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Low Energy 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.

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Motivation

Neutrino Energy reconstruction

Channel ID
Hadron production
neutrino vs antineutrinos detector response

$\sigma(\nu_e)/\sigma(\nu_\mu)$

ν oscillations

neutrino vs antineutrino

identification

Acceptance corrections
Near vs Far sites

Backgrounds

$NC\pi^{\pm 0}$

ν cross-sections is the “language” that allows to measure and transport the measurements across detectors and experiments.

Neutrino interactions

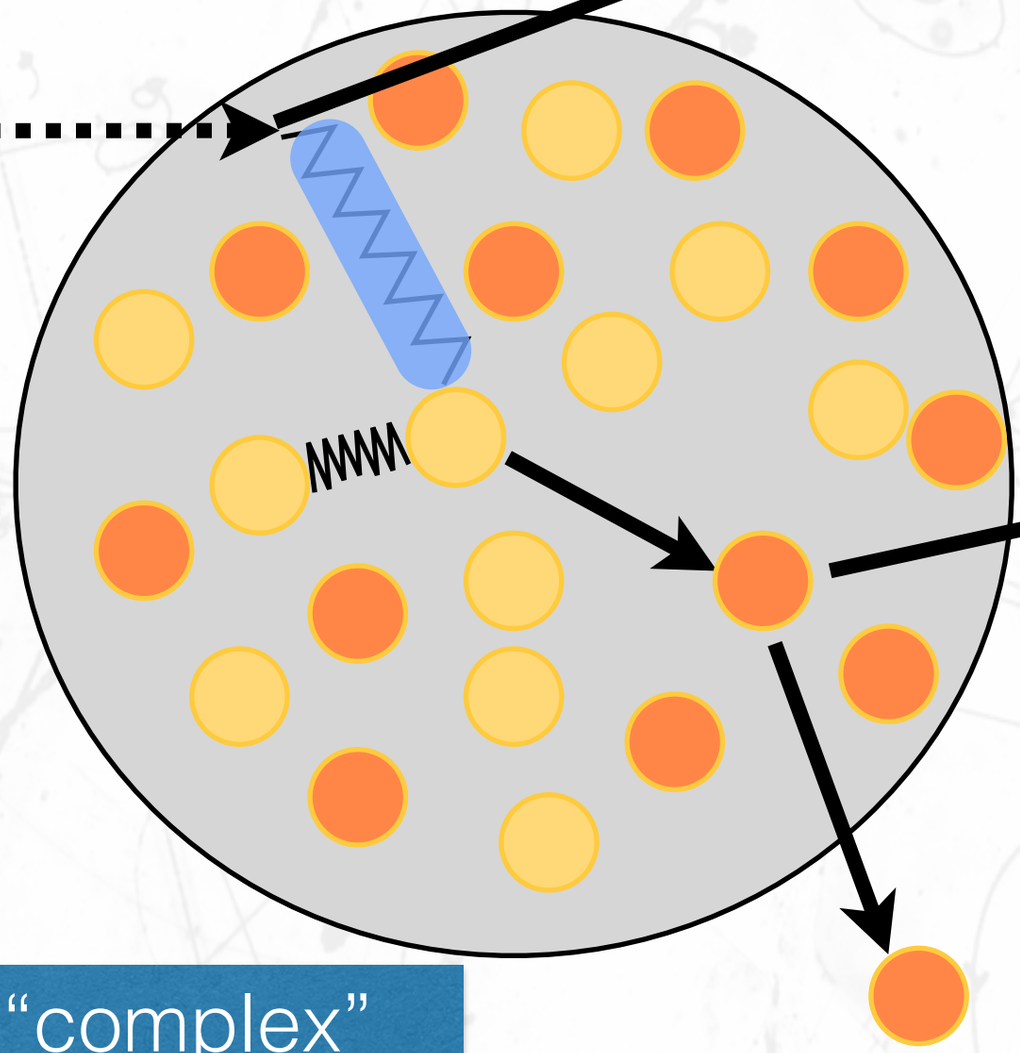
Nuclear
Coulomb
potential

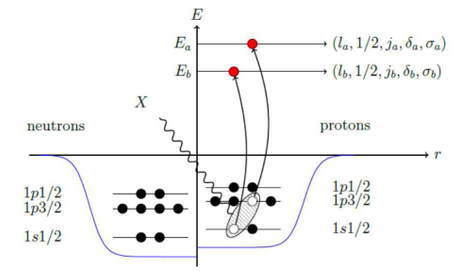
$l^{\pm}$

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”

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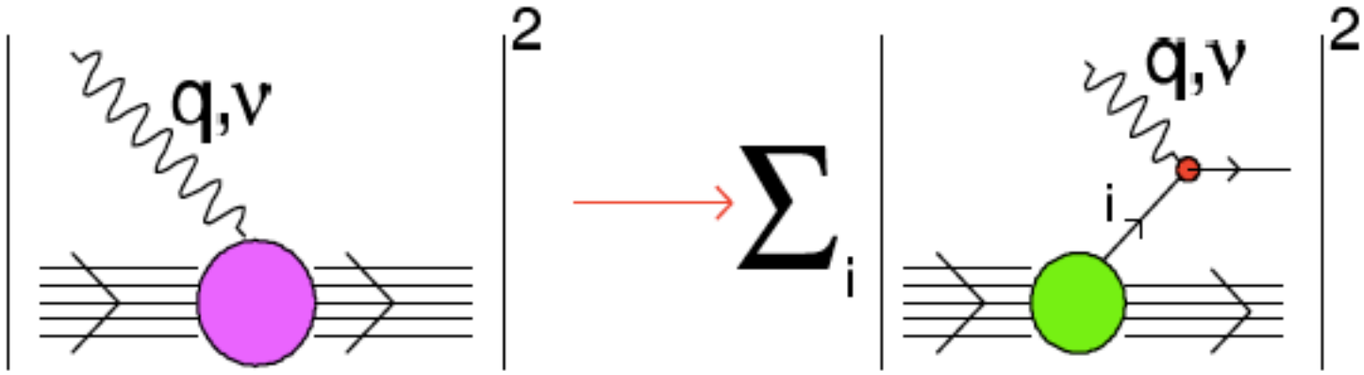
Impulse approximation

- IA approaches the nuclear interaction by the incoherent sum of single nucleon interactions.

- This is a better approximation for large momentum transfer ($\lambda \sim 1/|q|$)



- 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, …)

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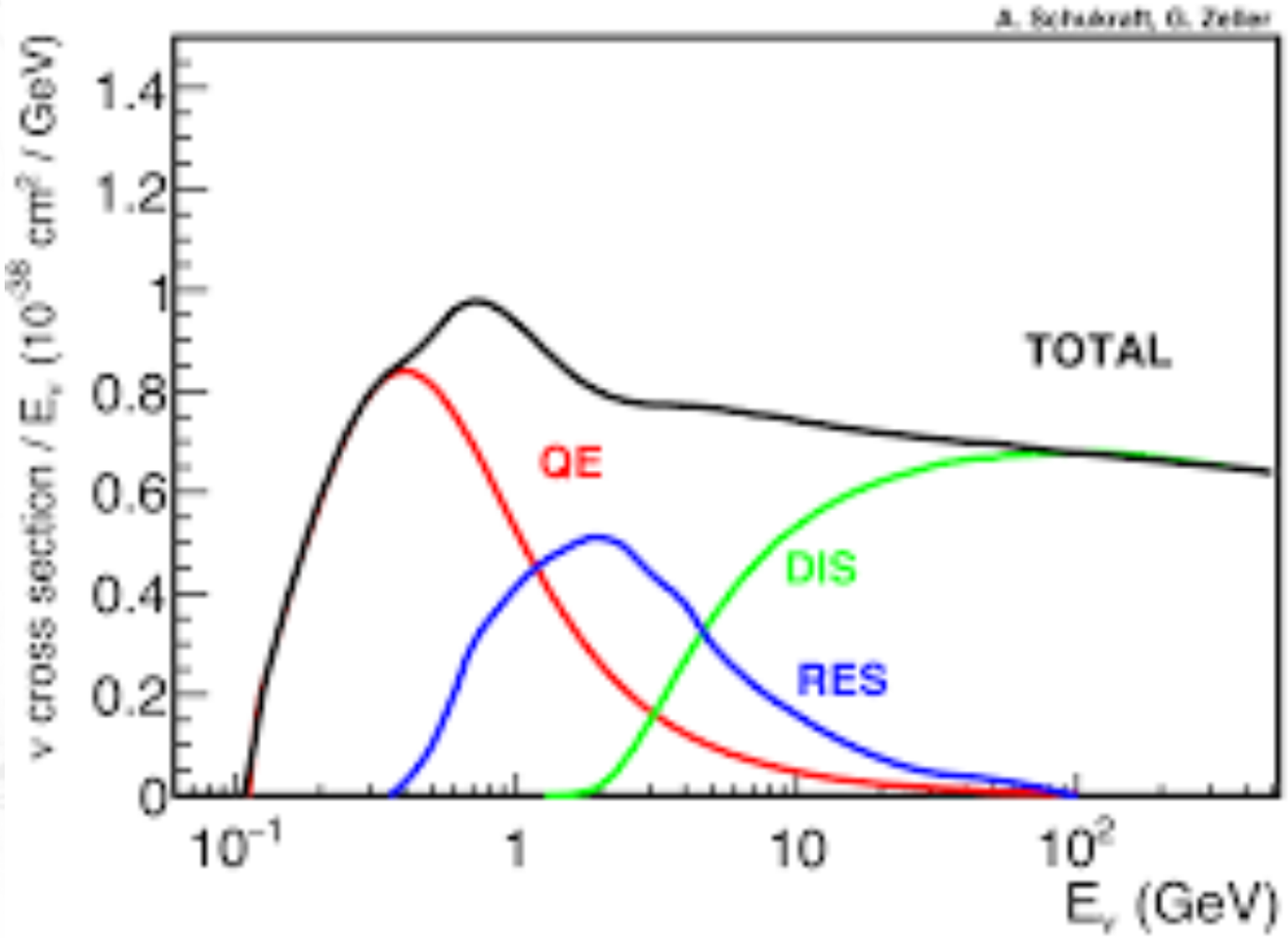
ν-nucleon interactions



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.

Old and sparse data from bubble chambers in hydrogen and deuterium

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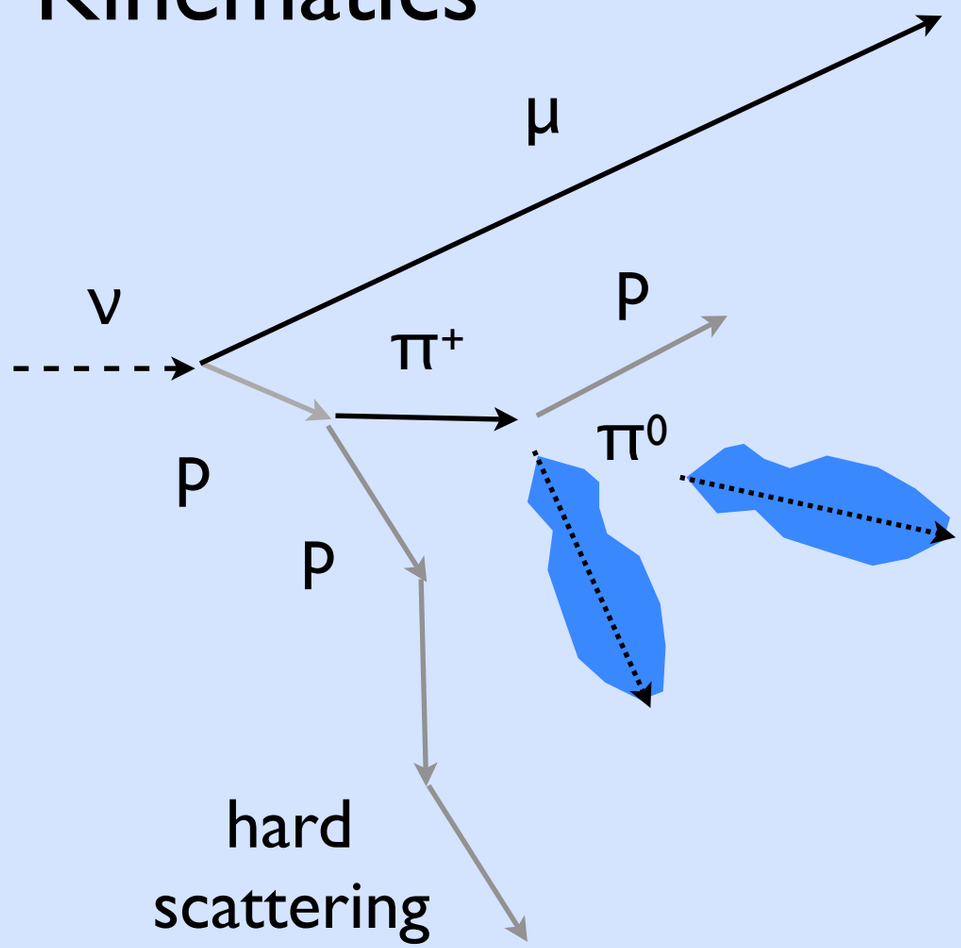
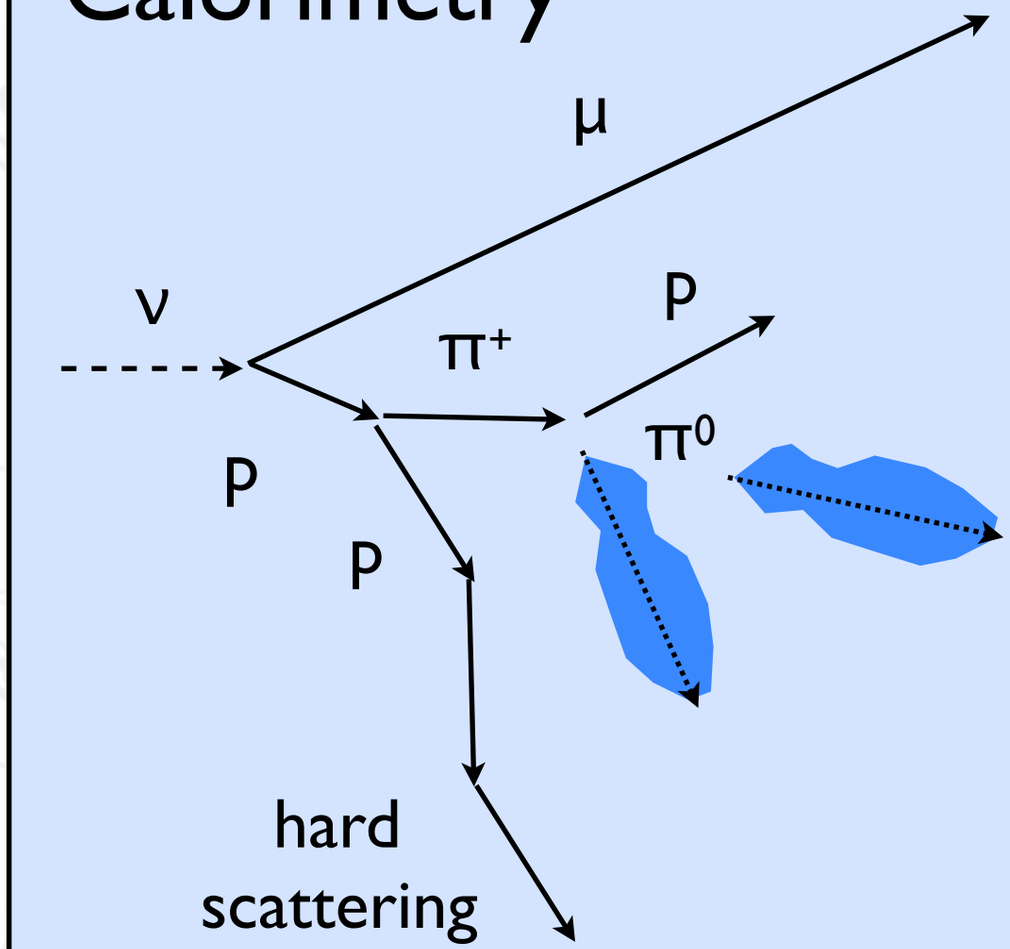
Energy reconstruction

Kinematics



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

Calorimetry



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

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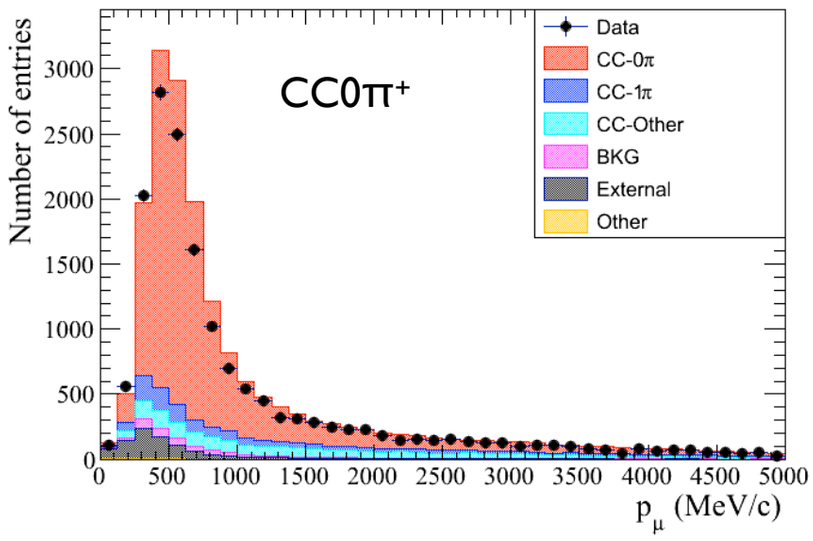
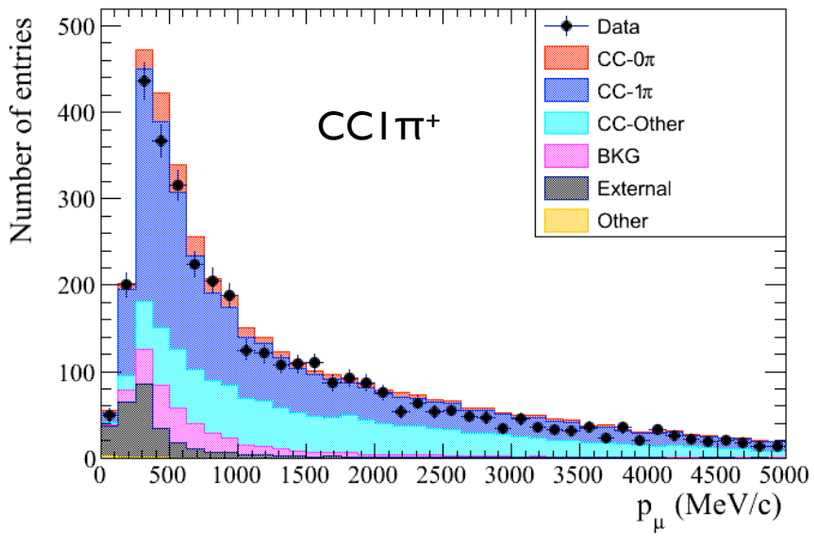
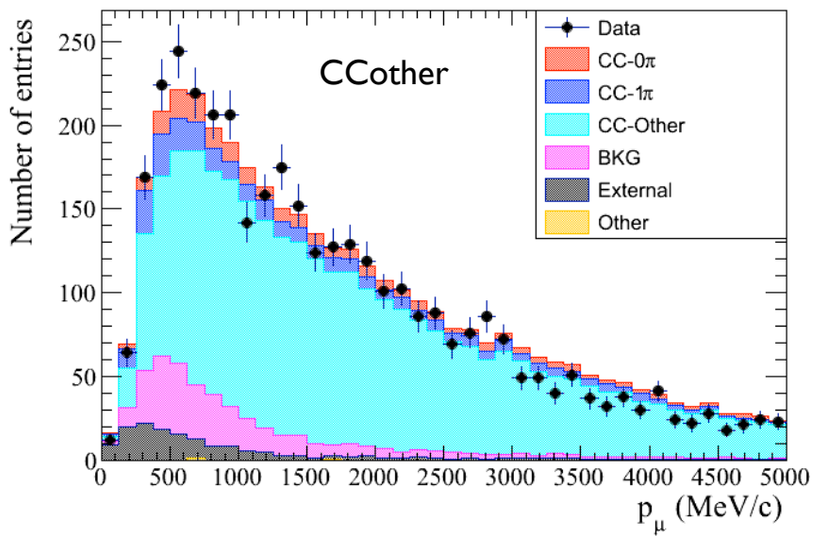
Event topologies







Topologies are used in T2K to identify interactions at the nucleon level for kinematic energy reconstruction.

- Minerva and T2K adopted the idea of the event topologies based on the presence of pions (easy to detect) and or protons in the final state.

This is an excellent way to unify data releases to allow for comparisons.
Do experiments mean the same when talk about CC0π?

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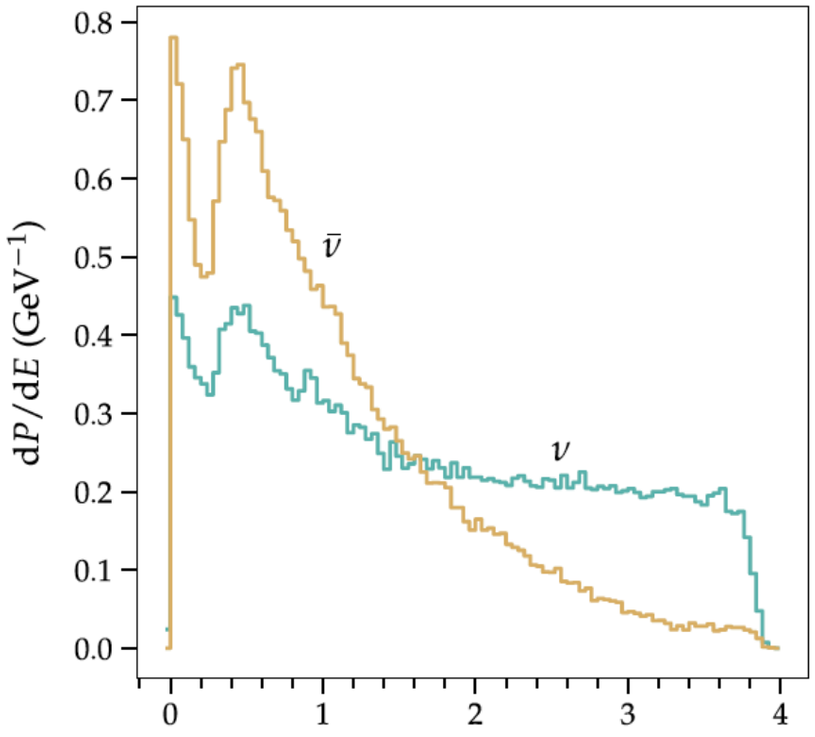
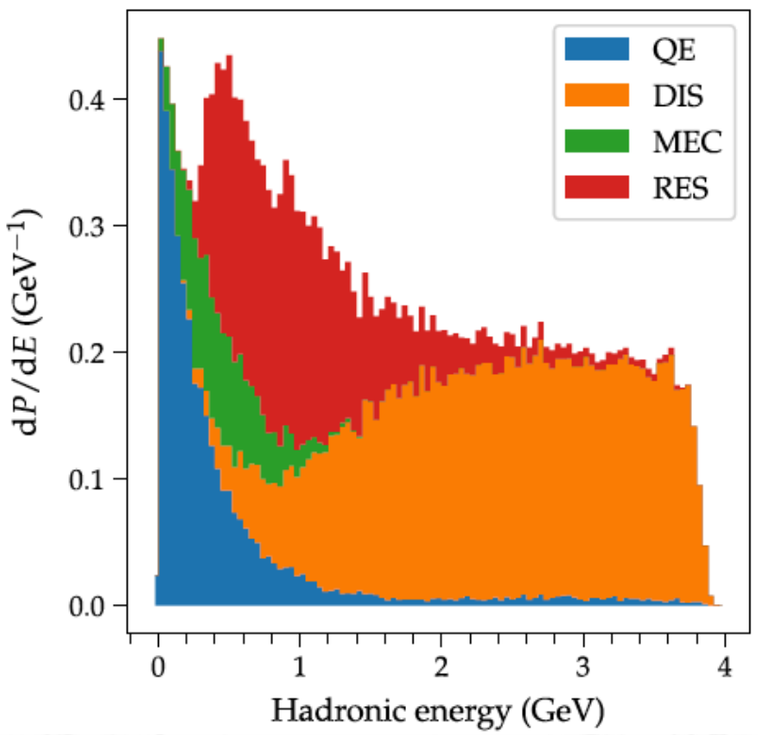
Calorimetric energy

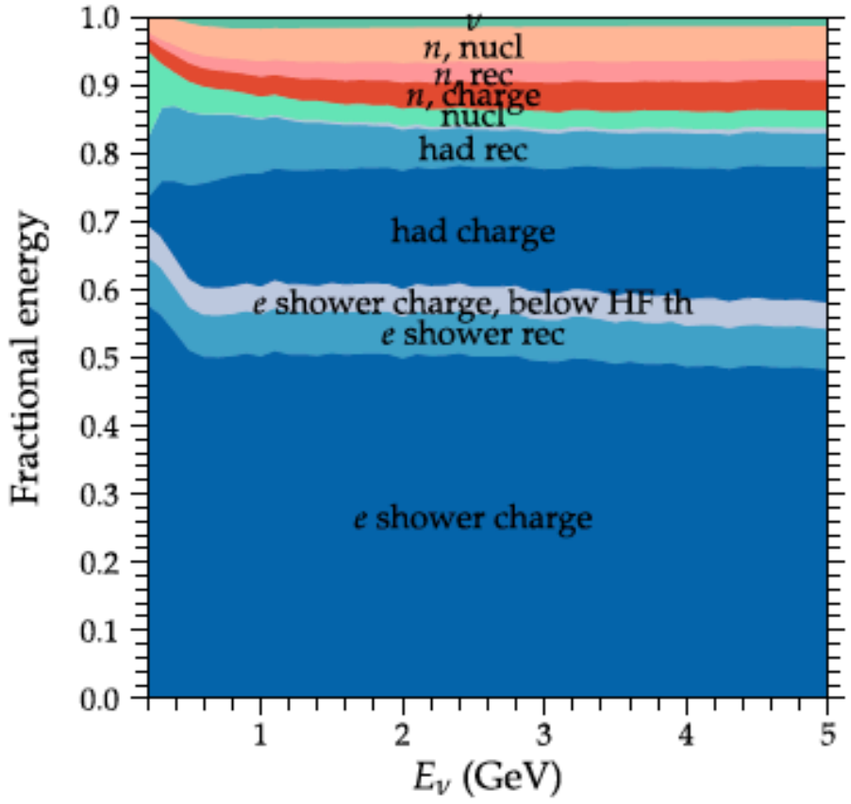


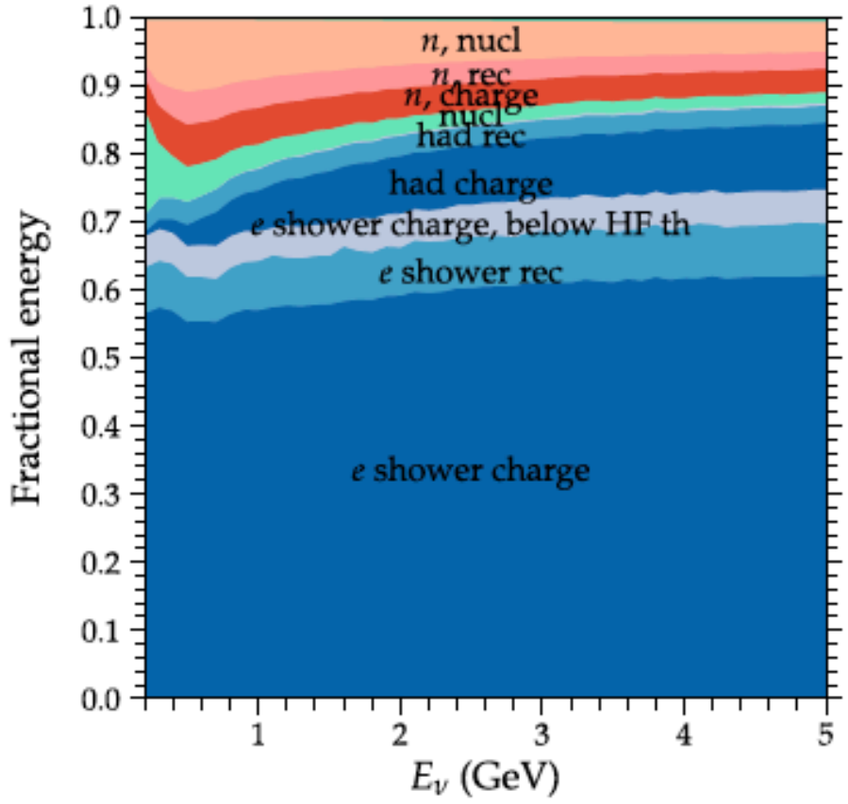


PHYSICAL REVIEW D 99, 036009 (2019)

Even calorimetric approach requirers understanding of cross-sections.

Even more critical when comparing neutrinos and antineutrinos.





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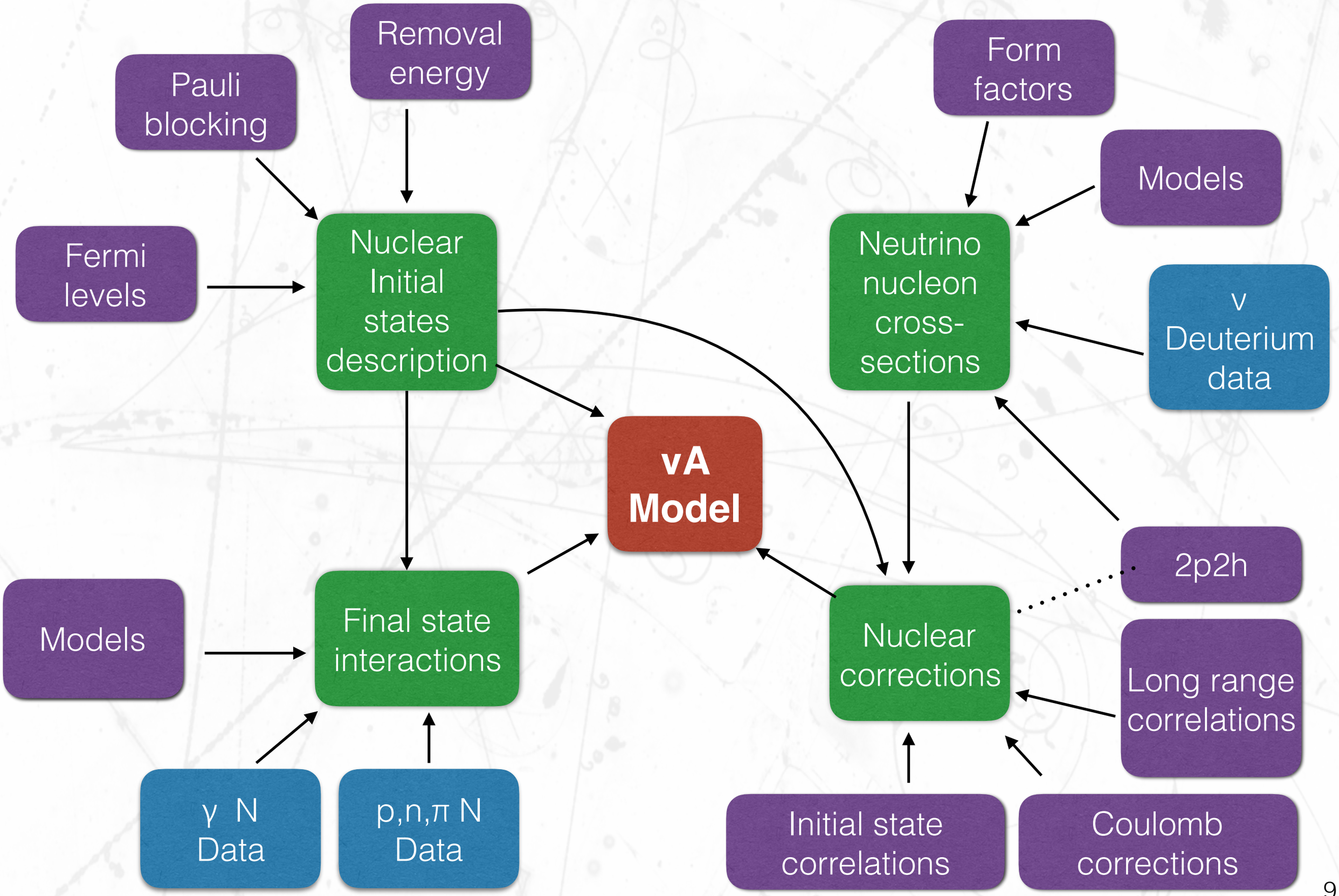
Model ingredients



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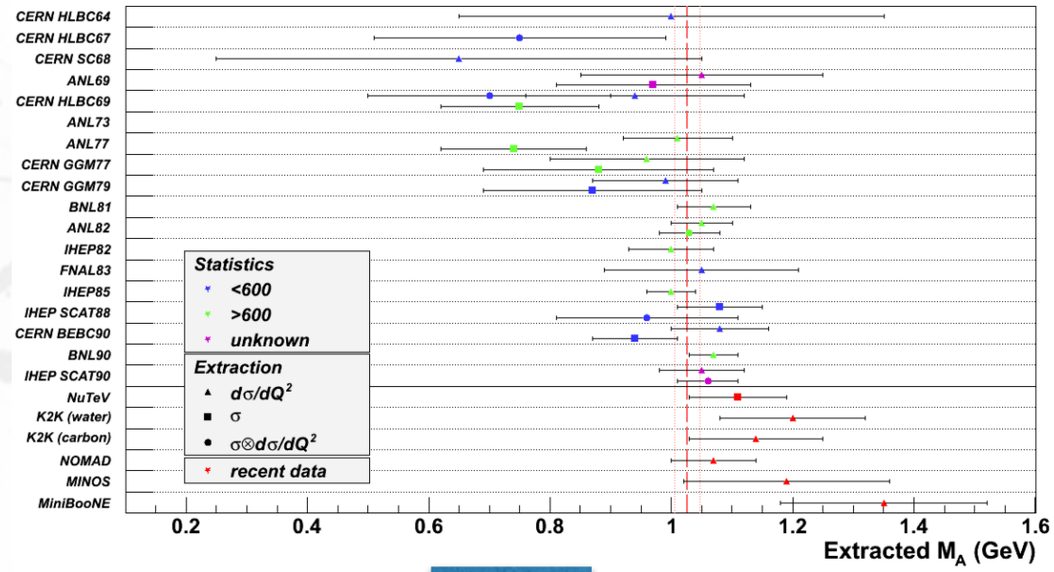
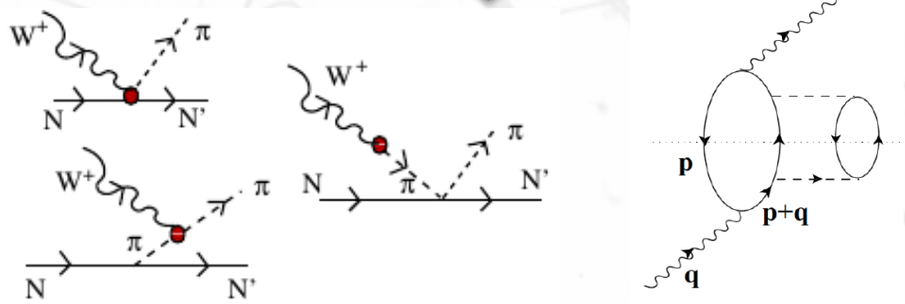
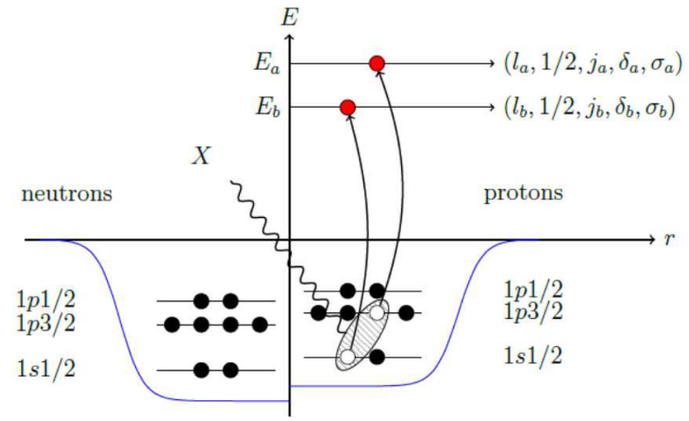
A bit of history

- 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….







■ ■ ■

Effective M_A was adjusting experimental results but it was not a self consistent theory.

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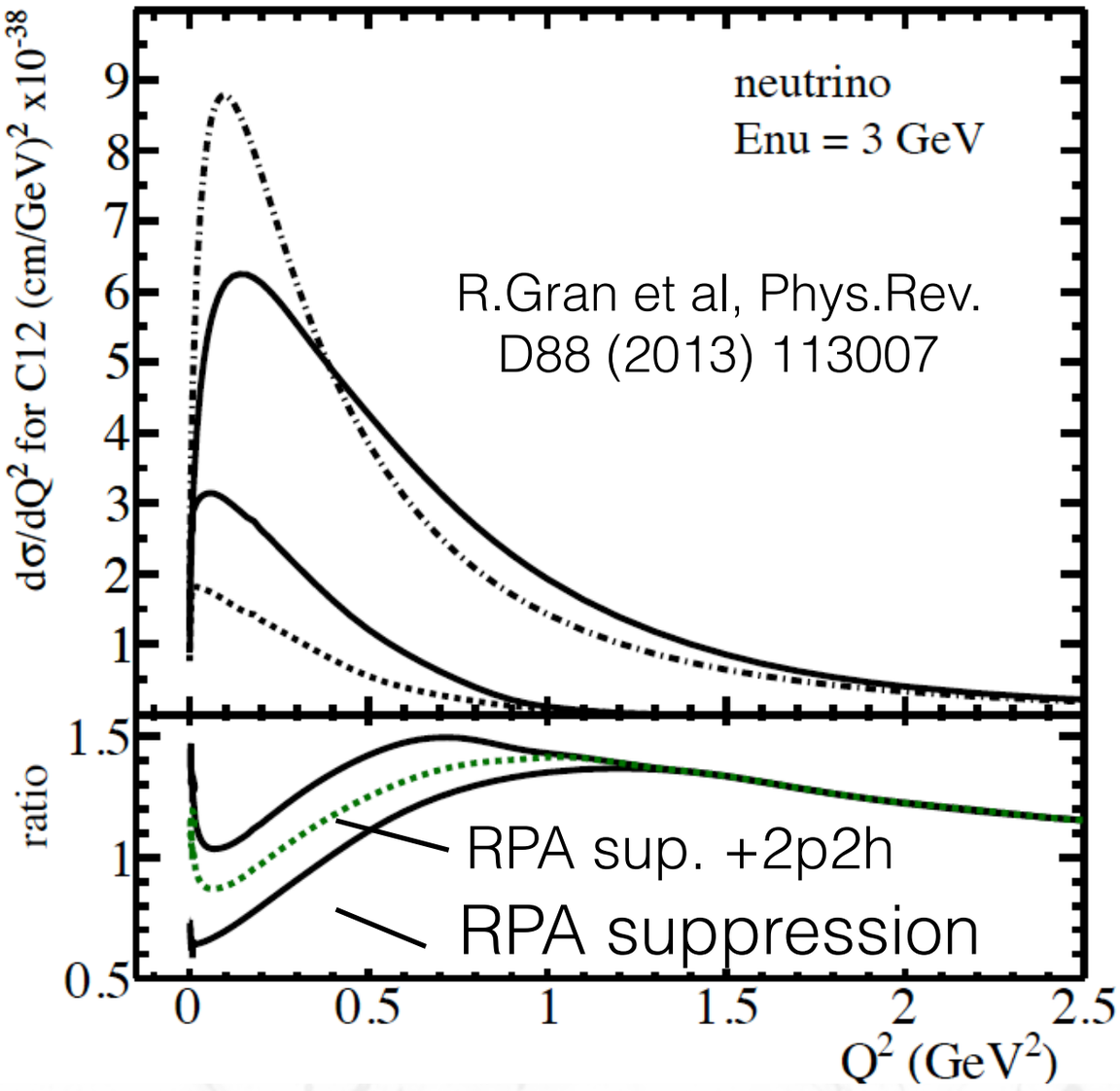
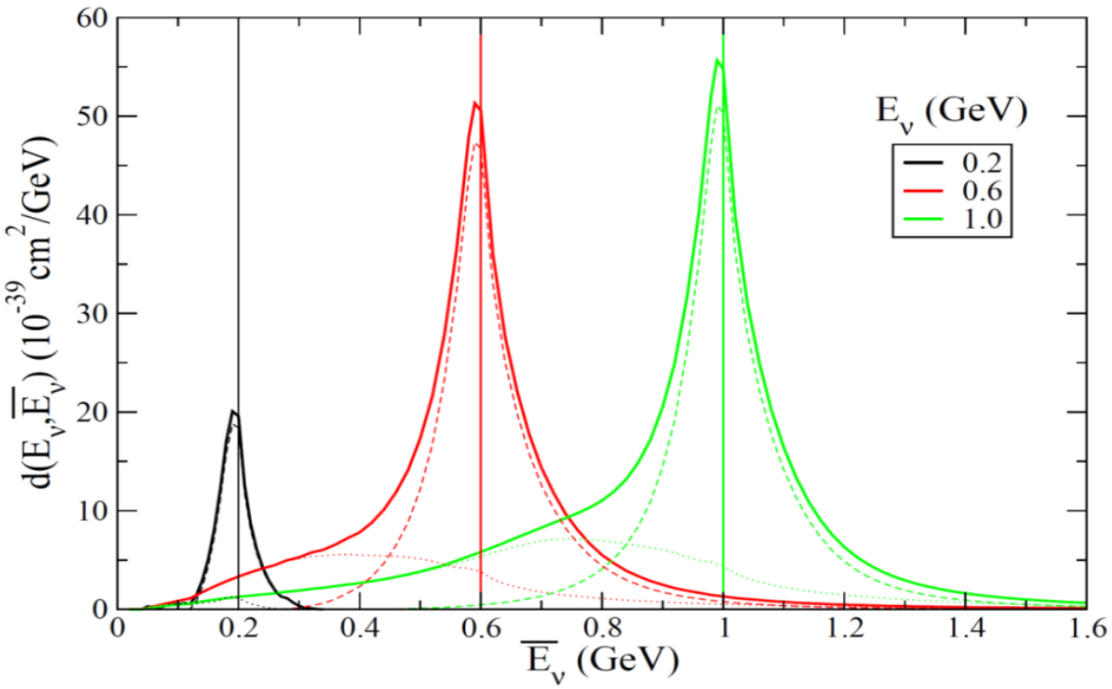
How to be fooled!

- Based on RPA & 2p2h calculations.



M_A was actually an effective parameter!

Different energies provided different Q^2 values with different proportions of RPA and 2p2h → effective M_A



Even if lepton kinematics was nicely fit, the energy of the neutrino was not!

Every model should have a solid theoretical background!

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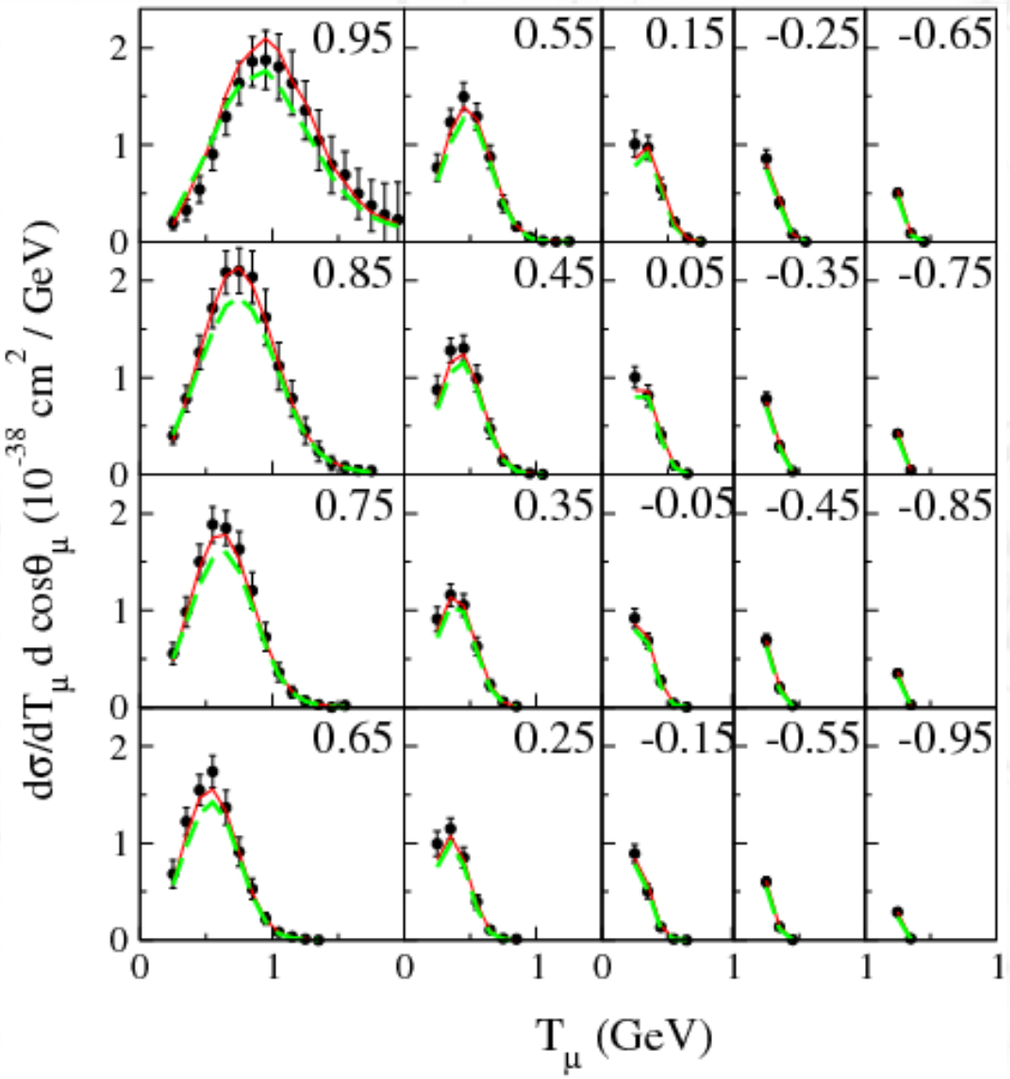
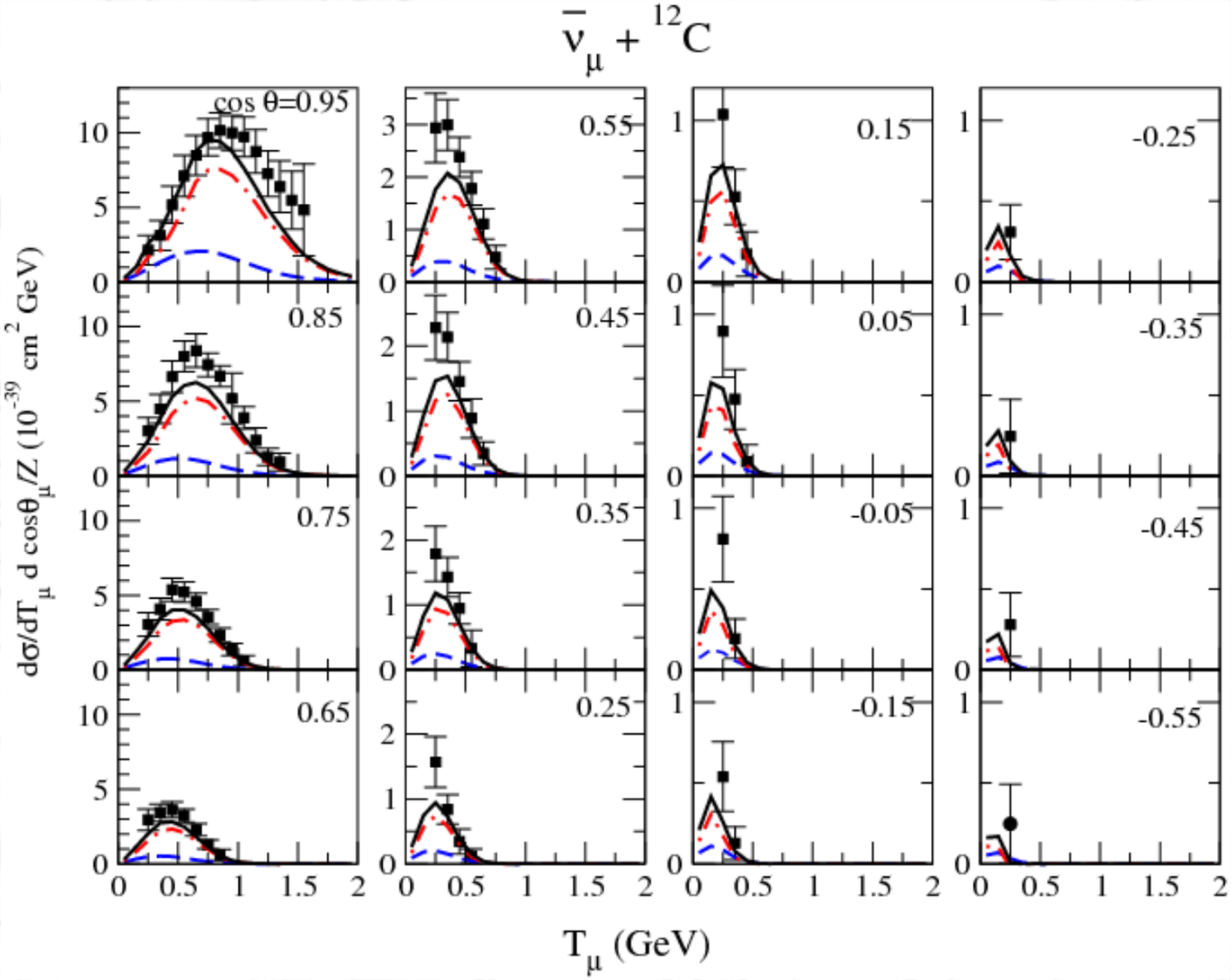
Actually…

we have an acceptable model



Phys.Lett. B707 (2012) 72-75



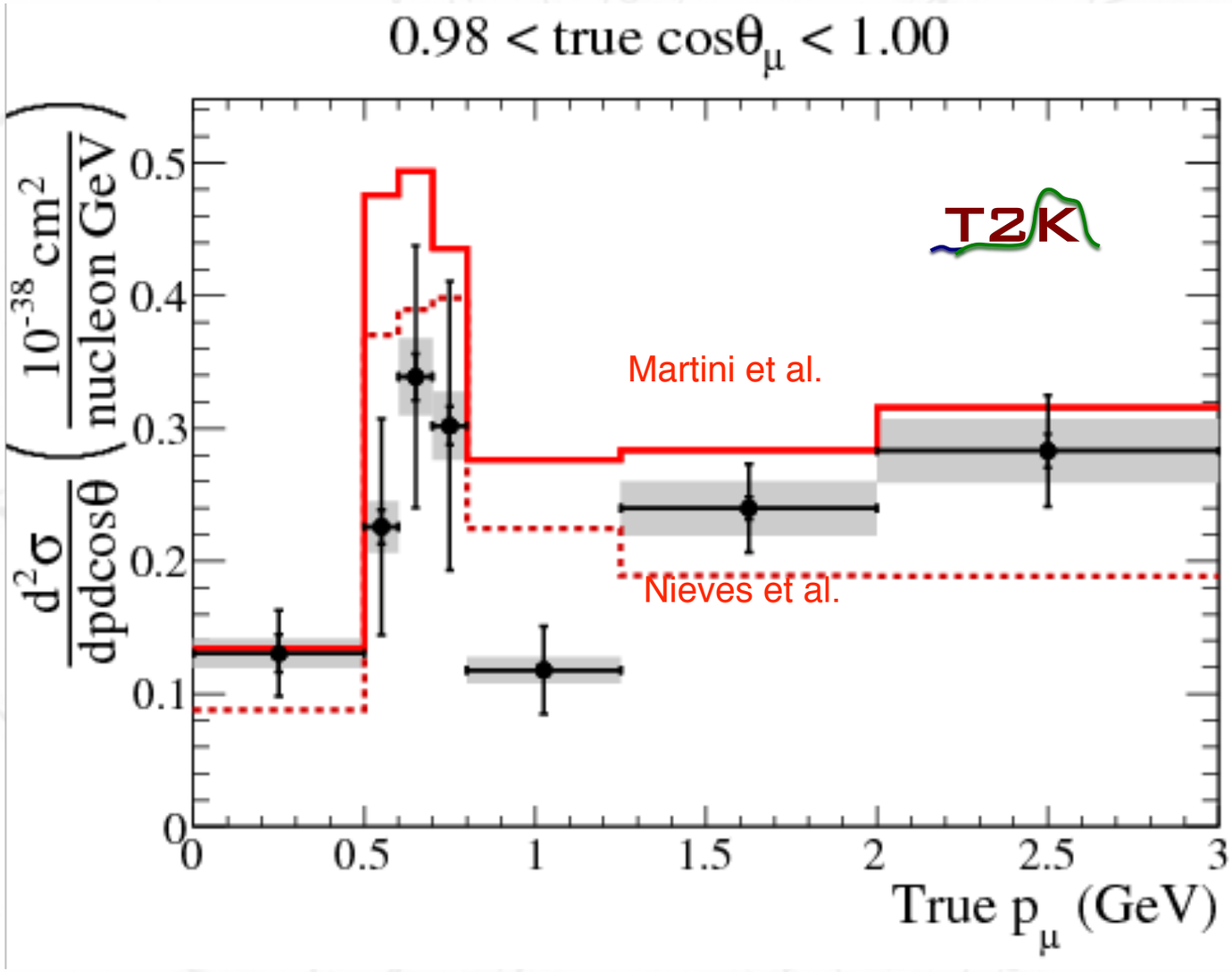
Phys.Lett. B721 (2013) 90-93

New models tends to fit well the MiniBoone data

But…not perfect

μ momentum distribution in the forward direction

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



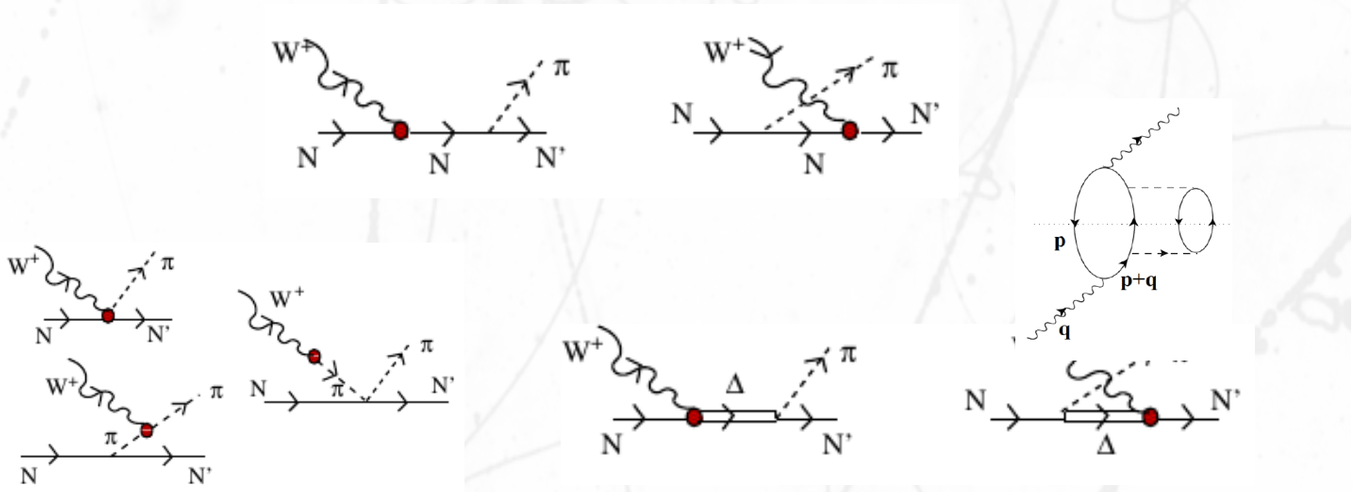
- In one bin we get different E_ν (flux) & Q^2 (x-section) contributions.
- The flux is constrained from the hadro-production.
- Adjusting the model to the flux will migrate problems from flux to cross-section and viceversa.

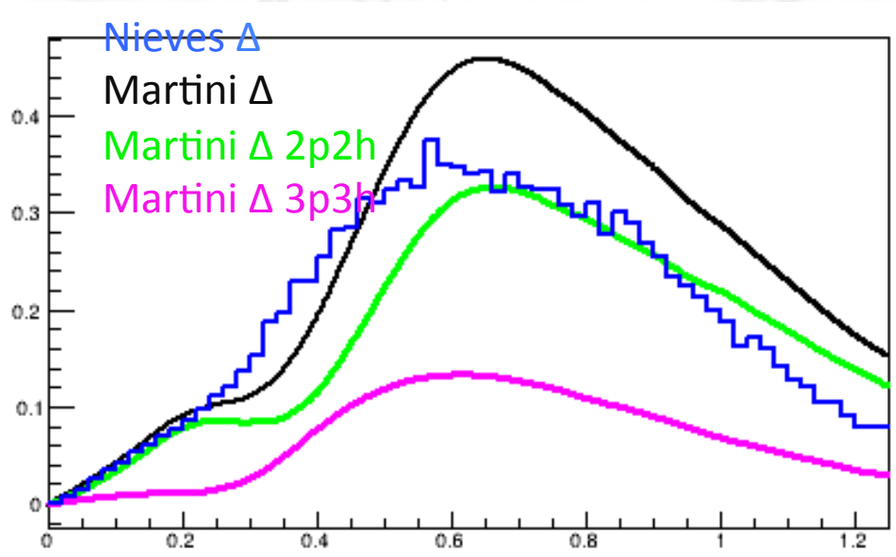
Low and High Q^2 contains different level of uncertainties at the nucleon level (form factors) and nuclear level (short and long range correlations)

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

Might it be the model is not equally good across neutrino energies ?

Models vs calculations





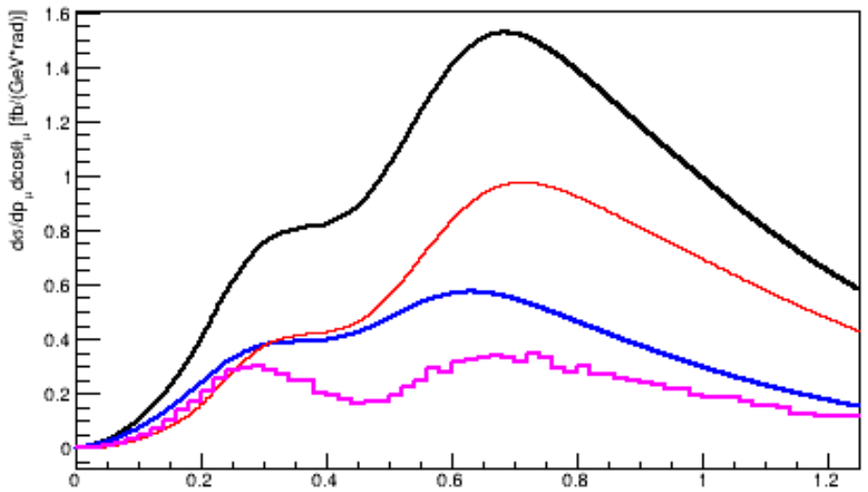
"A priori" very similar models (microscopic) give very different results.

Models have parameters!

Models have limits!

Models have approximations!

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



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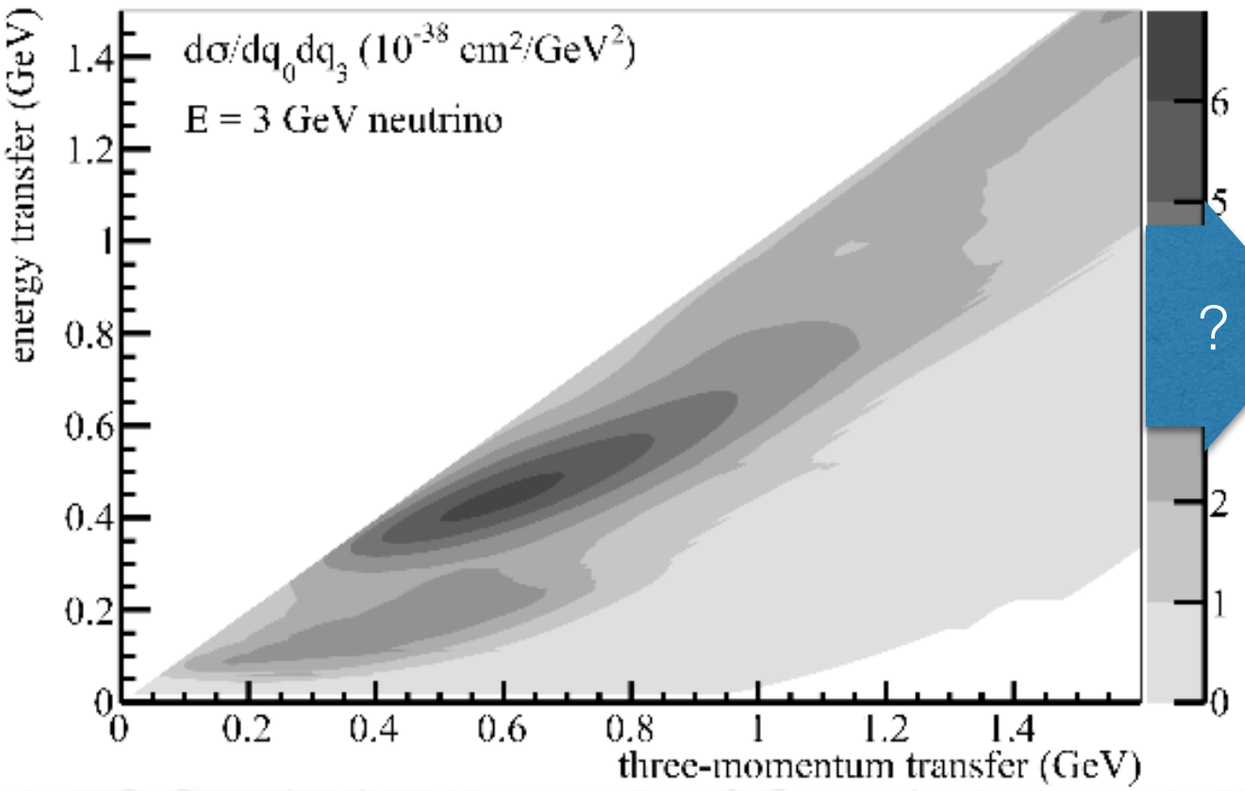
Limits of models

- 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 reaction channels included in the model !

Critical for inclusive measurements like oscillations neutrino beams!

These limits are not very precise and may vary from model to model

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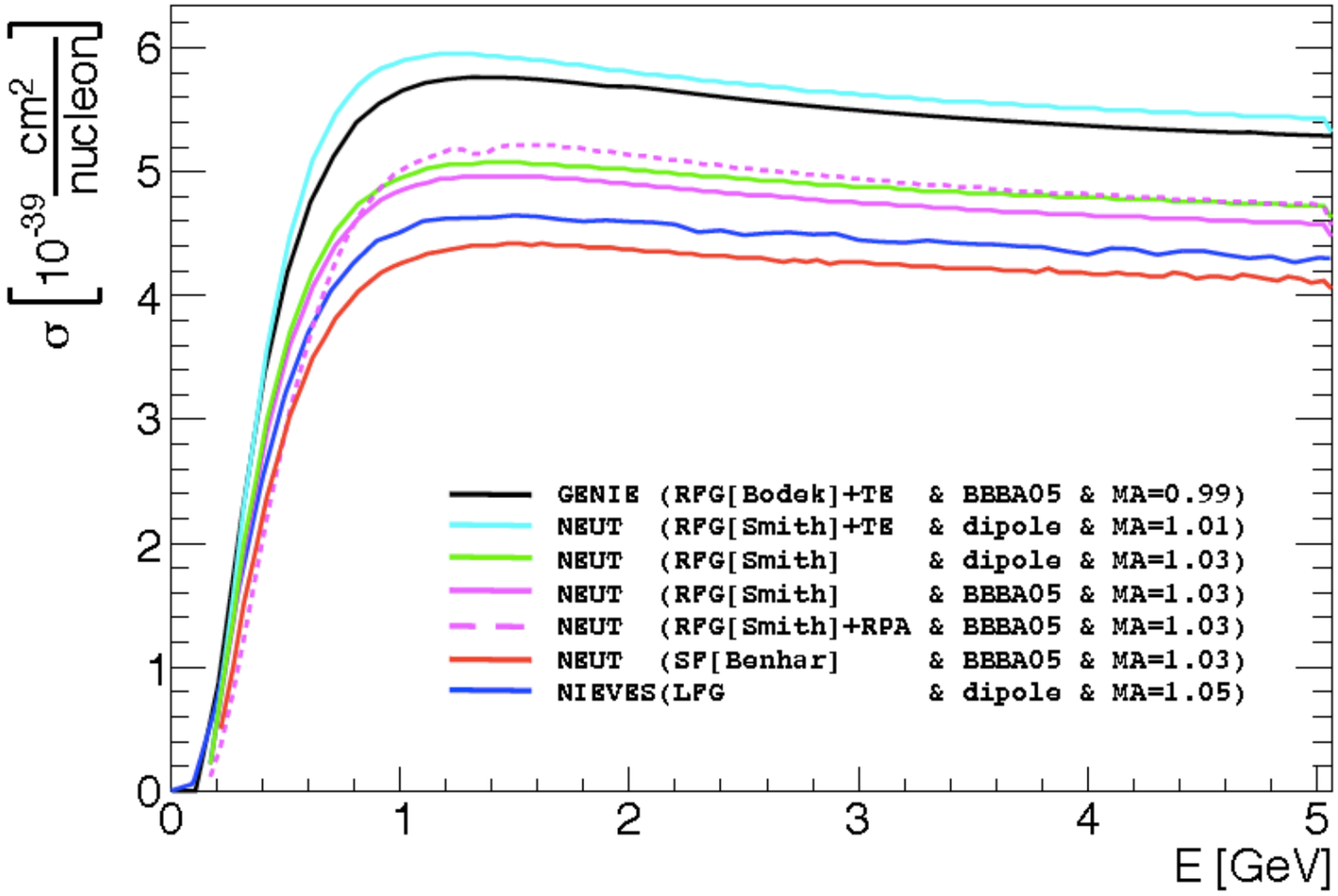
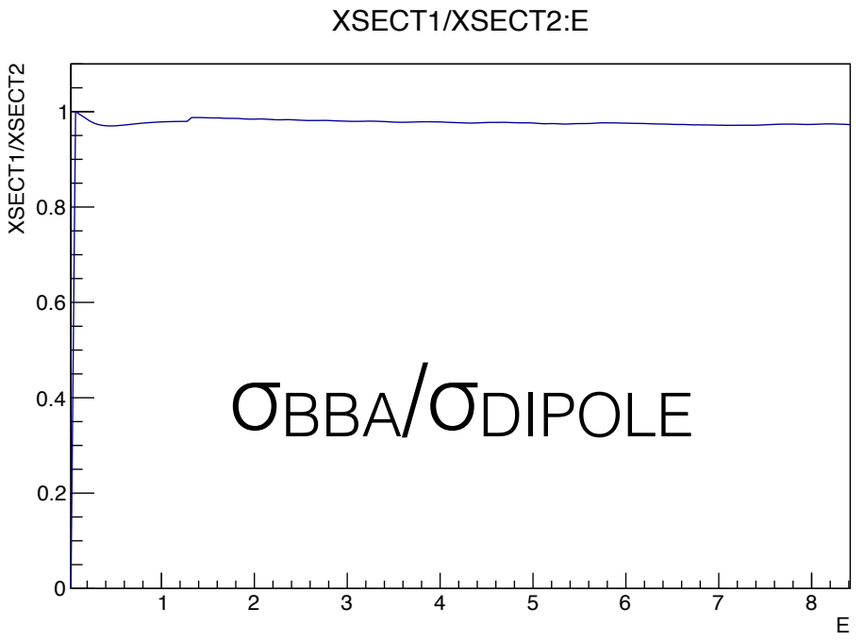
Nucleon level

Are these differences only Nuclear effects ?

- Do MC models agree at nucleon level?
- A one to one nucleon level comparison might be enlightening?.

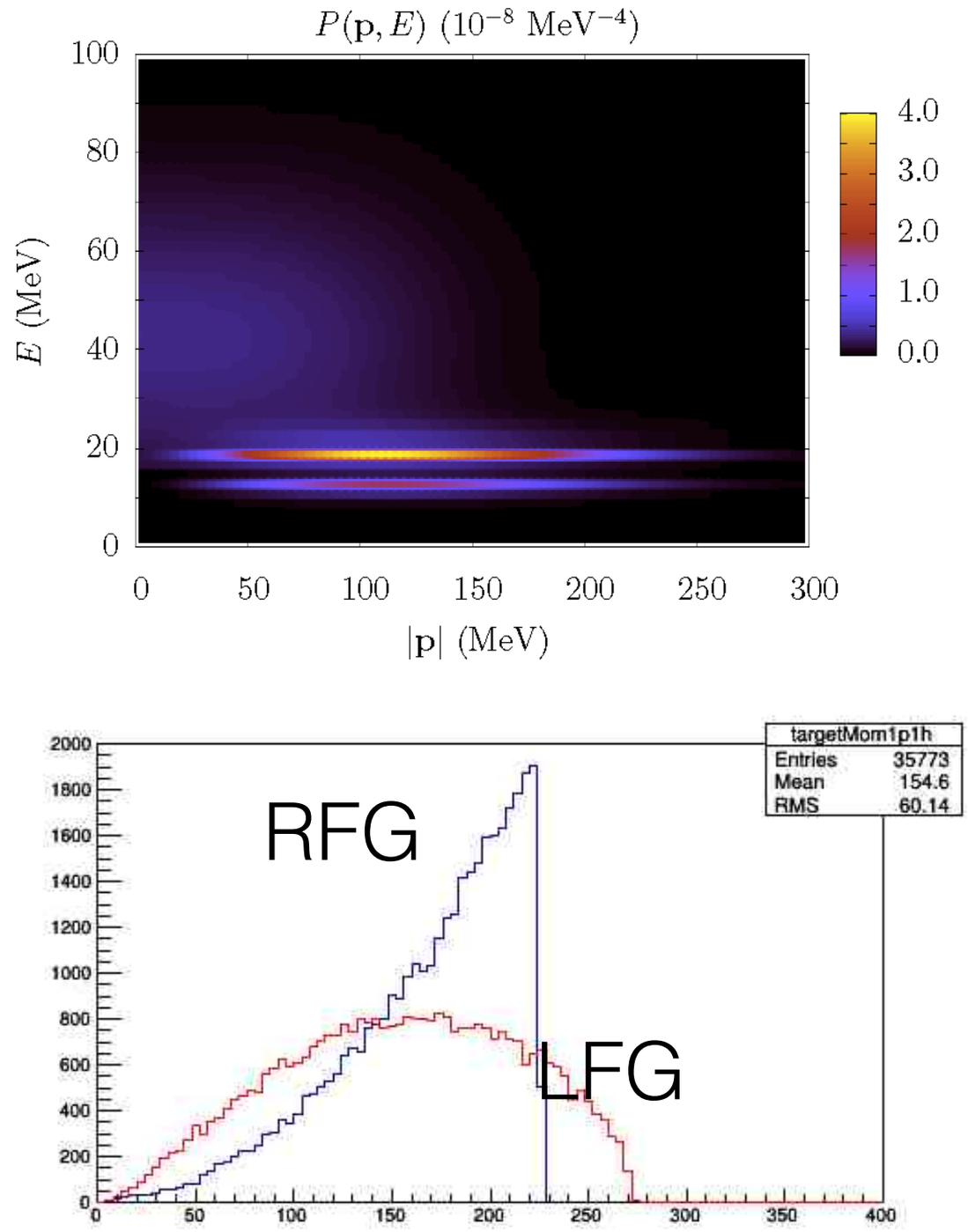


- What is the effect of the z expansion ?



Fermi momentum

- Actually 4 different implementations:
  - **Relativistic Fermi gas.**
  - **Local Fermi gas:** radial dependency of Fermi level
  - **Spectral functions:** available for light nuclei and now also for Ar!.
  - **“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

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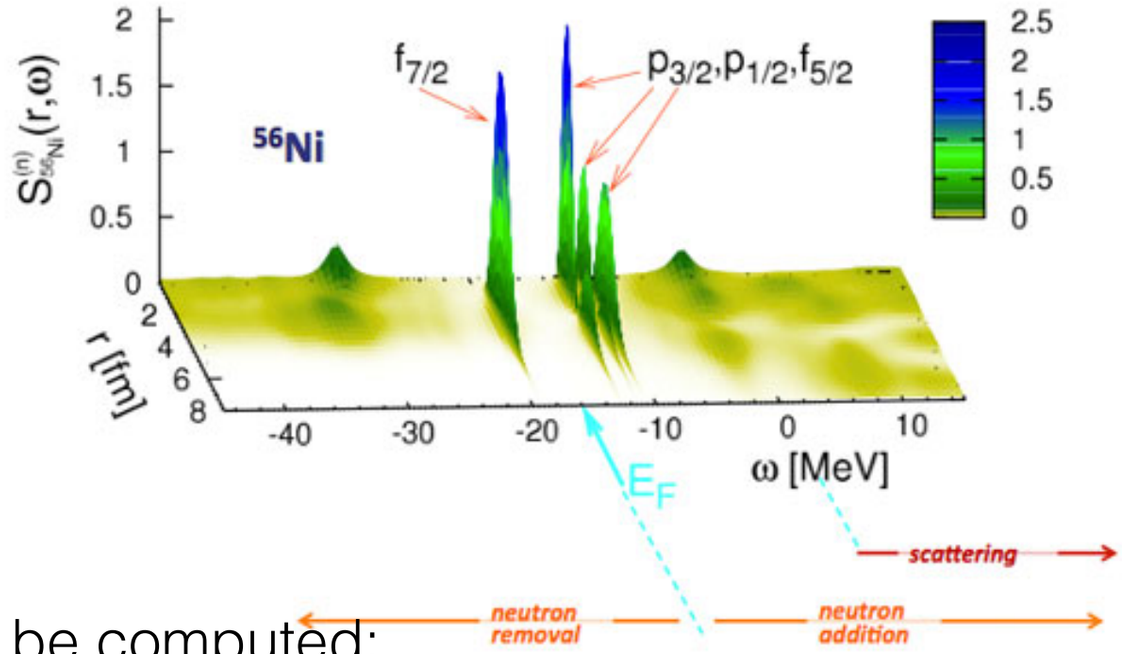
Spectral functions

- 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.

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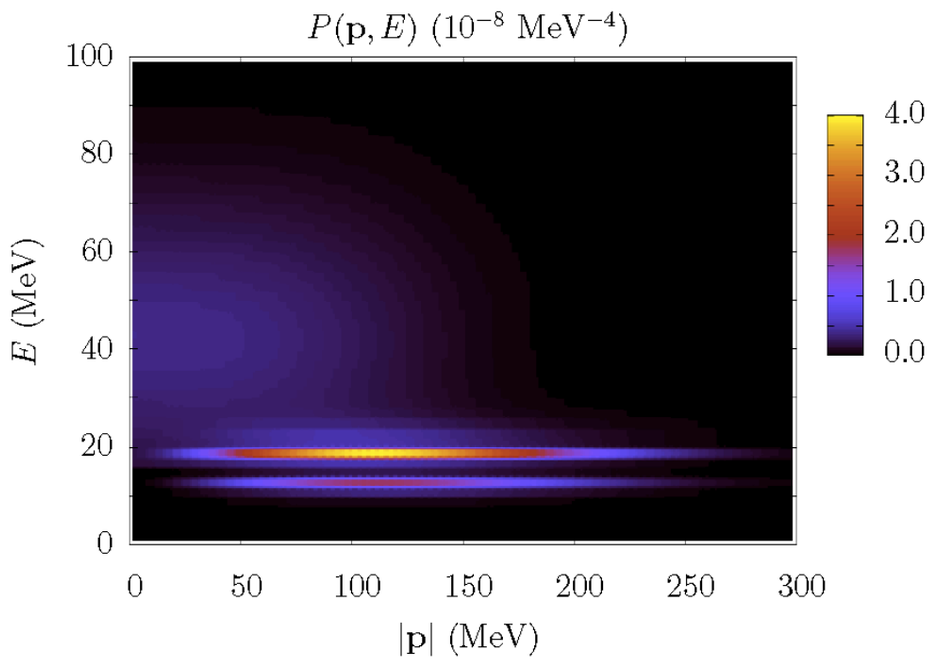
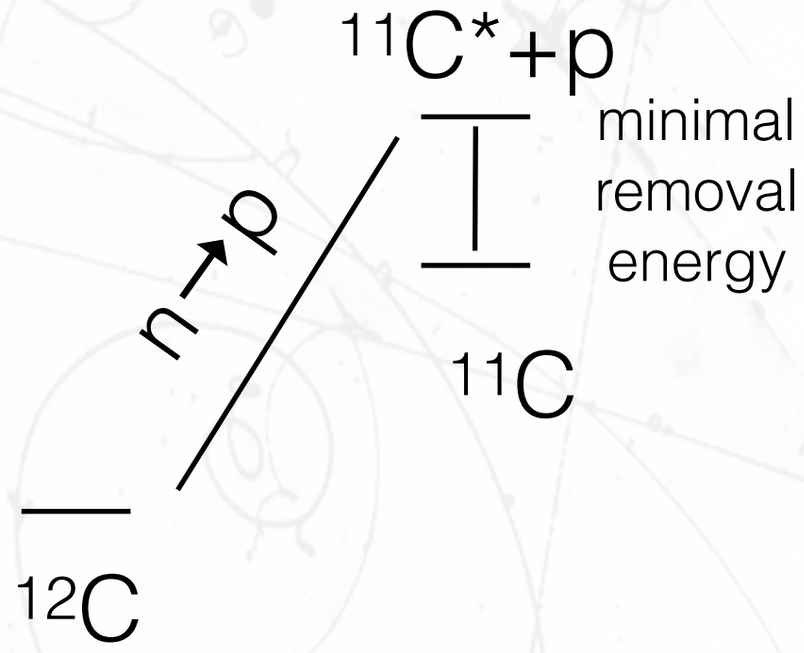
Bind Energy

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





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

Some energy such as nuclear recoil is not accounted normally (~ few MeV).

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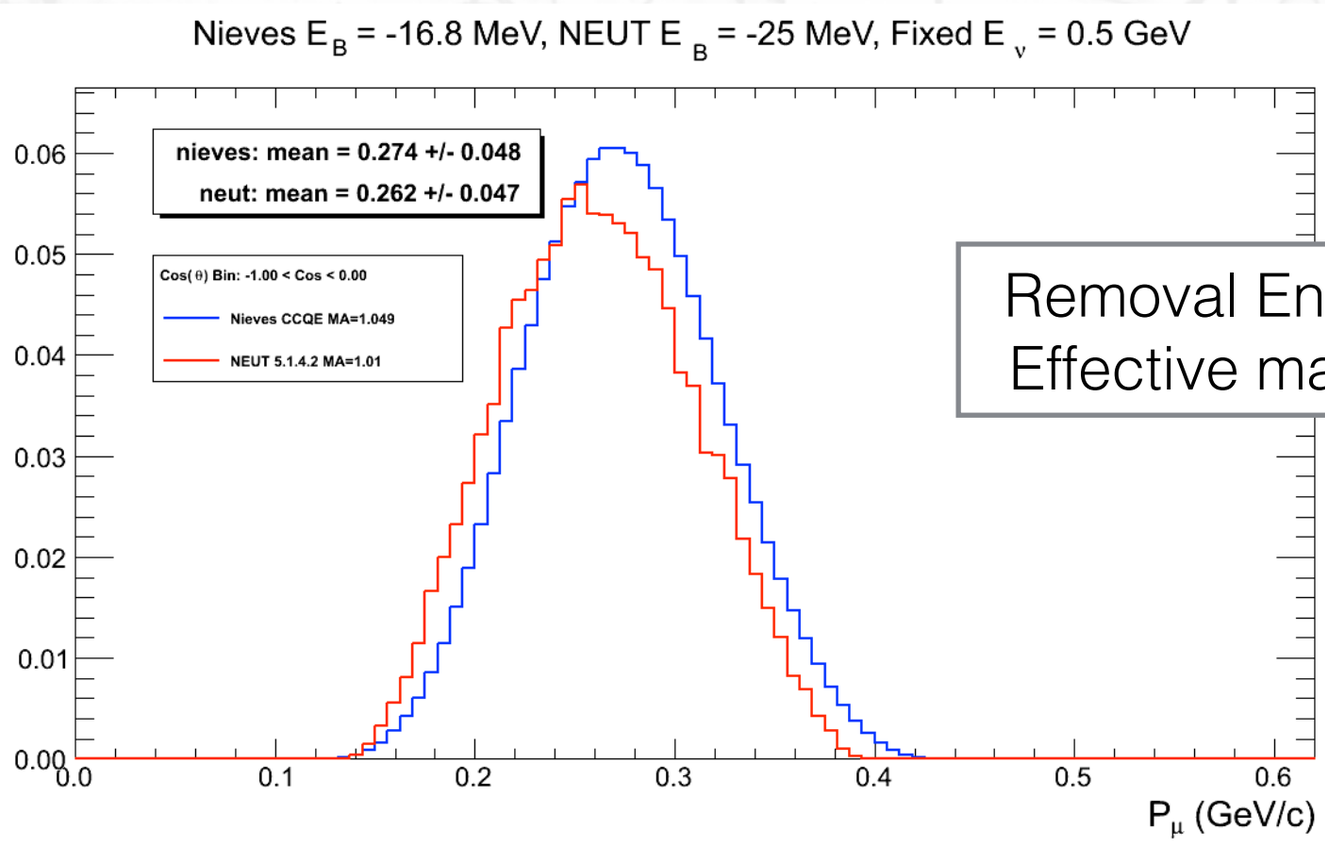
Bind Energy



Removal Energy E_b = -16.8 MeV
Effective mass E_b = -25.0 MeV

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

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

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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 sign 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 and/or a consistent treatment of nuclear potential before and after the interaction.**

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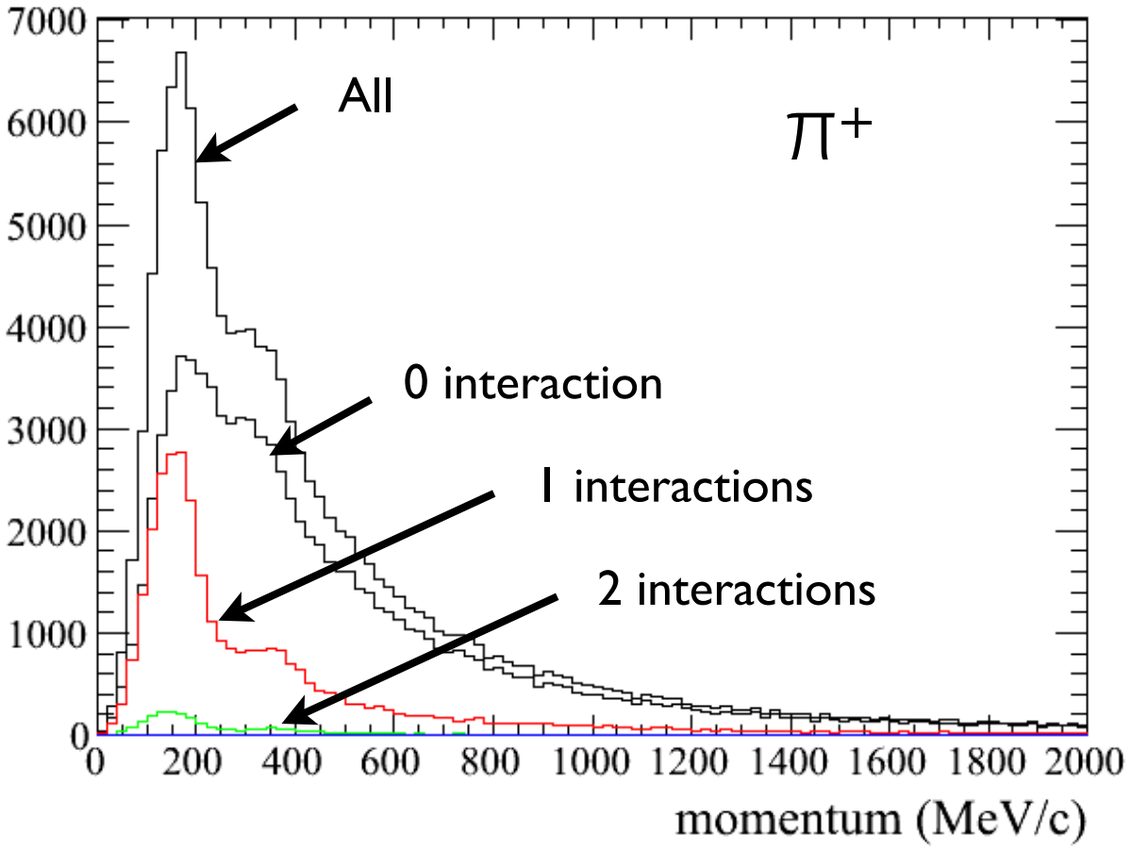
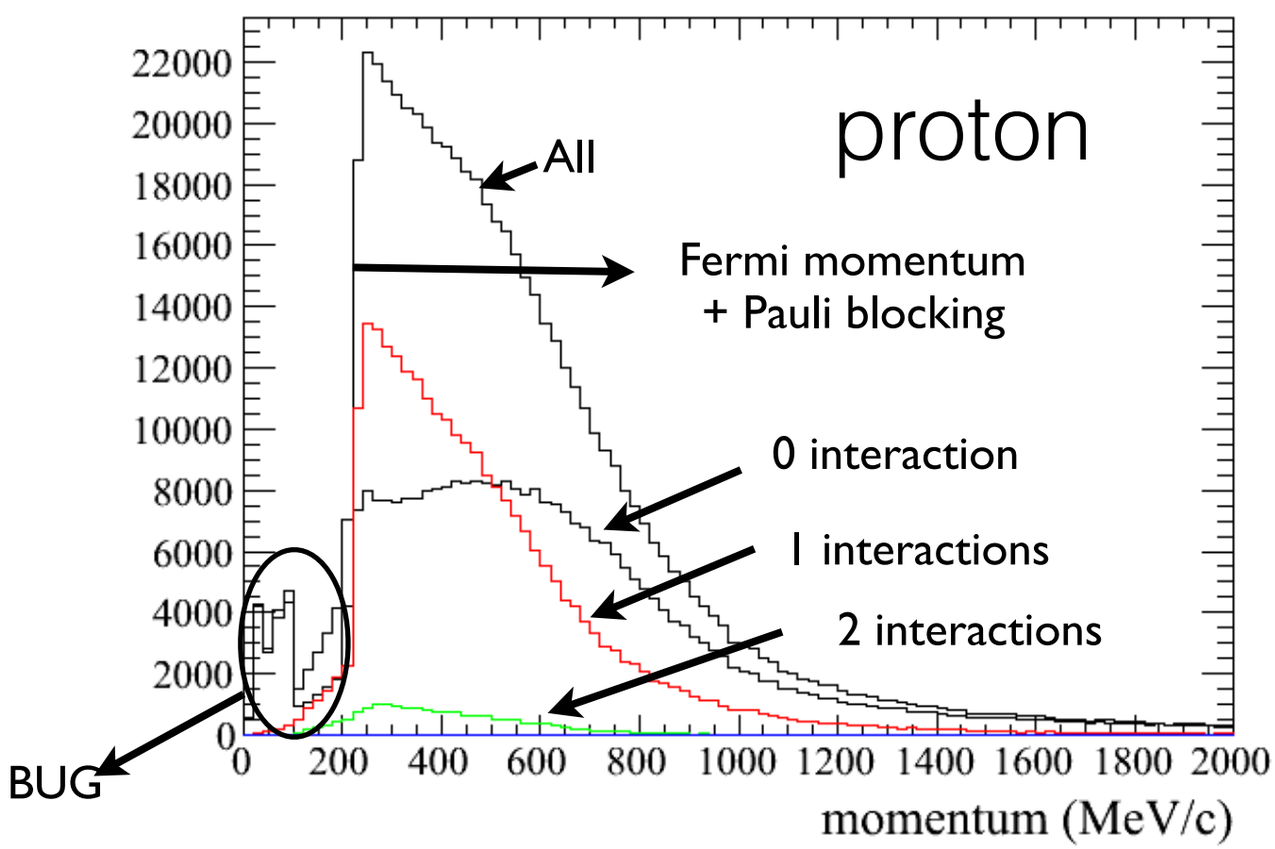
FSI

- 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.





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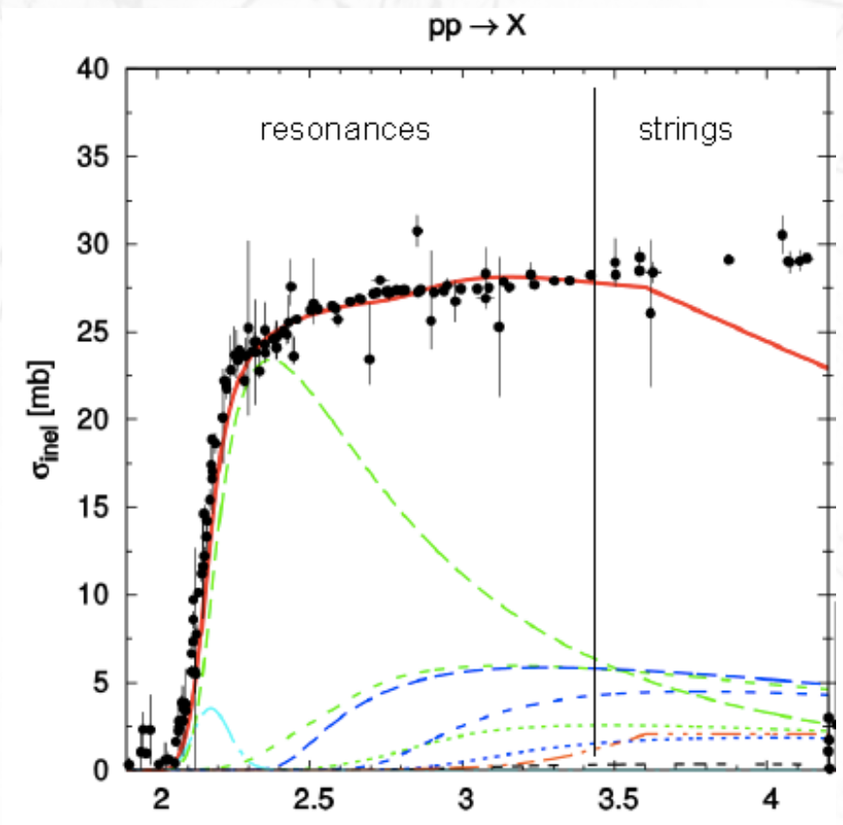
Cascade vs Transport

NEUT/GENIE

GIBUU

- 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.

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



Excellent results in different interactions beyond neutrinos.

Limitations of experimental data

- We always start from an ν **flux prediction** that is not perfect.
- **Lepton observables** (lepton angle and momentum) follow distributions with little structure.
  - **Radically different models can reproduce simple observables.**
- A good part of the information is in the new observables that:
  - include **hadronic information.**
  - try to reconstruct the **neutrino energy.**
  - avoid the neutrino energy reconstruction through **transverse variables.**

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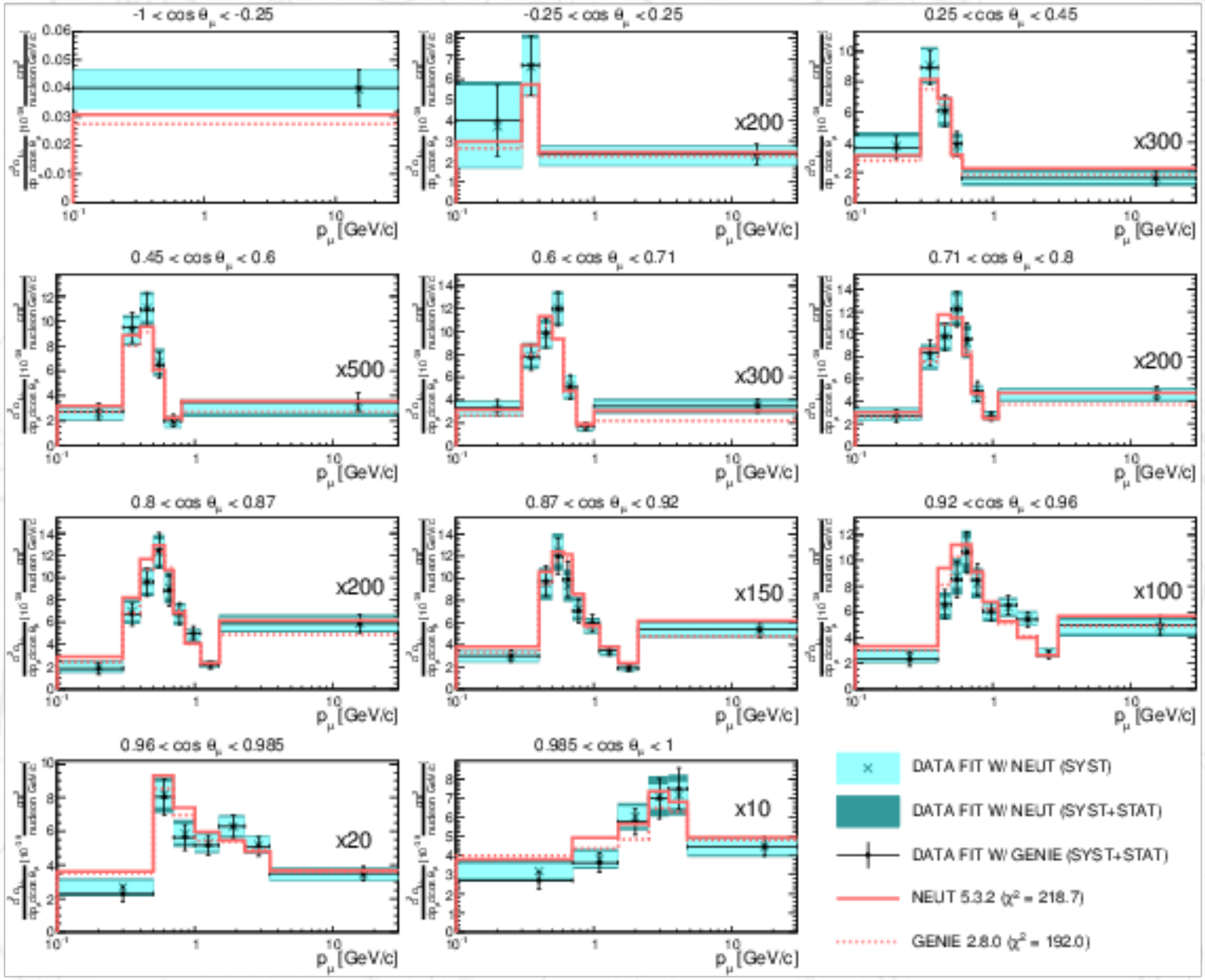
Lepton observables

T2K



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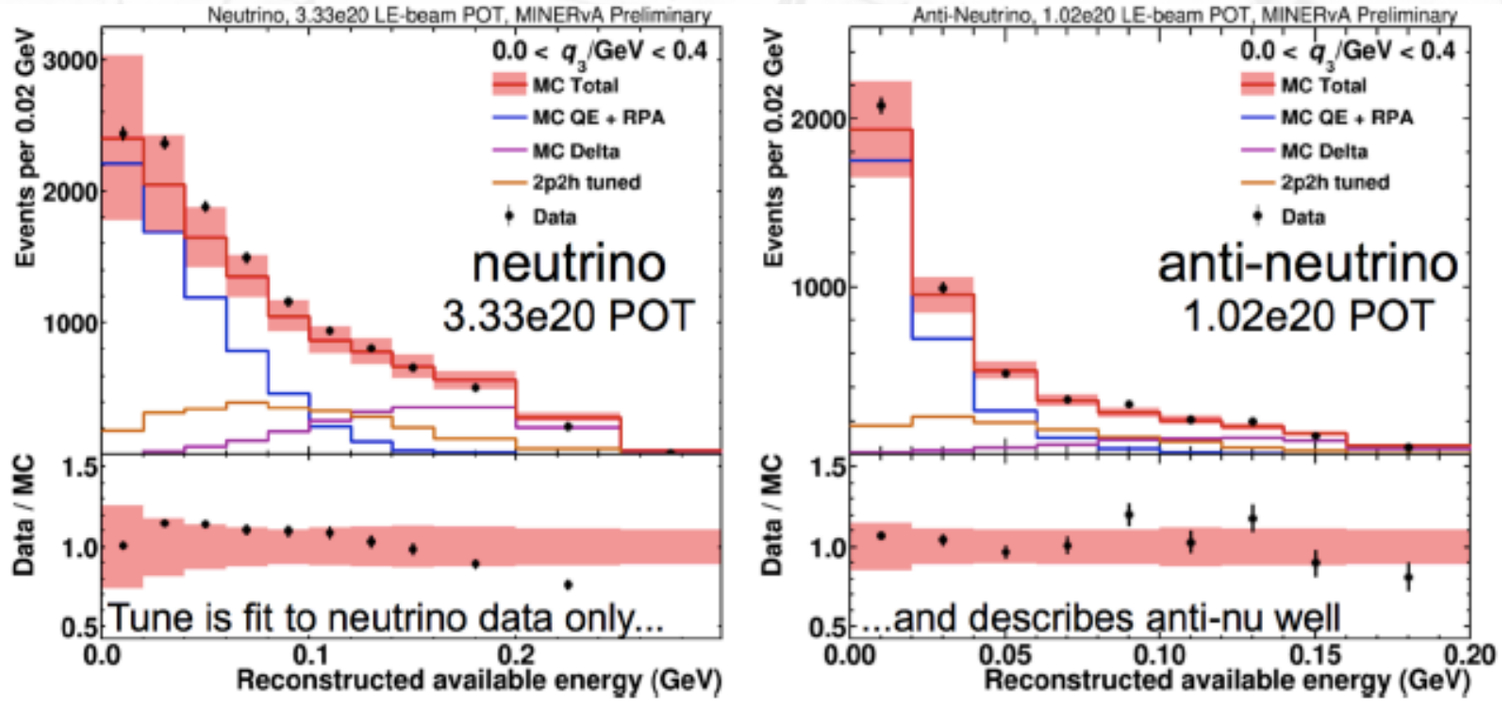
Energy reconstruction with hadrons

- 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.

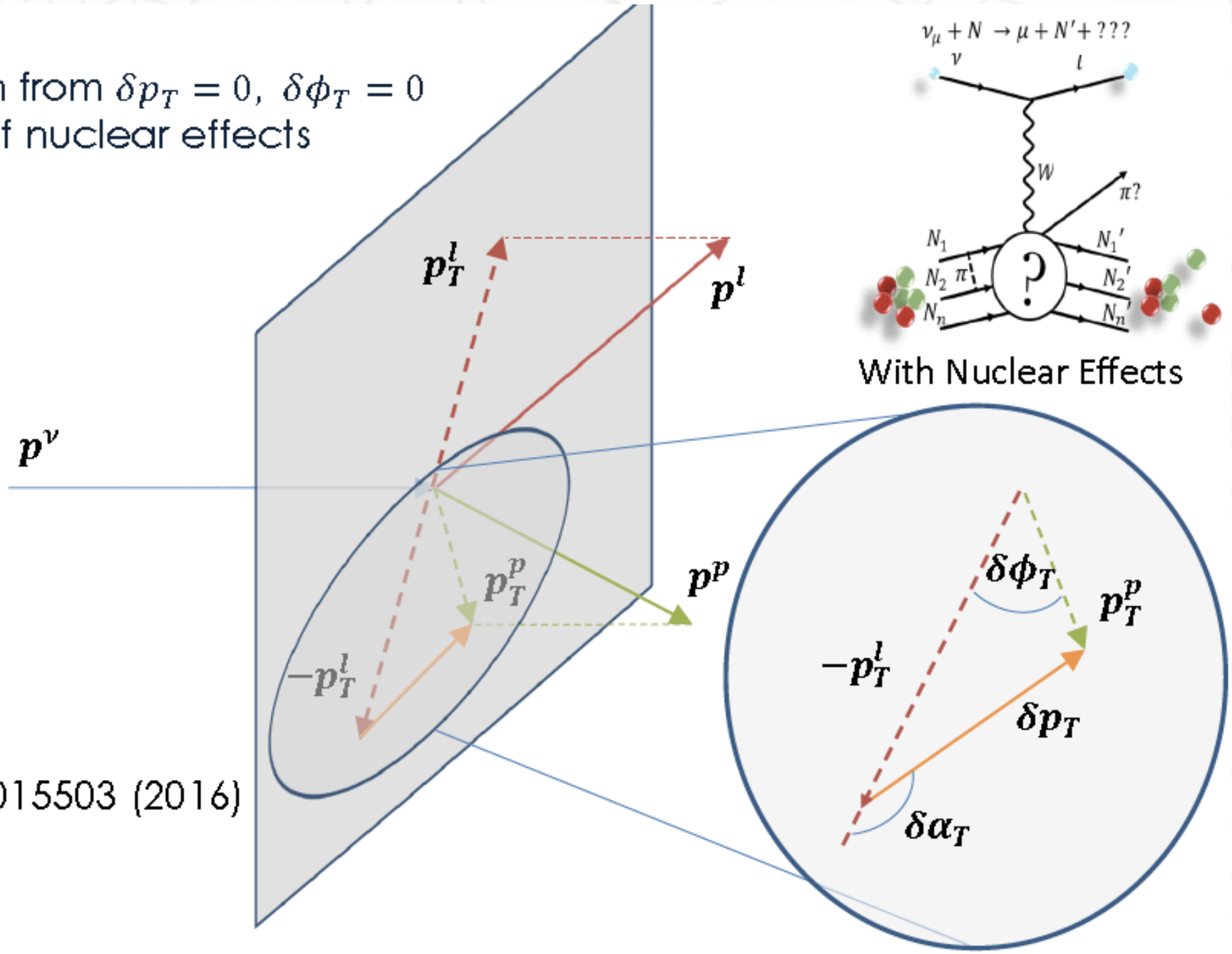


Available energy in Minerva is the sum of proton and charged pion kinetic energy and neutral pion, electron, and photon total energy

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



With Nuclear Effects

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

S.Dolan ECT Trento 2018

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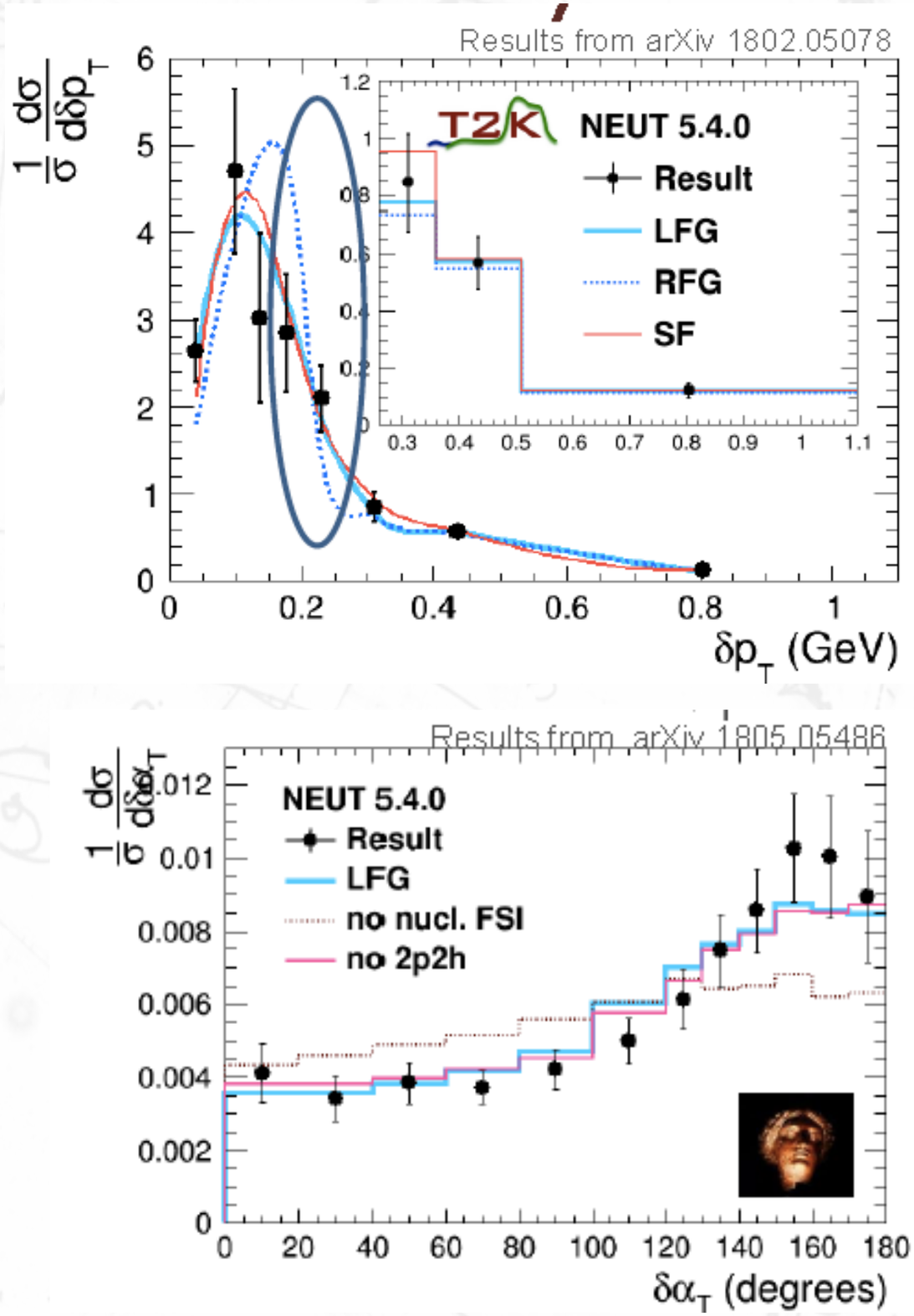
Transverse variables

- Local Fermi Gas is not a good model.
  - We knew this but ….
  - this is probably the first time we it in neutrino data.
- We need some sort of Final State Interactions.



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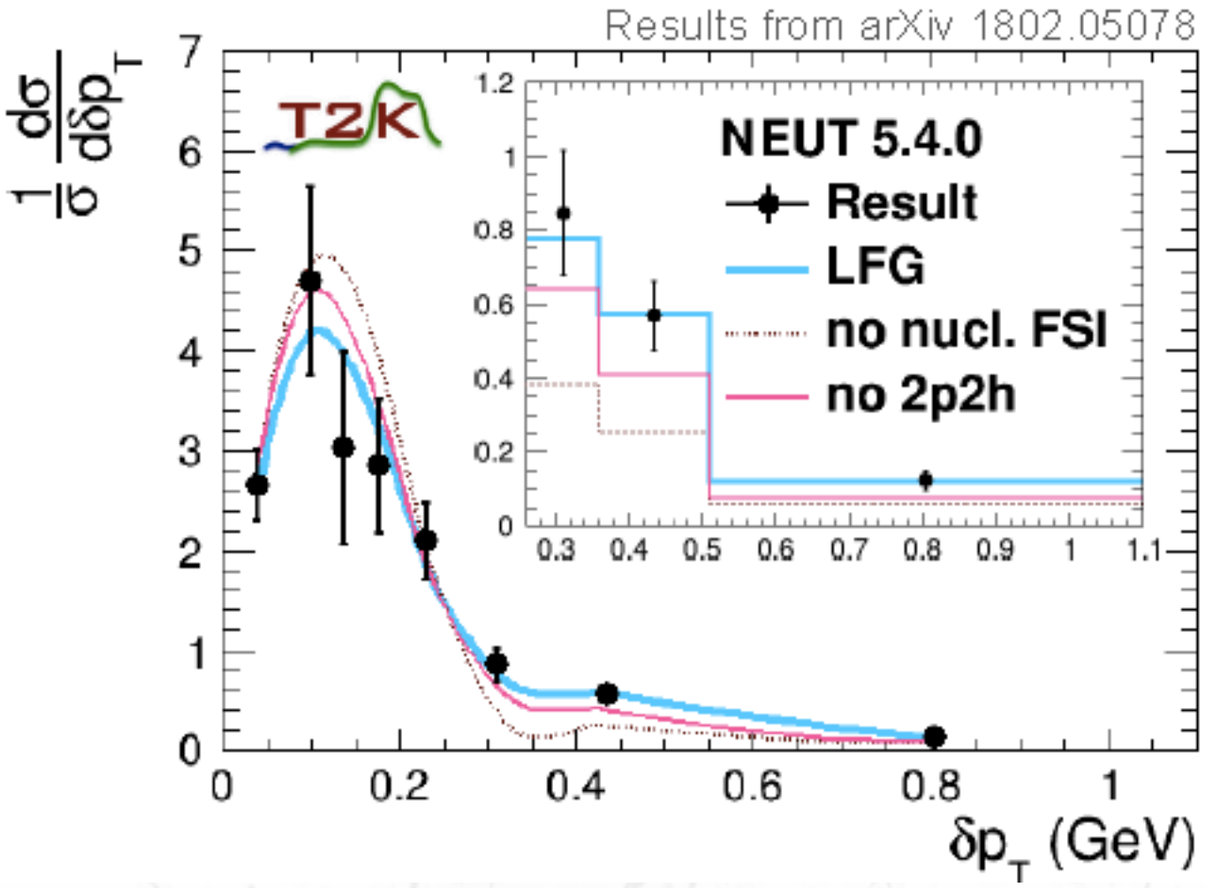
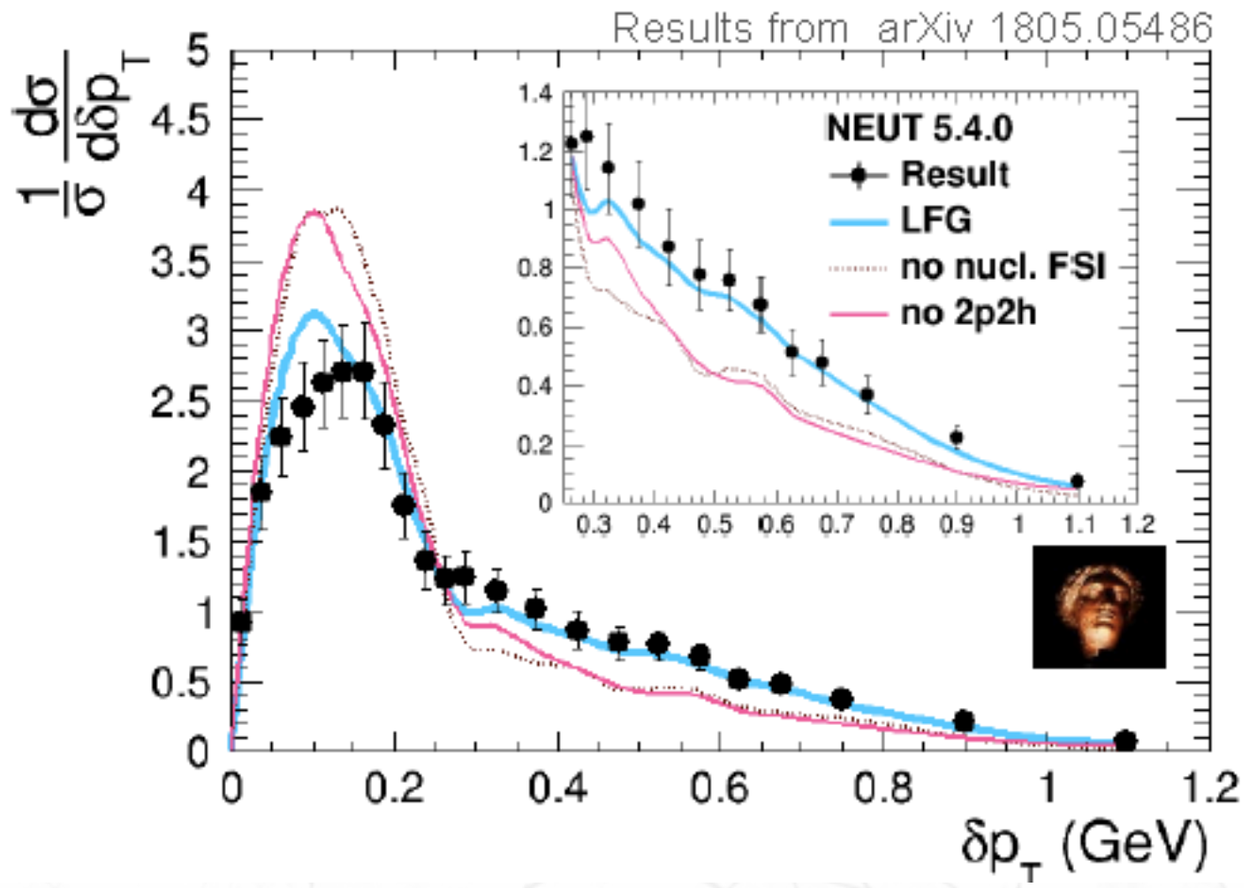
Transverse variables

- 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.

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Computing 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

New observables might require more and more precise modelling:
migration from Inclusive to Practical!

Too practical : Hadron tensor

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

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

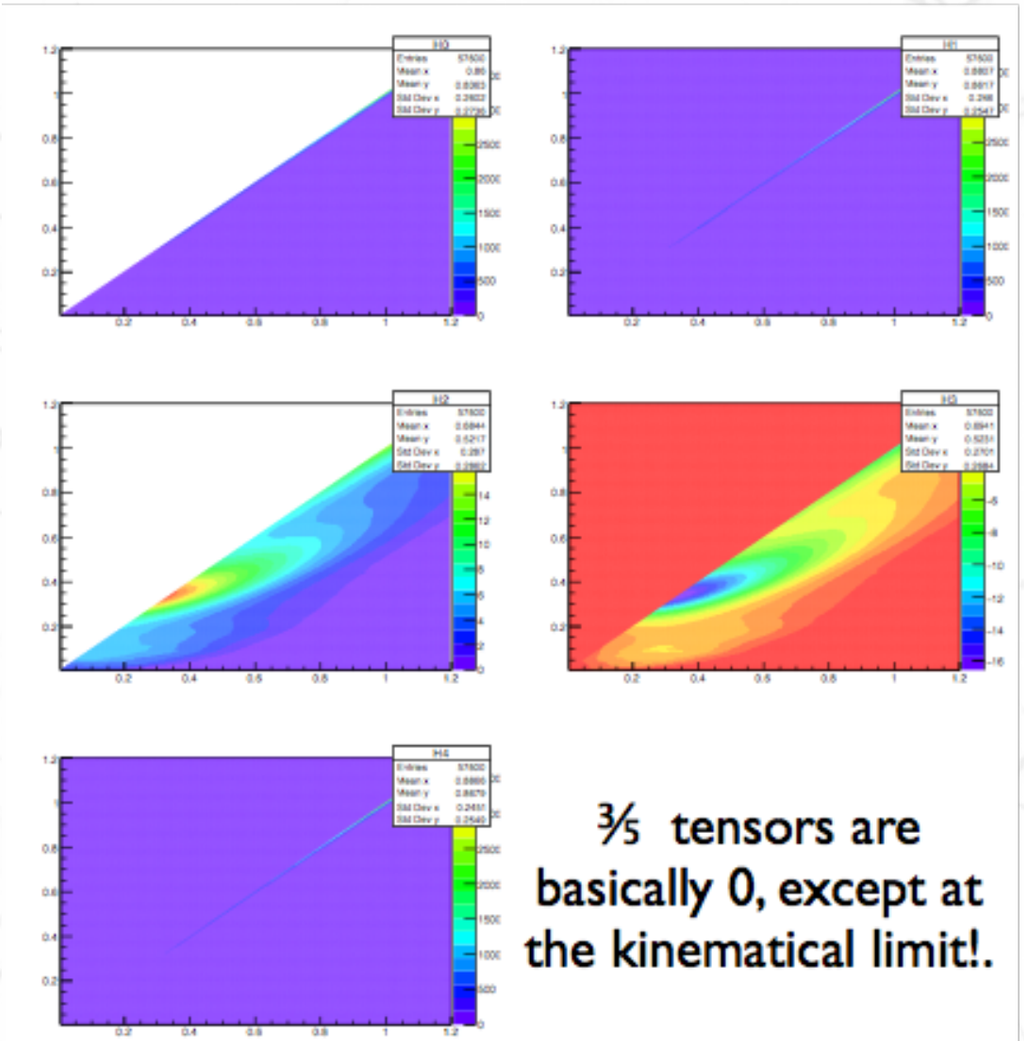
- The Hadron tensor is precomputed in an “slow” MC.

- Limitations: the hadron-tensor do not predict the hadron kinematics!

  - This can be used to understand contributions or to implement MC re-weights.

Complex models implemented as tensor contraction

Many models stay at the lepton level, we need more



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

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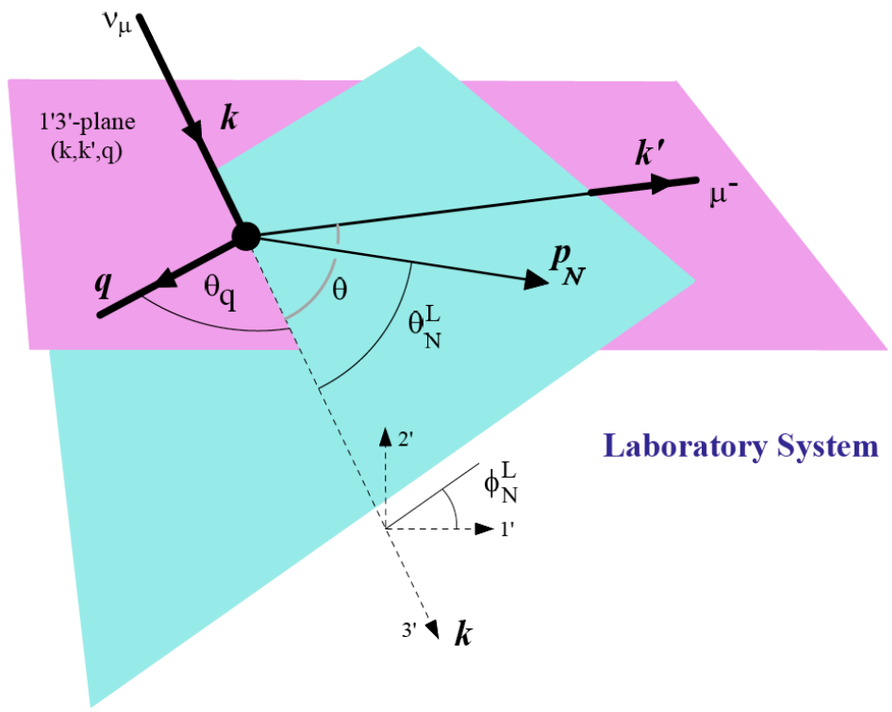
Fully inclusive reactions



- 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 $(k; q, \omega; p, \mathcal{E})$:

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

Donnelly, Trento 2018

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New models

- New models based on some version of **Mean Field approximations** are appearing.
  - Probably the best Impulse Approximation we could have.
- The new models include most of the **nuclear effects in a more realistic potential.**
- These models agree on a small contribution from the long range correlations (RPA and CRPA) which effects are absorbed in the nucleus potential treatment.

Close relation to experimentalists, so the developments are integrated in the MC much faster.

Be careful with model merging.

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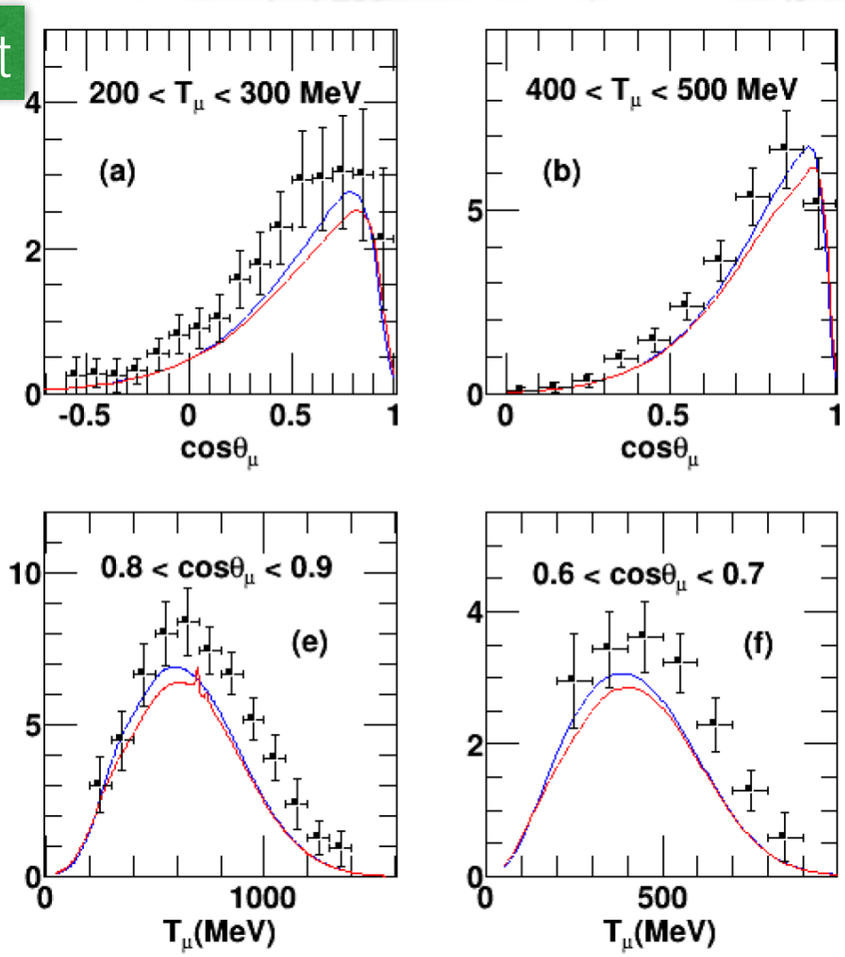
Long range correlations

- 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.

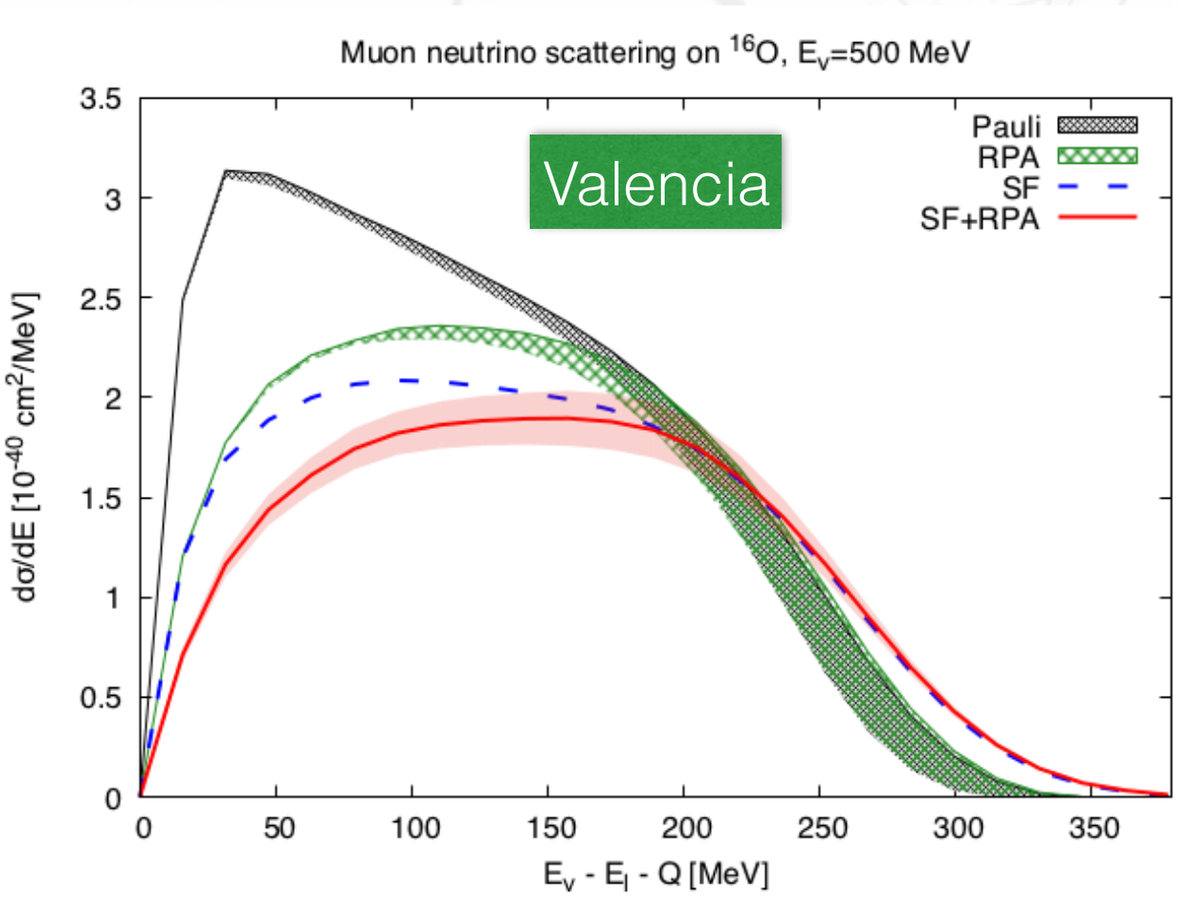
It is worth to ask yourself if your model is consistent and compare with other approaches.

Ghent



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

Valencia



Phys.Rev. C99 (2019) no.1, 014610

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

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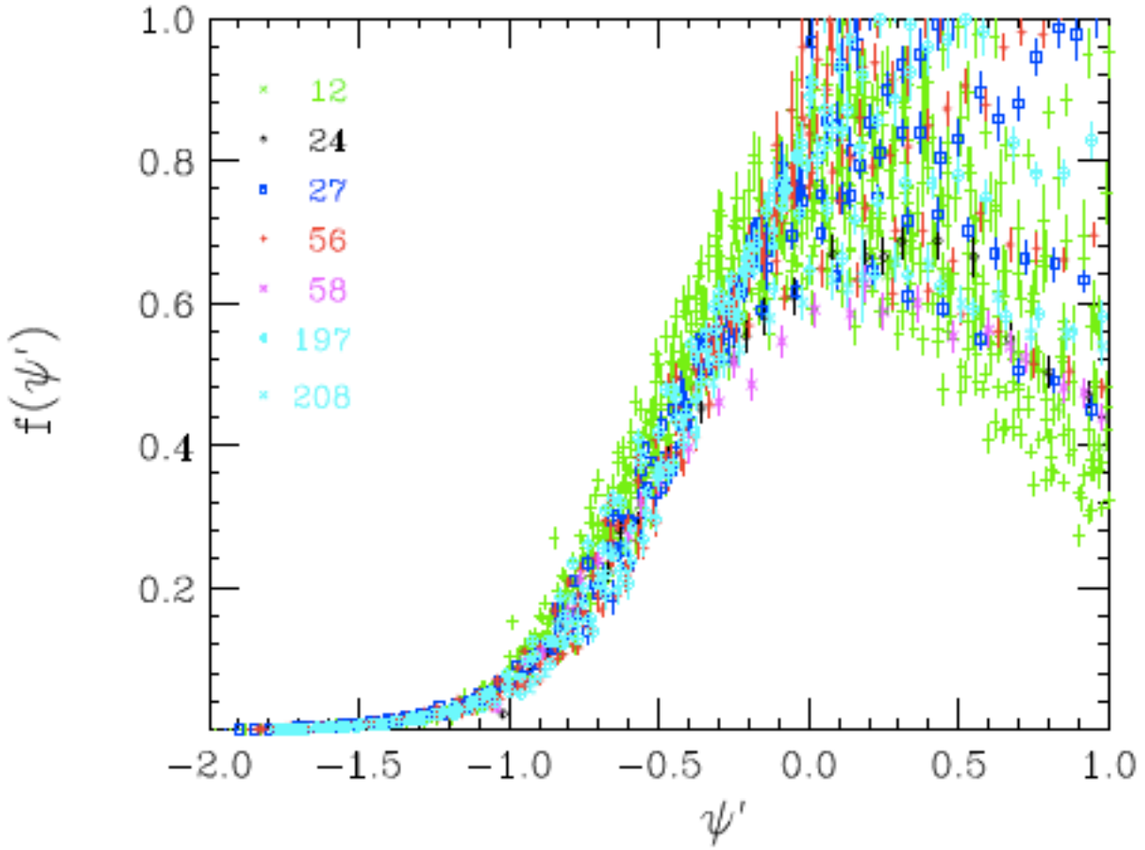
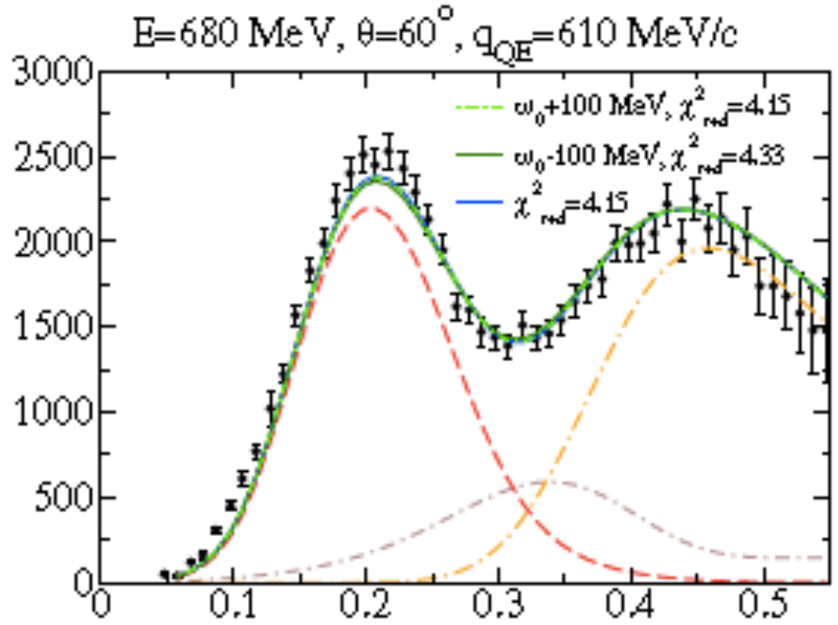
Susa model

Phys.Rev. D97 (2018) no.11, 116006





- 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.

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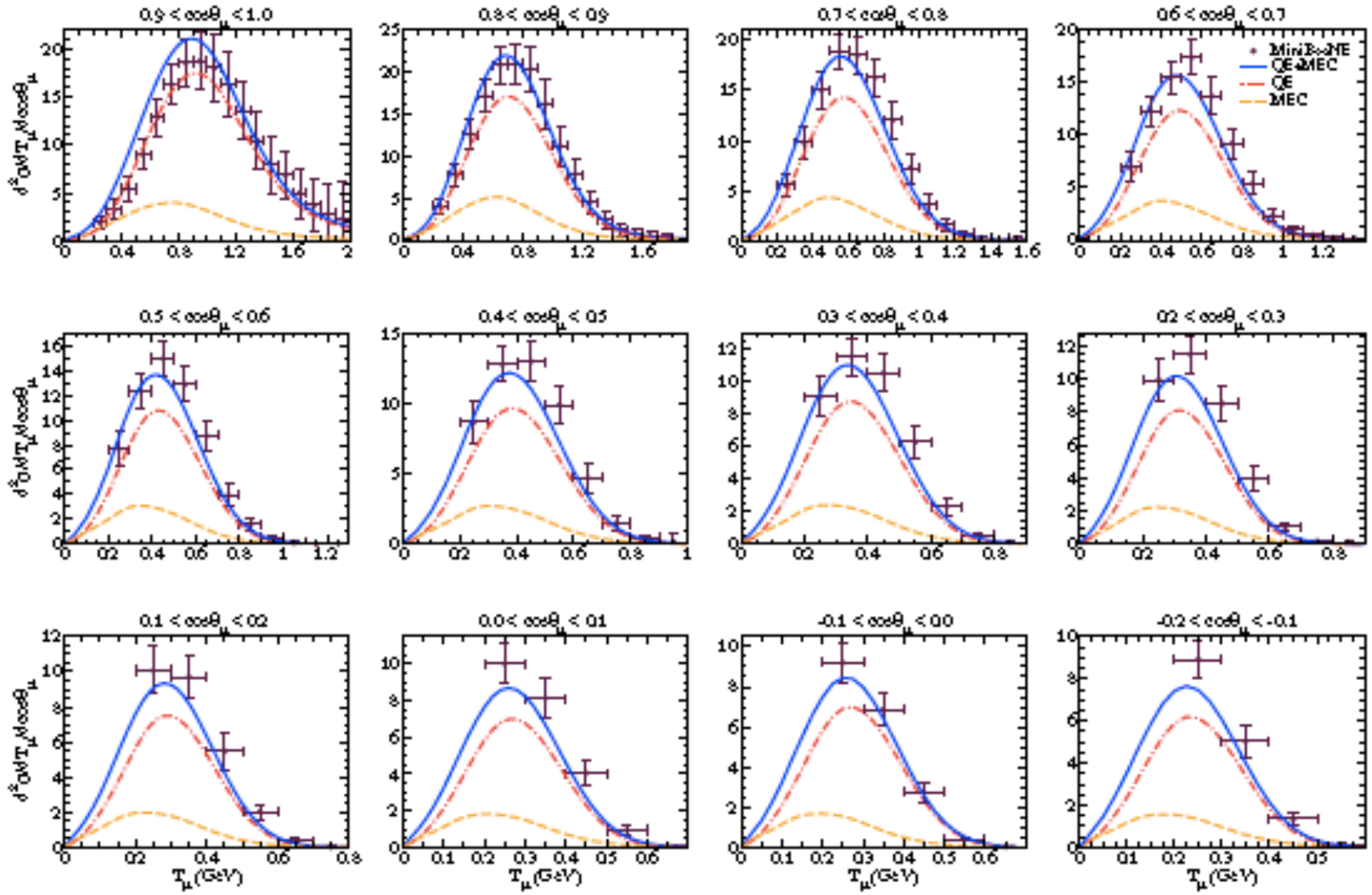
SusaV2 and Mean Field

- 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

The model also superscales!!!



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2body (2p2h) 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.
  - New recalculation of Valencia model on its way.
- 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.

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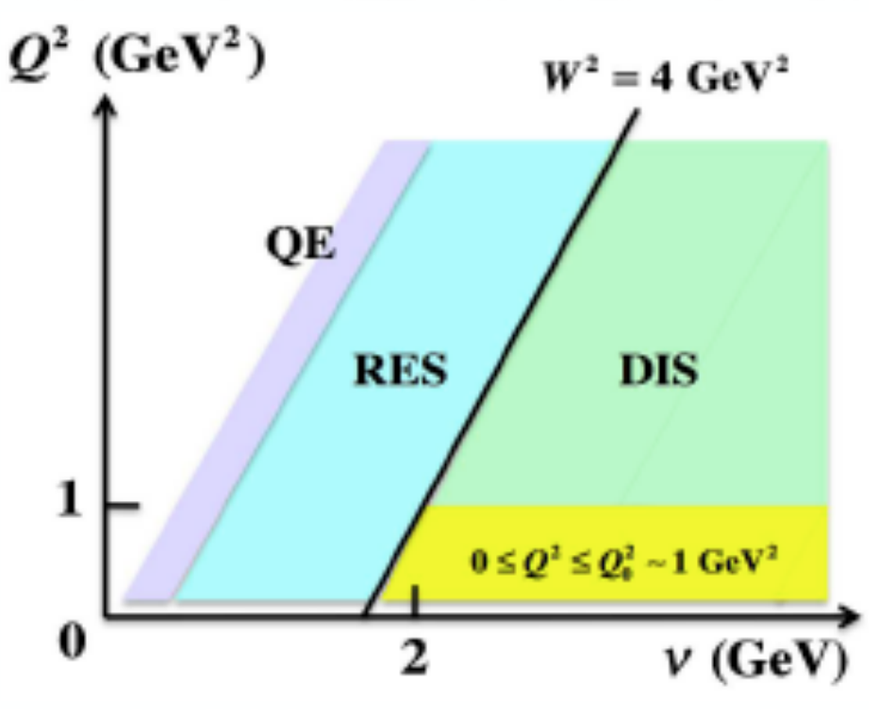
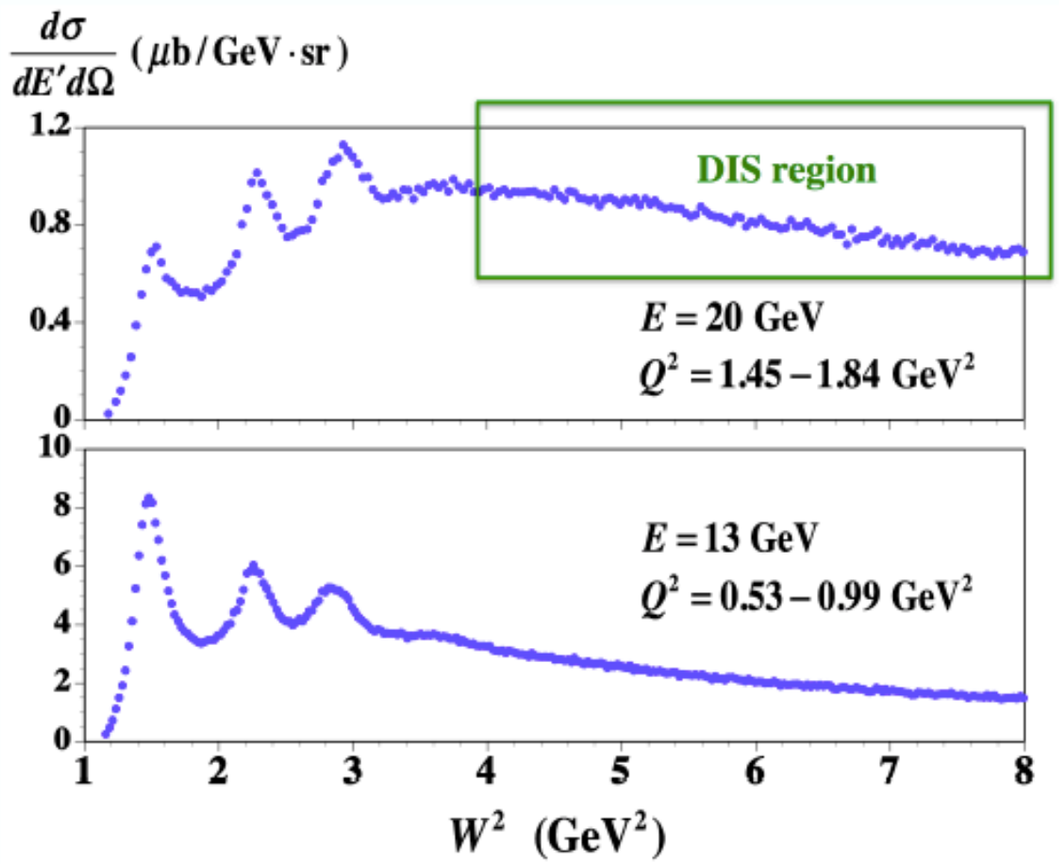
π production

- 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.





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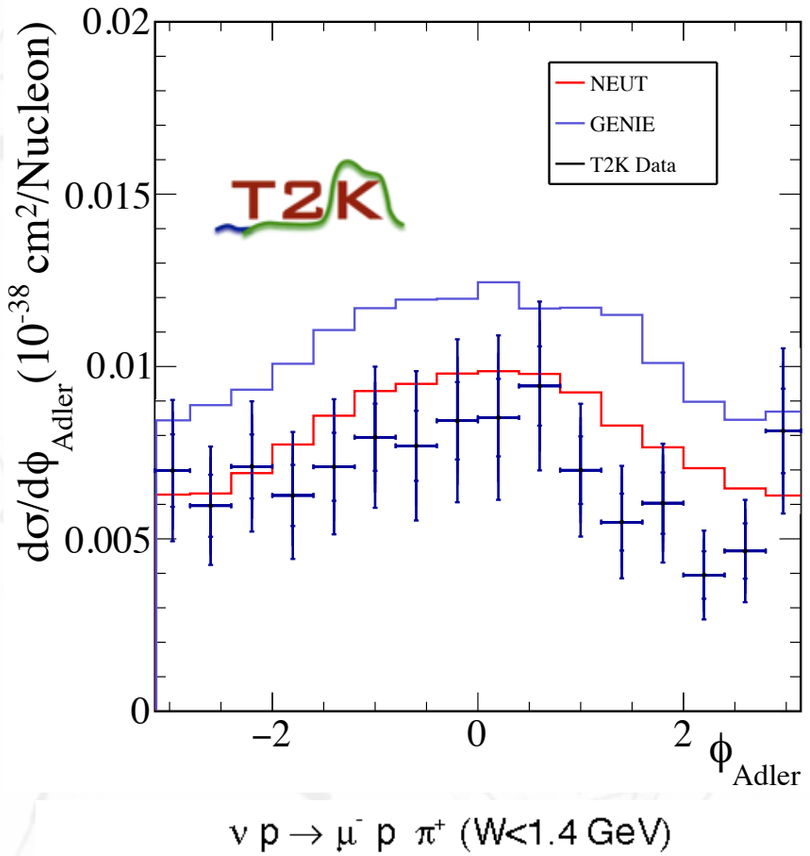
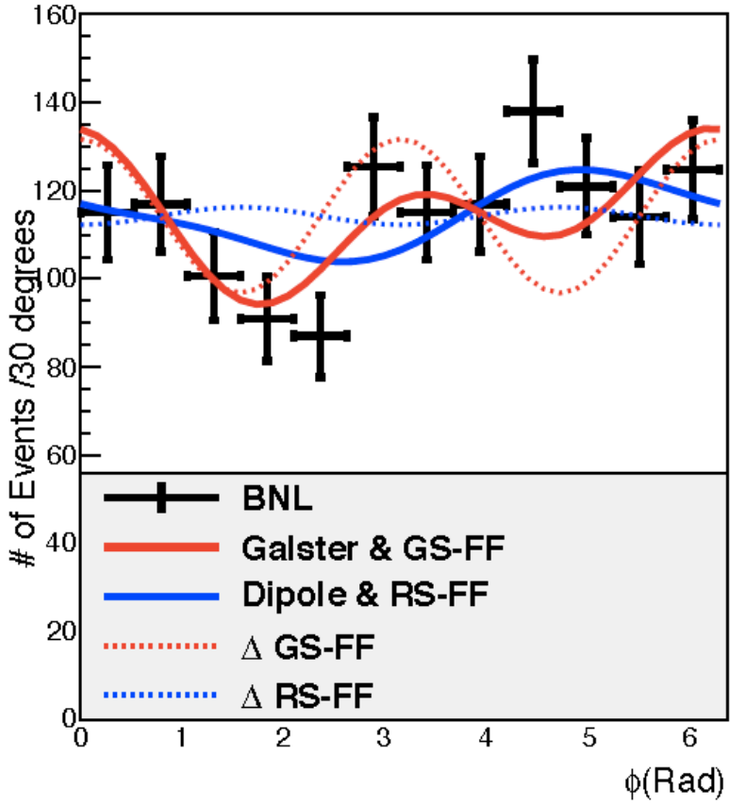
π production

- 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).



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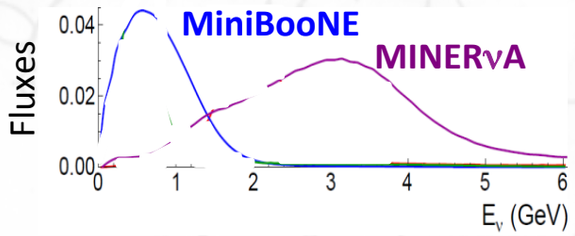
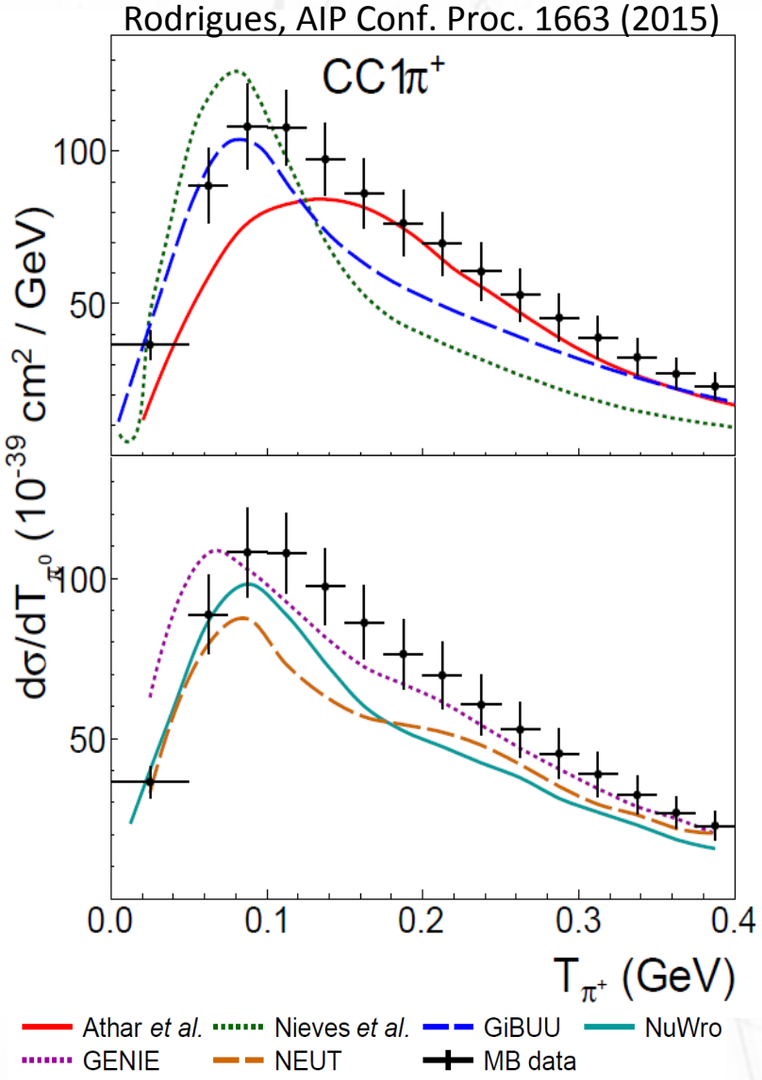
The pion puzzle

Few words on other channels: I) The CC1π puzzle



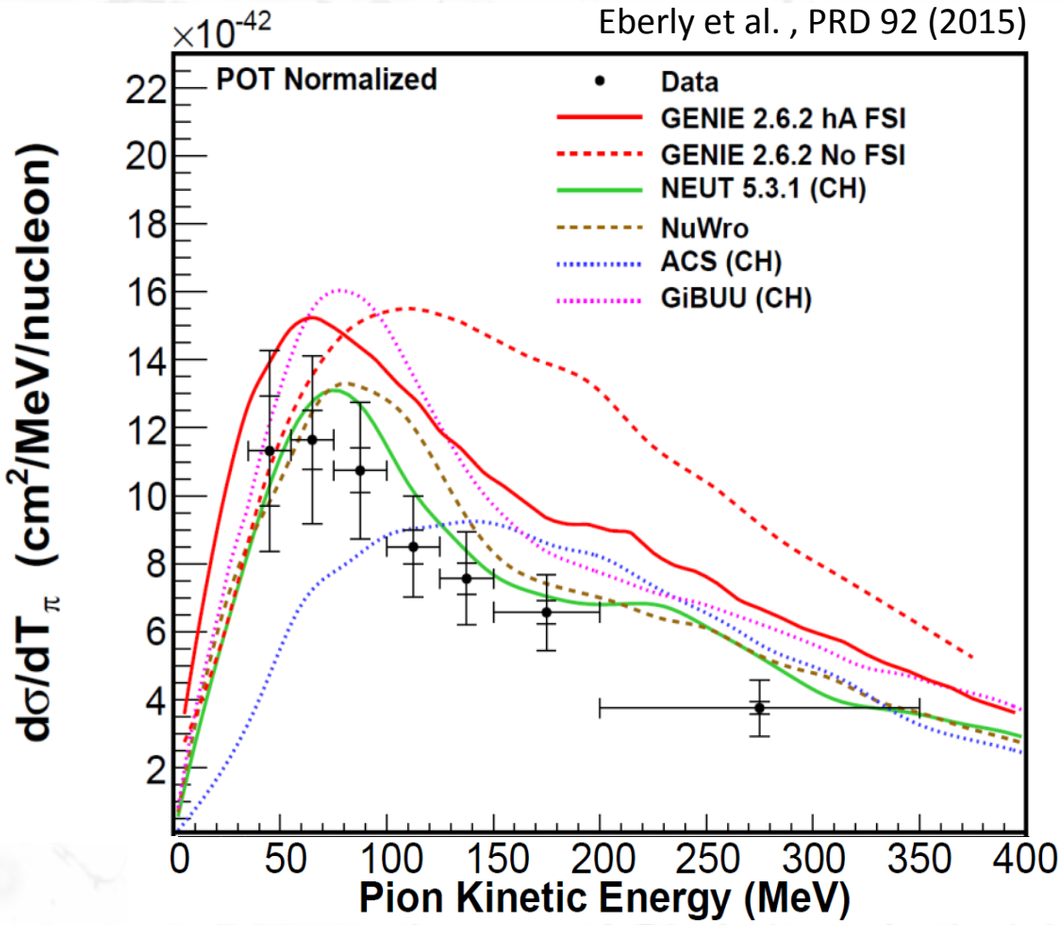
MiniBooNE

Rodrigues, AIP Conf. Proc. 1663 (2015)



MINERνA

Eberly et al. , PRD 92 (2015)



The pion puzzle
is an open question

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

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π production

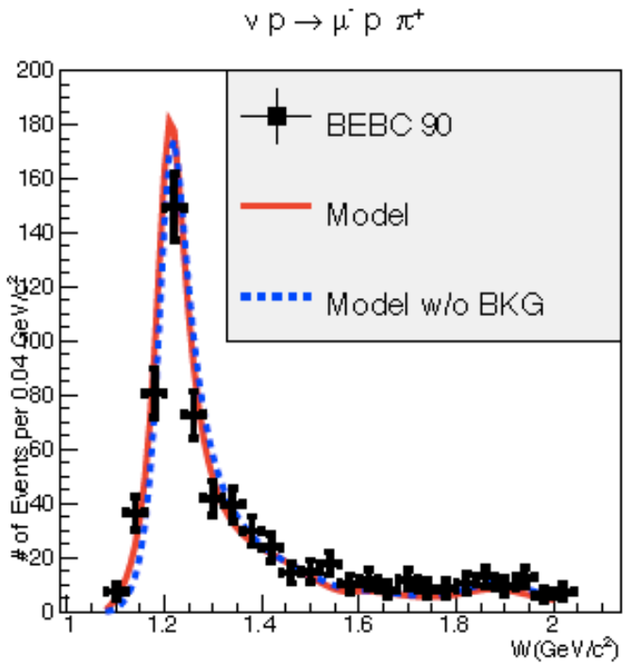
Phys.Rev. D97 (2018) no.1, 013002

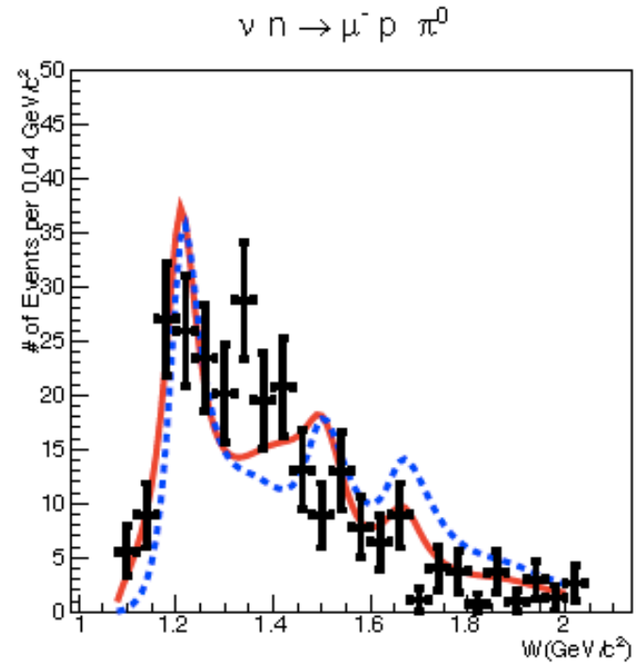
Model implemente in MC

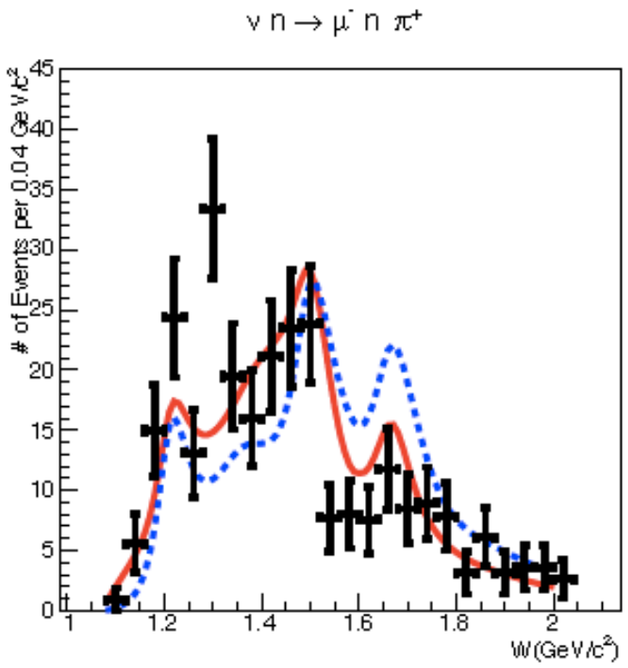
- This model is being implemented in the MC:
  - FSI is immediately provided by cascade models.
- Big improvement wrt previous models

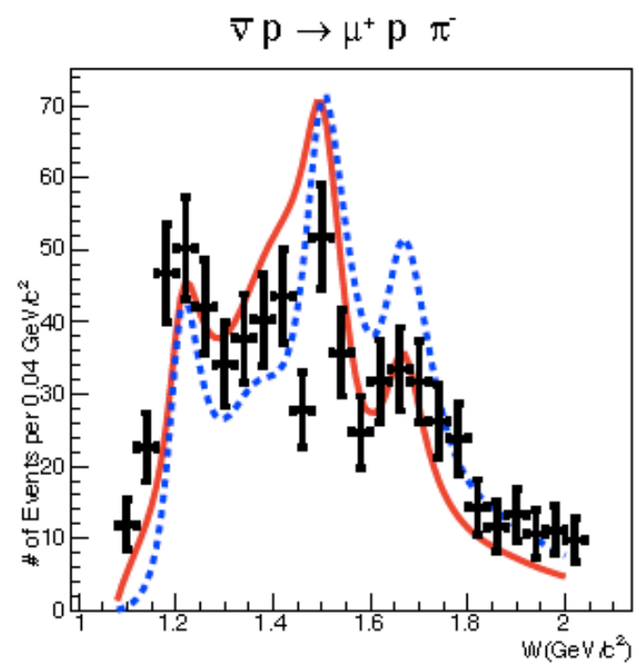
TABLE I. Nucleon-resonances below $2GeV/c^2$

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 helicity base

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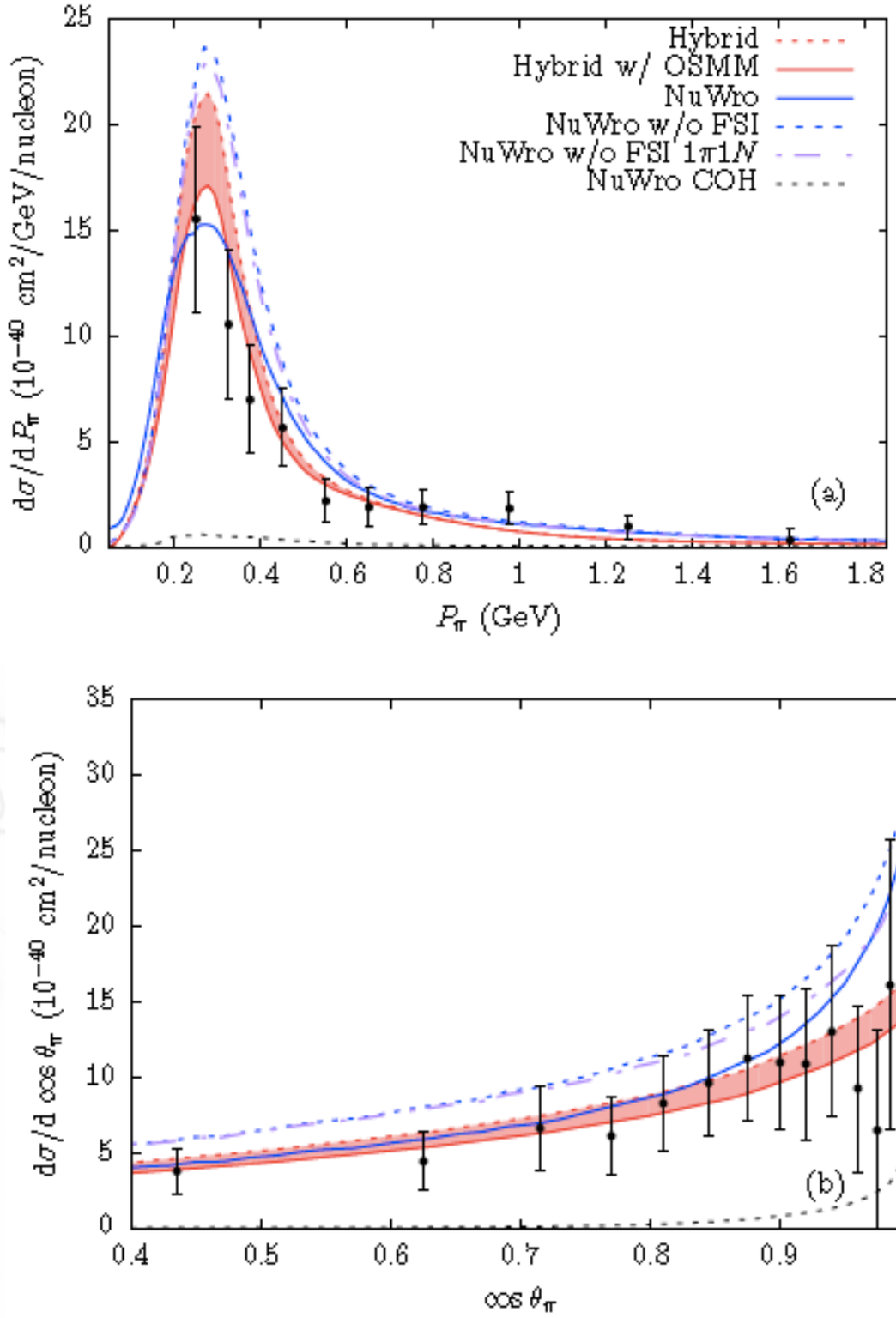
π production

- 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



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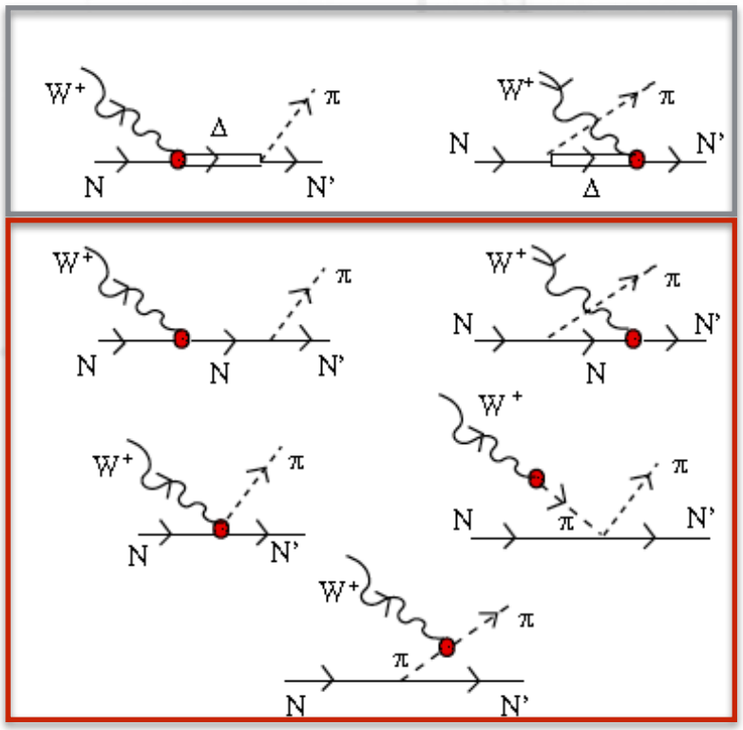
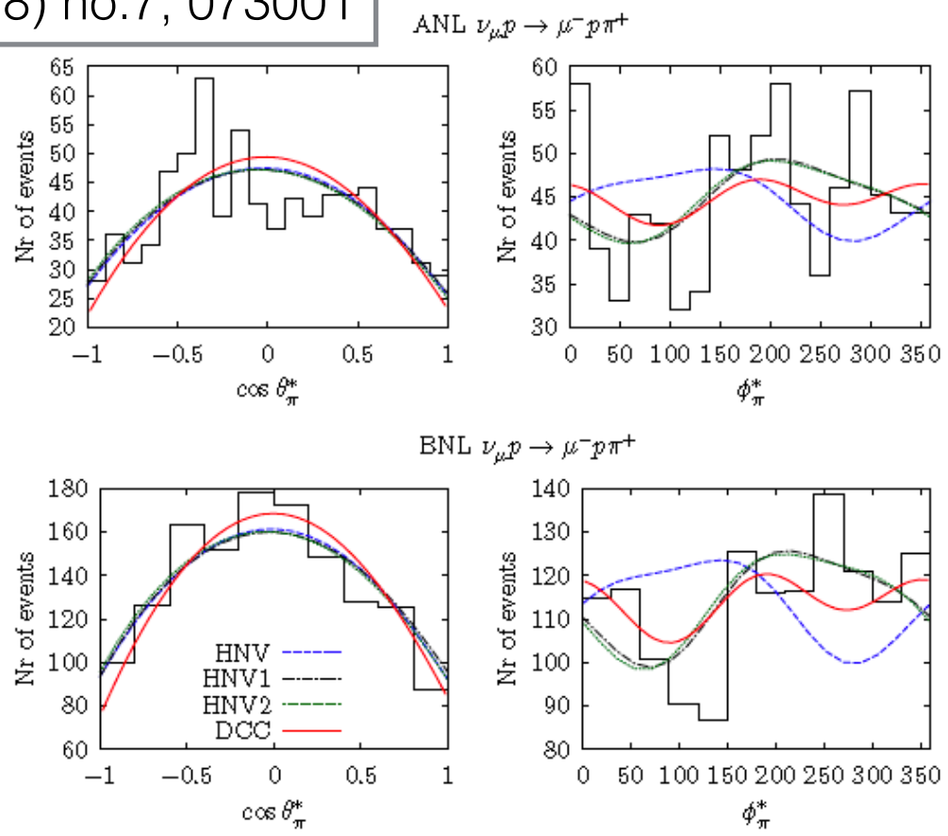
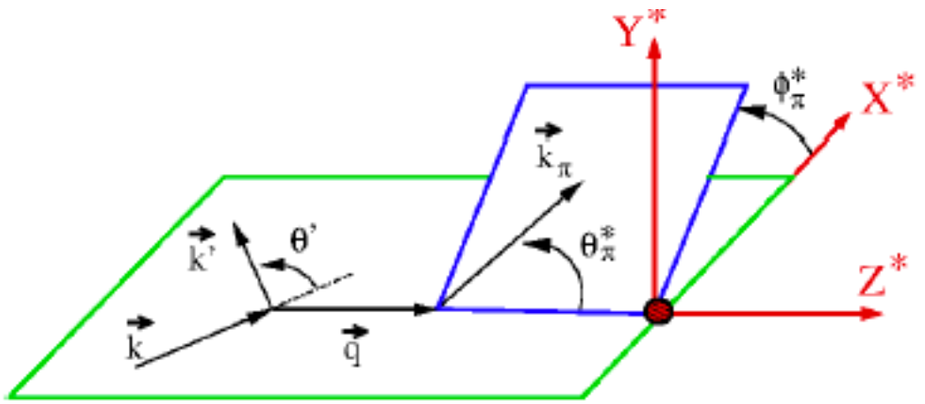
π production

Improved Valencia model with full event kinematics

Phys.Rev. D98 (2018) no.7, 073001







relevant P and T violating contributions from the interference of prompt and resonance pion productions. Information about the microscopy level interactions.

Some of the developments already included in 2p2h Δ mediated interactions.

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Transition region

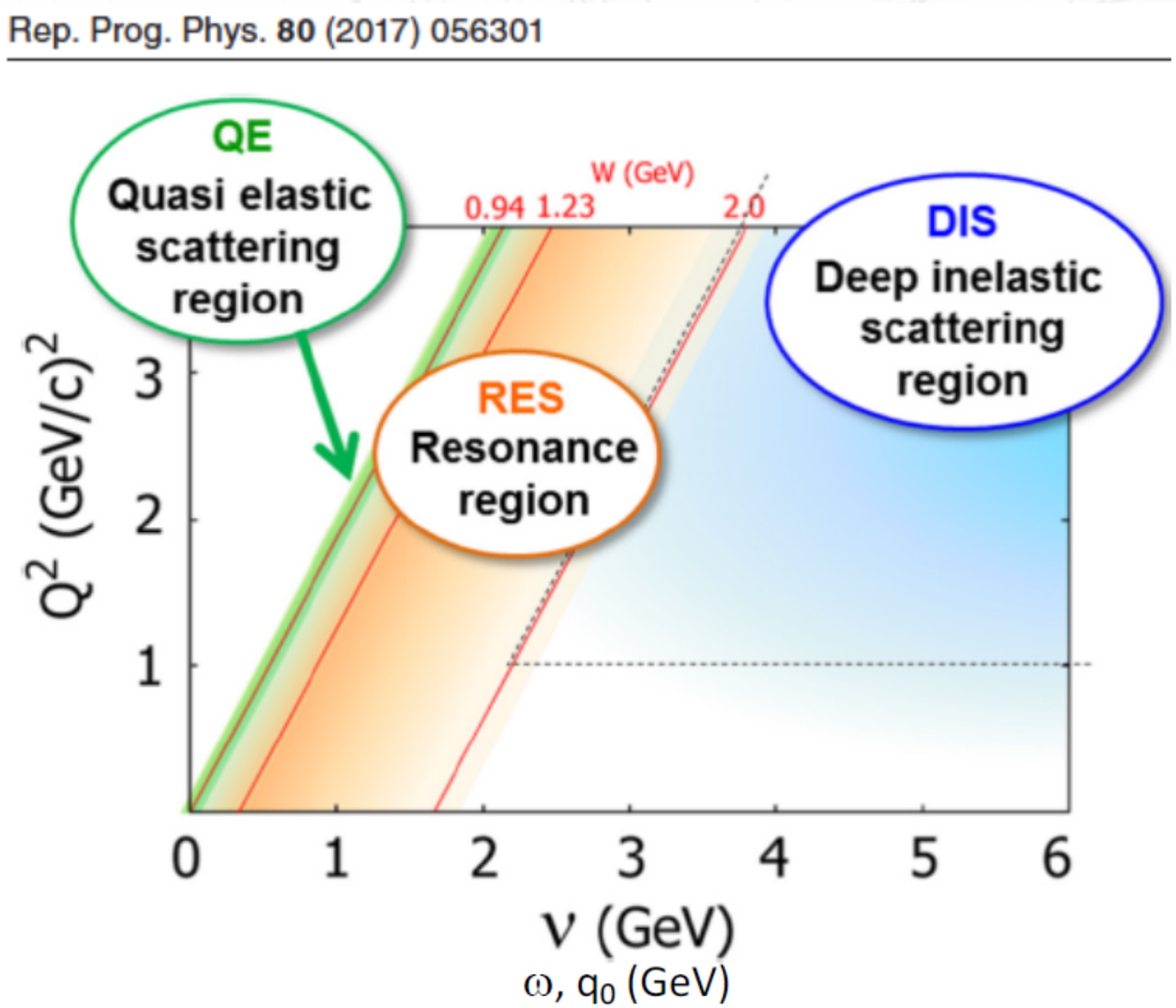

Figure 1. Kinematical regions of the neutrino-nucleus interaction relevant to the next-generation neutrino-oscillation experiments. The energy transfer to a nucleus and the squared four-momentum transfer are denoted by ν and Q^2, respectively.

- 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.

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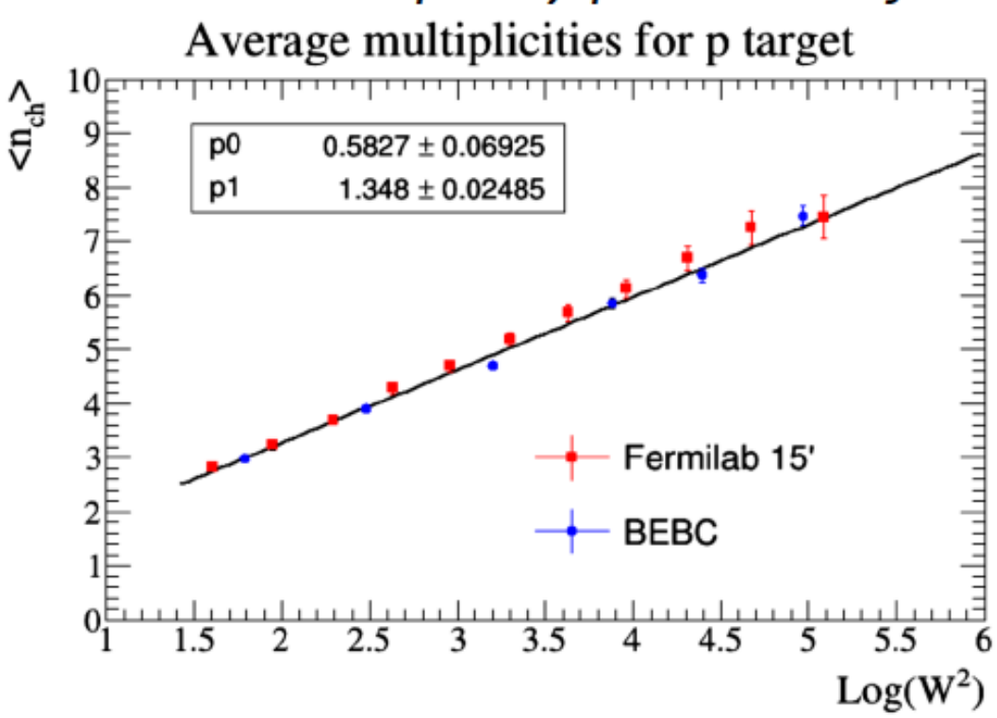
For example…

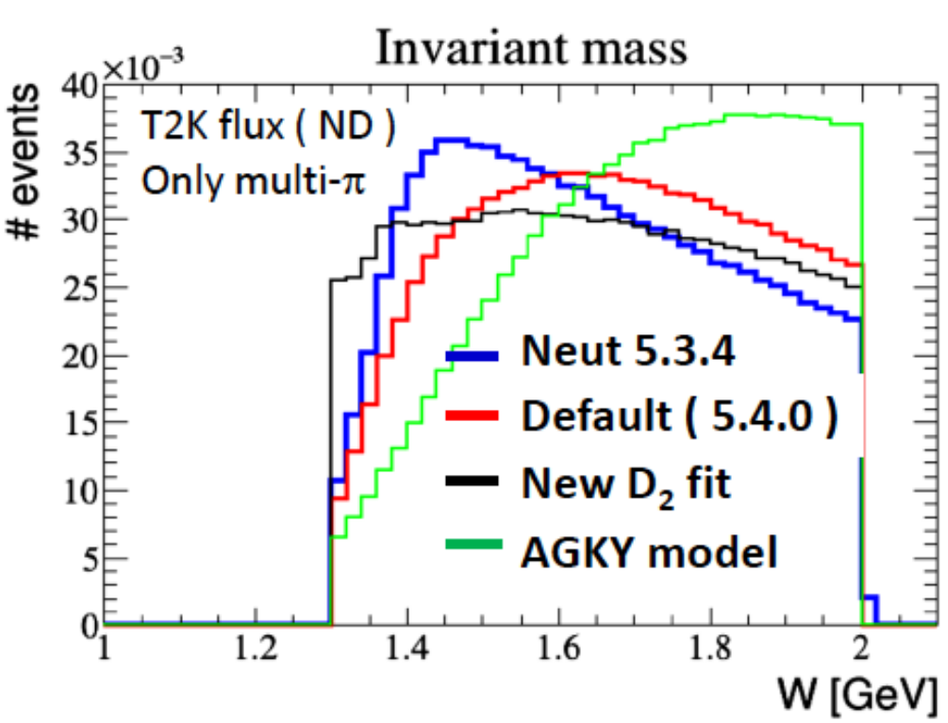
Multi-pion production & DIS improvements in Neut

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]





Can we do it better ?

Critical for high energy (Dune) experiments

ν_e/ν_μ

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

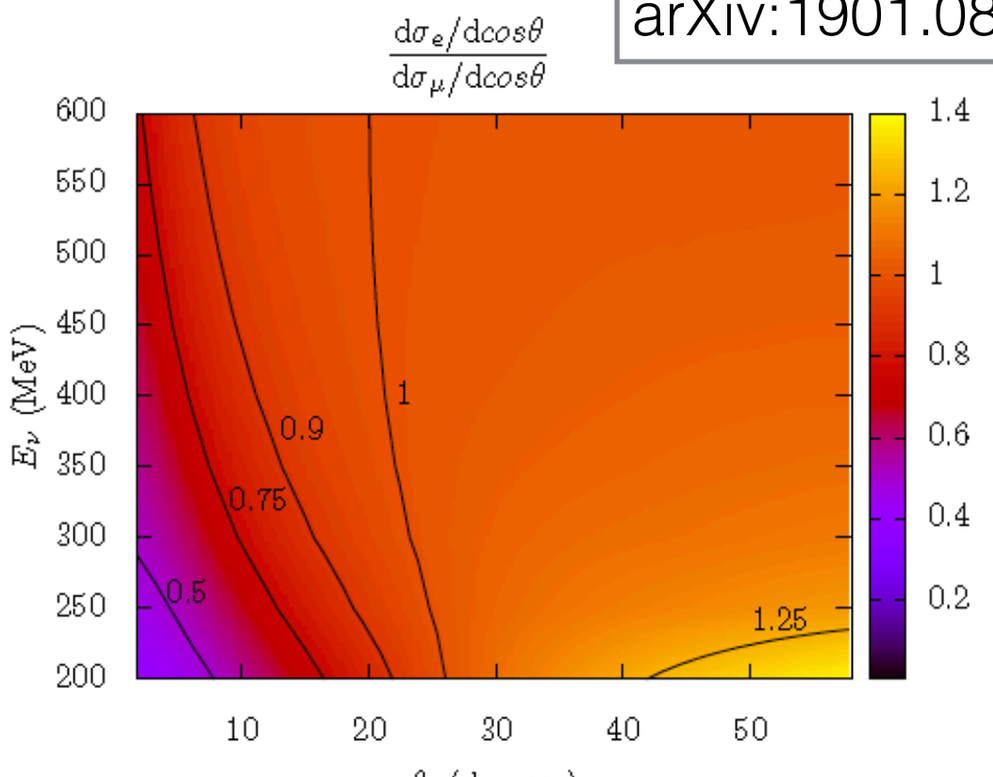
- The low neutrino mass makes the interaction sensitive to a different **nucleus region of (q_3,q_0)**

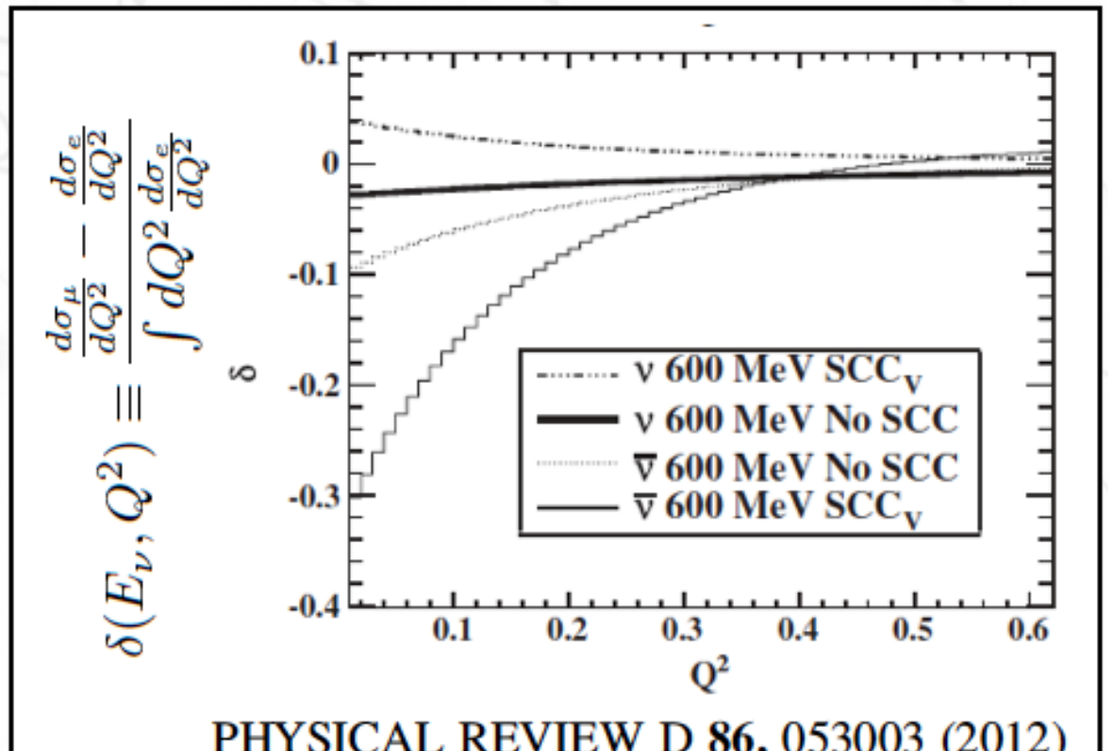
- These corrections will **alter the cross-section and the energy reconstruction** depending on the detector technology.

- **Only one prediction** was available until recently.

Something similar will happen to ν_τ being relevant for DUNE and atmospheric neutrinos.

arXiv:1901.08050





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

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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 generators to run on eA data**.
    - We have to **factorise the model in vA and e,eA** to determine what we are actually testing.
  - 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.

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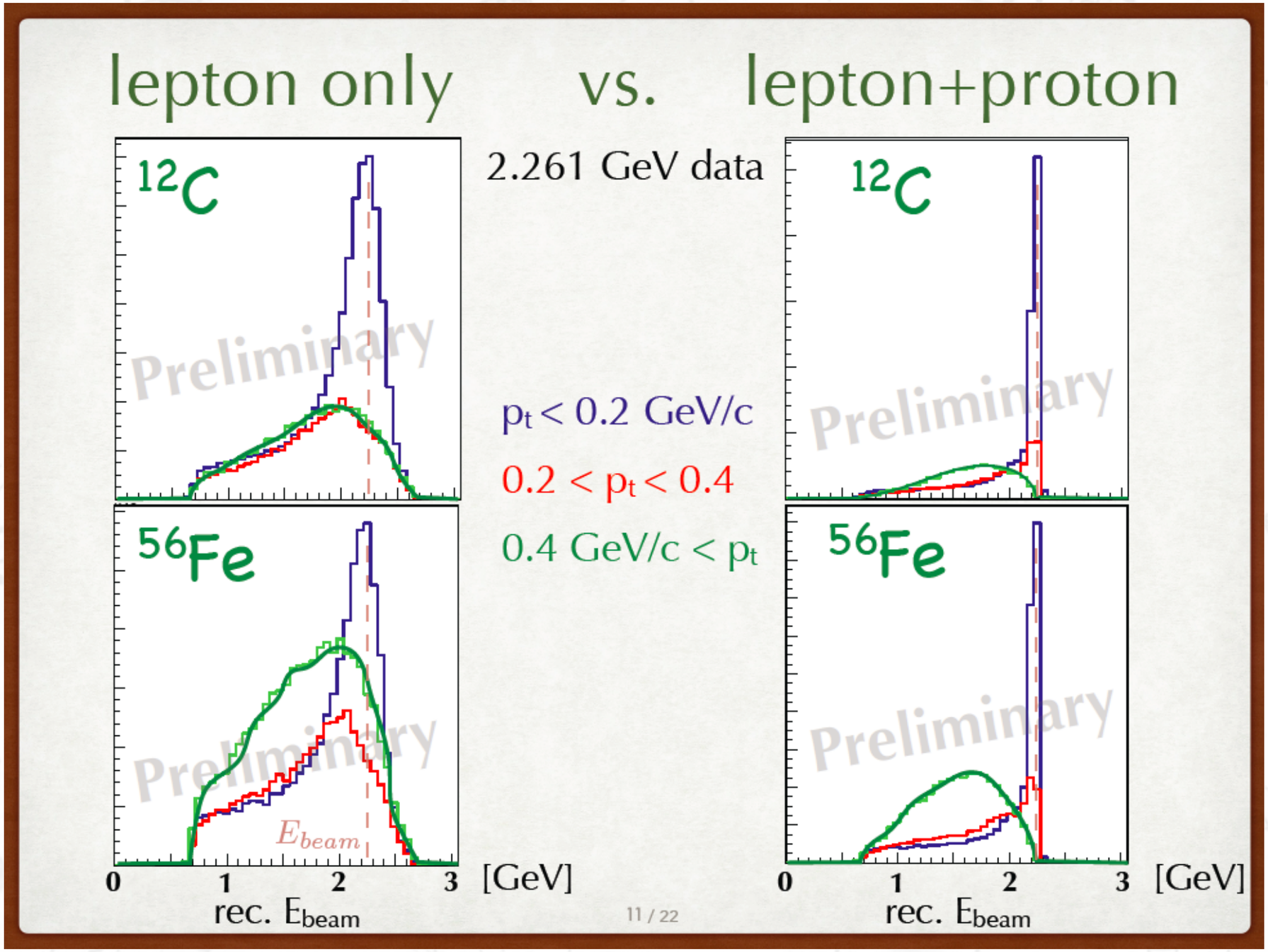
New ideas!



Mimic neutrino energy reconstruction in (e,e')

Erez O.Cohen

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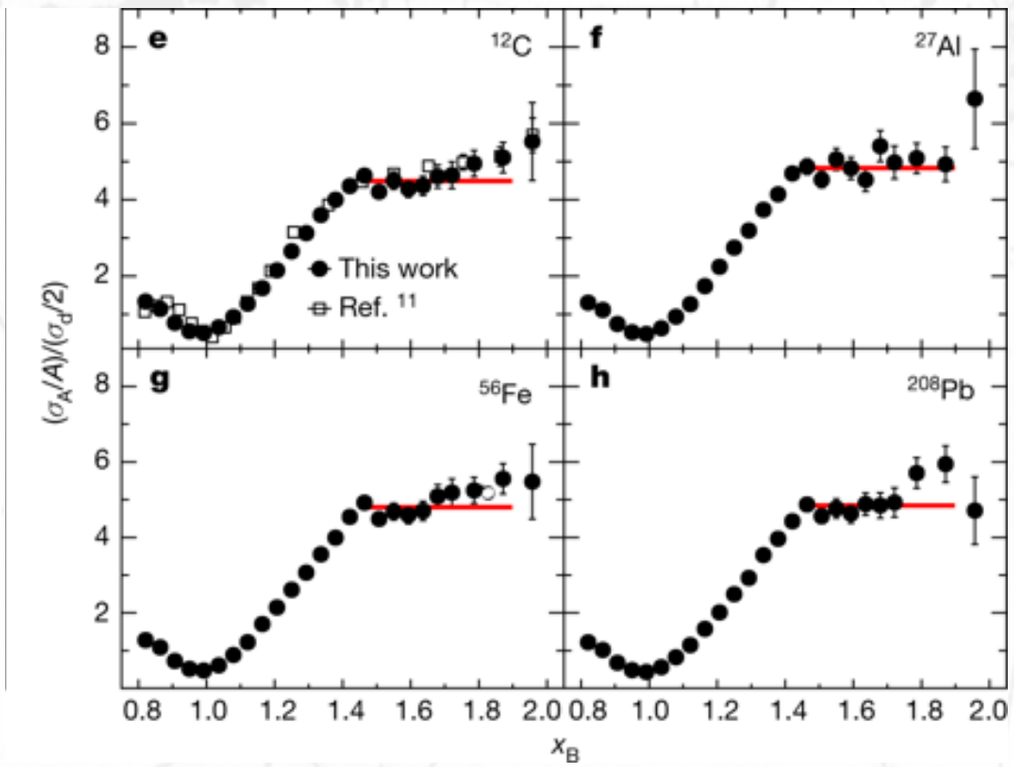
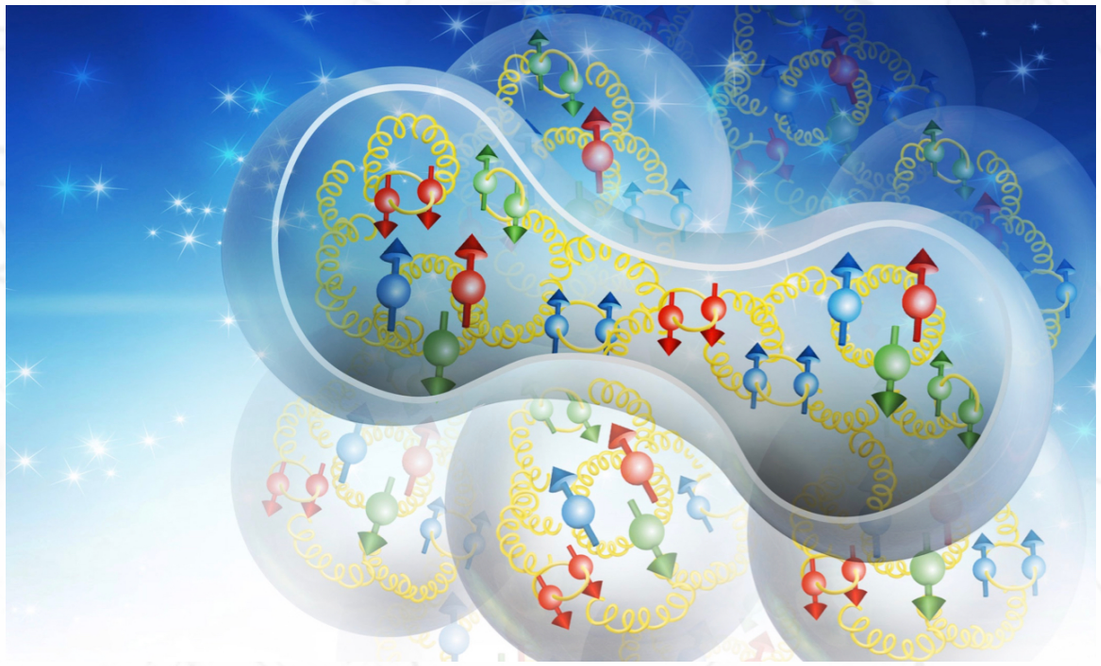
Initial state correlations

Nature volume 566, pages 354–358 (2019)

- Recent publication shows a correlation between the initial state pairs in a nuclei and the so called “EMC” effect (quenching of cross-section @ heavy nuclei).

- The paper suggest the modification of the proton and neutron form factors in nuclear media.





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Conclusions

- The **community is growing rapidly** both from the theory and the experimental part thanks to the boost given by Dune activities.
  - **Young and skilful members.**
  - But, this topic falls in the interface between particle and nuclear physics and none of the communities is willing to provide positions to **stabilise the community.**
- **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 in a much faster manner. Strong theory-experiment collaborations.
- **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.

Conclusions

- Many **new observables:** transverse variables, available energy, Adler angles, etc…
  - They improve our knowledge of the models.
  - They require a more detailed description of the final state kinematics moving from semi-exclusive to exclusive cross-sections (Technical difficulties)

- Looking into our brother field of **electron scattering:**
  - Learning from their models.
  - Challenging our models with their “more precise” data.
  - We might start joining their research interest very soon.

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

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Backups

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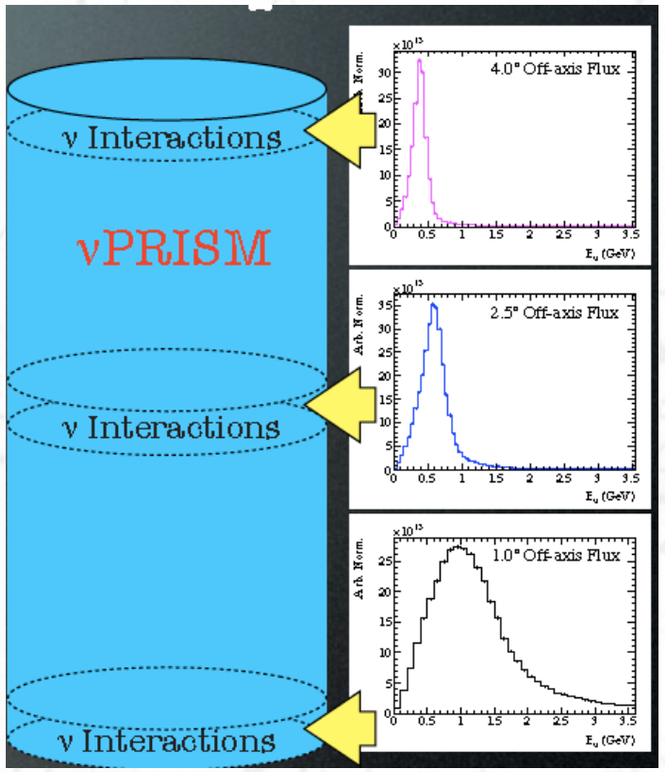
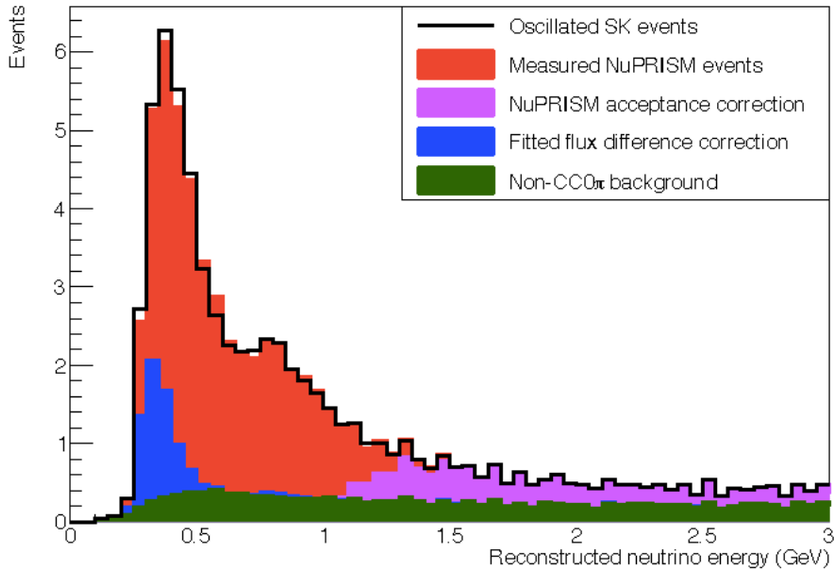
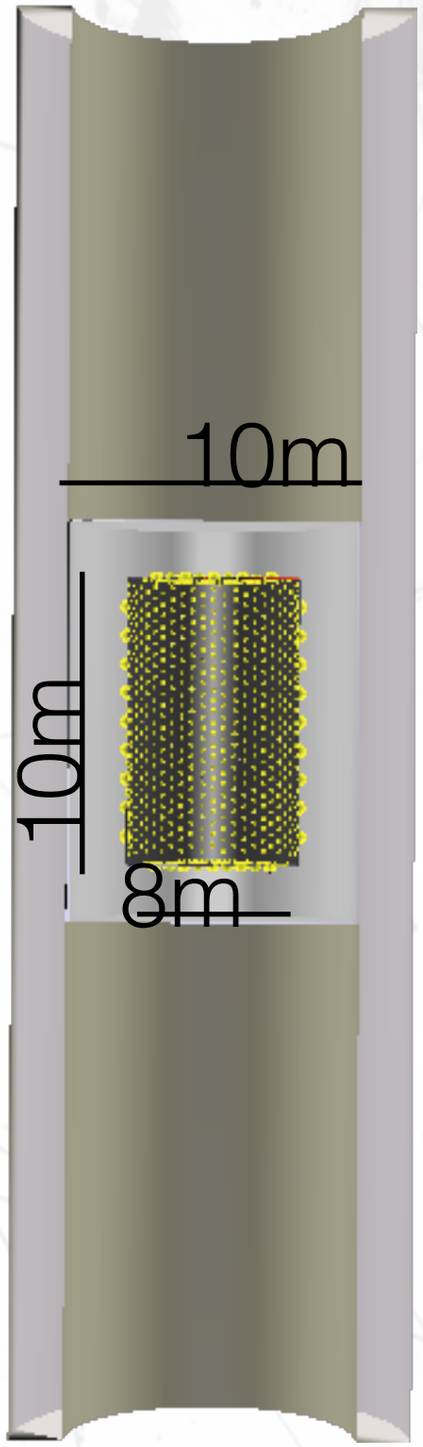
NuPrism

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.

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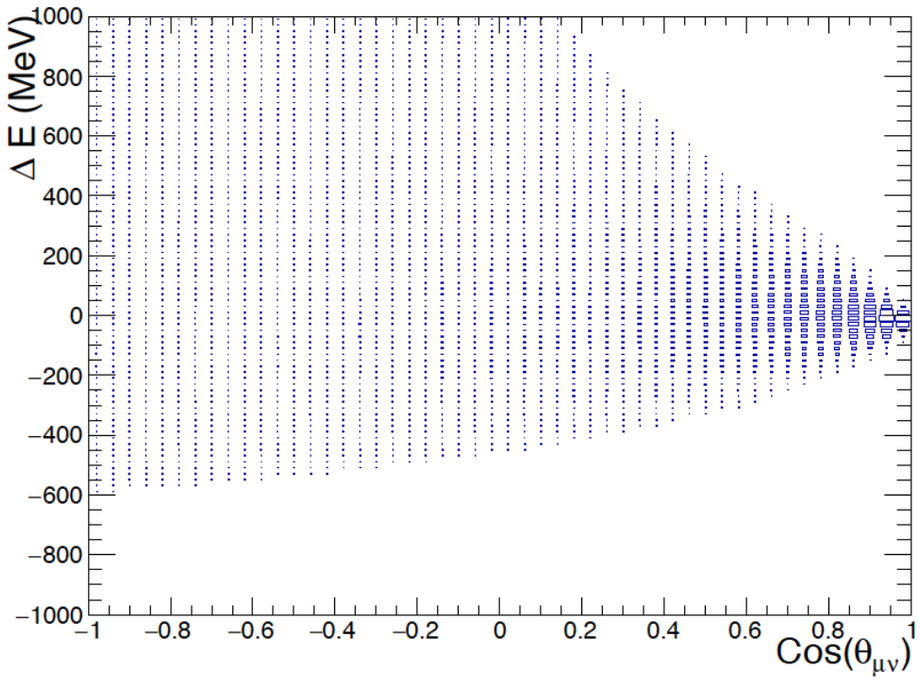
Energy reconstruction

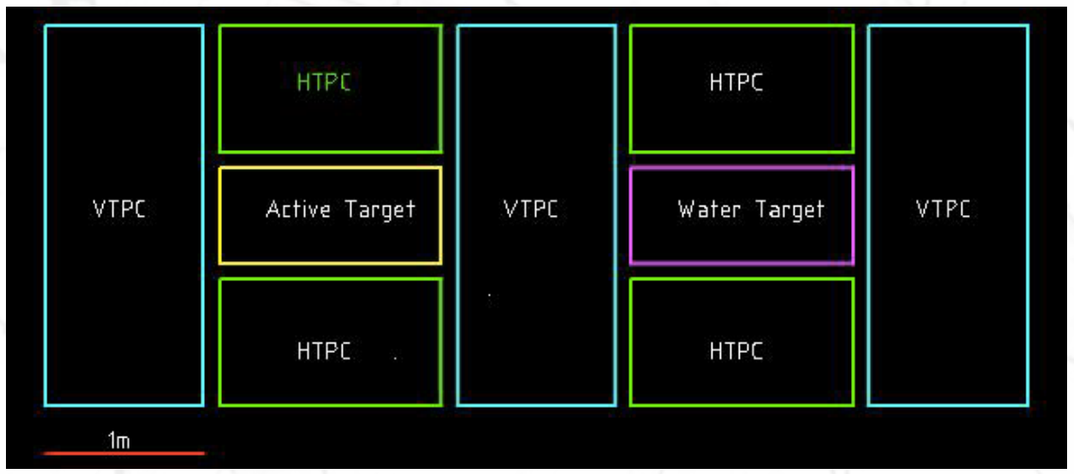
- Nuclear effects are very relevant to the Energy reconstruction.

- How can we calibrate the energy?

- One option is to explore the dependencies to look for systematic dependencies:

  - 4π detector acceptance might help.





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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.

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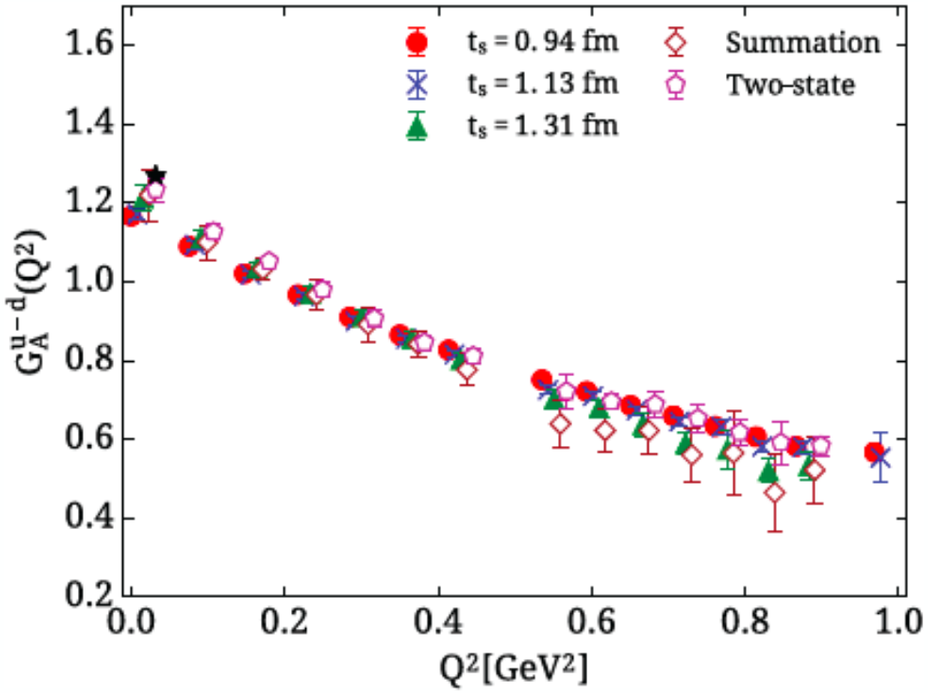
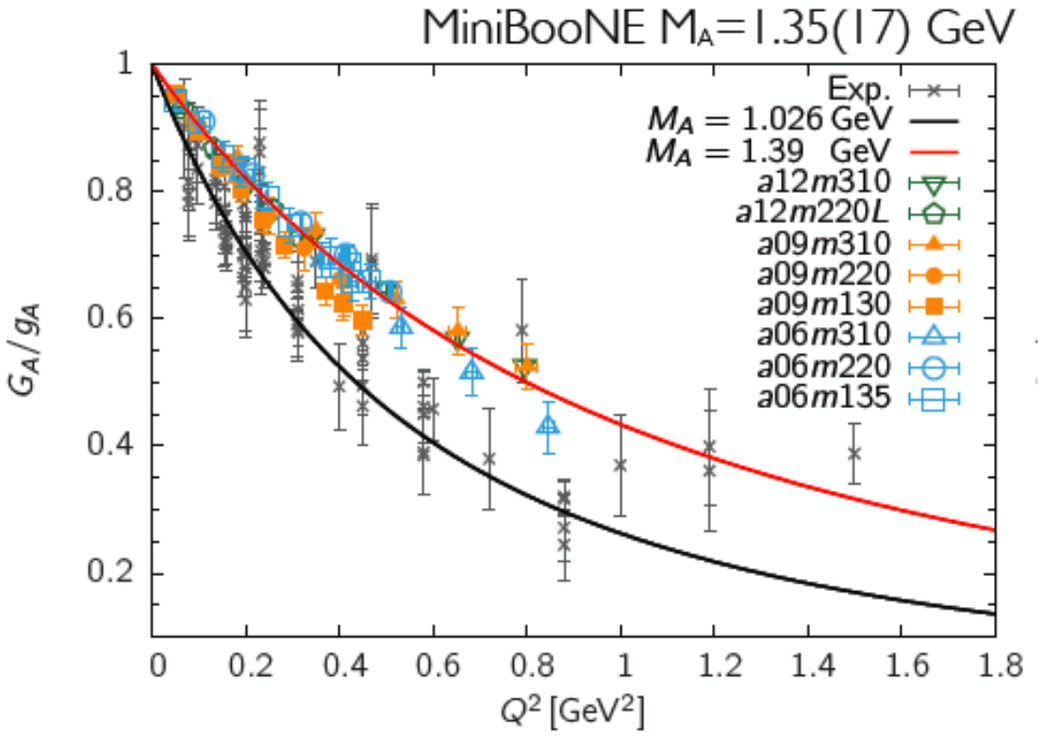
Axial-Vector FF in the lattice

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



Gupta et al., arXiv:1705.06834

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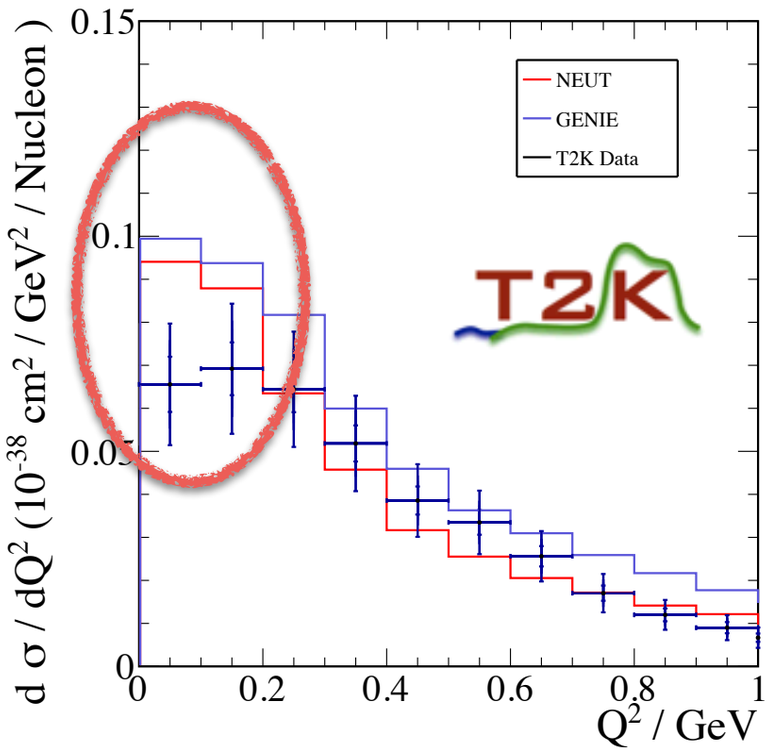
Long Range Correlations

- 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!

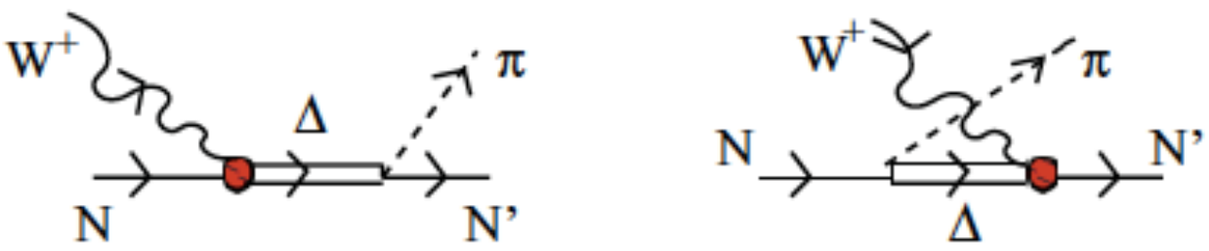
LRC are also different for neutrino and electron scattering

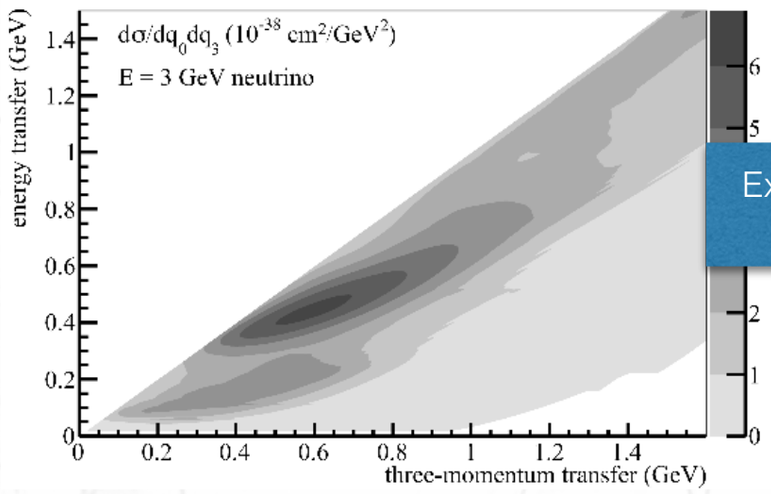
2 body currents in π

- 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.

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.

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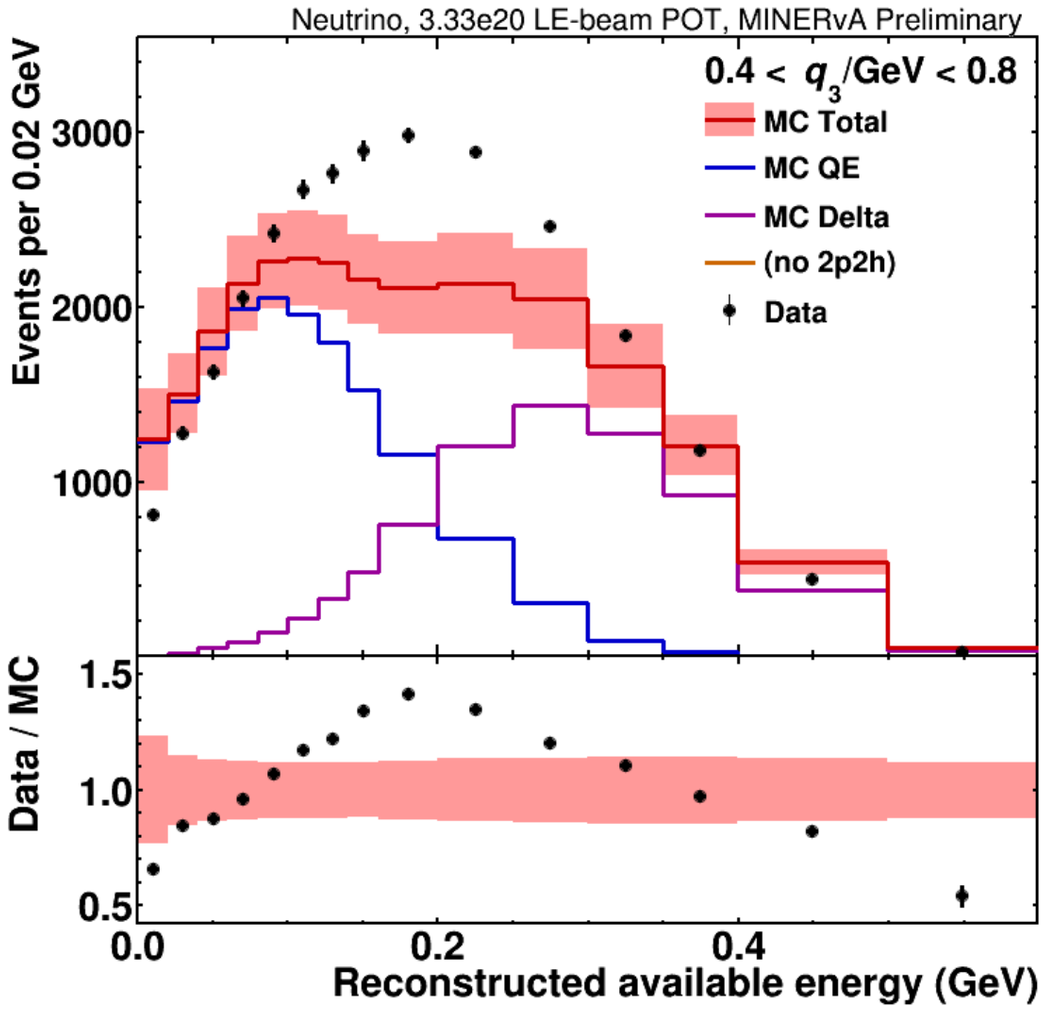
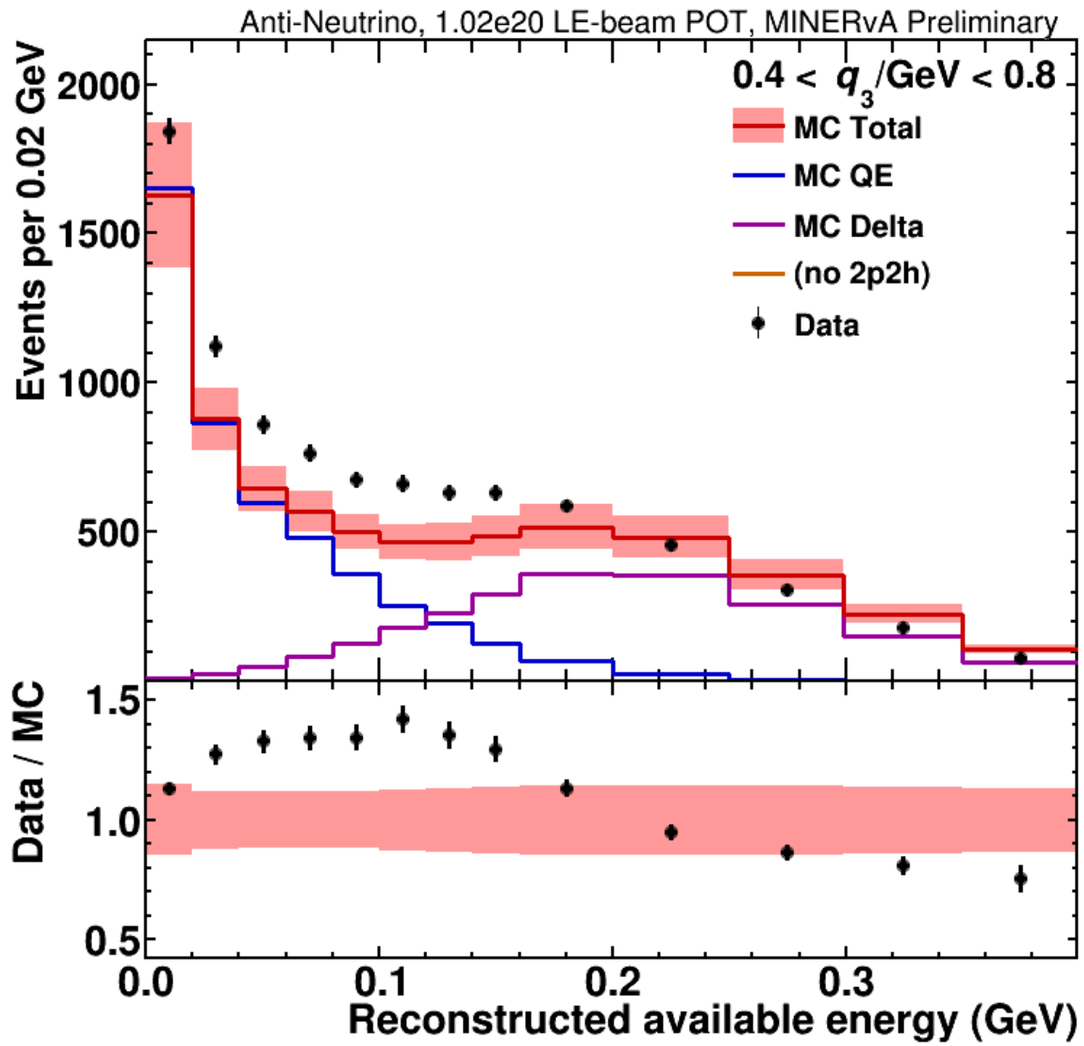
Energy reconstruction





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

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And beyond….

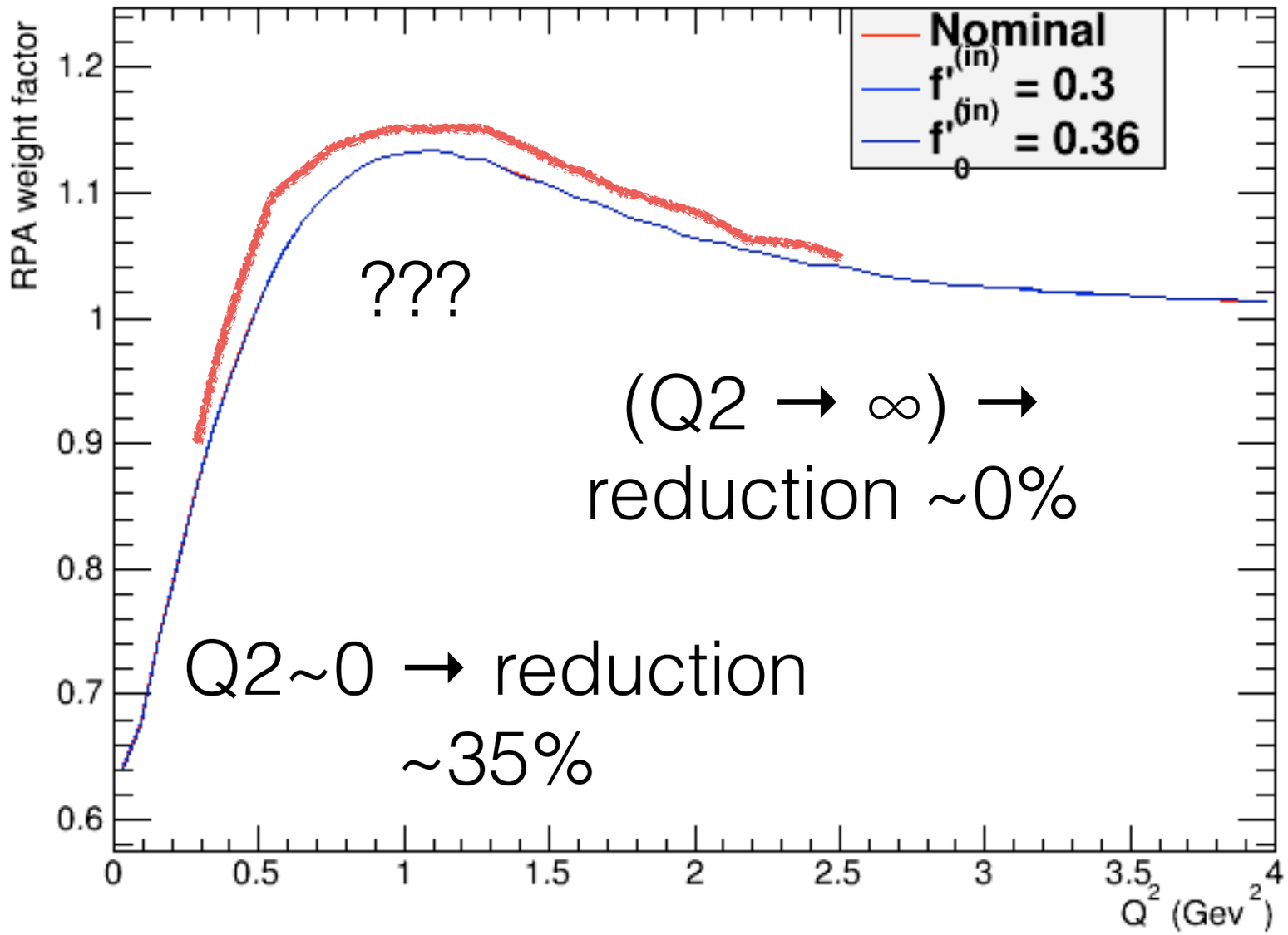
- The region above the Δ has been ignored systematically by theory and recent experiments (except Minerva).

- New generation of experiments will rely on this region to do oscillation physics:

  - Critical for Dune.

- We saw that Neut is revisiting this region.

Example: Long range correlations



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

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

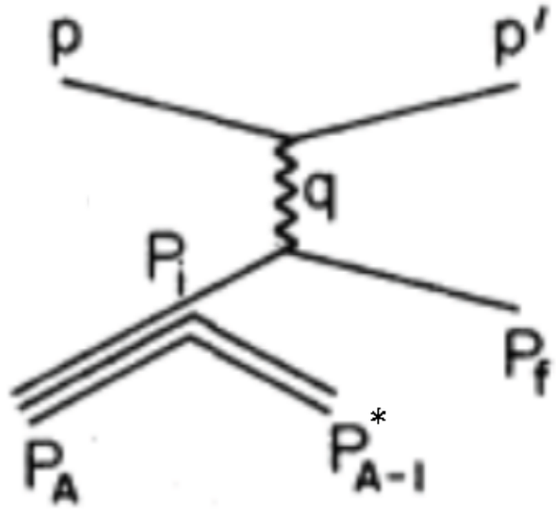
Experiments re-weight cross-section models in a coarse manner More knowledge of free parameters the model will improve the process.

Improve != lower errors

Impulse approximation in kinematics

arXiv:1801.07975

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



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

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

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

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

- 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.

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

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

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

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

Calculations are more complex if consider the FSI

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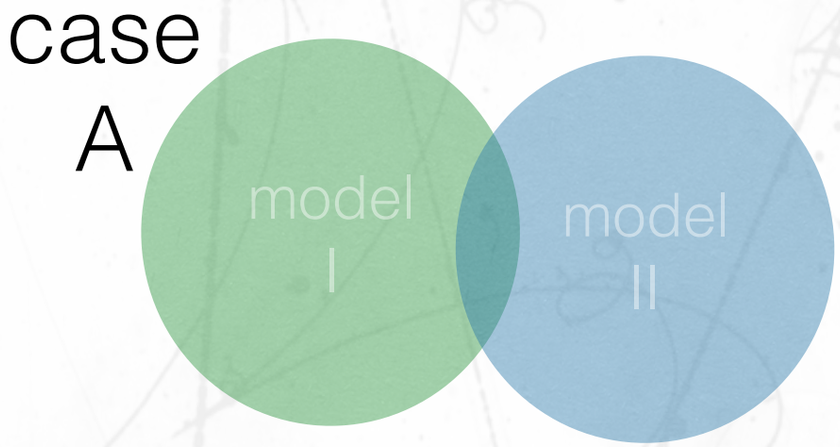
Models overlap



- 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.

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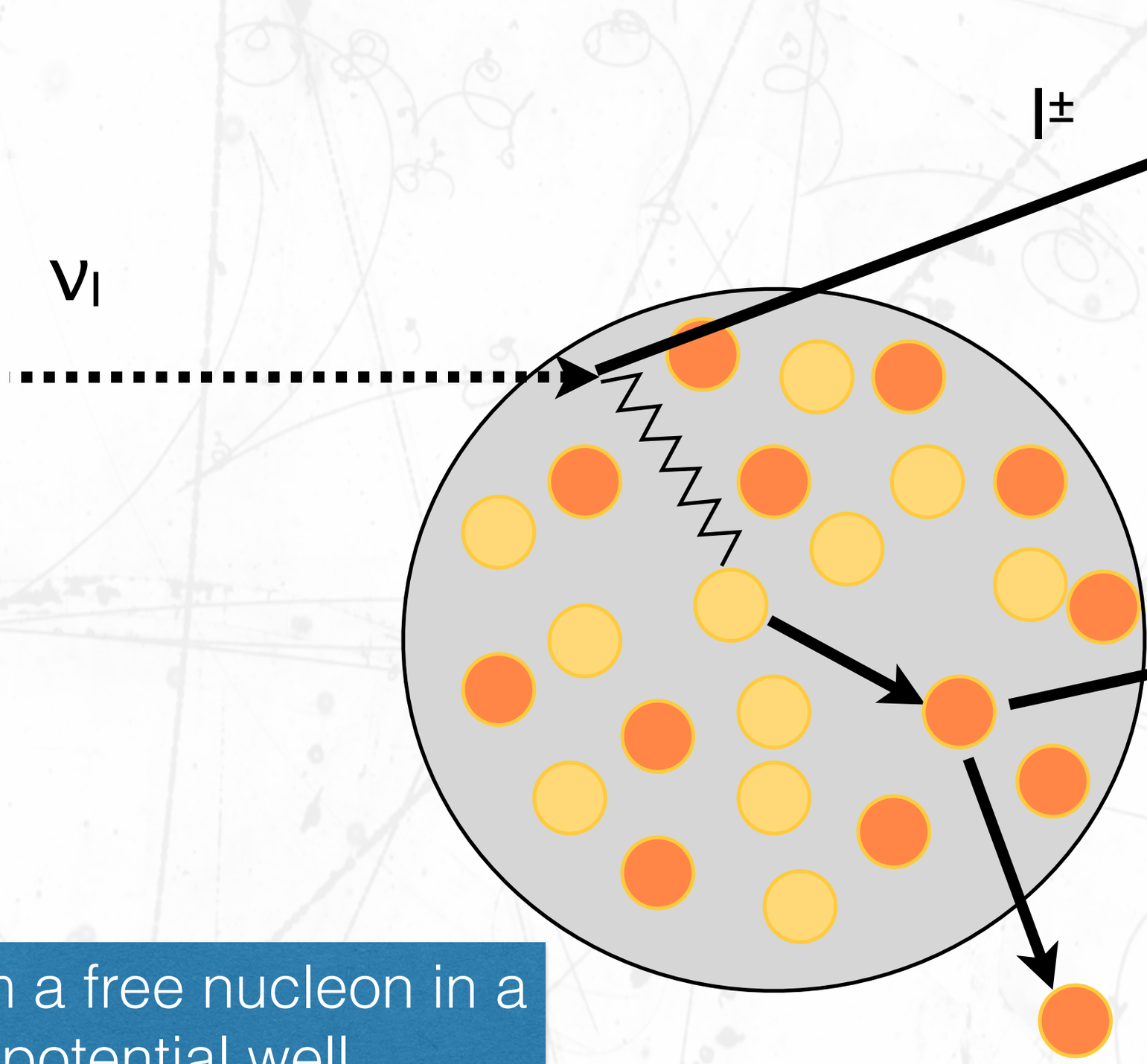
Neutrino interactions



Fermi motion
&
Pauli blocking

FSI

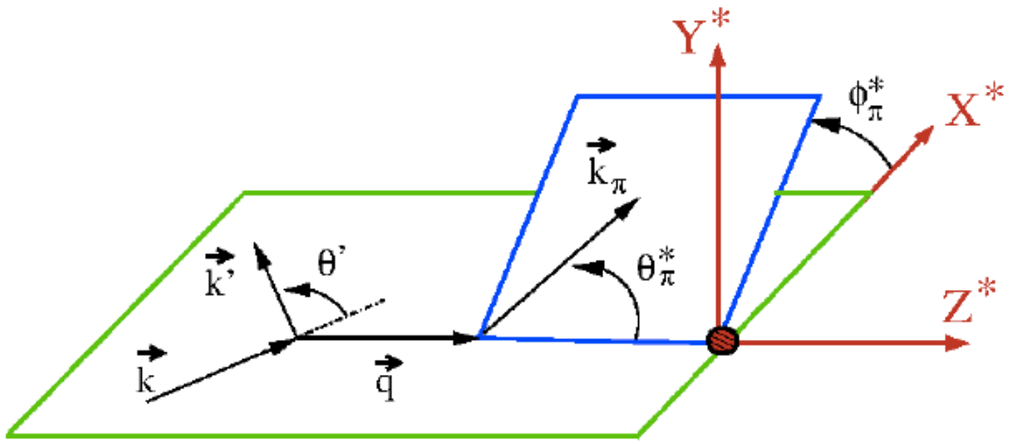
Impulse approximation

From a free nucleon in a potential well…

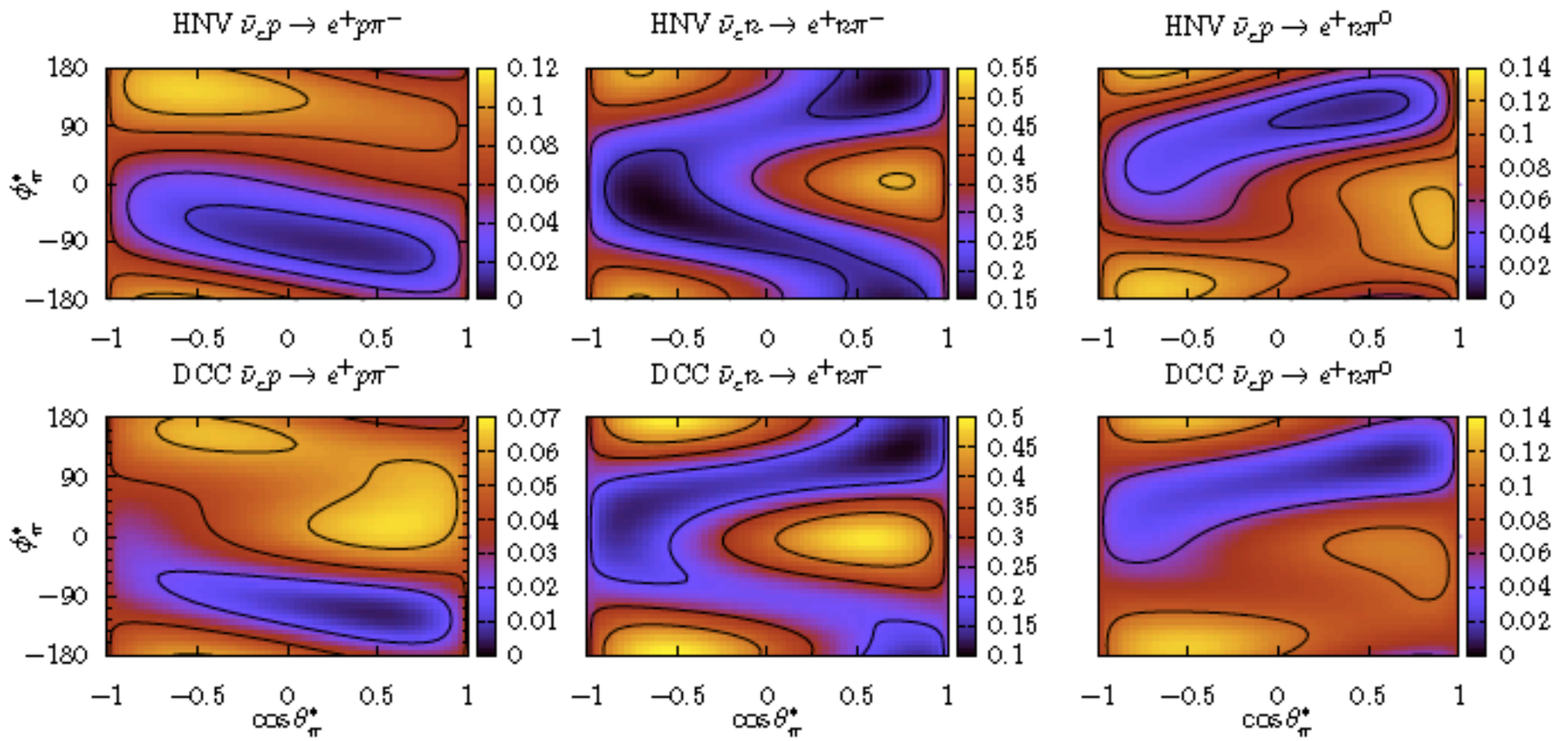
π production

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.



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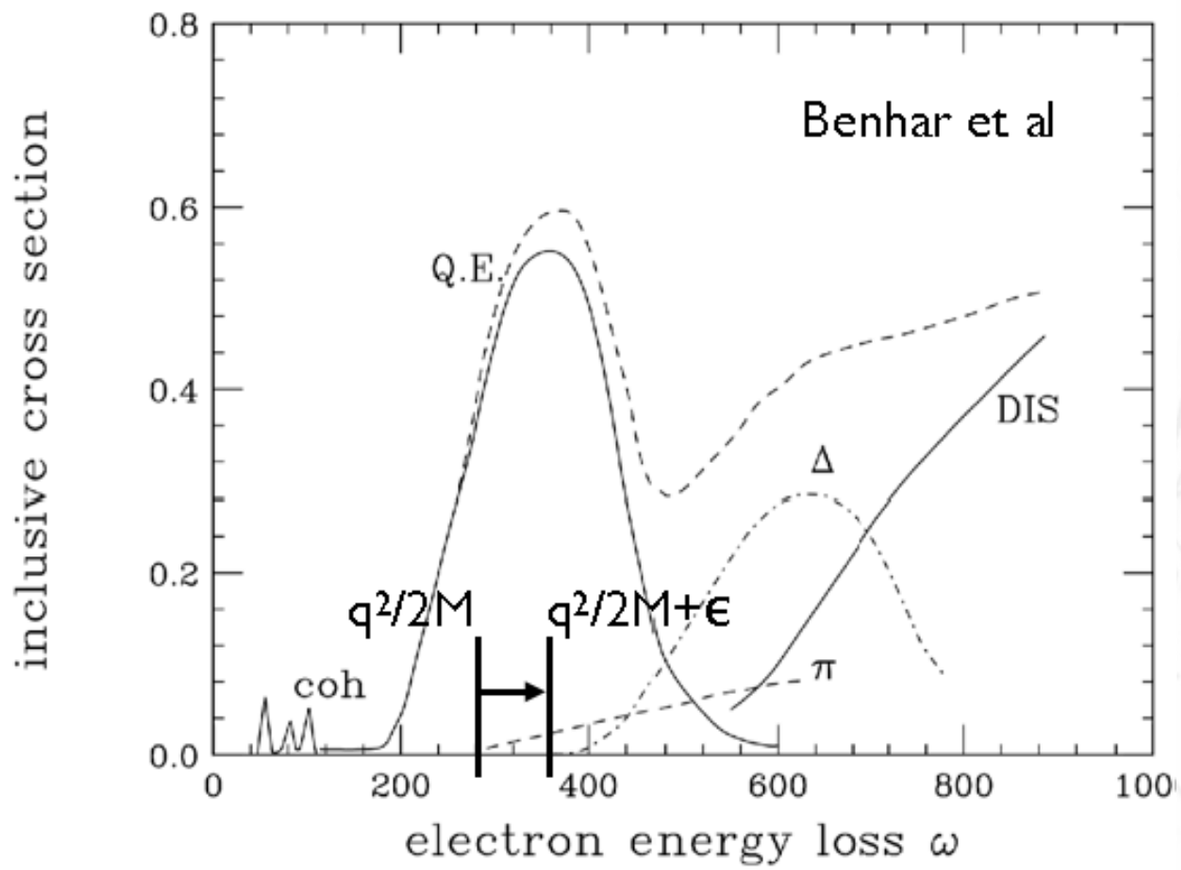
Bind energy in ee'A

- 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.

There are effects in the initial and final state that are convolved in the ee'A interaction and needs to be treated correctly