SUPERSCALING OF NON-QUASIELASTIC ELECTRON-NUCLEUS SCATTERING

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C.M, J.E. Amaro, M.B. Barbaro, J.A. Caballero, T.W. Donnelly and C.F. Williamson, PRC 80, 035504 (2009)

Workshop "Electroweak interactions with nuclei.....", ECT* Trento, 28/10/2009

GENERAL FRAMEWORK

- Scaling properties of lepton-nucleus scattering at and above the quasi-elastic peak
- Interesting in itself
- Important to asses validity of superscaling based model of neutrino scattering

SPECIFIC TOPIC

- Phenomenological study of (1st kind) scaling violation beyond the QE peak up to the Δ peak
- "Phenomenological": study behavior of data + use simple and phenomenology-based models

OUTLINE

Antefact I: QE region

- previous formalism and results
- SS-based model for cross sections (SSM-QE)

Antefact II: beyond the QE peak

- previous formalism, results and SuSA
- previous results revisited , scaling violations

SS-based model for inelastic eA scattering

- formalism
- results, scaling violations

"Non-impulsive" contributions

Summary and conclusions

QE region: basic formalism

RFG expressions for L and T QE response functions:

$$R^{QE}_{L,T;RFG}(\kappa,\lambda) = \frac{1}{k_F} f^{RFG}(\psi) G^{QE}_{L,T}(\kappa,\lambda)$$

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Single nucleon responses

$$\begin{aligned} G^{QE}_L &= \frac{\kappa}{2\tau}\left[ZG^{p^2}_E + NG^{n^2}_E\right] + \mathcal{O}(\eta_F^2) \\ G^{QE}_T &= \frac{\tau}{\kappa}\left[ZG^{p^2}_M + NG^{n^2}_M\right] + \mathcal{O}(\eta_F^2) \end{aligned}$$

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$$G^{QE}_T = \frac{\tau}{\kappa}\left[Z G_M^{p^2} + N G_M^{n^2}\right] + \mathcal{O}(\eta_F^2)$$

Dimensionless variables:

$$\lambda = \frac{\omega}{2m_N} \quad ; \kappa = \frac{q}{2m_N}$$

$$\tau = \kappa^2 - \lambda^2 = \frac{|Q^2|}{4m_N^2}$$

$$\eta_F = \frac{k_F}{m_N}$$

$$\xi_F = \sqrt{\eta_F^2 + 1} - 1$$

Scaling function and variable

$$f^{RFG}(\psi) = \frac{3}{4}\left(1-\psi^2\right)\theta\left(1-\psi^2\right)$$

$$\psi = \frac{1}{\sqrt{\xi_F}} \frac{\lambda - \tau}{\sqrt{(1+\lambda)\tau + \kappa\sqrt{\tau(1+\tau)}}}$$

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➔ **experimental**

$$f_{exp} \equiv k_F \frac{d\sigma}{\sigma_M \left(v_L G_L^{QE} + v_T G_T^{QE}\right)}$$

$$f^L_{exp} \equiv k_F \frac{R_L}{G_L^{QE}} \qquad f^T_{exp} \equiv k_F \frac{R_T}{G_T^{QE}}$$

QE region: previous results – total f

Scaling: independence of q (1st kind) [and of nuclear species (2nd)]

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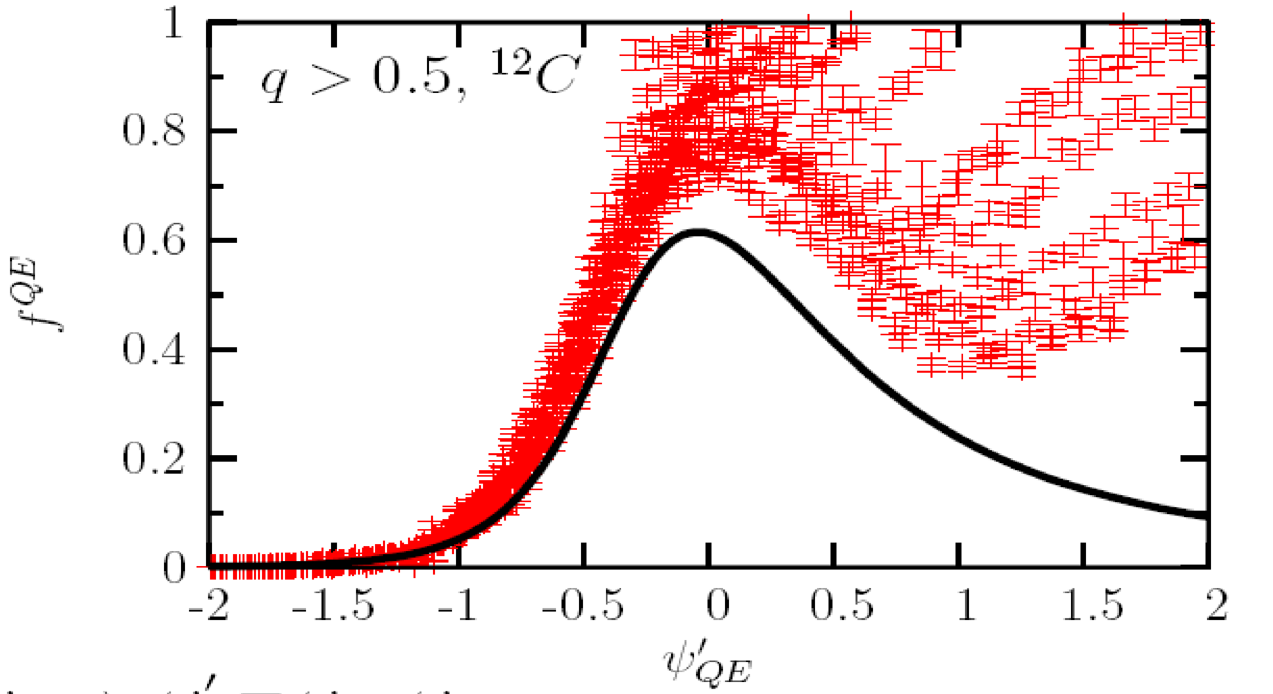

Carbon 12

K_F=228 MeV/c

ω_{shift}= 20 MeV

$$\omega \longrightarrow \omega' = \omega - \omega_{shift}$$

$$\lambda \longrightarrow \lambda' = \frac{\omega'}{2m_N}$$

$$\tau \longrightarrow \tau' = \kappa^2 - \lambda'^{\,2}$$

$$\psi \longrightarrow \psi' = \psi(\lambda', \tau')$$

Present study focused on 1st kind scaling

QE region: previous results – $f_{L,T}$

[RFG: $f_L = f_T = f$ (0[th] kind)]

Donnelly&Sick, PRL**82** & PRC**90**(1999)

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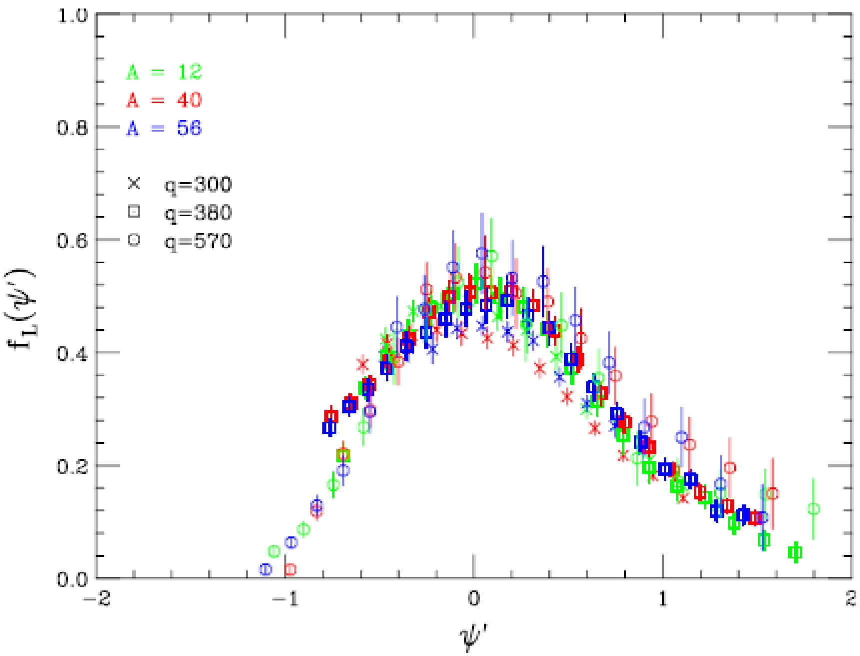

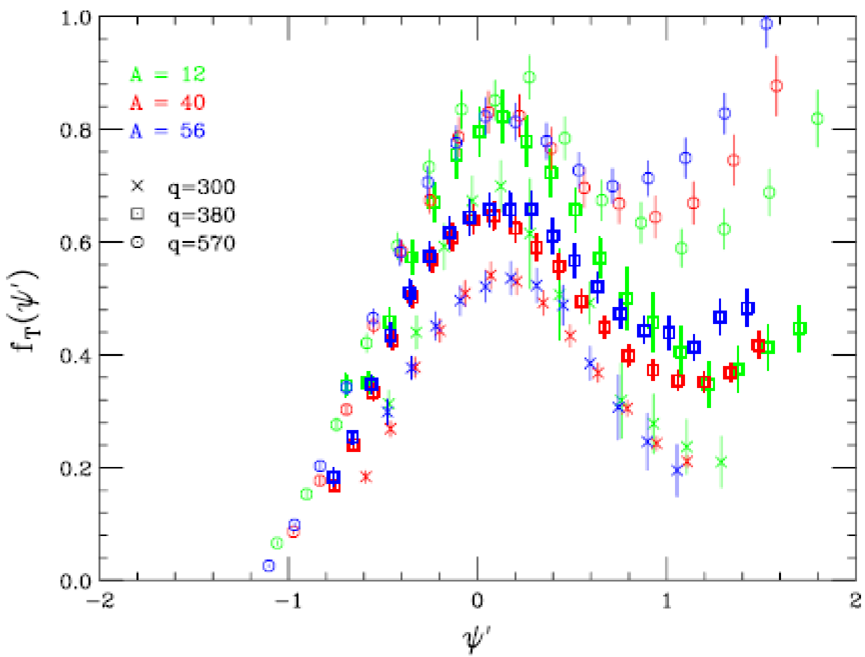

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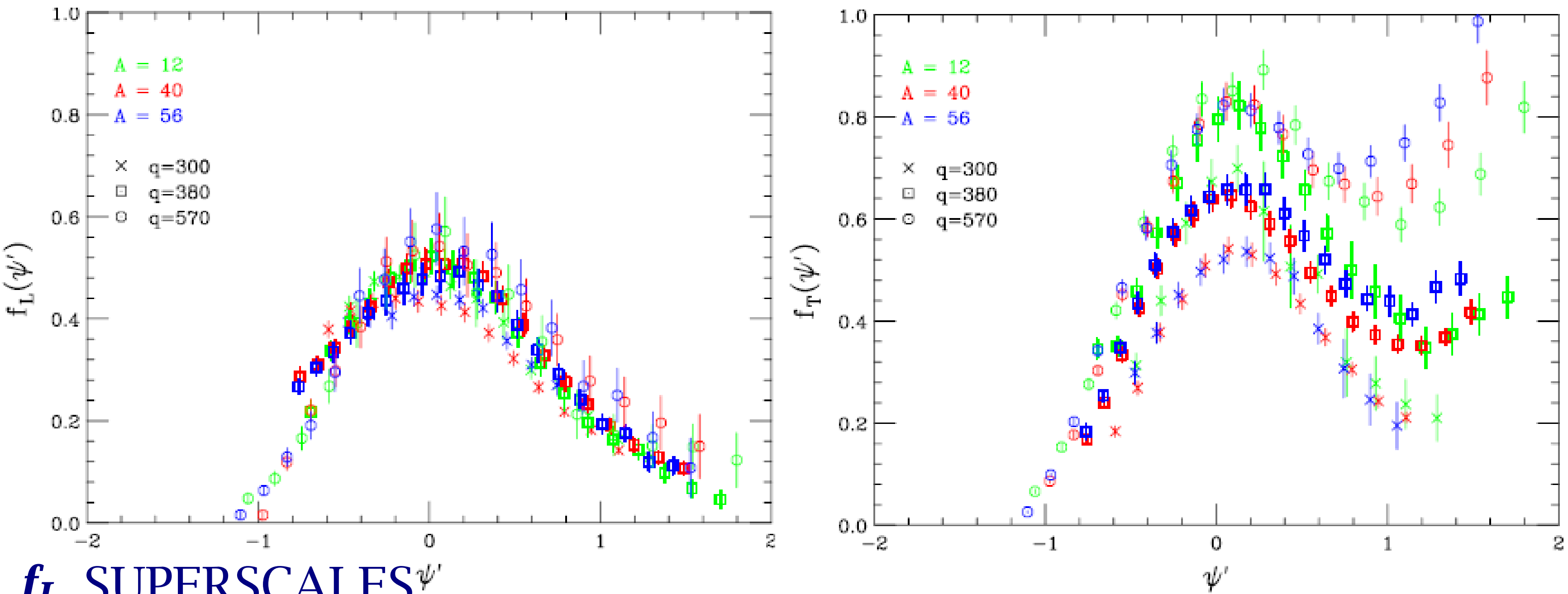
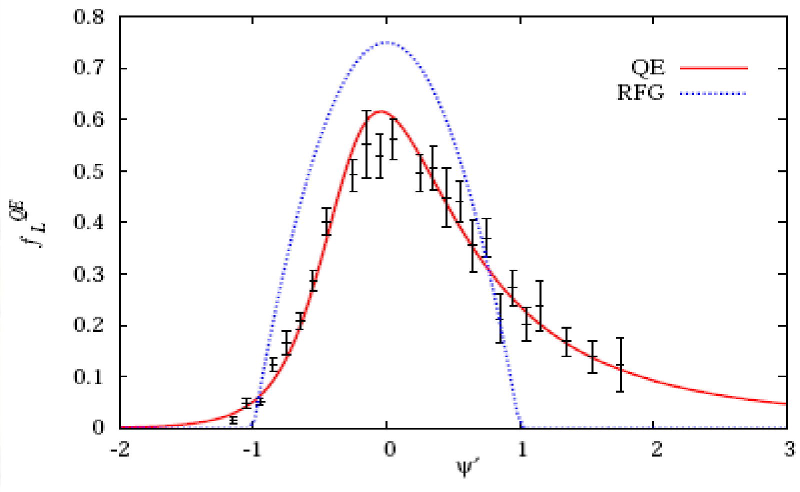


f_L SUPERSCALES

f_T differs from ***f_L***, shows excellent scaling of 2nd kind , but breaking of scaling of 1st kind increasing with increasing ψ' : "non-QE" contributions (meson production, resonances, DIS, MEC) active in transverse channel

"SUPERSCALING HYPOTHESIS"

There exists only one universal (QE) scaling function, which contains the nuclear physics information of the process and it can be identified with the "experimental" f^{QE}_{L}



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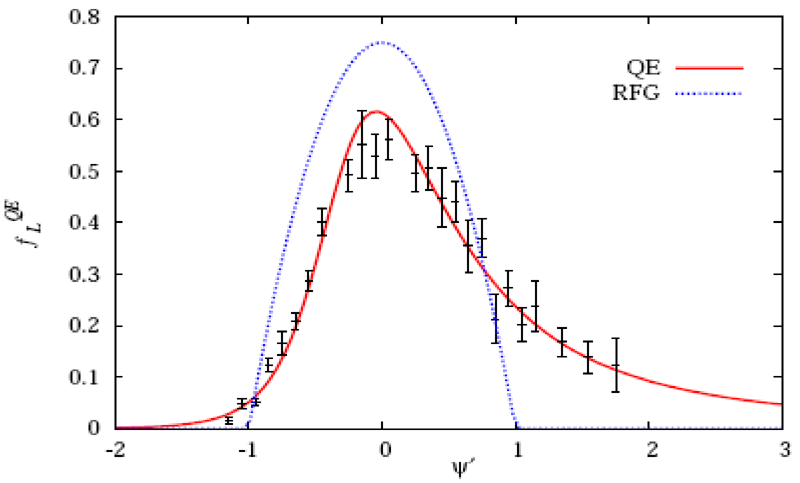

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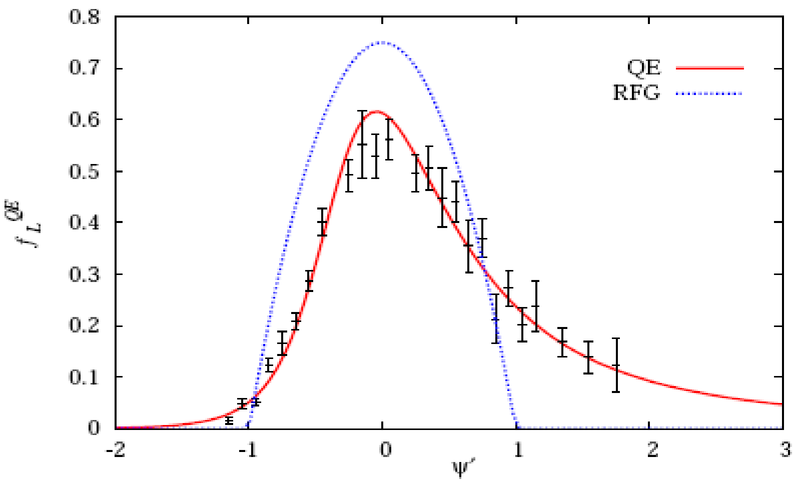

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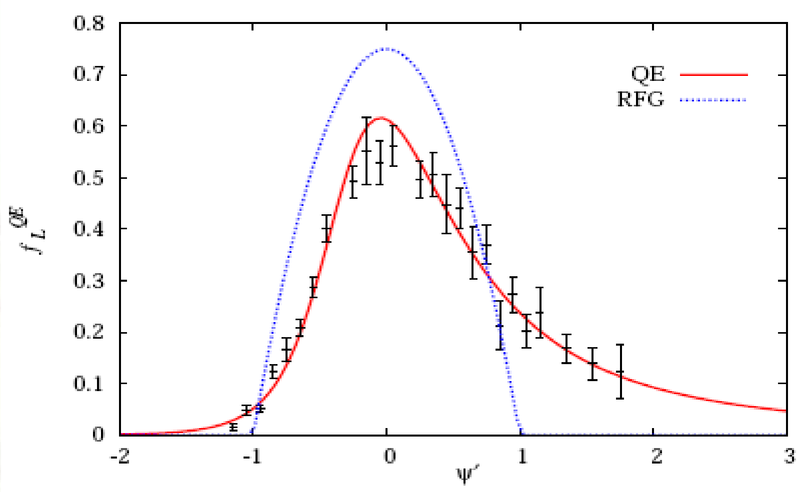

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Warning:

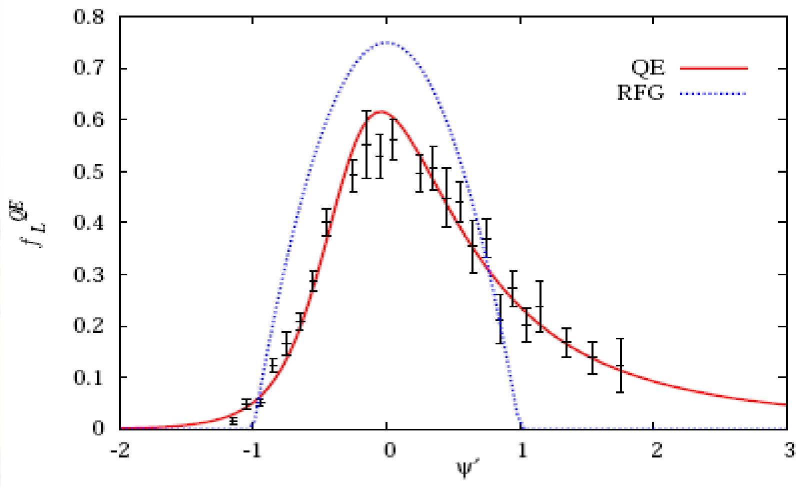
Calculations (RMF) indicate a moderate breaking of 0th kind scaling (larger f_T), 1p-1h MEC (not considered here seem to give opposite effect): details about f_T not yet clear

SUPERSCALING BASED MODEL (**SSM-QE**) FOR THE QUASIELASTIC PEAK

Use RFG expressions for response functions

$$R^{QE}_{L,T}(\kappa,\lambda) = \frac{1}{k_F} \underline{f^{QE}(\psi)} G^{QE}_{L,T}(\kappa,\lambda)$$

but with f^{QE} obtained from fit of QE-L data



In the following f^{QE} or eqivalently f^{SMM} will be used to indicate the QE-L fit assumed to be "universal"

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BEYOND THE QE-PEAK: DELTA REGION - formalism

(Amaro,Barbaro,Caballero,Donnelly,Molinari&Sick, PRC **71**(2005))

RFG responses for excitation of a stable Δ

$$R^{\Delta}_{L,T}(\kappa,\lambda) = \frac{1}{k_F} f^{\Delta}(\psi_\Delta) G^{\Delta}_{L,T}$$

$$f^{\Delta}(\psi_\Delta) = f_{RFG}(\psi_\Delta)$$

$$\psi_\Delta = \frac{1}{\sqrt{\xi_F}} \frac{\lambda - \tau\rho_\Delta}{\sqrt{(1+\lambda\rho_\Delta)\tau + \kappa\sqrt{\tau(1+\tau\rho_\Delta^2)}}}$$

$$\rho_\Delta = 1 + \frac{\mu_\Delta^2 - 4\tau}{4\tau} \; ; \; \mu_\Delta = \frac{m_\Delta}{m_N}$$

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$$G^{\Delta}_L = \frac{\kappa}{2\tau}\frac{A}{2}\left[\left(1+\tau\rho_\Delta^2+1\right)w_2^{\Delta} - w_1^{\Delta}\right]\mathcal{O}(\eta_F^2)$$

$$G^{\Delta}_T = \frac{1}{\kappa}\frac{A}{2} w_1^{\Delta} + \mathcal{O}(\eta_F^2)$$

$$w_1^{\Delta} = \frac{1}{2}(\mu_\Delta+1)^2(2\tau\rho_\Delta+1-\mu_\Delta)\left(G^2_{M,\Delta}+3G^2_{E,\Delta}\right)$$

$$w_2^{\Delta} = \frac{1}{2}(\mu_\Delta+1)^2\frac{(2\tau\rho_\Delta+1-\mu_\Delta)}{\tau\rho_\Delta}\left(G^2_{M,\Delta}+3G^2_{E,\Delta}+4\frac{\tau}{\mu_\Delta^2}G^2_{C,\Delta}\right)$$

$$G_{M,\Delta}(\tau) = 2.97 g_\Delta(\tau) \qquad G_{C,\Delta}(\tau) = -0.15 G_{M,\Delta}(\tau)$$

$$G_{E,\Delta}(\tau) = -0.03 g_\Delta(\tau) \qquad g_\Delta(\tau) = \left[\sqrt{1+\tau}(1+4.97\tau)^2\right]^{-1}$$

BEYOND THE QE-PEAK: DELTA REGION
formalism & previous results

$$f^{non-QE}(\psi_\Delta) \equiv k_F \frac{\left(\frac{d\sigma}{d\epsilon' d\Omega}\right)^{non-QE}}{S^\Delta}$$

$$S^\Delta \equiv \sigma_M \left[v_L G_L^\Delta + v_T G_T^\Delta \right]$$

$$\left(\frac{d\sigma}{d\epsilon' d\Omega}\right)^{non-QE} \equiv \left(\frac{d\sigma}{d\epsilon' d\Omega}\right)^{exp} - \left(\frac{d\sigma}{d\epsilon' d\Omega}\right)^{SSM-QE}$$

[Amaro et al, PRC 71, 015501(2005)]

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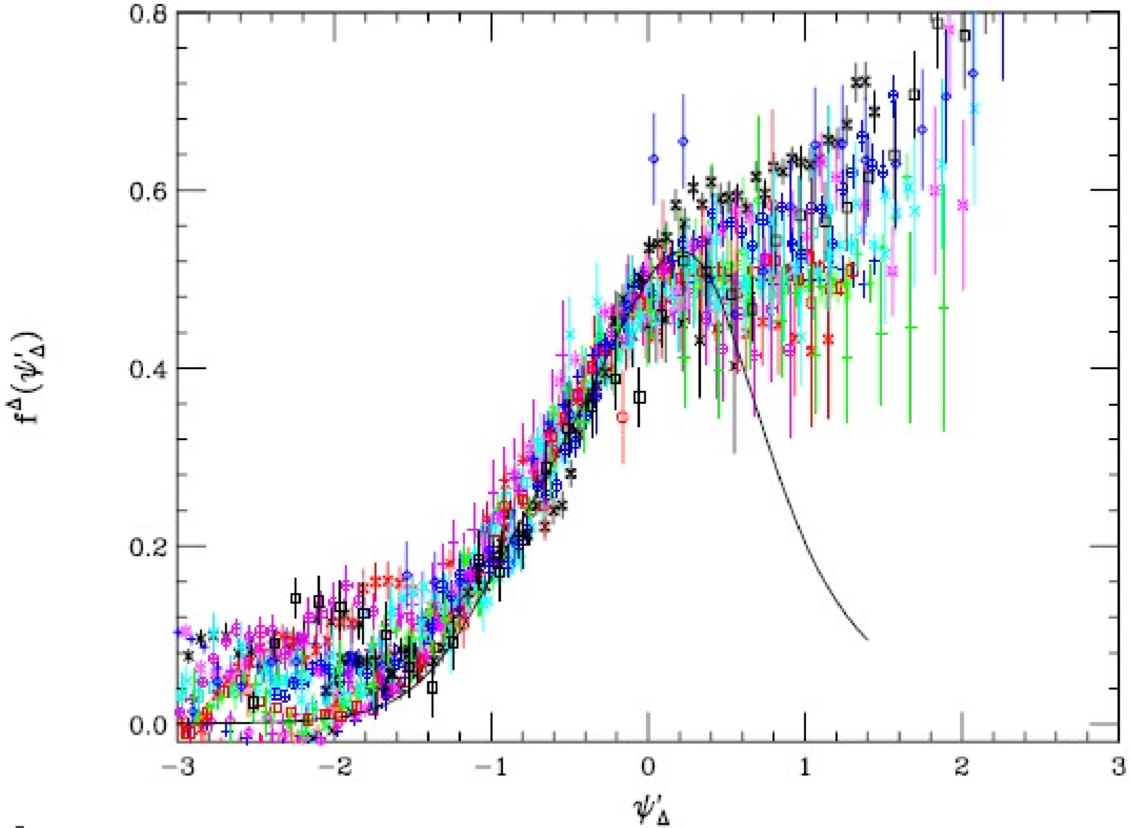

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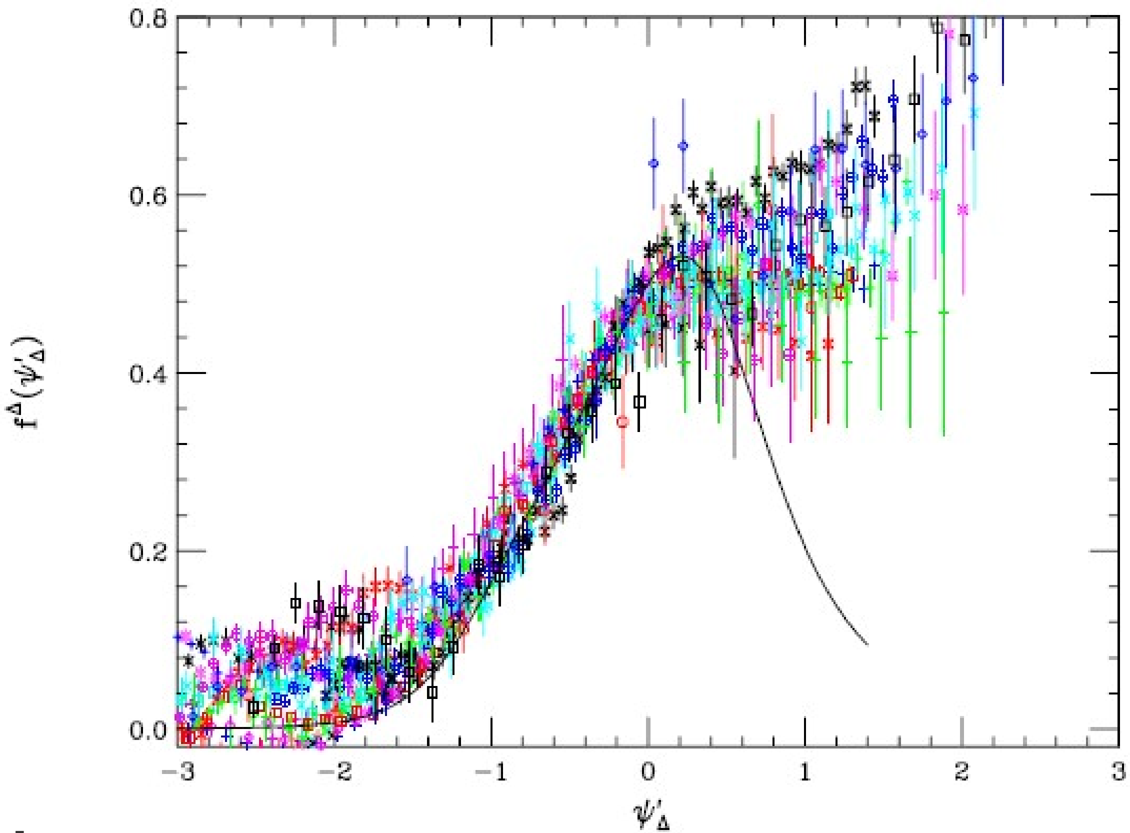


[Amaro et al, PRC 71, 015501(2005)]

Reasonable scaling at the left of the Δ peak (with noise at large negative ψ_Δ

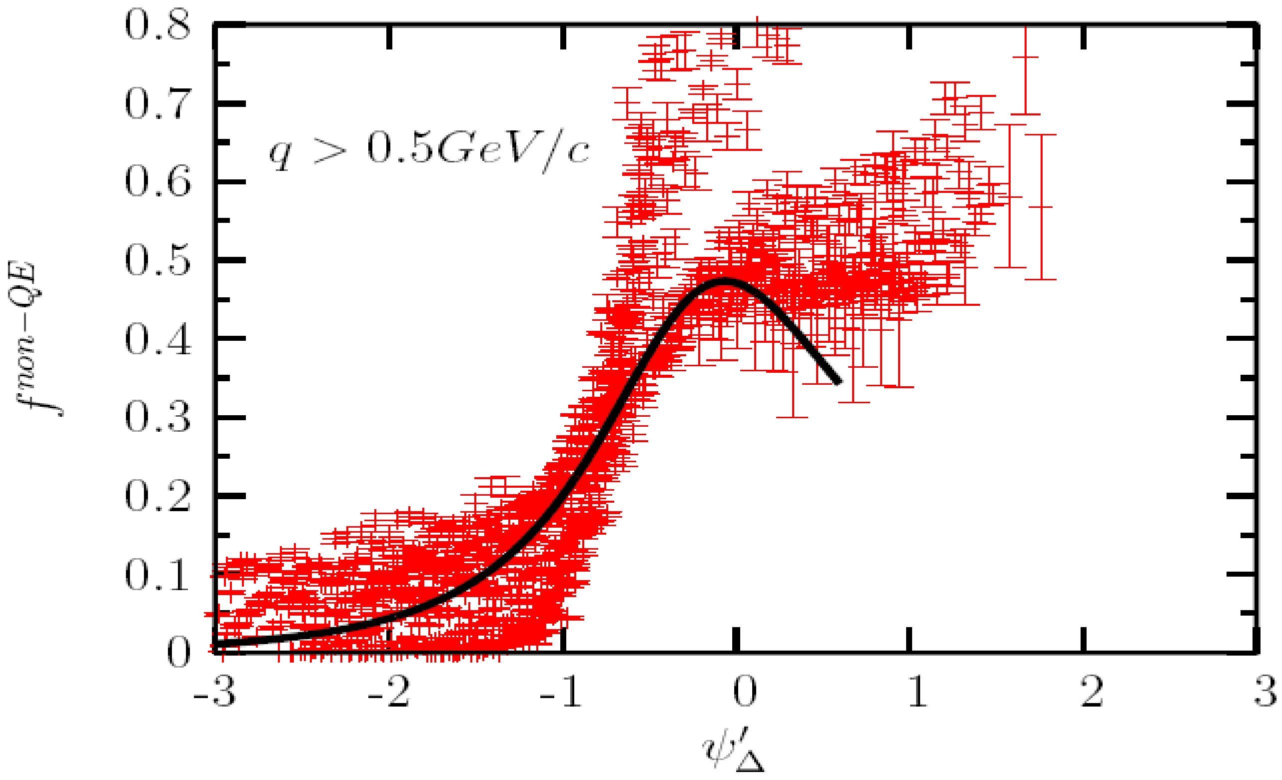
$$R_{L,T}^{SuSA-\Delta,}(\kappa,\lambda)$$

$$= \frac{1}{k_F} f_{SuSA}^{non-QE}(\psi_\Delta) G_{L,T}^\Delta$$

SuSA

Fit to data checked vs eA cross sections where Δ is dominant (10-15%); then used to predict cross sections in the Δ region for neutrino scattering

BEYOND THE QE-PEAK: previous results revisited



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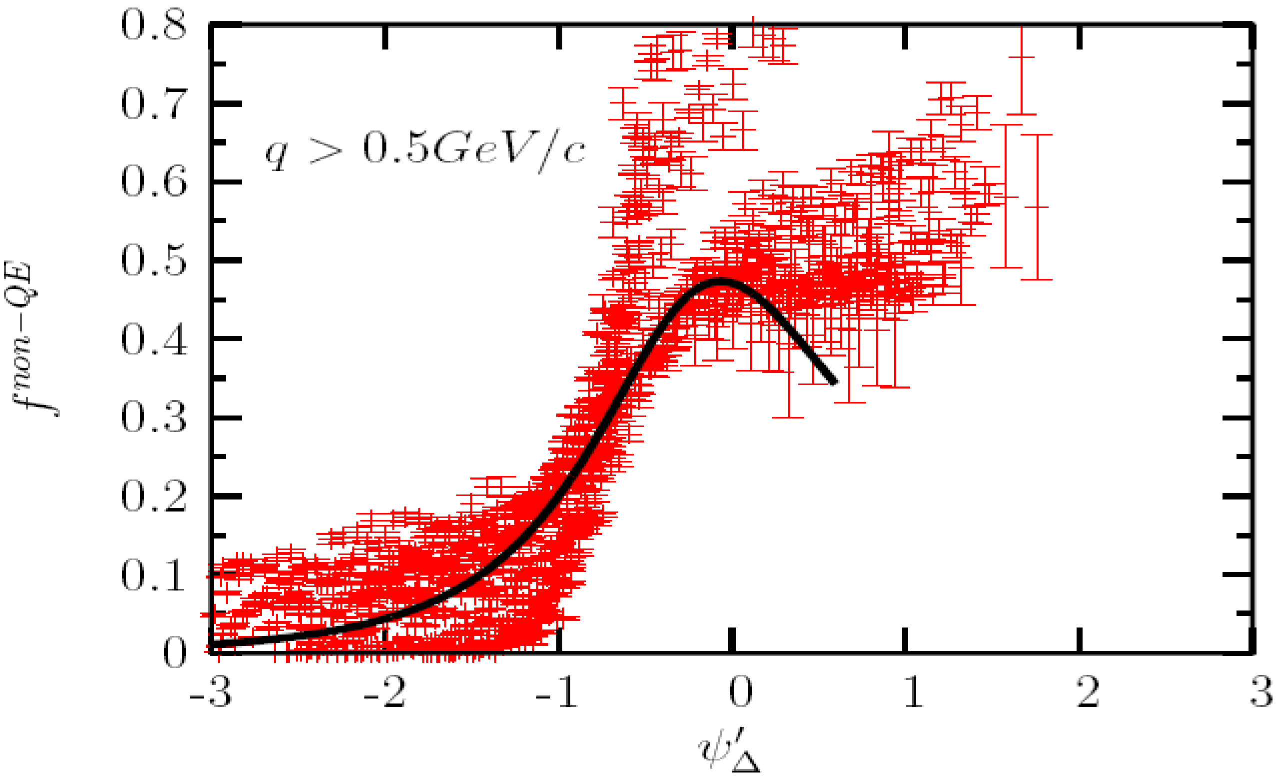

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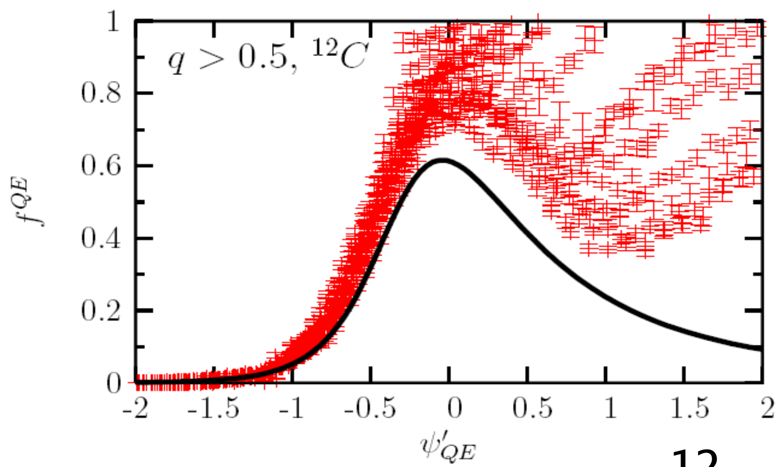
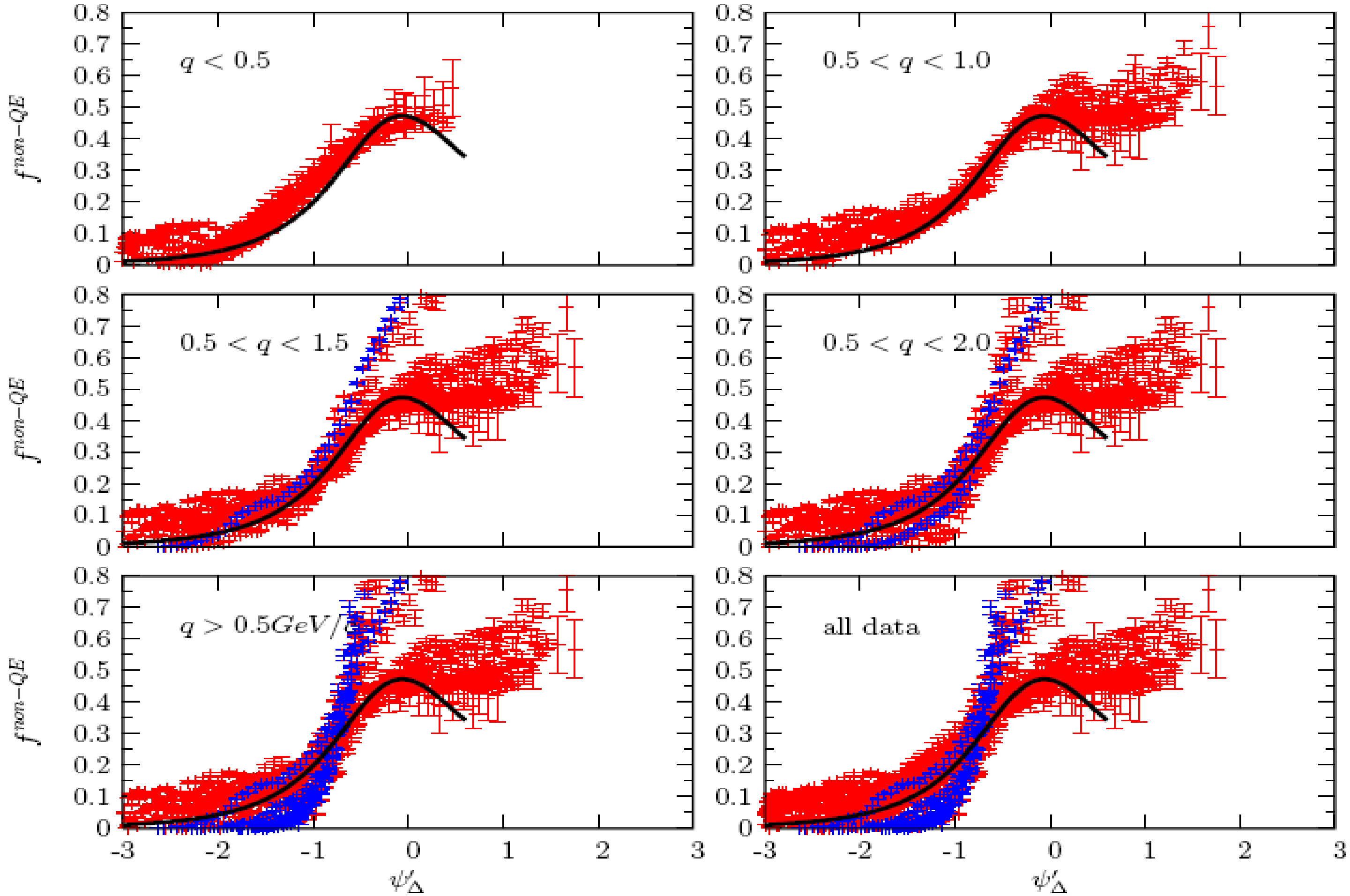


BEYOND THE QE-PEAK: previous results revisited

(Blue: Arrington et al, Jlab data $E_e = 4.045\,Gev$, $\theta_e = 15\text{-}74^{\circ}$)

(Data have rather strong overlap of various resonances)



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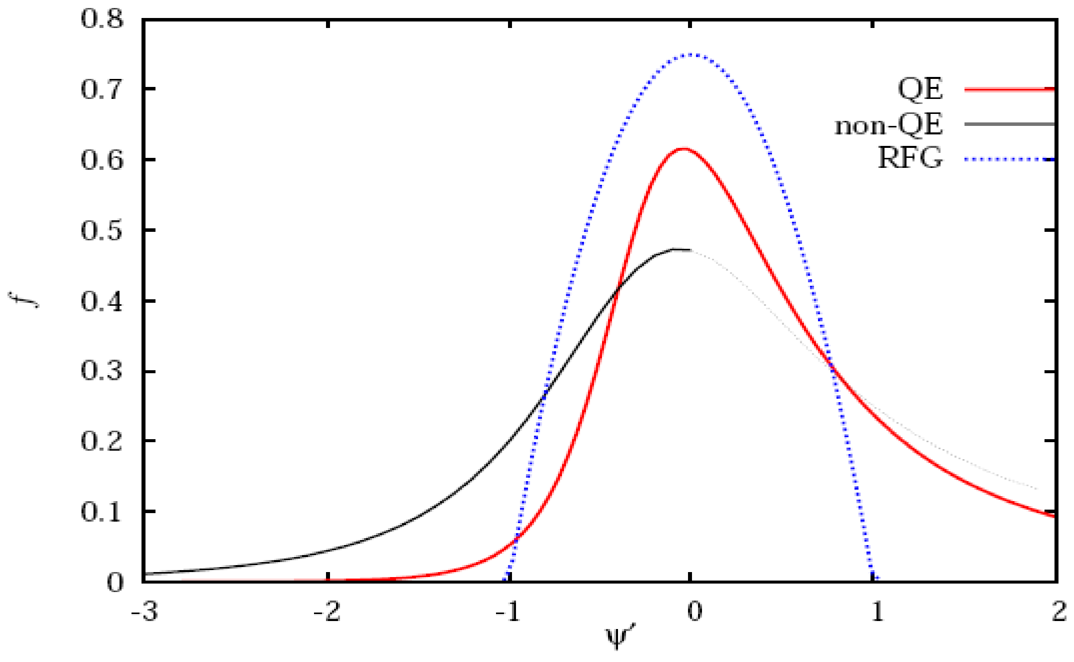
- Some scaling violations for $-1 < \psi'_\Delta < -0$ mainly due to higher resonances: support SuSA modeling when Δ dominates
- Model needed for deeper investigation

BEYOND THE QE-PEAK:
QE vs non-QE vs RFG scaling functions



Non-QE differs from QE:

- expected
- is it just due to trivial physics (Delta finite width) ? Need further modeling to answer

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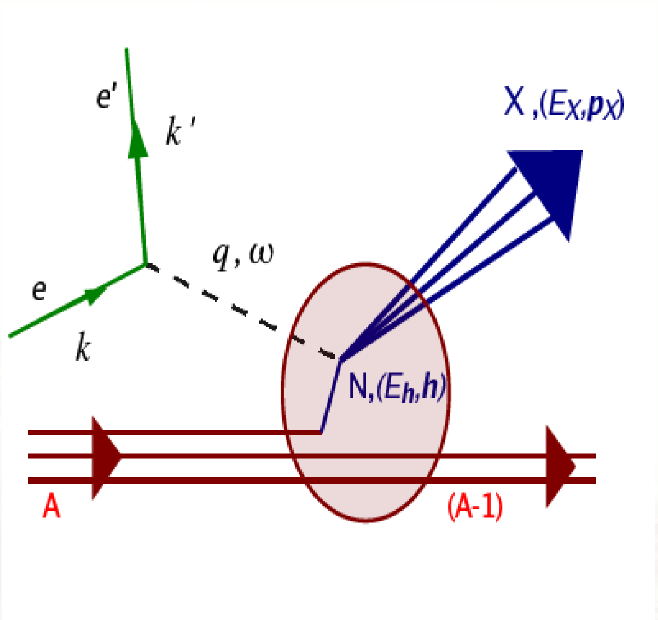

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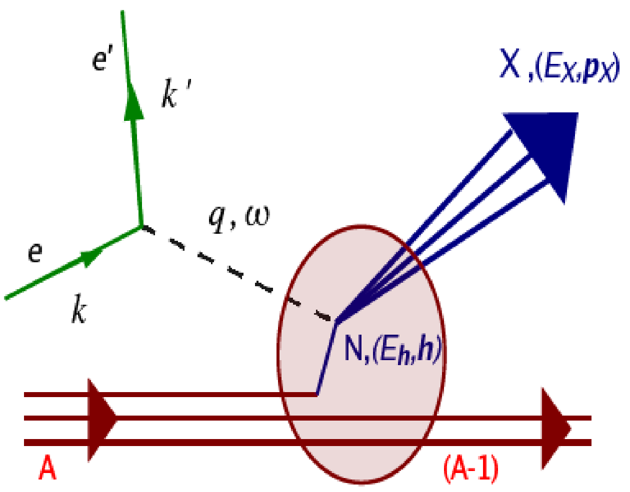

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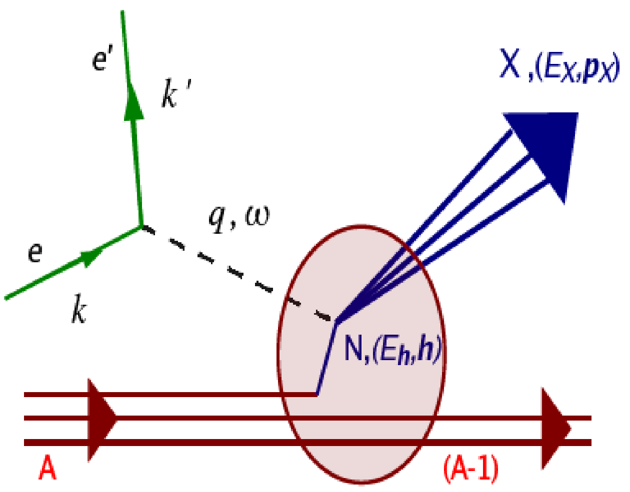

Same structure as QE with generalized ψ

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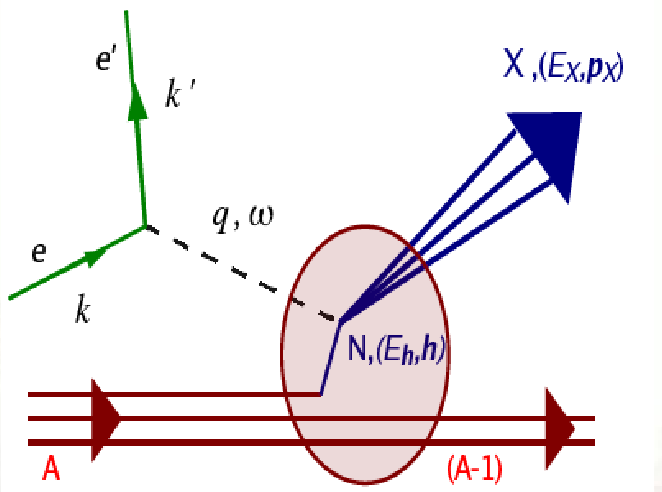

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Inelastic single nucleon responses

$$G_L^{inel} = m_N \frac{\kappa}{2\tau}\left\{Z\left[(1+\tau\rho_X^2)\tilde{w}_2^p - \tilde{w}_1^p\right] + N\left[(1+\tau\rho_X^2)\tilde{w}_2^n - \tilde{w}_1^n\right]\right\}$$

$$G_T^{inel} = m_N \frac{1}{\kappa}\left\{Z\tilde{w}_1^p + N\tilde{w}_1^n\right\} ,$$

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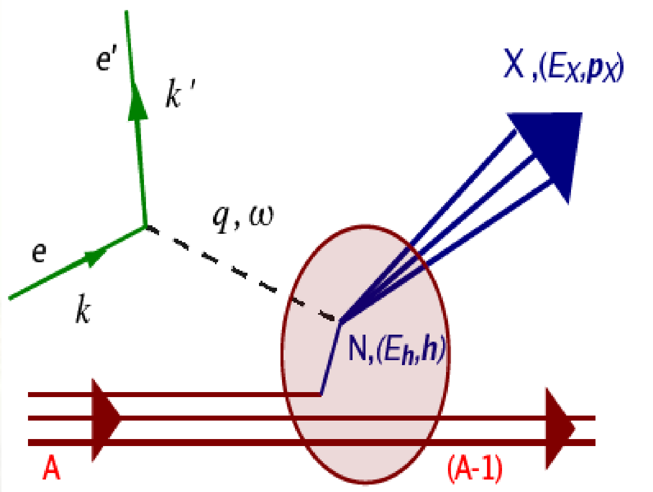

Extra integration over final energy

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Inelastic single nucleon responses

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$$G_T^{inel} = m_N \frac{1}{\kappa} \left\{ Z\tilde{w}_1^p + N\tilde{w}_1^n \right\} ,$$

Superscaling based model for inelastic scattering (**SSM-inel**)

Use RFG expressions with *f* fitted on QE-L data

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Single nucleon content:

Bosted-Christy parameterization of neutron and proton structure functionsin resonance region (Christy&Bosted, PRC77, 065206 (2008), Bosted&Christy arXiv:0711.0159[hep-ph] + codes by P. Bosted)

No in-medium-modification considered
Finite widths automatically included

"SSM-Δ" model

Simpler model focused on the Delta region : useful to investigate effects due to higher resonances

$$R^{\Delta}_{L,T} = \int_{\mu_1}^{\mu_2} \frac{1}{\pi} \frac{\Gamma(\mu_X)/2m_N}{(\mu_X - \mu_\Delta)^2 + \Gamma(\mu_X)^2/4m_N^2} R^{\Delta}_{L,T}(\kappa, \lambda, \mu_X) d\mu_X$$

$$\Gamma(\mu_X) = \Gamma_0 \frac{\mu_\Delta}{\mu_X} \left(\frac{p^\star_\pi}{p^{res}_\pi} \right)^3$$

$$p^\star_\pi = \frac{m_N}{\mu_X} \left[\frac{(\mu_X^2 - 1 - \mu_\pi^2)^2}{4} - \mu_\pi^2 \right]^{\frac{1}{2}}$$

$$\Gamma_0 = 120 \text{ MeV}$$

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RFG responses for Δ excitation with generic mass μ_X (ψ_X) and with f^{QE} instead of f^{RFG}

$$\Gamma(\mu_X) = \Gamma_0 \frac{\mu_\Delta}{\mu_X} \left(\frac{p_\pi^\star}{p_\pi^{res}} \right)^3$$

$$p_\pi^\star = \frac{m_N}{\mu_X} \left[\frac{(\mu_X^2 - 1 - \mu_\pi^2)^2}{4} - \mu_\pi^2 \right]^{\frac{1}{2}}$$

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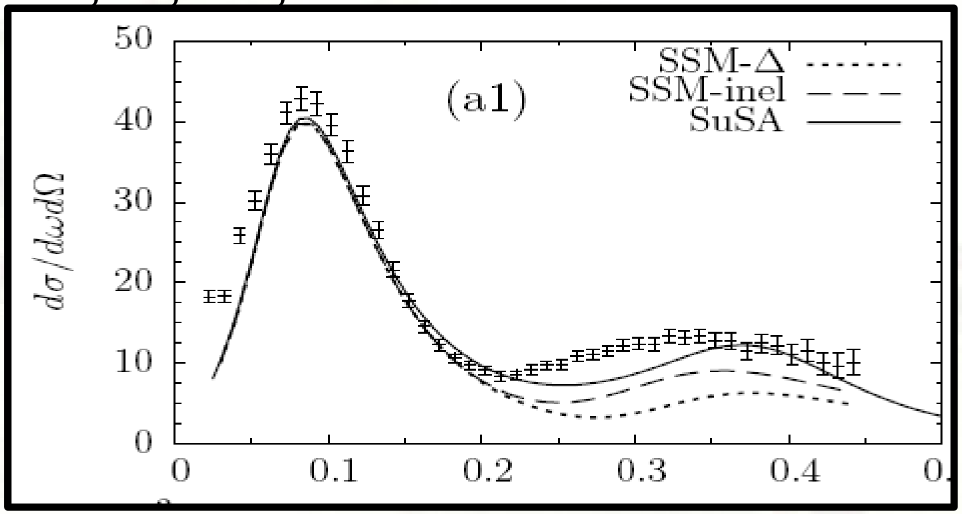
SS based model for inelastic scattering: results

- First focus on x-sections: “real” and more familiar data
- Limited range of q: Δ peak present but higher resonances not too important
- Scattering angle dependence

Case	ϵ [MeV]	θ [deg]	q_{QE} [MeV/c]	q_{Δ} [MeV/c]
a	620	36	366	460
b	680	60	606	600
c	1299	37.5	791	850
d	3595	16.02	1056	1189

SS-model for inelastic scattering: x-sections *vs* ω

ε(MeV)θ(deg),q-QE,q-Δ(MeV/c):
620, 36, 366, 460



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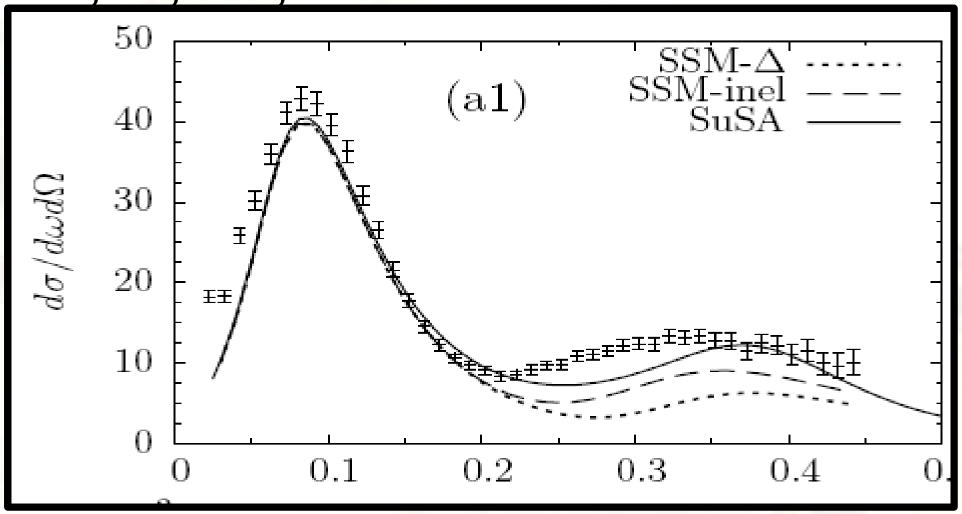

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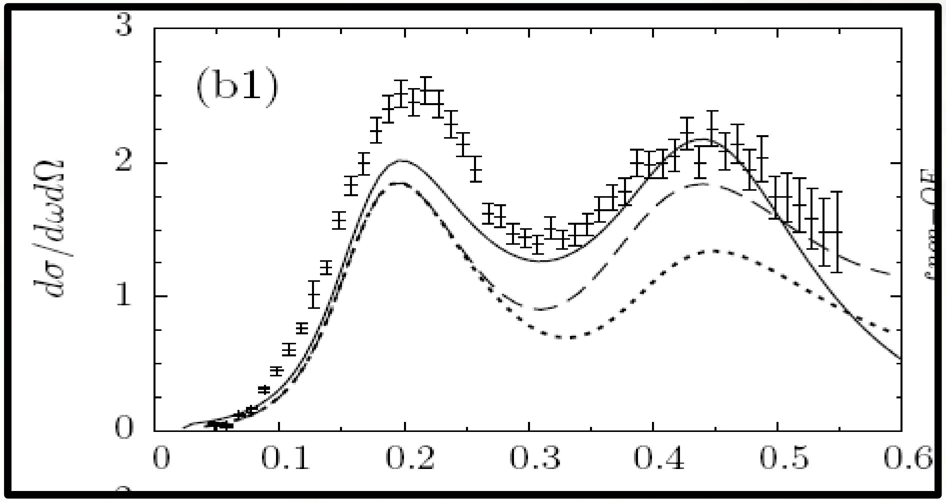

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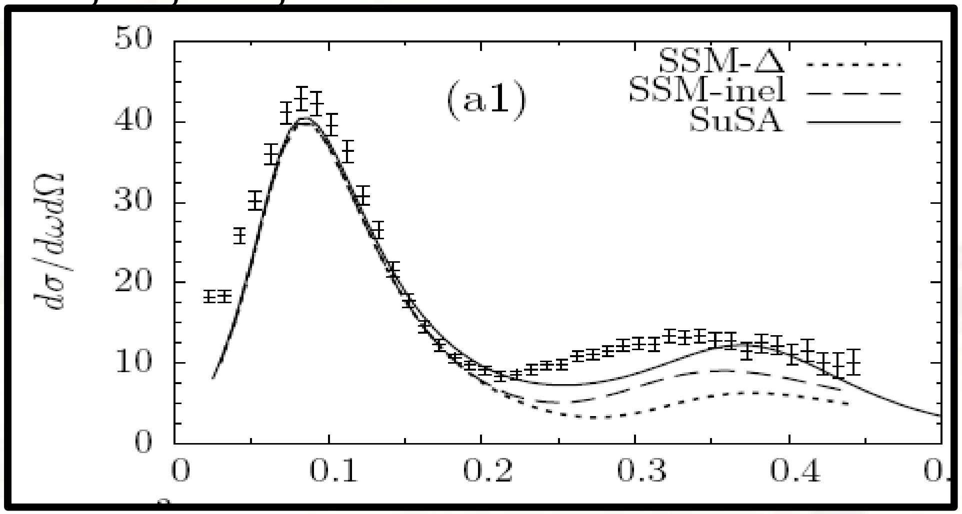

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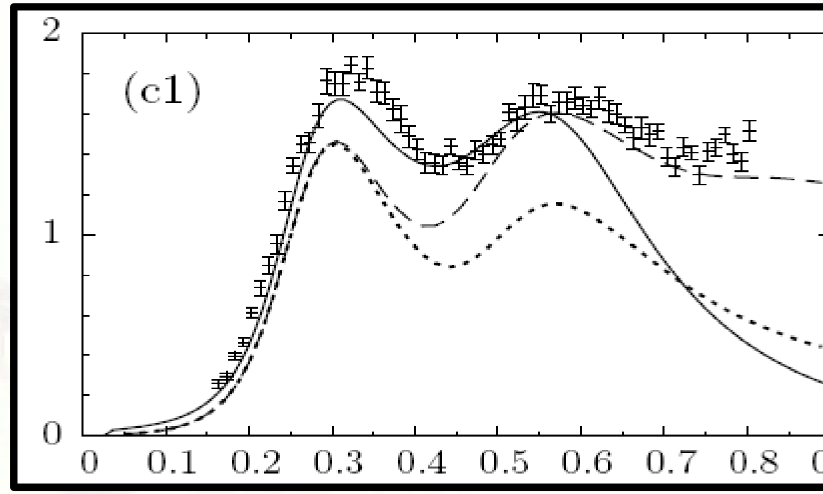

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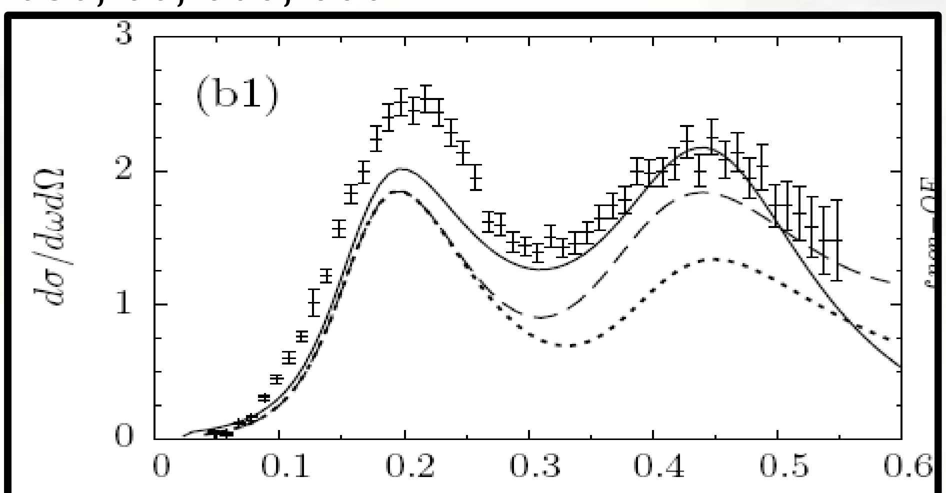

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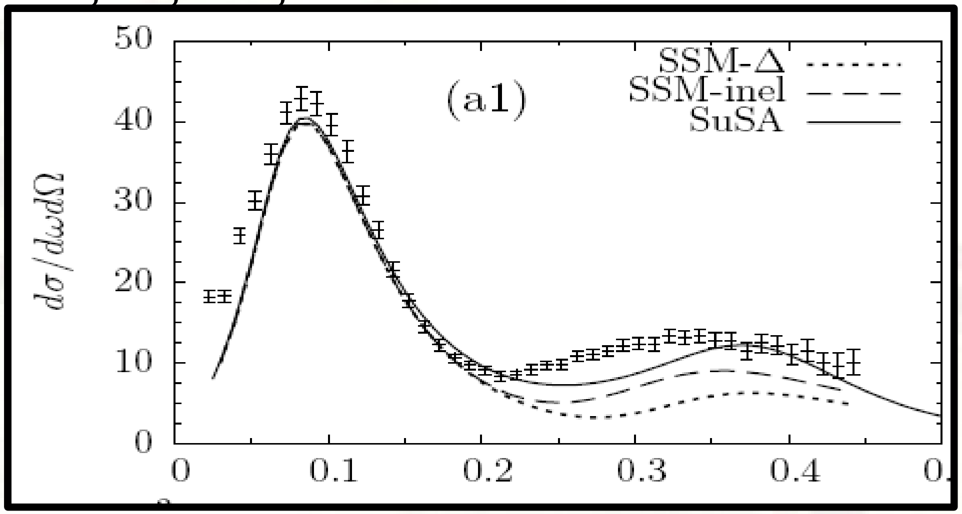

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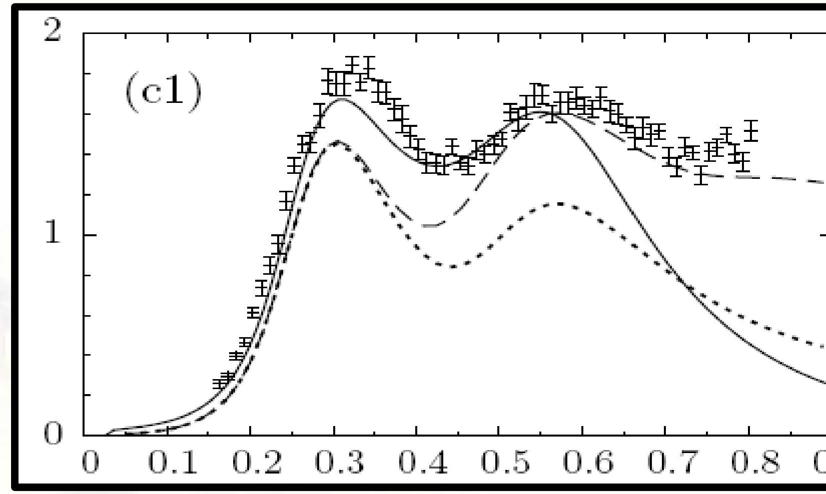

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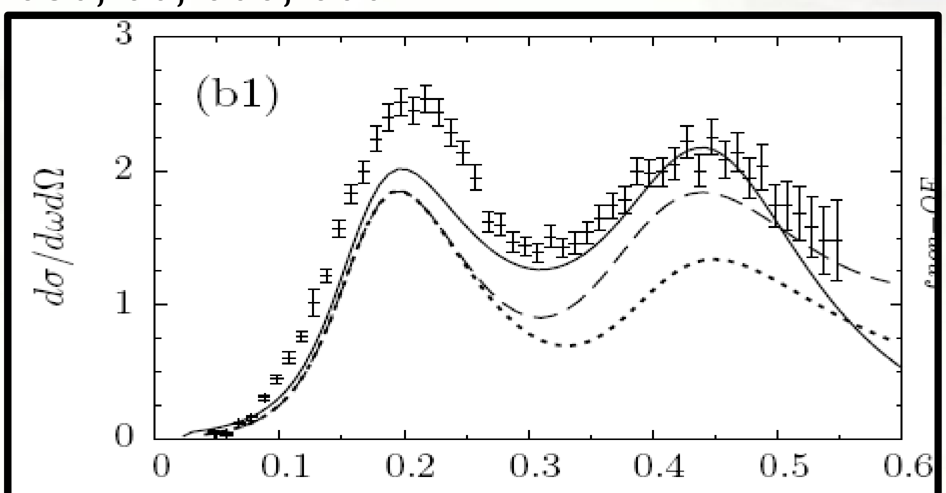
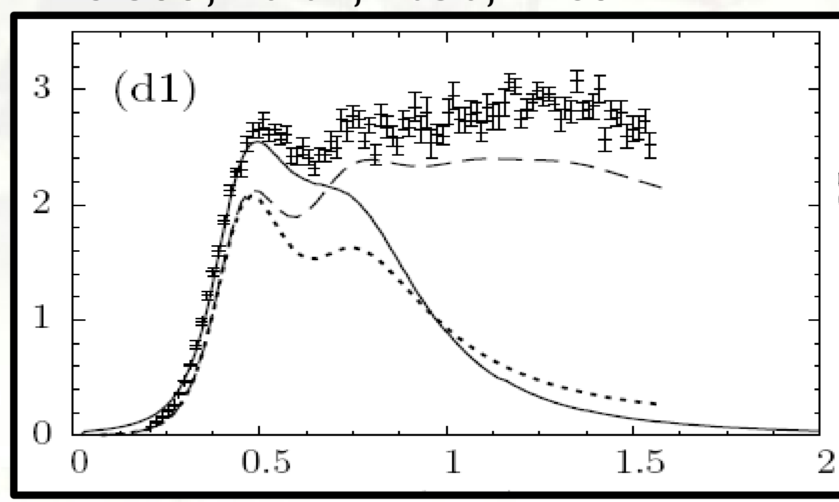
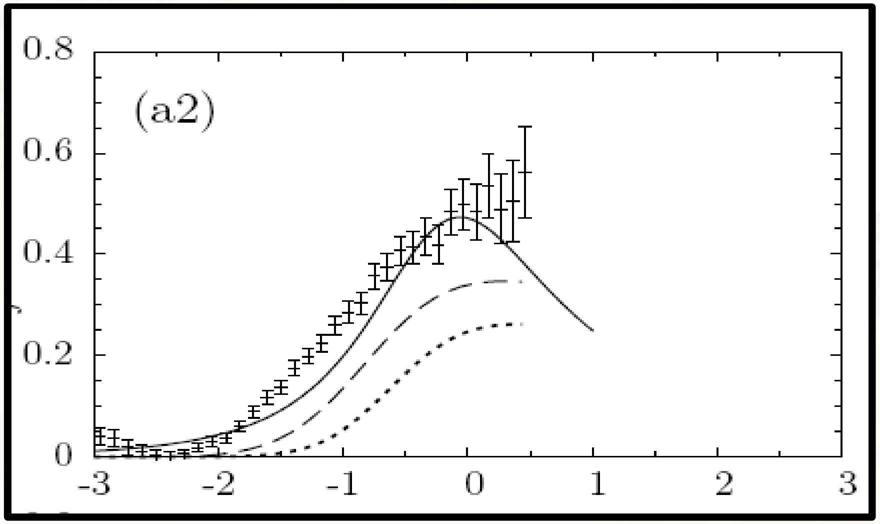


3.599, 16.02, 1056, 1189



SS-model for inelastic scattering: nonQE scaling functions vs ψ'_{Δ}

620, 36, 366, 460



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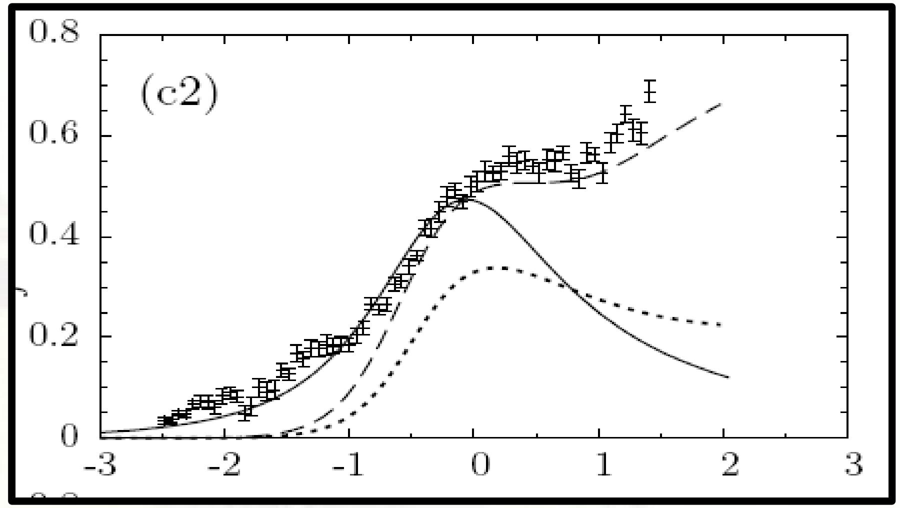

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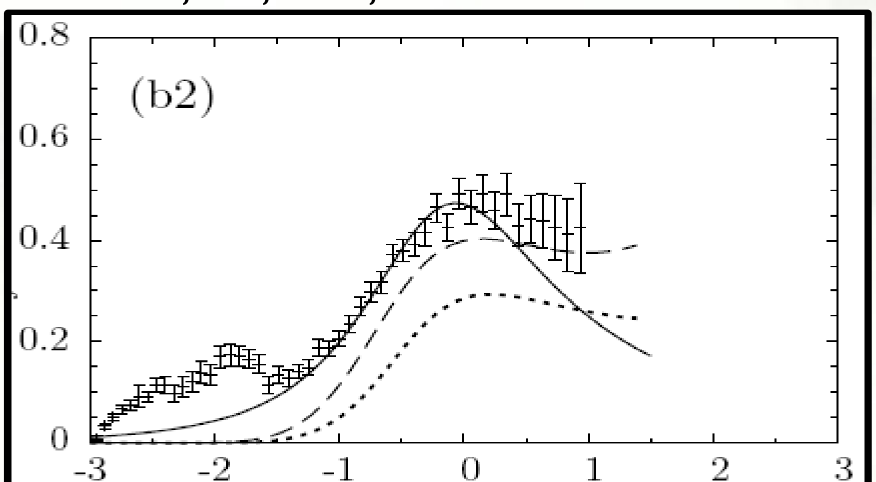

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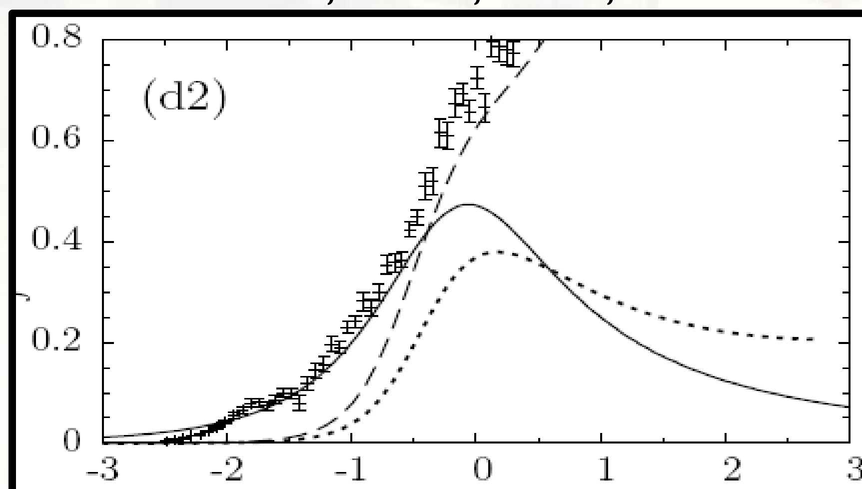
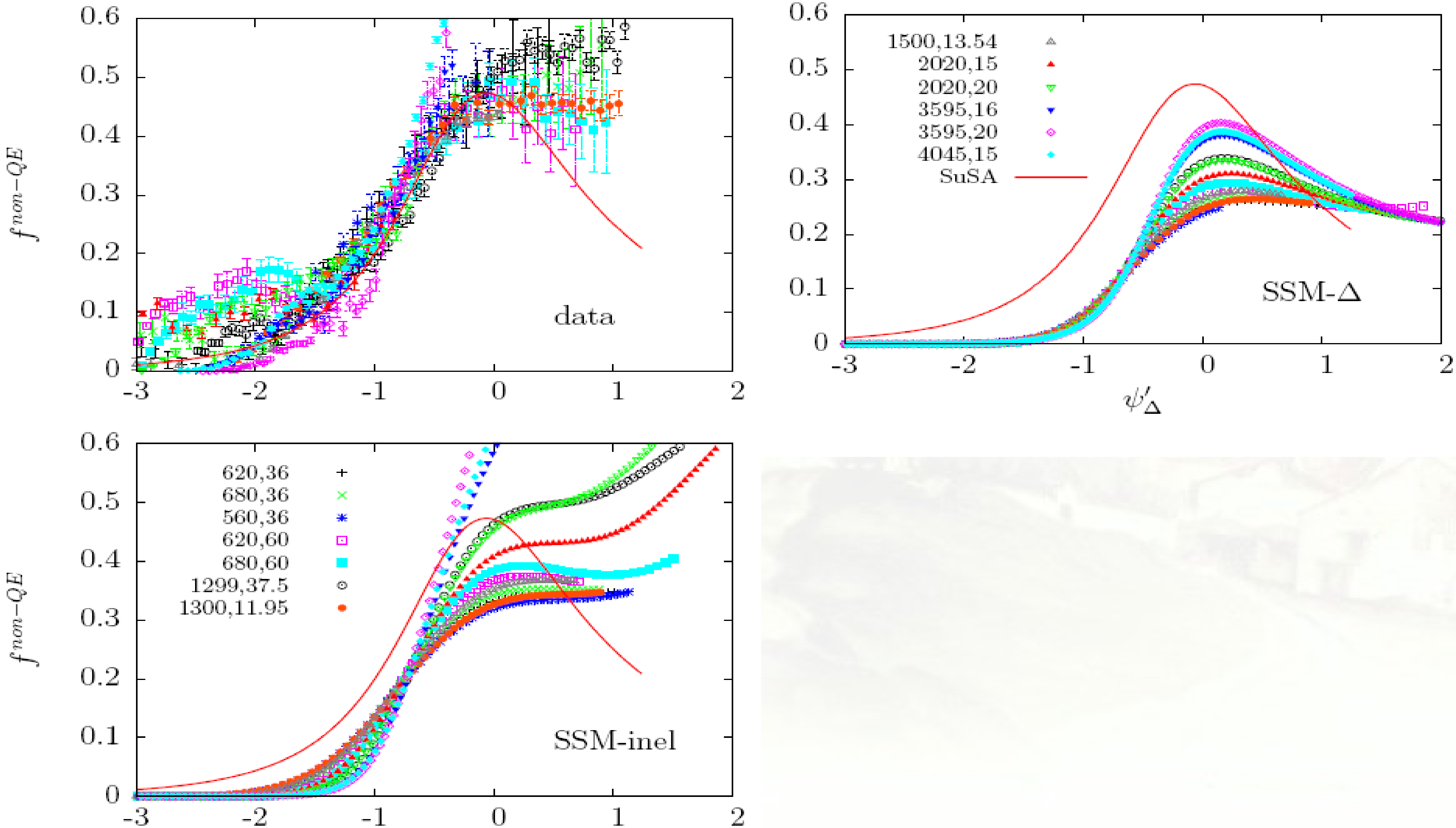


SS-model for inelastic scattering: non-QE scaling functions *vs* ψ'_Δ



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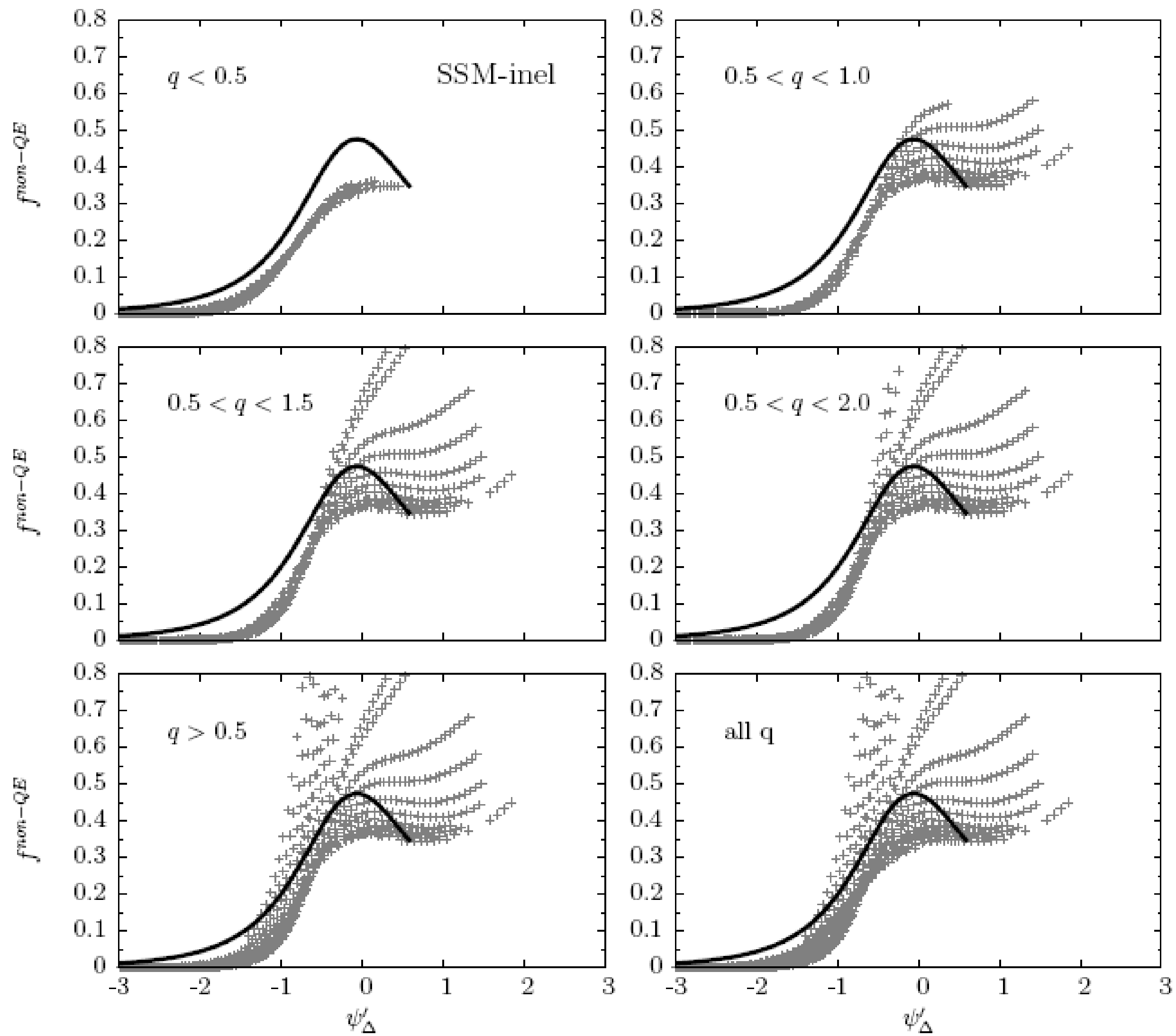

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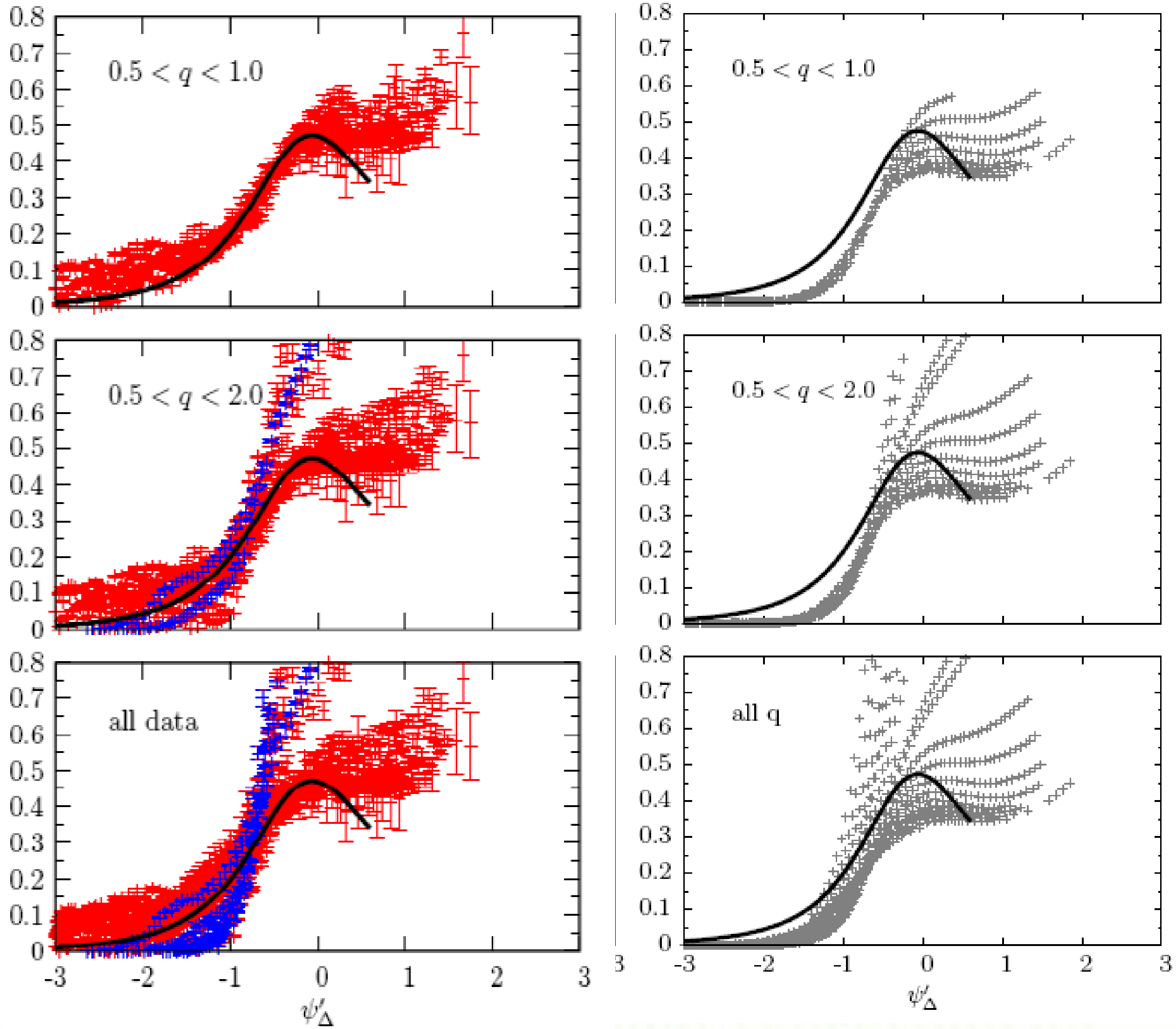

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- (possible issue about 0th kind scaling violations)
- **Role of 2p-2h MEC contributions**

OUTLINE

Antefact I: QE region

- previous formalism and results
- SS-based model for cross sections (SSM-QE)

Antefact II: beyond the QE peak

- previous formalism, results and SuSA
- previous results revisited , scaling violations

SS-based model for inelastic eA scattering

- formalism
- results, scaling violations

“Non-impulsive” contributions

Summary and conclusions

“NON-IMPULSIVE” CONTRIBUTIONS

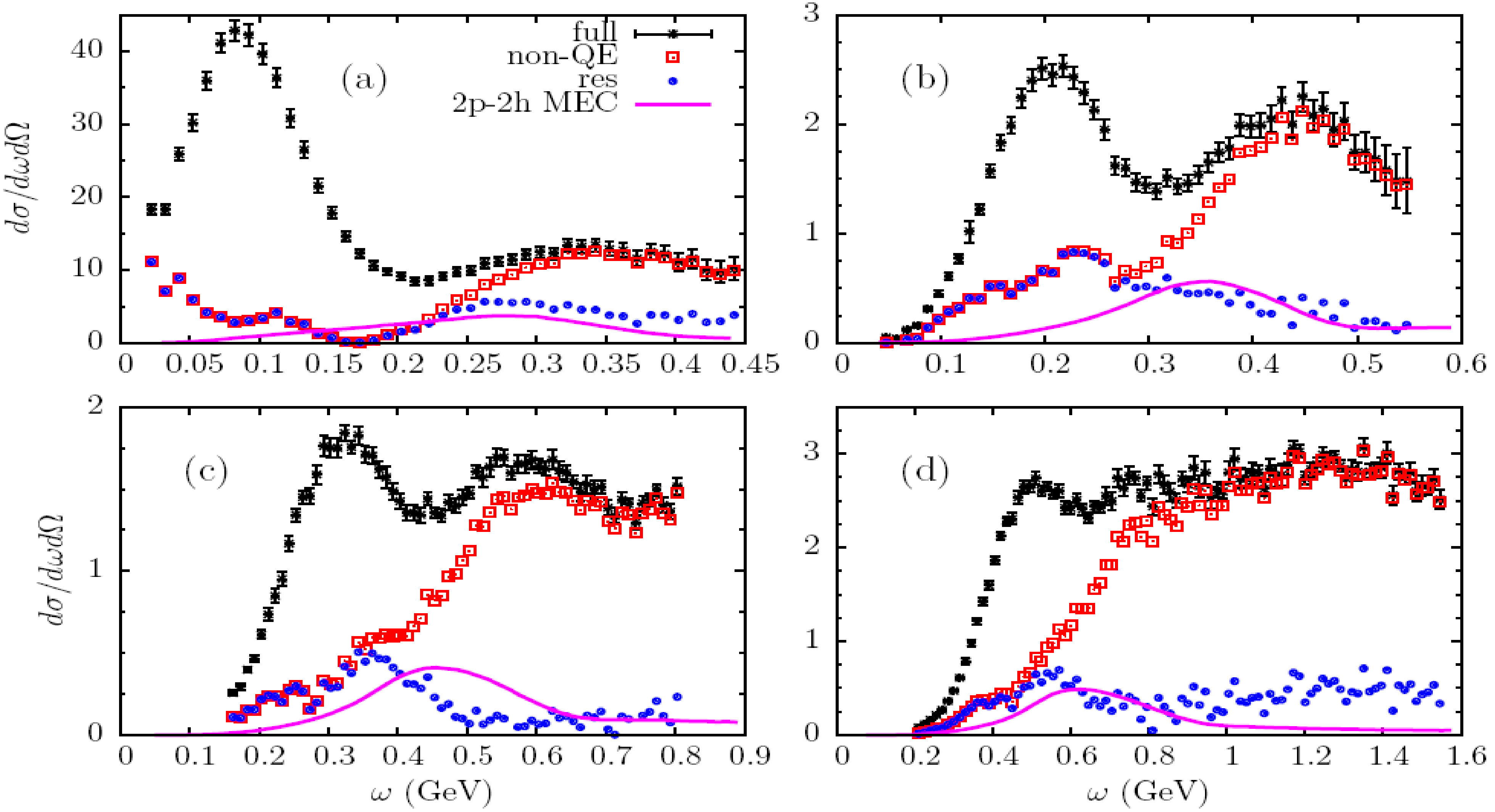
In the “philosophy” of scaling based model we define a RESIDUAL NON IMPULSIVE cross setion

$$\left(\frac{d\sigma}{d\epsilon' d\Omega}\right)^{res} \equiv \left(\frac{d\sigma}{d\epsilon' d\Omega}\right)^{exp} - \left(\frac{d\sigma}{d\epsilon' d\Omega}\right)^{SSM-QE} - \left(\frac{d\sigma}{d\epsilon' d\Omega}\right)^{SSM-inel}$$

to be compared with theoretical calculations of non-impulsive contributions:

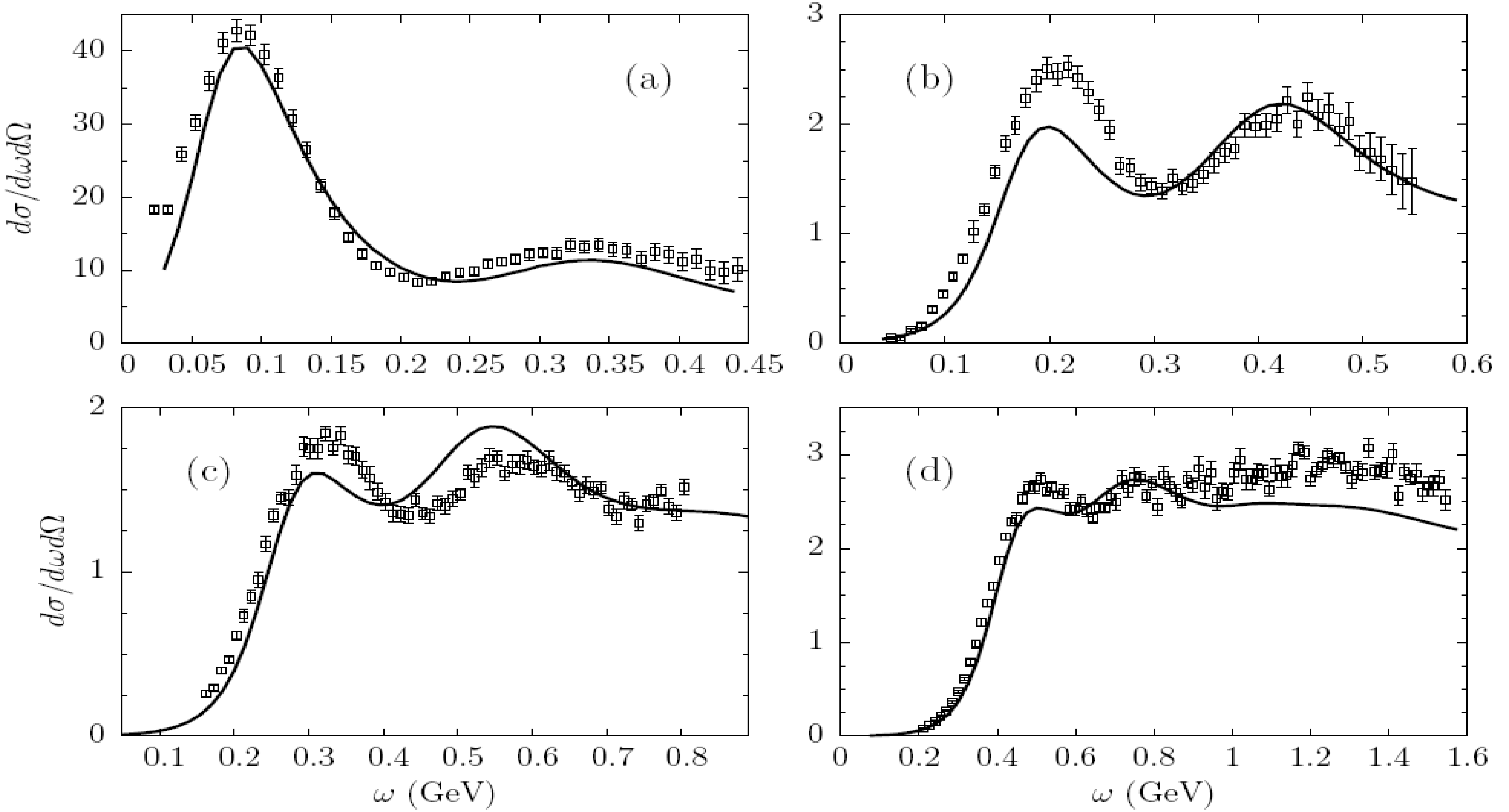
2p-2h MEC: Nardi, De Pace et al NPA 726, 303 (2003); 741, 299 (2004)

"NON-IMPULSIVE" CONTRIBUTIONS

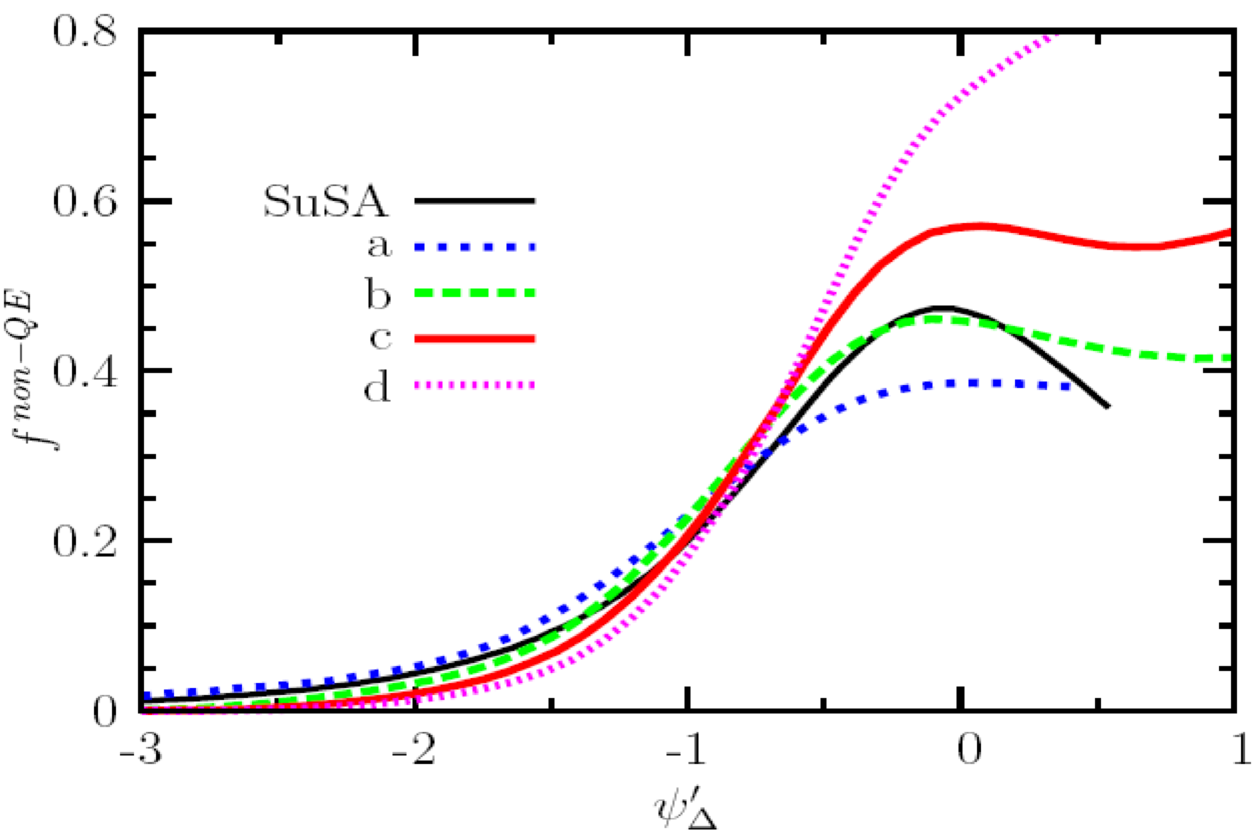


2p-2h MEC courtesy of A. De Pace

(SSM-QE) + (SSM-inel) + (2p-2h MEC) cross sections



(SSM-inel) + (2p-2h MEC) non-QE scaling function



SUMMARY AND CONCLUSIONS

1) Study of on-QE “experimental” data : (i) reasonable scaling approaching the D peak, with (ii) f^{nonQE} different from f^{QE}, (iii) strong scaling violations at large negative ψ_{Δ}

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5) Subtraction of impulsive contributions: (i) different point of view on scaling violating contributions, (ii) qualitative agreement with existing results but need to explore these contributions futher.

THANK YOU

REFERENCES for experimental data

R. R. Whitney, I. Sick, J. R. Ficenec, R. D. Kephart and W. P. Trower, Phys. Rev. C **9**, 2230 (1974).

P. Barreau *et al.*, Nucl. Phys. A **402** (1983) 515.

R. M. Sealock *et al.*, Phys. Rev. Lett. **62** (1989) 1350.

D. B. Day *et al.*, Phys. Rev. C **48**, 1849 (1993).

J. S. O'Connell *et al.*, Phys. Rev. C **35**, 1063 (1987).

D. T. Baran *et al.*, Phys. Rev. Lett. **61**, 400 (1988).

J. Arrington *et al.*, Phys. Rev. C **53**, 2248 (1996).

J. Arrington *et al.*, Phys. Rev. Lett. **82**, 2056 (1999)

EXTRA SLIDES

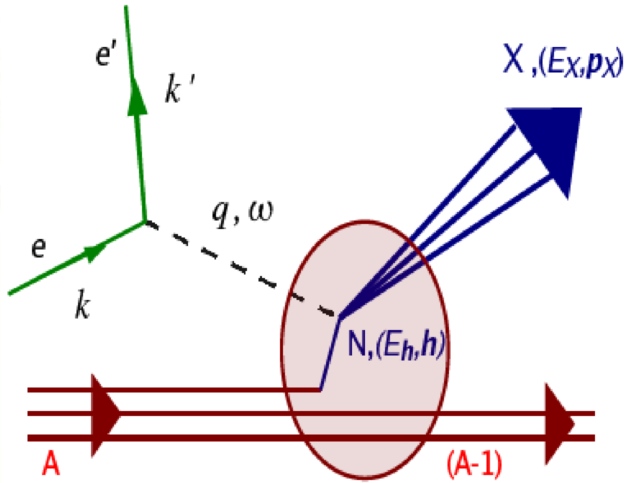
Integration limits:

$$\mu_1 = 1 + \frac{m_\pi}{m_N}$$

Pion threshold

$$\mu_2 = 1 + 2\lambda - \epsilon_s$$

$(m_N+\omega-e_S)$



General argument following studies of (y)scaling in QE scattering:

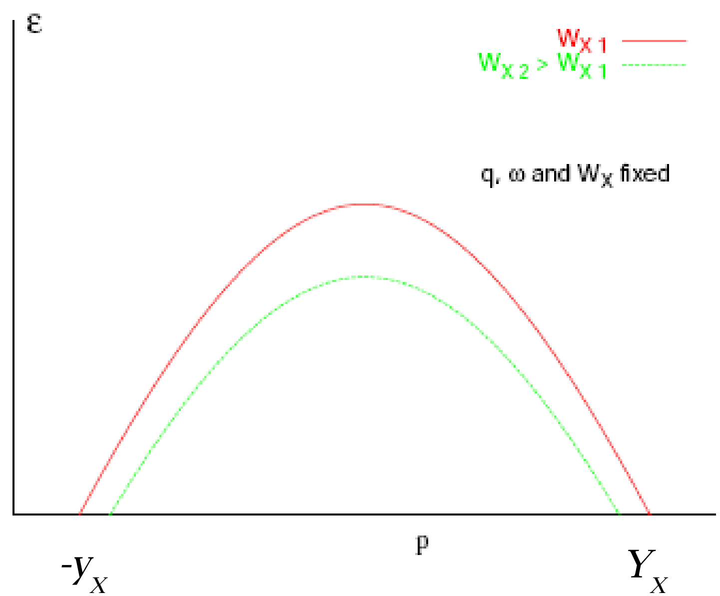
inclusive hadronic tensor obtained starting from tensor for "exclusive (e,e' X)" process to final state $(W_X,\mathbf{p}_X) \Rightarrow$ function of q,ω and of missing momentum p= p_X-q and excitation energy of residual system

$$\mathcal{E} \equiv \sqrt{\mathbf{p}^2 + (M^*_{A-1})^2} - \sqrt{\mathbf{p}^2 + (M^0_{A-1})^2}$$

$$= M^0_A + \omega - \sqrt{\left(M^0_{A-1}\right)^2 + p^2} - \sqrt{W_X^2 + q^2 + p^2 + 2pq\cos\theta}$$

$$W^{\mu\nu} \rightarrow \int dW_X \int_{-y_X}^{Y_X} dp \int_{\mathcal{E}_{min}}^{\mathcal{E}_{max}} d\mathcal{E} W^{\mu\nu}_{\text{“exclusive”}}$$

$$\max[\mathcal{E}(\theta = 0), 0] \le \mathcal{E} \le \mathcal{E}(\theta = \pi)$$



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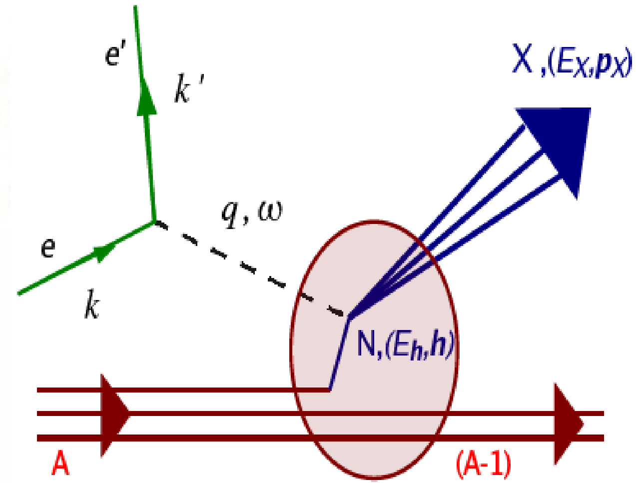

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$$y_X = \frac{1}{2W^2}\left[(M_A^0+\omega)\sqrt{(W-M_{A-1}^0)^2-W_X^2}\right.$$
$$\left.\times\ \sqrt{(W+M_{A-1}^0)^2-W_X^2} - 2q\Lambda_X\right]$$

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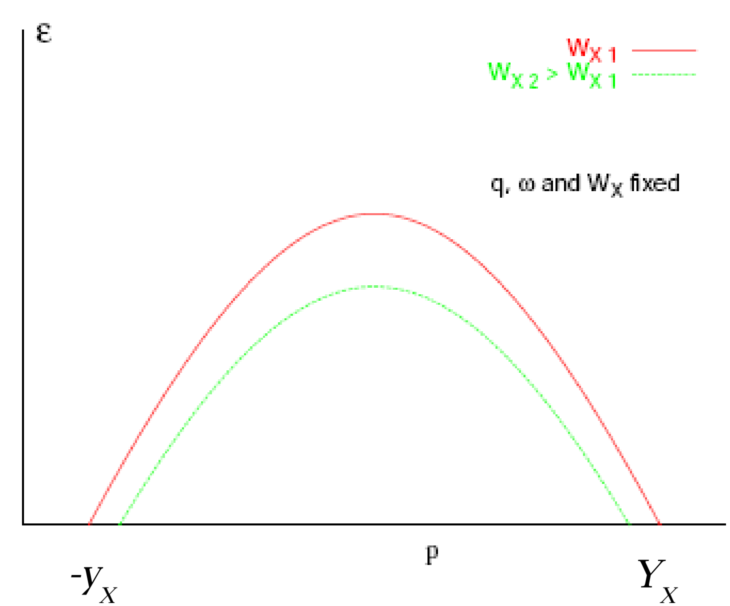
$$W = \sqrt{(M_A^0+\omega)^2-q^2} \text{ and } \Lambda_X = \frac{1}{2}\left[W^2+(M_{A-1}^0)^2-W_X^2\right]$$



q-dependence at the Δ peak (SSM-Δ)

$$R_{L,T}^{\Delta\Gamma} = \int_{m_N+m_\pi}^{W_X^{max}} dW_X \frac{1}{\pi} \frac{\Gamma(W_X)/2}{(W_X - m_\Delta)^2 + \Gamma(W_X)^2/4} \frac{1}{k_F} f_{QE}(\psi_X) G_{L,T}^{\Delta,X}$$

$$G_L^\Delta = \frac{\kappa}{2\tau} \frac{A}{2} \left[\left(1 + \tau \rho_X^2 + 1\right) w_2^\Delta - w_1^\Delta \right] \qquad G_T^\Delta = \frac{1}{\kappa} \frac{A}{2} w_1^\Delta$$

$$w_1^\Delta = \frac{1}{2} (\mu_X + 1)^2 (2\tau \rho_X + 1 - \mu_X) \left(G_{M,\Delta}^2 + 3G_{E,\Delta}^2\right)$$

$$w_2^\Delta = \frac{1}{2} (\mu_X + 1)^2 \frac{(2\tau \rho_X + 1 - \mu_X)}{1 + \tau \rho_X} \left(G_{M,\Delta}^2 + 3G_{E,\Delta}^2 + 4\frac{\tau}{\mu_X^2} G_{C,\Delta}^2 \right)$$

$$f_\Delta^{SMM-\Delta\Gamma} = k_F \frac{\sigma_M \left(v_L R_L^{\Delta\Gamma} + v_T R_T^{\Delta\Gamma}\right)}{\sigma_M \left(v_L G_L^\Delta + v_T G_T^\Delta\right)}$$

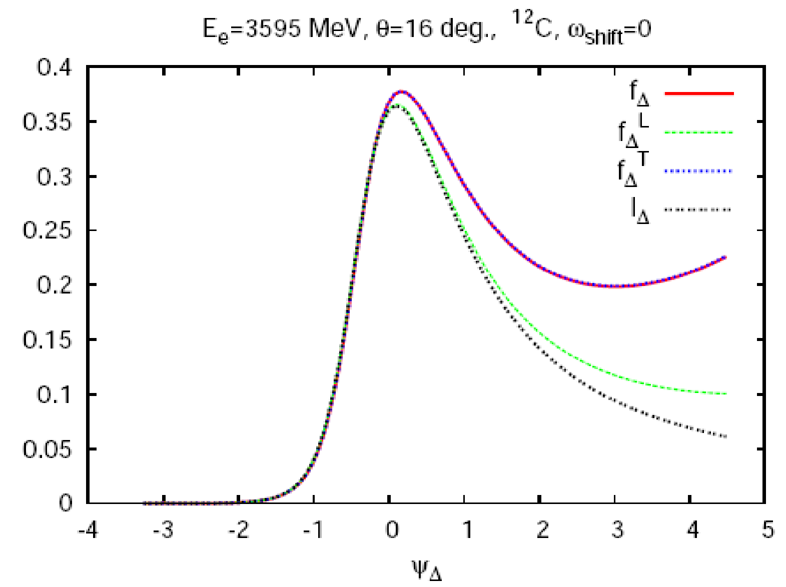
$$I_\Delta \equiv \int_{m_N+m_\pi}^{W_X^{max}} dW_X \frac{1}{\pi} \frac{\Gamma(W_X)/2}{(W_X - m_\Delta)^2 + \Gamma(W_X)^2/4} f_{QE}(\psi_X)$$

Residual q-dependence

For simplicity :
explore scaling violations using

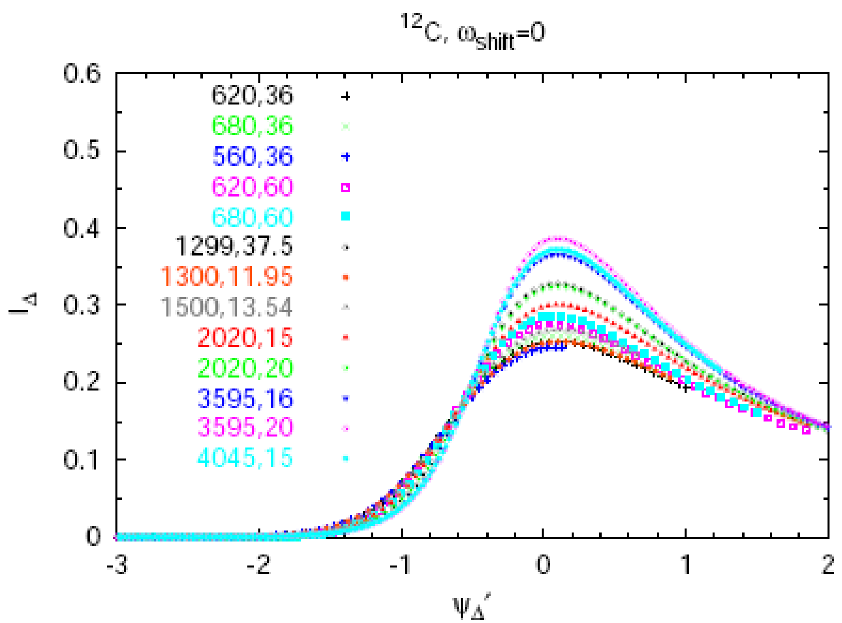
$$I_\Delta \equiv \int_{m_N+m_\pi}^{W_X^{max}} dW_X \frac{1}{\pi} \frac{\Gamma(W_X)/2}{(W_X - m_\Delta)^2 + \Gamma(W_X)^2/4} f_{QE}(\psi_X)$$

with $\omega_{shift} = 0$



I_Δ almost coincides with f_Δ

and shows same q-dependence



Fix q and ω ⇒ q and ψ_Δ and have a look at integrand where

$\psi_X = \psi_X(\psi_\Delta, q; W_X)$

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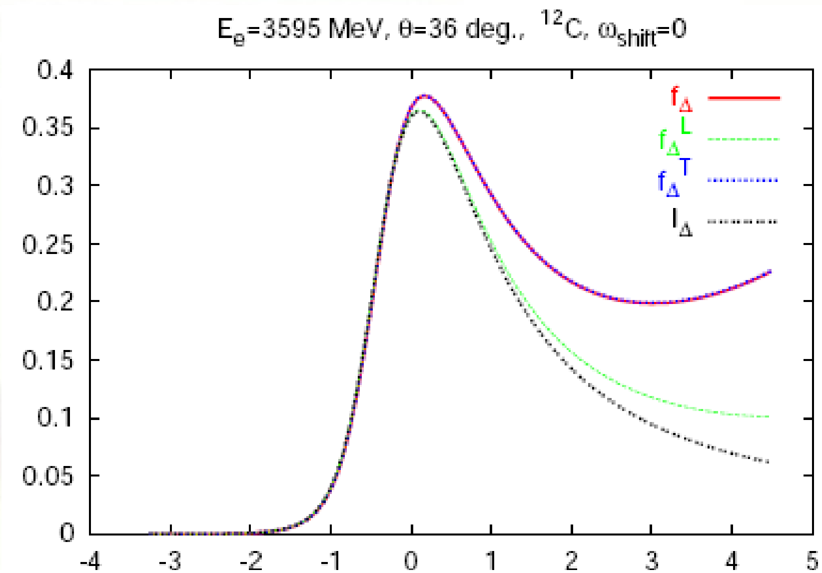

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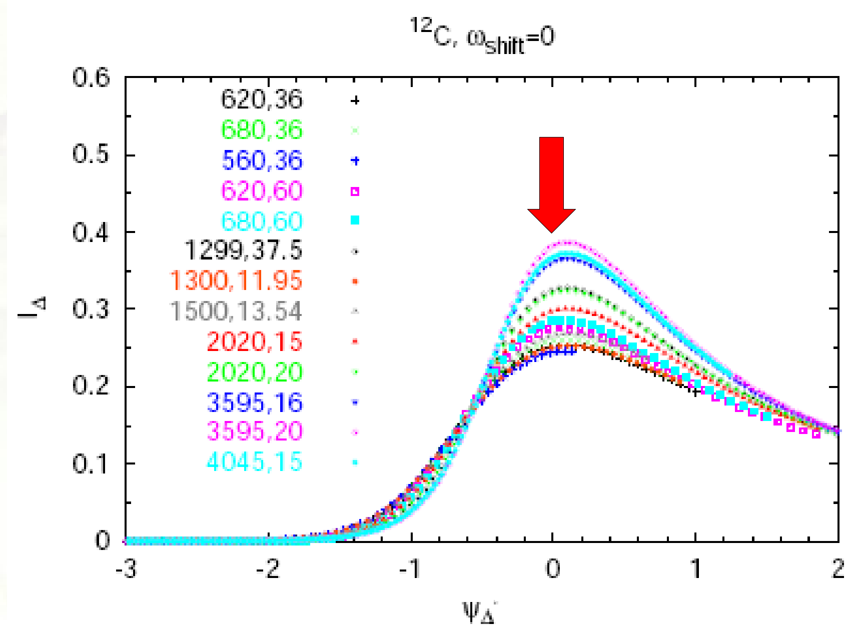

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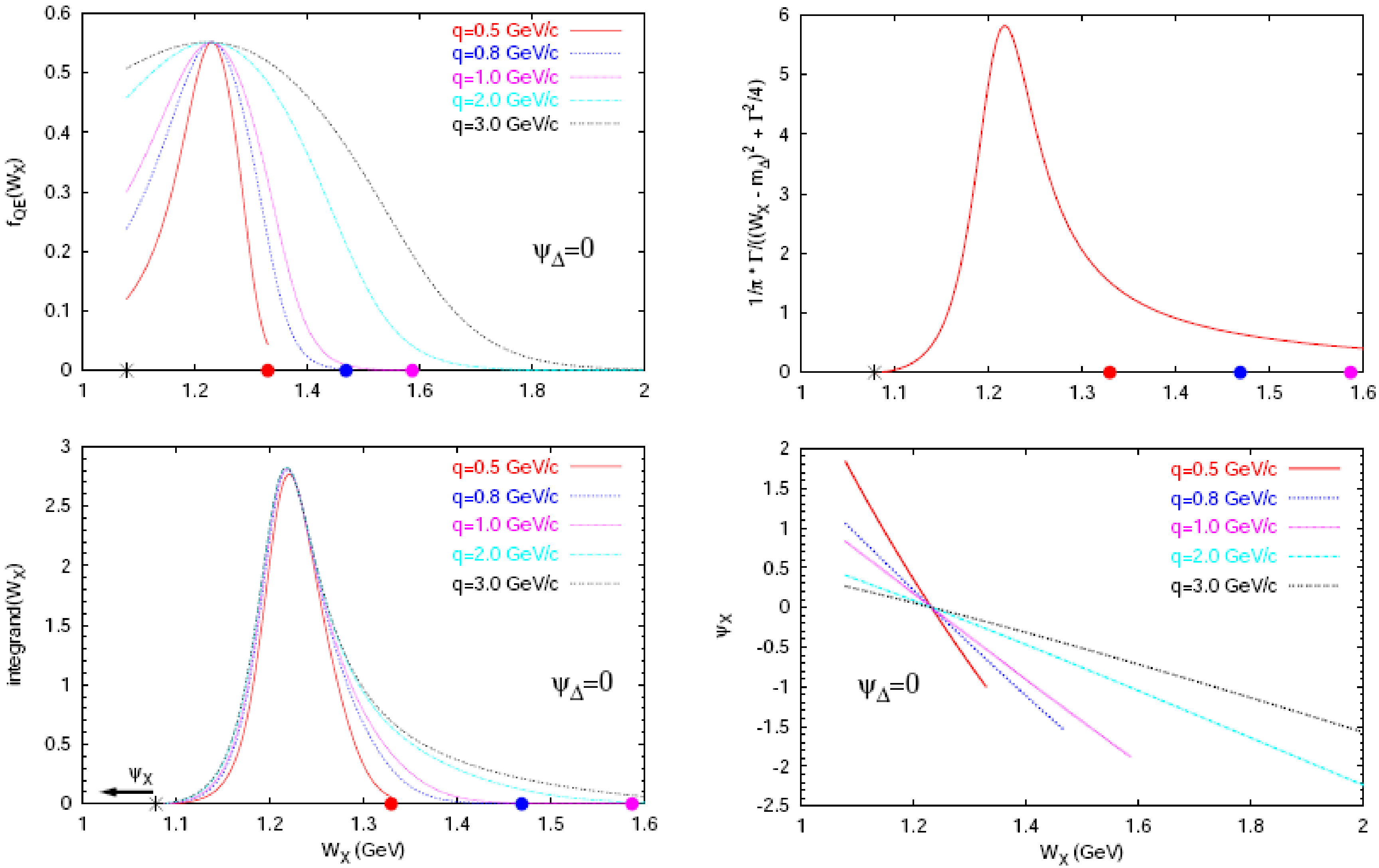
Integral and integrand at the Δ peak



Would it be useful to define an “average” ψ_Δ ?

Residual q-dependence

For simplicity :
explore scaling violations using

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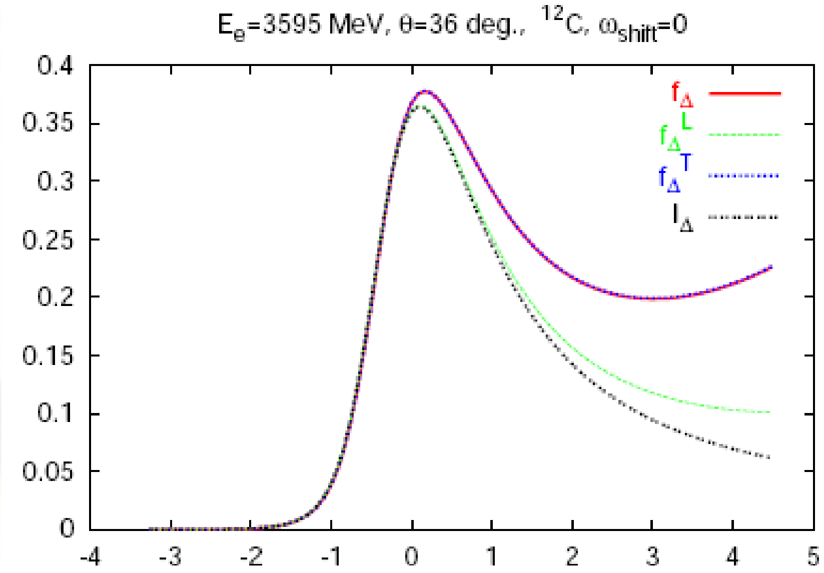

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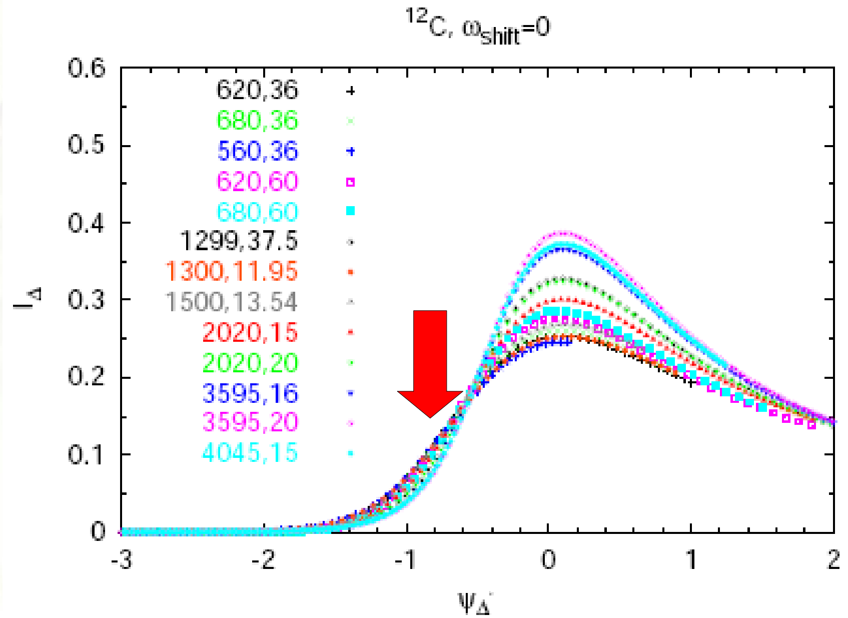

Fix q and $\omega \Rightarrow$ q and ψ_Δ and have a look at integrand where
$\psi_X = \psi_X(\psi_\Delta, q; W_X)$

Integral and integrand at the left of the Δ peak