Electromagnetic reactions with light nuclei

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Ohio University and Universität Bonn

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Plan

- Single-photon processes in the NN system
- Extension to 3N and 4N systems
- Compton scattering in A=2 and 3
- A word on weak processes
- Conclusion

Testing NN forces in elastic electron-deuteron scattering

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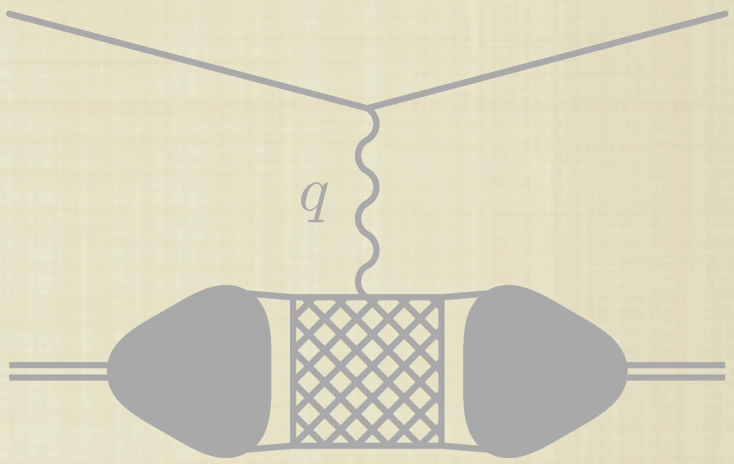
- LO QED: electron couples to J_μ



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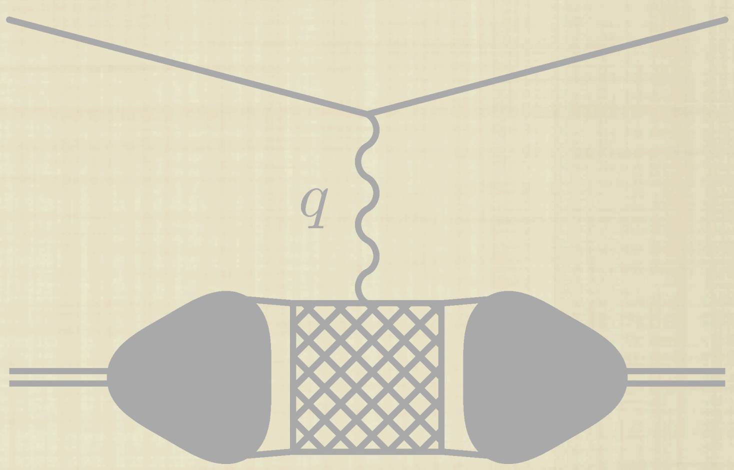
- LO QED: electron couples to J_μ
- χET: apply counting to J_μ



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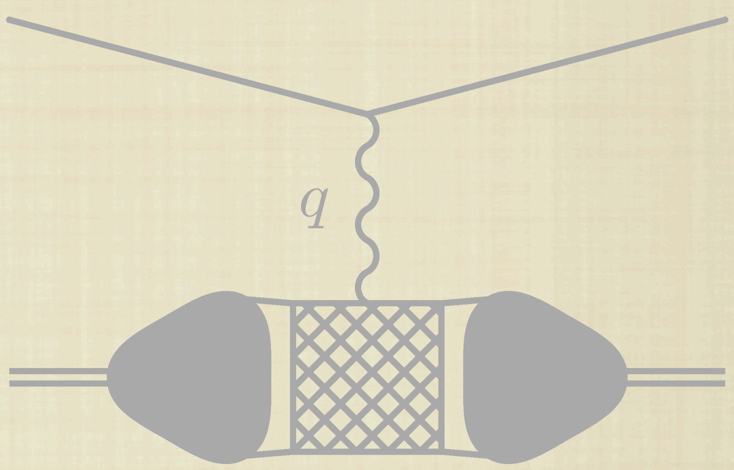

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- LO χET, O(e): $J_0(\mathbf{r}) = |e|\delta^{(3)}(r - r_p)$
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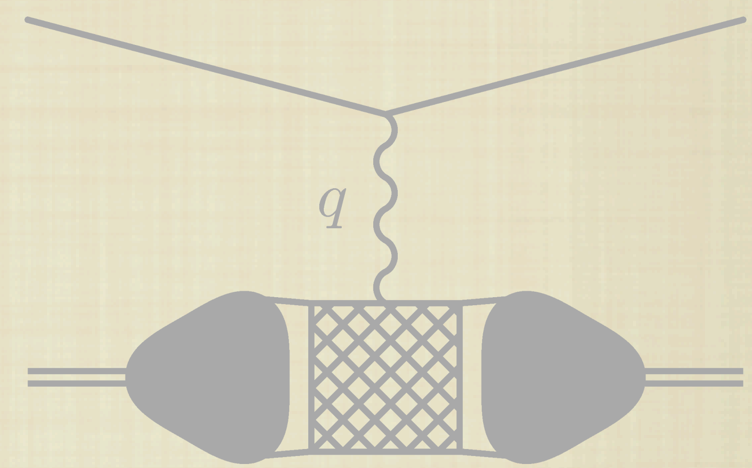

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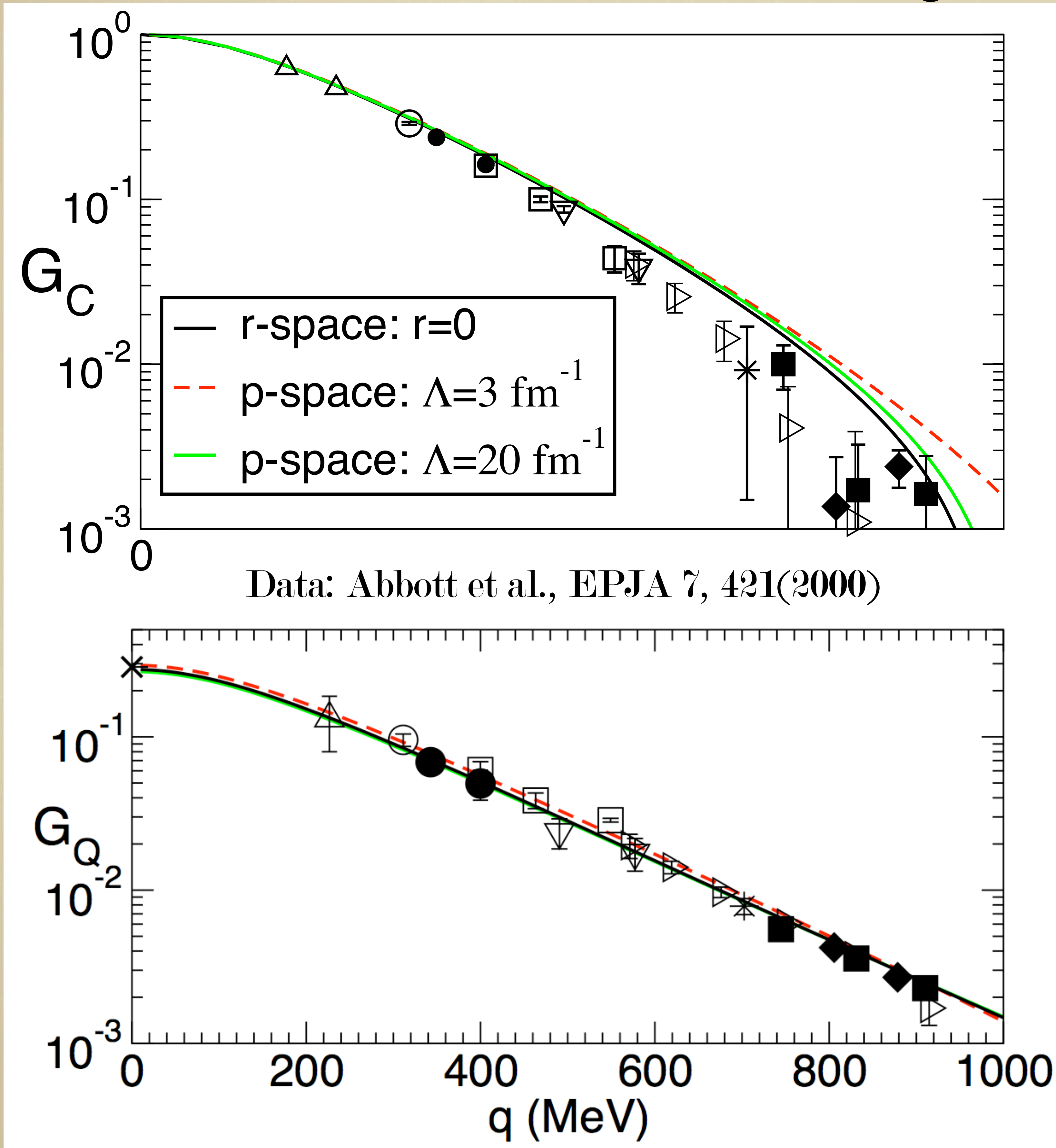
- Change $Q^2=-q^2$⇒change spatial resolution
- **Prediction** of QED and NN force model

Results for G_C and G_Q at leading order



Data: Abbott et al., EPJA 7, 421(2000)

DP and Cohen (1999); Pavon Valderrama, Ruiz Arriola, Nogga, DP (2008)

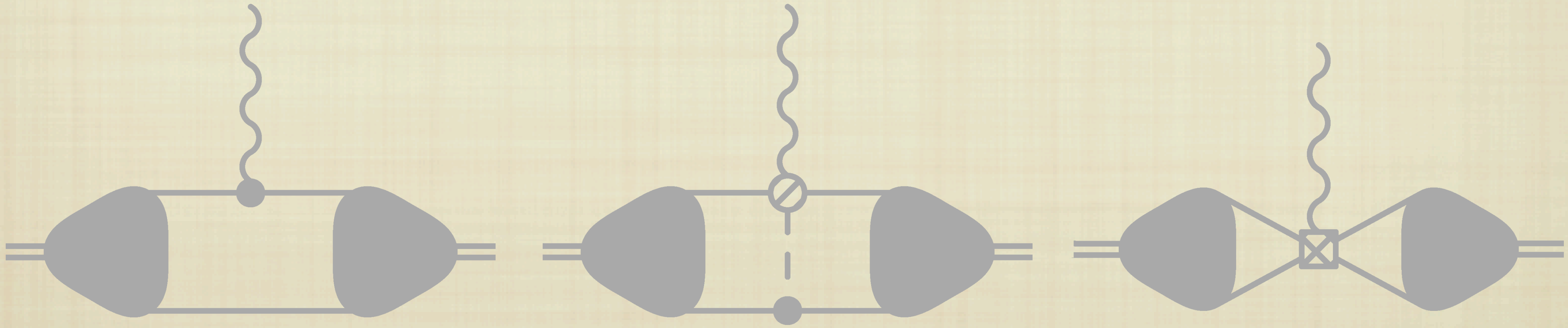
Nucleon form factors included via:

$$\frac{G_C}{G_E^{(s)}} = \langle\psi|e|\psi\rangle + O(P^2)$$

Only |**q**|/2 transferred to relative degree of freedom

G_C and G_Q beyond LO

Meissner and Walzl (2001); DP (2003, 2007)



$O(e)$ $O(eP^3)$ $O(eP^5)$

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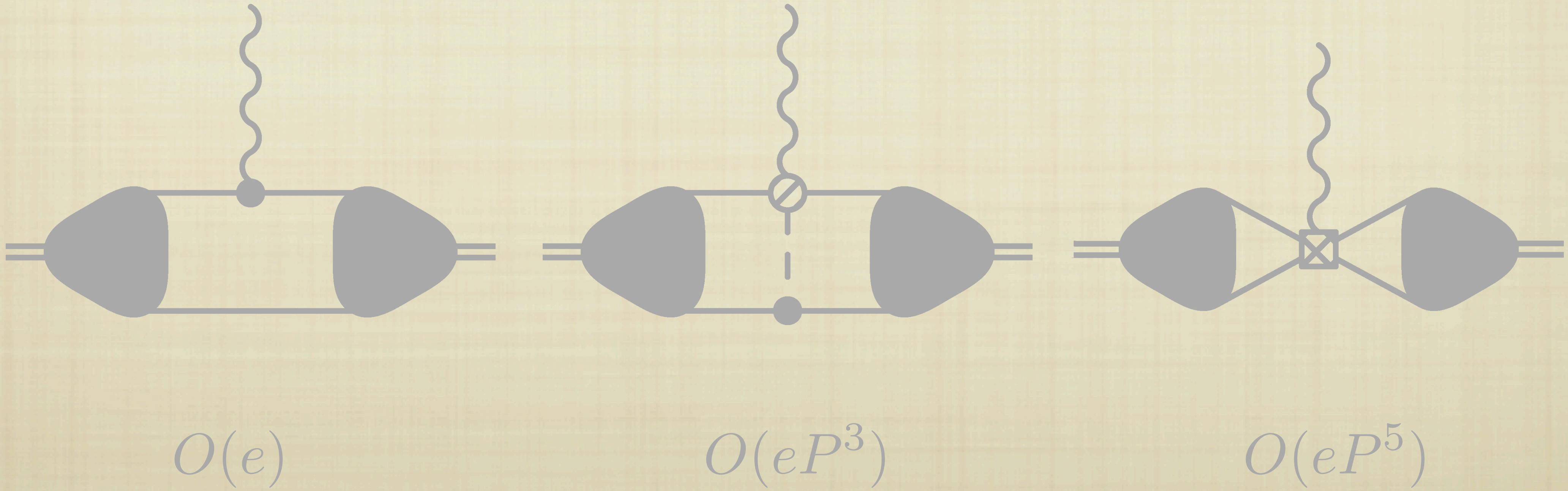
- Higher orders require corrections to V **and** J_0

At O(eP³) we can test chiral TPE



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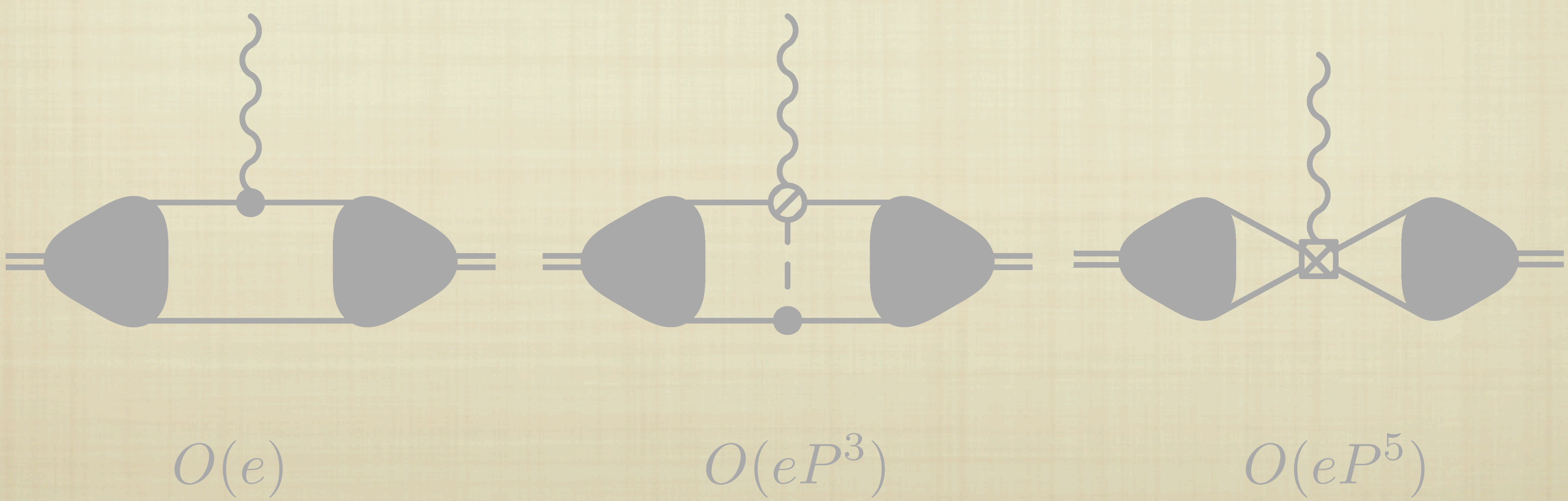

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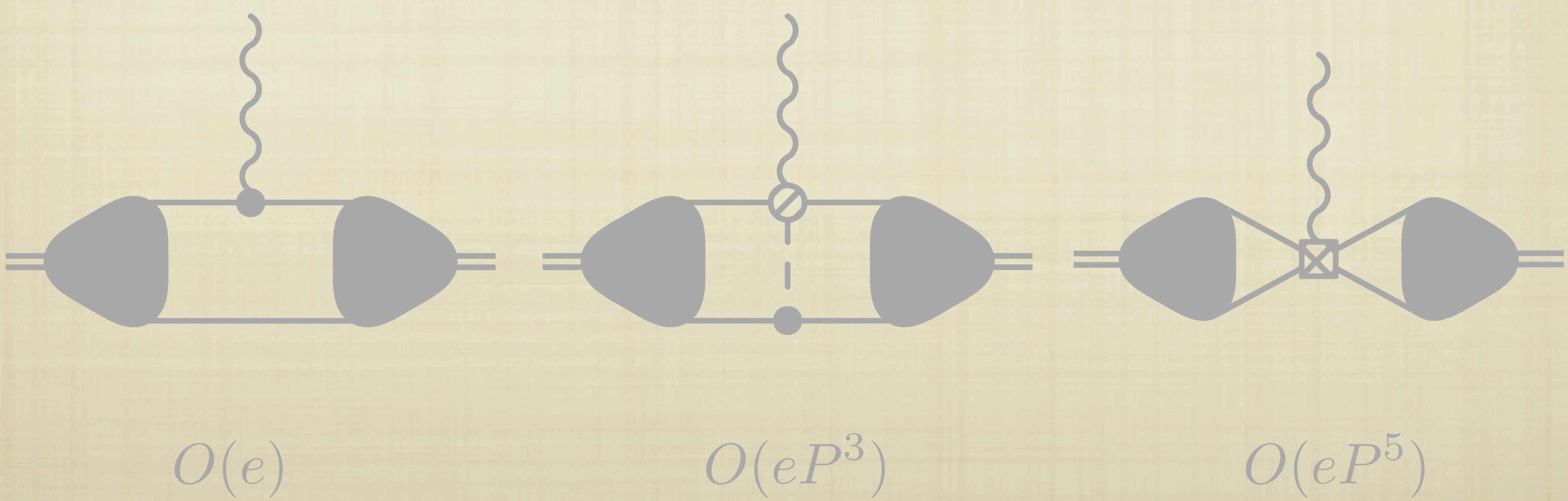
- O(eP^2): $1/M^2$ effects
- O(eP^3): 2B mechanism enters, but no free parameters
- O(eP^4): Two-pion exchange pieces of J_0:but =0 for $J_0^{(s)}$



χET for G_C to $O(eP^3)$ [N^2LO]

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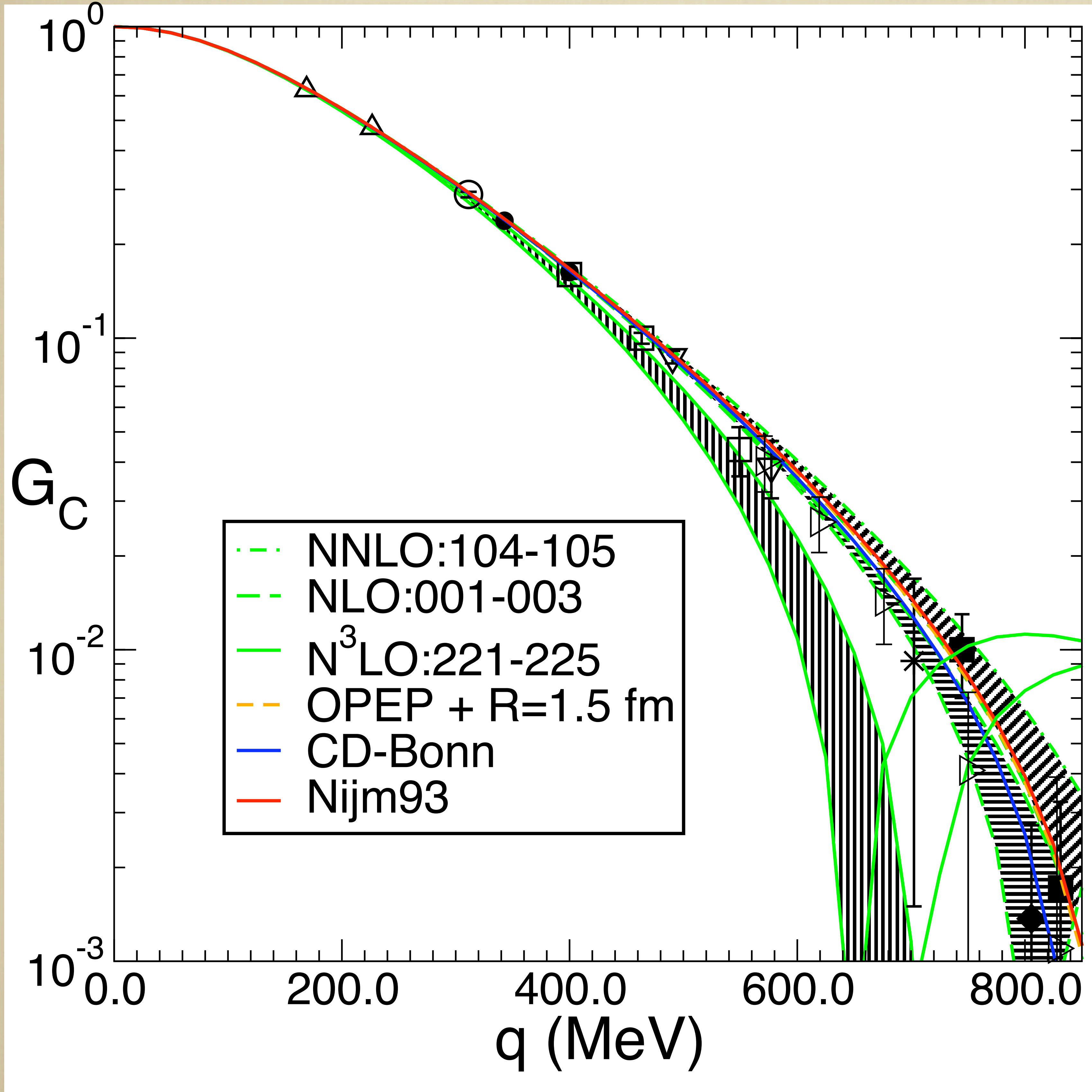

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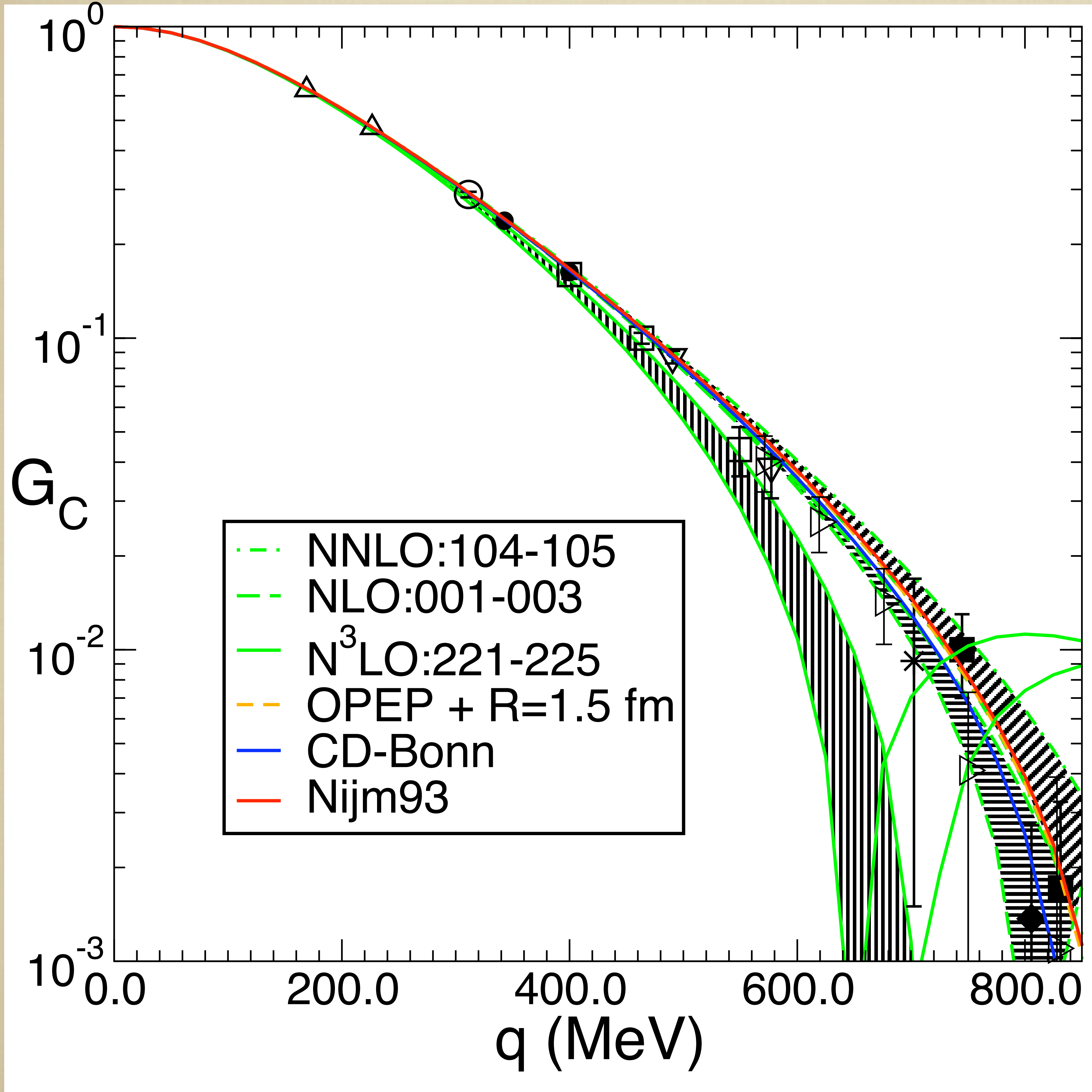

- Good J_0 convergence
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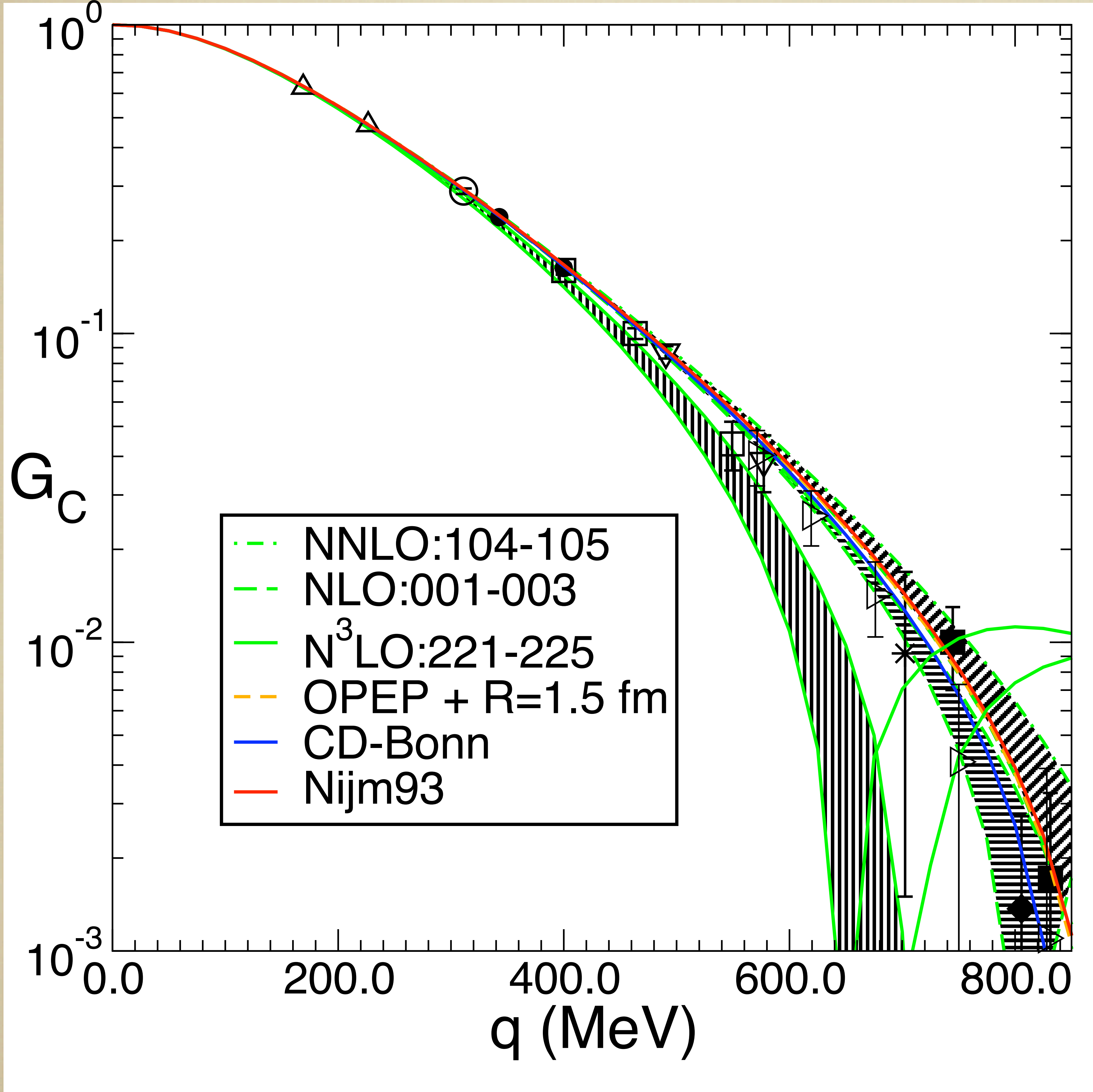
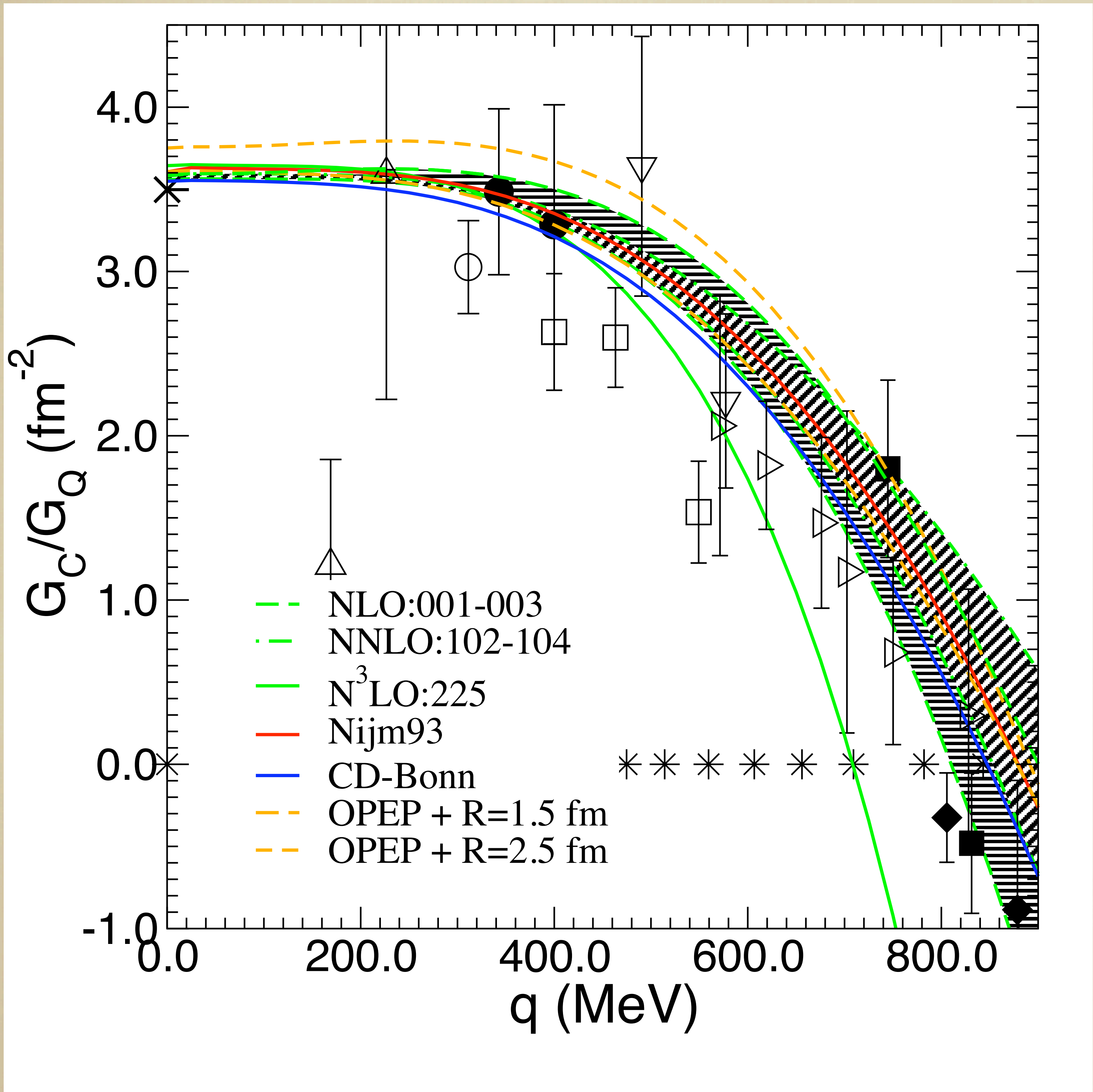


- Good J_0 convergence
- G_C insensitive to r~1/Λ physics for |**q**|<0.6 GeV
- G_M: calculation exists, observable sensitive to r~1/Λ once |q|≈0.45 GeV≡contact term at $O(eP^4)$

G_C/G_Q beyond N^2LO



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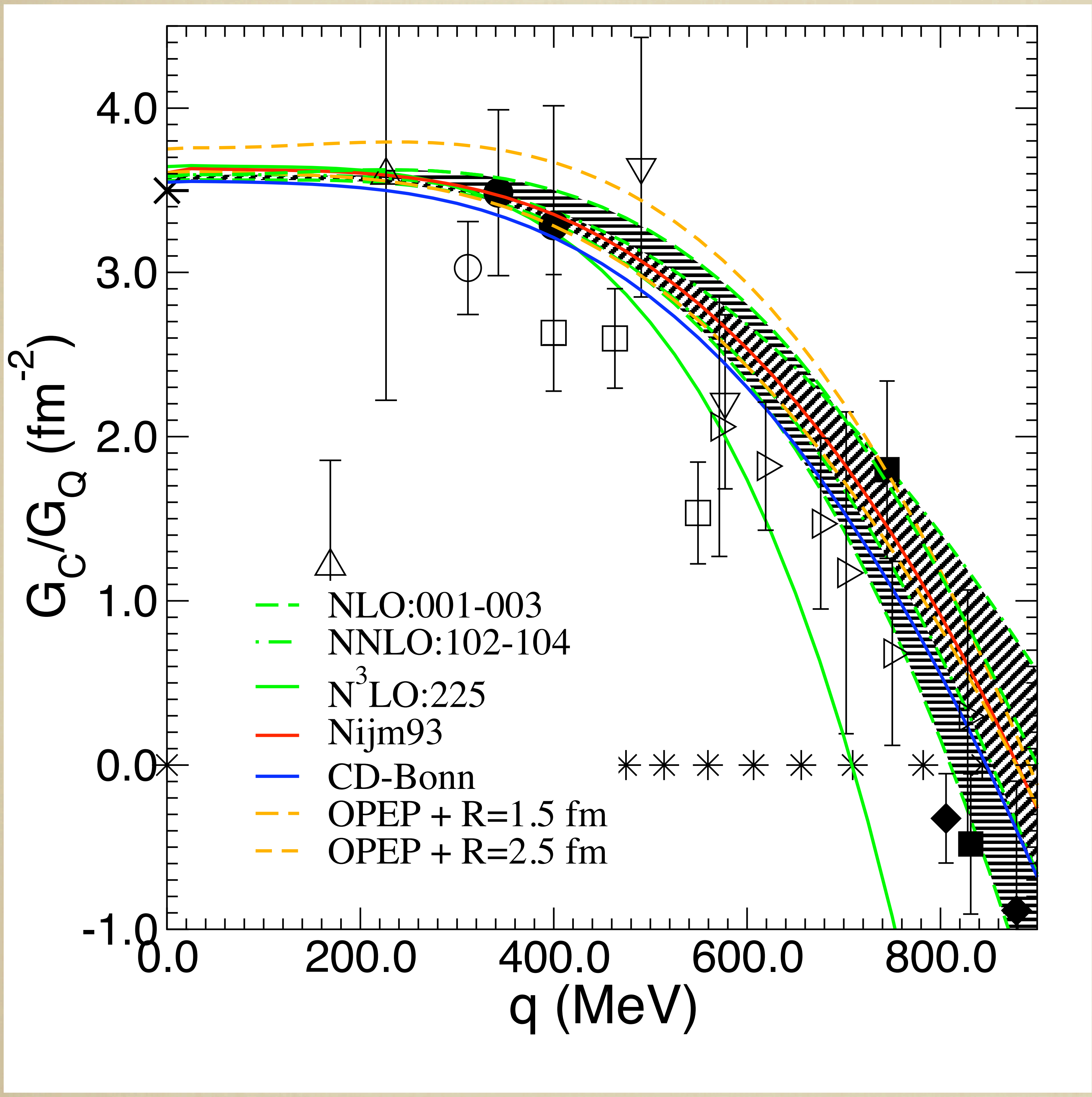

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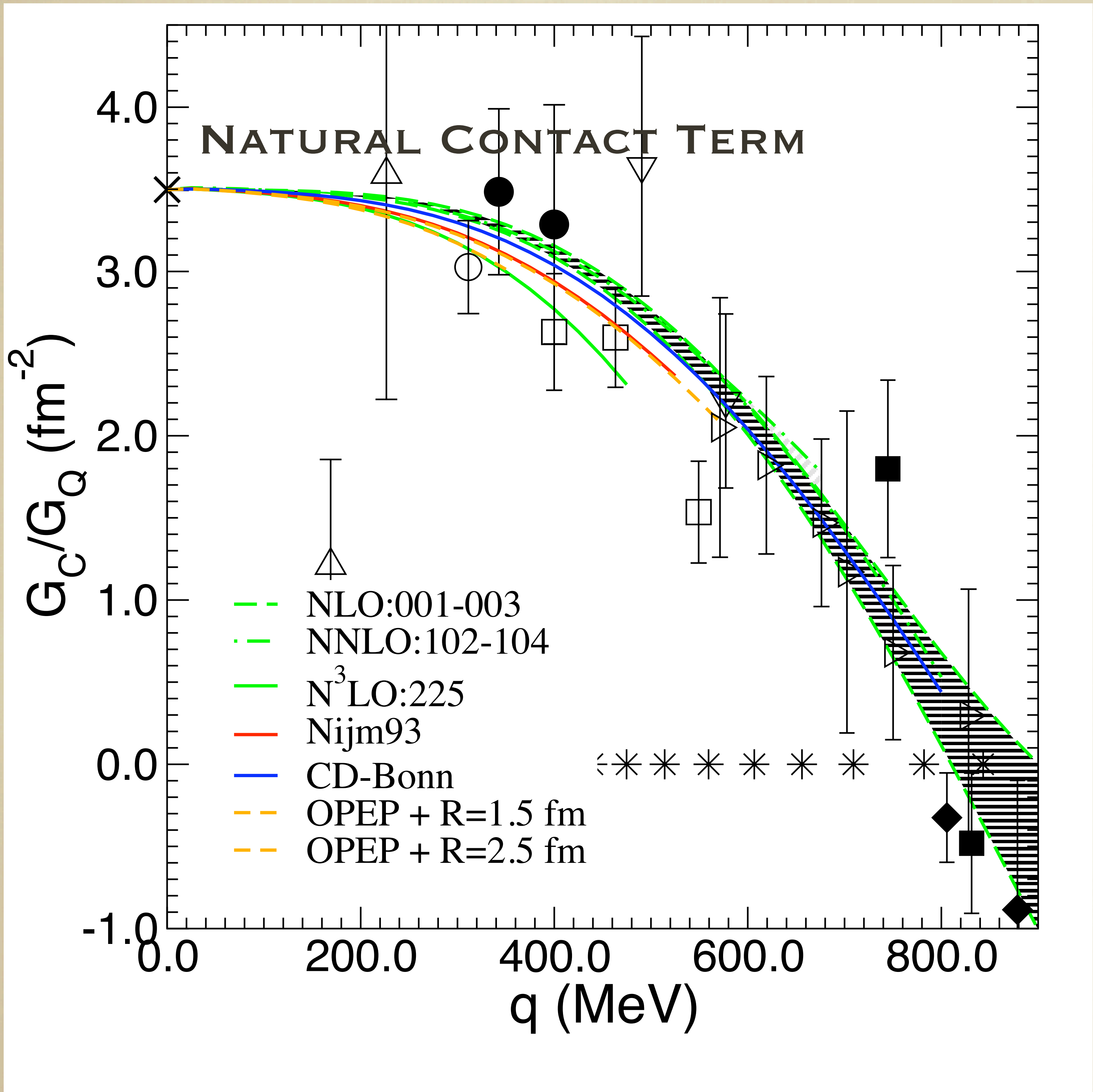

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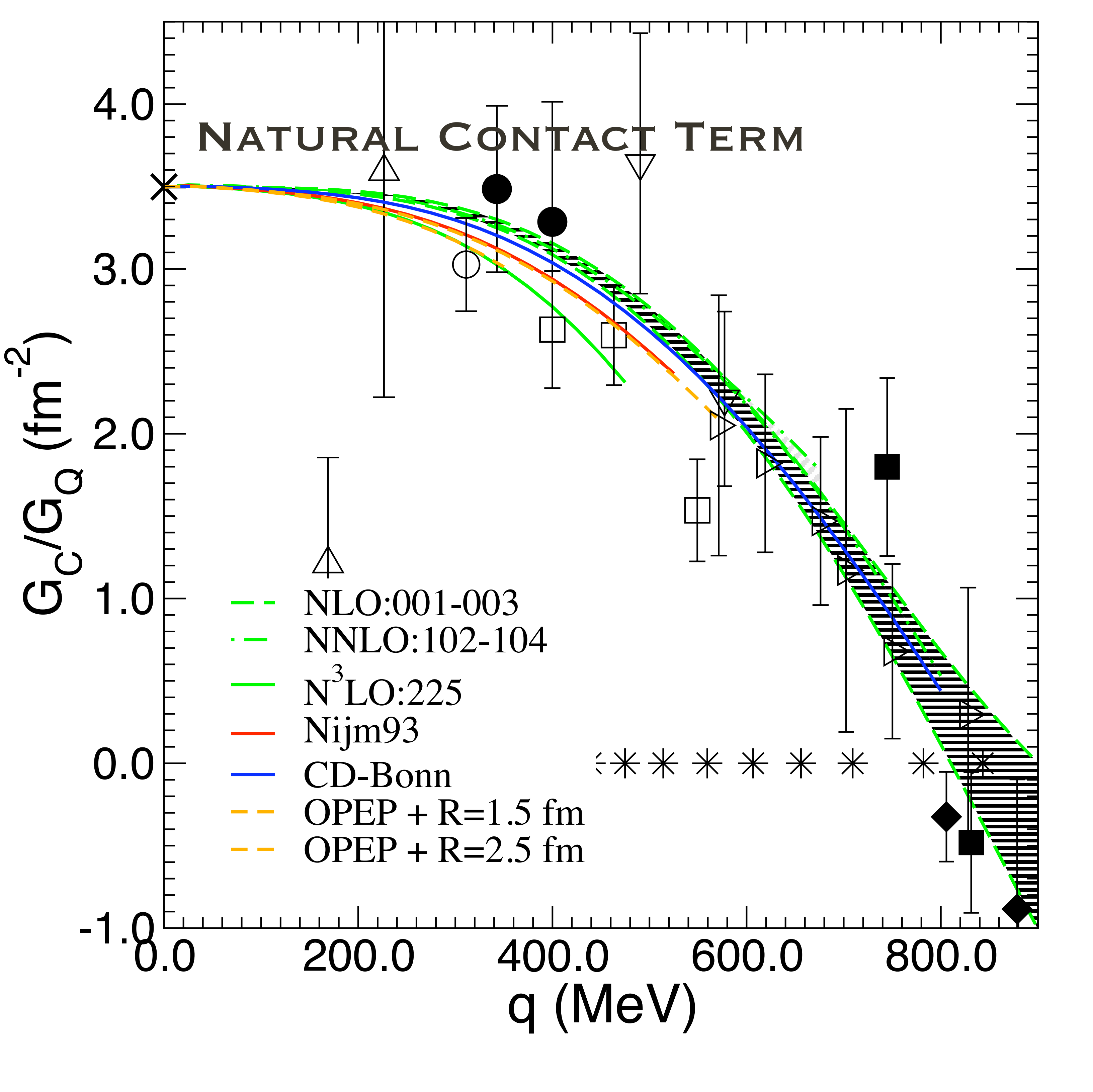
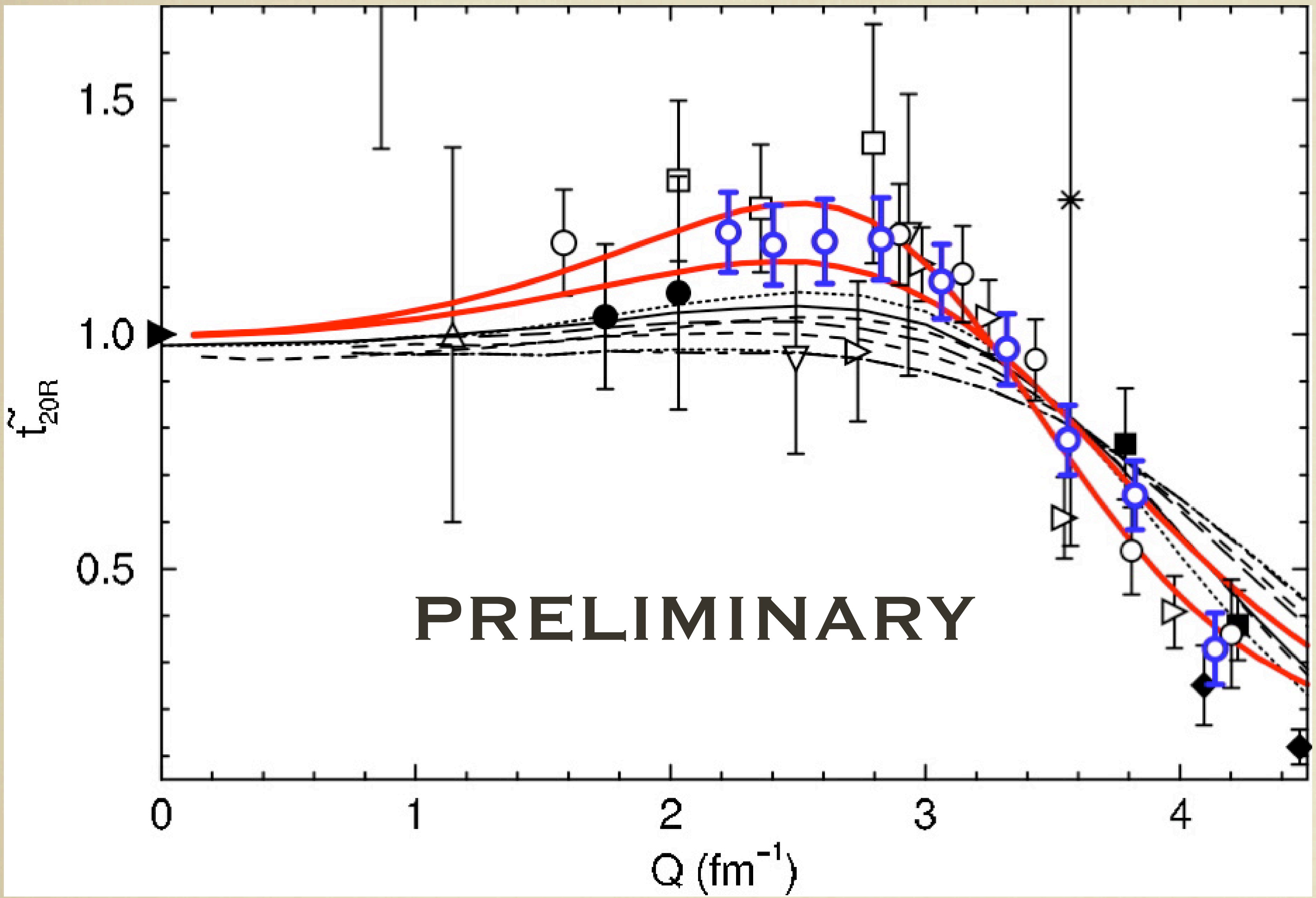


- Adjust $O(eP^5)$ contact term to reproduce Q_d: predict ratio up to $O(eP^6)$ effects
- Ratio largely independent of short-distance physics for q<0.6 GeV
- G_C/G_Q to 3% at q= 0.39 GeV

BLAST data on t_{20}



FIRST TWO POINTS GIVE NORMALIZATION

Courtesy M. Garcon

$$\tilde{t}_{20\,R} = -\frac{3\tilde{t}_{20}}{\sqrt{2}Q_d Q^2} \quad \leftrightarrow \quad G_C/G_Q$$

Deuteron electro-disintegration

$$\left(\frac{d\sigma^5}{d\epsilon' d\Omega_e d\Omega_p}\right)_h = \frac{m_p m_n p_p}{8\pi^3 M_d}\sigma_{Mott} f_{rec}^{-1}\left[v_L R_L + v_T R_T\right.$$
$$\left. + v_{TT} R_{TT} \cos 2\phi_p + v_{LT} R_{LT} \cos\phi_p + h v_{LT'} R_{LT'} \sin\phi_p\right]$$

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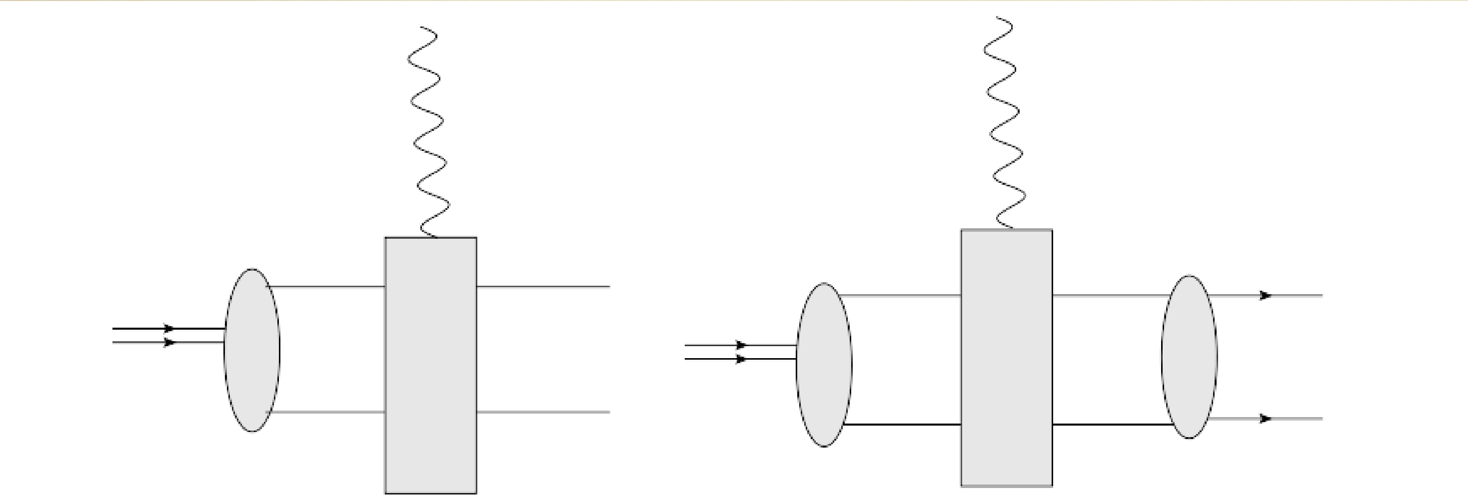

Probe NN dynamics as a function of energy and momentum transfer

The role of current conservation

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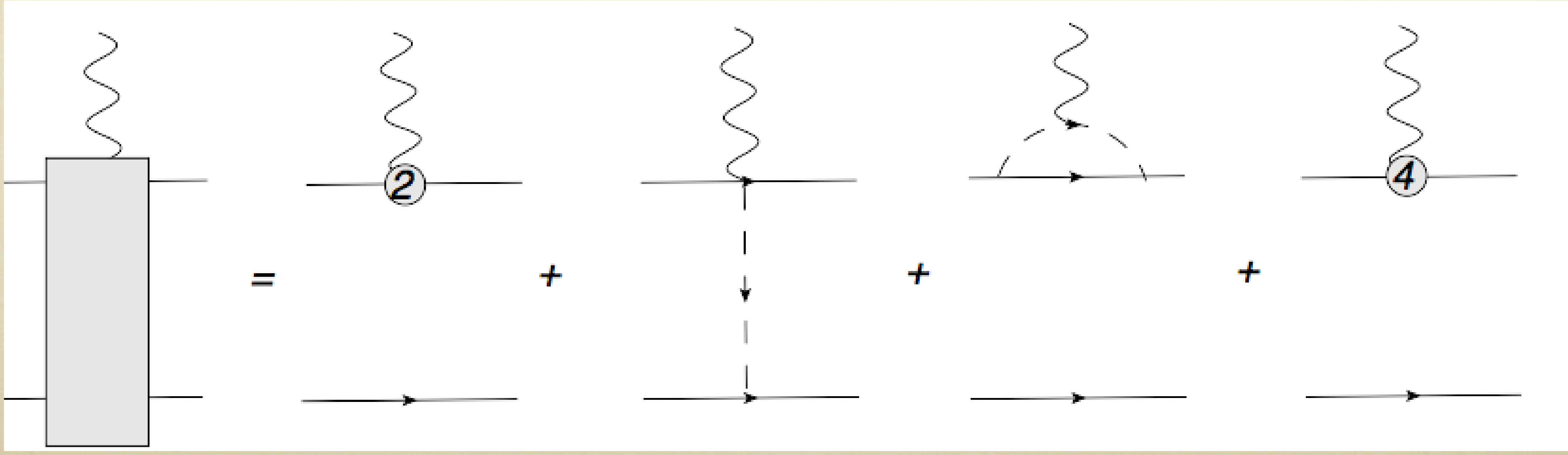
- Does not determine piece of **J** that is orthogonal to **q**

J to O(eP^3)

- O(eP): "convection" current $e\mathbf{p}/M$ and single-nucleon magnetic-moment operators
- O(eP^2): 2B current, constrained by OPE part of V, one-loop correction to nucleon isovector form factor
- O(eP^3):$1/M^2$ corrections to one-body current, and sub-leading nucleon-structure effects



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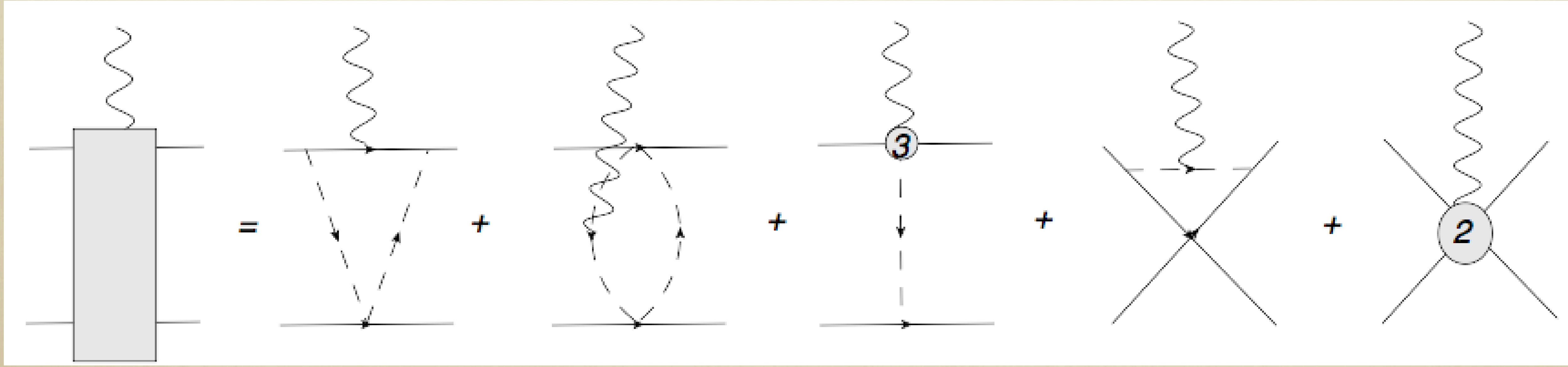

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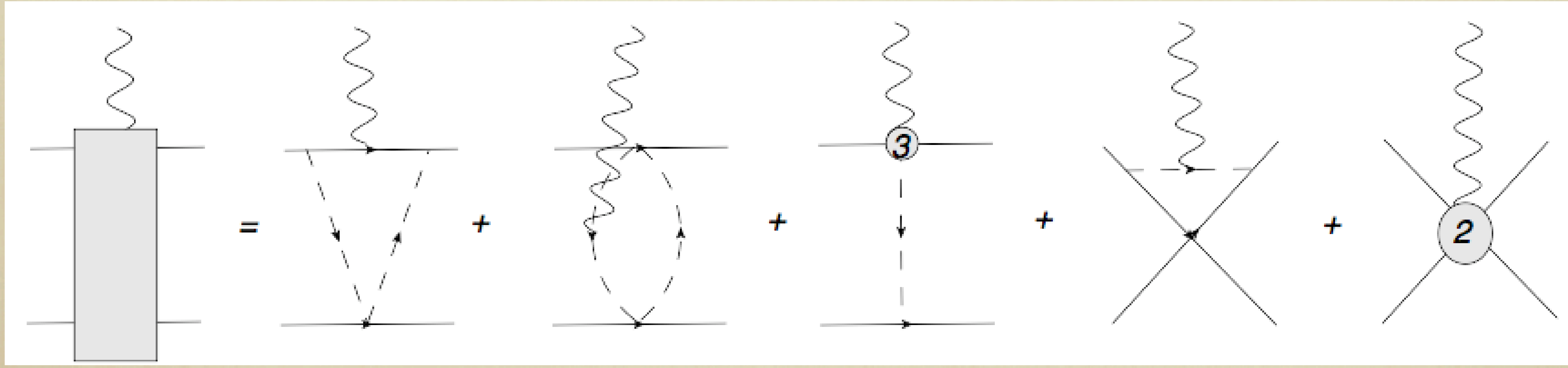
- Derived for use in $\vec{n}p \rightarrow d\gamma$ for $\omega \sim |\mathbf{q}| \sim m_\pi^2/M$

Park, Min, Rho (1999)



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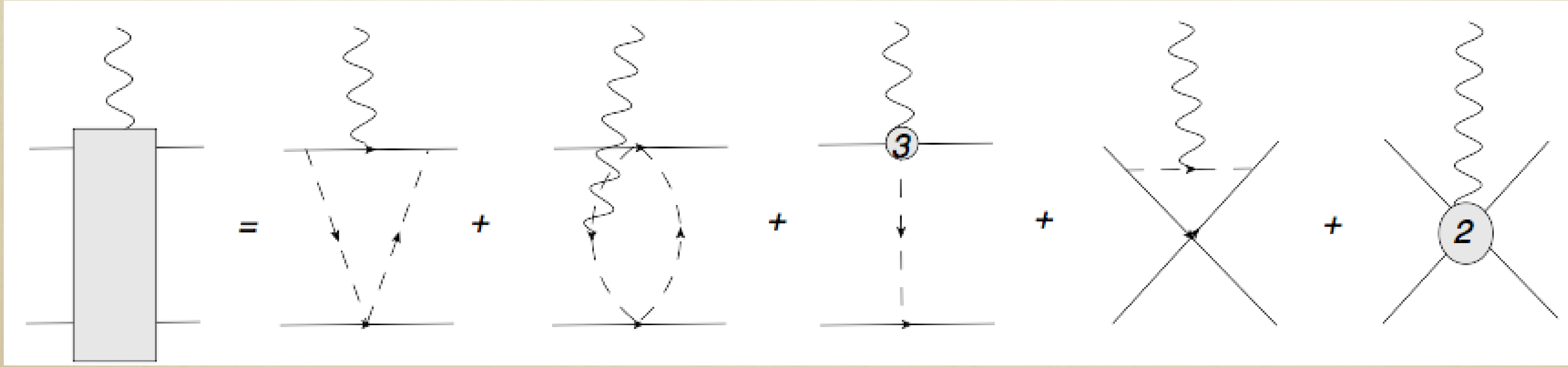
- Re-derived for $\omega \sim m_\pi^2/M$, $|\mathbf{q}| \sim m_\pi$

Pastore et al. PRC 78, 064002 (2009), arXiv:0906.1800; Talk of Stefan Koelling



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- Should fit two undetermined NN operators at $O(eP^4)$

Cumulative to:	μ_d (n.m.)	M_{np} ($fm^{1/2}$)
$O(eP)$	0.8469	393.1
$O(eP^2)$	0.8469	401.8
$O(eP^3)$	0.8400	401.7
$O(eP^4)$=Expt	0.8574	410.2(4)

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- Prediction for ω and Q^2-dependence AND for A=3

Open questions and future work

- 1/M pieces: $M \sim \Lambda$ or $M \sim \Lambda^2$, irreducibility, formalism?
- Consistent V and **J**
- Treating nucleon structure?
- Predictions for photo- and electro-disintegration

Rozpedzik, Golak

c.f. Christlmeier, Griesshammer (2008)

- Form-factor extractions
- $\omega \sim m_\pi$; Different **J**; Delta(1232) expected important

Testing currents and forces in A=3, 4

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- Tri-nucleon magnetic moments

Song, Park, Lazauskas, Min (2007)

Cumulative to:	$\mu_{H\text{-}3}$(n.m.)	$\mu_{He\text{-}3}$(n.m.)
$O(eP)$	2.585	-1.774
$O(eP^2)$	2.790	-1.979
$O(eP^3)$	2.772	-1.986
$O(eP^4)$	3.035(12)	-2.198(12)
Experiment	2.979	-2.128

- Note importance of $O(eP^4)$ contributions, not in SNPA

M1 properties of 3N systems to O(eP^4)

Song, Lazauskas, Park (2009)

- Threshold nd→tγ cross section and R_c

Experiment: 0.508(15) mb; R_c=-0.420(30)

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$$\sigma_{nd} = \underbrace{0.279}_{eP} + \underbrace{0.044(25)}_{eP^2} + \underbrace{0.175(3)}_{eP^4} \text{ mb}$$

- Total: σ_{nd}=0.498(3) mb; R_c=-0.465.

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- EFT($\not\pi$) to N^2LO: σ_{nd}=0.503(3) mb; R_c=-0.412

Sadeghi, Bayegan, Griesshammer (2005); Sadeghi (2007)

A=4: capture and photodisintegration

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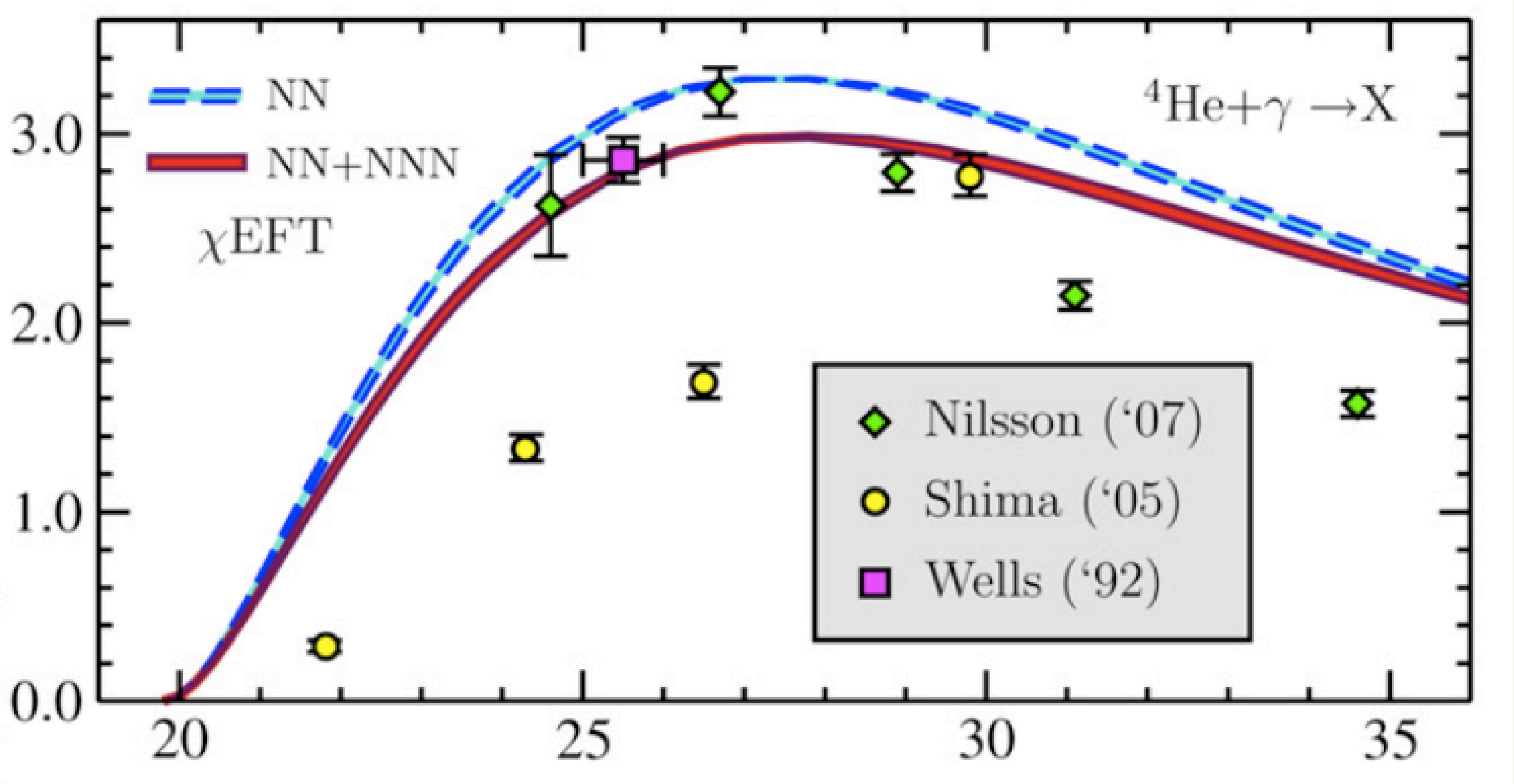

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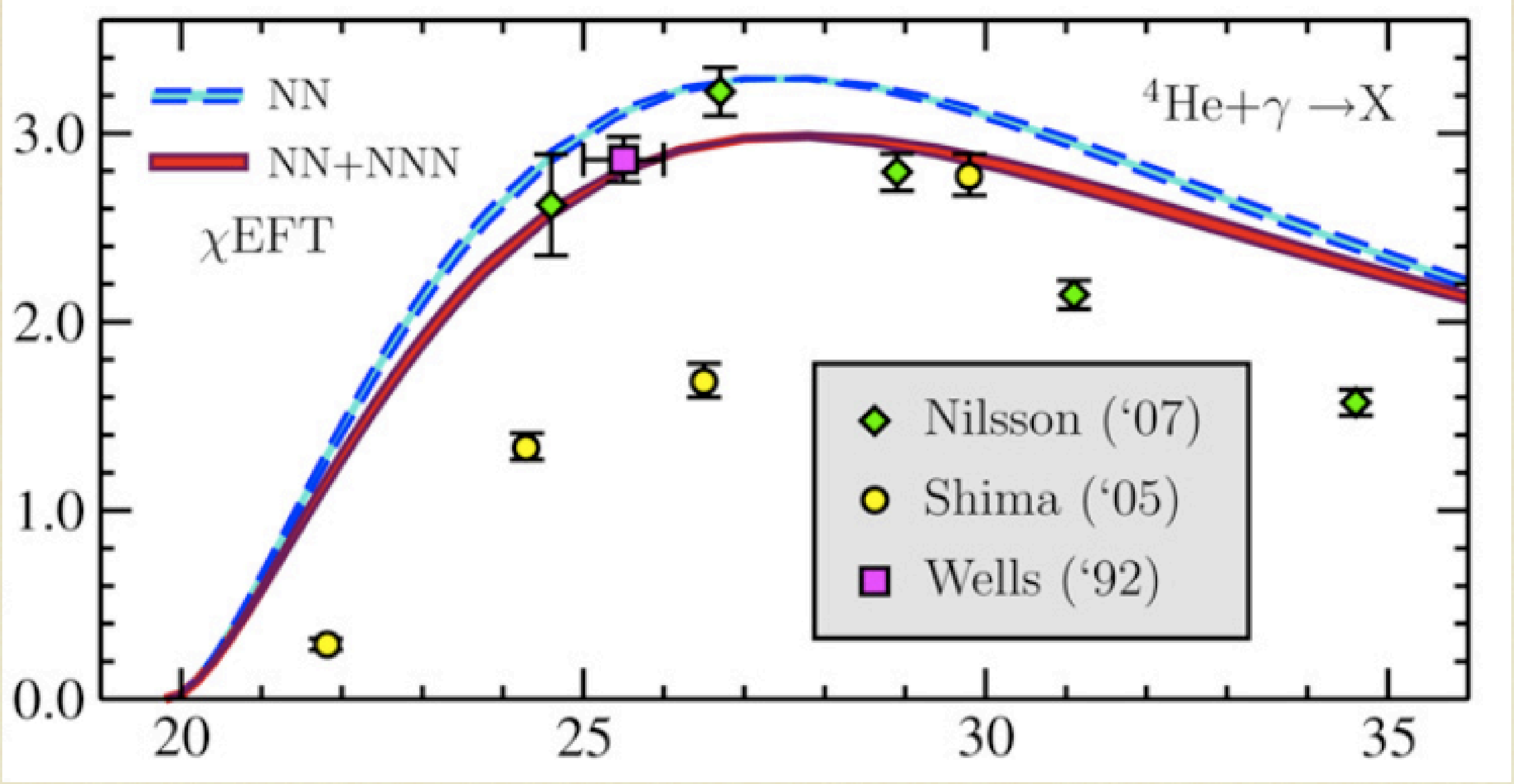

- χET + NCSM + LIT
- Impact of 3NFs in peak region, but only E1 operator
- Experimental situation confused

Future work: A=3, 4

- Importance of consistent potential and current?
- Predictions for ^{3}He photodisintegration
- Identify truly "chiral" dynamics: EFT($\not\pi$) vs χET
- Novel 3NF effects: HIγS $\vec{\gamma}{}^3\vec{\mathrm{He}} \rightarrow npp$

  Gao talk
- Photodisintegration of ^{4}He: clean up data?

  Shima talk
- Electro-disintegration: somewhat untouched in χET

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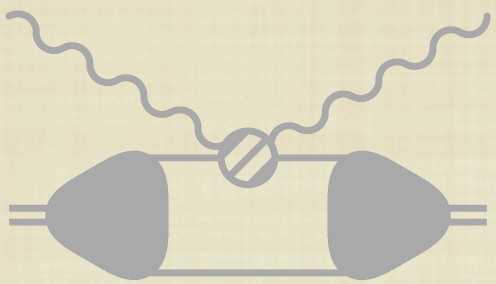

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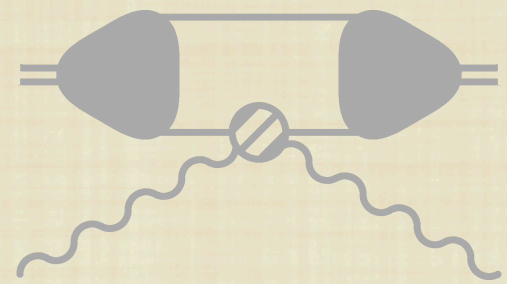

$\mathcal{A}_{\gamma p}$ $\mathcal{A}_{\gamma n}$

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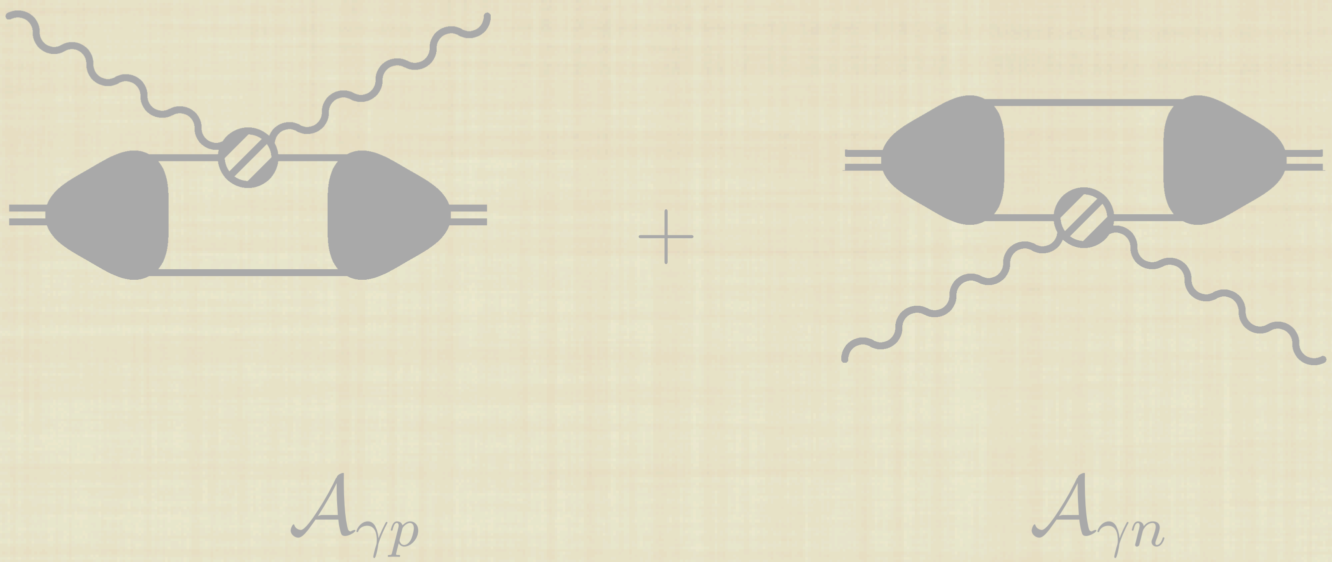
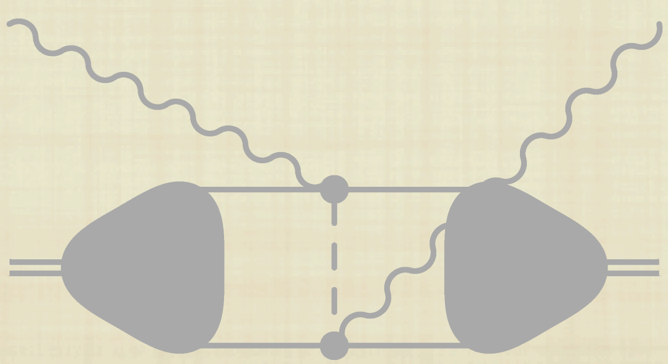
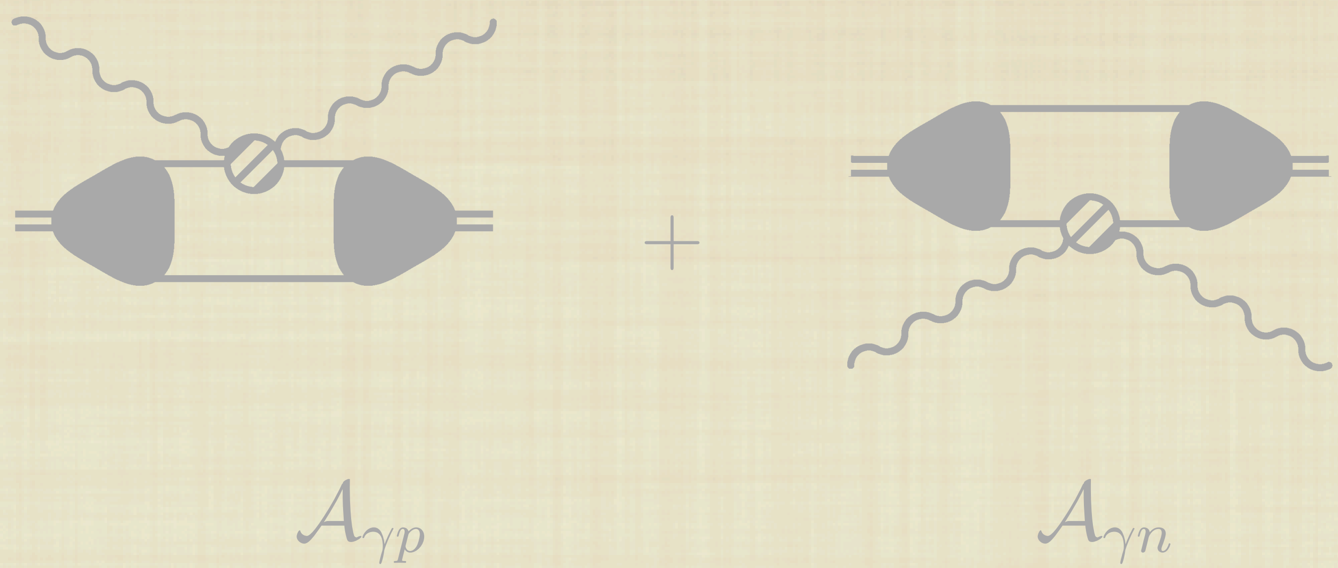


But two-body currents are large



Why Compton Scattering from Deuterium?

Goal is to investigate neutron Compton scattering



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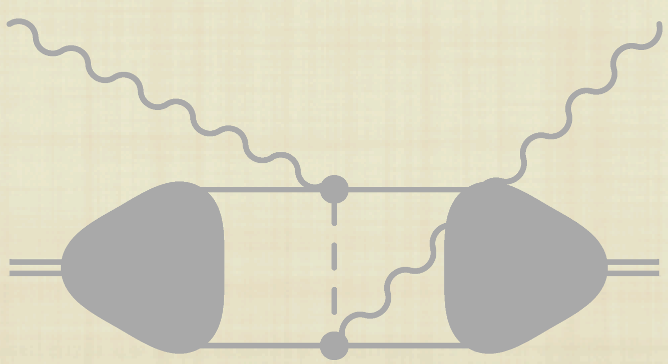

Need systematic way to compute γNN→γNN kernel

Power counting for γd scattering

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- $\omega \sim m_\pi^2/M$: χPT counting for J_μ and $W_{\mu\nu}$

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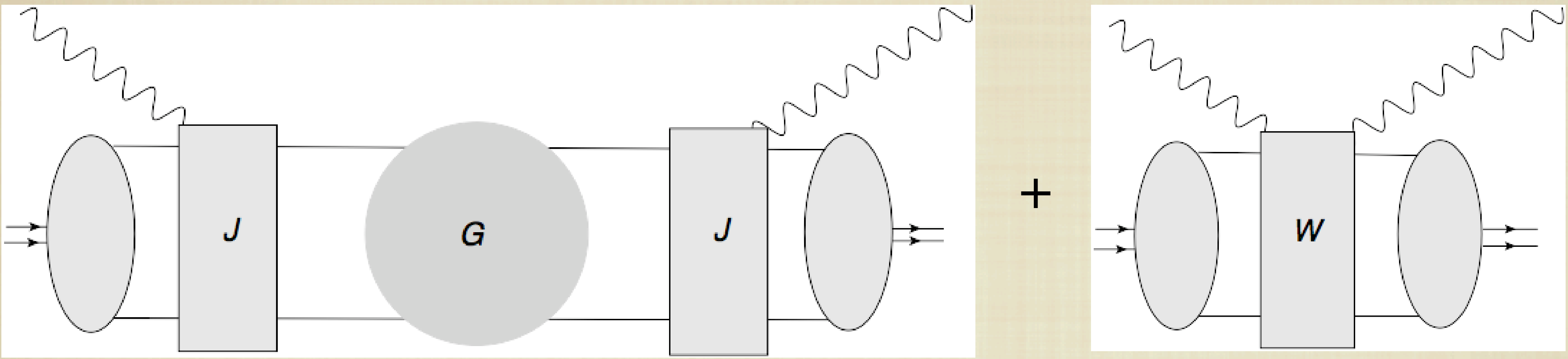

+ crossed

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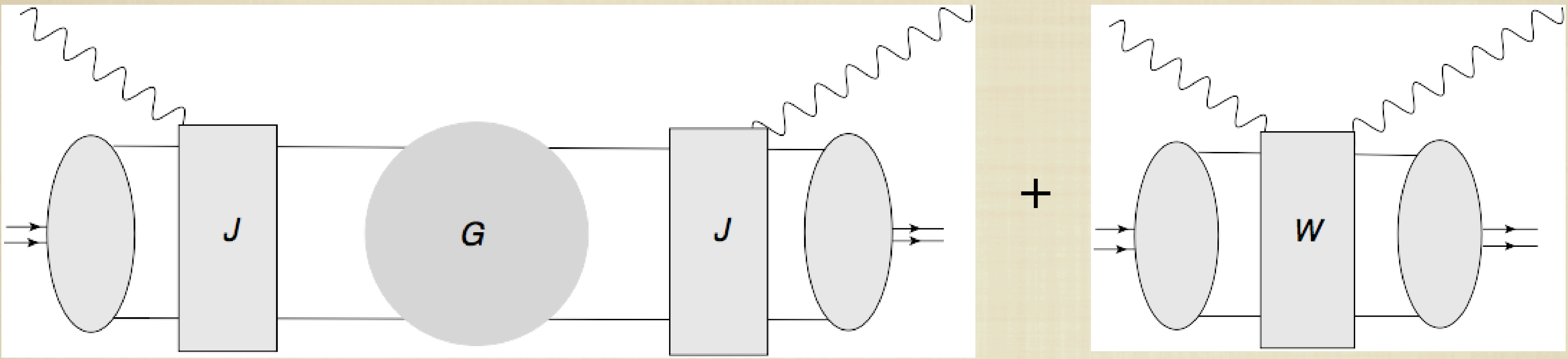

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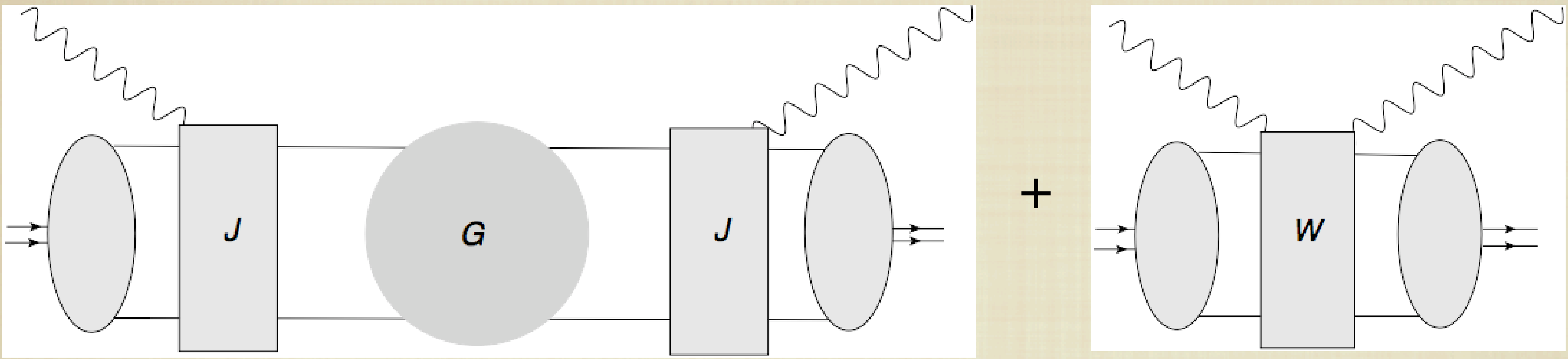

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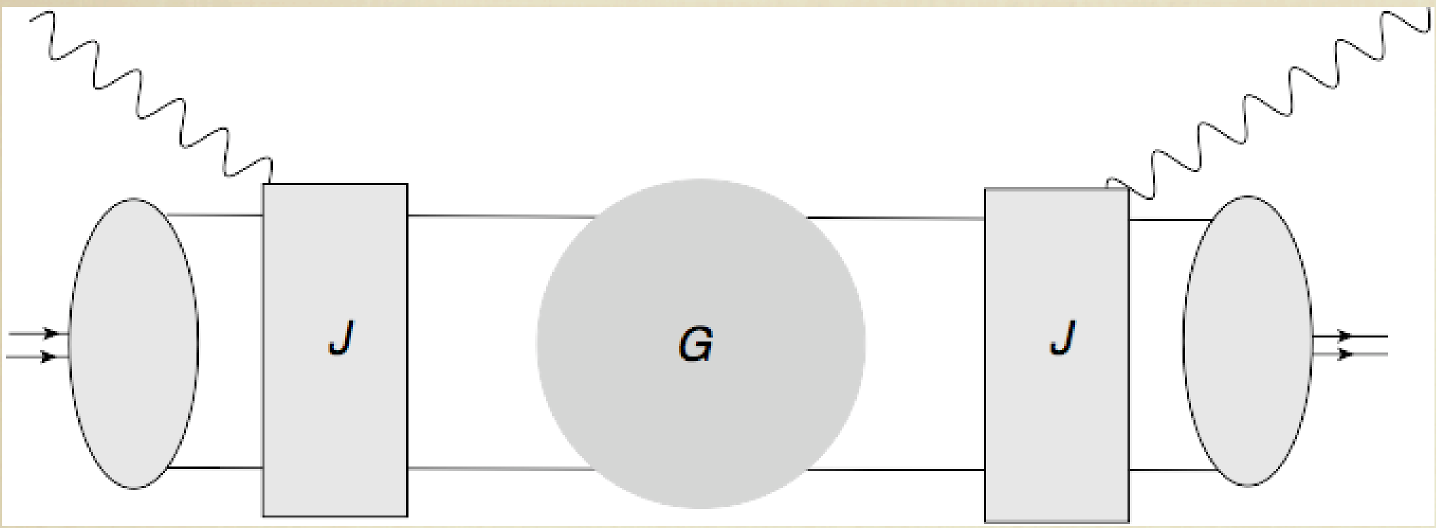

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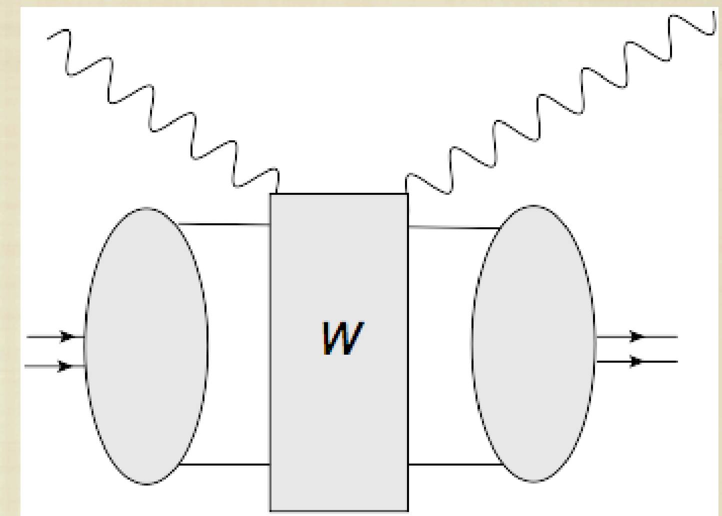

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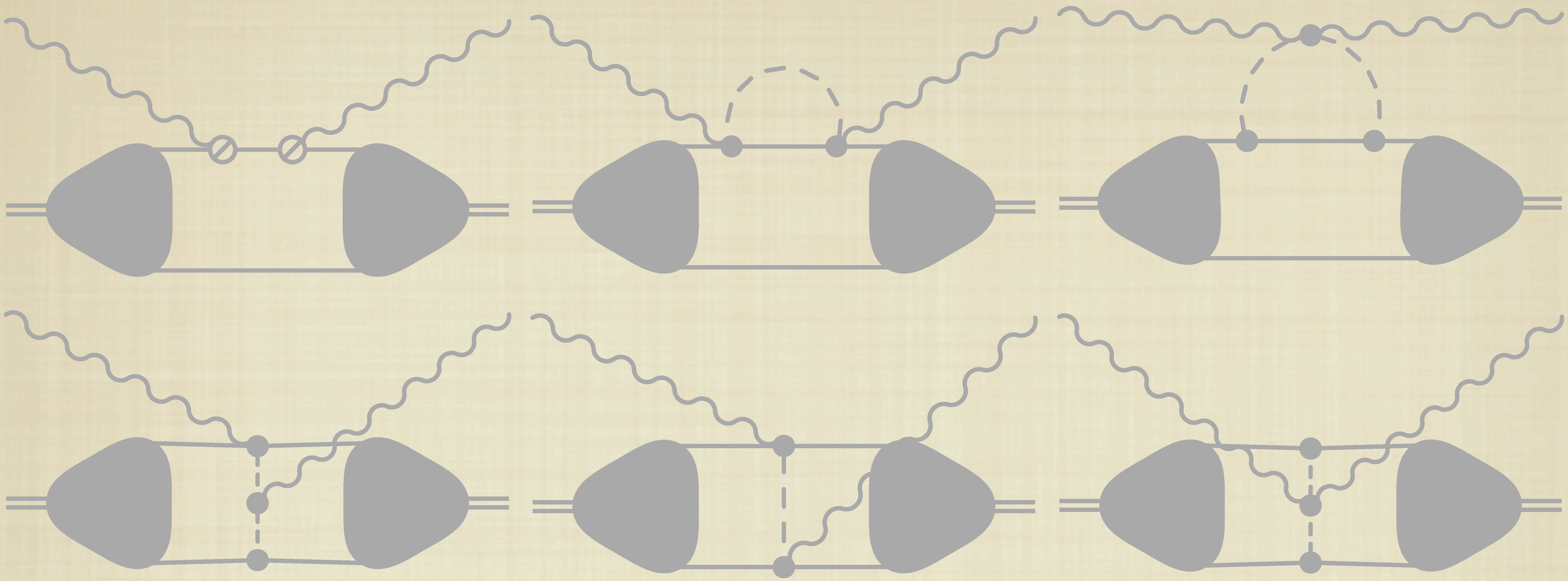
- Terms that maintain current conservation shifted to higher chiral order

γd scattering at $O(e^2P)$ [NLO]



Beane, Malheiro, DP, van Kolck, Nucl. Phys. A (1999)

- For $\omega \sim m_\pi$ only $W_{\mu\nu}$ contributes at this order
- Related to one-pion exchange by minimal substitution
- 50% of dcs at 80 MeV: related to polarizabilities

χET and γd: state-of-the-art

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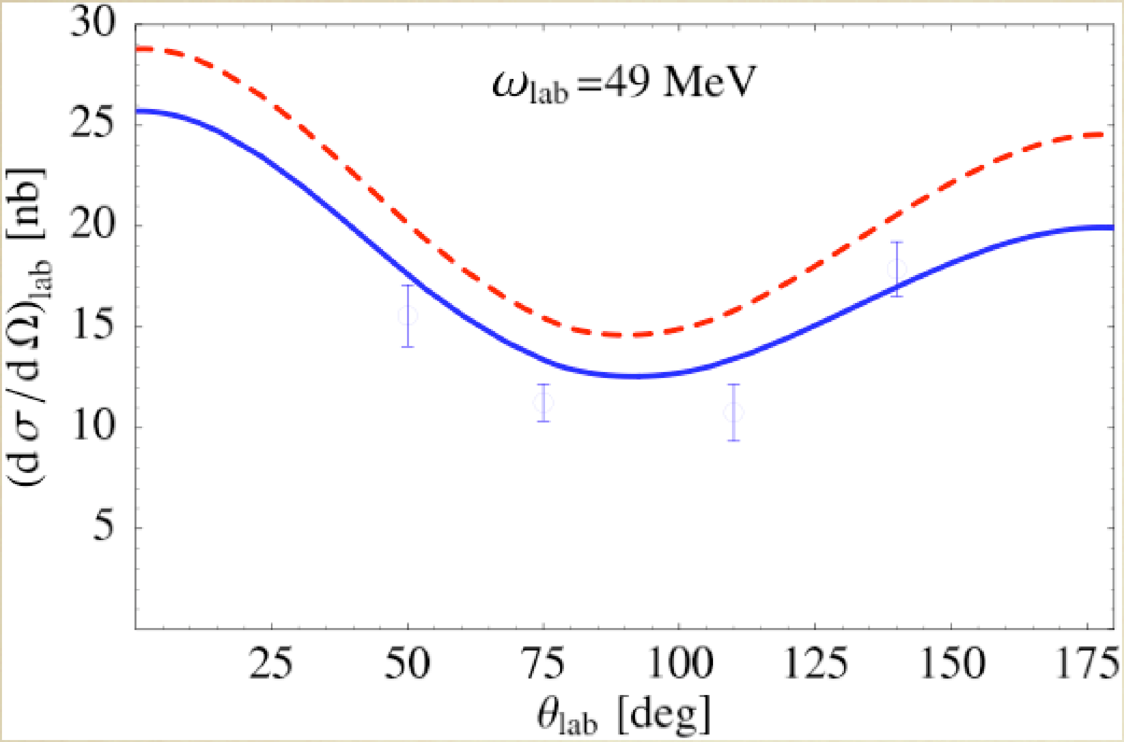
Harald Griesshammer, Talk at Chiral Dynamics 06



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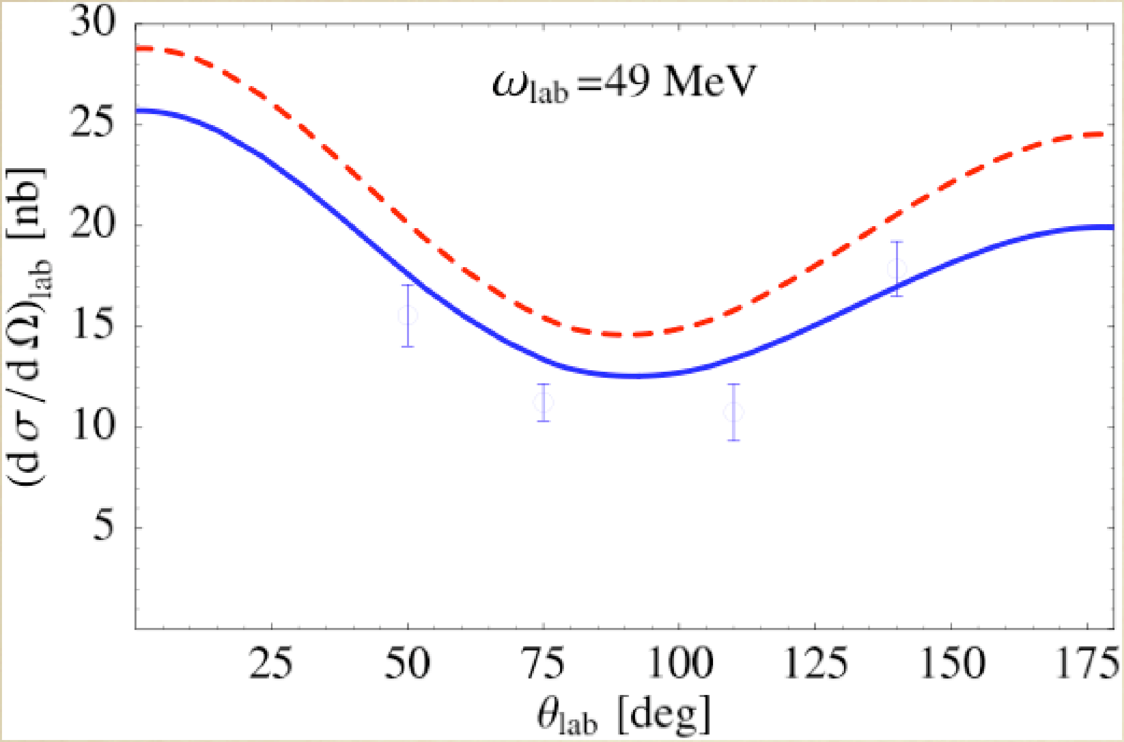

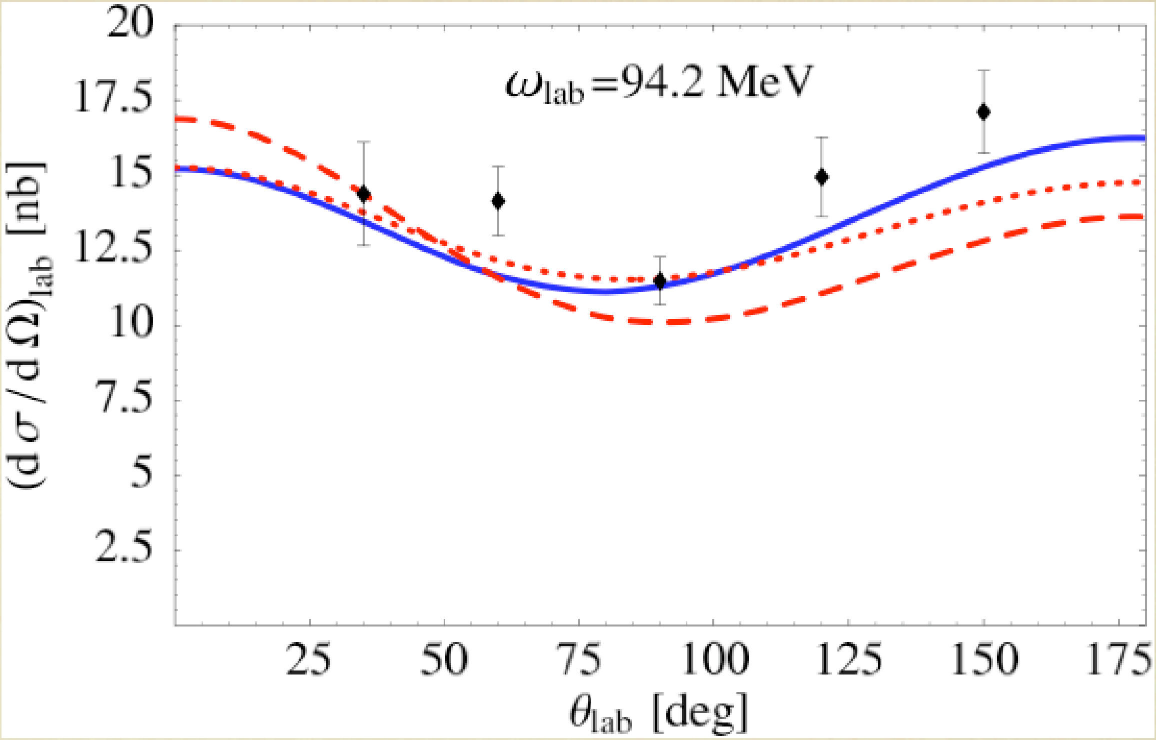

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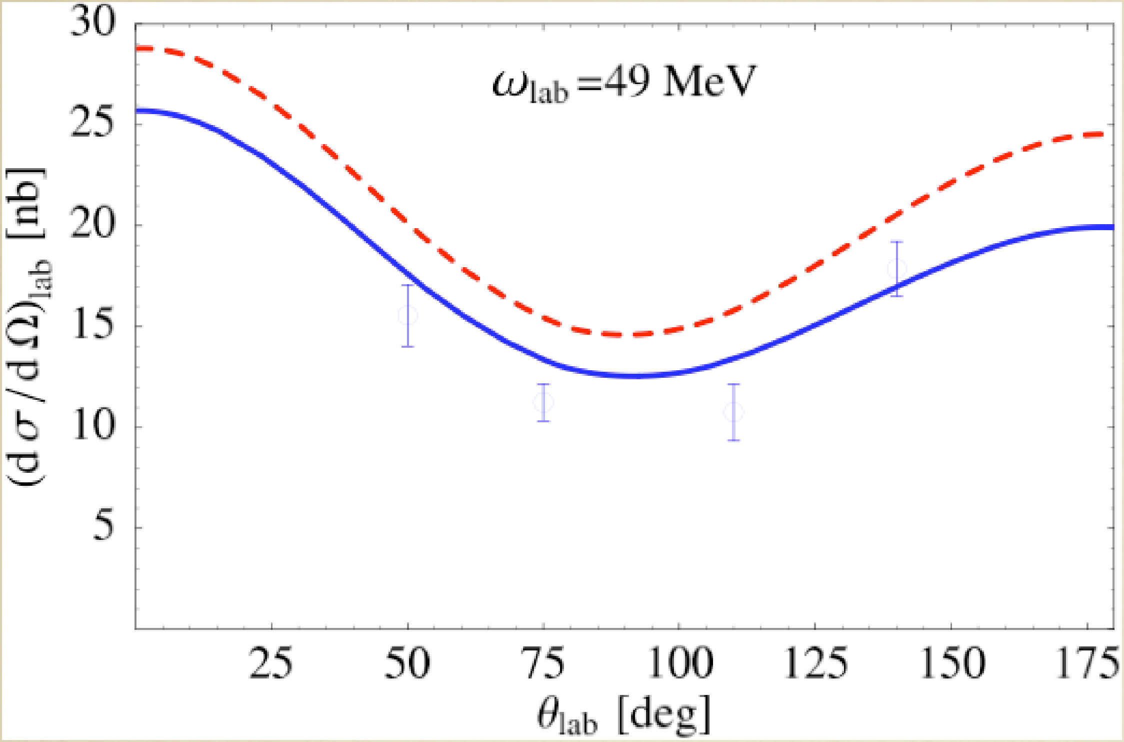

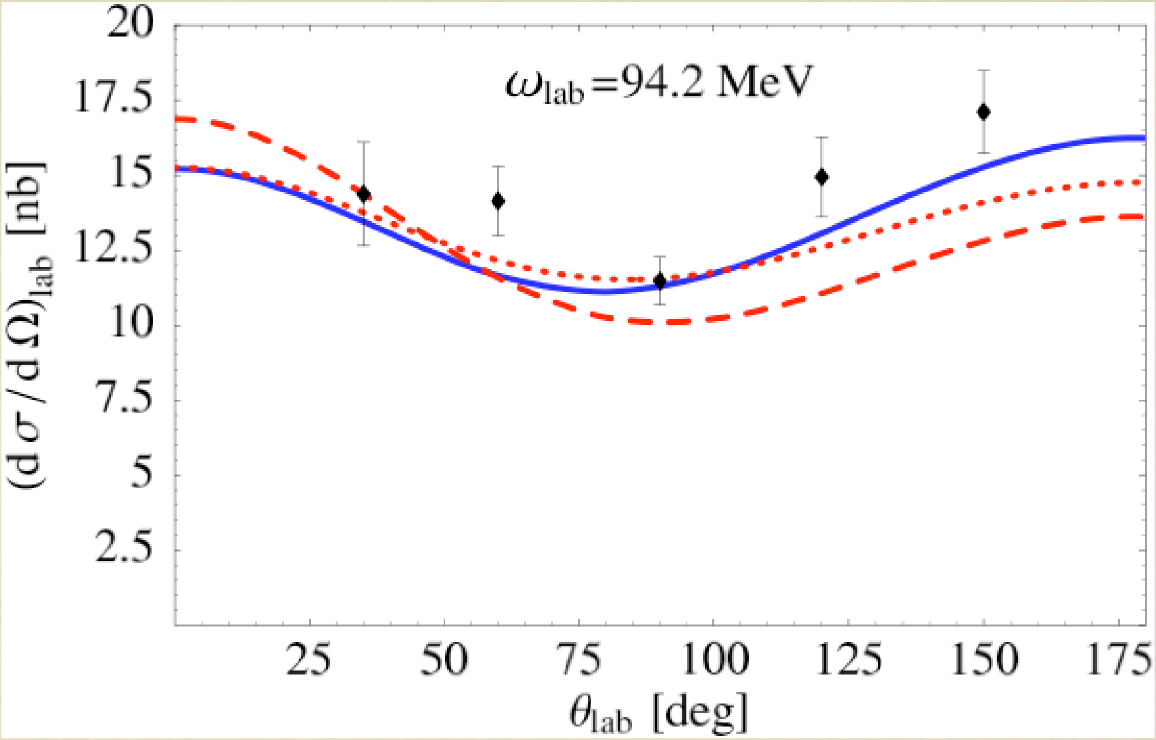

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- Need better data: Compton@MAX-Lab, HIγS

γ^3He scattering in χET

Choudhury-Shukla, Nogga, DP (2007, 2009)

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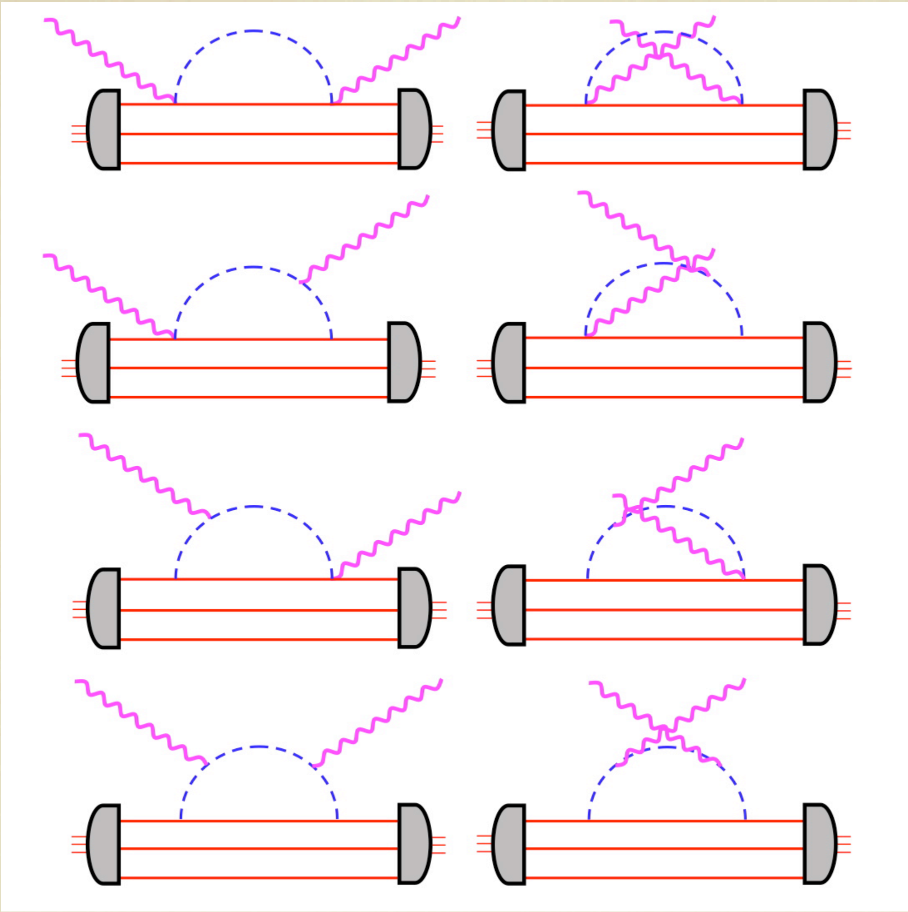

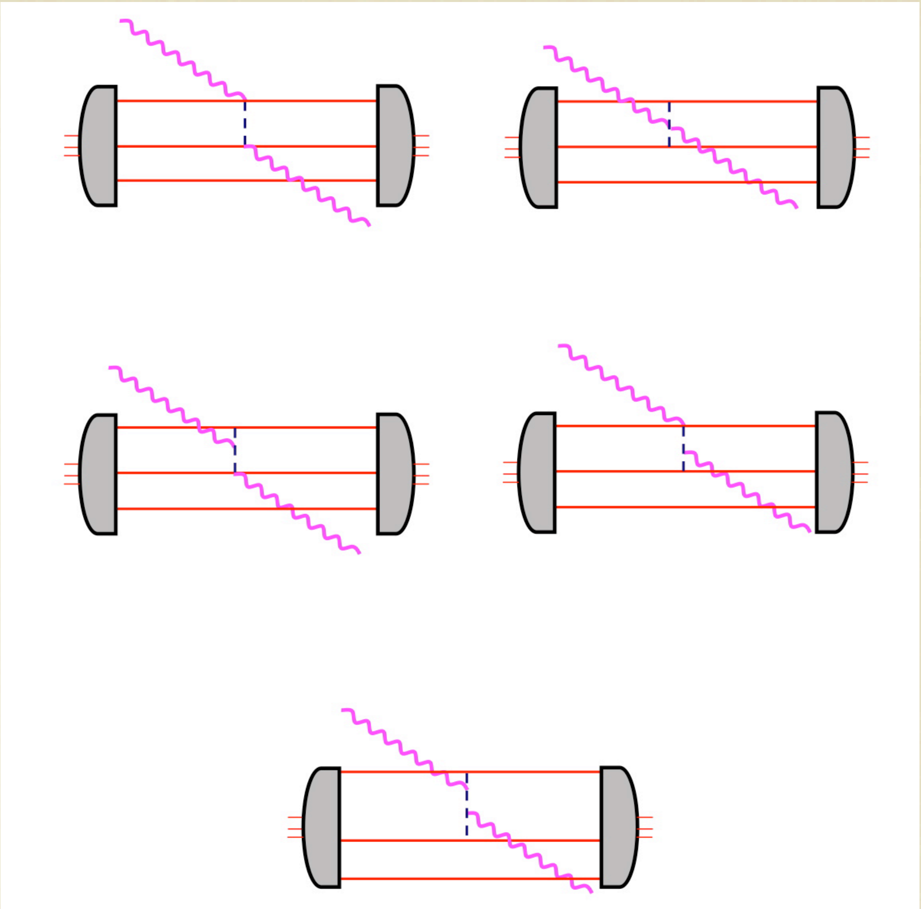

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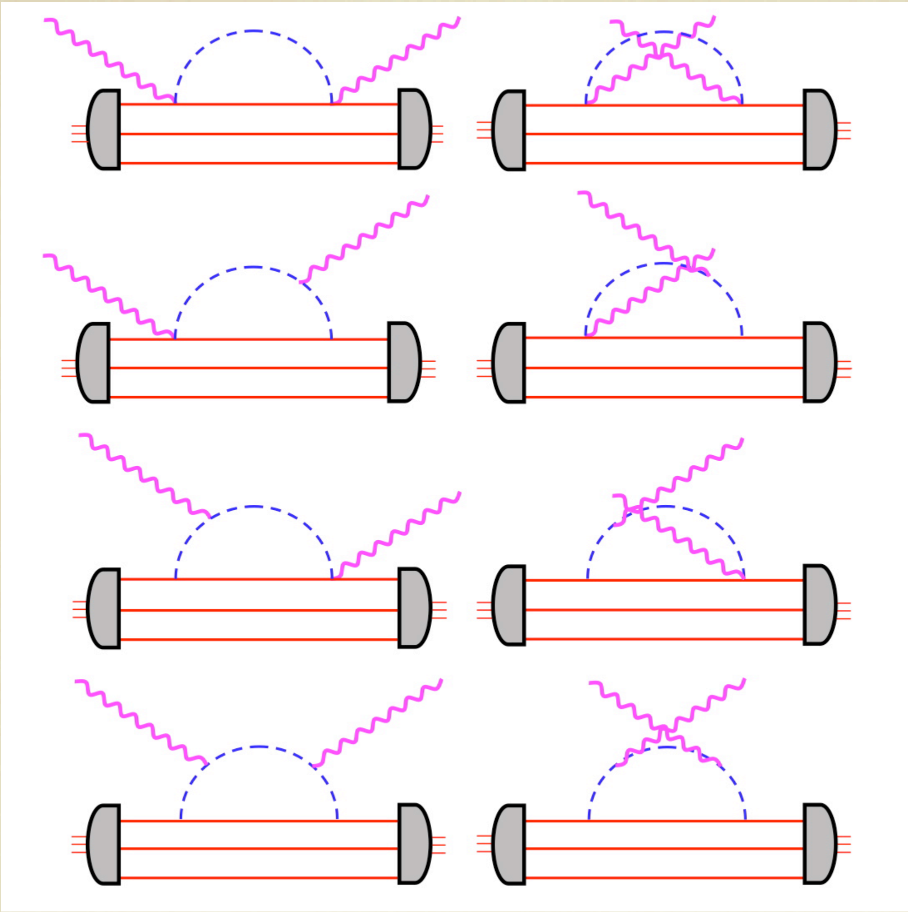

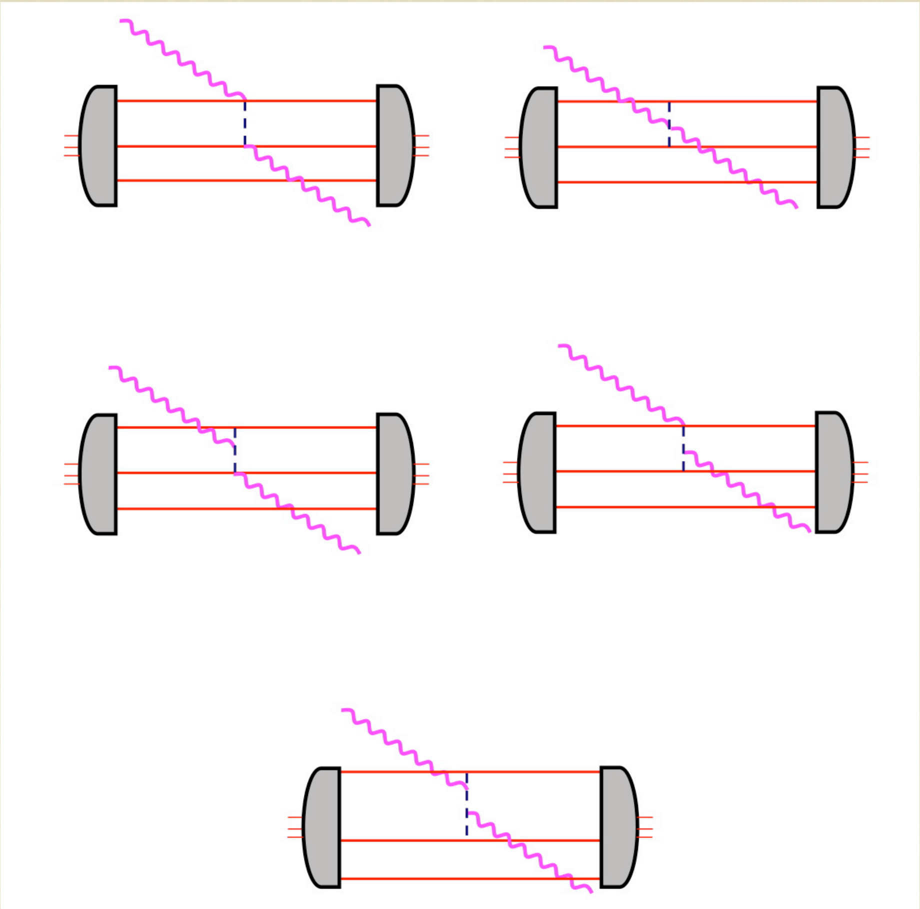

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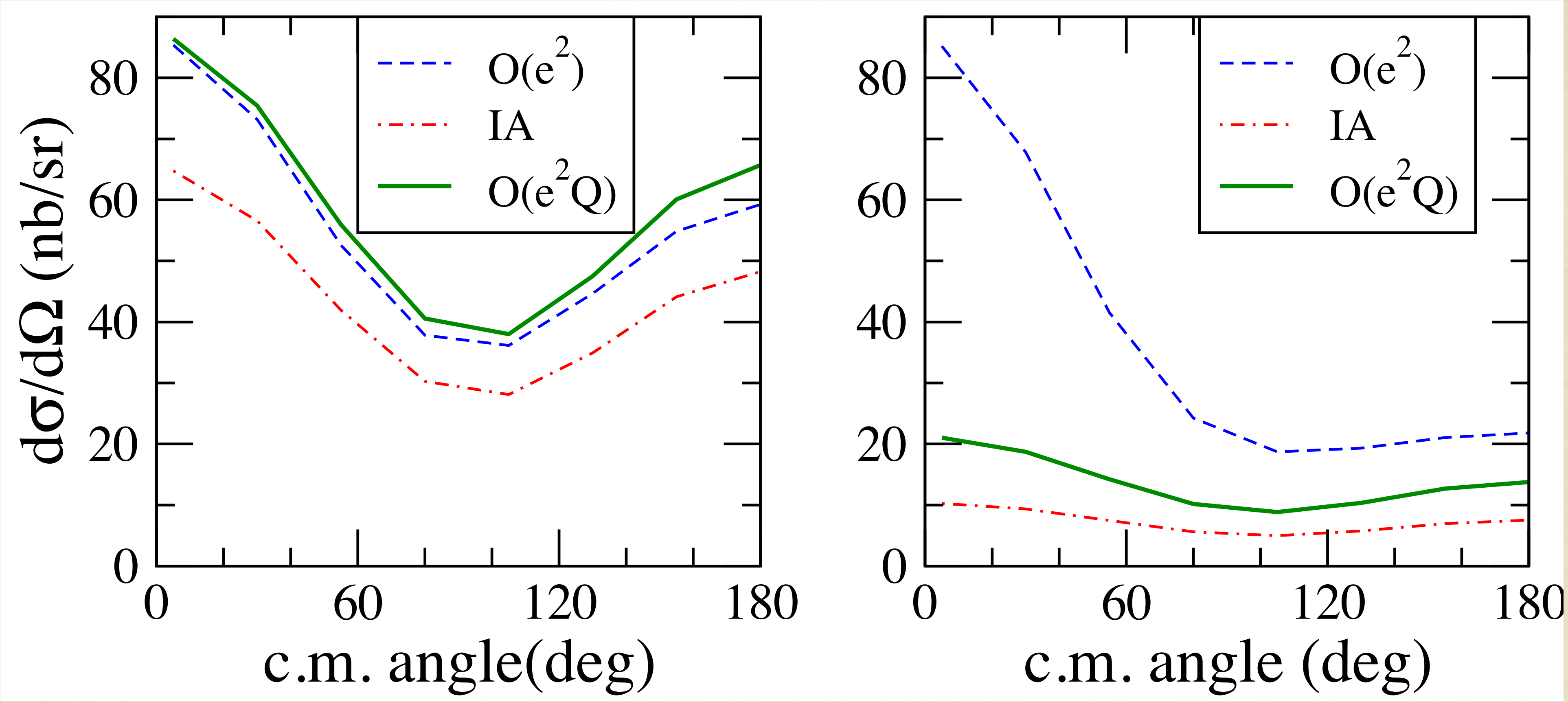

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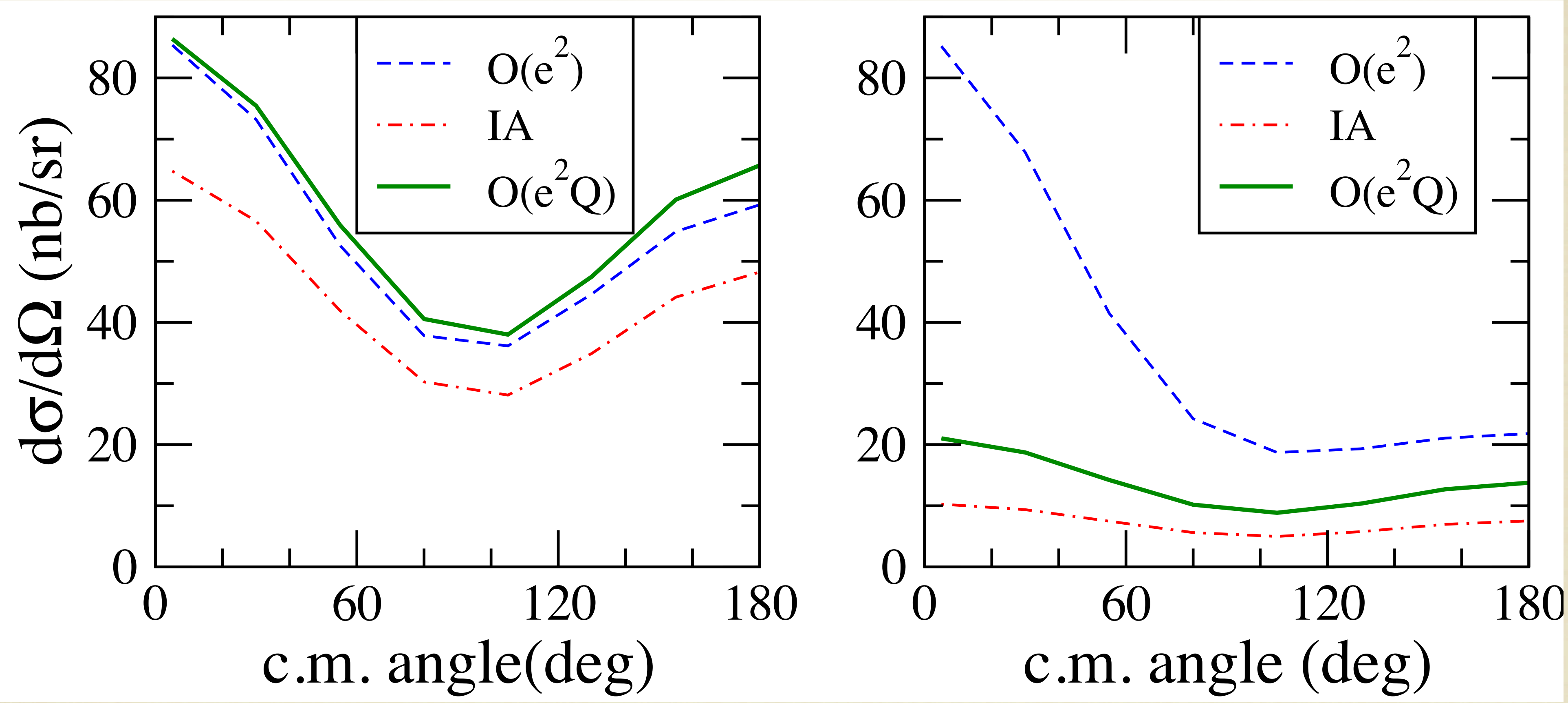

- $O(e^2P)$[NLO] calculation: same operator as in NN case
- Various χET ^{3}He wave functions of consistent order
- Successful extension of χET to A=3 EM observables

γ^3He scattering to extract $\alpha^{(n)}$, $\beta^{(n)}$, $\gamma^{(n)}$'s

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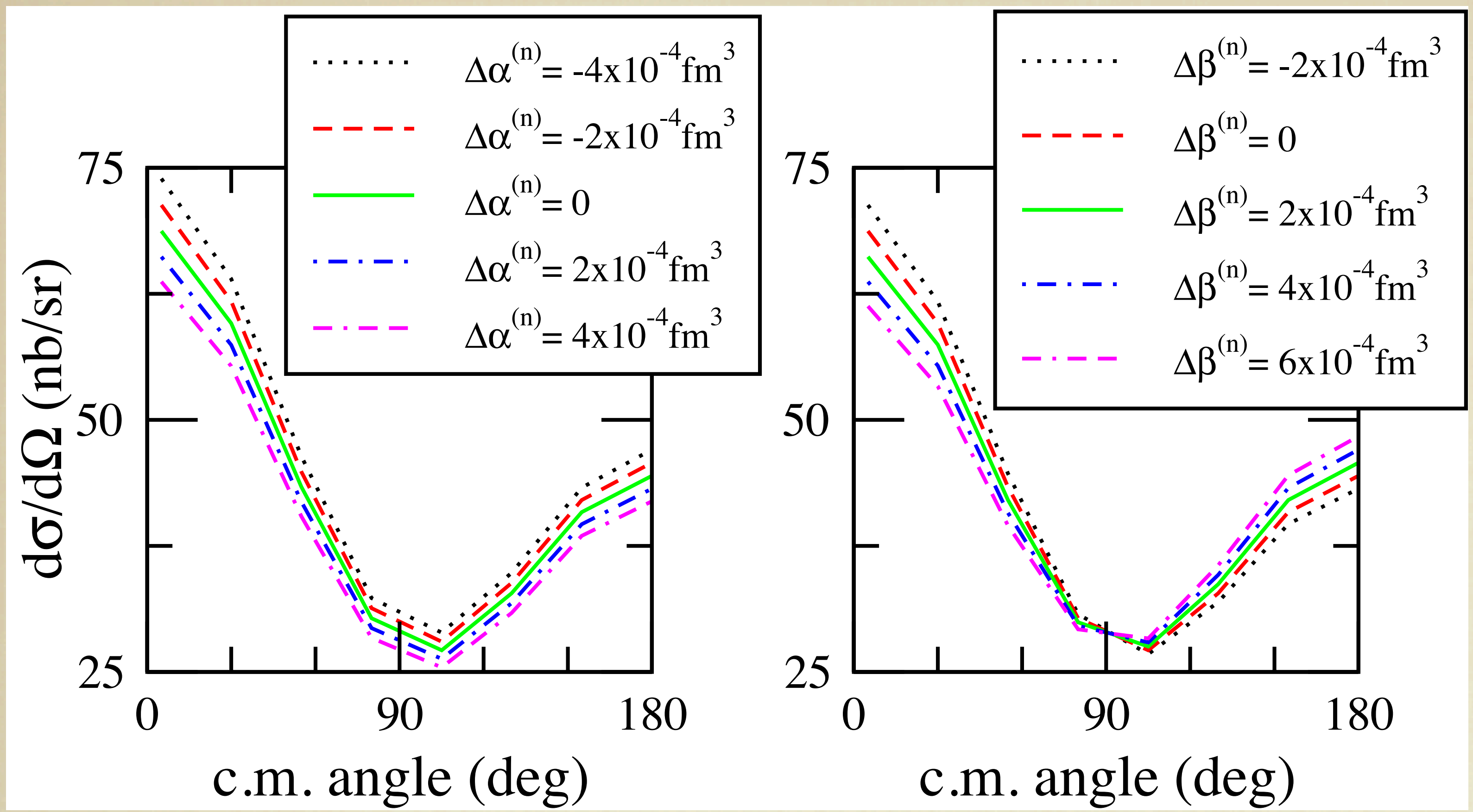

Measure neutron polarizabilities with larger dcs

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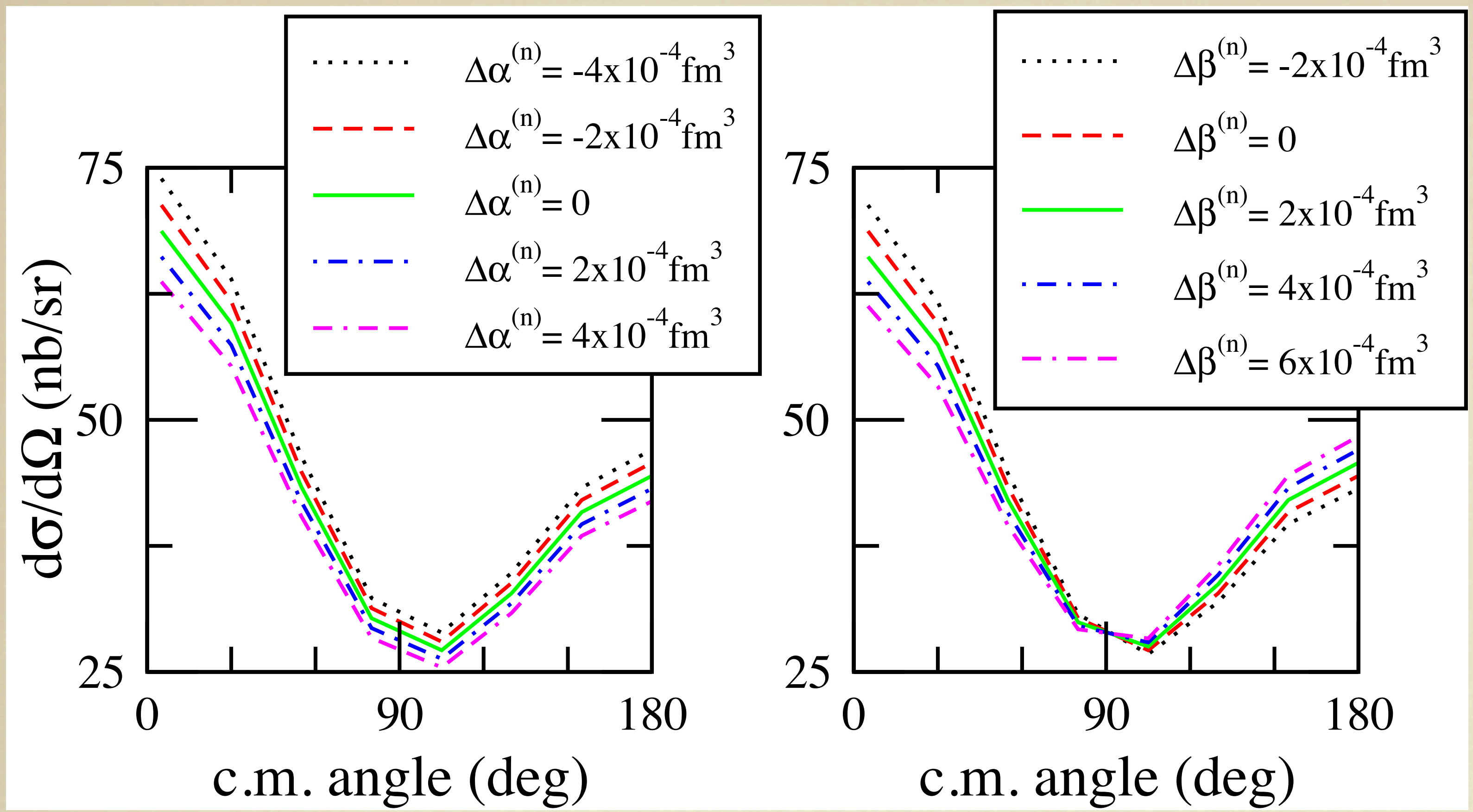

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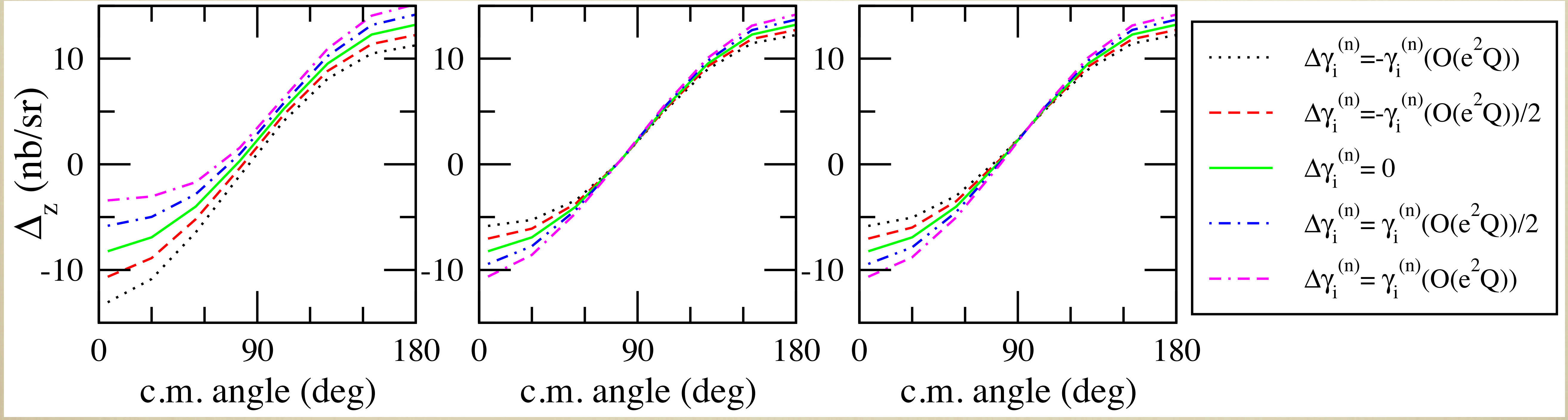

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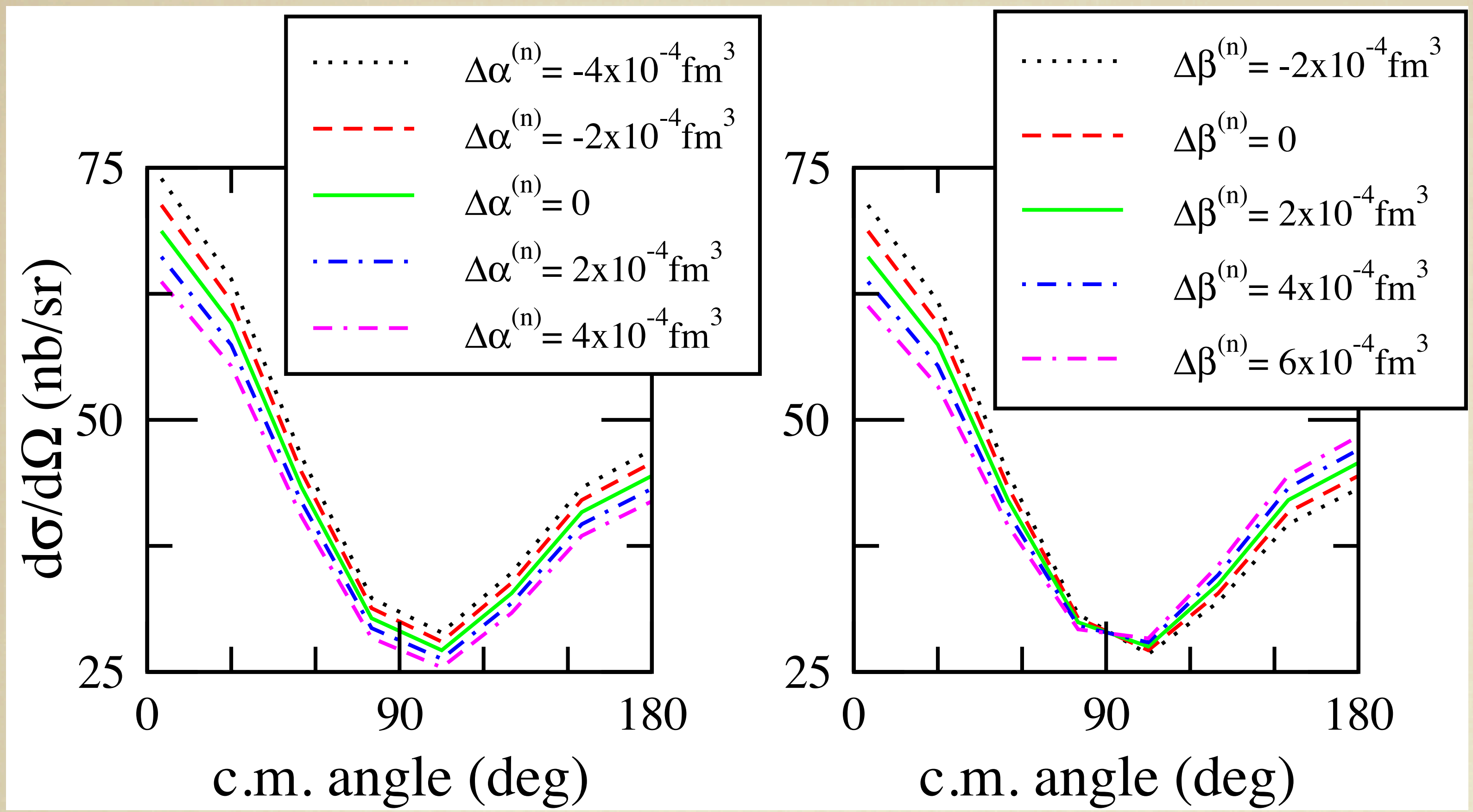

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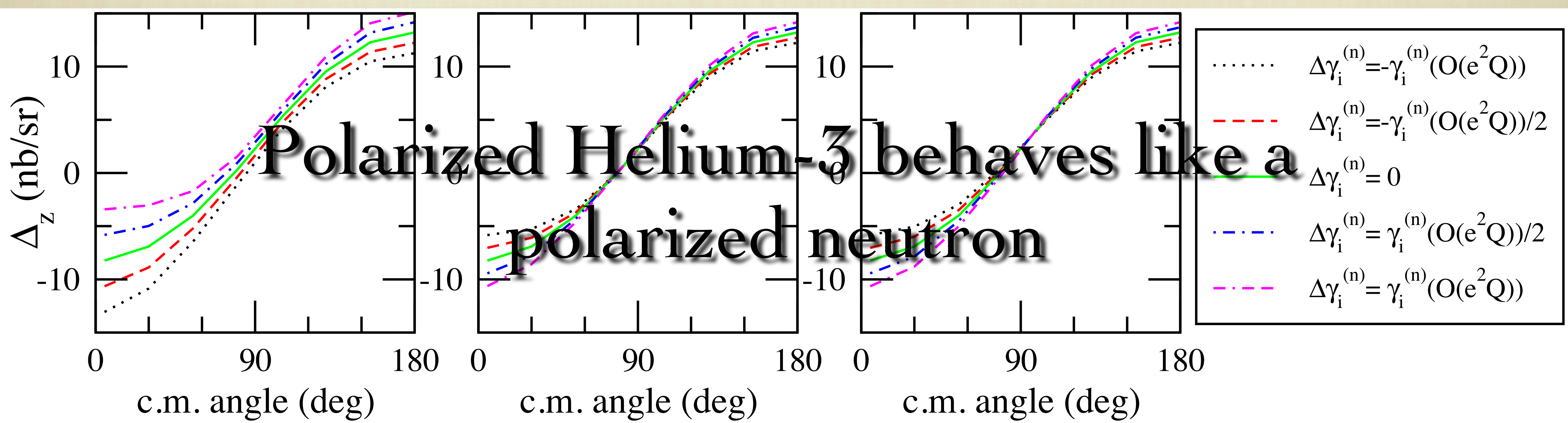

Polarized Helium-3 behaves like a polarized neutron

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- γd: O(e^2P^2) mechanisms⇒3% calculation of dcs
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- Breakup processes
- Data!

Compare A=2 & 3 extractions of polarizabilities (incl. spin plarizabilities)

A word on weak processes

Gazit (2008)

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- $\mu\,^3He \rightarrow \nu_\mu\,^3H$: Γ=1499(2)$_\Lambda$(3)$_{NM}(5)_t(6)_{RC}$ Hz;

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- Two-body Goldberger-Trieman relation relates c_D to tritium beta decay: $-0.3 \leq c_D \leq -0.1$

Gardestig and DP (2006); Gazit, Quaglioni, Navratil (2008)

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- Experimental landscape: HIGS, MAXLab, ???
- Interplay of long- and short-range dynamics systematically captured by χET
- This interplay is key to an accurate understanding of a variety of electroweak reactions in few-nucleon systems

Four bodies: neutron capture on ^{3}He

- Full FY calculation of threshold n-^{3}He interaction

	BE(^{3}H)	BE(^{3}He)	BE(^{4}He)	r_{He4}	P_D(^{4}He)	$a_{n\mathrm{He3}}$
Av18	7.623	6.925	24.23	1.516	13.8	$3.43 - 0.0082i$
I-N3LO	7.852	7.159	25.36	1.52	9.30	$3.56 - 0.0070i$
INOY	8.483	7.720	29.08	1.377	5.95	$3.26 - 0.0058i$
Av18+UIX	8.483	7.753	28.47	1.431	16.0	$3.23 - 0.0054i$
I-N3LO+UIX*	8.482	7.737	28.12	1.475	10.9	$3.44 - 0.0055i$
Exp.:	8.482	7.718	28.30	1.475(6)		$3.278(53) - 0.001(2)i$

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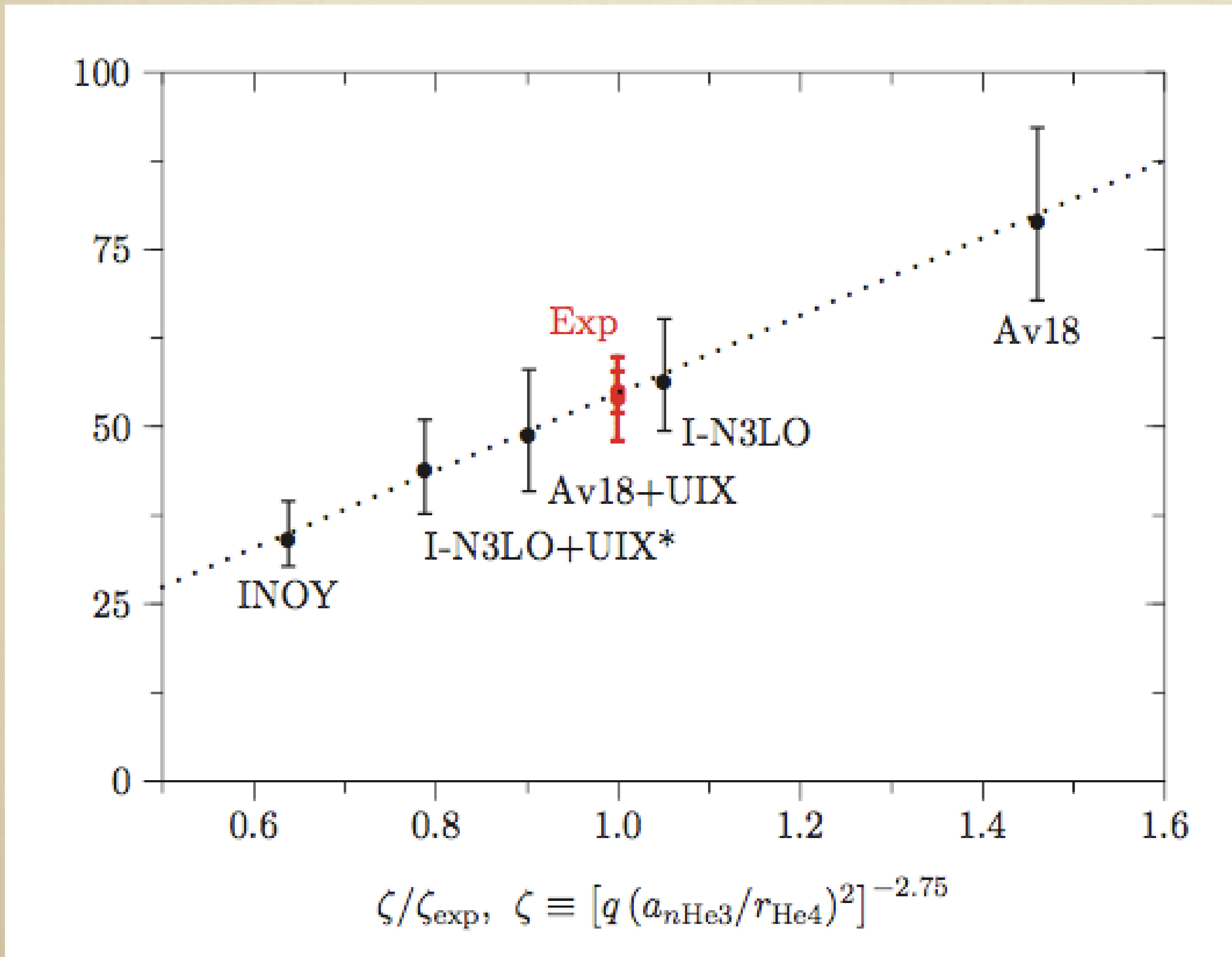

Electron-deuteron observables

$$G_C = \frac{1}{3|e|}\left(\langle 1\,|J^0|\,1\rangle + \langle 0\,|J^0|\,0\rangle + \langle -1\,|J^0|-1\rangle\right),$$

$$G_Q = \frac{1}{2|e|\eta M_d^2}\left(\langle 0\,|J^0|\,0\rangle - \langle 1\,|J^0|\,1\rangle\right)$$

THEORY

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$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Mott}}\left[A(Q^2) + B(Q^2)\tan^2\left(\frac{\theta_e}{2}\right)\right]; \qquad T_{20}(Q^2;\theta_e)$$

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$$A = G_C^2 + \frac{2}{3}\eta G_M^2 + \frac{8}{9}\eta^2 M_d^4 G_Q^2,$$

$$B = \frac{4}{3}\eta(1+\eta)G_M^2,$$

$$T_{20} = -\frac{1}{\sqrt{2}}\frac{1}{A(Q^2)+B(Q^2)\tan^2\left(\frac{\theta_e}{2}\right)}\left[\frac{8}{3}\eta G_C(Q^2)G_Q(Q^2) + \frac{8}{9}\eta^2 G_Q^2(Q^2) + \frac{1}{3}\eta\left\{1+2(1+\eta)\tan^2\left(\frac{\theta_e}{2}\right)\right\}G_M^2(Q^2)\right].$$

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Recent experiments; strategy

PRELIMINARY

IN PROGRESS

Recent experiments; strategy

- JLab Hall A: $A(Q^2)$ Q^2=0.7-6 GeV^2, $B(Q^2)$=?
- JLab Hall C: $T_{20}(Q^2)$, $A(Q^2)$ Q^2=0.66-1.8 GeV^2
- Novosibirsk: $T_{20}(Q^2)$ Q^2=0.32-0.84 GeV^2
- BLAST: $T_{20}(Q^2)$ Q^2=0.137-0.667 GeV^2 PRELIMINARY
- JLab Hall A: $A(Q^2)$=0.04-0.64 GeV^2 IN PROGRESS

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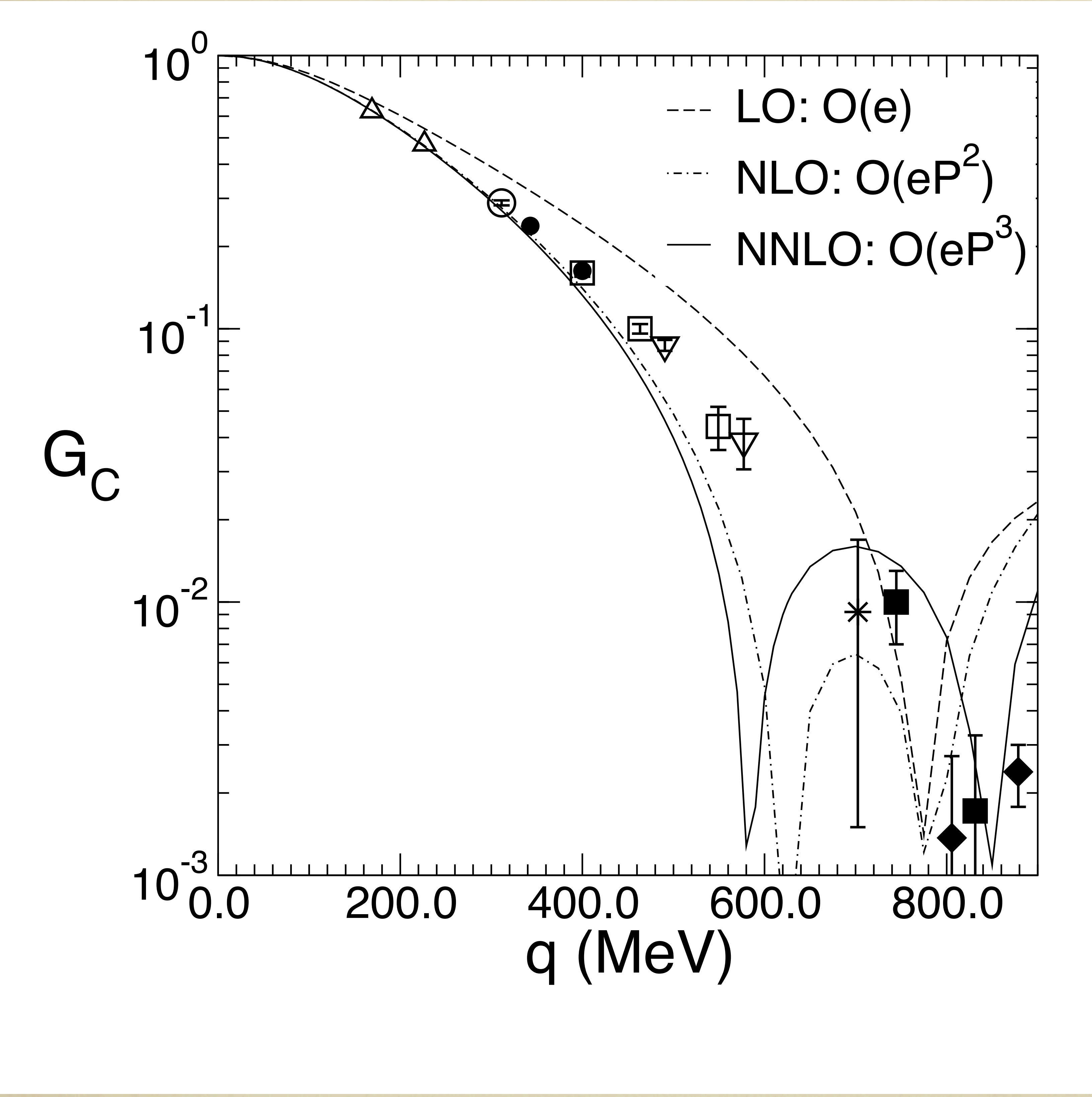
STRATEGY

- B gives G_M
- T_{20} gives G_C/G_Q; A yields $G_C^2 + G_Q^2$

Abbott et al., Eur. Phys. J. A47, 421 (2000) up to Q^2=1.4 GeV^2

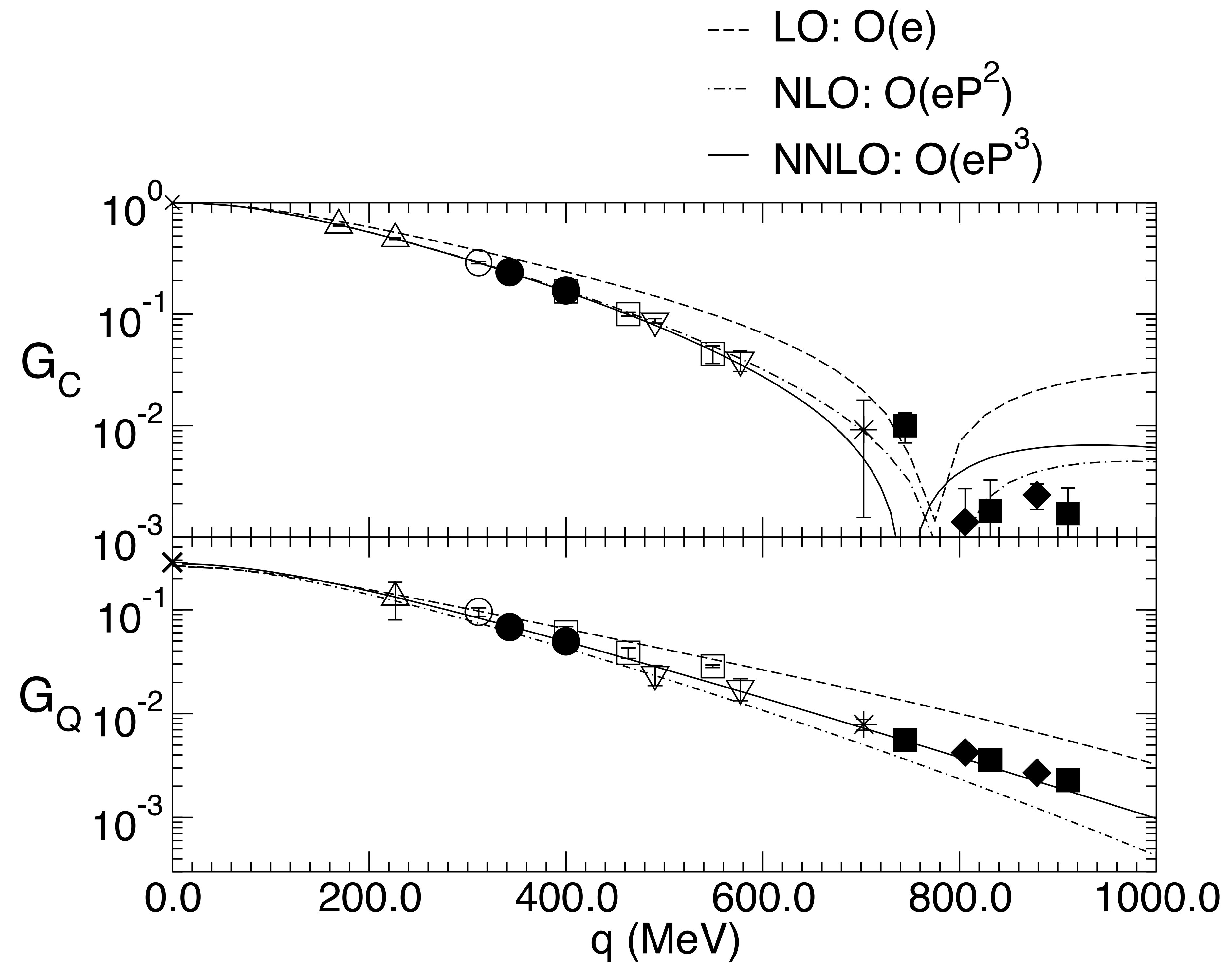
G_c and factorization

DP (2003)



- "Direct" χET prediction fails
- Failure to describe **nucleon** structure
- G_c/G_E has good chiral expansion
- Test predictions for deuteron

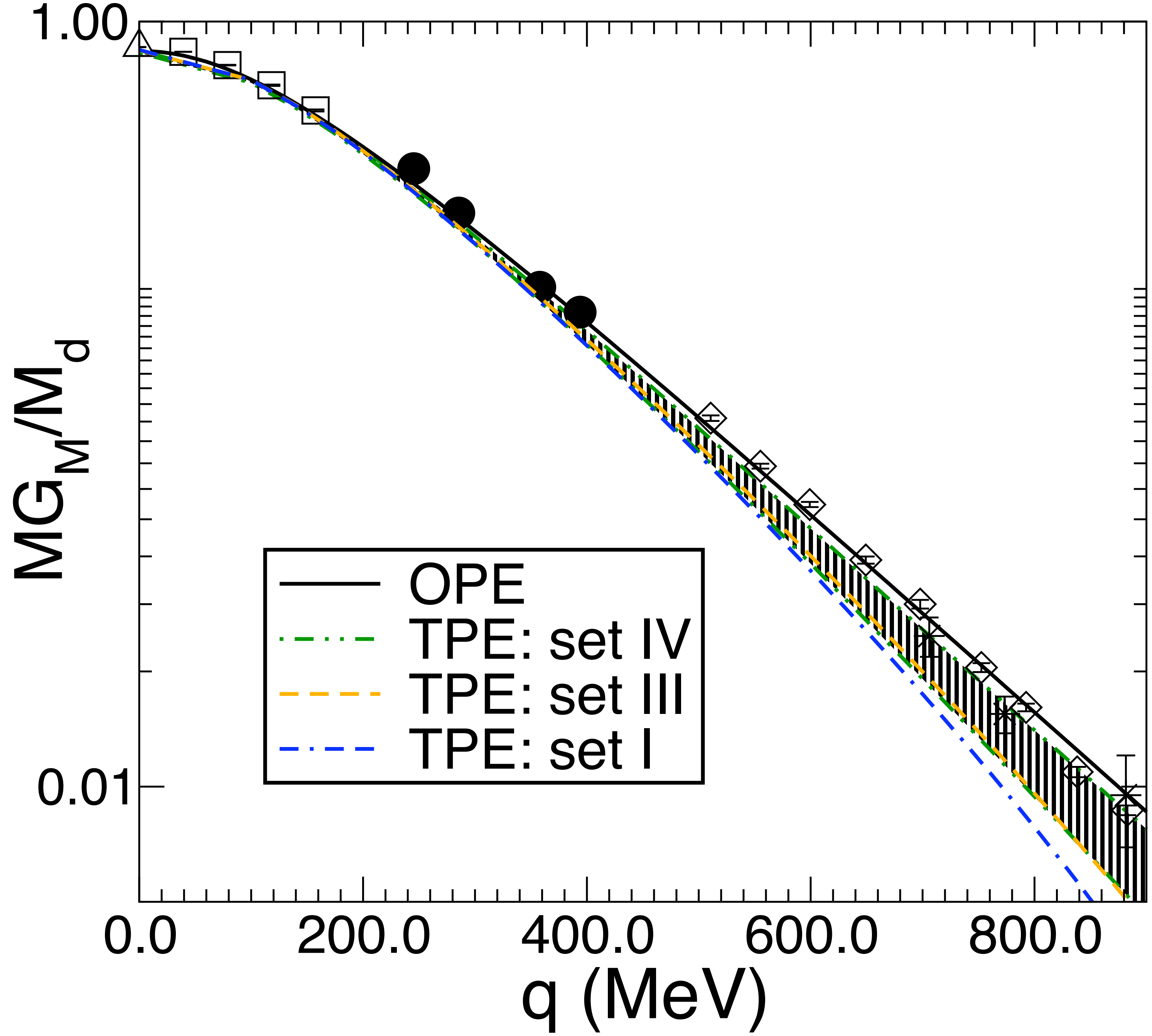
Results for form factors



- $O(P^2)$ ChiPT wf, Λ=600 MeV
- Factorization
- Good J_0 convergence
- G_M breaks down earlier

DP, Phys. Lett. B567, 12 (2003)

Results for G_M



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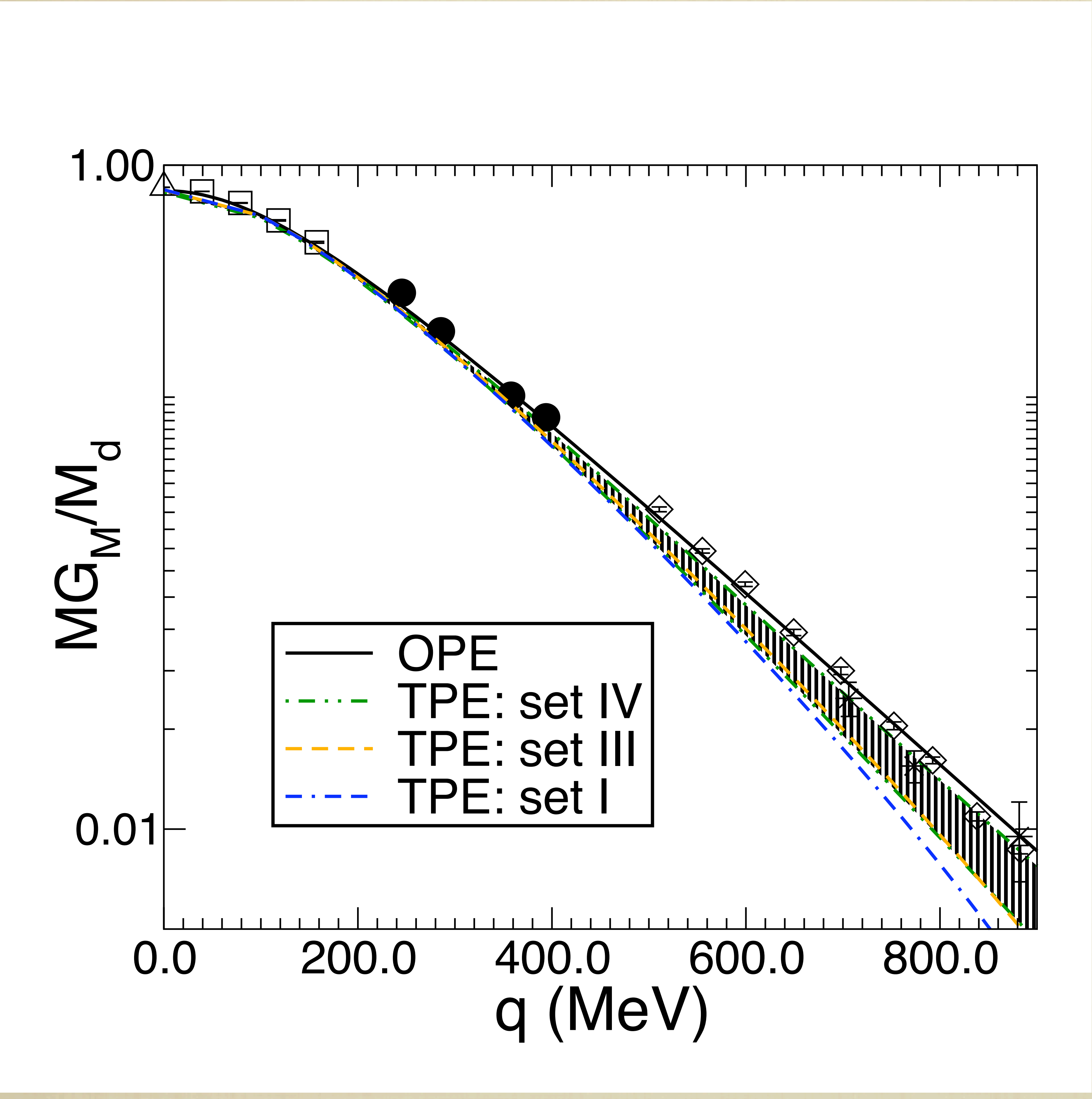

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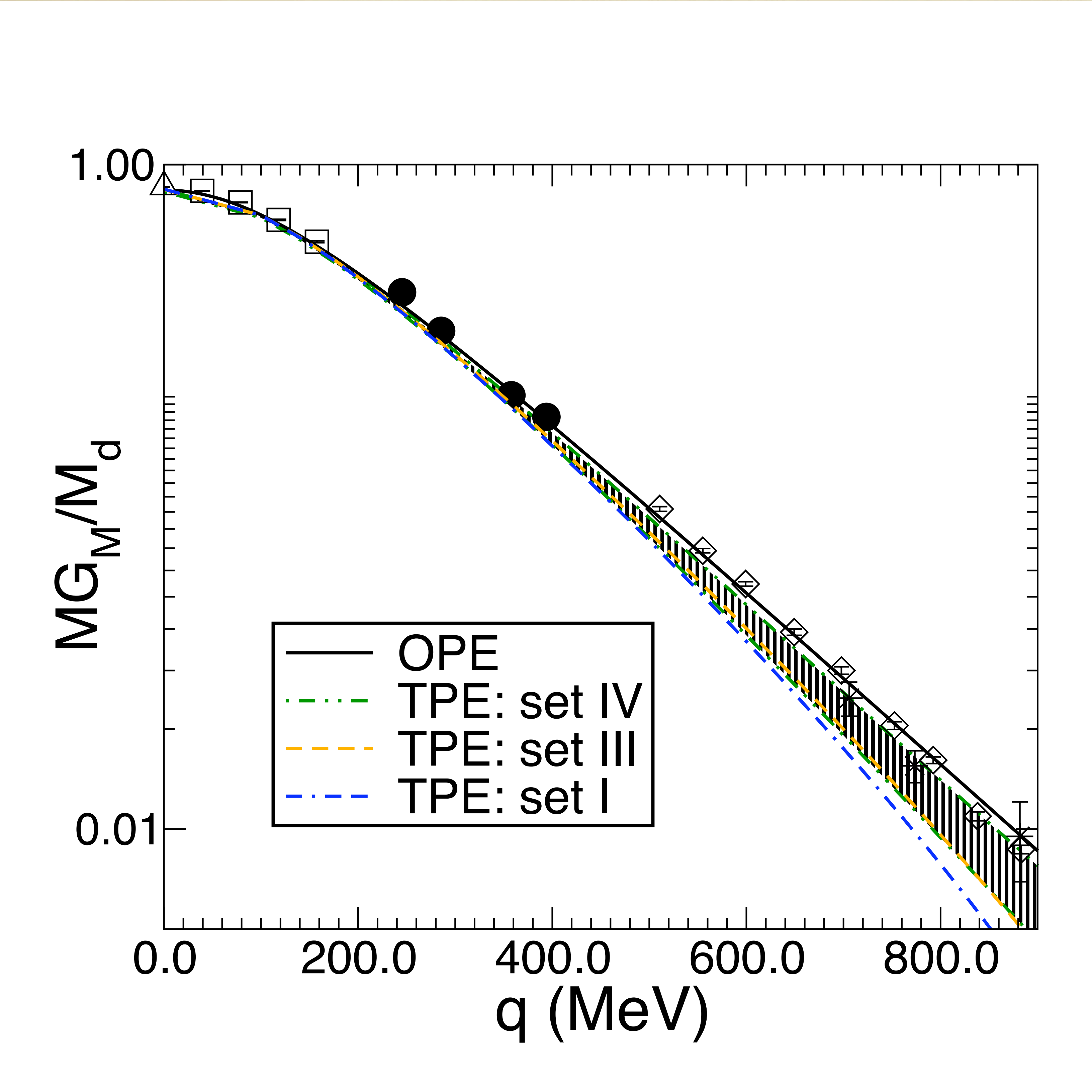

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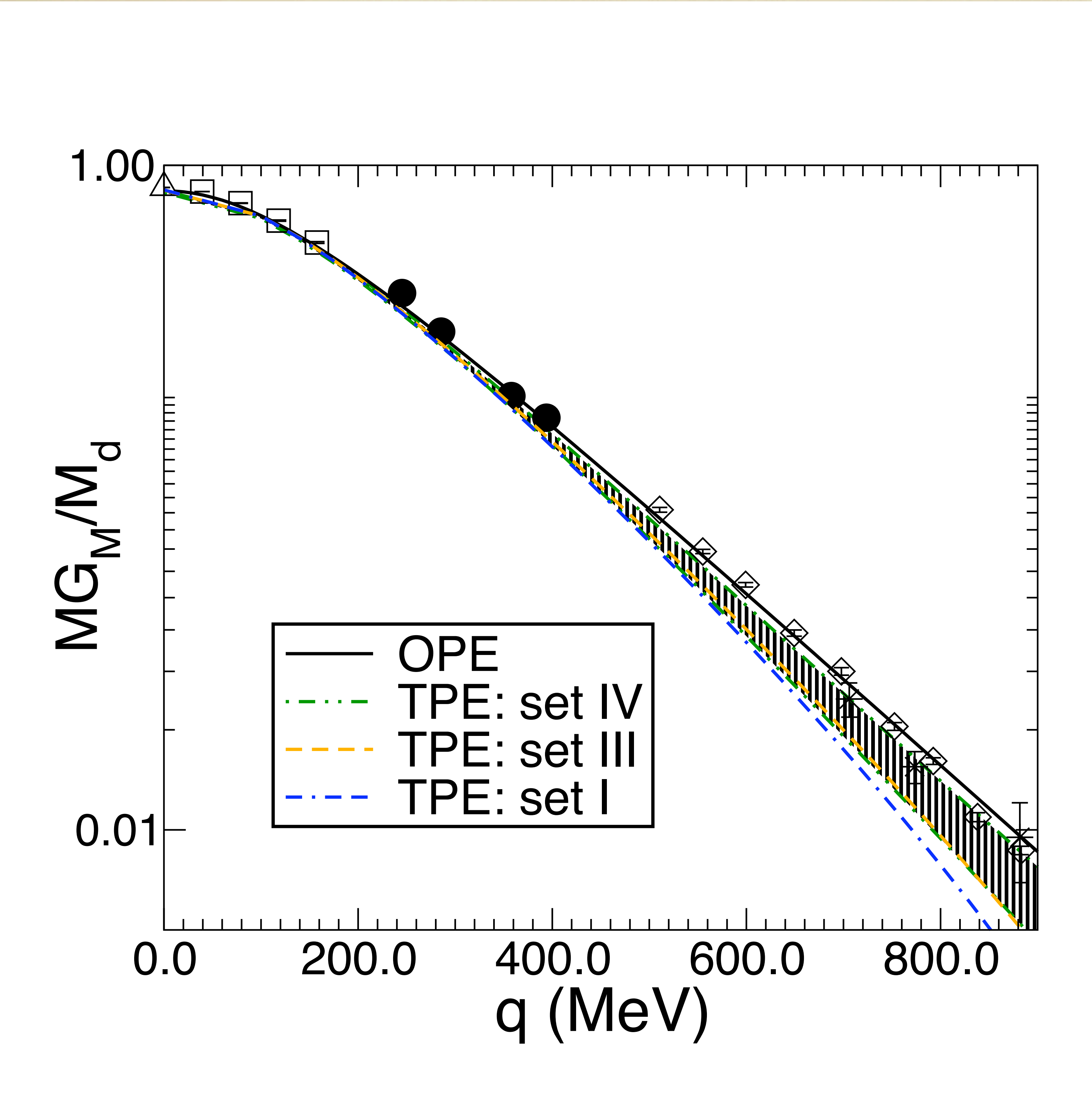

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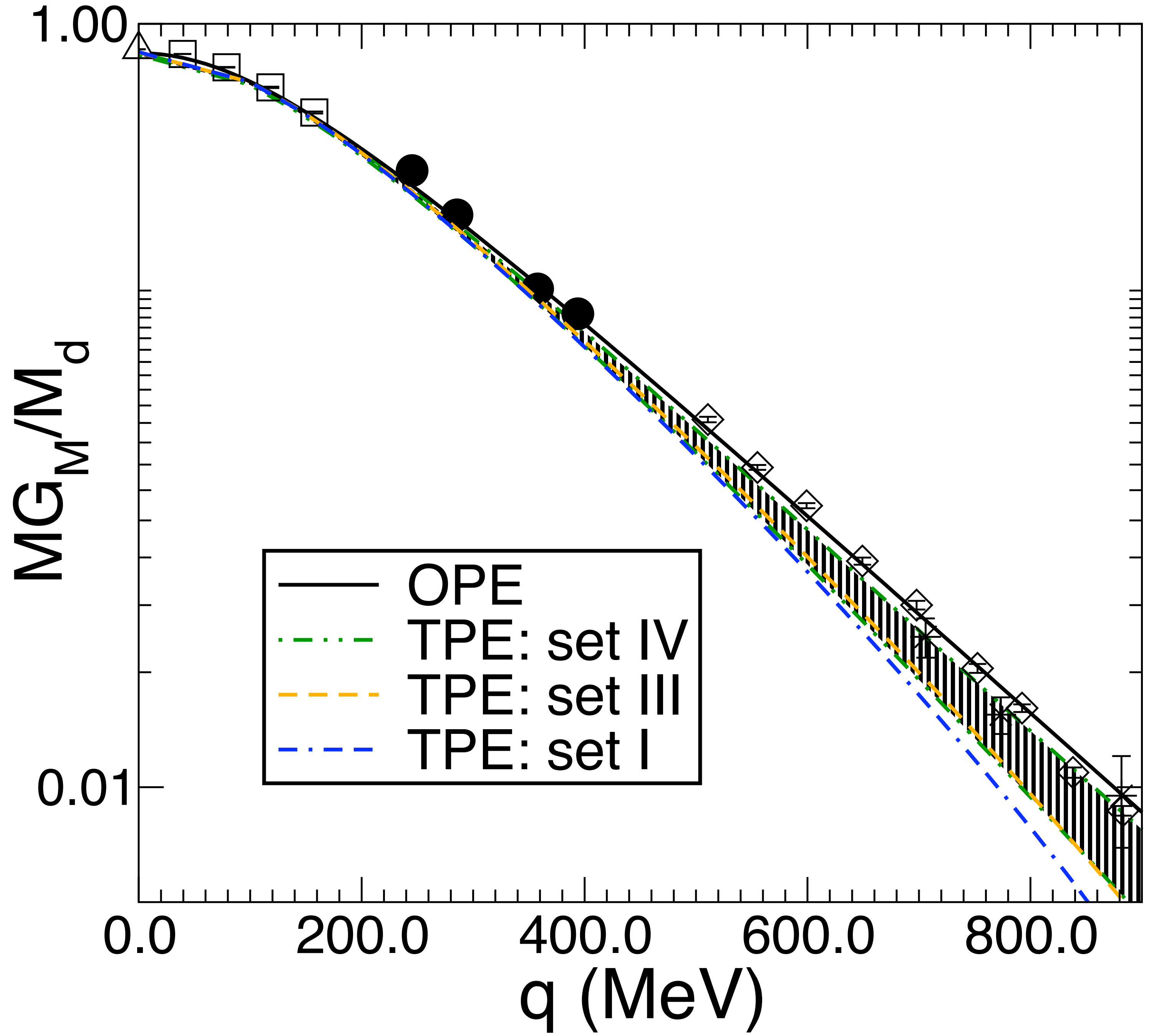

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- Counterterm at $O(eP^4)$
- Shifts possibly perturbative at q<600 MeV

Static properties and renormalization

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	Expt.	NNLO	Nijm93
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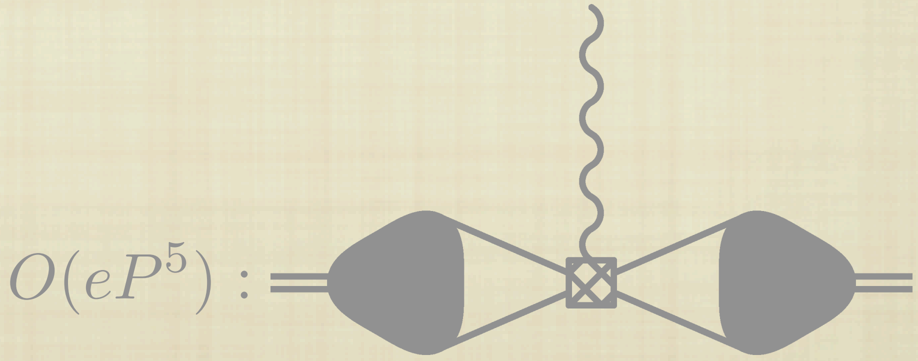

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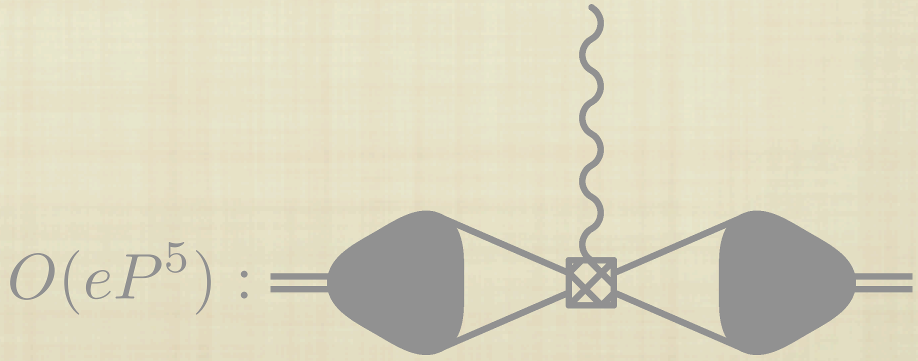

$\Delta Q_d = 0.004\ fm^2 \Rightarrow \Lambda_Q = 1.4$ GeV

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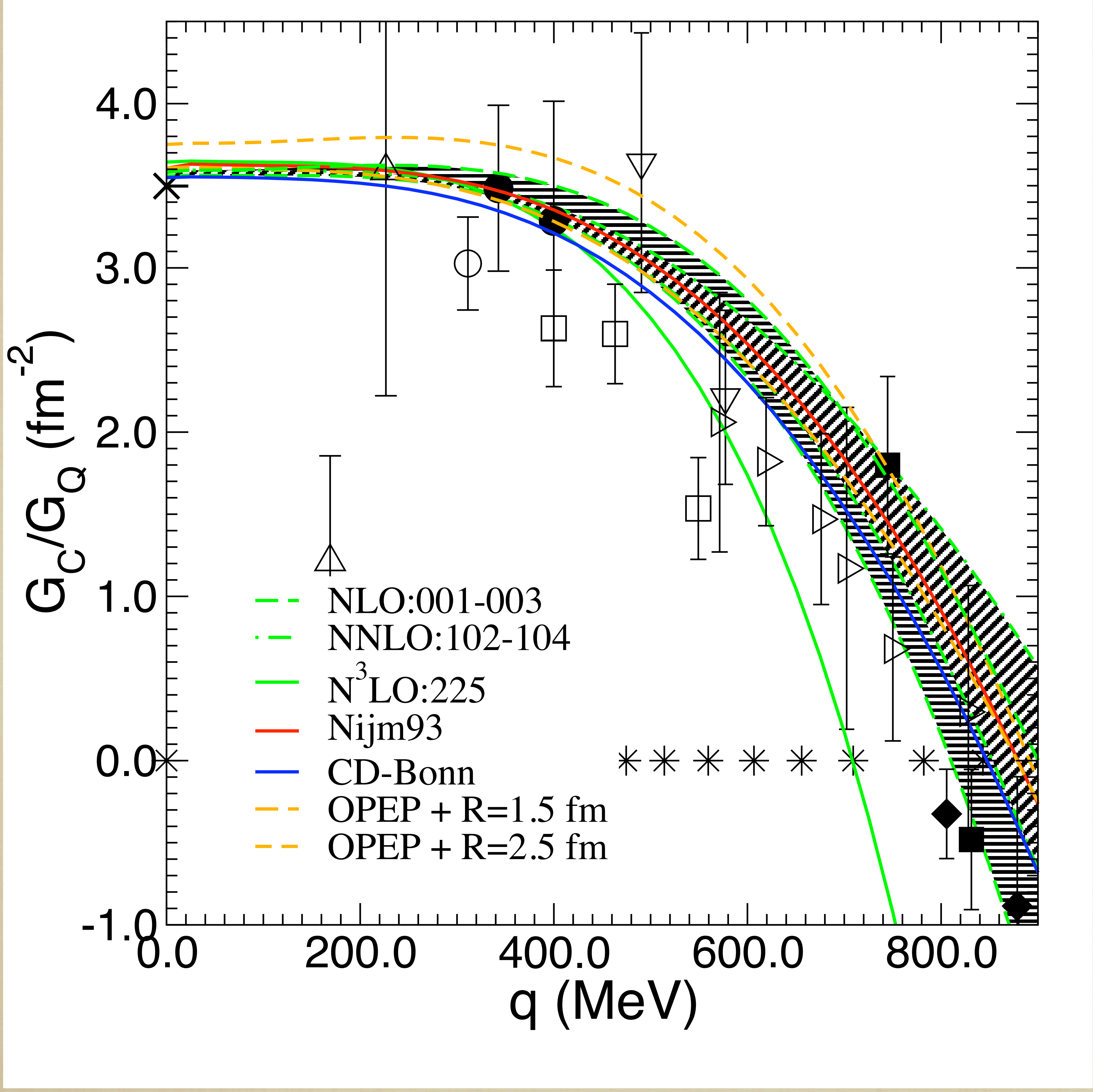
χET for G_C/G_Q at NNLO



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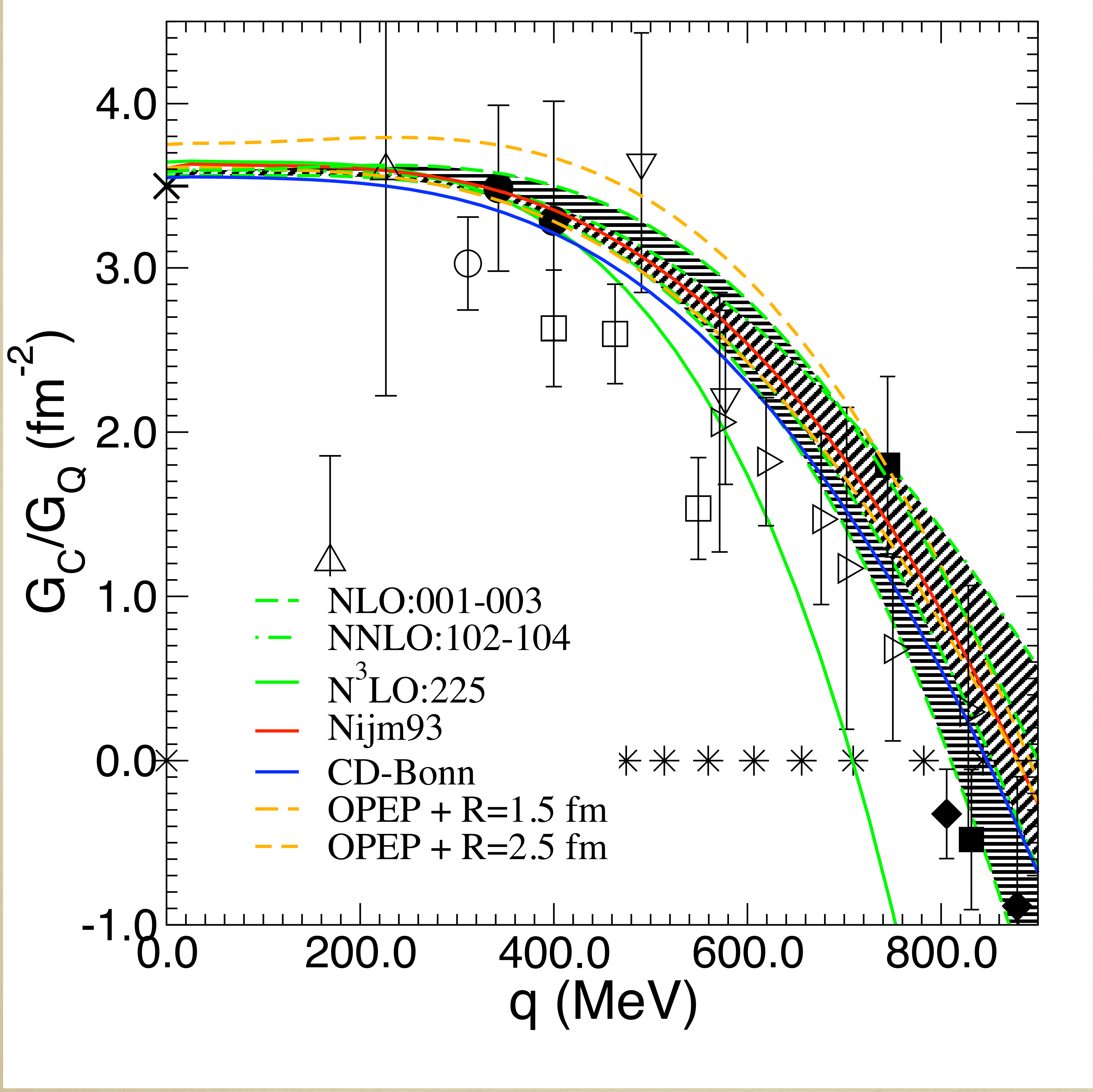

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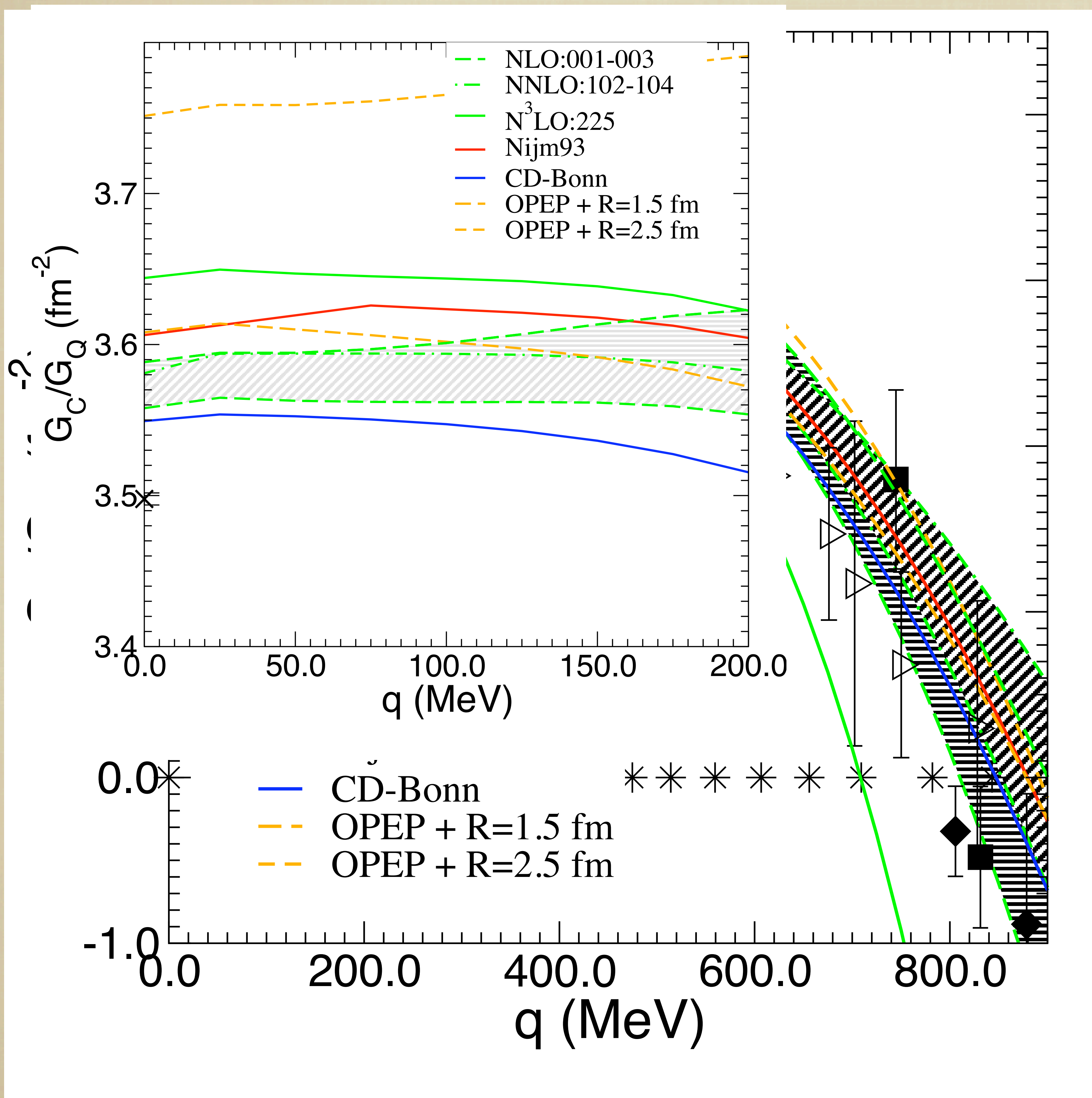

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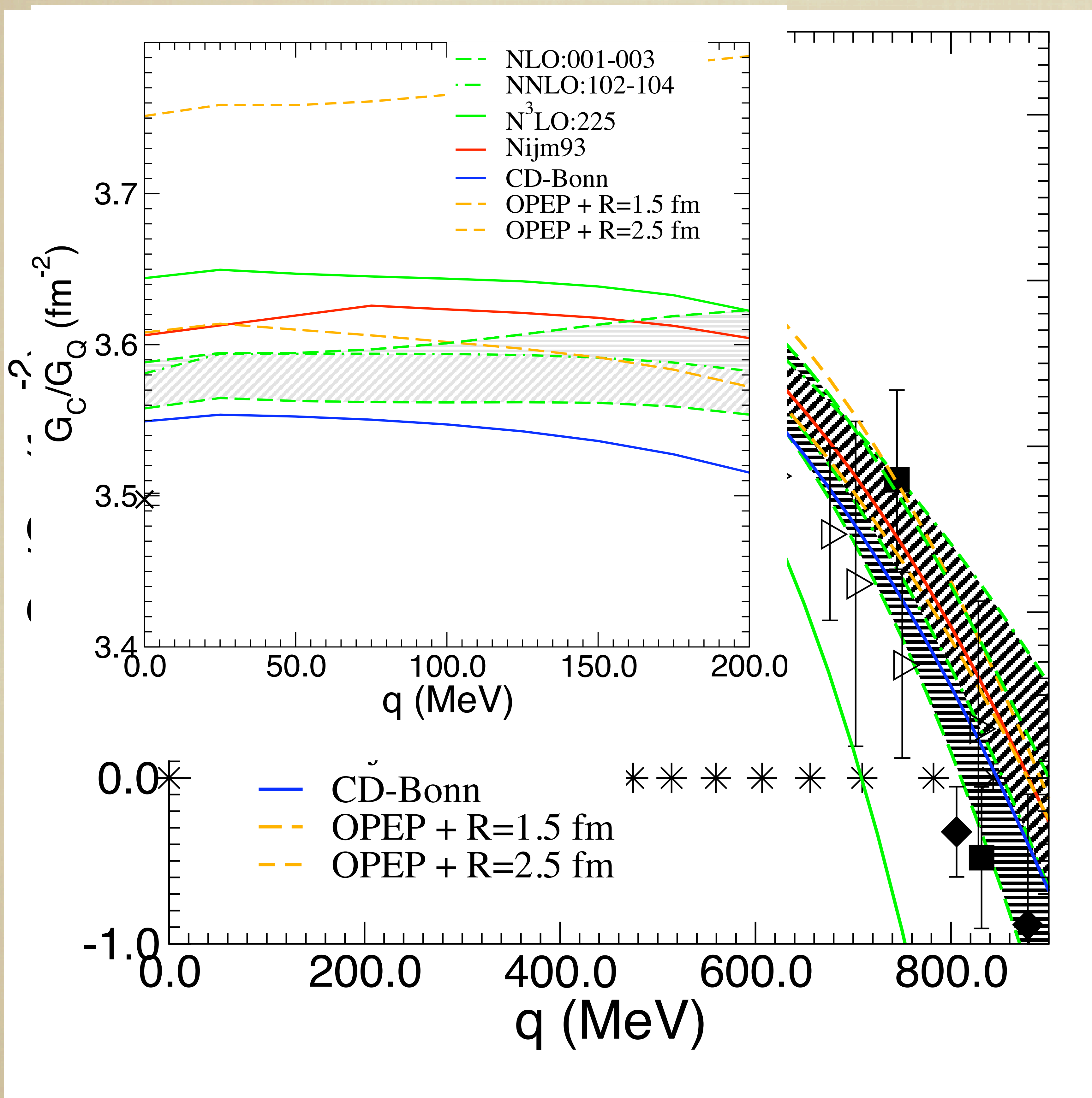

- Nucleon structure cancels out
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- Variation in value of Q_d associated with physics at $r \sim 1/\Lambda$.

Nucleon Polarizabilities

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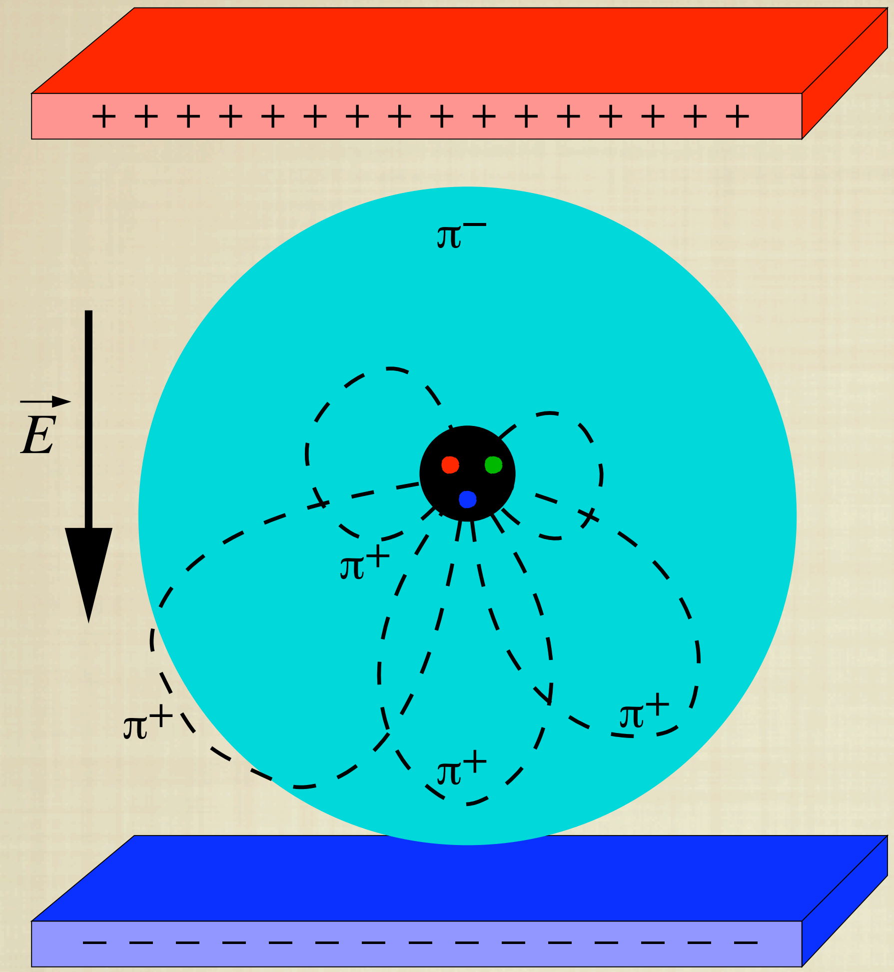

Pictures courtesy H. Griesshammer

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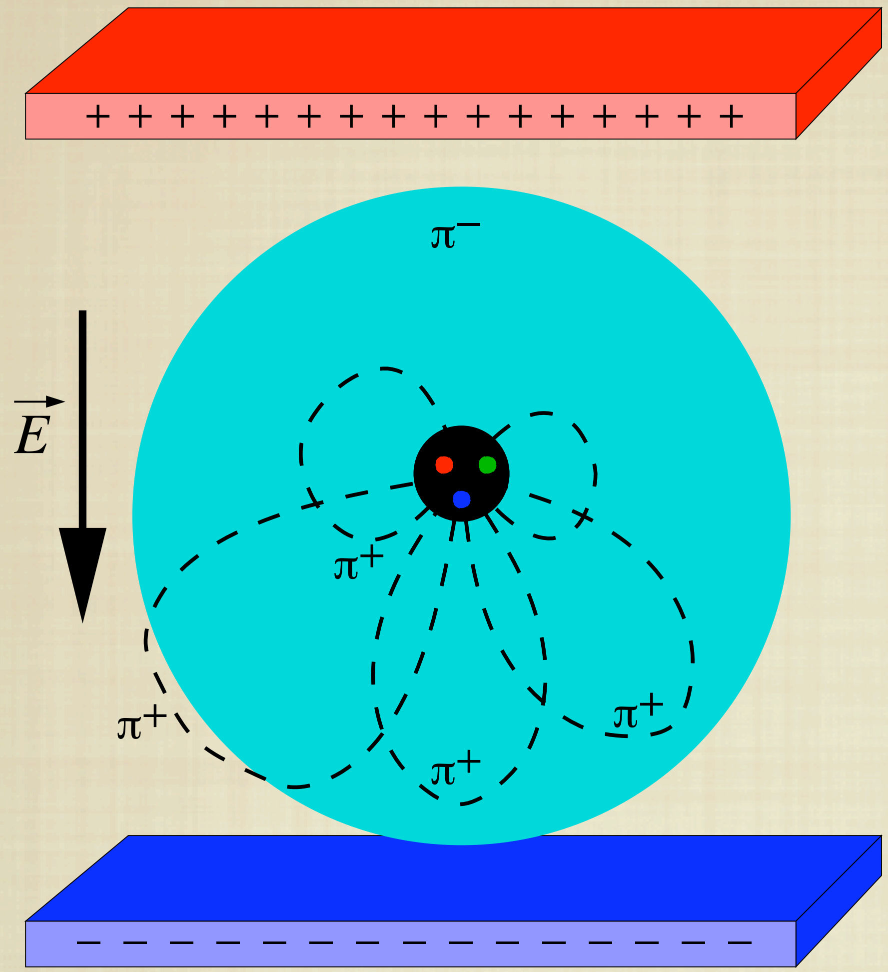

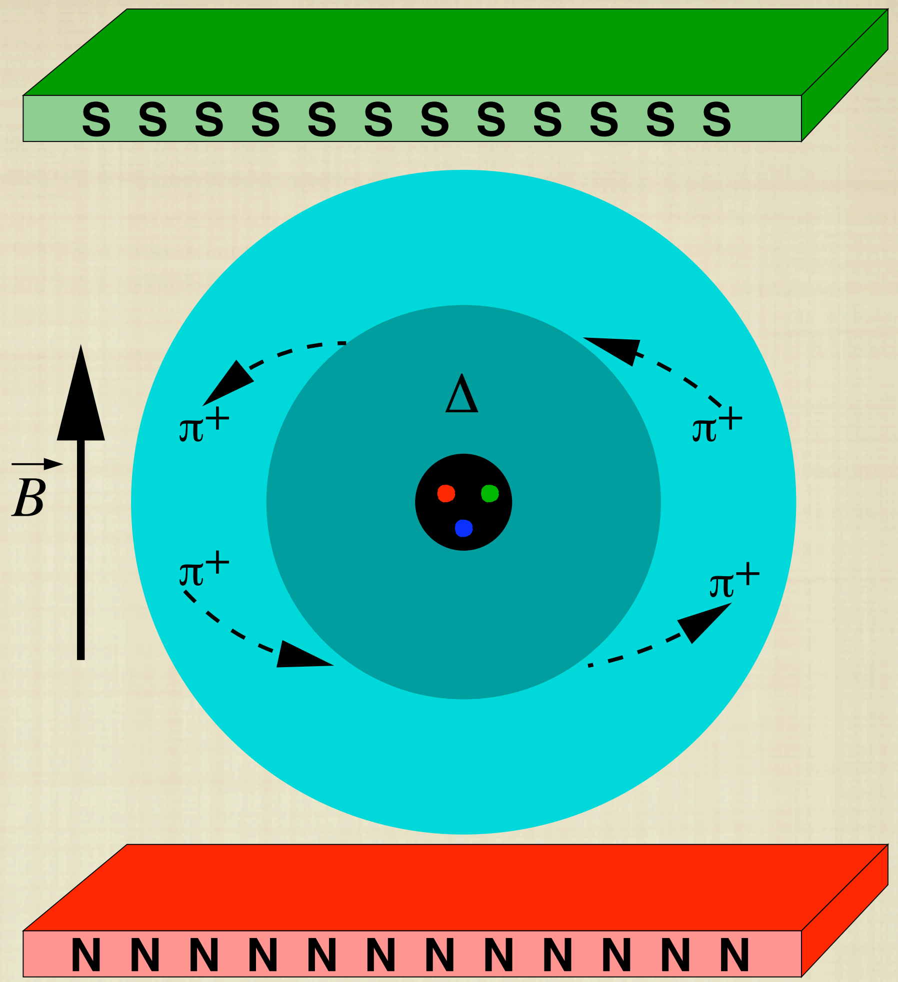

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$$H = -2\pi\alpha_E \mathbf{E}^2 - 2\pi\beta_M \mathbf{B}^2$$

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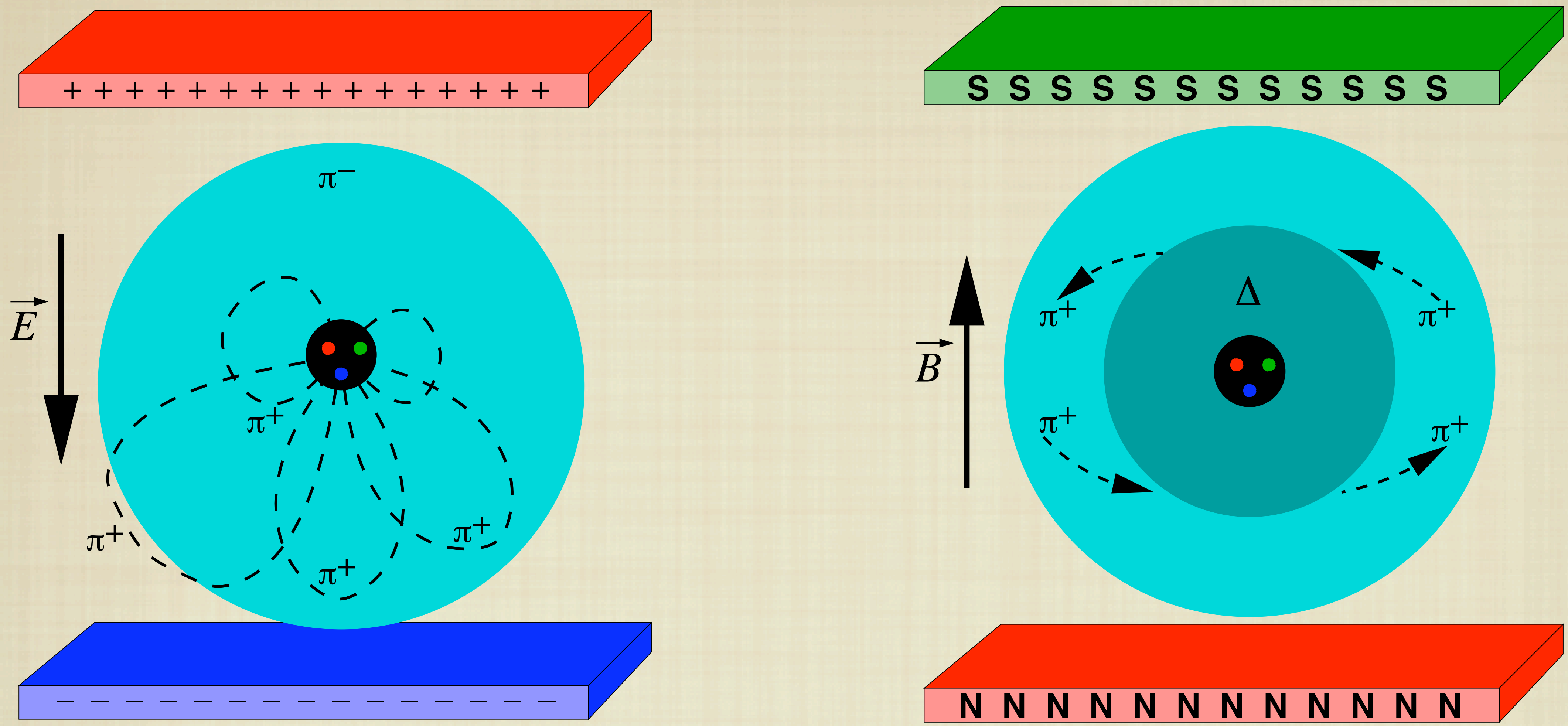

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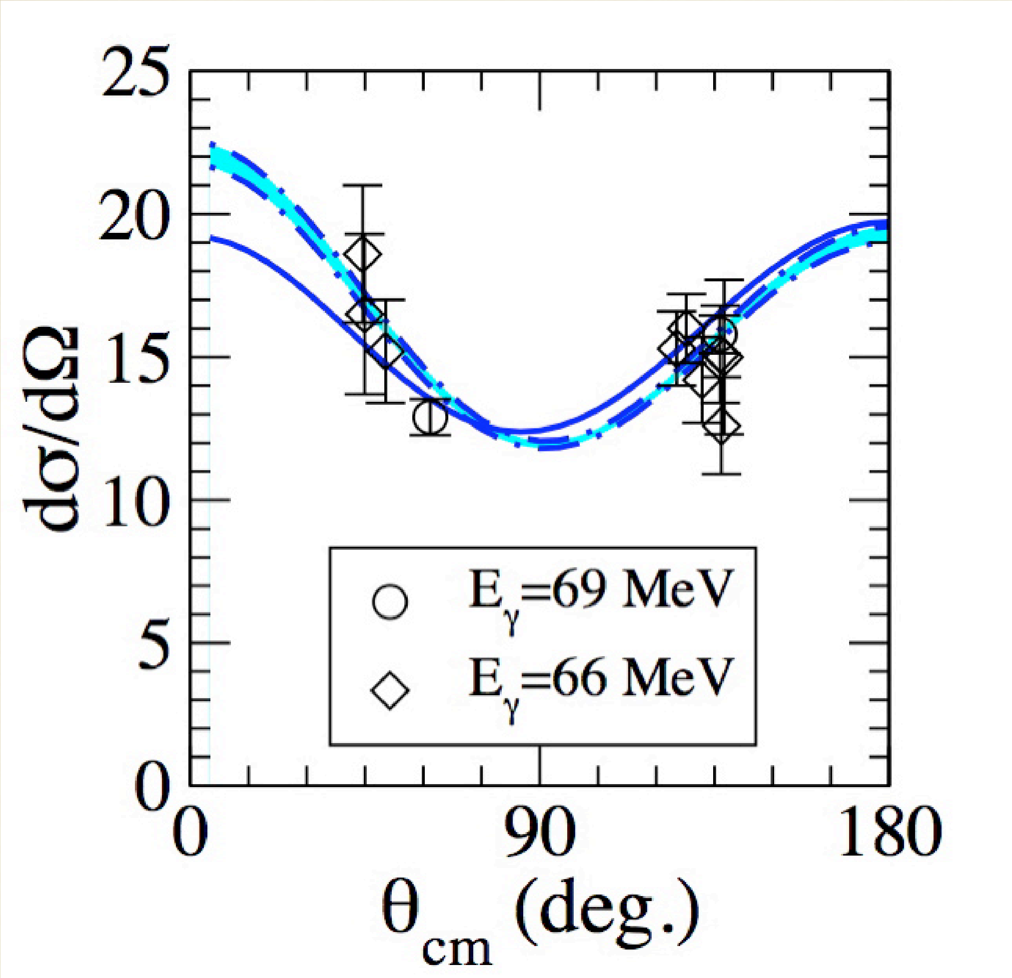
$$H = -2\pi\alpha_E \mathbf{E}^2 - 2\pi\beta_M \mathbf{B}^2$$

$$\chi\text{PT } O(e^2 P): \alpha_E^{(p)} = 10\beta_M^{(p)} = 12.5 \times 10^{-4}\ \text{fm}^3$$

$$\alpha_E^{(p)} = \alpha_E^{(n)}; \quad \beta_M^{(p)} = \beta_M^{(n)}$$

Bernard, Kaiser, Meissner (1991)

Results of the NLO γd calculation



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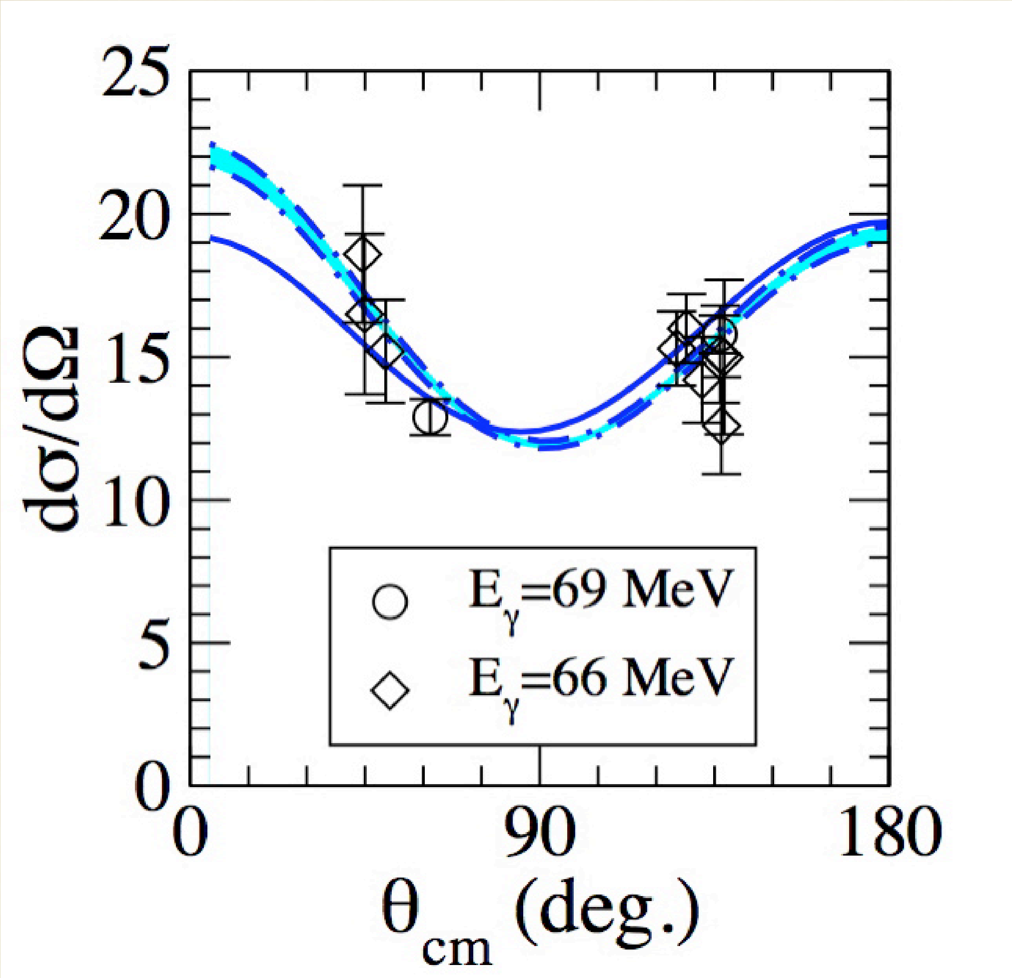

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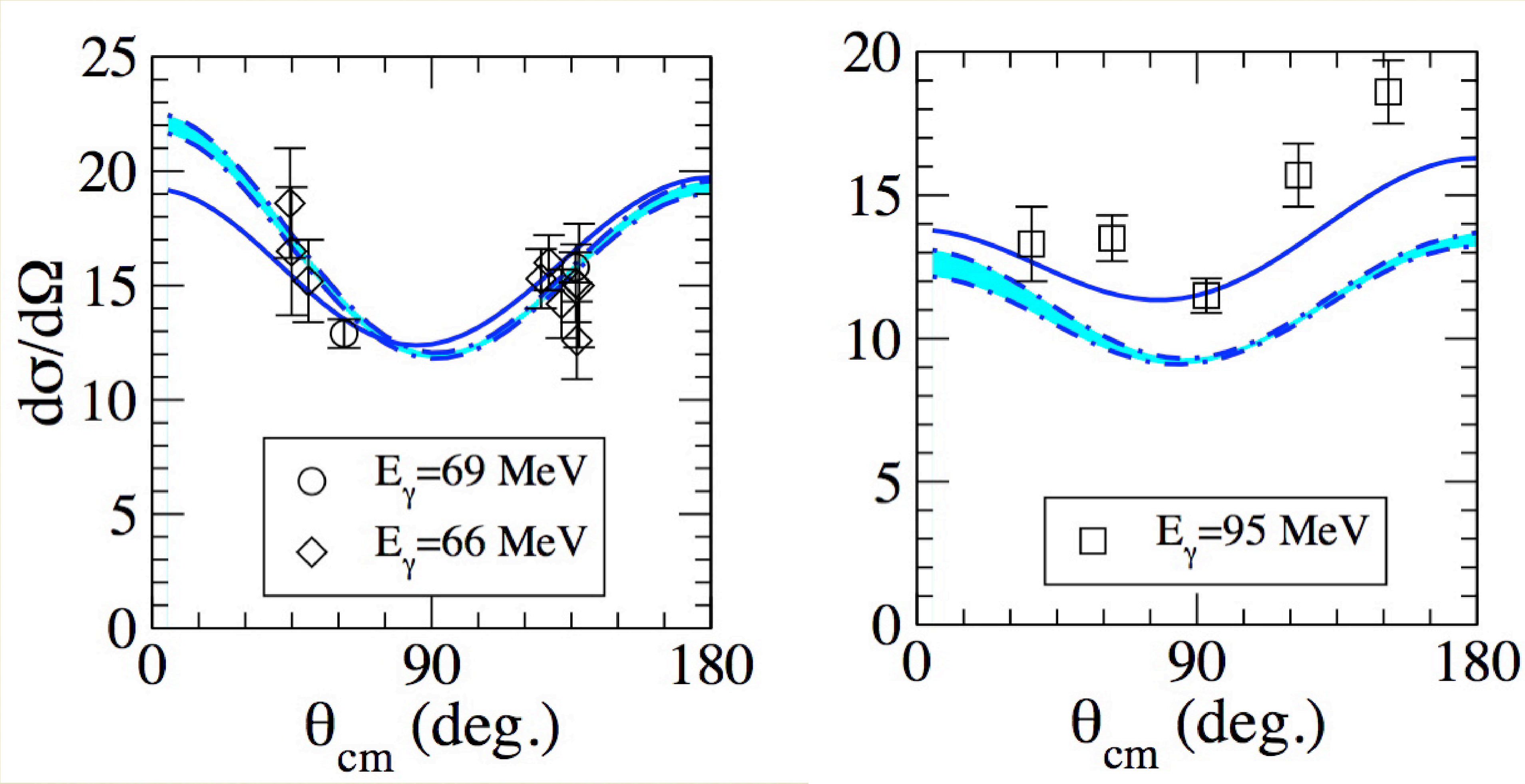

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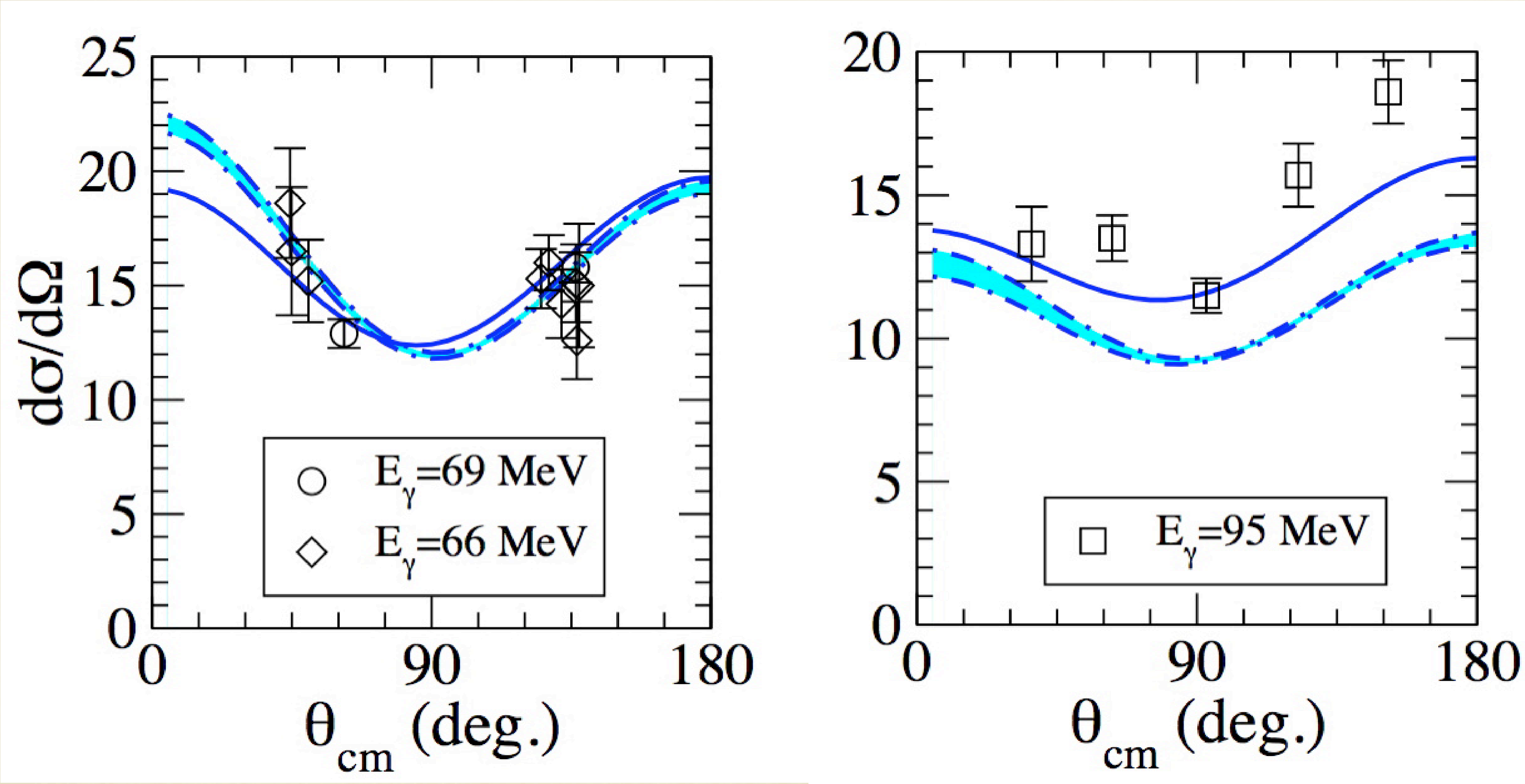

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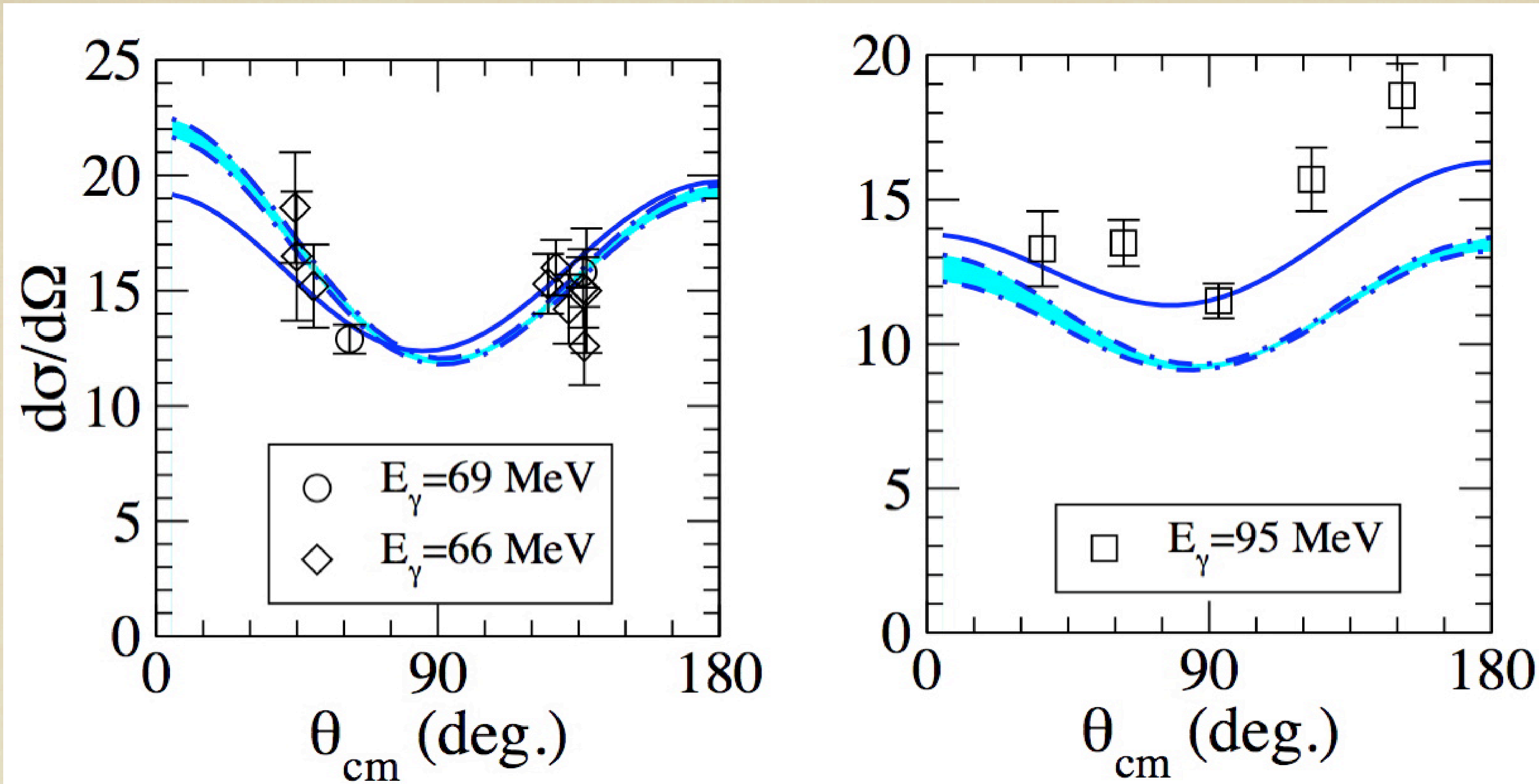

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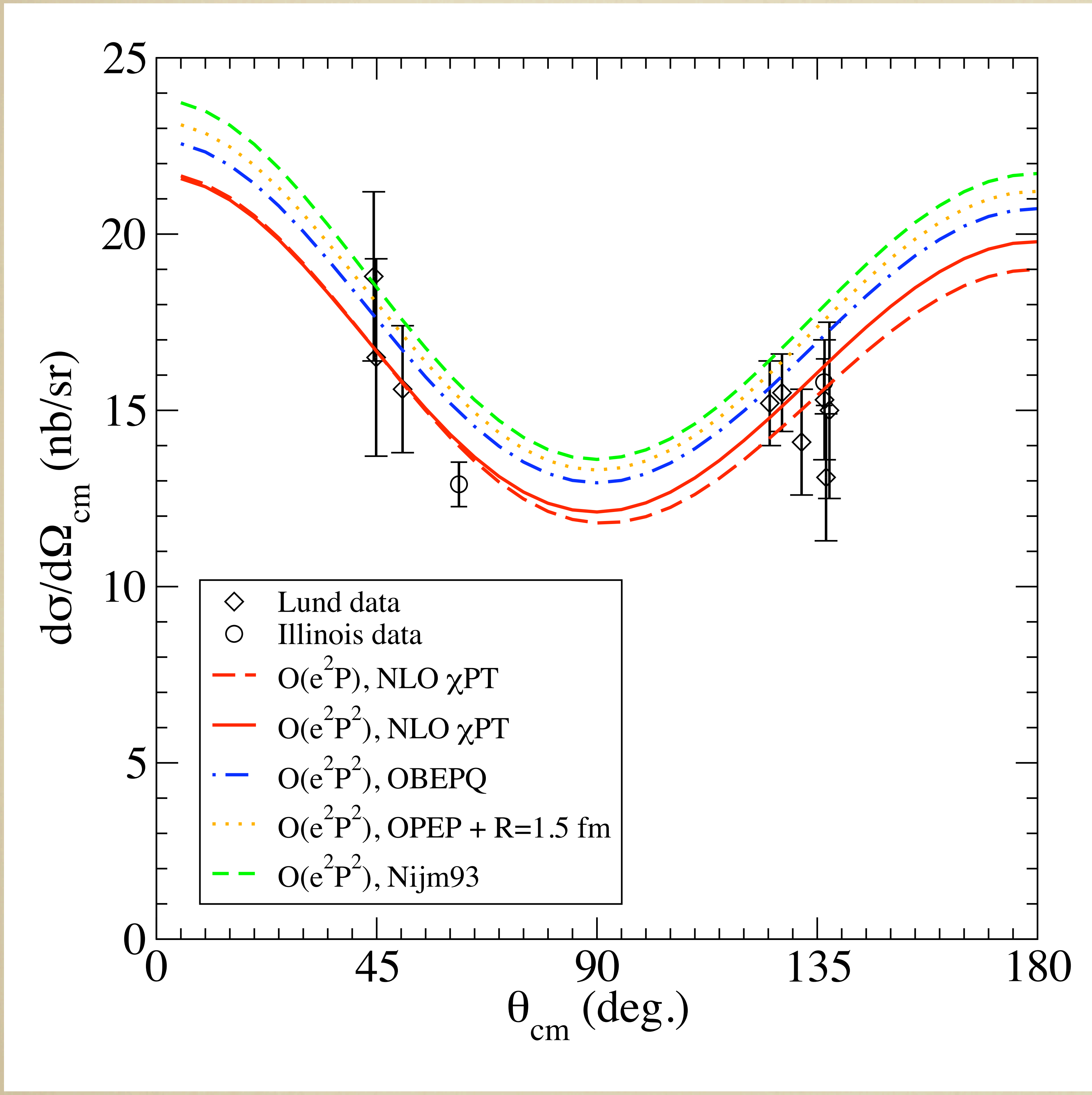
Beane, Malheiro, McGovern, DP, van Kolck, Phys. Lett. B (2003), Nucl. Phys. A (2005)

Results at E_{lab}=66 MeV



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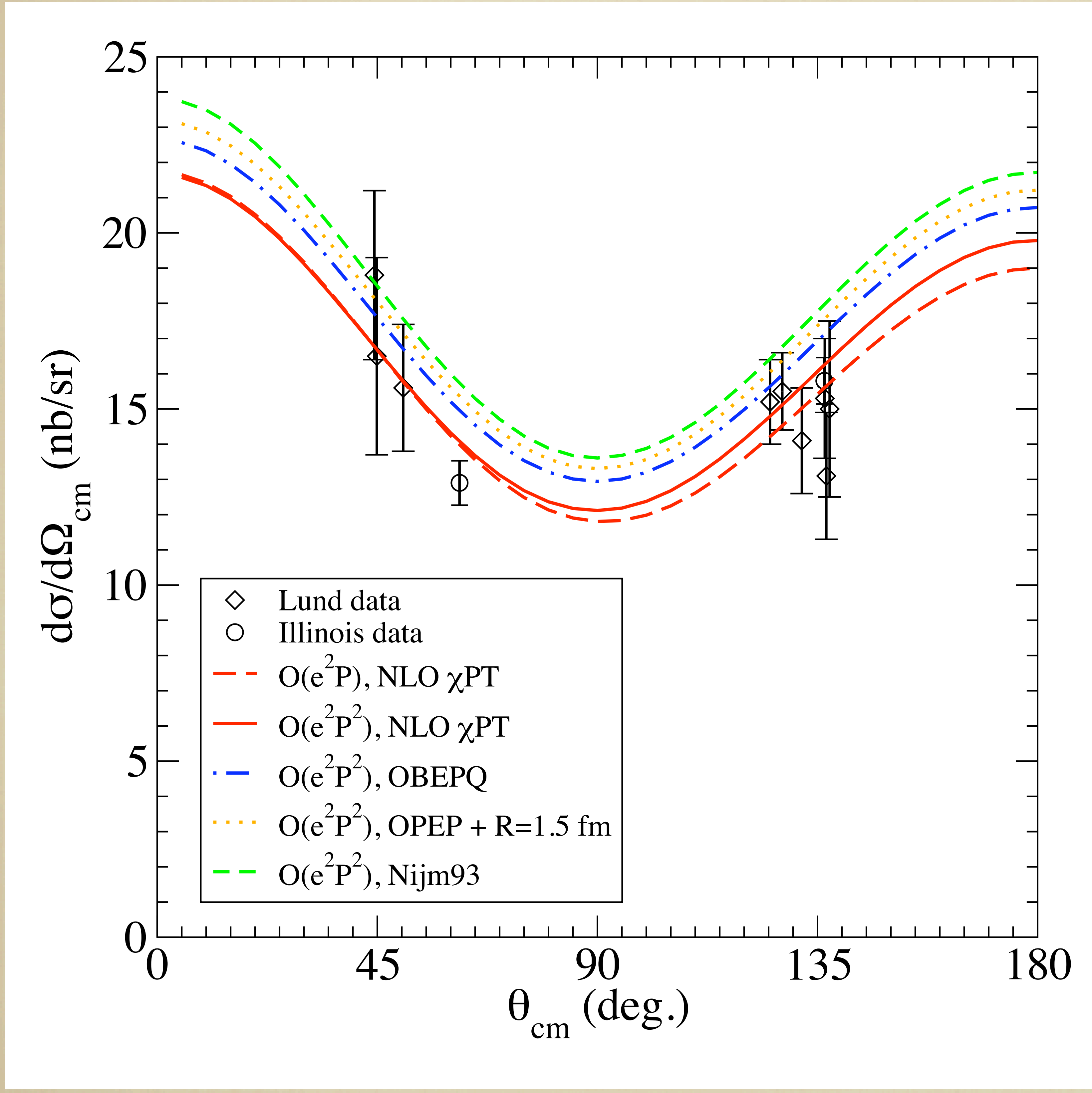

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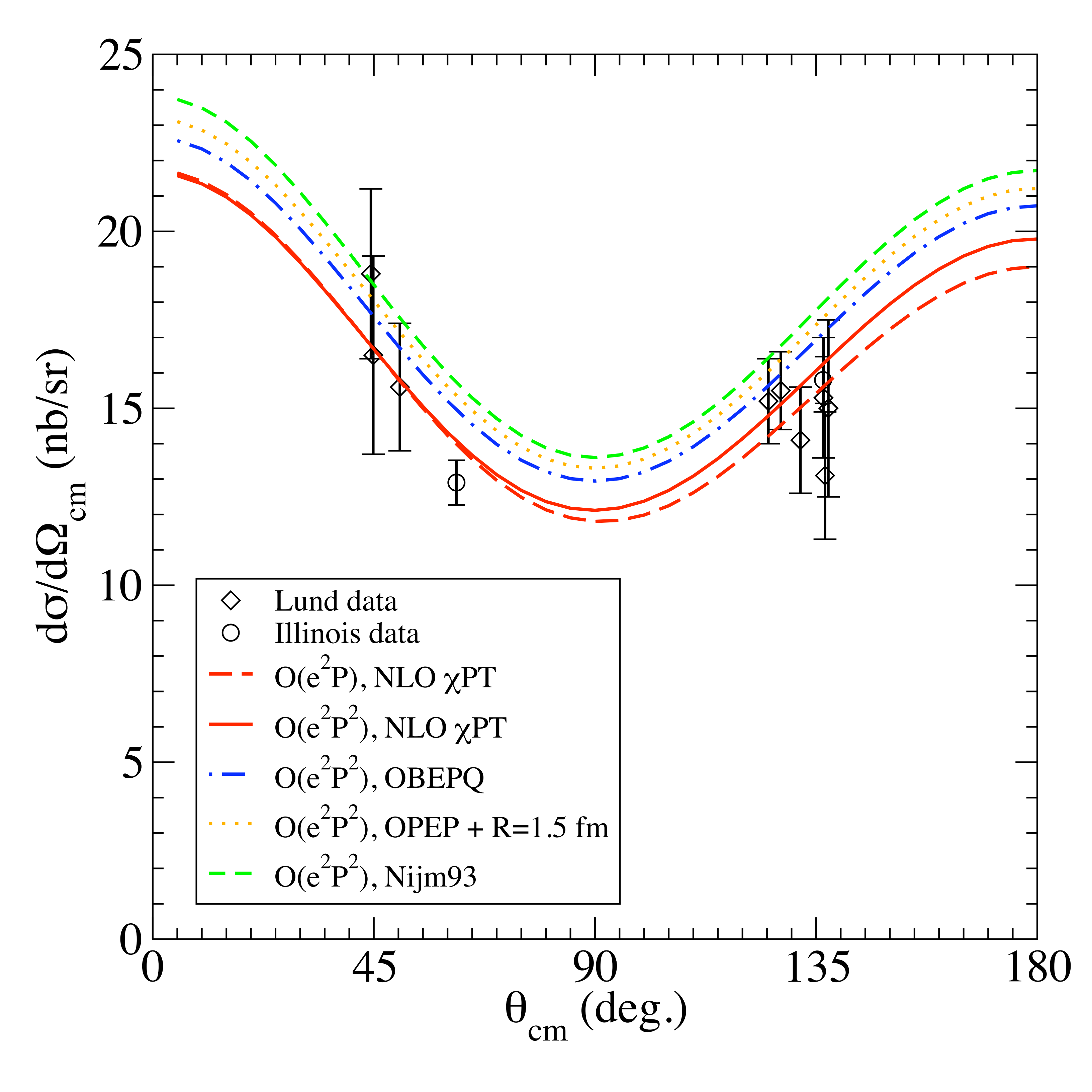

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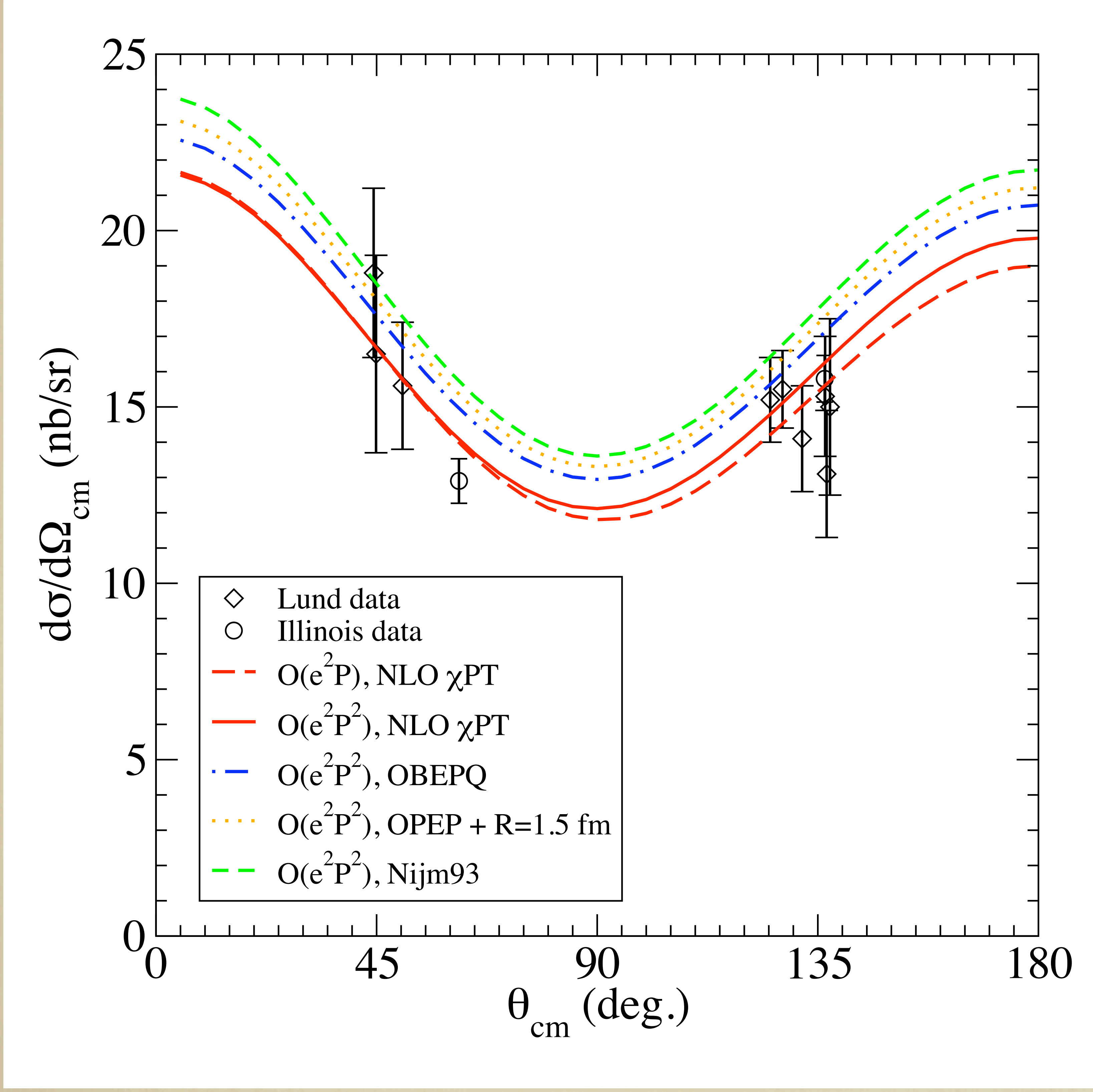

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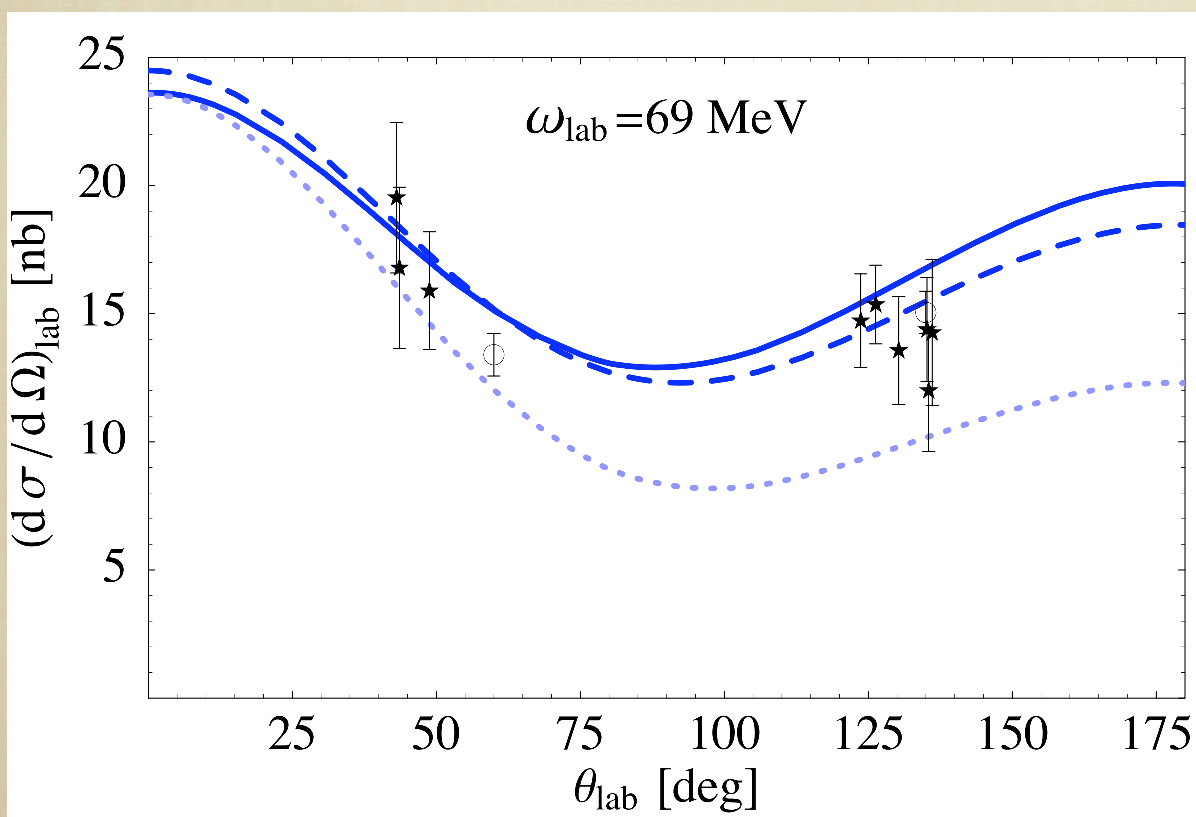
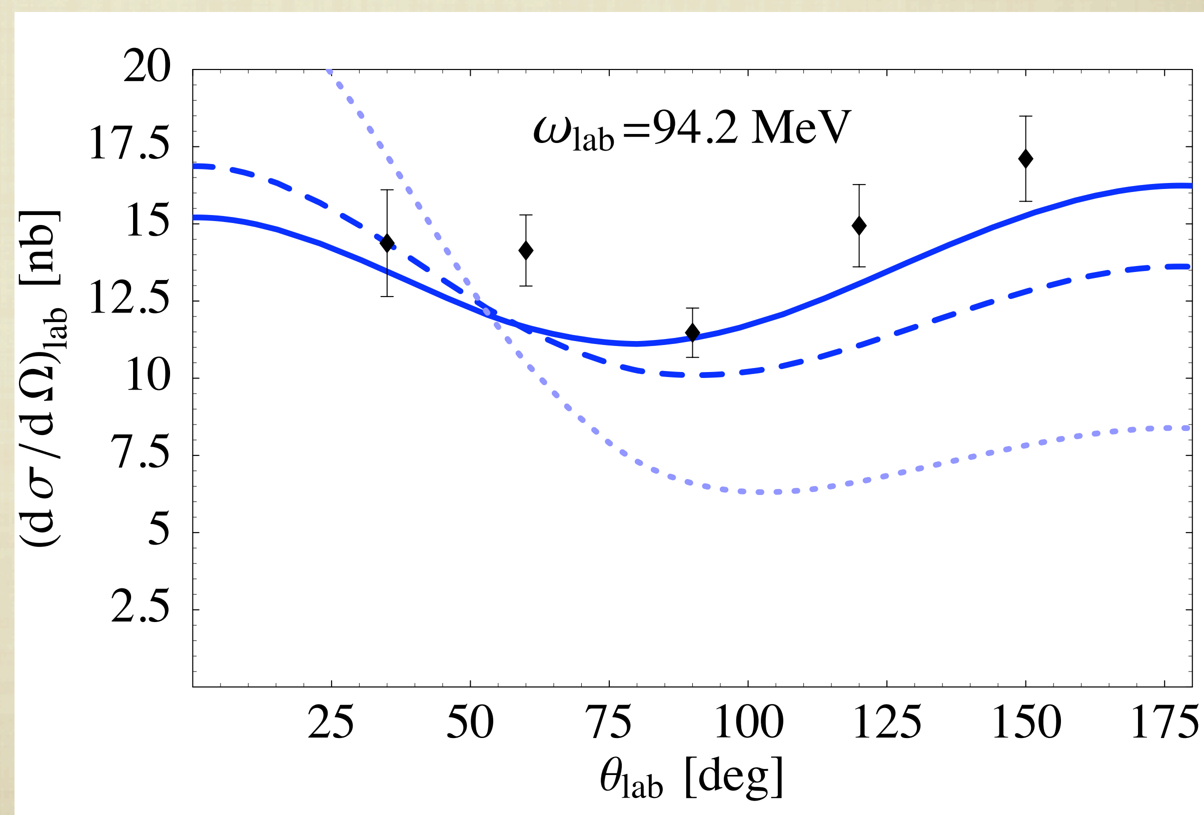
- Little sensitivity to polarizabilities here

γd scattering with explicit Δs

Hildebrandt, Griesshammer, Hemmert, DP, Nucl. Phys. A (2005)

- Calculation to NLO in χET with Δs
- Only Δ effects in γN amplitude: no 2B Δ effects at NLO
- Assume $\alpha_E^{(s)} = 11.0 \times 10^{-4}\ \text{fm}^3; \beta_N^{(s)} = 2.8 \times 10^{-4}\ \text{fm}^3$





Compton from Helium-3 at HIγS

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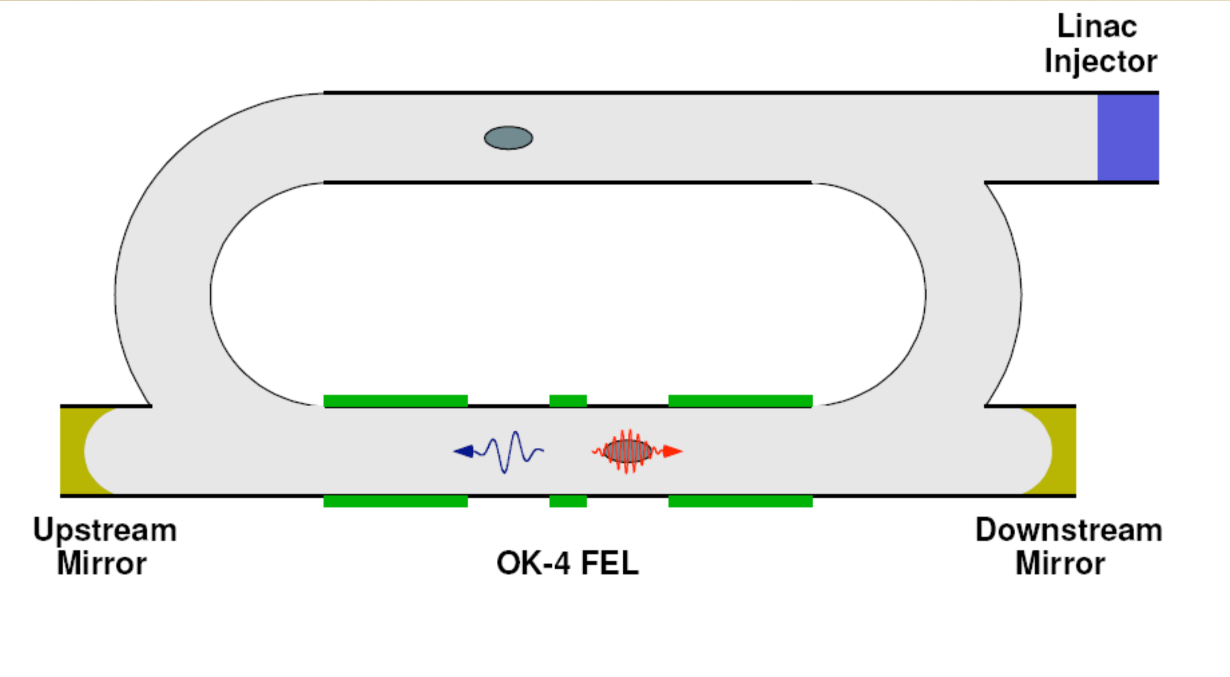

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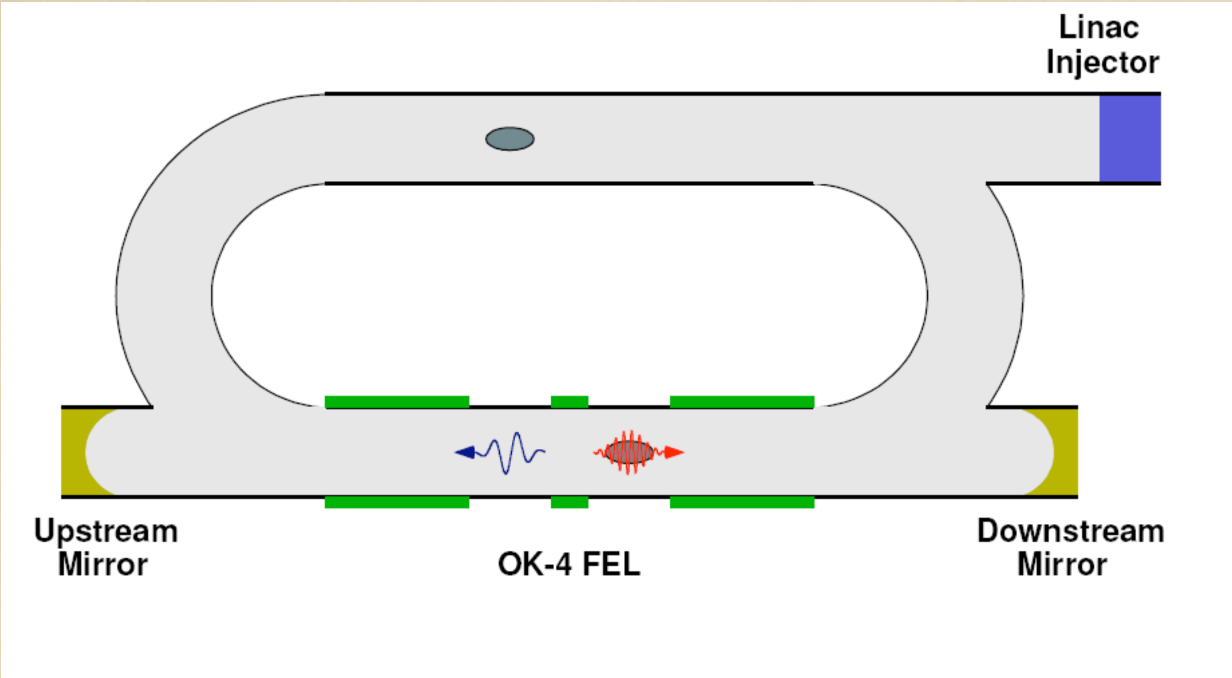

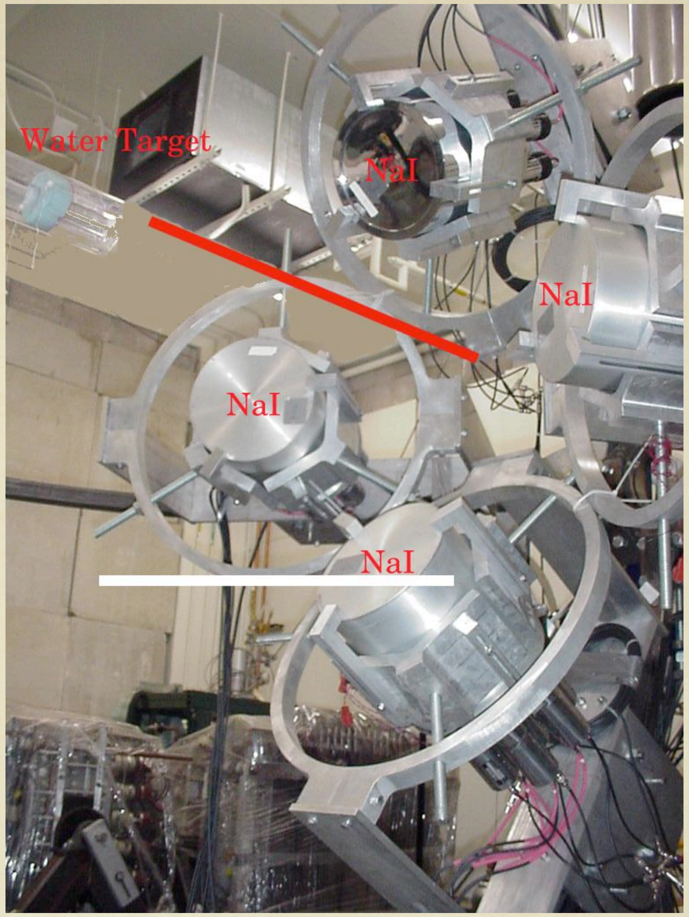

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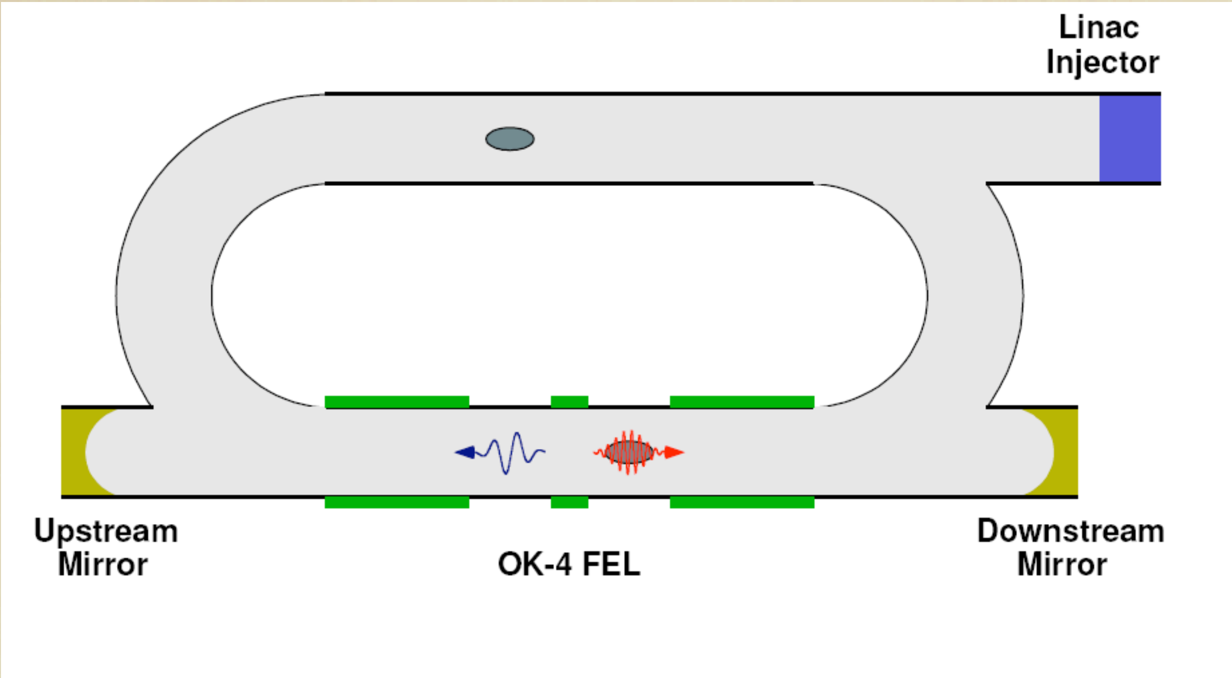

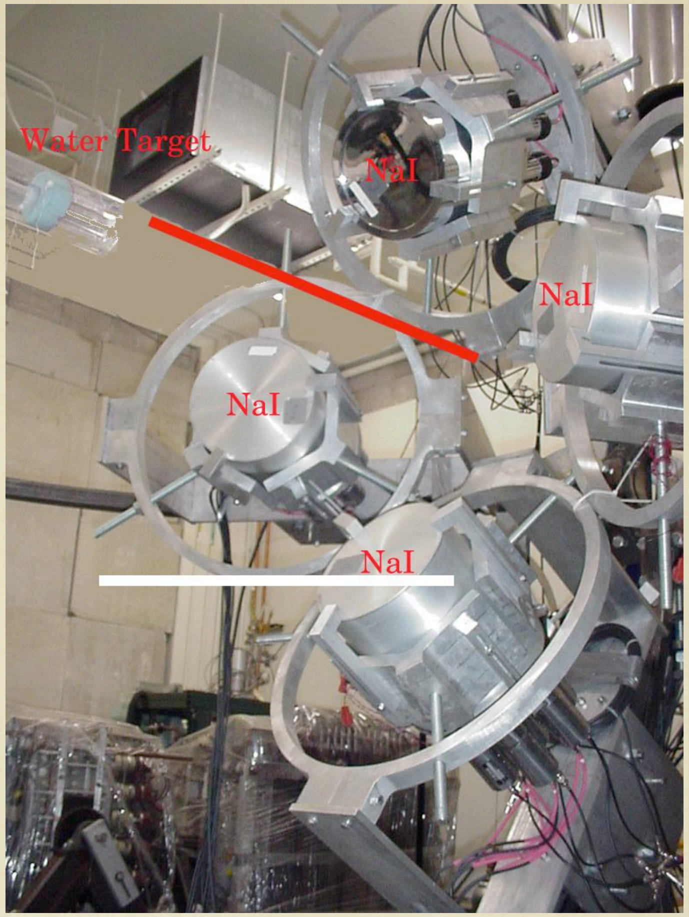

HIGS@TUNL: Polarized γs on polarized He-3 (Gao)

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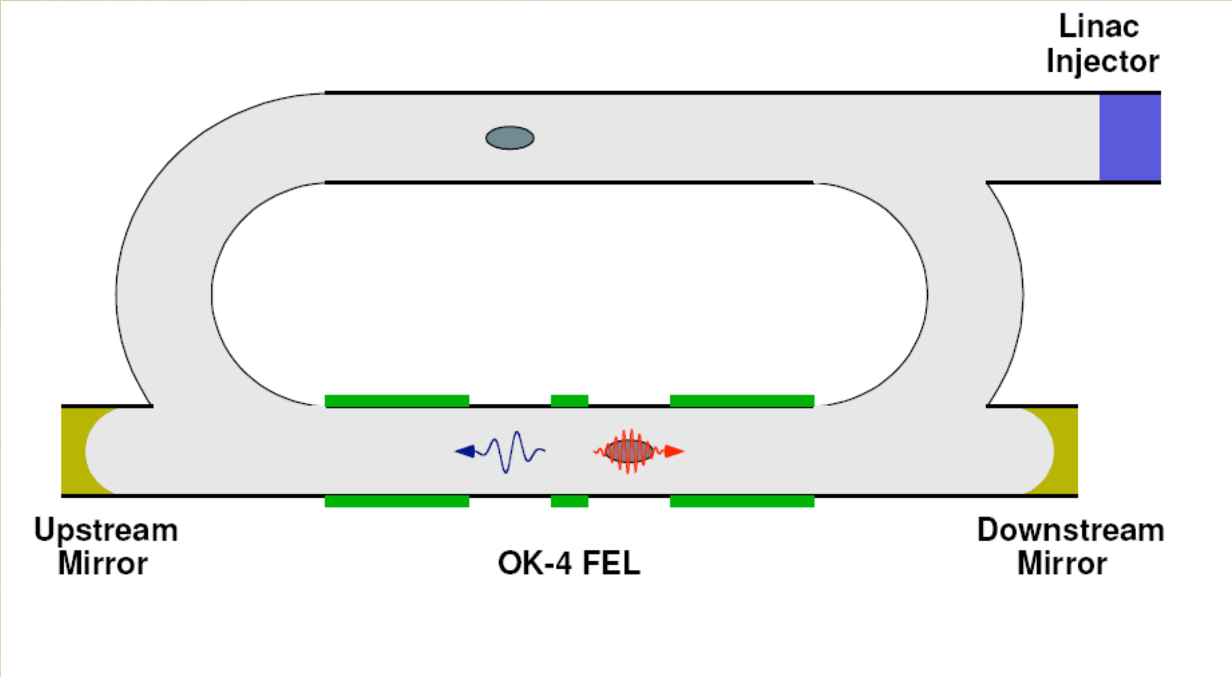

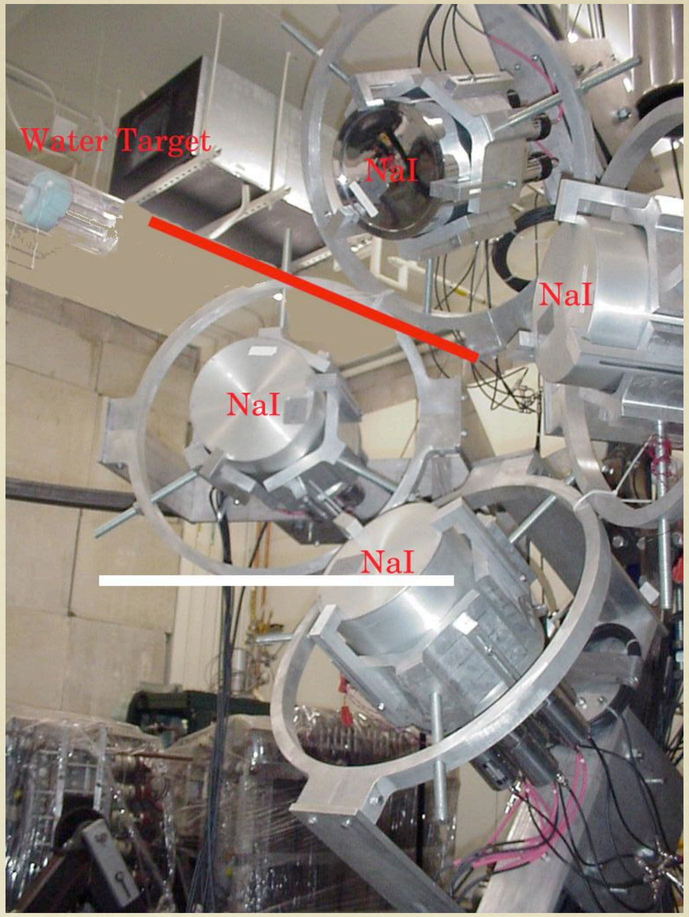

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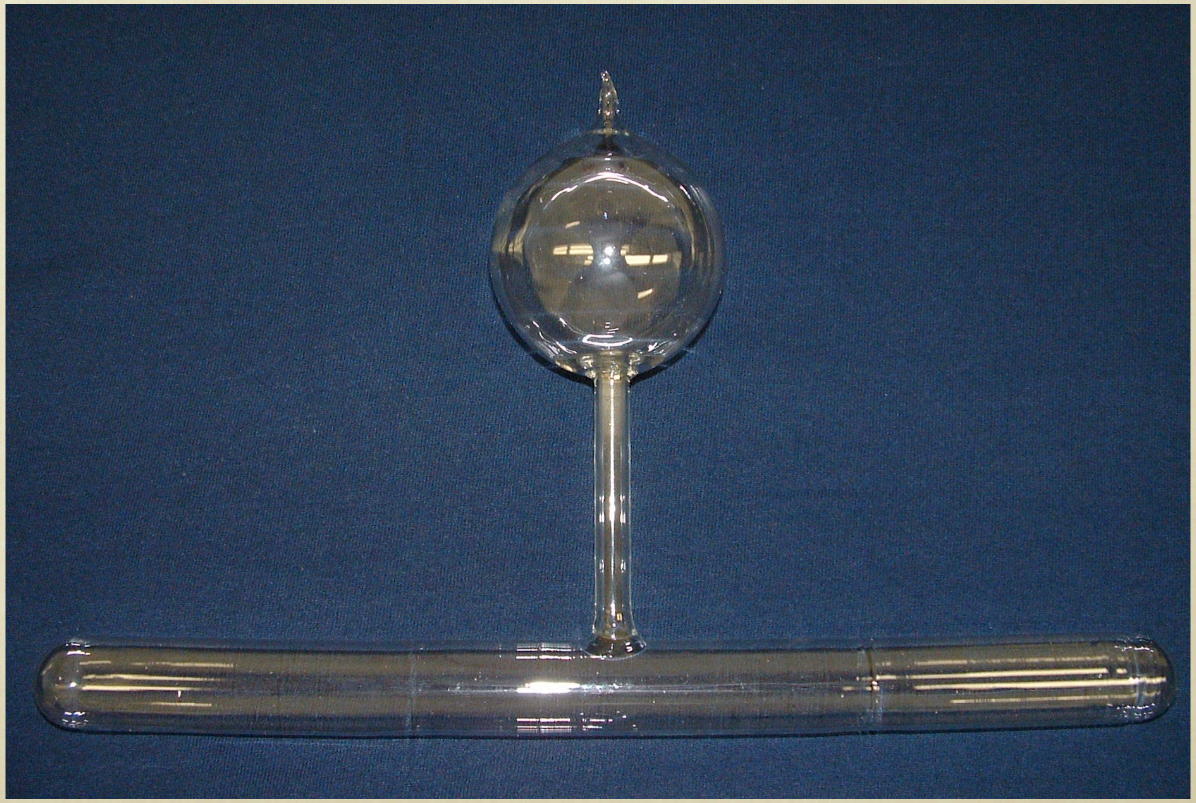
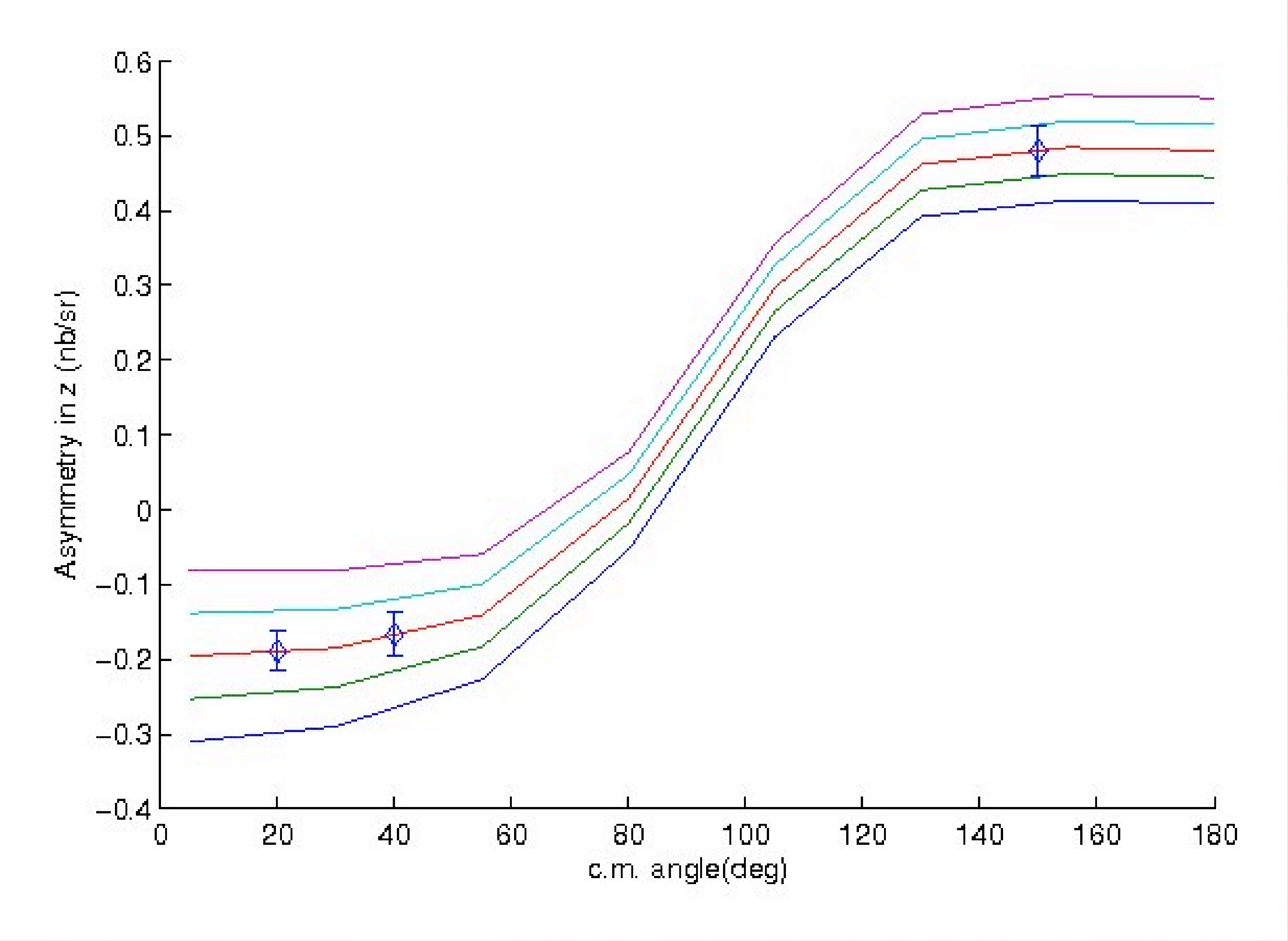
$$\gamma_1^{(n)} = (3.7 \pm 0.6_{\rm stat}) \times 10^{-4}\ \mathrm{fm}^4$$



Picture credits: Haiyan Gao

HIγS projections with polarized tgt



- Photon flux: 5×10^7/s
- Target: $10^{22}/cm^2$
- 45% polarization
- 500 hours

Plot and numbers courtesy Haiyan Gao