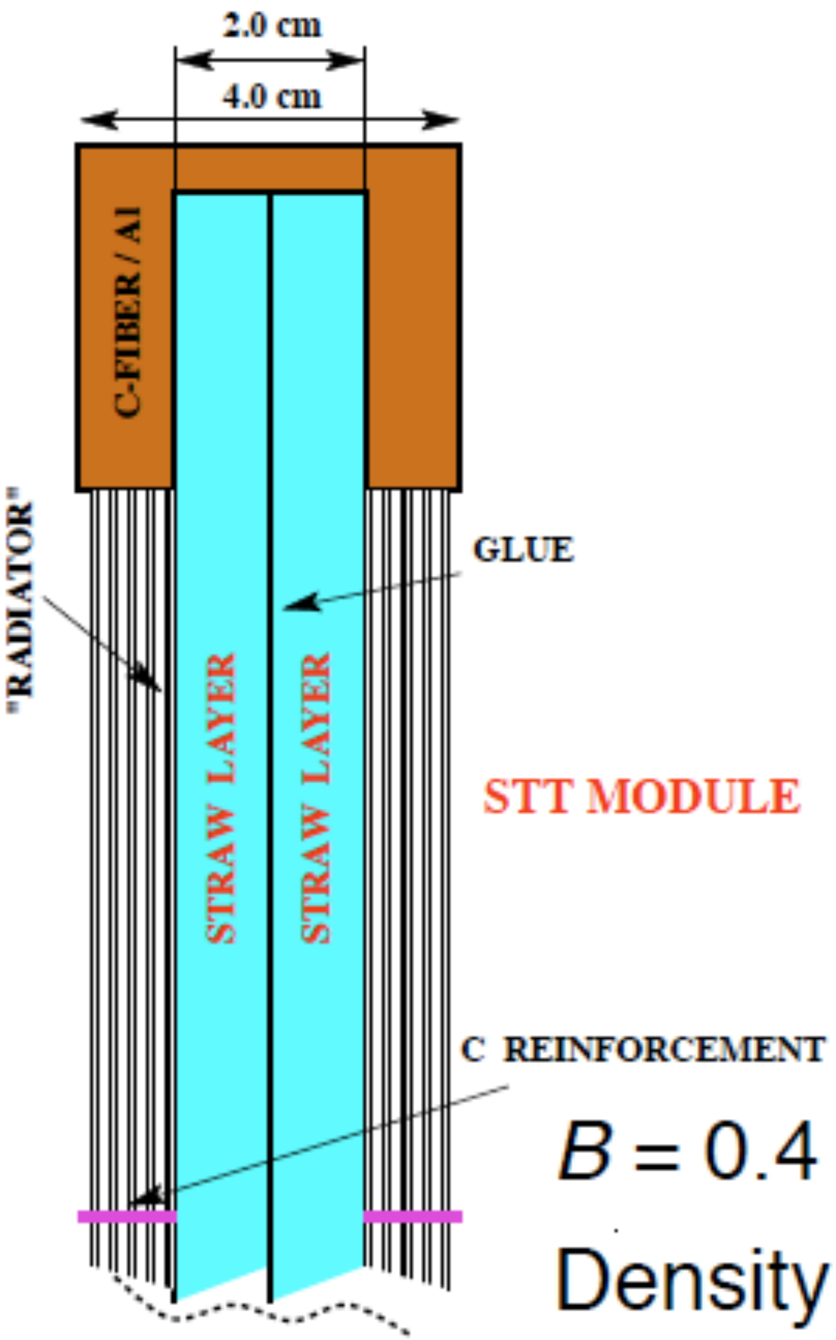
- *Measurement of the weak-mixing angle, sin$^2\theta_W$, with a precision of about 0.2%, using independent measurements:*
  - $\nu(\overline{\nu})$*-q (DIS);*
  - $\nu(\overline{\nu})$*-e$^-$ (NC).*

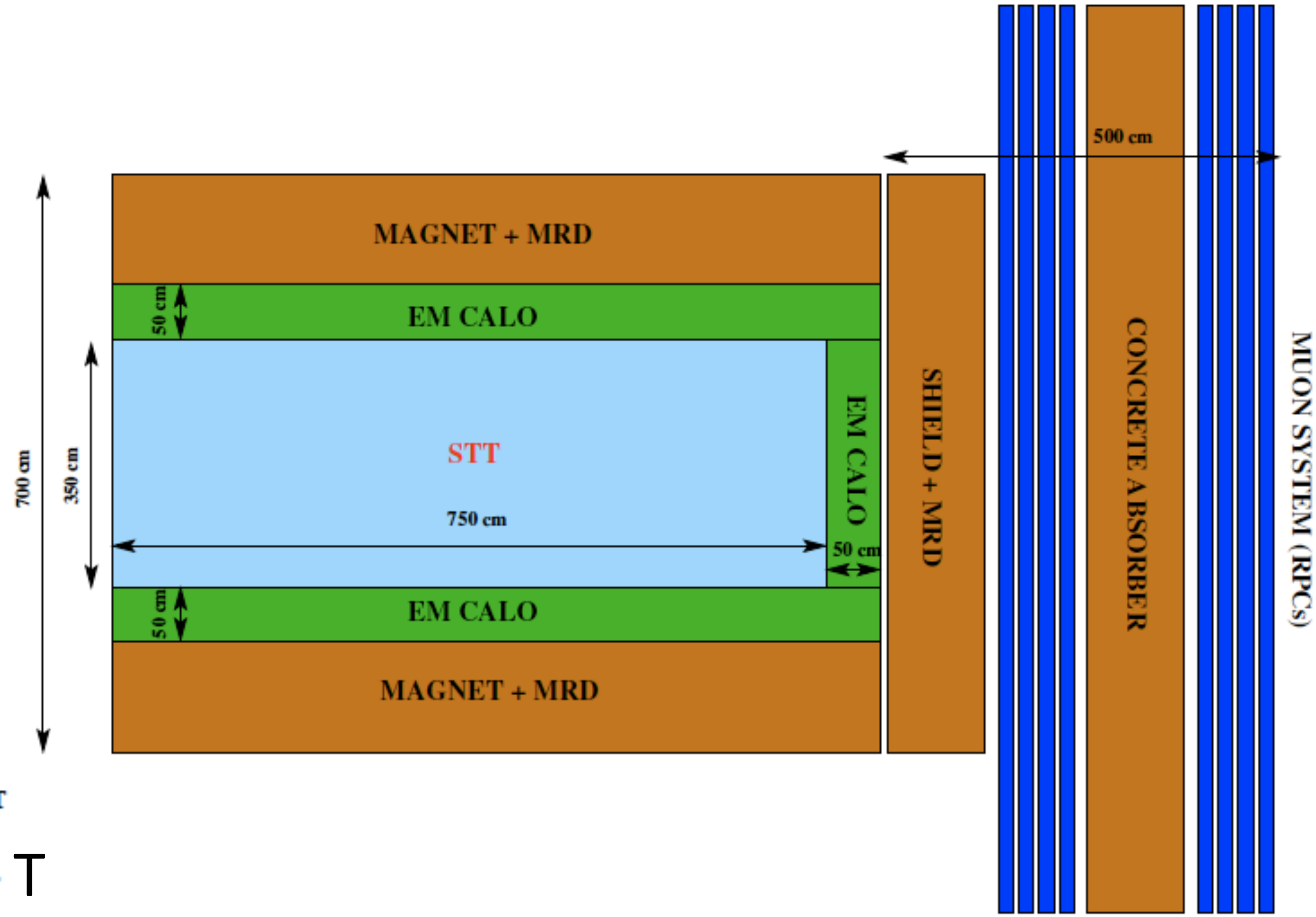
  ⇐Example of Precision Measurement

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

- *Precise determination of the exclusive processes such as $\nu$ 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.*




$B = 0.4$ T

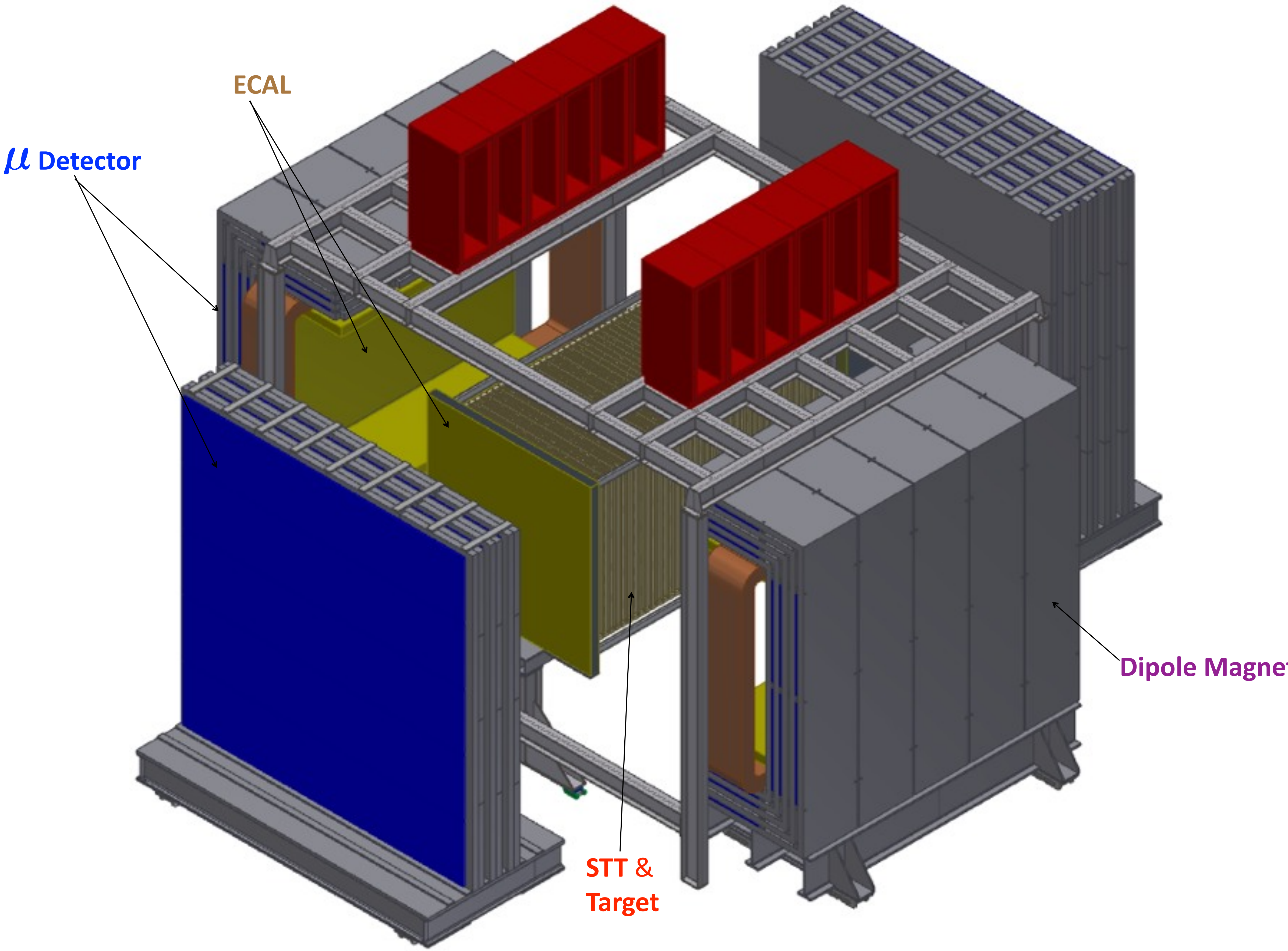
Density = 0.1 g/cm3, 85% in the radiator foils.

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

dE/dx ⤔ Proton, π, K ID

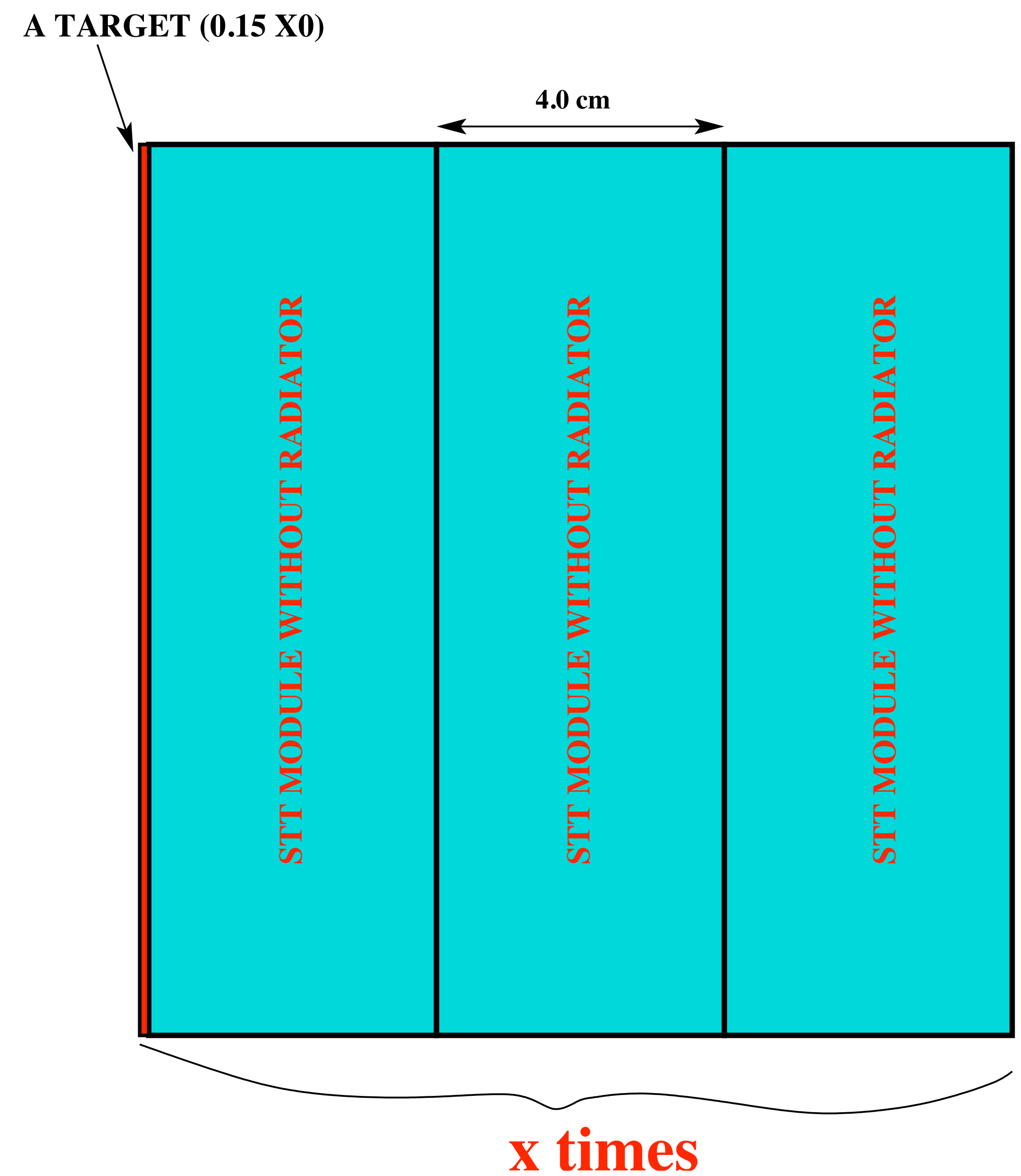
Magnet/Muon Detector ⤔ μ

# *ℋIRESMNU*: Near Detector for *LBNE*

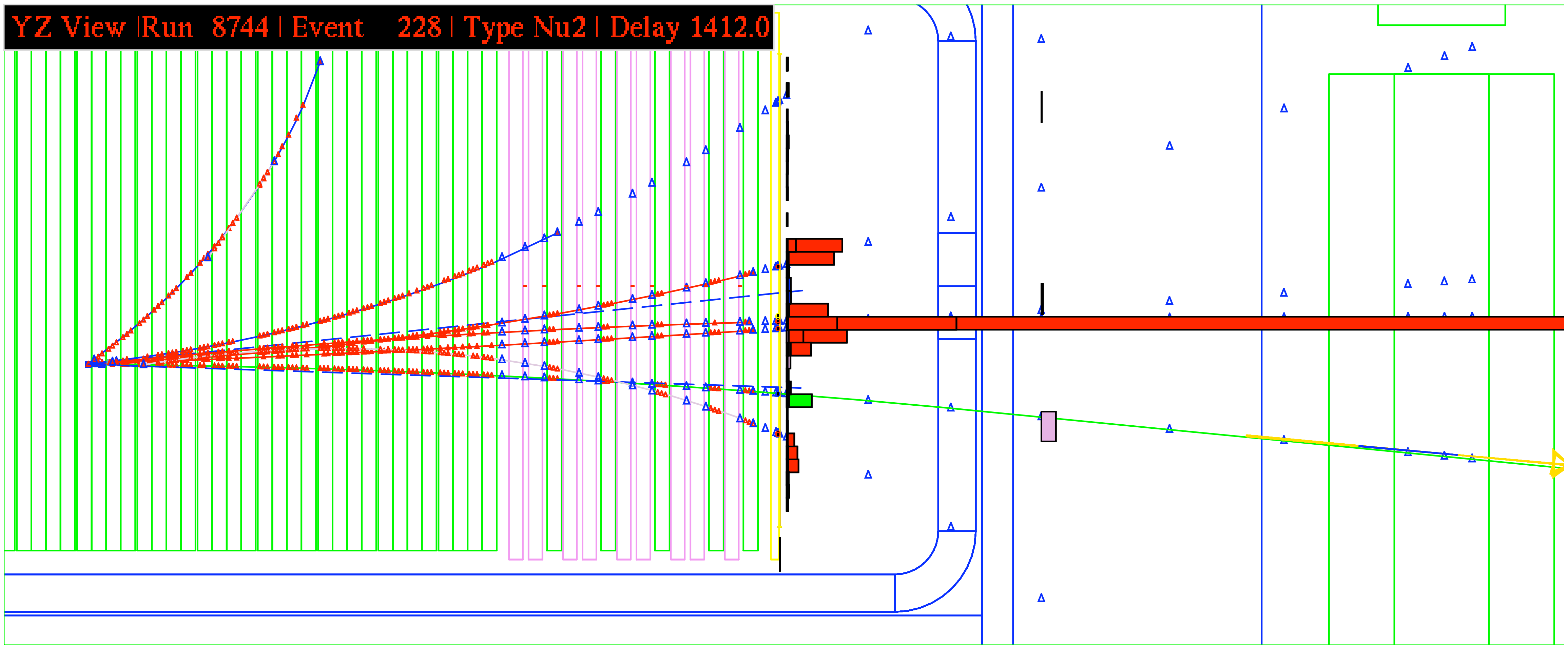


# MEASURING NUCLEAR EFFECTS *(Fe, Ar, ..)*

- *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 0.15$X_0$ 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.).*

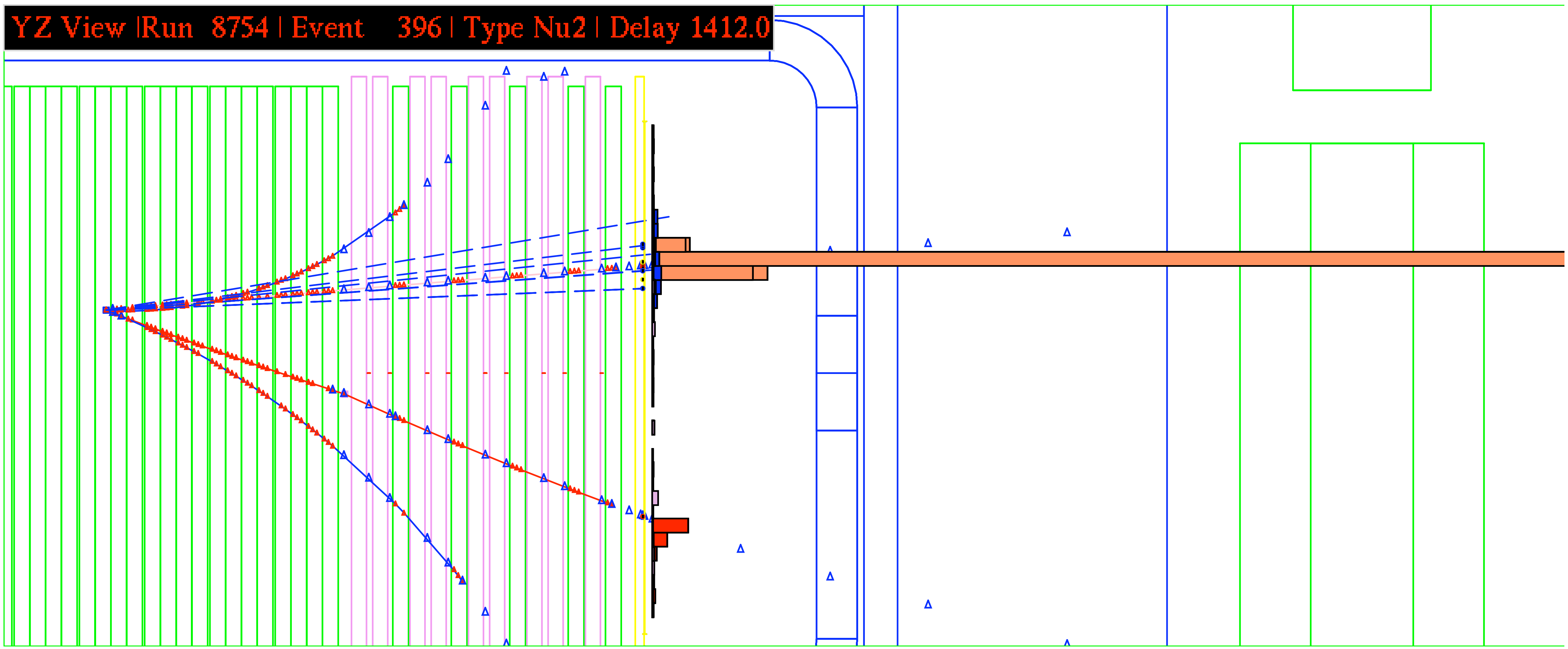


# A $\nu_\mu$ CC candidate in NOMAD



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

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

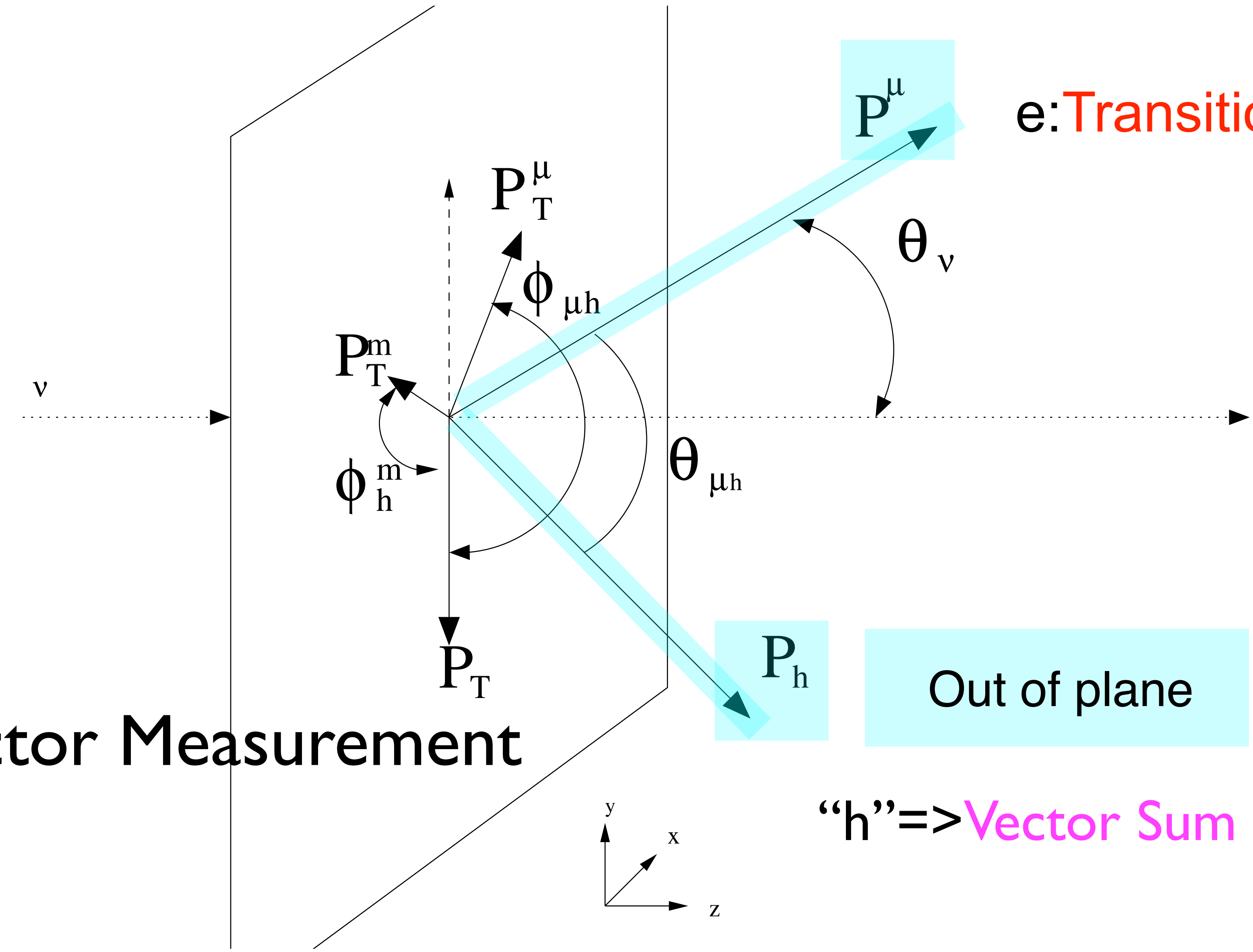



*Conclusion* ⇛

*(1)* $\mu$ *from* $\nu_\mu$ *and* e *from* $\nu_e$ *are Tracks: Determined with very high precision*

*(2) Universality equivalence:* $\mu$ -$\nu_\mu$ ↔ e -$\nu_e$

# Kinematics in HiResMnu



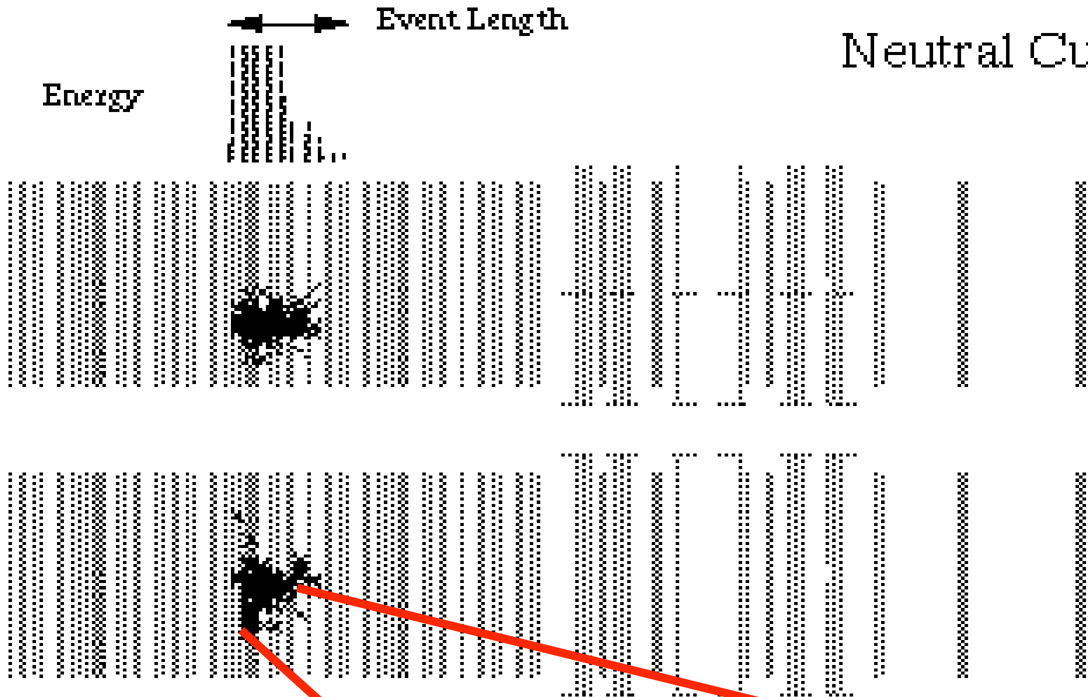

e:Transition Radiation

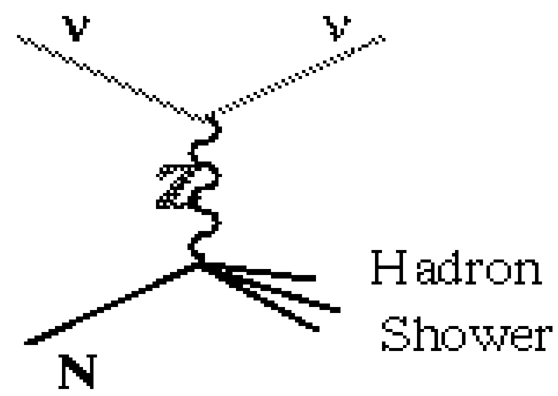
Out of plane

Pt-Vector Measurement

“h”=>Vector Sum of Tracks

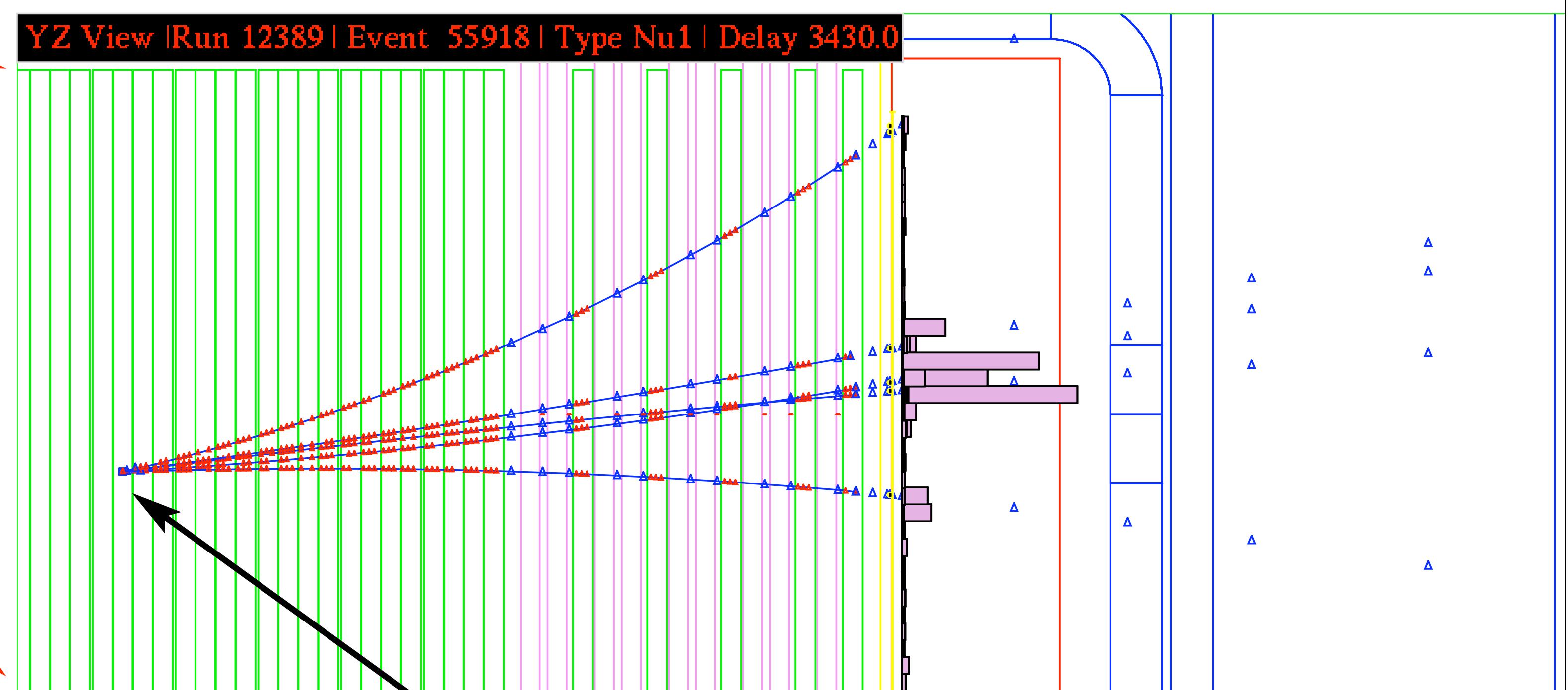
Neutral Current Event




**MASSIVE CALO**
**(NuTeV)**

**PRECISE TRACKER**
**(NOMAD)**




**Missing transverse momentum**

**HiResMν : order of mag. higher segmentation**

## Improvements over the NOMAD: HiResMnu-Concept

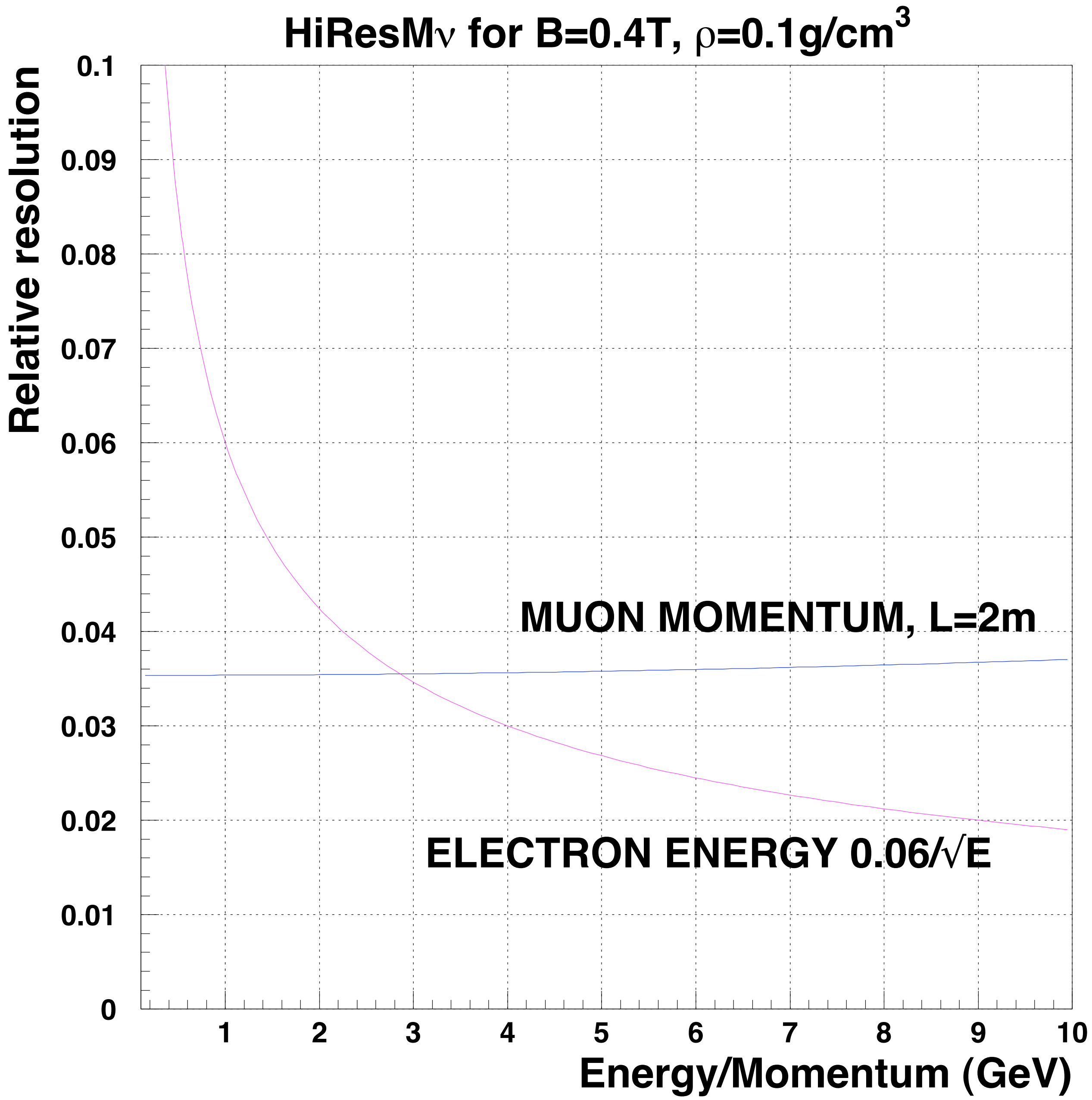
- ✴ Tracking Charged Particles
  - ❧ x6 more hits in the Transverse-Plane (X-Y)
  - ❧ x2 more hits along Z-axis
- ✴ Electron/Positron ID
  - ❧ Continuous TR providing e+/e- ID
- ✴ Calorimetry: 4π-Coverage
  - ❧ Downstream ECAL: fine Longitudinal & Transverse segmentation
  - ❧ Barrel & Upstream ECAL
- ✴ μ-ID
  - ❧ 4π-Coverage: min-$P_\mu$ ➳ 0.3 GeV

## *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 $\mu \succ \nu_e \, \nu_\mu$

## ✶ *Flux*

❧Inverse Muon Decay $\nu_x$ + e- ➻ $\nu_x$ + μ- *(*Single, forward μ-*)*

$\nu_\mu$ (t-channel) or Anti-$\nu_e$ (s-channel)

❧ ν-Elas $\nu_x$ + e- ➻ $\nu_x$ + e- *(*Single, forward e-*)*

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

***Working on:***

*Determination of Beam-Divergence using ν -Data*

❧E ν -Dependence

Fixed-ν0 Method

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

*Eν-Scale*

## ✶ *Interactions*

❧$\nu_\mu$-QE Analysis:

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

❧ $\nu_e$-CC *(inclusive)* Analysis:

⇛ *For ν-Factory, $\nu_e$-CC: Eff ~ 55% with 99%-purity*

⇛ *For ν-Factory, $\nu_e$Bar-CC: Eff ~ 55% with 99%-purity*

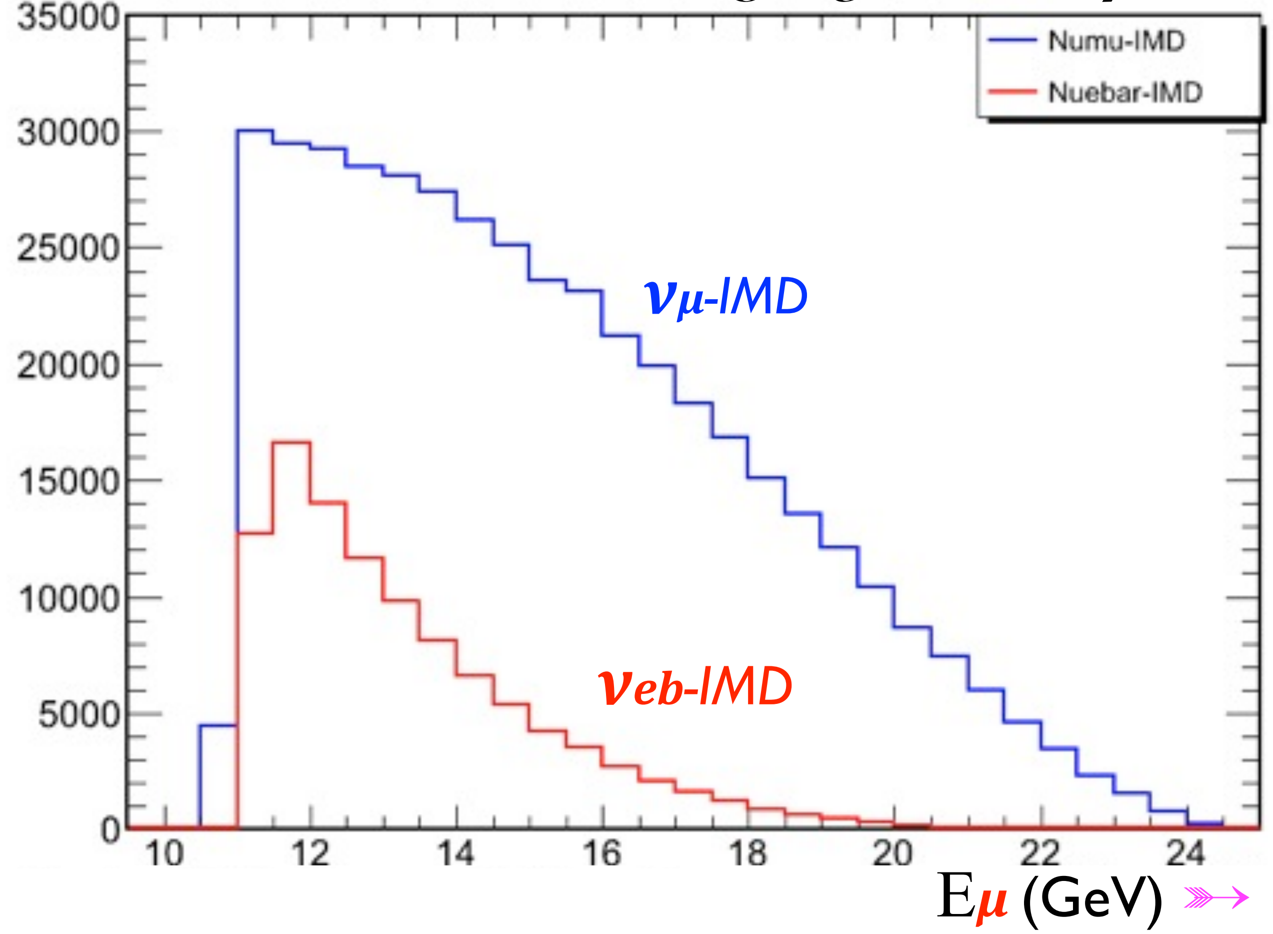
❧π0-Reconstruction:

⇛ *with one γ ➻ 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:* $\delta(\sin^2\theta_W)$ ➻ 0.0003

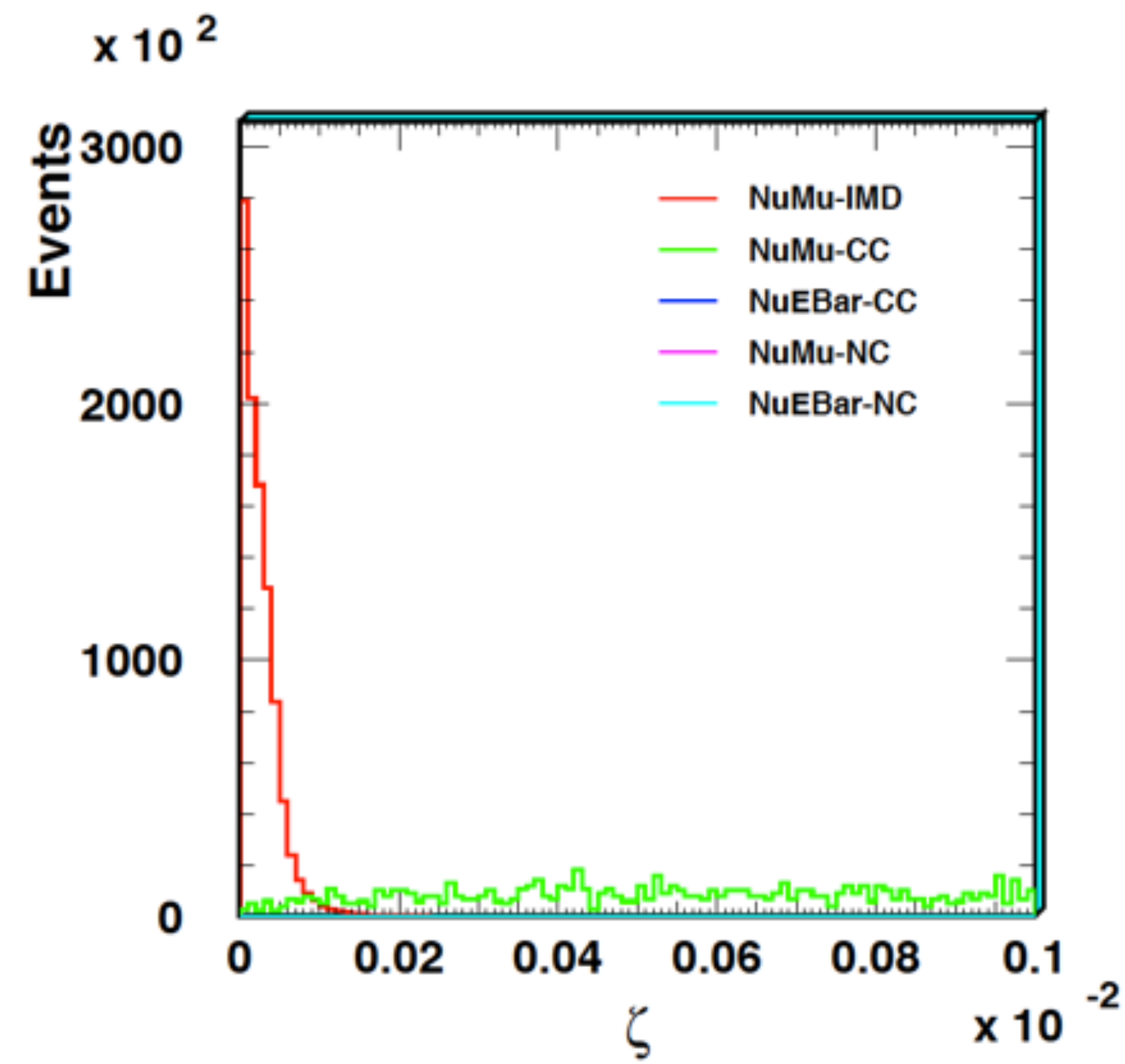
## $\nu_x + e^- \twoheadrightarrow \nu_x + \mu^-$ (*Single, forward $\mu^-$*)

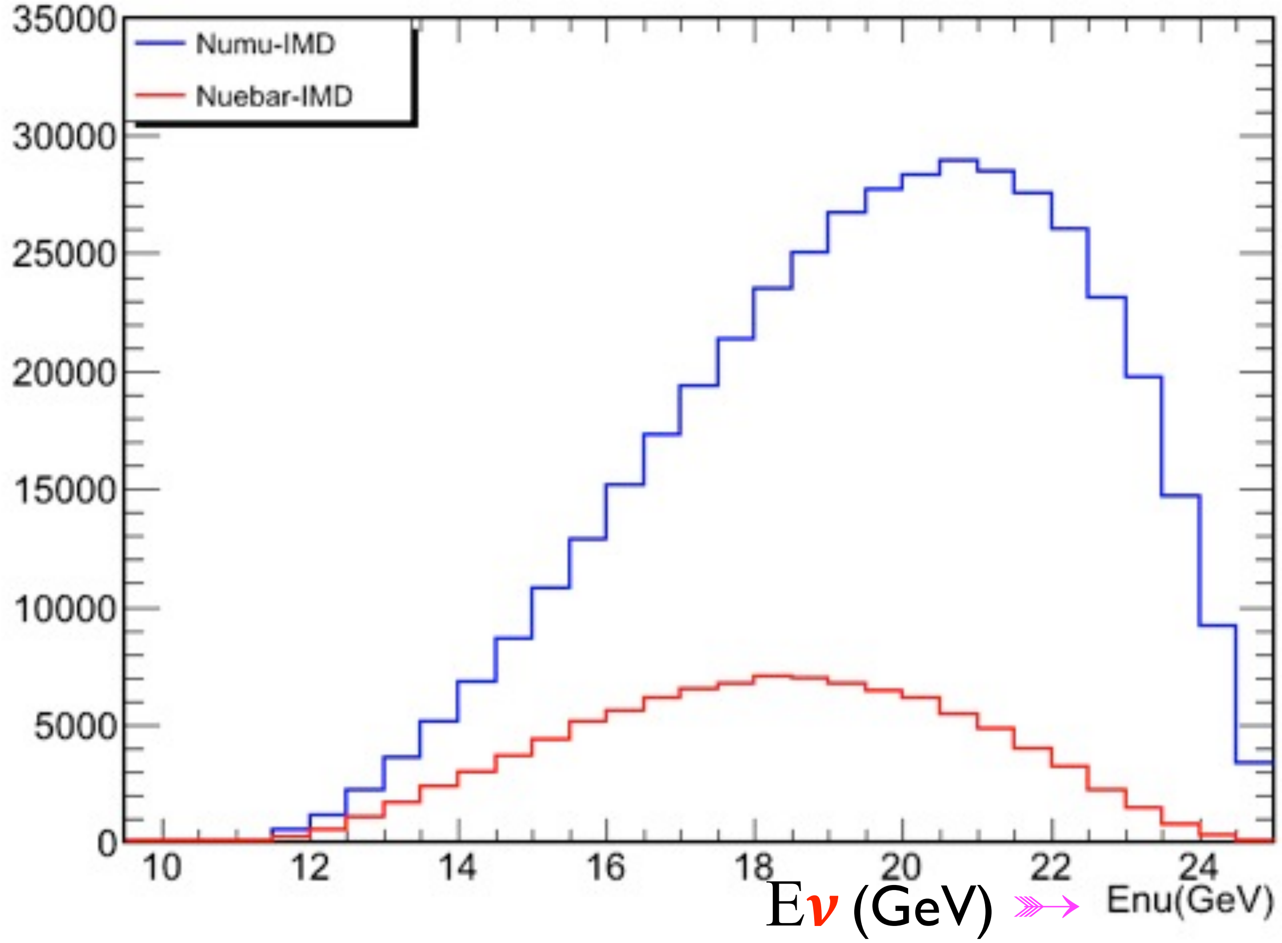



*νμ-Efficiency*

*Sig* ⇛ *95%*

*Back* ⇛ *5e-05*




*νeb- Efficiency*

*Sig* ⇛ *95%*

*Back* ⇛ *15e-05*

***How to measure the background, @5%--10%, with a ≤1% precisoin?***

✴ *(i)* $\nu_\mu$-N CC: Measure 2-Track ($\mu^-$,X) to measure when Ex ~ 0 ⇒ ($\mu^-$,0)

✴ *(ii)* $\nu_e$-N CC: Measure 1- and 2-Track ($e^-$,X) ⇒ ($e^-$,0)

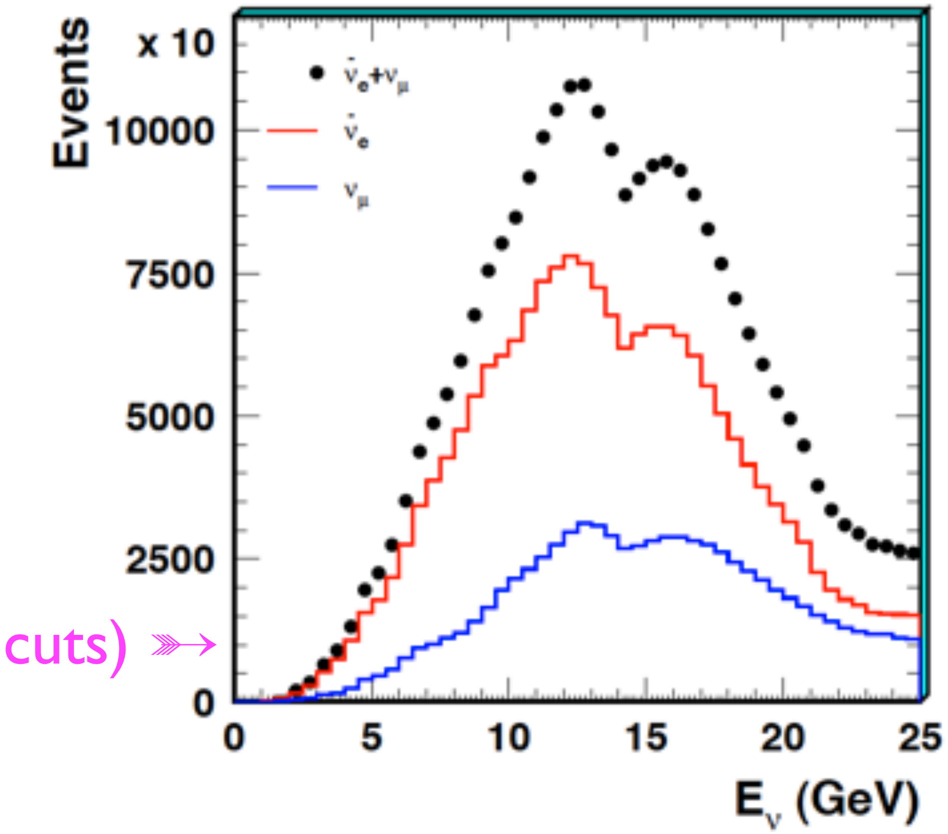
✴ *(iii)* Figures show what CC: Measure 1- and 2-Track ($e^-$,X) with E$e$ ≥ *Cut* (*15, 10*) *GeV*

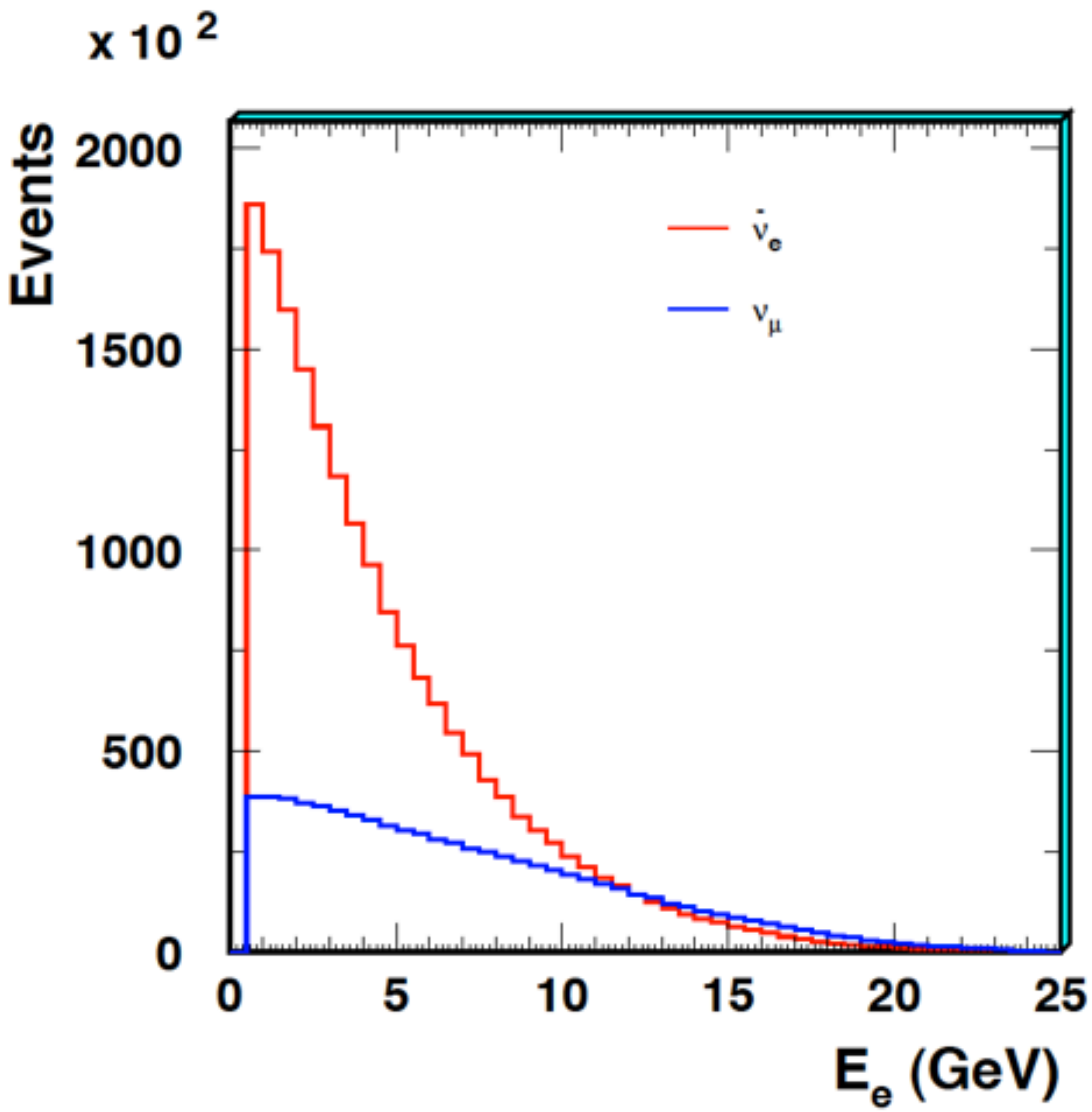
✴ *(iv)* Less reliance on anti-neutrino 1-Track ($\mu^+$,X)

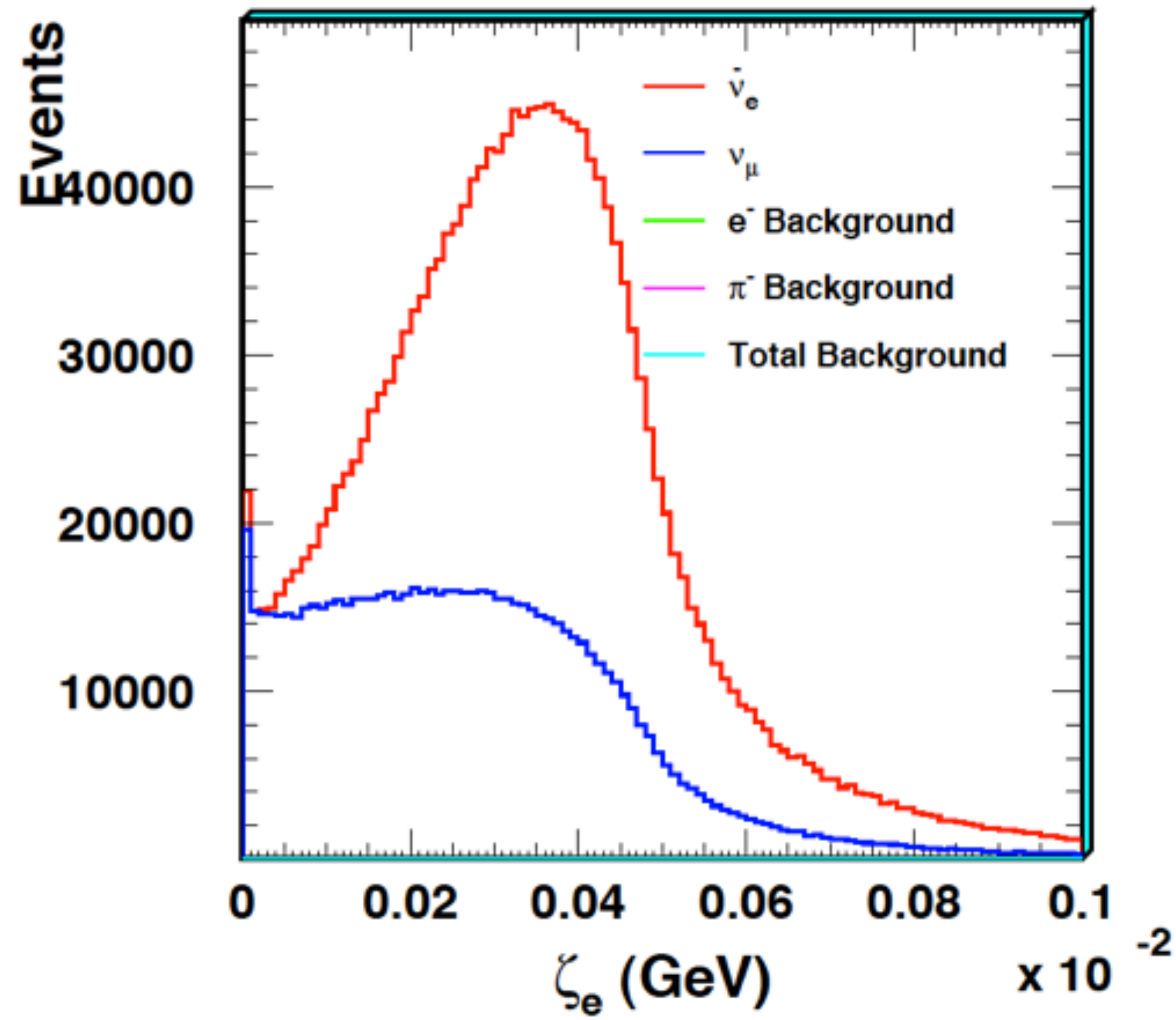
$\nu_x + e^- \twoheadrightarrow \nu_x + e^-$ (Single, forward e-)

*Distribution of Kinematic Quantities* ⇛

$E\nu$ (passing cuts) ⇝



## *Sensitivity Analysis* **νEl:** $\nu_\mu$(ebar) + e- ⤜ e- + $\nu_e$ (*Single, forward e-*)

✶ $\nu_\mu$(ebar)-N NC background due to single, asymmetric $\gamma \to e^- e^+$ and $\pi^- / \mu^-$

| $\gamma \to e^- e^+$ ⇒ | $\bar{\nu}_e$ | $\nu_\mu$ | $\bar{\nu}_e$-CC | $\nu_\mu$-CC | $\bar{\nu}_e$-NC | $\nu_\mu$-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*

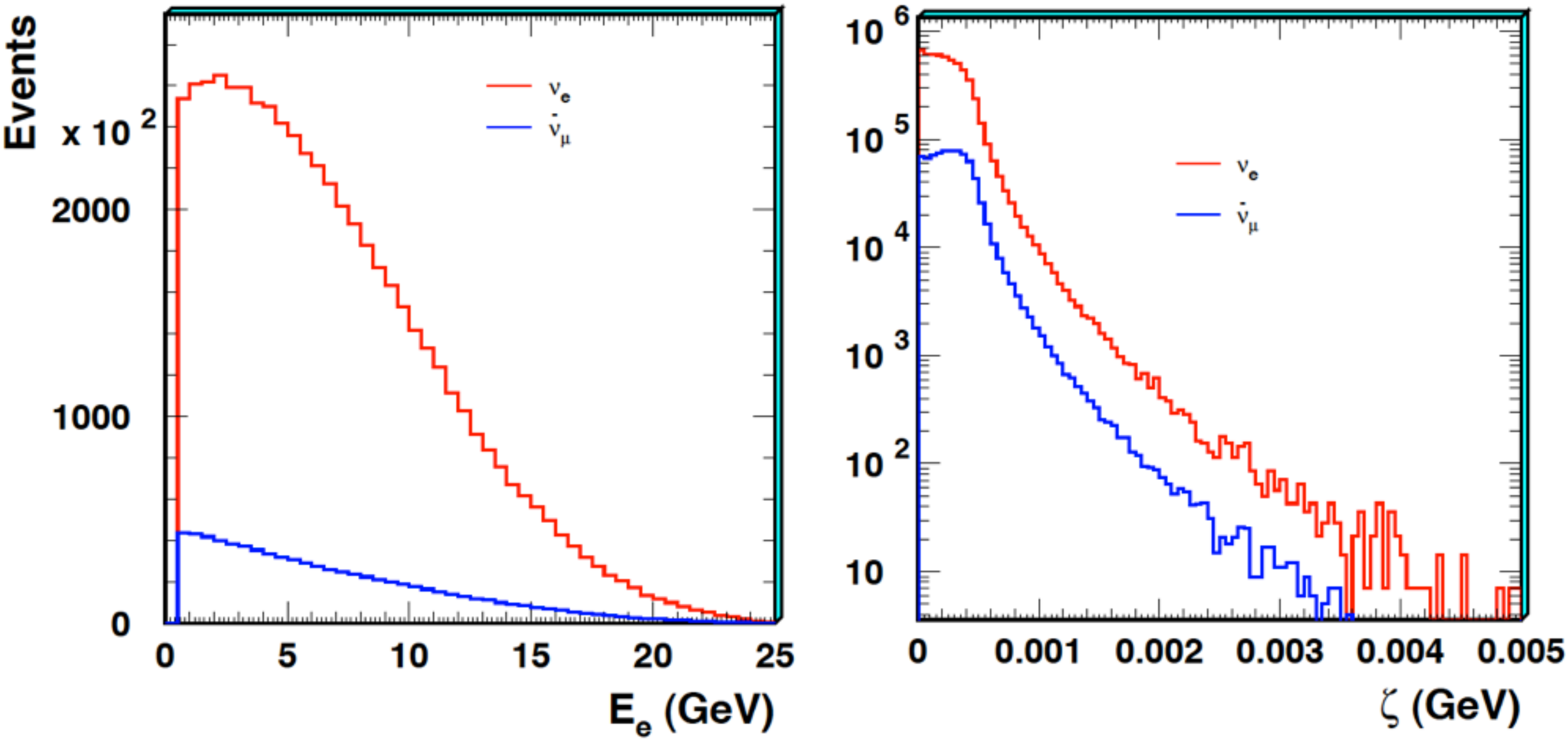
| $\pi^-$ ⇒ | $\bar{\nu}_e$ | $\nu_\mu$ | $\bar{\nu}_e$-CC | $\nu_\mu$-CC | $\bar{\nu}_e$-NC | $\nu_\mu$-NC |
|---|---|---|---|---|---|---|
| | 1,000,000 | 1,000,000 | 1,000,000 | 1,000,000 | 1,000,000 | 1,000,000 |
| Positron veto | 1,000,000 | 1,000,000 | 40,168 | 50,219 | 1,000,000 | 1,000,000 |
| 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* $\nu$*El:* $\mu^+$ *Beam* $\nu_{e(\bar{\mu})}$ + e- ⤀ e- + $\nu_e$ (*Single, forward e-*)

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




*Conclusion* ⇛ *The cleanest separation of* $\nu_e$–e *interaction*

*among all* --- $\nu_\mu$–e, $\nu_{eBar}$–e, $\nu_{\mu bar}$–e --- *the leptonic channels*

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

*(1)* Low-$\nu$0 Method

*(2)* Neutrino-Electron Scattering: $\mu$-sample (IMD)

*(3)* Neutrino-Electron Scattering: $e$-sample

*(4)* Quasi-Elastic and Coherent-$\pi^{+-}$ :

For Relative flux determination

## LOW-$\nu_0$ METHOD ⇐Shape of $\nu_\mu$ or Anti-$\nu_\mu$ Flux

- *Relative flux vs. energy from low-$\nu_0$ method:*

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

⇐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 $\nu$ 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*

USC

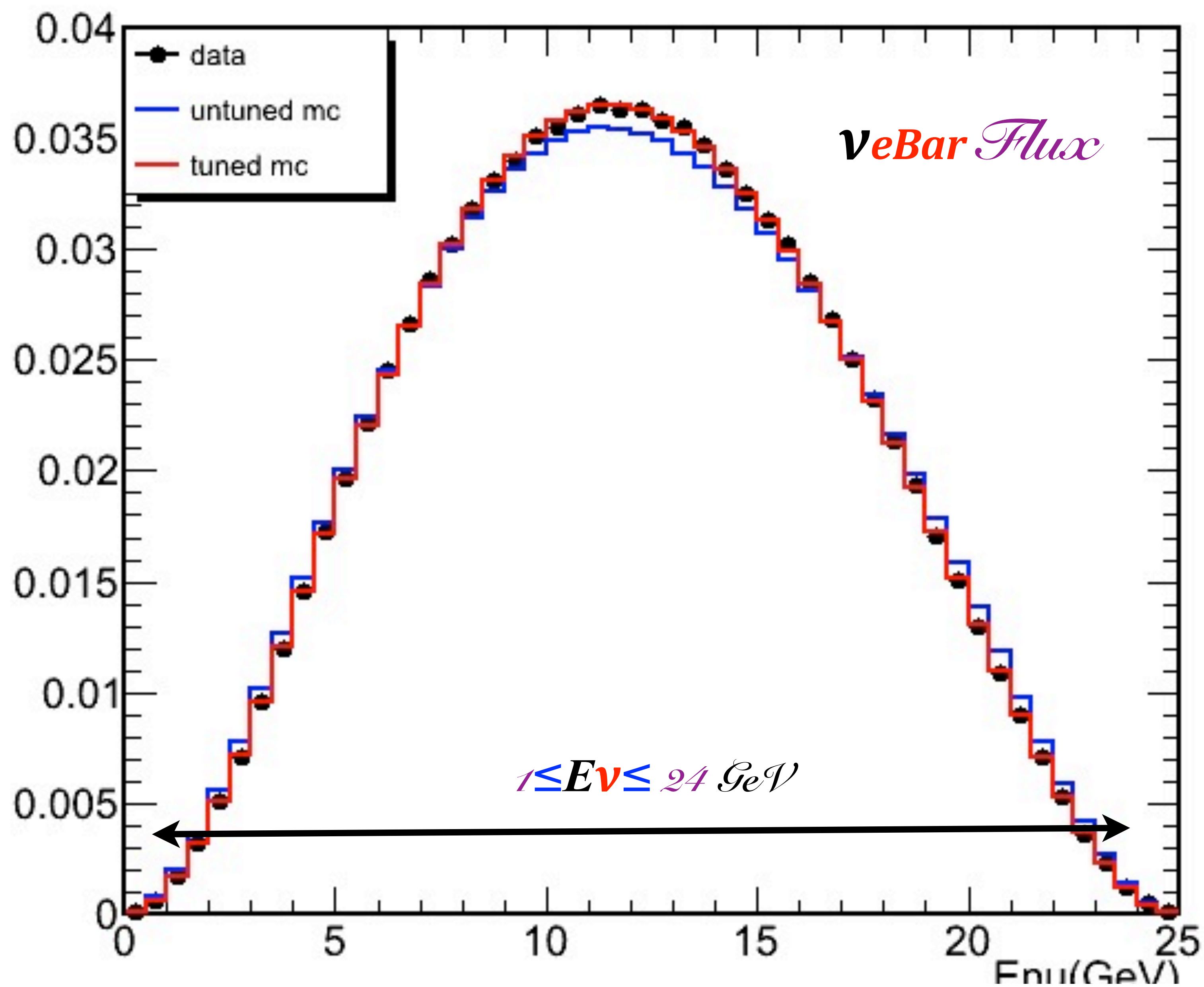
*Low-ν0:*

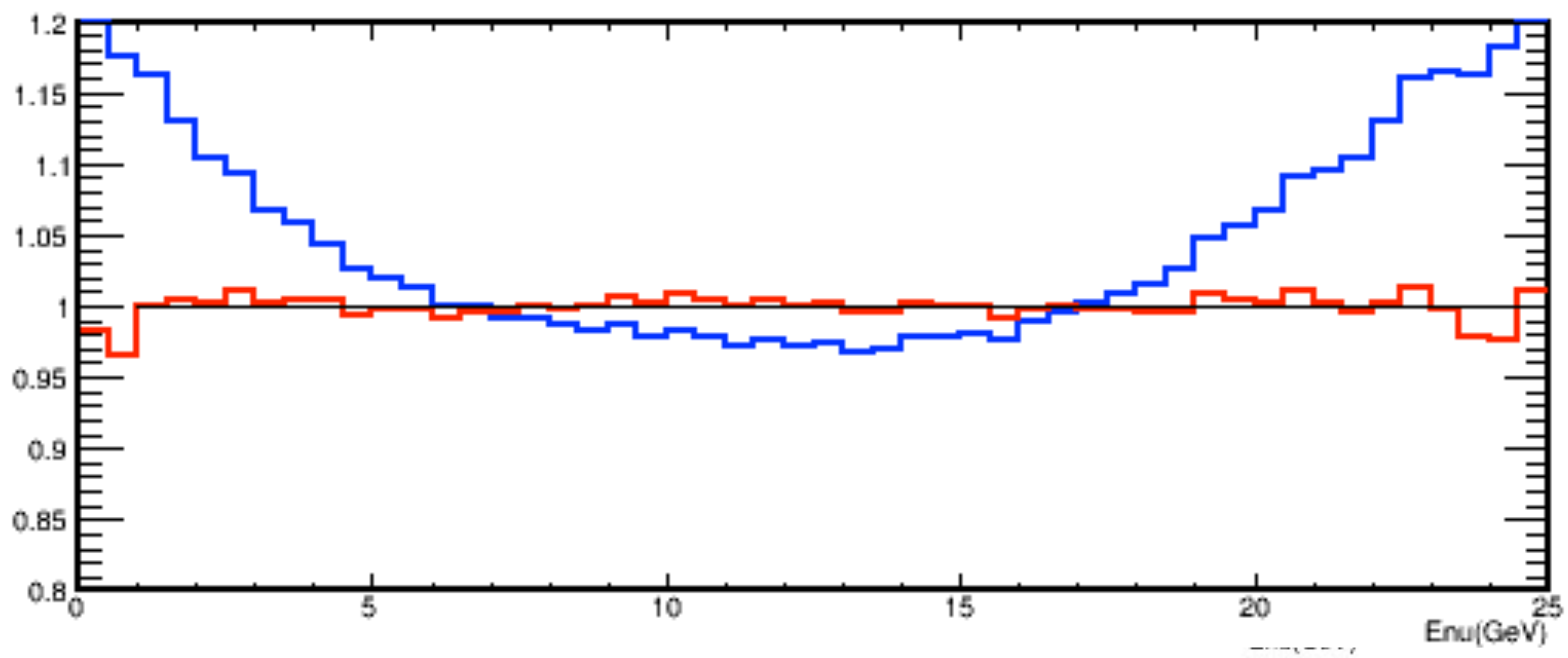
$\nu$eBar + N ⇛ $e^+$ + X (Ex<0.5 GeV)

*Observation* ⇛ *The Low-ν0 method should permit flux determination of $\nu_\mu$ and $\nu$eBar within ± ~1-% at ND;*

*Ditto for ($\nu$e and $\nu_\mu$Bar).*

⇛ *FD/ND will be more precise*



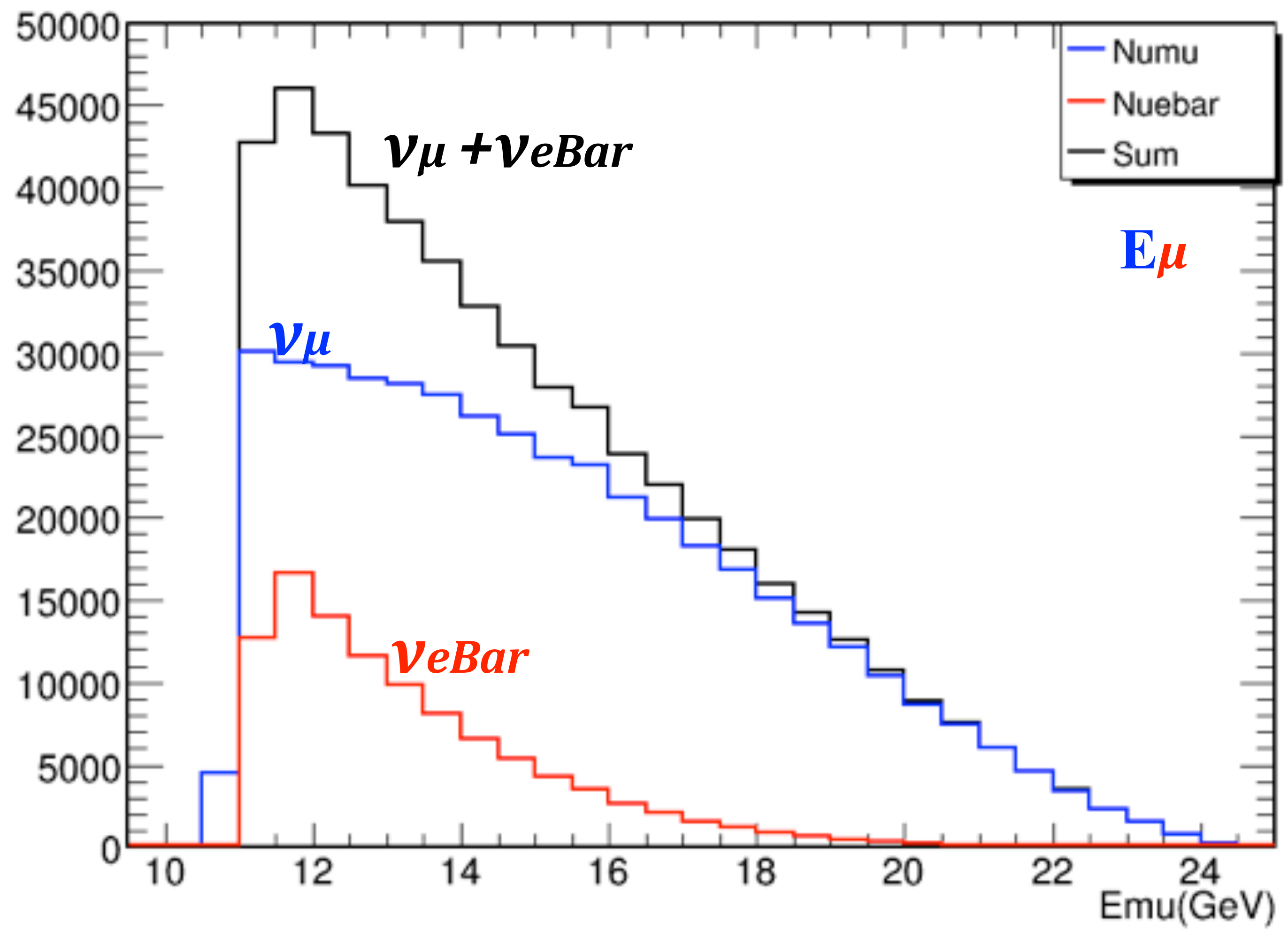



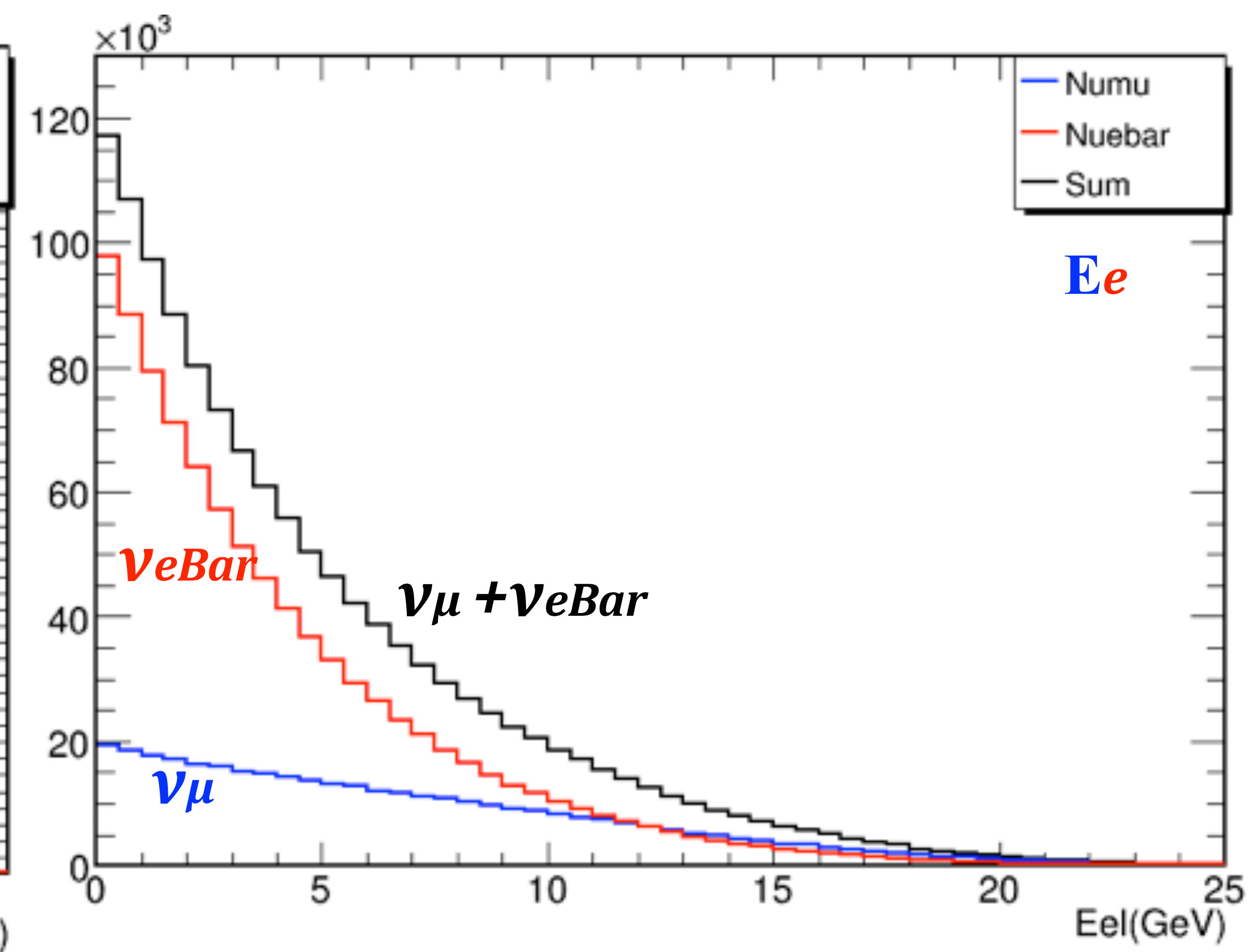
## *Fitting* $\nu\mu$ *and* $\nu eBar$ *using Elastic* $\nu$*-Electron Scattering*

- *(iii)* Mock Data: IMD ($\mu$-sample) and $\nu e$ ($e$-sample); $10^6$ $\nu\mu$-IMD-events
  *For now, ignore background*

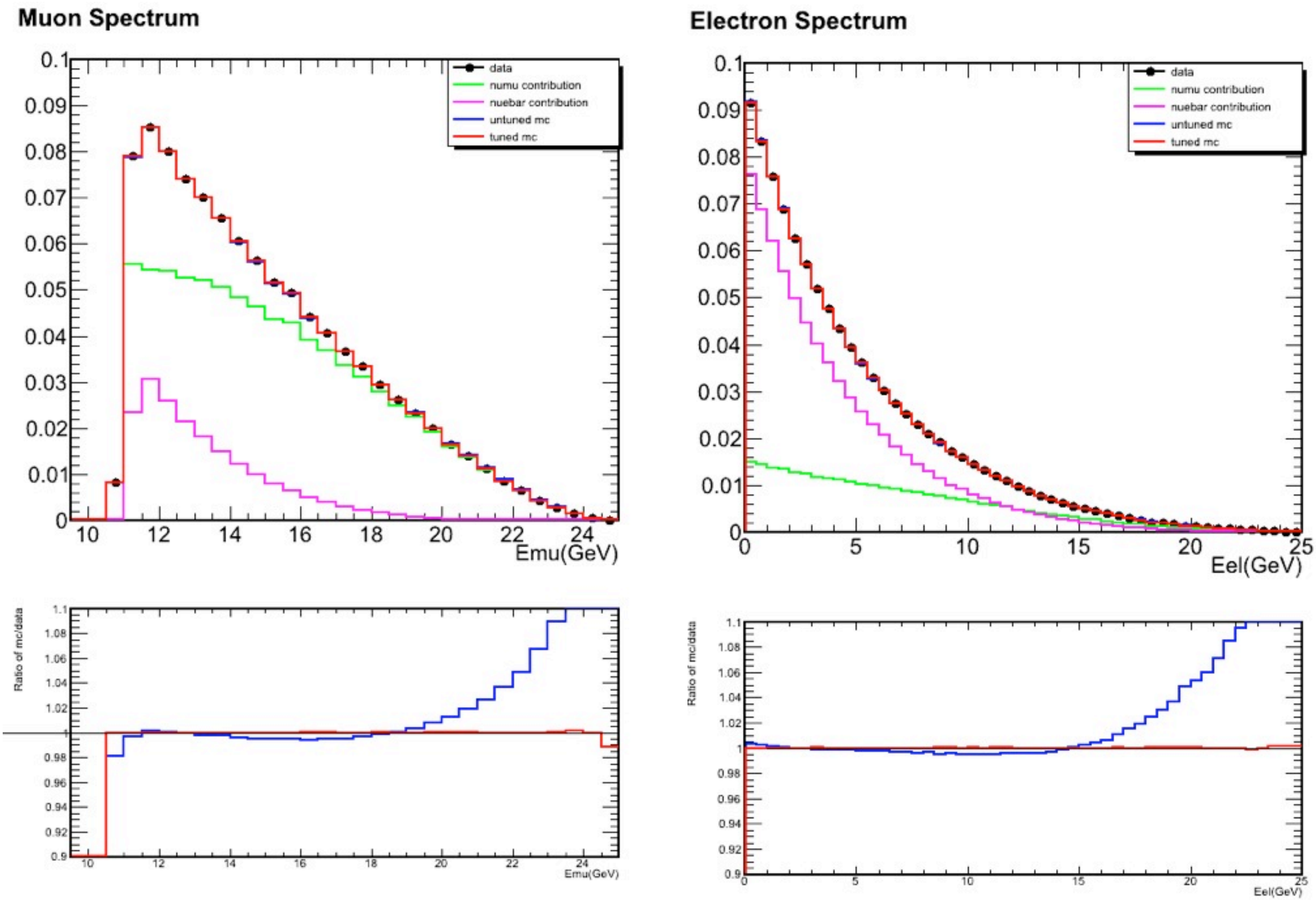
  - *(a)* Start with a Trial $\nu\mu$ & $\nu eBar$ Flux
  - *(b)* Simulate IMD and El-samples
  - *(c)* Reconstruct $E\mu$ *and* $Ee$

- *(1)* Compare samples *(iii)* with *(c)* : From $\chi^2$
- *(2)* Vary Flux parameter; Go to *(a)*; arrive at *(b)*; go to *(1)*
- *(3)* Minimize $\chi^2$: ⇒ Fitted $\nu\mu$ *and* $\nu eBar$ Flux



## *Both* IMD ($\mu$-sample) and $\nu e$ ($e$-sample)



## *Observation on Measurement of $\nu_\mu$ and $\nu_{ebar}$ Flux($E\nu$) using Leptonic-Channels*

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

## APPENDIX A: Physics Potential of HiResM$\nu$

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 HiResM$\nu$; the many theses it will engender.

### About NuMI and Service to LBL$\nu$

**1:** The energy scale and relative flux of $\nu_\mu$ Flux in NuMI

**2:** The $\overline{\nu}_\mu$ relative to $\nu_\mu$ as a function of $E_\nu$ in NuMI

**3:** Relative abundance of $\nu_e$ and $\overline{\nu}_e$ -vs- $\nu_\mu$ 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 $\pi^+$, $K^+$, $\pi^-$, $K^-$, and $K^0_L$ yields in NuMI using the $\nu_\mu$, $\overline{\nu}_\mu$, $\nu_e$, and $\overline{\nu}_e$ induced charged current interactions

### Neutral-Pion Production in $\nu$-Interactions

**6:** Coherent and single $\pi^0$ production in $\nu$-induced neutral current interactions

**7:** Multiplicity and energy distribution $\pi^0$ production in neutral current and charged current processes as a function of hadronic energy

**8:** The cross section of $\pi^0$ production as a function of $X_F$ and $P_T$ in the $\nu$-CC interactions

### Charged-Pion & Kaon and Proton & Neutron Production in $\nu$-Interactions

**9:** Coherent and single $\pi^+$ production in $\nu$-induced charged current interactions

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

**11:** Charged $\pi$/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 $\nu$-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 $\nu_\mu$-$e^-$ 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 $\nu_\mu$-$e^-$ and $\overline{\nu}_\mu$-$e^-$ neutral current interactions

### $\nu$-Nucleon Neutral Current Scattering

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

### Non-Scaling Charged and Neutral Current Processes

**20:** Measurement of $\nu_\mu$ 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 $\nu_\mu$ 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 $\nu$-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 $\Delta S$

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

### Inclusive Charged Current Processes

**33:** Measurement of the inclusive $\nu_\mu$ 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 $\nu_e$ and $\overline{\nu}_e$ charged current cross-section in the range $0.5 \leq E_\nu \leq 40$ GeV

**36:** Measurement of the differential $\nu_\mu$ charged current cross-section as a function of $x_{bj}$, $y_{bj}$ and $E_\nu$.

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

**38:** Determination of $xF_3$ and $F_2$ structure functions in $\nu_\mu$ 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 $\nu_\mu$ 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 $\nu_\mu$ 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 $\mu^-e^+$) processes

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

**56:** Measurement of J/$\psi$ production in neutral current interactions

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

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

**59:** Measurement of $K^0_S$, $\Lambda$ 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 $\Lambda$ and $\overline{\Lambda}$ polarization in neutrino charged current interactions

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

**63:** Measurement of the $\Lambda$ 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 $D^0, D^+, D_s, \Lambda_c$ 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 $\nu_\mu$-$\nu_e$ universality down to $10^{-4}$ level

**77:** A test of $\nu_\mu$-$\nu_\tau$ coupling down to $10^{-5}$ level

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

South Carolina Group

## HIRESMNU: RLS

Carolina Gr. with Dave Lee, Bill Louis, C.Mauger [LANL] with Carolina Gr.

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*

## Future Plans

✴ Error in FD/ND

✴ Estimation of backgrounds to

$\nu_e \twoheadrightarrow \nu_\mu$

$\nu_e \twoheadrightarrow \nu_\tau$

✴ Synergy between the LBNE and Nu-Factory Efforts // support ?? ⇐ *Biggest hurdle*

# *Backup Slides*

## *Salient steps of the IMD-Analysis*

| | $\nu_\mu$-IMD | $\nu_\mu$-CC | $\nu_\mu$-CCQE | $\bar{\nu}_e$-CC | $\nu_\mu$-NC | $\bar{\nu}_e$-NC |
|---|---|---|---|---|---|---|
| | 1,000,000 | 1,000,000 | 1,000,000 | 1,000,000 | 1,000,000 | 1,000,000 |
| 1 negative Track | 1,000,000 | 67,851 | 414,856 | 102,961 | 14,219 | 14,679 |
| Neutral Veto ($E_\gamma \gtrsim 0.1$ GeV) | 1,000,000 | 34,660 | 411,019 | 57,765 | 4,722 | 5,891 |
| Neutral Veto ($E_{neutron} \gtrsim 0.5$ GeV) | 1,000,000 | 20,703 | 375,027 | 33,536 | 2,454 | 3,348 |
| Neutral Veto ($E_{K_S,K_L} \gtrsim 0.5$ GeV) | 1,000,000 | 20,266 | 375,027 | 32,759 | 2,111 | 2,972 |
| $E > 11$ GeV | 983,355 | 13,544 | 257,736 | 661 | 341 | 419 |
| $\varsigma_\mu < 0.001$ GeV | 979,403 | 831 | 16,614 | 49 | 2 | 3 |
| $\varsigma_\mu < 0.0001$ GeV | 959,227 | 50 | 829 | 8 | 0 | 2 |

*Efficiency* $\Rrightarrow$ *95%* *5e-05*

- ✴ ***Neutral Veto:*** ***(i)*** E $\gamma \geq 0.1$ GeV ***(ii)*** En/K0 $\geq 0.5$ GeV
- ✴ ***Diacritical Kinematic Variable:*** $\varsigma_\mu = E_\mu (1 - \cos\vartheta_\mu)$
- ✴ ***Composition of surviving*** $\nu_\mu$-CC $\Rightarrow$

| | |
|---|---|
| QE | 68.1% |
| DIS | 1.1% |
| Res | 24.9% |
| Others | 5.9% |

## *Fitting $\nu_\mu$ and $\nu_e$Bar flux as a function of $E_\nu$*

- ✴ *(i)* Mock Data: simulate a signal/back --- IMD ($\mu$-sample), or $\nu e$ ($e$-sample), or $\nu_\mu$-N CC
- ✴ *(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 $\chi^2$
- ✴ *(2)* Vary Flux parameter; Go to *(a)*; arrive at *(c)*; go to *(1)*
- ✴ *(3)* Minimize $\chi^2$: ⇒ Fitted Flux

*Missing:*

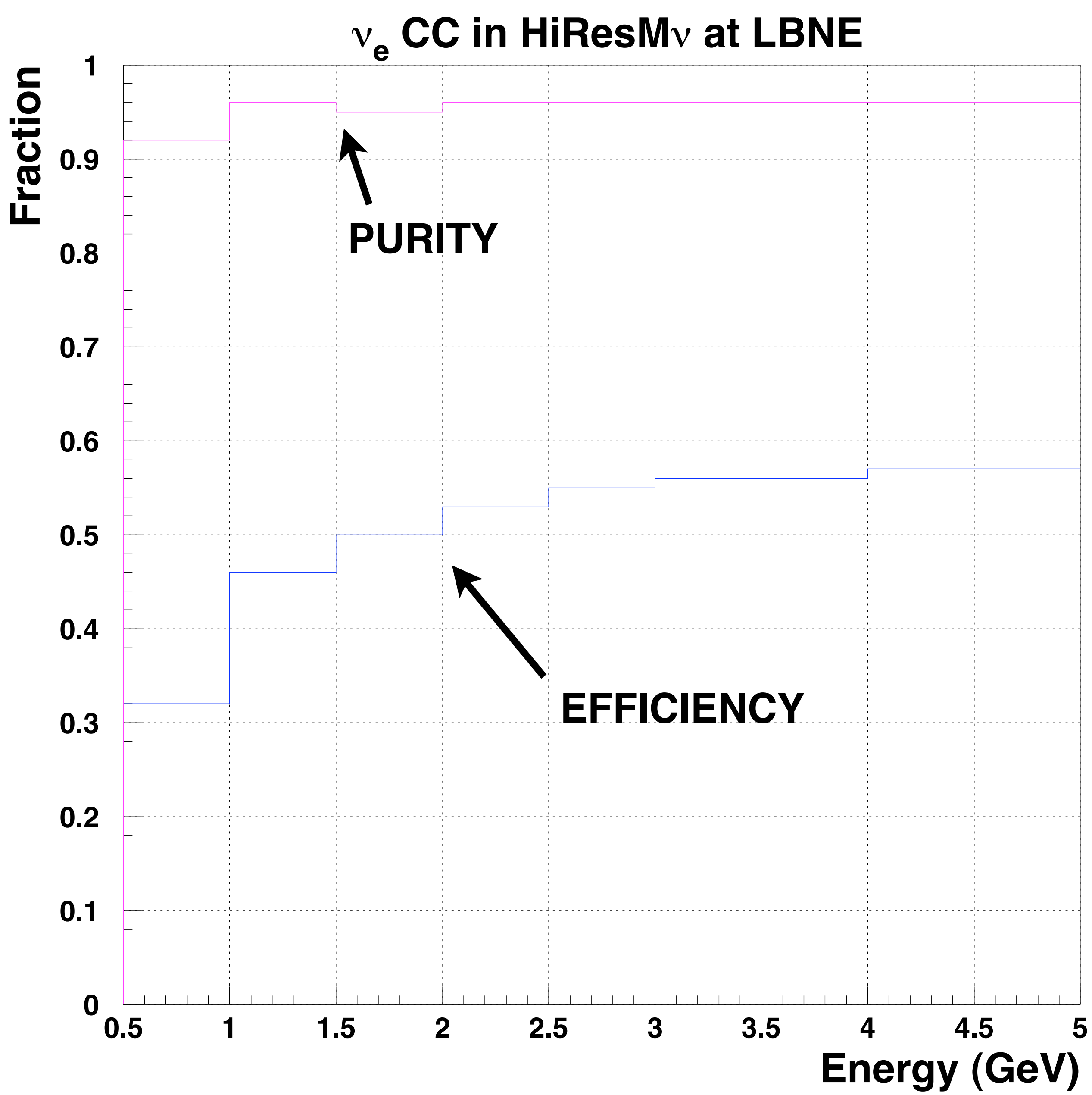
*Determination of Beam-Divergence using $\nu$ -Data*

Systematic-Errors in Low-$\nu_0$ Relative Flux: $\nu_\mu$ & Anti-$\nu_\mu$

- Variation in $\nu_0$-cut
- Variation in $\nu_0$-correction
- Systematic shift in Ehad-scale
- Vary $\sigma$(QE) ±10%
- Vary $\sigma$(Res) ±10%
- Vary $\sigma$(DIS) ±10%
- Vary functional-forms
- Systematic shift in Emu-scale

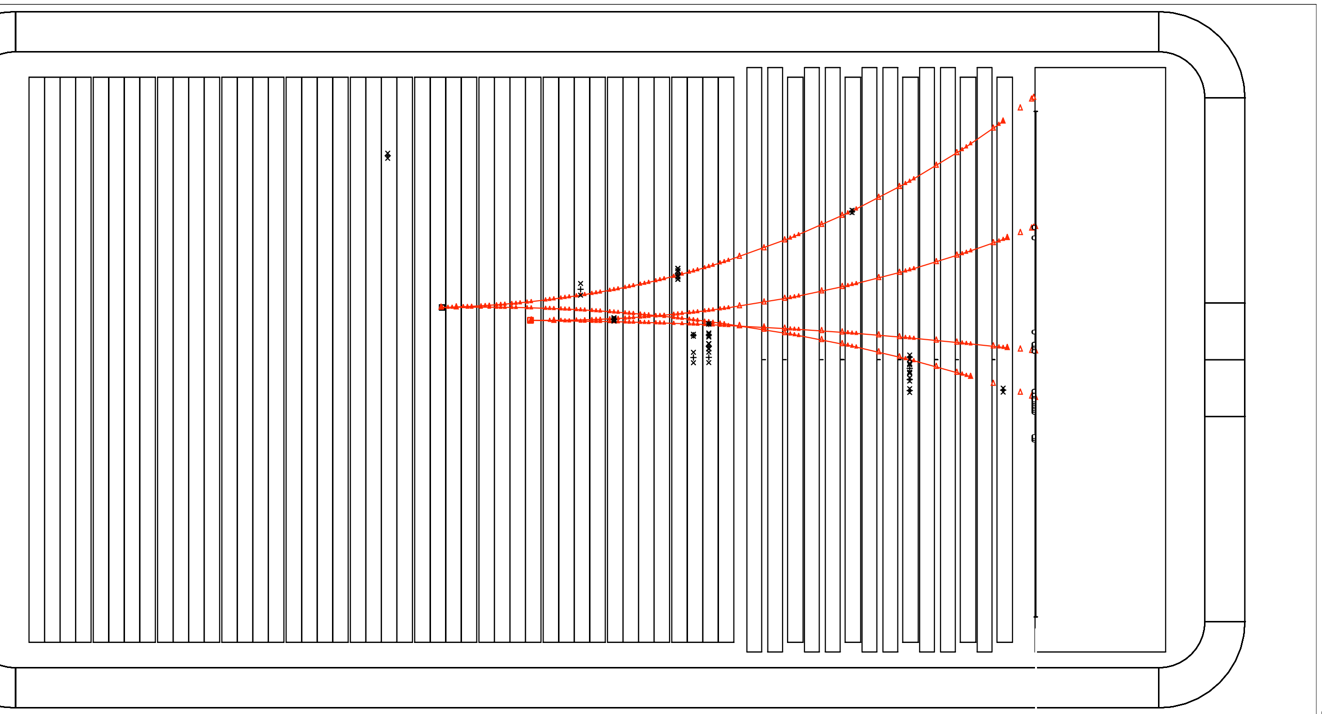
- Beam-Transport ⇐ Missing

# IDENTIFICATION OF $\nu_e$ CC INTERACTIONS




- *The HiResM$\nu$ 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 $\pi$ rejection of $10^{-3}$ for $\varepsilon \sim 90\%$*
- *Use multi-dimensional likelihood functions incorporating the full event kinematics to reject non-prompt backgrounds ($\pi^0$ in $\nu_\mu$ CC and NC)*
  $\Longrightarrow$ *On average $\varepsilon =$* **55%** *and $\eta =$* **99%** *for $\nu_e$ CC at LBNE*

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



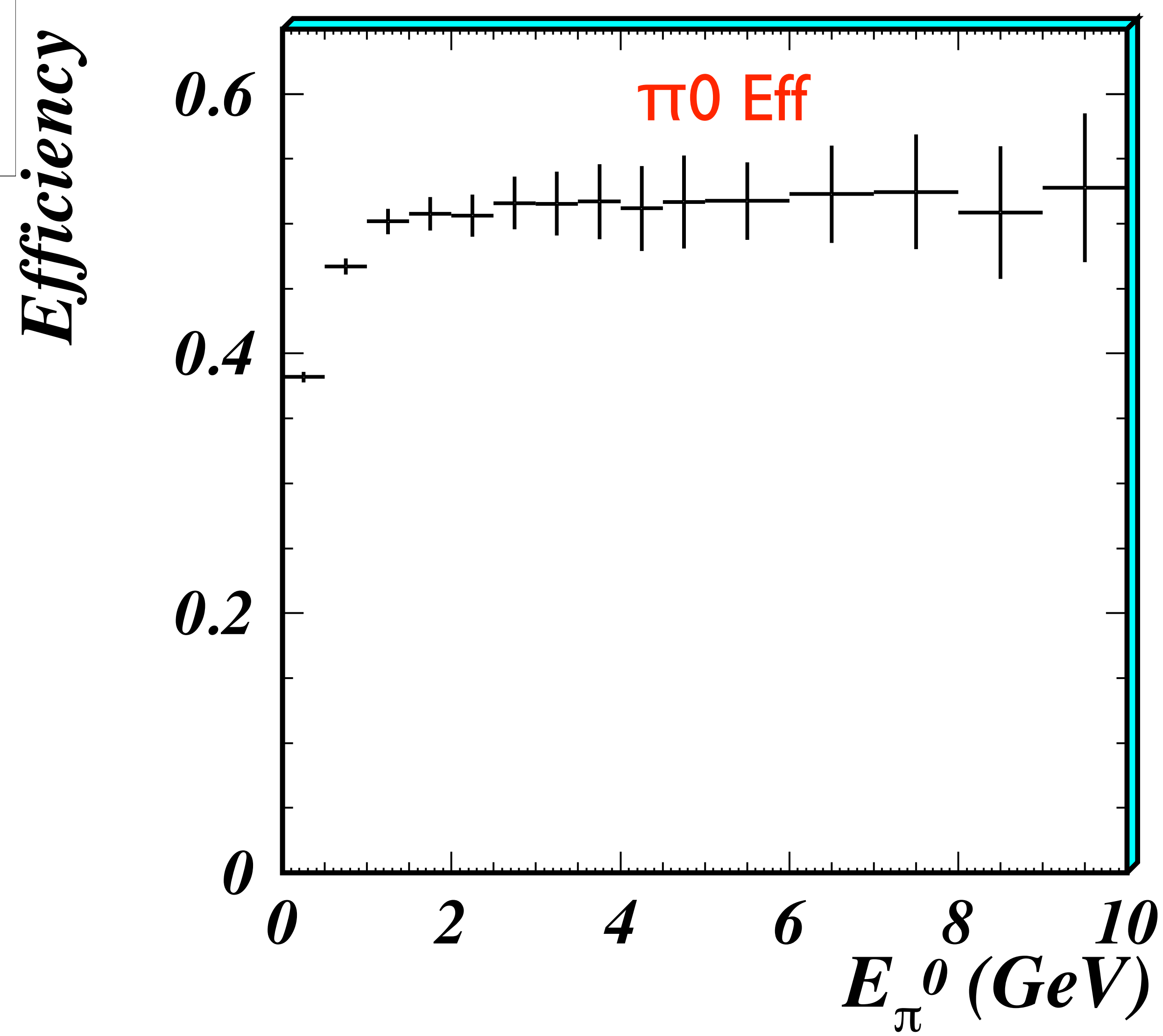
π0-Reconstruction

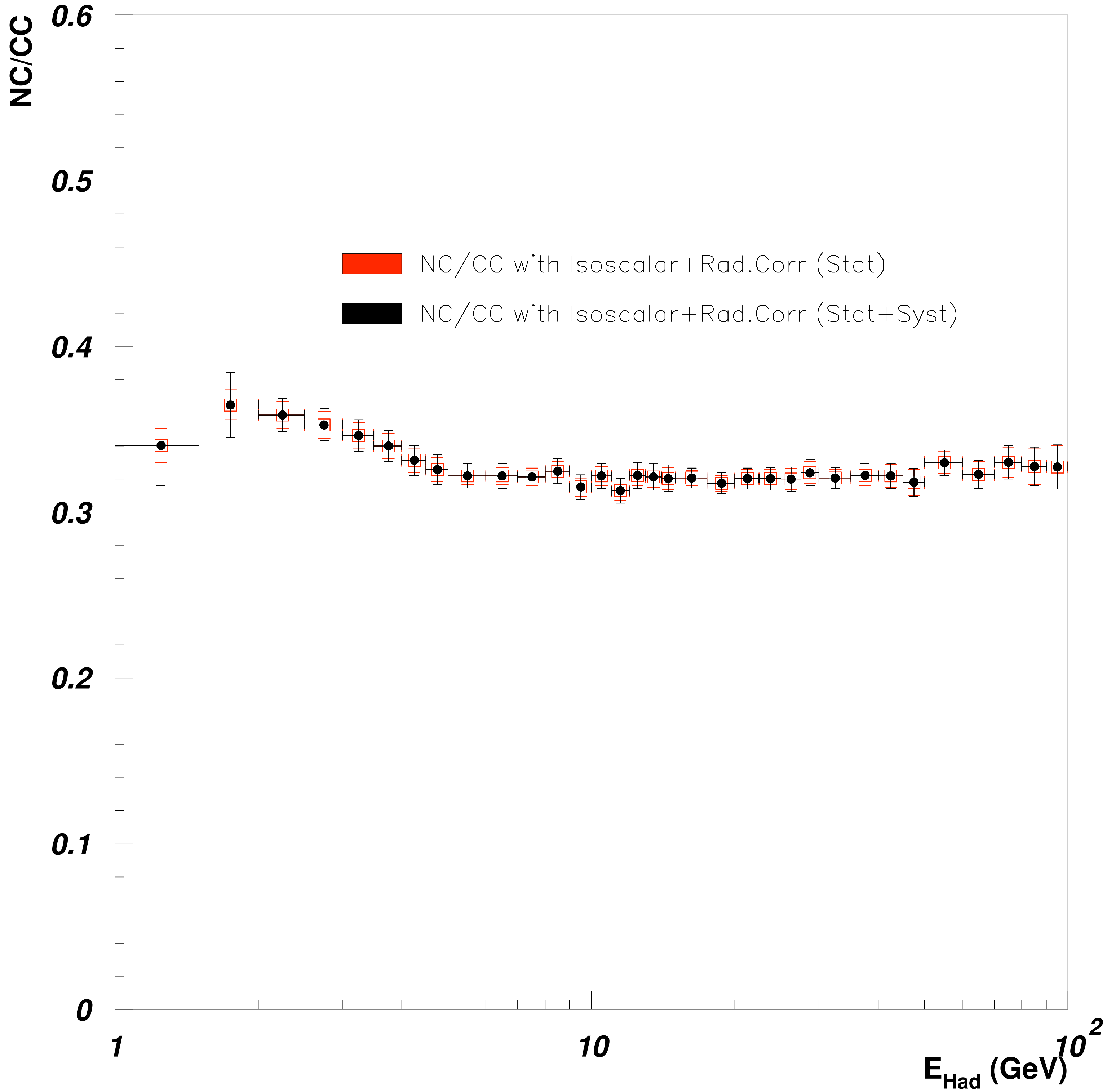
✳ Clean Π0- and γ-signatures in STT

✳ ν-NC & CC ➻ π0 ➻ γγ
~50% of the γ ➻ e+e- will convert in the STT, away from the primary vertex.

✳ 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






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

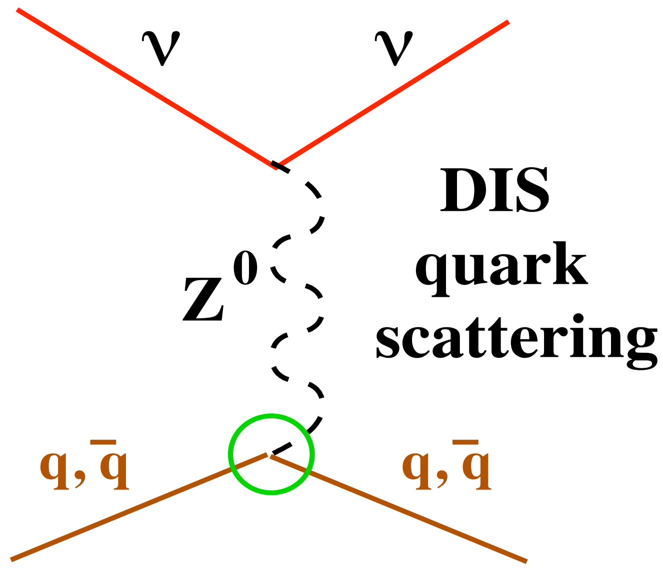
# PRECISION MEASUREMENTS

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

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

- $\delta sin^2\theta_W / sin^2\theta_W =$ ___ *0.1%* $\Leftarrow$ *Goal*
- *19(6)$\times 10^6$ NC selected events in $\nu(\bar{\nu})$ mode*

$\Longrightarrow$ *Dominated by systematics*

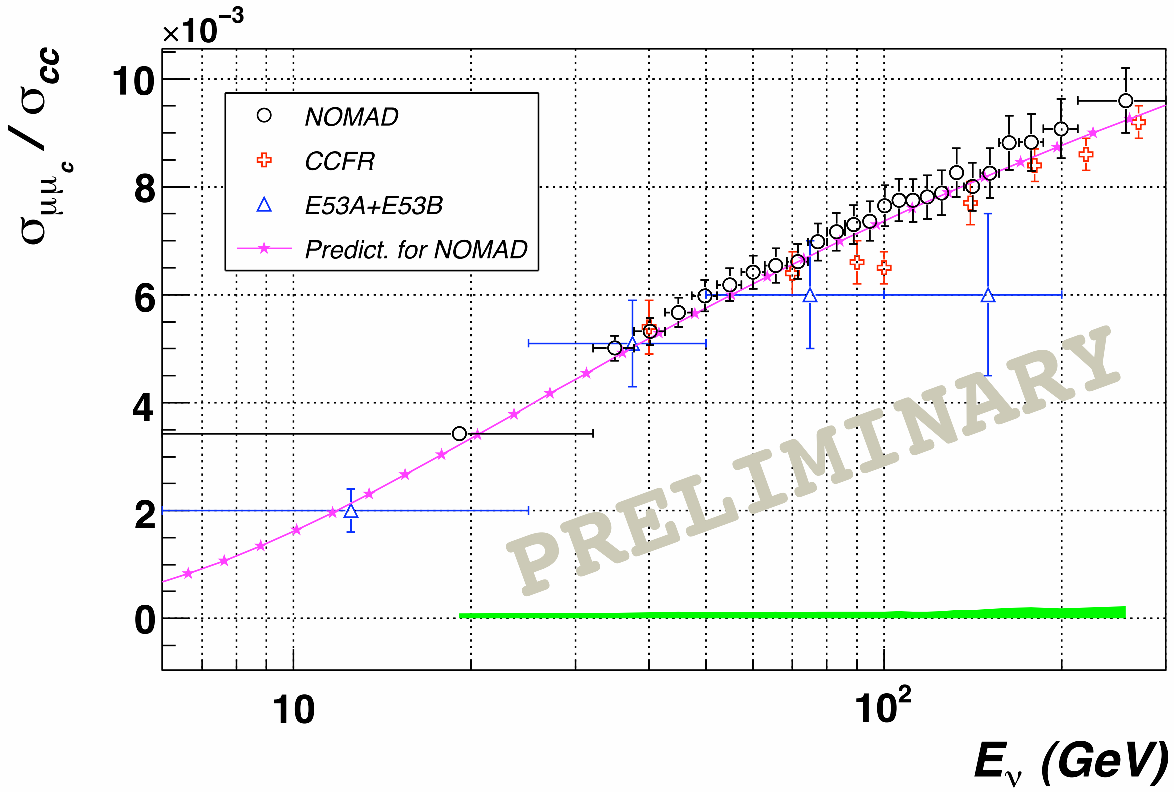


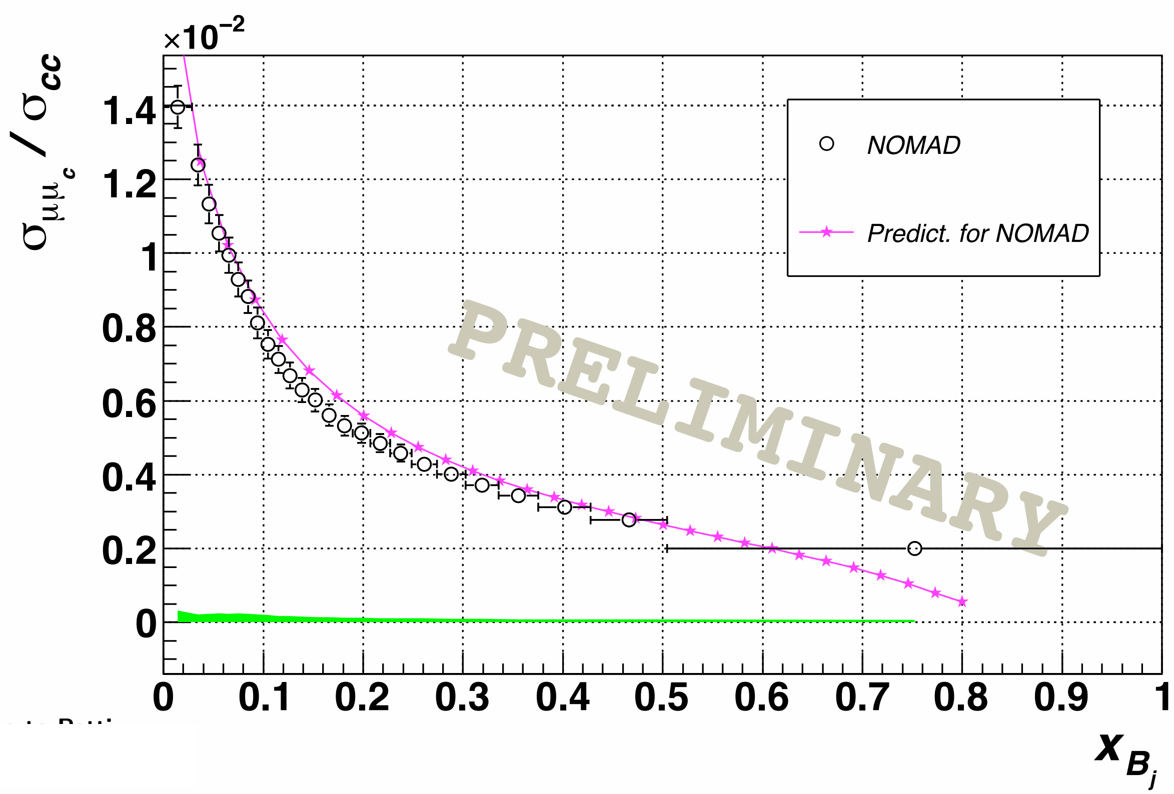
| Source of uncertainty | $\delta\mathcal{X}/\mathcal{X}$ | $\delta R^{\nu}/R^{\nu}$ | $\delta R^{\bar{\nu}}/R^{\bar{\nu}}$ | $\delta\mathcal{X}/\mathcal{X}$ | $\nu$ -*Factory* |
|---:|---|---|---|---:|---|
| Data statistics | 0.00593 | 0.00176 | 0.00393 | | |
| Monte Carlo statistics | 0.00044 | 0.00015 | 0.00025 | | |
| **Total Statistics** | **0.00593** | **0.00176** | **0.00393** | **0.0008** | → 0.0000 |
| $\nu_e, \bar{\nu}_e$ flux ($\sim 1.7\%$) | 0.00171 | 0.00064 | 0.00109 | 0.0001 | |
| Energy measurement | 0.00079 | 0.00038 | 0.00059 | 0.0004 | → 0.0000 |
| 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. | → 0.0000 |
| Other | | | | 0.0008 | |
| **Experimental systematics** | **0.00277** | **0.00112** | **0.00141** | **0.0010** | → 0.0000 |
| d,s→c, s-sea | 0.00206 | 0.00227 | 0.00454 | 0.0011 | |
| Charm sea | 0.00044 | 0.00013 | 0.00010 | n.a. | → *Fig* |
| $r = \sigma^{\bar{\nu}}/\sigma^{\nu}$ | 0.00097 | 0.00018 | 0.00064 | 0.0005 | → 0.0000 |
| 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 | → 0.0003 |
| **Model systematics** | **0.00281** | **0.00258** | **0.00523** | **0.0014** | → 0.000? |
| **TOTAL** | **0.00711** | **0.00332** | **0.00672** | **0.0019** | → 0.000? |
| | | | | | → 0.000? |

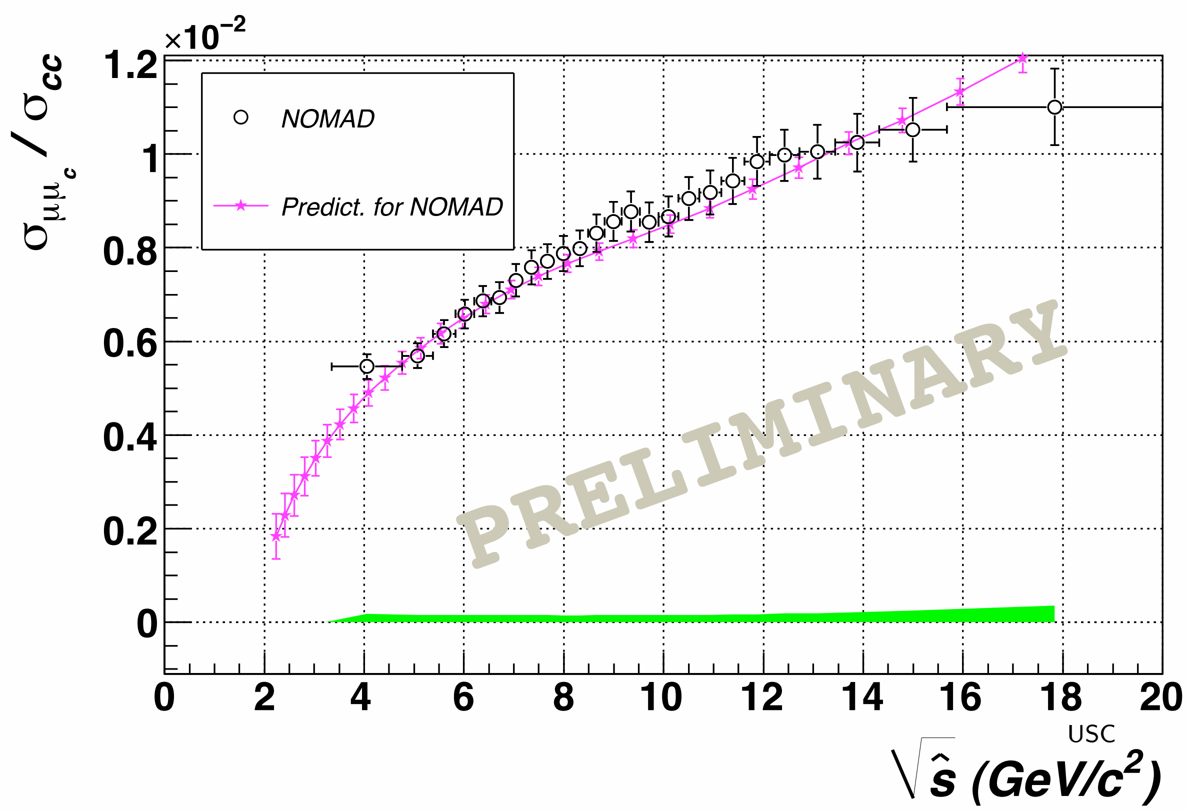
Table 4: Summary of uncertainties on the extraction of the weak mixing angle ($\mathcal{X} = \sin^2\theta_W$) based upon the Pascos-Wolfenstein relation. The first three columns refer to the published NuTeV errors [12] while the last column indicates the corresponding projection for our experiment.

## TO BE PRESENTED AT DIS *2011*

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



## MEASUREMENT OF $\Delta s$

✦ $\boxed{\text{NC ELASTIC SCATTERING}}$ *neutrino-nucleus is sensitive to the strange quark contribution to nucleon spin, $\Delta s$, 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* $\boxed{\text{NC/CC RATIOS}}$ *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 HiResM$\nu$ will be at the $10^{-3}$ level: $\sim$ 1.5 $\times 10^6$ $\nu$ NC and $\sim$ 800k $\bar{\nu}$ NC events*
- *High resolution tracking for protons down to momenta of 250 MeV/c in HiResM$\nu$ 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 $R_\nu$ and $R_{\bar{\nu}}$;*
- *Need to check neutron background.*