How neutrino energy reconstruction is affected by nuclear effects?

Artur M. Ankowski
Okayama University

NuFact 2014
Glasgow, 25-30 August 2014

Outline

1. Why nuclear effects are relevant for oscillation studies
2. Does the binding energy in E_{rec} depend on kinematics?
3. Pion production and multinucleon processes as CCQE-like backgrounds
4. How does the binding energy differ in ν and $\bar{\nu}$ scattering?
5. Can we improve the energy reconstruction method?
6. Summary

Why nuclear effects are relevant for oscillation studies

Neutrino oscillations

In the 2 flavor case, the oscillation probability is

$$P_{\alpha\rightarrow\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4\underline{E_\nu}}\right)$$

True neutrino energy

Neutrino oscillations

In **CCQE** scattering off free nucleons at rest,

$$\nu_\ell + n \to \ell^- + p,$$

$$\bar{\nu}_\ell + p \to \ell^+ + n,$$

the neutrino energy can be determined from

$$E_\nu^{\mathrm{rec}} = \frac{2E_\mu M - M^2 - m_\mu^2 + M'^2}{2(M - E_\mu + |\mathbf{k}_\mu| \cos\theta)},$$

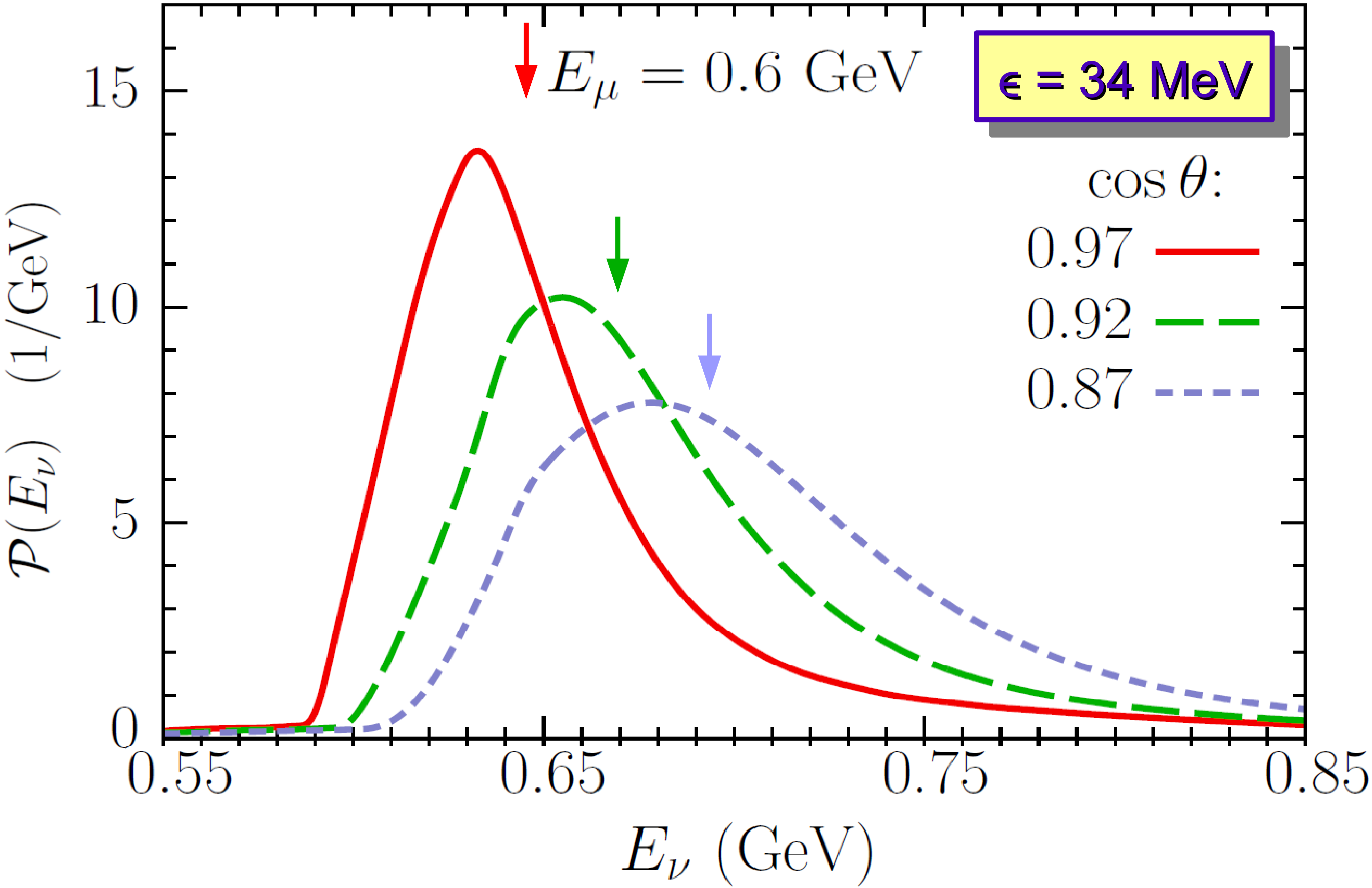
Neutrino oscillations

In CCQE scattering off nucleus, the true energy is

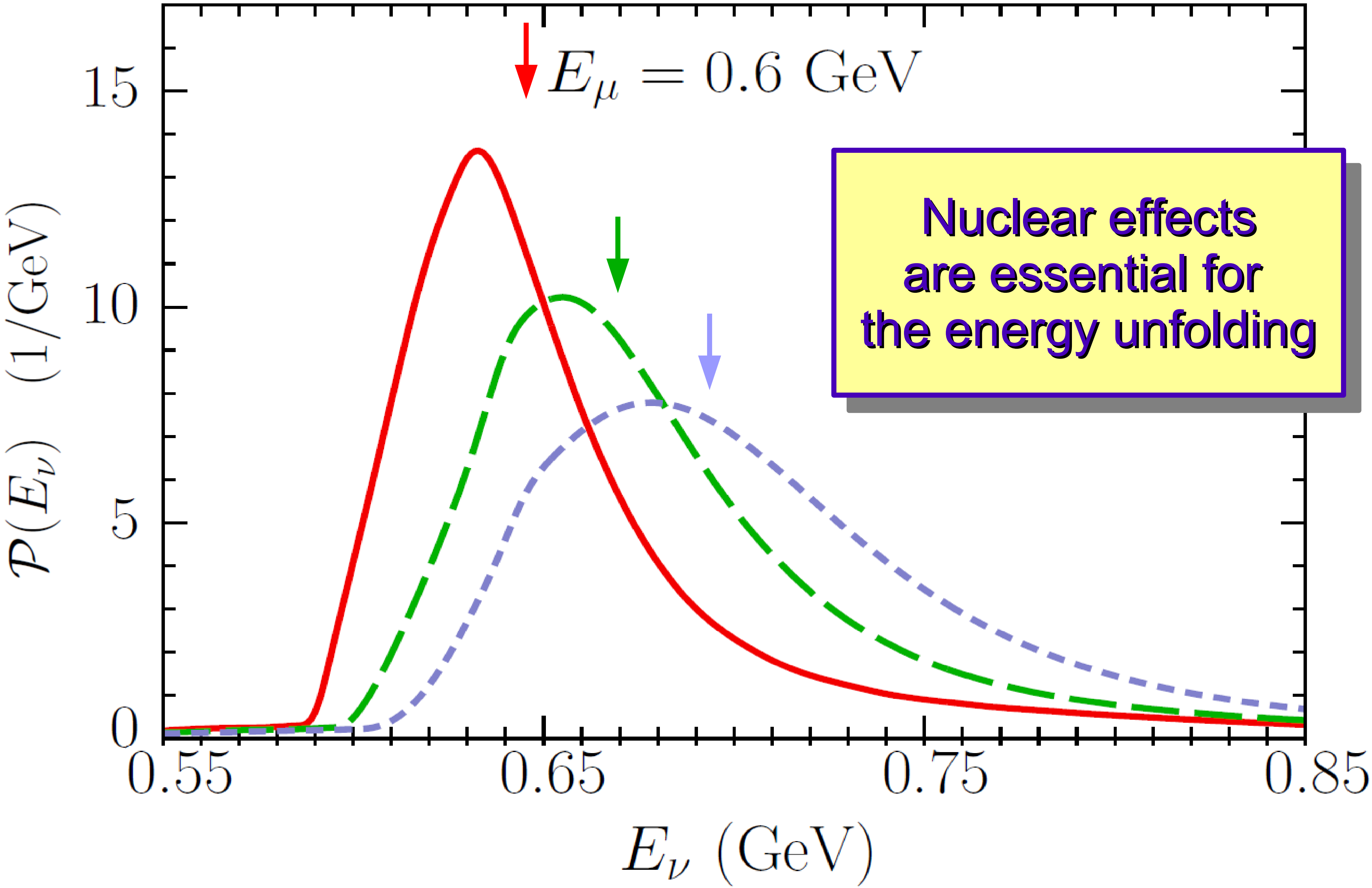
$$E_\nu = \frac{2E_\mu E_N - 2\mathbf{p}\cdot\mathbf{k}_\mu - (E_N^2 - \mathbf{p}^2 + m_\mu^2 - M'^2)}{2(E_N - |\mathbf{p}|\cos\theta_h - E_\mu + |\mathbf{k}_\mu|\cos\theta)},$$

compared to the reconstructed energy (~QE peak)

$$E_\nu^{\rm rec} = \frac{2E_\mu(M-\epsilon) - (M-\epsilon)^2 - m_\mu^2 + M'^2}{2[(M-\epsilon) - E_\mu + |\mathbf{k}_\mu|\cos\theta)},$$



$E_\mu = 0.6$ GeV
ϵ = 34 MeV
$\cos\theta$:
0.97
0.92
0.87
$\mathcal{P}(E_\nu)$ (1/GeV)
0
5
10
15
0.55
0.65
0.75
0.85
E_ν (GeV)



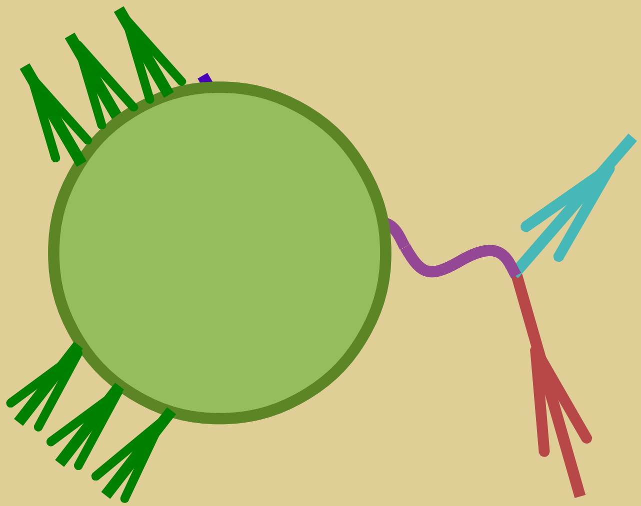
$E_\mu = 0.6$ GeV
Nuclear effects are essential for the energy unfolding
$\mathcal{P}(E_\nu)$ (1/GeV)
15
10
5
0
0.55
0.65
0.75
0.85
E_ν (GeV)

Simplest (unrealistic) case

Unknown monochromatic beam

Consider the simplest (unrealistic) case:

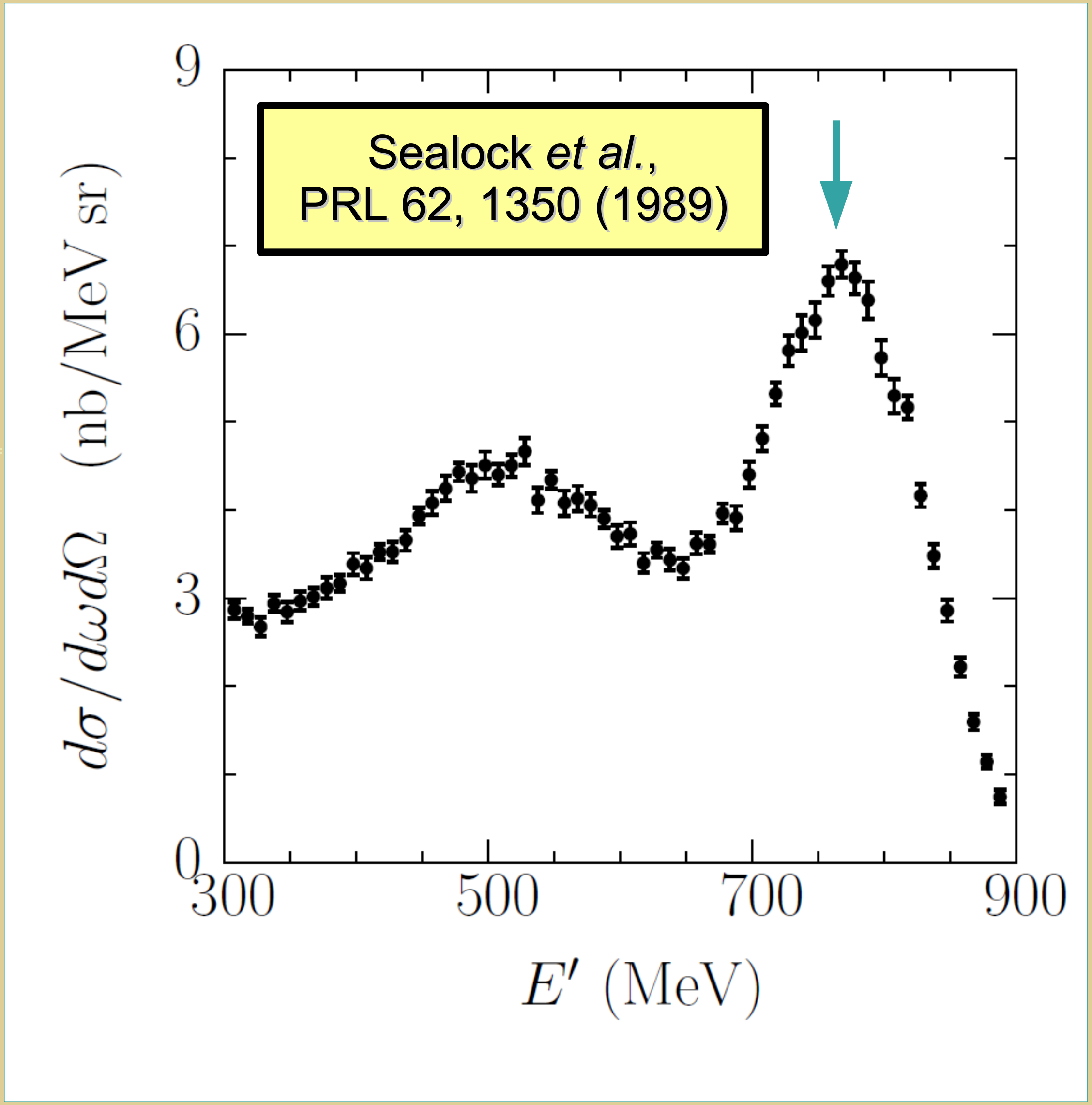
the beam is monochromatic but its energy is unknown and has to be reconstructed



E' and θ known

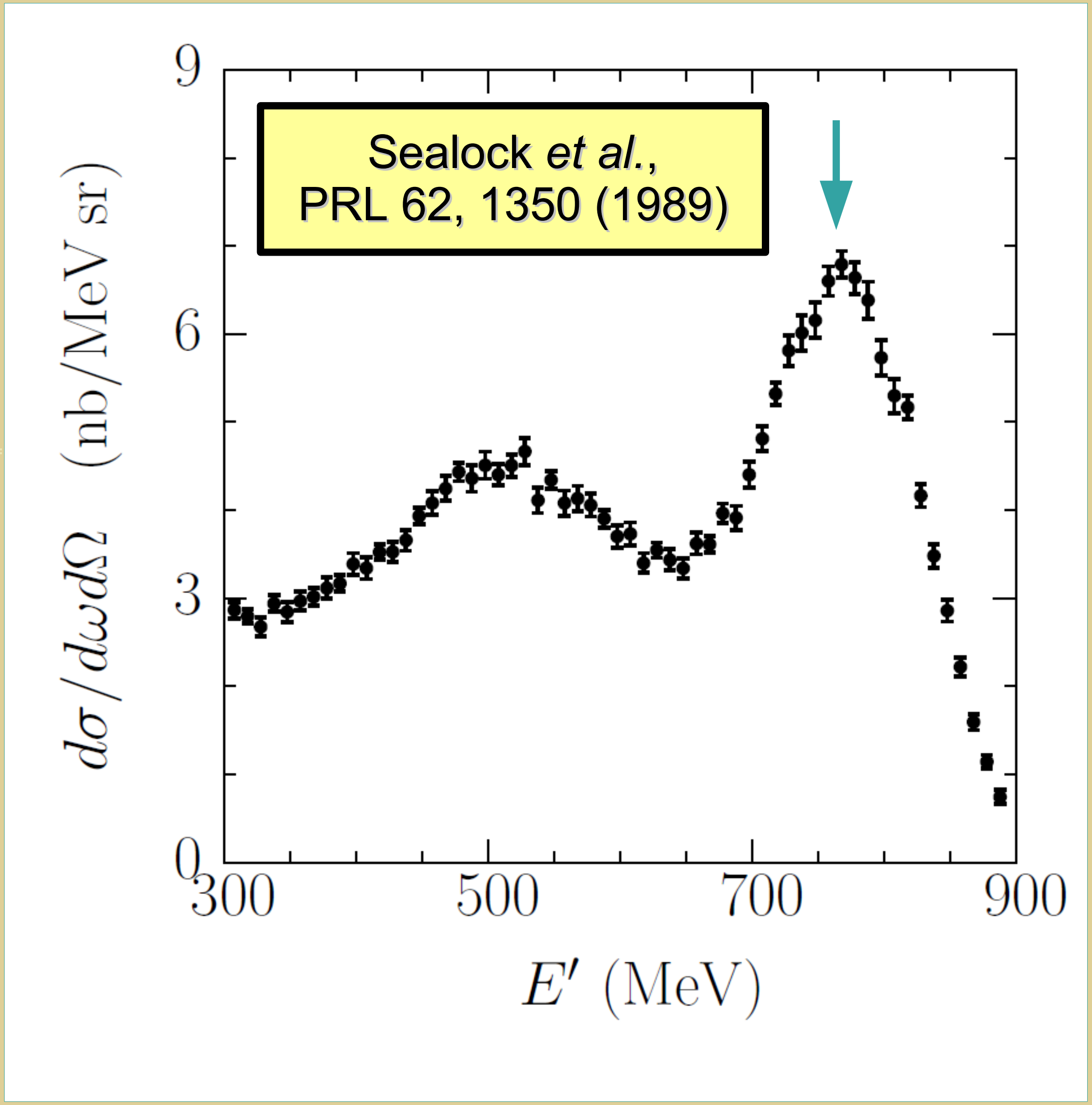
$E = ?$

“Unknown” monochromatic e^- beam



$E' = 768$ MeV
$\theta = 37.5$ deg
$\Delta E' = 10$ MeV

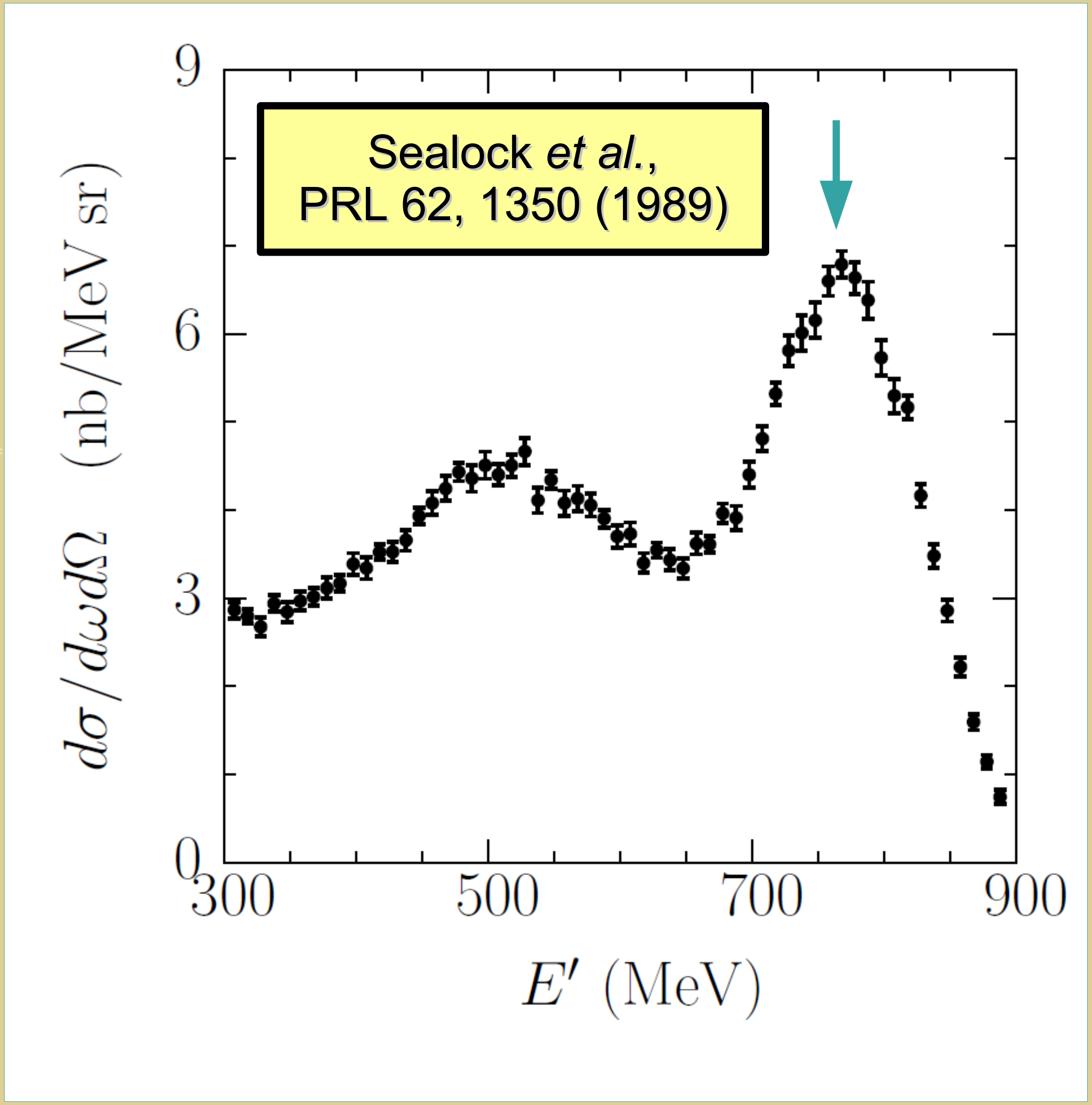
“Unknown” monochromatic e^- beam



$E' = 768$ MeV
$\theta = 37.5$ deg
$\Delta E' = 10$ MeV

for $\epsilon = 25$ MeV
$E = 960$ MeV
$\Delta E = 15$ MeV

"Unknown" monochromatic e^- beam



$E' = 768$ MeV
$\theta = 37.5$ deg
$\Delta E' = 10$ MeV

for $\epsilon = 25$ MeV
$E = 960$ MeV
ΔE=15 MeV

true value
$E = 961$ MeV

“Unknown” monochromatic e^- beam

θ (deg)	37.5	37.1	36	36
E' (MeV)	768	615.0	487.5	287.5
$\Delta E'$ (MeV)	10	10	10	5

$\epsilon = 25$ MeV

rec. *E*	**960±15**	**741±13**	**571±12**	**333±6**
true *E*	**961**	**730**	**560**	**320**

Sealock et al., PRL 62, 1350 (1989)

O'Connell *et al.*, PRC 35, 1063 (1987)

Barreau *et al.*, NPA 402, 515 (1983)

“Unknown” monochromatic e^- beam

θ (deg)	37.5	37.1	36	36
E' (MeV)	768	615.0	487.5	287.5
$\Delta E'$ (MeV)	10	10	10	5

true E	**961**	**730**	**560**	**320**
ϵ	**26 ± 10**	**16 ± 10**	**16 ± 10**	**13 ± 5**

“Unknown” monochromatic e^- beam

θ (deg)	37.5	37.1	36	36
E' (MeV)	768	615.0	487.5	287.5
$\Delta E'$ (MeV)	10	10	10	5

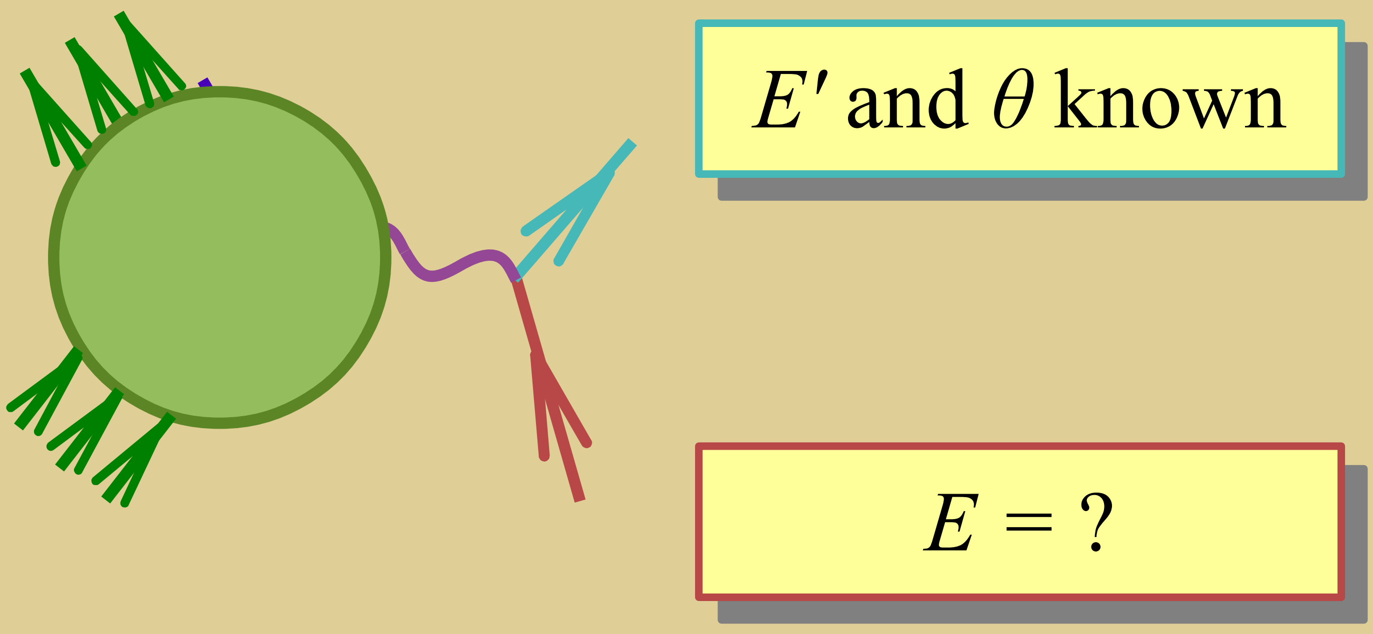
true E	**961**	**730**	**560**	**320**
ϵ	**26 ± 10**	**16 ± 10**	**16 ± 10**	**13 ± 5**

different E ≡ different Q^2 ≡ different θ
→ different ϵ

Realistic case

Polychromatic beam

In modern experiments, the neutrino beams are not monochromatic, and the energy must be reconstructed from the observables, typically E' and $\cos\theta$ under the CCQE event hypothesis.



CCQE events

In practice, CCQE event candidates are defined as containing no pions observed.

CCQE (1p1h and 2p2h)

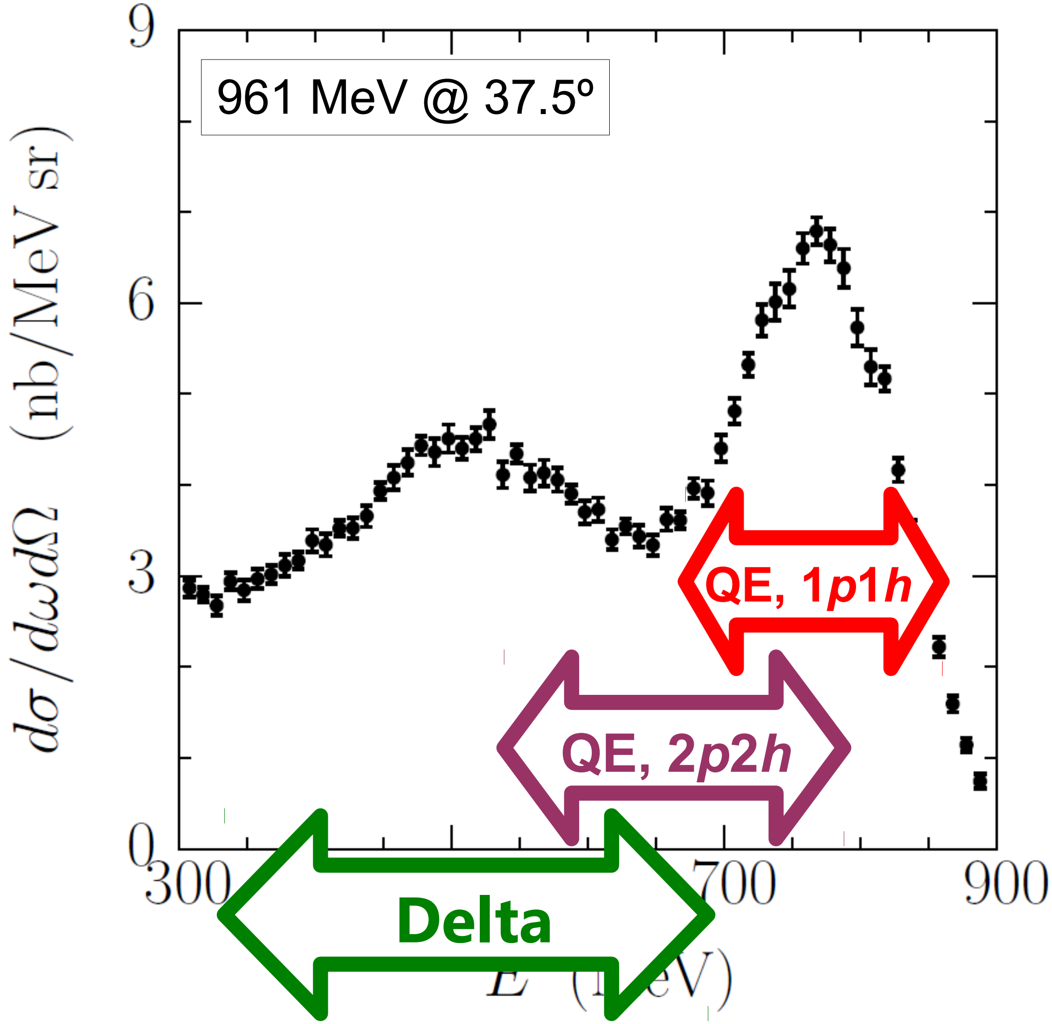
pion production and reabsorption

$+$ undetected pions

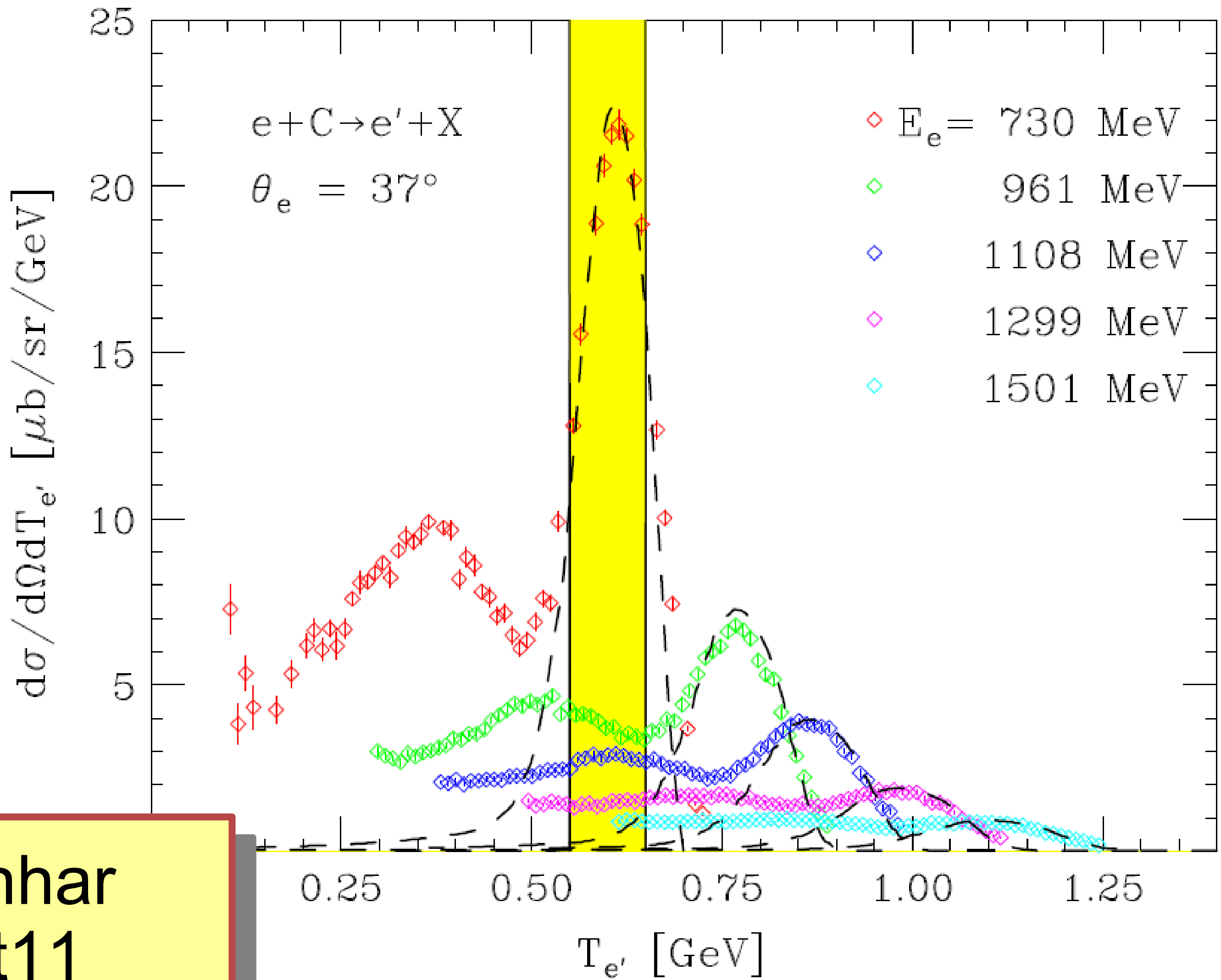
$-$ CCQE with pions from FSI

CCQE-like events

Recall the monochromatic beam case



CCQE events of given $l^{\pm}$ kinematics



Omar Benhar
@ NuInt11
PRL 105, 132301 (2010)

Difficulties

- Clearly different **processes** and **neutrino energies** contribute to CCQE-like events of a given E' and cos θ.

- The backgrounds have to be accurately accounted for and subtracted in Monte Carlo simulations.

Absorbed or undetected pions

Analyzed within the Giessen Boltzmann-Uehling-Uhlenbeck (GiBUU) transport model [Buss *et al.*, Phys. Rept. 512, 1 (2012)] for hadron-, photon-, electron-, neutrino-, and heavy-ion-induced reactions on nuclei.

- nucleus described as the **local Fermi gas** in a momentum- and coordinate-dependent potential
- **emphasis put on final-state interactions**, the produced mesons and baryons propagate and collide in mean-field potentials, the evolution of all the channels (61 baryons, 21 mesons) is coupled

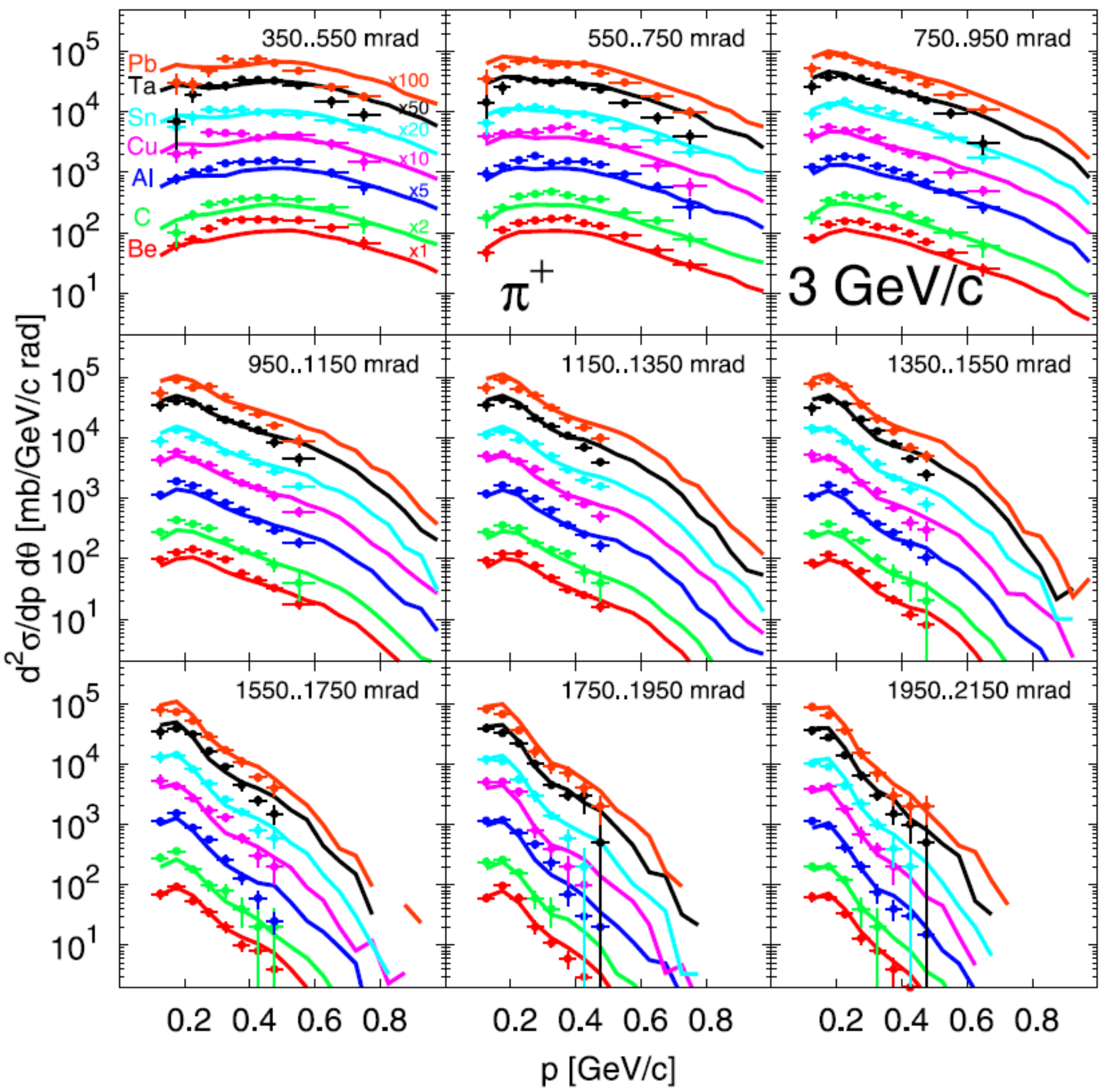
GiBUU results for pions

$$p + A \to \pi^+ + X$$

@ mom. 3 GeV/c

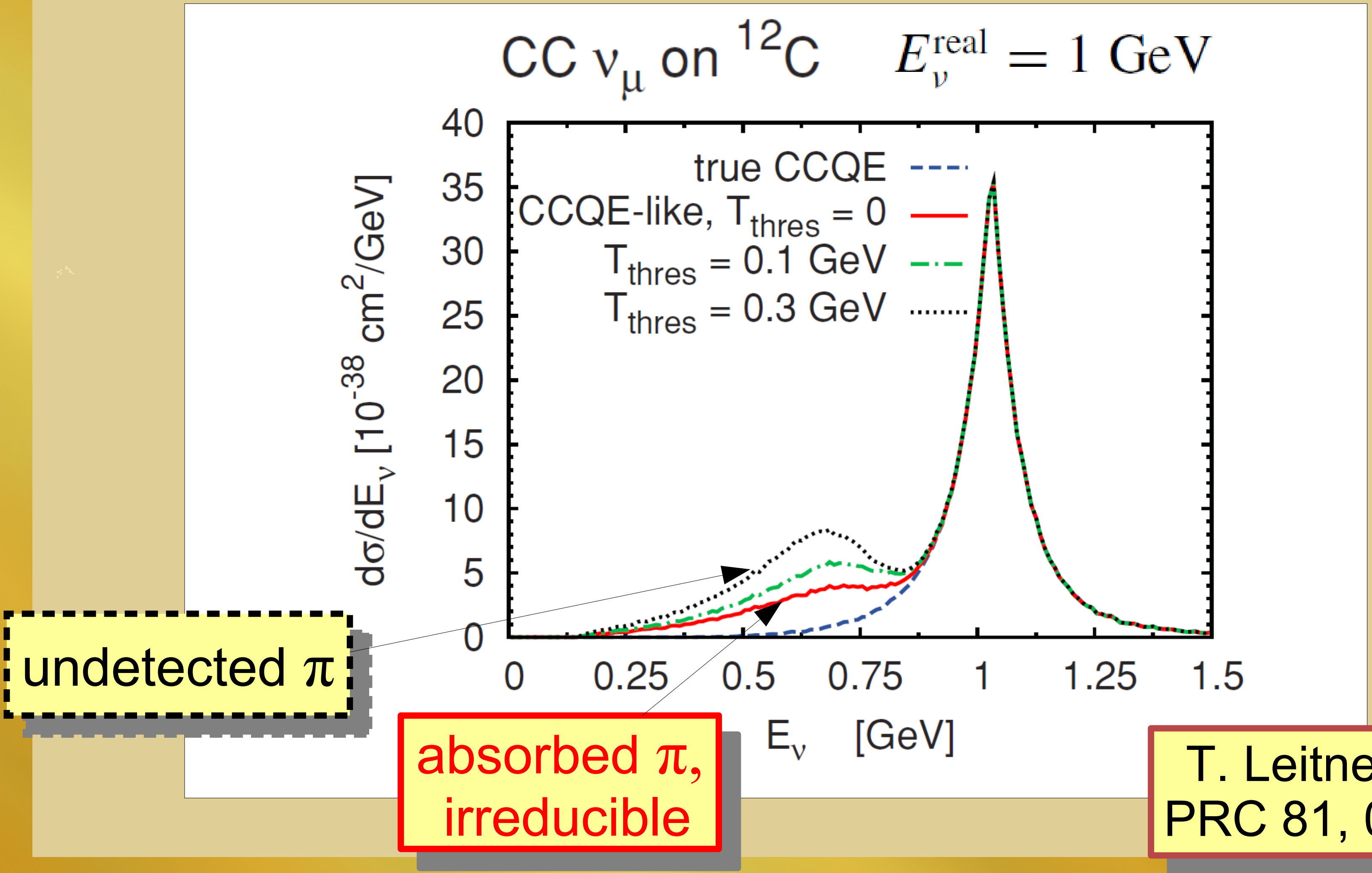
calcs.:
Gallmeister & Mosel
NPA 826, 151 (2009)

data:
Catanesi *et al.*
(HARP Collab.)
PRC 77, 055207
(2007)



Absorbed or undetected pions

The reconstructed energy typically lower by ~300 MeV



T. Leitner & U. Mosel
PRC 81, 064614 (2010)

$2p2h$ final states

Final states involving two (or more) nucleons may originate from

- initial-state correlations: ~20% of nucleons in the nucleus strongly interact, typically forming a deuteron-like np pair of high relative momentum
- final-state interactions
- 2-body reaction mechanisms, such as by meson-exchange currents

Alberico *et al.*
Ann. Phys. 154, 356 (1984)

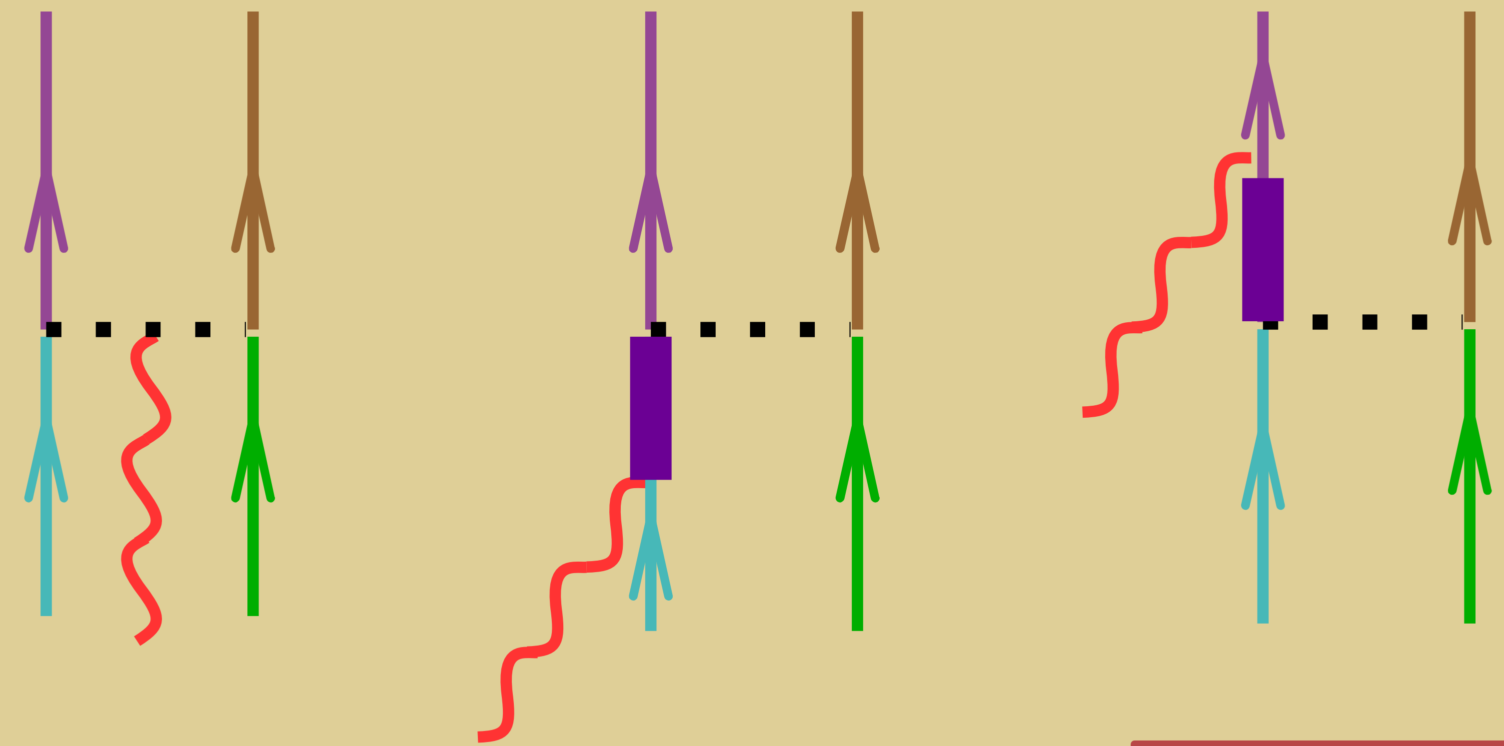
2*p*2*h* final states

Final states involving two (or more) nucleons may originate from

- initial-state correlations: ~20% of nucleons in the nucleus strongly interact, typically forming a deuteron-like *np* pair of high relative momentum
- final-state interactions
- 2-body reaction mechanisms, such as by meson-exchange currents

recently observed in ArgoNeuT,
Acciarri *et al.*, D 90, 012008 (2014)
see A. Ereditato's talk on Thursday

2-body reaction mechanisms



Donnelly *et al.*
PLB 76, 393 (1978)

Existing approaches

detailed comparison:
M. Martini @ NuInt14

- **Martini *et al.***: local Fermi gas + RPA effects, formalism of Marteau [EPJ A 5, 183 (1999)]
  2*p*2*h* contribution deduced from Alberico *et al.* [electron scattering off ^{56}Fe, Ann. Phys. **154**, 356 (1984)],
  3*p*3*h* from Oset & Salcedo [NPA 468, 631 (1987)]

  PRC **80**, 065501 (2009); PRC **84**, 055502 (2011);
  PRC **87**, 065501 (2013)

- **Nieves *et al.***: dressed local Fermi gas in a mean-field potential + RPA effects; extension of the studies on electron-, photon-, and pion-scattering off nuclei

  PRC **83**, 045501 (2011) ; PLB **707**, 72 (2012);
  PLB **721**, 90 (2013)

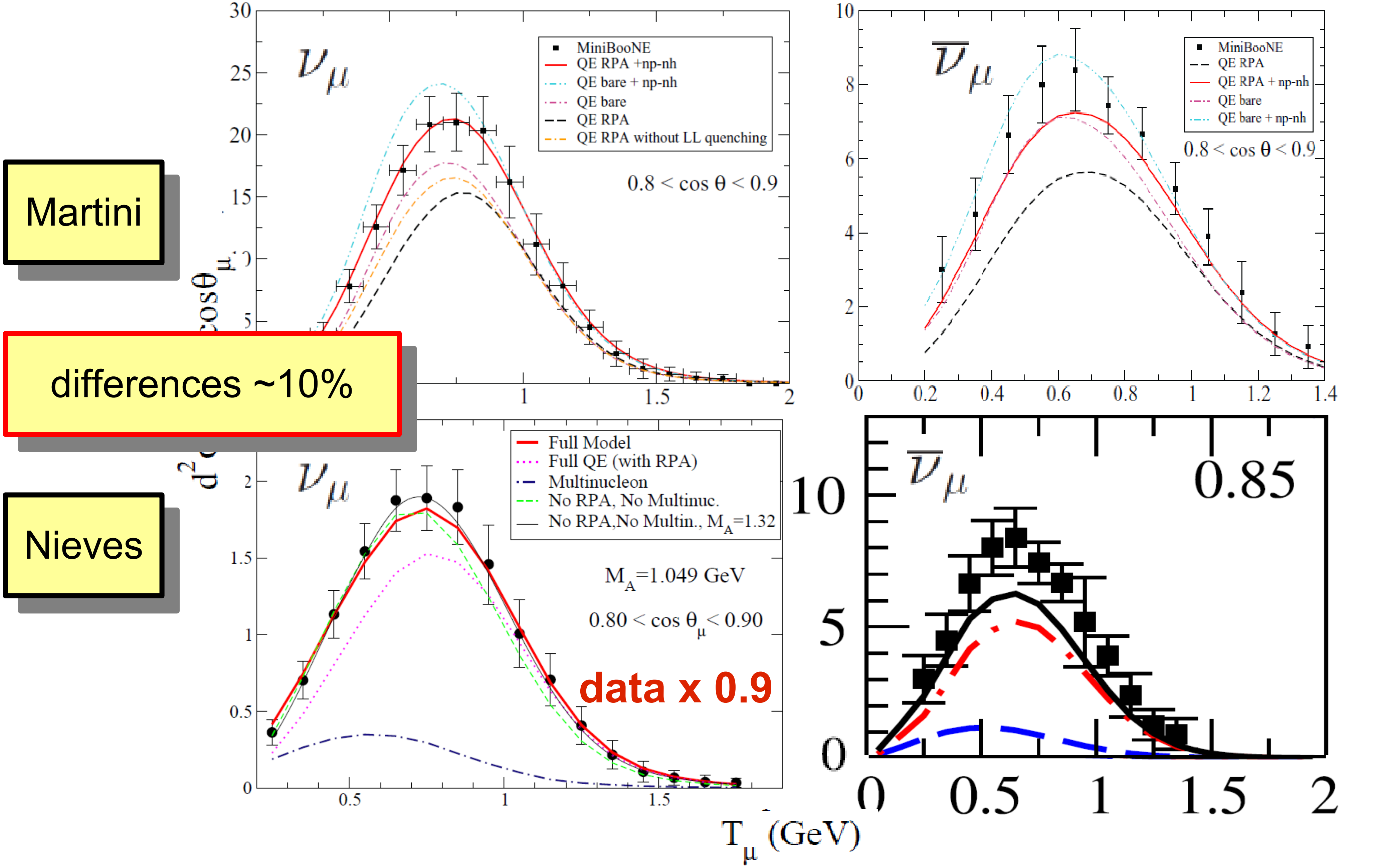
Existing approaches ctd.

- **Mosel *et al*.**: GiBUU + well-motivated physically fit to the MiniBooNE data, PRC **86**, 014614 (2012)
- **Amaro *et al*.**: phenomenological superscaling approach + vector contrib. of MEC; PRL **108**, 152501 (2012)

talk of I. Ruiz Simo on Thursday

- **Lovato *et al*.**: ground state wave function of ^{12}C from Green's function MC solution of the Schrödinger eqn. with 2N (Argonne v_{18}) and 3N (Illinois-7) interaction; PRL **112**, 182502 (2014)
- **TEM**: Bodek *et al*. [EPJ C71, 1726 (2012)]: Q^2 dependent modification of $G_M(Q^2)$ brings the RFG model into agreement with C(e,e') data in the dip region; comparison to the MiniBooNE data analyzed by J. Sobczyk [EPJ C72, 1850 (2012)]

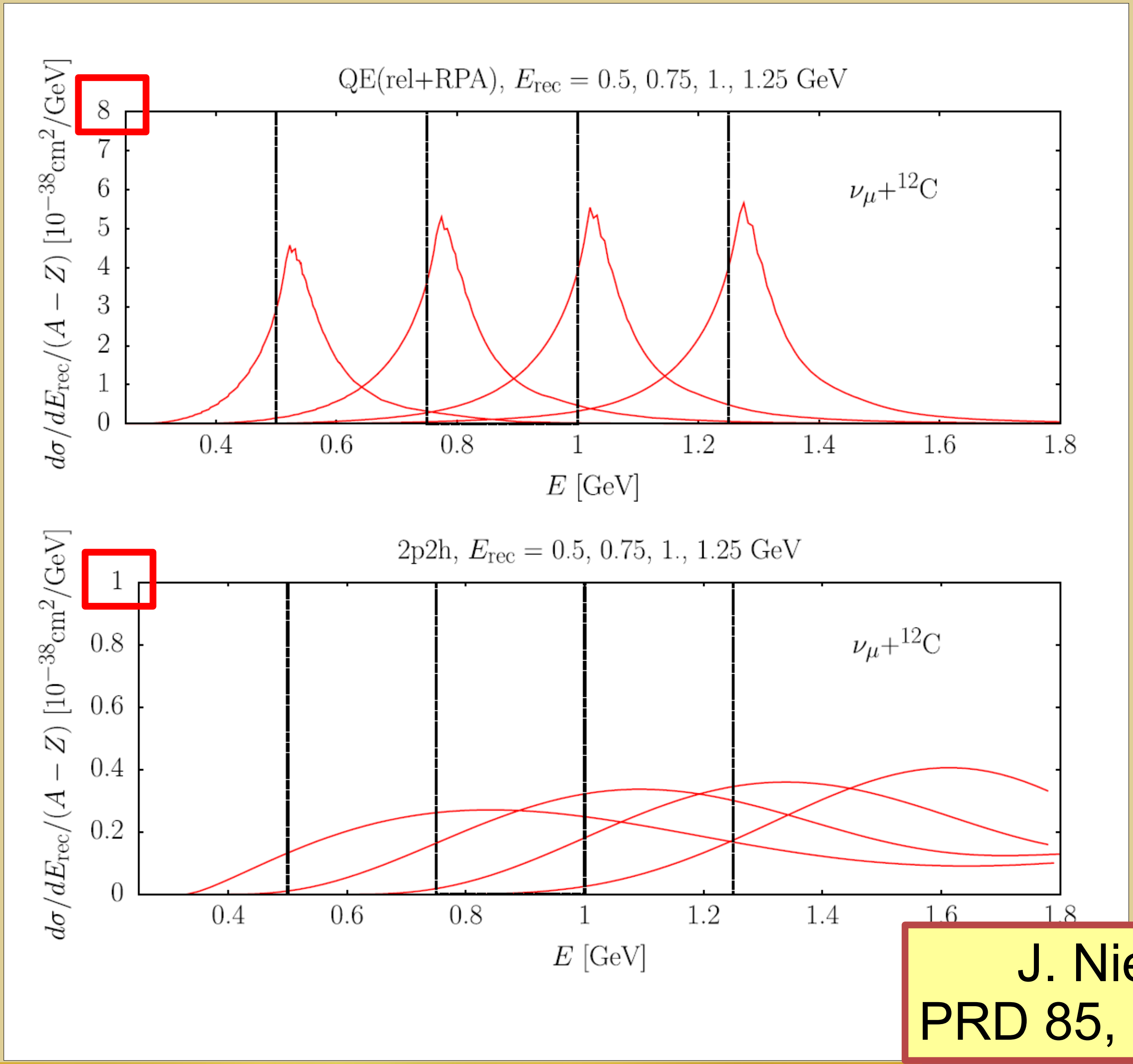
Comparison with MiniBooNE data



Consequences for E_{rec}

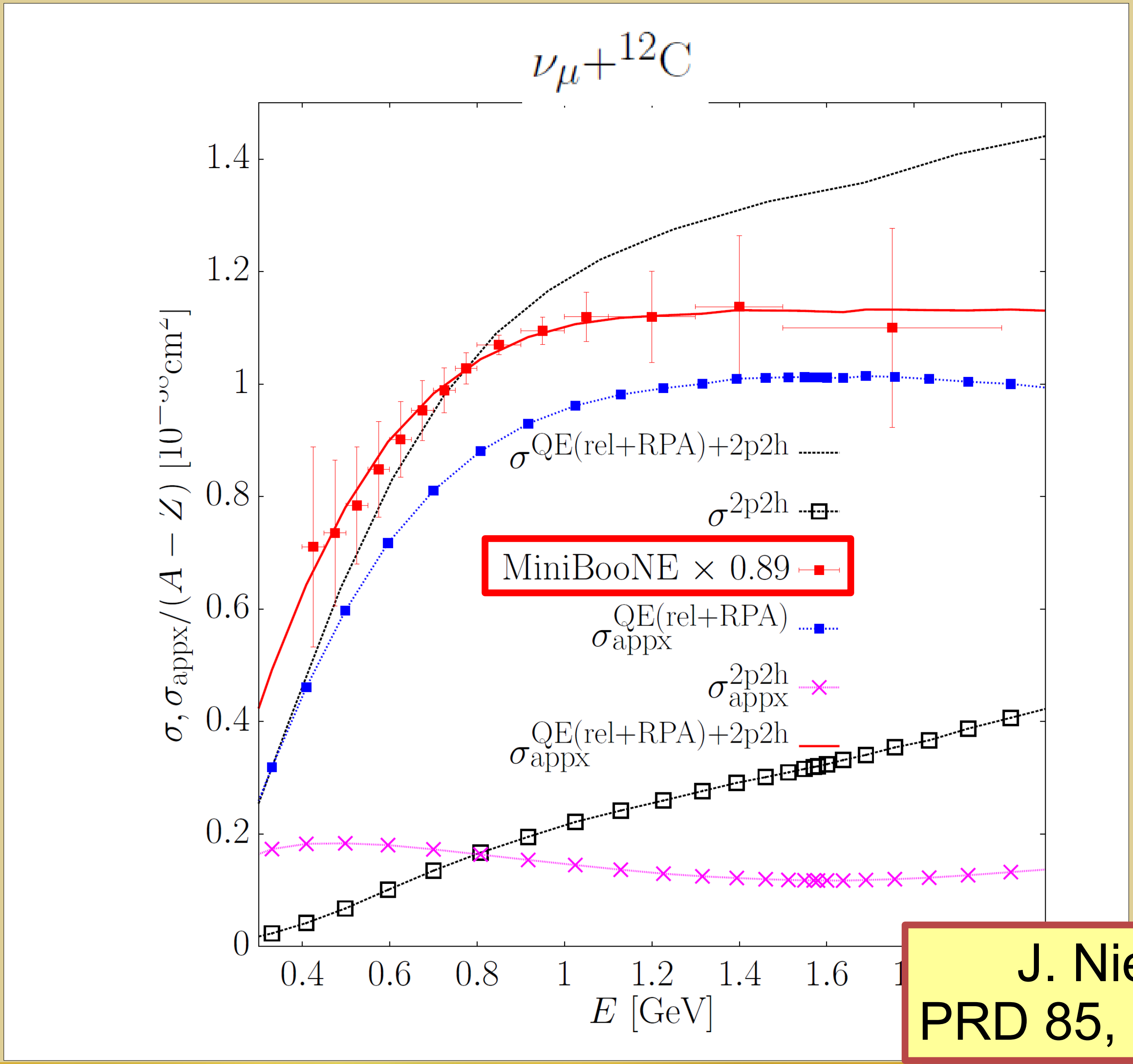
1p1h

2p2h



J. Nieves *et al.*,
PRD 85, 113008 (2012)

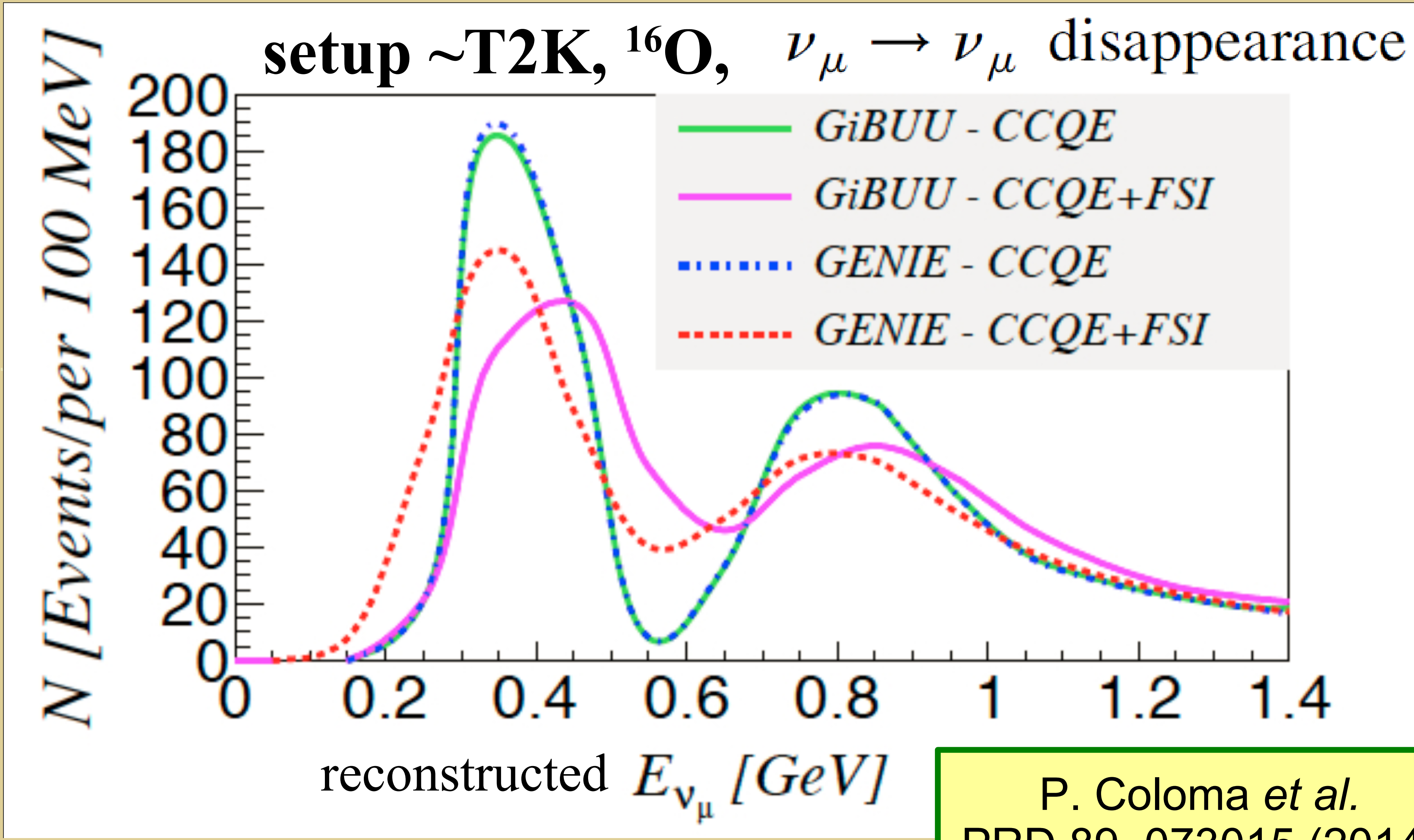
Consequences for x-section unfolding



J. Nieves *et al.*,
PRD 85, 113008 (2012)

Quasielastic scattering

How relevant are FSI?



P. Coloma *et al.*
PRD 89, 073015 (2014)

Description of the approach

Nuclear structure described by the **realistic hole SF** [Benhar *et al*., NPA 579, 493 (1994)] calculated in the local-density approximation, combining

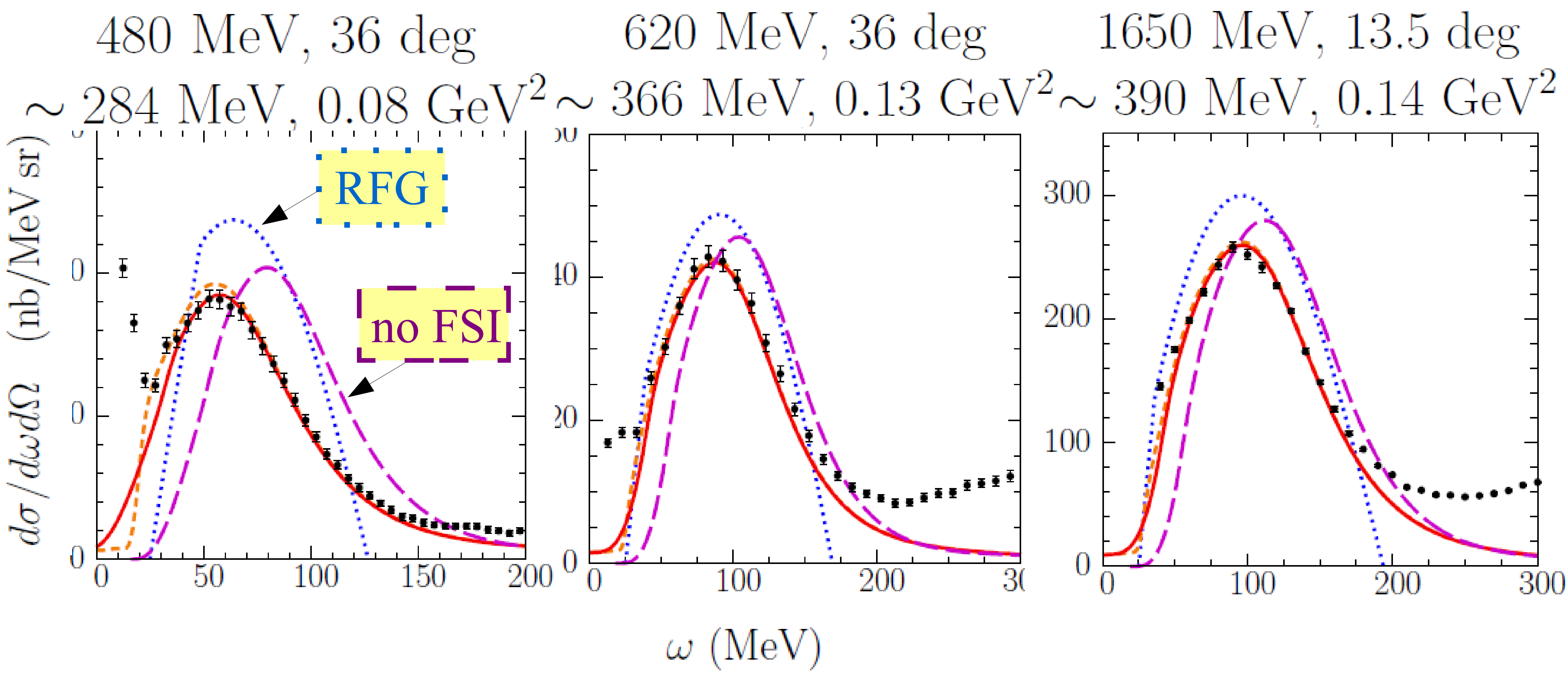
- the shell structure from the Saclay *(e,e'p)* data
- the correlation contribution resulting from NN (Urbana v_{14}) and 3N interactions

Final-state interactions accounted for in the correlated Glauber approximation [Benhar, PRC 87, 024606 (2013)] including the effect of the real part of the optical potential [Cooper et al., PRC 47, 297 (1993)]

No free parameters

A. M. A., O. Benhar, and M. Sakuda arXiv:1404.5687

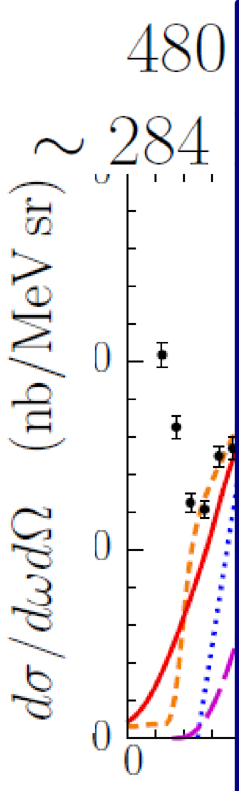
Comparisons to C(*e*,*e*′) data



Barreau *et al.*,
NPA 402, 515 (1983)

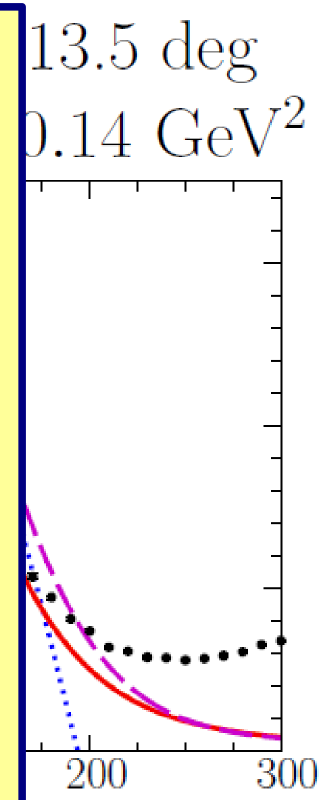
Baran *et al.*,
PRL 61, 400 (1988)

Comparisons to C(*e*,*e*′) data



Comparisons at 54 kinematical setups
given in the ancillary file of arXiv:1404.5687

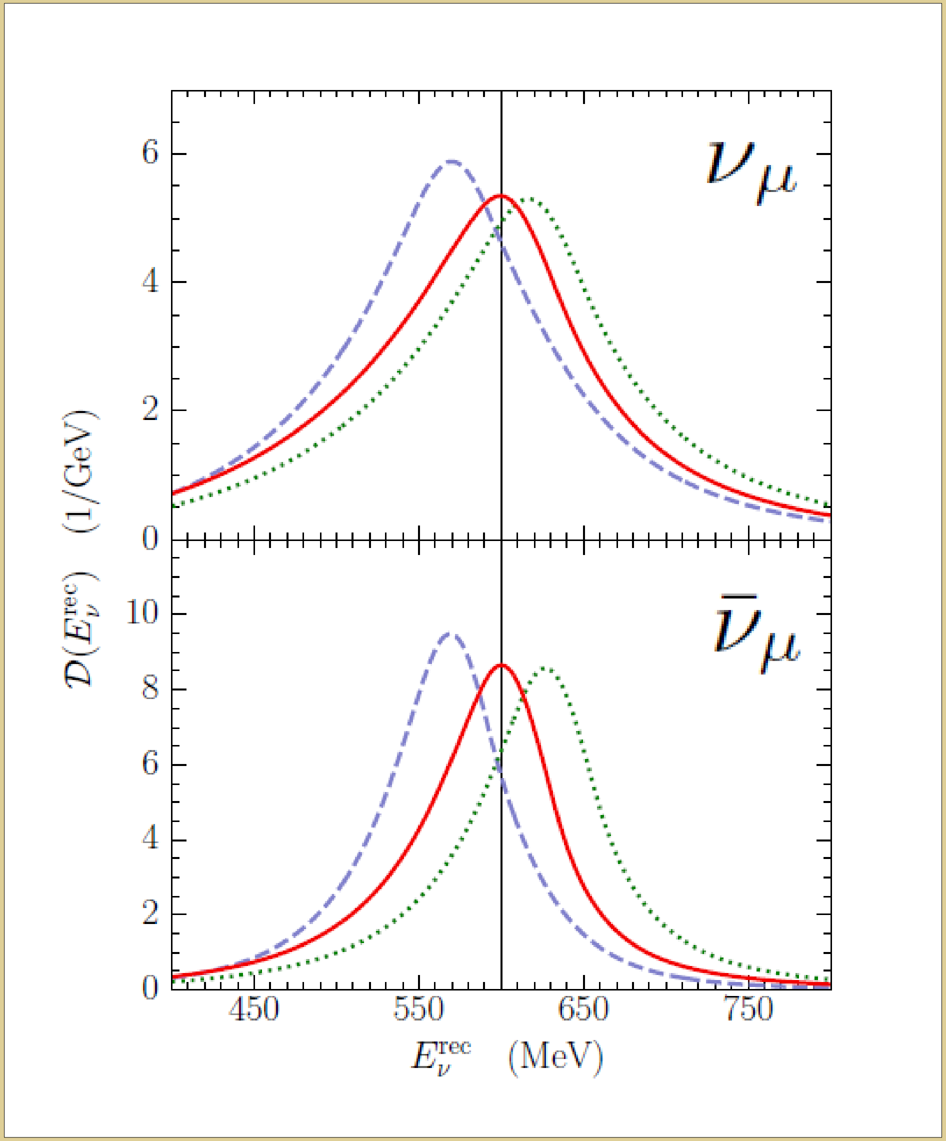
- energies from ~160 MeV to ~4 GeV,
- angles from 12 to 145 degrees,
- ~145 ≤ |q| ≤ 1060 MeV/*c*,
- $0.02 \leq Q^2 \leq 0.86$ (GeV/*c*)^2



Barreau *et al.*,
NPA 402, 515 (1983)

Baran *et al.*,
PRL 61, 400 (1988)

Reconstructed E distributions



ν_μ at ~600 MeV

For $\epsilon = 34$ MeV, max at 617 MeV, best choice $\epsilon = 19$ MeV

FSI yield a 30-MeV shift

$\bar{\nu}_\mu$ at ~600 MeV

For $\epsilon = 30$ MeV, max at 627 MeV, best choice $\epsilon = 6$ MeV

Neutrino-antineutrino difference

deeper binding

deceleration

$$\nu_\ell + n \to \ell^- + p,$$

$$\bar{\nu}_\ell + p \to \ell^+ + n,$$

acceleration

deeper potential

Neutrino-antineutrino difference

deeper binding

deceleration

$$\nu_\ell + n \to \ell^- + p,$$

$$\bar{\nu}_\ell + p \to \ell^+ + n,$$

acceleration

deeper potential

For ^{12}C, it gives 2.8 + 3*3.5 ≈ 13 MeV,
the difference relevant for $\not{CP}$ measurements

Improved energy reconstruction

The standard method uses

$$E_\nu^{\text{rec}} = \frac{2E_\mu(M-\epsilon) - (M-\epsilon)^2 - m_\mu^2 + M'^2}{2[(M-\epsilon) - E_\mu + |\mathbf{k}_\mu|\cos\theta)},$$

with

$$\epsilon = \text{const.}$$

Improved energy reconstruction

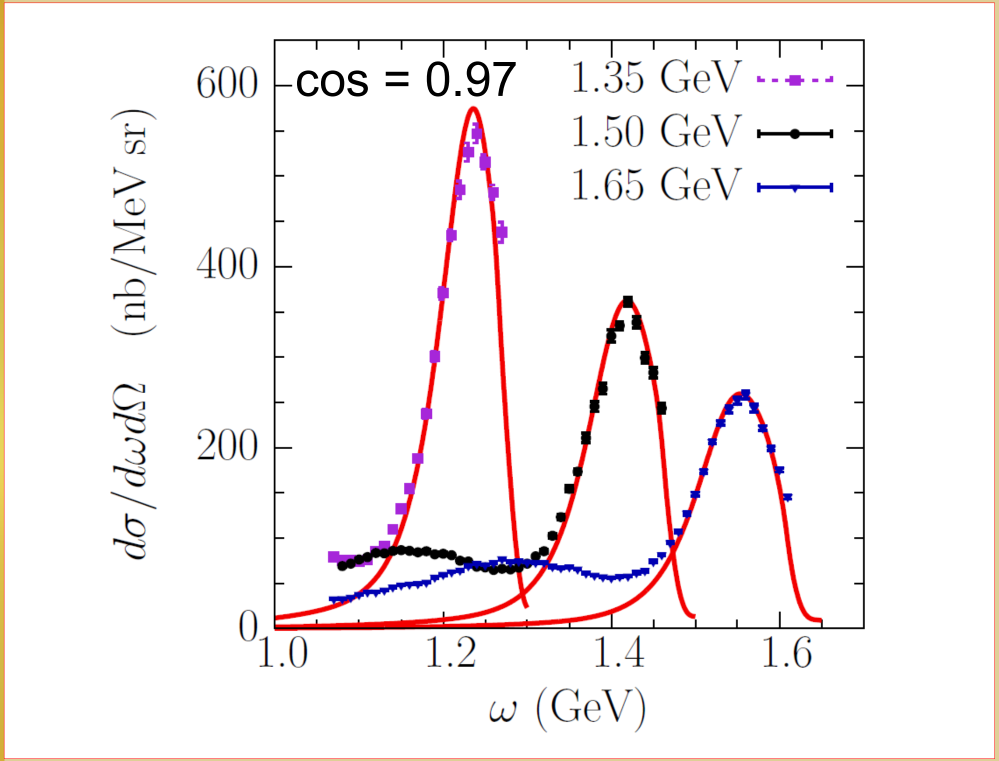
We could use

$$E_\nu^{\rm rec} = \frac{2E_\mu(M-\epsilon) - (M-\epsilon)^2 - m_\mu^2 + M'^2}{2[(M-\epsilon) - E_\mu + |\mathbf{k}_\mu|\cos\theta)},$$

with

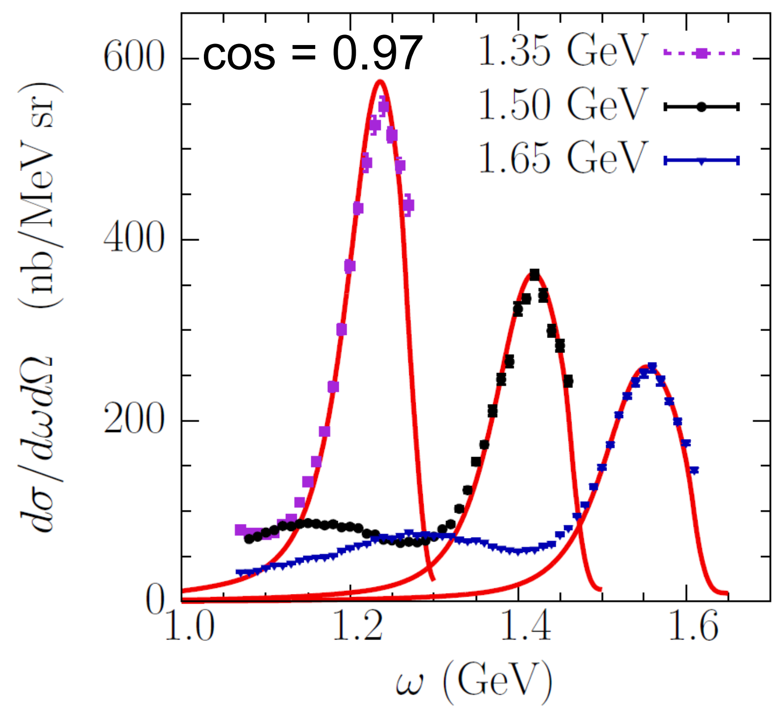
$$\epsilon = \epsilon(E_\mu,\ \cos\theta).$$

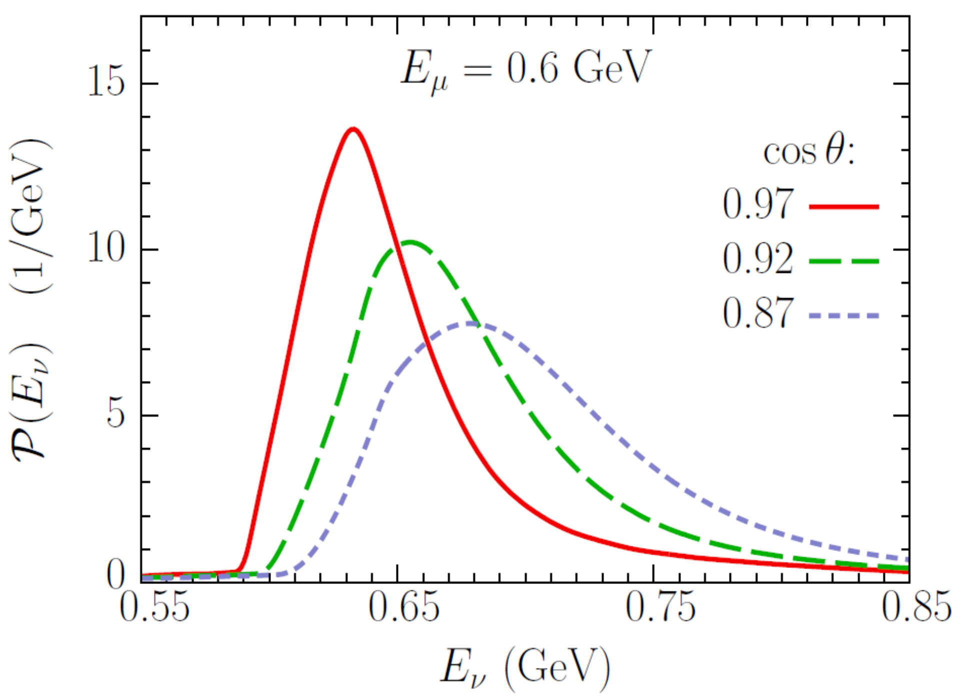
Improved energy reconstruction



$$\frac{d\sigma^{eA}}{dE' d\Omega}$$

Improved energy reconstruction





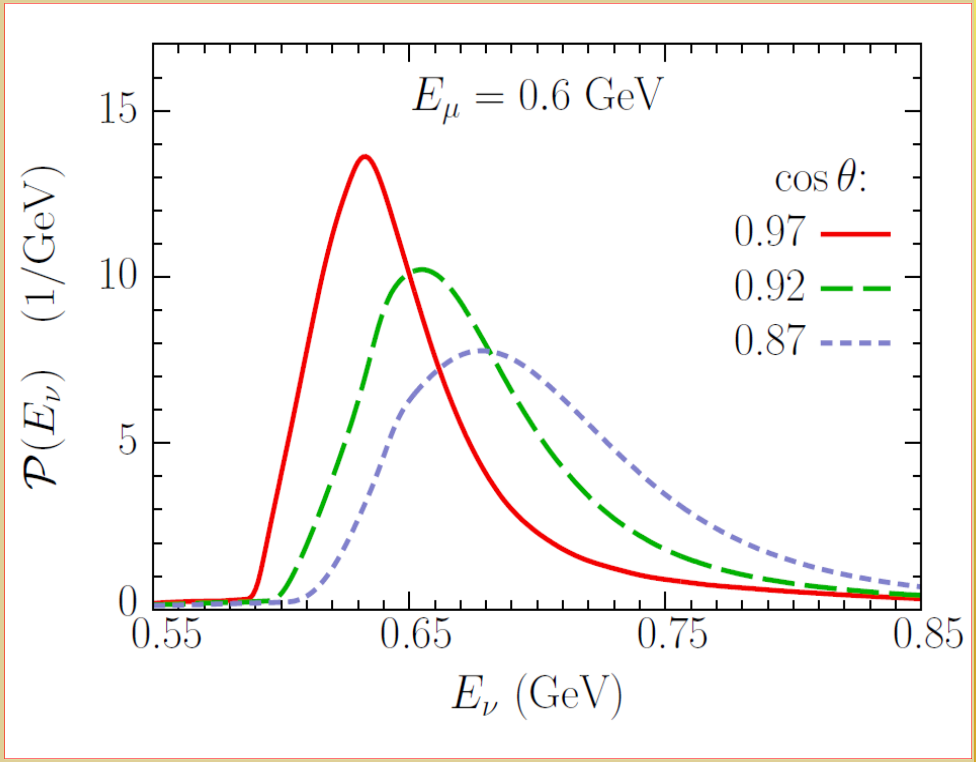
$$\frac{d\sigma^{eA}}{dE' d\Omega}$$

$$\frac{d\sigma^{\nu_\mu A}}{dE_\mu d\cos\theta}$$ normal. to 1

Improved energy reconstruction

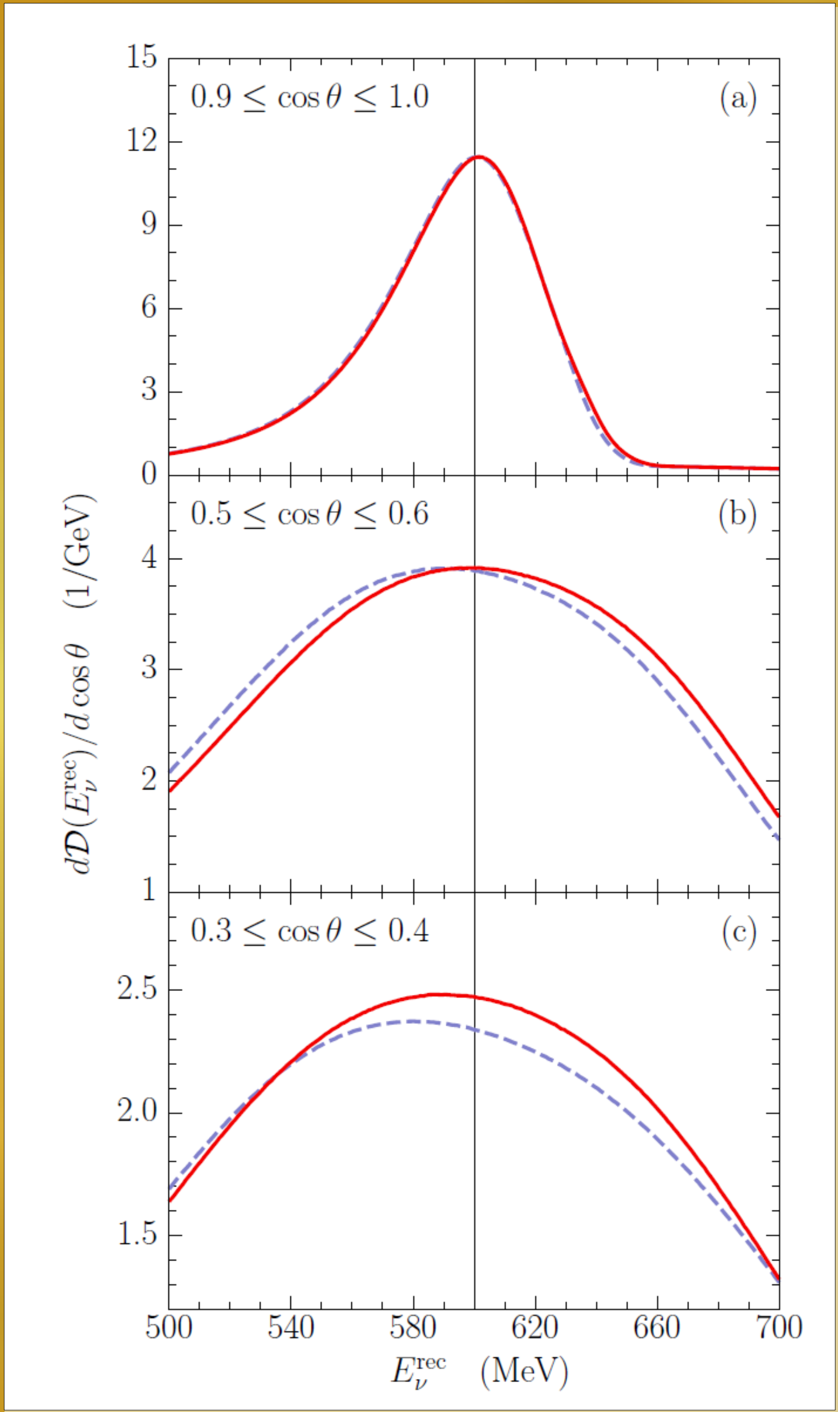
Peak positions can be used to determine the function

$$\epsilon = \epsilon(E_\mu,\ \cos\theta).$$



No beam dependence
No free parameters

Rec. E distributions in different $\cos\theta$ bins $E_\nu = 600$ MeV



	Peak position	
$\cos\theta$	**Const. ϵ**	**$\epsilon(E_\mu, \cos\theta)$**
[0.9; 1.0]	601	602
[0.5; 0.6]	591	599
[0.3; 0.4]	581	591

Summary

1. An accurate description of nuclear effects, including final-state interactions, is crucial for accurate reconstruction of neutrino energy from charged lepton's kinematics.

2. CCQE-like backgrounds have to be precisely estimated and subtracted.

3. Coulomb effects yield a neutrino-antineutrino difference which is for determination of the CP violating phase.

4. Accurate energy reconstruction over a broad angle range requires improved approach.

Backup slides

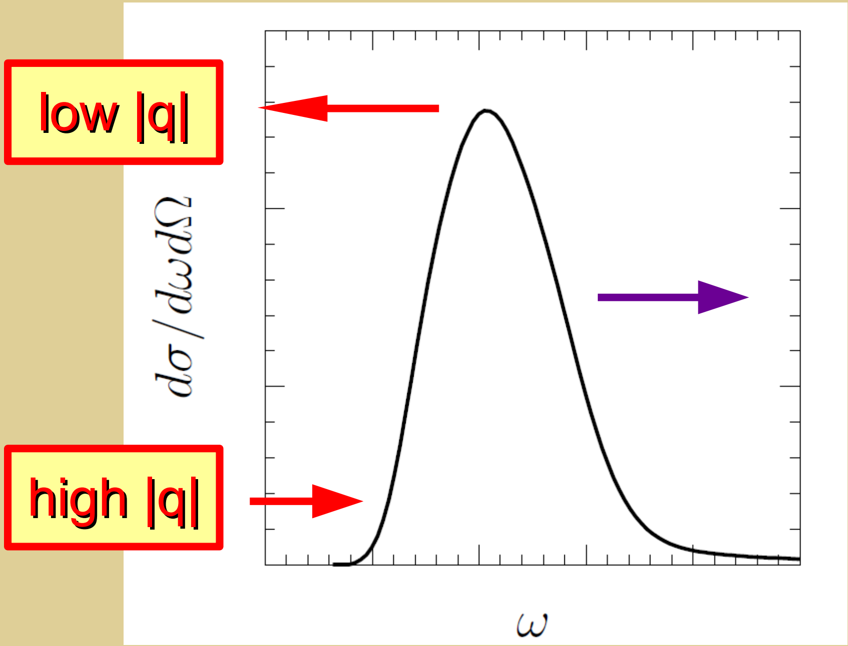
Quick and dirty comparison

Real part of the OP

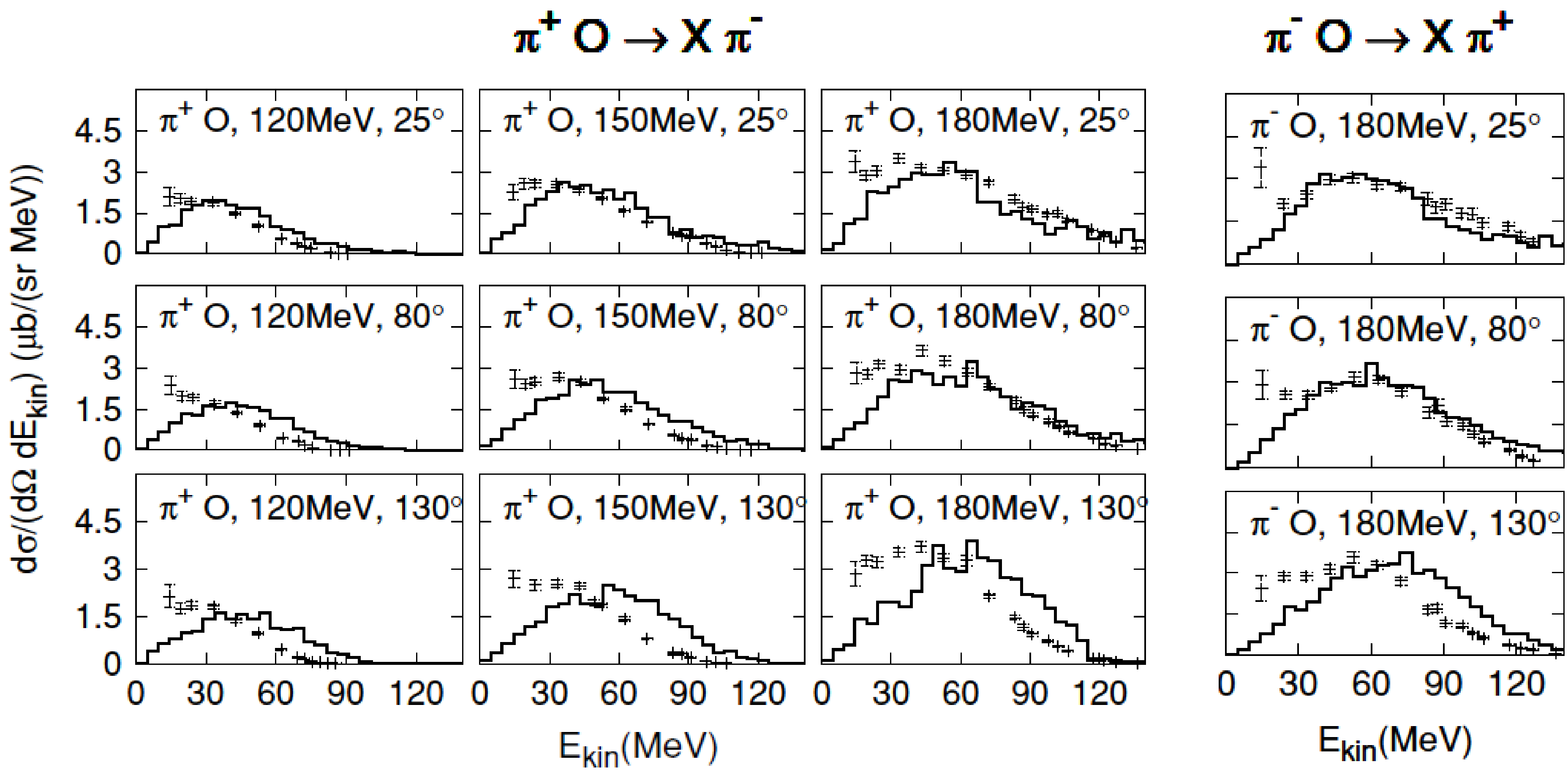
- acts in the final state
- shifts the QE peak to low ω at low $|\mathbf{q}|$ (to high ω at high $|\mathbf{q}|$)

Binding energy

- acts in the initial state
- shifts the QE peak to high ω

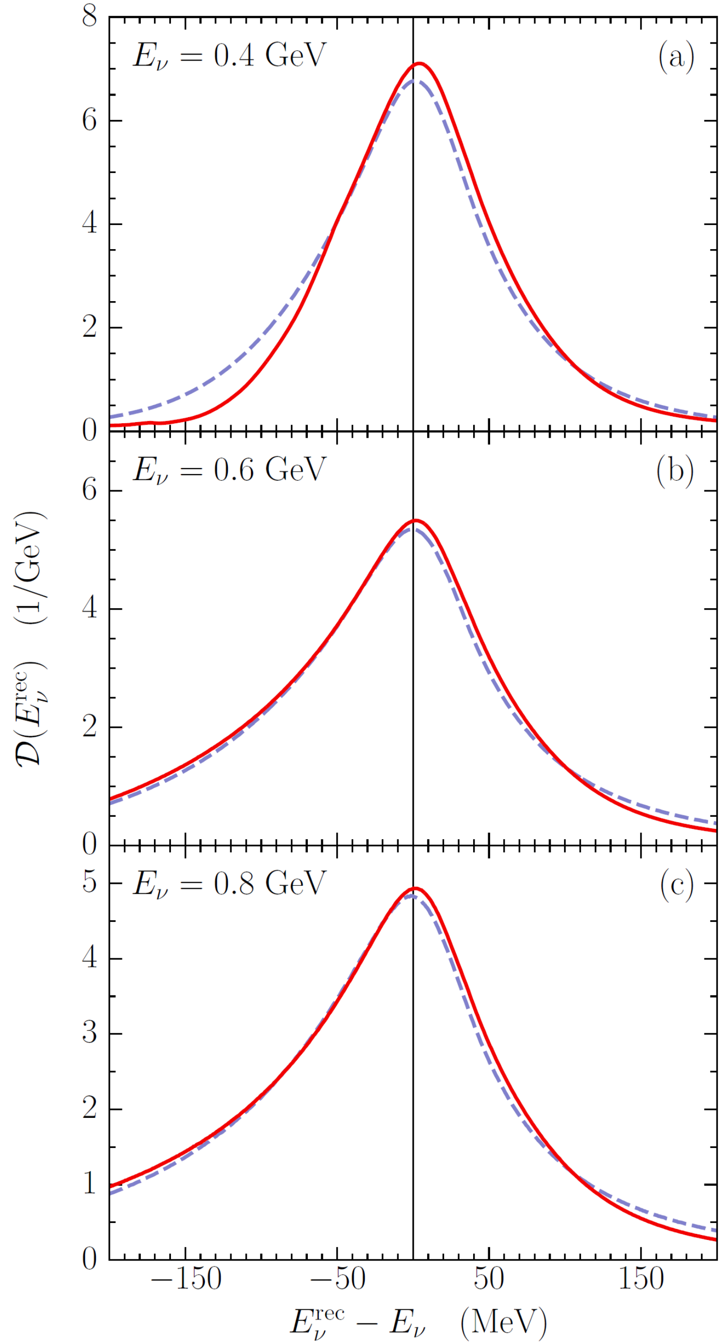


GiBUU results for pions



calcs.: Buss *et al.*
PRC 74, 044610 (2006)

data: Wood *et al.*
PRC 46, 1903 (1992)



$E_\nu = 0.4$ GeV
(a)
$E_\nu = 0.6$ GeV
(b)
$E_\nu = 0.8$ GeV
(c)
$\mathcal{D}(E_\nu^{\rm rec})$ (1/GeV)
$E_\nu^{\rm rec} - E_\nu$ (MeV)
−150
−50
50
150

Neutrino vs antineutrino

muon energy 600 MeV

	cos θ = 0.97	cos θ = 0.92	cos θ = 0.87
neutrino	633	655	678
antineutrino	619	639	661
difference	13.9	16.0	17.6

muon energy 450 MeV

	cos θ = 0.97	cos θ = 0.92	cos θ = 0.87
neutrino	476	488	502
antineutrino	461	474	485
difference	15.1	14.5	16.9

Neutrino vs antineutrino

muon energy 700 MeV

	cos θ = 0.97	cos θ = 0.92	cos θ = 0.87
neutrino	736	768	801
antineutrino	723	752	782
difference	13.9	15.9	19.2

muon energy 500 MeV

	cos θ = 0.97	cos θ = 0.92	cos θ = 0.87
neutrino	529	542	561
antineutrino	515	528	544
difference	14.2	14.9	16.8