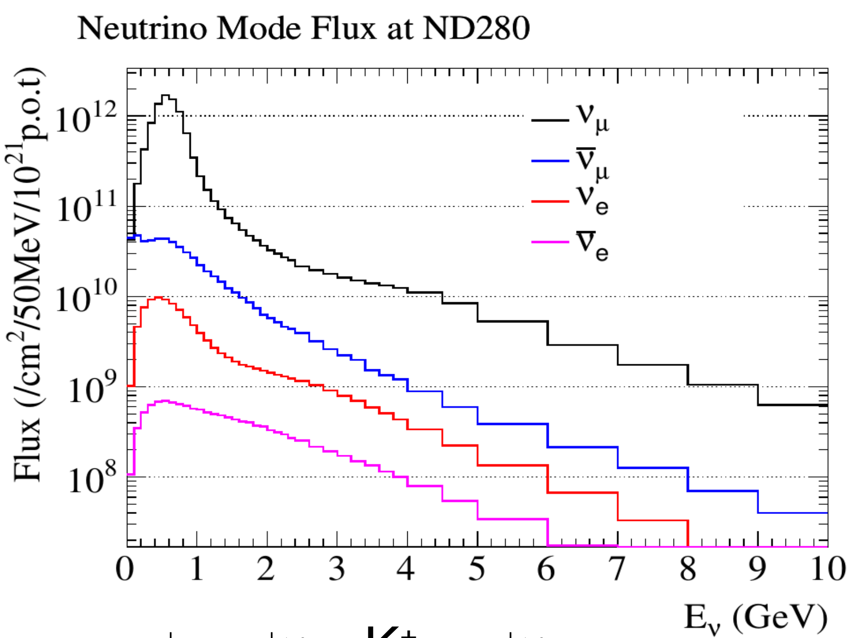
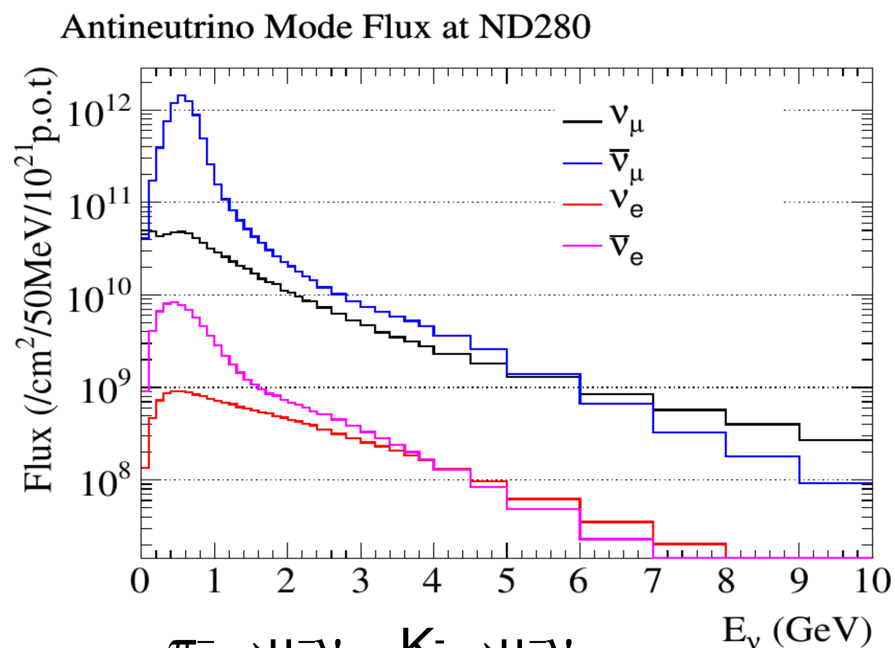
Question from yesterday (1)

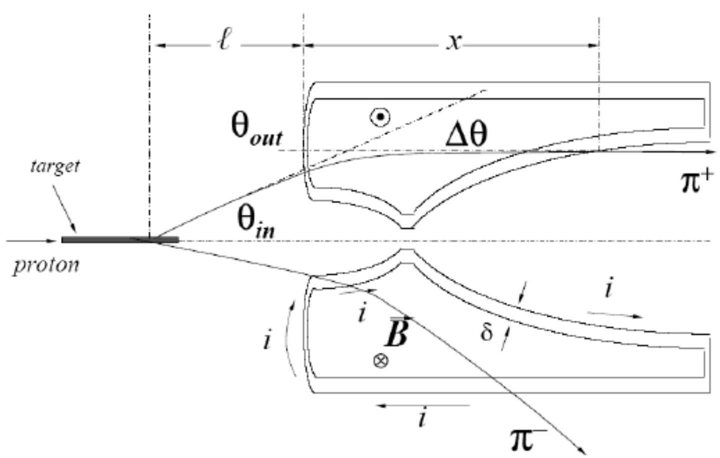


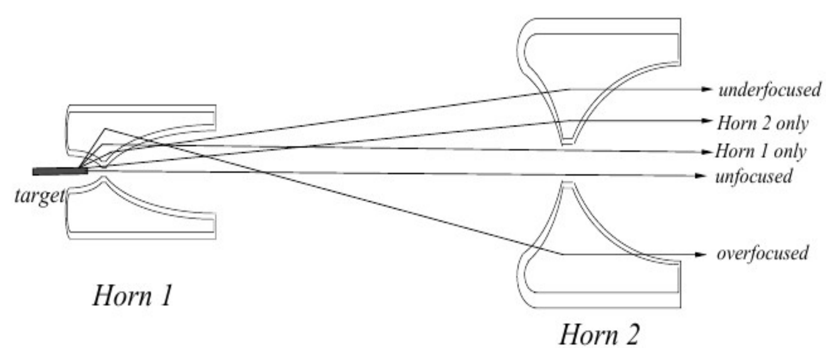
$\pi^+ \rightarrow \mu^+ \nu_\mu$ $K^+ \rightarrow \mu^+ \nu_\mu$



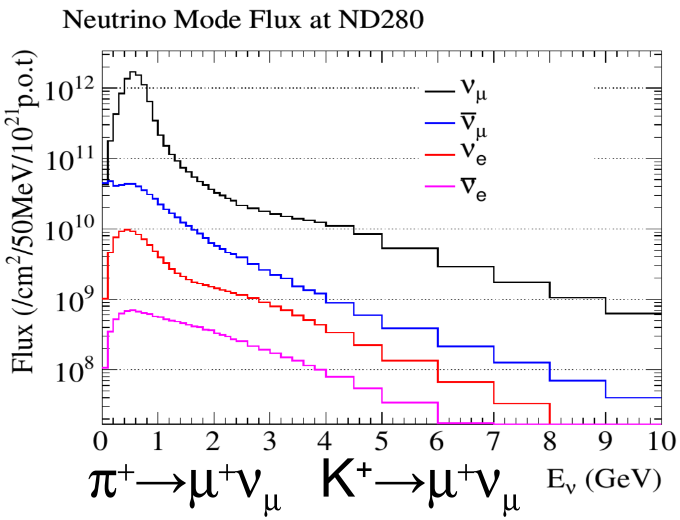
$\pi^- \rightarrow \mu^- \nu_\mu$ $K^- \rightarrow \mu^- \nu_\mu$

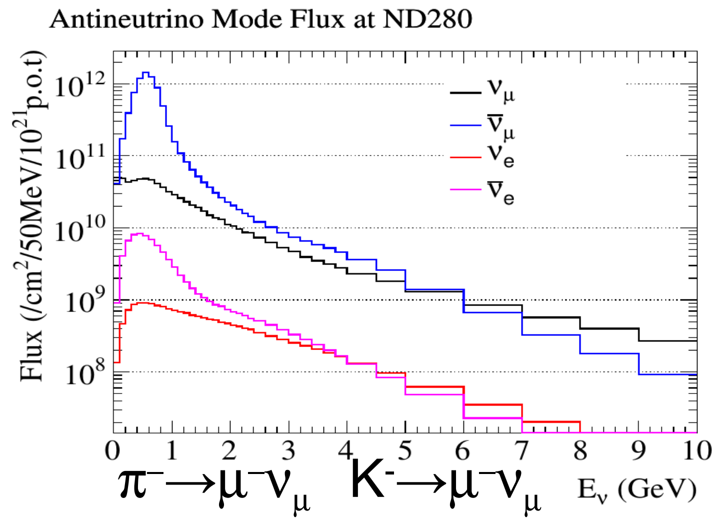
The 'wrong sign' background comes from high p_L pions (kaons) which cannot be defocused properly because they miss the horns



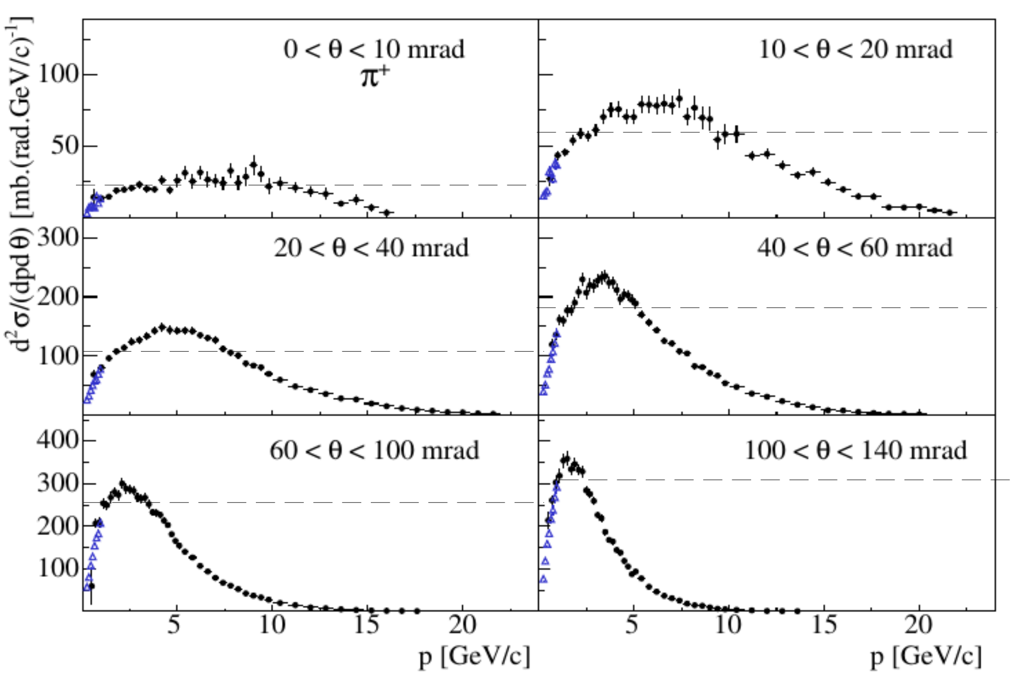


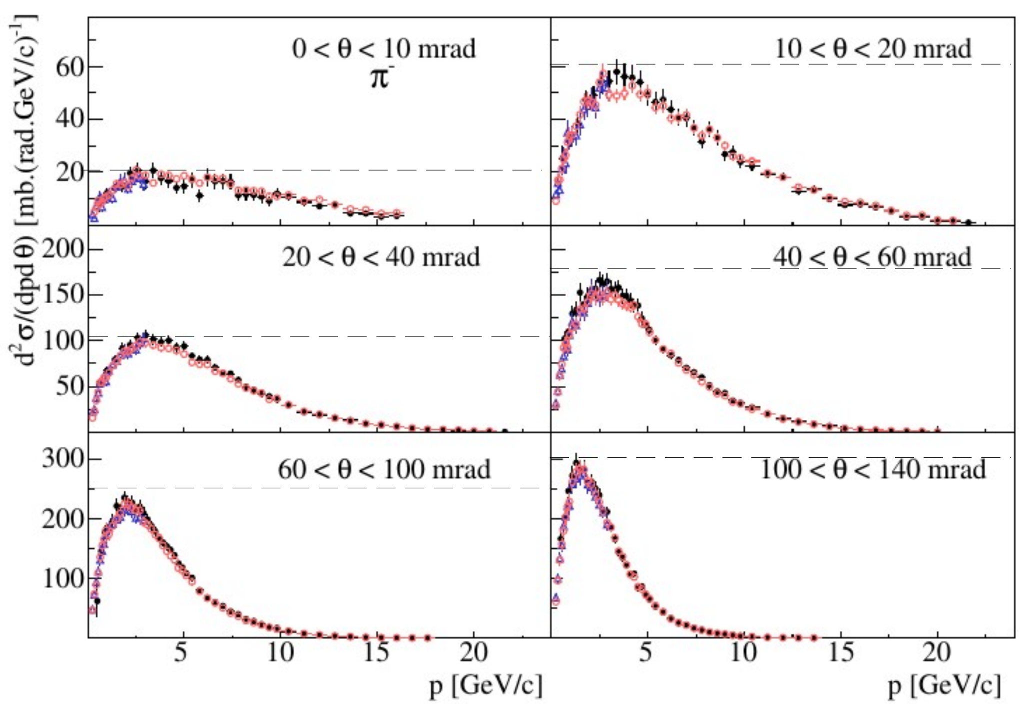
Question from yesterday (2)





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





Cross-sections and their importance for the oscillation analysis

- Most relevant processes at long baseline energies
- Uncertainties in modeling nuclear effects
- Their impact on the oscillation analysis

(This is fast developing area … we will touch problems which are still open and very important for next and far future of neutrino long baseline experiments!)

Reminder

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

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

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

TODAY

We need to constrain the flux

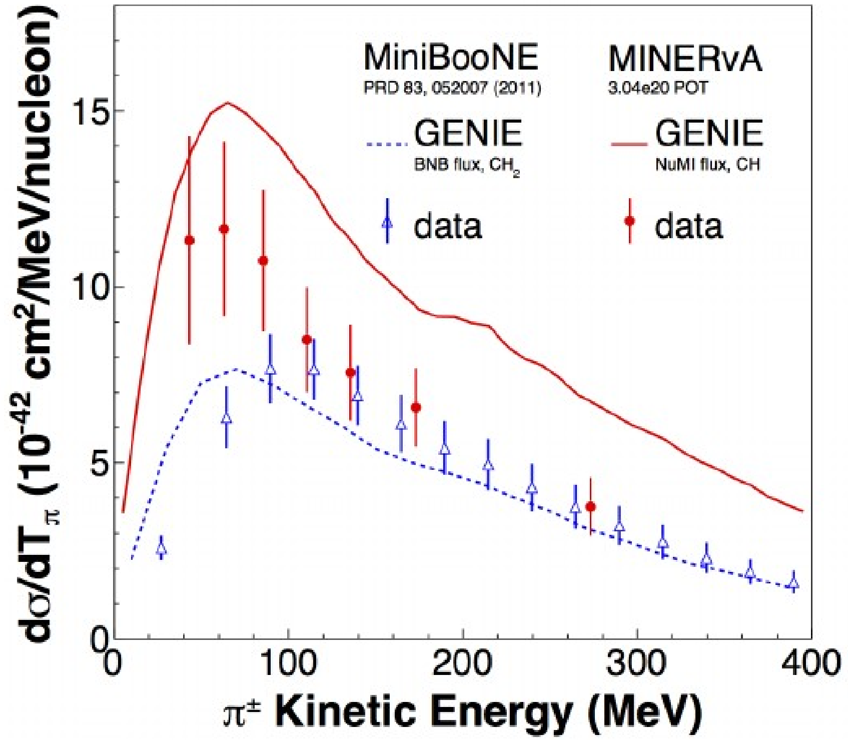
PREVIOUS LECTURE

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

TODAY

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:

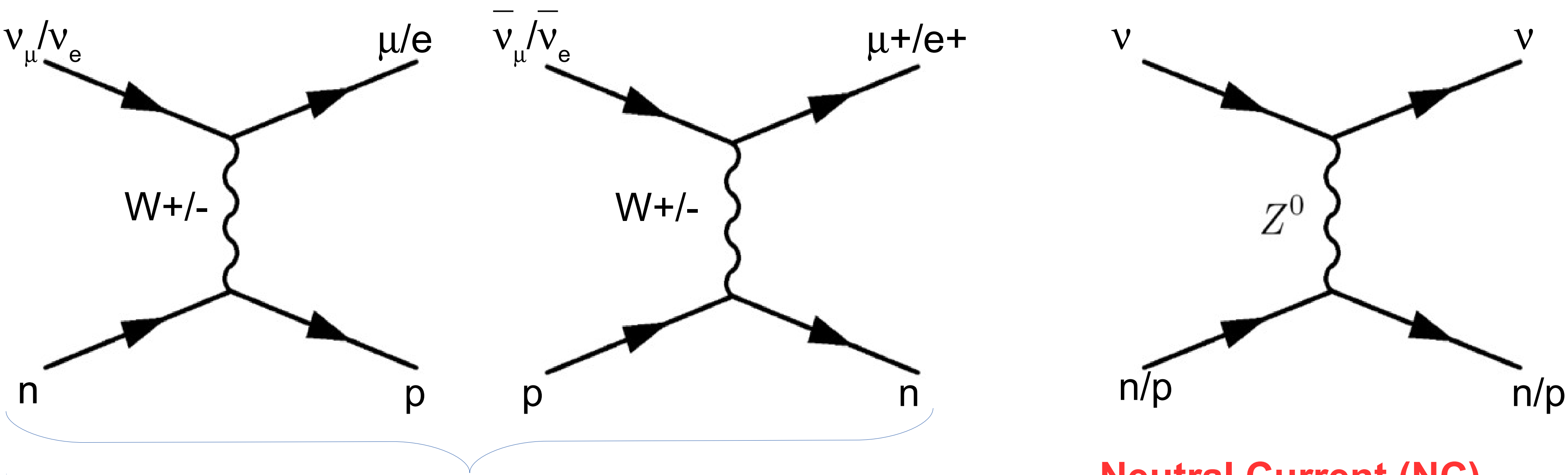
$$\sigma = \frac{\left(N^{data}_{selected} - B\right) \cdot 1/\epsilon}{\Phi \cdot N_{nucleons}}$$

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

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

Charged current and neutral current

Neutrino can interact with target nucleons in our detector materials with



Charged Current (CC) main signal:

- outgoing lepton well visible in the detector to tag interactions → allow to **identify the incoming neutrino flavour and 'charge'**
- full final state can be (in principle) reconstructed in the detector → allow to **estimate the incoming neutrino energy**

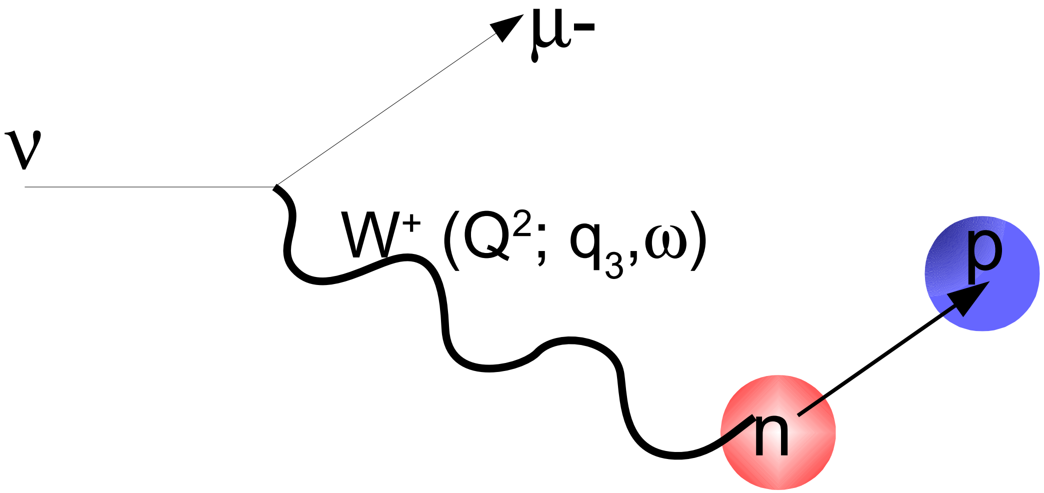
(in realistic detectors this actually relies on various approximations)

Neutral Current (NC) background

Sometimes the outgoing hadrons can be misidentified as lepton in the detector → background that need to be estimated and subtracted from data distributions

(I will discuss CC but everything can be 'easily' extended to NC)

The basic variables

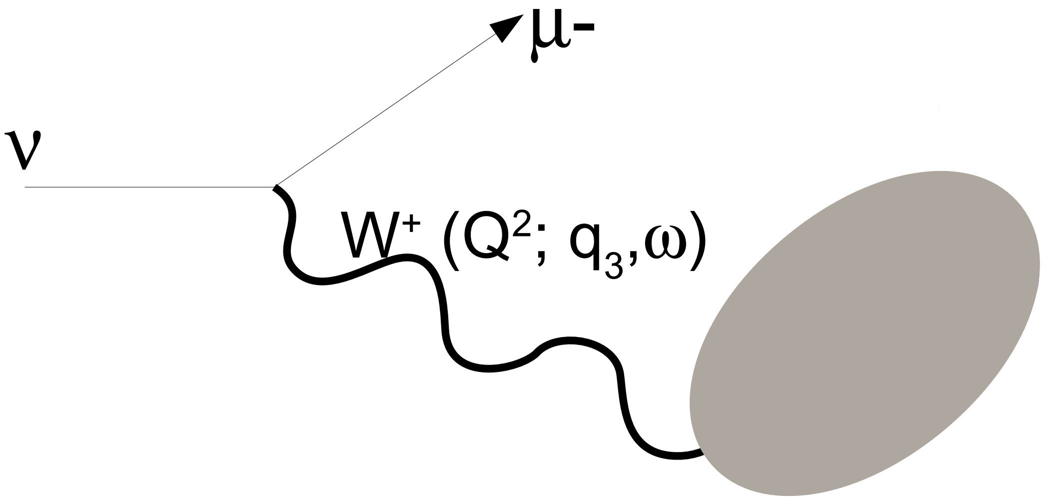


$q_3=\bar{p}_\nu-\bar{p}_\mu$

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

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

The basic variables



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

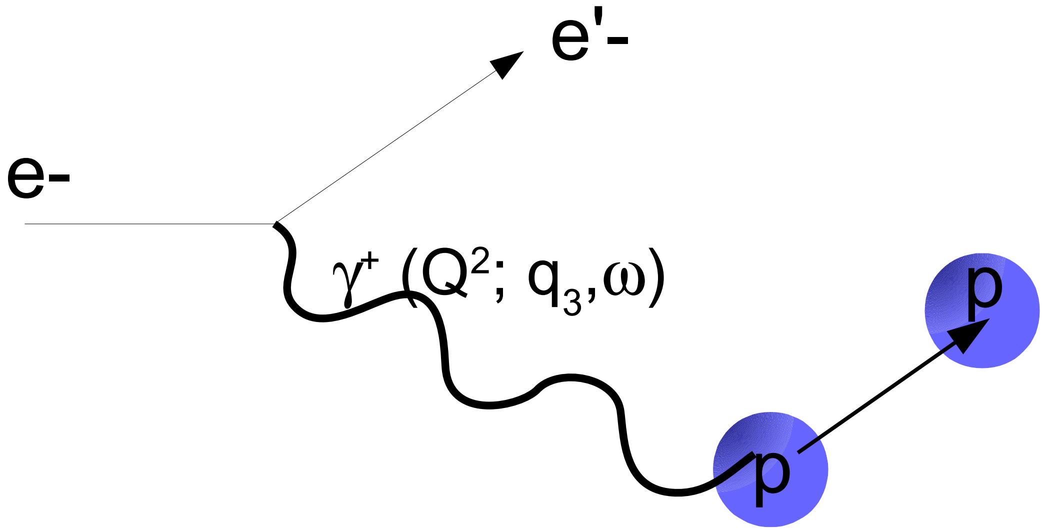
$\omega = E_\nu - E_\mu$

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

Only leptonic leg !

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

The basic variables: e^-p scattering



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

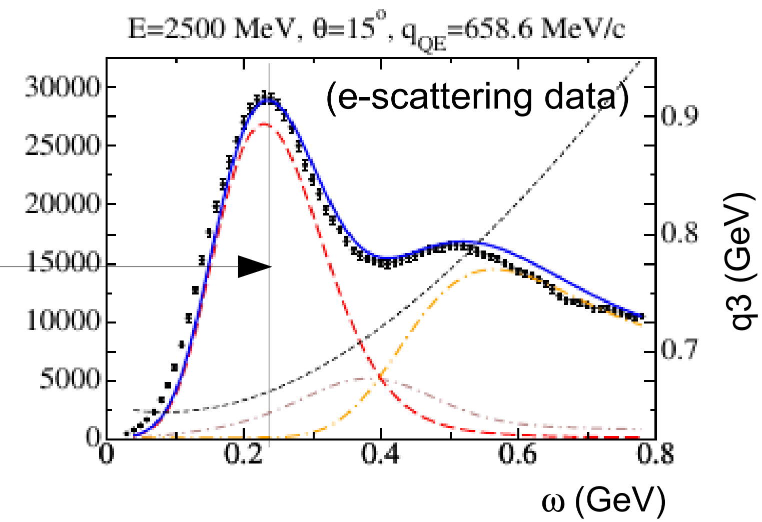
$\omega=E_e-E_{e'}$

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

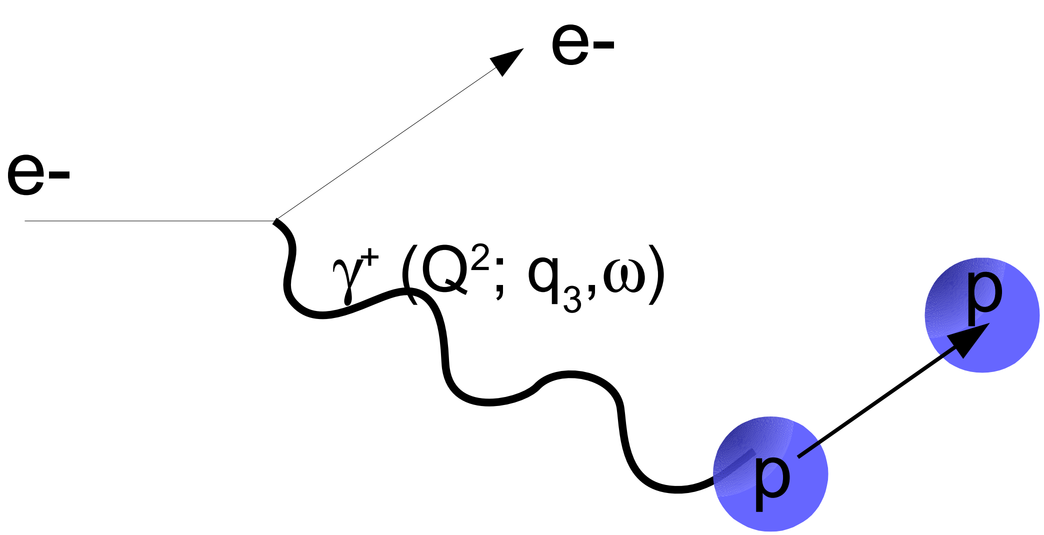
Only leptonic leg !

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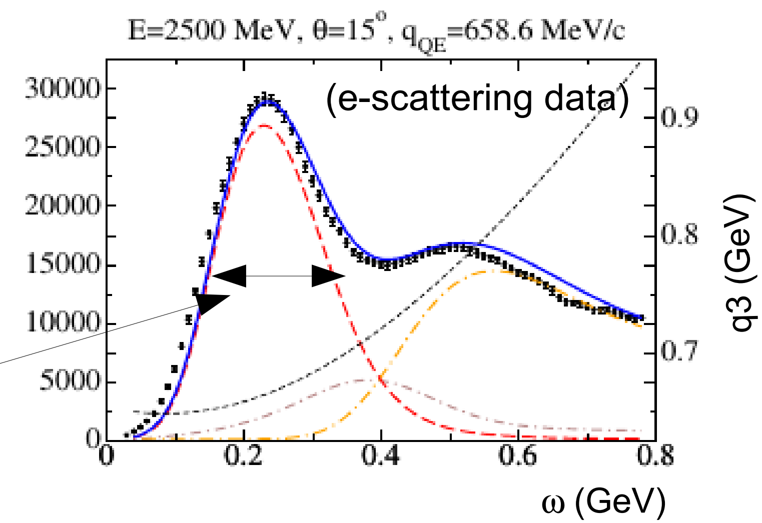
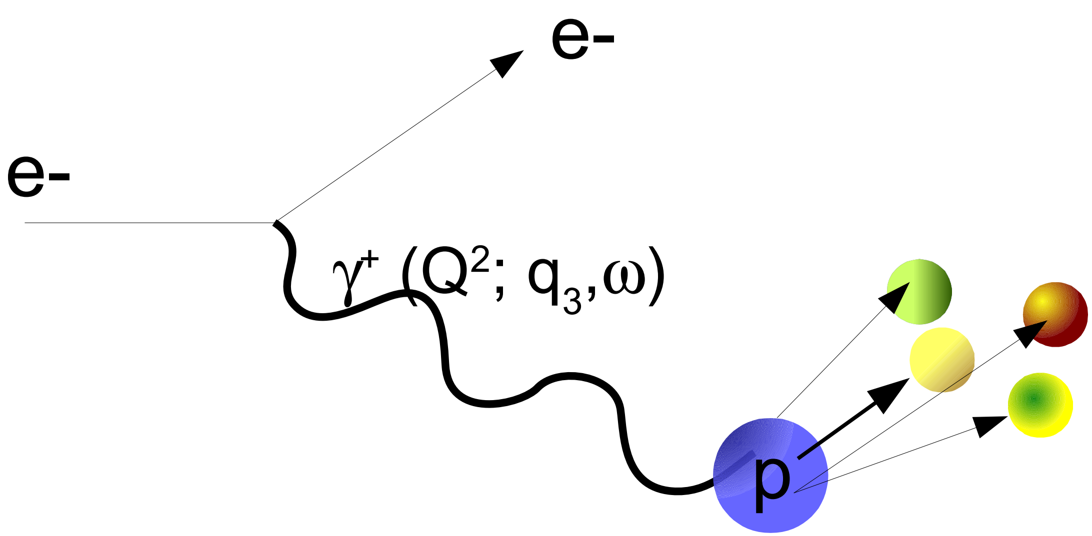
Cross-section can be parametrized as a function of E_e, q_3,ω

- Quasi-Elastic scattering on nucleon at rest

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



The basic variables: e^-p scattering



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

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

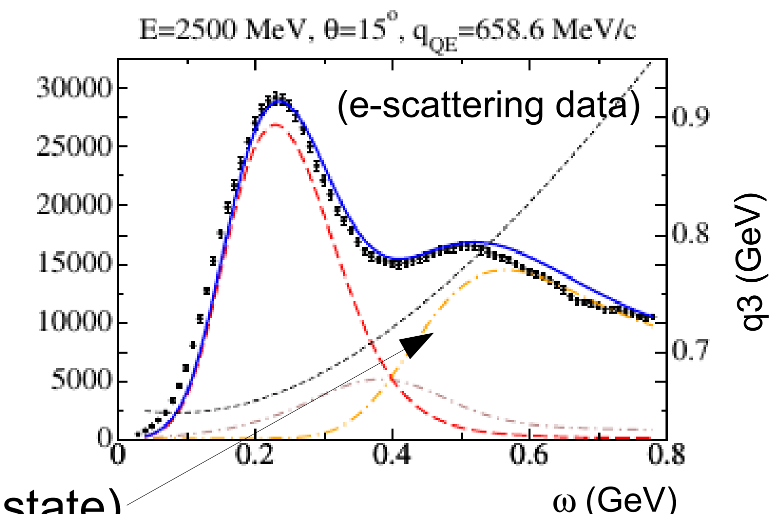
$Q^2 = (p_e-p_{e'})^2 \sim 2E_eE_{e'}(1-\cos\theta)$

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

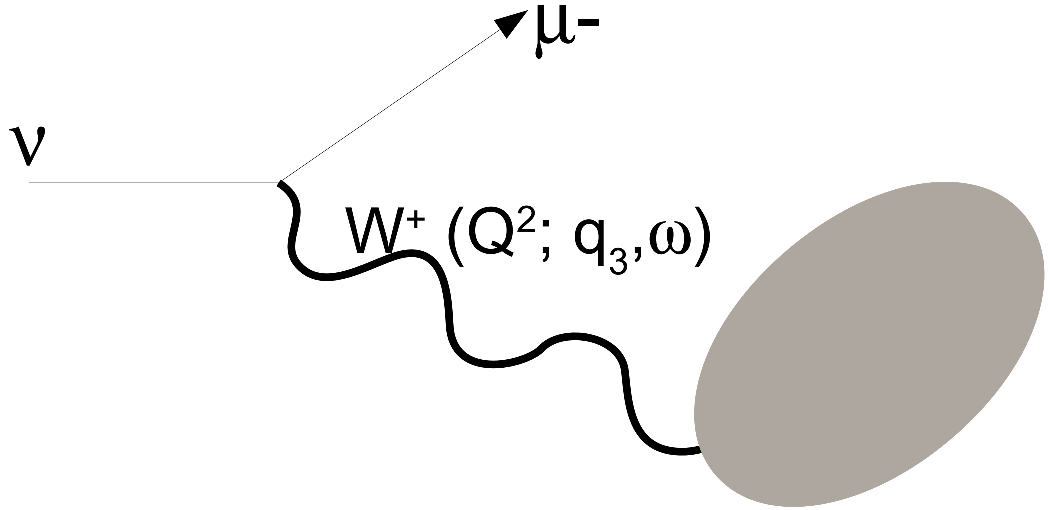
- QE scattering on nucleon at rest

- QE scattering: nuclear effects on initial state nucleon

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



Back to neutrinos...



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

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

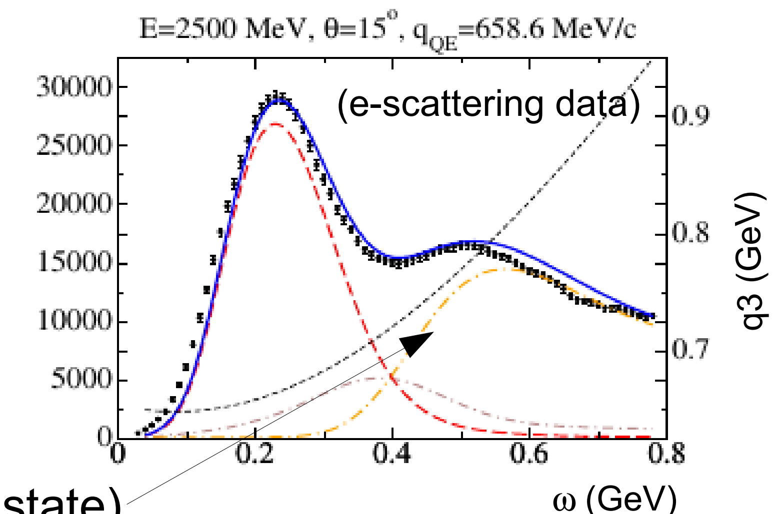
$Q^2 = (p_\nu-p_\mu)^2 \sim 2E_\mu E_\nu(1-\cos\theta)$

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

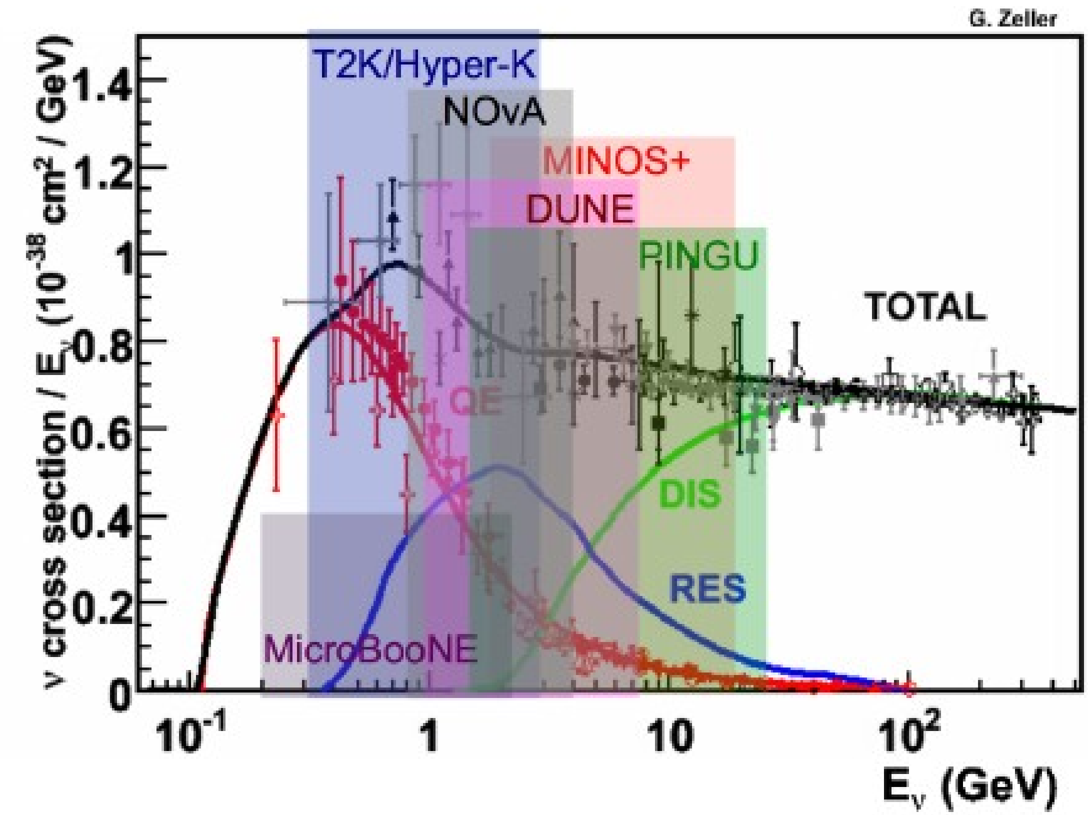
- non-QE event (multiple particle in the final state)



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

(need to look at the hadronic leg to get Eν: strongly affected by nuclear effects)

All the processes



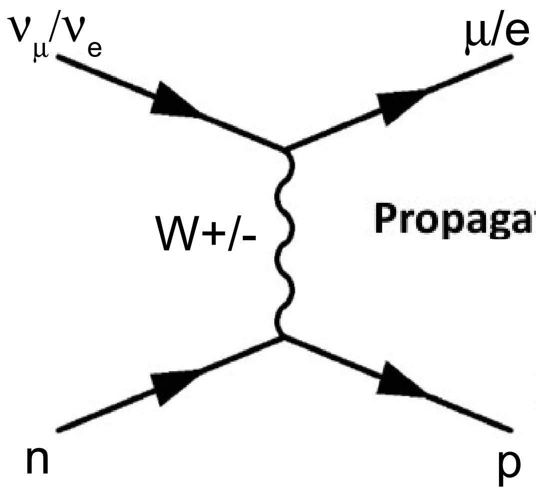
- **QE** = Quasi-Elastic
- **RES** = Pion production in the final state through excitation of the nucleon to a resonant state
- **DIS** (Deep Inelastic Scattering) = the nucleon is broken → probing the quark structure of the nucleons → shower of outgoing hadrons

Reminder: need to **measure/control the cross-section as a function of energy** for the oscillation measurement →
since the measured cross-section at the near detector need to be extrapolated to the far detector which has a different energy spectrum

→ **need to measure/constrain each process separately**

Charged-Current Quasi-Elastic (CCQE)

- **Amplitude ~ leptonic current x propagator x hadronic current**



Leptonic current $J_\mu = \bar{\nu}_l\, \gamma_\mu (1-\gamma_5)\, l = \bar{\nu}_l\, \gamma_\mu\, l - \bar{\nu}_l\, \gamma_\mu \gamma_5\, l$

Propagator $\approx \frac{1}{Q^2 - M_W^2}\,, \quad Q^2 \ll M_W^2$

Where Q^2 is the transferred 4-momentum
$Q^2 = (p_l - p_\nu)^2$

Hadronic current

$$J^\mu = \bar{u}_N \left[\gamma^\mu F_1(Q^2) + \frac{i}{2M_N} \sigma^{\mu\nu} q_\nu F_2(Q^2) + \gamma^\mu \gamma_5 F_A(Q^2) + \frac{1}{2M_N} q^\mu \gamma_5 F_P(Q^2) \right] u_N$$

- **Cross-section ~ Amplitude² x phase pace**

$$\frac{d\sigma}{dQ^2}\left({}^{\nu n \to l^- p}_{\bar{\nu} p \to l^+ n}\right) = \left[A(Q^2) \mp B(Q^2) \frac{s-u}{M^2} + C(Q^2) \frac{(s-u)^2}{M^4} \right] \times \frac{M^2 G_F^2 \cos^2\theta_c}{8\pi E_\nu^2}$$

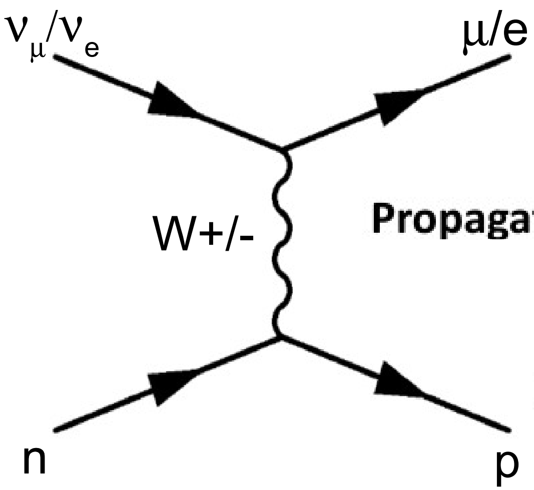
- $s\text{-}u = 4ME_\nu - Q^2 - m^2$
- A, B, C depend on Q^2, M, m and the form factors (M = nucleon mass; m = lepton mass)

C.H. Llewellyn Smith, Phys. Rep. 3C, 261 (1972)

The only unknown are the form factors!

Charged-Current Quasi-Elastic (CCQE)

- **Amplitude ~ leptonic current x propagator x hadronic current**



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- $s\text{-}u = 4ME_\nu - Q^2 - m^2$
- *A,B,C* depend on Q^2, *M*, *m* and the form factors (*M* = nucleon mass; *m* = lepton mass)

C.H. Llewellyn Smith, Phys. Rep. 3C, 261 (1972)

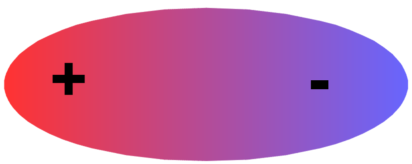
Also present in electron scattering!
(note F_P suppressed by m/M)

The only unknown are the from factors!

Tuning from bubble chamber data

Form factors are ***effective parametrization***s which describe how the nucleon 'reacts' to a W (or γ) probe (can be interpreted as the distribution of the electroweak charge in the nucleus)

The most simple distribution of charge you can think of is a **dipole:**

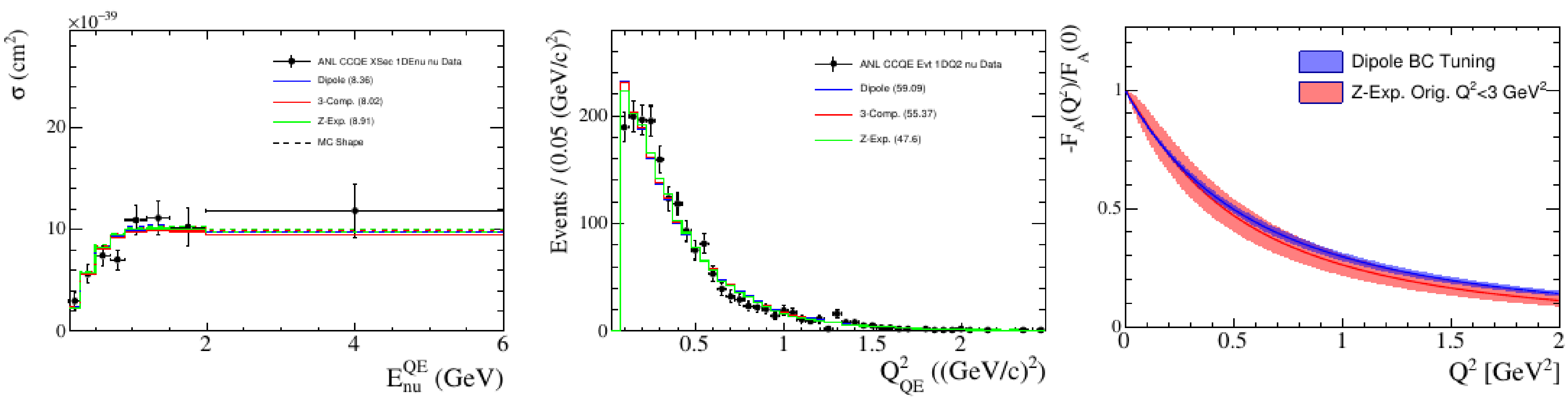


$$F_A(Q^2) = \frac{g_A}{(1 + Q^2/M_A^{QE\,2})^2}$$

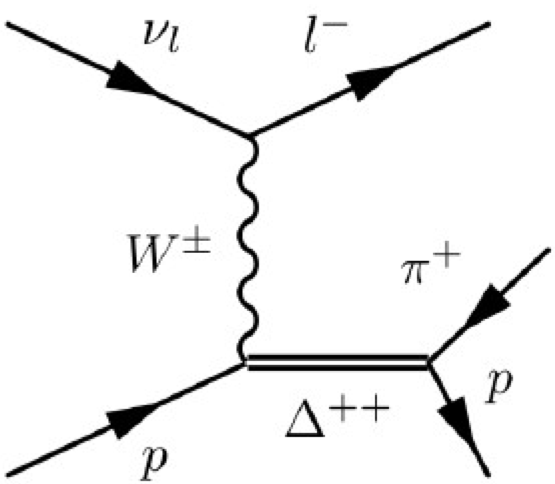
- g_A constrained from neutron β decay : $n \rightarrow \bar{\nu}_e\, p\, e^-$
- M_A^{QE} constrained from scattering of neutrino on deuterium H_2 (bubble chamber experiments from 70's)

Problem! **There are other (better?) parametrizations** which describes bubble chamber data well and give different residual uncertainties

Example from ANL data



Single pion production (RES)

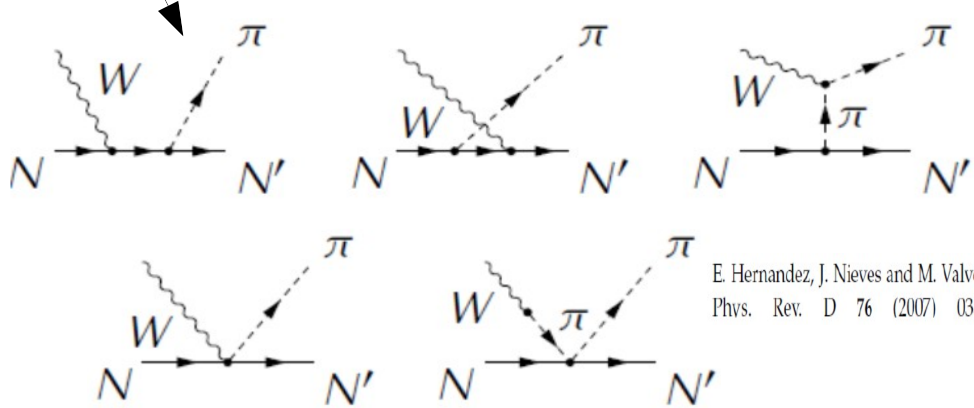


Pion production through excitation of the nucleon to a resonant state

$$\nu_l + p \rightarrow l^- + \pi^+ + p$$
$$\nu_l + n \rightarrow l^- + \pi^+ + n$$
$$\nu_l + n \rightarrow l^- + \pi^0 + p$$

(and corresponding ones for antineutrinos)

The Δ is only one of the possible resonances + continuum + interferences between them



E. Hernandez, J. Nieves and M. Valverde, Phys. Rev. D 76 (2007) 033005

Resonance	M_R	Γ_0	χ_E
$P_{33}(1232)$	1232	117	1
$P_{11}(1440)$	1430	350	0.65
$D_{13}(1520)$	1515	115	0.60
$S_{11}(1535)$	1535	150	0.45
$P_{33}(1600)$	1600	320	0.18
$S_{31}(1620)$	1630	140	0.25
$S_{11}(1650)$	1655	140	0.70
$D_{15}(1675)$	1675	150	0.40
$F_{15}(1680)$	1685	130	0.67
$D_{13}(1700)$	1700	150	0.12
$D_{33}(1700)$	1700	300	0.15
$P_{11}(1710)$	1710	100	0.12
$P_{13}(1720)$	1720	250	0.11
$F_{35}(1905)$	1880	330	0.12
$P_{31}(1910)$	1890	280	0.22
$P_{33}(1920)$	1920	260	0.12
$F_{37}(1950)$	1930	285	0.40

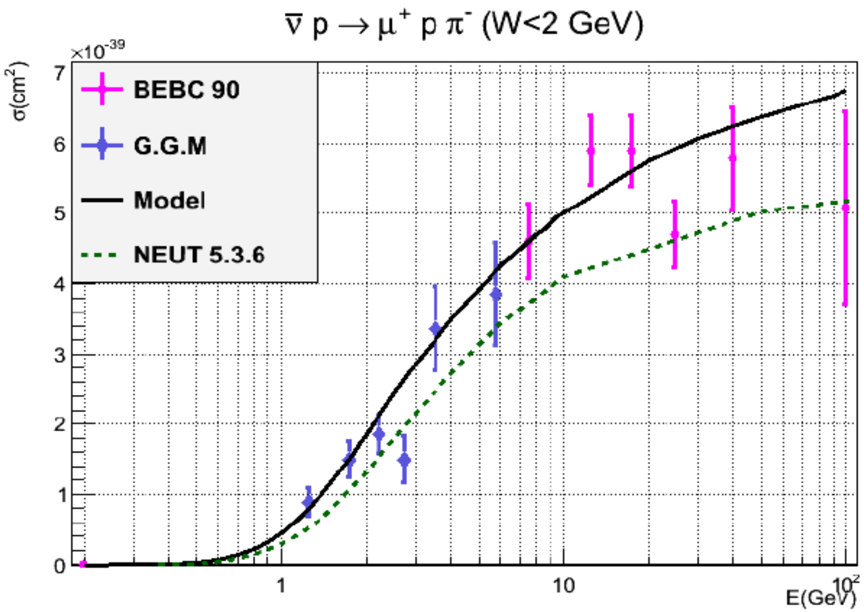
D. Rein, Z.Phys. C – Particles and Fields 35,43-64 (1987)[4]

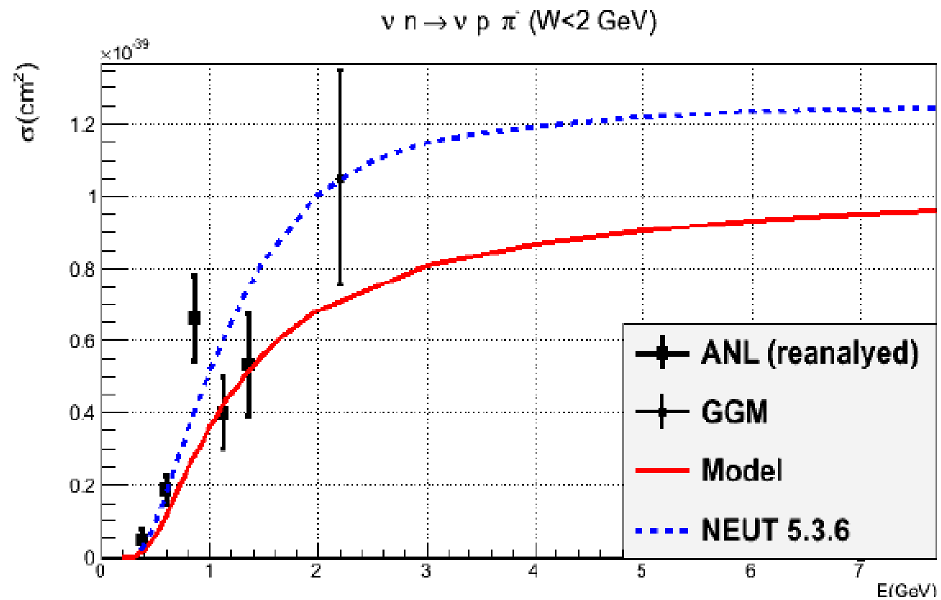
1. D. Rein and L. M. Sehgal, Annals Phys. 133 (1981) 79.[5]
2. K. M. Graczyk and J. T. Sobczyk, Phys. Rev. D 77 (2008) 053001.

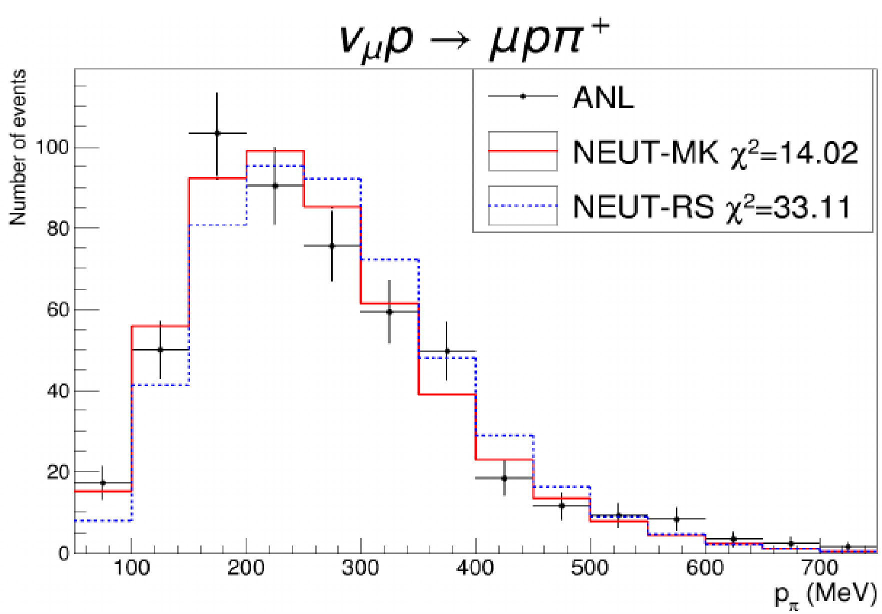
(Full computation is being implemented in the MC)

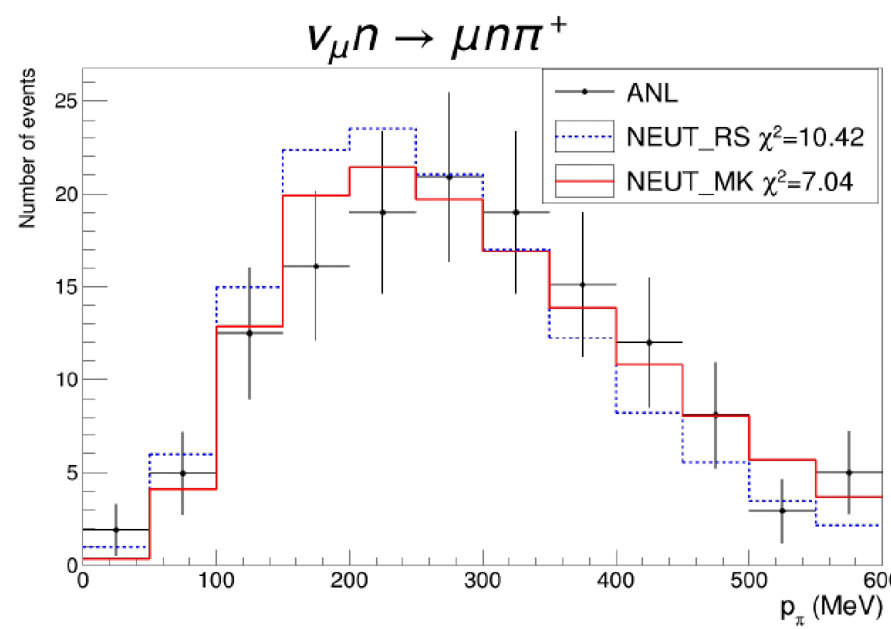
Tuning to bubble chamber data

Impact of 'beyond Δ' on the neutrino cross-section on single nucleus
(I'm showing here the channel were the impact is larger)









Multi-pion and Deep Inelastic Scattering (DIS)

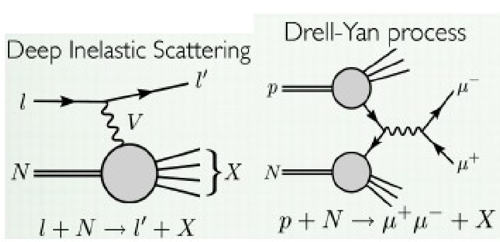
- Multiple pion can be produced **through resonances (as single pion)**
- At **higher neutrino energy the quark structure of the nucleon get exposed** → completely different model

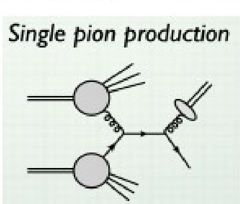
$$\sigma_N(Q^2) \sim \sum_q \int dx\, f(x, Q^2)\, \sigma_q(x, Q^2)$$

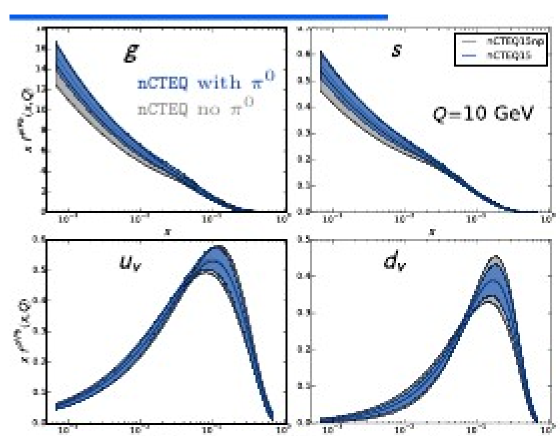
at high energy the hard scattering part is actually the easiest part (perturbative physics)

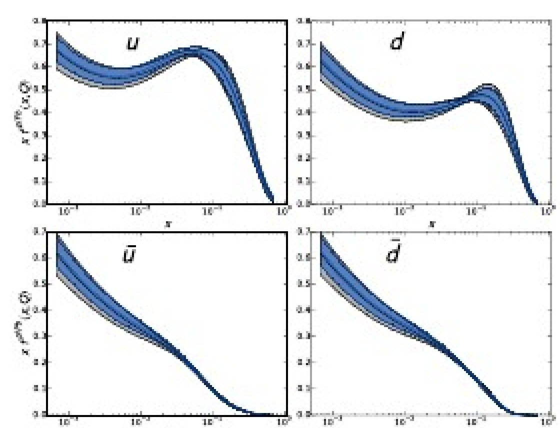
Parton Density Function: probability to find a quark with momentum $p_q = x^* p_N$ inside the nucleon

Such formula assumes factorization between 'low' and high energy (true only for $Q^2 \gg m_p^2$) and assures universality (same PDF indipendently from the probe)
→ can be extracted using multiple sets of data





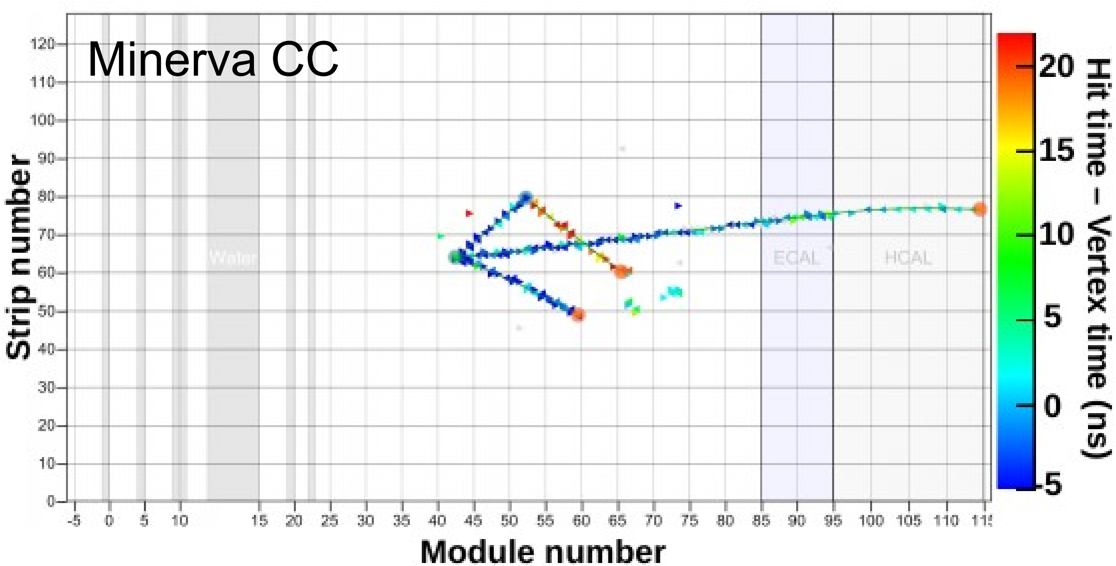


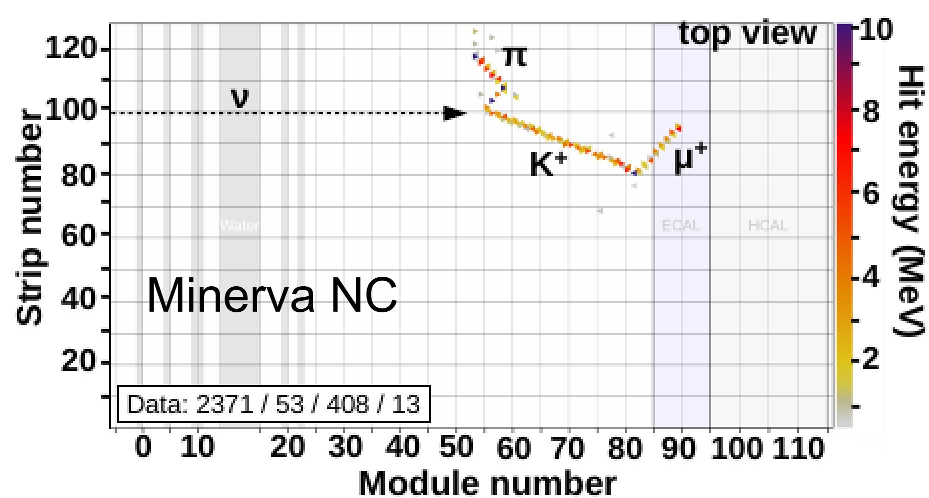


Kaon production

- **Background to proton decay search** (p → K+ν) and useful to tune FSI
- Same resonance + DIS production mechanism as pions but strange hadron
  → at low energy Cabibbo suppressed (Δs=1), above 2 GeV created together with -1 strange hadrons (Λ, Σ)

→ delayed (12.4 ns lifetime) decay at rest $K^+ \to \mu^+ \nu$





Nuclear effects!!!

OK... I cheated again!

The situation in neutrino long baseline experiments is much more complicated: the neutrino doesn't interact with free nucleons but with nucleons bounded in (relatively) heavy nucleus like Carbon, Oxygen, Argon, Iron...

The nuclear effects change the cross-section:
they change the rate, the kinematics of the outgoing particles (i.e. the shape of the differential xsec) and even which particles are in the final state!

- **Initial state effects:** nucleons bound in the nucleus
- **Final state effects:** the particles produced in the interactions need to 'pass through' the nuclear matter to exit from the nucleus
- Brand **new interactions processes** which are not present for free nucleons

Basic approximations

- **Impulse Approximation**

  the interaction is considered on each nucleon separately (and the total amplitude is summed up over all the nucleons)

$$\sum_{nucleons} \langle \psi(x) | O | \psi'(x) \rangle$$

initial state → $\psi(x)$; interaction → O; final state → $\psi'(x)$

- **Plane Wave Approximation**

  plane wave (same as for free nucleons) are used to describe the initial and final state

The nuclear effects are considered by

- giving a **certain momentum to the initial nucleons** and considering that **a certain energy (binding energy) is necessary to extract the nucleon** from the nuclear potential
- the **final state effects** are implemented with semi-classical Monte Carlo technique (described later)

- Few models (SuSa, GIBUU, Ghent...) use modified wave function for the initial and/or final state which already incorporate (at least part) of the nuclear effects on the nucleon

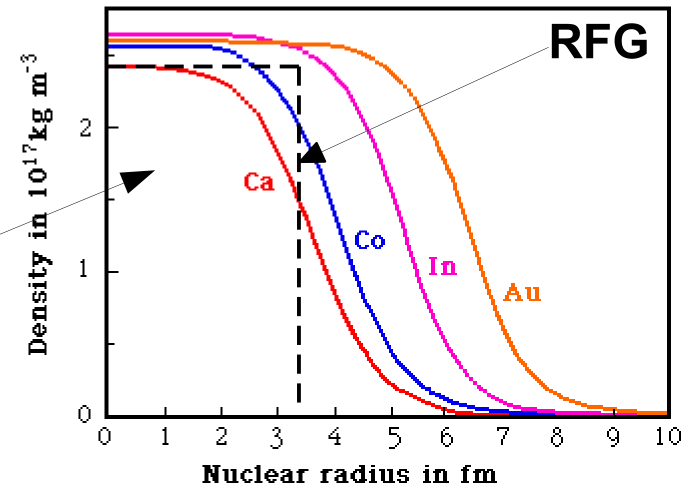
(I will not describe those here)

Initial state: bounded nucleons

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

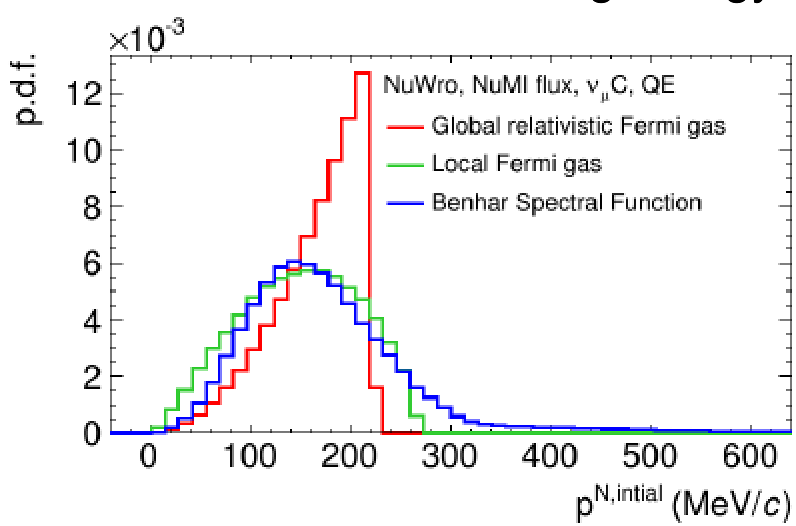


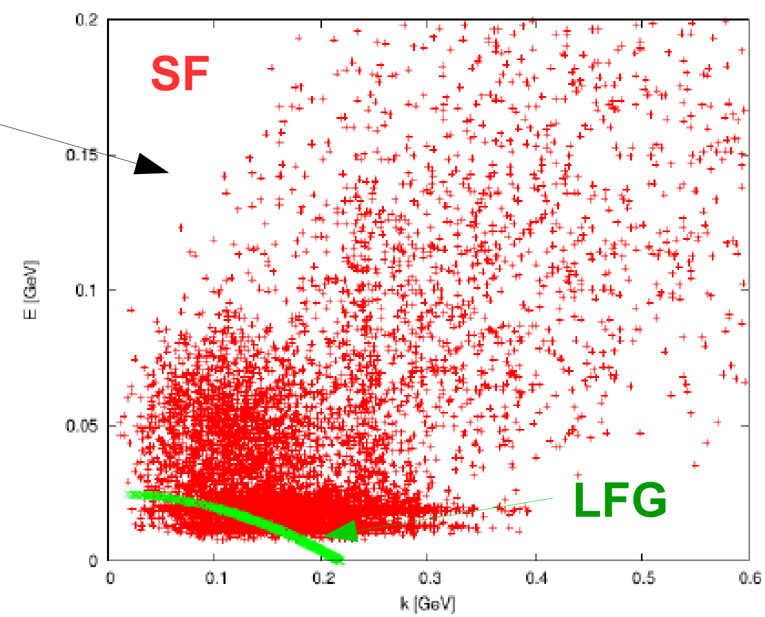
Local Fermi Gas (LFG)

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

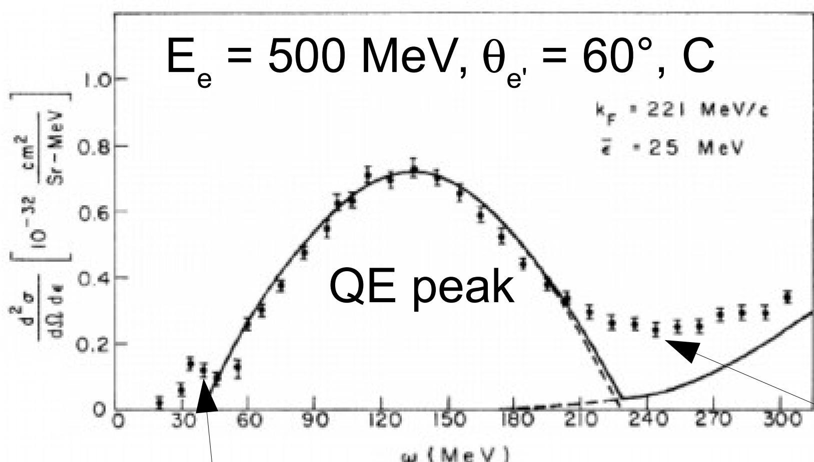




Tuning to electron scattering data

Yes, it is pretty clear that RFG is a very crude model, still is the most used in MC → but we don't use it blindly, we tune to electron scattering data (and to ND data!)

- RFG has 2 parameters: maximum momentum of the nucleons **(Fermi momentum kF)** and **binding energy** (= the energy needed to extract the nucleon from the nucleus). These can be tuned to e-scattering data:



xsec vs ω = the energy trasferred to the nucleus ($E_{e'}$-E_e)

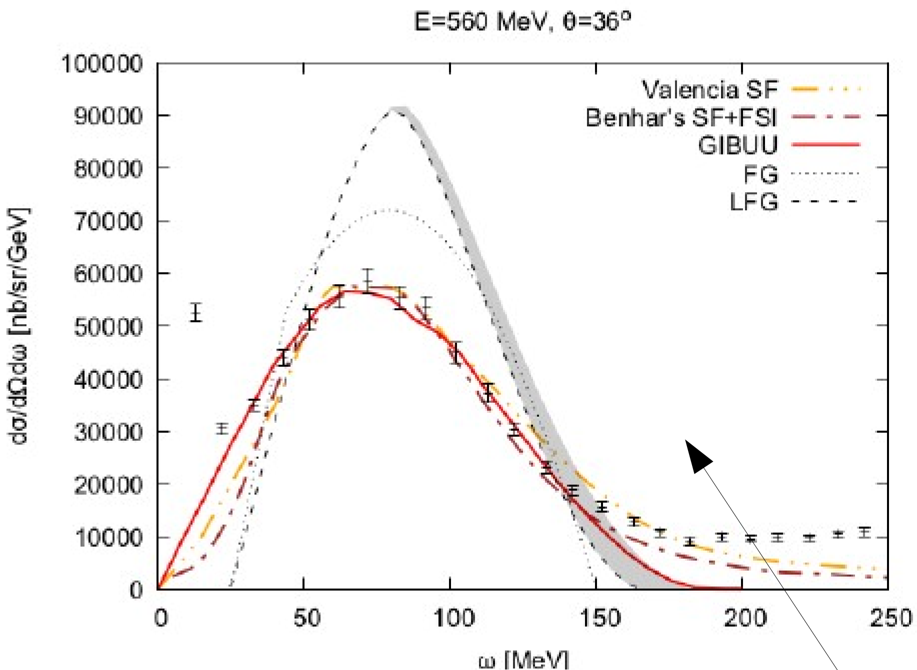
- position of the peak depends on binding energy
- width and height of the peak depends on k_F

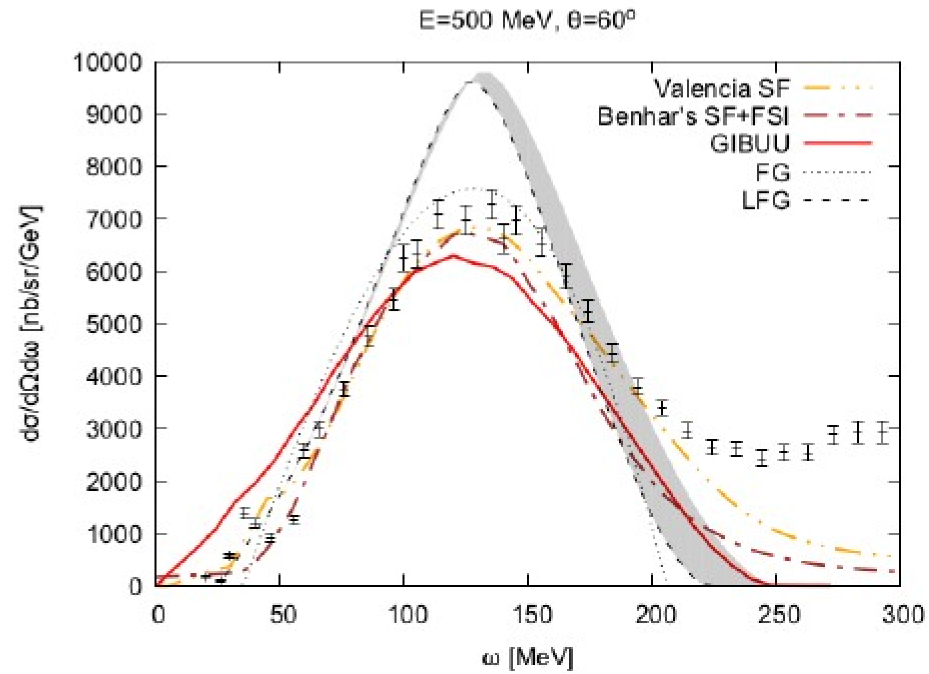
- But the best parameters values depend partially on non-QE processes which are present in data: low w nuclear resonances and high-w inelastic (2p2h)

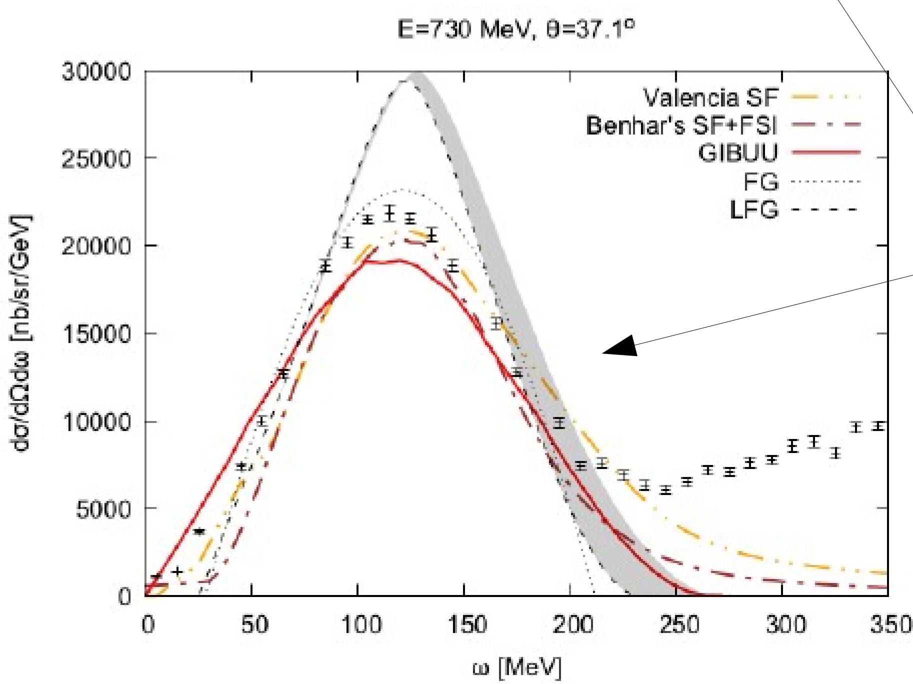
In general even after such tuning, is difficult to describe the electron data well for all E_e, scattering angles ($\theta_{e'}$) and targets … **this is a very approximated approach**

arXiv:1706.06739

A recent example...







Spectral function approach better describes electron scattering data

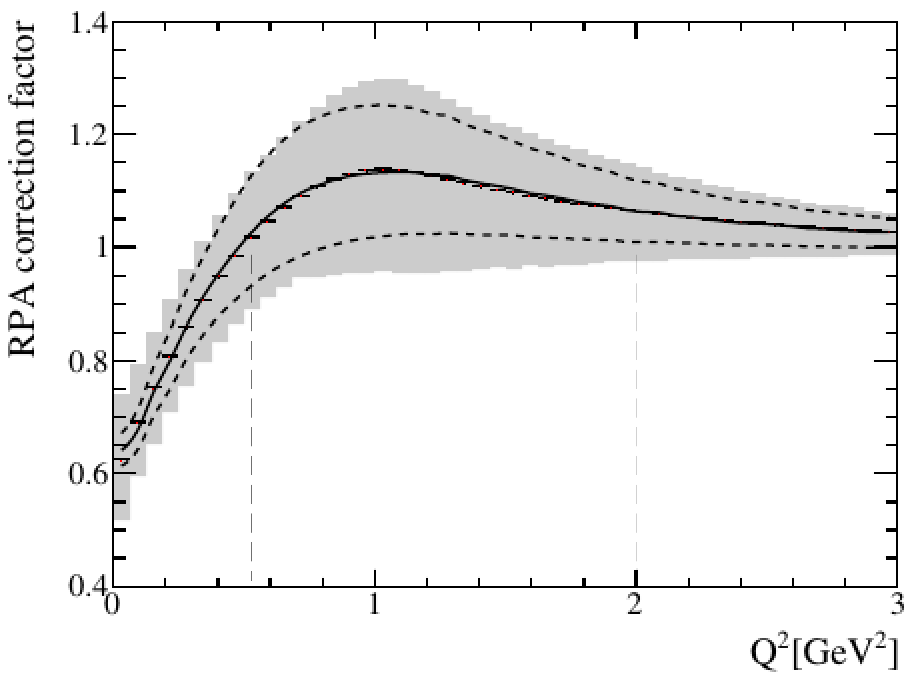
Plots at fixed E_e and $\theta_{e'}$ have different level of data-model agreement

The Fermi gas used in MC by the experiments are further tuned to try to improve the agreement
(e.g. suppression of xsec with RPA)

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



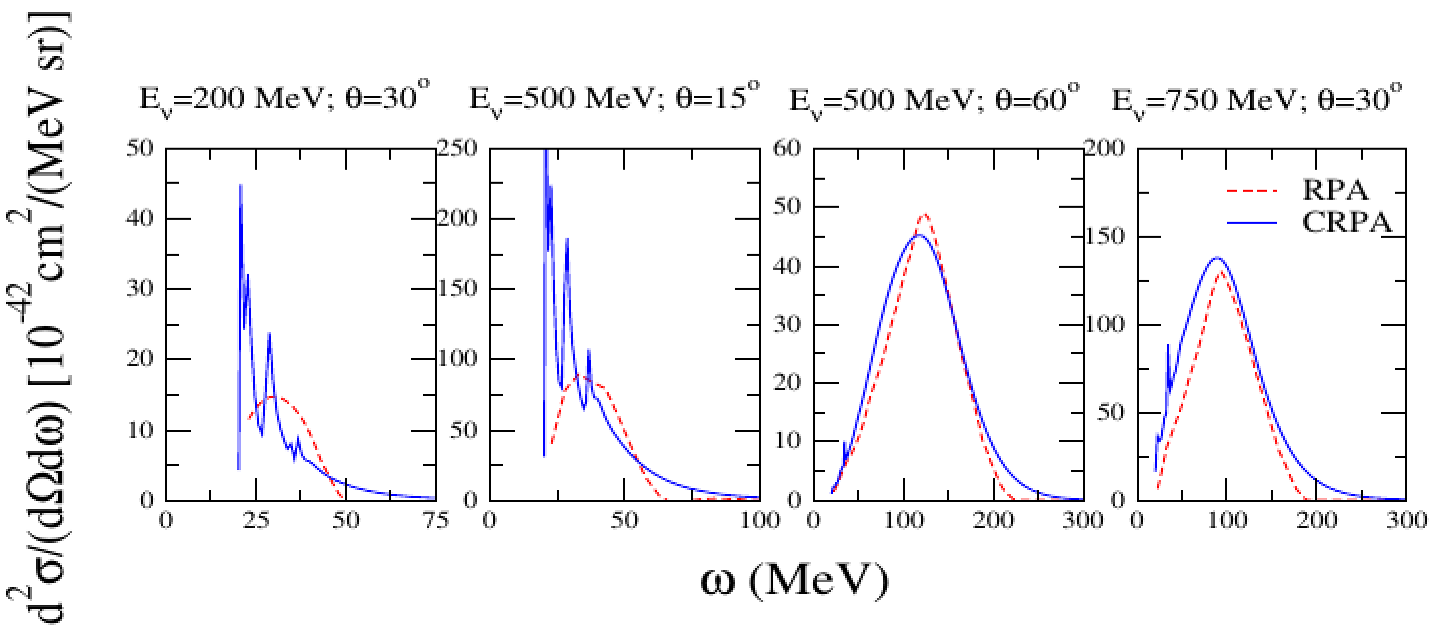
- **Q^2<0.5 GeV^2 screening:**
  nucleons embedded in nuclear potential

- **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



Nuclear effects in the DIS region

PDF are modified if the nucleon is bounded: the nuclear effects can be different for neutrino scattering (axial term in the interaction, ...)

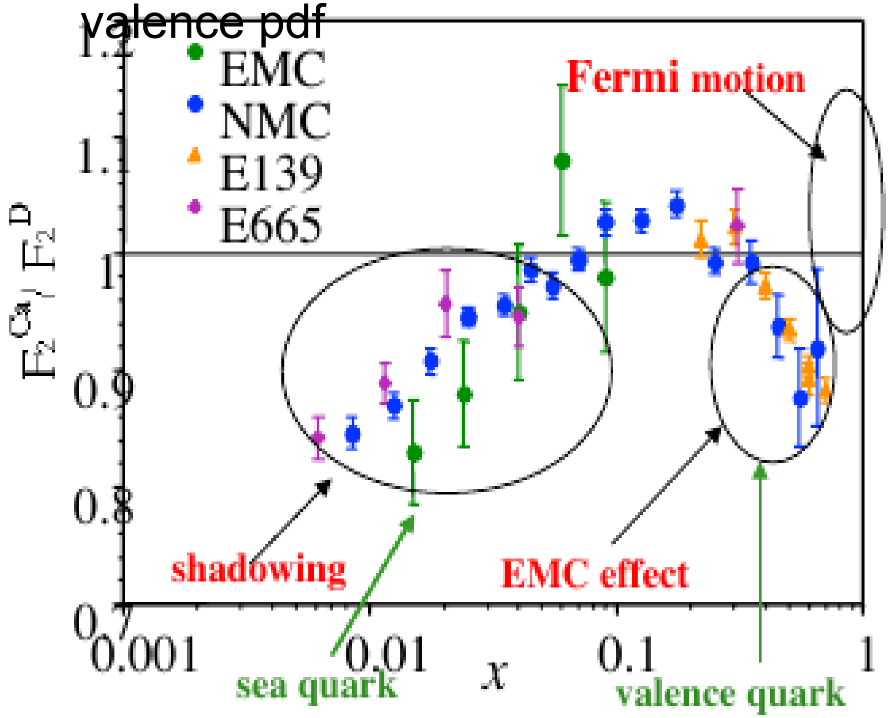
- **Multiplicative nuclear correction factors**

$$f_i^{p/A}(x_N, \mu_0) = R_i(x_N, \mu_0, A)\ f_i^{free\ proton}(x_N, \mu_0)$$

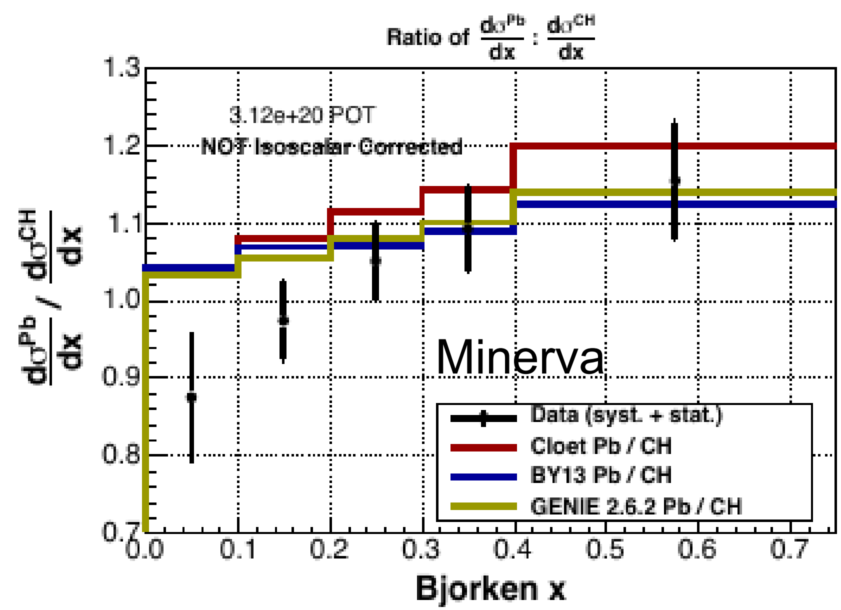
- **Native nuclear PDFs**

$$f_i^{p/A}(x_N, \mu_0) = f_i(x_N, A, \mu_0)$$
$$f_i(x_N, A=1, \mu_0) \equiv f_i^{free\ proton}(x_N, \mu_0)$$

- F_2 structure function= combination of u,d valence pdf



- Data on very heavy targets not well described by the models

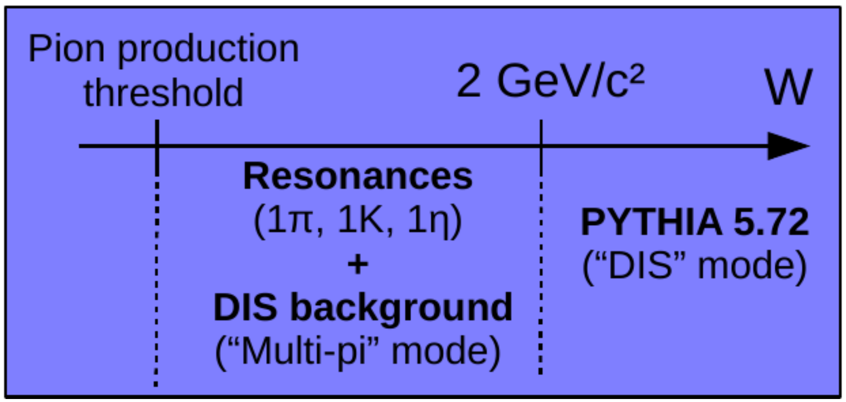


Physics interpretation of these effects is still very much open!

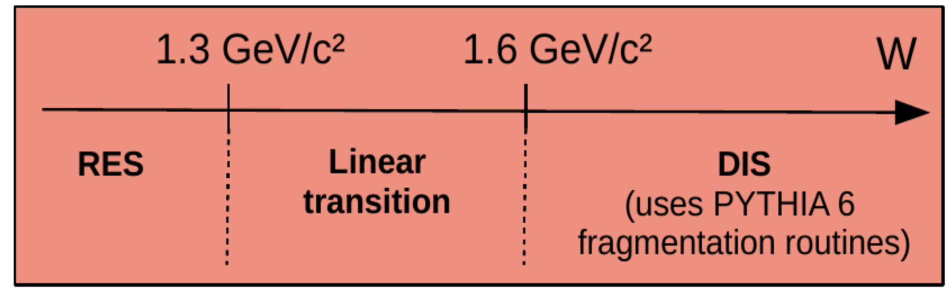
MC implementation: SIS and DIS

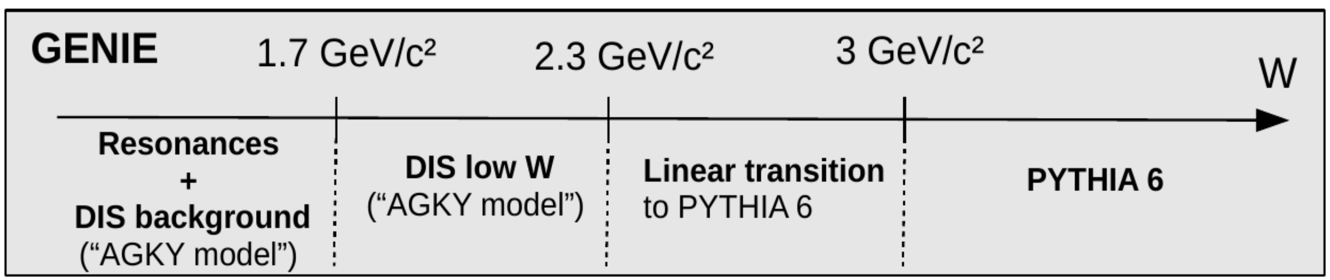
C.Bronner (NuINT 2015)

NEUT



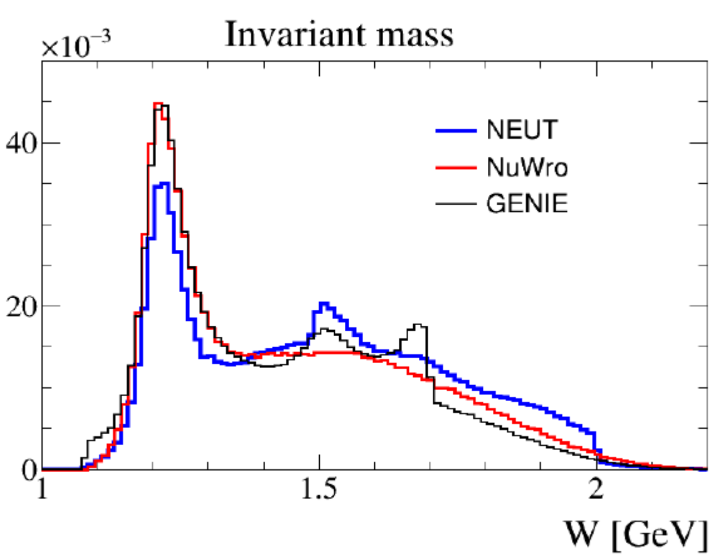
NuWro

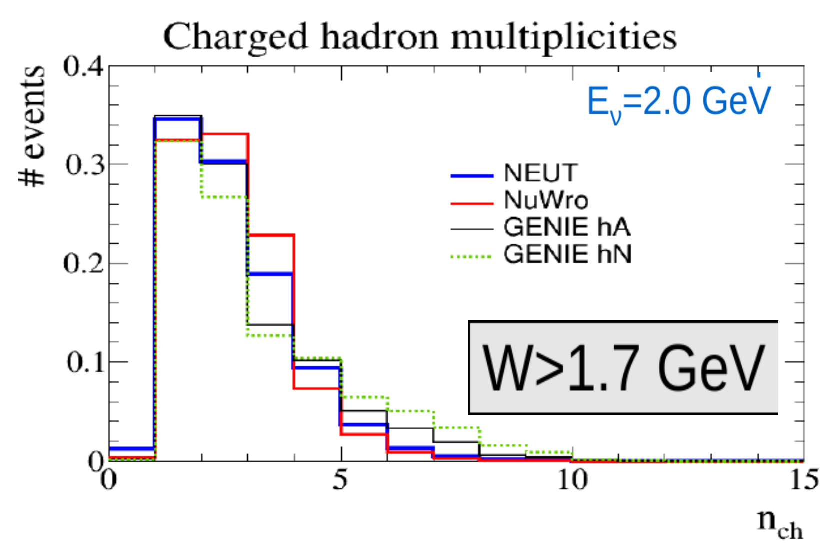




PYTHIA also used for the hadronization: transform the scattered quark into hardons

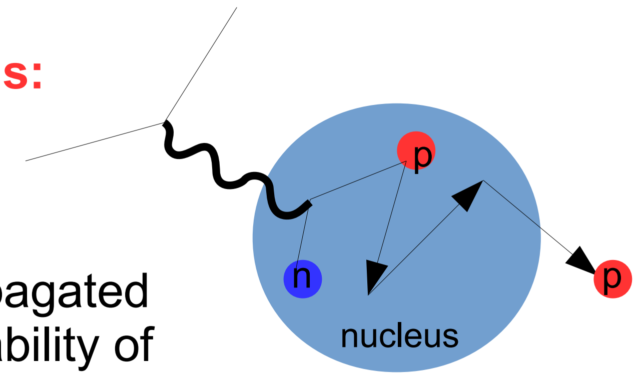
Neutrino on CH (outdated MC versions)





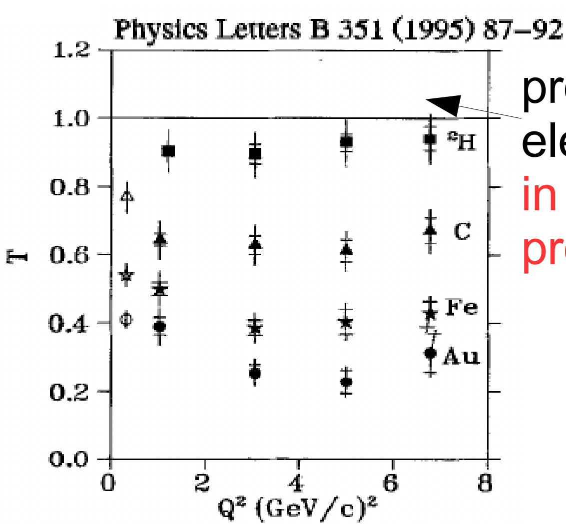
Nuclear effects in the final state

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



Simulate with Monte Carlo cascade models: the particle is propagated in small step and, on the basis of his mean free path, the probability of interaction is computed (elastic, absorption, charge exchange)

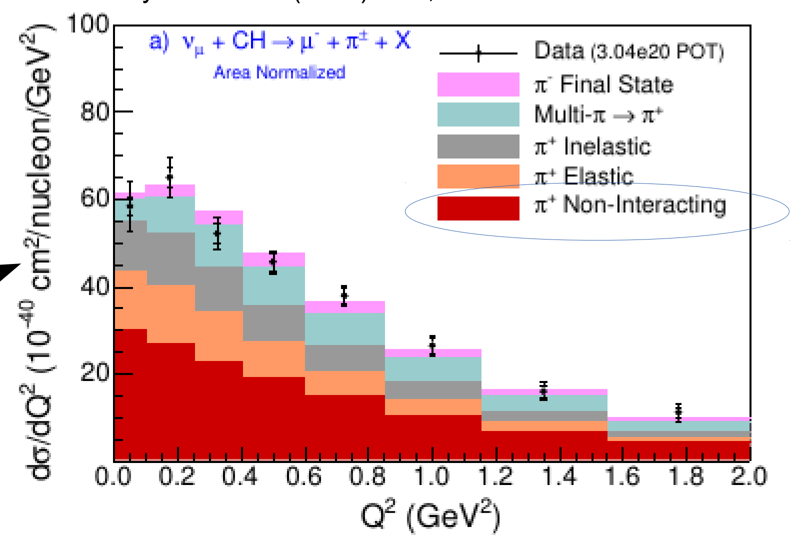
<u>This is not a small effect!</u>



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

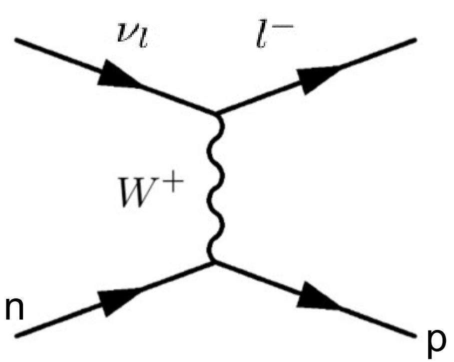


Experimental channels

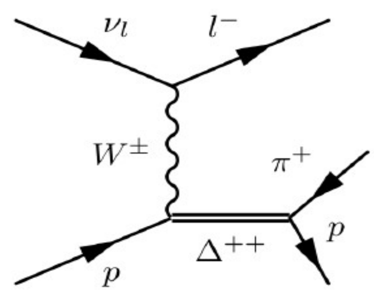
The experiments cannot measure the fundamental interaction but only the final state after nuclear effects.

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



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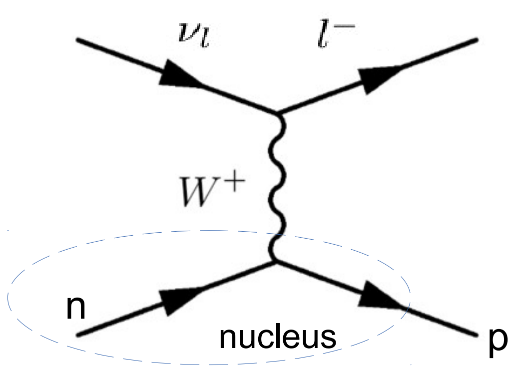

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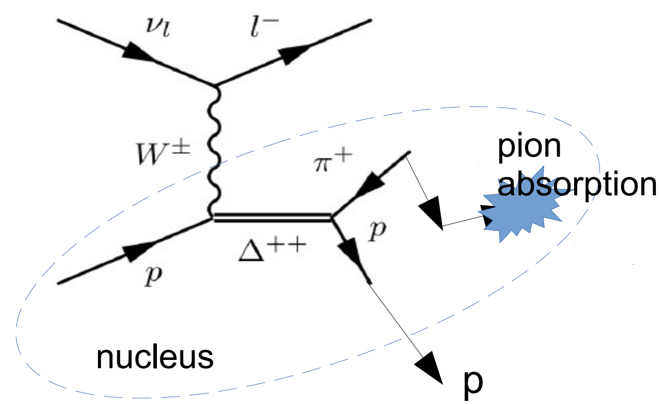


therefore we say that we measure **'CC0π'** events. Similarly:

- CC1π events can also receive contribution from multipion production (and viceversa)
- also the charge of the pion or of the nucleon can change by FSI

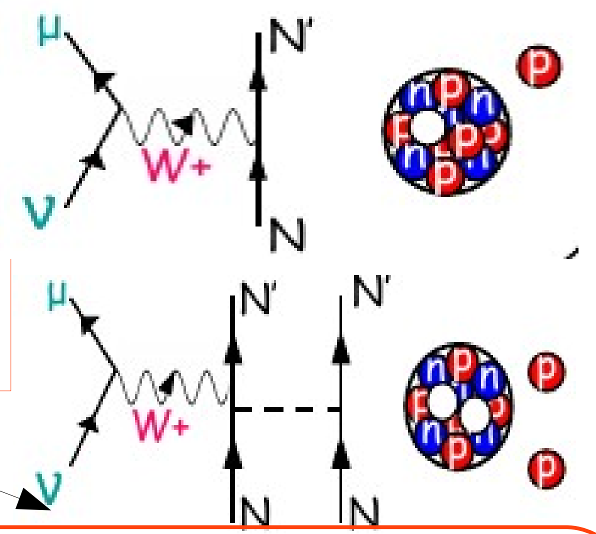
Additional process: 2particles-2holes (only in nuclei)

from Gran (Minerva) at
2p2h Saclay workshop

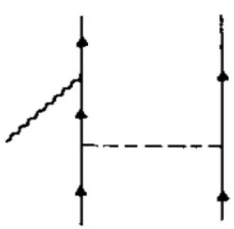
CCQE (aka **1p1h**)

+

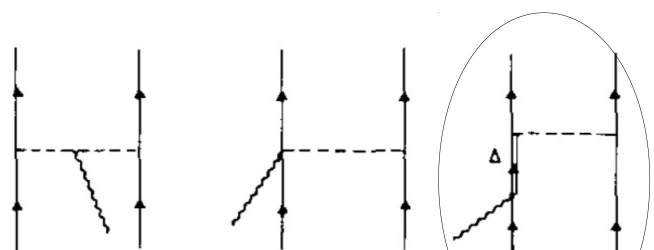
2p2h : interaction with correlated nucleons



Nucleon-Nucleon correlations



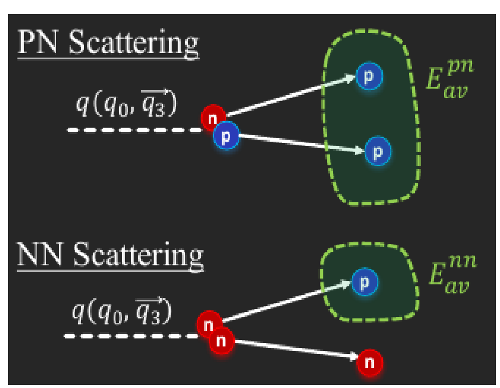
Meson Exchange Currents (MEC)



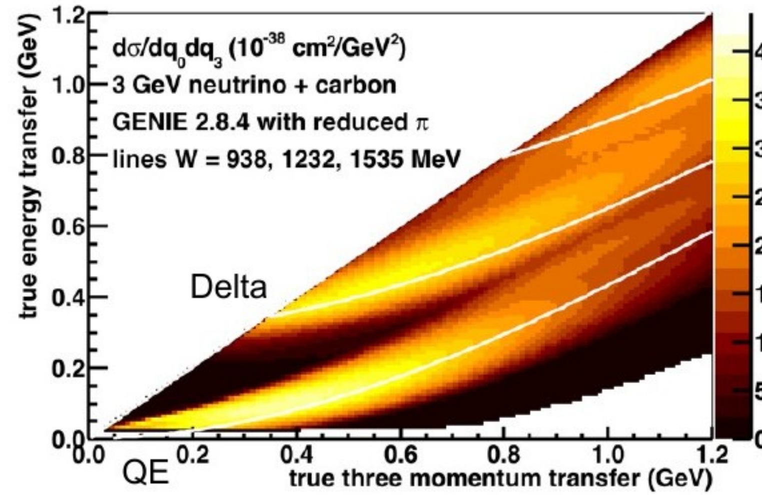
Pion in flight
Contact
Delta
Dominant in MEC

+ interference

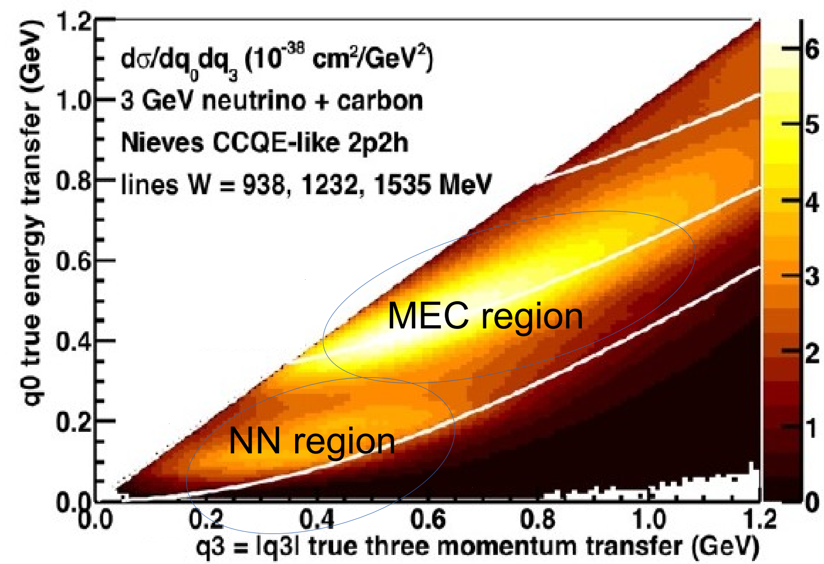
Experimentally difficult to disentangle: final state can be pn or pp with low energy protons



CCQE + CC1pi (+DIS)

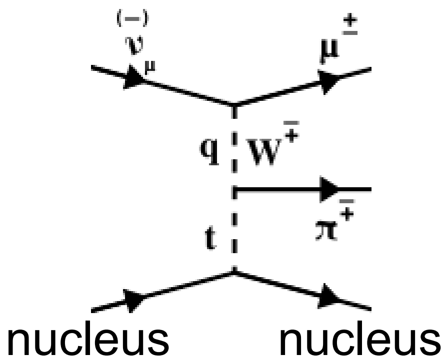


2p2h (Nieves)



Additional process: coherent pion production (only in nuclei)

- Small component (~1% of **CC**) :



- very small momentum transferred to the nucleus (**|t|**) which remains intact and unaffected

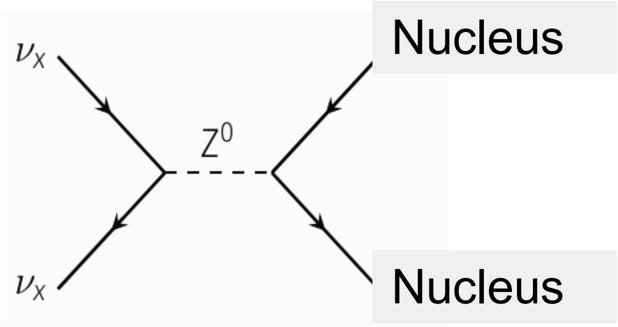
Very difficult to isolate experimentally from the RES CC1π: requirement of no energy around the nucleus

- Actually, a similar process should happen for scattering on nucleons: **diffractive pion production**

Coherent eleastic ν-nucleus scattering (CEνNS)

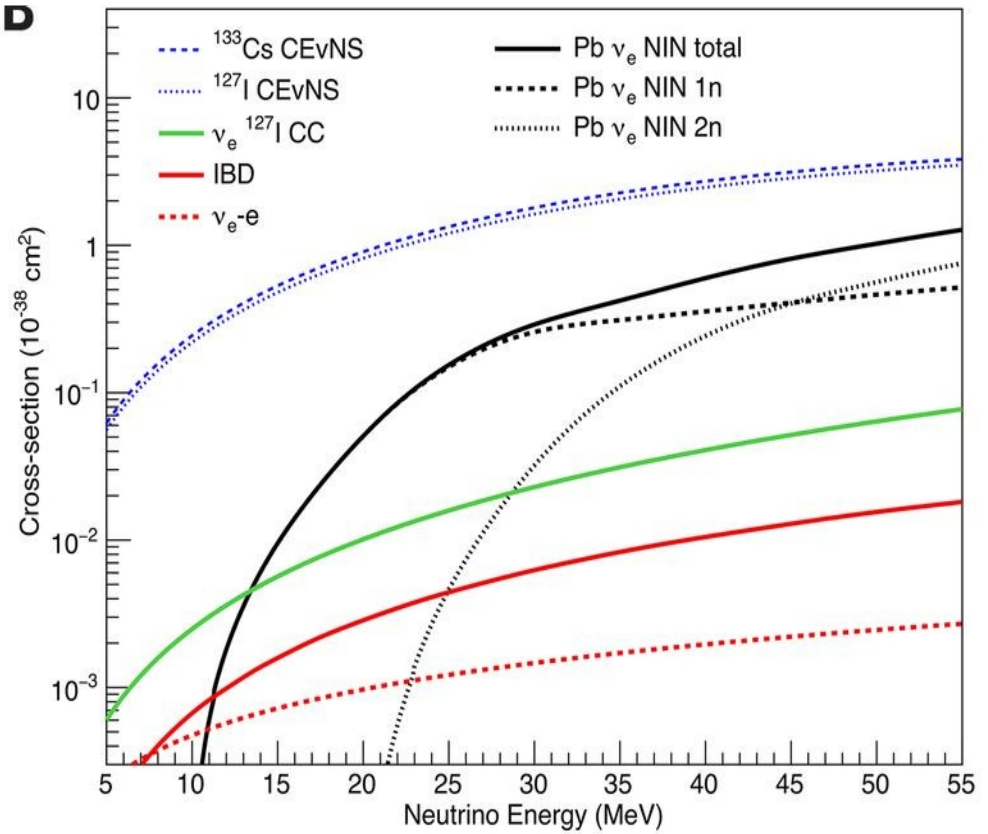
Large xsec (1-100 MeV) but never observed

- Possible only if energy transferred to the nucleus is very low → very difficult to detect... basically nothing happen except some (small) recoil energy of the nucleus
- (coherent xsec on nucleus) / (xsec on nucleons) ~A^2
- Larger the nucleus size (A) smaller the recoil energy



Useful for

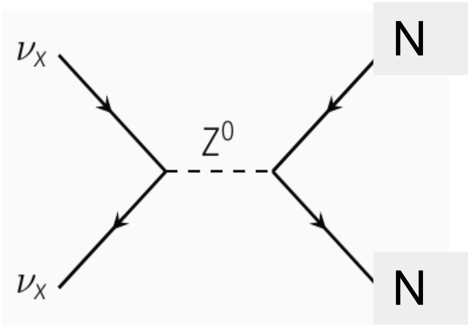
- ν processes in SuperNova → modeling energy transport in SuperNova
- irreducible background to Dark Matter detection
- monitoring of reactors



CEνNS

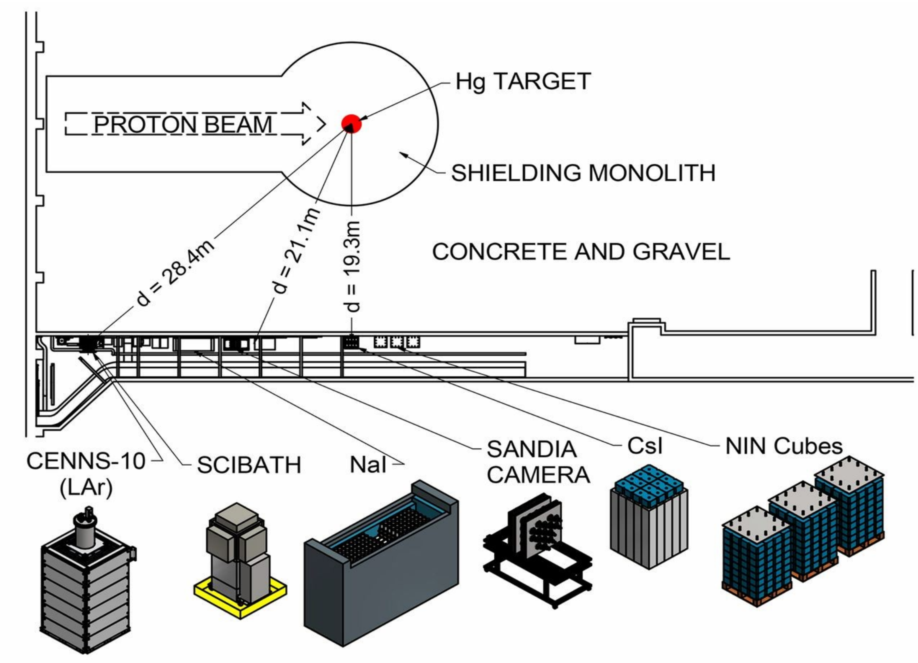
Large xsec (1-100 MeV) but never observed

Measure of nuclear recoil in neutral current events

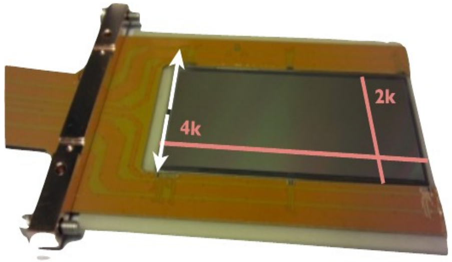


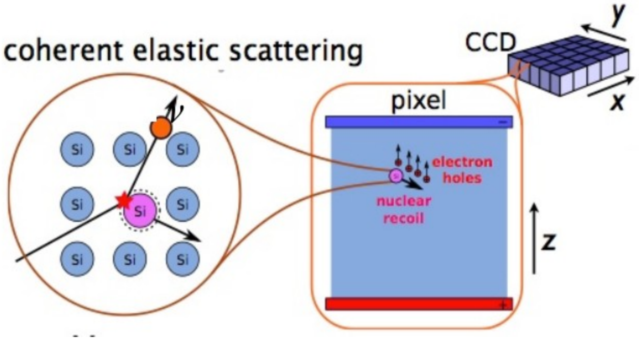
COHERENT: various detector technologies at neutron spallation source at Oak Ridge

- single phase LAr (28 Kg)
- NaI[Tl] crystals (185 Kg)
- Cesium Iodide scintillator (14.6 Kg)



CONNIE: Charged Coupled Device at Angra Nuclear Power Plant (Brasil)

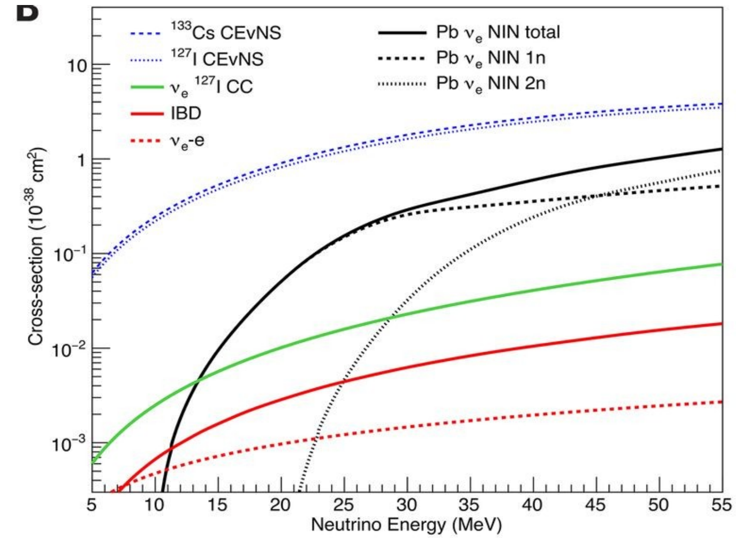




CEνNS

! **Large xsec (1-100 MeV) but ~~never observed~~**

Measure of nuclear recoil in neutral current events



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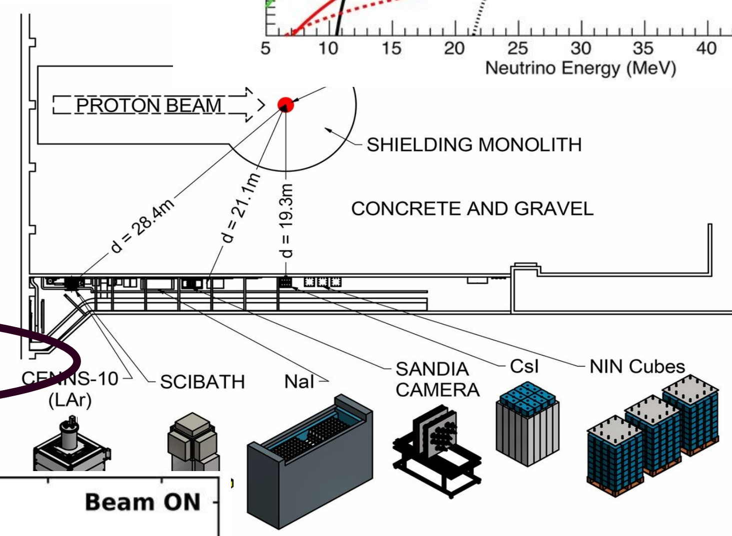
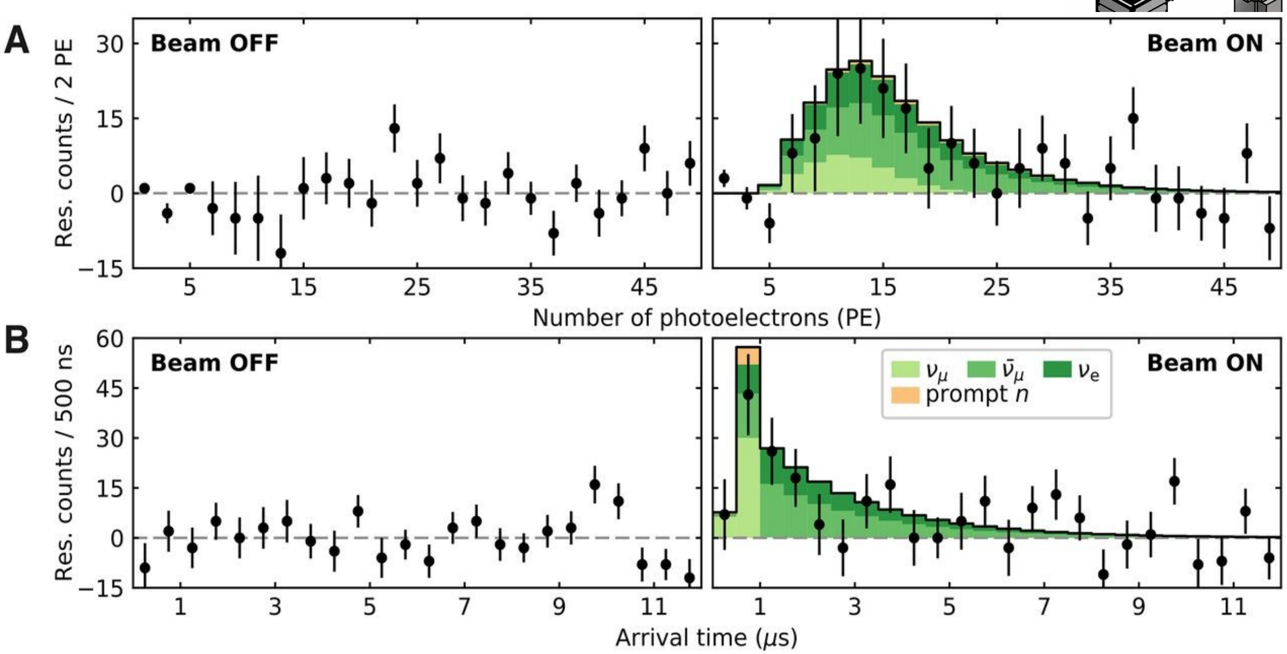




Primary neutrons are shielded + neutrons induced by neutrino scattering in the shielding (NIN) measured with dedicated detectors

134 +/- 22 events (6.7 σ)

173 +/- 48 events expected in SM (1σ agreement)

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

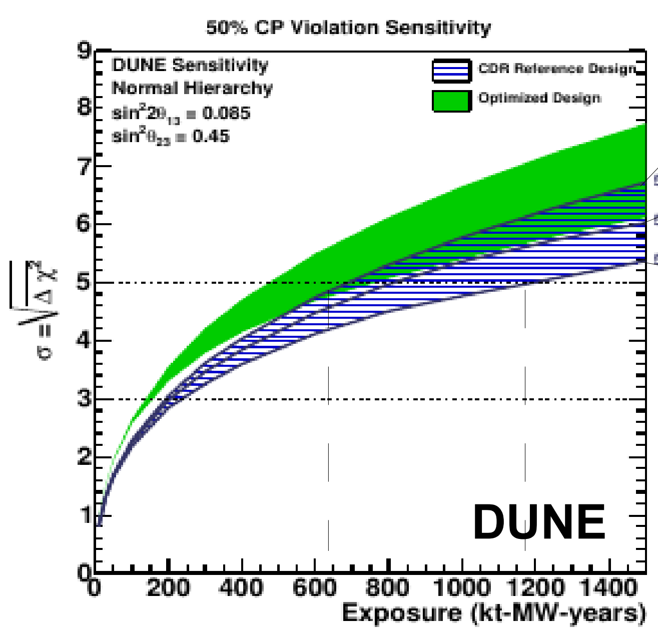
$$\sin(\delta_{CP}) \approx \frac{(\nu_\mu \to \nu_e) - (\bar{\nu}_\mu \to \bar{\nu}_e)}{(\nu_\mu \to \nu_e) + (\bar{\nu}_\mu \to \bar{\nu}_e)}$$

→ 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!

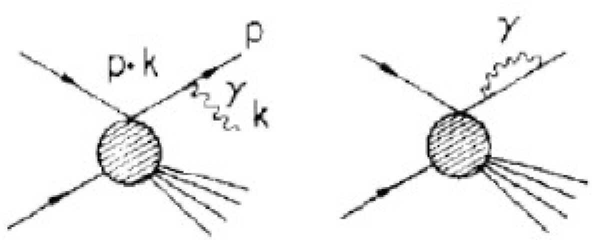
Different neutrino species

- 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 $\nu_e \rightarrow e$ and $\nu_\mu \rightarrow \mu$ (because of different lepton mass)



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

→ **need less approximated calculation?**

Importance of neutrino interaction uncertainties on the oscillation analysis

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

What else do we need to control?

Uncertainties in ND→FD extrapolation :

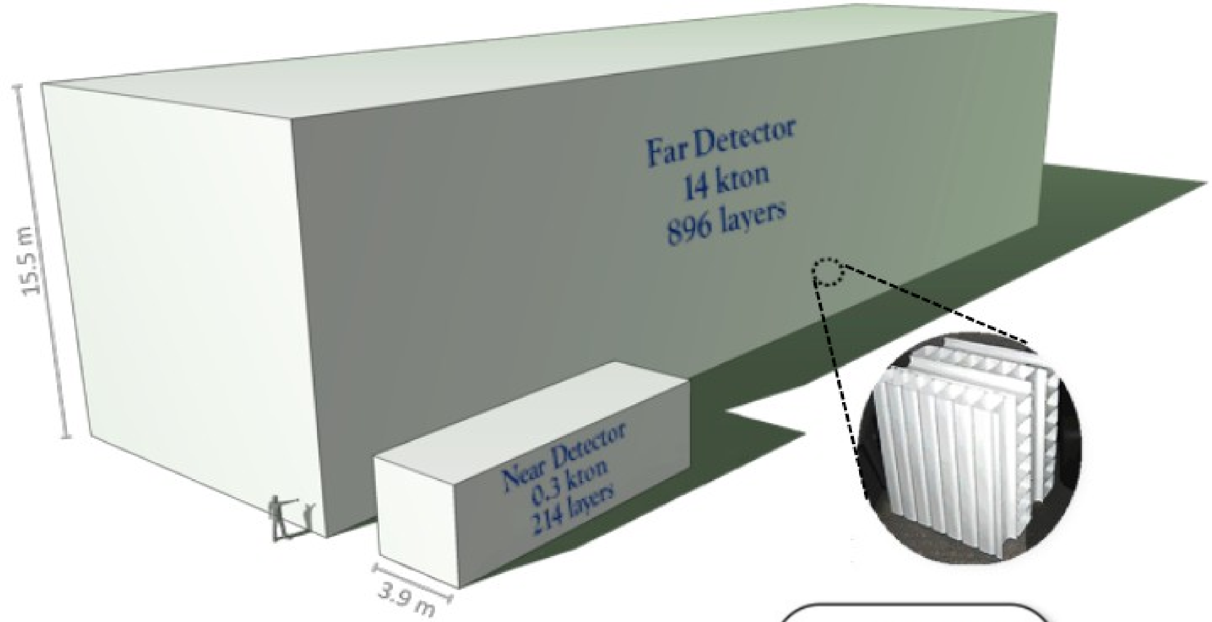
- different E_ν distribution (because of oscillation) ⇨ measure all particles in the final state: threshold and calibration at low energy (neutrons? FSI?)
- different target ⇨ A-scaling: measure cross-sections on different targets (and/or on the same target of FD)
- different acceptance ⇨ measurement 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

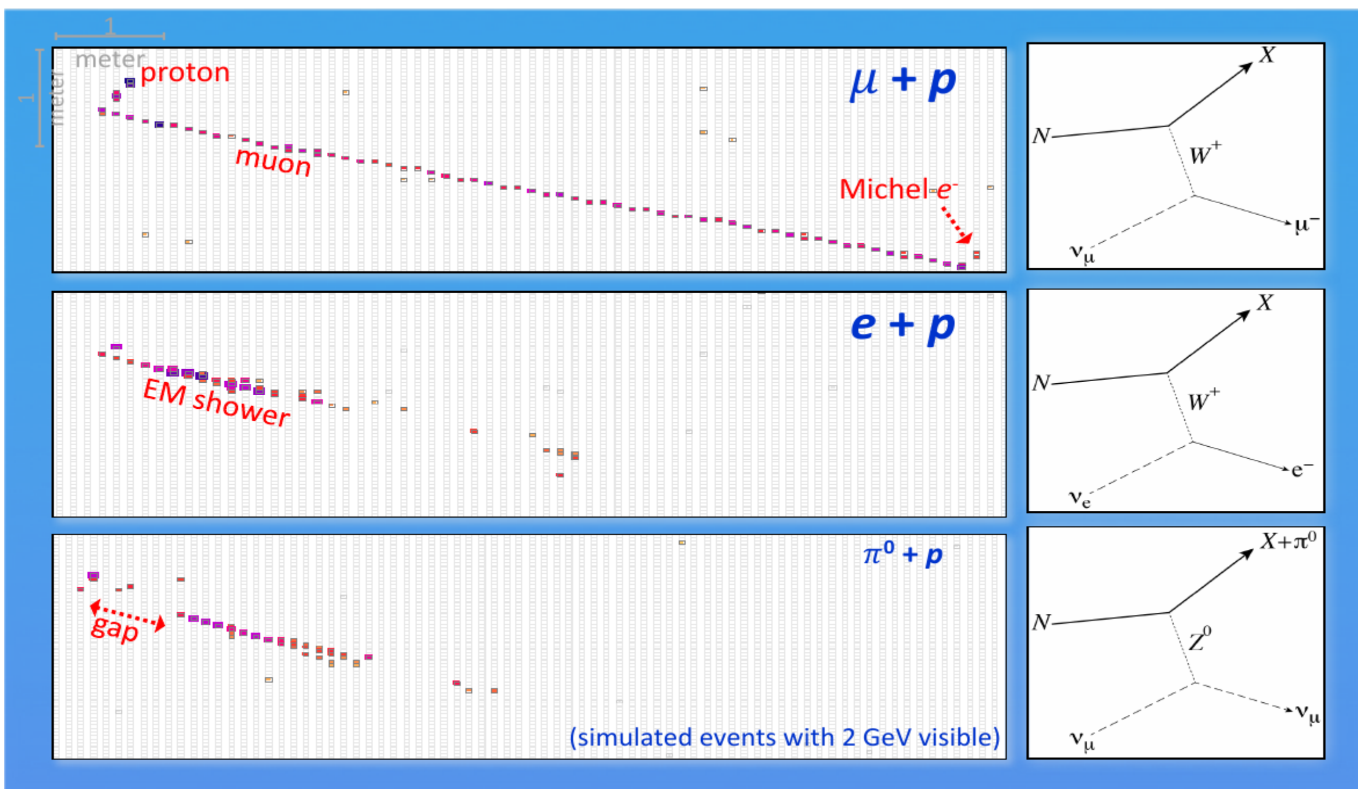
⇨ 'control' cross-section asymmetries between different neutrino species

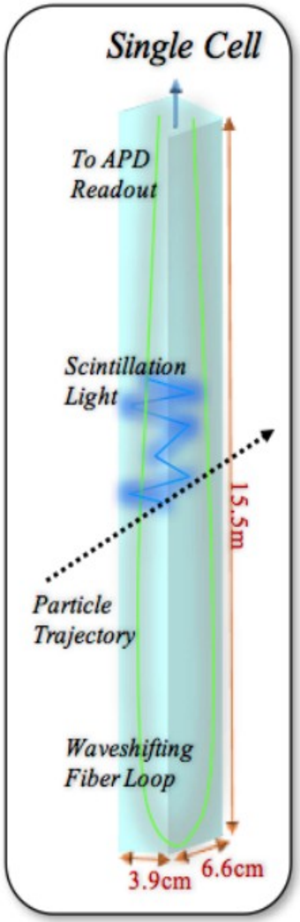
NOVA

Same technology at ND and FD
(not same size → different containment)

Scintillator oil → collect light and use topological info for PID

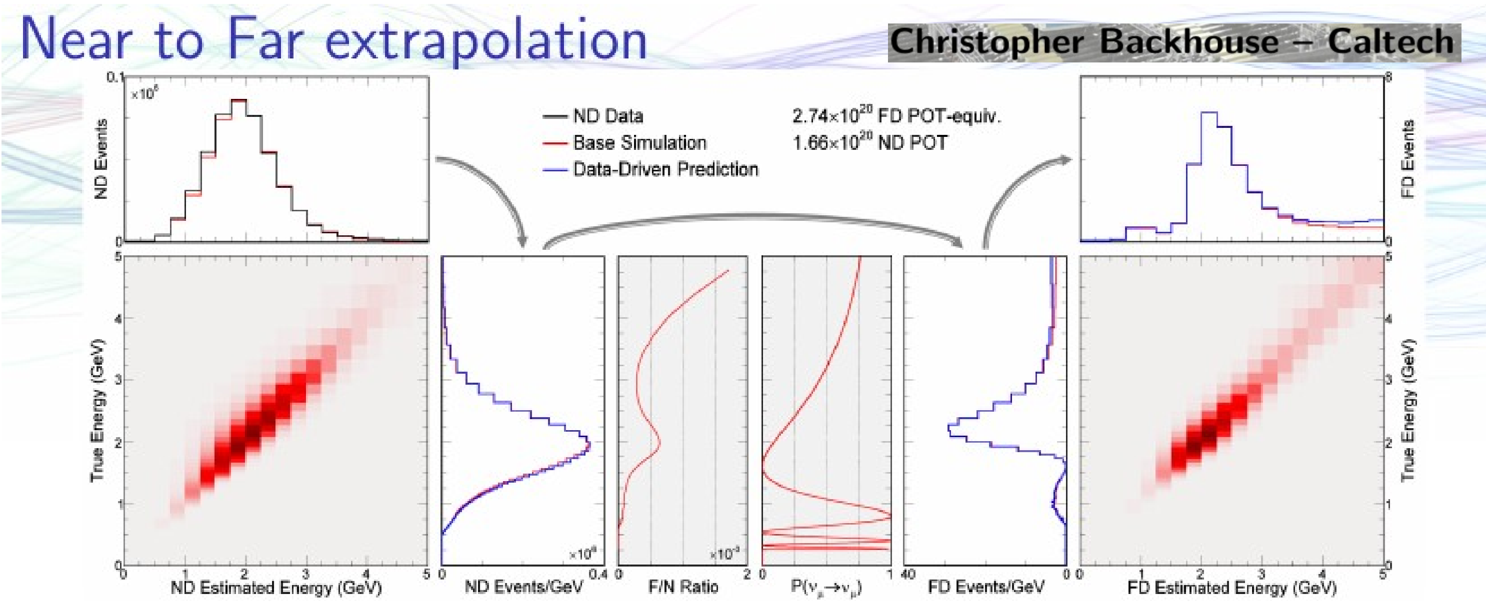






Calorimetric approach (NOVA)

- Measurement of all the (visible!) energy in the event to estimate the neutrino energy



- Subtract NC expectation in ND, reweight MC in reco energy to match
- Transform to true energy, transport to FD with oscillations
- Transform to reco energy, add FD NC expectation back in
- Dependence on MC for background subtraction and true/reco matrix

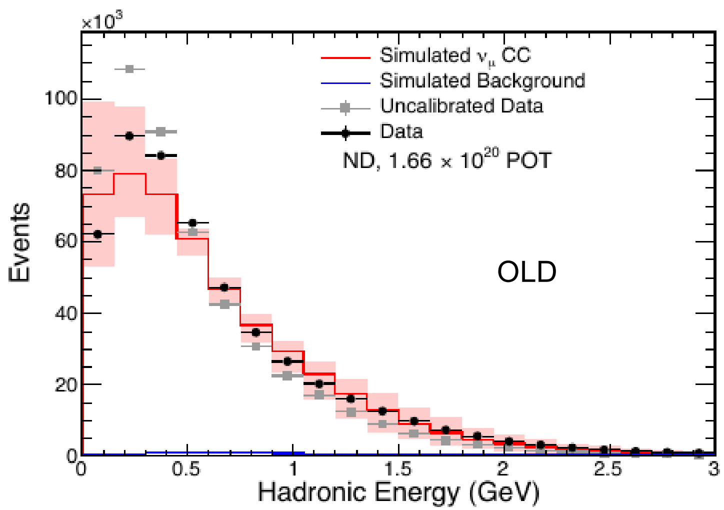
Not only detector systematics but also theoretical uncertainties (FSI, multiplicity in the final state, fraction of neutrons...) do affect the true ↔ reco correspondance

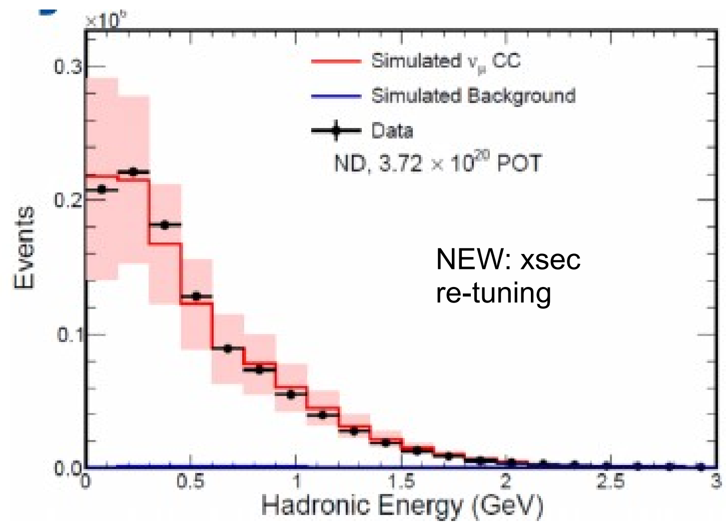
Calorimetric approach: limits

- **Main limitation:**
  - Calibration issues (no sensitivity to neutrons, energy threshold...)
  - Very limited predictivity from models regarding the hadronic final state!

The two problems are tightly convoluted and difficult to disentangle

Example from NOVA:



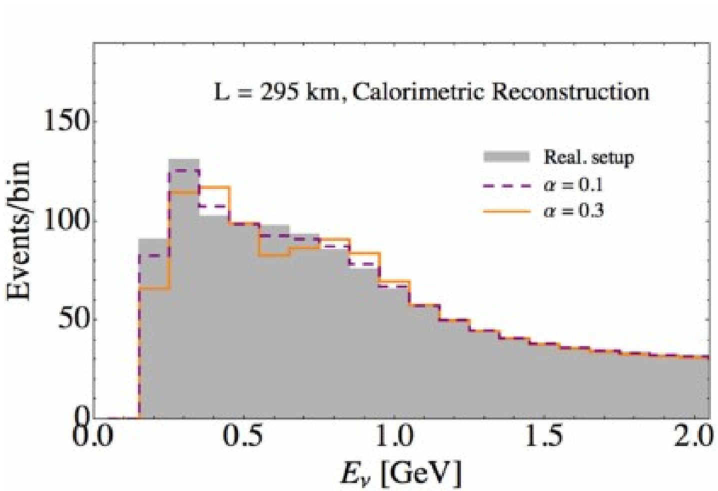


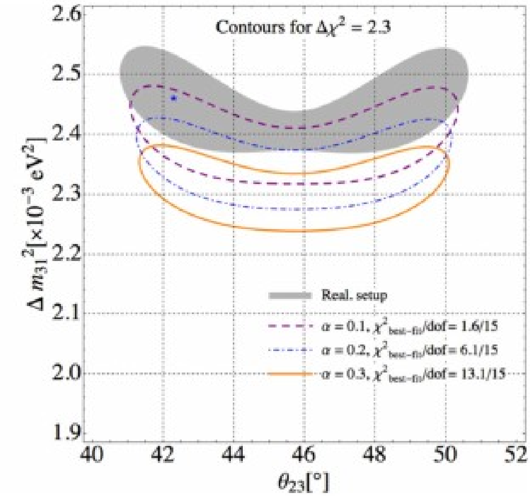
- **A taste of the future → DUNE:**
  - need to reconstruct precise E_ν shape for good sensitivity (two oscillation maxima)
  - capability of full reconstruction of tracks and showers down to very low threshold

→ **need to reach very good control on detector calibration/uniformity *and* on neutrino interaction modelling which have convoluted effected in E_ν**

Calorimetric approach biases

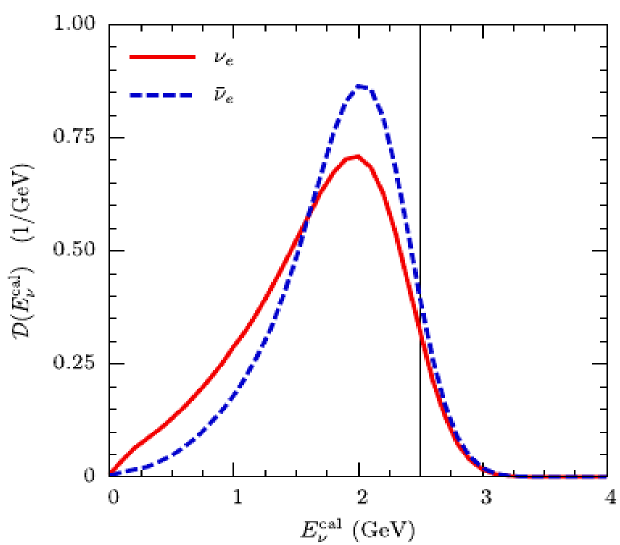
- Phenomenological study with 'realistic' detector smearing and resolution:

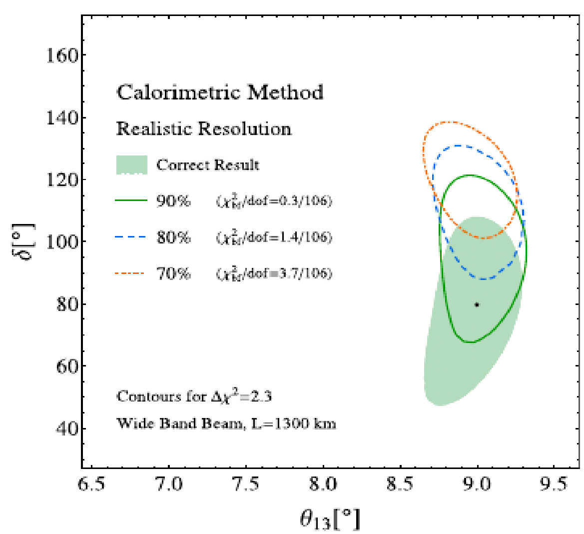




→ bias on ν_μ analysis due to incorrect estimation of detector efficiency and resolution

- NOTE: fraction of visible energy is different for different neutrino species!!





→ bias on δ_{CP} due to incorrect estimation of missing energy

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A M Ankowski and C Mariani

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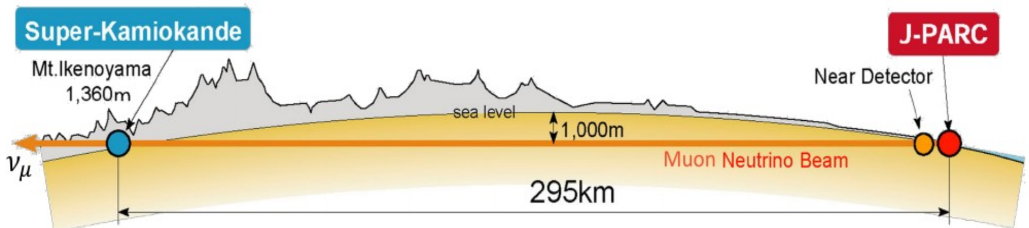
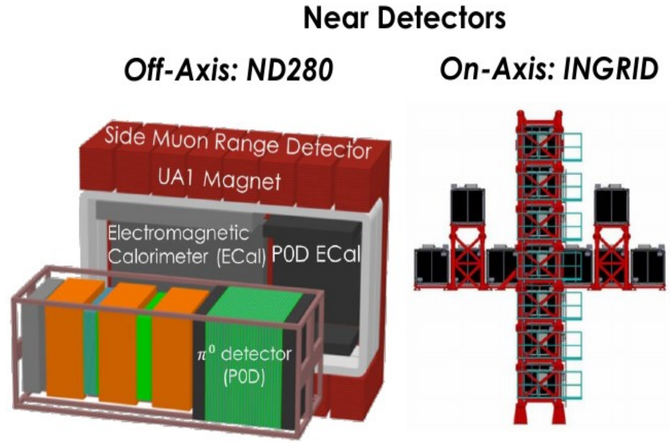
T2K: Tokai (JPARC) to Kamioka (SuperKamiokande)

Long baseline (295 km) neutrino oscillation experiment with off-axis technique:



Far Detector:

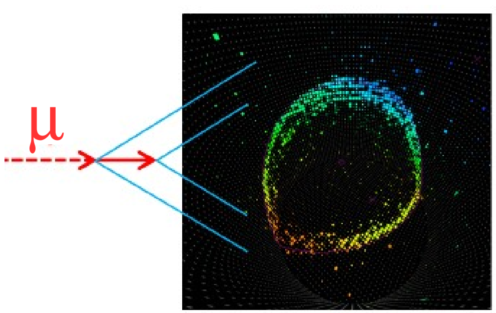
huge water cherenkov detector (50 kTon) with optimal μ/e identification to distinguish ν_e, ν_μ



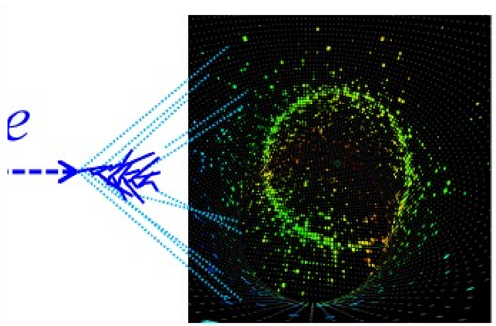
Near Detectors:

On-axis:
iron/CH scintillator
monitoring of beam angle and position

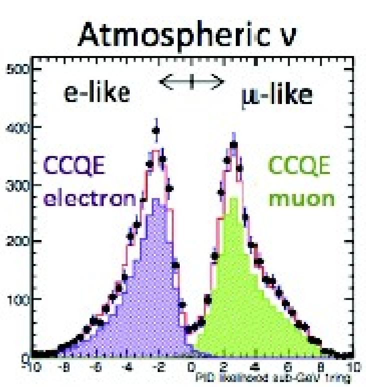
Off-axis:
full tracking and particle reconstruction in near detectors
(magnetized TPC!)



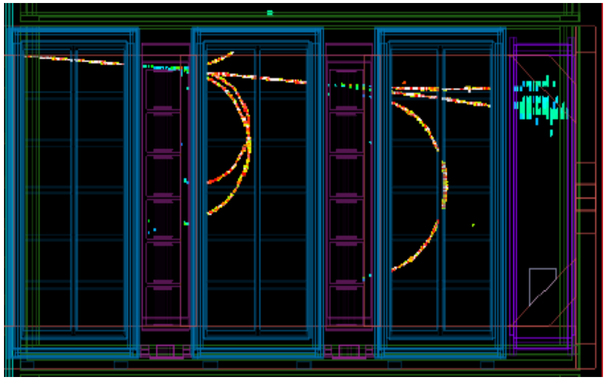
clear ring



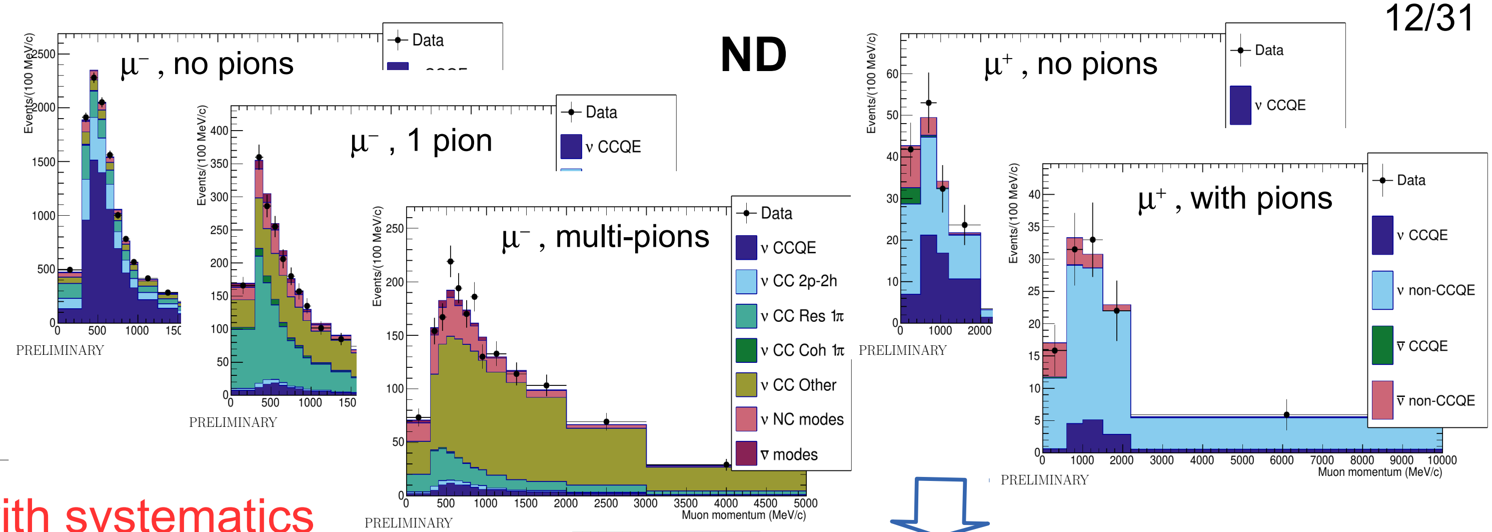
fuzzy ring



1% mis-id



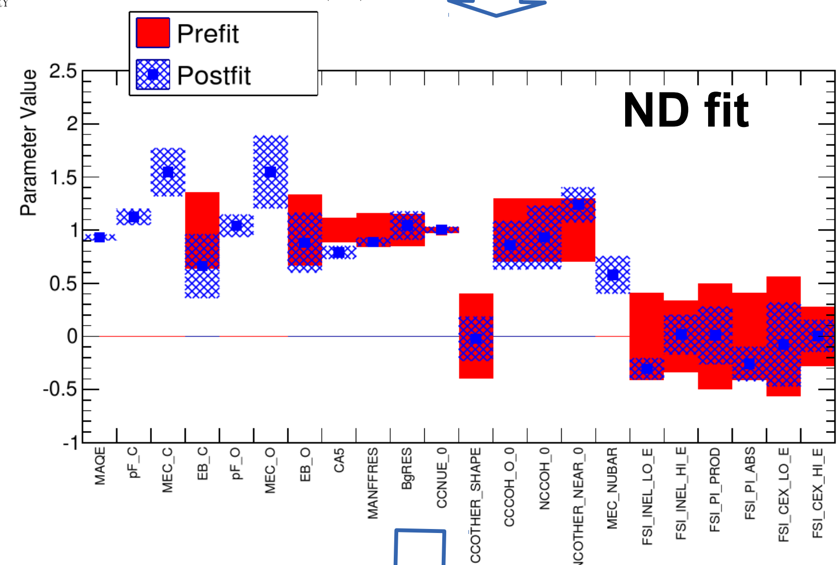
Muon kinematics (T2K)



Full cross-section model with systematics parametrized with variable parameters

→ ND data divided in samples to **fit cross-section parameters** (+flux)

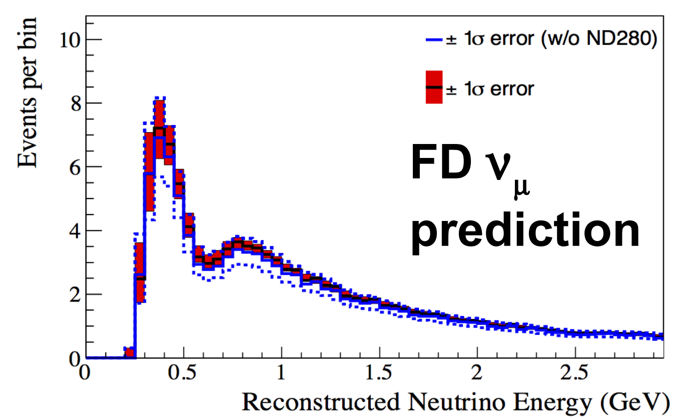
Using only muon kinematics



Prediction at FD: neutrino energy estimated from approximated formula

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

(valid for 2-body scattering with nucleon at rest + correction for binding energy of nucleon)

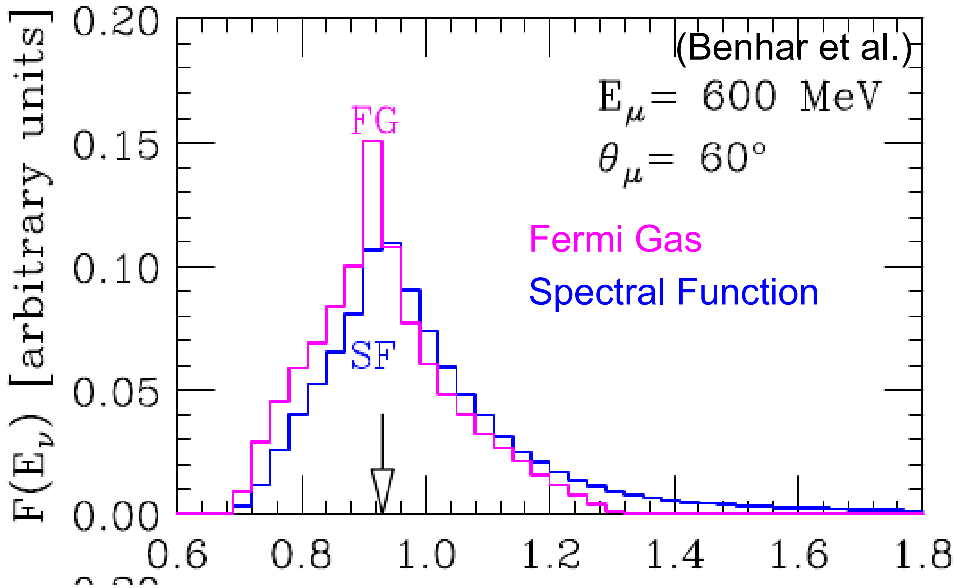


Nuclear effects (initial nucleon momentum or additional final state particle) are estimated from MC **to correct to true neutrino energy** (MC fully tuned to fit to ND data!)

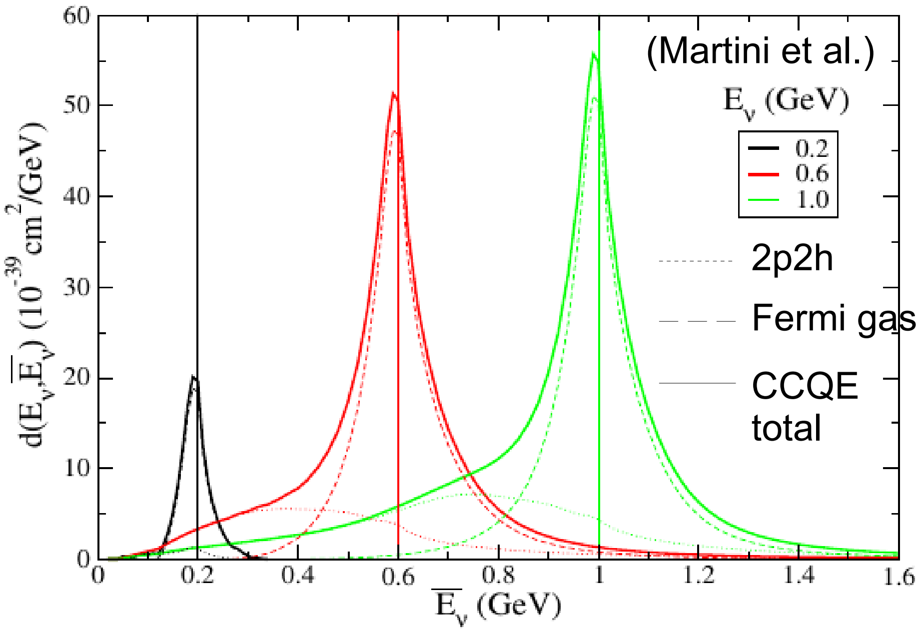
Muon kinematics: limitations

- **Estimation of neutrino energy from muon kinematics depends on nuclear model**

Spreading of reconstructed E_ν for fixed true E_ν due to nuclear model



Some nuclear effects (scattering on correlated nucleon pairs, aka 2p2h) can also give a bias.



- Very important to have proper parametrization of such effects at ND to correct for them:
  - possible bias **if the model is wrong** and/or underestimation of the uncertainties **if the model is not complete**
  - remaining **unconstrained uncertainties from what cannot be measured at ND** (eg: different acceptance or ν_e xsec)

How we are going to improve the xsec model uncertainty for the OA?

- **In a direct way adding new samples:** eg, improve efficiency for high angle and low momentum particles and include those in the ND fit of OA

- **In a indirect way measuring neutrino interactions at ND (and elsewhere):** measure protons, vertex energy, … which are not directly included in OA but **help us understanding the goodness of our models and/or constrain the prior uncertainties**

Effects on the cross-section which are very small (eg different neutrino flavours or carbon versus oxygen difference) will be very difficult to constrain directly from the data (need very large statistics and/or complex experimental setup/analysis)

But if we do **high precision measurements in ν_μ on a given target** to better constrain the nuclear model then we will know **how to extrapolate to different target and neutrino species**

(ie... we will never get rid of our models... better to have good ones !!)