Extraction of Nucleon Polarisabilities from light nuclei

Judith McGovern

University of Manchester

Work done in collaboration with Harald Grießhammer, Daniel Phillips, Vadim Lensky, Vladimir Pascalutsa, Mike Birse, Jerry Feldman, Luke Myers *et al.* , Bruno Strandberg, Arman Margaryan, Vahe Sokhoyan, Edoardo Mornacchi, Evie Downie and others

Prog. Nucl. Part. Phys. **67** 841 (2012) Eur. Phys. J. A **49** (2013) 12

Phys. Rev. Lett. **113** (2014) 262506 Eur. Phys. J. C **75** (2015) 604

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(1) Compton Scattering and polarisabilities

(2) Quick review of EFT calculations

(3) State of current calculations and fits and future directions

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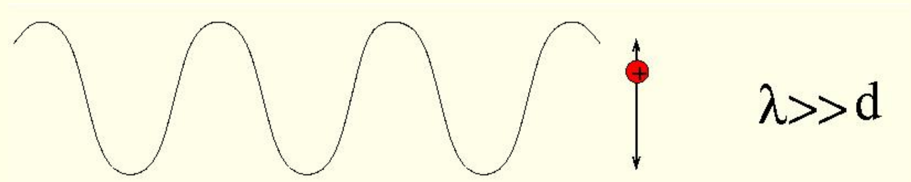
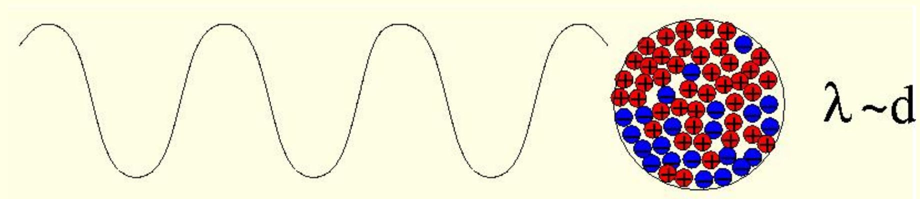
Compton Scattering

For large wavelengths, only sensitive to overall charge: Thomson scattering



But for smaller wavelengths, the target is polarised by the electric and magnetic fields



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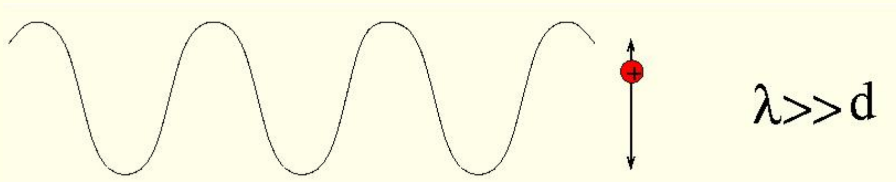

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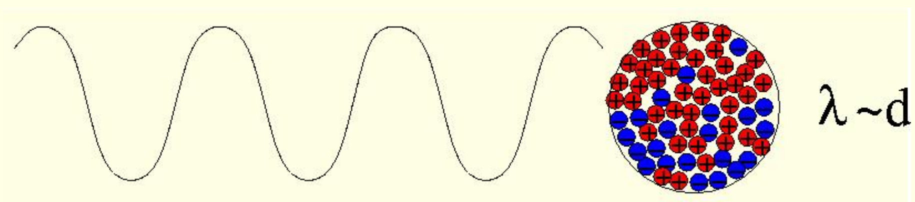
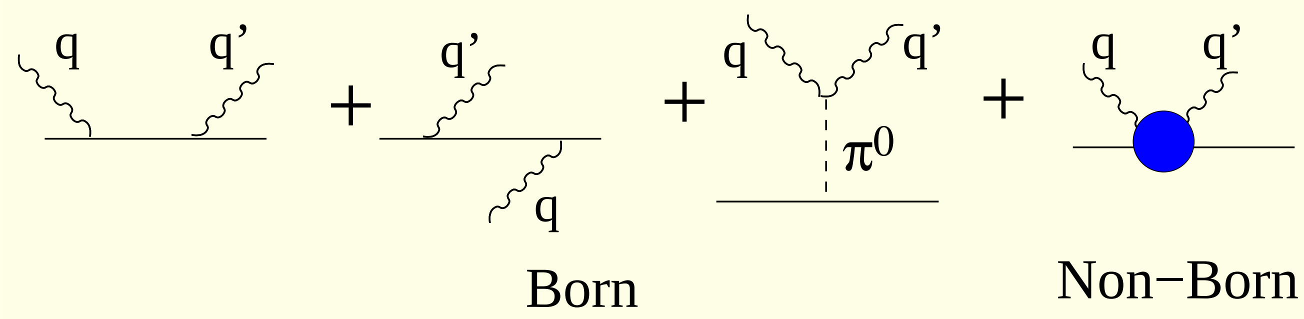


To leading order

$$\begin{aligned} H_{eff} &= \frac{(\mathbf{p}-Q\mathbf{A})^2}{2m} + Q\phi - \frac{1}{2}4\pi\left(\alpha\vec{E}^2 + \beta\vec{H}^2\right. \\ &+ \left.\gamma_{E1E1}\vec{\sigma}\cdot\vec{E}\times\dot{\vec{E}} + \gamma_{M1M1}\vec{\sigma}\cdot\vec{H}\times\dot{\vec{H}} - 2\gamma_{M1E2}E_{ij}\sigma_i H_j + 2\gamma_{E1M2}H_{ij}\sigma_i E_j\right) \end{aligned}$$

where $E_{ij} = \frac{1}{2}(\nabla_i E_j + \nabla_j E_i)$ and $H_{ij} = \frac{1}{2}(\nabla_i H_j + \nabla_j H_i)$

Compton Scattering from the nucleon



The scattering amplitude has Born and non-Born pieces. The latter probe the structure of the nucleon; polarisabilities are leading signs of non-pointlike nucleons as we increase the photon energy.

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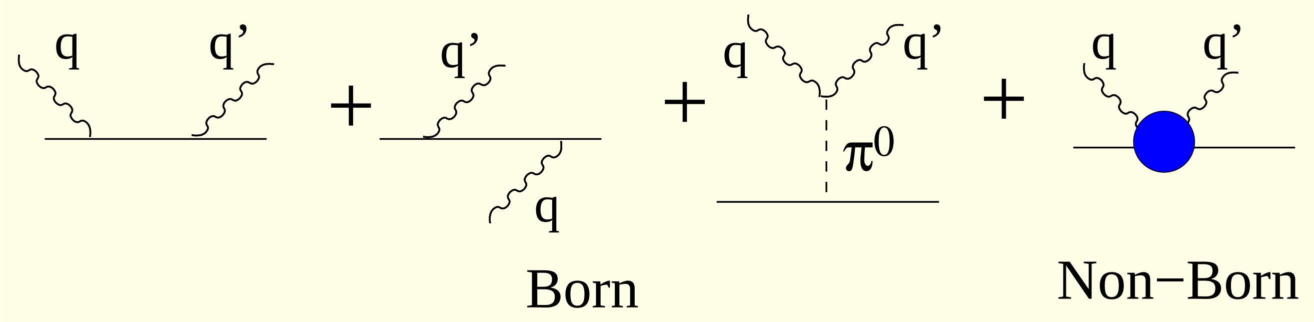

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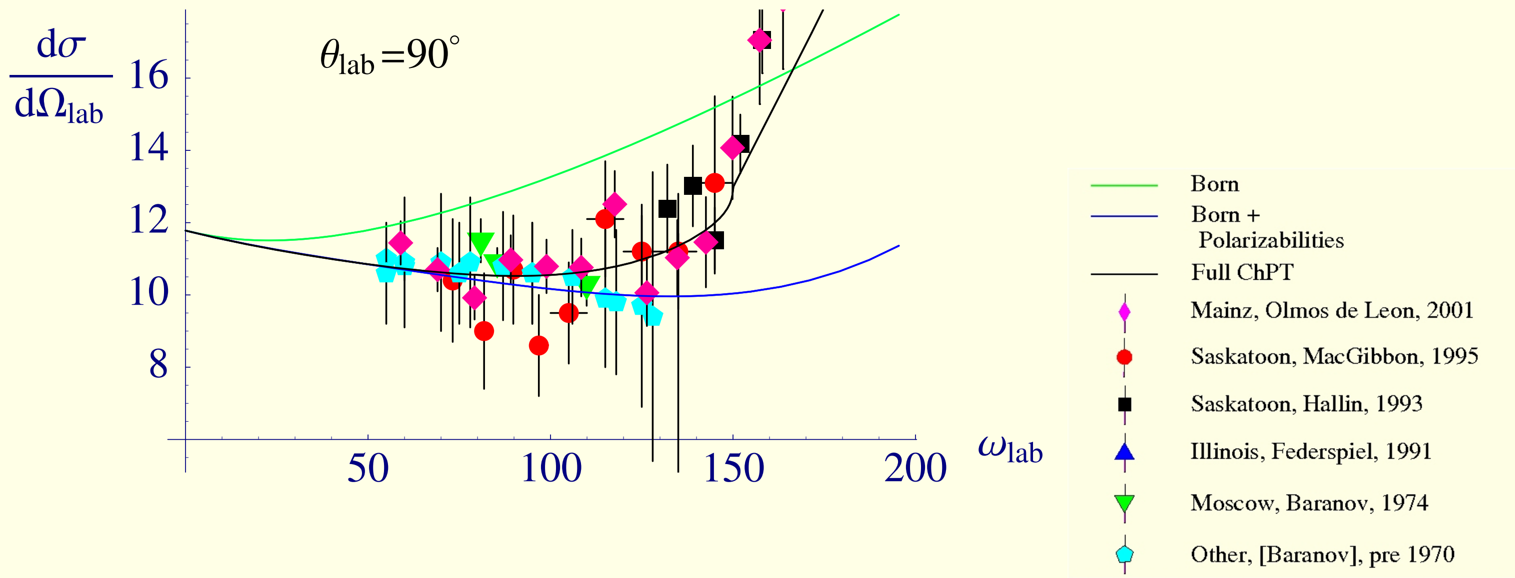
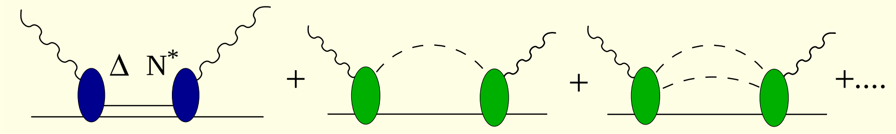


Compton as a probe of structure

At a hadronic level, we consider Compton scattering from the nucleon as probing its excitations and particularly its pionic cloud.



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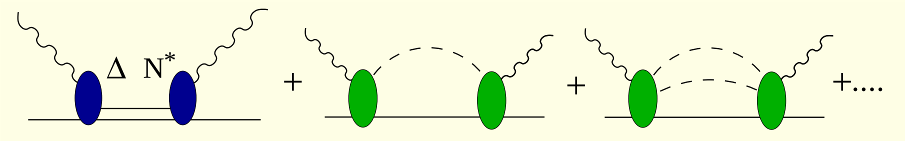

Two common methods: Dispersion relations and Chiral Perturbation Theory

Both consider pions as crucial source of energy-dependence in amplitudes (Delta resonance also captured)

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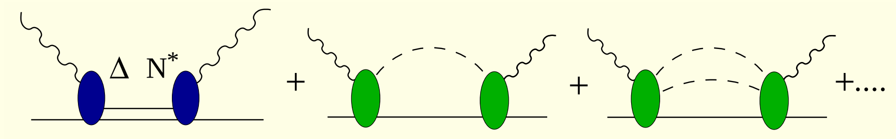

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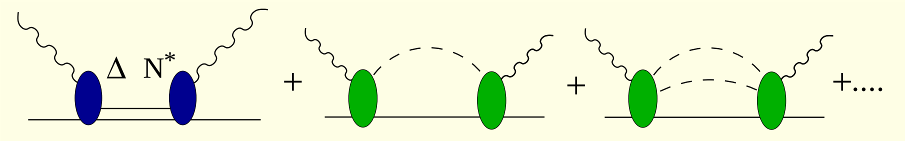

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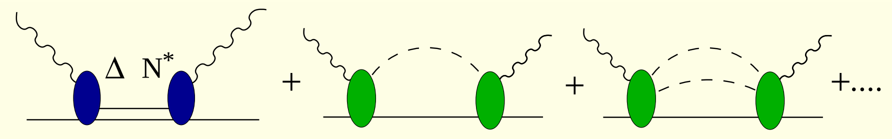

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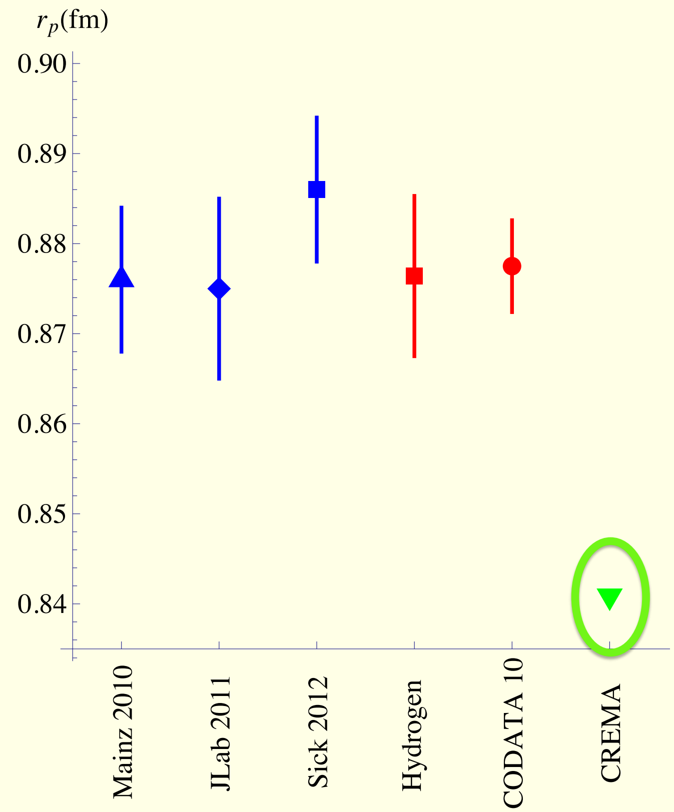
Both have difficulties with parameter-free predictions; both can be used to fit nucleonic Compton scattering data and extract polarisabiltiies; only χPT is actively being used for few-nucleon systems.

Proton radius puzzle



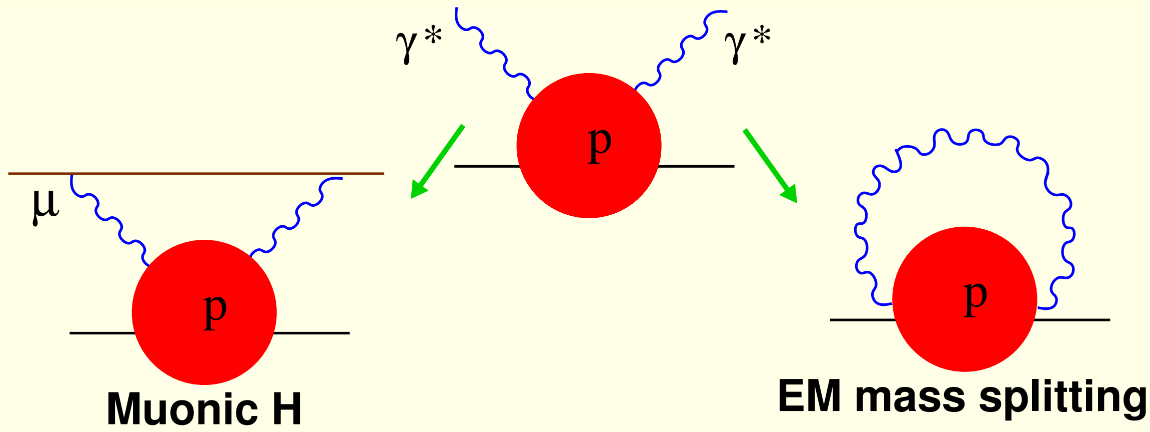
Hydrogen etc: $r_p = 0.8775(51)$ fm, CODATA 2010

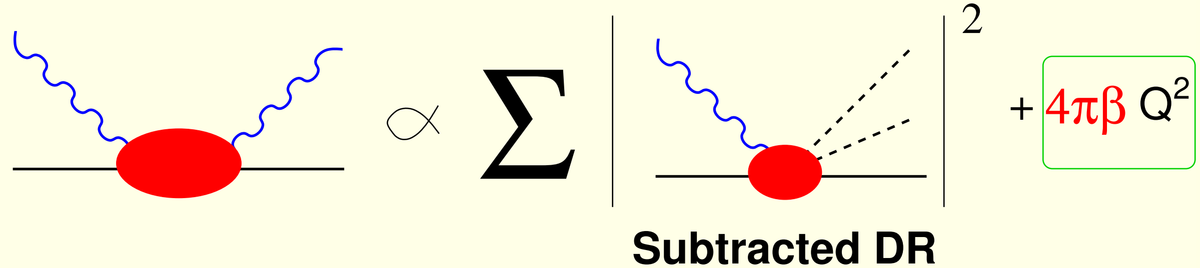
Muonic hydrogen: $r_p = 0.84087 \pm 0.00039$ fm

Pohl et al, Nature **466**, 213 (2010)Antognini et al, Science **339** 417

7σ deviation! (Or maybe 5 sigma with revised CODATA value)

Connection to β



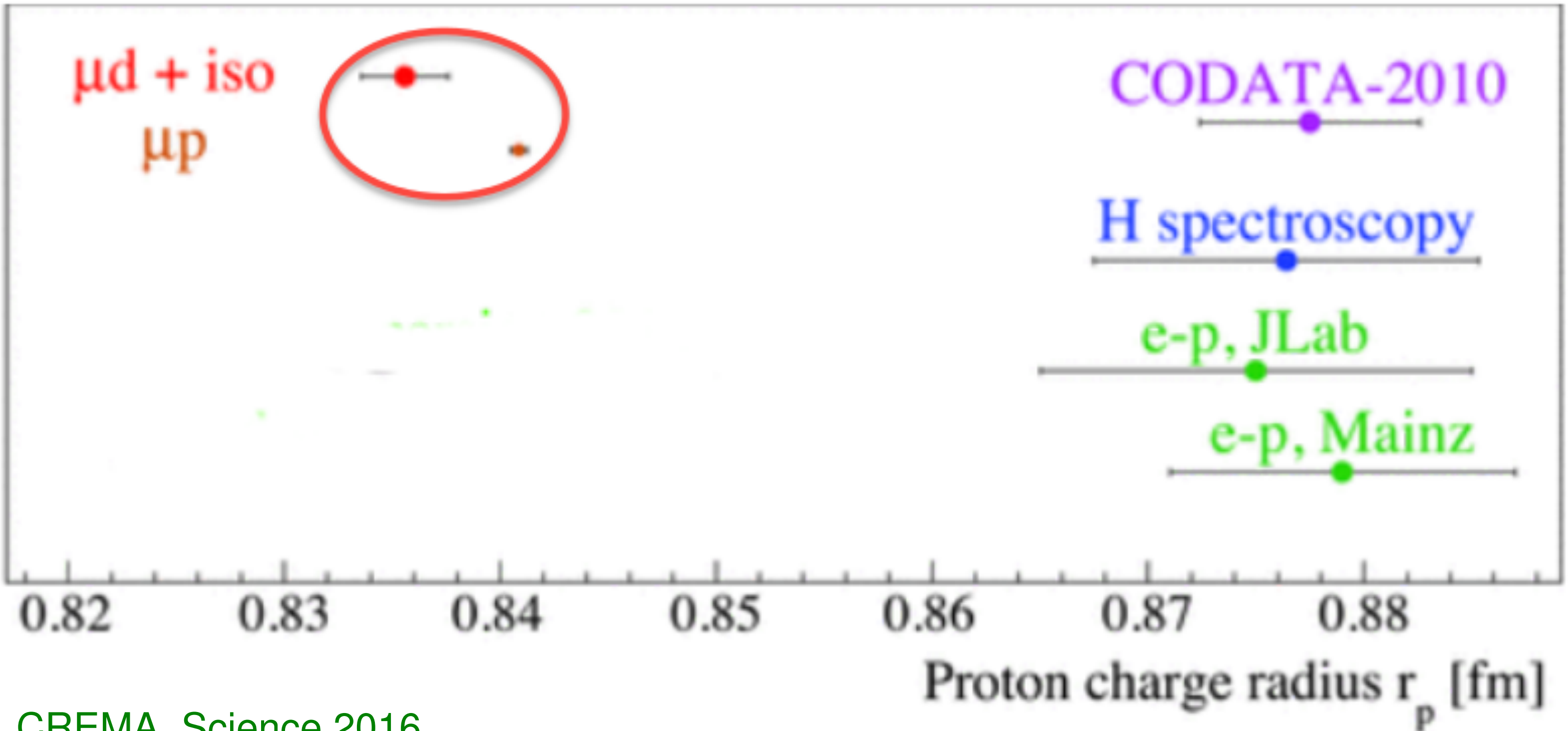


$$\overline{T}_1(\nu,Q^2) = -\nu^2 \int_{\nu_{th}^2}^{\infty} \frac{d\nu'^2}{\nu'^2} \frac{W_1(\nu',Q^2)}{\nu'^2-\nu^2} + 4\pi\beta Q^2 + O(Q^4)$$

$\beta = 3.1 \pm 0.5 \quad \Longrightarrow \Delta E_{\rm pol} = -8.5(1.1)\mu\text{eV} \quad \Delta E_{2\gamma} = -33.5(2.0)\mu\text{eV}$

M. Birse & JMcG, Eur. Phys. J. A **48** (2012) 120

Is there a deuteron radius puzzle?

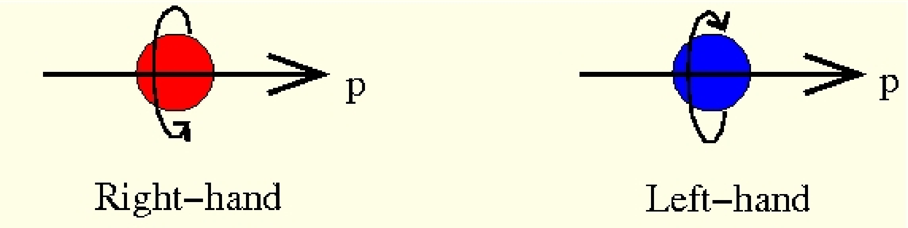


CREMA, Science 2016

Possible $\sim 2.5\sigma$ discrepancy between muonic value and prediction based on "small" proton radius and precisely-known (electronic) isotope shift
but interplay between nuclear and nucleonic structure still to be worked out.

Chiral symmetry: Why the pion is special

Chiral symmetry is an extension of isospin symmetry which is exact for massless quarks: we are free to redefine up and down for right- and left-handed quarks separately.



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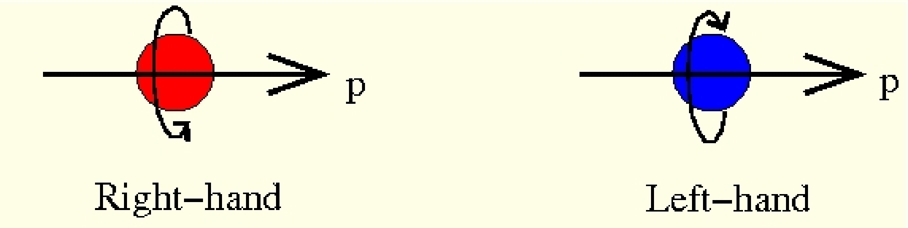

The symmetry is hidden – it is a symmetry of the QCD Lagrangian but not of the vacuum or hadron spectrum (isospin multiplets but no parity doublets).

This is the "Higgs mechanism" of QCD: hadrons get (almost all of) their mass from their interactions with the QCD vacuum; $\langle \overline{q} q \rangle \neq 0$.

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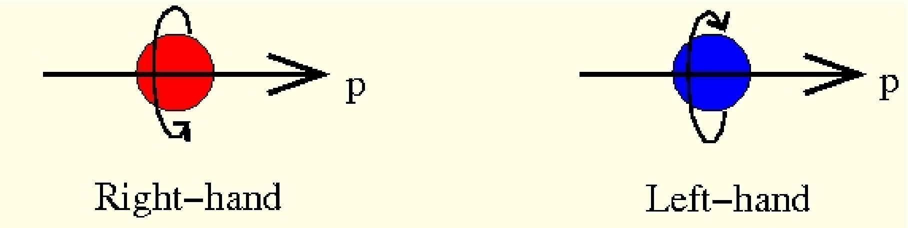

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The hidden symmetry shows up as a massless Goldstone bosons — the pion.

m_π is not quite zero because the quark masses also couple to the Higgs condensate (also contributes 5-10% of the mass of other hadrons)

Chiral Perturbation theory

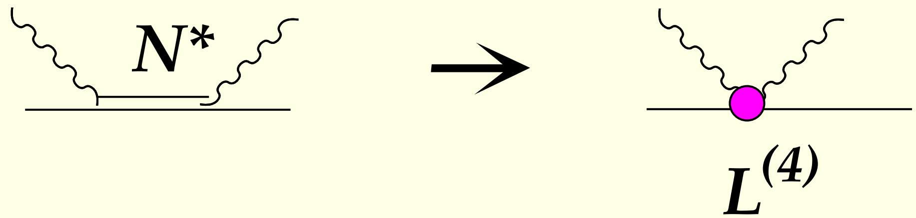
Effective field theory of QCD– relies on separation of scales

- pions are light ($m_\pi \ll m_\rho$)
- low-energy pions interact weakly with other matter ($L_{\pi NN} \propto \overline{N}\partial_\mu \pi N$).

Thus pion loops are suppressed by $\approx m_\pi^2/\Lambda^2$ where $\Lambda \approx m_\rho$. The Lagrangian contains infinitely many terms:

$$\mathcal{L} = \sum_n \mathcal{L}^{(n)}(c_i^{(n)})$$

Non-pionic nucleon structure shows up in low energy constants $c_i^{(n)}$, but is suppressed by power of momentum: $(k/\Lambda)^n$:



Systematic: Calculations to nth order involve vertices from $\mathcal{L}^{(n)}$ and pion loops with vertices from $\mathcal{L}^{(n-2)}$; truncation errors are $\sim (k/\Lambda)^{(n+1)}$.

MANCHESTER 1824

χPT for Compton Scattering from the nucleon

We include nucleons, pions and the Delta in our Lagrangian.

$$\mathcal{L}_{\pi N}^{(4),\mathrm{CT}} = 2\pi e^2 H^\dagger \left[\left(\delta\beta^{(s)} + \delta\beta^{(v)} \tau_3 \right) \left(\tfrac{1}{2} g_{\mu\nu} - v_\mu v_\nu \right) - \left(\delta\alpha^{(s)} + \delta\alpha^{(v)} \tau_3 \right) v_\mu v_\nu \right] F^{\mu\rho} F^\nu{}_\rho H.$$

Counterterms shift α and β at 4th order. Counterterms for spin pols at 5th order.

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$\Delta \equiv M_\Delta - M_N \approx 271$ MeV is a rather small scale. Traditionally it is counted as $\Delta/\Lambda_\chi \sim m_\pi/\Lambda_\chi$ ("SSE"). But in Compton scattering the pion is clearly important at lower energies than the Delta.

Alternative: count $$\frac{m_\pi}{\Delta} \sim \frac{\Delta}{\Lambda_\chi} \quad \Rightarrow \quad \delta^2 \equiv \left(\frac{\Delta}{\Lambda_\chi} \right)^2 \sim \frac{m_\pi}{\Lambda_\chi}$$

Then graphs with one Δ propagator are one order of δ higher than the corresponding nucleon graphs in low energy region.

Pascalutsa and Phillips, Phys. Rev. C67 (2003) 055202

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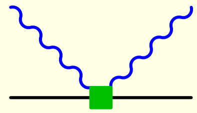
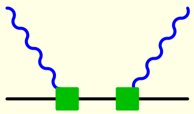
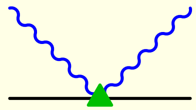
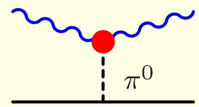
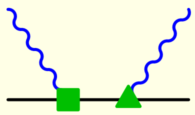
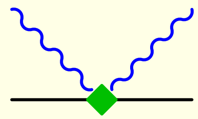
Different counting in resonance region; we work to at least NLO in both.

Tree graphs

Born terms give the Thomson term and spin-dependent LETs (ensured by gauge and Lorentz invariance)

contribution with typical size		$\omega \sim m_\pi$	$\omega \sim \Delta$
(i)		$e^2\delta^0$ (LO)	$e^2\delta^0$
(ii)	(a)  (b)  (c) 	$e^2\delta^2$	$e^2\delta^1$
(iii)	(a)  (b) 	$e^2\delta^4$	$e^2\delta^2$

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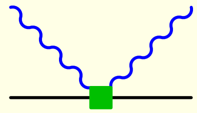
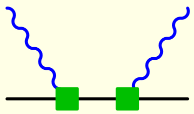
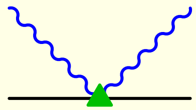
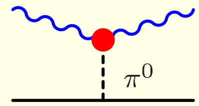
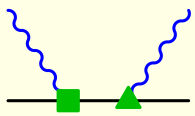
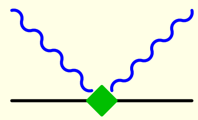
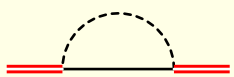
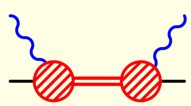
(i)		$e^2\delta^0$ (LO)	$e^2\delta^0$
(ii)	(a)  (b)  (c) 	$e^2\delta^2$	$e^2\delta^1$
(iii)	(a)  (b) 	$e^2\delta^4$	$e^2\delta^2$

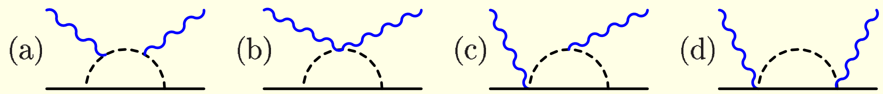
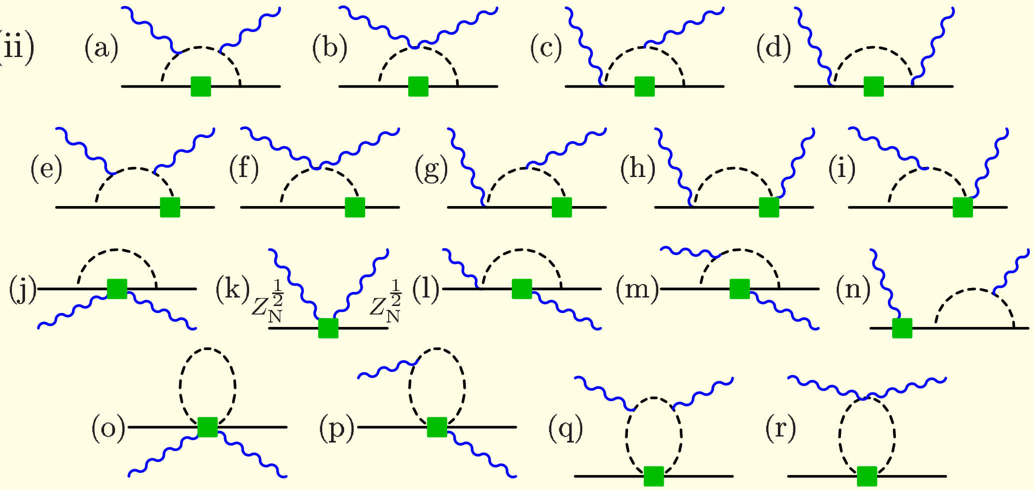
In resonance region Delta-pole graph dominates: width from resuming self-energy



$$\Rightarrow \quad S_\Delta \sim \frac{1}{\omega - (M_\Delta - M_N) + i\Gamma(\omega)}$$

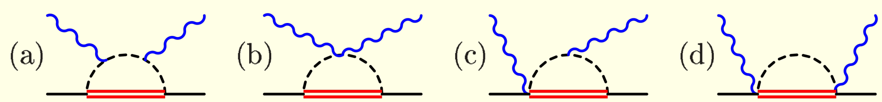
(i)		$e^2\delta^3$	$e^2\delta^{-1}$ (LO)

Loops

contribution with typical size		$\omega \sim m_\pi$	$\omega \sim \Delta$
(i)		$e^2\delta^2$	$e^2\delta^1$
(ii)		$e^2\delta^4$	$e^2\delta^2$

At 4th order we have $1/M$ corrections and c_i contributions

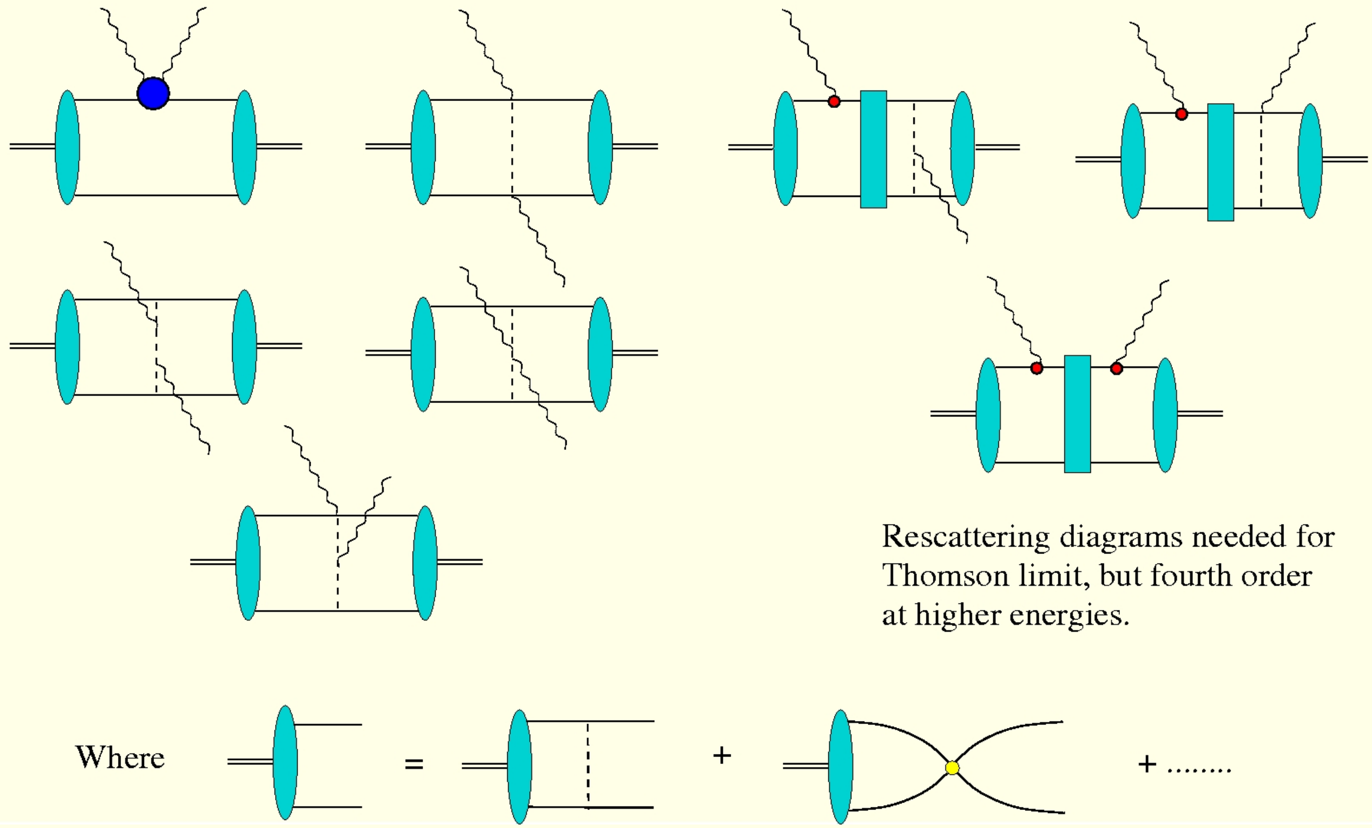
Delta loops are less important in low-energy region

(ii)		$e^2\delta^3$	$e^2\delta^1$

Important: predicts full energy-dependent amplitudes, not just polarisabilities

Deuteron

Consistent treatment of one- and two-body diagrams

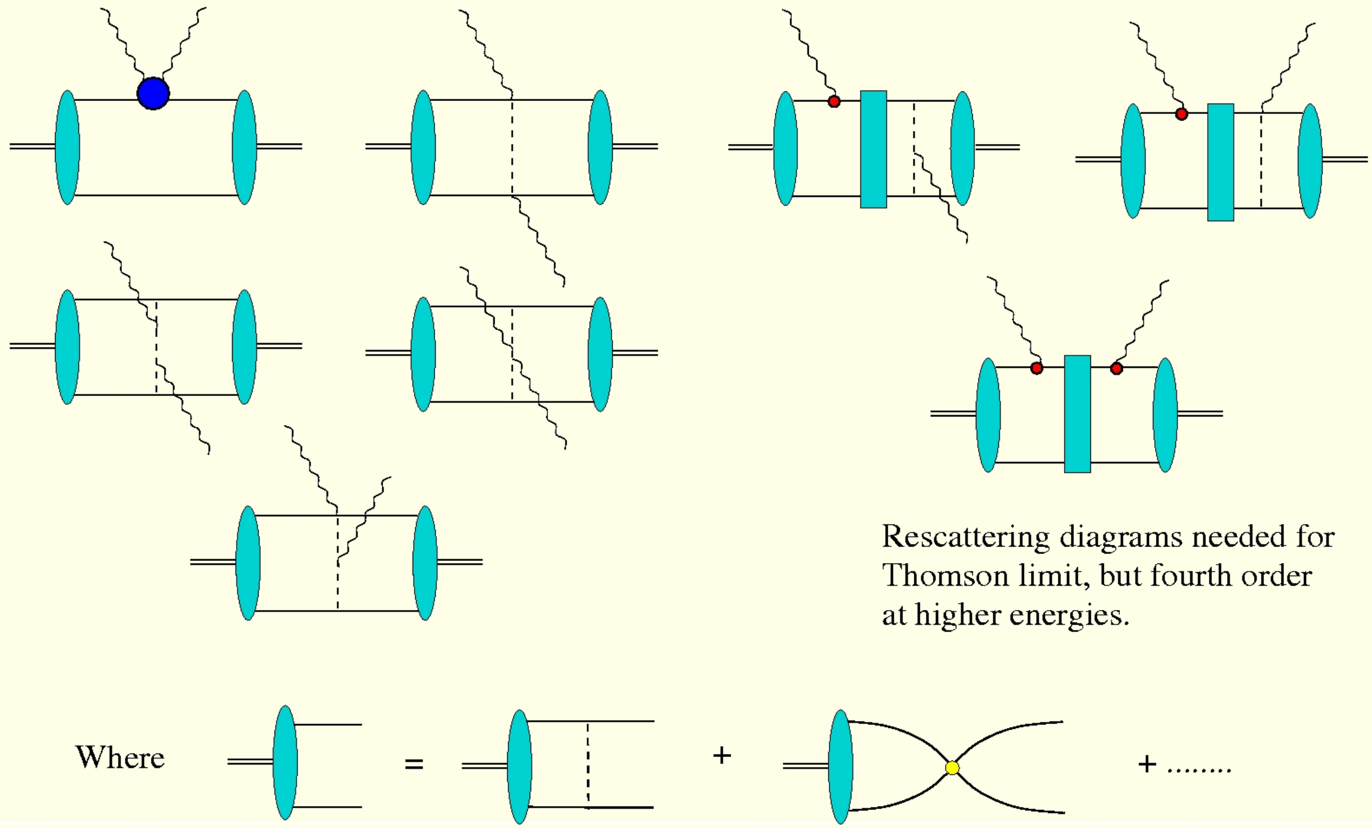


● all one-body diagrams from previous slides. the Δ only enters here at this order.

Ensuring correct Thomson limit for deuteron is important even at 50-60 MeV.

Deuteron

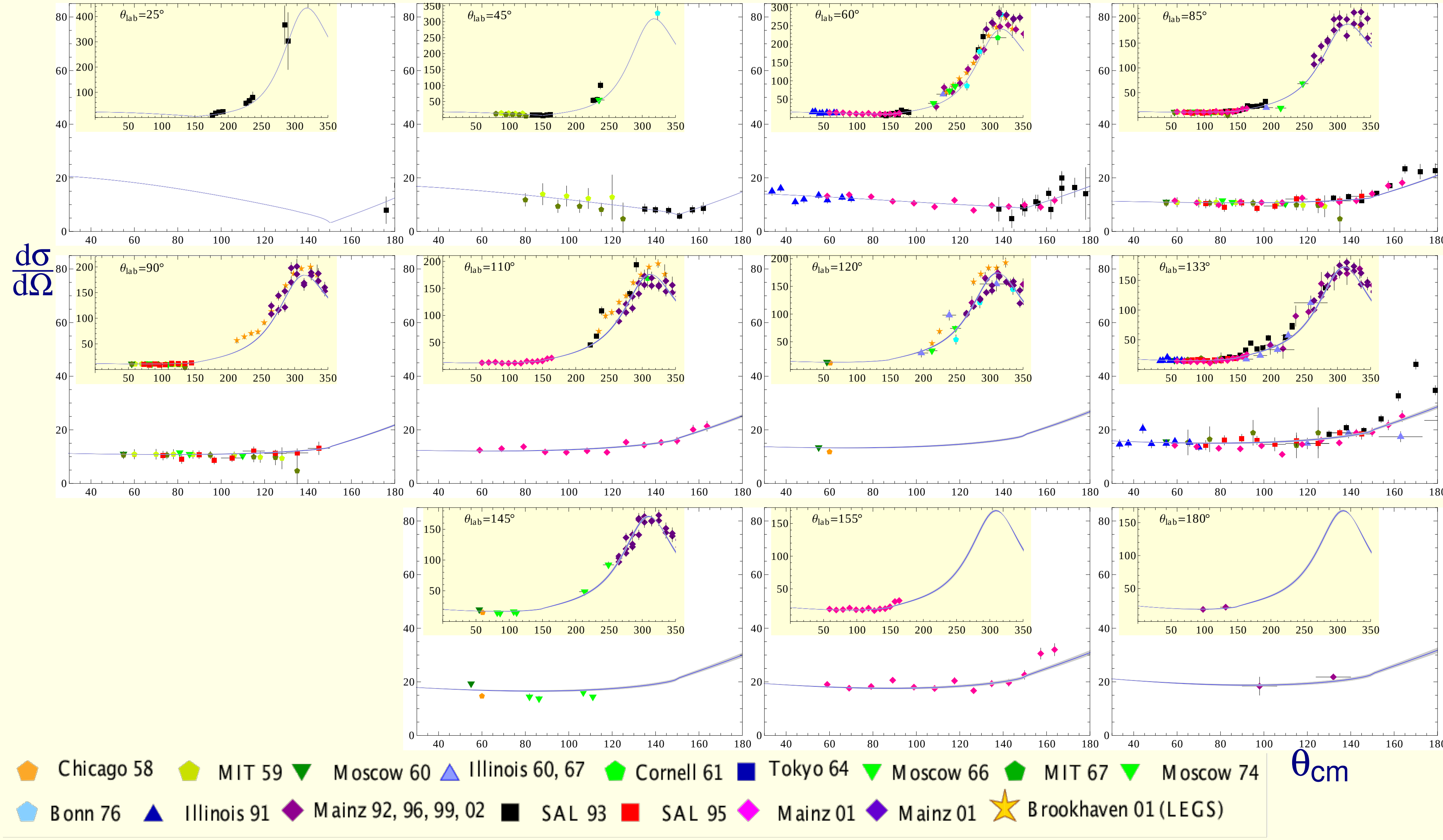
Consistent treatment of one- and two-body diagrams



● all one-body diagrams from previous slides. the Δ only enters here at this order. Ensuring correct Thomson limit for deuteron is important even at 50-60 MeV.

^{3}He and ^{4}He consist only of the same $N \leq 2$ diagrams with one or two spectator nuclei.

Fitting the proton data



Constraining $\alpha + \beta$ with Baldin Sum rule and fitting consistent data set up to 170 MeV:

$$\alpha_p = (10.65 \pm 0.35(\text{stat}) \pm 0.2(\text{Bald}) \pm 0.3(\text{theory})) \times 10^{-4}\,\text{fm}^3$$

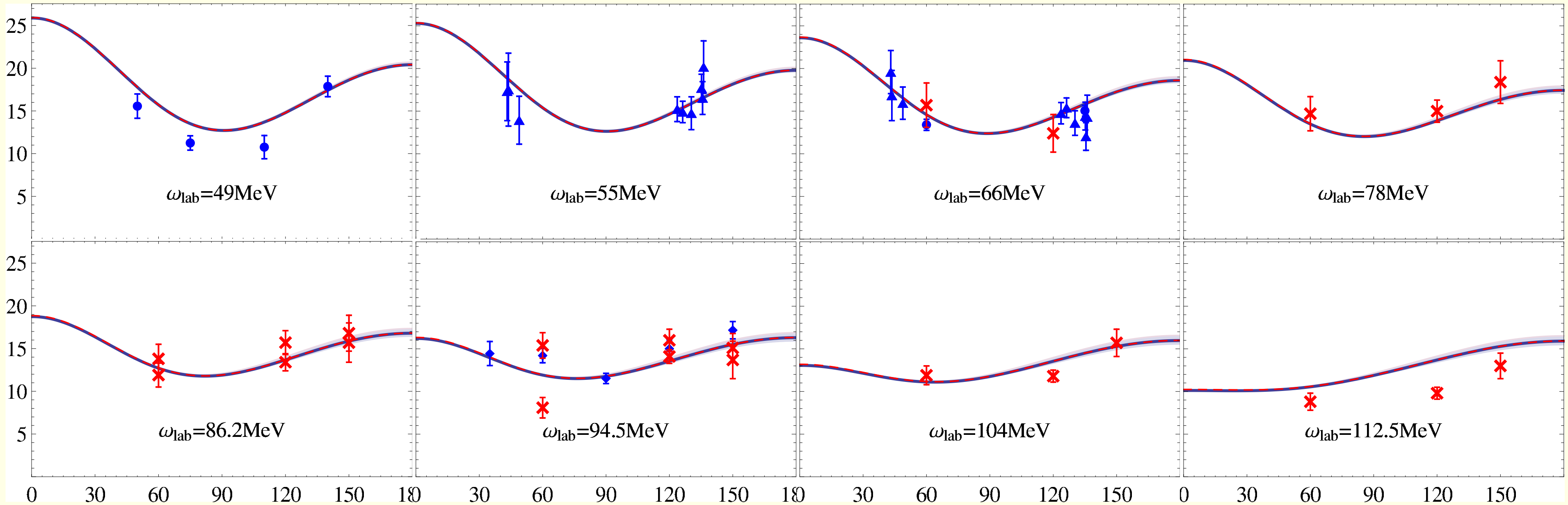
$$\beta_p = (3.15 \mp 0.35(\text{stat}) \pm 0.2(\text{Bald}) \mp 0.3(\text{theory})) \times 10^{-4}\,\text{fm}^3$$

Extraction of isoscalar polarisabilities from deuteron

So far only $O(Q^3)$; further work required to go above pion threshold.

Older data from Illinois ●, Saskatoon, ◆ and Lund ▲ (29 pts in total)

New data from Lund ×, 23 points. Myers *et al.* , Phys. Rev. Lett. **113,** 262506 (2014)



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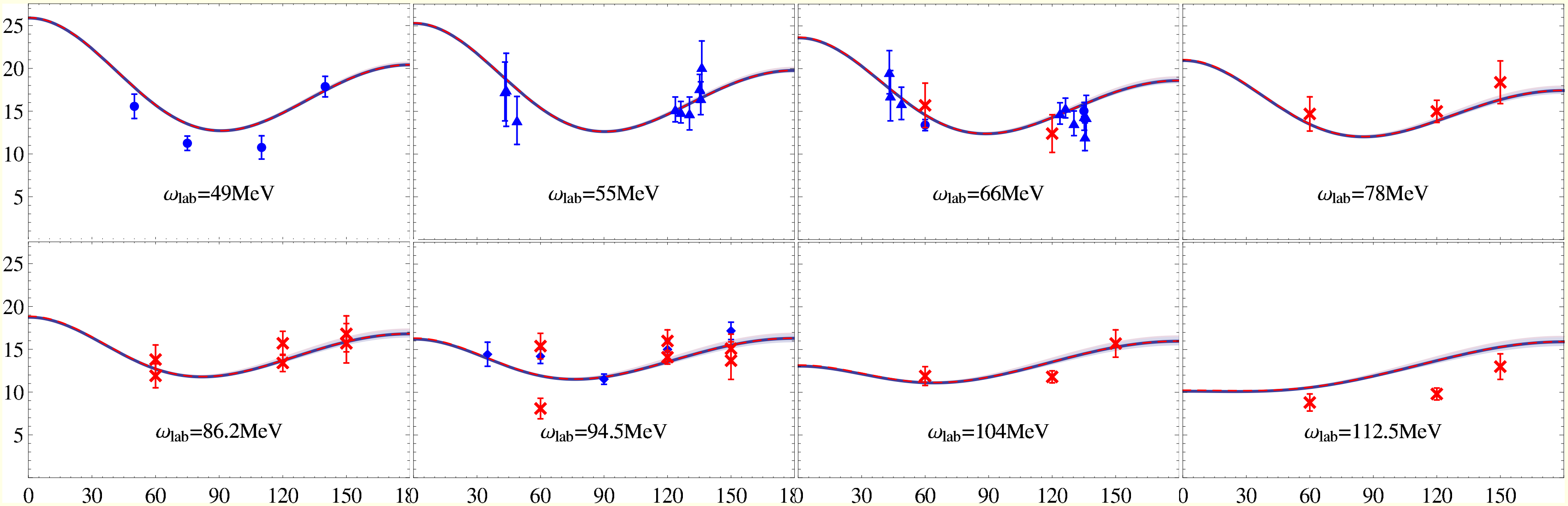

$$\alpha_s = 11.1 \pm 0.6(\text{stat}) \pm 0.2(\text{BSR}) \pm 0.8(\text{th})$$
$$\beta_s = 3.4 \mp 0.6(\text{stat}) \pm 0.2(\text{BSR}) \mp 0.8(\text{th}).$$

$$\alpha_n = 11.65 \pm 1.25(\text{stat}) \pm 0.2(\text{BSR}) \pm 0.8(\text{th})$$
$$\beta_n = 3.55 \mp 1.25(\text{stat}) \pm 0.2(\text{BSR}) \mp 0.8(\text{th})$$

Comparison

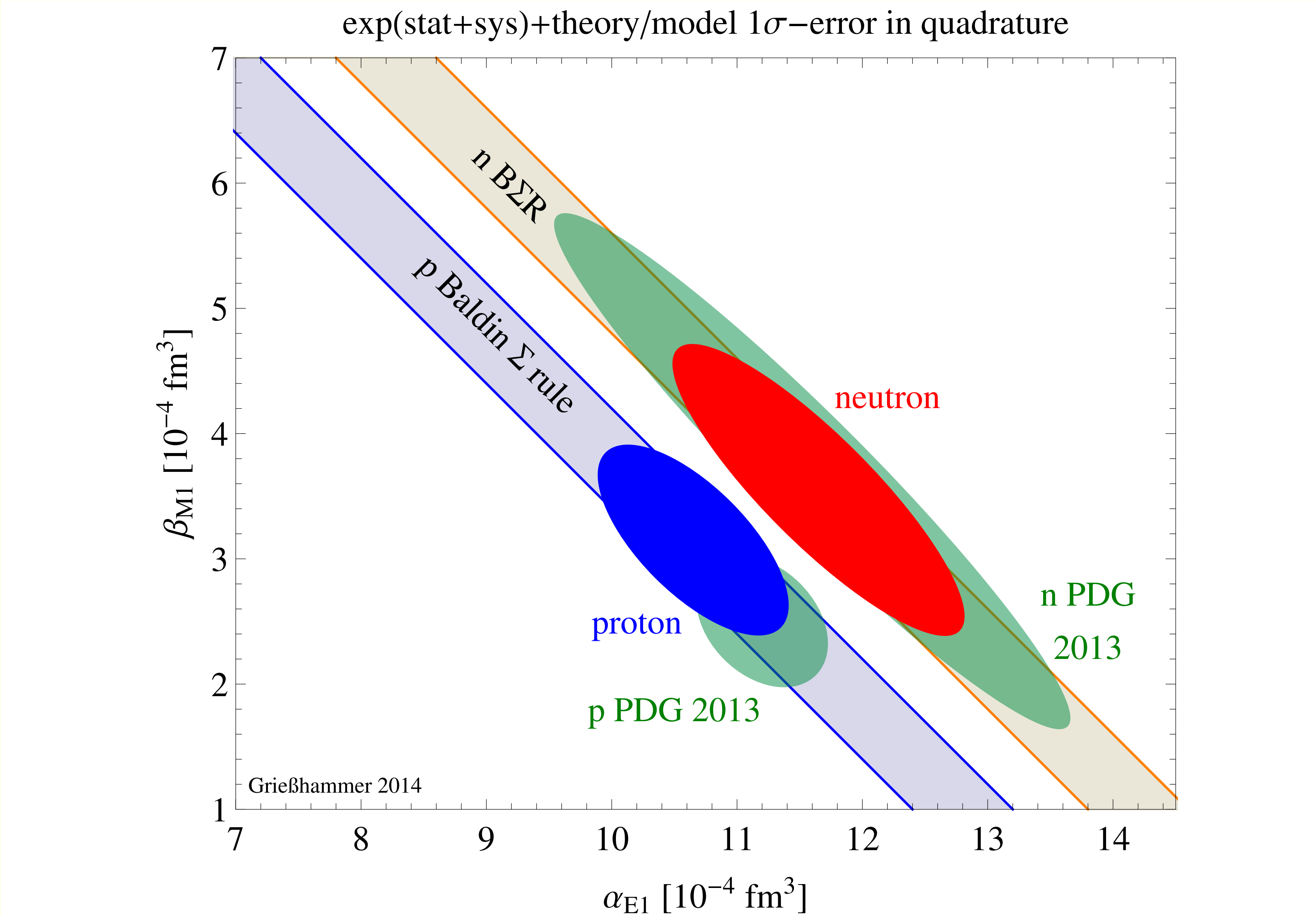

figure courtesy of H. Grießhammer

Multipoles for proton theory comparison

Restricting to lowest photon angular momentum, but at finite photon energy, we can write the effective Hamiltonian

$$
\begin{aligned}
H_{eff} &= \frac{(\mathbf{p}-Q\mathbf{A})^2}{2m} + Q\phi - \frac{1}{2}4\pi\Big(\alpha_{E1}(\omega)\vec{E}^2 + \beta_{M1}(\omega)\vec{H}^2 \\
&+ \gamma_{E1E1}(\omega)\vec{\sigma}\cdot\vec{E}\times\dot{\vec{E}} + \gamma_{M1M1}(\omega)\vec{\sigma}\cdot\vec{H}\times\dot{\vec{H}} \\
&- 2\gamma_{M1E2}(\omega)E_{ij}\sigma_i H_j + 2\gamma_{E1M2}(\omega)H_{ij}\sigma_i E_j\Big)
\end{aligned}
$$

with $\alpha \equiv \alpha_{E1}(0)$ etc

Multipoles for proton theory comparison

Restricting to lowest photon angular momentum, but at finite photon energy, we can write the effective Hamiltonian

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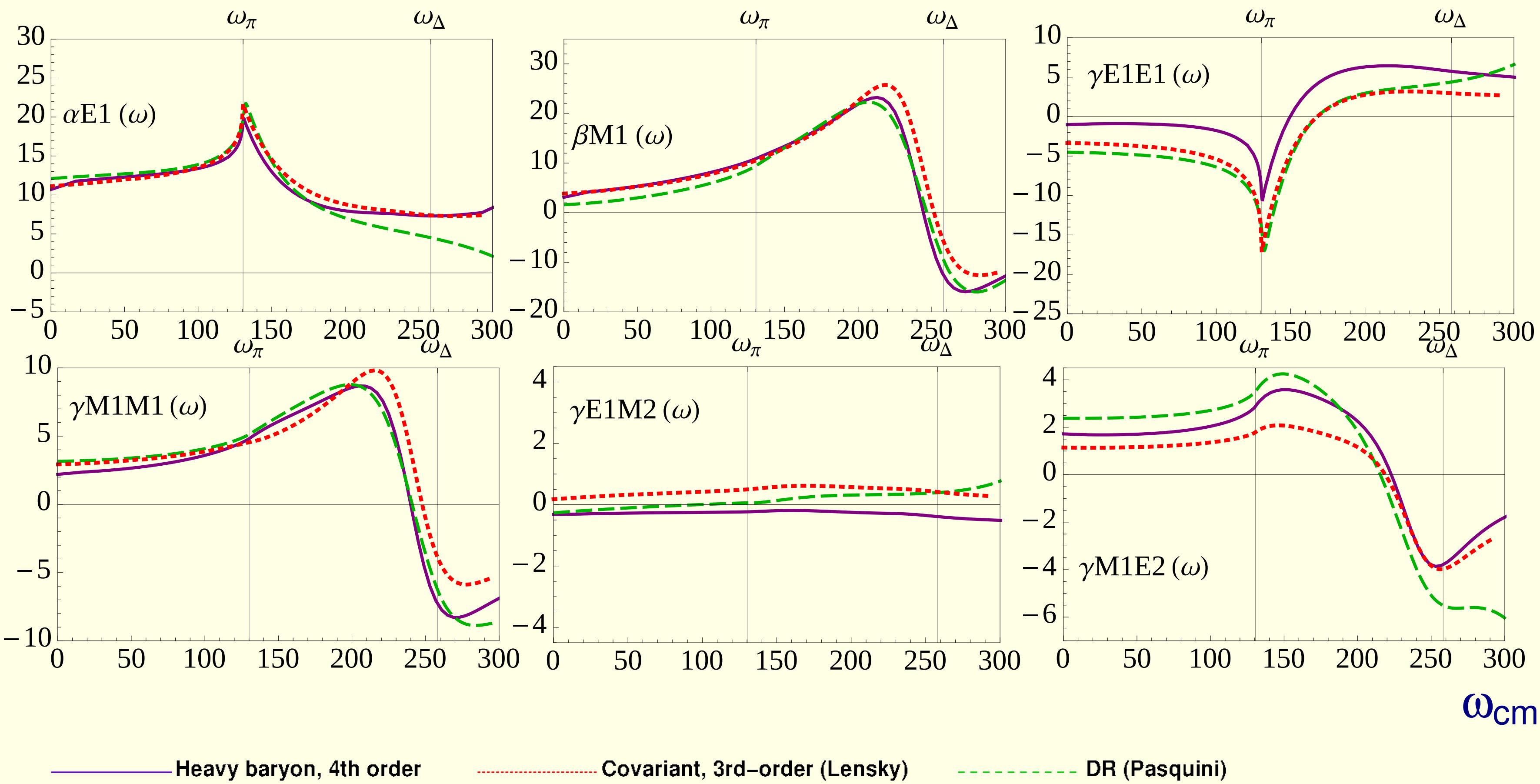
&- 2\gamma_{M1E2}(\omega)E_{ij}\sigma_i H_j + 2\gamma_{E1M2}(\omega)H_{ij}\sigma_i E_j\Big)
\end{aligned}
$$

with $\alpha \equiv \alpha_{E1}(0)$ etc

We can predict the full energy-dependence of the amplitudes, and only the value at the origin for α, β and γ_{M1M1} are fitted.

Comparison of theoretical predictions for multipoles

Different predictions do not fully agree on the physical origins of the polarisabilities. But Chiral and DR predictions agree very well for the shape of the energy dependence of corresponding multipoles



DR: Hildebrandt *et al.* , Eur. Phys. J. A **20** 293 (2004) Chiral: V Lensky *et al.* EPJC **75** 604 (2015)

Our strategy: Static polarisabilities best obtained from Compton scattering.

Comparison

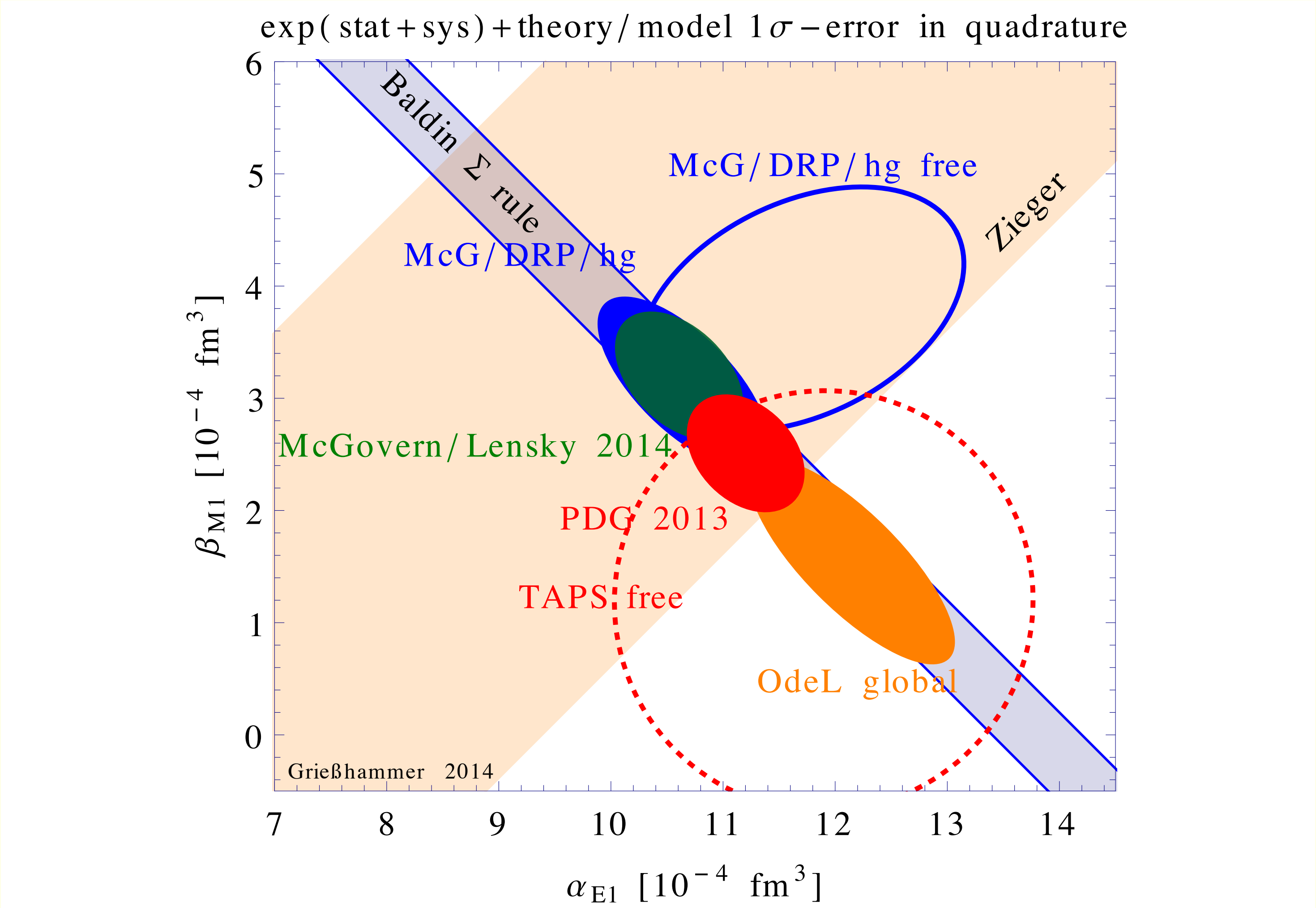
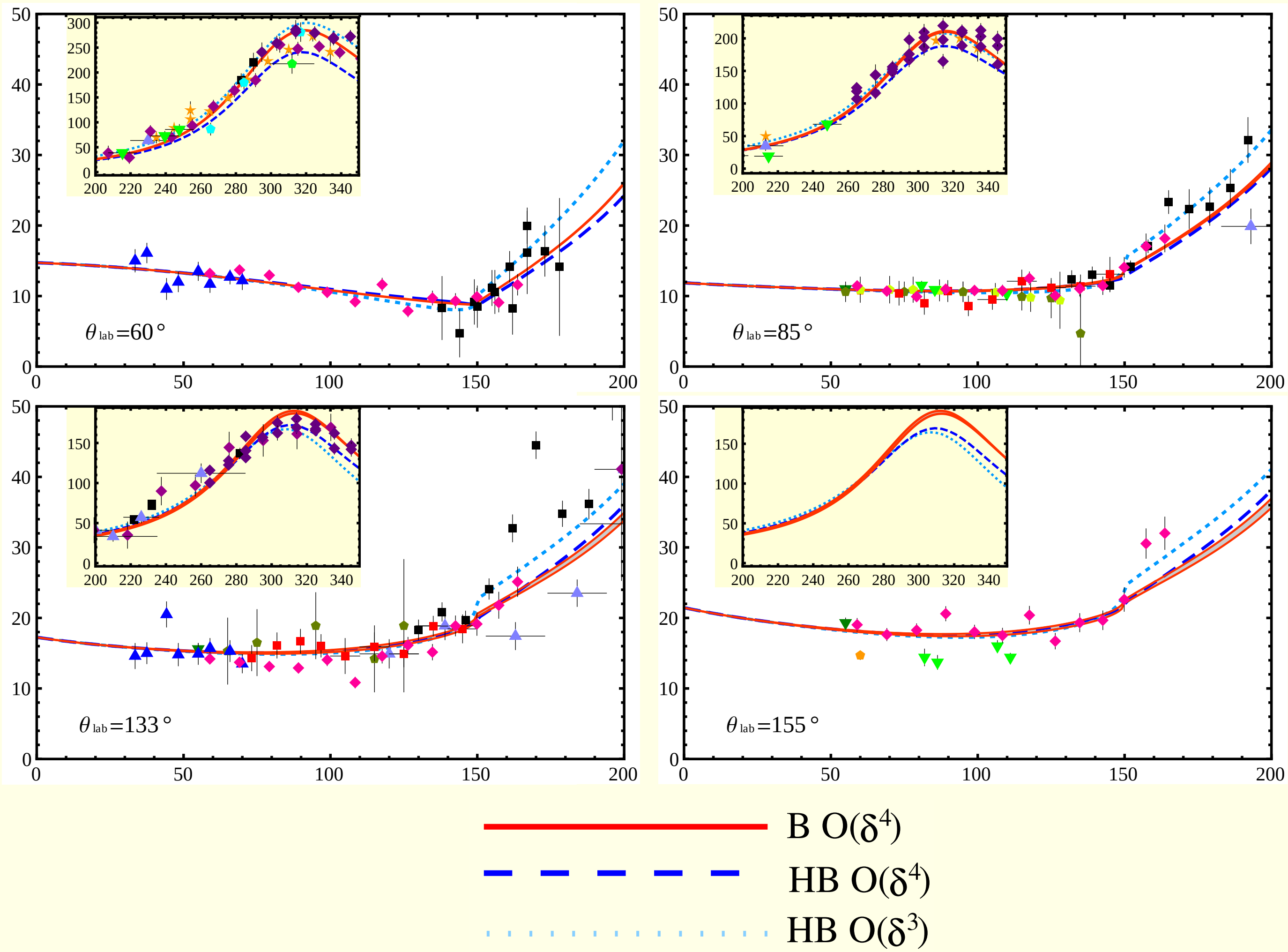


figure courtesy of H. Grießhammer

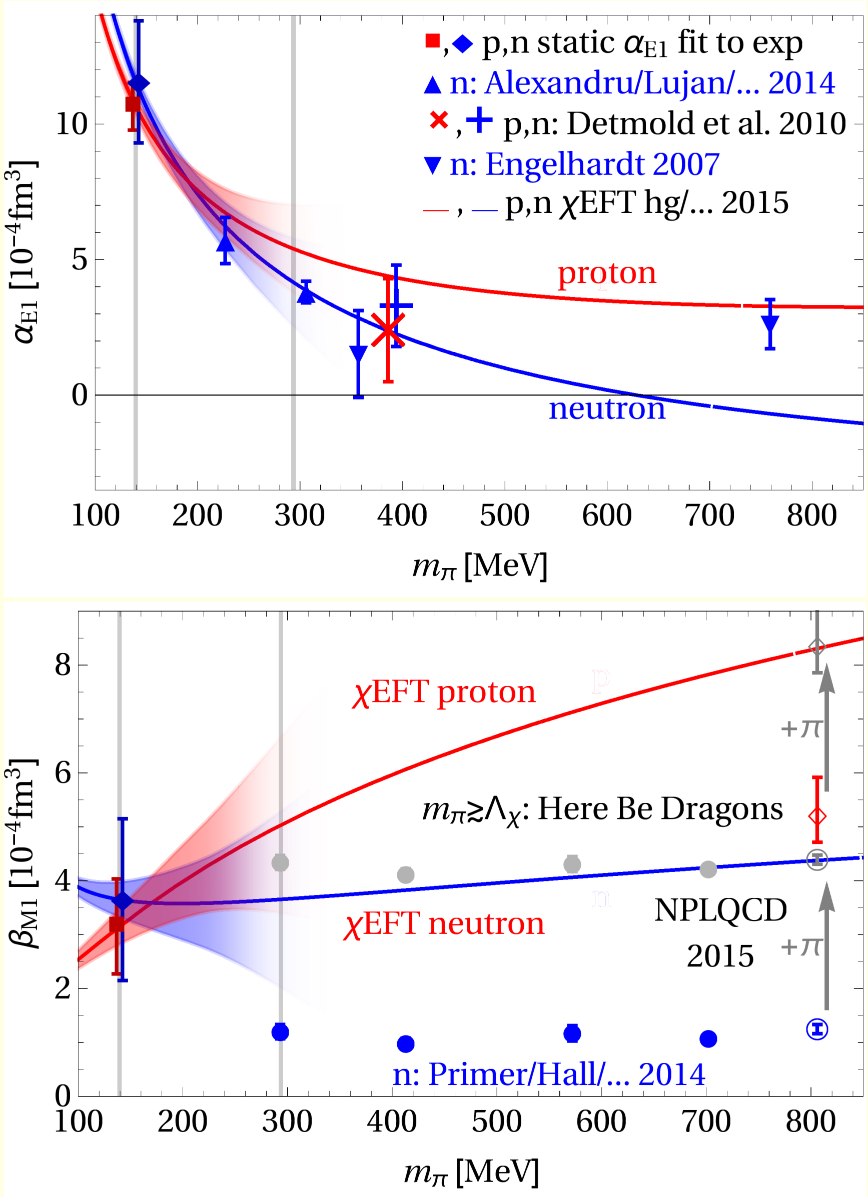
Checking in covariant framework (3rd order)



$$\alpha_p = (10.6 \pm 0.25(\text{stat}) \pm 0.2(\text{Bald}) \pm 0.4(\text{theory})) \times 10^{-4}\,\text{fm}^3$$
$$\beta_p = (3.2 \mp 0.25(\text{stat}) \pm 0.2(\text{Bald}) \pm 0.4(\text{theory})) \times 10^{-4}\,\text{fm}^3$$

V. Lensky & JMcG Phys. Rev. **C89** 032202 (2014) ; V. Lensky *et al.* Phys. Rev. **C86** 048201 (2012)

Lattice and chiral extrapolations



H. Grießhammer, JMcG, D. Phillips Eur. Phys. J. A **52** (2016) 139

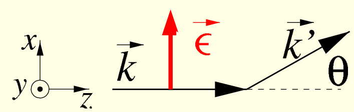
Accessing spin polarisabilities

$$H_{\text{eff}} = \frac{(\mathbf{p}-Q\mathbf{A})^2}{2m} + Q\phi - \frac{(Q+\kappa)}{2m}\sigma\cdot H - \frac{1}{2}4\pi\left(\alpha\vec{E}^2+\beta\vec{H}^2 + \gamma_{E1E1}\vec{\sigma}\cdot\vec{E}\times\dot{\vec{E}} + \gamma_{M1M1}\vec{\sigma}\cdot\vec{H}\times\dot{\vec{H}} - 2\gamma_{M1E2}E_{ij}\sigma_i H_j + 2\gamma_{E1M2}H_{ij}\sigma_i E_j\right)$$

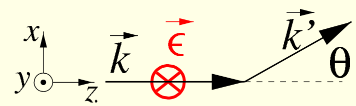
Spin-polarisabities have most influence if the beam or target or both are polarised.

Linearly polarised beam $\Sigma_3 = \dfrac{\sigma^{\parallel}-\sigma^{\perp}}{\sigma^{\parallel}+\sigma^{\perp}}$

$\left[\dfrac{d\sigma}{d\Omega}\right]_x^{\text{lin}}$:

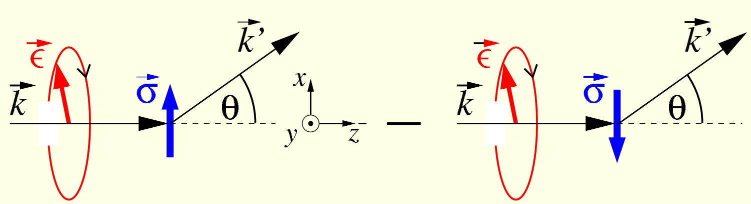


$\left[\dfrac{d\sigma}{d\Omega}\right]_y^{\text{lin}}$:

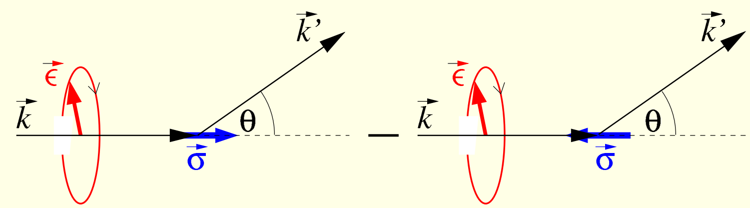


Circular beam, polarised target $\qquad \Sigma_{2x} = \dfrac{\sigma^R_{\perp}-\sigma^L_{\perp}}{\sigma^R_{\perp}+\sigma^L_{\perp}} \qquad \Sigma_{2z} = \dfrac{\sigma^R_{\parallel}-\sigma^L_{\parallel}}{\sigma^R_{\parallel}+\sigma^L_{\parallel}}$

Δ_x^{circ}:

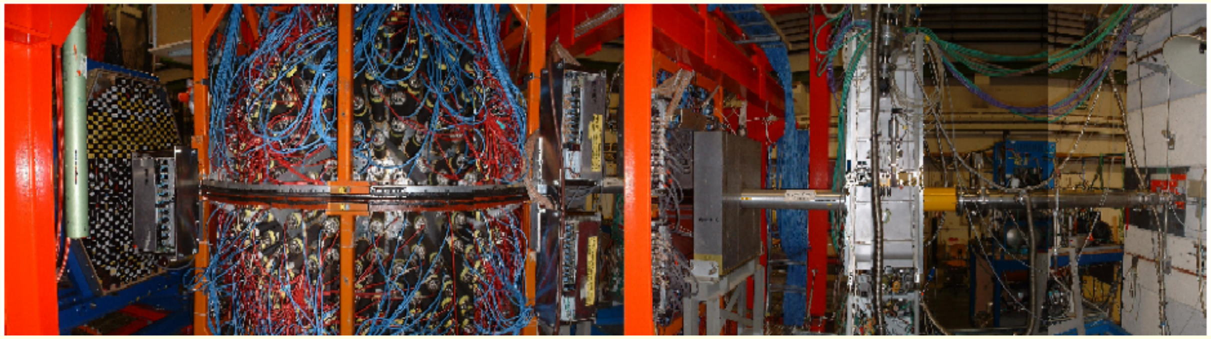


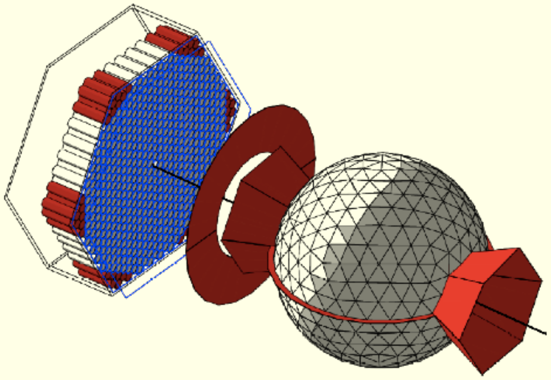
Δ_z^{circ}:



Compton @MAMI

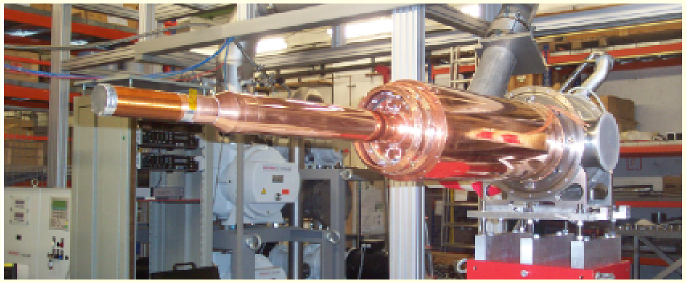
New programme at A2 experiment using Crystal Ball and TAPS detectors





Large-acceptance detector

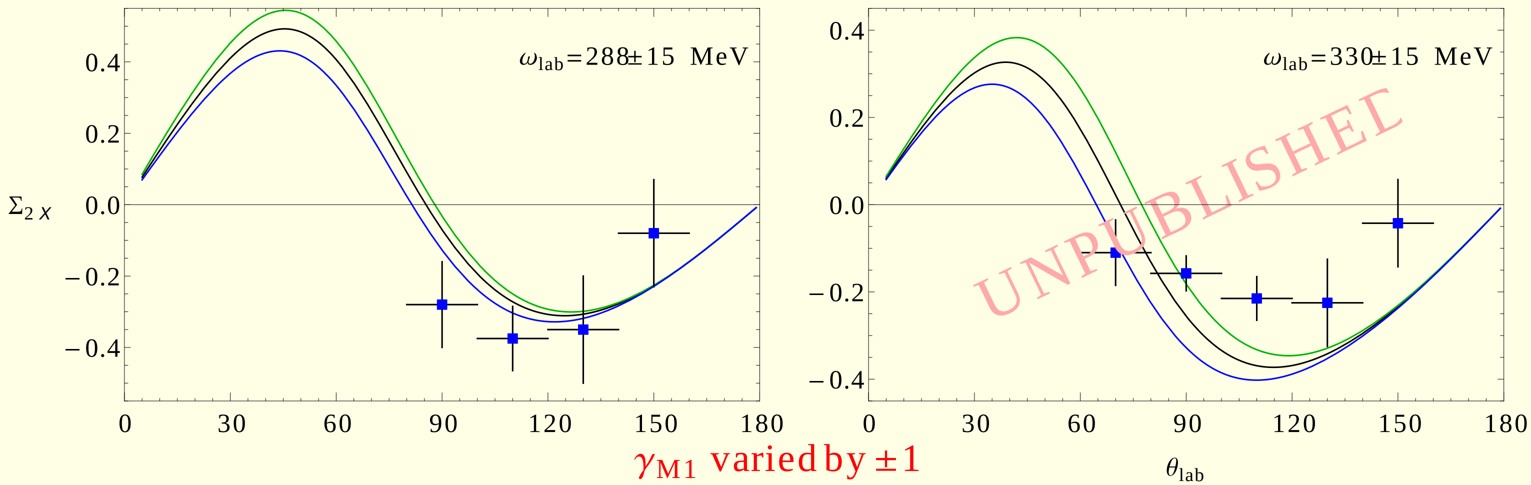
Tagged photon beam, circ. or lin. polarised or unpolarised,



Unpolarised (liquid hydrogen)... or polarised (butanol) protons

First results from MAMI

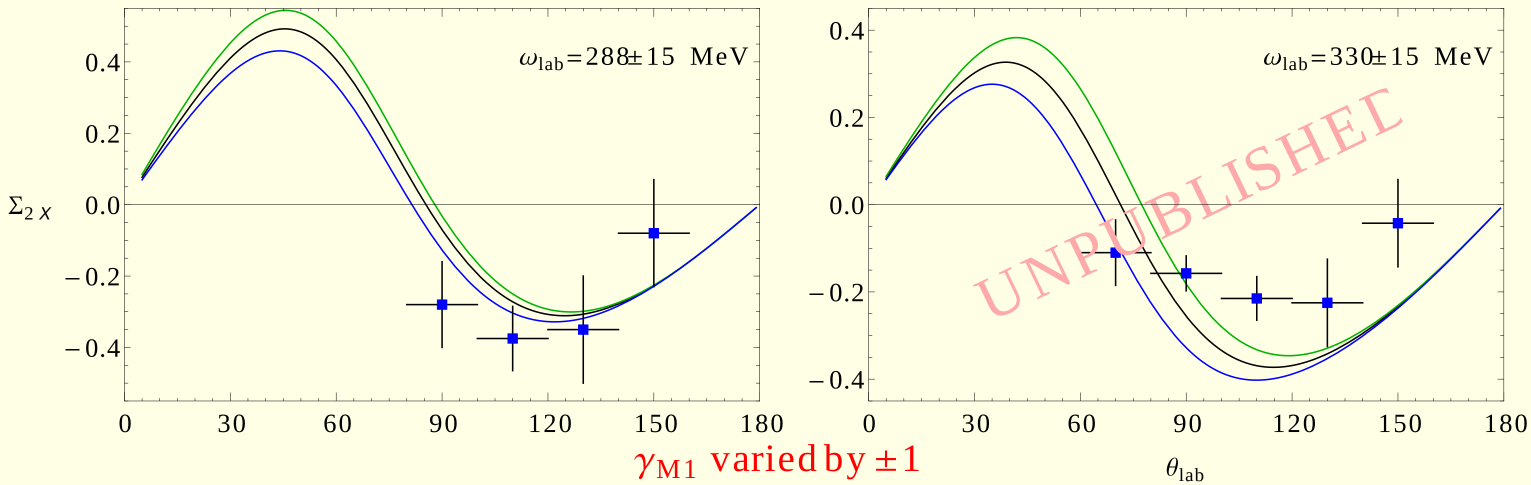
Σ_{2x}: Target polarised perpendicular to reaction plane, RH or LH circularly polarised photons P. Martell, PhD thesis



γ_{M1} varied by ±1

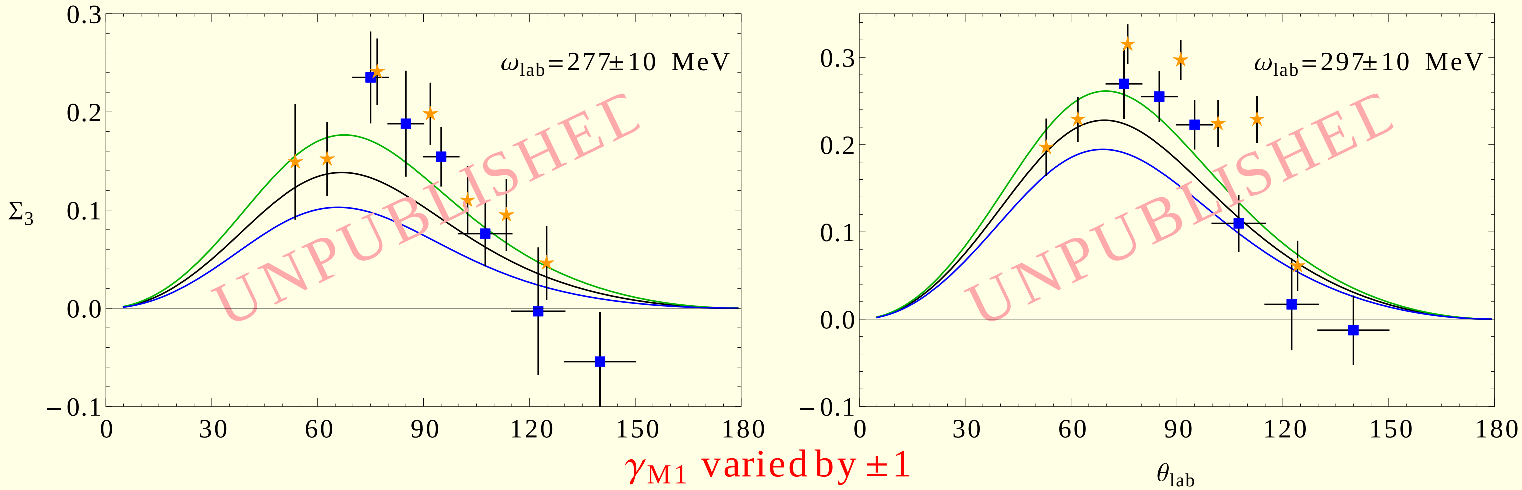
First results from MAMI

Σ_{2x}: Target polarised perpendicular to reaction plane, RH or LH circularly polarised photons P. Martell, PhD thesis



Σ_3: Unpolarised target, photons polarised in or perpendicular to reaction plane

■ C. Collicott, PhD thesis (LEGS data ☆)



Predictions and fits for proton polarisabilities

Chiral prediction (δ^3, BChPT, Lensky *et al.* , EPJC **75** 604 (2015)) and NLO (δ^4, HBChPT, JMcG *et al.* E. P. J. A **49** 12 (2013), Grießhammer *et al.* 1511.01952

	$\alpha+\beta$	$\alpha-\beta$	γ_0	γ_π
δ^3 B	15.1 ± 1.0	7.3 ± 1.0	-0.9 ± 1.4	$[-46.4]+7.2\pm1.7$
δ^4 HB	$13.8\pm0.4^*$	$7.5\pm0.7\pm0.6$	$-2.6\pm0.5_{\text{stat}}\pm0.6^*_{\text{th}}$	$[-46.4]+5.5\pm0.5_{\text{stat}}\pm1.8^*_{\text{th}}$
SR/DR	13.8 ± 0.4	10.7 ± 0.2	-0.9 ± 0.14	$[-46.4]+7.6\pm1.8$

DR: fixed-angle, Drechsel *et al.* Phys. Rep. **378** 99;

	γ_{E1E1}	γ_{M1M1}	γ_{E1M2}	γ_{M1E2}
δ^3 B	-3.3 ± 0.8	2.9 ± 1.5	0.2 ± 0.2	1.1 ± 0.3
δ^4 HB	-1.1 ± 1.9	$2.2\pm0.5_{\text{stat}}\pm0.6^*_{\text{th}}$	-0.4 ± 0.6	1.9 ± 0.5
DR	-3.85 ± 0.45	2.8 ± 0.1	-0.15 ± 0.15	2.0 ± 0.1
MAMI1	-3.5 ± 1.2	3.2 ± 0.9	-0.7 ± 1.2	2.0 ± 0.3
MAMI2	-5.0 ± 1.5	3.1 ± 0.9	1.7 ± 1.7	1.3 ± 0.4

DR: fixed-t, summarised in HG, JMcG, DP & GF Prog. Nucl. Part. Phys. **67** 841 (2012)

MAMI1: published extraction from MAMI Σ_{2x} and LEGS Σ_3 Martel

MAMI2: unpublished extraction from Σ_{2x} and Σ_3 Collicott

δ^4: theory errors from convergence. *: γ_{M1M1} from fit, otherwise $\gamma_{M1M1}=6.4$

Note DR errors only reflect spread from two databases

see also Pasquini, Pedroni and Sconfietti, Phys. Rev. **C** 98 (2018) 015204
and Krupina, Lensky and Pascalutsa, PLB 782 (2018) 34

Predictions and fits for neutron polarisabilities

Chiral prediction (δ^3, BChPT, Lensky *et al.* , EPJC **75** 604 (2015)) and NLO (δ^4, HBChPT, Grießhammer *et al.* 1511.01952

	$\alpha+\beta$	$\alpha-\beta$	γ_0	γ_π
δ^3 B	18.3 ± 4.1	9.1 ± 4.1	0 ± 1.4	$[46.4]+9.0\pm2.0$
δ^4 HB	15.2 ± 0.4	$8.1\pm2.5\pm0.8$	$0.5\pm0.5_{\text{stat}}\pm1.8^*_{\text{th}}$	$[46.4]+7.7\pm0.5_{\text{stat}}\pm1.8^*_{\text{th}}$
SR/DR	15.2 ± 0.4	11.5	-0.25	$[46.4]\pm13.35$

DR: fixed-t, Drechsel *et al.* Phys. Rep. **378** 99;

	γ_{E1E1}	γ_{M1M1}	γ_{E1M2}	γ_{M1E2}
δ^3 B	-4.7 ± 1.1	2.9 ± 1.5	0.2 ± 0.2	1.6 ± 0.4
δ^4	-4.0 ± 1.9	$1.3\pm0.5_{\text{stat}}\pm0.5^*_{\text{th}}$	-0.1 ± 0.6	2.4 ± 0.5
DR	-5.75 ± 0.15	3.8 ± 0.1	-0.8 ± 0.1	3.0 ± 0.1

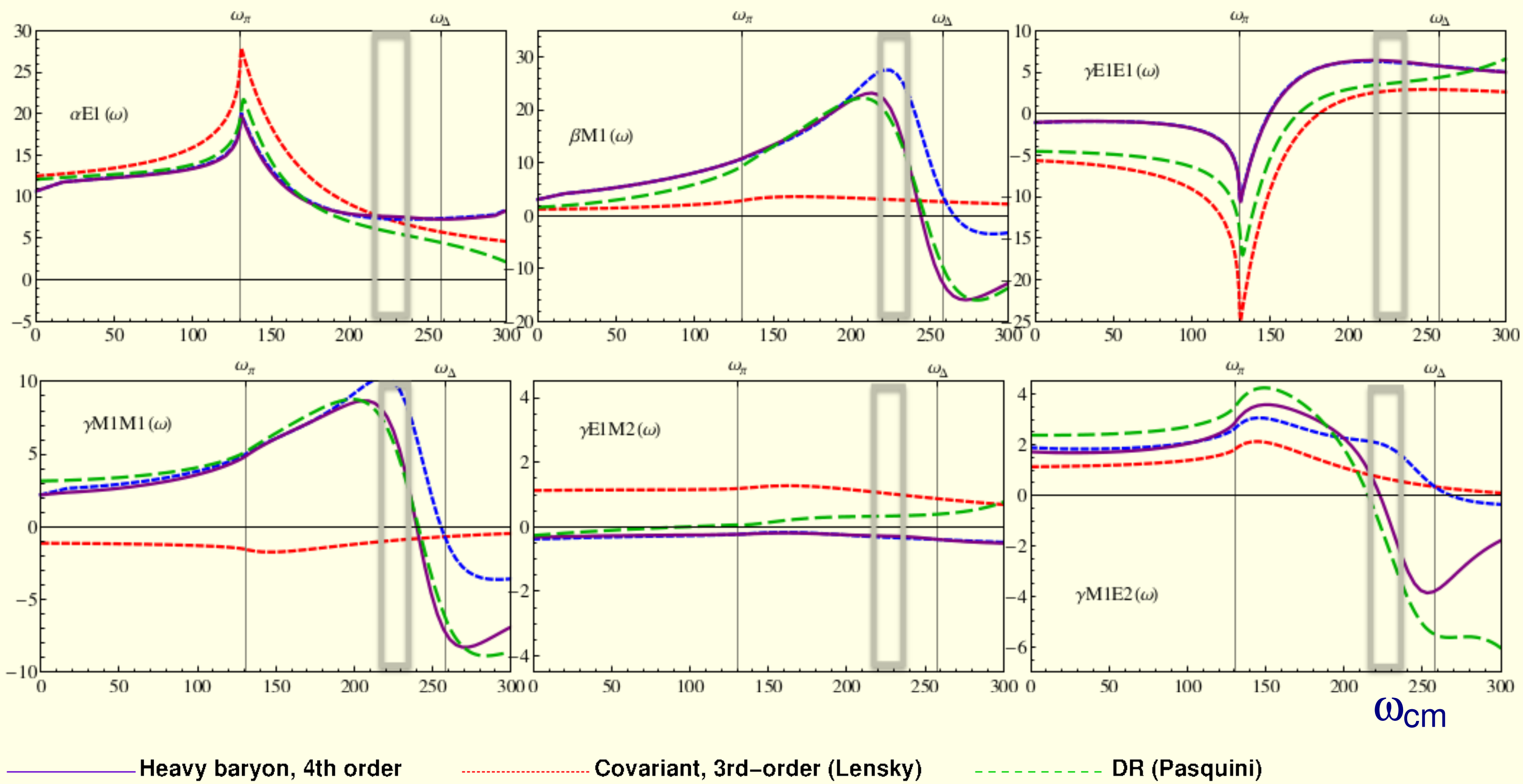
DR: fixed-t, Holstein *et al.* , Babusci *et al.*

δ^4: theory errors as proton. *: including input from proton fit.

Multipoles again

MAMI data is taken well into the resonance region....

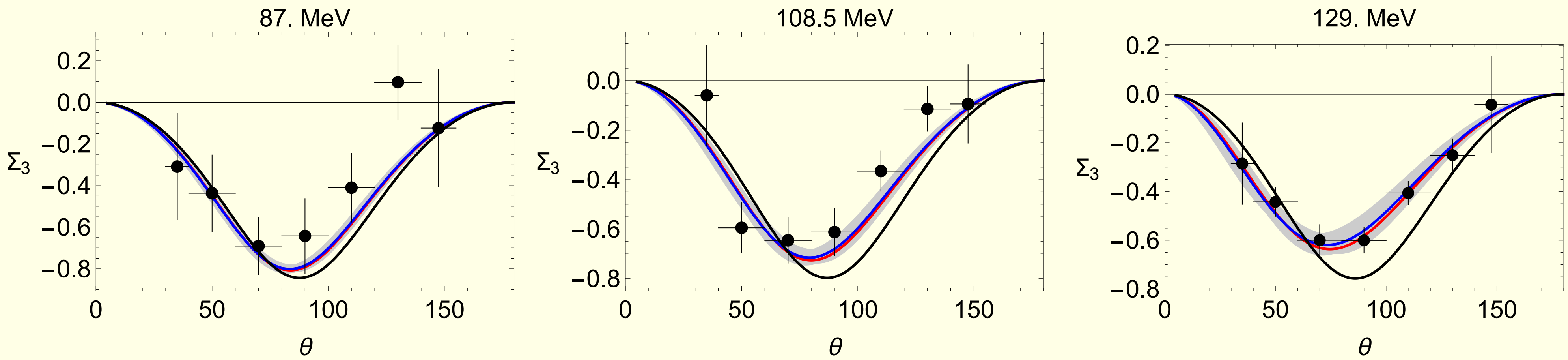
Not ideal for extracting zero-energy polarisabilities!



Lower energy experiments

Data on Σ_3 from MAMI V. Sokhoyan, E. J. Downie, E. Mornacchi, JMcG, N. Krupina, *et al.* ,

Eur. Phys. J. A (2017) 53: 14

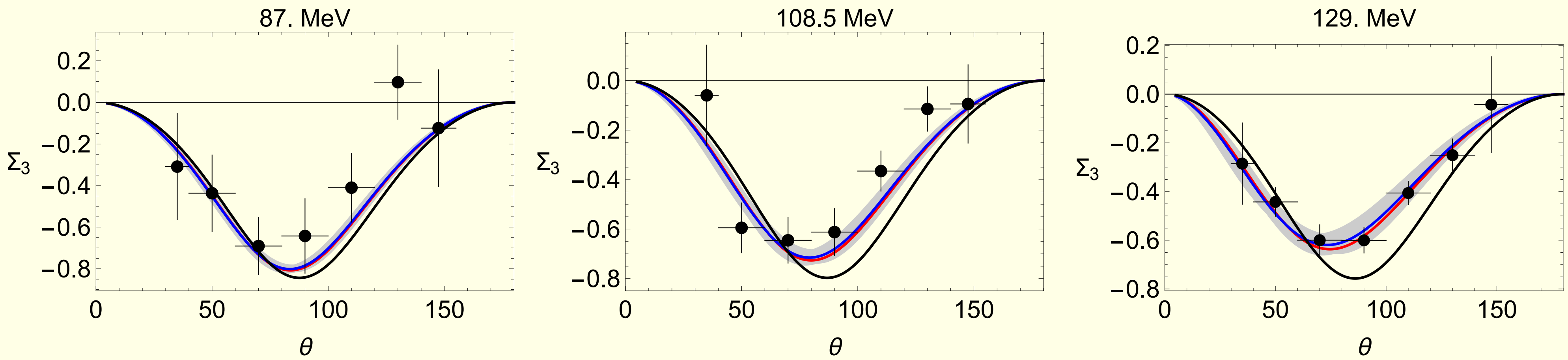


$$\beta = 3.7^{+2.5}_{-2.3} \times 10^{-4}\ \text{fm}^3.$$

More data taking planned

Lower energy experiments

Data on Σ_3 from MAMI V. Sokhoyan, E. J. Downie, E. Mornacchi, JMcG, N. Krupina, *et al.* ,
Eur. Phys. J. A (2017) 53: 14

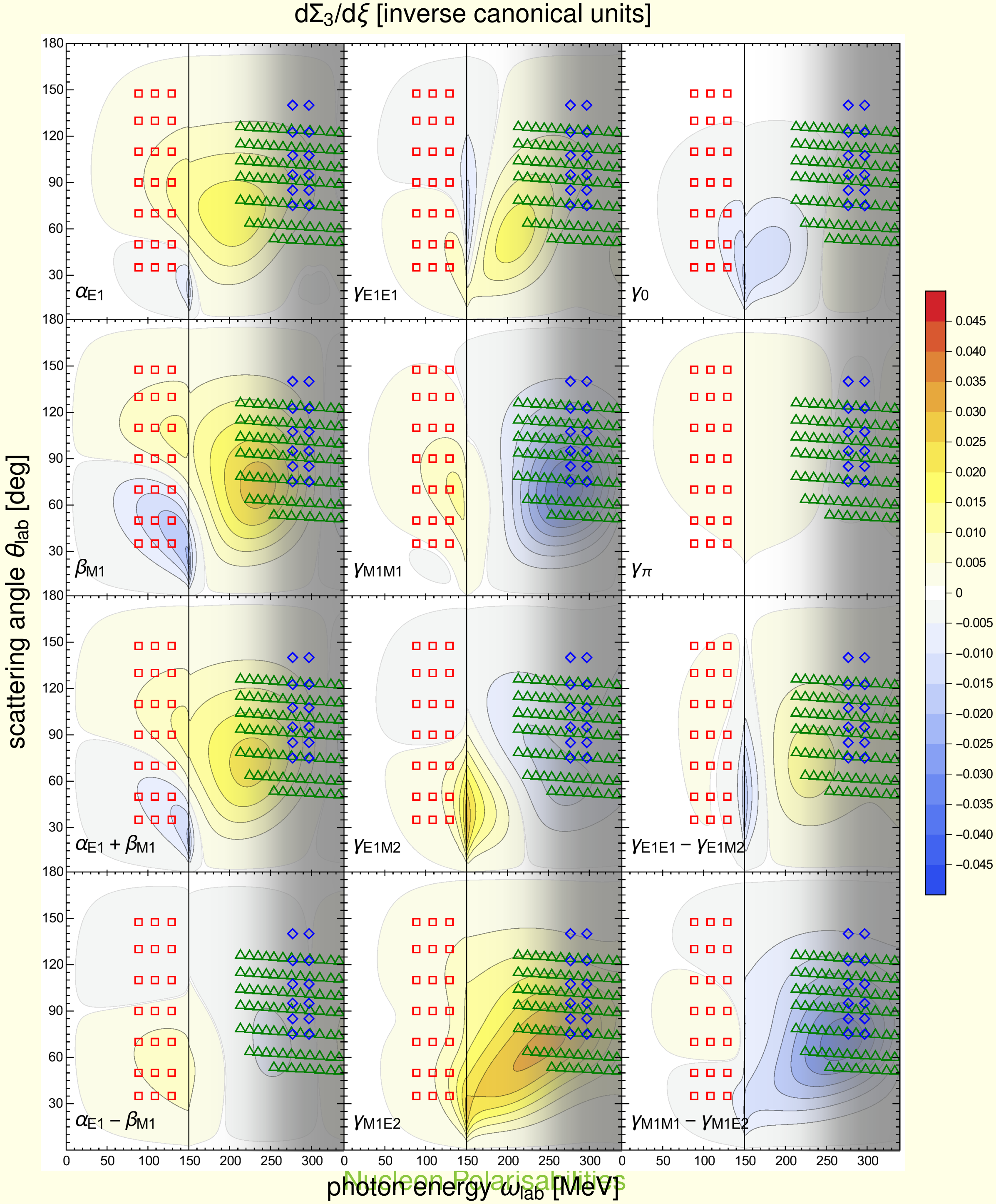


$$\beta = 3.7^{+2.5}_{-2.3} \times 10^{-4}\ \text{fm}^3.$$

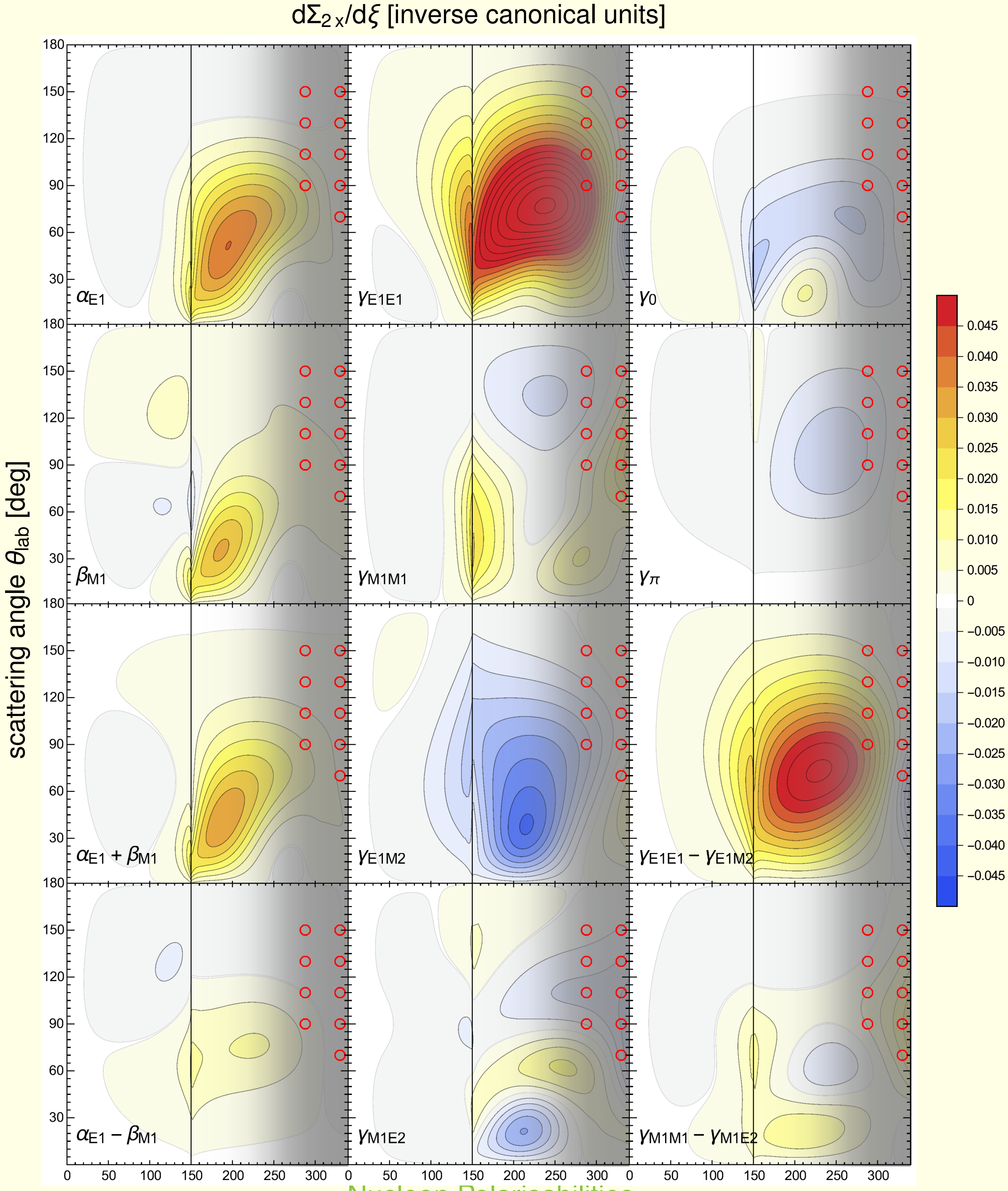
More data taking planned

Experiments also planned at HIγS @TUNL
low energy–up to about 80 MeV currently, 120 MeV after upgrades?.

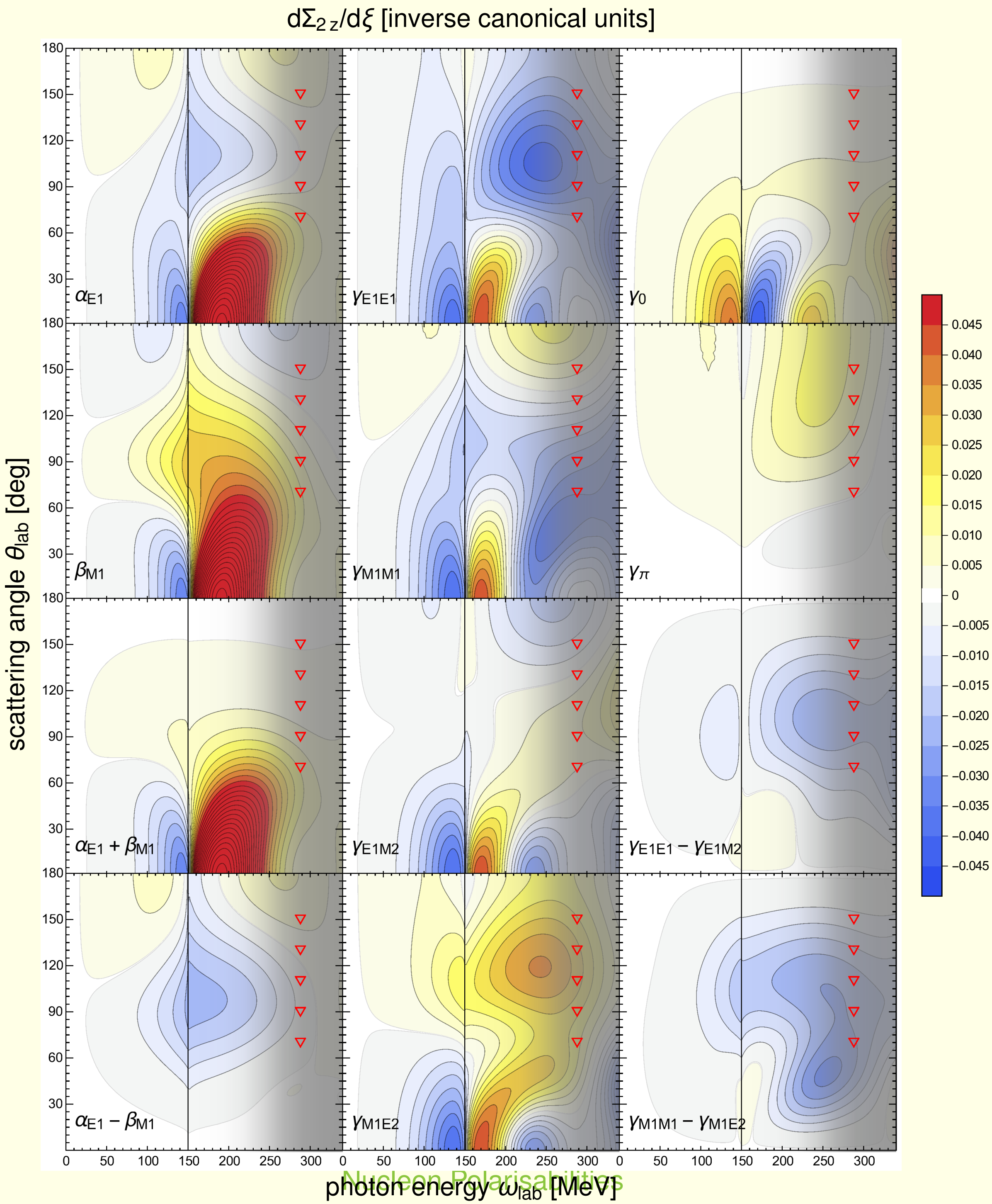
Sensitivity studies: Σ_3



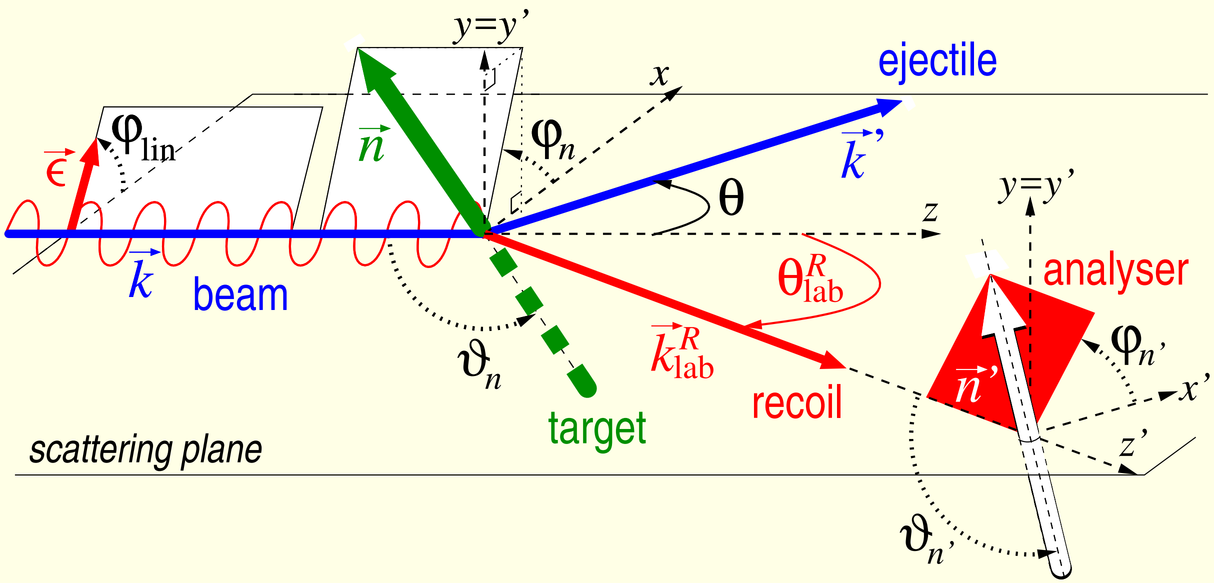
Sensitivity studies: Σ_{2x}



Sensitivity studies: Σ_{2z}



Other asymmetries and polarisability transfer observables



$$\Sigma_{2x}$$

Numerical index: polarisation of light

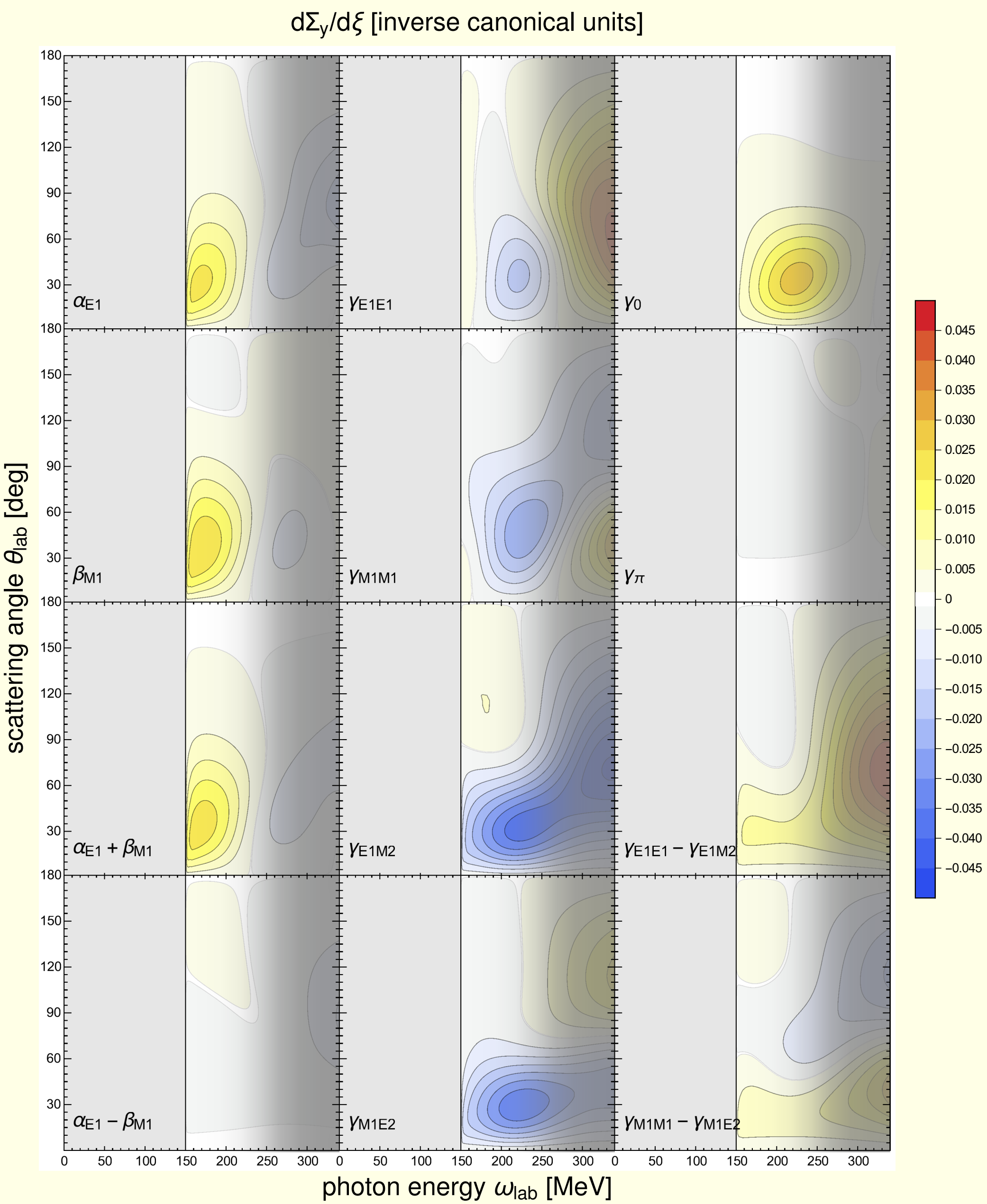
- 3: linear, 0 or π
- 1: linear, $\pm\frac{\pi}{2}$
- 2: right/left circular

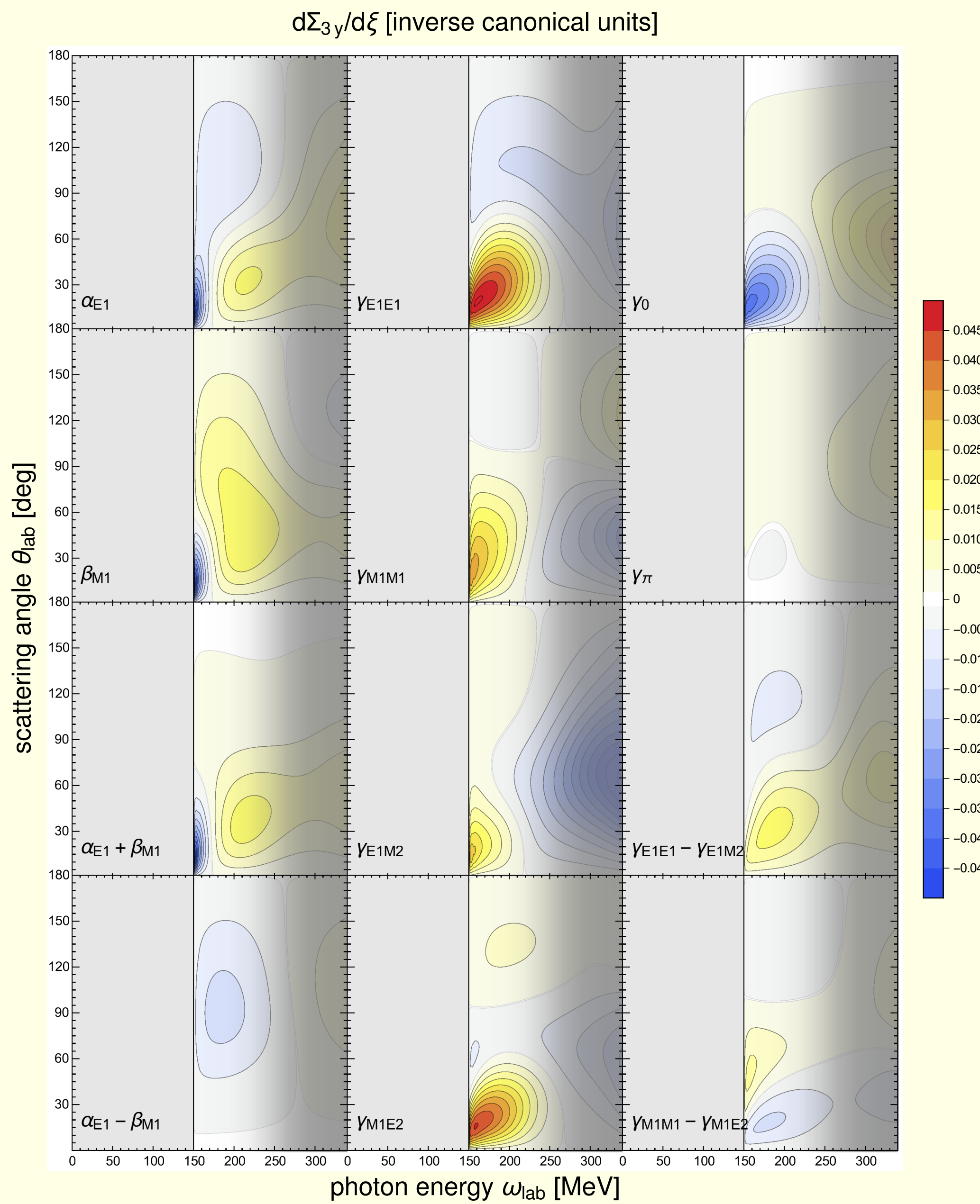
Cartesian index: polarisation of nucleon

- z: along beam
- y: $\perp$ to reaction plane
- x: in reaction plane, $\perp$ to z

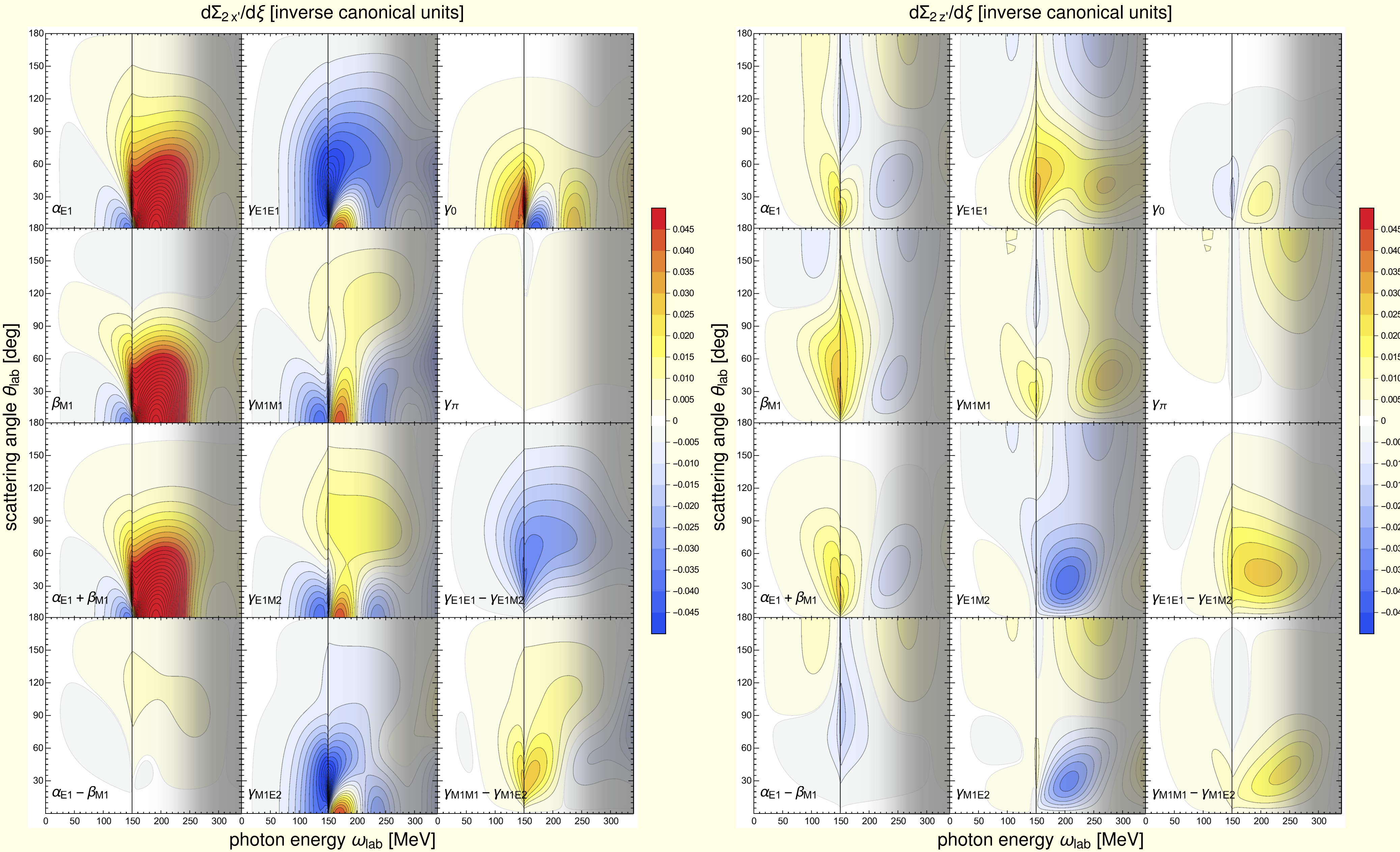
Prime on either indicates scattered photon or nucleon: polarisation transfer.
polarised scattered nucleon might be detectable.

Sensitivity studies: Σ_y and Σ_{3y}



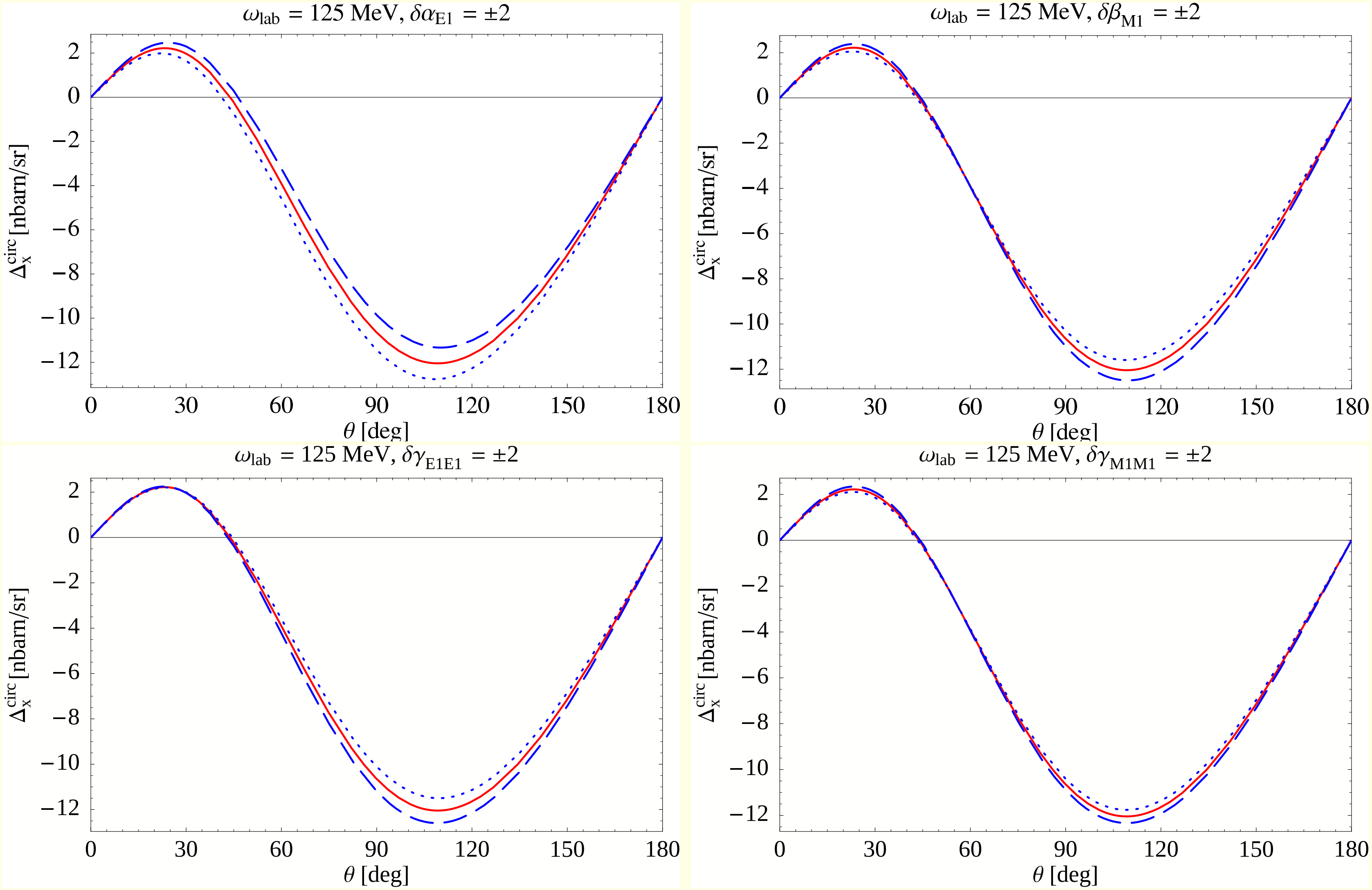


Sensitivity studies: $\Sigma_{2x'}$ and $\Sigma_{2z'}$



Polarised scattering from deuterium

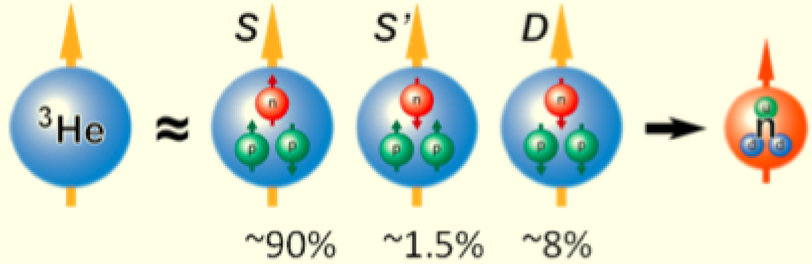
$$\Delta_x^{\mathrm{circ}} = \frac{d\sigma}{d\Omega}_{\uparrow\rightarrow} - \frac{d\sigma}{d\Omega}_{\uparrow\leftarrow}$$



Δ included, 3rd order.

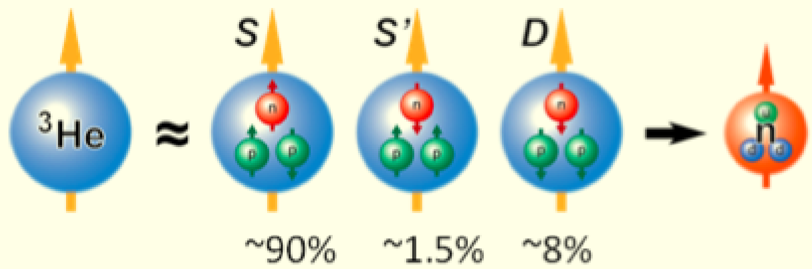
source: Griesshammer and Shukla Eur. Phys. J. A46:249, 2010

Polarised scattering from ^{3}He and neutron polarisabilities



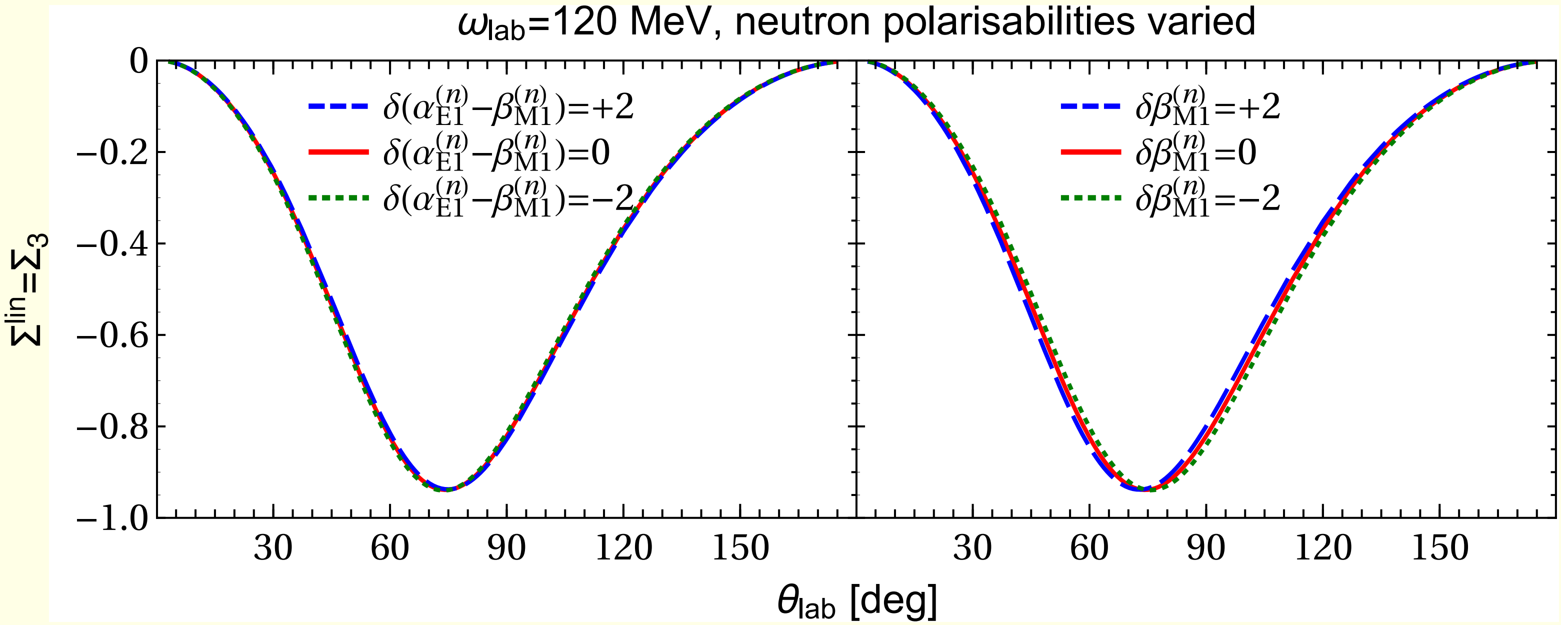
The spin of ^{3}He is largely carried by the neutro-n enhanced sensitivity in some polarised observables to neutron polarisabilities

Polarised scattering from ^{3}He and neutron polarisabilities



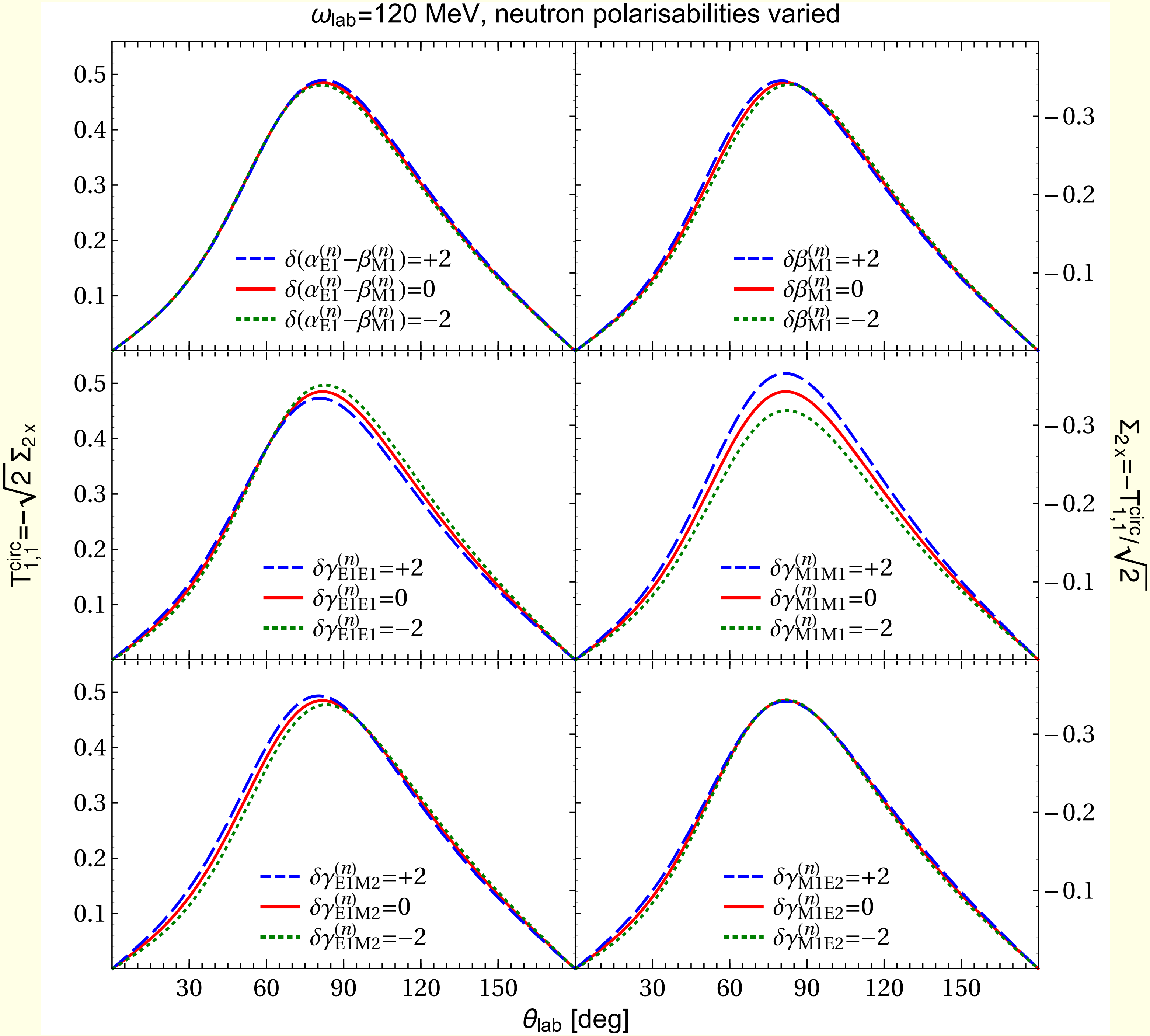
The spin of ^{3}He is largely carried by the neutro-n enhanced sensitivity in some polarised observables to neutron polarisabilities

Σ_3



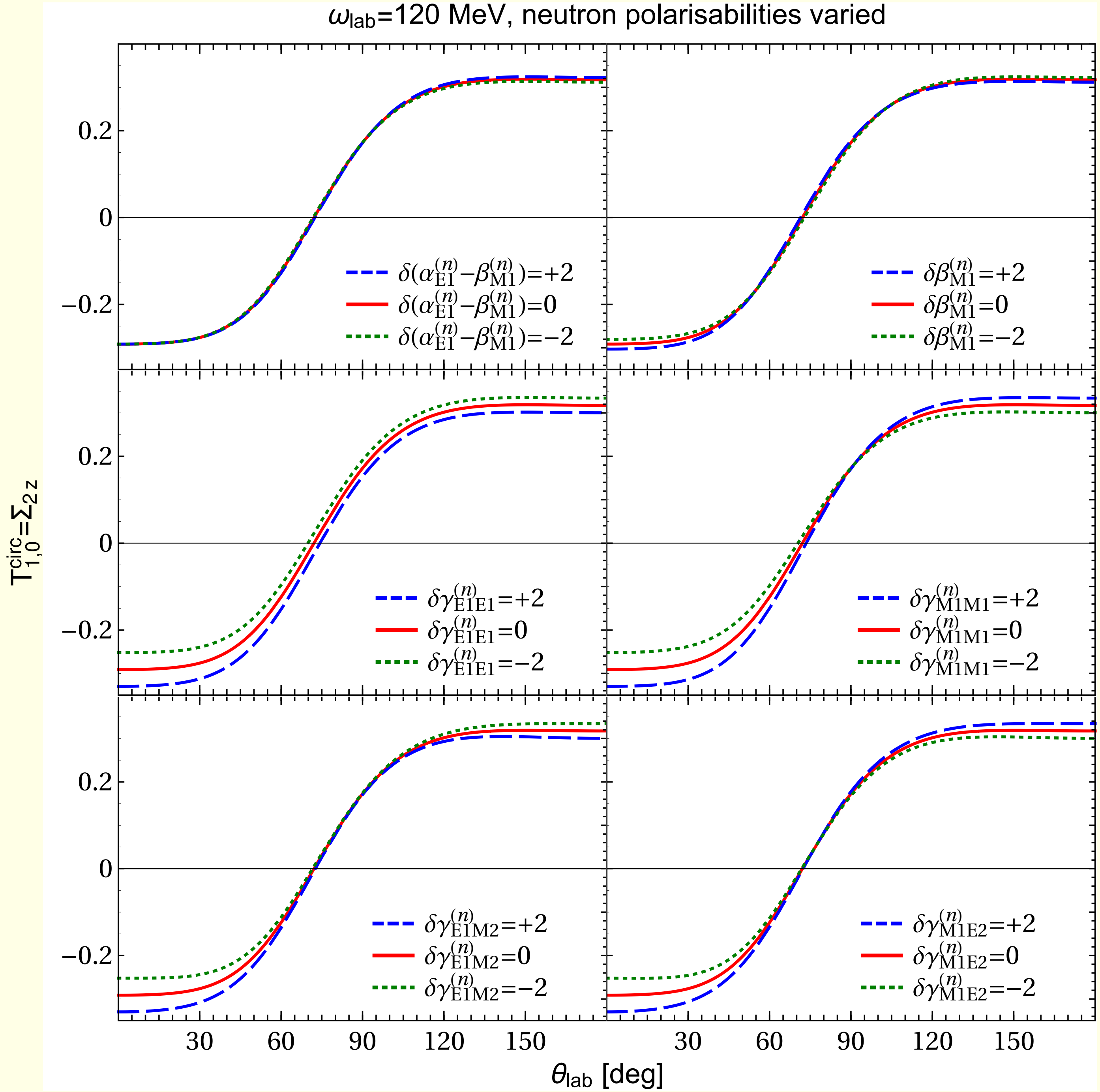
Polarised scattering from ^{3}He and neutron polarisabilities

Σ_{2x}



Polarised scattering from ^{3}He and neutron polarisabilities

Σ_{2z}



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Should soon know much more about the polarisabilities of the proton and neutron

Backup slides

Details of fit

Resonance region—very sensitive to magnetic γNΔ coupling ($\sim g_M^4$). We iteratively fit g_M; value 10% lower than fit to photo production.

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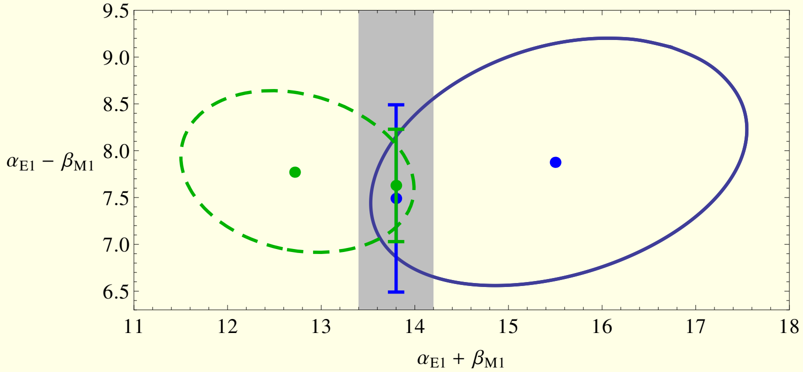
We cannot get an acceptable fit with the predicted value of $\gamma_{M1M1} = 6.4$ (large contributions both from Δ and $O(Q^4)$ πN loops).

We FIT it to give $\gamma_{M1M1} = 2.2 \pm 0.5(\text{stat})$. Final fit good: χ^2=113.2 for 135 d.o.f.

4th-order statistical errors on $\alpha - \beta$ are larger than 3rd order.



Deduce theory error from convergence:

LO ($O(e^2\delta)$, BKM) $\alpha - \beta = 11.25$

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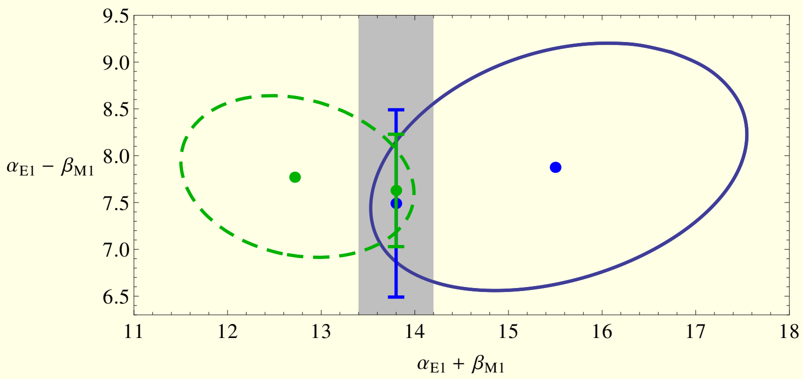

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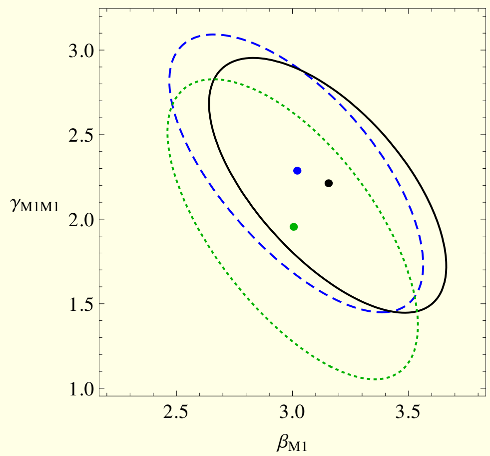

Also check sensitivity to data: need to be somewhat selective of old data sets to get a good χ^2, can't fit Hallin data above 150MeV.