Role of the MPT/FGT in the DUNE ND Complex

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3rd DUNE ND Workshop
CERN, November 06, 2017

MEASUREMENT STRATEGY FOR LAr+MPT/FGT ND

Events of exclusive process X *(signal and backgrounds) in both ND* ($P_{\rm osc} \sim 1$) *and FD:*

$$N_{\rm X}(E_{\rm rec}) = \int_{E_\nu} dE_\nu \;\; \Phi(E_\nu) \;\; P_{\rm osc}(E_\nu) \;\; \sigma_{\rm X}(E_\nu) \;\;\; R_{\rm phys}(E_{\rm rec}, E_\nu) \;\;\; R_{\rm det}(E_{\rm rec}, E_\nu)$$

$R_{\rm phys}$ *describes the physics smearing (e.g. final state interactions)*
$R_{\rm det}$ *describes the detector smearing (e.g. readout, pile-up)*

- *The ND complex must provide in-situ constraints on* $\Phi, \sigma_{\rm X}, R_{\rm phys}, R_{\rm det}$, *to be extrapolated at the FD location (FD/ND ratio)*

  $\Longrightarrow$ *Uncertainties at FD must be* $<$ *than FD statistics:* $\sim$ *1,000* ν_e *CC, 10,000* ν_μ *CC*

- *Optimize LAr and MPT/FGT to constrain different factors above* (complementary):
  - *Cross-check with multiple measurements from both LAr and MPT/FGT (redundancy);*
  - *FD predictions from higher resolution MPT/FGT can be validated in-situ with the ND LAr.*

- *Different flux spectra (e.g. oscillated spectra, different on-axis and off-axis locations/measurements, different beam focusing options) can further constrain the overall response matrix, as discussed by Xin Quian at last Coll. meeting*

Events of exclusive process X *(signal and backgrounds) in both ND* ($P_{\mathrm{osc}} \sim 1$) *and FD:*

$$N_{\mathrm{X}}(E_{\mathrm{rec}}) = \int_{E_\nu} dE_\nu \; \boxed{\Phi(E_\nu)} \; P_{\mathrm{osc}}(E_\nu) \;\; \sigma_{\mathrm{X}}(E_\nu) \; \boxed{R_{\mathrm{phys}}(E_{\mathrm{rec}}, E_\nu)} \; R_{\mathrm{det}}(E_{\mathrm{rec}}, E_\nu)$$

MPT/FGT **MPT/FGT**

✦ $\boxed{\Phi(E_\nu)}$ *benefits from high resolution and light* A *target(s) in MPT/FGT:*

- *Absolute* ν_μ *flux from* ν*-e elastic scattering and Inverse Muon Decay (IMD);*
- *Relative* ν_μ *flux vs.* E_ν *from low-*ν *and* ν*-e elastic;*
- $\bar{\nu}_\mu/\nu_\mu$ *vs.* E_ν *from coherent* $\pi^\pm$ *production;*
- ν_e/ν_μ *AND* $\bar{\nu}_e/\bar{\nu}_\mu$ *vs.* E_ν *from* $\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$ *CC spectra.*

✦ $\boxed{R_{\mathrm{phys}}(E_{\mathrm{rec}}, E_\nu)}$ *requires suite of multiple nuclear targets in MPT/FGT:*

- *Model-independent determination of nuclear effects from free nucleon or electron targets;*
- *Modeling constraints by studying a few nuclei different from Ar in addition to LAr.*

✦ *In addition, MPT/FGT offers synergy with LAr to measure* $\sigma_{\mathrm{X}}(E_\nu)$ *of several exclusive processes, e.g.* π^0 *and* γ *in NC and CC events*

Events of exclusive process X *(signal and backgrounds) in both ND* ($P_{\rm osc} \sim 1$) *and FD:*

$$N_{\rm X}(E_{\rm rec}) = \int_{E_\nu} dE_\nu \, \boxed{\Phi(E_\nu)} \, P_{\rm osc}(E_\nu) \, \boxed{\sigma_{\rm X}(E_\nu)} \, \boxed{R_{\rm phys}(E_{\rm rec}, E_\nu)} \, \boxed{R_{\rm det}(E_{\rm rec}, E_\nu)}$$

MPT/FGT ($\Phi(E_\nu)$) — **LAr** ($\sigma_{\rm X}(E_\nu)$) — **MPT/FGT** ($R_{\rm phys}(E_{\rm rec}, E_\nu)$) — **LAr** ($R_{\rm det}(E_{\rm rec}, E_\nu)$)

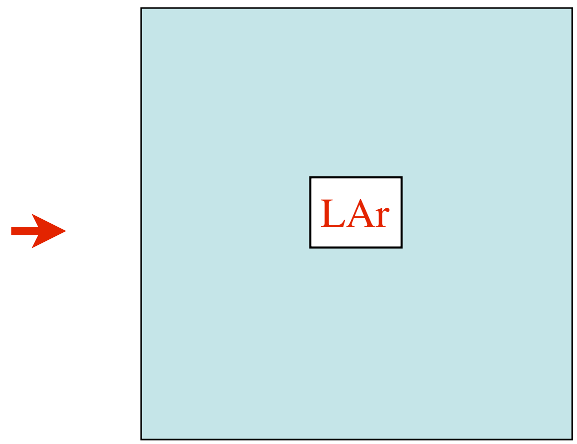
✦ $\boxed{R_{\rm det}(E_{\rm rec}, E_\nu)}$ *can only be provided by LAr:*

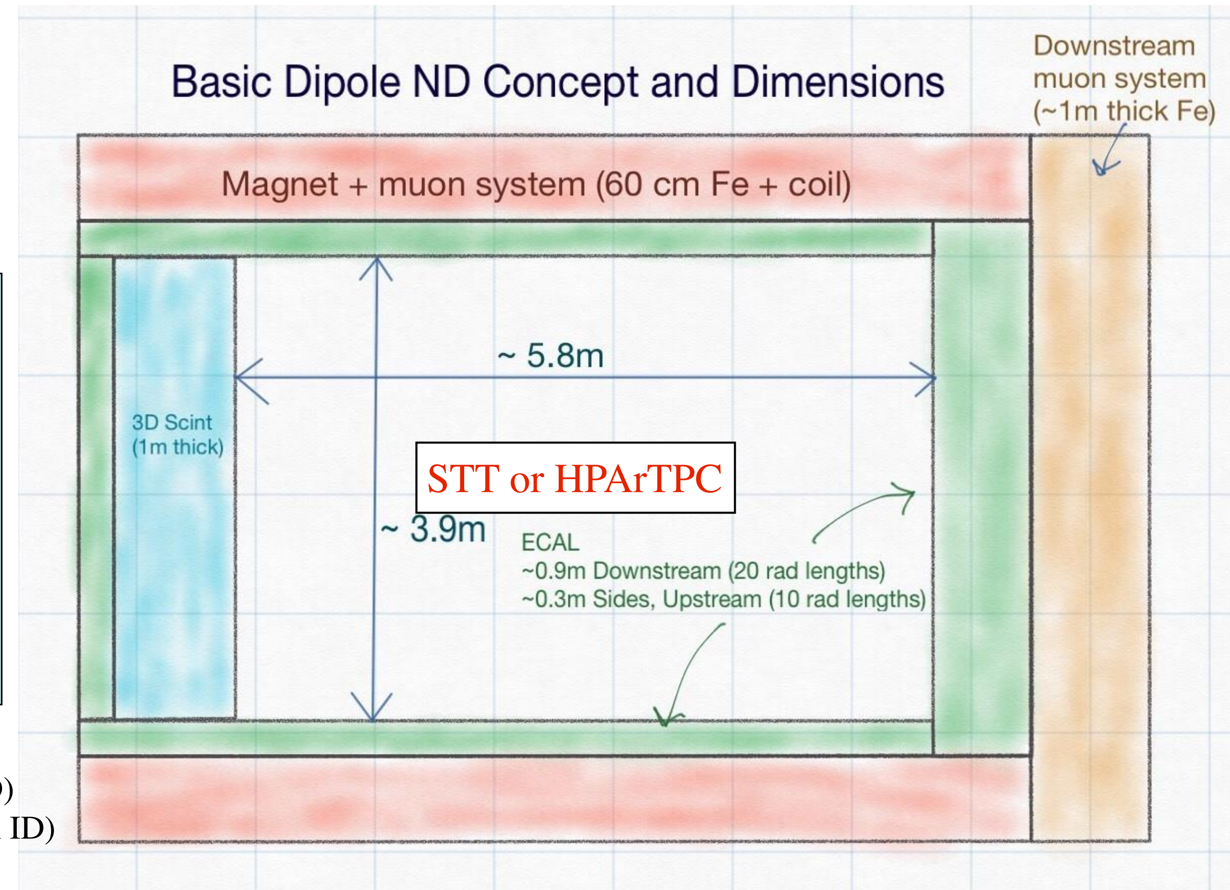
- *Evaluate impact of the differences in the detector response of ND and FD;*
- *Additional constraints from test-beam exposure of LAr detectors with similar readout.*

✦ $\boxed{\sigma_{\rm X}(E_\nu)}$ *requires an Ar target and can be constrained by LAr:*

- *Need to measure various exclusive processes on Ar target;*
- *LAr benefits from precise calibration of backgrounds and event topologies in MPT/FGT.*

✦ *In addition, LAr offers synergy with MPT/FGT to validate the effect of the nuclear smearing in* $R_{\rm phys}(E_{\rm rec}, E_\nu)$ *and some of the flux measurements.*





C. Marshall 09/13:
2.5m x 2.5m x 3.25m (Muon ID)
4.0m x 4.0m x 3.25m (no Muon ID)

STT OFFERS A UNIQUE TRACKER DESIGN

✦ *Excellent angular, momentum & timing resolution:*

- *Low density design allows precise tracking of charged particles;*
- $\delta\theta \sim$ *1-2 mrad*, $\delta p/p \sim 3.5\%$, *momentum scale uncertainty* $< 0.2\%$;
- *Time resolution* $\sim 1ns$, *can resolve beam structure & withstand high rates (max. drift* $\sim$ *125* ns*).*

✦ *Excellent particle ID over the entire tracking volume & energy range:*

- *Electron ID with Transition Radiation (TR) and dE/dx* $\Longrightarrow \pi$ *rejection* $\sim 10^{-3}$;
- $\pi/K/p$ *ID with dE/dx and range.*

✦ *Low* A *target material:*

- *Main target polypropylene radiator foils* $(C_3H_6)_n$ *with high chemical purity;*
- *Reduced systematic uncertainties for measurements not requiring Ar target.*

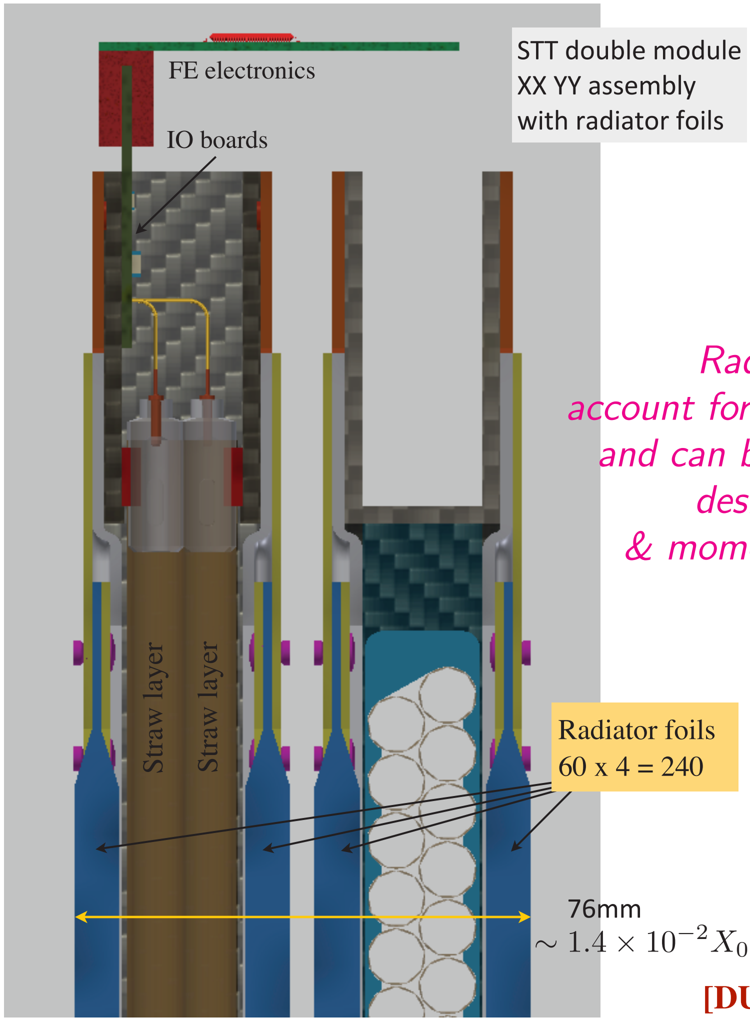
✦ *Modular design (flexible):*

- *Allows to vary target mass by removing/adding radiator foils* ($\sim 83\%$ *of STT mass) with average density ranging from 0.017* g/cm^3 *to 0.10* g/cm^3;
- *Can accomodate a number of different nuclear targets.*

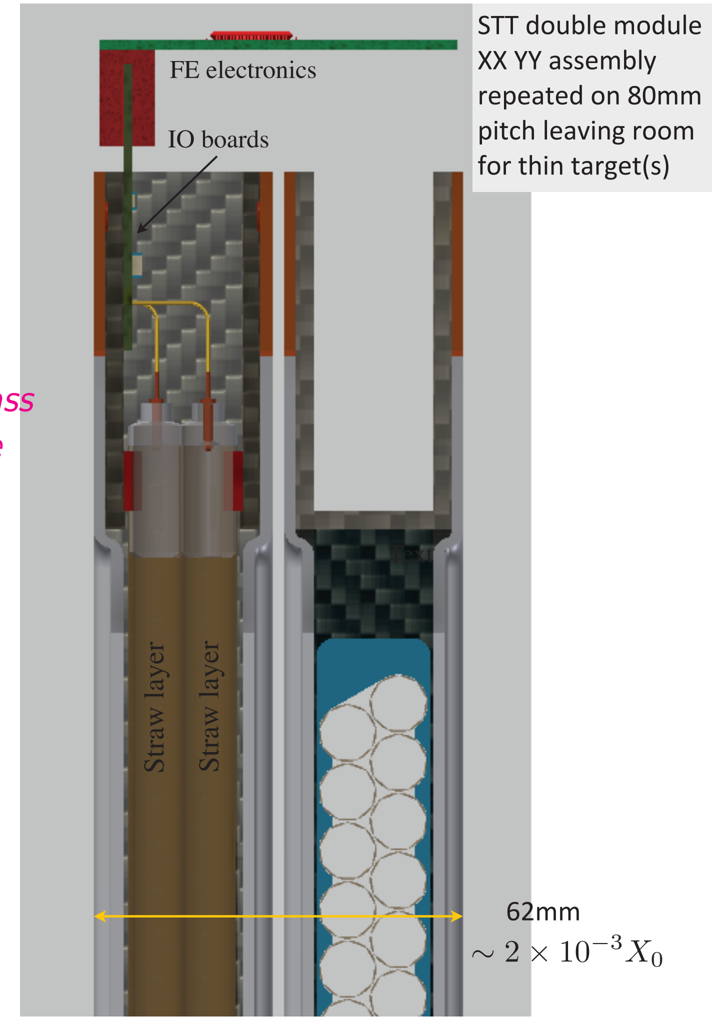
$\Longrightarrow$ *Find optimal compromise between target mass (statistics) & resolution*

$\Longrightarrow$ *Ideal for quantifying the (anti)neutrino source (fluxes) & for precision measurements including rare processes*

STT module with radiators



STT module for nuclear targets



Radiator targets account for 82.6% of STT mass and can be tuned to achieve desired statistics & momentum resolution

[DUNE CDR Volume 4]

ADVANTAGES/DISADVANTAGES OF HPArTPC

✦ *Improved angular and momentum resolution*:

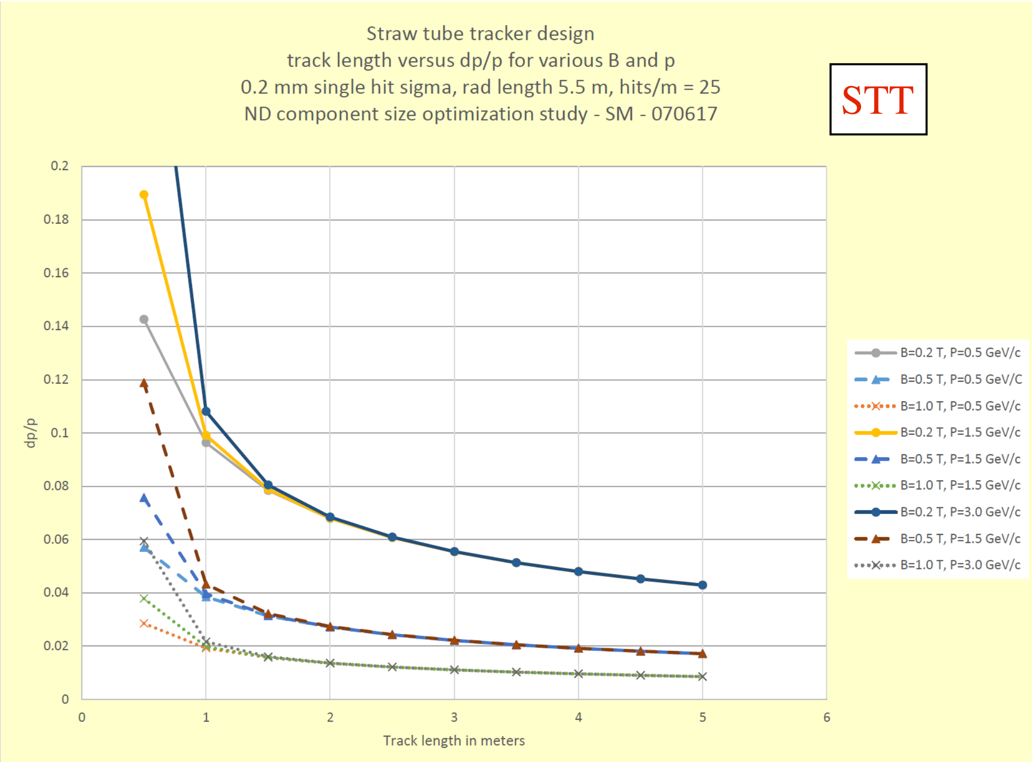
- *Lower density reduces multiple scattering contribution;*
- *3D track reconstruction capability in B field;*
- *Worse single hit resolution compensated by higher sampling.*

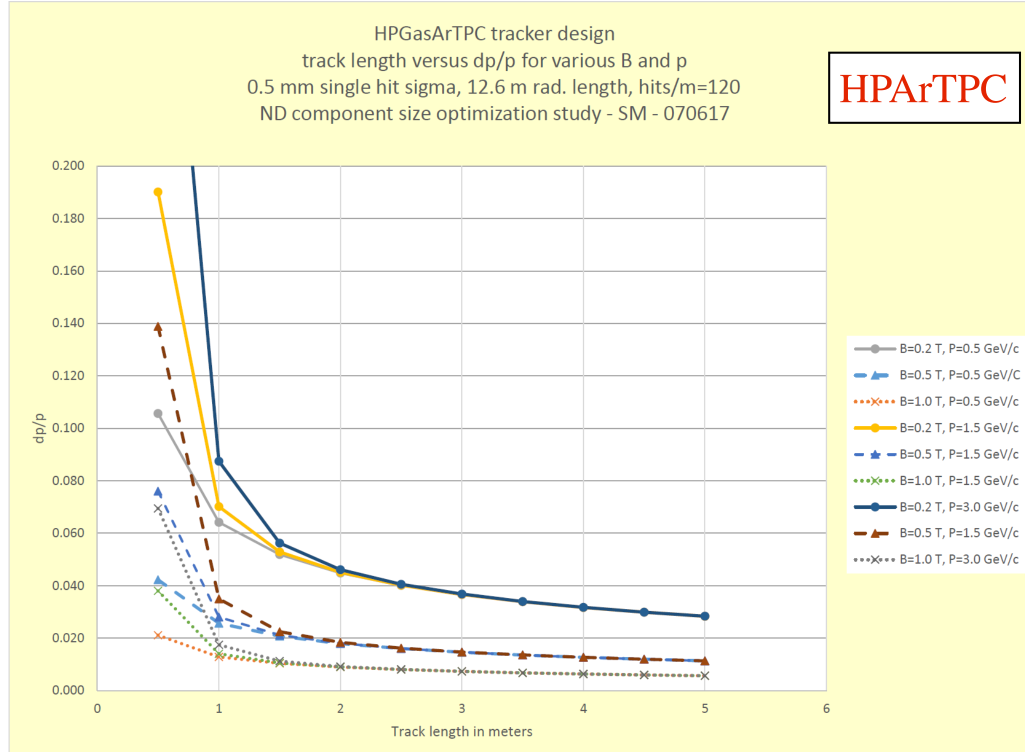
✦ *Excellent detection of low energy/momentum particles*:

- *Reconstruct tracks with* $1cm < L < 10cm$ *in STT;*
- *Proton momentum down to* ~ 60 *MeV;*
- *Vertex activity visualization.*

✦ *Disadvantages of HPArTPC*:

- *Worse timing cannot resolve beam structure and results in higher pile-up;*
- *No Transition Radiation* $\Longrightarrow e^{\pm}$ *ID;*
- *Not many* γ *convert in tracking volume* $\Longrightarrow \pi^0/\gamma$ *ID;*
- *No suite of nuclear targets & target purity;*
- *Smaller fiducial mass for same volume* $\Longrightarrow$ *statistics;*
- *Needs a pressure vessel.*





S. Manly, DUNE collaboration meeting, August 2017

ANGULAR DEPENDENCE

- *NOMAD used a planar design with drift distance $d = 3.2$ cm $\perp$ to the beam direction*
  $\Longrightarrow$ *Significant variation of space resolution with angle*

- *In STT use small cylindrical tubes ($d = 0.5$ cm) providing a single hit resolution roughly insensitive to track angle*

- *Sampling in direction $\perp$ to beam factor of 2 larger than along beam direction*

- *Geometrical effect varying the number of hits vs. the track angle*
  - *B bending mitigates the effect for soft tracks;*
  - *Largest effect for low momentum protons (short tracks);*
  - *Can be estimated with MC by counting hits along track helix*

  $\Longrightarrow$ *Try to get rough estimate without full reconstruction*

STT OPTIMIZED FOR $e^{\pm}$ AND π^0/γ

- *Continuous TR+dE/dx detection over entire STT volume, NOMAD only limited forward coverage*
  $\Longrightarrow$ *Improved acceptance and e^+/e^- ID*

- *Need $\sim$ 12 double STT modules (track $\sim$ 1 m) to match the total foils of the NOMAD TRD*

- *Performance of TR in STT evaluated with simulation package from ATLAS TRT (P. Nevski)*

Most critical measurements in DUNE ND involve $e^{\pm}$: ν-e, $\nu_e(\bar{\nu}_e)$ CC, π^0/γ, etc.

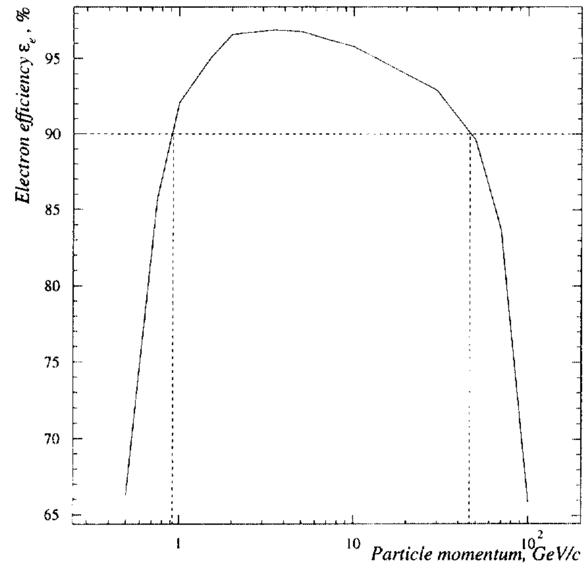
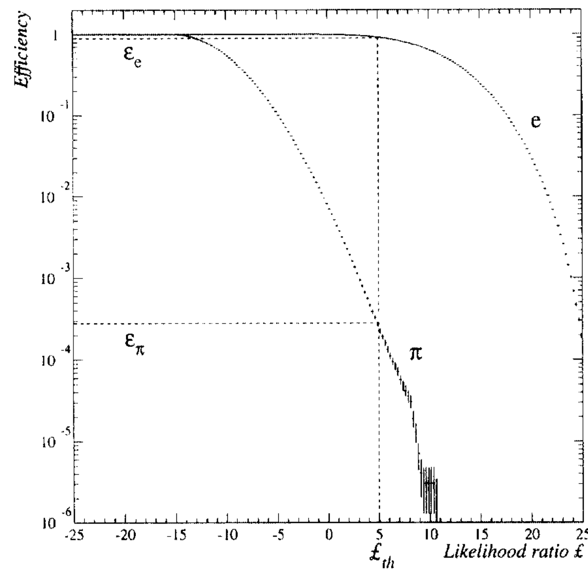


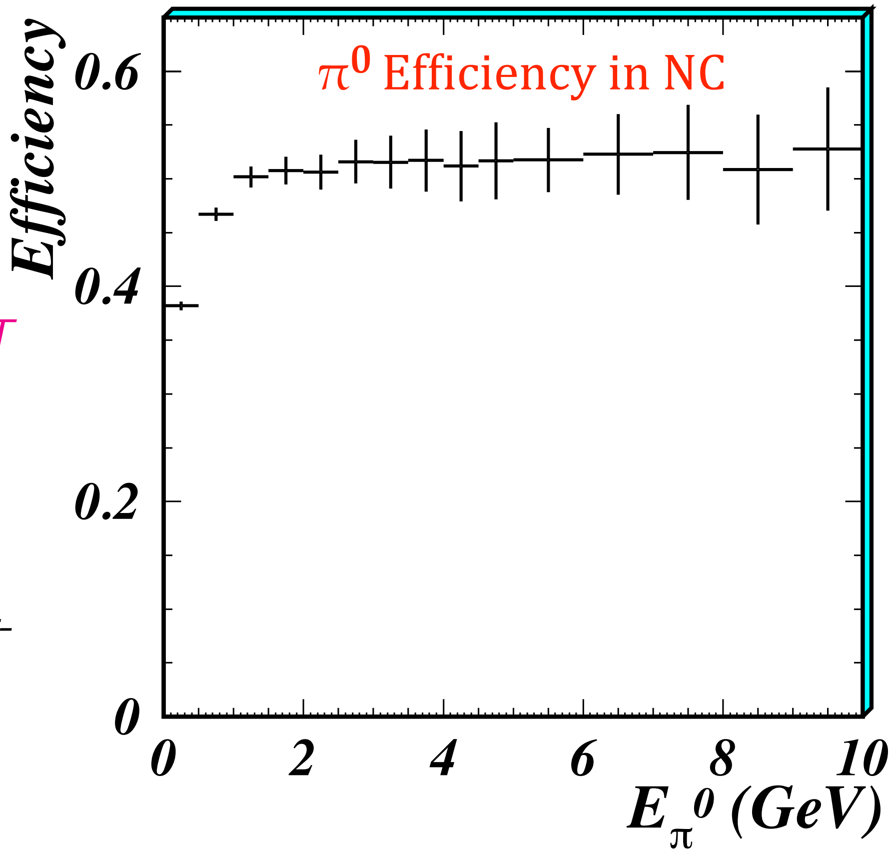
Fig. 8. Monte Carlo predicted electron efficiency ε_e corresponding to $\varepsilon_\pi = 10^{-3}$ as a function of the momentum of the particle



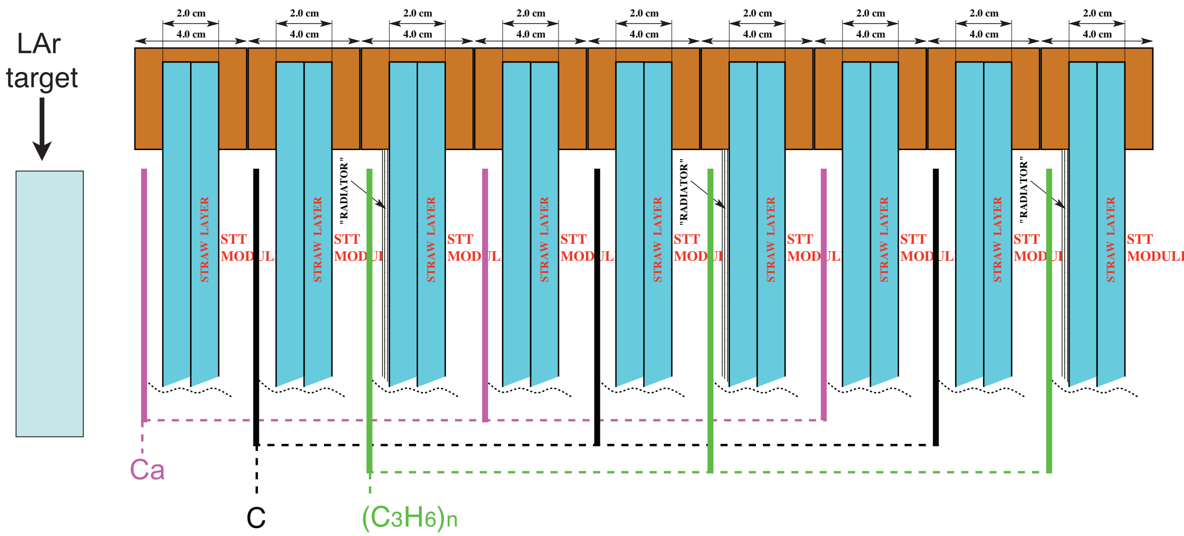
- *Clean γ ID in STT:*
  - *$e^{\pm}$ ID from TR+dE/dx;*
  - *Kinematic cuts: mass, opening angle.*

- *For π^0 ID require at least one γ converted in STT (e^+e^- pair) and another in ECAL*
  - *$\sim$ 50% of γ converted in STT;*
  - *Kinematic selection of π^0 in NC & CC.*

- *Measure the π^0/γ background for the ν_e appearance analysis vs. E_ν, E_π, P_T*



NUCLEAR TARGETS IN STT



- *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* C TARGET *from polypropylene* $(C_3H_6)_n$ RADIATORS *provides neutrino AND anti-neutrino interactions on free proton target*
  $\Longrightarrow$ *Model-independent measurement of nuclear effects and FSI from RATIOS A/H*

- *In addition to the* LAr TARGET *in front of STT, a solid* Ca TARGET *(compact & effective) inside STT provides a detailed understanding of the FD $A = 40$ target*
  $\Longrightarrow$ *Study of flavor dependence & isospin physics*

STATISTICS & TRACKER DIMENSIONS

- *Number of events/ton for the key processes for ND flux determination expected in ν beam mode with 1.2 MW beam (80 GeV, 1.47 $\times 10^{21}$ pot/year):*

Process	Evt/ton (3 y)	Evt/ton (5 y)
ν-e elastic scattering	582	970
Inverse Muon Decay	53	88
$\bar{\nu}_e$ CC	5,160	8,600
Coherent π^+	43,659	72,765
Coherent π^-	1,628	2,714
ν_μ CC $\nu < 0.25$ GeV	397,031	661,718

3 horn optimized

- *For same tracking volume STT has 6 times the target mass as HPArTPC at 10 atm*

- *Minimum transverse dimensions for STT 3.5m $\times$ 3.5m (fiducial 3.0m $\times$ 3.0m)*
  $\Longrightarrow$ *Smaller size compromises $e^\pm$ ID, π^0/γ ID & large angle p/π*

- *Longitudinal size of 5.8m gives fiducial STT target of $\sim 5m$ and $\sim 4.5t$ (0.1 g/cm^3)*
  $\Longrightarrow$ *Try to keep fiducial mass $\sim 5t$ for $e^\pm, \pi^0/\gamma$, statistics*

$\nu(\bar{\nu})$-e ELASTIC SCATTERING

✦ *Benefits offered by STT:*

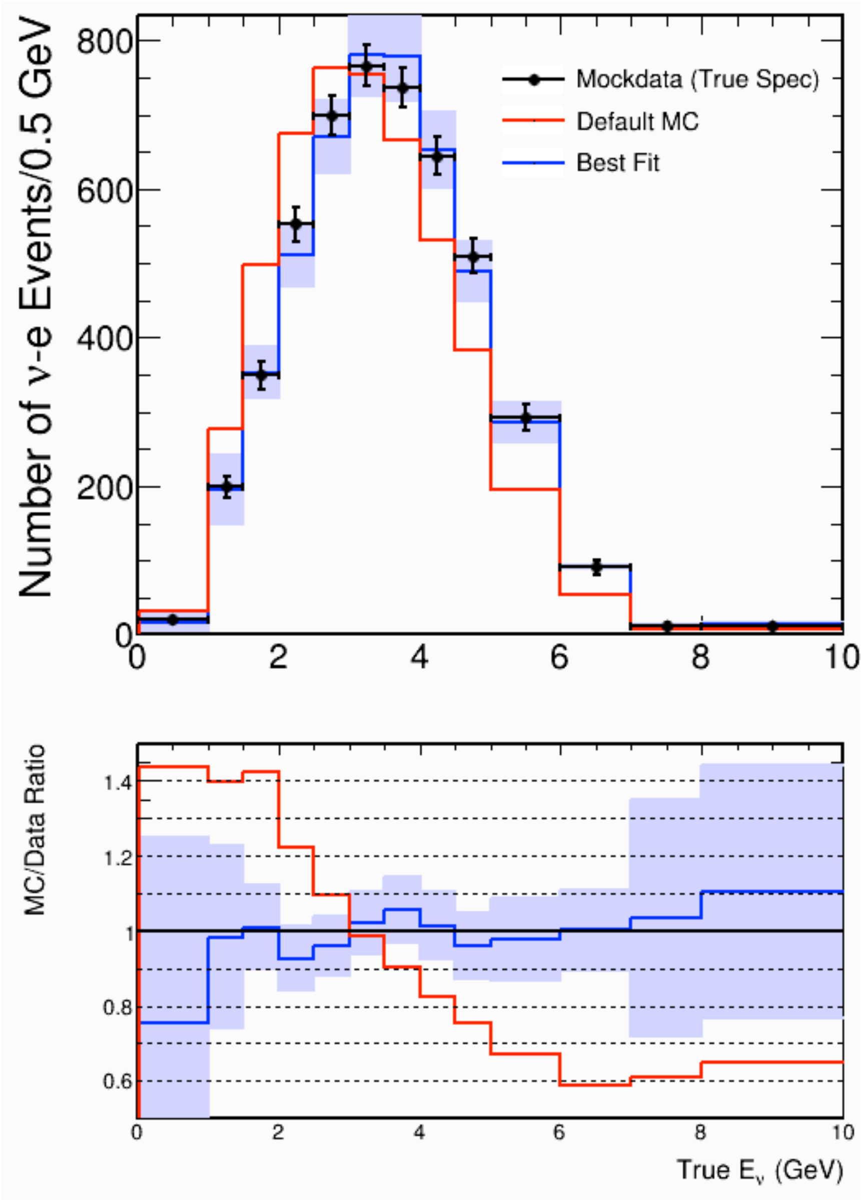
- *Statistics sufficient to measure BOTH absolute ν_μ flux and the corresponding energy spectrum*
  $\Longrightarrow$ *Additional constrain on relative ν_μ flux and neutrino energy scale;*
- *Excellent electron ID with TR and angular resolution to reduce backgrounds;*
- *Clean low background event selection.*

✦ *Combined analysis of LAr+STT to make optimal use of all available statistics to determine the neutrino energy spectrum*

$\Longrightarrow$ *STT provides background measurements to exploit the additional LAr statistics.*

✦ *Determination of ν_μ energy spectrum (see talk by H. Duyang):*

- *Promising results by fitting the 2D distribution (θ_e, E_e) of the measured electron;*
- *Need to apply correction for beam divergence from parent meson decays;*
- *Beam simulations predict uncertainty on FD/ND extrapolation $< 2\%$*
  $\Longrightarrow$ *This result implies that the uncertainty on beam divergence is under control*
- *Investigating possible in-situ constraints on beam divergence.*



H. Duyang

No function used in fit

LOW-ν RELATIVE FLUX

✦ *Relative bin-to-bin ν_μ flux from low-ν method:*

$$N(E_\nu,\ E_{\rm Had} < \nu_0) \propto \Phi(E_\nu) f_c(\tfrac{\nu_0}{E_\nu}) \qquad f_c \to 1 \text{ for } \nu_0 \to 0$$

- *Measurement of the relative bin-to-bin $\nu_\mu(\bar{\nu}_\mu)$ flux vs. energy in ND;*
- *Extrapolation of flux spectra to FD/ND(E) ratio by extracting parent meson distributions.*

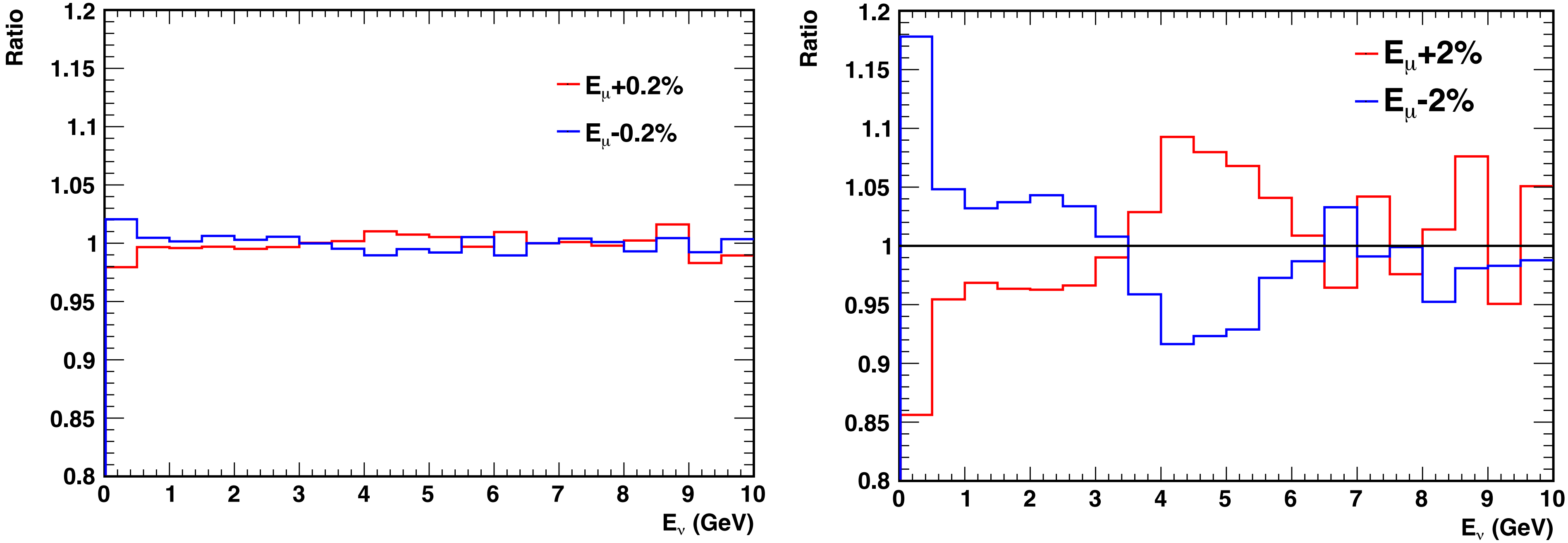
✦ *Benefits offered by STT:*

- *Small muon energy scale uncertainty (dominant systematics) $< 0.2\%$;*
- *Fractional energy carried by neutrons in $(C_3H_6)_n$ radiator target factor 2 smaller than in Ar* $\Longrightarrow$ *Smaller uncertainty associated to the ν cut & hadronic smearing*
- *Large statistics allowing same stringent ν cut for all energies.*

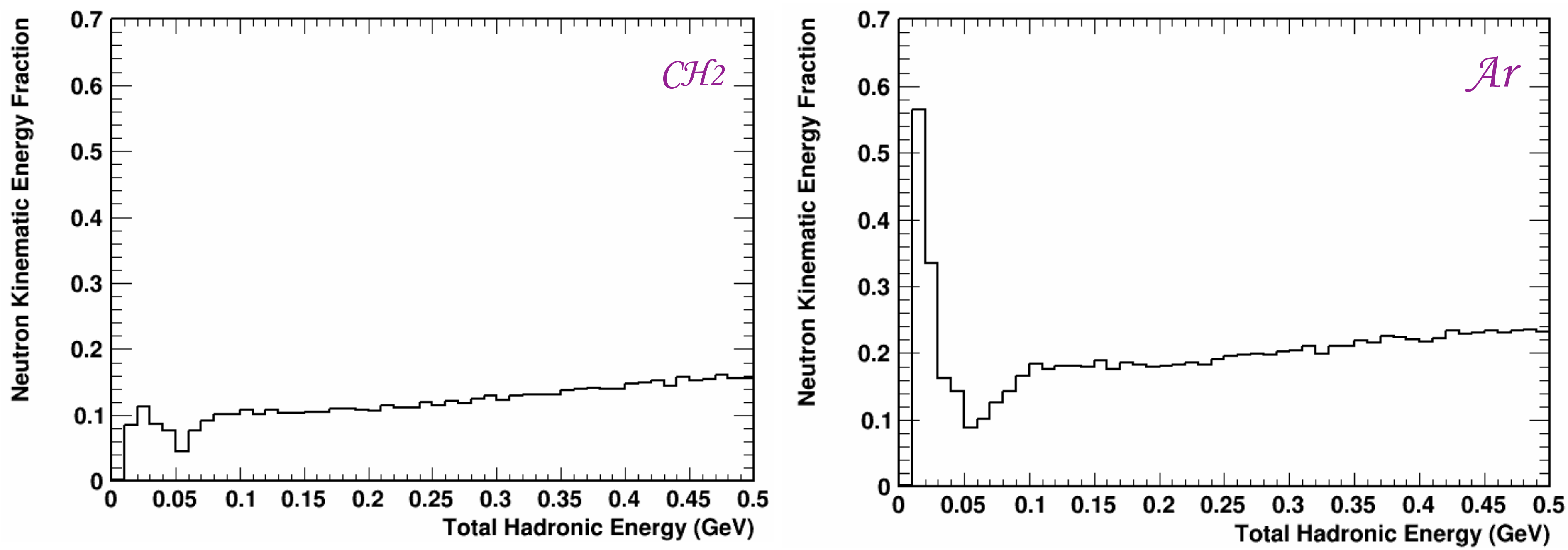
✦ *Possible to constrain in-situ neutron production:*

- *Use kinematics in transverse plane (p_T) to reduce neutron impact;*
- *Constrain production of primary neutrons with exclusive resonance production;*
- *Calibrate neutrons with charge exchange interactions in STT.*

H. Duyang



H. Duyang



CH2
Neutron Kinematic Energy Fraction
Total Hadronic Energy (GeV)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.05
0.15
0.25
0.35
0.45
Ar
Neutron Kinematic Energy Fraction
Total Hadronic Energy (GeV)

COHERENT $\pi^{\pm}$ PRODUCTION

✦ *Coherent $\pi^{\pm}$ with minimal momentum transfer to nucleus $\mid t \mid < 0.05$ GeV^2*

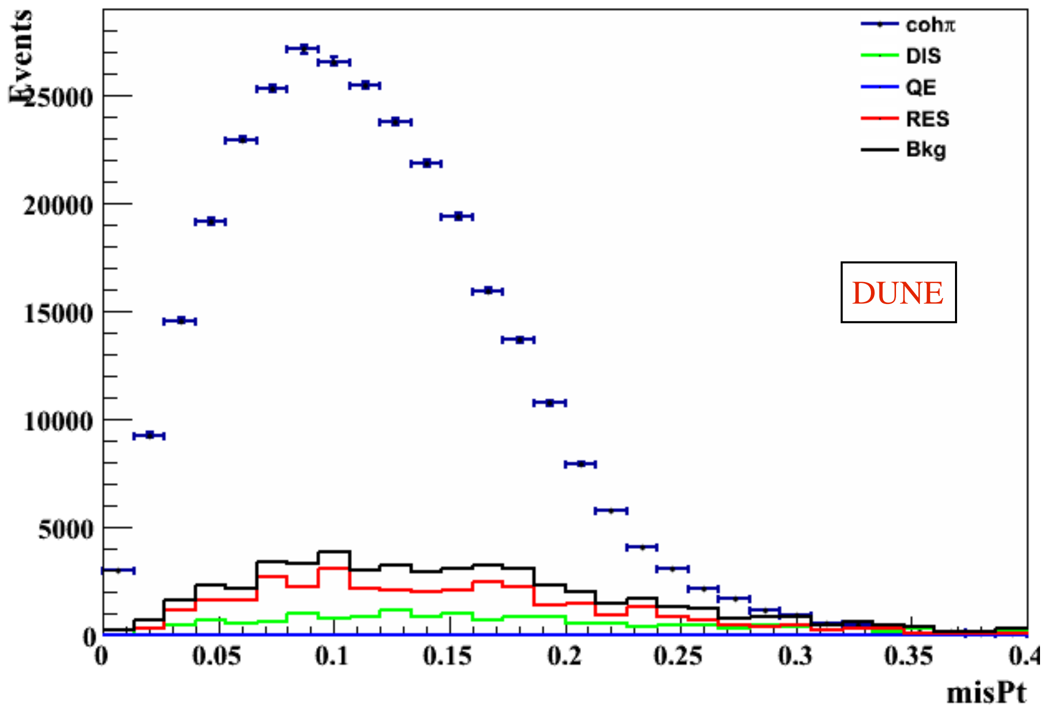
- *Small missing p_T and closest approximation to neutrino beam direction;*
- *Little nuclear effects compared to other channels.*

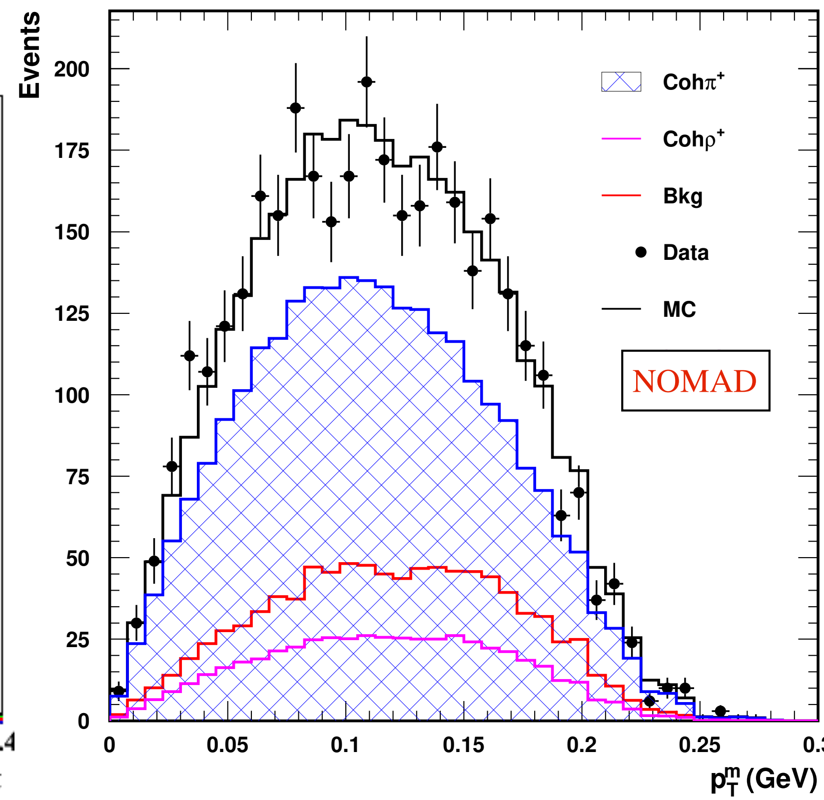
✦ *Benefits offered by STT:*

- *Light isoscalar target (C) implies same neutrino and anti-neutrino cross-sections*
  $\Longrightarrow$ *Most precise technique to measure the ratio $\bar{\nu}_\mu/\nu_\mu$ vs. E_ν*
- *Statistics allowing an accurate measurement of $\bar{\nu}_\mu$ (coherent π^-)*
- *Excellent angular & momentum resolution (t resolution) for background rejection.*

✦ *Ongoing study to quantify the sensitivity of coherent $\pi^{\pm}$ production to the neutrino beam parameters (beam monitoring)*

B. Guo


Events
25000
20000
15000
10000
5000
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
misPt
cohπ
DIS
QE
RES
Bkg
DUNE


Events
200
175
150
125
100
75
50
25
0
0
0.05
0.1
0.15
0.2
0.25
0.3
p_T^m (GeV)
Cohπ+
Cohρ+
Bkg
Data
MC
NOMAD

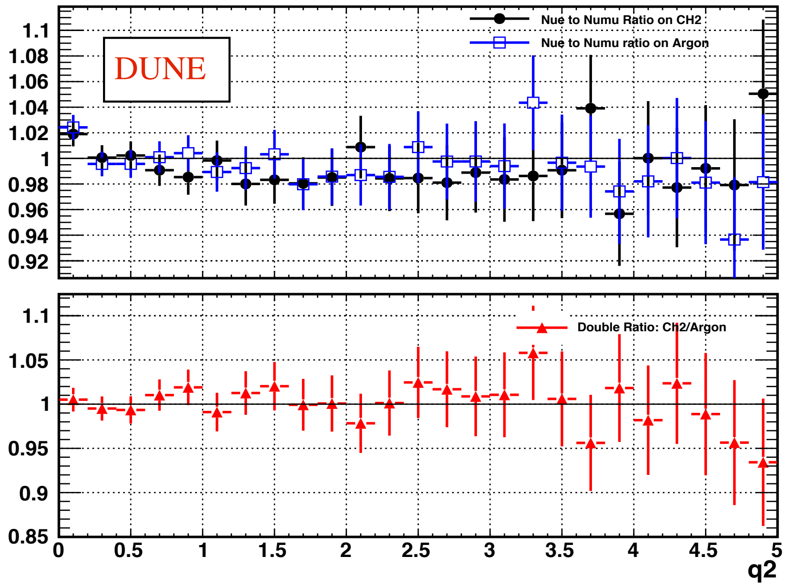
ν_e/ν_μ & $\bar{\nu}_e/\bar{\nu}_\mu$ FLUX RATIOS

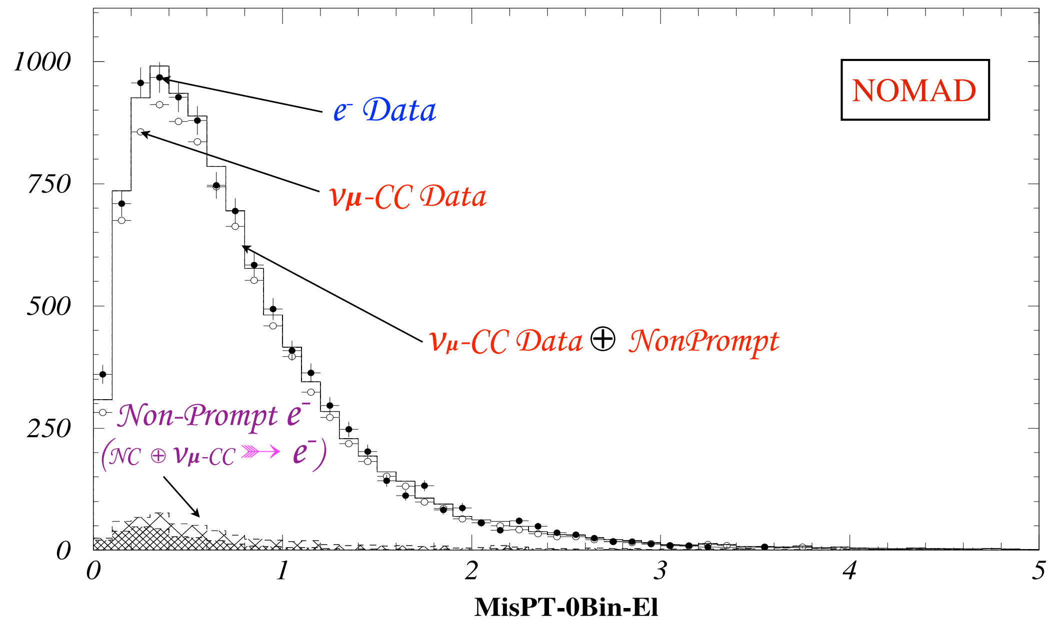
✦ *Simultaneous fit to $\nu_\mu(\bar{\nu}_\mu)$ disappearance AND $\nu_e(\bar{\nu}_e)$ appearance samples in FD*
$\Longrightarrow$ *Key quantities to constrain are RATIOS ν_e/ν_μ & $\bar{\nu}_e/\bar{\nu}_\mu$*

✦ *Nuclear effects cancel out in the ratios ν_e/ν_μ & $\bar{\nu}_e/\bar{\nu}_\mu$, which can be measured with higher accuracy on light target materials.*

✦ *Benefits offered by STT:*

- *Excellent $e^\pm$ ID with TR for background rejection;*
- *Large statistics of reconstructed $\bar{\nu}_e$ CC;*
- *Low A target material;*
- *Accurate measure of all four CC spectra $\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$ constraining parent meson distributions.*





ν_e/ν_μ in Ar and CH_2 in DUNE

e^-/μ^- universality in NOMAD

MEASURING NUCLEAR EFFECTS IN STT

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

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

  $\Longrightarrow$ *Validation of FD predictions from STT in LAr ND (+ rec. effects)*

- *Dedicated measurements of nuclear effects with the complete suite of nuclear targets (H, C_3H_6, C, Ar, Ca) in STT 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;*
  - *Missing trasverse momentum in exclusive topologies;*
  - *Backward going pions and protons.*

  $\Longrightarrow$ *Systematic uncertainties on response (smearing) function $R_{\rm phys}(E_{\rm rec}, E_\nu)$*

SUMMARY

- *A ND complex based upon the combination of a LAr and a low density MPT/FGT can constrain all key factors: flux Φ, cross-section $\sigma_{\rm X}$, and response functions $R_{\rm phys}, R_{\rm det}$*

- *An effective use of MPT/FGT is to measure/constrain all (anti)neutrino fluxes & the nuclear smearing (response function)*

- *Synergies between LAr and MPT/FGT allow combined analyses & validations of predictions (redundancy)*

- *Key measurements in MPT/FGT: ν-e elastic, low-ν, coherent $\pi^{\pm}$, ν_e/ν_μ, $\bar{\nu}_e/\bar{\nu}_\mu$, nuclear effects*

  $\Longrightarrow$ *Ongoing work for STT focused on these studies and related detector performance*

Backup slides

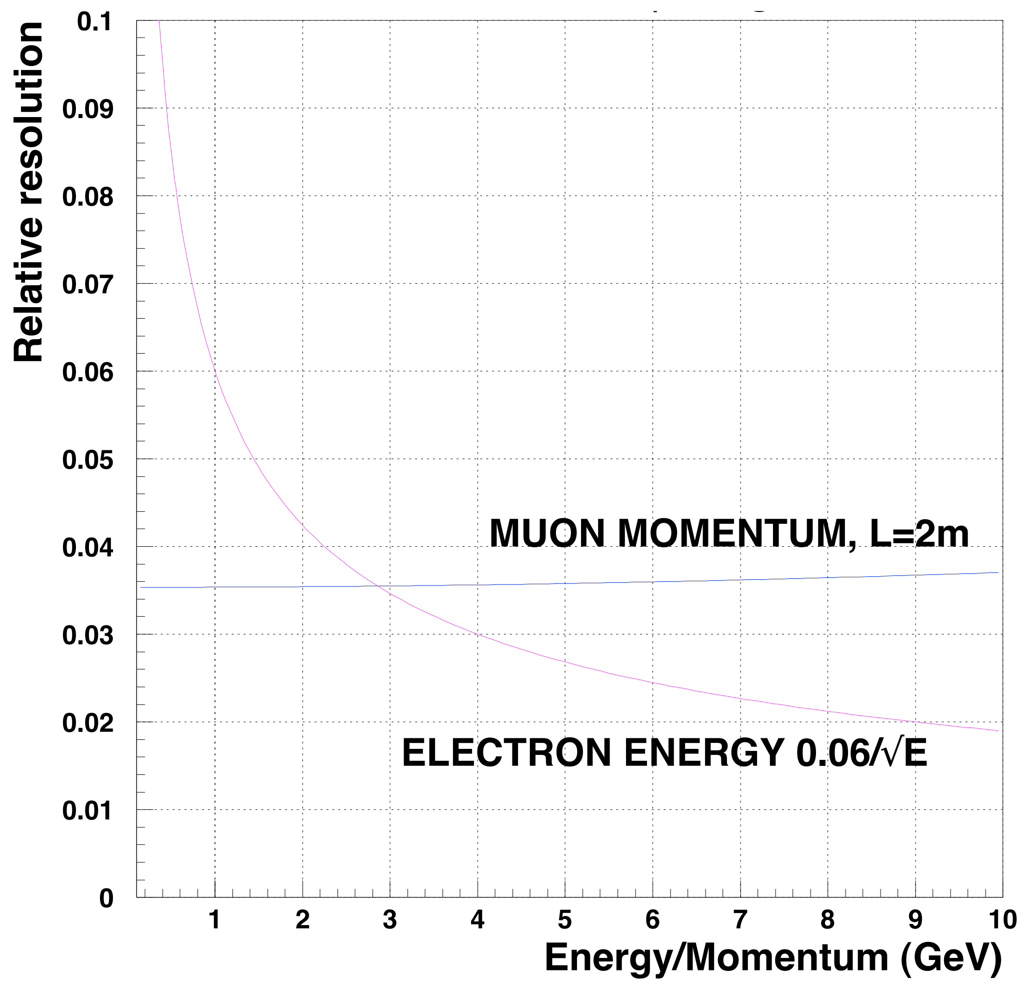
EXPECTED STT PERFORMANCE

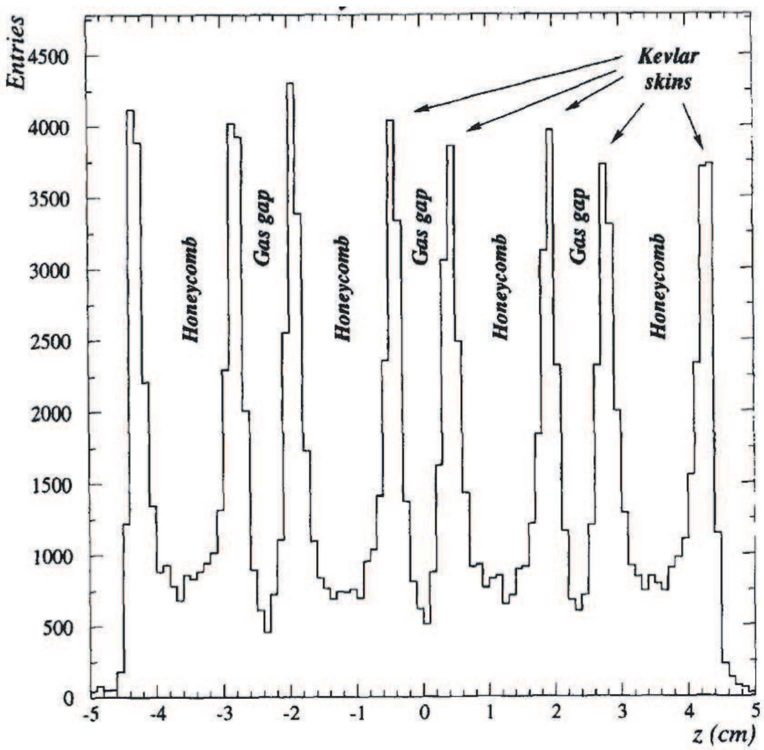
- ✦ *Single hit resolution* $< 200\mu m$
- ✦ *Time resolution* $\simeq 1ns$

- ✦ *CC-Events Vertex:* $\Delta(X,Y,Z) \simeq \mathcal{O}(100\mu m)$
- ✦ *Angular resolution:* ~ 2 *mrad*

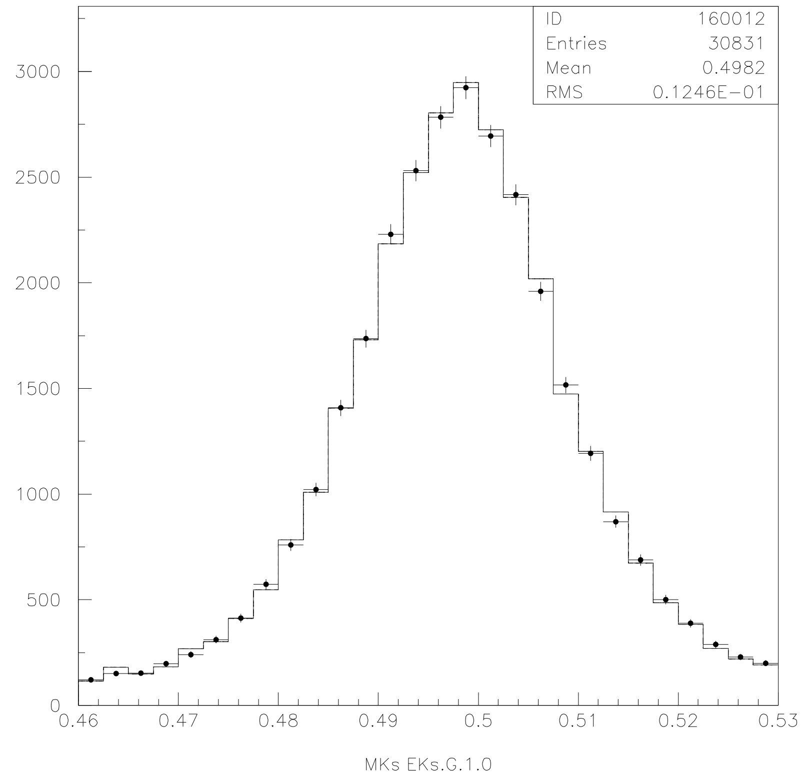
- ✦ *Momentum res.* (ρ=0.1g/cm^3, B=0.4T)
  - *Multiple scattering term* 0.05 *for* $L = 1m$
  - *Measurement error term* 0.006 *for* $L = 1m$ *and* $p = 1$ *GeV/c* ($N = 50$)
- ✦ *Downstream-ECAL res.* $\simeq 6\%/\sqrt{E}$

- ✦ e^+/e^- *down to 80 MeV from curvature*
- ✦ *Protons down to* $\sim$ *200 MeV/c*
- ✦ π^0 *with at least 1 converted* γ ($\sim 50\%$)



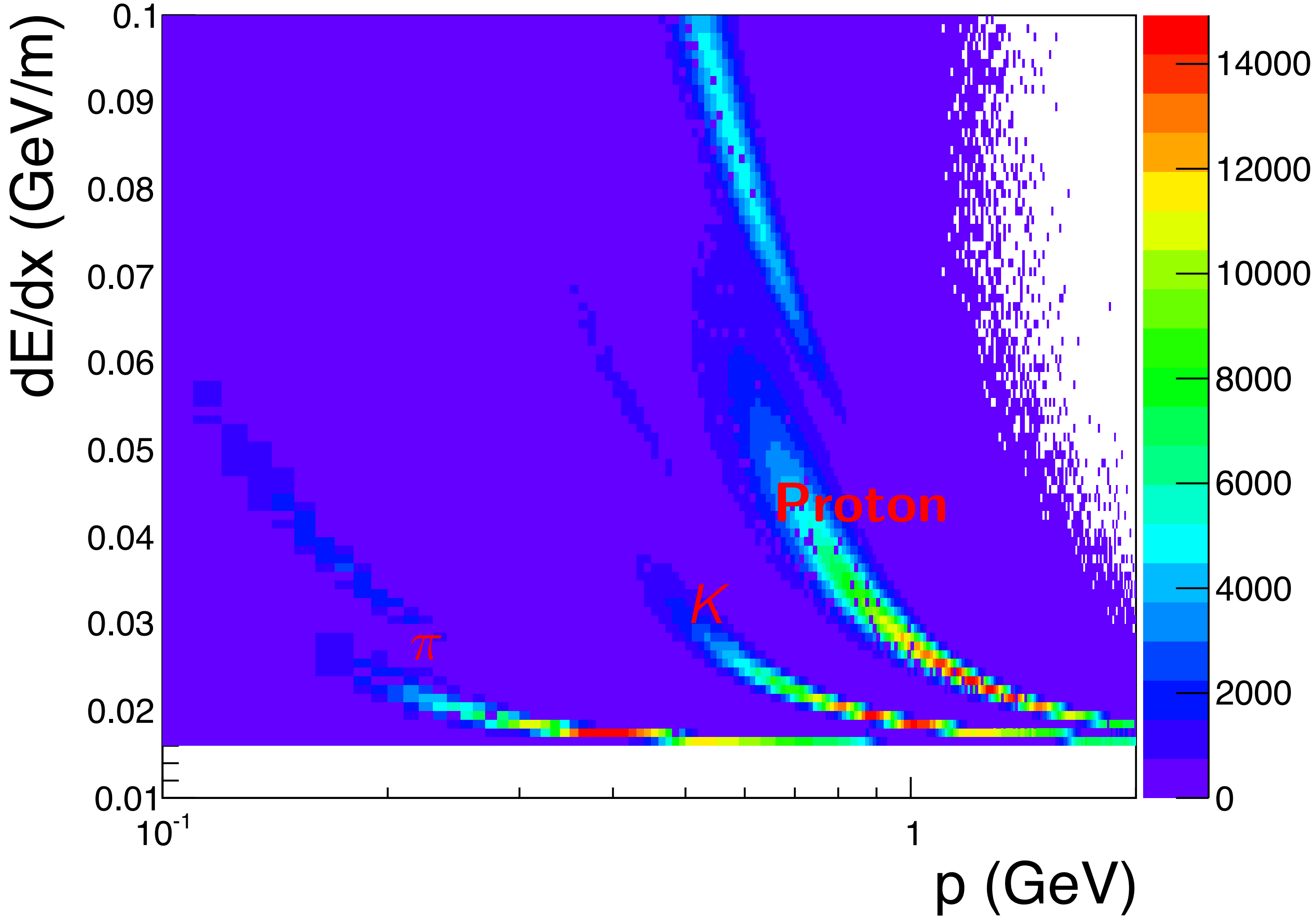


Neutrino radiography of one drift chamber



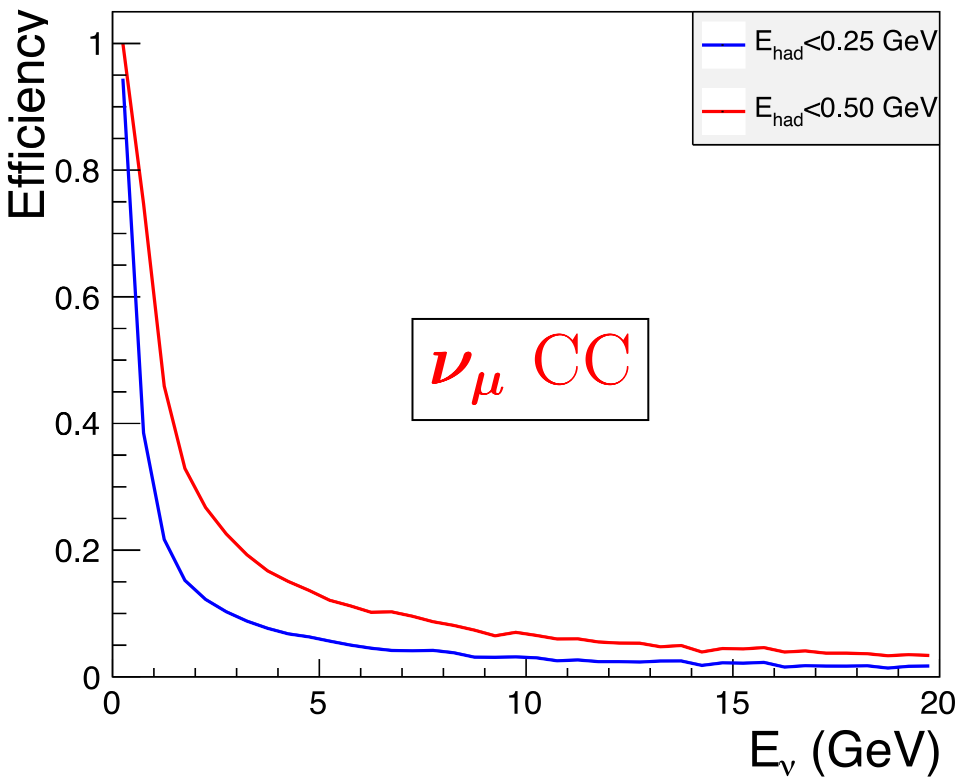
Reconstructed K^0 mass

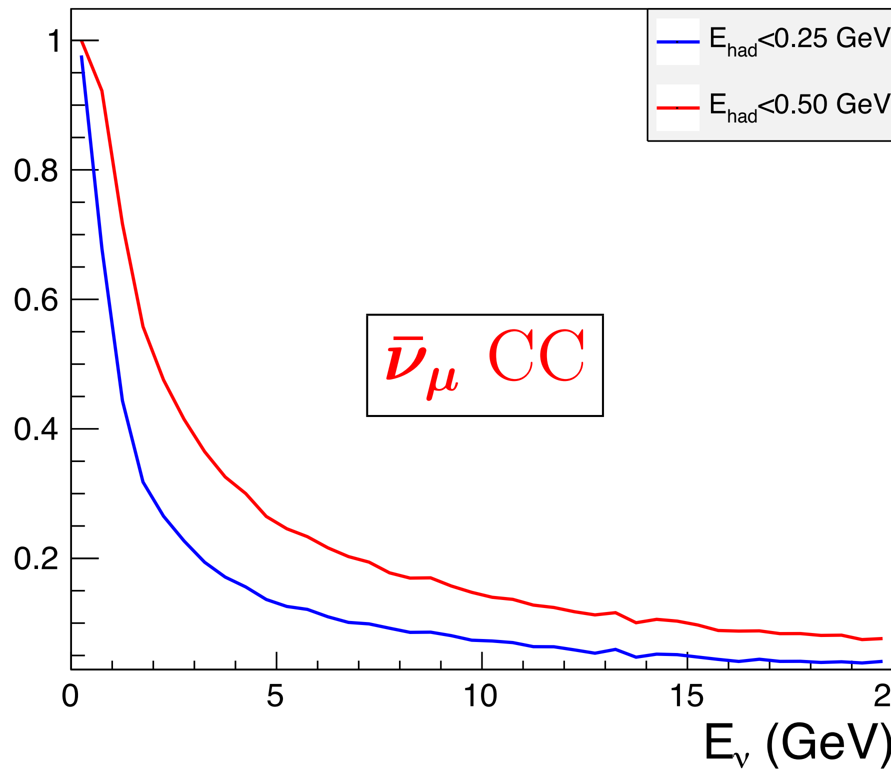
- *NOMAD: charged track momentum scale known to* $< 0.2\%$
- *DUNE STT:* $\sim$ *100* $\times$ *more statistics and* *12* $\times$ *higher segmentation*



STT has good dE/dx particle ID: $\pi^{\pm}/K^{\pm}/p$

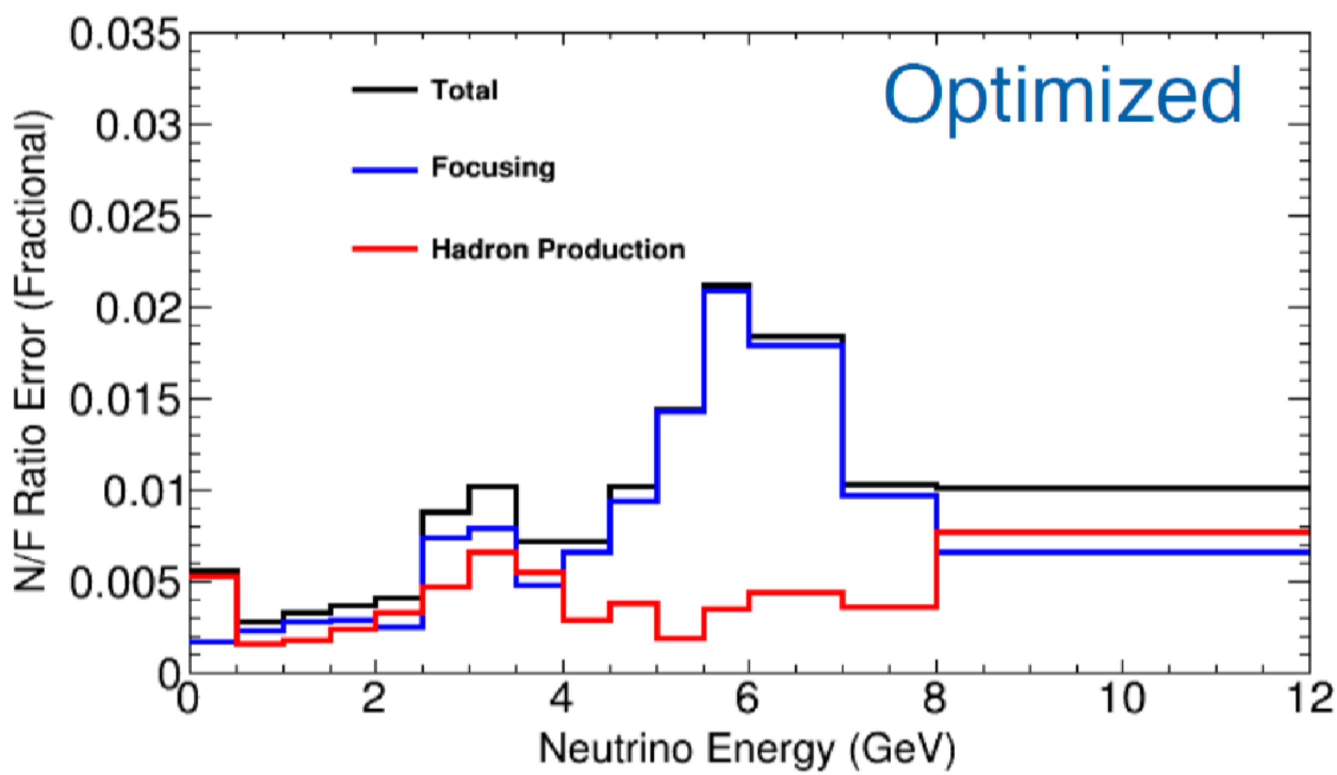
Relative efficiency of the cut $\nu < \nu_0$ in DUNE ND
reconstruction efficiencies not included (typically $> 90\%$)





Cut	$\nu < 0.25$ *GeV*	$\nu < 0.50$ *GeV*
$\langle \varepsilon \rangle$	*9%*	*19%*

Cut	$\nu < 0.25$ *GeV*	$\nu < 0.50$ *GeV*
$\langle \varepsilon \rangle$	*11%*	*22%*


Optimized
Total
Focusing
Hadron Production
N/F Ratio Error (Fractional)
Neutrino Energy (GeV)
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0
2
4
6
8
10
12