Discoveries in Long Baseline ν- Experiments:

Precision Ingredients

Questions

#1: 1st → 3rd Generation ν-mixing θ_{13}? ~0.005

#2: CP-Violation in Lepton-sector δ?

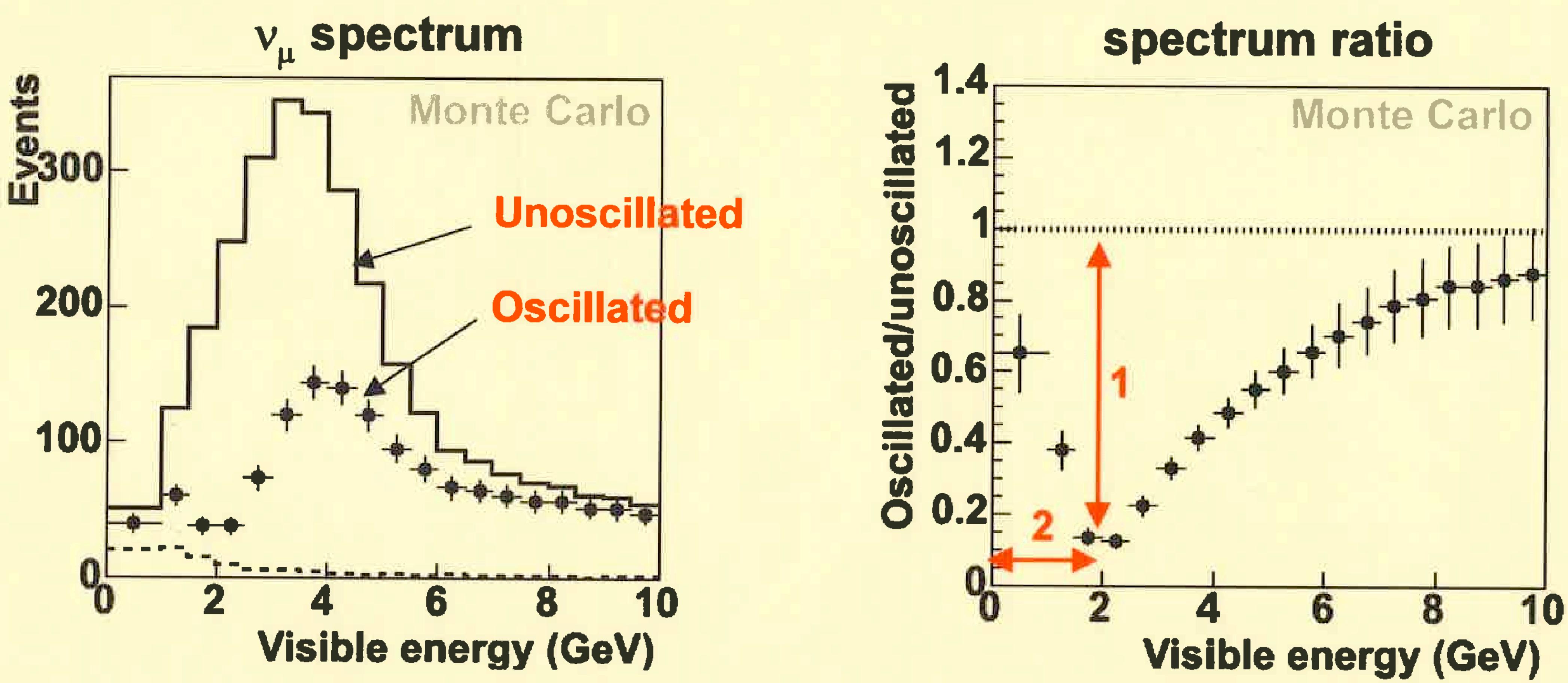
#3: ν-Mass Hierarchy $\Delta m^2 \gtrless 0$?

#4: Is $\nu_2 - \nu_3$ mixing maximal $\theta_{23} = 45°$?

Example of a ν_μ disappearance measurement

- Look for a deficit of ν_μ events at Soudan…

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \boxed{\sin^2 2\theta}_{\,1} \sin^2(1.267 \boxed{\Delta m^2}_{\,2} L / E)$$



Ubeity of the Neutrino Mass Matrix

MIXING

KNOWN PARAMETERS:

- *sin*$^2(2\Theta_{12}) = 0.86^{+0.03}_{0.04}$
  ($\theta_{12} \sim 33^0$*)*
  from Solar and Reactor neutrino oscillations
- *sin*$^2(2\Theta_{23}) \geq 0.92$
  ($\Theta_{23} \sim 45^0$*)*
  from Atmospheric and NuMI/MINOS oscillations

TO BE DETERMINED:

- *sin*$^2(2\Theta_{13}) \leq 0.19$ *at 90% CL*
  ($\Theta_{13} < 9^0$ *at 90% CL)*
  from Reactor experiments
- δ *CP phase*
  $\Longrightarrow P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
- $\nu_2 - \nu_3$ *mixing Maximal (*$\Theta_{23} \equiv 45^0$*)?*

MASSES

KNOWN PARAMETERS:

- $\Delta m^2_{32} = 2.4 \times 10^{-3}$, $\Delta m^2_{21} = 8.0 \times 10^{-5}$
- *One* ν *has a mass of AT LEAST 0.05 eV*
- *Masses must be AT MOST 2.5 eV*
  ($m_{electron}$ *511000 eV!)*
- $\Longrightarrow \Delta m^2_{32} \simeq 1.9 - to - 3.0 \times 10^{-3}$

TO BE DETERMINED:

- *Mass hierarchy (Normal or Inverted?)*
- *Absolute* ν *mass scale*
- *Spinoza: That which is not forbidden needs necessarily must happen*

CORRELATIONS & DEGENERACIES

$\nu_\mu \leftrightarrow \nu_e$ and $\nu_e \longrightarrow \nu_\tau$

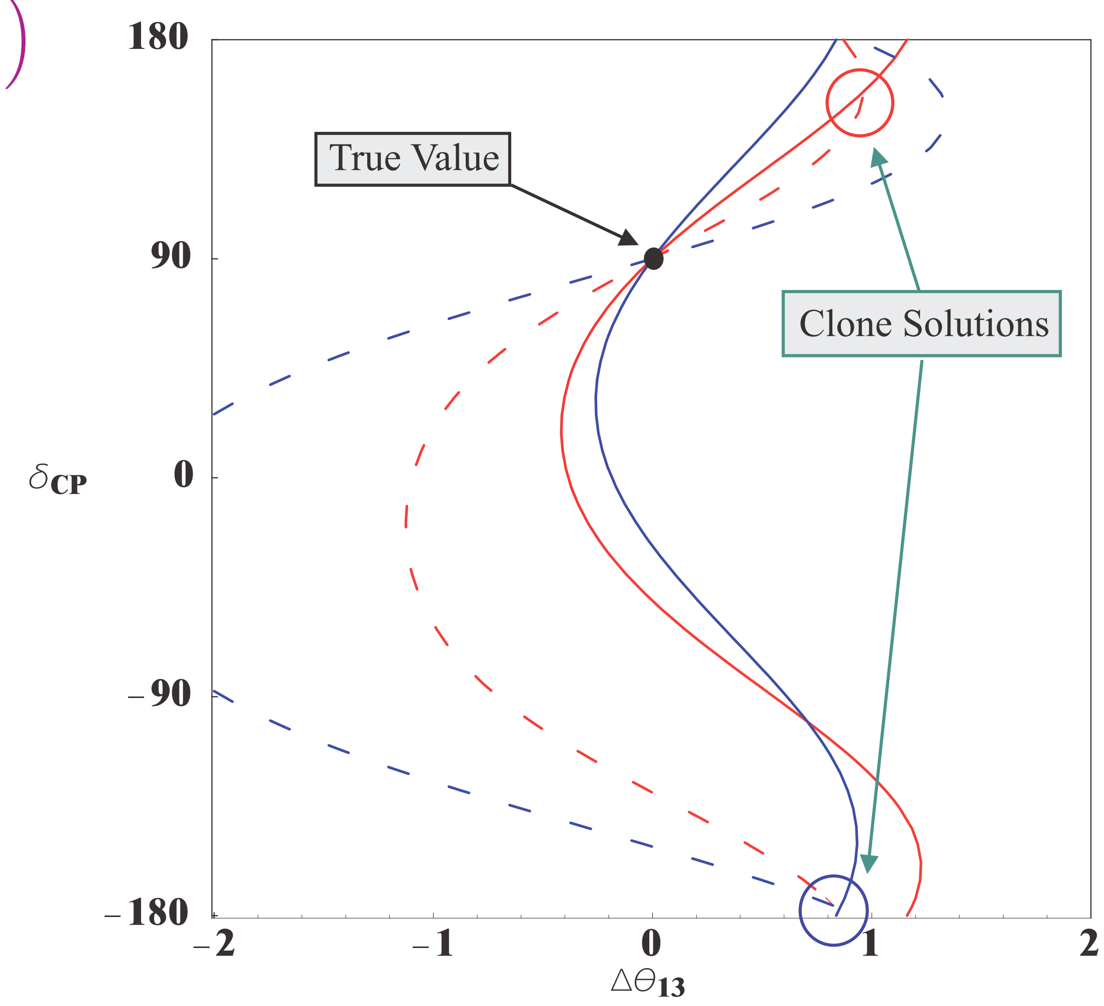
$$P^{\pm}_{\alpha\beta} \equiv P^{\pm}_{\alpha\beta}\left(\theta_{\alpha\beta}, \delta_{\text{CP}}, sign\left[\Delta m^2_{23}\right], sign\left[\tan(2\theta_{23})\right]\right)$$

Need independent measurements to solve eightfold degeneracy:

- *ν and $\bar{\nu}$;*
- *Different L/E values;*
- *Complementary channels: $P_{\mu e}$ vs. $P_{e\tau}$;*
- *$\nu_{e,\mu,\tau}$ appearance vs. $\nu_{e,\mu}$ disappearance.*

$\Downarrow$

Complex experimental program
Sensitivity to oscillation parameters affected by systematics in backgrounds & signal detection



To Establish a DISCOVERY in $\mathcal{LBL}$ ν-Experiments

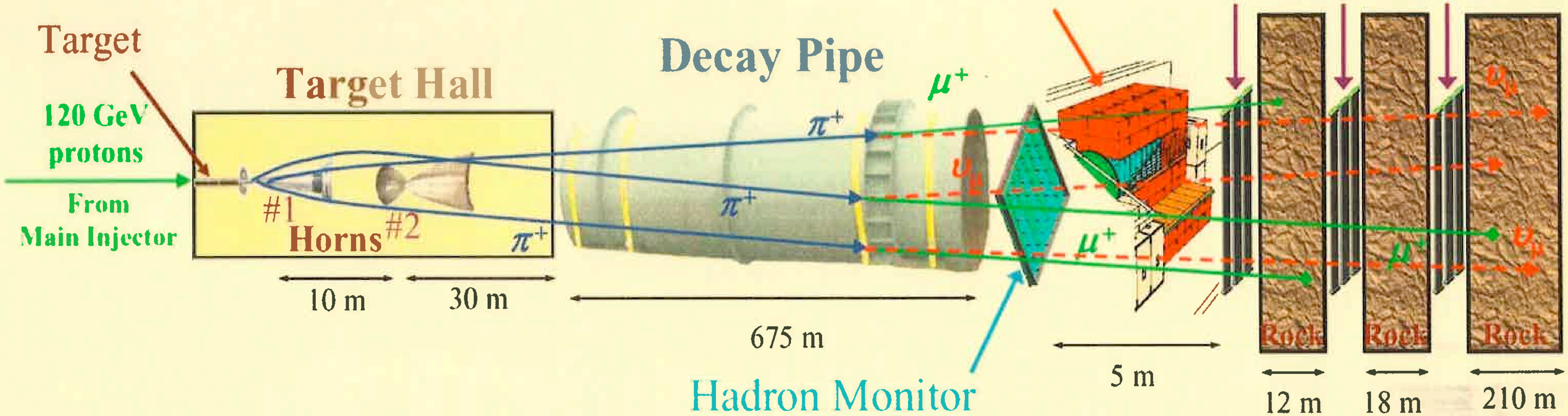
I $\mathcal{PRECISION}$

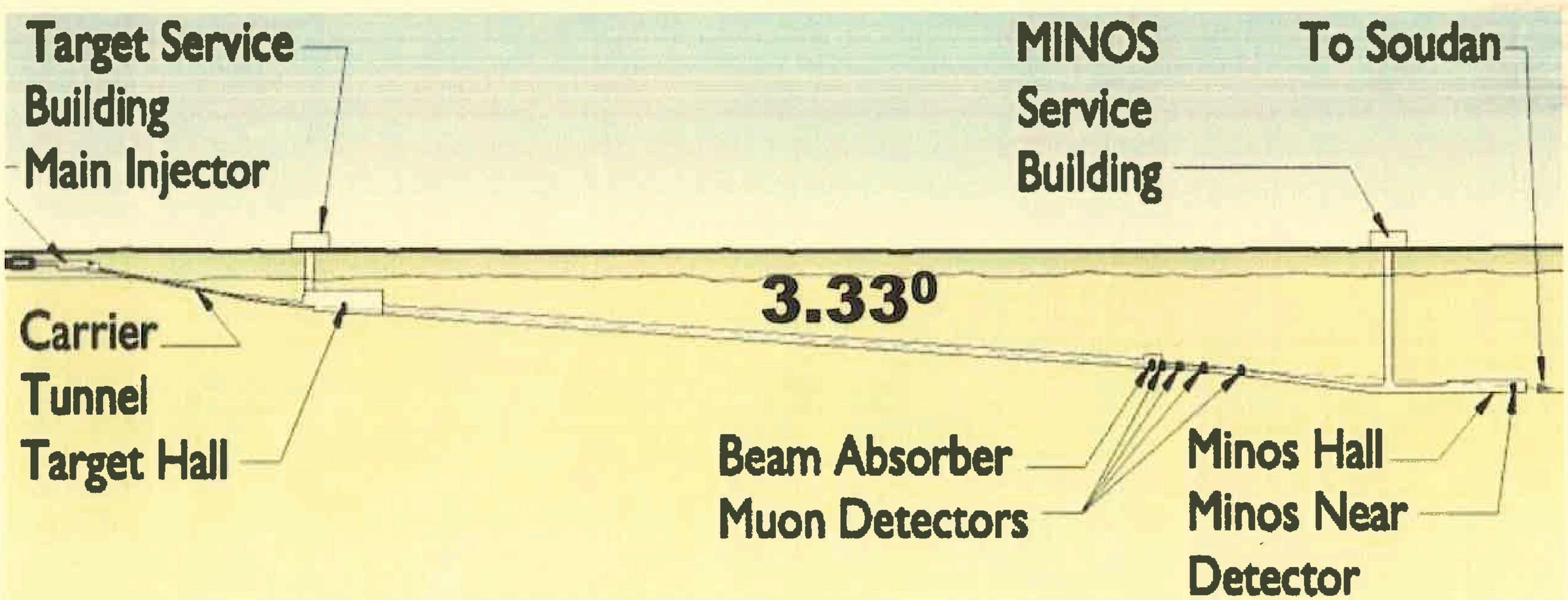
- *Statistics: accelerator, tonnage;*
- *Near detector(**s**): resolution;*
- $\sigma_{\nu,\bar{\nu}}$*: inclusive and exclusive channels;*
- ν *Neutral Current (NC) and Charged Current (CC) interactions.*
- *Topology: multiplicity of* ν*-induced* $\pi^{\pm}/K^{\pm}/\pi^{0}$*;*
- *Nuclear effects*

II $\mathcal{REDUNDANCY}$

- *Complementary projects;*
- *Hadro-production* $(\pi^{\pm}, K^{\pm}, K^{0})$ *data;*
- *Flux measurement* $\Phi(\nu_{\mu}, \bar{\nu}, \nu_{e}, \bar{\nu}_{e})$ *as a function of* (E_{ν}, θ_{ν}).

Experimental setup: NuMI beam





Hadro-Production Measurement

- M.I.P.P. — E907 & upgrade at FNAL
  H.A.R.P. & expts at CERN

$$p + \mathcal{N} \rightarrow \pi^{\pm}, K^{\pm}, p, K^0_S, \Rightarrow \frac{d^2\sigma}{dx_F\, dP_T^2}(\pi^{\pm}/K^{\pm}/..)$$

- use ν-target
- use nuclear targets used in ν-Beam Elements
- $P_{\pi^{\pm}/K^{\pm}} \Rightarrow$ precise systematic measurements
- modeling of beam-transport : emperically constrained

$\Rightarrow$ powerful constraint on E_ν-scale

$\Rightarrow$ $\phi(E_\nu, \theta_\nu)$ for $\nu_\mu(\pi^+, K^+)$, $\bar{\nu}_\mu(\pi^-, K^-)$,

$\nu_e(K^+, K^0_L, \mu^+)$, $\bar{\nu}_e(K^0_L, K^-, \mu^-)$

REDEFINING THE CONCEPT OF NEAR DETECTOR

✦ *Use of "identical" small detector at a near site insufficient for future LBL experiments:*

- $\Phi^{\nu,\bar{\nu}}(E_\nu, \theta_\nu)$ *different at near & far sites;*
- *Impossible to have really "identical" for* $\mathcal{O}(100kt)$ *detectors at projected luminosities;*
- *Different compositions of event samples* (ν_e, ν_μ, *NC, CC)*

$\Longrightarrow$ *Coarse resolution dictated by* $\mathcal{O}(100kt)$ *compromises measurements at near site*

✦ *Need additional high resolution detector to address systematics affecting LBL:*

- $\nu_\mu, \bar{\nu}$, $\boxed{\nu_e}$, $\boxed{\bar{\nu}_e}$ *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 LBL*

✦ *Fine grained near detectors at future LBL facilities are natural candidates to study neutrino scattering physics.*

Can they achieve a physics potential comparable to LEP?

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

S.R. Mishra, R. Petti, C. Rosenfeld

University of South Carolina

HiResMν

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.*

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

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

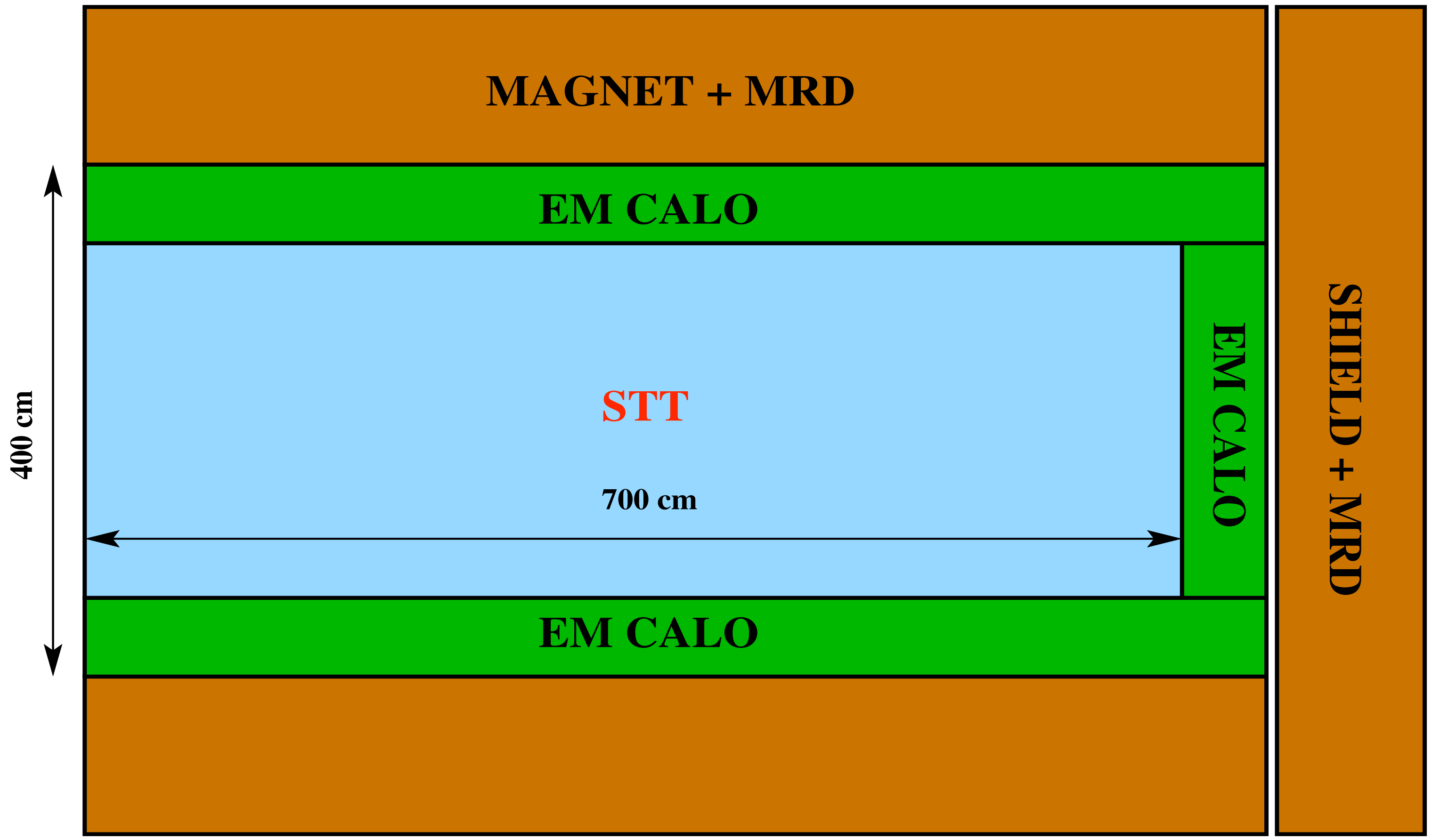
  Direct probe of the running of $\sin^2\theta_W$ *within a single experiment.*

- *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.*

PROPOSED DETECTOR

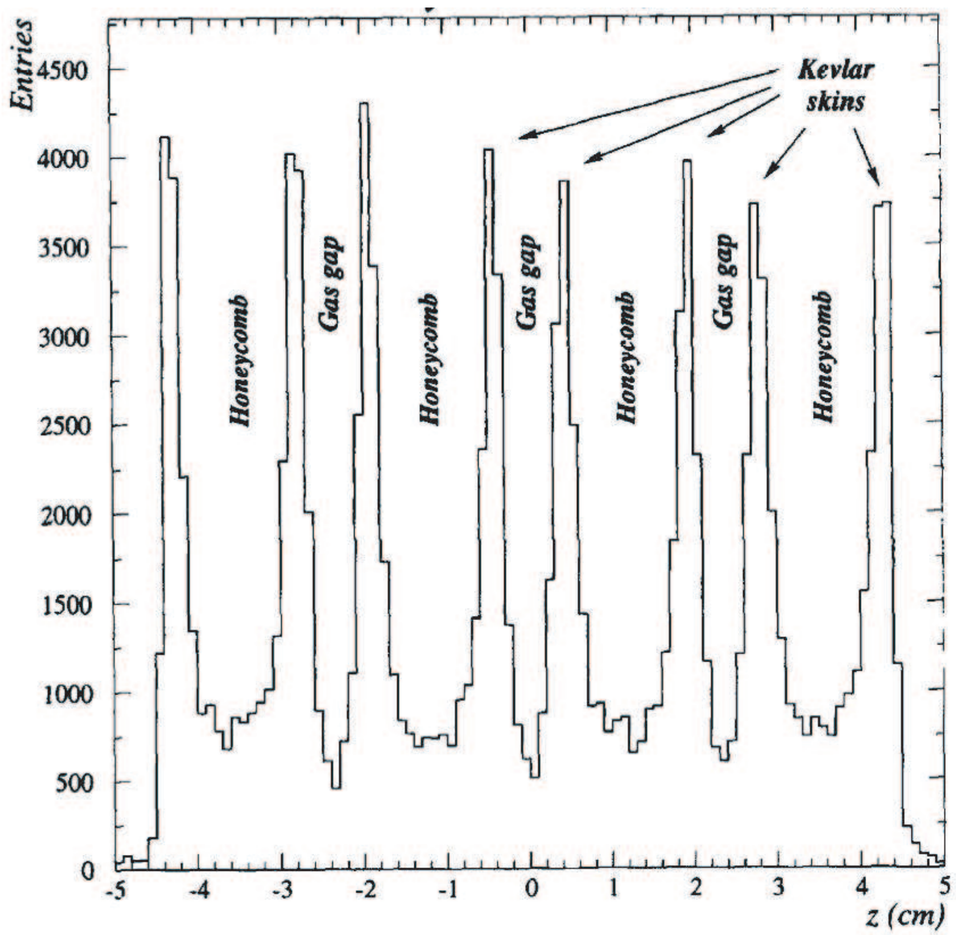
Fiducial Mass ~ 7.4 tons



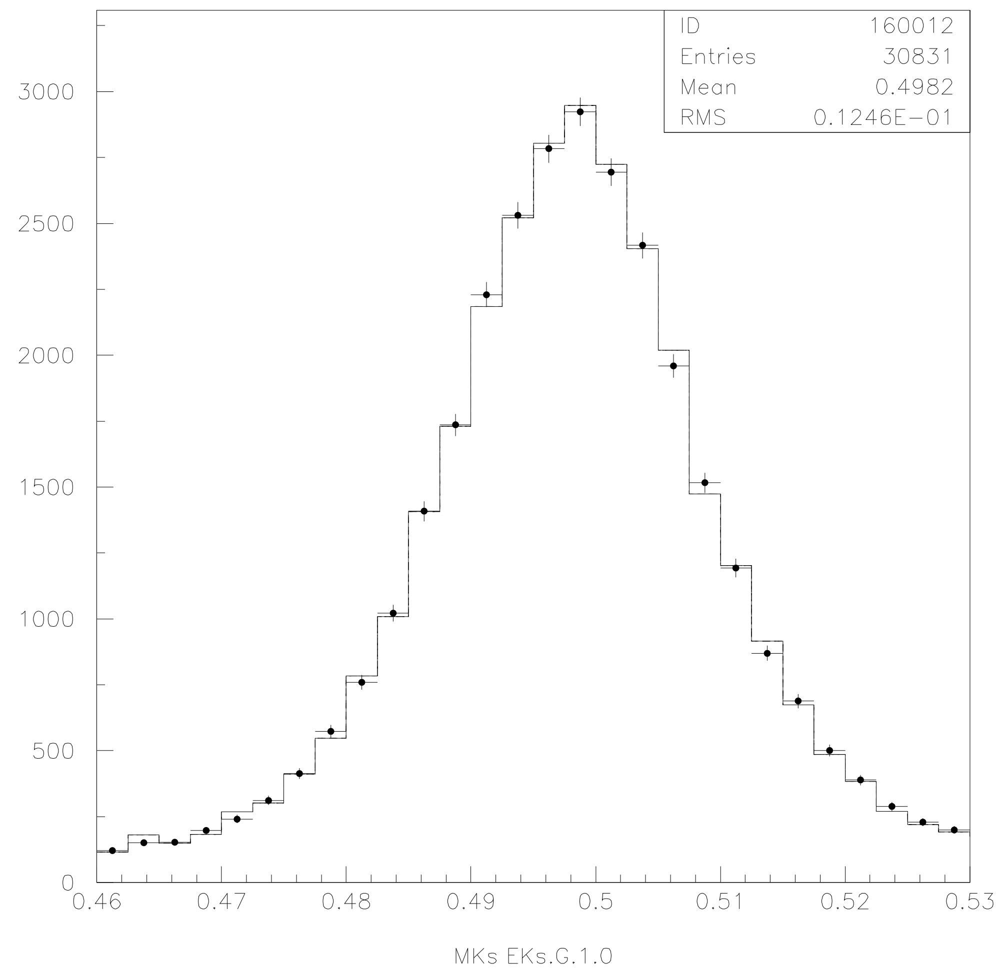
- *Build upon the NOMAD experience:*
  - *Simple inner detector combining high resolution tracking & particle identification;*
  - *Low density design with target embedded.*
- *Side coverage of EM calorimeter needed for π^0 detection*

$\Longrightarrow$ *Will describe the STT detector in the following*

What we build on: NOMAD DATA



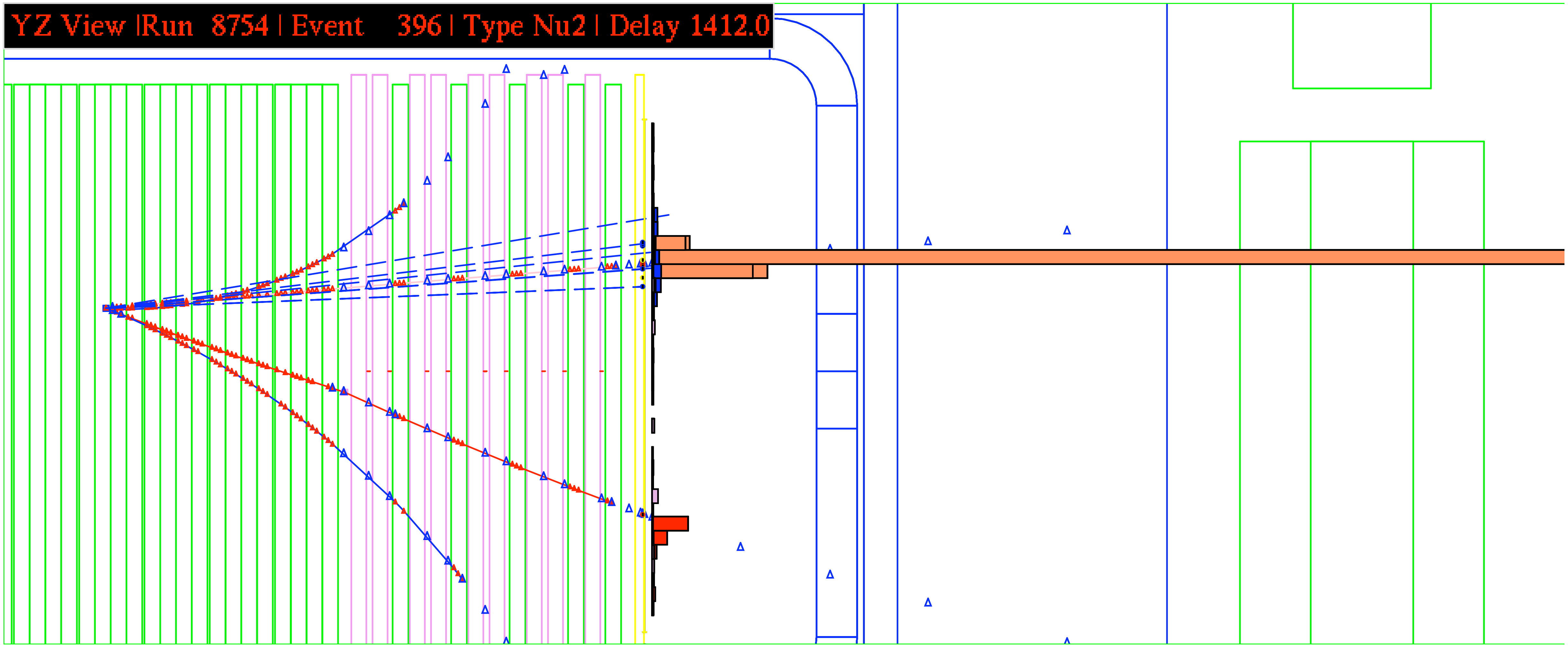
Neutrino radiography of one drift chamber



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*

$\bar{\nu}_e$-CC

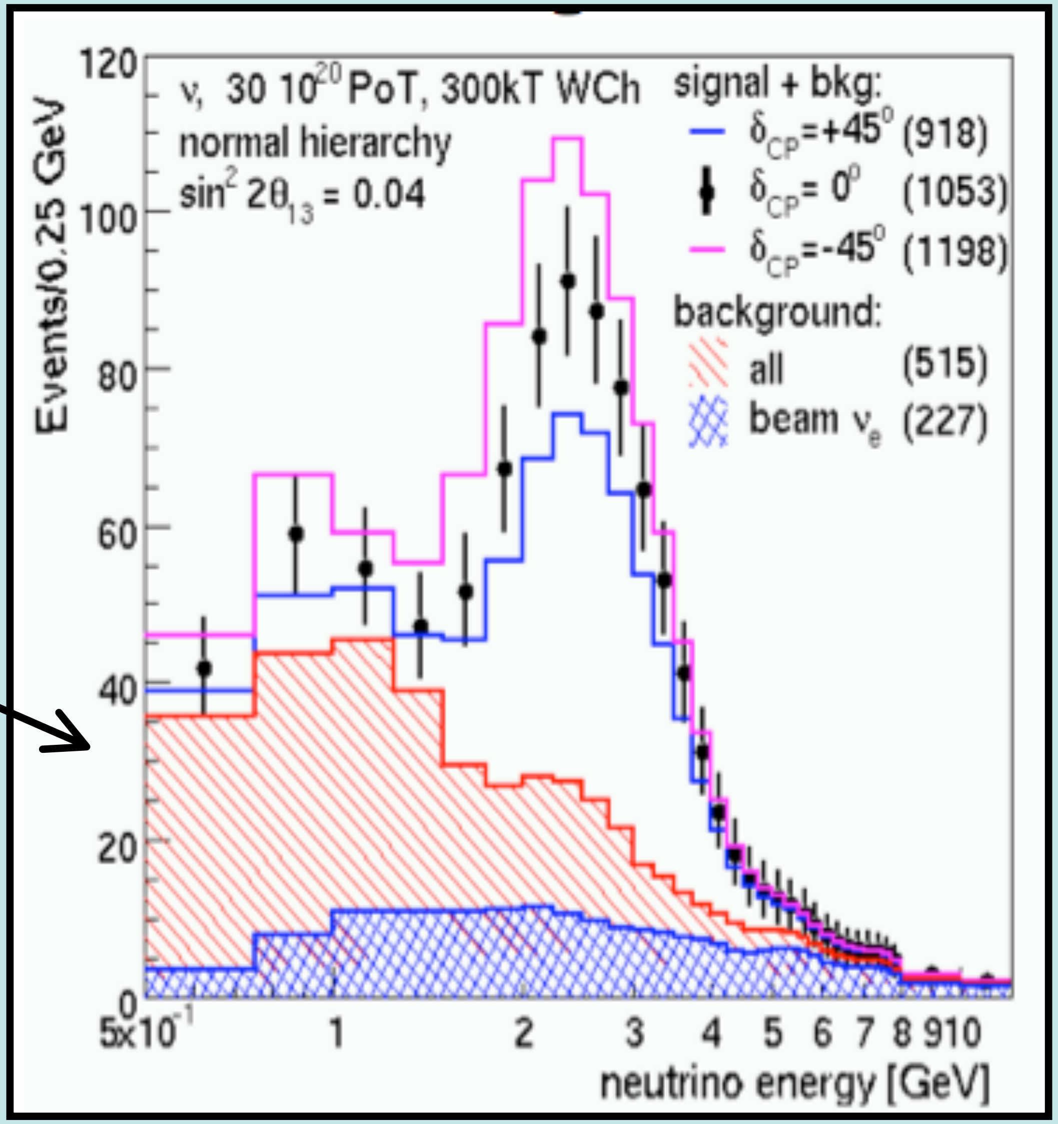


A $\bar{\nu}_e$ CC Event Candidate in NOMAD. The positron track with bremsstrahlung photons are clearly visible. The HiResMν will have more sampling points, TR, and and better γ acceptance.

ν Cross Section Needs

- Expected #-NuE Like Event Spectrum

$\nu_\mu \rightarrow \nu_e$ at far detector
1st and 2nd oscillation maxima
at **2.4** and **0.8** GeV



(M. Bishai, 02/27/09 UCDavis)

Cross - Sections

- Oscillation measurements ⇒ $\dfrac{\#\text{Events in Far}}{\#\text{Events in Near}}(E_\nu)$

to 1st order error in σ cancels

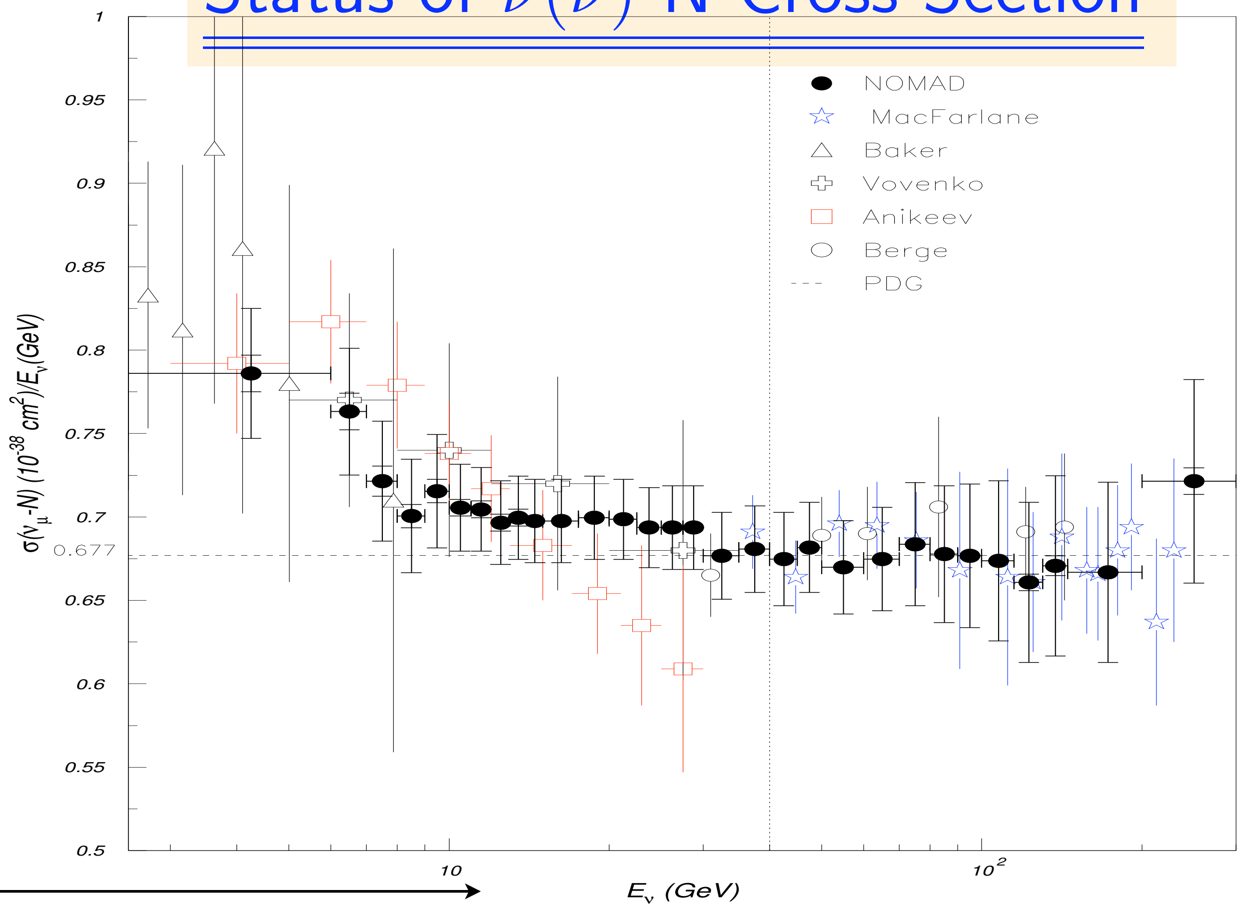
But while measuring effects $O(1/100)$ or $O(1/1000)$, require precision.

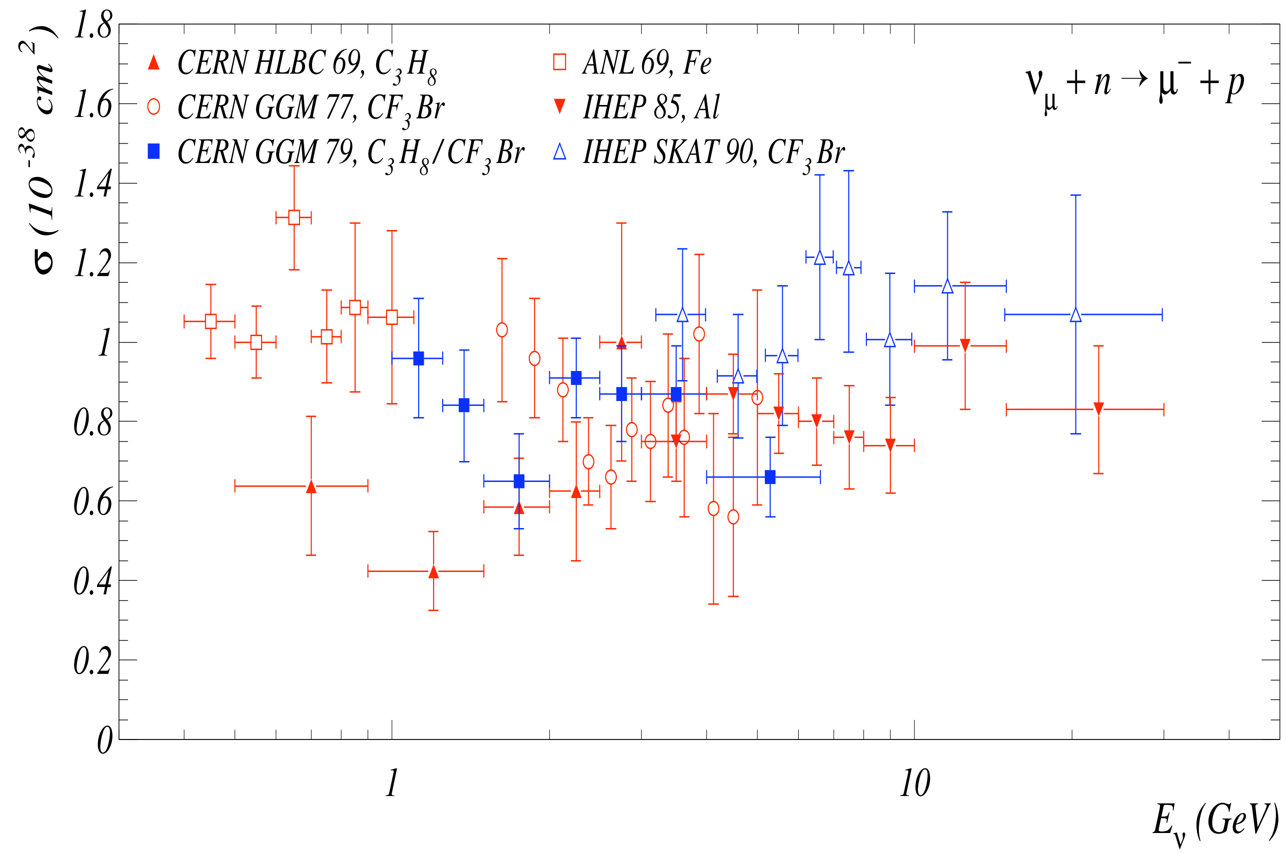
- Inclusive $\sigma(\nu_\mu N \to \mu^- X)$ CC
  Quasi-Elastic $\sigma(\nu_\mu n \to \mu^- p)$ CC
  } $1 \lesssim E_\nu \lesssim 10$ GeV known to $\pm 20\%$

- Worse precision $\sigma(\bar{\nu}_\mu\text{-CC})$ $E_{\bar{\nu}} \lesssim 10$ GeV

- Poorly measured $\dfrac{\sigma(NC)}{\sigma(CC)}(E_{HADR})$ $E_H \lesssim 5$ GeV

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%)*

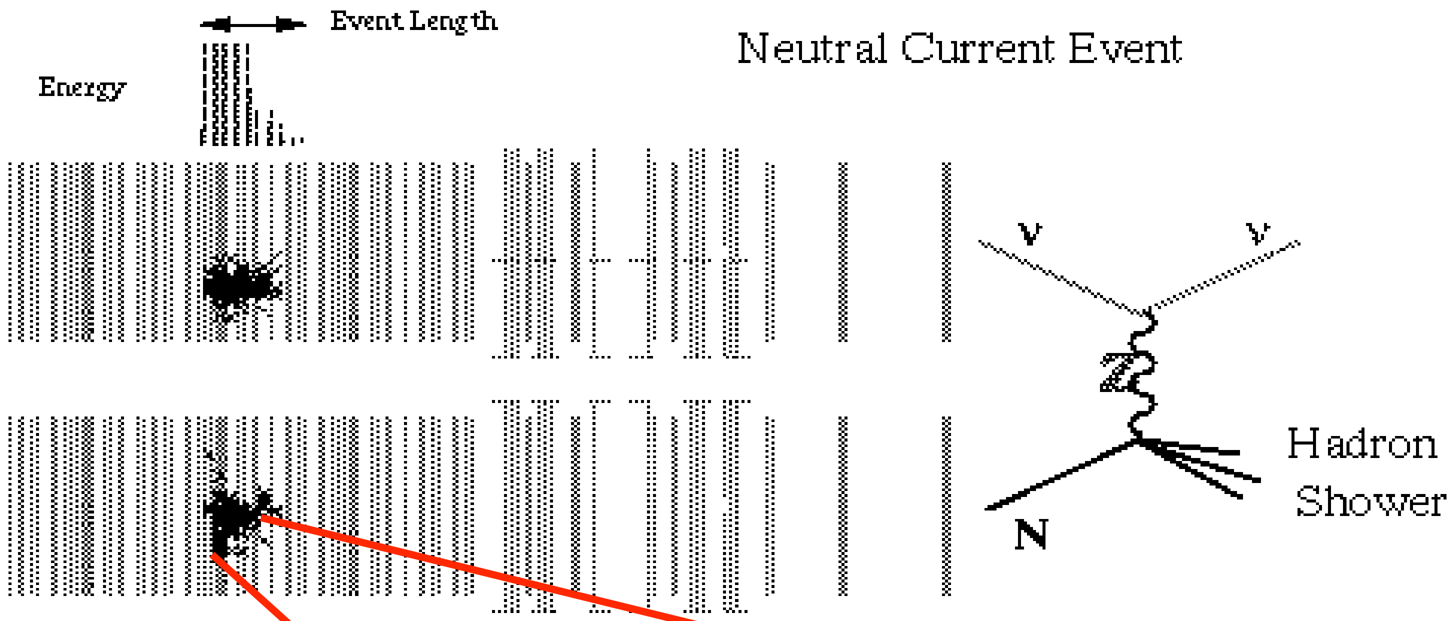
- *Poorly known $\bar{\nu}$ cross-sections and $\bar{\nu}$-induced processes*

- *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*

Particle Multiplicity in ν-Induced Hadron Jet

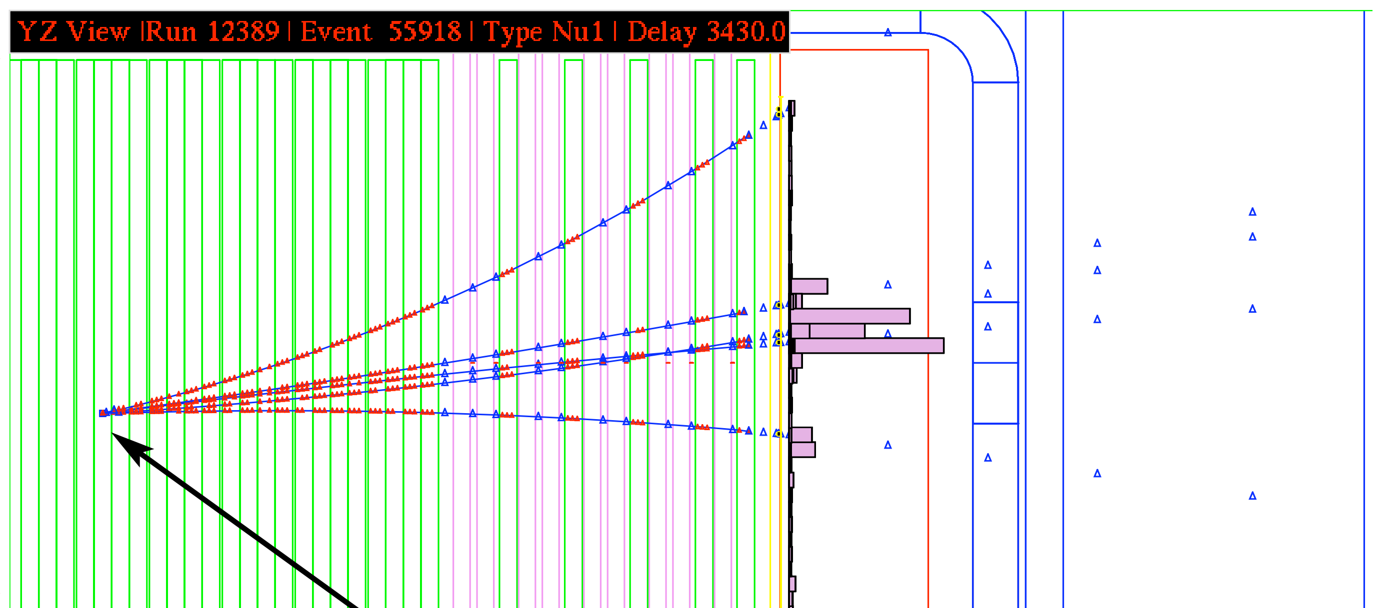
- ν_μ-CC :⇒ identified by μ^-
  - ⇒ $\pi^-/K^- \to \mu^-$ is an irreducible background
  - ⇒ hadron punchthrough : additional background
- $\bar{\nu}_\mu$-CC :⇒ Still higher background due to larger contaminant ν_μ
- π^0 :⇒ NC-π^0 single largest background to ν_e-appearance
- NC :⇒ similar backgrounds

⇒ Measure in situ Particle Multiplicity in ν-hadron jet in ν_μ-CC , $\bar{\nu}_\mu$-CC , NC, ...



MASSIVE CALO
(NuTeV)

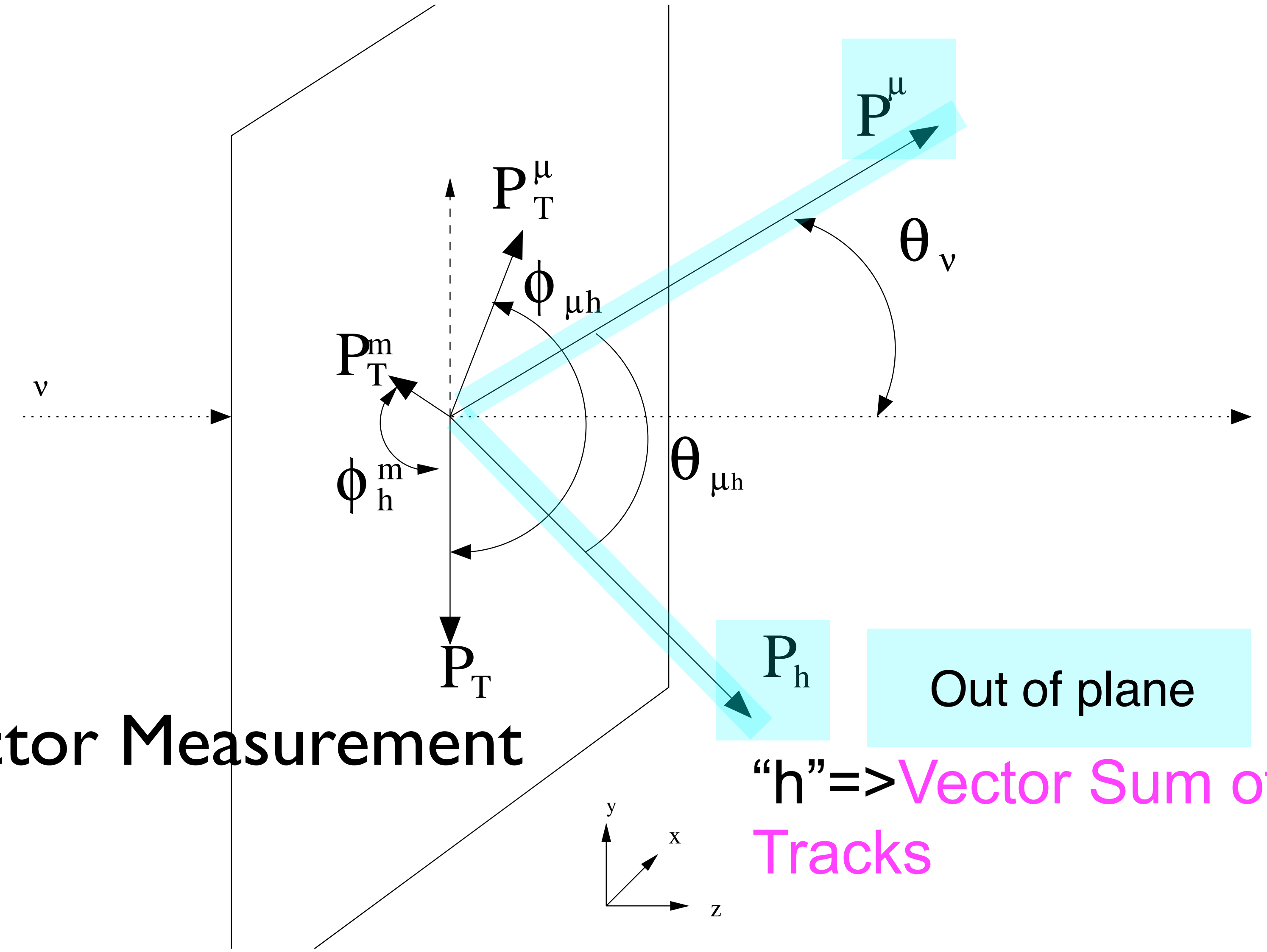
PRECISE TRACKER
(NOMAD)



Missing transverse momentum

HiResMν : order of mag. higher segmentation

Kinematics in HiResMnu

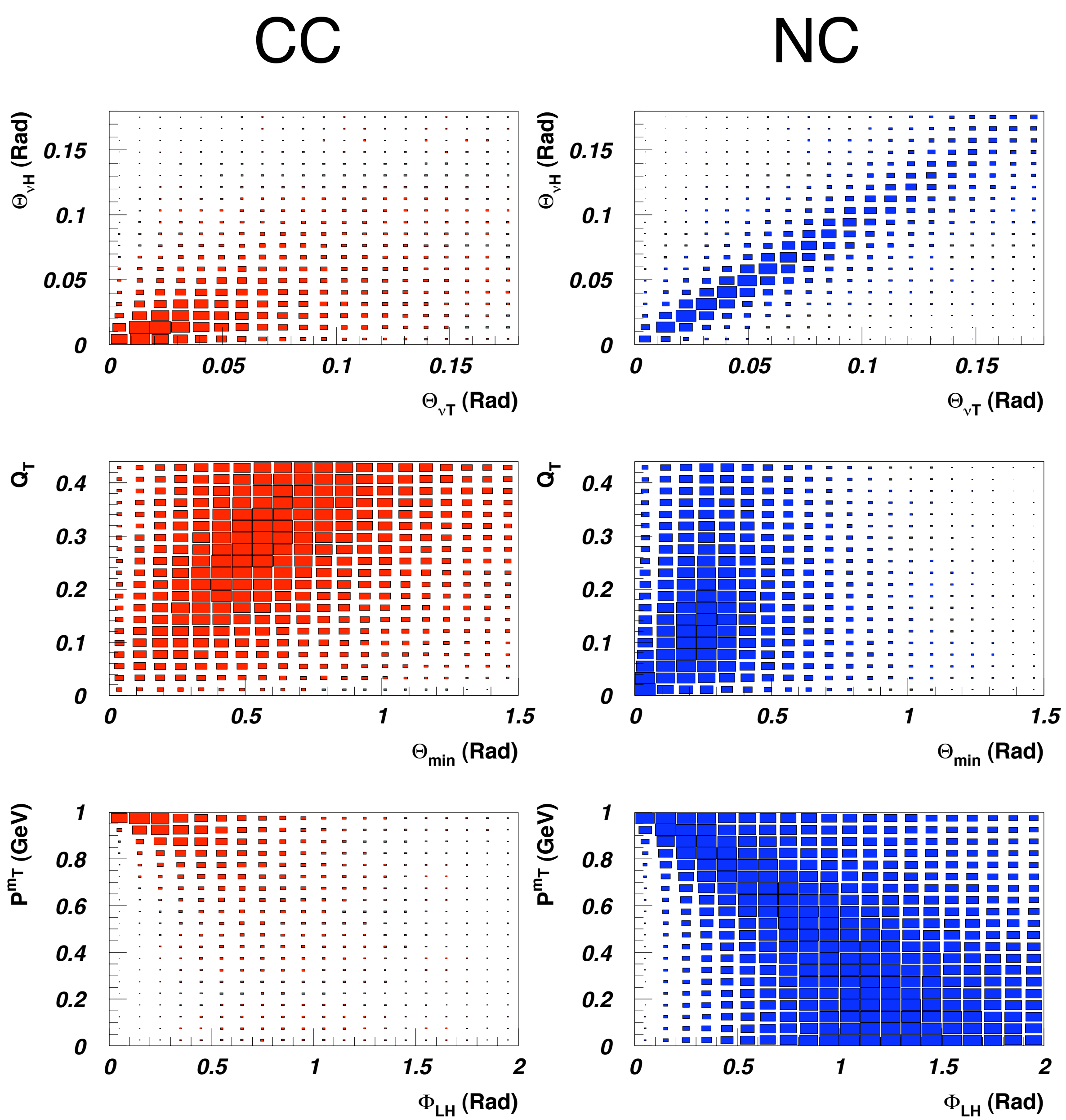


Out of plane

Pt-Vector Measurement

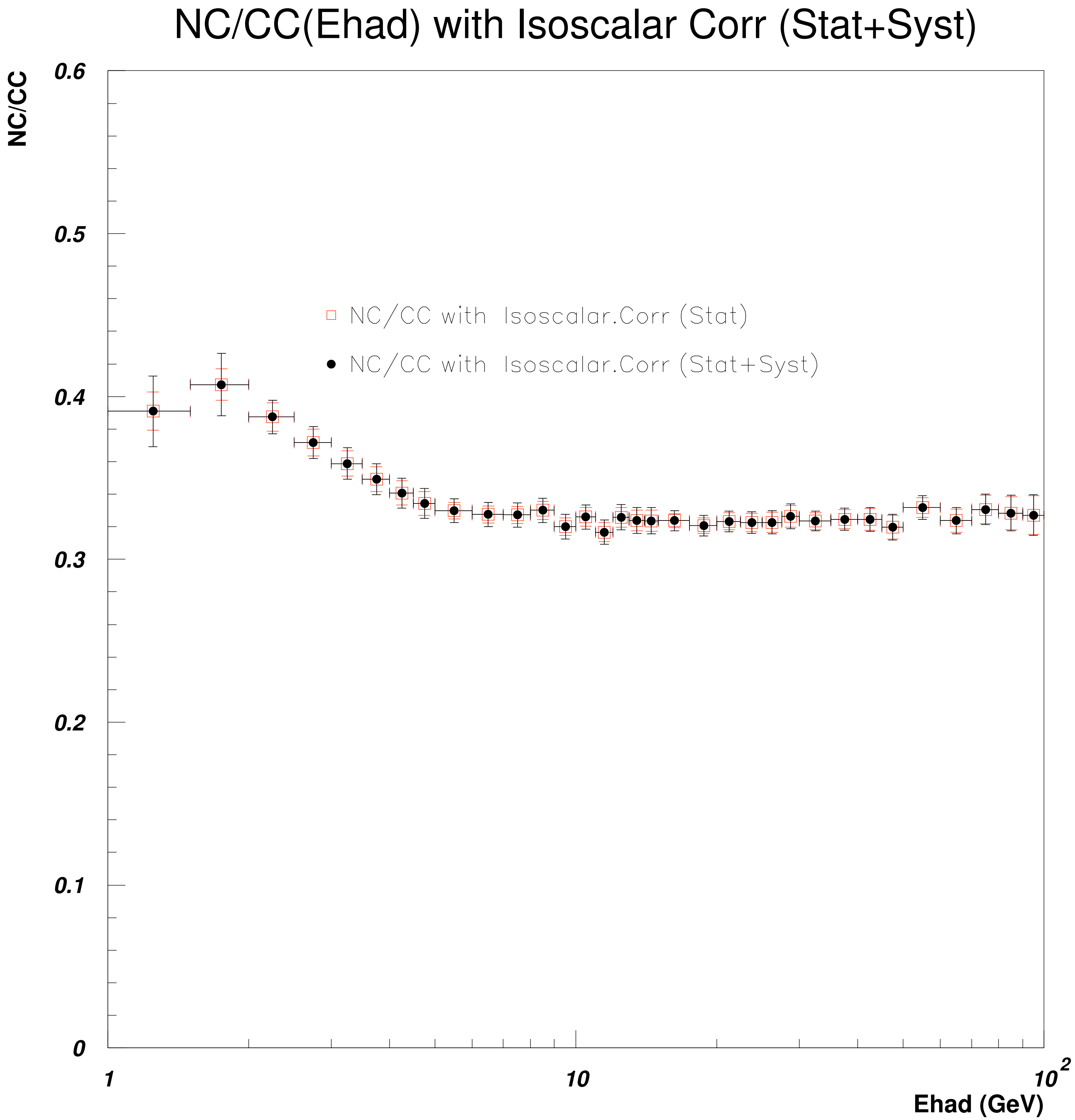
“h”=>Vector Sum of Tracks

Distributions of kinematic discriminants for NC vs CC in NOMAD MC.



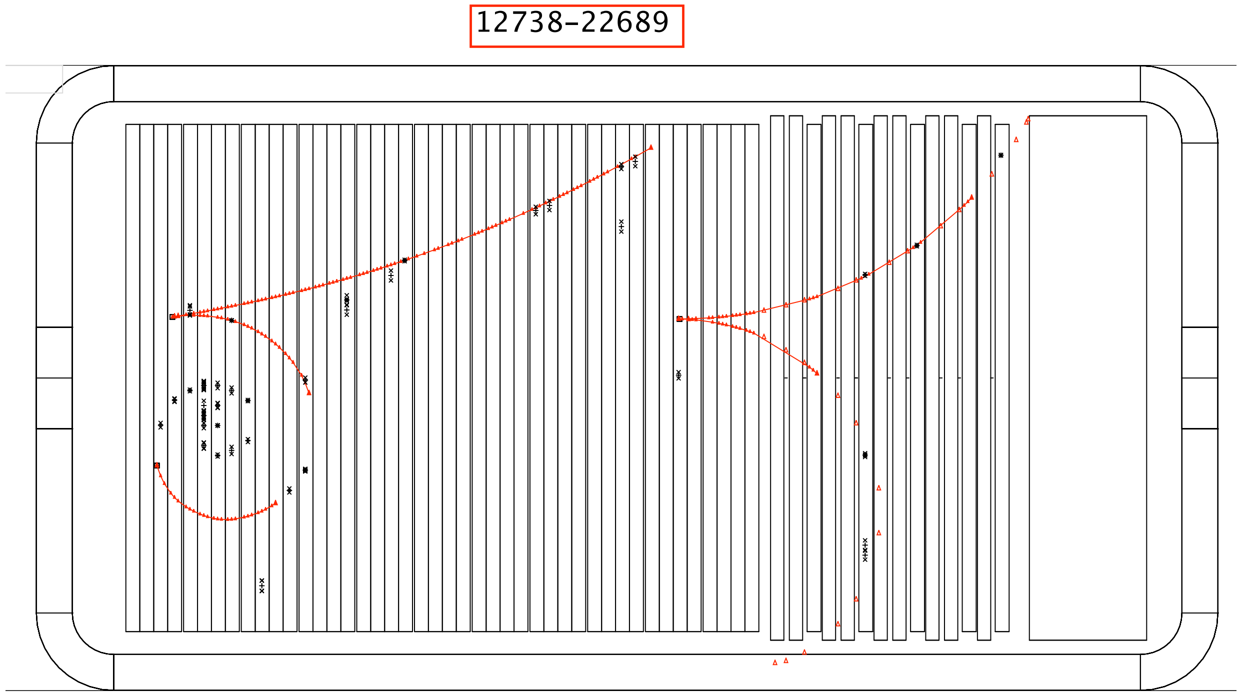
1. All plotted events fail the criteria that identify any of the charged tracks as a muon.

2. The separability of the NC events is manifest.

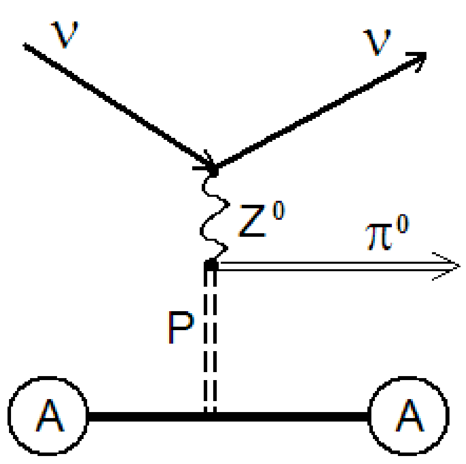


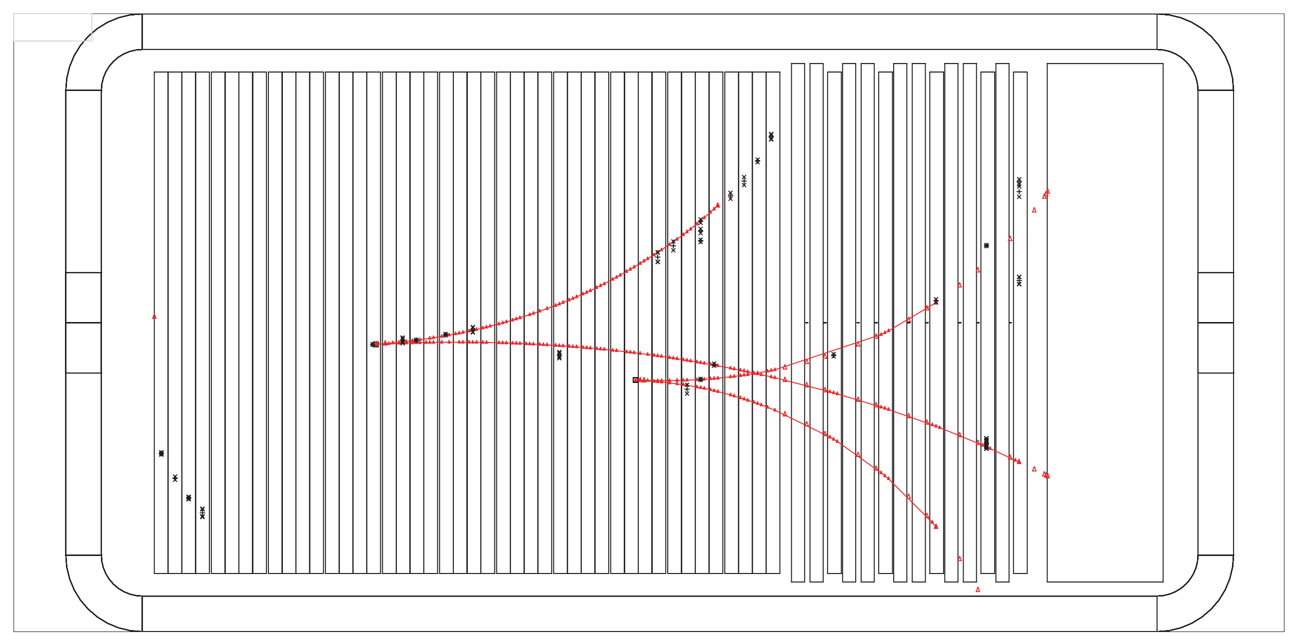
First Measurement of NC/CC(Ehad):
1<Ehad<100 GeV (NOMAD)

What about Pi0's ?



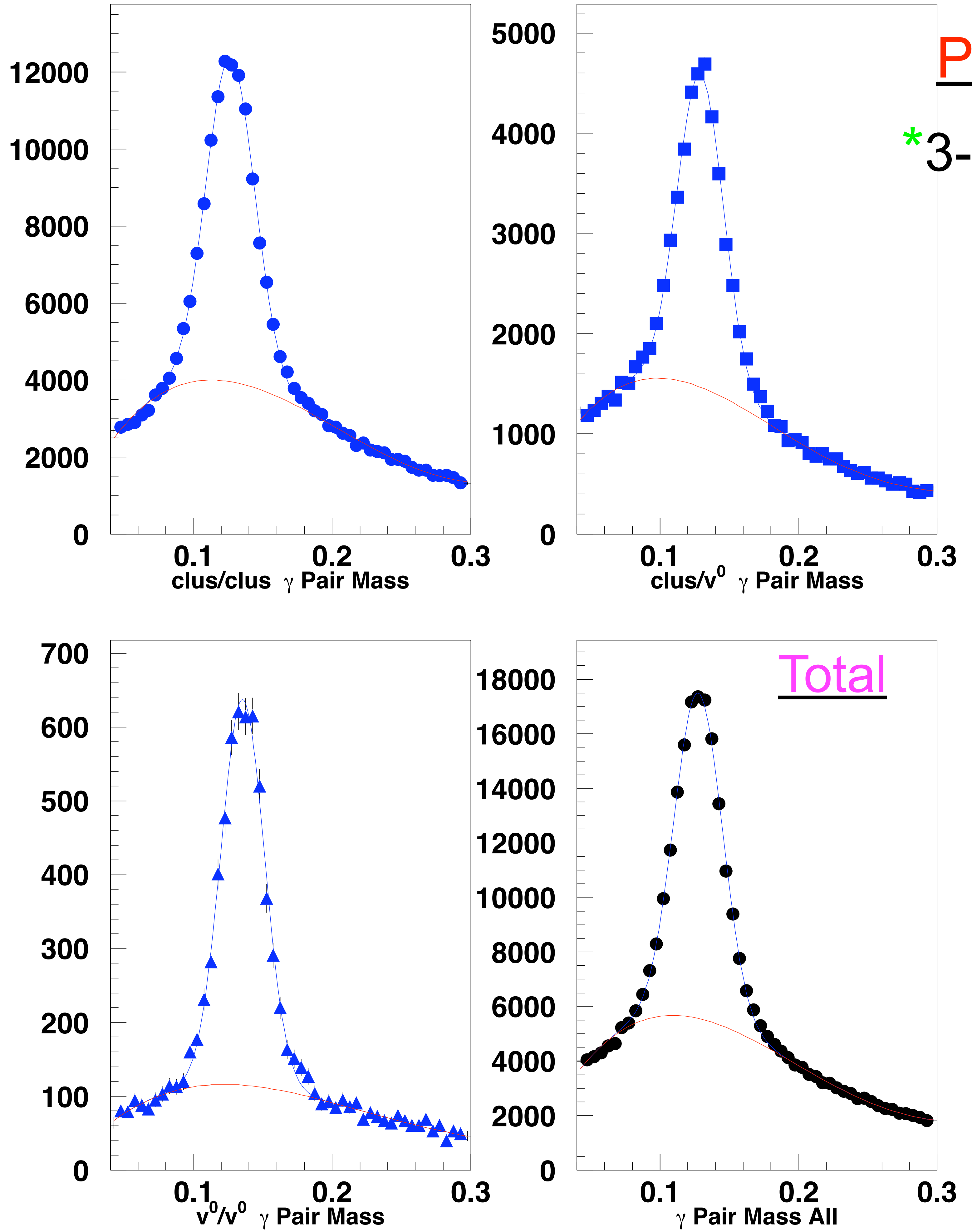
CohPi0 Candidates in NOMAD





Pi0 Reconstruction

*3-Topologies



E_ν - SCALE

- $\overset{(-)}{\nu}_\mu N \rightarrow \mu^{\overset{(+)}{-}} \underbrace{X}_{\text{HADRON}} \Rightarrow (E_\mu + E_{HAD}) \overset{?}{\Longleftrightarrow} E_\nu$
- $E_\nu \sim 3$ GeV, $E_H \sim 1$ GeV $\Leftarrow$ composed of $p/n/\pi^0/\pi^\pm$

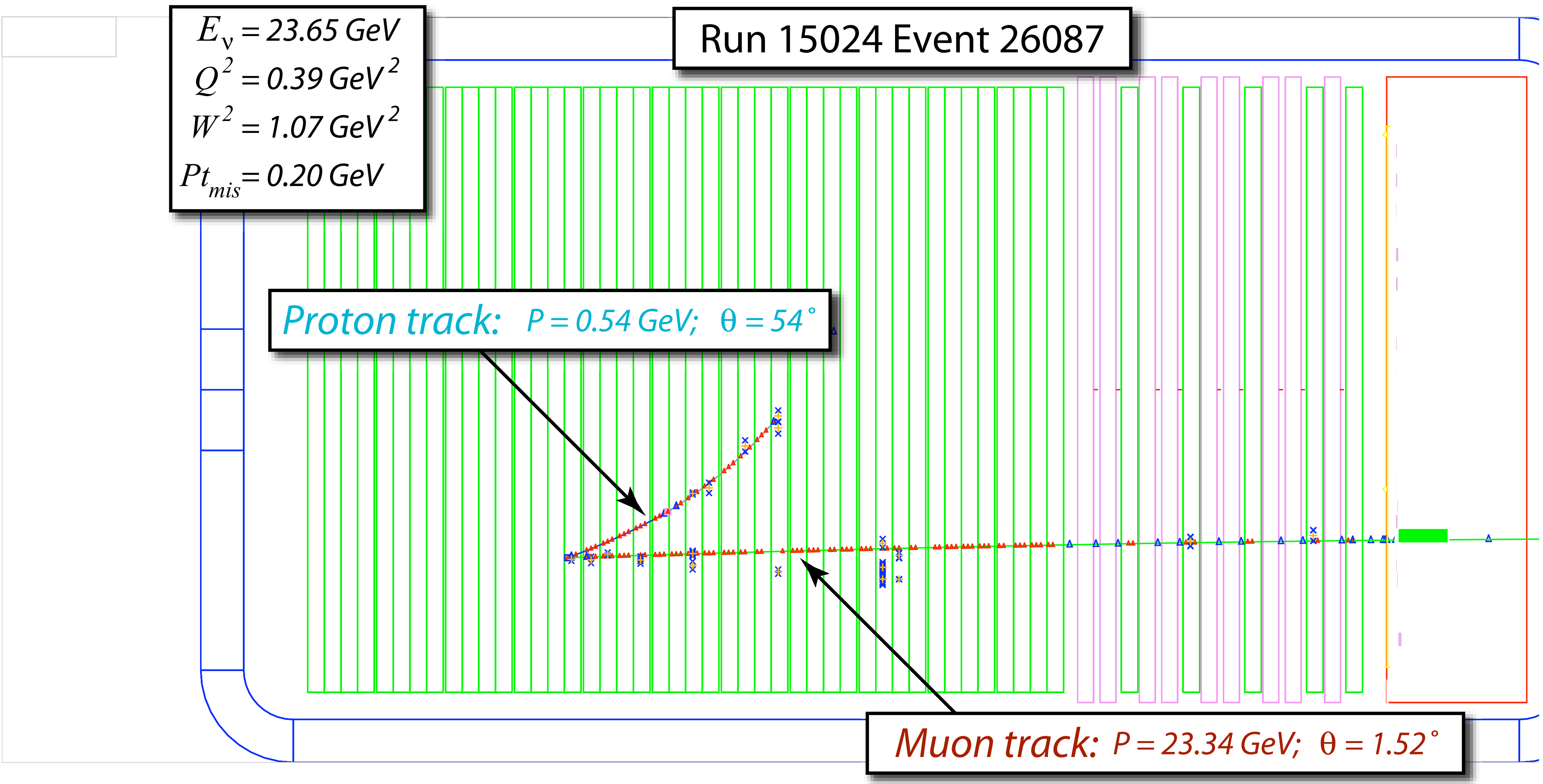
  $\Rightarrow$ Hadronic multiplicity in ν-jet

Hadrons need to clear nuclear medium

  $\Rightarrow$ Nuclear Effects

- Not sufficient to calibrate ν-detector in a TEST-BEAM

ν_μ-QE Candidate



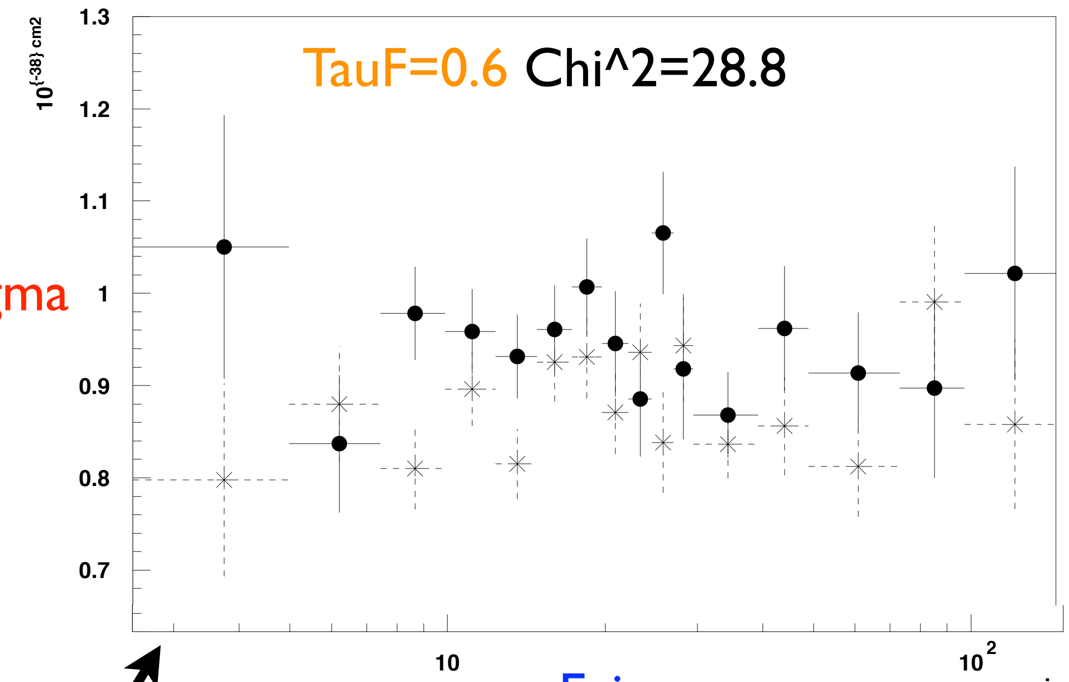
A Quasi-Elastic ν_μ CC event candidate in NOMAD with reconstructed kinematics. The HiResMν will have much better resolution to track the emergent proton.

QE: (1)Enu-Scale & Fermi-Motion

(2)Final State Interaction

USC HEP
University of South Carolina
High Energy Physics

FSI: Mean free path of hadrons inside a nucleus, TauF

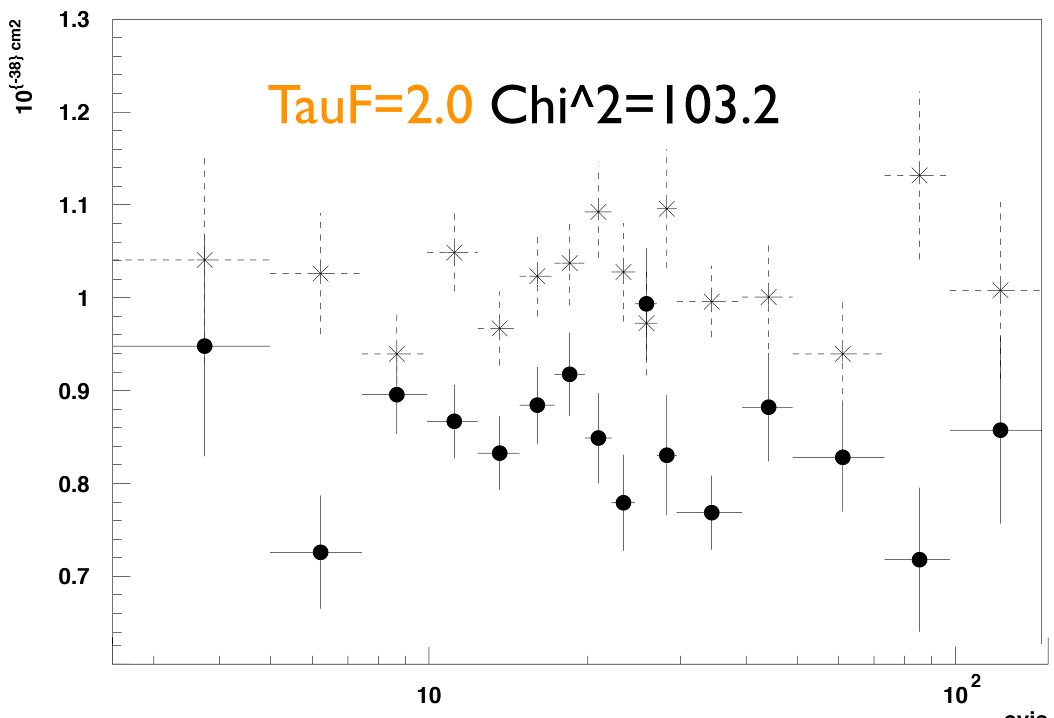


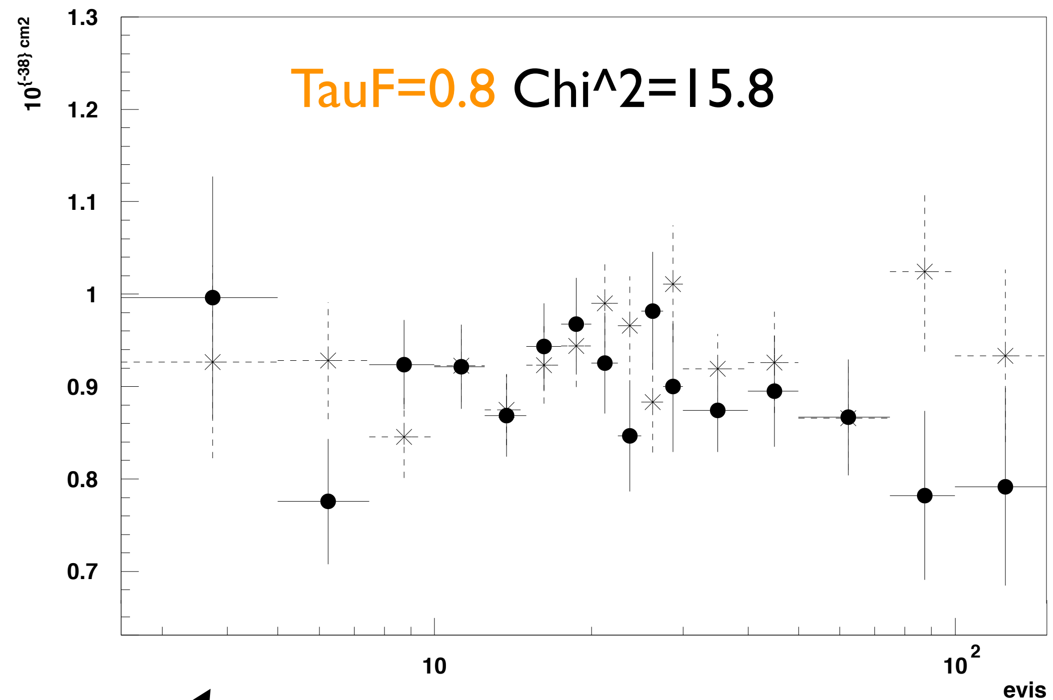
Sigma

Evis

Poor fits

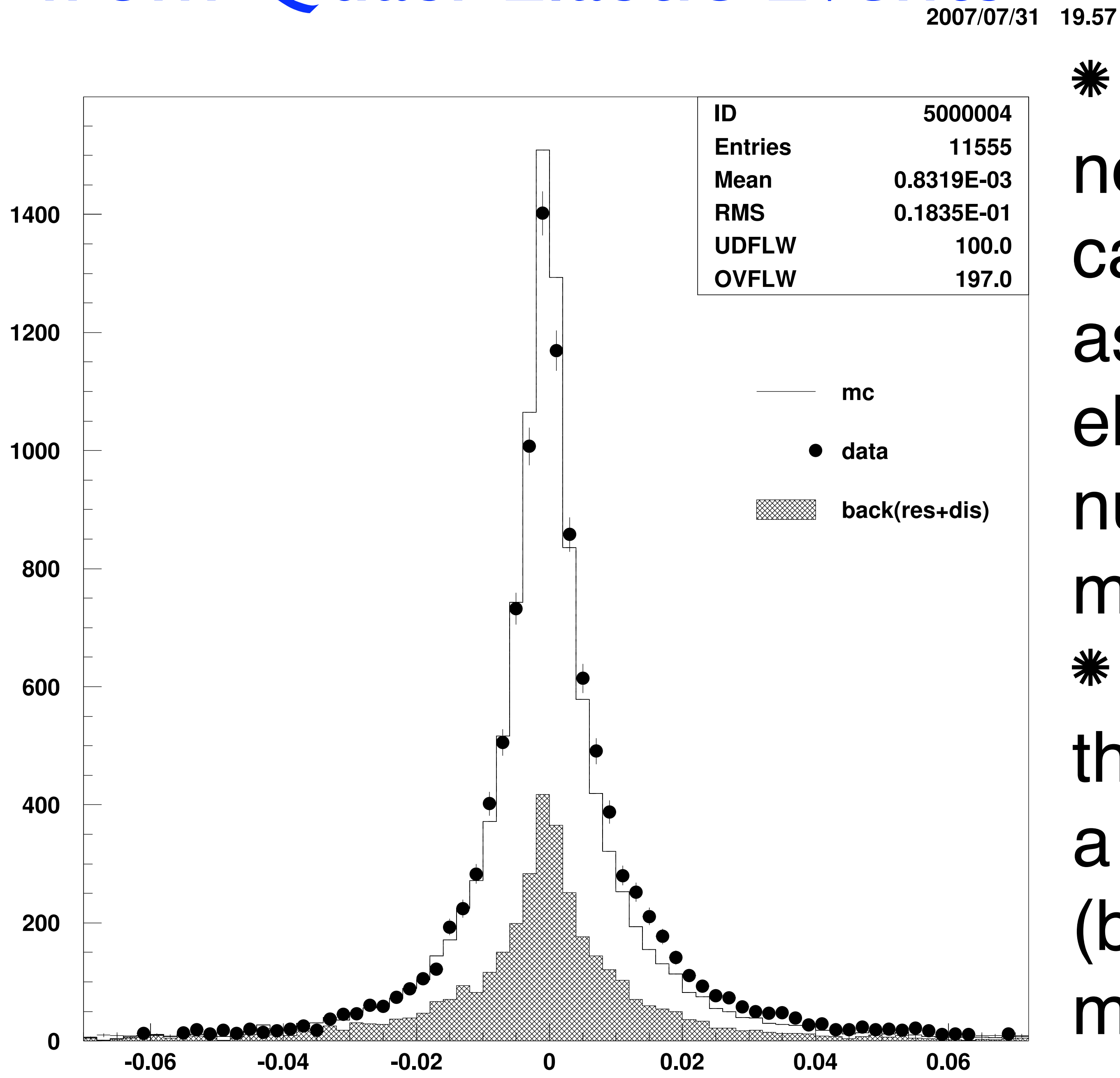
QE 1-trk vs 2-trk cross section





Good fit

Measure of Fermi Motion from Quasi-Elastic Events



(2-track Evis) - (muon-only Enu) - Mproton (GeV)

- Muon-only Enu is the neutrino energy calculated on the assumption of perfectly elastic scattering on a nucleon and using only muon measurements.
- Without Fermi motion this distribution would be a delta function at zero (but what does measurement error contribute?).

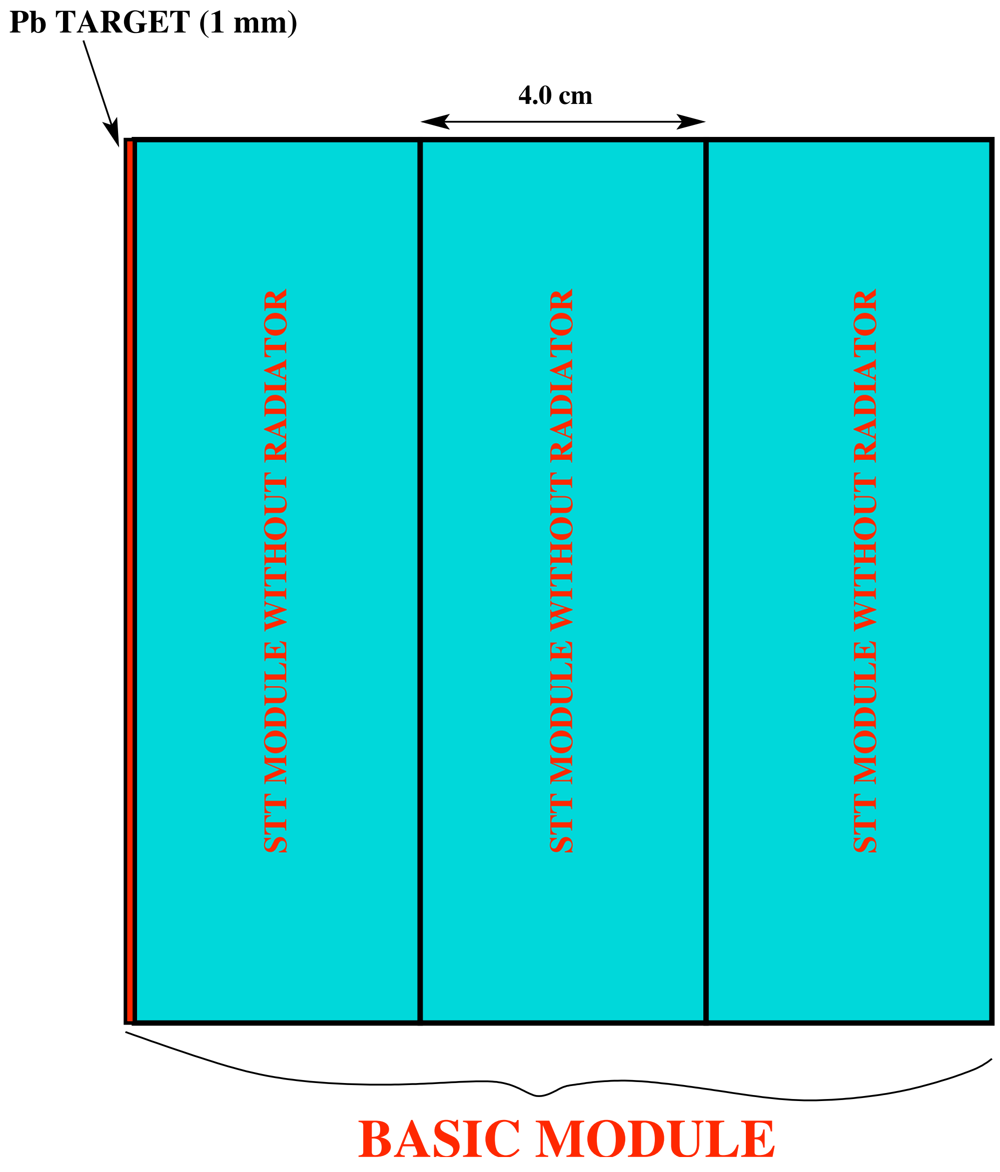
MEASURING NUCLEAR EFFECTS

✦ *Best procedure would be to measure the A dependence with few points (e.g. C, Fe, Pb):*

- *Determine ratios of structure functions of different nuclei: F_2 AND xF_3;*
- *Comparisons with charged leptons.*

✦ *Use 1mm ($0.18X_0$) Pb plates in front of three straw modules (providing 6 space points) without radiators in the upstream part of the detector:*

- *Total Pb target mass for one such module $\sim$ 70 kg;*
- OPTION *: possible to install other materials (Fe, etc.) downstream by keeping a constant thickness in X_0.*



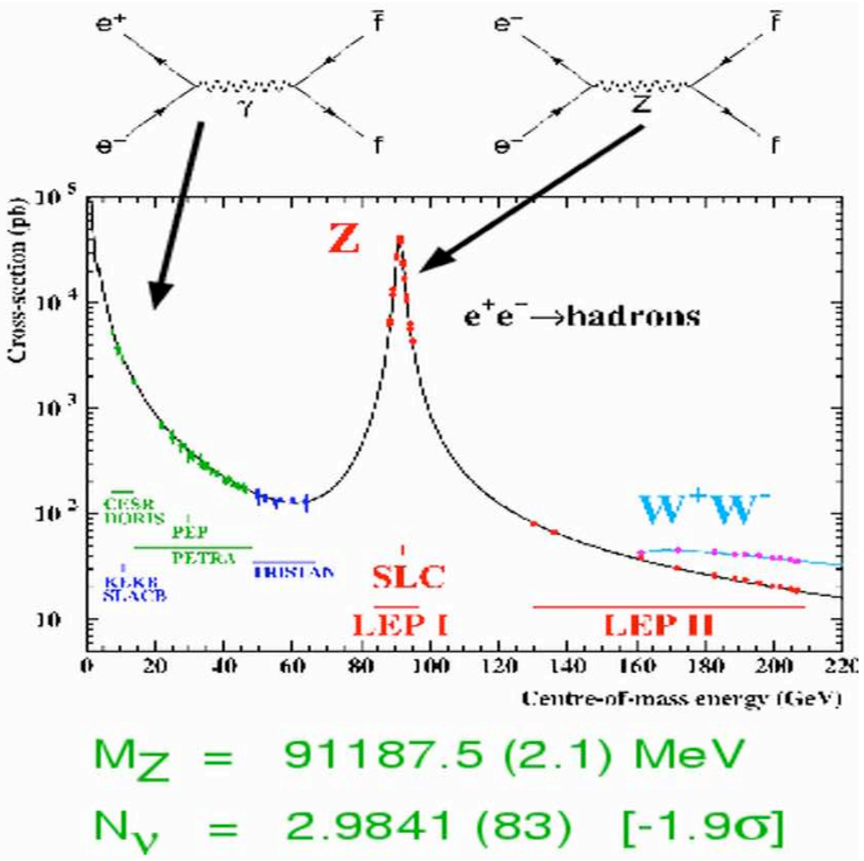
THE POTENTIAL OF HiResMν

Weak Mixing Angle

- *In e^+e^- collisions it is possible to enhance the weak cross-section by running at the Z^0 mass pole:*

$$\frac{\sigma_Z}{\sigma_\gamma} \propto \frac{E^4}{[(2E)^2 - (M_Z c^2)^2]^2 + (h\Gamma_Z M_Z c^2)^2}$$

$\Longrightarrow$ *High-statistics electroweak measurements at LEP/SLC reached a precision $\sim 10^{-3}$.*



- *Neutrinos the most natural probe to investigate both electroweak parameters and hadronic structure of matter since they experience only one interaction*

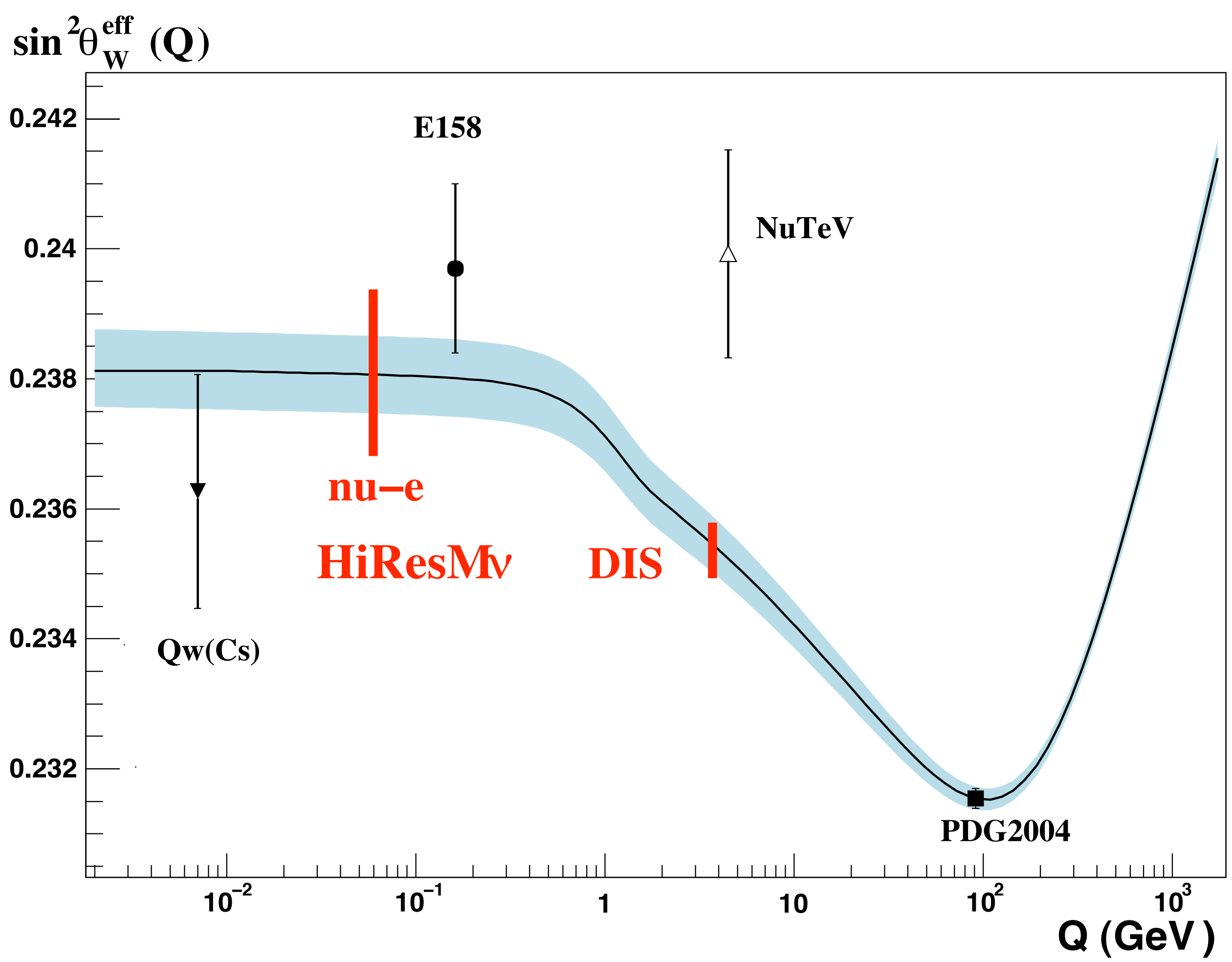
$\Longrightarrow$ *Due to limited statistics ν measurements $\sim 10^{-2}$*

- *The collection of $\mathcal{O}(10^8)$ $\nu(\bar{\nu})$ CC statistics with HiResMν could have, for neutrino physics, the same impact LEP had for e^+e^-:*

	Number of Z^0	*Number of W*
LEP	18×10^6	80×10^3

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*

PHYSICS POTENTIAL

✦ About NuMI and Service to $\mathcal{LBL}\nu$

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

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

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

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

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

✦ Neutral-Pion Production in ν-Interactions

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

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

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

✦ Charged-Pion, Kaon and Proton Production in ν-Interactions

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

10: *Charged π/K/p production in the the NC and CC interactions as a function of hadronic energy*

11: *Cross section of $\pi^\pm$/K$^\pm$/p production as a function of X_F and P_T in the ν-CC interactions*

✦ Neutrino-Electron Scattering

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

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

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

✦ ν-Nucleon Neutral Current Scattering

15: *Measurement of NC to CC ratio, R^{ν}, as a function of hadronic energy $0.25 \leq E_{Had} \leq 20$ GeV*

16: *Measurement of NC to CC ratio, R^{ν} and $R^{\overline{\nu}}$, for $E_{Had} \geq 3$ GeV and determination of the electroweak parameters $\sin^2\theta_W$ and ρ.*

✦ Non-Scaling Charged and Neutral Current Processes

17: *Measurement of ν_μ and $\overline{\nu}_\mu$ quasi-elastic interaction and determination of M_A*

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

19: *Measurement of ν_μ and $\overline{\nu}_\mu$ induced resonance processes*

20: *Measurement of resonant form-factors and structure functions*

21: *Study of the transition between scaling and non-scaling processes*

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

23: *Coherent $\rho^{\pm}$ production in ν-induced charged current interactions*

24: *Neutral current elastic scattering on protons $\nu(\bar{\nu})p \rightarrow \nu(\bar{\nu})p$*

25: *Measurement of the strange quark contribution to the nucleon spin Δs*

26: *Determination of the weak mixing angle from NC elastic scattering on protons*

✦ Inclusive Charged Current Processes

27: *Measurement of the inclusive ν_μ and $\overline{\nu}_\mu$ CC cross-section in the range $0.5 \leq E_\nu \leq 40$ GeV*

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

29: *Measurement of the differential ν_μ and $\overline{\nu}_\mu$ CC cross-section as a function of x_{bj}, y_{bj} and E_ν.*

30: *Determination of xF_3 and F_2 structure functions in ν_μ and $\overline{\nu}_\mu$ CC and the QCD evolution*

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

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

33: *Precise tests of sum-rules in QPM/QCD*

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

35: *Measurement of scaled momentum, rapidity, sphericity and thrust in (anti)neutrino CC*

36: *Search for rapidity gap in neutrino charged current interactions.*

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

38: *Verification of the PCAC hypothesis at low momentum transfer*

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

40: *Precision tests of the Conservation of the Vector Current*

✦ Nuclear Effects

41: *Measurement of nuclear effects on* F_2 *in* $\nu(\bar{\nu})$ *scattering from ratios of Pb,Fe and C targets*

42: *Measurement of nuclear effects on* xF_3 *in* $\nu(\bar{\nu})$ *scattering from ratios of Pb,Fe and C targets*

43: *Study of (anti)shadowing in* ν *and* $\bar{\nu}$ *interactions and impact of axial-vector current*

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

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

✦ Semi-Exclusive and Exclusive Processes

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

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

48: *Measurement of J/*ψ *production in neutral current interactions*

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

50: *Measurement of exclusive strange hadron and hyperon production in (anti)neutrino CC and NC*

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

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

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

54: *D*+ production in neutrino charged current interactions*

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

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

✦ Search for New Physics and Exotic Phenomena

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

58: *Search for eV (pseudo)scalar penetrating particles*

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

60: *Search for heavy neutrinos mixing with tau neutrinos*

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

62: *Search for anomaly mediated neutrino induced photons*

63: *Search for the magnetic moment of neutrinos*

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

$\Longrightarrow$ *More than 100 physics papers on a broad range of topics*

Rethinking Near Detector Concept

- Fix $\pi^{\pm}/K^{\pm}/K^0/p\ (x_F, P_T)$ on ν-tgt & nucl. target
  ⇒ MIPP, ...
- Pin down beam-transport error
- Measure $\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e\ (E_\nu)$ & CC/NC multiplicity
  ⇒ 'Event-Generator' measurement ⇒ HiResMν
- Calibrate "NEAR-DETECTOR" in a test-beam
  & Operate, periodically, in a low-intensity $\overset{(-)}{\nu}$-mode.

⇒ make discoveries

Concluding Thoughts

Discover, establish, and precisely measure the elements of ν-Mass Matrix in LBLν:

- Reinvent 'Near Detector' concept
- A High-Resolution near detector providing in situ 'Event Generator' like measurements of
  - ⇒ ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$ (E_ν)
  - ⇒ E_ν-scale & σ : CC & NC
  - ⇒ Particle multiplicity in ν-jet
- A precision programme in ν-sector at a par with Collider EW-measurement
- With MIPP, offer precision and redundancy to discover something entirely new

OUTLOOK

✦ *Precision measurements are essential for discoveries in particle physics and require redundancy and high resolution detectors*

✦ *The Project-X with HiResMν offers a unique opportunity to do neutrino physics: for oscillation studies and for standard model physics*

- *Ultimate Near Detector for Long Baseline Neutrino Oscillation experiments;*
- *Precise measurement of $\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$ as a function of E_ν & detaled topology;*
- *Measurement of $\sin^2\theta_W$ in neutrino interactions to a precision comparable to LEP/SLC & check of NuTeV anomaly. Direct probe of running of $\sin^2\theta_W$;*
- *Precision tests of isospin symmetry;*
- *Measurement of strange sea contribution to the nucleon spin Δs;*
- *Precision tests of the structure of the weak current: PCAC, CVC;*
- *Search for weakly interacting massive particles and other exotic phenomena;*
- *Studies of QCD and hadron structure of nucleons and nuclei;*
- *etc., etc. .....*

✦ *Precision measurements of W/Z production at the LHC and a complete flavour separation (PDFs) are crucial to control backgrounds and signal efficiencies in all searches for new physics*

Backup slides

Vacuum Oscillation

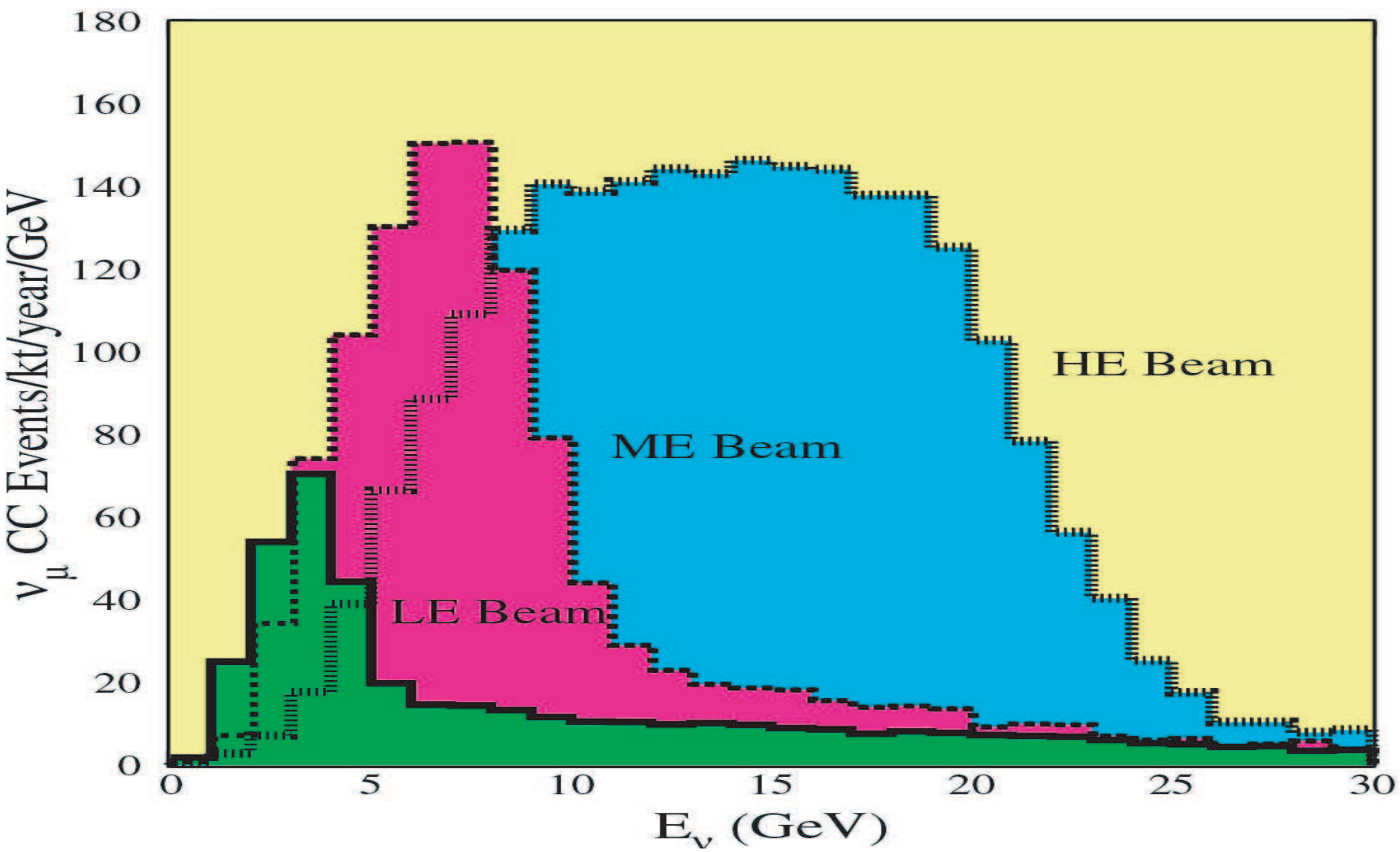
* For 2-Generation mixing in vacuum

$$i\hbar \frac{d}{dt}\begin{pmatrix}\nu_e \\ \nu_x\end{pmatrix} = \mathcal{H}\begin{pmatrix}\nu_e \\ \nu_x\end{pmatrix}$$

$$\Rightarrow \mathcal{P}(\nu_e \to \nu_x) = \sin^2 2\theta \, \sin^2\left[1.27 \, \Delta m^2 \frac{L}{E}\right]$$

$$\mathcal{H} = \begin{bmatrix} \frac{\Delta m^2}{4E}\cos 2\theta & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & -\frac{\Delta m^2}{4E}\cos 2\theta \end{bmatrix}$$

THE NEUTRINO BEAM

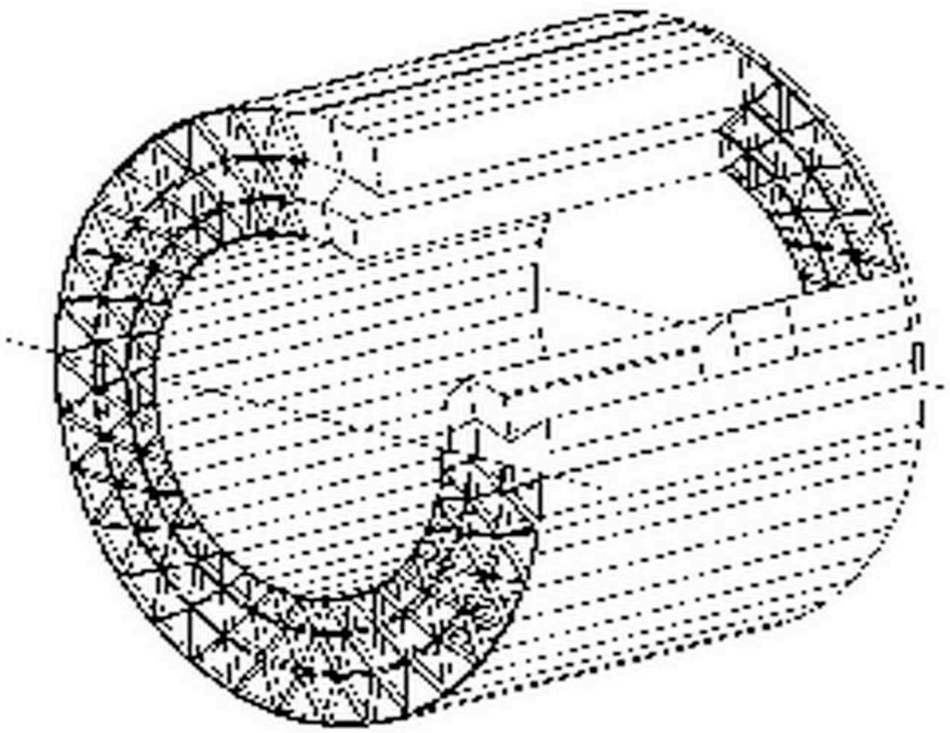


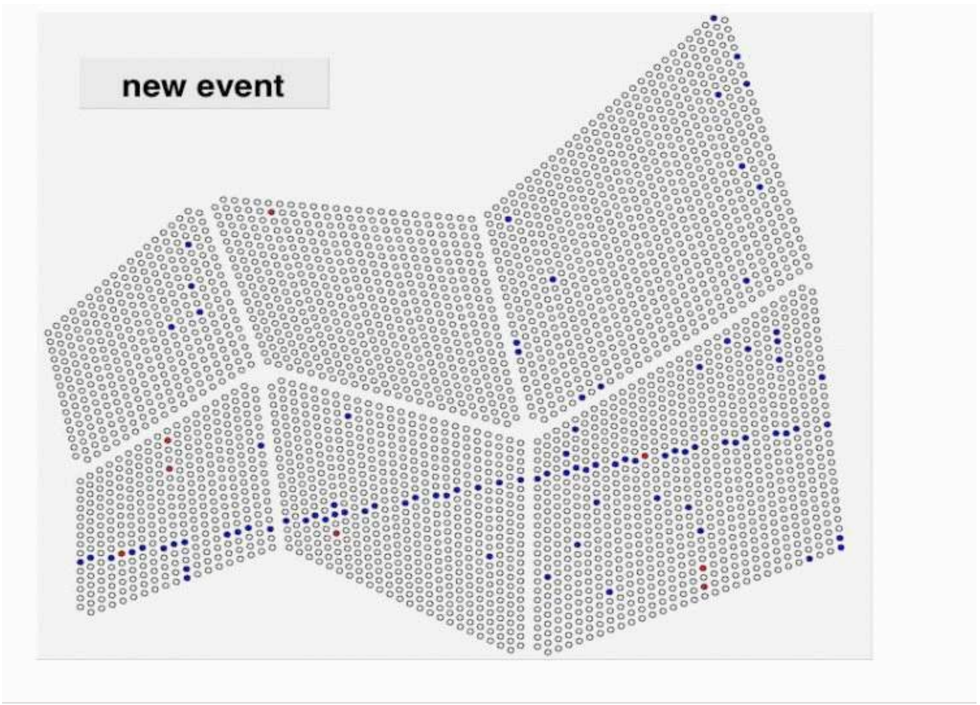
- *Project-X at FNAL (2016): new 8 GeV linac + Recycler + Main Injector: beam power of 2.3 MW at 120 GeV, 30×10^{20} pot/y.*

- *Event rates on axis with the Medium Energy (ME) configuration (default for LBLν): $6.3 \times 10^6 \nu_\mu$ CC/t/y at few 100 m from the neutrino source*
  $\Longrightarrow$ *Increase by about a factor of 3 with High Energy configuration*

THE ATLAS TRT TECHNOLOGY

- *Compact design combining tracking & particle identification in the same detector:*
  - *Radiator foils for Transition Radiation (TR) for electron identification ($\gamma > 1000$);*
  - *Drift straw tubes for tracking (400k channels with 4mm diameter filled with $Xe/CO_2/O_2$);*
  - *Low density $1X_0 \sim 5\ m$.*
- *Electronic readout chain developed to match the challenging rate & radiation problems in ATLAS:*
  - *Drift time measurement;*
  - *Signal pulses are fed to discriminators with Low (tracking) and High (electron ID) Thresolds (no analog readout of charge).*
- *Standard resolution achieved on space points 130 μm at testbeam.*
- *Straw Tracker also built for the COMPASS detector, where only the drift time information is used (tracking without particle identification).*





TRIGGER

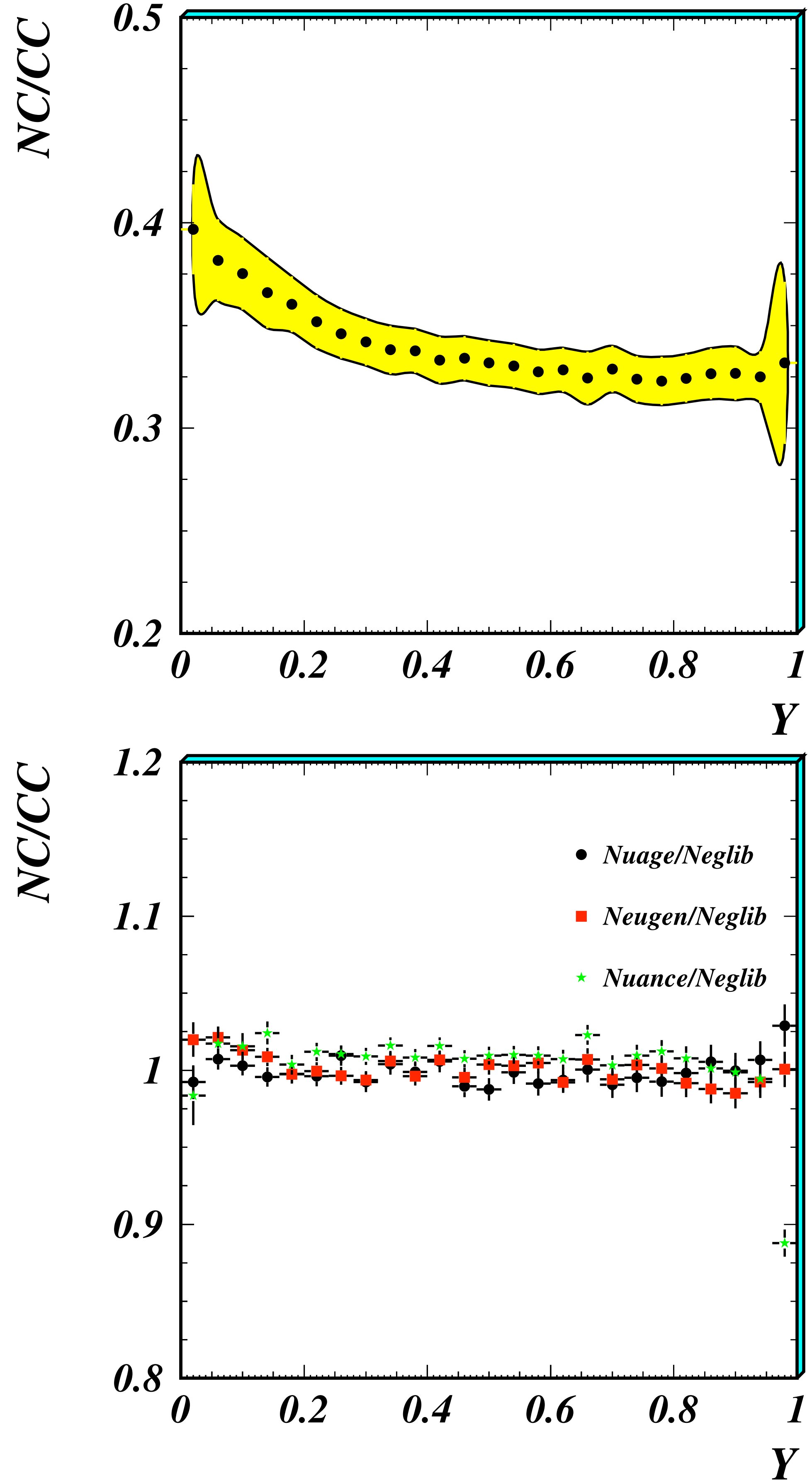
- *The maximum drift time for a Xe/CO_2 gas mixture is 125 ns for a distance of 5mm (lower for Ar), as measured in testbeam.*

- *The STT can resolve individual beam bunches*

- *Possible a self-triggering scheme in which hits are stored in pipelines (can use FE ADC - e.g. 8 bit - to operate in digital domain) waiting a later decision:*
  - *ATLAS FE has pipeline 256 $\times$ clock;*
  - *Avoid trigger based upon geometrical acceptance (problem in NOMAD).*

- *Depending upon the background rate, it should be possible to read and timestamp everything within one spill and to take a decision later in the cycle.*

- *In addition, calorimetric trigger (complementary)*



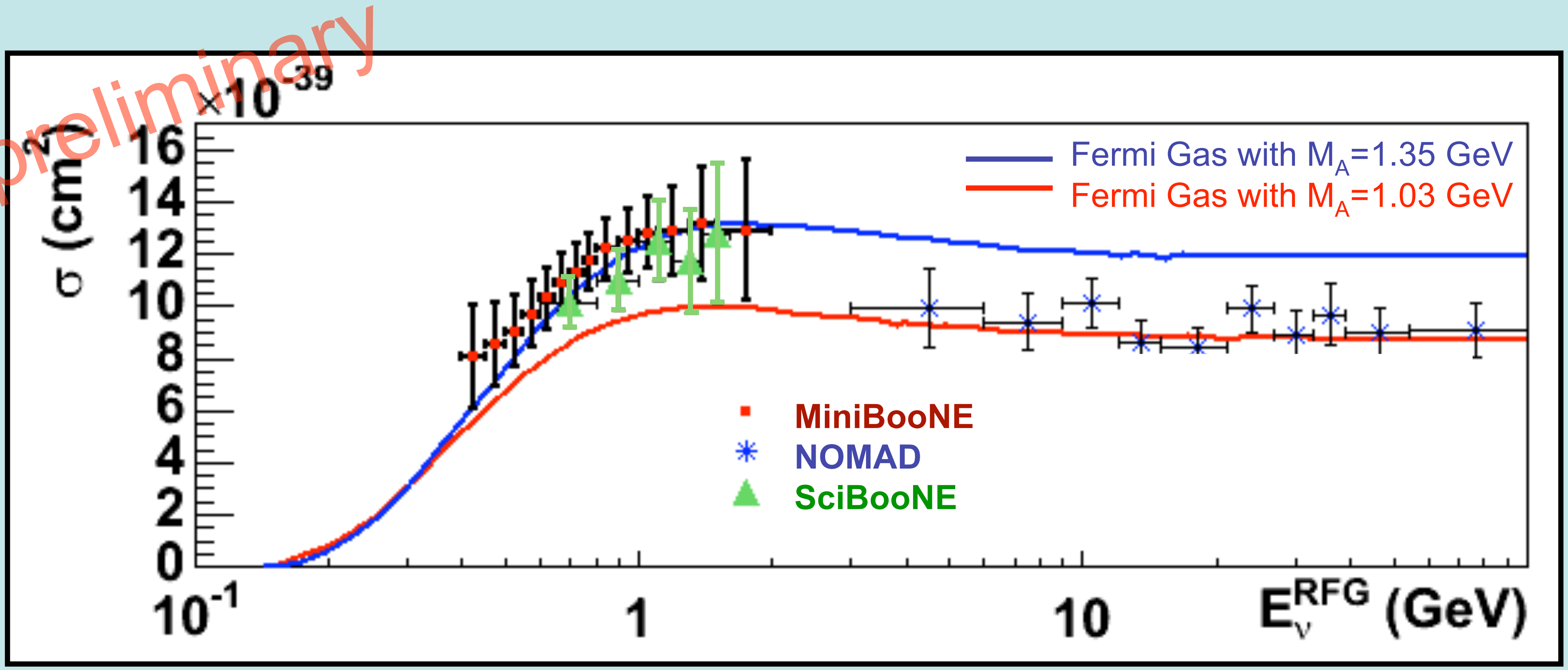
*HiResMnu will yield NC/CC ratio with very high precision

*NC-Events affect the NuMu-NuE & NuMu-NuTau

Figure 51: The comparison of NC/CC-$\boldsymbol{Y_{bj}}$ distributions between Nuage, Neglib, Neugen and Nuance without radiative correction.

Quasi-Elastic Scattering

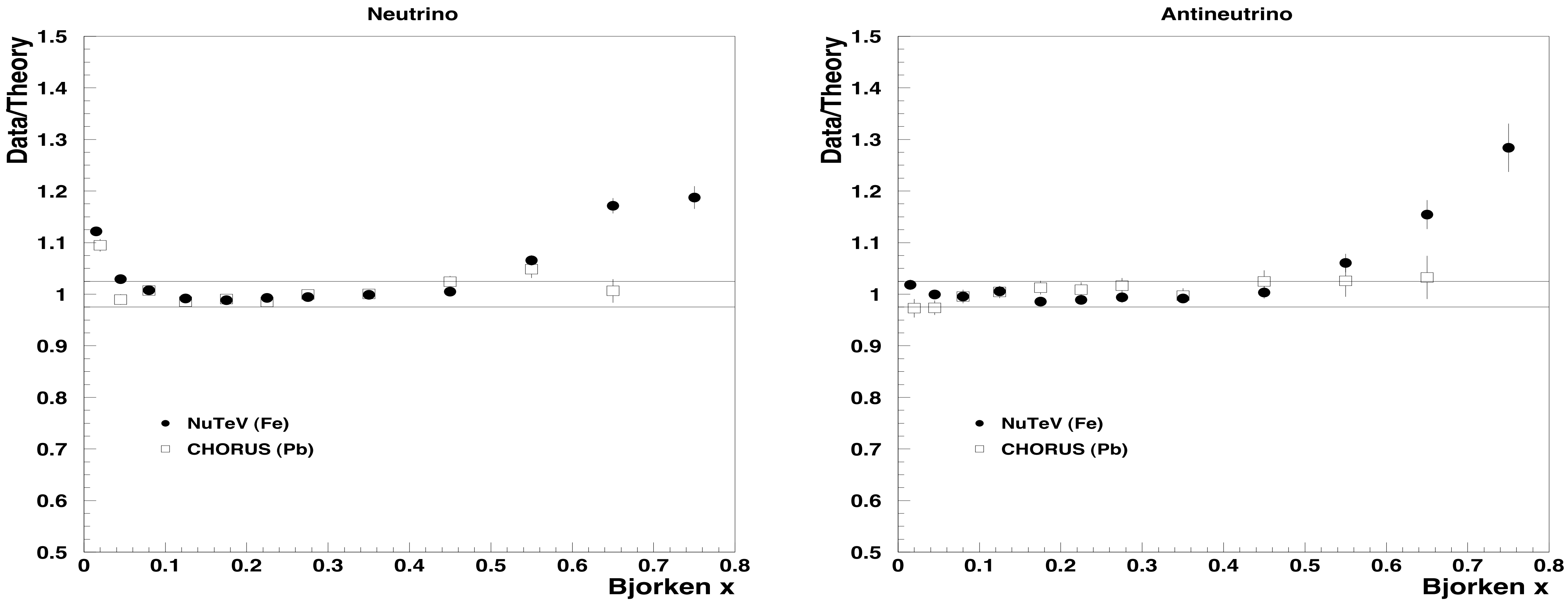
- new, modern measurements of QE σ at these energies (on ^{12}C)



(T. Katori, NuInt09)

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

NUCLEAR EFFECTS



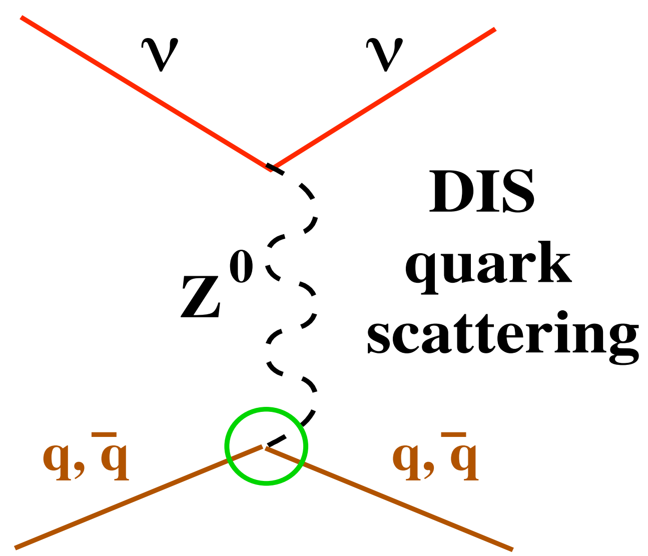
- *Detailed phenomenological model including Fermi motion and binding energy, off-shell effect of bound nucleons, nuclear pion excess and shadowing correction (S. Kulagin and R.P., NPA 765 (2006) 126; PRD 76 (2007) 094023).*

- *Predictions for (anti)neutrino scattering consistent with NuTeV (Fe) and CHORUS (Pb) cross-section data over main kinematic range (band in plots $\pm 2.5\%$).*
  $\Longrightarrow$ *NOMAD data on C and Fe targets (prel.) don't support NuTeV excess at large x*

MEASUREMENT OF $\sin^2\theta_W$ IN HiResMν

- *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:*

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

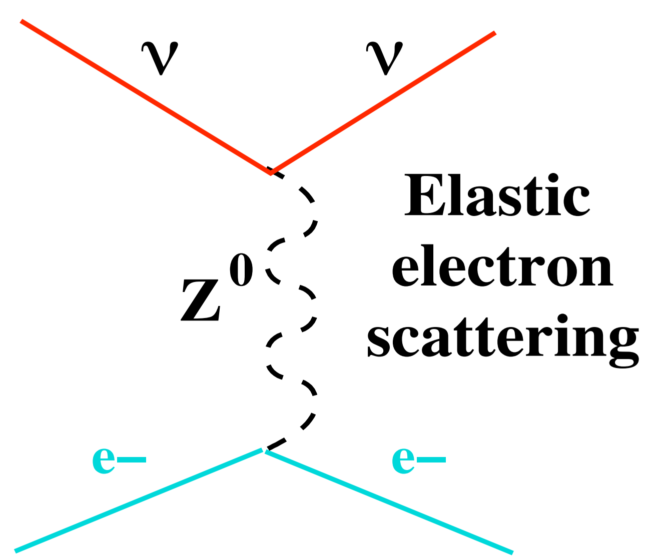


  - $\delta sin^2\theta_W / sin^2\theta_W = \boxed{2.0 \times 10^{-3}}$
  - *19(6)*$\times 10^6$ *NC selected events in* $\nu(\bar{\nu})$ *mode*

  $\Longrightarrow$ *Dominated by systematics*

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

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



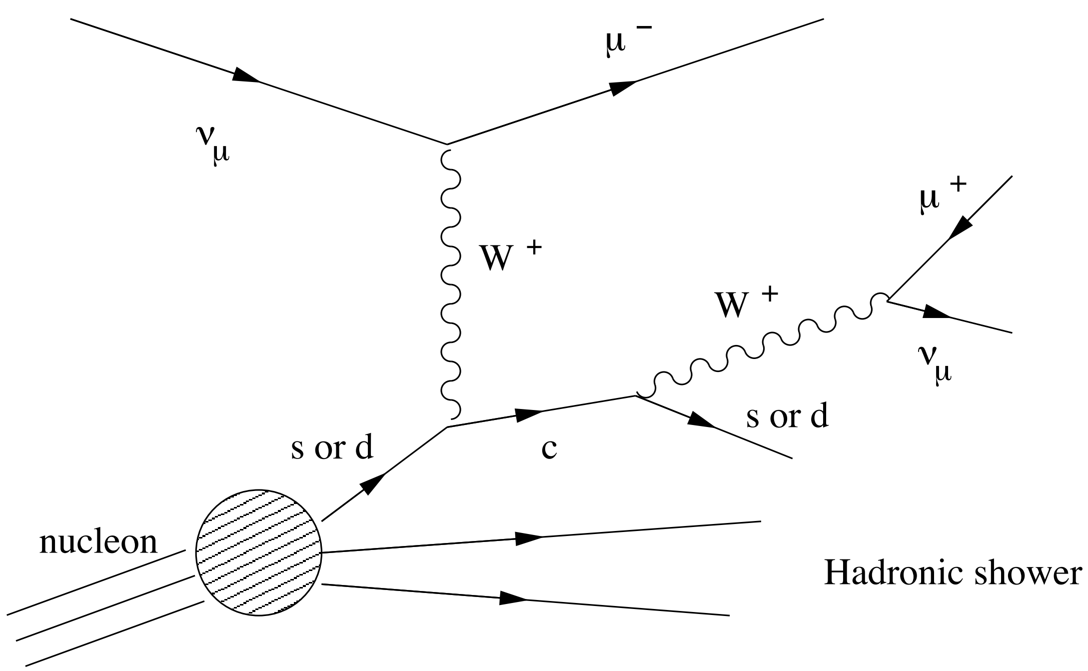
  - $\delta sin^2\theta_W / sin^2\theta_W = \boxed{5.6 \times 10^{-3}}$
  - *31(17)* $\times 10^3$ *NC selected events in* $\nu(\bar{\nu})$ *mode*

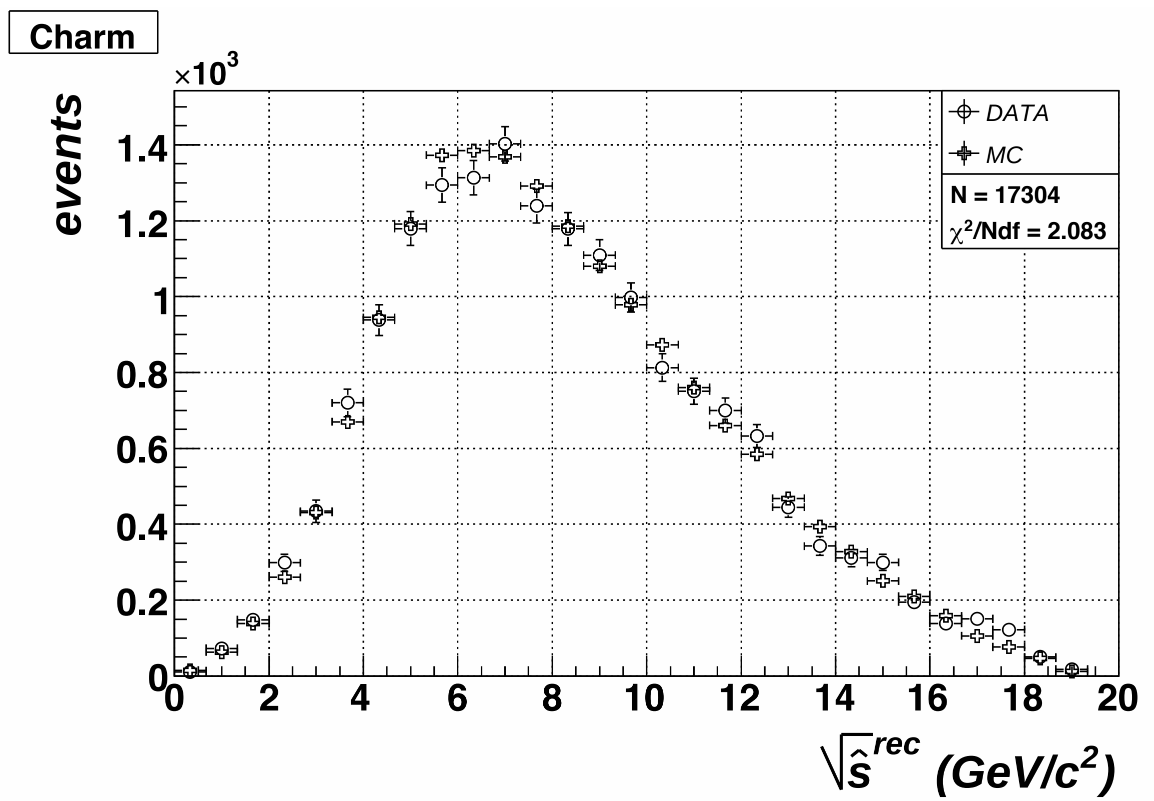
  $\Longrightarrow$ *Dominated by statistics*

Relative uncertainties for NuTeV analysis (published) and expectations for HiResMν:

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

DETERMINATION OF STRANGE SEA





- *Direct probe of the strange content of the nucleon*

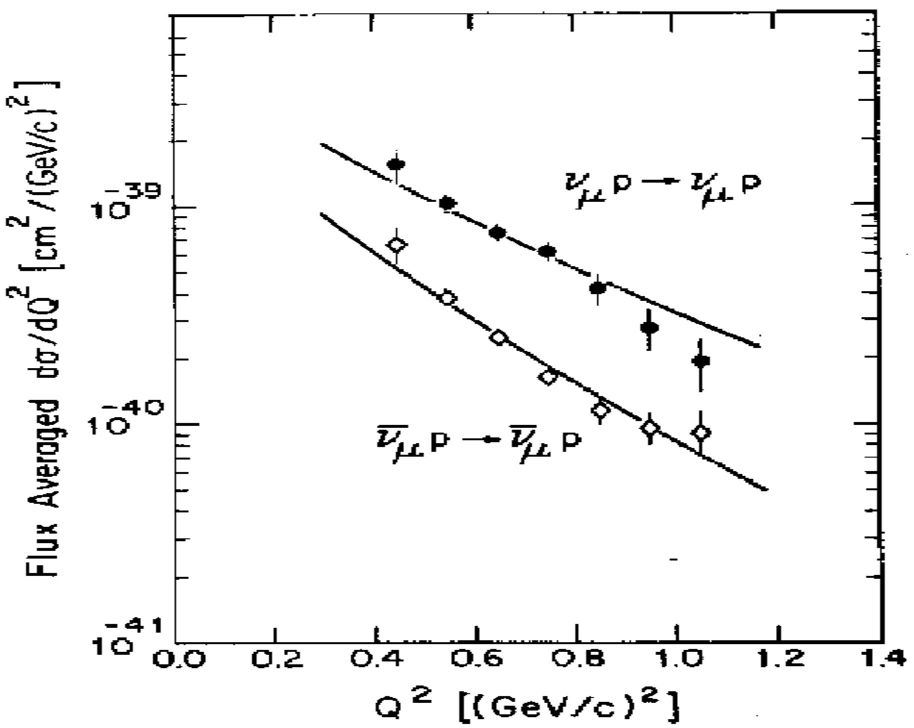
- *Dimuon $\nu(\bar{\nu})$ cross-section data from NuTeV and CCFR included in global PDF fit of DIS and Drell-Yan data.* (S. Alekhin, S. Kulagin and R.P., arXiv:0812.4448 [hep-ph])

Type	*NuTeV*	*CCFR*	*Total*
ν	*5012*	*5030*	**10042**
$\bar{\nu}$	*1458*	*1060*	**2518**

$\Longrightarrow$ **NOMAD** $\sim$ **17000** *ν-induced charm dimuon events (ongoing analysis by O. Samoylov and R.P.)*

MEASUREMENT OF Δs

BNL E734



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

✦ *Measure* NC/CC RATIOS *at low Q^2 to reduce systematic effects ($\sin^2\theta_W$ as well):*

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

- *Need high resolution tracking*
- *Systematics to address: nuclear effects, form factors (Q^2 dependence), neutrons*

$\Longrightarrow$ *T2K-ND280 expect $\sim$ 120k ν NC events in Fine Grained Detector (FGD)*
$\Longrightarrow$ *HiResMν expect $\sim$ 1.5 $\times 10^6$ ν NC and $\sim$ 800k $\bar{\nu}$ NC events*
$\Longrightarrow$ *β-beam ultimate precision (flux and statistics)*

CURRENT CONSERVATION

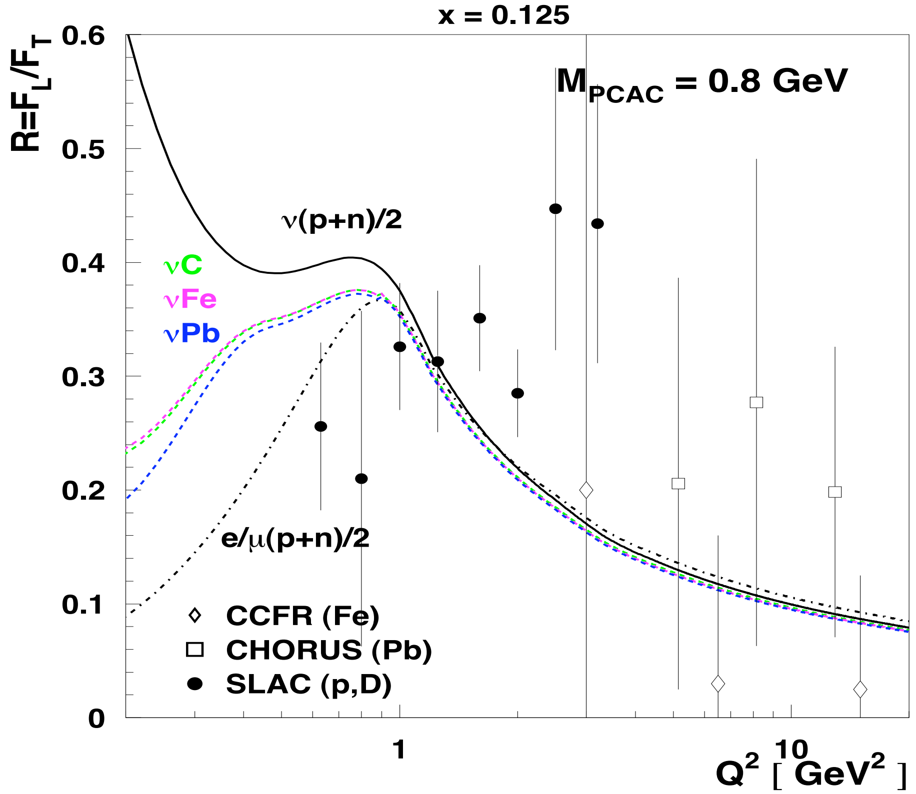
✦ PCAC: *Axial Current is only Partially Conserved.*
Axial-vector contributions dominate at low Q^2:

- *Adler relation for ν cross-section:*

$$\frac{d\sigma^2(\nu T \to lF)}{dQ^2 d\nu}|_{Q^2=0} \quad \propto \quad \sigma(\pi T \to F; E_\pi = \nu)$$

- *For $Q^2 \to 0$ $F_2, F_L \neq 0,\ R = \sigma_L/\sigma_T \to \infty$*

$\Longrightarrow$ *T2K-ND280 & HiResMν can do precision tests of PCAC at $Q^2 < 0.1$ GeV^2*



✦ *The Vector Current is Conserved,* CVC. *Vector contributions vanish for $Q^2 \to 0$*

- *Test CVC from momenta & polarization (Λ) in exclusive channels (S. Adler):*

$$\nu A \to l A' \pi\pi; \qquad \nu A \to l A' \Lambda K$$

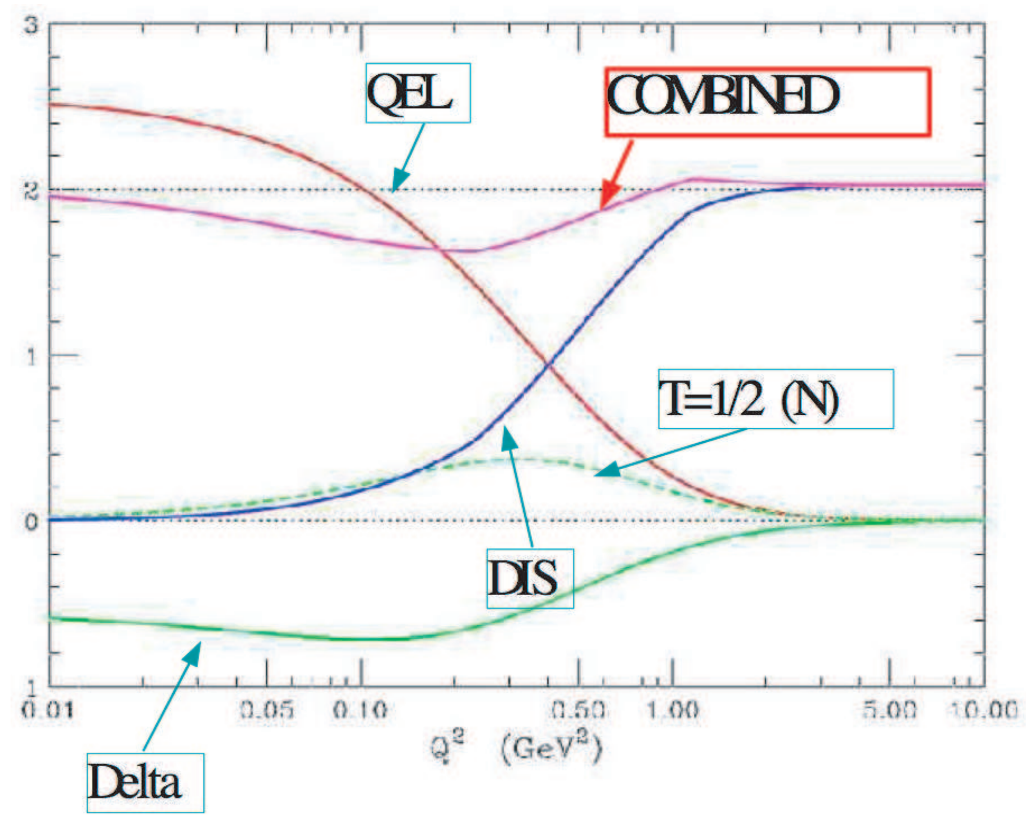
$\Longrightarrow$ *T2K-ND280 and HiResMν since high resolution & π/K separation*

- *At low energy β-beam from tensor form factor f_2 (weak magnetism) in $\bar{\nu}_e p \to e^+ n$ (A. Balantekin al.)*

$$CVC \longrightarrow f_2(0) = \frac{\mu_p - \mu_n}{2m_N}$$

TEST OF ADLER SUM RULE

P. Lipari



✦ *The Adler integral provides the* ISOSPIN *of the target and is an exact sum rule from current algebra:*

$$S_A = \int_0^1 \frac{dx}{x} \left(F_2^{\bar{\nu} p} - F_2^{\nu p} \right) = 2$$

- *At large Q^2 (quarks) sensitive to $(s - \bar{s})$ asymmetry, isospin violations*
- *At low Q^2 cancellation QE, Res, DIS*
- *Generalize the integral to nuclear targets and test nuclear effects*

✦ *Physics case for exposing liquid H_2 and/or D_2 targets to $\nu(\bar{\nu})$ beams, in combination with precision trackers (e.g. HiResMν)*

$\Longrightarrow$ *Fluxes at Project-X and ν-factory would allow to extract S_A at different Q^2*

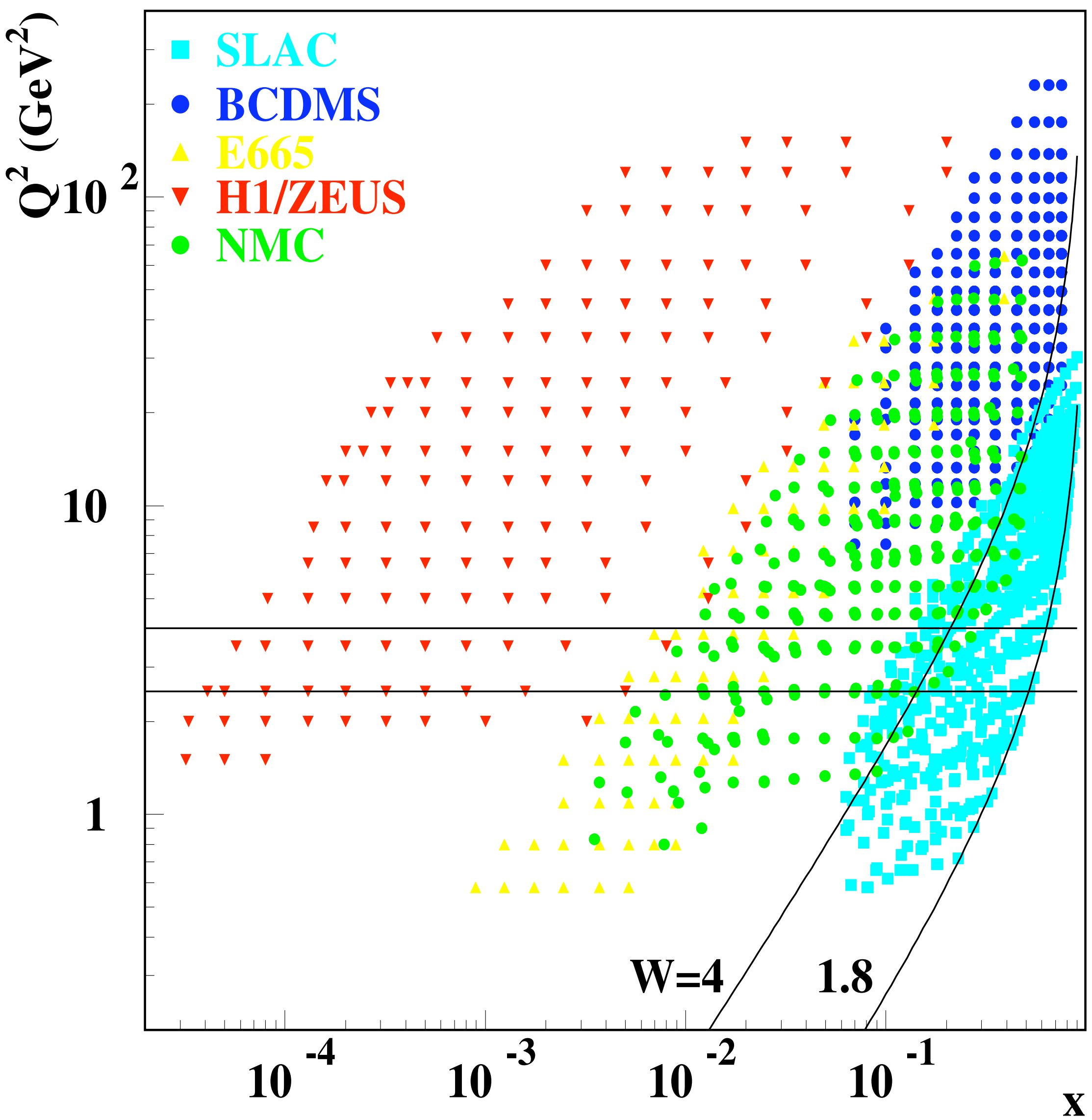
$\Longrightarrow$ *Measurement of $F_2^{\nu p}/F_2^{\bar{\nu} p} = d/u$ at large (Q^2, x) free from nuclear uncertainties*

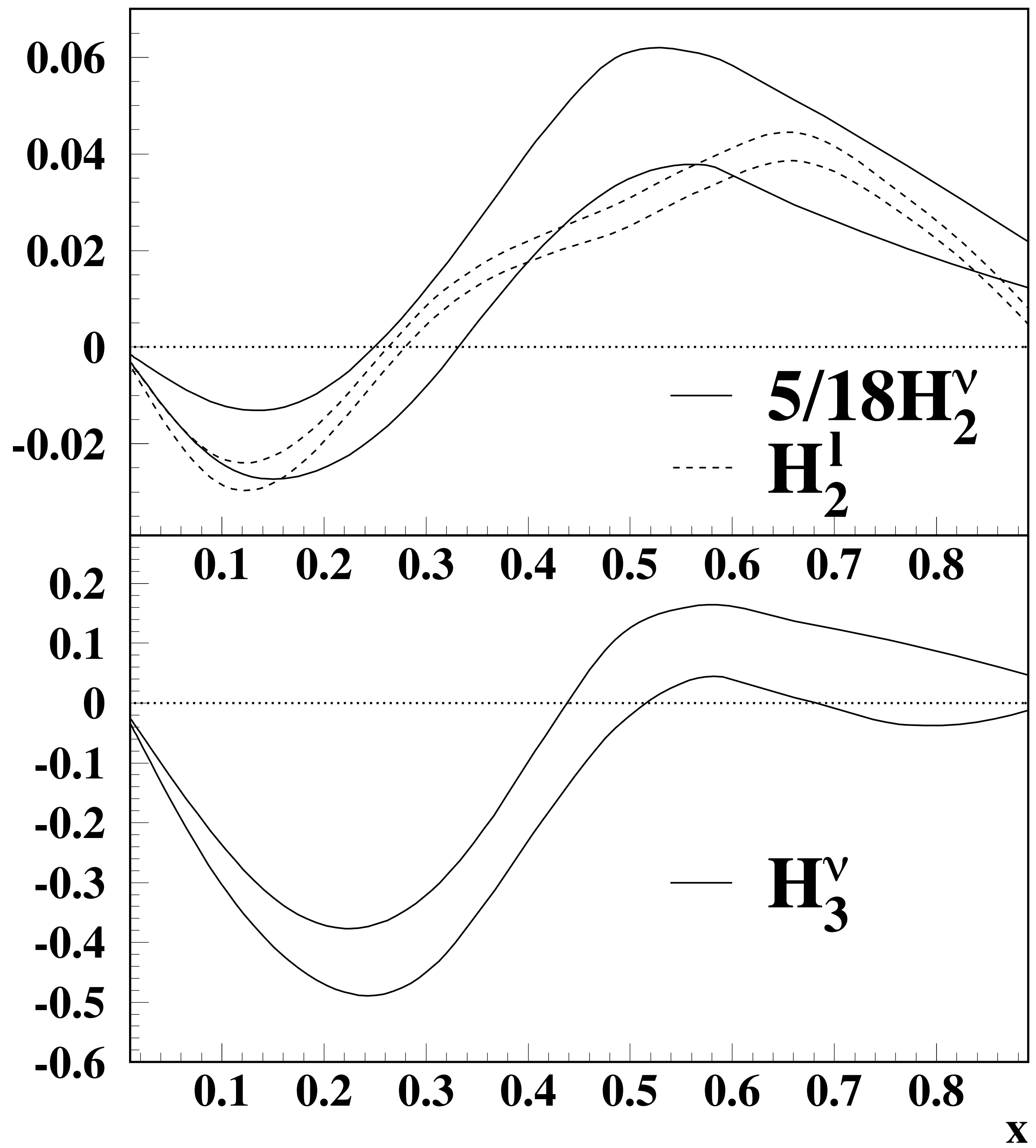
DETERMINATION OF DYNAMICAL HIGH TWISTS

- *Perform global fit to the charged lepton DIS and Drell-Yan data samples with* $\boldsymbol{Q^2 > 1.0}$ ***GeV²*** *and* $W > 1.8$ *GeV is used. The leading twist is calculated in the NNLO approximation, with parton distributions evolved from* $Q_0^2 = 9$ *GeV².*

- *The dynamical twist-4,6 terms,* $H_{2,T}^{\tau 4,\tau 6}(x)$*, are parameterized in a model-independent way by cubic splines with values at* $x = 0.1, 0.3, 0.5, 0.7, 0.9$ *which are fitted from data.*

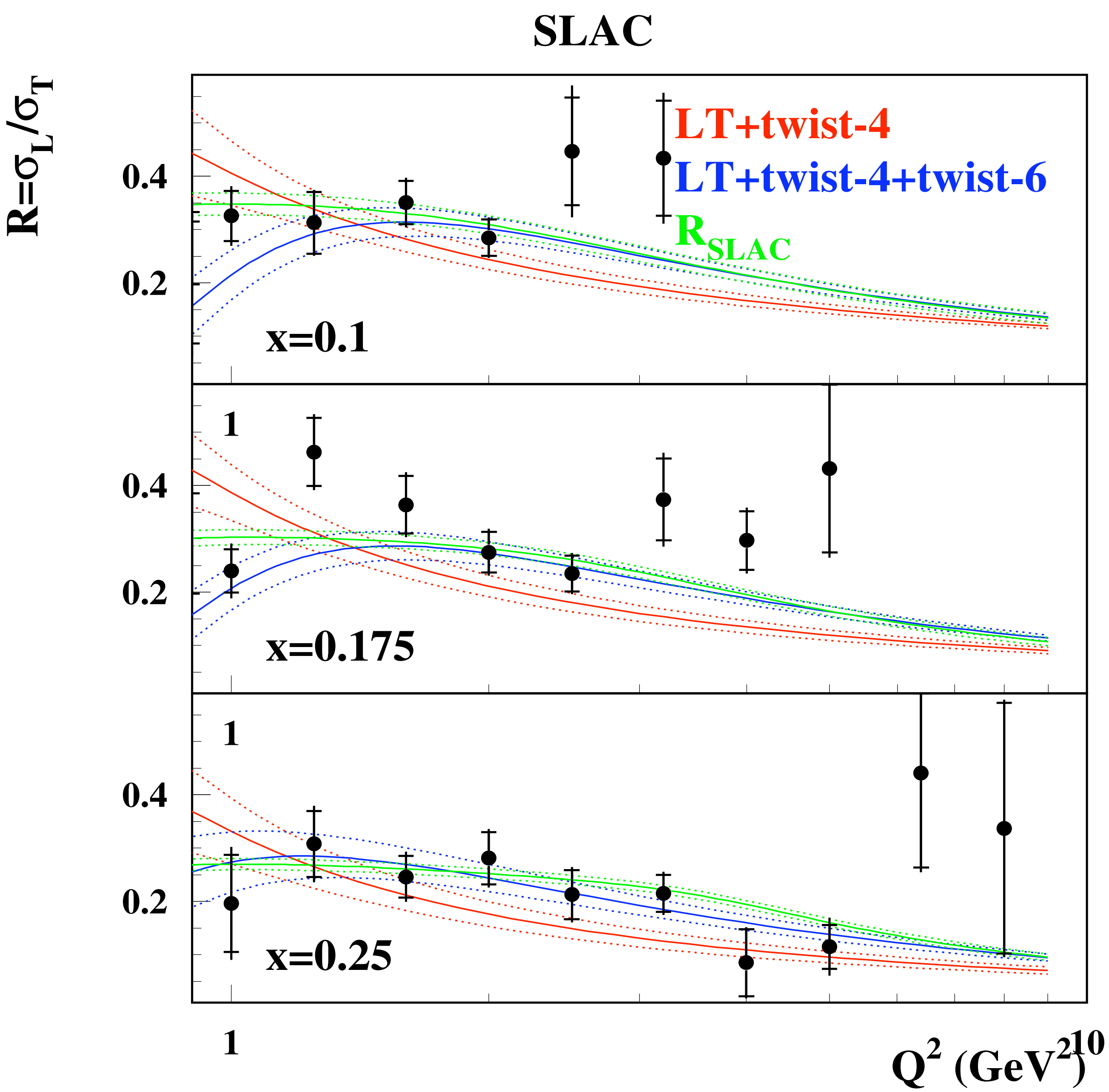
- *Few external constraints are imposed:*
  - $H_{2,T}^{\tau 4,\tau 6}(0) = 0$ *since no clear evidence for saturation effects is found at HERA;*
  - $H_{2,T}^{\tau 6} = 0$ *at* $x > 0.5$ *due to the impossibility to extract them out of the resonance region.*





- *Non-perturbative corrections on F_2 and F_T (High Twists) from CHORUS $\nu(\bar{\nu})$ cross-section data consistent with charged leptons after charge rescaling.*
- *Simultaneous extraction of HT in xF_3 from neutrino data*
- *Results in S. Alekhin, S. Kulagin and R.P., arXiv:0710.0124 [hep-ph], arXiv:0810.4893 [hep-ph]*

EVALUATION OF $R = \sigma_L/\sigma_T$



- The excess in SLAC data for $R = \sigma_L/\sigma_T$ at $x \sim 0.2$ with respect to the QCD predictions was considered as evidence of the large high twist contribution to R and F_L (Miramontes 92)

- Our results show instead such excess is connected with the discrepancy between SLAC and BCDMS and can be hardly attributed to the high twist contributions

Kulagin-Petti