TENSIONS IN NEUTRINO-NUCLEUS MODELING

Joanna Sobczyk, IFIC (Valencia, Spain)

27 August 2019, NuFACT

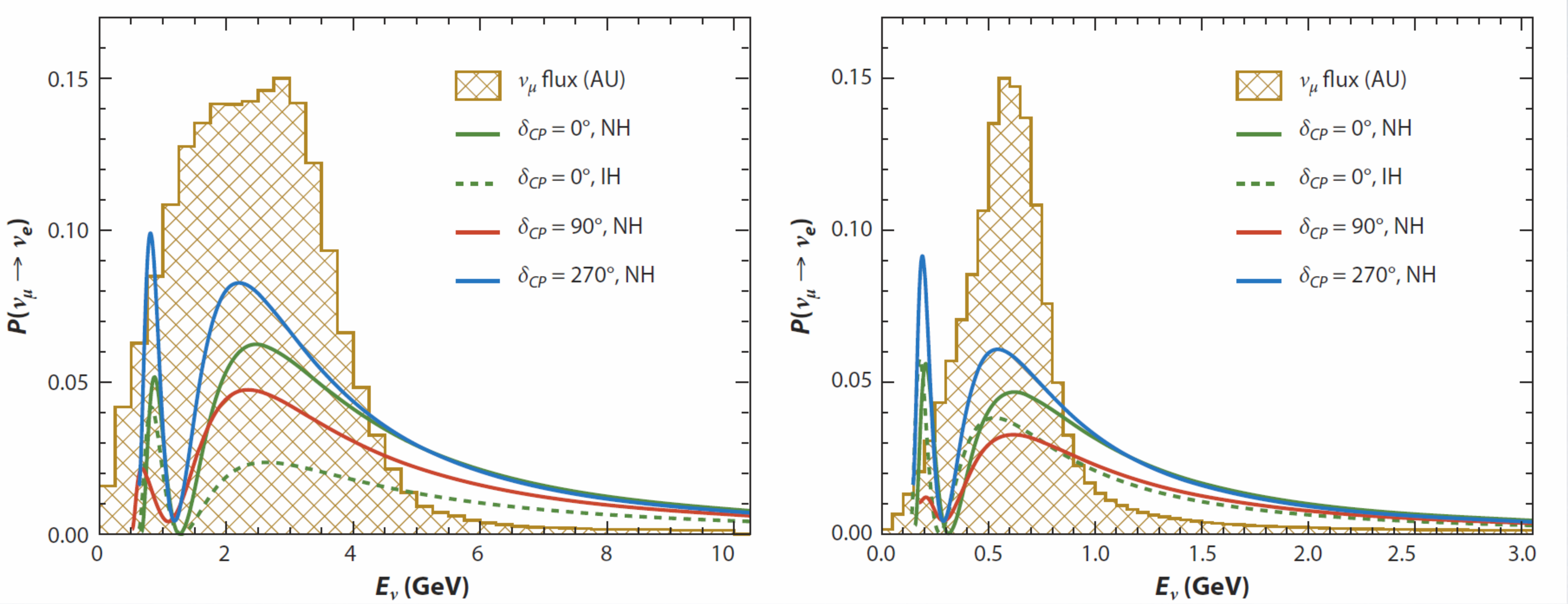
CSIC
Consejo Superior de Investigaciones Científicas

IFIC
Institut de Física Corpuscular

Vniversitat de València

MOTIVATION

DUNE T2HK



From: Diwan et al, Ann. Rev. Nucl. Part. Sci 66 (2016)

Systematic errors should be small since statistics will be high.

MOTIVATION

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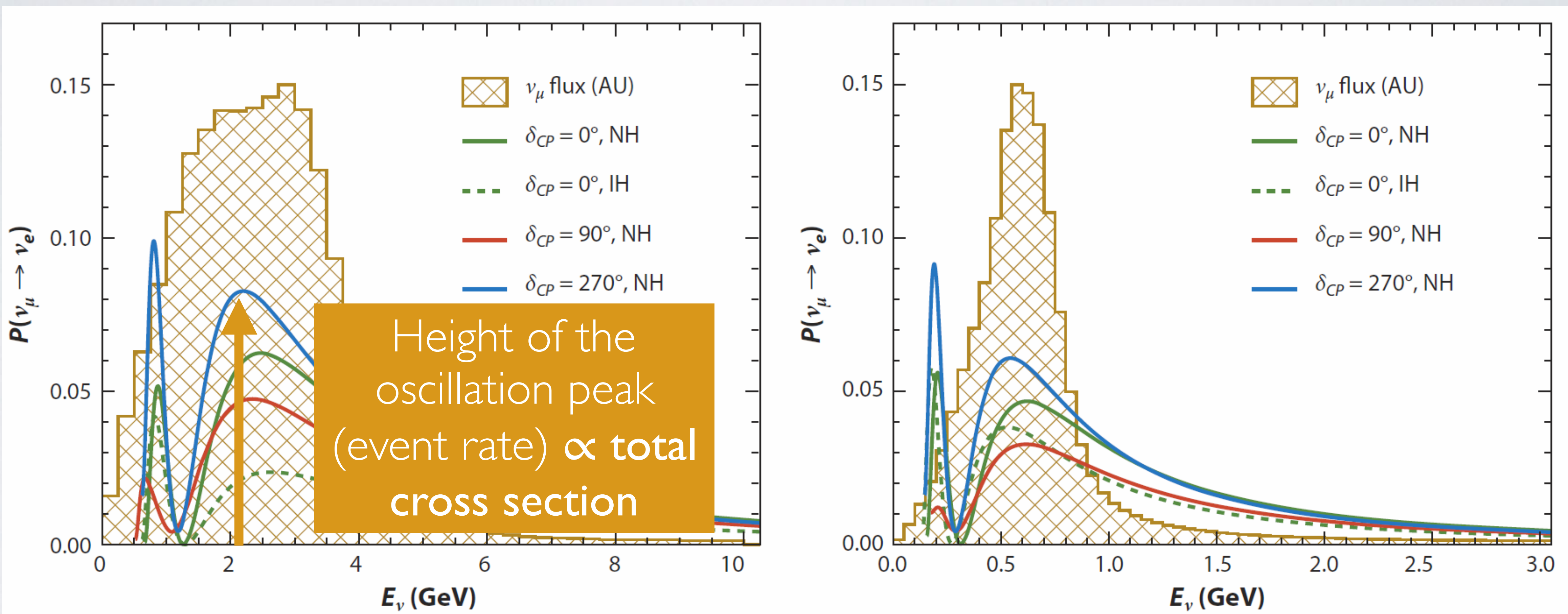
DUNE

T2HK



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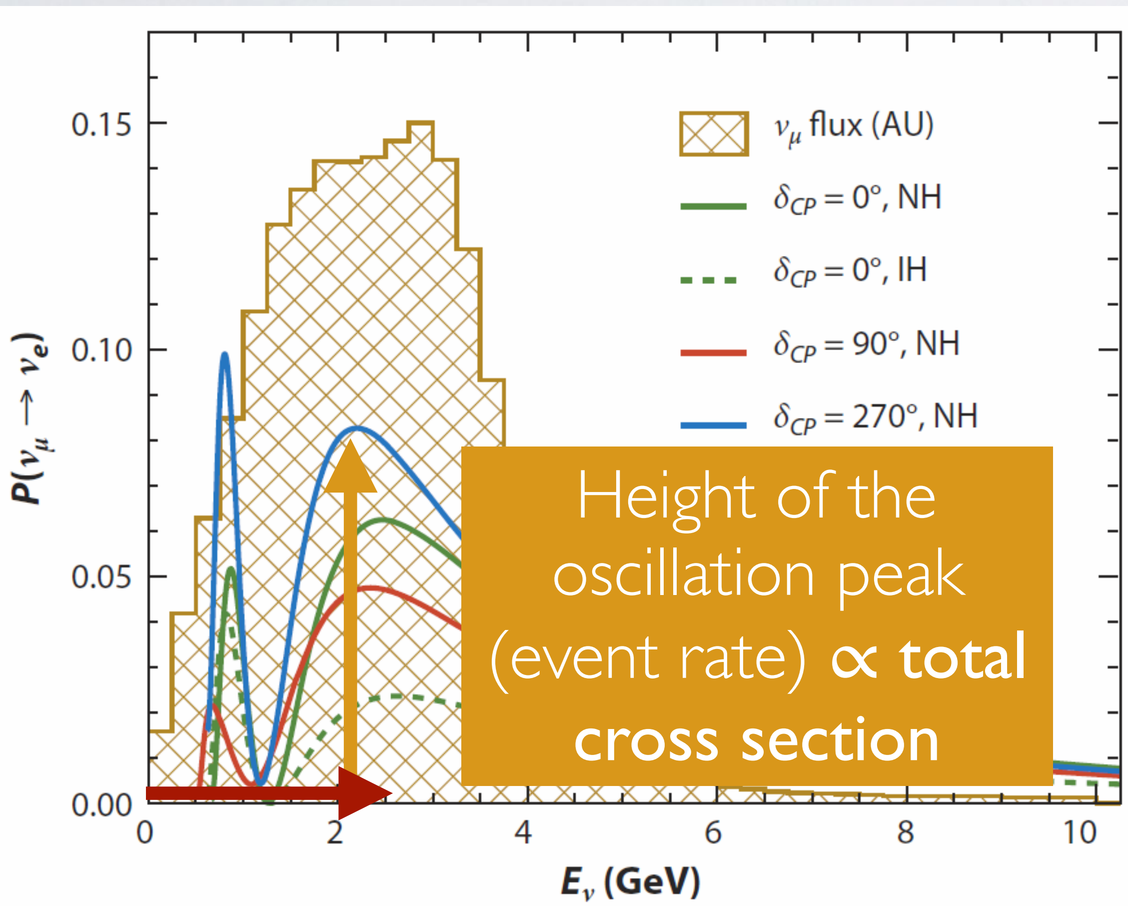
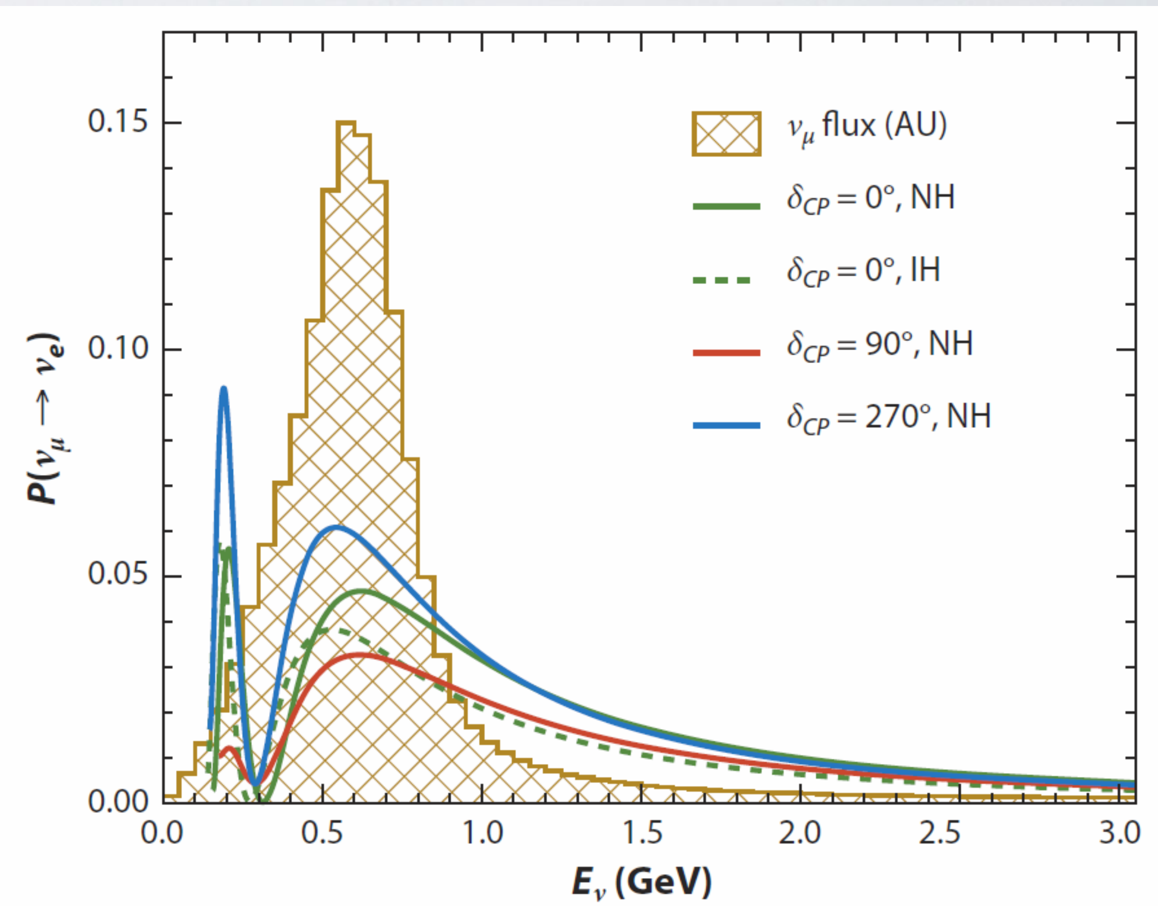
MOTIVATION

DUNE



T2HK



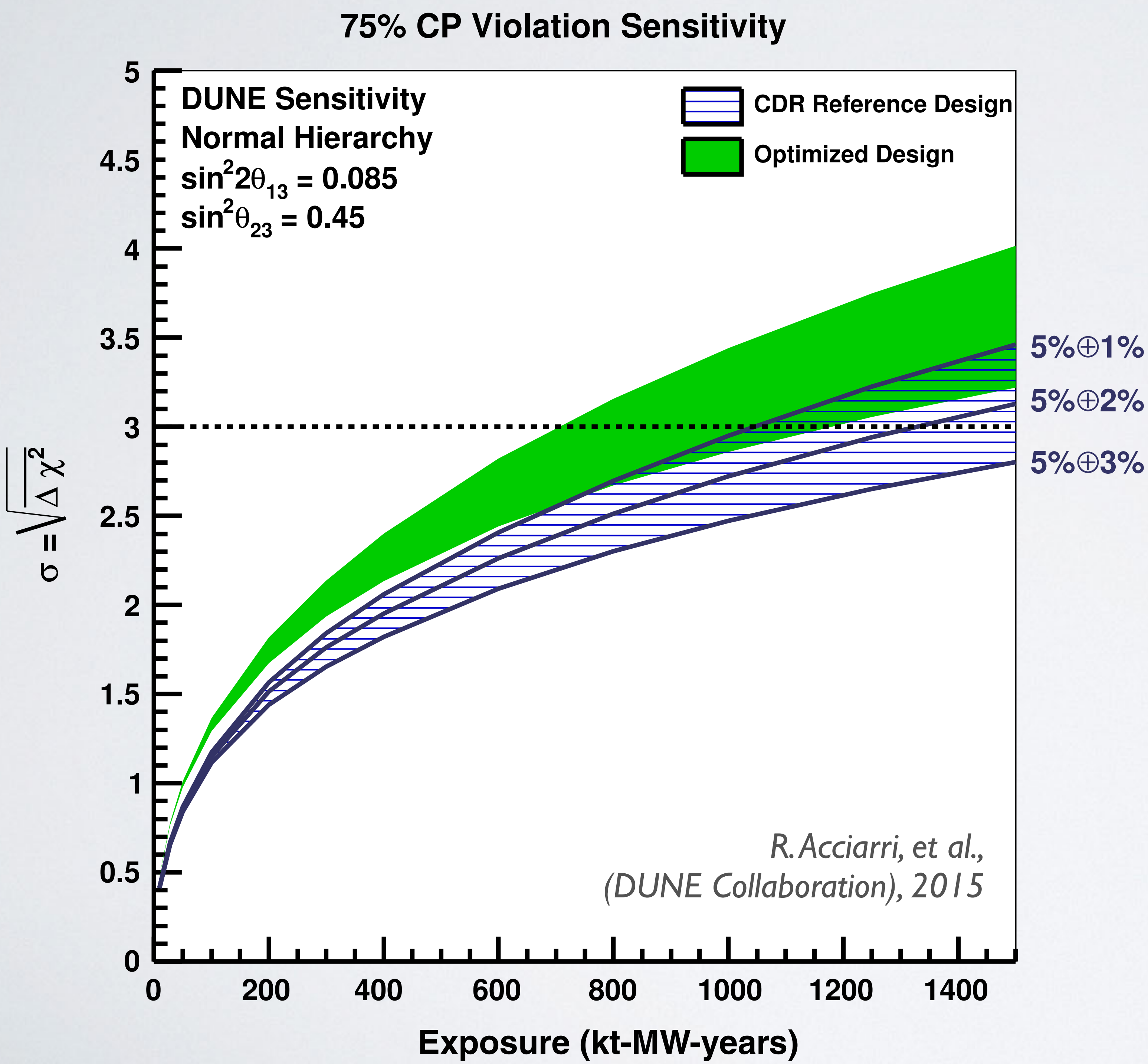
From: Diwan et al, Ann. Rev.Nucl. Part. Sci 66 (2016)

Position of the oscillation peak depends on **energy reconstruction**

DUNE aims at uncertainties < 1% meaning O(25 MeV) precision of energy reconstruction

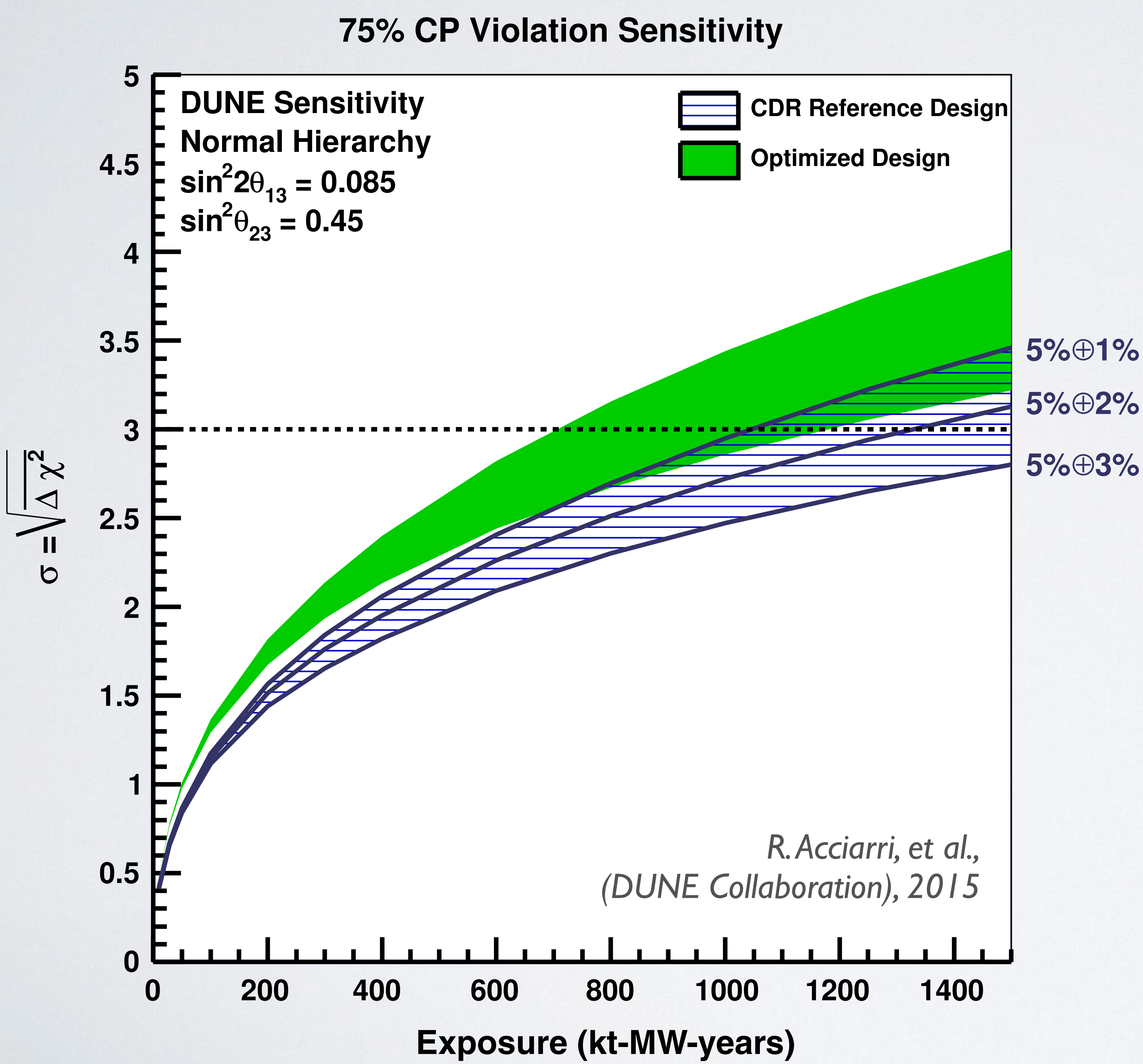
Systematic errors should be small since statistics will be high.

MOTIVATION



Lower systematic uncertainties can considerably lower the exposure needed to detect CP violation.

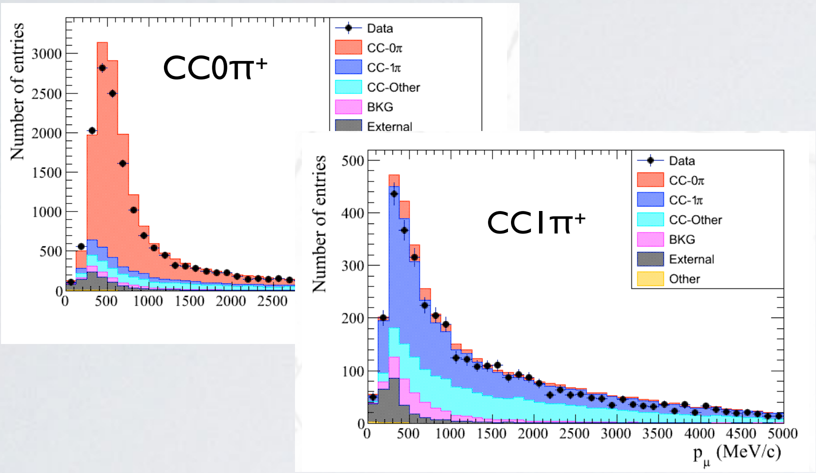
MOTIVATION

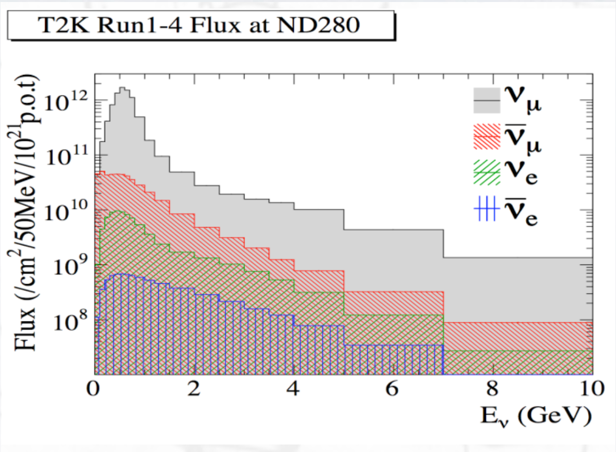


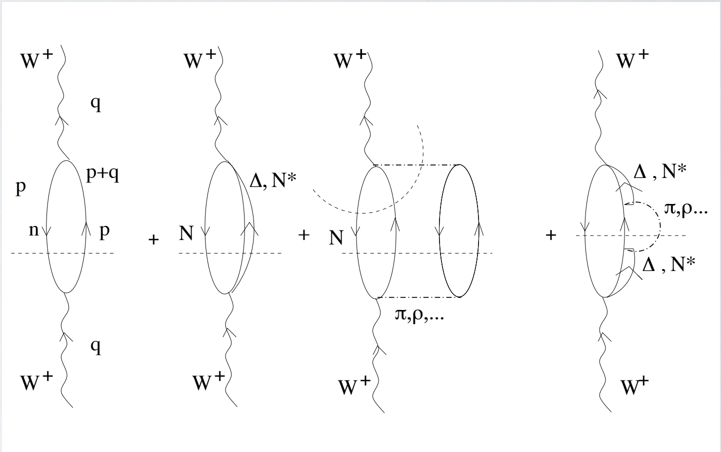
Lower systematic uncertainties can considerably lower the exposure needed to detect CP violation.

30/08 (Friday) 14:00h
WG2 L. Pickering

NEAR DETECTOR







Data at near detector

Flux prediction

x-sec models

corrected flux

corrected x-section prediction

correlation between flux & x-sec

(T2K example)

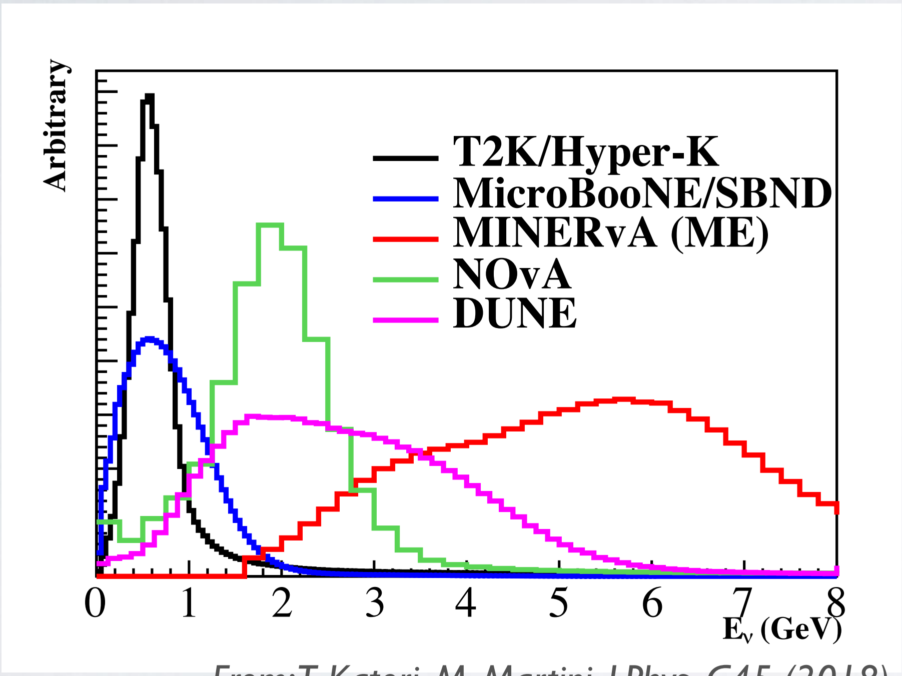
MOTIVATION

Far detector

- Different acceptance in near/far detector (different nuclear targets, backgrounds, position with respect to the beam…)
- $$\int \underbrace{\phi}_{\text{flux}} \times \underbrace{\sigma}_{\text{x-section}} \, dE \neq \int \phi \times \sigma \times \underbrace{\mathscr{P}}_{\text{oscillation probability}} \, dE$$ cancellation from the near detector is never full

Neutrino-nucleus interaction models are still crucial.

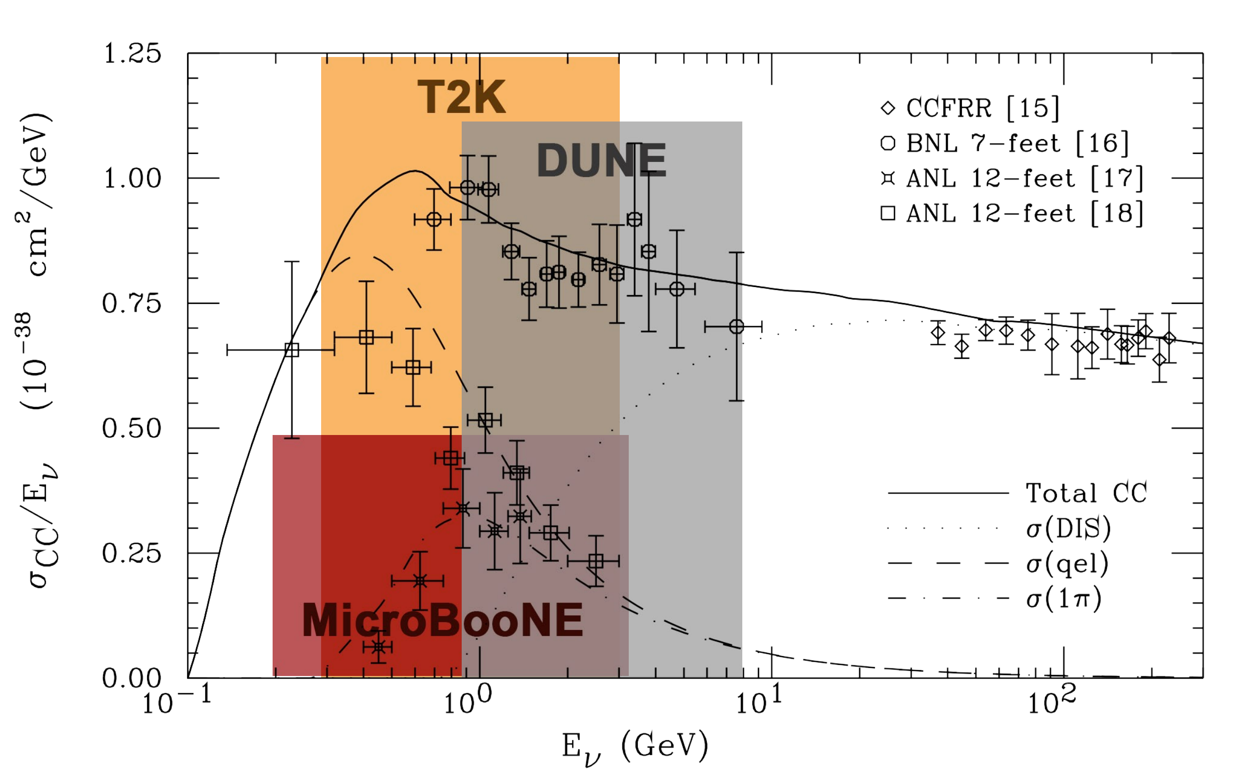
COMPLEX DYNAMICAL MECHANISMS



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

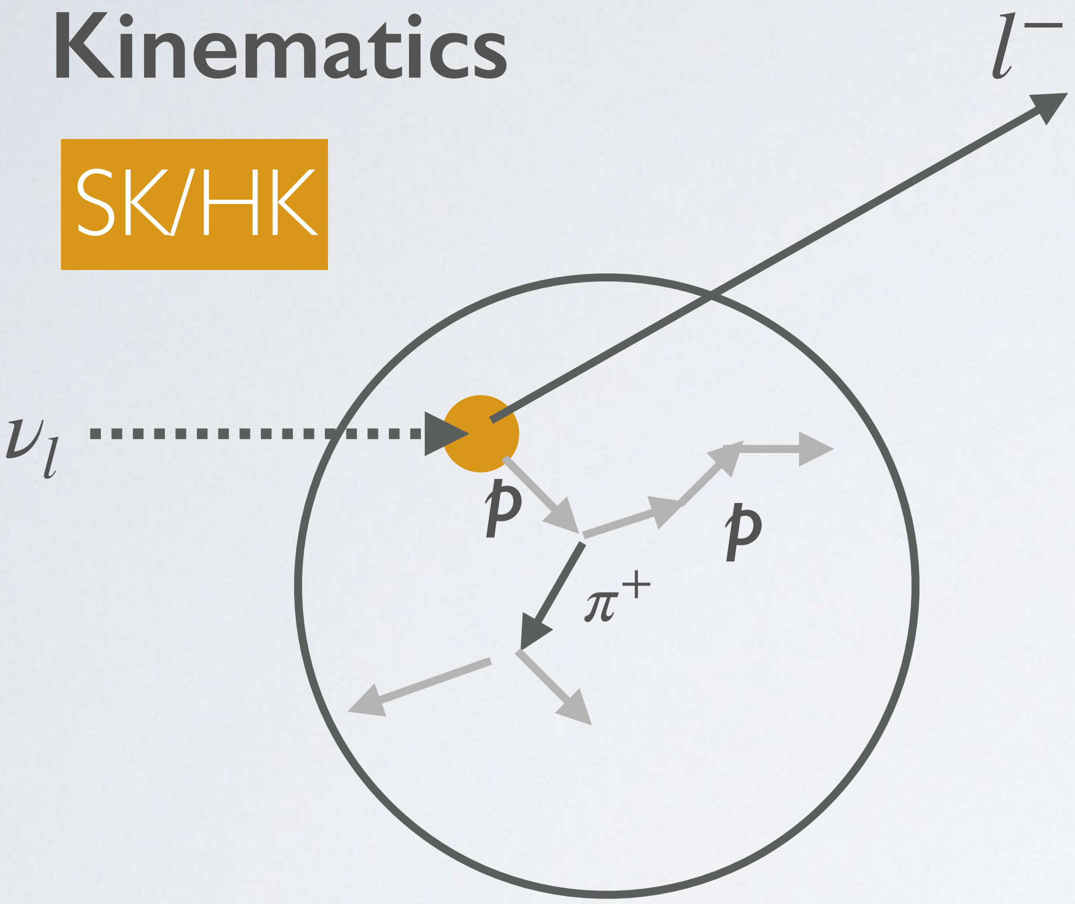


From: P. Lipari et. atl., PRL 74 (1995)

ENERGY RECONSTRUCTION

Kinematics

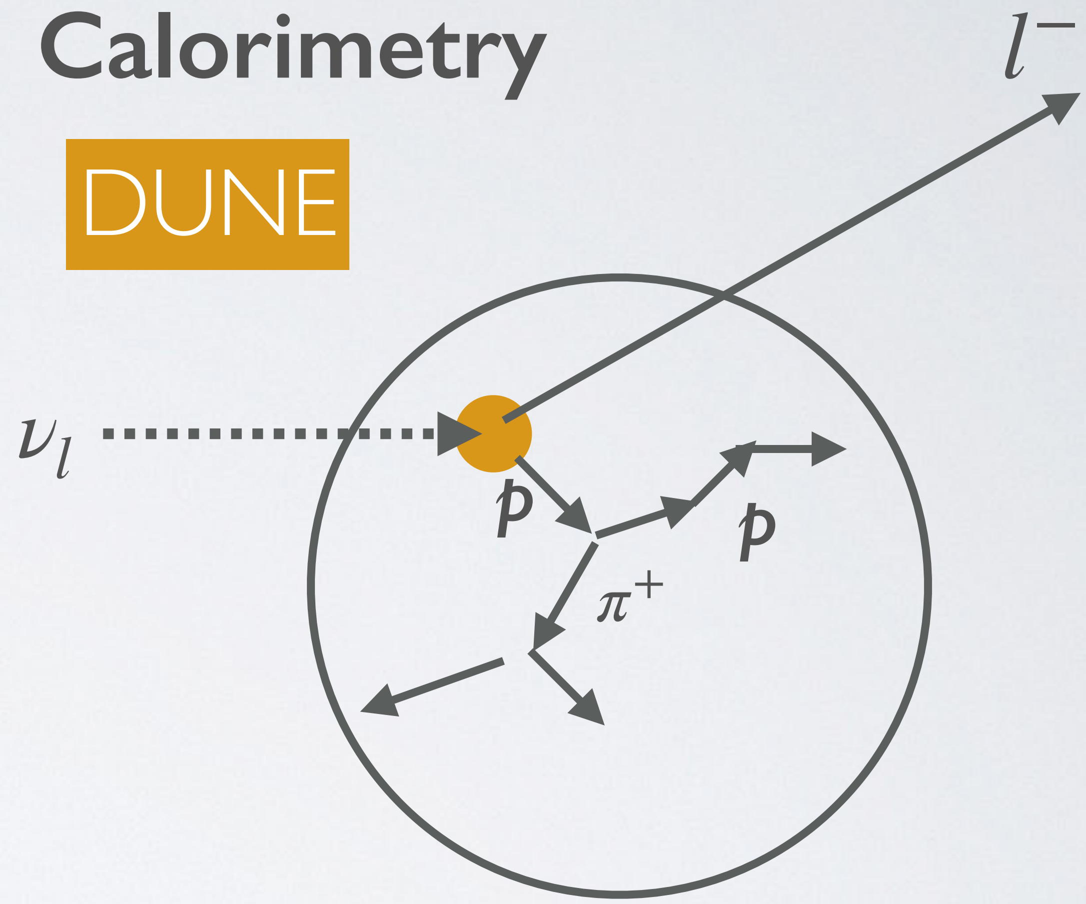
SK/HK



- 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.

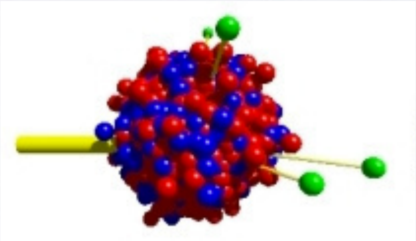
EXPERIMENTAL WISH LIST TO THEORISTS

- Predictions for a wide energy-transfer range (MeV-GeV)
- Different targets
- Both inclusive and exclusive cross-sections (exclusive = outgoing hadrons)
- Estimation of theoretical uncertainties

MONTE CARLO EVENT GENERATORS

connection point between
experiment and theory

GENIE



GiBUU

NuWro

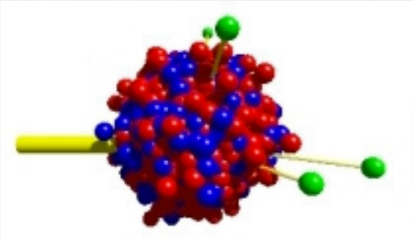
NEUT

"Testing and Improving Models of Neutrino Nucleus Interactions in Generators", ECT* June 2019

MONTE CARLO EVENT GENERATORS

connection point between experiment and theory

GENIE



GiBUU

NuWro

NEUT

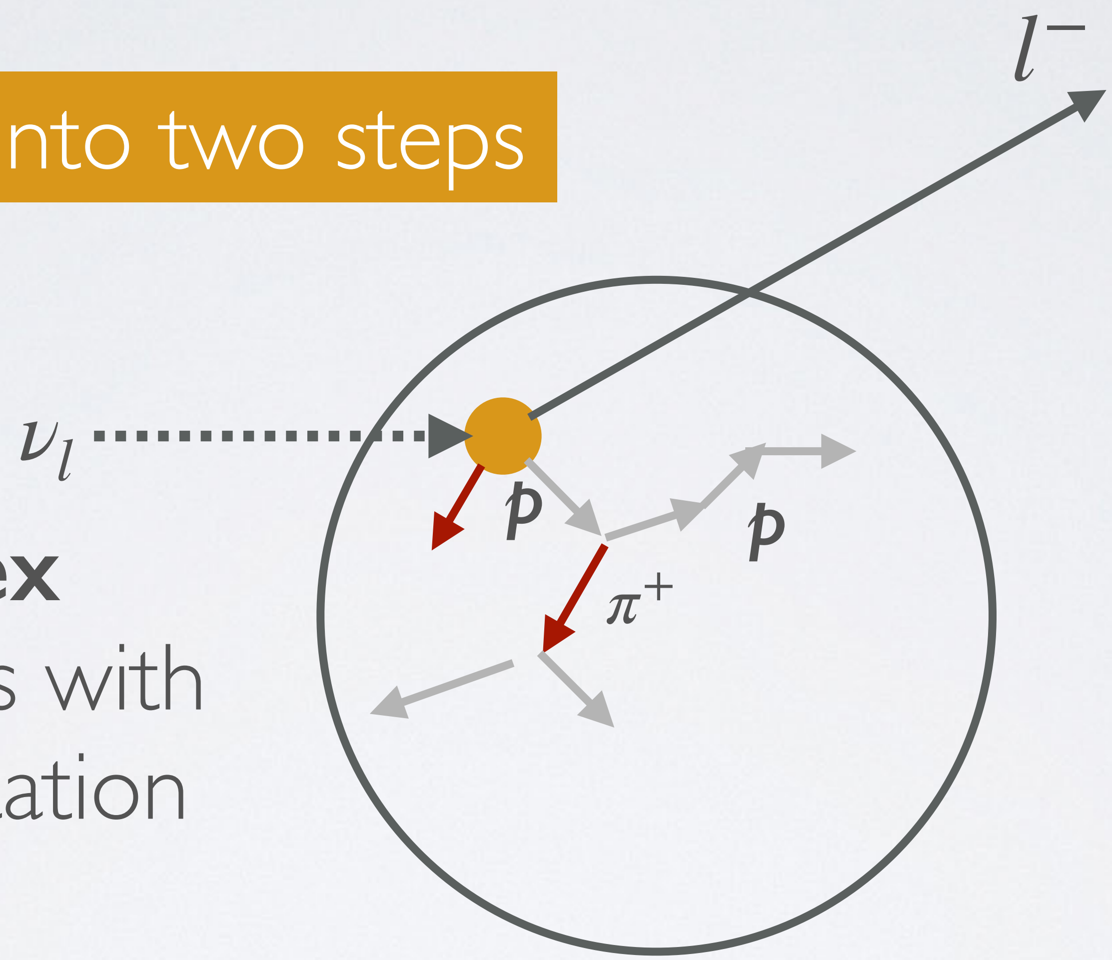
30/08 (Friday) 14:30h
WG2 A. Ashkenazi

"Testing and Improving Models of Neutrino Nucleus Interactions in Generators", ECT* June 2019

MONTE CARLO EVENT GENERATORS

Process factorised into two steps

primary vertex
(theoretical models with various implementation methods)



FSI=final state interactions
(each MC has a different model)

Inherent problems of **factorization**:
- quantum process split in a classical way
- possible double-counting

But this is the only way to compare theoretical models with experiment

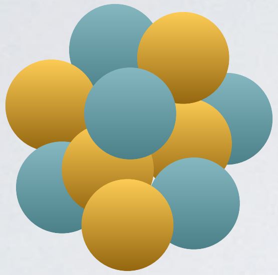
MONTE CARLO WISH LIST FOR THEORISTS

- fast implementation of theoretical models (in particular: description of all the outgoing hadrons)

- possible free parameters of theory to "tune"

- validation of models to make them trustworthy and estimate precision (e.g. using electron data)

NUCLEAR THEORY PERSPECTIVE



$$\mathscr{H} = \sum_i \frac{p_i^2}{2M} + \sum_{i<j} v_{ij} + \ldots$$

non-relativistic theory!

$\mathscr{H}\,|i\rangle = E\,|i\rangle$ ground state of correlated nucleons

charge-current operator: $j^\mu_{cc} = \bar{u}\,\gamma^\mu(1+\gamma_5)(\cos\theta_C\,d + \sin\theta_C\,s)$

we want to calculate a transition to final state:

$$J^\mu = \langle f\,|\,j^\mu_{cc}\,|\,i\rangle$$

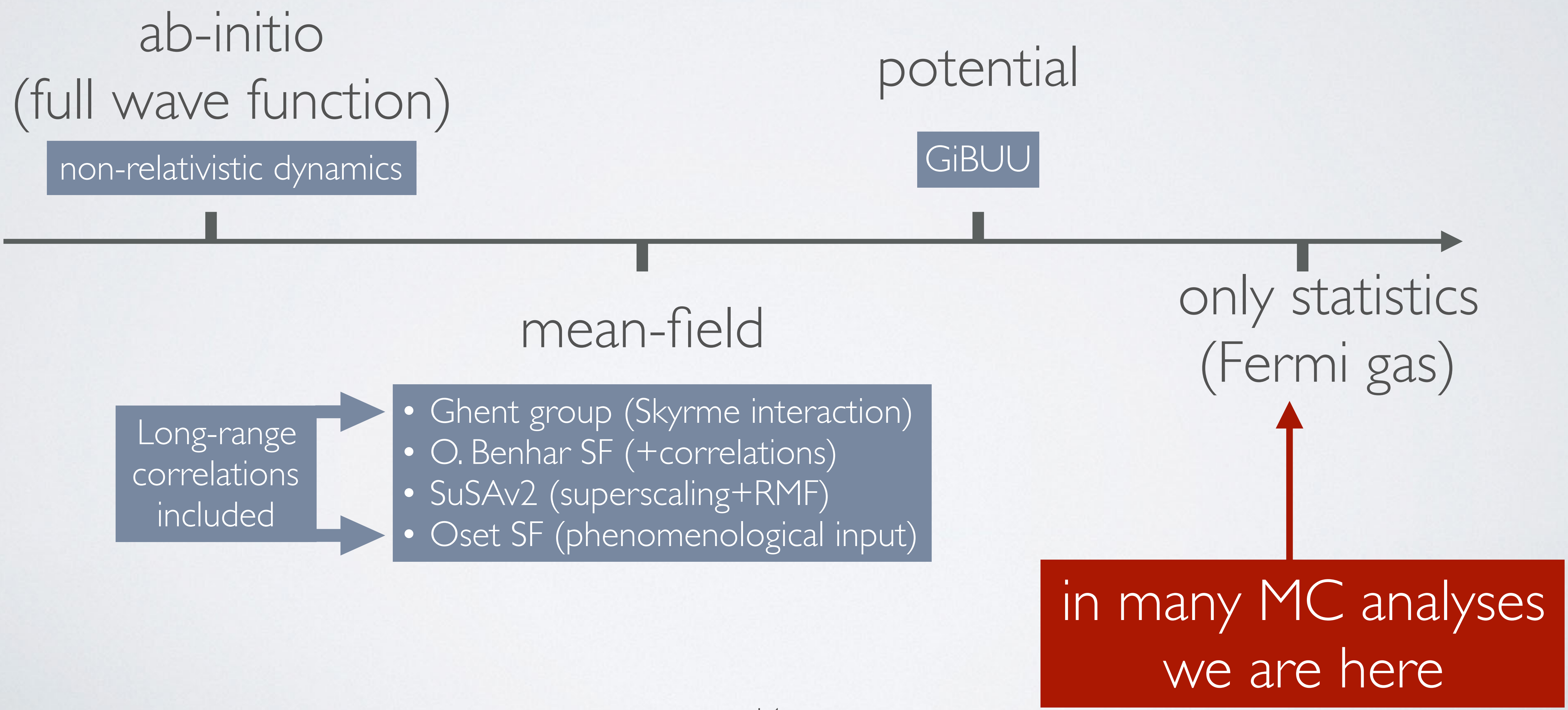
$$\frac{d\sigma}{dQ^2 dW} \propto L^{\mu\nu}(J_\mu J_\nu^\dagger)$$

THEORETICAL PERSPECTIVE

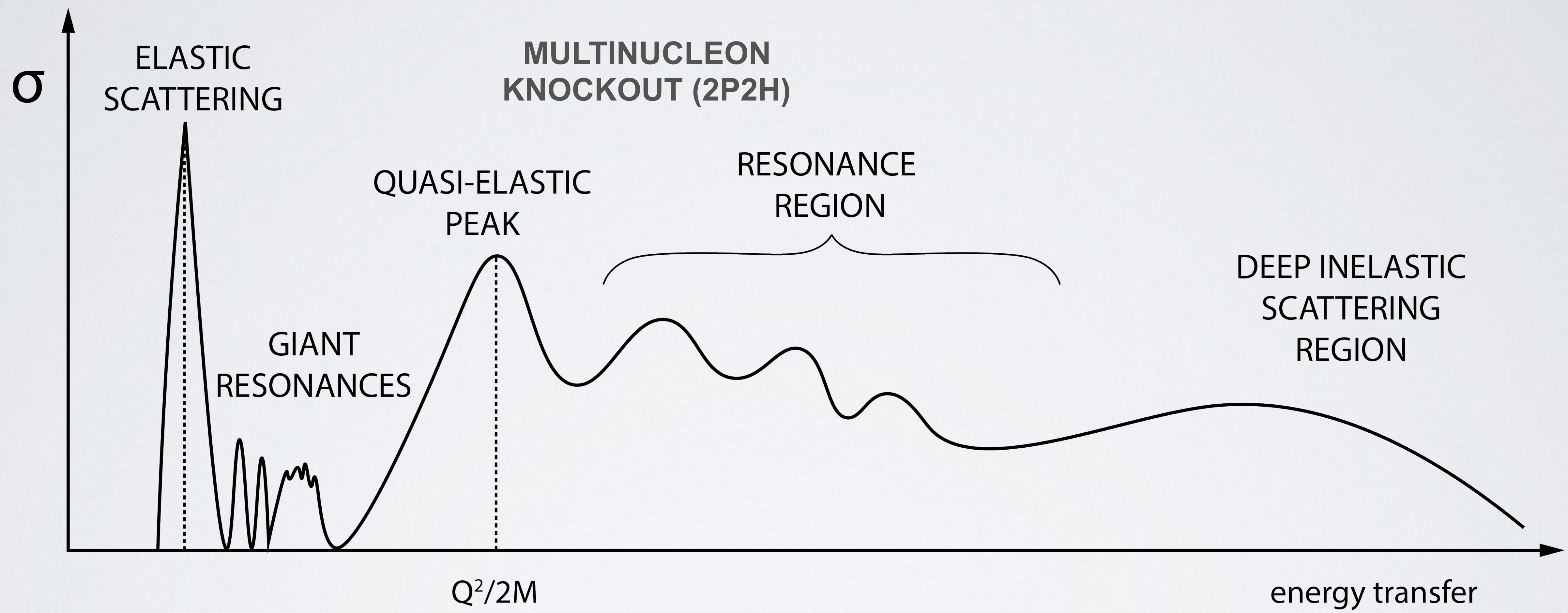
- Two levels of difficulties:
  - **Hadron dynamics** (axial form-factors, pion production,…)
  - **Nuclear physics** (non-relativistic, nucleon dynamics in nuclear medium, multinucleon knockout, long-range correlations…)
- (which are connected e.g. Δ description in nuclear medium, off-shell nucleons,…)

INITIAL STATE

Each approach has its virtues and limitations.



HOW WELL ARE WE DOING?

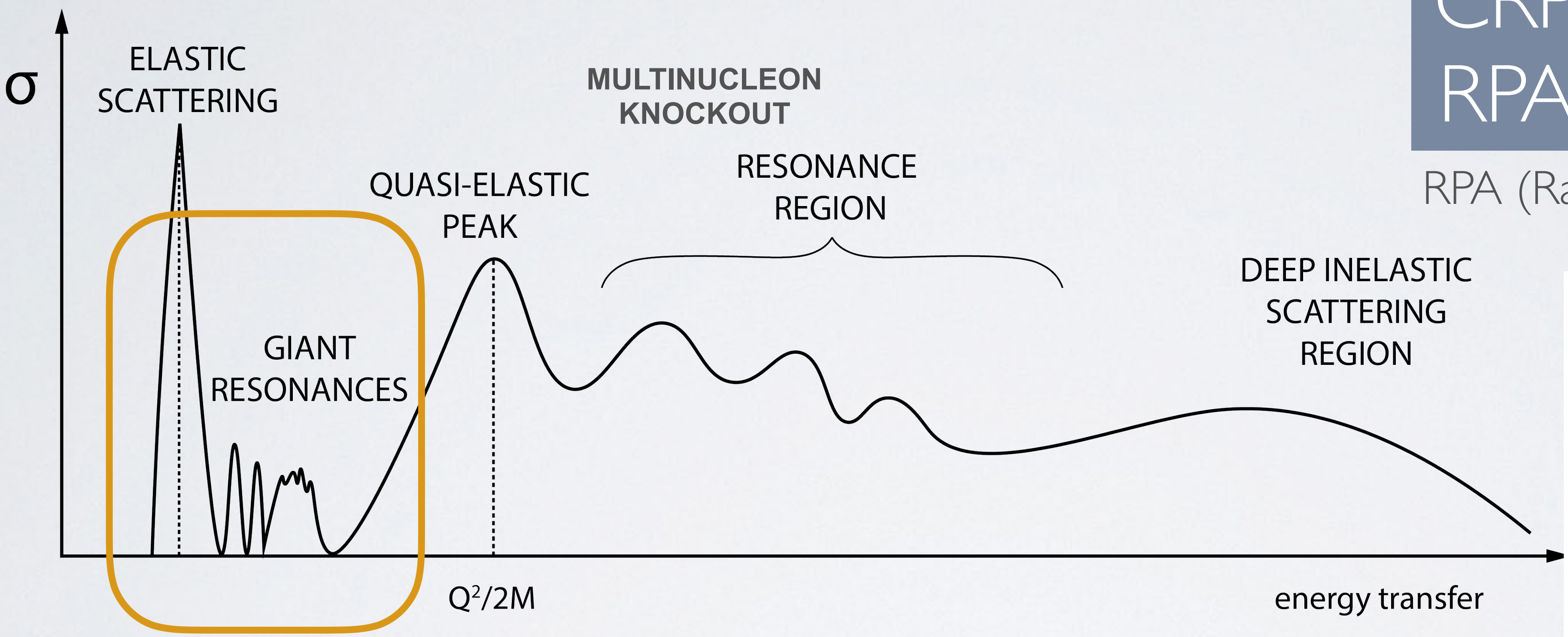


We need a consistent theoretical description of all mechanisms.

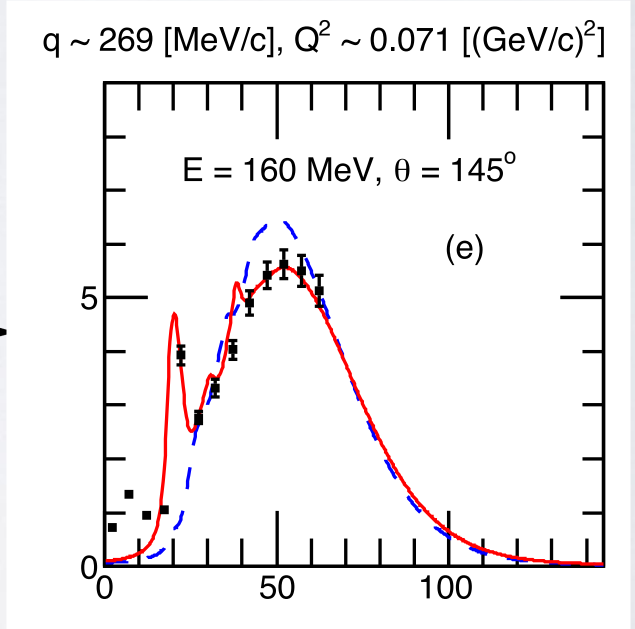
HOW WELL ARE WE DOING?

CRPA - Ghent group
RPA - Valencia group

RPA (Random Phase Approximation)

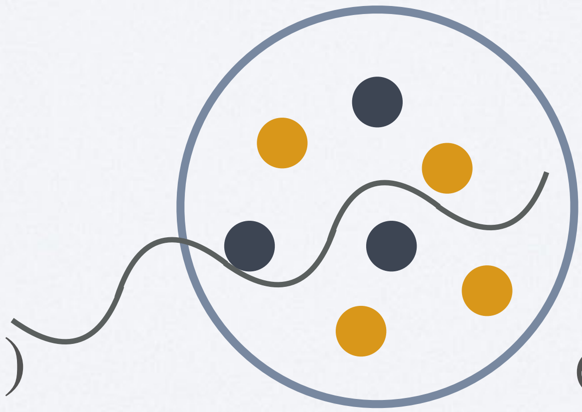


requires careful nuclear structure



V. Pandey, N. Jachowicz, et al
PRC92 (2015) no.2, 024606

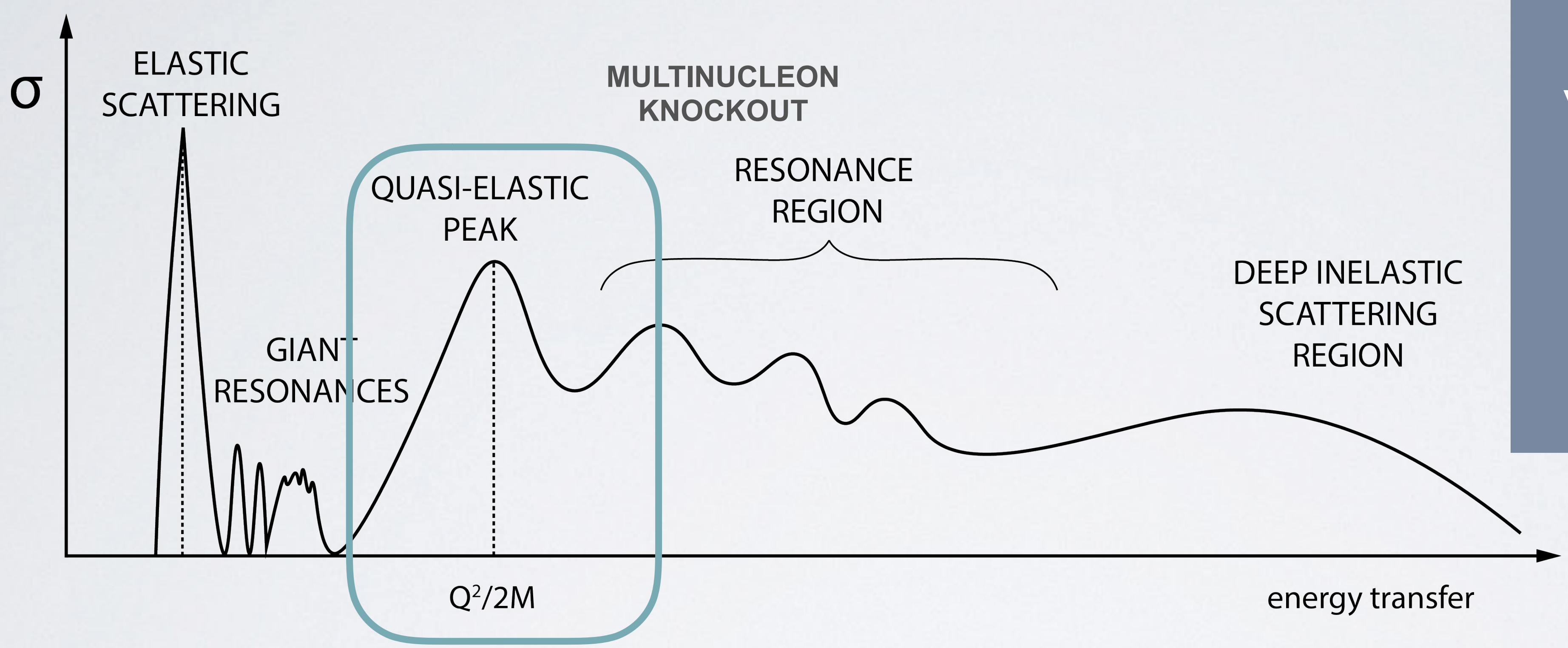
$W^+(q^0, \vec{q})$



excited states of nucleus

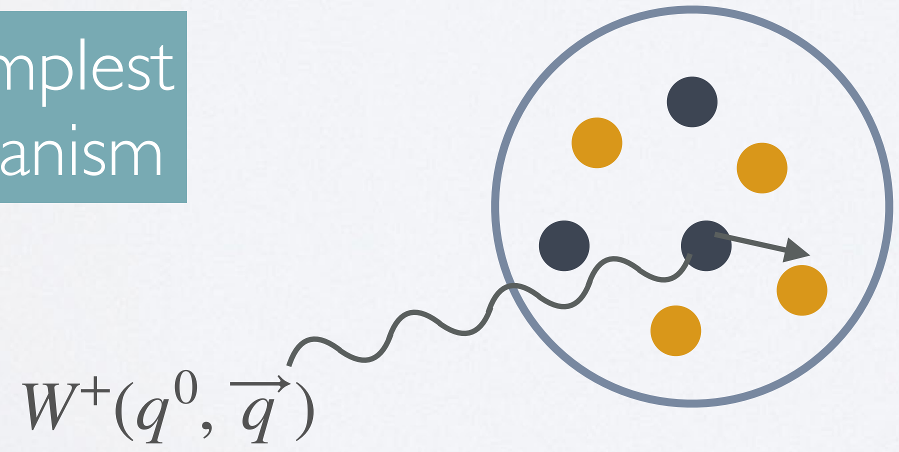
M. Martini, N. Jachowicz et al
Phys.Rev. C94 (2016) no.1, 015501

HOW WELL ARE WE DOING?



Benhar SF
Ghent group
Valencia group
GiBUU
SuSAv2
. . .

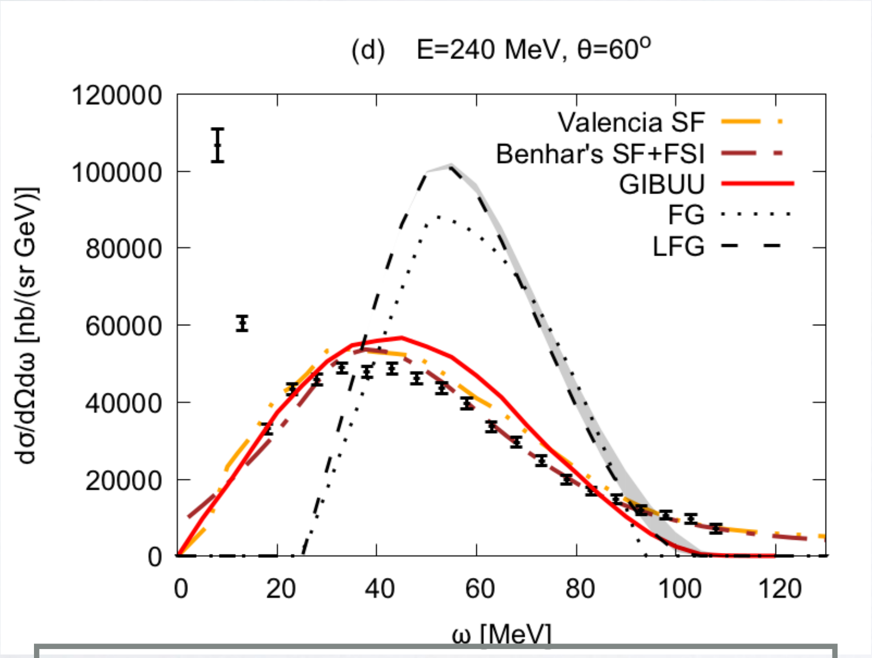
the simplest mechanism



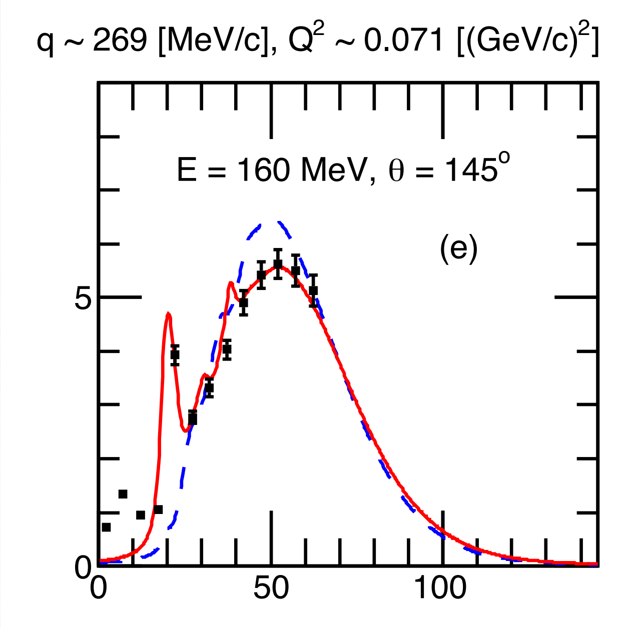
- interaction on a single bound nucleon
- one nucleon produced at the primary vertex

QUASI-ELASTIC MECHANISM

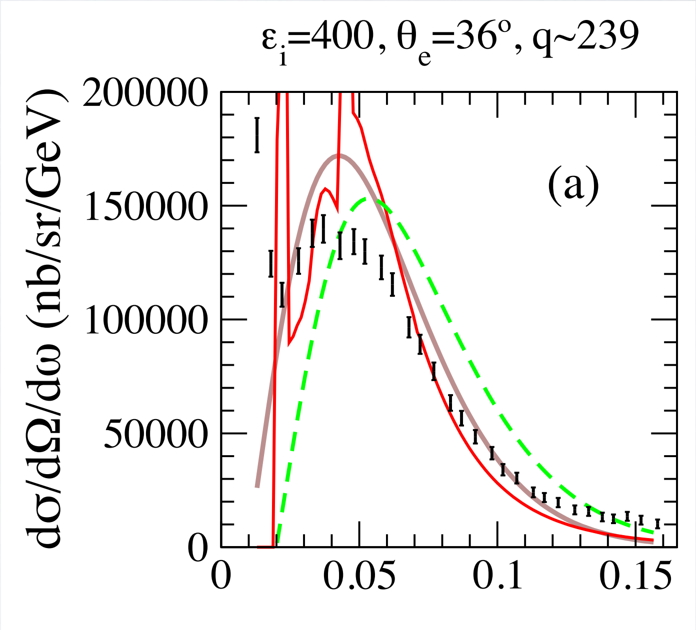
- For **inclusive** cross-section, many theoretical models seem to work reasonably well (benchmark with electron data)



Valencia/Benhar/GiBUU



Ghent



RMF/SuSA/SuSAv2

V. Pandey, N. Jachowicz, et al. PRC92 (2015) no.2, 024606
R. González-Jiménez, G. D. Megias, et al. PRC 90, 035501
J.E.S., PRC96 (2017) no.4, 045501

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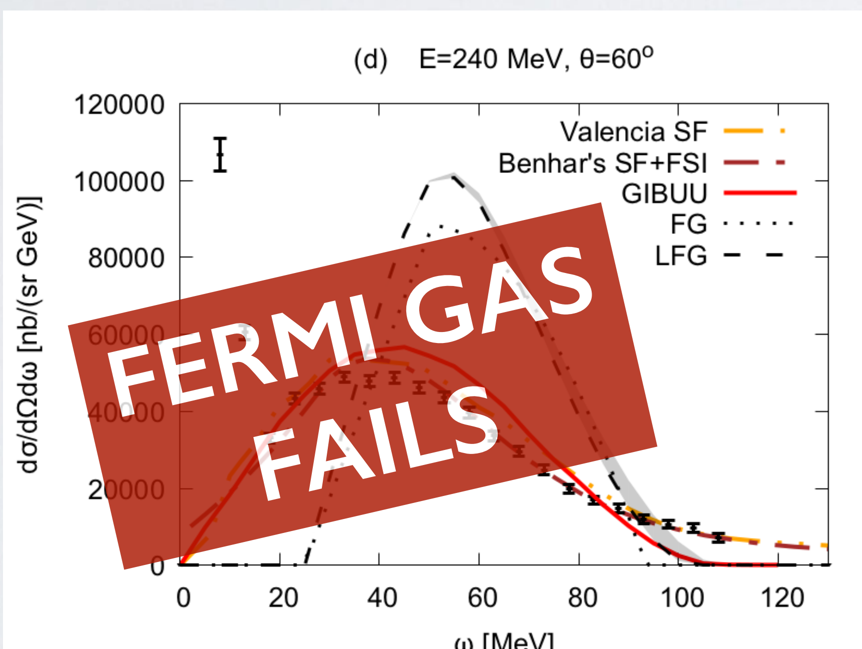
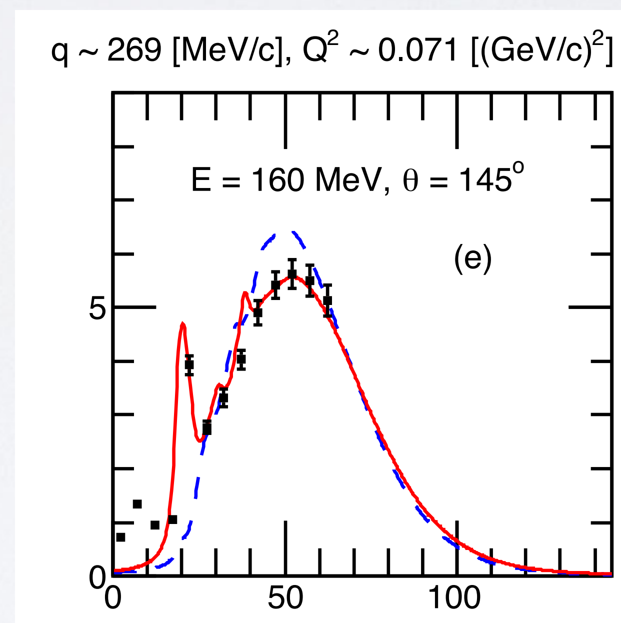
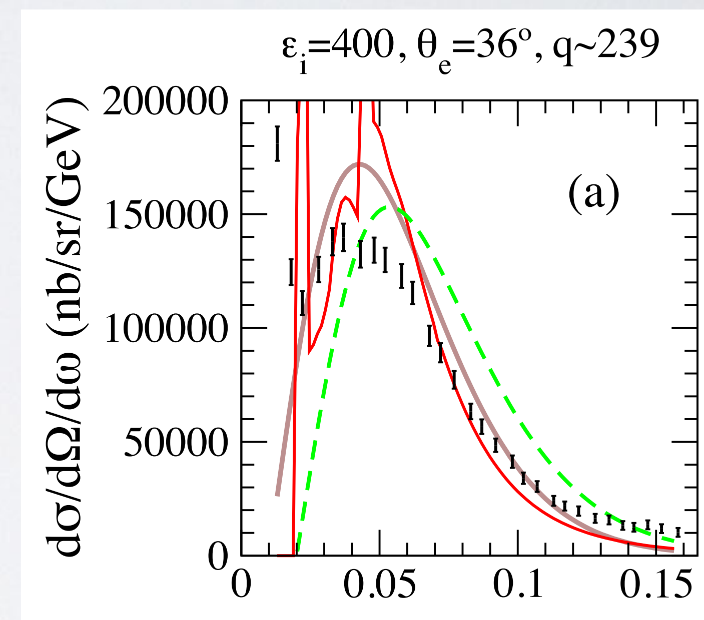


Valencia/Benhar/GiBUU



Ghent



RMF/SuSA/SuSAv2

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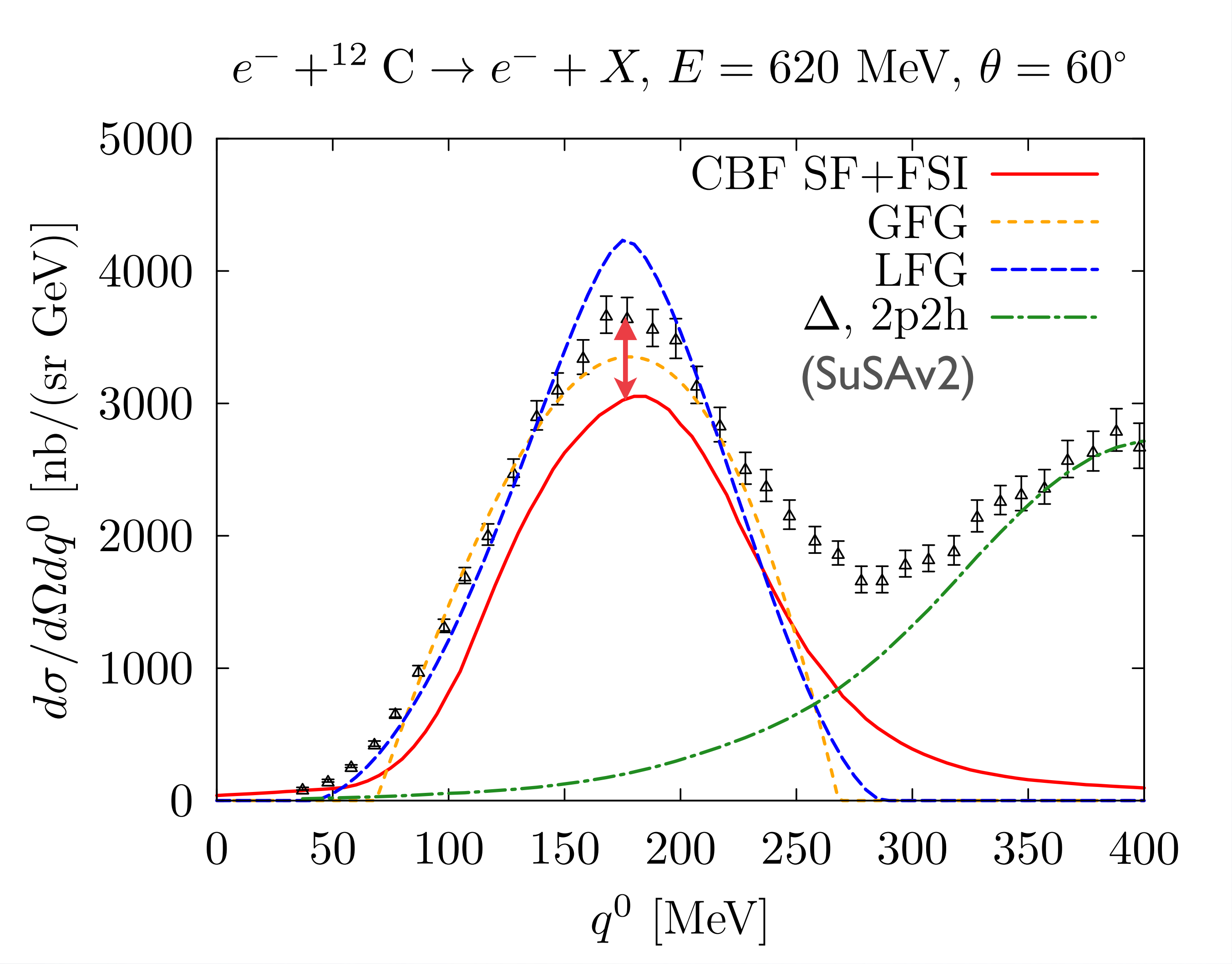
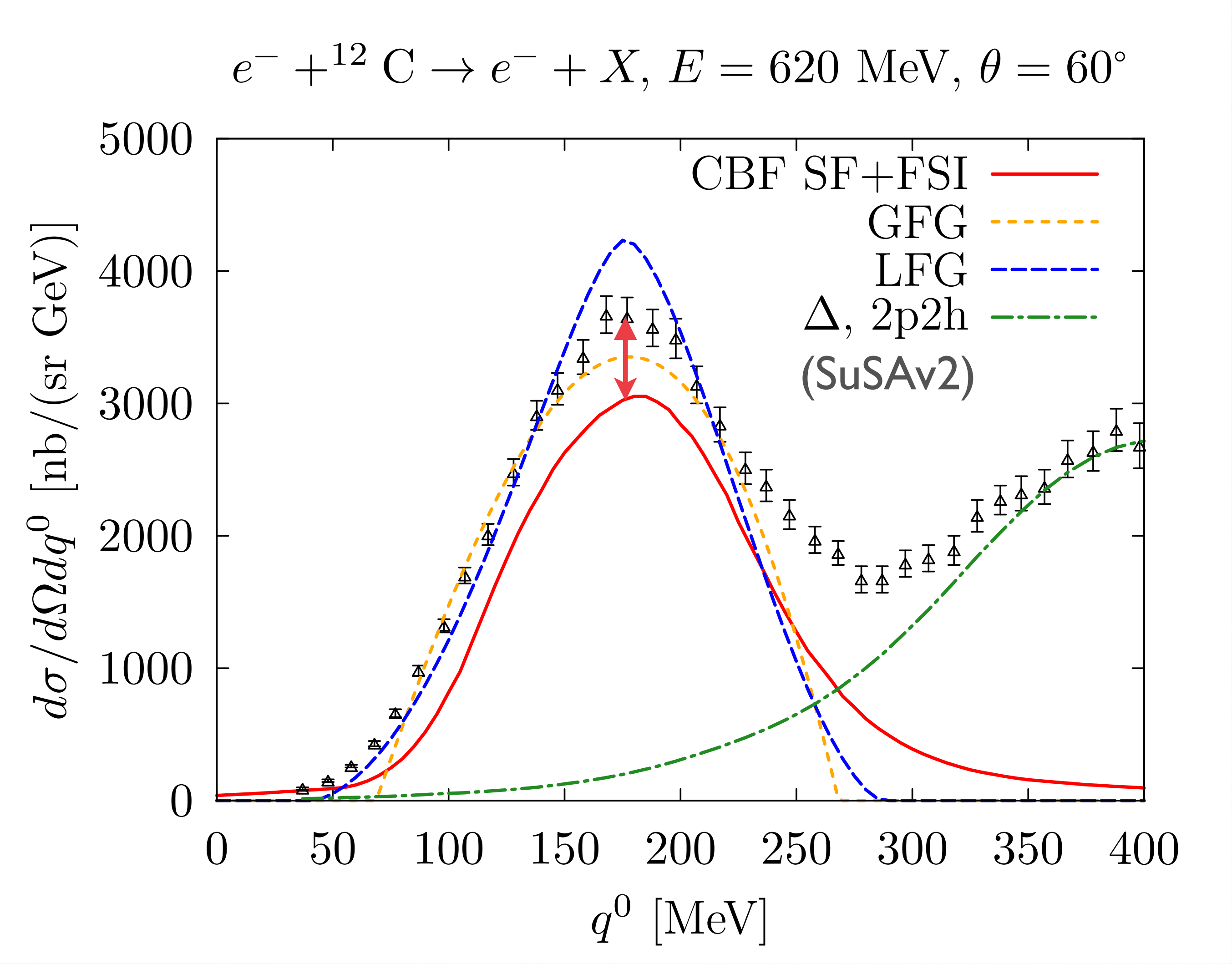
J.E.S., PRC96 (2017) no.4, 045501

QUASI-ELASTIC MECHANISM



To make a precise comparison with inclusive data we need to include other mechanisms (multinucleon knockout, resonance region).

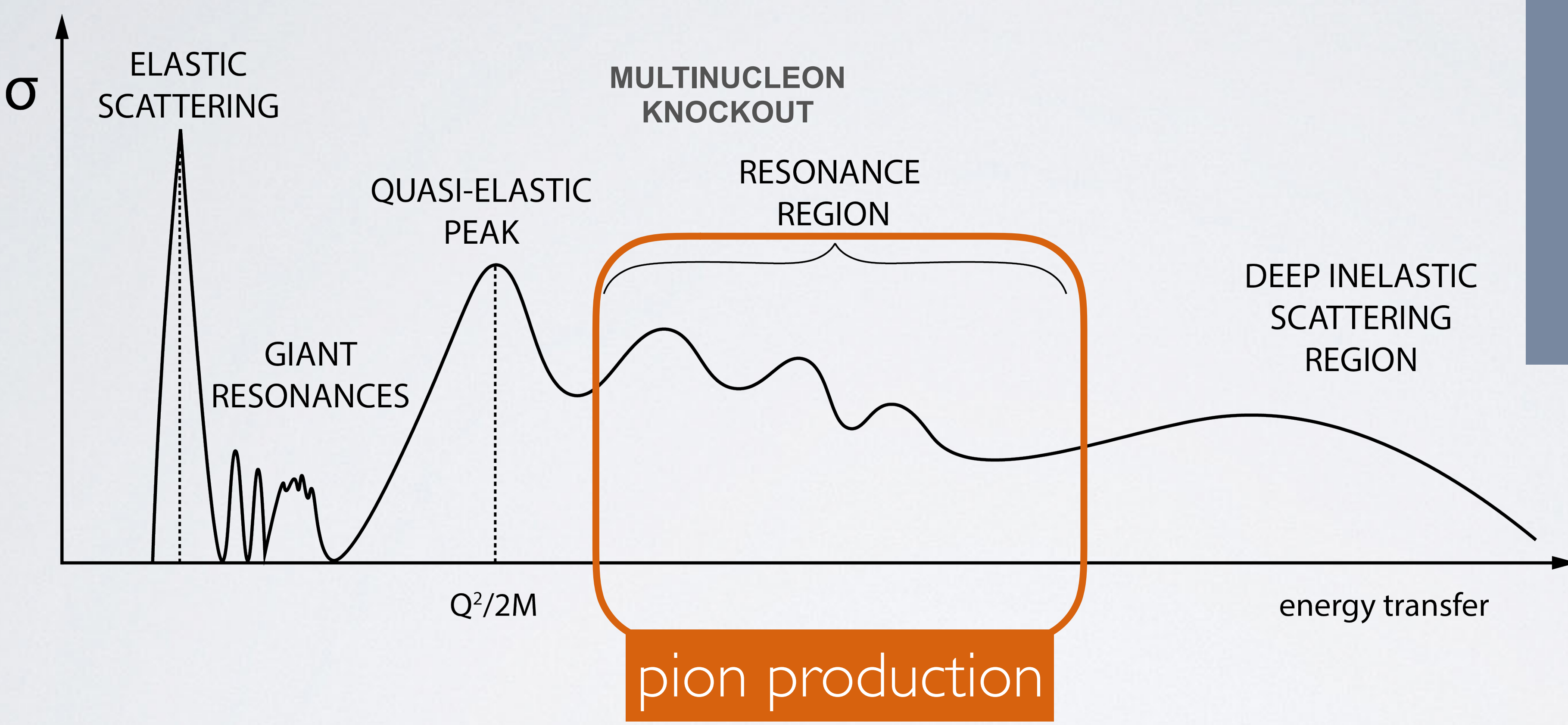
QUASI-ELASTIC MECHANISM



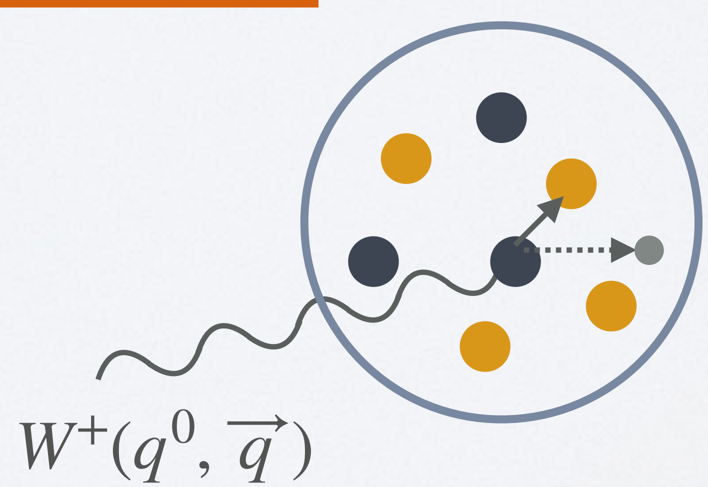
To make a precise comparison with inclusive data we need to include other mechanisms (multinucleon knockout, resonance region).

How do models work for exclusive cross-sections (outgoing nucleon)?

HOW WELL ARE WE DOING?



DCC
Valencia group
GiBUU
Rein-Sehgal



- interaction on a single bound nucleon
- nucleon and pion produced at the primary vertex

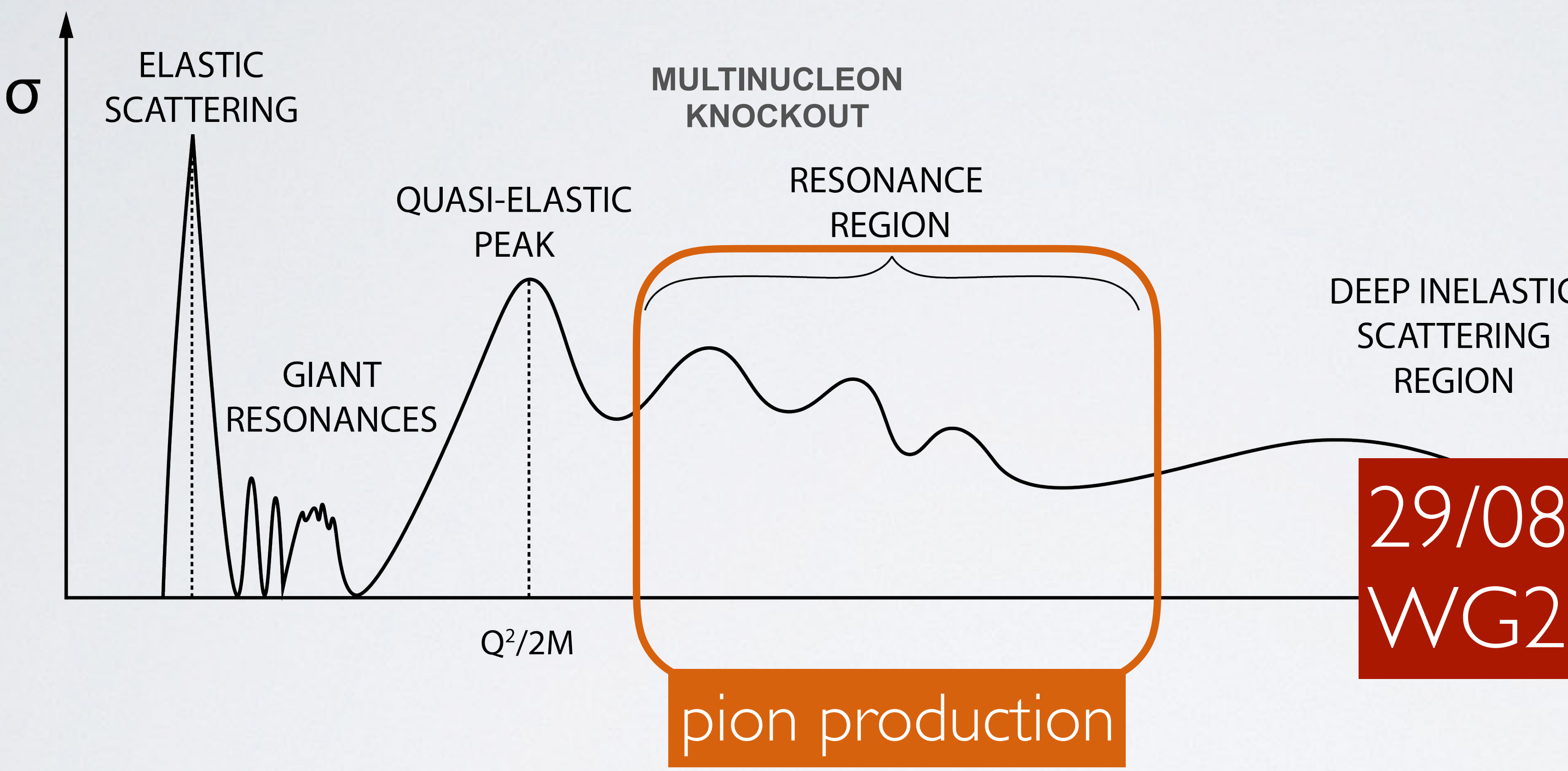
DCC: S.X.Nakamura, H. Kamano, T.Sato, PRD92(2015), T.Sato, D. Uno, H.Lee PRC67(2003)

Valencia: E. Hernandez, J. Nieves, M. Valverde PRD76(2007)

GiBUU: T. Leitner, O.Buss, L.Alvarez-Ruso, U. Mosel, PRC79(2009)

Rein-Sehgal: D. Rein, L. M. Sehgal AP133(81)

HOW WELL ARE WE DOING?



DCC
Valencia group
GiBUU
Rein-Sehgal

29/08 (Thursday) 12:00h
WG2 E. Hernandez

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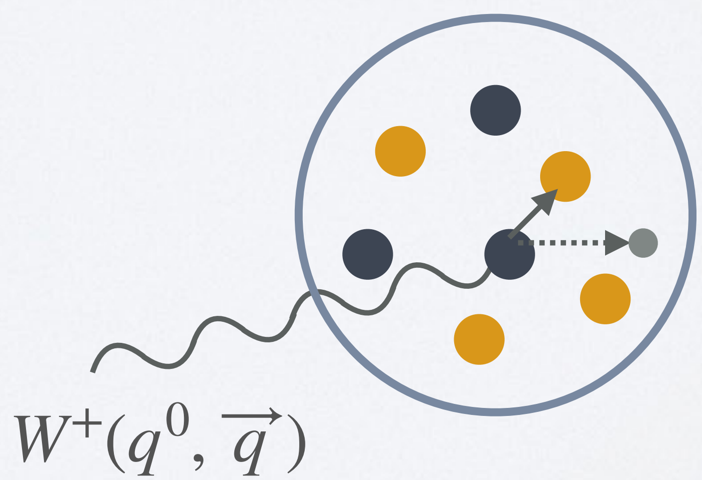

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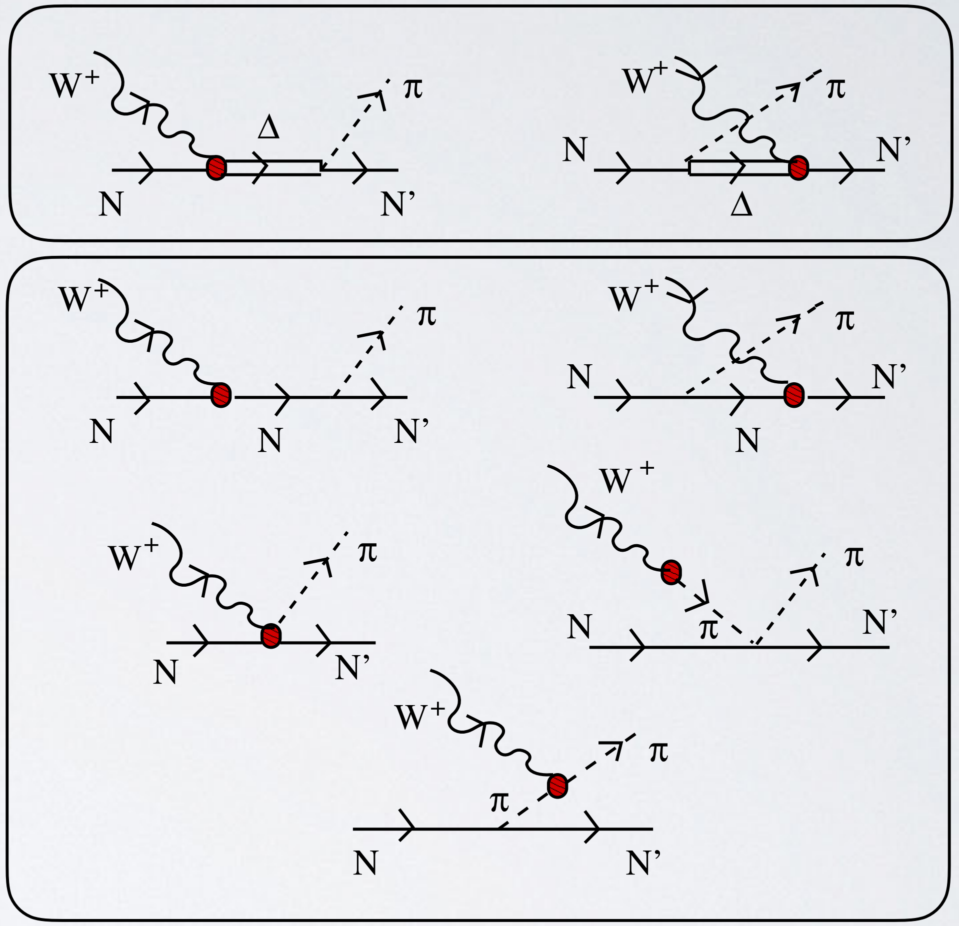
PION PRODUCTION

- Hadron dynamics should be checked first (interaction on a single nucleon, without nuclear effects)
- Background coming from chiral perturbation theory + resonances + phases between various contributions
- Important: unitary condition
- Models should be confronted with electron scattering data.



J.E.S., E.Hernandez, S.Nakamura, J. Nieves, T. Sato
PRD 98, 073001

PION PRODUCTION

	resonances	background	unitarity	1pion	2pions
Rein-Sehgal	Δ, N*,…	✗	✗	✓	possible
Valencia model	Δ, N*	✓ ChPT	✓ (partial)	✓	✓
GiBUU	Δ, N*,…	✓ phenomenological, incoherent	✗	✓	✓
DCC	Δ, N*,…	✓	✓	✓	✓

CHALLENGES

- More hadrons in the final state (pion production, multinucleon knockout) # of integrals is high → computational time grows.

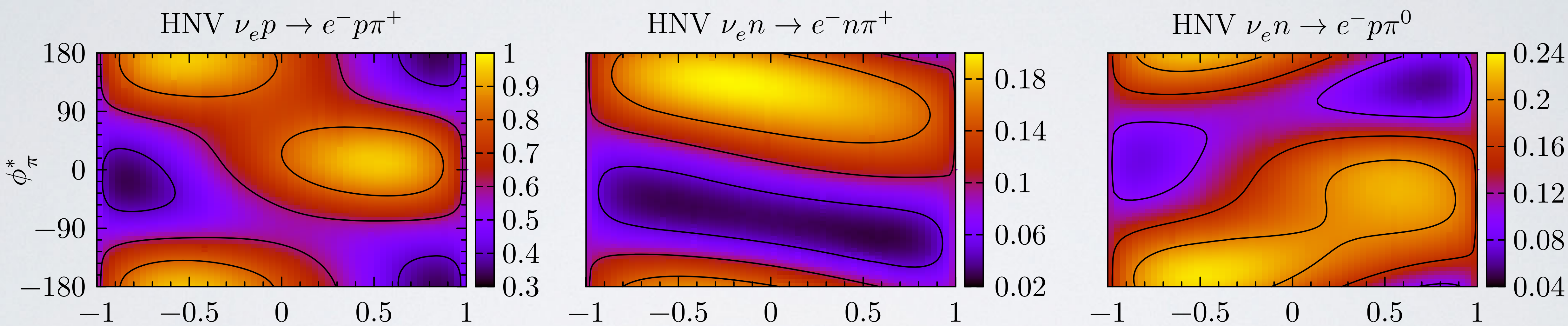
- Usual **prescription** used in the MC generators:

    1. Inclusive cross-section gives a weight of an event $d\sigma/dQ^2dW$

    2. initial nucleon(s) below the Fermi level is generated

    3. final hadrons are generated in CM according to the phase space (so-called factorization)

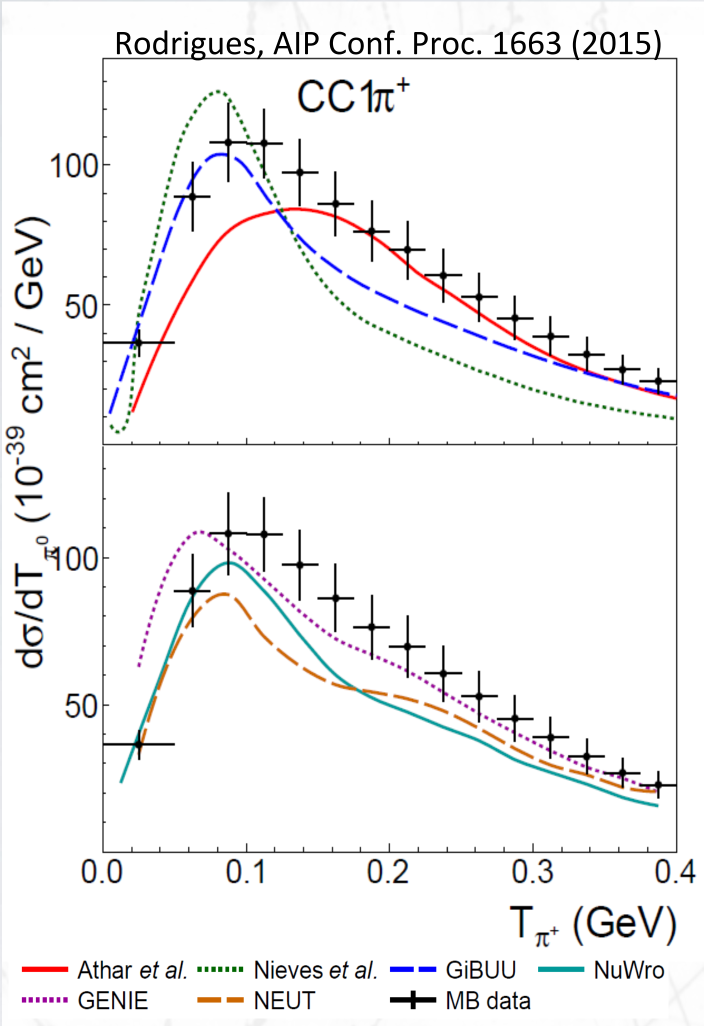
OUTGOING PION DISTRIBUTION



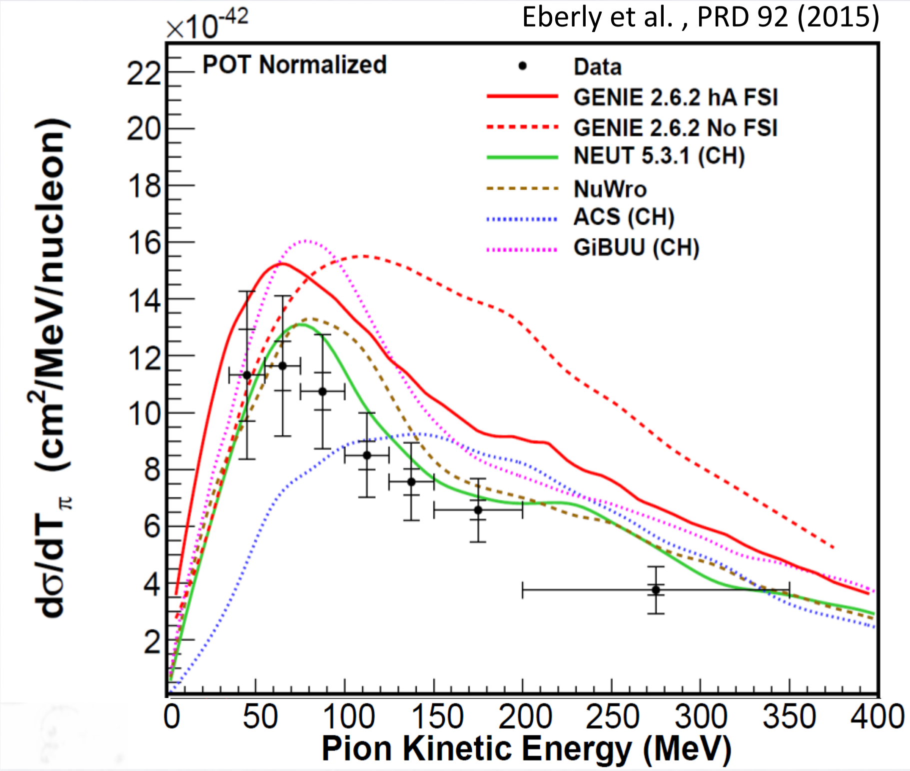
- ✓ Pion distribution is not isotropic (not generated according to phase space).
- ✓ This information is lost in MC if we use factorization.
- ✓ Anisotropy can be measured in neutrino-nucleus interaction experiments (despite FSI effects)

F. Sanchez PRD 93, 093015 (2016)
J.E.S., E.Hernandez, S.Nakamura, J. Nieves, T. Sato PRD 98

PION PUZZLE

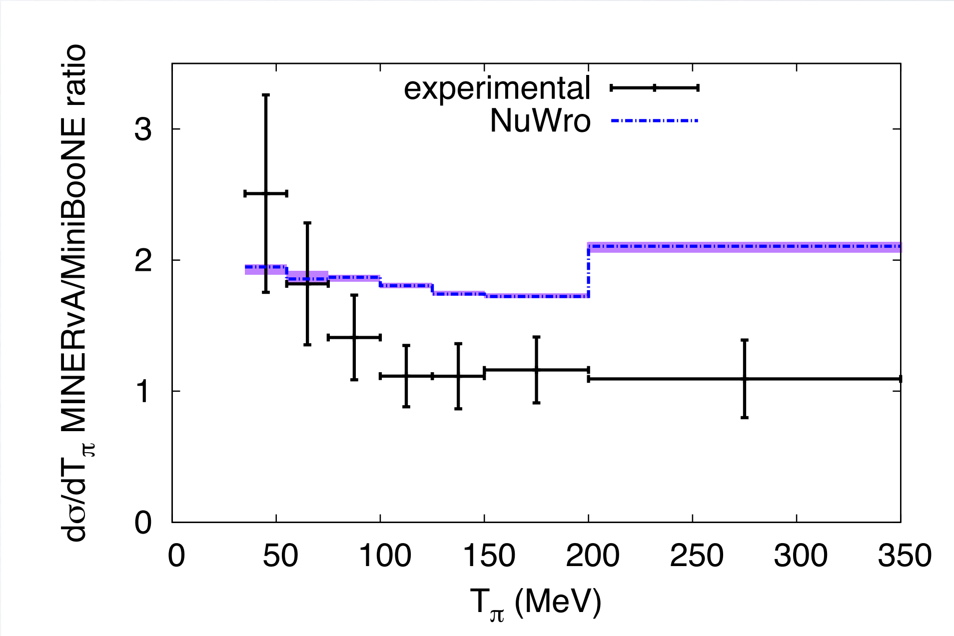


MiniBooNE



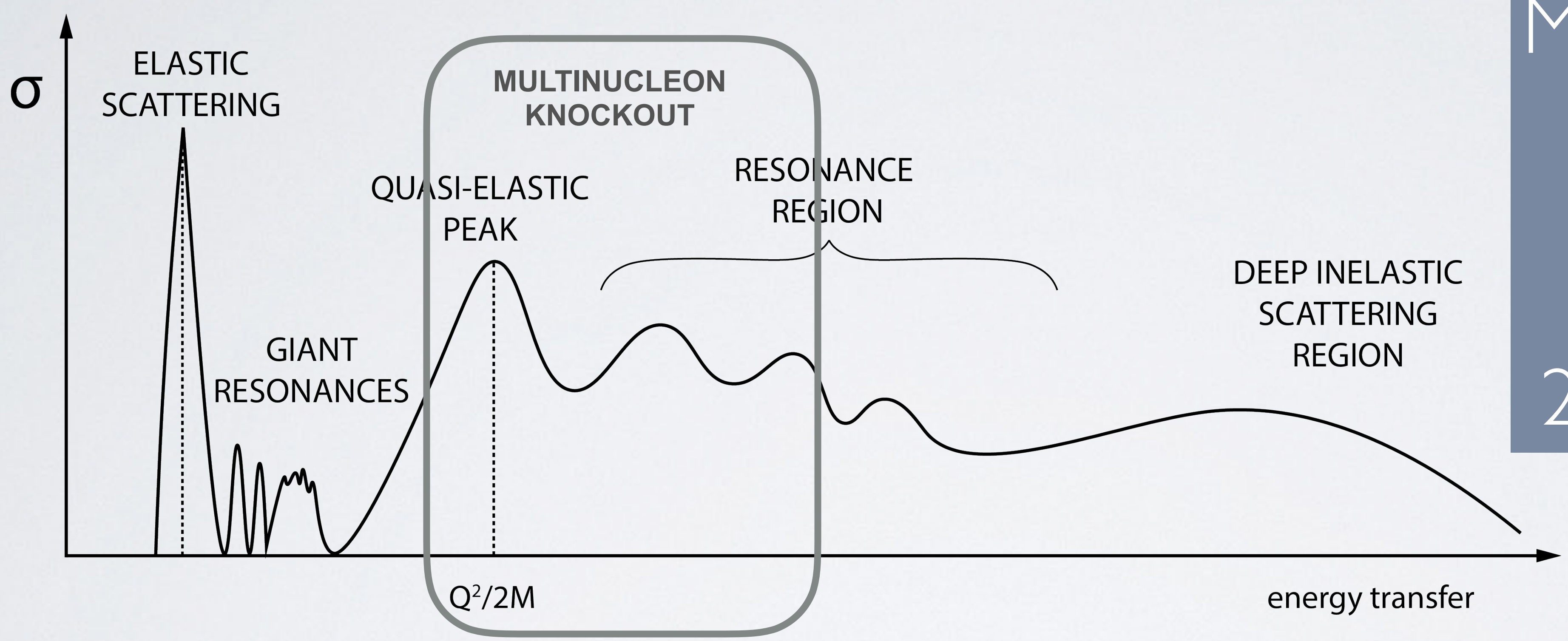
Minerva

According to MC the ratio between both results should be flat



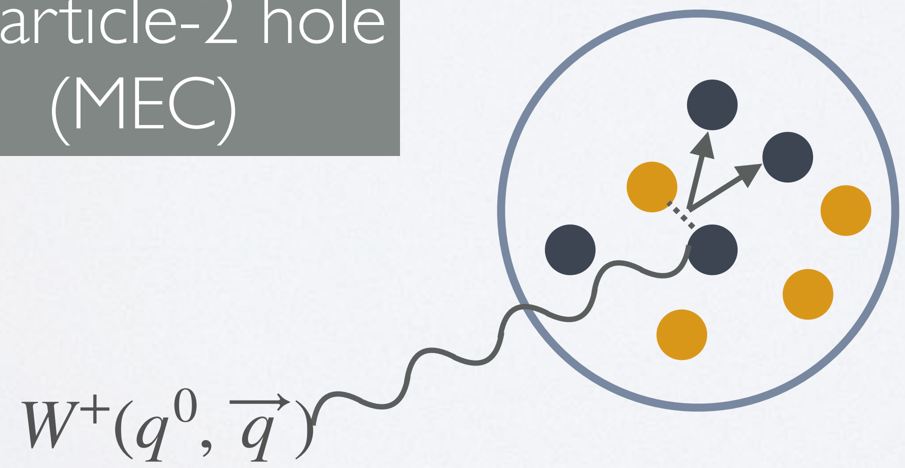
Models are not capable of describing both sets of data

HOW WELL ARE WE DOING?



Valencia group
M. Martini model
GiBUU
SuSAv2
Benhar SF +
2-body currents

2 particle-2 hole
(MEC)



- interaction on a pair of nucleons
- purely nuclear mechanism

2P2H MODELS

Implemented in MC event generators

✓ **Valencia model**
initial nucleons: Fermi Gas
pion & rho exchange
various nuclear medium corrections

✓ **SuSAv2**
initial nucleons: Fermi Gas
only pion exchange

✓ **Martini model**
initial nucleons: Fermi Gas
phenomenological fit + Δ

✓ **GiBUU**
initial nucleons: Fermi Gas
phenomenological fit

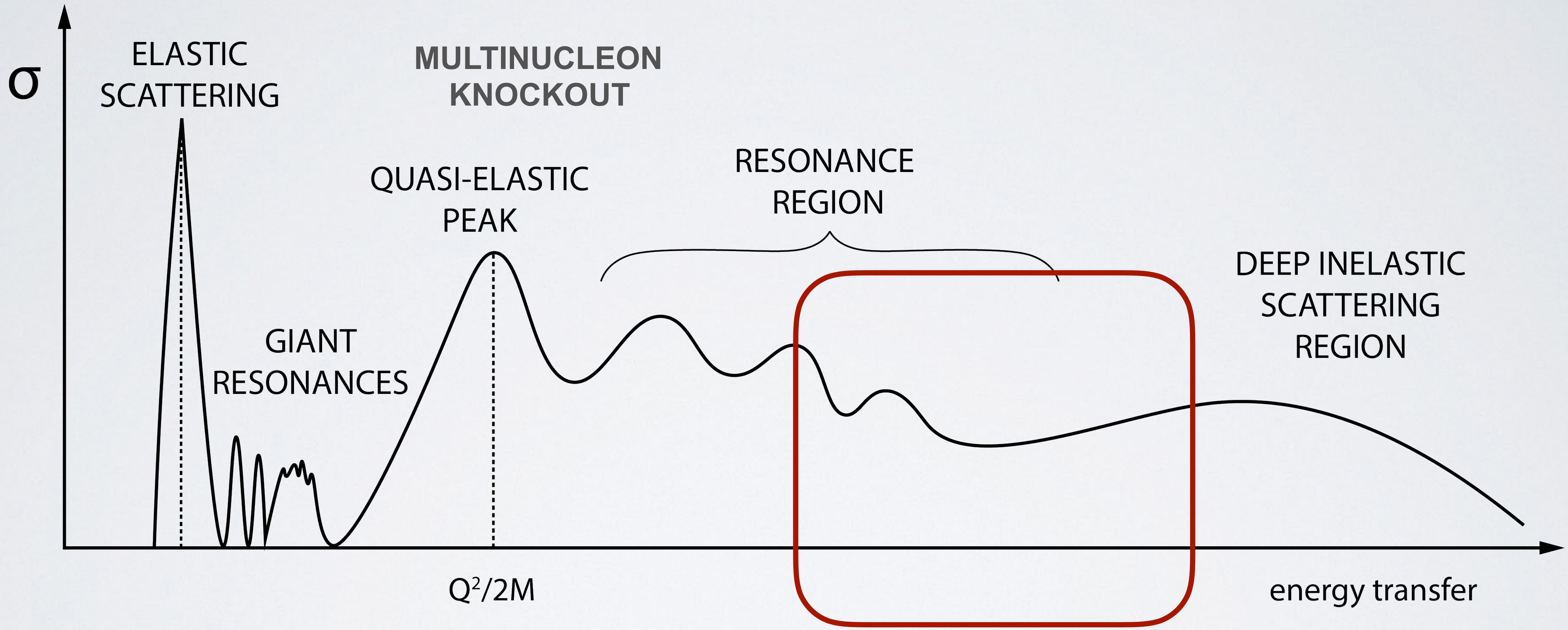
Theoretical calculation in progress

✓ **Benhar model**
initial nucleons: Benhar spectral function
currents: pion exchange

✓ **Ghent group**
mean field (both initial and final nucleons)
currents: pion exchange

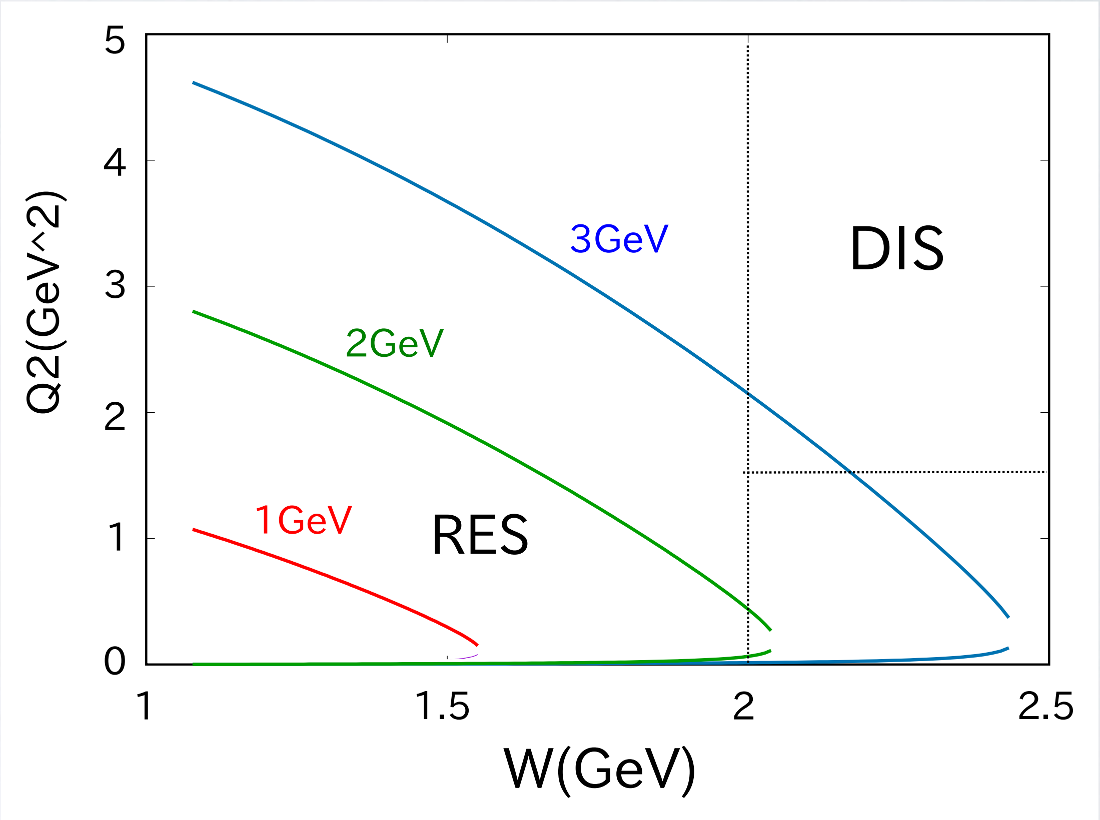
✓ **ab-initio calculations**
first results using GFMC (Green Function MC)
non relativistic

SIS/DIS REGION



SIS/DIS TRANSITION REGION

- Until recently less activity in this region
- Important for DUNE and NOvA
- 2 pion production starts to be increasingly important for W>1.4 GeV
- Difficult region because language changes (quark-hadron duality observed in electron scattering)



(source: T. Sato)

NuSTEC Workshop on Shallow- and Deep-Inelastic Scattering (October 2018)
arxiv.org/pdf/1907.13252

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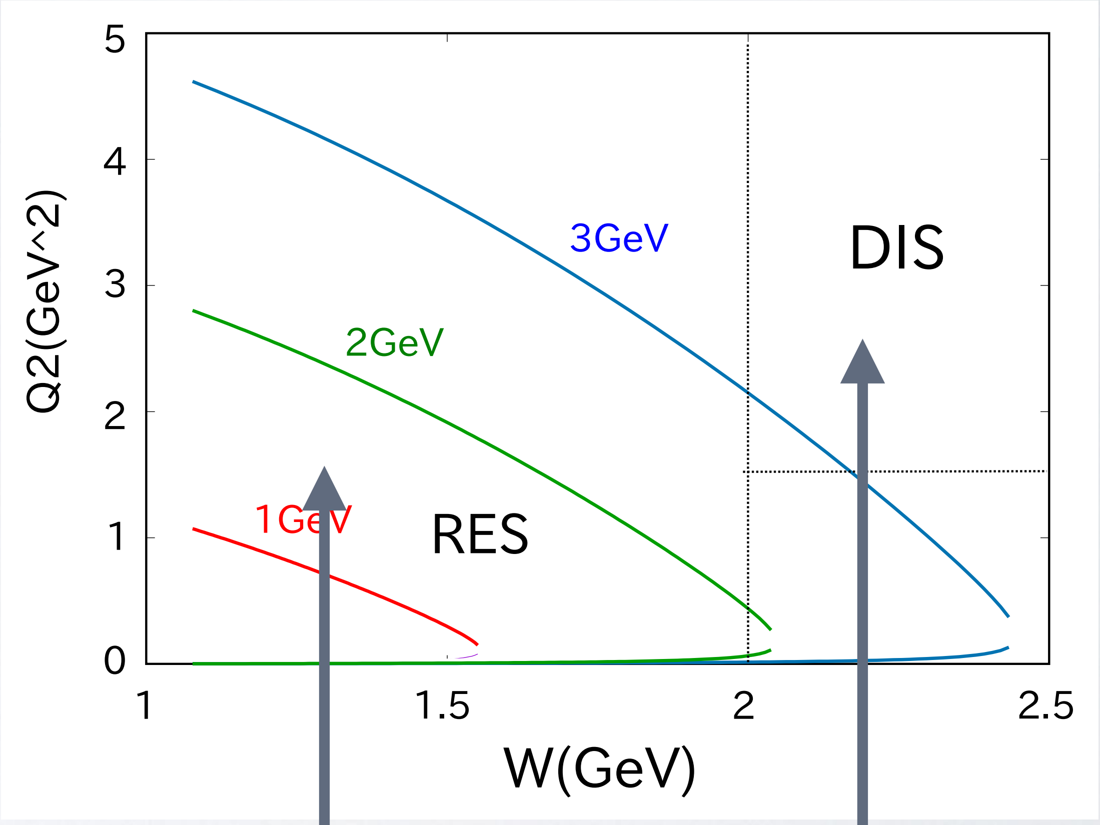

(source: T. Sato)

hadron degrees of freedom

quark degrees of freedom

NuSTEC Workshop on Shallow- and Deep-Inelastic Scattering (October 2018)
arxiv.org/pdf/1907.13252

CONCLUSIONS

A lot of activity in community of neutrino-nucleus interactions

EXPERIMENT

MC GENERATORS

THEORY

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There is a huge **gap** between theoretical developments and models implemented in MCs.

We need a **consistent** implementation of theoretical models (all mechanisms) in MCs.

A careful **validation** of models & MCs with electron data is needed

A step from inclusive to **exclusive** observables

Still many **open questions** and theoretical discussion

THANK YOU

BACKUP

PION PUZZLE

MiniBooNE $\mathrm{CC}\pi^+$

- target is CH_2
- peak at 600 MeV
- coherent π^+ is part of the signal
- signal defined as $1\pi^+$ (no other pions)

Minerva $\mathrm{CC}\pi^+$

- target is CH
- $\langle E_\nu \rangle \approx 4$ GeV
- cut $W < 1.4$ GeV
- coherent π^+ is part of the signal
- signal defined as $1\pi^+$ (and arbitrary $\#\pi^0$)

MOTIVATION

Far detector

$$N_{\alpha\to\beta}(p_{\text{reco}}) = \sum_i \phi_\alpha(E_{\text{real}}) \times \boxed{\mathscr{P}_{\alpha\to\beta}(E_{\text{real}})} \times \sigma^i_\beta(p_{\text{real}}) \times \epsilon_\alpha(p_{\text{real}}) \times R_i(p_{\text{real}}; p_{\text{reco}})$$

event rate

flux

x-section

efficiency

affects an overall normalization

energy reconstruction migration

obtained from Monte Carlo simulations

…partial information from a near detector

$$N_{\alpha\to\alpha}(p_{\text{reco}}) = \sum_i \phi_\alpha(E_{\text{real}}) \times \sigma^i_\alpha(p_{\text{real}}) \times \epsilon_\alpha(p_{\text{real}}) \times R_i(p_{\text{real}}; p_{\text{reco}})$$

In the ratio of the two, the nuclear effects do not cancel

MOTIVATION

total x-sections
(normalisation)

(1 step) How do oscillation parameters influence our predictions of the final lepton?

(2 step) Resolve a possible degeneracy (looking at the final hadron states)

backgrounds