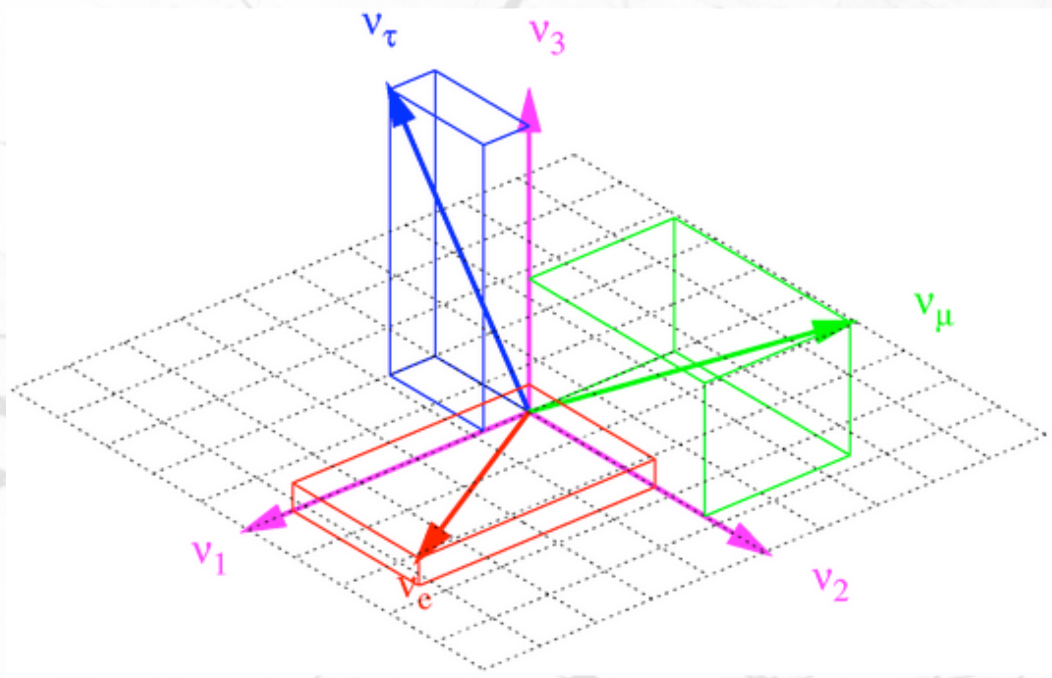
Precision oscillation neutrino experiments, nuclear physics and the need for near detectors

Federico Sanchez
IFAE/BIST (Barcelona)

ν oscillation

Pontecorvo–Maki–Nakagawa–Sakata matrix

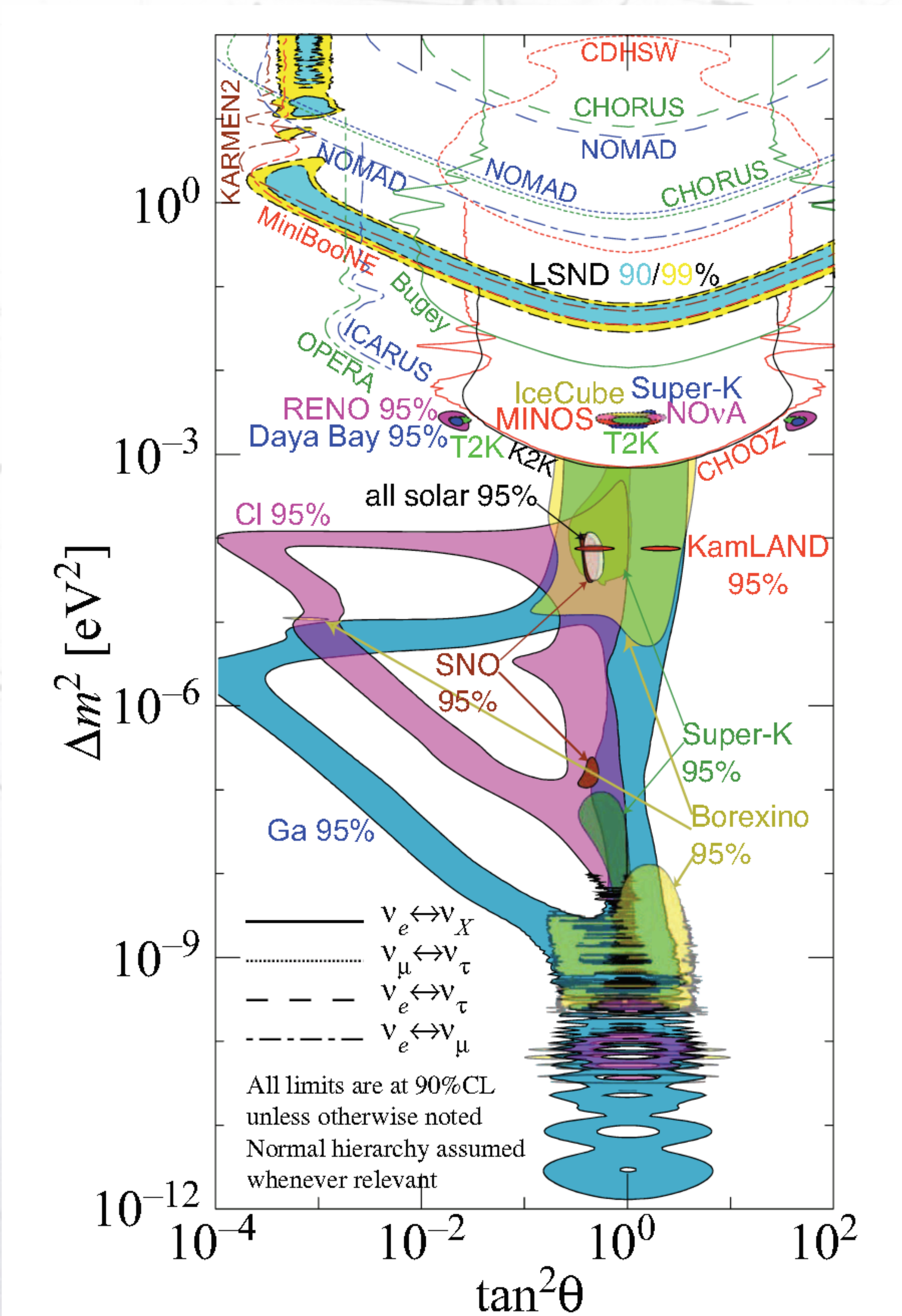
$$\begin{pmatrix}\nu_e & \nu_\mu & \nu_\tau\end{pmatrix} = U_{PNMS}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



$$U_{PNMS} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & e^{-\delta_{CP}}\sin\theta_{13}\\ 0 & 1 & 0\\ -e^{\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

- With 3ν: there are 3 angles and 1 imaginary phase δ_{CP} (complex 3x3 matrix).
  - The phase allows for CP violation similar to the quark sector (CKM)
- There are also 2 values of Δm^2, traditionally Δm^2_{12} & Δm^2_{31}.

ν oscillation



$$U_{PNMS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Many parameters measured the last 15 years!
- But not all!

	Parameter	best-fit	3σ
	Δm^2_{21} [10^{-5} eV ^{2}]	7.37	6.93 – 7.97
Hierarchy	$\|\Delta m^2\|$ [10^{-3} eV ^{2}]	2.50 (2.46)	2.37 – 2.63 (2.33 – 2.60)
	$\sin^2\theta_{12}$	0.297	0.250 – 0.354
	$\sin^2\theta_{23}$, $\Delta m^2 > 0$	0.437	0.379 – 0.616
	$\sin^2\theta_{23}$, $\Delta m^2 < 0$	0.569	0.383 – 0.637
	$\sin^2\theta_{13}$, $\Delta m^2 > 0$	0.0214	0.0185 – 0.0246
	$\sin^2\theta_{13}$, $\Delta m^2 < 0$	0.0218	0.0186 – 0.0248
CP violation	δ/π	1.35 (1.32)	(0.92 – 1.99) ((0.83 – 1.99))

Missing measurements

- Two remaining parameters to measure

Hierarchy : is $m_3 > m_1$?

Neutrinos interacting with matter alter the oscillation angles and Δm!

It requires ***long base line*** experiments through earth (matter effects)

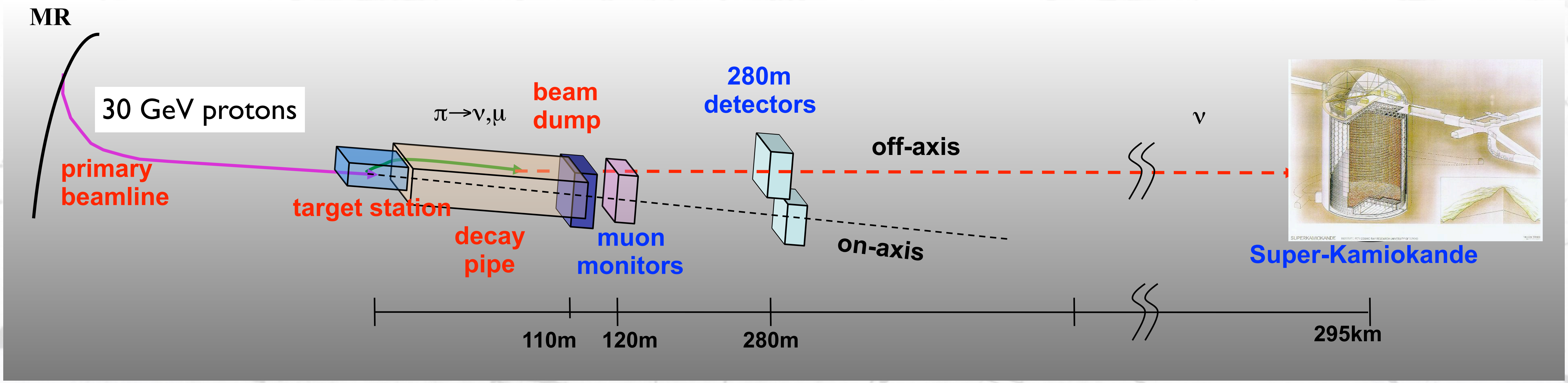
CP violation : Matter = Antimatter?

The probabilities:

$$P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

Measured with ***long base line*** oscillations of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Typical Long Base Line experiment layout



Neutrinos produced in a particle accelerators:

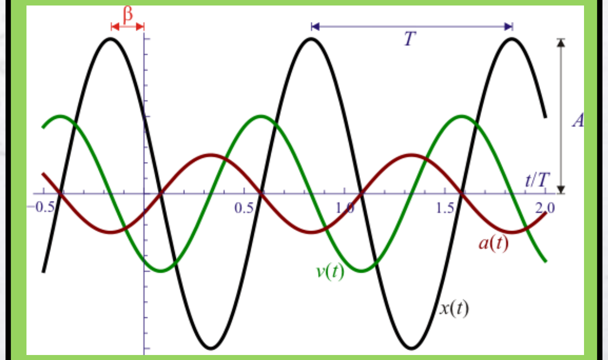
$pA \rightarrow \pi^+ \pi^+ \pi^- \ldots$

$\pi^+ \rightarrow \mu^+ \nu$

$\pi^- \rightarrow \mu^- \bar{\nu}$

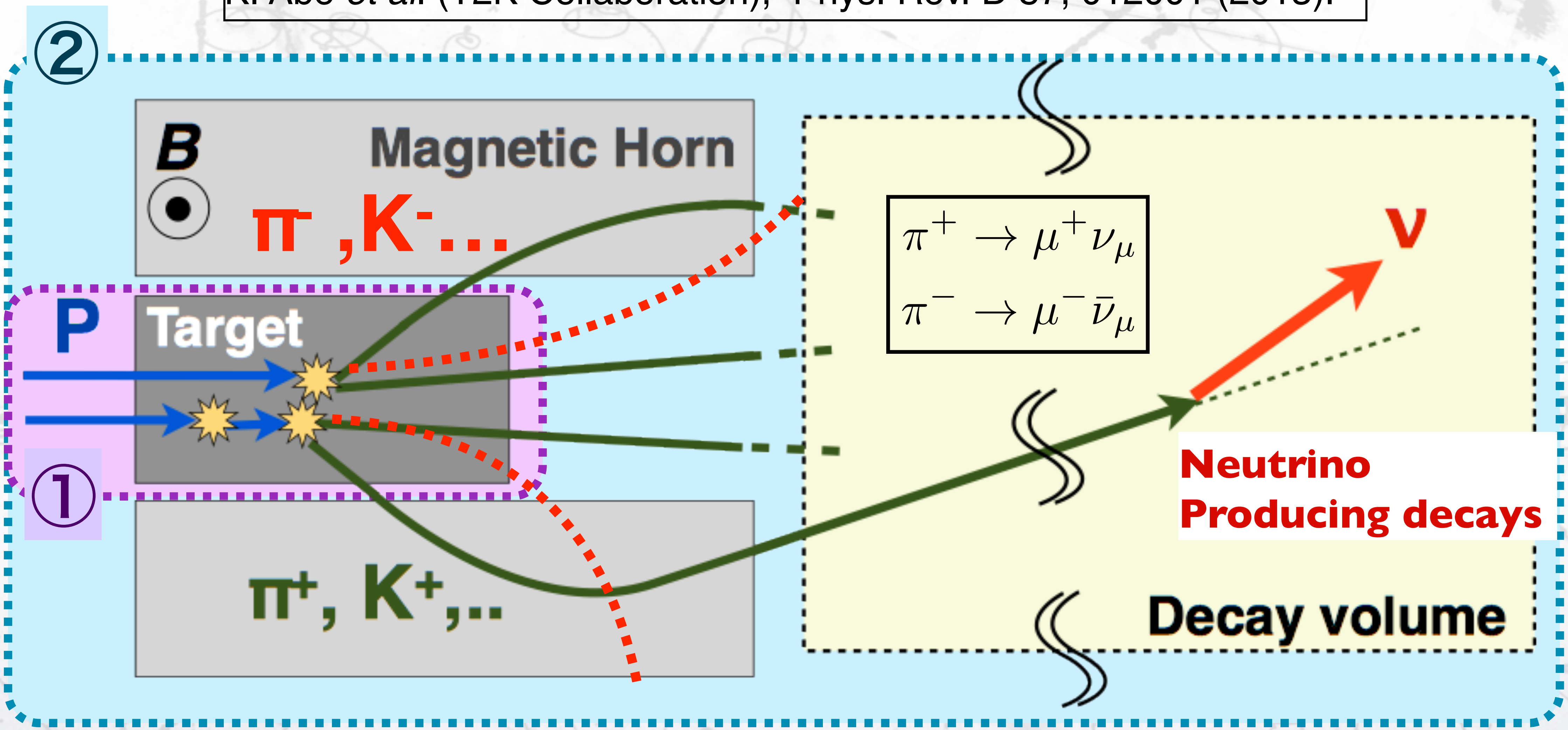
Neutrino flux meas

Oscillations



Neutrino flux meas

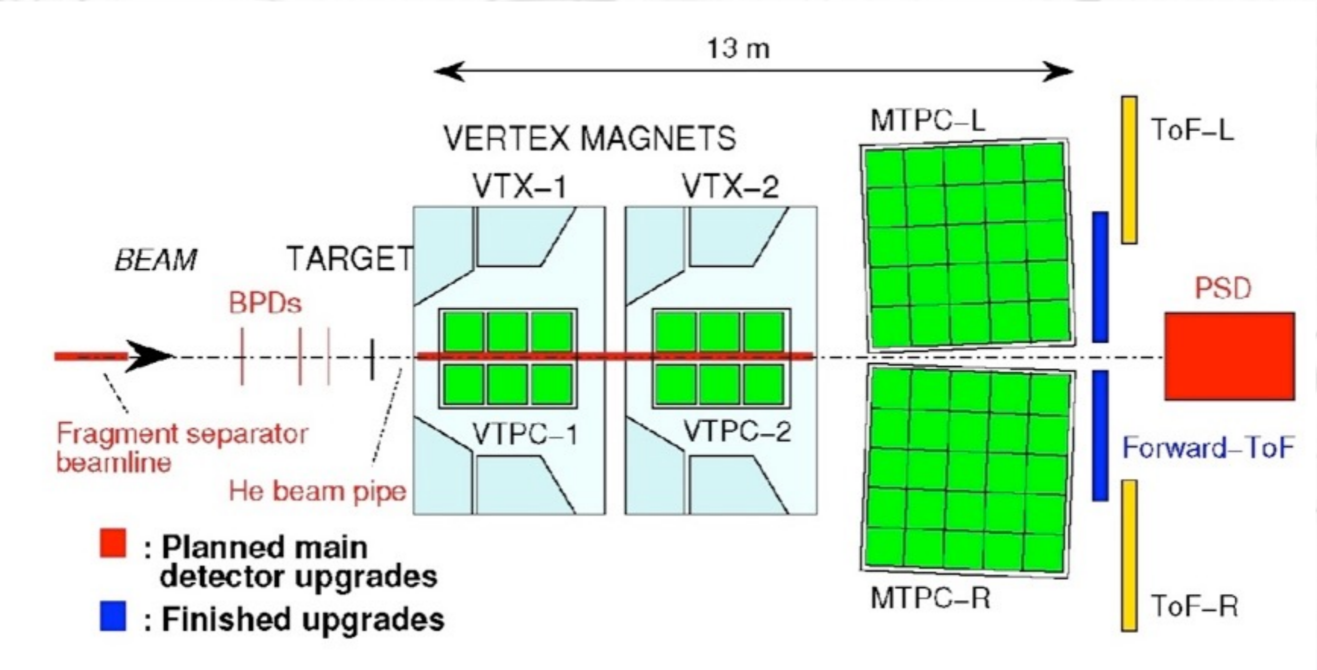
K. Abe *et al.* (T2K Collaboration), Phys. Rev. D 87, 012001 (2013).

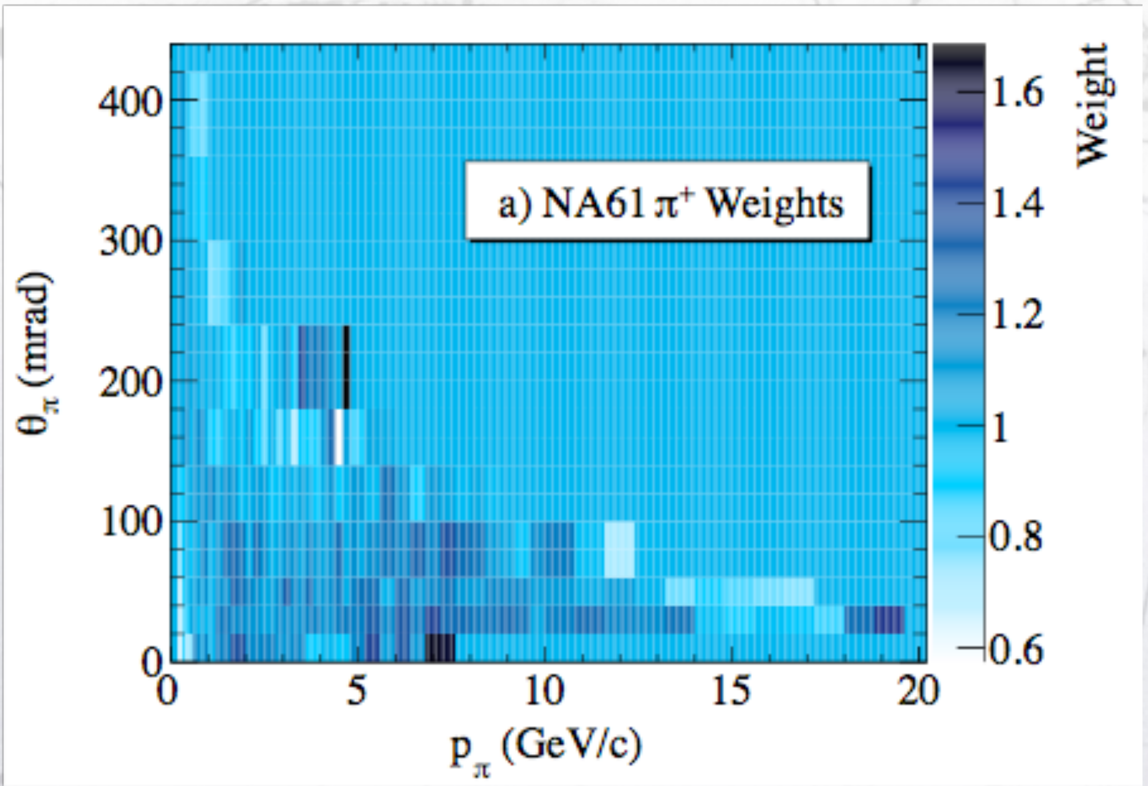


Other source of neutrinos is the low energy electron antineutrinos from nuclear reactors.

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$
$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu$$

NA61/Shine measures the production of pions and kaons as function of the momentum and angle for protons interacting with carbon.

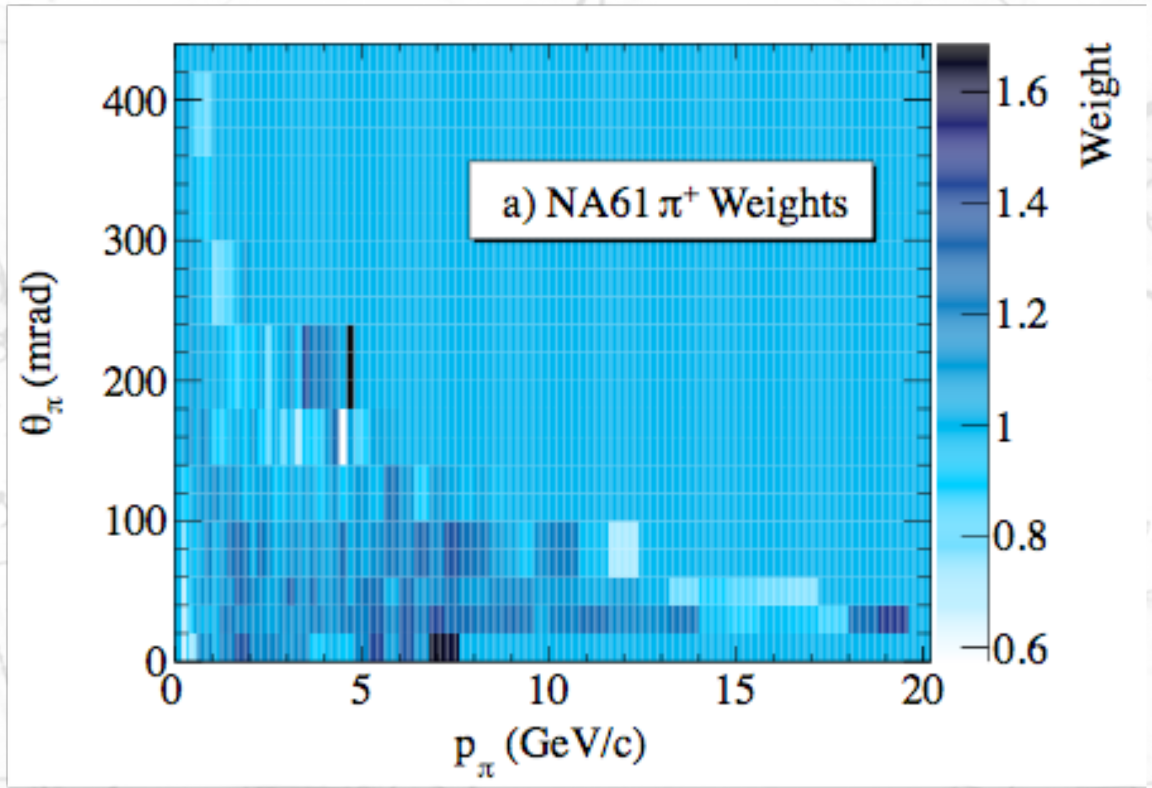




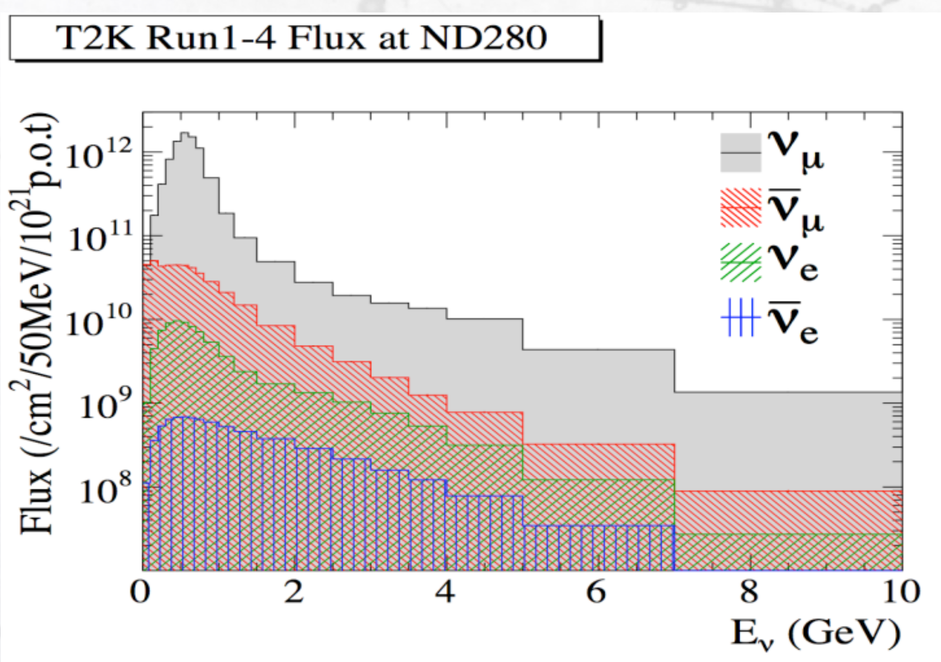
NA61/Shine measures a thin target for absolute production and thick target that is a copy of the ν target and provides also the reinteractions of particles.

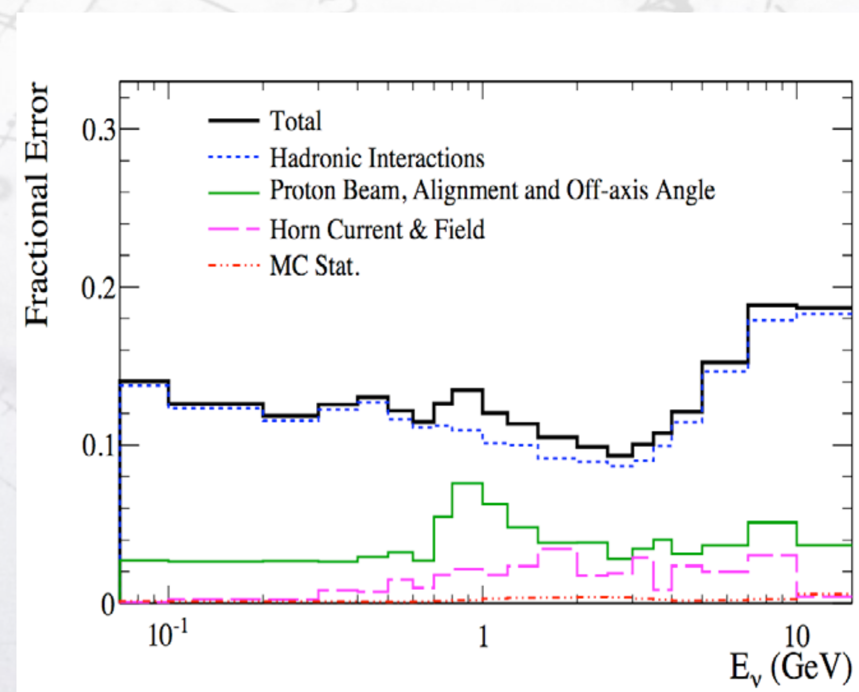
Flux prediction

pion and kaon production



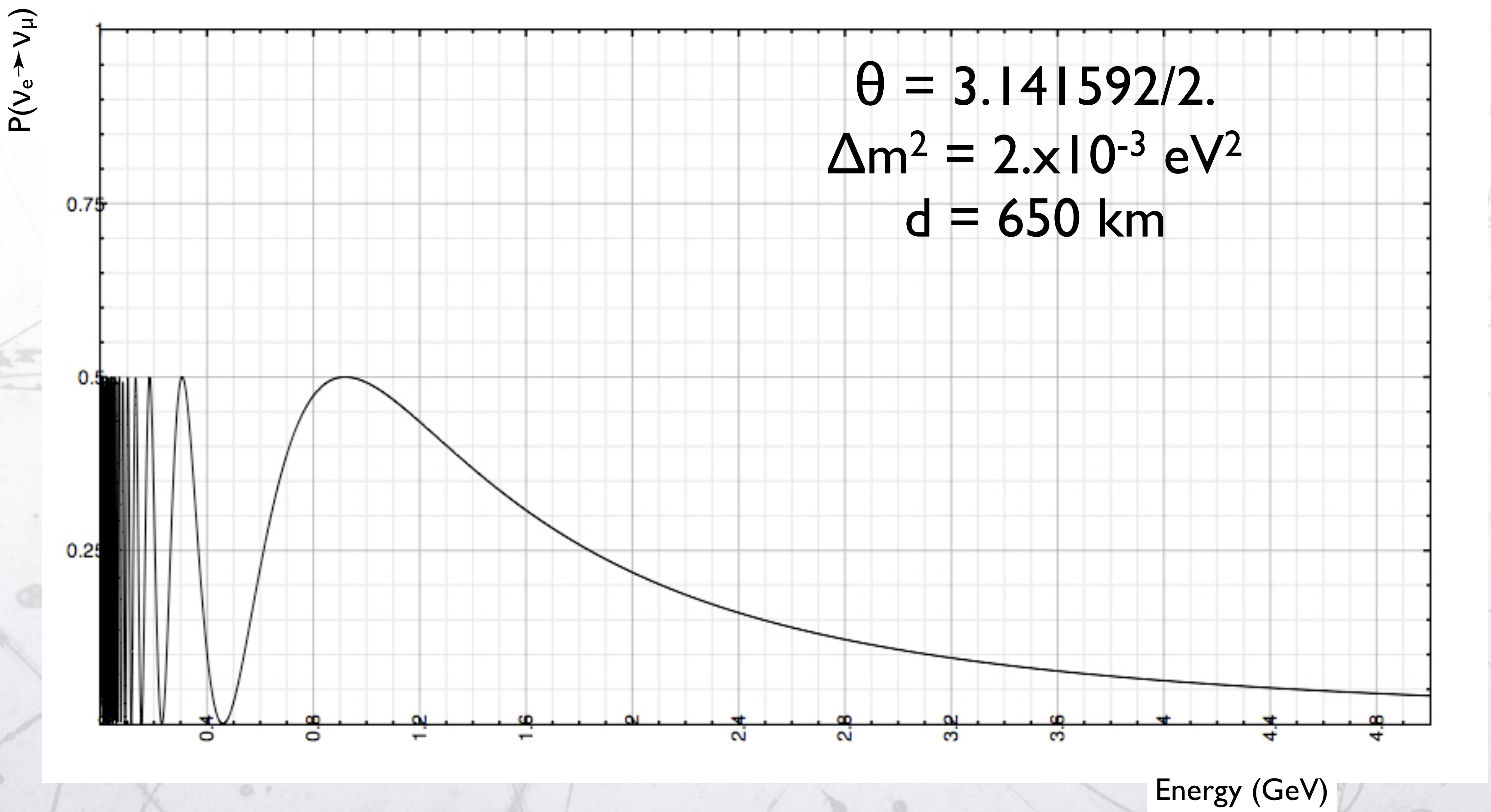
"A priori" flux error: ~15% below @ 1 GeV.





ν Oscillation

For a fixed distance we need to measure the Energy



Neutrino oscillations

- Neutrino oscillation experiments are carried out by comparing neutrino interactions at a near and far sites.
  - The number of events depends on the cross-section & flux:

$$N_{events}(E_\nu) = \sigma_\nu(E_\nu)\Phi(E_\nu)$$

  - at the far detector

$$N^{far}_{events}(E_\nu) = \sigma_\nu(E_\nu)\Phi(E_\nu)P_{osc}(E_\nu)$$

- The ratio cancels flux and cross-section:
-

$$\frac{N^{far}_{events}(E_\nu)}{N_{events}(E_\nu)} = P_{osc}(E_\nu)$$

Neutrino oscillations

- Since the neutrino energy is not monochromatic:
    - we need to determine event by event the energy of the neutrino.
- This estimation is not perfect and the cross-section does not cancels out in the ratio.

$$\frac{N^{far}_{events}(E_\nu)}{N_{events}(E_\nu)} = \frac{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)P_{osc}(E'_\nu)dE'_\nu}{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)dE'_\nu}$$

- The neutrino oscillations introduce differences in the flux spectrum and the ratio does not cancel the cross-sections.

Neutrino oscillations

$$\frac{N^{far}_{events}(E_\nu)}{N_{events}(E_\nu)} = \frac{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)P_{osc}(E'_\nu)dE'_\nu}{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)dE'_\nu}$$

Oscillation experiments require to know:

Neutrino flux:	$\Phi(E_\nu)$
Neutrino cross-section	$\sigma(E_\nu)$
True neutrino energy	$P(E_\nu\|E'_\nu)$

$P(E_\nu|E'_\nu)$ is not only caused by detector smearing
Neutrino interaction channels are critical.

Neutrino interactions

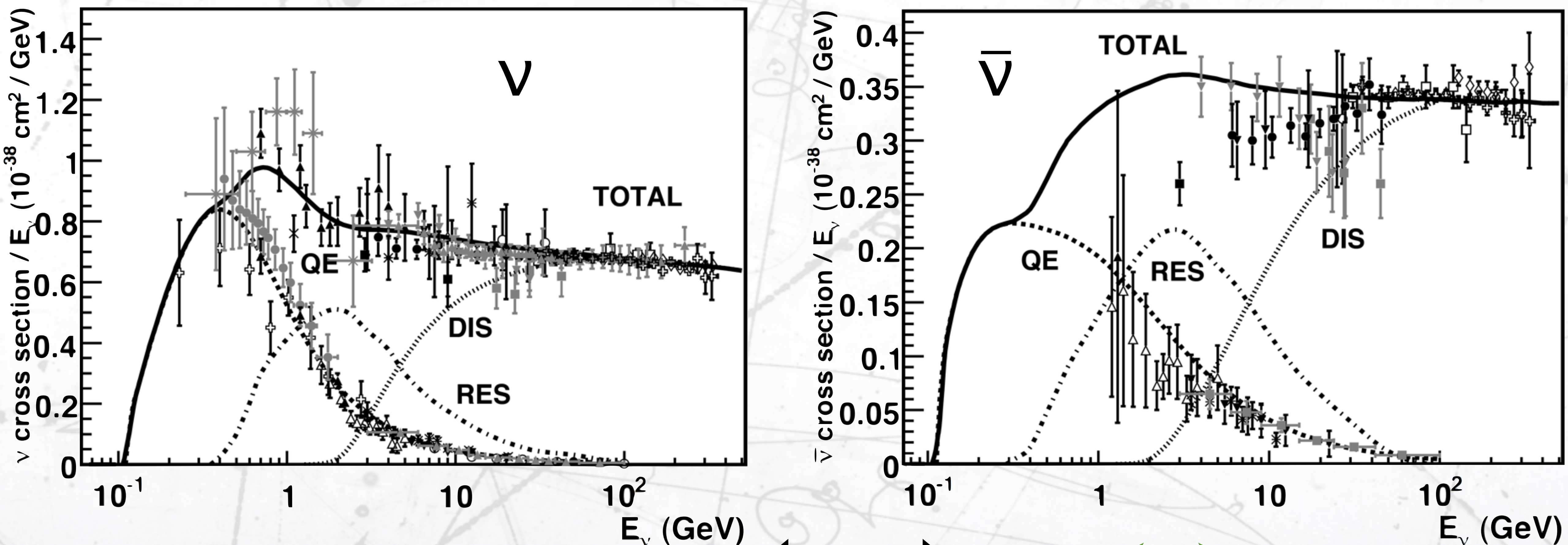
Neutrino interations @ the nucleon level !

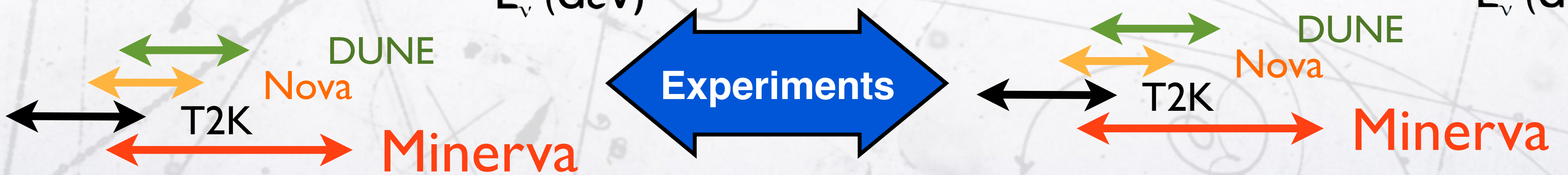
$CCQE$	$\nu_\mu n \to \mu^- p$
$CC1\pi$	$\nu_\mu p \to \mu^- \Delta^{++} \to \mu^- \pi^+ p$
	$\nu_\mu n \to \mu^- \Delta^{+} \to \mu^- \pi^+ n$
	$\nu_\mu n \to \mu^- \Delta^{+} \to \mu^- \pi^0 p$
$CCN\pi$	$\nu_\mu N \to \mu^- \Delta^{+,++} \to \mu^- N' \pi\pi \ldots$
$CCDis$	$\nu_\mu N \to \mu^- N' \pi, \pi, \ldots$

Complementary for antineutrinos.

X-sections

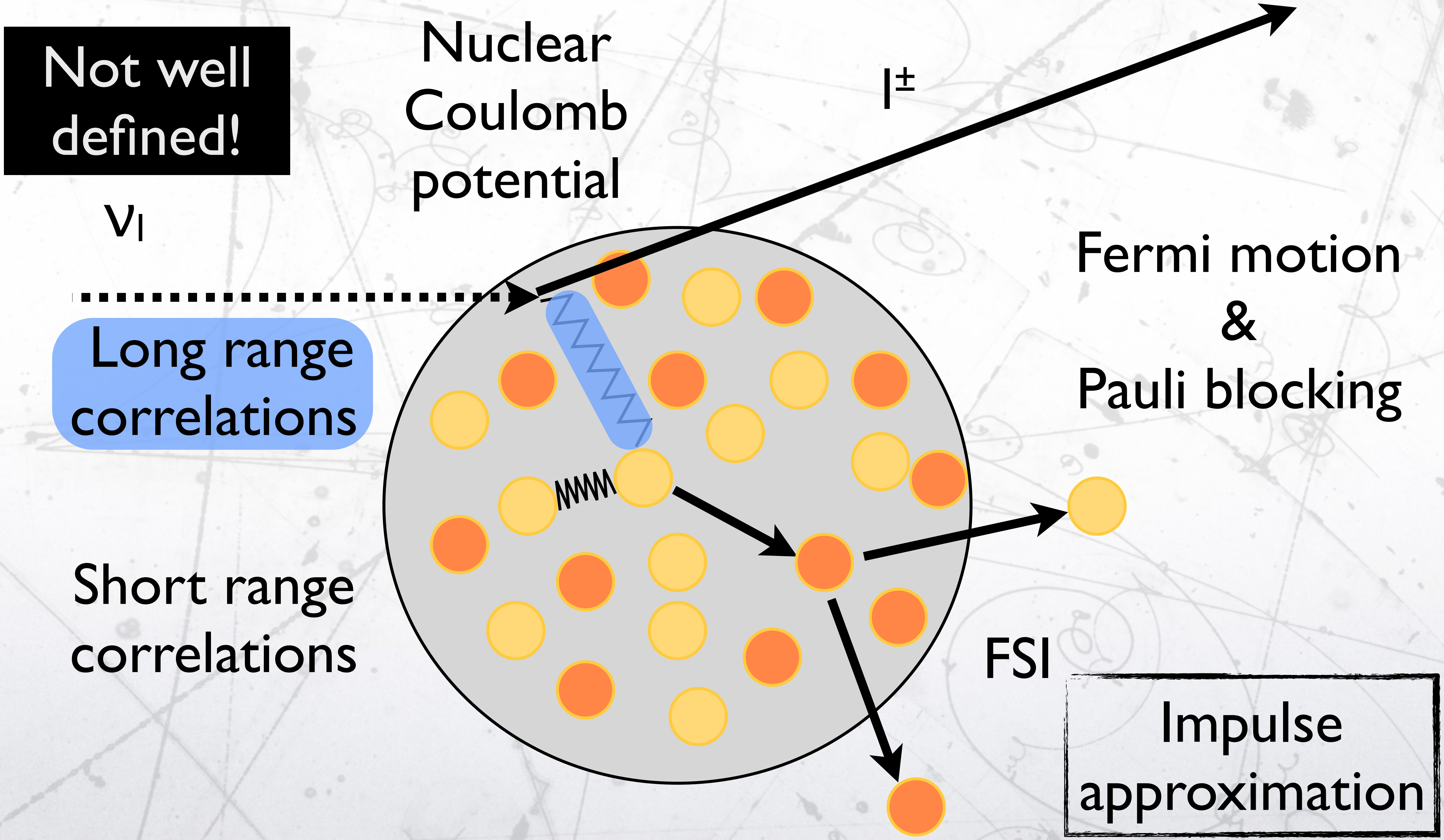
J.A.Formaggio, G.P.Zeller, Rev.Mod.Phys. 84 (2012) 1307





Present and future oscillation experiments cover a complex region full of reaction thresholds and sparse data.

Neutrino interactions



Neutrino Nucleon

- Calculated as contraction of lepton and hadronic currents.

$$\frac{d\sigma}{dk'_0 d\Omega(\vec{k}')} = \frac{G_F^2}{(2\pi)^2}\frac{|\vec{k}'|}{k_0} L_{\mu\nu} W^{\mu\nu}$$

CCQE case

$$W^{\mu\nu} = \frac{1}{2M}\int \frac{d^3p'}{2E'}\delta^4(k'+p'-k-p)H^{\nu\mu}$$

$$H^{\alpha\beta} = \mathrm{Tr}\left[(\not p + M)\,\gamma^0\,(\Gamma^\alpha)^\dagger\,\gamma^0\,(\not p' + M)\,\Gamma^\beta\right]$$

$$\langle N'|\,J^\mu\,|N\rangle = \bar{u}(p')\Gamma^\mu u(p) = \mathcal{V}^\mu - \mathcal{A}^\mu$$

- $W^{\mu\nu}$ are the hadron tensors

$$\mathcal{V}^\mu = \bar{u}(p')\left[\gamma^\mu F_1 + \frac{i}{2M}\sigma^{\mu\nu}q_\nu F_2 + \frac{q^\mu}{M}F_S\right]u(p)$$

$$\mathcal{A}^\mu = \bar{u}(p')\left[\gamma^\mu\gamma_5 F_A + \frac{i}{2M}\sigma^{\mu\nu}q_\nu\gamma_5 F_T + \frac{q^\mu}{M}\gamma_5 F_P\right]u(p)$$

The functional form of $F_A(Q^2)$ is the only degree of freedom.

Vector

Sachs form factors: $G_E = F_1 + \frac{q^2}{2m_N}F_2$

CVC from (e,e') $G_M = F_1 + F_2$

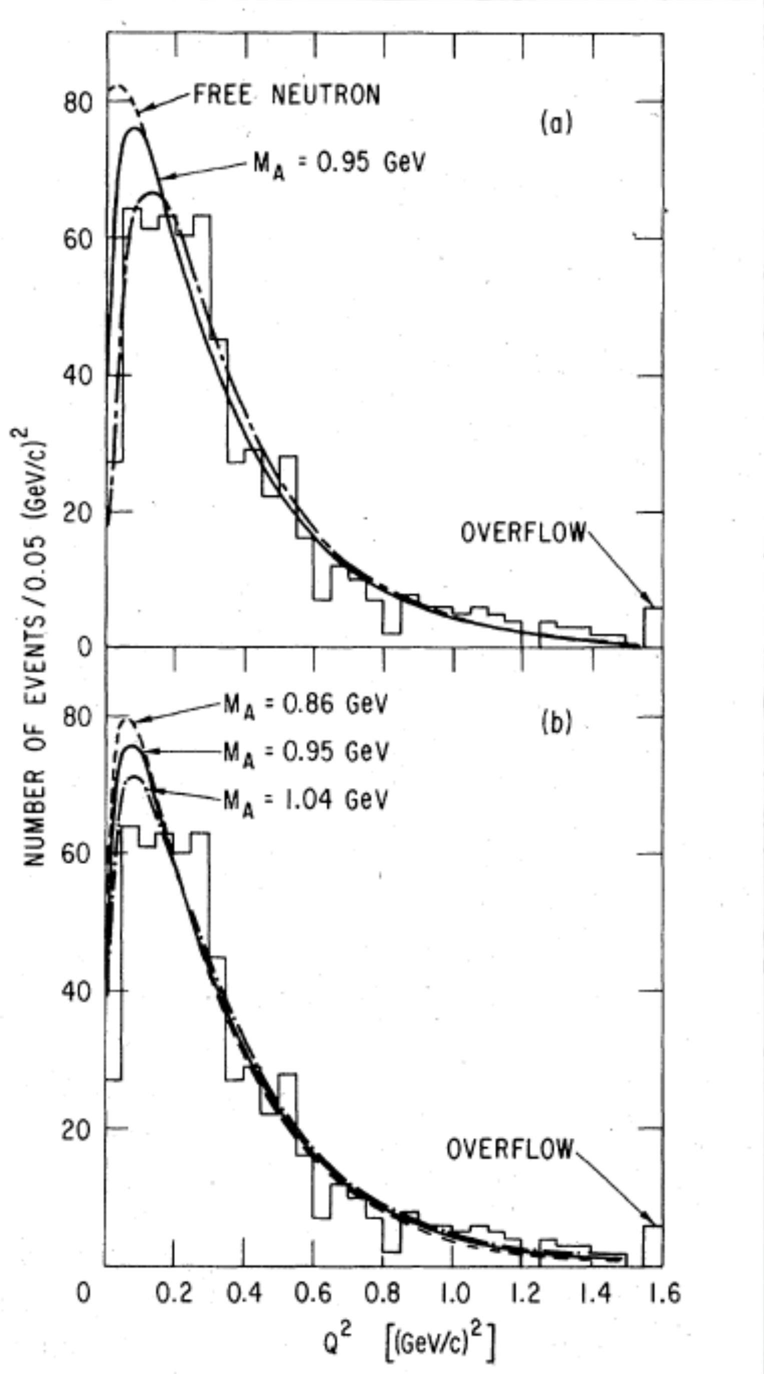
Axial

$$F_P(Q^2) = \frac{2M^2}{Q^2+m_\pi^2}F_A(Q^2)$$

PCAC

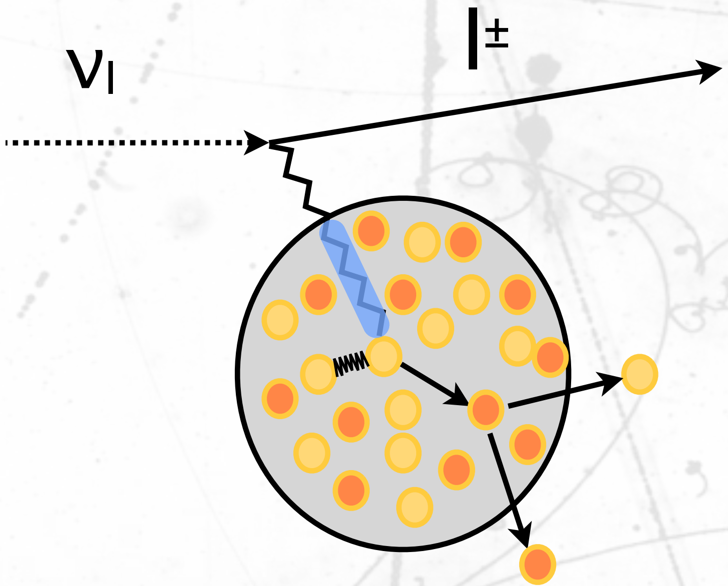
$F_A(0) \equiv g_A = 2g_{NN\pi}$ ← Goldberger-Treiman relation

Neutrino Nucleon

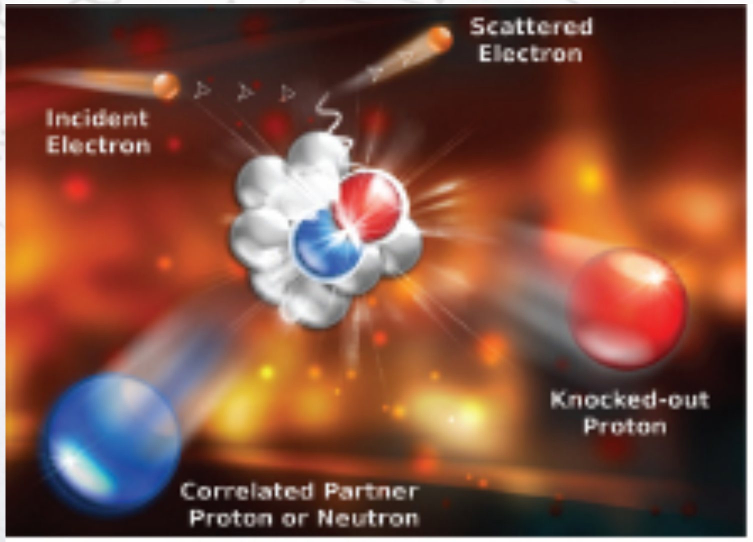


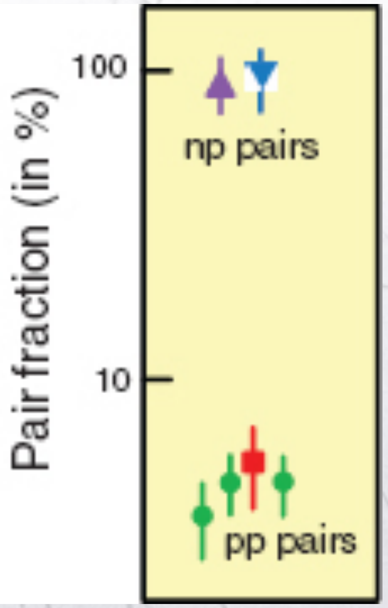
PHYSICAL REVIEW D
VOLUME 16, NUMBER 11
1 DECEMBER 1977

- Free nucleon (H and D) data is very limited.
- Many of the assumptions of the basic cross-section can't be accurately tested with nuclei:
  - Conserved Vector Current
  - Partially Conserved Axial Current.
  - Dipole form factor
  - Vanished scalar and tensor form factors.
- …



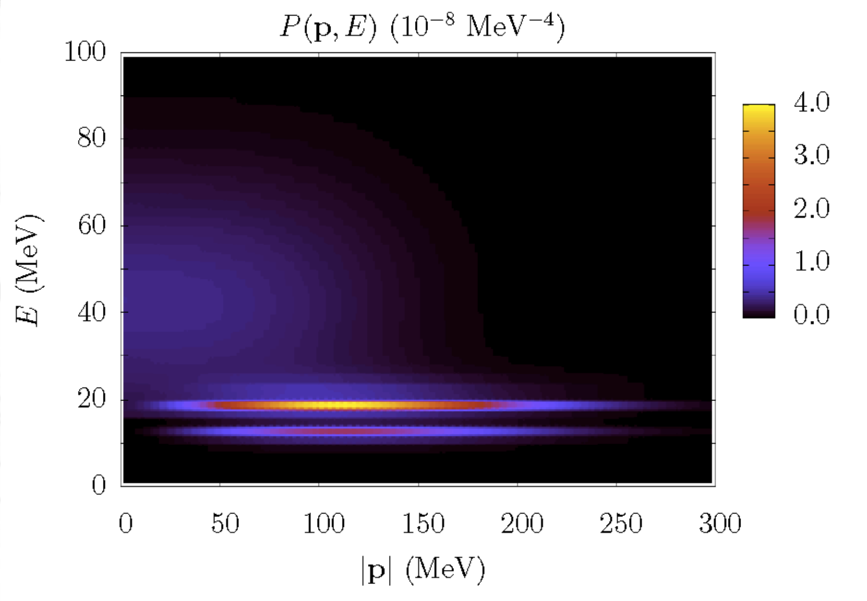
- Normally considered the "impulse approximation" or factorisation:
  - nucleon **assumed** free in nuclear media !
  - nucleon free in nuclear potential: no nucleon correlations!.
- Nuclear effects added on the top:
  - Fermi momentum.
  - Pauli blocking.
  - Short and long range nuclear correlations.

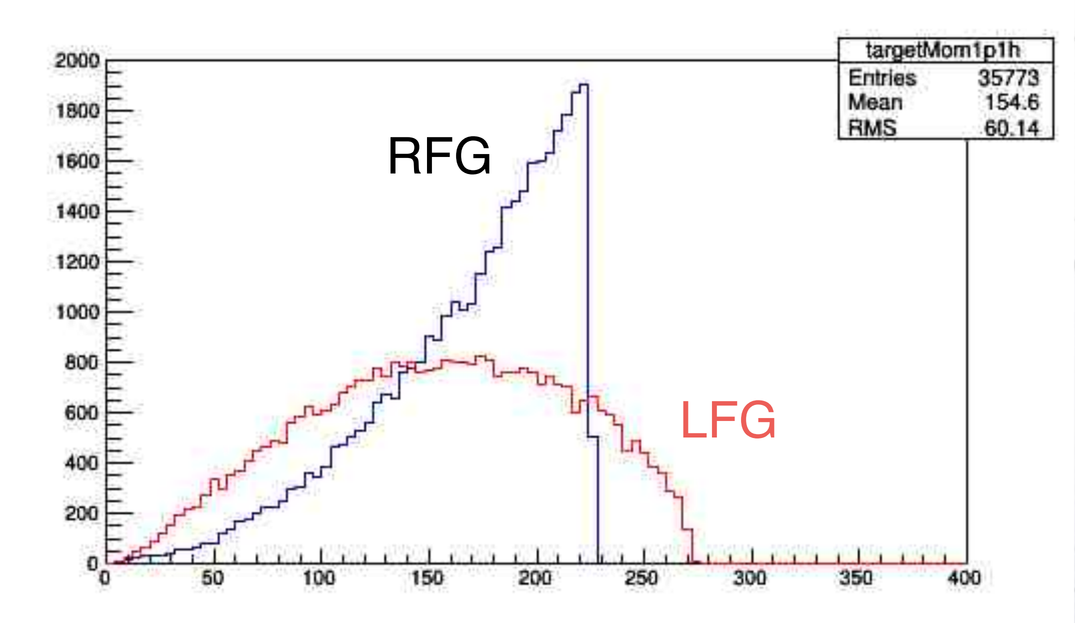




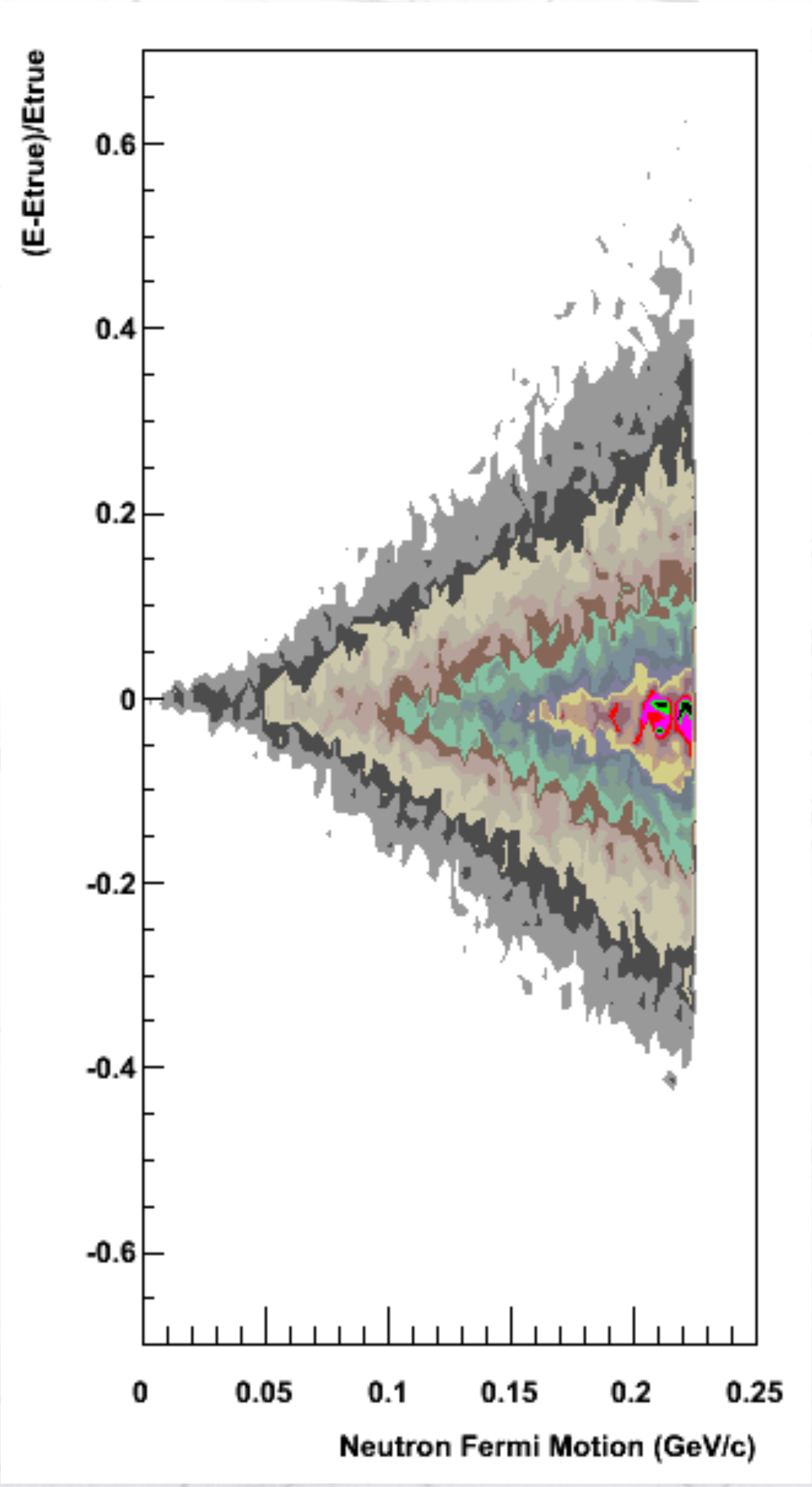
Fermi Momentum

- Actually 4 different implementations:
  - Relativistic Fermi gas.
  - Local Fermi gas. (Radial dependency)
  - Spectral functions (for light nuclei)
  - "Ab initio" calculations (non impulse approximation).
- Except for the "Ab initio" all the others can be applied to the usual "impulse" approximation.





Fermi and Energy



$$E_\nu = \frac{m_n E_\mu + \frac{m_p^2 - m_n^2 - m_\mu^2}{2}}{m_n - E_\mu + P_\mu \cos\theta_\mu}$$

- The Fermi energy affects the Energy reconstruction.
- It is very difficult to identify its contribution and it can bring up to 250 MeV/c to the total momentum balance.

Pauli blocking

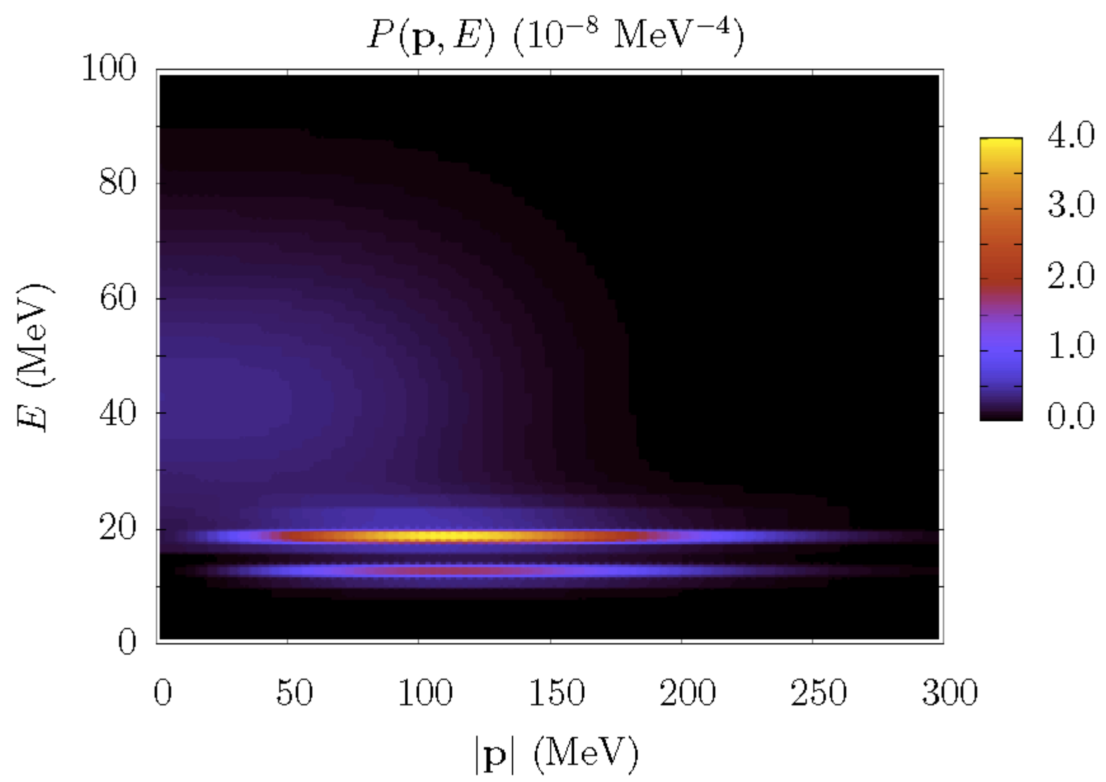
- Same 4 different implementations:
  - Relativistic Fermi gas.
  - Local Fermi gas.
  - Spectral functions
  - "Ab initio" calculations (non impulse approximation).

Pauli blocking should be also implemented consistently for the Final State Interactions.

Pauli blocking is delicate to re-weight in case of single Fermi level (RFG).

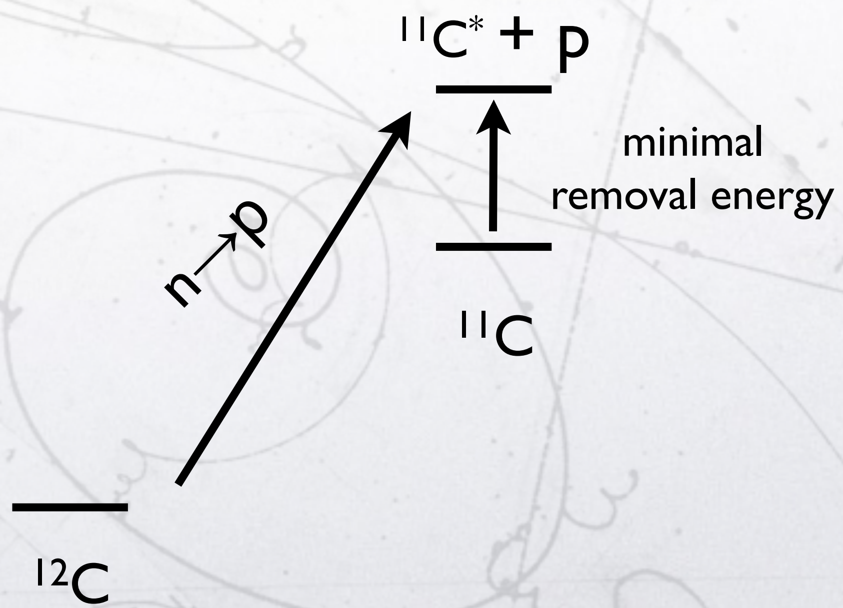
Bind Energy

- (As far as I know) for impulse approximation there are 3 ways to implement it:
  - Effective target mass (m→m-E_b)
  - Dispersion relation (Spectral function).
  - Nuclear removal energy.



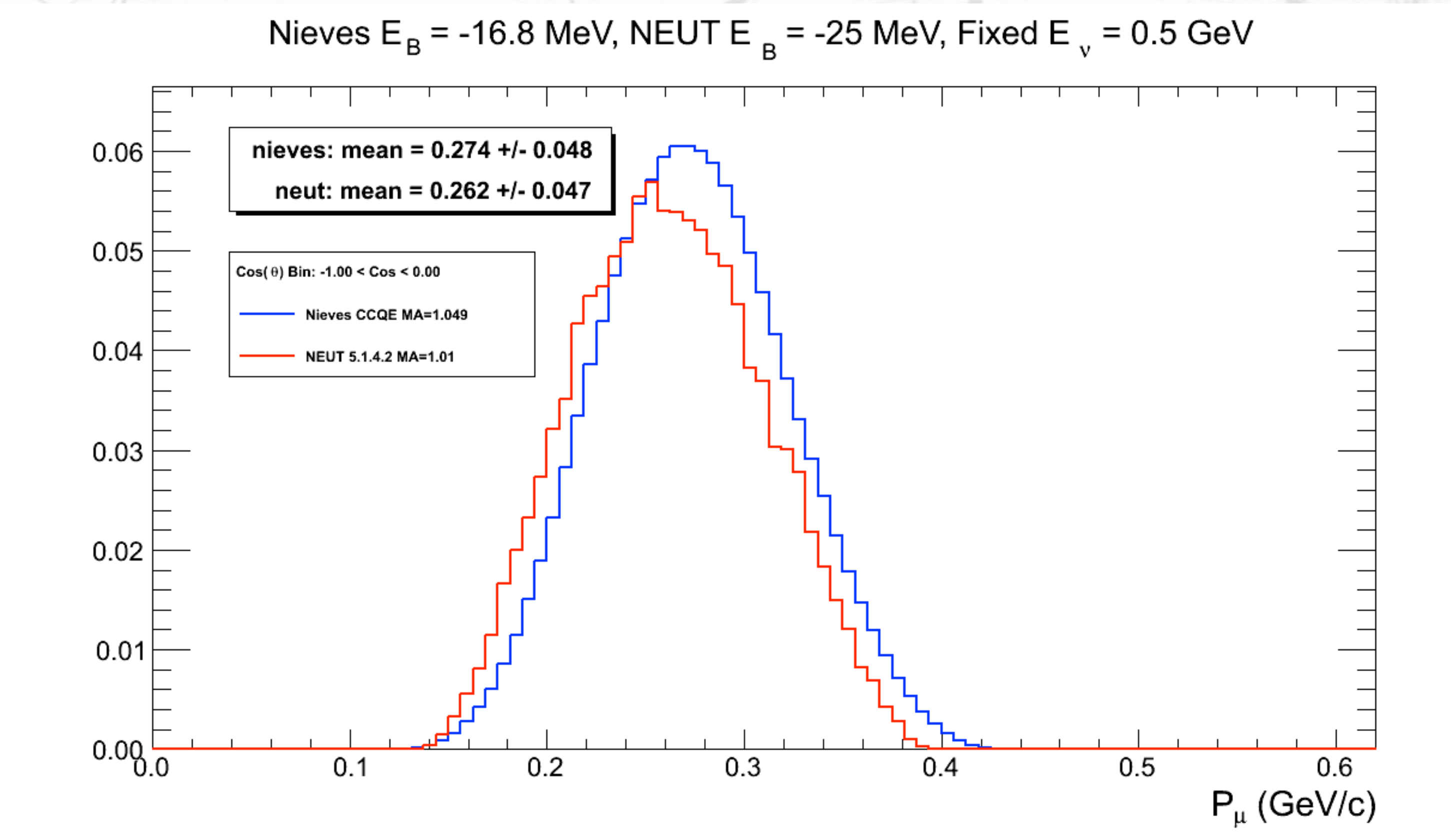
Bind energy is variable because final nuclear states might be excited.

~6 MeV γ in SK



Bind Energy

- Effect is visible at T2K energies.
- Since the Bind Energy is not a fixed value (0- 10 MeV) this could smear distributions.



Nieves E_b = -16.8 MeV
Neut E_b = -25.0 MeV

Bind energy is a delicate parameter for event re-weight making calculations complicated.

Bind Energy

- And consistent for neutrinos and antineutrinos:

Target	ν	ν	NEUT
^{12}C	$^{12}C \rightarrow {}^{12}C + p$ $\Delta E = 17.43$ MeV	$^{12}C \rightarrow {}^{12}B + n$ $\Delta E = 17.25$ MeV	25 MeV
^{16}O	$^{16}O \rightarrow {}^{16}O + p$ $\Delta E = 14.37$ MeV	$^{16}O \rightarrow {}^{16}N + n$ $\Delta E = 13.48$ MeV	27 MeV

Coulomb potential

- Global nucleus charge is seen by the produced lepton: Coulomb potential.
- This is model as a deviation from the dispersion relation:

$$\vec{p} \rightarrow \vec{p}$$

$$E \rightarrow E \pm V_c$$

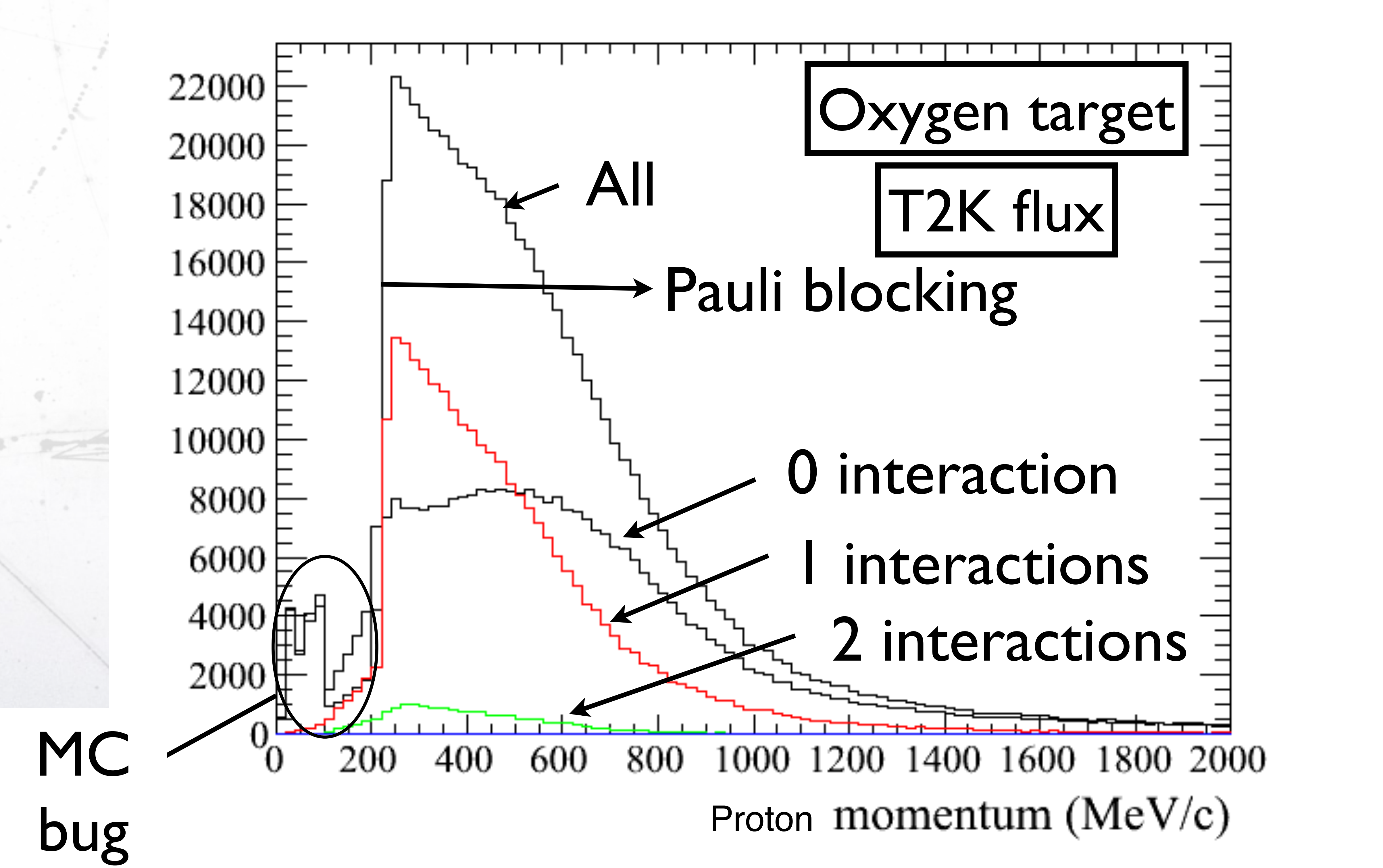
Different effect for neutrinos and antineutrinos

- The value depends on the radial position of the interaction.
- It can be as large as 5-7 MeV to be compared with the typical (in T2K) 200-400 MeV muons.

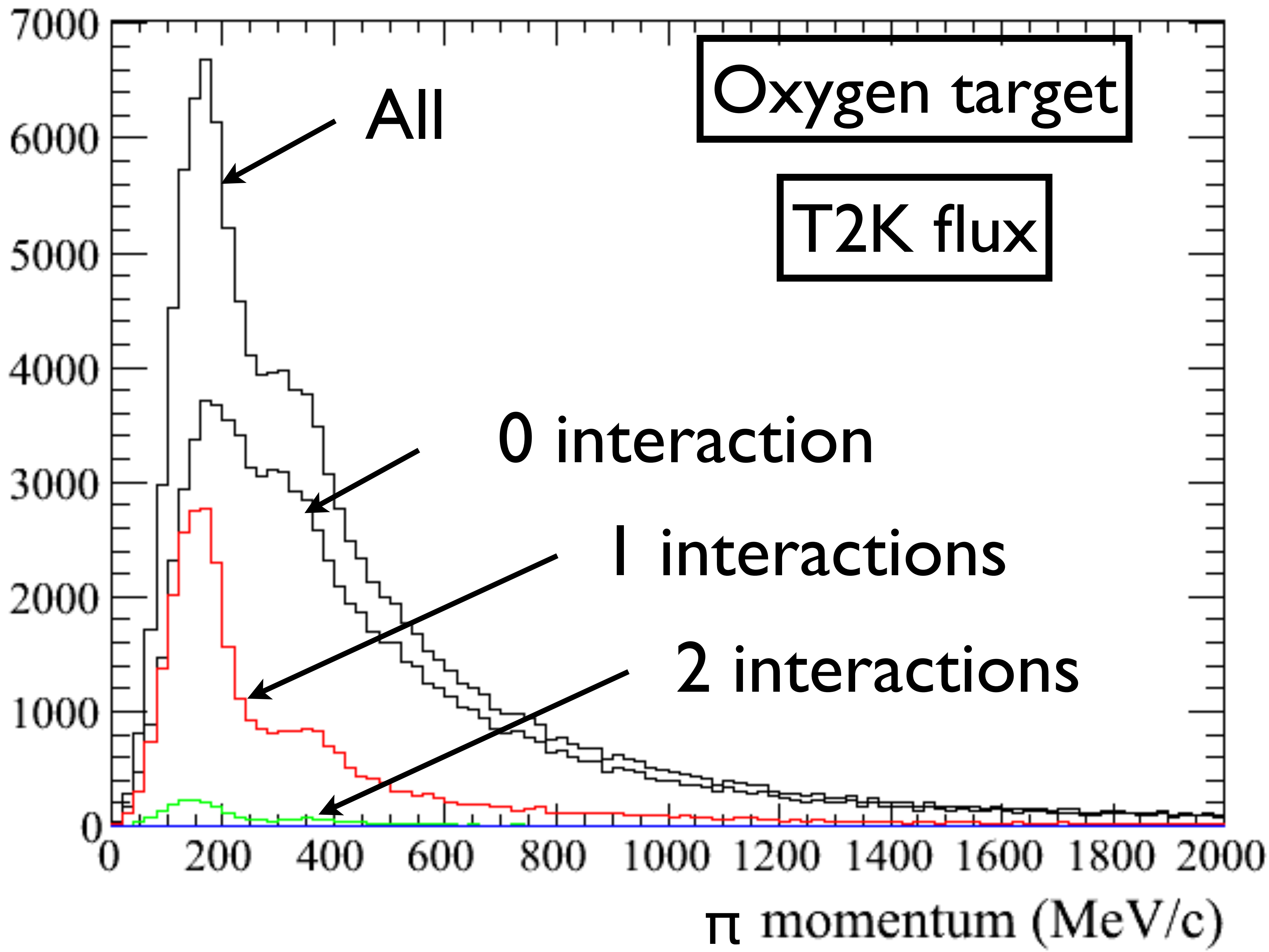
Final State Interactions

- Strong interactions are complicated. Many channels, unknown cross-section, resonances, etc…
- Several models:
  - Semi-classical Cascade model with(out) medium corrections based on the old Oset et al.
  - Quantum kinetic transport theory.
- Normally tuned to external data.
  - Assumption: Interactions with nucleons in medium = free nucleons.

Not sure what to do here. We need eA data and probably a direct comparison for the two main models from initial hadrons inside the nucleus.

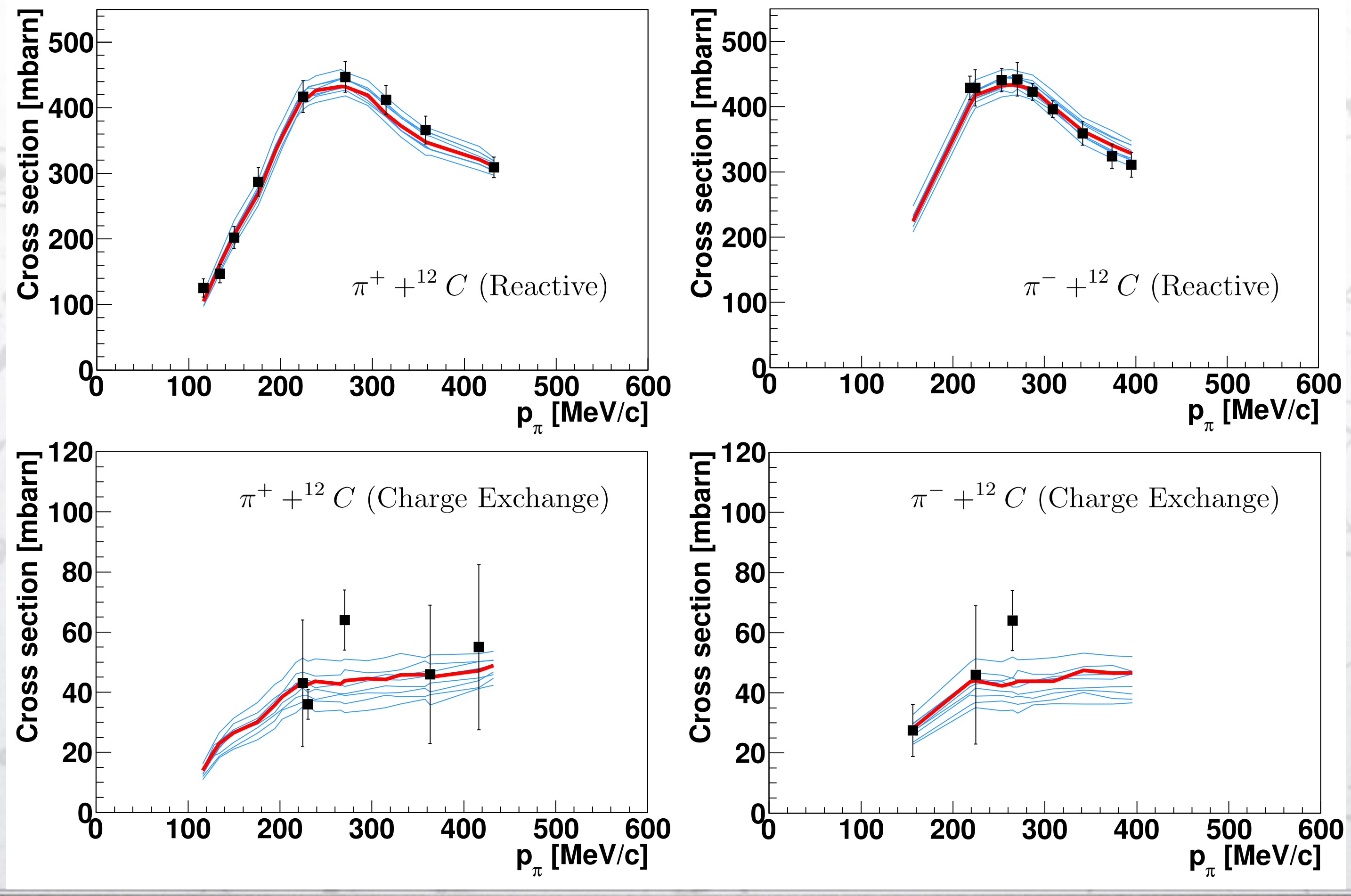

Oxygen target
T2K flux
All
Pauli blocking
0 interaction
1 interactions
2 interactions
MC bug
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
22000
0 200 400 600 800 1000 1200 1400 1600 1800 2000
Proton momentum (MeV/c)

Final state interactions



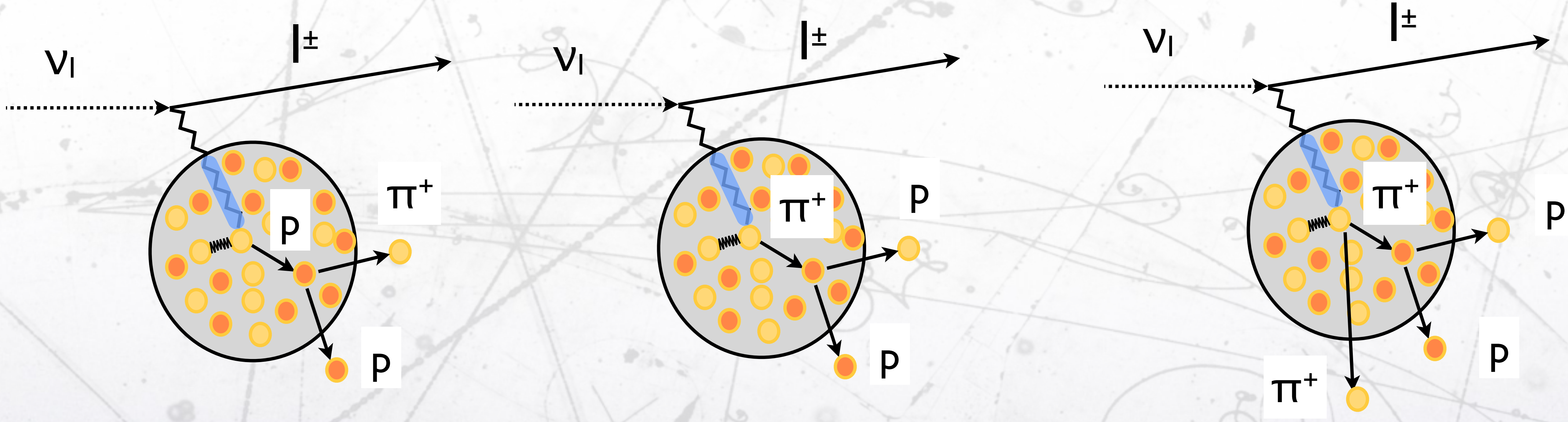
Final state interactions

- Experimental data includes only (external) pion scattering with the Nuclei.
    - It does not include full range of kinematics.
- Some models (GIBBU) include mean field calculations and are available for both Neutrino and heavy ion collisions.



- Example: events with $\mu^{-}+\pi^{+}$ in the final state.
- Topology is altered by FSI.

FSI alters the definition of the event



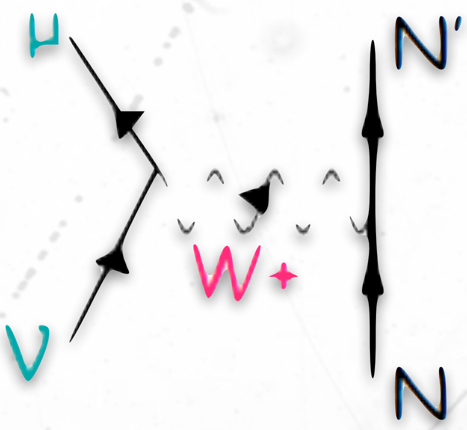
1. CCQE
2. proton in final state
3. p p -> p π^{+}

1. CC1 π^{+}
2. π^{+} in final state
3. π^{+} p -> p p

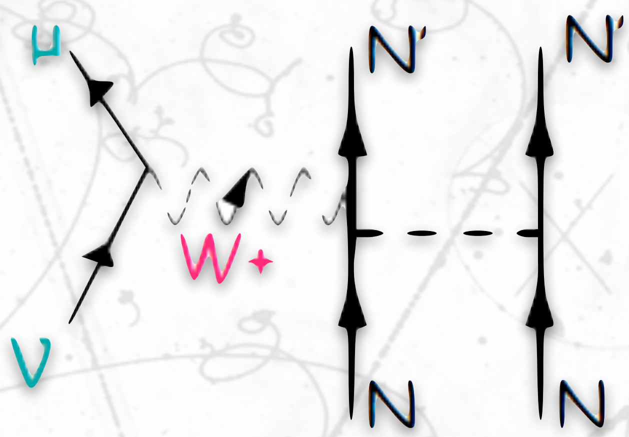
1. CC 2π^{+}
2. 2π^{+} in final state
3. π^{+} p -> p p

Modelling interactions

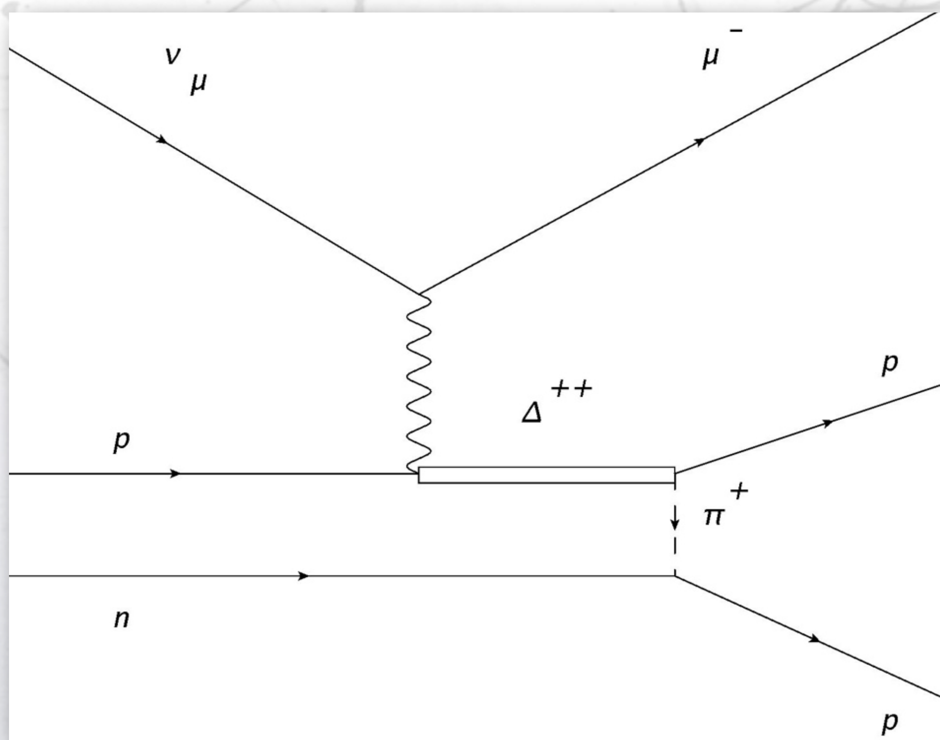
CCQE

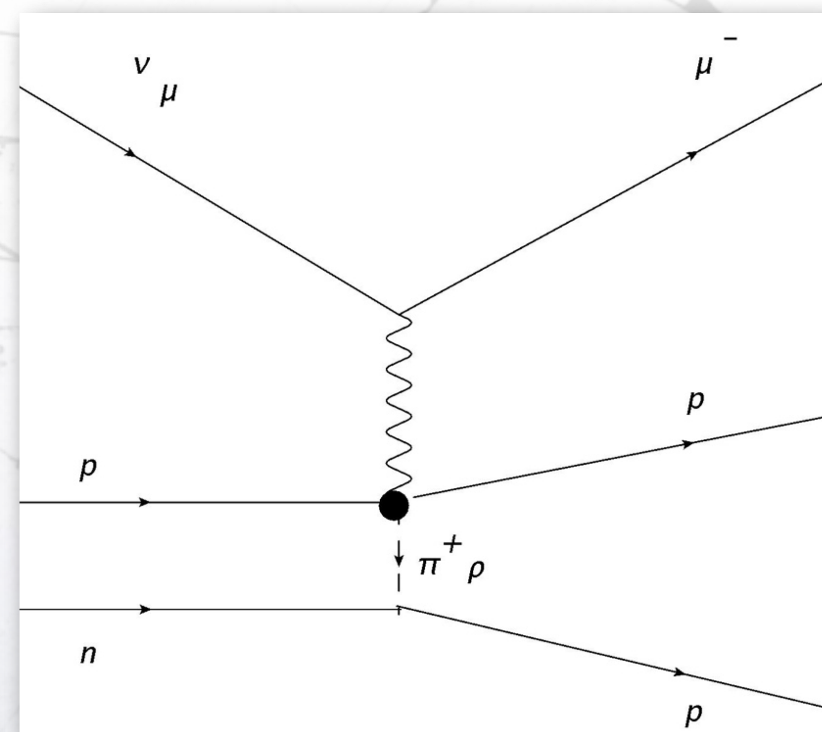


CC-2p2h



- Charge current without pions are made of several interactions
- 2p2h is basically the exchange of a meson between two close by nucleons in the nucleons with the emission of 2 nucleons.

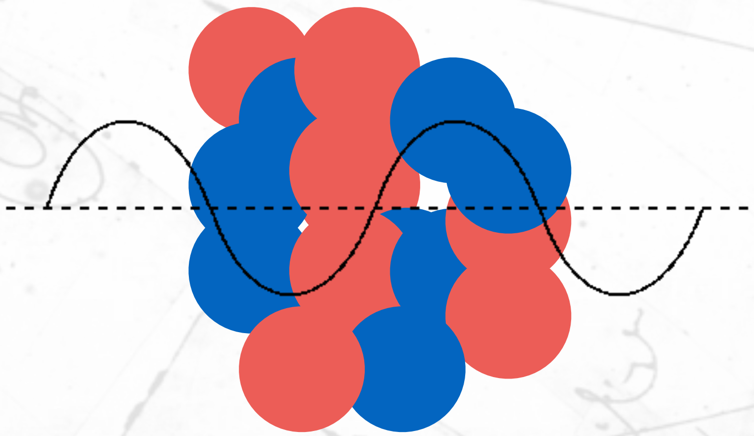




- The pion can be produced in a contact point or virtual Δ^{++}.

Long range correlations

- The typical wavelength of the particles in ν interactions are the size of the nucleus.
- Particles see the nucleus as whole.
- Long range correlations modify the W self-energy in the presence of high density nuclear media.
- Long Range Correlations alter the cross-section dependency on virtual energy of the W

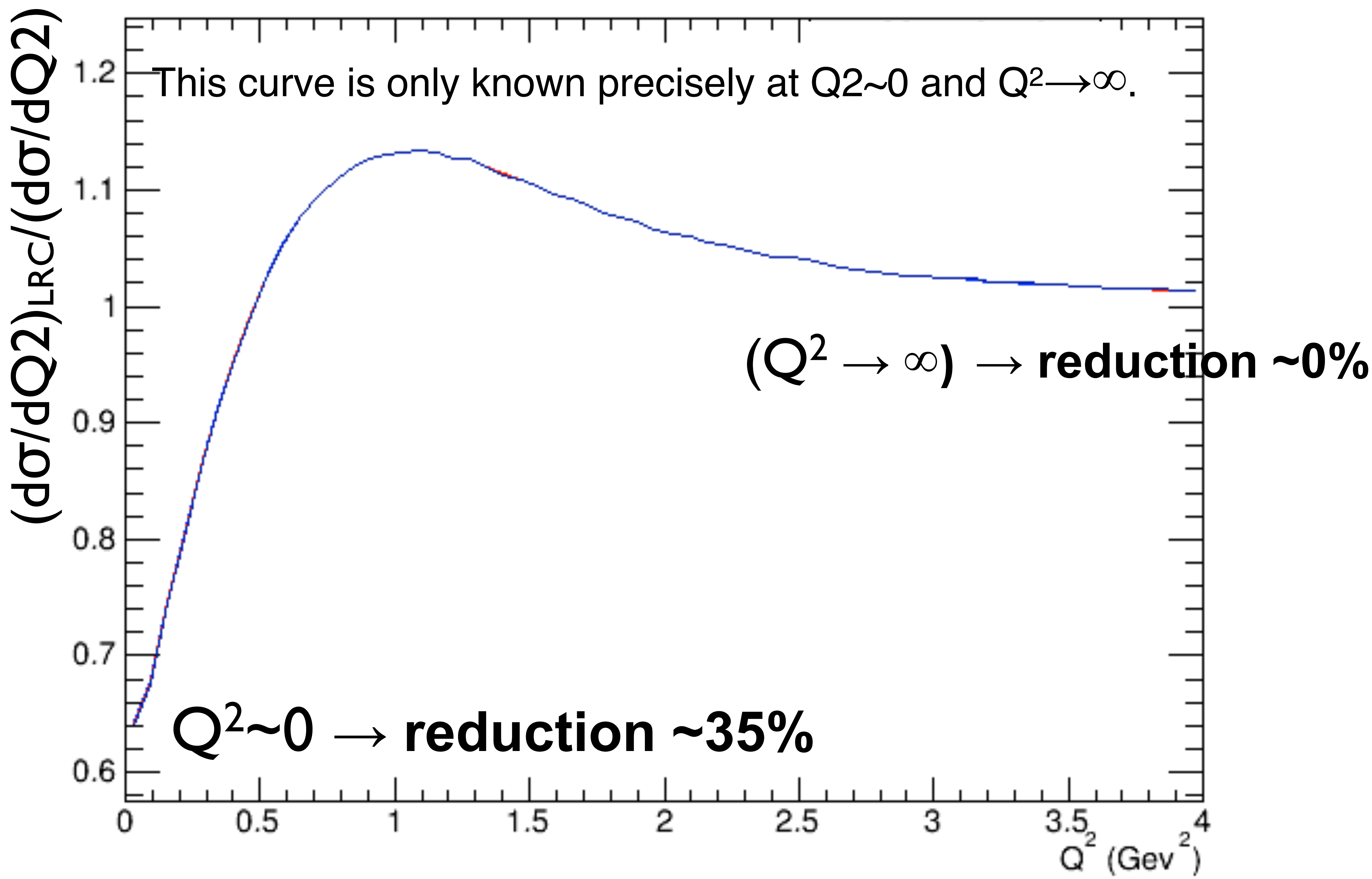


De Broglie particle wavelength

$$\lambda = \frac{\hbar}{E} = \frac{197.3nm}{E(eV)}$$

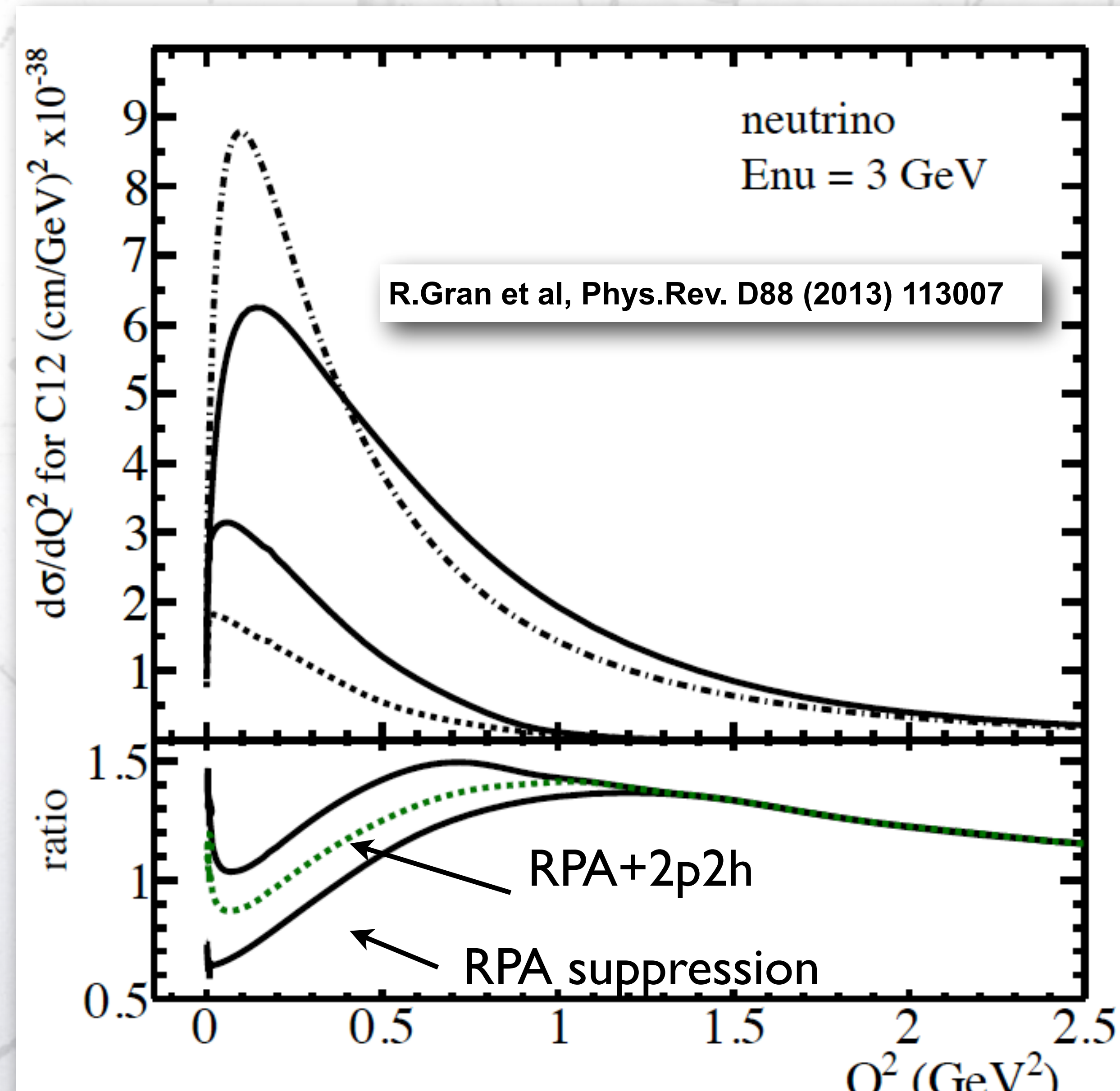
$$\lambda_{100MeV} = 1.97fm$$

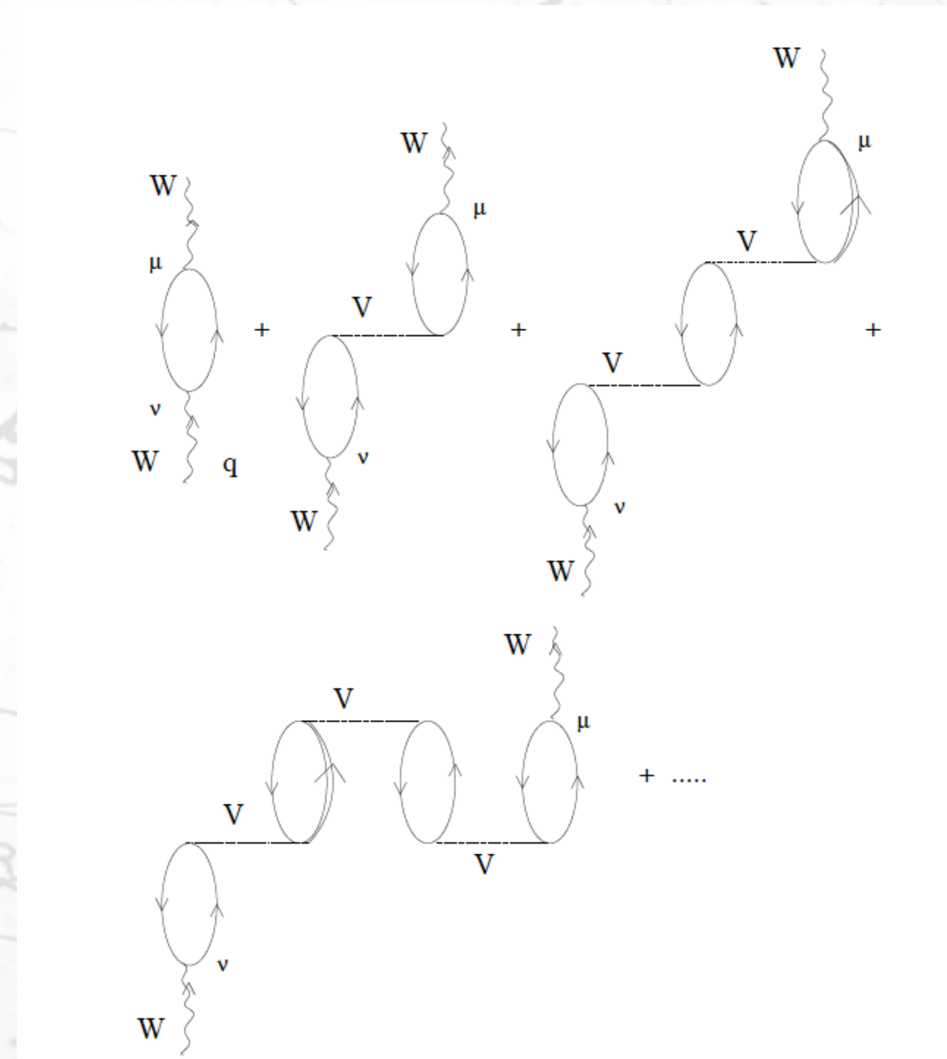
$$R_{Carbon} \approx 2.7fm$$



This curve is only known precisely at Q2~0 and Q²⟶∞.
(Q² → ∞) → reduction ~0%
Q²~0 → reduction ~35%
(dσ/dQ2)LRC/(dσ/dQ2)
1.2
1.1
1
0.9
0.8
0.7
0.6
0
0.5
1
1.5
2
2.5
3
3.5
4
Q² (Gev²)

- Based on RPA calculations.





$$V_L^{rel} = 0.08 \frac{4\,\pi}{m_\pi^2} \left(0.63 - \frac{\Lambda_\pi^2 - m_\pi^2}{\Lambda_\pi^2 - q^2} \frac{q^2}{q^2 - m_\pi^2} \right)$$

$$V_T^{rel} = 0.08 \frac{4\,\pi}{m_\pi^2} \left(0.63 - 2. \frac{\Lambda_\rho^2 - m_\rho^2}{\Lambda_\rho^2 - q^2} \frac{q^2}{q^2 - m_\rho^2} \right)$$

RPA

- Very uncertain in many regions of q^2:
  - MC needs to be implemented with uncertainties.
  - Need data to constrain the parameters.
- Phenomenological calculations points to a multiplicative factors:

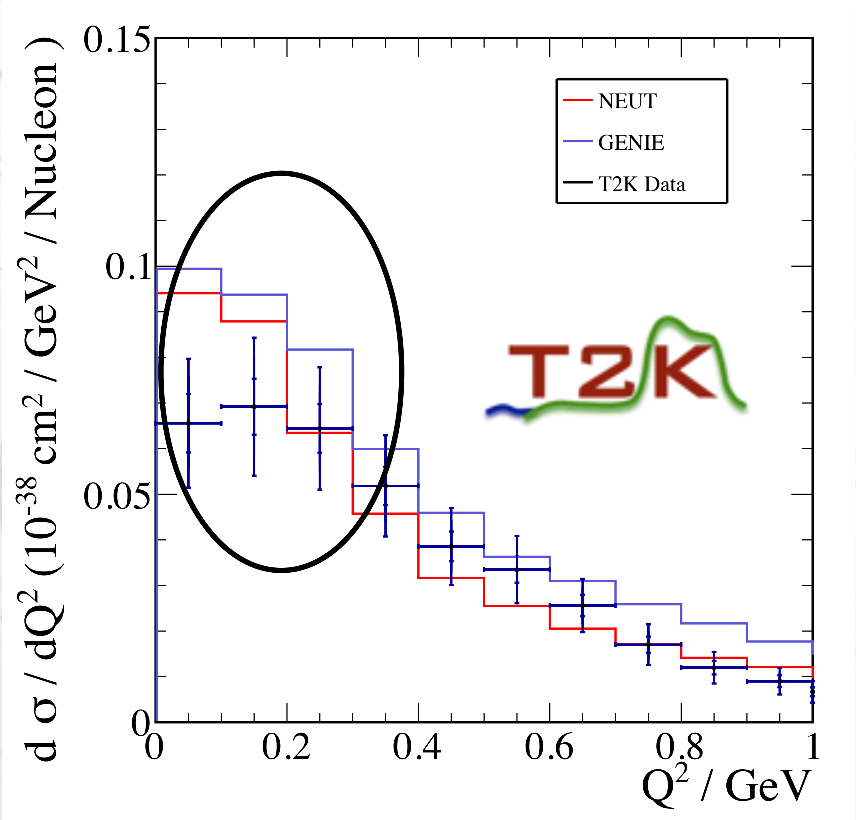
$$\frac{d\sigma}{dq^2} = f_{RPA}(q^2) \frac{d\sigma_{Nucleon}}{dq^2}$$

- But!, this is only computed for CCQE.

Same should be present for CCΔ !!!!

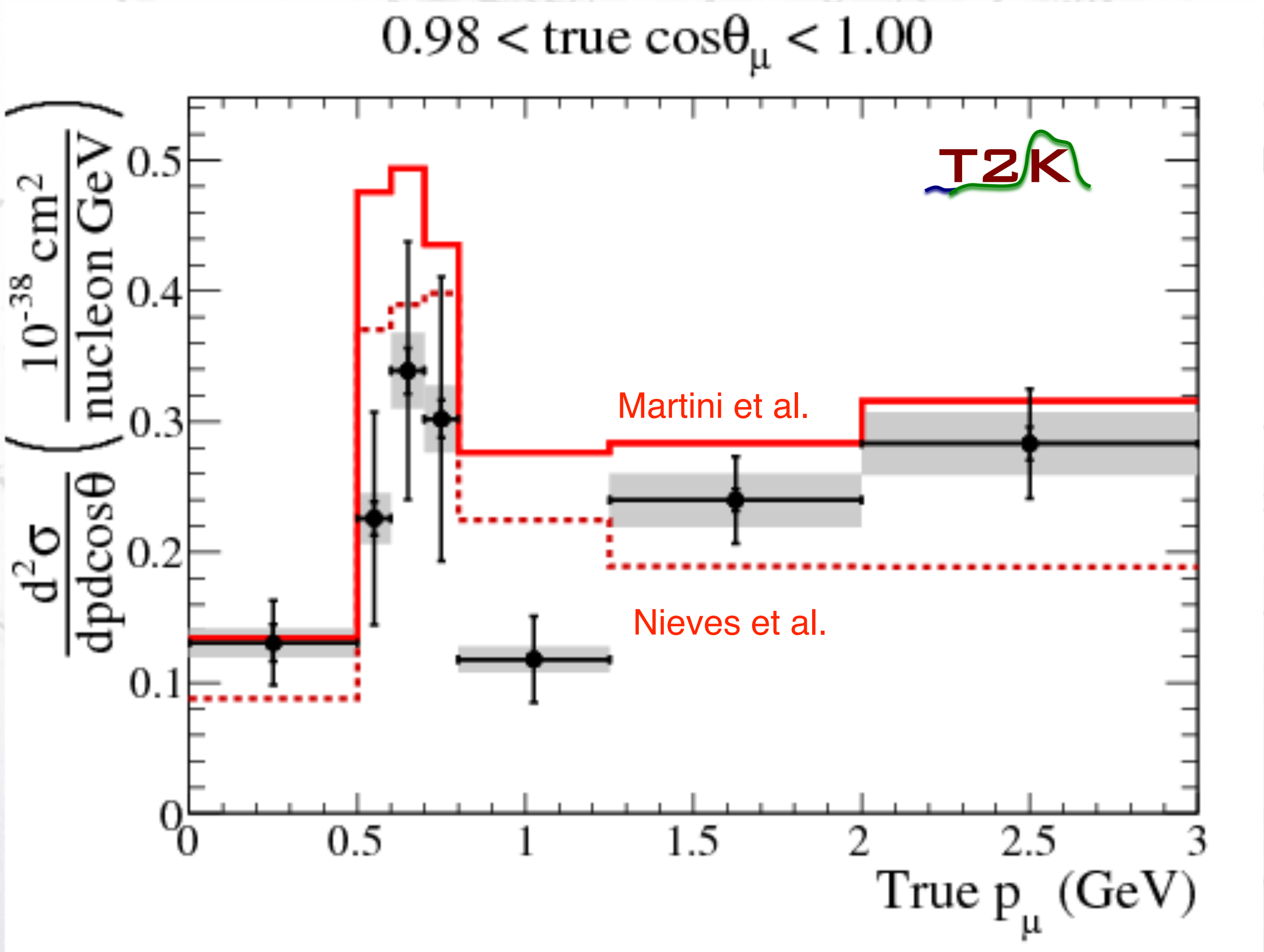
Is $RPA_{CCQE} \sim RPA_{CC\Delta}$?

Calculations needed !



How bad is bad I ?

μ momentum distribution in the forward direction

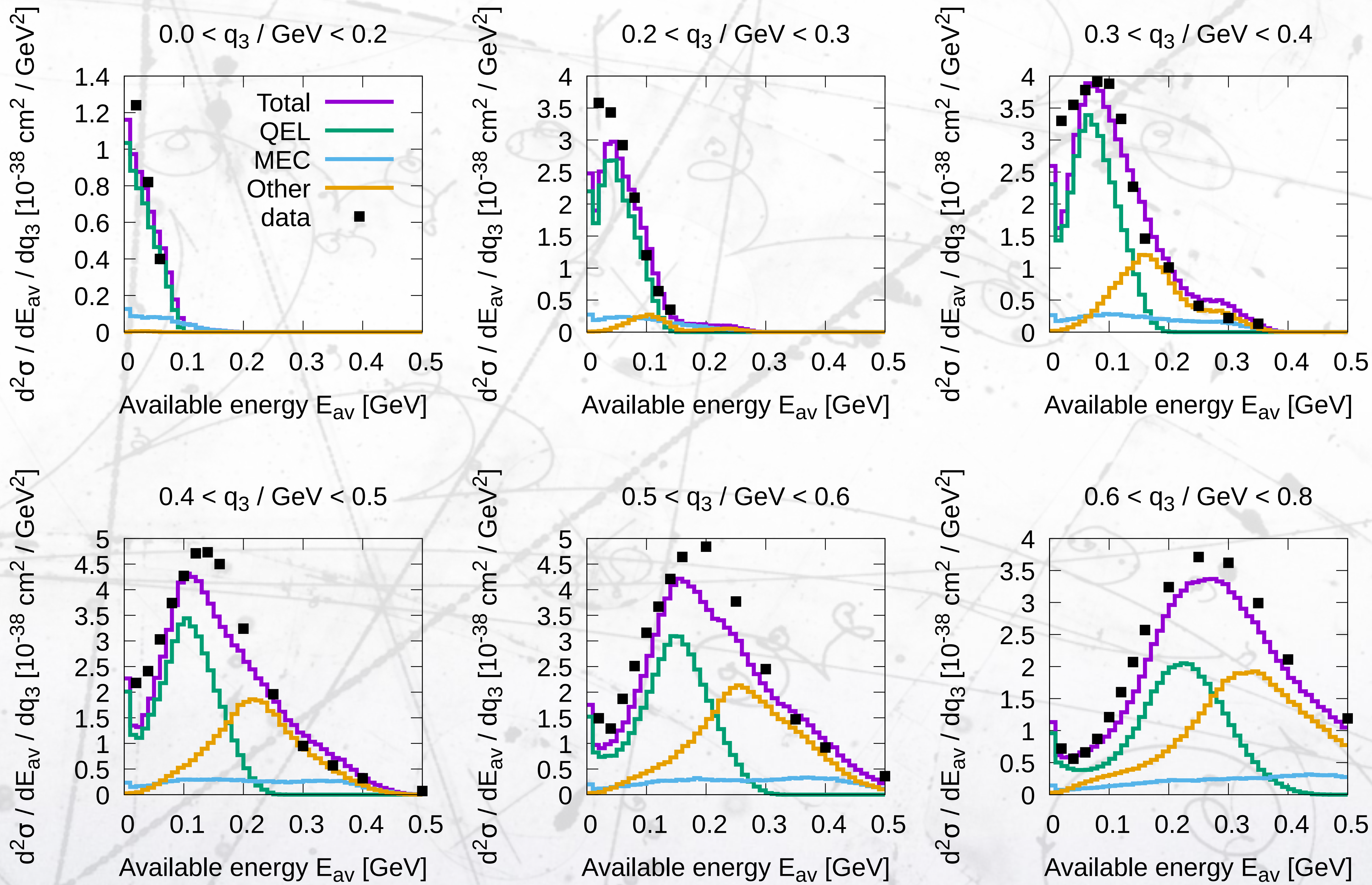


$$Q^2 = -q^2 = 2(E_\nu E_\mu - p_\nu p_\mu \cos\theta_m u) - m_\mu^2$$

- In one bin we get different E_ν (flux) & Q^2 (x-section) contributions.
- The flux is constrained from the hadro-production.
- Adjusting the model to the flux will migrate problems from flux to cross-section and viceversa.

Low and High Q2 contains different level of uncertainties at the nucleon level (form factors) and nuclear level (short and long range correlations)

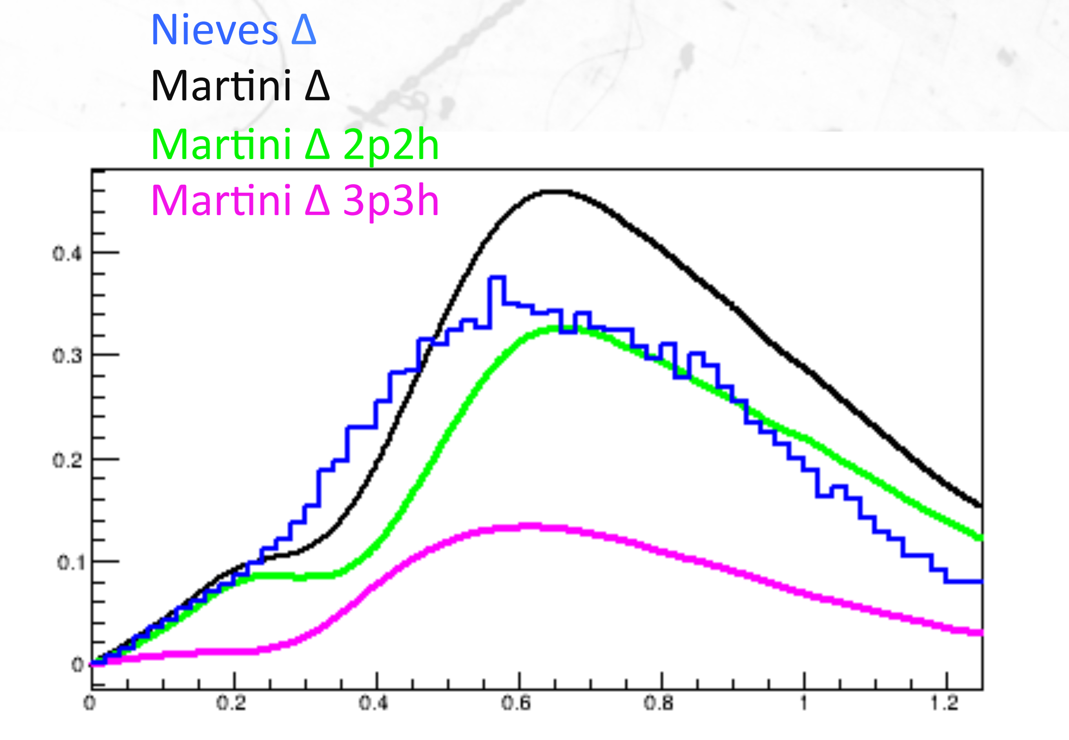
Nieves et al. and Martini et al. are the best two models in the market. Same physics but two implementations !

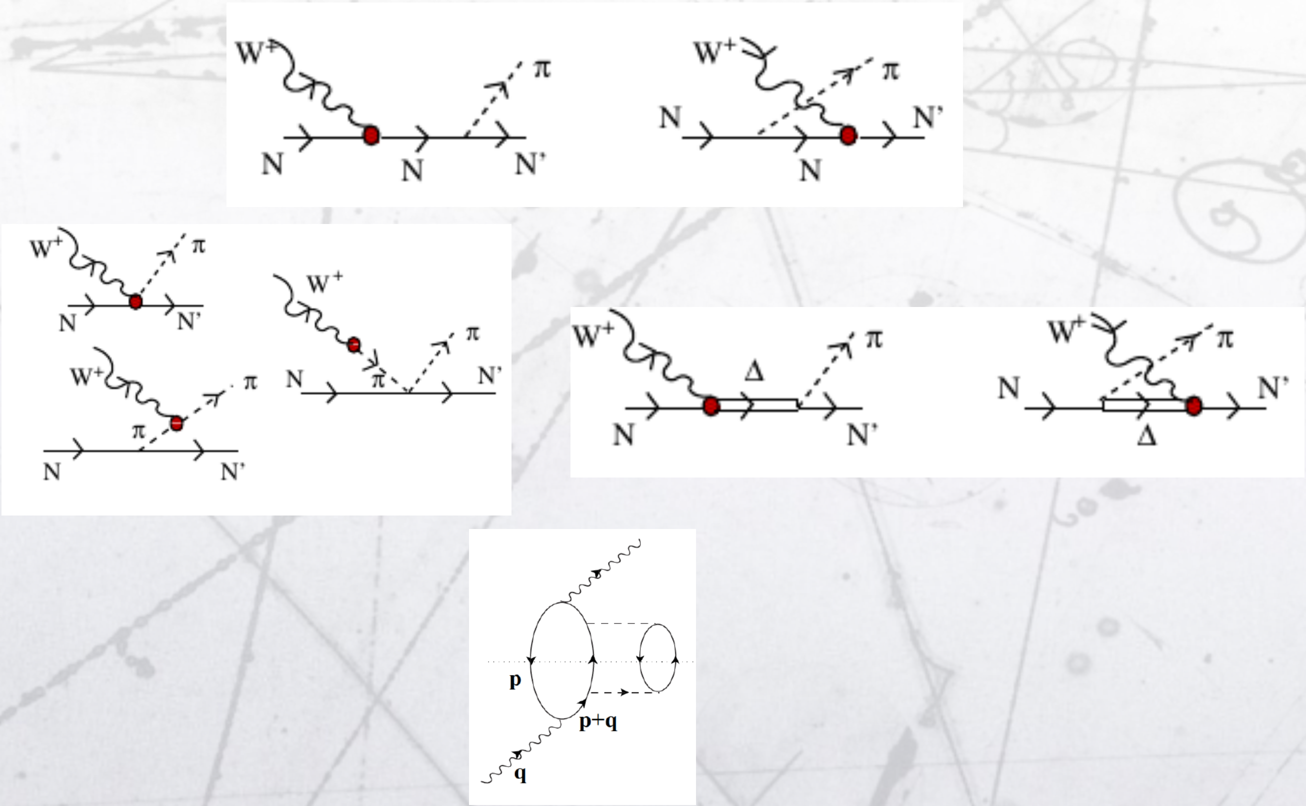


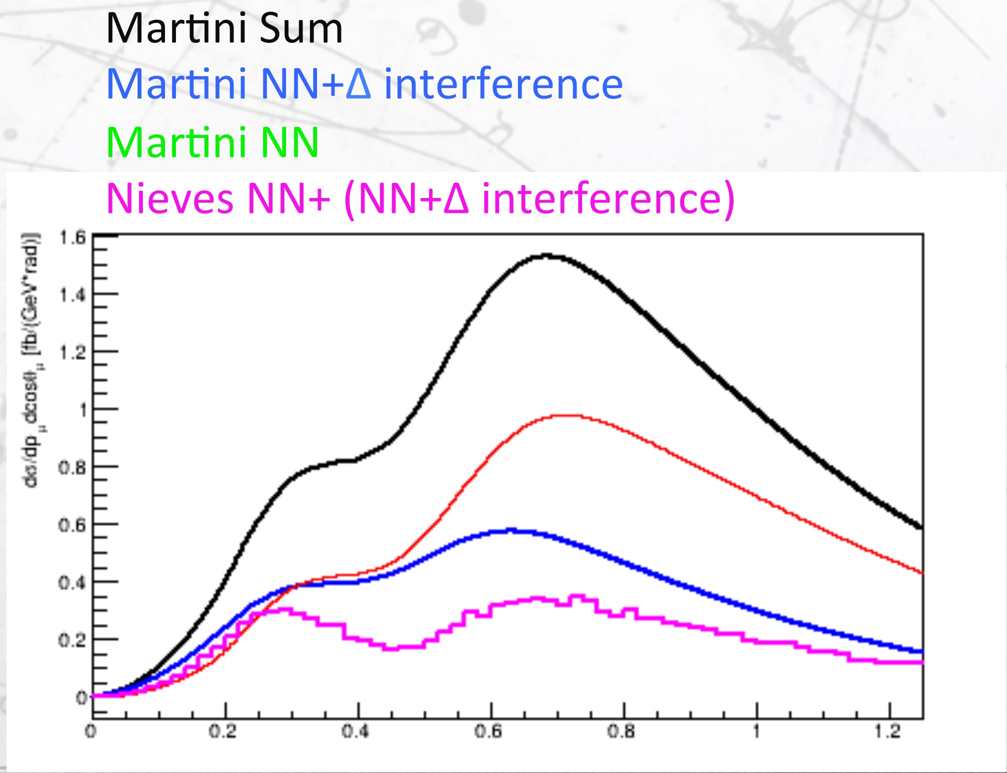
Available energy in Minerva is the sum of proton and charged pion kinetic energy and neutral pion, electron, and photon total energy

How bad is bad III ?

- Very similar models (microscopic)) give very different results.

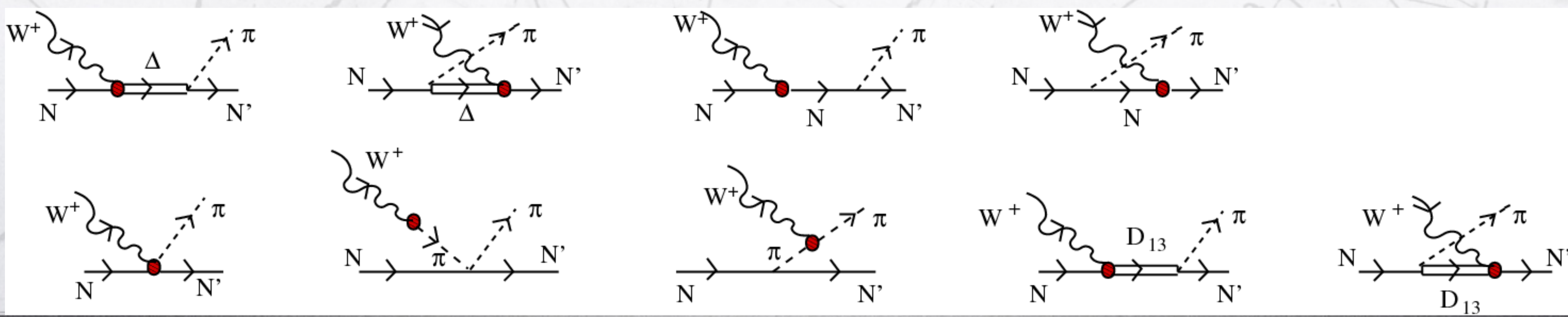






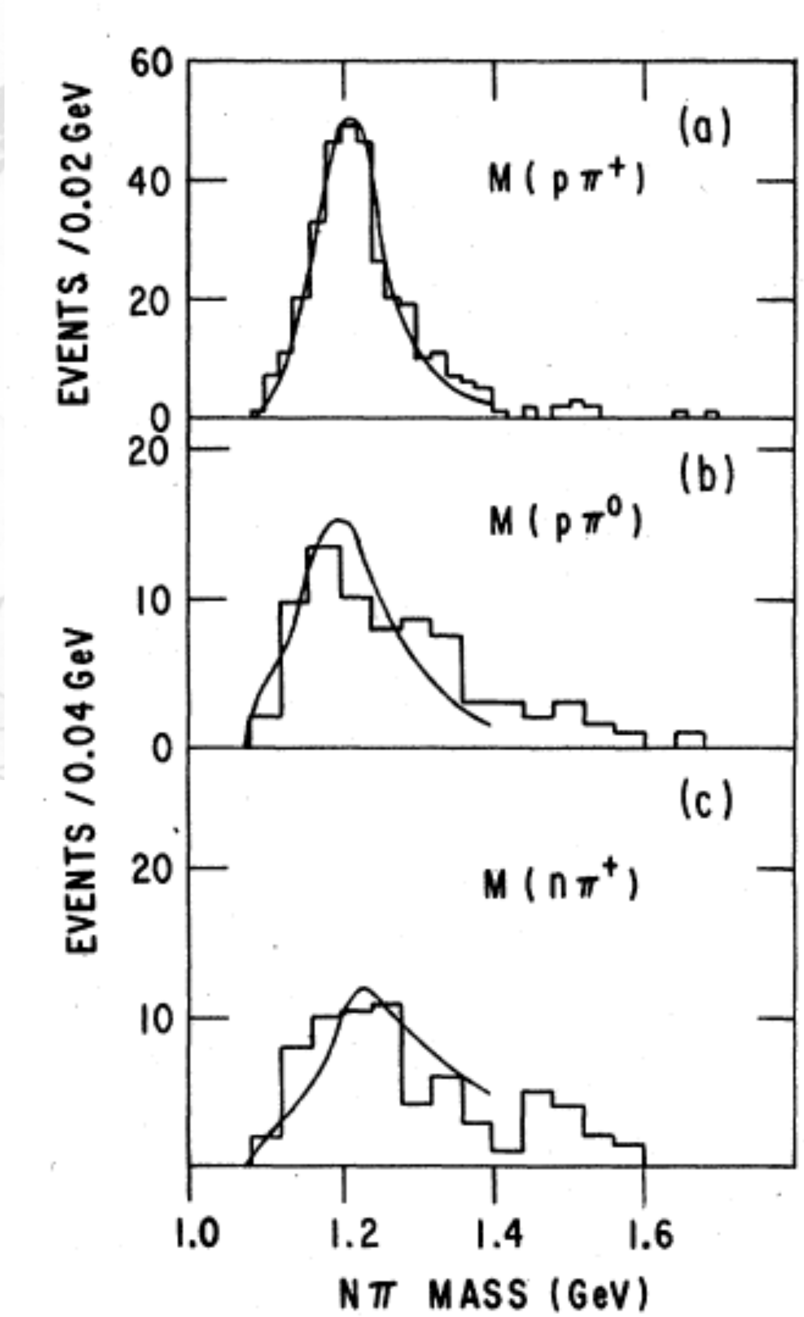
Single pion production

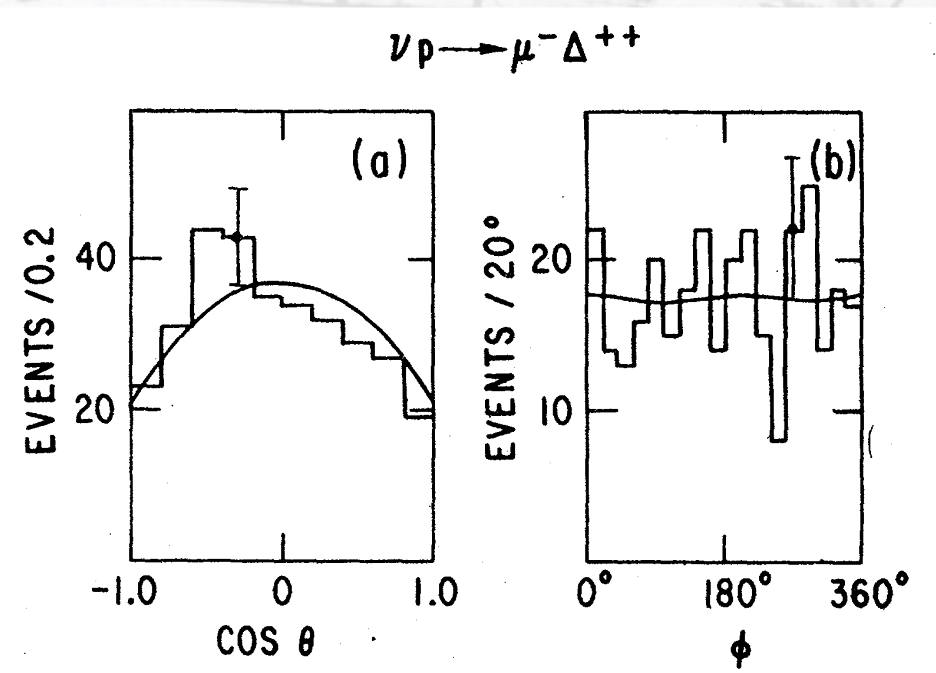
- CCπ Second most relevant cross-section in oscillation experiments.
- Cross-section unknown @ the nucleon level.
  - Complex modelling with many intermediate resonances and non-resonant contributions.
- All set of long and short rage correlation effects in CC1π are ignored in actual pion production models.

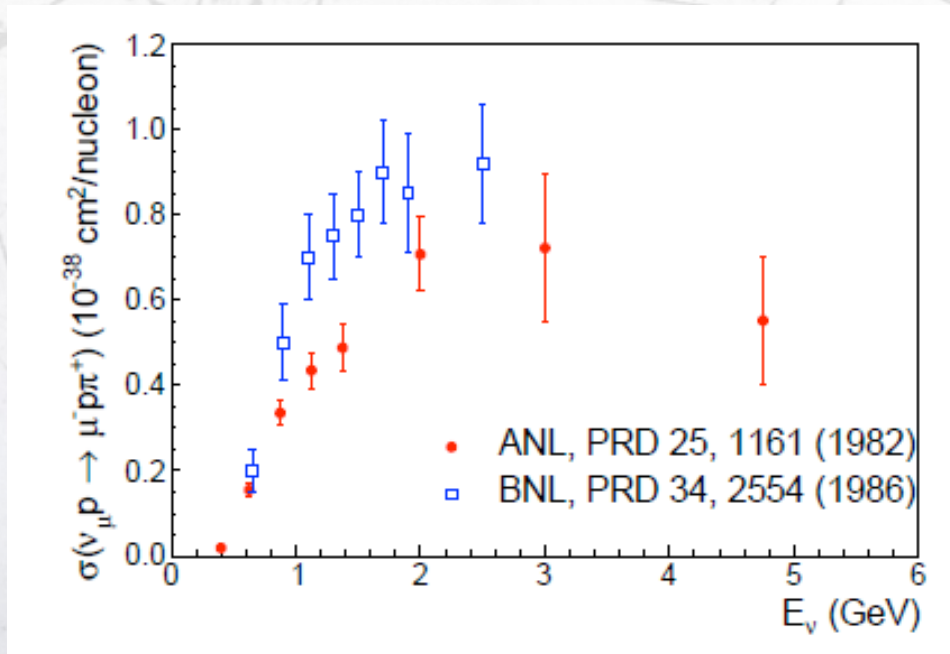


Single pion production

- Poor knowledge at nucleon level both theory and experiment:
  - Mixture between resonant and non-resonant interactions.
  - many resonances and spin amplitudes.
  - poor data.

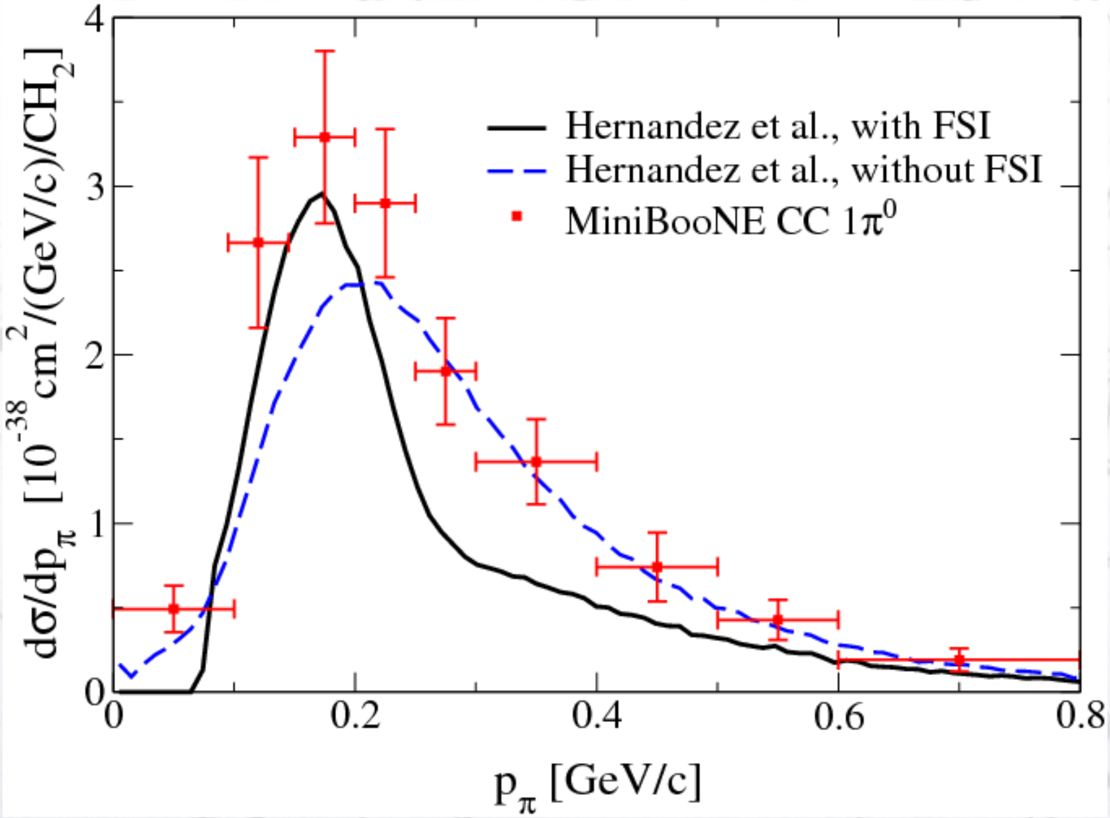


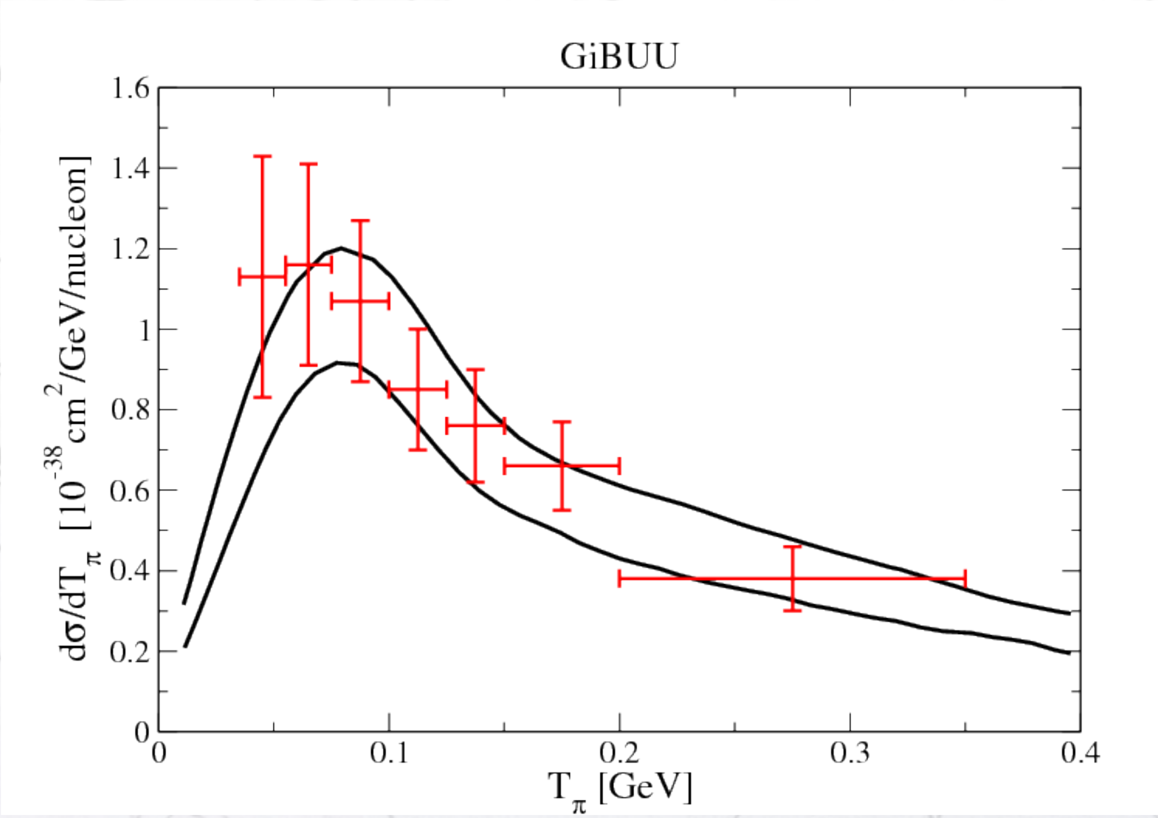




Single pion production

- The nucleus distorts severely the distributions.
- Experiments normally define "topological" signal based on the particles emitted by the nucleus and not at the nucleon level.

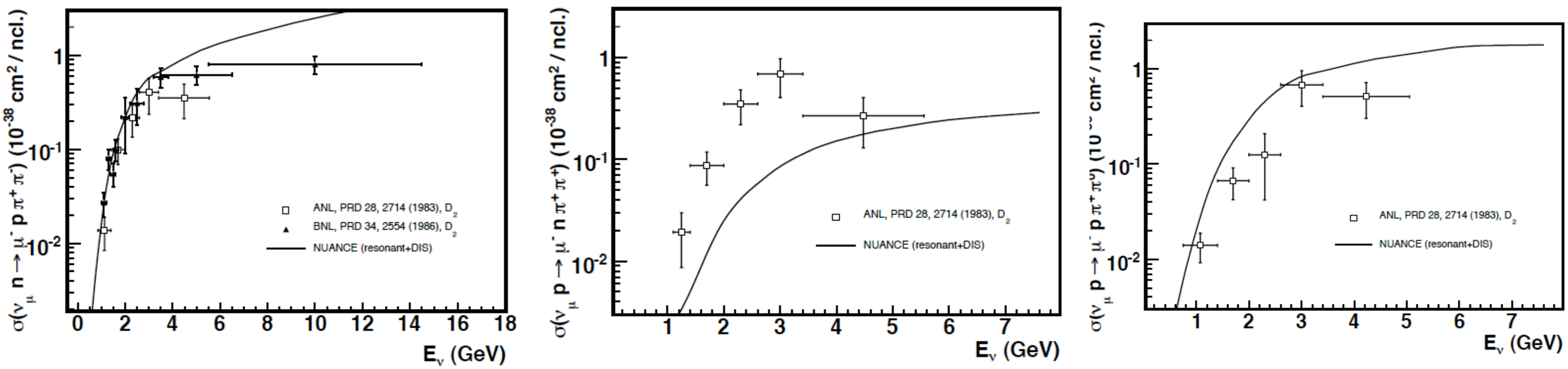




Modern Data

- Experimental errors or faulty models ?

J.A.Formaggio, G.P.Zeller, Rev.Mod.Phys. 84 (2012) 1307

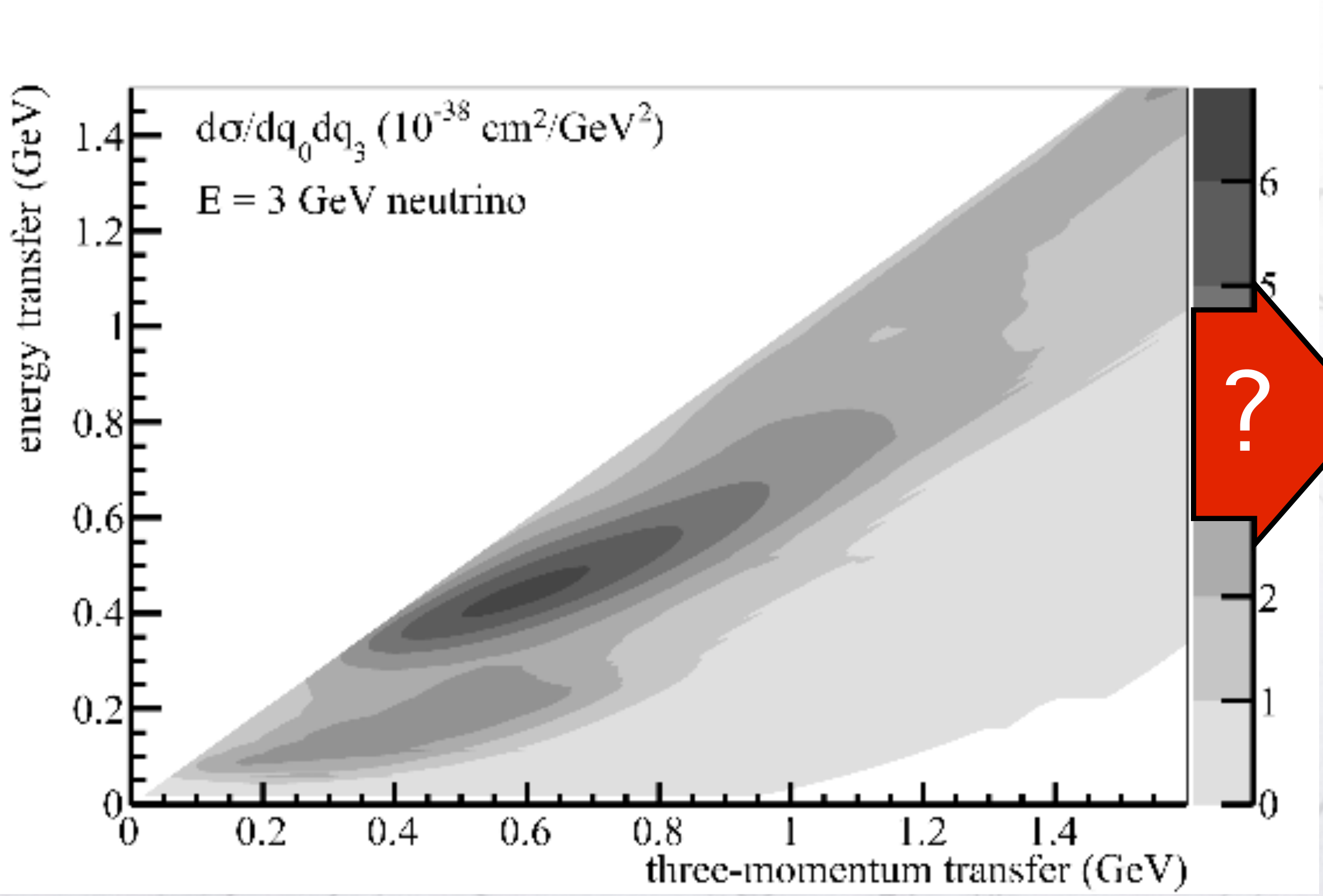


- Complex region with contributions from high mass Δ resonances and low ω DIS. Mixture of models from Pythia to add-hoc pion production.
- There is no new data since ANL and BNL back to the 80's.
- No data in nuclei: difficult measurement due to FSI.
- No detailed pion kinematics available.
- Critical for Dune!.

No data for NC potential background

Limits of models

- The main problem with models is that they are valid only in certain regions of the available kinematic space. Nominally, the low q^2 region.
- Extrapolations to the high q^2 region are complex since it implies a different treatment of the nucleus (relativistic vs. non-relativistic, etc...).
- Agreement with experiments might vary with experiment energy range.

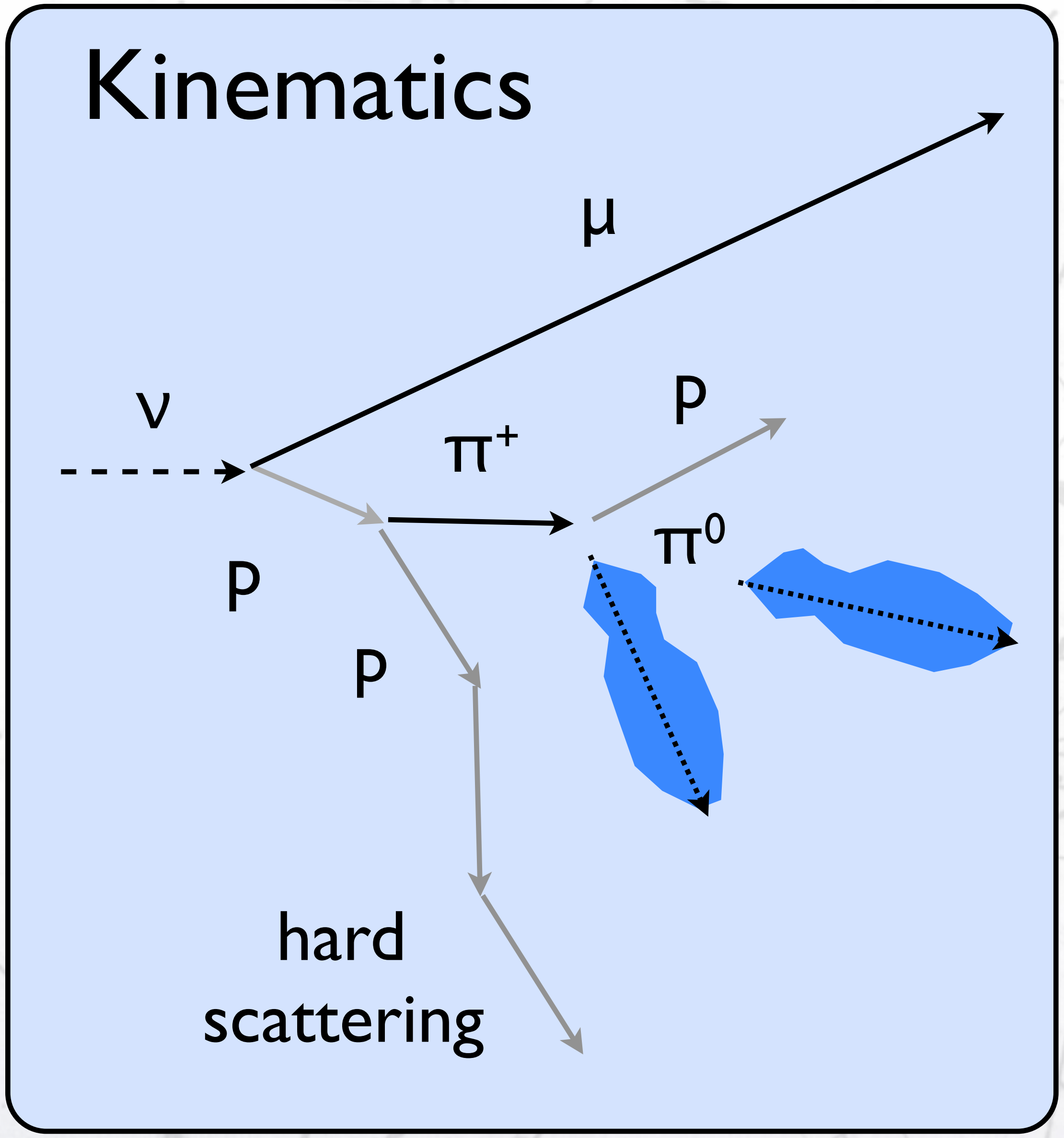


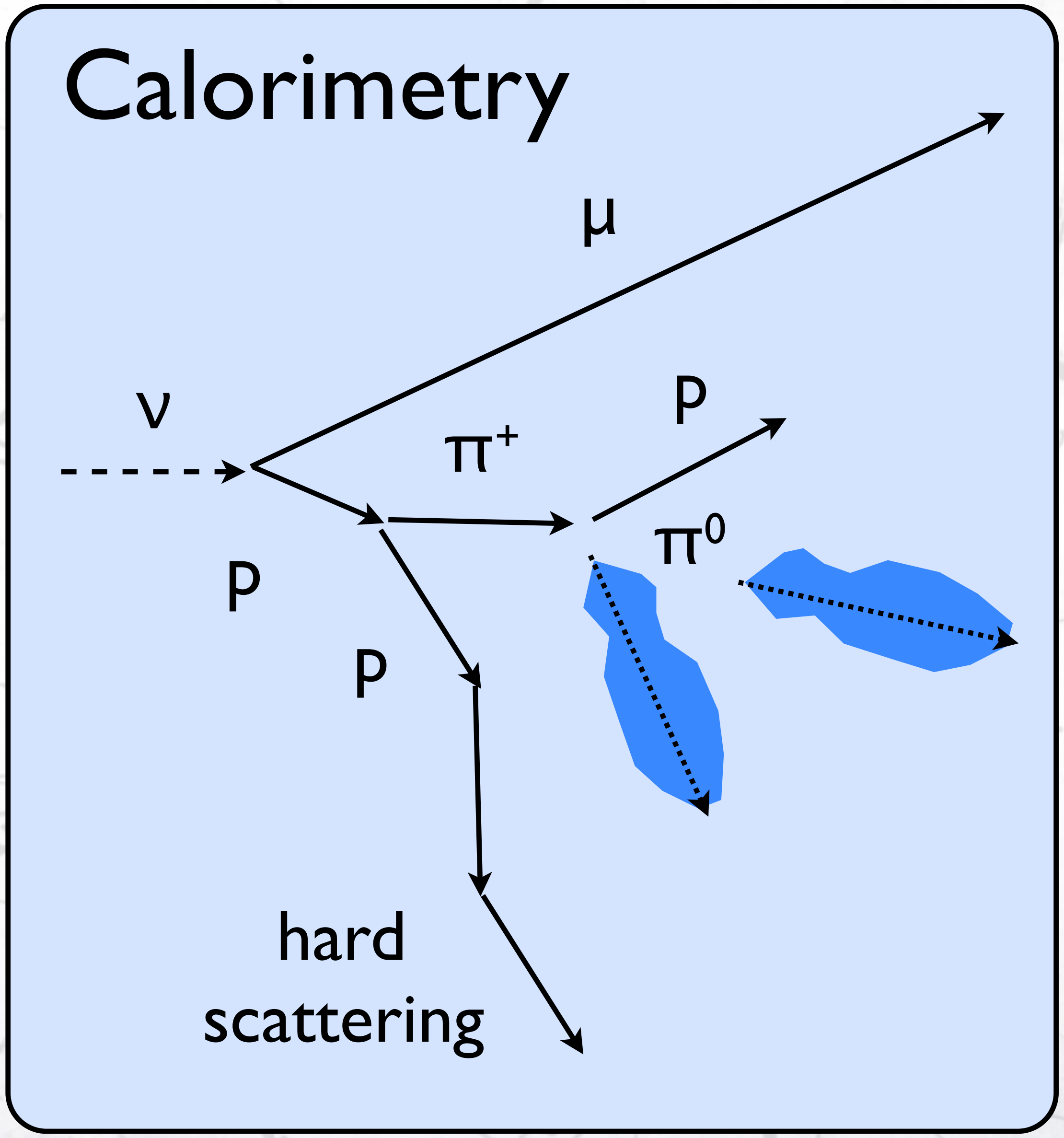
?

Gran, R. *et al.* Phys.Rev. D88 (2013) 11, 113007

Proposed to use the momentum transfer to the nucleus as a reference cut and not neutrino energy.

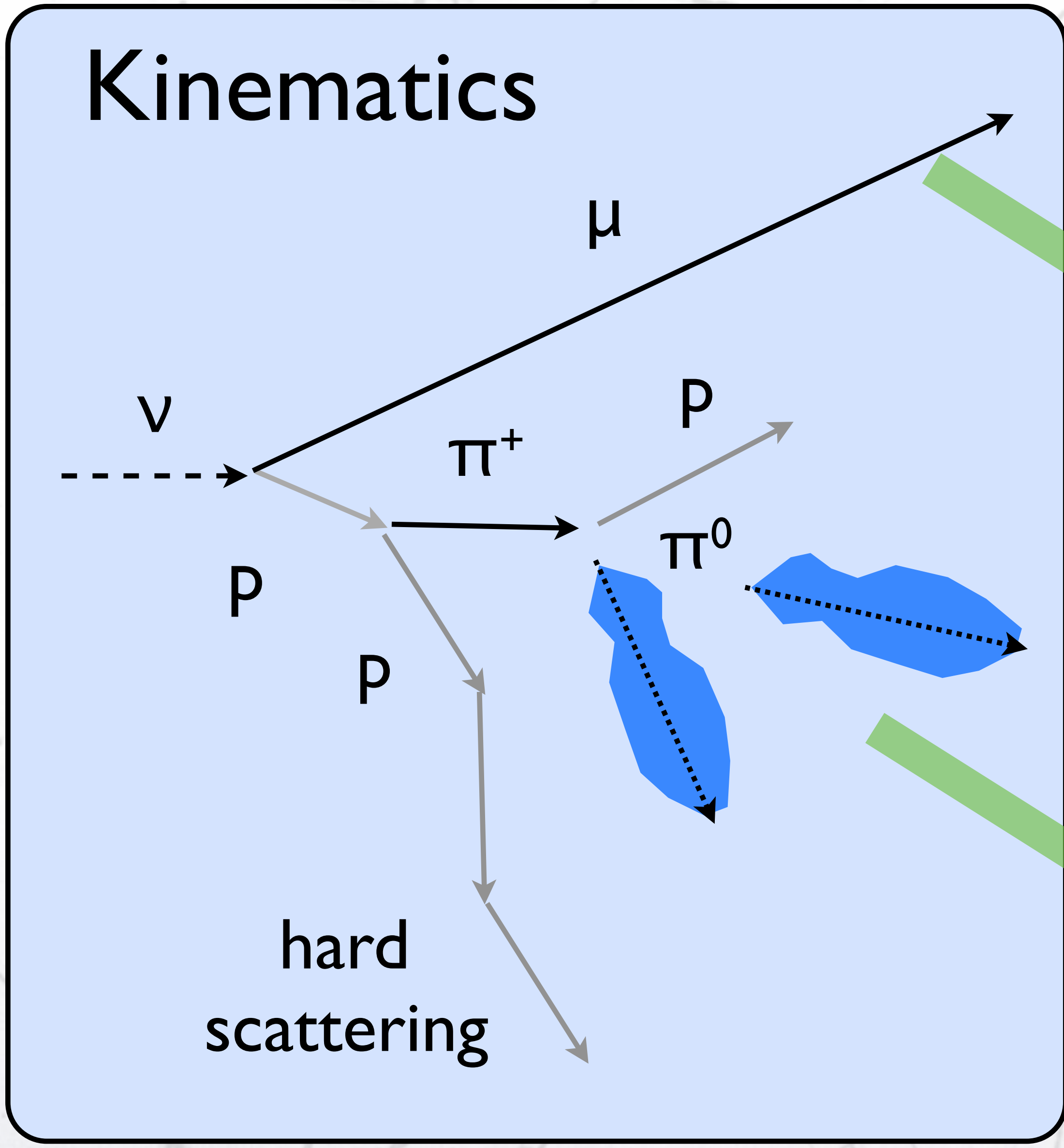
Theorists are needed!





- Only a fraction of the energy is visible.
- Rely on channel interaction id.

- The visible energy is altered by the hadronic interactions and it depends on hadron nature.



- Only a fraction of the energy is visible.
- Rely on channel interaction id.

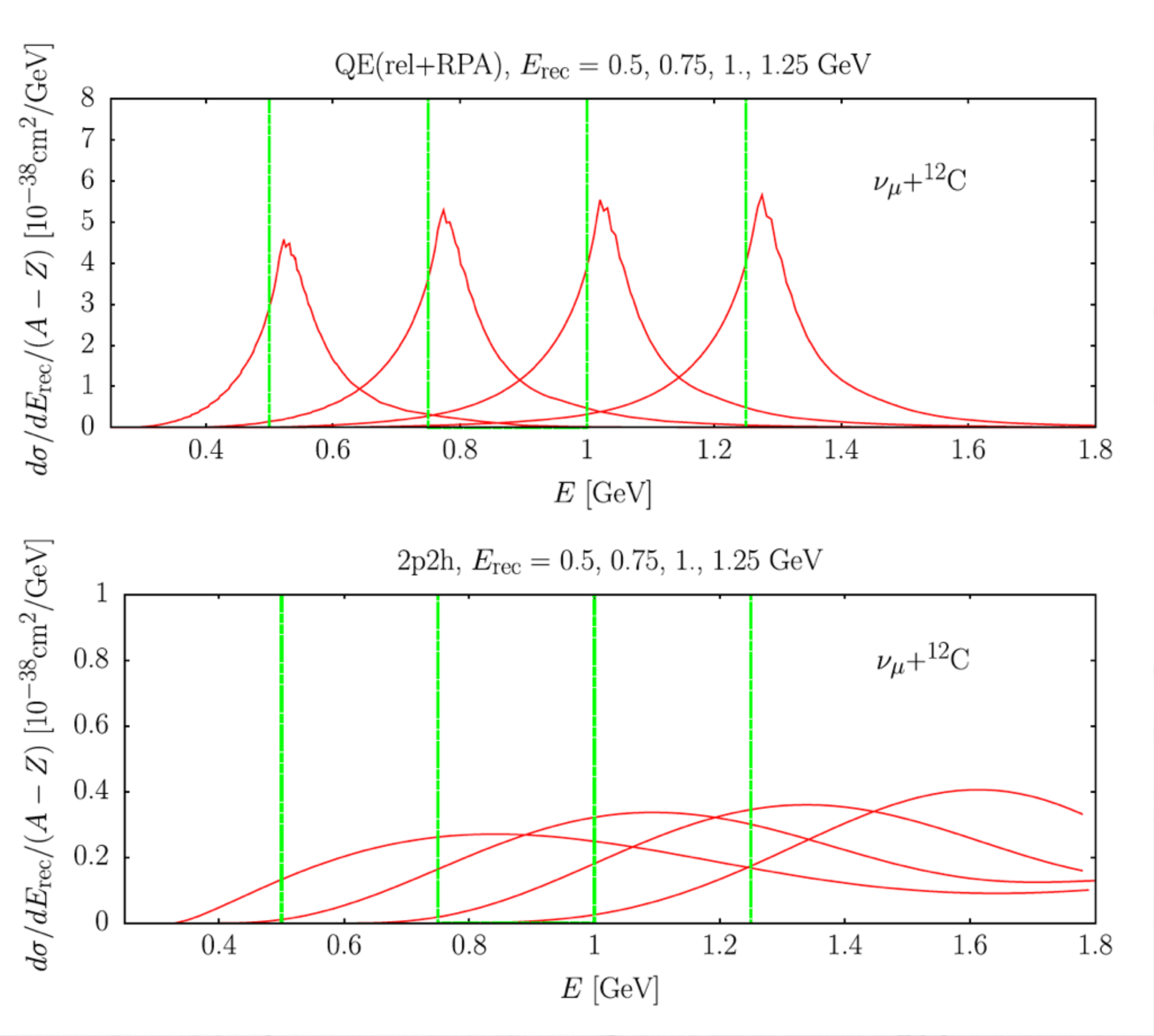
- From conservation of momentum and energy:

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

- Assumptions:
  - We know the reaction channel: CCQE, CCΔ, etc…
    - Normally identified with presence of pions in the event.
  - The target nucleon is at rest (no fermi momentum).

Kinematic Approach

- The kinematic approach relies on the knowledge of the reaction channel.
- If two reactions are confused the energy is wrongly reconstructed.
- Experimentally we can confuse the channel because:
    - nuclear effects (absorption).
    - detector effects (thresholds).



PHYSICAL REVIEW D **85,** 113008 (2012)

ν Energy reconstruction

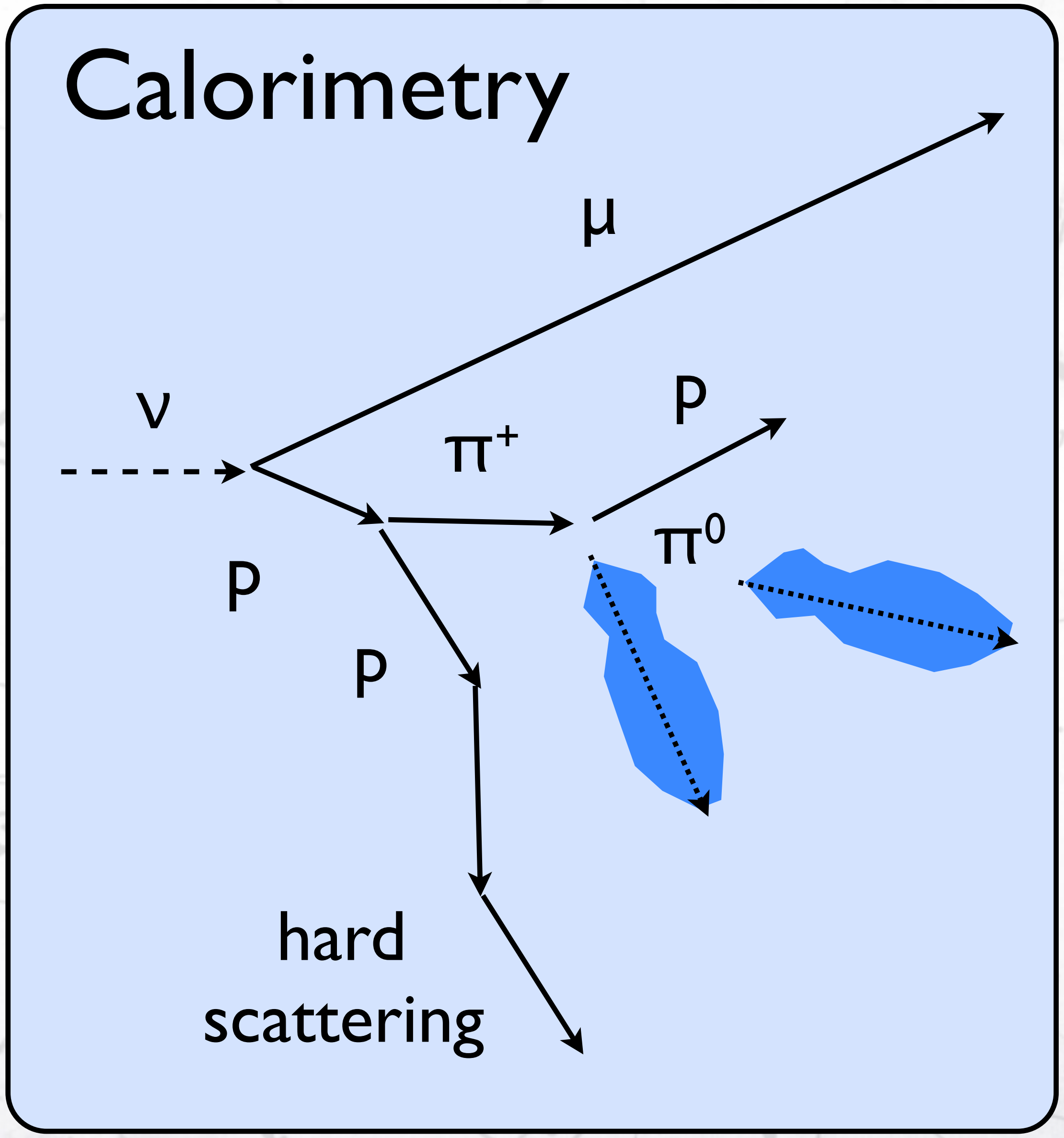
- The energy is reconstructed by summing all detected energy:

$$E_{reco} = E_{\mu} + \sum_{hadron} E_{hadron}$$

- The deposited energy is only the kinetic energy. The total energy requires the identification of particles:

$$E = E_{kin} + mass$$

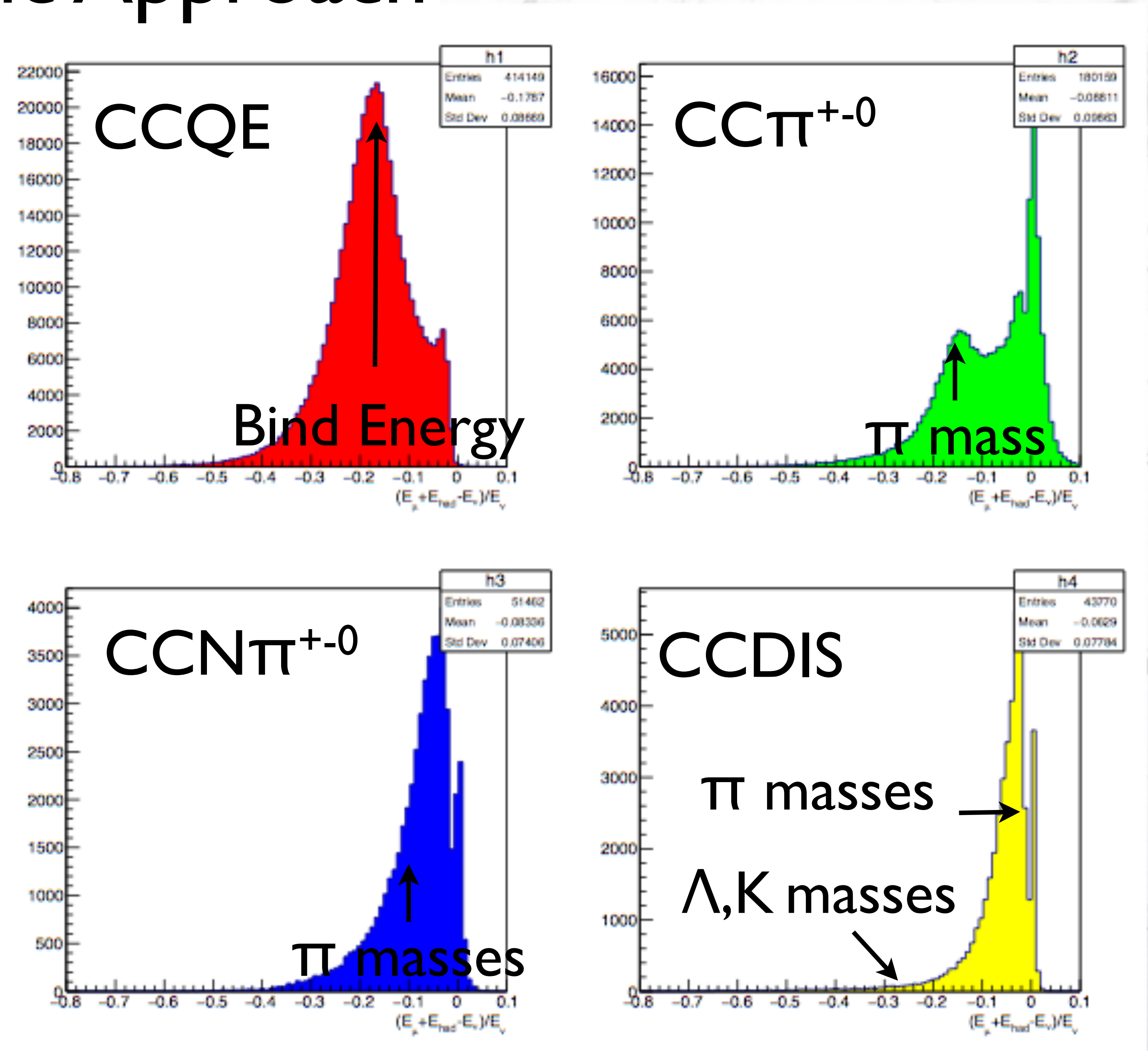
- This approach requieres:
  - fully sensitive detector.
  - Understanding of the energy deposition by different particles.



- The visible energy is altered by the hadronic interactions and it depends on hadron nature.

Calorimetric Approach

- Simple exercise (Simulations):
  - Plot the relative energy deviation (E_μ+E_{had}-E_ν)/E_ν for different channels.
  - The response depends on the channel and the topology of events outside the nucleus.
  - The energy to change nuclear state (bind energy) needs to be considered.
- Part of the pion and kaon mass can be recovered through its decay chain.

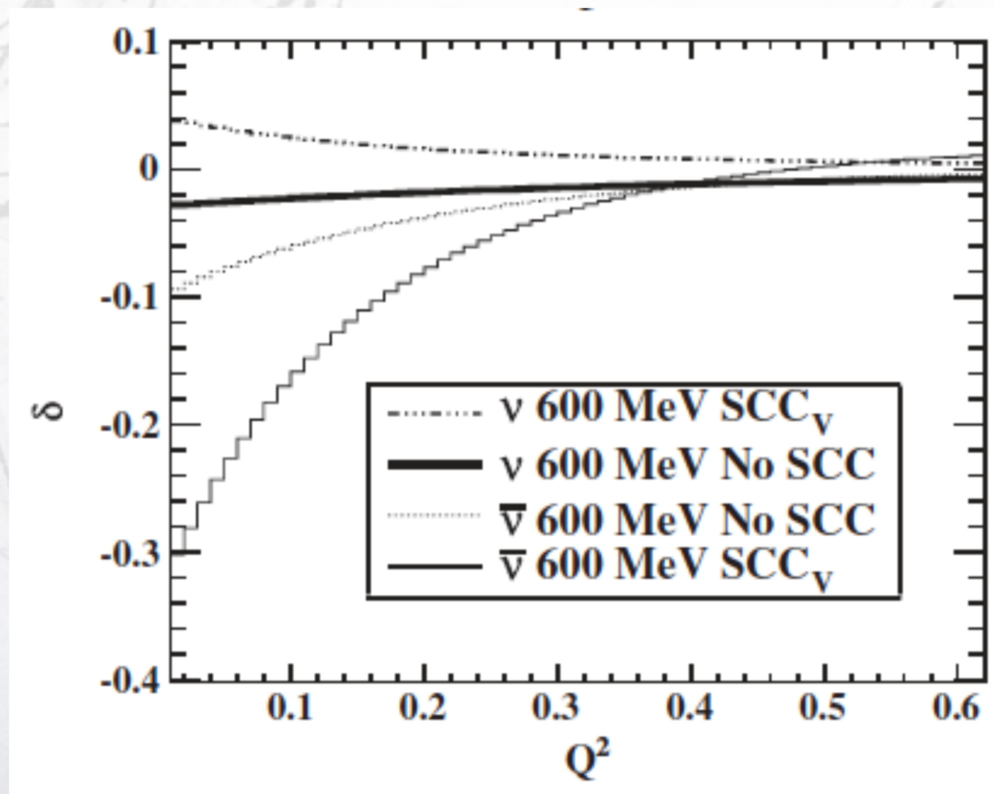


Calorimetric energy reconstruction requires x-section knowledge!

ν_e/ν_μ

- CP violation requires in addition the knowledge of the ratio $\sigma(\nu_\mu)/\sigma(\nu_e)$ for neutrinos and anti-neutrinos.
- The ratio does not need to be trivial due to the Breemstrahlung and convolution with nuclear effects.

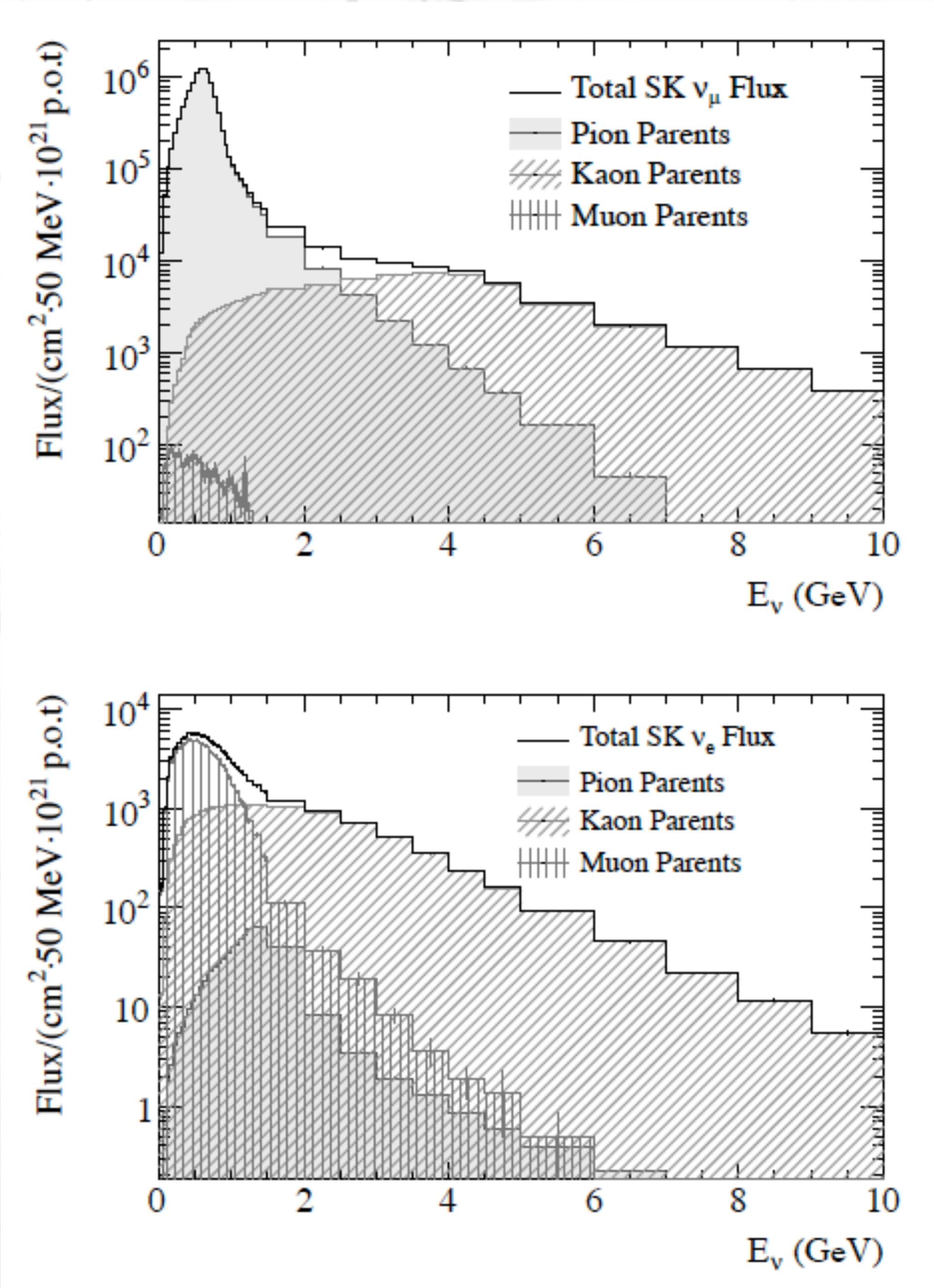
$$\delta(E_\nu, Q^2) \equiv \frac{\frac{d\sigma_\mu}{dQ^2} - \frac{d\sigma_e}{dQ^2}}{\int dQ^2 \frac{d\sigma_e}{dQ^2}}$$



PHYSICAL REVIEW D **86**, 053003 (2012)

Theoretical calculations needed

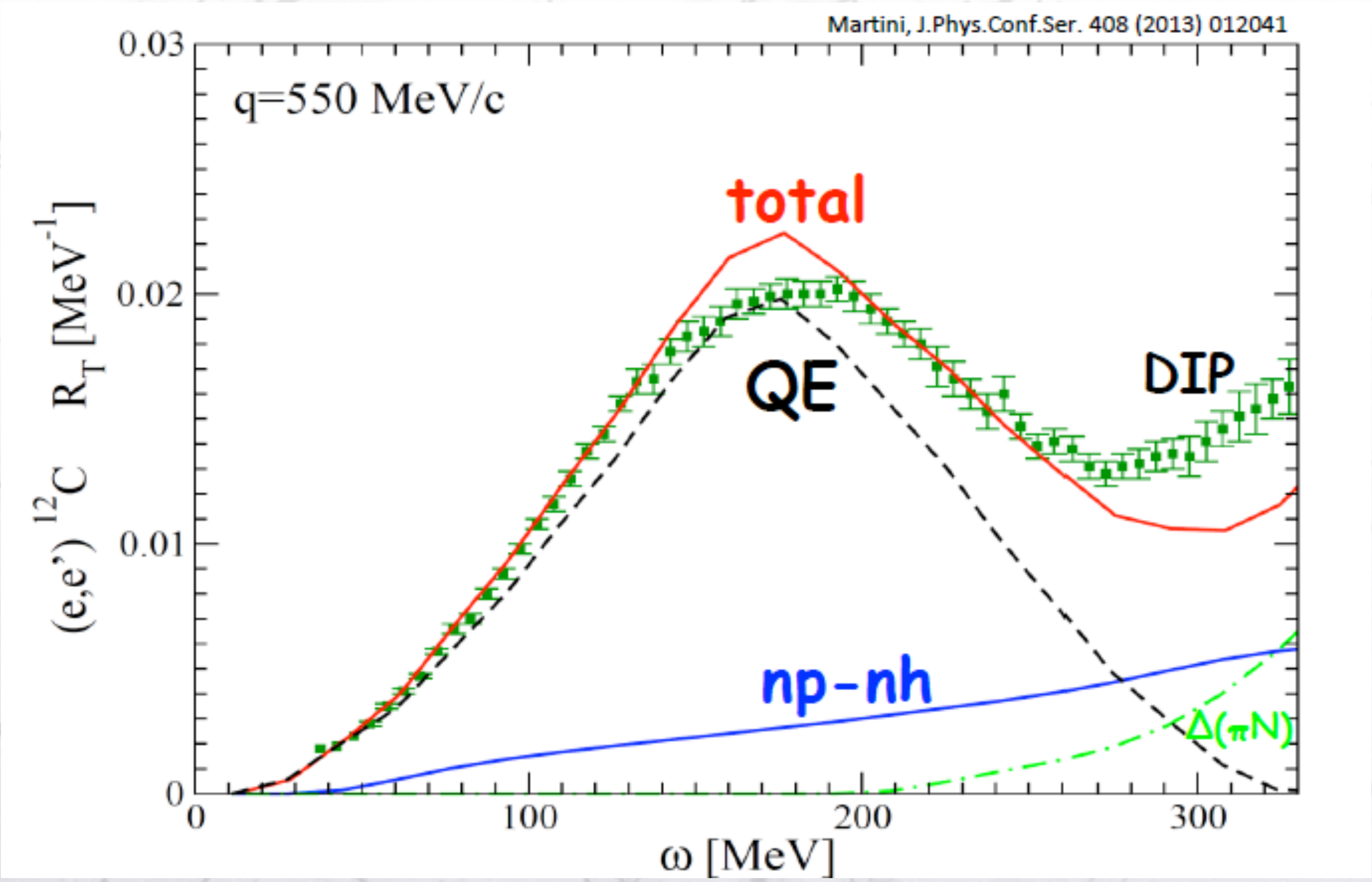
ν_e/ν_μ



- Conventional neutrino beams are very bad places to perform this measurement:
  - Low flux with respect to muon neutrinos.
  - Production process is very different:
    - ν_e mainly from muon and kaon decays
    - ν_μ mainly from pion decays.

Electron scattering

- (e,e') experiments allow to make measurements in known kinematical conditions.
- (e,e') samples only vector components (non Axial).
- But, they are very useful to study the nuclear response.



Caveat
(e,e') experiments normally ignore the hadronic part of the interaction and do not cover the full kinematics

CLAS and other new projects might help.

Conclusions

- νA cross-section is a key topic for the success of near future and far future oscillation experiments.
- We lack a consistent model to describe the data.
  - deficit at nucleon level modelling.
  - deficit at nucleus level even for "light" nuclei.
- Experiments are difficult to carry out :
  - broad energy spectrum.
  - high mass detector but low energy particle detection.

Conclusions

- The solution does not come (probably) from a single approach but a combination of actions (an experimental program rather than an experiment):
  - Theory (nuclear) including lattice (nucleon).
  - Several νA experiments with different nuclei and beam spectrum to break degeneracies.
    - experiments should be more sensitive than the running ones.
  - (e,e') experiments to explore nuclear responses under controlled kinematical conditions.
  - Ancillary experiments : γA, πA, …


ONLY THOSE WHO SEE THE INVISIBLE
CAN DO THE IMPOSSIBLE
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