EXCLUSIVE-FINAL-STATE HADRON OBSERVABLES FROM NEUTRINO-NUCLEUS **MULTINUCLEON** KNOCKOUT

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Phys.Rev.C 102 (2020) 024601
J.S., J. Nieves, F. Sanchez

Phys.Rev.C 83 (2011) 045501
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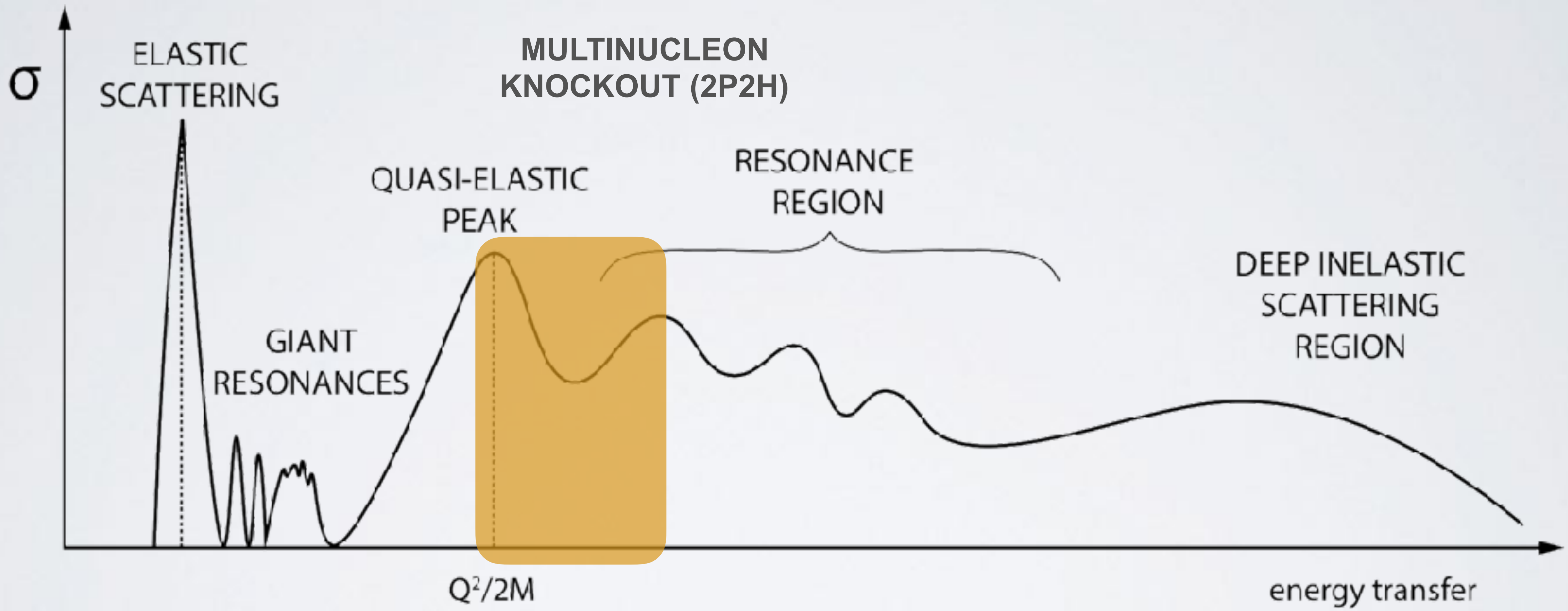
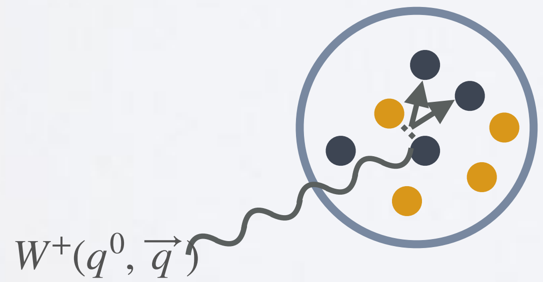
Cluster of Excellence
PRISMA+
Precision Physics, Fundamental Interactions and Structure of Matter

OUTLINE

- Motivation. Why exclusive observables?
- How is it done in Monte Carlo generators?
- Theoretical framework: Valencia model
- More on 2p2h in Valencia model
- Conclusions & outlook

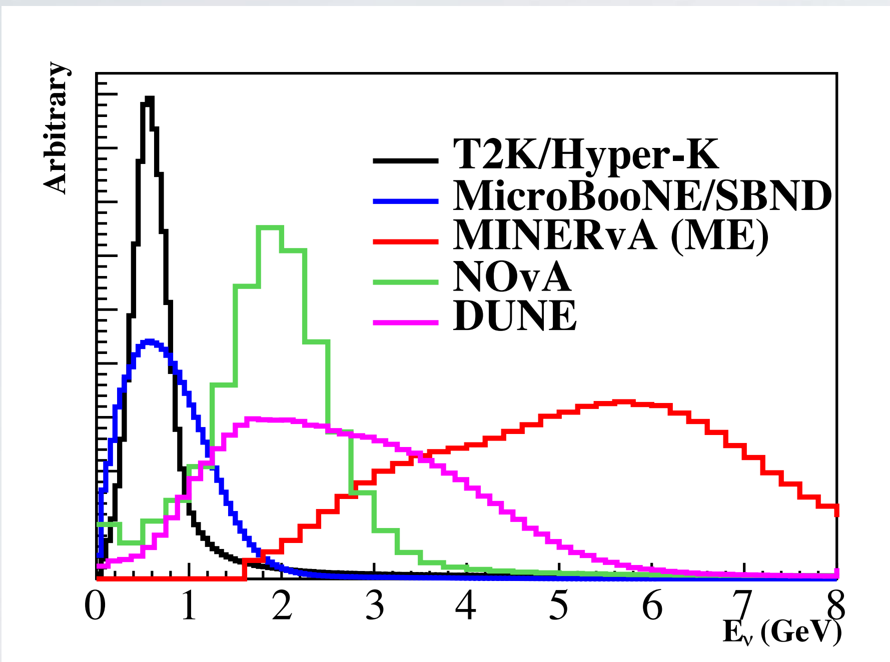
MOTIVATION





DIP region quite often underestimated

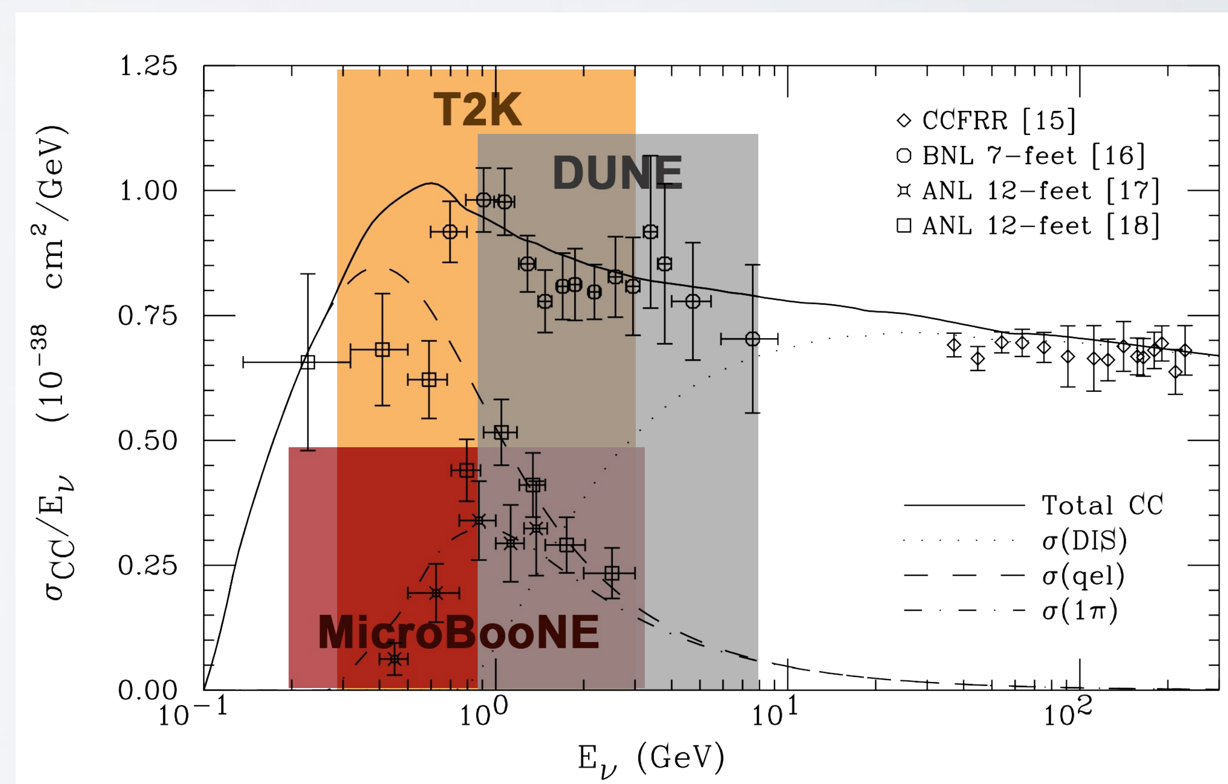
MOTIVATION



From: T. Katori, M. Martini, J.Phys. G45 (2018)

- neutrino energy is unknown (flux is not monochromatic & uncertainties)
- Each experiment probes different energies (various physical mechanisms dominate)

- In every accelerator neutrino experiment we are sensitive to all dynamical mechanisms
- Spectrum is rich and mostly requires relativistic description

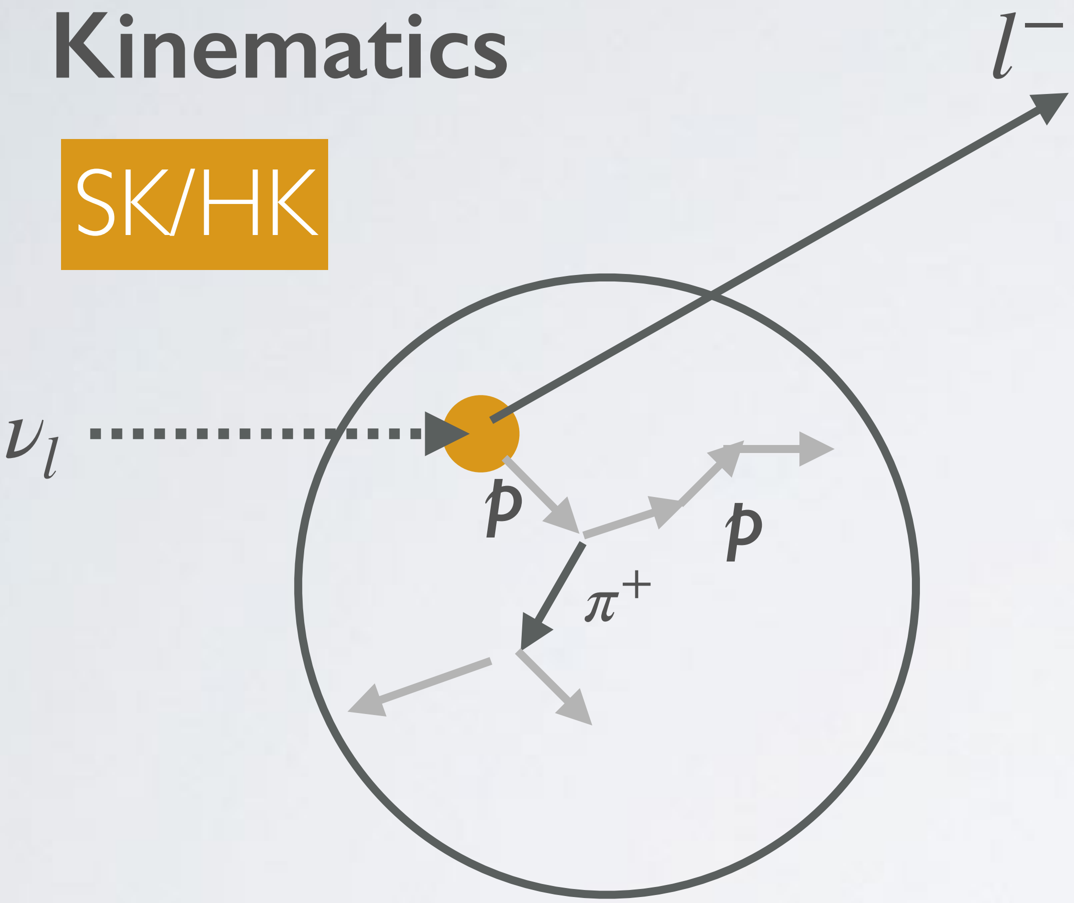


From: P. Lipari et. atl., PRL 74 (1995)

ENERGY RECONSTRUCTION

Kinematics

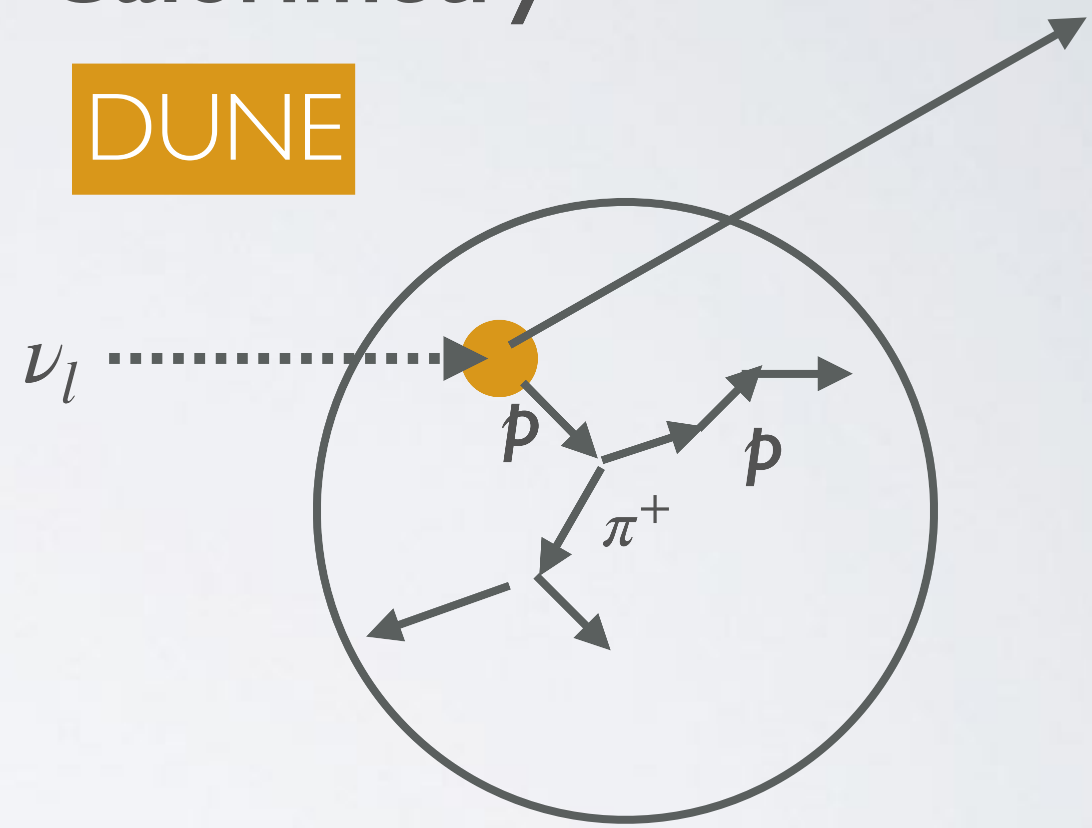
SK/HK



- depends on lepton reconstruction
- relies on identification of interaction channel. (for CCQE works well)

Calorimetry

DUNE

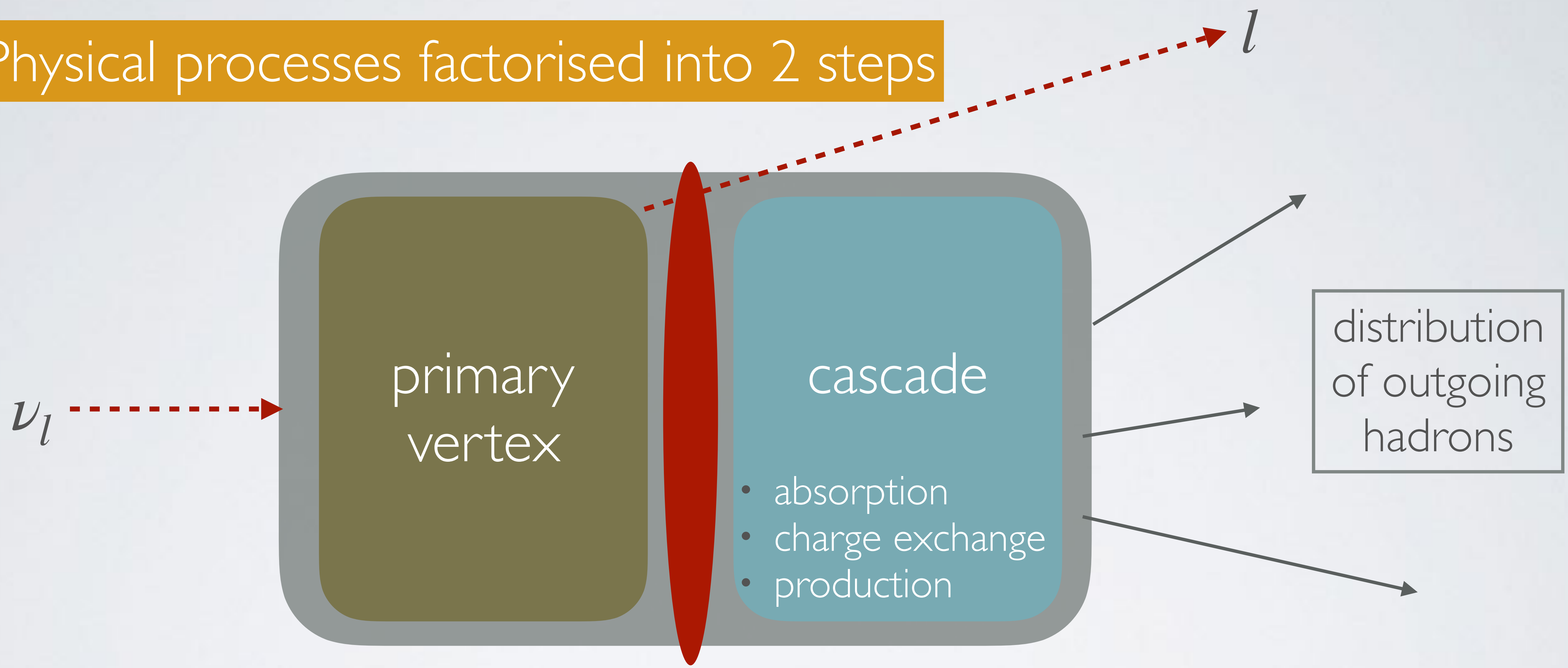


- energy conservation
- relies on visible energy
- hadron masses influence the energy balance

In both cases nuclear models play crucial role.
We need **exclusive** observables.

MONTE CARLO GENERATORS

Physical processes factorised into 2 steps

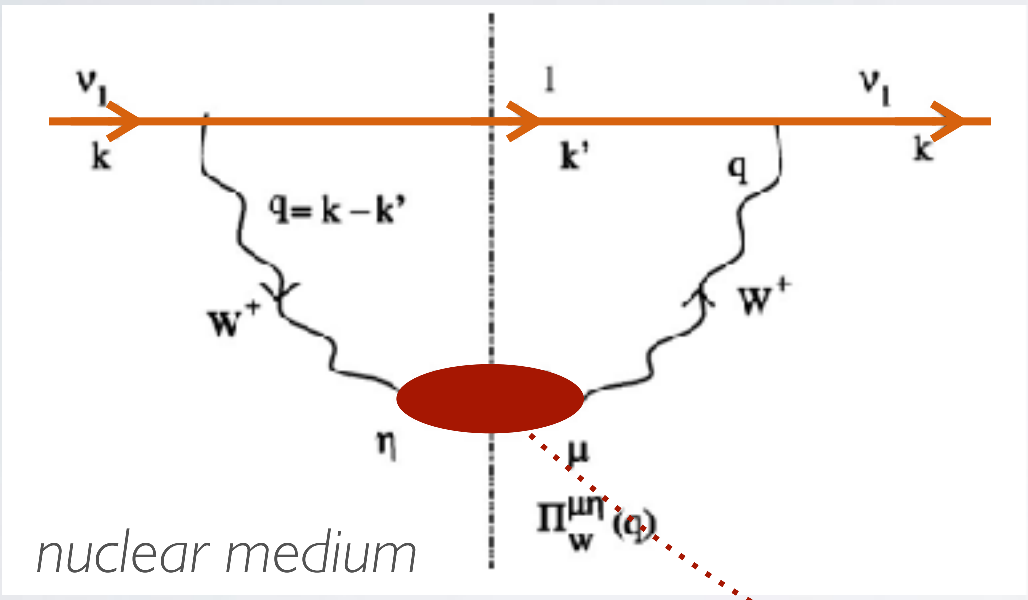


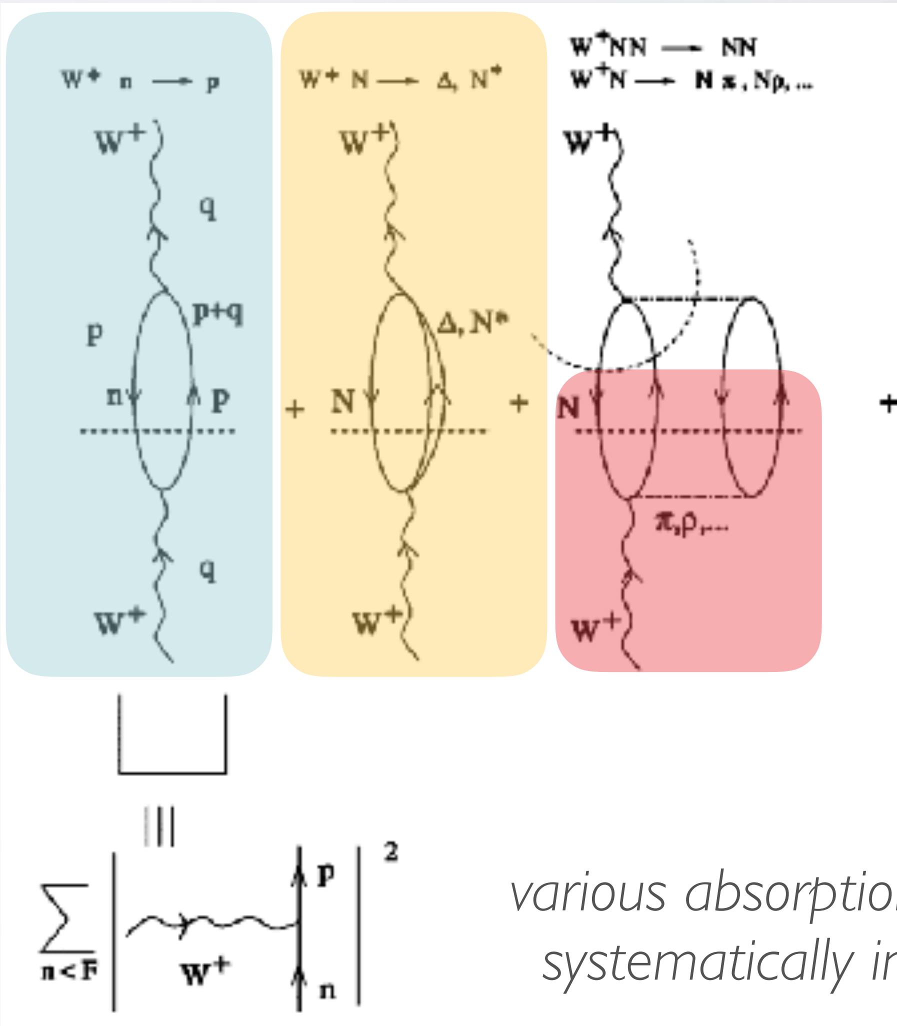
Currently:

1. weight of the event $d\sigma/dq\,d\omega$
2. outgoing nucleons distributed according to available phase-space

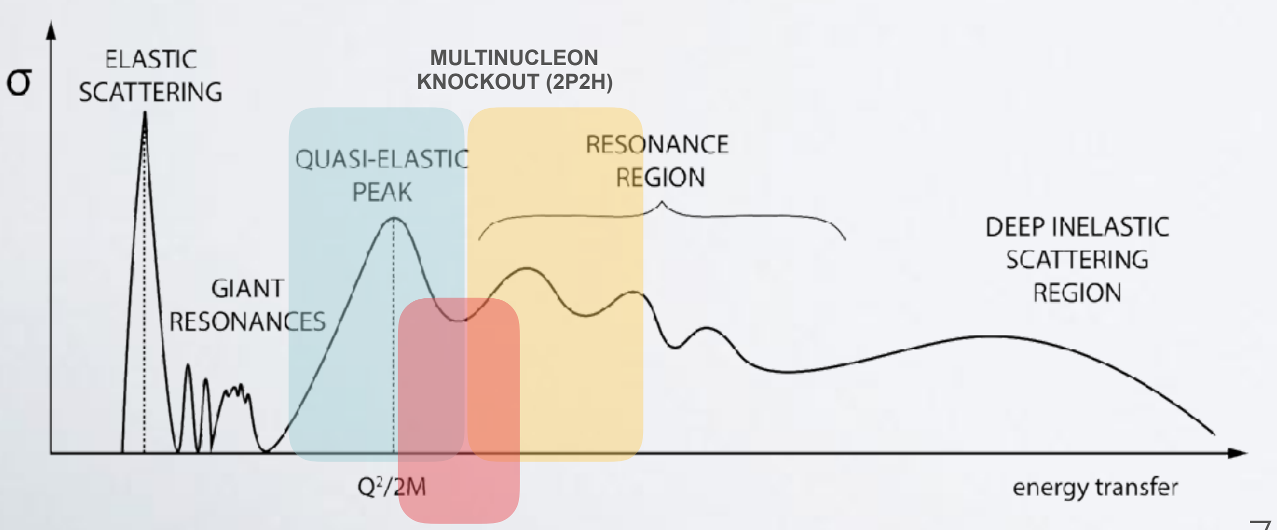
What is the actual nucleons distribution from primary vertex?

THEORETICAL FRAMEWORK: VALENCIA MODEL





various absorption modes are systematically incorporated



THEORETICAL FRAMEWORK: VALENCIA MODEL

- Initial nuclear state: Local Fermi gas (Local density approximation)
- Polarisation (RPA) effects taken into account

  Phys.Rev.C 70 (2004) 055503

- Particularly renowned for Δ-degrees of freedom (Δ self-energy) and pion production

  Phys.Rev.D 76 (2007) 033005

  Phys.Rev.D 87 (2013) 11, 113009

- Spectral function of nucleons

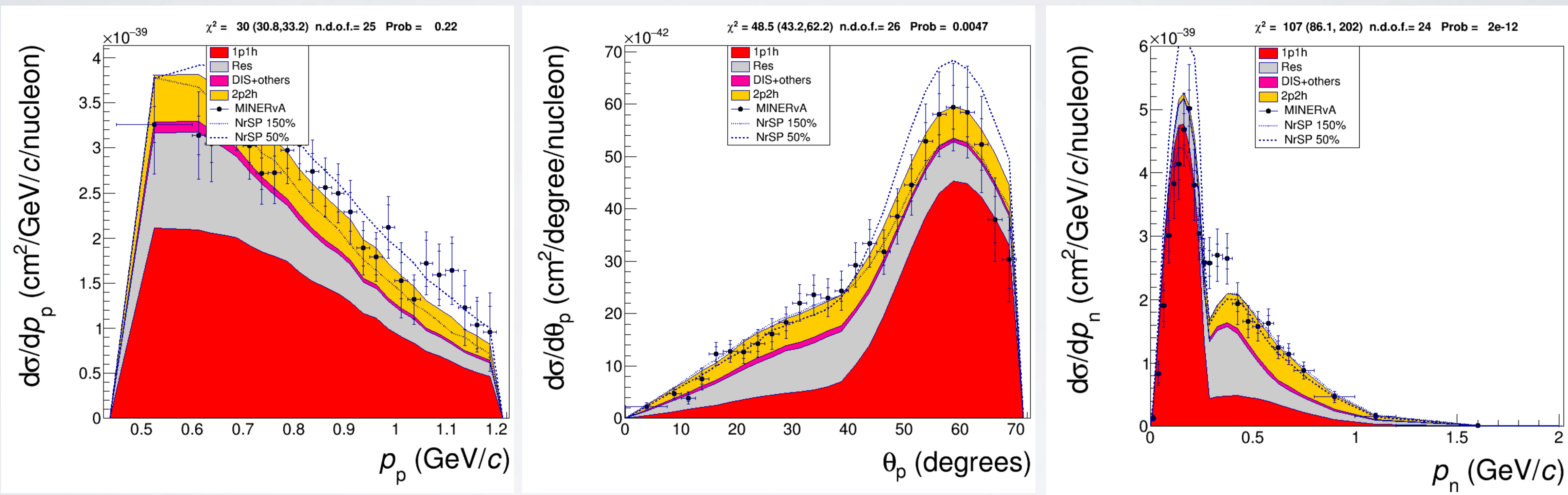
  Annals Phys. 383 (2017) 455-496

- Predictions for other processes: Σ, Λ, K production…

  Phys.Rev.D 74 (2006) 053009

  Phys.Rev.C 99 (2019) 6, 065503

THEORETICAL FRAMEWORK: VALENCIA MODEL



NEUT implementation simultaneously compared to the most recent T2K and MINERvA charged current (CC) inclusive, CC0π and transverse variable results.

arXiv:2012.12653
B. Bourguille, J. Nieves, F. Sanchez

WHAT IS NEW IN 2P2H MODEL?

1. How does the distribution of final nucleons look like?

2. Implement new Δ treatment in the Valencia model

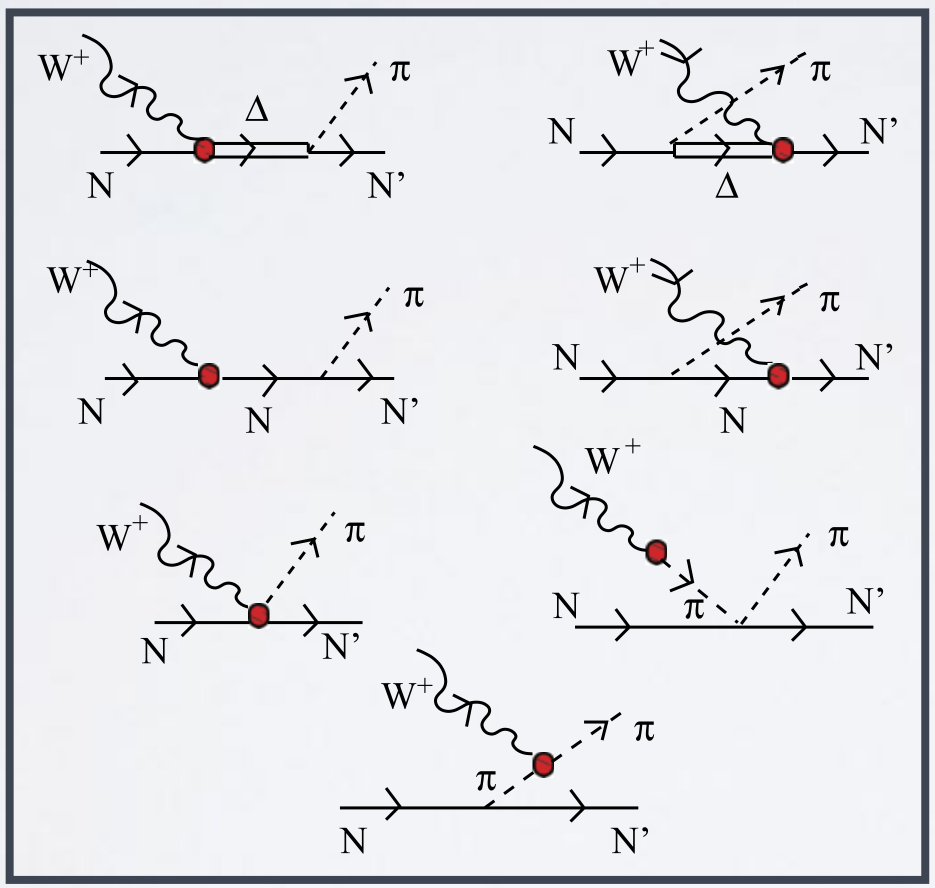
3. To get information (1) in the Valencia model: disentangle 2p2h and 3p3h

4. Check previous implementation

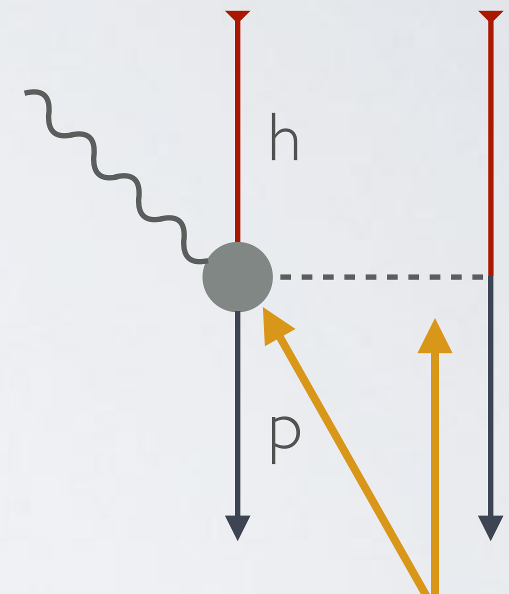
2P2H FORMALISM

Local Fermi Gas

Interaction vertex



initial nucleons distribution



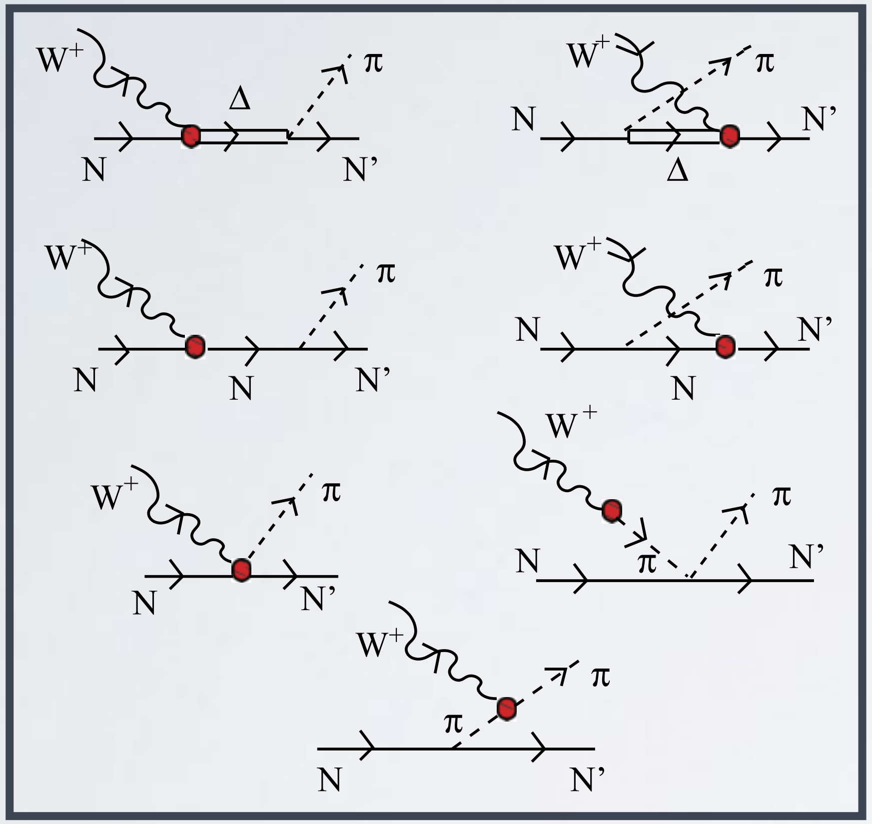
interaction vertex?
NN potential?

NN potential

$$V(p) = V_\pi(p) + V_\rho(p) + \frac{f^2_{\pi NN}}{m^2_\pi}\, g'_l(p)\,(\vec{\sigma}_1 \cdot \hat{p})\;(\vec{\sigma}_2 \cdot \hat{p})\;\vec{\tau}_1 \cdot \vec{\tau}_2 + C_\rho \frac{f^2_{\pi NN}}{m^2_\pi}\, g'_t(p)\,(\vec{\sigma}_1 \times \hat{p})\;(\vec{\sigma}_2 \times \hat{p})\;\vec{\tau}_1 \cdot \vec{\tau}_2$$

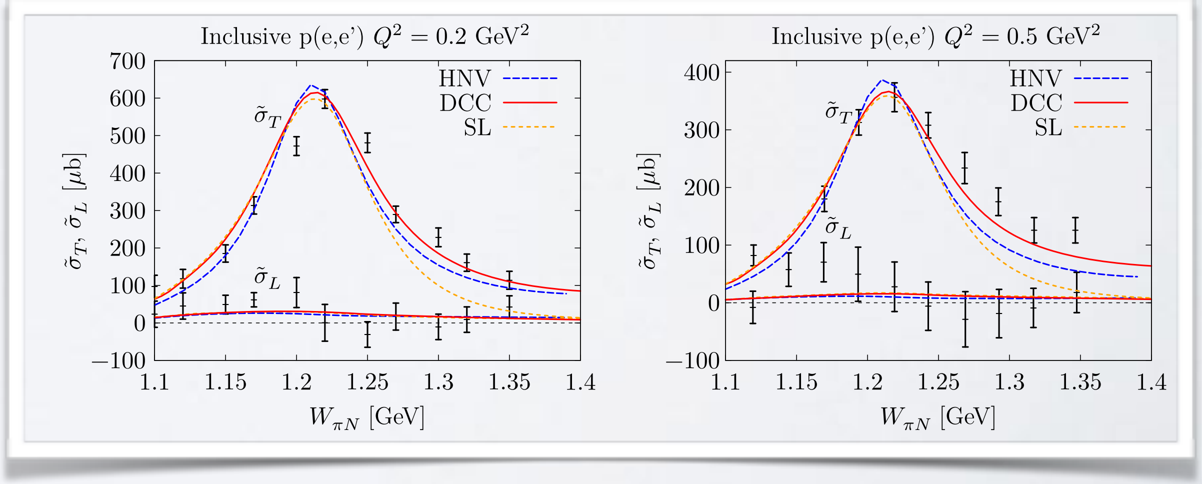
Much more than one-pion exchange

INTERACTION VERTEX

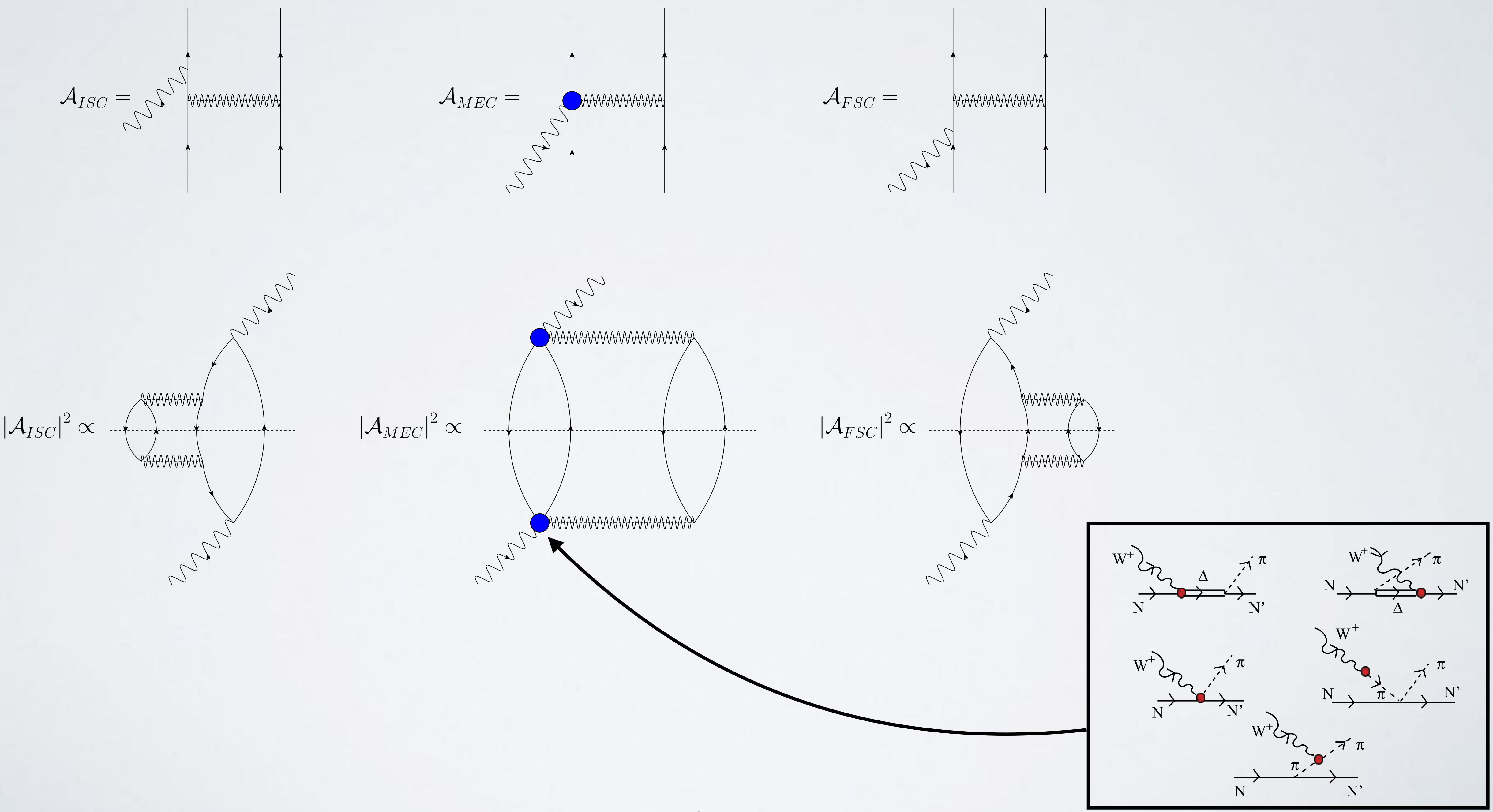


The same set of diagrams as for the pion production.

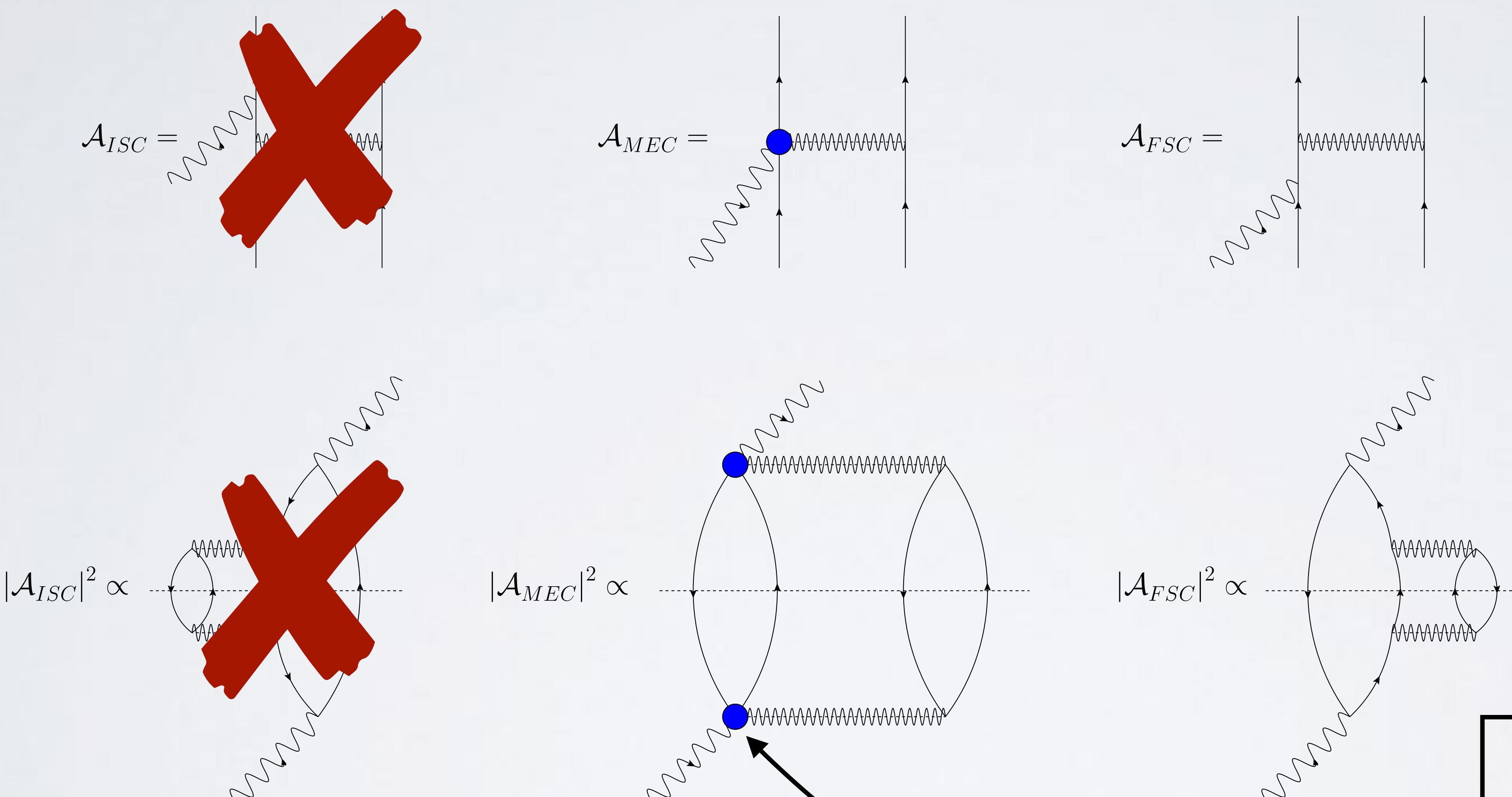
Recently benchmarked with electron data and with Sato-Lee and DCC models (Phys. Rev. D98. 073001)

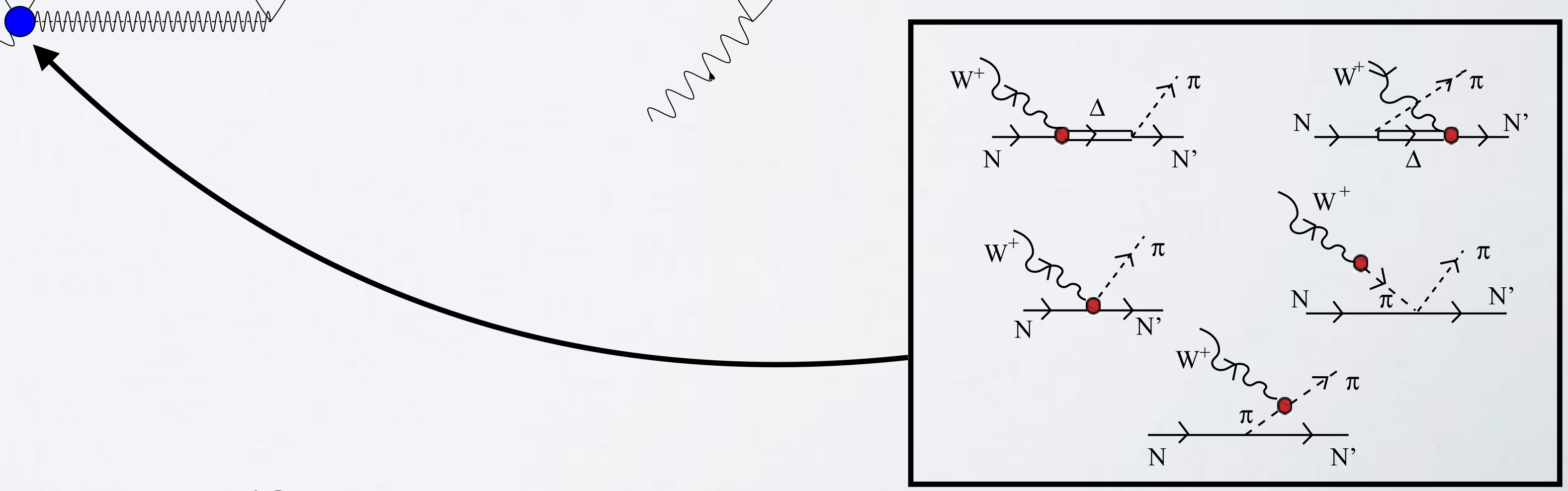


INITIAL / FINAL STATE CORRELATIONS



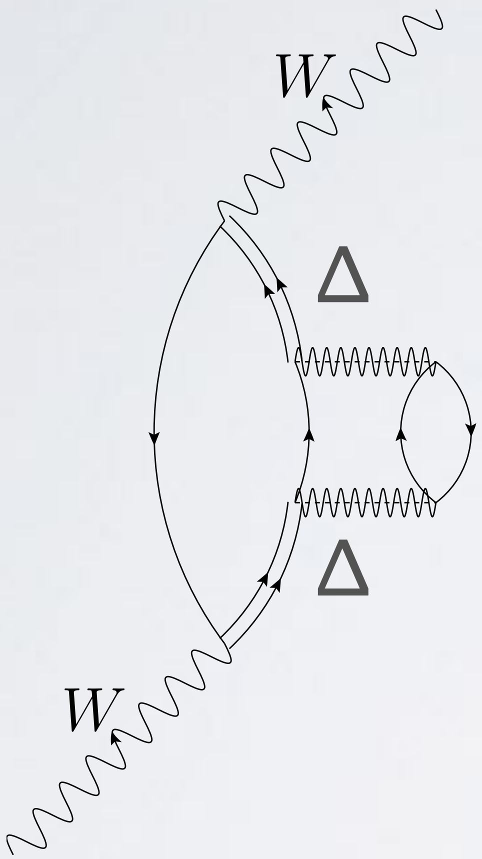
INITIAL / FINAL STATE CORRELATIONS

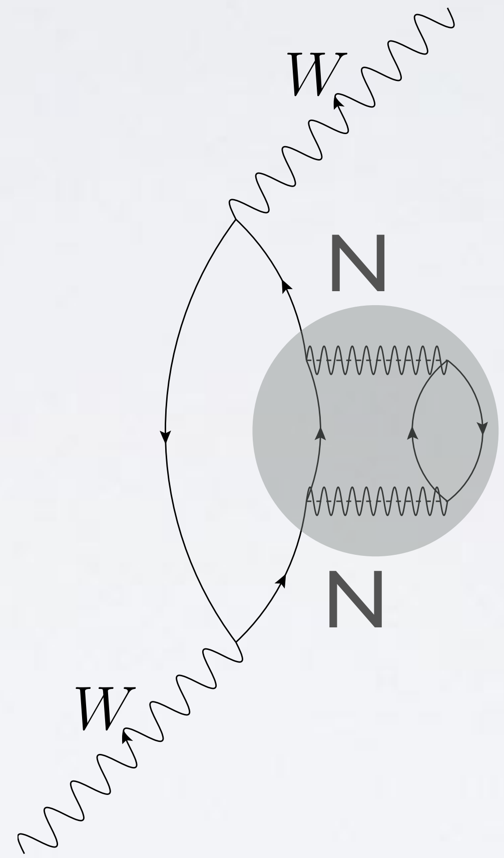


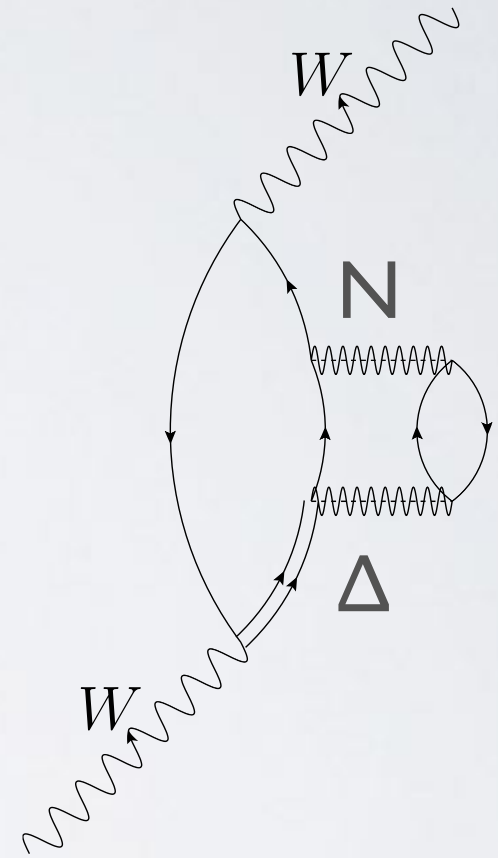


in our approach it is higher order correction

VARIOUS CONTRIBUTIONS





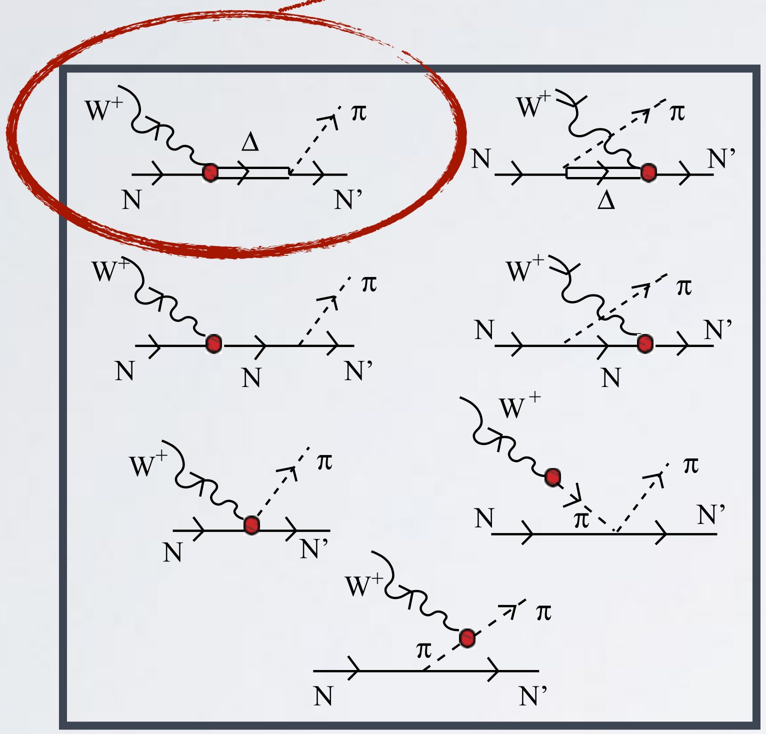


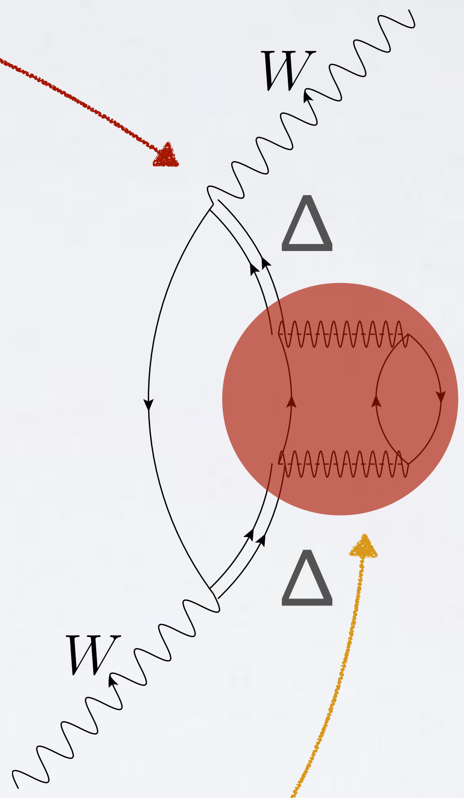
More on this contribution later

FSC not considered (contribution to nucleon self-energy)

Interference diagram between FSC and Δ (important!)

WHAT IS NEW?



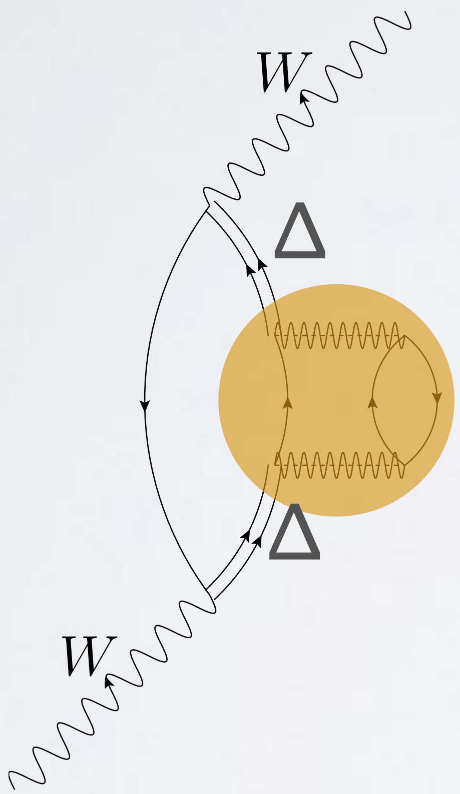


This diagram gives a major contribution to the cross section

One can look at this diagram as a contribution to the Δ self-energy

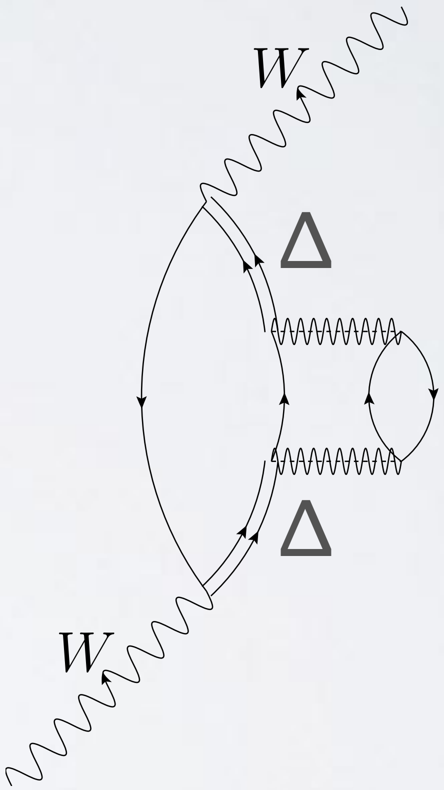
WHAT IS NEW?

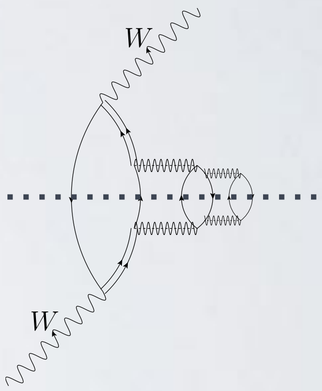
Previously



Self-energy parametrised and taken from **Nucl. Phys. A468, 631 (1987)**

Currently

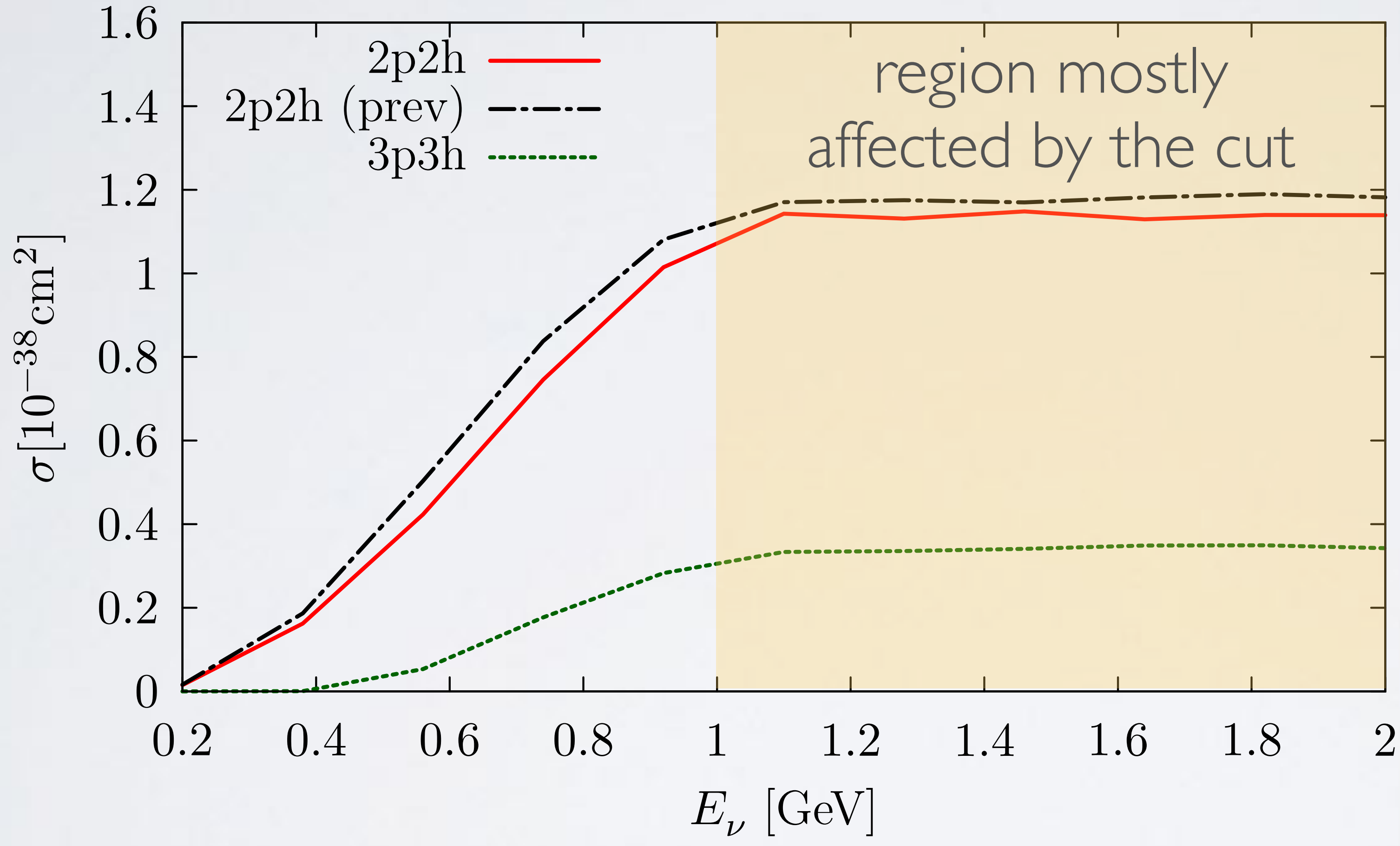




3p3h diagram

This diagram is directly calculated

RESULTS

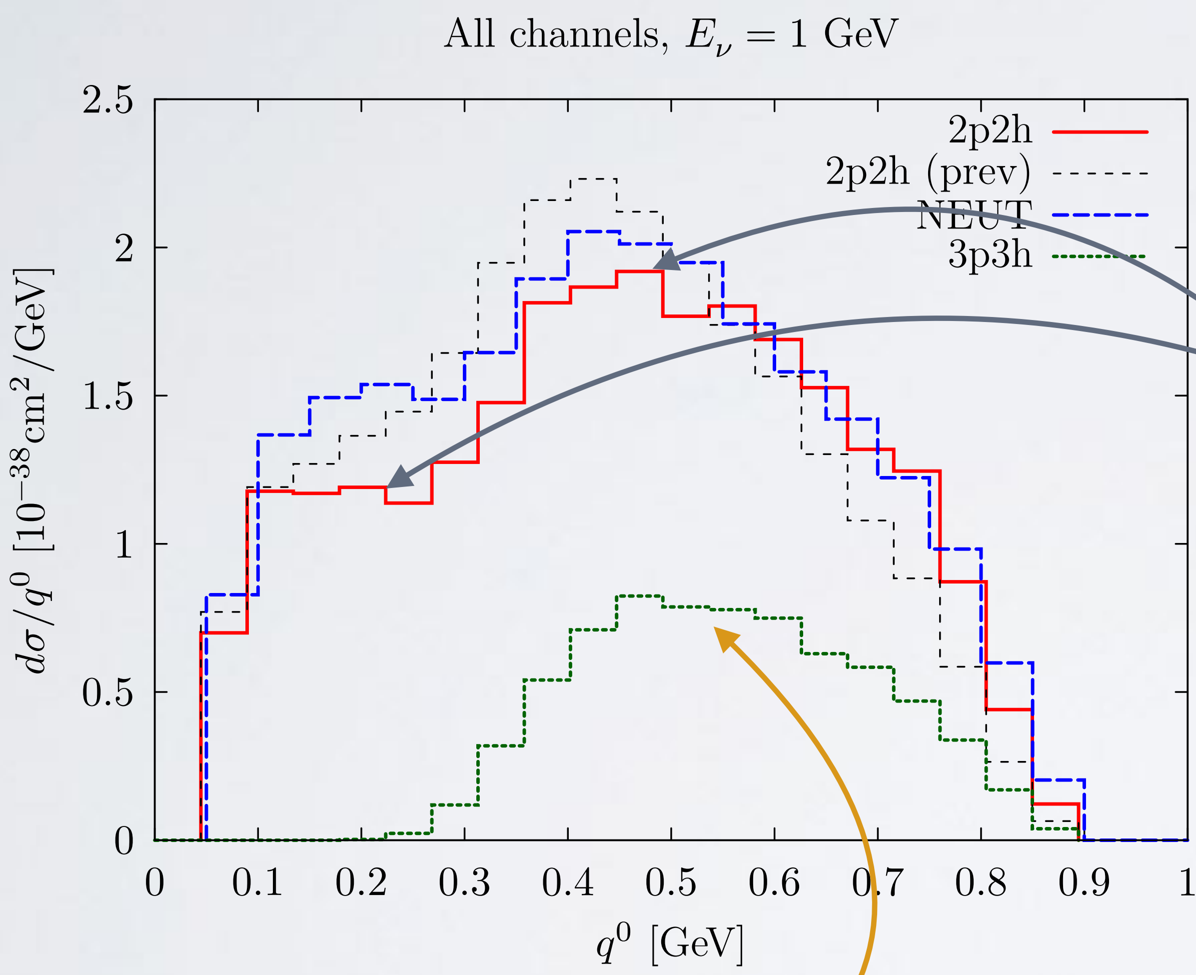


Cut in momentum transfer
$|\mathbf{q}| \leq 1.2$ GeV

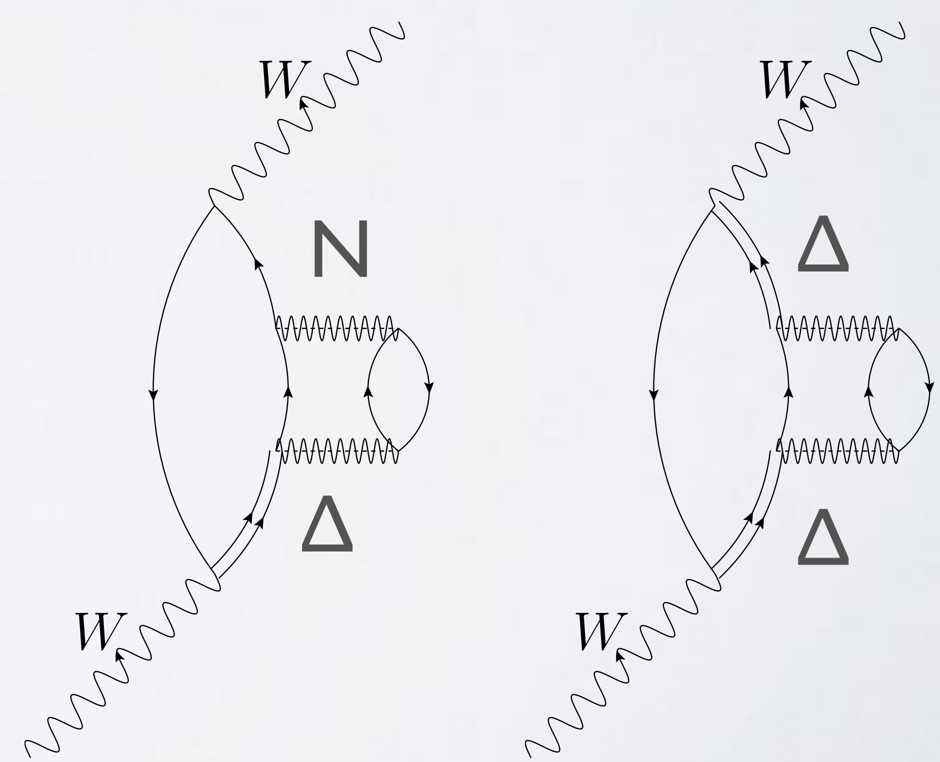
Red: new calculation

Black: using Δ self-energy parametrisation

DIFFERENTIAL CROSS SECTION



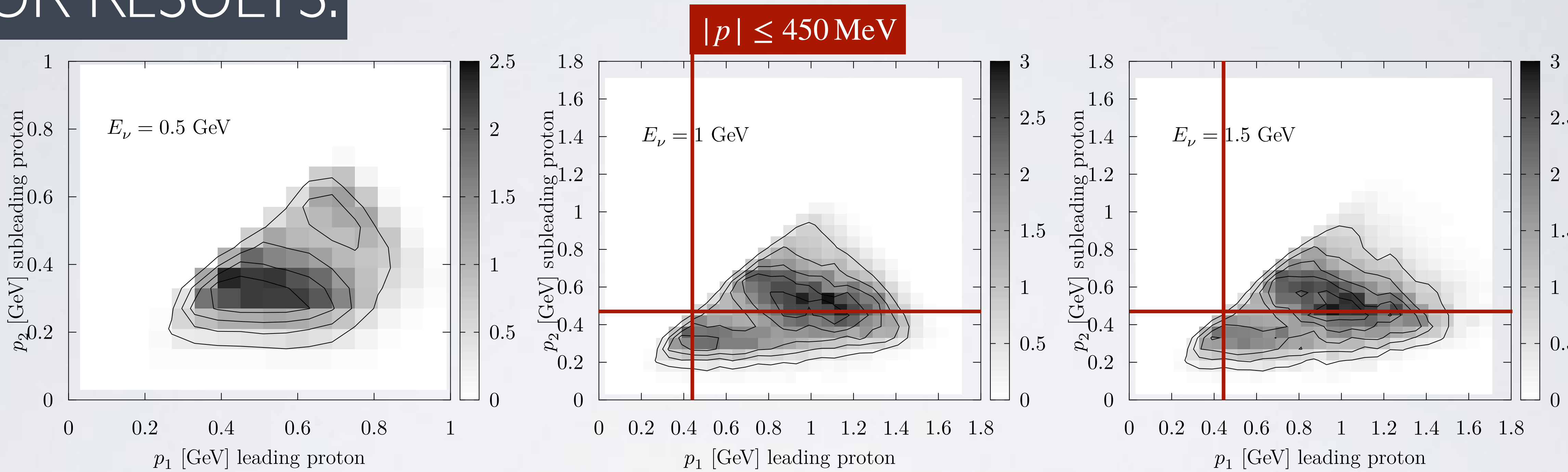
"Irregular" shape of the distribution because there are two leading dynamical mechanisms:



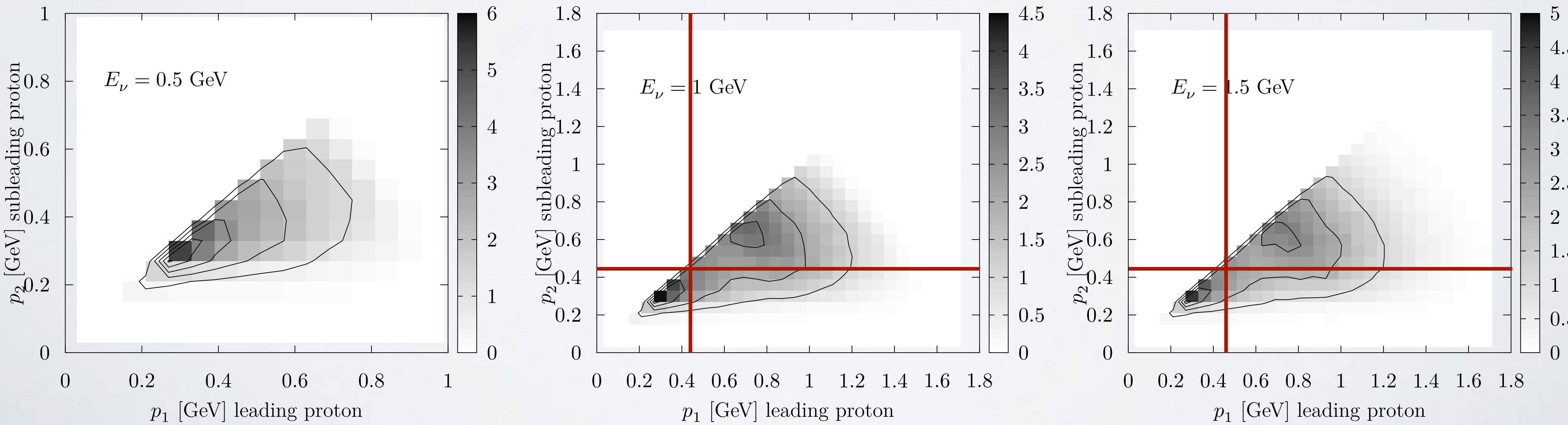
3p3h needs more energy transfer (3 particles produced above the Fermi level)

OUTGOING PROTON PAIR

OUR RESULTS:

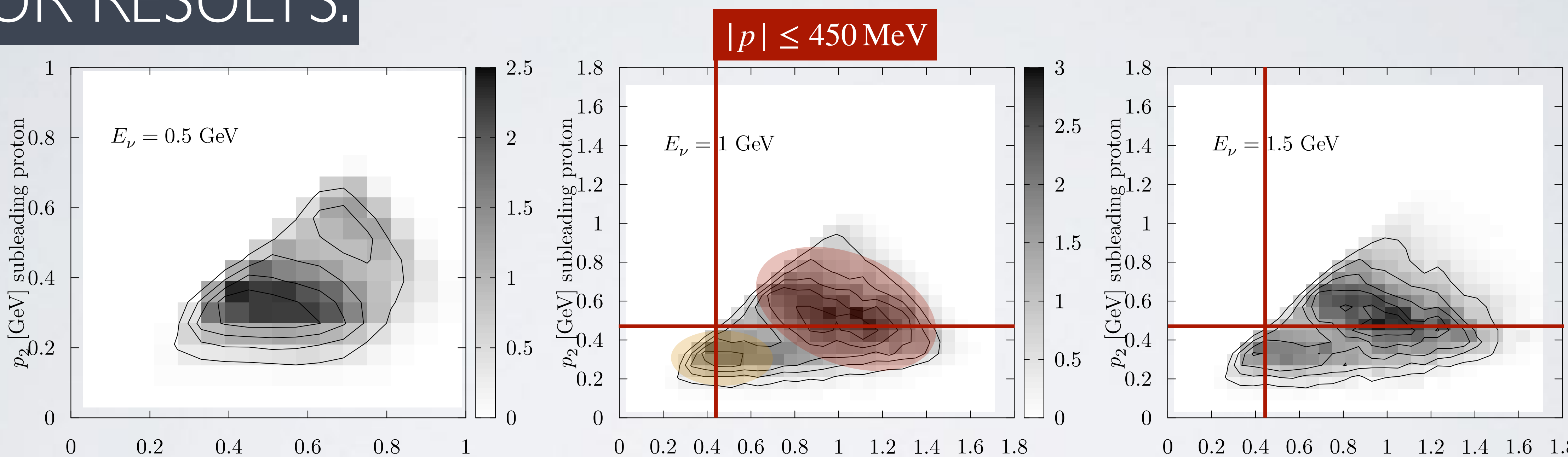


NEUT:



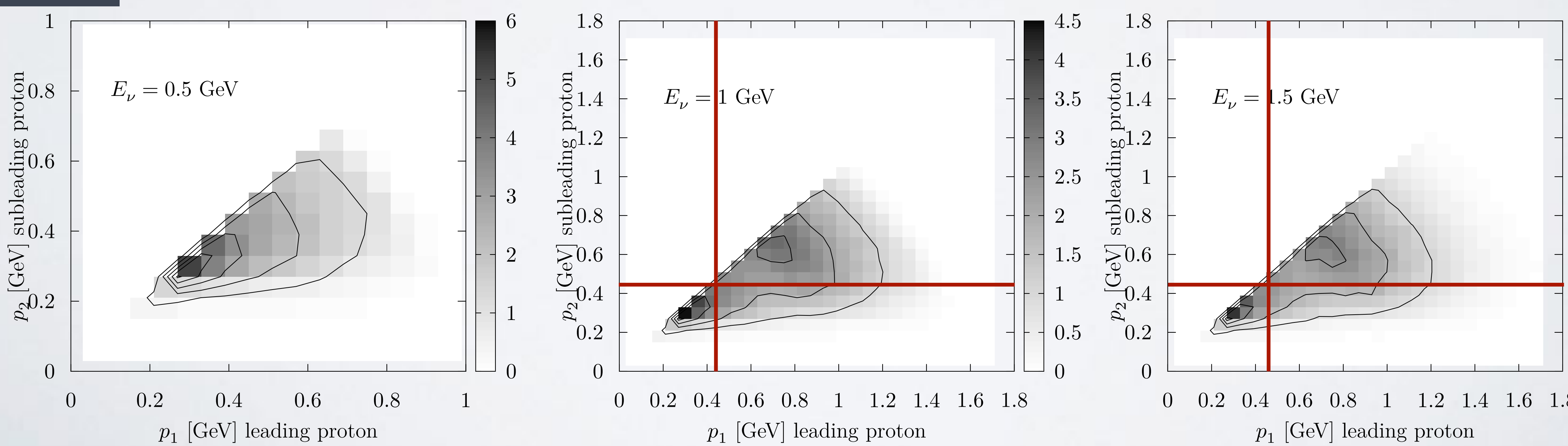
OUTGOING PROTON PAIR

OUR RESULTS:

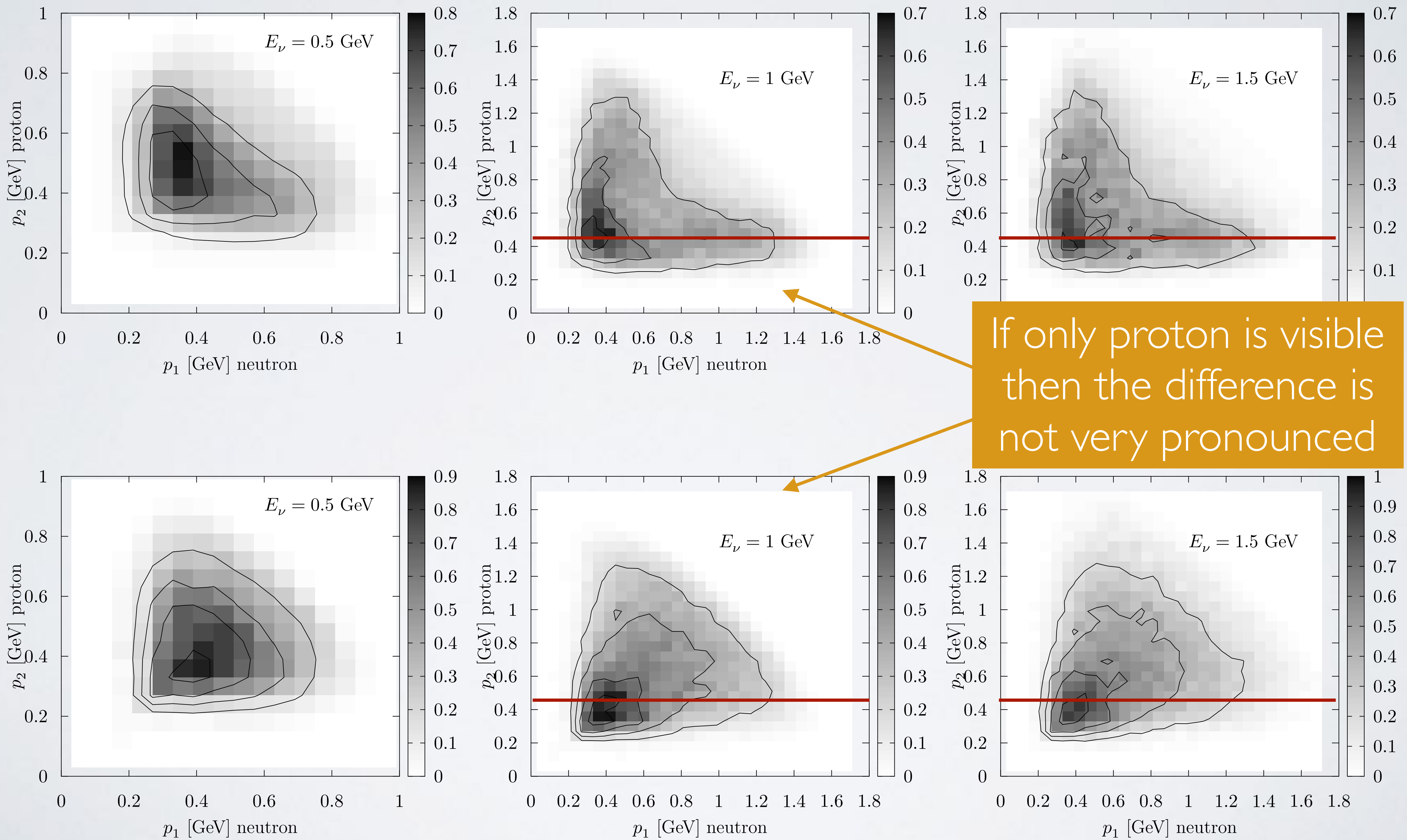


- Two dynamical mechanisms observed
- One leading proton clearly seen

NEUT:



OUTGOING NEUTRON-PROTON PAIR



OUTLOOK

Implementation of theoretical models into the MC generators

Exhaustive Neural Importance Sampling applied to Monte Carlo event generation

Sebastian Pina-Otey,[1,2,*] Federico Sánchez,[3] Thorsten Lux,[2] and Vicens Gaitan[1]

[1] *Aplicaciones en Informática Avanzada (AIA), Sant Cugat del Vallès (Barcelona) 08172, Spain*
[2] *Institut de Física d´Altes Energies (IFAE) - Barcelona Institute of Science and Technology (BIST), Bellaterra (Barcelona) 08193, Spain*
[3] *University of Geneva, Section de Physique, DPNC, Geneva 1205, Switzerland*

(Dated: July 22, 2020)

The generation of accurate neutrino-nucleus cross-section models needed for neutrino oscillation experiments require simultaneously the description of many degrees of freedom and precise calculations to model nuclear responses. The detailed calculation of complete models makes the Monte Carlo generators slow and impractical. We present Exhaustive Neural Importance Sampling (ENIS), a method based on normalizing flows to find a suitable proposal density for rejection sampling automatically and efficiently, and discuss how this technique solves common issues of the rejection algorithm.

CONCLUSIONS

- We revised a computation of 2p2h in Valencia model. It does not influence the inclusive x-section too much. But we get an insight into the nucleons distribution.
- We predict a strong asymmetric signal for proton-proton final state (some differences should be visible due to the proton's momentum thresholds + might help to discern between various theoretical approaches)
- 3p3h amounts to ~20% of 2p2h strength (but difficult to calculate)
- Next step: benchmark of theoretical models for semi-exclusive processes (combine it with a cascade model)

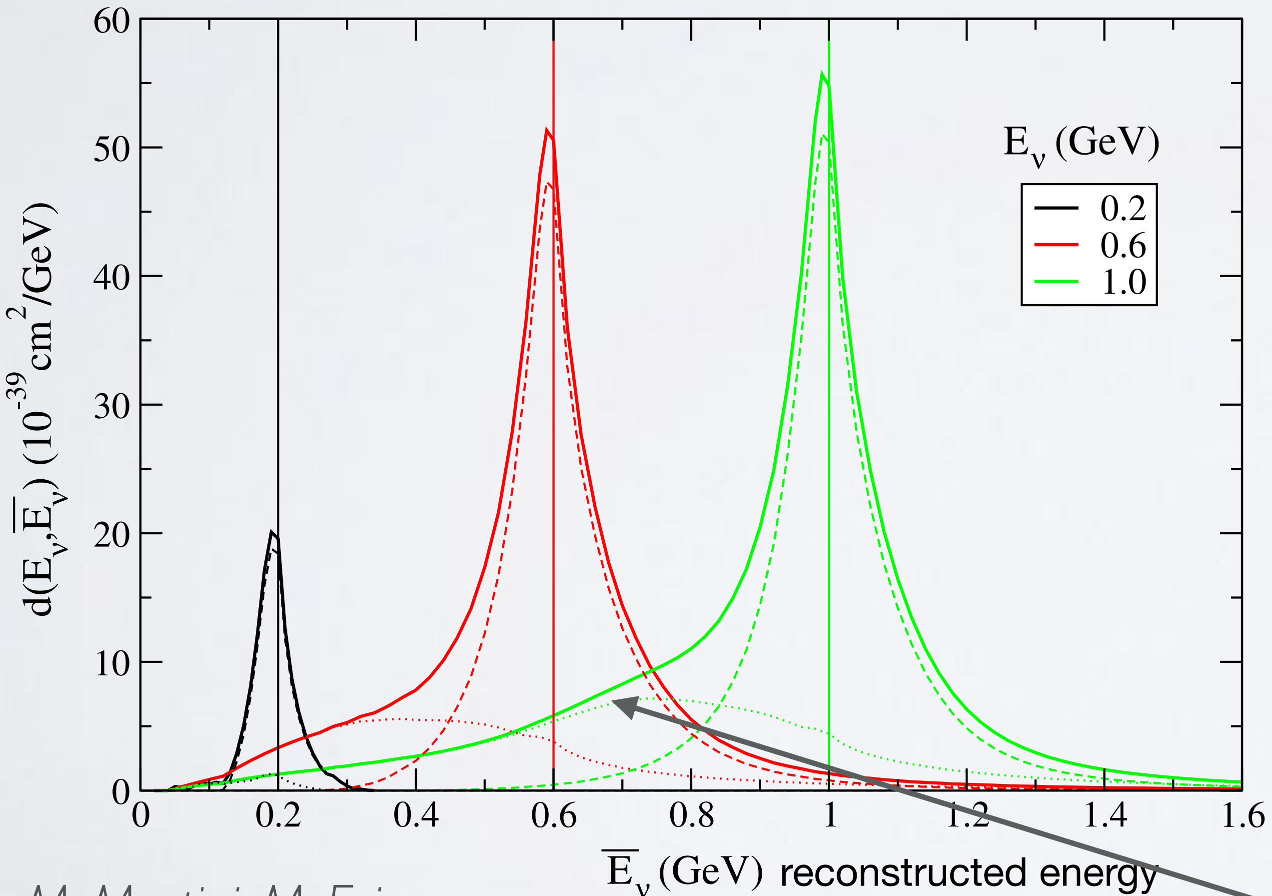
THANK YOU!

BACKUP

WHY IS 2P2H IMPORTANT?

assuming $\nu_l + n \rightarrow l^- + p$

energy reconstruction $E_{rec} = \dfrac{ME_l - m_l^2/2}{M - E_l + |p_l|\cos\theta_l}$



M. Martini, M. Ericson
PRD 87, 013009

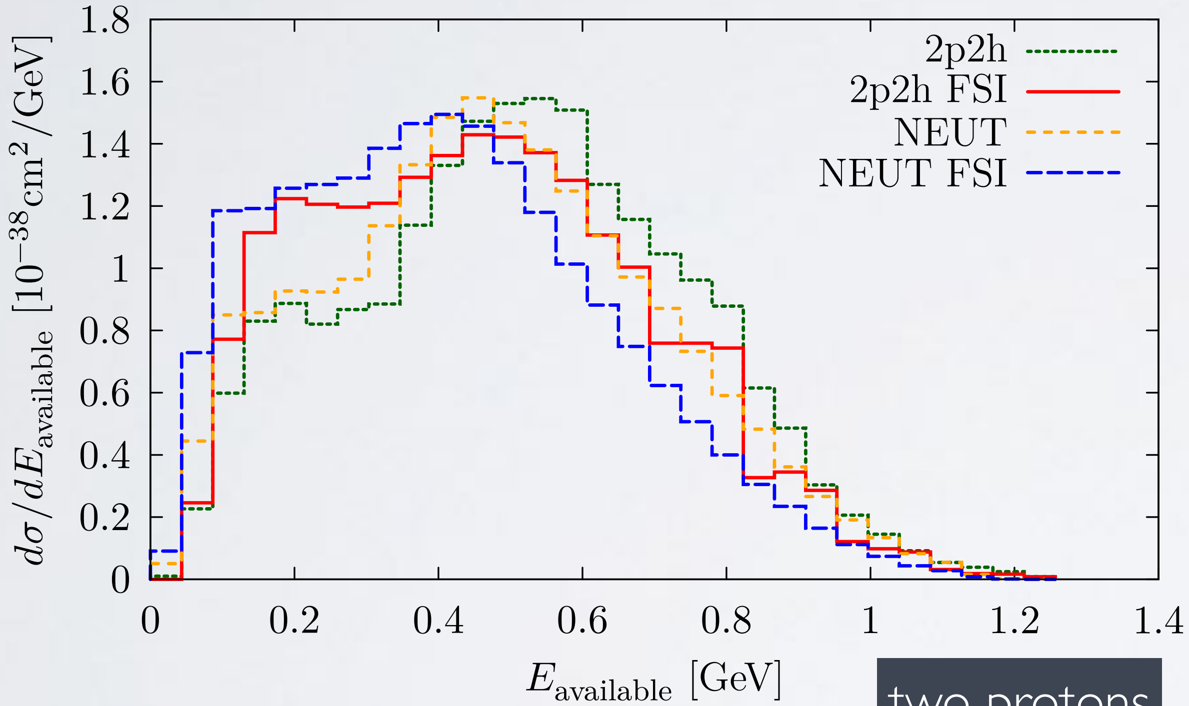
MC generators should correct for this bias

2p2h mechanism responsible for this tail

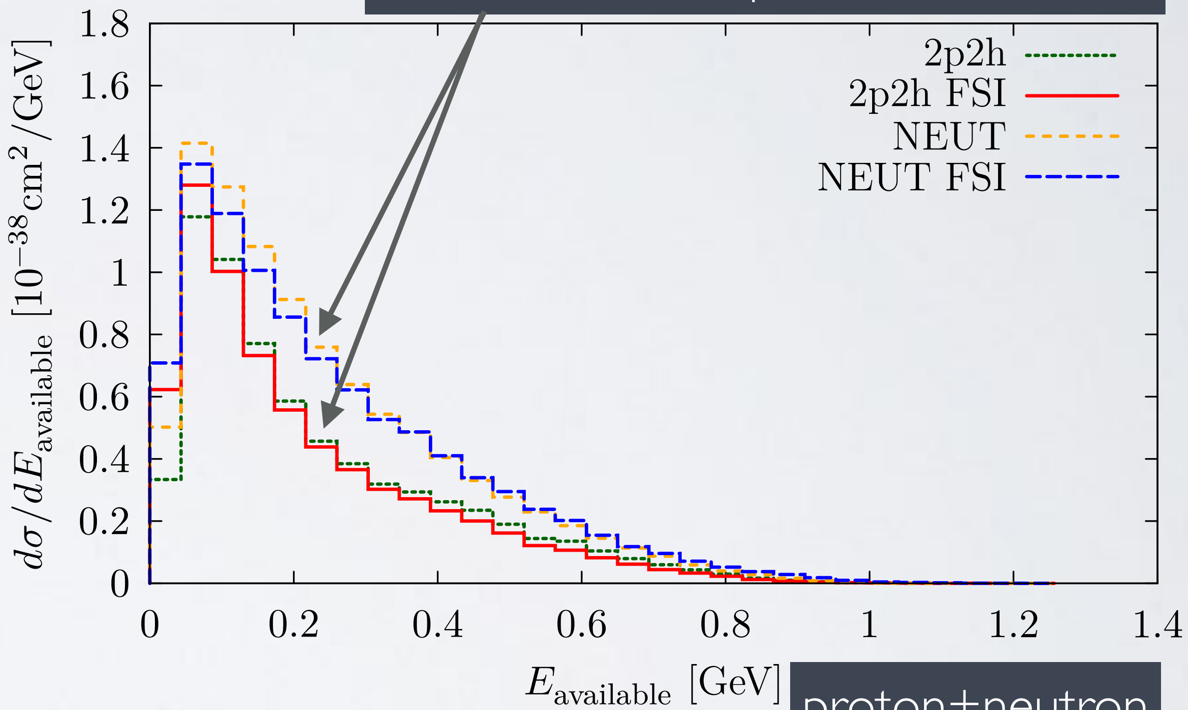
AVAILABLE ENERGY

Kinetic energy of outgoing proton(s)

We predict less energetic proton than in isotropic distribution



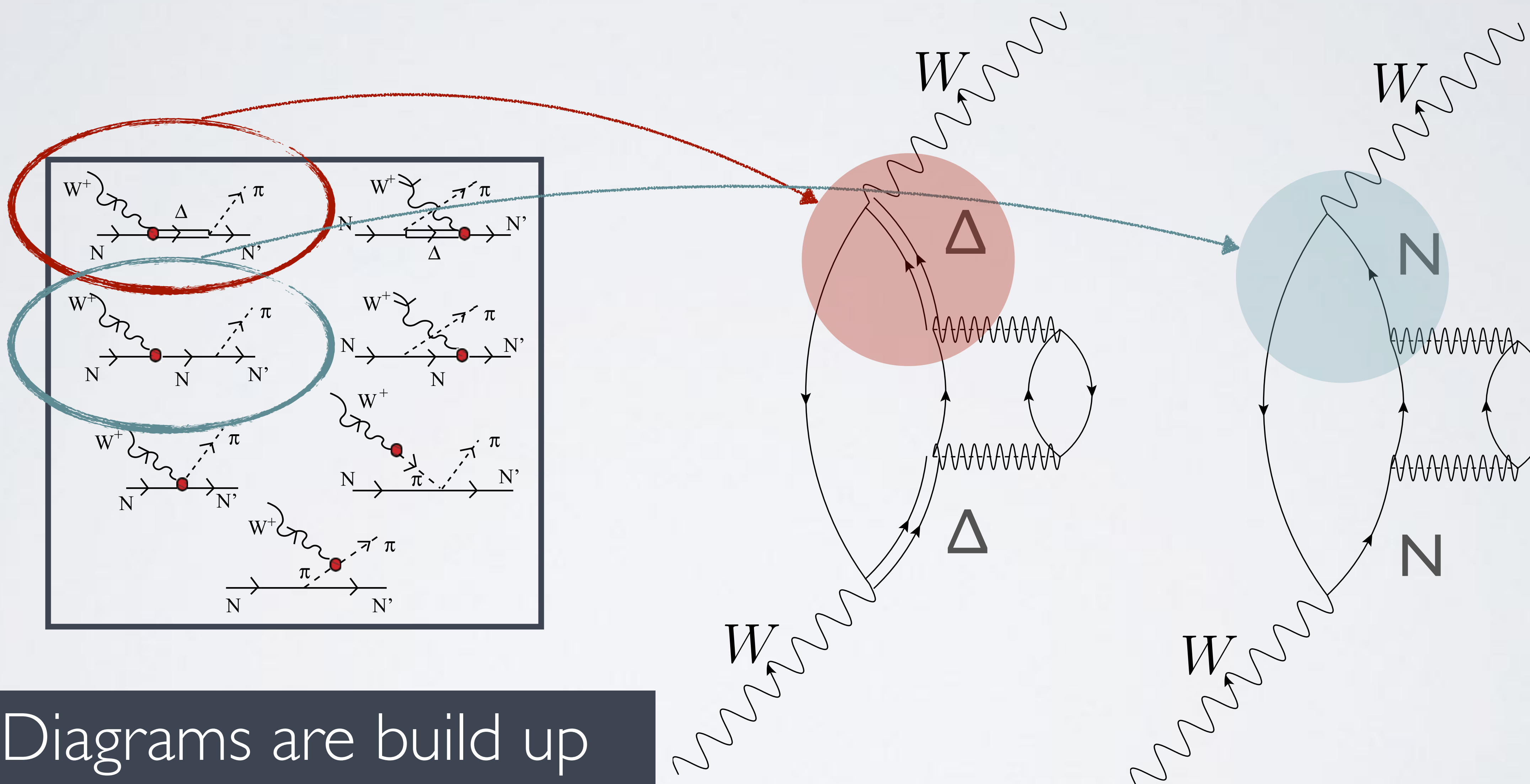
two protons



proton+neutron

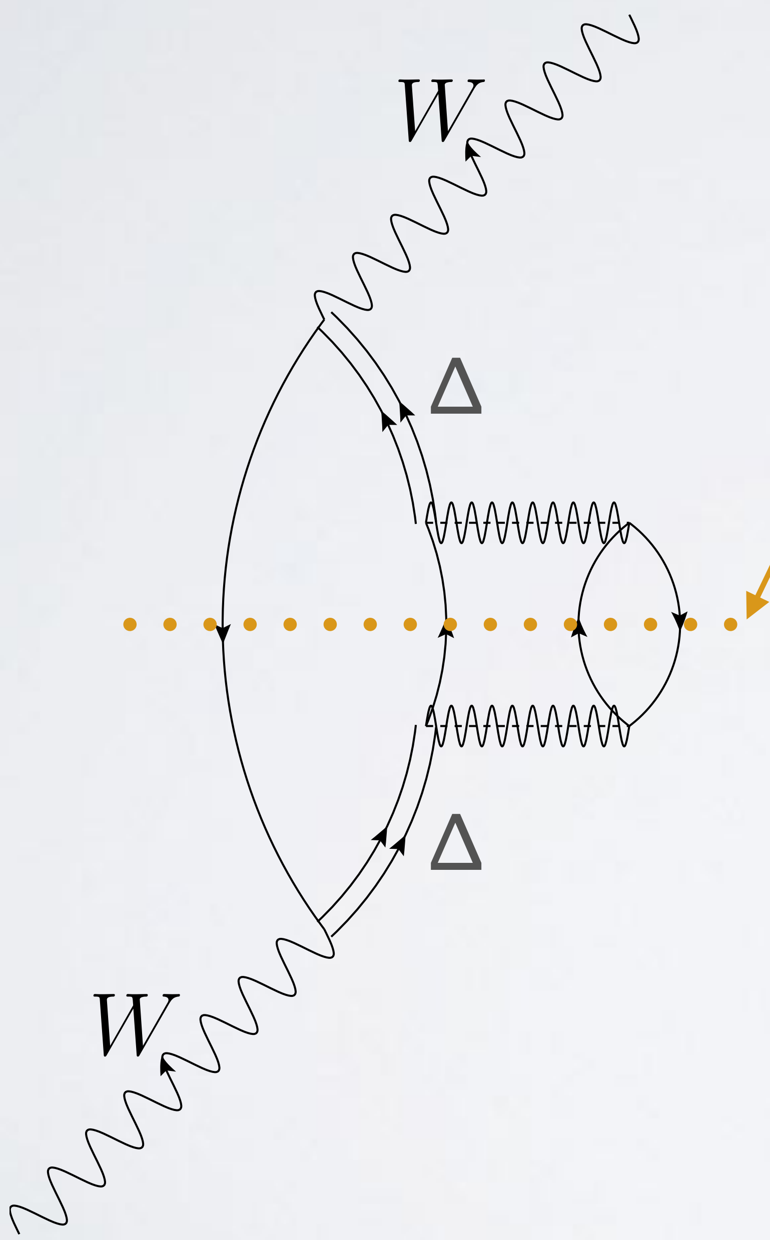
- we implement FSI taking the migration matrices from NEUT
- we observe the energy dissipation

INTERACTION VERTEX



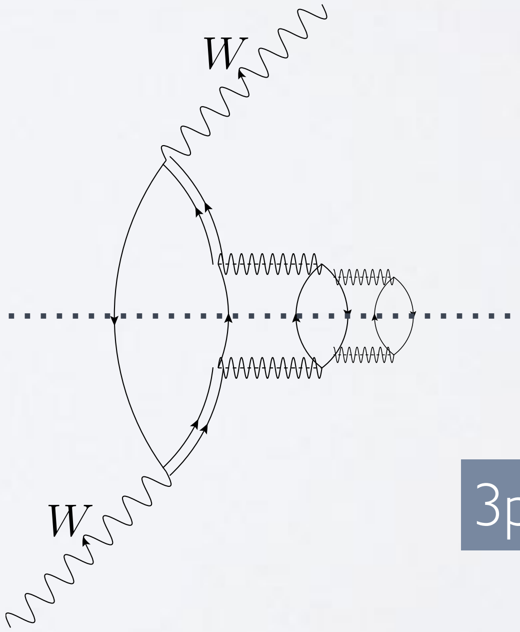
Diagrams are build up from different interaction vertices

WHAT IS NEW?



With this cut we get insight into nucleon distribution

We separate 2p2h and 3p3h contribution (earlier they were taken together)



3p3h diagram

RPA EFFECTS

Effective Landau-Migdal interaction

$$V(\vec{r}_1, \vec{r}_2) = c_0\delta(\vec{r}_1 - \vec{r}_2)\left(f_0(\rho) + f_0'(\rho)\vec{\tau}_1\vec{\tau}_2 + g_0(\rho)\vec{\sigma}_1\vec{\sigma}_2 + g_0'(\rho)\vec{\sigma}_1\vec{\sigma}_2\tau_1\vec{\tau}_2 \right)$$

isoscalar