From low to high Q2: comparisons with preliminary results from JLab E04-001

Artur M. Ankowski
SLAC, Stanford University

based on Phys. Rev. D 91, 033005 (2015)

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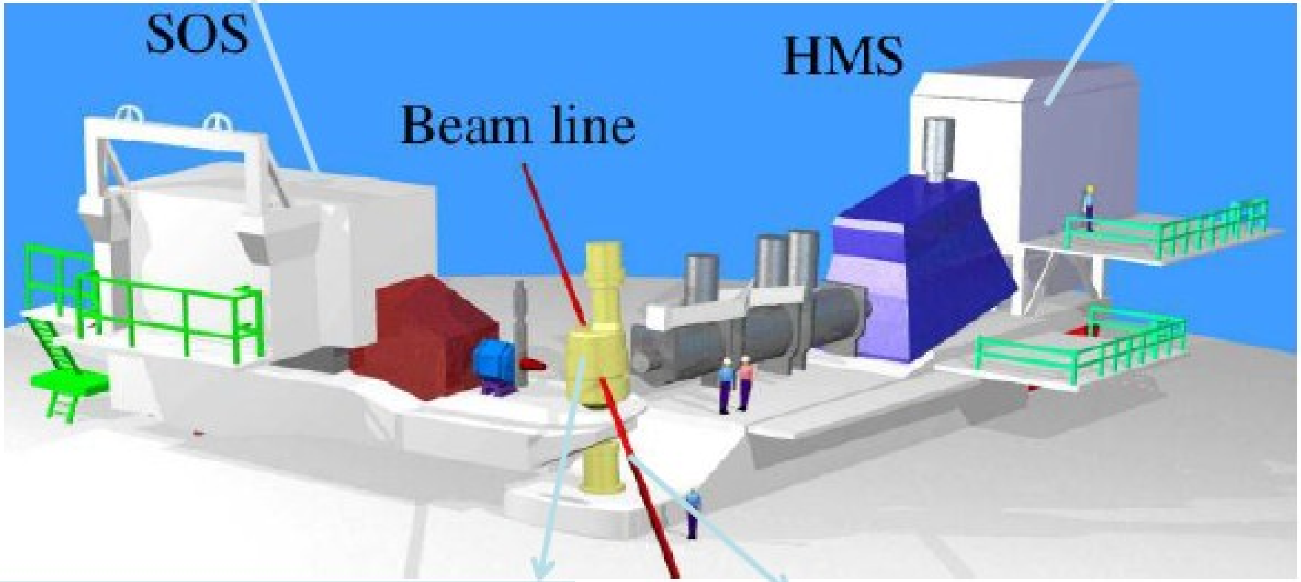
Experimental Overview: E02-109/E04-001(2005)

→ Inclusive measurement in Hall C, A(e,e'), unpolarized beam, unpolarized target

SOS -> background measurements (e^+)
E' = 0.47 - 1.68 GeV/c, θ = 20-70 deg
(last data ever taken by SOS)

HMS -> cross section measurements (e^-)
E' = 0.4 - 4.5 GeV/c, θ = 10.7-70 deg



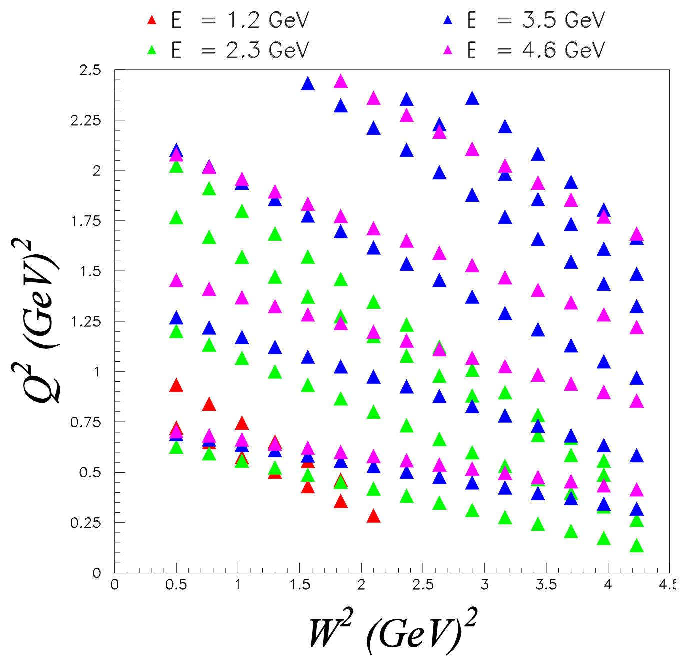
Targets: D, C, Al, Fe, some H

Beam Energies: 1.2, 2.3, 3.5, 4.6 GeV

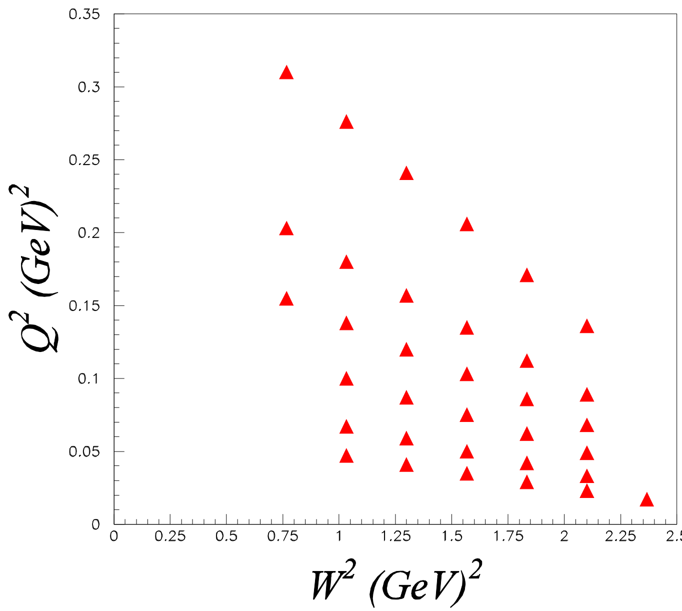
Spokespersons:
A. Bodek, E. Christy, C. Keppel

Simona Malace
https://www.jlab.org/Hall-C/talks/01_15_15/malace.pdf

E02-109/E04-001



Low Q^2 run



experiment	target	interaction region	Q^2 range	L/T
E02-109	D	QE + RR	0.2—2.5	yes
E04-001-I	***C***, Al, Fe	QE + RR	0.2—2.5	yes
E04-001-II	***C***, Al, Fe, Cu	QE + RR	0.7—4.0	yes
Low-Q^2 run	H, D, ***C***, Al	QE + Δ	0.02—0.25	no

Quasielastic scattering

- **Realistic spectral function**: shell-structure from (*e*,*e'p*) data combined with correlated tail from theoretical calculations for nuclear matter (Urbana v_{14} *NN* interactions and 3N interactions by Lagaris & Pandharipande)
[O. Benhar *et al.*, Nucl. Phys. **A579**, 493 (1994)]
- **FSI in the convolution approach**:
[O. Benhar, PRC **87**, 024606 (2013)]
- **LDA Pauli blocking**: depletion probability from the momentum distribution of nuclear matter
[AMA *et al.*, PRD **82**, 013002 (2010)]

AMA *et al.*, PRD **91**, 033005 (2015)

Final-state interactions

Their effect on the cross section is easy to understand in terms of the complex optical potential:

- the **real part** modifies the struck nucleon's energy spectrum: it differs from $\sqrt{M^2 + \mathbf{p}'^2}$
- the **imaginary part** reduces the single-nucleon final states and produces multinucleon final states

$$e^{i(E+U)t} = e^{i(E+U_V)t} e^{-U_W t}$$

Horikawa *et al.*, PRC 22, 1680 (1980)

Final-state interactions

In the convolution approach,

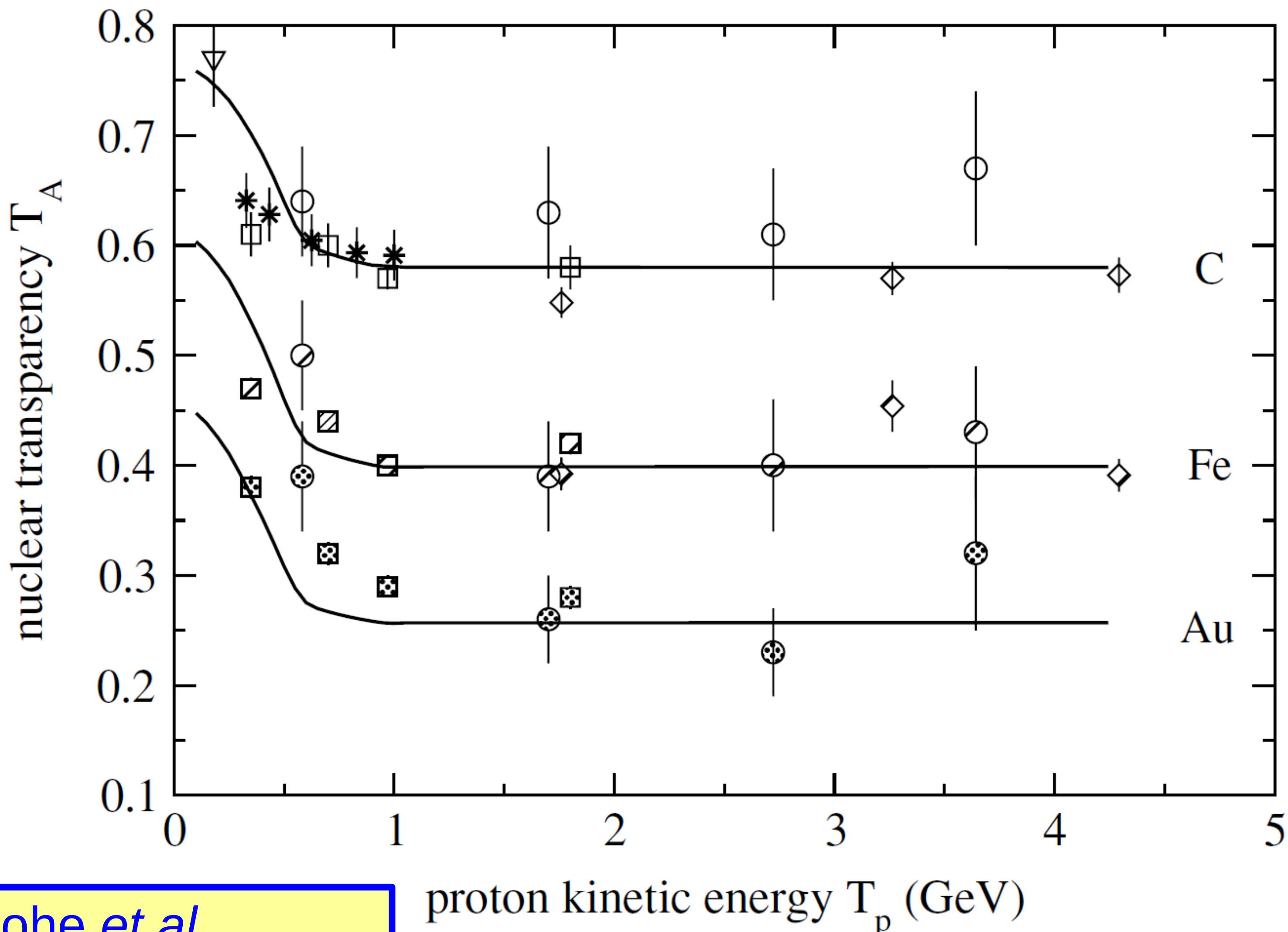
$$\frac{d\sigma^{\mathrm{FSI}}}{d\omega d\Omega} = \int d\omega' f_{\mathbf{q}}(\omega - \omega') \frac{d\sigma^{\mathrm{IA}}}{d\omega' d\Omega},$$

with the folding function

$$f_{\mathbf{q}}(\omega) = \delta(\omega)\sqrt{T_A} + \left(1 - \sqrt{T_A}\right) F_{\mathbf{q}}(\omega),$$

Nuclear transparency

Nuclear transparency



Rohe *et al.*,
PRC 72, 054602 (2005)

Real part of the optical potential

We account for the spectrum modification by

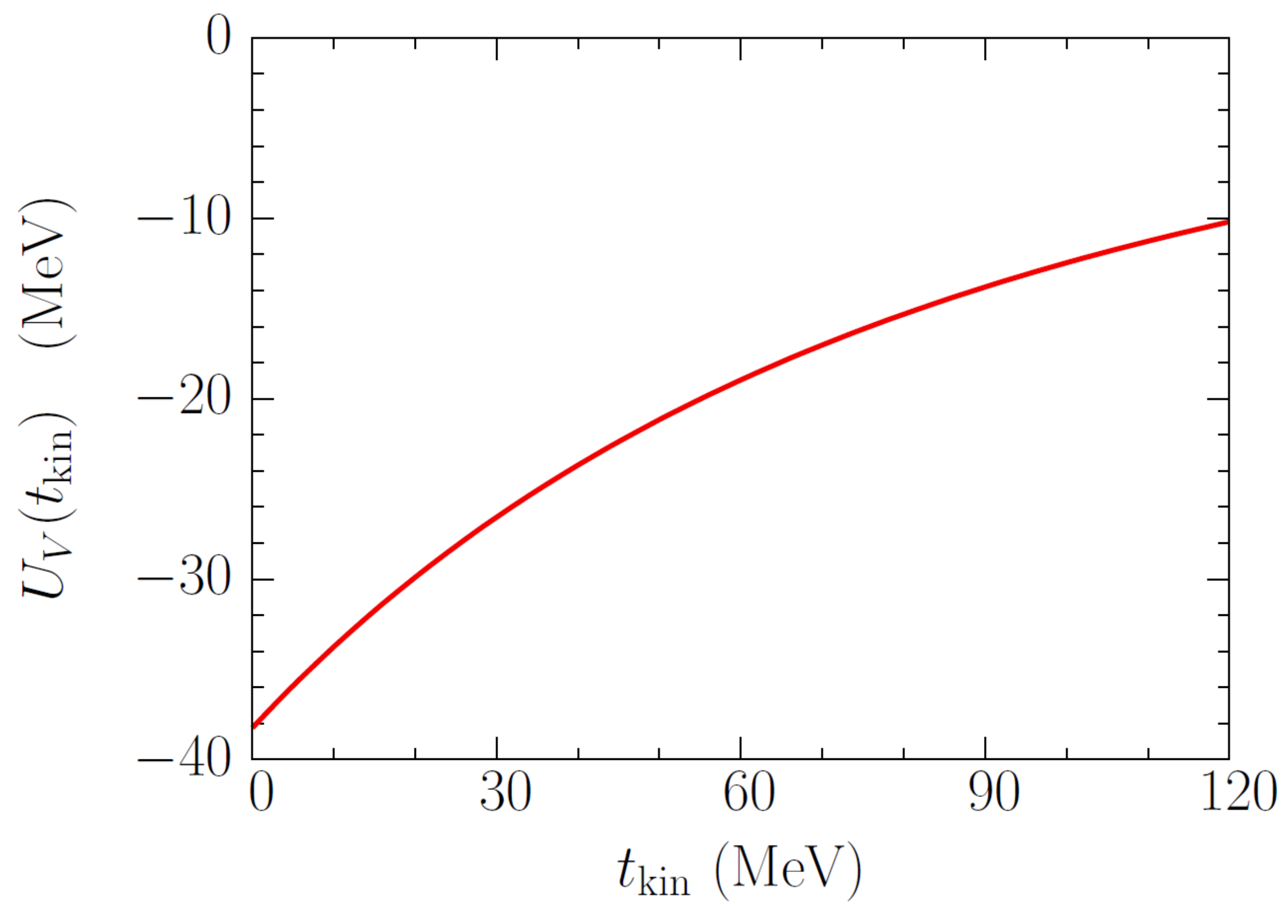
$$f_{\mathbf{q}}(\omega - \omega') \to f_{\mathbf{q}}(\omega - \omega' - U_V).$$

This procedure is similar to that from the Fermi gas model to introduce the binding energy in the argument of $\delta(...)$.

$$U_V = U_V(t_{\rm kin})$$

$$t_{\rm kin} = \frac{E_{\mathbf{k}}^2(1-\cos\theta)}{M + E_{\mathbf{k}}(1-\cos\theta)}$$

Optical potential by Cooper *et al.*



obtained from
Cooper *et al.*, PRC 47, 297 (1993)

Pion production

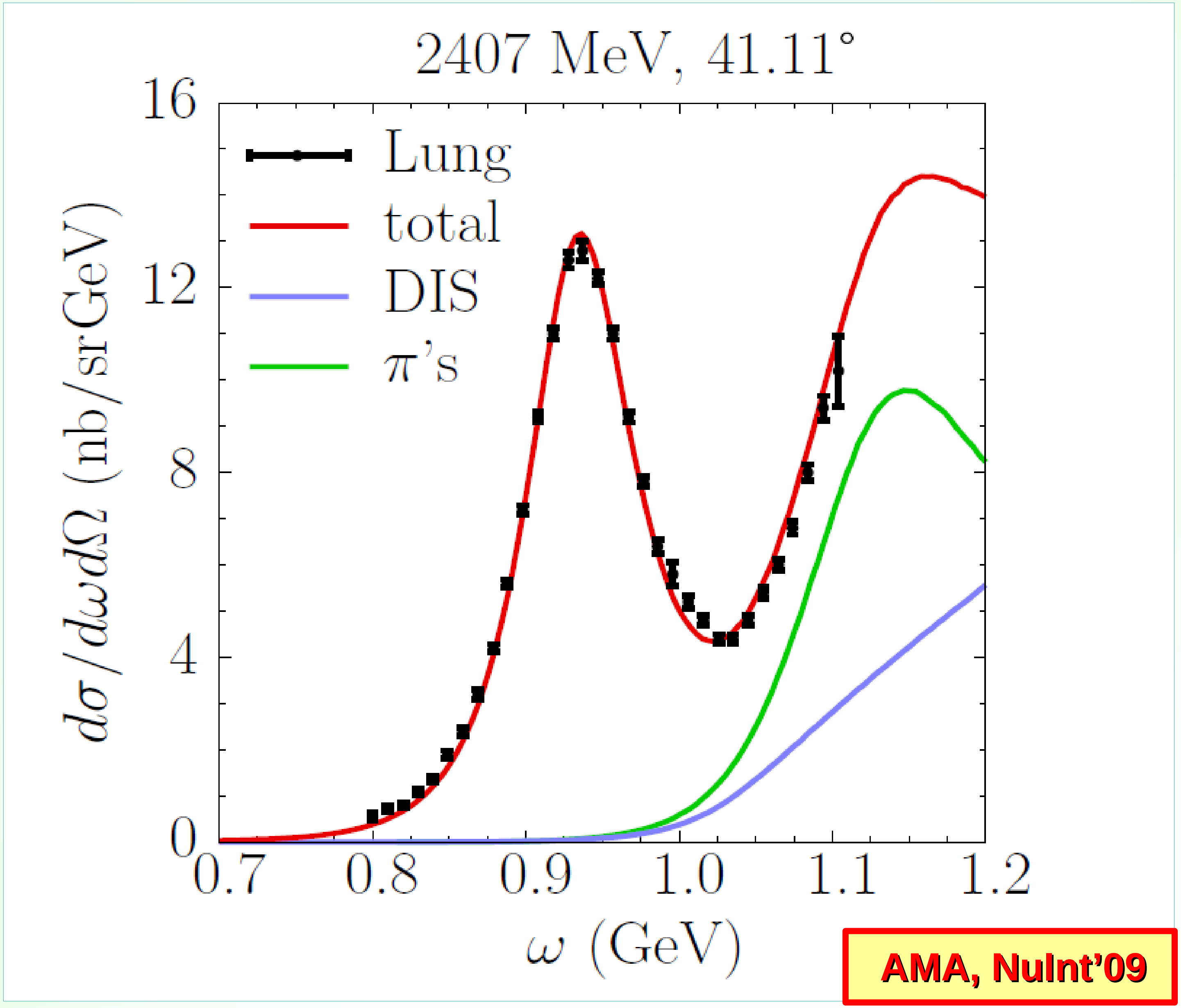
Old ingredients (see my talk at NuInt'09):

- **MAID 2007**: resonances with $W < 2$ GeV
  D. Drechsel *et al.*, EPJ. A 34 (2007) 69
- **Nonresonant pion production** and **DIS:**
  T.C. Ferrée and D.S. Koltun, PRC 55, 253 (1997)

Modifications:

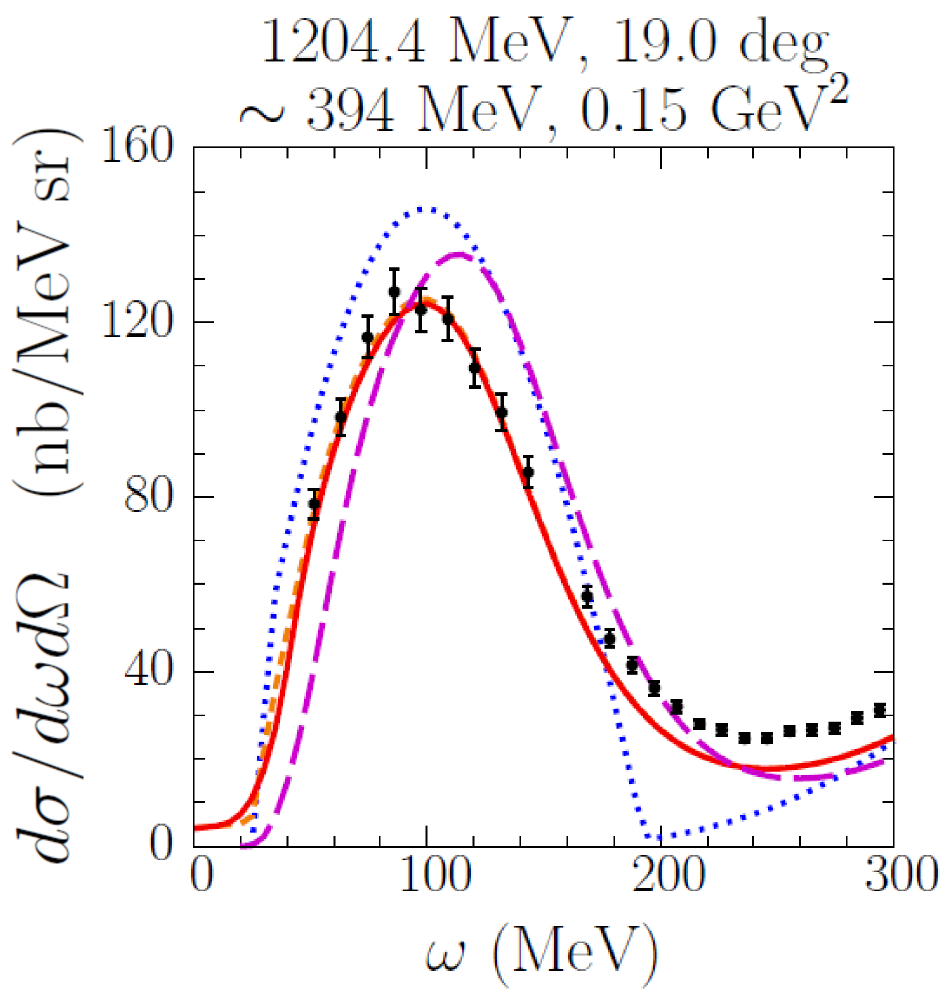
- Free-nucleon structure functions:
  evaluated for Q^2 not $\widetilde{Q}^2$
- FSI partly accounted for. The proton optical potential used, no broadening [folding function = $\delta(\ldots)$]

D(*e*, *e'*)



AMA, NuInt'09

Compared calculations



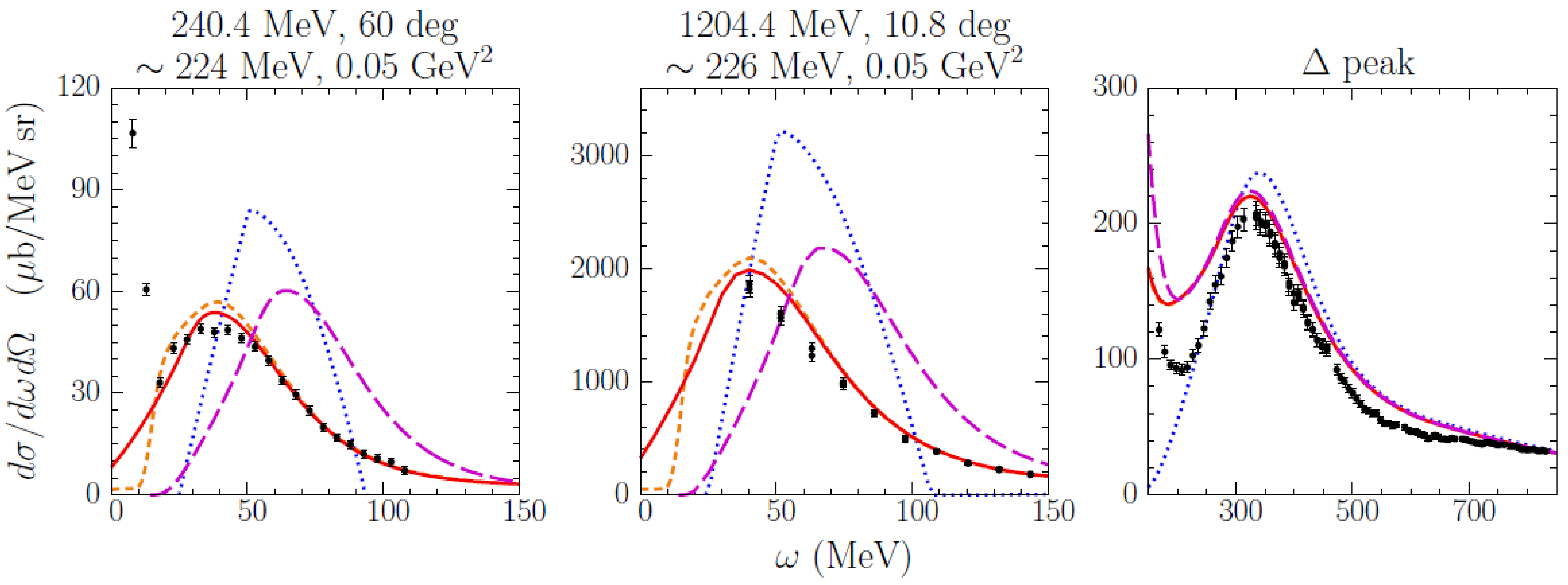
RFG model
ε = 25 MeV
p_F = 221 MeV

SF calculation without FSI

SF calculation, LDA treatment of Pauli blocking

SF calculation, step function

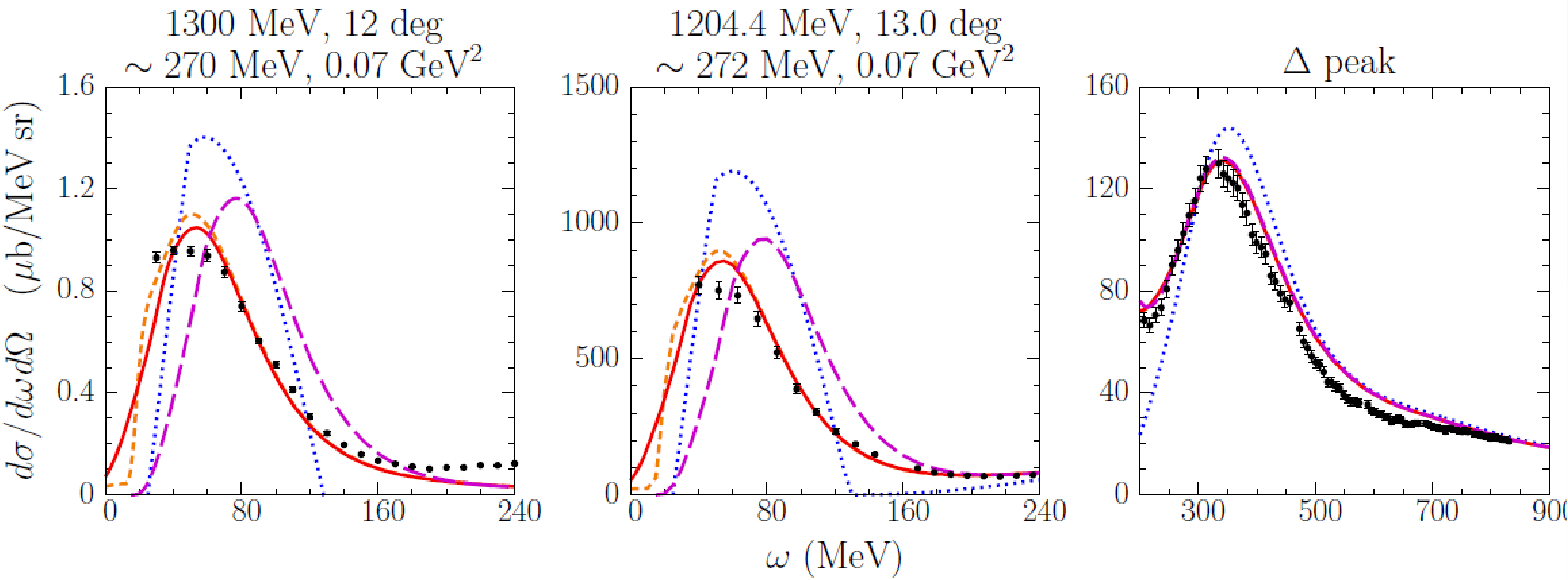
Comparisons with C(*e*,*e'*) data



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

Jlab E04-001,
preliminary

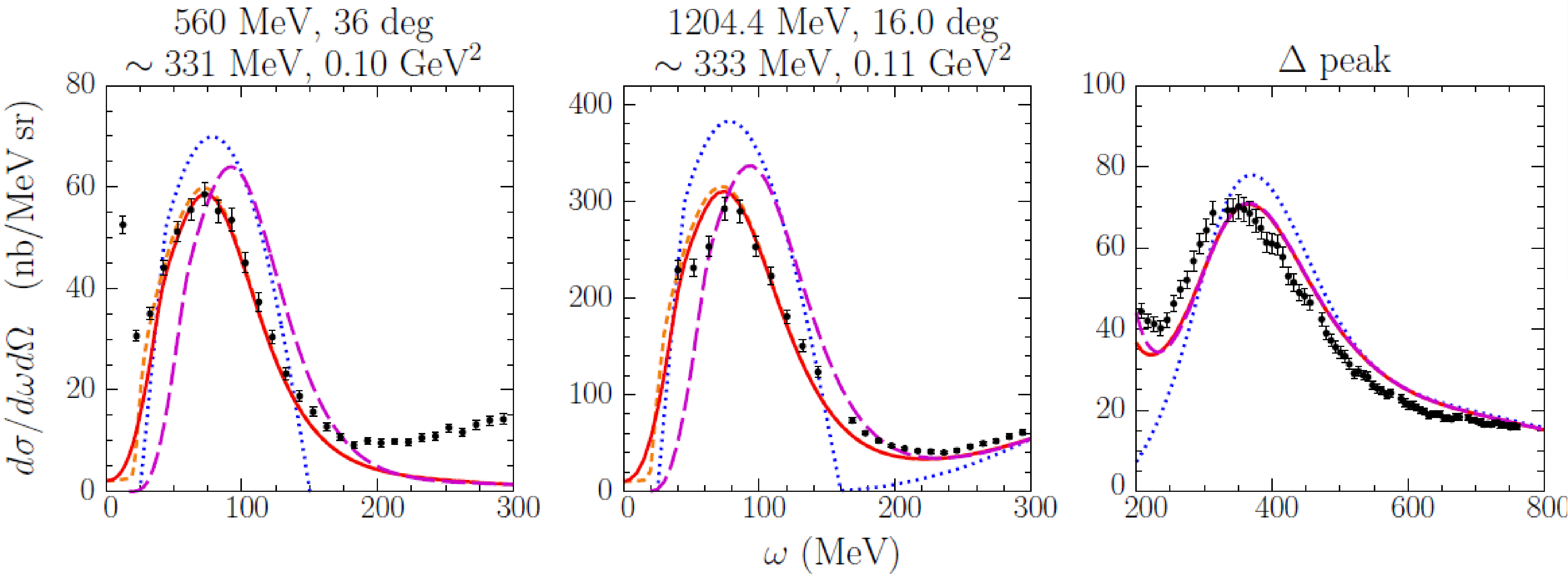
Comparisons with C(*e*,*e*′) data



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

Jlab E04-001,
preliminary

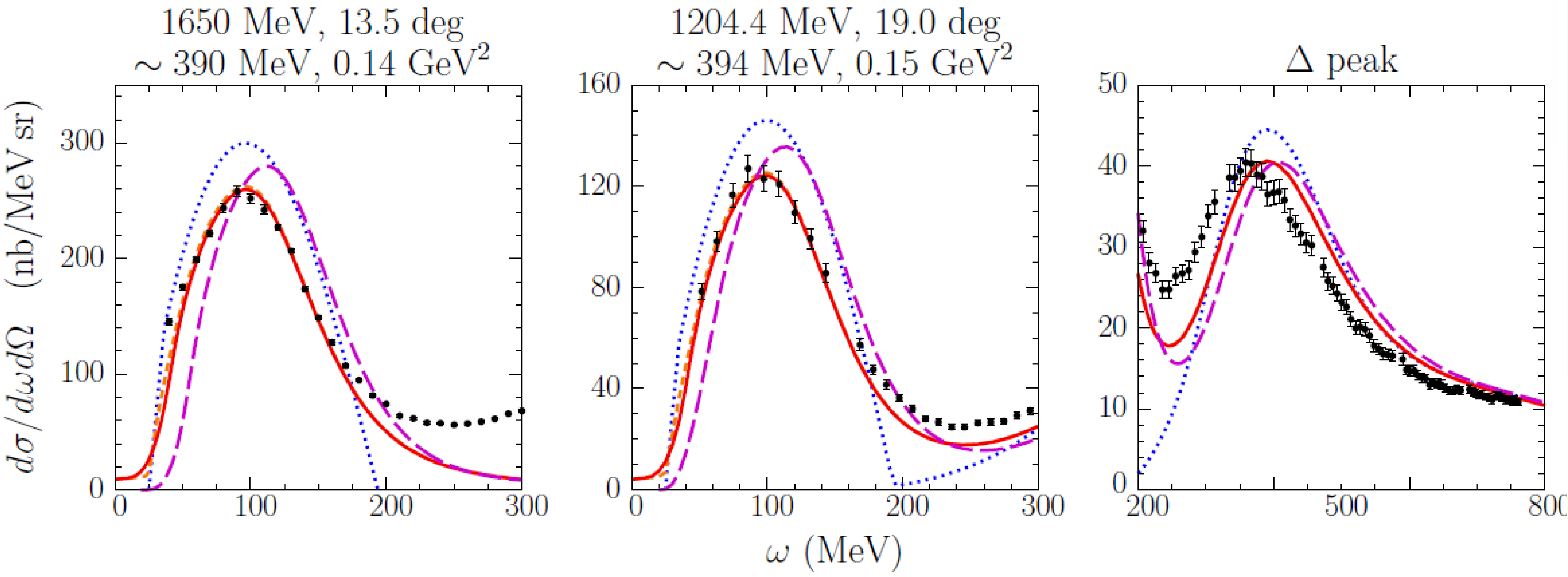
Comparisons with C(*e*,*e*′) data



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

Jlab E04-001, preliminary

Comparisons with C(e,e') data

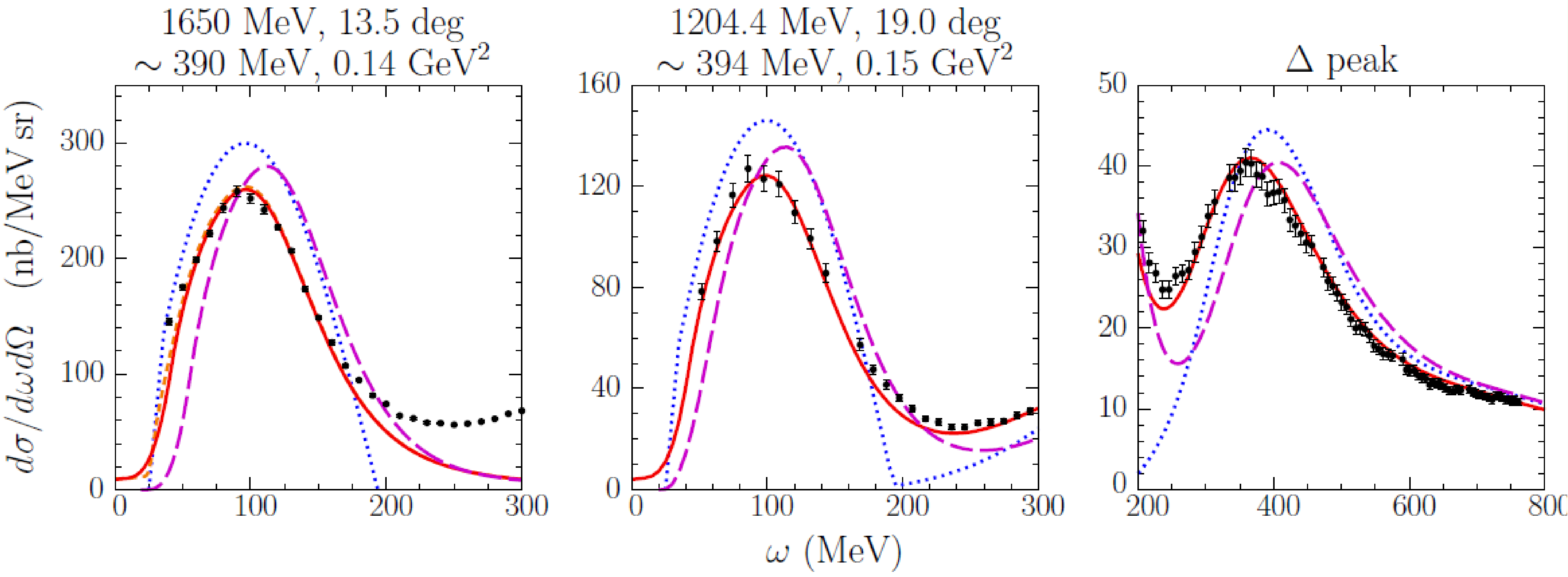


Baran *et al.*,
PRL 61, 400 (1988)

Jlab E04-001,
preliminary

Side remark: potential for Δ

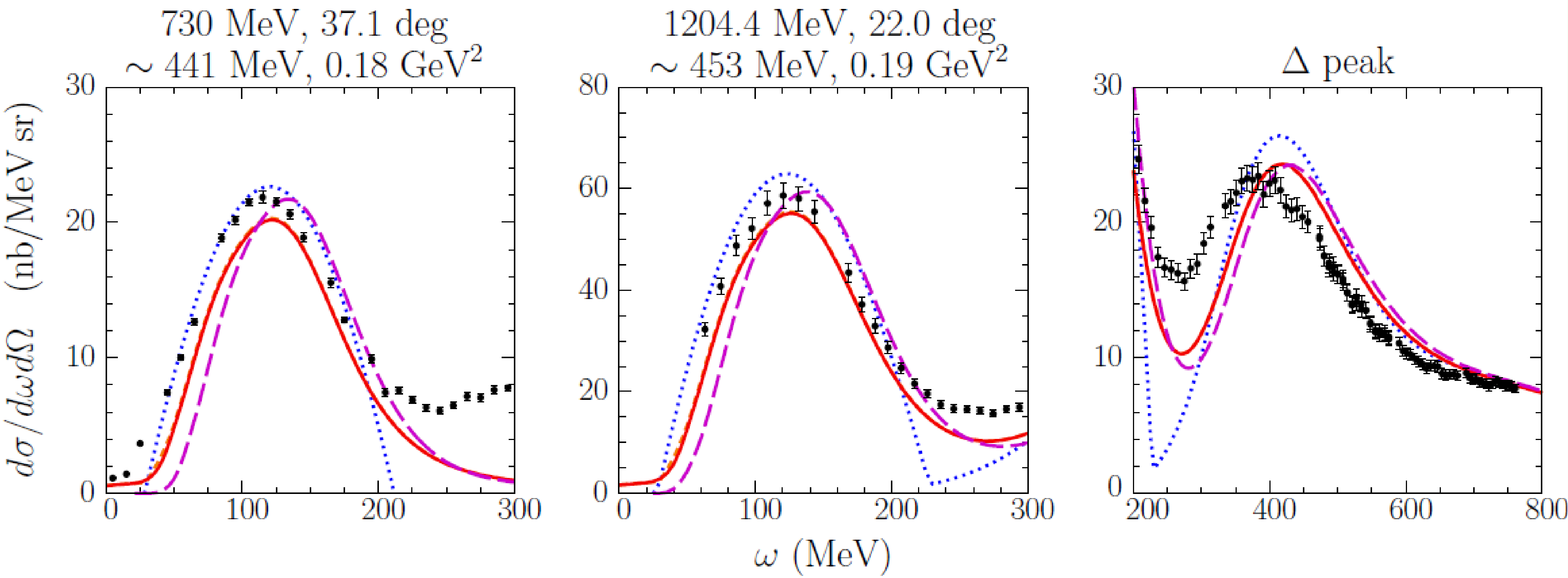
Potential adjusted “by eye” from -15.5 to -40 MeV



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

Jlab E04-001,
preliminary

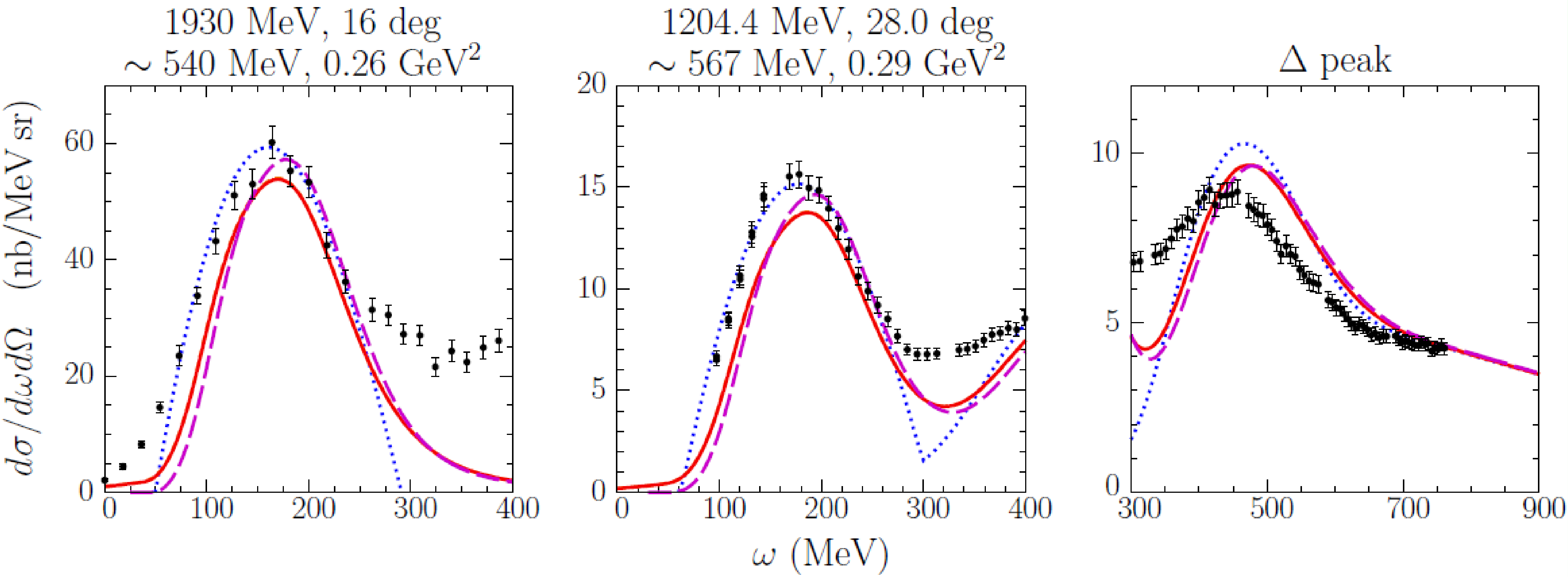
Comparisons with C(*e*,*e*′) data



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

Jlab E04-001,
preliminary

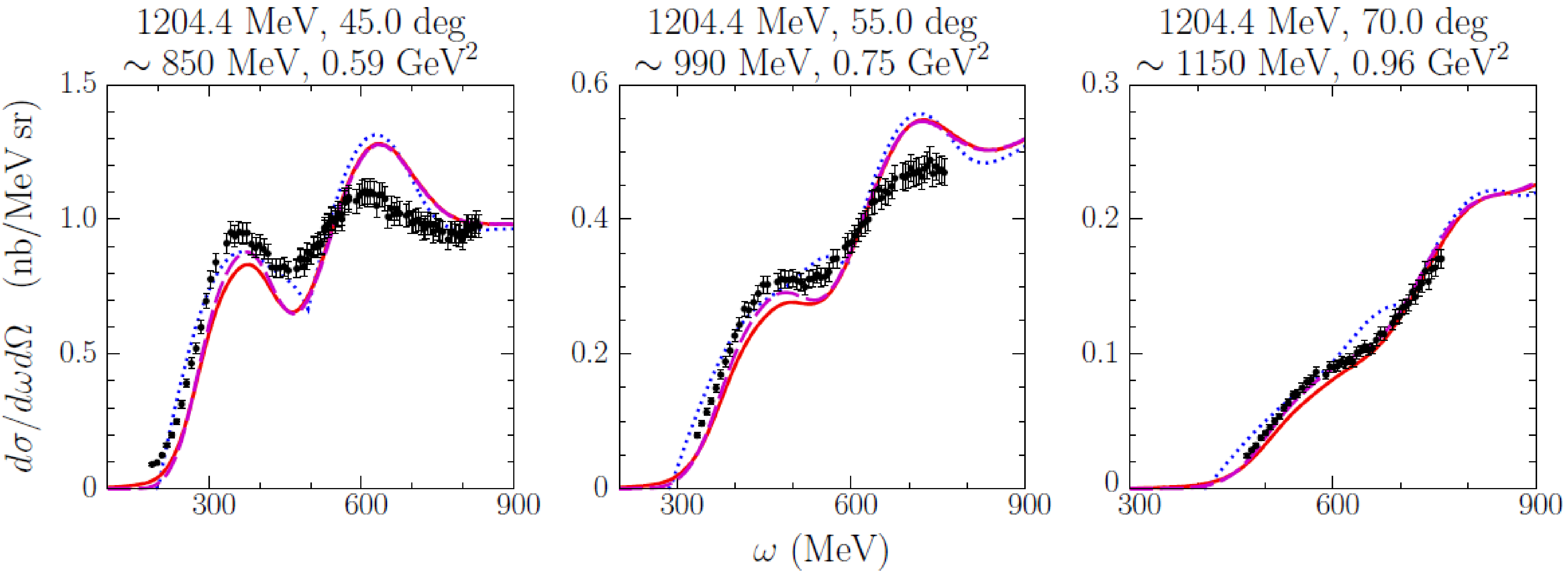
Comparisons with C(*e*,*e'*) data



Baghdasarian *et al.*, YERPHI-1077(40)-88

Jlab E04-001, preliminary

Comparisons with C(*e*,*e*′) data



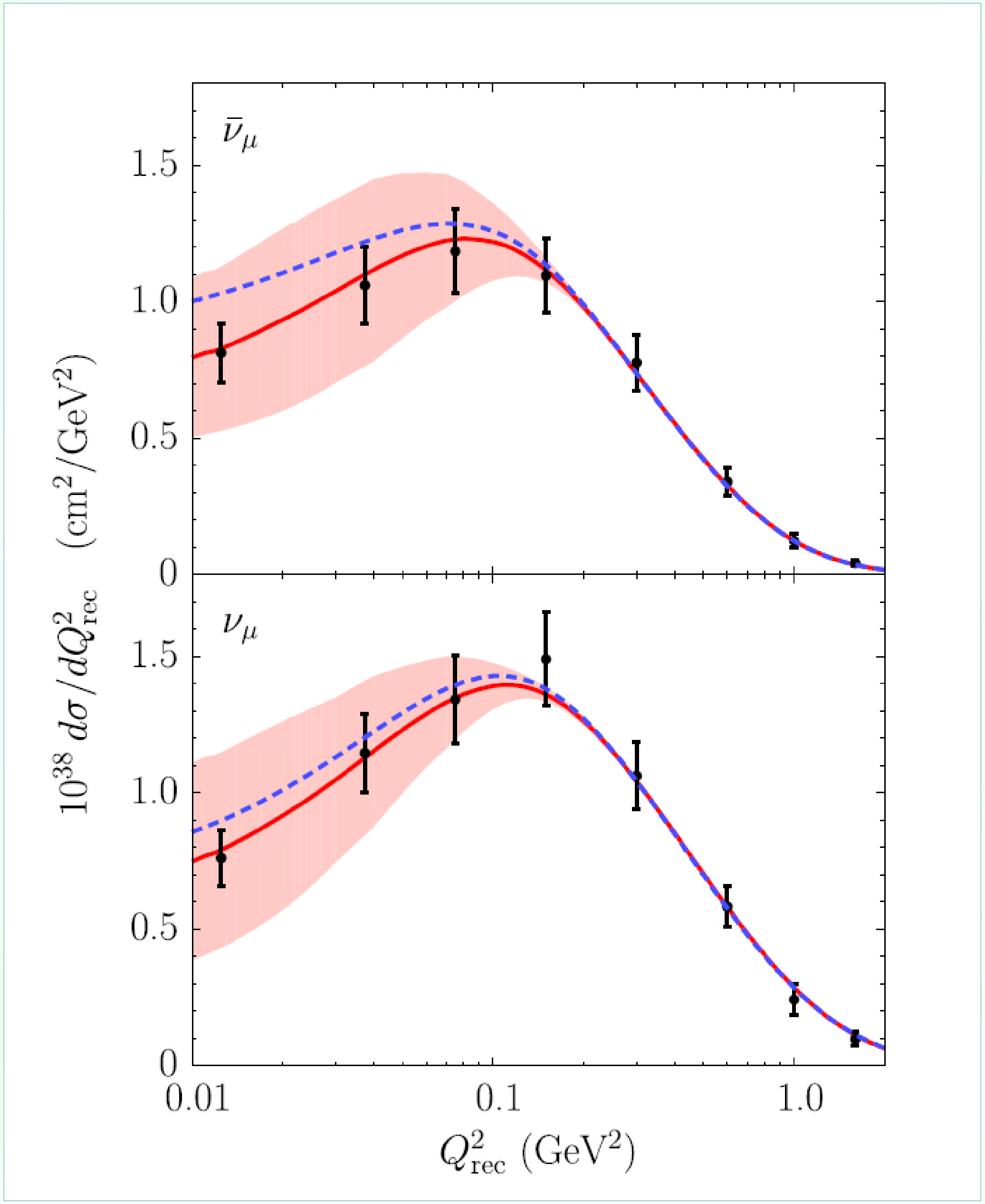
Jlab E04-001, preliminary

CCQE MINERvA data

SF calculations with FSI

vs.

SF calculation without FSI



Fields *et al.*, PRL 111, 022501 (2013)

A. M. A., PRD 92, 013007 (2015)

Fiorentini *et al.*, PRL 111, 022502 (2013)

CCQE MINERvA data

TABLE I. Fit results to the CC QE MINERvA data.

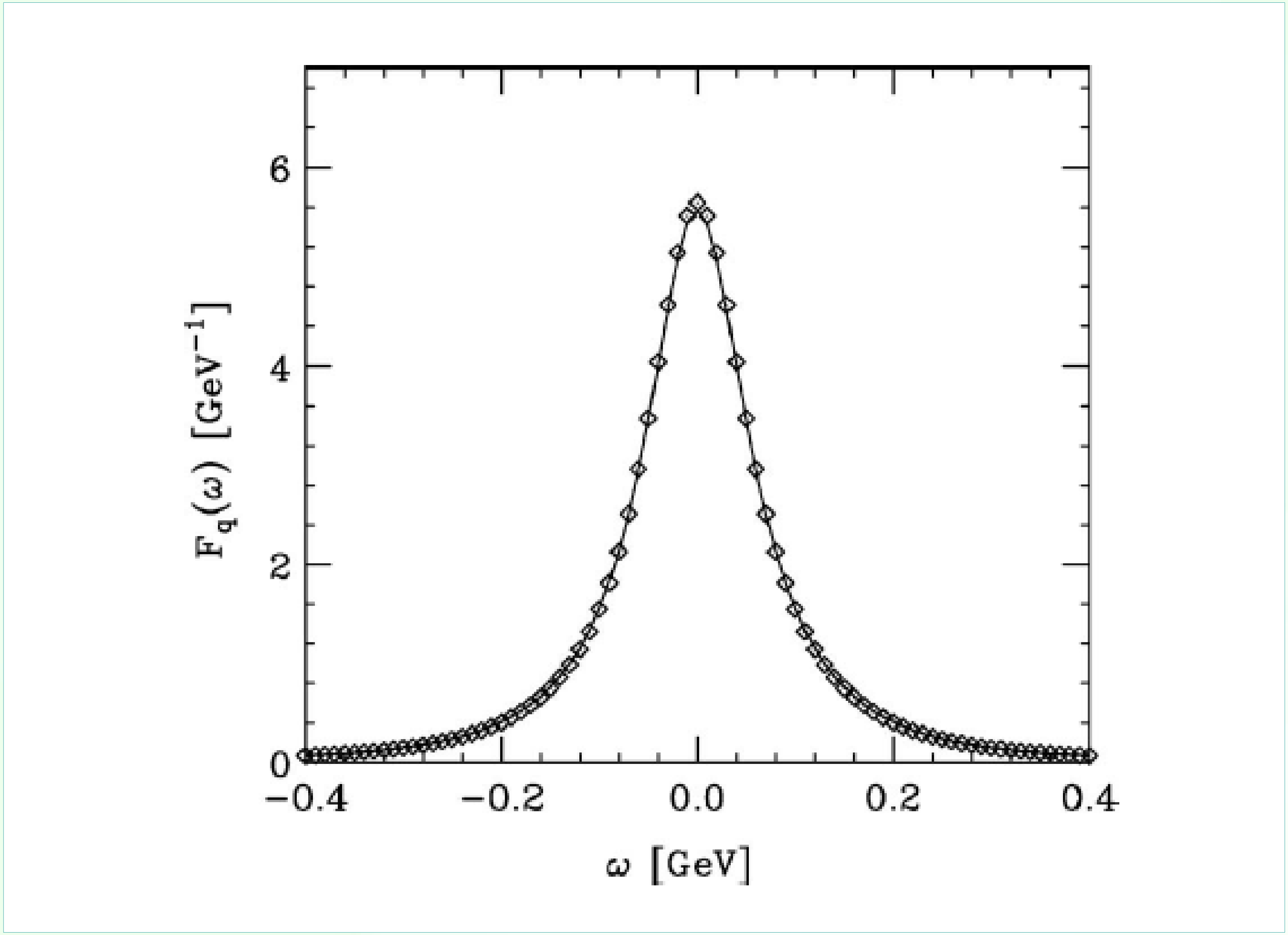
	antineutrino	neutrino	combined fit
	including theoretical uncertainties:		
M_A (GeV)	1.16 ± 0.06	1.17 ± 0.06	1.16 ± 0.06
χ^2/d.o.f.	0.38	1.33	0.93
	neglecting theoretical uncertainties:		
M_A (GeV)	1.15 ± 0.10	1.15 ± 0.07	1.13 ± 0.06
χ^2/d.o.f.	0.44	1.38	1.00
	neglecting FSI ($M_A = 1.16$ GeV):		
χ^2/d.o.f.	2.49	2.45	2.42

Summary

- Accurate description of the QE cross section requires accounting for FSI. At low |q|'s they mainly shift the peak, at high |q|'s FSI mainly broaden it.
- Preliminary results from Jlab E04-001 described with the same precision as existing data in the approach from AMA, O. Benhar, & M. Sakuda, PRD **91**, 033005 (2015).
- New data span broad range of ω's, allowing comparisons up to higher resonances and onset of DIS. Uncertainties will be further reduced. Great chance for testing nuclear models in the T2HK and DUNE era!

Backup slides

$F_q(\omega)$



Simple 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 in RFG

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