

Precision Measurements of Fundamental Interactions in the DUNE Near Detector

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Goals of the DUNE Near-Detector (ND) Complex

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

⇒ Neutrino Source: ν_μ , ν_e , $anti-\nu_\mu$, $anti-\nu_e$ in

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

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

⇒ Asymmetries in ν vs. $anti-\nu$ 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

◆ STATISTICS

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

⇒ Shift 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 & **REDUNDANCY** through multiple measurements

⇒ A major physics program requires **HIGH RESOLUTION**

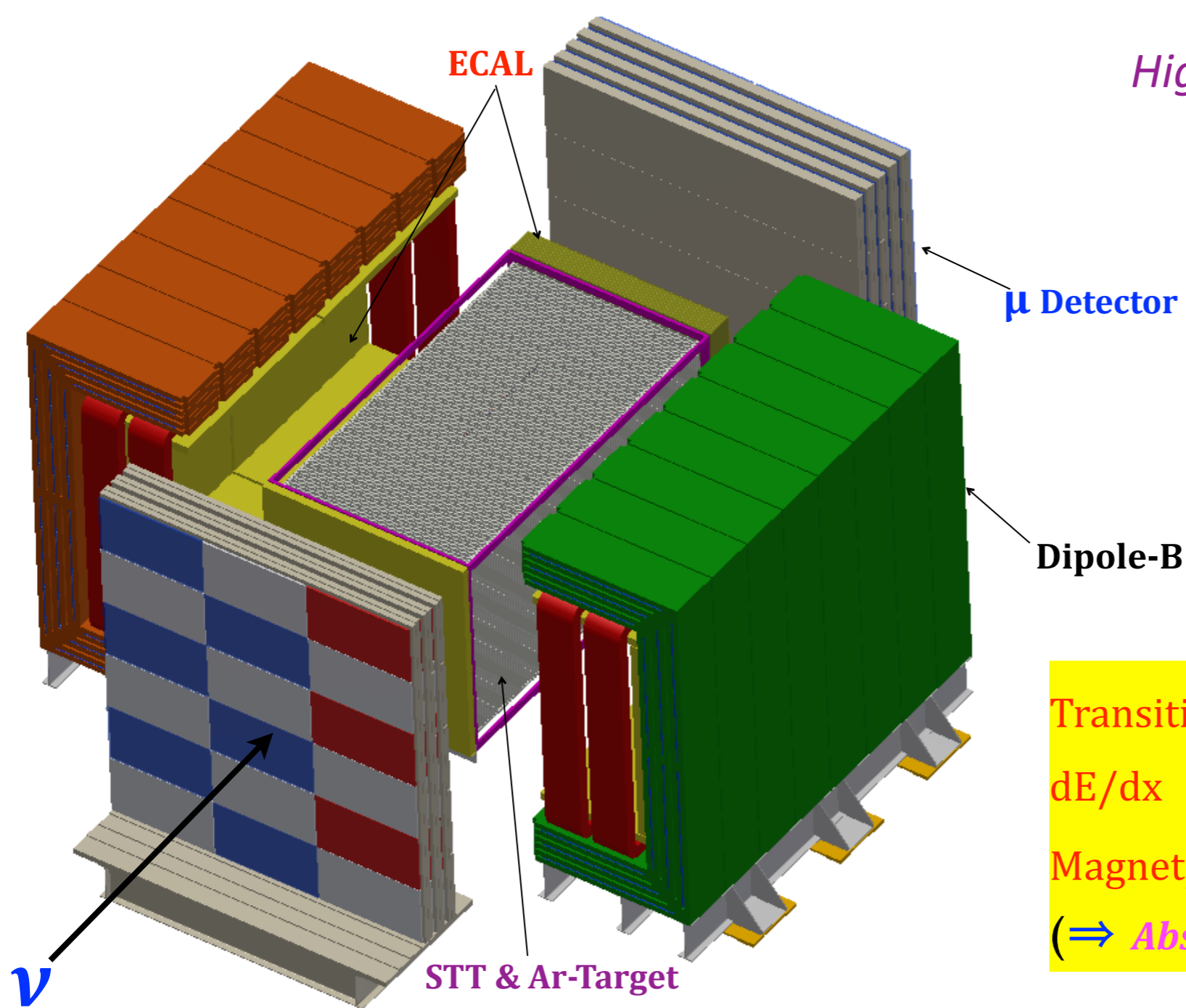
Quantifying the Neutrino Source

Precision measurement of ALL four species of Neutrinos in:

“PMNS-Oscillation $\Rightarrow 0.5 \leq E\nu \leq 10 \text{ GeV}$ ” & “Control & New-Physics $\Rightarrow 10 \leq E\nu \leq 50 \text{ GeV}$ ” 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) \Rightarrow FD/ND ($E\nu$);
 - * $\nu_e \Rightarrow e^-$ as a function of $E\nu$ ($\sim 8 \times 10^5$ Events) \Rightarrow FD/ND ($E\nu$);
 - * $\text{anti-}\nu_\mu \Rightarrow \mu^+$ as a function of $E\nu$ ($\sim 5 \times 10^6$ Events) \Rightarrow FD/ND ($E\nu$);
 - * $\text{anti-}\nu_e \Rightarrow e^+$ as a function of $E\nu$ ($\sim 5 \times 10^4$ Events) \Rightarrow FD/ND ($E\nu$);
- $\Rightarrow \phi_\beta(E\nu, E\nu_{\text{vis}}) / \phi_\alpha(E\nu, E\nu_{\text{vis}})$ for Neutrino and Anti-Neutrinos



High-Resolution Fine Grain Tracker:

Reference ND for *DUNE*

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

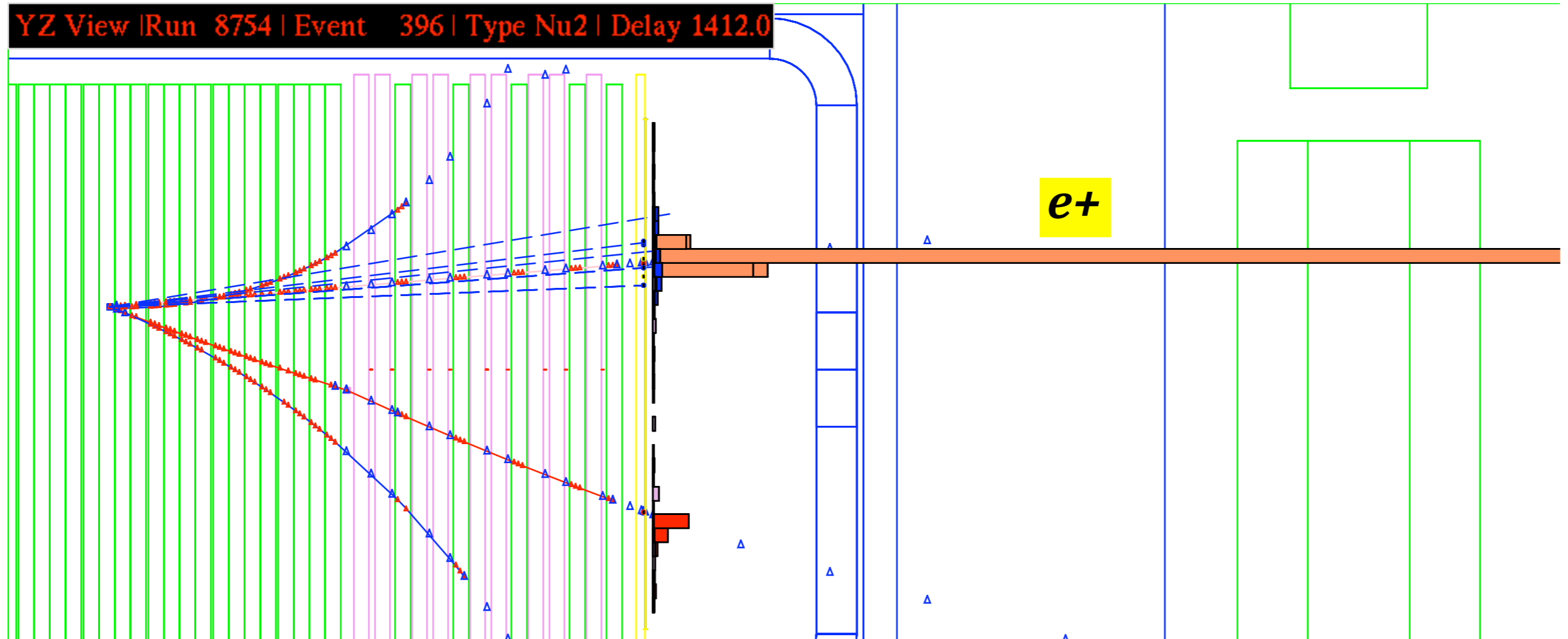
Transition Radiation $\Rightarrow e^{+/-}$ ID $\Rightarrow \gamma$
 dE/dx \Rightarrow Proton, $\pi^{+/-}$, $K^{+/-}$
 Magnet/Muon Detector $\Rightarrow \mu^{+/-}$ $e^{+/-}$
 (\Rightarrow *Absolute Flux measurement*)

- ☞ $\sim 3.5\text{m} \times 3.5\text{m} \times 7\text{m}$ STT ($\rho \simeq 0.1\text{gm/cm}^3$)
- ☞ 4π -ECAL in a Dipole-B-Field (0.4T)
- ☞ 4π - μ -Detector (RPC) in Dipole and Downstream
- ☞ Pressurized Ar-target ($\simeq \times 68$ FD-Stat) \Rightarrow 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, $\sim x10$ tracking points



Conclusion ⇒

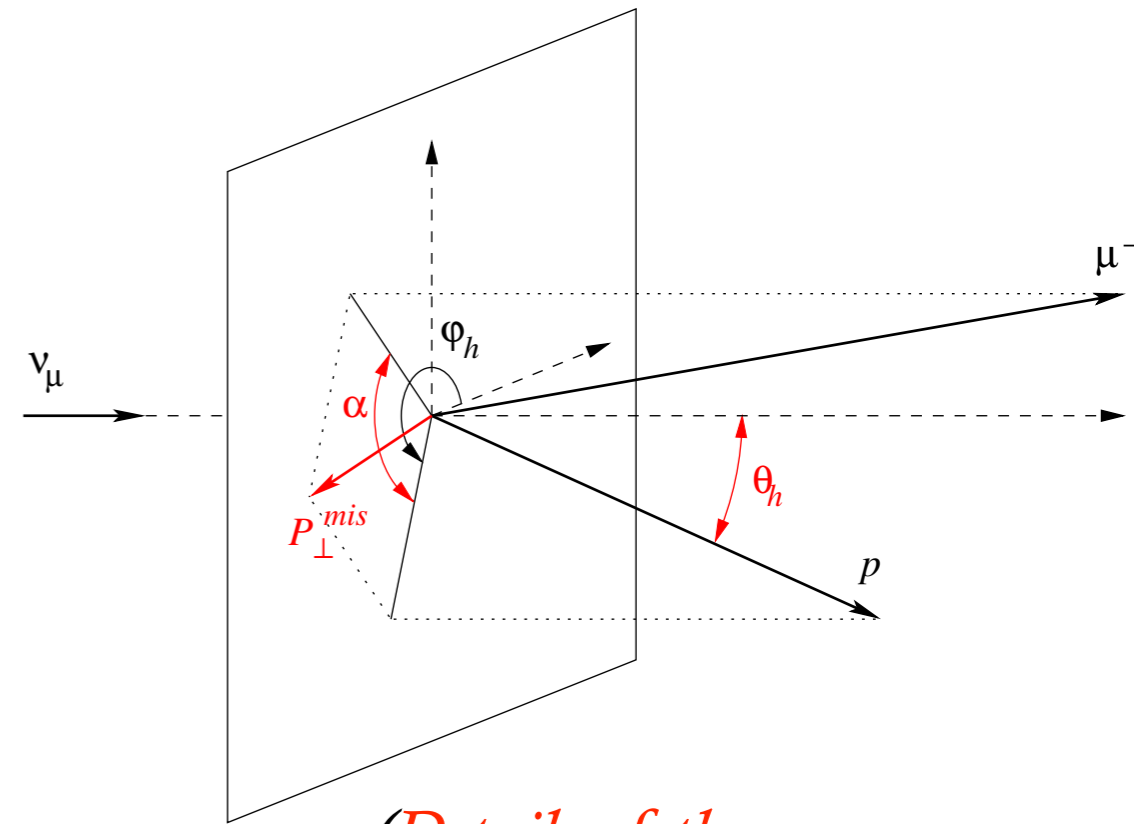
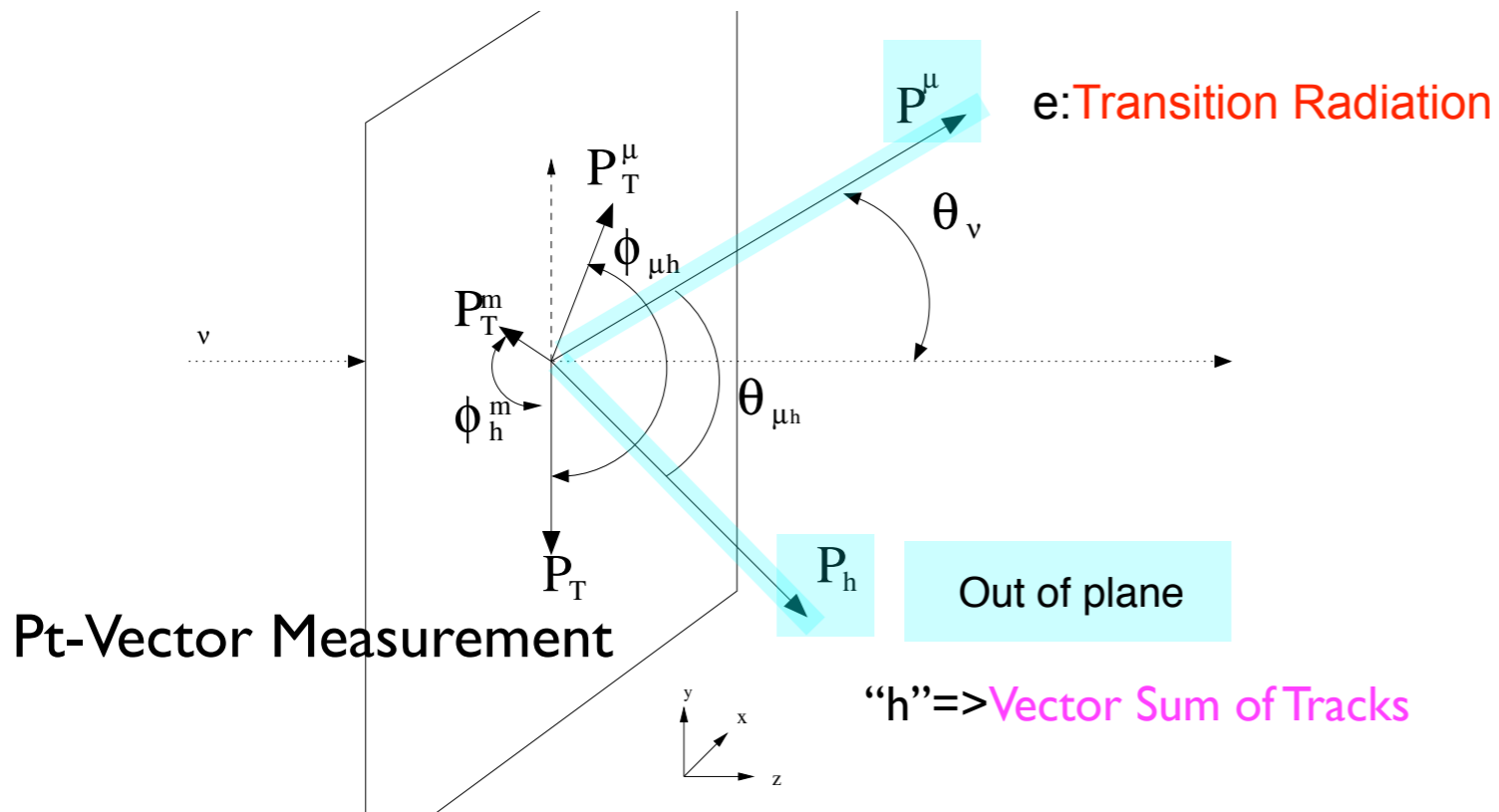
(1) μ from $\nu\mu$ and e from νe are Tracks: Determined with very high precision

(2) Universality equivalence: $\mu - \nu\mu \leftrightarrow e - \nu e$

Missing-PT Vector Measurement in CC

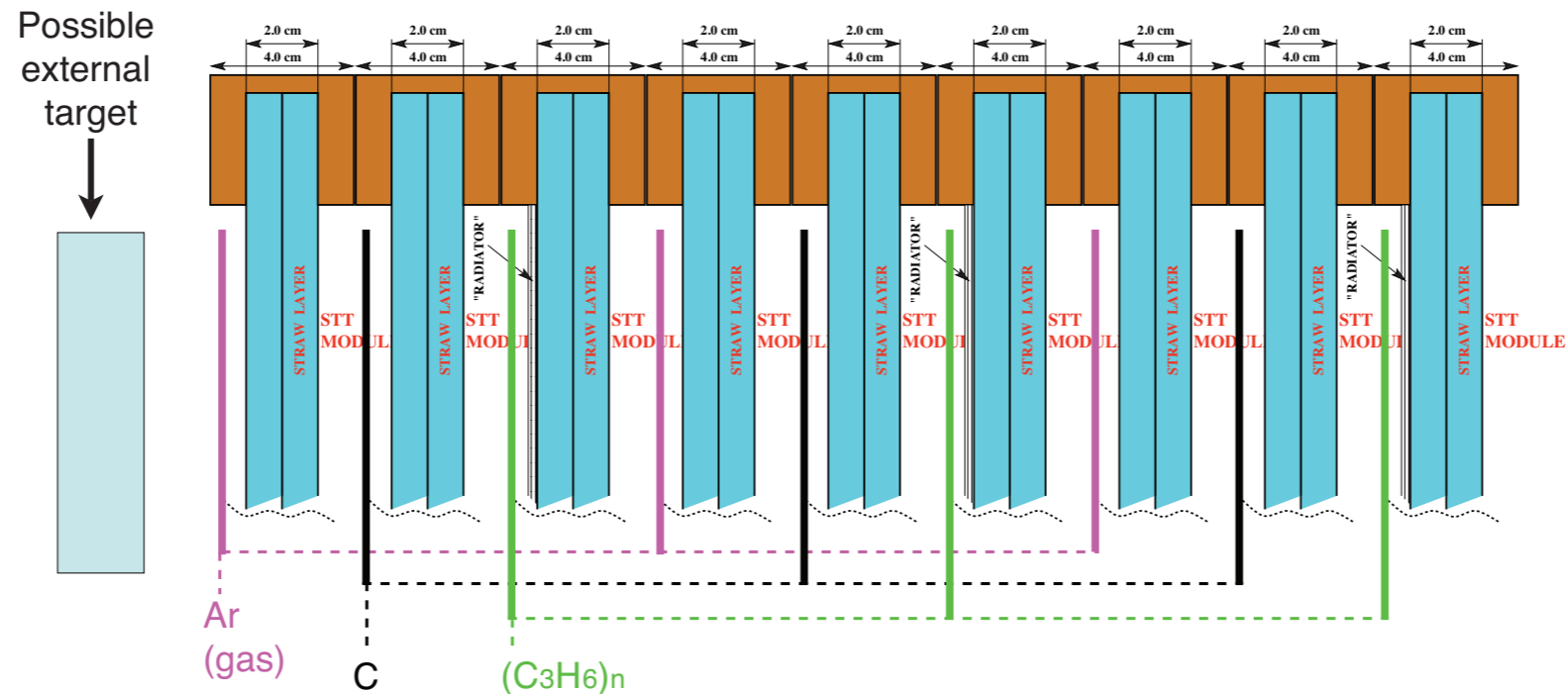
Missing-PT an invaluable constraint on the Ev-scale

* Lepton & Hadron Momentum Vectors \Rightarrow Miss-PT



(Details of the Missing-PT Measurement)

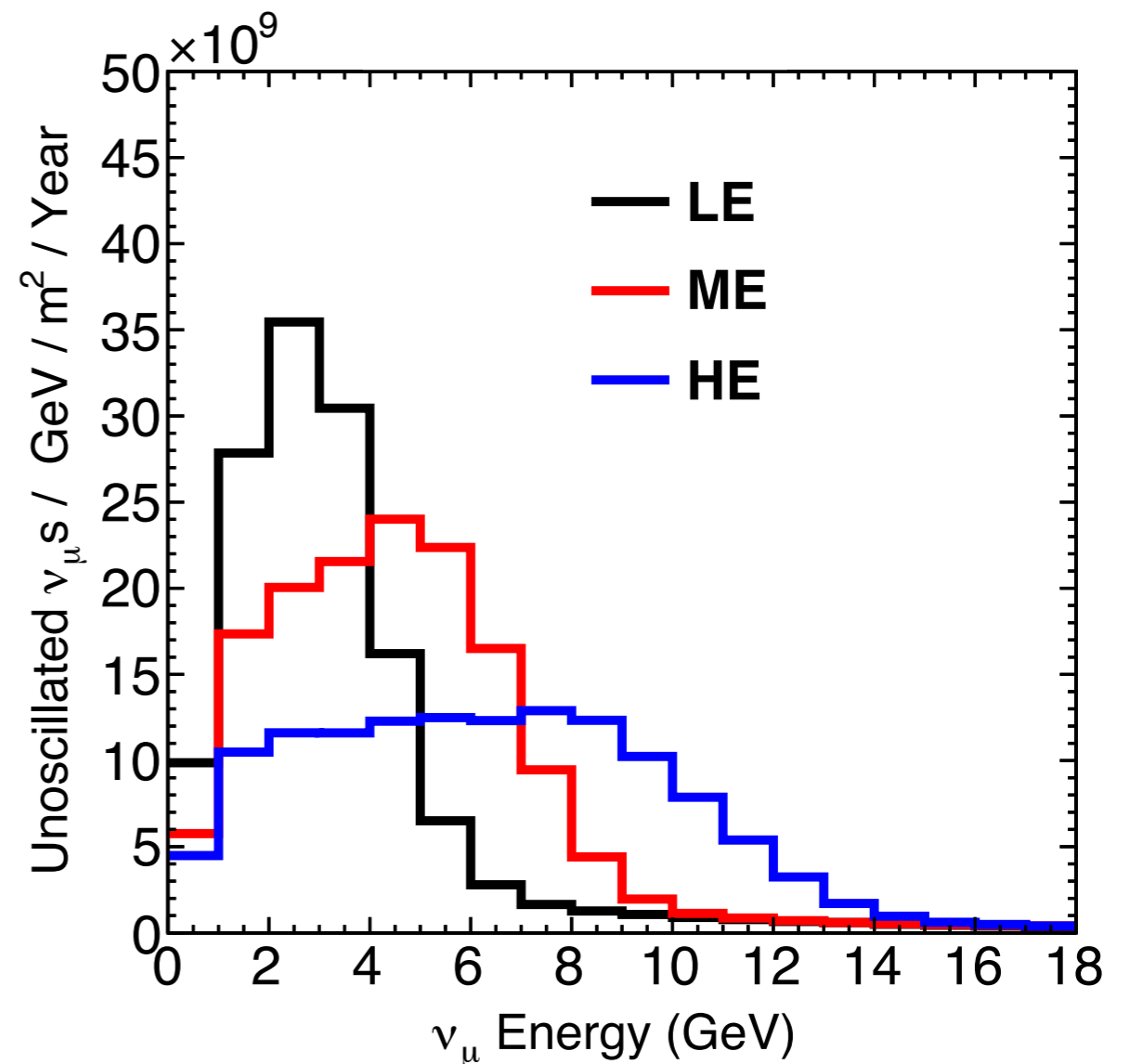
NUCLEAR TARGETS IN FGT



- ◆ Multiple nuclear targets in FGT: $(C_3H_6)_n$ radiators, C, Ar gas, Ca, Fe, etc.
 ⇒ Separation from excellent vertex ($\sim 100\mu m$) and angular (< 2 mrad) resolutions
- ◆ Subtraction of **C TARGET** from polypropylene **$(C_3H_6)_n$ RADIATORS**
 provides neutrino AND anti-neutrino interactions on free proton target
 ⇒ Absolute $\bar{\nu}_\mu$ flux from QE
 ⇒ Model-independent measurement of nuclear effects and FSI from RATIOS A/H
- ◆ Pressurized **Ar GAS** target (~ 140 atm) inside C tubes and solid **Ca TARGET**
 (more compact & effective) provide detailed understanding of the FD $A = 40$ target
 ⇒ Collect more than **x68** oscillated FD statistics on Ar target
 ⇒ 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
 \implies 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 $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$

⇒ Expect a $\sim 2\%$ precision in the absolute flux for $0.5 \leq E_\nu \leq 10$ GeV

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

⇒ Expect a $\sim 2.5\%$ precision in the absolute flux for $E_\nu \geq 11$ GeV

Using quasi-elastic CC scattering off free proton (hydrogen) target $\bar{\nu}_\mu + p \rightarrow \mu + n$

⇒ Estimate a $\sim 3\%$ precision in the absolute flux for $0.5 \leq E_\nu \leq 20$ GeV

◆ RELATIVE FLUXES

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

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

Use *coherent π^\pm* production to determine $\bar{\nu}/\nu$ flux ratio

⇒ Expect $\sim 1\%$ precision on the flux ratio

⇒ Crucial ingredient for Exclusive (QE, Resonance, Coh-Meson, DIS,) & Inclusive (CC & NC) differential cross-section measurements ⇒ 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:*

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

- *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*

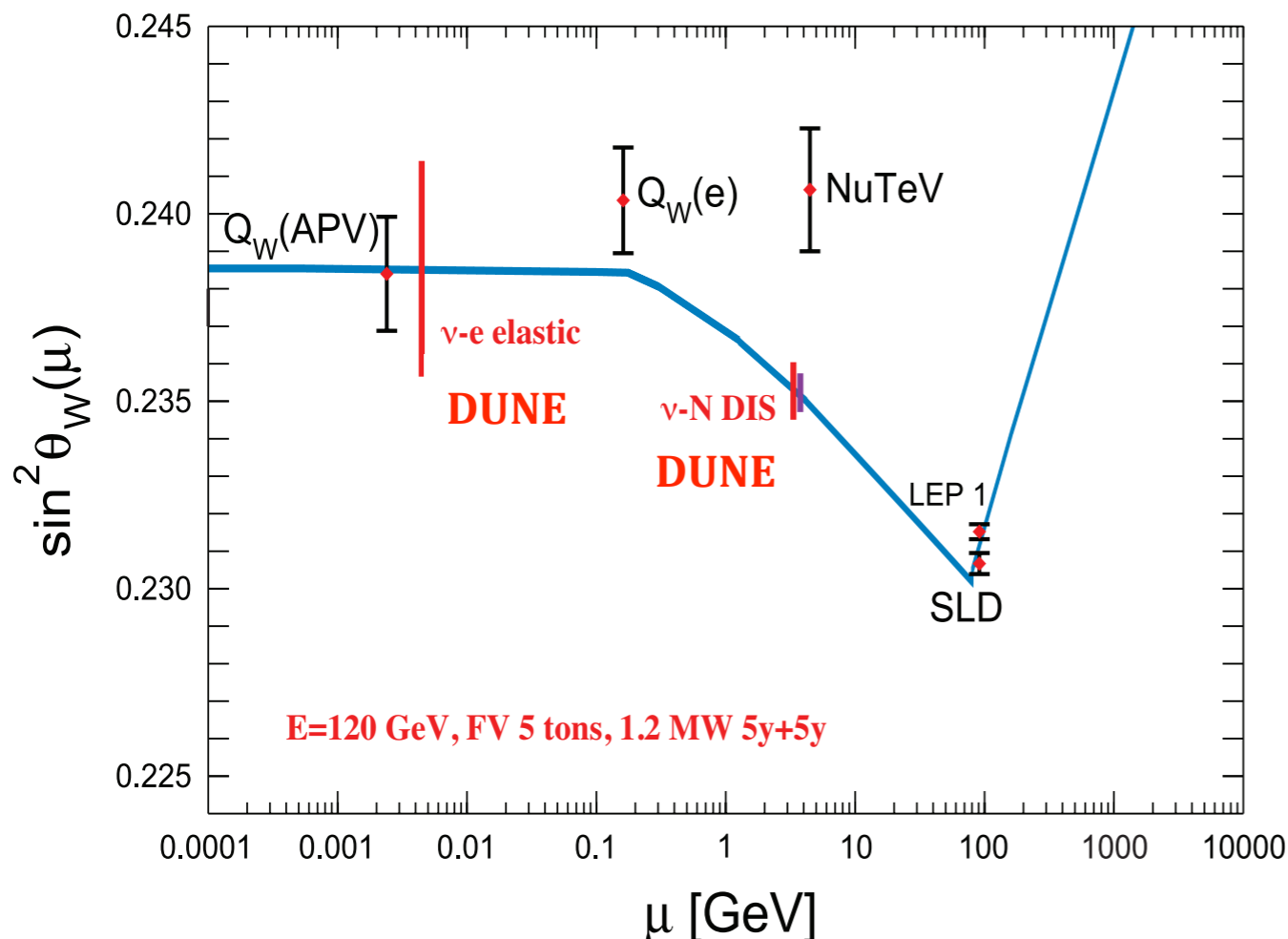
\implies *A measurement on H at the percent level at LBNF could bring to discoveries!*

- ◆ *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
⇒ 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:

- $\mathcal{R}^\nu = \frac{\sigma_{\text{NC}}^\nu}{\sigma_{\text{CC}}^\nu}$ in ν -N DIS ($\sim 0.35\%$)
- $\mathcal{R}_{\nu e} = \frac{\sigma_{\text{NC}}^{\bar{\nu}}}{\sigma_{\text{NC}}^\nu}$ in ν - e^- NC elastic ($\sim 1\%$)
- NC/CC ratio $(\nu p \rightarrow \nu p)/(\nu n \rightarrow \mu^- p)$ in (quasi)-elastic interactions
- NC/CC ratio ρ^0/ρ^+ in coherent processes

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

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

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

- Statistical precision in **DUNE/LBNF ND** will be at the $\sim 10^{-3} \Rightarrow \sim 2.0 (1.2) \times 10^6 \nu (\bar{\nu})$ 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 ($F_{1,2}^s$) and axial (G_A^s) 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 , $\text{anti-}\nu_\mu$, $\text{anti-}\nu_e$

⇒ Neutrino and Antineutrino Energy-Scale

⇒ Relative flux: energy-to-energy, $\text{Anti-}\nu/\nu$, ν_e/ν_μ

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

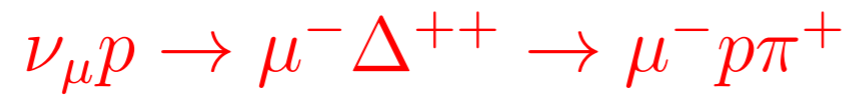
To precisely measure the neutrino-yield of e^-/e^+ , need to have:

* Magnetized tracker to ID Positive from Negative particle:

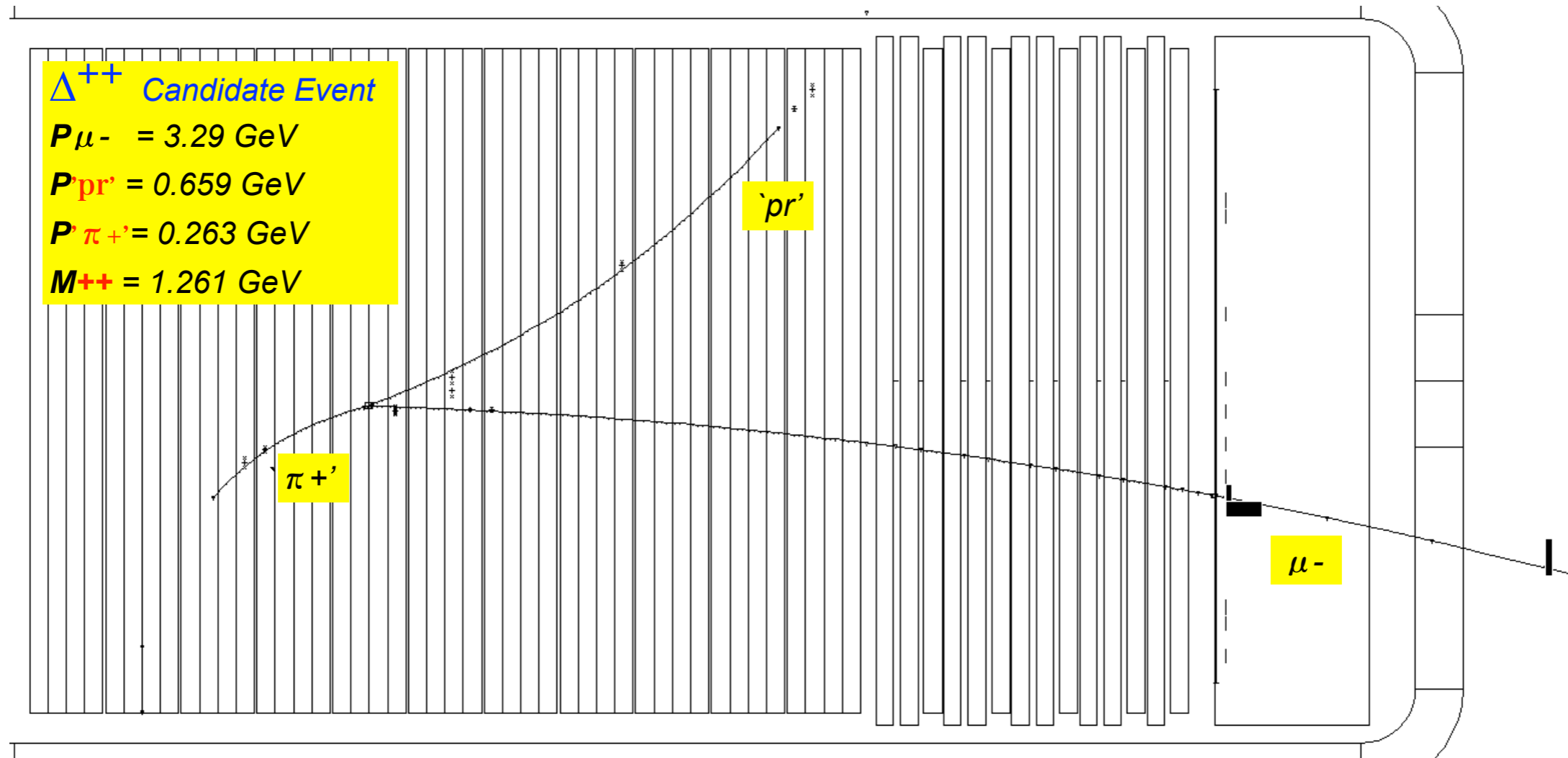
* Low-Density medium to track electron/positron:

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

* Large statistics $\sim 10^8$ ν -Interactions

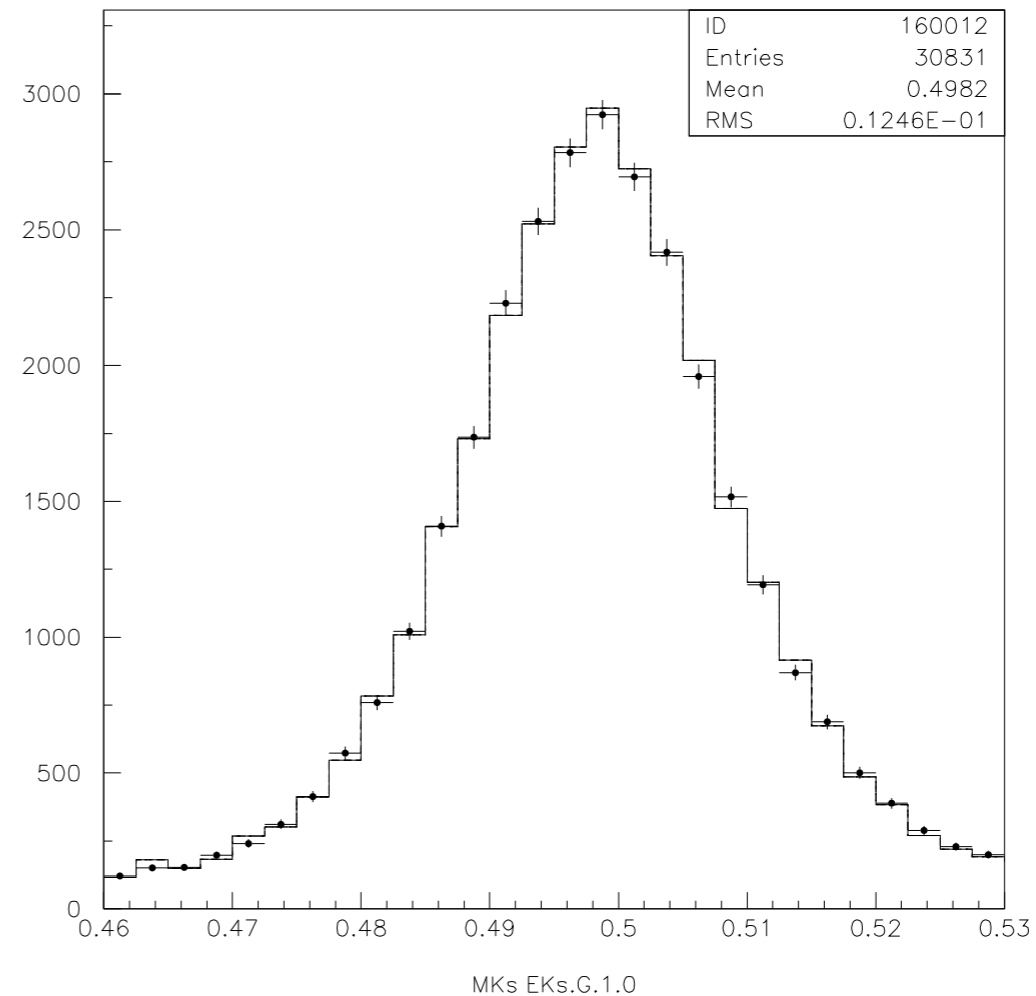
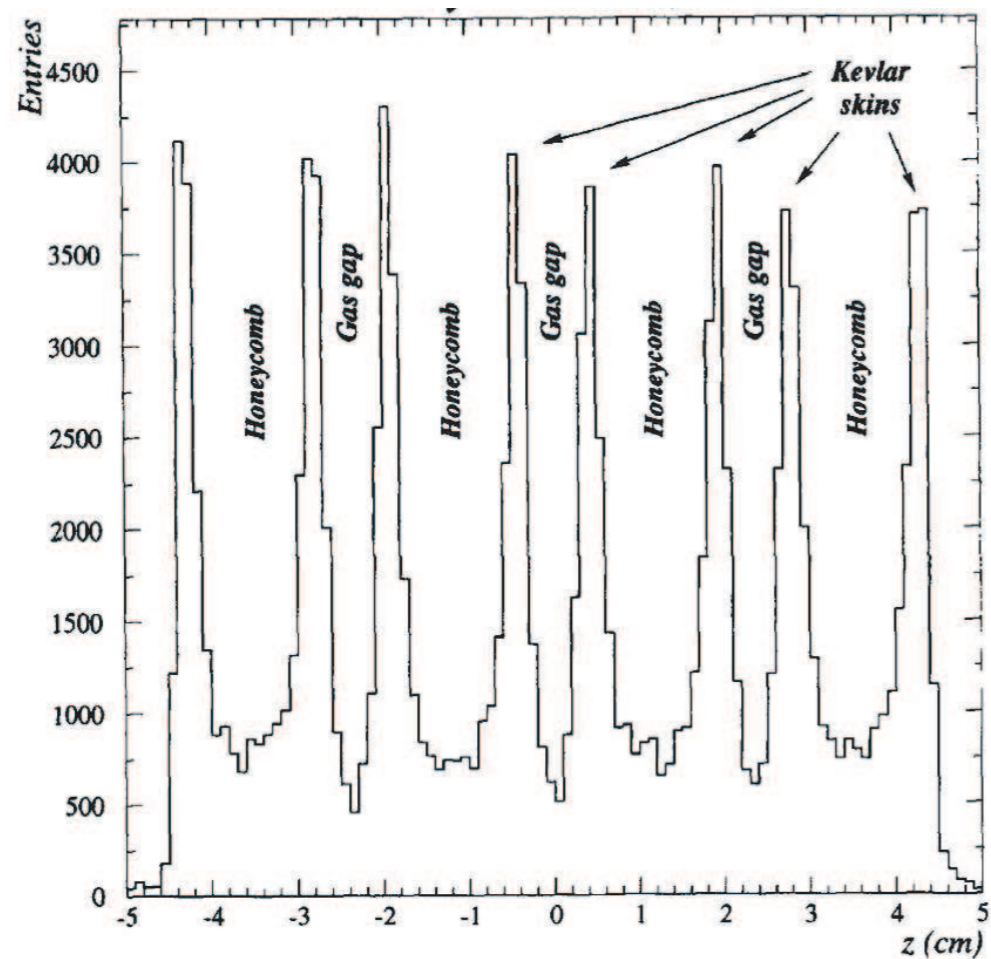


*p reconstruction & ID
wide angle hadrons*



Event candidate from NOMAD data \implies 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 $< 0.2\%$
hadronic energy scale known to $< 0.5\%$
- ◆ *DUNE ND*: $\sim 100 \times$ more statistics and $12 \times$ 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 \rightarrow $\times(22)68$ FD (un)oscillated*
 - *In FGT expect about 685,000 ν_μ CC events per year on Ca \rightarrow $\times(74)228$ 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 $(C_3H_6)_n$*

$\nu(\bar{\nu})$ -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*
 - \implies *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, C₃H₆, 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 $\Delta E = E_{\text{rec}}^{\nu}(2 \text{ trk}) - E_{\text{rec}}^{\text{QE}}(1 \text{ trk})$ 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*
 - \implies *Systematic uncertainties on extrapolations/predictions of FD event rates in LAr*

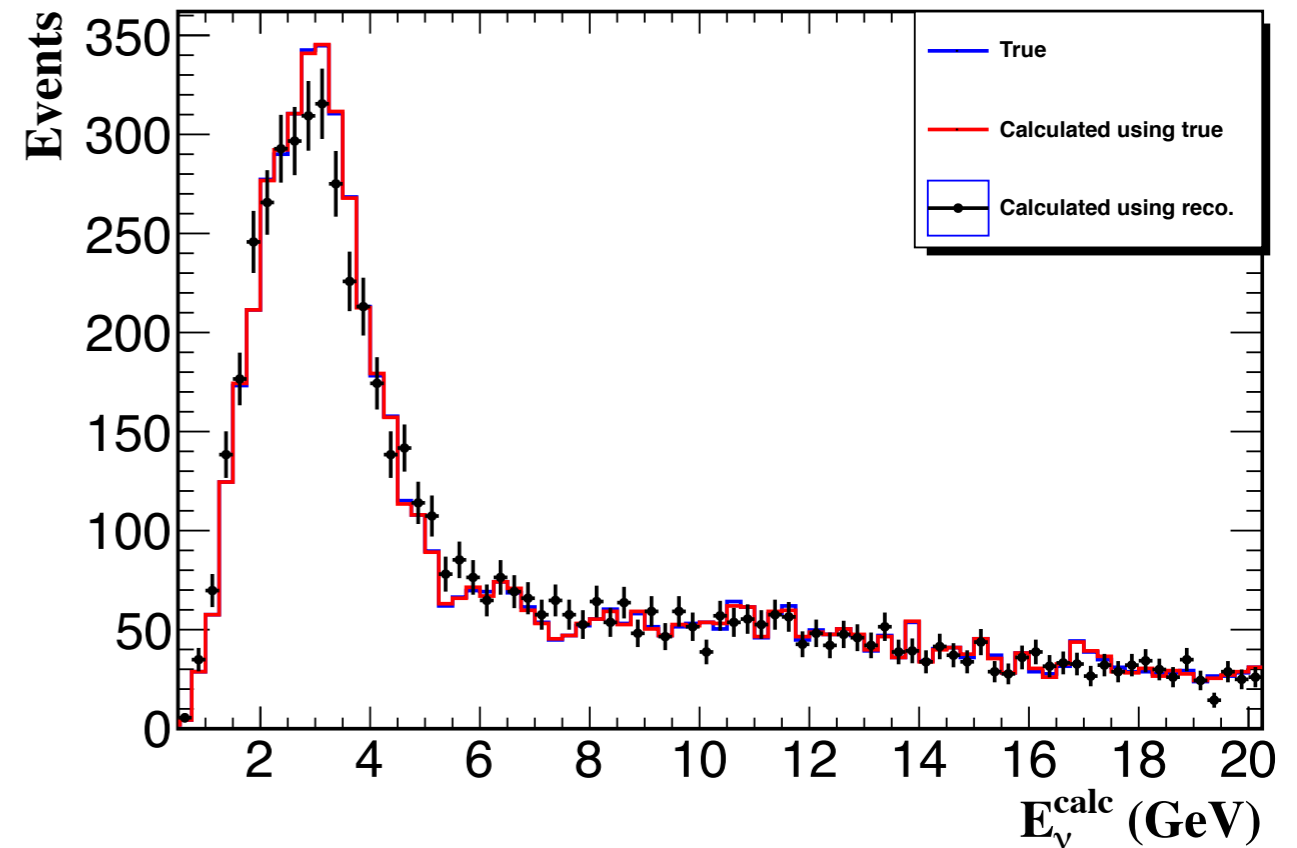
Absolute Flux Measurement

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

* Signal Eff \Rightarrow 73% // Background \Rightarrow Benign;
in situ constraints

* Neutrino Energy
High-resolution tracker allows the
reconstruction of E_{ν} from (E_e, θ_e)

* Absolute Flux \Rightarrow $\sim 2\%$ precision in
 $0.5 \leq E_{\nu} \leq 10$ GeV range

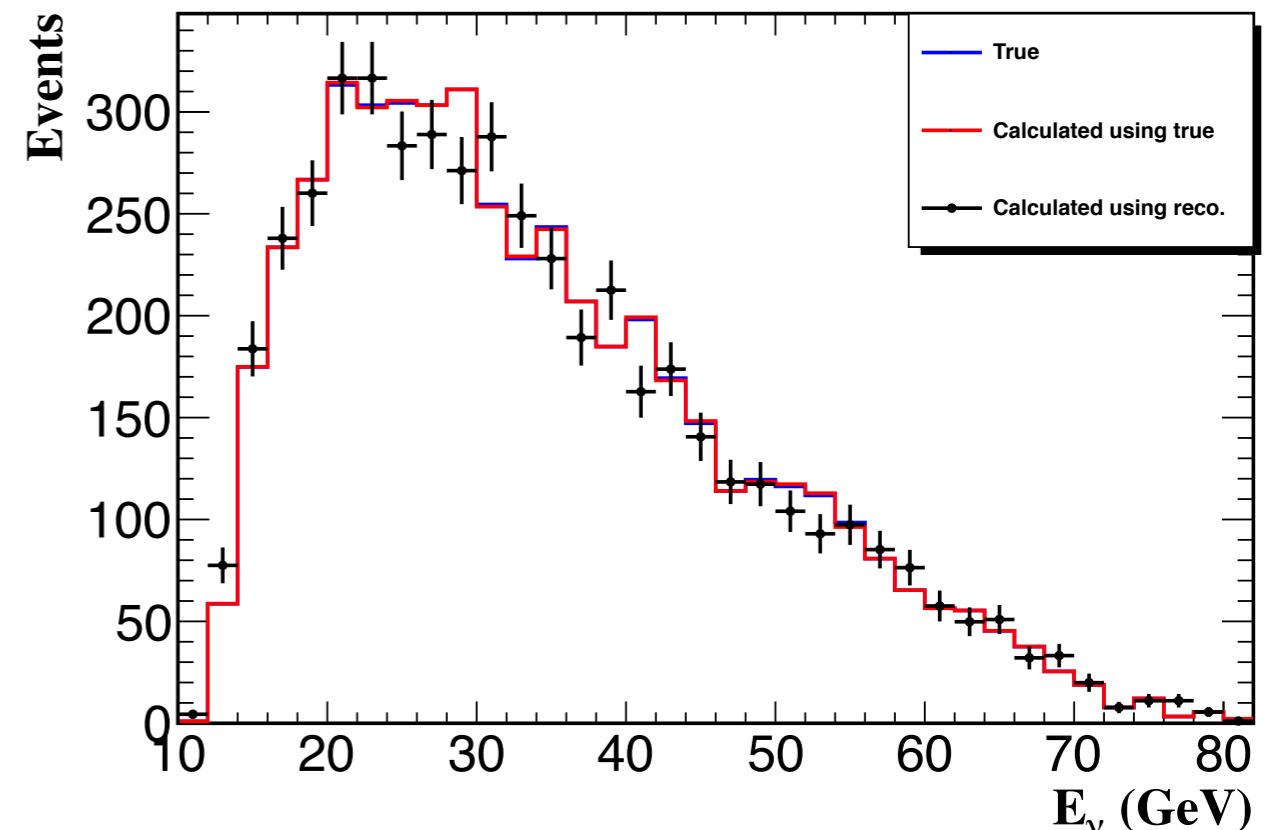


(2): ν -Electron CC Scattering: $\nu_{\mu} + e \rightarrow \nu_{\mu} + \mu^{-}$

* Signal Eff \Rightarrow 82% // Background \Rightarrow 20%;
constrained by 2-Track ν_{μ} -CC analysis

* Neutrino Energy
High-resolution tracker allows the
reconstruction of E_{ν} from (E_{μ}, θ_{μ})

* Absolute Flux \Rightarrow $\sim 2.5\%$ precision in
 $15 \leq E_{\nu} \leq 50$ GeV range



Source of uncertainty	$\delta R^\nu / R^\nu$		Comments
	NuTeV	DUNE	
Data statistics	0.00176	0.00074	
Monte Carlo statistics	0.00015		
<i>Total Statistics</i>	<i>0.00176</i>	<i>0.00074</i>	
$\nu_e, \bar{\nu}_e$ 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.	
$\bar{\nu}_\mu$ flux	n.a.	0.00070	Large $\bar{\nu}$ contamination
Kinematic selection	n.a.	0.00060	Kinematic identification of NC
<i>Experimental systematics</i>	<i>0.00112</i>	<i>0.00102</i>	
d,s\rightarrowc, s-sea	0.00227	0.00140	Based on existing knowledge
Charm sea	0.00013	n.a.	
$r = \sigma^{\bar{\nu}} / \sigma^\nu$	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	
<i>Model systematics</i>	<i>0.00258</i>	<i>0.00212</i>	
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 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, ${}^{40}_{20}\text{Ca}$, to verify nuclear effects in ${}^{12}_6\text{C}$;
- Use *second target with isovector component but same A as Ca*: ${}^{40}_{18}\text{Ar}$.