Investigating nucleon polarizabilities in Compton scattering on the proton and the deuteron

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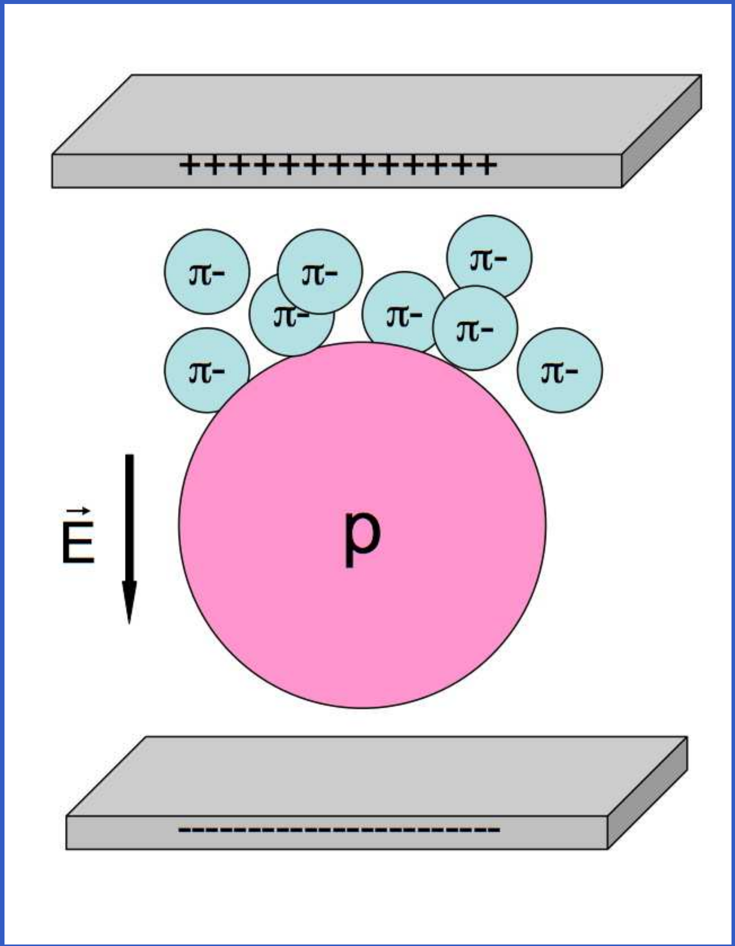
Outline

- Polarizabilities: the promise and the problem
- Compton scattering on the proton in chiral perturbation theory for $\omega \sim m_\pi$
- Compton scattering on the deuteron: motivation and a first χPT calculation [$O(e^2P)$]
- Improving on the $O(e^2P)$ χPT calculation: $O(e^2P^2)$, effects of the Delta(1232), and striving for wave-function independence
- Conclusion and future work

What are polarizabilities?



- EM moments that encode nucleon-structure information;

Figure courtesy R. Miskimen

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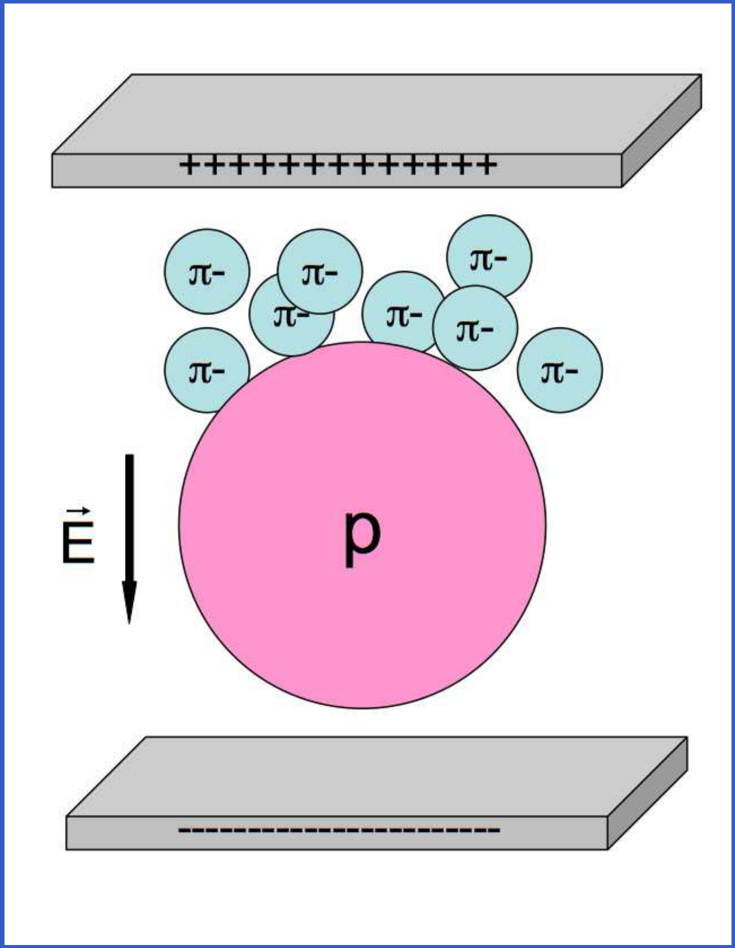

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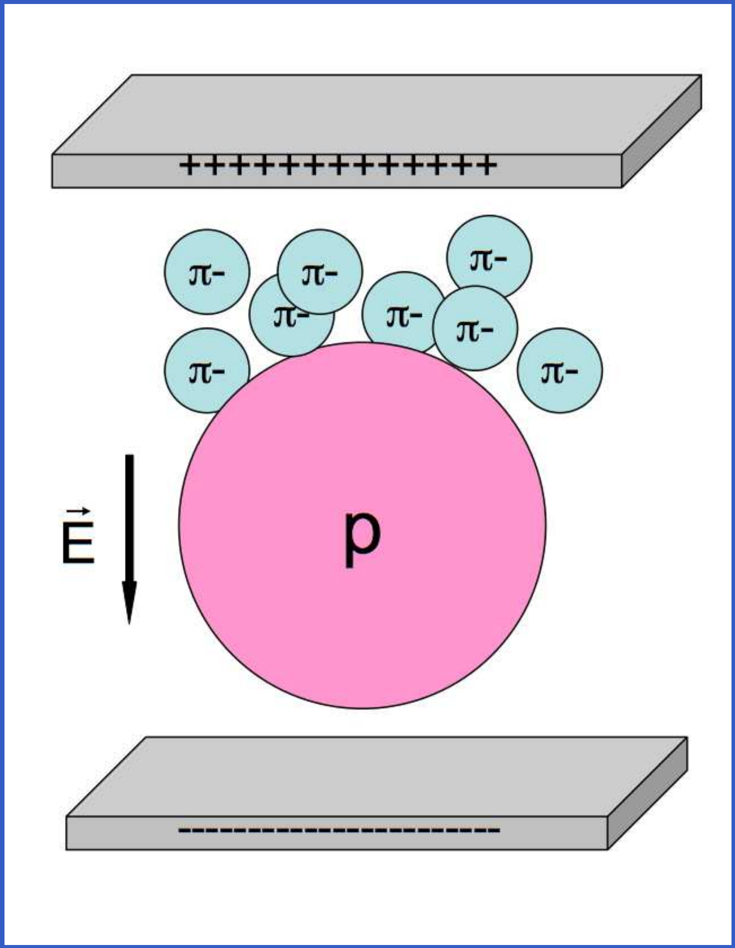

- EM moments that encode nucleon-structure information;
- Mix long- ($r \gtrsim 1/m_\pi$) and short-distance physics in interesting way;
- Probe pattern of breaking of QCD's chiral symmetry **below pion-production threshold.**

Figure courtesy R. Miskimen

Polarizabilities: promise and problem

$$\mathbf{d} = 4\pi\alpha_N \mathbf{E}; \qquad \mu = 4\pi\beta_N \mathbf{B}$$

$$\Rightarrow H = \frac{(\mathbf{p} - \mathcal{Z}e\mathbf{A})^2}{2M} \quad - \quad 2\pi\alpha_N \mathbf{E}^2 - 2\pi\beta_N \mathbf{B}^2$$

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The problem: α_N and β_N are defined at $\omega = 0$, but their influence grows with ω.

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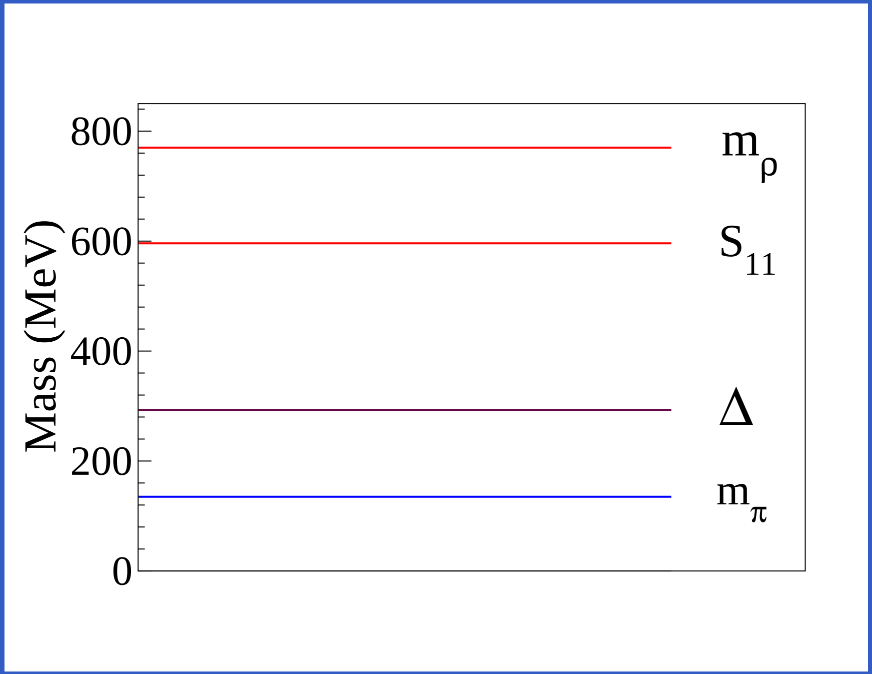
- Whole $\mathcal{A}_{\gamma N}$ test of low-energy QCD dynamics

EFTs and low-energy scales



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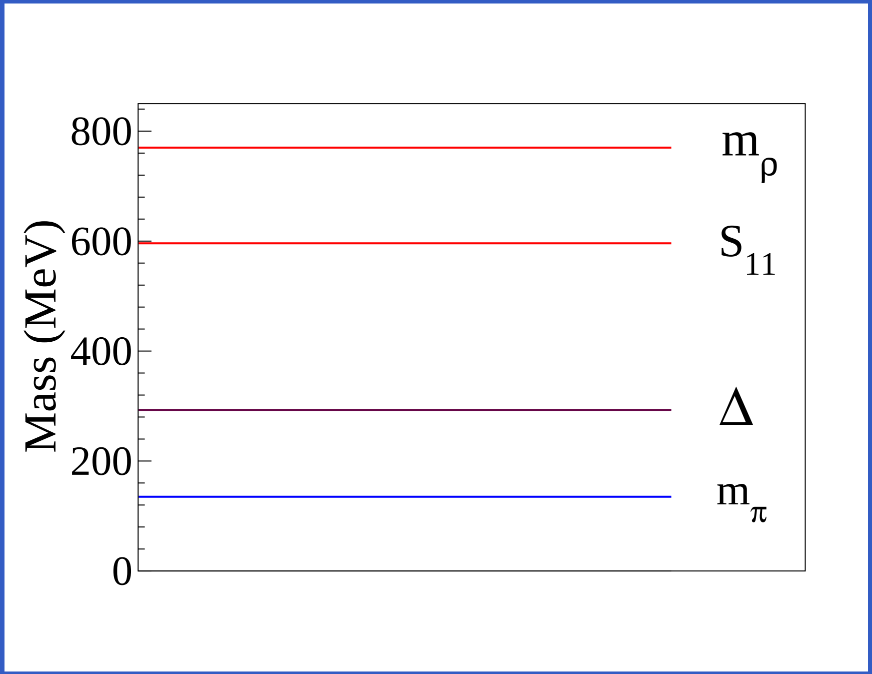

Three possible EFTs:

- EFT($\not\pi$): $\omega < m_\pi$;
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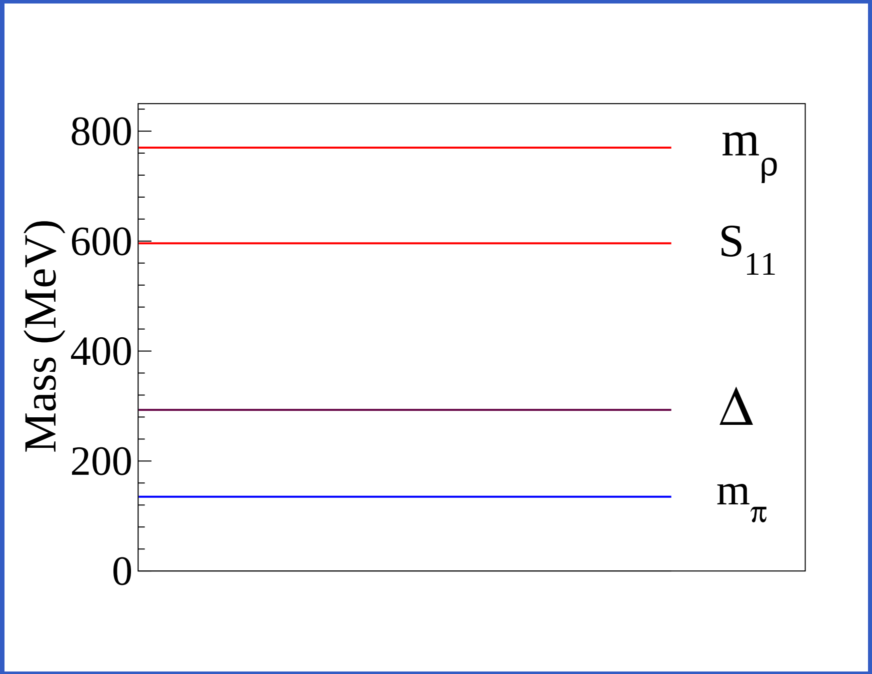

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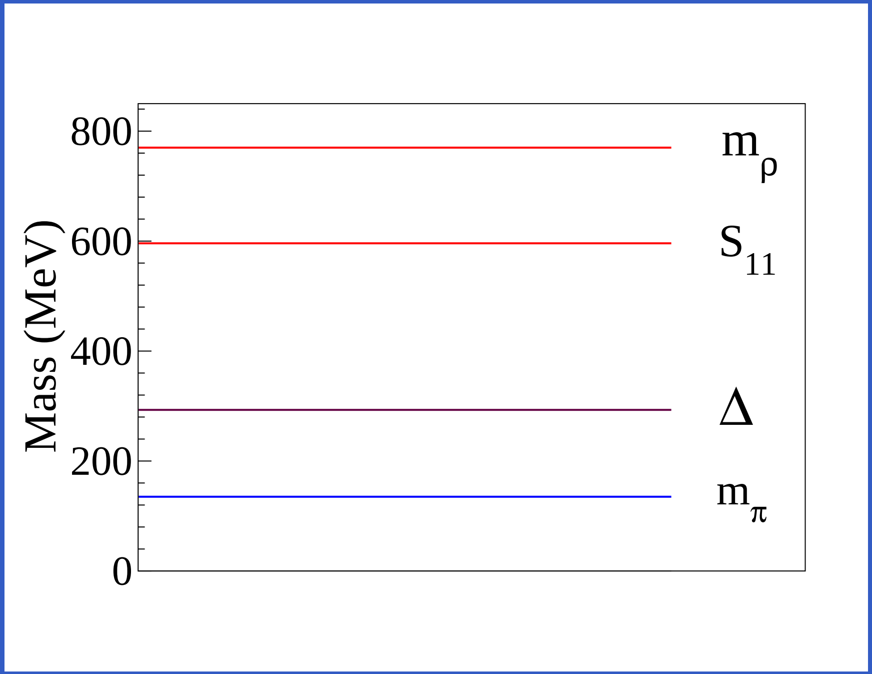

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Each can be applied in A=1 AND A=2 (and A=3 . . .)

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p/M expansion employed: (usually) useful, not essential.

Unknown coefficients at a given order need to be determined.

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χPT without explicit $\Delta \Rightarrow \omega, |\mathbf{q}| < \Delta$

Power counting in χPT($\not\Delta$)

- P^n for a vertex with n powers of p or m_π: $\mathcal{L}^{(n)}$;
- P^{-2} for each pion propagator: $\frac{1}{q^2 - m_\pi^2}$;
- P^{-1} for each nucleon propagator: $\frac{1}{p_0 - \mathbf{p}^2/(2M)}$;
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Power counting for loops as well as for $\mathcal{L}$

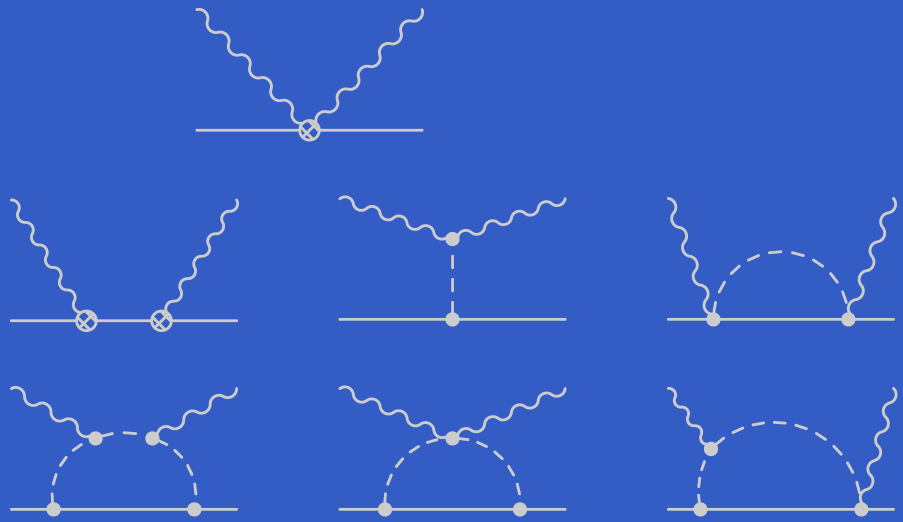
$$\Rightarrow \mathcal{A}_{\gamma N} = \sum_n \mathcal{F}_n \left(\frac{p}{m_\pi} \right) P^n,$$

$\mathcal{F}_n$ has non-analytic pieces from pion loops, and constant pieces from "short-distance physics" (Δ, ρ, M-branes, . . .)

Nucleon Compton Scattering in χPT

$O(e^2)$:

$O(e^2 P)$:



$$\frac{-e^2}{M}\epsilon' \cdot \epsilon$$

Powell X-Sn +

non-analyticity

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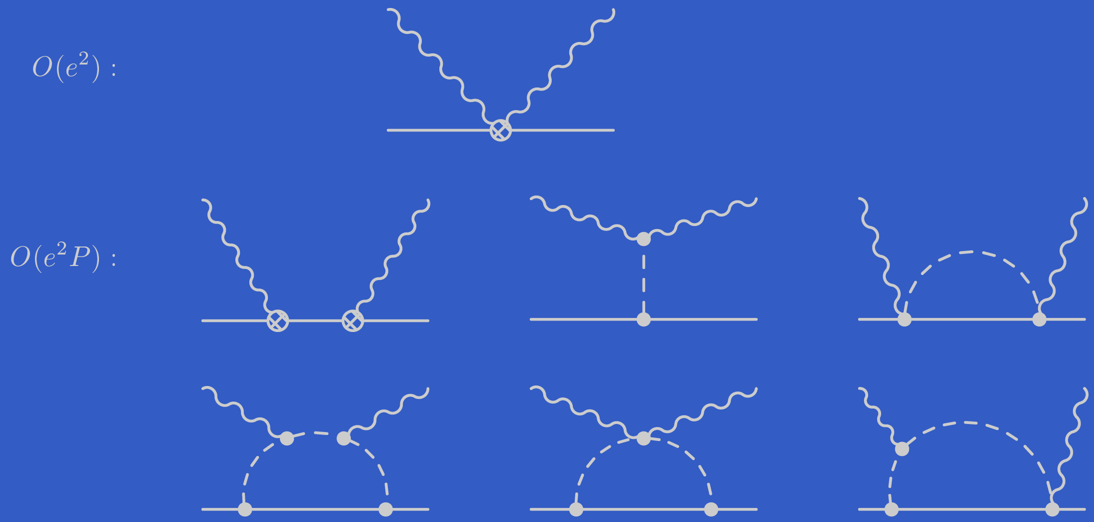


$\frac{-e^2}{M}\epsilon' \cdot \epsilon$

Powell X-Sn + non-analyticity from loops

Matching to a polynomial in ω yields

$$\alpha_N = \frac{5e^2 g_A^2}{384\pi^2 f_\pi^2 m_\pi} = 12.2 \times 10^{-4}\ \text{fm}^3; \quad \beta_N = 1.2 \times 10^{-4}\ \text{fm}^3.$$

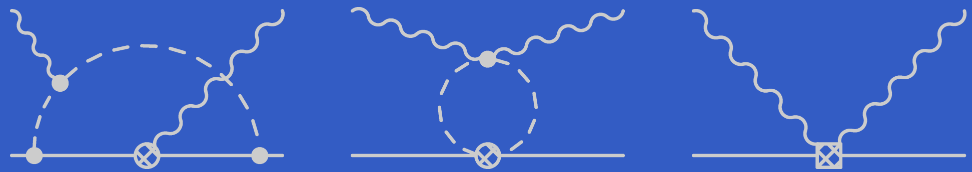
Bernard, Kaiser, Meißner (1992)

PDG average:

$$\alpha_p = (12.0 \pm 0.7) \times 10^{-4}\ \text{fm}^3;$$
$$\beta_p = (1.6 \pm 0.6) \times 10^{-4}\ \text{fm}^3.$$

$\mathbf{N^2LO}$: $O(e^2 P^2)$

γN amplitude at $O(e^2 P^2)$



J. McGovern, Phys. Rev. C **63**, 064608 (2001)

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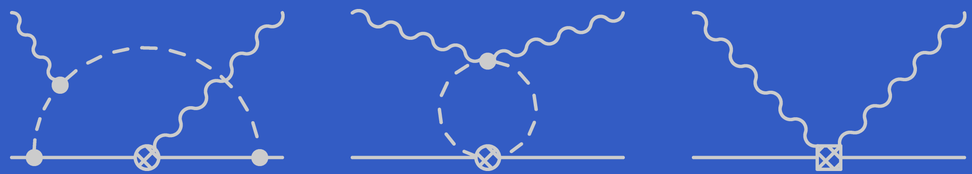

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Short-distance pieces of polarizabilities should be fit:

$$4\pi\alpha_{\rm high}\mathbf{E}^2, 4\pi\beta_{\rm high}\mathbf{B}^2 \qquad \sim \omega^2 e^2$$

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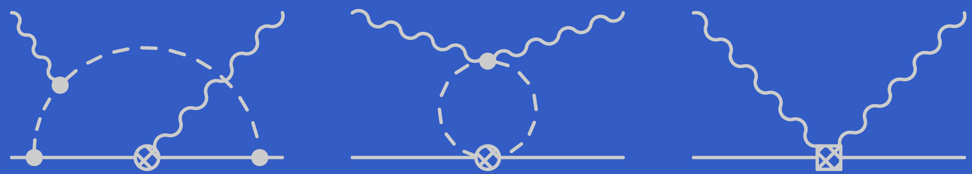

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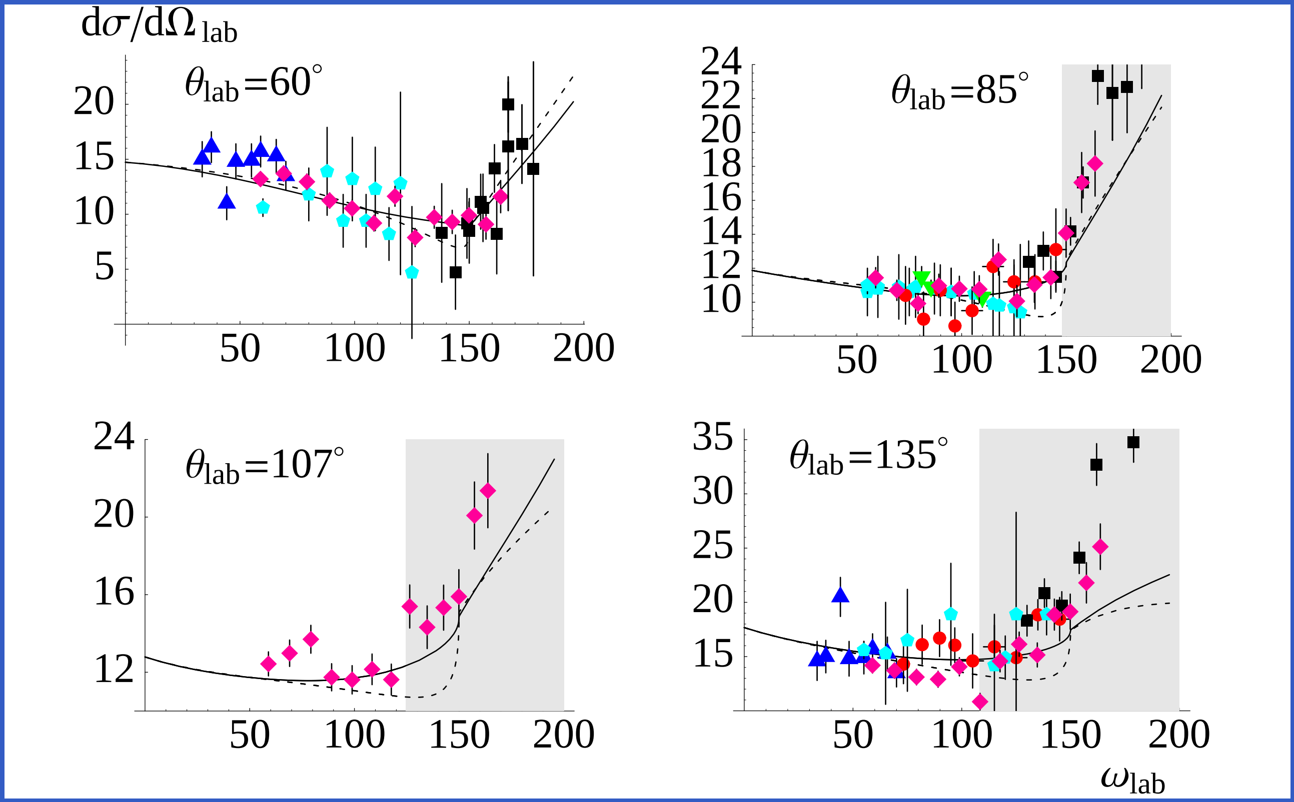
Experiments: SAL/Illinois, LEGS, MAMI, ...

Kinematic restriction (Δ-less χPT): $\omega, \sqrt{|t|} \leq 180$ MeV.

Results



χ^2/d.o.f.=170/131

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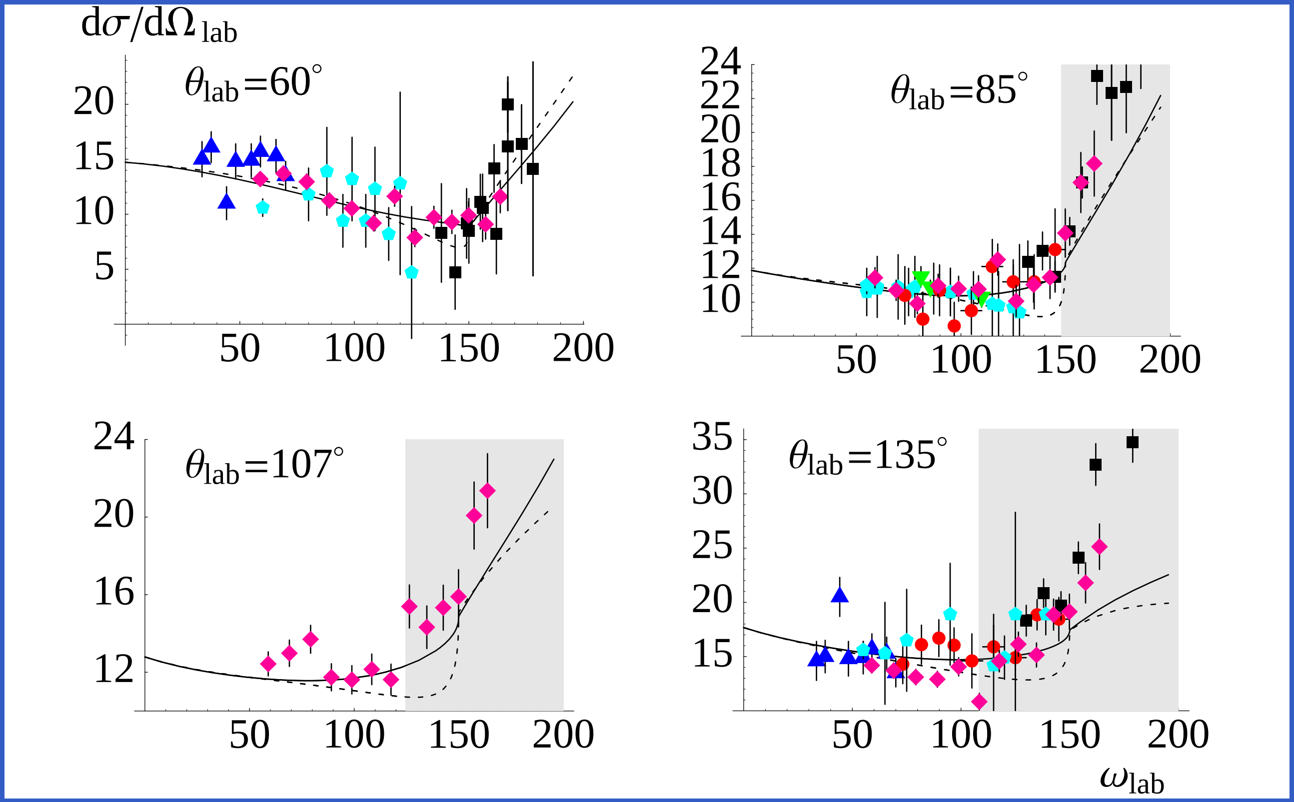

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S. R. Beane, J. McGovern, M. Malheiro, D. P., U. van Kolck, PLB, **567**, 200 (2003).

Going higher for γp

Breakdown set by first omitted mass scale: $\Delta \equiv M_\Delta - M_N$.

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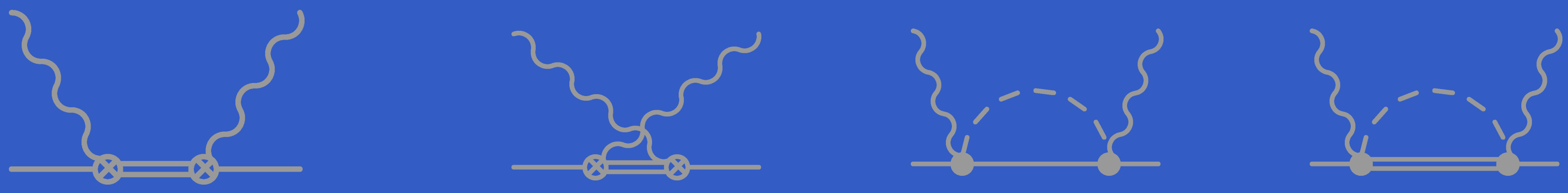

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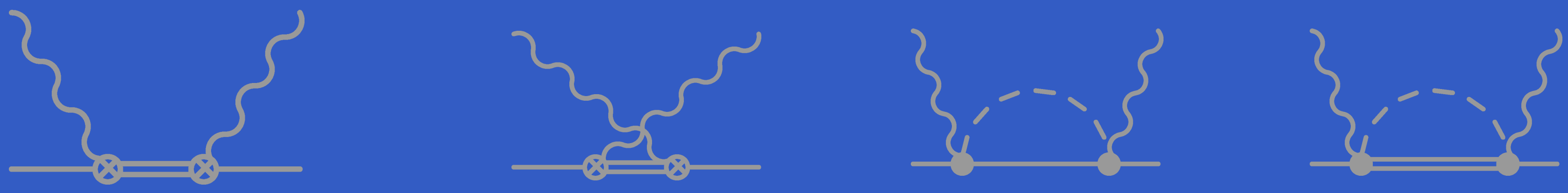

Also add (isoscalar) counterterms $\delta\alpha_{\rm high}\mathbf{E}^2 + \delta\beta_{\rm high}\mathbf{B}^2$

Fitting to higher energies

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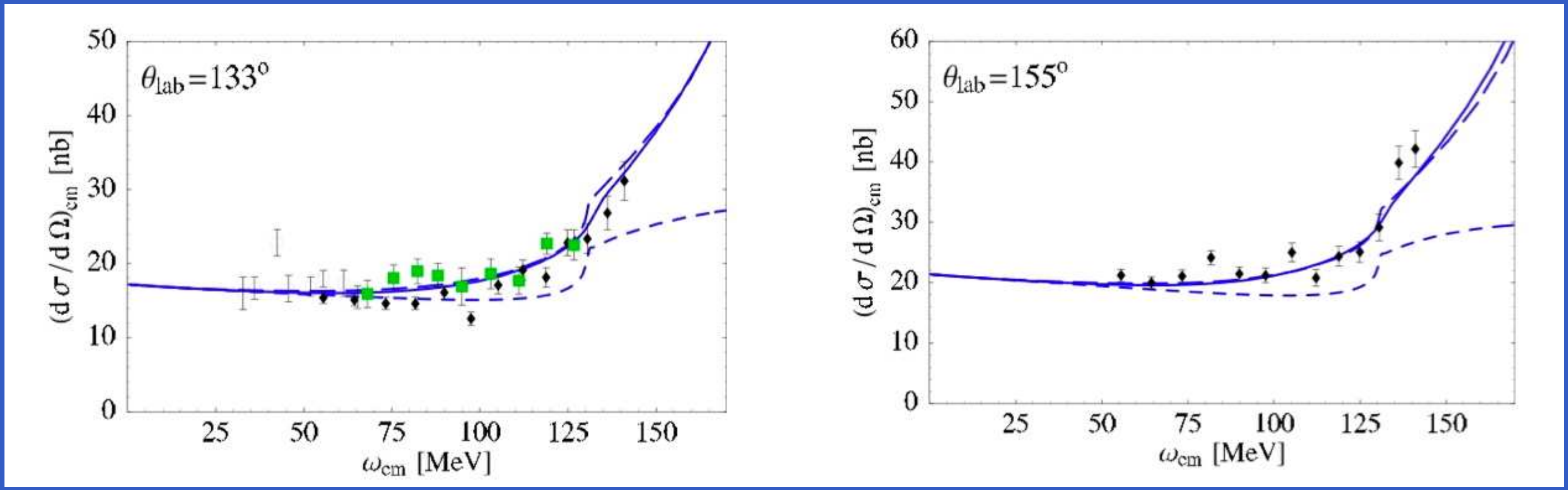

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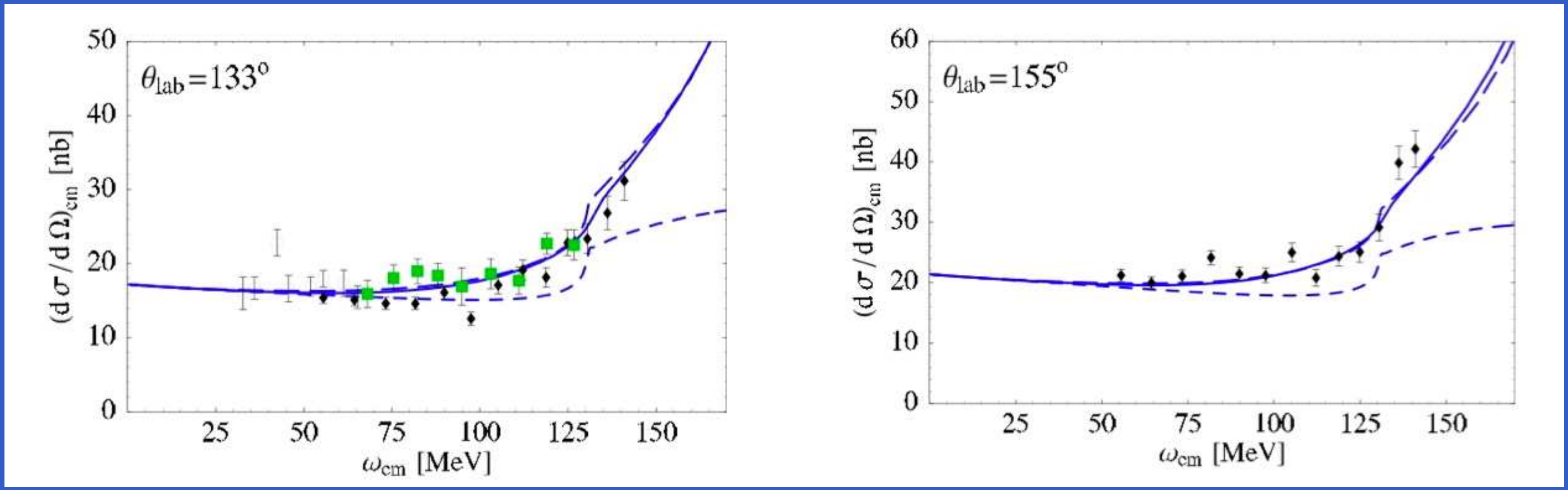

Fit to γp data with $\omega < 200$ MeV

$$\alpha_p = (11.04 \pm 1.3 \pm 1.0) \times 10^{-4}\ \mathrm{fm}^3$$
$$\beta_p = (2.76 \mp 1.3 \pm 1.0) \times 10^{-4}\ \mathrm{fm}^3$$

Baldin Sum Rule constraint used here

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- Issues with experimental database: can χPT help?

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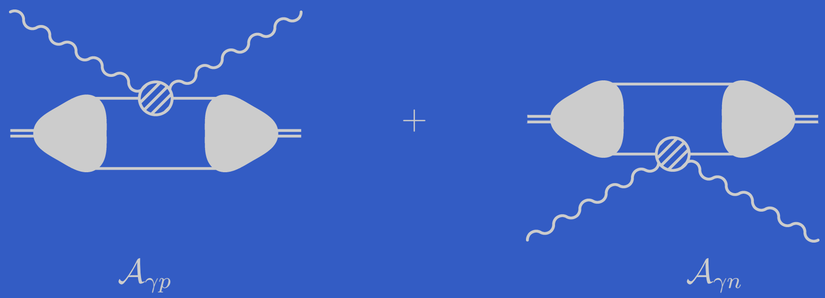
- Use elastic cross γd section not quasi-free γd $\rightarrow$ γnp: exploit quantum coherence!

Compton scattering on deuterium

Want to determine α_N and β_N. Naive idea:



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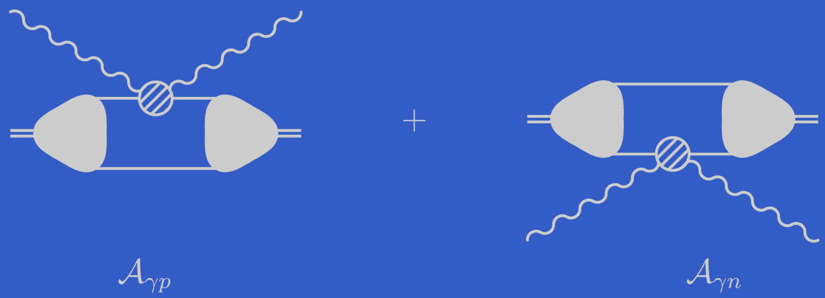

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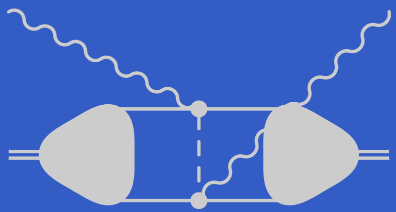

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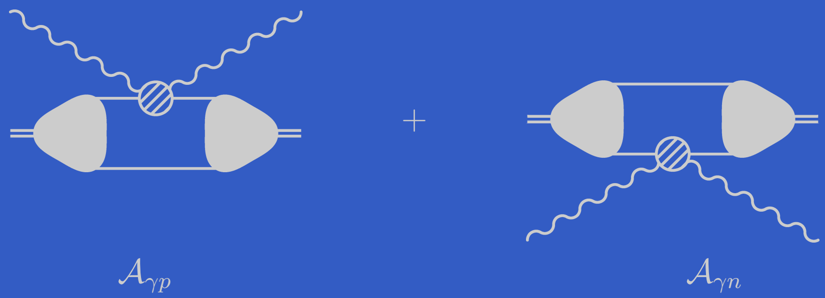

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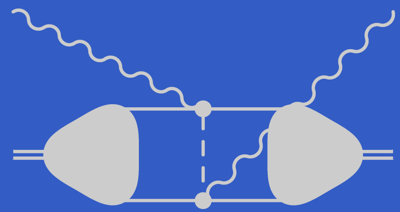
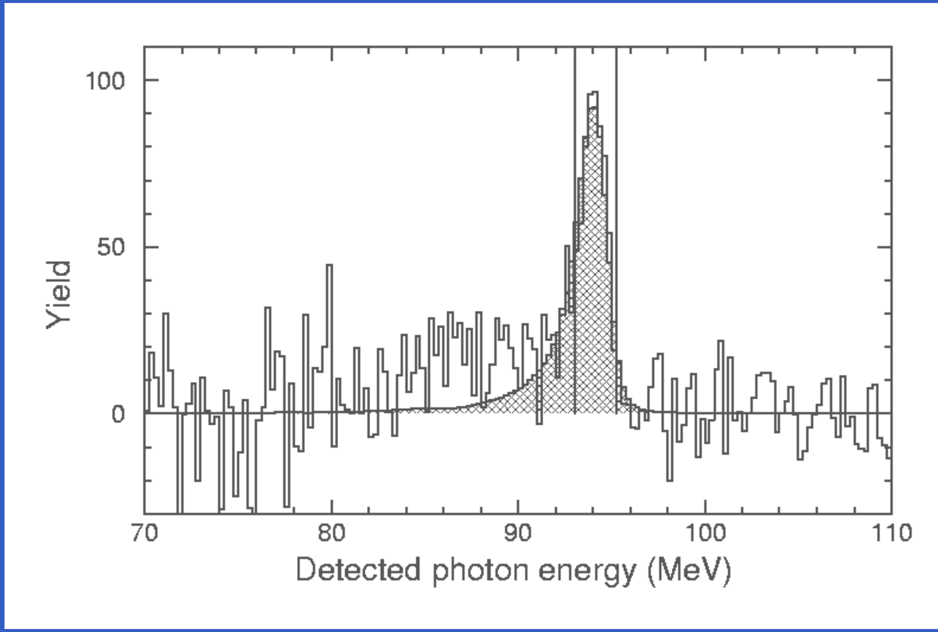


Possible to extract α_N and β_N from γd$\rightarrow$ γd data, but need to treat 2B effects SYSTEMATICALLY.

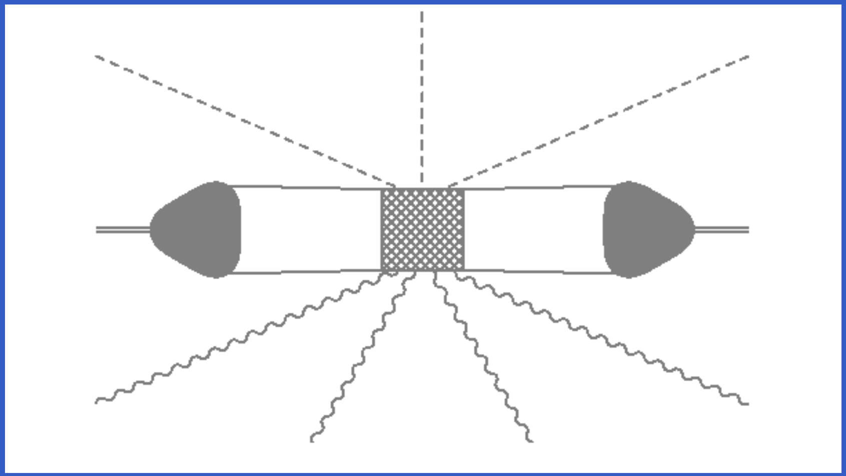
γd experiments

- Illinois (1994): M. Lucas, Ph.D. thesis, $\omega = 49, 69$ MeV;
- SAL (2000): D. Hornidge et al., PRL 84, 2334 (2000), $\omega = 85 - 105$ MeV;
- Lund (2003): M. Lundin et al., PRL 90, 192501 (2003), $\omega = 55, 65$ MeV.



D. Hornidge, PhD thesis (1999)

Reactions on deuterium



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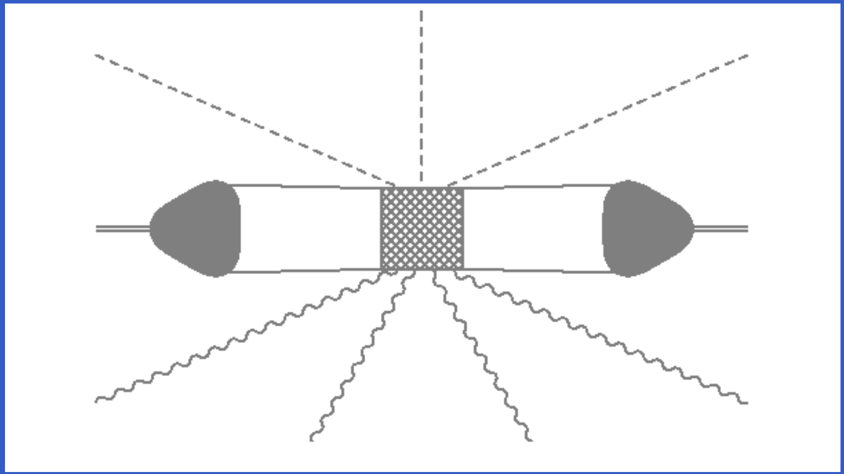
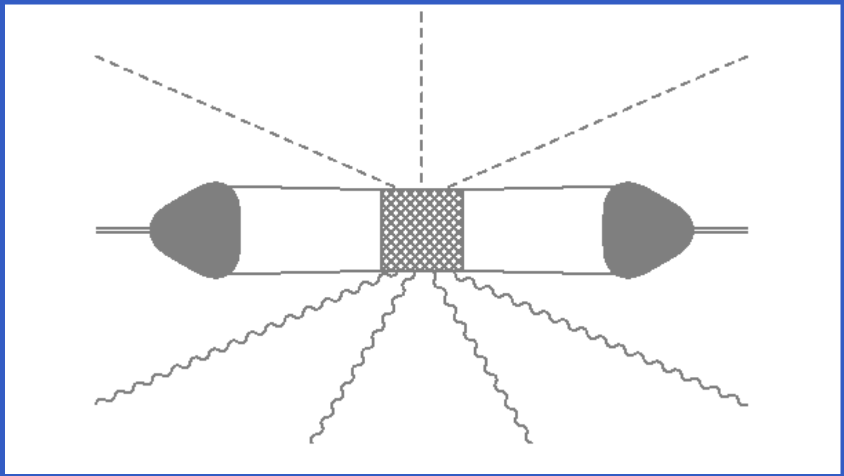


$$\langle \psi | \hat{O} | \psi \rangle$$

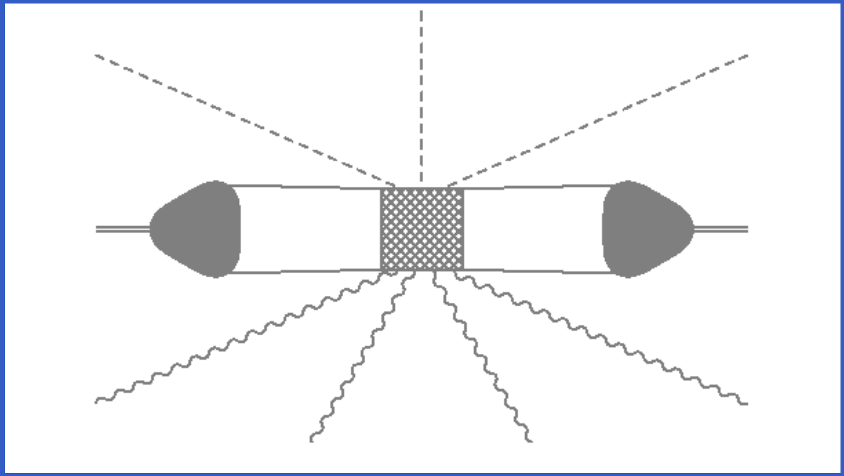
Reactions on deuterium



$$\langle\psi|\hat{O}|\psi\rangle$$

$|\psi\rangle$: from chiral NN potential,

Reactions on deuterium



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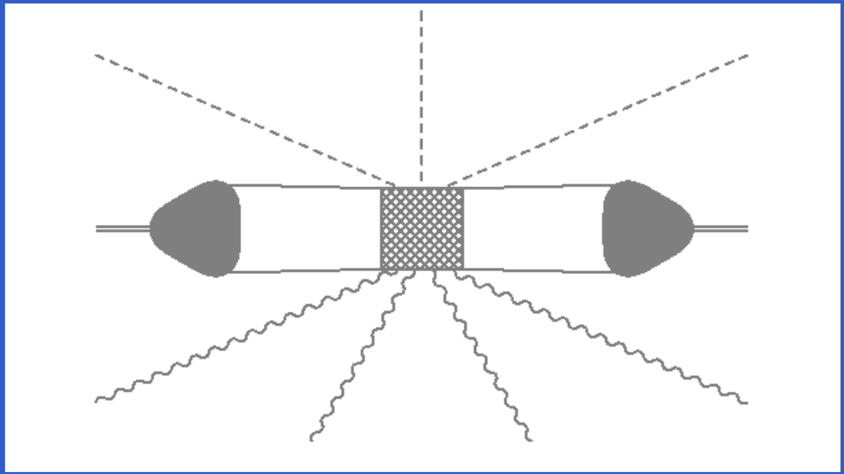
$|\psi\rangle$: from chiral NN potential, or from a potential model.

Reactions on deuterium



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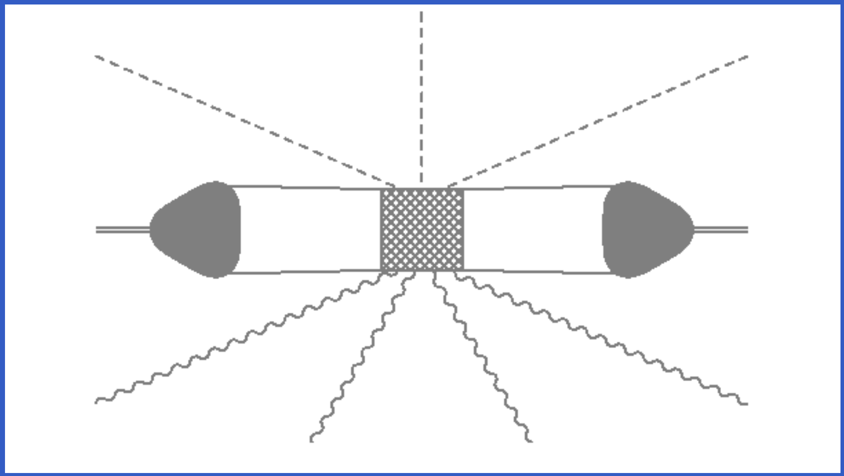

$$\langle\psi|\hat{O}|\psi\rangle$$

$|\psi\rangle$: from chiral NN potential, or from a potential model.

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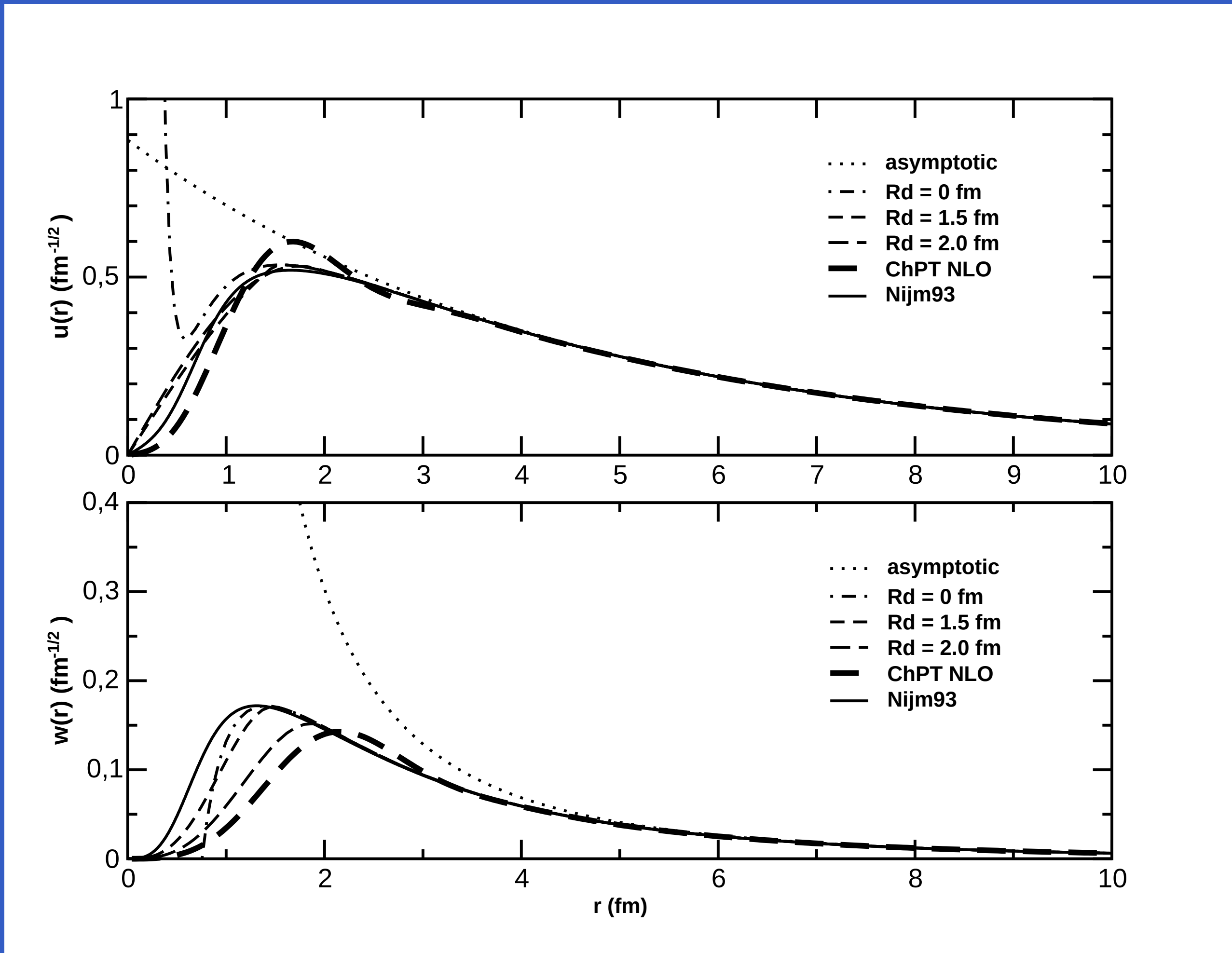
Should be model independent, systematically improvable, accurate at low momentum/energy transfer.

Deuteron wave functions



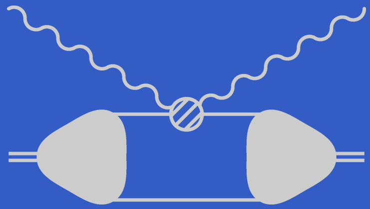
Same at long range: B, A_S, A_D, $f_{\pi NN}$, m_π.

Some differences at two-pion range.

γd in χPT to $O(e^2 P)$

S. R. Beane, M. Malheiro, D. P., U. van Kolck, Nucl. Phys. **A656**, 367 (1999)

$O(e^2)$:



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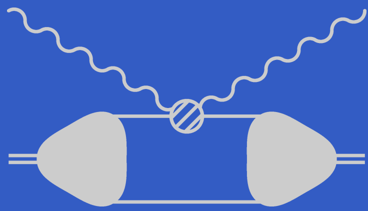

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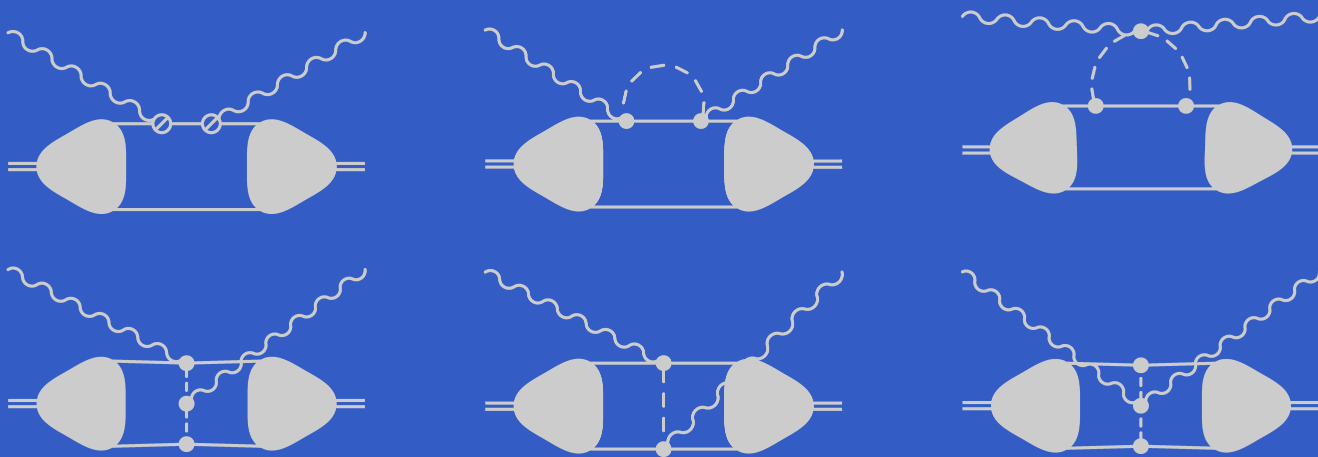

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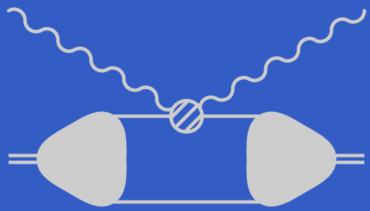

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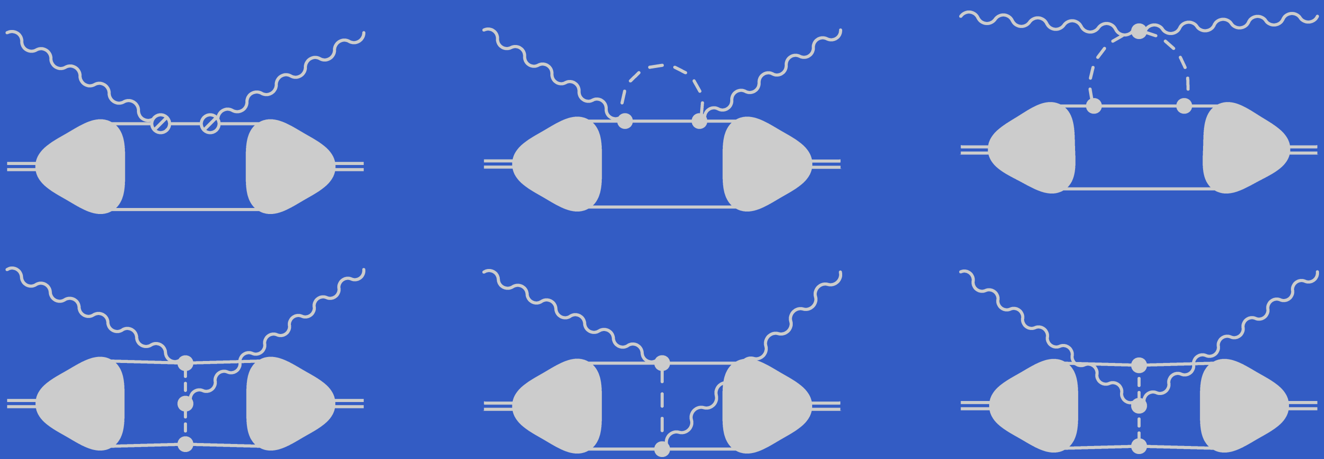
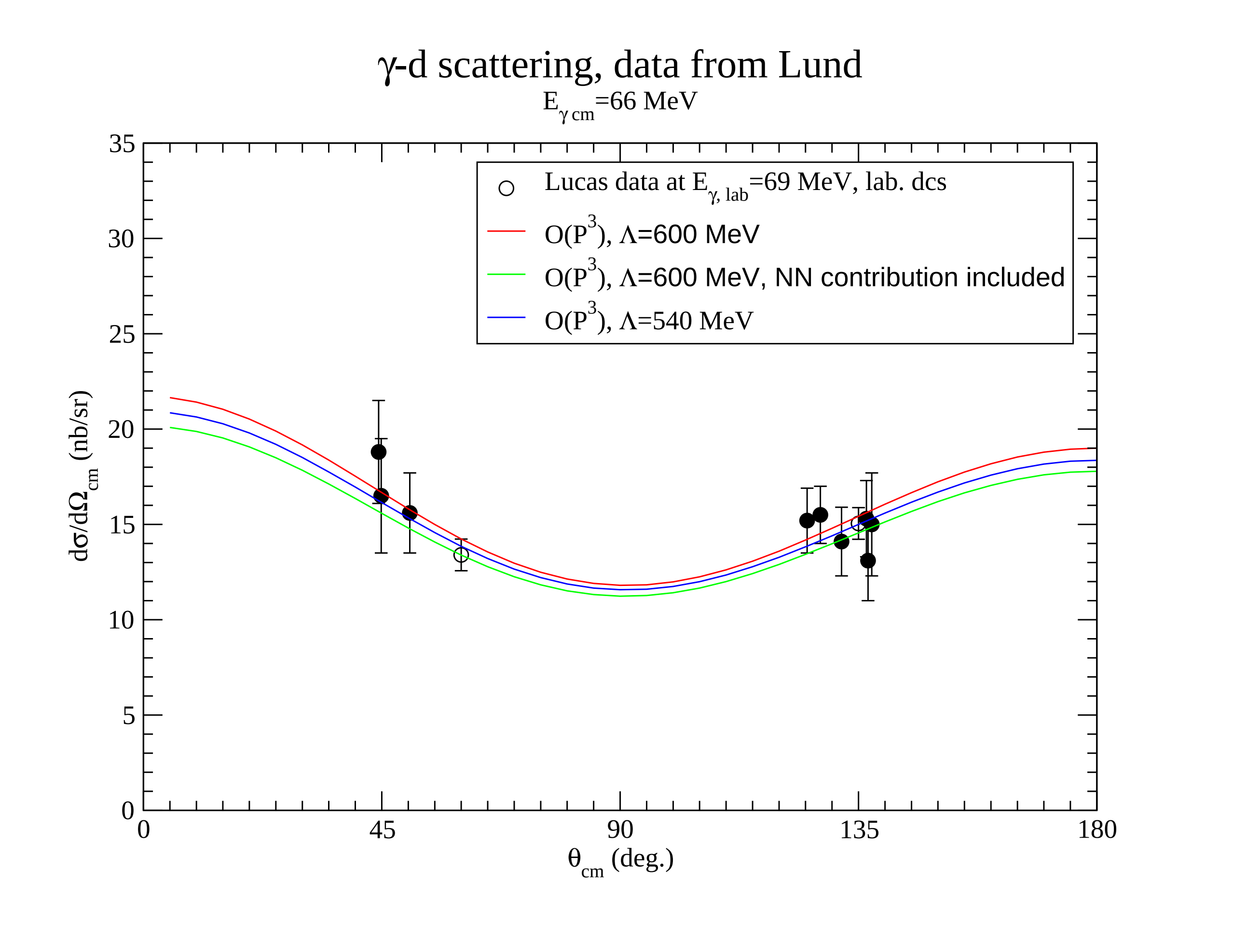


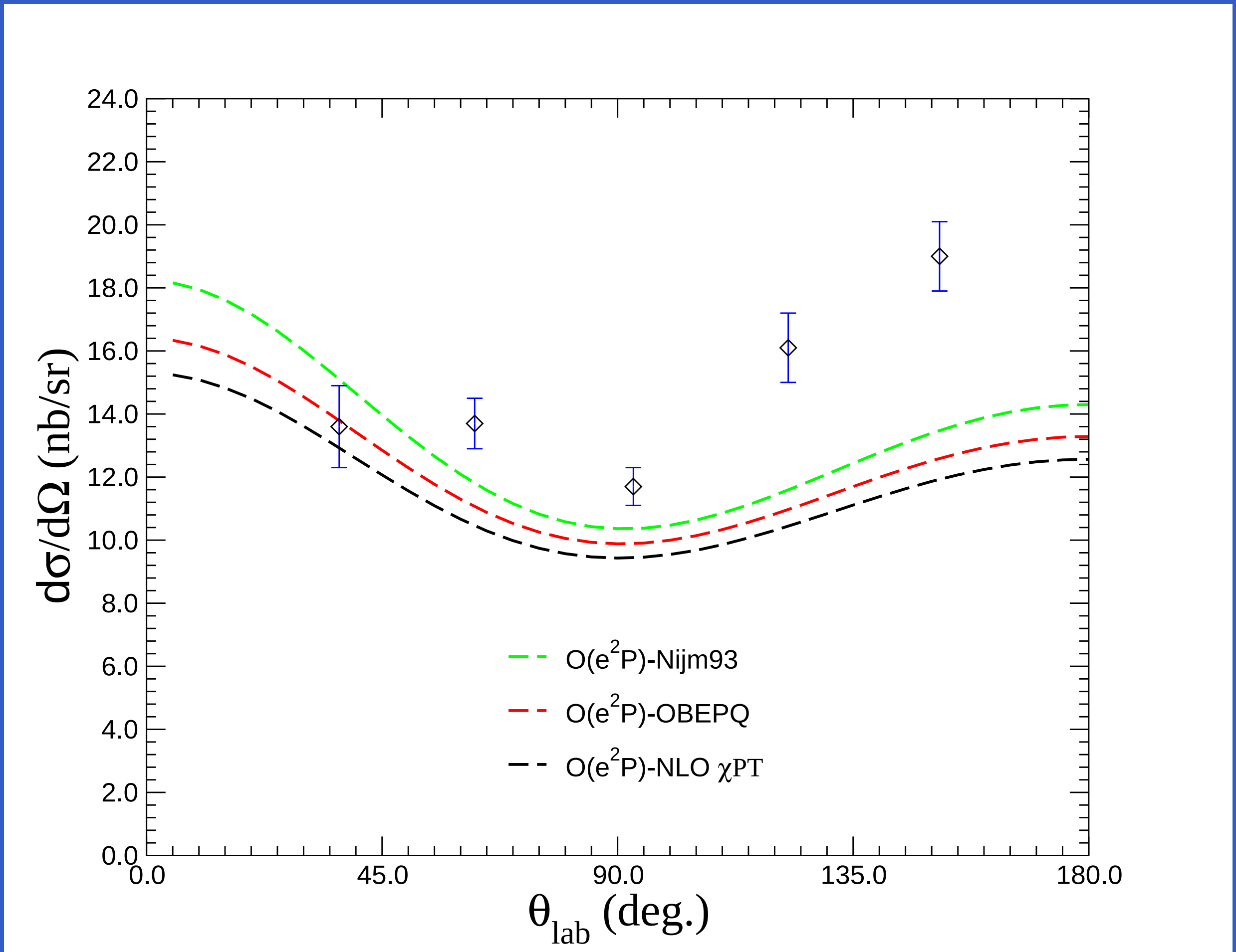
No free parameters at $O(e^2 P) \Rightarrow$ PREDICTION

Results: I



Wave-function dependence $\lesssim$ theoretical uncertainty.

A couple of problems



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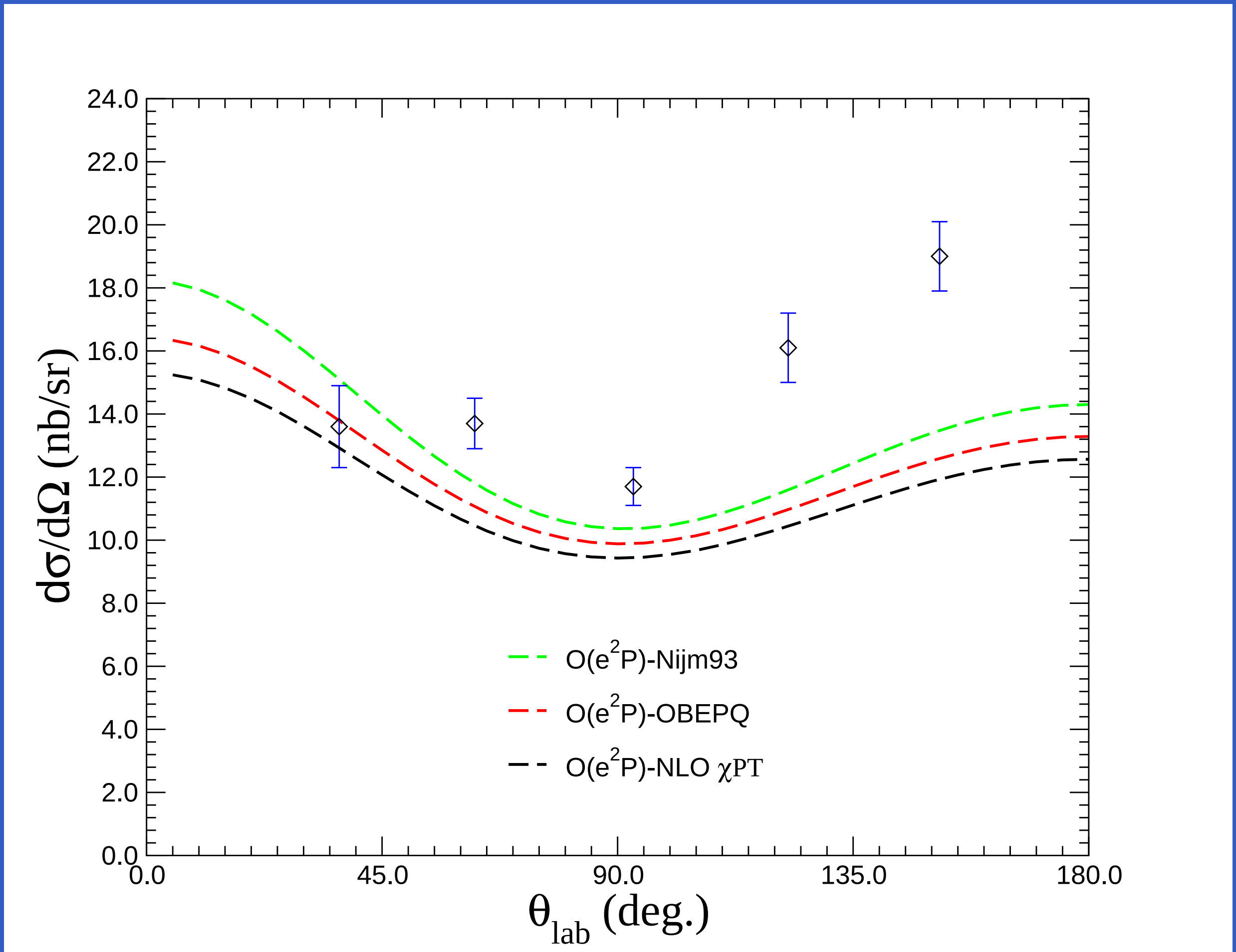

- Shape at $|\mathbf{q}| \approx 150$ MeV
- Wave-function dependence

γd scattering at $O(e^2P^2)$

S. R. Beane, M. Malheiro, J. McGovern, D. P., U. van Kolck, PLB (2003) & NPA (2005)

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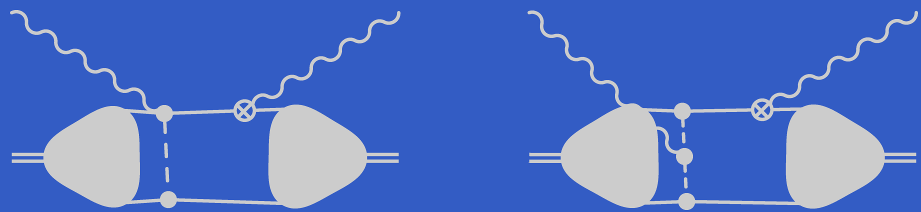

Calculable in terms of f_π, g_A, κ_V, m_π, and M.

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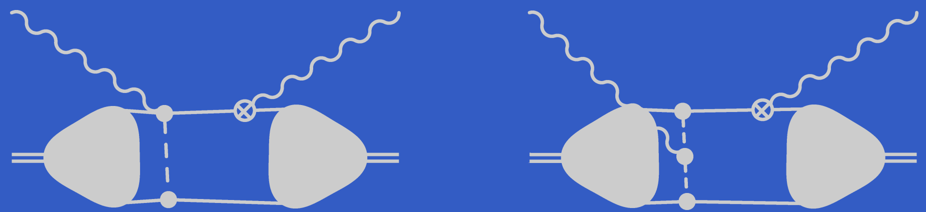
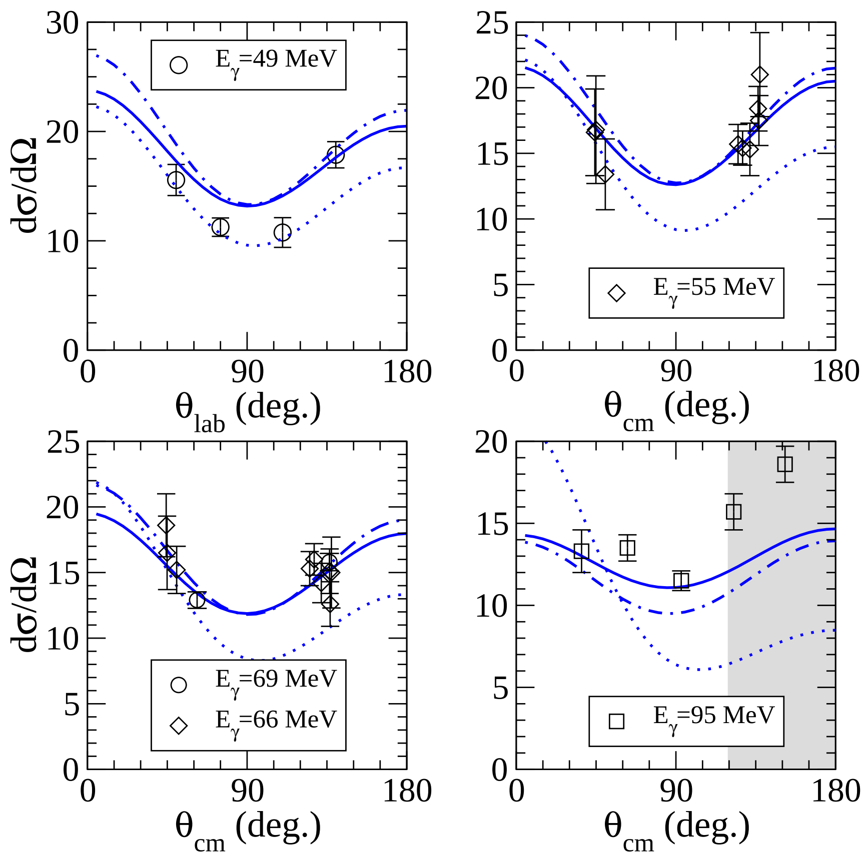


Calculable in terms of f_π, g_A, κ_V, m_π, and M.

Only free parameters are α_N and β_N.

Best-fit results



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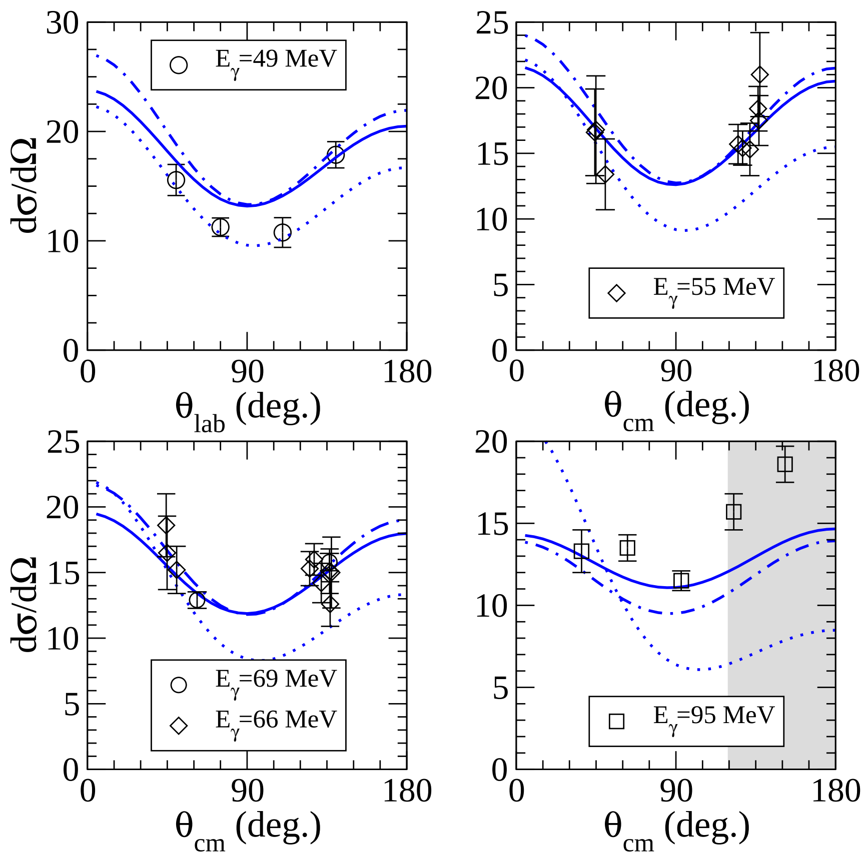

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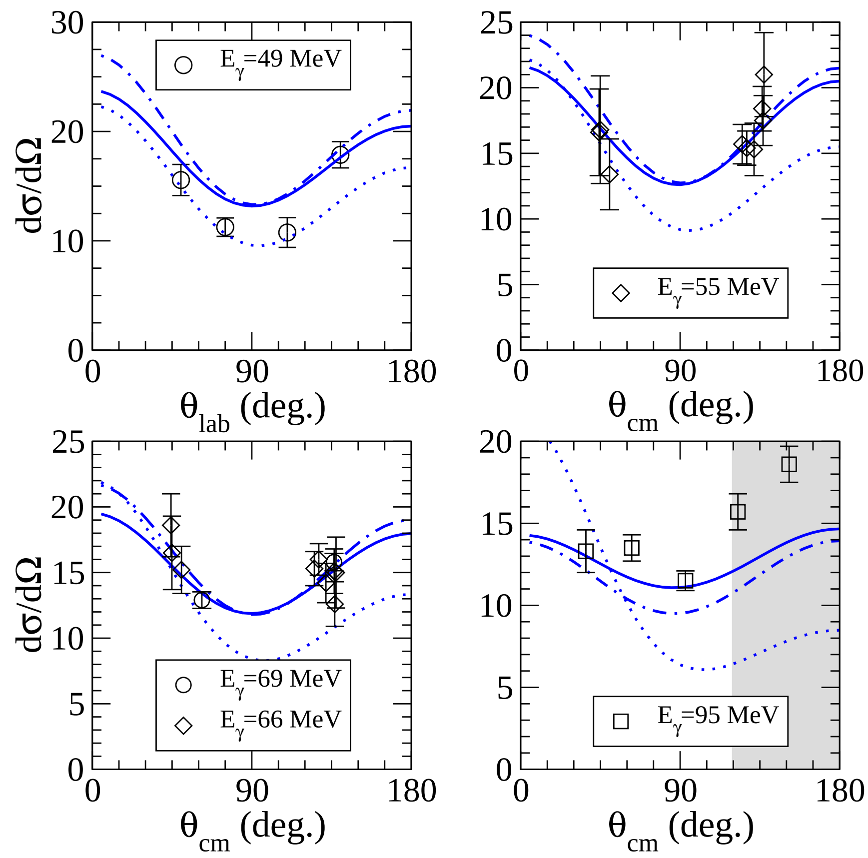

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$$\alpha_N = (13.0 \pm 1.9)^{+3.9}_{-1.5} \times 10^{-4}\ \mathrm{fm}^3$$
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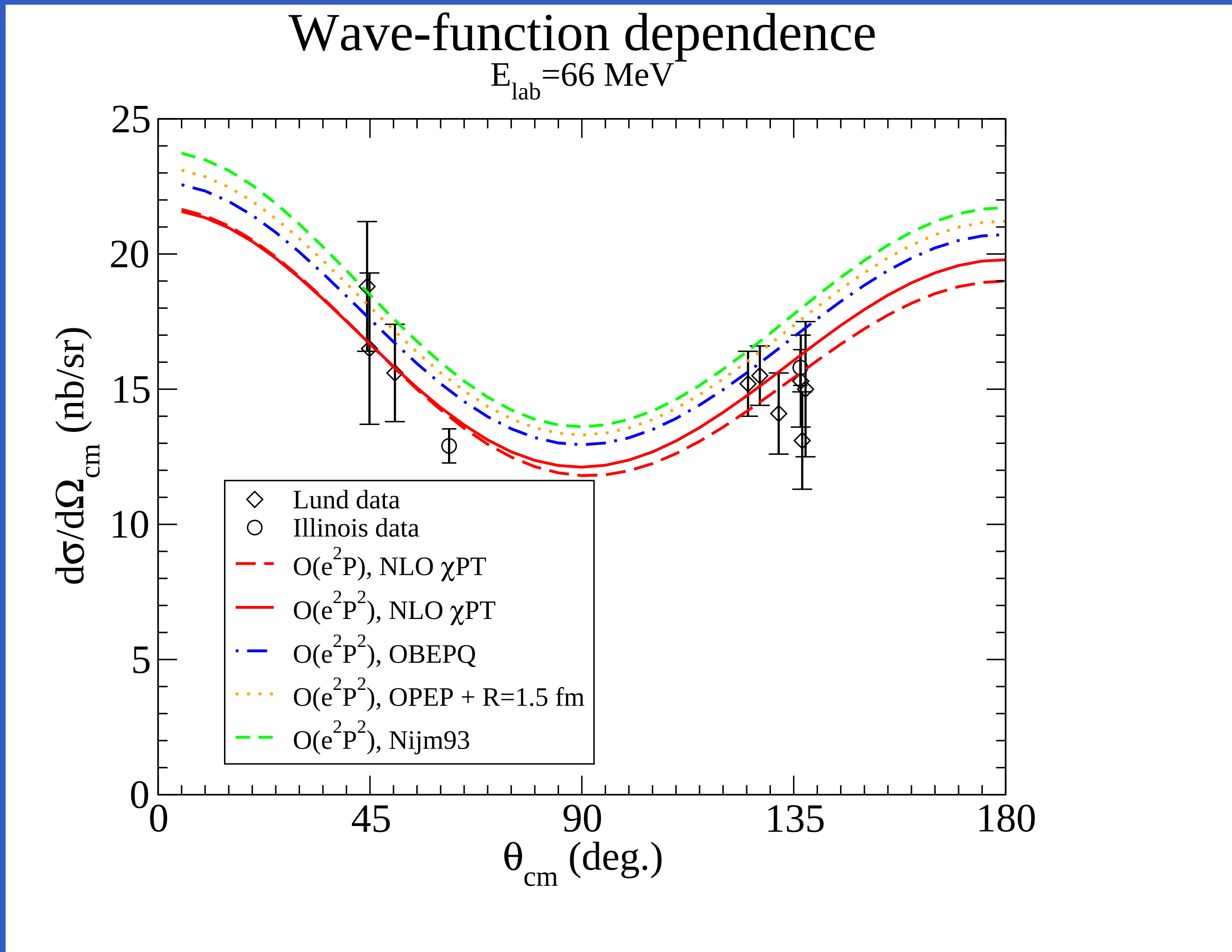
Dependence of cross section on $|\psi\rangle$



γd with an explicit Delta(1232)

R. Hildebrandt, H. Grießhammer, T. Hemmert, D.P., Nucl. Phys. A (2005)

- Calculation to $O(e^2\epsilon)$ in χPT with Delta(1232)
- $\alpha_{\rm high}$ and $\beta_{\rm high}$ promoted by one order, use values from fit to γp scattering

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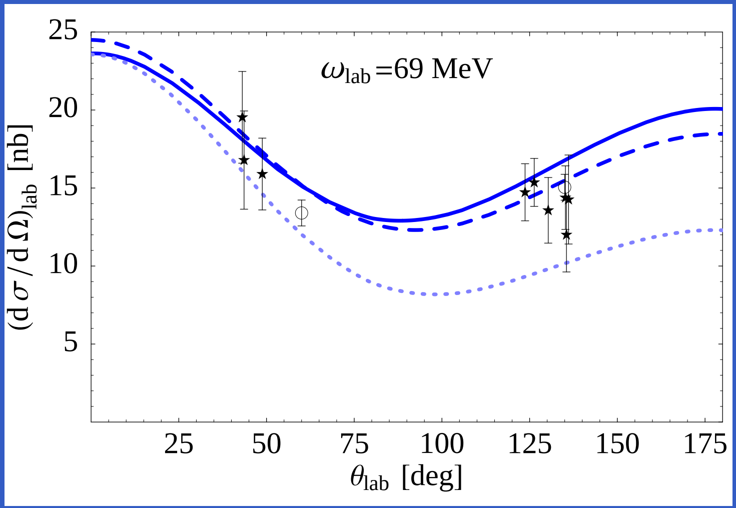

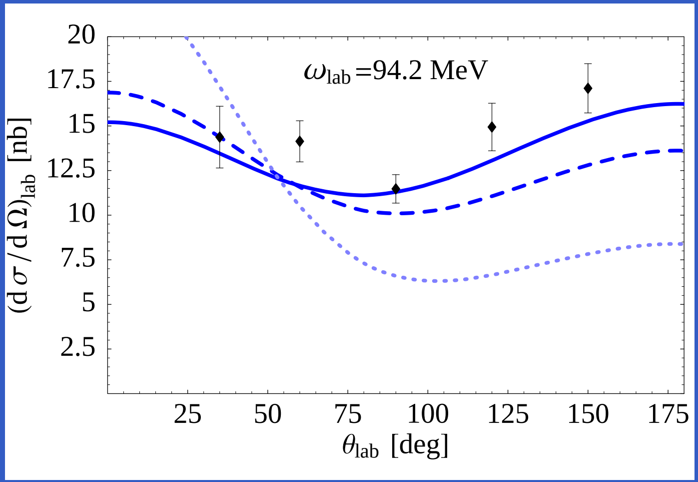

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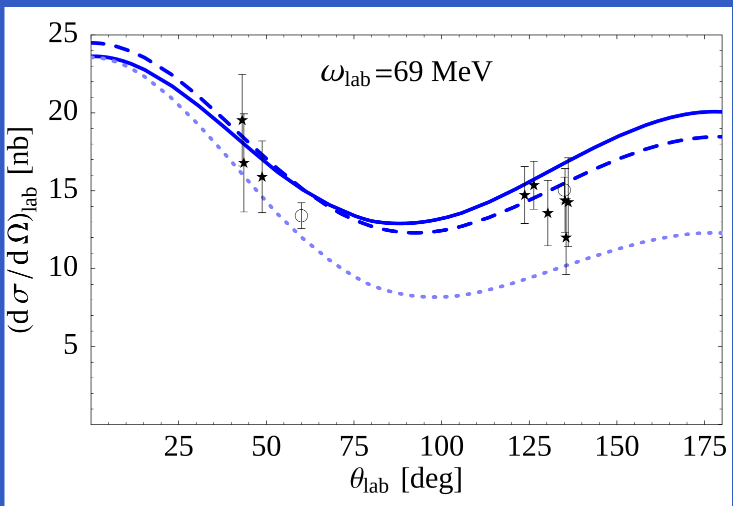
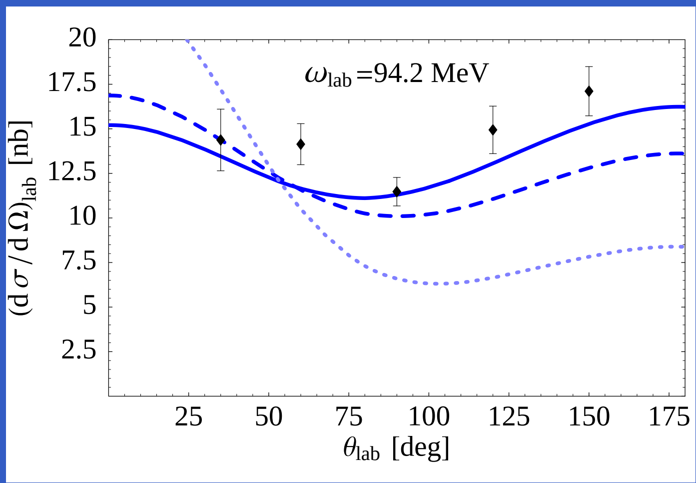
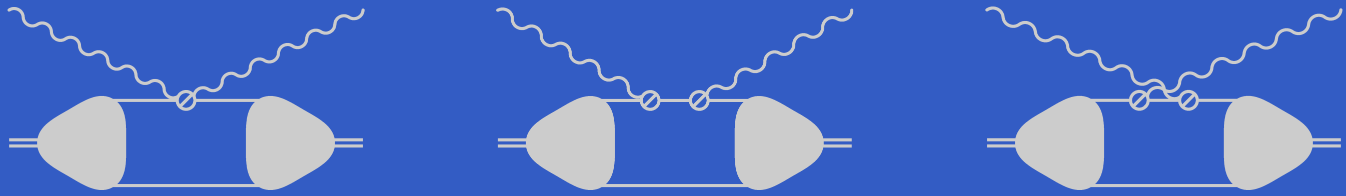




Prediction at $O(e^2\epsilon)$

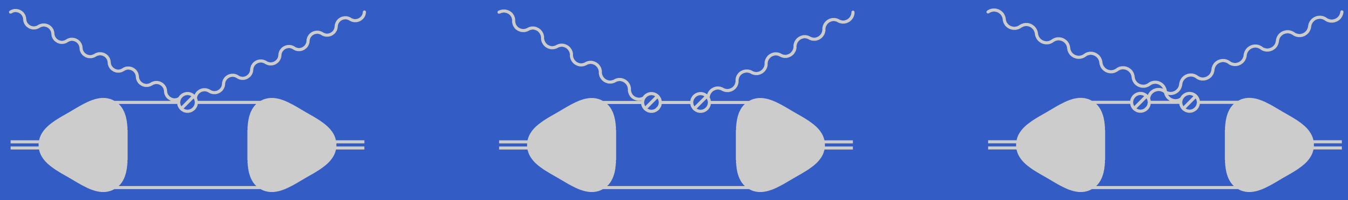
Going to low energies



In EFT($\not\pi$) (b) and (c) crucial for recovery of

$$T(\omega = 0) = -\frac{e^2}{M_d}\ \epsilon' \cdot \epsilon$$

Going to low energies



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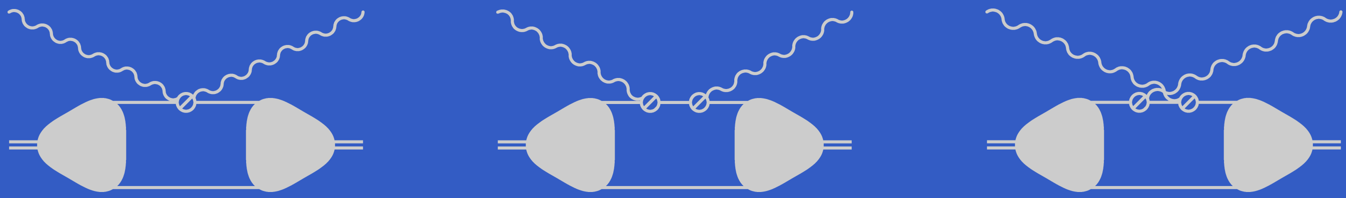

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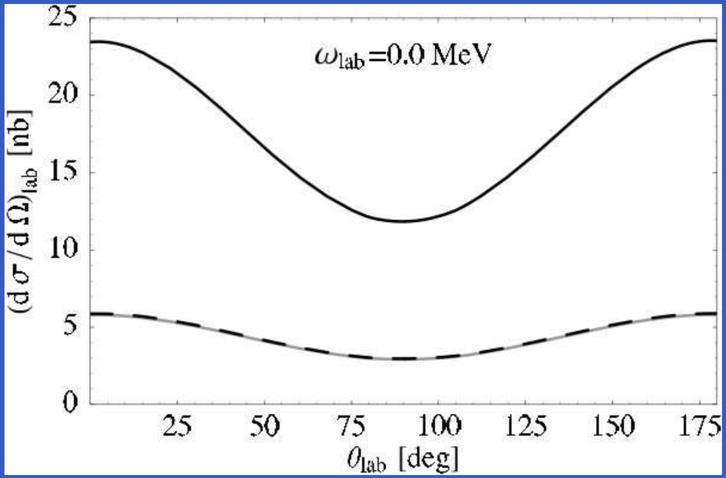
Also crucial is to use: $\frac{1}{\omega - p^2/M}$ NOT $\frac{1}{\omega}$

- Modification of power-counting needed for $\omega \sim m_\pi^2/M$;
- Estimates $\Rightarrow$ significant at 49 and 55 MeV. Higher order at 95 MeV.

The solution

Hildebrandt, Grießhammer, Hemmert, nucl-th/0512063



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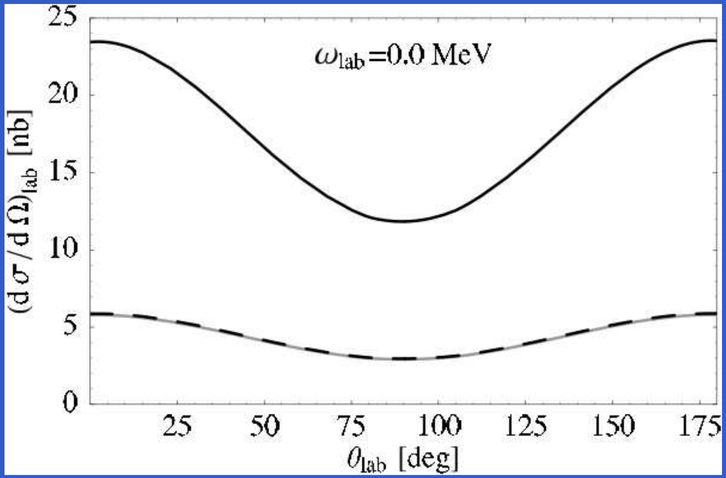
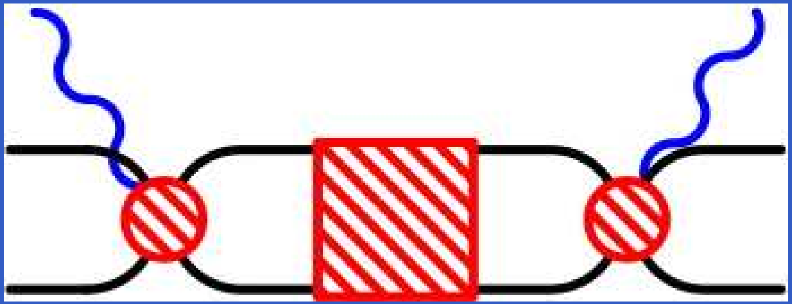
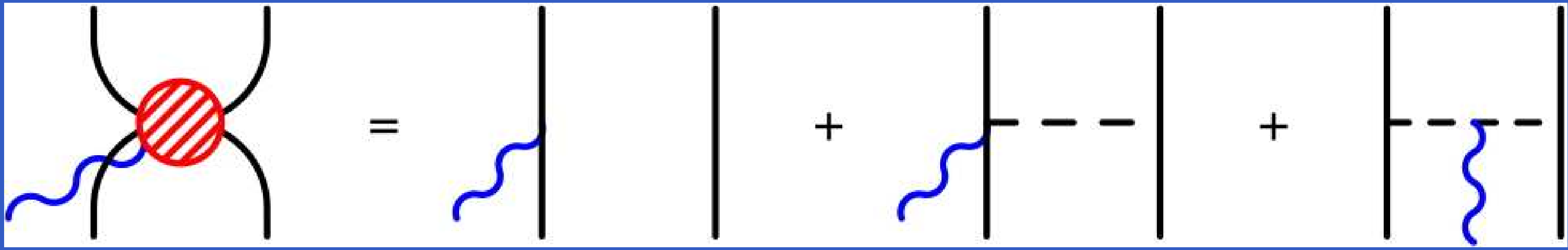
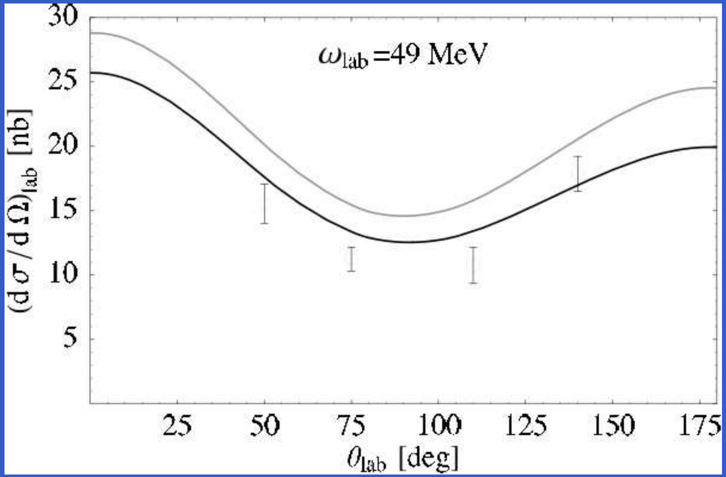


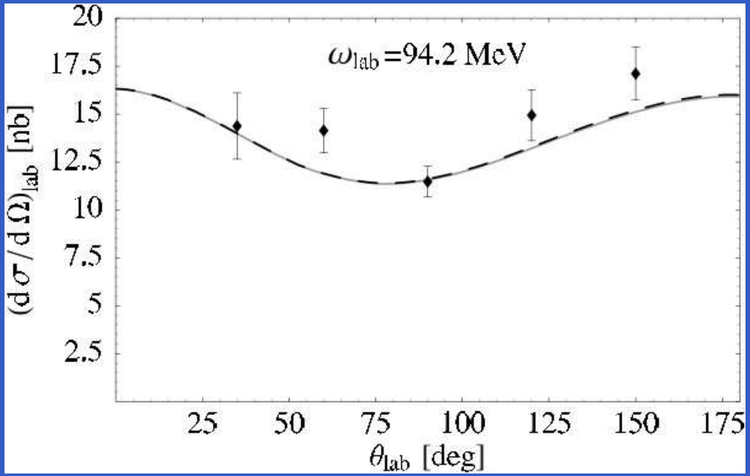
How is Thomson limit repaired?





The benefits of clean living





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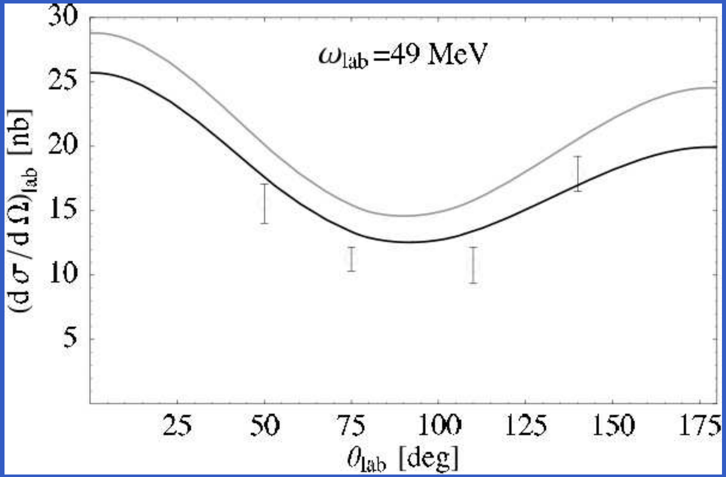

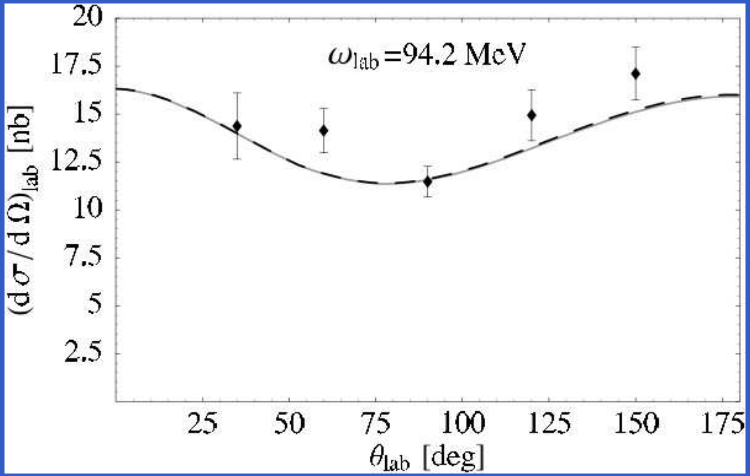

$$\alpha_N = (11.3 \pm 0.7 \pm 0.6) \times 10^{-4}\ \mathrm{fm}^3$$
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Theoretical uncertainty much smaller now

γd at MAX-Lab

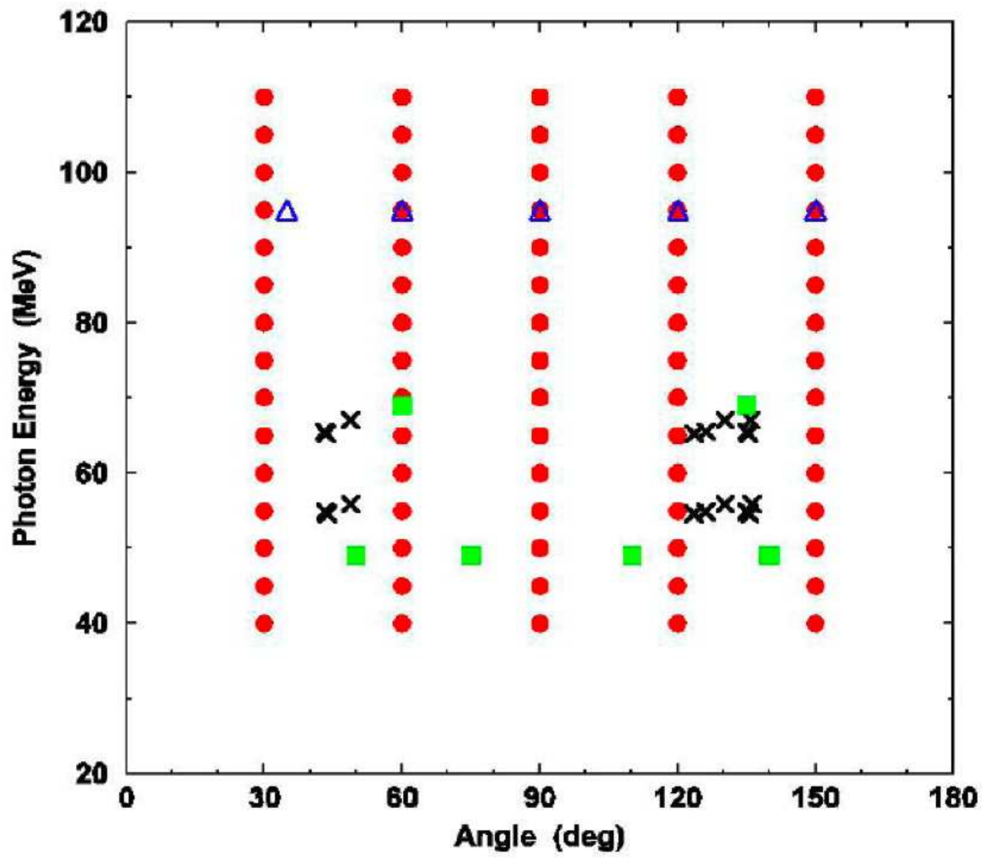

figure courtesy J. Feldman

Conclusions: γd

- $O(e^2 P)$ [NLO]: Parameter-free predictions.

  $\surd$ $\omega \leq 80$ MeV.

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Thanks to the U.S. Department of Energy for support.

Naive dimensional analysis for $\hat{O}$

- P^n for a vertex with n powers of p or m_π: $\mathcal{L}^{(n)}$;
- P^{-2} for each pion propagator: $\frac{1}{q^2 - m_\pi^2}$;
- P^{-1} for each NN propagator: $\frac{1}{E - \mathbf{p}^2/M}$;
- P^4 for each loop: $\int d^4k$;
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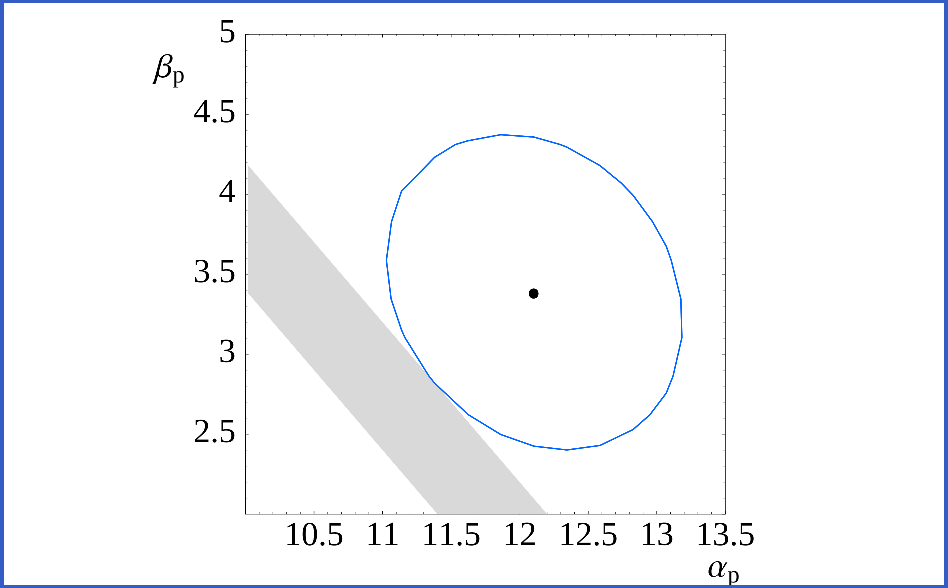
Loops, many-body effects, and vertices from $\mathcal{L}^{(2,3)}$ etc. suppressed by powers of P.

Baldin Sum Rule



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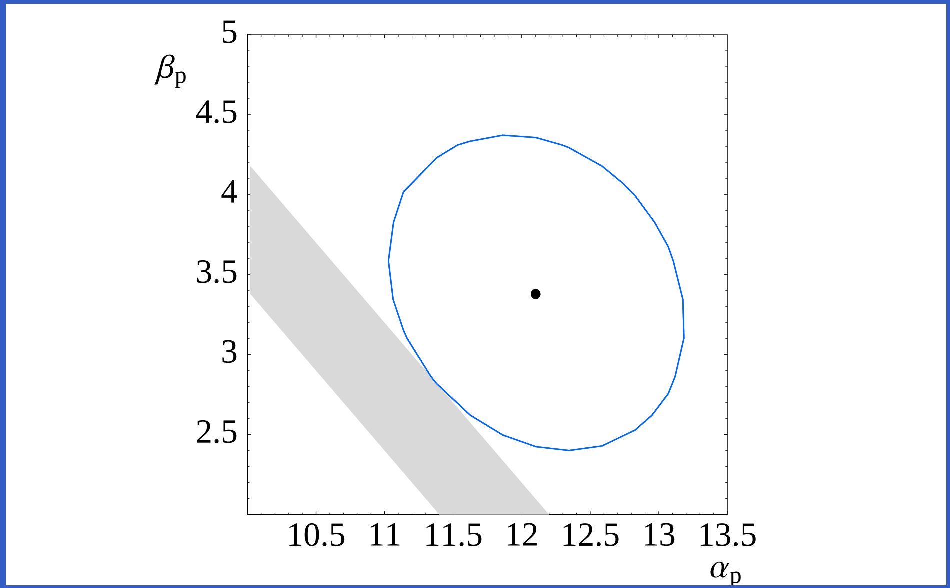

With Baldin Sum Rule constraint:

$$\alpha_p + \beta_p = (13.8 \pm 0.4) \times 10^{-4}\ \mathrm{fm}^3$$

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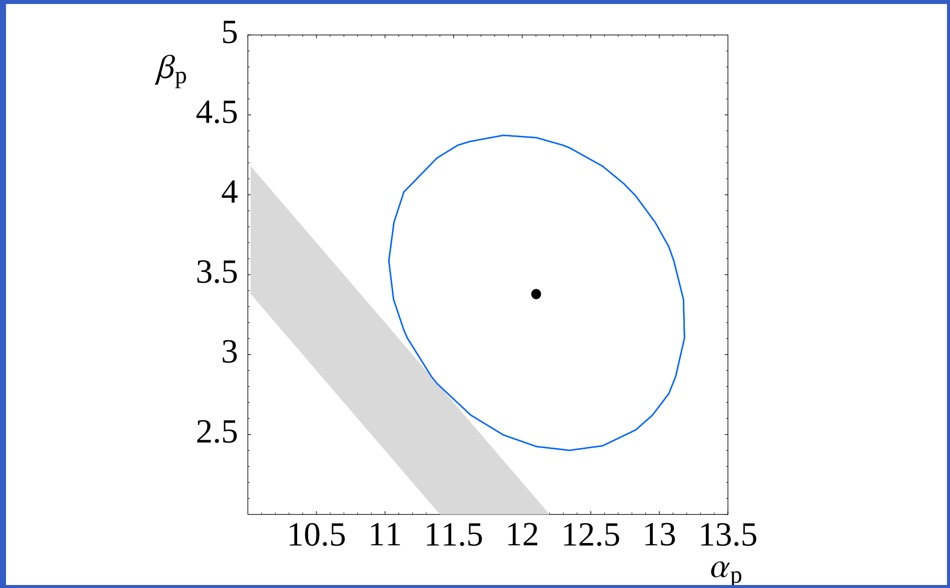

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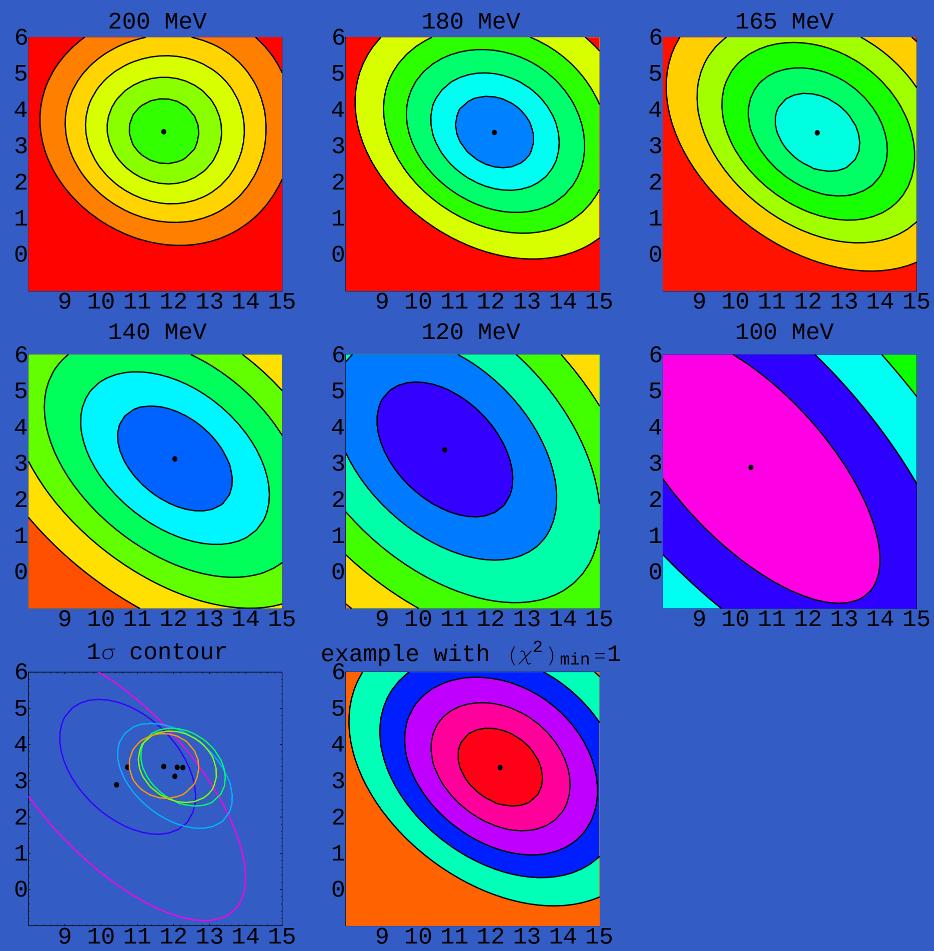
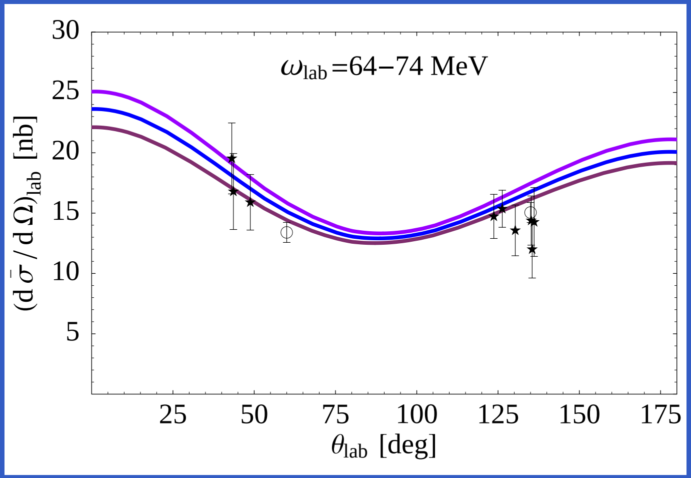
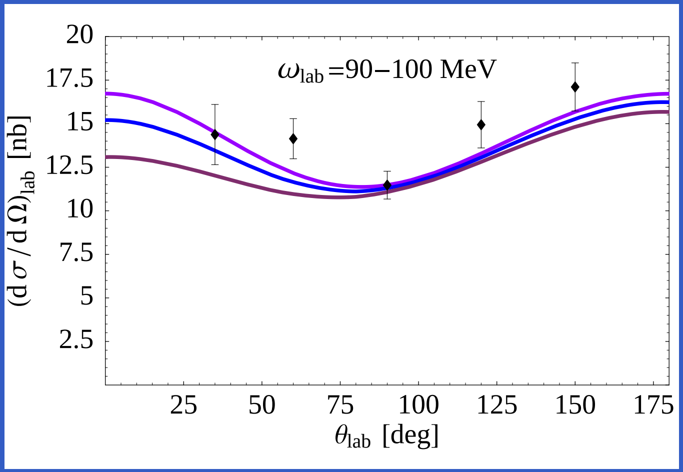
Cutoff dependence of γp fit

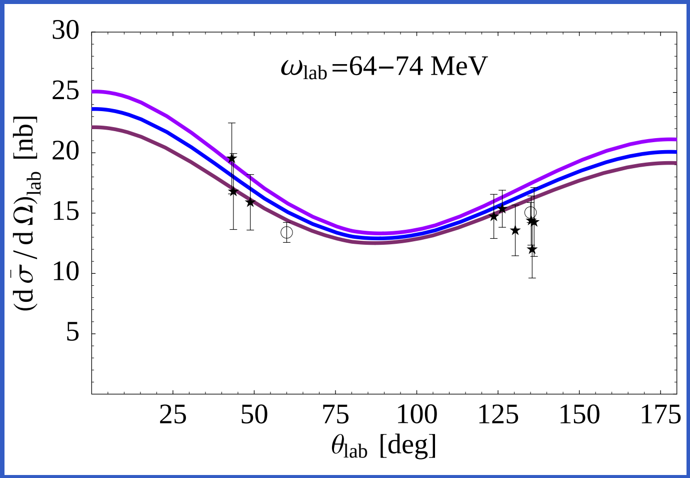


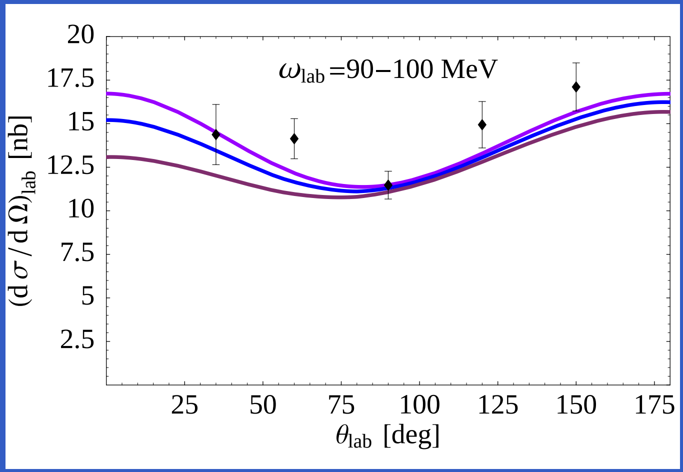
Energy dependence of $T_{\gamma N}$?

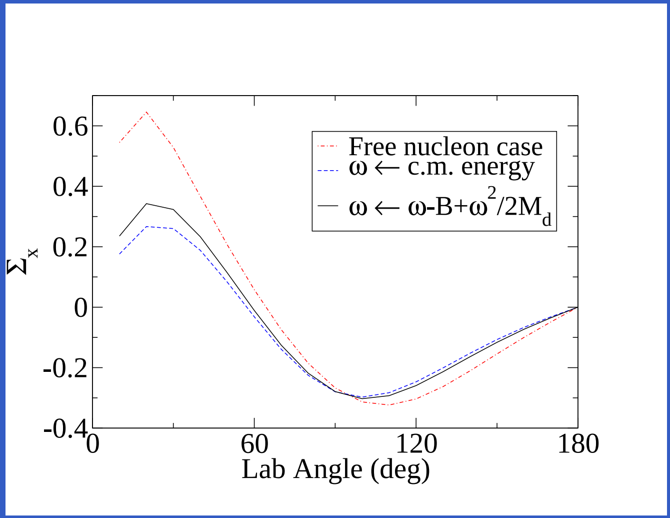




Energy dependence of $T_{\gamma N}$?







c.f. Lensky, Hanhart, *et al.*