Systematics on (long-baseline) neutrino oscillation measurements

- **Introduction on oscillation measurements:** present results from T2K and NOVA and precision needed for next generation HyperKamiokande, DUNE

- Overview of the systematics:
  - How **neutrino flux and cross-section** affect neutrino oscillation measurements ?
  - **Flux** simulation and tuning
  - Main neutrino **cross-section uncertainties** (from an experimentalist point of view)

- Neutrino oscillation analyses and xsec systematics in details: **the T2K and NOVA examples**

S.Bolognesi (CEA Saclay) - T2K

Neutrino xsec uncertainties
(from an experimentalist point of view)

Reminder

What we need to control to extract the neutrino oscillation probability:

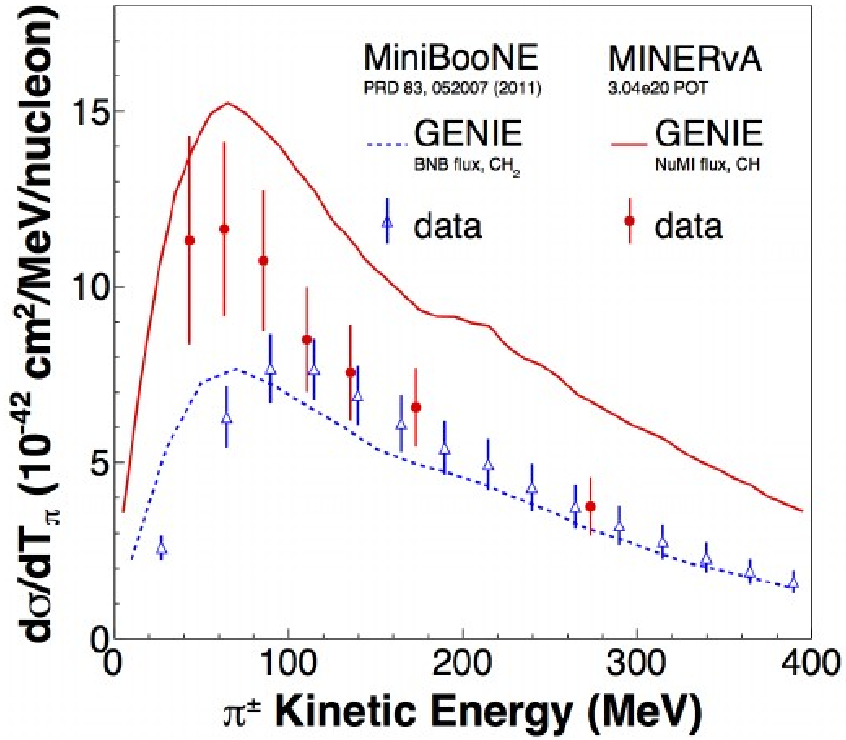
$$\frac{N^{FD}_{\nu_{\alpha'}}(E_\nu)}{N^{ND}_{\nu_\alpha}(E_\nu)} \approx P_{\nu_\alpha \to \nu_{\alpha'}}(E_\nu) \times \frac{\varphi^{FD}_{\nu_{\alpha'}}(E_\nu)}{\varphi^{ND}_{\nu_\alpha}(E_\nu)} \times \frac{\sigma^{FD}_{\nu_{\alpha'}}(E_\nu)}{\sigma^{ND}_{\nu_\alpha}(E_\nu)}$$

We need to reconstruct the incoming neutrino energy from the kinematics of the final state particles

We need to constrain the flux

We need to know the cross-section as a function of neutrino energy

How you measure a cross-section



Counting **how many events of your process happen in your detector** (as a function of a certain variable, eg: momentum and angle of the particles which are produced in the interactions)

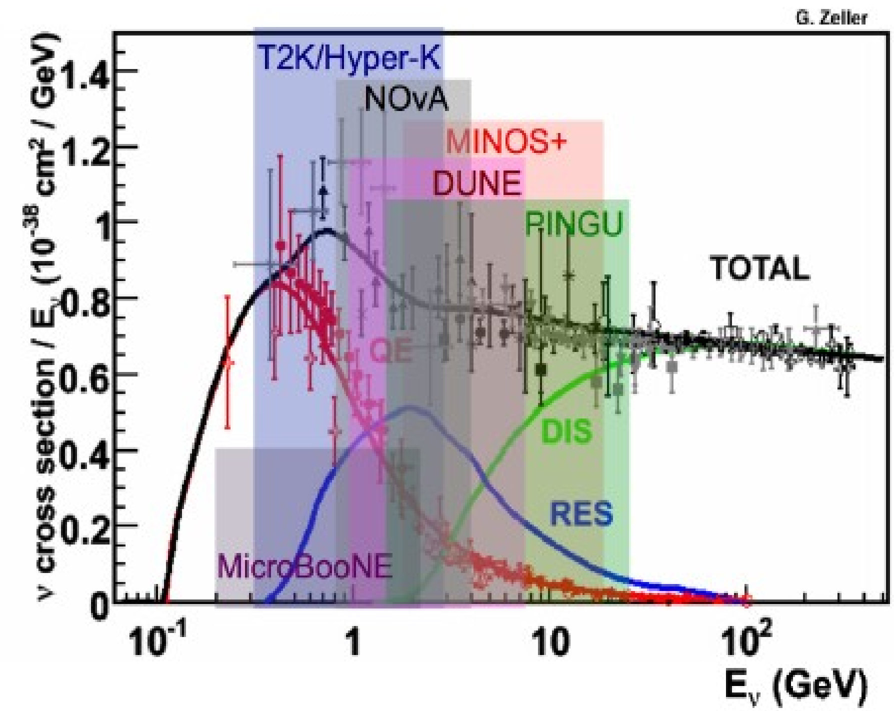
In each bin the xsec is estimated from:

$$\sigma = \frac{\left(N^{data}_{selected} - B\right) \cdot 1/\epsilon}{\Phi \cdot N_{nucleons}}$$

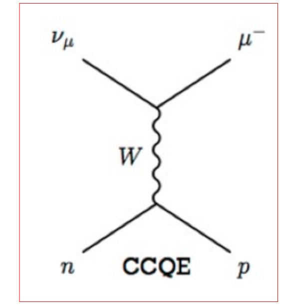
where the **efficiency and background are computed from Monte Carlo simulations** and possibly motivated by studies in other sets of data: 'control region' or other experiments)

$$\epsilon = \frac{S^{MC}_{selected}}{S^{MC}_{generated}}$$

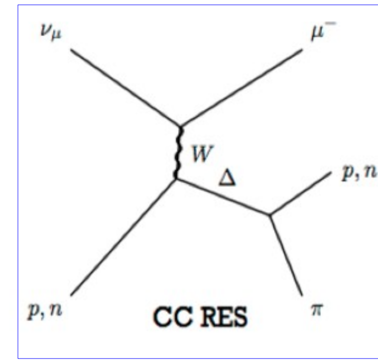
σ vs E_ν for different processes



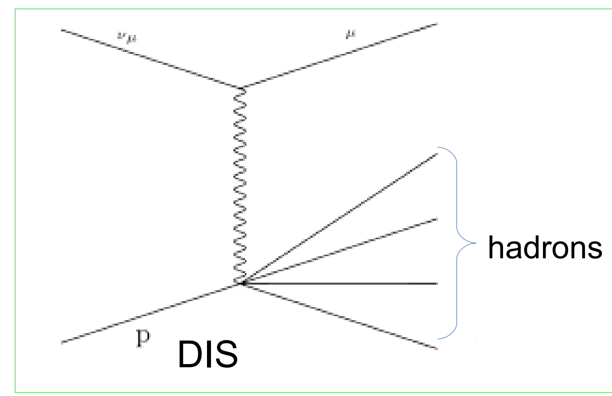
- **QE** = Quasi-Elastic



- **RES** = Pion production in the final state through excitation of the nucleon to a resonant state



- **DIS** (Deep Inelastic Scattering) = the nucleon is broken → probing the quark structure of the nucleons → shower of hadrons

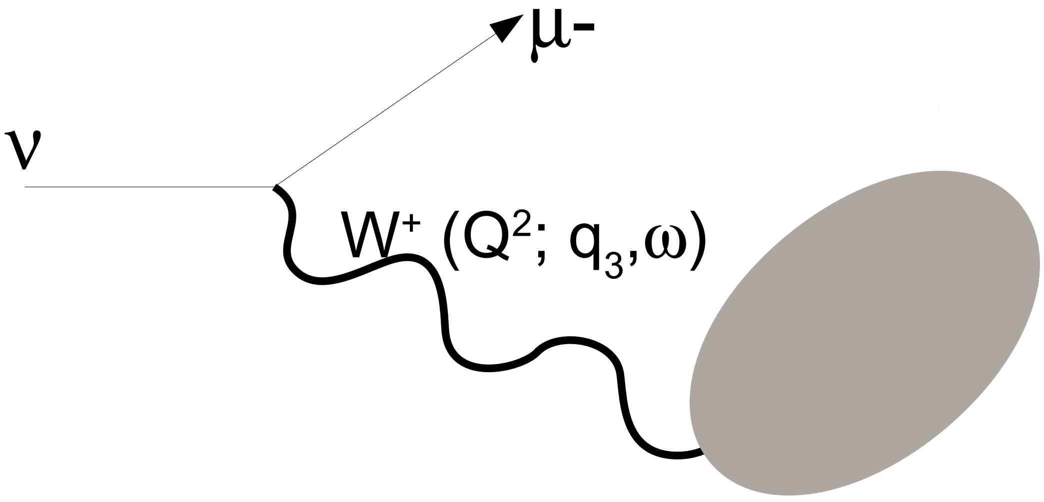


- Can we just measure the inclusive flux x xsec at ND and extrapolate it at the FD?

$$R_{FD}^{\nu'} = \int \Phi^{\nu}(E_\nu) P_{osc}^{\nu\rightarrow\nu'}(E_\nu) \frac{d\sigma^{\nu'}}{dE_\nu} dE_\nu$$

No! Even for identical near and far detector, even if you measure perfectly ALL the energy in the detector → **you still need to propagate the xsec from ND to FD which have different neutrino energy spectrum** (because of the oscillation)

The basic variables: q_3, ω



$q_3 = \bar{p}_\nu - \bar{p}_\mu$

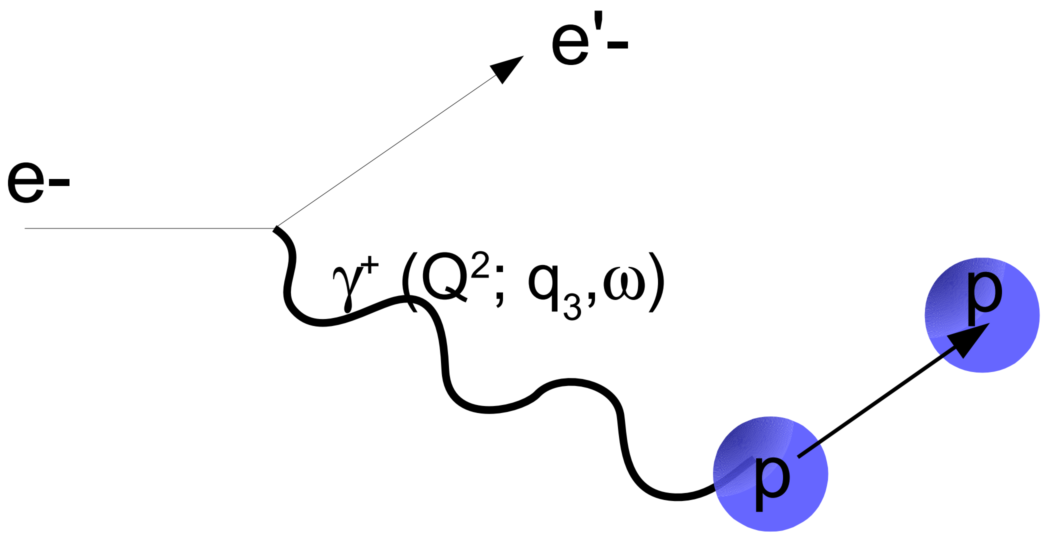
$\omega = E_\nu - E_\mu$

$Q^2 = (p_\nu - p_\mu)^2 \sim 2E_\mu E_\nu(1-\cos\theta)$

Only leptonic leg !

Cross-section can be parametrized as a function of E_ν, q_3, ω

The basic variables: $e^- p$ scattering



$q_3 = \bar{p}_e - \bar{p}_{e'}$

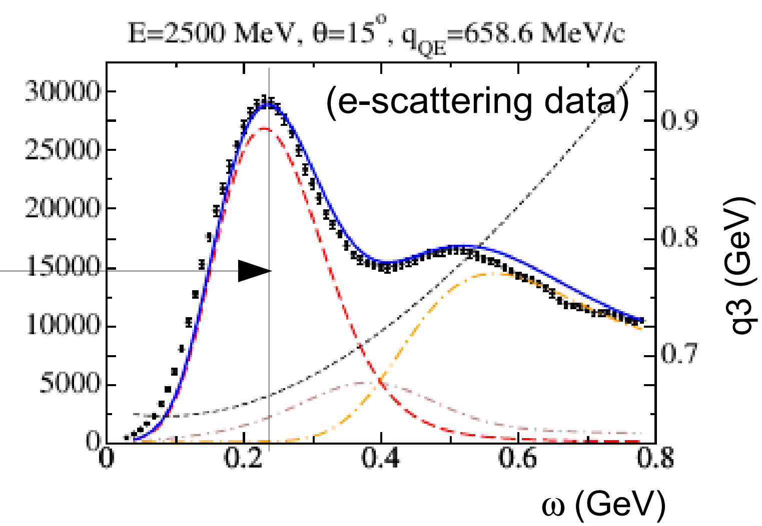
$\omega = E_e - E_{e'}$

$Q^2 = (p_e - p_{e'})^2 \sim 2E_e E_{e'}(1-\cos\theta)$

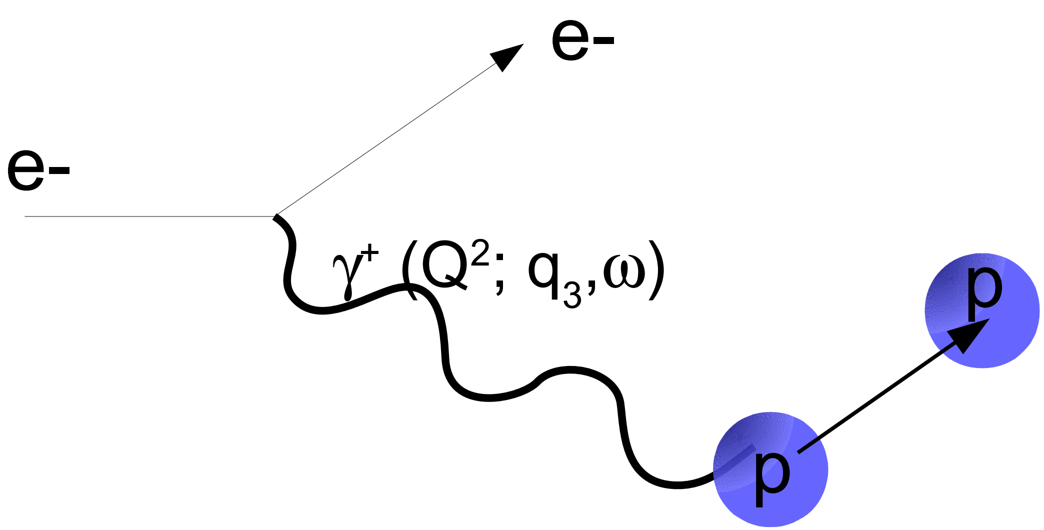
Only leptonic leg !

Cross-section can be parametrized as a function of E_e, q_3,ω

- Quasi-Elastic scattering on nucleon at rest



The basic variables: e^-p scattering



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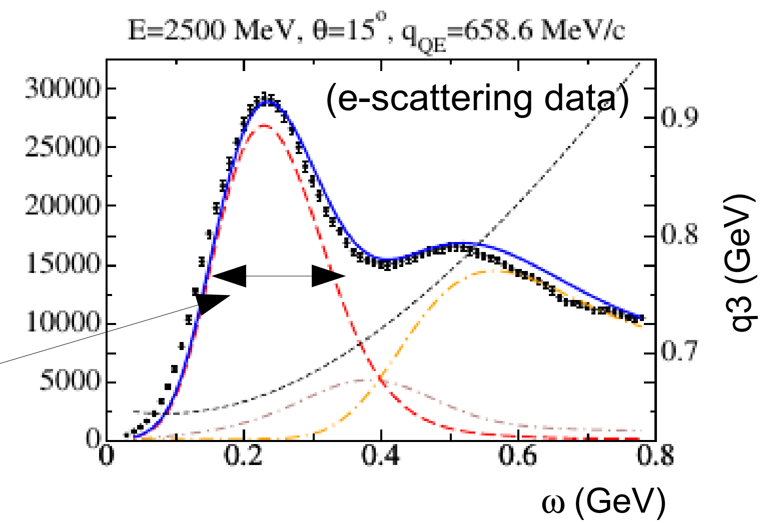
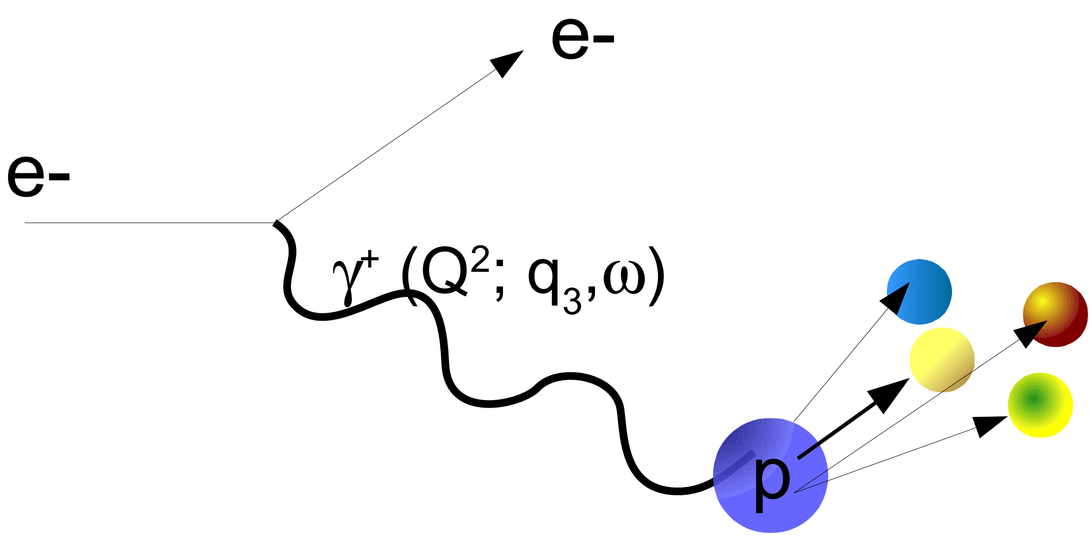
Cross-section can be parametrized as a function of E_e, q_3,ω

- Quasi-Elastic scattering on nucleon at rest

- Quasi-Elastic scattering: nuclear effects on initial state nucleon



The basic variables: $e^{-}p$ scattering



$q_3 = \bar{p}_e - \bar{p}_{e'}$

$\omega = E_e - E_{e'}$

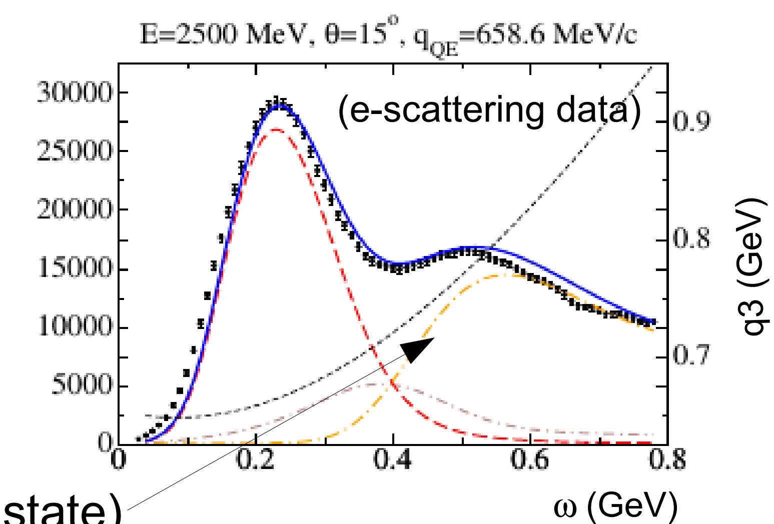
$Q^2 = (p_e - p_{e'})^2 \sim 2E_e E_{e'}(1-\cos\theta)$

Cross-section can be parametrized as a function of E_e, q_3, ω

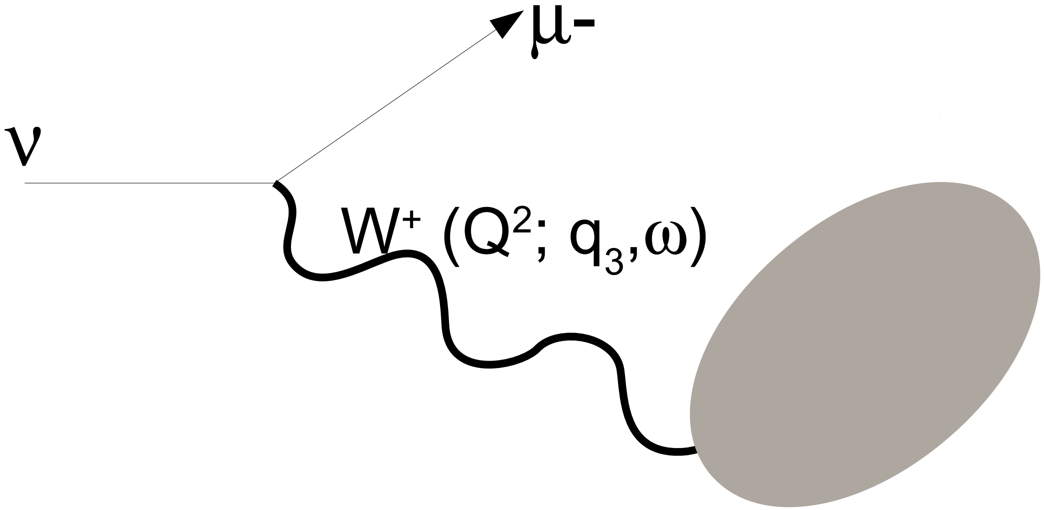
- QE scattering on nucleon at rest

- QE scattering: nuclear effects on initial state nucleon

- non-QE event (multiple particle in the final state)



Back to neutrinos...



$q_3 = \bar{p}_\nu - \bar{p}_\mu$

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$Q^2 = (p_\nu - p_\mu)^2 \sim 2E_\mu E_\nu(1-\cos\theta)$

Cross-section can be parametrized as a function of E_ν, q_3,ω

- QE scattering on nucleon at rest

- QE scattering: nuclear effects on initial state nucleon

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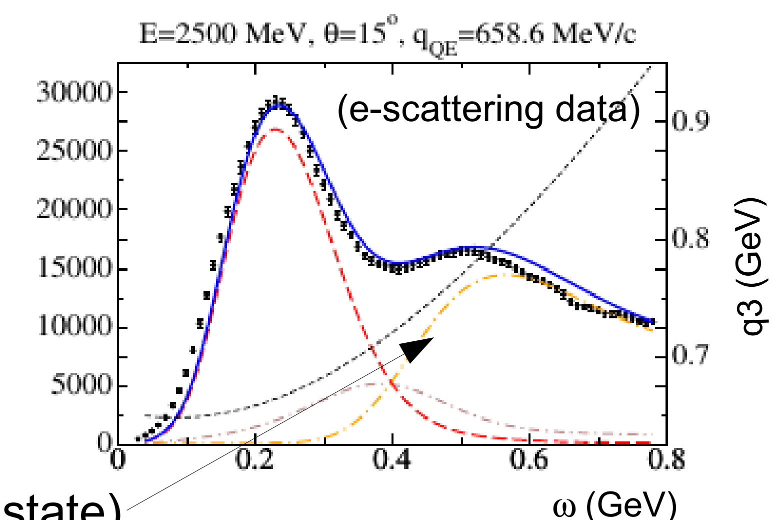
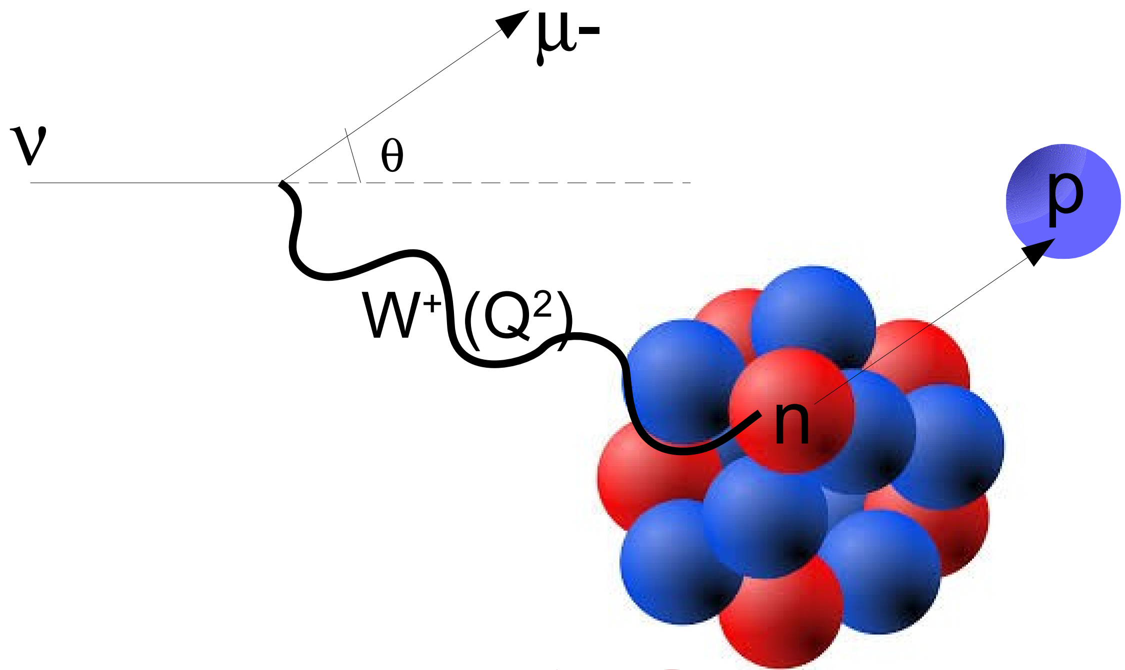


but the E_ν is only known on average (flux) → **q_3, ω cannot be measured directly from the leptonic leg**

→ Need to consider the **hadronic leg to get Eν: strongly affected by nuclear effects**
e.g intial nucleon momentum distribution, binding energy...

Neutrino cross-section: Q^2 dependence

The fundamental variable is the transferred 4-momentum to the nucleus (Q^2)



$$Q^2 = (p_\mu - p_\nu)^2 \approx$$
$$\approx 2 E_\mu E_\nu (1 - \cos\theta)$$

$$\sigma(\nu - Nucleus) \sim |F(Q^2)|^2 \times \sigma_{point-like}(p_n, E_n) \times R(Q^2)$$

Nucleon form factors

Nuclear effects on the initial state

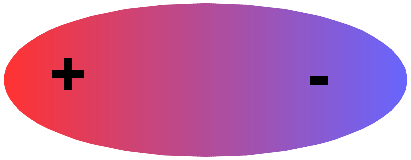
collective nuclear effects of xsec screening/enhancement (RPA)

Need to measure the muon in large phase space (high angle and backward) to measure the Q^2 dependence

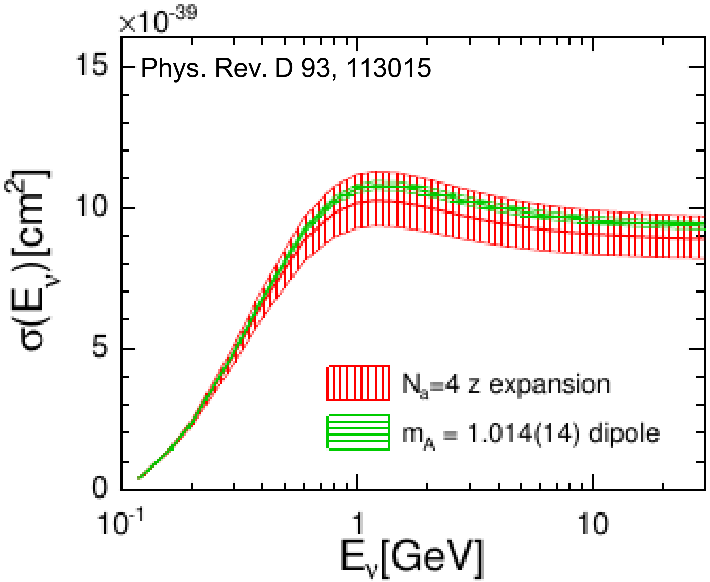
Nucleon form factors

- The vector form factors are well known from electron scattering data → but what about the **axial form factor?**
  Tuned from old bubble chamber data neutrino on deuterium (ANL, BNL, BEBC, FNAL, ...) and old data of pion photo-production

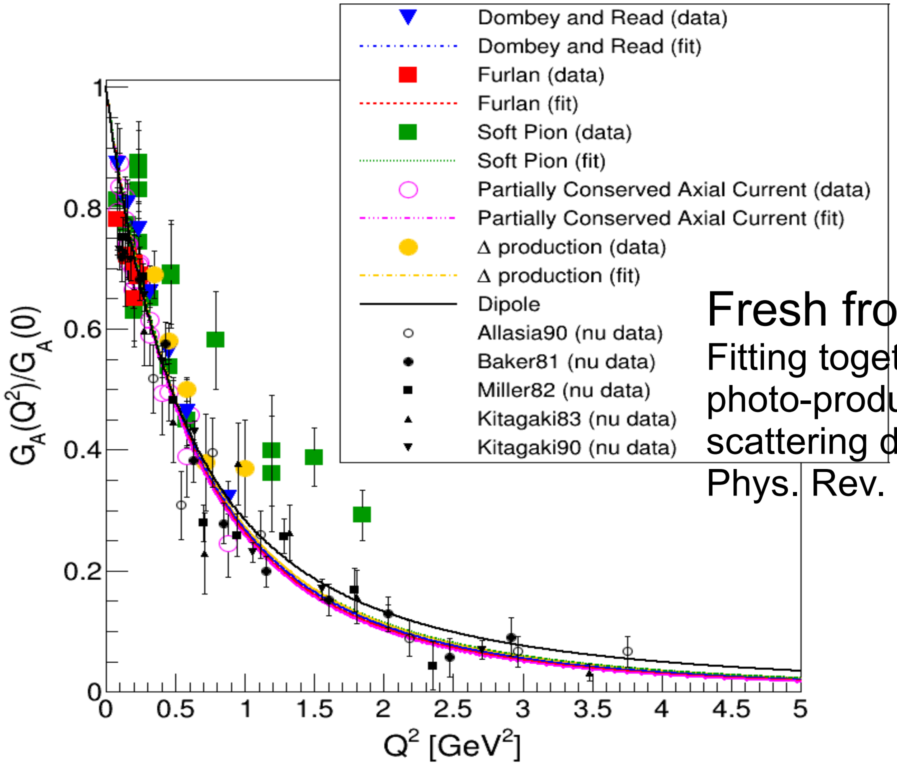
  Dipole function usually assumed: $F_A(Q^2) = \frac{g_A}{(1+Q^2/M_A^{QE\,2})^2}$



- Not well motivated! A lot of interest recently: fit to bubble chamber data repeated with other models based on QCD rules ('z expansion') or informed from pion photo-production



Neutrino-nucleon xsec uncertainties re-evaluated



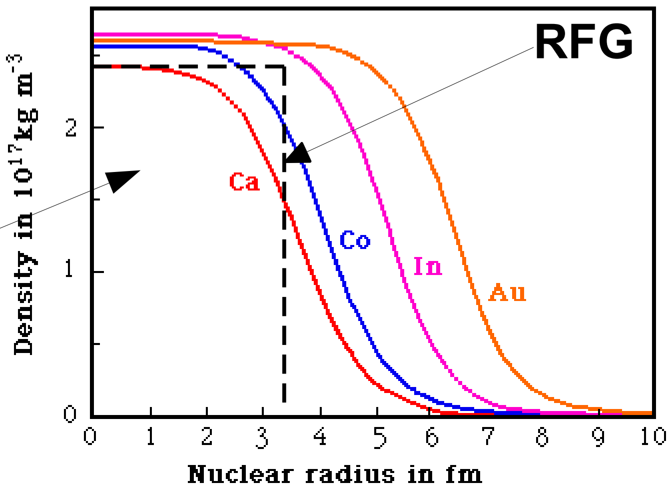
Fresh from my laptop...
Fitting together pion photo-production and neutrino scattering data with model in Phys. Rev. C 78, 031201

Nuclear model

Various distributions of the momentum and energy of the nucleons in the nucleus

Relativistic Global Fermi Gas (RFG)

all momenta equally probable up to a maximum value which depends on the size of the nucleus.
Fixed binding energy
Nucleus is a box of constant density

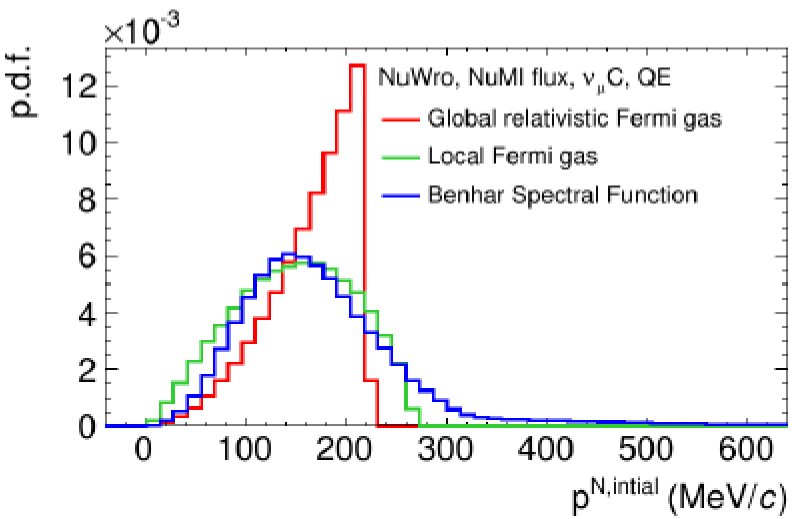


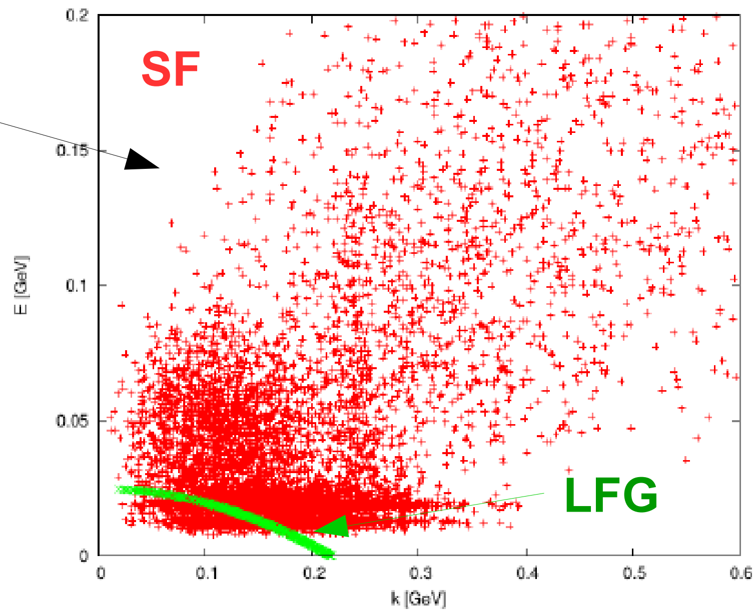
Local Fermi Gas (LFG)

momentum (and binding energy) depends on the radial position in the nucleus, following the density profile of the nuclear matter

Spectral function

More sophisticated 2-dimensional distribution of momentum and binding energy

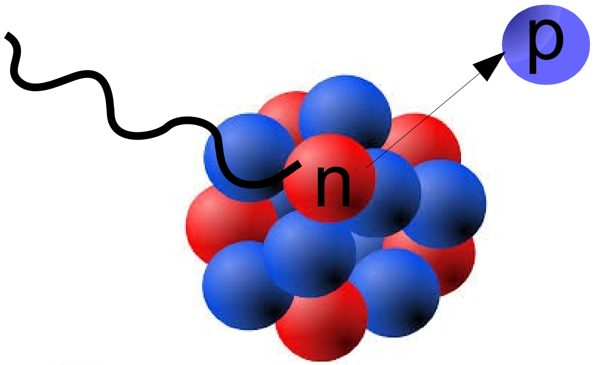




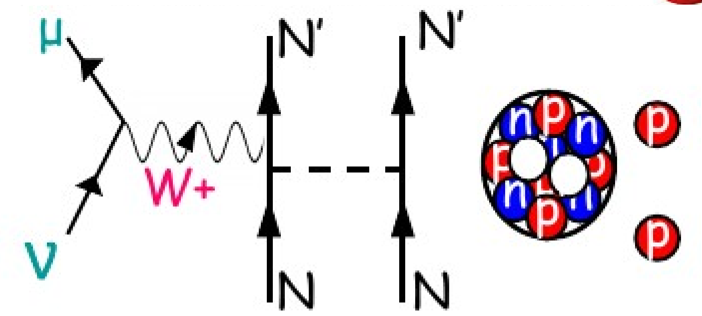
Missing energy

Some modeling uncertainties which affect the neutrino energy reconstruction:

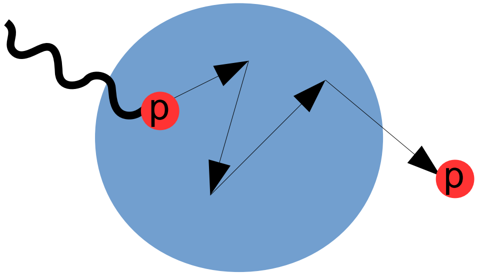
- **Binding energy:** energy needed to extract the nucleon from the nucleus (**oversimplified, still used, way of treating uncertainty on nuclear model**)



- **2p2h interactions**: how many neutrons in the final state?



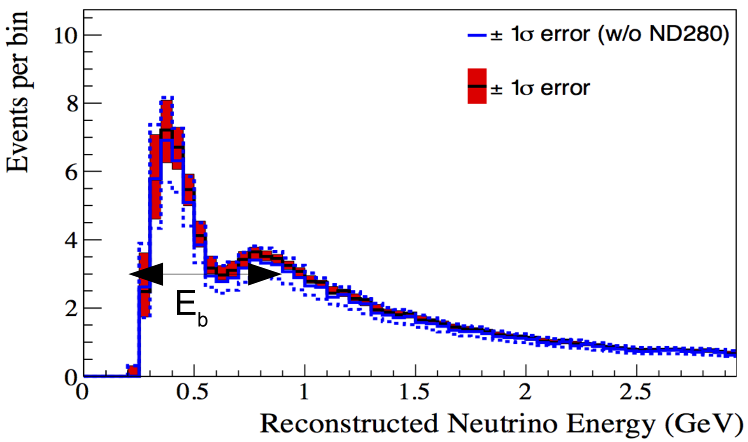
- **Final state interactions of pions and protons** before exiting the nucleus

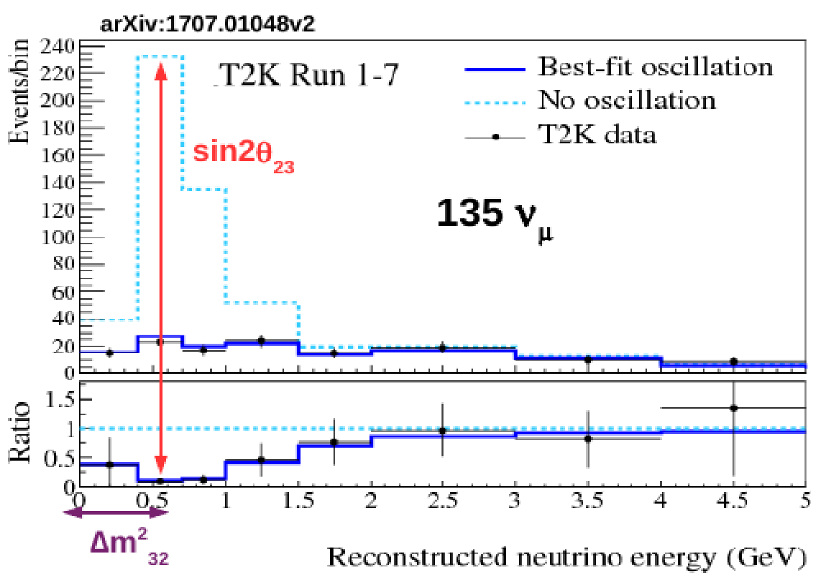


Effect of E_b on estimation of oscillation parameters

- **Binding energy is the energy needed to extract the nucleons from the nucleus** → does not go into the final state but it's 'lost' in the process.

The main effect of a wrong Eb modelling is to move the overall E_ν distribution → bias on Δm^2_{32} which is mostly sensitive to the position of the dip





Reminder from yesterday:

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

- $\sin 2\theta_{23}$ proportional to the depth of the dip
- Δm^2_{32} position of the dip

Binding energy (1)

The meaning of binding energy depends on the model.

Example 1:

- **effective parameter tuned from QE interactions in electron scattering data** (E_b determines the position of QE peak)

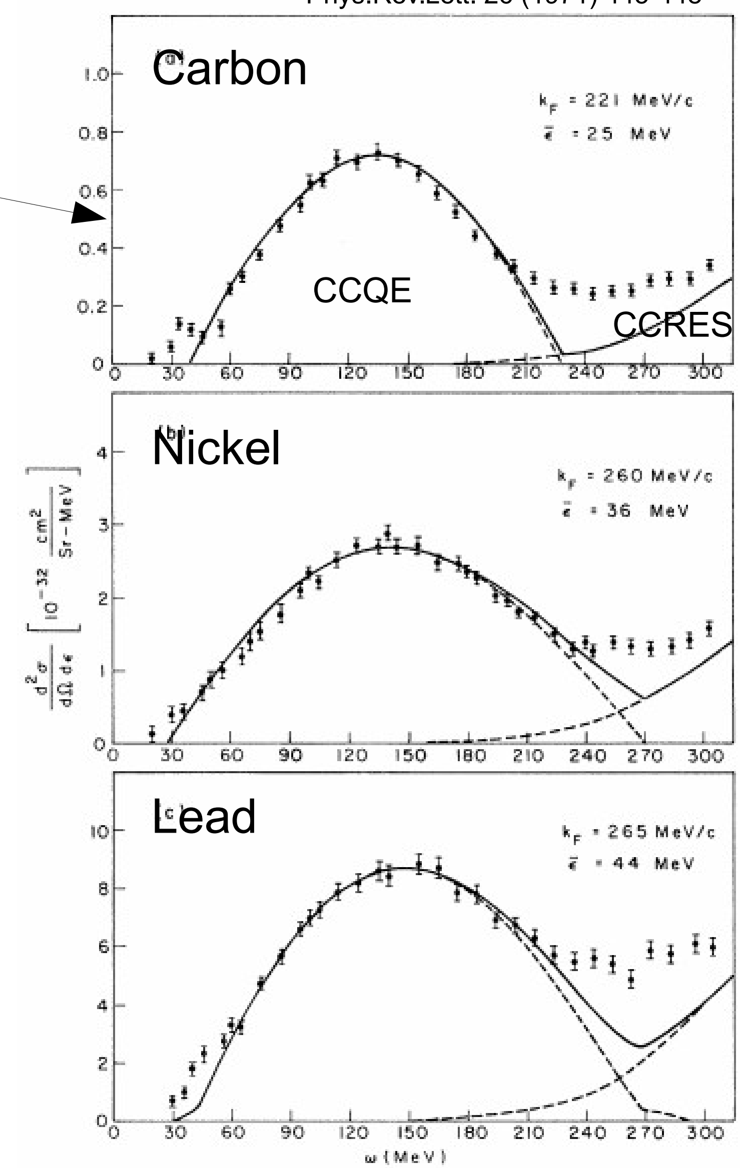
  Evaluated on old data with Fermi gas model and no 2p2h contribution (clear discrepancy in 'dip' region)

- More recent model (eg SuSa v2) is updating this fits → **need to update this** in our MC and oscillation analyses and estimate remaining systematics for different target nuclei

Need models which can predict neutrino but also electron scattering!

electron scattering data

Phys.Rev.Lett. 26 (1971) 445-448



$E_{e'} - E_e$ (MeV)

Binding energy (2)

The meaning of binding energy depends on the model.

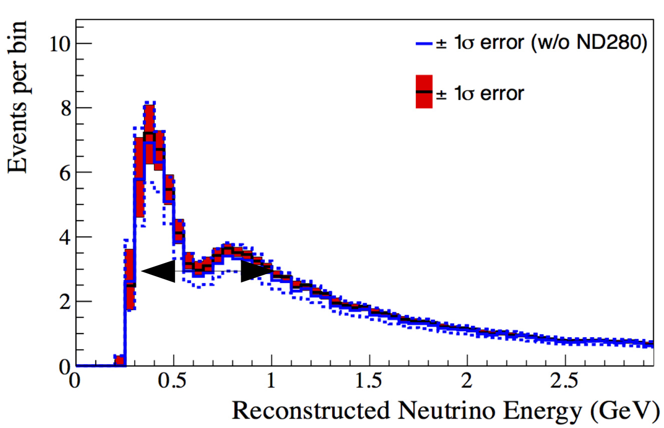
Example 2:

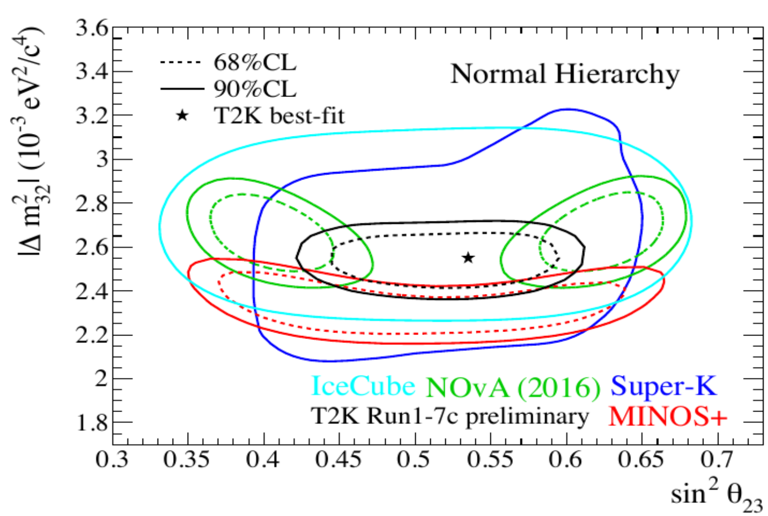
calculation of **difference in energy between the initial and remnant nucleus**

Phys. Rev., C83:045501, 2011.

Target	Nieves ν	Nieves $\bar{\nu}$	approach of previous slide
C	${}^{12}_{6}C \to {}^{12}_{7}N$ $\Delta E \sim 16.5$ MeV	${}^{12}_{6}C \to {}^{12}_{5}B$ $\Delta E \sim 14$ MeV	25 MeV
O	${}^{16}_{8}O \to {}^{16}_{9}F$ $\Delta E \sim 15.5$ MeV	${}^{16}C \to {}^{16}_{7}N$ $\Delta E \sim 12.5$ MeV	27 MeV

→ all boils down to E_b uncertainty of ~10 MeV or more: sizable effect on $|\Delta m_{32}|$



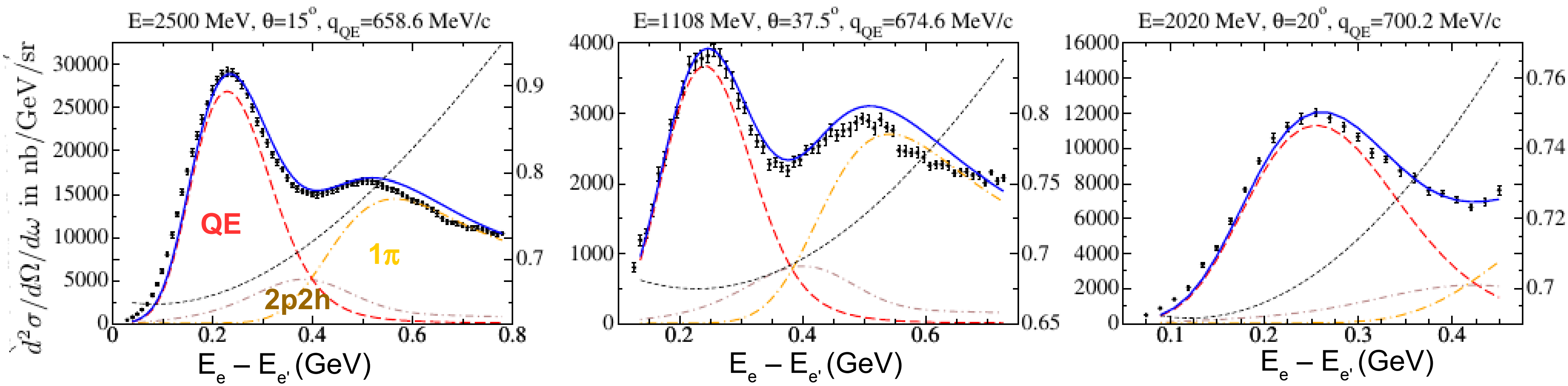


2 particles-2 holes

Interaction with pairs of correlated nucleons in the nucleus and Meson Exchange Currents

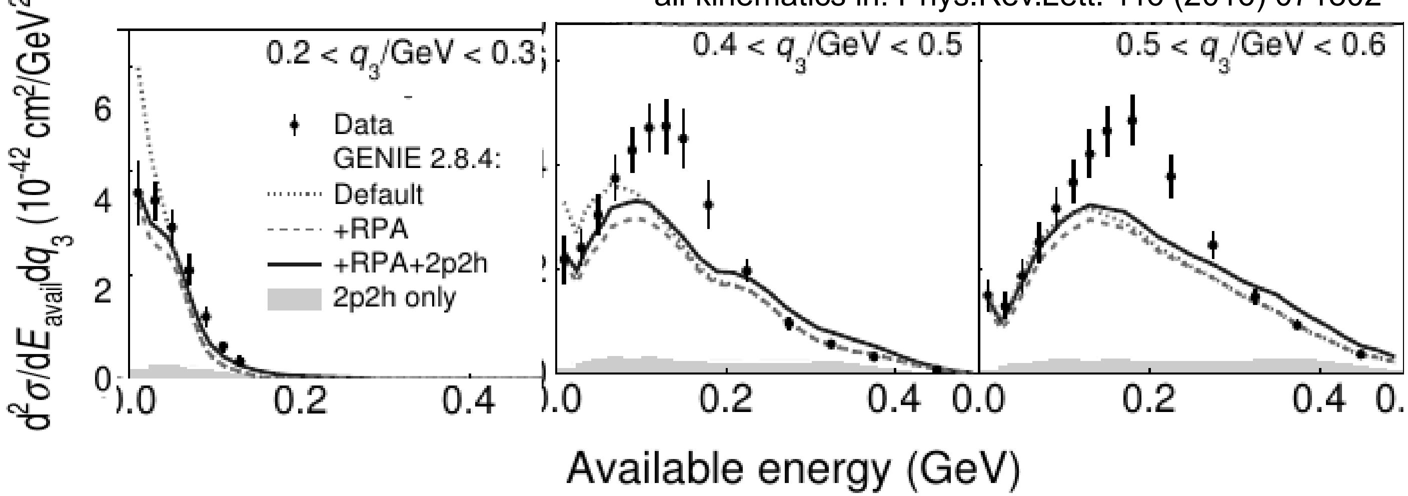
- well established in electron-scattering data:

few examples from SuSav2, all kinematics in: Phys.Rev. D94 (2016) 013012



- **still large uncertainties in neutrino scattering:**

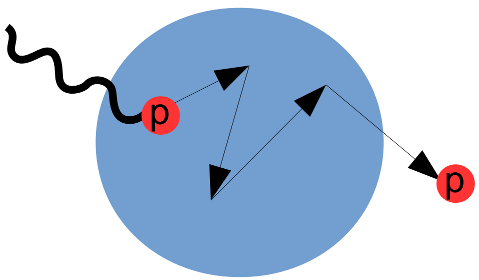
all kinematics in: Phys.Rev.Lett. 116 (2016) 071802



Minerva analysis:
$\omega = E_\nu - E_\mu \sim E_{had}$
reconstructed from hadronic energy in the detector

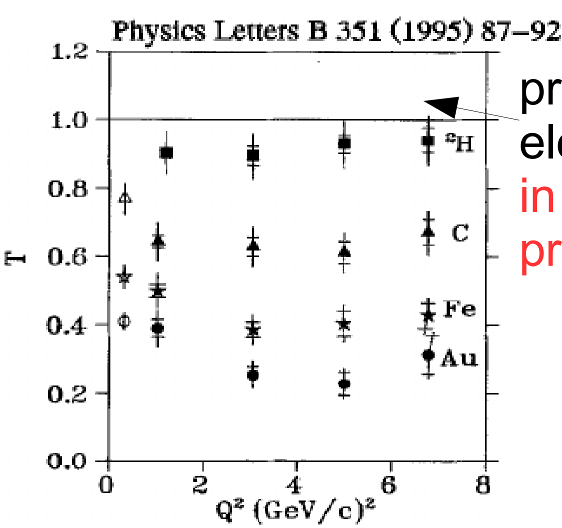
Final state interactions

- Both **pions and protons rescatter before exiting the nucleus:** this change the kinematics, multiplicity and charge of the hadrons in the final state



This process is simulated with approximated 'cascade' models tuned to pion-nucleus and proton-nucleus scattering cross-section

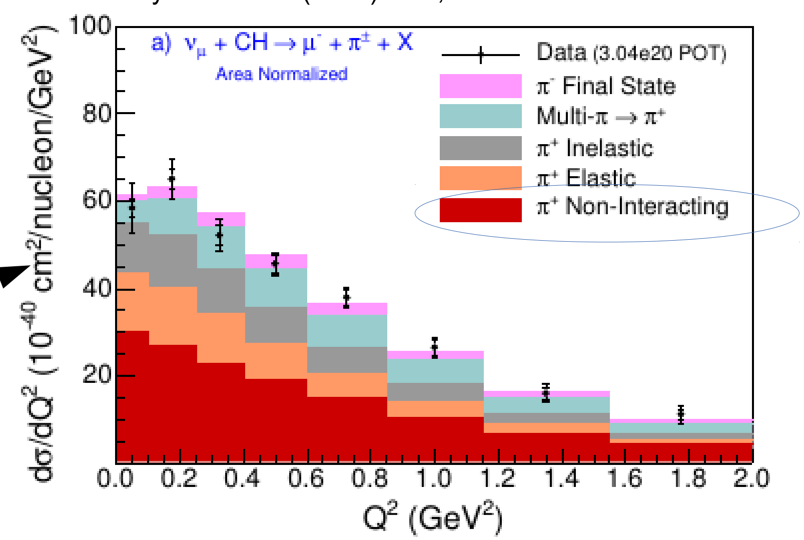
This is not a small effect!



proton transparency in electron scattering:
in Ar FSI corrections for proton production is ~50%

Minerva CC1π sample:
>50% pions re-interacted in the nucleus

Phys.Rev. D94 (2016) no.5, 052005

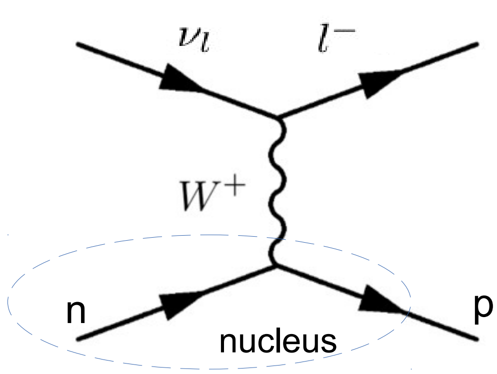


FSI effect on topology reconstruction

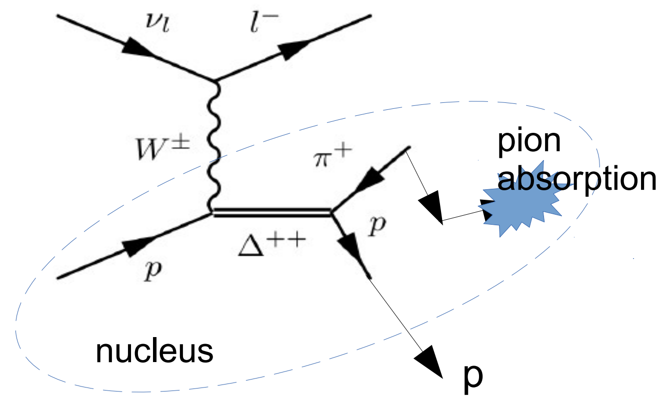
- CC-RES events move into CCQE-like signal (CC0π)

If we observe **a muon and proton in the final state and no pions**, we do not know if that event was:

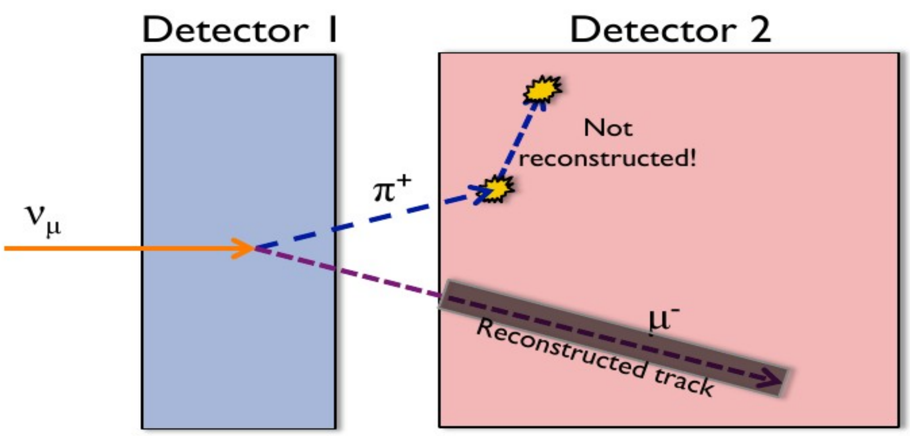
a 'real' CCQE event



or a RES event where the pion has been reabsorbed in the nucleus



The rescattering of the pion in the detector (outside) the original interacting nucleus is also relevant (**Secondary Interactions**)

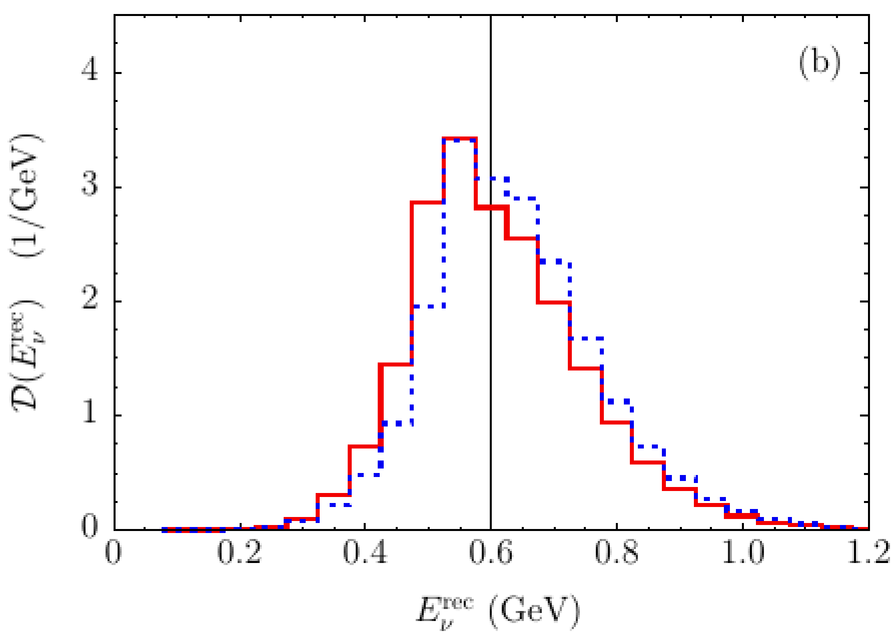


FSI effects on calorimetric energy

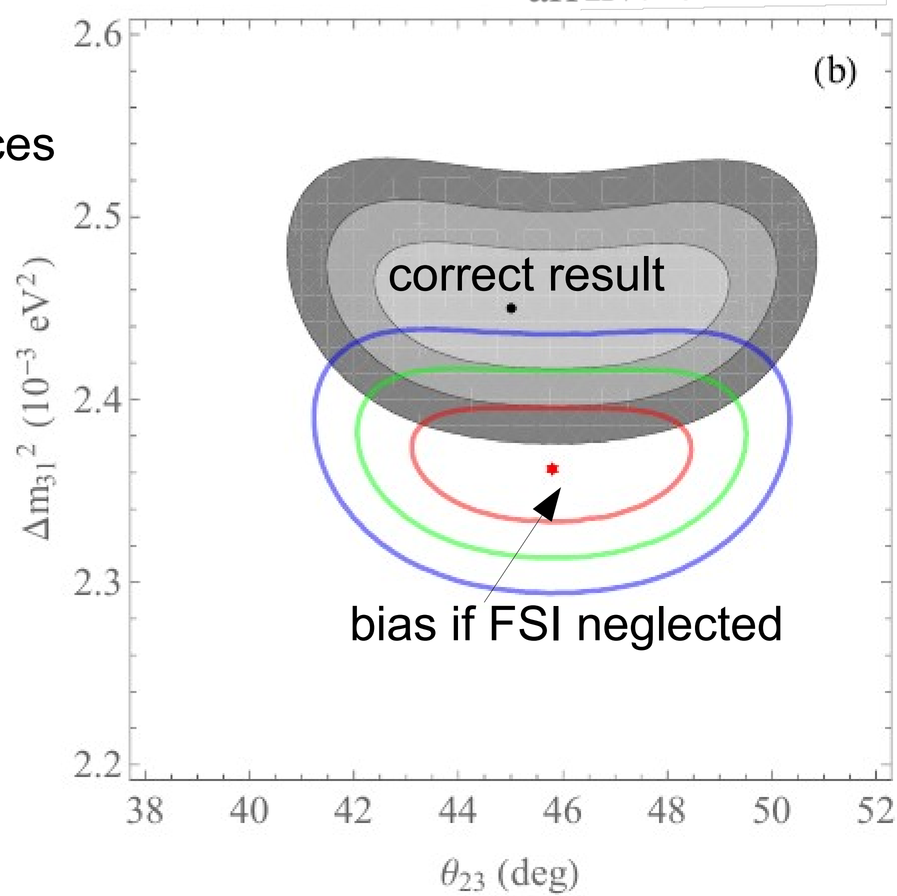
→ **Effects on neutrino calorimetric energy reconstruction for oscillation analysis:**

- efficiency corrections for low momentum particles from MC need reliable model of charge, multiplicity and kinematics of outgoing hadrons
- some energy get lost in the rescattering in the nucleus and cannot be reconstructed

Bias in the reconstructed energy if FSI are neglected with 'realistic' detector performances

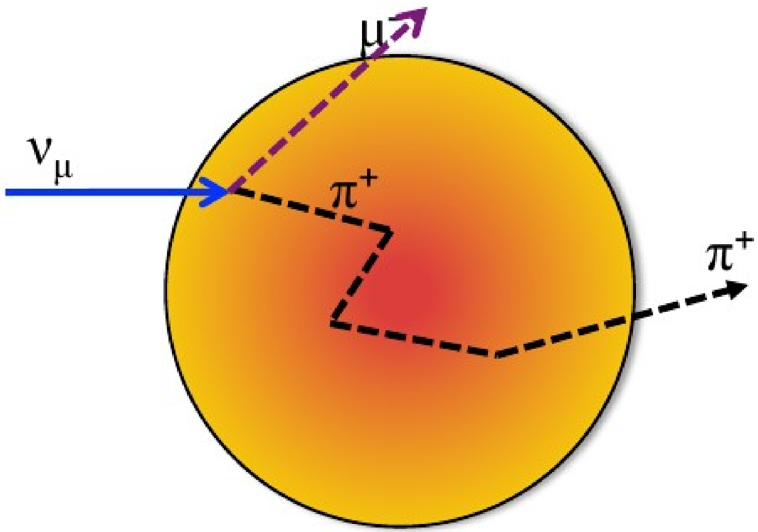


arXiv:1704.07835

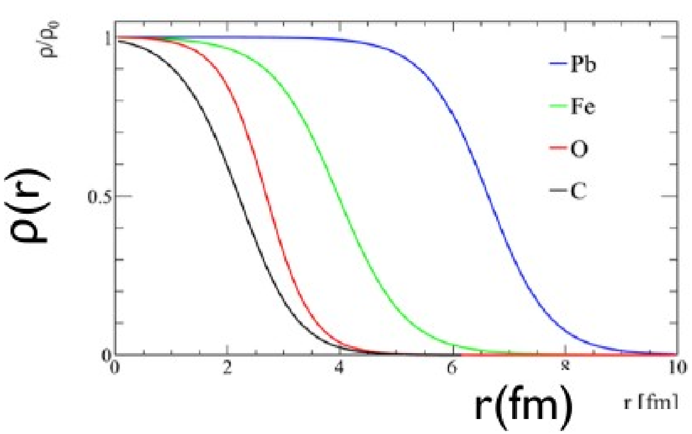


How FSI is modeled

❖ NEUT, NuWro, GENIE hN, FLUKA, Geant4 use Intra-Nuclear **Cascade Models**



- Particles are stepped within the nucleus
- At each step within the nuclear radius the mean free path is calculated:
  - $\lambda_{step}(r) = [\sigma_{microsopic}\rho(r)]^{-1}$
  - Using Monte Carlo method decide if interaction takes place
  - If not, continue to next step

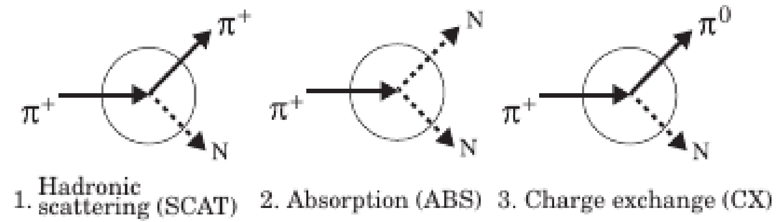


- A-dependence introduced through $\rho(r)$
- Different options for $\sigma_{microscopic}$ (Oset and Salcedo or data-based)
- Dedicated f_{FSI} parameters in the MC cascade

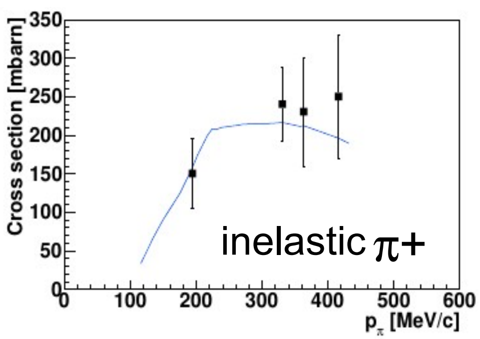
$$\lambda_{step}(r) = f_{FSI}\,[\sigma_{microscopic}\rho(r)]^{-1}$$

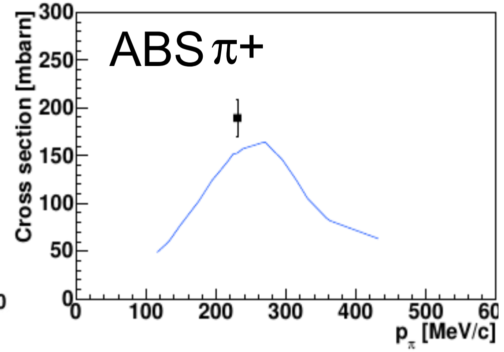
tuned to reproduce external data of pion-nucleus scattering

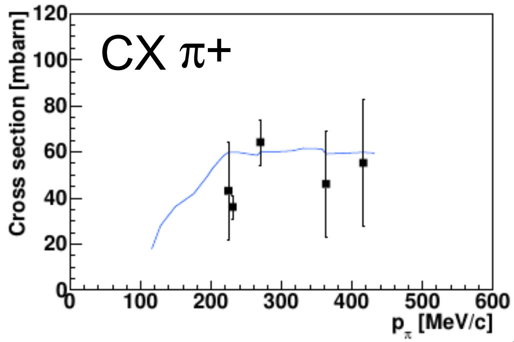
Pions data

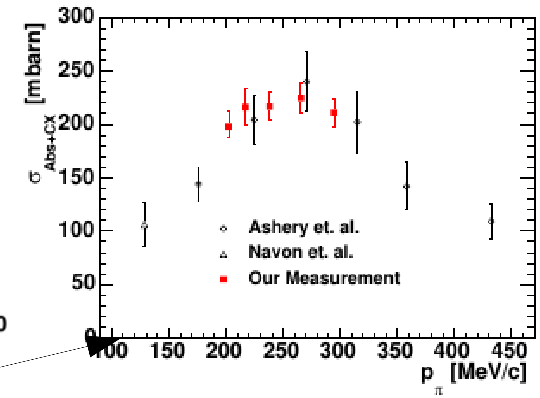


- Pion-nucleus cross-section: **very sparse data available**



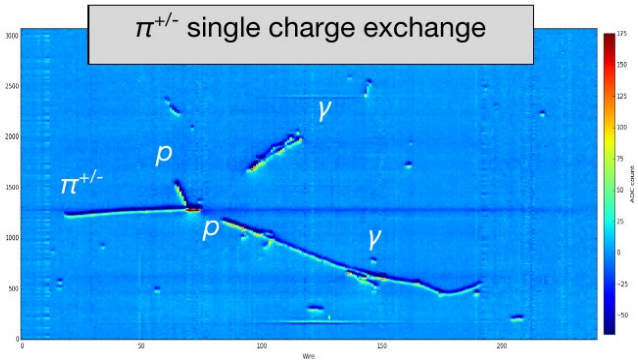




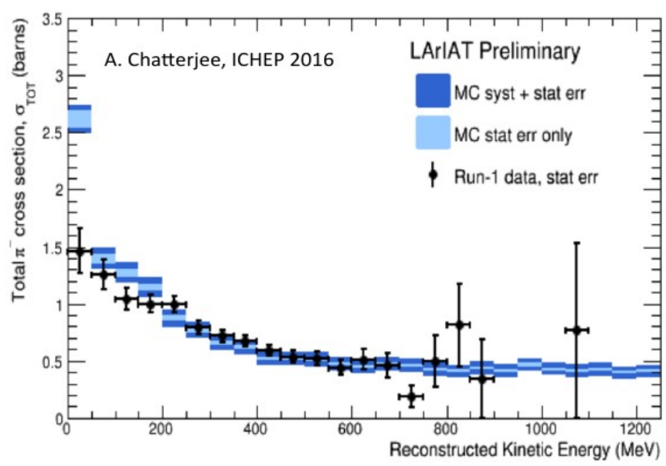


- New measurement from **DUET** experiment at TRIUMF

- **LArIAT:** FNAL LAr on charged test beam



Run I (May 1, 2015-July 4, 2015)



- **Large potential from DUNE prototypes on CERN test beam!**

Different targets

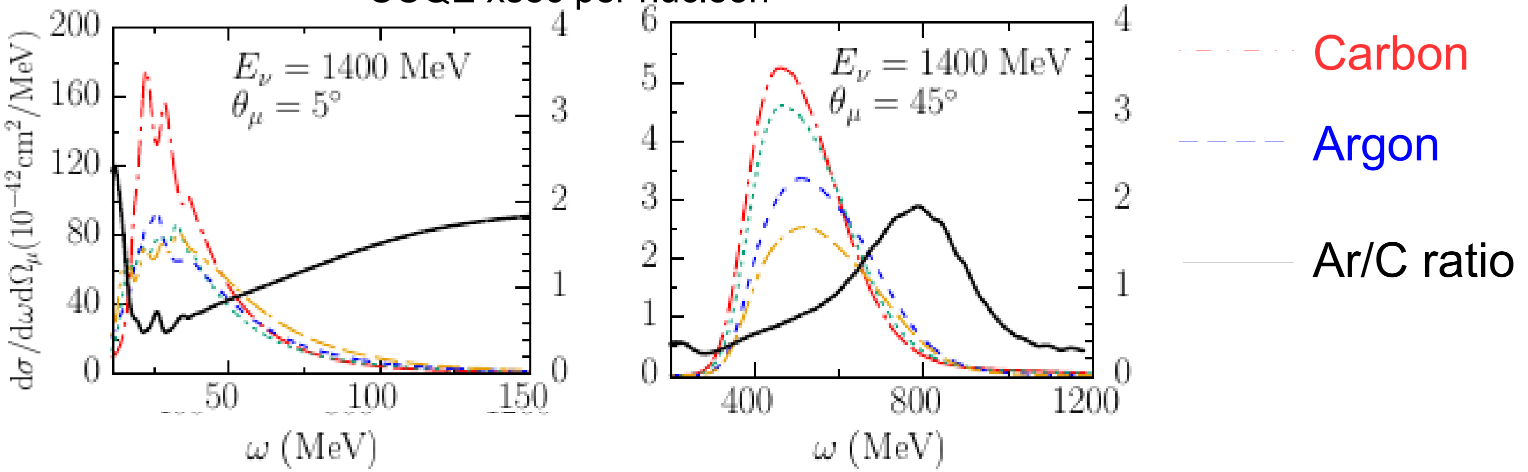
Nuclear effects changes as a function of nucleus 'size' (number of nucleons A)

- **binding energy** and Fermi momentum to be tuned vs A
  (similarly in more advanced models like Spectral Function the energy-momentum correlation function need to established from electron scattering on Argon → plan at CLAS experiment at JLab)

- **2p2h:** how the number of nn and np correlated pairs scale with A ?

- **C-RPA** = corrections for collective nuclear effects computed down to very low transferred energy → shown very not trivial A-dependency:

CCQE xsec per nucleon



Important for DUNE to have Ar target in the Near Detector

- at higher energy DIS xsec depends on **nuclear PDF**: A-scaling observed in data is not well reproduced by the model

δ_{CP} and $\nu_e/\bar{\nu}_e$ xsec

- Measure of CPV relies on the rate of ν_e and $\bar{\nu}_e$ appearance after oscillation

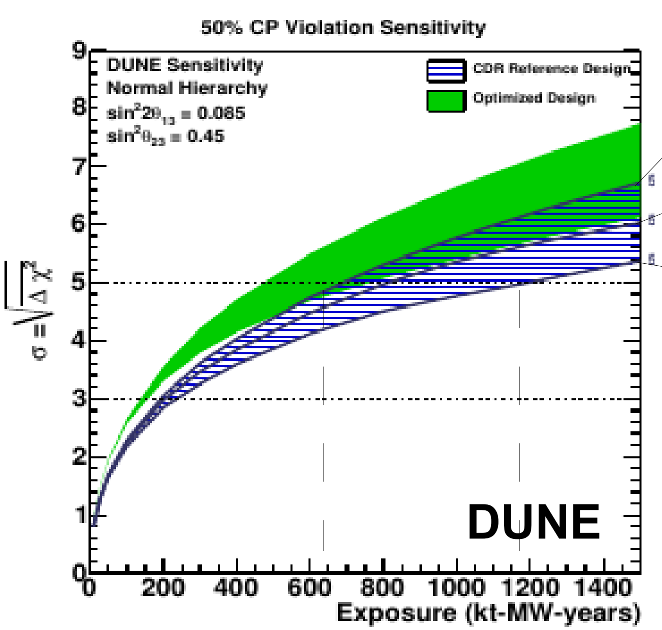
$$\sin(\delta_{CP}) \approx \frac{(\nu_\mu \rightarrow \nu_e) - (\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{(\nu_\mu \rightarrow \nu_e) + (\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}$$

→ difference between ν_μ and ν_e / $\bar{\nu}_e$ xsec has a direct impact on δ_{CP}

- Very low statistics of ν_e in 'standard' beam → cannot be constrained at ND

ν_e / $\bar{\nu}_e$ largest systematics for DUNE and HyperKamiokande

- What matter are the uncorrelated uncertainty between different neutrino flavors and 'charge':



5% ± 1%

5% ± 2%

5% ± 3%

5% $\nu_\mu - \bar{\nu}_\mu$ +
uncorrelated ν_e - $\bar{\nu}_e$ 1-3%

→ equivalent to factor 2 in exposure!

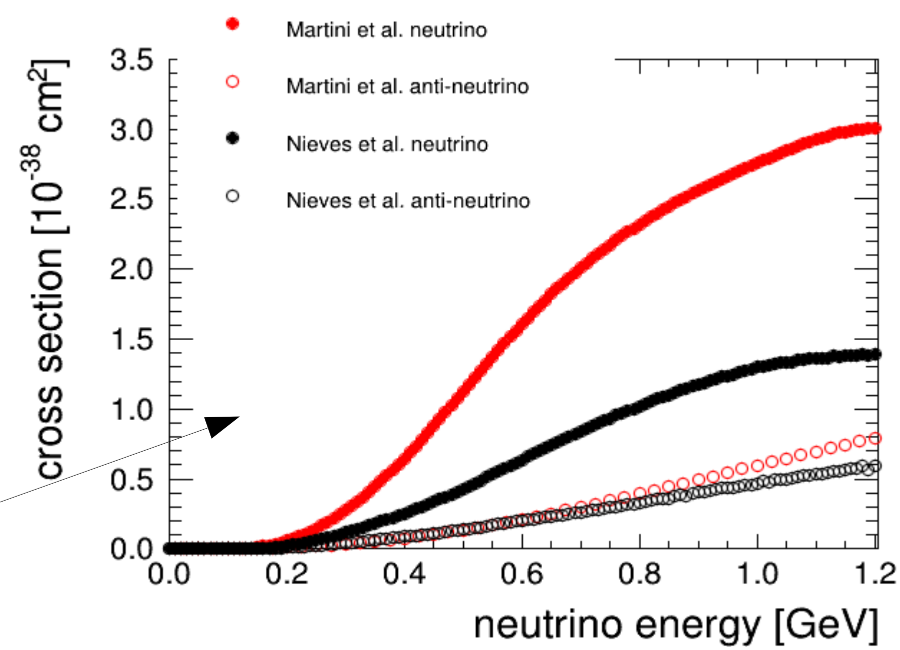
T2K uncertainties

Uncertainty on ν_e apperance

Source of uncertainty	$\delta N_{SK}/N_{SK}$
SKDet+FSI+SI	3.46%
SKDet only	2.39%
FSI+SI only	2.50%
Flux	3.64%
Flux (pre-fit)	8.94%
2p-2h (corr)	3.87%
2p-2h bar (corr)	0.05%
NC other (uncorr)	0.16%
NC 1gamma (uncorr)	1.44%
XSec nue/numu (uncorr)	2.65%
XSec Tot (corr)	4.13%
XSec Tot	5.12%
XSec Tot (pre-fit)	7.17%
Flux+XSec (ND280 constrained)	2.88%
Flux+XSec (All)	4.17%
Flux+XSec+SKDet+FSI+SI	5.41%
Flux+XSec+SKDet+FSI+SI (pre-fit)	11.9%

Uncertainty on $\bar{\nu}_\mu$ disapperance

Source of uncertainty	$\delta N_{SK}/N_{SK}$
SKDet+FSI+SI	3.90%
SKDet only	3.31 %
FSI+SI only	2.06 %
Flux	3.77%
Flux (pre-fit)	7.10%
2p-2h (corr)	2.96%
2p-2h bar (corr)	1.81%
NC other (uncorr)	0.75%
NC 1gamma (uncorr)	0.00%
XSec nue/numu (uncorr)	0.00%
XSec Tot (corr)	4.13%
XSec Tot	4.19%
XSec Tot (pre-fit)	9.32%
Flux+XSec (ND280 constrained)	3.26%
Flux+XSec (All)	3.35%
Flux+XSec+SKDet+FSI+SI	5.22%
Flux+XSec+SKDet+FSI+SI (pre-fit)	12.5%



Example: different $\nu/\bar{\nu}$ predictions for 2p2h

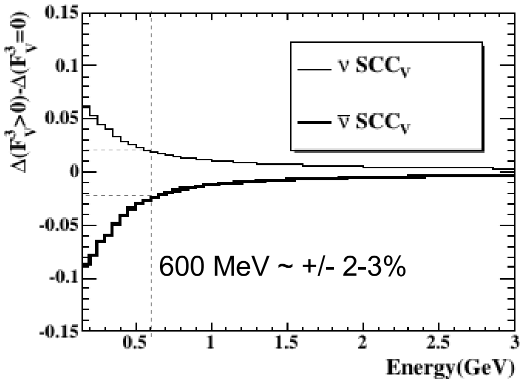
ν_e / ν_μ

arXiv:1206.6745v2

arXiv:1602.00230

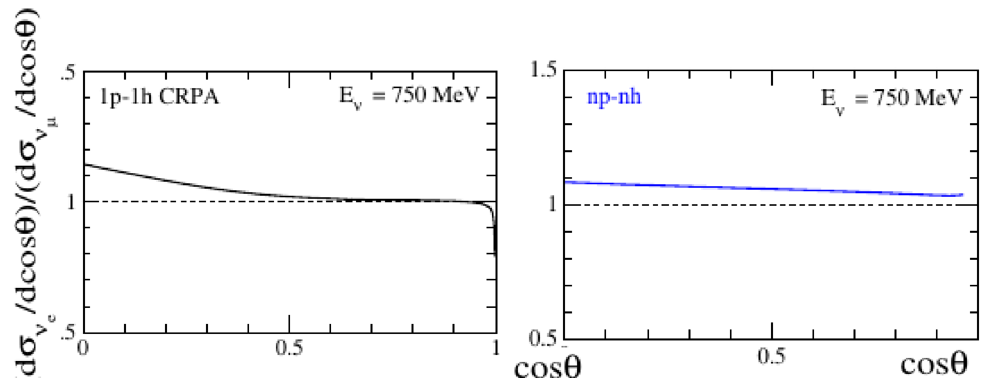
- Differences between ν_e and ν_μ: different kinematics, alter Q^2 limits of integration for each Eν value

are calculable (and included in MC) but uncertainties arise from convolution of those effects with nucleon form factors and with nuclear response functions which have large uncertainties.



- **nucleon form factors:** largest effect from secondary-class current (usually not included for symmetry reasons but not strongly constrained from data)

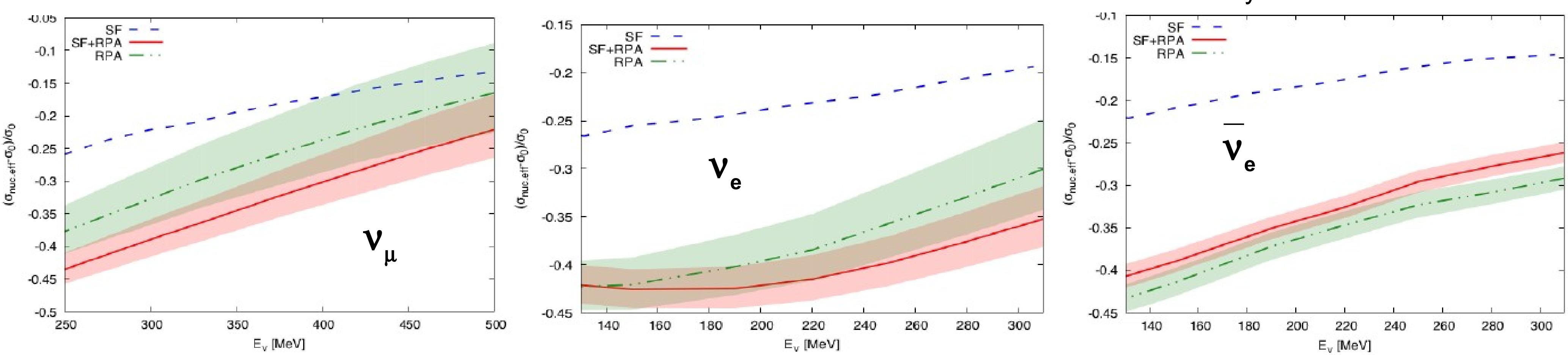
→ largest uncertainty from F_3^V (less constrained from data)



- **ν_e/ν_μ ratio for 2p2h** → since 2p2h is not well known then the difference between ν_e and ν_μ is not well known either

- **Nuclear effects on 1p1h** may gives different effects to different neutrino types:

Correction to the CC inclusive cross-section due to different nuclear effects with theoretical uncertainty band:



Different neutrino species

- In principle, **if ν_μ xsec is perfectly known, the model can be "easily" used to extrapolate to $\bar{\nu}_\mu$ and ν_e** (lepton universality and CP symmetry hold in neutrino interactions)

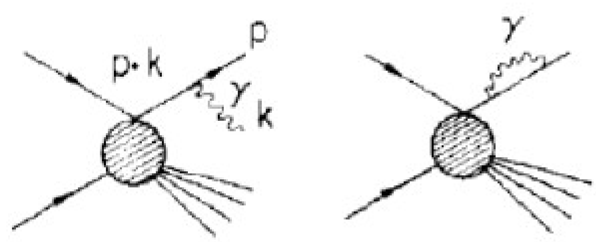
  In practice, large uncertainty on ν_μ due to nucleon form factors and nuclear effects, may affect differently ν_μ, $\bar{\nu}_\mu$ and ν_e

  → **Uncorrelated uncertainty between ν_μ, $\bar{\nu}_\mu$ and ν_e are just a product of our limited knowledge on ν_μ interactions**

- **Different radiative corrections for $\nu_e \to e$ and $\nu_\mu \to \mu$** (because of different lepton mass)

  correction to Born xsec ~

  $$\frac{\alpha_{EM}}{2\pi} \log \frac{4E_\ell^*}{m^2}$$



~10% effect on the difference between ν_μ and ν_e cross-section !

→ **need less approximated calculation?**

What we need to control?

Uncertainties in ND→FD extrapolation :

- different E_ν distribution (because of oscillation)

measure all particles in the final state: threshold and calibration at low energy (neutrons? FSI?)

- different target

A-scaling: measure cross-sections on different targets (and/or on the same target of FD)

- different acceptance

measurement of cross-section in the larger possible phase-space: increase angular acceptance and containment at ND

- different neutrino flavor (because of oscillation)
- ν ($\bar{\nu}$) flux has typically a wrong sign component

'control' cross-section asymmetries between different neutrino species

Near detector constraints

Near detector is used to tune the xsec model but...

- some nuclear effects can be degenerate (indistinguishable) with near detector data but still give you different spectrum at far detector
- detector effects (calibration and threshold) can also be degenerate with nuclear effects
- anticorrelation between the xsec and the flux → difficult to constrain them separately (and they propagate differently at FD)

you can perfectly describe ND data and still be wrong in FD prediction

Impact of such problems on the oscillation analysis depends on the detector and how the analysis is done

BACK-UP

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What we need to control?

Uncertainties in ND→FD extrapolation :

- different E_ν distribution (because of oscillation) ⇨ measure all particles in the final state: threshold and calibration at low energy (neutrons? FSI?)

- different target ⇨ A-scaling: measure cross-sections on different targets (and/or on the same target of FD)

- different acceptance ⇨ measurement of cross-section in the larger possible phase-space: increase angular acceptance and containment at ND

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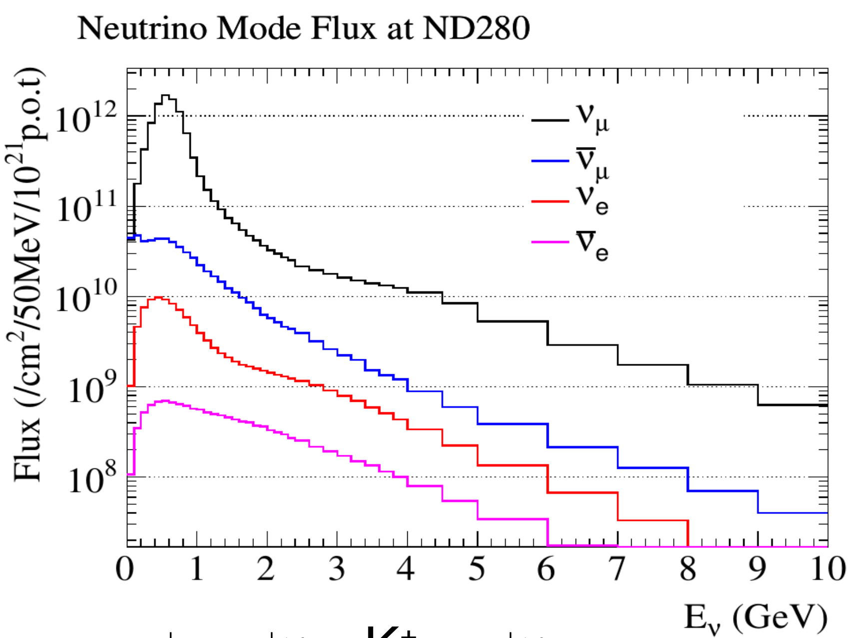
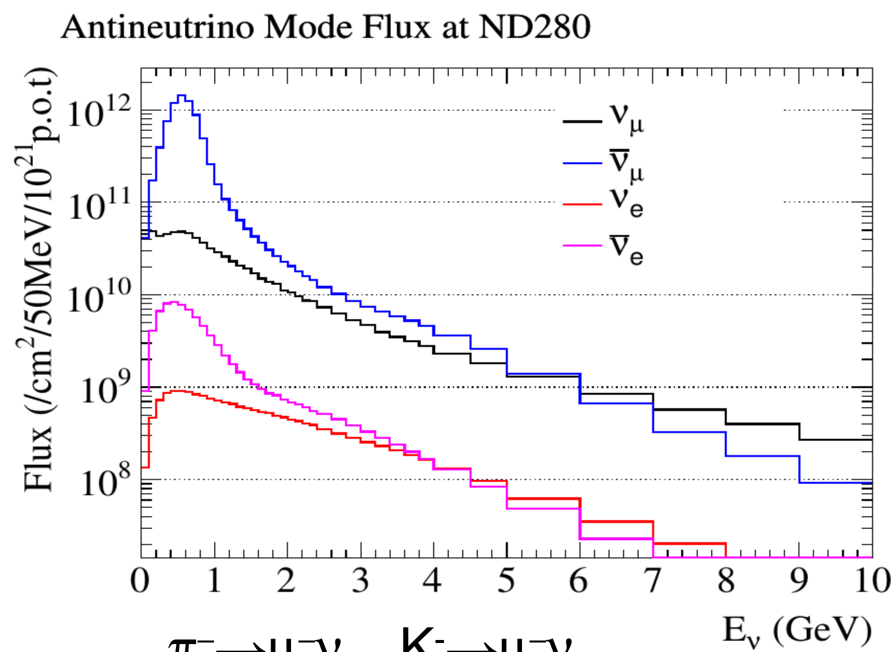
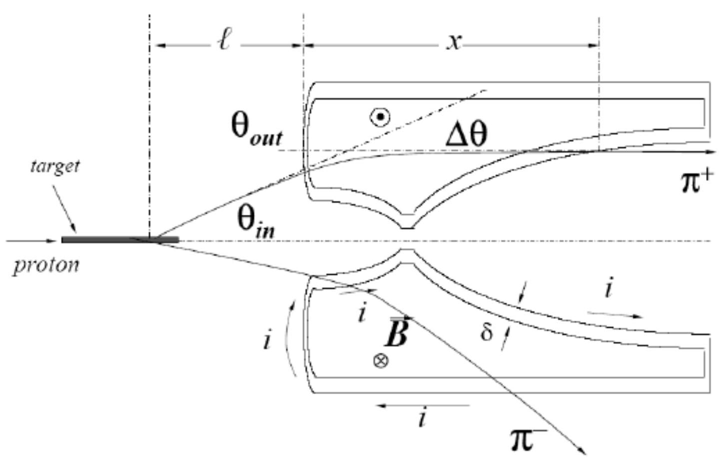
Question from yesterday (1)

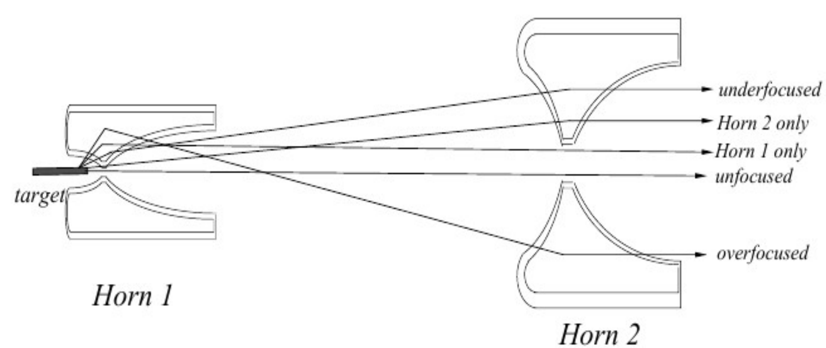




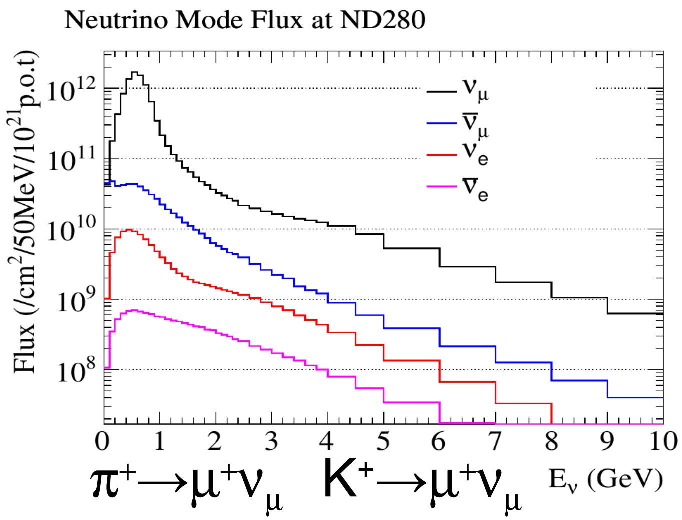
$\pi^+ \rightarrow \mu^+ \nu_\mu$ $K^+ \rightarrow \mu^+ \nu_\mu$ $\pi^- \rightarrow \mu^- \nu_\mu$ $K^- \rightarrow \mu^- \nu_\mu$

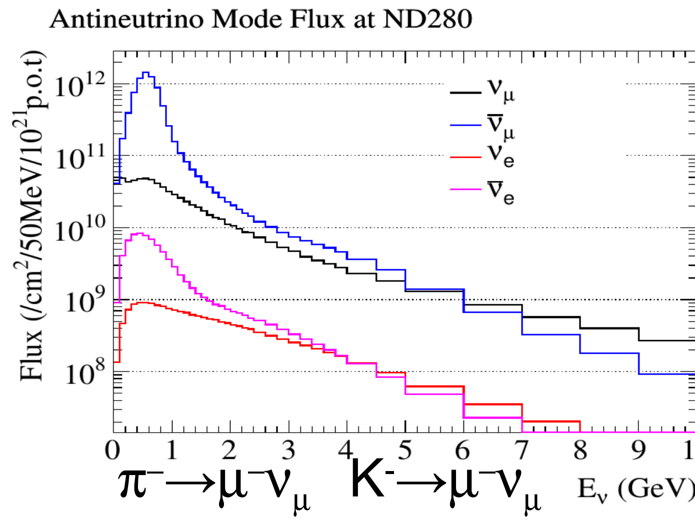
The 'wrong sign' background comes from high p_L pions (kaons) which cannot be defocused properly because they miss the horns



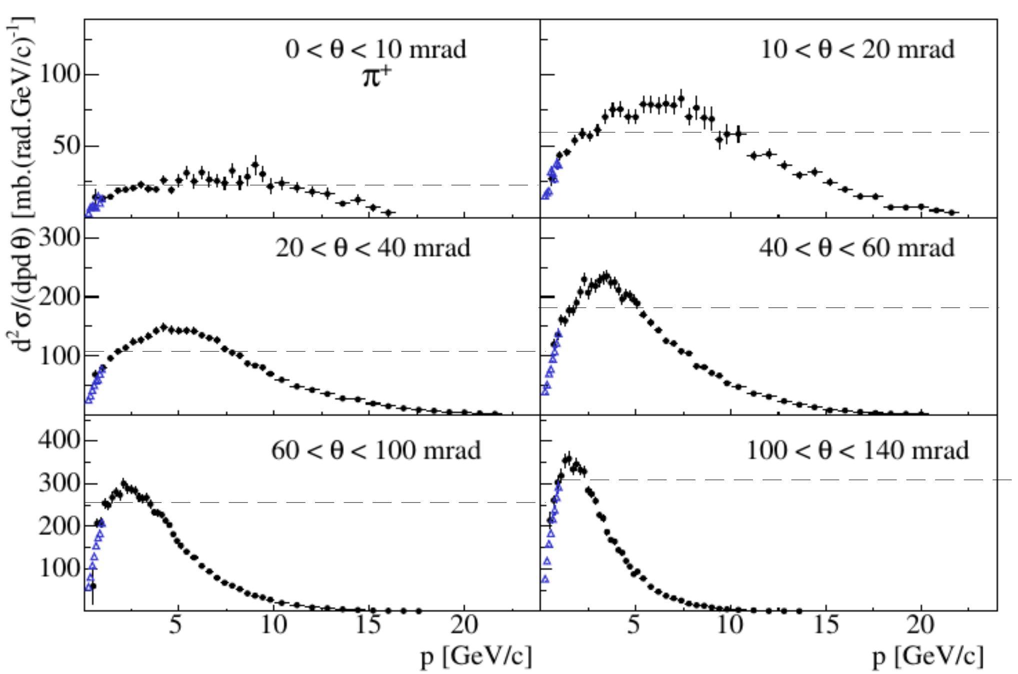


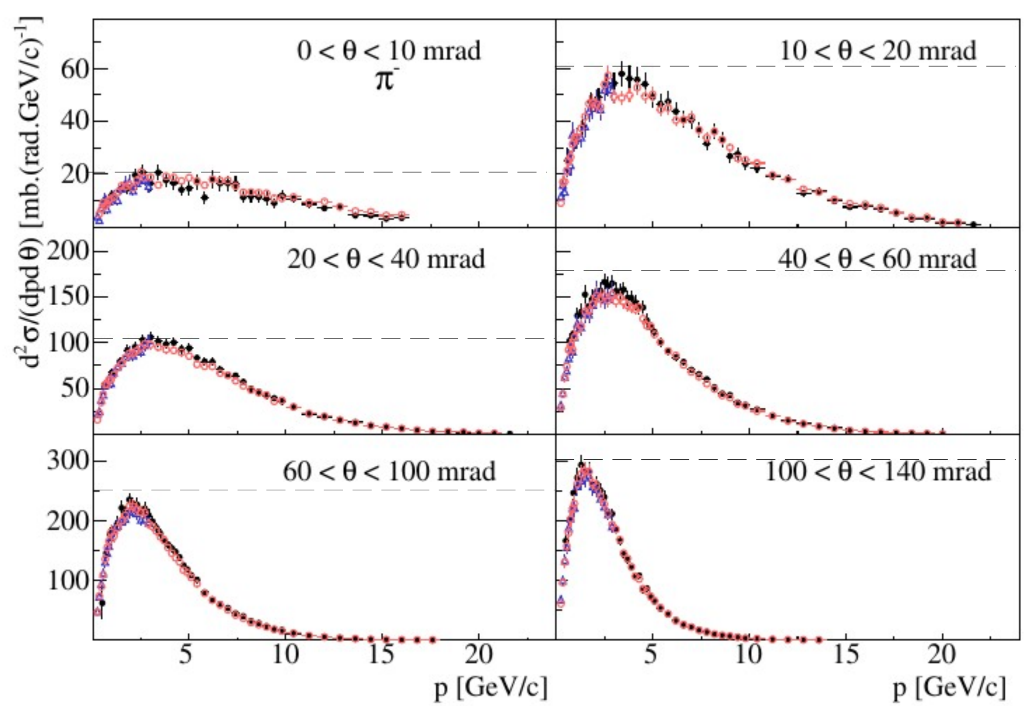
Question from yesterday (2)





When proton hits the target it is more probable to create positive charged hadrons than negative ones



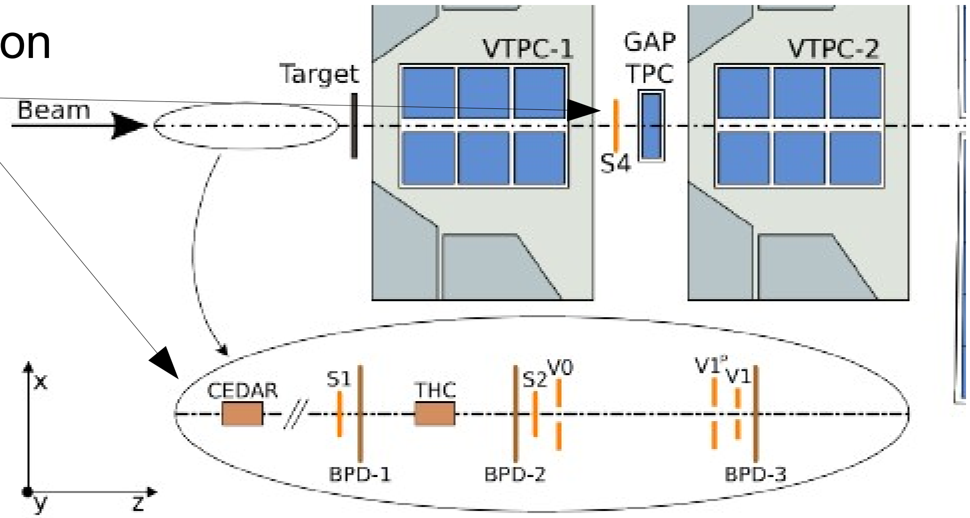


Cross-section normalization

$$\sigma_{hadroprod} = \sigma_{tot} - \sigma_{el} - \sigma_{qe}$$

σ_{tot} can be extracted from beam instrumentation in anti-coincidence with S4
(normalized to number of carbon nuclei in the target)

Need to correct for events with actual interactions in S4 using model



σ_{el} elastic scattering on carbon nucleus
(from previous measurements compared to GEANT → largest uncertainty)

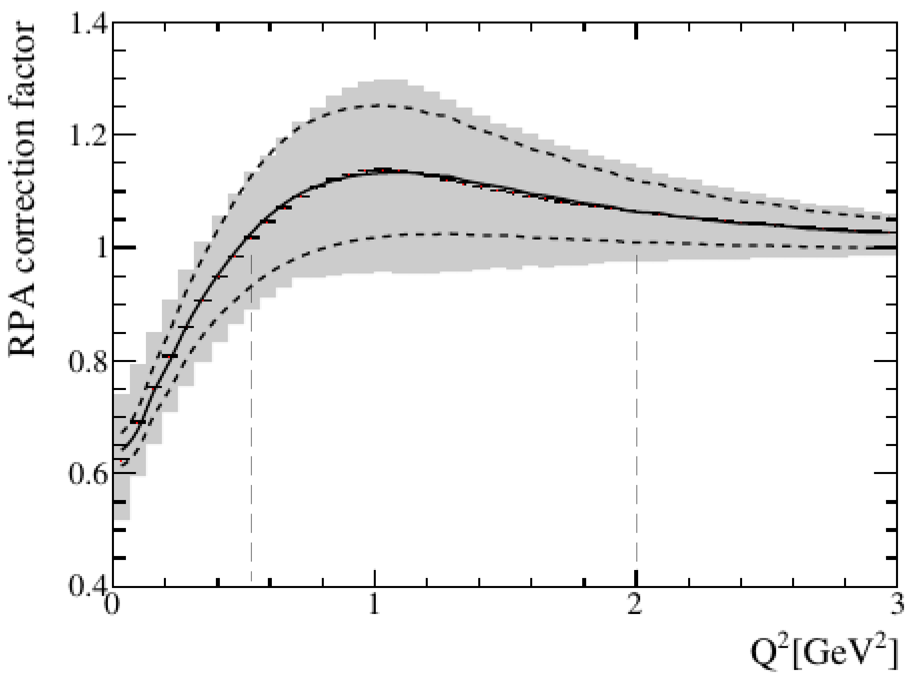
σ_{qe} quasi-elastic scattering on single nucleon in the carbon nucleus which get ejected (from GEANT)

$$\sigma_{\mathrm{prod}} = 230.7 \pm 2.8(\mathrm{stat}) \pm 1.2(\mathrm{det})\,^{+6.3}_{-3.5}(\mathrm{mod})\,\mathrm{mb}$$

RPA

Random Phase Approximation is a non-perturbative method to describe microscopic quantum mechanical interactions in complex systems of many bodies.

The many-body system constituted by the mutual interactions of nucleons inside the nucleus cannot be resolved exactly → approximated calculation which parametrize the impact of such collective effects on the ν-N cross-section

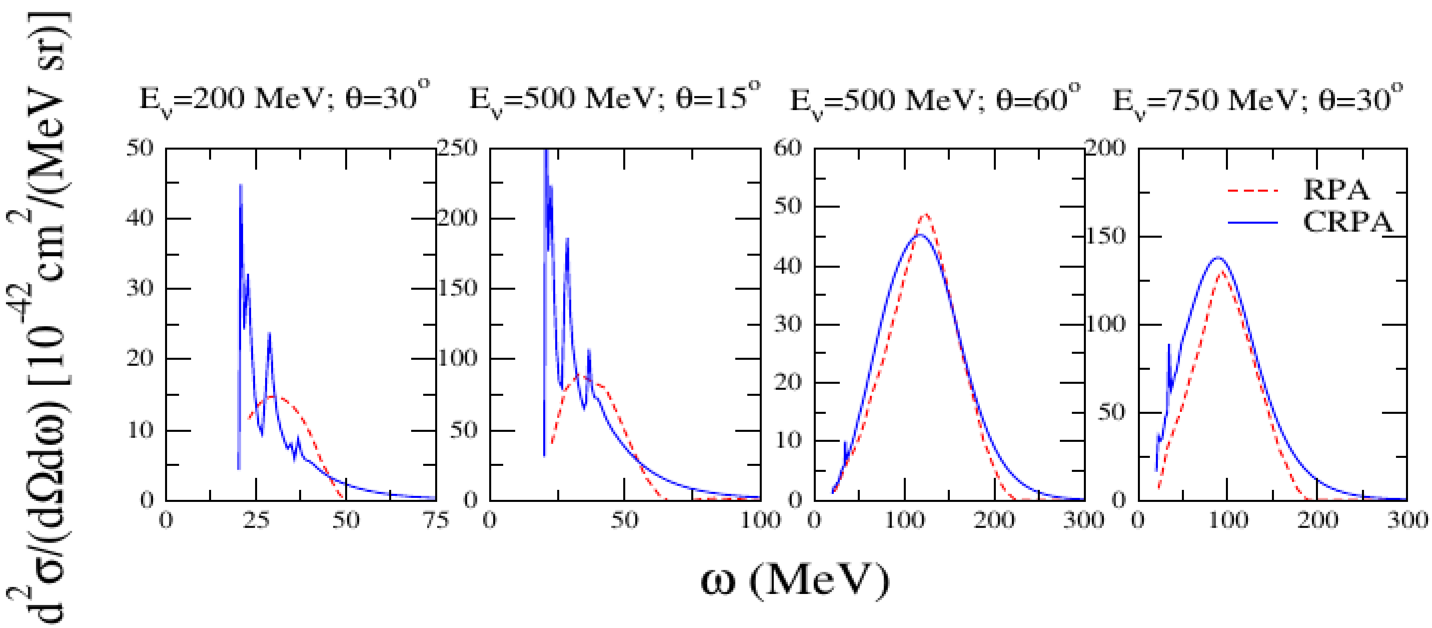


- **Q^2<0.5 GeV^2 screening:** nucleons embedded in nuclear potential
- **Q^2->inf no RPA effect:** if high energy transferred to nucleus than nucleons (→ quarks) ~ free

C-RPA

RPA is an ***approximation*** → a more sophisticated computation **Continuum-RPA** describes the very reach details of the nuclear structure

Resonances at low energy transferred to the nucleus (ω), ie low E_ν or very forward muon



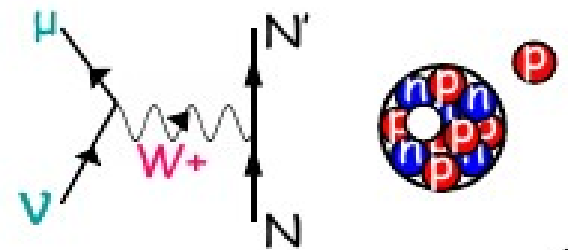
Additional process: 2particles-2holes (only in nuclei)

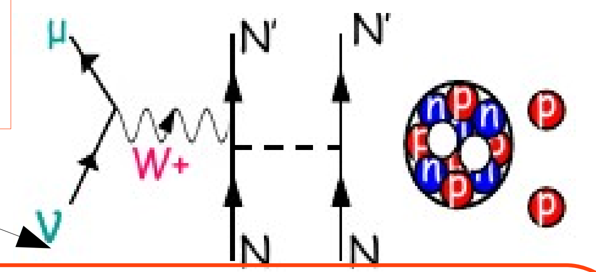
from Gran (Minerva) at
2p2h Saclay workshop

CCQE (aka **1p1h**)

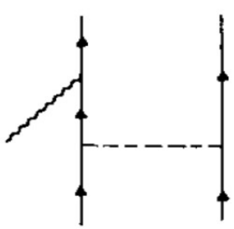
+

2p2h : interaction with correlated nucleons

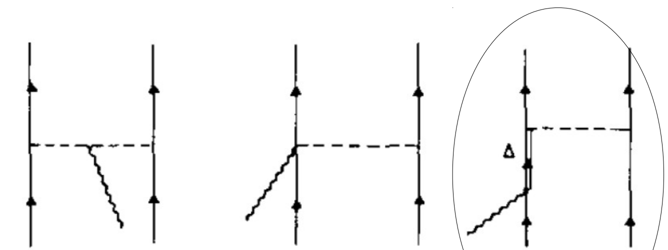




Nucleon-Nucleon correlations



Meson Exchange Currents (MEC)



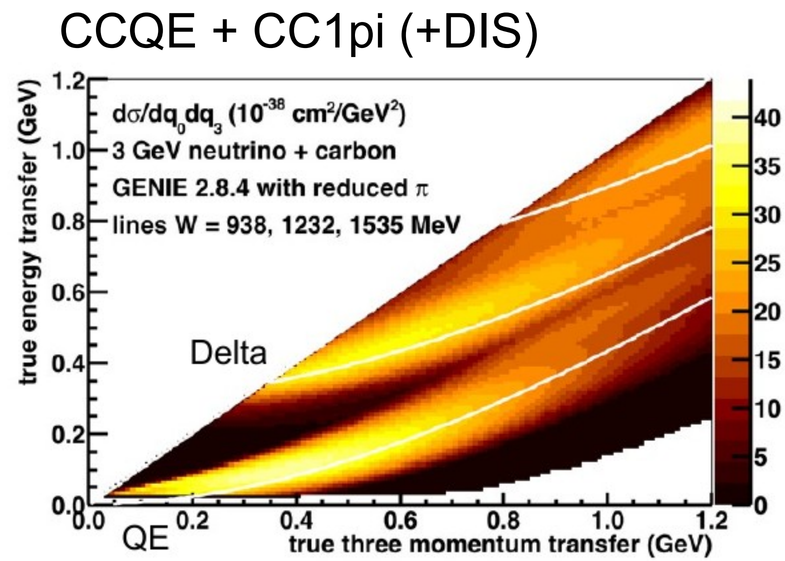
Pion in flight

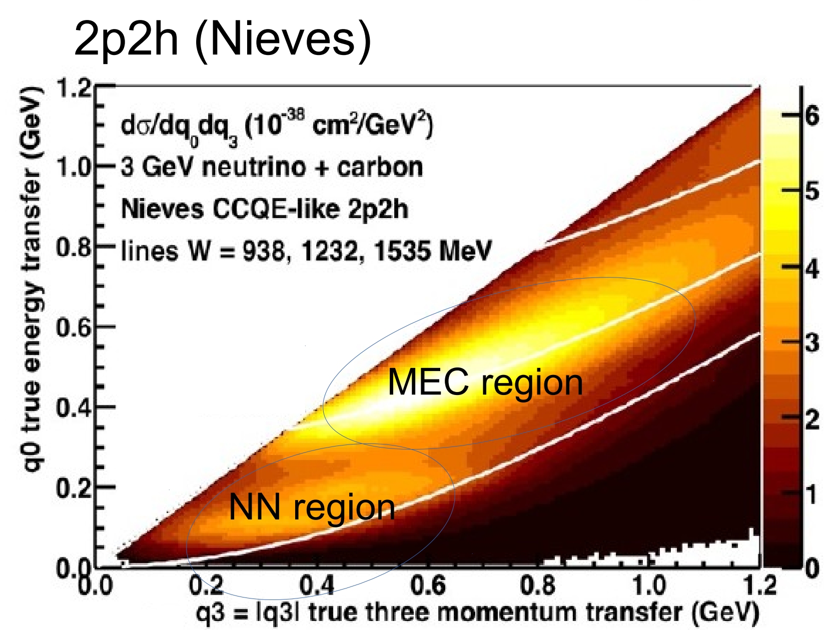
Contact

Delta

Dominant in MEC

+ interference





Experimentally difficult to disentangle: final state can be pn or pp with low energy protons