Overview and Performance of STT

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STT OFFERS A UNIQUE TRACKER DESIGN

✦ *All neutrino detectors face major tension (compromise):*

- *Target mass large enough to achieve good statistical accuracy of exclusive processes;*
- *High resolutions needed for precise measurements of event topologies.*

✦ *STT offers a novel solution:*

- *Physically separate target mass from tracking (negligible mass) to precisely control target(s);*
- *Spread out uniformly target mass throughout the tracking volume keeping STT length* $\sim 1X_0$*;*
- *Optimize target material and use it for particle identification (transition radiation).*

✦ *Modular design (flexible):*

- *Vary target mass by removing/adding radiator foils –* $\sim 83\%$ *(95%) of STT mass – with average density ranging from 0.017 (0.005)* g/cm^3 *to 0.10* g/cm^3*;*
- *Can accomodate a variety of dedicated thin (*$< 0.1X_0$*) 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

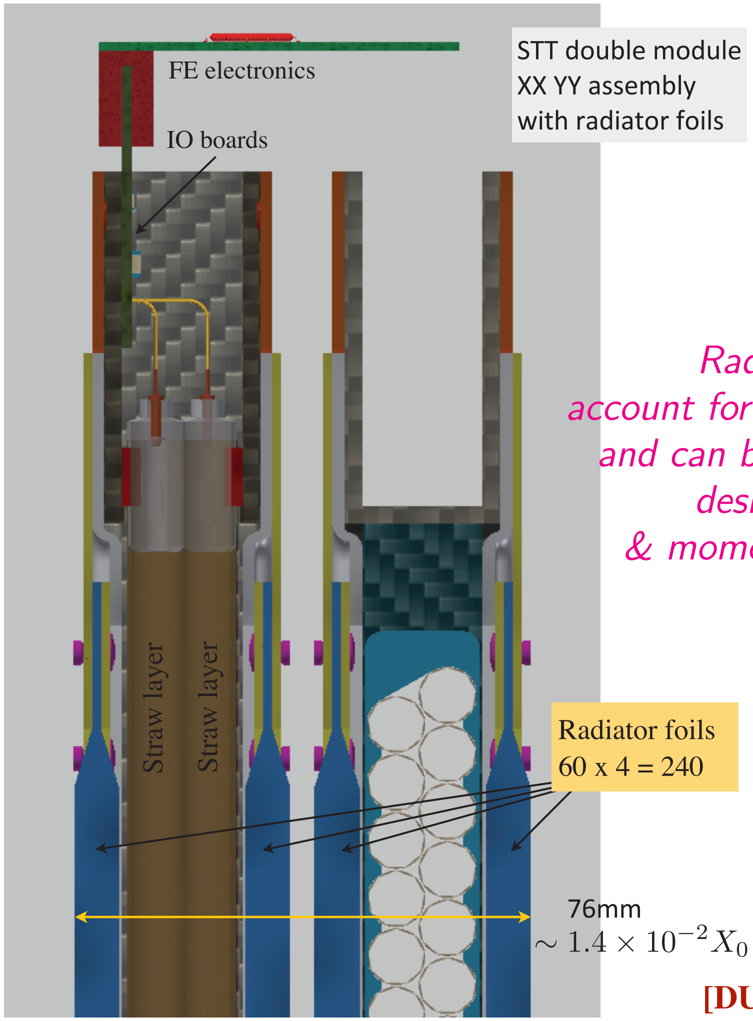
- ✦ Excellent angular, momentum & timing resolution:
  - Low density design for precise tracking;
  - $\delta\theta \sim$ 1-2 mrad, $\delta p/p \sim 3.5\%$, momentum scale uncertainty $< 0.2\%$;
  - Time resolution $\sim 1ns$, can resolve beam structure & withstand high rates (max. drift $\sim$ 125 ns).

- ✦ e^+/e^- & other particle ID over the entire tracking volume:
  - Electron ID with Transition Radiation (TR) and dE/dx $\Longrightarrow$ π rejection $\sim 10^{-3}$;
  - 4π detection of π^0 from γ conversions ($\sim 50\%$) within the STT volume;
  - $\pi/K/p$ ID with dE/dx and range.

- ✦ Low A target material:
  - Polypropylene radiators $(C_3H_6)_n$ with high chemical purity $\Longrightarrow$ H content (free proton);
  - Reduced systematic uncertainties from nuclear effects.

- ✦ Suite of different nuclear targets:
  - Ar and Ca targets to characterize $A = 40$ nucleus & C (graphite) target for H measurement;
  - Direct measurement of nuclear effects and constraints on nuclear response (smearing) function.

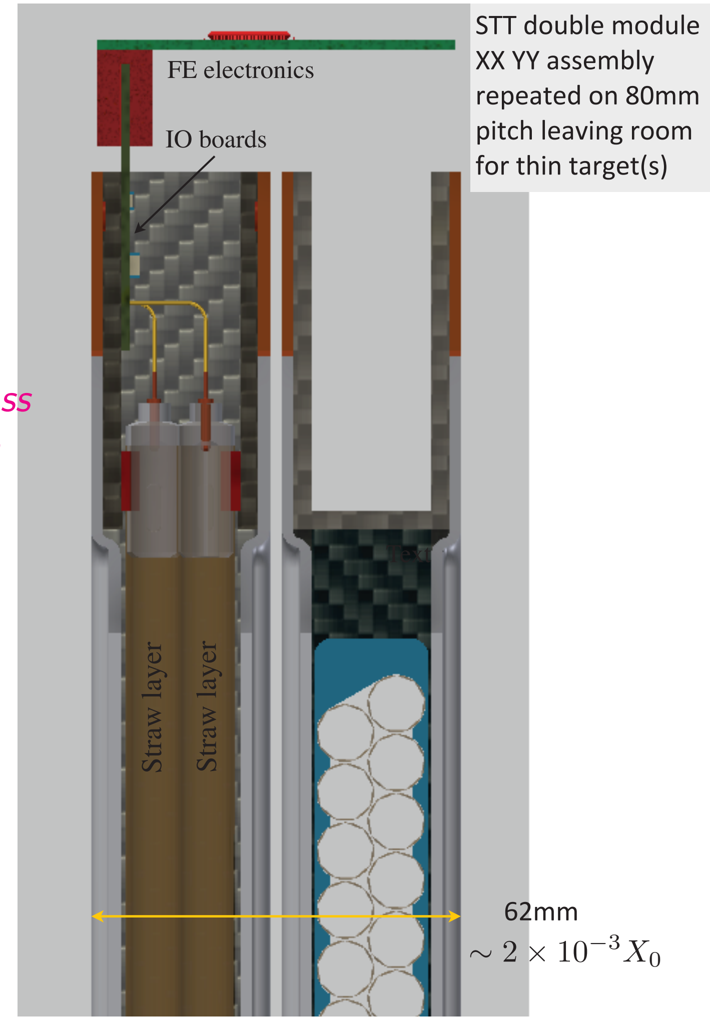
STT module with radiators



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

[DUNE CDR Volume 4]

STT module for nuclear targets



INNOVATIVE APPLICATION OF PROVEN TECHNOLOGY

✦ *STT based upon proven detector concept and technology:*

- *Improve upon the successful NOMAD concept of a low density spectrometer – $\rho = 0.1$ g/cm^3, $B = 0.4T$ – as neutrino target;*
- *Design/geometry of straws & mechanical layout after COMPASS straw tracker (2004-date)*
- *Combine tracking & particle identification in the same detector based upon the compact ATLAS TRT design (2006-date).*

✦ *Many modern detectors for precision physics use straw trackers:*

- *SHIP detector at CERN with straws 5.5m long, 9.8mm diameter (wall 20 μm, hit res. 120 μm);*
  $\Longrightarrow$ *Factor ~ 2 improvement on STT single hit resolution with respect to CDR value (200 μm)*
- *Mu2e detector at Fermilab with 5mm diameter straws (wall 15 μm).*

✦ *New technology available using ultrasonic welding instead of winding for straws:*

- *Used for modern detectors NA62, COMET, SHIP, Mu2e;*
- *Reduction of straw mass by factor > 3 with respect to CDR: wall thickness 70 μm $\longrightarrow$ 20 μm;*
  $\Longrightarrow$ *Density of STT without radiators 0.005 g/cm^3 and radiators give 95% of total STT mass*
- *Reduced cost of straw fabrication and straw materials.*

HISTORICAL OVERVIEW

- ✦ 2008:
  Proposal of STT as part of new detector for precision physics at Project X
- ✦ 2009: *LBNE*
  STT/FGT as high resolution ND for the LBNE project
- ✦ 2012:
  Detailed Project Report (DPR) & proposal to Indian DAE/DST
  to fund FGT and the corresponding R&D activity within the LBNE project
- ✦ 2013:
  Proposal for a 3 year R&D plan for FGT submitted to Indian DAE
- ✦ 2014:
  Proposal for R&D efforts for FGT submitted to Indian DST
- ✦ 2009-2015:
  STT conceptual design (USC)
  Mechanical engineering & system integration (LANL, USC)
  Simulation & sensitivity studies (USC, Indian institutions)
  Cost & schedule RLS (LANL, USC)
  Project management (LANL)
  R&D activities (Indian institutions, USC, Dubna)
- ✦ 2015: *LBNE ⟶ DUNE*
  Independent technical design review of the DUNE near detector conceptual design
  Directors CD-1 refresh review of LBNF/DUNE
  DOE/SC CD-1 review of LBNF/DUNE project
- ✦ 2016-2017:
  ND Task Force (TF) and G4 simulation of complete detector geometry
  ND concept study and detector performance

OUTCOME OF STT EXTERNAL REVIEWS

- *Independent technical design review of the DUNE near detector conceptual design (Fermilab, 28-29 May 2015)*

  Excerpts from the final report:

  "The reference design of a straw based system is a good choice and appears likely to satisfy the primary physics goals. Many components have been demonstrated in other experiments. This alleviates many risks. The design is mature enough to move from the conceptual design to the preliminary design phase."

  "[...] an excellent team is in place to design and construct this detector." (Recommendations: none)

- *Director's CD-1 refresh review of LBNF/DUNE (Fermilab, 2-4 June 2015)*

  Excerpts from the closeout report:

  "The near detector plan presented appears to be well organized and advanced."

- *DOE/SC CD-1 review of LBNF/DUNE project (Fermilab, 14-16 July 2015)*

  Excerpts from the closeout report:

  "The near detector uses well validated detection techniques and its design is therefore rather advanced. **Its standalone physics program is strong***."*

STT R&D ACTIVITIES

- *R&D activities performed:*
  - *3D engineering model of STT and R&D prototypes (PU,LANL,USC);*
  - *FEM analysis of mechanical structure and R&D ptototypes (PU);*
  - *Procurement of detector components, tooling, and testing facility (PU, Dubna);*
  - *Test of detector components and small straw chamber (PU, Dubna);*
  - *Readout electronics design (BARC).*

- *Main aspects to be studied to optimize/finalize the STT design:*
  - *Mechanical structure of STT modules and assembly;*
  - *Nuclear targets and radiators, integration with STT modules;*
  - *Readout electronics (common to ND complex), gas system, cooling, etc.*

- *R&D activities planned:*
  - *Build small scale prototype 1.8m × 0.6m with 2 straw layers;*
  - *Build half scale prototype 1.8m × 1.8m with 4 straw layers XX+YY;*
  - *Build full scale prototype with 4 straw layers XX+YY;*
  - *Laboratory test and test-beam exposure of STT prototypes;*
  - *Design, integration and prototyping of nuclear targets & radiators;*
  - *Readout prototypes and testing.*

STT answers to questions from the 3^{rd} ND Workshop

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Abstract

The Straw Tube Tracker (STT) has been part of the reference Near Detector (ND) for the DUNE experiment, as described in details in the DUNE conceptual design report. In this document we summarize the unique features offered by the STT design, as well as the corresponding key detector performance. In particular, we outline the STT answers to the questions related to the ND tracking performance emerged from the 3^{rd} ND workshop at CERN.

Write-up with detailed answers to questions available in INDICO

QUESTIONS FROM $3^{\rm rd}$ ND WORKSHOP

- ✓ *What is the tracking efficiency as a function of track angle, especially when the track is along the wire in the case of the STT?*
  $\Longrightarrow$ *Answered in slides 11-13.*
- ✓ *What is the energy threshold for detecting p/π and how important is this to reduce systematics?*
  $\Longrightarrow$ *Answered in slide 14.*
- ✓ *Momentum/angular resolution of all particles*
  $\Longrightarrow$ *Answered in slide 10.*
- ✓ π^0 *energy resolution and efficiency in neutrino interactions*
  $\Longrightarrow$ *Answered in slides 16-17.*
- ✓ *What are the uncertainties in energy scale for e/μ?*
  $\Longrightarrow$ *Answered in slide 15.*
- ✓ *What are the uncertainties in angular resolution?*
  $\Longrightarrow$ *Answered in slide 10. Dominated by multiple scattering.*
- ✓ *What are the key performance parameters for the ECAL to detect NC π^0?*
  $\Longrightarrow$ *Answered in slide 17. Relying mainly on STT.*
- ✓ *Can neutrons be detected in the tracker?*
  $\Longrightarrow$ *Answered in slides 18-20.*
- ✓ *What is the expected performance for key channels (see appendix A) including yields?*
  $\Longrightarrow$ *Answered in slides 22-38 for all channels.*

ANGULAR DEPENDENCE

- *NOMAD used a planar design with drift distance $d = 3.2$ cm $\perp$ to the beam direction*

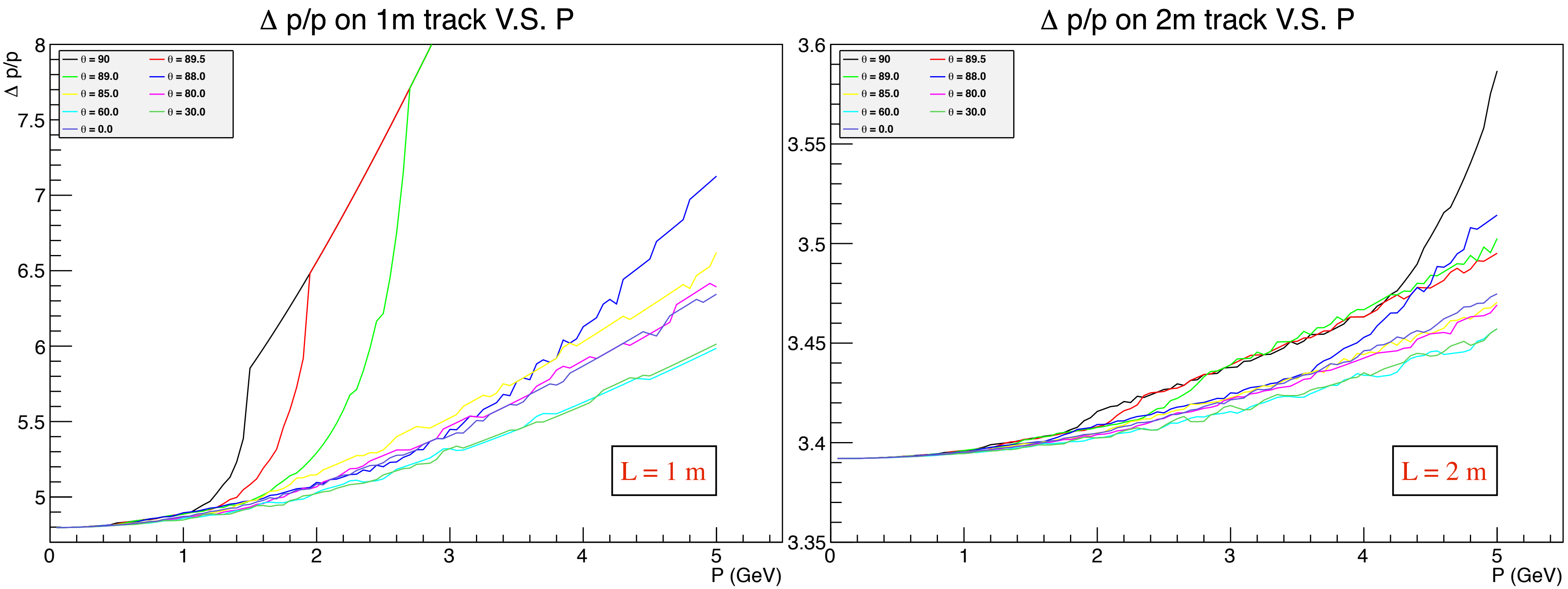
  $\Longrightarrow$ *Significant variation of space resolution with angle*

- *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;*
  - *Estimated with MC by counting hits along track helix and using parameterized resolutions.*

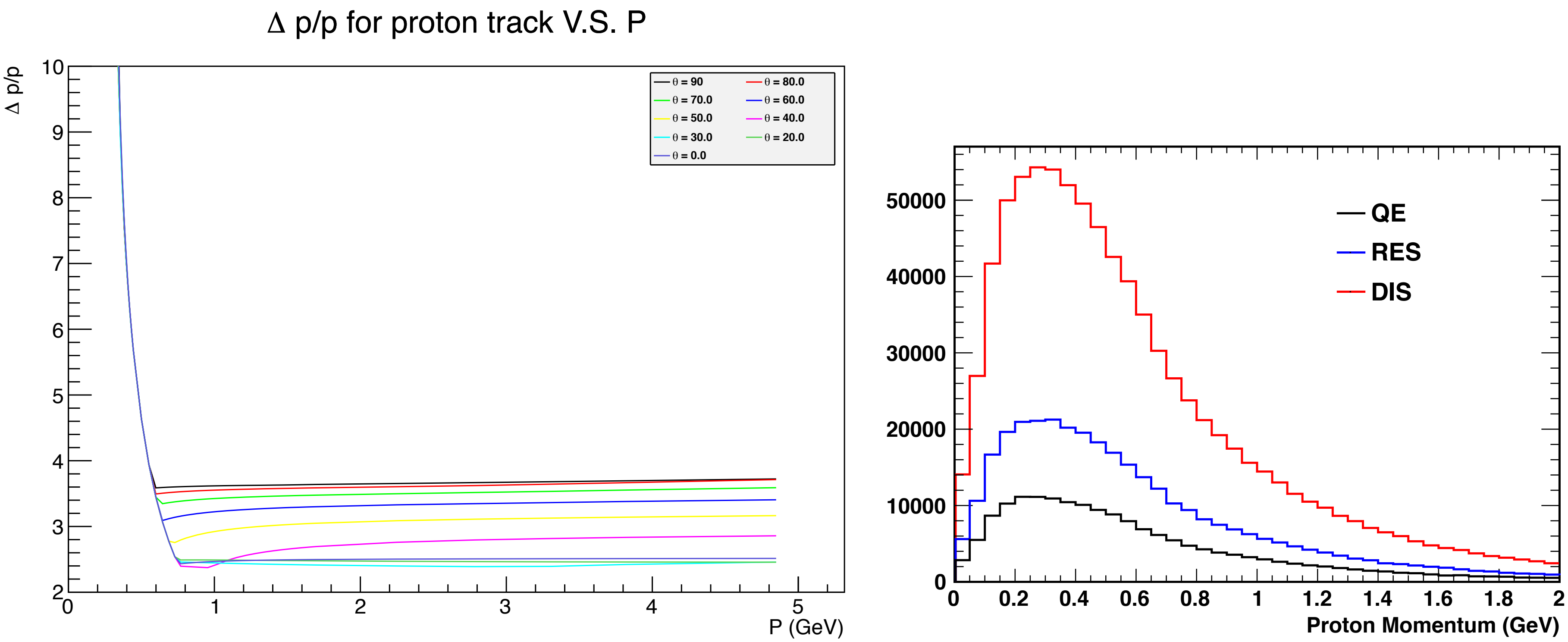
  $\Longrightarrow$ *Significant effect only for high energy tracks close to 90 deg*



Δ p/p on 1m track V.S. P

Δ p/p on 2m track V.S. P

Momentum resolution for pions/muons at different angles w.r.t. the beam



Momentum resolution for protons at different angles w.r.t. the beam

DETECTION THRESHOLDS

✦ $\boxed{\text{p}}$:

- *Threshold for momentum measurement:* $p \sim 200$ *MeV (KE=21 MeV);*
- *Detection threshold from hits/energy in straws (dE/dx):* $p \sim 85$ *MeV (KE=4 MeV).*

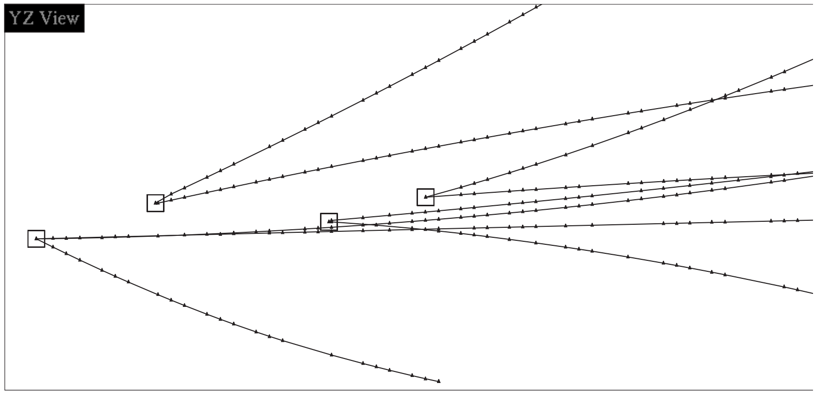
✦ $\boxed{\mu/\pi}$:

- *Threshold for momentum measurement:* $p \sim 40/50$ *MeV;*
- *Detection threshold from hits/energy in straws (dE/dx):* $p \sim 30/35$ *MeV.*

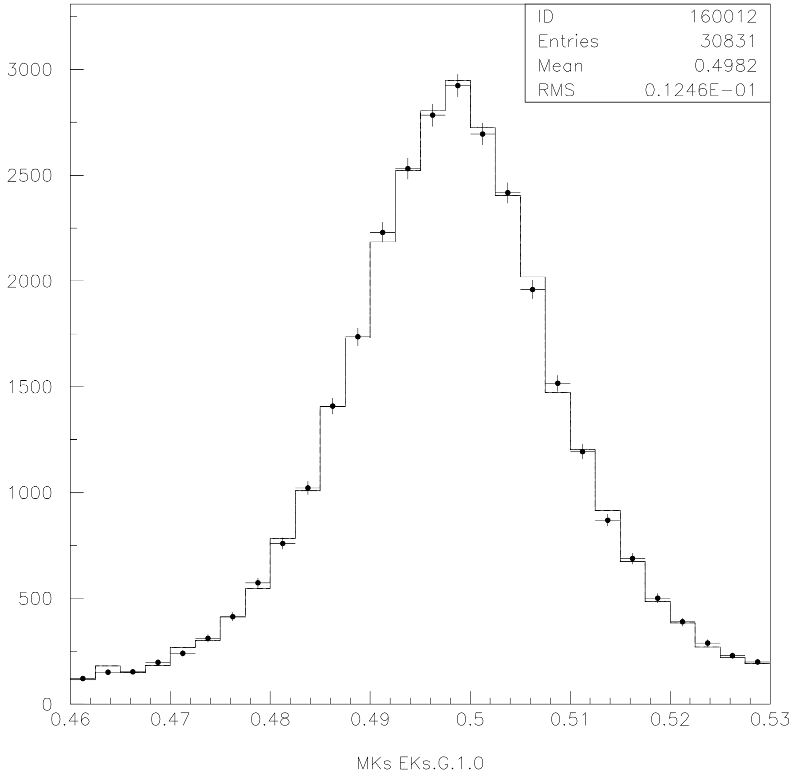
✦ $\boxed{e^{\pm}}$:

- *Threshold for momentum measurement:* $p \sim 80$ *MeV;*

ENERGY SCALE UNCERTAINTY



Use mass constraint from reconstructed K^0 to define momentum scale of tracks



Reconstructed K^0 mass

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

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.

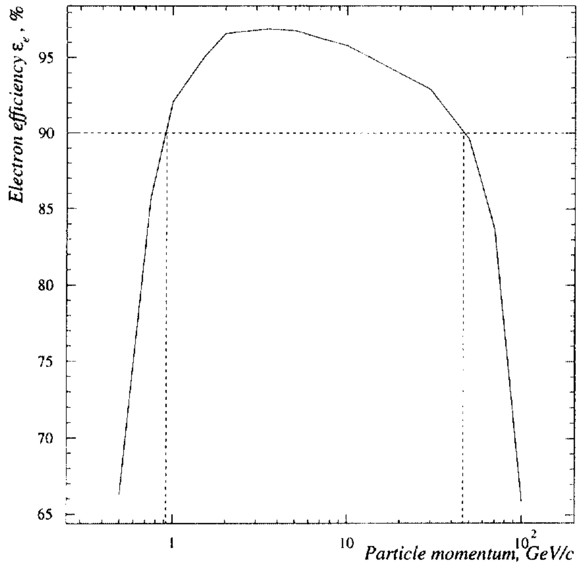
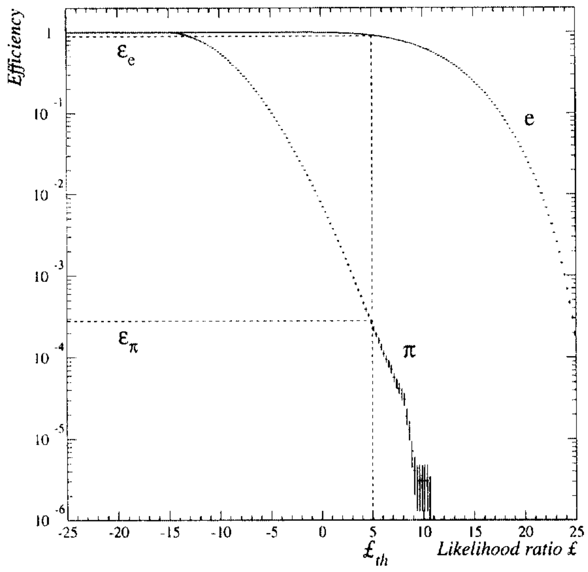


Fig. 8. Monte Carlo predicted electron efficiency ε_e corresponding to $\varepsilon_\pi = 10^{-3}$ as a function of the momentum of the particle

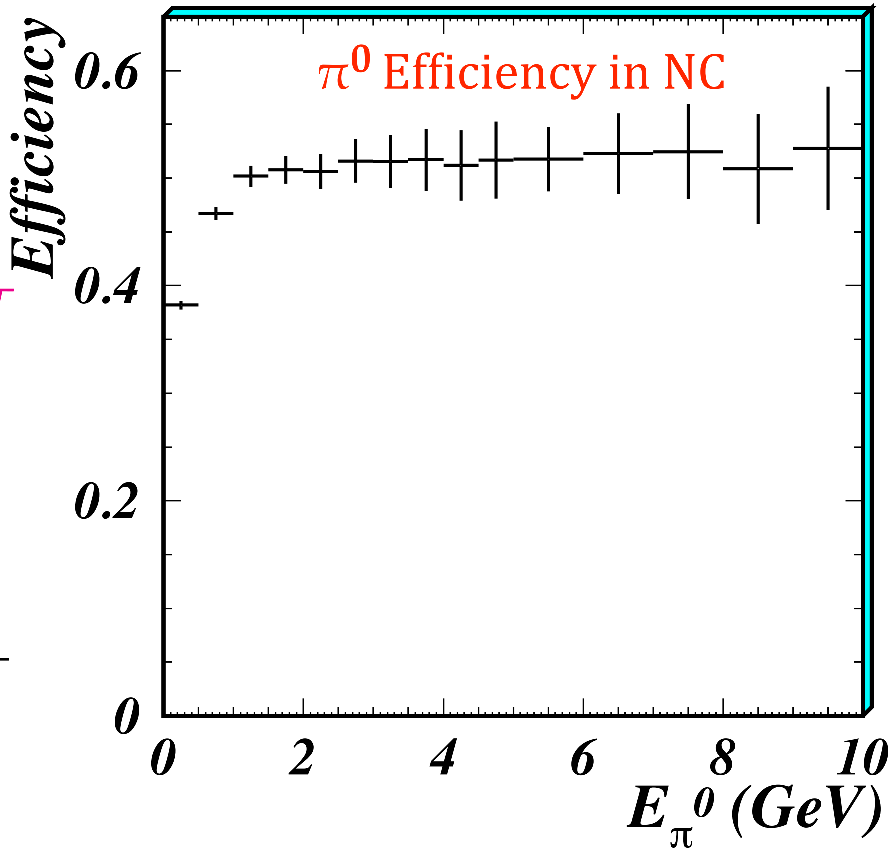


- ✦ *Clean γ ID in STT (4π):*
  - $e^{\pm}$ ID from TR+dE/dx;
  - Kinematic cuts: mass, opening angle.

- ✦ *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.

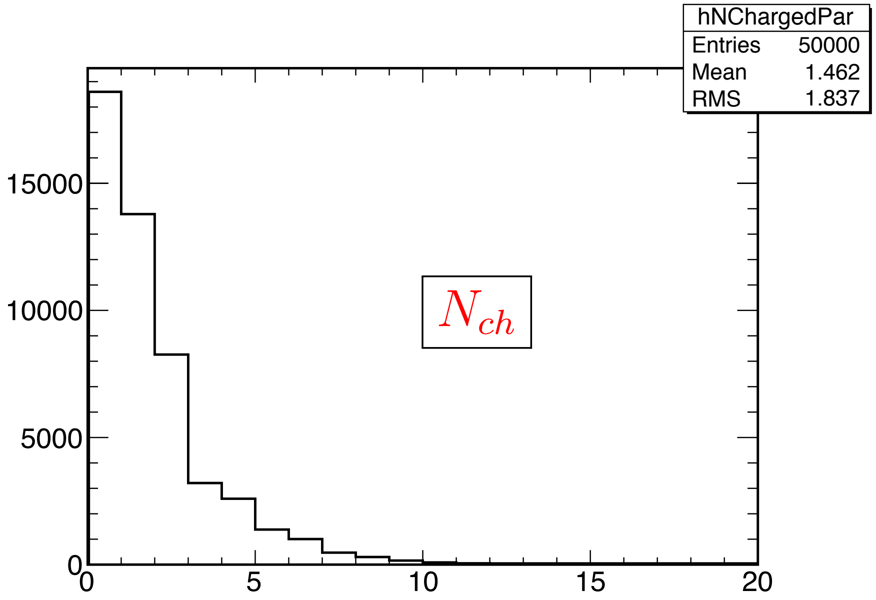
$\Longrightarrow$ *Less stringent requirements on ECAL*

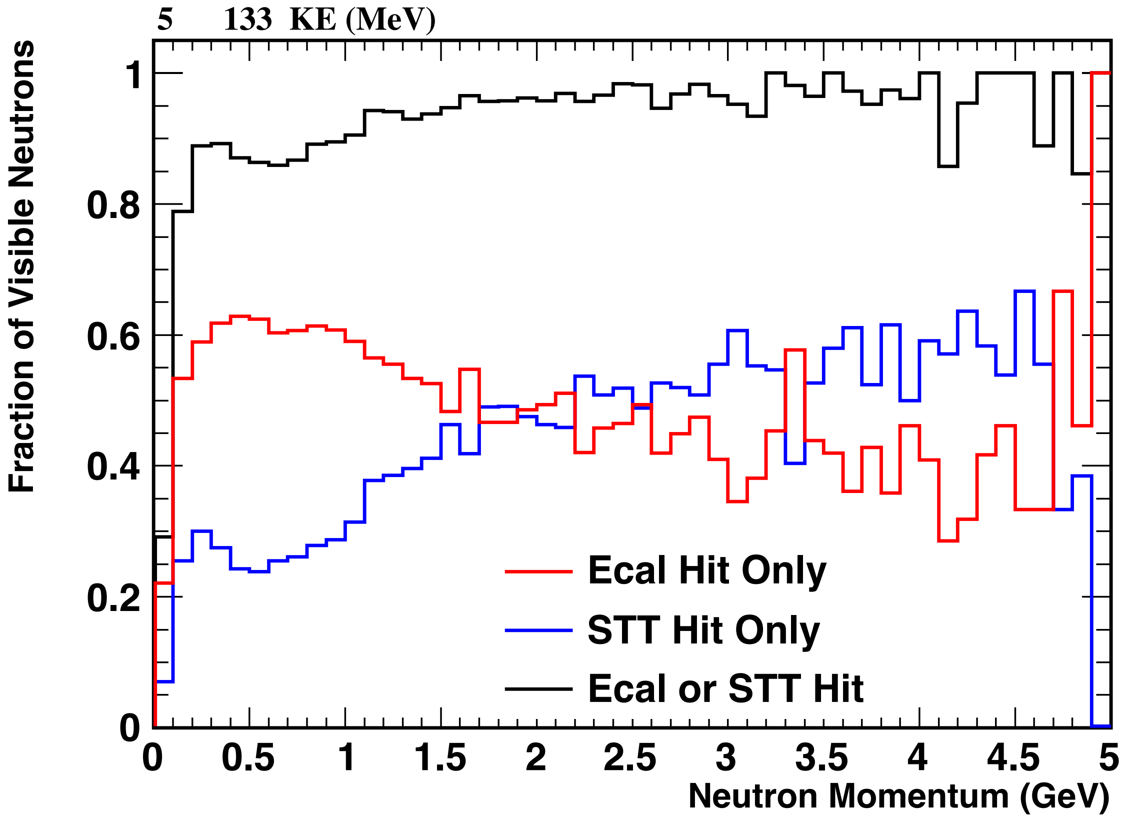
- ✦ *Measure the π^0/γ background for the ν_e appearance analysis vs. E_ν, E_π, P_T*



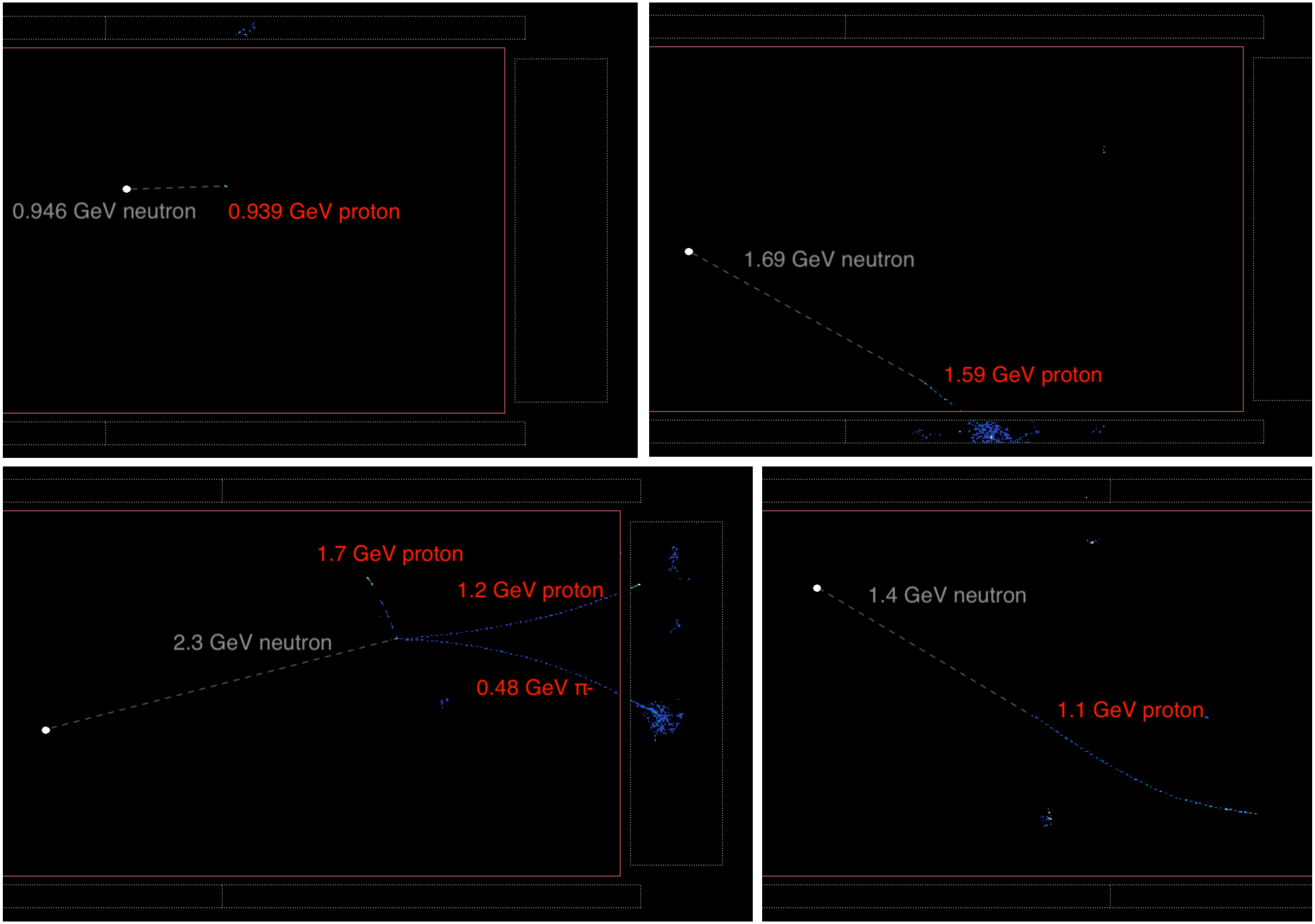
NEUTRON DETECTION

- *Use G4 simulation from TF with complete detector geometry (help by Tyler Alion)*
- *Generate neutrons with 2D (E,θ) distribution from inclusive ν_μ CC events*
- *Smearing and detection thresholds:* $N_{\rm HIT} \geq 1$ *in STT and* $E_{\rm rec} > 50$ *MeV in ECAL*
- *63% of n interactions detected "star" secondary vertices ($N_{\rm ch} \geq 2$), 37% single visible proton*

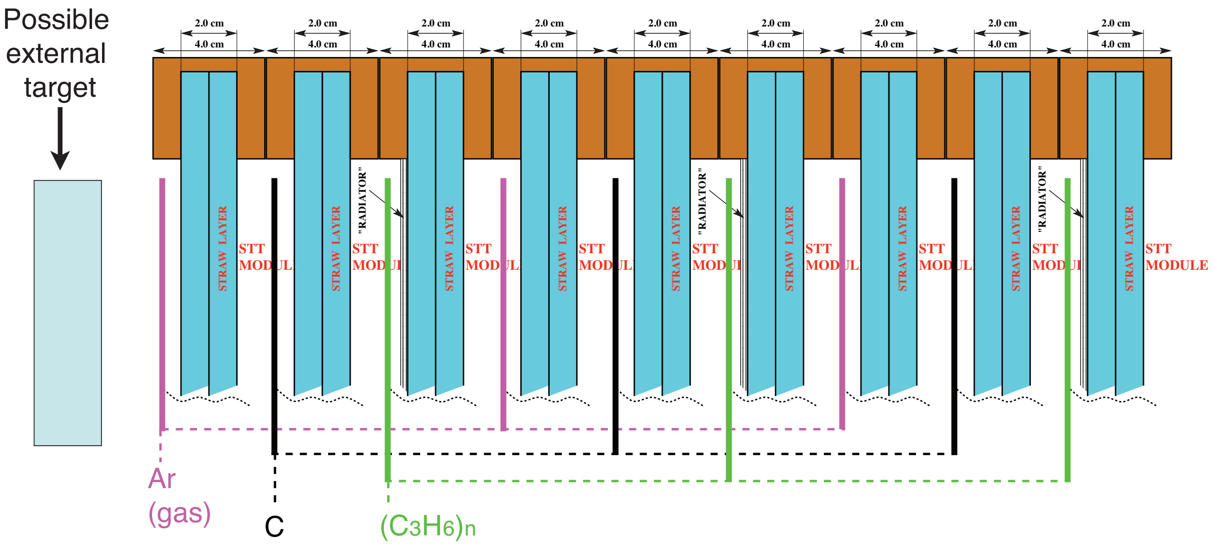




Average fractions of n detected: 31% in STT, 58% in ECAL (89% total)


0.946 GeV neutron
0.939 GeV proton
1.69 GeV neutron
1.59 GeV proton
1.7 GeV proton
1.2 GeV proton
2.3 GeV neutron
0.48 GeV π-
1.4 GeV neutron
1.1 GeV proton

NUCLEAR TARGETS IN STT



- ✦ *Multiple nuclear targets in FGT: $(C_3H_6)_n$ radiators, C, Ar gas, Ca, Fe, etc.*
  $\Longrightarrow$ *Separation from vertex ($\sim 100\mu m$), angular (< 2mrad) & time ($1ns$) resolutions*

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

- ✦ *In addition to the* LAr/GAr TARGET, *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 EXPECTED IN STT

- *Number of events for the key processes in default 5 tons radiator FV* ($\rho \sim 0.1$ g/cm^3) *with the 3 horn optimized beam (1.07 MW, 80 GeV, 1.47 $\times 10^{21}$ pot/year):*

Process	FHC (ν mode 5y)	RHC ($\bar{\nu}$ mode 5y)
ν_μ CC	36,762,200	2,540,860
$\bar{\nu}_\mu$ CC	750,380	11,350,200
ν_e CC	450,685	126,365
$\bar{\nu}_e$ CC	46,350	125,618
ν-e elastic	4,851	3,271
Coherent π^+	363,759	21,138
Coherent π^-	13,565	301,134
ν_μ CC $\nu < 0.25$ GeV	3,308,598	228,677
$\bar{\nu}_\mu$ CC $\nu < 0.25$ GeV	82,542	1,248,522
$\nu_\mu(\bar{\nu}_\mu)$ CC on H	3,410,000	2,760,000

714 kg
of H in FV!

- *For same tracking volume STT has 5.9 times the target mass as HPArTPC at 10 atm*

- *Density of STT without radiators similar to HPArTPC at 3 atm:* $\rho \sim 0.005$ g/cm^3

DO WE NEED Ar IN STT/MPT?

✦ *All flux measurements prefer/benefit from targets much lighter than Ar:*

- *Absolute ν_μ flux from ν-e elastic scattering;*
- *Relative ν_μ flux vs. E_ν from low-ν, ν-e elastic, and $\nu(\bar{\nu})$ scattering on H;*
- *$\bar{\nu}_\mu/\nu_\mu$ 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.*

✦ *Once the fluxes are precisely measured using lighter targets, the cross-sections on Ar can be measured with the large statistics from the LAr detector*

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

✦ *The only case for an Ar target inside STT/MPT is to measure nuclear effects and to constrain the nuclear response (smearing) function*

- *Require different nuclear targets to unfold the detector response: Ar alone not enough!*
- *Sufficient a relatively small target mass of Ar;*
- *Two possible options for STT: passive high pressure Ar gas (CDR), small active Ar target upstream;*
- *Use of Ca target in STT with $A = 40$.*

$\nu(\bar{\nu})$-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;*
- *In-situ measurement of backgrounds* $\Longrightarrow$ *reduced systematics.*

✦ *Determination of ν_μ energy spectrum from template fit to the 2D distribution (θ_e, E_e) of the measured electron.*

$\Longrightarrow$ *Combined analysis of LAr+STT to make optimal use of all available statistics*

✦ *STT crucial impact on the combined LAr+STT analysis:*

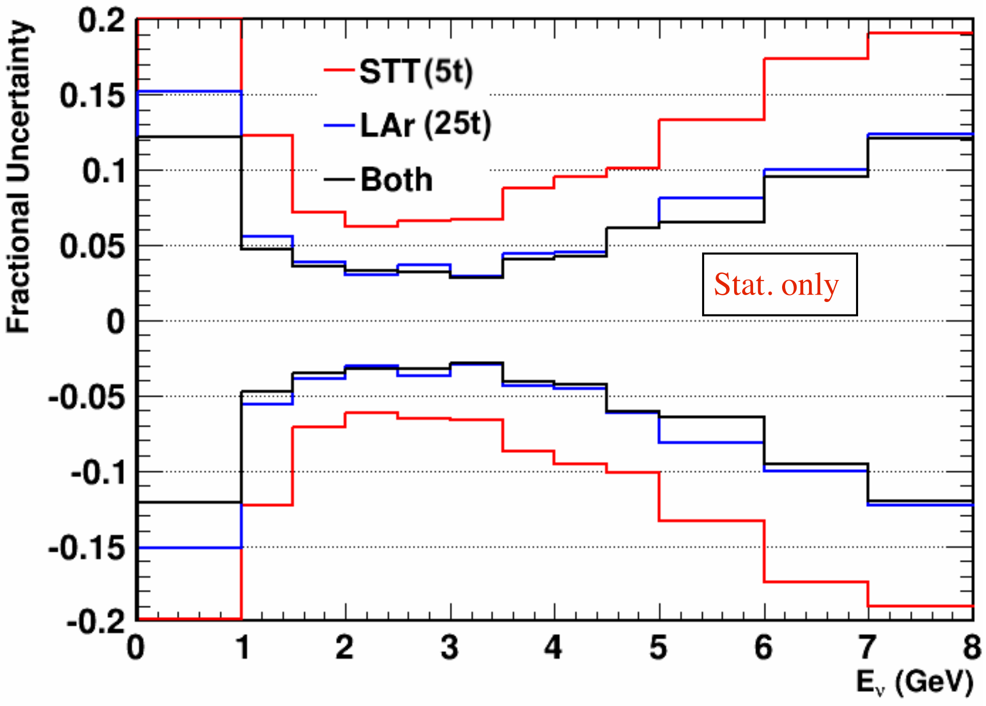
- $\boxed{\text{STT sample}}$: *statistics dominated, small bkgnd, in-situ measurement of bkgnd;*
- $\boxed{\text{LAr sample}}$: *systematics dominated, larger bkgnd, total stat+sys uncertainty $\geq$ STT.*

- ✦ *LAr cuts & assumptions from C. Marshall*

- ✦ *Backgrounds:*
  - ν_e *CC quasi-elastic (dominant)*
  - *NC single* π^0

- ✦ *Signal events with* $E\theta^2$ *cut (same* ε*): 11,933 in LAr and 4,079 in STT*

- ✦ *Different bkgnd levels:*
  - *STT:* $\sim 5\%$ *total (3% QE, 2% NC)*
  - *LAr:* $\sim 14\%$ *total (11% QE, 3% NC)*



Without systematic uncertainties 25t LAr significantly better than 5t STT

- ✦ *Impact of ν-e rate constraint larger than shape only (see C. Marshall & C. Wilkinson)*

- ✦ *Measurement in LAr will be dominated by systematics given the statistical accuracy:*
  - *Realistic LAr systematics require dedicated analysis;*
  - *LAr systematics larger than STT ones: ×10 less sampling, ×15 higher density, heavier target nucleus.*

Detector	*Signal events*	$\delta_{\text{stat.}}$	$\delta_{\text{sys.}}$	δ_{tot}
STT (5t)	*4,079*	*1.6%*	*1.0%*	**1.9%**
LAr (25t)	*11,933*	*0.9%*		

With DUNEprism
LAr ∼ 7,000 evts.

- ✦ *MINERνA systematics: ν_e QE 3.1%, electron efficiency 2.7%, energy scale 1.8%*
  NOνA analysis has uncertainties not too different from MINERνA

  $\Longrightarrow$ *With realistic systematics STT comparable or better sensitivity than LAr*

- ✦ *STT offers precise in-situ constraints on background (and signal) systematics:*
  - *NC π^0 background from wrong sign e^+ analysis;*
  - *Uncertainty from nuclear effects (dominant in LAr) from measurements on H (free proton).*

  $\Longrightarrow$ *Use of STT can lower LAr systematics and further improve combined fit*

LOW-ν RELATIVE FLUX

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

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

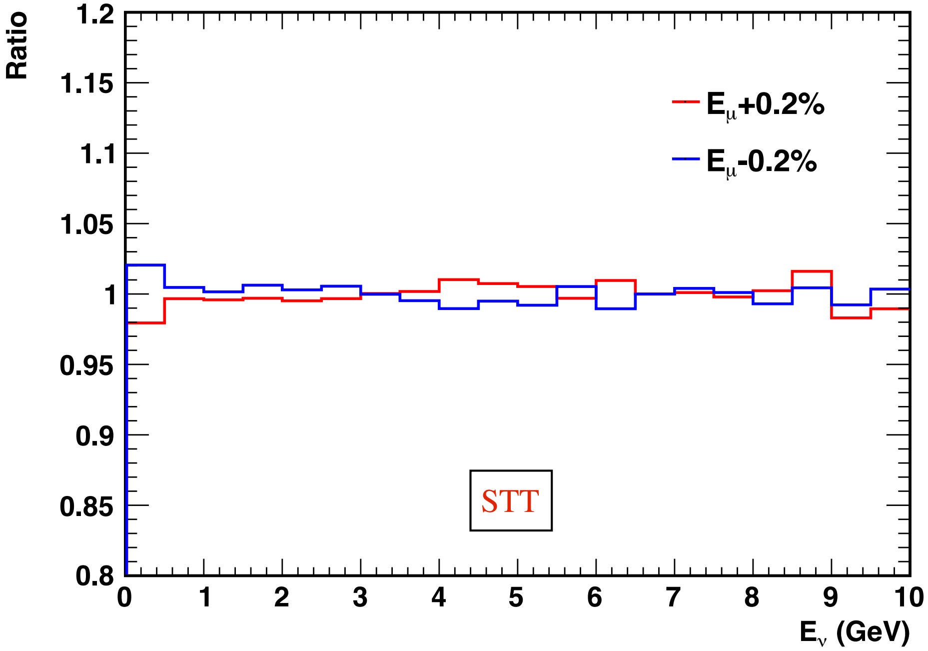
- *Measurement of the relative bin-to-bin $\nu_\mu(\bar{\nu}_\mu)$ flux vs. energy in ND;*
- *Extrapolation of flux spectra to FD/ND(E) ratio by extracting parent meson distributions.*

✦ *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.*

✦ *In-situ constraints of neutron production with STT:*

- *Use kinematics in transverse plane (p_T) to reduce neutron impact;*
- *Constrain production of primary neutrons with exclusive resonance production;*
- *Calibrate neutrons with detected neutron interactions in STT ($\sim 31\%$).*


Ratio
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1.1
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0.9
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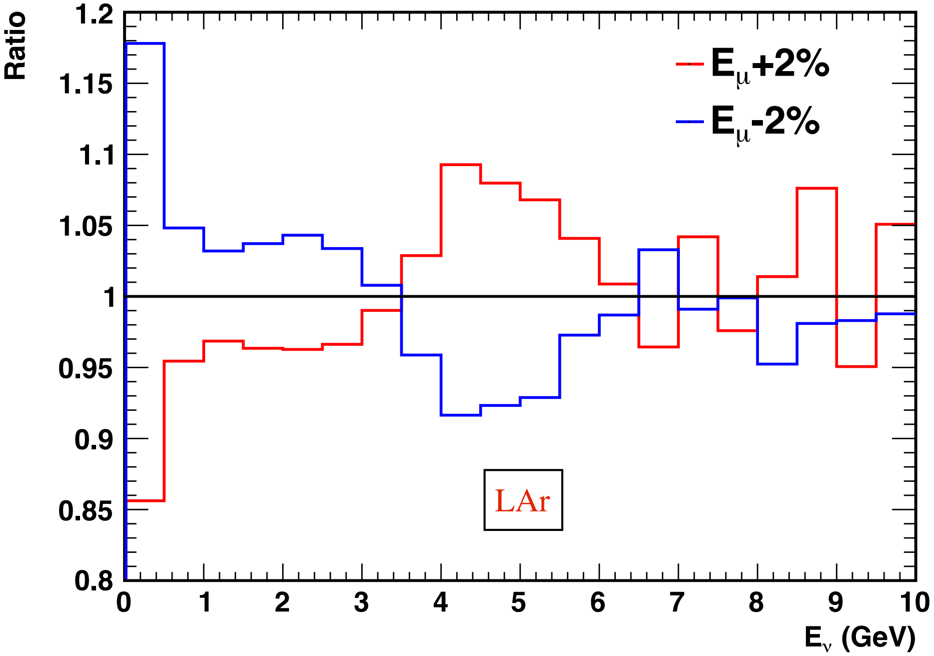
10
E_ν (GeV)
E_μ+0.2%
E_μ-0.2%
STT


Ratio
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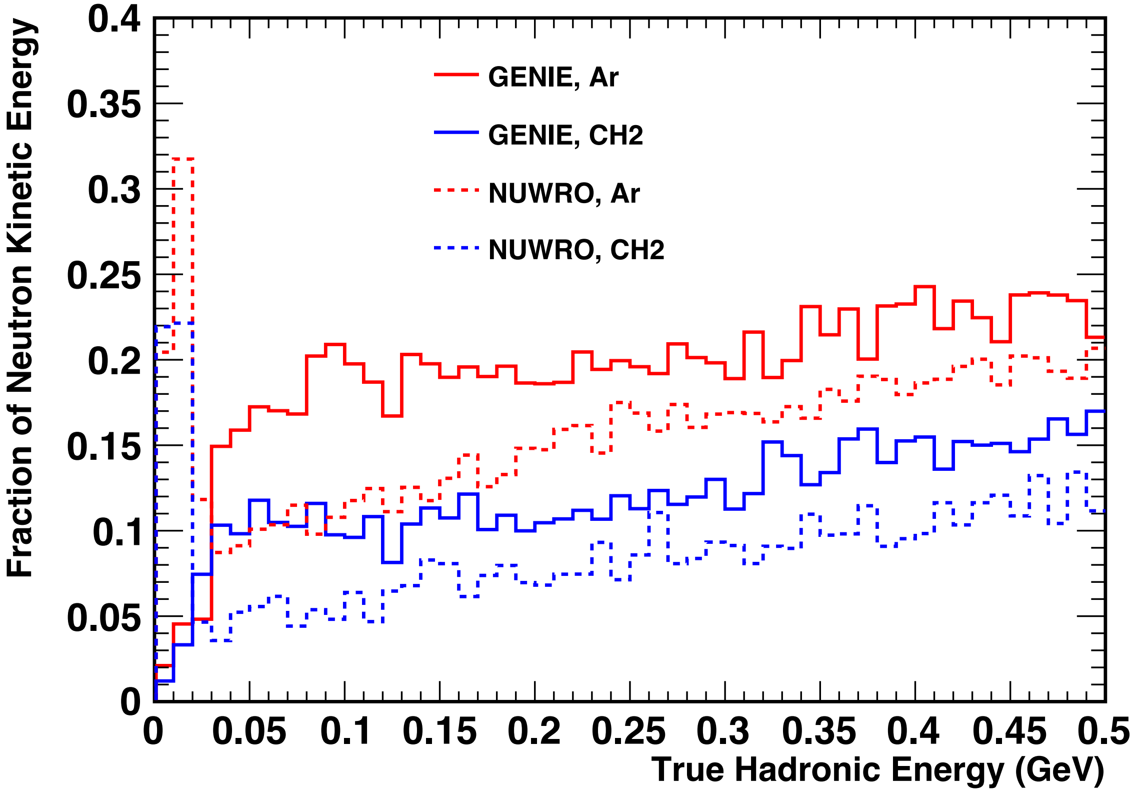
E_ν (GeV)
E_μ+2%
E_μ-2%
LAr



Ar not a good target for low-ν!

Fraction of neutrons detected in STT 31%, in ECAL 58% (total 89%)

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

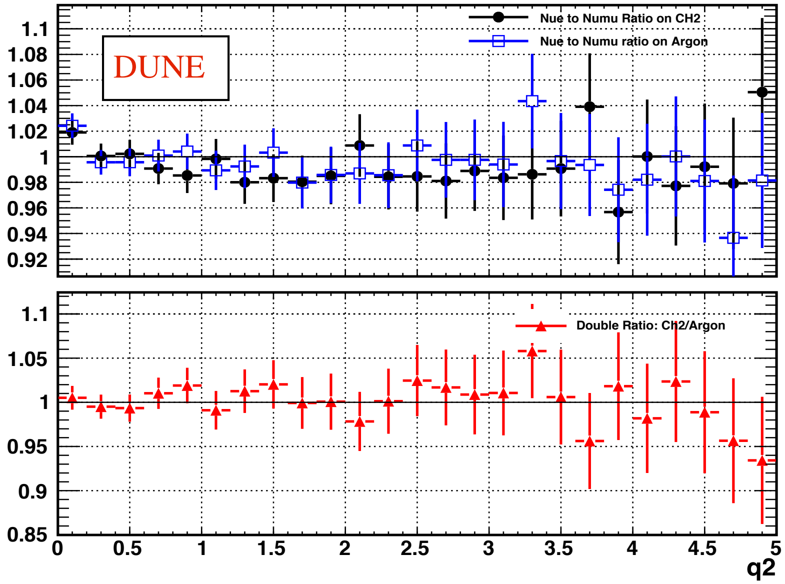
✦ *Simultaneous fit to $\nu_\mu(\bar{\nu}_\mu)$ disappearance AND $\nu_e(\bar{\nu}_e)$ appearance samples in FD*
$\Longrightarrow$ *Key quantities to constrain are RATIOS ν_e/ν_μ & $\bar{\nu}_e/\bar{\nu}_\mu$*

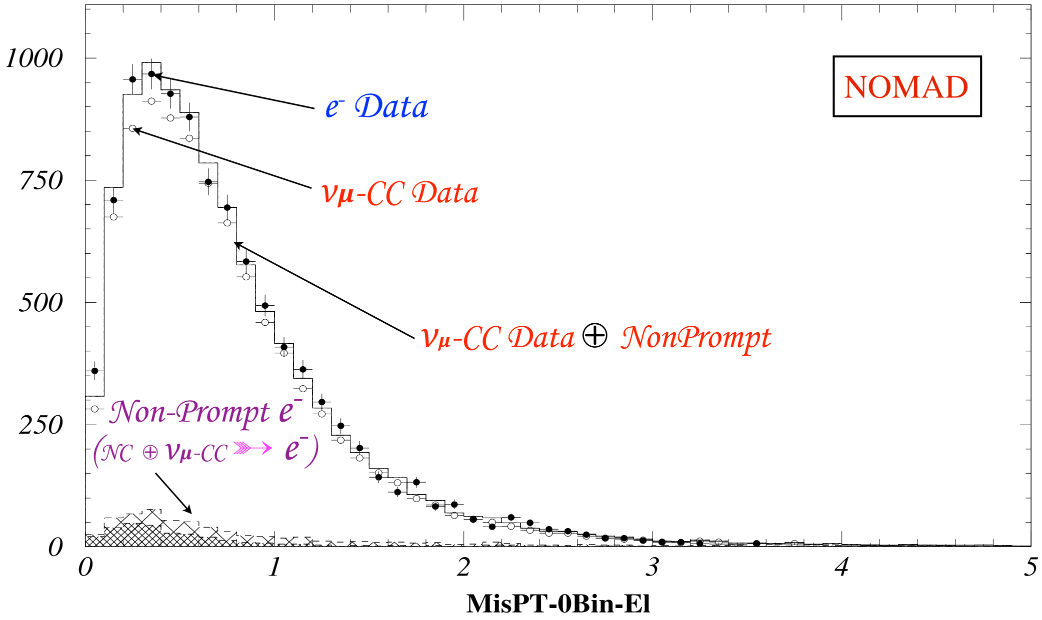
✦ *Nuclear effects cancel out in the ratios ν_e/ν_μ & $\bar{\nu}_e/\bar{\nu}_\mu$, which can be measured with higher accuracy on light target materials.*

✦ *Benefits offered by STT:*

- *Excellent $e^\pm$ ID with TR & dE/dx 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.*

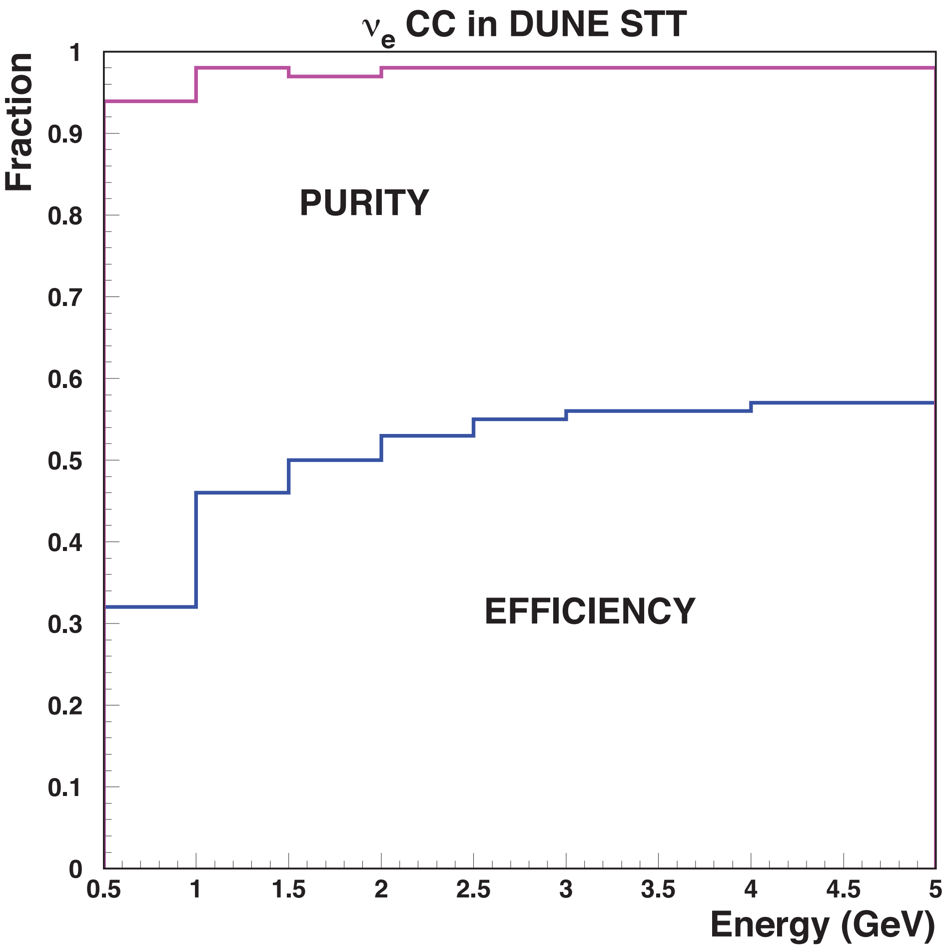
$\Longrightarrow$ *Measure ν_e CC with 55% efficiency and 98% purity in STT*
$\Longrightarrow$ *Measure $\bar{\nu}_e$ CC with 55% efficiency and 95% purity in STT*





ν_e/ν_μ in Ar and CH_2 in DUNE

e^-/μ^- universality in NOMAD



- ✦ *$e^{\pm}$ ID against charged hadrons from both TR & dE/dx*

  $\Longrightarrow$ *TR* π 10^{-3} *for* $\varepsilon \sim 90\%$

- ✦ *e/γ separation based upon $e^{\pm}$ tracks from conversion in STT*

- ✦ *Multivariate rejection of non-prompt backgrounds (π^0 in ν_μ CC and NC)*

COHERENT $\pi^{\pm}$ PRODUCTION

✦ *Coherent $\pi^{\pm}$ with minimal momentum transfer to nucleus $\mid t \mid < 0.05$ GeV²*

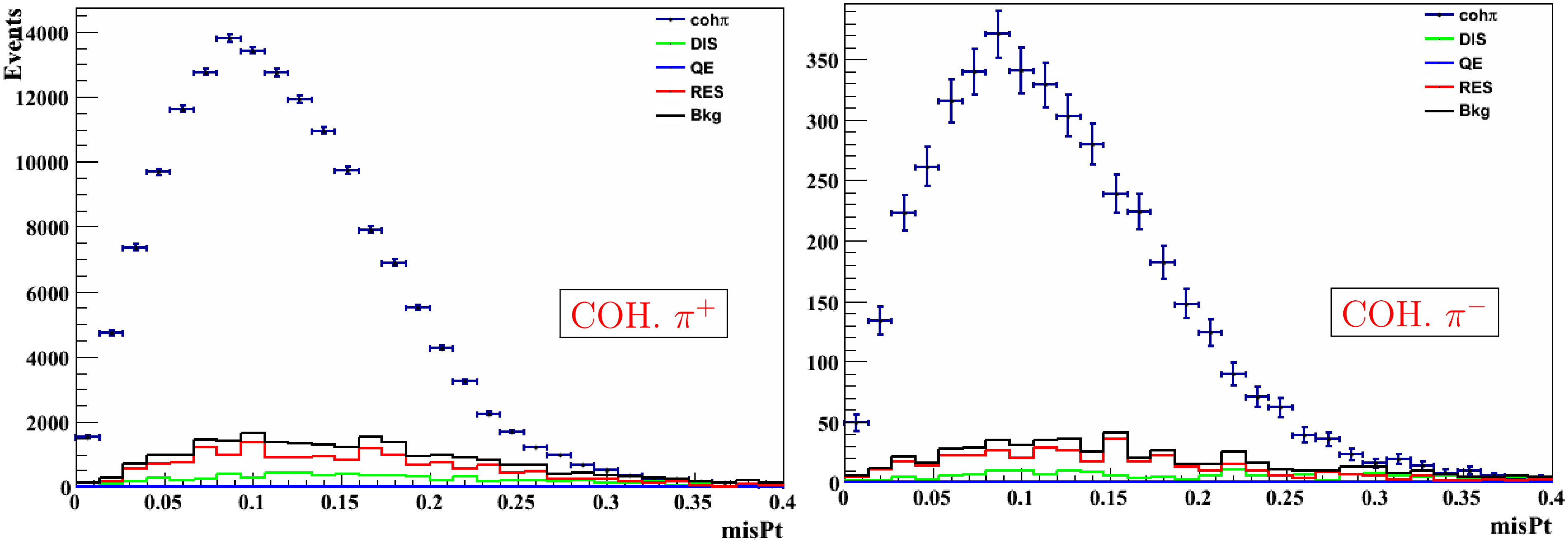
- *Small missing p_T and closest approximation to neutrino beam direction;*
- *Little nuclear effects compared to other channels.*

✦ *Benefits offered by STT:*

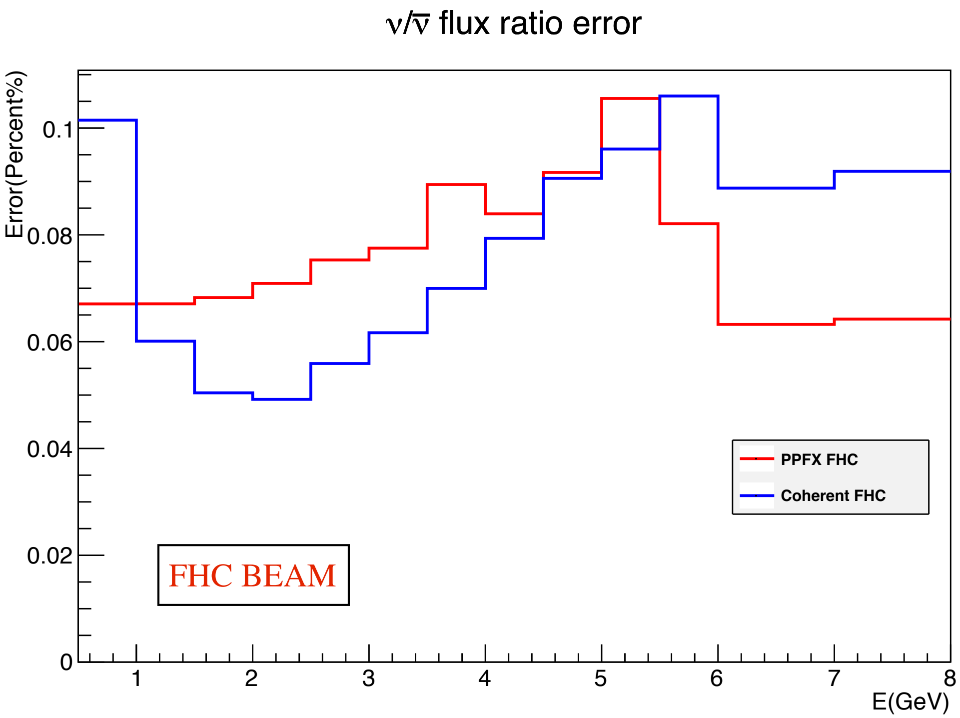
- *Light isoscalar target (C) reduces cross-section uncertainties;*
- *Statistics allowing an accurate measurement of $\bar{\nu}_\mu$ (coherent π^-);*
- *Excellent angular & momentum resolution (t resolution) for background rejection.*

✦ *Determine the flux ratio $\bar{\nu}_\mu / \nu_\mu$ vs. E_ν by using identical selection for $(\mu^- \pi^+)$ and $(\mu^+ \pi^-)$ & kinematic rejection of backgrounds*

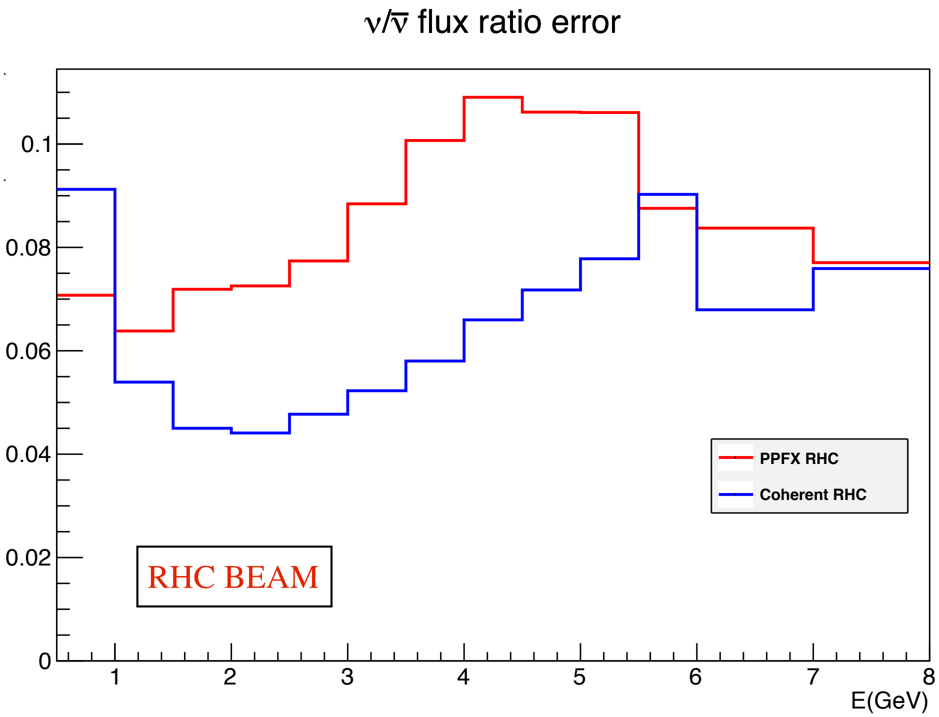
$\Longrightarrow$ *Measure CC coherent π^+ with 43% efficiency and 87% purity in STT*
$\Longrightarrow$ *Measure CC coherent π^- with 42% efficiency and 86% purity in STT*



Expected coherent pion events in STT with FHC beam



$\nu/\bar{\nu}$ flux ratio error



$\nu/\bar{\nu}$ flux ratio error

INTERACTIONS ON H (FREE PROTON)

✦ *STT offers the unique feature of a measurement of $\nu(\bar{\nu})$ interaction on hydrogen:*

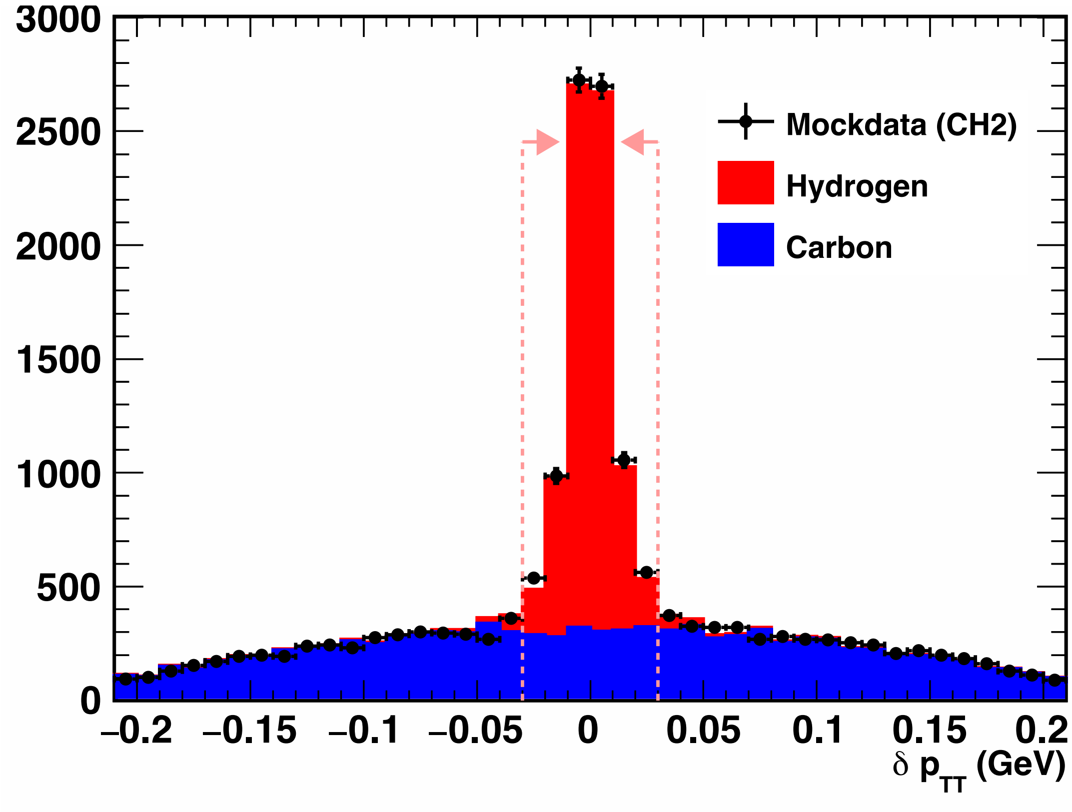
- *Independent determination of relative flux as a function of energy;*
- *Constraint of the nuclear response (smearing) function $R(E_{\rm rec}, E_{\rm true})$ of FD.*

✦ *Hydrogen interactions (14.4%) obtained from $(C_3H_6)_n$ radiators by subtracting the (normalized) interactions measured on the C (graphite) target*

✦ *Kinematic selection of 3-tracks ($\mu^- p\pi^+$) RES events in STT:*

- *Total 1.88×10^6 ν_μ CC resonance events (55% of total) expected on H in STT;*
- *Exploit the excellent reconstruction of event kinematics & vertex location in STT;*
- *Model-independent subtraction of C backgrounds using data on dedicated C target.*

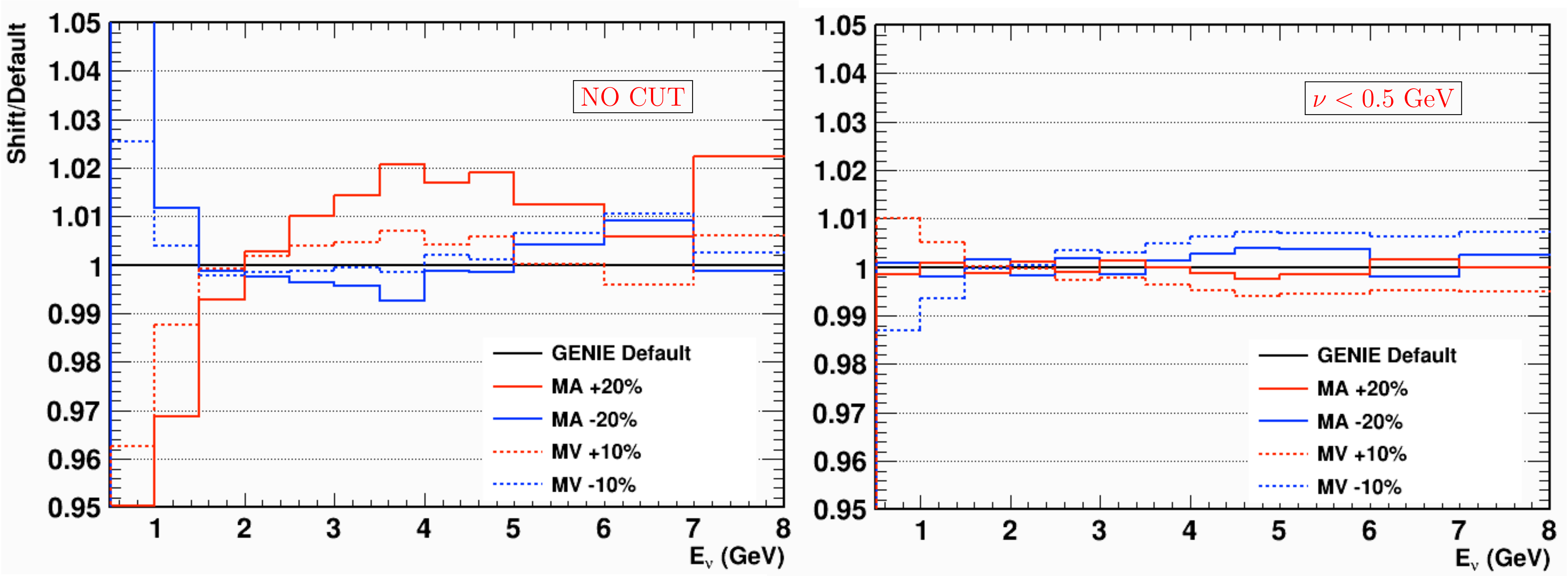
$\Longrightarrow$ *Small uncertainty from the subtraction due to high purity of selection*



Clean selection of RES events on H (free proton) with 77% purity and $\varepsilon \sim 94\%$

see Duyang's talk

Selected events on hydrogen



Effect of cross-section uncertainties on flux reduced with $\nu < 0.5$ GeV cut

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.*

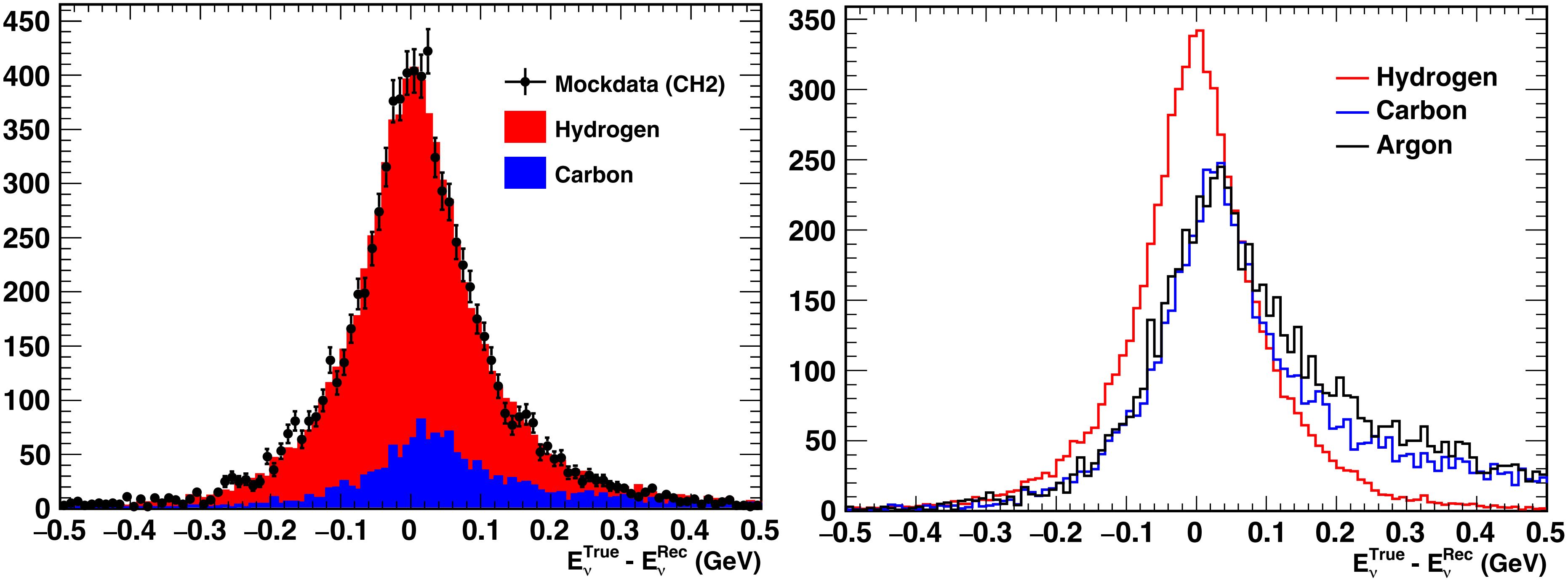
- ✦ *Direct model-independent measurement of nuclear effects in Ar from the ratios Ar/H and Ca/H with BOTH neutrino and anti-neutrino interactions*

  $\Longrightarrow$ *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 $R_{\rm phys}(E_{\rm rec}, E_{\nu})$*

see Duyang's talk



Calibration of neutrino energy scale and measurement of response (smearing) function

UNIQUE OPPORTUNITY FROM SBL PHYSICS

- ✦ *The intensity and (tunable) flux spectra at LBNF offer a unique opportunity for short-baseline (anti)neutrino physics over the next 2-3 decades*

- ✦ *Most of the physics output from DUNE will mostly come from the ND complex*

- ✦ *Selecting the ND complex with the highest physics potential is a necessary condition to exploit the unrepeatable chance we have in front of us*

  $\Longrightarrow$ *Here our physics ambition makes the difference:*
  service measurements vs. search for potential discoveries!

- ✦ *A (very) high resolution ND coupled with a factor* ~ 100 *increase in statistics can open up 100s precision studies of fundamental interactions & structure of matter*

  $\Longrightarrow$ *The SBL physics program in DUNE ND can have*
  the same impact for ν *physics as LEP had for* e^+e^- *and SM!*

Potential to attract colleagues from other fields
& in line with DOE CD1-R

STT COST ESTIMATES

- *Multiple cost estimates based upon vendor quotes for individual items & actual costs of components for similar detectors built in the past:*
  - *$16,500,000 for the detector procurement;*
  - *$8,000,000 for assembly and tests calculated with Fermilab rates.*

- *Room for cost reduction:*
  - *Use new welding technology for straw fabrication;*
  - *Design optimization and value engineering;*
  - *Common readout development with other ND technologies;*
  - *New vendor quotes.*

- *The detector cost should not be the driving factor for the conceptual design since it will ultimately depend on many factors and will require a cost optimization study.*

POSSIBLE CONTRIBUTIONS

- *Fair to say at this stage nobody has put money on the table for any technology (especially considering we do not have a conceptual design yet)*

- *Indian institutions remain committed to the R&D and construction of STT:*
  - *Initial positive response by DAE/DST about the FGT project;*
  - *Provisional approval of Phase I (R&D) by DAE/DST (about $10M) in 2014 during the LBNE era;*
  - *Transition from LBNE to DUNE interfered with the final approval of the project;*
  - *In principle a quick turnaround is possible once Annex II is signed between DOE and DAE;*
  - *Need unambiguous signal from the management.*

- *Interest expressed by Russian groups with large experience in the construction of straw detectors (Dubna, PNPI)*

- *Interest from institutions contributing to the SHIP experiment and other modern straw detectors?*

- *USC interested in construction of nuclear targets and contributing to other efforts*

Open to any new groups willing to join (more than welcome!)

SUMMARY

- *The STT offers unique advantages enhancing sensitivity of DUNE ND:*
  - *Transition radiation for efficient $e^{\pm}$ identification;*
  - *Clean selection of $\nu(\bar{\nu})$ interactions on Hydrogen target, free from nuclear effects;*
  - *Timing resolving the beam structure & withstanding high rates;*
  - *Suite of dedicated nuclear targets to constrain the response (smearing) function;*
  - *4π detection of π^0 from γ conversions in tracker;*
  - *Flexible design allowing a variation of target configuration with density $0.005 \leq \rho \leq 0.1$ g/cm^3;*
  - *Substantial target mass combined with high angular, momentum, and space resolution.*

- *Excellent synergy between the LAr detector and a STT-based MPT, allowing combined analyses & validations of predictions (redundancy)*

- *We have addressed all the questions from the 3rd ND workshop and quantified the STT (standalone) performance for all the key ND measurements*

Backup slides

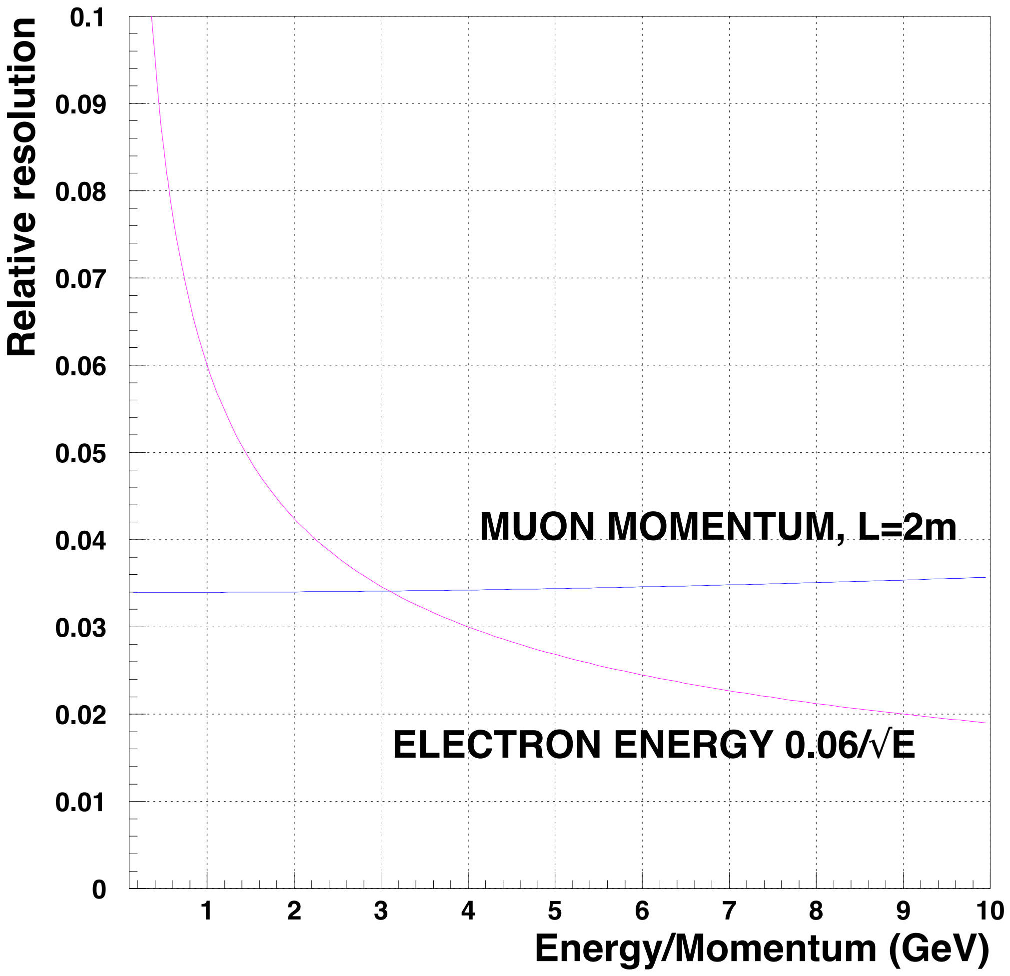
EXPECTED STT PERFORMANCE

- ✦ *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* $\boxed{0.048}$ *for* $L = 1m$
  - *Measurement error term* $\boxed{0.006}$ *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 ($\sim 50\%$)



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:*

$$N_{\rm X}(E_{\rm rec}) = \int_{E_\nu} dE_\nu \; \underset{\textbf{MPT/FGT}}{\underset{\Big\downarrow}{\boxed{\Phi(E_\nu)}}} \; P_{\rm osc}(E_\nu) \;\; \sigma_{\rm X}(E_\nu) \; \underset{\textbf{MPT/FGT}}{\underset{\Big\downarrow}{\boxed{R_{\rm phys}(E_{\rm rec}, E_\nu)}}} \;\; R_{\rm det}(E_{\rm rec}, E_\nu)$$

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

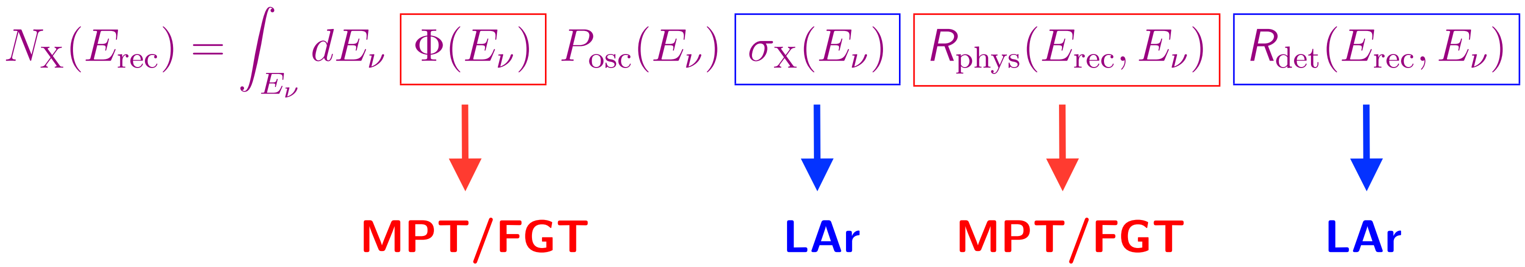
- *Absolute* ν_μ *flux from* ν*-e elastic scattering and Inverse Muon Decay (IMD);*
- *Relative* ν_μ *flux vs.* E_ν *from low-*ν *and* ν*-e elastic;*
- $\bar\nu_\mu/\nu_\mu$ *vs.* E_ν *from coherent* $\pi^\pm$ *production;*
- ν_e/ν_μ *AND* $\bar\nu_e/\bar\nu_\mu$ *vs.* E_ν *from* $\nu_\mu, \bar\nu_\mu,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

✦ $\boxed{R_{\rm phys}(E_{\rm rec}, E_\nu)}$ *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* $\sigma_{\rm X}(E_\nu)$ *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 (*$P_{\mathrm{osc}} \sim 1$*) and FD:*



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

MPT/FGT **LAr** **MPT/FGT** **LAr**

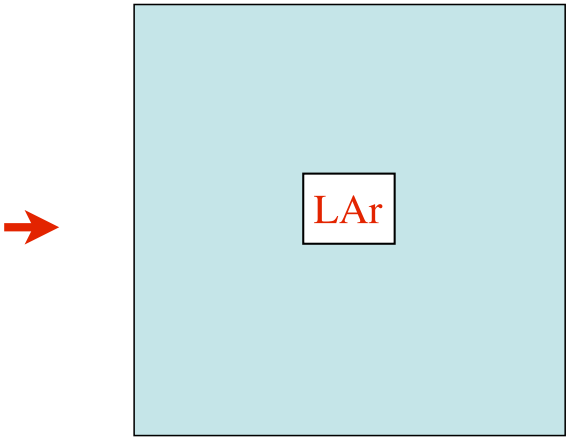
✦ $\boxed{R_{\mathrm{det}}(E_{\mathrm{rec}}, E_\nu)}$ *can only be provided by LAr:*

- *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.*

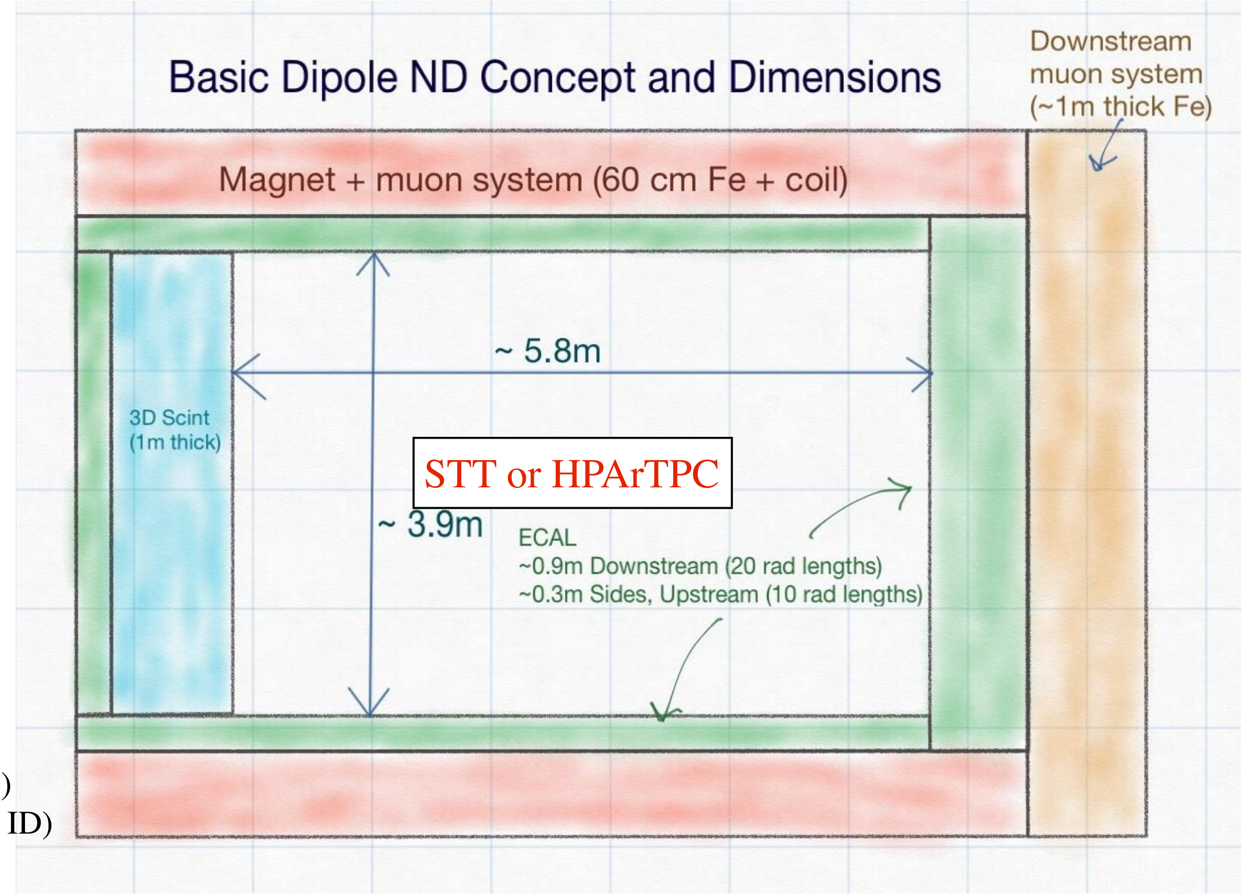
✦ $\boxed{\sigma_{\mathrm{X}}(E_\nu)}$ *requires an Ar target and can be constrained by LAr:*

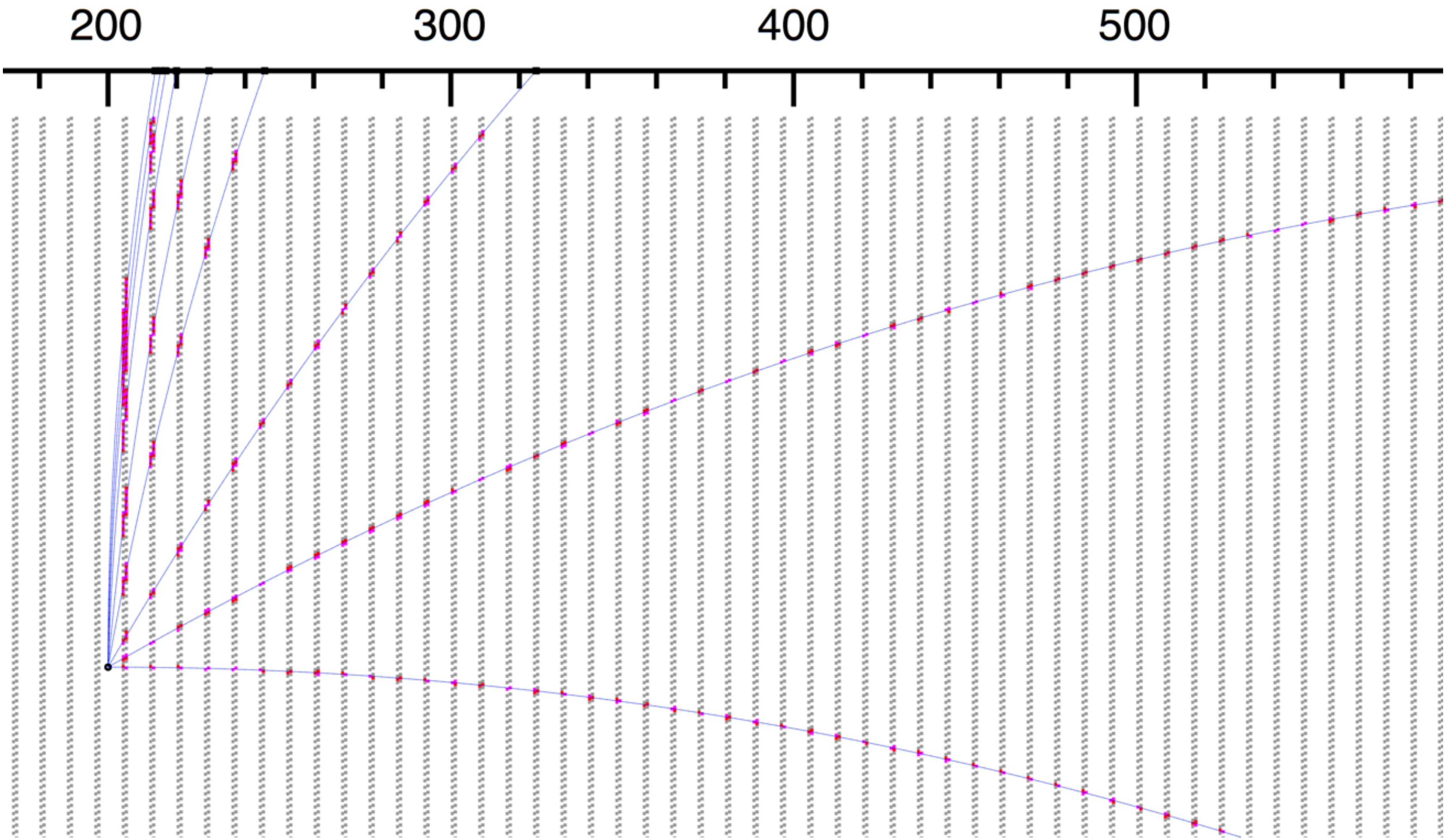
- *Need to measure various exclusive processes on Ar target;*
- *LAr benefits from precise calibration of backgrounds and event topologies in MPT/FGT.*

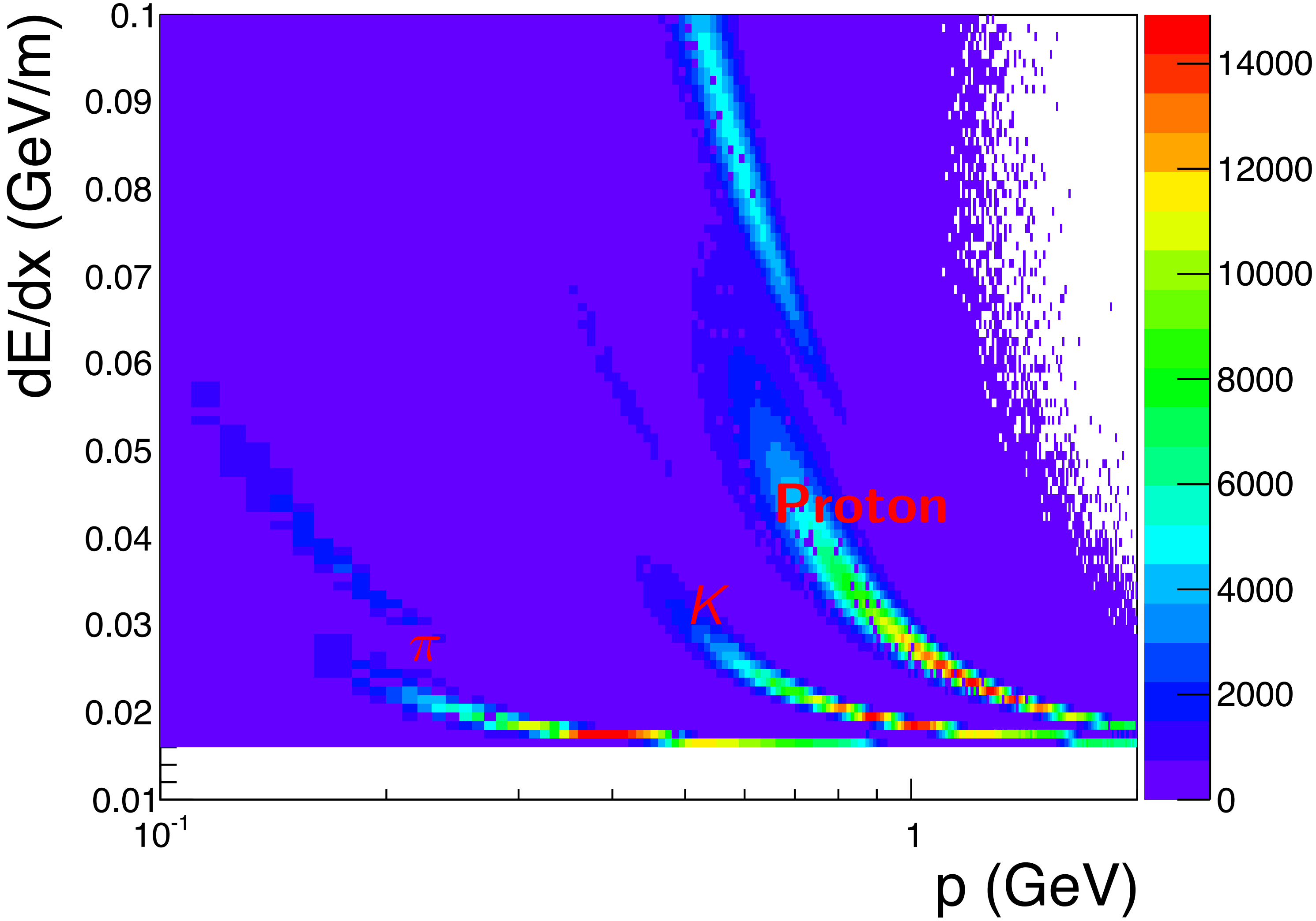
✦ *In addition, LAr offers synergy with MPT/FGT to validate the effect of the nuclear smearing in* $R_{\mathrm{phys}}(E_{\mathrm{rec}}, E_\nu)$ *and some of the flux measurements.*



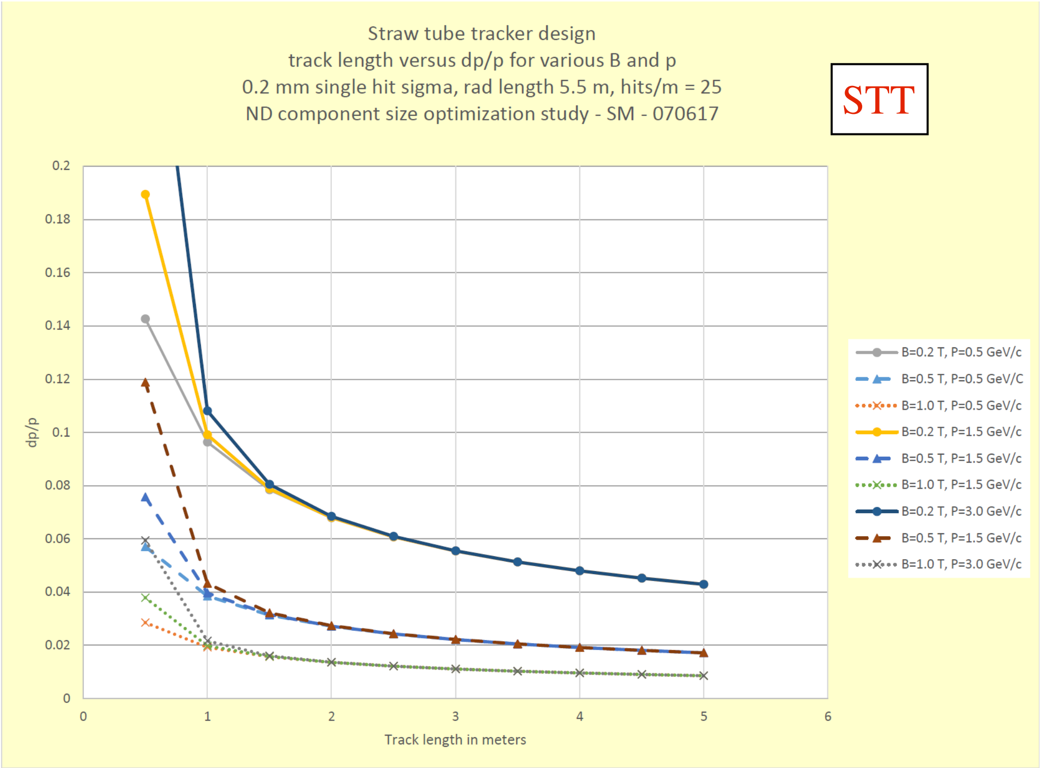
C. Marshall 09/13:
2.5m x 2.5m x 3.25m (Muon ID)
4.0m x 4.0m x 3.25m (no Muon ID)




200
300
400
500

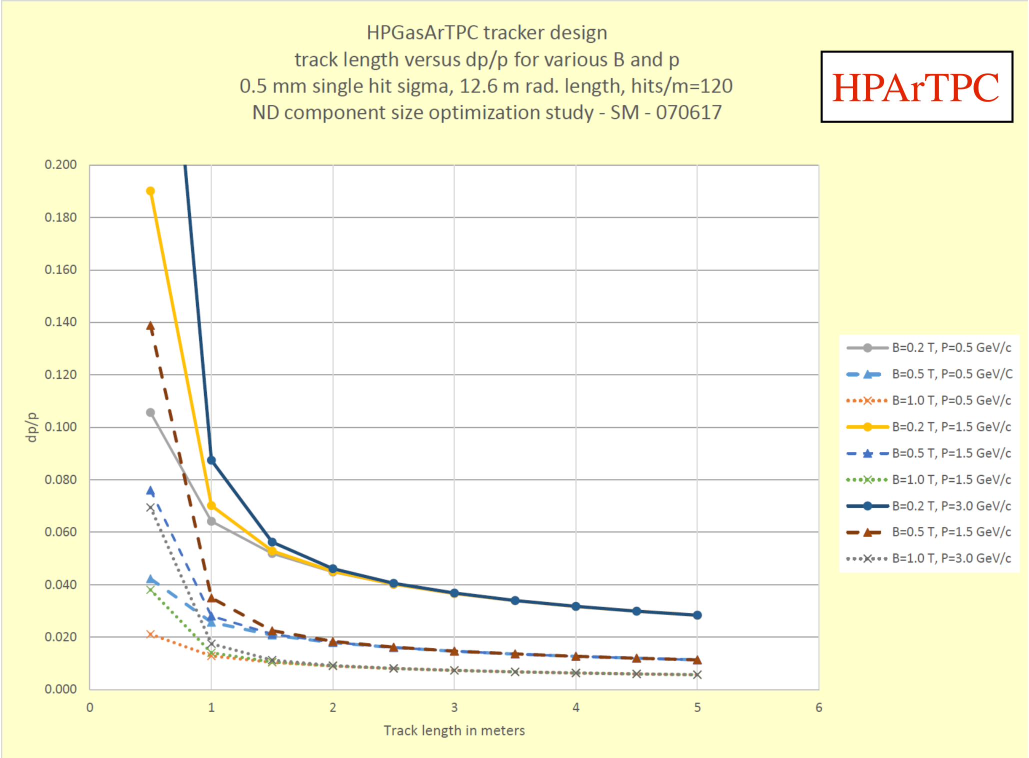


STT has good dE/dx particle ID: $\pi^{\pm}/K^{\pm}/p$



Straw tube tracker design
track length versus dp/p for various B and p
0.2 mm single hit sigma, rad length 5.5 m, hits/m = 25
ND component size optimization study - SM - 070617

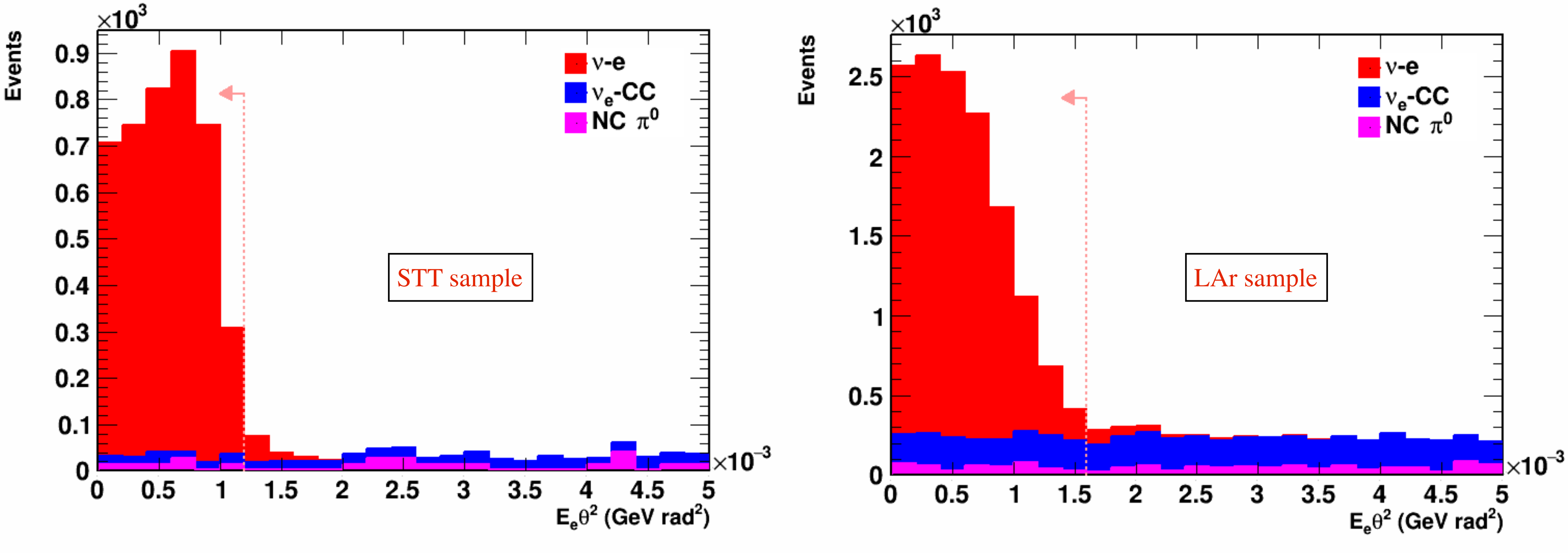
STT

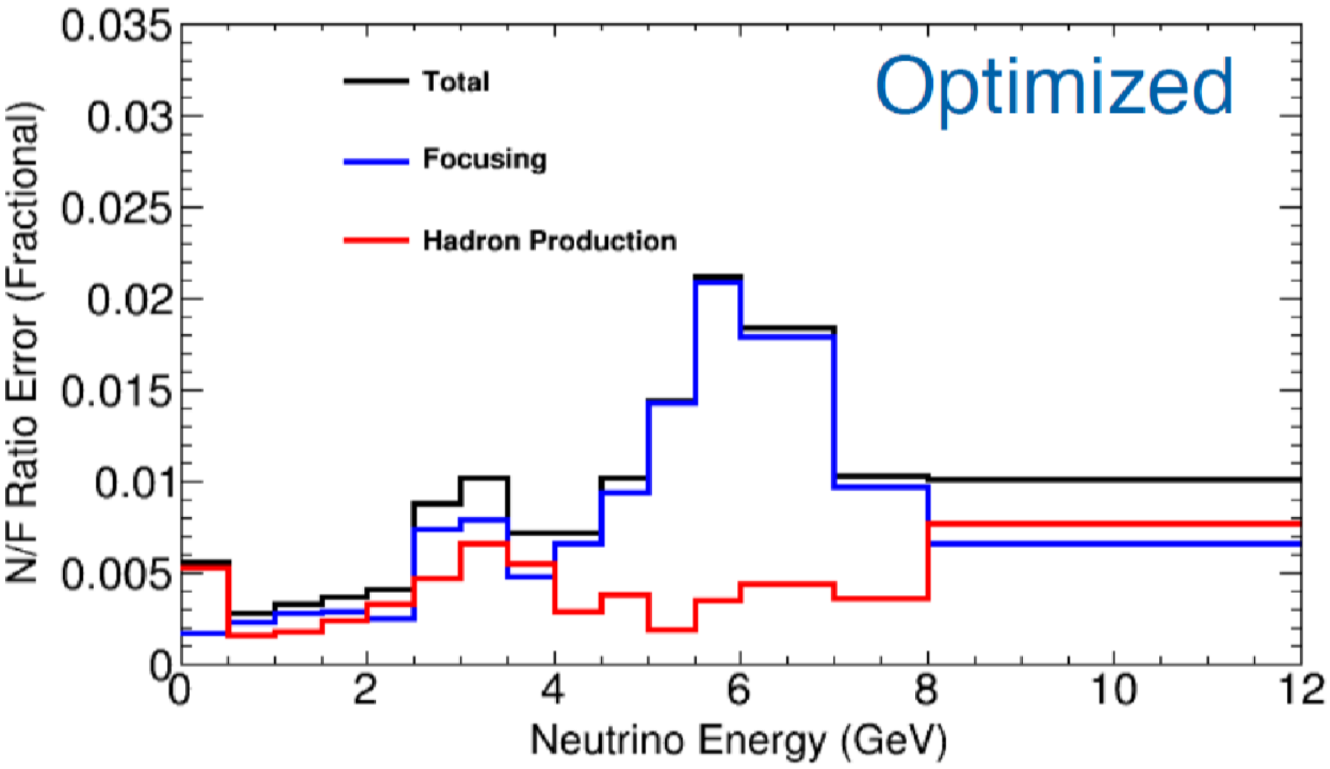


HPGasArTPC tracker design
track length versus dp/p for various B and p
0.5 mm single hit sigma, 12.6 m rad. length, hits/m=120
ND component size optimization study - SM - 070617

HPArTPC

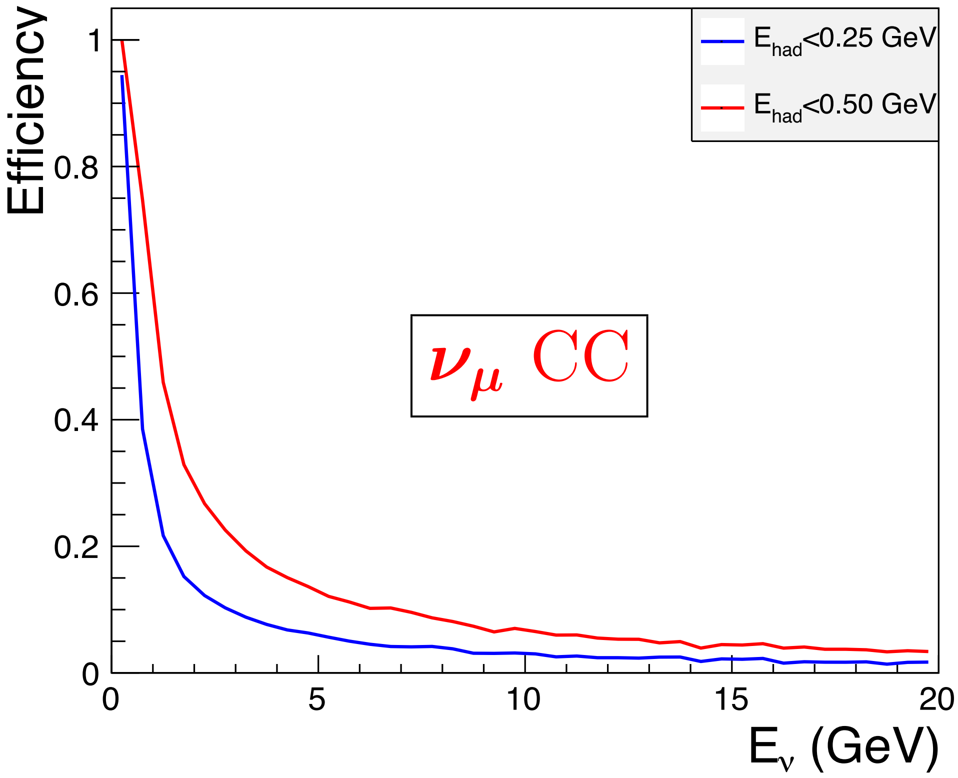
S. Manly, DUNE collaboration meeting, August 2017

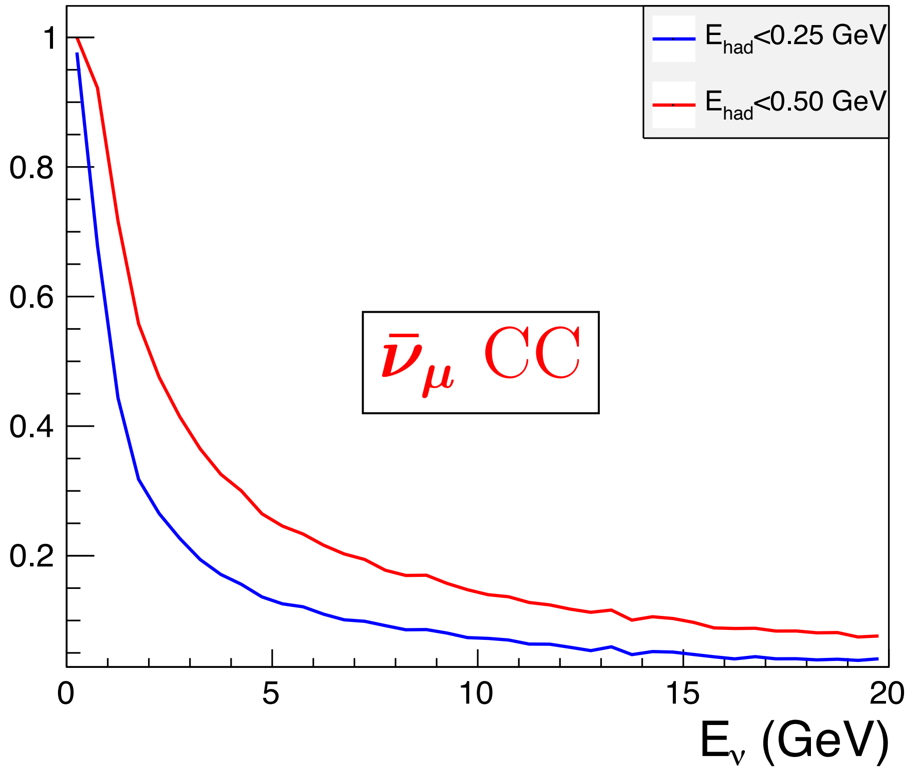

Events
×10^3
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
×10^-3
E_eθ^2 (GeV rad^2)
ν-e
ν_e-CC
NC π^0
STT sample
Events
×10^3
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
×10^-3
E_eθ^2 (GeV rad^2)
ν-e
ν_e-CC
NC π^0
LAr sample


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

Relative efficiency *of the cut* $\boxed{\nu < \nu_0}$ *in DUNE ND*

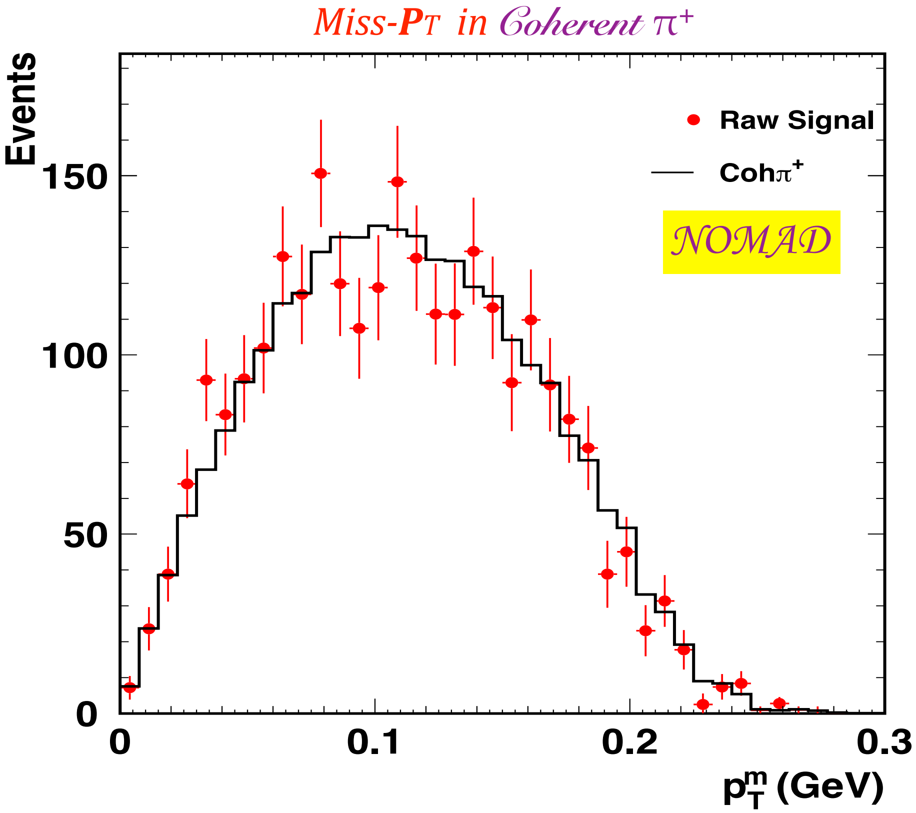
reconstruction efficiencies not included (typically $> 90\%$*)*



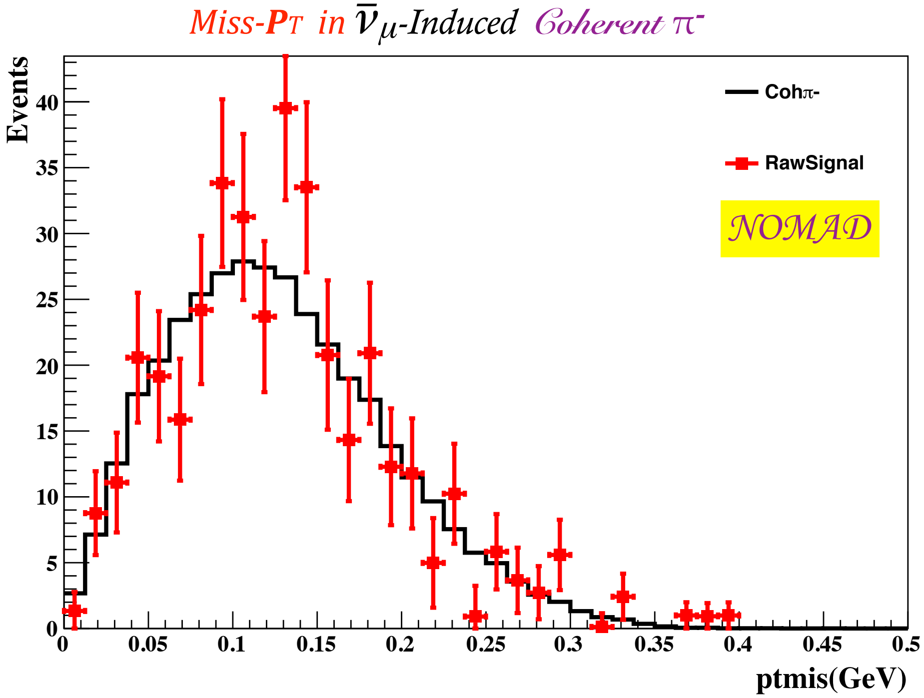


Cut	$\nu < 0.25$ *GeV*	$\nu < 0.50$ *GeV*
$\langle \varepsilon \rangle$	*9%*	*19%*

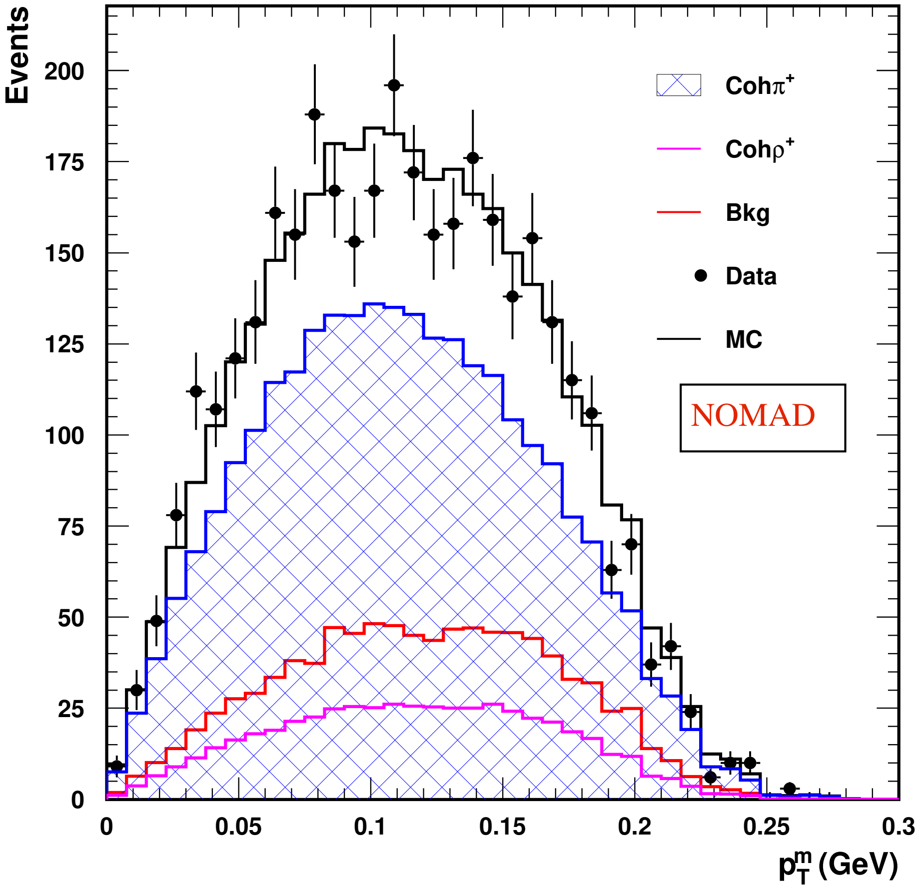
Cut	$\nu < 0.25$ *GeV*	$\nu < 0.50$ *GeV*
$\langle \varepsilon \rangle$	*11%*	*22%*



Miss-P_T in Coherent π^+



Miss-P_T in $\bar{\nu}_\mu$-Induced Coherent π^-


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