Prospects for enhanced sensitivity to neutrino oscillation measurements at T2K

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Outline

Upgrade of the near detector for T2K and T2HK → physics capabilities

Improvement to SuperKamiokande analysis

T2K – SuperKamiokande combination

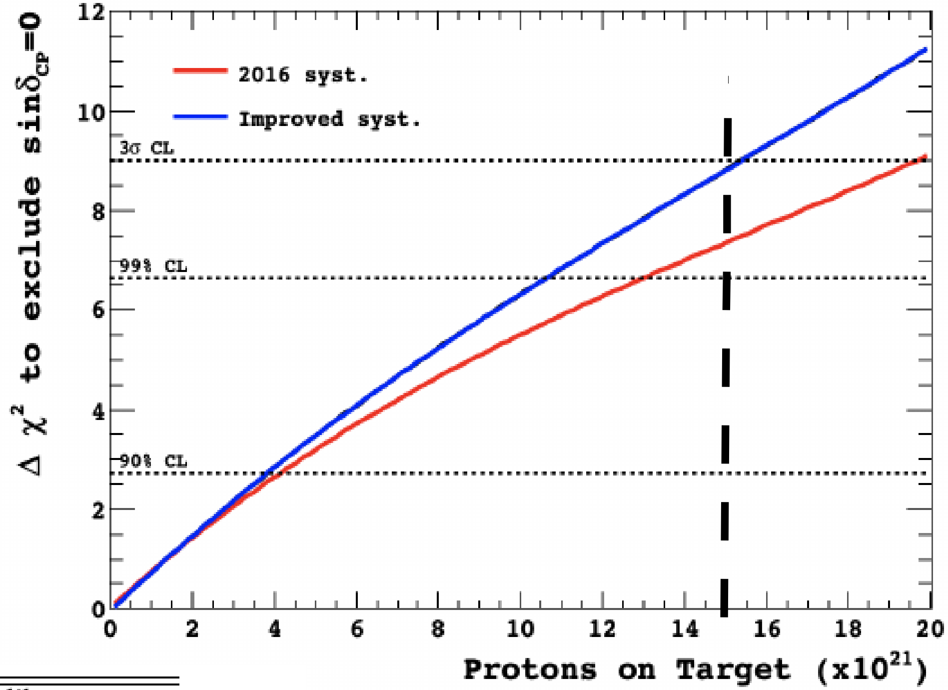
T2K-like analysis using ND280 Upgrade

- For ND280 Upgrade we expect ~a factor 2 increase in statistics with respect ND280 for the same POTs (only muons in the TPCs!)

Number of events per 10^{21} POT:

Selection	Current-like	Upgrade-like
ν_μ (ν beam)	~100000	~200000
$\bar{\nu}_\mu$ ($\bar{\nu}$ beam)	~30000	~60000
ν_μ ($\bar{\nu}$ beam)	~15000	~30000

3σ CPV at ~15x10²¹ POT



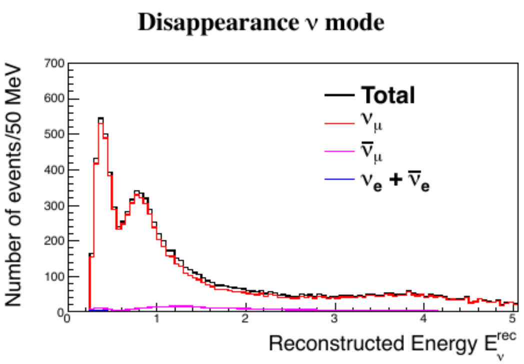
- Improved systematics=4% on ν_e,ν_μ samples→ requires at least $8\text{x}10^{21}$ POT with ND280 Upgrade

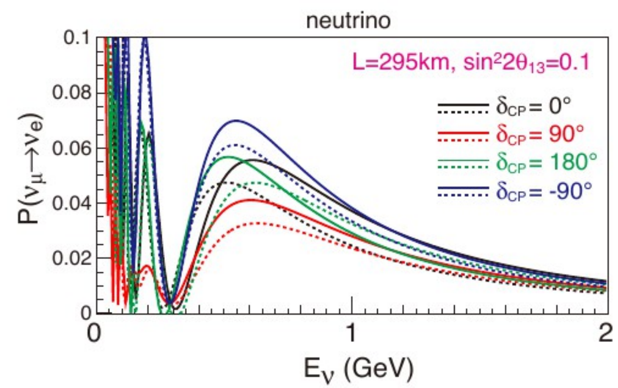
Source of uncertainty	ν_e CCQE-like $\delta N/N$	ν_μ $\delta N/N$
ND280 unconstrained cross-section	3%	1%
Flux + cross-section (constrained by ND280 upgrade)	1.8%	1.9%
SuperKamiokande detector systematics	1%	1%
Hadronic re-interactions	1%	1%
Total	3.8	2.6

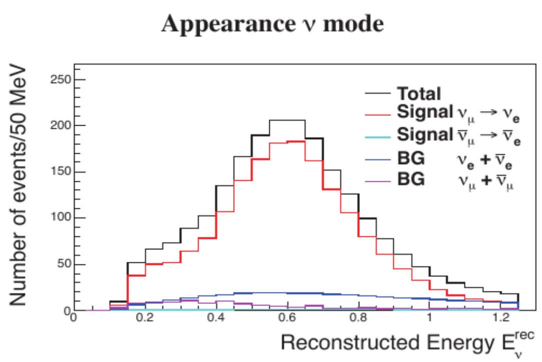
ND Upgrade: understanding systematics

The projected HK sensitivity requires an understanding of the neutrino-nucleus uncertainty **which we do not have yet today**

A lot of work with new ND280 Upgrade measurements is needed to achieve the **few-% systematics on the neutrino-nucleus interaction modelling**

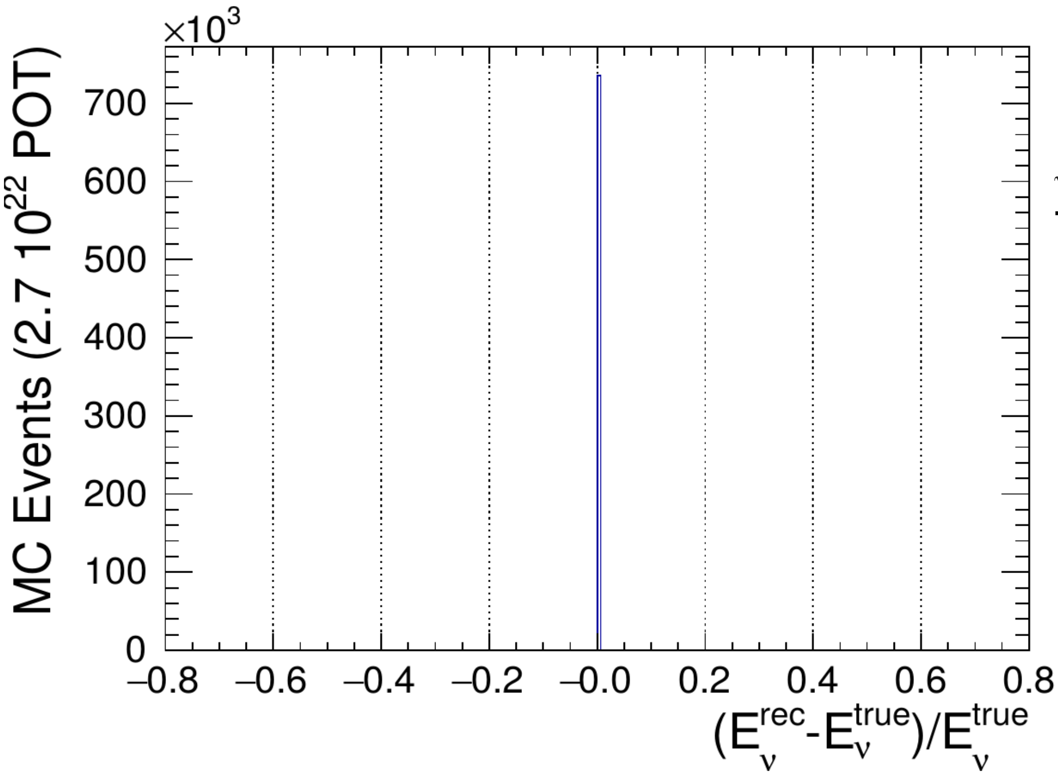


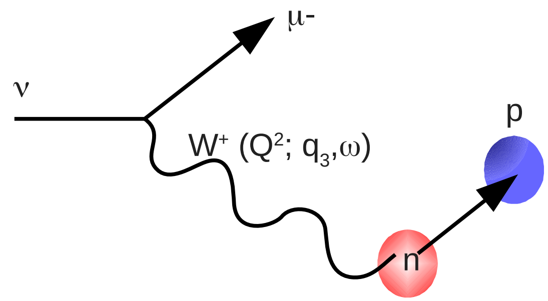




The 'first order' problem to solve (largest impact on oscillation analysis) is the capability of reconstructing the neutrino energy

Neutrino energy reconstruction

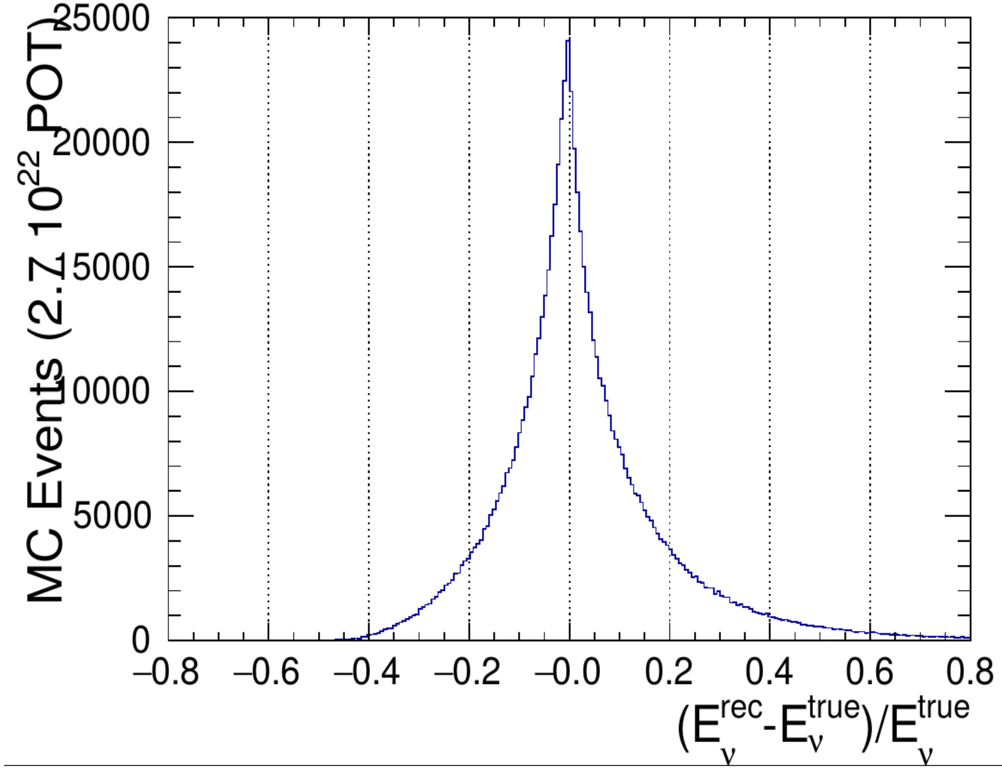


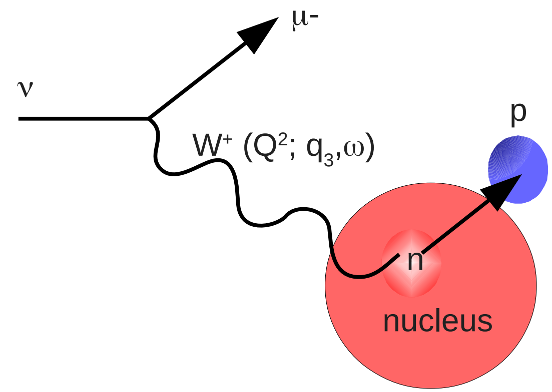


$$E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu cos\,\theta_\mu)}$$

Calculation from lepton kinematics is perfect only for elastic scattering off a free nucleon at rest

Neutrino energy reconstruction

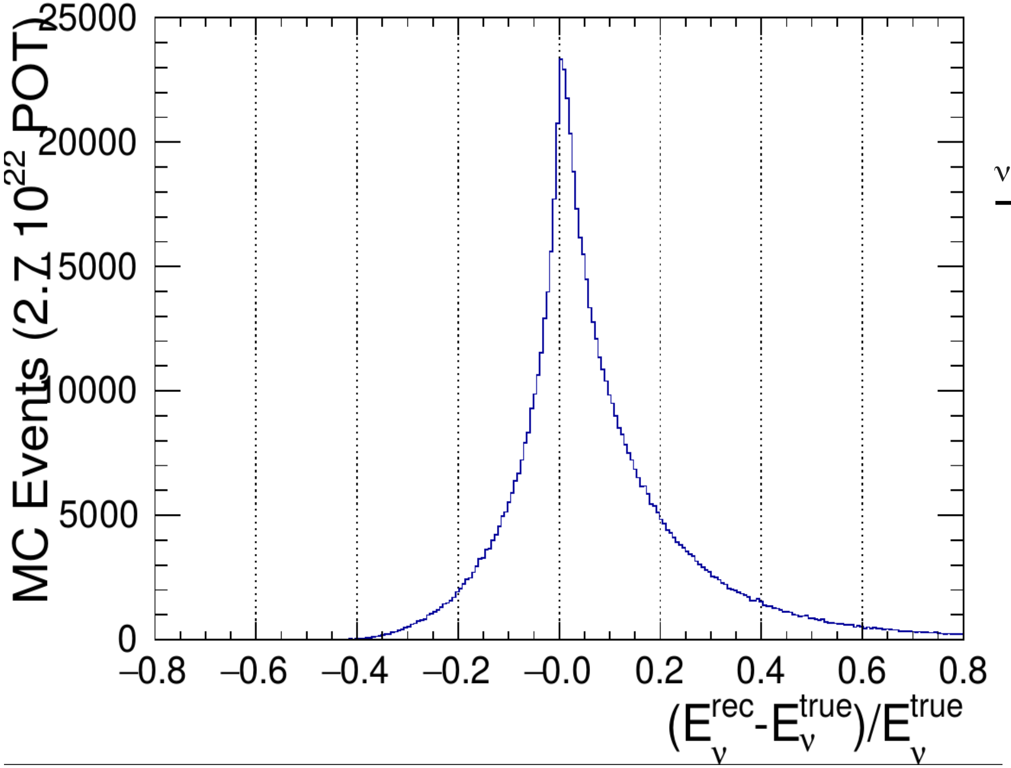


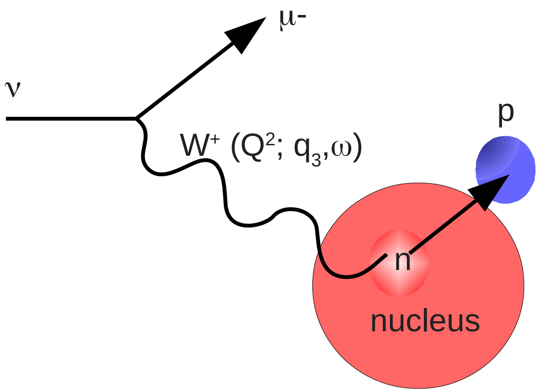


$$E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu cos\,\theta_\mu)}$$

The motion of the nucleons inside the nucleus (*Fermi motion*) causes a **smearing** on reconstructed energy

Neutrino energy reconstruction

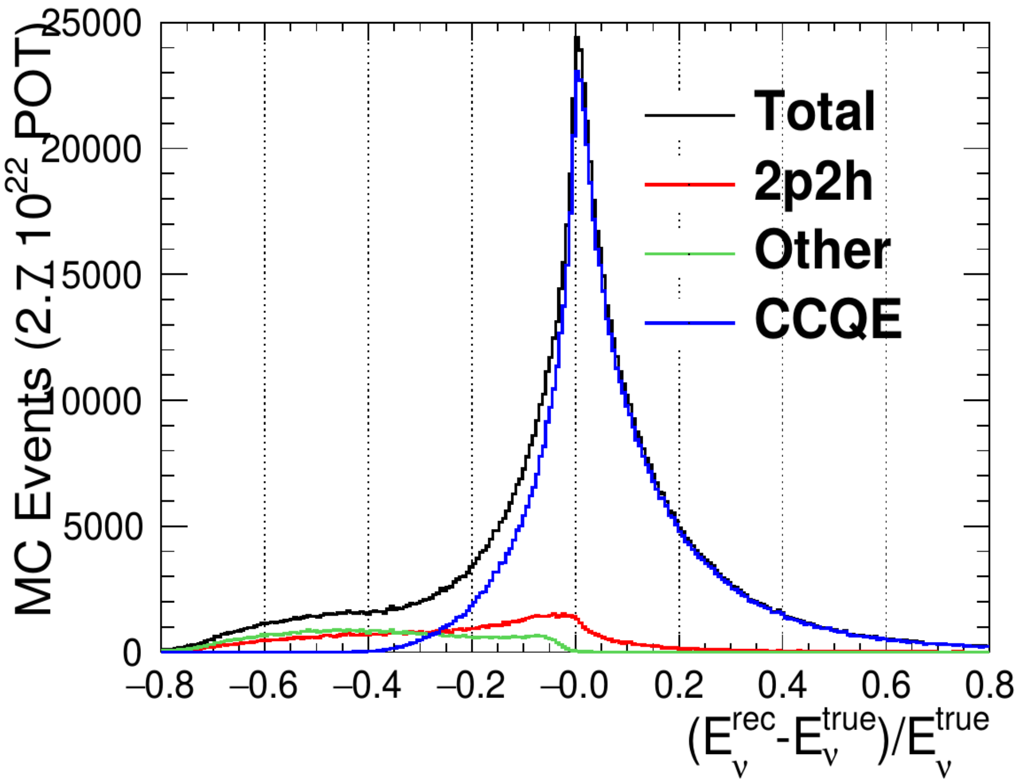


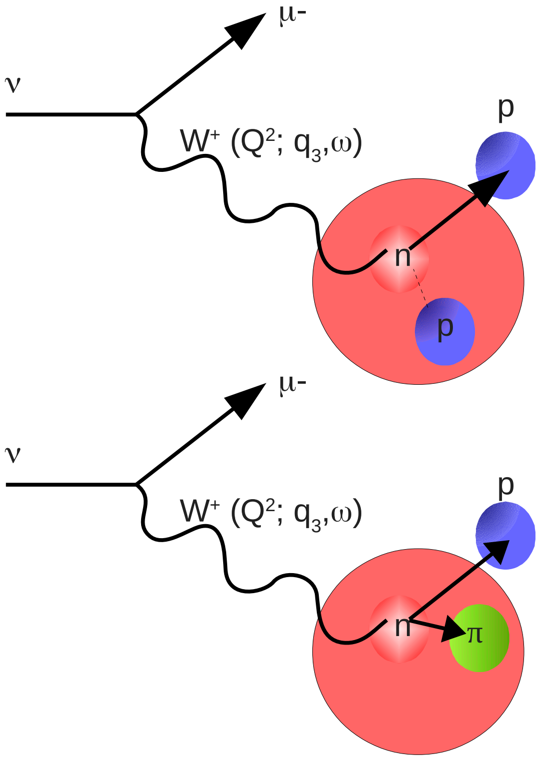


$$E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu cos\,\theta_\mu)}$$

The energy loss in the nucleus (to extract the struck nucleon from its shell) introduces a **bias** on the reconstructed energy

Neutrino energy reconstruction

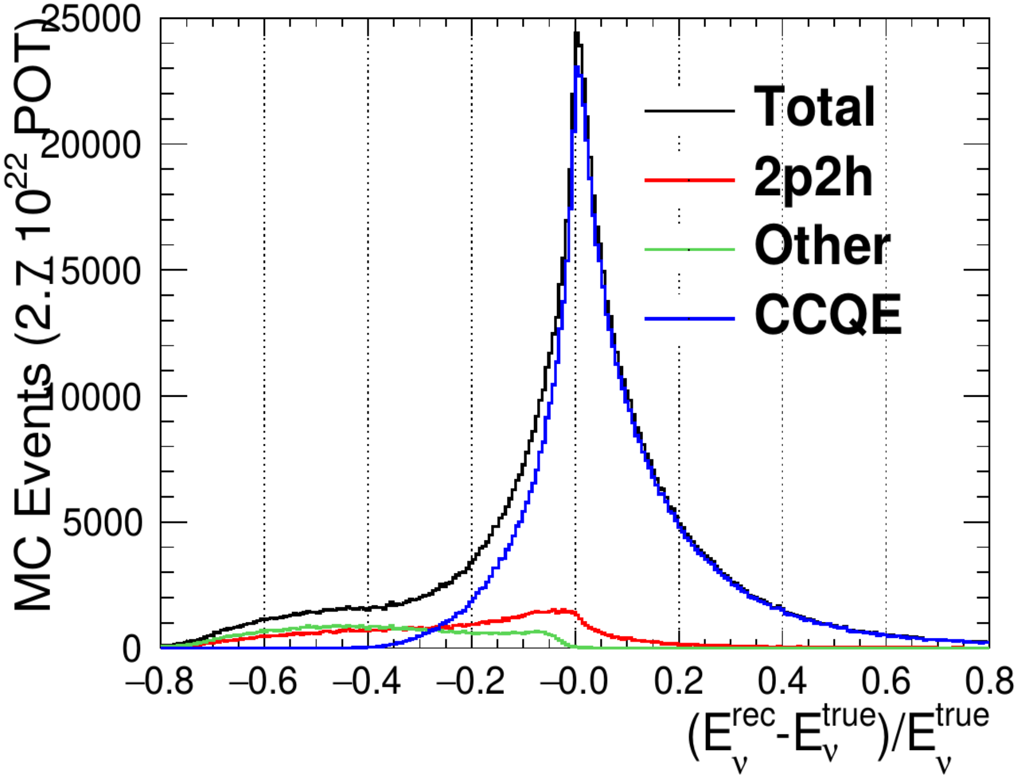




$$E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu cos\,\theta_\mu)}$$

Does not work well for non-CCQE events: 2p2h and CC1π with pion abs. FSI)

Neutrino energy reconstruction



'First order' uncertainties:

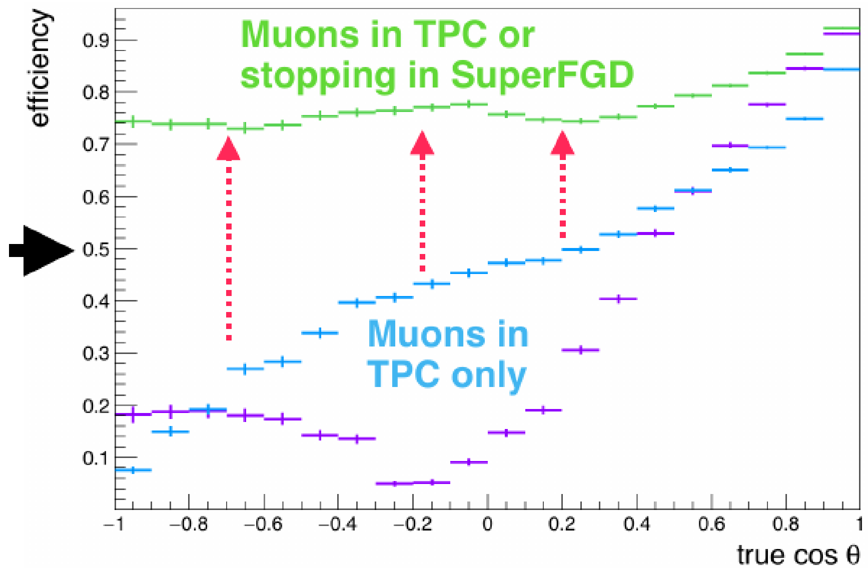
CCQE: Fermi motion and removal ("binding") energy

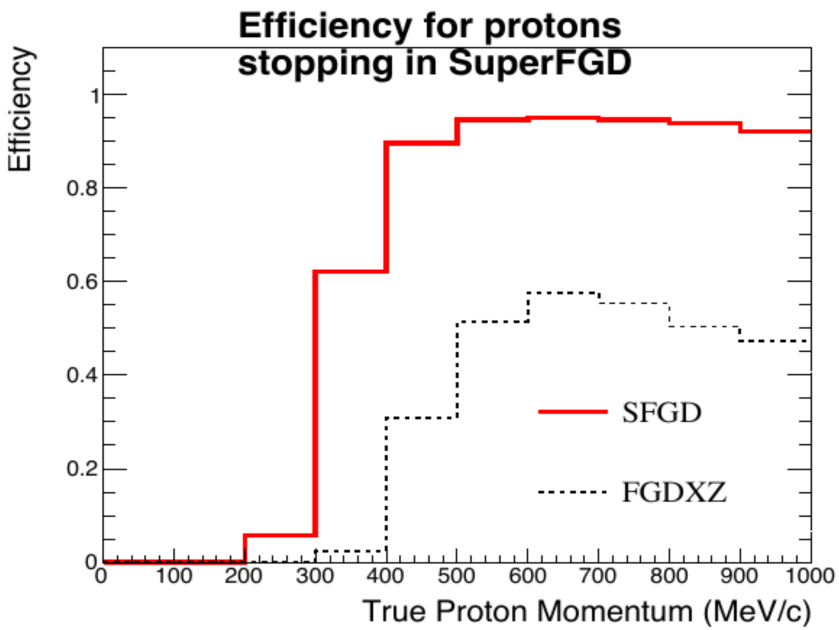
2p2h cross-section (10-20% of CCQE?)

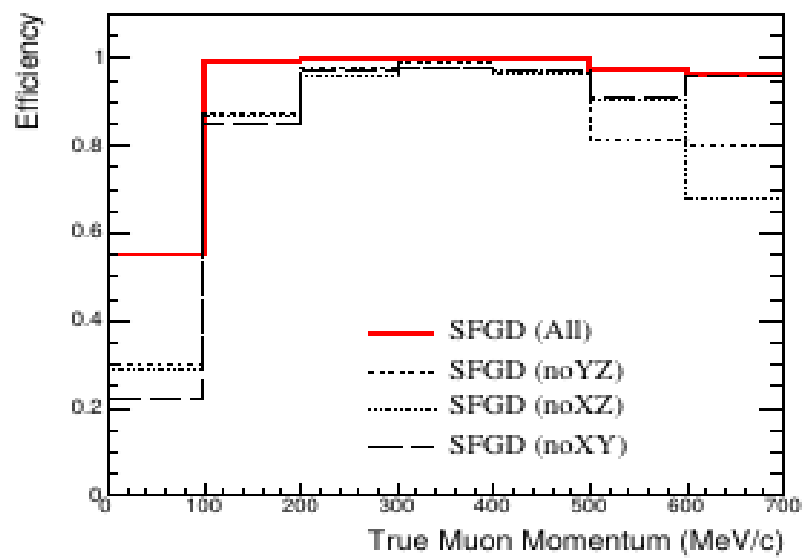
Accessing important new phase space

- ND Upgrade will allow us more statistics and a better acceptance (to match that of SK) for measuring muons.

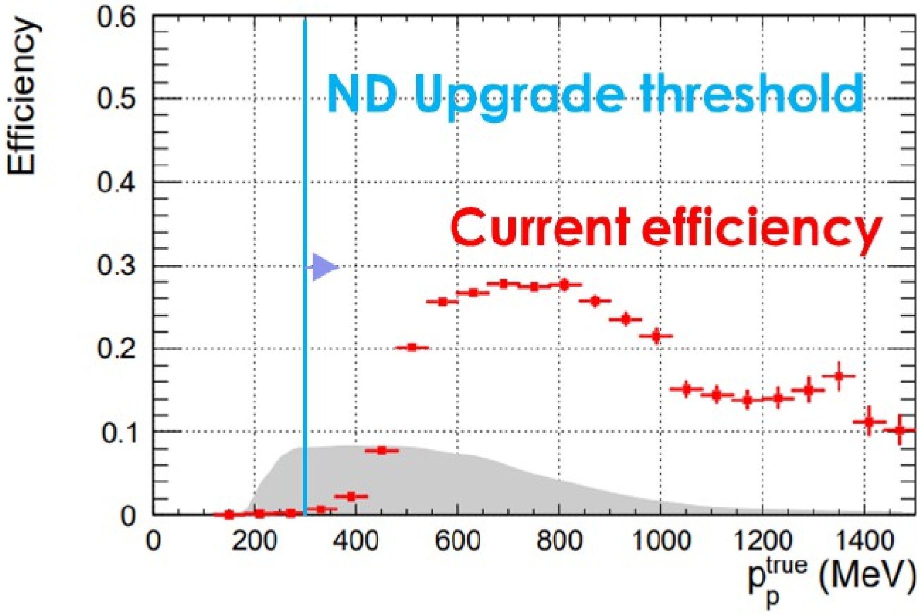
- ND Upgrade will also allow us a unique measurement of nucleons.

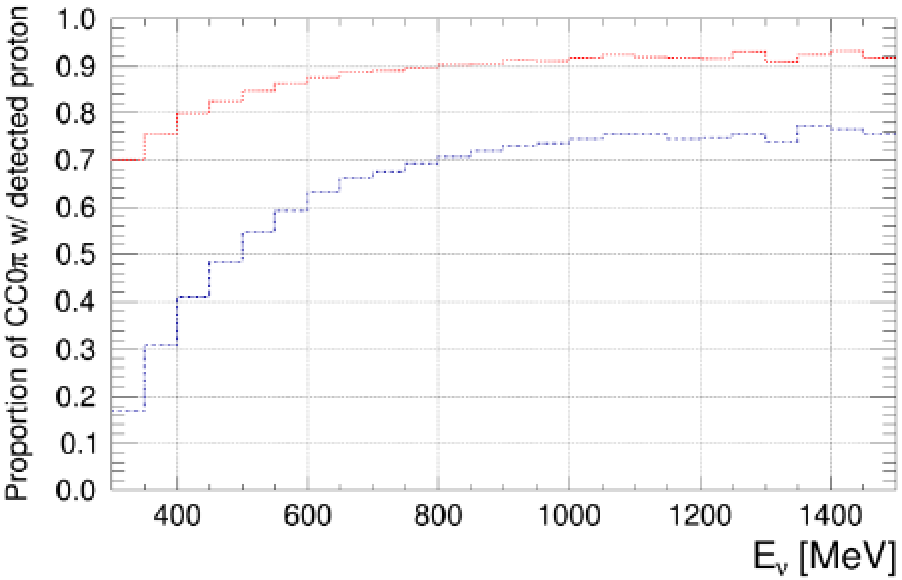






Nucleons for oscillation analyses





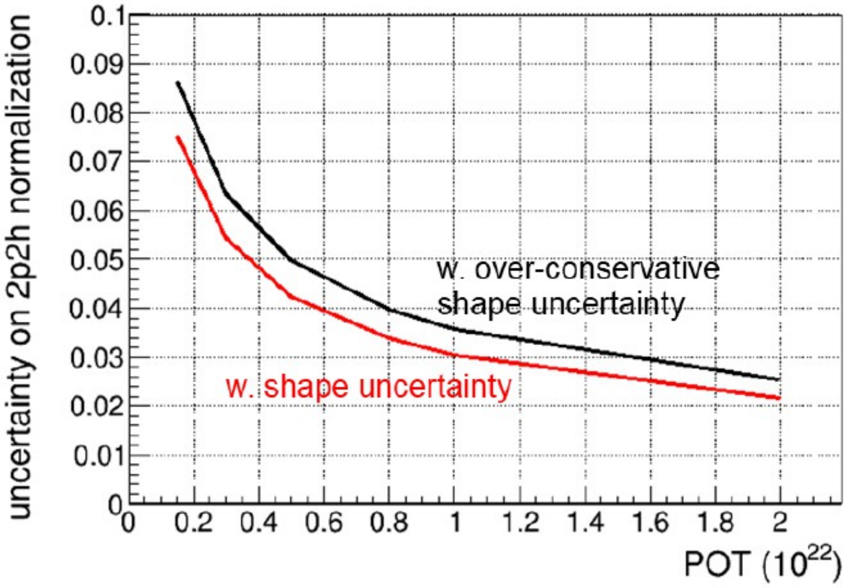
More beam, more mass, more acceptance:

- Upgrade: 500k CCQE events **with protons**/ 10^{22}POT
  (Recent T2K (~ POT): 50k muons, 20k protons)

- **Critical point**: we will start measuring protons in the region that is relevant for the oscillation analysis

Fitting 2p2h using SuperFGD protons

- An attempt to be quantitative: sensitivity studies which include all the largest uncertainties and effects we know
- Simplified simulation (smearing on top of MC)
- 2D fit proton-related variables (Single Transverse Variables, see backup) with simplified but realistic uncertainties

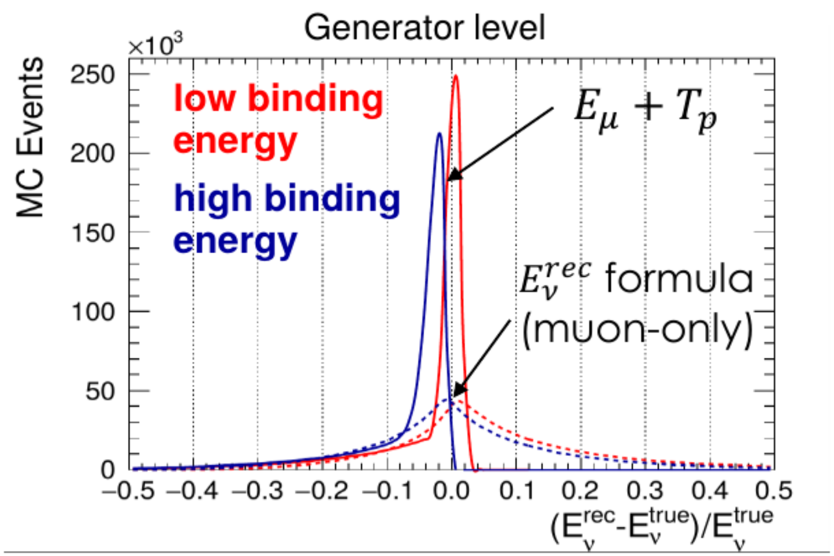


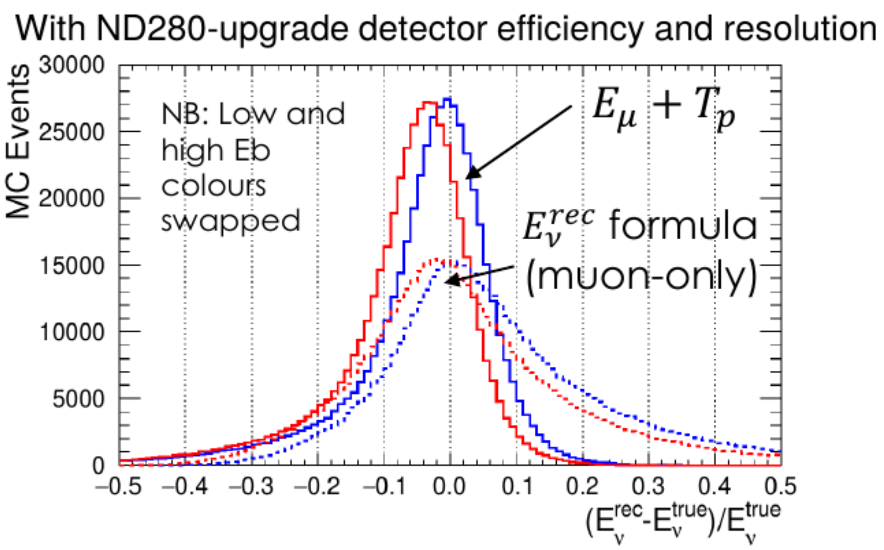
ND280 w/ 10^{22} POT: ~20% (today)
Upgrade w/ 10^{22} POT: ~3%

This is using only these two variables → even better sensitivity by fitting proton variables and muon kinematics together

Another variable: total energy

- The $E\nu^{rec}$ reconstruction formula does not include the outgoing proton
- $E\mu$+Ep is a much better estimator of true neutrino energy





- Smearing of $E\nu^{rec}$ is dominated by Fermi momentum,
- Smearing of $E\mu$+Ep is dominated by flux (and detector effects)

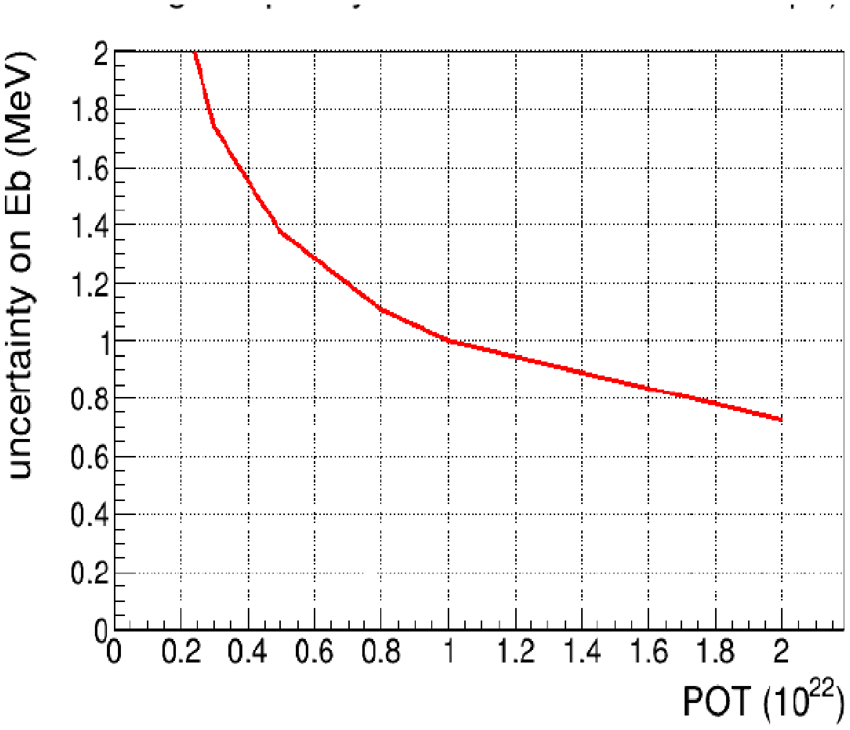
  → is a much more robust estimator of and of binding energy

This is just the appetizer! We are starting investigating possible other variables and combinations → a lot of new sensitivity

Fitting binding energy using total energy

Same idea as before: simplified simulation of SuperFGD fitting hadron related variables with all the relevant effects we could think of

2D fit of proton variable and Eμ+Ep



ND280 w/ 10^{22} POT: ~7 MeV (today)
Upgrade w/ 10^{22} POT: ~1 MeV!

This is using only these two variables → even better sensitivity by fitting proton variables and muon kinematics together

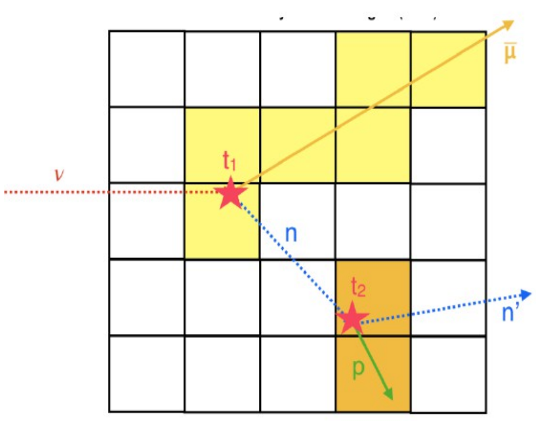
Neutrons with the SuperFGD

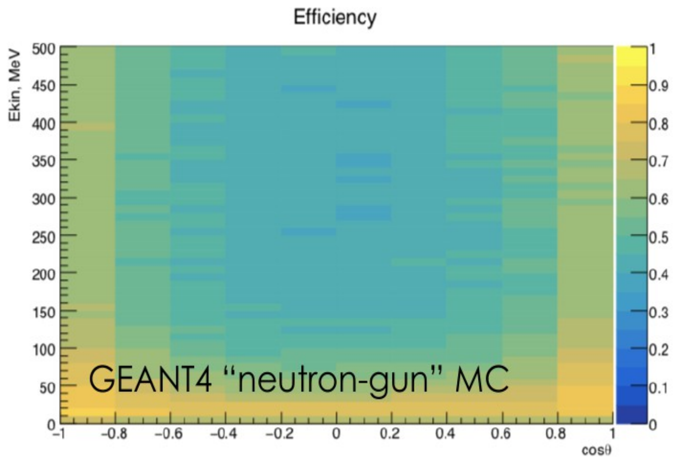
Can go beyond protons: superFGD can detect neutrons with **~60% efficiency**

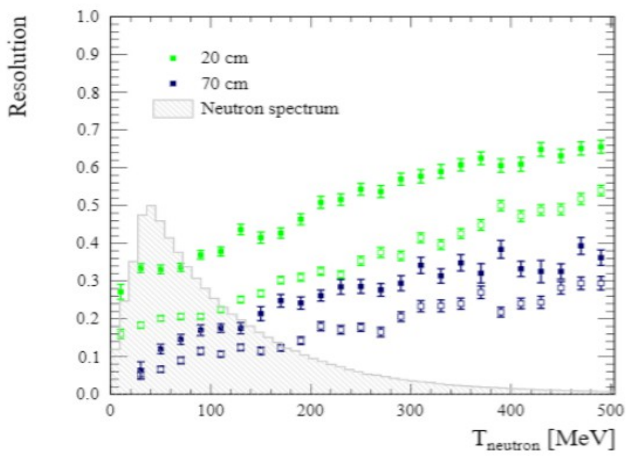
Before thermalisation, ideally the first neutron rescatter within the detector

If the path is long enough and depending on electronics time precision (~0.95 ns MIP) → neutron energy is measured using the time of flight with **resolution 15-30%**

(to be calibrated with neutron test beam)



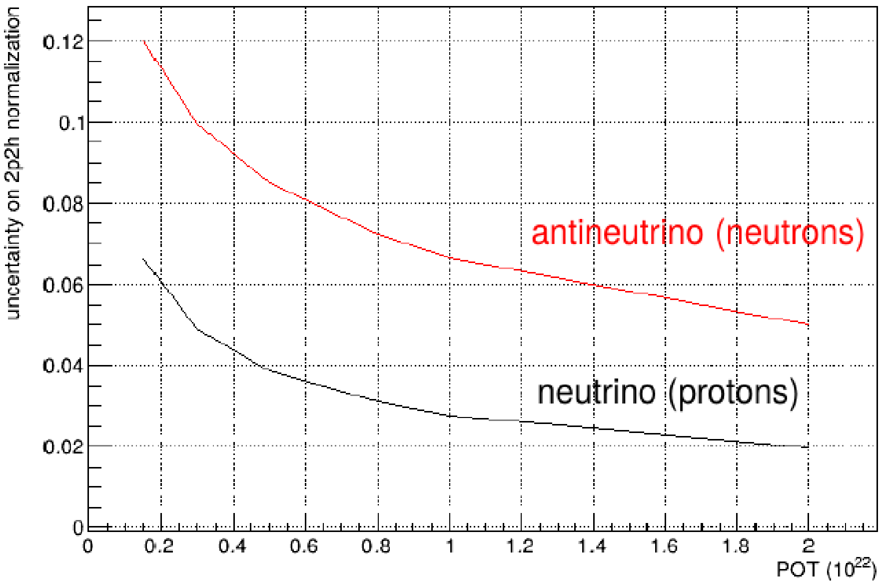




SuperFGD: neutrons

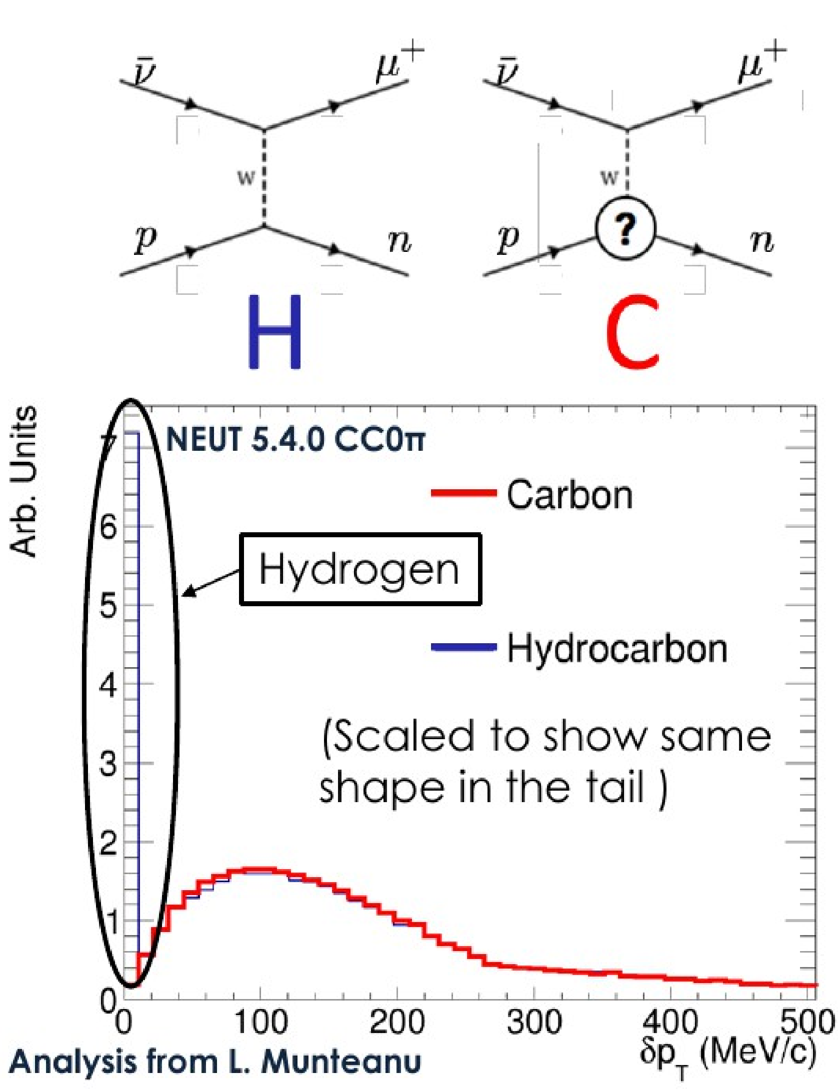
- Repeat previous 2p2h normalisation sensitivity study with neutrons
- Use neutron particle gun MC to simulate neutron momentum resolution and efficiency

Example of fitting single transverse variables



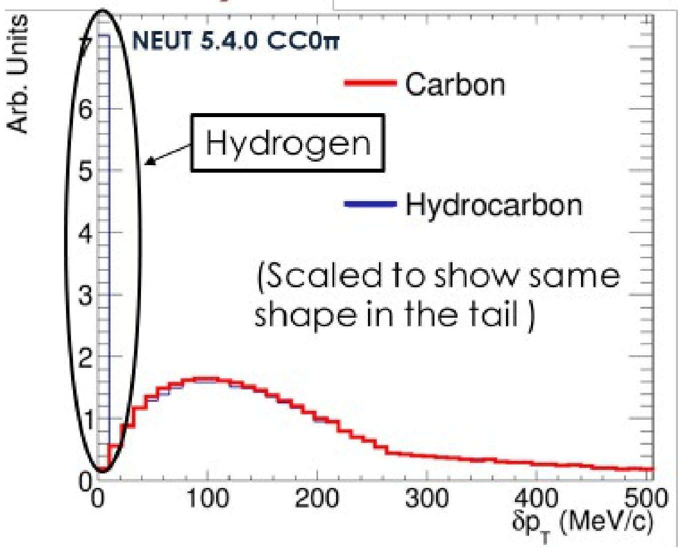
- Constraints from neutrons much more limited, but essential to understand xsec asymmetries

Neutrons and transverse imbalance



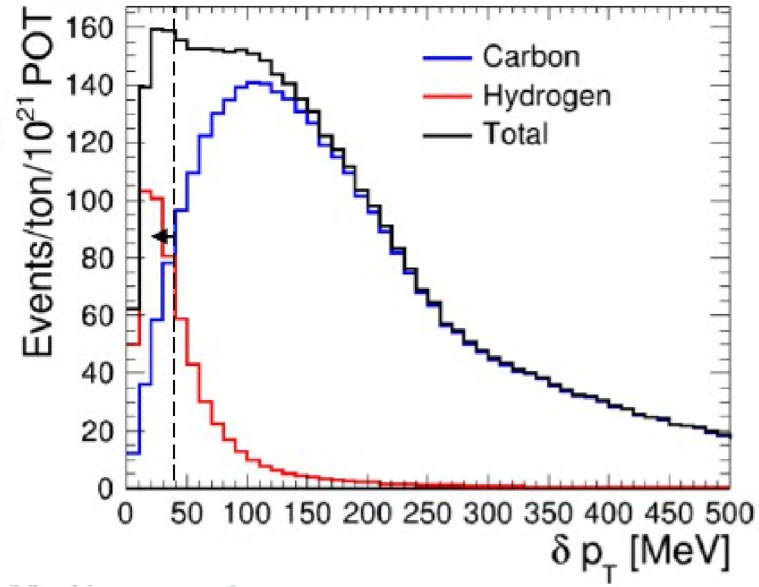
- H has no nuclear effects, so neutron and mu+ are back to back in the plane transverse to incoming neutrino (no transverse imbalance)
- Could use STV to extract H and make a ~ nuclear-effect free cross-section!
- Factorise nuclear from nucleon physics
- Can also have near perfect kinematic neutrino energy reconstruction

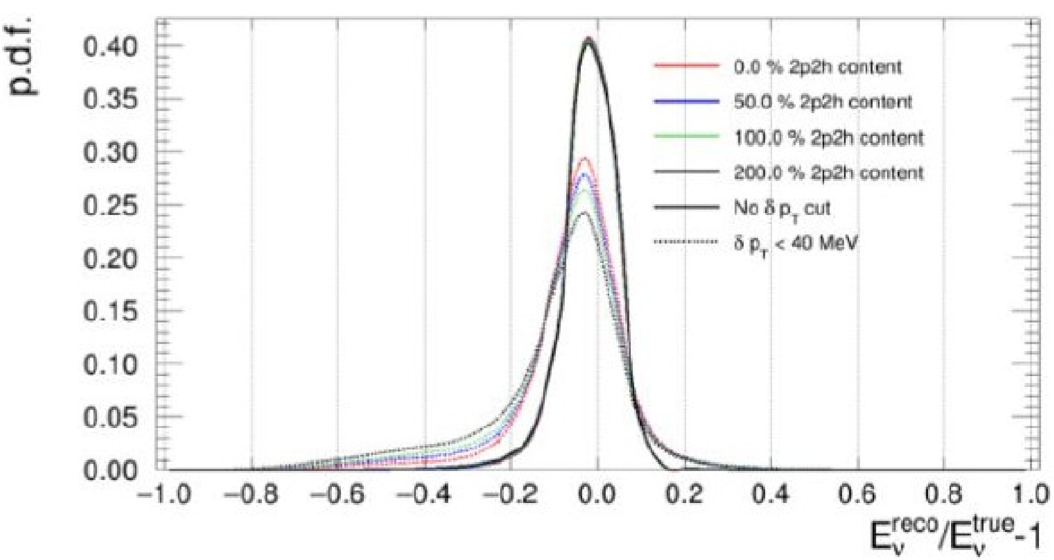
Can you do this in a real detector?



Detector smearing

Uses GEANT4-based neutron simulation

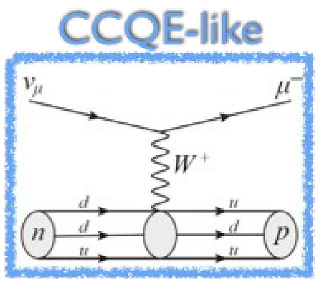


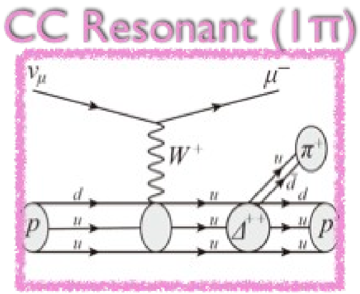


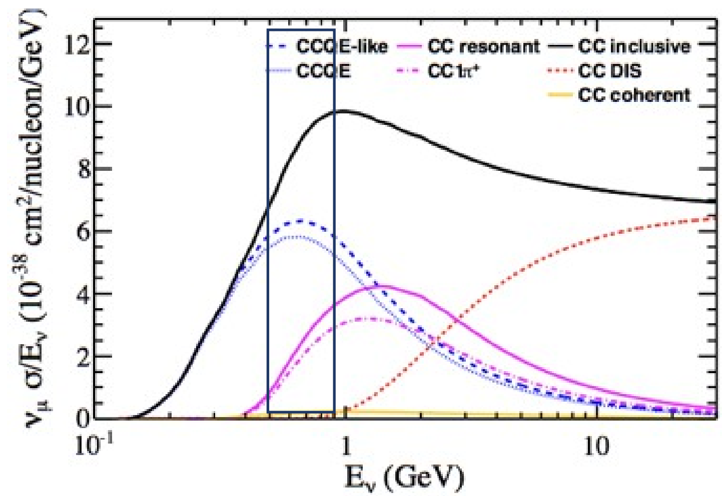
- Improved E_ν resolution
  - RMS: 16% → 7%
- Insensitive to nuclear effects (even the carbon events are the ones that aren't much affected)
- Useful for in-situ flux constraints or measurements of form-factors?

Multi-ring at SK

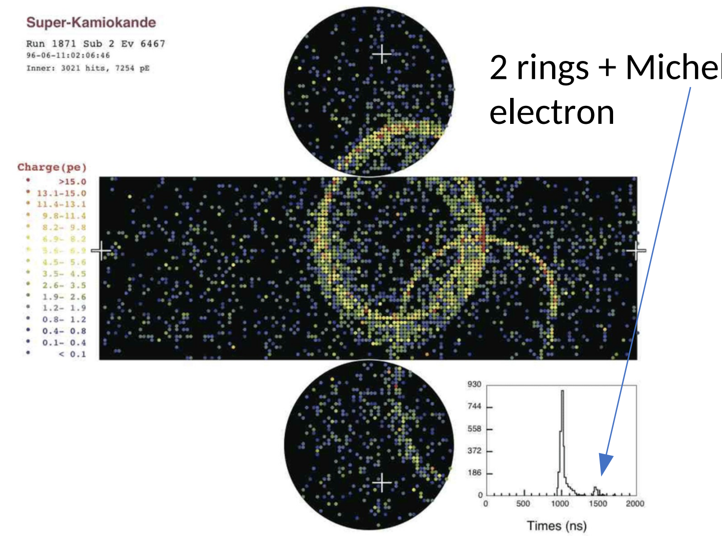
- T2K flux centered at E~600 MeV where most of the interactions are quasi-elastic





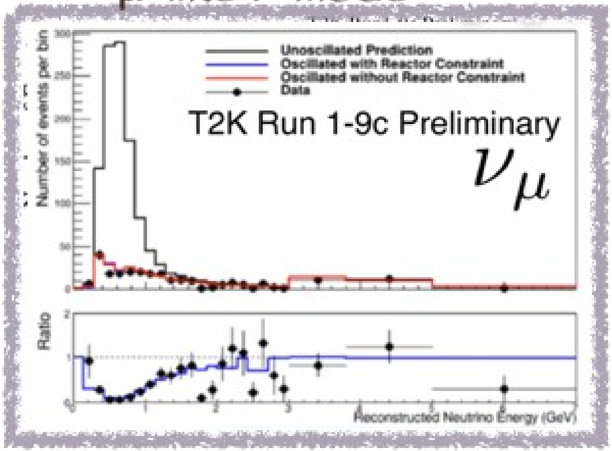


- Non-negligible amount of CC1pi interactions
  - Either reconstruct the pion ring (2 ring samples)
  - Either observe delayed signal from Michel electron (pi -> mu -> e)

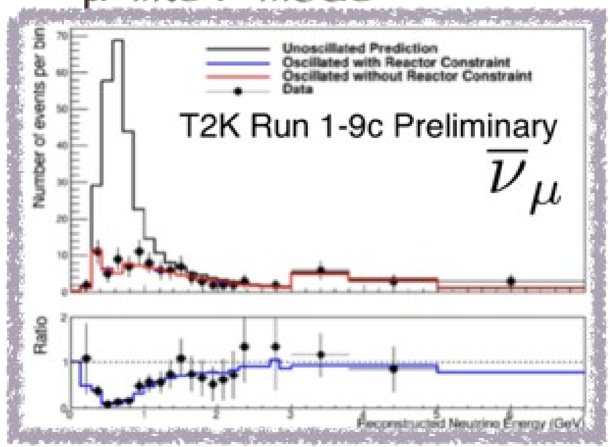


SK event selection

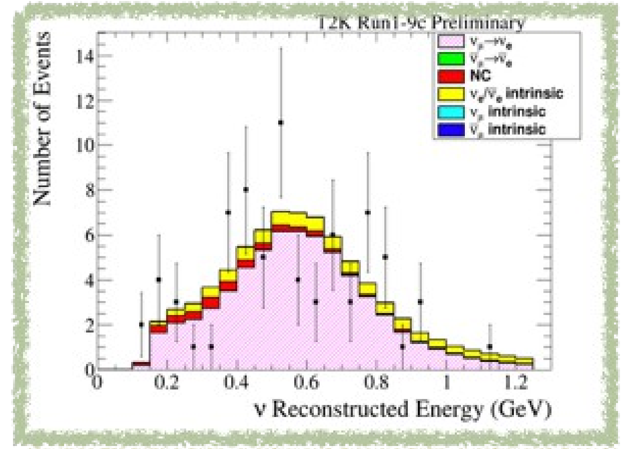
μ-like ν-mode

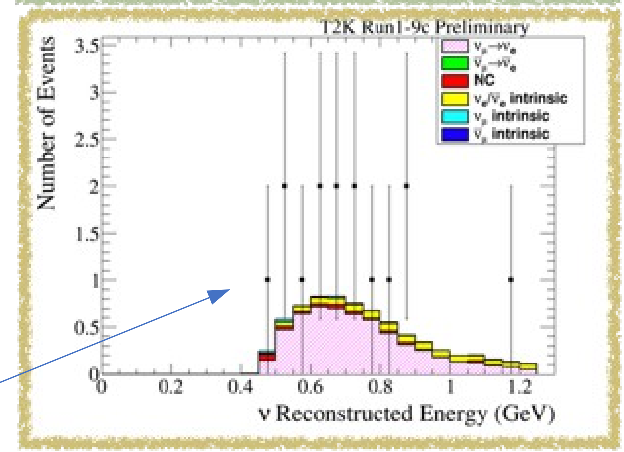


μ-like $\overline{\nu}$-mode

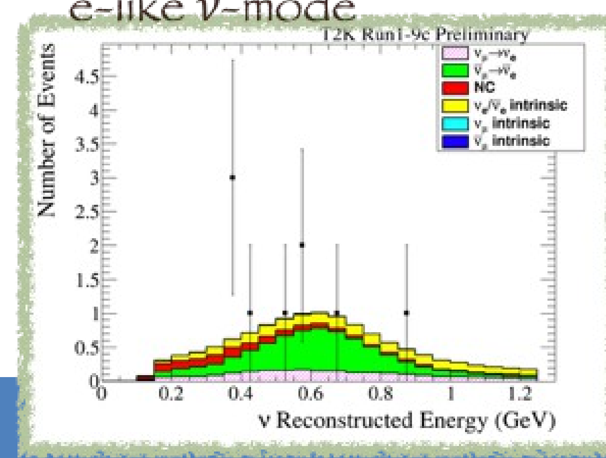


e-like ν-mode





e-like $\overline{\nu}$-mode

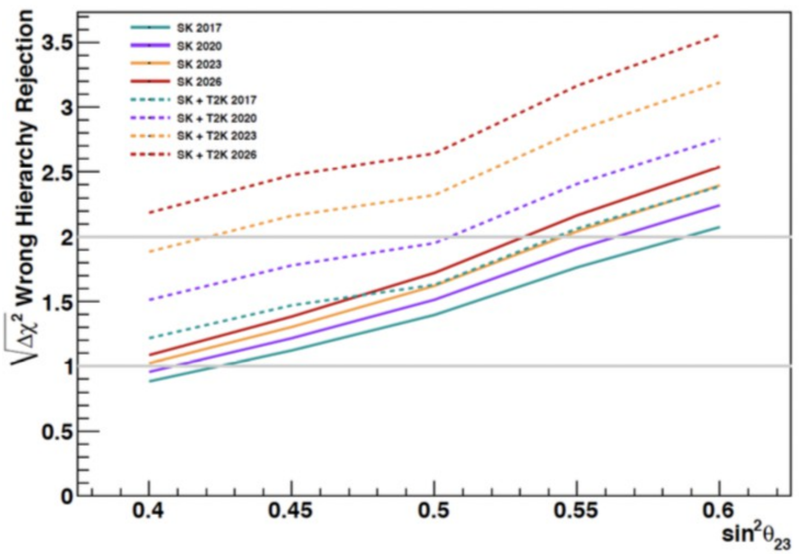


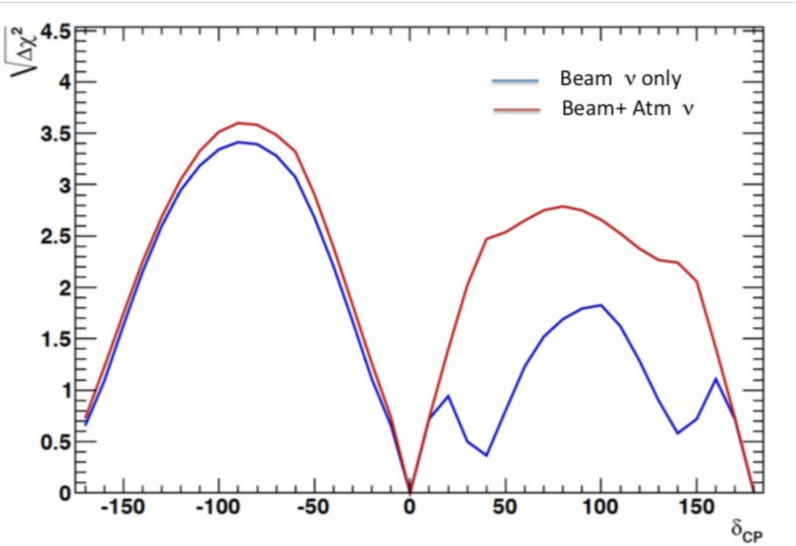
- Currently we have 4 single-ring selections (CCQE) and 1 CC1pi selection for electron neutrinos with Michel electrons
  - upper flucation in number of events (15 vs 7 expected, p-value of 6%)
  - Important to cross-check if it's a statistical fluctuation or a problem with our model -> Add samples with two reconstructed rings at SK
  - Work is on-going, expect to increase the available statistics by ~40% in neutrino mode

T2K/SK combined analysis

- Already done by SK collaboration using public T2K data as external constraints (Phys. Rev. D 97, 072001 (2018))

- Recently an MoU between T2K and SK collaborations has been signed in order to produce an official T2K/SK combined analysis
  - Use Near Detector data to improve SK atmospheric model
  - Combine T2K and SK samples to improve sensitivity to mass ordering and to δ_{CP} (by breaking some degenaracies)





Conclusions

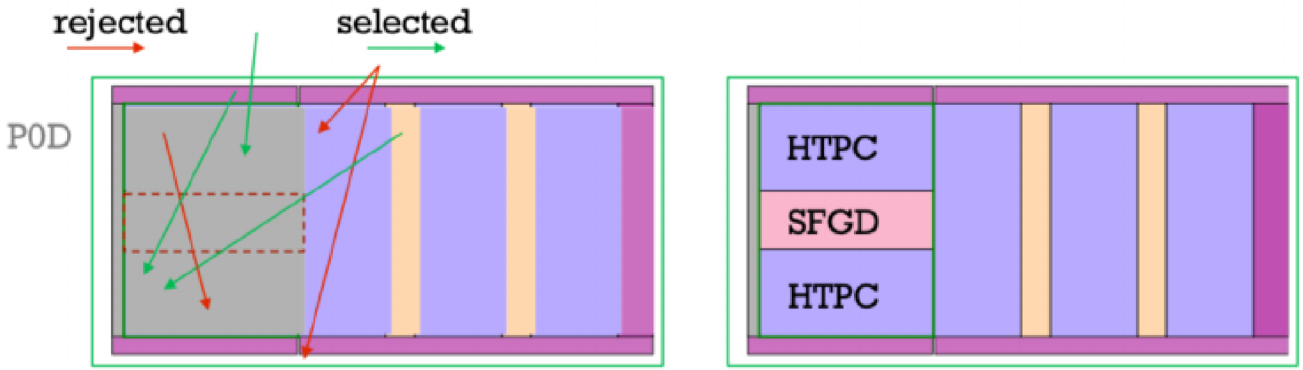
A lot of interesting physics results along the 4 years of JENNIFER2 project !

Backups

External neutron background

Analysis from S. Suvorov

- Neutrons produced from interactions outside of the SuperFGD (usually the magnet) can act as background. How critical is this?



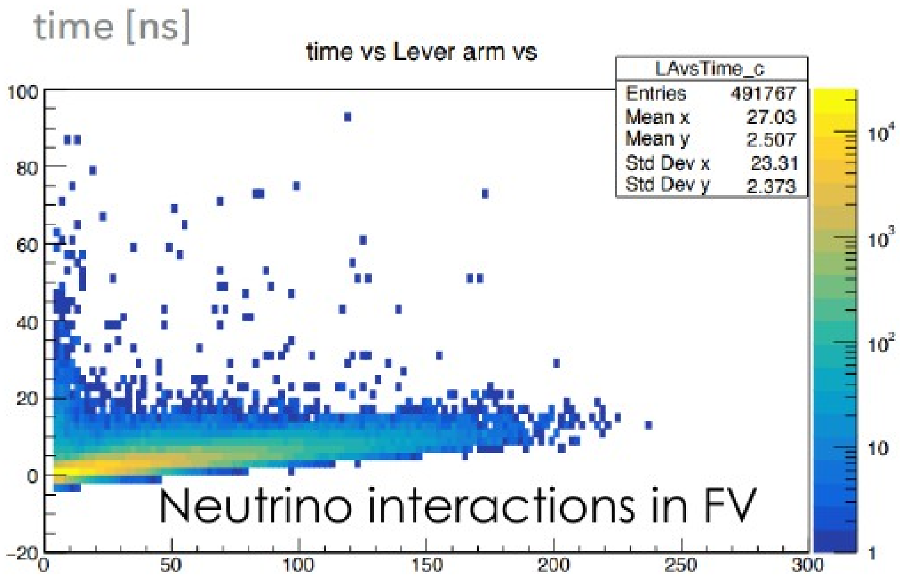
- Take current ND280 simulation of external neutrons in ECal and magnet
- See how often an interaction causes a neutron to pass into SuperFGD
- Take these neutrons and simulate them in SuperFGD with particle gun
- Evaluate pile up from this: **1%(2%) for 500 kW (1 MW) anti-neutrino beam**

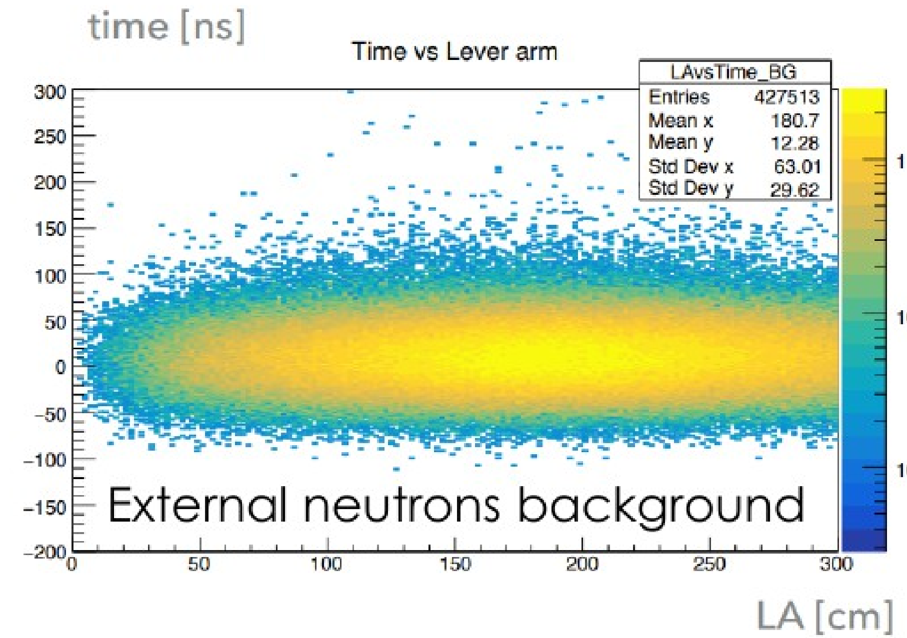
Caveat: this doesn't include "sand neutrons". Expect this to be second order: most of will not arrive in coincidence with the beam and may be partially moderated by the magnet

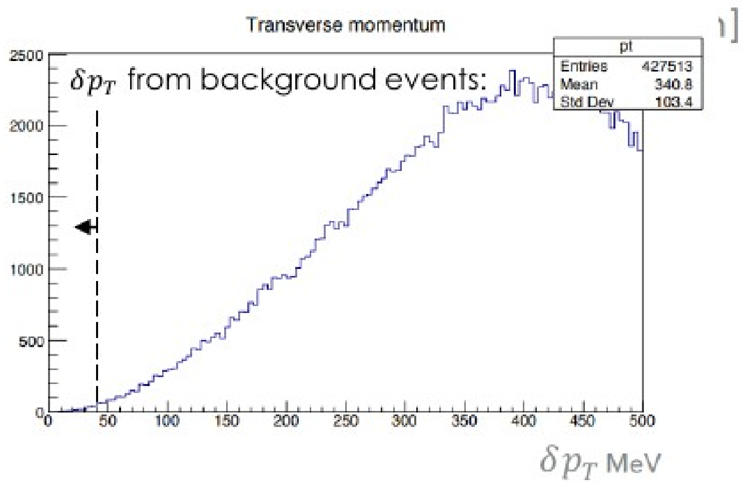
Analysis from S. Suvorov

External neutron background

- Lever arm cut allows a rejection of about half the background





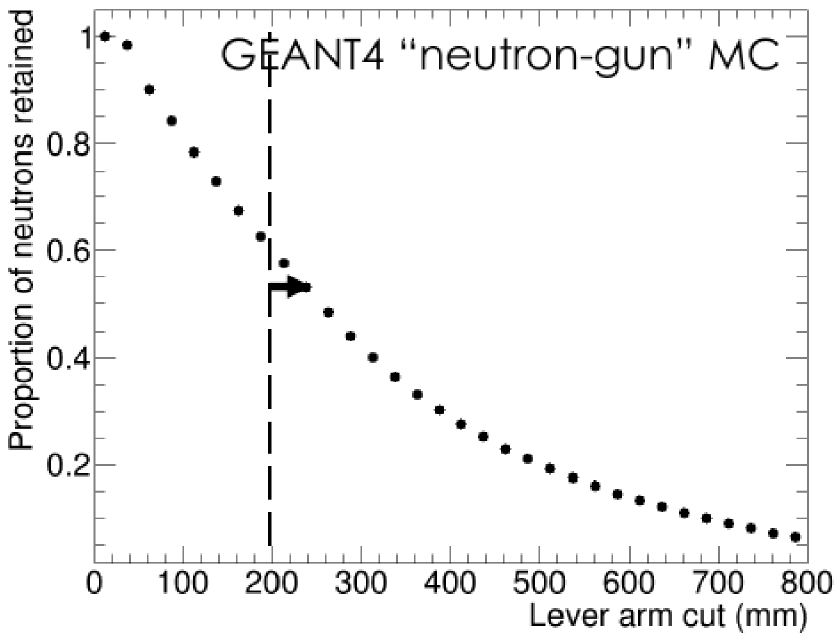


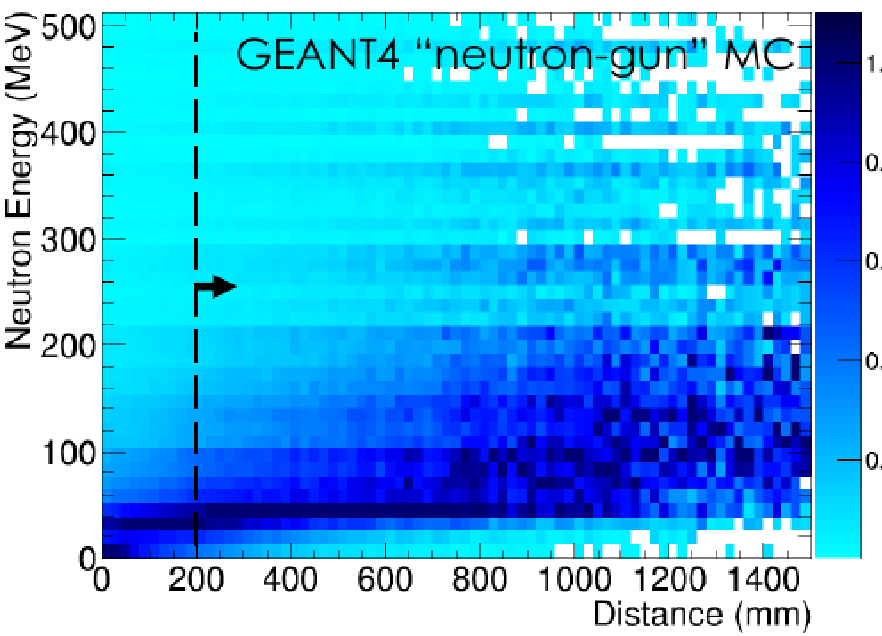
- Will continue to investigate, but does not seem to be a critical issue

Analysis from S. Suvorov

Neutrons with the SuperFGD

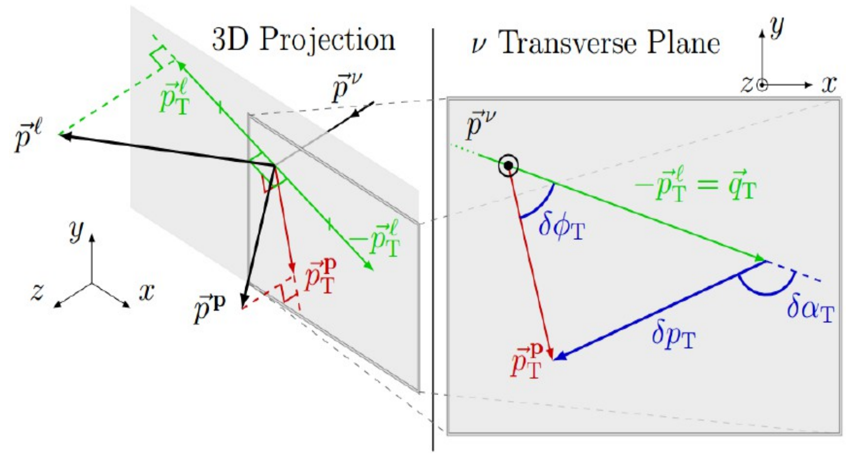
- Can go beyond protons: superFGD can detect neutrons with ~60% efficiency
- If the path is long enough (>20 cm) neutron energy is measured using the time of flight with resolution 15-30% (to be calibrated with neutron test beam)
- Imposing a "lever arm" cut on observed neutrons does not strongly sculpt the neutron energies we see





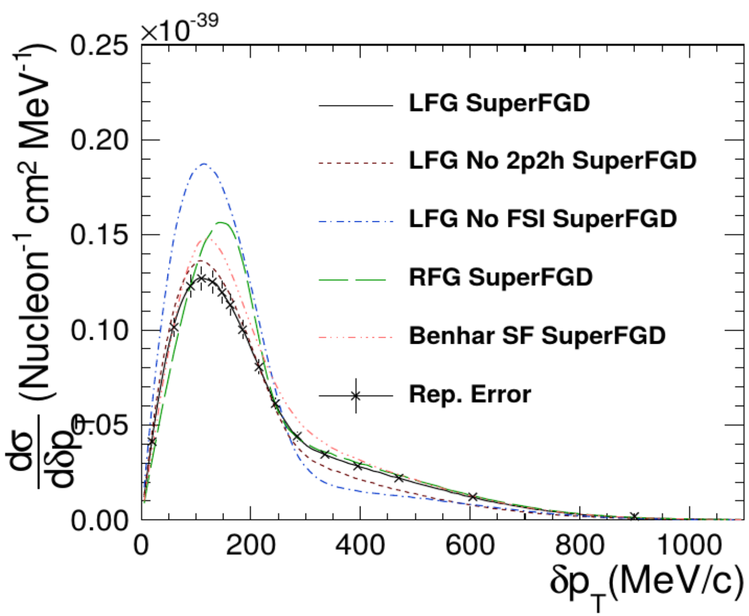
How to use this new phase space

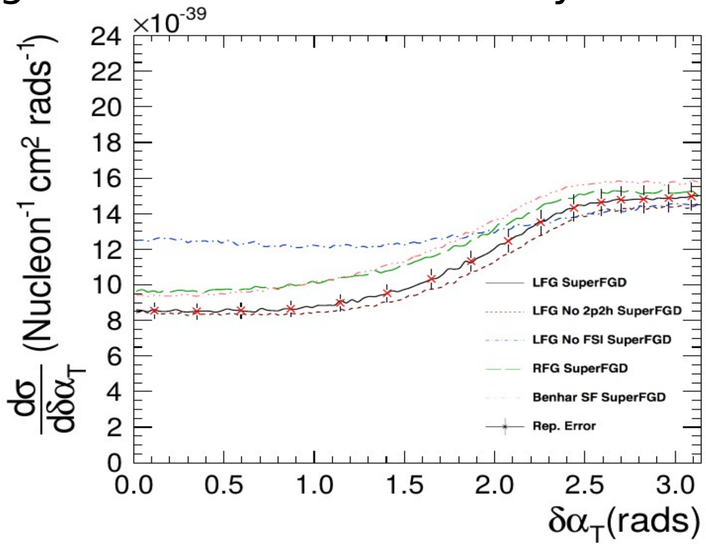
"Single Transverse Variables" and beyond!
→ measurements of Fermi momentum, binding energy, 2p2h...



is almost a direct measurement of the Fermi momentum (can also use "")
TDR: measurement w/ <10% precision in each bin for POT

shape is v. sensitive to proton FSI, allows few-% constraints (today ~30% from e-scatting): FSI will no longer prevent proton information being useful in oscillation analyses





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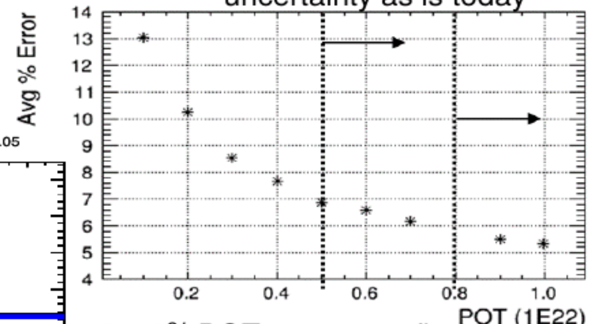
A change of paradigm

- Muon only today → “close” kinematics w/ hadron variables @NDUpgrade

Can measure interactions’ lepton and hadron side (and their correlations) directly to tune models beyond the “**factorisation approach**” (i.e. stop treating lepton and hadron side of the events as independent)

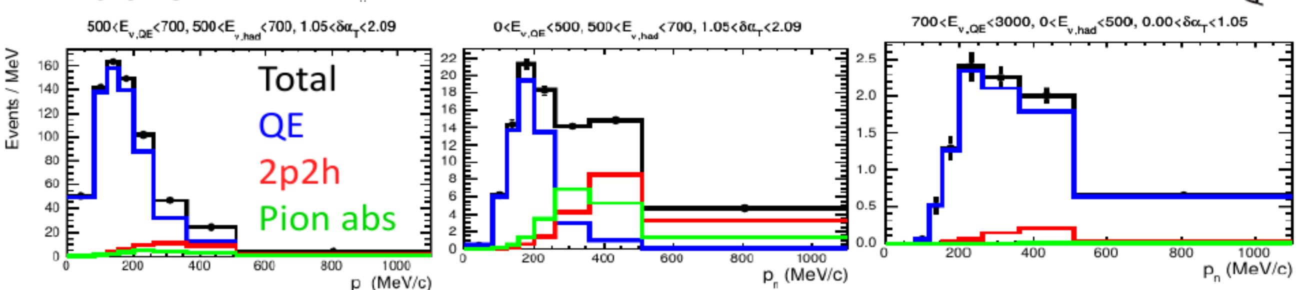
Uncertainty on the lepton side (and today’s limitations in constraining it) are due to 'factorization' not in both the model and in the way we do the analysis!
→ Require multidimensional analyses: statistics is crucial!!

5x10^{21} POT: stat error~flux uncertainty as is today



8x10^{21} 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) – 216 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 controling systematics on the lepton to the precision needed for HK!

[even the most complex uncertainty on numu/nue comes from that: how the different nuclear effects affect different q3,omega distributions, see backup slide]