Neutrino Induced Resonance Interaction in a Fine-Grained Tracker Detector

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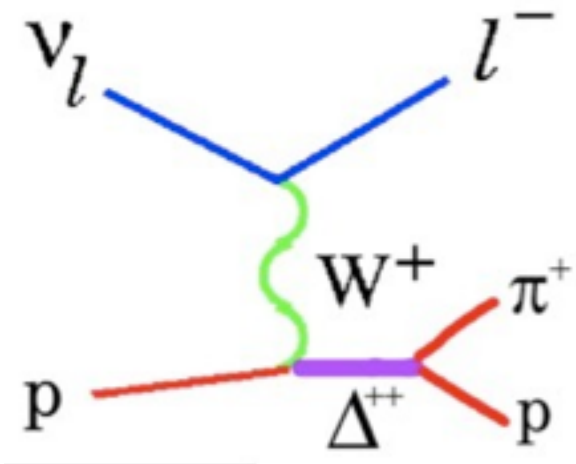
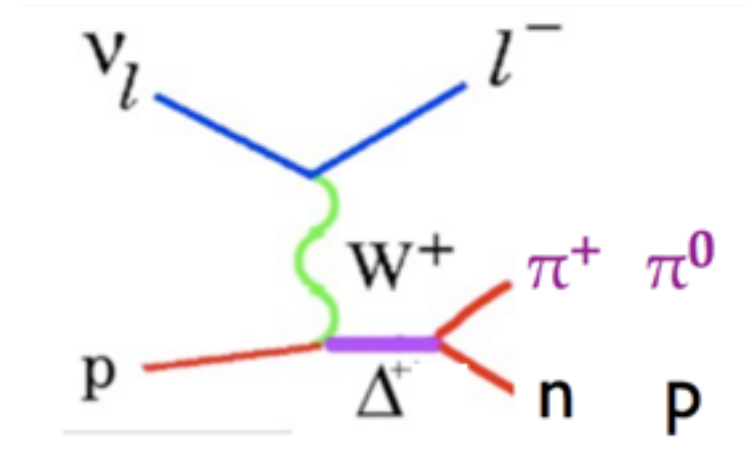
Introduction

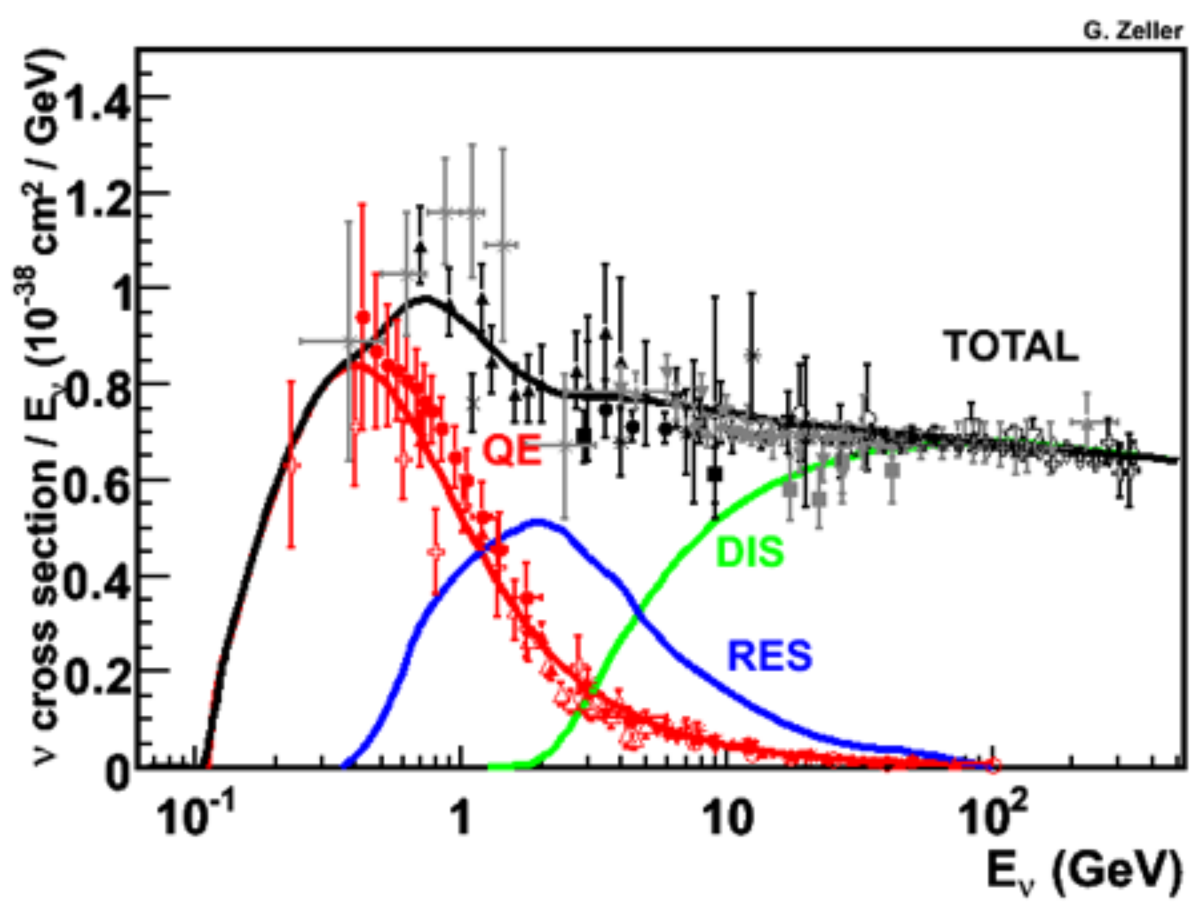
- We study the neutrino induced resonance interaction (RES) in a Fine-Grained Tracker proposed as reference near detector design for DUNE.
- Use Fast MC to study the sensitivity and kinematics.
- Constrain nuclear effect.
- Similar analysis applied to NOMAD data for validation.
- Preliminary NOMAD measurement result will be reported.

Resonance Interaction

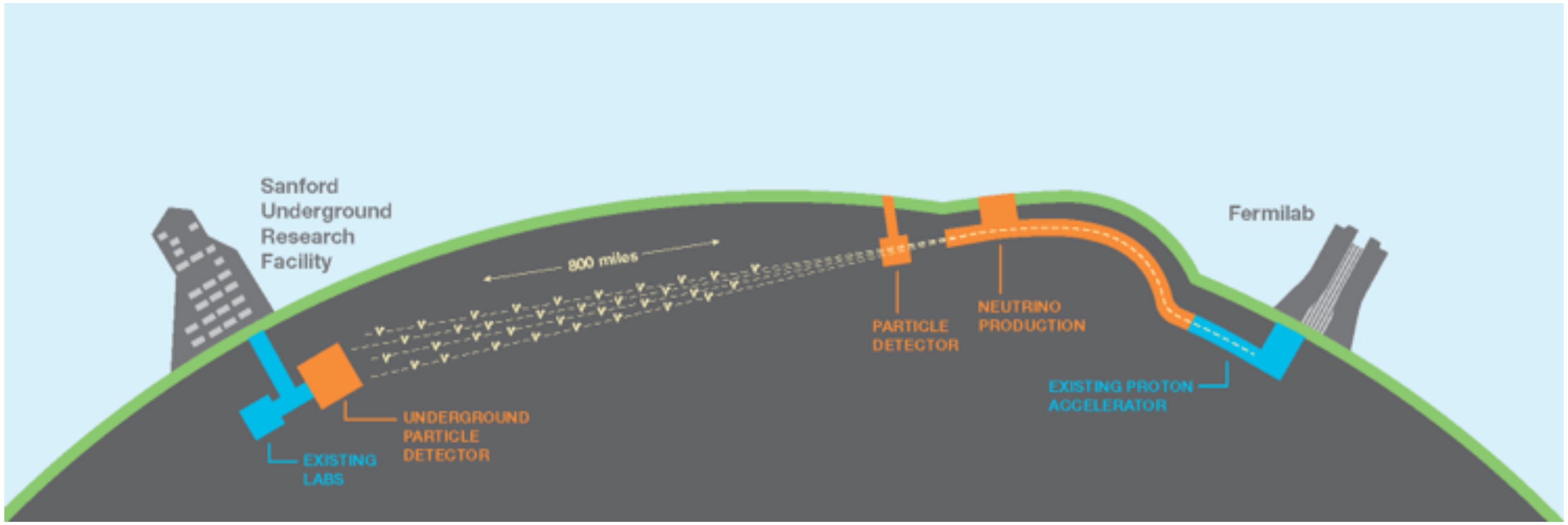




- A neutrino inelastically scatters off target nucleon, with a short-lived resonant state of the excited target nucleon created, which decay into a nucleon and a single pion.
  - $\nu_\mu + p \longrightarrow \mu^- + \Delta^{++} \longrightarrow \mu^- + p + \pi^+$
  - $\nu_\mu + n \longrightarrow \mu^- + \Delta^{+} \longrightarrow \mu^- + n + \pi^+$
  - $\nu_\mu + n \longrightarrow \mu^- + \Delta^{+} \longrightarrow \mu^- + p + \pi^0$
- The most important channel for the next generation long-baseline neutrino experiments in few-GeV energy region such as DUNE (first oscillation maxima at 2.4GeV).
- Theoretically described by Rein-Seghal (RS) model, used in event generators like GENIE.
- Unfortunately also the least measured.

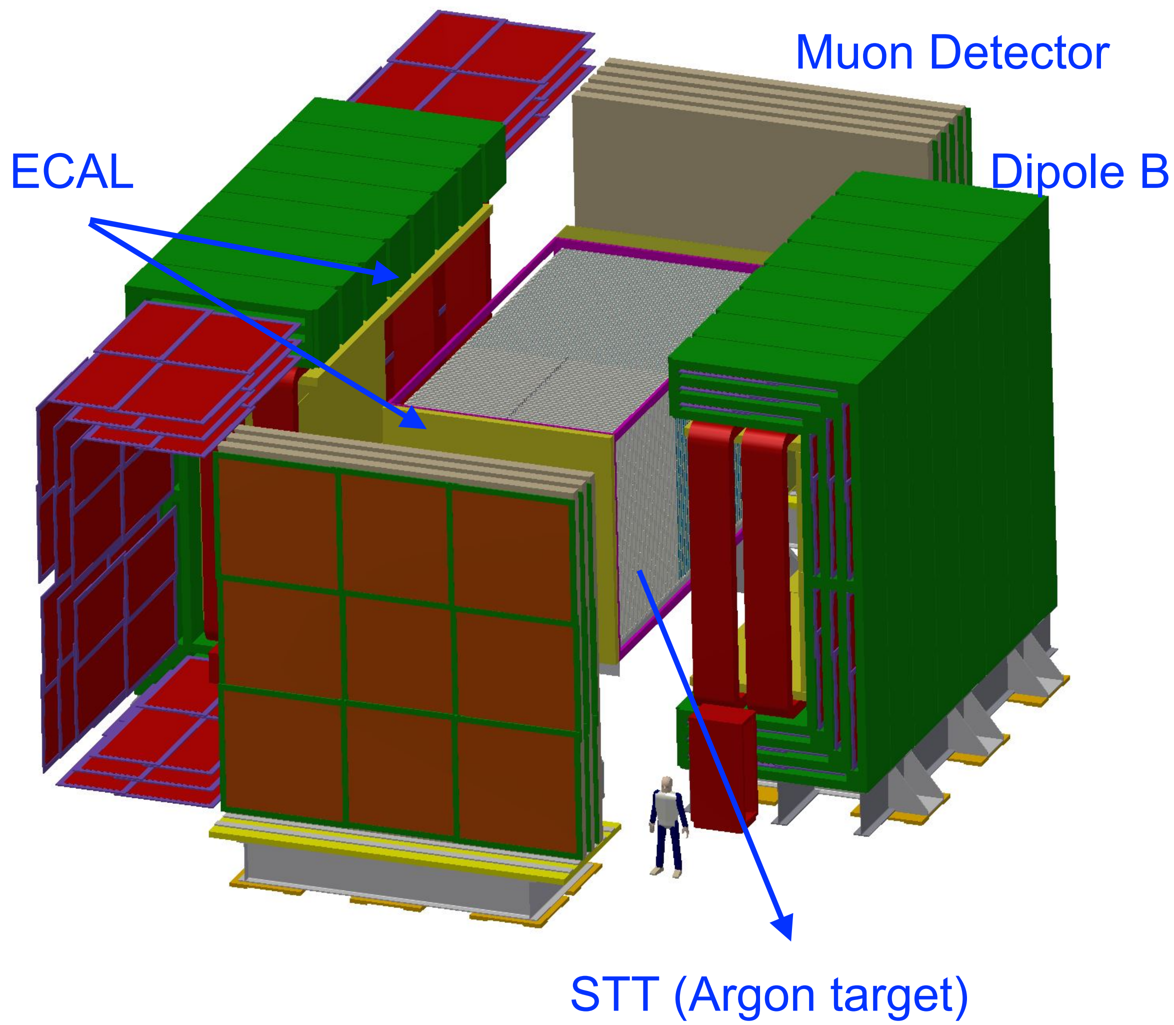


DUNE Experiment



- Deep Underground Neutrino Experiment (DUNE), formerly the Long-Baseline Neutrino Experiment (LBNE)
- Primary goal is to study long-baseline neutrino oscillation.
- Four 10 kt (fiducial) LAr-TPCs underground at SURF, SD (1300km from source).
- A Fine-Grained Tracker near detector is proposed as the reference design at Fermilab.

A Fine-Grained Tracker Near Detector For DUNE



Performance Metric	FGT
Straw Tube Detector Volume	3.5m x 3.5m x 6.4m
Straw Tube Detector Mass	8 tonnes
Vertex Resolution	0.1 mm
Angular Resolution	2 mrad
E_e Resolution	5%
E_μ Resolution	5%
$\nu_\mu/\bar{\nu}_\mu$ ID	Yes
$\nu_e/\bar{\nu}_e$ ID	Yes
NCπ^0/CCe Rejection	0.1%
NCγ/CCe Rejection	0.2%
CCμ/CCe Rejection	0.01%

- High resolution, low-density, magnetized detector built upon NOMAD experience.
- Determine the unoscillated neutrino flux with high precision for all neutrino species.
- Argon target nucleus allow cancellation of systematics.
- Constrain background to the ν_e appearance measurement.
- Precision physics measurements on its own.

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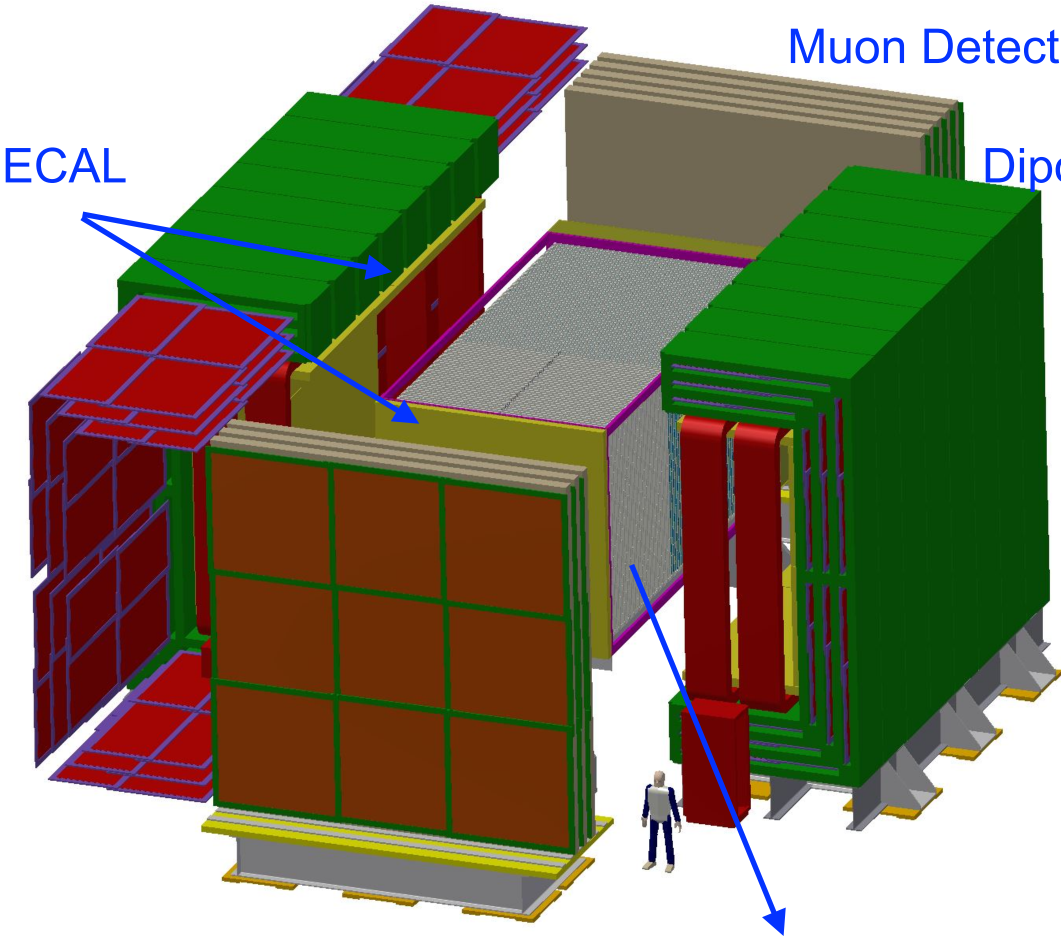

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Excellent resoluton

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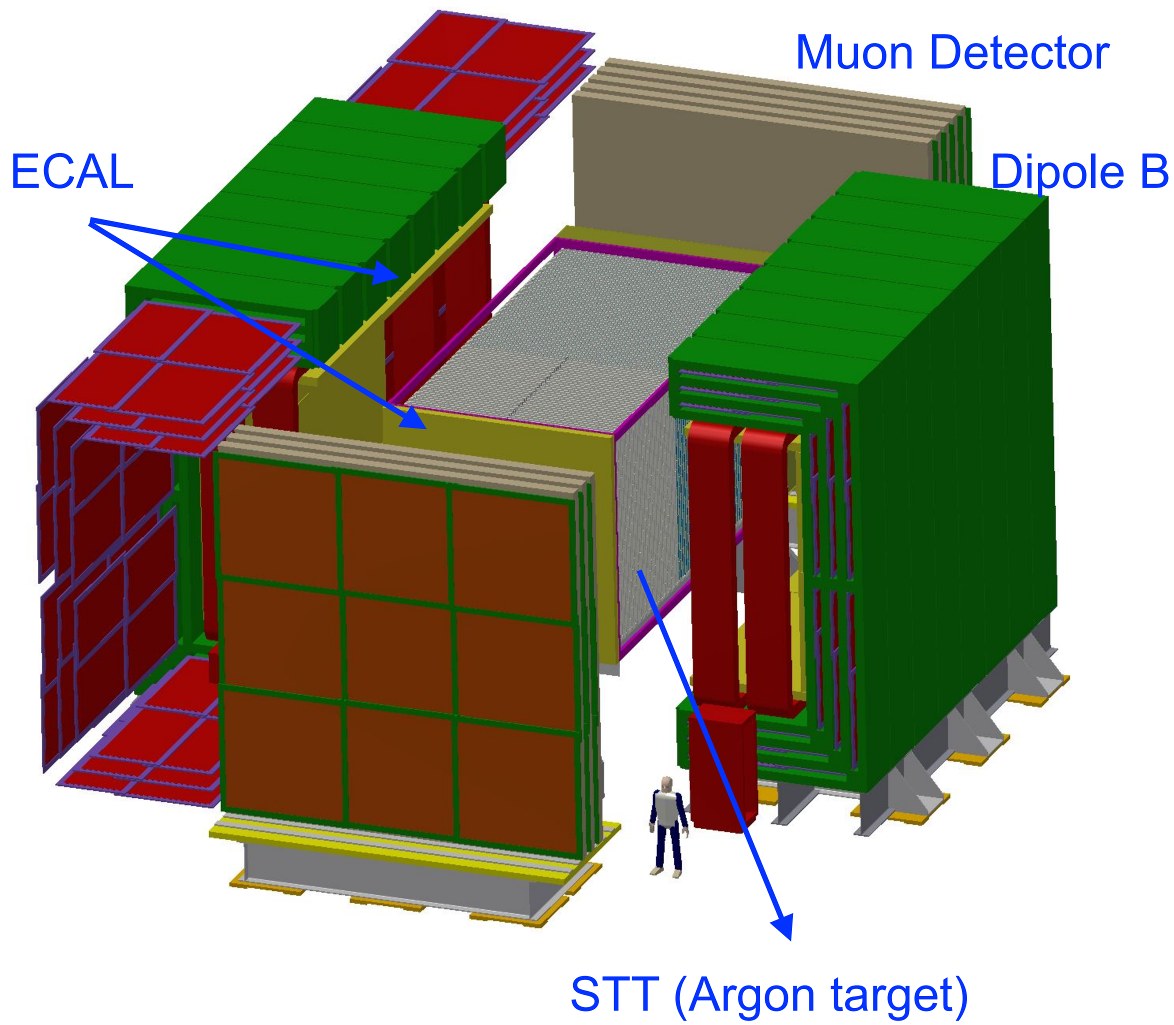

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e+e-, μ+μ- ID

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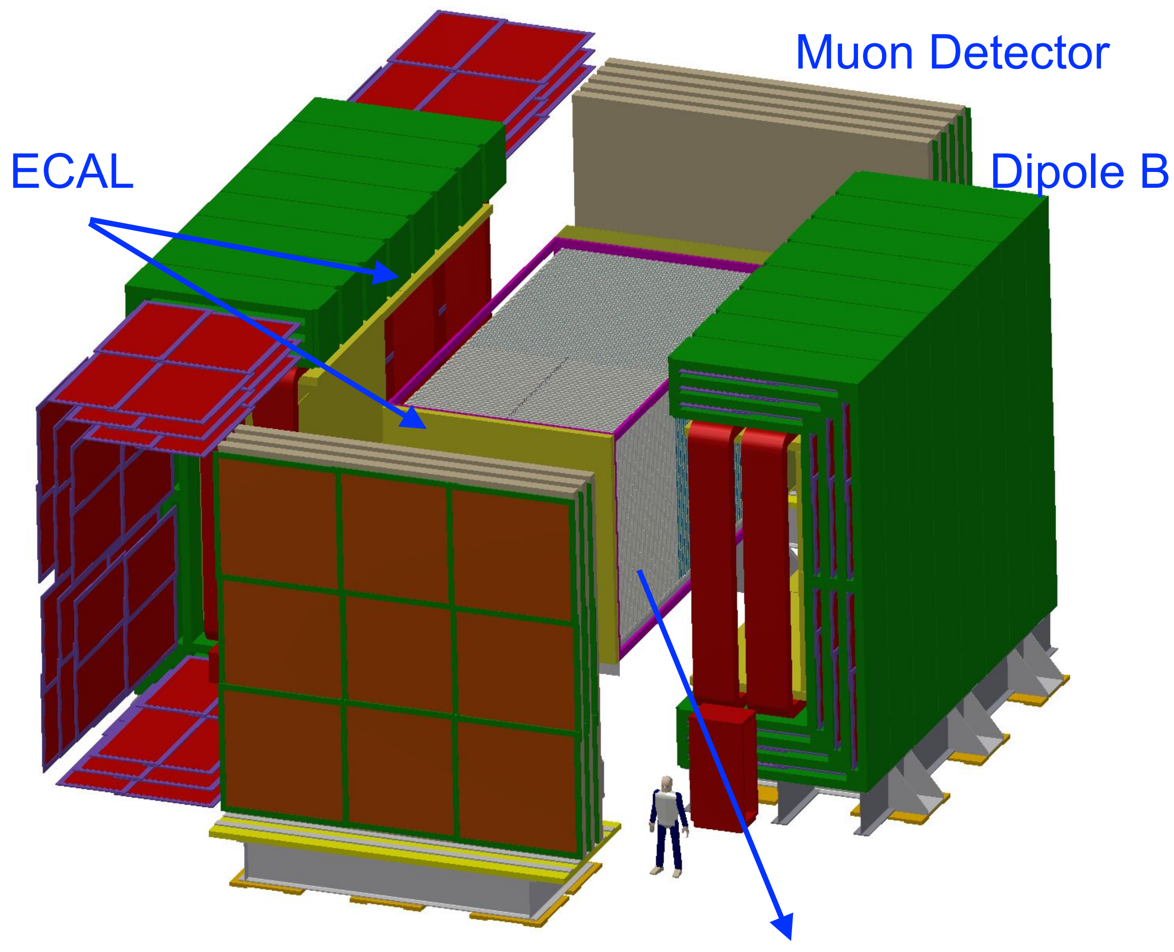

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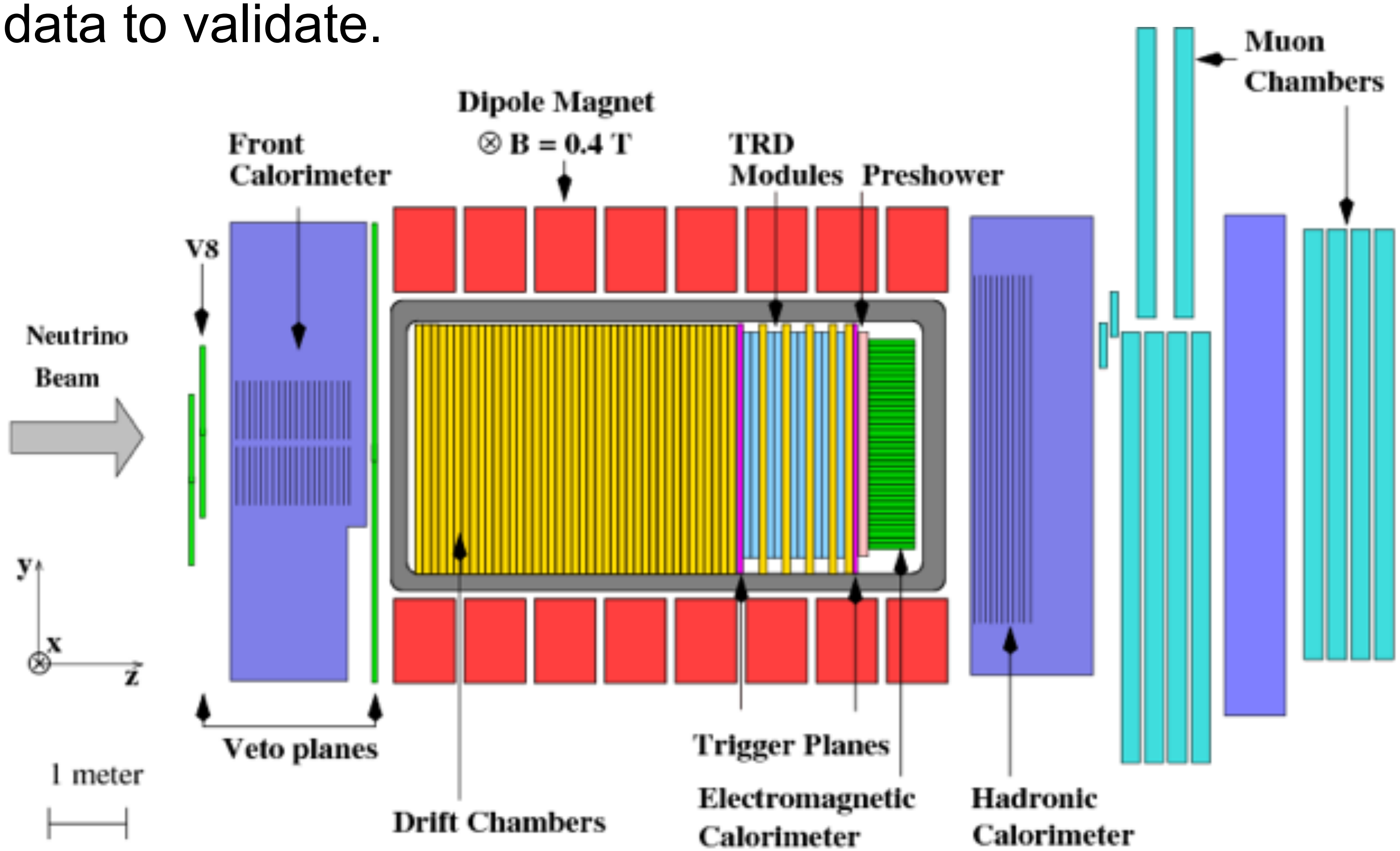
Excellent background rejection

- High resolution, low-density, magnetized detector built upon NOMAD experience.
- Determine the unoscillated neutrino flux with high precision for all neutrino species.
- Argon target nucleus allow cancellation of systematics.
- Constrain background to the ν_e appearance measurement.
- Precision physics measurements on its own.

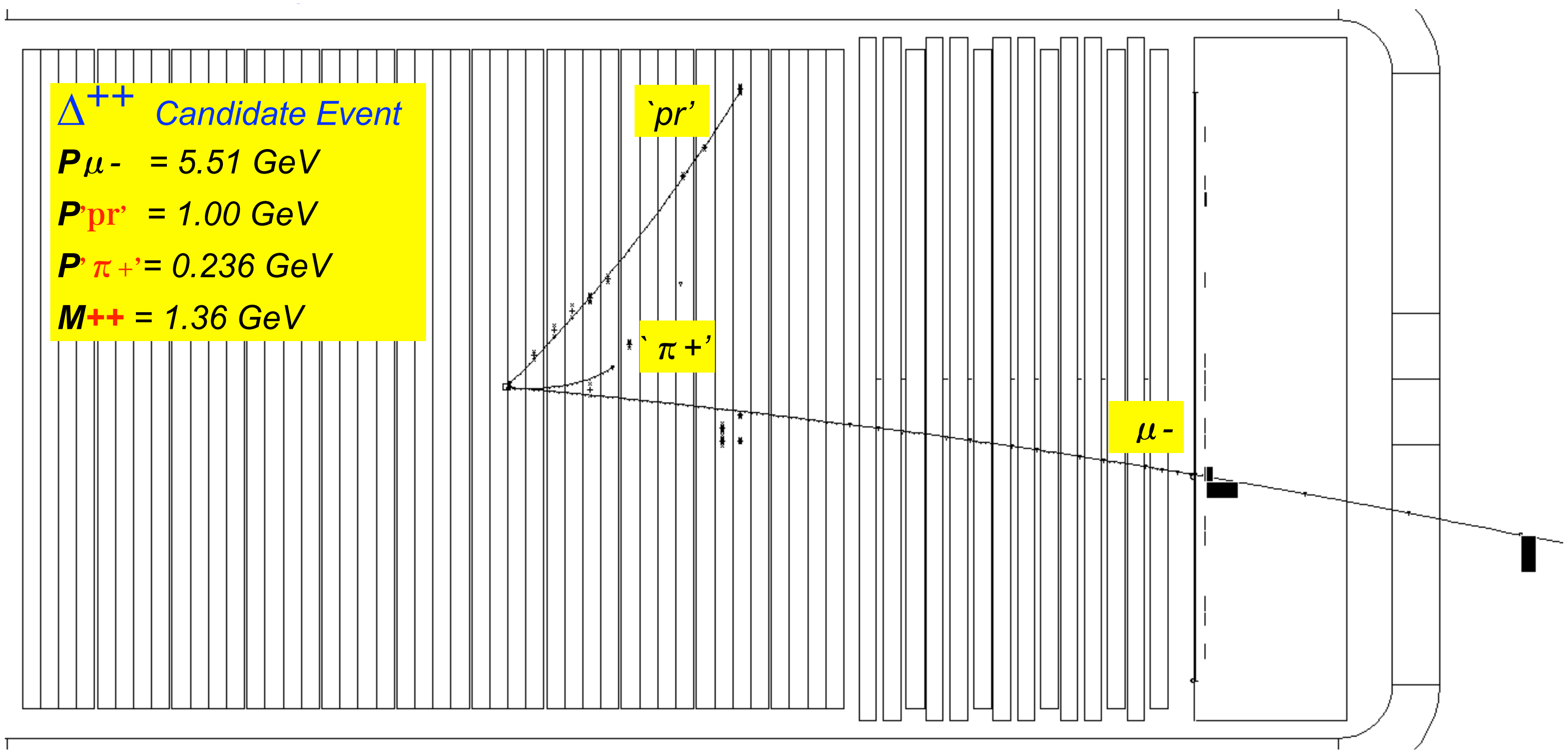
Analysis Strategy: Fast MC and NOMAD Data

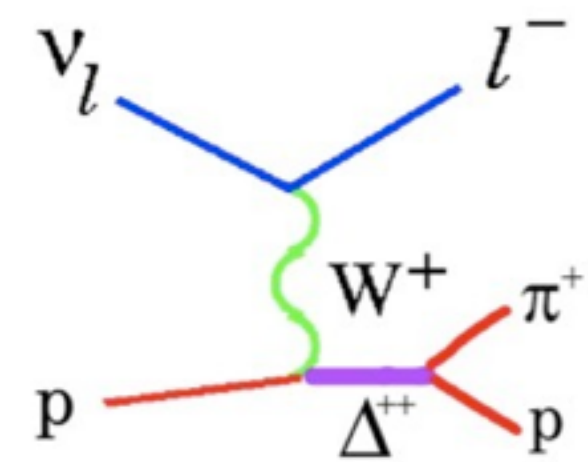
- We don't have a full GEANT4 detector simulation yet at this early stage of detector design.
- Instead, developed fast MC to mimic detector simulation and reconstruction.
- Use NOMAD data to validate.



- NOMAD was a detector at CERN upon which the proposed DUNE ND is designed.
- Accumulated ~2M neutrino events which serves as a benchmark to validate the ideas developed in the designing of DUNE FGT.
- Also leads to precise measurements of neutrino interactions on its own.

Resonance Topology in FGT



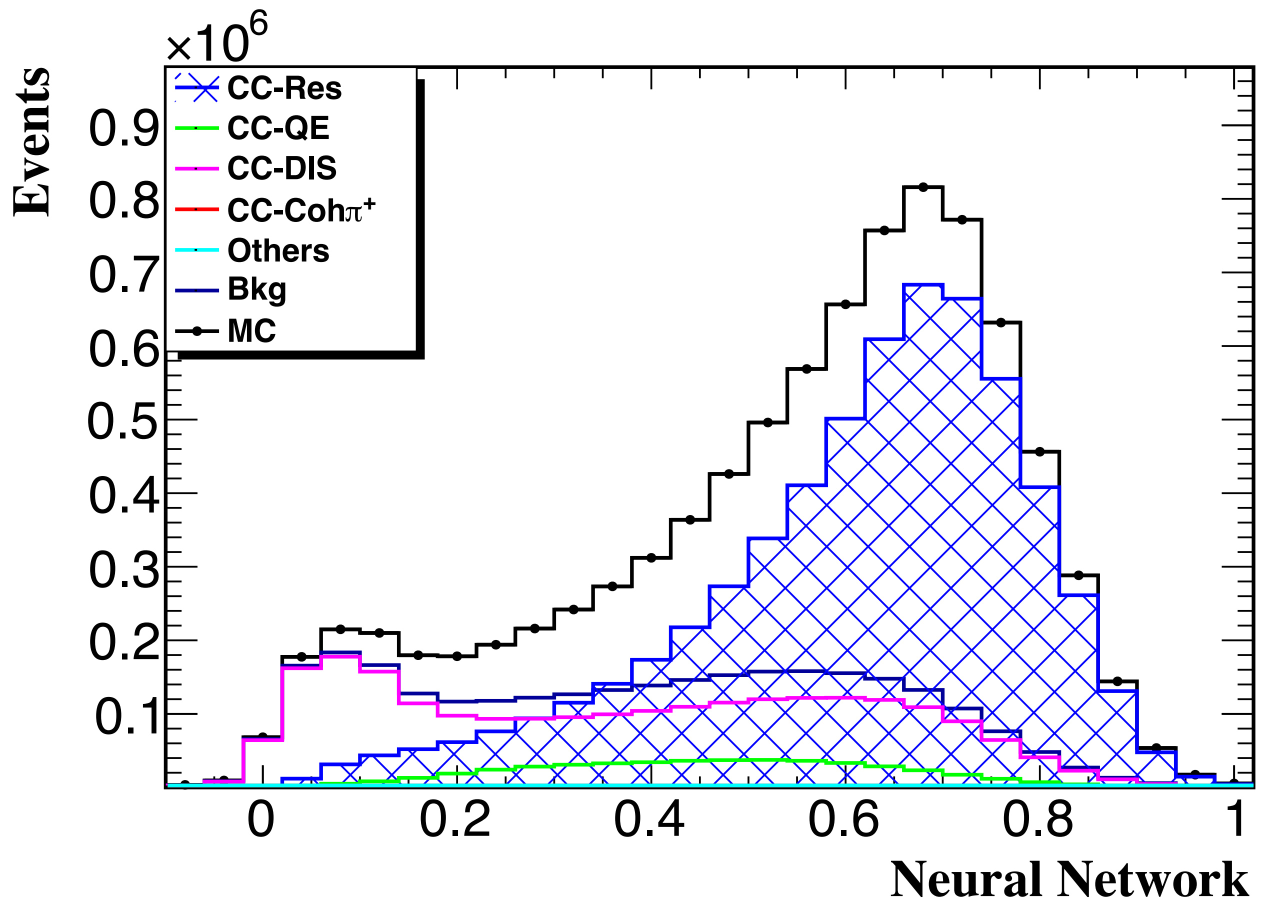


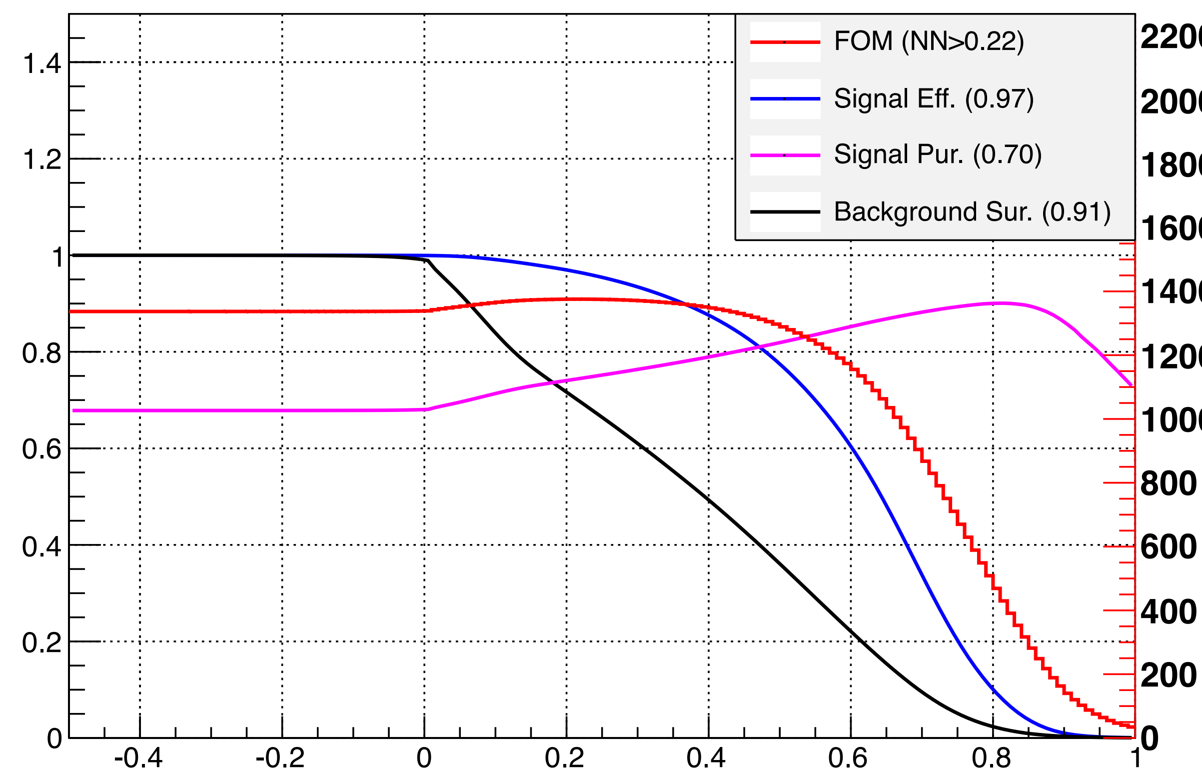
- Looking for 3-track topology:

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

- Select μ^- and (+, +) events.
- Soft preselection cuts to reduce backgrounds, dominated by Deep Inelastic (DIS).
- Put selected events into Multivariate analysis.

Multivariate Neural Network Analysis



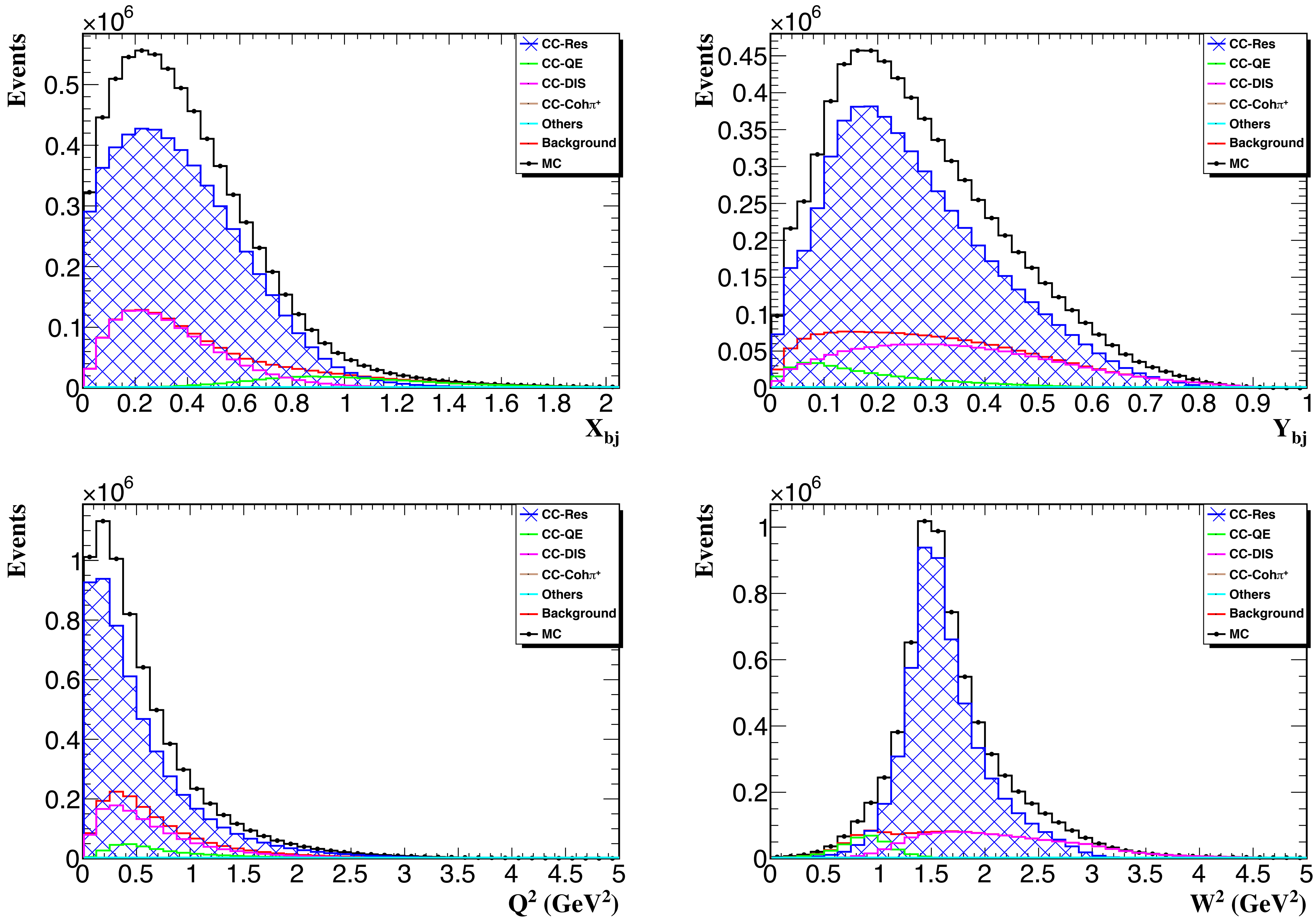


- Using fast MC, built Neural Network on 9 variables:
  $p_\mu^x,\ p_\mu^y,\ p_\mu^z,\ p_{Proton}^x,\ p_{Proton}^y,\ p_{Proton}^z,\ p_\pi^x,\ p_\pi^y,\ p_\pi^z$

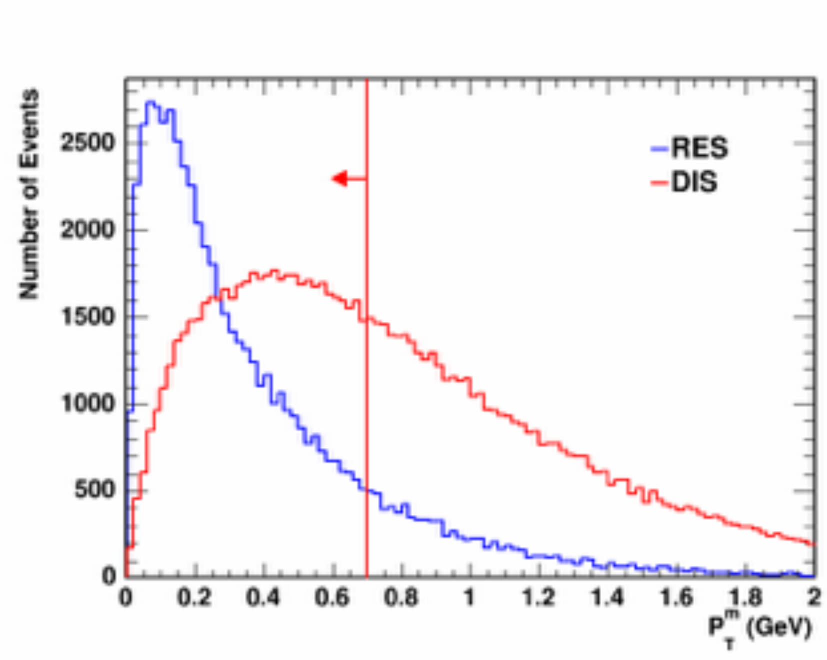
Cut	Sig.	Sig. Eff.	Back.	Back. Surv. Prob.
2 positive track	5.928e+06	0.3609	2.811e+06	0.06659
$NN > 0.22$	5.723e+06	0.3484	1.97e+06	0.04668
$NN > 0.35$	5.405e+06	0.3291	1.571e+06	0.03722

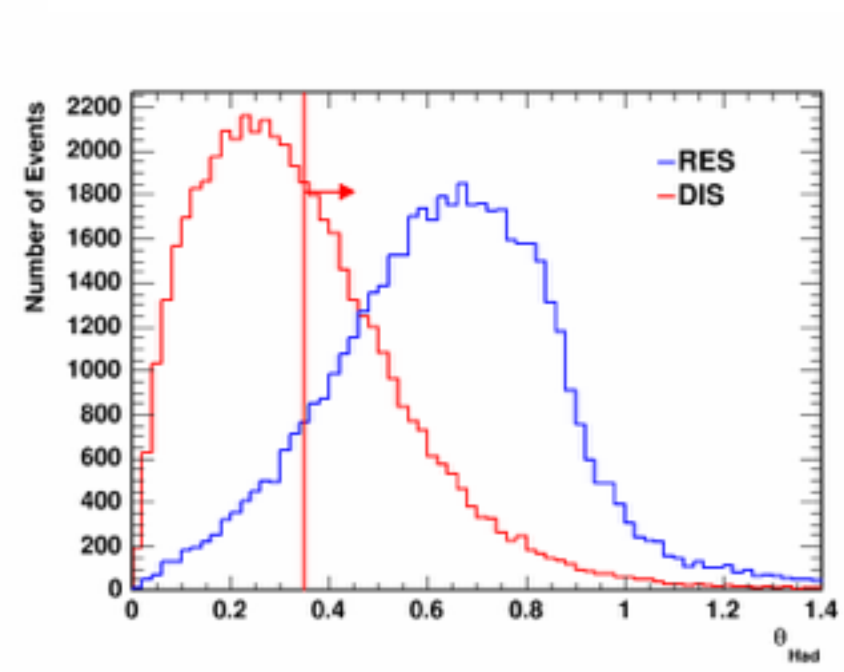
- Signal efficiency is 33% with 23% background.

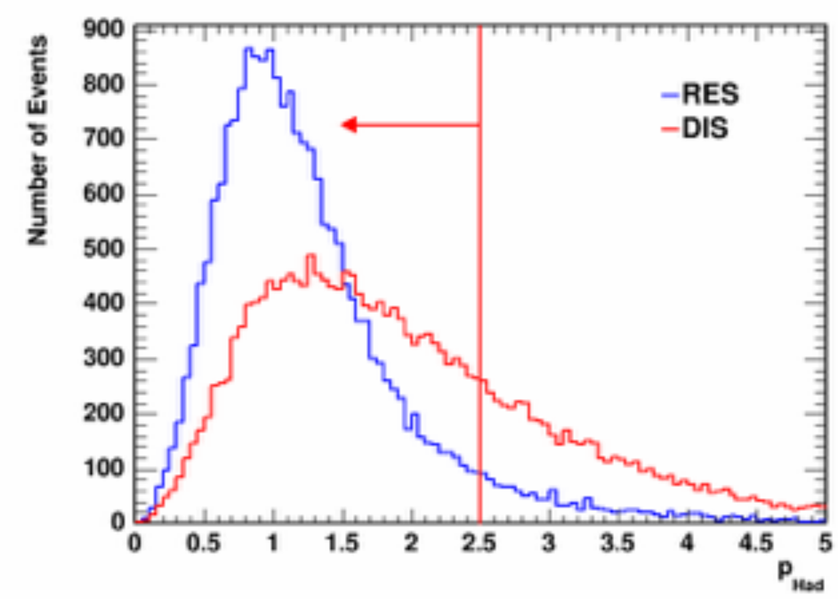
Res Kinematics in Signal Region



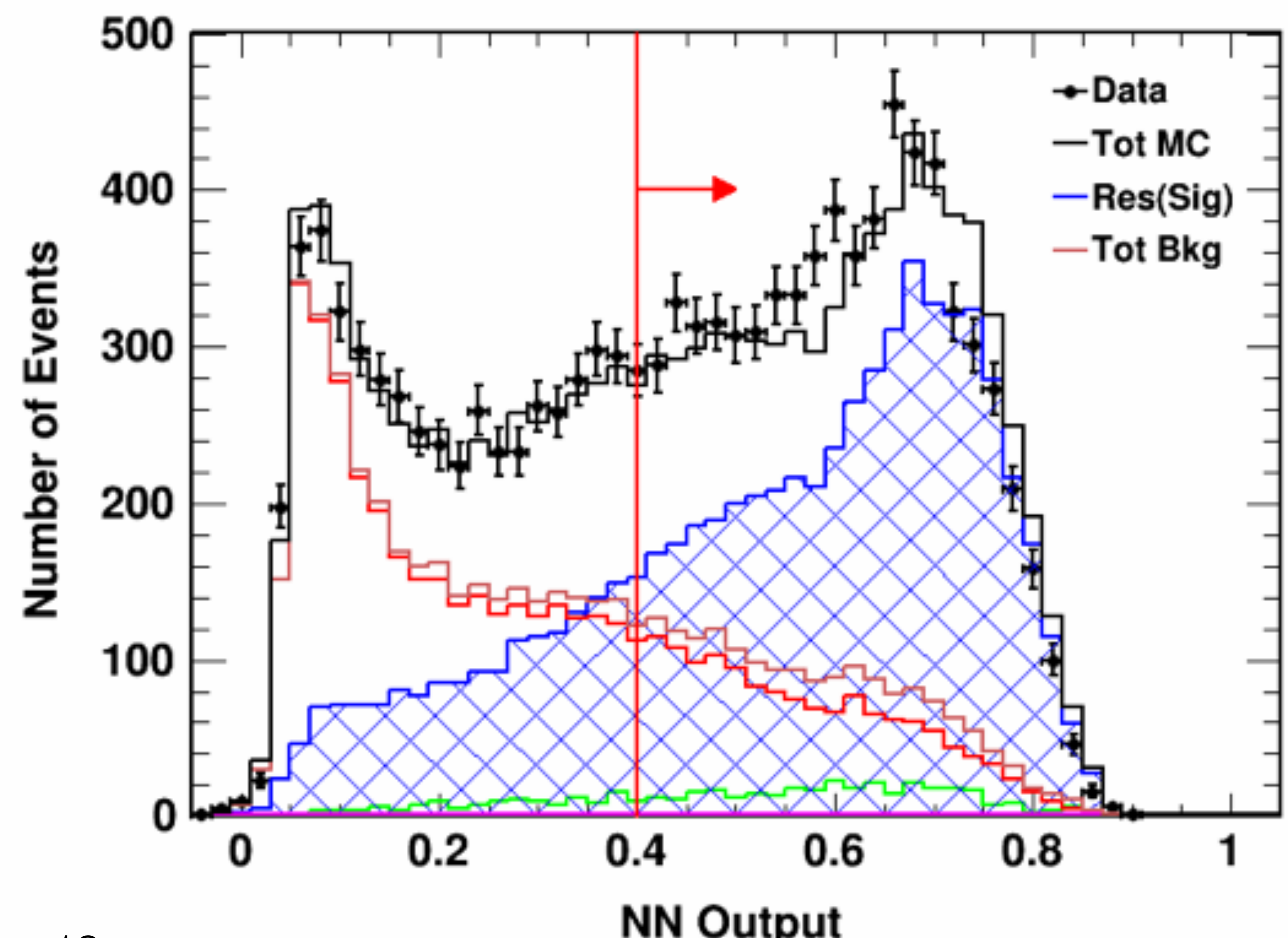
NN Analysis on NOMAD Data



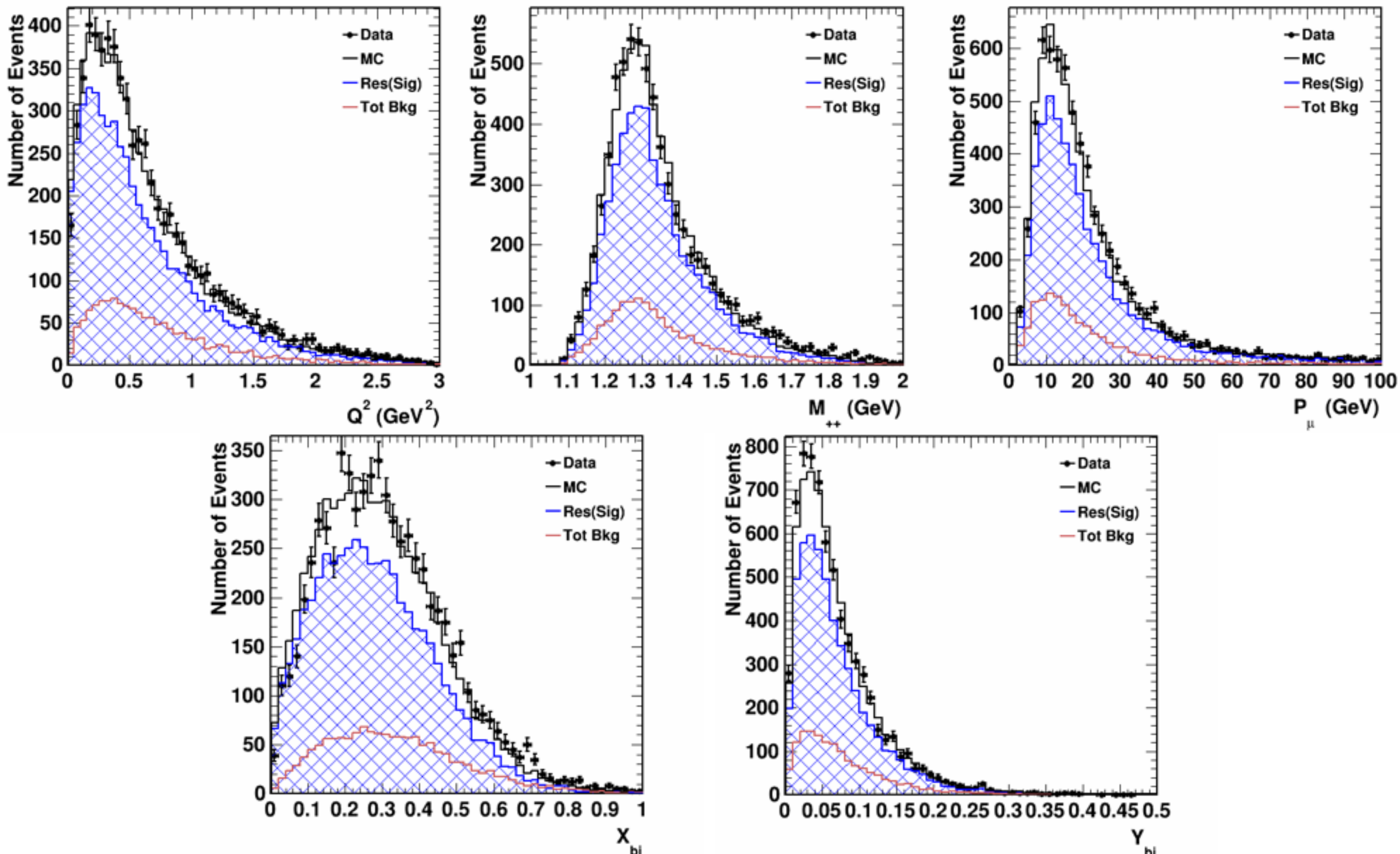




- Select one μ^- track and two positive hadron tracks events in NOMAD.
- Pre-selection cuts to reduce backgrounds, dominated by DIS.
- Events selected are taken into neural network analysis built upon track momentums.
- Normalize background to fit data.
- Compare kinematic variables in data vs MC.

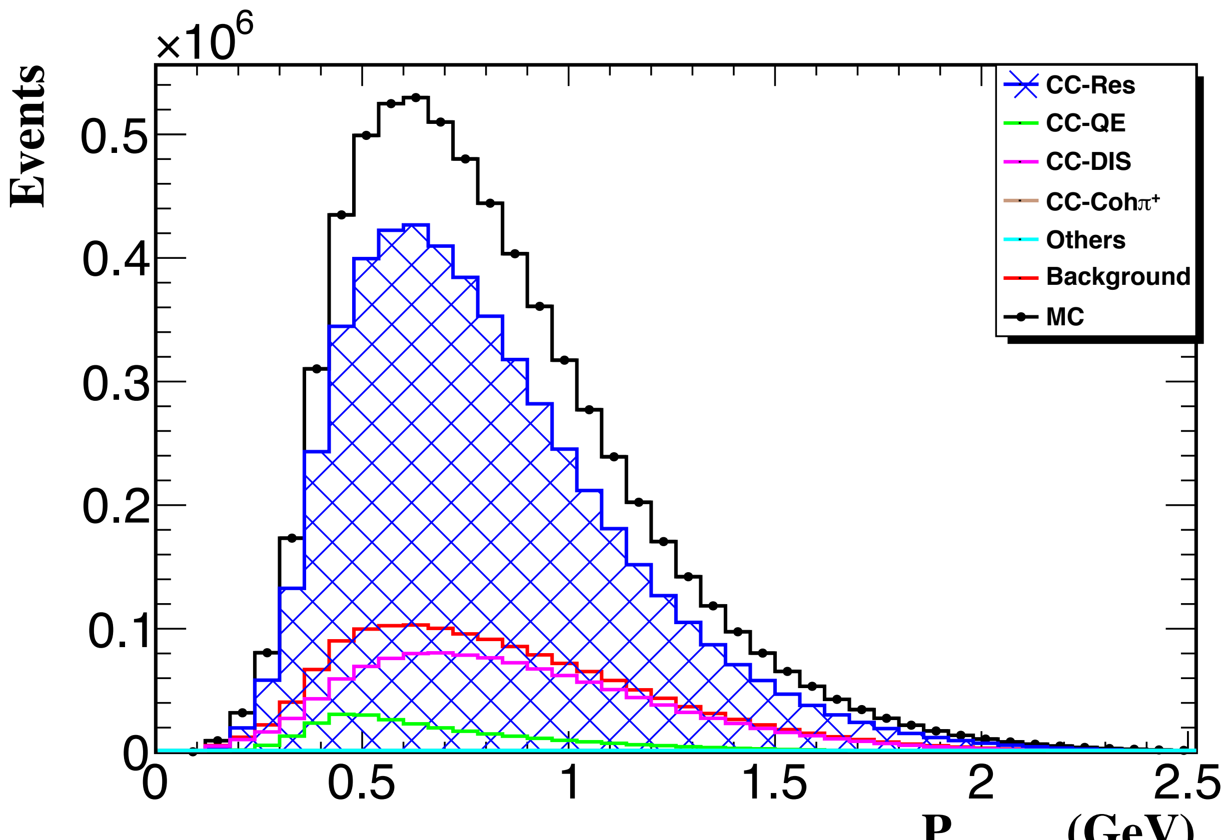


Data vs MC

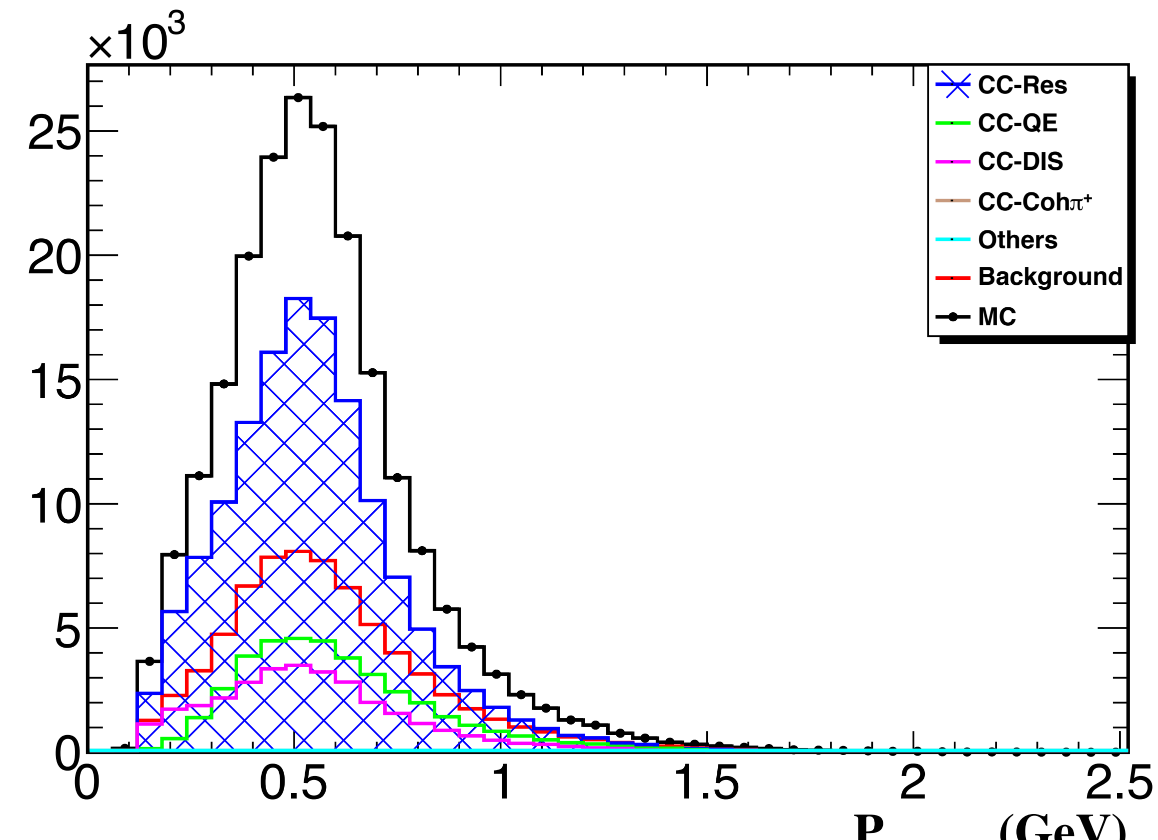


GENIE prediction agrees quite well with data.

Backward-Going Pions



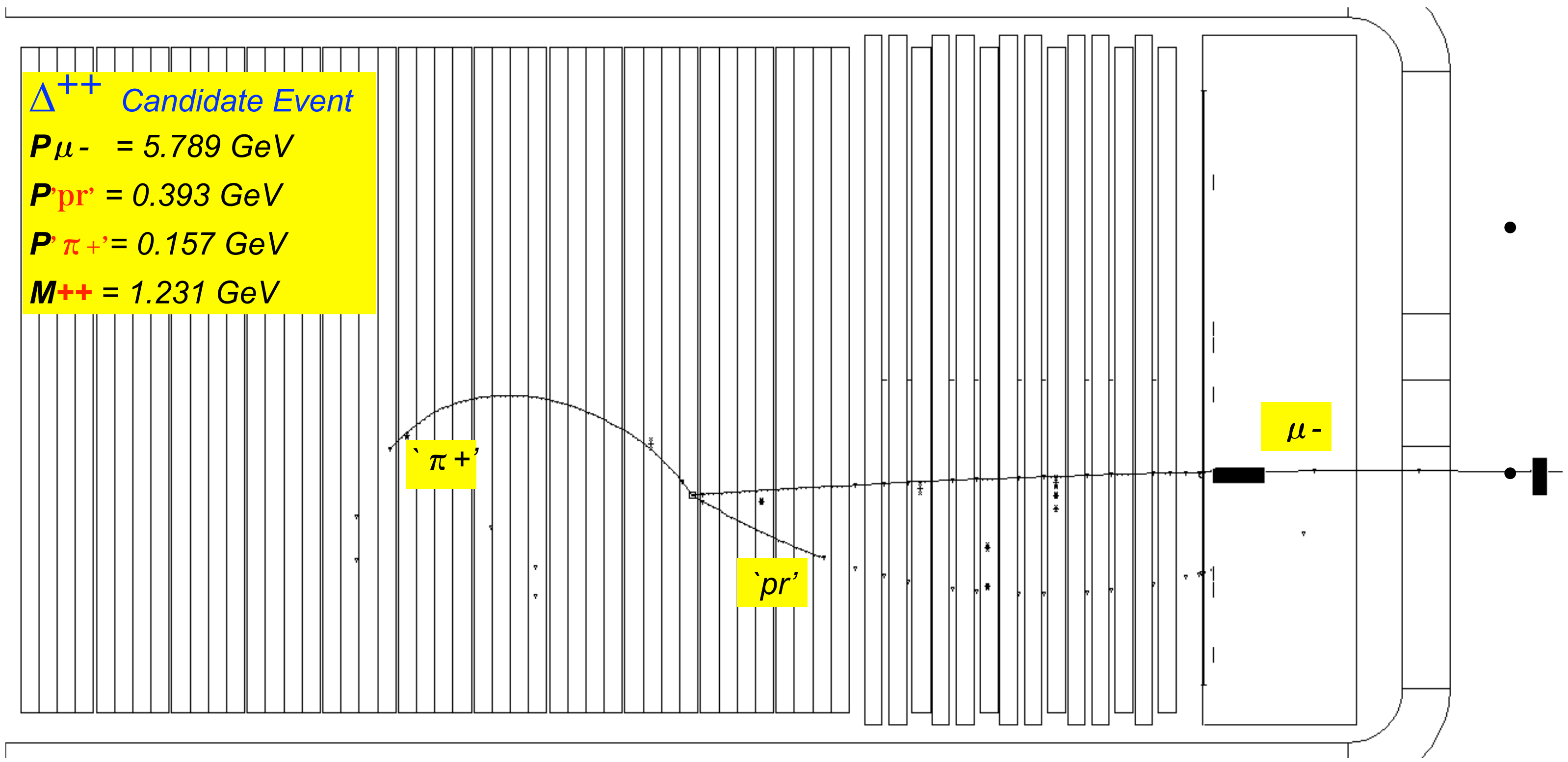
Pz > 0



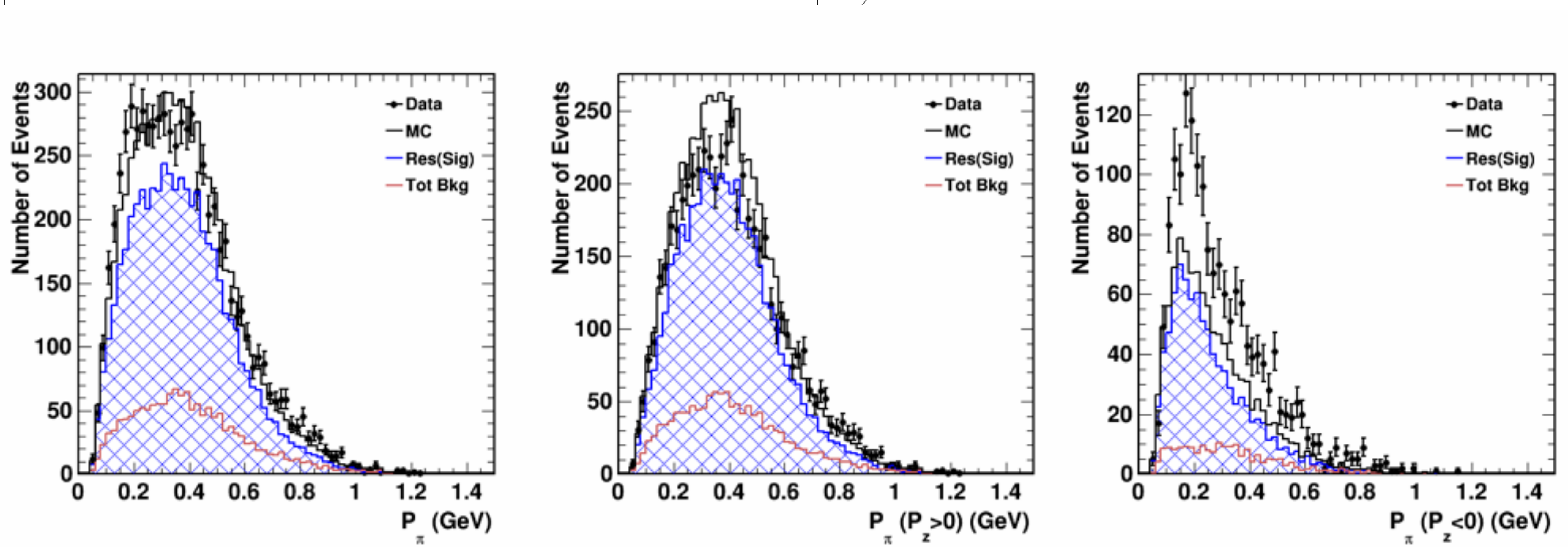
Pz < 0

- 32.7% of the pions are backward-going according to GENIE.
- Backward-going pions are most sensitive to nuclear effects and provide an excellent probe to constrain nuclear effects such as Fermi-motion and FSI.

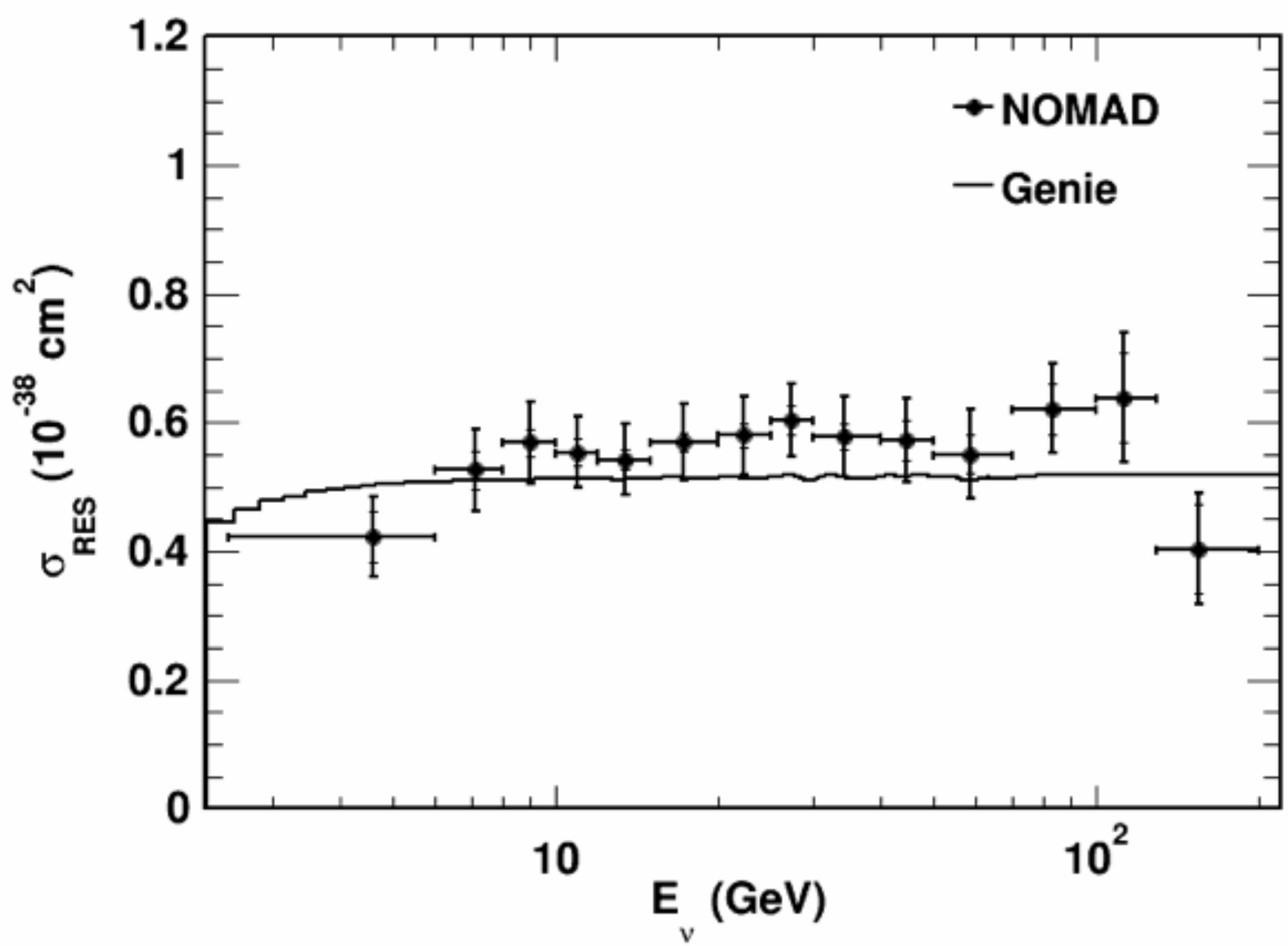
Backward-Going Pions in NOMAD



- Although overall MC agree with data, backward-going pions are not well described by GENIE.
- Could provide a handle to constrain nuclear effect.



Resonance Cross-Section: NOMAD Preliminary



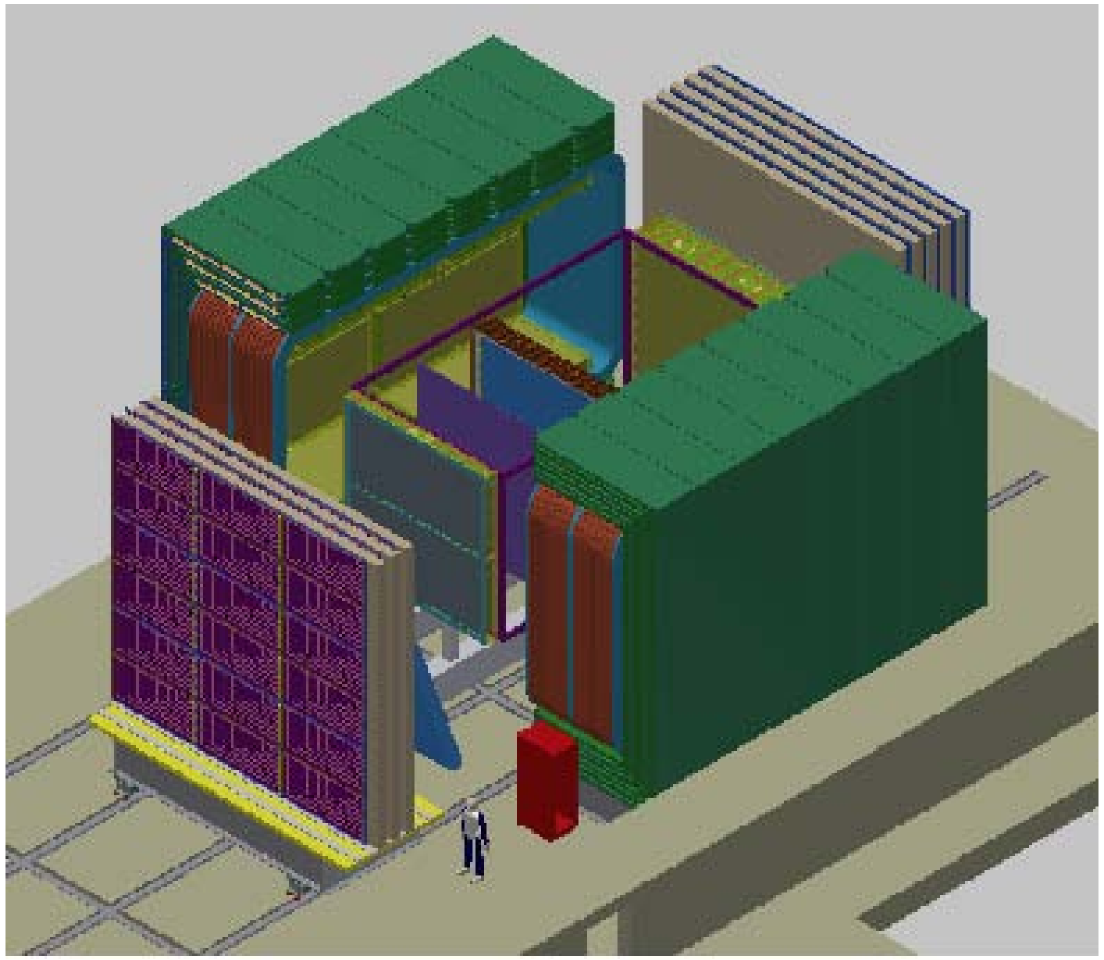
- A similar NN analysis with 2-track sample which is statistically independent from 3-track: (muon tack + one positive hadron track).
- Subtract background from data, and fully correct it. Got Consistent result from 3-track analysis and 2-track analysis.
- Combine 3-track result with 2-track result to get a final measurement.
- Take flux measurement from earlier NOMAD publication to calculate the cross-section.

Summary

- We use fast MC to study the resonance interaction sensitivity in a Fine-Grained Track detector.
- Similar analysis applied to NOMAD data for validation.
- Overall GENIE prediction agrees with NOMAD data.
- Backward-going pions are poorly predicted by GENIE and can be used as a handle to constrain nuclear effects.
- NOMAD data provide the most precise measurement of resonance interaction in 2.5 GeV ~ 200 GeV.
- The proposed FGT for DUNE is expected to do even better.

Backup Slides

A Fine-Grained Tracker Near Detector For DUNE



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Angular Resolution	2 mrad
E_e Resolution	5%
E_μ Resolution	5%
$\nu_\mu/\bar{\nu}_\mu$ ID	Yes
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NCπ^0/CCe Rejection	0.1%
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- Determine the unoscillated neutrino flux with high precision for all neutrino species.
- Argon target nucleus allow cancellation of systematics.
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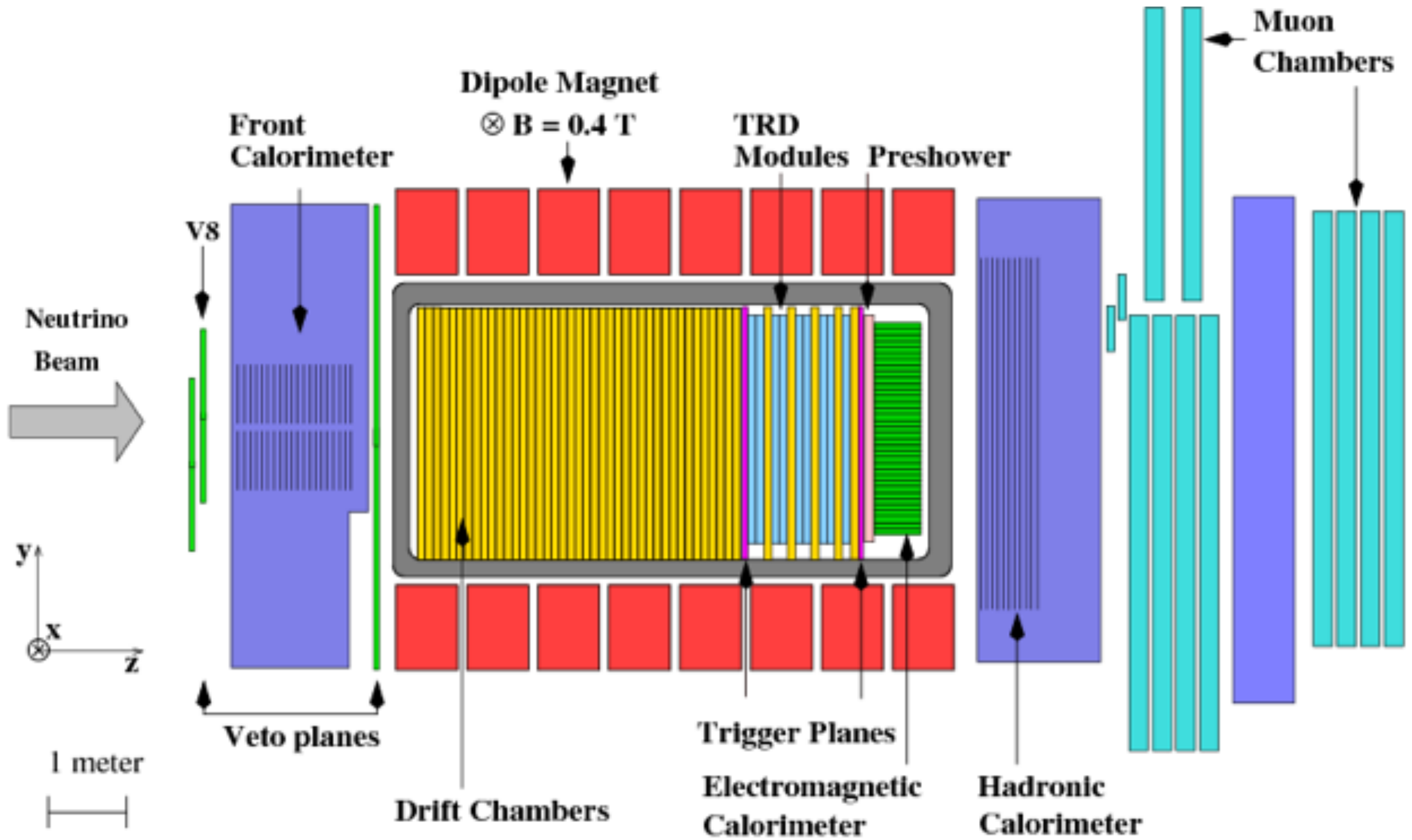
ND Specs

- These are defined in the configuration file: $FMC_CONFIG/FastMC_DetParams.xml within the block of <param_set name="STT_1">
- Internal Magnetic Volume: $4.0 \times 4.0 \times 8.1$ m
- Tracker volume (STT): $3.5 \times 3.5 \times 7.04$ m (6.40 m), density = 0.1 g/cm^3
- Fiducial volume: $|x, y| < 150$ cm, $25 < z < 550$ cm
- Radiation length: $X_0 \simeq 600$ cm
- hadronic interaction length: 1,200 cm
- Charged particle momentum resolution: $\sigma_p/p = \frac{0.05}{\sqrt{L}} + 0.008p/\sqrt{L^5}$, where L is the track length
- Angular resolution: $\theta_0 = \frac{13.6\,\mathrm{MeV}}{\beta cp} z \sqrt{x/X_0}[1 + 0.038 \ln(x/X_0)]$
- EM shower energy resolution: $\sigma_E/E = 1\% + 0.06/\sqrt{E}$
- Hadronic shower energy resolution: $\sigma_E/E = 1\% + 0.50/\sqrt{E}$

Fast MC

- Fast MC = Fast Detector Simulation + Fast Reconstruction
- The Chain: G4LBNE$\rightarrow$GENIE$\rightarrow$ND Fast MC$\rightarrow$Analyzing the output ROOT files
  - G4LBNE produces the flux
  - GENIE produces the interactions with a homogeneous detector with approximately the same composition as the current design of HiResMν
  - ND Fast MC will mimic the detector simulation and recontruction to produce the "reconstructed" variables for downstream analysis
  - Analyzing the output "reconstructed" ROOT files for specific topics
- Use the exisiting NOMAD data to benchmark the whole chain
- Re-use as much as possible the existing Fast MC codes developed by Dan and Rik. It is also a good cross check of the existing code

NOMAD



- The Neutrino Oscillation MAgnetic Detector (NOMAD) was designed to search for ν_μ to ν_τ appearing in the CERN SPS wide band neutrino beam.
- A FGT detector upon which the proposed DUNE ND is designed.
- Accumulated ~2M neutrino events which can be used to validate the ideas developed in the designing of DUNE FGT
- Also leading to precise measurements of neutrino interactions on its own.

NOMAD vs FGT

NOMAD -vs- HiResFGT

✴ *Tracking Charged Particles* ⇒

✴ *Electron/Positron ID* ⇒

✴ *Calorimetry* ⇒

✴ *μ-ID* ⇒

✴ *Trigger* ⇒

Sub-Detector	NOMAD	HiResMnu	Improvement
Tracking		$\times$6 more hits in X-Y $\times$2 more hits along Z	$\times$2 higher QE-Proton Eff. $e^{\pm}$ down to 80 MeV γ-Conv. Reconstruction
TR: Electron-ID	Downstream	Continuous	$\simeq \times 3$ $e^{\pm}$-Eff
Calorimetry Segmentation E-shower Resolution	Downstream No Longitudinal Transverse $3\%/\sqrt{E}$	4π Coverage Fine Longitudinal Finer Transverse $6\%/\sqrt{E}$	Much better converage $e^{\pm}/\pi$ Separation Better miss-P_T Powerful 'Dirt'-Veto Poorer resolution
μ-ID	Downstream $P_\mu \geq 2.5$ GeV	4π Coverage	P_μ down to 0.3 GeV
Trigger	Downstream No Cal.Trigger	Continuous in STT Calorimetric Trigger	P down to 0.1 GeV $E \simeq 0.3$ GeV

Preselection Cuts

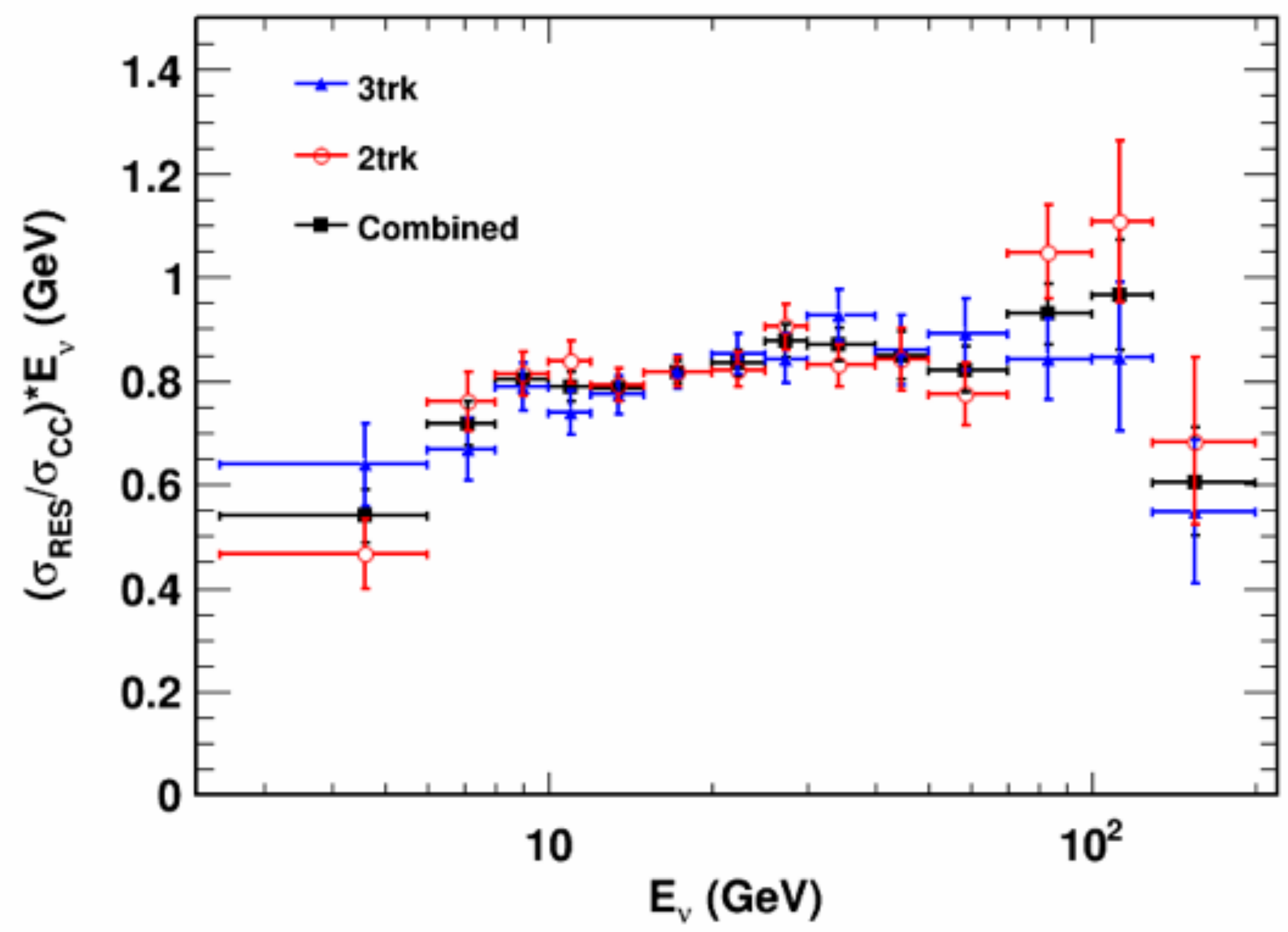
Cut	Sig.	Sig. Eff.	Back.	Back. Surv. Prob.
Fiducial	1.643e+07	1	4.221e+07	1
$p_\mu > 0.2$ GeV/c	1.619e+07	0.9856	4.136e+07	0.9799
$n_\mu^{\mathrm{hits}} > 12$	1.593e+07	0.9695	4.074e+07	0.9652
μ_{ID}	1.43e+07	0.8705	3.668e+07	0.869
$\pi^0/n/K_0$ veto	1.081e+07	0.6582	1.758e+07	0.4165
$>= 2$ track w/ $n_{\mathrm{Had}}^{\mathrm{hits}} >= 4$	8.283e+06	0.5043	8.017e+06	0.1899
$>= 2$ track w/ $p > 0.10$ GeV/c	8.063e+06	0.4908	7.892e+06	0.187
2 positive track	5.928e+06	0.3609	2.811e+06	0.06659

- μ_{ID}:
  $\mu_{\mathrm{ID}} = 60\%$ @ $p_\mu \in [0.2, 0.6]$ GeV/c,
  $\mu_{\mathrm{ID}} = 80\%$ @ $p_\mu \in [0.6, 1.0]$ GeV/c,
  $\mu_{\mathrm{ID}} = 95\%$ @ $p_\mu > 1.0$ GeV/c.
- π^0 veto: Require $p_\gamma < 0.08$ GeV,
- neutron veto: Require $T_n < 0.25$ GeV,
- K_0 veto: Require $T_{K_0} < 0.25$ GeV.

Background Decomposition

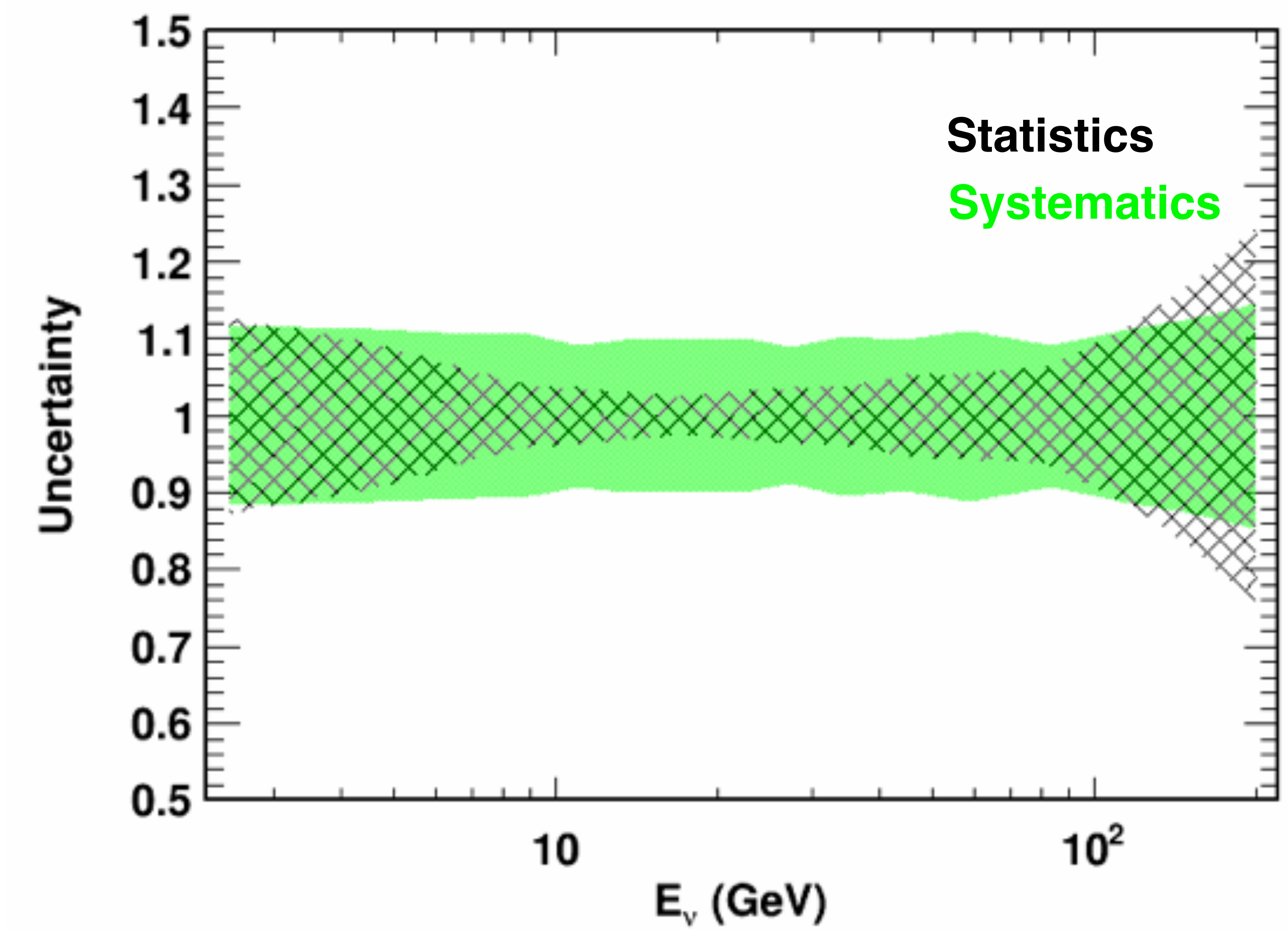
Cut	QE	DIS	Coh	Other	Background
Fiducial	9.269e+06	3.179e+07	4.663e+05	6.846e+05	4.221e+07
$p_{\mu} > 0.3$ GeV/c	9.259e+06	3.096e+07	4.65e+05	6.747e+05	4.136e+07
$n_{\mu}^{\mathrm{hits}} > 12$	9.129e+06	3.047e+07	4.649e+05	6.719e+05	4.074e+07
μ_{ID}	8.408e+06	2.723e+07	4.299e+05	6.174e+05	3.668e+07
$\pi^0/n/K_0$ veto	8.135e+06	8.806e+06	4.299e+05	2.103e+05	1.758e+07
$>=$ 2 track w/ $n_{\mathrm{Had}}^{\mathrm{hits}} >= 4$	7.793e+05	7.042e+06	0	1.955e+05	8.017e+06
$>=$ 2 track w/ $p > 0.10$ GeV/c	7.563e+05	6.941e+06	0	1.944e+05	7.892e+06
2 positive track	7.427e+05	3.533e+06	0	6186	4.282e+06
$NN > 0.22$	4.791e+05	2.327e+06	0	4855	2.811e+06
$NN > 0.35$	3.367e+05	1.233e+06	0	1311	1.571e+06

3-Track Analysis + 2-Track Analysis



- Similar analysis with 2-track sample which is statistically independent from 3-track: (muon tack + one positive hadron track).
- Result shown as ratio of fully-corrected resonance events to inclusive charged-current events.
- 2-track result is consistent with 3-track analysis.
- Combine 3-track result with 2-track result to reduce statistic uncertainty. Also the combined analysis is less sensitive to some systematics.

Systematics



- Systematic uncertainties come from resonance modeling (M_A, M_V, MFP), signal selections(pre-selection cuts, NN) and flux measurement.
- Cross-section measurement agrees with GENIE prediction (M_A = 1.12 GeV, M_V = 0.84 GeV).