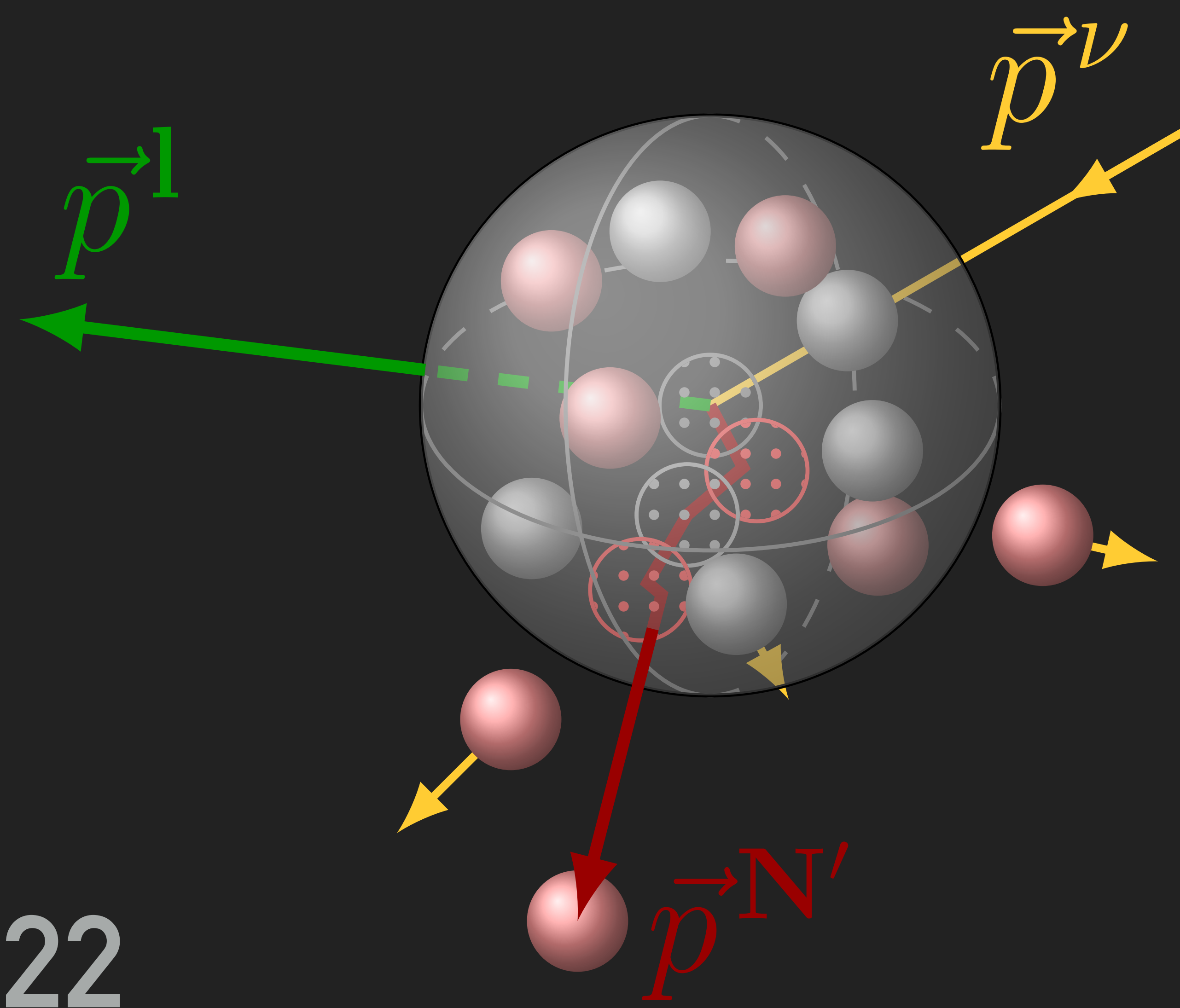
IOP HEPP and APP, Sussex University



LUKE PICKERING

IOP SUSSEX 2016-03-22

TRANSVERSE IMBALANCE IN THE FEW GEV RANGE

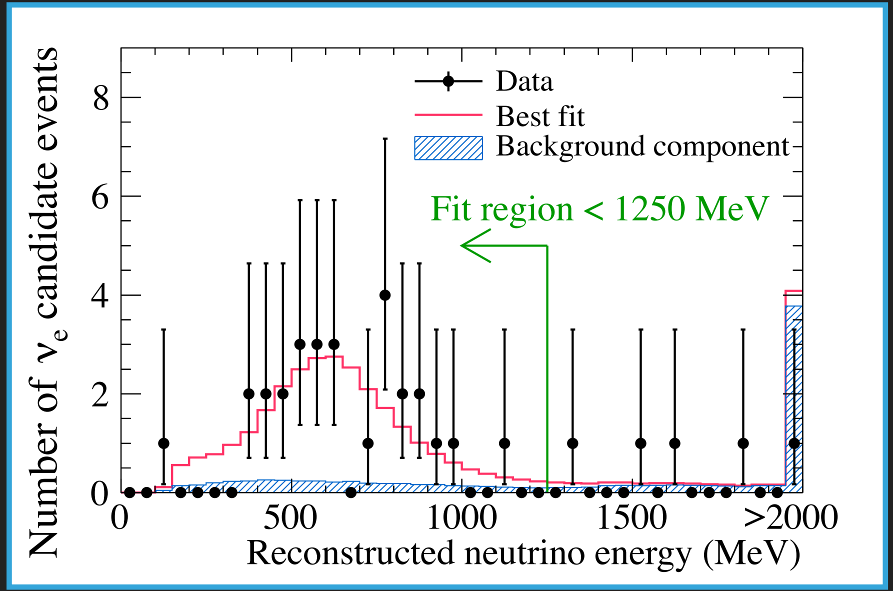
Imperial College London

TRANSVERSE IMBALANCE IN THE FEW GEV RANGE

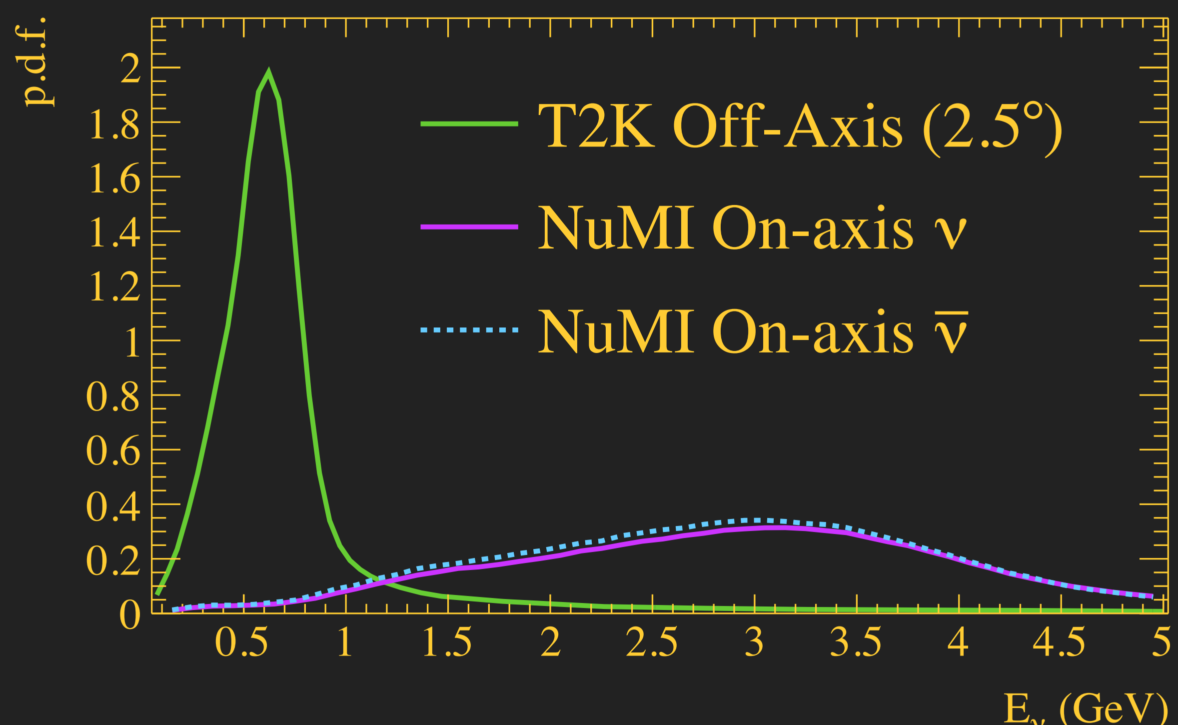
- Few GeV physics and interactions
- Transverse imbalance
  - Quasi-elastic
  - Single pion production
- Prospects

CONTEXT — PHYSICS IN THE FEW GEV REGION

- T2K observed electron neutrino appearance in a muon neutrino beam.
- Now entered a precision era of oscillation physics.
- Need to understand neutrino interactions and beams very well.



T2K reconstructed electron neutrino energy spectrum
Phys. Rev. Lett. 112, 061802 (2014)

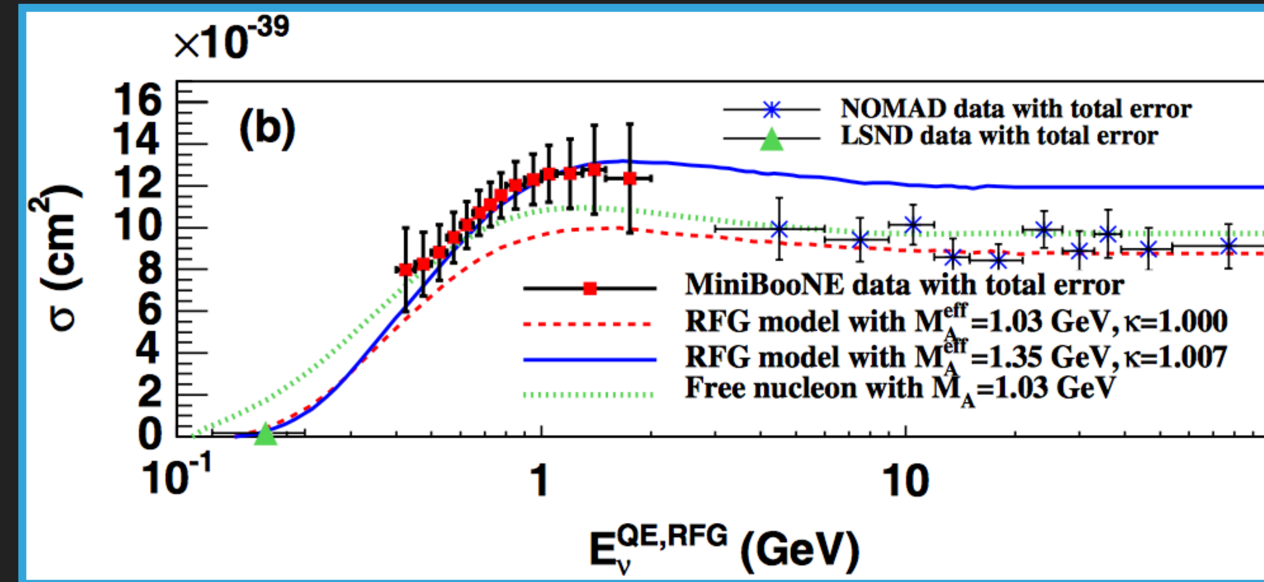


Spectral beam shape of T2K and NuMI beams

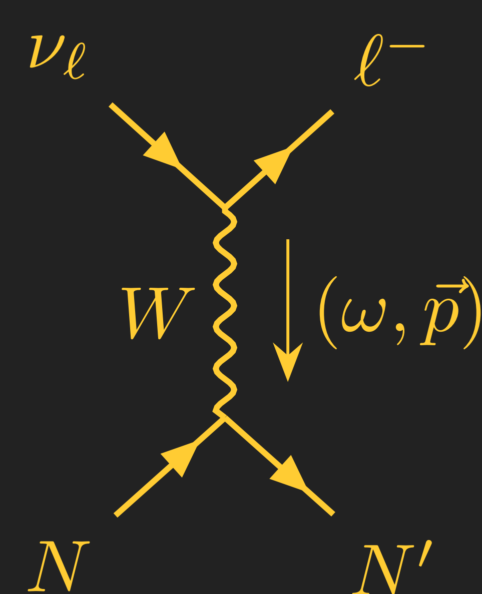
THE NEED FOR MODELS

- Experimental discrepancies in the last decade show that models based around CCQE on free nucleons do not adequately explain observed event selections.

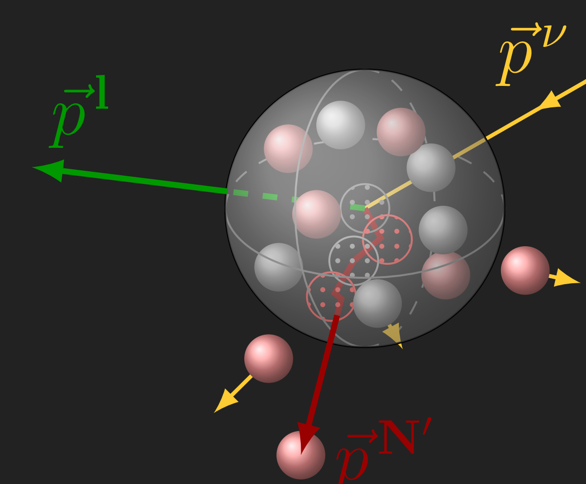
- Modern models include many 'nuclear effects' to try and account for the discrepancies between simplistic CCQE models and observed data.



MiniBooNE and NOMAD charged current measurements are not well explained by the same model.



Charged Current Quasi-Elastic (CCQE)

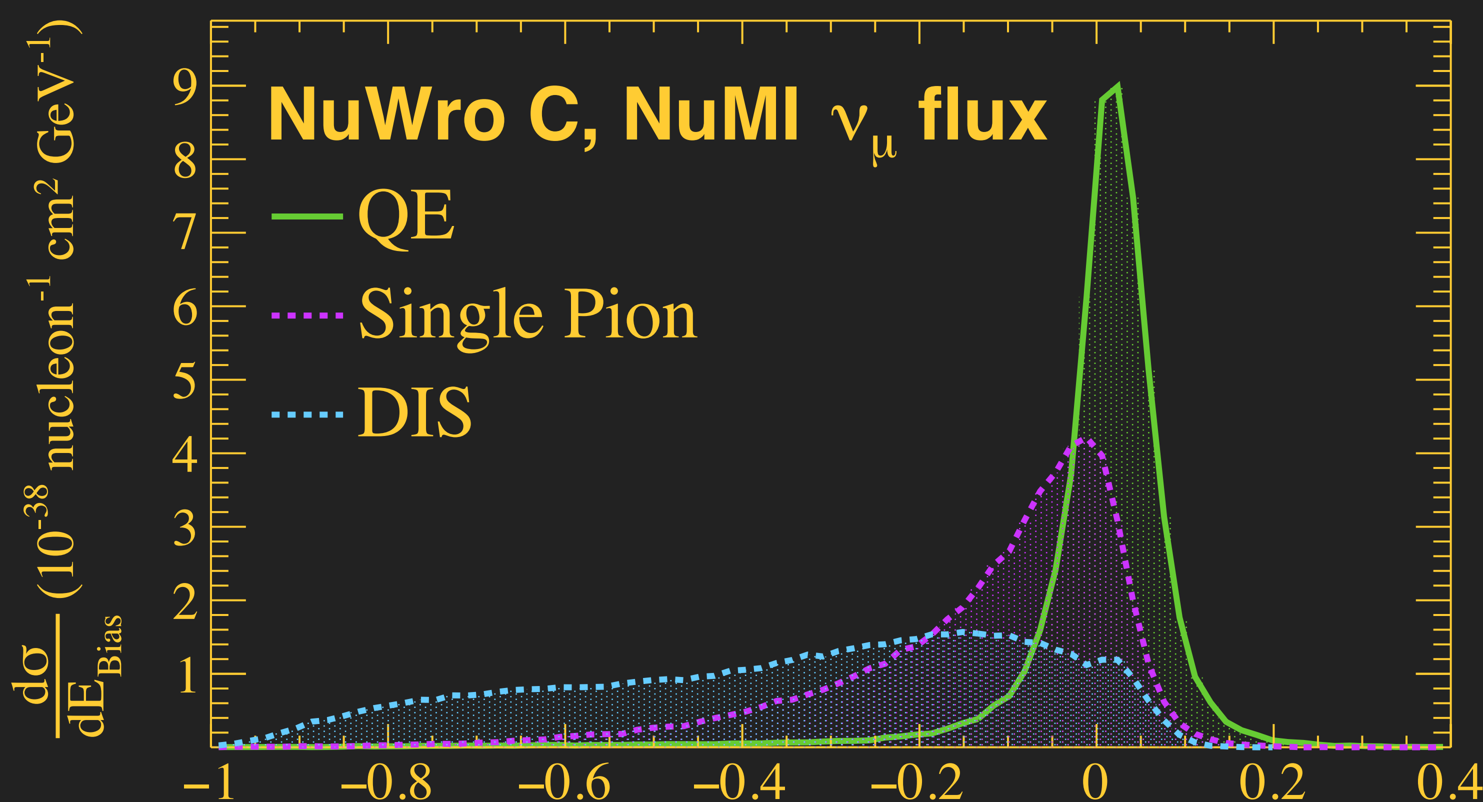


Theoretical effects included to account for interactions in a nuclear environment

Imperial College London

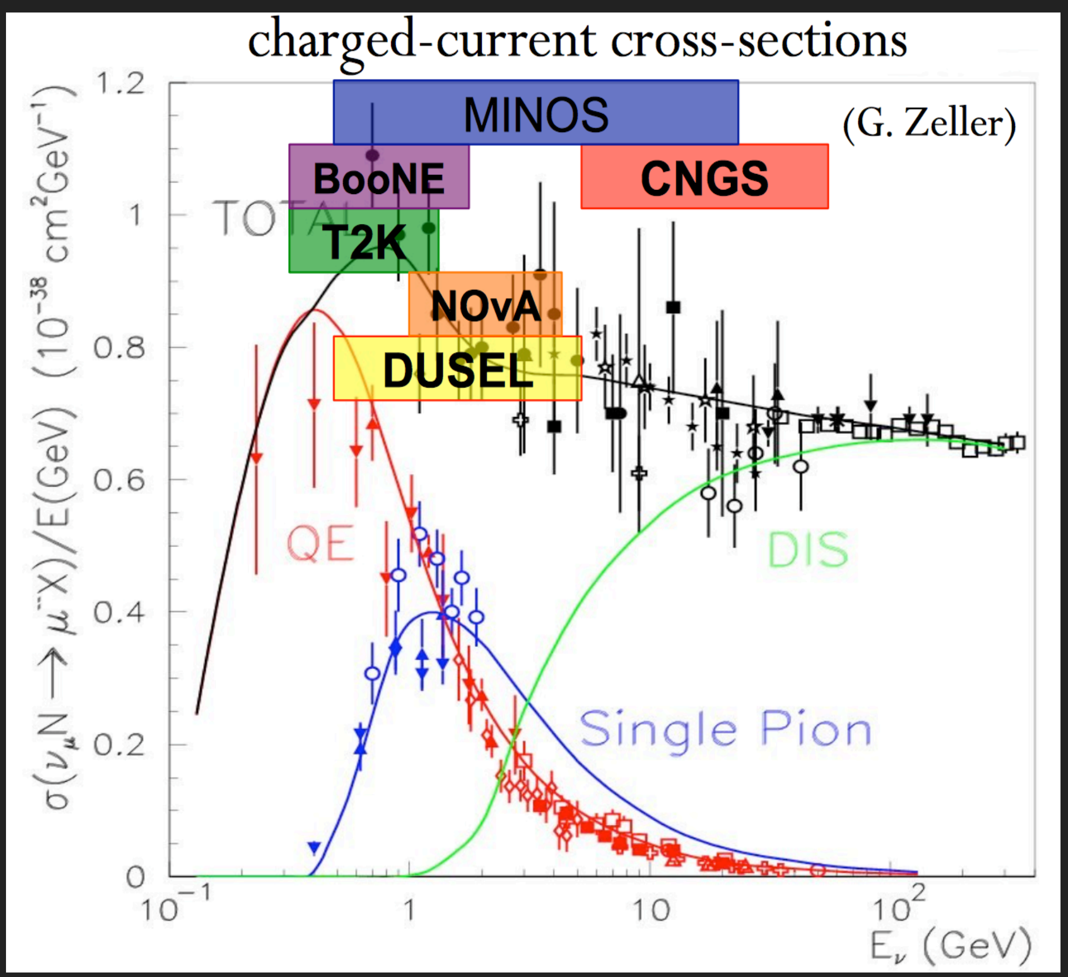
NEUTRINO ENERGY RECONSTRUCTION

- Two main approaches to neutrino energy reconstruction:
  - **Kinematic**: Calculate the neutrino energy from muon kinematics alone, assumes CCQE.
  - **Calorimetric**: Sum up the visible final state energy – Better for higher energy beams where QE is not the dominant interaction.



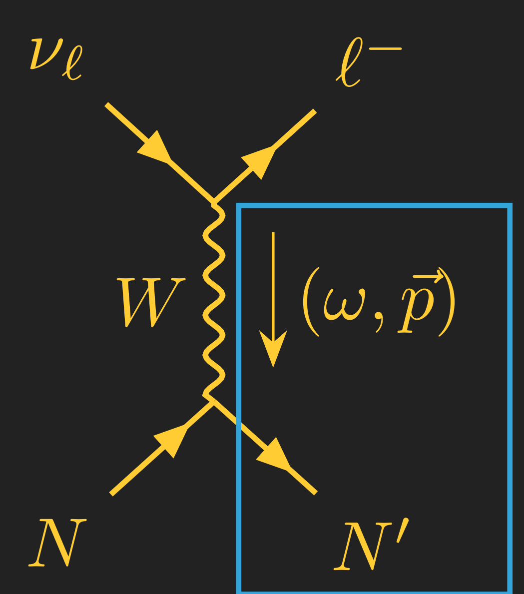
Kinematic:
Reconstructed neutrino energy bias due to wrong event classification.

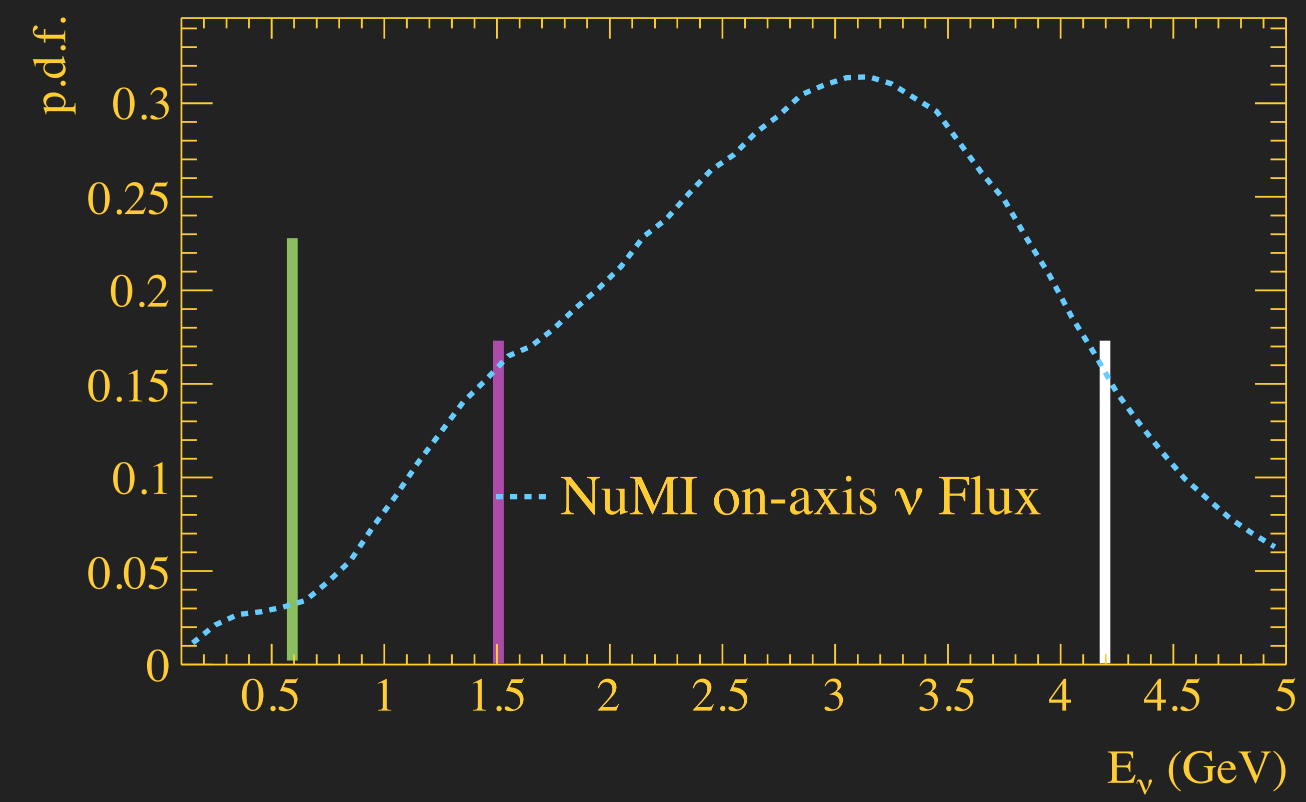
$$E_{Bias} = \left(\frac{E_{\nu,Recon}}{E_{\nu,True}} - 1\right)$$

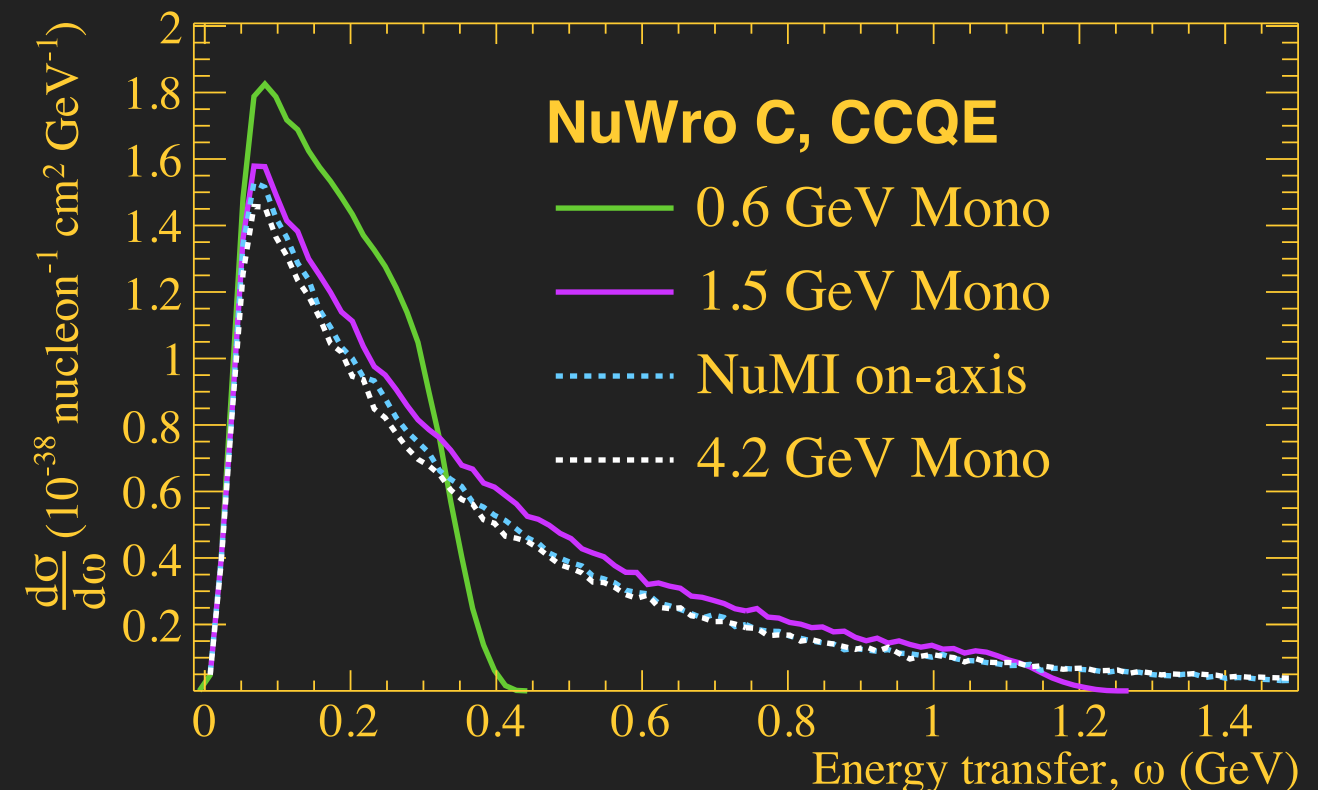


HADRONIC SYSTEM

- Hard to disentangle 'nuclear effects' from the impact of unknown neutrino energy on inclusive measurements.
- In a higher energy beam, the hadronic system energy distribution is insensitive to the event-by-event neutrino energy.
- So, lets try to use the whole hadronic system.





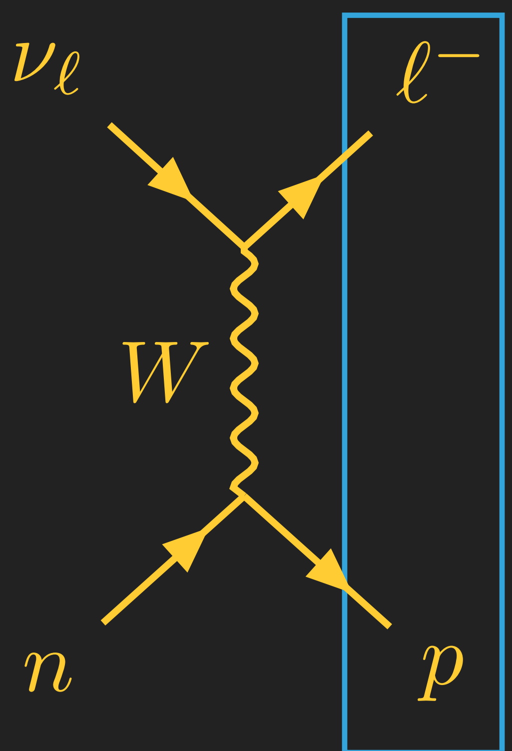


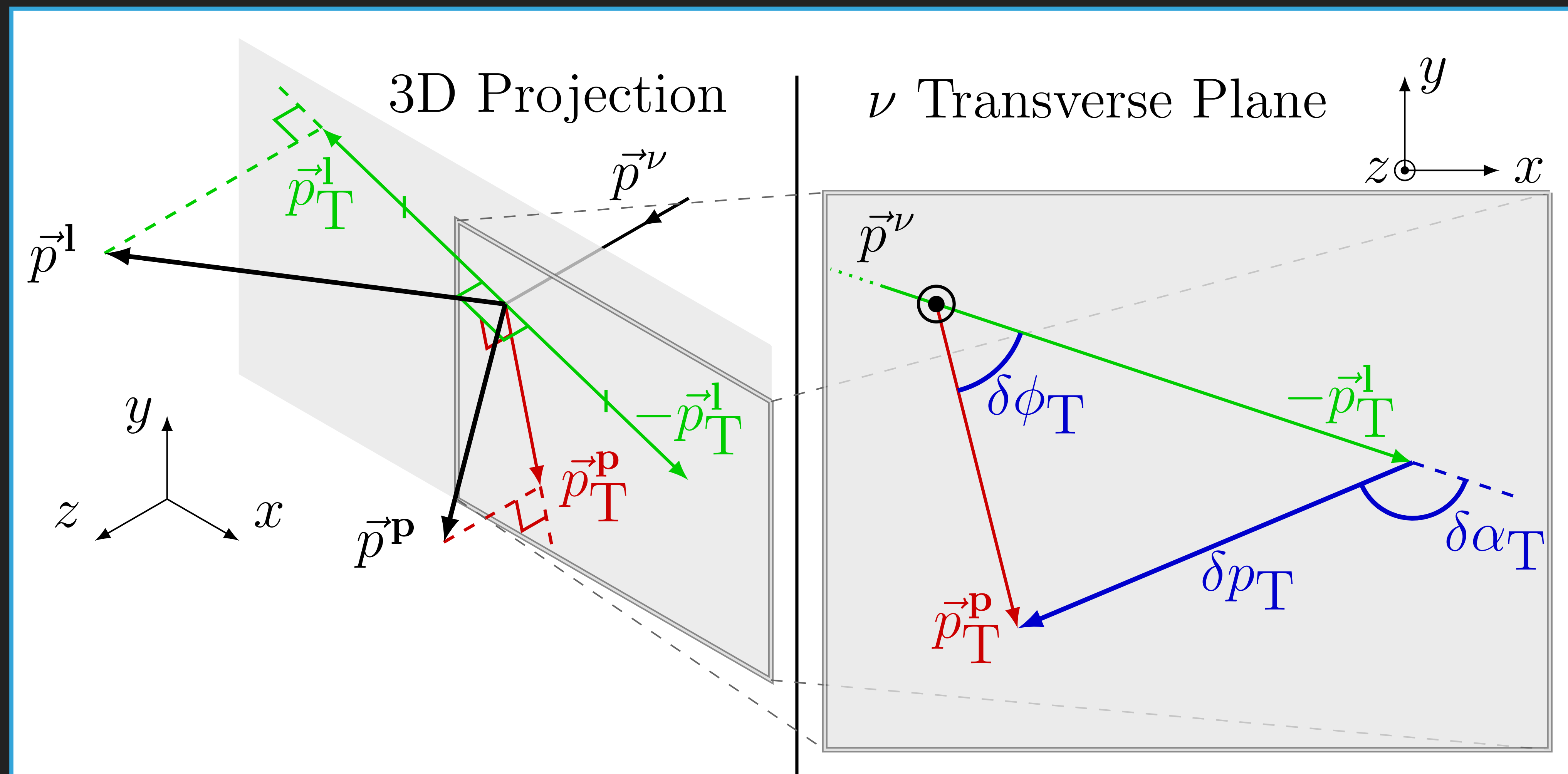
Energy transfer distributions for QE events in a number of neutrino beams.

TRANSVERSE IMBALANCE

- Variables defined in the transverse plane:
  - naturally include both the leptonic and hadronic final states.
  - are more insensitive to event-by-event neutrino energy
  - will be differential measurements that can provide tight constraints on full, experimental simulations and models.

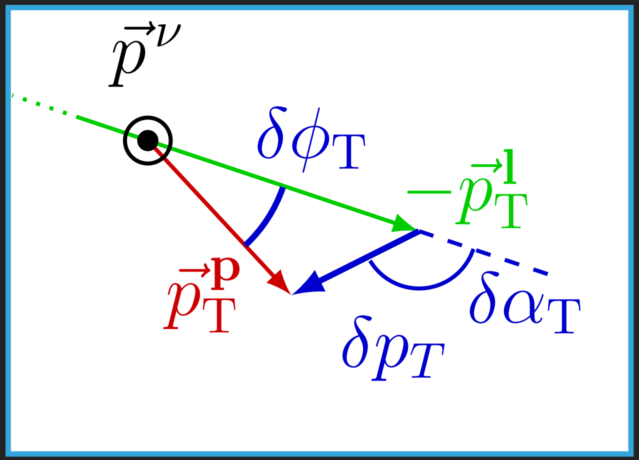
TRANSVERSE VARIABLES





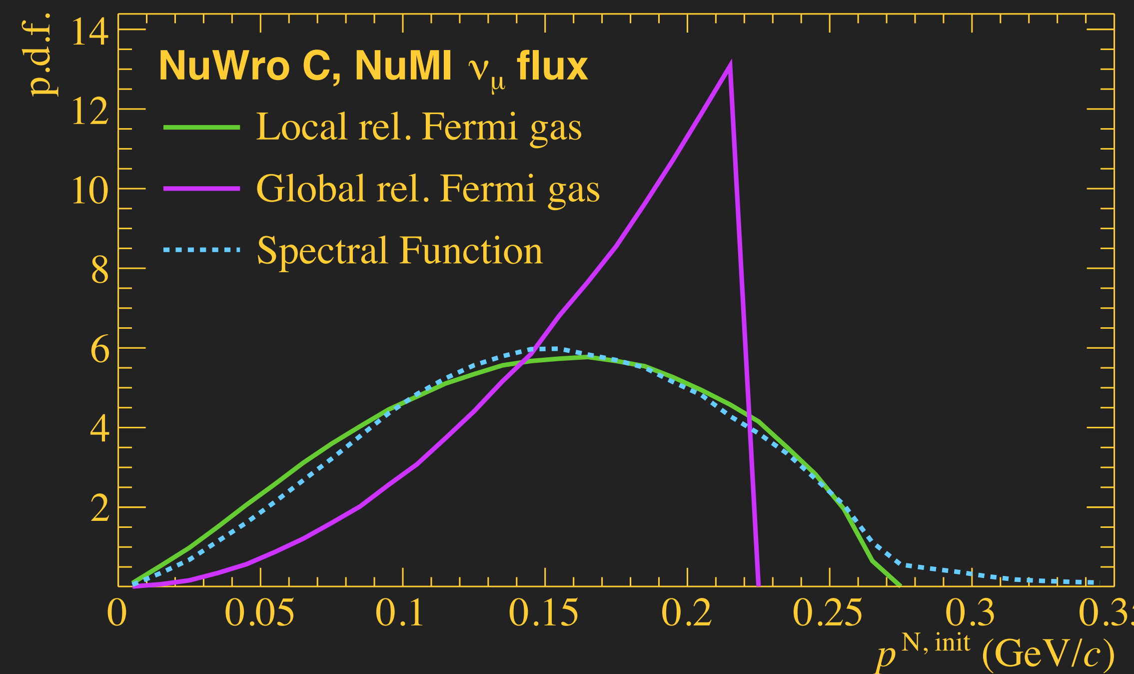
- We define 3 complementary transverse imbalances: $\delta\Phi_T$, $\delta\alpha_T$, and δp_T.
- Look for transverse imbalances between the lepton and hadronic final states to test our models.
- Deviations from predictions of free-nucleon model – ‘nuclear effects’.

NUCLEAR EFFECTS — FERMI MOTION

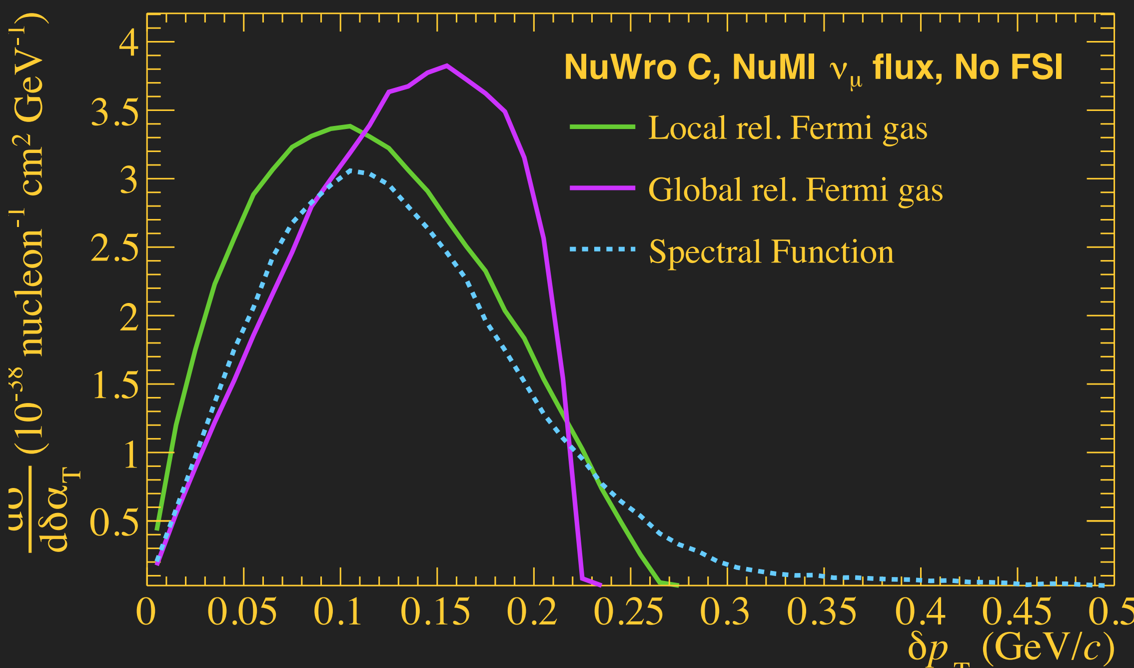


δp_T

- δp_T: The magnitude of the overall observable transverse momentum imbalance.
- In the absence of any other nuclear effects δp_T is the transverse projection of the nucleon momentum distribution.



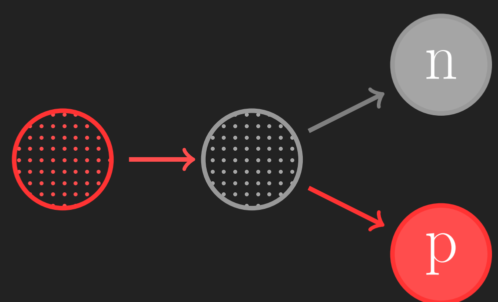
Nucleon momentum distribution for three different nuclear models.



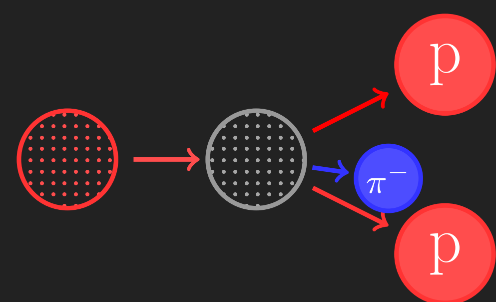
Fermi motion-only δp_T distributions.

NUCLEAR EFFECTS — FSI

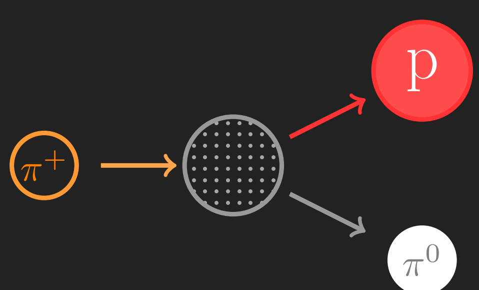
- Energetic hadrons produced inside a nucleus are unlikely to always exit without re-interactions.
- Can cause:



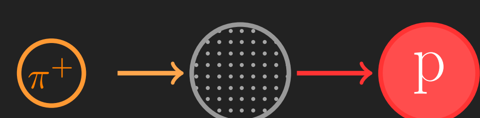
Elastic Scattering



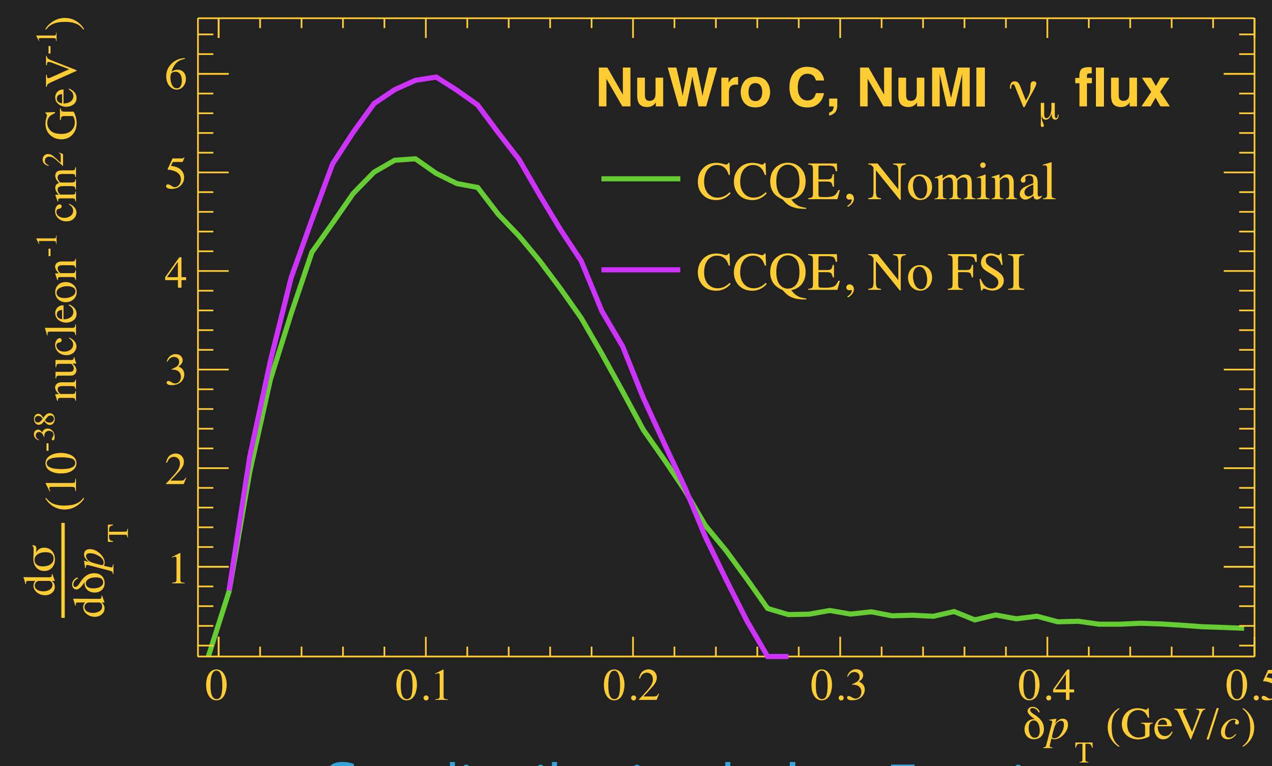
Pion Production



Charge Exchange



Absorption

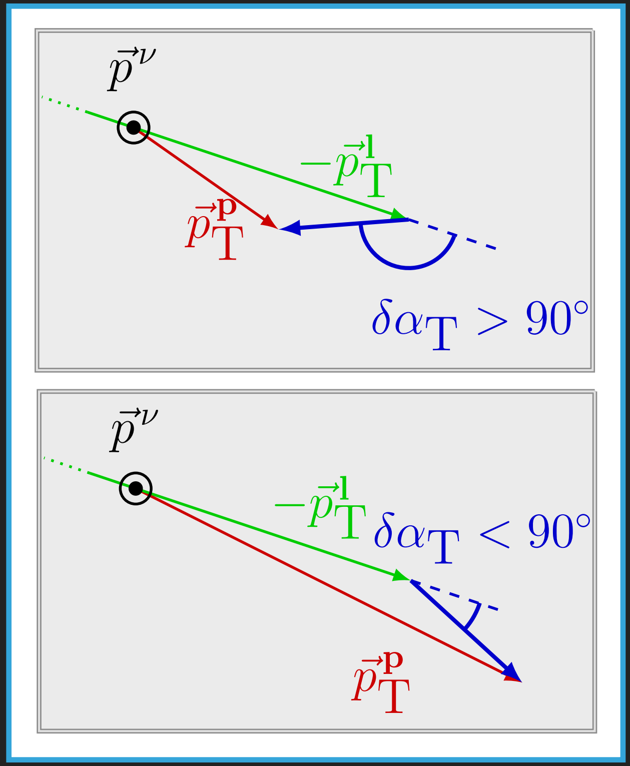


δp_T distribution below Fermi surface sensitive to FSIs.

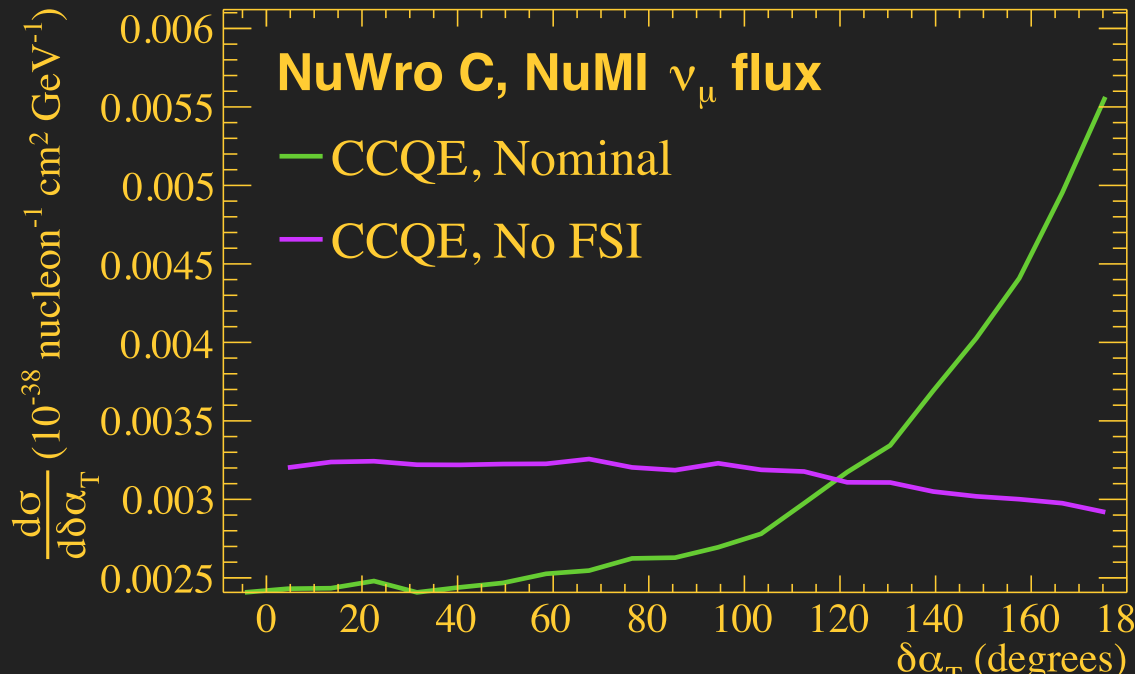
- Alters final state kinematics and **obscures primary interaction.**
  - Primary Single Pion Production can look CCQE-like (1 muon)!

FSI — DECELERATING EFFECTS

- In the absence of final state interactions:
- Transverse components of the initial state nucleon and final state lepton momentum should be uncorrelated.
- No preference for a 'direction' of δp_T ⇒ $\delta\alpha_T$ flat.
- FSI processes generally result in momentum transfer *to* the nuclear medium.
  - The hadronic system has less transverse momentum than the leptonic system.

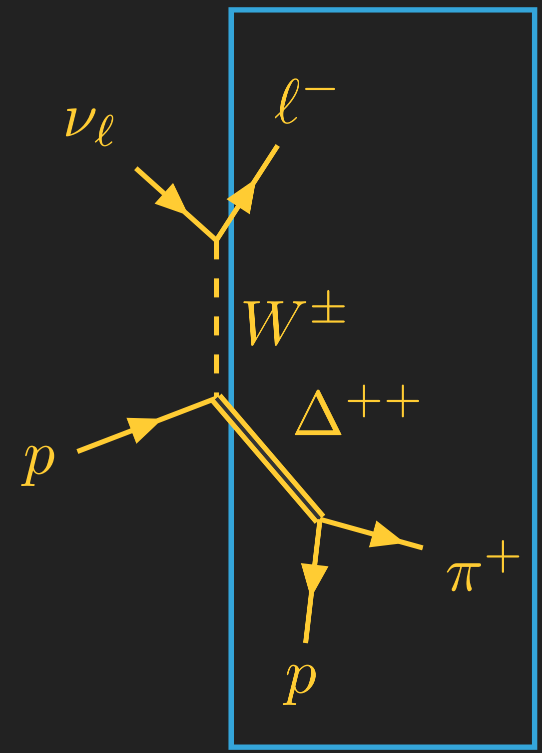


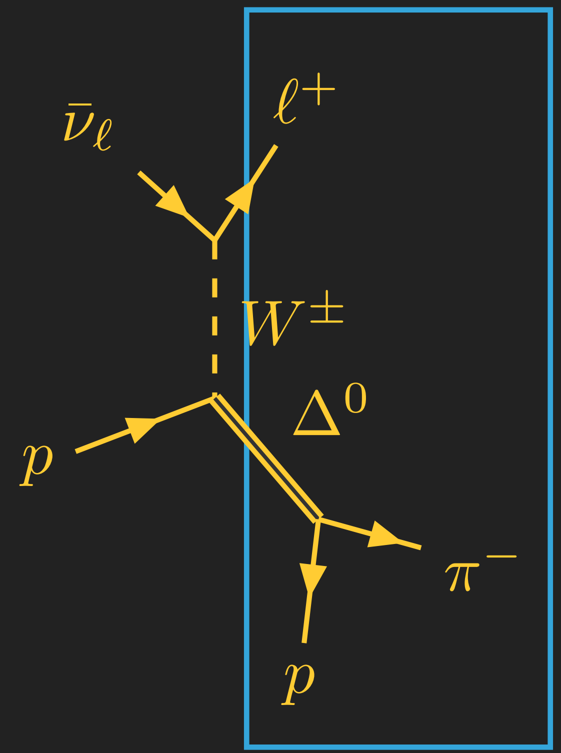
$\delta\alpha_T$ characterises apparent hadronic system acceleration.

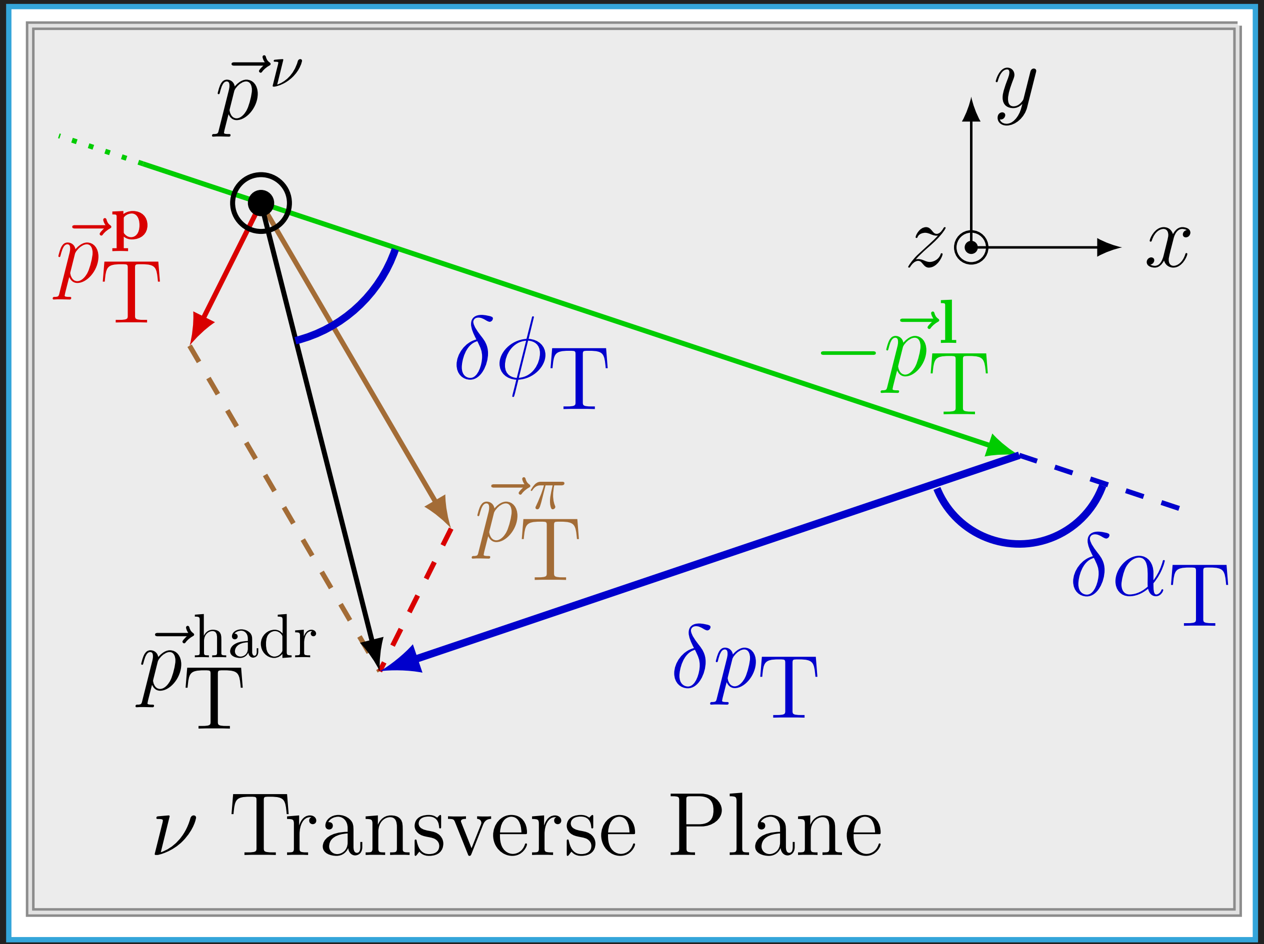


FSI results in a pile up of events at high $\delta\alpha_T \Longrightarrow$ 'deceleration'

TRANSVERSE VARIABLES — SINGLE PION PRODUCTION



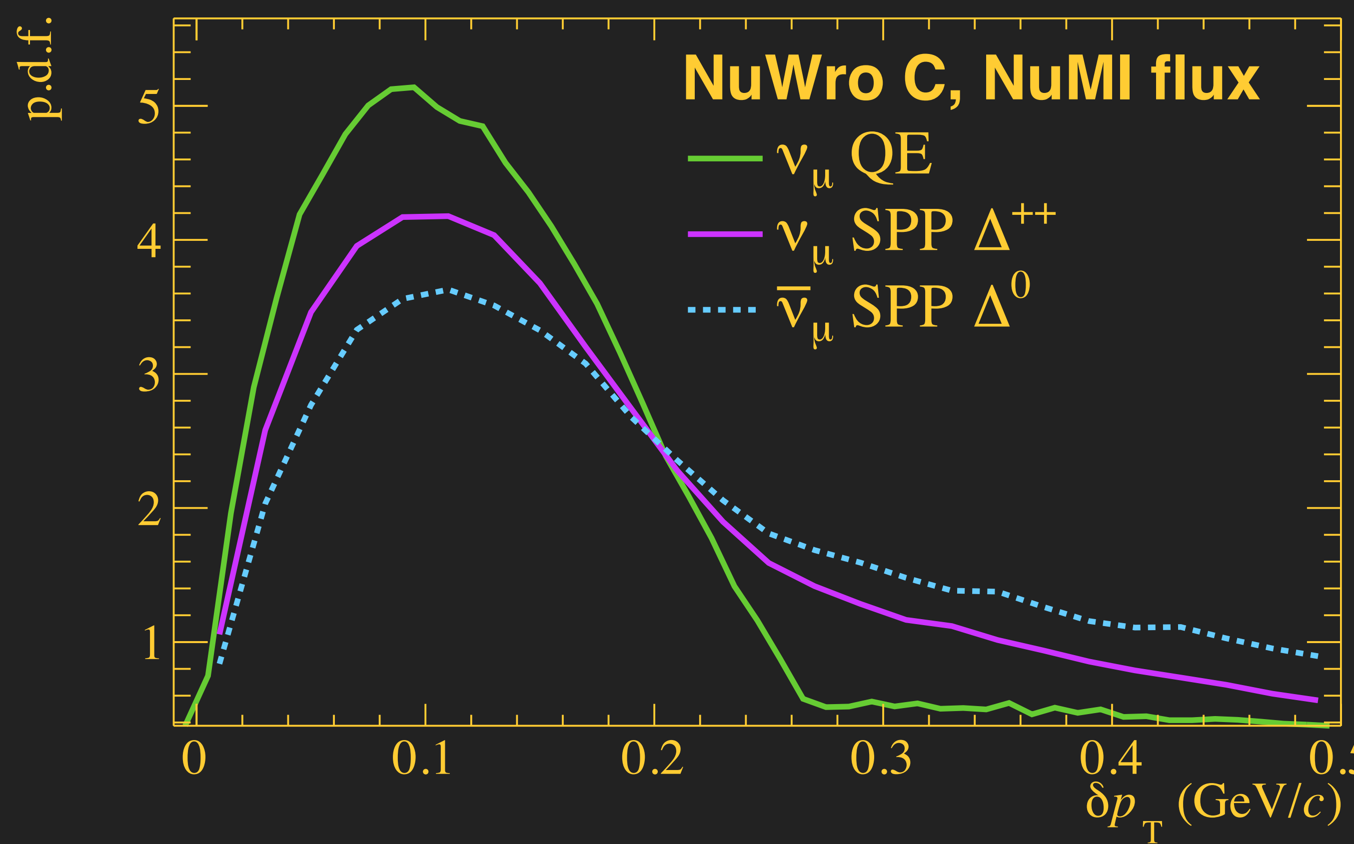




- Looking for imbalances between lepton and hadronic systems.
- Can also use Single Pion Production.
- Form variables between charged lepton and proton+charged pion system.

TRANSVERSE VARIABLES — SPP

- In an anti-neutrino beam, we can look for $\Delta^0 \rightarrow \pi^- + p$.
- Using the three interaction modes, in two beams, allows for FSI comparisons between p, $p + \pi^-$, and $p + \pi^+$.



Primary interactions with higher final state multiplicity naturally suffer more from final state interactions.
Do our current models do a good job of predicting the data?

- FSI model tuning often performed using hadron beams on thin targets.
  - ? Are extra- and intra-nuclear forces really so similar that this is a good procedure.
  - ➡ Transverse imbalance will provide FSI model constraints using neutrino beams.

PROSPECTS

- Measurements of transverse kinematic imbalance in both QE-like and single pion event selections are ongoing at accelerator neutrino scattering experiments.
- Such measurements will offer new insight into nuclear effects–a significant source of uncertainty for future long bass-line experiments.
- Measurements of transverse imbalance will provide more exclusive model constraints than charge lepton kinematics alone.

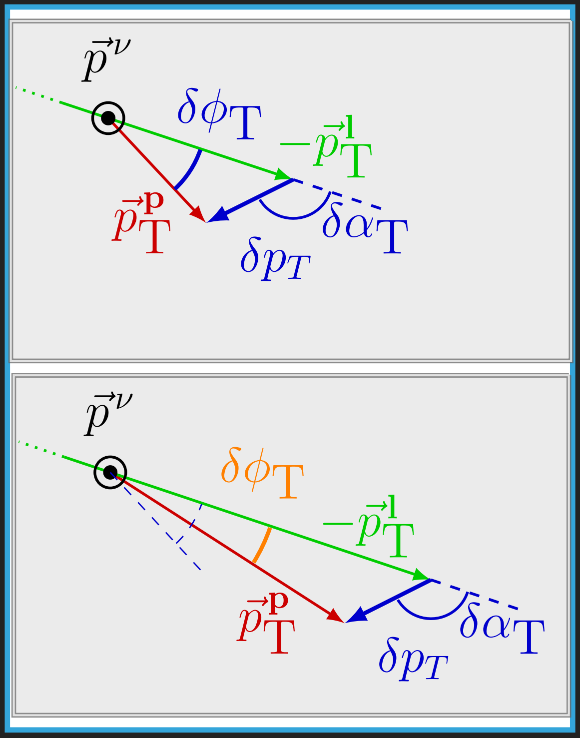
WE APOLOGISE FOR ANY INCONVENIENCE

Imperial College
London

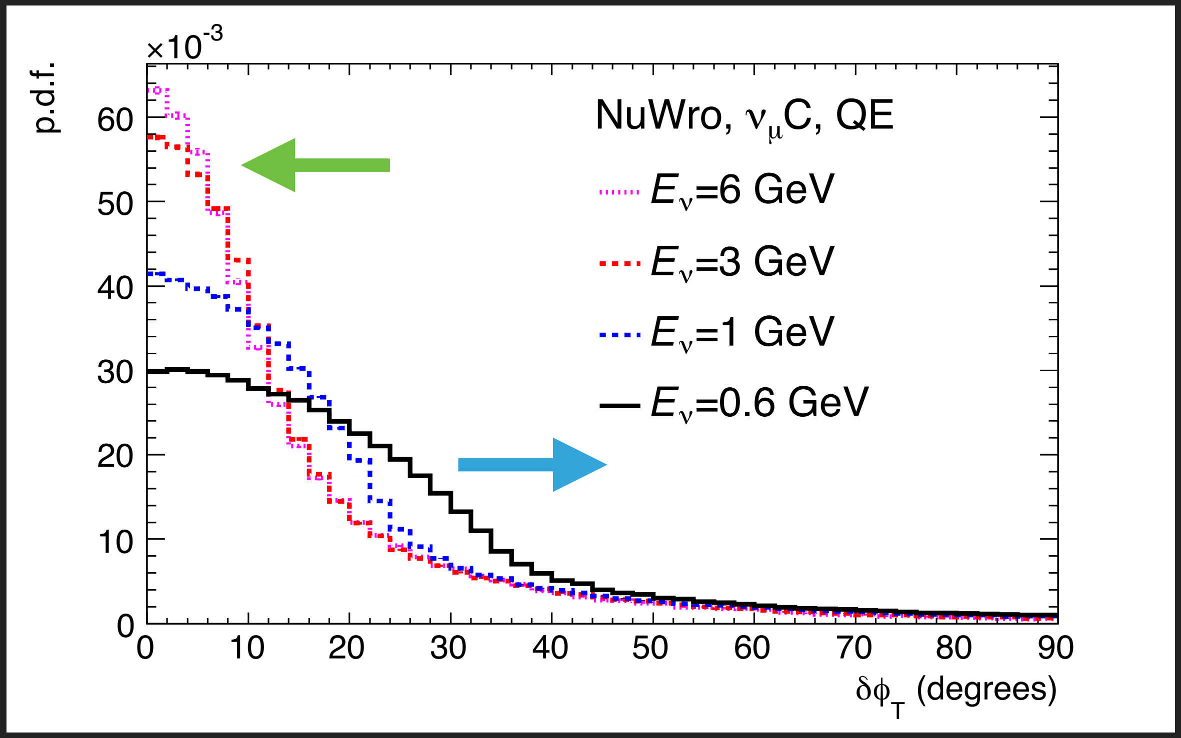
REFERENCES

FSI — DPHIT ENERGY DEPENDENCE

- $\delta\Phi_T$: The angular difference from the lepton and proton being 'back-to-back' in the transverse plane.
- δp_T, and $\delta\alpha_T$ determined by the nucleon momentum distribution and FSIs.
  - Largely factorisable from neutrino energy.
- $\delta\Phi_T$ includes more dependence on interaction kinematics.
  - Energy evolution below Q^2 saturation is pronounced.
- $\delta\Phi_T$ evolution for **higher energy** is opposite to evolution with **stronger FSIs**.



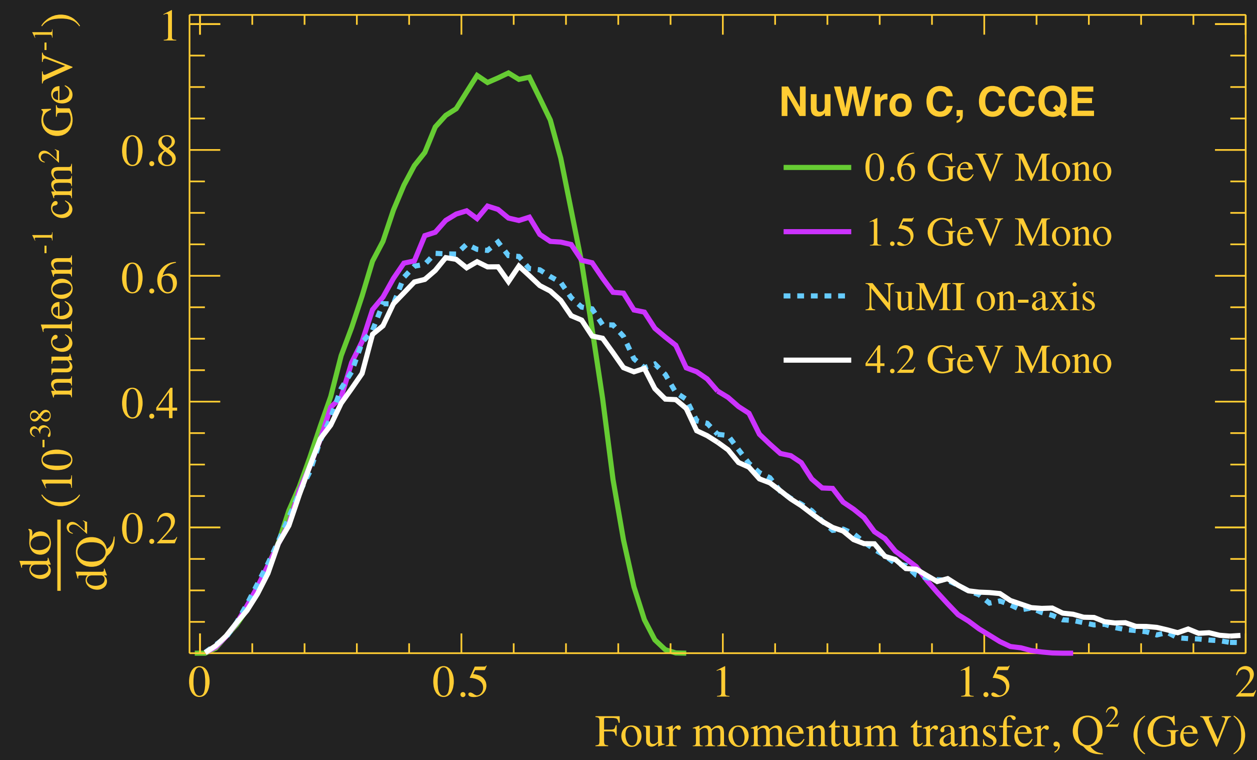
For given momentum loss (δp_T), $\delta\Phi_T$ scales inversely with muon p_T



Imperial College London

HADRONIC SYSTEM

- 'nuclear effects' affect on muon kinematics often conflated with unknown neutrino energy.
- For QE and RES interactions, the Q2 phase space is limited.
- Using a beam which makes the full Q2 phase space accessible for QE (and RES) causes a saturation in energy transfer.
- **In the right beam, the hadronic system energy is bounded.**
- So, lets use the hadronic system.

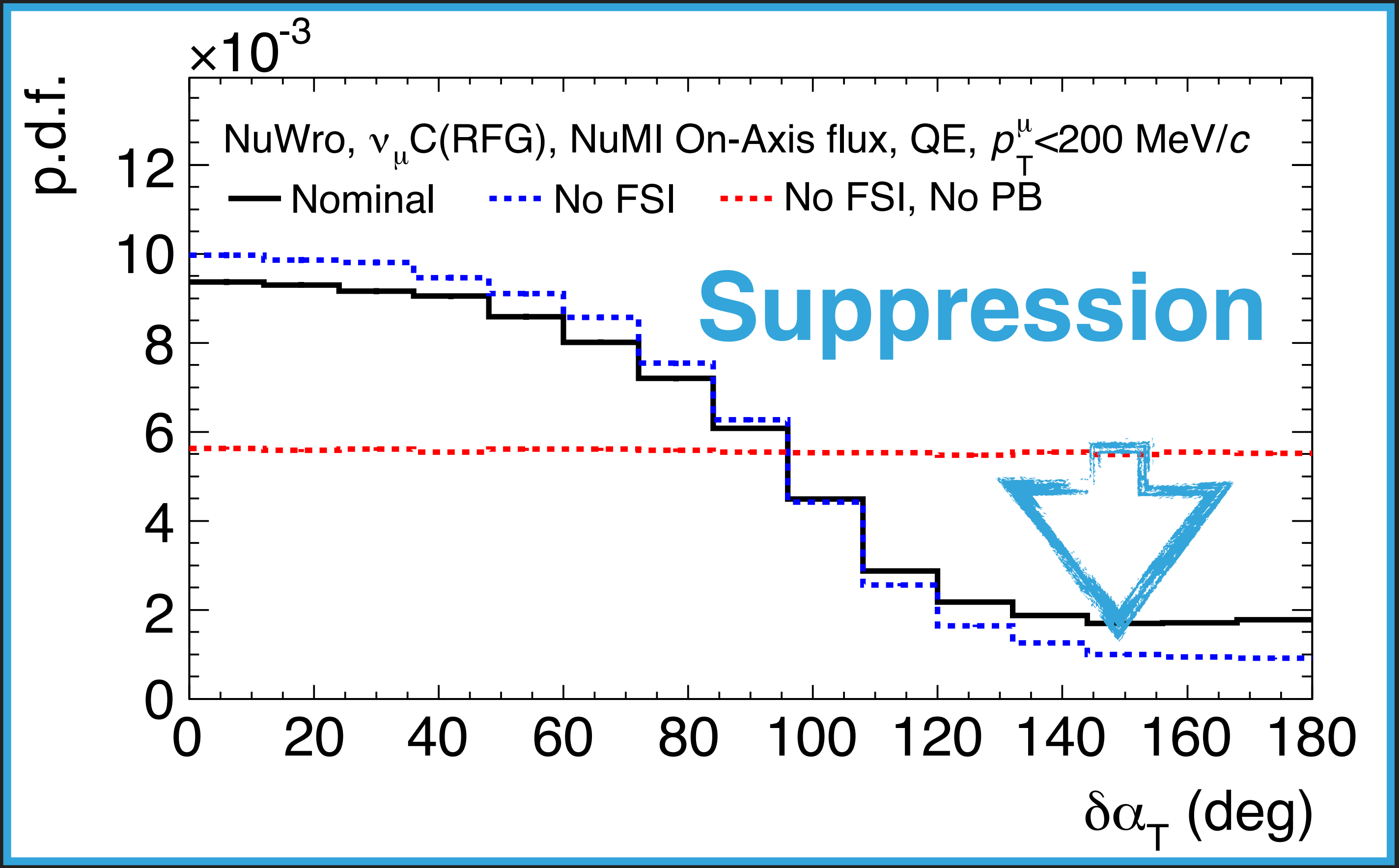


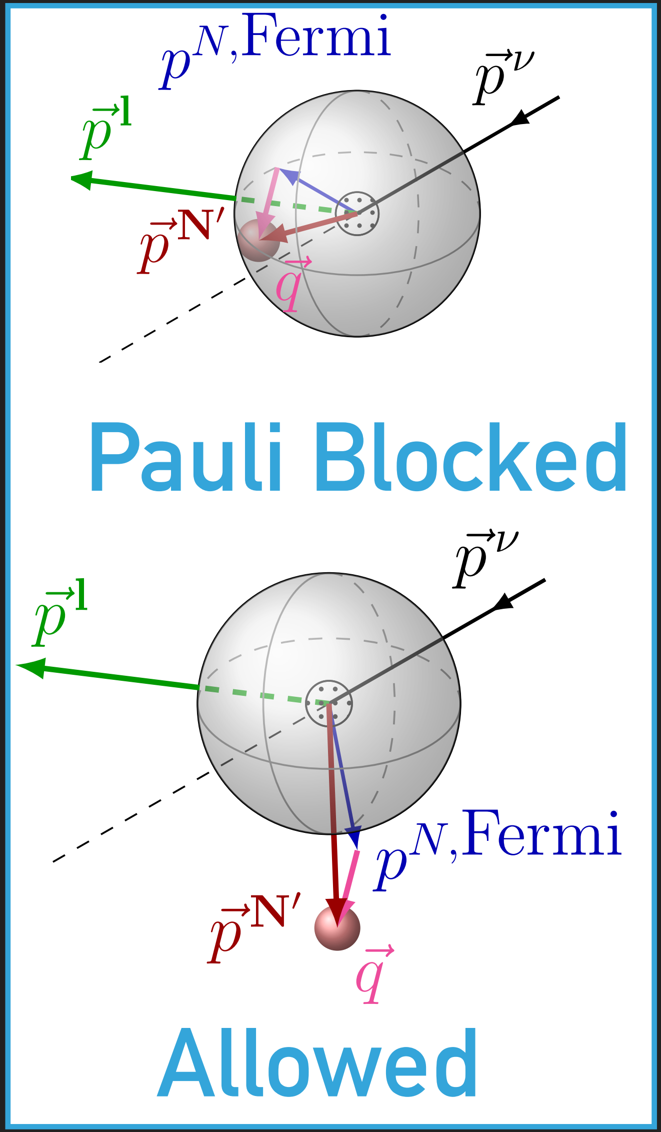
Q2 distributions for QE events in a number of neutrino beams.

$$\omega \sim \frac{Q^2 + W^2 - m_{\mathrm{N}}^2}{2\sqrt{m_{\mathrm{N}}^2 + p_{\mathrm{N}}^2}},$$

Energy transfer as a function of hadronic mass, four momentum transfer, and nucleon momentum distribution.

NUCLEAR EFFECTS — PAULI BLOCKING





- At low p^μ_T Pauli blocking suppresses QE events with low three momentum transfer, ***q***, when ***q*** is not aligned with the initial nucleon momentum.
  - ➡ High $\delta\alpha_T$ region is suppressed for low $\boldsymbol{q}_T$.

NUCLEAR EFFECTS — MULTI-NUCLEON CORRELATIONS AND PION PRODUCTION