T2K preparation for 2p2h

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for the T2K collaboration

NuInt

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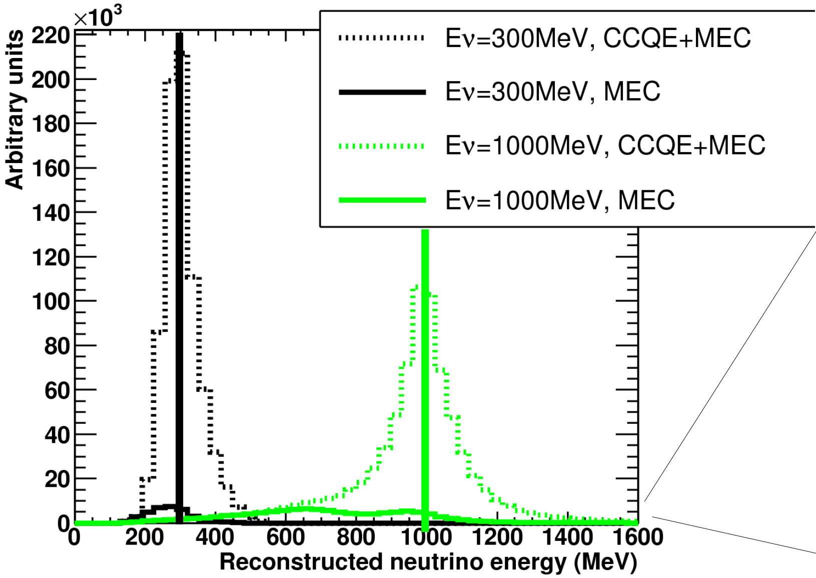
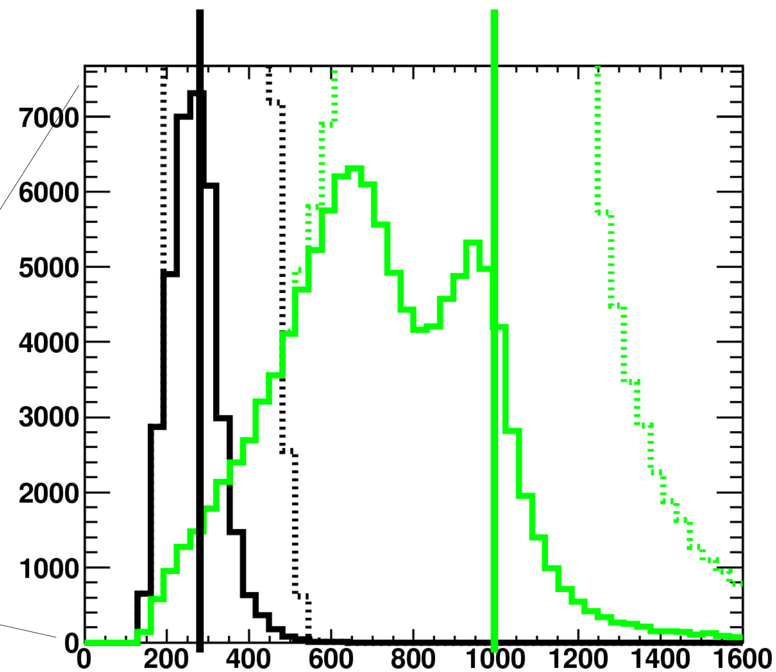
- **Why do osc. experiments care about 2p2h?**
- **Implementation of 2p2h model into NEUT**
  - Leptonic prediction
  - Nucleon prediction
- **Confronting the model with data**
  - Basic selection, goodness-of-fit (GoF)
  - Towards a measurement

Why do we care?

If you think 2p2h are CCQE, reconstructed energy bias

300 MeV 1000 MeV





In T2K, nucleons hard to see → 2p2h looks like CCQE
Can account for this if 2p2h is in the generator

Previous NEUT (<v5.3)

Primary generator in T2K: **NEUT**

NEUT models: measurement → far-detector flux

In all T2K publications to date, NEUT contains (amongst other things..):

In NEUT	**Not in NEUT**
• FSI cascade model • π-less Δ decay	• Two body current (nucleon-level 2p2h)

Different kinematics of 2p2h → different extraction of flux from measurement. Need to get this right!

Putting 2p2h into NEUT

Which model? How to implement?

Physics needs

- T2K flux: 0-30GeV, (600MeV peak)
- Most power from outgoing lepton
- Potential to see nucleons

Model availability

- Model of Nieves et al. [1] available to T2K
- No nucleon prediction → effective model of J. Sobczyk [2]

[1] J. Nieves et al. Phys. Rev. C 83:045501 (2011)
[2] J. T. Sobczyk Phys. Rev. C 86:015504 (2012)

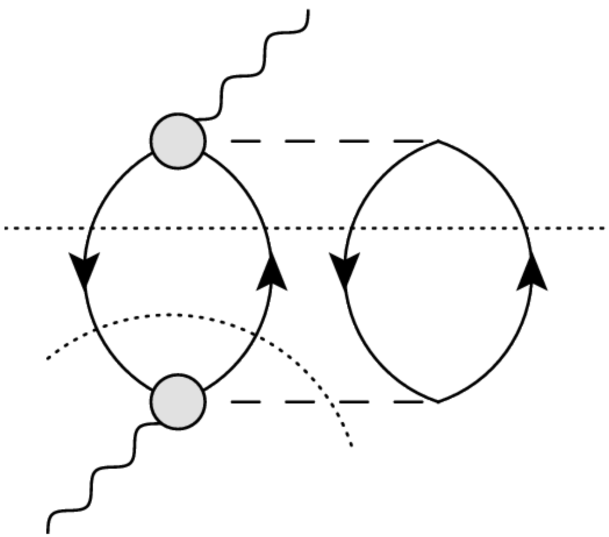
2p2h in NEUT: Nieves model

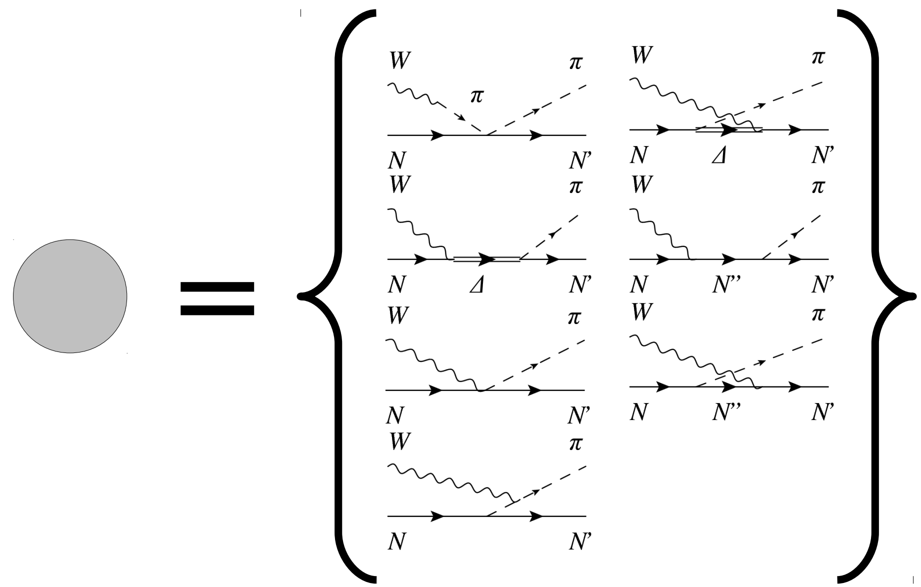
Nieves: **multi-body expansion of W-propagator** in nucleus

Various diagrams, but **use only 2p2h part**

Two vertices, seven vertex diagrams → **49 diagrams**

Many additional details: double-counting of diagrams, in-medium effects etc...



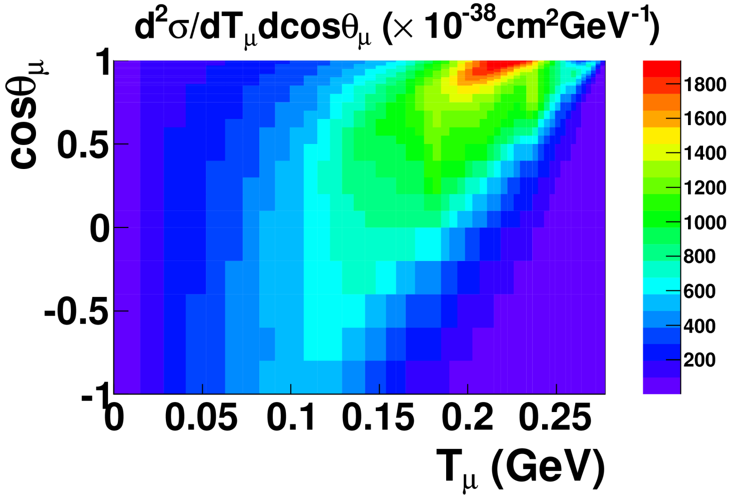


Model prediction

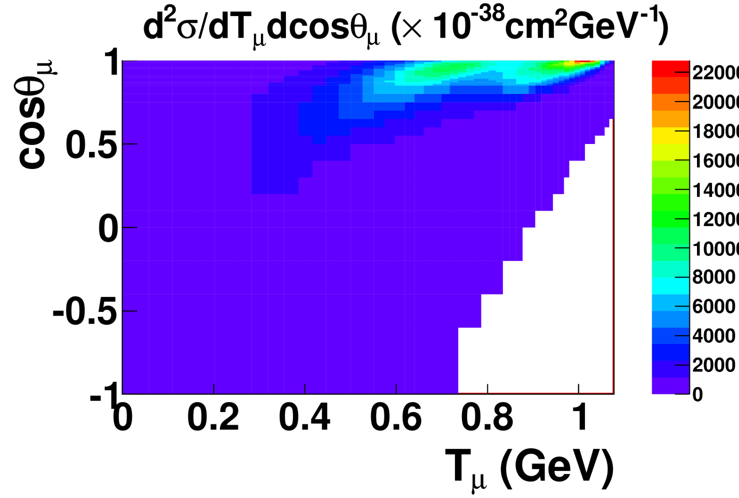
Nieves' model gives prediction of lepton double-differential cross section given parameters:

E_ν, T_μ, $\cos\theta_\mu$, neutrino type, target

E_ν=400MeV



E_ν=1200MeV



Lepton kinematics implemented via look-up tables

Nieves' model and the kinematic limit

Nieves' model includes diagrams which contribute at O(100MeV). Limit of validity of E_{ν}~1.5GeV.

- Δ resonance simulated, but no higher-mass resonances
- Calculation not configured for high momentum transfer (numerical accuracy)

But model can be extended by only using **low three-momentum transfer (q3) part of the cross-section** [3].

- Low q3 part remains accurate at high-energy
- Low q3 part contains most of the 'interesting physics' - processes which are 'interesting' at high q3 not simulated!

Prediction can then be extended to arbitrary energy

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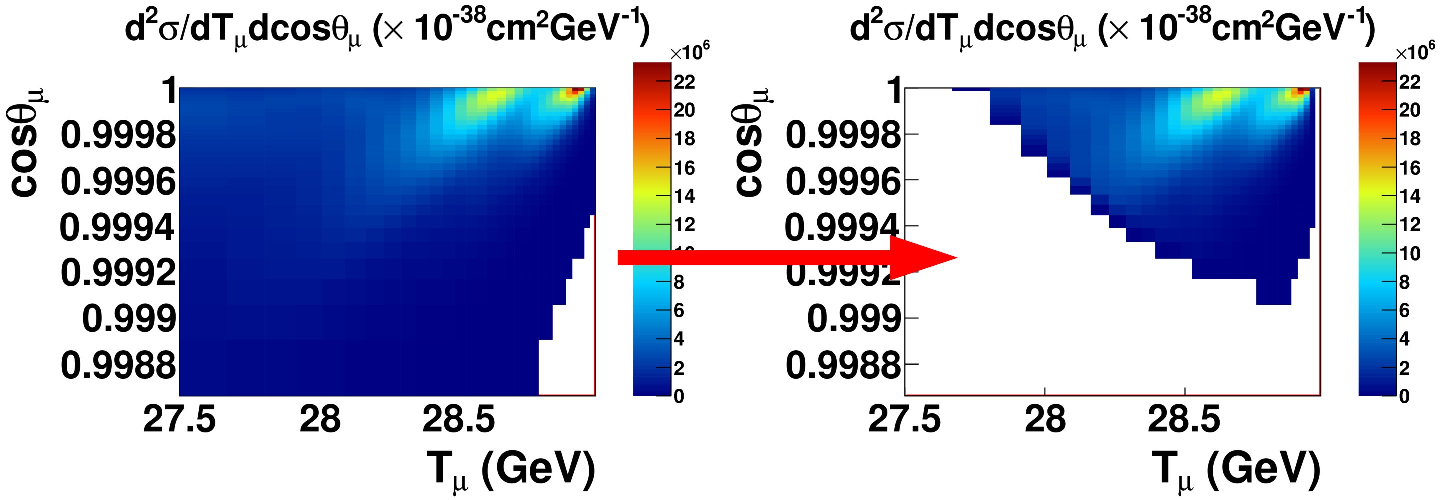
[3] R. Gran et al. Phys. Rev. D88 113007 (2013)

Effect of the kinematic limit

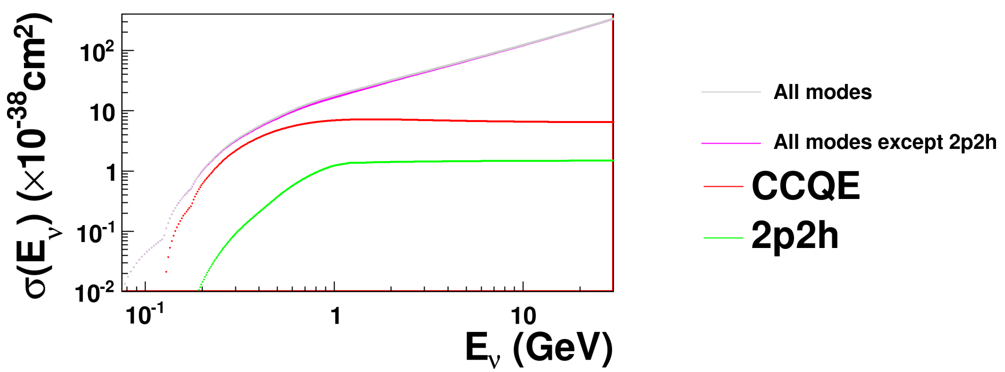
Imposing a kinematic limit cuts out large area of lepton phase space. Effect is larger at larger energies.



Double-differential xsec, Enu = 29GeV

Left: lepton phase-space before cut
Right: after cut

Note: range of plots is very restricted



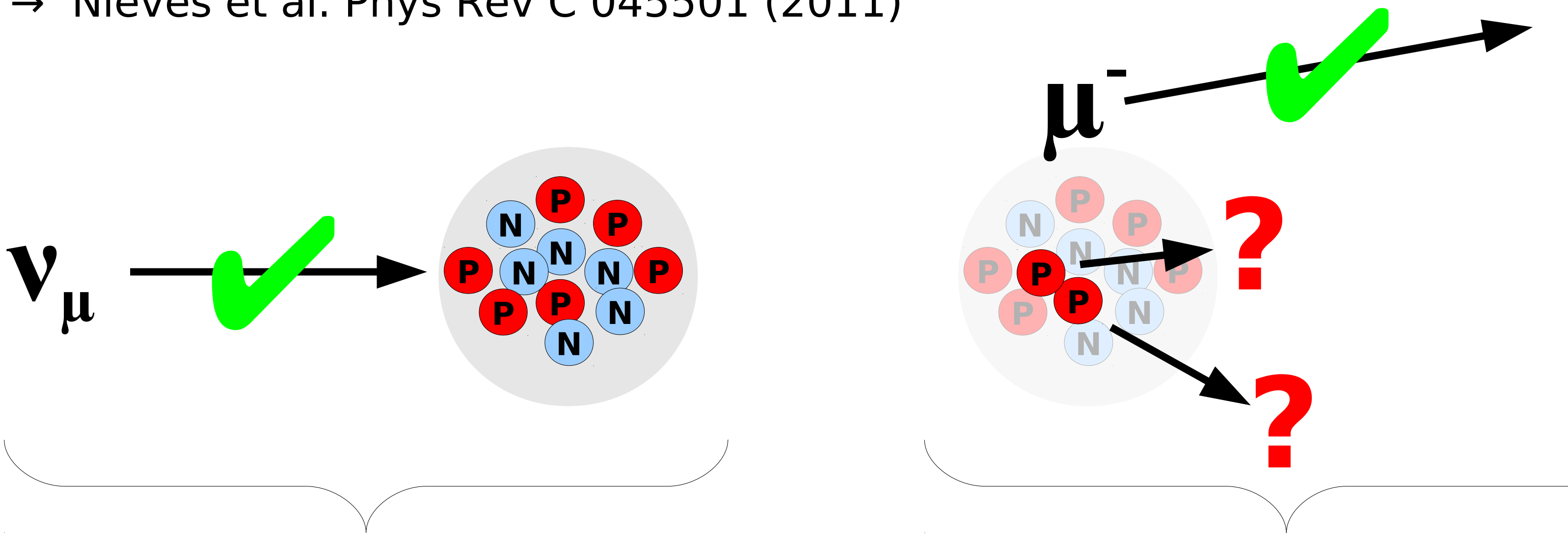
Total cross-section for 2p2h and various modes. Kinematic cut causes plateau of 2p2h cross section

Post-cut tables are the input to NEUT for the 2p2h mode

Ejection of nucleons

We have lepton information from theory

→ Nieves et al. Phys Rev C 045501 (2011)

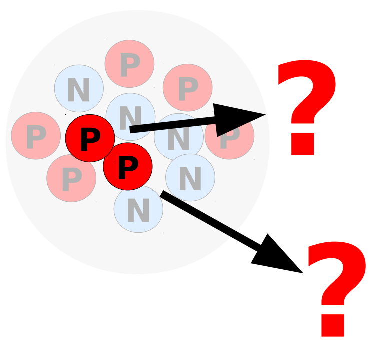


Initial state

Final state

For simulation in detector, need prediction for all final-state particles

Nucleon ejection method



How do you model the nucleon behaviour?

Choose set of assumptions to constrain behaviour

Jan Sobczyk's multi-nucleon ejection model

→ Phys. Rev. C 86 015504 (2012)

1) Initial state nucleons uncorrelated
2) Nucleon momenta same as 1p1h
3) Energy shared equally between F.S. Nucleons
4) Energy conserved

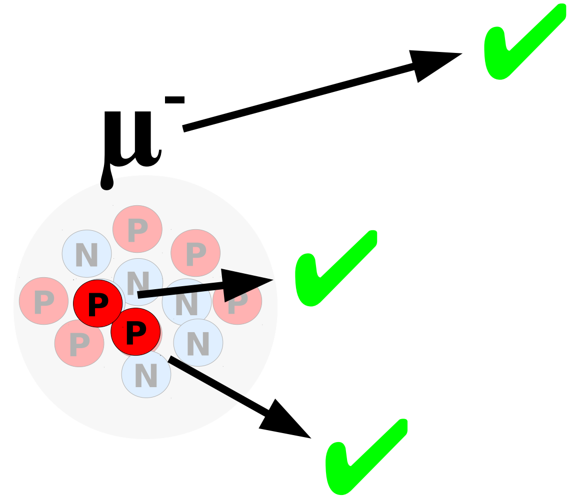
(All nuclear effects as normal)

NEUT nucleon simulation method (v5.3.0)

1) In lab frame, pick E_ν, Pμ, cosθμ. This defines the Q^2.
2) Choose int. position in nucleus (defines p_f)
3) Choose two uncorrelated nucleon momenta. (Check energy conservation)
4) Boost to CoM frame of nucleon system (momentum + Q)
5) Divide energy between two nucleons, eject in random direction
6) Boost back to lab frame
7) Pauli-blocking, FSI etc. as normal

Current limitations

Lepton part + hadron part
= full model!



Limitations:

1) **No isospin breakdown**
   - i.e. how many spectator nucleons are p or n?
   - Available in code, probable upgrade in future

2) **Limited target nuclei**
   - Only calculate for C12, O16, Ca40, linear interpolation for others
   - No calculation on non-isoscalar possible (different numbers of p,n) so must interpolate

3) **Simple hadron model**
   - Currently both F.S. nucleons treated the same, but maybe some asymmetry due to pion propagator

Use of 2p2h model

Now 2p2h model is in NEUT, what to do with it?

1) Include into osc. analysis
2) Confront with data
3) Search/measurement using T2K data

Comparison with T2K data

Quick goodness-of-fit study

1) Use same dataset as osc. analyses (not optimised for 2p2h search!)
   P_μ-$\cos\theta_\mu$ from three near-detector selections

2) Fit full model to data, as in near-detector part of 2013 osc. analysis
   Many, many flux and xsec parameters are fit [4]

3) Compare goodness-of-fit using Bayesian goodness-of-fit technique [5]

P-Value: **0.1136** with old model (no 2p2h)
0.1188 with new model (incl. 2p2h)

i.e. can't tell the difference with this study
(by design, many flux/xsec parameters in fit to provide flexibility → good agreement)

[4] A. Kaboth arXiv:1310.6544 [hep-ex]
[5] A. Gelman et al. Stat. Sin. 733-807 (1996)

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MEC in the T2K data

T2K

Several early-stage studies currently exploring how to perform a measurement making best use of T2K data

Goals:

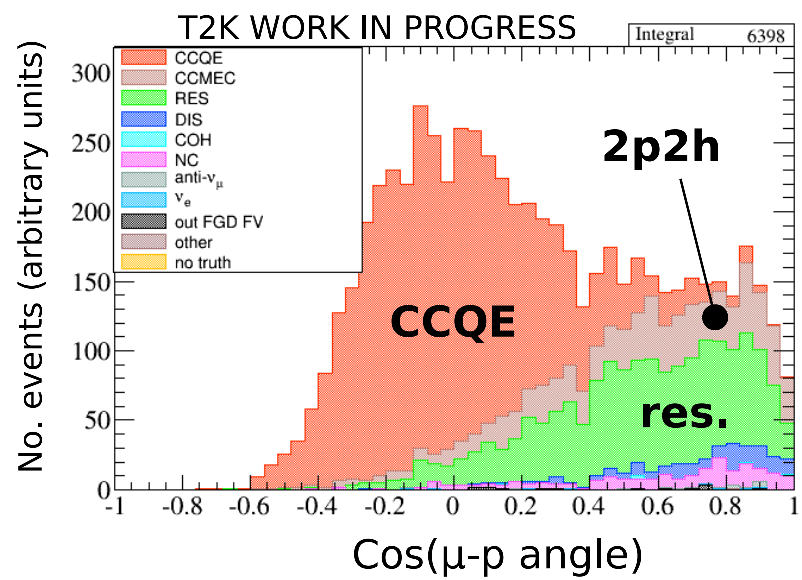
- Find variables to distinguish CCQE from 2p2h
- Constrain/measure CCQE/2p2h fraction in a sample
- Measurement of 2p2h mode

(Final goal to be informed by power of the data)

Progress:

Several studies ongoing using p,μ kinematics to get sensitivity to 2p2h. Most promising so far: μ-p opening angle

Challenge: how to establish separation between 2p2h, resonant.



Summary

Simulation of 2p2h now in NEUT. Able to simulate 2p2h from $\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$ in T2K.

Leptonic part from model of Nieves et al. with momentum transfer cut.

Hadronic part from model of Sobczyk

First comparison to T2K data: inconclusive with current (very non-optimal) selection. Studies for search/measurement have begun.

Supplementary slides

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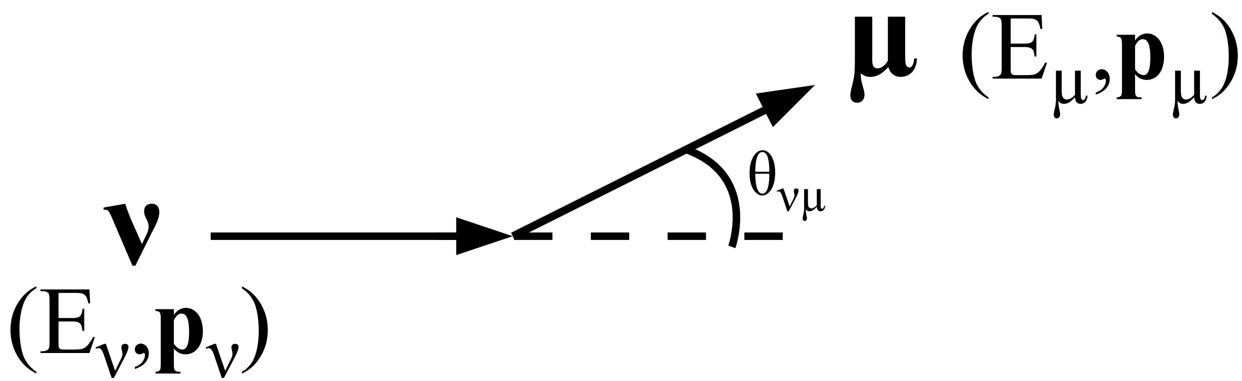
Kinematic limit in practice

T2K

q3 cut manifests on a limitation of the outgoing lepton kinematic space (i.e. a minimum momentum and a maximum scattering angle)

Definition

|q3| = magnitude of three-momentum transfer $\mathsf{q}_3 = \mathsf{p}_\mu - \mathsf{p}_\nu$



$$|\mathsf{q}_3| = (|\mathsf{p}_\mu|^2 + |\mathsf{p}_\nu|^2 - 2|\mathsf{p}_\mu||\mathsf{p}_\nu|\cos(\theta_{\nu\mu}))^{1/2}$$

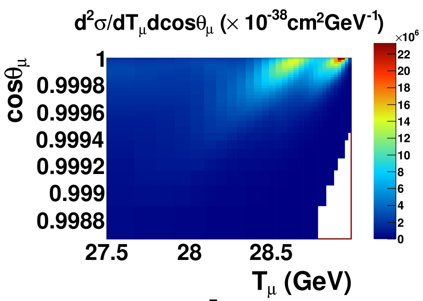
Kinematic cut-off: $|\mathsf{q}_3| \leq \alpha$, where α = some value, taken in the paper to be **1.2GeV**

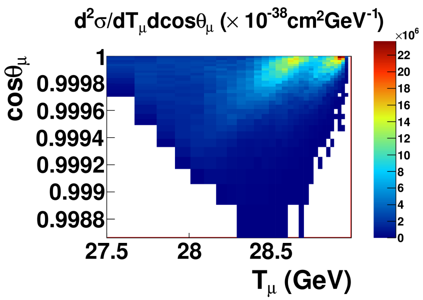
Validation

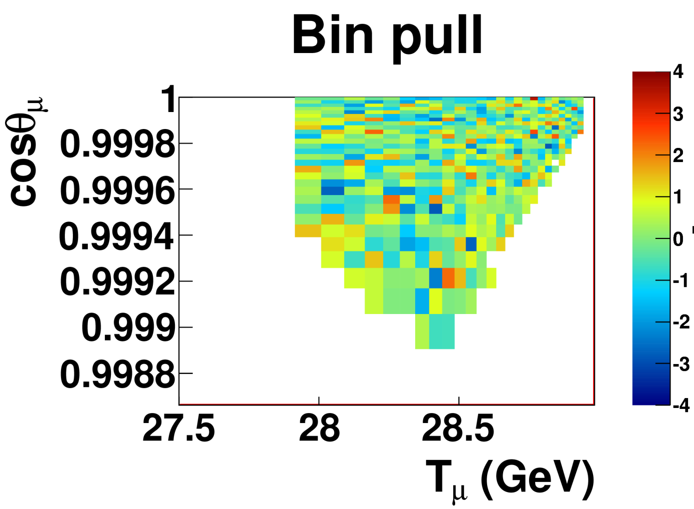
Quantify statistical agreement: look at pull distribution

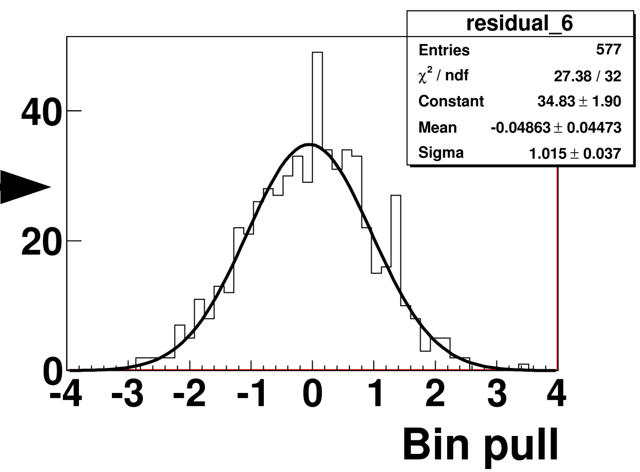
$$\mathrm{Pull} = \frac{N^{\mathrm{MC}} - N^{\mathrm{exp}}}{\sigma^{\mathrm{MC}}}$$

Defined in each histogram bin
Error from MC statistics





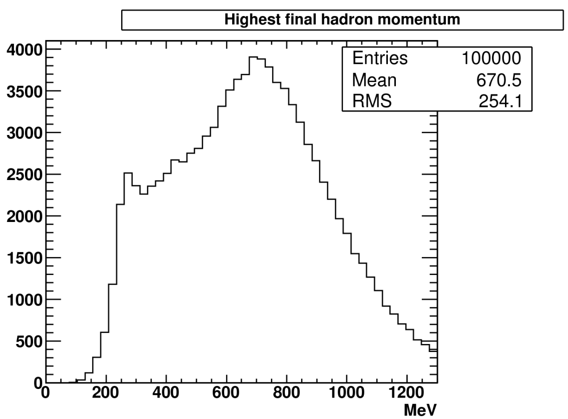




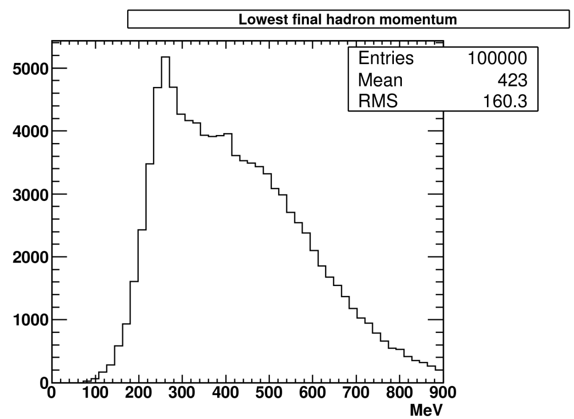
If MC is consistent with having been drawn from prediction, pull should have mean of zero and width of unity.

Misc. kinematic plots

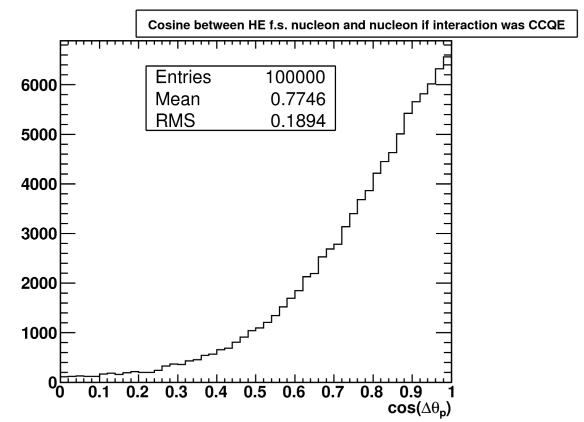
Some interesting plots from the hadronic simulation



Highest final-state hadron momentum



Lowest final-state hadron momentum



'Delta theta p'