Compton scattering from Protons and Light Nuclei: pinning down the nucleon polarizabilities

Judith McGovern

University of Manchester

Work done in collaboration with Harald Grießhammer, Daniel Phillips, Jerry Feldman

Prog. Nucl. Part. Phys. **67** 841 (2012)

Eur. Phys. J. A **49** 12(2013)

(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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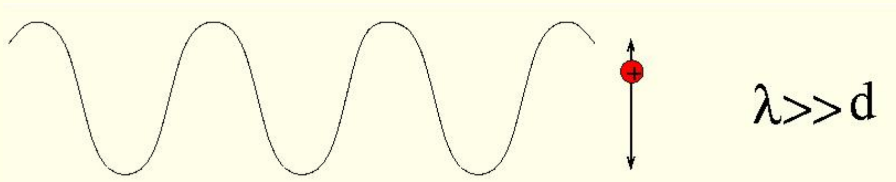
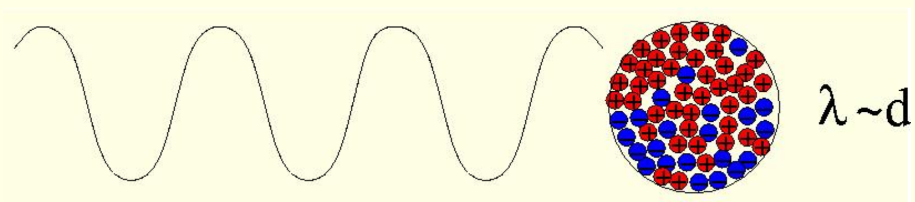
Compton Scattering

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



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

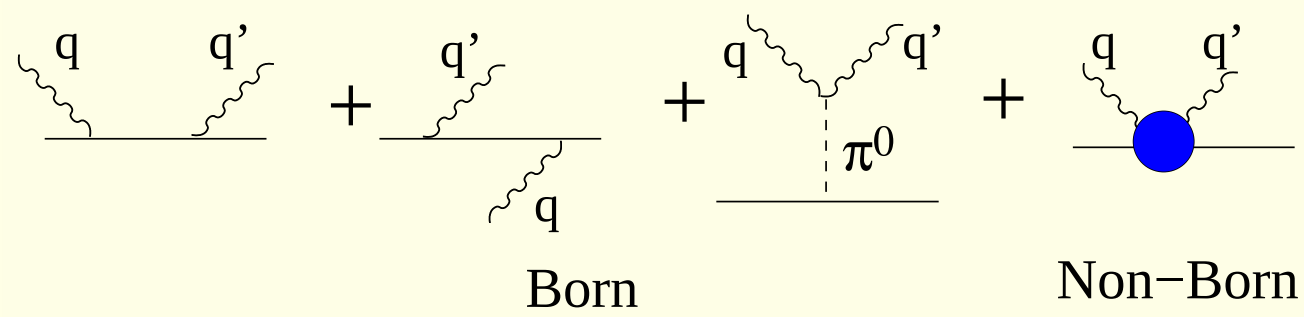


To leading order

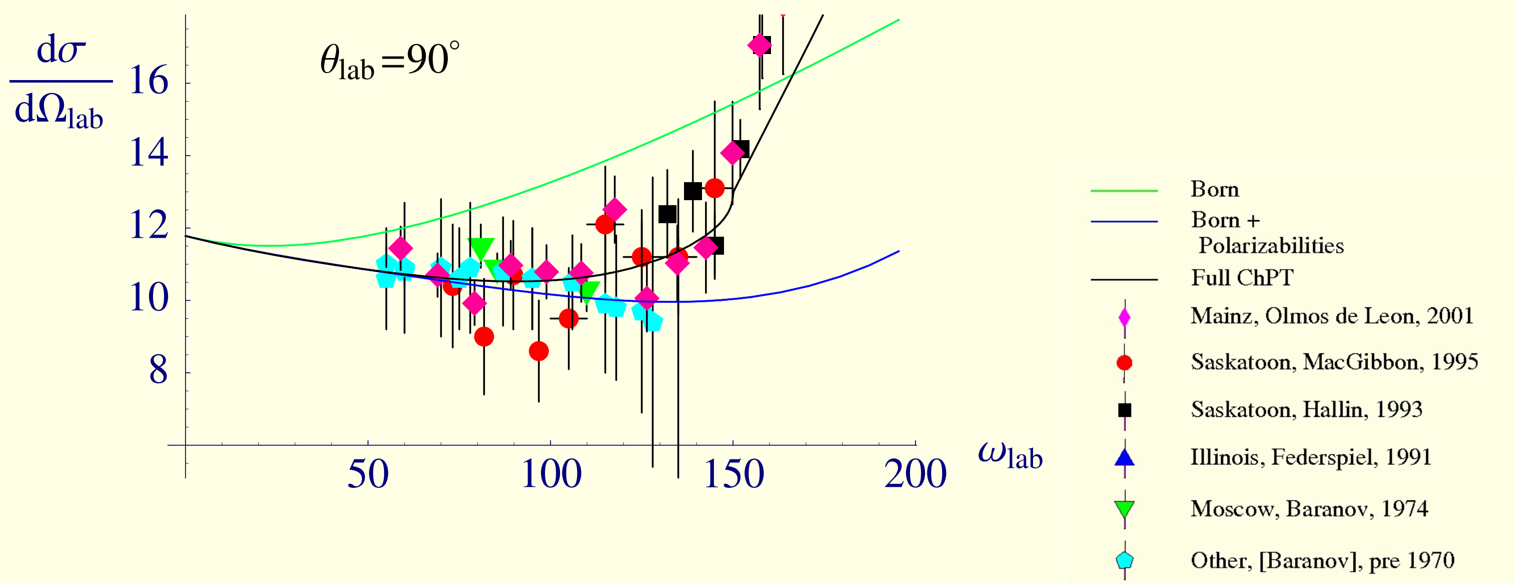
$$\begin{aligned} H_{eff} &= \frac{(\mathbf{p}-Q\mathbf{A})^2}{2m} + Q\phi - \frac{1}{2}4\pi\Big(\alpha\vec{E}^2 + \beta\vec{H}^2 \\ &+ \gamma_{E1}\vec{\sigma}\cdot\vec{E}\times\dot{\vec{E}} + \gamma_{M1}\vec{\sigma}\cdot\vec{H}\times\dot{\vec{H}} - 2\gamma_{E2}E_{ij}\sigma_i H_j + 2\gamma_{M2}H_{ij}\sigma_i E_j\Big) \end{aligned}$$

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

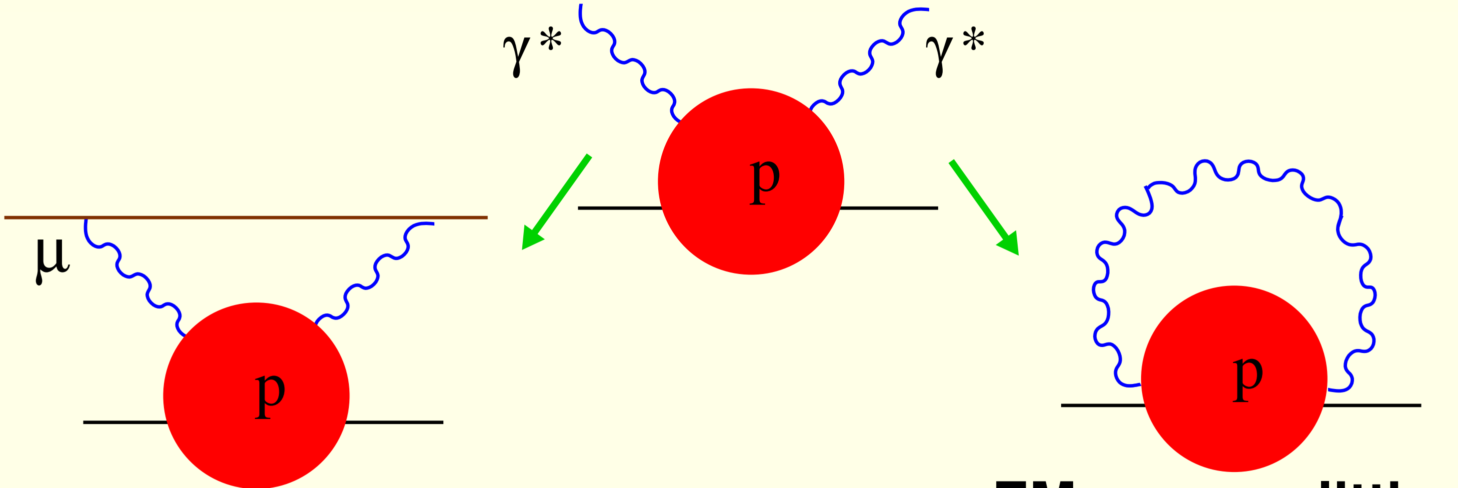
Compton Scattering from the nucleon



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.

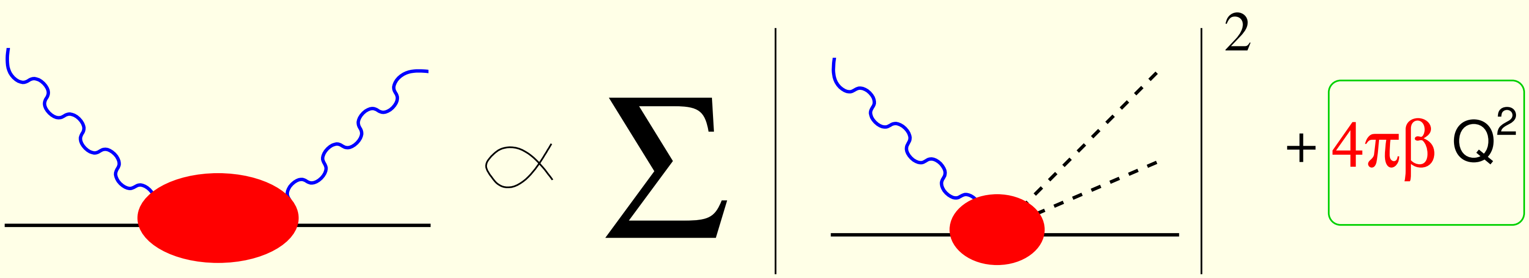


Why β matters



Muonic H

EM mass splitting



Subtracted DR

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

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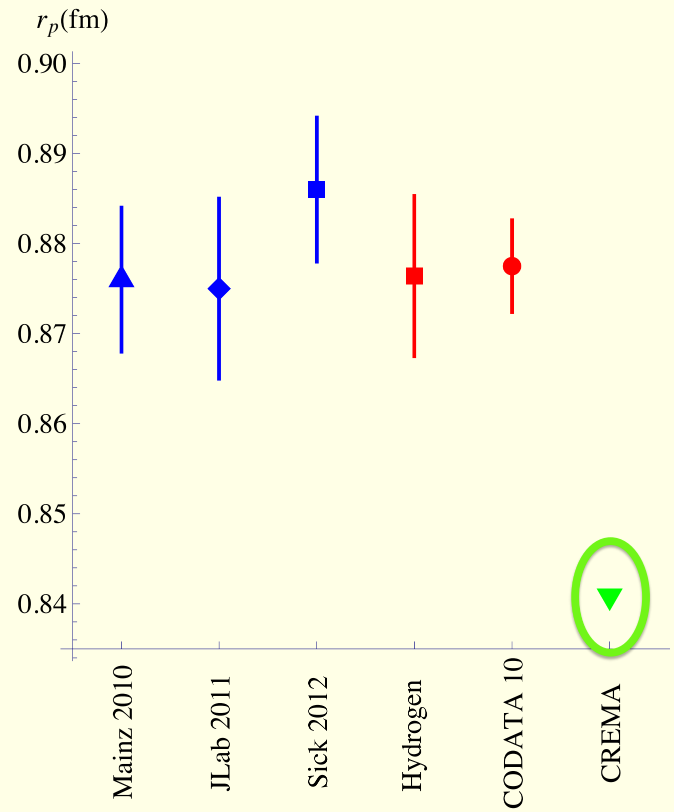
Proton radius puzzle



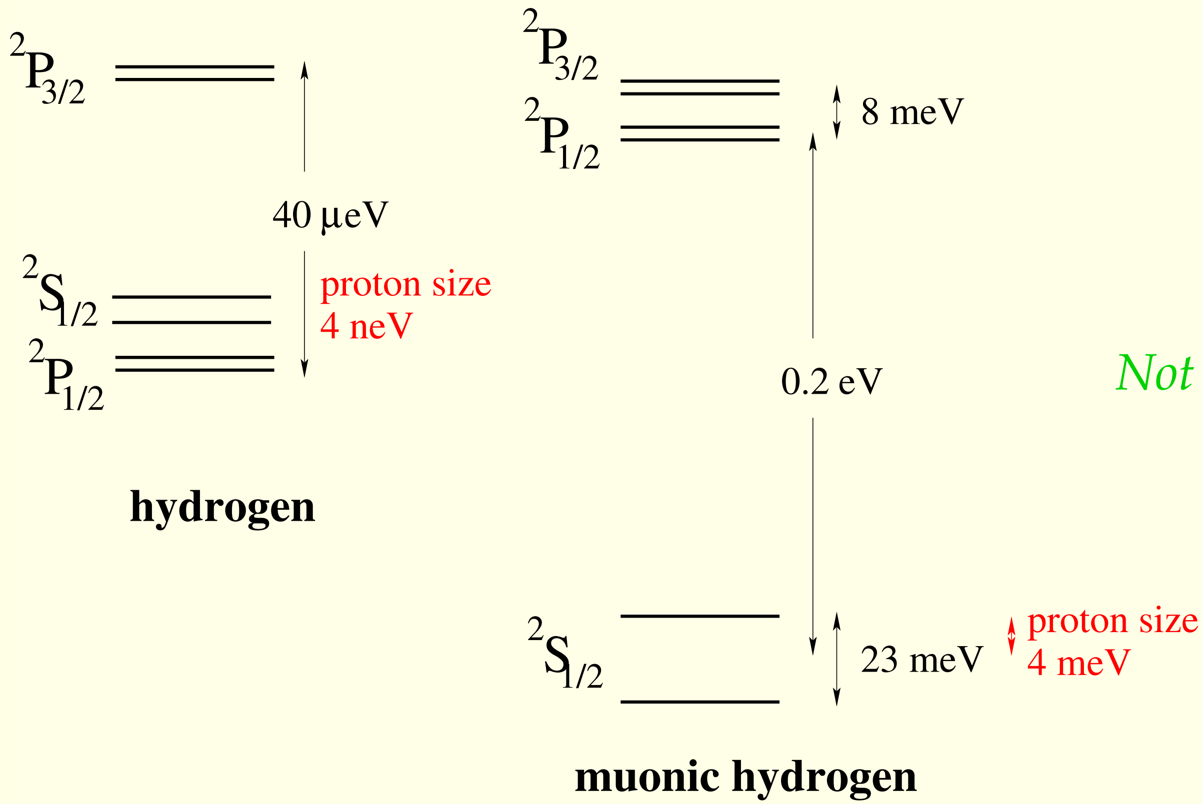
Hydrogen etc: $r_p = 0.8775(51)$ fm, CODATA 2010

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

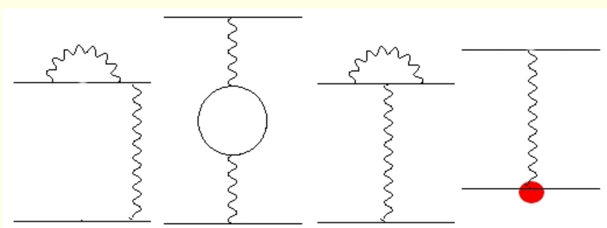
Pohl et al, Nature **466**, 213 (2010)Antognini et al, Science **339** 417

7σ deviation!

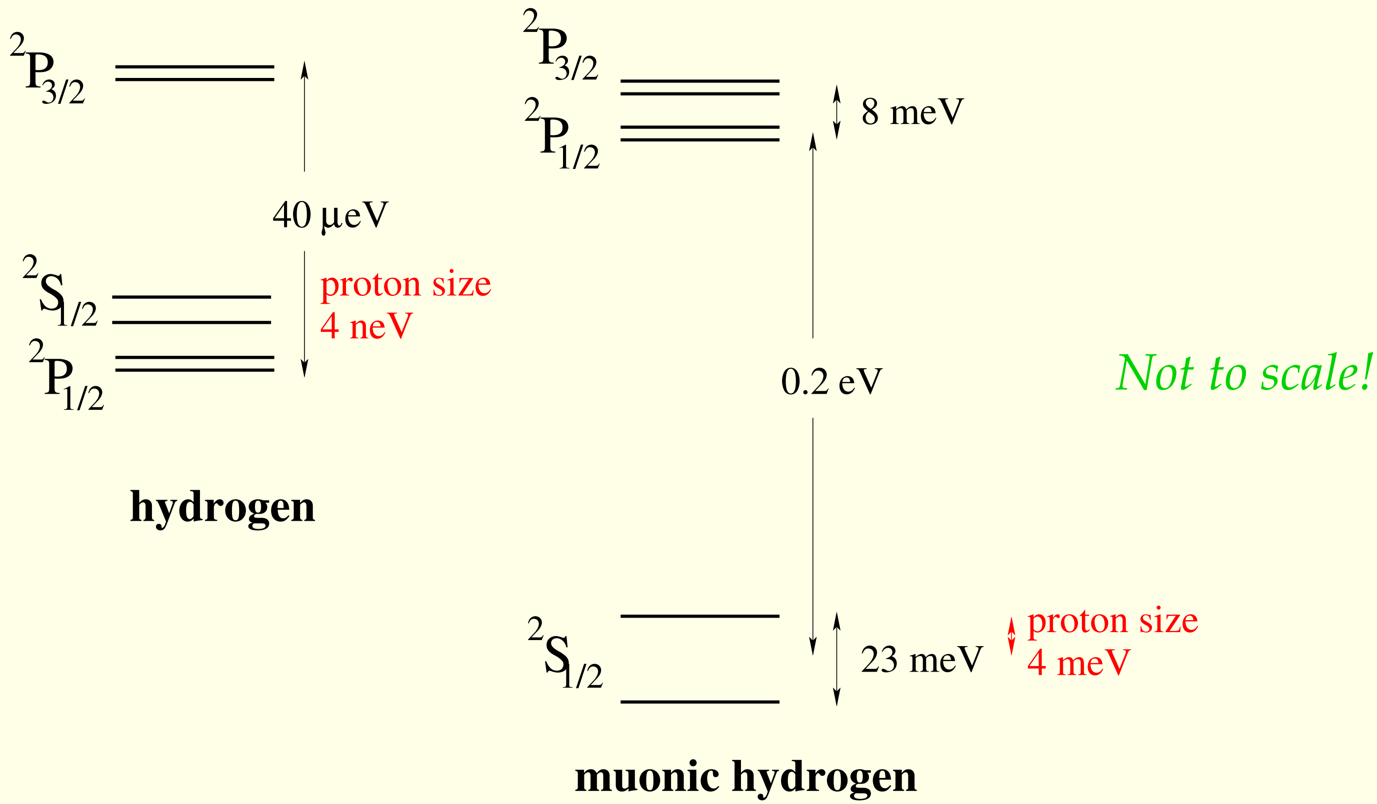
Lamb shift



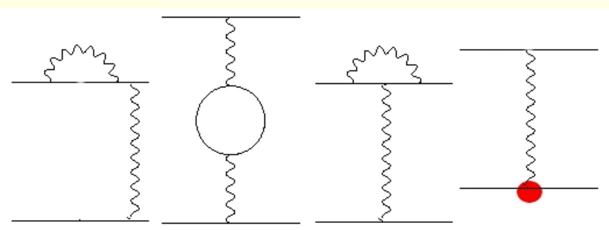
Not to scale!

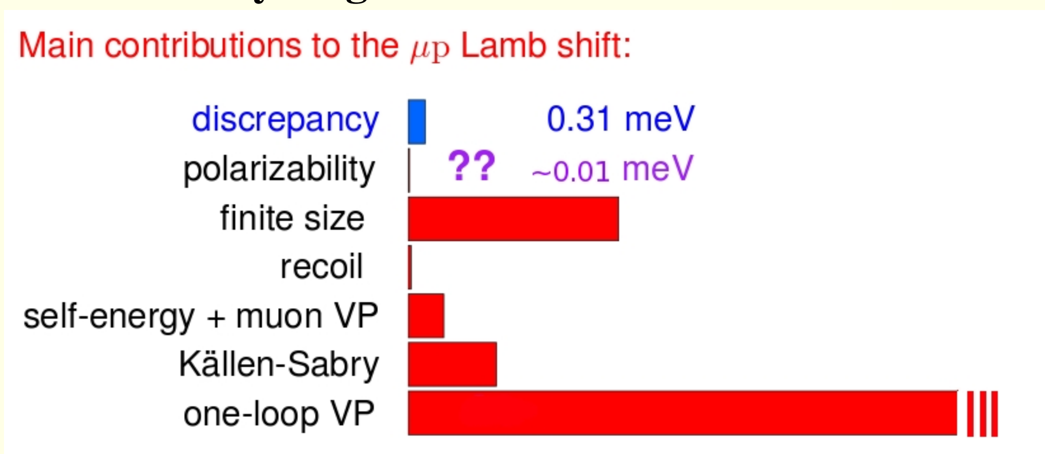


Lamb shift



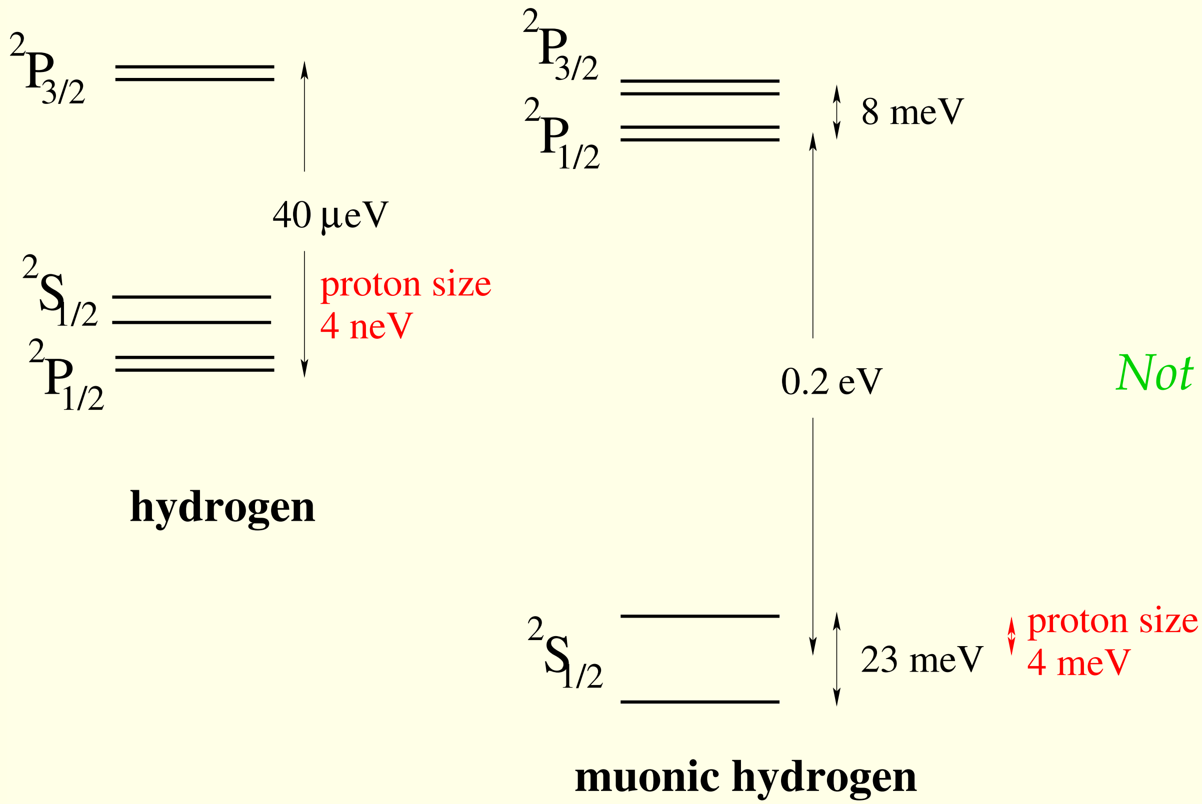
$^2P_{3/2}$
40 μeV
$^2S_{1/2}$
$^2P_{1/2}$
proton size
4 neV
hydrogen
$^2P_{3/2}$
$^2P_{1/2}$
8 meV
0.2 eV
$^2S_{1/2}$
23 meV
proton size
4 meV
muonic hydrogen
Not to scale!



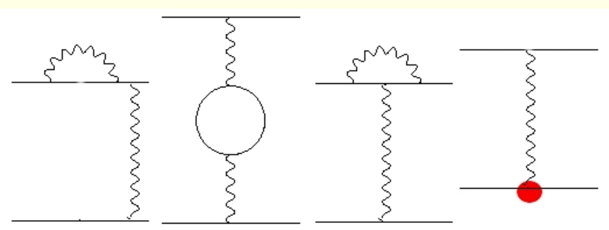


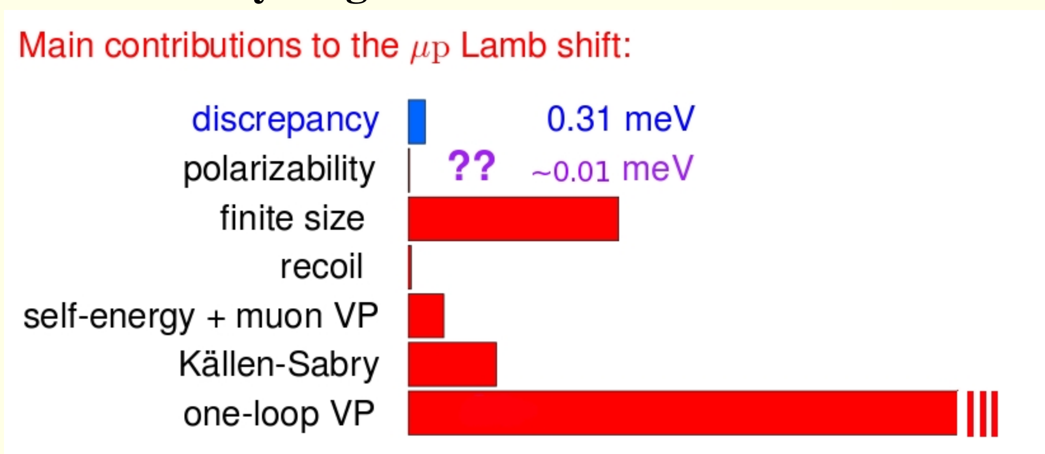
Main contributions to the μp Lamb shift:
discrepancy
0.31 meV
polarizability
??
~0.01 meV
finite size
recoil
self-energy + muon VP
Källen-Sabry
one-loop VP

Lamb shift



Not to scale!



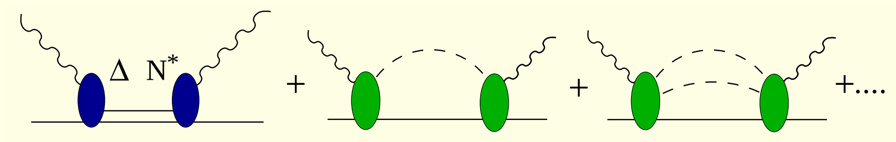


$\beta = 3.1 \pm 0.5 \implies$

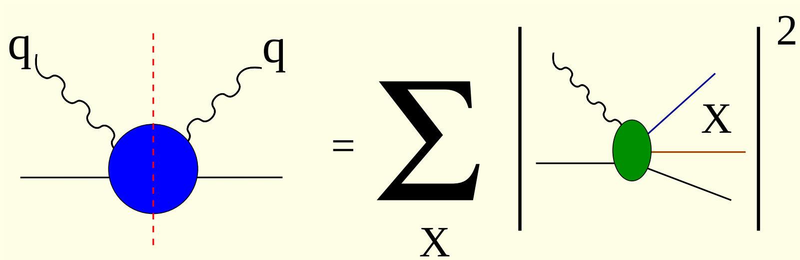
$\Delta E_{\text{pol}} = -0.0085(11)\text{meV}$

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

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



Optical theorem leads to sum rules for forward scattering



Baldin SR: $\alpha+\beta = \frac{1}{2\pi^2}\int_{\omega_{th}}^{\infty}\frac{\sigma_{tot}(\omega)}{\omega^2}d\omega$ and $\gamma_0 = \frac{1}{4\pi^2}\int_{\omega_{th}}^{\infty}\frac{\sigma_{1/2}(\omega)-\sigma_{3/2}(\omega)}{\omega^3}d\omega$

Both quite accurately evaluated for the proton:
$\alpha^{(p)}+\beta^{(p)} = (13.8\pm 0.4)\times 10^{-4}$ fm^3 Olmos de Léon *et al.* EPJA **10** 207 (2001);
$\gamma_0 = (-0.90\pm 0.08(\text{stat})\pm 0.11(\text{sys}))\times 10^{-4}$ fm^4 as byproduct of GDH expt. at MAMI and ELSA. Pasquini *et al.* Phys. Lett. B **687** 160 (2010)

Non-forward scattering

For the full non-Born contribution (6 independent amplitudes) need different approach.

Two common methods: Dispersion relations and Chiral Perturbation Theory

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

DR uses partial wave analysis of $\gamma N \to \pi N$ data as input

Chiral Perturbation Theory is a field theory which treats pions and nucleons as basic degrees of freedom

Both have difficulties with parameter-free predictions; both can be used to fit Compton scattering data and extract polarisabiltiies.

Anatomy of Compton amplitude

$$
\begin{aligned}
T(\omega,z) \;=\; & A_1(\omega,z)\,(\vec{\varepsilon}\,'^{*}\cdot\vec{\varepsilon}) + A_2(\omega,z)\,(\vec{\varepsilon}\,'^{*}\cdot\hat{\vec{k}})\,(\vec{\varepsilon}\cdot\hat{\vec{k}}') \\
& + \mathrm{i}A_3(\omega,z)\,\vec{\sigma}\cdot\left(\vec{\varepsilon}\,'^{*}\times\vec{\varepsilon}\right) + \mathrm{i}A_4(\omega,z)\,\vec{\sigma}\cdot\left(\hat{\vec{k}}'\times\hat{\vec{k}}\right)(\vec{\varepsilon}\,'^{*}\cdot\vec{\varepsilon}) \\
& + \mathrm{i}A_5(\omega,z)\,\vec{\sigma}\cdot\left[\left(\vec{\varepsilon}\,'^{*}\times\hat{\vec{k}}\right)(\vec{\varepsilon}\cdot\hat{\vec{k}}') - \left(\vec{\varepsilon}\times\hat{\vec{k}}'\right)(\vec{\varepsilon}\,'^{*}\cdot\hat{\vec{k}})\right] \\
& + \mathrm{i}A_6(\omega,z)\,\vec{\sigma}\cdot\left[\left(\vec{\varepsilon}\,'^{*}\times\hat{\vec{k}}'\right)(\vec{\varepsilon}\cdot\hat{\vec{k}}') - \left(\vec{\varepsilon}\times\hat{\vec{k}}\right)(\vec{\varepsilon}\,'^{*}\cdot\hat{\vec{k}})\right] .
\end{aligned}
$$

ω - photon energy, $z = \cos\theta$; Breit or cm frame

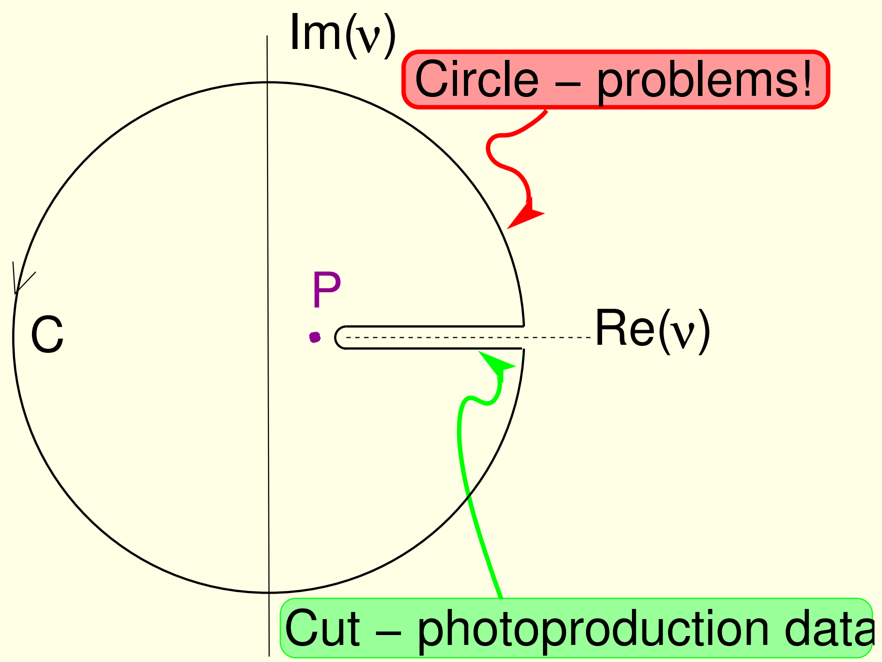
Non-Born pieces:

$$
\begin{aligned}
\bar{A}_1(\omega,z) &= 4\pi\,[\alpha_{E1} + z\beta_{M1}]\,\omega^2 + \ldots \\
\bar{A}_2(\omega,z) &= -4\pi\,\beta_{M1}\,\omega^2 + \ldots \\
\bar{A}_3(\omega,z) &= -4\pi\,[\gamma_{E1E1} + z\gamma_{M1M1} + \gamma_{E1M2} + z\gamma_{M1E2}]\,\omega^3 + \ldots \\
\bar{A}_4(\omega,z) &= 4\pi\,[-\gamma_{M1M1} + \gamma_{M1E2}]\,\omega^3 + \ldots \\
\bar{A}_5(\omega,z) &= 4\pi\,\gamma_{M1M1}\,\omega^3 + \ldots \\
\bar{A}_6(\omega,z) &= 4\pi\,\gamma_{E1M2}\,\omega^3 + \ldots
\end{aligned}
$$

$$
\begin{aligned}
\gamma_0 &= -\gamma_{E1E1} - \gamma_{M1M1} - \gamma_{E1M2} - \gamma_{M1E2} \\
\gamma_\pi &= -\gamma_{E1E1} + \gamma_{M1M1} - \gamma_{E1M2} + \gamma_{M1E2}.
\end{aligned}
$$

DR in a nutshell

Cauchy's theorem



$$\mathrm{Re}\, A_i(\nu,t) = A_i^{\mathrm{Born}}(\nu,t) + \frac{2}{\pi} P \int_{\nu_0}^{\infty} \mathrm{d}\nu' \nu' \frac{\mathrm{Im} A_i(\nu',t)}{\nu'^2 - \nu^2},$$

PROVIDED the closure at infinity vanishes.

When it doesn't: subtract, find $A_i(0,t)$ by extrapolating from $\gamma\gamma \to \bar{p}p$

"fixed-t subtracted" Drechsel *et al.* Phys. Rep. **378** 99

or keep circle finite and model its contribution - σ meson?

"fixed-t unsubtracted" Schumacher Prog. Part. Nucl. Phys. 55 567 (2005)

Effective field theories

Fundamental principle: details of high energy interactions do not affect low energy phenomena: QCD is irrelevant to chemistry, strings are irrelevant to LHC.

Use effective field theories instead of theories of everything. Particles which don't appear asymptotically are integrated out to leave only the appropriate degrees of freedom for the problem in hand.

Resulting theory not renormalisable — the Lagrangian contains infinitely many terms. BUT predictions can be written as a power series in the ratio of the energy to the scale of the physics which has been integrated out. Thus a successful effective theory requires a separation of scales.

Fermi theory was the first term in an effective theory of weak interaction; the standard model is presumably the effective theory of strings!

For low energy QCD the degrees of freedom are photons, pions and nucleons, and the effective theory is chiral perturbation theory.

Chiral Perturbation theory

Effective field theory of QCD– relies on separation of scales

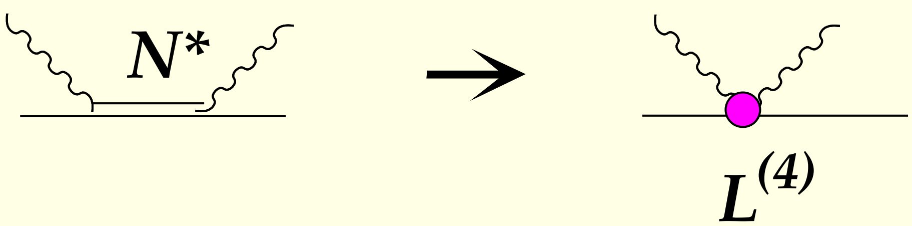
- pions are light ($m_\pi \ll m_\rho$)
- low-energy pions interact weakly with other matter ($L_{\pi NN} \propto \overline{N}\partial_\mu \pi N$).

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: $(k/\Lambda)^n$:



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

χPT for Compton Scattering from the nucleon

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

$$\mathcal{L}_{\pi N}^{(4),\mathrm{CT}} = 2\pi e^2 H^\dagger \left[\left(\delta\beta_{M1}^{(s)} + \delta\beta_{M1}^{(v)}\tau_3\right) \left(\tfrac{1}{2} g_{\mu\nu} - v_\mu v_\nu\right) - \left(\delta\alpha_{E1}^{(s)} + \delta\alpha_{E1}^{(v)}\tau_3\right) v_\mu v_\nu \right] F^{\mu\rho} F^{\nu}_{\ \rho} H.$$

Counterterms shift α_{E1} and β_{M1} at 4th order

$$\mathcal{L}_{\gamma N\Delta}^{\mathrm{PP},(2)} = \frac{3e}{2M_N(M_N+M_\Delta)} \left[\bar{\psi}(ig_M \tilde{F}^{\mu\nu} - g_E \gamma_5 F^{\mu\nu}) \partial_\mu \Psi^3_\nu - \bar{\Psi}^3_\nu \overleftarrow{\partial}_\mu (ig_M \tilde{F}^{\mu\nu} - g_E \gamma_5 F^{\mu\nu}) \psi \right],$$

$\Delta \equiv M_\Delta - M_N \approx 271$ 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 $\dfrac{m_\pi}{\Delta} \sim \dfrac{\Delta}{\Lambda_\chi} \quad \Rightarrow \quad \delta^2 \equiv \left(\dfrac{\Delta}{\Lambda_\chi}\right)^2 \sim \dfrac{m_\pi}{\Lambda_\chi}$

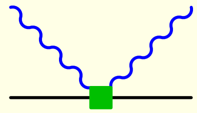
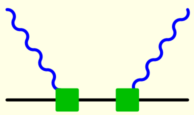
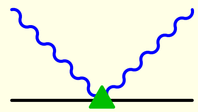
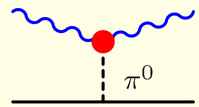
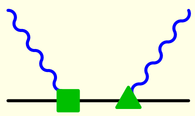
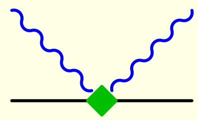
Then graphs with one Δ propagator are one order of δ higher than the corresponding nucleon graphs in low energy region.

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

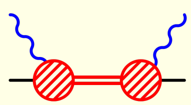
Pascalutsa and Phillips, Phys. Rev. C67 (2003) 055202

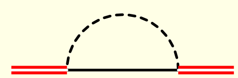
Tree graphs

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

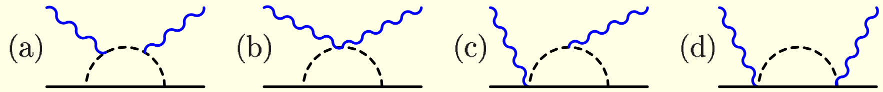
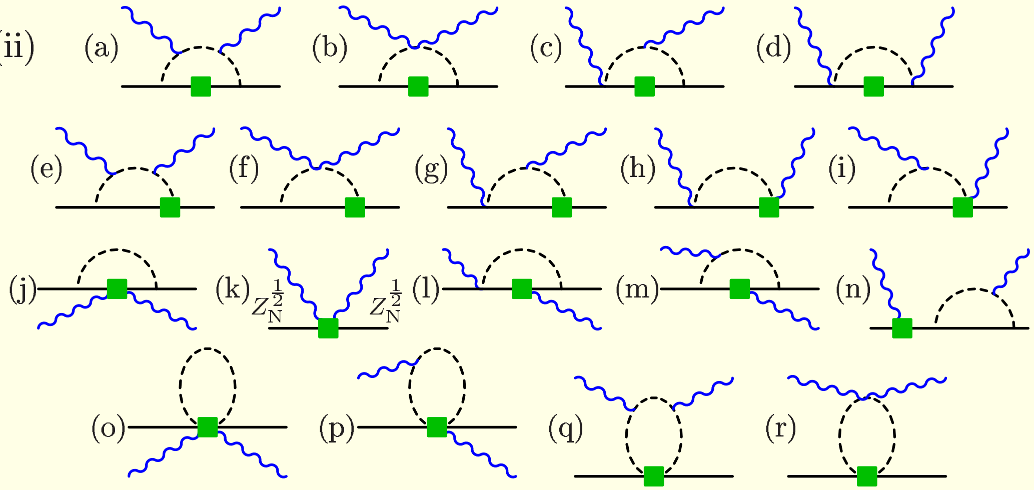
	contribution with typical size	$\omega \sim m_\pi$	$\omega \sim \Delta$
(i)		$e^2\delta^0$ (LO)	$e^2\delta^0$
(ii)	(a)  (b)  (c) 	$e^2\delta^2$	$e^2\delta^1$
(iii)	(a)  (b) 	$e^2\delta^4$	$e^2\delta^2$

In resonance region Delta-pole graph dominates

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

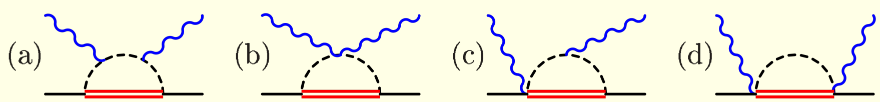
Include Delta width by resuming self-energy: 

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

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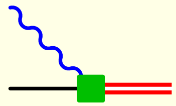
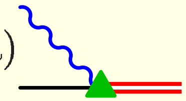
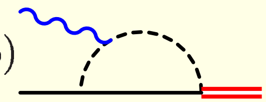
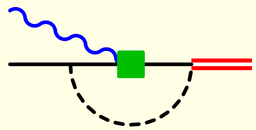
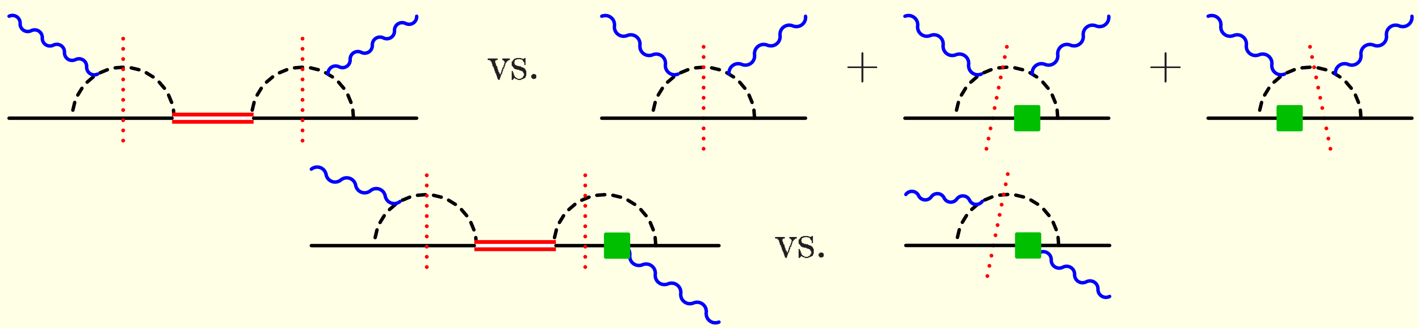
Running of γNΔ vertex

contribution with typical size			$\omega \sim m_\pi$	$\omega \sim \Delta$
(i)			$e\delta^2$	$e\delta^1$
(ii)	(a) 	(b) 	$e\delta^4$	$e\delta^2$
(iii)			$e\delta^6$	$e\delta^3$

The inclusion of the imaginary part of running vertices satisfies Watson's theorem - cancellation of $I = 3/2$ loops at resonance

(i)

(ii)



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Anatomy of Compton amplitude—reminder

$$\begin{aligned} T(\omega,z) \;=\; & A_1(\omega,z)\,(\vec{\varepsilon}'^* \cdot \vec{\varepsilon}) + A_2(\omega,z)\,(\vec{\varepsilon}'^* \cdot \hat{\vec{k}})\,(\vec{\varepsilon} \cdot \hat{\vec{k}}') \\ & + \mathrm{i}A_3(\omega,z)\,\vec{\sigma} \cdot (\vec{\varepsilon}'^* \times \vec{\varepsilon}) + \mathrm{i}A_4(\omega,z)\,\vec{\sigma} \cdot \left(\hat{\vec{k}}' \times \hat{\vec{k}}\right)(\vec{\varepsilon}'^* \cdot \vec{\varepsilon}) \\ & + \mathrm{i}A_5(\omega,z)\,\vec{\sigma} \cdot \left[\left(\vec{\varepsilon}'^* \times \hat{\vec{k}}\right)(\vec{\varepsilon} \cdot \hat{\vec{k}}') - \left(\vec{\varepsilon} \times \hat{\vec{k}}'\right)(\vec{\varepsilon}'^* \cdot \hat{\vec{k}})\right] \\ & + \mathrm{i}A_6(\omega,z)\,\vec{\sigma} \cdot \left[\left(\vec{\varepsilon}'^* \times \hat{\vec{k}}'\right)(\vec{\varepsilon} \cdot \hat{\vec{k}}') - \left(\vec{\varepsilon} \times \hat{\vec{k}}\right)(\vec{\varepsilon}'^* \cdot \hat{\vec{k}})\right] \;. \end{aligned}$$

ω - photon energy, $z = \cos\theta$; Breit or cm frame

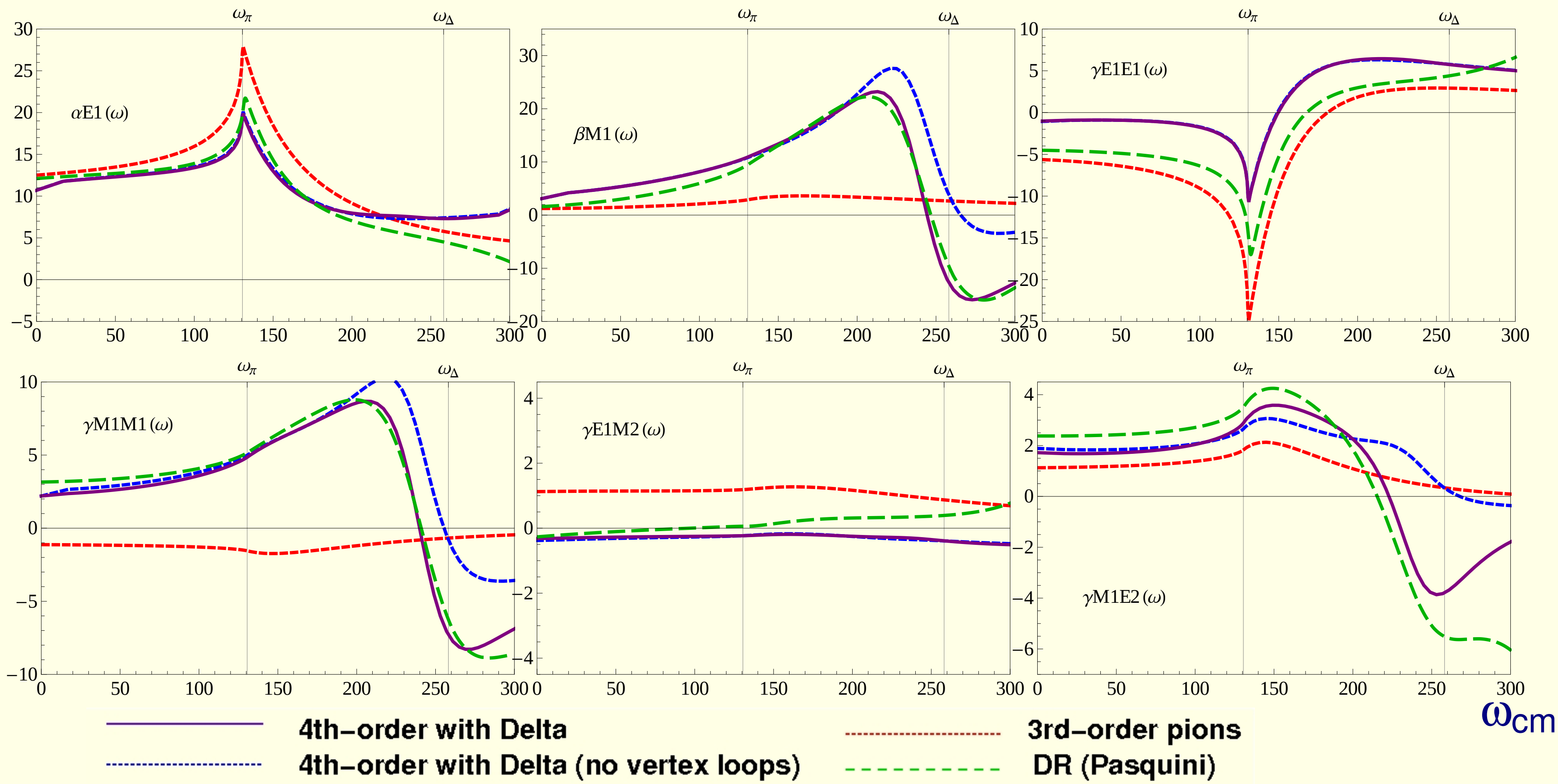
Non-Born pieces:

$$\begin{aligned} \bar{A}_1(\omega,\, z) &= 4\pi\,[\alpha_{E1} + z\beta_{M1}]\,\omega^2 + \ldots \\ \bar{A}_2(\omega,\, z) &= -4\pi\,\beta_{M1}\,\omega^2 + \ldots \\ \bar{A}_3(\omega,\, z) &= -4\pi\,[\gamma_{E1E1} + z\gamma_{M1M1} + \gamma_{E1M2} + z\gamma_{M1E2}]\,\omega^3 + \ldots \\ \bar{A}_4(\omega,\, z) &= 4\pi\,[-\gamma_{M1M1} + \gamma_{M1E2}]\,\omega^3 + \ldots \\ \bar{A}_5(\omega,\, z) &= 4\pi\,\gamma_{M1M1}\,\omega^3 + \ldots \\ \bar{A}_6(\omega,\, z) &= 4\pi\,\gamma_{E1M2}\,\omega^3 + \ldots \end{aligned}$$

If we write $\alpha_{E1} \to \alpha_{E1}(\omega)$ etc we have $l = 1$ in a multipole expansion

Multipoles

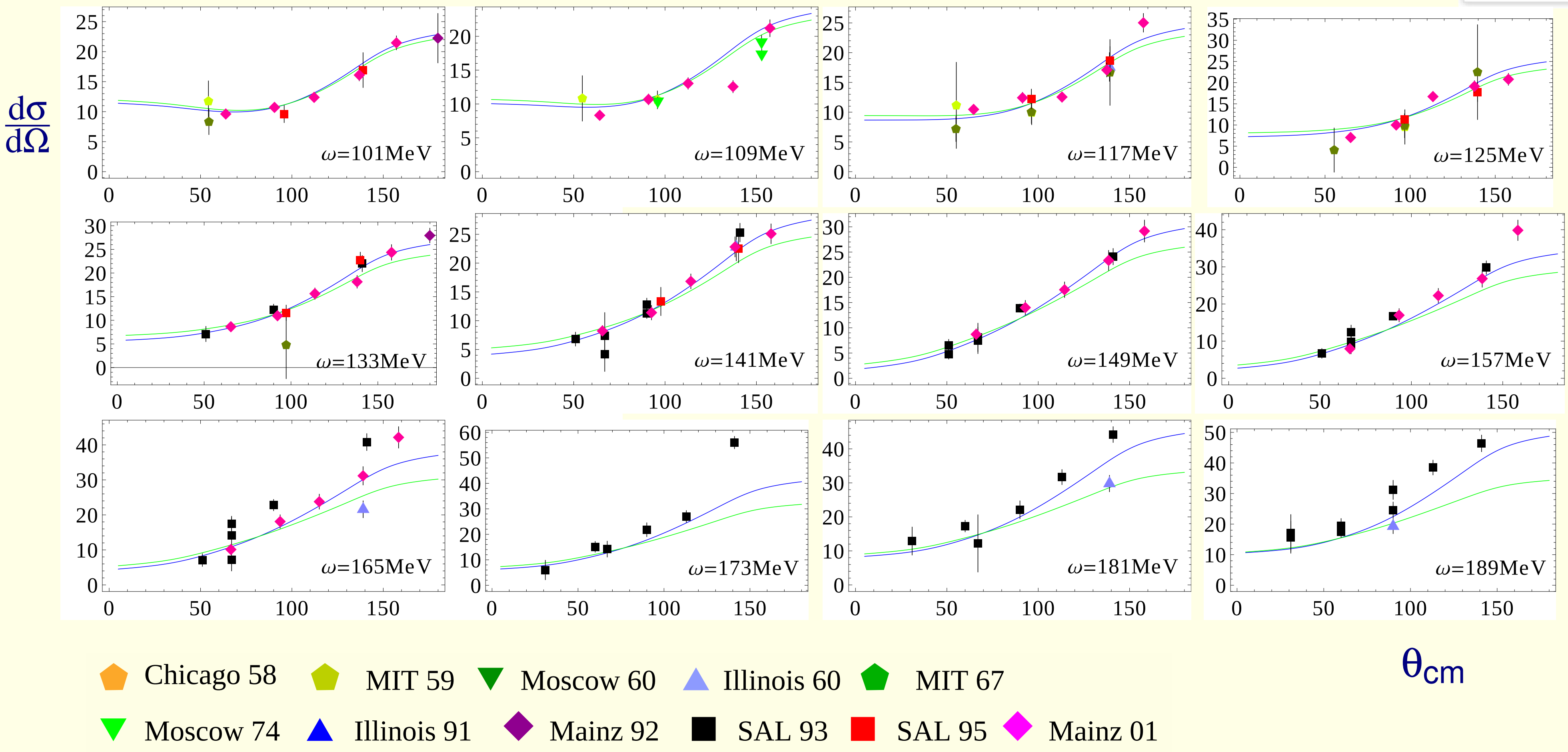
Different predictions do not fully agree on the physical origins of the polarisabilities. But Chiral and DR predictions agree very well for the shape of the energy dependence of corresponding multipoles (angle-integrated amplitude)



DR: Hildebrandt *et al.* , Eur. Phys. J. A **20** 293 (2004) Chiral: JMcG *et al.* , in preparation

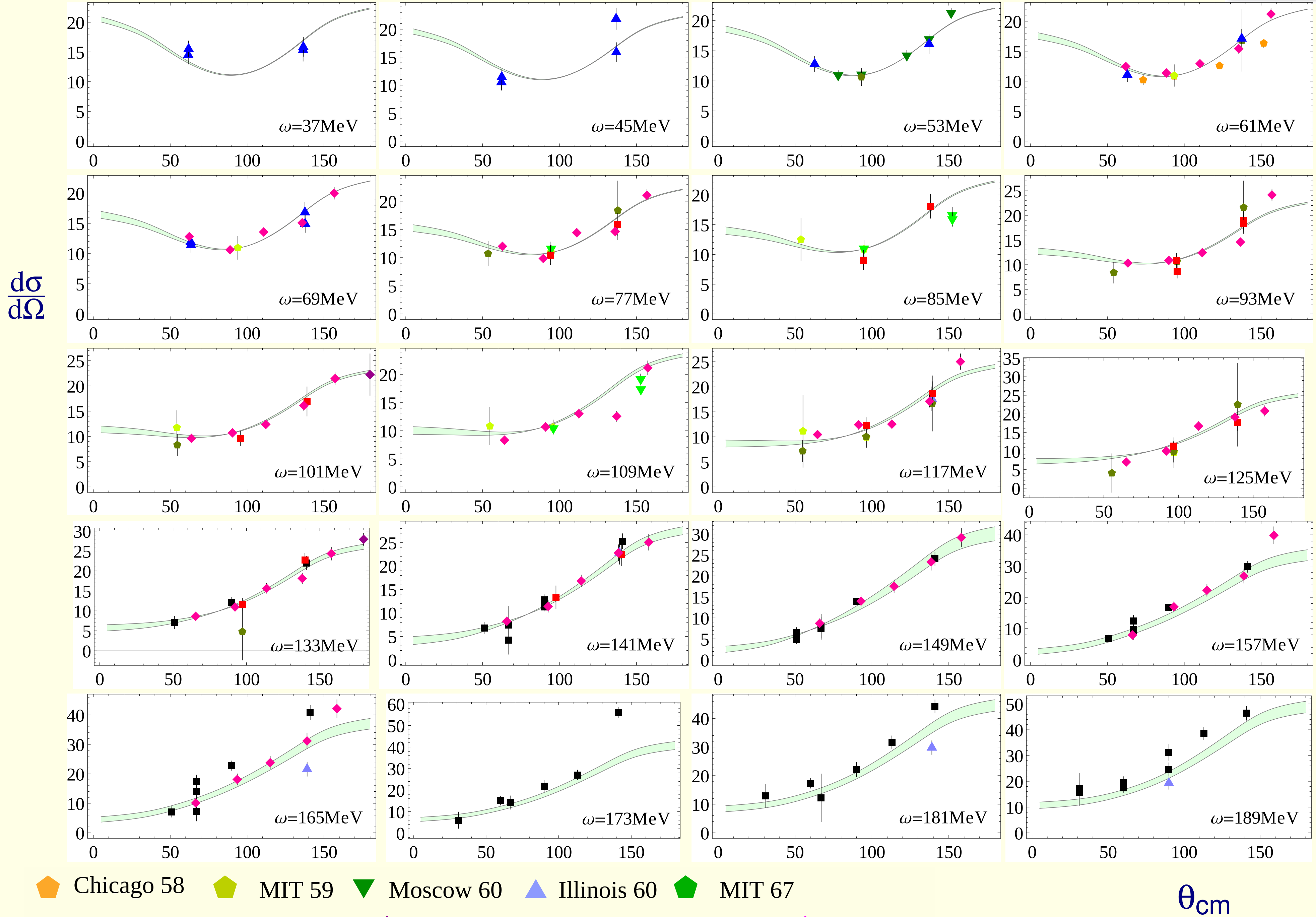
Our strategy: Static polarisabilities best obtained from Compton scattering.

Effects of Delta

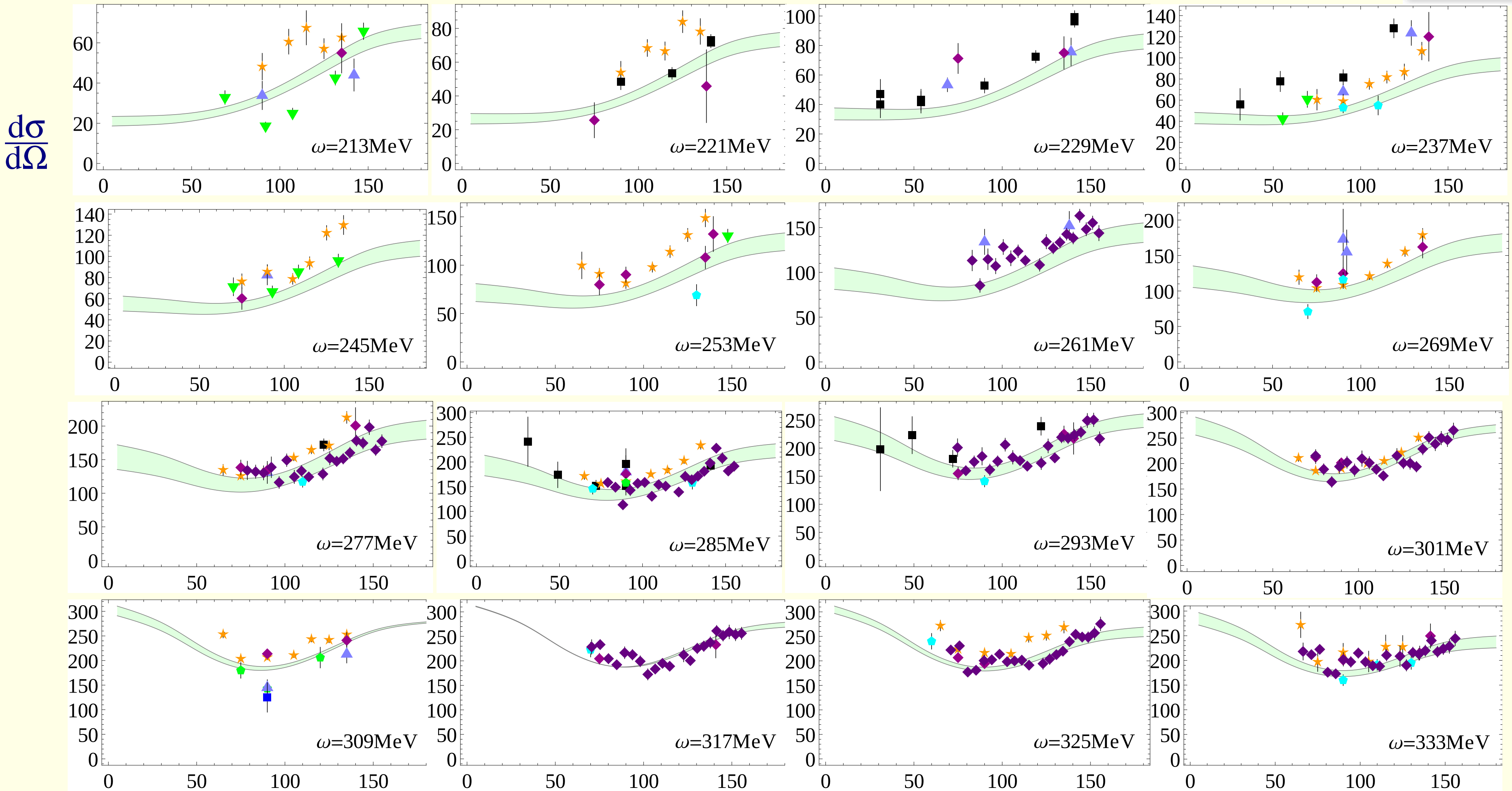


Δ significant from around 140MeV upward—especially at backward angles

Fitting the proton data



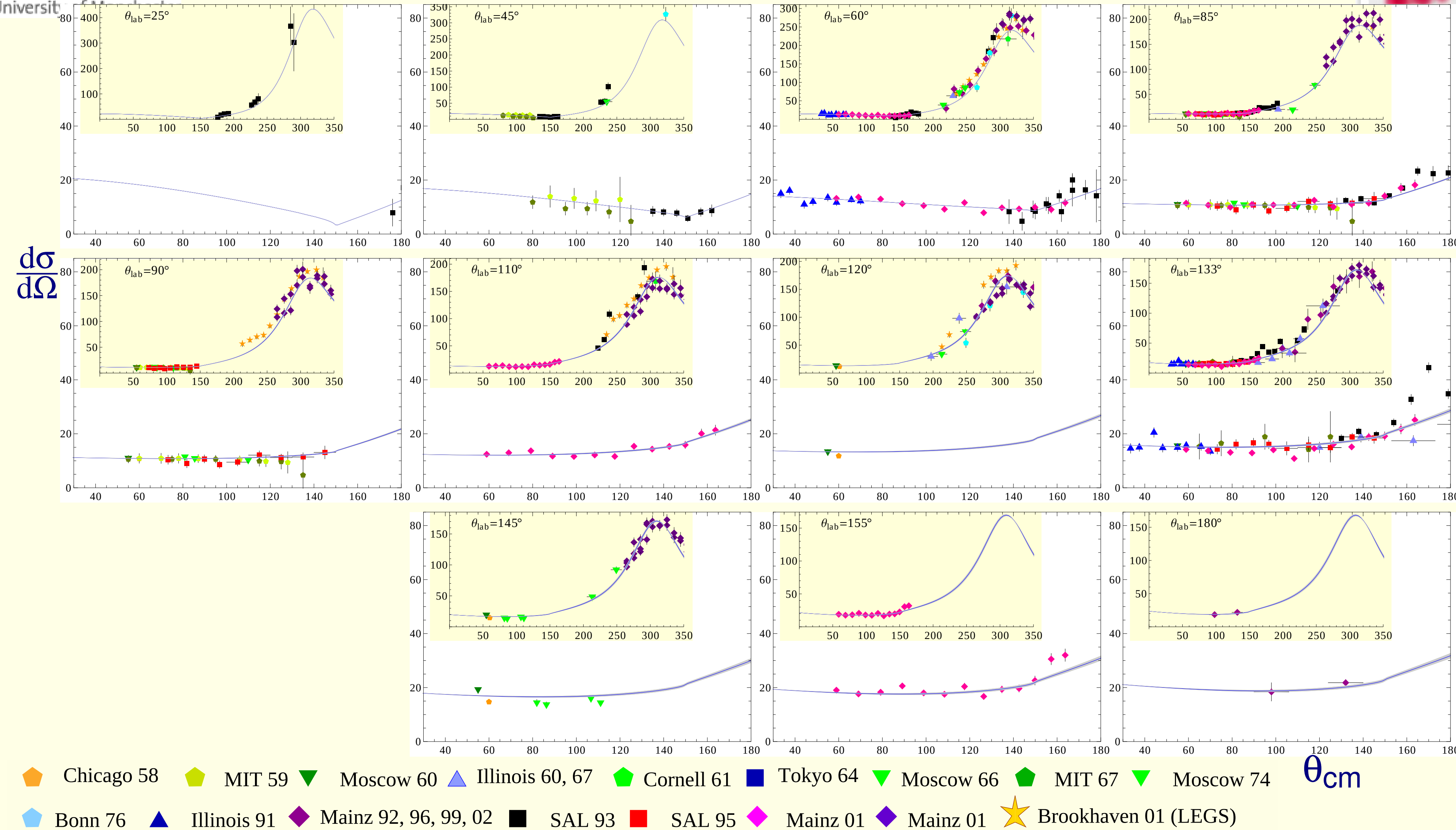
band: energy spread



Illinois 60, 67 Cornell 61 Moscow 60s Bonn 76 SAL 93 θ_{cm}

Mainz 92, 96, 99, 02 Mainz 01 Brookhaven 01 (LEGS)

band gives spread of theory curve due to energy binning



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

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

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

Comparison

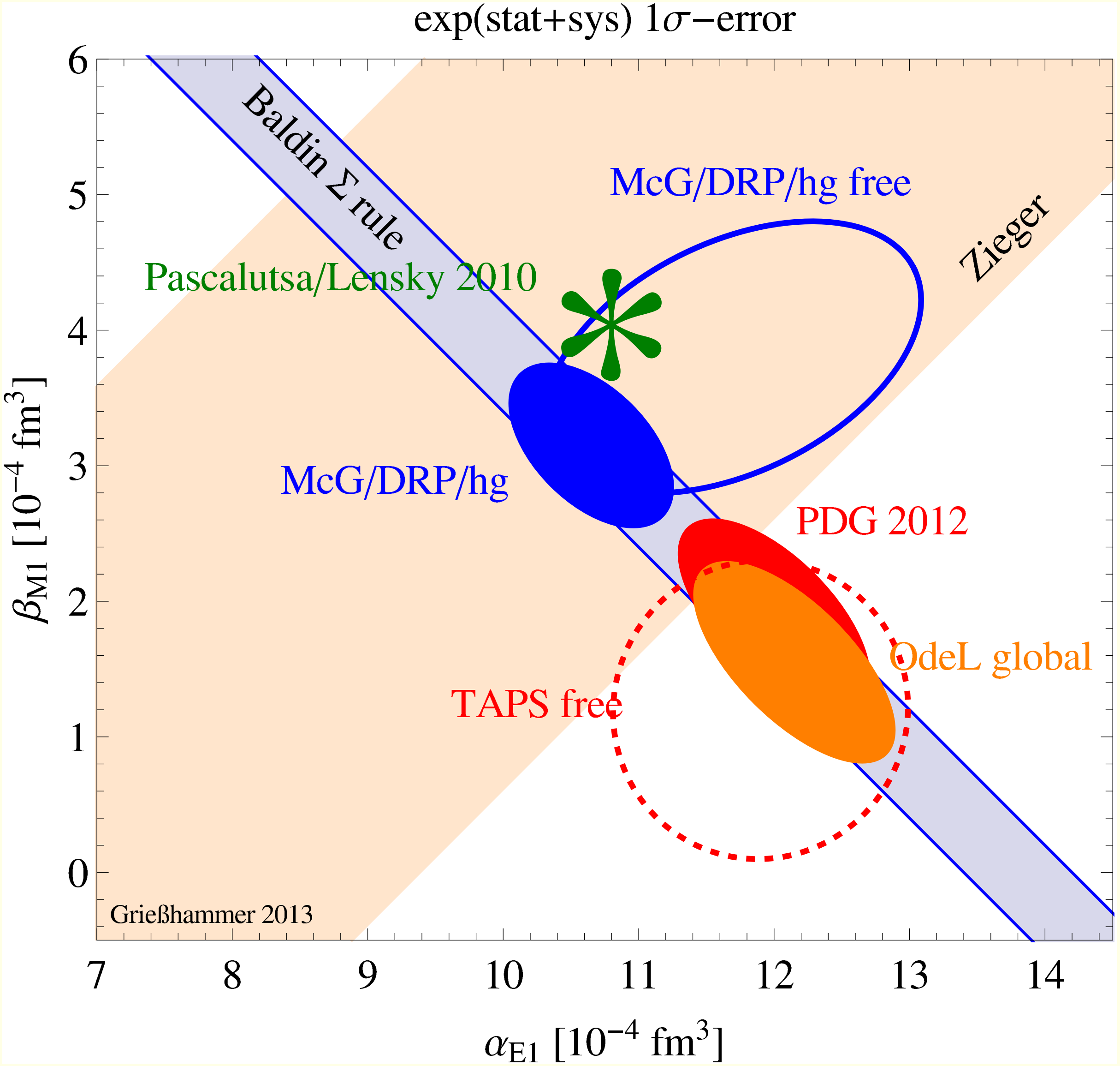


figure courtesy of H. Grießhammer

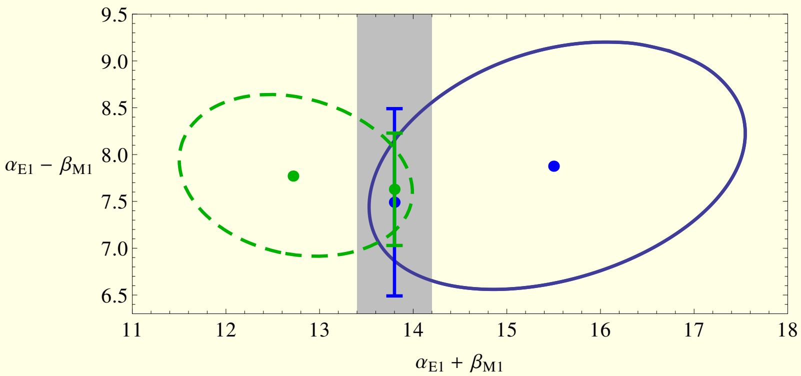
Details of fit

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

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.

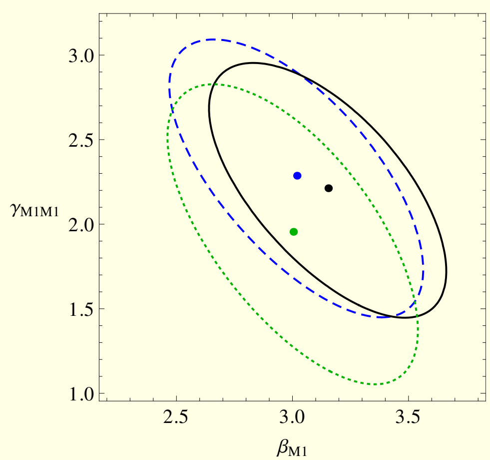
4th-order statistical errors on $\alpha - \beta$ are larger than 3rd order.



Deduce theory error from convergence:

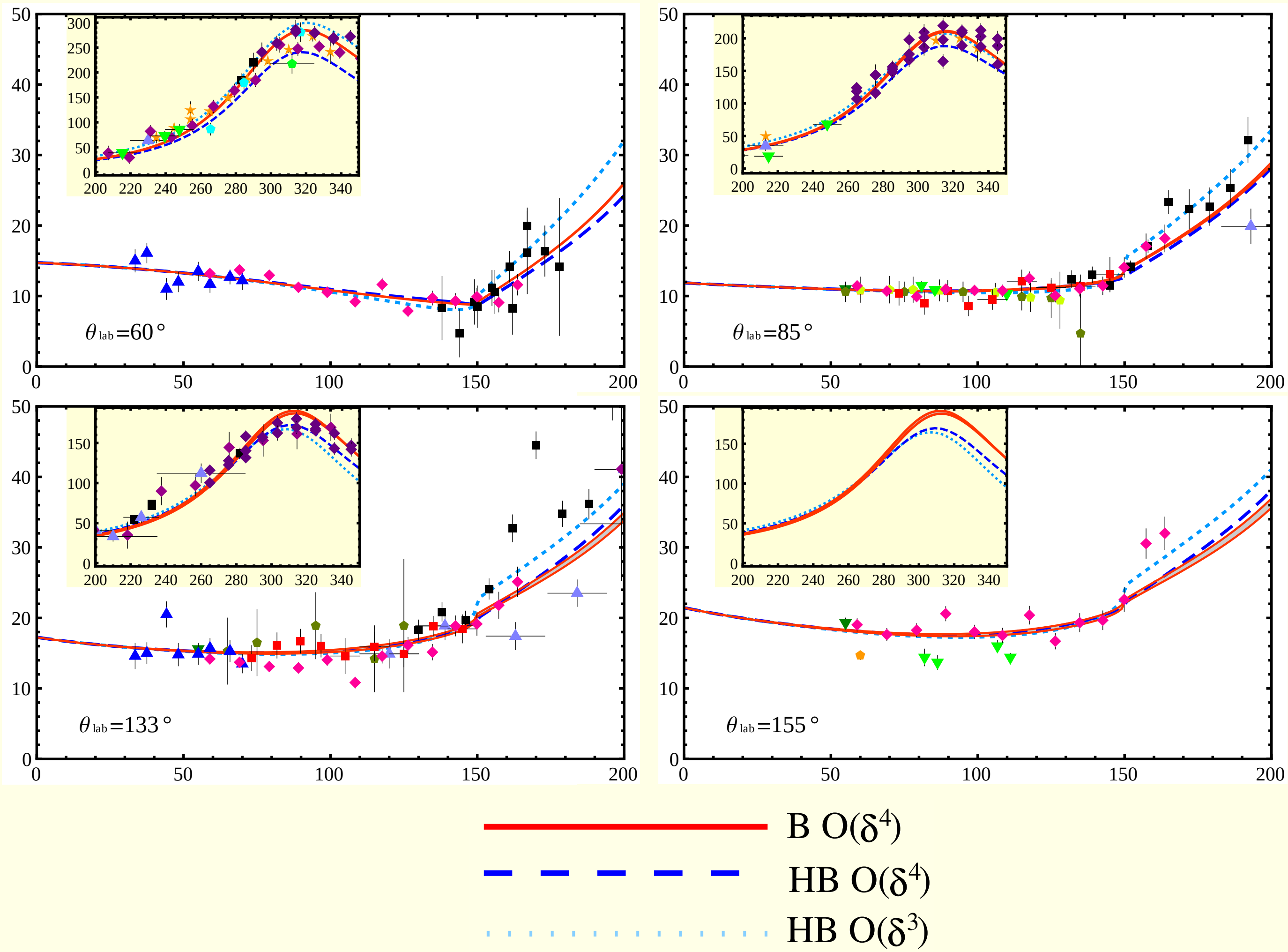
LO ($O(e^2\delta)$, BKM) $\alpha - \beta = 11.25$

N^{2}LO ($O(e^2\delta^4)$ $\alpha - \beta = 7.5$



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.

Checking in covariant framework (3rd order)



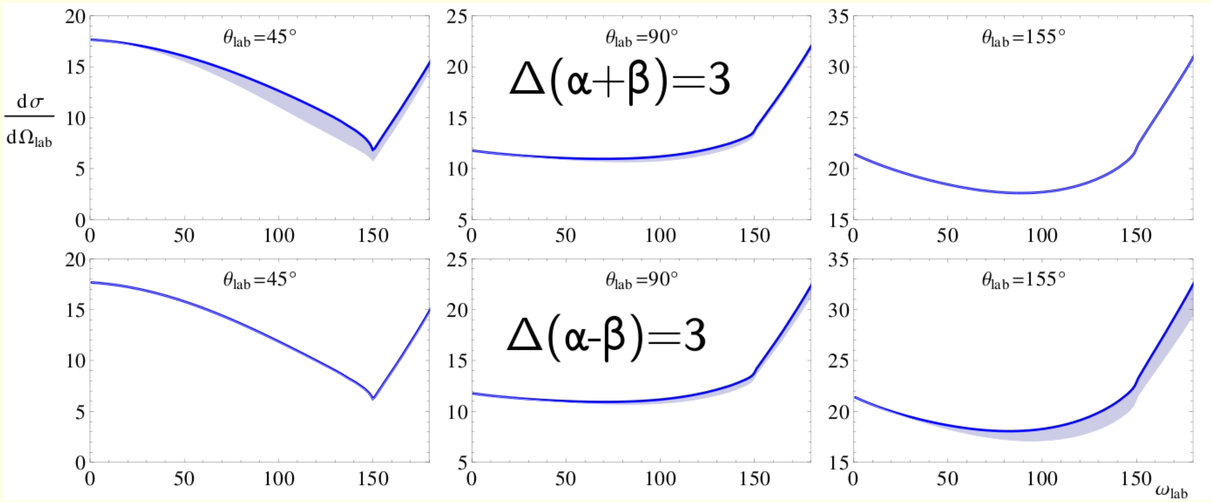
$$\alpha_p = (10.6 \pm 0.25(\text{stat}) \pm 0.2(\text{Bald}) \pm 0.4(\text{theory})) \times 10^{-4}\,\text{fm}^3$$
$$\beta_p = (3.2 \mp 0.25(\text{stat}) \pm 0.2(\text{Bald}) \pm 0.4(\text{theory})) \times 10^{-4}\,\text{fm}^3$$

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

More data needed?

We fit to low-energy data (up to 180-200 MeV), but with constraints from the higher-energy data to ensure the Δ parameters are sensible.

In spite of the amount of data, the sensitivity to the polarisabilities especially β is not very high. Magnetic response varies rapidly with energy and zero-energy value is only a small fraction of the total by 150 MeV.



What would help

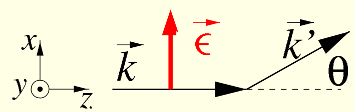
- Better data! (Theorist's view...)
- More data in the region 160-250 MeV
- More data at forward and backward angles
- Data for polarised scattering (beam and target)

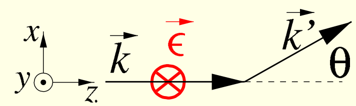
Spin-dependent Compton scattering

$$H_{\text{eff}} = \frac{(\mathbf{p}-Q\mathbf{A})^2}{2m} + Q\phi - \frac{(Q+\kappa)}{2m}\sigma\cdot H - \frac{1}{2}4\pi\Big(\alpha\vec{E}^2+\beta\vec{H}^2$$
$$+ \gamma_{E1}\vec{\sigma}\cdot\vec{E}\times\dot{\vec{E}} + \gamma_{M1}\vec{\sigma}\cdot\vec{H}\times\dot{\vec{H}} - 2\gamma_{E2}E_{ij}\sigma_i H_j + 2\gamma_{M2}H_{ij}\sigma_i E_j\Big)$$

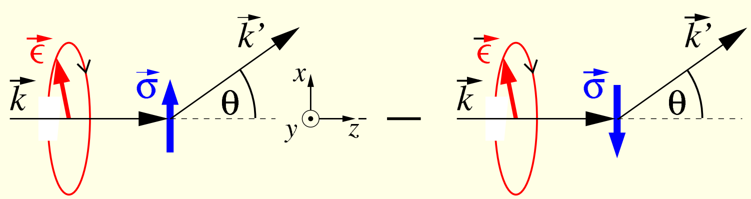
Spin-polarisabities have most influence if the beam or target or both are polarised.

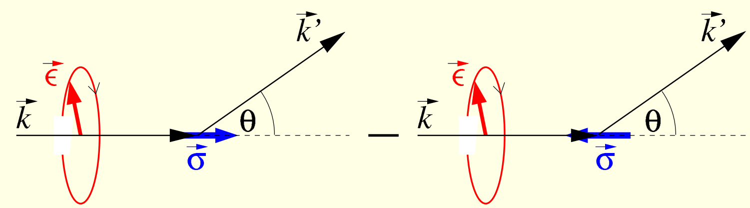
Linearly polarised beam $\Sigma_3 = \dfrac{\sigma^{\parallel}-\sigma^{\perp}}{\sigma^{\parallel}+\sigma^{\perp}}$

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

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

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

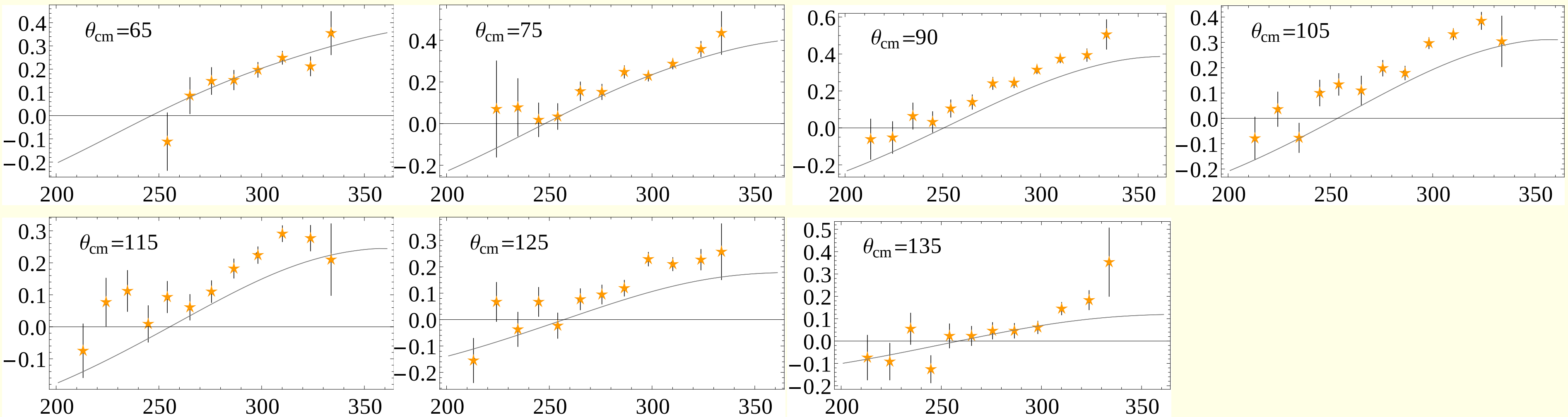
Δ_x^{circ}: 

Δ_z^{circ}: 

Photon beam asymmetry

Until very recently only the 2001 LEGS data for Σ_3: Unpolarised target, photons linearly polarised parallel or perpendicular to reaction plane

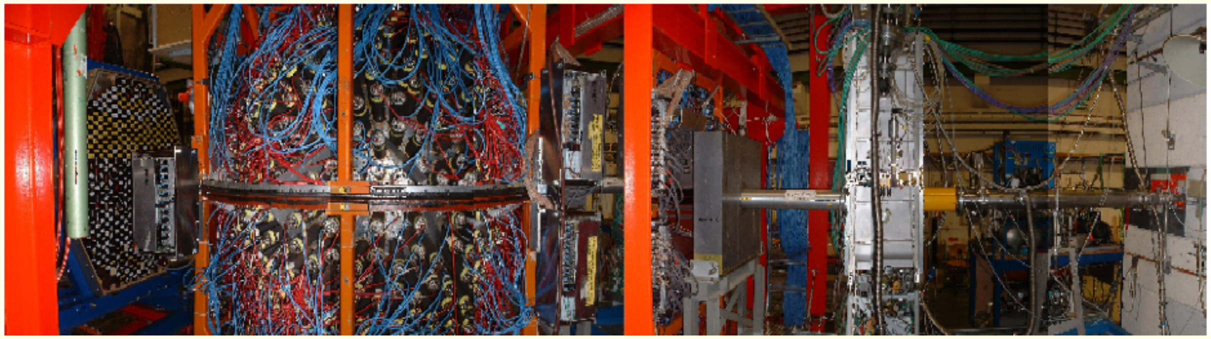
$$\Sigma_3 = \frac{\sigma^{\parallel} - \sigma^{\perp}}{\sigma^{\parallel} + \sigma^{\perp}}$$

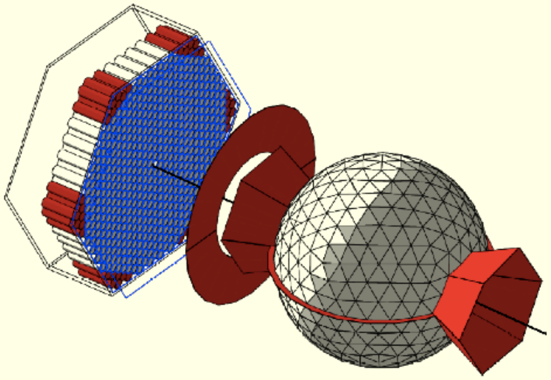


Note for the higher-energy region the calculation is only NLO...

Compton @MAMI

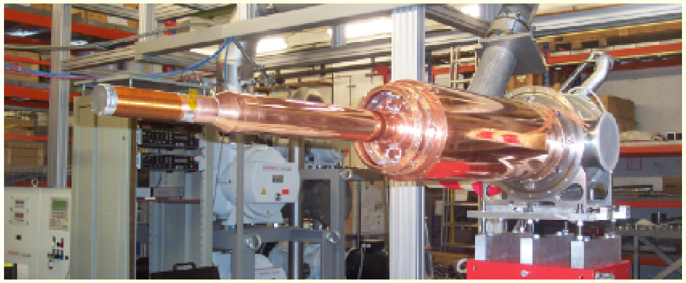
New programme at A2 experiment using Crystal Ball and TAPS detectors





Large-acceptance detector

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

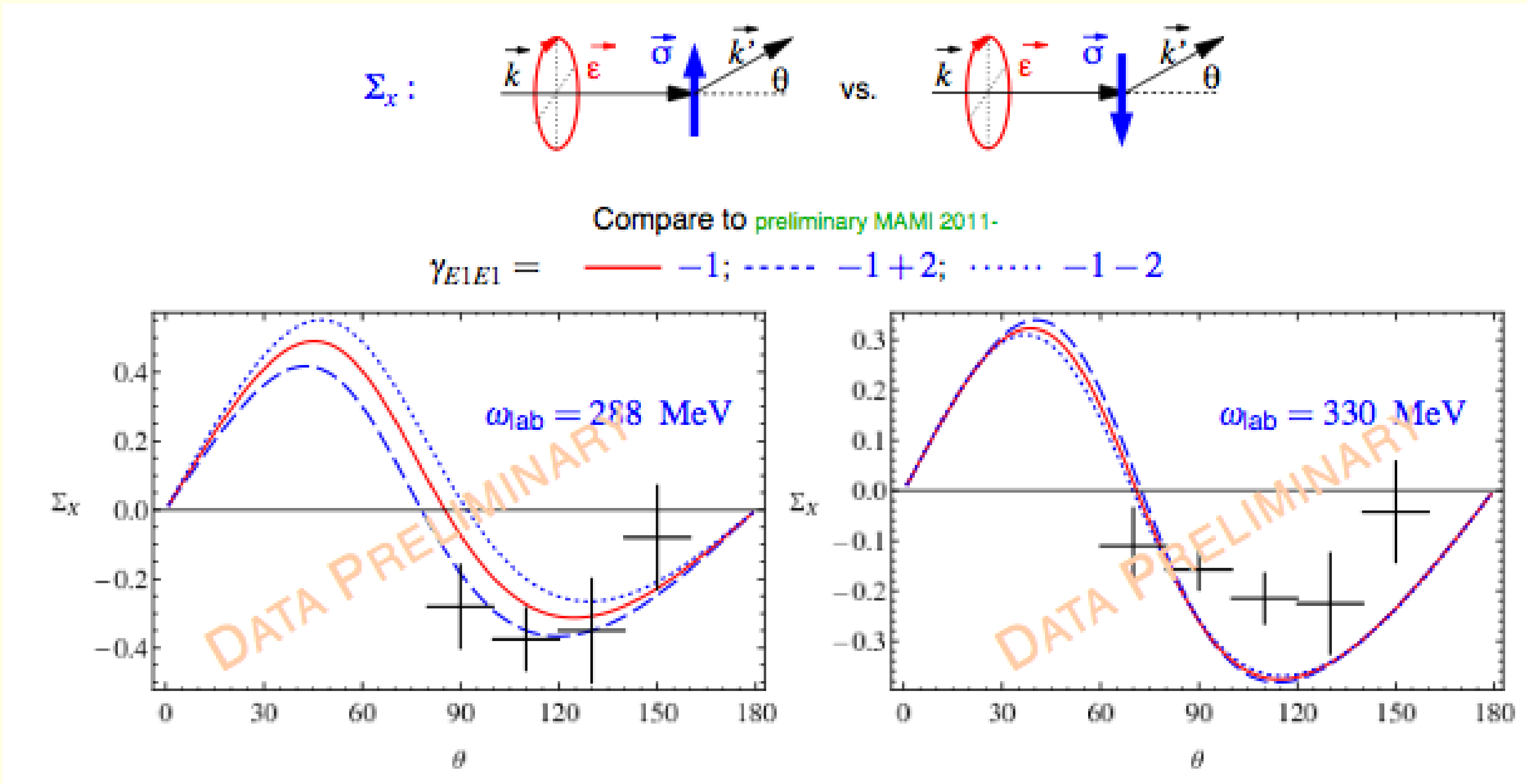


Unpolarised (liquid hydrogen)...

or polarised (butanol) protons

First results

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



Sensitivity more reliable than overall magnitude

Results to come for Σ_3 (Cristina Collicott) and Σ_{2z}

Predictions and fits for proton polarisabilities

Chiral prediction at LO (Q^3, Bernard)

also with Delta LO (δ^3, BChPT, Lensky) and NLO (δ^4, HBChPT, JMcG)

	$\alpha+\beta$	$\alpha-\beta$	γ_0	γ_π
Q^3 HB	13.8	11.3	4.6	[−46.4]+4.6
δ^3 B	15.1	7.4	-0.9	[−46.4]+7.3
δ^4 HB	$10.65\pm0.35\pm0.2\pm0.3$	$3.15\mp0.35\pm0.2\mp0.3$	-6.8	[−46.4]+9.7
SR/DR	13.8 ± 0.4	10.7 ± 0.2	-0.9 ± 0.14	$[-46.4]+4\pm1.8$

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

	γ_{E1E1}	γ_{M1M1}	γ_{E1M2}	γ_{M1E2}
Q^3 HB	-5.7	-1.1	1.1	1.1
δ^3 B	-3.3	3.0	0.2	1.1
δ^4	-1.1 ± 1.8	$2.2\pm0.5_{\text{stat}}\pm0.7^*_{\text{th}}$	-0.4 ± 0.4	1.9 ± 0.4
DR	-3.85 ± 0.45	2.8 ± 0.1	-0.15 ± 0.15	2.0 ± 0.1
MAMI	-3.2 ± 1.1	3.2 ± 0.8	-0.9 ± 1.1	2.0 ± 0.2

DR: fixed-t,

summarised in HG, JMcG, DP & GF Prog. Nucl. Part. Phys. **67** 841 (2012)

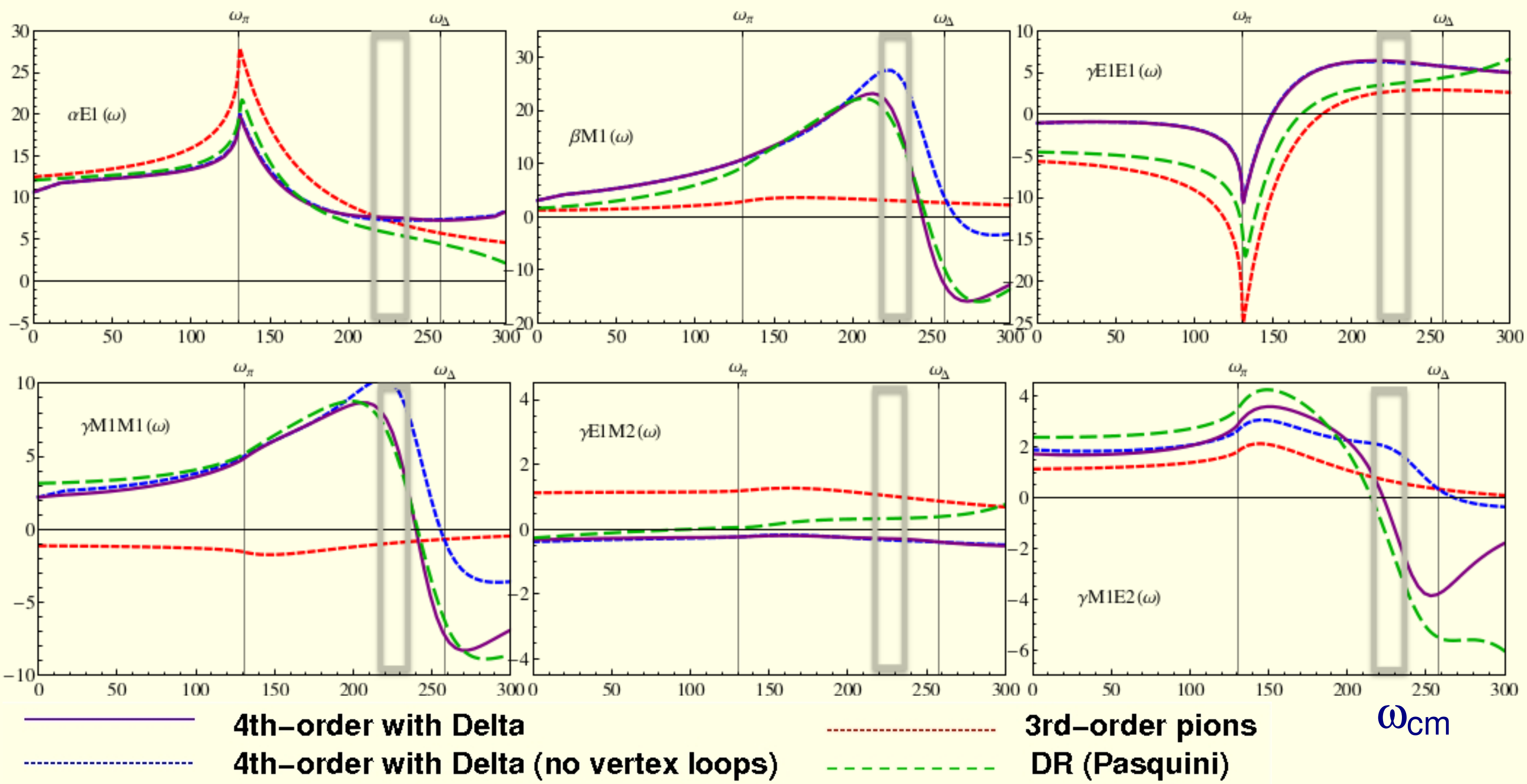
MAMI: unpublished extraction from Σ_{2x} Miskimin

δ^4: theory errors from convergence. *: from fit, otherwise 6.4 ± 1.3

Multipoles again

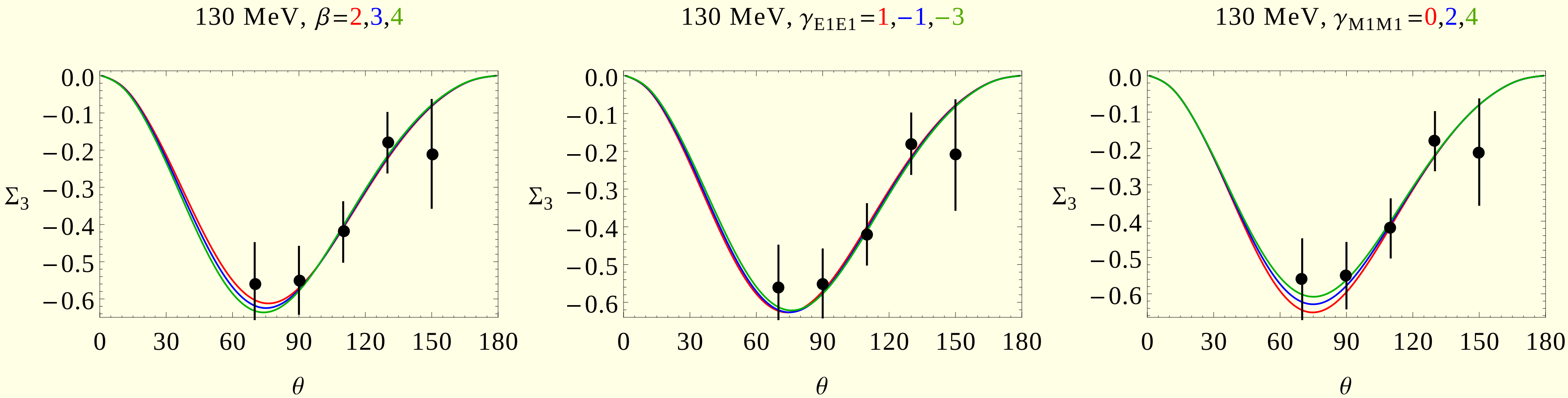
MAMI data is taken well into the resonance region....

Not ideal for extracting zero-energy polarisabilities!



Lower energy experiments

Some PRELIMINARY data on Σ_3 from MAMI V. Sokhoyan and E. Downie



Experiments also planned at HIγS @TUNL

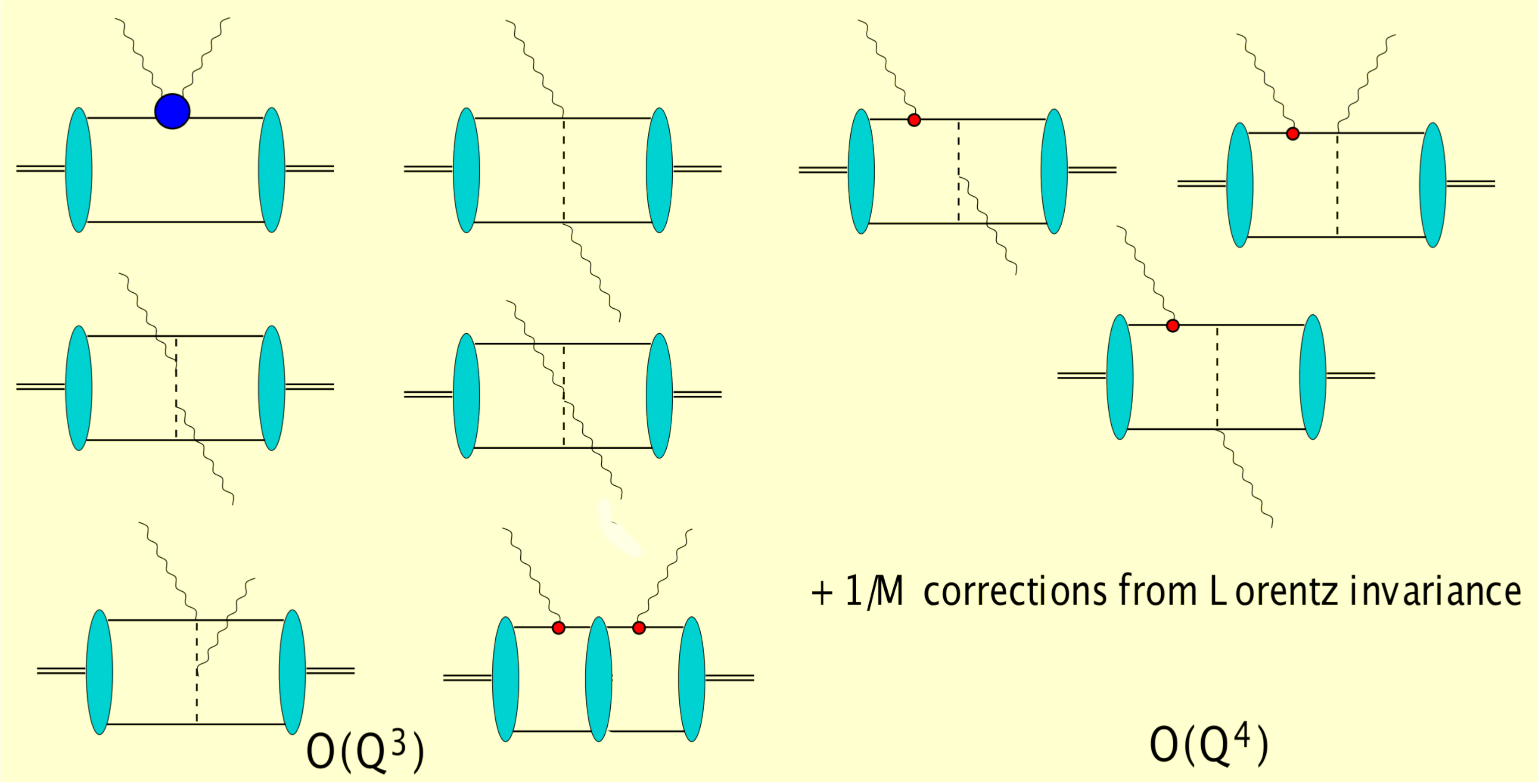
low energy–up to about 100 MeV currently, 150 MeV after upgrades.

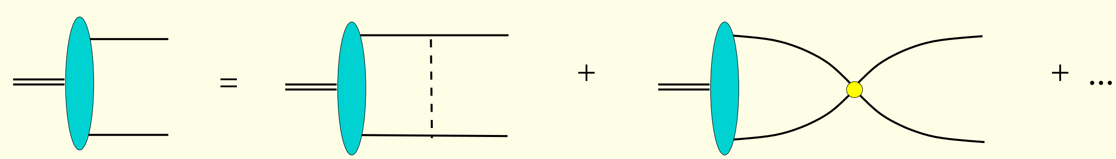
Polarised beam and targets; also light nuclei (d, ^{3}He, ^{4}He)

Also plans for ^{3}He at MAMI J. Annand and B. Strandberg

Deuteron

Consistent treatment of one- and two-body diagrams



where 

The Δ only enters in ● at this order.

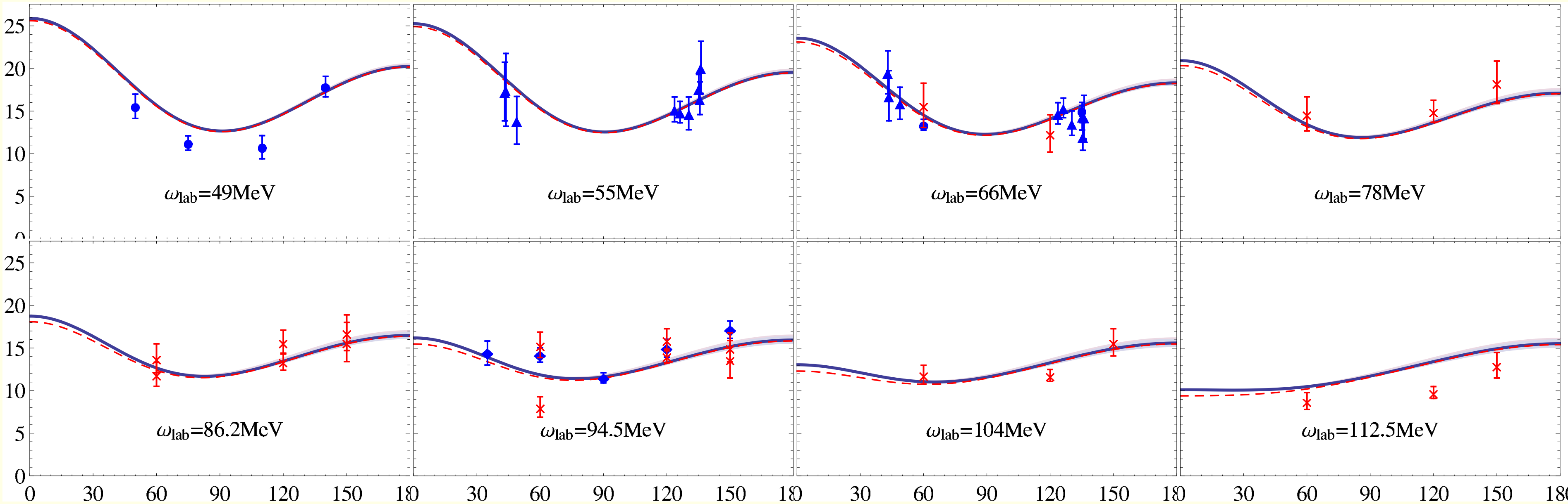
Ensuring correct Thomson limit for deuteron is important even at 50-60 MeV.

Extraction of isoscalar polarisabilities

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.* in preparation



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

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

PRELIMINARY! HG, JMcG, DP in preparation

Comparison

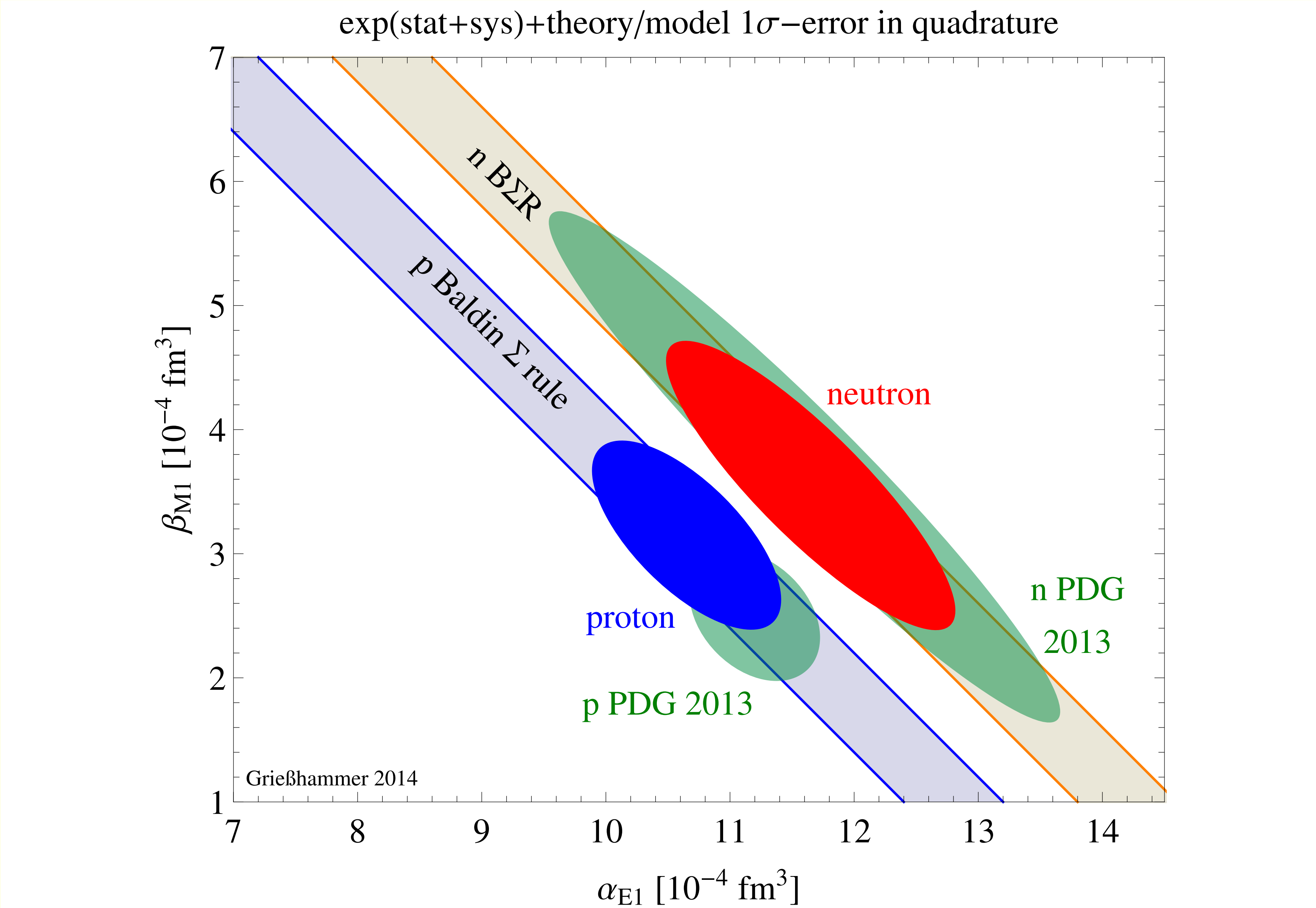


figure courtesy of H. Grießhammer

Lattice for α_n

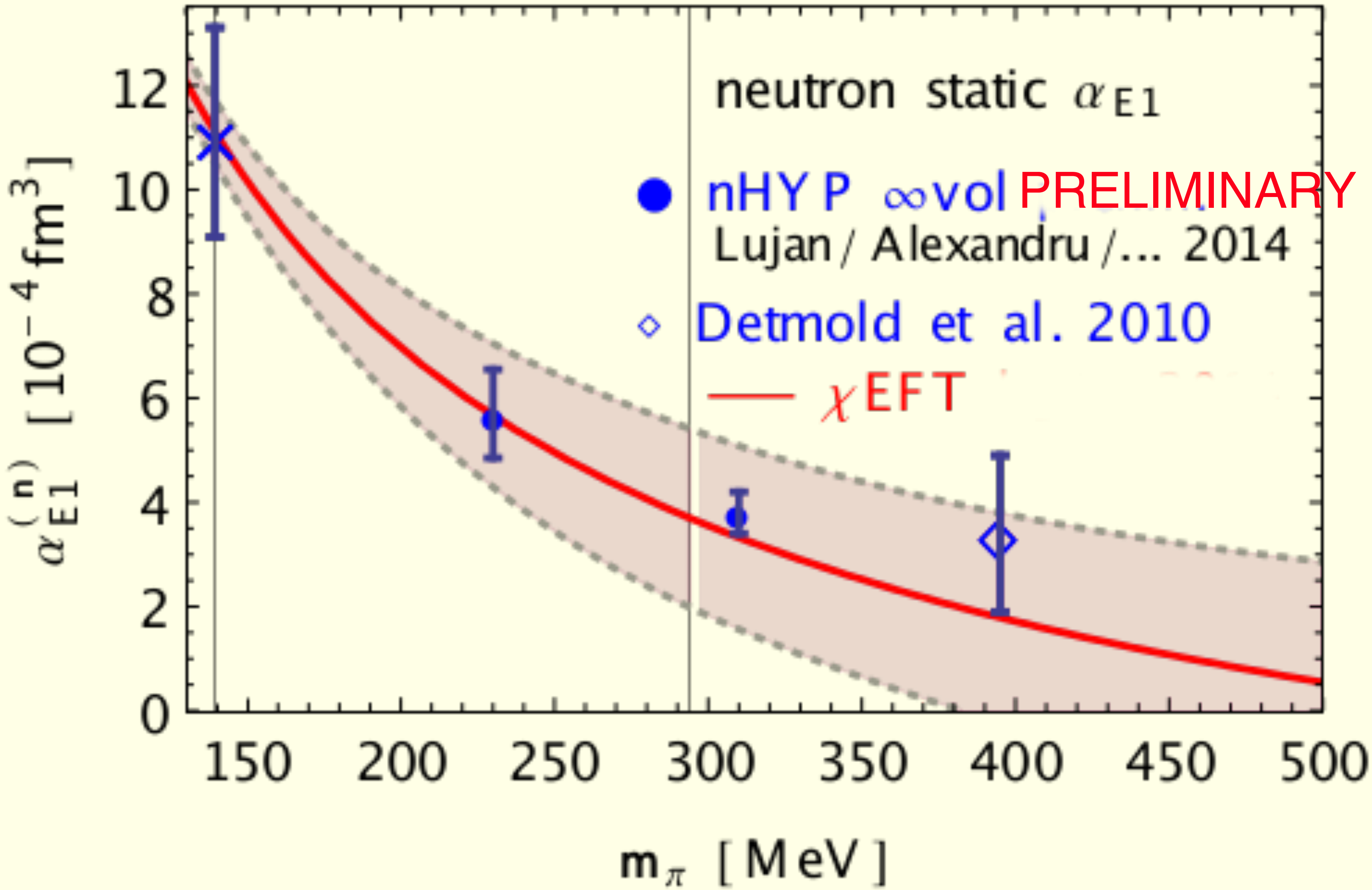
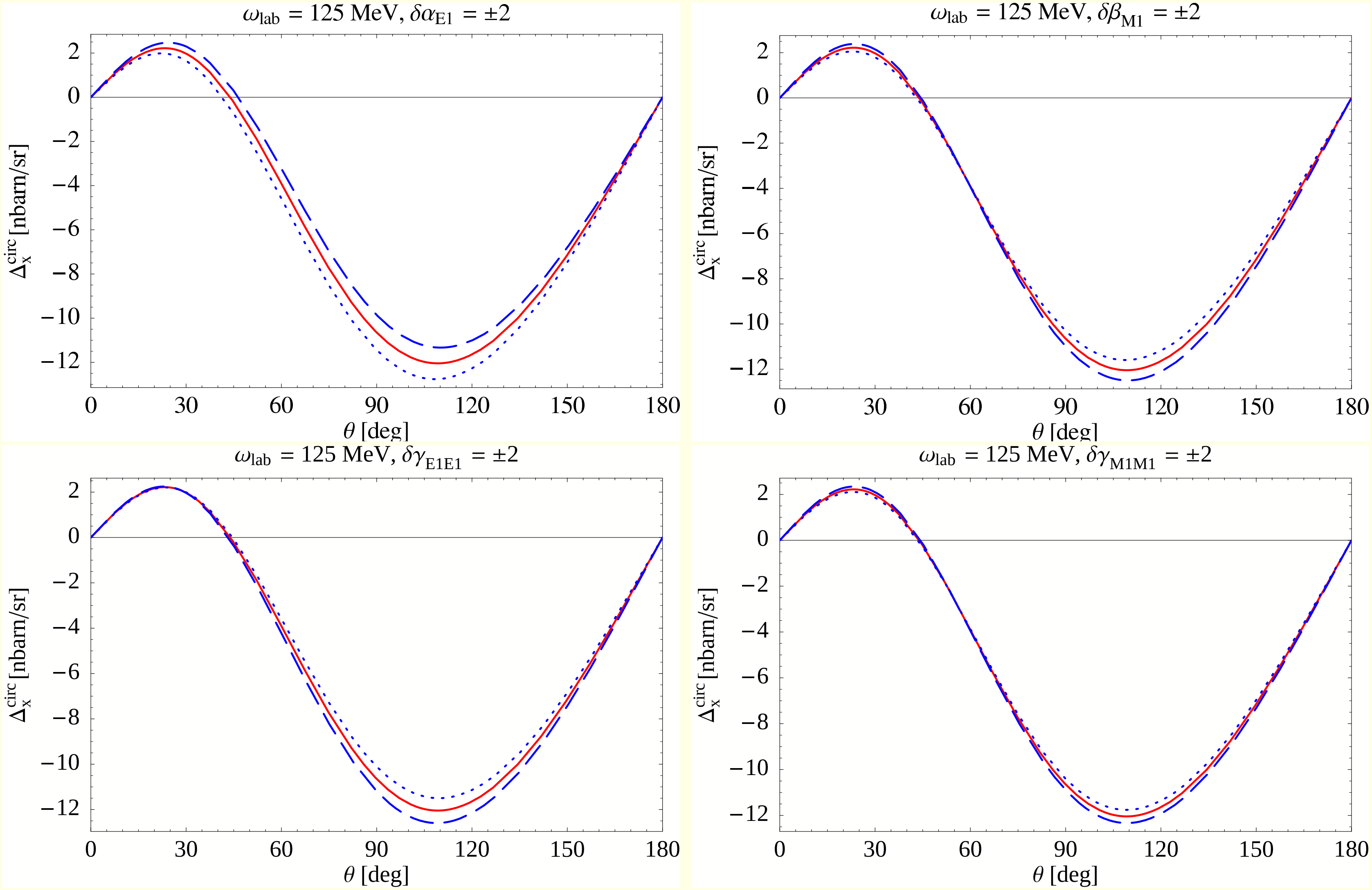


figure courtesy of H. Grießhammer

Polarised scattering from deuterium

$$\Delta_x^{\text{circ}} = \frac{d\sigma}{d\Omega_{\uparrow\rightarrow}} - \frac{d\sigma}{d\Omega_{\uparrow\leftarrow}}$$

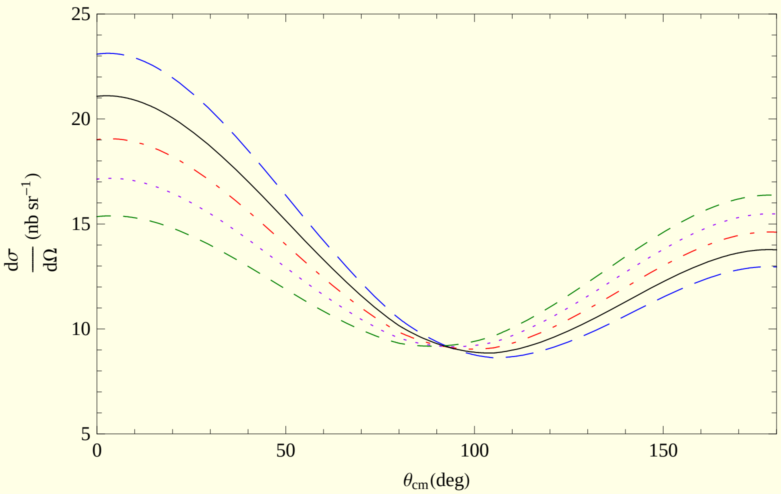


Δ included, 3rd order.

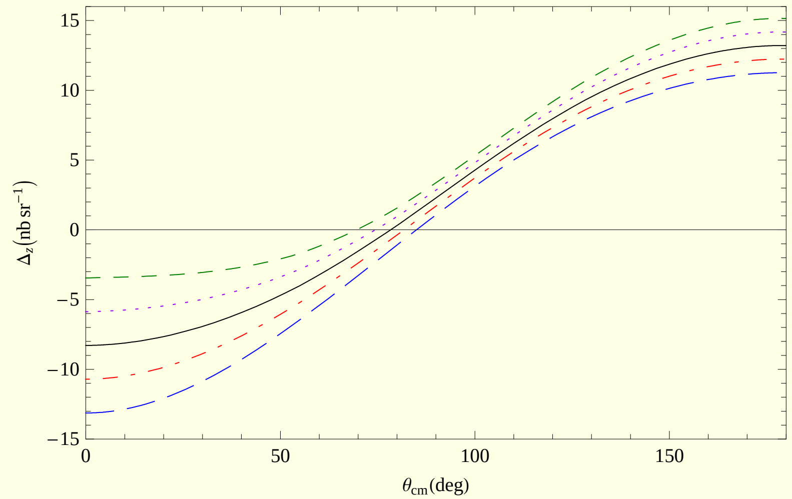
source: Griesshammer and Shukla Eur. Phys. J. A46:249, 2010

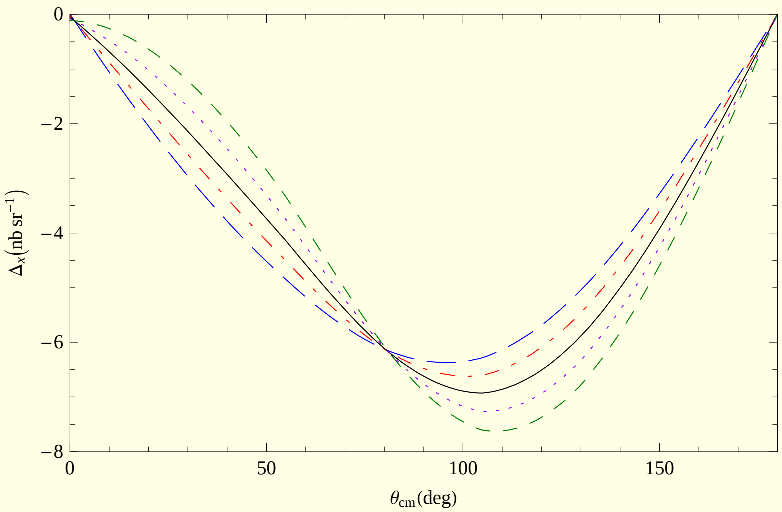
Polarised scattering from ^{3}He

Unpolarised, varying β_n

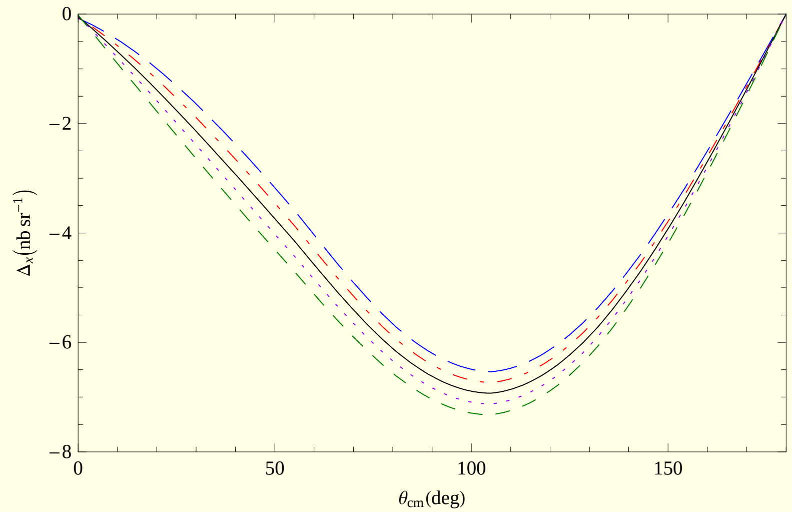


Δ_z, varying γ_{1n}





Δ_x, varying γ_{1n}



Δ_x, varying γ_{4n}

120 MeV, 3rd order, no Δ

source: Shukla, Nogga and Phillips Nucl. Phys. A 819 (2009) 98

Future

Experimental programme at MAMI, MAXlab and HIγS

Polarised γp scattering at MAMI: data being analysed; 120 MeV data especially interesting for polarisabilities. Active target being developed for double-polarised experiments at low energies

Plans for ^{3}He

Further data on deuteron at higher energies expected from MAX-lab / MAX-IV

HIγS up to about 100 MeV: approved experiments on polarised proton, deuteron and ^{3}He

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