Compton Scattering from the proton, deuteron, and neutron

DANIEL PHILLIPS

Department of Physics and Astronomy
Ohio University, Athens, Ohio

Outline

- Compton scattering on the proton in chiral perturbation theory for $\omega \sim m_\pi$
- An EFT for γp scattering in the Delta region
- Compton scattering on deuterium and the extraction of nucleon polarizabilities
- Conclusions, Future Work, and Shameless Advertising

Chiral perturbation theory

$\mathcal{L}(N, \pi)$ constrained by (approximate) $SU(2)_L \times SU(2)_R$ of QCD.

Chiral perturbation theory

$\mathcal{L}(N, \pi)$ constrained by (approximate) $SU(2)_L \times SU(2)_R$ of QCD.

Chiral perturbation theory is the most general $\mathcal{L}(N, \pi)$ consistent with the symmetries of QCD and the pattern of their breaking, up to a given order in the small expansion parameter:

$$P \equiv \frac{p, m_\pi}{m_\rho, 4\pi f_\pi}$$

Unknown coefficients at a given order need to be determined.

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

Chiral perturbation theory

$\mathcal{L}(N, \pi)$ constrained by (approximate) $SU(2)_L \times SU(2)_R$ of QCD.

Chiral perturbation theory is the most general $\mathcal{L}(N, \pi)$ consistent with the symmetries of QCD and the pattern of their breaking, up to a given order in the small expansion parameter:

$$P \equiv \frac{p, m_\pi}{m_\rho, 4\pi f_\pi}$$

Unknown coefficients at a given order need to be determined.

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

χPT is:

- Model-independent;
- Systematically improvable.

Many successful applications to A=1 at low energy. (Also $A = 0$.)

Chiral perturbation theory

$\mathcal{L}(N, \pi)$ constrained by (approximate) $SU(2)_L \times SU(2)_R$ of QCD.

Chiral perturbation theory is the most general $\mathcal{L}(N, \pi)$ consistent with the symmetries of QCD and the pattern of their breaking, up to a given order in the small expansion parameter:

$$P \equiv \frac{p, m_\pi}{m_\rho, 4\pi f_\pi}$$

Unknown coefficients at a given order need to be determined.
p/M expansion employed: (usually) useful, not essential.

χPT is:

- Model-independent;
- Systematically improvable.

Many successful applications to A=1 at low energy. (Also $A = 0$.)

The Δ: to include or not to include? $m_\pi \ll \Delta \ll m_\rho$?

Jenkins, Manohar, Hemmert, Holstein, …

Power counting in χPT

Rules:

- 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: $\frac{1}{p_0-\mathbf{p}^2/(2M)}$;
- P^4 for each loop: $\int d^4k$;

Power counting in χPT

Rules:

- 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: $\frac{1}{p_0 - \mathbf{p}^2/(2M)}$;
- P^4 for each loop: $\int d^4k$;

Power counting for loops as well as for $\mathcal{L}$

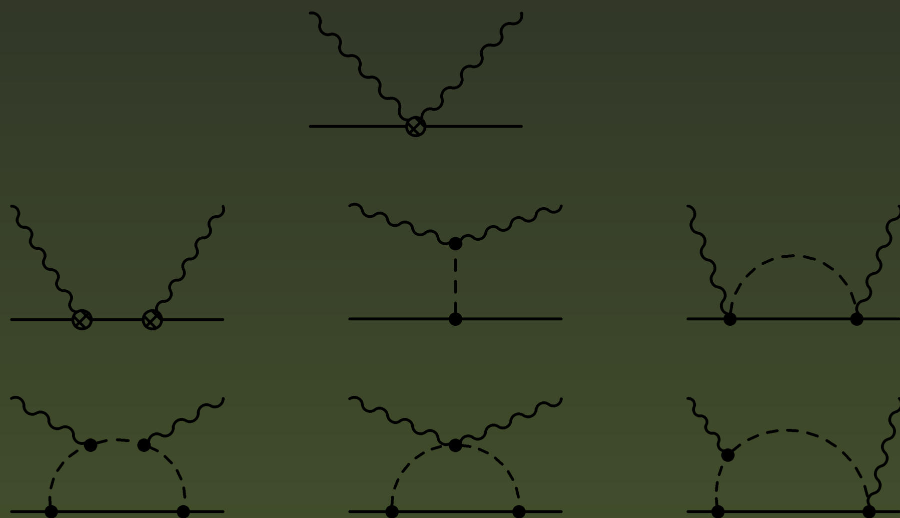
$$\Rightarrow \mathcal{A}(\pi s, \gamma s, N) = \sum_n \mathcal{F}_n \left(\frac{p}{m_\pi}\right) P^n,$$

$\mathcal{F}_n \sim O(1)$: "naturalness".

Nucleon Compton Scattering in χPT

$O(e^2)$:

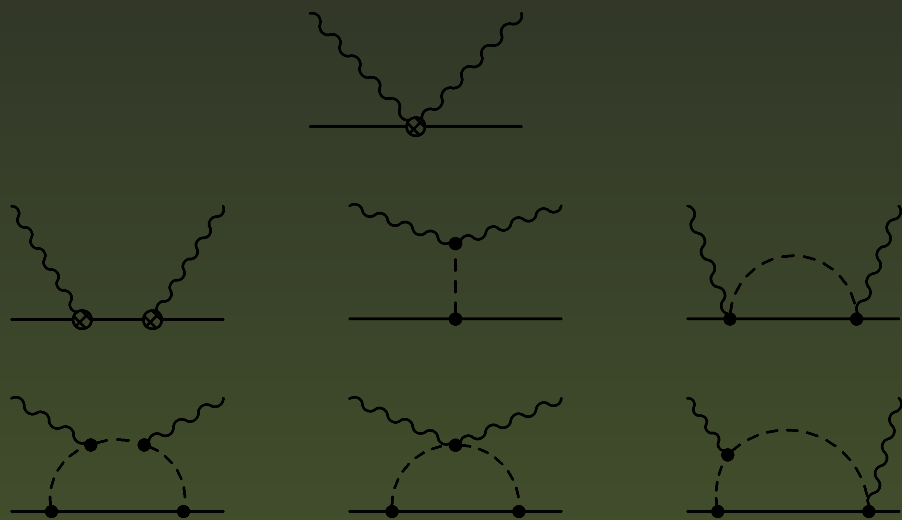
$O(e^2 P)$:



Nucleon Compton Scattering in χPT

$O(e^2)$:

$O(e^2 P)$:



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

Powell X-Sn +

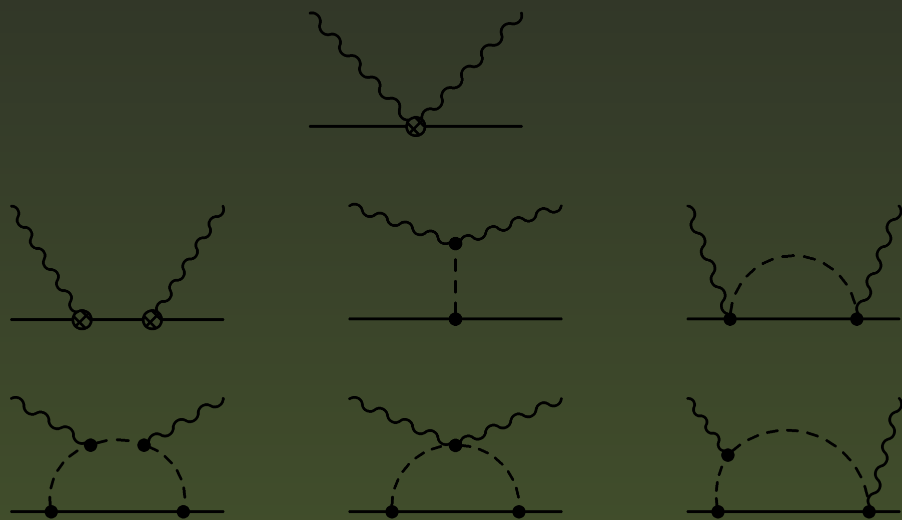
non-analyticity

from loops

Nucleon Compton Scattering in χPT

$O(e^2)$:

$O(e^2 P)$:



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

Powell X-Sn +

non-analyticity

from loops

Small ω expansion:

$$\mathcal{A}_{\gamma N}(\omega) = \left[-\frac{e^2}{M} + 4\pi\alpha_N \omega^2\right]\epsilon' \cdot \epsilon + 4\pi\beta_N \omega^2 (\epsilon \times \mathbf{k}) \cdot (\epsilon' \times \mathbf{k}')$$

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

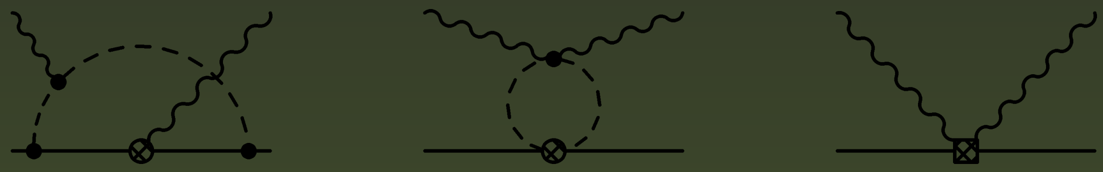
Bernard, Kaiser, Meißner (1992)

PDG average:

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

N²LO: $O(e^2 P^2)$

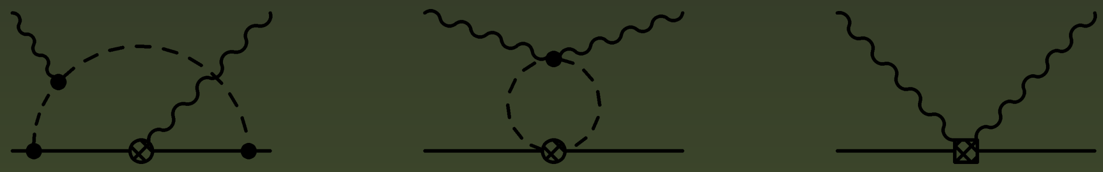
γN amplitude at $O(e^2 P^2)$



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

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

γN amplitude at $O(e^2P^2)$



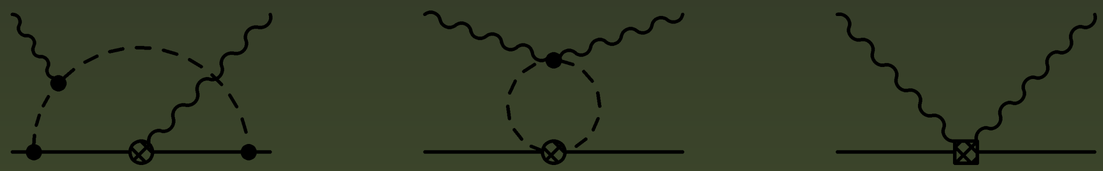
J. McGovern, Phys. Rev. C **63**, 064608 (2001)

Short-distance physics via contact terms , with coefficients which should be fit to data:

$$4\pi\Delta\alpha_N \mathbf{E}^2, 4\pi\Delta\beta_N \mathbf{B}^2 \qquad \sim \omega^2 e^2$$

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

γN amplitude at $O(e^2P^2)$



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

Short-distance physics via contact terms , with coefficients which should be fit to data:

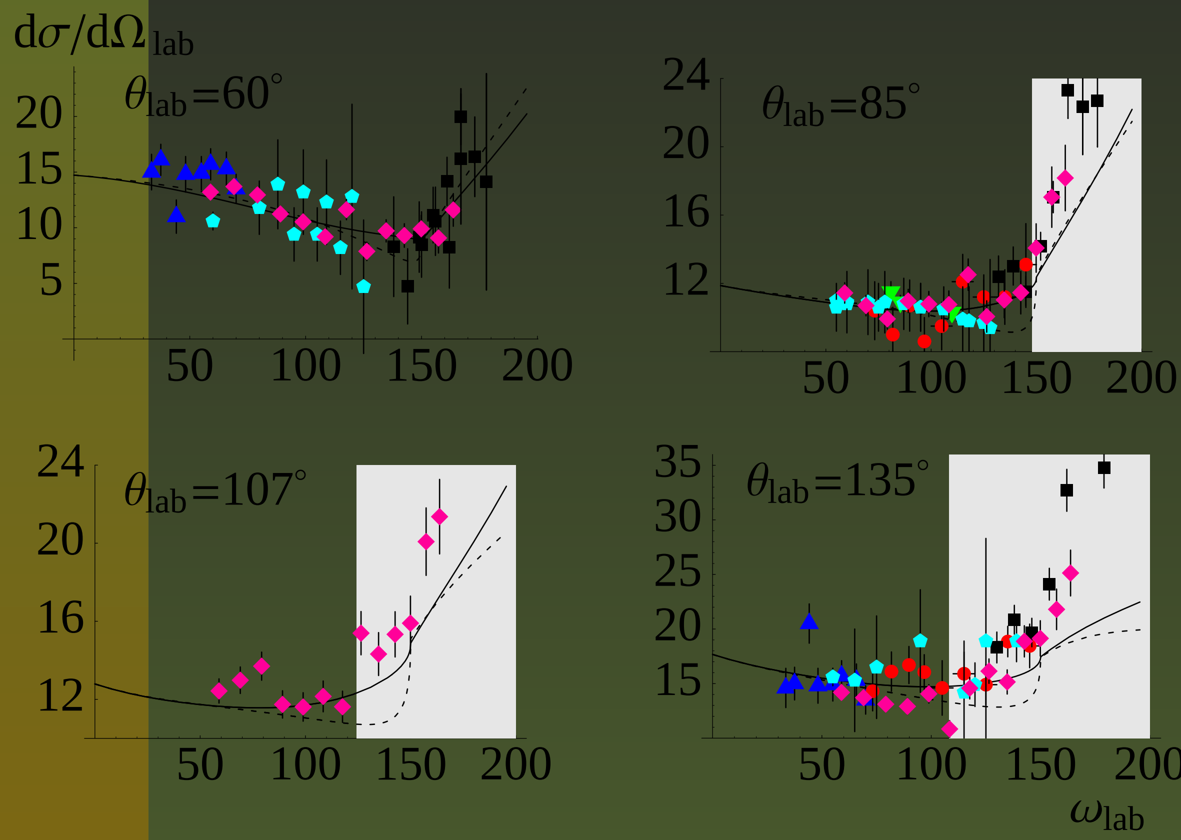
$$4\pi\Delta\alpha_N\mathbf{E}^2, 4\pi\Delta\beta_N\mathbf{B}^2 \qquad \sim \omega^2 e^2$$

Experiments: SAL/Illinois, LEGS, MAMI, $\ldots$.

Kinematic restriction (Δ-less χPT): ω, $\sqrt{|t|} \leq 200$ MeV.

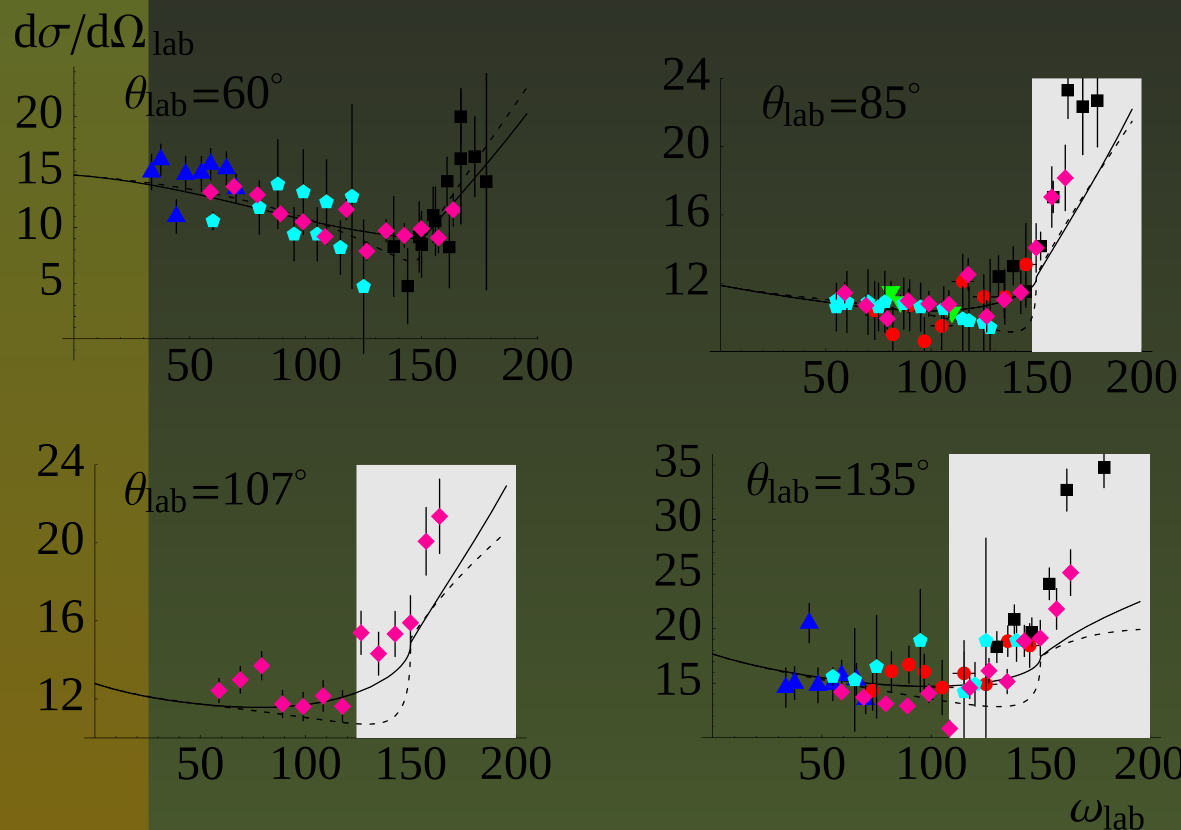
Fits with explicit Δ: R. Hildebrandt *et al.*, `nucl-th/0307070`.

Results



χ^2/d.o.f.=170/131

Results



χ^2/d.o.f.=170/131

$$\alpha_p = (12.1 \pm 1.1)^{+0.5}_{-0.5} \times 10^{-4}\ \mathrm{fm}^3$$
$$\beta_p = (3.4 \pm 1.1)^{+0.1}_{-0.1} \times 10^{-4}\ \mathrm{fm}^3$$

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

What's in a name?

Washington-Arizona-Rio-Manchester-Ohio: WARMO

What's in a name?

Washington-Arizona-Rio-Manchester-Ohio: WARMO

Fluminense-Ohio-Arizona-Manchester-INT: FOAMI

What's in a name?

Washington-Arizona-Rio-Manchester-Ohio: WARMO

Fluminense-Ohio-Arizona-Manchester-INT: FOAMI

COMPTON

What's in a name?

Washington-Arizona-Rio-Manchester-Ohio: WARMO

Fluminense-Ohio-Arizona-Manchester-INT: FOAMI

COMPTON

Computing One Much-discussed Process That Occurs in Nature

What's in a name?

Washington-Arizona-Rio-Manchester-Ohio: WARMO

Fluminense-Ohio-Arizona-Manchester-INT: FOAMI

COMPTON

Computing One Much-discussed Process That Occurs in Nature

Calculating the Outcome of Many Photons Targetted On a Nucleus

What’s in a name?

Washington-Arizona-Rio-Manchester-Ohio: WARMO

Fluminense-Ohio-Arizona-Manchester-INT: FOAMI

COMPTON

Computing One Much-discussed Process That Occurs in Nature

Calculating the Outcome of Many Photons Targetted On a Nucleus

Collaboration Of Many Physicists: Theorists or Nincompoops?

What's in a name?

Washington-Arizona-Rio-Manchester-Ohio: WARMO

Fluminense-Ohio-Arizona-Manchester-INT: FOAMI

COMPTON

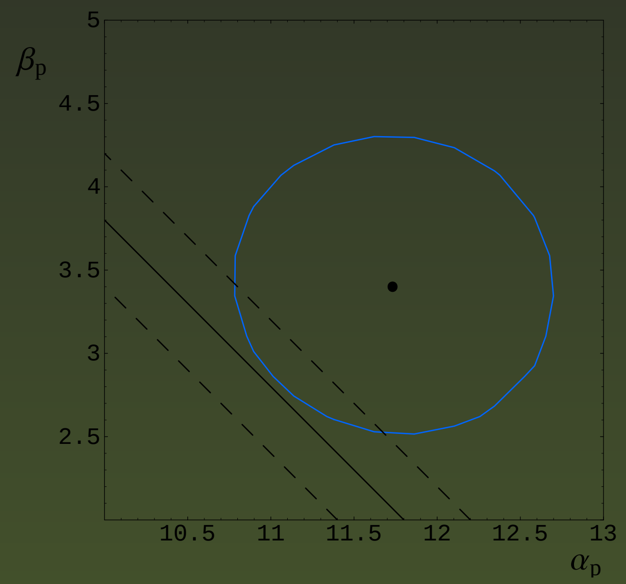
Computing One Much-discussed Process That Occurs in Nature

Calculating the Outcome of Many Photons Targetted On a Nucleus

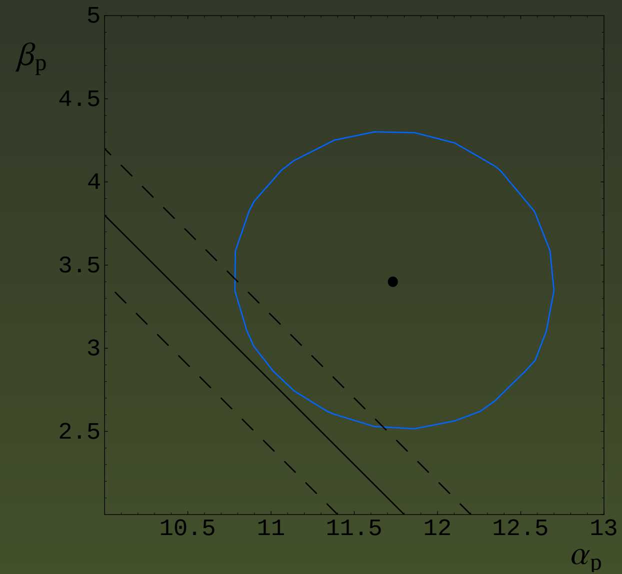
Collaboration Of Many Physicists: Theorists or Nincompoops?

Manchester-Athens-Fluminense-INT-Arizona: MAFIA

Baldin Sum Rule



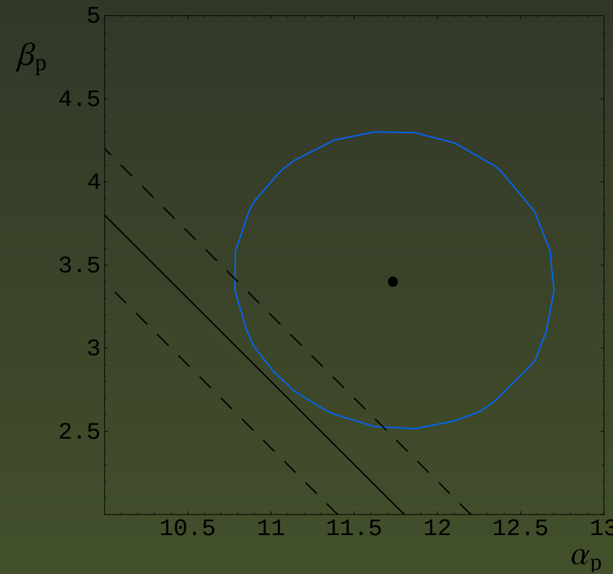
Baldin Sum Rule



With Baldin Sum Rule constraint:

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

Baldin Sum Rule



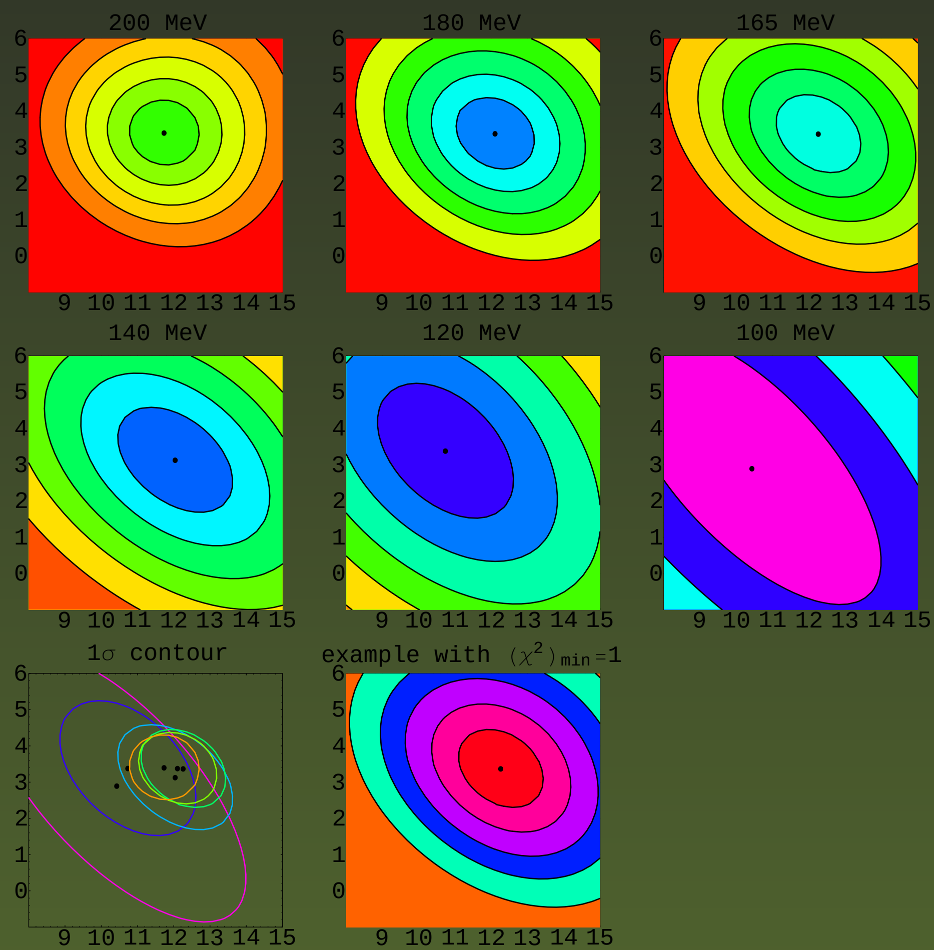
With Baldin Sum Rule constraint:

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

$$\alpha_p = (11.0 \pm 0.5 \pm 0.2)^{+0.5}_{-0.5} \times 10^{-4}\ \mathrm{fm}^3;$$

$$\beta_p = (2.8 \pm 0.5 \mp 0.2)^{+0.1}_{-0.1} \times 10^{-4}\ \mathrm{fm}^3$$

Cutoff dependence of γp fit



Going higher for γp

Breakdown scale set by first omitted degree of freedom: Δ isobar.

$$\mathcal{L}(N,\pi) \rightarrow \mathcal{L}(N,\pi,\Delta)$$

Going higher for γp

Breakdown scale set by first omitted degree of freedom: Δ isobar.

$\mathcal{L}(N,\pi) \rightarrow \mathcal{L}(N,\pi,\Delta)$ But how to count m_π c.f. Δ?

Going higher for γp

Breakdown scale set by first omitted degree of freedom: Δ isobar.

$\mathcal{L}(N, \pi) \to \mathcal{L}(N, \pi, \Delta)$ But how to count m_π c.f. Δ?

"Small-scale expansion" (Hemmert, Holstein, et al.), count:

$$\frac{m_\pi}{\Lambda} \sim \frac{\Delta}{\Lambda} \equiv \epsilon$$

Going higher for γp

Breakdown scale set by first omitted degree of freedom: Δ isobar.

$\mathcal{L}(N,\pi) \rightarrow \mathcal{L}(N,\pi,\Delta)$ But how to count m_π c.f. Δ?

"Small-scale expansion" (Hemmert, Holstein, et al.), count:

$$\frac{m_\pi}{\Lambda} \sim \frac{\Delta}{\Lambda} \equiv \epsilon$$

"δ-expansion" (Pascalutsa and D.P.):

$$\frac{m_\pi}{\Delta} \sim \frac{\Delta}{\Lambda} \equiv \delta.$$

Going higher for γp

Breakdown scale set by first omitted degree of freedom: Δ isobar.

$\mathcal{L}(N,\pi) \rightarrow \mathcal{L}(N,\pi,\Delta)$ But how to count m_π c.f. Δ?

"Small-scale expansion" (Hemmert, Holstein, et al.), count:

$$\frac{m_\pi}{\Lambda} \sim \frac{\Delta}{\Lambda} \equiv \epsilon$$

"δ-expansion" (Pascalutsa and D.P.):

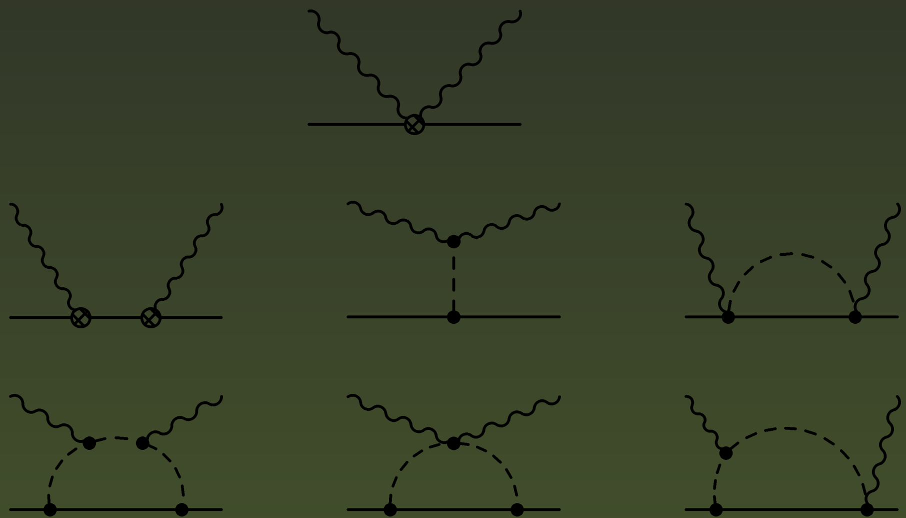
$$\frac{m_\pi}{\Delta} \sim \frac{\Delta}{\Lambda} \equiv \delta.$$

- We should consider two distinct kinematic regions for γp scattering;
- m_π's and Δ's must be kept track of separately, then to get overall counting index of graph set $m_\pi \sim \delta^2$, $\Delta \sim \delta$.

Power counting for $\omega \sim m_\pi$

$O(e^2)$:

$O(e^2\delta^2)$:

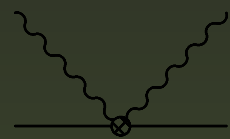


$\sim e^2 \frac{\omega^2}{m_\pi} \sim e^2\delta^2$

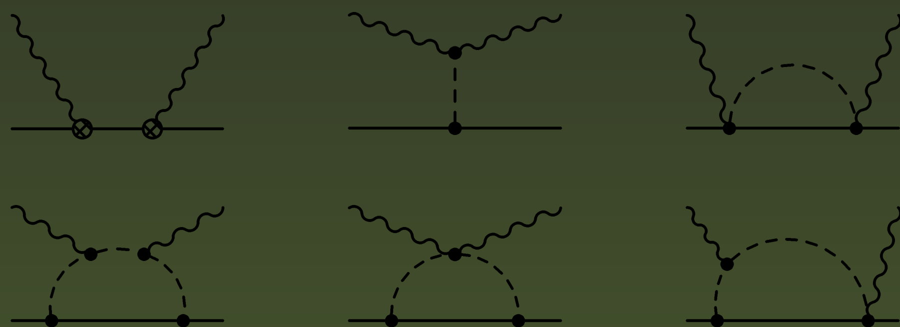
if $\omega \sim m_\pi \sim \delta^2$.

Power counting for $\omega \sim m_\pi$

$O(e^2)$:



$O(e^2\delta^2)$:

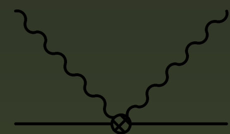


$\sim e^2 \frac{\omega^2}{m_\pi} \sim e^2\delta^2$
if $\omega \sim m_\pi \sim \delta^2$.

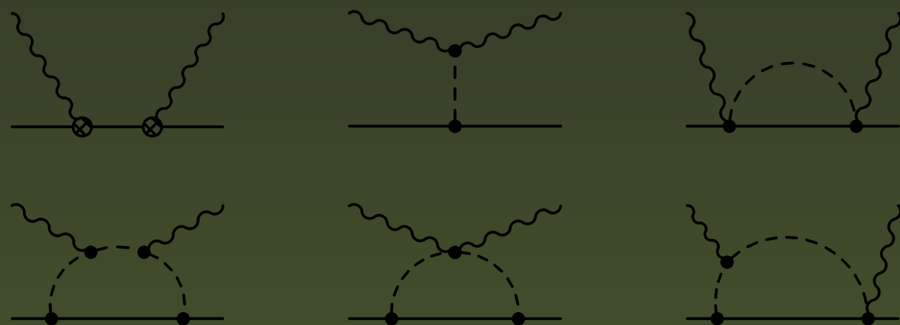
Diagrams with no Δ's: count as in HBχPT but with $P \sim \delta^2$.

Power counting for $\omega \sim m_\pi$

$O(e^2)$:



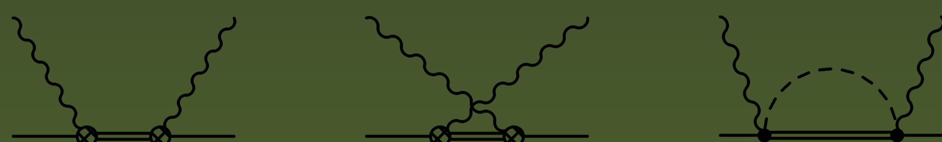
$O(e^2\delta^2)$:



$\sim e^2 \frac{\omega^2}{m_\pi} \sim e^2\delta^2$
if $\omega \sim m_\pi \sim \delta^2$.

Diagrams with no Δ's: count as in HBχPT but with $P \sim \delta^2$.

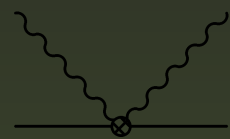
$O(e^2\delta^3)$:



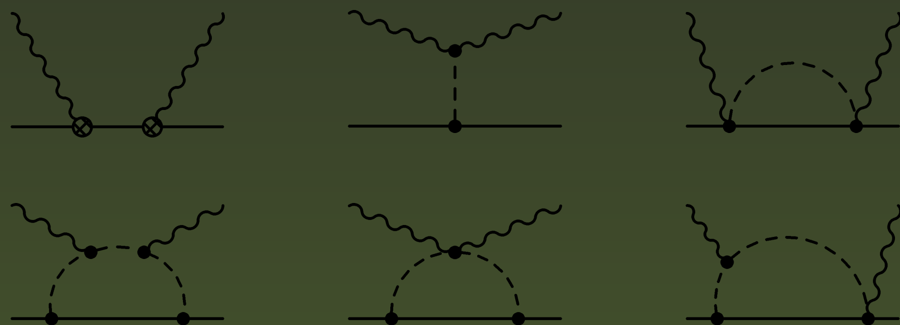
$\sim e^2 \frac{\omega^2}{\Delta} \sim e^2\delta^3$
if $\omega \sim m_\pi \sim \delta^2$.

Power counting for $\omega \sim m_\pi$

$O(e^2)$:



$O(e^2\delta^2)$:

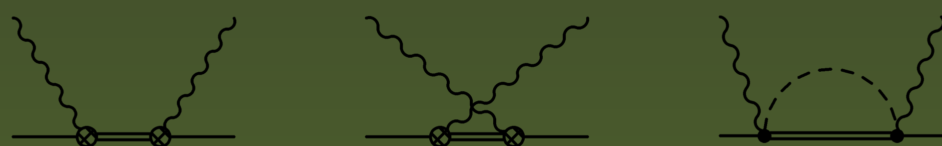


$\sim e^2 \frac{\omega^2}{m_\pi} \sim e^2\delta^2$

if $\omega \sim m_\pi \sim \delta^2$.

Diagrams with no Δ's: count as in HBχPT but with $P \sim \delta^2$.

$O(e^2\delta^3)$:



$\sim e^2 \frac{\omega^2}{\Delta} \sim e^2\delta^3$

if $\omega \sim m_\pi \sim \delta^2$.

$O(e^2\delta^4)$: πN loops with insertions from $\mathcal{L}_{\pi N}^{(2)}$, $\pi\Delta$ loops too.

Counterterms: $4\pi\Delta\alpha_N \mathbf{E}^2$, $4\pi\Delta\beta_N \mathbf{B}^2$.

$\omega \sim \Delta$: OΔR diagrams

$$\sim \frac{1}{\omega - \Delta}$$

Diverges for $\omega = \Delta$. Problem with all OΔR diagrams.

$\omega \sim \Delta$: OΔR diagrams

$$\sim \frac{1}{\omega - \Delta}$$

Diverges for $\omega = \Delta$. Problem with all OΔR diagrams.

Solution: Dyson equation

Σ begins with $\Sigma^{(3)}$

$\omega \sim \Delta$: OΔR diagrams

$\sim \frac{1}{\omega - \Delta}$

Diverges for $\omega = \Delta$. Problem with all OΔR diagrams.

Solution: Dyson equation

Σ begins with $\Sigma^{(3)}$

$|\omega - \Delta| \sim \frac{\Delta^3}{\Lambda^2} \Rightarrow$ all terms $\sim \delta^{-3} \Rightarrow$ Use dressed Δ propagator.

Dressing the Δ propagator

$$S^{(0)}_{\mu\nu}(p) = -\frac{\mathcal{P}^{(3/2)}_{\mu\nu}(p)}{\not{p} - M_\Delta} + \text{non spin} - 3/2 \text{ pieces}$$

$$\Sigma_{\mu\nu} = \Sigma^{(3)}_{\mu\nu} + \Sigma^{(4)}_{\mu\nu} + \ldots$$

Treat $\Sigma^{(4)}$ etc. in perturbation theory

Dressing the Δ propagator

$$S^{(0)}_{\mu\nu}(p) = -\frac{\mathcal{P}^{(3/2)}_{\mu\nu}(p)}{\not{p} - M_\Delta} + \text{non spin} - 3/2 \text{ pieces}$$

$$\Sigma_{\mu\nu} = \Sigma^{(3)}_{\mu\nu} + \Sigma^{(4)}_{\mu\nu} + \ldots$$

Treat $\Sigma^{(4)}$ etc. in perturbation theory

Consistent couplings $\Rightarrow \Sigma_{\mu\nu}(p) = \Sigma(p)\mathcal{P}^{(3/2)}_{\mu\nu}(p)$

Resum *renormalized* third-order self-energy

$$\tilde{S}_{\mu\nu}(p) = -\frac{Z(p^2)}{\not{p} - M(p^2)}\mathcal{P}^{(3/2)}_{\mu\nu}(p)$$

$$= -\frac{Z(M_\Delta^2)}{\not{p} - M_\Delta - i\,\mathrm{Im}\,M(p^2)}\mathcal{P}^{(3/2)}_{\mu\nu}(p) + O\left(\frac{1}{\Lambda}\right)$$

Consistent couplings

$\mathcal{L}$ invariant under $\Delta_\mu \rightarrow \Delta_\mu + \partial_\mu \epsilon$

$\Rightarrow \Delta$ has correct number of spin degrees of freedom

Consistent couplings

$\mathcal{L}$ invariant under $\Delta_\mu \to \Delta_\mu + \partial_\mu \epsilon$

$\Rightarrow \Delta$ has correct number of spin degrees of freedom

Spin-3/2 gauge invariance $\Rightarrow p_\mu \Gamma^\mu(p, \ldots) = 0$

Consistent couplings

$\mathcal{L}$ invariant under $\Delta_\mu \to \Delta_\mu + \partial_\mu \epsilon$

$\Rightarrow \Delta$ has correct number of spin degrees of freedom

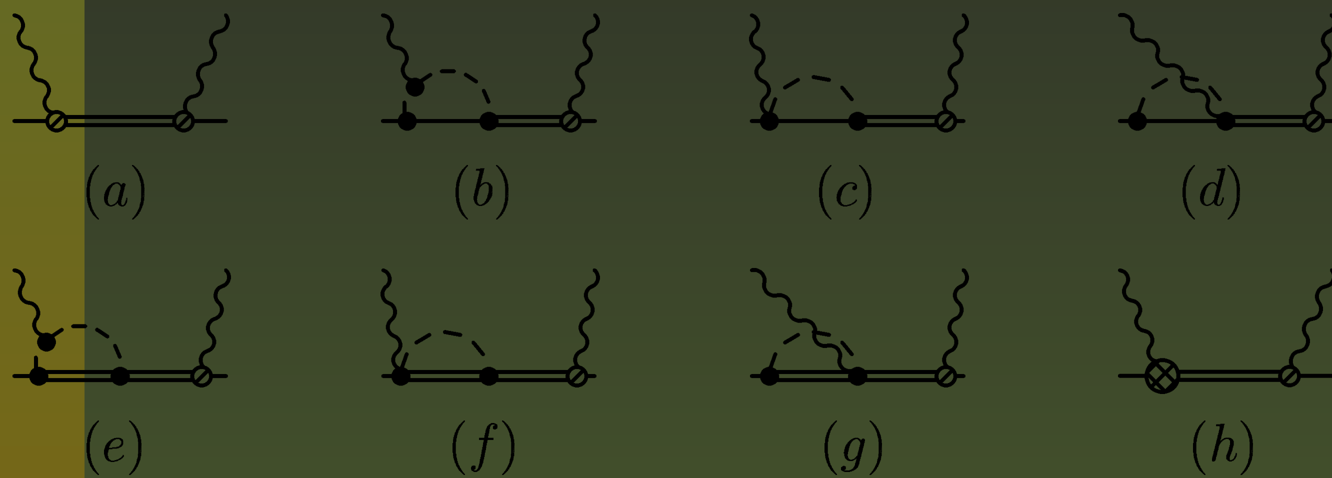
Spin-3/2 gauge invariance $\Rightarrow p_\mu \Gamma^\mu(p, \ldots) = 0$

$$\Gamma^\mu S_{\mu\nu}(p)\Gamma^\nu = -\frac{\Gamma^\mu \mathcal{P}^{(3/2)}_{\mu\nu}(p)\Gamma^\nu}{\not{p} - M_\Delta}$$

Unphysical spin-1/2 degrees of freedom do not enter any physical amplitude

$\omega \sim \Delta$: power counting

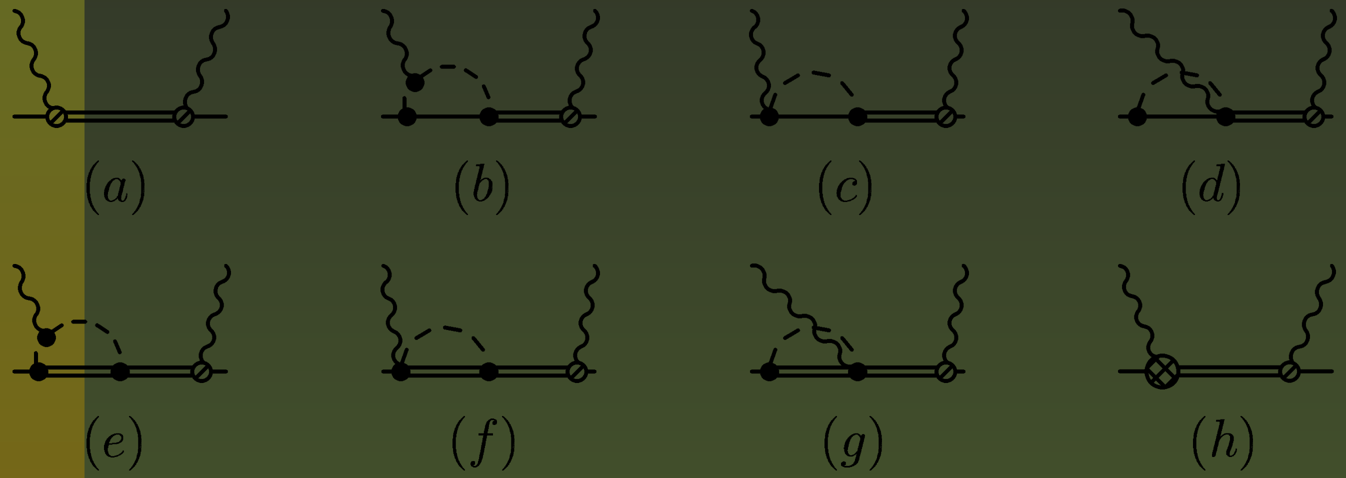
LO and NLO OΔR diagrams:



These + Thomson term define NLO calculation: $O(e^2\delta^{-1}) + O(e^2)$

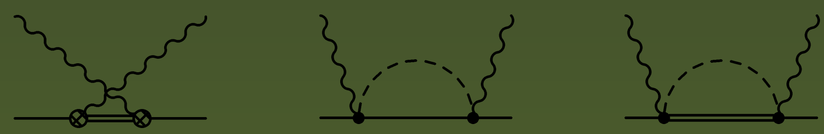
$\omega \sim \Delta$: power counting

LO and NLO OΔR diagrams:



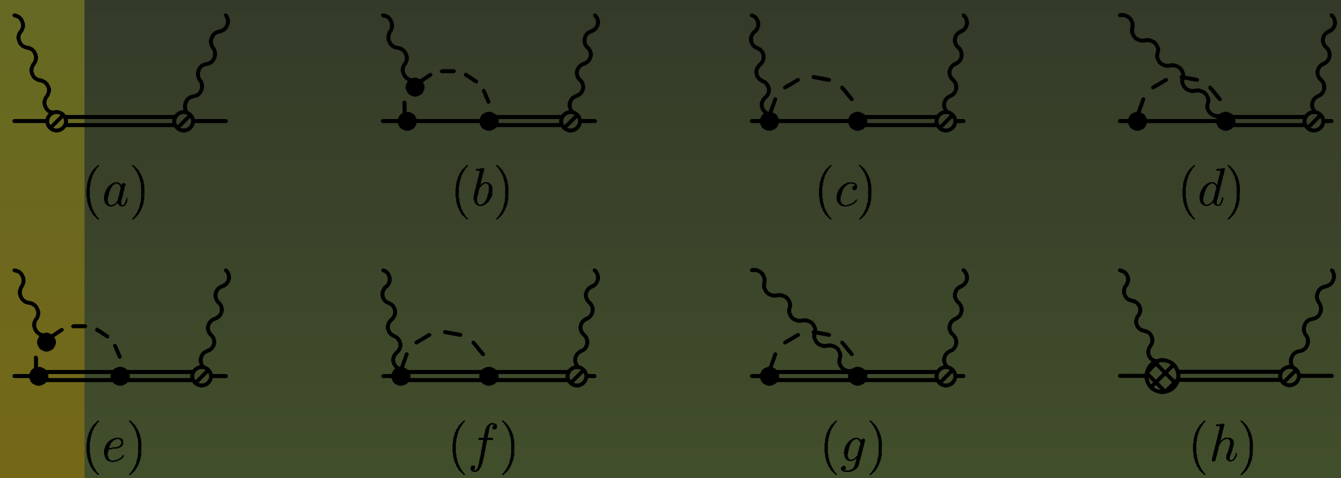
These + Thomson term define NLO calculation: $O(e^2\delta^{-1}) + O(e^2)$

N^{2}LO, $O(e^2\delta)$:



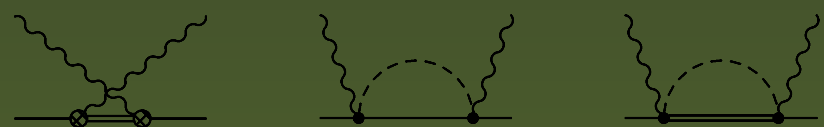
$\omega \sim \Delta$: power counting

LO and NLO OΔR diagrams:

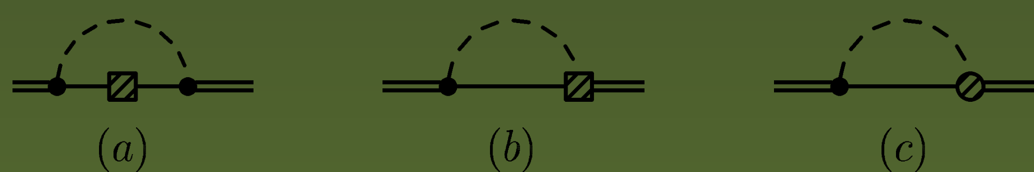


These + Thomson term define NLO calculation: $O(e^2\delta^{-1}) + O(e^2)$

N^{2}LO, $O(e^2\delta)$:



$\Sigma^{(4)} =$



δ-expansion for γp: Summary

V. Pascalutsa and D. R. Phillips Phys. Rev. C **67**, 0552002 (2003).

- $\omega \sim m_\pi$, as in χPT, pole graphs + pion loops $\Rightarrow$ LETs;

δ-expansion for γp: Summary

V. Pascalutsa and D. R. Phillips Phys. Rev. C **67**, 0552002 (2003).

- $\omega \sim m_\pi$, as in χPT, pole graphs + pion loops $\Rightarrow$ LETs;
- $\omega \sim \Delta$, dominated by dressed Δ with energy-dependent width:

$$\Gamma(s) = \frac{h_A^2}{2 f_\pi^2} \frac{s + M^2 - m_\pi^2}{24 \pi M_\Delta^2} k^3 \theta(k)$$

δ-expansion for γp: Summary

V. Pascalutsa and D. R. Phillips Phys. Rev. C **67**, 0552002 (2003).

- $\omega \sim m_\pi$, as in χPT, pole graphs + pion loops $\Rightarrow$ LETs;
- $\omega \sim \Delta$, dominated by dressed Δ with energy-dependent width:

$$\Gamma(s) = \frac{h_A^2}{2f_\pi^2} \frac{s + M^2 - m_\pi^2}{24\pi M_\Delta^2} k^3 \theta(k)$$

- To describe $0 < \omega \leq \Delta$ amplitude includes all mechanisms which are NLO in *either region*;

δ-expansion for γp: Summary

V. Pascalutsa and D. R. Phillips Phys. Rev. C **67**, 0552002 (2003).

- $\omega \sim m_\pi$, as in χPT, pole graphs + pion loops $\Rightarrow$ LETs;
- $\omega \sim \Delta$, dominated by dressed Δ with energy-dependent width:

$$\Gamma(s) = \frac{h_A^2}{2f_\pi^2} \frac{s + M^2 - m_\pi^2}{24\pi M_\Delta^2} k^3 \theta(k)$$

- To describe $0 < \omega \leq \Delta$ amplitude includes all mechanisms which are NLO in *either region*;
- Tools of field theory: Ward-Takahashi identities, consistent number of spin d.o.f., . . .

δ-expansion for γp: Summary

V. Pascalutsa and D. R. Phillips Phys. Rev. C **67**, 0552002 (2003).

- $\omega \sim m_\pi$, as in χPT, pole graphs + pion loops $\Rightarrow$ LETs;
- $\omega \sim \Delta$, dominated by dressed Δ with energy-dependent width:

$$\Gamma(s) = \frac{h_A^2}{2f_\pi^2} \frac{s + M^2 - m_\pi^2}{24\pi M_\Delta^2} k^3 \theta(k)$$

- To describe $0 < \omega \leq \Delta$ amplitude includes all mechanisms which are NLO in *either region*;
- Tools of field theory: Ward-Takahashi identities, consistent number of spin d.o.f., ...
- Power counting $\Rightarrow$ error estimates

Results: I

Fit to γp data from threshold to ~ 300 MeV

Free parameters: h_A, g_M, g_E

$$\Gamma(M_\Delta^2) = 111 \text{ MeV} \rightarrow h_A\text{=2.81}$$

$$g_M = 2.6 \pm 0.2, g_E = -6.0 \pm 0.9$$

Errors: estimate of N^{2}LO effect

Results: I

Fit to γp data from threshold to ~ 300 MeV

Free parameters: h_A, g_M, g_E

$$\Gamma(M_\Delta^2) = 111 \text{ MeV} \rightarrow h_A\text{=2.81}$$

$$g_M = 2.6 \pm 0.2, g_E = -6.0 \pm 0.9$$

Errors: estimate of N^{2}LO effect

c.f. large-N_c, $h_A = \frac{3}{\sqrt{2}} g_A \approx 2.67$, $g_M = \frac{2\sqrt{2}}{3}(1 + \kappa_p) \approx 2.63$;

Results: I

Fit to γp data from threshold to $\sim$ 300 MeV

Free parameters: h_A, g_M, g_E

$$\Gamma(M_\Delta^2) = 111\text{ MeV} \rightarrow h_A\text{=2.81}$$

$$g_M = 2.6 \pm 0.2, g_E = -6.0 \pm 0.9$$

Errors: estimate of N^{2}LO effect

c.f. large-N_c, $h_A = \frac{3}{\sqrt{2}} g_A \approx 2.67$, $g_M = \frac{2\sqrt{2}}{3}(1 + \kappa_p) \approx 2.63$;

Reference	α_p	β_p
NLO HBχPT	12.2	1.2
NLO δ	$10.2^{+4.2}_{-2.0}$	$3.9^{+2.7}_{-0.4}$
NLO SSE	16.4	9.1
PDG average	12.0 ± 0.7	1.6 ± 0.6
Beane *et al.*	12.1 ± 1.6	3.2 ± 1.2

Results: I

Fit to γp data from threshold to $\sim$ 300 MeV

Free parameters: h_A, g_M, g_E

$$\Gamma(M_\Delta^2) = 111 \text{ MeV} \rightarrow h_A\text{=2.81}$$

$$g_M = 2.6 \pm 0.2, g_E = -6.0 \pm 0.9$$

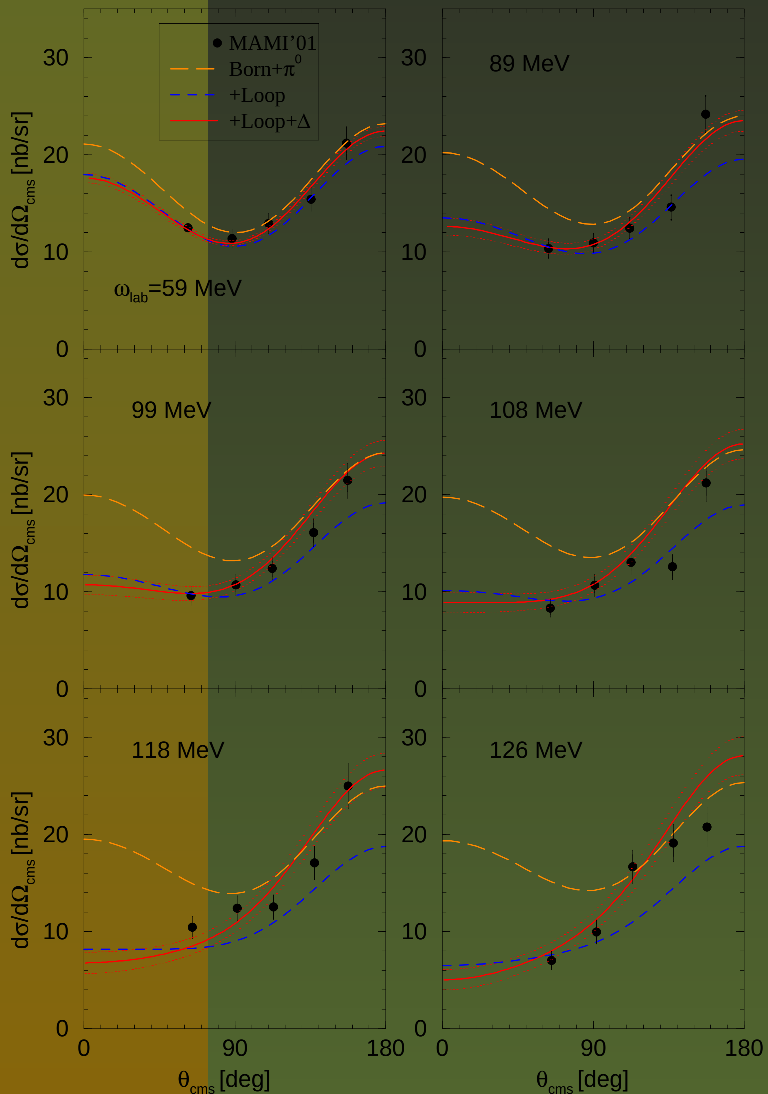
Errors: estimate of N^{2}LO effect

c.f. large-N_c, $h_A = \frac{3}{\sqrt{2}} g_A \approx 2.67$, $g_M = \frac{2\sqrt{2}}{3}(1+\kappa_p) \approx 2.63$;

Reference	α_p	β_p
NLO HBχPT	12.2	1.2
NLO δ	$10.2^{+4.2}_{-2.0}$	$3.9^{+2.7}_{-0.4}$
NLO SSE	16.4	9.1
PDG average	12.0 ± 0.7	1.6 ± 0.6
Beane *et al.*	12.1 ± 1.6	3.2 ± 1.2

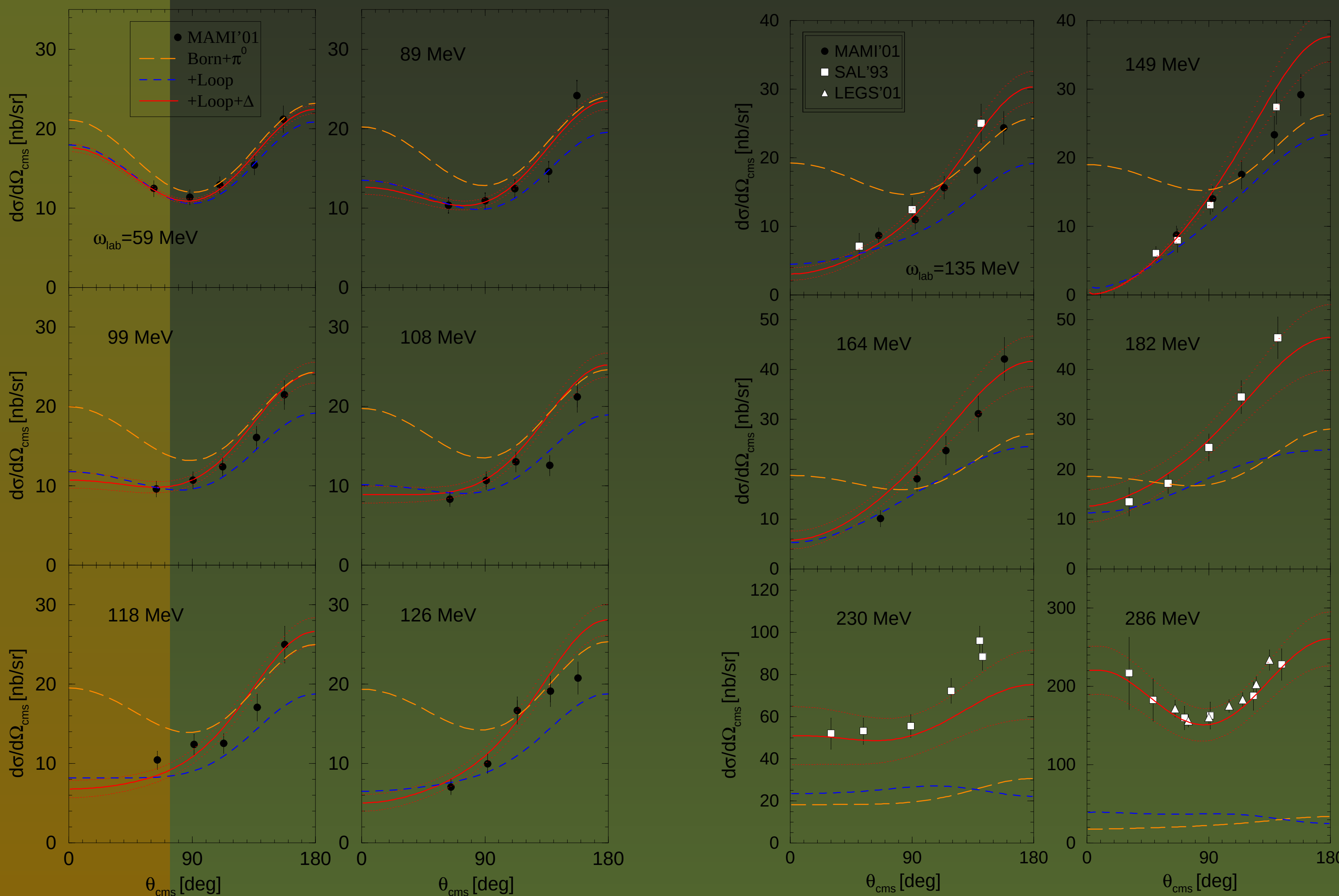
Large Δ/M corrections to spin polarizabilities (especially γ_π), Pascalutsa and D.P., PRC, in press.

Results: II



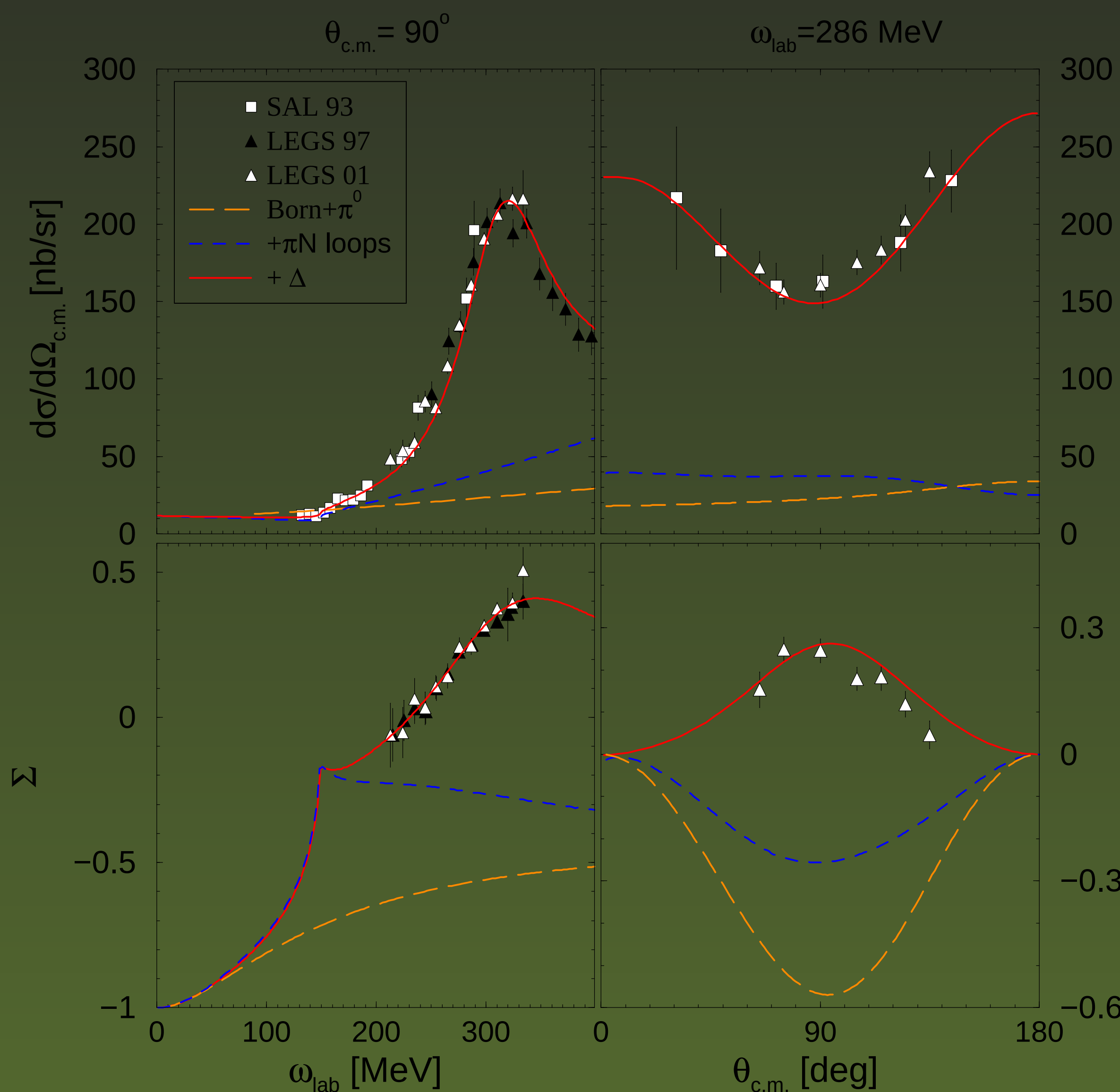
MAMI'01
Born+π^0
+Loop
+Loop+Δ
ω_{lab}=59 MeV
89 MeV
99 MeV
108 MeV
118 MeV
126 MeV
$d\sigma/d\Omega_{cms}$ [nb/sr]
θ_{cms} [deg]

Results: II



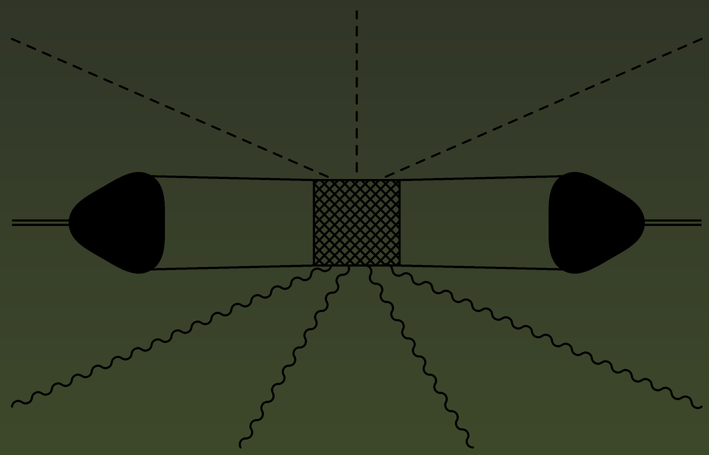
MAMI'01
Born+π0
+Loop
+Loop+Δ
ωlab=59 MeV
89 MeV
99 MeV
108 MeV
118 MeV
126 MeV
MAMI'01
SAL'93
LEGS'01
ωlab=135 MeV
149 MeV
164 MeV
182 MeV
230 MeV
286 MeV
dσ/dΩcms [nb/sr]
θcms [deg]

Results: III

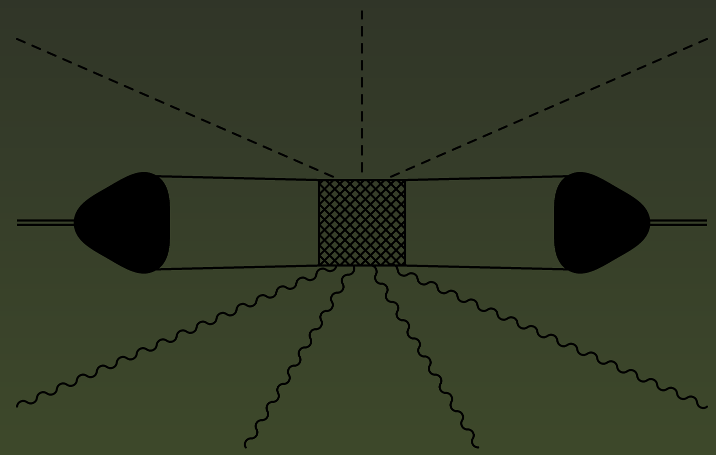


$\theta_{c.m.} = 90^o$
ω_{lab}=286 MeV
SAL 93
LEGS 97
LEGS 01
Born+π^0
+πN loops
+ Δ
$d\sigma/d\Omega_{c.m.}$ [nb/sr]
Σ
ω_{lab} [MeV]
$\theta_{c.m.}$ [deg]
300
250
200
150
100
50
0
0.5
0
−0.5
−1
0.3
0
−0.3
−0.6
0
100
200
300
0
90
180

Reactions on deuterium

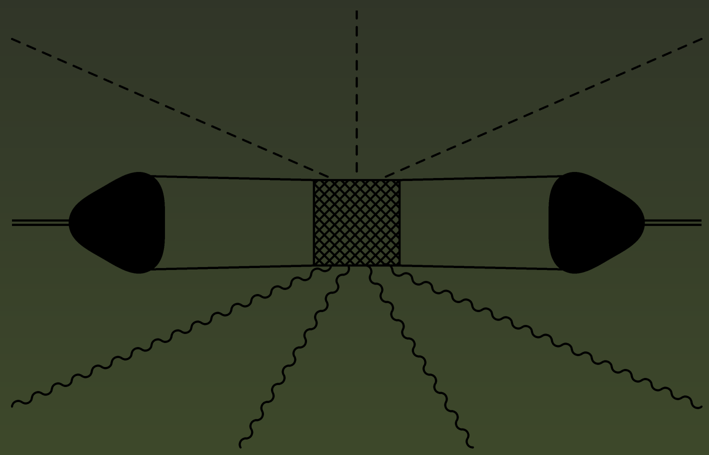


Reactions on deuterium



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

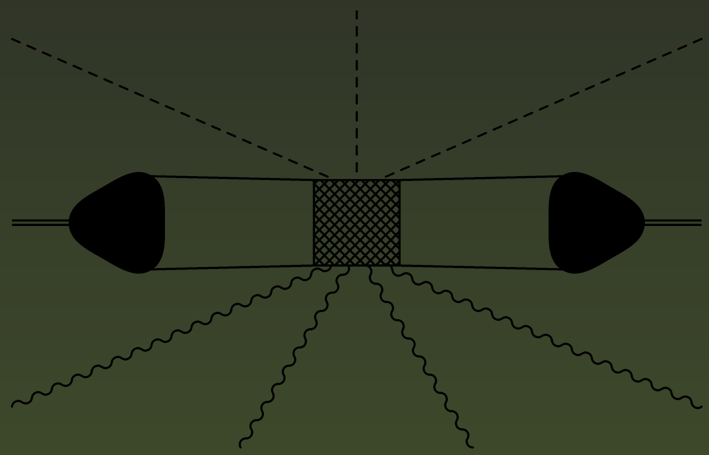
Reactions on deuterium



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

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

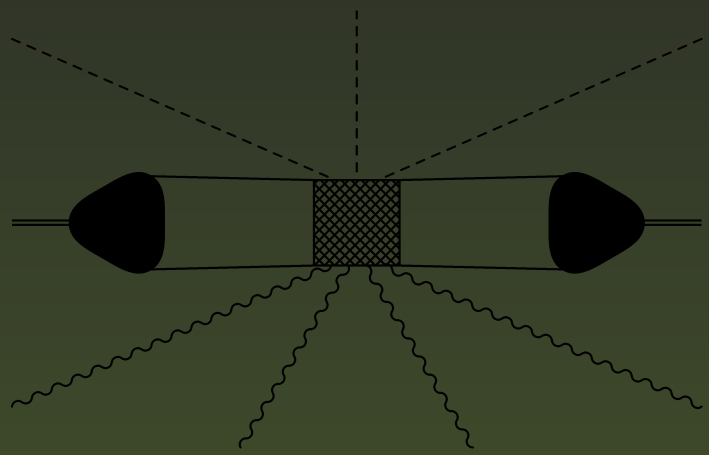
Reactions on deuterium



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

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

Reactions on deuterium

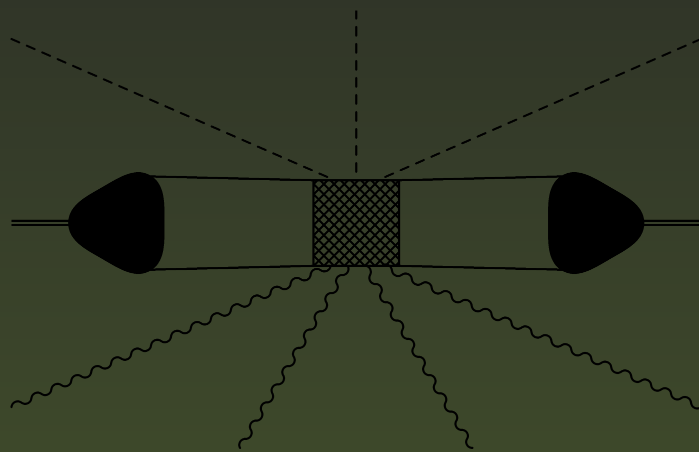


$$\langle\psi|\hat{O}|\psi\rangle$$

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

$\hat{O}$: also has a χPT expansion. (Weinberg, van Kolck)

Reactions on deuterium



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

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

$\hat{O}$: also has a χPT expansion. (Weinberg, van Kolck)

Description of observables which should be: model independent, systematically improvable, and accurate at low momentum/energy transfer.

Naive dimensional analysis for $\hat{O}$

$$\hat{O} = \sum_n c_n \frac{(p, m_\pi)^n}{\Lambda^n}$$

Rules:

- 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: $\int d^4k$;
- P^3 for a two-body diagram: $\delta^{(3)}(p_2' - p_2)$ absent.

Naive dimensional analysis for $\hat{O}$

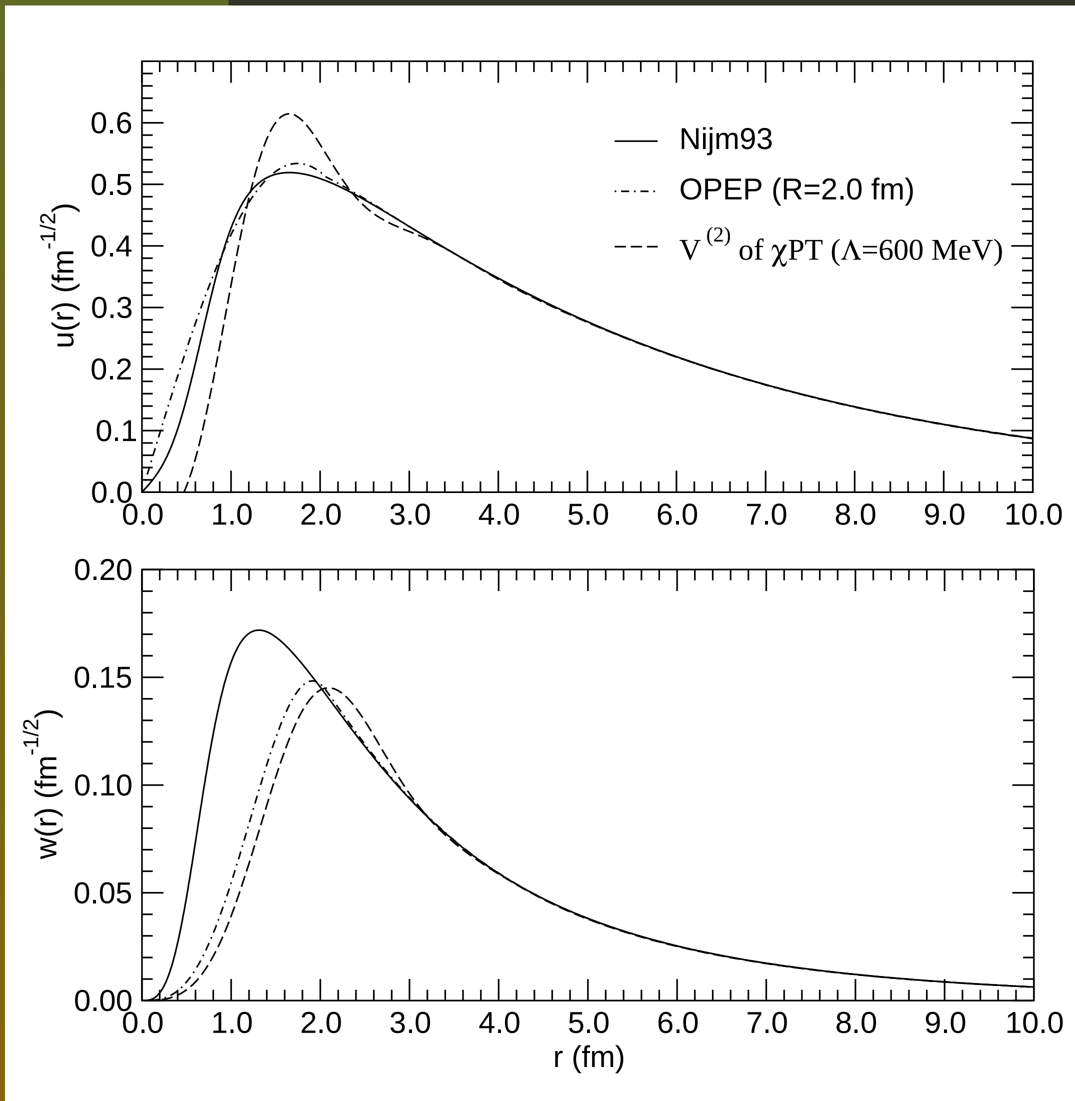
$$\hat{O} = \sum_n c_n \frac{(p, m_\pi)^n}{\Lambda^n}$$

Rules:

- 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: $\int d^4k$;
- P^3 for a two-body diagram: $\delta^{(3)}(p_2' - p_2)$ absent.

Loops, many-body effects, and vertices from $\mathcal{L}^{(2,3)}$ etc. suppressed by powers of P.

Deuteron wave functions

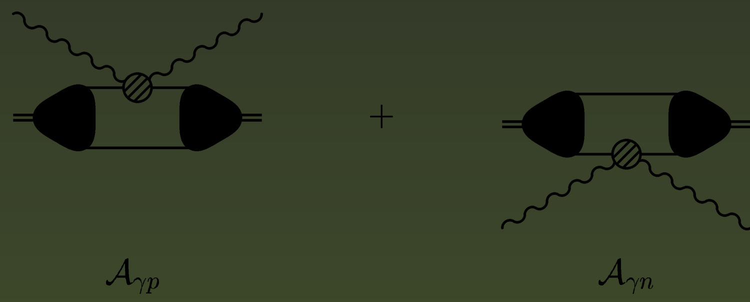


Same at long distances: B, A_S, A_D, $f_{\pi NN}$, m_π.

Some differences at two-pion range.

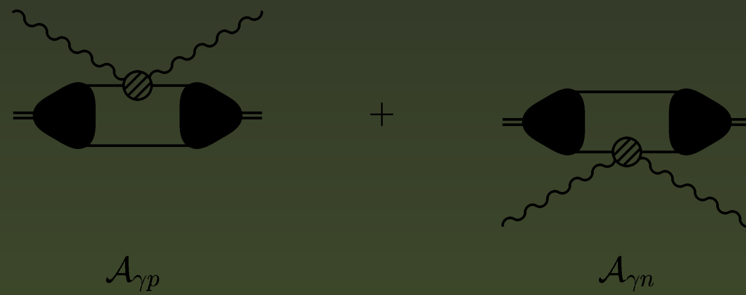
Compton scattering on deuterium

Want to determine α_N and β_N. Naive idea:



Compton scattering on deuterium

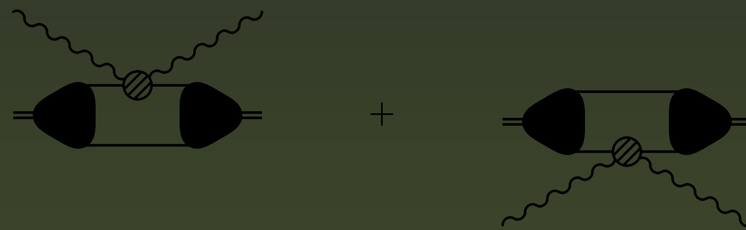
Want to determine α_N and β_N. Naive idea:



INCORRECT

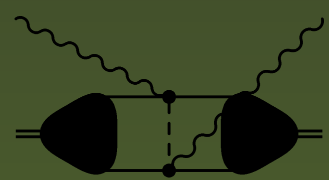
Compton scattering on deuterium

Want to determine α_N and β_N. Naive idea:



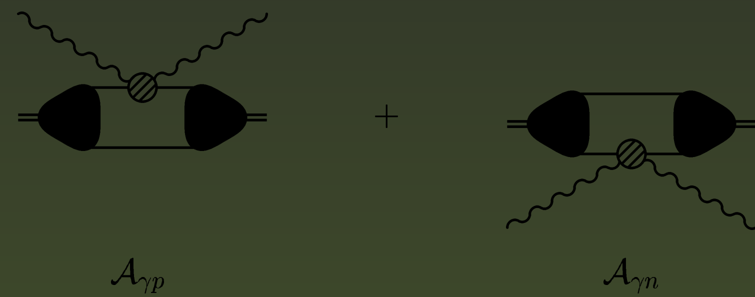
$\mathcal{A}_{\gamma p}$ + $\mathcal{A}_{\gamma n}$

INCORRECT

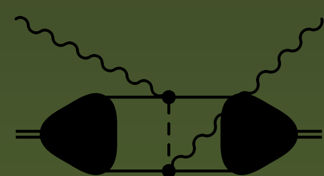


Compton scattering on deuterium

Want to determine α_N and β_N. Naive idea:



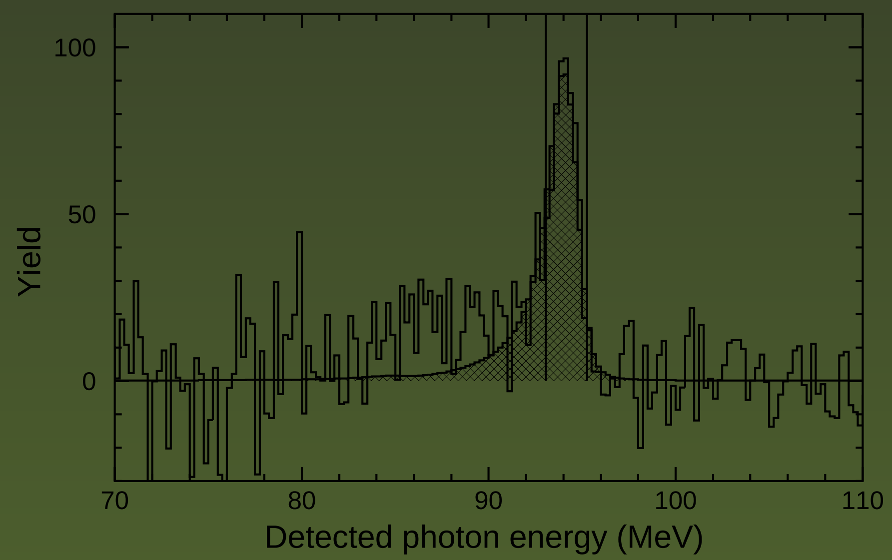
INCORRECT



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

γd experiments

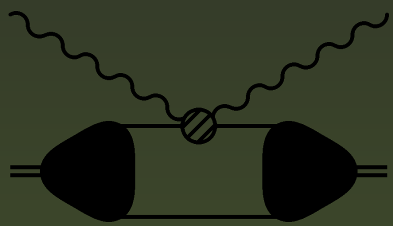
- Illinois (1994): M. Lucas, Ph.D. thesis, $\omega = 49, 69$ MeV;
- SAL (2000): D. Hornidge et al., PRL 84, 2334 (2000), $\omega = 85 - 105$ MeV;
- Lund (2003): M. Lundin et al., PRL 90, 192501 (2003), $\omega = 55, 65$ MeV.



γd in χPT to $O(e^2 P)$

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

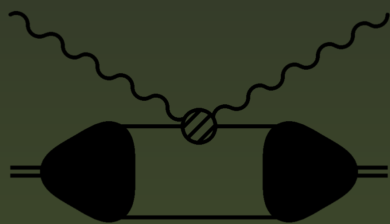
$O(e^2)$:



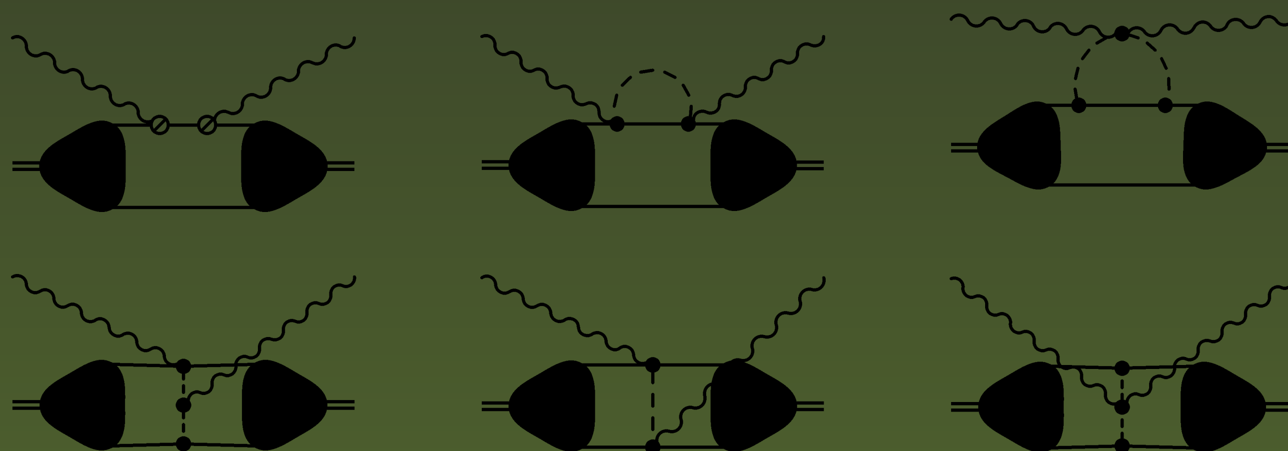
γd in χPT to $O(e^2 P)$

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

$O(e^2)$:



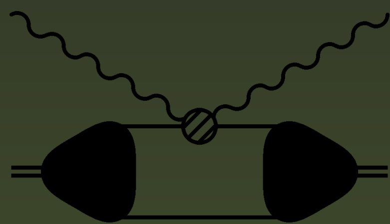
$O(e^2 P)$:



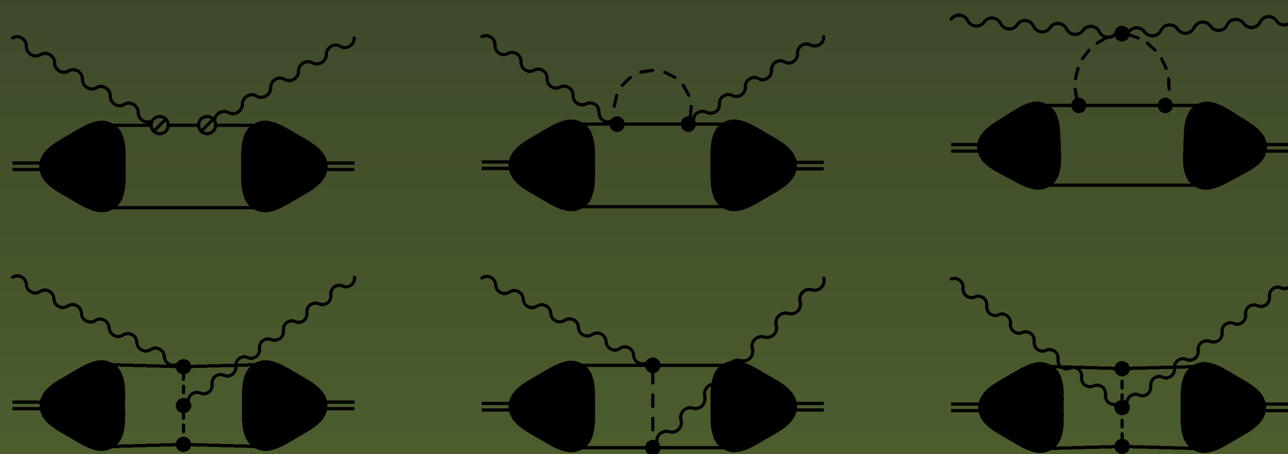
γd in χPT to $O(e^2 P)$

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

$O(e^2)$:

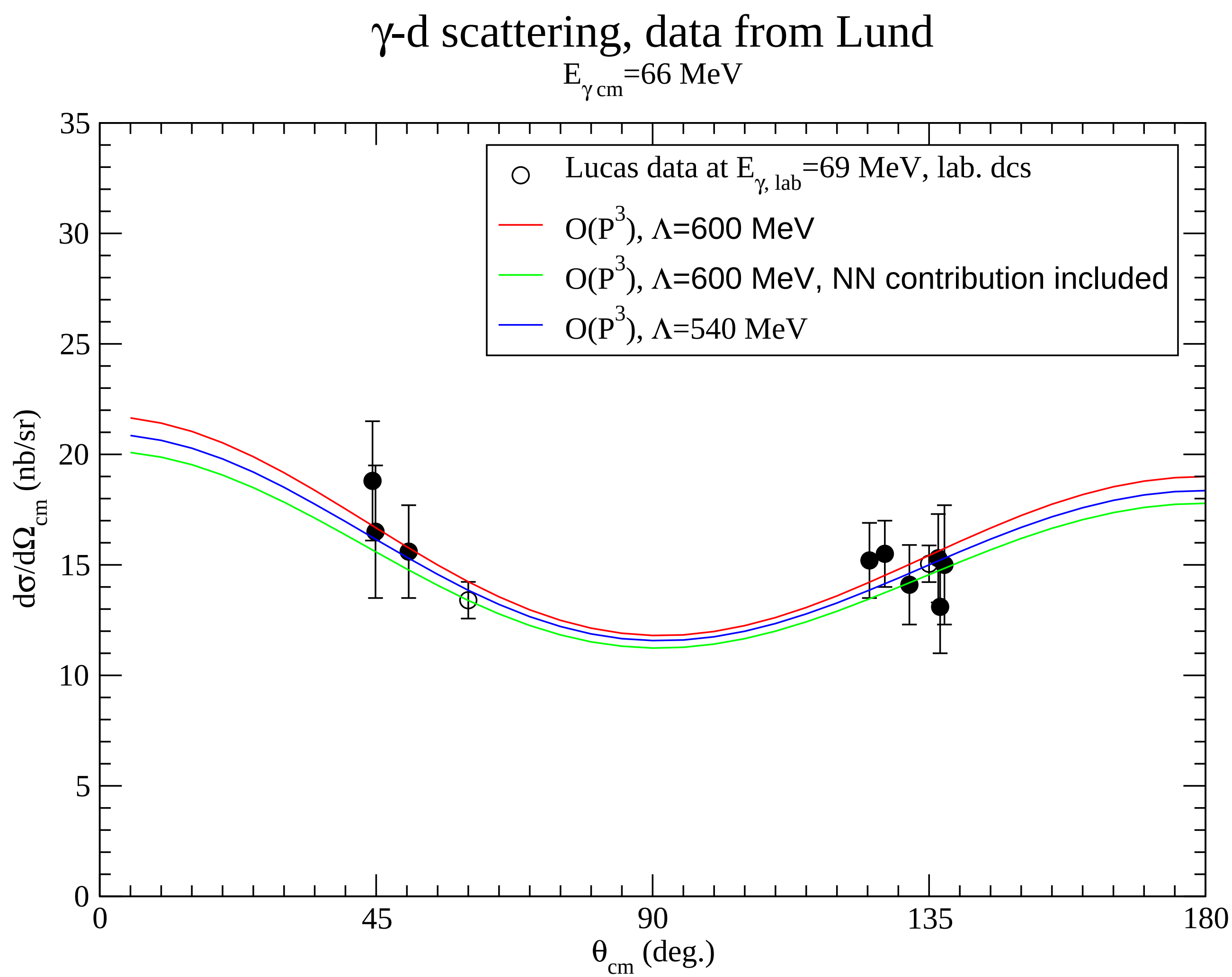


$O(e^2 P)$:



No free parameters at this order $\Longrightarrow$ PREDICTION

Results



Wave-function dependence gives estimate of theory error.

γ**d scattering at** $O(e^2P^2)$

S. R. Beane, M. Malheiro, J. McGovern, D. P., U. van Kolck, Phys. Lett. B, in press

Ingredients:

γd scattering at $O(e^2 P^2)$

S. R. Beane, M. Malheiro, J. McGovern, D. P., U. van Kolck, Phys. Lett. B, in press

Ingredients:

1. γN amplitude at $O(e^2 P^2)$;

γd scattering at $O(e^2 P^2)$

S. R. Beane, M. Malheiro, J. McGovern, D. P., U. van Kolck, Phys. Lett. B, in press

Ingredients:

1. γN amplitude at $O(e^2 P^2)$; boosted to γd centre-of-mass frame.

γd scattering at $O(e^2P^2)$

S. R. Beane, M. Malheiro, J. McGovern, D. P., U. van Kolck, Phys. Lett. B, in press

Ingredients:

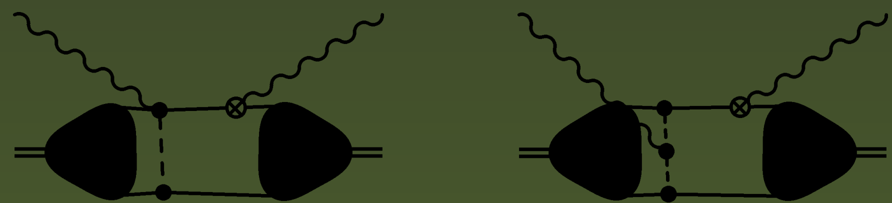
1. γN amplitude at $O(e^2P^2)$; boosted to γd centre-of-mass frame.
2. γd two-body pieces at $O(e^2P)$.

γd scattering at $O(e^2P^2)$

S. R. Beane, M. Malheiro, J. McGovern, D. P., U. van Kolck, Phys. Lett. B, in press

Ingredients:

1. γN amplitude at $O(e^2P^2)$; boosted to γd centre-of-mass frame.
2. γd two-body pieces at $O(e^2P)$.
3. γd two-body pieces at $O(e^2P^2)$.



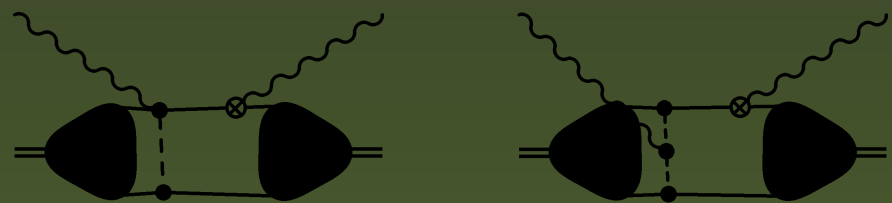
Calculable in terms of f_π, g_A, κ_V, m_π, and M.

γd scattering at $O(e^2P^2)$

S. R. Beane, M. Malheiro, J. McGovern, D. P., U. van Kolck, Phys. Lett. B, in press

Ingredients:

1. γN amplitude at $O(e^2P^2)$; boosted to γd centre-of-mass frame.
2. γd two-body pieces at $O(e^2P)$.
3. γd two-body pieces at $O(e^2P^2)$.



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

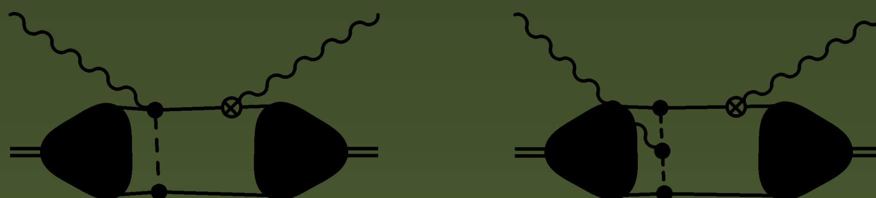
4. Resummation to deal with very-low-energy region $\omega \sim m_\pi^2/M$ (relevant only for lower-energy data sets).

γd scattering at $O(e^2P^2)$

S. R. Beane, M. Malheiro, J. McGovern, D. P., U. van Kolck, Phys. Lett. B, in press

Ingredients:

1. γN amplitude at $O(e^2P^2)$; boosted to γd centre-of-mass frame.
2. γd two-body pieces at $O(e^2P)$.
3. γd two-body pieces at $O(e^2P^2)$.

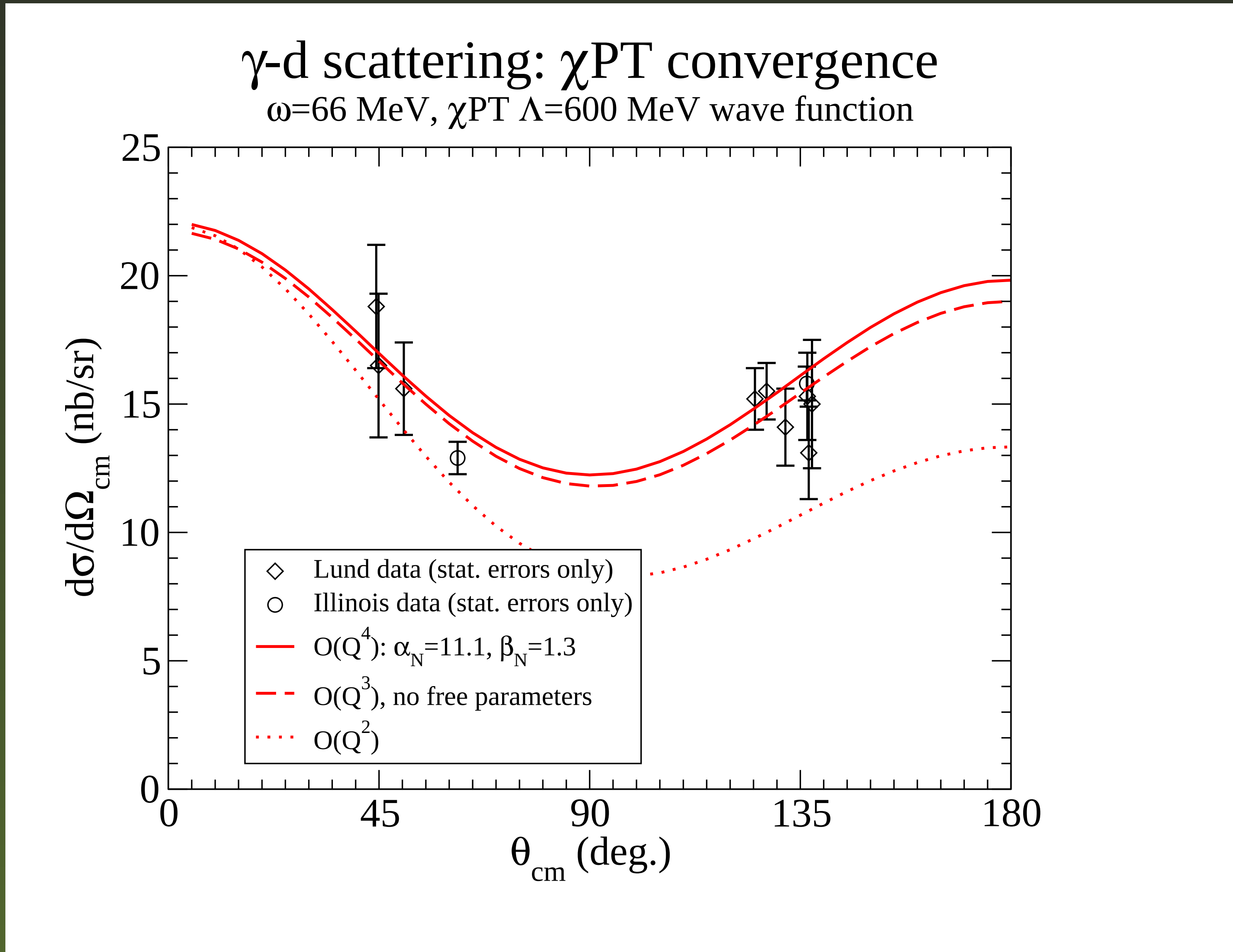


Calculable in terms of f_π, g_A, κ_V, m_π, and M.

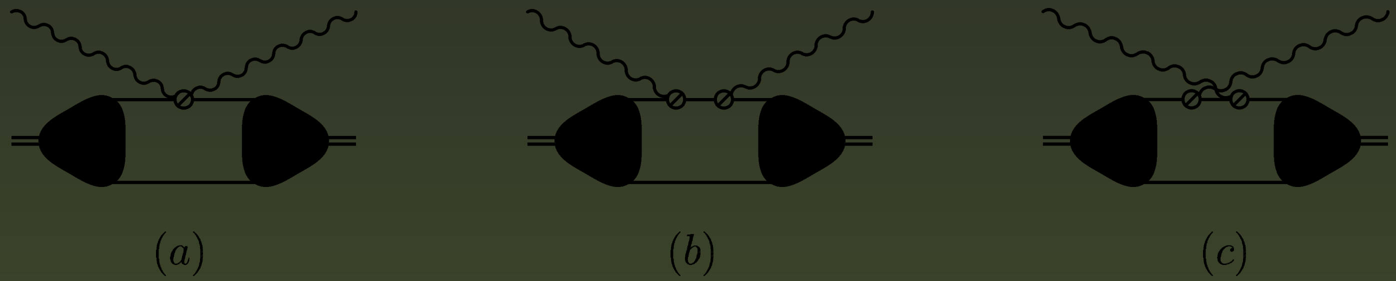
4. Resummation to deal with very-low-energy region $\omega \sim m_\pi^2/M$ (relevant only for lower-energy data sets).

Only free parameters are α_N and β_N.

Convergence



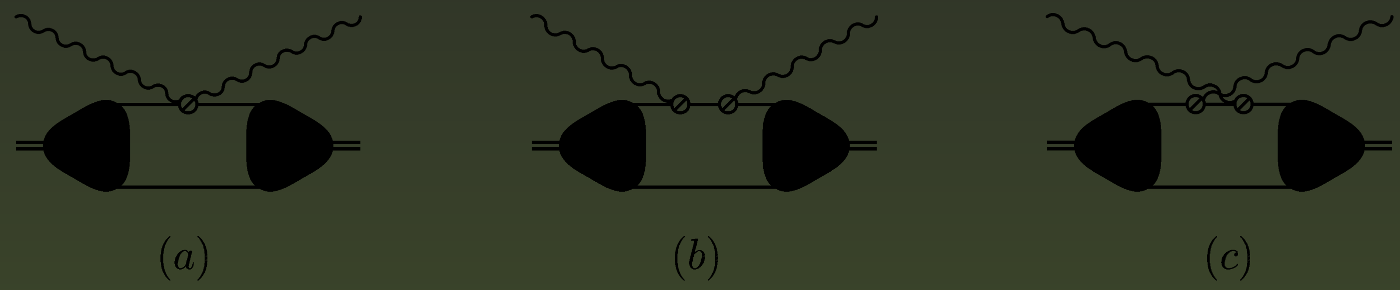
Very-low-energy resummation



Diagrams (b) and (c) crucial for recovery of γd Thomson limit:

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

Very-low-energy resummation

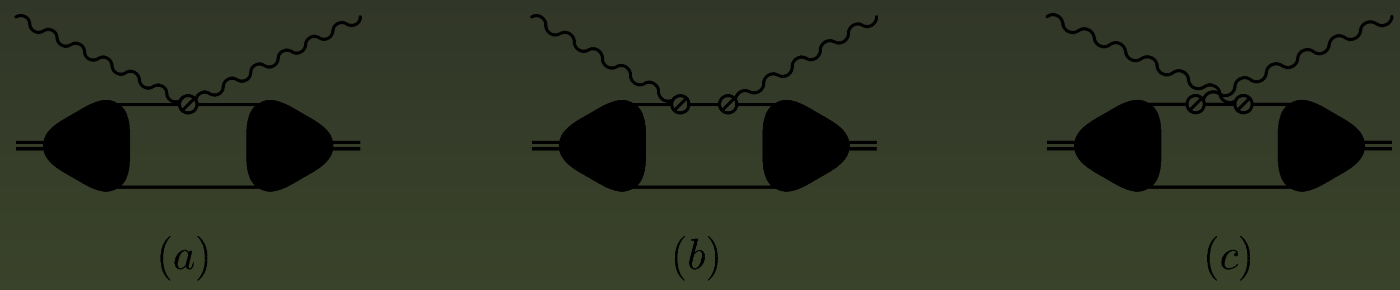


Diagrams (b) and (c) crucial for recovery of γd Thomson limit:

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

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

Very-low-energy resummation



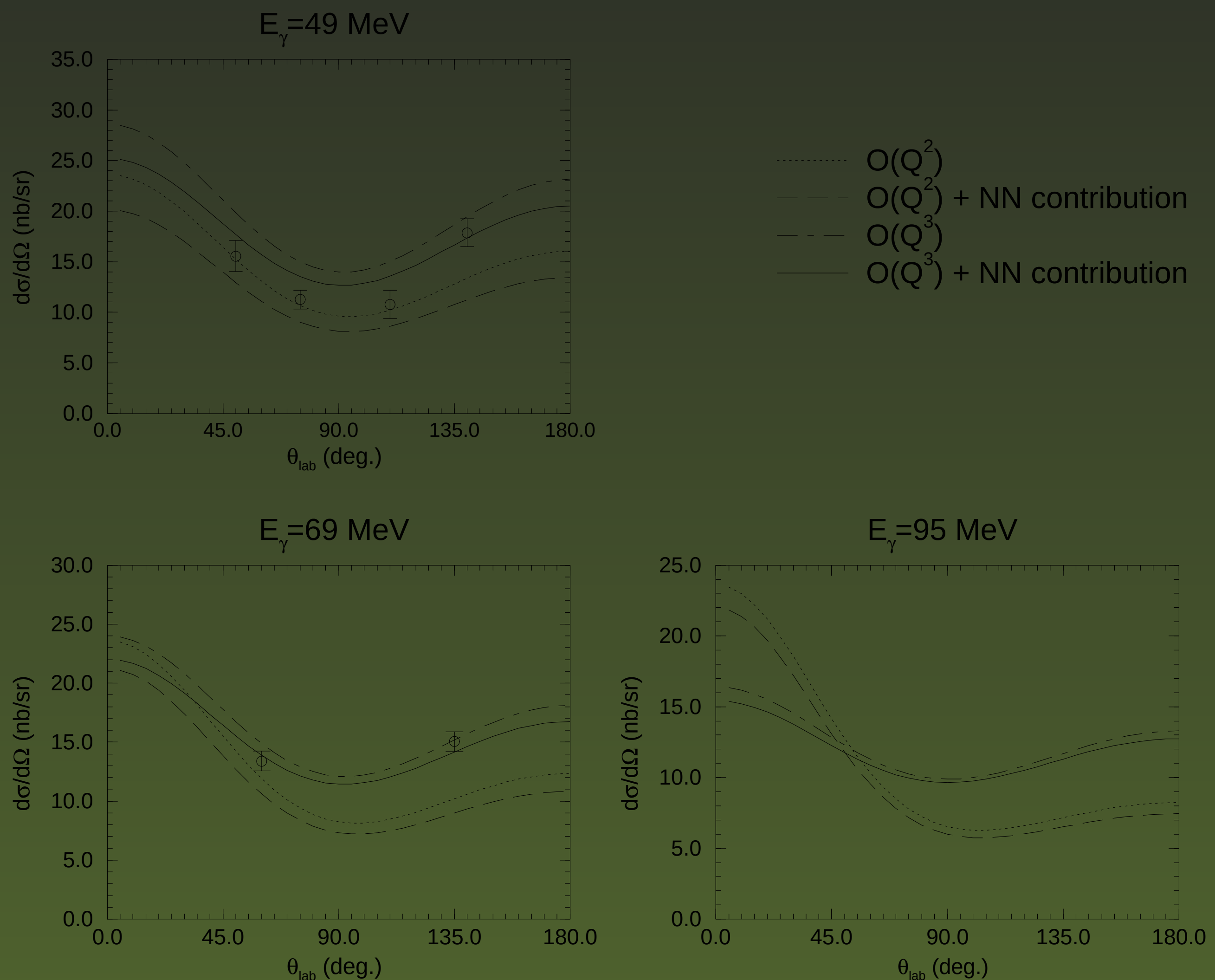
Diagrams (b) and (c) crucial for recovery of γd Thomson limit:

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

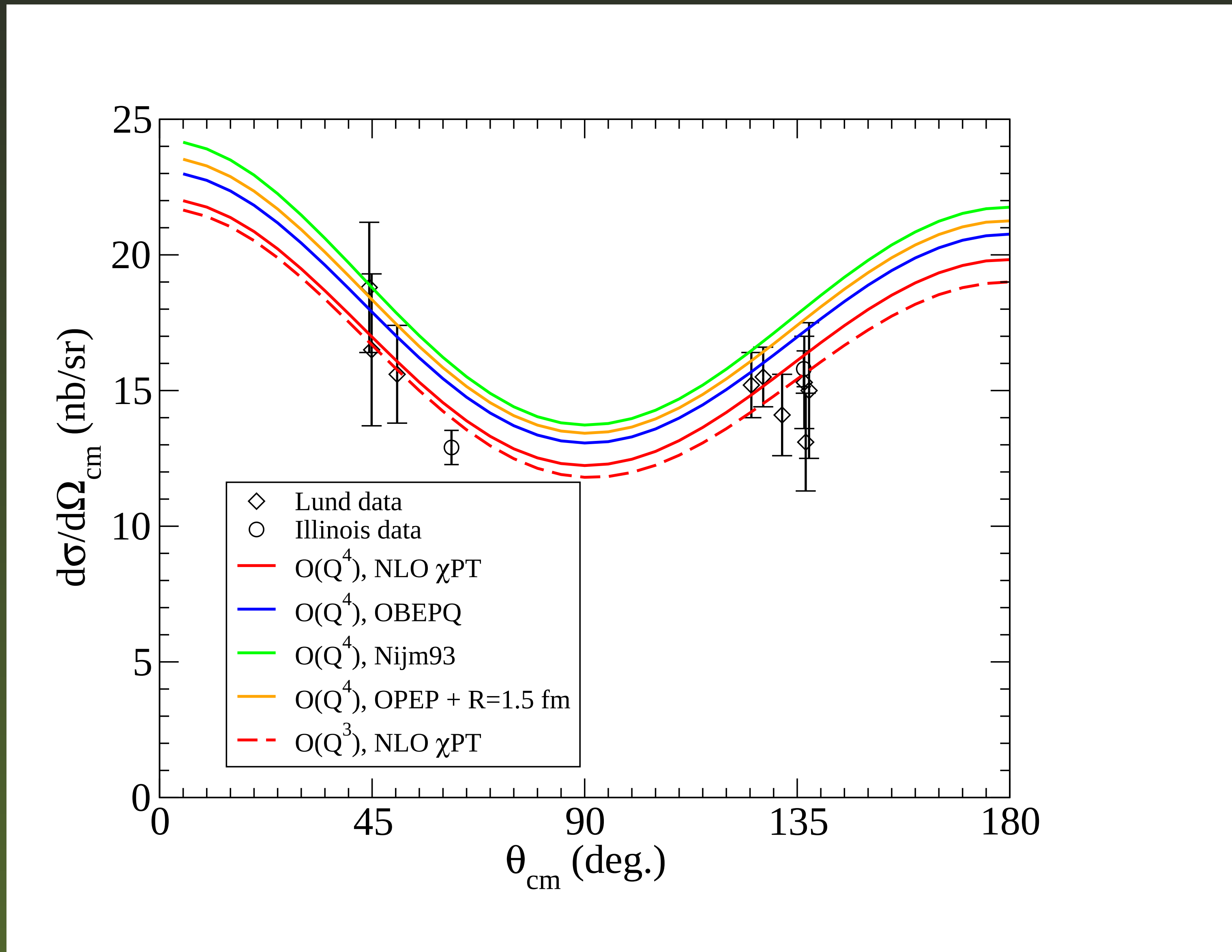
Also crucial is to use: $\frac{1}{\omega - p^2/M}$ NOT $\frac{1}{\omega}$

- Modification of power-counting necessary for $\omega \sim m_\pi^2/M$;
- Leading effect [in EFT($\not\pi$)] comes from diagrams (b) and (c);
- Significant effects at 49 and 55 MeV. Negligible at 95 MeV.

Very-low-energy resummation effect



Dependence of cross section on $|\psi\rangle$



Polarizability extractions

Wave function	$\omega, \sqrt{\lvert t \rvert}$	$\alpha_N (10^{-4}\ \mathrm{fm}^3)$	$\beta_N (10^{-4}\ \mathrm{fm}^3)$	χ^2/d.o.f.
NLO χPT	< 160 MeV	9.0	1.7	1.48
NLO χPT	< 200 MeV	8.2	3.1	1.58
Nijm93	< 160 MeV	12.6	1.1	2.95

Polarizability extractions

Wave function	$\omega, \sqrt{\lvert t \rvert}$	$\alpha_N (10^{-4}\ \mathrm{fm}^3)$	$\beta_N (10^{-4}\ \mathrm{fm}^3)$	χ^2/d.o.f.
NLO χPT	< 160 MeV	9.0	1.7	1.48
NLO χPT	< 200 MeV	8.2	3.1	1.58
Nijm93	< 160 MeV	12.6	1.1	2.95

Including backward-angle SAL points $\Longrightarrow \alpha - \beta$ increases markedly. ?Δ dynamics.

Polarizability extractions

Wave function	$\omega, \sqrt{\|t\|}$	$\alpha_N (10^{-4}\ \mathrm{fm}^3)$	$\beta_N (10^{-4}\ \mathrm{fm}^3)$	χ^2/d.o.f.
NLO χPT	< 160 MeV	9.0	1.7	1.48
NLO χPT	< 200 MeV	8.2	3.1	1.58
Nijm93	< 160 MeV	12.6	1.1	2.95

Including backward-angle SAL points $\Longrightarrow \alpha - \beta$ increases markedly. ?Δ dynamics.

Results for α and β rather different with Nijm93 wave function: differential cross section larger by about 10%, shape similar.

Polarizability extractions

Wave function	$\omega, \sqrt{\lvert t\rvert}$	$\alpha_N (10^{-4}\ \text{fm}^3)$	$\beta_N (10^{-4}\ \text{fm}^3)$	χ^2/d.o.f.
NLO χPT	$<$ 160 MeV	9.0	1.7	1.48
NLO χPT	$<$ 200 MeV	8.2	3.1	1.58
Nijm93	$<$ 160 MeV	12.6	1.1	2.95

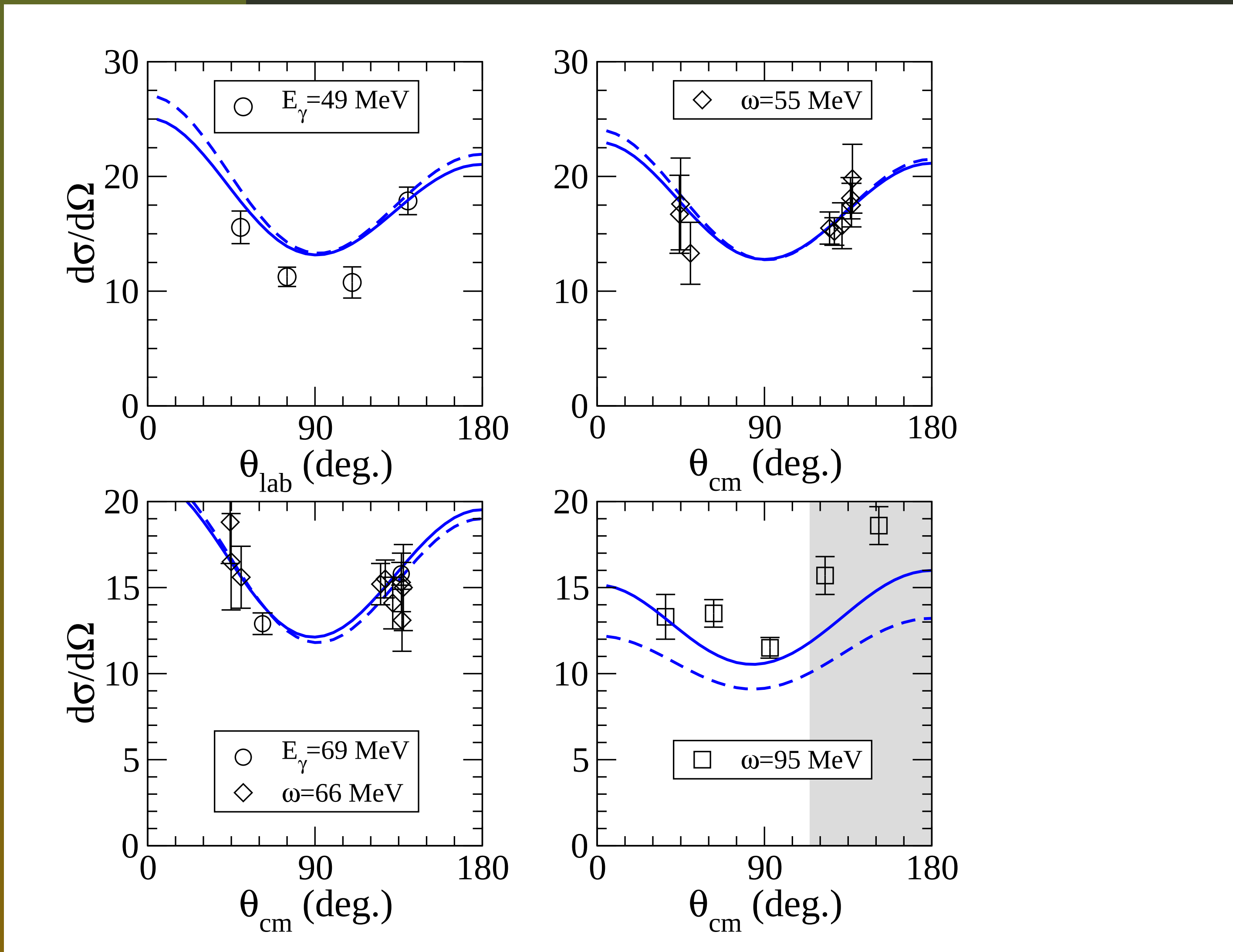
Including backward-angle SAL points $\Longrightarrow \alpha - \beta$ increases markedly. ?Δ dynamics.

Results for α and β rather different with Nijm93 wave function: differential cross section larger by about 10%, shape similar.

Isoscalar polarizabilities from low-energy γd$\rightarrow$ γd:

$$\alpha_N = (9.0 \pm 1.5)^{+3.6}_{-0.8} \times 10^{-4}\ \text{fm}^3$$
$$\beta_N = (1.7 \pm 1.5)^{+1.4}_{-0.6} \times 10^{-4}\ \text{fm}^3$$

Results



Fit to data with $\omega, \sqrt{|t|} \leq 160$ MeV shown.

Conclusions and Future Work

γp scattering:

N^{2}LO HBχPT calculation yields α_p, β_p $\quad\surd\quad \omega, \sqrt{|t|} \leq 200$ MeV

δ-expansion: $m_\pi \ll \Delta \ll \Lambda \Rightarrow$ dressed Δ $\quad\surd\quad \omega \leq 300$ MeV

Conclusions and Future Work

γp scattering:

N^{2}LO HBχPT calculation yields α_p, β_p $\surd$ $\omega, \sqrt{|t|} \leq 200$ MeV

δ-expansion: $m_\pi \ll \Delta \ll \Lambda \Rightarrow$ dressed Δ $\surd$ $\omega \leq 300$ MeV

γd scattering:

$O(e^2 P)$ [NLO]: Parameter-free predictions: $\surd$ $\omega \leq 80$ MeV.

$O(e^2 P^2)$ [N^{2}LO]: Extraction of α_N and β_N

Conclusions and Future Work

γp scattering:

N^{2}LO HBχPT calculation yields α_p, β_p $\surd$ $\omega, \sqrt{|t|} \leq 200$ MeV

δ-expansion: $m_\pi \ll \Delta \ll \Lambda \Rightarrow$ dressed Δ $\surd$ $\omega \leq 300$ MeV

γd scattering:

$O(e^2 P)$ [NLO]: Parameter-free predictions: $\surd$ $\omega \leq 80$ MeV.

$O(e^2 P^2)$ [N^{2}LO]: Extraction of α_N and β_N

Future work:

- Other processes in δ-expansion
- Δ degrees of freedom in γd (in progress with R. Hildebrandt, T. Hemmert, H. Grießhammer);
- Better understanding of $|\psi\rangle$ dependence;
- More data on γd $\rightarrow$ γd!
- $\gamma d \rightarrow \gamma np$ (Kossert *et al.* Phys. Rev. Lett. **88**, 162301 (2002)).

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

γd with explicit Δ's

R. Hildebrandt, H. Grießhammer, T. Hemmert, D.P.

- Calculation to N^{2}LO—$O(e^2\delta^3)$—in δ-counting;
- $\Delta\alpha_N$ and $\Delta\beta_N$ promoted by one order, and (here) fixed at values extracted from fit to γp data:

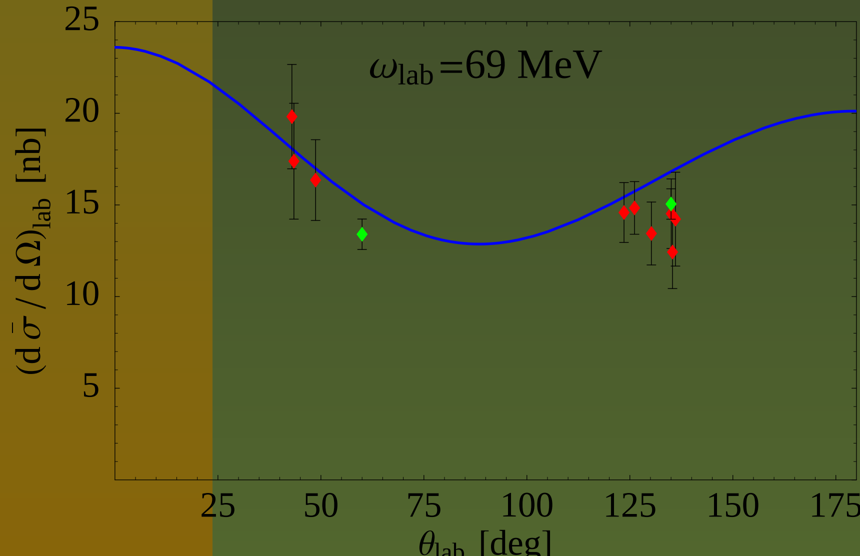
$$\alpha_N = 11.04 \times 10^{-4}\ \text{fm}^3, \quad \beta_N = 2.76 \times 10^{-4}\ \text{fm}^3$$

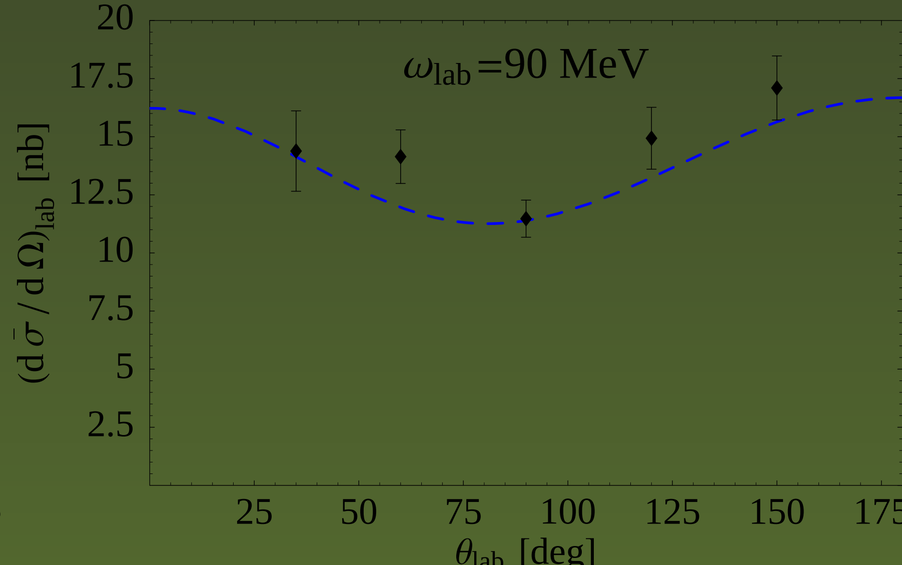
γd with explicit Δ's

R. Hildebrandt, H. Grießhammer, T. Hemmert, D.P.

- Calculation to N^{2}LO—$O(e^2\delta^3)$—in δ-counting;
- $\Delta\alpha_N$ and $\Delta\beta_N$ promoted by one order, and (here) fixed at values extracted from fit to γp data:

$$\alpha_N = 11.04 \times 10^{-4}\ \mathrm{fm}^3, \quad \beta_N = 2.76 \times 10^{-4}\ \mathrm{fm}^3$$





2004 Photonuclear GRC

MARK YOUR CALENDARS!

2004 Gordon Research Conference
on Photonuclear Reactions

August 1–6, 2004
Tilton School, Tilton, NH

Organizers: D. Phillips (Ohio), A. Sarty (St. Mary's), B. Krusche (Basel)

Topics:

- Chiral dynamics and the Delta
- Nucleon resonances
- Theory: present and future
- Z^0-nuclear physics
- The transition to the scaling regime
- Strong interactions at the Standard Model frontier
- Photonuclear interactions in the nuclear medium
- Electromagnetic probes of few-nucleon systems