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Progress on neutrino nucleus interactions

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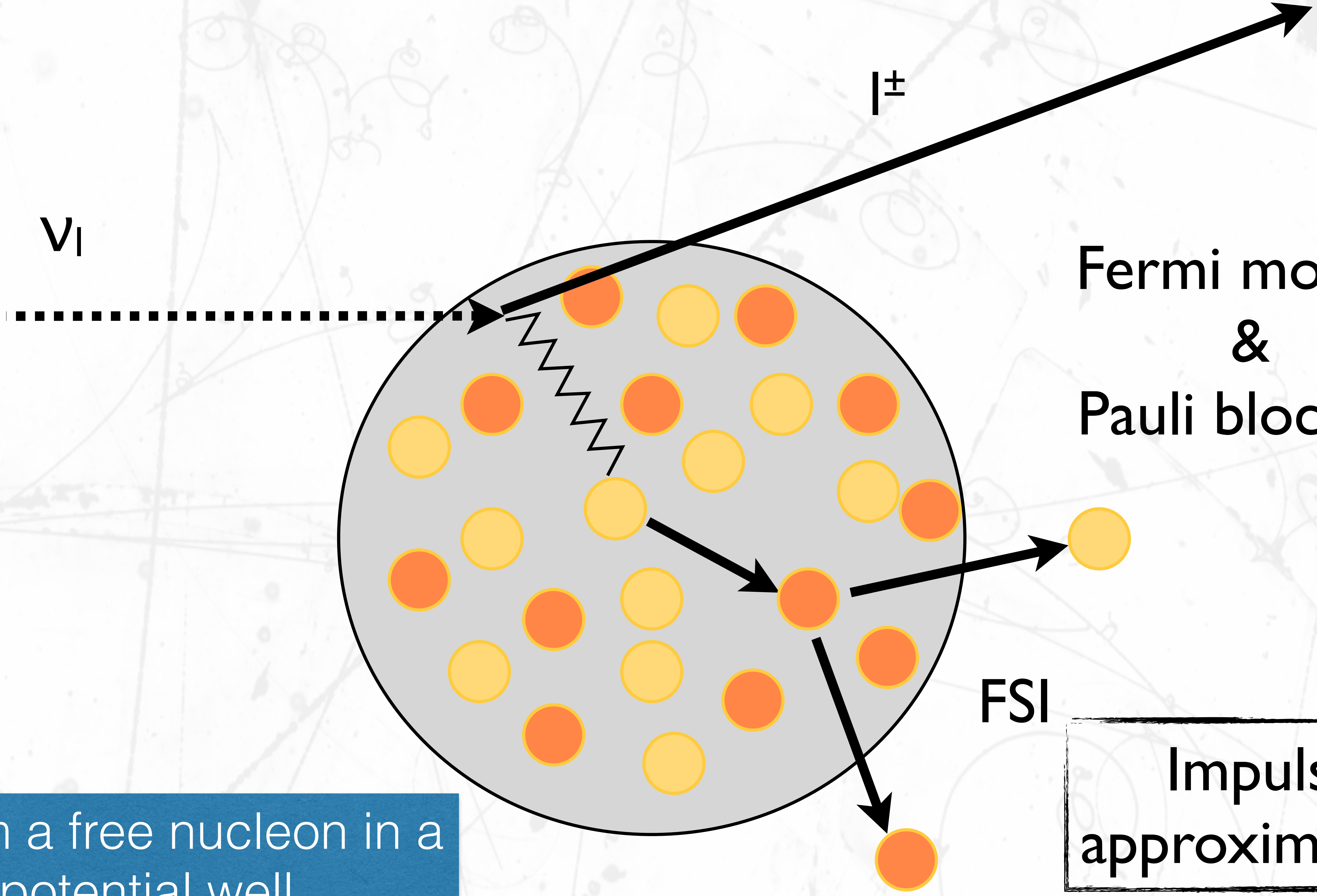
This is personal view of the status of the field, not expected to be exhaustive. Sorry if I missed some developments.

Neutrino interactions

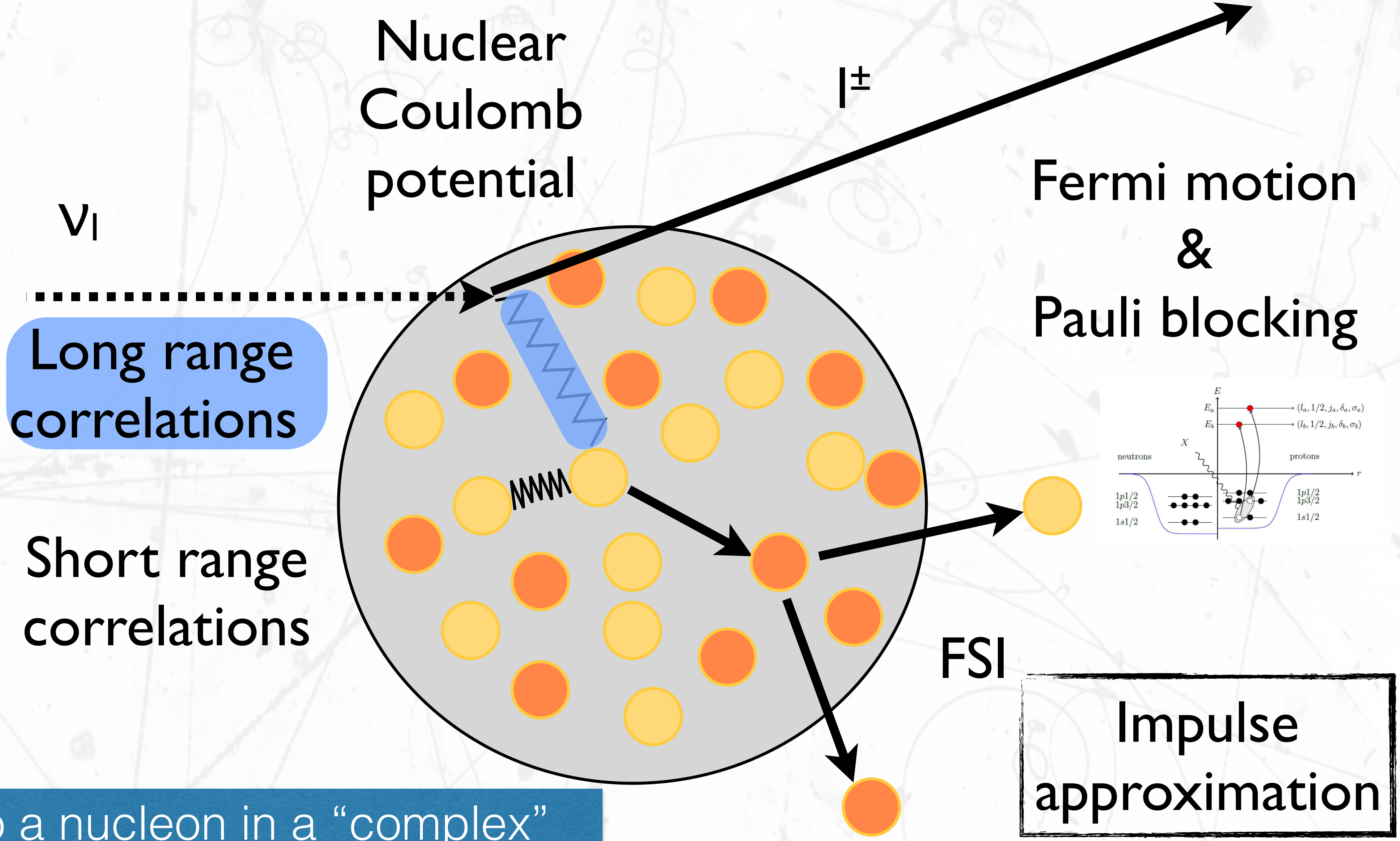


Fermi motion
&
Pauli blocking

Impulse approximation

From a free nucleon in a potential well…

Neutrino interactions



Nuclear
Coulomb
potential

$l^{\pm}$

ν_l

Fermi motion
&
Pauli blocking

Long range
correlations

Short range
correlations

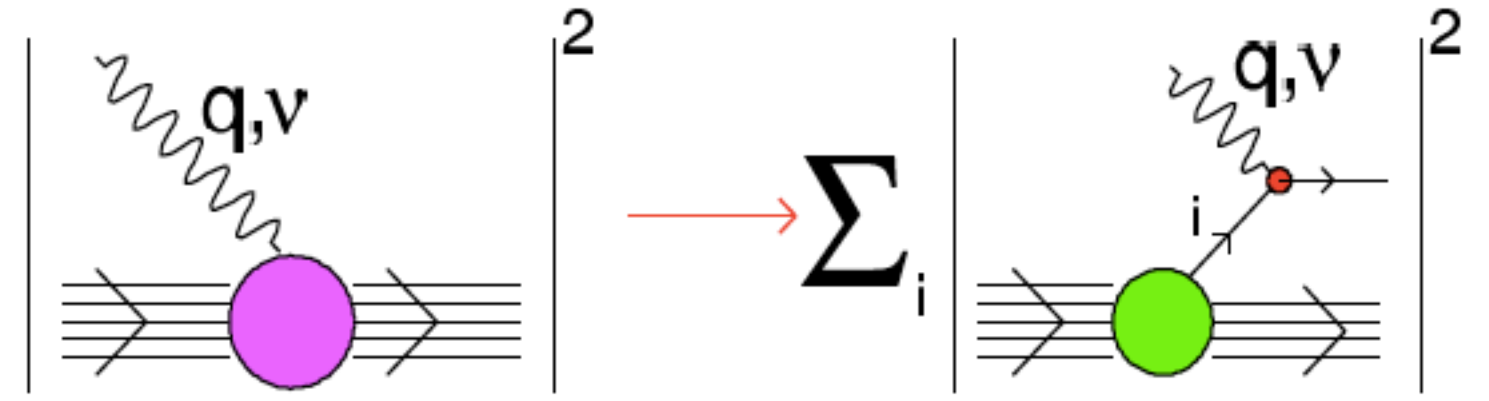
FSI

Impulse
approximation

to a nucleon in a “complex”
potential well with “toppings”

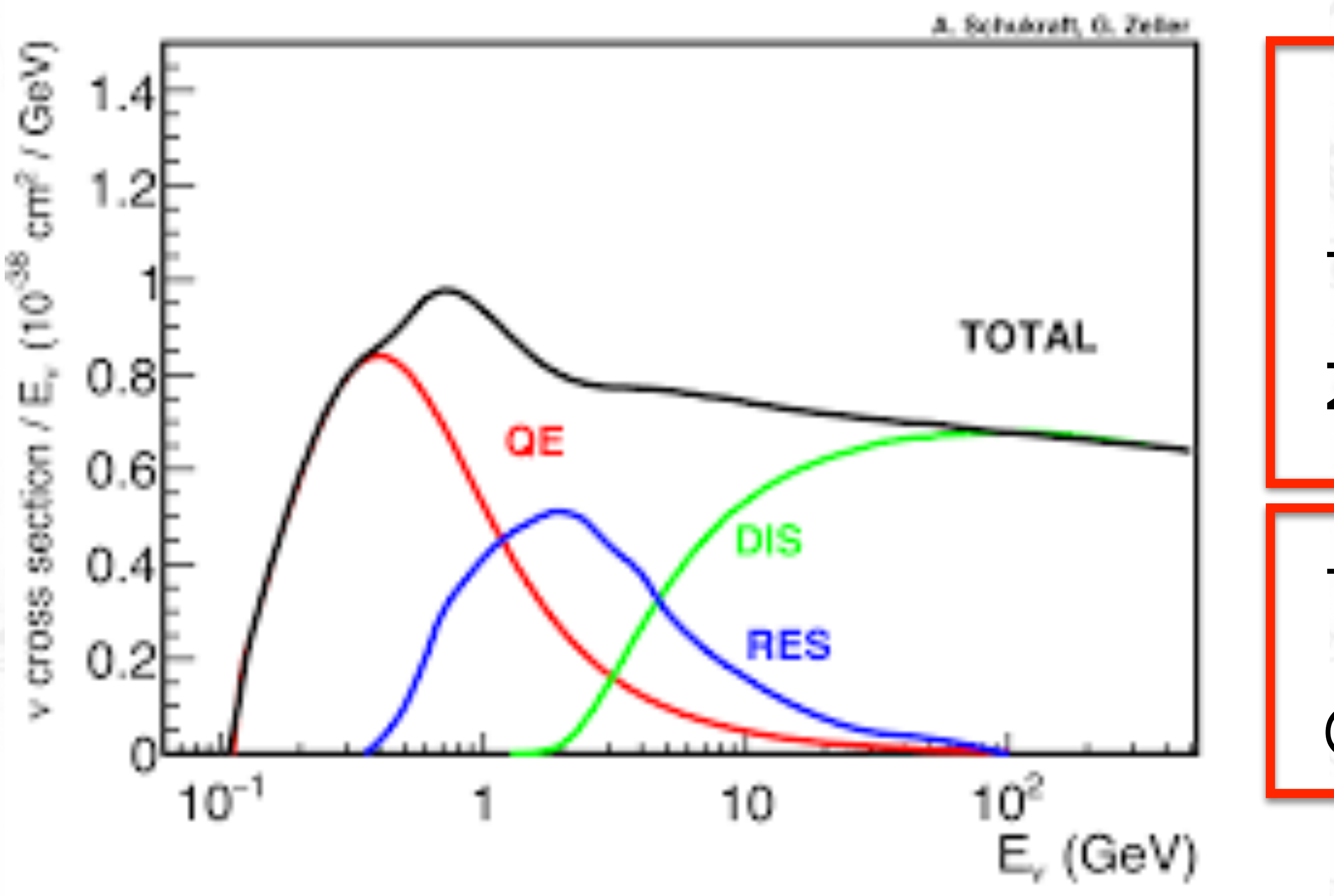
Impulse approximation

- IA approaches the nuclear interaction by the incoherent sum of single nucleon interactions.
- This is a better approximation for large momentum transfer (λ ~ 1 /|q|)



- Normally in Monte Carlos, this implies the implementation of the single nucleon interaction decoupled from the initial and final state of the nucleus.
  - Initial and final states are taking on average modifying the interaction (Fermi Momentum, pauli blocking, bind energy, …)

ν-nucleon interactions



Nucleon

QE has no π

Res has more than 1π

Quark

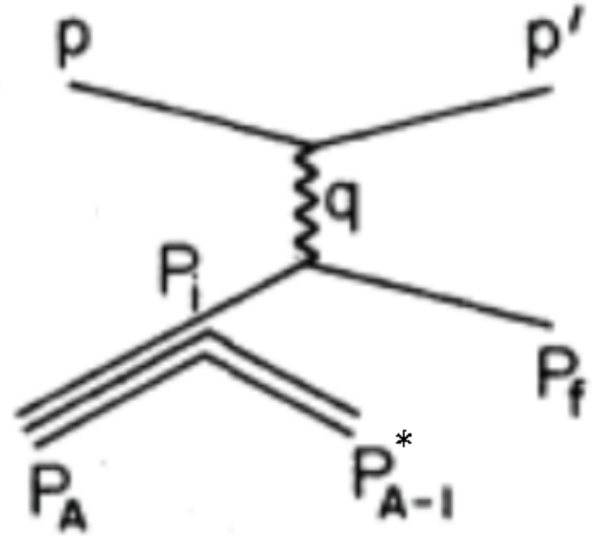
DIS has more than 1π

- In the above 100 MeV the neutrino nucleon cross-section crosses several thresholds.
- Track multiplicity (1p1h, 2p2h, etc…) and particle production (0π,1π,…) are enabled when sufficient energy is available.

Impulse approximation in kinematics

arXiv:1801.07975

- The impulse approximation also defines the way we compute the kinematics in the reaction.



$$\boxed{\vec{p}_\nu = \vec{p}_\mu + \vec{p}_{prot} + \vec{p}_{A'}}$$

$$\vec{p}_\nu + \vec{p}_{neut} - \vec{p}_{neut} = \vec{p}_\mu + \vec{p}_{prot} + \vec{p}_{A'}$$

$$-\vec{p}_{neut} \approx \vec{p}_{A'}$$

$$\vec{p}_\nu + \vec{p}_{neut} = \vec{p}_\mu + \vec{p}_{prot}$$

- The dispersion relation is broken by the E_b energy that is actually function of the neutron initial momentum.

- Generators normally have E_b fixed.

$$\boxed{E_\nu + M_A = E_\mu + E_{prot} + E_{A'}}$$

$$E_\nu + E_{neut} - E_{neut} + M_A = E_\mu + E_{prot} + E_{A'}$$

$$E_\nu + E_{neut} + (M_A - E_{A'} - E_{neut}) = E_\mu + E_{prot}$$

$$E_\nu + E_{neut} + E_b = E_\mu + E_{prot}$$

Calculations are more complex if consider the FSI

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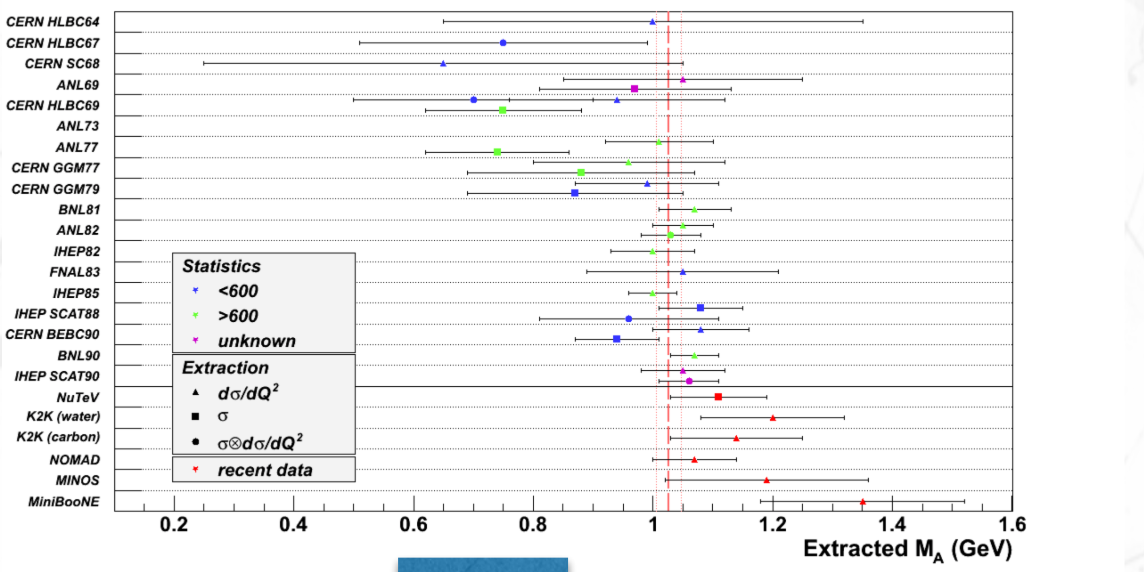
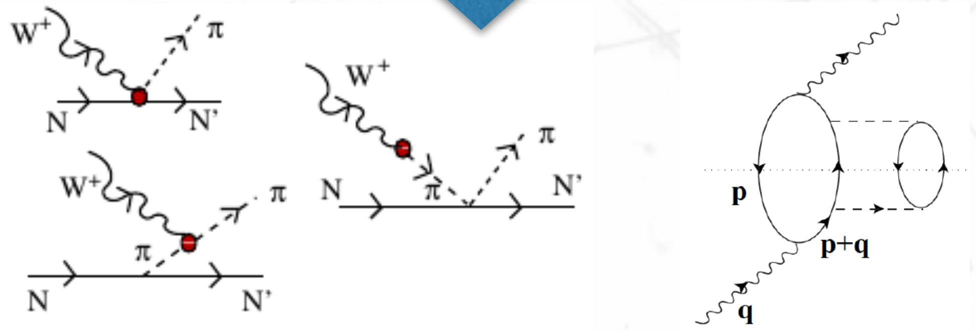
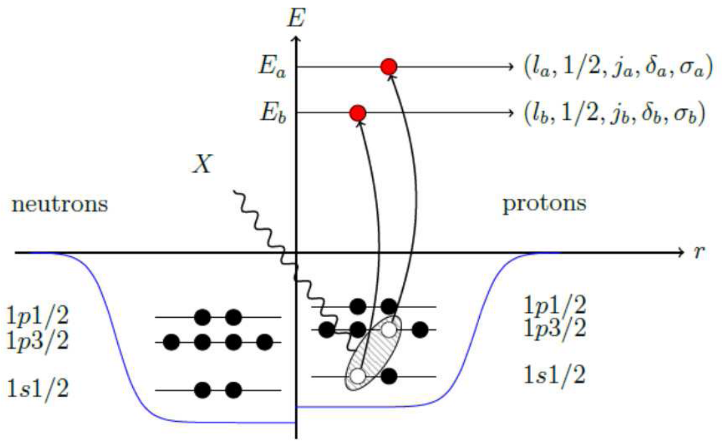
A bit of history

- In a decade we have moved from discussing the M_A anomaly as effective parameter to talk about:
  - Long range correlations.
  - Two body currents.
  - Nuclear correlations.
  - Spectral functions.
  - Initial state interactions.
  - SUSA, “ab initio”,…
  - z-expansion
  - Mean Field….







…

The community recognises we have a problem!

Why is this so important?

Oscillation experiments require neutrino energy reconstruction.

neutrino energy reconstruction is based on the products of the nucleus interaction with nuclei (leptons and hadrons)

The nucleus:
smears the values through Fermi momentum, pauli blocking and energy removal

Different neutrino interaction channels require different models.

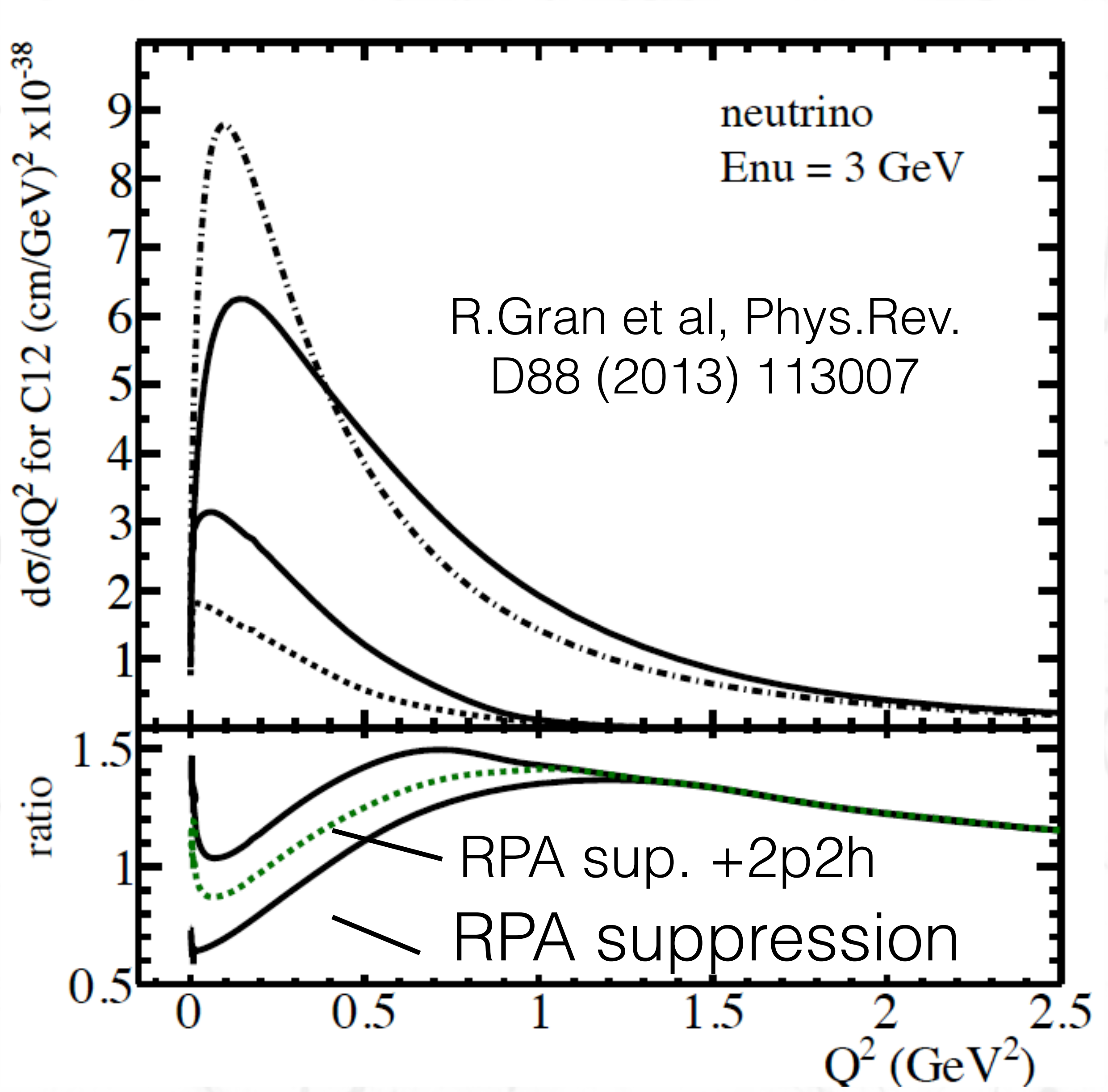
Neutrino energy is a complicated function of the final state particle energyies

The connection can be done only through models.

Models need to be checked using data:
very low energy threshold detectors are challenging when combined with large masses.

How to be fooled!

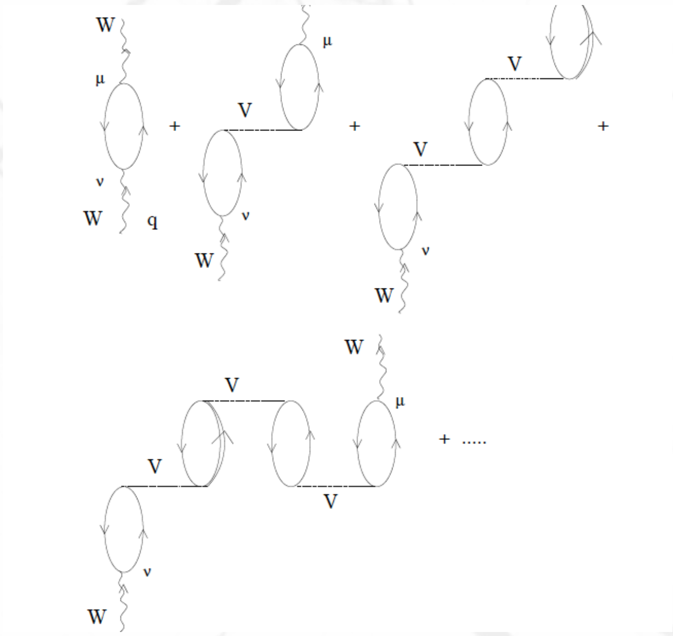
- Based on RPA calculations.



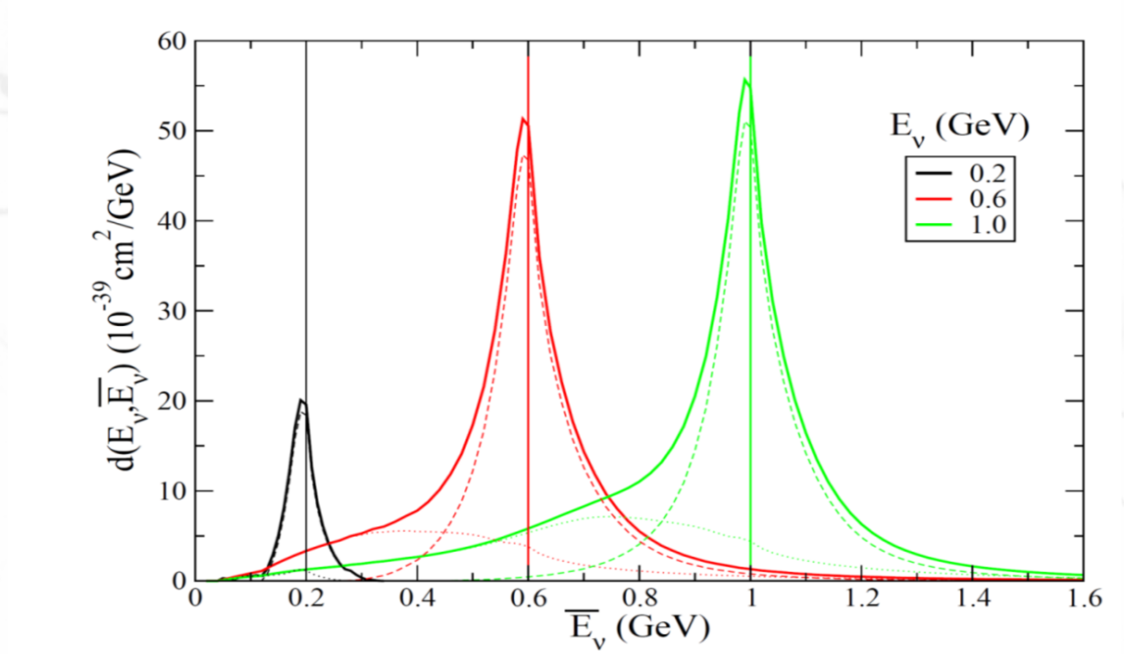
R.Gran et al, Phys.Rev. D88 (2013) 113007

RPA sup. +2p2h

RPA suppression

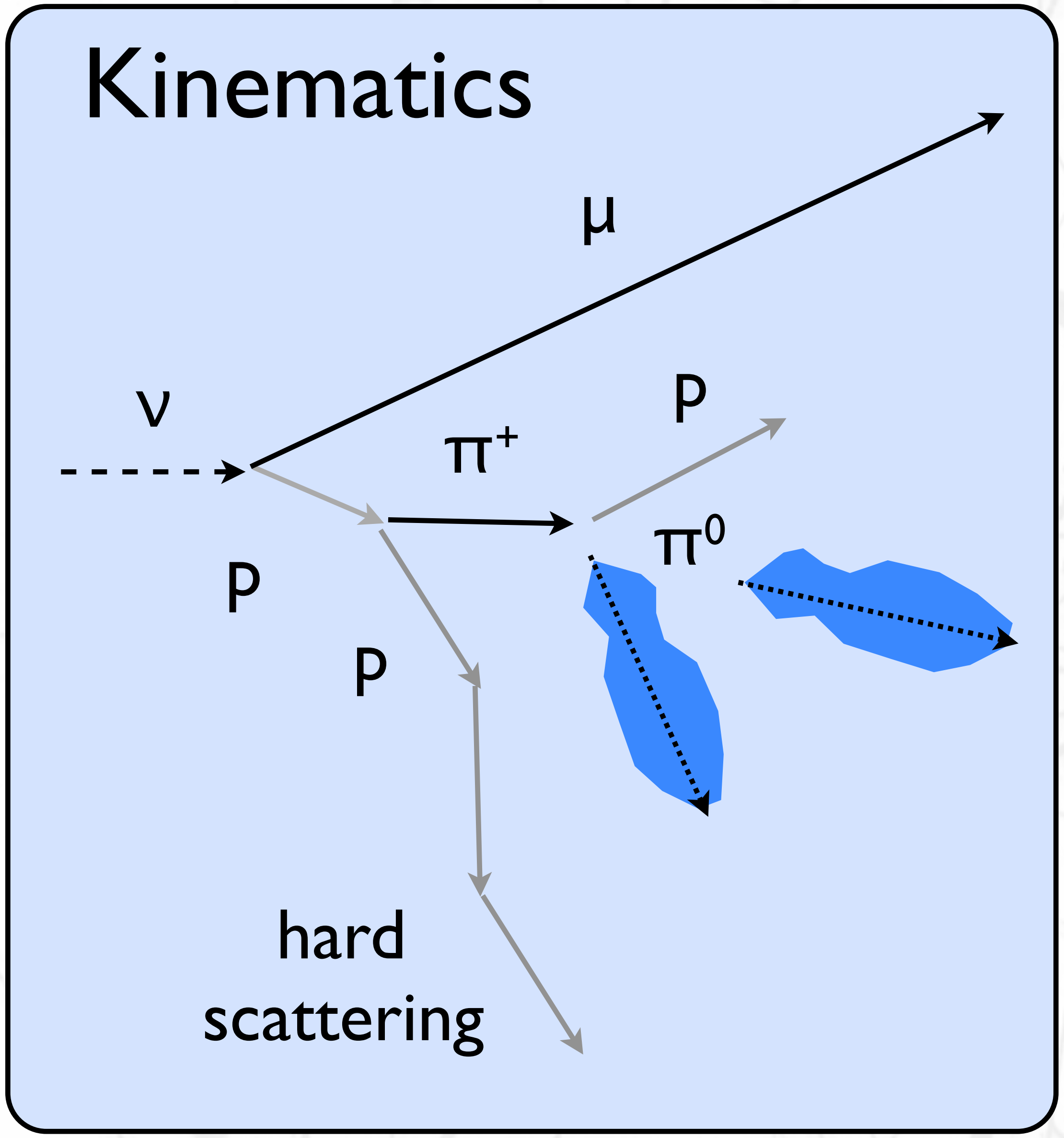


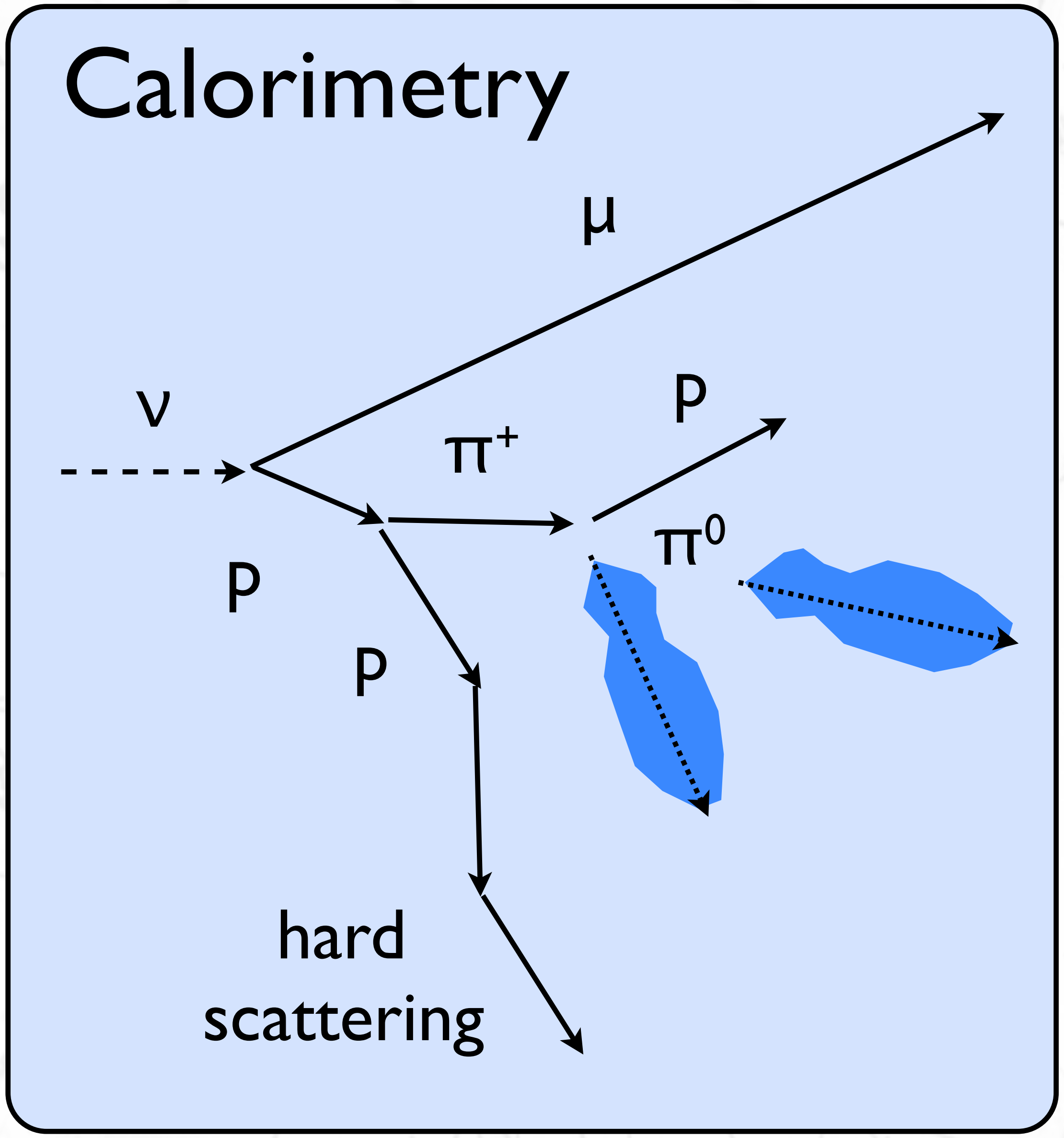
M_A was actually an effective parameter!



Every model should have a solid theoretical background!

Energy reconstruction

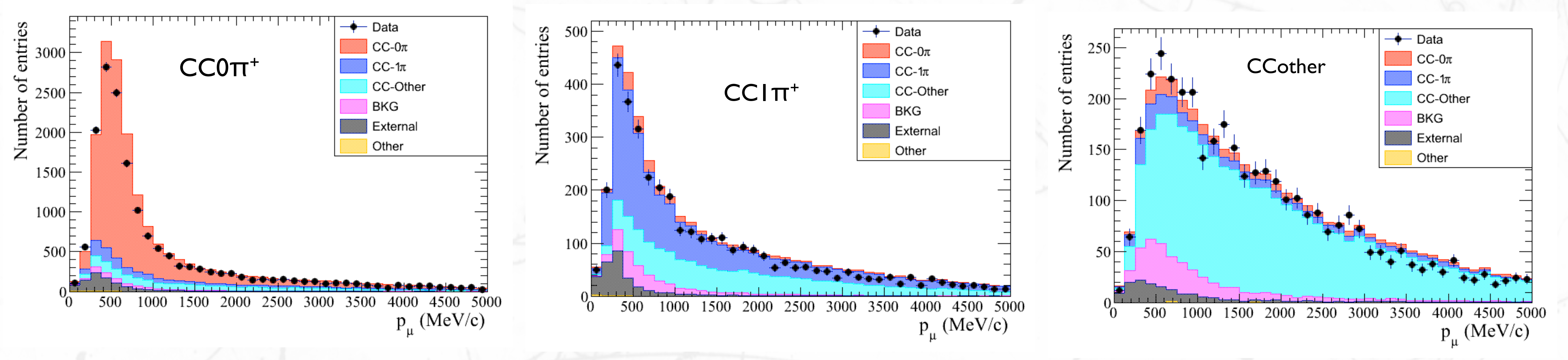




- Only a fraction of the energy is visible.
- Rely on channel interaction id.

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

Event topologies



- Minerva and T2K already adopted the idea of the event topologies based on the presence of pions and or protons in the final state.

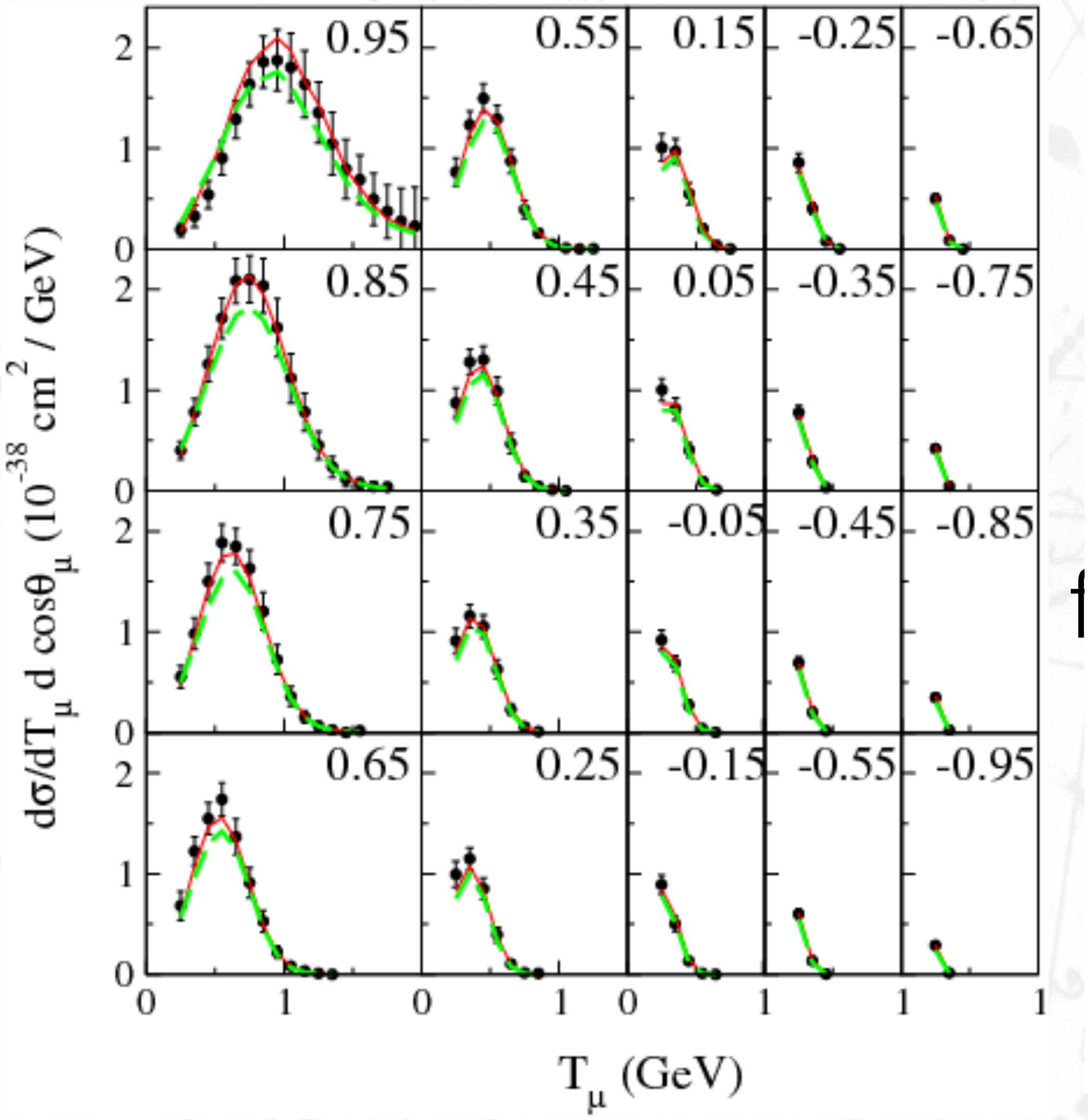
- This is an excellent way to unify data releases to allow for comparisons.

- Is this enough ? Do Minerva and T2K mean the same when talk about CC0π?

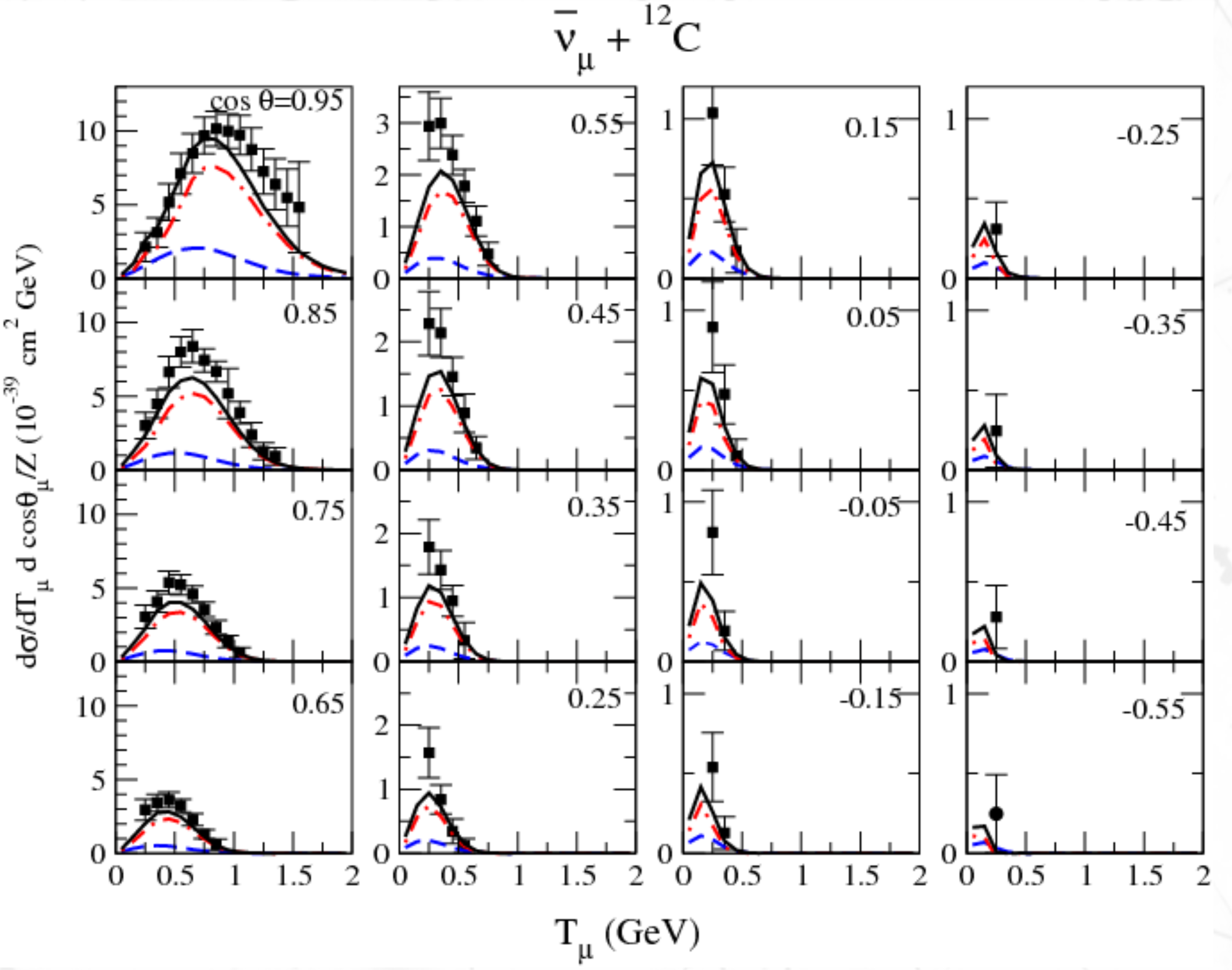
What do we need ?

- Initial state and correlations description of the nucleus.
- Collective effects of the nucleus.
- Neutrino-nucleon cross-section.
- Final state interactions
- Particle propagation inside the nucleus.
- Final state nucleus description.

We have a good model



Phys.Lett. B707 (2012) 72-75

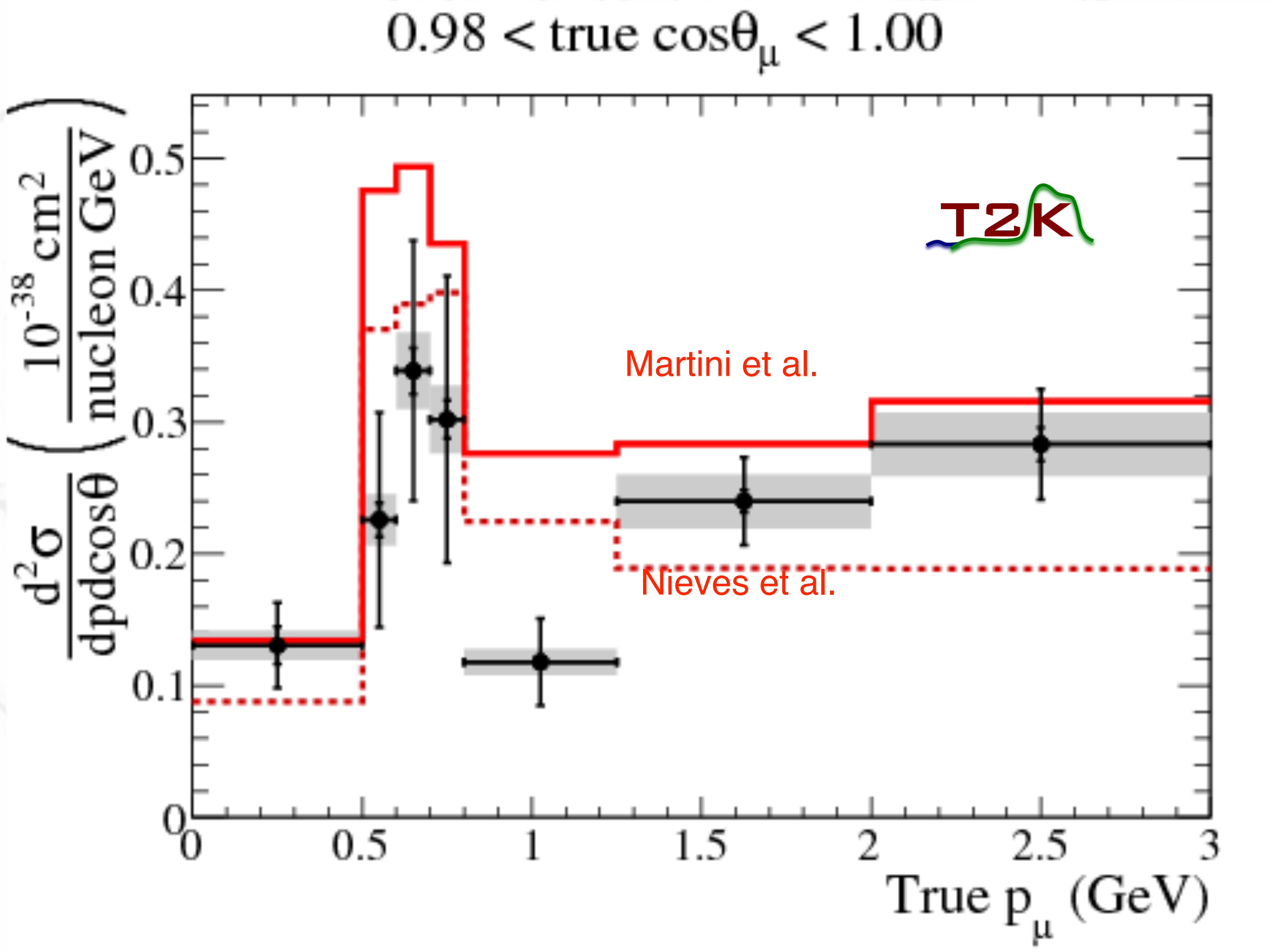


Phys.Lett. B721 (2013) 90-93

But…not perfect

μ momentum distribution in the forward direction

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



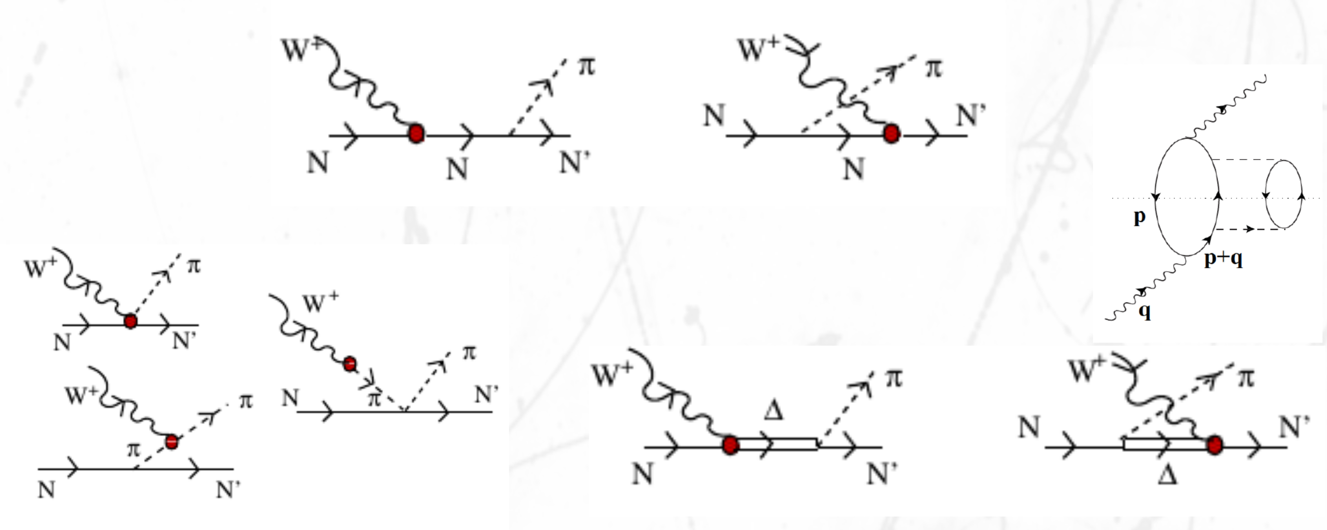
- In one bin we get different E_ν (flux) & Q^2 (x-section) contributions.
- The flux is constrained from the hadro-production.
- Adjusting the model to the flux will migrate problems from flux to cross-section and viceversa.

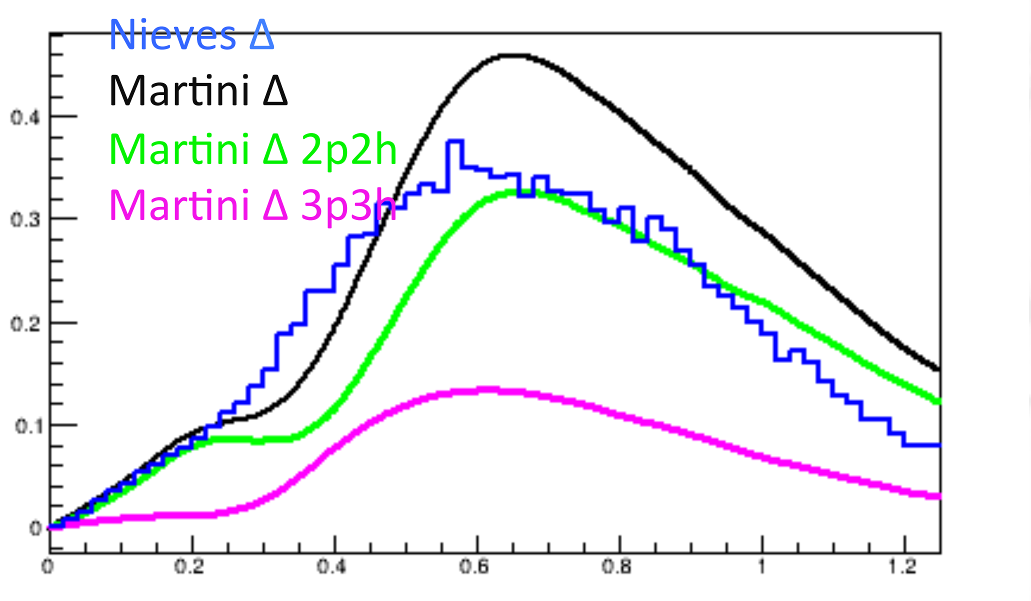
Low and High Q2 contains different level of uncertainties at the nucleon level (form factors) and nuclear level (short and long range correlations)

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

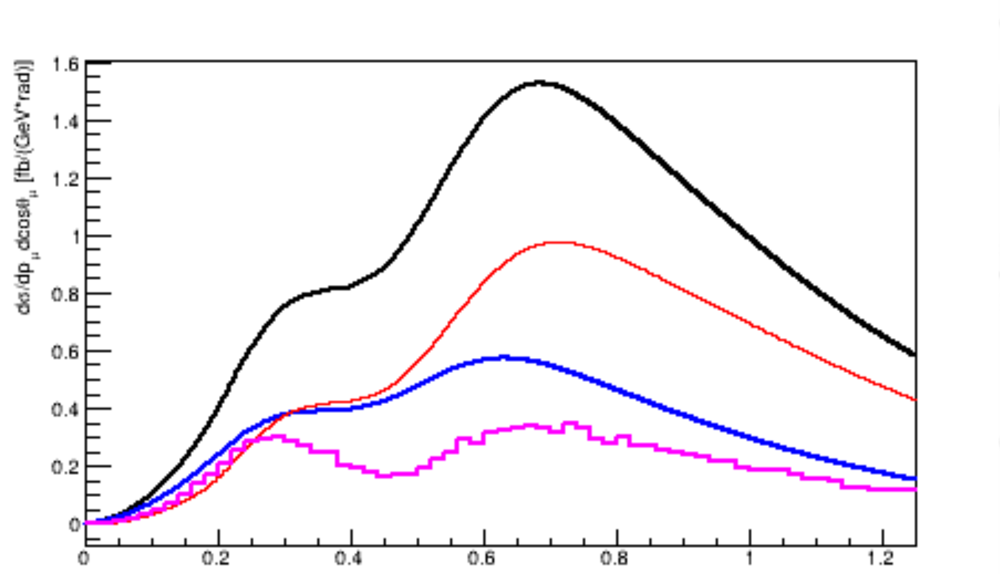
It might be the model is not equally good across neutrino energys.

Similar models





- “A priori” very similar models (microscopic) give very different results.

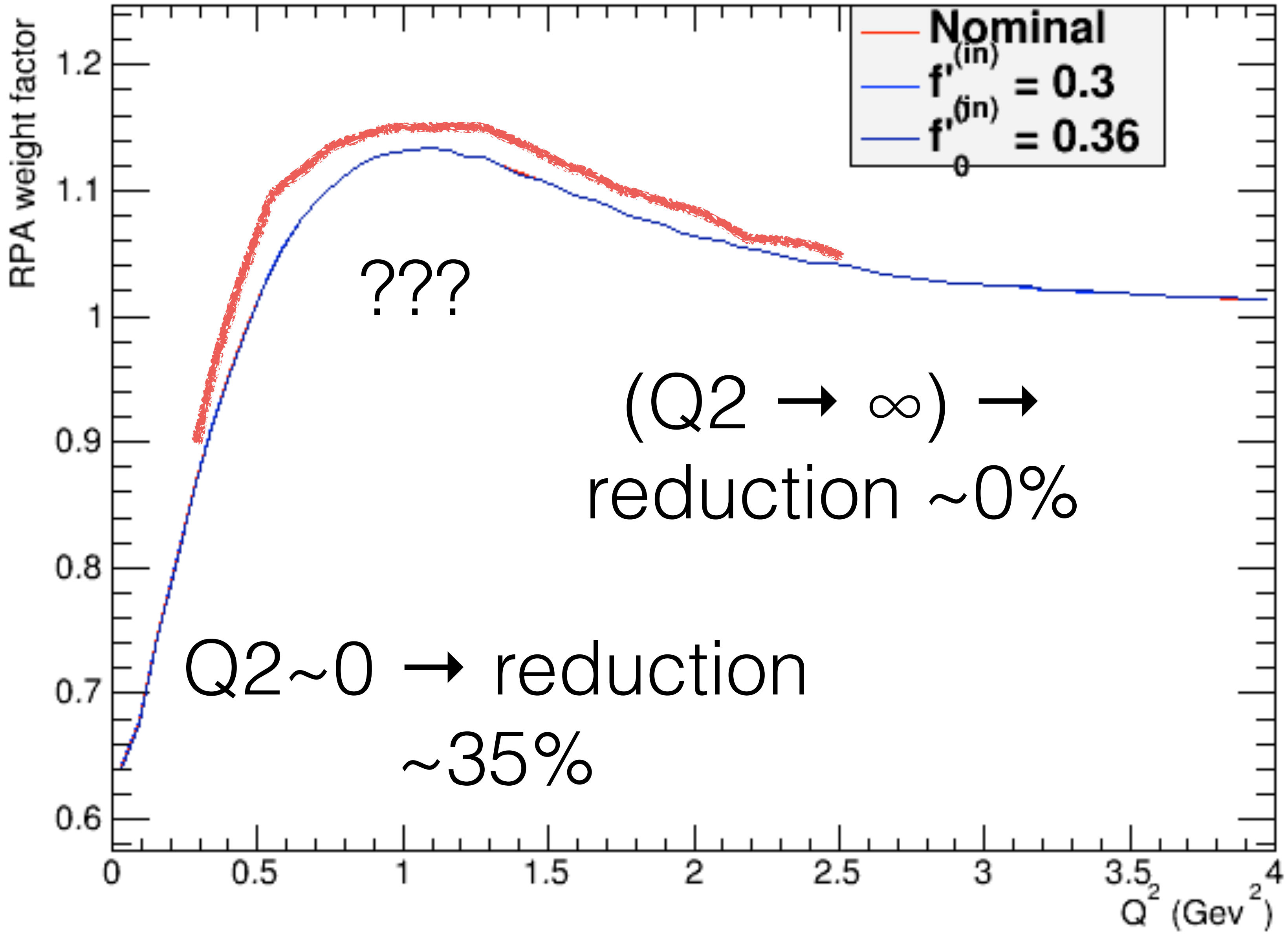


Martini Sum
Martini NN+Δ interference
Martini NN
Nieves NN+ (NN+Δ interference)

Models have parameters!

Models have limits!

Example: Long range correlations



???

(Q2 → ∞) → reduction ~0%

Q2~0 → reduction ~35%

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

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

Experiments reweight cross-section models in a coarse manner More knowledge of free parameters the model will improve the process.

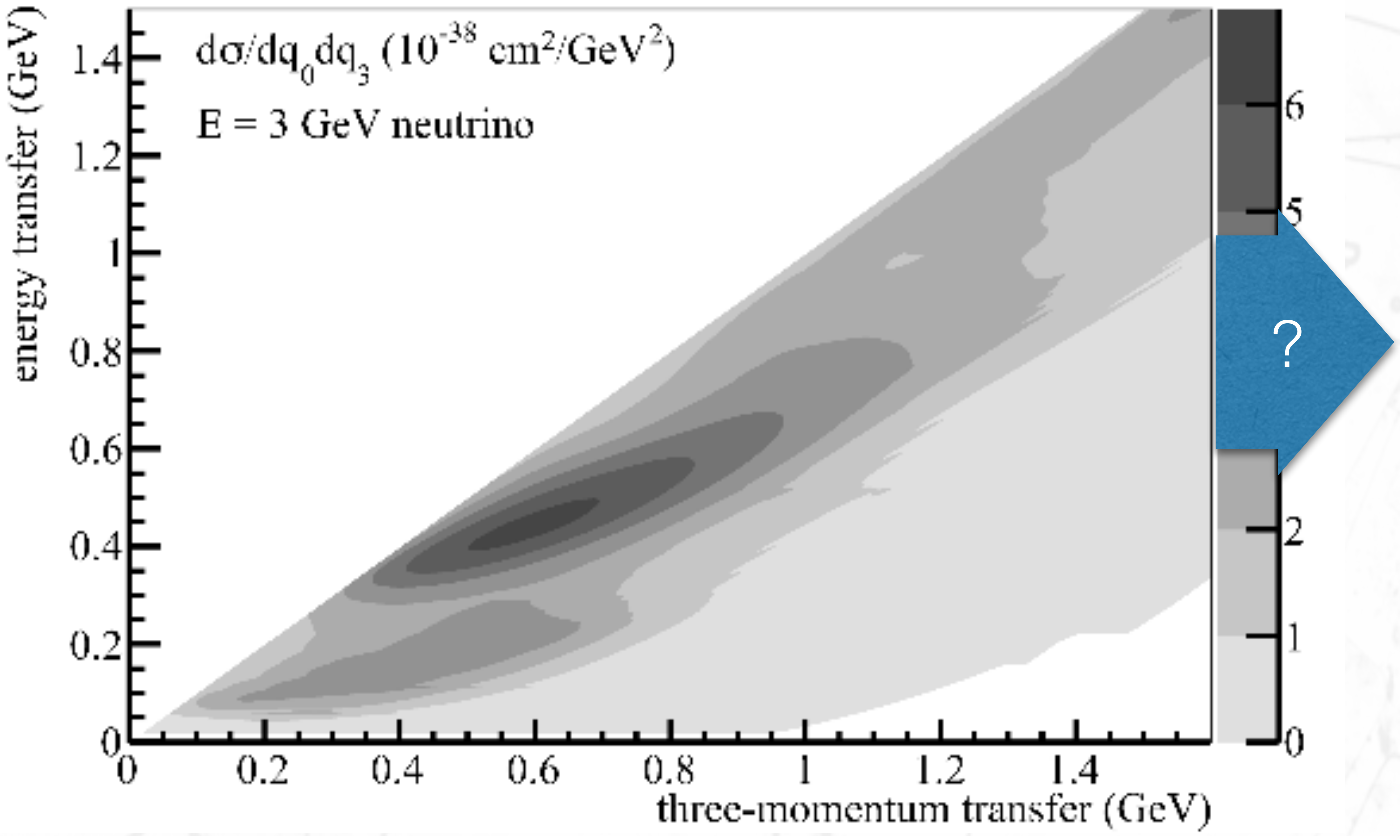
Improve != lower errors

Limits of models

- The validity of the models is normally restricted to some kinematical phase space.

- This is a critical point for broad band beam neutrino MC's.

- One of the most relevant cases now is the 2p2h.



Not only a limit of the model but also the channels included in the model !

Critical for inclusive measurements like oscillations & broad neutrino beams!

Monte Carlos

- Modern experiments require event simulations including:
  - Many different Nuclei: H, C, O, Si, Al, Fe, Pb, Ar, …
  - The full kinematics of the event including all final state hadrons.
    - This will be even more relevant with the new Liquid Argon detectors.

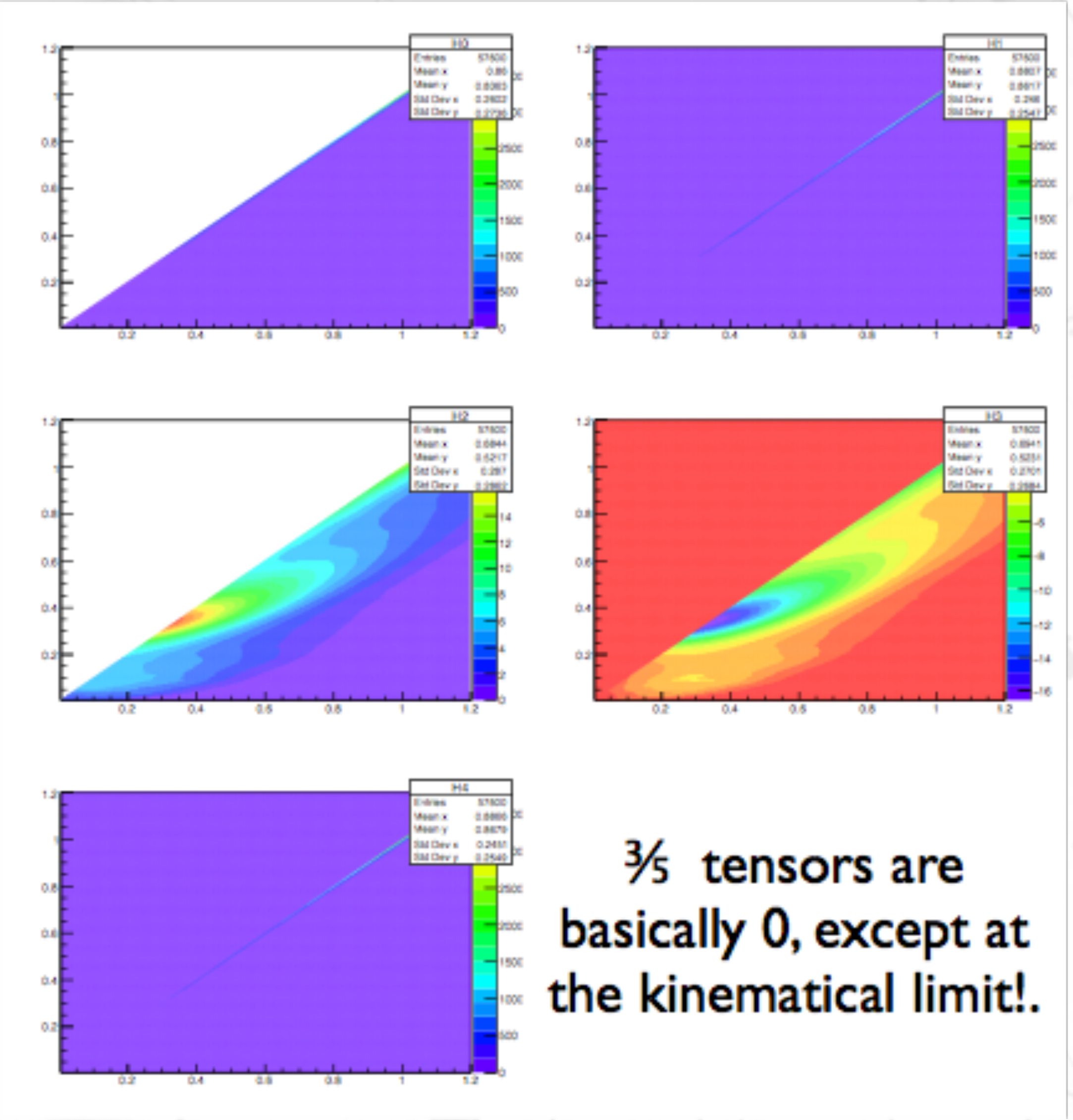
Hadron tensor

- The cross-section is, in IA, a contraction of the Lepton ($L_{\mu\nu}$) and the Hadron tensors ($H_{\mu\nu}$)

$$\frac{d^2\sigma}{d\cos\theta\, dT_\mu} = G\, k'\, k_0' \left| L_{\mu\nu}^{Nieves} H^{\mu\nu} \right|$$

- The Hadron tensor is precomputed in an “slow” MC.

- Limitations: the hadron-tensor do not predict (easily) the hadron kinematics!
  - This can be used to understand contributions or to implement MC re-weights.

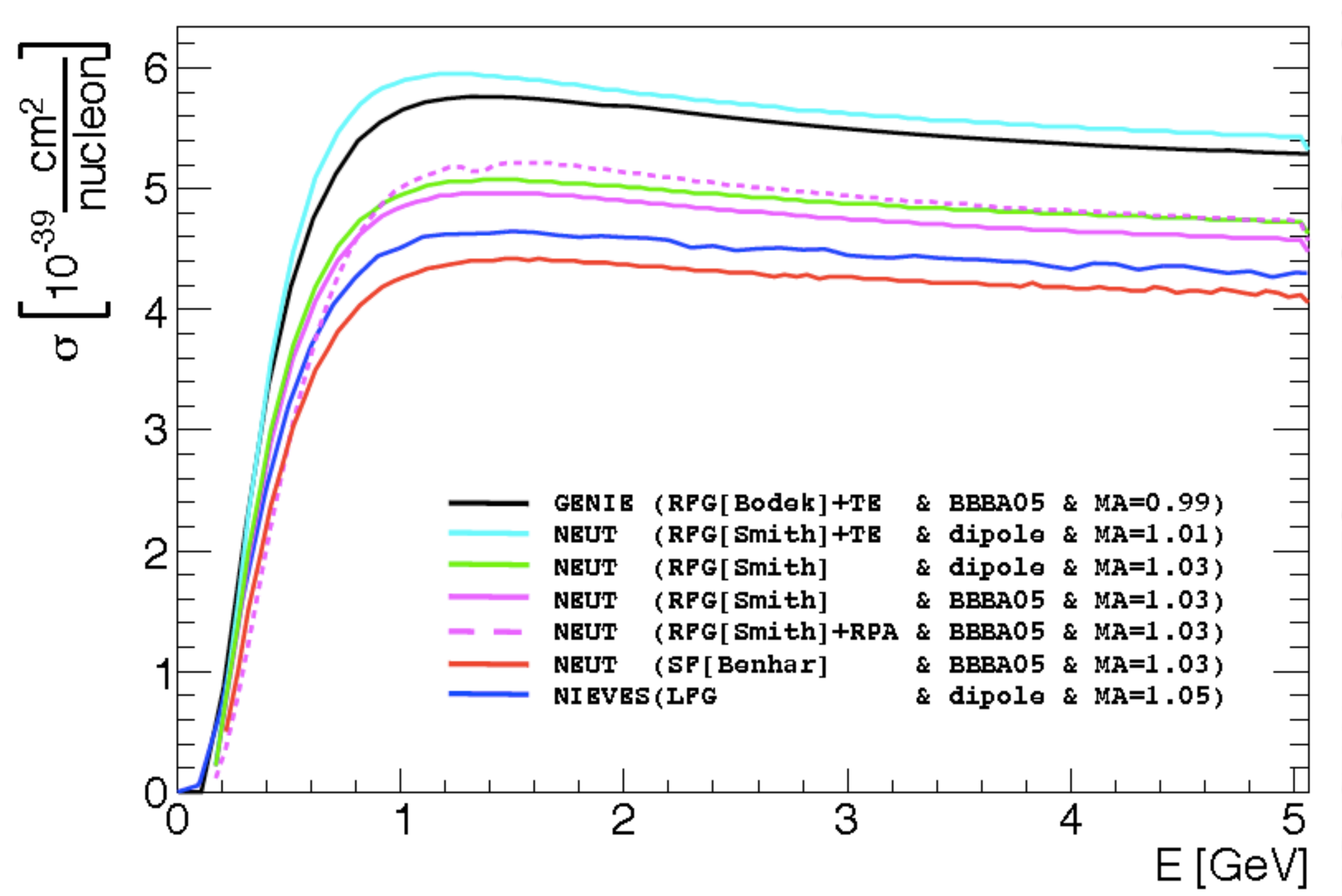


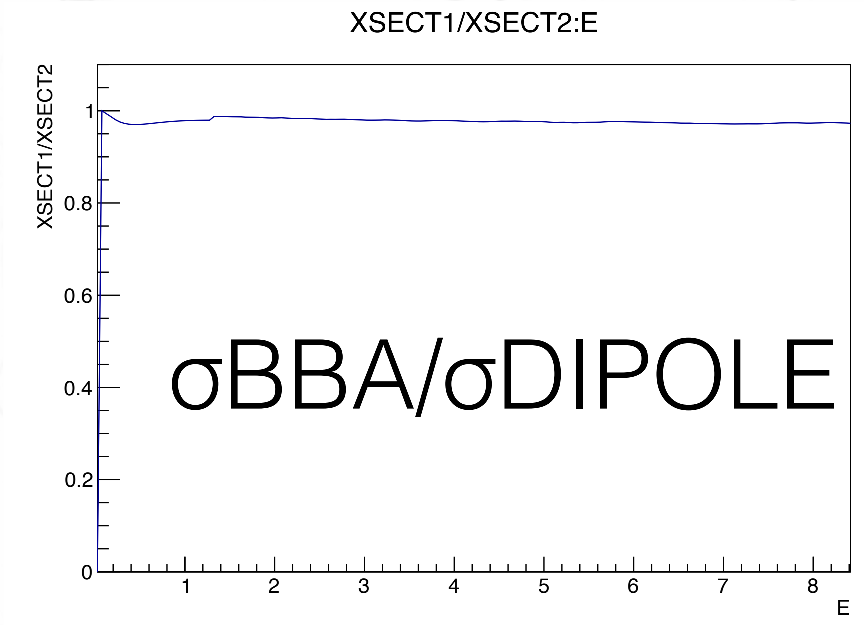
⅗ tensors are basically 0, except at the kinematical limit!.

Nucleon level

Are these differences only Nuclear effects ?

- Do MC models agree at nucleon level?
- A one to one nucleon level comparison might be enlightening?.
- What is the effect of the z expansion ?

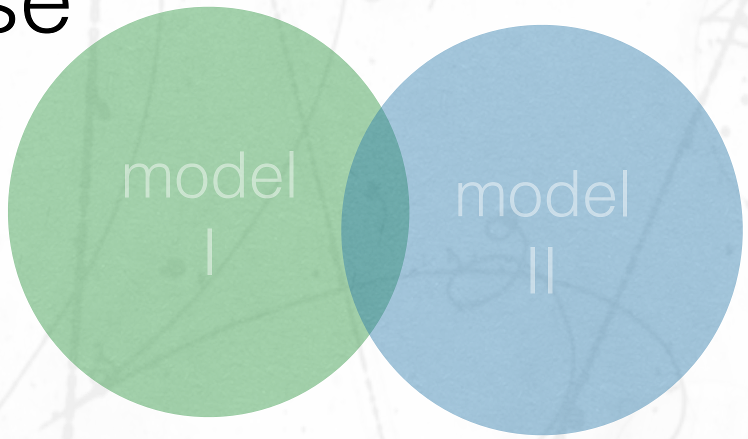




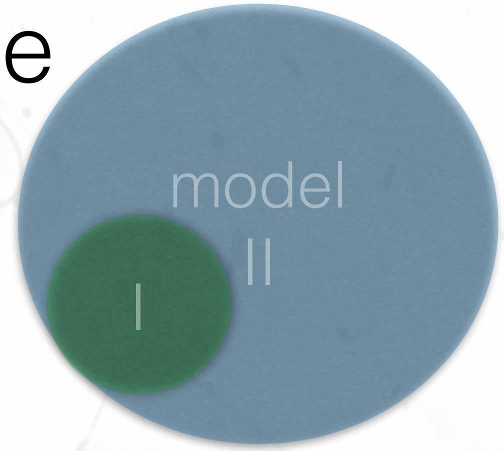
σBBA/σDIPOLE

Models overlap

case A



case B



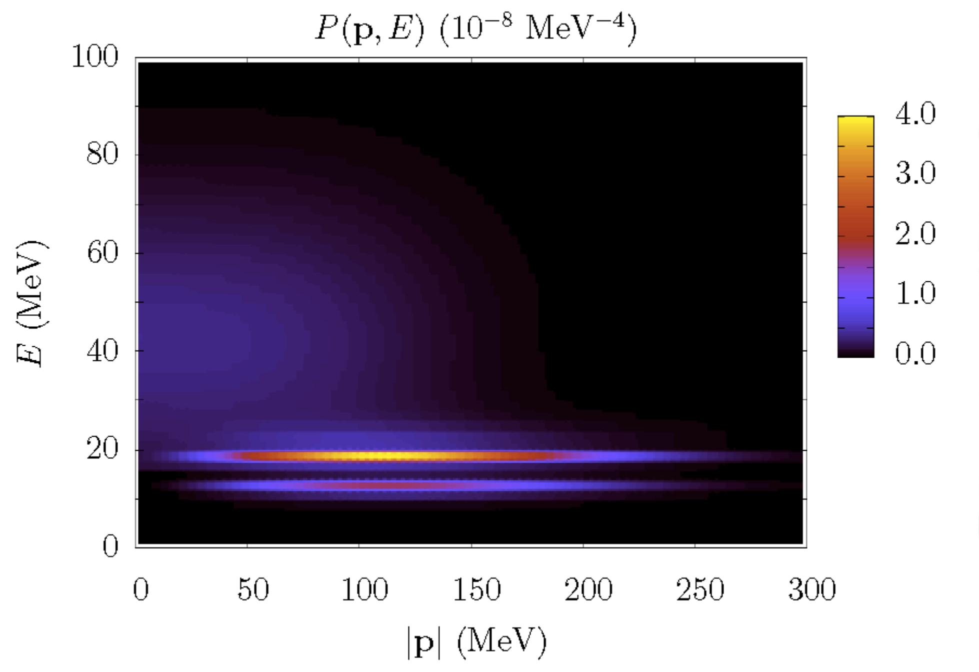
- One of the main problems to understand difference between models is the “overlapping processes” or the “double counting” problem.

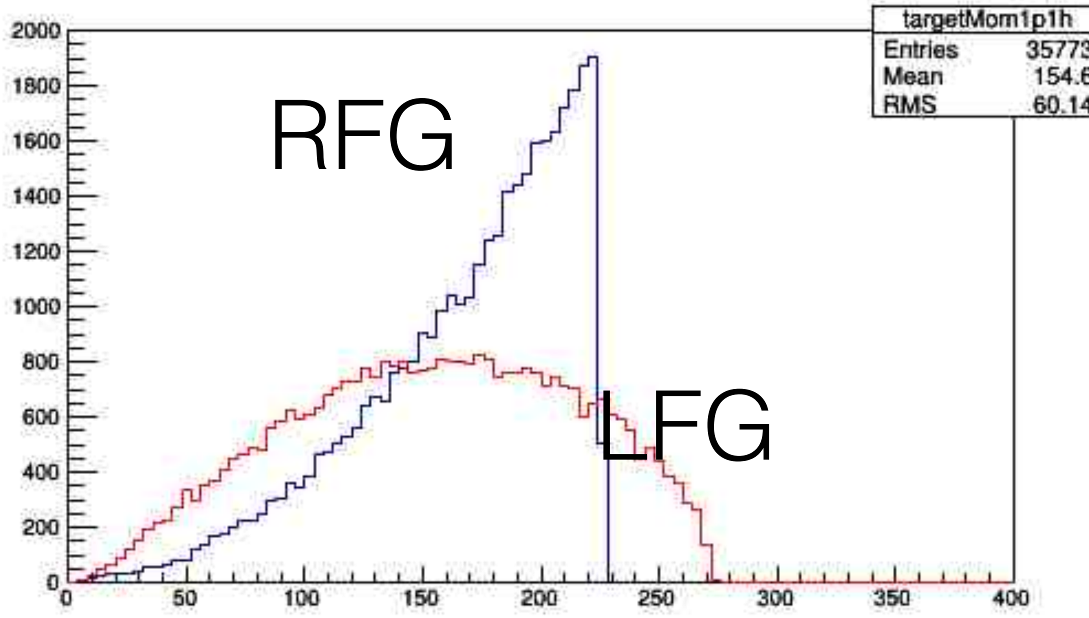
- Even if the overlap is well defined (case A), we need to understand the way to handle it correctly (Interferences!!!)

- In case B, we might substitute the common region by the best model.

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.

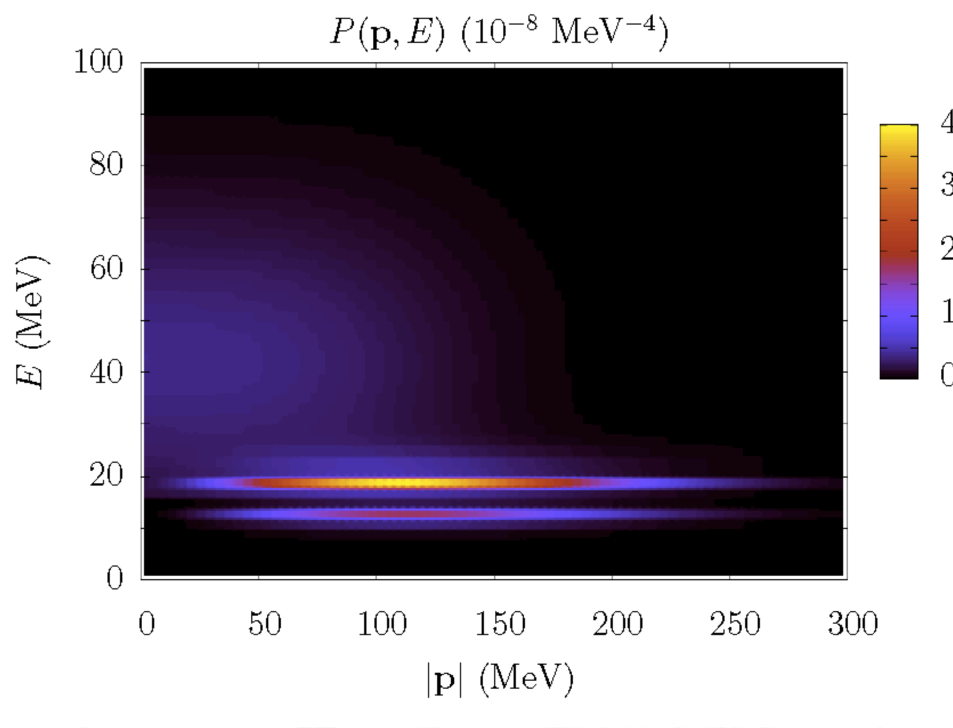




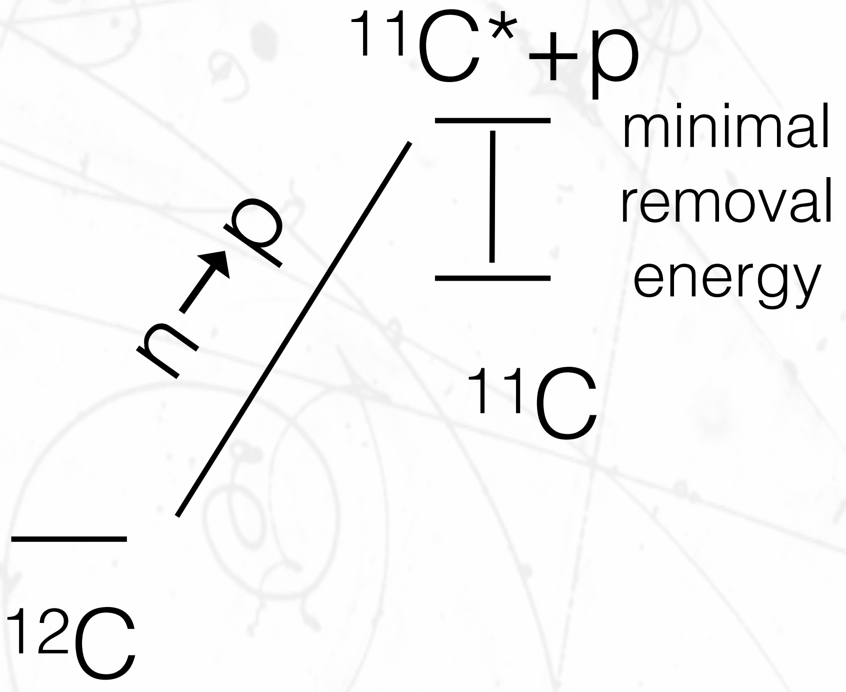
Experiments and MC are already looking intensively on the differences

Bind Energy

- For impulse approximation there are 3 ways to implement bind energy:
    - Effective target mass (m → m-Eb)
    - Dispersion relation (Spectral function).
    - Nuclear removal energy.

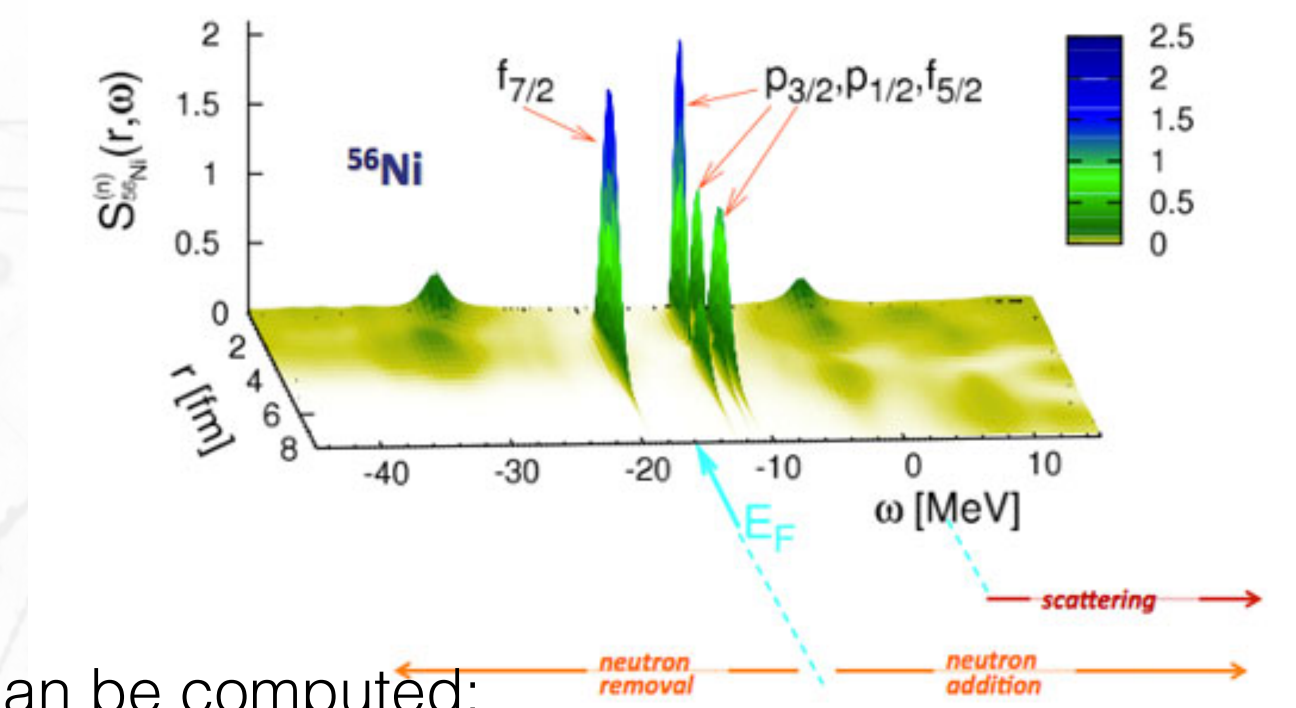


Bind energy is variable because final nuclear
states might be excited.
~6 MeV γ in SK



Spectral functions

- Take the full response of the nuclei in momentum and energy within the Impulse Approximation.
- It provides the “probability” to find a nucleon in an equivalent state of Energy and Momentum.
    - It incorporates this way also the removal energy.



- The response can be computed:

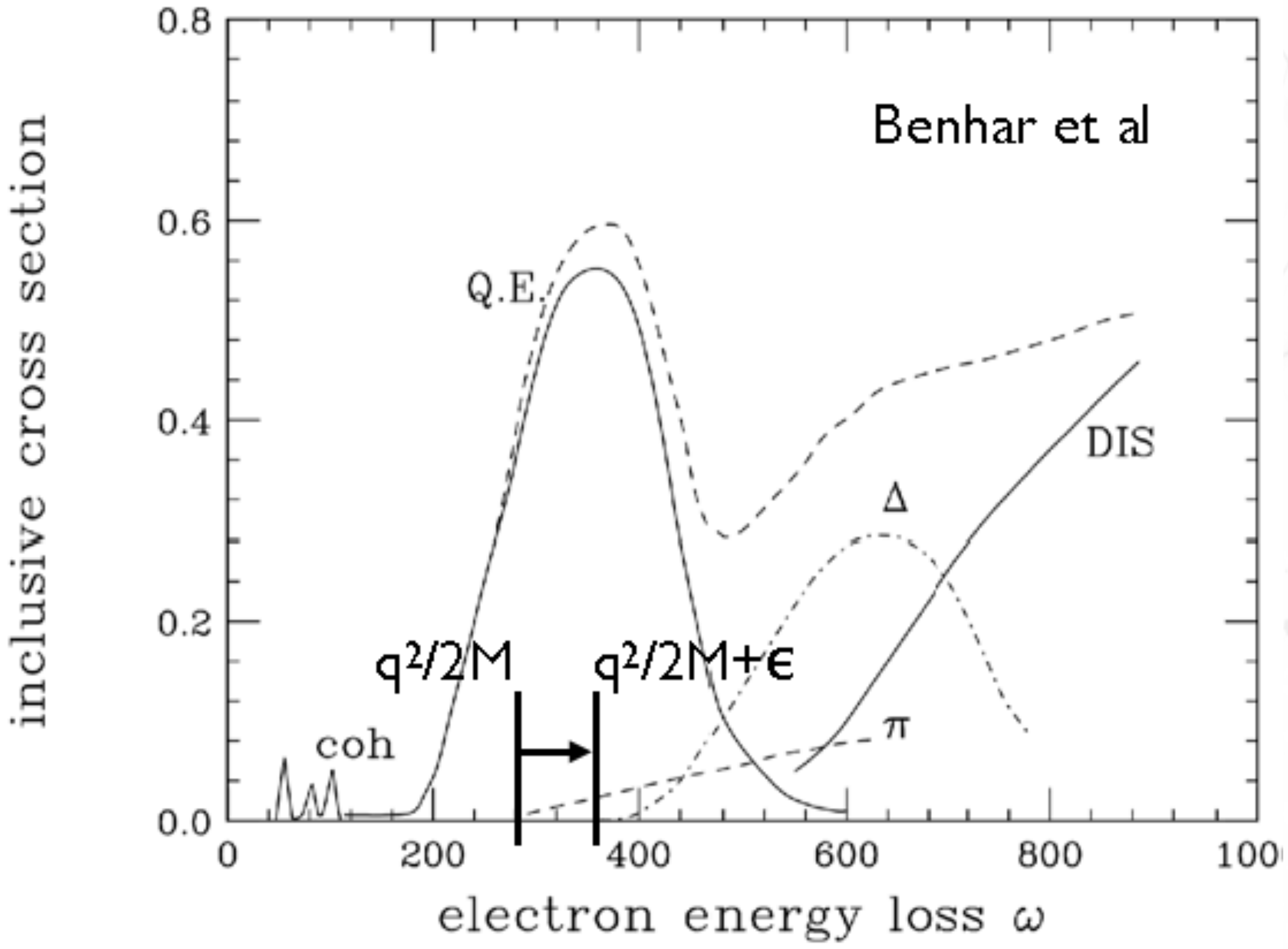
NEW

    - “Ab initio” for light nuclei.
    - Based on electron scattering.

Careful with this approach since we can be double counting if not implement consistently.

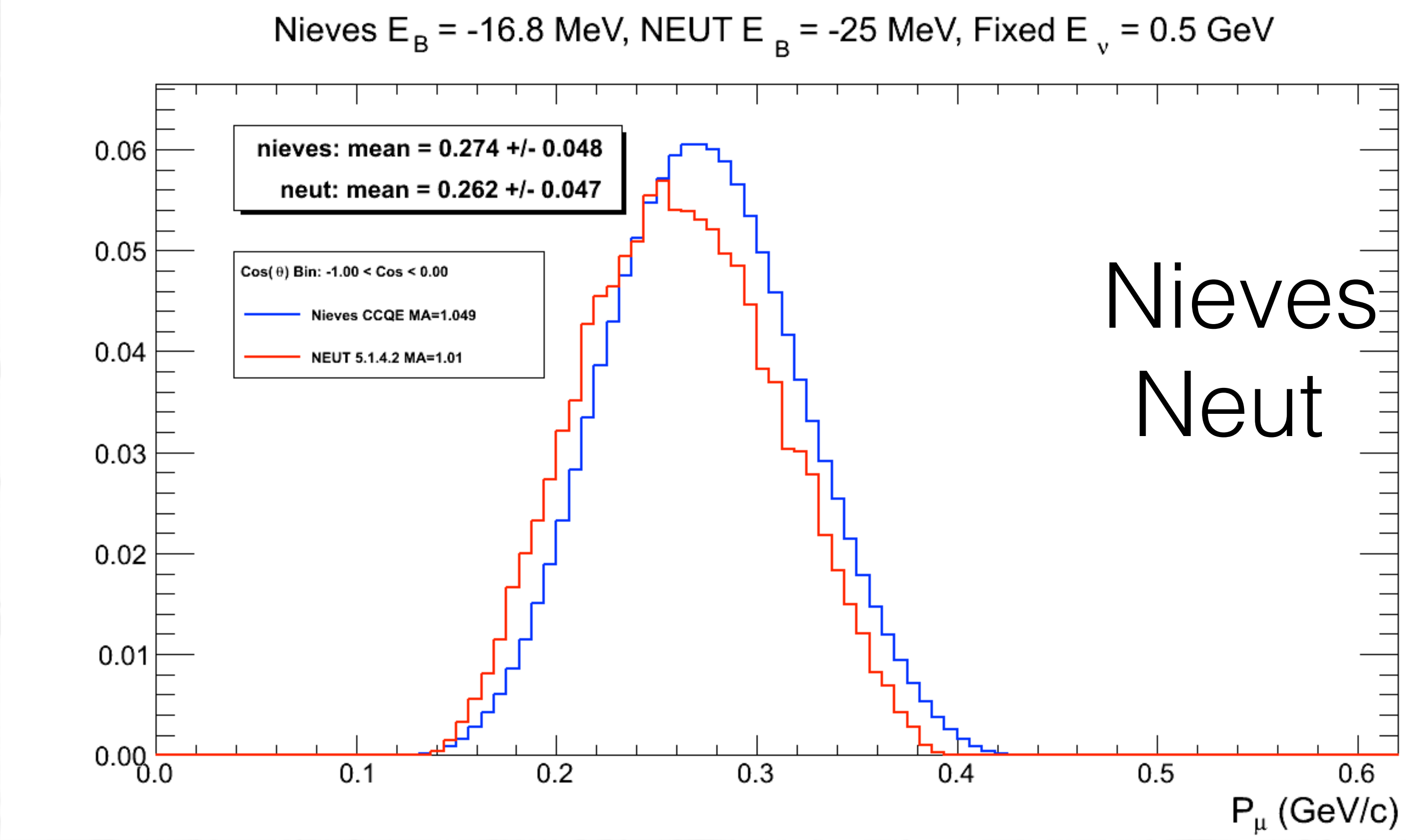
Bind energy in e,e’

- Fermi gas parabola peaks at $q^2/2M+\epsilon$ (binding energy shift) and has width related to Fermi momentum.
- Origin of ϵ may appear different in finite nucleus vs local density approximation
- Finite nucleus: initial state nucleon is bound with energy $E_i = -\epsilon$ and momentum $p_i<k_F$.
- Final nucleon has momentum $p_f = p_i + q$ and energy $E_f=p_f^2/2M$.
- Electron E loss: $\omega=E_f-E_i$.



- Fermi gas parabola described by width k_F and binding energy shift ϵ.

Bind Energy



Nieves E_b = -16.8 MeV

Neut E_b = -25.0 MeV

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

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

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 MeV to be compared with the typical (in T2K) 200-400 MeV muons.

- The proper treatment will require a departure of the Impulse Aproximation.

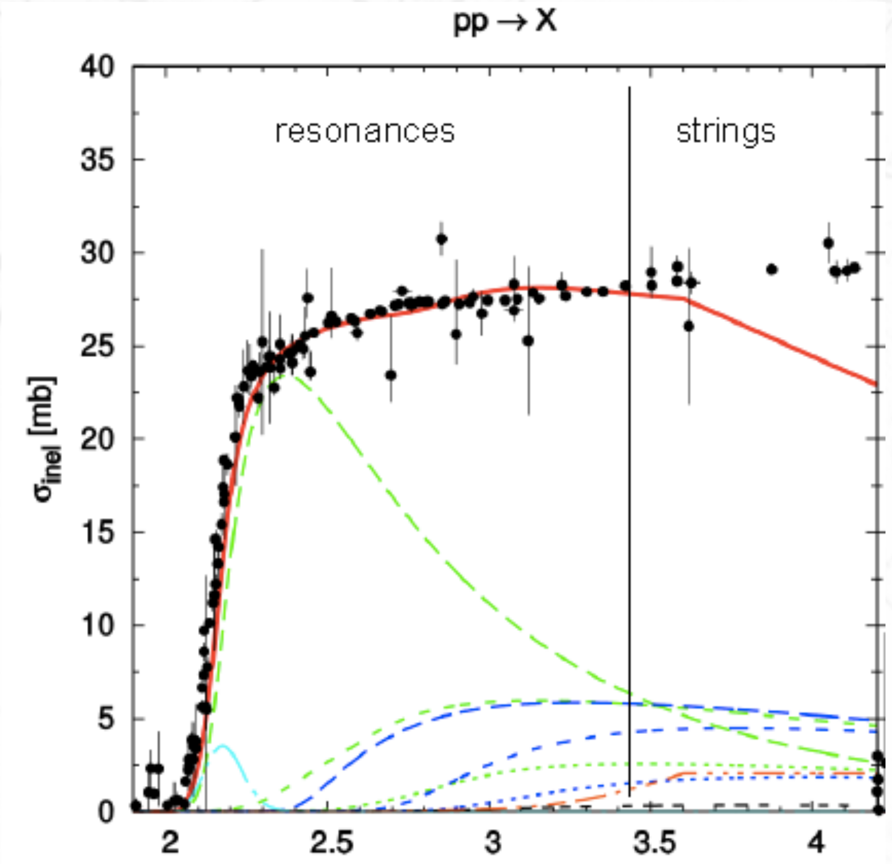
FSI

- FSI at this level is a relevant parameter because it affects the energy reconstruction:
  - channel identification.
    - The confusion on the channel produces the application of the wrong formulae.
  - available energy.
    - Nucleus can easily add, remove, modify (hadronic to electromagnetic) the energy of the final state particles altering the event calorimetry.

Cascade vs Transport

- Two approaches:
  - Cascade treats the particles as proyectiles inside de nuclei (Local Femi Gas). It follows each one as in the case of GEANT4.
  - Transports builds a model for the full nuclei (Local Femi Gas) including interactions and propagates it in time slices.

$$\left[\partial_t + (\nabla_p H_i)\nabla_r - (\nabla_r H_i)\nabla_p\right] f_i(\vec{r},t,\vec{p}) = C\left[f_i, f_j, \ldots\right]$$

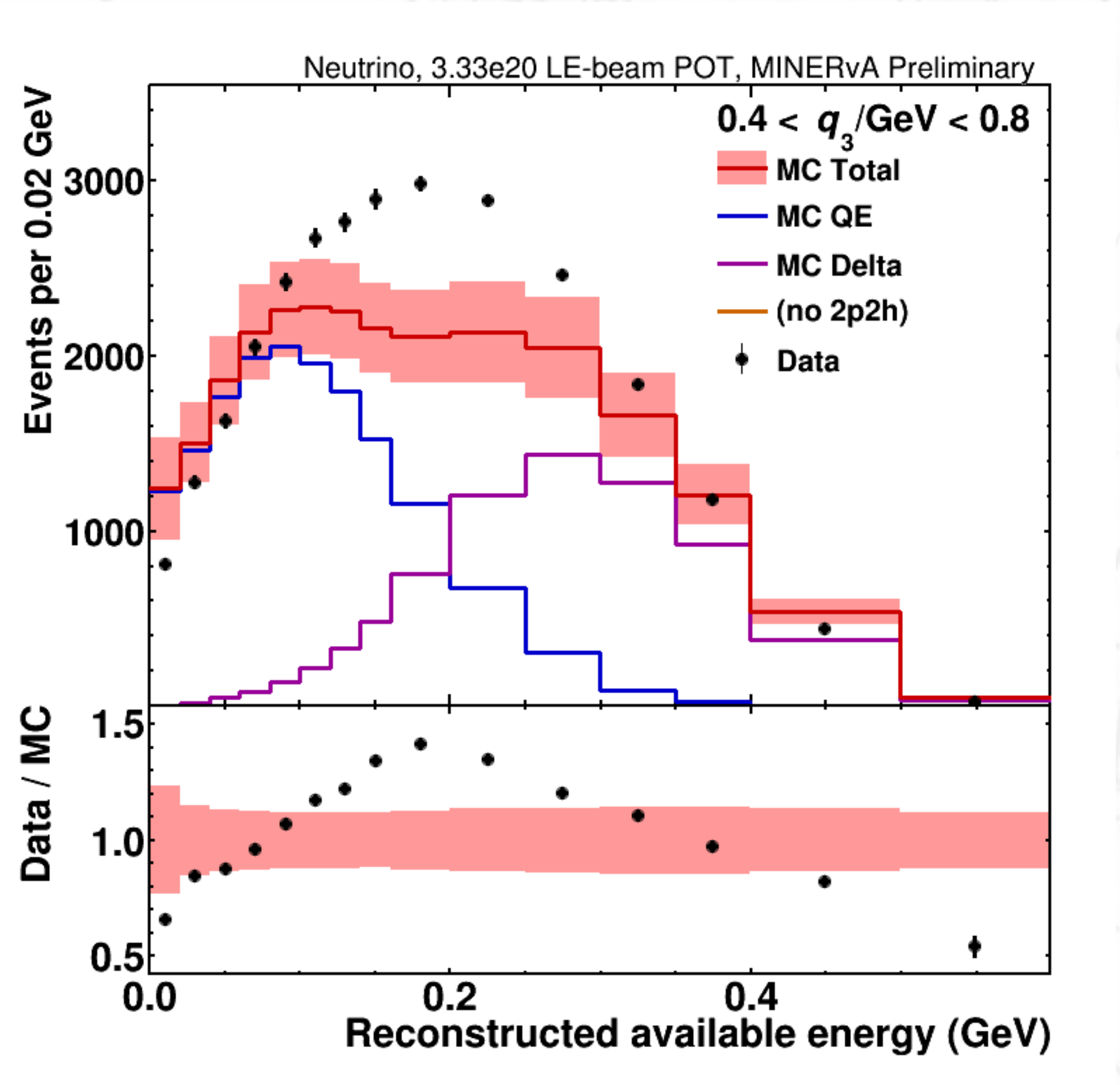


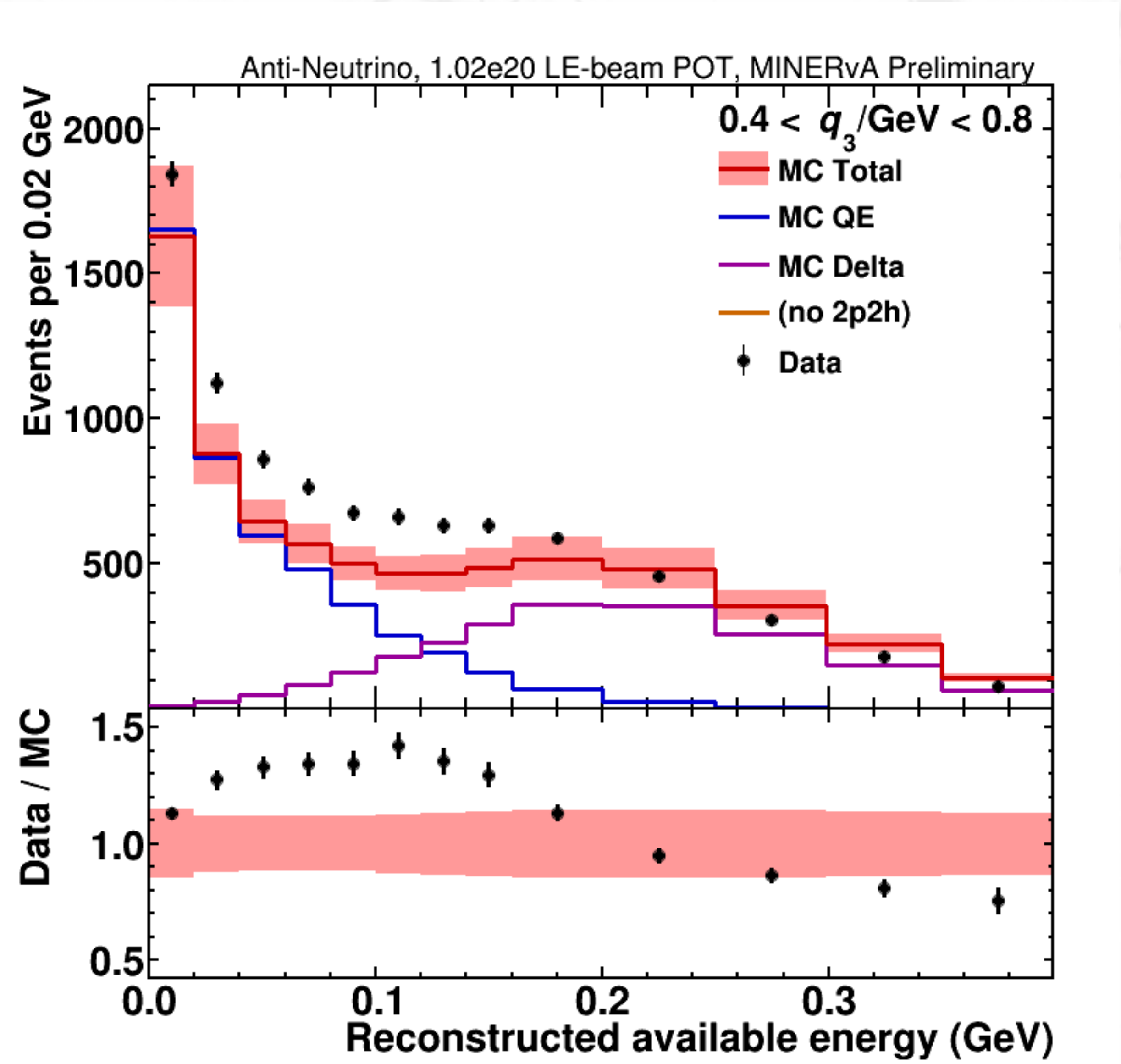
Excellent results in different interactions beyond neutrinos.

New observables

- The experience with the “effective” M_A taught us a lesson:
  - Radically different models can reproduce simple observables.
- Experiments are starting to look into alternative models involving the hadronic component of the interactions:
  - Transverse kinematics.
  - Vertex activity and “available energy”.
  - Low energy tracks in fully active low threshold experiments (LiqAr).

Energy reconstruction

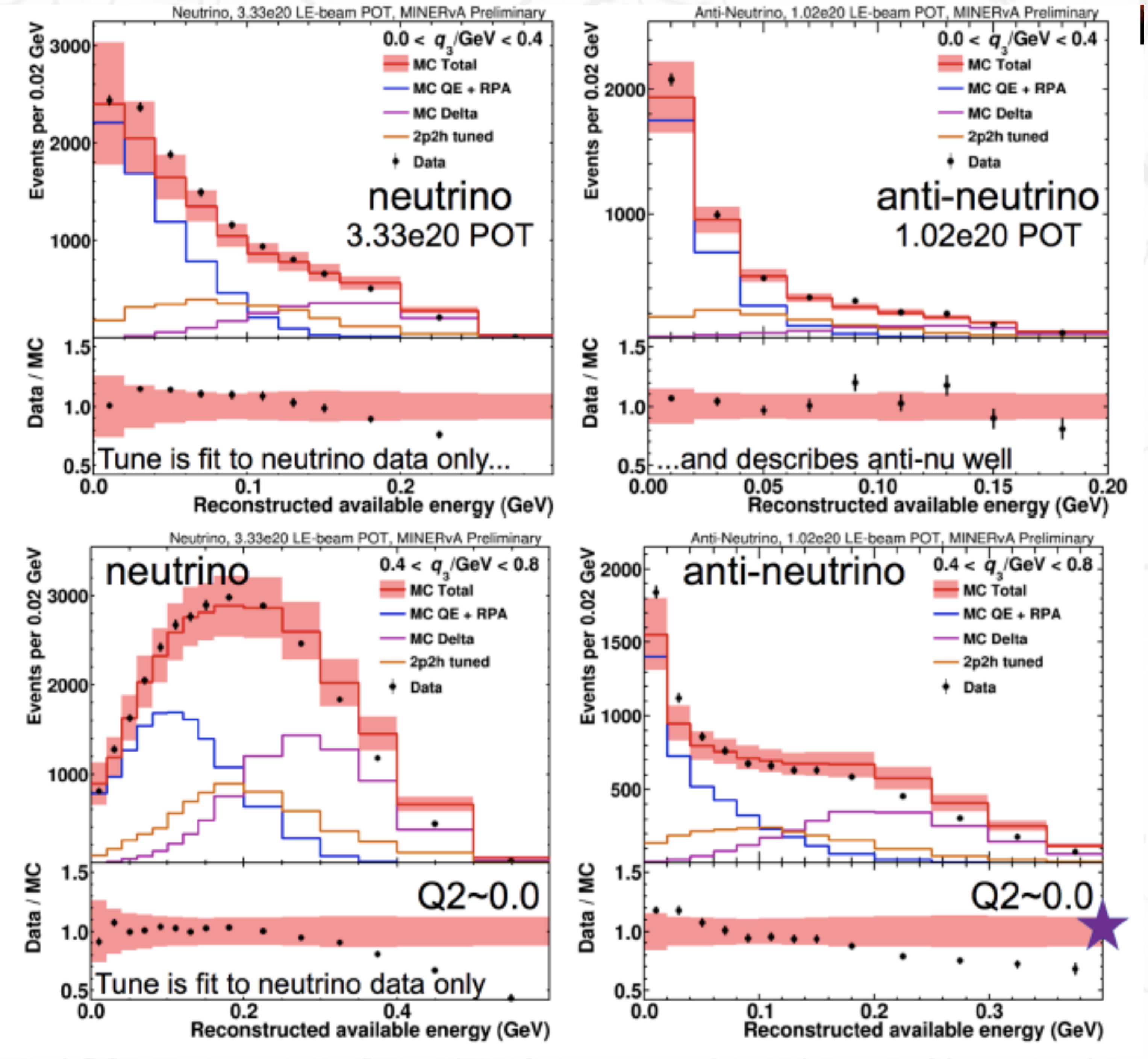




Available energy in Minerva is the sum of proton and charged pion kinetic energy and neutral pion, electron, and photon total energy

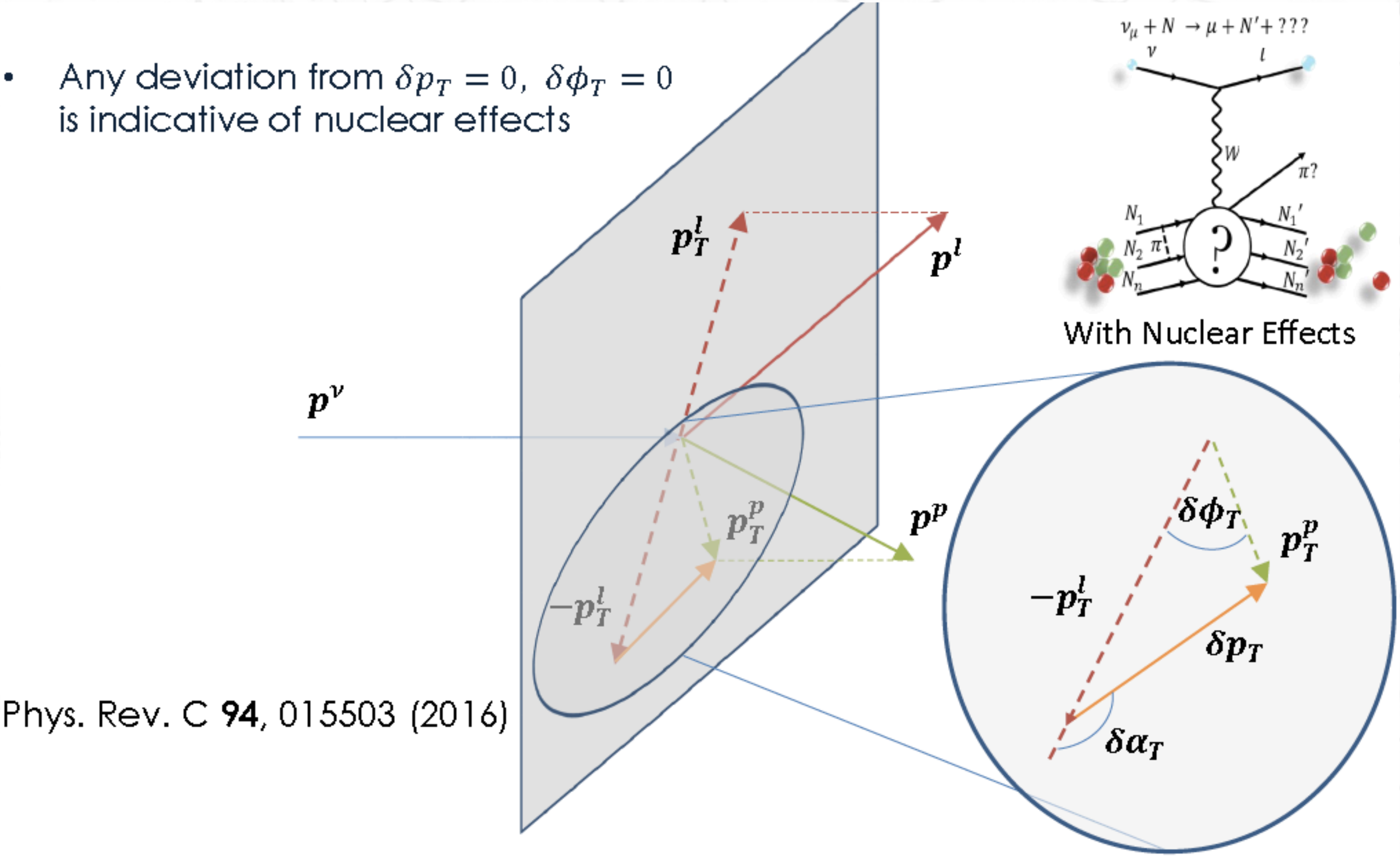
Energy reconstruction

- Data request additional strength to 2p2h models at high neutrino energies (not needed at T2K energies).
- The same strength applied to antineutrinos fit nicely the data.
- This implies a wrong model by x 2.



Phys. Rev. Lett. 116, 071802 (2016) and R. Gran FNAL JTEP seminar Nov 2017

Transverse variables

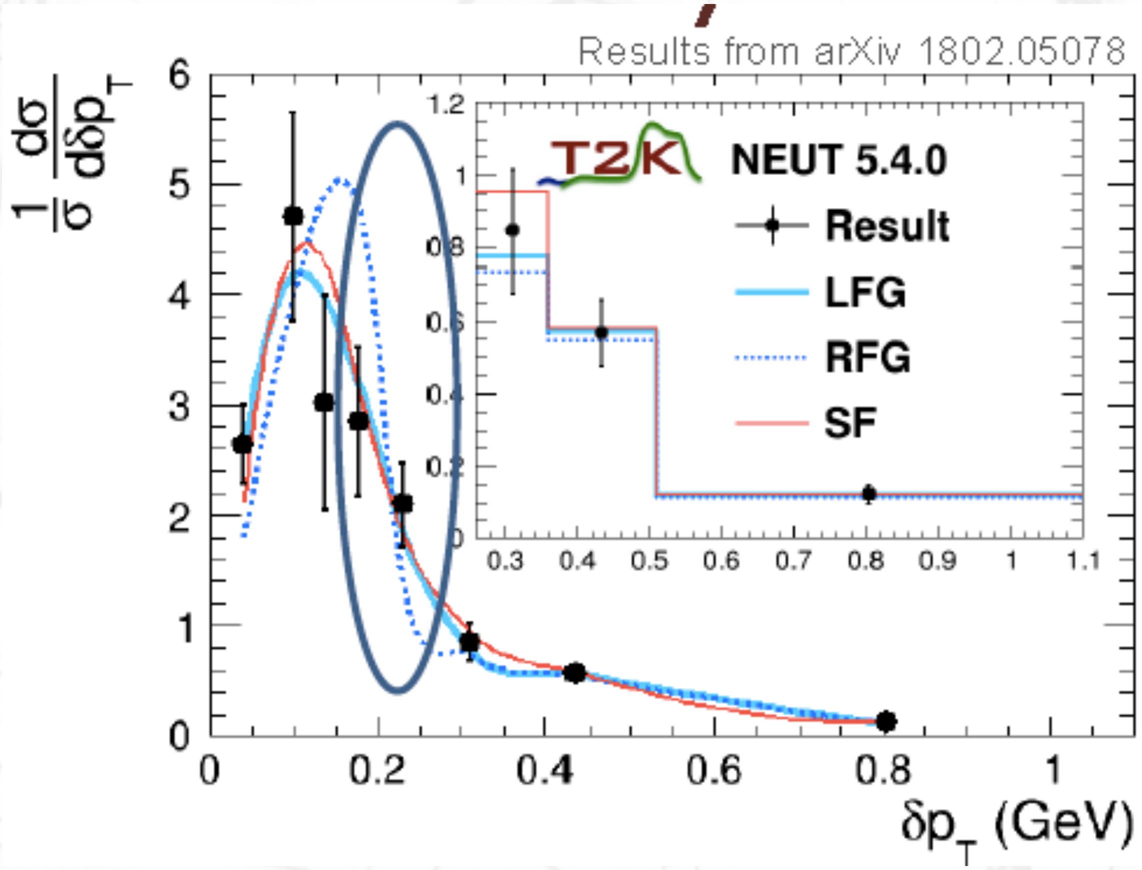


- Any deviation from $\delta p_T = 0,\ \delta\phi_T = 0$ is indicative of nuclear effects

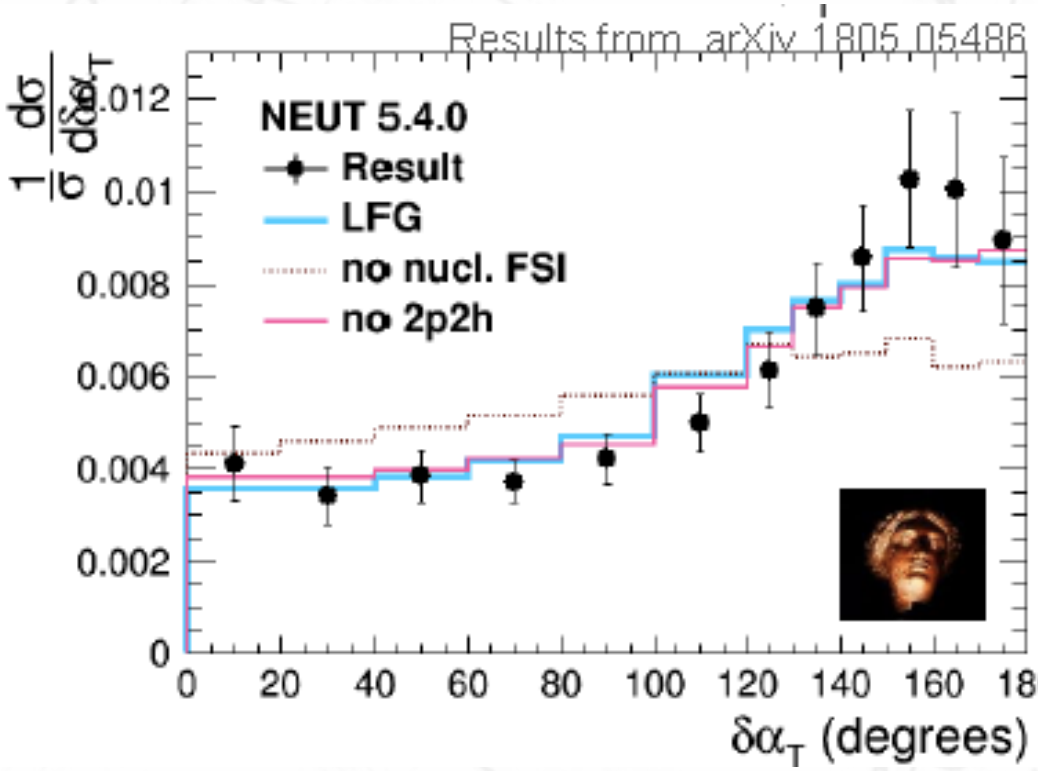
Phys. Rev. C **94**, 015503 (2016)

Transverse variables

- Local Fermi Gas is not a good model.
    - Probably the first time we see this in neutrino data.



- We need some sort of Final State Interactions.



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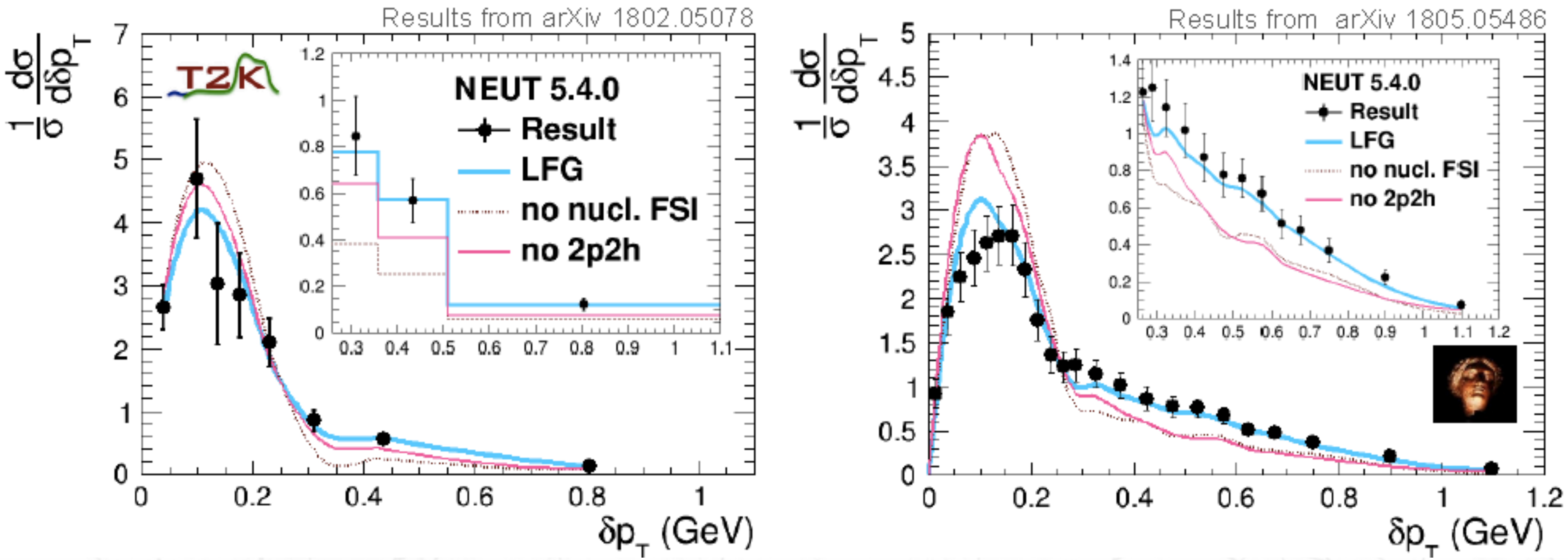
Transverse variables

- Similar conclusions in T2K and Minerva.



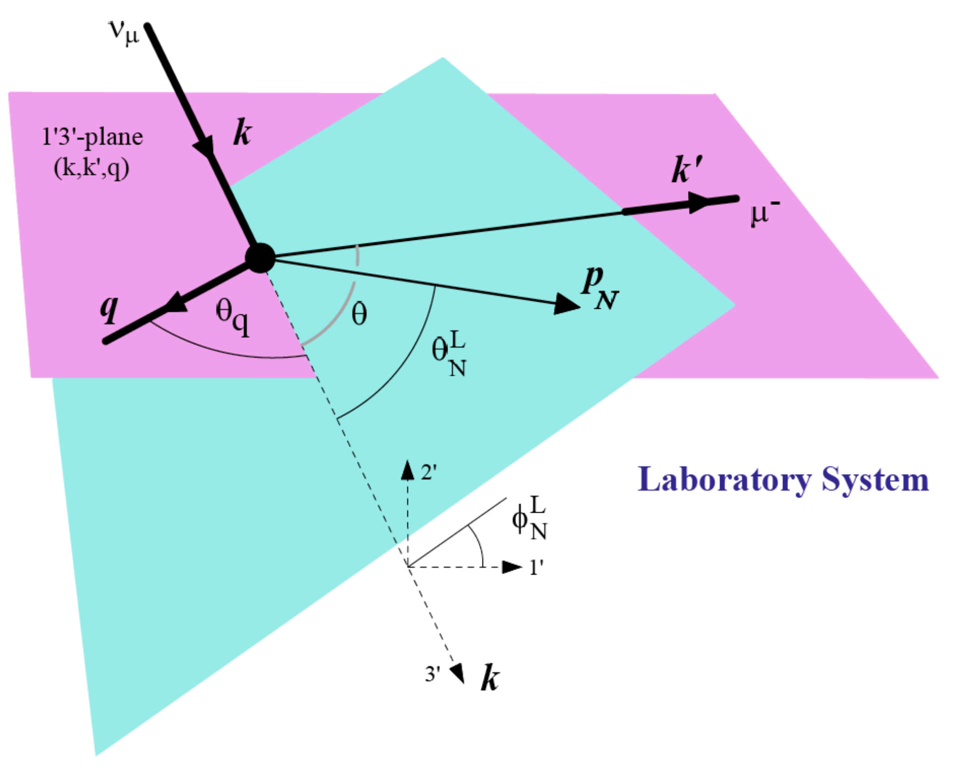
- This is a good set of observables:
  - More and more statistics to come.
  - Better detectors design with this measurements in mind.

Two ways to compute cross-sections

- **‚Inclusives‘**: interesting response of nuclei to electro weak interactions
    - Methods: Scaling, GFMC, SF
- **‚Practical‘:** Oscillation experiments need control of energy reconstruction
    - Full event description needed, inclusive is not enough!
    - Methods: Generators that produce four-vectors of all outgoing particles, must be compatible with the inclusive.

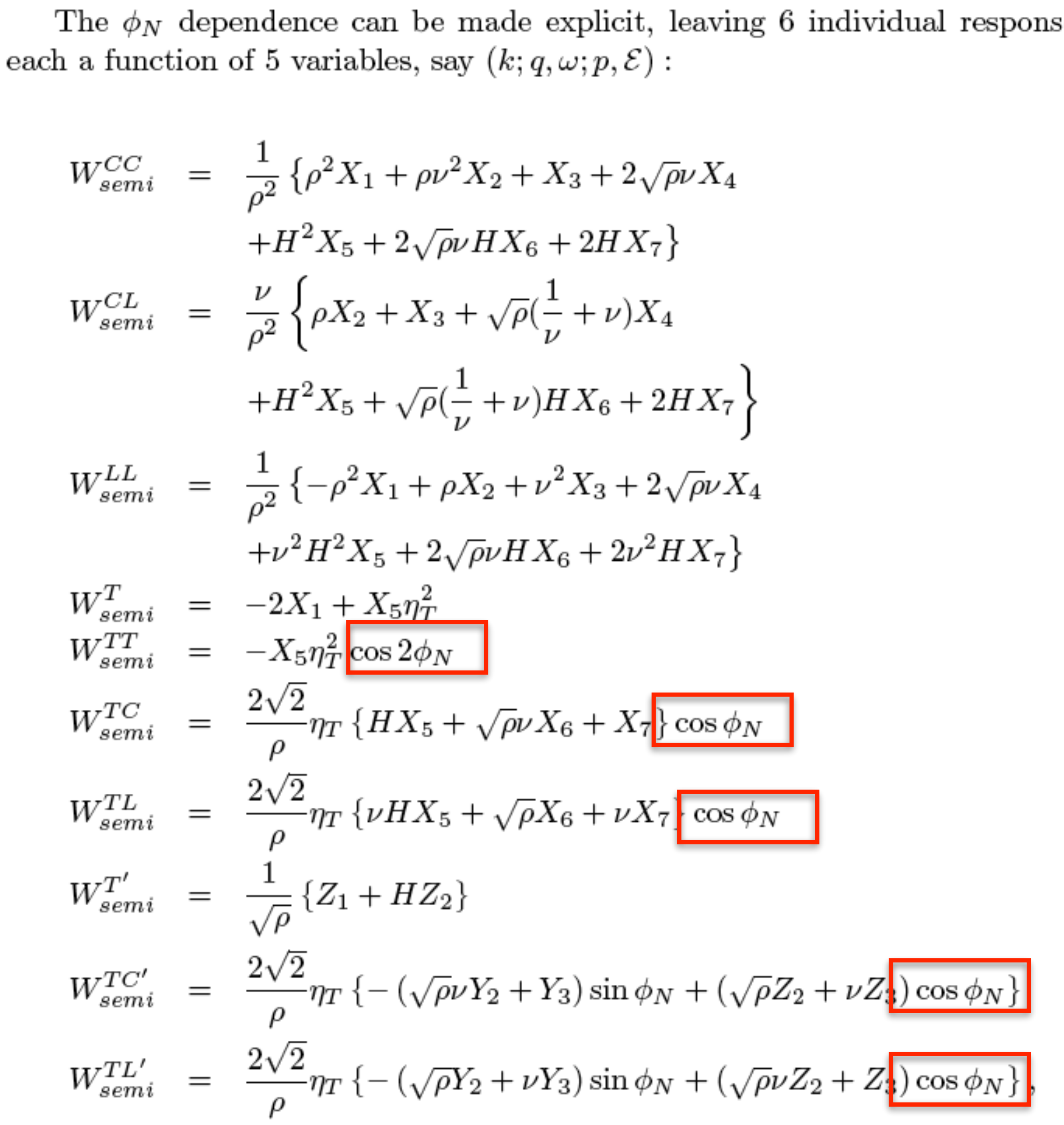
U.Mosel ETC Trento July 2018

Inclusive reactions



- ϕ_N is normally ignored in models and simulators.
- Accessing ϕ_N might give us valuable information.
- Ignoring ϕ_N might provide wrong conclusions as for complex transverse variables.
- Ignoring ϕ_N might impact the precision on efficiency calculations.

CCQE-like, other channels are more challenging.



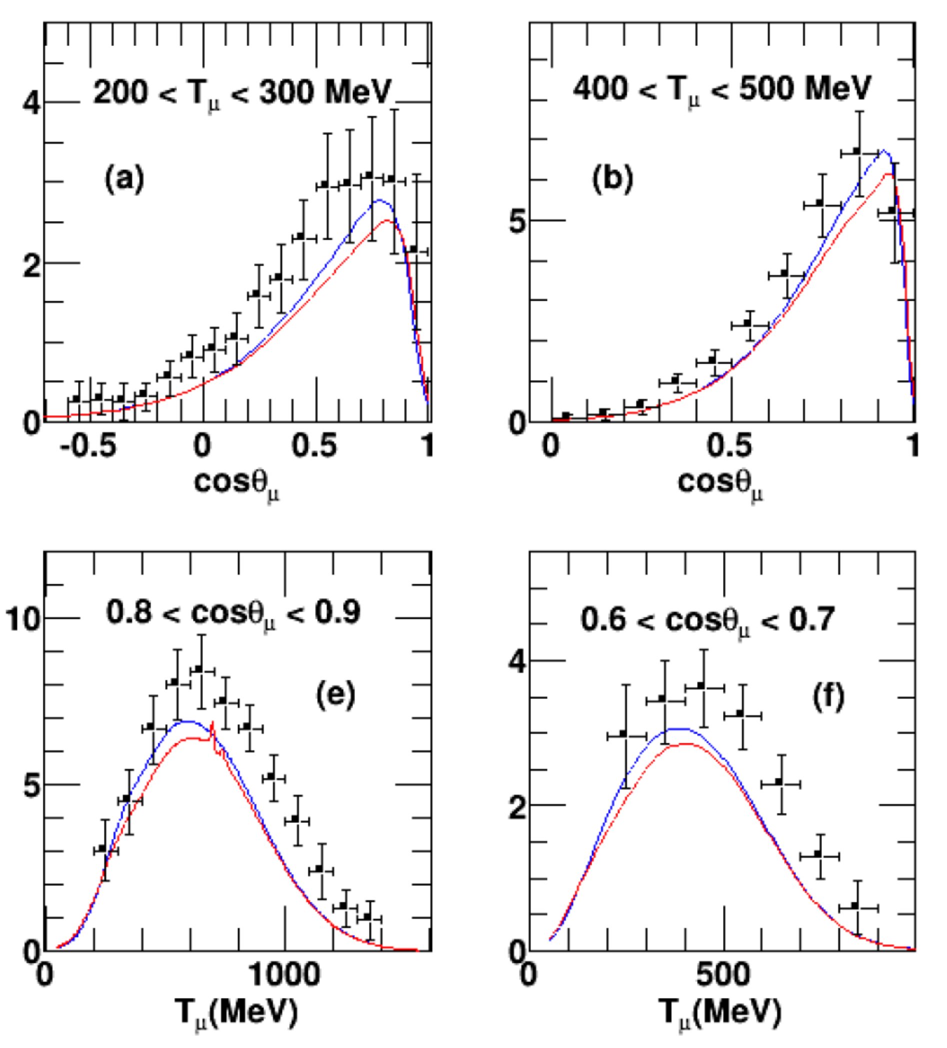
The ϕ_N dependence can be made explicit, leaving 6 individual responses, each a function of 5 variables, say $(k; q, \omega; p, \mathcal{E})$:

$$
\begin{aligned}
W^{CC}_{semi} &= \frac{1}{\rho^2}\{\rho^2 X_1 + \rho\nu^2 X_2 + X_3 + 2\sqrt{\rho}\nu X_4 \\
&\quad + H^2 X_5 + 2\sqrt{\rho}\nu H X_6 + 2H X_7\} \\
W^{CL}_{semi} &= \frac{\nu}{\rho^2}\left\{\rho X_2 + X_3 + \sqrt{\rho}(\frac{1}{\nu} + \nu) X_4 \right. \\
&\quad \left. + H^2 X_5 + \sqrt{\rho}(\frac{1}{\nu} + \nu) H X_6 + 2H X_7 \right\} \\
W^{LL}_{semi} &= \frac{1}{\rho^2}\{-\rho^2 X_1 + \rho X_2 + \nu^2 X_3 + 2\sqrt{\rho}\nu X_4 \\
&\quad + \nu^2 H^2 X_5 + 2\sqrt{\rho}\nu H X_6 + 2\nu^2 H X_7\} \\
W^{T}_{semi} &= -2X_1 + X_5 \eta_T^2 \\
W^{TT}_{semi} &= -X_5 \eta_T^2 \boxed{\cos 2\phi_N} \\
W^{TC}_{semi} &= \frac{2\sqrt{2}}{\rho}\eta_T \{H X_5 + \sqrt{\rho}\nu X_6 + X_7\} \boxed{\cos\phi_N} \\
W^{TL}_{semi} &= \frac{2\sqrt{2}}{\rho}\eta_T \{\nu H X_5 + \sqrt{\rho} X_6 + \nu X_7\} \boxed{\cos\phi_N} \\
W^{T'}_{semi} &= \frac{1}{\sqrt{\rho}}\{Z_1 + H Z_2\} \\
W^{TC'}_{semi} &= \frac{2\sqrt{2}}{\rho}\eta_T \{-(\sqrt{\rho}\nu Y_2 + Y_3)\sin\phi_N + (\sqrt{\rho} Z_2 + \nu Z_3) \boxed{\cos\phi_N\}} \\
W^{TL'}_{semi} &= \frac{2\sqrt{2}}{\rho}\eta_T \{-(\sqrt{\rho} Y_2 + \nu Y_3)\sin\phi_N + (\sqrt{\rho}\nu Z_2 + Z_3) \boxed{\cos\phi_N\}},
\end{aligned}
$$

Donnelly, Trento 2018

CC-QE like

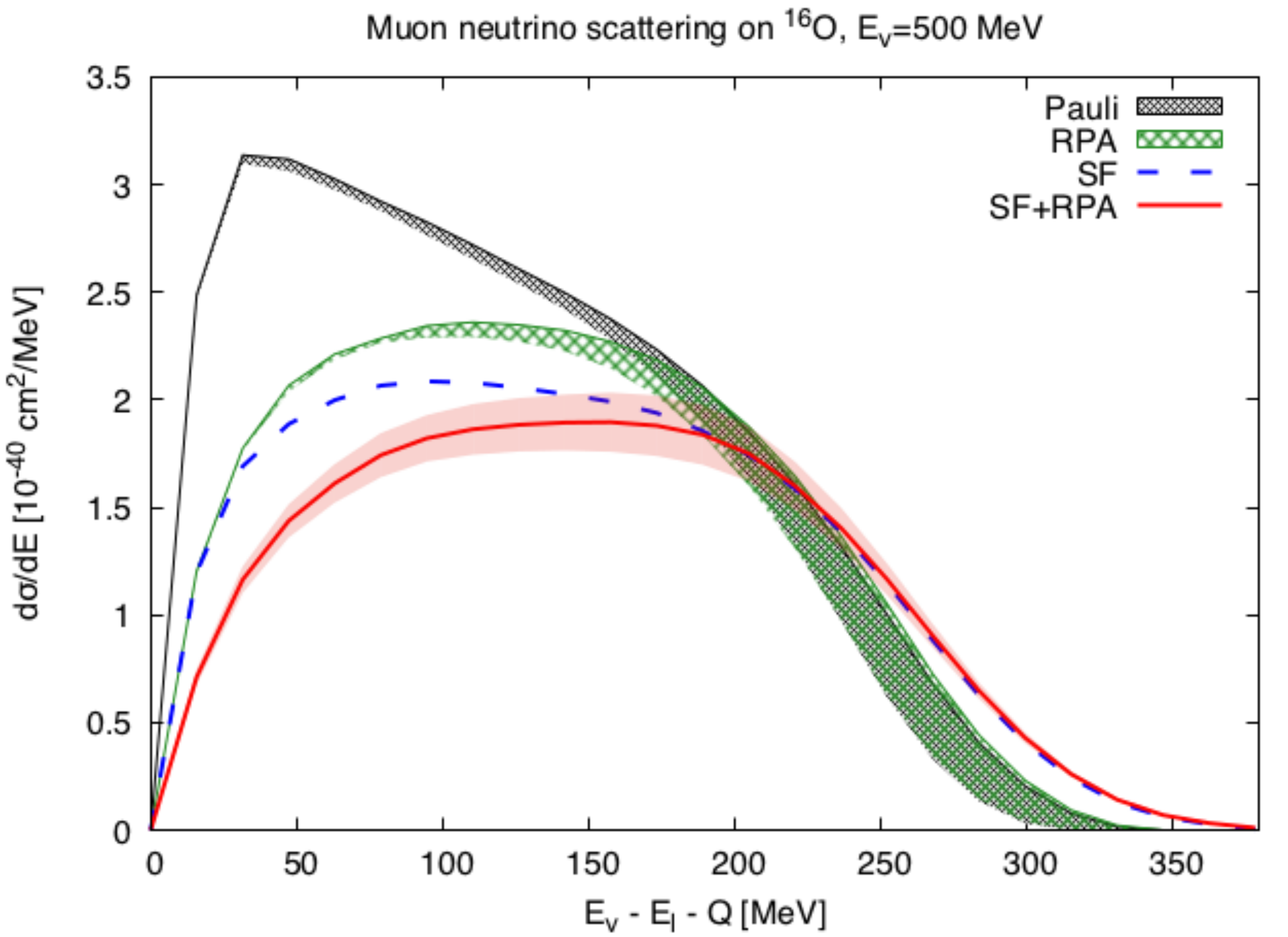
- Recent development by several groups with better nucleus description



Mean Field approximation and continuum Random Phase.

Ghent

Phys.Rev. C92 (2015) no.2, 024606



Approximative Spectral Function

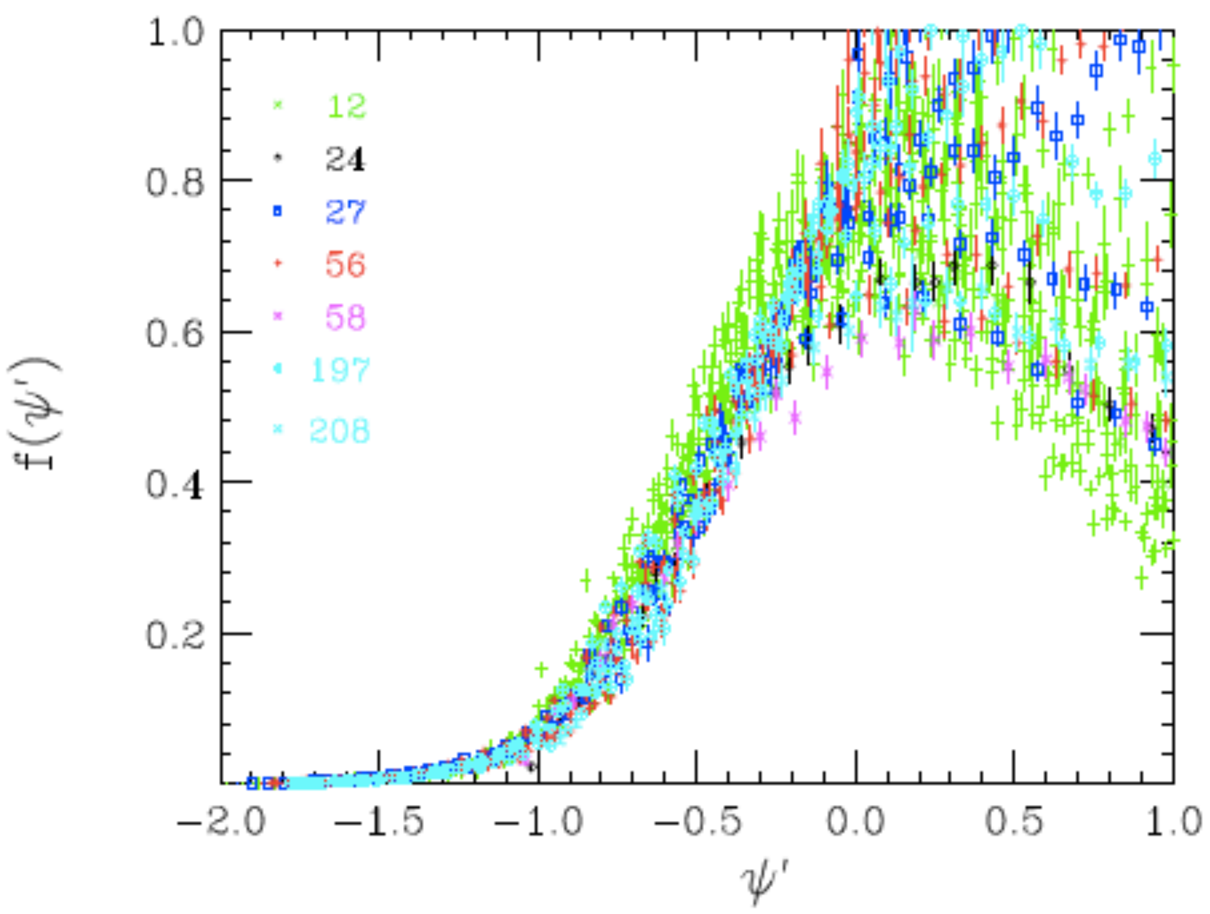
Annals Phys. 383 (2017) 455-496

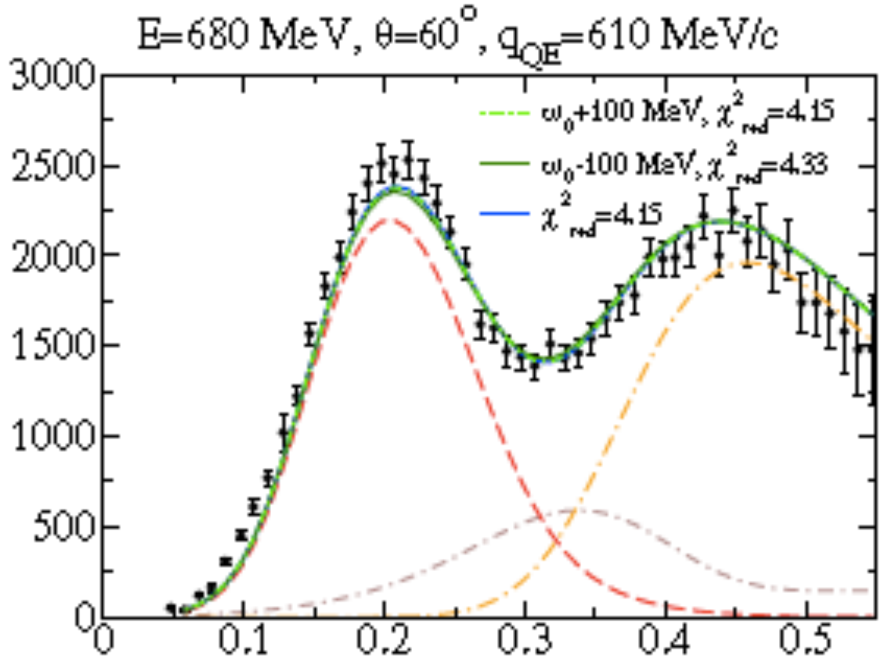
Phys.Rev. C97 (2018) no.3, 035506

Valencia

Susa model

Sevilla, Turin,
MIT, Granada





- SuperScaling is a quasi-phenomenological approach.
- All cross-sections behave the same independently of the momentum transfer (1st order scaling) and nuclei (superscaling) up to QE peak as function of

$$\psi' \equiv \frac{1}{\sqrt{\xi_F}} \frac{\lambda' - \tau'}{\sqrt{(1+\lambda')\tau' + \kappa\sqrt{\tau'(\tau'+1)}}}$$

- All models should reproduce this dependency.
- Excellent results with electron-scattering.

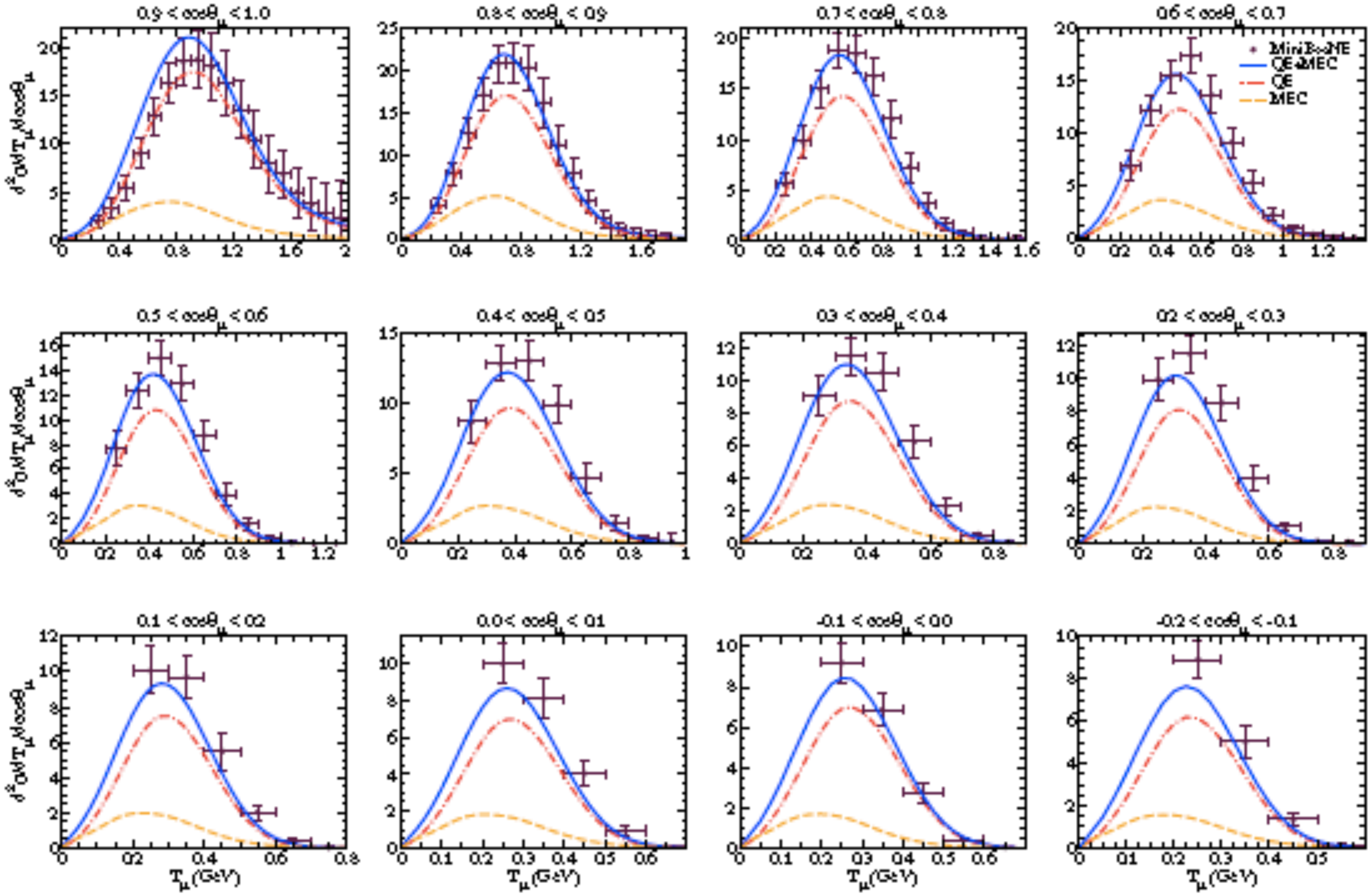
Excellent check to be done for your prefer MC.

SusaV2 and Mean Field

- SusaV2 is an extension of the Susa model based on numerical models that includes also 2p2h

- A complete Relativistic Mean Field Approximation and 2p2h model developed within the SUSA model.

J.Phys.Conf.Ser. 724 (2016) no.1, 012020

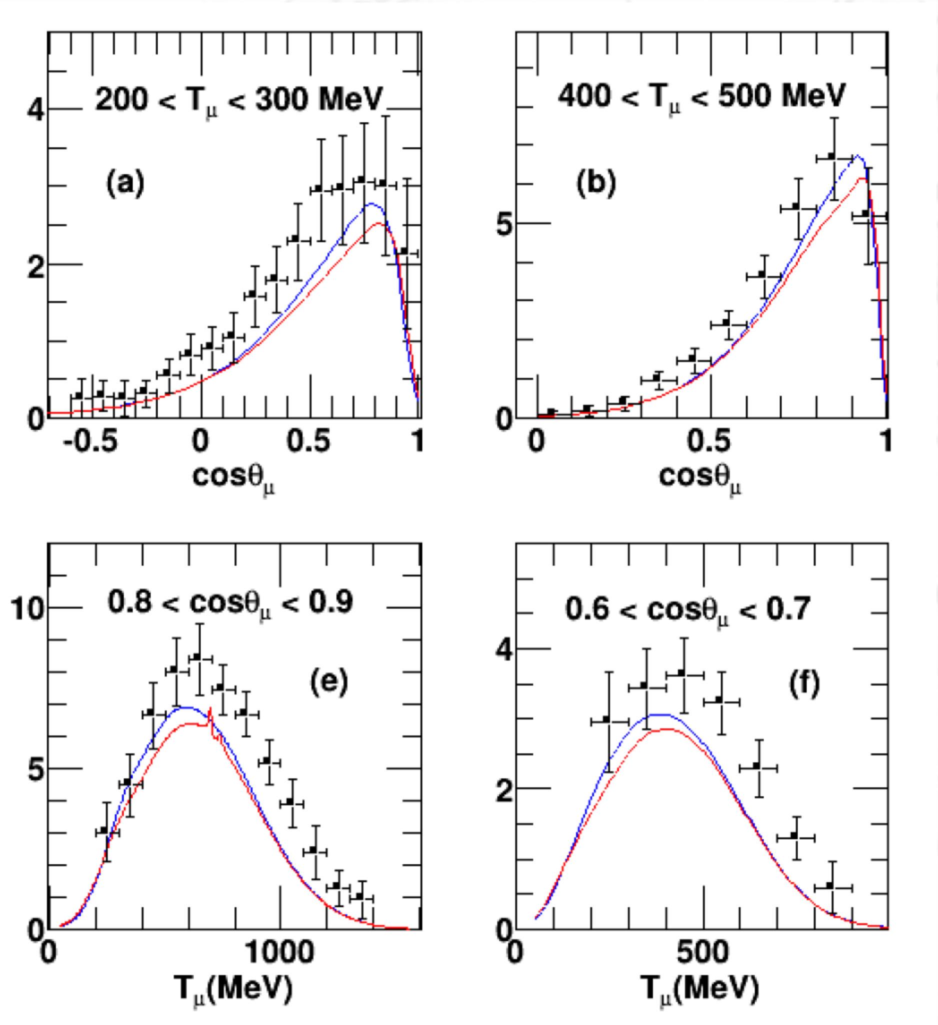


Model overlap

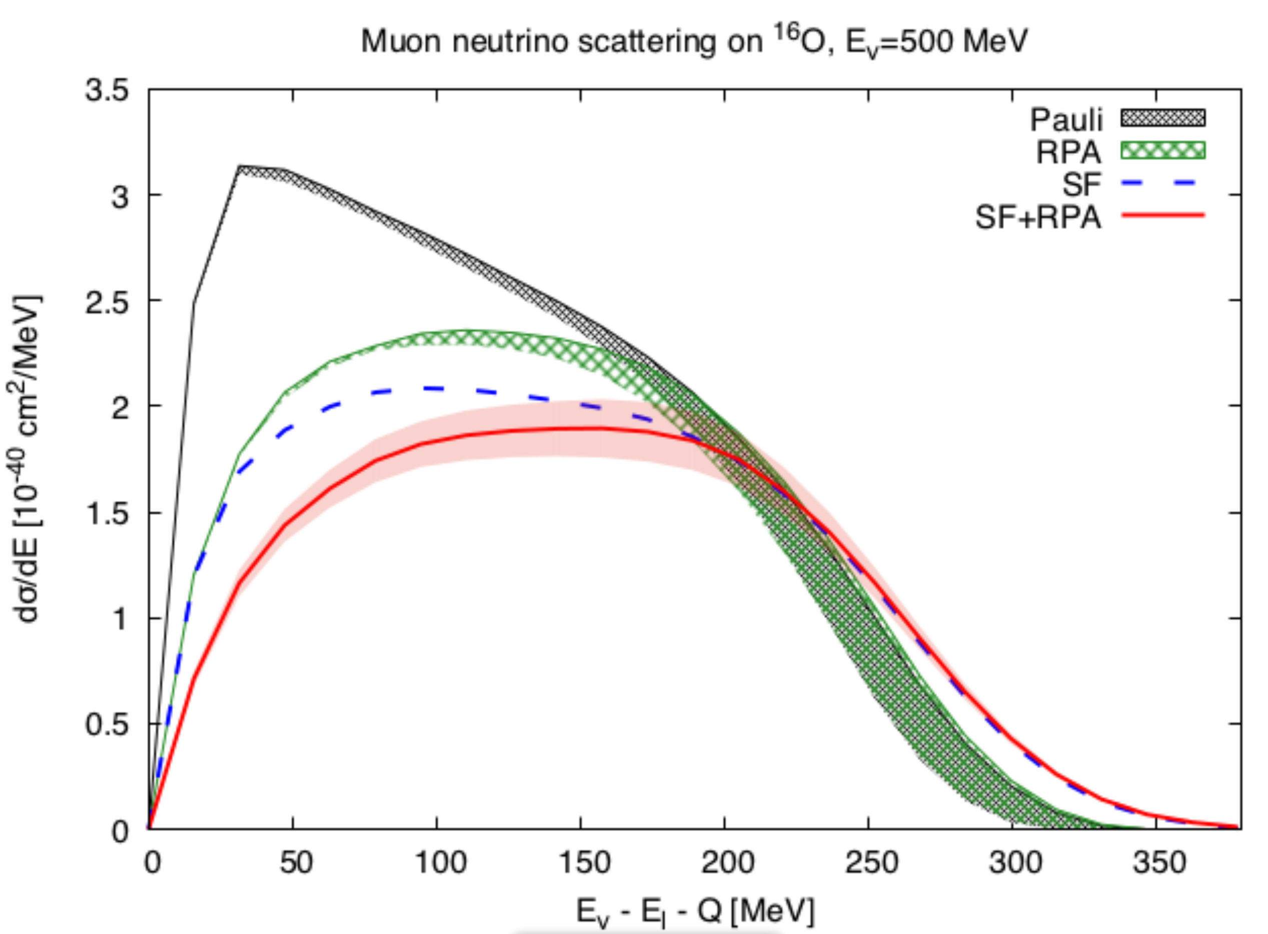
- A lot of progress in the relation between models.
  - CRPA and Mean Field.
  - Spectral functions + RPA

Traditional RPA seems to absorb defects on the underlying model.

It is worth to ask yourself if your model is consistent and compare with other approaches.



Ghent



Valencia

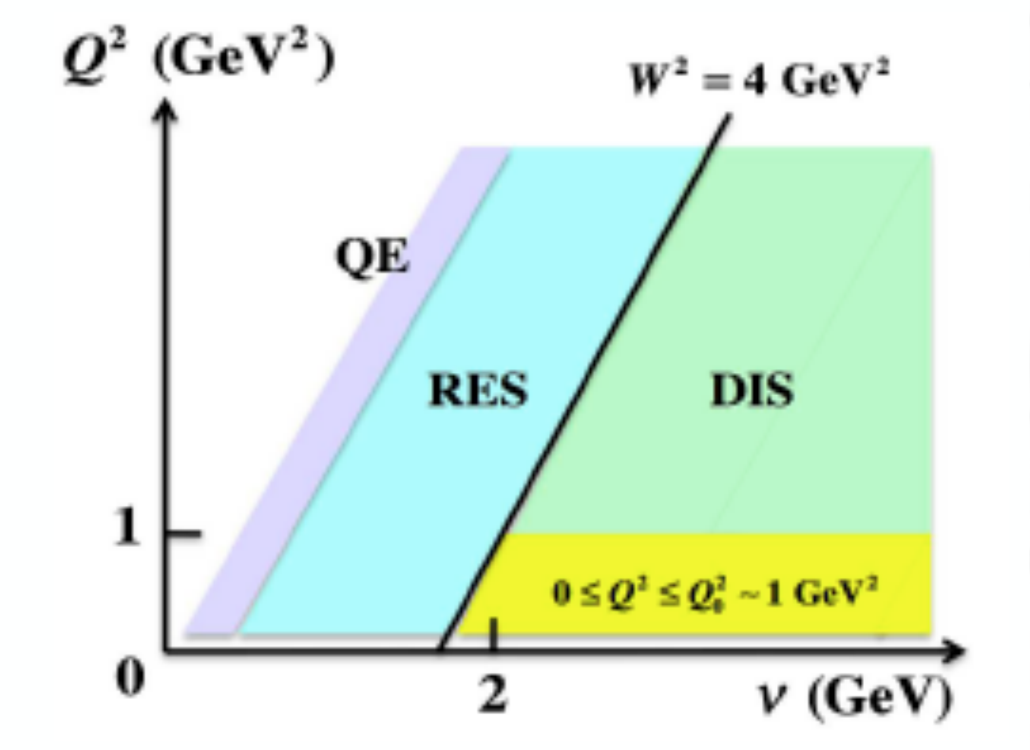
2body currents

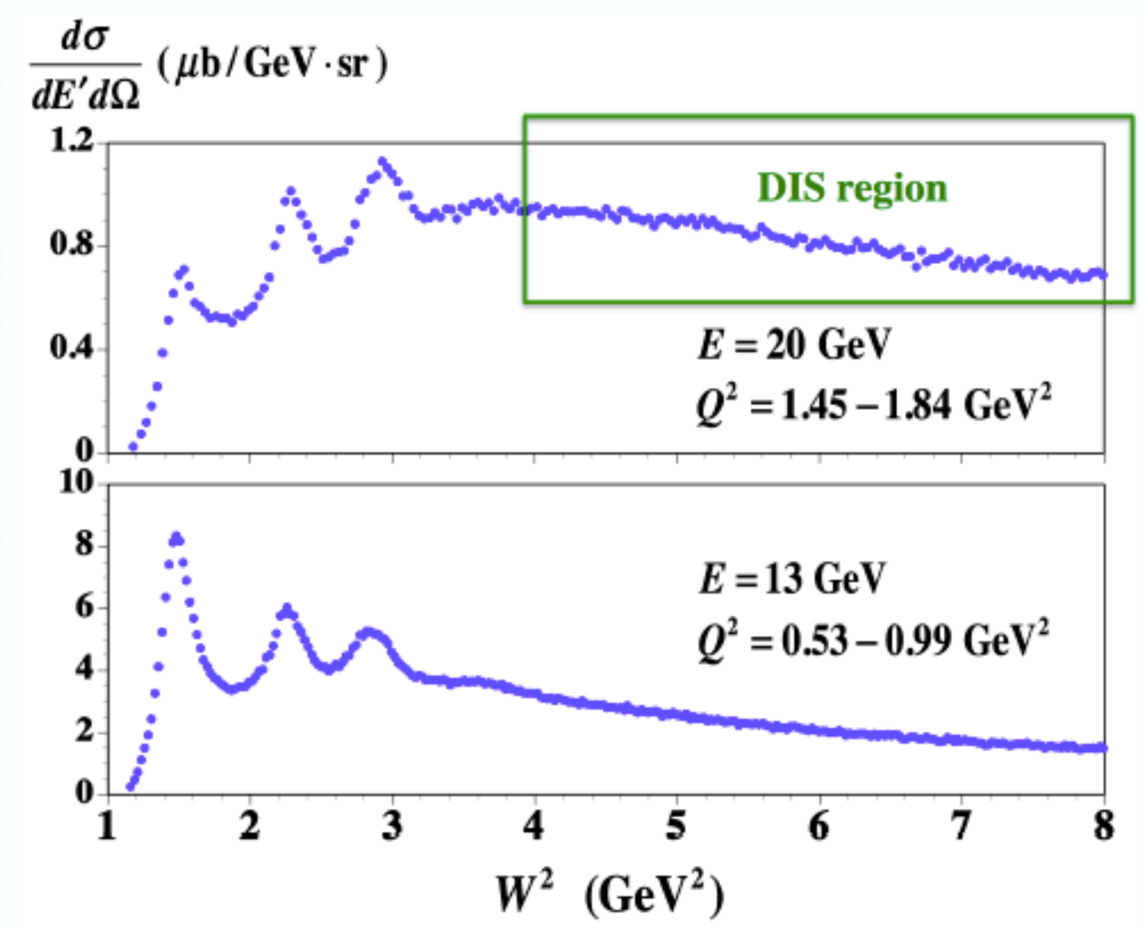
- The (re)discovery of 2body currents was the beginning of the new era of neutrino-nucleus interactions.
- But, not much happen since the first models by Nieves, Martini and others.
    - New model from Granada group incorporated in SuSaV2.
- Differences between models being observed but not explained.
- Poor fit to data, probably only at high energy: results from Minerva
- One of the main problems now is the description of the final state nucleons. Actual models ignore relation between initial and final states.
- Limited to low transferred momentum region.

π production

- There are many ways to produce a pion in a final state:
  - through resonances.
  - direct production (prompt)
  - through rescattering of baryons with the nuclei.

They have a different response function for energy reconstruction.





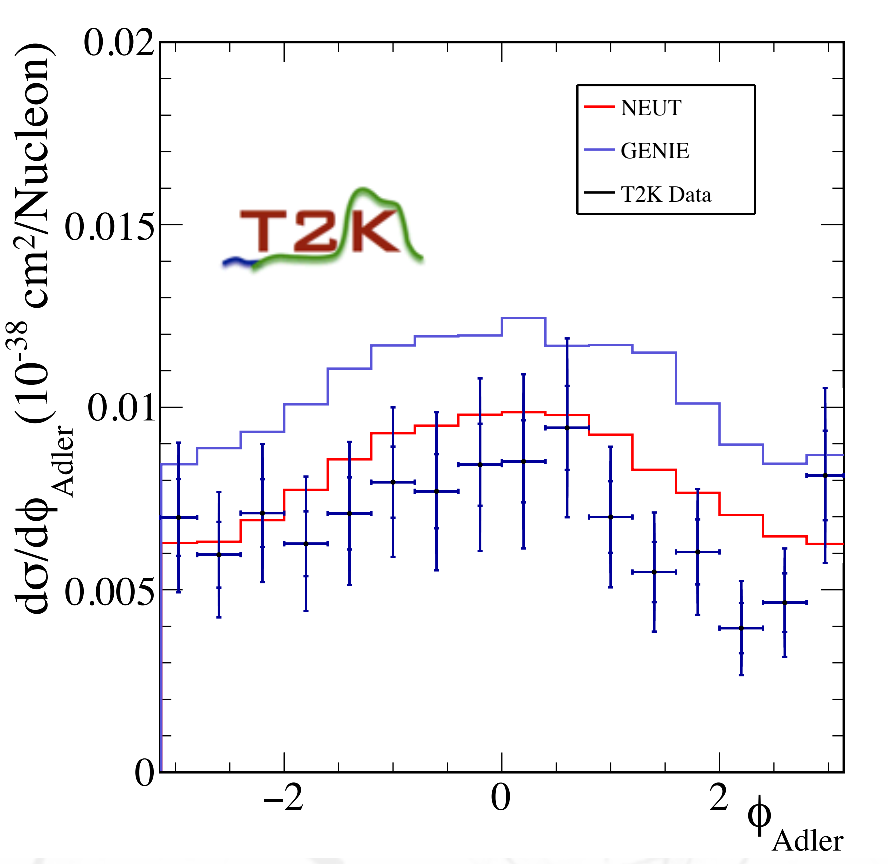
π production

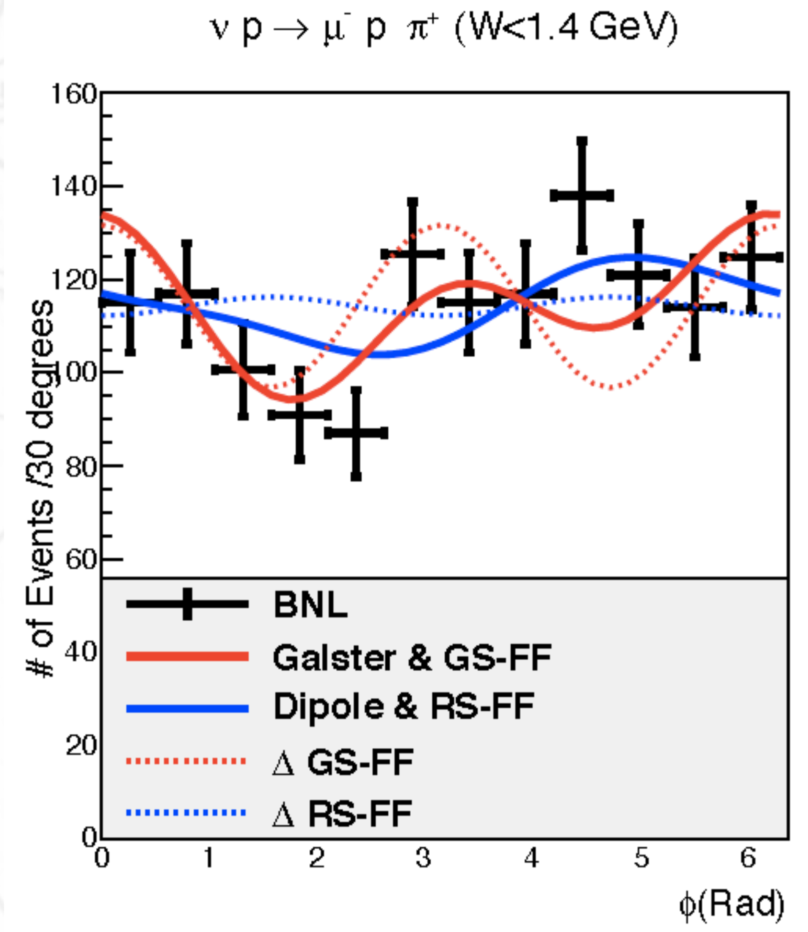
- New data is more and more precise exploring new observables.

- The “standard” Rein and Sehgal is not able to account for these details.

- New developments.
  - Resonant and non-resonant contributions using helicity amplitudes.

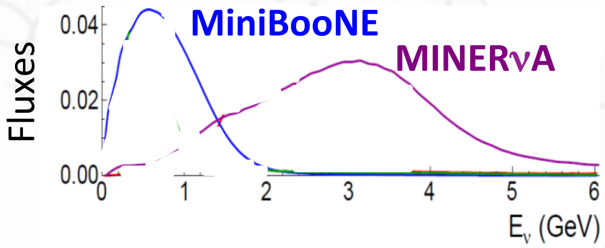
- Some development are done already in a way to be included in MC (Neut).





The pion puzzle

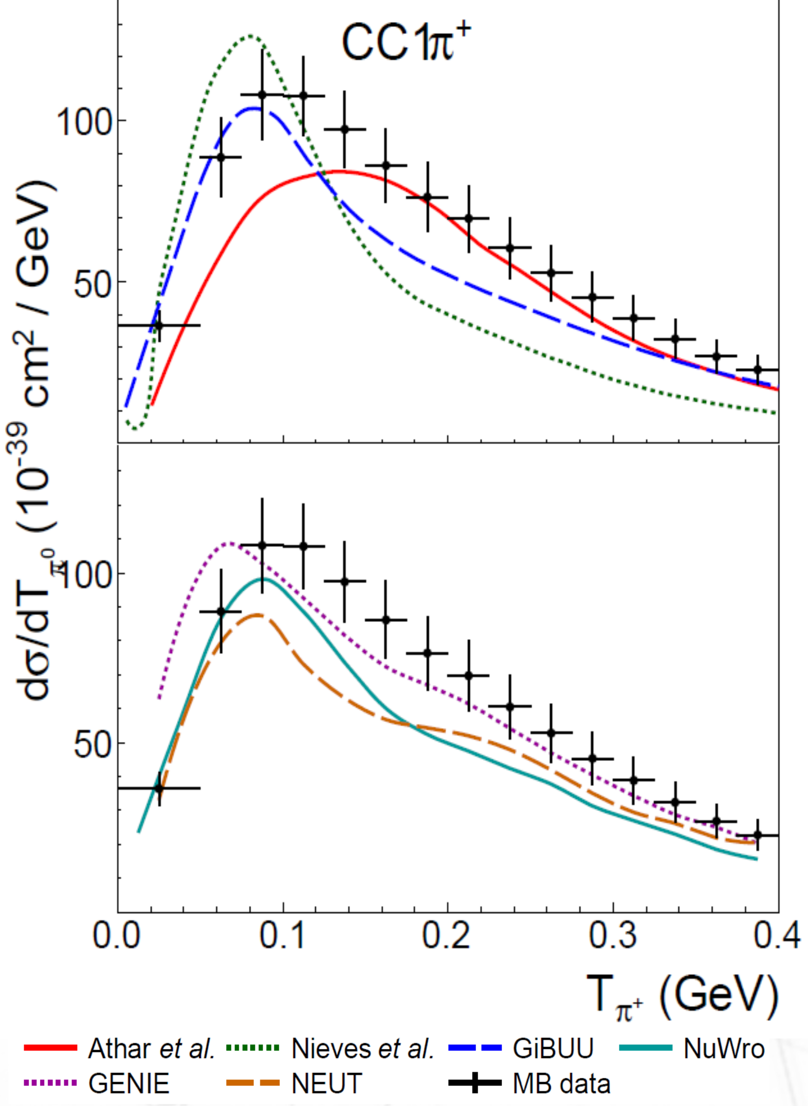
Few words on other channels: I) The CC1π puzzle



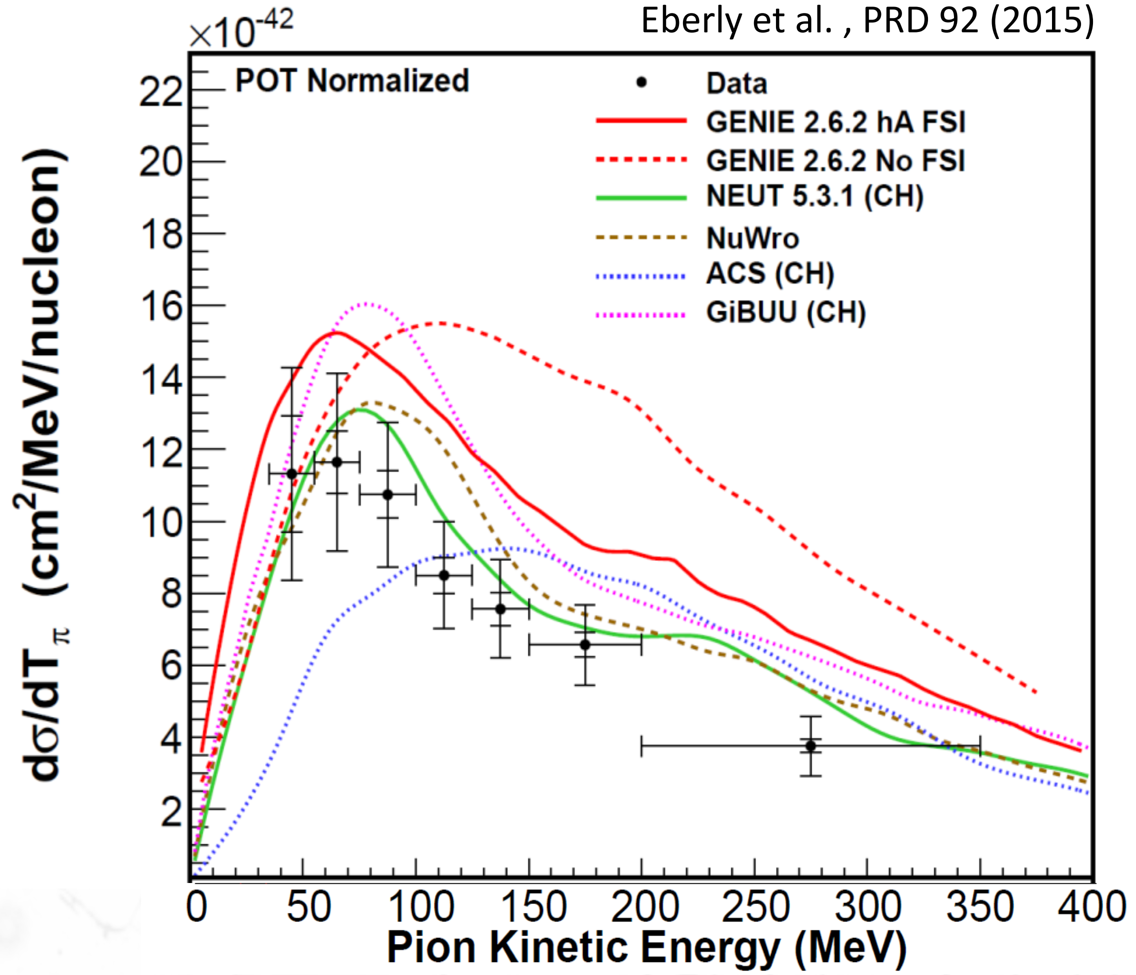
MiniBooNE

MINERνA

Rodrigues, AIP Conf. Proc. 1663 (2015)



Eberly et al. , PRD 92 (2015)



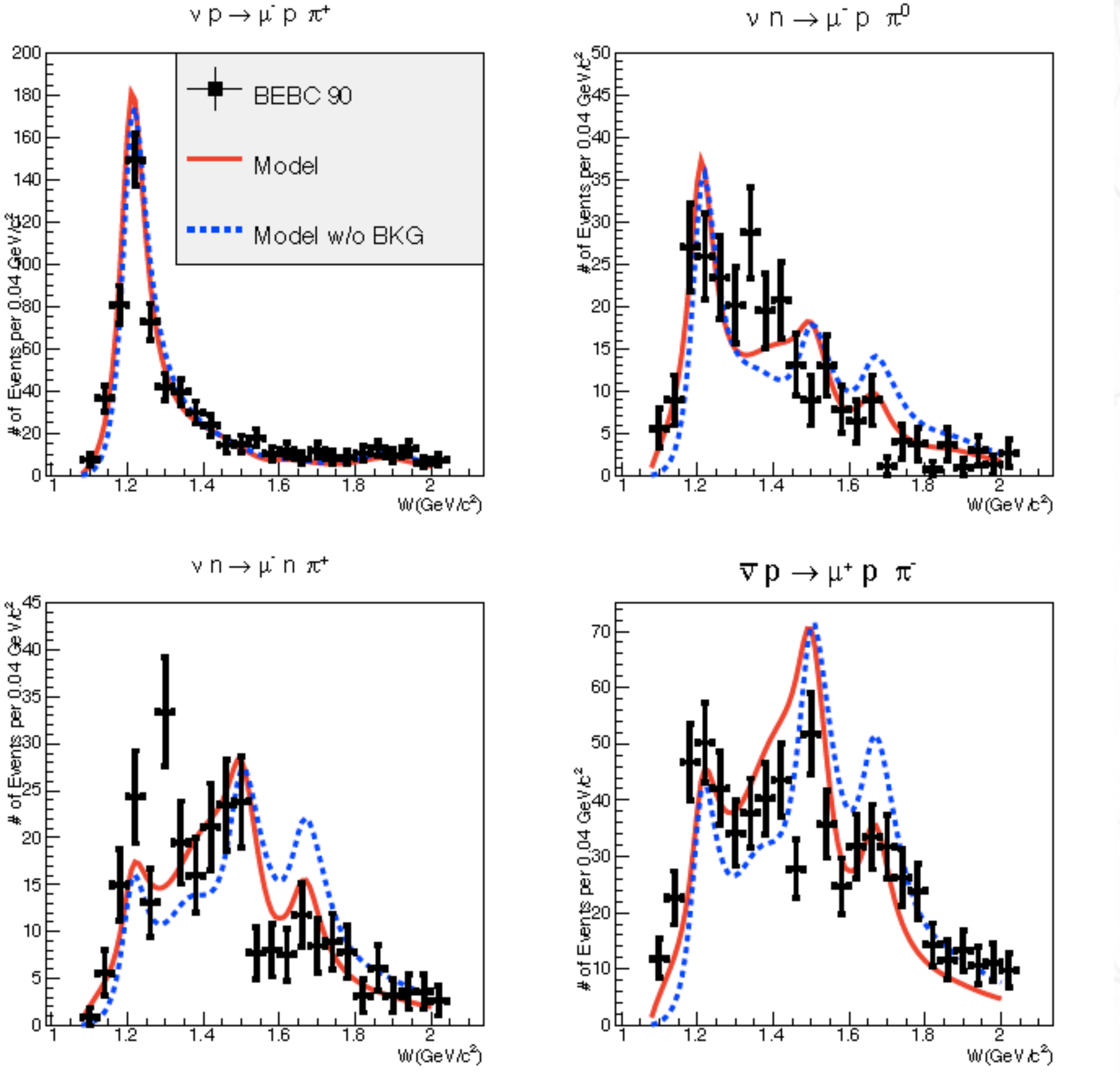
The pion puzzle
is an open question

normalization of data, normalization of theory, πFSI, DIS, hadronization, detector efficiency,…?

π production

Phys.Rev. D97 (2018) no.1, 013002

- This model is being implemented in the MC:
  - FSI is immediately provided by cascade models.
- Big improvement wrt previous models.

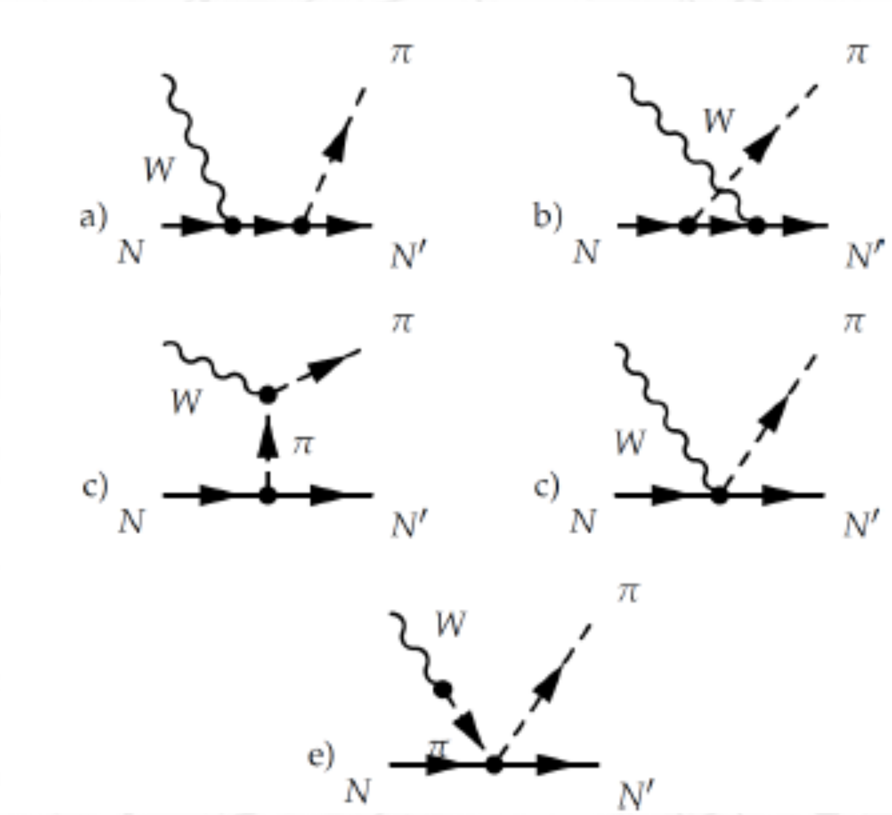


Improved Rein Sehgal model with pion background in helixity base

π production

Phys.Rev. D97 (2018) no.1, 013002

- Pion production is a coherent sum of the resonant and non resonant contributions.



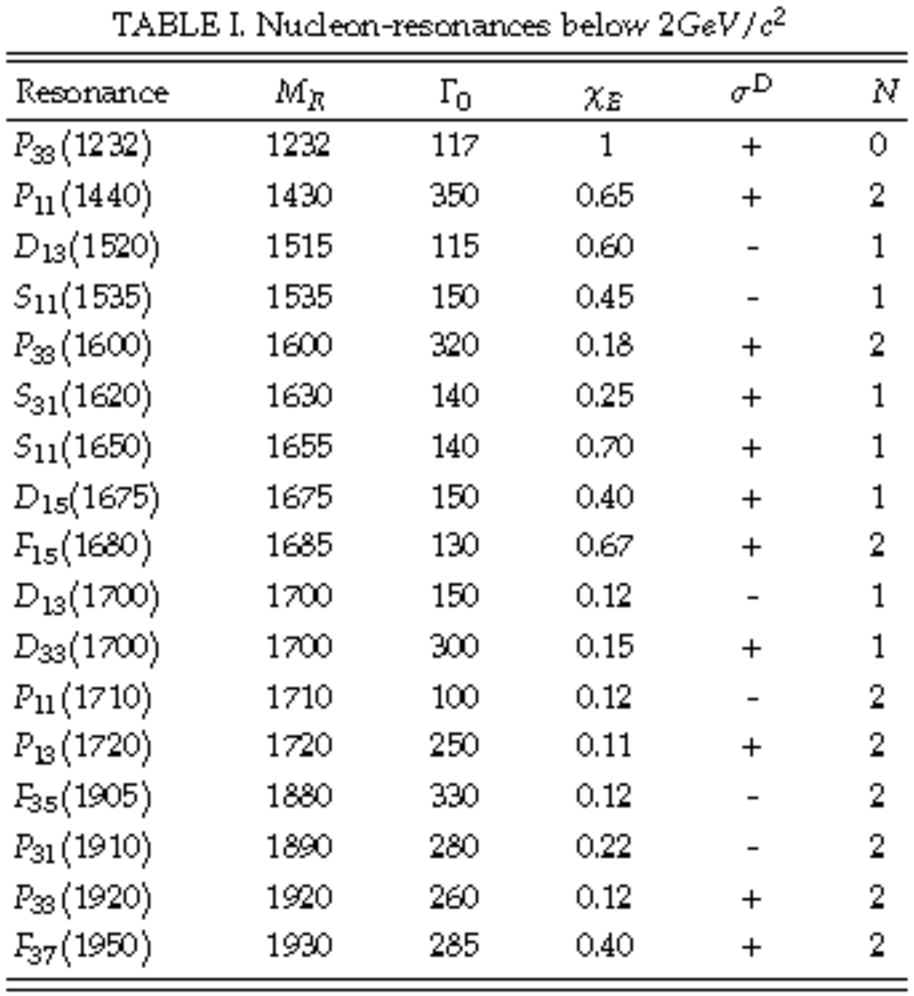


TABLE I. Nucleon-resonances below $2GeV/c^2$

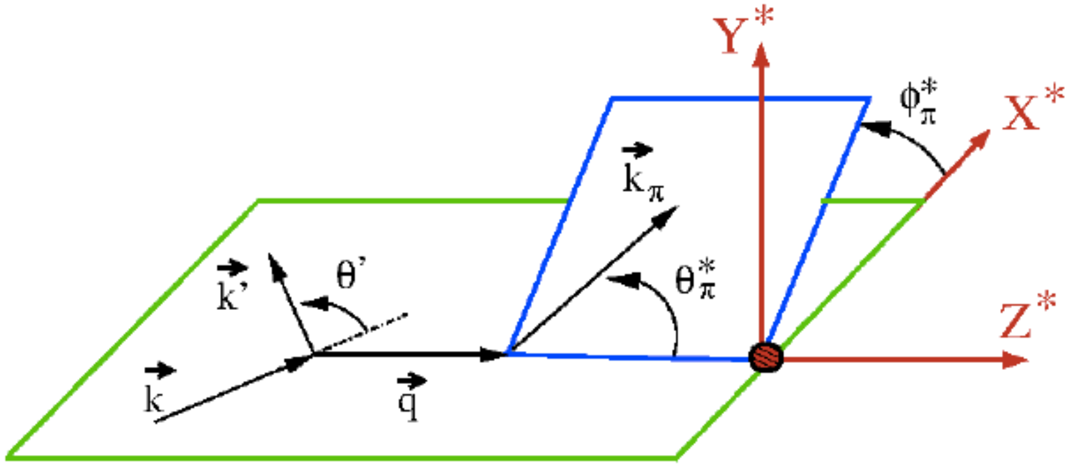
Resonance	M_R	Γ_0	χ_E	σ^D	N
$P_{33}(1232)$	1232	117	1	+	0
$P_{11}(1440)$	1430	350	0.65	+	2
$D_{13}(1520)$	1515	115	0.60	-	1
$S_{11}(1535)$	1535	150	0.45	-	1
$P_{33}(1600)$	1600	320	0.18	+	2
$S_{31}(1620)$	1630	140	0.25	+	1
$S_{11}(1650)$	1655	140	0.70	+	1
$D_{15}(1675)$	1675	150	0.40	+	1
$F_{15}(1680)$	1685	130	0.67	+	2
$D_{13}(1700)$	1700	150	0.12	-	1
$D_{33}(1700)$	1700	300	0.15	+	1
$P_{11}(1710)$	1710	100	0.12	-	2
$P_{13}(1720)$	1720	250	0.11	+	2
$F_{35}(1905)$	1880	330	0.12	-	2
$P_{31}(1910)$	1890	280	0.22	-	2
$P_{33}(1920)$	1920	260	0.12	+	2
$F_{37}(1950)$	1930	285	0.40	+	2

Improved Rein Sehgal model with pion background in helixity base

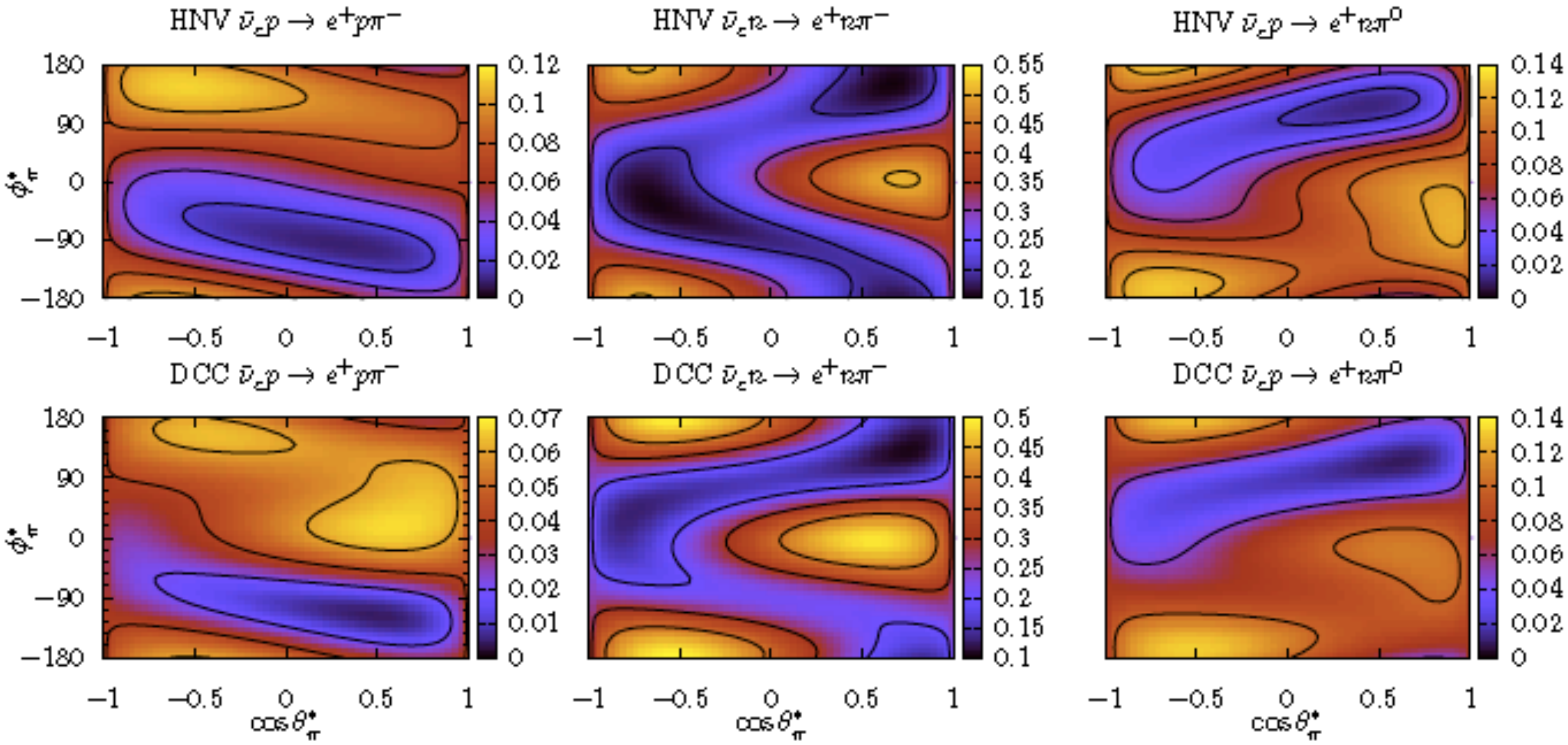
π production

e-Print: arXiv:1807.11281

- More formal approach with an exhaustive analysis of the Adler angles @ the nucleon interaction level

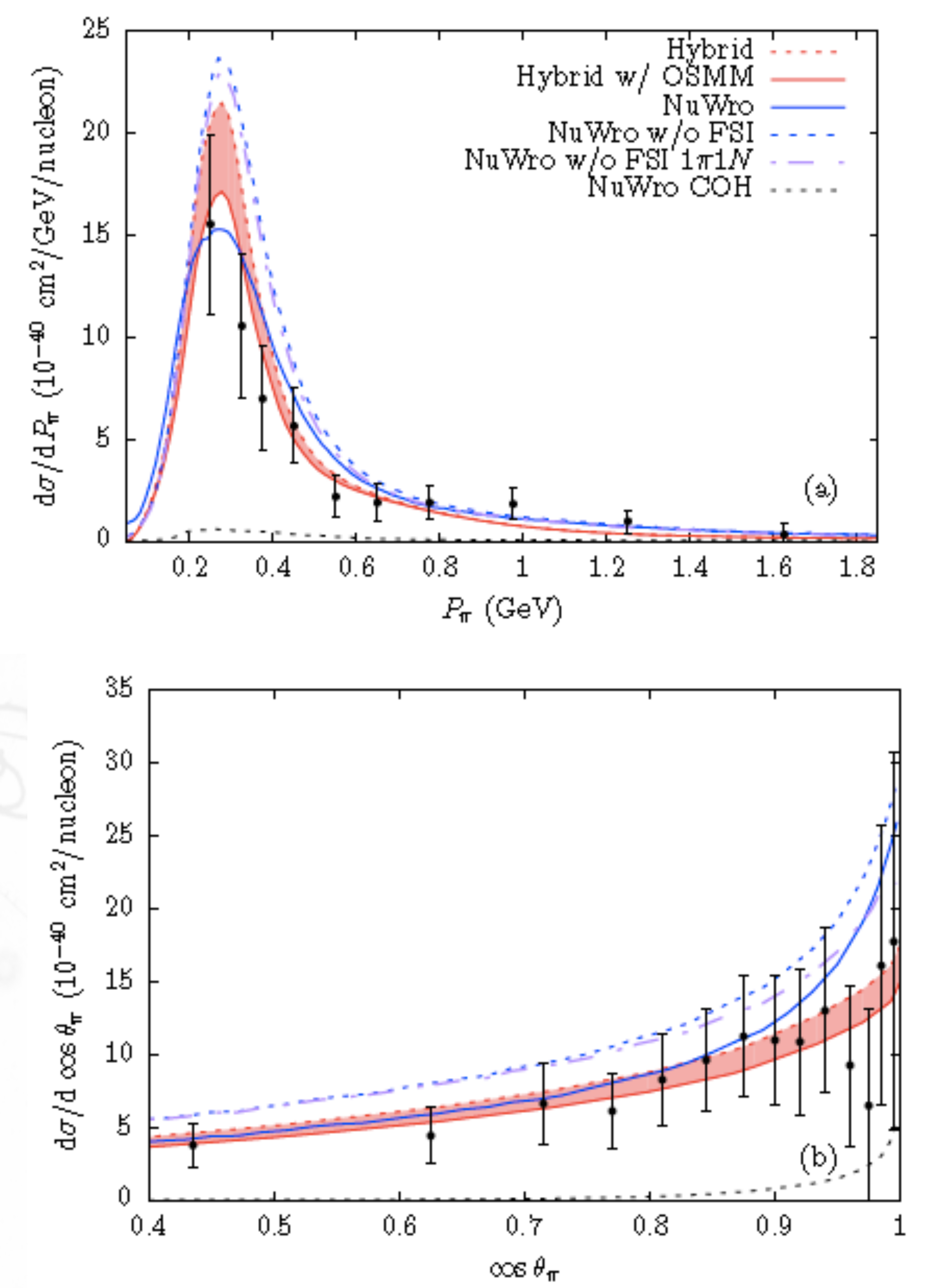


- Background pion level is fundamental to describe these dependencies.



π production

- Low- and a high energy approach. The low-energy model (LEM) contains resonances and background terms.
- At high invariant masses, a high-energy model based on a Regge approach is employed.
- The model is implemented in the nucleus using the relativistic plane wave impulse approximation (RPWIA).
  - Consistent with the CC0pi model.



Ghent group

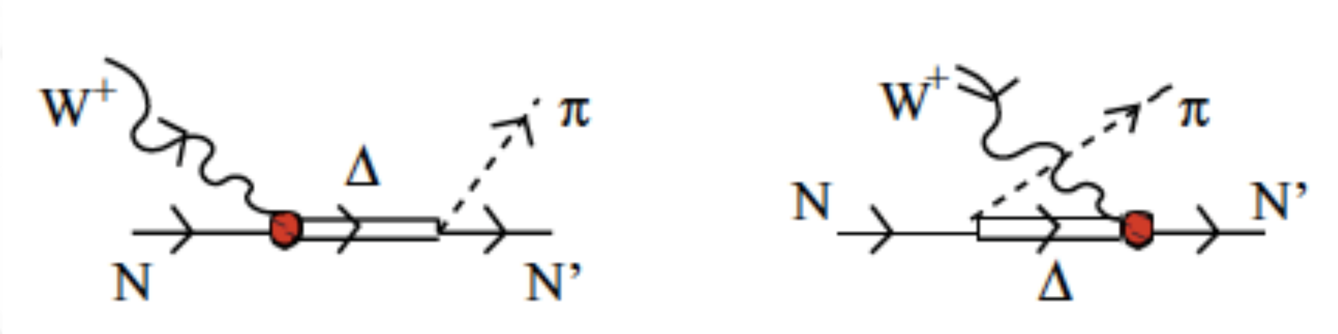
Phys.Rev. D97 (2018) no.9, 093008

2 body currents in π

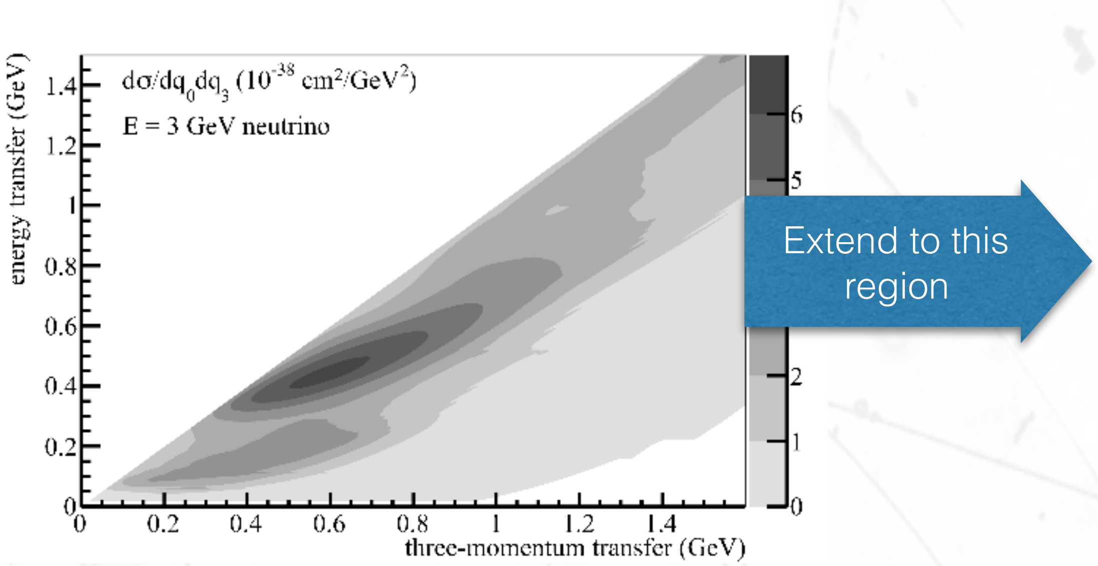
- Similar to CCQE-like there should be some CCπ-like two body currents.
  - Two body current with pion emission.
  - Is this relevant ? Can we estimate it ?

We could start with a process similar to the pion-less Δ decay for 2π emission.

- There should be also CCQE-like with some higher mass resonance contribution (following the microscopic model):



We need models and implementations in MC.



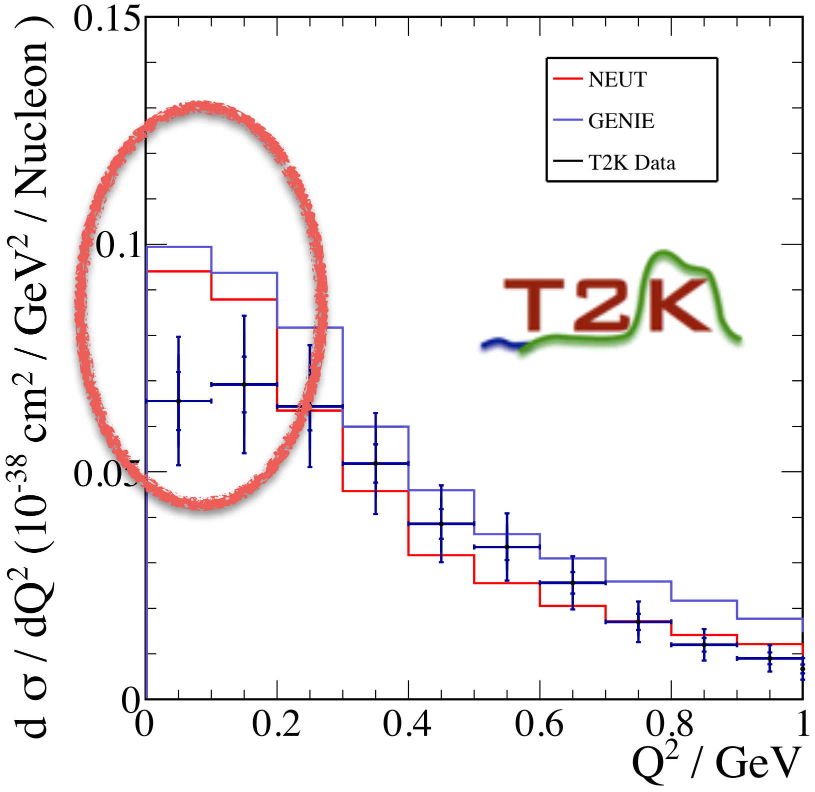
Extend to this region

Long Range Correlations

- 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.



RPA should be present for CCΔ !!!!
Is RPACCQE ~ RPACCΔ ?

New results show that the LRC might be small if proper initial state is used!

LRC are also different for neutrino and electron scattering

And beyond….

- The region above the Δ has been ignored systematically by theory and recent experiments (except Minerva).
- New generation of experiments will rely on this region to do oscillation physics:
  - Critical for Dune.
- We saw that Neut is revisiting this region.

Transition region

Rep. Prog. Phys. **80** (2017) 056301

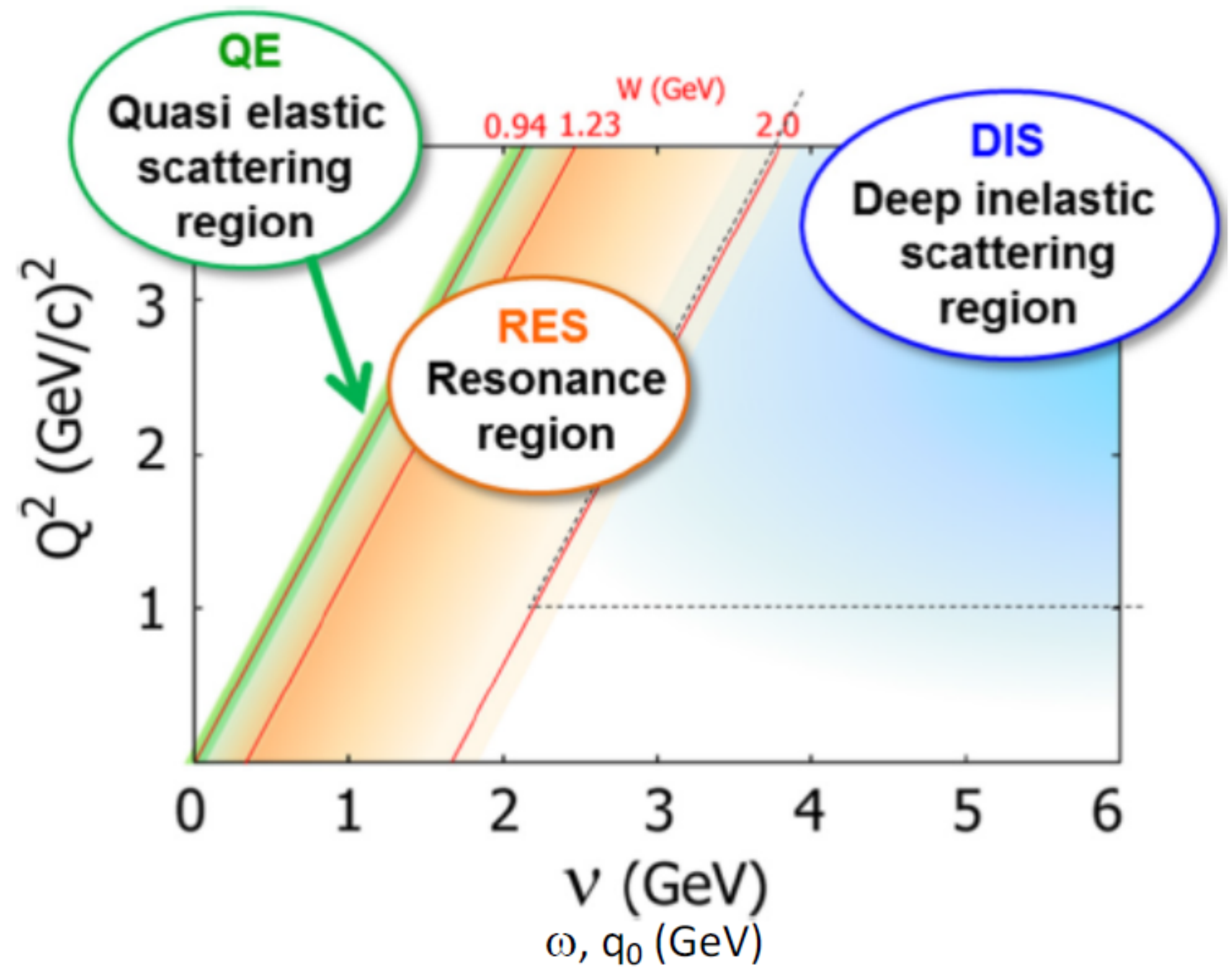
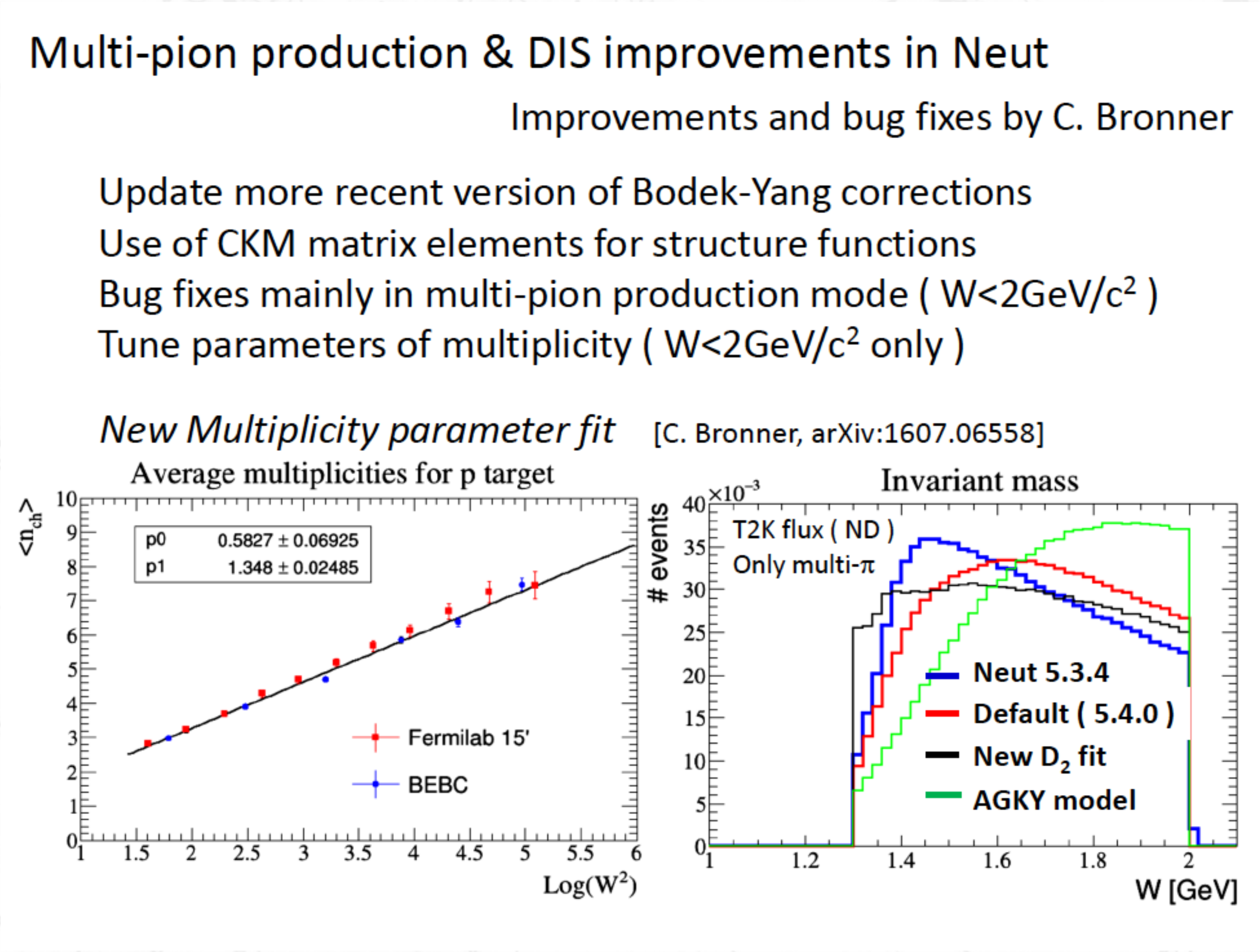


Figure 1. Kinematical regions of the neutrino-nucleus interaction relevant to the next-generation neutrino-oscillation experiments. The energy transfer to a nucleus and the squared four-momentum transfer are denoted by ν and Q^2, respectively.

- This is a tough region that is boundary to DIS and Resonance.
- Models are basically phenomenological.
- Try to avoid double counting with high mass resonances and DIS.

For example…



Multi-pion production & DIS improvements in Neut

Improvements and bug fixes by C. Bronner

Update more recent version of Bodek-Yang corrections
Use of CKM matrix elements for structure functions
Bug fixes mainly in multi-pion production mode ($W<2GeV/c^2$)
Tune parameters of multiplicity ($W<2GeV/c^2$ only)

New Multiplicity parameter fit [C. Bronner, arXiv:1607.06558]

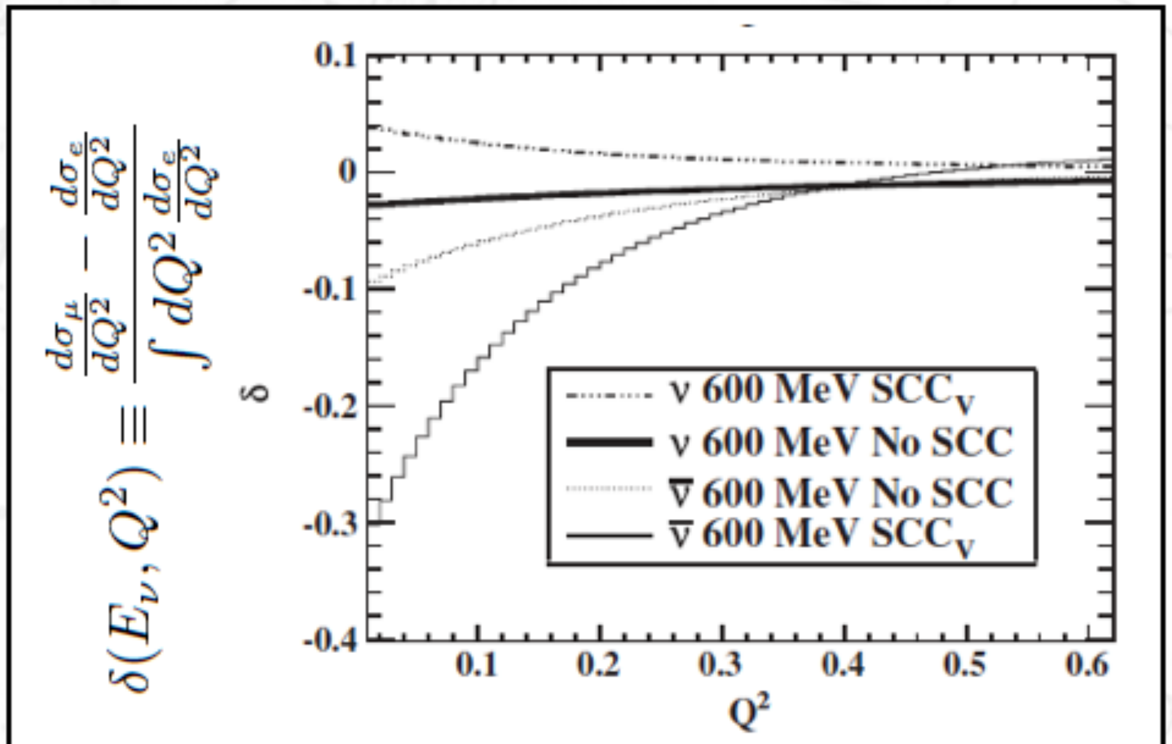
Ve

- Soon the knowledge of the electron neutrino cross-section will be critical.

- Electron neutrino suffers from radiative corrections in the final state that needs to be computed inside of the nucleus.

- These corrections will alter the cross-section and the energy reconstruction depending on the detector technology.

- Only one prediction on this topic available (to my knowledge).



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

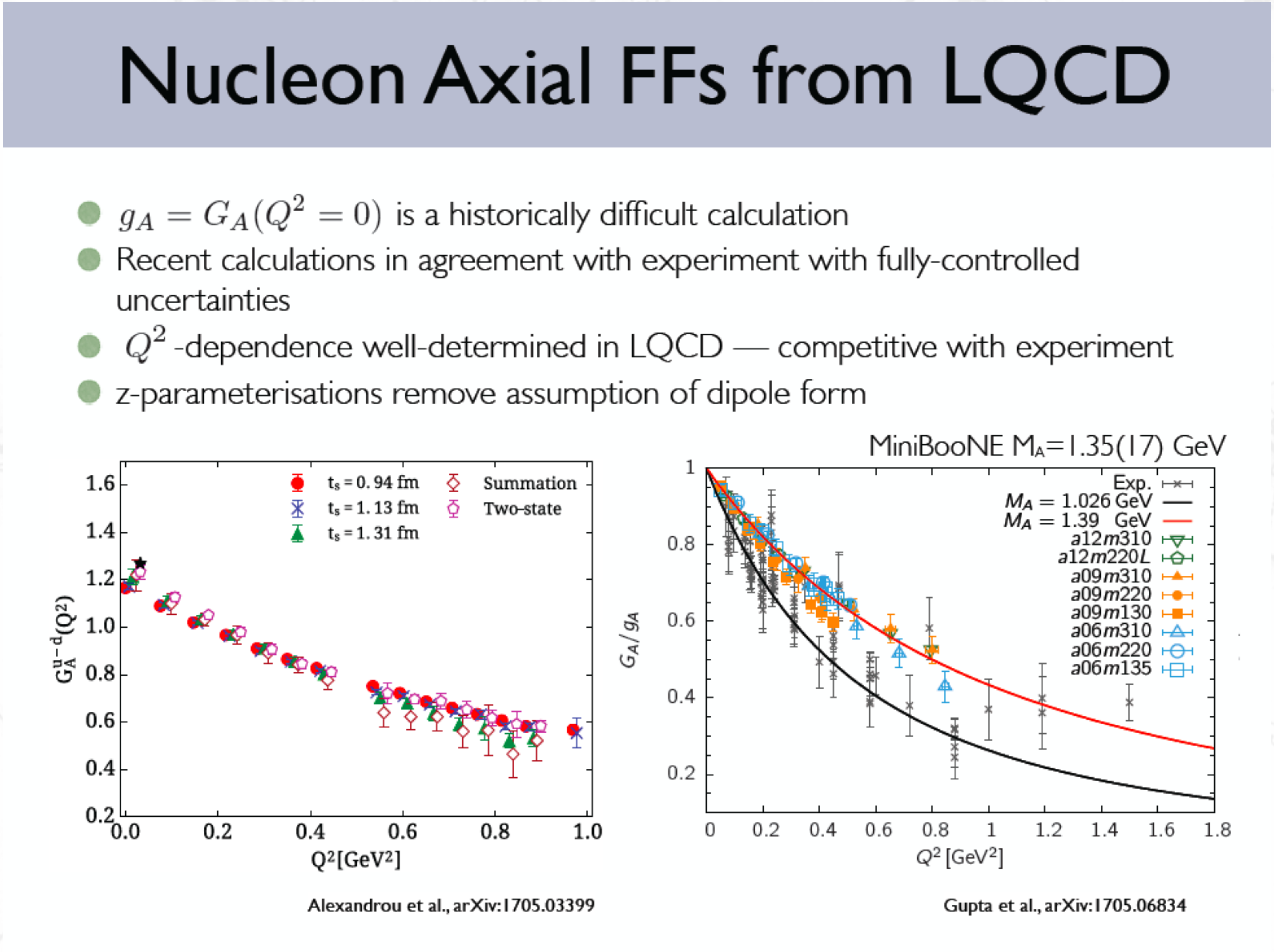
Electron scattering

- Electron scattering can be very valuable:
  - allows to check our nuclear model under control conditions and associate errors to it:
    - Fermi Gas, spectral functions,….
  - In complex 4π experiments (CLAS), they can help to control FSI and associate errors:
    - correlation of momentum transfer and hadron kinematics.

Electron scattering

- But:
  - we need our MC models to run on eA data.
  - we need to coordinate efforts in both communities.
  - we need to understand if the data available is sufficient for the broad neutrino phase space and act accordingly.

Axial-Vector FF in the lattice



Nucleon Axial FFs from LQCD

- $g_A = G_A(Q^2 = 0)$ is a historically difficult calculation
- Recent calculations in agreement with experiment with fully-controlled uncertainties
- Q^2-dependence well-determined in LQCD — competitive with experiment
- z-parameterisations remove assumption of dipole form

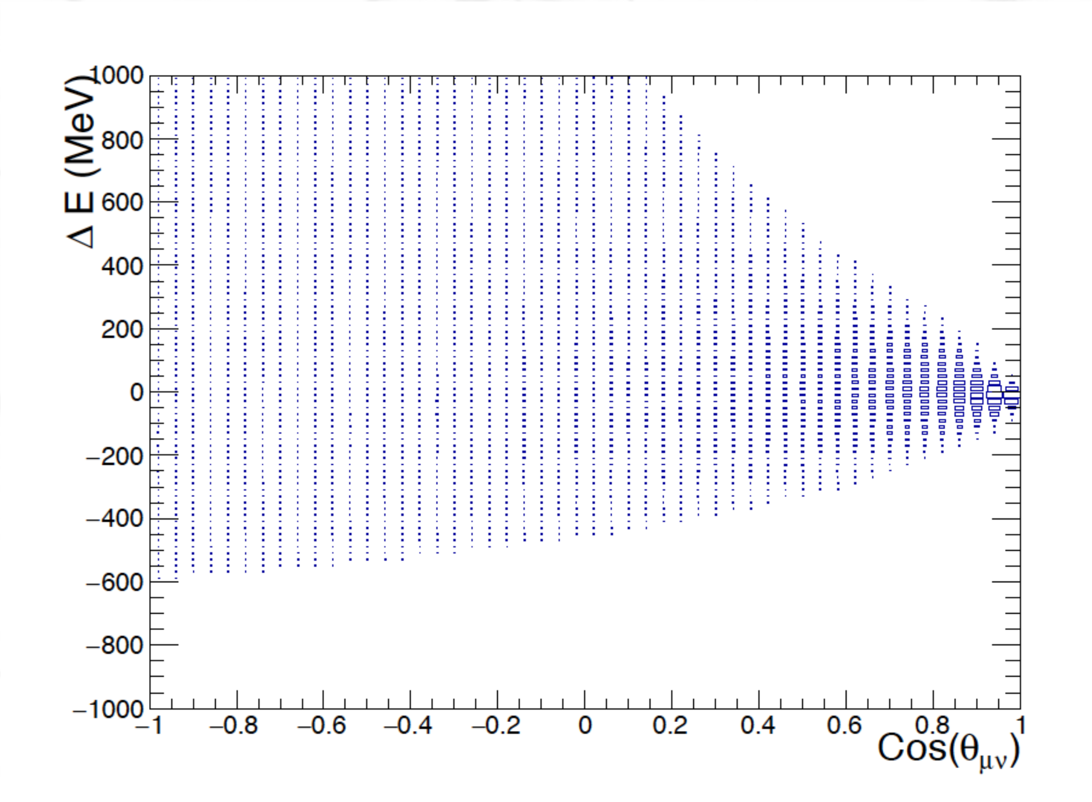
Alexandrou et al., arXiv:1705.03399

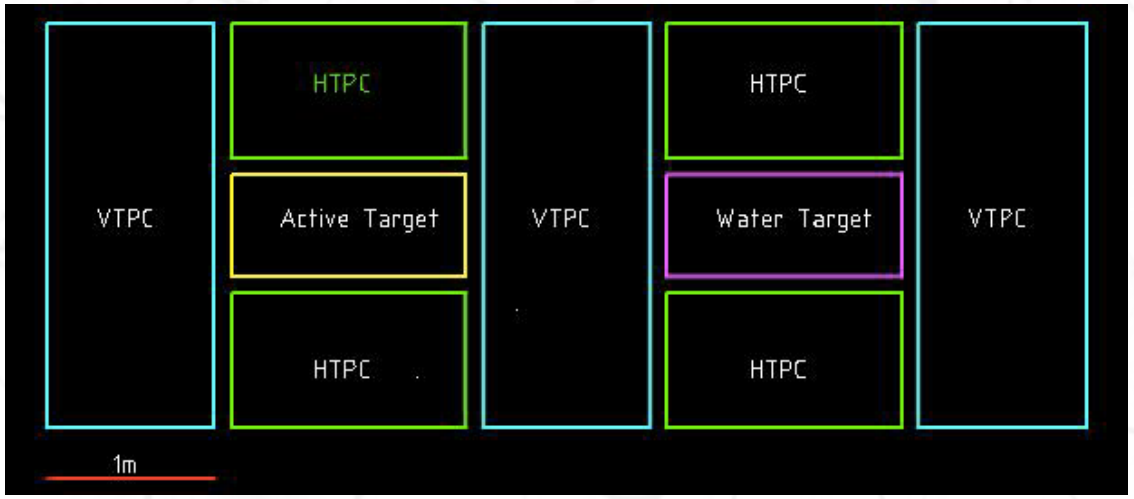
MiniBooNE M_A=1.35(17) GeV

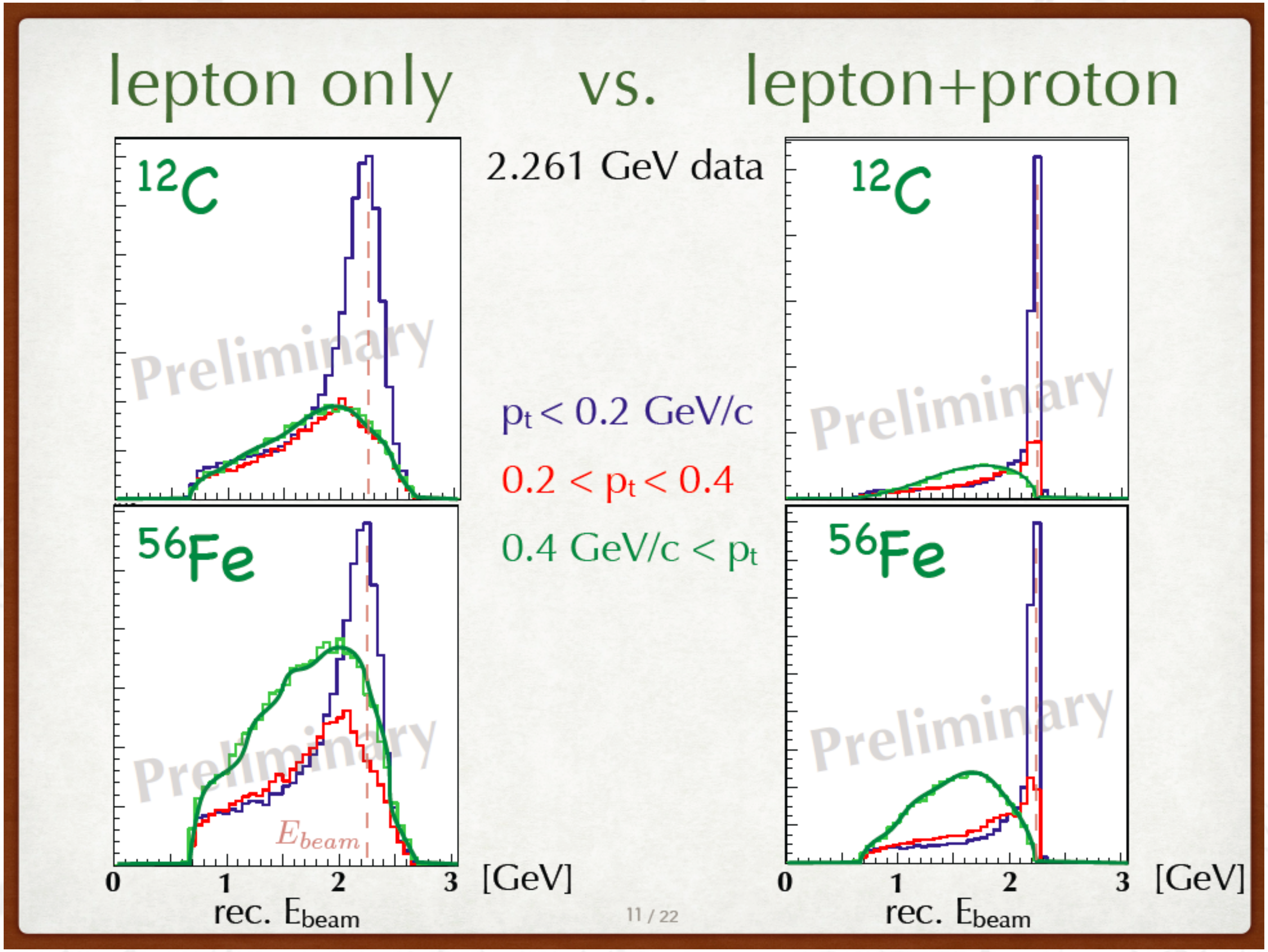
Gupta et al., arXiv:1705.06834

Energy reconstruction

- Nuclear effects are very relevant to the Energy reconstruction.
- How can we calibrate the energy?
- One option is to explore the dependencies to look for systematic dependencies:
  - 4π detector acceptance might help.







lepton only vs. lepton+proton

2.261 GeV data

$p_t < 0.2$ GeV/c

$0.2 < p_t < 0.4$

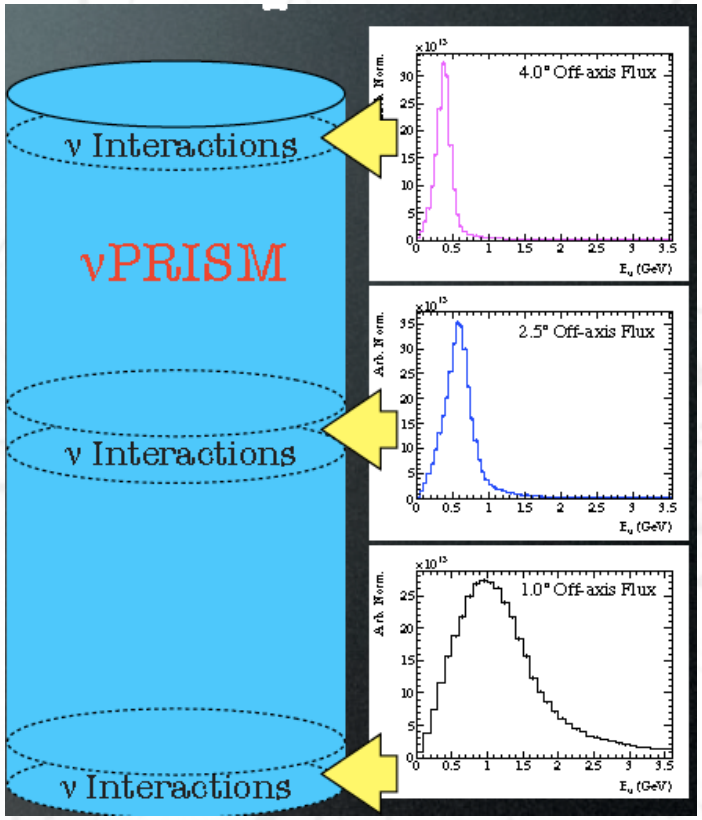
0.4 GeV/c $< p_t$

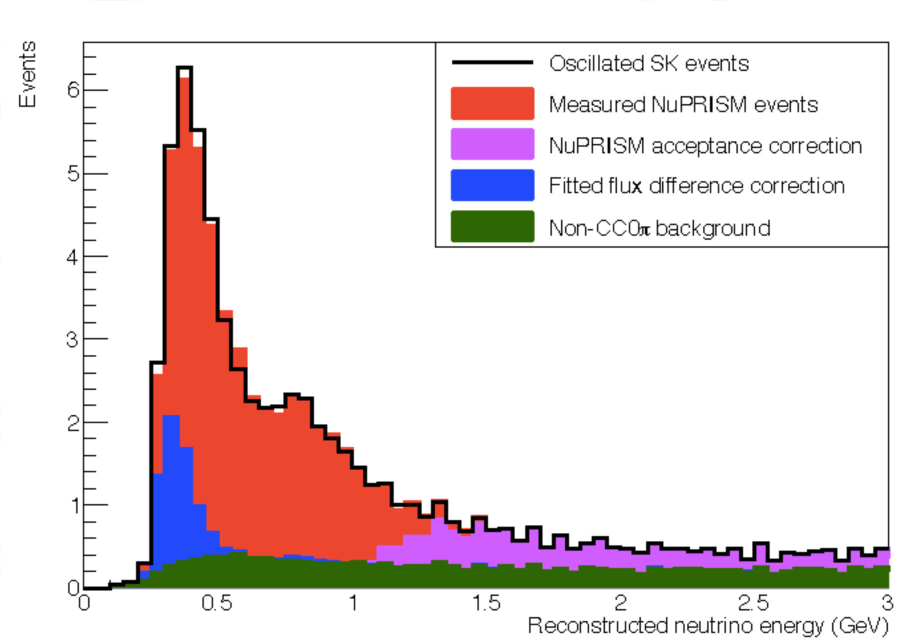
Mimic neutrino energy reconstruction in (e,e’) Erez O.Cohen

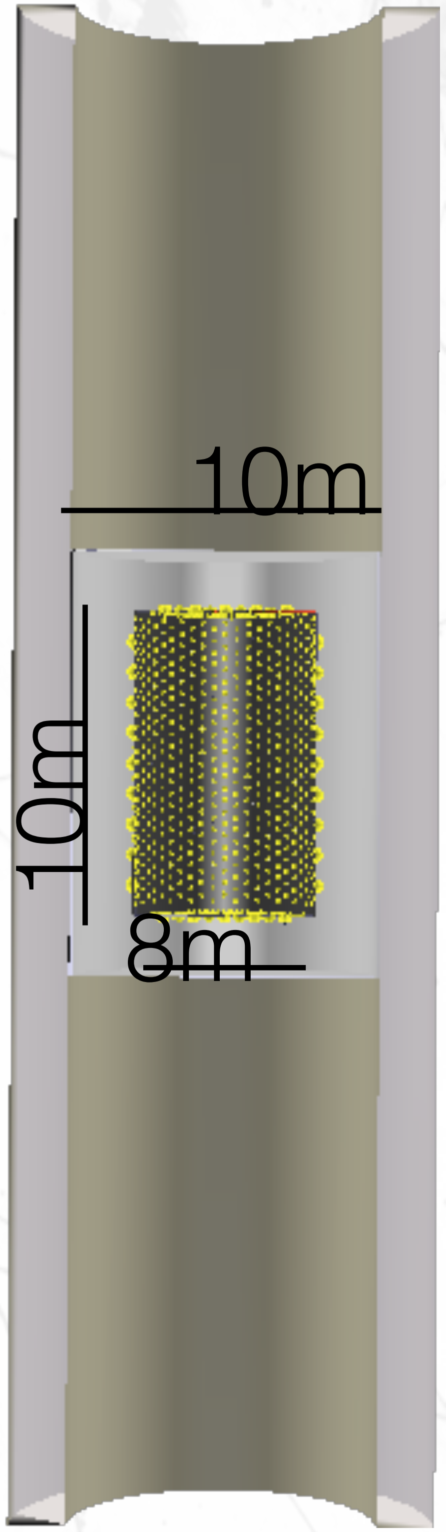
NuPrism

NuPrism relies on the off-axis properties of the beam to provide a quasi-monochromatic beam.

Σi ai







This is useful for oscillations but also for cross-section studies.

Conclusions

- The community is growing rapidly both from the theory and the experimental part thanks to the boost given by Dune activities.
- The first generation of developments in CCQE-like already in MC:
    - RPA, MEC, LFG,
- Disagreements observed for different observables.
    - Second generation of more solid models (MF,CRPA, SuSA…) available and in their way to MC's.
- Activities shifting to pion production. Some developments departing from the old Rein and Sehgal and including background interactions.
    - Many of the activities on the nucleon level. Nuclear level effects need to be consistently provided.
- Many new observables: transverse variables, available energy, Adler angles, etc…
    - They require a more detailed description of the final state kinematics moving from semi-exclusive to exclusive cross-sections (Technical difficulties).

- The community as a whole prepared recently a compelling review of challenges and status of the field
-
  - **NuSTEC White Paper: Status and challenges of neutrino–nucleus scattering** L. Alvarez-Ruso *et al.*. **Jun 12, 2017. 68 pp.** **v**Published in **Prog.Part.Nucl.Phys. 100 (2018) 1-68**

Backups