Extracting Nucleon Polarisabilities

from Proton and Deuteron Compton Scattering

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How do constituents of the nucleon react to external fields?

How to reliably extract neutron and spin polarisabilities?

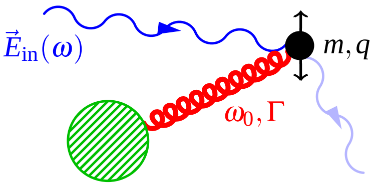
Comprehensive Theory Effort:
hg, J. McGovern (Manchester), D. R. Phillips (Ohio U)

$+$ G. Feldman (GW): **Prog. Part. Nucl. Phys. 2012**

Precursors: R. Hildebrandt/T. R. Hemmert/B. Pasquini/hg. . . 2000-05, . . . ,
Beane/Malheiro/McGovern/Phillips/van Kolck 1999-2005; Choudhury Shukla/Phillips 2005-08
Friar 1975, Arenhövel/Weyrauch 1980-83, Karakowski/Miller 1999, Levchuk/L'vov 1994-2000

1. Why Polarisabilities?

Example: induced electric dipole radiation from harmonically bound charge, damping Γ Lorentz/Drude 1900/1905



$$\vec{d}_{\text{ind}}(\omega) = \frac{q^2}{m} \underbrace{\frac{1}{\omega_0{}^2 - \omega^2 - \mathrm{i}\Gamma\omega}}_{=:\,4\pi\,\alpha_{E1}(\omega)} \vec{E}_{\text{in}}(\omega)$$

$$\mathcal{L}_{\text{pol}} = 2\pi\Big[\ \underbrace{\alpha_{E1}(\omega)\vec{E}^2 + \beta_{M1}(\omega)\vec{B}^2}_{\text{electric, magnetic scalar dipole}}\ + \dots\Big]$$

Energy- (ω)-dependent multipole-decomposition dis-entangles

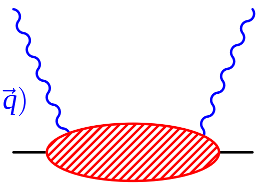
scales, symmetries & mechanisms of interactions with & among constituents.

Clean, perturbative probe explores:

- spontanelously broken **chiral symmetry** of pion cloud
- $\Delta(1232)$ **resonance** properties
- constituents of the **nucleon spin**
- **proton** $\Longleftrightarrow$ **neutron** iso-spin breaking:

  $\Longrightarrow$ elmag. p-n self-energy difference from $\beta_{M1}^{\text{p}} - \beta_{M1}^{\text{n}}$ Walker-Loud/...2012
- 2γ contribution to Lamb shift in muonic H (β_{M1})

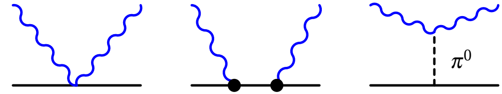
$q^\mu = (\omega, \vec{q})$



(a) Microscopic processes: χEFT with Δ

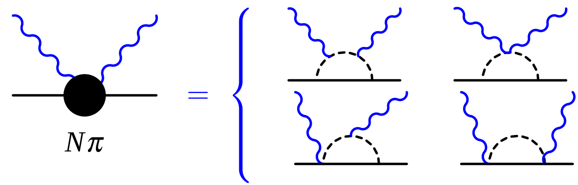
Bernard/Kaiser/Meißner 1994, ...
hg/Hemmert/Hildebrandt/Pasquini 2003-
hg/McGovern/Phillips 2012

– **Powell**: point-like spin-$\frac{1}{2}$ with anom. mag. moment



– **Chiral Dynamics**:

Cusp at 1-π production threshold.



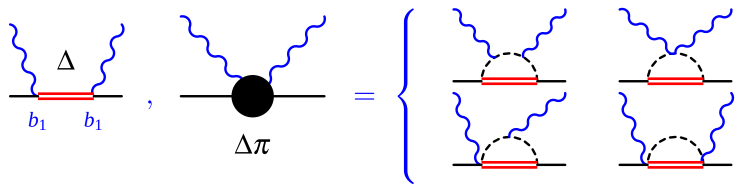
$+$ permutations $+$ crossed

– **Large Δ para-magnetism**

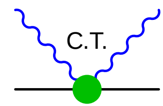
from N-to-Δ $M1$ transition.

$\delta\bar{\beta}_\Delta \approx +10 \times 10^{-4}$ fm^3

$\Longrightarrow \bar{\beta}^p \approx 2$ "fine-tuned"



– **Core Contribution** only for α_{E1}, β_{M1}: ω-indep. dia-magnetism.

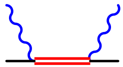


Different scales and mechanisms dis-entangled by ω-dependence.

(b) Including the $\Delta(1232)$ in χEFT

$\Delta(1232)$ lowest hadronic excitation above 1-pion threshold m_π, below χEFT breakdown scale $\Lambda_\chi \approx 1000$ MeV

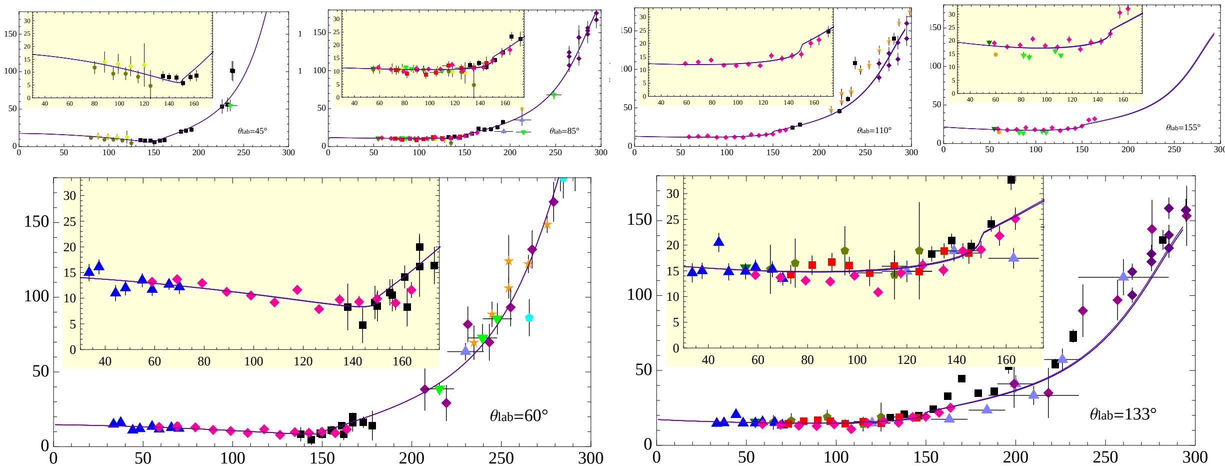
$\Longrightarrow$ **Expand in** $\delta = \frac{M_\Delta - M_N}{\Lambda_\chi} \approx \sqrt{\frac{m_\pi}{\Lambda_\chi}} = \frac{p_{\text{typ}}}{\Lambda_\chi} \ll 1$ **(numerical fact)** Pascalutsa/Phillips 2002

Higher Energy: Δ propagator  $\propto \frac{1}{E-(M_\Delta - M_N)}$ enhanced as $E \to M_\Delta - M_N$

$\Longrightarrow$ **re-order & re-sum**  $+ \ldots = \frac{1}{E-(M_\Delta - M_N) - \text{[loop]}}$  + relativity

Complete at $\mathcal{O}(e^2\delta^3)$ (N^{2}LO). Probe non-zero Δ width, $M1$ and $E2$ transition strengths.

(c) Determine Proton Polarisabilities from All Low-Energy Data

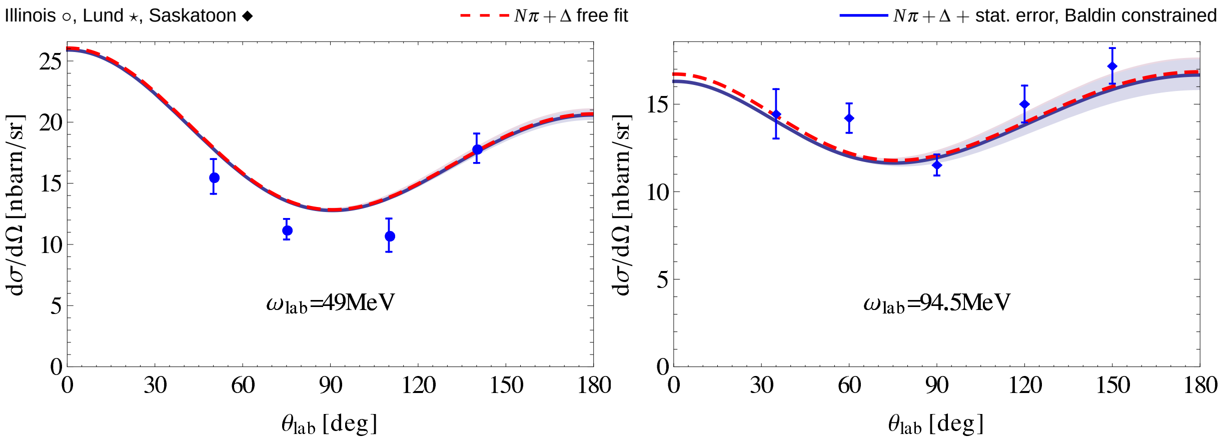


Iterate: $> 200\ \text{MeV}$: **Δ parameters ($b_1 = 3.7$; $b_2/b_1 = -0.34$ fixed)** $\Longrightarrow$ $< 170\ \text{MeV}$: **polarisabilities**

	$\bar{\alpha}^p_{E1}$ $[10^{-4}\ \text{fm}^3]$	$\bar{\beta}^p_{M1}$ $[10^{-4}\ \text{fm}^3]$	χ^2/d.o.f.
LO, parameter-free Bernard/Kaiser/Meißner 1994	12.5	1.25	no fit
NLO, free fit	$10.5 \pm 0.5_{\text{stat}} \pm 0.8_{\text{theory}}$	$2.7 \pm 0.5_{\text{stat}} \pm 0.8_{\text{theory}}$	$106.1/124$
NLO, Baldin constrained $\bar{\alpha}^s_{E1} + \bar{\beta}^s_{M1} = 13.8 \pm 0.4$	$10.7 \pm 0.3_{\text{stat}} \pm 0.2_{\Sigma} \pm 0.8_{\text{theory}}$	$3.1 \mp 0.3_{\text{stat}} \pm 0.2_{\Sigma} \pm 0.8_{\text{theory}}$	$106.5/125$
Olmos de Leon MAMI/global 2001	$12.1 \pm 1.2_{\text{stat+model}} \pm 0.4_{\Sigma}$	$1.6 \mp 1.2_{\text{stat+model}} \pm 0.4_{\Sigma}$	

(d) Determine Neutron Polarisabilities from all Deuteron Data

hg/McGovern/Phillips/
Feldman PPNP 2012

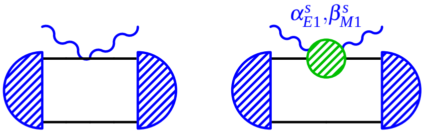


	$\bar{\alpha}^s_{E1}$ $[10^{-4}\ \text{fm}^3]$	$\bar{\beta}^s_{M1}$ $[10^{-4}\ \text{fm}^3]$	χ^2/d.o.f.
free fit	$10.5\pm2.0_{\text{stat}}\pm0.8_{\text{theory}}$	$3.6\pm1.0_{\text{stat}}\pm0.8_{\text{theory}}$	$24.3/24$
Baldin constrained $\bar{\alpha}^s_{E1}+\bar{\beta}^s_{M1}=14.5\pm0.3$	$10.9\pm0.9_{\text{stat}}\pm0.2_{\Sigma}\pm0.8_{\text{theory}}$	$3.6\mp0.9_{\text{stat}}\pm0.2_{\Sigma}\pm0.8_{\text{theory}}$	$24.4/25$
proton (Baldin) hg/...2012	$10.7\pm0.3_{\text{stat}}\pm0.2_{\Sigma}\pm0.8_{\text{theory}}$	$3.1\mp0.3_{\text{stat}}\pm0.2_{\Sigma}\pm0.8_{\text{theory}}$	$106.5/125$
previous ranges:	$[6\dots18]$	$[-4\dots9]$	

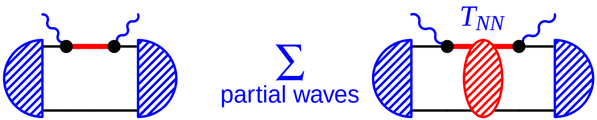
$\Longrightarrow$ **neutron $\approx$ proton polarisabilities**

One-body: electric, magnetic moment couplings

$\omega \sim \frac{Q^2}{M} \approx 20$ MeV $\quad \omega \sim Q \approx 100$ MeV



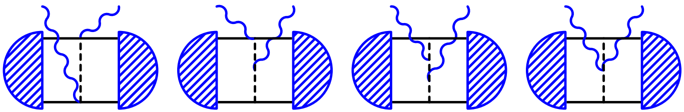
LO, N^{3}LO — LO, ↗ NLO



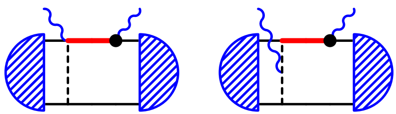
LO — ↘ NLO, N^{3}LO

2N correlated $\frac{\mathrm{i}}{B_d \pm \omega - \frac{q^2}{M}}$ uncorrelated

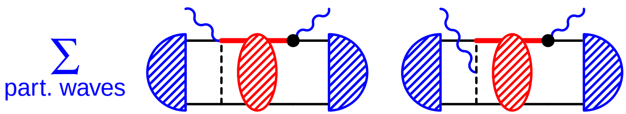
χEFT pion-exchange currents: Beane et al. 1999-2005; hg/...2005



NLO — → NLO



NLO — ↘ N^{2}LO



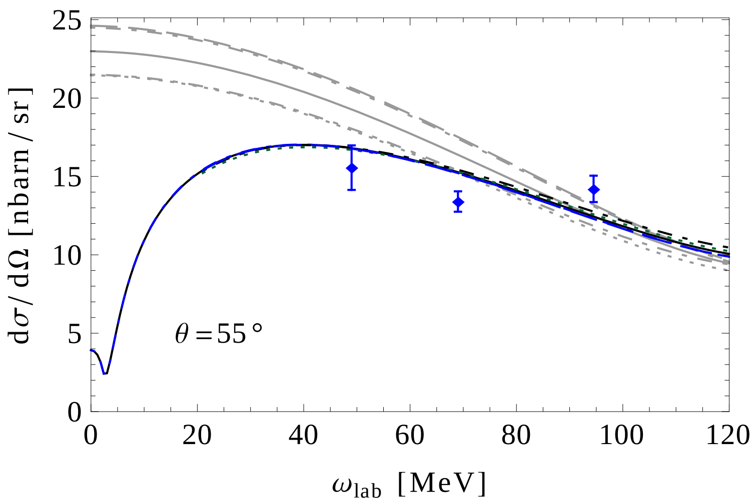
NLO — ↘ N^{3}LO, pert.

Full LO T_{NN} pivotal for current conservation. Arenhövel 1980

Low-Energy Theorem: Thomson limit $\mathcal{A}(\omega=0) = -\frac{e^2}{M_d}\vec{\varepsilon}\cdot\vec{\varepsilon}\,'$.

Thirring 1950, Friar 1975, Arenhövel 1980: Thomson limit $\Longleftrightarrow$ current conservation $\Longleftrightarrow$ gauge invariance.

Exact Theorem $\Longrightarrow$ At each χEFT order $\Longrightarrow$ Checks numerics.



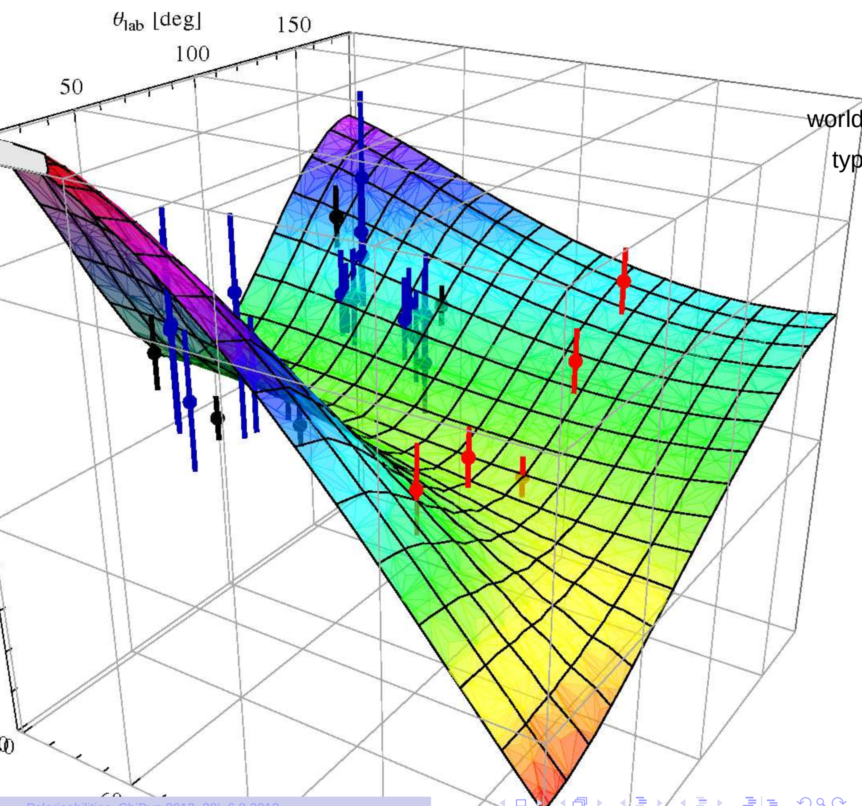
Significantly reduces cross section for $\omega \lesssim 70$ MeV. Urbana, Lund data

Numerically confirmed to $\lesssim 0.2\%$, irrespective of deuteron wave function & potential. model-independence

Wave function & potential dependence significantly reduced even as $\omega \to 150$ MeV $\Longrightarrow$ **gauge invariance**.

(a) Un-Polarised Deuteron Compton Scattering

hg/. . . 2005-2010
hg/McGovern/Phillips/Feldman PPNP 2012



$\left.\frac{d\sigma}{d\Omega}\right|_{lab}$ [nbarn/sr]

world data: **29 points** Illinois, Saskatoon, Lund

typ. stat.+uncorrel. sys.: $\pm[7\ldots10]\%$

typ. correl. sys.: $\pm[3\ldots5]\%$

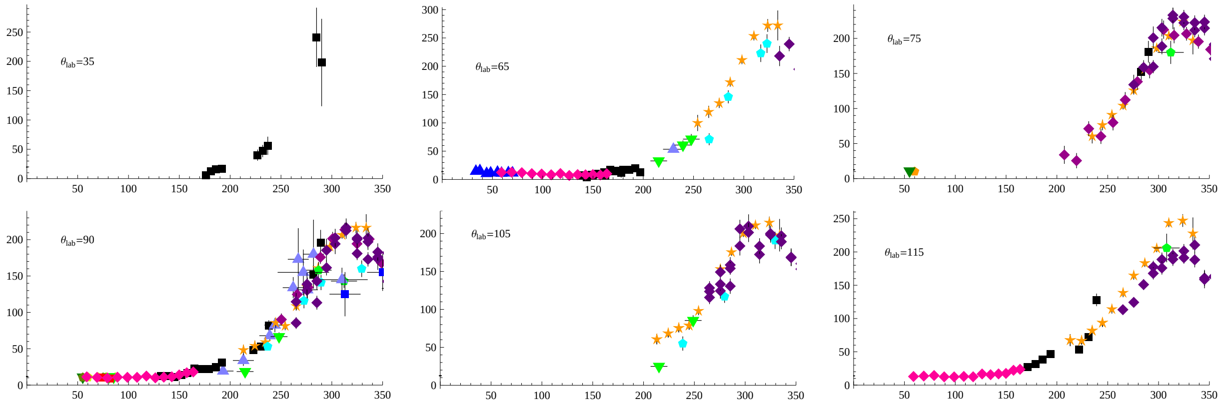
limited energy & angle converage

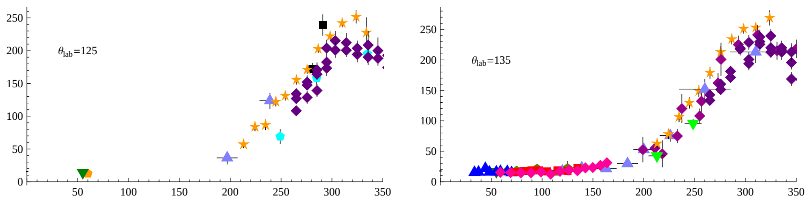
Upcoming

MAXlab: $[60;200]$ MeV, data taken;

HIγS: $[65;100]$ MeV, approved

(b) Proton Compton Data





~ 300 data, mostly 1991-2001

New effort for better data:

MAMI, MAXlab, HIγS,...

Gaps for: $\omega \in [160; 250]$ MeV; $\theta \to 0°$: Baldin check; $\theta \to 180°$ for $\Delta(1232)$!

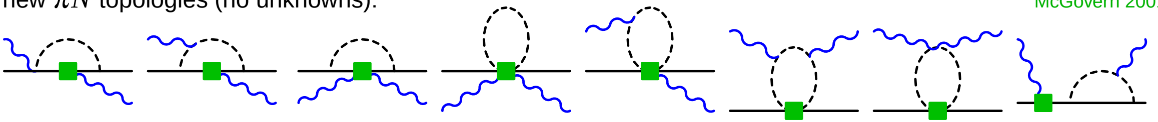
Small quoted systematics $\Longrightarrow$ tensions: MAMI vs. LEGS, but also others $\Longrightarrow$ $\frac{\chi^2}{\text{d.o.f.}} \approx 1$ cannot be achieved.

Not *more*, but *more reliable* data needed for unpolarised proton.

(c) Next order: δ^4 (N^{3}LO) – Work In Progress

– higher-order πN interactions in same topologies from $\mathcal{L}_{\chi\text{EFT}}$ only unknowns: $\delta\alpha_{E1}, \delta\beta_{M1}$

– new πN topologies (no unknowns): McGovern 2001



– No new $\Delta(1232)$ contributions.

– πN loops push intermed. angles too high $\Longrightarrow$ Fit γ_{M1M1}?? Why only this? 6 parameters: flat directions.

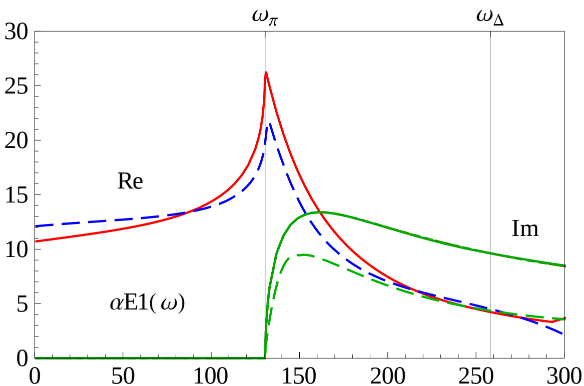
– Preliminary: Small changes N^{2}LO $\rightarrow$ N^{3}LO $\Longrightarrow$ Extraction stable, converges.

Dynamical Polarisabilities: **Multipole decomposition of real Compton scattering at fixed energy.**

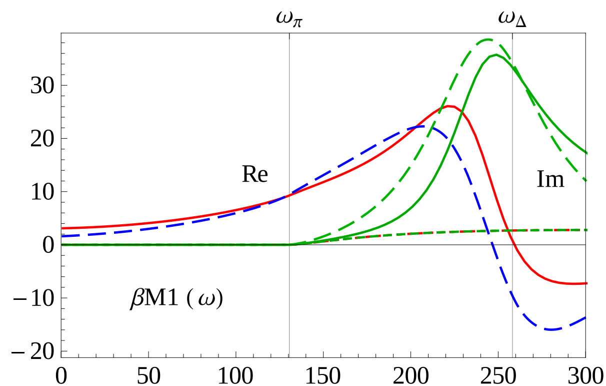
$$2\pi\left[\alpha_{E1}(\omega)\vec{E}^2+\beta_{M1}(\omega)\vec{B}^2+\gamma_{E1E1}(\omega)\vec{\sigma}\cdot(\vec{E}\times\dot{\vec{E}})+\gamma_{M1M1}(\omega)\vec{\sigma}\cdot(\vec{B}\times\dot{\vec{B}})+\dots\right]$$

Neither more nor less information about response of constituents, but **more readily accessible.**

$\alpha_{E1}(\omega)$: Pion cusp well captured by single-$N\pi$.

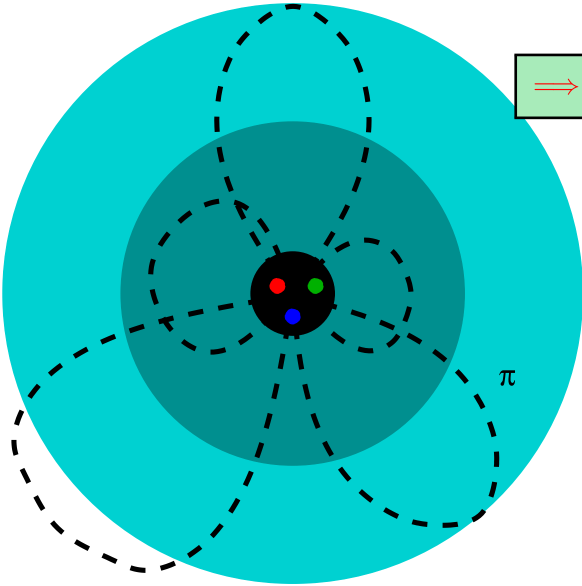


$\beta_{M1}(\omega)$: para-magnetic N-to-Δ $M1$-transition.



Re: **refraction**; Im: **absorption**

(e) What is the Physics of the Fit Parameters?



Pion & Δ dynamics capture ω-dependence.

$\Longrightarrow$ *Hypothesis:* $\delta\alpha_{E1}, \delta\beta_{M1}$ parameterise nucleon core.

– χ^2/**d.o.f.** $\approx 1 \Longrightarrow\ \sim \omega$-indep. $\lesssim 250$ MeV.

– **Naïvely NLO:** $|\delta\alpha_{E1}|, |\delta\beta_{M1}| \sim \dfrac{\alpha}{\Lambda_\chi^2\, M} \approx 1$

– ***Anomalously large:***

$$\delta\bar{\alpha}_{E1} = -5.4\ , \quad \delta\bar{\beta}_{M1} = -10.1$$

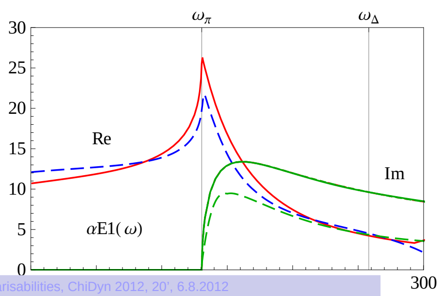
– **Cancel Δ, $\Delta\pi$ effects** in static pols.

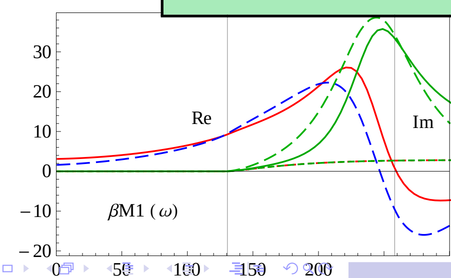
– **Iso-spin independent:** proton $\approx$ neutron values.

– **Not necessary for spin-polarisabilities γ_i?**

Speculation: Guichon, Schumacher

Correlated 2π exchange in 0^{++} t-channel??





4. Concluding Questions

Dynamical polarisabilities: Energy-dependent multipole-decomposition dis-entangles scales, symmetries & mechanisms of interactions with & among constituents: χiral symmetry of pion-cloud, iso-spin breaking, $\Delta(1232)$ properties, nucleon spin-constituents.

$\Longrightarrow$ **χEFT: unified frame-work off light nuclei: model-independent, systematic, reliable errors.**

Scalar Dipole Polarisabilities from *all Compton data below* $200\ \mathrm{MeV}$:

proton	$\bar{\alpha}^p = 10.7 \pm 0.3_{\text{stat}} \pm 0.2_\Sigma \pm 0.8_{\text{theory}}$	$\bar{\beta}^p = 3.1 \mp 0.3_{\text{stat}} \pm 0.2_\Sigma \pm 0.8_{\text{theory}}$
iso-scalar	$\bar{\alpha}^s = 10.9 \pm 0.9_{\text{stat}} \pm 0.2_\Sigma \pm 0.8_{\text{theory}}$	$\bar{\beta}^s = 3.6 \mp 0.9_{\text{stat}} \pm 0.2_\Sigma \pm 0.8_{\text{theory}}$
neutron	$\bar{\alpha}^n = 11.1 \pm 1.8_{\text{stat}} \pm 0.4_\Sigma \pm 0.8_{\text{theory}}$	$\bar{\beta}^n = 4.1 \mp 1.8_{\text{stat}} \pm 0.4_\Sigma \pm 0.8_{\text{theory}}$

Theory To-Do List: explore host of observables: expansion $\frac{p_{\text{typ}}}{\Lambda_\chi} \ll 1$ for credible error-bars. math notebooks

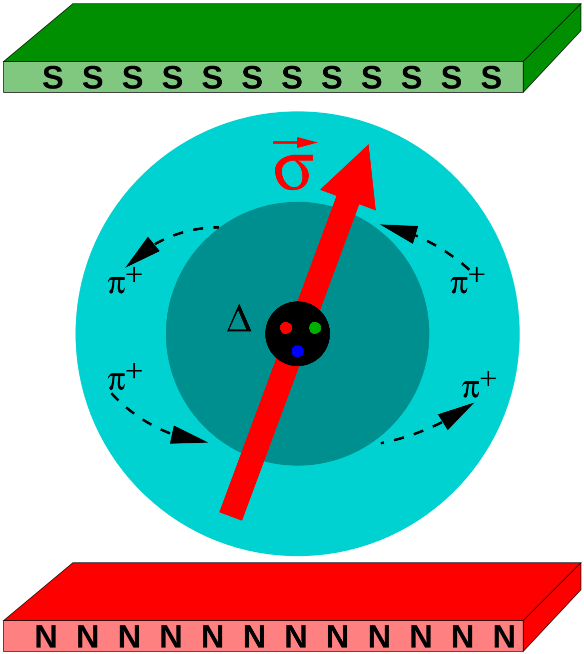
- **One Nucleon:** χEFT with $\Delta(1232)$ at δ^4 into resonance region — near-done
- **Deuteron:** extend beyond 1π-threshold into $\Delta(1232)$ region; break-up — now focus of attention
- **^{3}He & heavier:** Thomson limit; into $\Delta(1232)$ region; break-up — near-term

Data Needed: cross-sections & asymmetries – reliable systematics. $\Longrightarrow$ ***spin-polarisabilities.***

Clean probe to explore the strong force at low energies.

Response of **spin-degrees of freedom in nucleon** to real photon of definite multipolarity and non-zero energy ω.

$\Longrightarrow$ **Multipole Analysis.**



$$\mathcal{L}_{\text{pol}} = 4\pi\, N^\dagger \times$$

$$\Big\{ \tfrac{1}{2} \Big[\alpha_{E1}(\omega)\, \vec{E}^2 + \beta_{M1}(\omega)\, \vec{B}^2 \Big]$$ **scalar dipole**

$$+ \tfrac{1}{2} \Big[\gamma_{E1E1}(\omega)\, \vec{\sigma}\cdot(\vec{E}\times\dot{\vec{E}}) + \gamma_{M1M1}(\omega)\, \vec{\sigma}\cdot(\vec{B}\times\dot{\vec{B}})$$

"pure" spin-dependent dipole

$$-2\, \gamma_{M1E2}(\omega)\, \sigma_i\, B_j\, E_{ij} + 2\, \gamma_{E1M2}(\omega)\, \sigma_i\, E_j\, B_{ij} \Big]$$

"mixed" spin-dependent dipole

$$+ \dots \Big\} N$$ quadrupole etc.

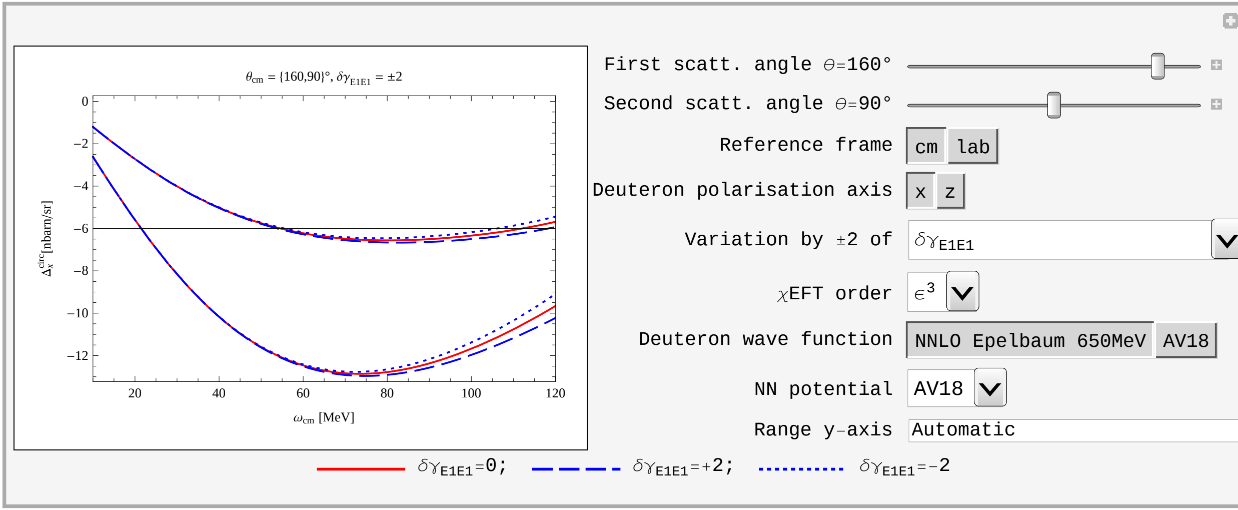
$E_{ij} := \frac{1}{2}(\partial_i E_j + \partial_j E_i)$ etc.

(b) Plethora of Polarisation Observables in Compton Scattering

2 $\times$ 6 observables, 6 polarisabilities, 3 kinemat. variables ω, θ, ϕ + additional constraints

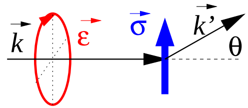
$\Longrightarrow$ **Interactive** *mathematica 8.0* **notebooks.** hg/...2010-

Example Screenshot

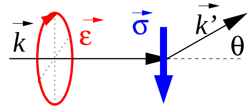


Proton Best: Incoming γ circularly polarised, sum over final states. N-spin in $(\vec{k},\vec{k}')$-plane, perpendicular to $\vec{k}$:

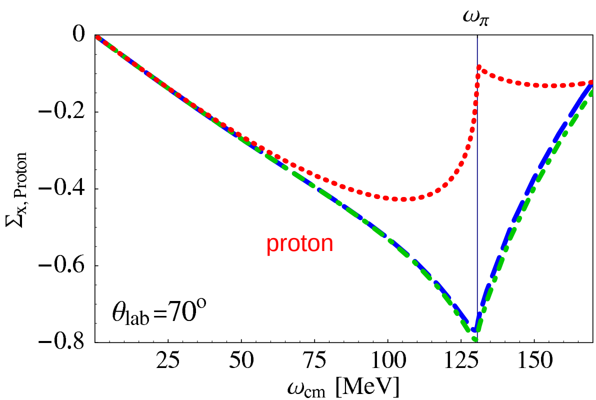
$$\Sigma_x = \frac{(\uparrow\rightarrow)-(\uparrow\leftarrow)}{(\uparrow\rightarrow)+(\uparrow\leftarrow)}$$

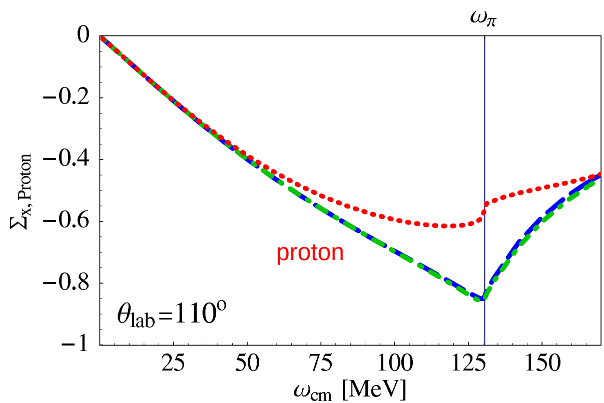


vs.



– – – full $N\pi+\Delta$ · · · · · · no γ_i's - · - · - no $l \geq 2$





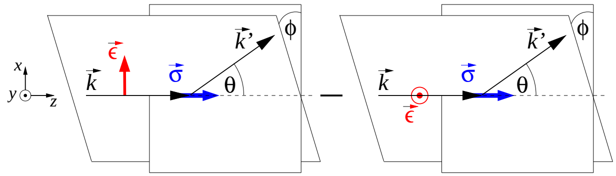
– Dominated by structure – Clear γ_i-dep. – Higher pols negligible – HIγS (?), MAMI(?)

Also good signal for linear polarisations.

(d) Spin-Polarisabilities from Linearly Pol. Photons at 125 MeV

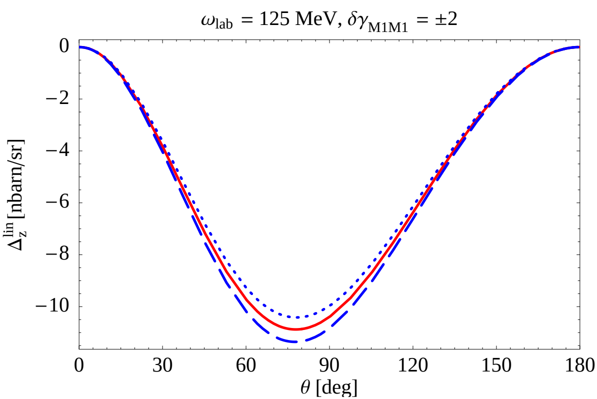
Deuteron Best: Incoming γ linearly polarised, sum over final states. N-spin in $(\vec{k},\vec{k}')$-plane, parallel to $\vec{k}$:

difference Δ_z^{lin}, asymmetry $\Sigma_z^{\text{lin}} = \frac{\Delta_z^{\text{lin}}}{\text{sum}}$



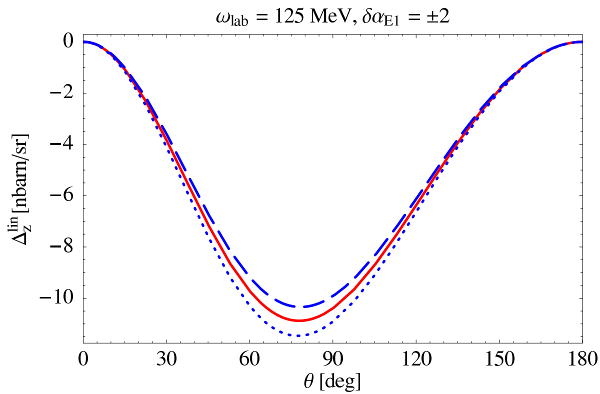
Sensitivity on neutron γ_{M1M1}

—— 3.2; - - - - - 3.2 + 2; ······ 3.2 − 2



Sensitivity on neutron α_{E1}

—— 11.3; - - - - - 11.3 + 2; ······ 11.3 − 2



Sensitive to γ_{M1M1}, but must nail down α_{E1}, β_{M1} at lower energy.

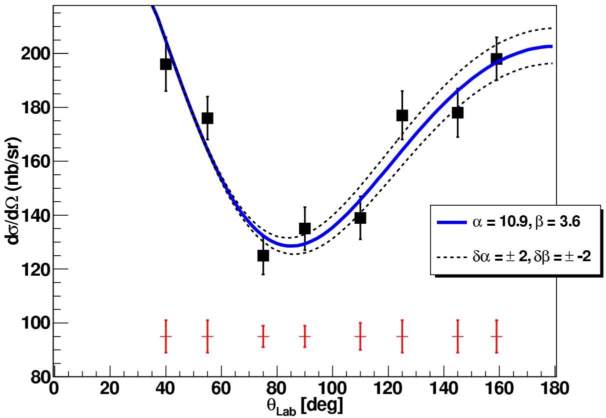
Experiment: coherent $\frac{d\sigma}{d\Omega} \propto$ (target-charge)$^{2 \text{ to } 1}$, more & easier targets $\Longrightarrow$ *heavier nuclei* for larger count-rates

Theory: To reliably extract nucleon pols., must accurately describe nuclear binding & levels

$\Longrightarrow$ *lighter nuclei* for simpler numerics & reliability

Find *sweet-spot* between competing forces: ^{4}He, ^{6}Li.

^{6}Li experiment at HIγS $\Longrightarrow$ Theory needs efficient method for $A > 3$ systems.



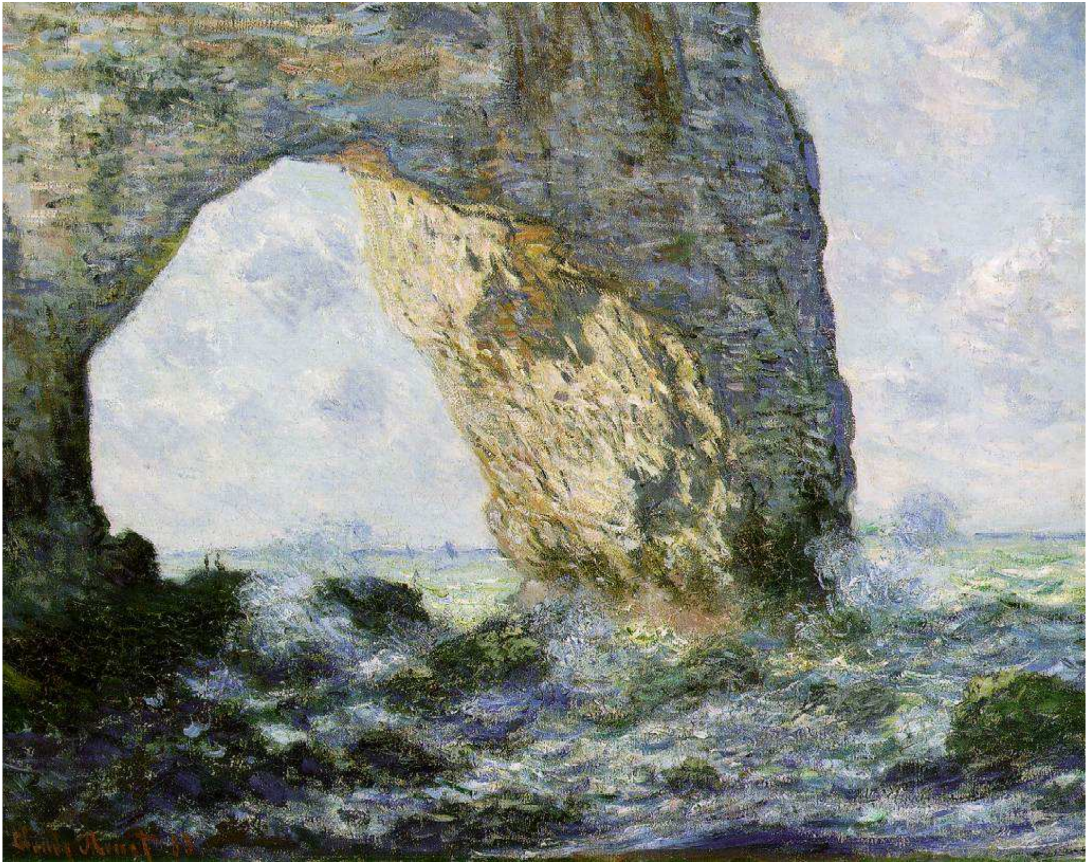
Myers/Feldman/. . . 2012 with shot-in-the-dark model

Promising:

Lorentz Integral Transformation method LIT

for rescattering contributions Efros/Leidemann/Orlandini 2000

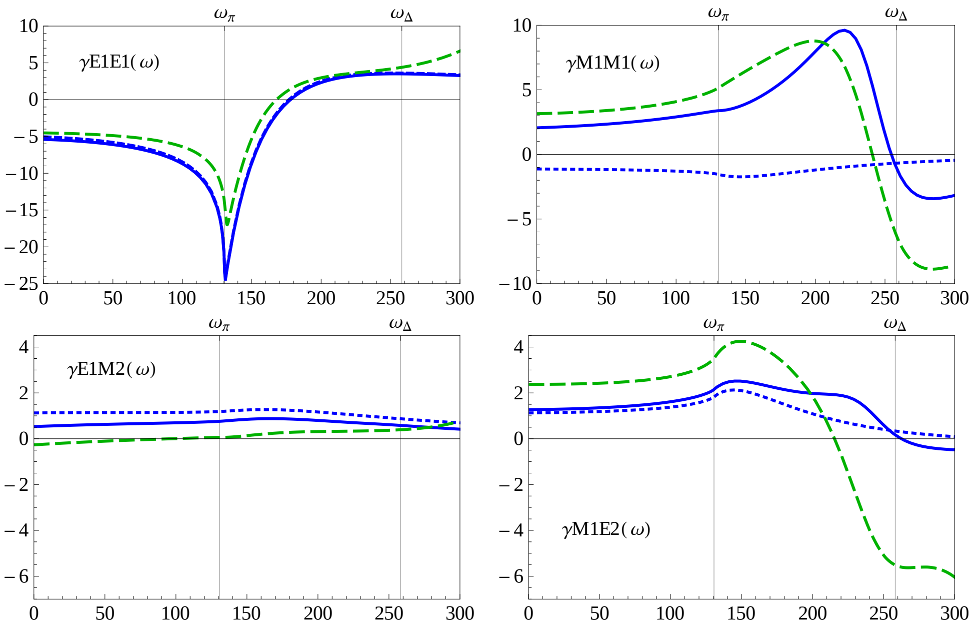
Now tackling ^{6}Li. Bampa/Leidemann/Arenhövel/. . . in progress



Claude Monet: Rock Arch West of Etretat (The Manneport), 1883

(a) Iso-Scalar Spin-Dependent Dynamical Polarisabilities Hildebrandt/TRH/hg/Pasquini 2002/03

Predicted in χEFT: No N-core contributions $\Longrightarrow$ Spin-physics dominated by pion-cloud $+\,\Delta$ (γ_{M1M1}, γ_{M1E2}).



Pure polarisabilities

γ_{E1E1}, γ_{M1M1} agree.

— $N\pi+\Delta$

- - - $N\pi$

— — Disp. Rel. .

Mixed polarisabilities

γ_{E1M2}, γ_{M1E2} small.

Uncertainties in DR?

Static values units: $[10^{-4}\ \mathrm{fm}^4]$	χEFT iso-scalar	DR iso-scalar	MAMI proton	LEGS proton	MAMI neutron
$\bar{\gamma}_0 = -(\gamma_{E1E1}+\gamma_{M1M1}+\gamma_{E1M2}+\gamma_{M1E2})$	-0.7	-0.4	-1		??
$\bar{\gamma}_\pi-(\pi^0-\mathrm{pole}) = -\gamma_{E1E1}+\gamma_{M1M1}-\gamma_{E1M2}+\gamma_{M1E2}$	8.6	12	~ 8	~ 18	$[12\ldots16]\pm4_{\mathrm{model}}$

(b) Consequences of NN-Rescattering: An Exact Low-Energy Theorem

Off-shell T_{NN} by Green's function method

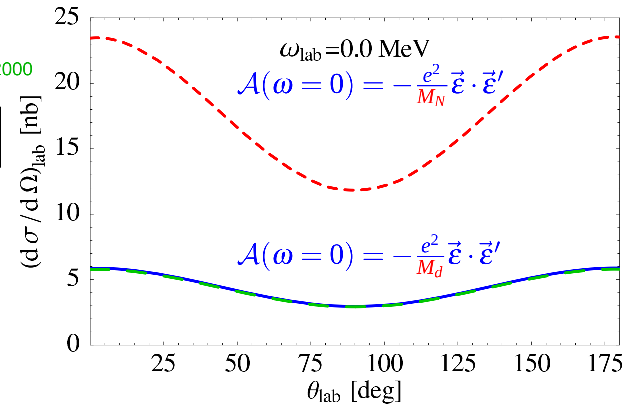
Arenhövel/Weyrauch 1980/83, Karakowski/Miller 1999, Levchuk/L'vov 2000

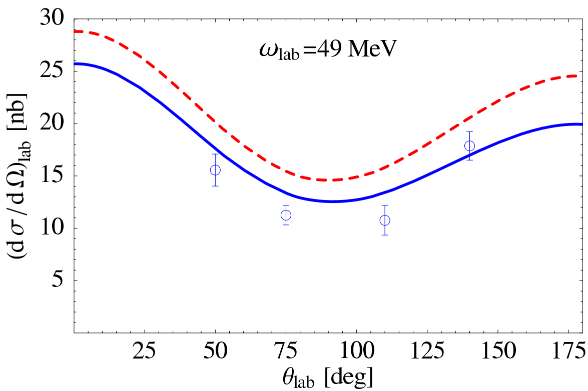
Thomson limit order-by-order in χEFT.

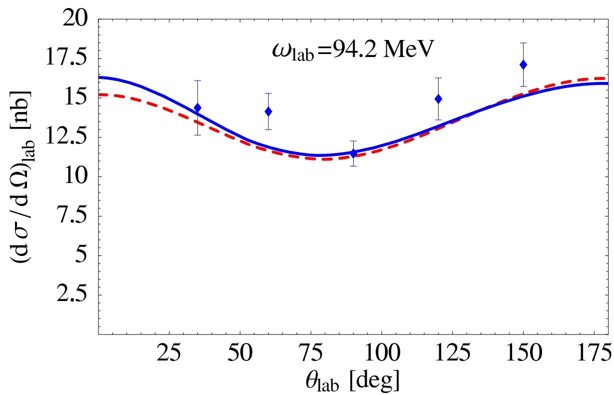
Statistically significant only for $\omega \lesssim 70$ MeV.

Included higher-order diagrams indeed small.

- - -: without T_{NN} ——: with T_{NN} - - - predicted Thomson



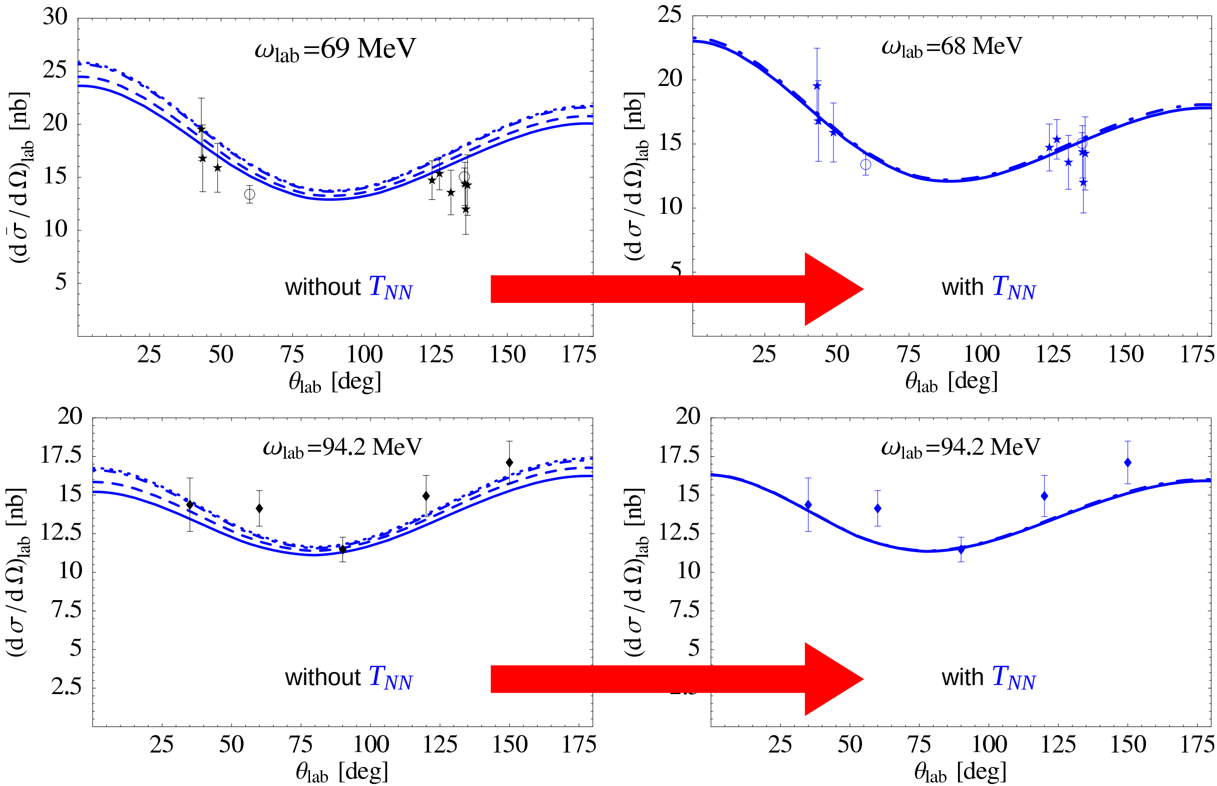




(b) Consequences of NN-Rescattering: An Exact Low-Energy Theorem

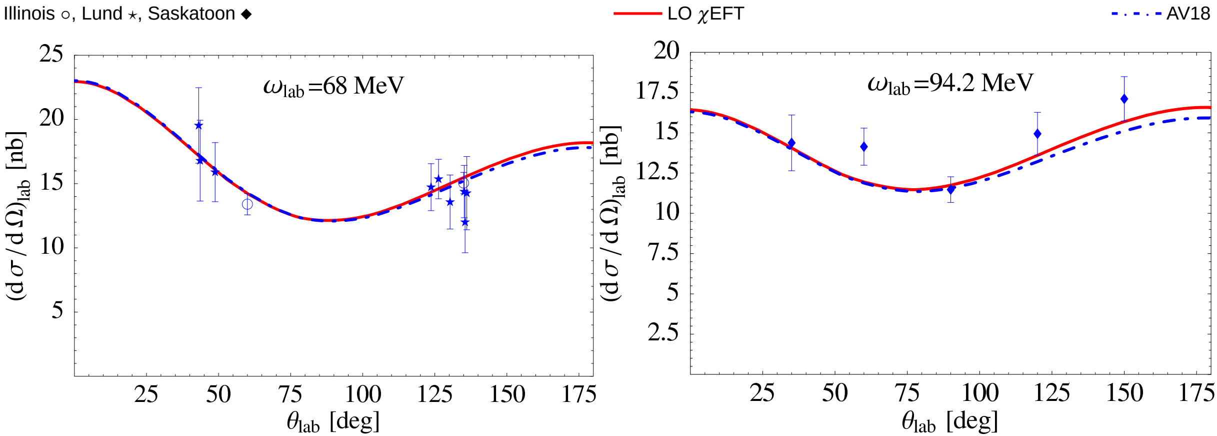
Eliminate Dependence on Deuteron Wave-function also at high ω, for $\omega \to 0$ clear from Thomson.

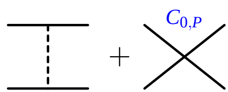
Illinois ○, Lund ⋆, Saskatoon ◆ — "NNLO χPT" - · - · AV18 – – CD-Bonn · · · · · Nijmegen 93



(b) Consequences of NN-Rescattering: An Exact Low-Energy Theorem

Dependence of T_{NN} on NN-potential $\cong$ short-distance, for $\omega \to 0$ clear from Thomson.



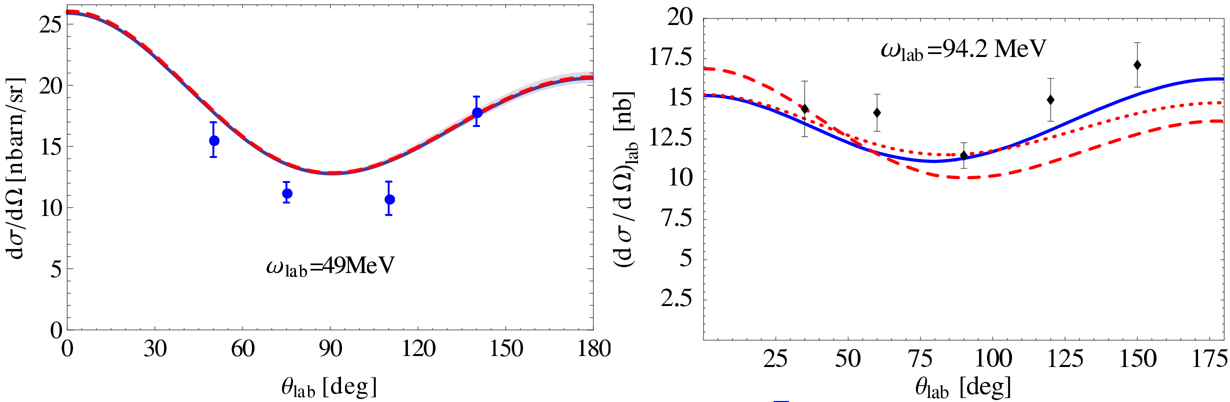
LO χEFT-potential:  $\sim Q^{-1}$

Consistent for Compton at NLO: $\mathcal{O}(Q^0)$-correction of NN-potential presumed zero.

AV18 provides $< 3\%$ corrections $\Longrightarrow$ suggests higher-order indeed $Q^1 \approx \left(\frac{1}{7}\right)^2$.

(c) Determine Neutron Polarisabilities from all Deuteron Data

Illinois ○, Lund ⋆, Saskatoon ◆ $N\pi$ only (LO); $N\pi$ only (NLO fit Beane et al.); $N\pi+\Delta+$ stat. error, Baldin constrained



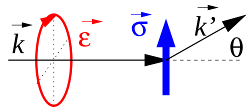
constrained:	$\bar{\alpha}^s = 11.0 \pm 0.9_{\text{stat}} \pm 0.3_\Sigma \pm 0.8_{\text{theory}}$	$\bar{\beta}^s = 3.2 \mp 0.7_{\text{stat}} \pm 0.3_\Sigma \pm 0.8_{\text{theory}}$
Proton hg/...2003:	$\bar{\alpha}^p = 11.0 \pm 1.4_{\text{stat}} \pm 0.4_\Sigma \pm 0.8_{\text{theory}}$	$\bar{\beta}^p = 2.8 \mp 1.4_{\text{stat}} \pm 0.4_\Sigma \pm 0.8_{\text{theory}}$
previous ranges:	$[6 \dots 18]$	$[-4 \dots 9]$

estimate theory uncertainty ($\lesssim \pm 1$): higher-order $1N$; AV18 vs. LO χEFT, d wave-fu., with vs. without T_{NN}.

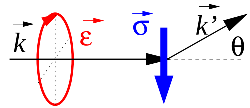
$\Longrightarrow$ **neutron ≈ proton polarisabilities**

Deuteron Best: Incoming γ circularly polarised, sum over final states. N-spin in $(\vec{k},\vec{k}')$-plane, perpendicular to $\vec{k}$:

difference Δ_x^{circ}, asymmetry $\Sigma_x^{\text{circ}} = \dfrac{\Delta_x^{\text{circ}}}{\text{sum}}$

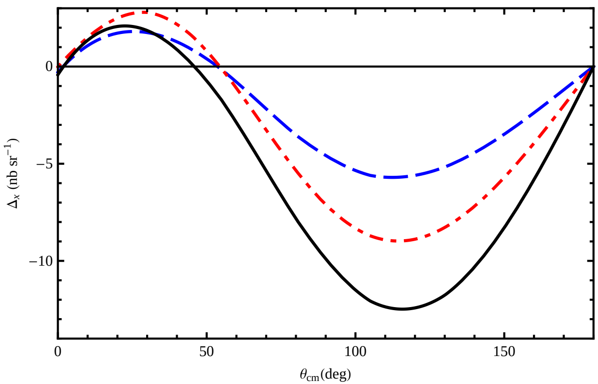


vs.



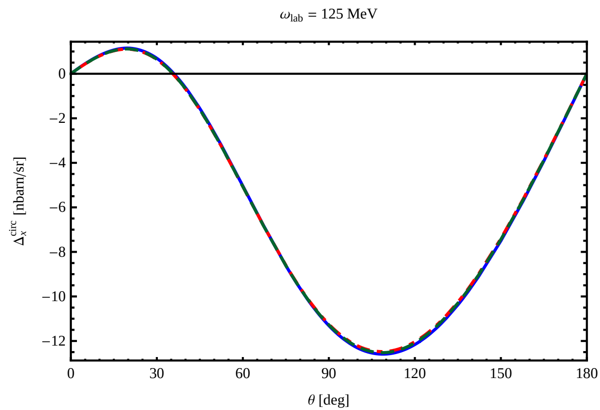
Sensitivity on Δ & NN-rescattering:

- - - - $N\pi$, no NN; - · - · - $N\pi+\Delta$, no NN; —— $N\pi+\Delta+NN$



Sensitivity on wave-function:

NNLO Epelbaum 650 MeV, AV18, Nijmegen 93



– More pronounced by explicit $\Delta(1232)$

– Thomson (NN rescatt.) important even at high $\omega = 125$ MeV

– No residual deuteron wave-function dependence

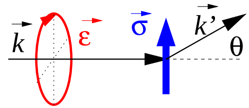
– Higher pols negligible

(d) Spin-Polarisabilities from Circularly Pol. Photons at 125 MeV

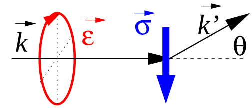
Shukla/Phillips 2005
Shukla/hg 2009

Deuteron Best: Incoming γ circularly polarised, sum over final states. N-spin in $(\vec{k},\vec{k}')$-plane, perpendicular to $\vec{k}$:

difference Δ_x^{circ}, asymmetry $\Sigma_x^{\text{circ}} = \frac{\Delta_x^{\text{circ}}}{\text{sum}}$

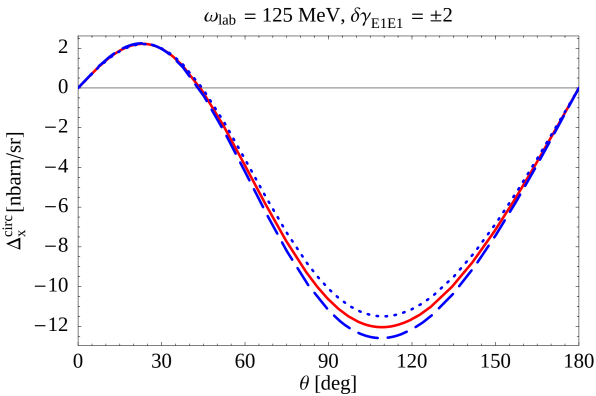


vs.



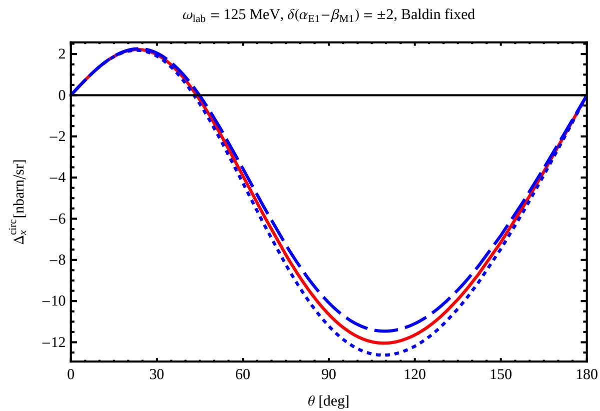
Sensitivity on neutron γ_{E1E1}

—— -5.2; - - - - - $-5.2+2$; ······ $-5.2-2$



Sensitivity on neutron $\alpha_{E1}-\beta_{M1}$; Baldin-Σ fixed

—— 8.2; - - - - - $8.2+2$; ······ $8.2-2$

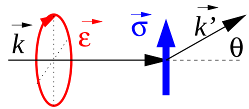


Sensitive to γ_{E1E1}, but must nail down α_{E1}, β_{M1} at lower energy.

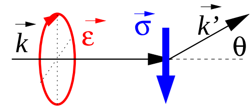
Similarly good signal for linear polarisation Δ_x^{lin}.

Deuteron Best: Incoming γ circularly polarised, sum over final states. N-spin in $(\vec{k},\vec{k}')$-plane, perpendicular to $\vec{k}$:

difference Δ_x^{circ}, asymmetry $\Sigma_x^{\text{circ}} = \frac{\Delta_x^{\text{circ}}}{\text{sum}}$

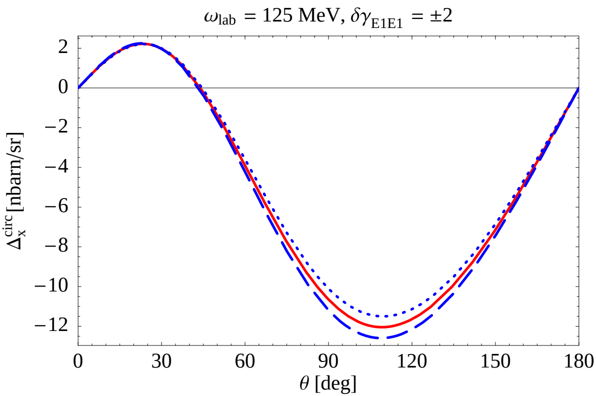


vs.



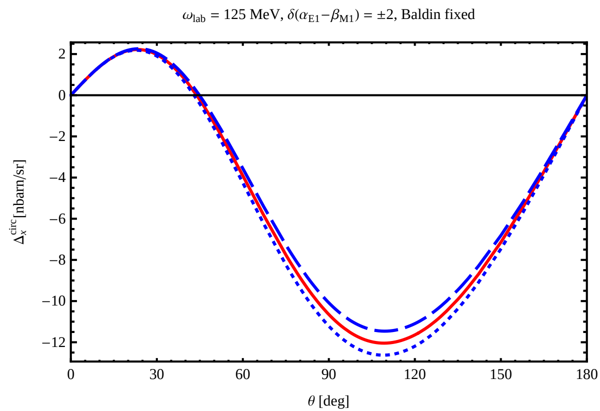
Sensitivity on neutron γ_{E1E1}

—— -5.2; - - - - - $-5.2+2$; ······ $-5.2-2$



Sensitivity on neutron $\alpha_{E1}-\beta_{M1}$; Baldin-Σ fixed

—— 8.2; - - - - - $8.2+2$; ······ $8.2-2$



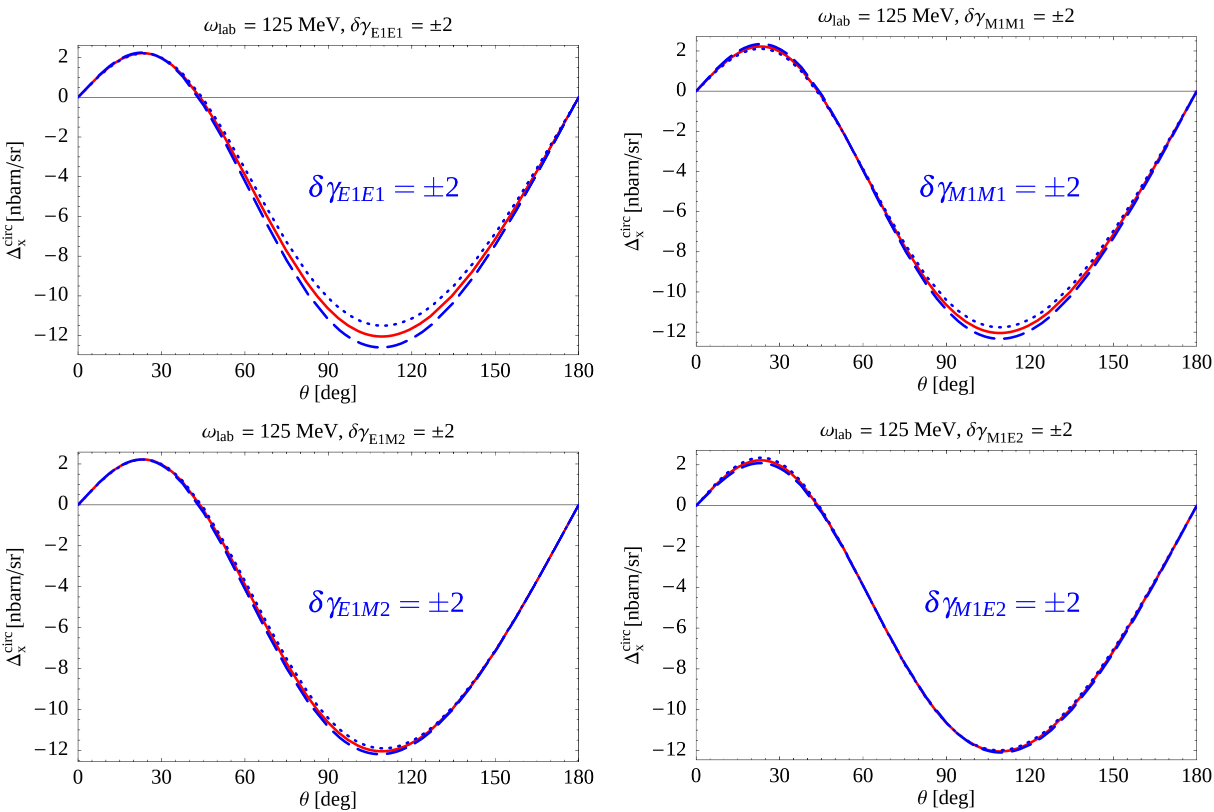
Sensitive to γ_{E1E1}, but must nail down α_{E1}, β_{M1} at lower energy.

$\Delta(1232)$ and re-scattering increase signal.

(d) Spin-Polarisabilities from Circularly Pol. Photons at 125 MeV

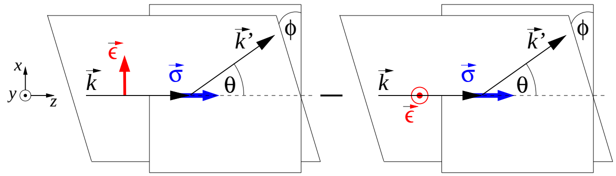
Shukla/Phillips 2005
Shukla/hg 2009

Deuteron Best: Incoming γ circularly polarised, sum over final states. N-spin in $(\vec{k},\vec{k}')$-plane, perpendicular to $\vec{k}$:



Deuteron Best: Incoming γ linearly polarised, sum over final states. N-spin in $(\vec{k},\vec{k}')$-plane, parallel to $\vec{k}$:

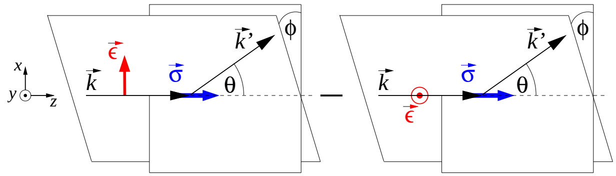
difference Δ_z^{lin}, asymmetry $\Sigma_z^{\text{lin}} = \frac{\Delta_z^{\text{lin}}}{\text{sum}}$



(e) Spin-Polarisabilities from Linearly Pol. Photons at 125 MeV

Deuteron Best: Incoming γ linearly polarised, sum over final states. N-spin in $(\vec{k},\vec{k}')$-plane, parallel to $\vec{k}$:

difference Δ_z^{lin}, asymmetry $\Sigma_z^{\text{lin}} = \frac{\Delta_z^{\text{lin}}}{\text{sum}}$

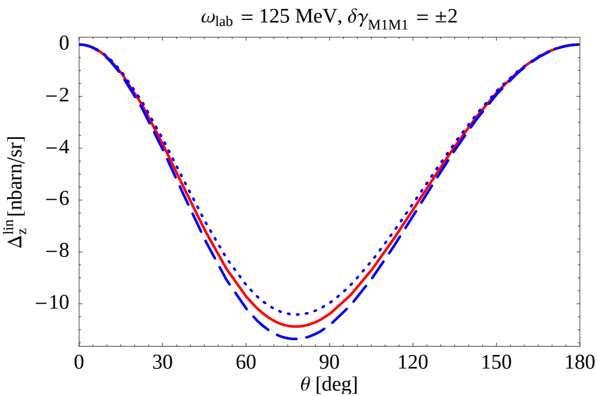


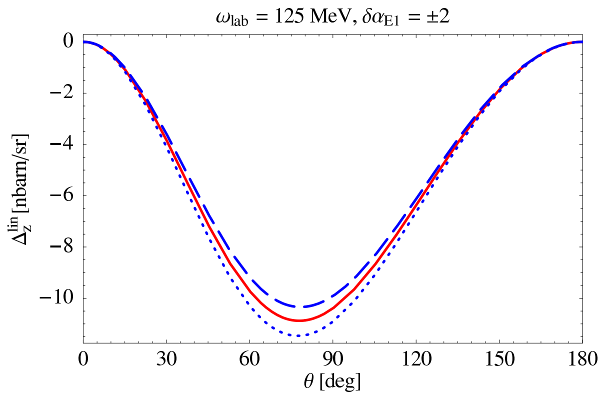
Sensitivity on neutron γ_{M1M1}

—— 3.2; - - - - 3.2 + 2; ⋯⋯ 3.2 − 2

Sensitivity on neutron α_{E1}

—— 11.3; - - - - 11.3 + 2; ⋯⋯ 11.3 − 2



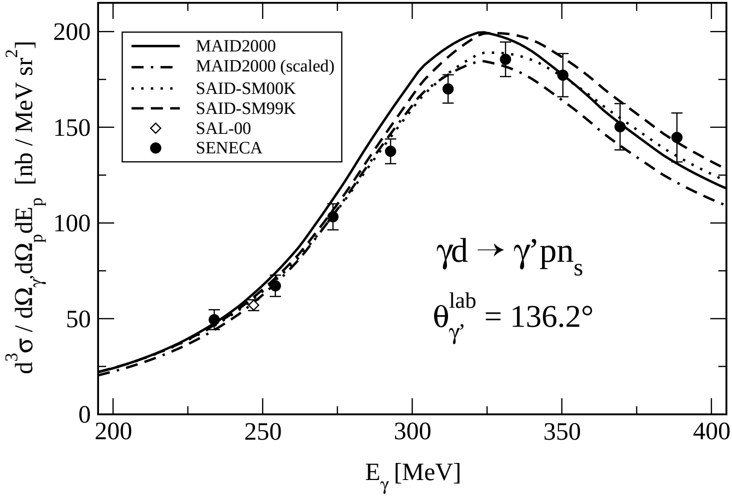


Sensitive to γ_{M1M1}, but must nail down α_{E1}, β_{M1} at lower energy.

(f) Inelastic Compton Scattering on Nuclei

Nucleon polarisabilities from centre of quasi-inelastic peak in $A(\gamma,\gamma A')N$

Only 10 data for $d(\gamma,\gamma p)n$ at $\omega \in [230;400]$ MeV.



Kossert et al. 2003 found $\alpha^n_{E1} = 12.5 \pm 1.8(\text{stat})^{+1.1}_{-0.6}(\text{syst}) \pm 1.1(\text{model})$, β_{M1} from Baldin

sys. & model-error *under-estimated?:*

π production, SAID/MAID-2000 amplitudes,

π-exchange currents not chirally consistent,

...

To Do: Theory starting up

Analyse elastic & inelastic in unified χEFT frame, test quasi-free hypothesis.

Enhancement by $\Delta(1232)$ peak $\Longrightarrow$ accurate Δ theory.

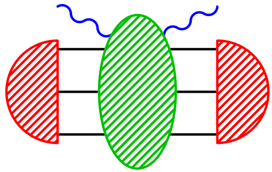
To Do: Experiment

Better data.

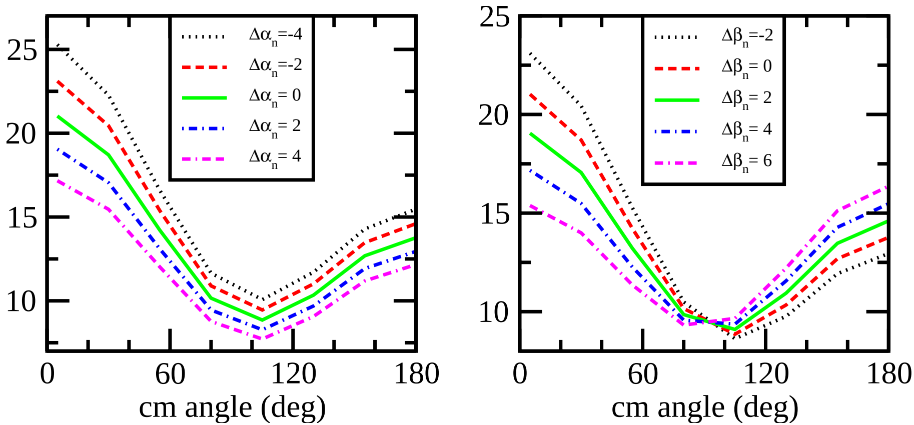
Lower energies.

Sensitivity of single-/double-polarised observables, breakup asymmetries.

Alternative targets: ^{3}He, ^{4}He, ^{6}Li, ..., also for proton?



Example: Sensitivity of unpolarised cross-section at $\omega_{\text{lab}} = 120\ \text{MeV}$ on α^n, β^n



– First Compton cross section on ^{3}He.

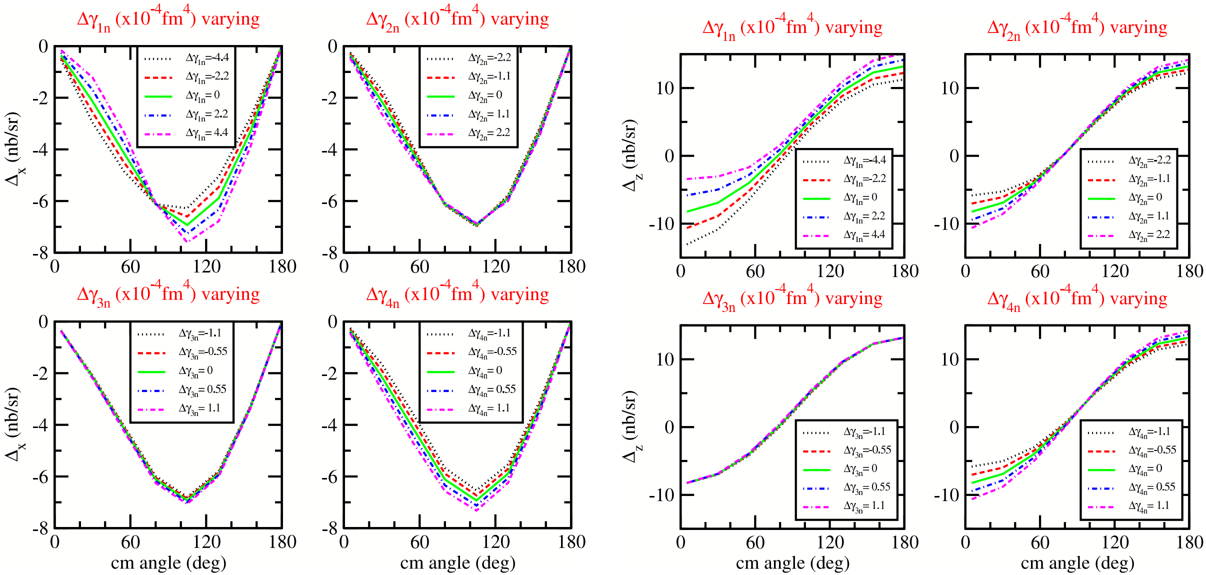
– ^{3}He as effective neutron spin target.

– Extend beyond $\omega \in [80;120]\ \text{MeV}$: re-scattering (Thomson, T_{NN}), explicit $\Delta(1232)$, threshold corrections

$\Longrightarrow$ Effects will become more pronounced.

(h) Starting with ^{3}He: Doubly-Polarised

Example: Sensitivity of polarised cross-section at $\omega_{\text{lab}} = 120\ \text{MeV}$ on γ_i^n's



– First Compton cross section on ^{3}He.

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