Compton Scattering and Nucleon Polarisabilities in Chiral EFT: The Next Steps

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON DC

H. W. Grießhammer

Institute for Nuclear Studies
The George Washington University, DC, USA

GW INS
Institute for Nuclear Studies
THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

1. Two-Photon Response Explores Low-Energy Dynamics
2. Polarisabilities from Compton Scattering
3. The Future: Per Aspera Ad Astra
4. Concluding Questions

Office of Science
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How do constituents of the nucleon react to external fields?

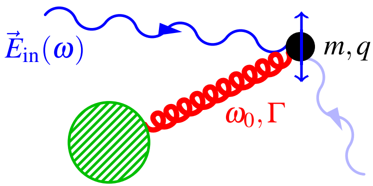
How to reliably extract proton, neutron and spin polarisabilities?

Office of Nuclear Physics
Exploring Nuclear Matter - Quarks to Stars

Comprehensive Theory Effort:
hg, J. A. McGovern (Manchester), D. R. Phillips (Ohio U): *Eur. Phys. J.* **A49** (2013), 12 (proton)
+ G. Feldman (GW): **Prog. Part. Nucl. Phys. 67 (2012) 841**
neutron in COMPTON@MAX-lab: *Phys. Rev. Lett.* **113** (2014) 262506 [1409.3705 [nucl-ex]] & subm. to PRC [1503.08094 [nucl-ex]]

(a) Polarisabilities: Stiffness of Charged Constituents in El.- Mag. Fields

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

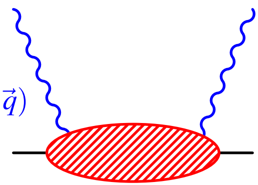


$$\vec{d}_{\text{ind}}(\omega) = \underbrace{\frac{q^2}{m}\,\frac{1}{\omega_0^2 - \omega^2 - \text{i}\Gamma\omega}}_{=:\,4\pi\,\alpha_{E1}(\omega)}\,\vec{E}_{\text{in}}(\omega)$$

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

electric, magnetic scalar dipole
"displaced volume" $[10^{-3}\ \text{fm}^3]$

$\Longrightarrow$ **Clean, perturbative probe of $\Delta(1232)$ properties, nucleon spin-constituents, χiral symmetry of pion-cloud & its breaking (proton-neutron difference).**



– fundamental hadron property $\Longrightarrow$ **link to emergent lattice-QCD results**
Alexandru/Lee/...2005-, NPLQCD 2006-, LHPC 2007-, Leinweber/...2013

Cottingham Sum Rule and VVCS:

– $\beta^{\text{p}}_{M1} - \beta^{\text{n}}_{M1}$ in elmag. p-n mass split $M^{\text{p}}_\gamma - M^{\text{n}}_\gamma \approx [1.1 \pm 0.5]$ MeV

– 2γ contribution to Lamb shift in muonic H (β_{M1}), proton radius

– dark-matter detection scenarios e.g. Appelquist/...2014-

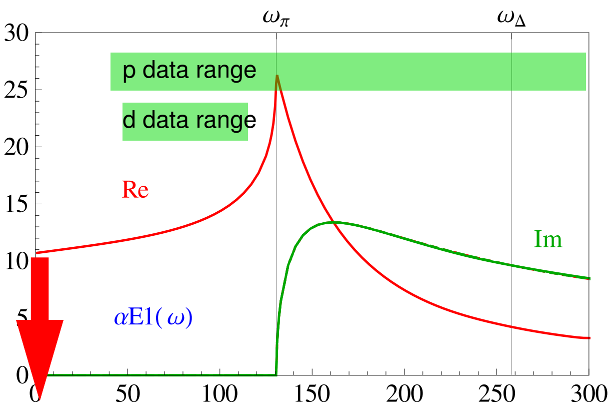
(b) Understanding Energy Dependence

Polarisabilities: Energy-dependent Multipoles of real Compton scattering.

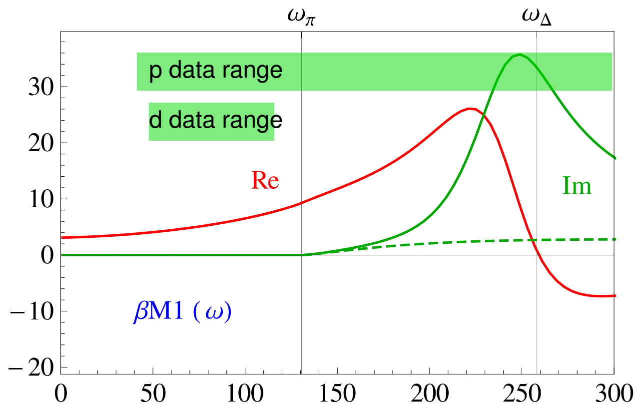
$$2\pi\left[\alpha_{E1}(\omega)\vec{E}^2+\beta_{M1}(\omega)\vec{B}^2+\gamma_{E1E1}(\omega)\vec{\sigma}\cdot(\vec{E}\times\dot{\vec{E}})+\gamma_{M1M1}(\omega)\vec{\sigma}\cdot(\vec{B}\times\dot{\vec{B}})+\dots\right]$$

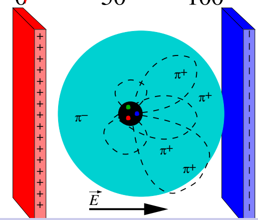
Neither more nor less information about ***two-photon response*** of constituents, but **more readily accessible.**

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



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





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

For $\omega \not\ll m_\pi$ more than "static+slope"! $\Longrightarrow$ Need to understand *dynamics!*

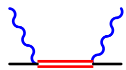
(a) The Method: Chiral Effective Field Theory

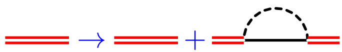
Degrees of freedom $\pi, N, \Delta(1232)$ + all interactions allowed by symmetries: Chiral SSB, gauge, iso-spin,. . .

$\Longrightarrow$ **Chiral Effective Field Theory χEFT $\equiv$ low-energy QCD**

Controlled approximation $\Longrightarrow$ model-independent, error-estimate.

Expand in $\delta = \dfrac{M_\Delta - M_N}{\Lambda_\chi \approx 1\,\mathrm{GeV}} \approx \sqrt{\dfrac{m_\pi}{\Lambda_\chi}} = \dfrac{p_{\mathrm{typ}}}{\Lambda_\chi} \ll 1$ **(numerical fact)** Pascalutsa/Phillips 2002.

$\omega \to M_\Delta - M_N$: Δ propagator enhanced  $\propto \dfrac{1}{\omega - (M_\Delta - M_N)} \sim \dfrac{1}{\delta^3}$

$\Longrightarrow$ **Re-order & dress**  $+ \ldots = \dfrac{1}{E - (M_\Delta - M_N) - \text{(loop)}}$  + relativity

Probe non-zero Δ width, $M1$ and $E2$ transition strengths.

Alternative PC: Alarcon in 50 min

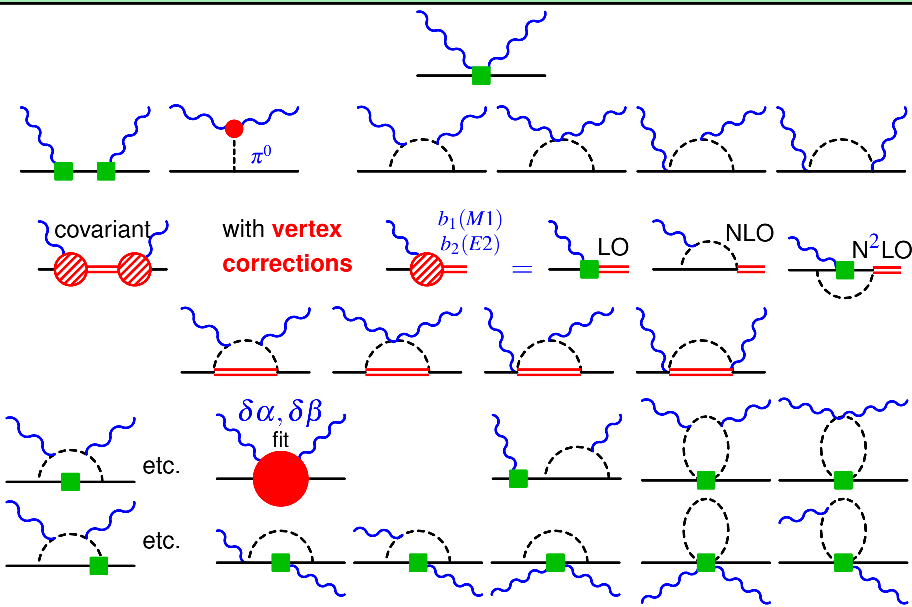
(b) All 1N Contributions to N^{4}LO

Unified Amplitude: gauge & RG invariant set of all contributions which are

in low régime $\omega \lesssim m_\pi$ at least N^{4}LO ($e^2\delta^4$): accuracy $\delta^5 \lesssim 2\%$;

or in high régime $\omega \sim M_\Delta - M_N$ at least NLO ($e^2\delta^0$): accuracy $\delta^2 \lesssim 20\%$.

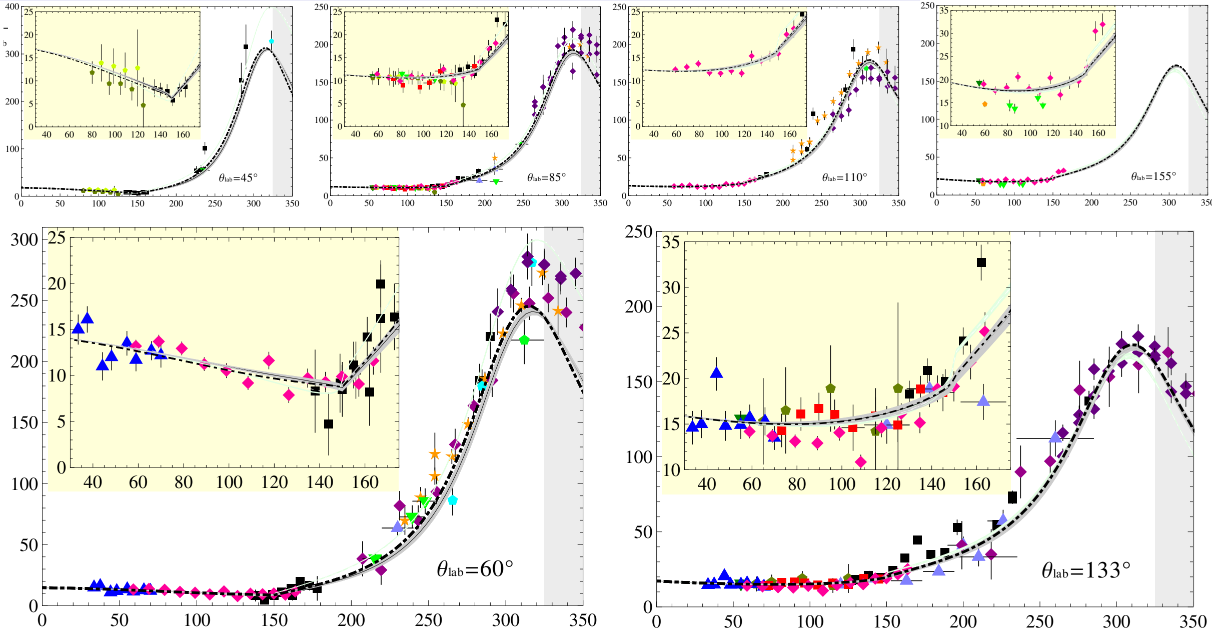
$\omega \lesssim m_\pi$	$\sim M_\Delta - M_N \approx 300$ MeV
$e^2\delta^0$ ***LO***	$e^2\delta^0$ ↘NLO
$e^2\delta^2$ N^{2}LO	$e^2\delta^1$ N^{2}LO
$e^2\delta^3$ N^{3}LO	$e^2\delta^{-1}$ ↗***LO***
$e^2\delta^3$ N^{3}LO	$e^2\delta^1$ N^{2}LO
$e^2\delta^4$ N^{4}LO	$e^2\delta^2$ N^{3}LO



Unknowns: short-distance $\delta\alpha, \delta\beta \Longleftrightarrow$ static α_{E1}, β_{M1}

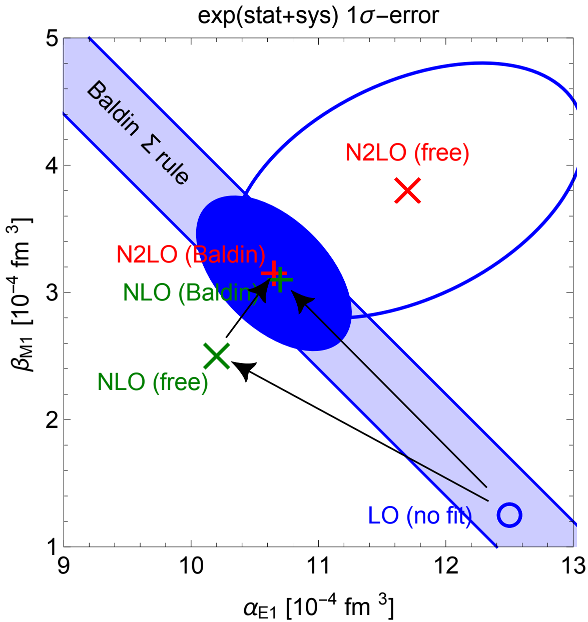
(c) Nucleon Polarisabilities from a Consistent Database

McGovern/Phillips/hg 2013
database: +Feldman PPNP 2012



$\Longrightarrow$ **Plenary McGovern Fri**

(d) Fit Discussion: Parameters and Uncertainties



1σ-contours

Consistent with Baldin Σ Rule

$$\alpha_{E1} + \beta_{M1} = \frac{1}{2\pi^2} \int_{\nu_0}^{\infty} d\nu \, \frac{\sigma(\gamma p \to X)}{\nu^2}$$

$$= 13.8 \pm 0.4$$ Olmos de Leon 2001

need more forward data to constrain.

Residual Theoretical Uncertainty

McGovern/Phillips/hg: EPJ**A49** 12 (2013); many before

Convergence pattern of $\alpha_{E1} - \beta_{M1}$ by

most conservative/worst-case of:

(1) $\delta \approx \frac{2}{5}$ of NLO⟶N²LO;

(2) $\delta^2 \approx \frac{1}{6}$ of LO⟶NLO;

(3) $\delta^2 \approx \frac{1}{6}$ of LO⟶N²LO. ⟸

Fit Stability: floating norms within exp. sys. errors; vary dataset, b_1, vertex dressing,. . .

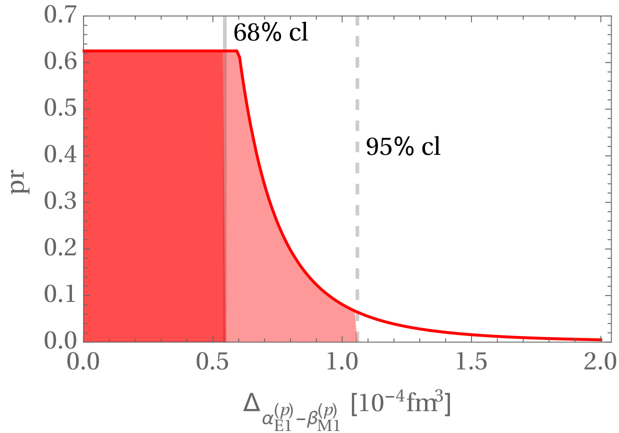
	α^p_{E1} $[10^{-4}\ \mathrm{fm}^3]$	β^p_{M1} $[10^{-4}\ \mathrm{fm}^3]$	χ^2/d.o.f.
N²LO Baldin constrained $\alpha^p_{E1} + \beta^p_{M1} = 13.8 \pm 0.4$	$10.65 \pm 0.4_{\mathrm{stat}} \pm 0.2_{\Sigma} \pm 0.3_{\mathrm{theory}}$	$3.15 \mp 0.4_{\mathrm{stat}} \pm 0.2_{\Sigma} \mp 0.3_{\mathrm{theory}}$	$113.2/135$

Bayesian reasoning Furnstahl/Phillips/. . . 1506.01343

Least-informed prior: *a priori*, correction may have *any* size.

Information: Convergence pattern LO→NLO→N^2LO of $\alpha_{E1} - \beta_{M1}$ gives probable "largest number".

For "high enough" order, largest number limits 68% **degree-of-belief interval.**



Posterior pdf *Not Gauß'ian:* Plateau & power-law tail. Interpret all our uncertainties this way.

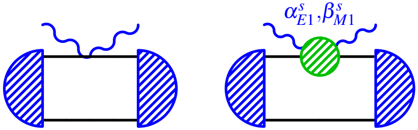
⟹ **Phillips FewB WG Tue**

(f) Deuteron Compton Scattering at $\omega = 0 \ldots 120$ MeV

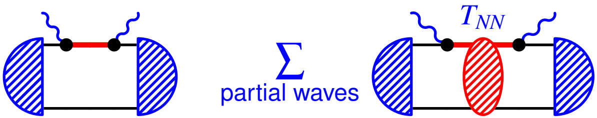
Hildebrandt/hg/Hemmert 2005-10, hg/…2012

One-body: electric, magnetic moment couplings

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



LO, N^3LO LO, ↗ NLO

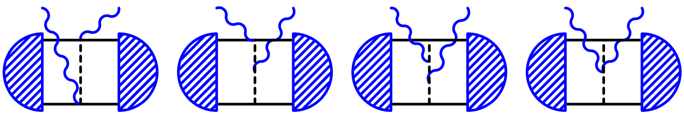


LO ↘ NLO, N^3LO

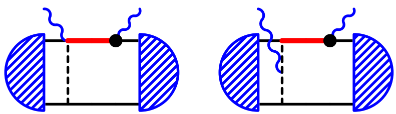
2N coherent $\frac{i}{B_d \pm \omega - \frac{q^2}{M}}$ incoherent

Test χEFT charged pion-exchange currents in NN force.

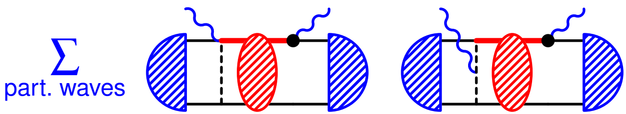
Beane et al. 1999-2005; hg/…2005



NLO → NLO



NLO ↘ N^2LO



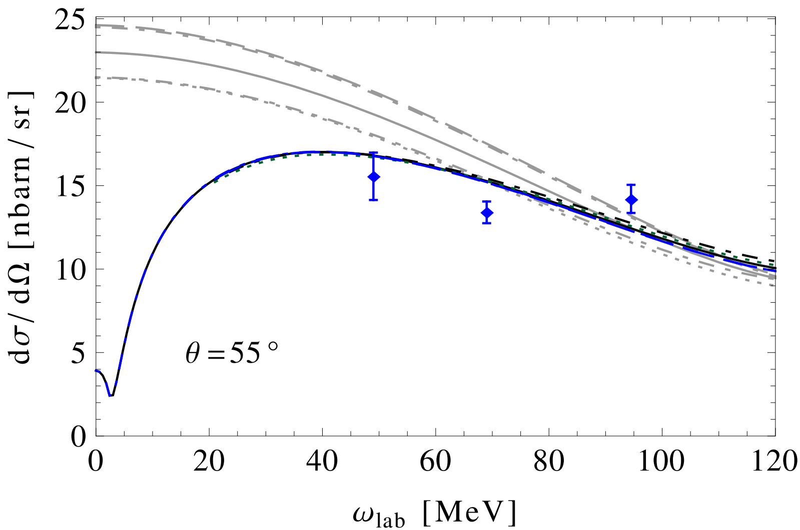
NLO ↘ N^3LO, pert.

Full LO T_{NN} pivotal for current conservation $\Longleftrightarrow$ Thomson limit $-\frac{e^2}{M_d}\vec{\epsilon}\cdot\vec{\epsilon}\,'$. Arenhövel 1980

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

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

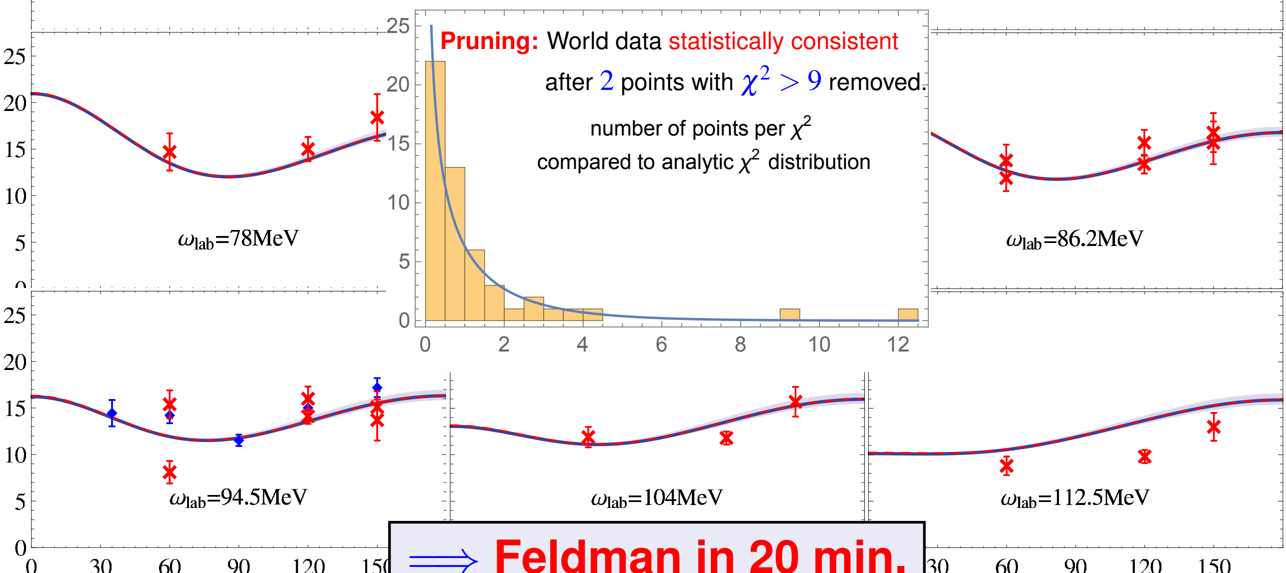
Numerically confirmed to $\lesssim 0.2\%$, irrespective of deuteron wave function & potential. model-independence

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

(h) Myers et al. 2014: MAX-lab Doubles & Improves Database

Illinois 1994 ●, Lund 2003 ▲, Saskatoon 2000 ♦, **Lund 2014** × — $N\pi+\Delta+$ stat. error, Baldin constrained

	α_{E1}^{s} $[10^{-4}\ \mathrm{fm}^3]$	β_{M1}^{s} $[10^{-4}\ \mathrm{fm}^3]$	χ^2/d.o.f.
NLO Baldin constrained $\alpha_{E1}^{s}+\beta_{M1}^{s}=14.5\pm0.4$	$11.1\ \pm0.6_{\mathrm{stat}}\pm0.2_{\Sigma}\pm0.8_{\mathrm{theory}}$	$3.4\ \mp0.6_{\mathrm{stat}}\pm0.2_{\Sigma}\mp0.8_{\mathrm{theory}}$	$45.2/44$
Before Myers 2014:	$10.9\ \pm0.9_{\mathrm{stat}}\pm0.2_{\Sigma}\pm0.8_{\mathrm{theory}}$	$3.6\ \mp0.9_{\mathrm{stat}}\pm0.2_{\Sigma}\mp0.8_{\mathrm{theory}}$	$24.4/25$

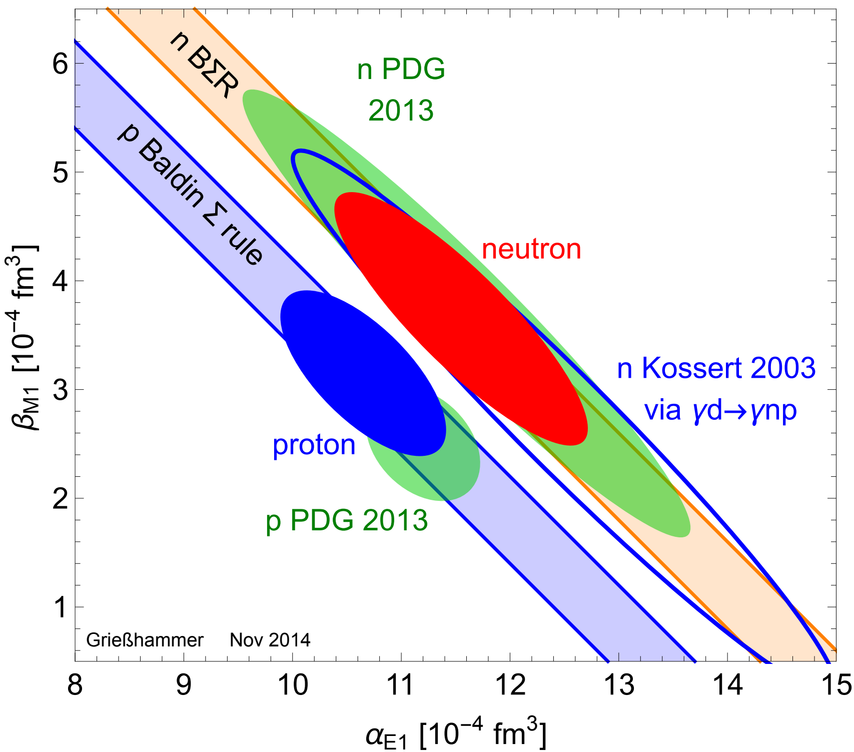


$\Longrightarrow$ **Feldman in 20 min.**

(i) Scalar Dipole Polarisabilities: Values, Data and Theory Errors in χEFT

Need better neutron data: proton-neutron differences test interplay short-distance $\Longleftrightarrow$ χSB in pion cloud.

exp(stat+sys)+theory/model 1σ–error in quadrature



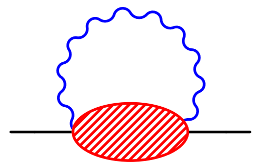
This extraction:

$$\alpha_{E1}^{(p)} - \alpha_{E1}^{(n)} = -0.9 \pm 1.6_{\text{tot}}$$

Cottingham Sum Rule explains

p-n self-energy difference if

$$\alpha_{E1}^{(p)} - \alpha_{E1}^{(n)} = -1.7 \pm 0.4_{\text{tot}}$$



Gasser/. . . 1506.06747

$\Longrightarrow$ **Leutwyler this morning**

(a) Improve on the Neutron: Target ^{3}He

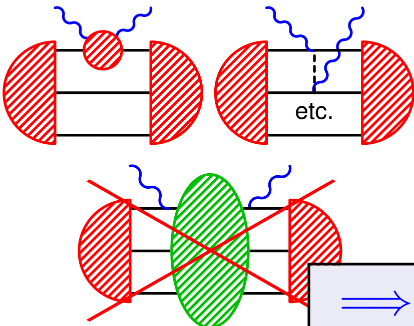
Shukla/Phillips/Nogga 2009
+Sandberg/hg/McG/Ph 2014-

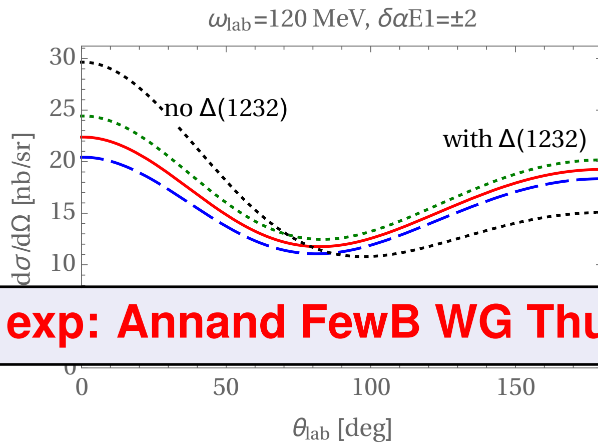
Experiment: $\frac{d\sigma}{d\Omega} \propto$ (target-charge)$^{2 \text{ to } 1}$ $\Longrightarrow$ more & easier targets & counts $\Longrightarrow$ *heavier nuclei*

Theory: Reliable extraction needs accurate description of nuclear binding & levels $\Longrightarrow$ *lighter nuclei*

Find *sweet-spot* between competing forces: ^{3}He at HIγS, MAMI, MAXlab, ^{4}He, ^{6}Li?

Example unpolarised ^{3}He: Sensitivity on $\Delta(1232)$ and α_{E1}^n at $\omega_{\text{lab}} = 120$ MeV





$\Longrightarrow$ **exp: Annand FewB WG Thu 17:20**

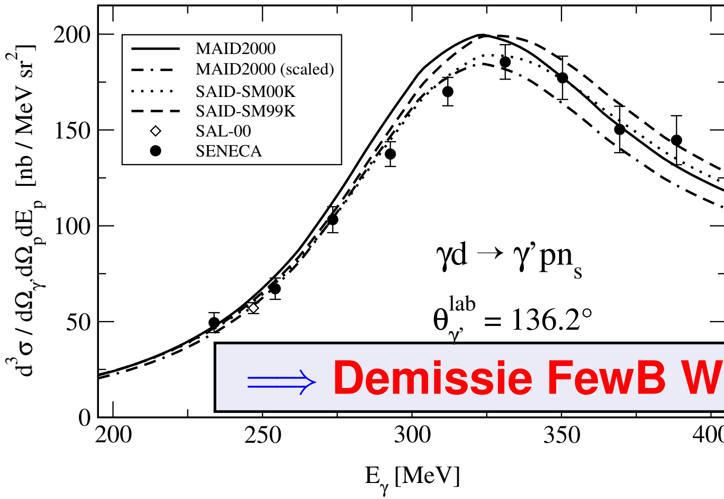
– ^{3}He as effective neutron spin target.

– Beyond $\omega \in [80; 120]$ MeV: rescattering (Thomson, T_{NN}); explicit $\Delta(1232)$ also in MECs

theory: Levckuk/L'vov/Petrunkin 1994-2000; Demissie/hg 2012-
exp: (Rose/. . . 1999); Kolb/. . . SAL 2000; Kossert/. . . MAMI 2002

Nucleon polarisabilities from centre of quasi-inelastic peak in $d(\gamma,\gamma p)n$.

9 data points at $\omega \in [230;400]$ MeV



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

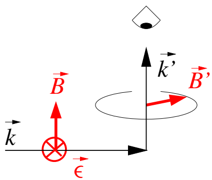
sys. & model-error ***under-estimated?:***
π production, SAID/MAID-2000 amplitudes,
π exchange currents not chiral, . . .

$\Longrightarrow$ Demissie FewB WG Thu 17:50

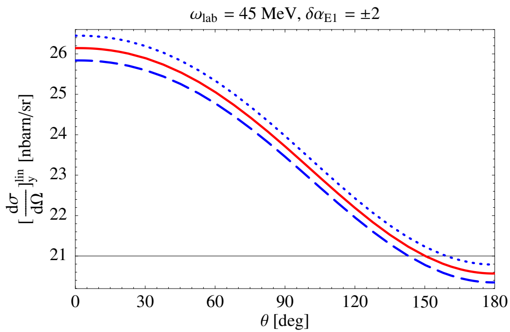
Forthcoming: Demissie PhD (GW)
Analyse elastic & inelastic in unified χEFT frame,
accurate $\Delta(1232)$ at peak, test quasi-free hypothesis.

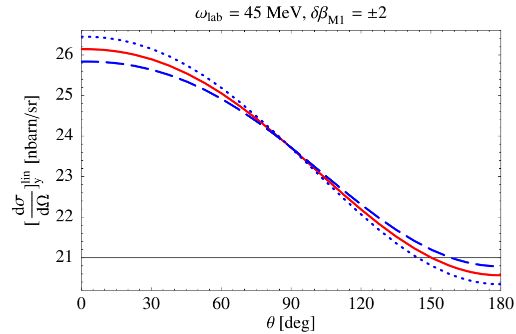
$$\mathcal{L}_{\text{pol}} = 4\pi\, N^\dagger \left\{ \frac{1}{2} \left[\alpha_{E1}(\omega)\, \vec{E}^2 + \beta_{M1}(\omega)\, \vec{B}^2 \right] + \dots \right\} N$$

Example: photon linearly polarised perp. to scatt. plane, $\omega = 45$ MeV, $\theta = 90^\circ$, deuteron unpolarised



no β_{M1} seen





Unaffected by orbital ang. momentum in deuteron; Weller HIγS approved for $\omega = 65$ MeV circpol.

Only in cross-sections of special configurations; not for asymmetries!

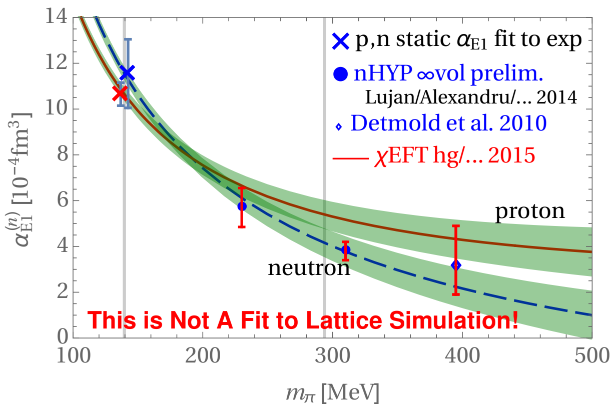
(d) Chiral Extrapolations for Lattice QCD Simulations

Towards comparable uncertainties in experiment, χEFT and lattice QCD:

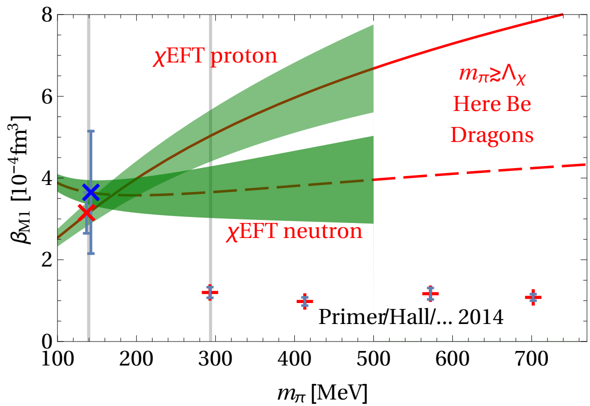
χEFT at $\mathcal{O}(e^2\delta^4)$ provides reliable error estimate for $\frac{m_\pi}{\Lambda_\chi}$ extrapolation. hg/McGovern/Phillips in prep.

At present, only *neutron* simulations fully dynamical, $m_\pi \ll \Lambda_\chi \approx 700$ MeV, infinite volume.

electric polarisability α_{E1}^n



magnetic polarisability β_{M1}^n



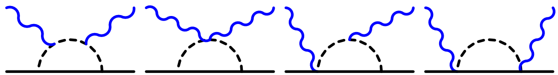
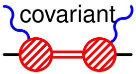
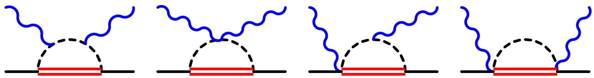
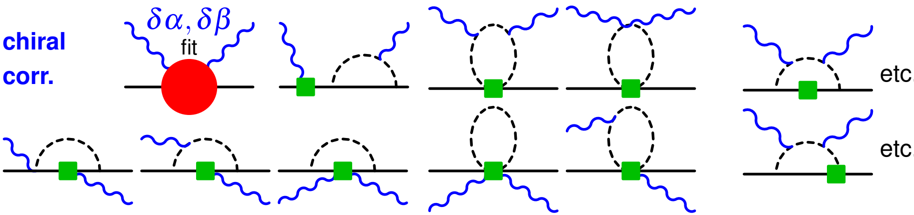
Active lattice groups: Lujan/Alexandru/...; Primer/Hall/Leinweber/...;

NPLQCD 1506.05518: different pols. def. $\Longrightarrow$ **Savage 2 hrs ago in FewB WG**

χEFT *predicts* substantial isospin splitting for $m_\pi \gtrsim 300$ MeV.

(e) Static Polarisabilities in χEFT

Bernard/Kaiser/Meißner 1992-4, Butler/Savage/Springer 1992-3, Hemmert/... 1998
Kumar/McGovern/Birse 2000, McGovern 2001
McGovern/Phillips/hg 2013 + forthcoming

contribution	size of m_π	$\sim m_\pi^{\text{phys}}$	$\sim M_\Delta - M_N \approx 300\ \text{MeV}$
charged pion cloud infinite in chiral limit		$e^2\delta^2$ LO	$e^2\epsilon^1$ **LO**
$\Delta(1232)$ + **its π cloud**	 	$e^2\delta^3$ NLO	
chiral corr.		$e^2\delta^4$ N^{2}LO	$e^2\epsilon^2$ NLO **incomplete** χcorr. to Δ, $\Delta\pi$ absent

$\Longrightarrow$ **Both *magnitude* and *relative* importance of contributions changes with m_π:**

(i) close to m_π^{phys} $\Longrightarrow$ $\sqrt{\dfrac{m_\pi}{\Lambda_\chi \approx 700\ \text{MeV}}} \approx \dfrac{M_\Delta - M_N}{\Lambda_\chi} =: \delta$**-counting** Pascalutsa/Phillips 2002

(ii) close to $300\ \text{MeV}$ $\Longrightarrow$ $\dfrac{m_\pi \sim (M_\Delta - M_N)}{\Lambda_\chi} =: \epsilon$**-counting** Manohar/Jenkins 1994,...

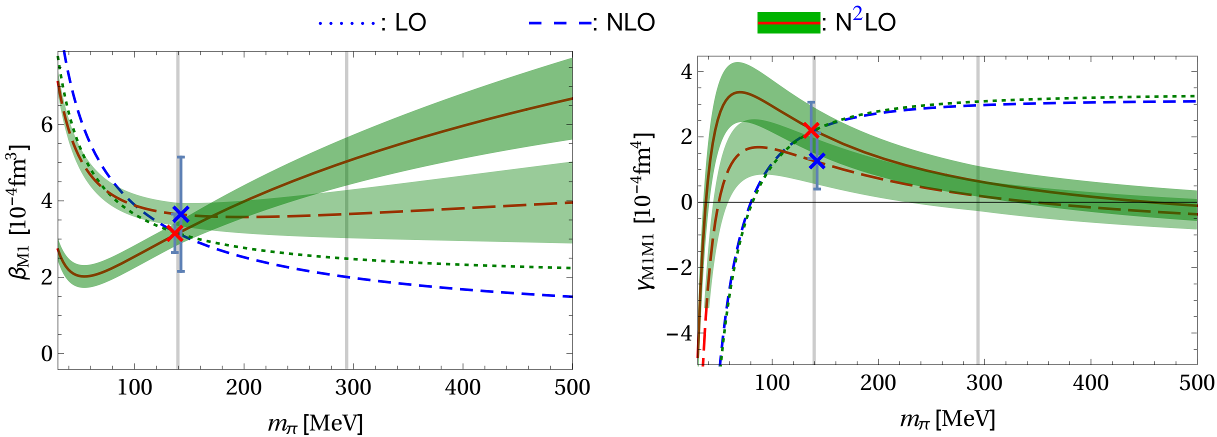
(iii) beyond $\Lambda_\chi \approx 700\ \text{MeV}$ $\Longrightarrow$ no small parameter, no convergence $\Longrightarrow$ ***at best qualitatively useful!***

Use unified amplitude: $\Longrightarrow$ **accuracy N^{2}LO ($\sim 6\%$) for $m_\pi \sim 140\ \text{MeV}$, LO ($\sim 40\%$) for $m_\pi \sim 300\ \text{MeV}$**

At this order, $g_A, f_\pi, M_N, (M_\Delta - M_N), \ldots$ indep. of m_π.

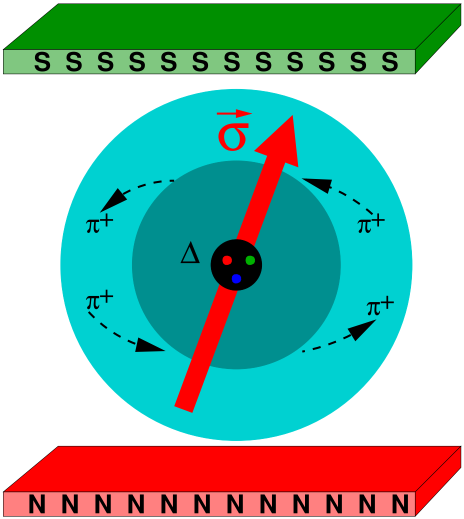
(f) m_π-Dependence Reveals Fine-Tuning

Order-by-order convergence sub-optimal for β_{M1} and γ_{M1M1}.



(g) Spin-Polarisabilities: Nucleonic Bi-Refringence and Faraday Effect

Optical Activity: Response of spin-degrees of freedom, experimental frontier.



$$\mathcal{L}_{\text{pol}} = 4\pi\, N^\dagger \times \Big\{ \tfrac{1}{2}\left[\alpha_{E1}\,\vec{E}^2 + \beta_{M1}\,\vec{B}^2\right]$$

scalar dipole

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

"pure" spin-dependent dipole

$$-2\,\gamma_{M1E2}\,\sigma_i\,B_j\,E_{ij} + 2\,\gamma_{E1M2}\,\sigma_i\,E_j\,B_{ij}\Big] + \dots \Big\}\, N$$

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

"mixed" spin-dependent dipole

$+$ quadrupole etc.

$\mathcal{O}(e^2\delta^4)$ χEFT prediction hg/McGovern/Phillips 2014 vs. MAMI extraction Martel/…2014

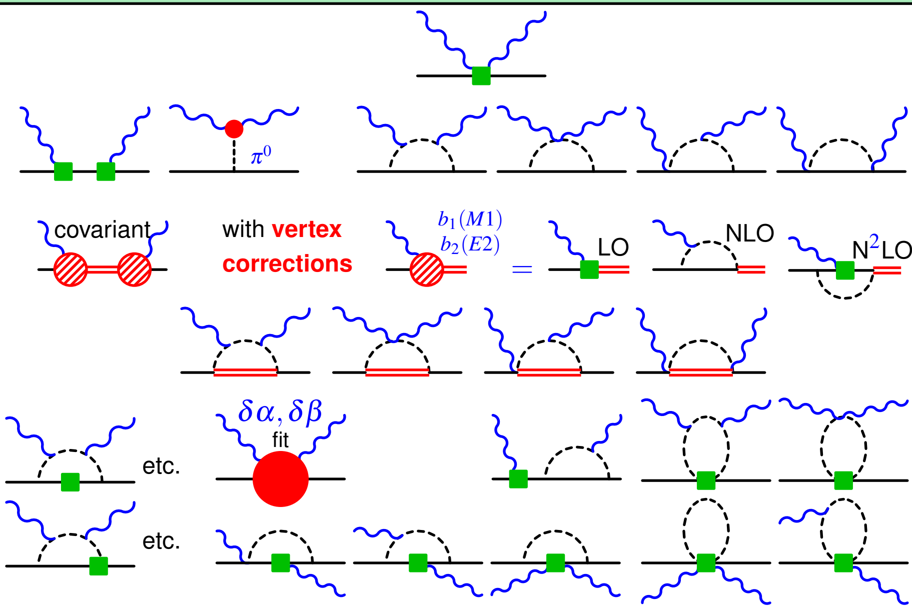
static $[10^{-4}\ \text{fm}^4]$	γ_{E1E1}	γ_{M1M1}	γ_{E1M2}	γ_{M1E2}
MAMI 2014 proton	-3.5 ± 1.2	3.2 ± 0.9	-0.7 ± 1.2	2.0 ± 0.3
χEFT proton	$-1.1\pm1.6_{\text{th}}$	$2.2\pm0.5_{\text{stat}}\pm0.6_{\text{th}}$ **fit to unpol.**	$-0.4\pm0.3_{\text{th}}$	$1.9\pm0.4_{\text{th}}$
χEFT neutron	$-4.0\pm1.6_{\text{th}}$	$1.3\pm0.5_{\text{stat}}\pm0.6_{\text{th}}$	$-0.1\pm0.3_{\text{th}}$	$2.4\pm0.4_{\text{th}}$

(h) All 1N Contributions to N^{4}LO

Unified Amplitude: **gauge & RG invariant set of all contributions which are**

in low régime $\omega \lesssim m_\pi$ **at least N^{4}LO** $(e^2\delta^4)$: **accuracy** $\delta^5 \lesssim 2\%$;

or **in high régime** $\omega \sim M_\Delta - M_N$ **at least NLO** $(e^2\delta^0)$: **accuracy** $\delta^2 \lesssim 20\%$.



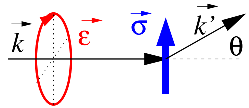
$\omega \lesssim m_\pi$	$\sim M_\Delta - M_N \approx 300$ MeV
$e^2\delta^0$ ***LO***	$e^2\delta^0$ ↘NLO
$e^2\delta^2$ N^{2}LO	$e^2\delta^1$ N^{2}LO
$e^2\delta^3$ N^{3}LO	$e^2\delta^{-1}$ ↗***LO***
$e^2\delta^3$ N^{3}LO	$e^2\delta^1$ N^{2}LO
$e^2\delta^4$ N^{4}LO	$e^2\delta^2$ N^{3}LO

Spin-polarisabilities: p-n split parameter-free *prediction*!

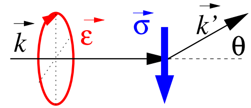
(i) Spin-Polarisabilities from Polarised Photons

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

Σ_x :

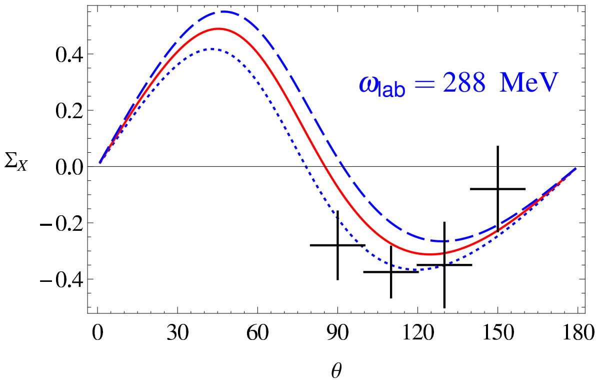


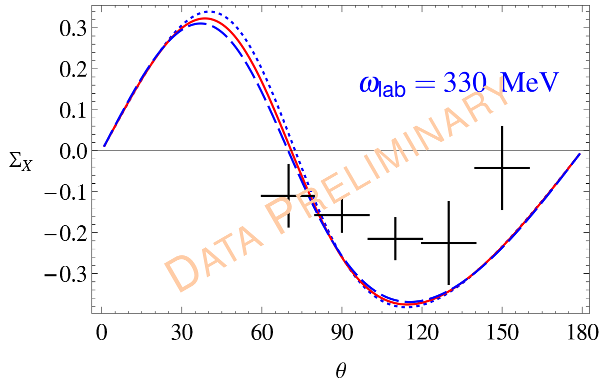
vs.



Compare to Martel/…(MAMI) PRL 2014

γ_{E1E1} = (solid red line) -1.1: χEFT prediction; (dashed) $-1.1+2$; (dotted) $-1.1-2=-3.1 \Longleftrightarrow$ Martel fit: -3.5 ± 1.2



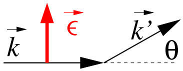


Polarisabilities beyond dipoles negligible – ω-dependence important.
Also good signal for linear polarisations.

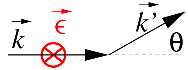
$\Longrightarrow$ Plenaries Downie & McGovern Fri

linpol. γ, unpol. target:

$\left.\frac{d\sigma}{d\Omega}\right|_x^{\text{lin}}$

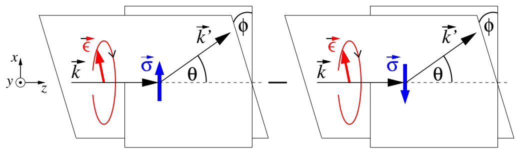


$\left.\frac{d\sigma}{d\Omega}\right|_y^{\text{lin}}$

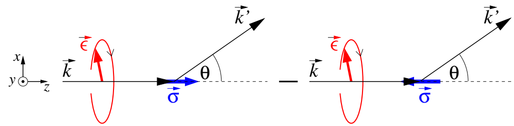


circpol. γ, vecpol. target:

Δ_x^{circ}

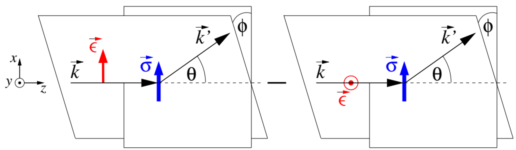


Δ_z^{circ}

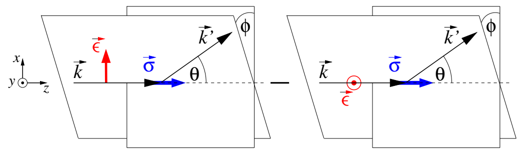


linpol. γ, vecpol. target:

Δ_x^{lin}



Δ_z^{lin}



Differences Δ and asymmetries $\Sigma = \frac{\Delta}{\text{sum}}$

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

– scalar polarisabilities α_{E1}, β_{M1} – γ_0, γ_π (???) – experiment: detector settings,...

$\Longrightarrow$ Kill too many trees when all presented.

(k) Plethora of Polarised Compton Observables: Deuteron/Spin-1

Parametrise $d\gamma \to X$: unpol./linear/circular beam on scalar/vector/tensor target.

$$\left.\frac{d\sigma}{d\Omega}\right|_{\text{unpol}} \times \Bigg[\; 1 + \Sigma^{\text{lin}}(\omega,\theta)\;\; P^{(\gamma)}_{\text{lin}}\,\cos 2\phi_{\text{lin}}$$

1 beam asymmetry

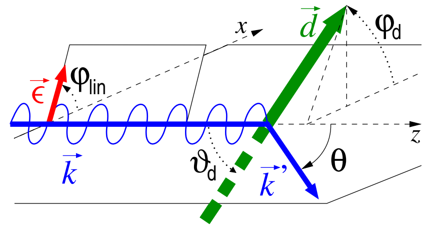
$$+ \sum_{\substack{I=1,2\\0\le M\le I}} T_{IM}(\omega,\theta)\quad P^{(\text{d})}_I\, d^I_{M0}(\theta_{\text{d}})\,\cos[M\phi_{\text{d}} - \frac{\pi}{2}\delta_{I1}]$$

4 target asymmetries

$$+ \sum_{\substack{I=1,2\\0\le M\le I}} T^{\text{circ}}_{IM}(\omega,\theta)\quad P^{(\gamma)}_{\text{circ}}\, P^{(\text{d})}_I\, d^I_{M0}(\theta_{\text{d}})\,\sin[M\phi_{\text{d}} + \frac{\pi}{2}\delta_{I1}]$$

4 circpol.
8 linpol. **double asymmetries**

$$+ \sum_{\substack{I=1,2\\-I\le M\le I}} T^{\text{lin}}_{IM}(\omega,\theta)\quad P^{(\gamma)}_{\text{lin}}\, P^{(\text{d})}_I\, d^I_{M0}(\theta_{\text{d}})\,\cos[M\phi_{\text{d}} - 2\phi_{\text{lin}} - \frac{\pi}{2}\delta_{I1}]\Bigg]$$



Differences Δ and asymmetries $\dfrac{\Delta}{\text{sum}}$

2×18 observables, 6 polarisabilities, 2 kinemat. variables ω, θ + additional constraints:

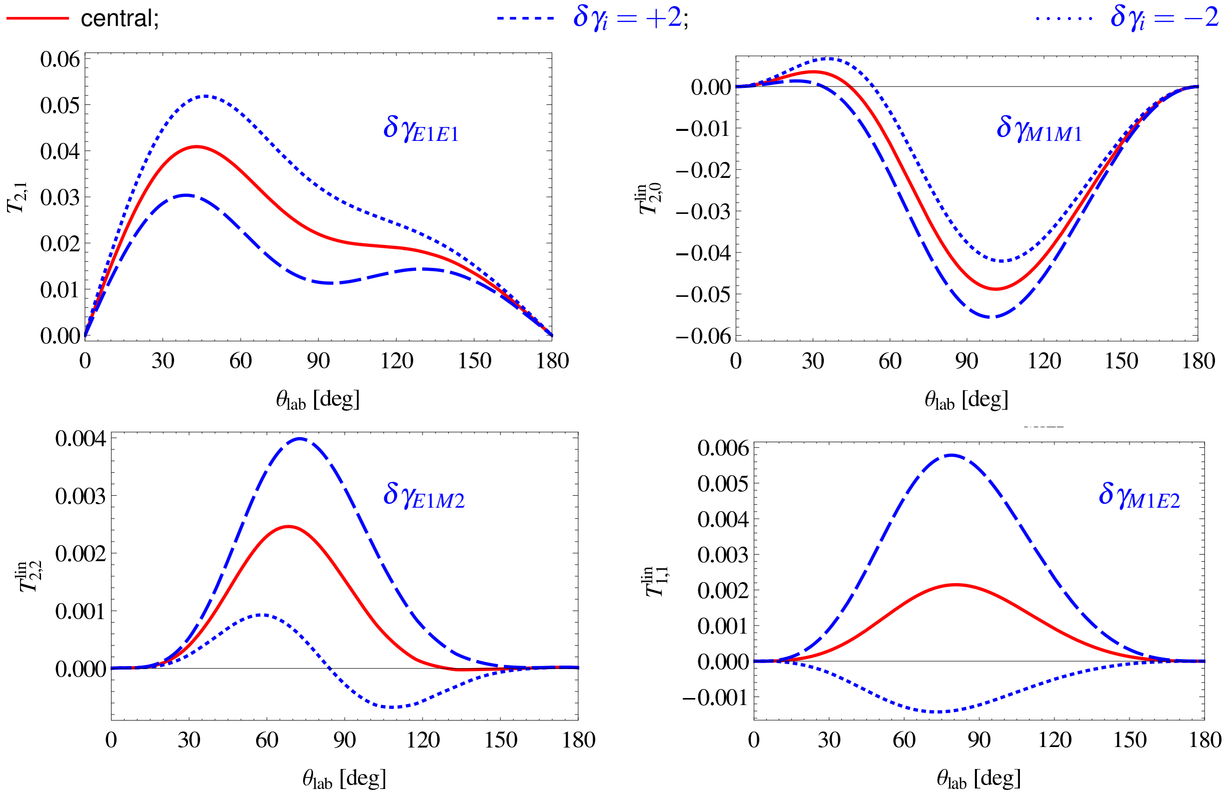
– scalar polarisabilities $\alpha_{E1},\ \beta_{M1}$ – $\gamma_0,\ \gamma_\pi$ (???)

– experiment: $P_1 \gtrsim 90\%,\ P_2 \lesssim 75\%$, detector settings,. . .

$\Longrightarrow$ **Interactive *mathematica 9.0* notebooks.** hg/. . . 2010-13

(m) Identifying Spin-Polarisabilities at $\omega_{\text{lab}} = 100$ MeV

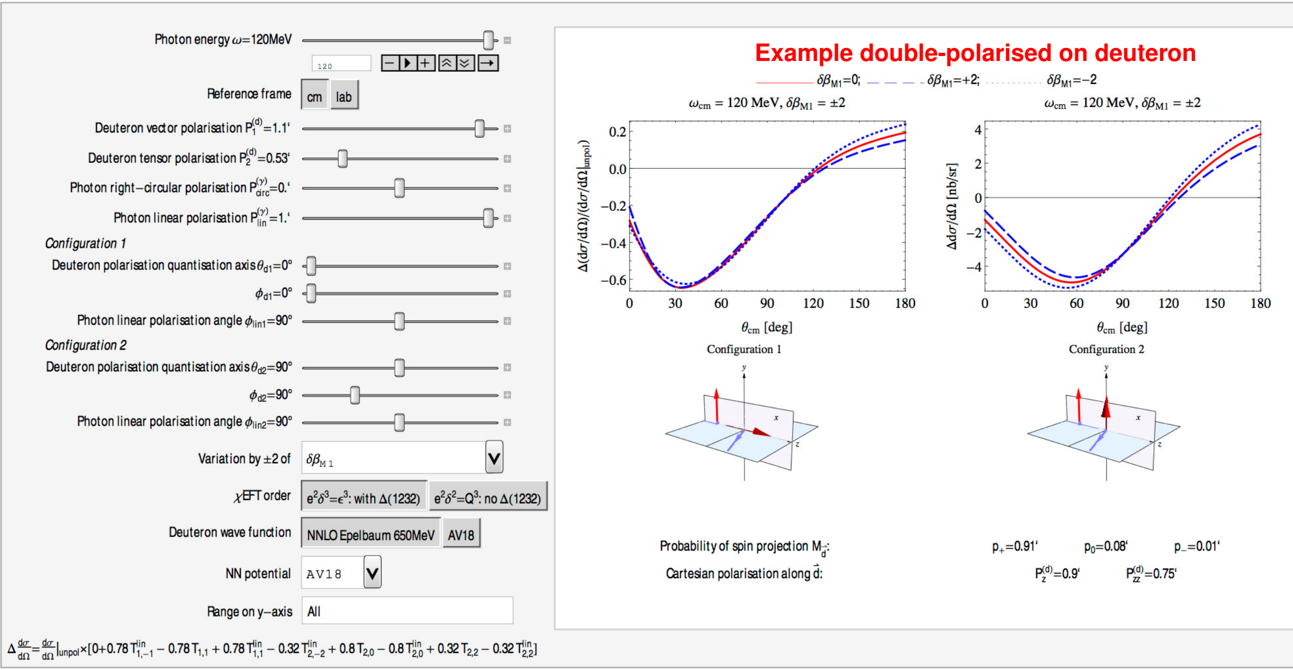
Want very clean observables: Large rates, insensitive to other pols, deuteron wave fu,...



(n) Guide, Support, Analyse, Predict Polarised Experiments

hg 2010-13
hg/McGovern/Phillips 2012-

⟹ **Interactive *mathematica 9.0* notebooks** from hgrie@gwu.edu



Goal: guide & analyse polarised experiments

extend deuteron analysis to $300\ \mathrm{MeV}$ — **In progress.**

Compton@Web **on DAC/SAID website** — **When all in place.**

(o) Multipole Analysis: Energy-Dependent Polarisabilities

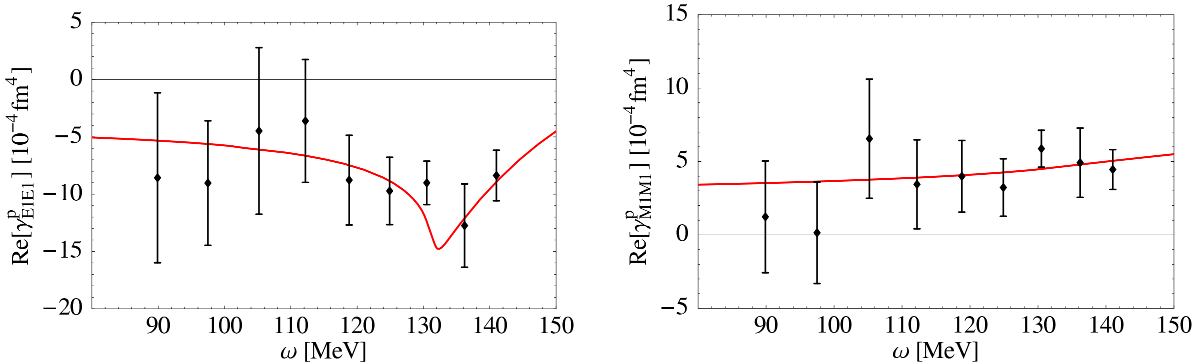
Do not reduce richness of information to just static values!

Multipole Analysis of two-photon response in infancy: Need asymmetry data!

$$4\pi\, N^\dagger \Big\{ \frac{1}{2}\Big[\alpha_{E1}(\omega)\,\vec{E}^2 + \beta_{M1}(\omega)\,\vec{B}^2\Big]$$ **spin-indep. dipole**

$$+\frac{1}{2}\Big[\gamma_{E1E1}(\omega)\,\vec{\sigma}\cdot(\vec{E}\times\dot{\vec{E}}) + \gamma_{M1M1}(\omega)\,\vec{\sigma}\cdot(\vec{B}\times\dot{\vec{B}})$$ **"pure" spin-dep. dipole**

$$-2\,\gamma_{M1E2}(\omega)\,\sigma_i\,B_j\,E_{ij} + 2\,\gamma_{E1M2}(\omega)\,\sigma_i\,E_j\,B_{ij}\Big] + \dots \Big\}\,N$$ **"mixed" spin-dep. dipole**



Assume $\alpha_{E1}(\omega)$, $\beta_{M1}(\omega)$ well captured, only $\gamma_{E1E1}(\omega)$, $\gamma_{M1M1}(\omega)$ large $\Longrightarrow$ superficial fit to data.

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.
Experiment, Low-Energy Theory, Lattice QCD in sync.

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

Goals: Guide, support, analyse, predict experiments. hg, J. McGovern (U. Manchester), D.R. Phillips (Ohio U.)

Compton amplitude to 350 MeV – Scalar Dipole Polarisabilities from *all Compton data below* 200 MeV:

proton N^2LO	$\alpha^p = 10.65 \pm 0.35_{\text{stat}} \pm 0.2_{\Sigma} \pm 0.3_{\text{theory}}$	$\beta^p = 3.15 \mp 0.35_{\text{stat}} \pm 0.2_{\Sigma} \mp 0.3_{\text{theory}}$
neutron NLO	$\alpha^n = 11.55 \pm 1.25_{\text{stat}} \pm 0.2_{\Sigma} \pm 0.8_{\text{theory}}$	$\beta^n = 3.65 \mp 1.25_{\text{stat}} \pm 0.2_{\Sigma} \mp 0.8_{\text{theory}}$

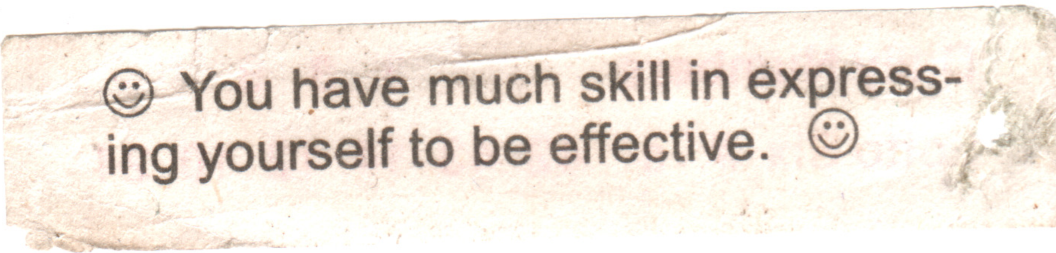
Theory To-Do List: explore host of observables; expansion $\dfrac{p_{\text{typ}}}{\Lambda_\chi} \ll 1$ for credible error-bars. math notebooks

Opportunities for high intensities, polarised beam and/or target: p, d, ^{3}He; ^{4}He?, ^{6}Li?
We Need Data: elastic & inelastic cross-sections & asymmetries – *reliable systematics!*

$\omega \in [80; 180]$ MeV: **Single- & double-polarisation observables, elastic & inelastic: p, d, ^{3}He; ^{4}He?, ^{6}Li?**

$\Longrightarrow$ sweet-spot increased count-rates $\Longleftrightarrow$ accurate theory; proton–neutron differences; cross-checks

Clean probe to explore strong force at low energies.


☺ You have much skill in express-
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