Precision Measurements of Fundamental Interactions in the DUNE Near Detector

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ICHEP, August 3-10, 2016

Chicago

Goals of the DUNE Near-Detector (ND) Complex

(A) Constrain the systematic uncertainties in the Oscillation Measurements/Searches

⇒ Neutrino Source: ν_μ, ν_e, *anti*-ν_μ, *anti*-ν_e in

“*PMNS-Oscillation⇒0.5* $\leq E\nu \leq$ *10 GeV*” & “*Control & New-Physics⇒10* $\leq E\nu \leq$ *20 GeV*” regions

⇒ Absolute Flux & Relative Flux (*FD/ND*) measured at the Near Detector

⇒ Asymmetries in ν *.vs. anti*-ν Interactions: E-Scale, Topologies, Xsec, Nuclear effect

⇒ Signal: e^-, e^+, μ^-, μ^+, NC, ··· // Background: π^0, π^-, π^+, ν_μ-CC···

(B) A generational advance in the Precision Neutrino Physics

⇒ Cross-sections (QE, Resonance, Coherent-Meson, DIS), Sum-Rules

⇒ Neutrino-Nucleus (Ar) interactions & Nucleon Structure

⇒ Electroweak and Isospin Physics

↕ .. *Synergy*

(C) Search for New Physics at Short baseline

⇒ Heavy neutrinos, including `Light Dark-Matter’ search

⇒ Large Δm**2 oscillation: Synergy with FNAL’s SBN program

⇒ ...

..for FD, talks by Elizabeth & Alex

REQUIREMENTS FOR $\nu(\bar{\nu})$ SCATTERING PHYSICS

✦ $\boxed{\text{STATISTICS}}$

- *Limiting factor for old experiments*;
- *Need increase* $\boxed{\times 10 \div \times 100}$ *with respect to current/past experiments;*
- *Detector mass not critical at the LBNF due to the large fluxes;*

$\Longrightarrow$ Shit focus from Measurements to
Precision Tests of fundamental interactions

✦ *Reduction of systematic uncertainties:*

- *Flux, energy & momentum scales, backgrounds, theoretical modeling etc.;*
- *Start to limit current ν-scattering experiments*;
- *Need fine-grained detectors &* $\boxed{\text{REDUNDANCY}}$ *through multiple measurements*

$\Longrightarrow$ *A major physics program requires* $\boxed{\text{HIGH RESOLUTION}}$

Quantifying the Neutrino Source

Precision measurement of ALL four species of Neutrinos in:

“PMNS-Oscillation⇒$0.5 \leq E\nu \leq 10$ GeV” & *“Control & New-Physics⇒$10 \leq E\nu \leq 50$ GeV”* regions

(No. Events in Nu-Mode for DUNE-ND—FGT)

- ✳ $\nu_\mu \Rightarrow \mu^-$ as a function of $E\nu$ *($\sim 50 \times 10^6$ Events)* ⇒ FD/ND ($E\nu$);

- ✳ $\nu_e \Rightarrow e^-$ as a function of $E\nu$ *($\sim 8 \times 10^5$ Events)* ⇒ FD/ND ($E\nu$);

- ✳ *anti*-$\nu_\mu \Rightarrow \mu^+$ as a function of $E\nu$ *($\sim 5 \times 10^6$ Events)* ⇒ FD/ND ($E\nu$);

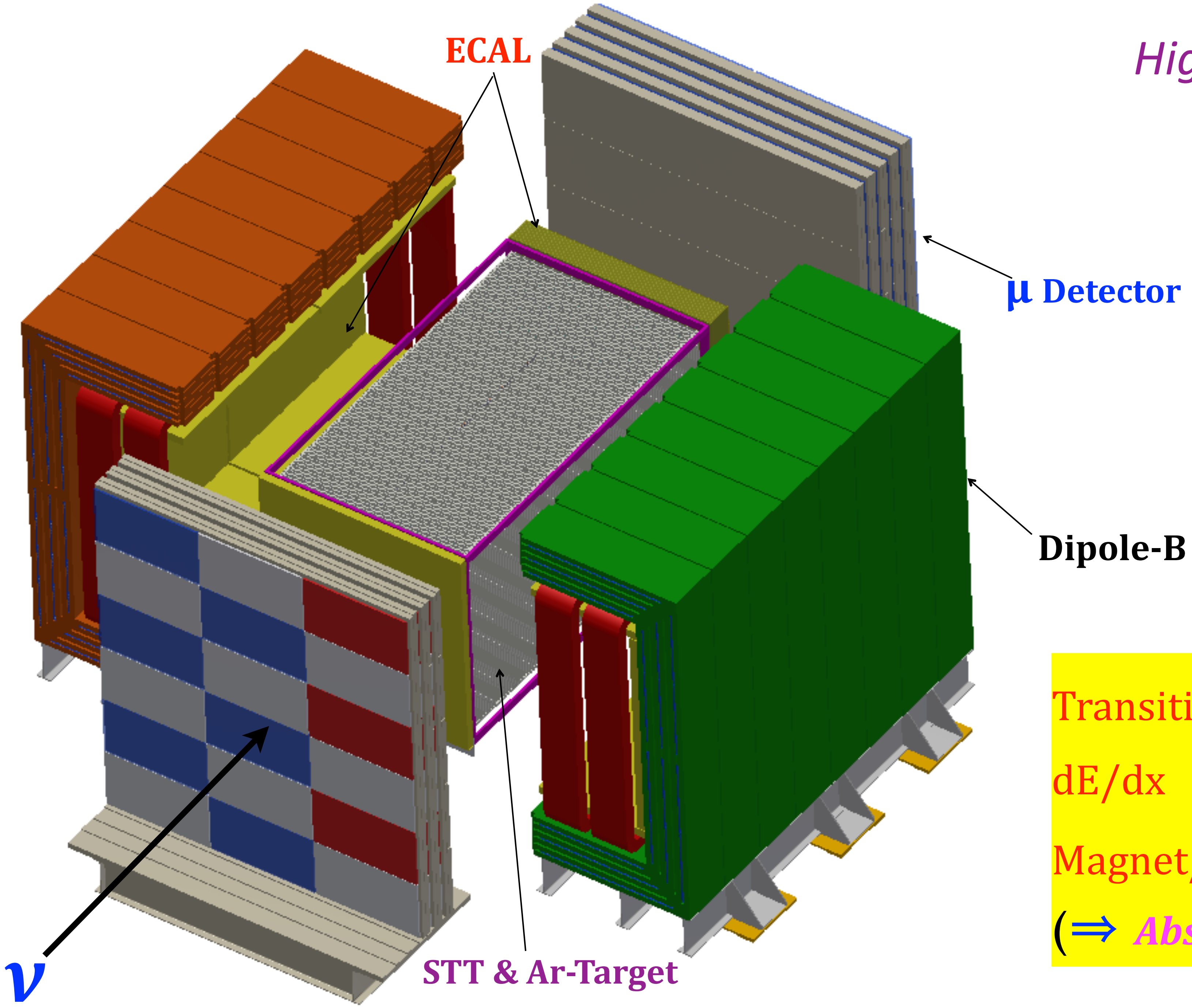
- ✳ *anti*-$\nu_e \Rightarrow e^+$ as a function of $E\nu$ *($\sim 5 \times 10^4$ Events)* ⇒ FD/ND ($E\nu$);

⇛ $\phi_\beta(E\nu, E_{vis}) / \phi_\alpha(E\nu, E_{vis})$ *for Neutrino and Anti-Neutrinos*

High-Resolution Fine Grain Tracker:

Reference ND for *DUNE*

Options: (1) LAr, (2) HP-GAr



Transition Radiation ↠ $e^{+/-}$ ID ⇒ γ

dE/dx ↠ Proton, $\pi^{+/-}$, $K^{+/-}$

Magnet/Muon Detector ↠ $\mu^{+/-}$ $e^{+/-}$

(⇒ ***Absolute Flux measurement***)

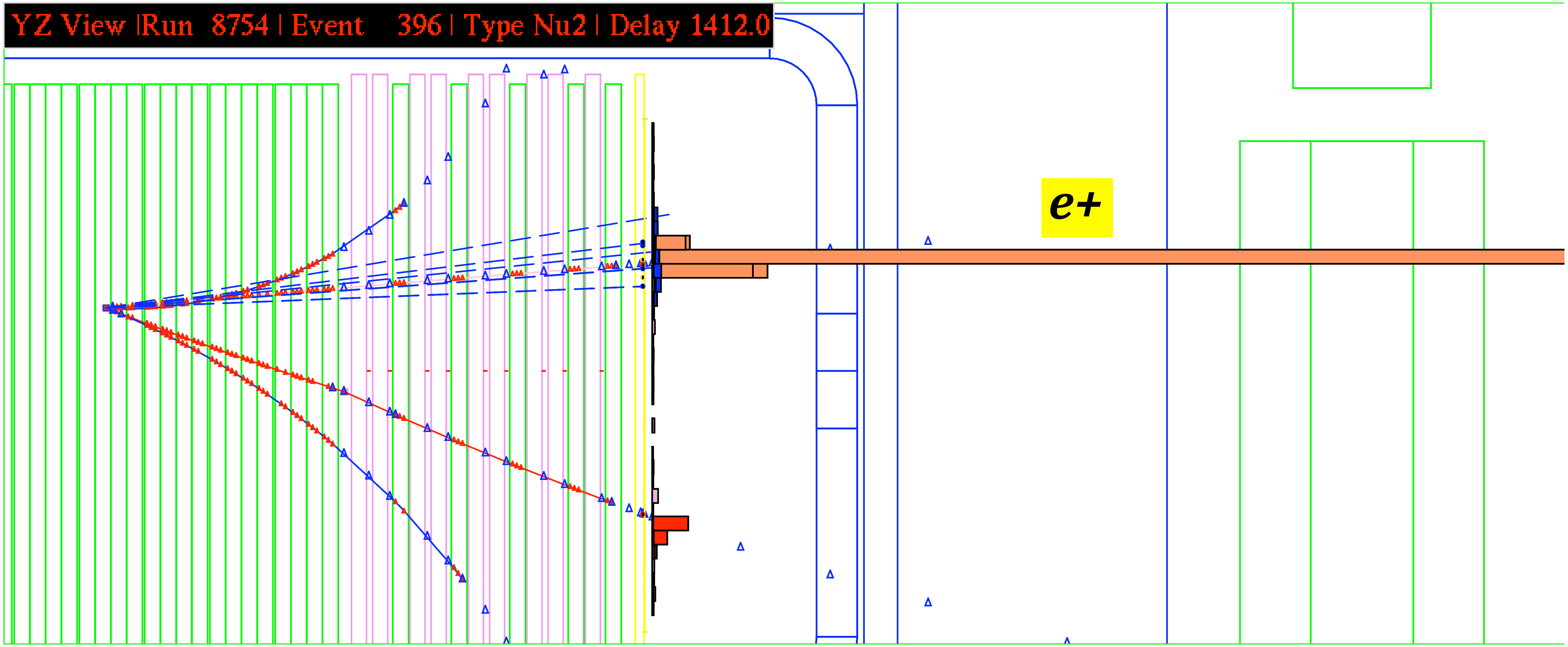
- ~3.5m x 3.5m x 7m STT ($\rho \simeq 0.1 gm/cm^3$)
- 4π-ECAL in a Dipole-B-Field (0.4T)
- 4π-μ-Detector (RPC) in Dipole and Downstream
- Pressurized Ar-target (≃***x68*** FD-Stat) ⇛ *LAr-FD*

..see FGT-talk by Bipul Bhuyan

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

⇛ *Most difficult to measure among the 4* ***ν****-species*

In FGT, ~x10 tracking points



Conclusion ⇛

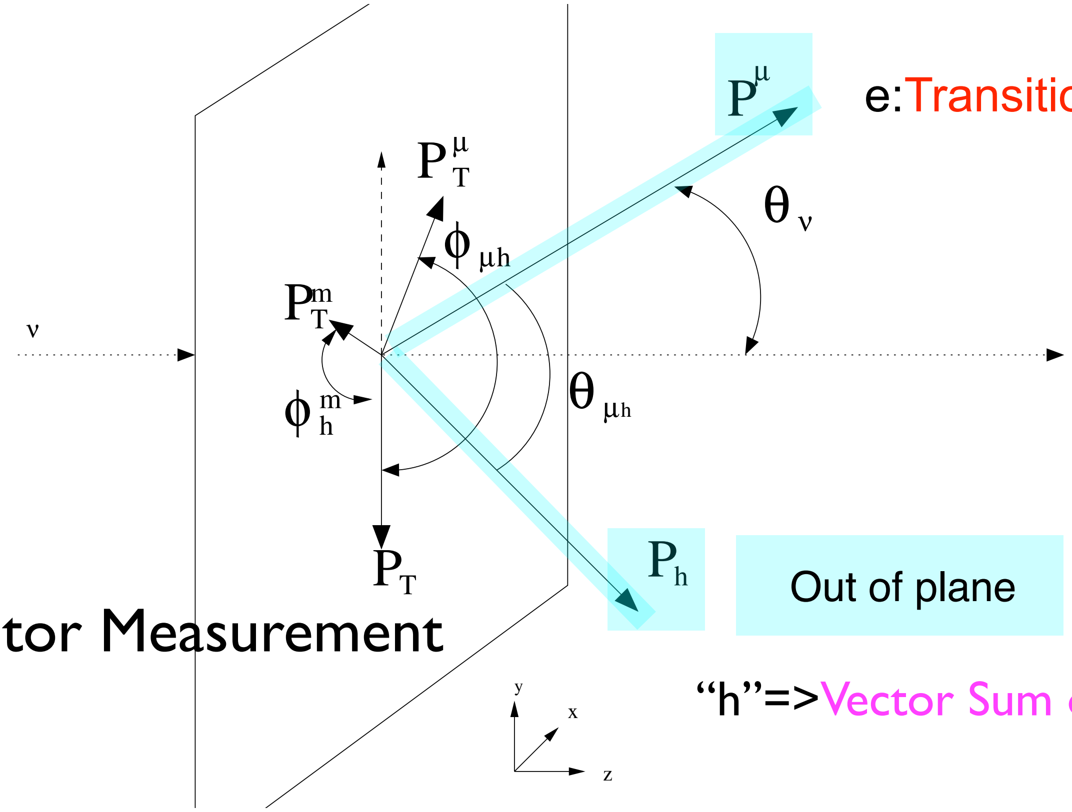
(1) μ from ***ν****μ and e from* ***ν****e are Tracks: Determined with very high precision*

*(2) Universality equivalence: μ -****ν****μ ↔ e -****ν****e*

Missing-PT Vector Measurement in CC

Missing-PT an invaluable constraint on the Ev-scale

- ✴ *Lepton & Hadron Momentum Vectors ⟹ Miss-PT*

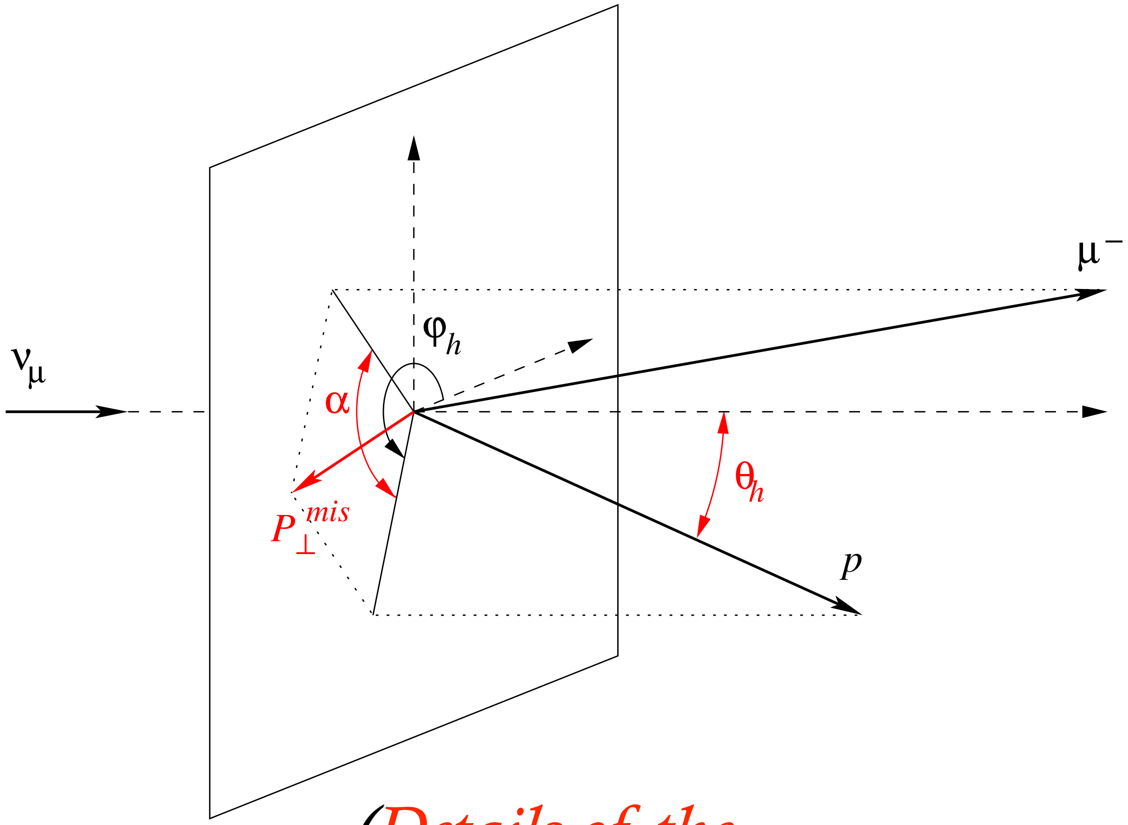


e:Transition Radiation

Out of plane

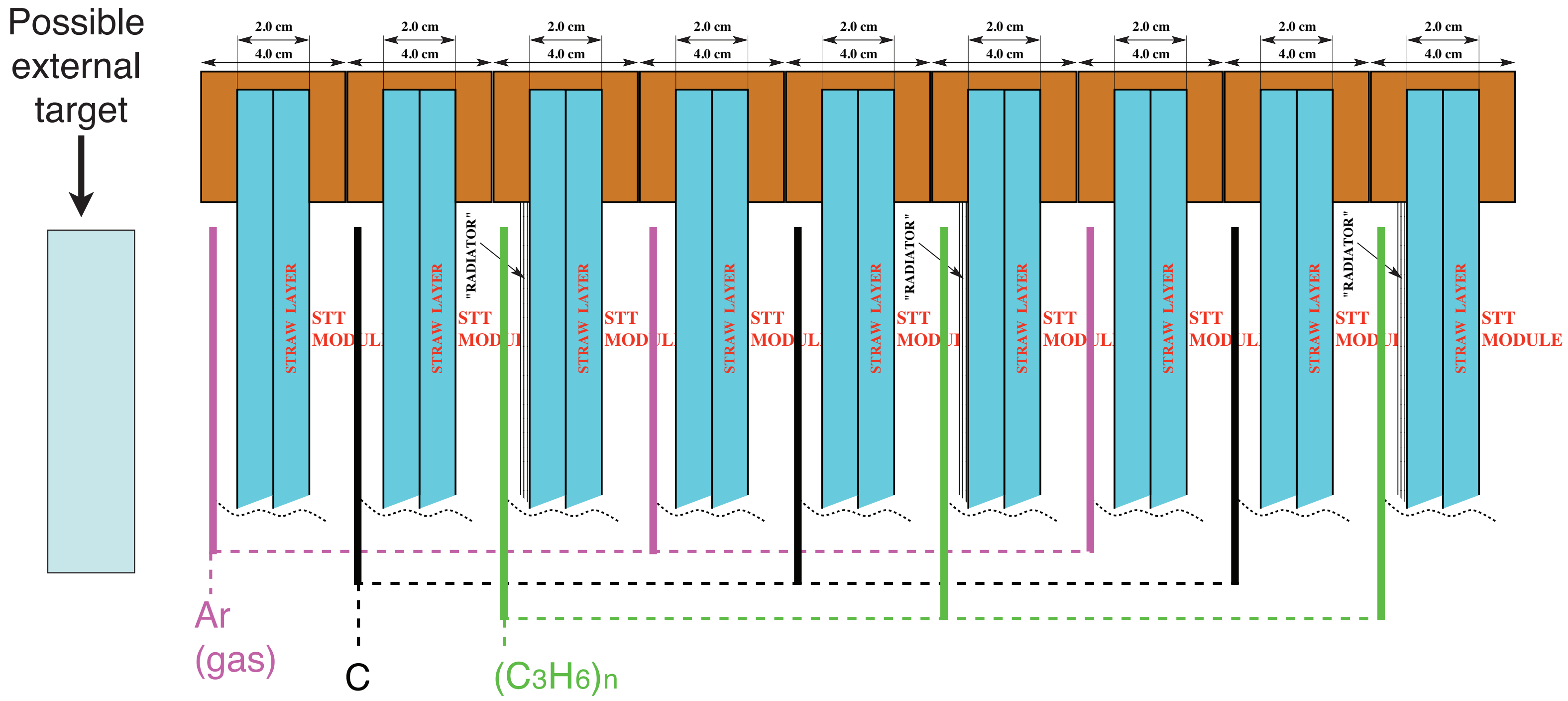
Pt-Vector Measurement

“h”=>Vector Sum of Tracks



(Details of the Missing-PT Measurement)

NUCLEAR TARGETS IN FGT



✦ *Multiple nuclear targets in FGT: $(C_3H_6)_n$ radiators, C, Ar gas, Ca, Fe, etc.*
$\Longrightarrow$ *Separation from excellent vertex ($\sim 100\mu m$) and angular (< 2 mrad) resolutions*

✦ *Subtraction of* $\boxed{\text{C TARGET}}$ *from polypropylene* $\boxed{(\mathrm{C_3H_6})_n \text{ RADIATORS}}$ *provides neutrino AND anti-neutrino interactions on free proton target*
$\Longrightarrow$ *Absolute $\bar{\nu}_\mu$ flux from QE*
$\Longrightarrow$ *Model-independent measurement of nuclear effects and FSI from RATIOS A/H*

✦ *Pressurized* $\boxed{\text{Ar GAS}}$ *target ($\sim$ 140 atm) inside C tubes and solid* $\boxed{\text{Ca TARGET}}$ *(more compact & effective) provide detailed understanding of the FD $A = 40$ target*
$\Longrightarrow$ *Collect more than* $\boxed{x68}$ *oscillated FD statistics on Ar target*
$\Longrightarrow$ *Study of flavor dependence & isospin physics*

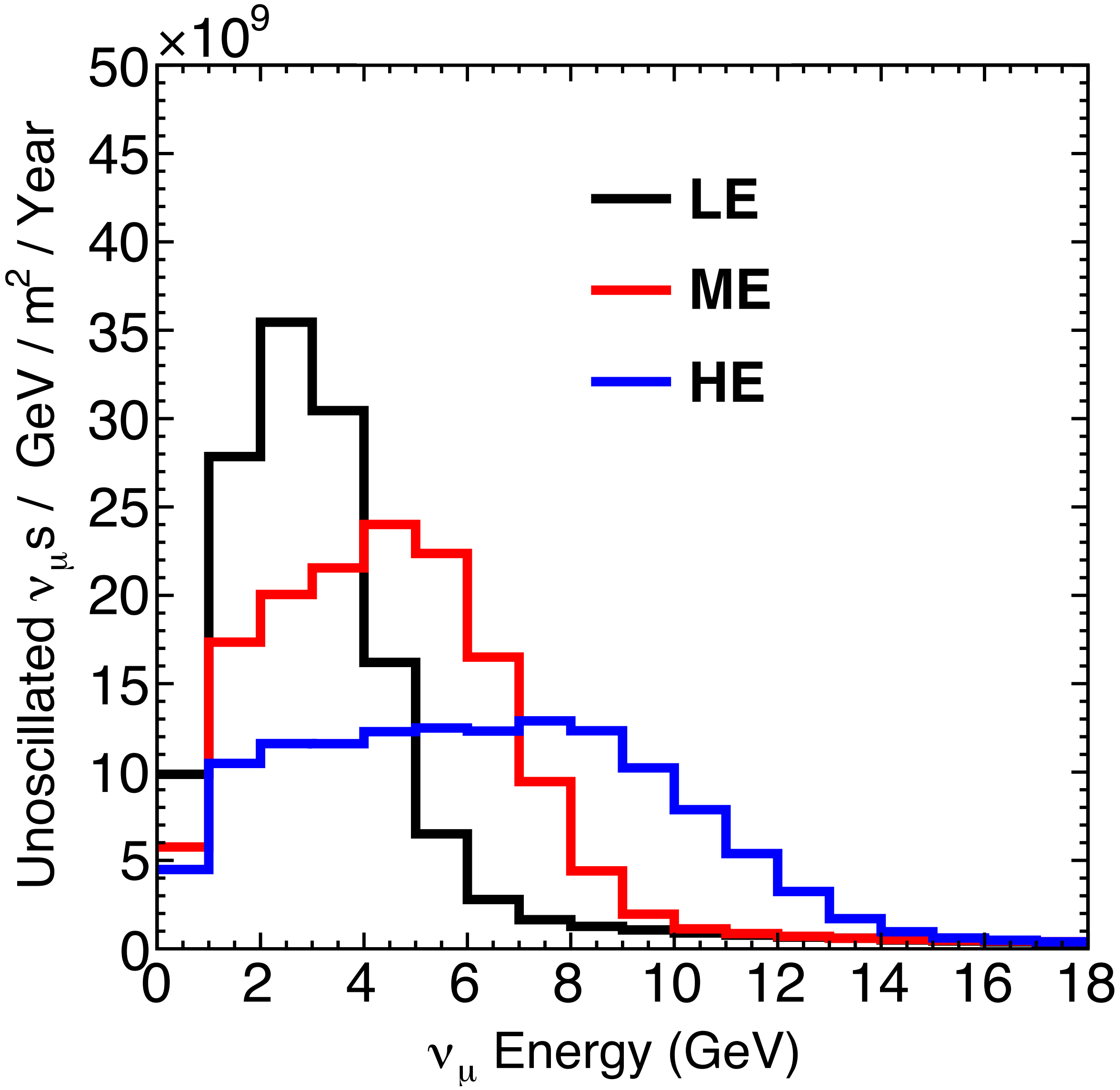
BEAM AND EVENT RATES

- *New high intensity (PIP-II) 1.2 MW proton beam at $E = 120$ GeV delivering 11×10^{20} pot/year for 5 (ν)+5($\bar{\nu}$) years*

  $\Longrightarrow$ *Upgradable to 2.4 MW*

- *Different energy tuning possible*

- *At ND location*
  expect to collect $90(40) \times 10^6$ $\nu_\mu(\bar{\nu}_\mu)$ CC inclusive interactions



..see talk by Vaia

FLUX MEASUREMENTS

- ✦ **ABSOLUTE FLUXES**

NC elastic scattering $\nu_\mu + e^- \to \nu_\mu + e^-$

$\Longrightarrow$ *Expect a* $\sim 2\%$ *precision in the absolute flux for* $0.5 \le E_\nu \le 10$ *GeV*

CC Inverse Muon Decay $\nu_\mu + e^- \to \nu_e + \mu$

$\Longrightarrow$ *Expect a* $\sim 2.5\%$ *precision in the absolute flux for* $E_\nu \ge 11$ *GeV*

Using quasi-elastic CC scattering off free proton (hydrogen) target $\bar\nu_\mu + p \to \mu + n$

$\Longrightarrow$ *Estimate a* $\sim 3\%$ *precision in the absolute flux for* $0.5 \le E_\nu \le 20$ *GeV*

- ✦ **RELATIVE FLUXES**

Use low-ν_0 *method to extract parent meson distributions and predict FD/ND*

$\Longrightarrow$ *Expect FD/ND to* $\sim$ *1-2% in fluxes vs.* E_ν *(bin-to-bin) for* $0.5 \le E_\nu \le 20$ *GeV*

Use coherent $\pi^\pm$ *production to determine* $\bar\nu/\nu$ *flux ratio*

$\Longrightarrow$ *Expect* $\sim 1\%$ *precision on the flux ratio*

$\Rightarrow$ *Crucial ingredient for Exclusive (QE, Resonance, Coh-Meson, DIS,) & Inclusive (CC & NC) differential cross-section measurements* $\Rightarrow$ *structure-functions, in situ constraints on nuclear effects, QCD & EW tests*

PRECISION TESTS OF THE ADLER SUM RULE

✦ *High statistics event samples on H target from the subtraction between $(C_3H_6)_n$ radiators and the C target allow high precision tests of the Adler sum rule*

✦ *The Adler integral provides the* ISOSPIN *of the target:*

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

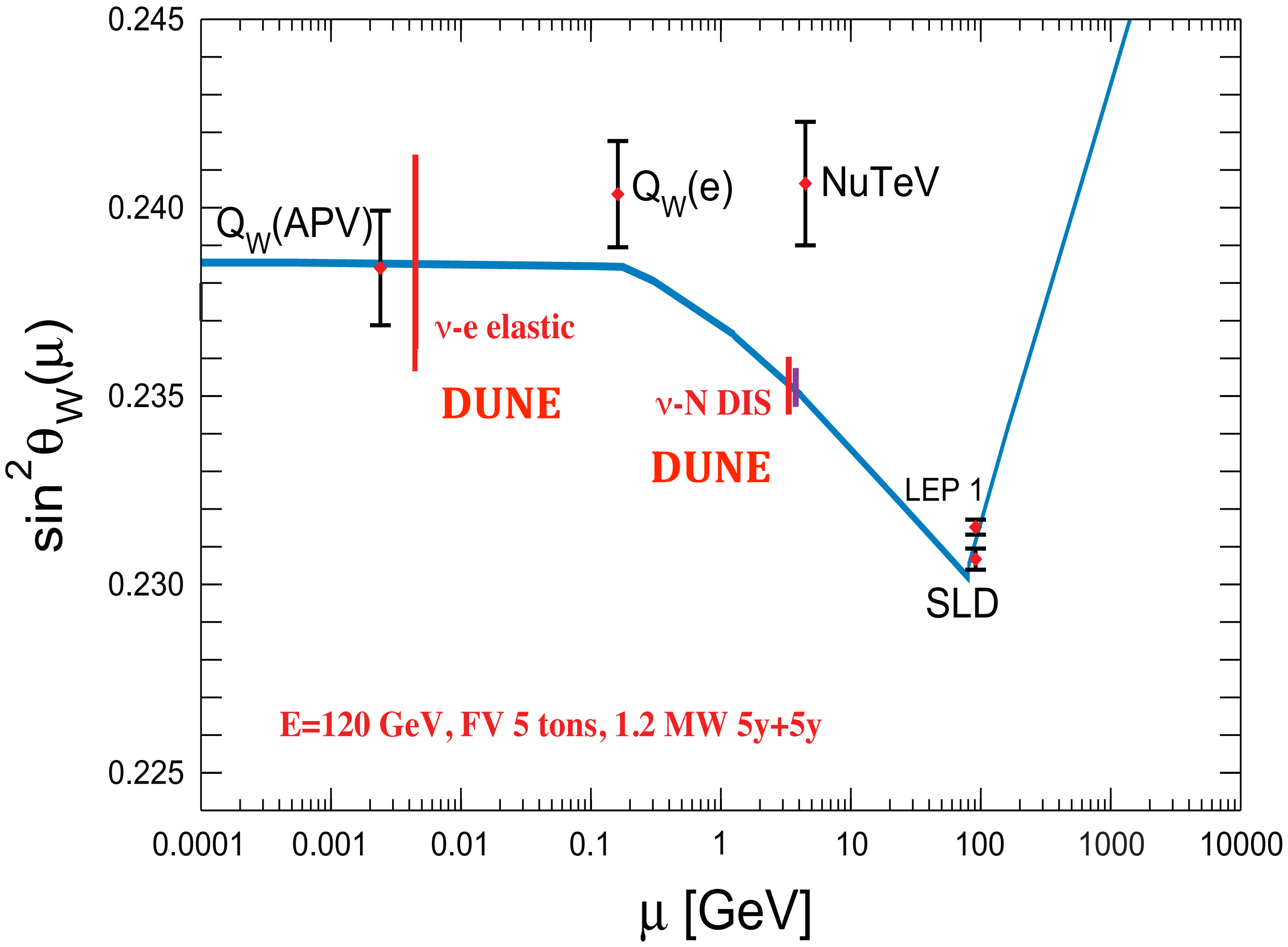
- *Exact sum rule from current algebra;*
- *At large Q^2 (quarks) sensitive to $(s - \bar{s})$ asymmetry, isospin violations;*
- *At low Q^2 cancellation QE, Res, DIS;*
- *Only measurement from BEBC with 5,000 (9,000) $\nu(\bar{\nu})$ events on H (Z.Phys.C28 (1985) 321).*
- *Expect $5.0(1.5) \times 10^6 \pm 13(6.6) \times 10^3 (sub.)$ $\nu(\bar{\nu})$ CC interactions on free proton*

$\Longrightarrow$ *A measurement on H at the percent level at LBNF could bring to discoveries!*

✦ *Interesting to measure the Adler sum rule in nuclei $S_A = (Z - N)/A$ like C, Ca and Ar to test possible isospin violations or flavor dependencies of nuclear effects*

PRECISION ELECTROWEAK MEASUREMENTS

- ✦ *Sensitivity from ν scattering in* **DUNE/LBNF** *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 ($\sim 3\sigma$ in ν data) in a similar Q^2 range*



- ✦ *Different independent channels:*
  - *$\mathcal{R}^\nu = \frac{\sigma^\nu_{\rm NC}}{\sigma^\nu_{\rm CC}}$ in ν-N DIS (∼0.35%)*
  - *$\mathcal{R}_{\nu e} = \frac{\sigma^{\bar\nu}_{\rm NC}}{\sigma^{\nu}_{\rm NC}}$ in ν-e^- NC elastic (∼1%)*
  - *NC/CC ratio $(\nu p \to \nu p)/(\nu n \to \mu^- p)$ in (quasi)-elastic interactions*
  - *NC/CC ratio ρ^0/ρ^+ in coherent processes*

  $\Longrightarrow$ *Combined EW fits like LEP*

- ✦ *Reduction of uncertainties to $\sim 0.2\%$ with 1-2 yr run in high energy mode*

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* ***DUNE/LBNF ND*** *will be at the* ***~10^{-3}*** $\Rightarrow$ *$\sim$ 2.0 (1.2) $\times 10^6$ ν ($\bar\nu$) NC events (best measurement BNL E734 with 951 (776) $\nu(\bar\nu)$ NC events, PRD 35 (1987) 785);*
- *A precision measurement over an extended Q^2 range reduces systematic uncertainties from the Q^2 dependence of vector ($F^s_{1,2}$) and axial (G^s_A) strange form factors;*
- *Need to check background subtraction (e.g. neutrons etc.);*

Role of Near-Detector in LBNF/DUNE: An Outlook

The ND-complex, with a high-resolution Fine-Grained Tracker (FGT), will:

(1) Quantify the Neutrino Source:

⇒ Neutrino Source: Neutrino Source: ν_μ, ν_e, *anti*-ν_μ, *anti*-ν_e

⇒ Neutrino and Antineutrino Energy-Scale

⇒ Relative flux: energy-to-energy, Anti-ν/ν, ν_e/ν_μ

in “*PMNS-Oscillation*⇒$0.5 \le E_\nu \le 10$ *GeV*” & “*Control & New-Physics*⇒$10 \le E_\nu \le 50$ *GeV*” regions

(2) measure Cross-section and topologies

⇒ 4-vectors of secondary hadrons in NC .vs. CC, ν .vs. Anti-ν

(3) Neutrino-Nuclear Interactions: Measurement over a variety of targets to provide a quantitative modeling

(4) Additional LAr-detector will enhance the capability of ND-complex

⇒ Conduct an Event-Generator Measurement, ν-Spectra & 4-vectors, for ND

(*Finally*) A generational advance in Precision Measurement and Searches

…rich canvas of >120 topics providing a program commensurate with the collider experiments

Backup

To precisely measure the neutrino-yield of e^-/e^+, need to have:

- ✴ Magnetized tracker to ID Positive from Negative particle:

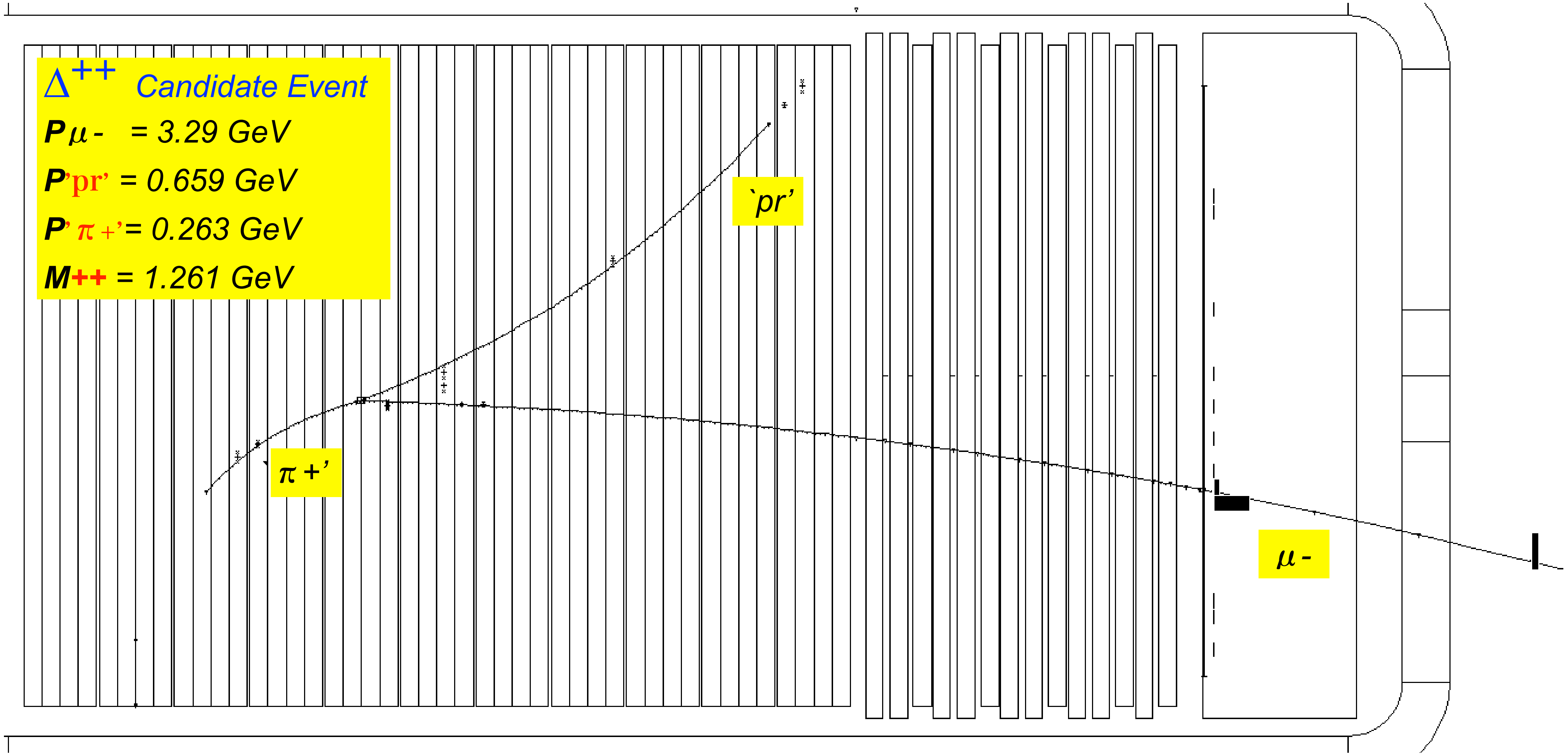
- ✴ Low-Density medium to track electron/positron:

  ⇒ Momentum vectors of hadrons $\pi^-/\pi^+/\pi^0$ / γ / $K^{0/+/-}$ & proton

- ✴ Large statistics ~ 10^8 ν-Interactions

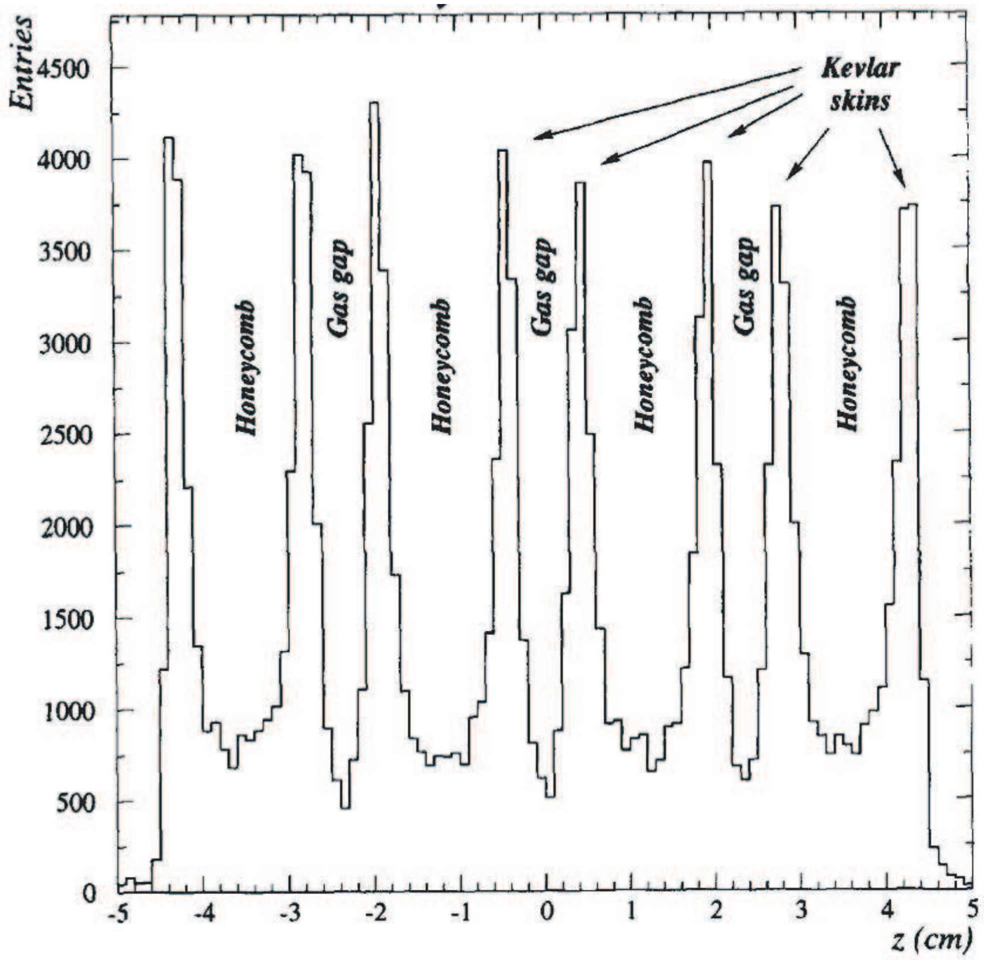
$$\boxed{\nu_\mu p \to \mu^- \Delta^{++} \to \mu^- p \pi^+}$$

p reconstruction & ID
wide angle hadrons

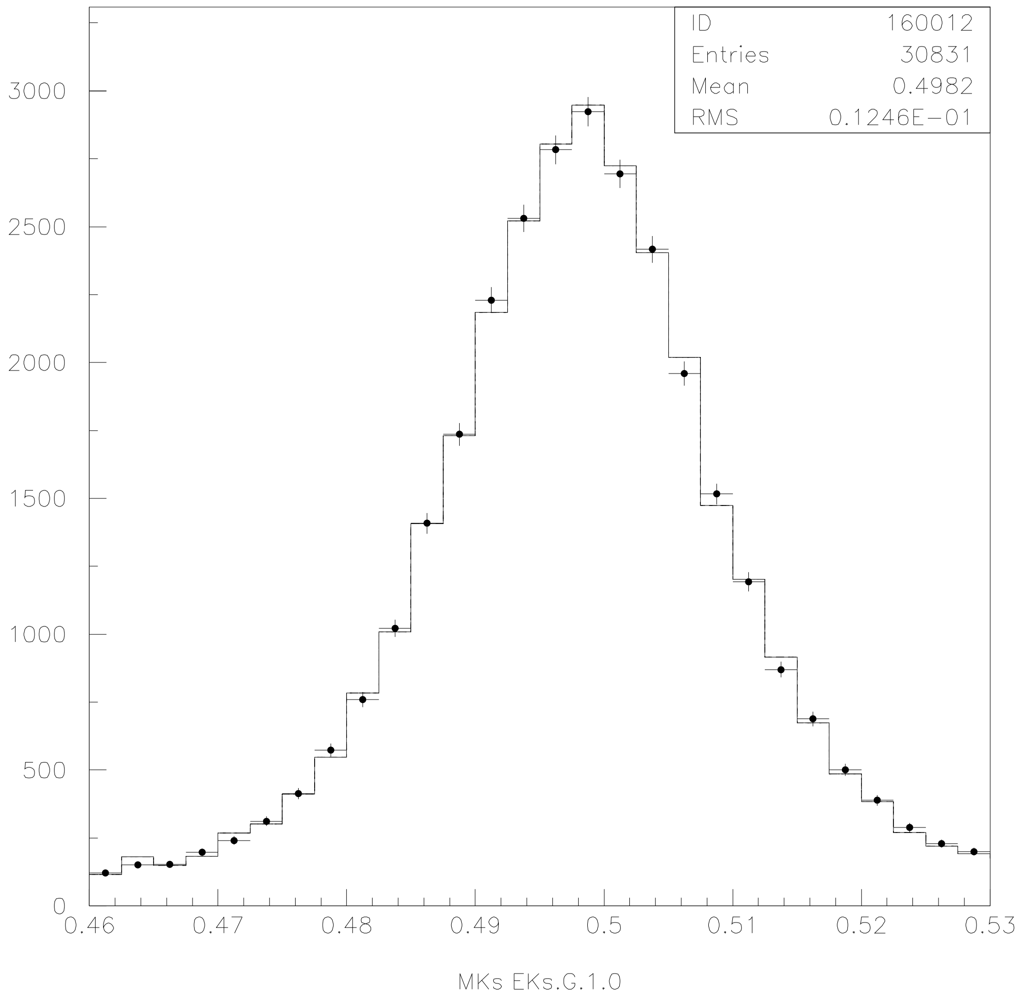


Event candidate from NOMAD data $\Longrightarrow$ *STT has* $\times 10$ *granularity*

VERTEX RESOLUTION AND ENERGY SCALES



Neutrino radiography of one drift chamber



Reconstructed K^0 mass

- ✦ *NOMAD: charged track momentum scale known to* $< 0.2\%$
  hardonic energy scale known to $< 0.5\%$
- ✦ *DUNE ND:* $\boxed{\sim 100 \times}$ *more statistics and* $\boxed{12 \times}$ *higher segmentation*

MEASUREMENT STRATEGY FOR $A = 40$ IN FGT

✦ *Contrary to other technologies (LAr TPC, HP-Ar TPC) FGT relies on a dedicated suite of nuclear targets to characterize interactions on the FD target nucleus (Ar)*

✦ *Disadvantages of FGT:*

- *Smaller Ar mass*
- *More complex analysis to measure nuclear effects*

✦ *Advantages of FGT:*

- *Model-independent characterization of nuclear effects in the* $A = 40$ *nucleus*
- *Multiple nuclear targets for accurate modeling of nuclear effects*
- *Excellent* γ *and* π^0 *detection (*$e^\pm$ *ID) improves reconstruction of hadronic component*

✦ *In FD expect about 3,000 (9,200)* ν_μ *CC (un)oscillated events per year on Ar:*

- *In FGT expect about 205,000* ν_μ *CC events per year on Ar* $\longrightarrow$ $\times(22)68$ *FD (un)oscillated*
- *In FGT expect about 685,000* ν_μ *CC events per year on Ca* $\longrightarrow$ $\times(74)228$ *FD (un)oscillated*
- *In FGT expect about 714,000* ν_μ *CC events per year on C*
- *In FGT expect about 857,000* ν_μ *CC events per year on H*
- *In FGT expect about 9,304,000* ν_μ *CC events per year on* $(C_3H_6)_n$

$\nu(\nu)$-Nuclear Effects …cont.

- *Direct model-independent measurement of nuclear effects in Ar from the ratio Ar/H with BOTH neutrino and anti-neutrino interactions*

- *Measurement of (anti)neutrino interactions in Ca ($A = 40$) and in-situ comparison of results with the corresponding measurements in pressurized Ar target*

- *Combine all FGT measurements from $A = 40$ nuclei (Ar and Ca $\sim \times 100$ FD) and extrapolate results to predict FD event rates in LAr*

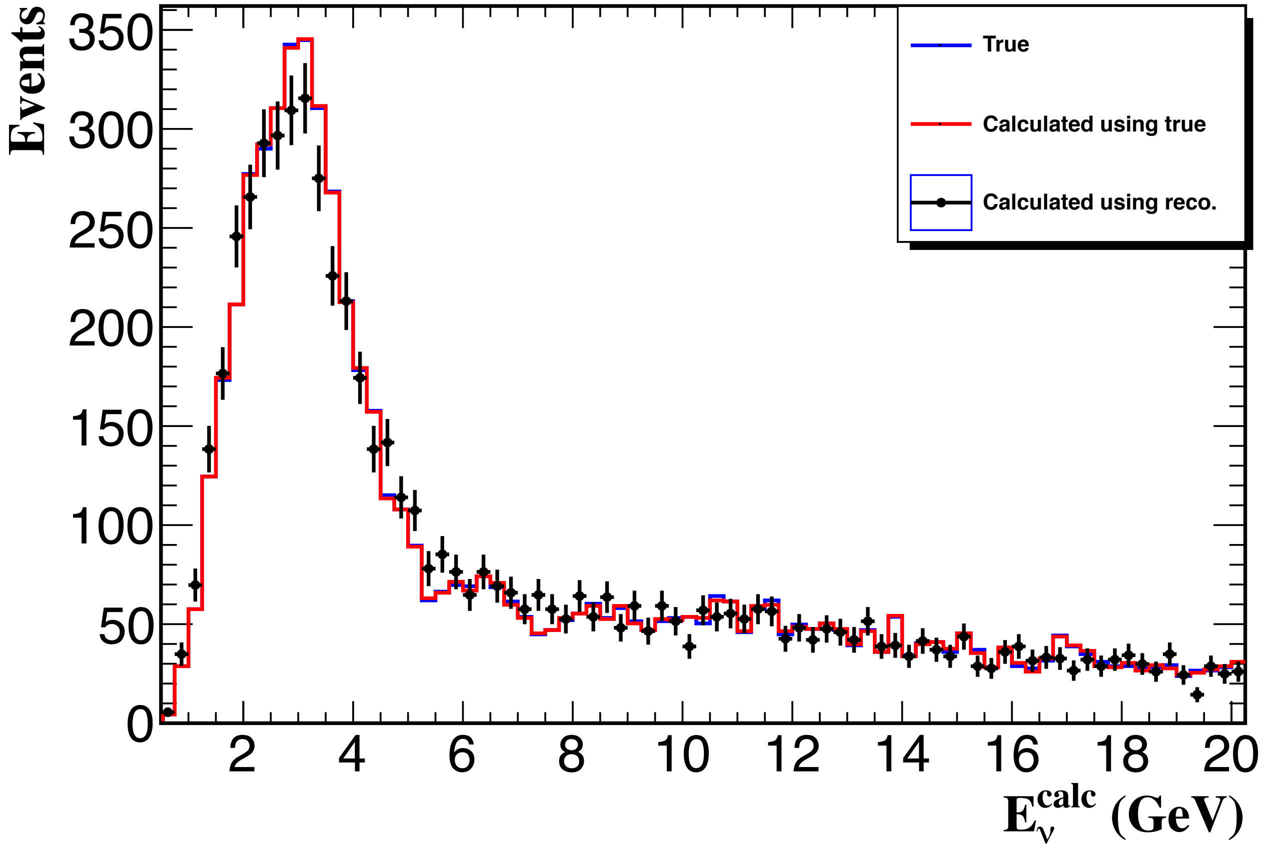
  $\Longrightarrow$ *Addition of small LAr TPC in front of FGT*
  would allow a further in-situ validation of FD predictions for LAr (+ rec. effects)

- *Dedicated measurements of nuclear effects with the complete suite of nuclear targets (H, C_3H_6, C, Ar, Ca, Fe) in FGT to refine/validate nuclear modeling of interactions*
  - *Ratios of cross-sections and structure functions for exclusive and inclusive processes*
  - *Difference $\Delta E = E^{\nu}_{\rm rec}(2\ trk) - E^{\rm QE}_{\rm rec}(1\ trk)$ in Quasi-elastic topologies*
  - *Difference between QE cross-sections determined from 1 track and 2 track samples*
  - *Differences between the 2 and 3 track samples from Resonance production*
  - *Backward going pions and protons*

  $\Longrightarrow$ *Systematic uncertainties on extrapolations/predictions of FD event rates in LAr*

Absolute Flux Measurement

(1):ν-Electron NC Scattering: $\nu_\mu + e \rightarrow \nu_\mu + e$



- ✴ Signal Eff ⇒ *73% //* Background ⇒ Benign;

in situ constraints

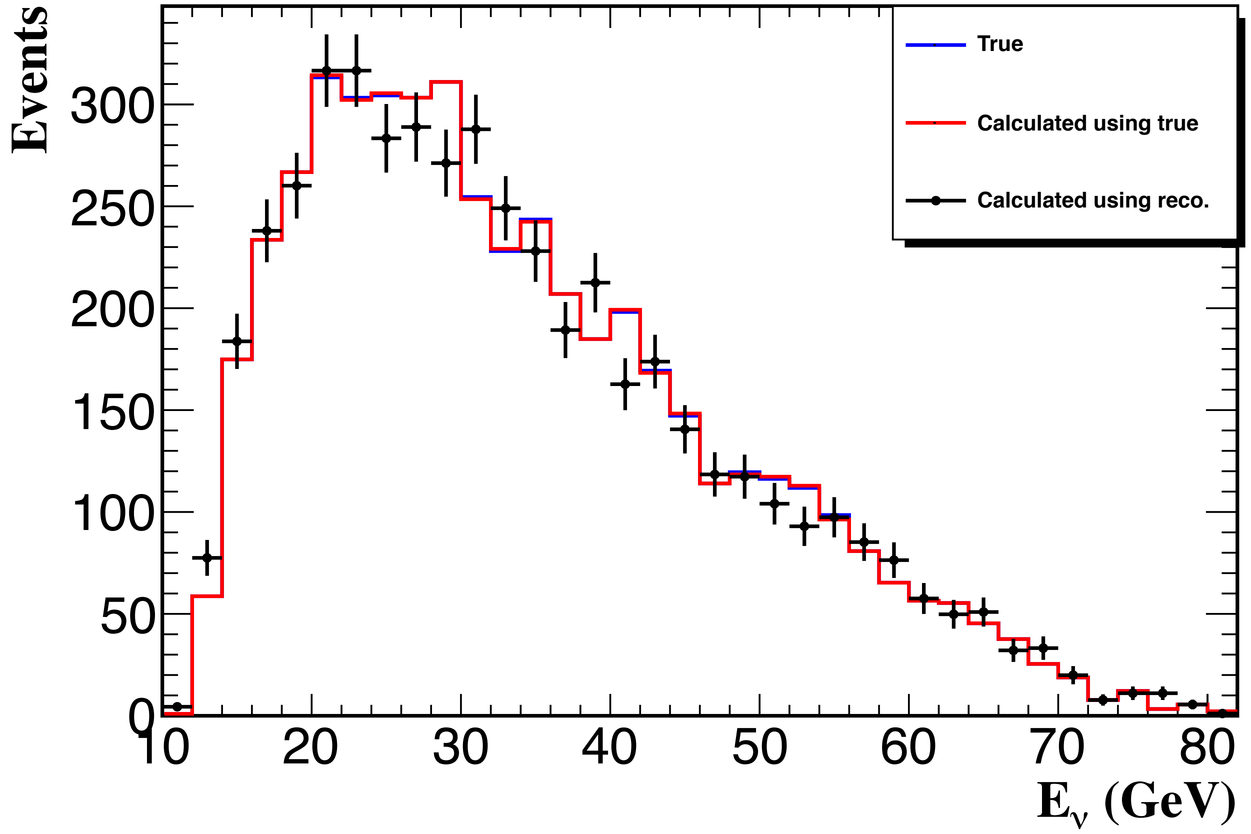
- ✴ Neutrino Energy

  High-resolution tracker allows thee reconstruction of E*ν* from (E*e*, *θ e*)

- ✴ Absolute Flux ⇒ *~2% precision in*

  *0.5 ≤**Eν**≤ 10 GeV range*

(2):ν-Electron CC Scattering: $\nu_\mu + e \rightarrow \nu_\mu + \mu^-$



- ✴ Signal Eff ⇒ *82% //*Background ⇒ 20%;

constrained by 2-Track *νμ*-CC analysis

- ✴ Neutrino Energy

  High-resolution tracker allows thee reconstruction of E*ν* from (E*μ*, *θ μ*)

- ✴ Absolute Flux ⇒ *~2.5% precision in*

  *15 ≤**Eν**≤ 50 GeV range*

Source of uncertainty	$\delta R^\nu / R^\nu$		**Comments**
	NuTeV	DUNE	
Data statistics	0.00176	0.00074	
Monte Carlo statistics	0.00015		
Total Statistics	*0.00176*	*0.00074*	
$\nu_e, \overline{\nu}_e$ flux ($\sim$ 1.7%)	0.00064	0.00010	e^-/e^+ identification
Energy measurement	0.00038	0.00040	
Shower length model	0.00054	n.a.	
Counter efficiency, noise	0.00036	n.a.	
Interaction vertex	0.00056	n.a.	
$\overline{\nu}_\mu$ flux	n.a.	0.00070	Large $\bar{\nu}$ contamination
Kinematic selection	n.a.	0.00060	Kinematic identification of NC
Experimental systematics	*0.00112*	*0.00102*	
d,s→c, s-sea	0.00227	0.00140	Based on existing knowledge
Charm sea	0.00013	n.a.	
$r = \sigma^{\overline{\nu}}/\sigma^\nu$	0.00018	n.a.	
Radiative corrections	0.00013	0.00013	
Non-isoscalar target	0.00010	N.A.	
Higher twists	0.00031	0.00070	Lower Q^2 values
R_L (F_2, F_T, xF_3)	0.00115	0.00140	Lower Q^2 values
Nuclear correction		0.00020	
Model systematics	*0.00258*	*0.00212*	
Total	**0.00332**	**0.00247**	

TESTS OF ISOSPIN (CHARGE) SYMMETRY

✦ *Experimental check of isospin symmetry in nucleon,* $u_{p(n)} \neq d_{n(p)}$. *Fine grained ND in DUNE/LBNF with* ν *AND* $\bar{\nu}$ *on isoscalar* C TARGET:

$$\frac{F_2^{\nu C}}{F_2^{\bar{\nu} C}}(x, Q^2) - 1$$

- *Structure function ratio reduces systematic uncertainties;*
- *Need to take into account charm quark effects* $\propto \sin^2\theta_C$. *Sensitivity to* $\boxed{m_c}$;
- *A non-vanishing strange sea asymmetry* $s(x) - \bar{s}(x)$ *would affect the result.* *Need combined analysis with charm production in* ν *and* $\bar{\nu}$ *interactions;*
- *Potential effect of nuclear environment e.g. with Coulomb field.*

✦ *Collect* ν *and* $\bar{\nu}$ *interactions on both* Ca AND Ar TARGETS *to disentangle nuclear effects from isospin effects in nucleon structure functions.*

- *Measure ratios* $F_2^{\nu A}/F_2^{\bar{\nu} A}(x, Q^2)$;
- *Use heavier isoscalar target,* ${}^{40}_{20}$*Ca, to verify nuclear effects in* ${}^{12}_{6}$*C;*
- *Use second target with isovector component but same A as Ca:* ${}^{40}_{18}$*Ar.*