Physics studies for near detector upgrade in T2K experiment

NBIA PhD School "Here, There & Everywhere"

NGUYEN Quoc Viet
LPNHE, Paris
Supervisor: Boris Popov

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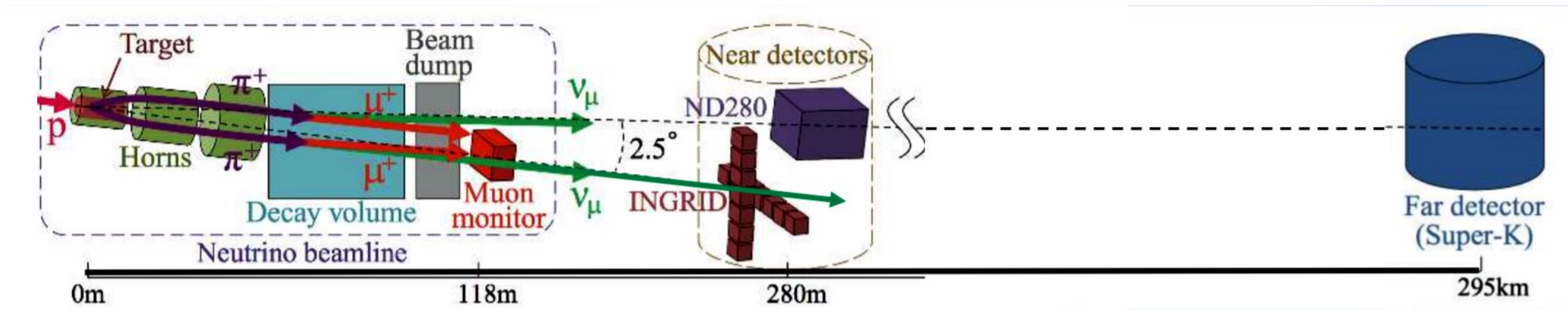
T2K experiment



T2K (Tokai to Kamioka) is a long-baseline neutrino experiment in Japan, and is studying neutrino oscillations.

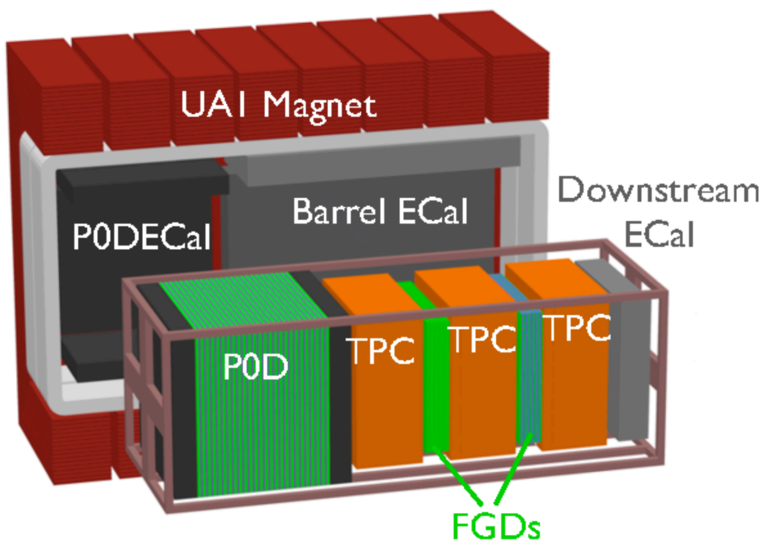
T2K goals:

- Precise measurements of oscillation parameters ($\theta_{23}, \theta_{13}, \Delta m^2_{32}$)
- Searching for the CP violation in the lepton sector by comparing the appearance probabilities of electron neutrino and electron antineutrinos.
- Neutrino mass hierarchy

T2K is under an upgrade program for the near detector ND280 (upgraded ND280)

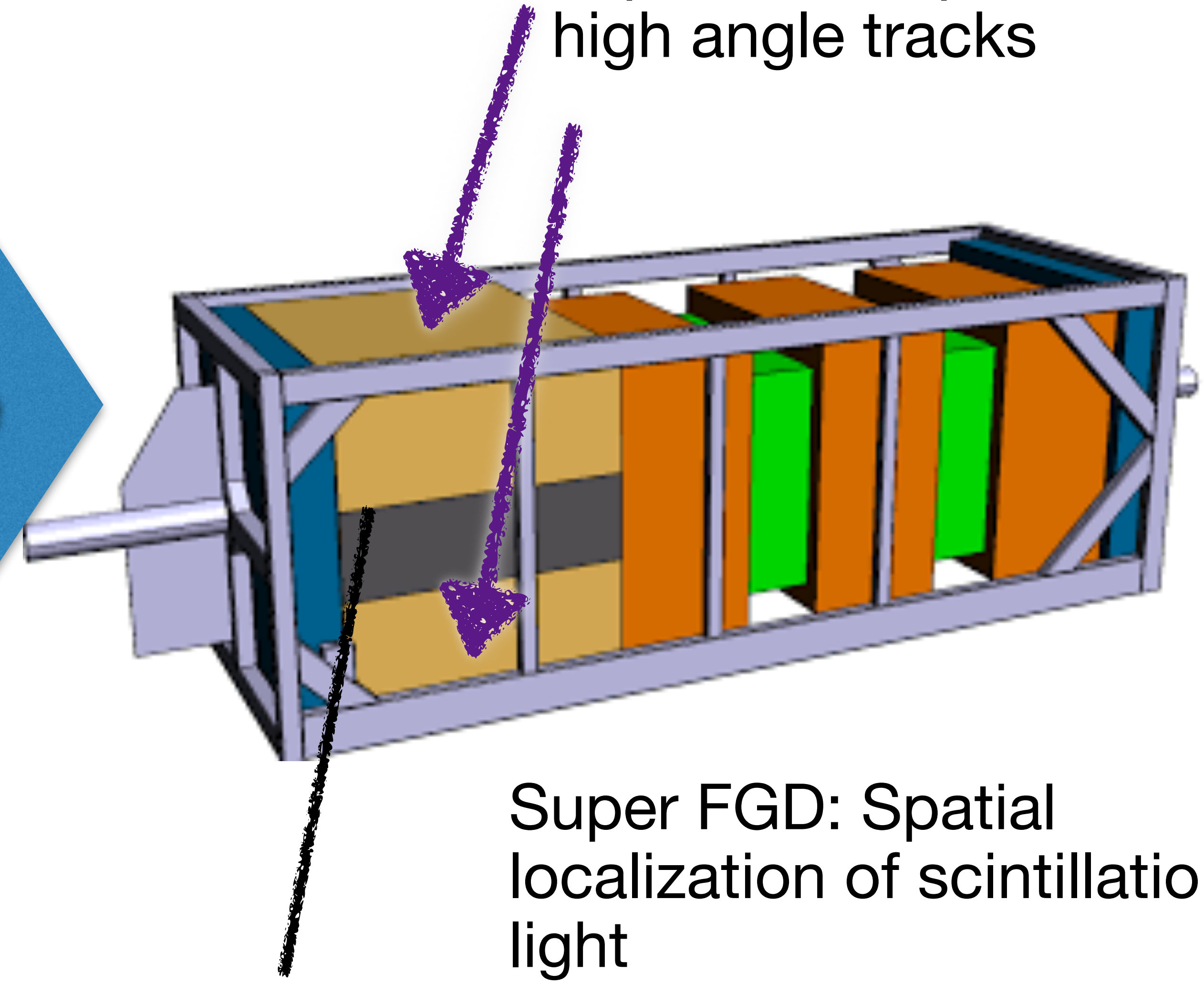
ND280 Upgrade

High Angle (HA) TPC: Improve acceptance for high angle tracks



FGD: fine grained detector

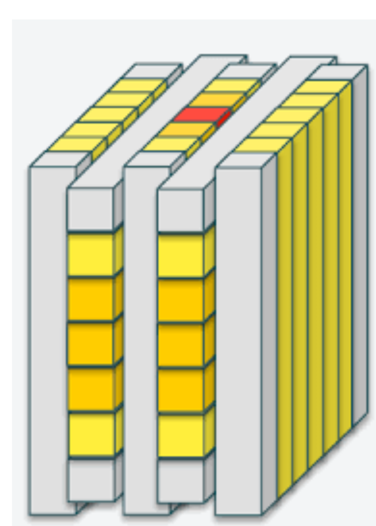
Upgrade



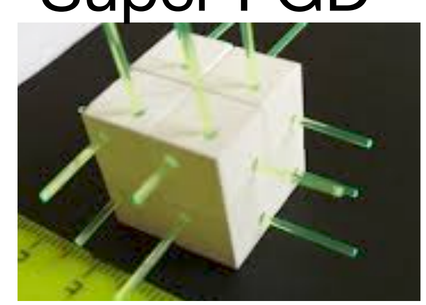
Super FGD: Spatial localization of scintillation light
-> Improve reconstruction of hadrons and low momentum leptons

Good acceptance only for forward tracks

plastic scintillators made by long bars —> poor angular acceptance



Super FGD

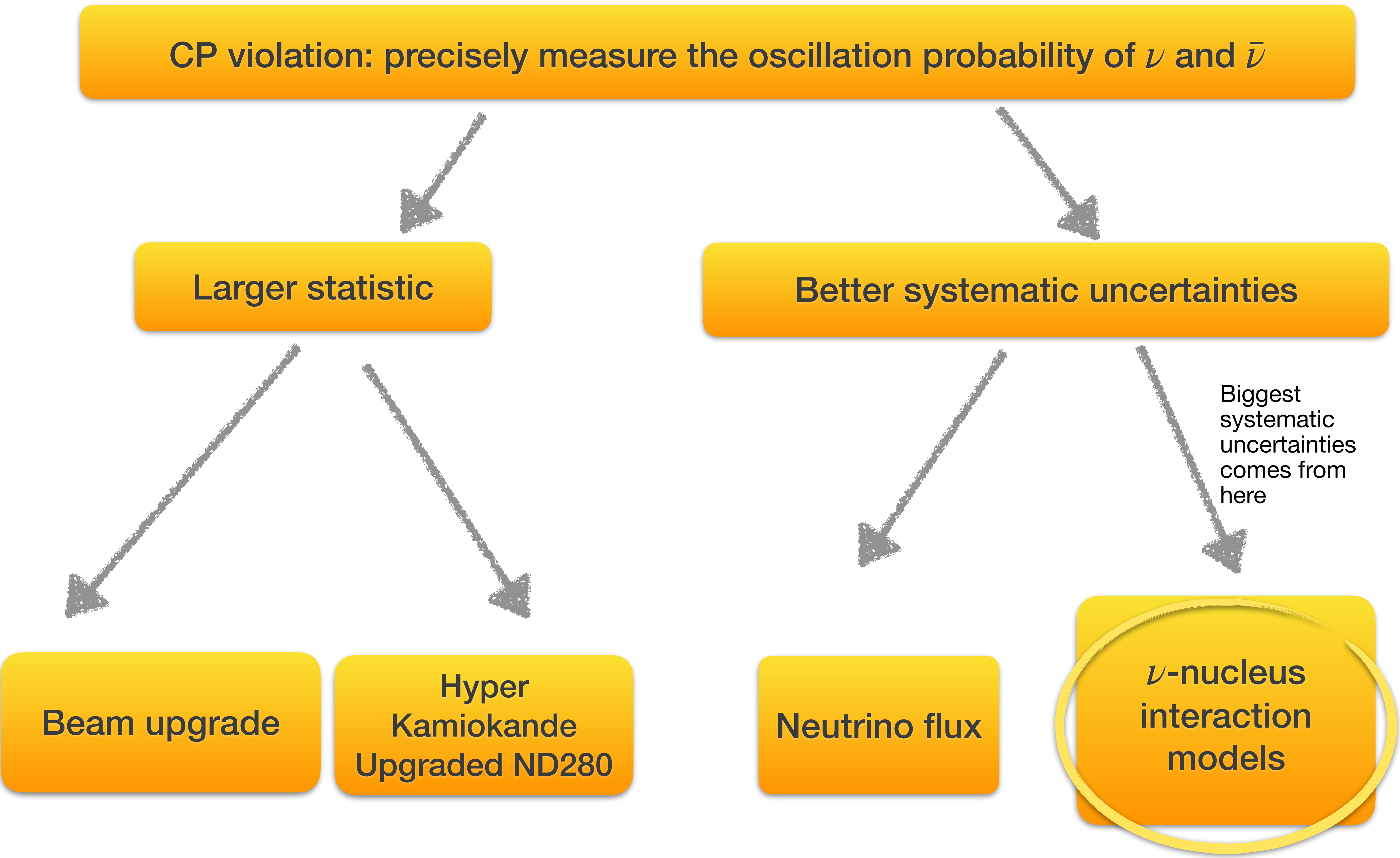


Plastic scintillator 1x1x1 cm3 cubes

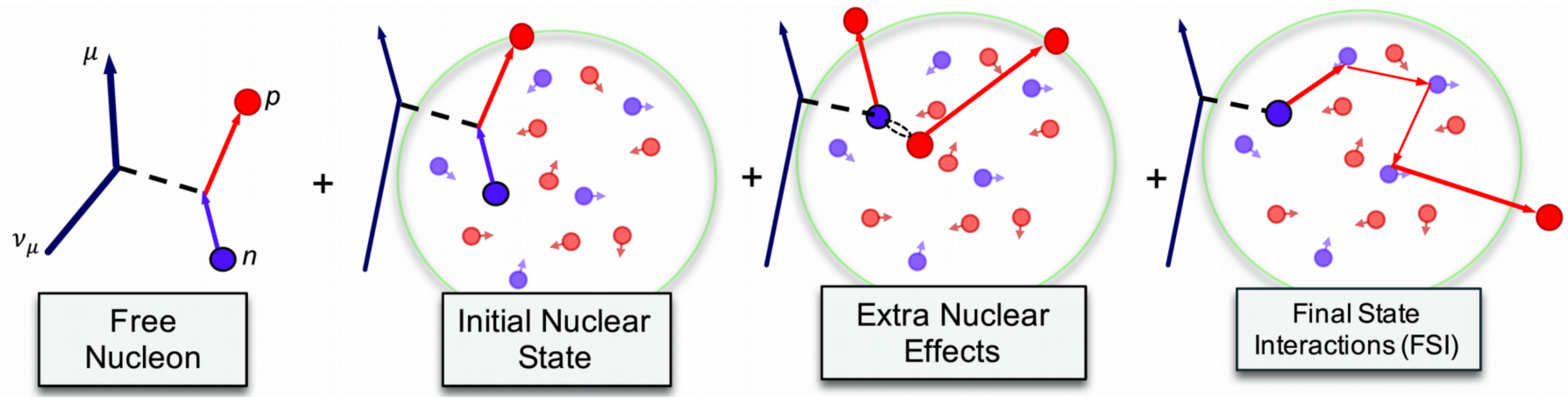
FGD is the target of ND280. Double the mass of detector=> more statistic

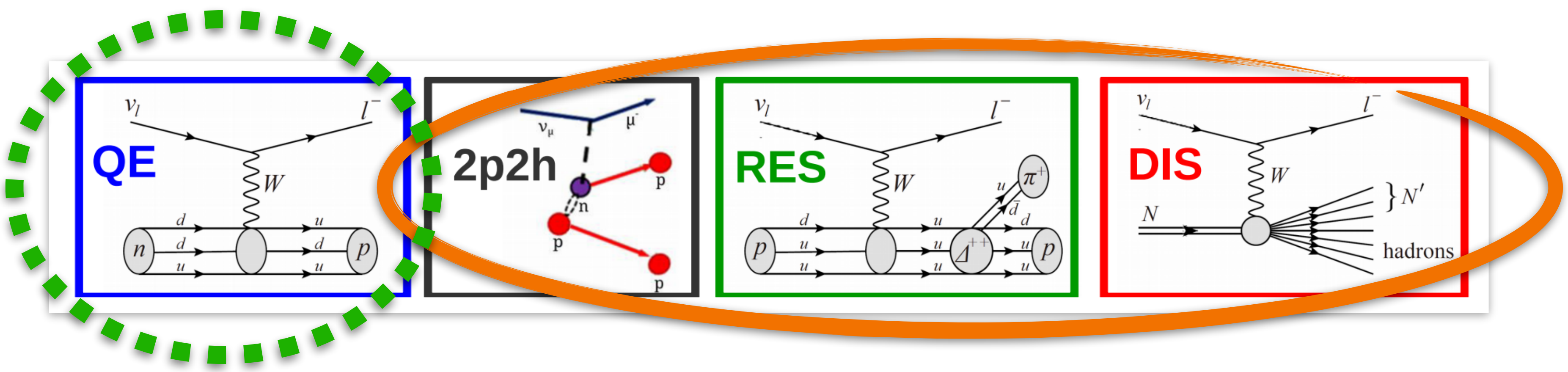
Physics Studies for ND280 upgrade

Quantitative sensitivities to neutrino-nuclei interaction mode



Neutrino-nucleus interaction





SuperK select single ring events, mostly populated by Charge Current Quasi-Elastic (CCQE) events. Neutrino energy reconstruction is based on the CCQE kinematics

$$E_\nu = \frac{m_p^2 - m_\mu^2 + 2E_\mu(m_n - E_b) - (m_n - E_b)^2}{2[(m_n - E_b) - E_\mu + p_\mu \cos\theta_\mu]}$$

Unfortunately, sometime the hadronic part is below Cherenkov threshold and hence not reconstructed. These modes could mimic CCQE events. In these cases the energy reconstruction will give biases.

near detector ND280 need to carefully model the QE and the non-QE interactions

ND280 physics study

2014

Error source	1Re sample	1Rμ sample
Beam only	7.41	6.08
M_A^{QE}	3.07	2.76
M_A^{Res}	1.02	2.36
CCQE norm.	6.22	4.60
CC1π norm.	2.03	2.99
NC1π^0 norm.	0.43	N/A
CC other shape	0.12	0.89
Spectral Function	1.11	0.21
E_b	N/A	0.21
p_F	0.11	0.14
CC coh. norm.	0.24	0.81
NC coh. norm.	0.24	N/A
NC 1$\pi^{\pm}$ norm.	N/A	0.76
NC other norm.	0.5	0.86
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$	2.86	$<$0.01
$\sigma_{\overline{\nu}}/\sigma_{\nu}$	0.14	1.2
W shape	0.23	0.26
pion-less Δ decay	2.0	4.03
SK parameters	3.56	4.92
SK momentum scale	0	0
Total	**6.28**	**7.35**

2015

Systematic	$\frac{\Delta N_{SK}}{N_{SK}}$ without ND	$\frac{\Delta N_{SK}}{N_{SK}}$ with ND
All common to ND/SK	9.2%	3.4%
Multinucleon effect on oxygen	9.5%	
All oxygen cross-section	10.0%	
Final state interaction/secondary interaction at SK	2.1%	
SK detector	3.8%	
Total	14.4%	11.6%

Addition of 2p2h (unknown before) changed error dramatically

The fitter code to constrain the the QE and the non-QE model interactions

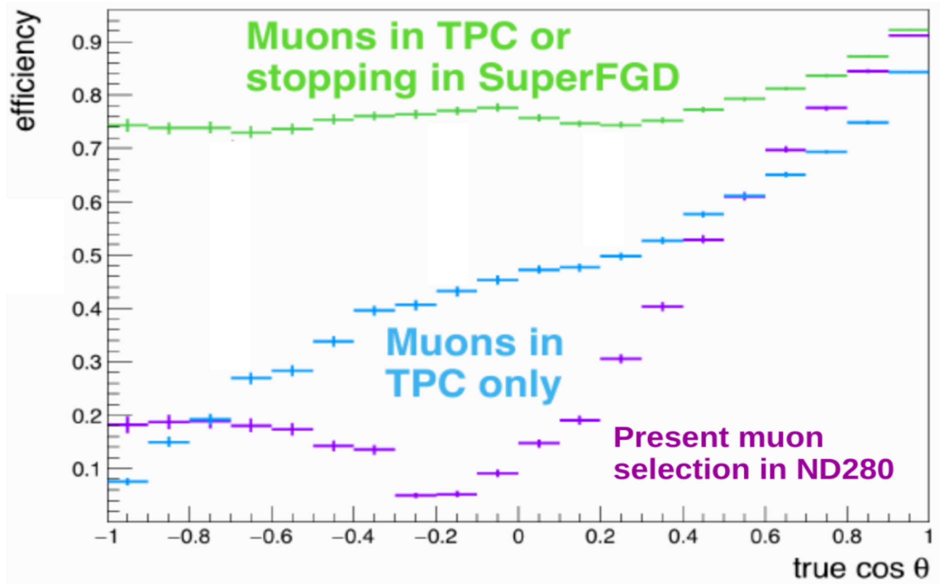
- We do a likelihood fit to evaluate sensitivity of the upgrade to flux and cross-section model by exploiting Single Traverse Variables (STVs)

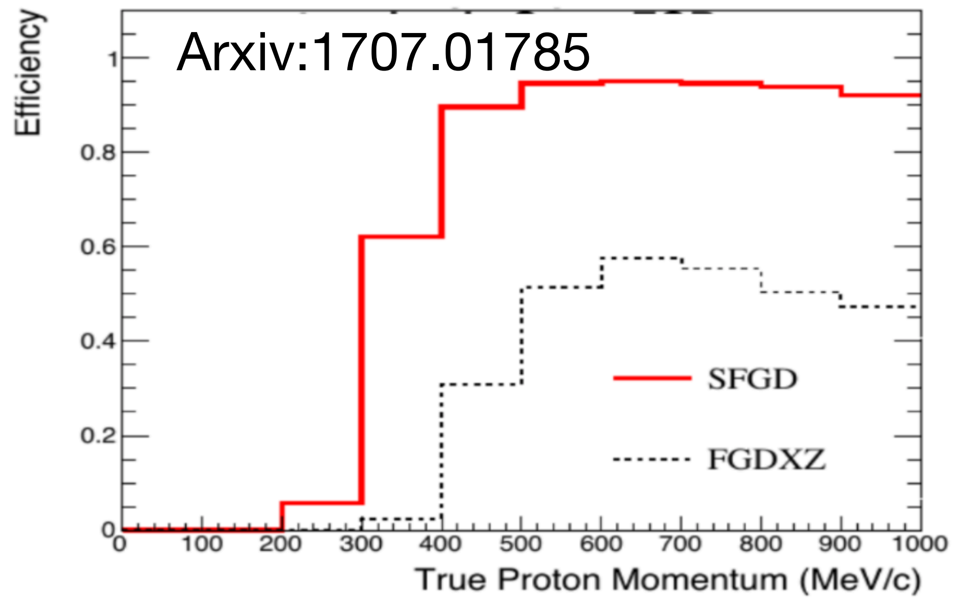
- The fitter aims to find the quantitative sensitivities to key systematic uncertainties such as CCQE, 2p2h, Proton Final State Interaction (FSI), Hydrogen normalisation.

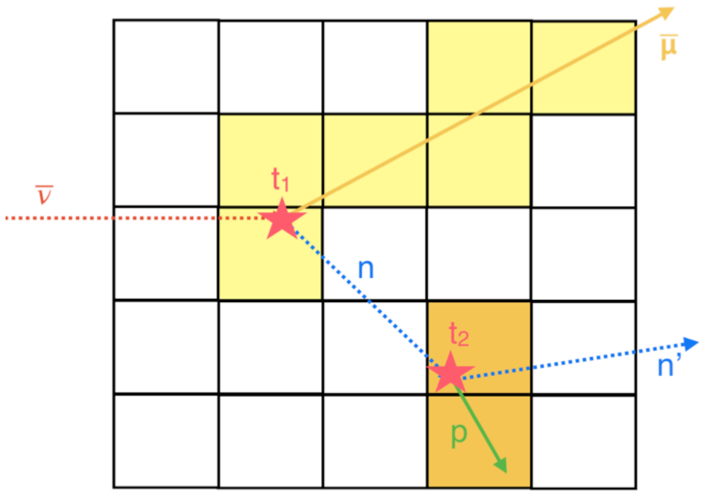
- This provides a broad estimate of the sensitivity of future near detector fits using ND280 Upgrade with better efficiency in momentum and in angle.

- We are using the fake data, the Monte Carlo is generated by NEUT generator. In this talk I will mention my studies with Spectral Function (SF) model for both neutrino and antineutrino.

Better efficiency: more events



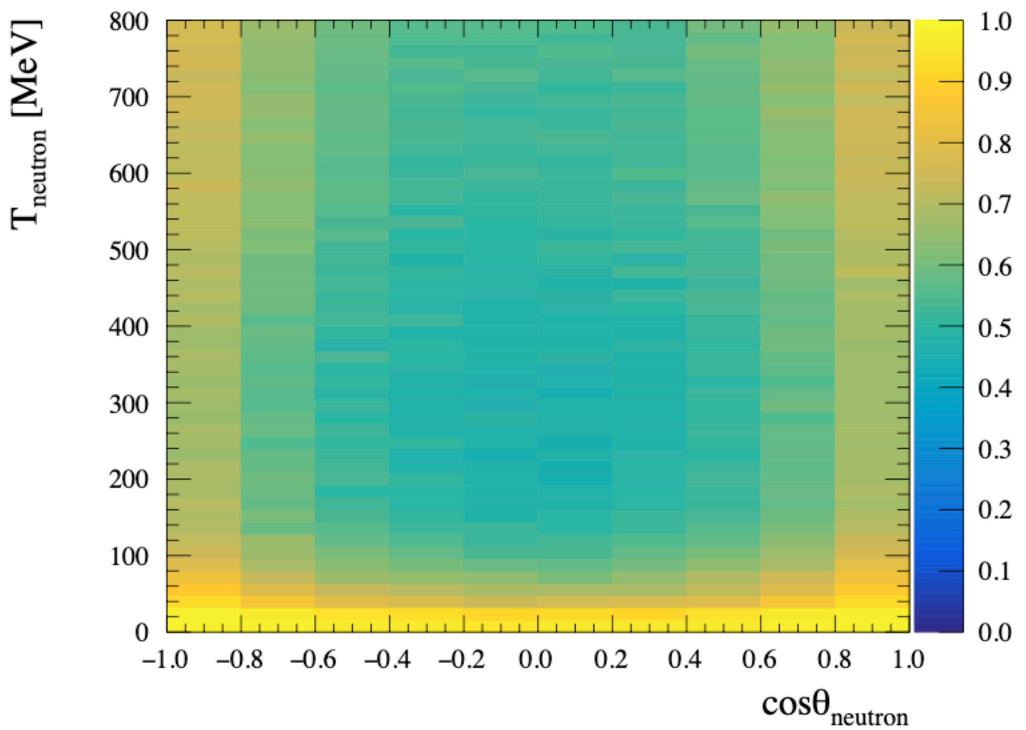




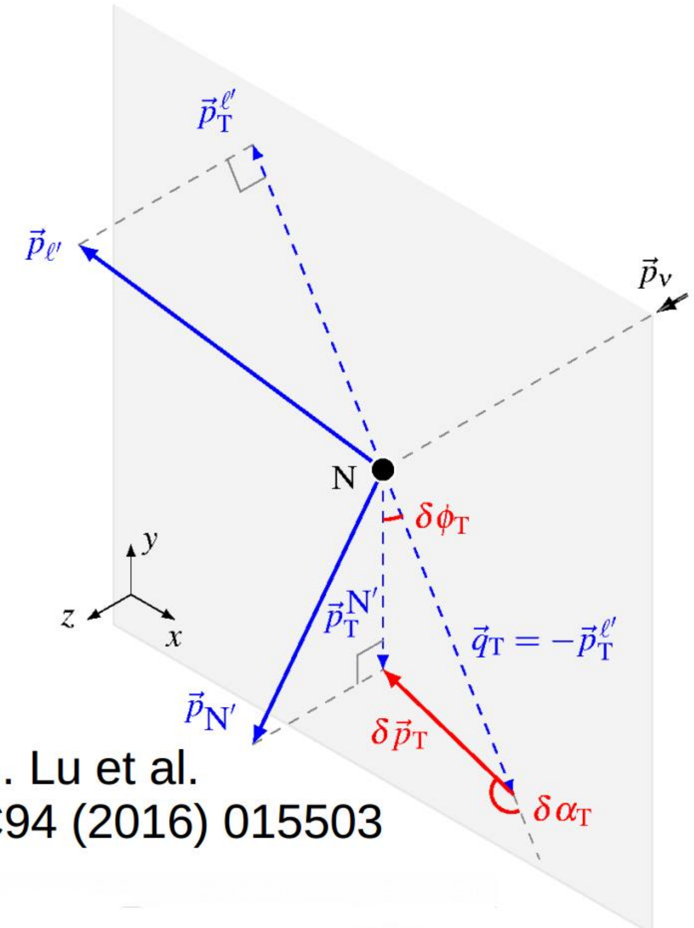
- Upgraded ND280 helps to better measure high angle tracks, lower momentum particles, and better reconstruction of the hadronic part.
  => It is thus more sensitive to important nuclear effects for our oscillation analyses.

- Events selection: CC0π
  Neutrino interaction: $\mu^- + p$ in the final state
  Anti neutrino interaction: $\mu^+ + n$ (with TOF in SFGD) in the final state.

Z-axis : neutron detection efficiency



Input



X -G. Lu et al.
PRC94 (2016) 015503

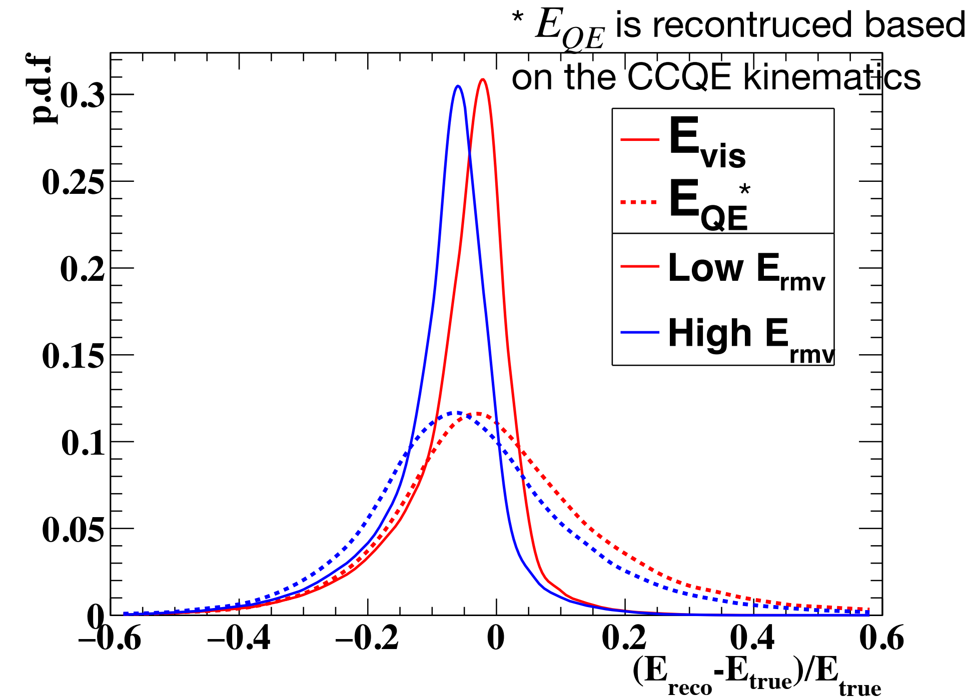
- 2D histograms of Single Transverse Variables $\delta\alpha_T$, δp_T, nucleon fermi momentum (pn), visible energy (Evis).

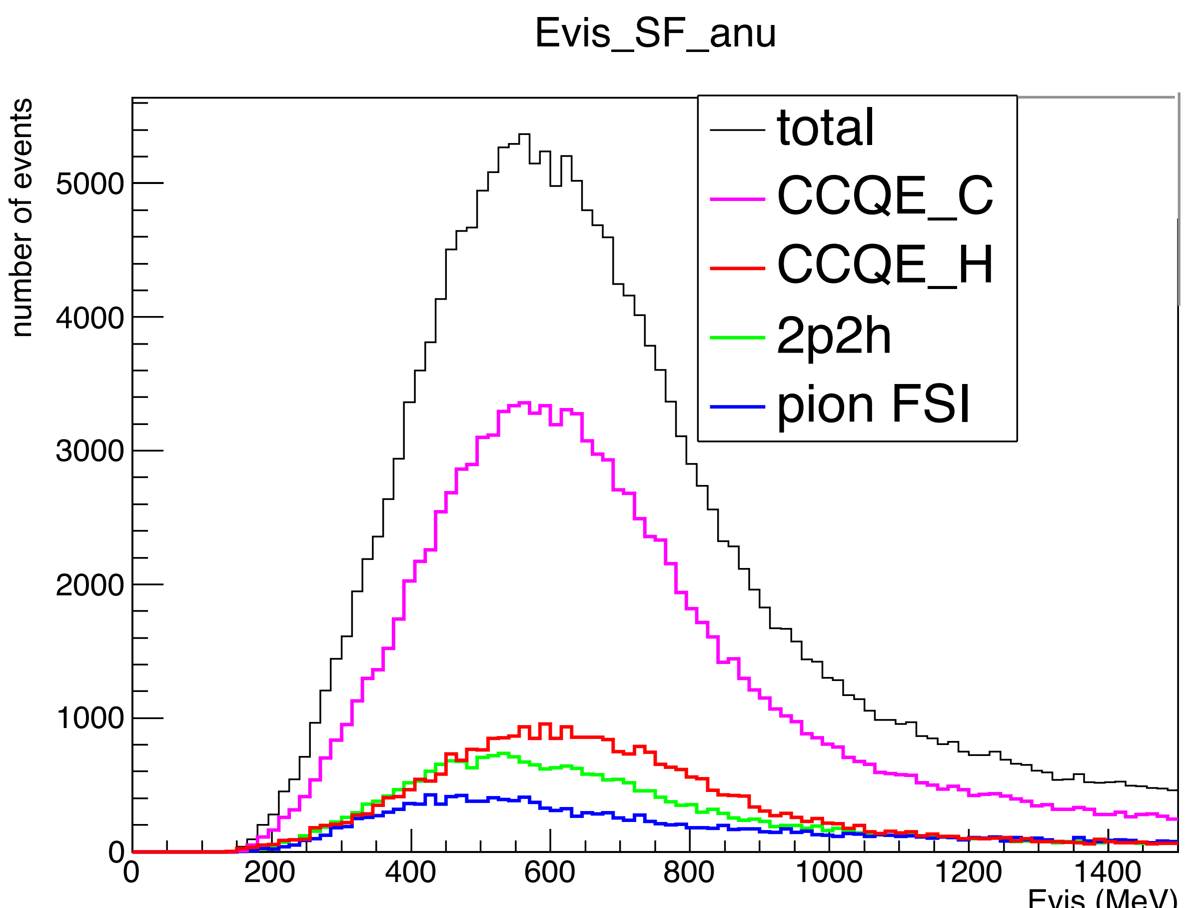
- These are reconstructed including detector effects (smearing and efficiency). The detector effects are simulated on the basis of TDR simulation.

- Focus on CC0π events
  CC0π = CCQE+2p2h+RES Pion Absorption(FSI)+ RES Pion undetected.

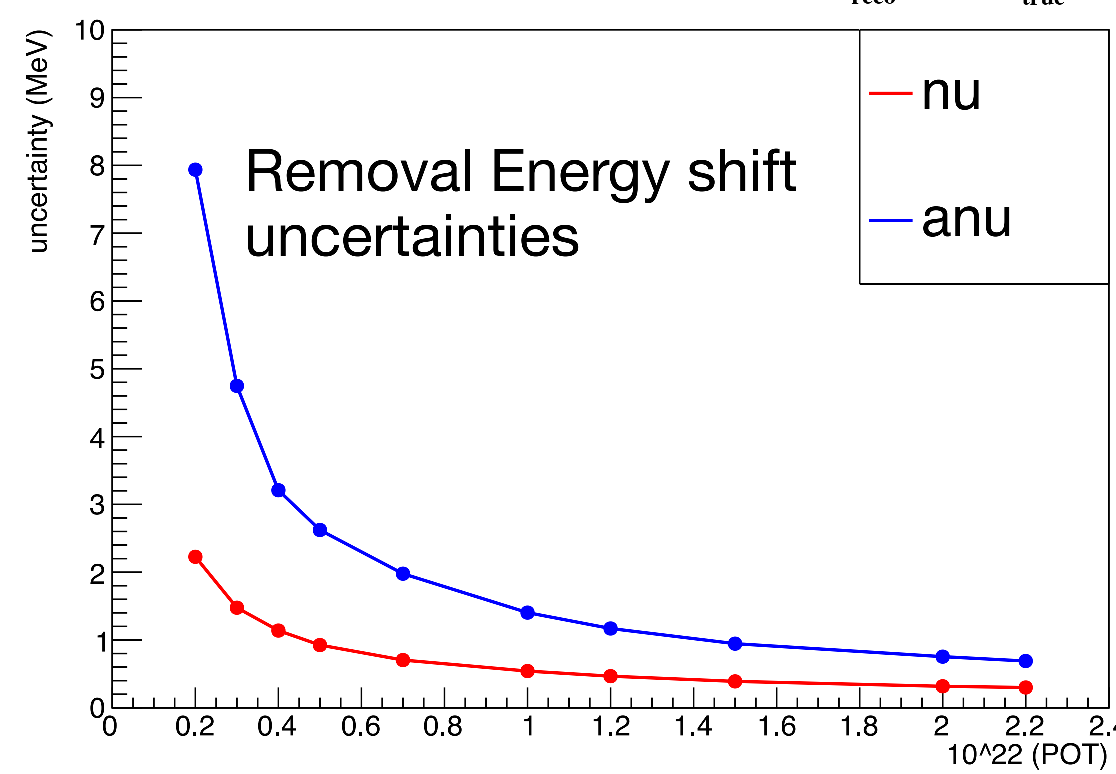
Input for fitter (Visible Energy)

- Evis = $E_\mu + T_p$ (nu interaction)
  Evis = $E_\mu + T_n$ (anti-nu interaction)
  => good estimator for neutrino energy
- Peak around 600 MeV, shape similar to the one of the T2K flux





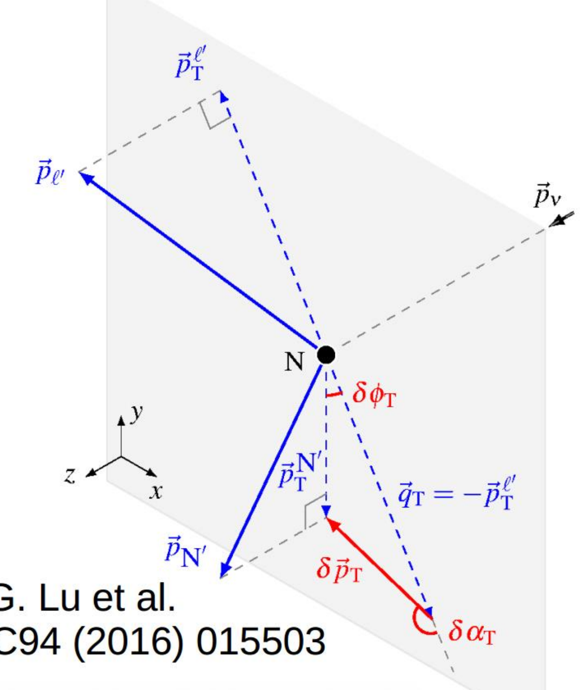
Anti-Neutrino



The Eb here is the model dependent removal energy.
I am fitting the Eb shifted within the SF.
This isn't the single value of Eb, but the parameter said how much the Eb shifting from its nominal value

Sensitivity of $\delta\alpha_T$

- $\delta\alpha_T = \arccos\left(-\frac{\mathbf{p}_T^{\mu} . \delta\mathbf{p}_T}{p_T^{\mu}\delta p_T}\right),$



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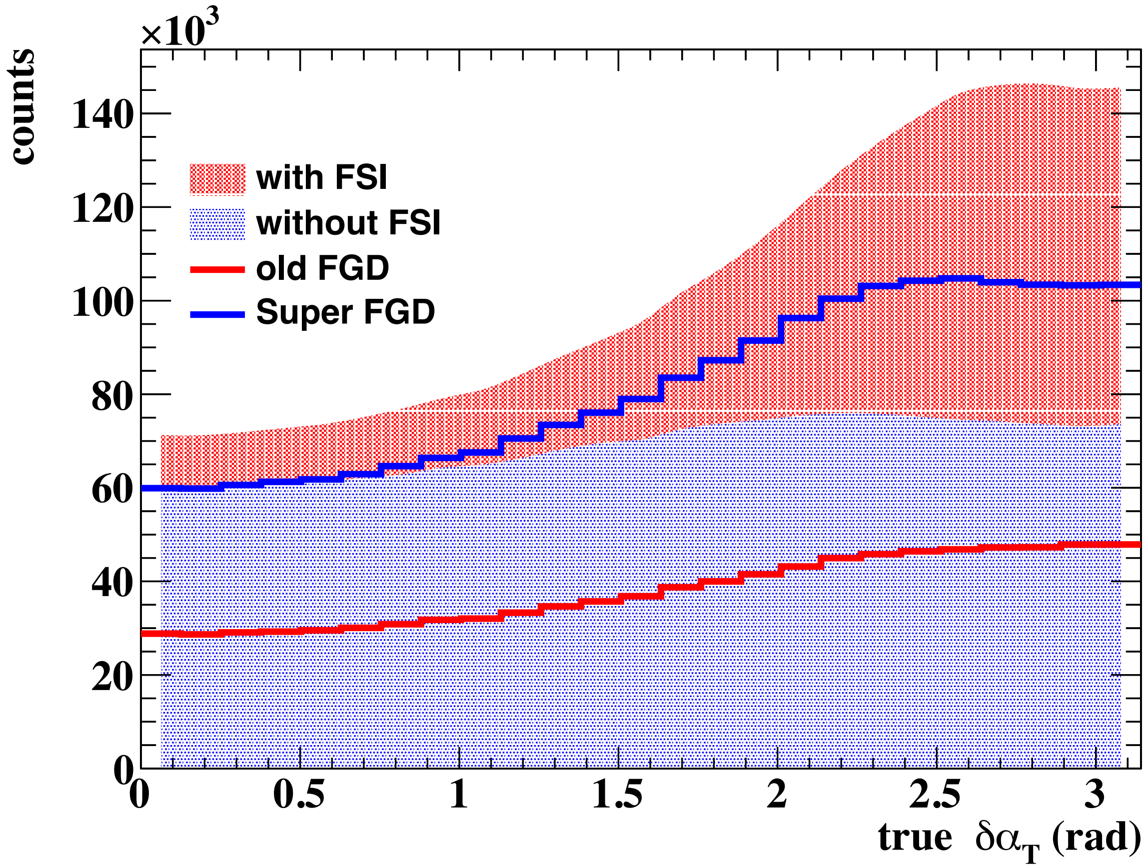
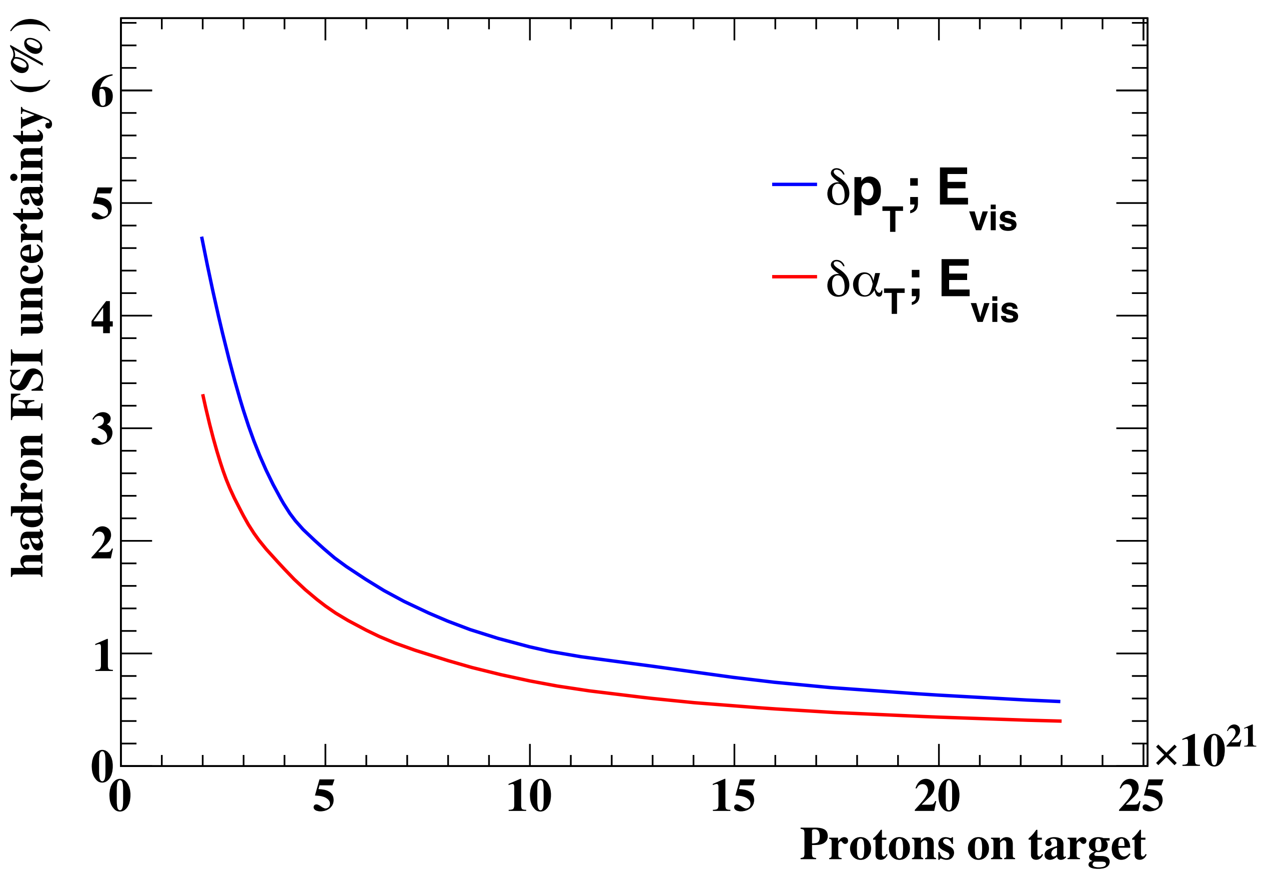
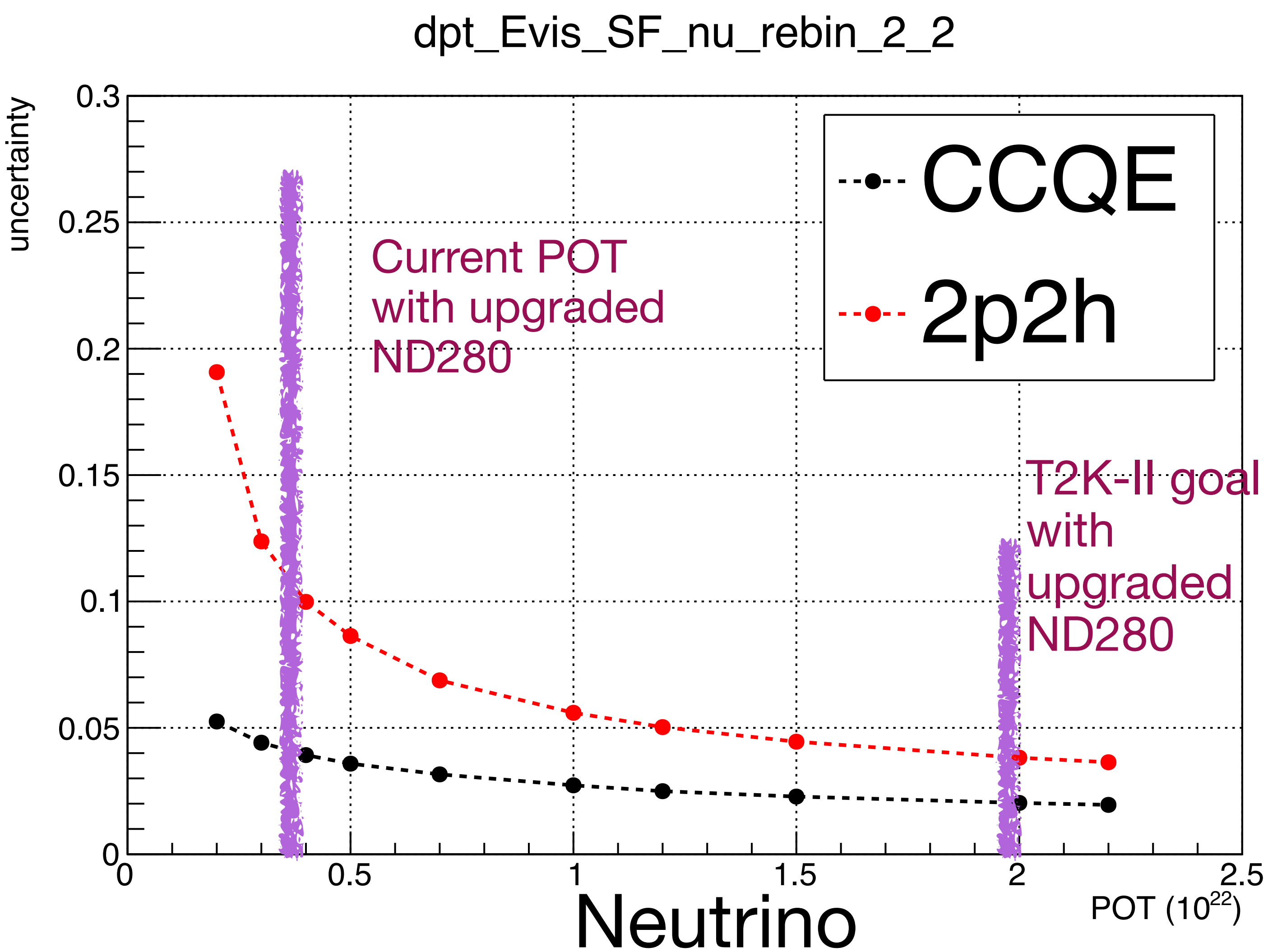


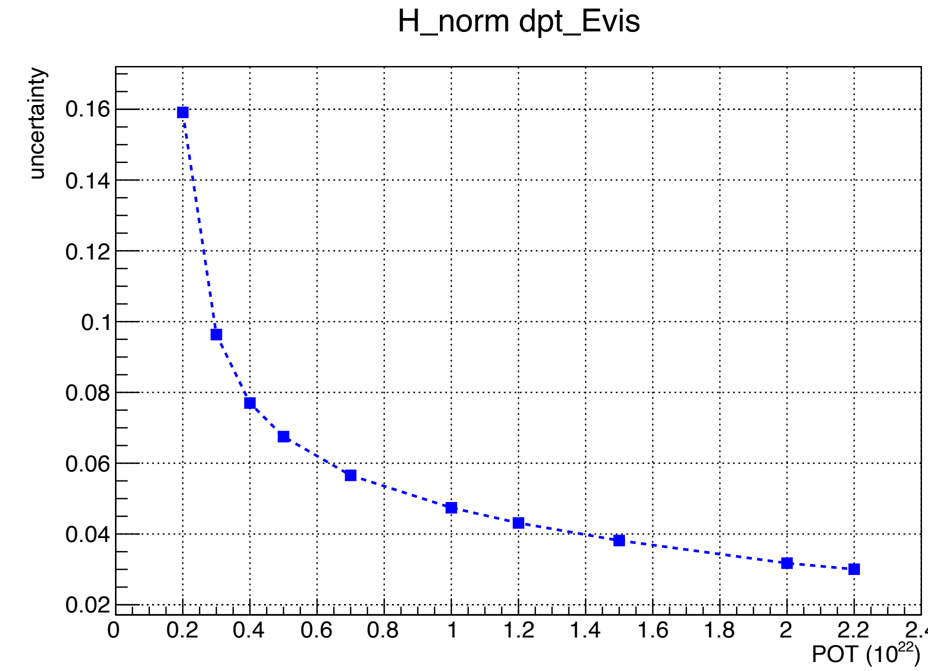


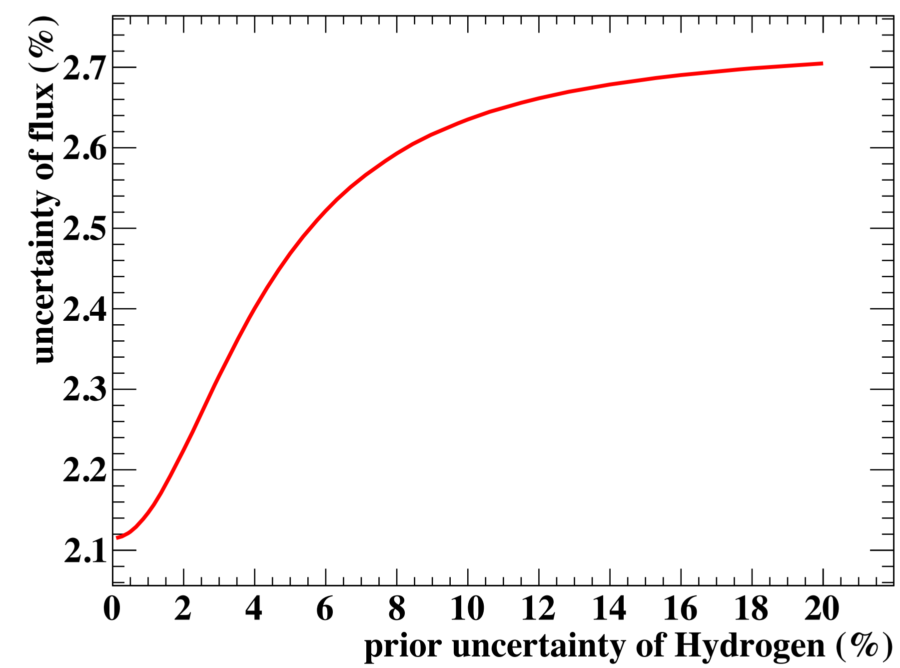
$\delta\alpha_T$ is the variable that is sensitive to the hadron FSI. Without the FSI, the $\delta\alpha_T$ distribution is expected to be flat because of the momentum conservation.
In reality, the FSI usually slows down the hadrons, which will result in a bigger $\delta\alpha_T$. Consequently, by looking at the shape of $\delta\alpha_T$ distribution, one can extract the strength of FSI.

CCQE, 2p2h, Hydrogen uncertainty



At 1×10^{22} POT : 2p2h uncertainty 5.6%
CCQE uncertainty 2.7%

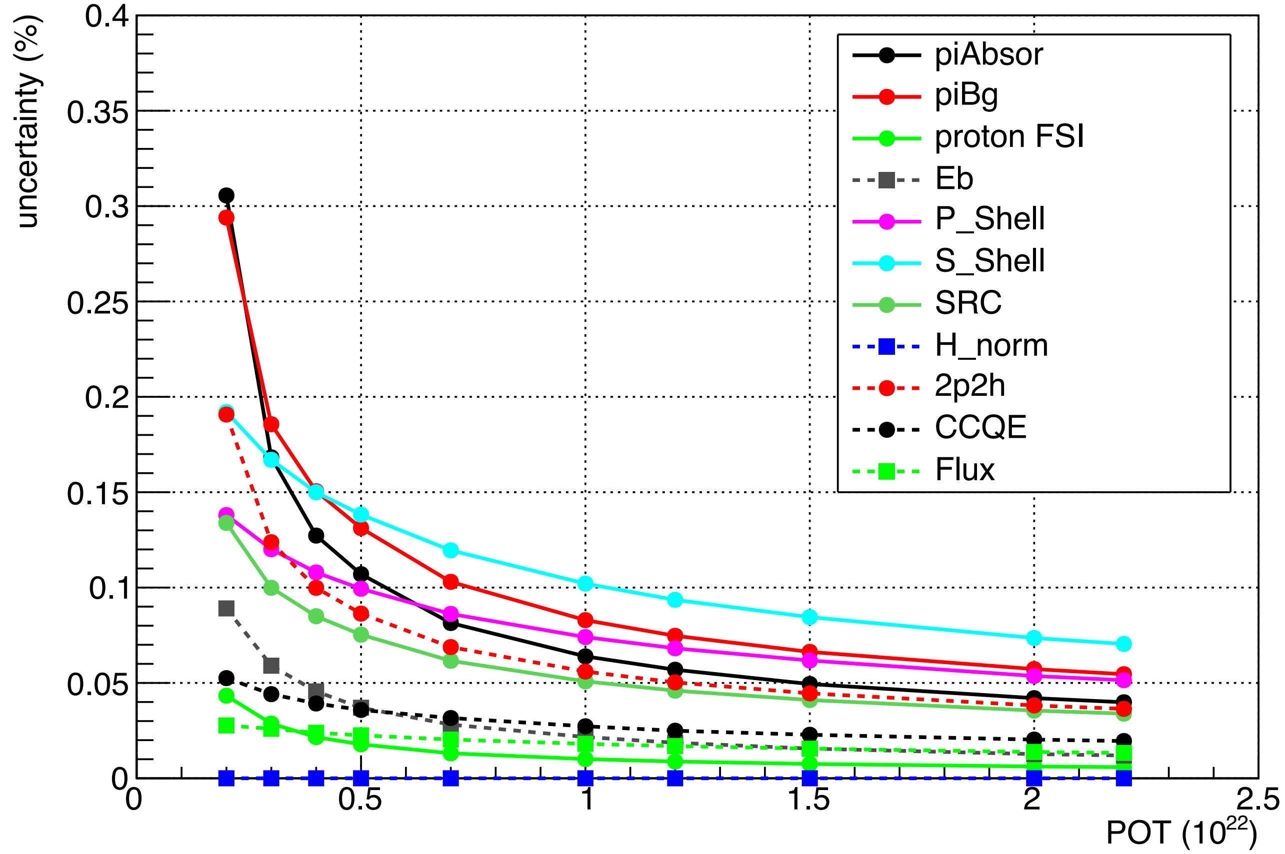




without ND we would have ~100% uncertainty on the 2p2h normalisation

The target of the neutrino beam contains Carbon and Hydrogen, while the Hydrogen does not have the nuclear effects. It's important to constrain the Hydrogen interaction component.

Summary



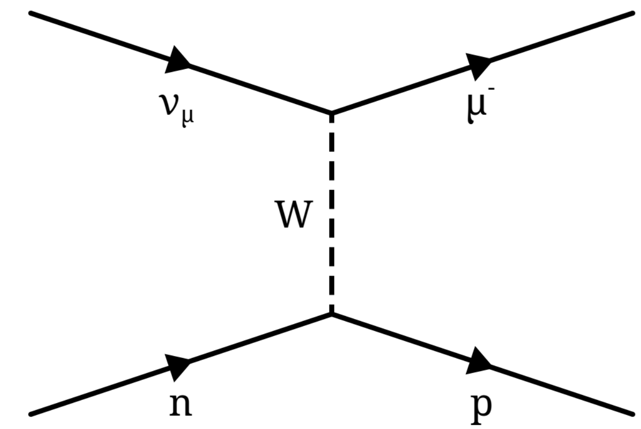
- This fitter is the first step to obtain the quick physics studies for ND280 Upgrade, before having a real complete fitter.
- The results show promising constraints on key parameters such as 2p2h component (5.6% for neutrino and 15% for anti neutrino with 1×10^{22}), Hydrogen interaction (6.5%). And all parameters uncertainties are below 10% for 1×10^{22} POT (in nu fit).
- I made the test with different smearing, binning and uncorrelated uncertainty. The results were meaningful and stable.
- This promising systematic uncertainties reduction can help to save a lot of data taking time.

Back up

Content

- T2K and Near Detector upgrade introduction.
- Quantitative sensitivities to neutrino-nuclei interaction mode
- Summary

Current difficulties



- Limitation: We only use the kinematic of outgoing lepton from ν interaction.
- Things affecting the oscillation measurements
  1. Fermi momentum of initial nucleus.
  2. Binding energy to extract nucleon from target nucleus.
  3. Component of non quasi-elastic events without pion in the final state such as 2p2h, Pion production.

ND280 physics study

2014

Error source	1Re sample	1Rμ sample
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W shape	0.23	0.26
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SK parameters	3.56	4.92
SK momentum scale	0	0
Total	**6.28**	**7.35**

2018/19

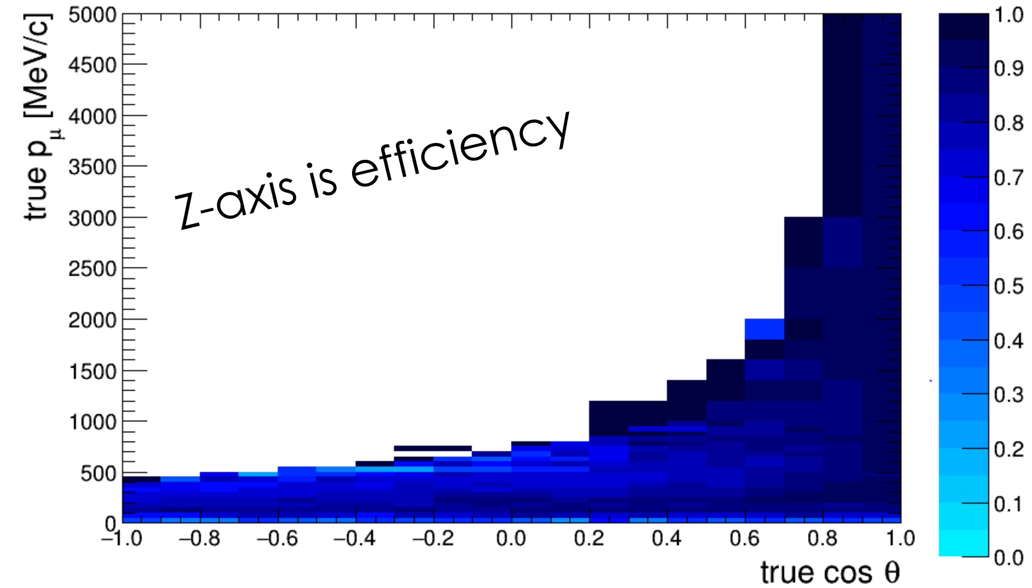
Source (T2K)	$N(\nu_e)$
Binding Energy	7.1%
Total Syst.	**8.8%**

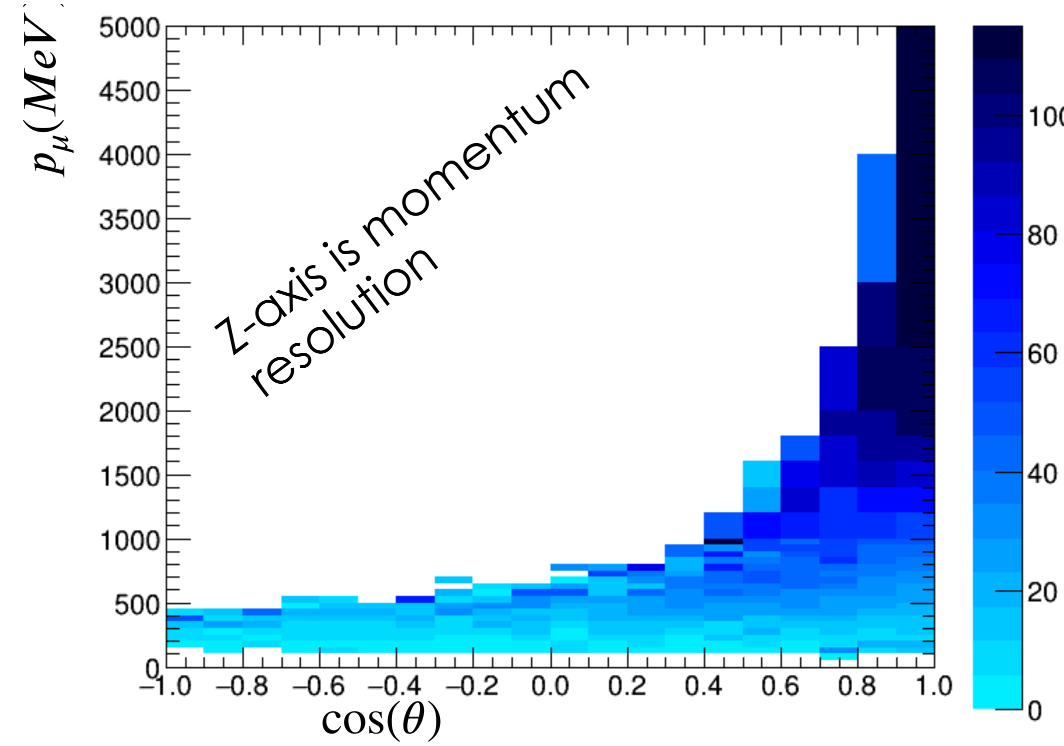
Addition of 2p2h (unknown before) changed error dramatically

Detector performance Inputs

Event Generators

Apply Smearing + Efficiencies





- We do not yet have a full detector simulation for ND280 Upgrade
- We take generator output and apply smearing + efficiencies based on expected detector performance
- Quasi–realistic detector performance
  - ✓ We have reasonable resolutions and thresholds
  - ✓ We simulate genuine backgrounds from untracked particles

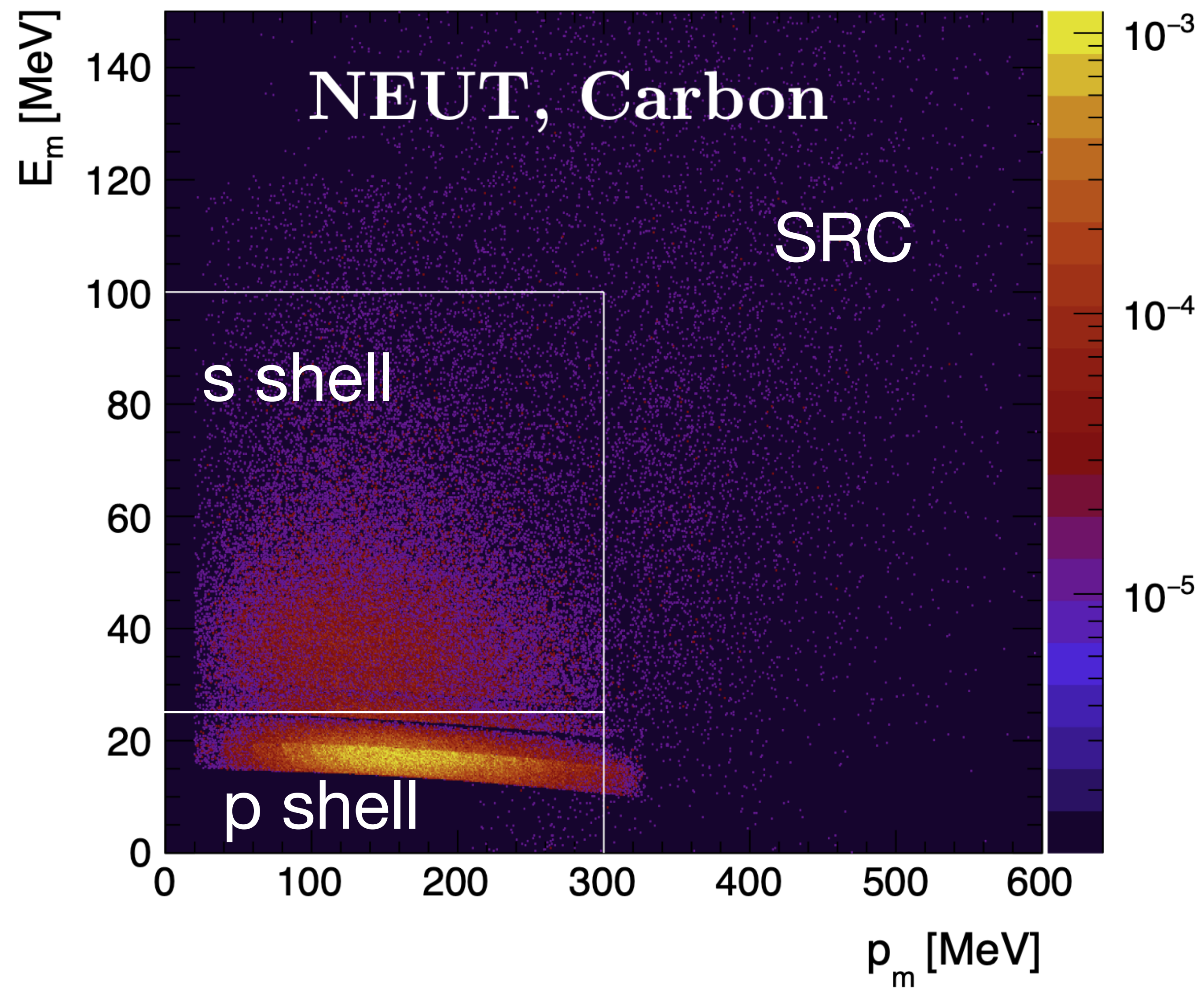
X Assumes perfect PID, some inputs are currently quite approximate (Work in Progress)

CCQE model systematic

Spectral Function

P shell and S shell: Independent nucleons, moving in a mean-field potential within the shell-model picture => One outgoing nucleons from the primary vertex

Short Range Correlations (SRC) pairs of strongly-correlated nucleons (20%)
=> Two outgoing nucleons from the primary vertex



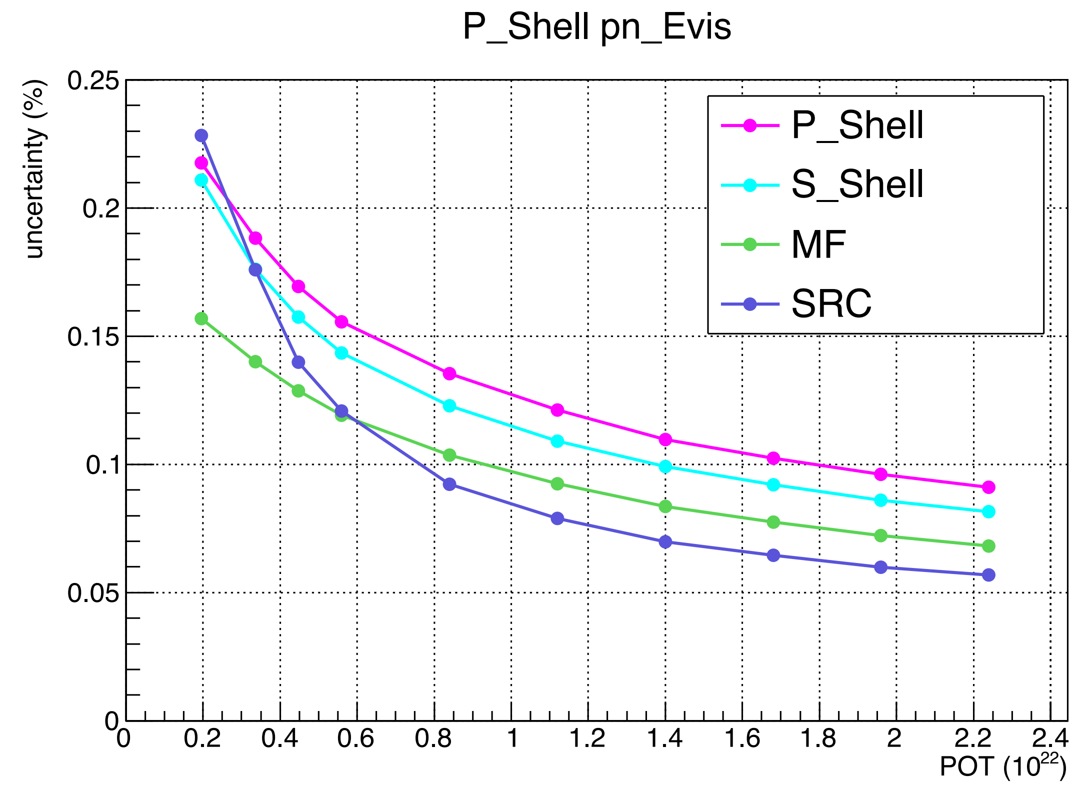
P Shell: Emiss < 25 MeV & pmiss<300MeV
S Shell: 25MeV < Emiss < 100 MeV &pmiss<300MeV
SRC: Emiss > 100 MeV or pmiss > 300 MeV

To evaluate the uncertainty on CCQE normalisation due to SF model, we throw toys from post-fit errors and covariance matrix and compute number of CCQE from each toy

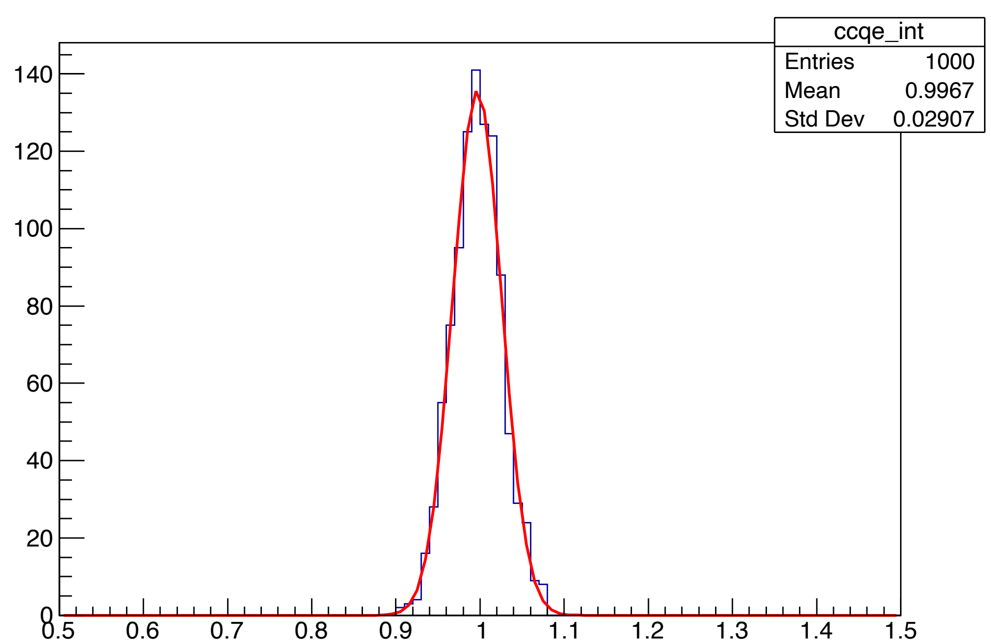
Each region (SRC, Pshell, Sshell) is treated as a normalisation systematics

CCQE uncertainty propagation

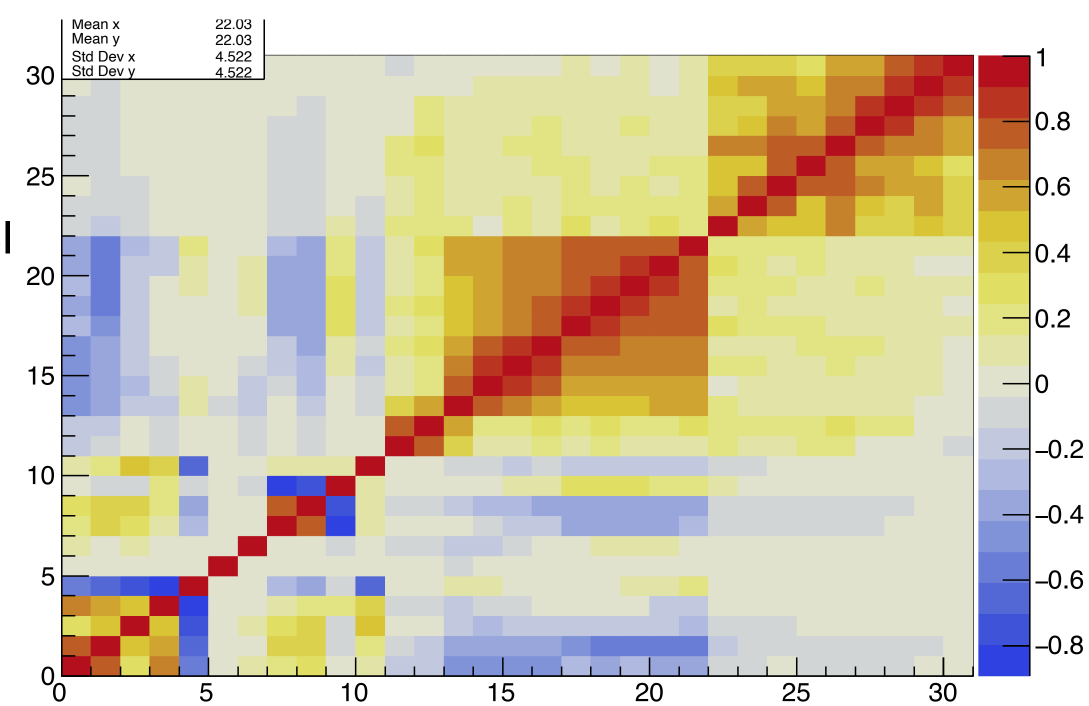
To evaluate the uncertainty on CCQE normalization due to SF model, we throw toys from postfit errors and covariance matrix and compute number of CCQE from each toy



The uncertainty = std dev/ mean ~=0.03 for CCQE



0->1: 2p2h
2->3: pion FSI
4: norm cyst
5: proton FSI
6: Eb
7: P Shell
8: S Shell
9: MF
10: SRC
>=11: flux



Pn_Evis nu fit

Systematic included in fitter

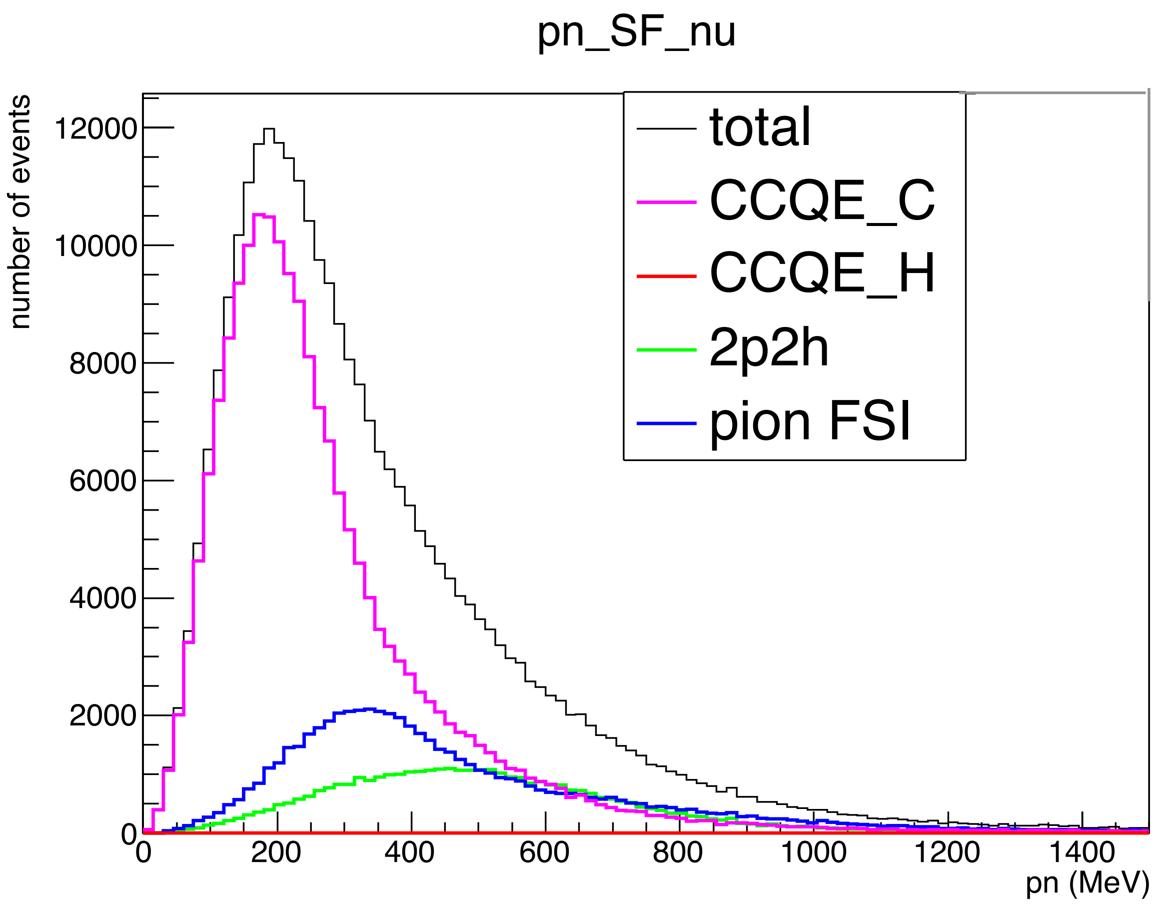
- 2p2h
  +2p2h_c1 < 600MeV
  +2p2h_c2 > 600MeV
- CCQE (modelled in Spectral Function)
  +P Shell normalisation
  +S Shell normalisation
  +Short Range Correlation (SRC)
- Pion Absorption normalisation
- Pion Background normalisation
- Strength of proton Final State Interaction (FSI)
- Eb: binding energy shift in SF model
- Hydrogen interaction normalisation
  (in anti-neutrino mode)
- Flux covariance uncertainty

Input for fitter
(Reconstructed Nucleon momentum)

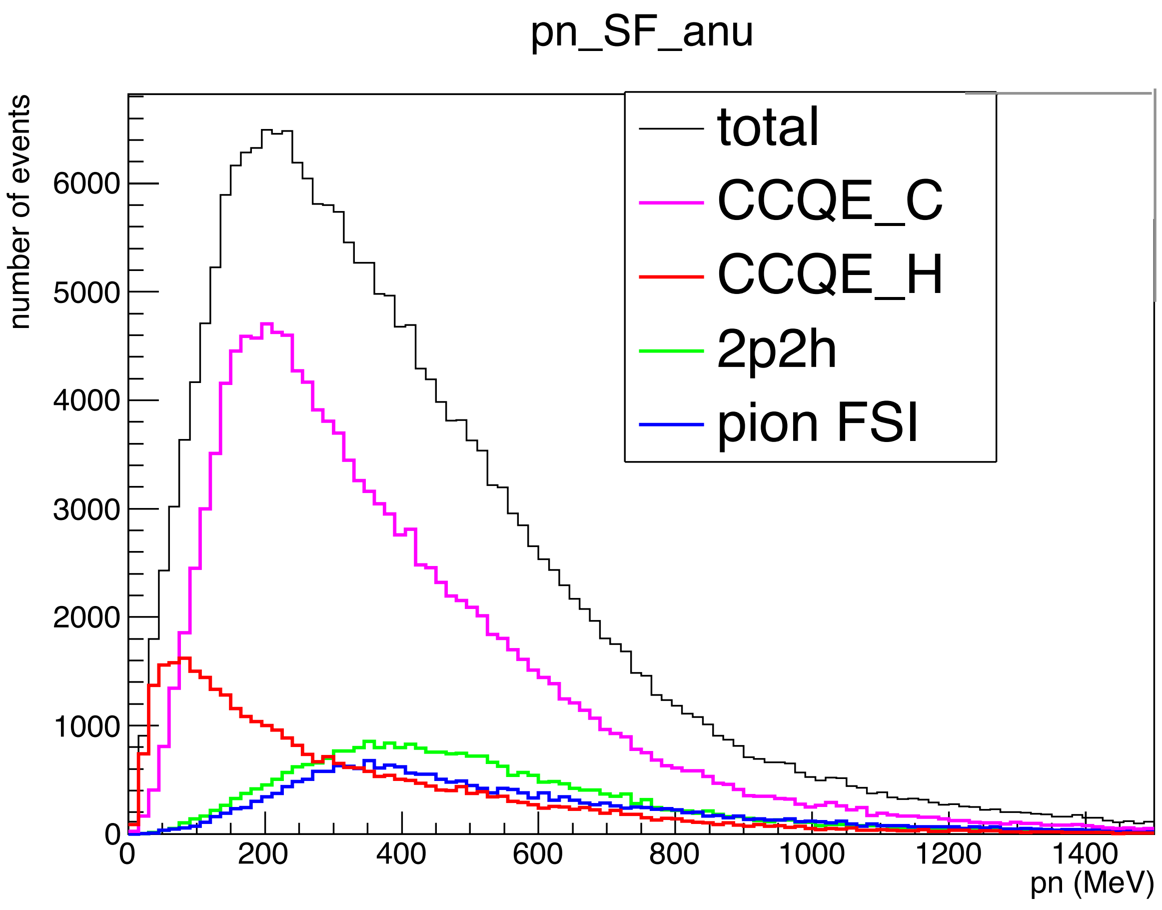
- The peaks are at around 200MeV (CCQE) which is the expectation

- In anti-neutrino we have a broader Pn distribution due to the better reconstruction of protons compared to that of neutrons in the final state.

- 1×10^{21} POT in nu mode => 51k events
  1×10^{21} POT in anti-nu mode => 11k events pass the selection



Neutrino



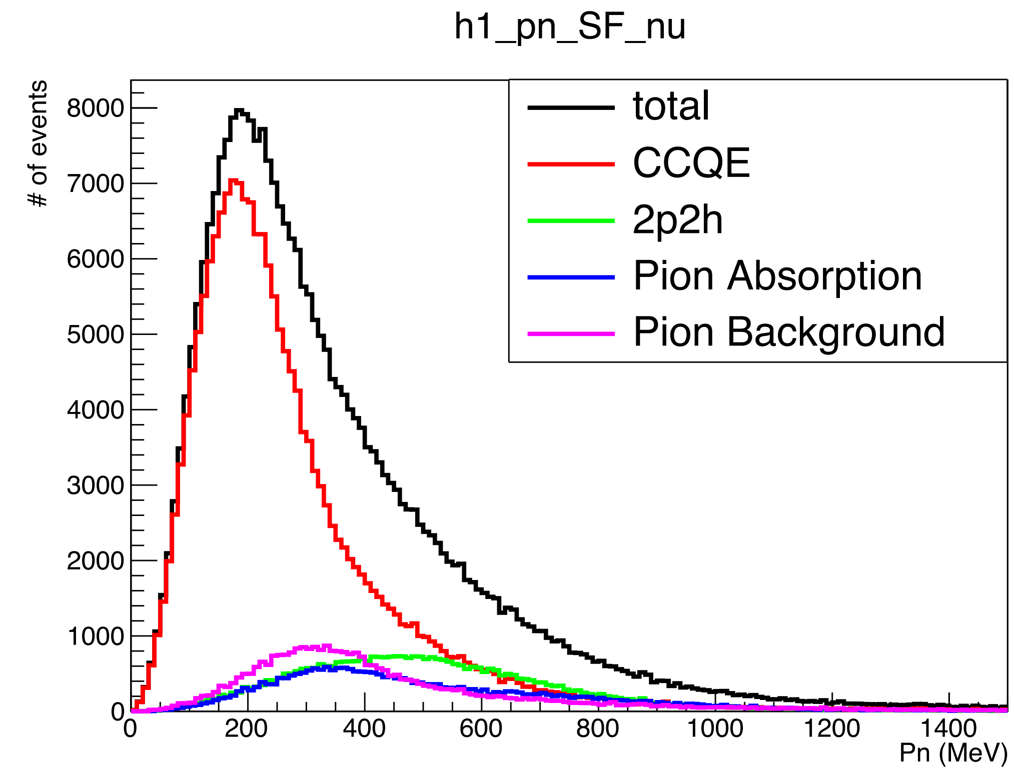
Anti-Neutrino

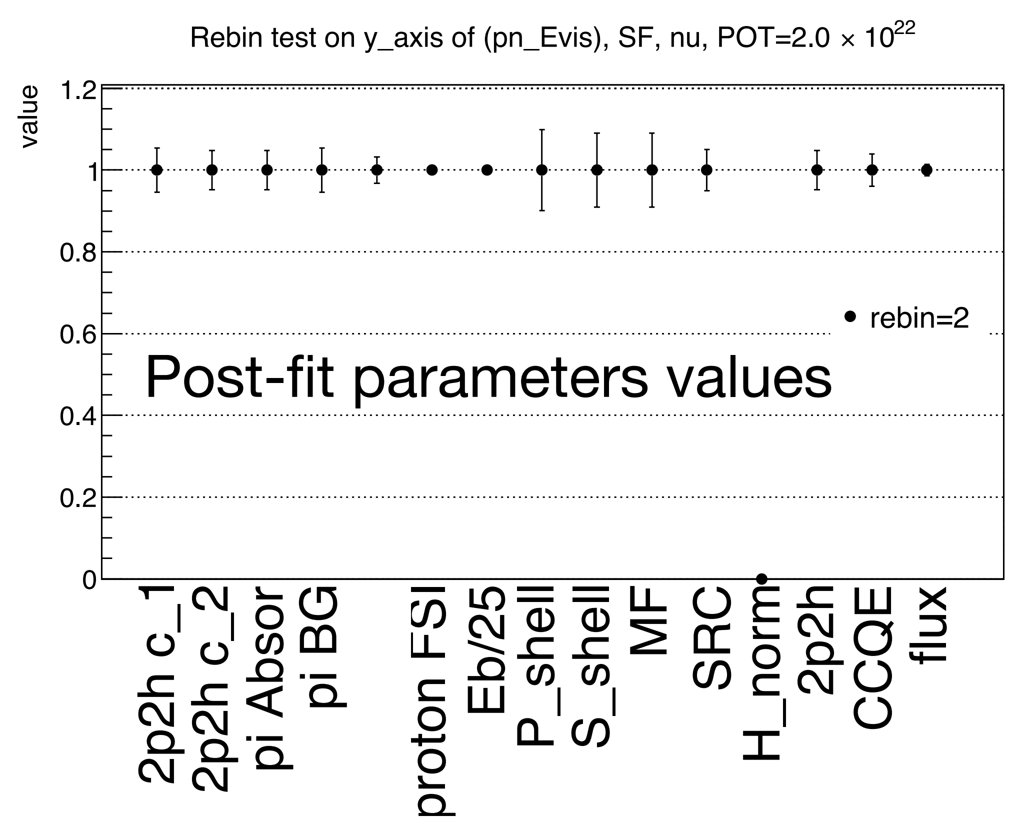
Fit results

We are using the TMinuit.

Each time we're just doing Asimov fit. We just fit the MC to itself in order to determine the sensitivity

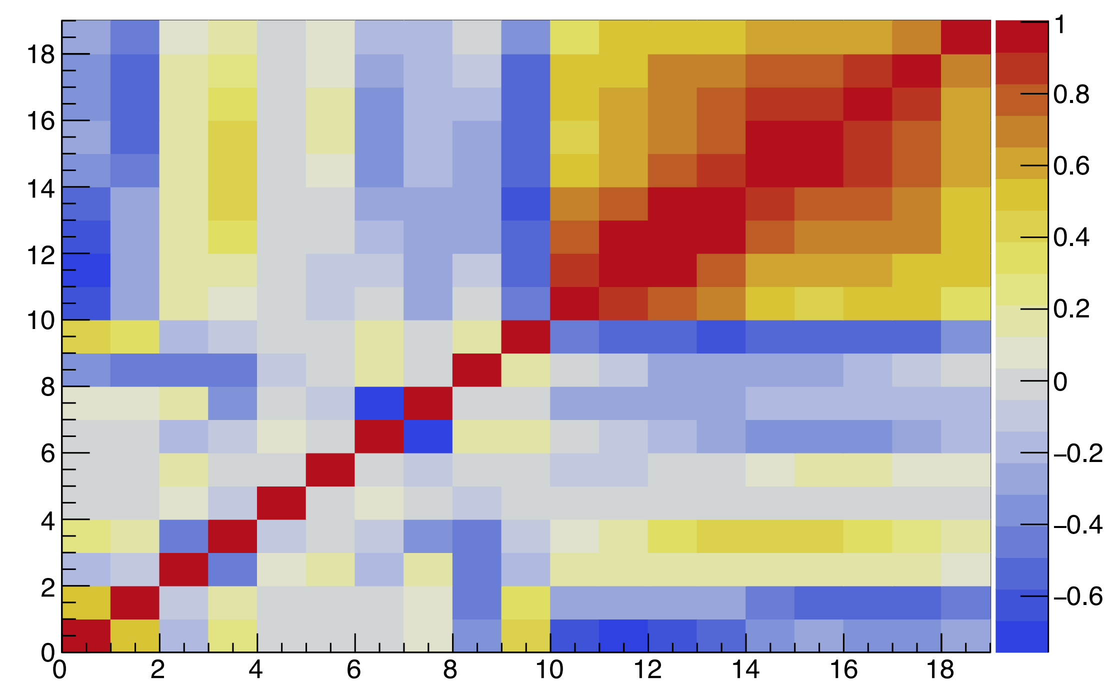
All plots here are shown in neutrino fit. => No Hydrogen





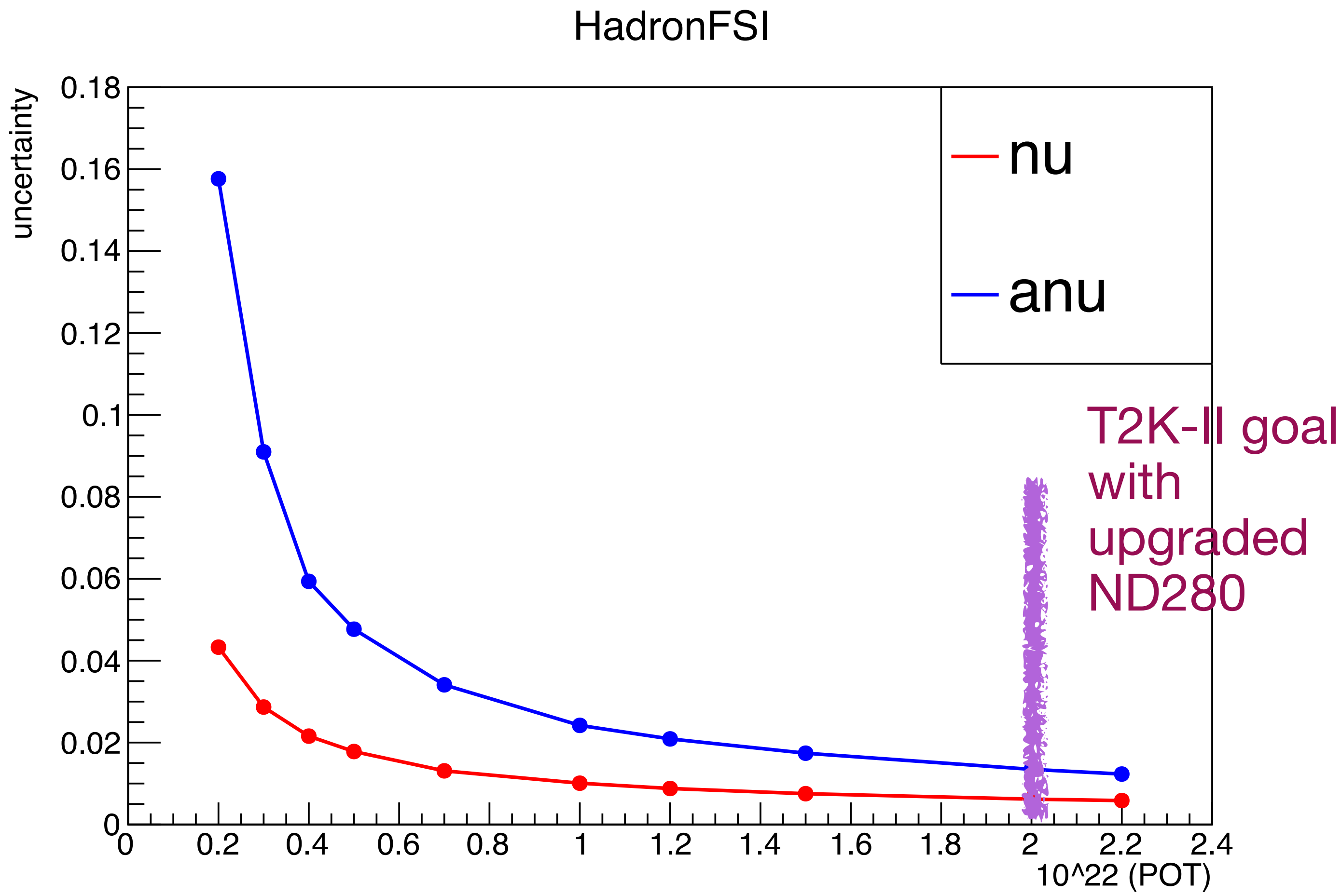
0->1: 2p2h
2: pion Absorp
3: pion Bg
4: proton FSI
5: Eb
6: P Shell
7: S Shell
8: MF
9: SRC
>=10: flux

Correlation matrix (pn_Evis, nu fit)



Constraint for hadron FSI and binding energy

- At 1×10^{22} POT, uncertainty of Hadron FSI is
  1% for neutrino
  less than 4% for anti-neutrino



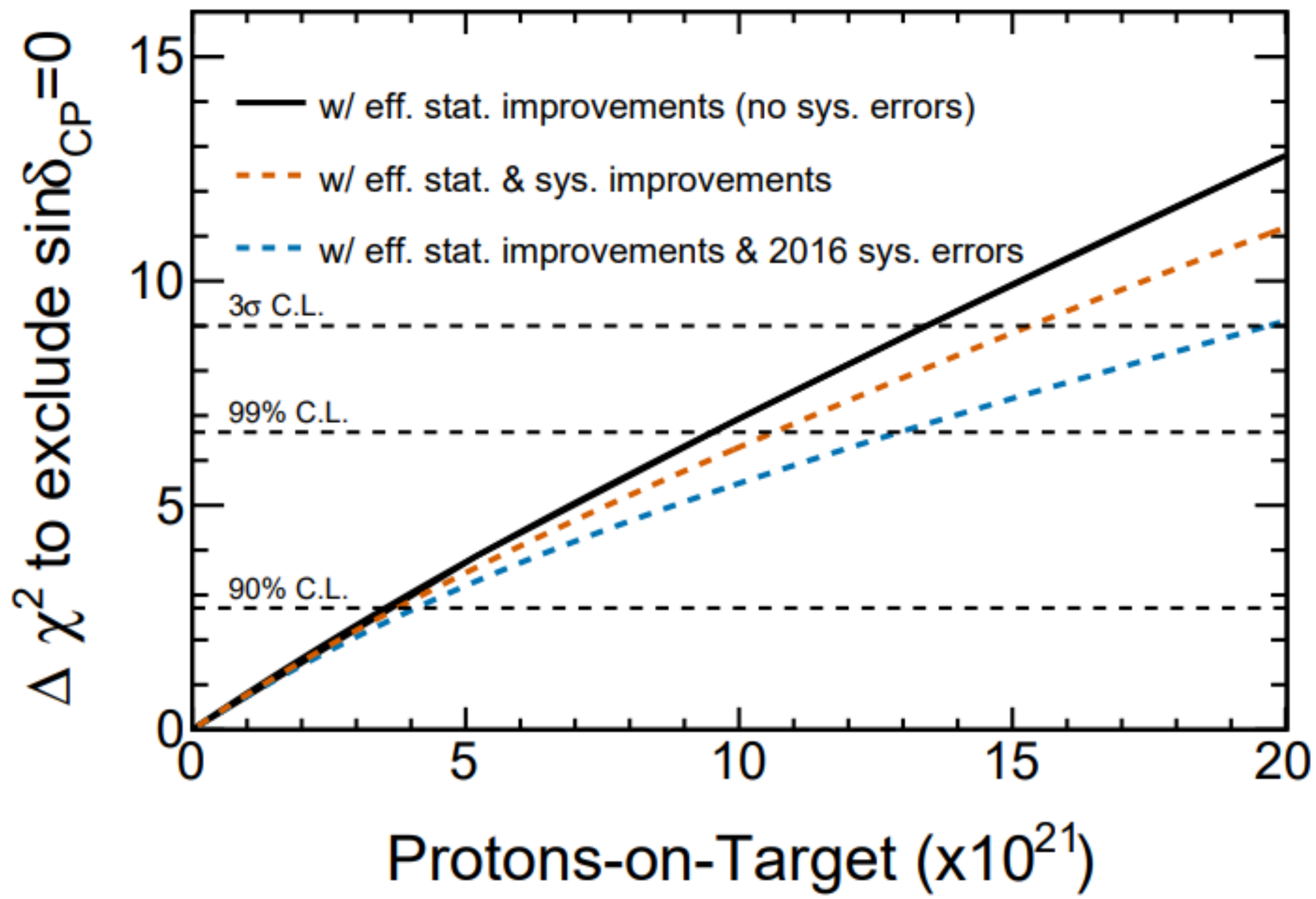
For anti neutrino, the uncertainties are bigger because the anti neutrino cross section is smaller than that of neutrino, which leads to the lower statistic

At 1×10^{22} POT, uncertainty of Eb is
0.54 MeV for neutrino
1.5 MeV for anti-neutrino

Quantitative contribution of ND280 upgrade physics

arXiv:1609.04111

- 5×10^{21} Protons on Target (POT) is the difference between with and without systematic improvements to reach 3σ exclusion.
- The current accumulated POT of T2K is about 3.7×10^{21}



Sensitivity to key cross-section parameters

- Things affect the oscillation measurements

    1. Fermi momentum of initial nucleus.
    2. Binding energy to extract nuleon from target nucleus.
    3. Component of non quasi-elastic events without pion in the final state such as 2p2h, Pion production.

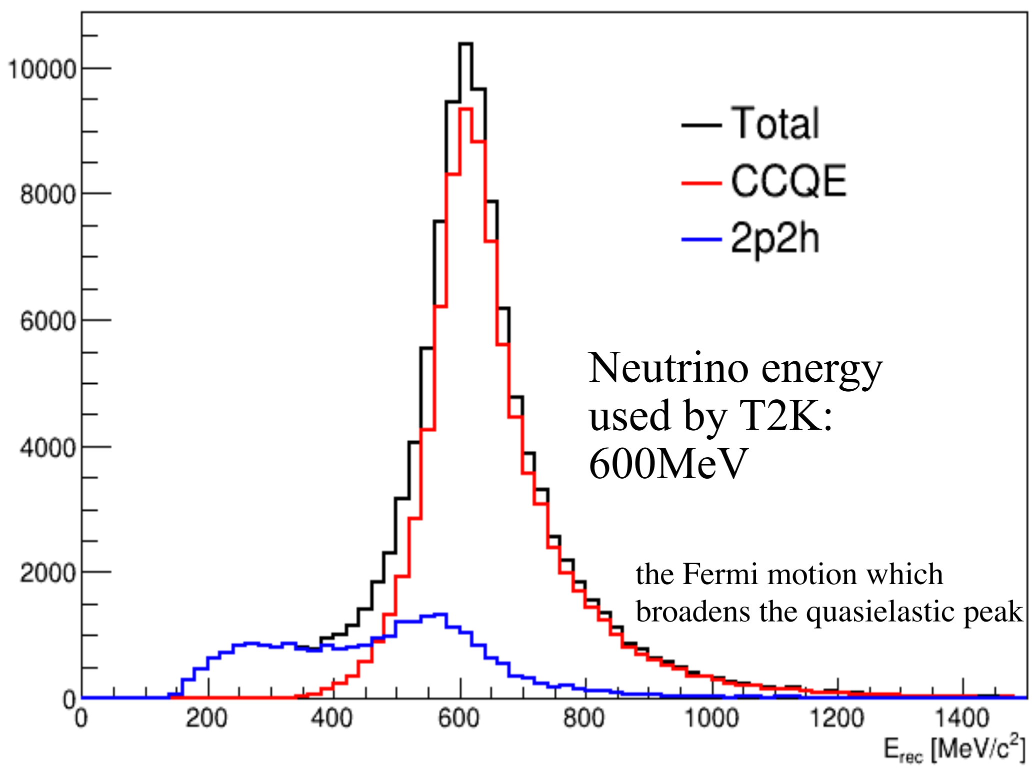
POT 1×10^{22}, observables: pn_Evis

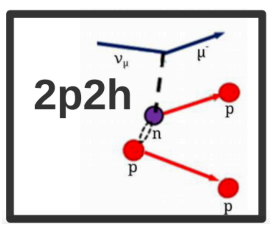
	Nu	Anti-nu
2p2h normalisation	6.5%	15.4%
CCQE normalisation	3.7%	5.3%
Eb	0.46 MeV	1.33 MeV
Pion absorption	6.4%	25.3%
Pion Background	7.1%	22.4%
Strength of Proton FSI	0.8%	2.0%
Hydrogen normalisation		6.5%

Why we need better constraint for 2p2h

2p2h component will bias the reconstructed neutrino energy over lower value

Reconstructed neutrino energy





2p2h = 20±20%

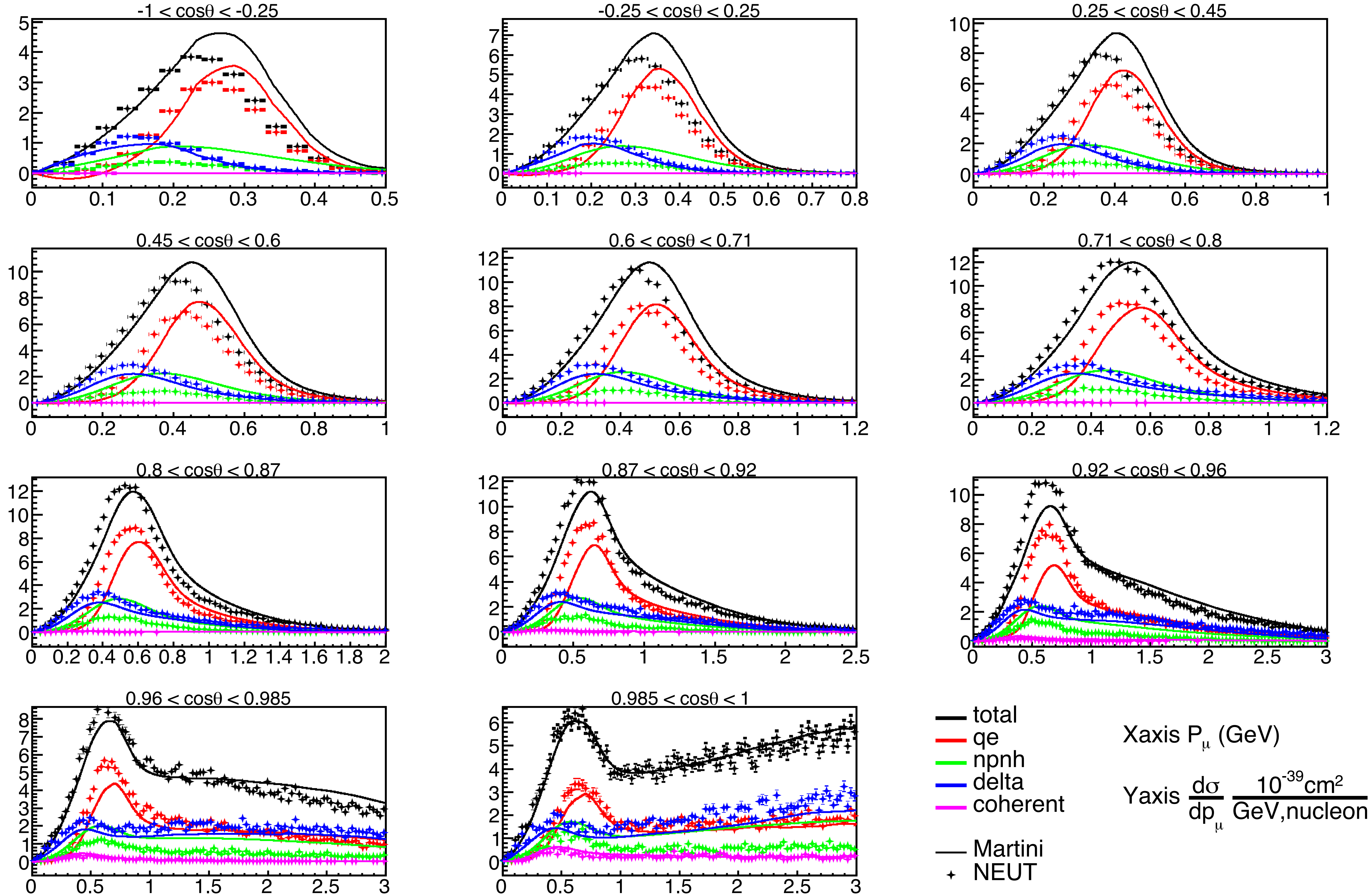
Neutrino oscillation probability

$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta_{13})\sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

=> Bias in E_ν results in bias measurements of neutrino oscillation parameters

- There are several way to model the 2p2h mode in neutrino interaction. The NEUT generator used in T2K use the 2p2h model from Nieves.

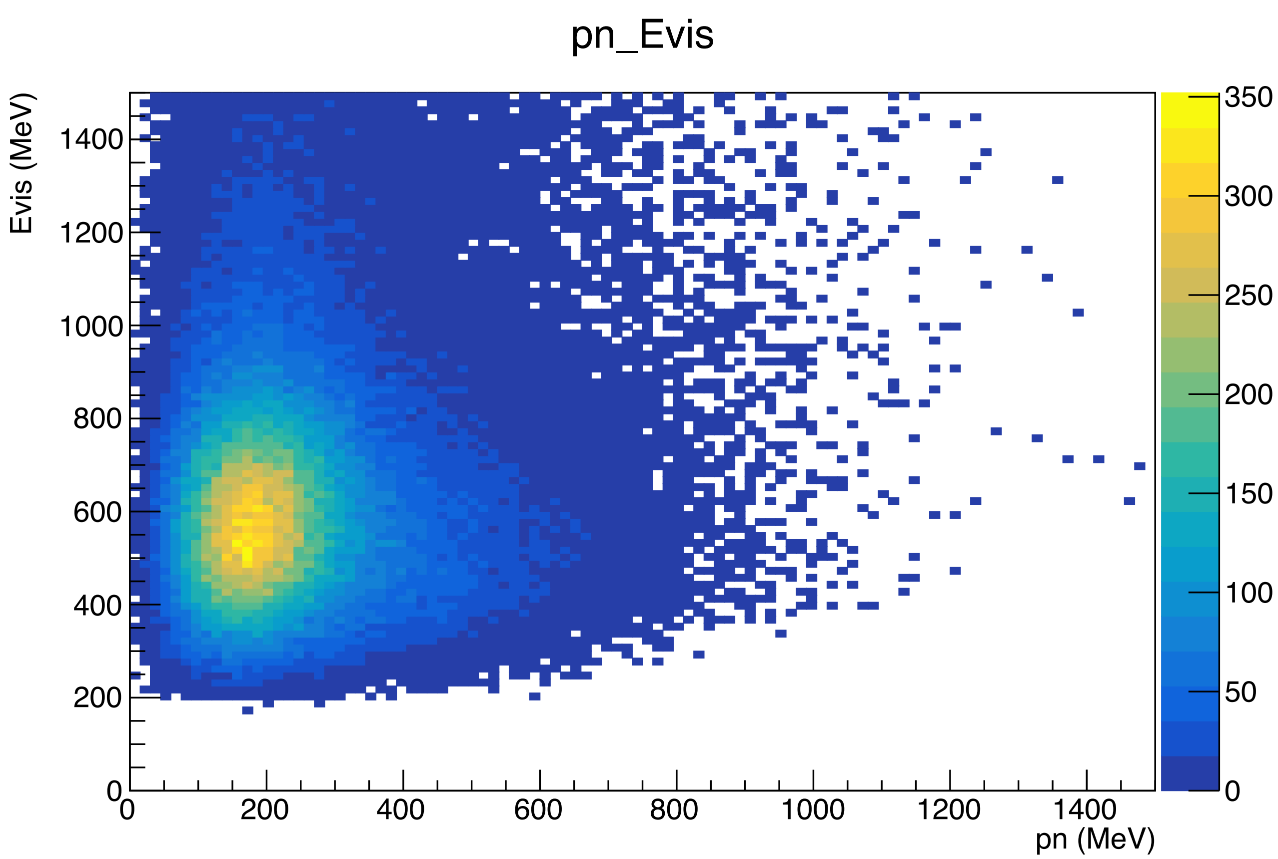
Cross section comparison between NEUT and Martini model

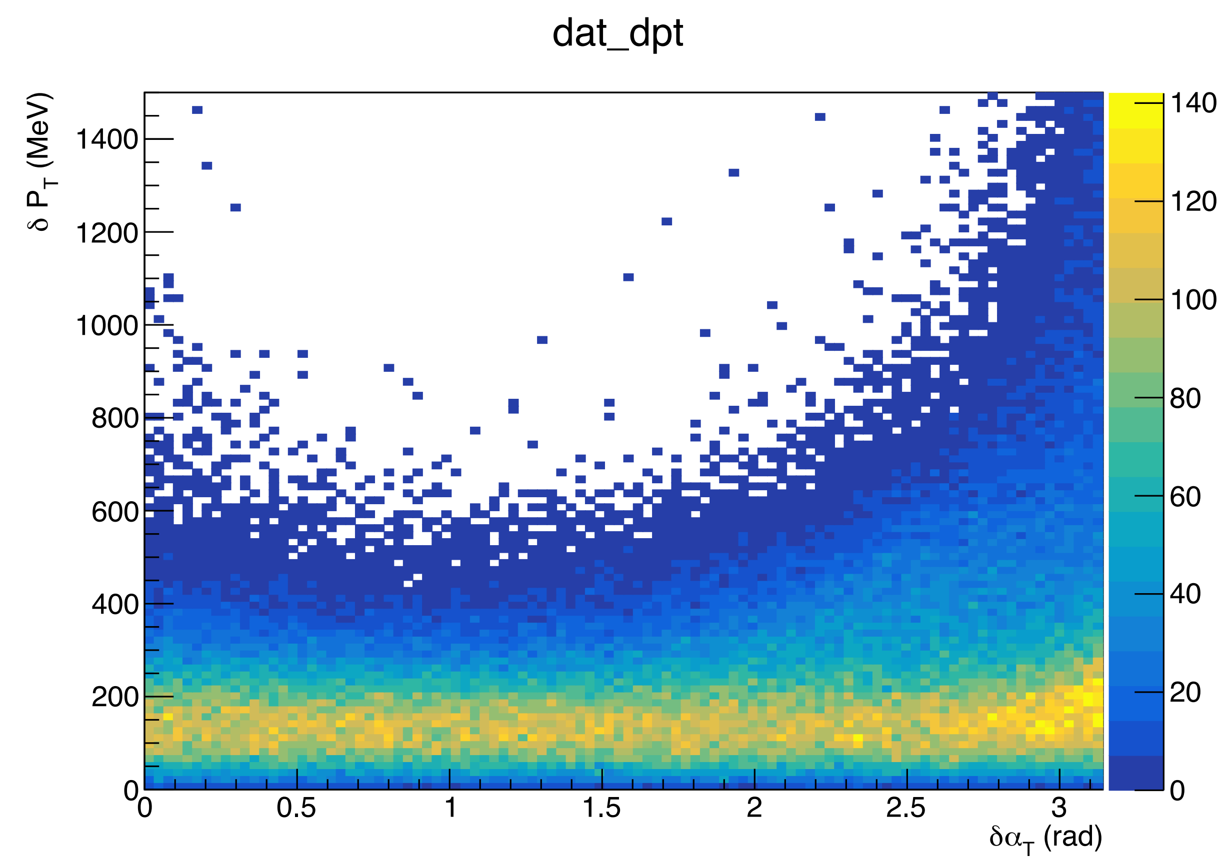


The NEUT file is for SF, Carbon interaction only

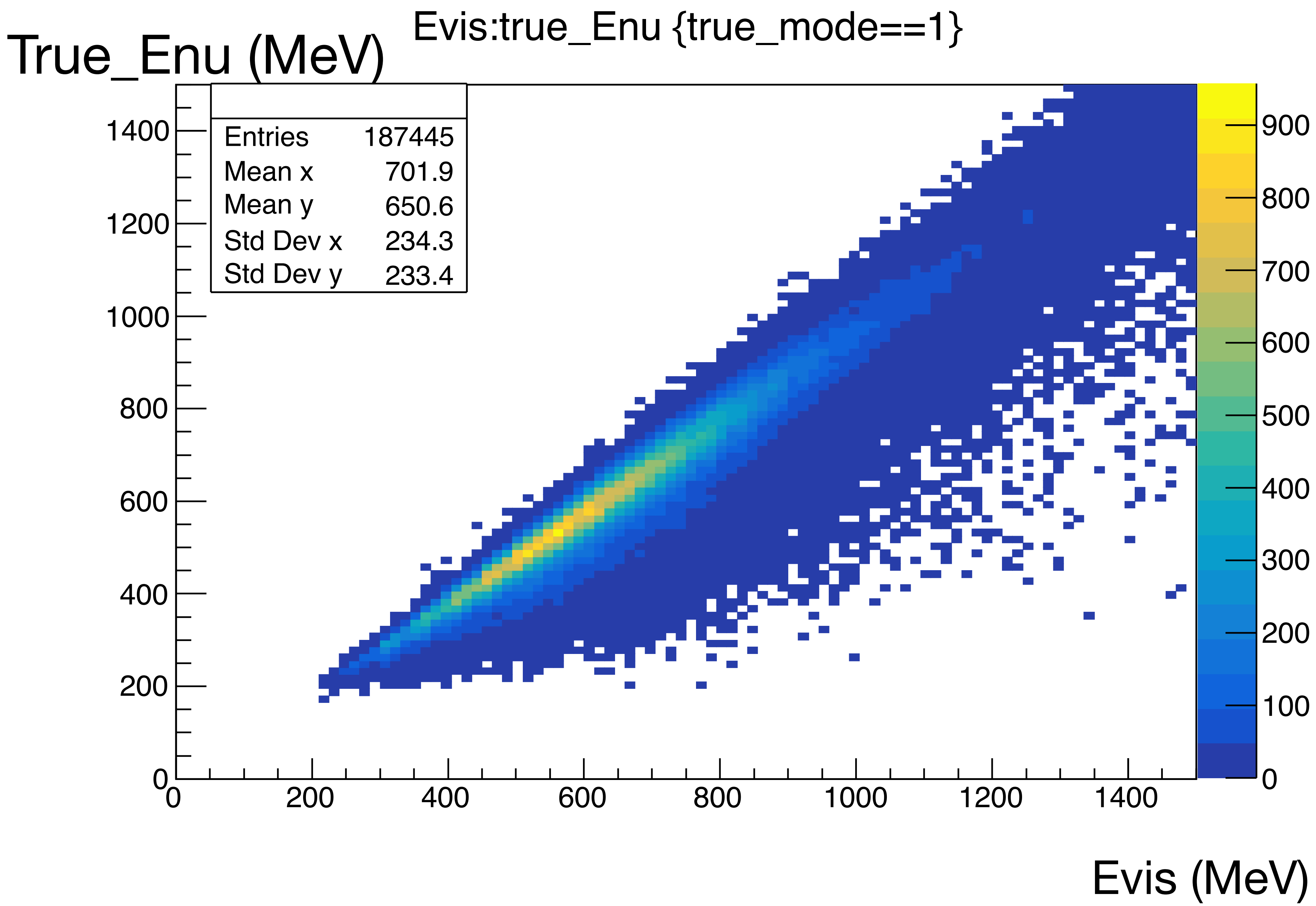
Input for fitter

In form of 2D histograms



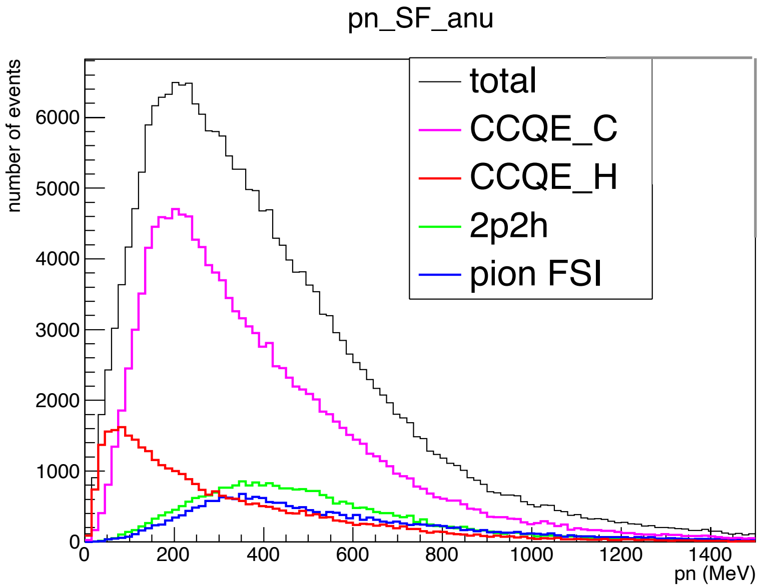


We do a binned likelihood fit with two variables pn and Evis



Evis:true_Enu {true_mode==1}
True_Enu (MeV)
Entries 187445
Mean x 701.9
Mean y 650.6
Std Dev x 234.3
Std Dev y 233.4
0
200
400
600
800
1000
1200
1400
0
100
200
300
400
500
600
700
800
900
Evis (MeV)

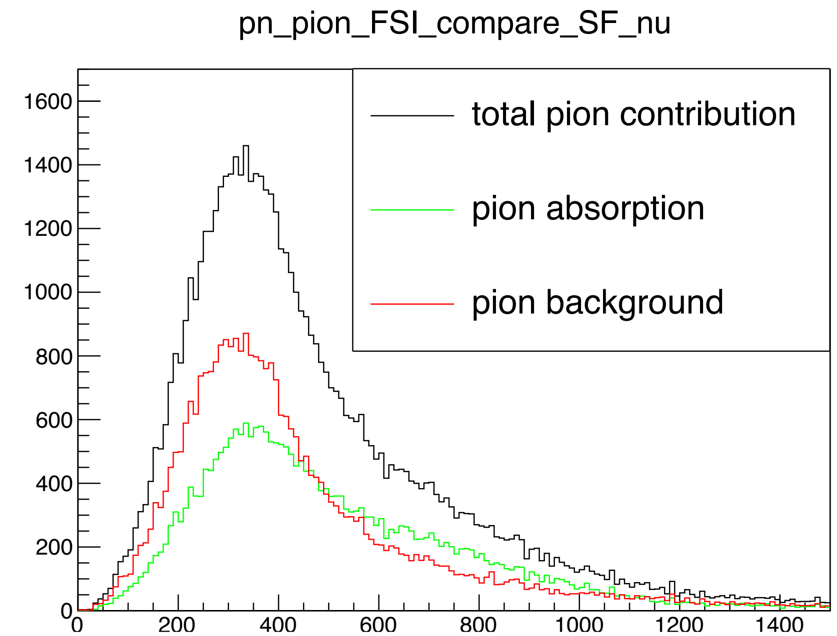
Hydrogen normalisation

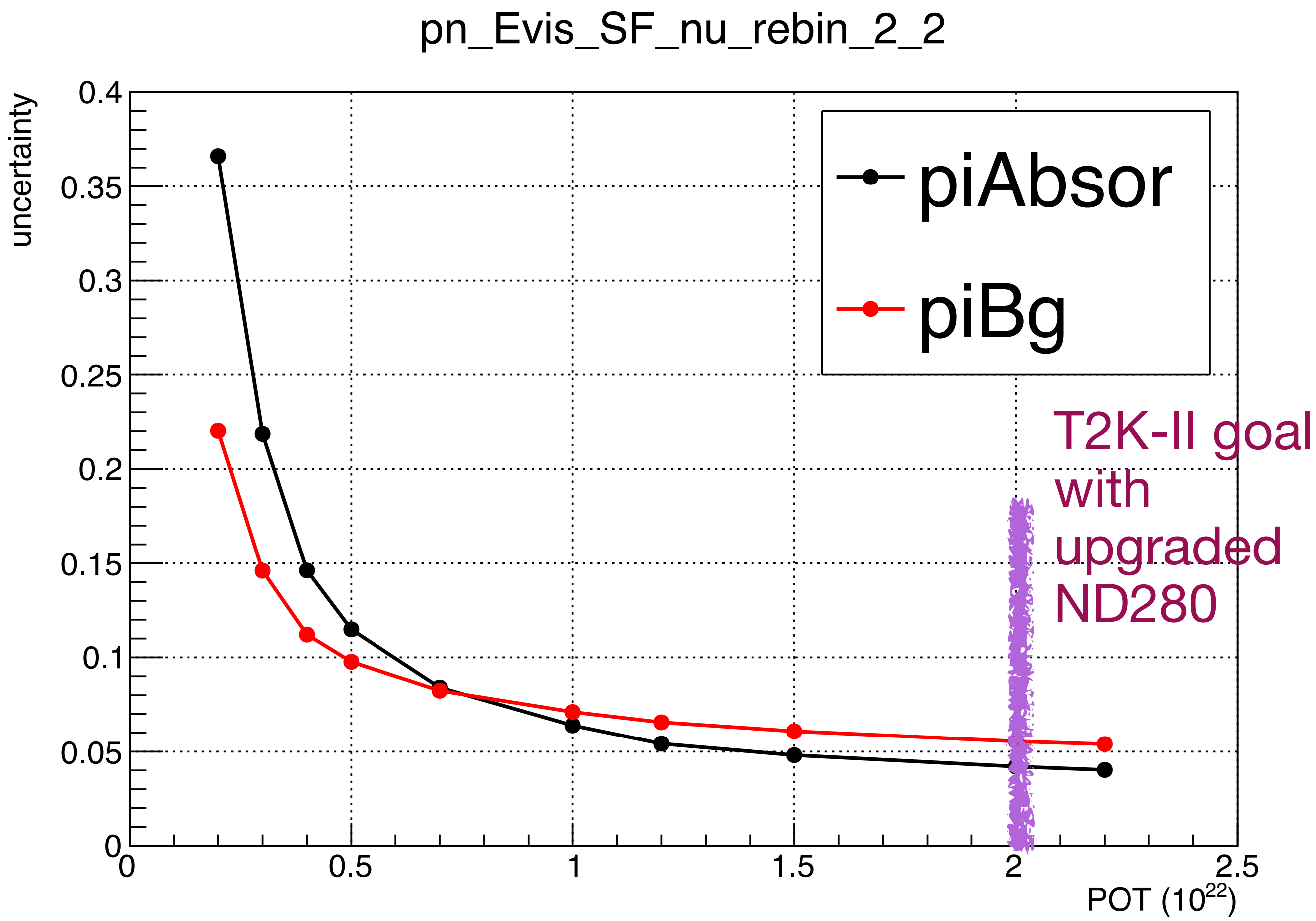


Further binning in Q^2 (square of the 4-momentum transfer) vector may allow the H contribution to be used to confront axial form factor and flux uncertainties.

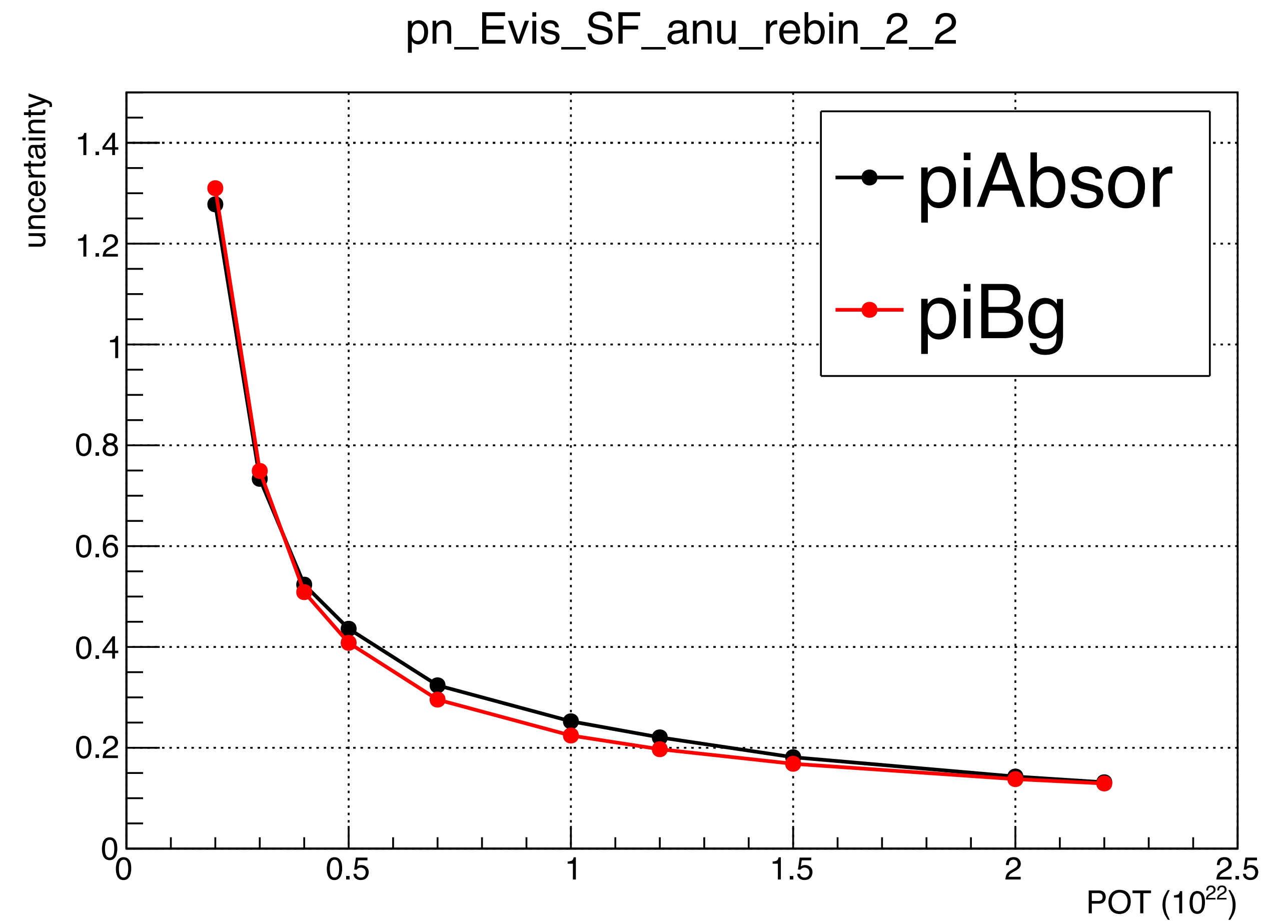
Pion production

- After: Pion uncertainty is divided into 2 new parameters:
  - Pion Absorption: (pion absorbed inside nucleus)
  - Pion Background:(pion was below detection threshold)
  Notice that all of them are CC0pi by reconstruction.





Neutrino

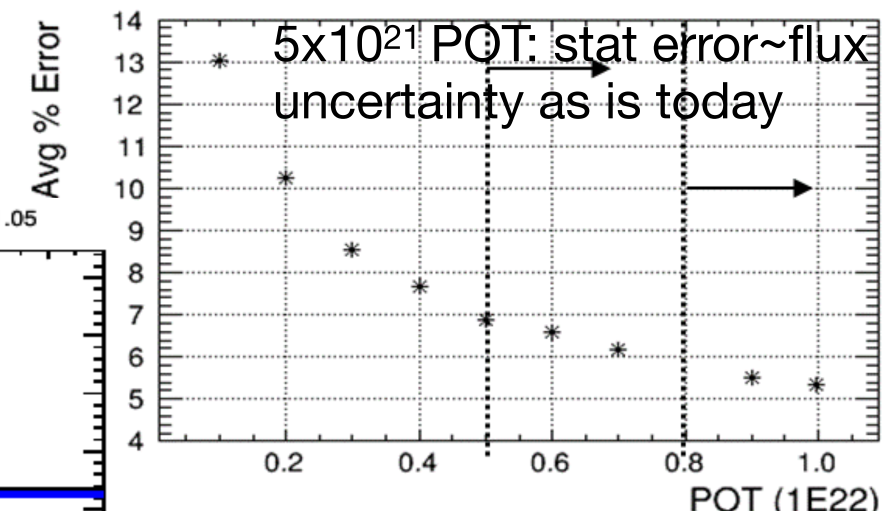


Anti-Neutrino

Extension: Multidimensional Analyses

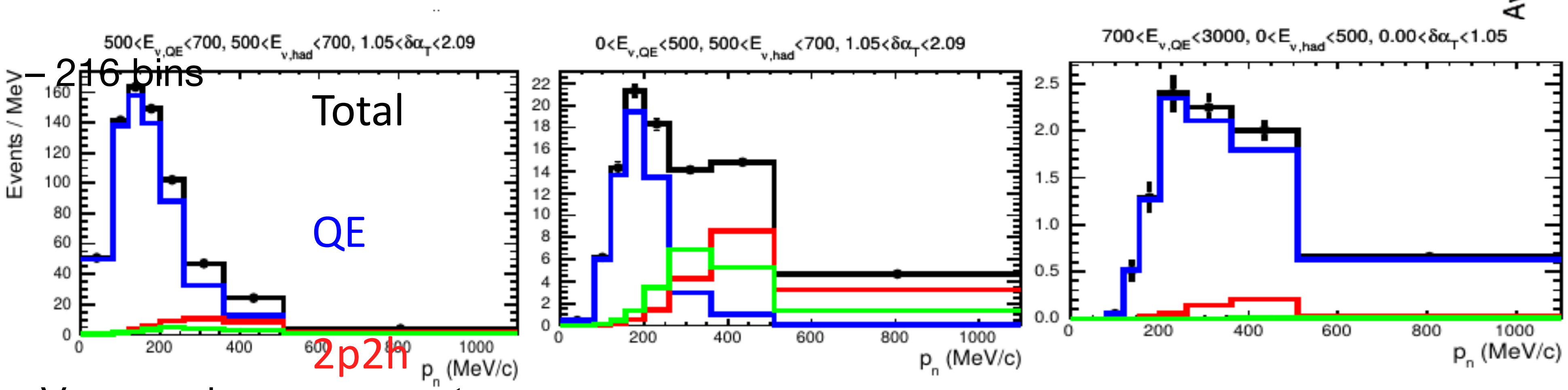
- The results I showed today focus on fitting variables focussed on the hadronic part of neutrino interactions. ND280 current looks at just the muon.

- In the full upgrade fits: put these two together, the power of the upgrade will be more than just what I have shown here.



8x10²¹ POT: stat error~flux uncertainty from replica target NA61

Example: measure p_n (8 bins) in bins of E_ν^{rec}, $E_\mu + T_p$ and $\delta\alpha_T$ (3 bins)



Very good measurement of Fermi momentum and Eb in the bulk

Clear sensitivity to 2p2h, pionFSI

Special phase space regions where CCQE behavior is atypical

(→ avoid biases in oscillation analysis)

→ This is a step toward controlling systematics on the lepton to the precision needed for HK!