A High Resolution and Highly Segmented Near Detector for ELBNF

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(for IIFC-νP and LBNE NDWG)

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ND TASKS FOR OSCILLATION ANALYSES

- ✦ *Determination of the relative abundance and of the energy spectrum of the four neutrino species in LBNF beam:* $\boxed{\nu_\mu}$, $\boxed{\bar{\nu}_\mu}$, $\boxed{\nu_e}$, *and* $\boxed{\bar{\nu}_e}$ *CC-interactions.*

  $\Longrightarrow$ *Extrapolation to FD and predictions of FD/ND(E_ν) fluxes to* $\sim 1\%$

- ✦ *Determination of the absolute* ν_μ *and* $\bar{\nu}_\mu$ *fluxes to* $\simeq 3\%$ *for oscillation measurements*

- ✦ *Measure cross-sections & exclusive topologies of NC & CC interactions*
  - *Event-by-event NC/CC separation as a function of hadronic energy* $E_{\rm had}$
  - *Measurement of* π^0 *and* γ *yields in BOTH NC and CC to better than 5%*
  - *Measurement of* $\pi^\pm/K^\pm$ *content in CC and NC to constrain* $\pi^\pm/K^\pm \to \mu^\pm$ *decays*
  - *Measure exclusive and semi-exclusive NC and CC* $\boxed{\nu\text{-Ar}}$ *processes:*
    Quasi-elastic, single π*, Deep Inelastic Scattering (DIS), and coherent.*

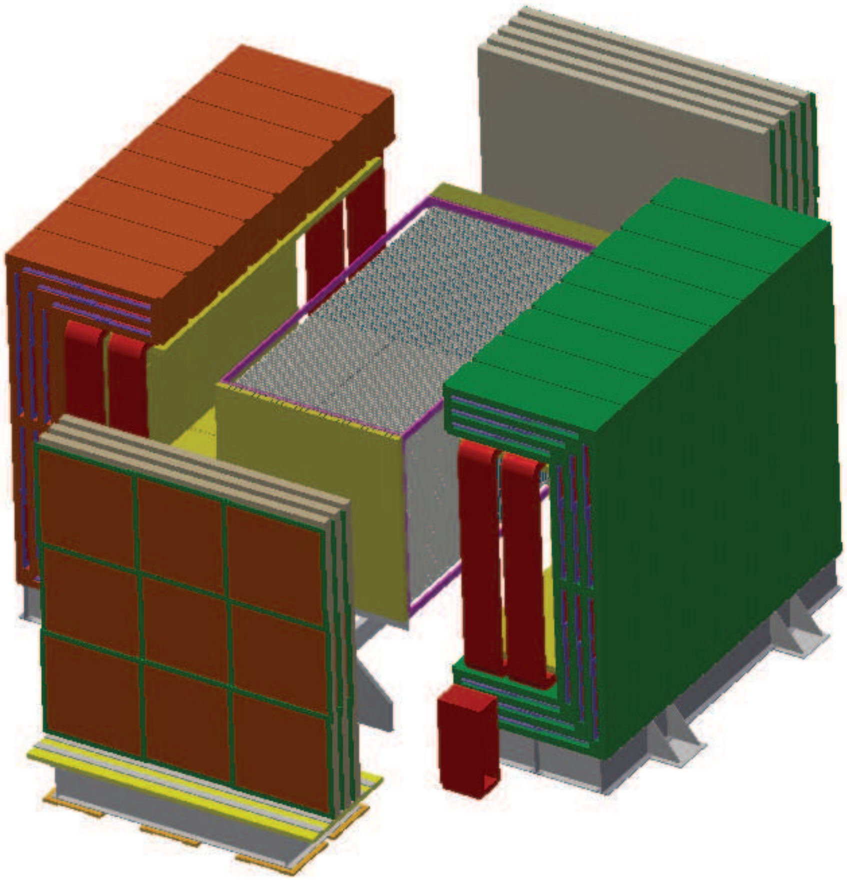
  $\Longrightarrow$ *Backgrounds to appearance & disappearance oscillation channels*

- ✦ *Calibration of the absolute neutrino energy scale in* ν*-Ar AND* $\bar{\nu}$*-Ar interactions.*

- ✦ *Quantify asymmetries between* ν *and* $\bar{\nu}$ *(energy scale, flux, interactions) for* $\delta_{\rm CP}$

  $\Longrightarrow$ *Provide 'Event-Generator Measurement' for FD*
  predicting 4-momenta of particles from NC & CC topologies for all 4 ν *species*

HIGH RESOLUTION NEAR DETECTOR



Based upon the NOMAD concept/experience

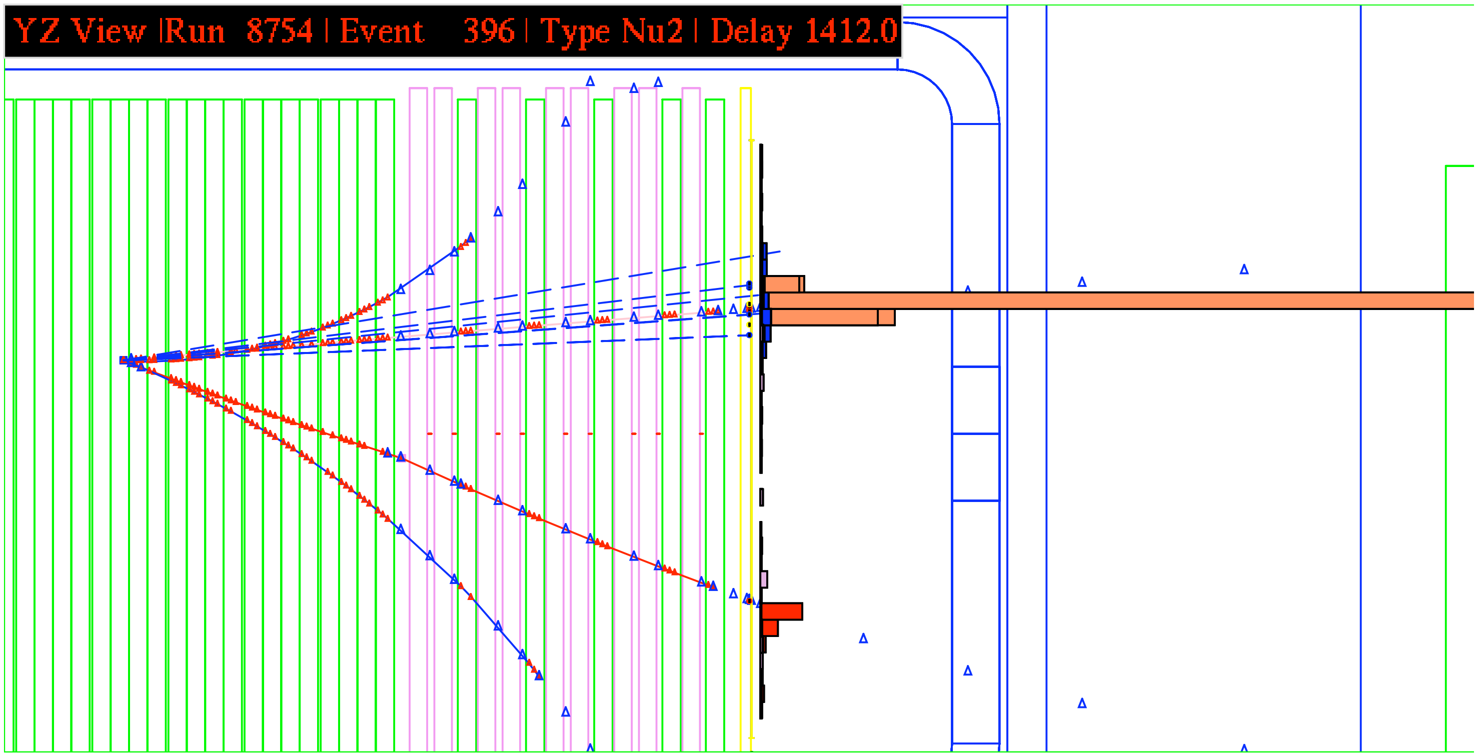
- *Straw Tube Tracker* 3.5m×3.5m×6.5m ($\rho \sim 0.1\ g/cm^3$) *with target embedded*
- *Target mass* ∼7t: $(C_3H_6)_n$,C,Ar,Ca,etc.
- 4π ECAL in dipole B field (0.4 T)
- 4π μ-Detector (RPC) in return yoke and downstream
- Pressurized Ar target $\sim \times 10$ FD Stat.
- *Precise measurement of 4-momenta*

- *Combined tracking and particle ID*
- Transition Radiation $\Longrightarrow e^-/e^+$ ID, γ
- $dE/dx \Longrightarrow$ Proton ID, $\pi^{+/-}$, $K^{+/-}$
- Magnet/Muon detector $\Longrightarrow \mu^+/\mu^-$

LOW-DENSITY "ELECTRONIC BUBBLE CHAMBER"

$\bar{\nu}_e$ Charged Current

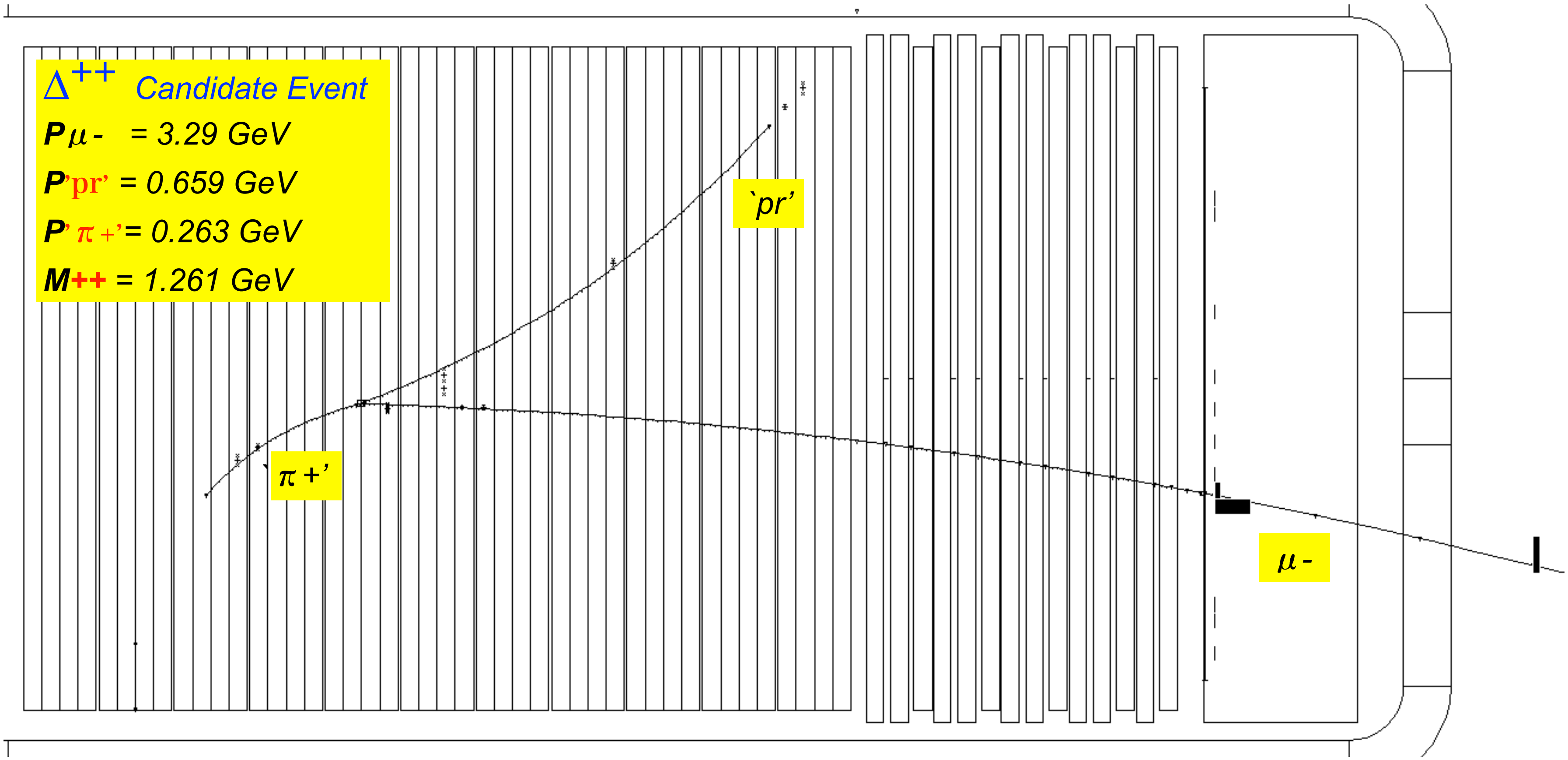
e^+ reconstruction & ID



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

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

p reconstruction & ID
wide angle hadrons



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

ROADMAP OF ACTIVITIES

- *Originally proposed for LBNE ND (reference design) by South Carolina (2008)*

- *Near Detector proposal with Indian funding agencies DAE/DST (Dec. 2012):*
  - *ND construction by Indian institutes with support from US Collaborators;*
  - *Infrastructure development/planning as per separate DAE/DST proposals;*
  - *Detector and simulation/software R&D efforts outlined in DPR.*

- *Proposal for 3 year R&D ND efforts submitted to DAE in Fall 2013, and, additionally, to DST in February 2014:*
  - *Mainly focused at STT, ECAL and magnet sub-systems for 2014-2017;*
  - *R&D activities (detector and software/simulation) needed to finalize design for ND construction;*

  $\Longrightarrow$ *Phase I funding approved by the DAE/DST scientific and technical committees*

PLANNED R&D

- *Ongoing and planned efforts:*
  - *Main detector and software/simulation R&D at Indian institutions: BHU, DU, HRI, IIT-G, PU;*
  - *Contributions from US institutions: USC, FNAL and LANL*

- *Phase I R&D activities (2015-2017):*
  - *Detector and physics simulations, sensitivity studies and detector optimization (HRI);*
  - *Straw Tube Tracker (PU): design and construction of development prototype;*
  - *ECAL (IIT-G): structural simulation, design and construction of development prototype;*
  - *Dipole magnet & readout (BARC): simulation, design and prototyping;*
  - *RPC (VECC): design optimization.*

We warmly welcome any ELBNF colleague to join this effort!

HIGH RESOLUTION ND FOR ELBNF

WHAT IT CAN DO :

- *Neutrino source:* $\Phi_\beta(E_\nu, E_{\rm vis}), \Phi_\alpha(E_\nu, E_{\rm vis})$
- *Cross-sections:* $\sigma_\beta(E_\nu), \sigma_\alpha(E_\nu)$
- *Energy scale* $\Longrightarrow$ ν *vs.* $\bar{\nu}$ *asymmetries*
- *Backgrounds to Oscillation signals*
- $\nu(\bar{\nu})$*-Nucleus Interactions: in-situ measurement but also detailed modeling*
- *Tight constraints beyond PNMS-oscillation*

WHAT IT CANNOT DO :

- *Reconstruction errors in FD (where FD/ND cancel)*
  $\Longrightarrow$ *Assumes FD knows how to reconstruct particles given 4-momenta*
  $\Longrightarrow$ *Calibration of FD response to* $e/\mu/\pi/p/n$

ABSOLUTE $\nu_\mu, \bar{\nu}_\mu$ FLUX MEASUREMENT

✦ **LEPTONIC CHANNELS**

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

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

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

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

✦ **QUASI-ELASTIC CHANNEL**

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

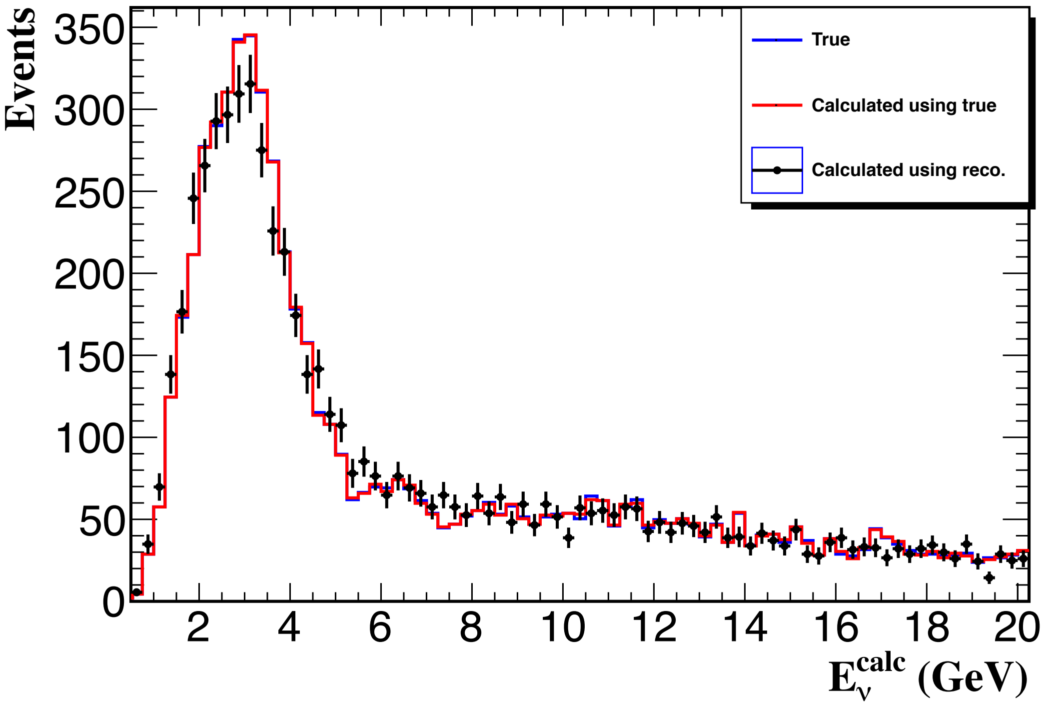
$\Longrightarrow$ *Estimate a* $\sim 3\%$ *precision in the absolute flux for* $0.5 \leq E_\nu \leq 20$ *GeV*

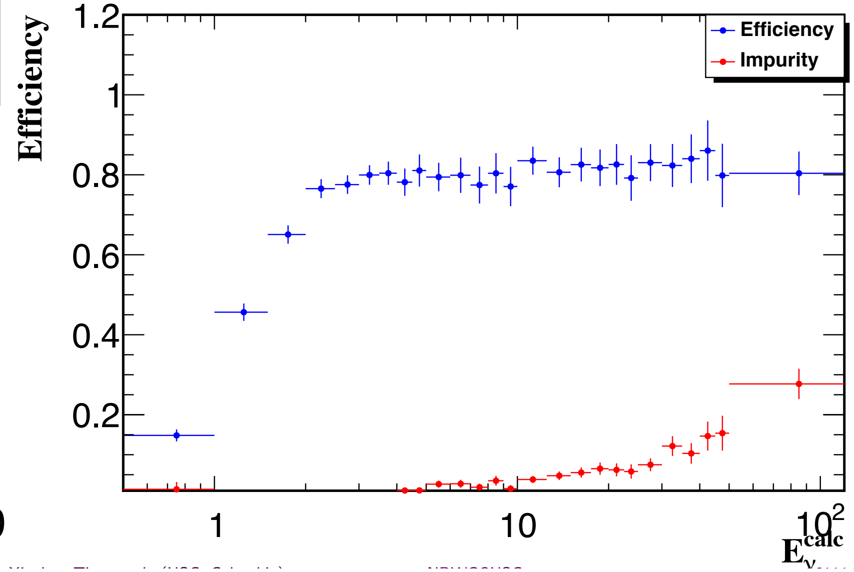
✦ **COHERENT CHANNEL**

Using coherent ρ *meson production off nuclear targets* $\nu_\mu + \mathcal{A} \to \mu + \rho + \mathcal{A}$

$\Longrightarrow$ *Estimate a* $\sim 5\%$ *precision in the absolute flux for* $4 \leq E_\nu \leq 20$ *GeV*

NC elastic $\nu e^- \rightarrow \nu e^-$





- *Main kinematic cut on* $E_e(1-\cos\theta_e) < 0.001$ *GeV to reject CC and NC backgrounds* $\Longrightarrow$ *Need excellent angular resolution*
- *Signal efficiency* $\sim 70\%$ *with benign background*
- *In-situ measurement of backgrounds from wrong sign analysis (e^+)* $\Longrightarrow$ *Need e^+/e^- separation*
- *Can measure absolute ν_μ flux to $\sim 2\%$ for $0.5 \leq E_\nu \leq 5.0$ GeV*

RELATIVE $\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$ FLUXES IN FD/ND

✦ LOW-ν METHOD

Using ν_μ CC: $\nu_\mu + N \to \mu^- + X$

$\Longrightarrow$ *Expect a FD/ND ratio vs. E_ν at $1 \div 2\%$ precision for $0.5 \leq E_\nu \leq 50$ GeV*

Using $\bar{\nu}_\mu$ CC: $\bar{\nu}_\mu + N \to \mu^+ + X$

$\Longrightarrow$ *Expect a FD/ND ratio vs. E_ν at $1 \div 2\%$ precision for $0.5 \leq E_\nu \leq 50$ GeV*

Determine ν_e/ν_μ ($\bar{\nu}_e/\bar{\nu}_\mu$) ratios vs. E_ν

$\Longrightarrow$ *Expect a precision $\ll 1\%$ on RATIOS for $0.5 \leq E_\nu \leq 50$ GeV*

✦ COHERENT CHANNEL

Using coherent π/ρ meson production off nuclear targets: $\nu_\mu + \mathcal{A} \to \mu^- + \pi^+/\rho^+ + \mathcal{A}$
$\bar{\nu}_\mu + \mathcal{A} \to \mu^+ + \pi^-/\rho^- + \mathcal{A}$

$\Longrightarrow$ *Estimate a precision $\ll 1\%$ on the RATIO $\bar{\nu}_\mu/\nu_\mu$ vs. E_ν for $0.5 \leq E_\nu \leq 50$ GeV*

- *Relative flux* vs. *energy from low-ν_0 method*:

$$N(E_\nu : E_{\rm HAD} < \nu_0) = C\Phi(E_\nu) f(\frac{\nu_0}{E_\nu})$$

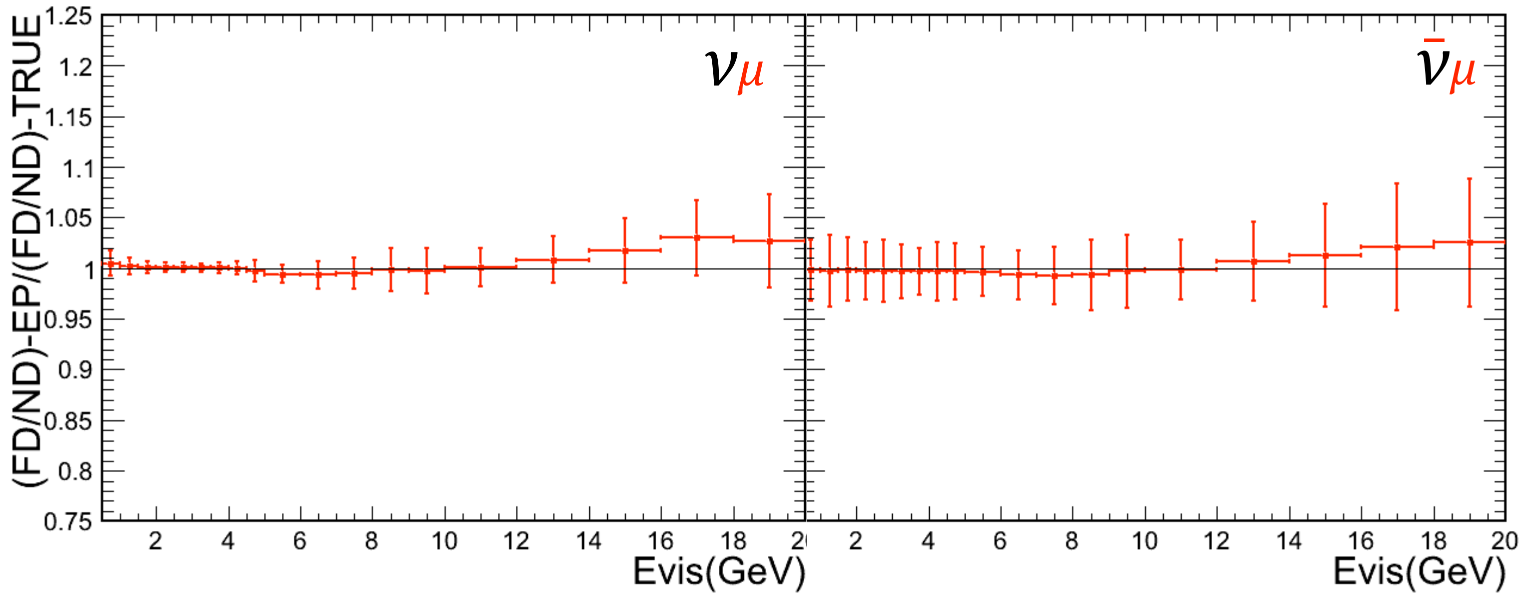
the correction factor $f(\nu_0/E_\nu) \to 1$ *for* $\nu_0 \to 0$.

$\Longrightarrow$ *Need precise muon energy scale (~ 0.2%) and good resolution at low* ν *values*

- *Need spectra for all 4 neutrino species:* $\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$ *with* $\boxed{\nu_0 = 0.25 \div 0.50 \text{ GeV}}$.

- *Empirical parameterization of parent* $\pi^\pm/K^\pm/K_0$ *distributions (fit + hadroproduction)*

- *Performed a detailed study of systematic uncertainties from empirical fits of simulated* ν_μ *and* $\bar{\nu}_\mu$ *CC spectra in the Near Detector* $\Longrightarrow$ *Obtain FD/ND ratio at 1-2%*



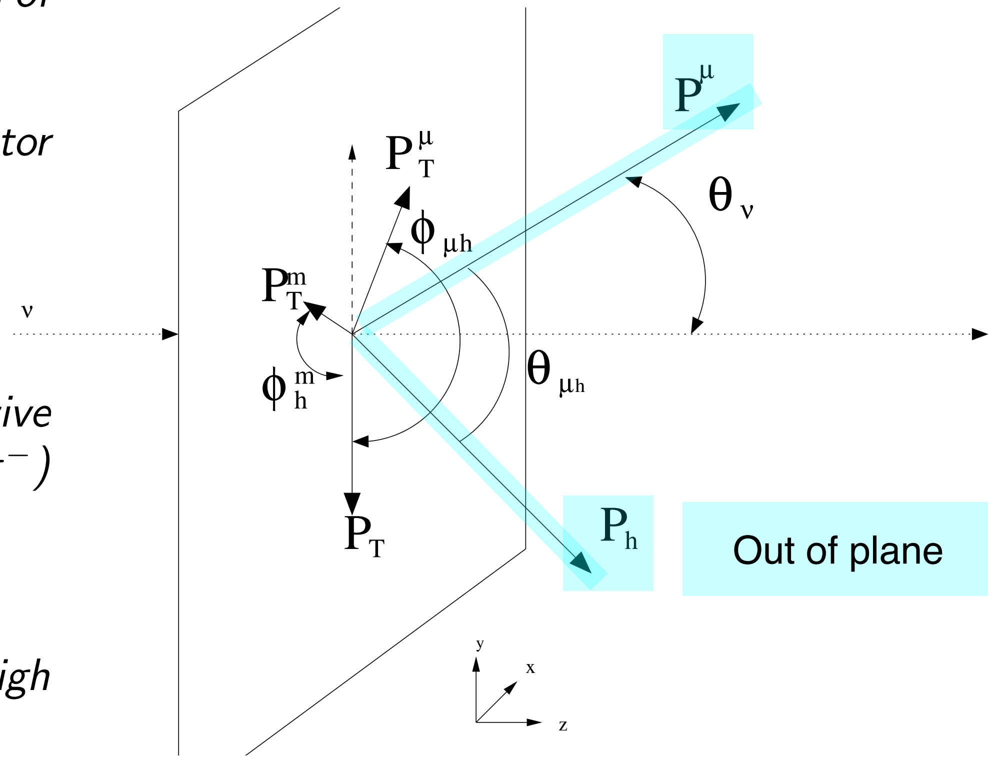
EVENT KINEMATICS & $\nu(\bar{\nu})$ ENERGY SCALES

- *High resolution on the reconstructed 4-momenta of visible secondary particles*
- *Measurement of total hadron vector from vector sum of individual particle momenta*

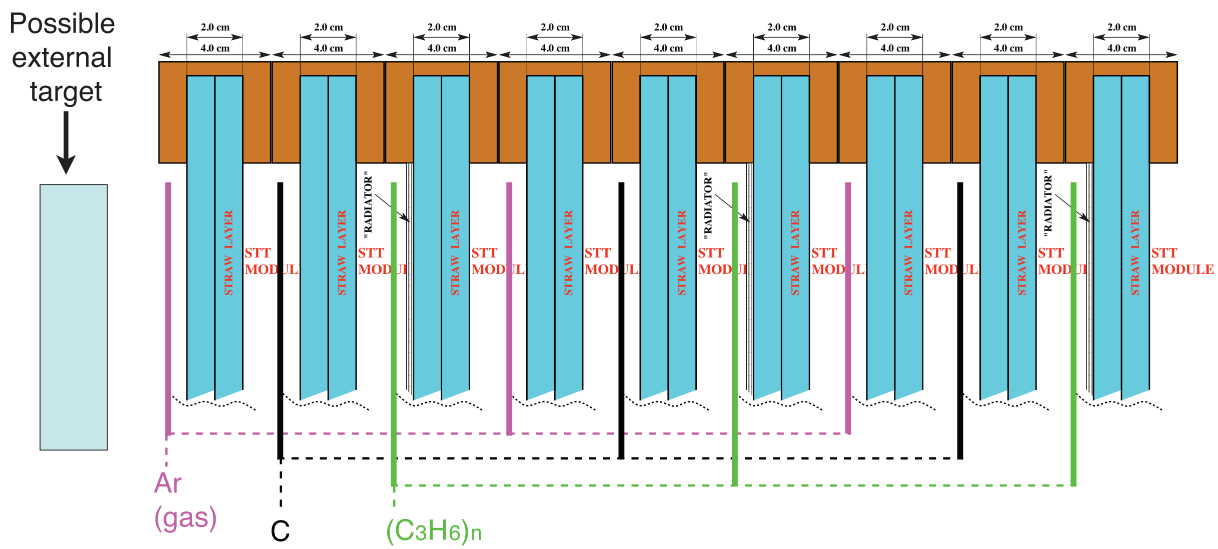
  $\Longrightarrow$ $\boxed{\text{MISSING } \mathrm{P_T}}$ *vector measurement*

  $\Longrightarrow$ *Detailed event topology*
- *Use hadron vector and missing P_T in exclusive topologies (QE 2-trk, RES 3/2-trk, Coh. π^+/π^-) to study $\nu(\bar{\nu})$ energy scale & constrain related nuclear effects (e.g. FSI)*
- *Event-by-event identification of* $\boxed{\text{NC/CC}}$ *with high efficiency and purity*

  $\Longrightarrow$ *Kinematic analysis of exclusive topologies*



DIRECT MEASUREMENT OF NUCLEAR EFFECTS

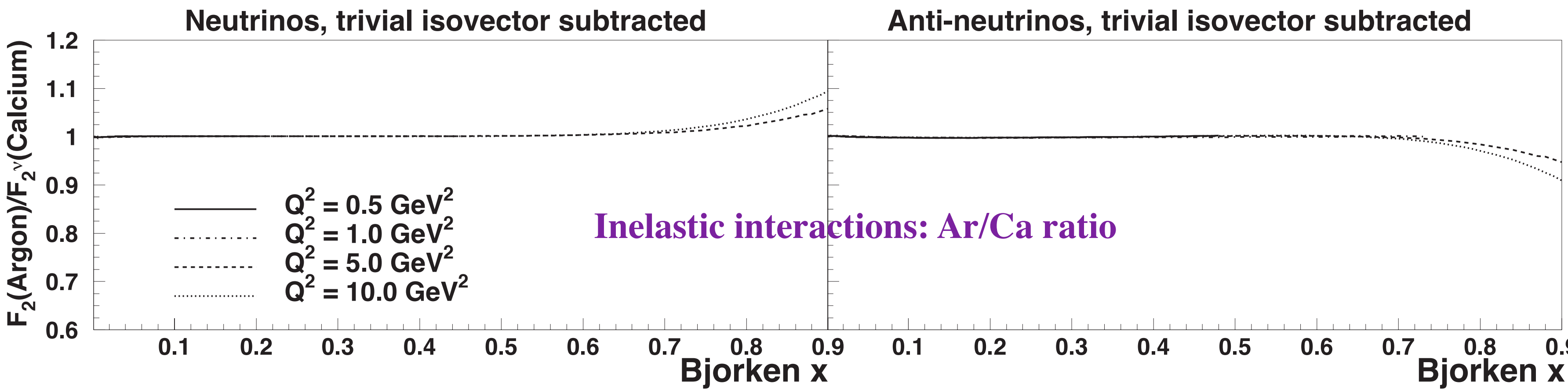


✦ *Multiple nuclear targets in STT: $(C_3H_6)_n$ radiators, C, Ar gas, Ca, Fe, H_2O, D_2O, etc.*
$\Longrightarrow$ *Separation from excellent vertex ($\sim 100\mu m$) and angular (~ 1 mrad) resolutions*

✦ *Subtraction of* C TARGET *(0.5 tons) from polypropylene $(C_3H_6)_n$ target provides* $5.0(1.5) \times 10^6 \pm 13(6.6) \times 10^3 (sub.)\ \nu(\bar{\nu})$ *CC interactions on free proton*
$\Longrightarrow$ *Absolute $\bar{\nu}_\mu$ flux from QE*
$\Longrightarrow$ *Model-independent measurement of nuclear effects and FSI from RATIOS A/H*

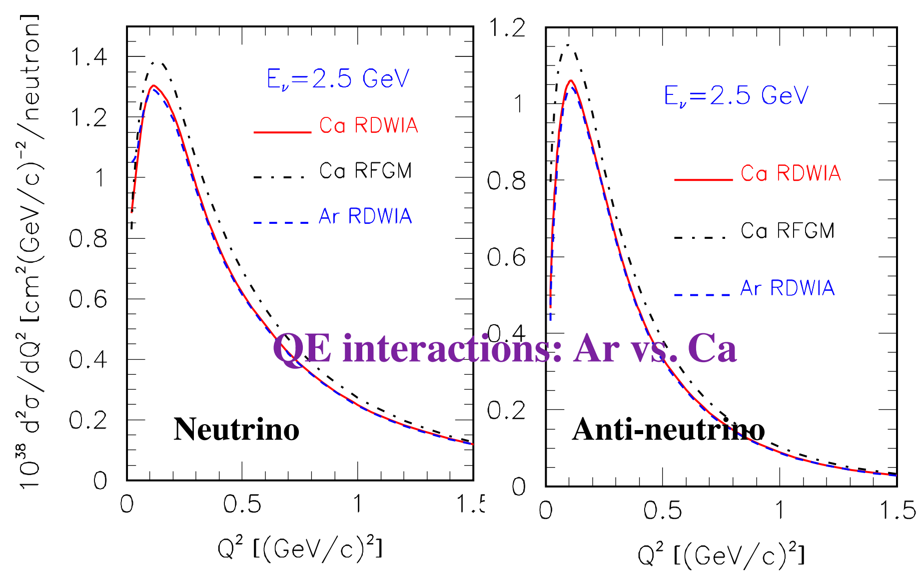
✦ *Pressurized* Ar GAS *target inside Al/C tubes and solid* Ca TARGET *provide detailed understanding of the FD $A = 40$ target*
$\Longrightarrow$ *Collect $\times 10$ unoscillated FD statistics on Ar target*
$\Longrightarrow$ *Study of flavor dependence & isospin physics*

Inelastic interactions: Ar/Ca ratio



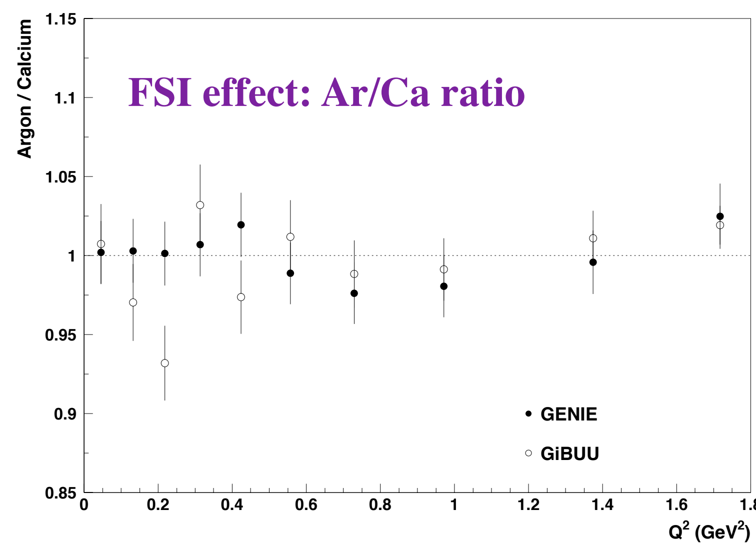
S. Kulagin and R.P, NPA 765 (2006) 126-187; PRD 76 (2007) 094023
PRC 82 (2010) 054614; arXiv:1405.2529 [hep-ph]

QE interactions: Ar vs. Ca



A.V. Butkevich, PRC 85 (2012) 065501; A.V. Butkevich and S. Kulagin, PRC 76 (2007) 045502

FSI effect: Ar/Ca ratio



HRI Group, GENIE and GiBUU simulations

SHORT BASELINE PHYSICS IN ELBNF

✦ **PRECISION MEASUREMENTS**:

- *Measurement of* $\sin^2\theta_W$ *and electroweak physics;*
- *Measurement of strange sea contribution to the nucleon spin* Δs*;*
- *Precision tests of isospin symmetry;*
- *Precision tests of the structure of the weak current: PCAC, CVC;*
- *Adler sum rule;*
- *Studies of QCD and hadron structure of nucleons and nuclei;*
- *Strange sea and charm production;*
- *Measurement of Nuclear effects in neutrino interactions;*
- *Precision measurements of cross-sections and particle production; etc. .....*

Deep synergy with the LBL oscillation program: same requirements and mutual feedback

✦ **SEARCHES FOR NEW PHYSICS**:

- *Search for weakly interacting massive particles (e.g.* ν*MSM sterile neutrinos);*
- *Search for high* Δm^2 *neutrino oscillations (e.g. LSND, MiniBooNE)*
- *Search for light (sub-GeV) Dark Matter; etc. .....*

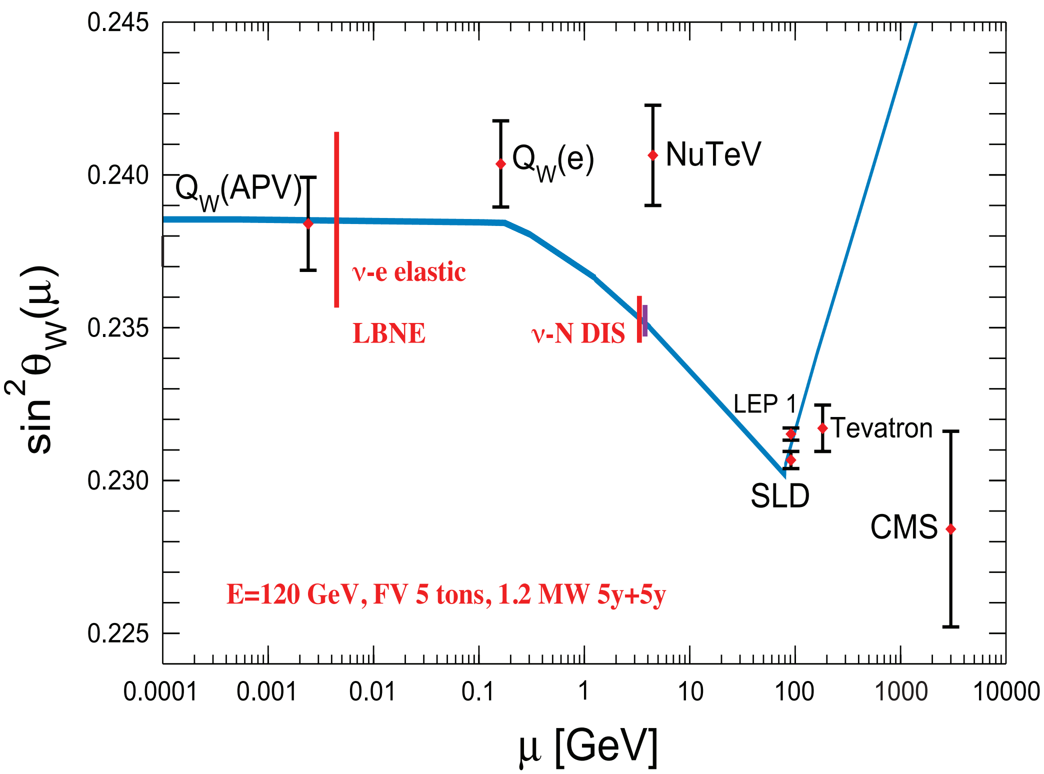
$\Longrightarrow$ *The combination of high resolution and unprecedented statistics* $(\times 100)$ *may led to discoveries of new physics in fundamental interactions / structure of matter!*

$\Longrightarrow$ *More than 200 physics papers and* > 100 *Ph.D. thesis expected*

PRECISION ELECTROWEAK MEASUREMENTS

✦ *Sensitivity expected from ν scattering in ELBNF 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*

SUMMARY

- *High resolution – low density ($\rho \sim 0.1$ g/cm^3) & magnetized (B=0.4T) – ND important to constrain systematics in ELBNF and fully achieve physics potential of oscillation analyses*

- *Detector originally proposed in the context of LBNE (reference design). Funding proposals for detector & corresponding R&D submitted to Indian DAE/DST agencies*

  $\Longrightarrow$ *Significant past and ongoing activities*

- *Rich Short Baseline (SBL) physics program, characterized by a deep synergy with Long Baseline oscillation analyses, allows a generational advance in precision measurements and searches for new physics*

  $\Longrightarrow$ *Discovery potential within SBL physics*

- *The addition of a LAr TPC in front of the high resolution tracker (spectrometer) could further enhance the capability of the ND-complex in ELBNF*

New groups / contributions are welcome!

Backup slides

THE STRAW TUBE TRACKER

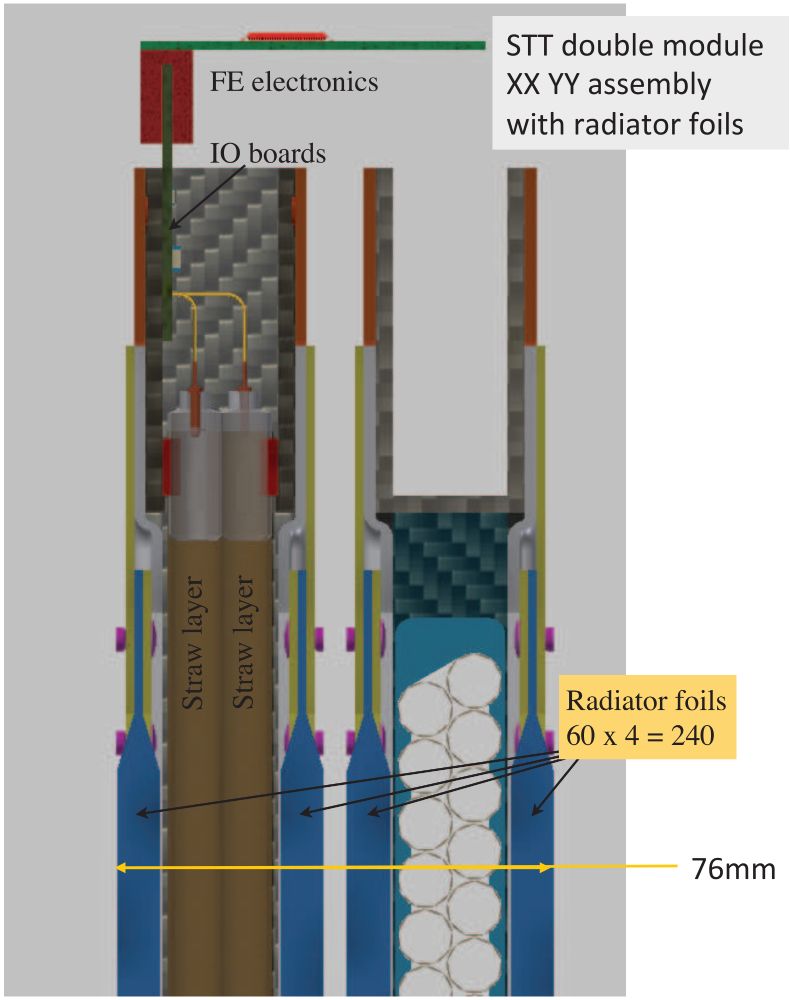
✦ *Main parameters of the STT design:*

- *Straw inner diameter* 9.530 ± 0.005 *mm;*
- *Operate with 70%/30% Xe/*CO_2 *gas mixture.*
- *Straws are arranged in double layers glued together (epoxy glue) inserted within C-fiber composite frames;*
- *Radiator/target integrated into front and back with 120* $(C_3H_6)_n$ *embossed foils (25* μm*) for Transition Radiation;*
- *Double module assembly (XX+YY) with FE electronics;*
- *160 modules arranged into 80 double modules over* ~ 6.5 *m (total 107,520 straws);*

✦ *Proven design and technology:*

- *Based upon the NOMAD experience*
- *Combine tracking & particle ID like the ATLAS TRT*
- *Basic design/geometry after COMPASS straw tracker*

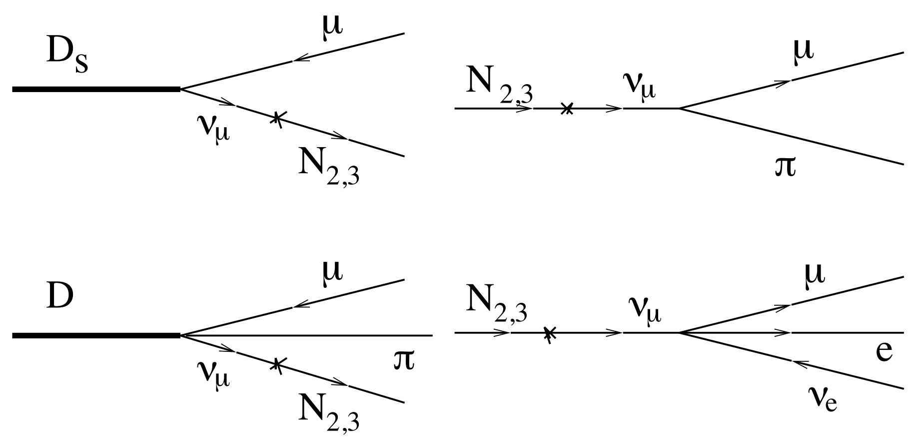
✦ *Mass of the active target dominated by the radiators (82.6% of total mass) and can be tuned to achieve desired events & momentum resolution*

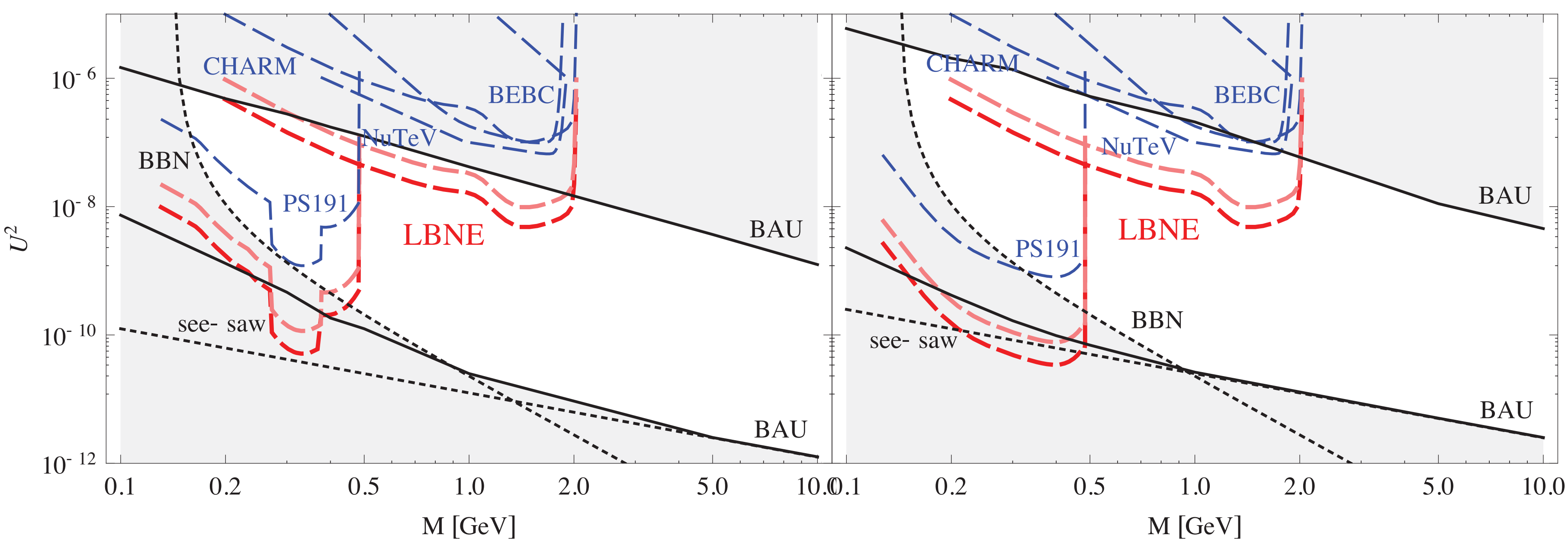


SEARCH FOR NEUTRAL LEPTONS

- ✦ *νMSM with 3 sterile RH neutrinos N_1, N_2, N_3:*
  (T. Asaka and M. Shaposhnikov, PLB 620 (2005) 17)
  - *N_1 with very large lifetime and $m(N_1) \sim 10$ keV;*
  - $\boxed{N_2, N_3}$ *almost degenerate $m \sim 100$ MeV-few GeV*

$\Longrightarrow$ *Search for weak decays*
$e^+e^-\nu, \mu e\nu, \mu^+\mu^-\nu, e^-\pi^+, \mu^-\pi^+$, *etc.*





Source of uncertainty	$\delta R^{\nu}/R^{\nu}$ NuTeV	LBNE	Comments
Data statistics	0.00176	0.00074	
Monte Carlo statistics	0.00015		
Total Statistics	*0.00176*	*0.00074*	
$\boldsymbol{\nu_e, \overline{\nu}_e}$ **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.	
$\boldsymbol{\overline{\nu}_\mu}$ **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**	