FROM COMPTON SCATTERING TO MUONIC HYDROGEN
AND BACK TO THE FUTURE

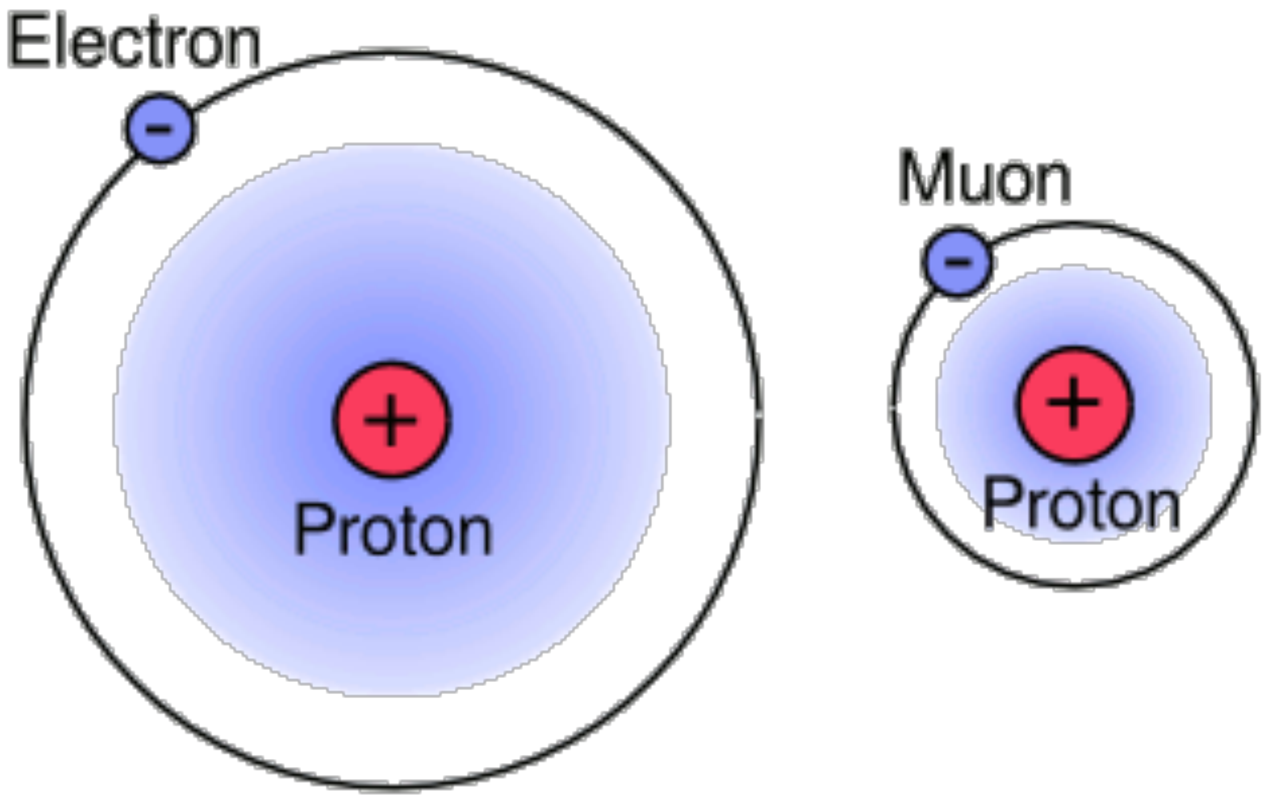
Vladimir Pascalutsa

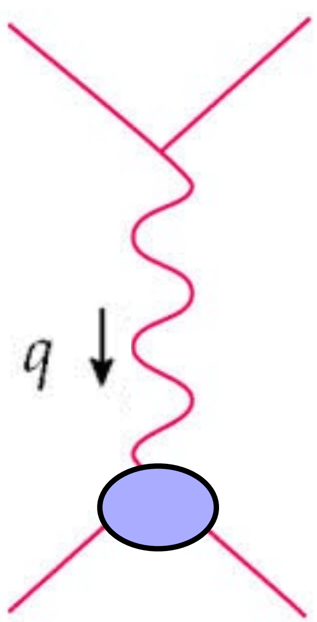
Institute for Nuclear Physics & PRISMA Cluster of Excellence
University of Mainz, Germany

SFB 1044
THE LOW-ENERGY FRONTIER
OF THE STANDARD MODEL

@ Intl Workshop LEPP 2016
Mainz, Germany, Apr 4 —7, 2016

Muonic hydrogen more sensitive to proton structure



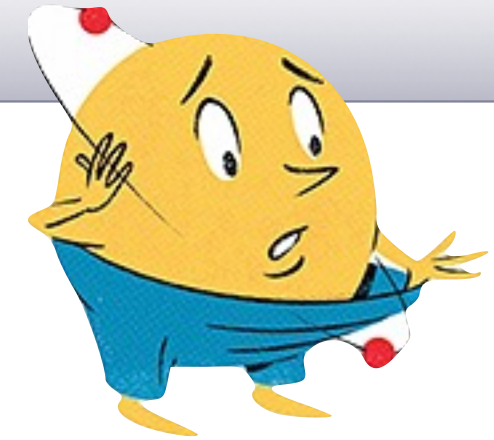


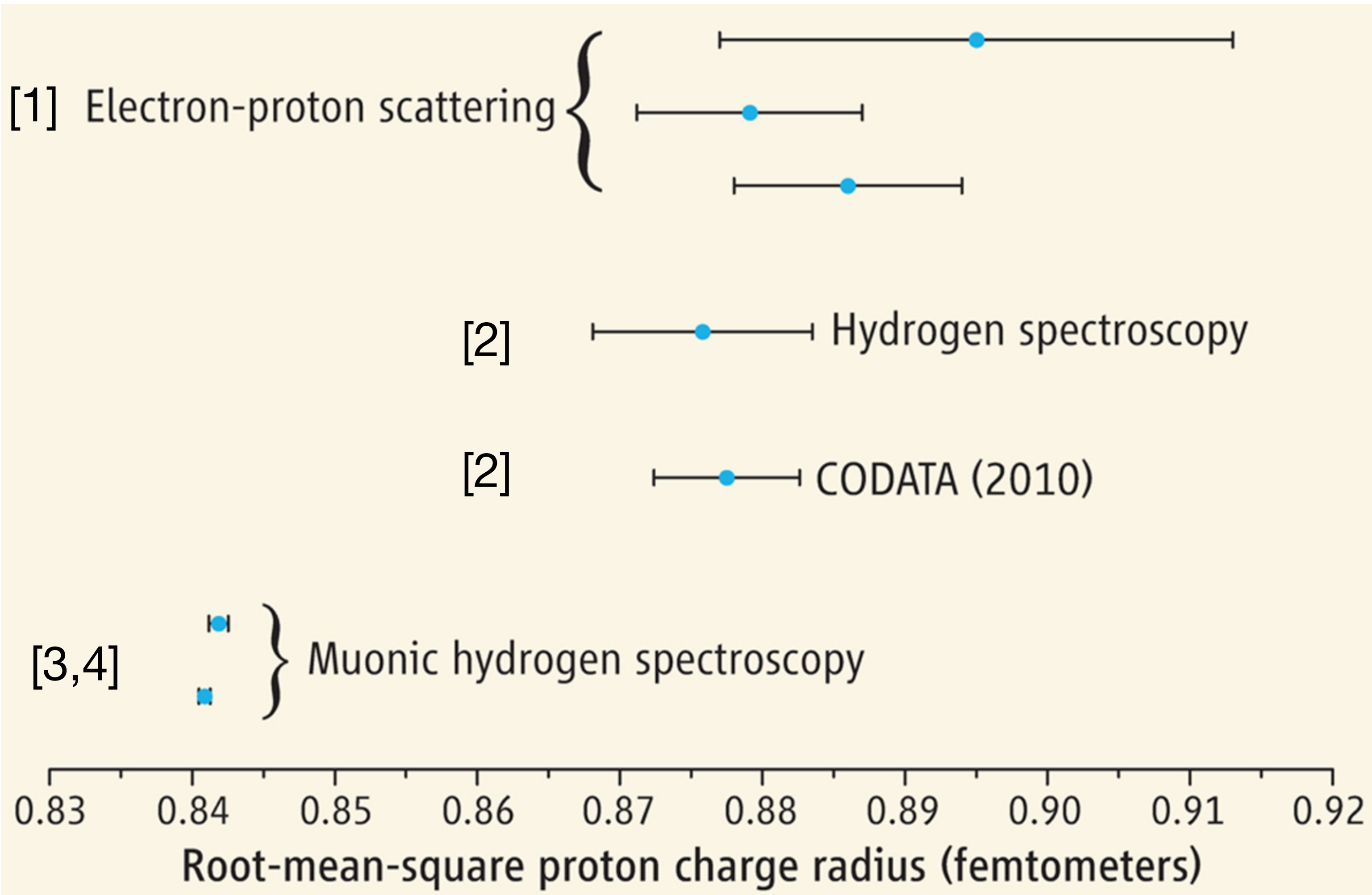
$$\delta V^{(1\gamma)} = -\frac{4\pi\alpha}{\vec{q}^{\,2}}[G_E(-\vec{q}^{\,2}) - 1] = \frac{2}{3}\pi\alpha\, r_E^2 + O(\vec{q}^{\,2})$$

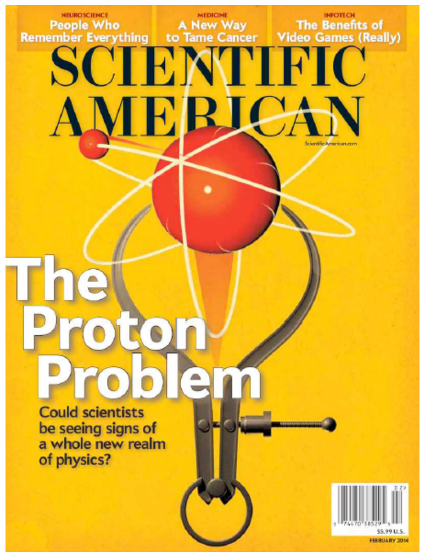
$$\Delta E_{nl}^{(\mathrm{FS})} = \left\langle nlm \right| \delta V^{(1\gamma)} \left| nlm \right\rangle = \delta_{l0}\frac{2}{3}\pi\alpha\, r_E^2\, \frac{\alpha^3 m_r^3}{\pi n^3} + O(\alpha^5)$$

wave function at origin

Proton radius puzzle







[1] J. C. Bernauer *et al.*, Phys. Rev. Lett. **105**, 242001 (2010).
[2] P. J. Mohr, et al., Rev. Mod. Phys. **84**, 1527 (2012).
[3] R. Pohl, A. Antognini *et al.*, Nature **466**, 213 (2010).
[4] A. Antognini *et al.*, Science **339**, 417 (2013).

7σ discrepancy

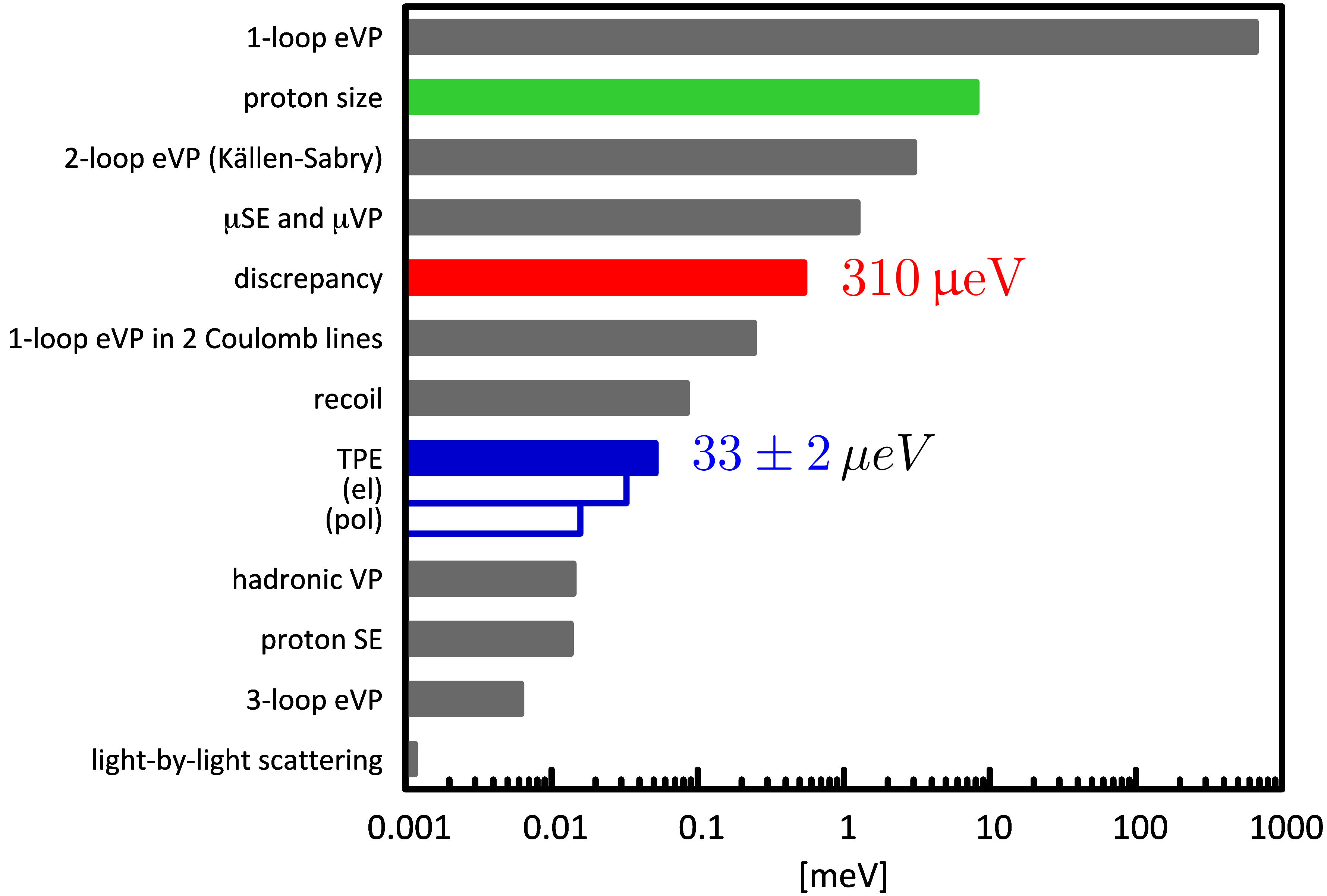
$$[R_E^{\mu\mathrm{H}} = 0.84087(39)\ \mathrm{fm}] \longleftrightarrow [R_E^{\mathrm{CODATA\ 2010}} = 0.8775(51)\ \mathrm{fm}]$$

Muonic Hydrogen Lamb shift

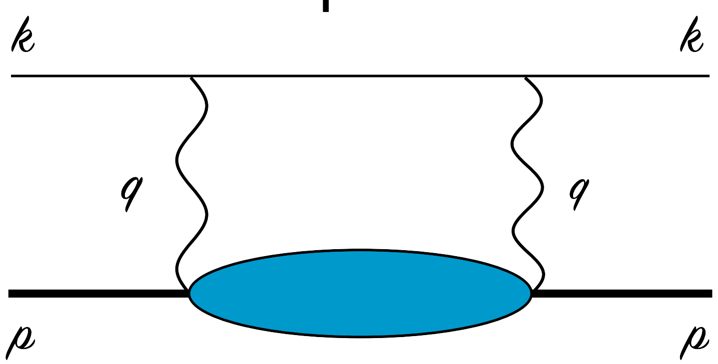
$$\Delta E^{\rm th}_{\rm LS} = 206.0668(25) - 5.2275(10)\,(R_E/{\rm fm})^2$$

numerical values reviewed in: A. Antognini *et al.*, Annals Phys. **331**, 127-145 (2013).

theory uncertainty: $2.5\ \mu eV$



subleading effects of proton structure proposed to resolve the puzzle

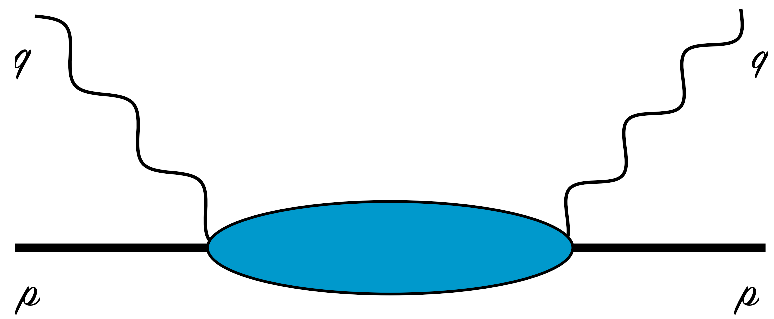


$$\delta V^{(2\gamma)} = \delta V^{(2\gamma)}_{\rm elastic} + \delta V^{(2\gamma)}_{\rm polariz.}$$

A. De Rujula, Phys. Lett. B693 (2010)

G. A. Miller, Phys. Lett. B718 (2013)

Forward (doubly-virtual) Compton scattering required as input

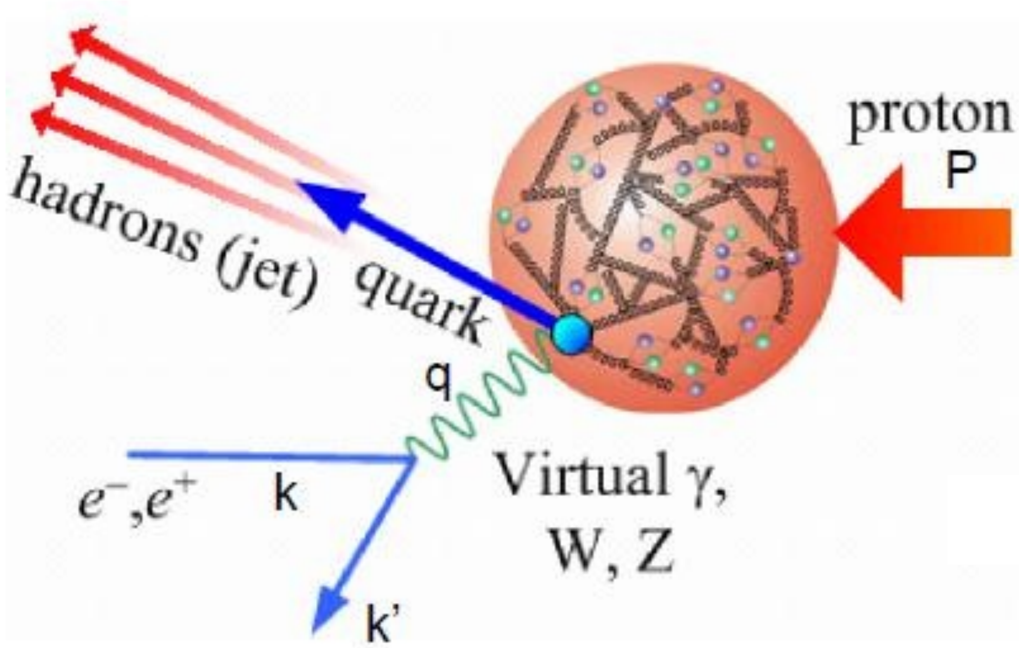


Forward Compton scattering: $N(p) + \gamma(q) \to N(p) + \gamma(q)$, with either real or virtual photons.

Split into Born (elastic form factors) and non-Born (polarizabilities)

Traditional probe of the Proton — electron scattering

Electron-proton scattering



$$Q^2 = -(k' - k)$$
$$x = Q^2/(2M_N \nu)$$

Yields 4 Structure functions:

$$f_1(\nu, Q^2),\ f_2(\nu, Q^2),\ g_1(\nu, Q^2),\ g_2(\nu, Q^2).$$

Lamb shift   hyperfine splitting

(i) Elastic part given by form factors

$$\begin{aligned} f_1^{\rm el}(\nu, Q^2) &= \tfrac{1}{2} G_M^2(Q^2)\,\delta(1-x), \\ f_2^{\rm el}(\nu, Q^2) &= \frac{1}{1+\tau}\left[G_E^2(Q^2) + \tau G_M^2(Q^2)\right]\delta(1-x), \\ g_1^{\rm el}(\nu, Q^2) &= \tfrac{1}{2} F_1(Q^2) G_M(Q^2)\,\delta(1-x), \\ g_2^{\rm el}(\nu, Q^2) &= -\tfrac{1}{2}\tau F_2(Q^2) G_M(Q^2)\,\delta(1-x), \end{aligned}$$

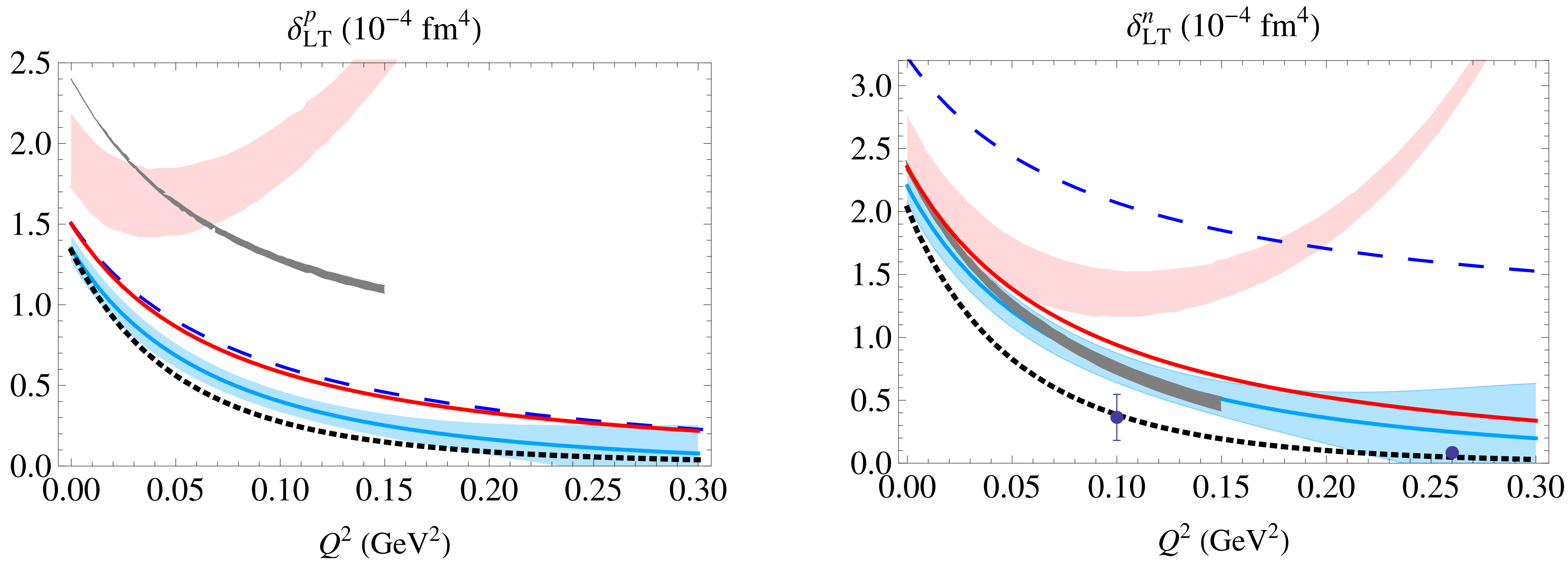
where $\tau = Q^2/4M^2$ and $G_E(Q^2), G_M(Q^2)$ are the Sachs FFs

Moments of the inelastic part — polarizabilities

$$\alpha_{E1}(Q^2) + \beta_{M1}(Q^2) = \frac{8\alpha M_N}{Q^4} \int_0^{x_0} \mathrm{d}x\, x F_1(x, Q^2),$$

$$\gamma_0(Q^2) = \frac{16\alpha M_N^2}{Q^6} \int_0^{x_0} \mathrm{d}x\, x^2 g_{TT}(x, Q^2), \qquad g_{TT} = g_1 - (4M_N^2 x^2/Q^2) g_2$$

$$\delta_{LT}(Q^2) = \frac{16\alpha M_N^2}{Q^6} \int_0^{x_0} \mathrm{d}x\, x^2 \left[g_1(x, Q^2) + g_2(x, Q^2) \right]$$



DeltaLT puzzle — none of chiral PT calculation describe neutron deltaLT.

Virtual photons: 4 VVCS amplitudes

$$T_1(\nu, Q^2) = \frac{8\pi\alpha}{M} \int_0^1 \frac{\mathrm{d}x}{x} \, \frac{f_1(x, Q^2)}{1 - x^2(\nu/\nu_{\mathrm{el}})^2 - i0^+} =$$

$$T_2(\nu, Q^2) = \frac{16\pi\alpha M}{Q^2} \int_0^1 \mathrm{d}x \, \frac{f_2(x, Q^2)}{1 - x^2(\nu/\nu_{\mathrm{el}})^2 - i0^+}$$

$$S_1(\nu, Q^2) = \frac{16\pi\alpha M}{Q^2} \int_0^1 \mathrm{d}x \, \frac{g_1(x, Q^2)}{1 - x^2(\nu/\nu_{\mathrm{el}})^2 - i0^+}$$

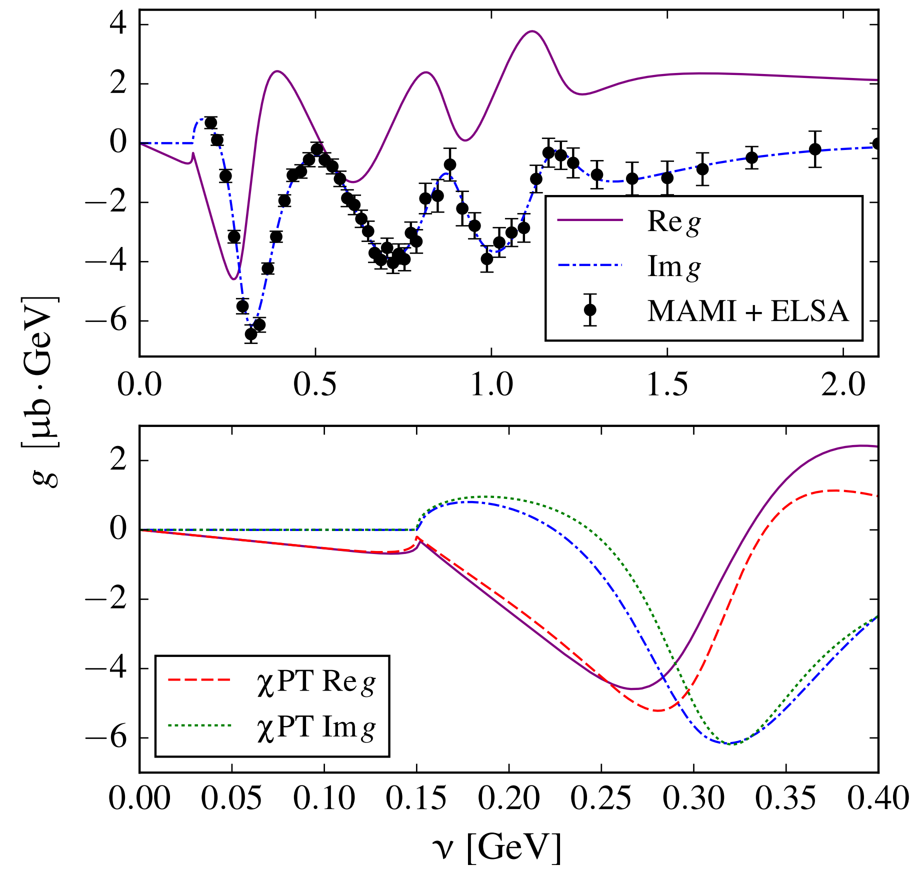
$$\nu S_2(\nu, Q^2) = \frac{16\pi\alpha M^2}{Q^2} \int_0^1 \mathrm{d}x \, \frac{g_2(x, Q^2)}{1 - x^2(\nu/\nu_{\mathrm{el}})^2 - i(}$$

Real photons: 2 amplitudes, 2 photoabsorption cross sections

$$f(\nu) = -\frac{Z^2\alpha}{M} + \frac{\nu^2}{2\pi^2}\int_0^\infty \mathrm{d}\nu' \, \frac{\sigma_T(\nu')}{\nu'^2-\nu^2-i0^+}$$

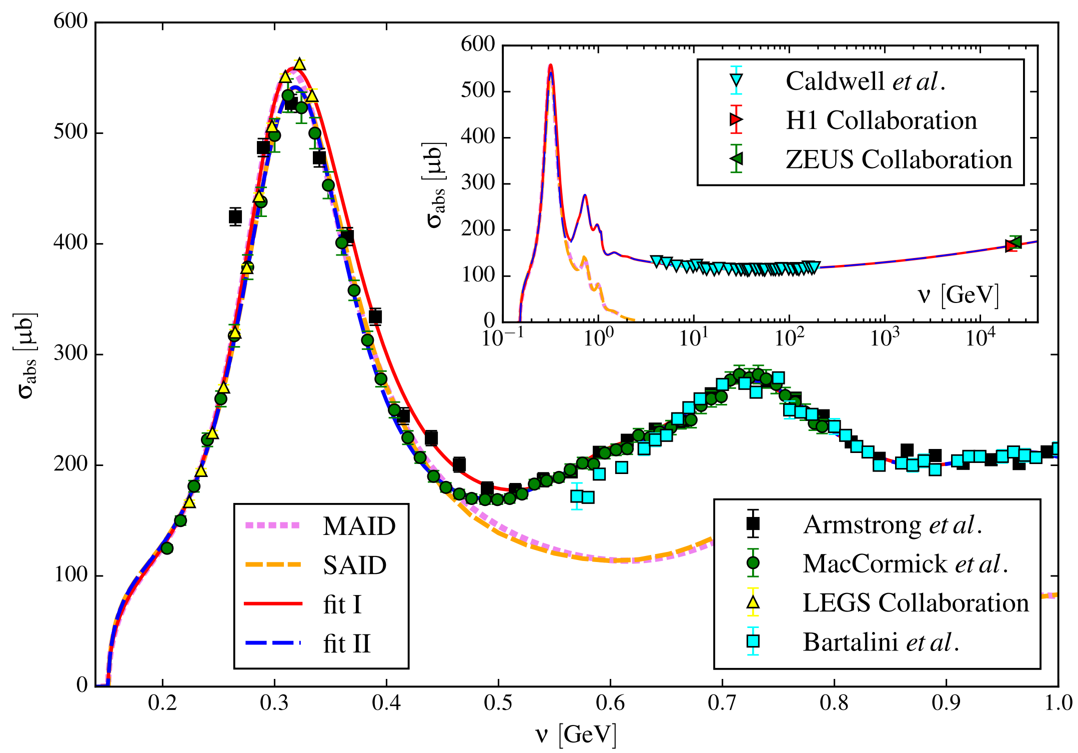
$$g(\nu) = \frac{\nu}{2\pi^2}\int_0^\infty \mathrm{d}\nu' \, \frac{\nu'\sigma_{TT}(\nu')}{\nu'^2-\nu^2-i0^+}.$$

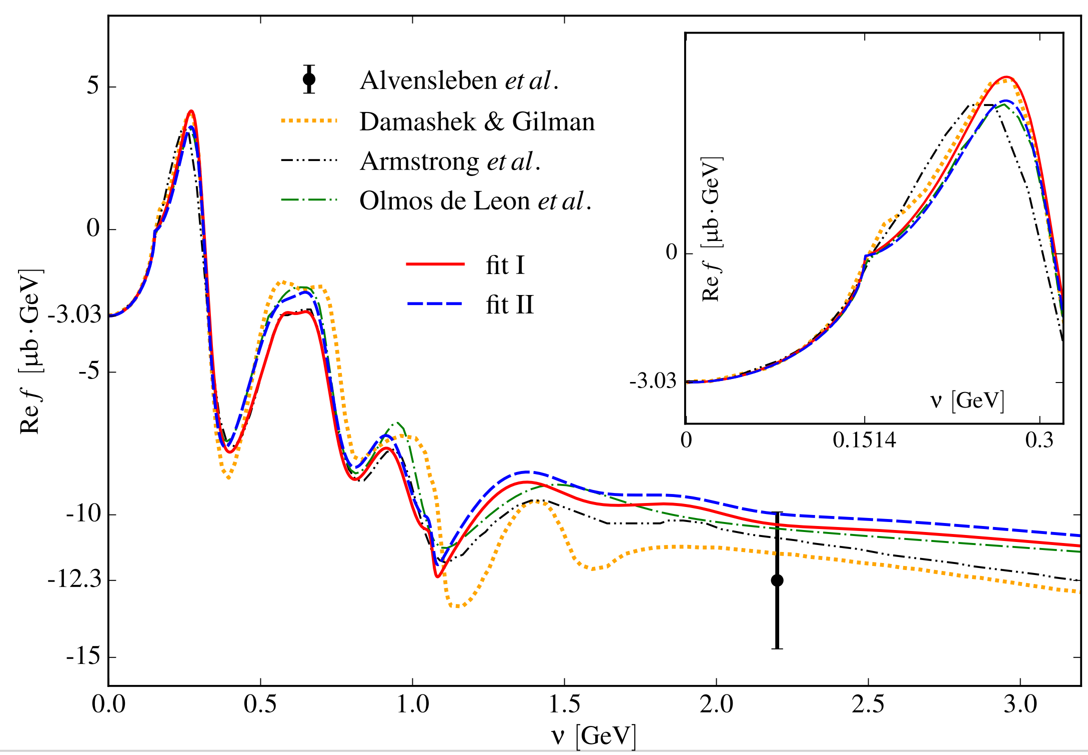
Gryniuk, Hagelstein & V.P., arXiv:1604.00789



Gryniuk, Hagelstein & V.P.

EVALUATION OF THE FORWARD COMPTON SCATTERING … PHYSICAL REVIEW D **92,** 074031 (2015)

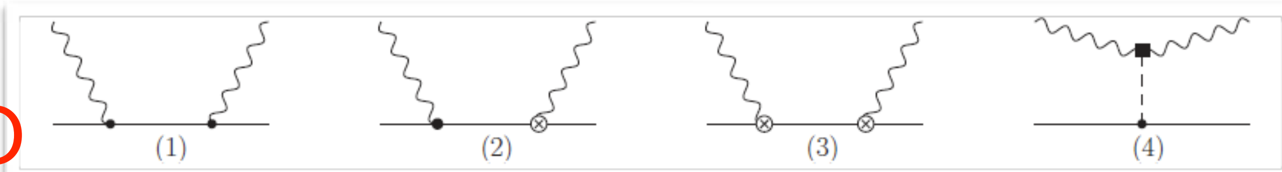


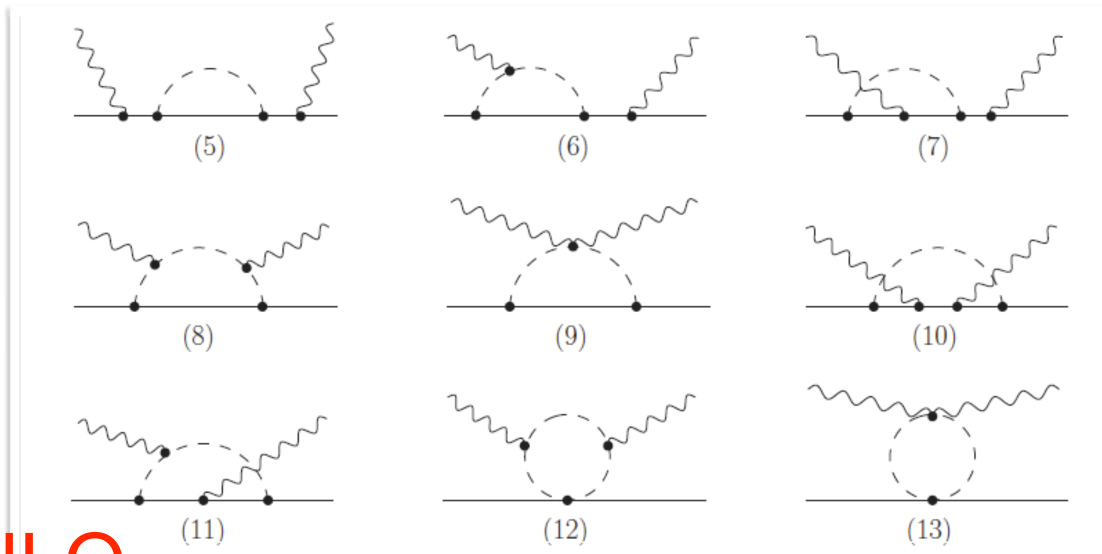


ChPT of Compton scattering off protons

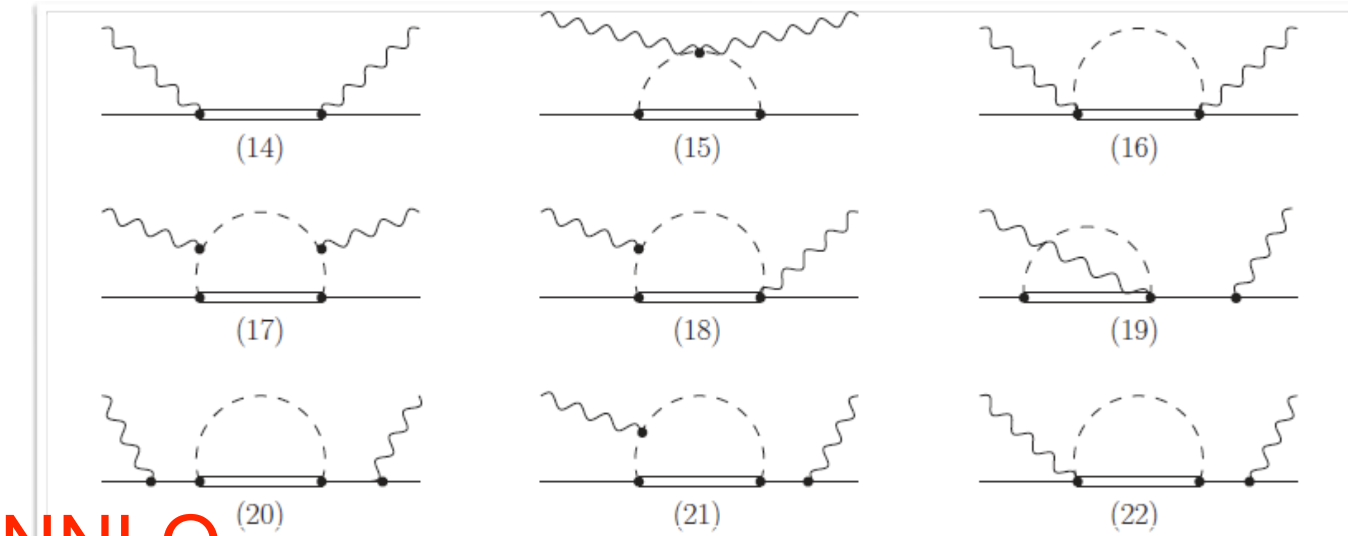
Lensky & V.P., EPJC (2010);
Lensky, McGovern & V.P., EPJC (2015)

LO



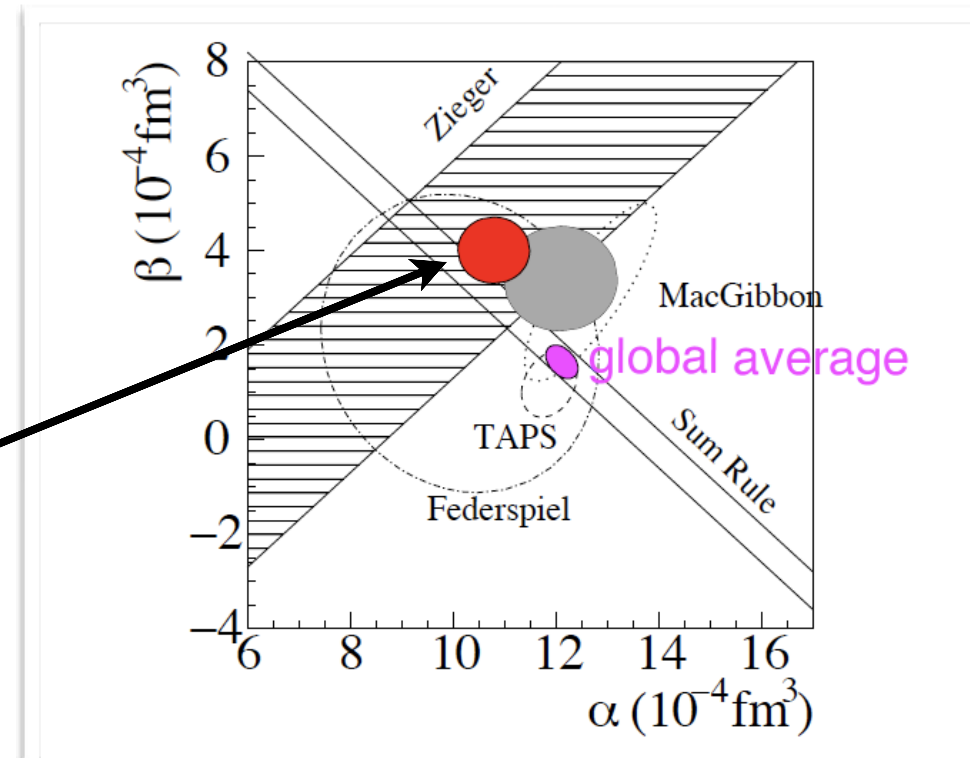


NLO

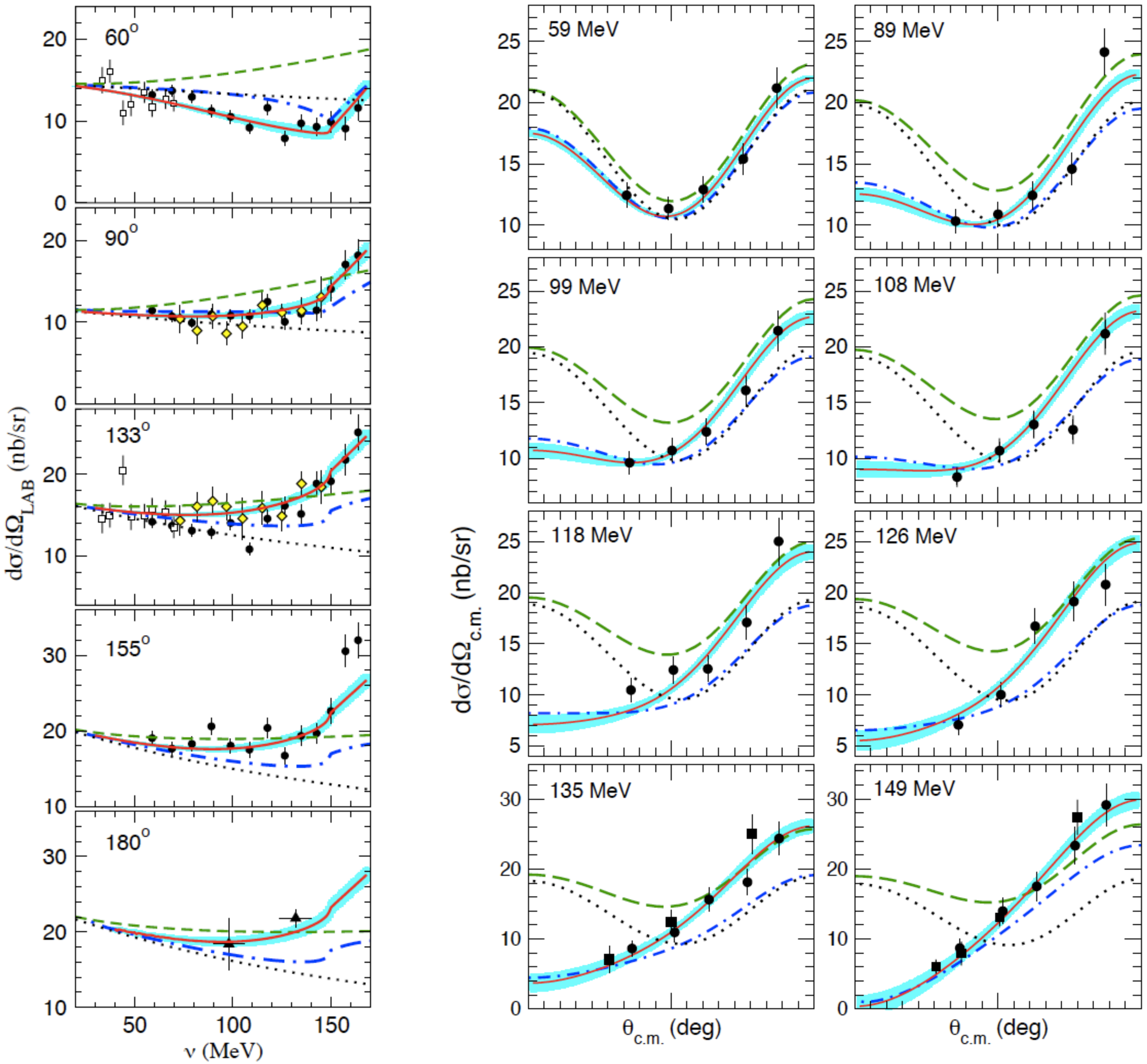


NNLO

$\mathscr{O}(p^2)$	$\frac{e^2}{4\pi} = \frac{1}{137}$, $M_N = 938.3$ MeV, $\hbar c = 197$ MeV$\cdot$fm
$\mathscr{O}(p^3)$	$g_A = 1.267$, $f_\pi = 92.4$ MeV, $m_\pi = 139$ MeV, $m_{\pi^0} = 136$ MeV, $\kappa_p = 1.79$
$\mathscr{O}(p^4/\Delta)$	$M_\Delta = 1232$ MeV, $h_A = 2.85$, $g_M = 2.97$, $g_E = -1.0$
$\mathscr{O}(p^4)$	$\alpha_0, \beta_0 = \pm \frac{e^2}{4\pi M_N^3}$ size of the red blob



Unpolarized cross sections for RCS



Data points:
MAMI/TAPS (2001)
SAL (1993)
Illinois (1991)

Curves:

Klein-Nishina

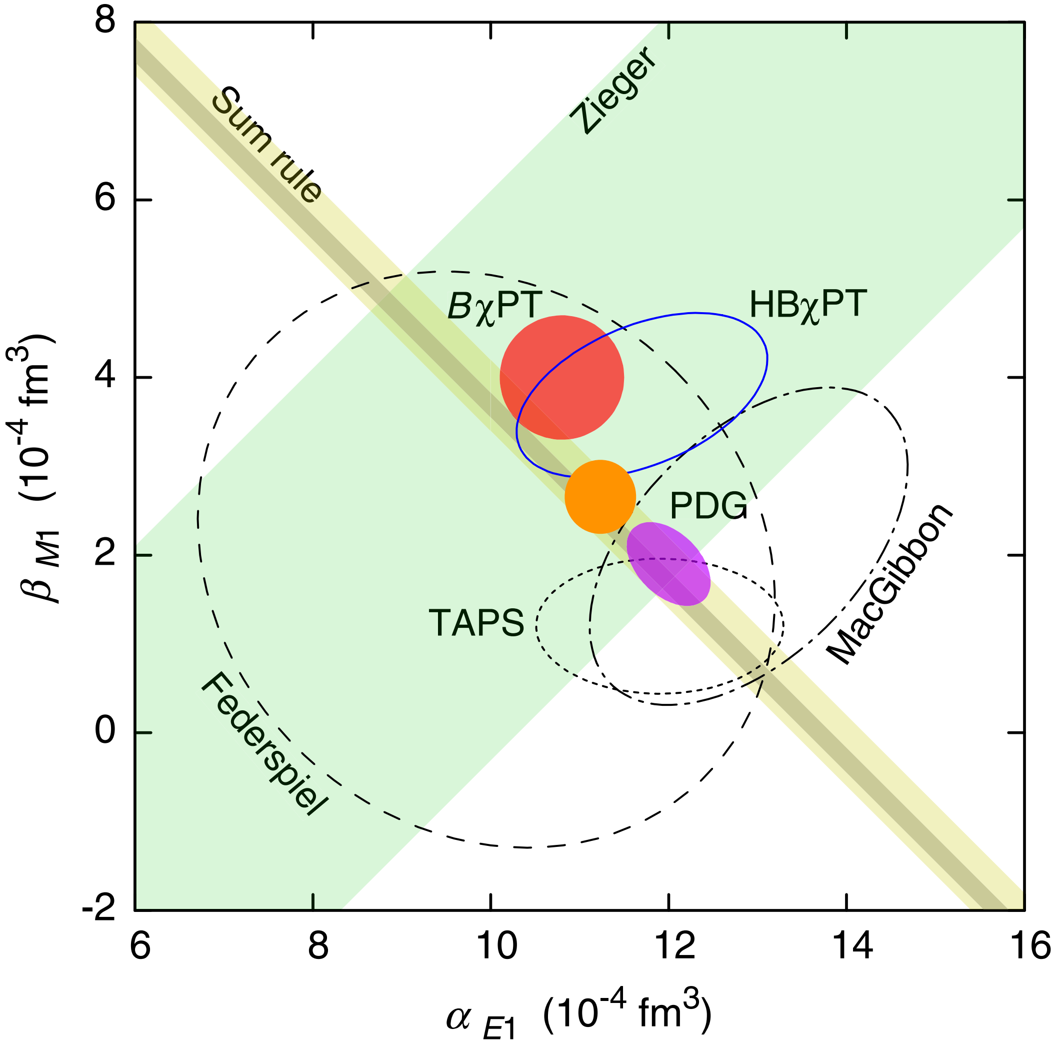
Born + WZW

+ p-qube

Total NNLO

Lensky & V.P.,EPJC (2010)

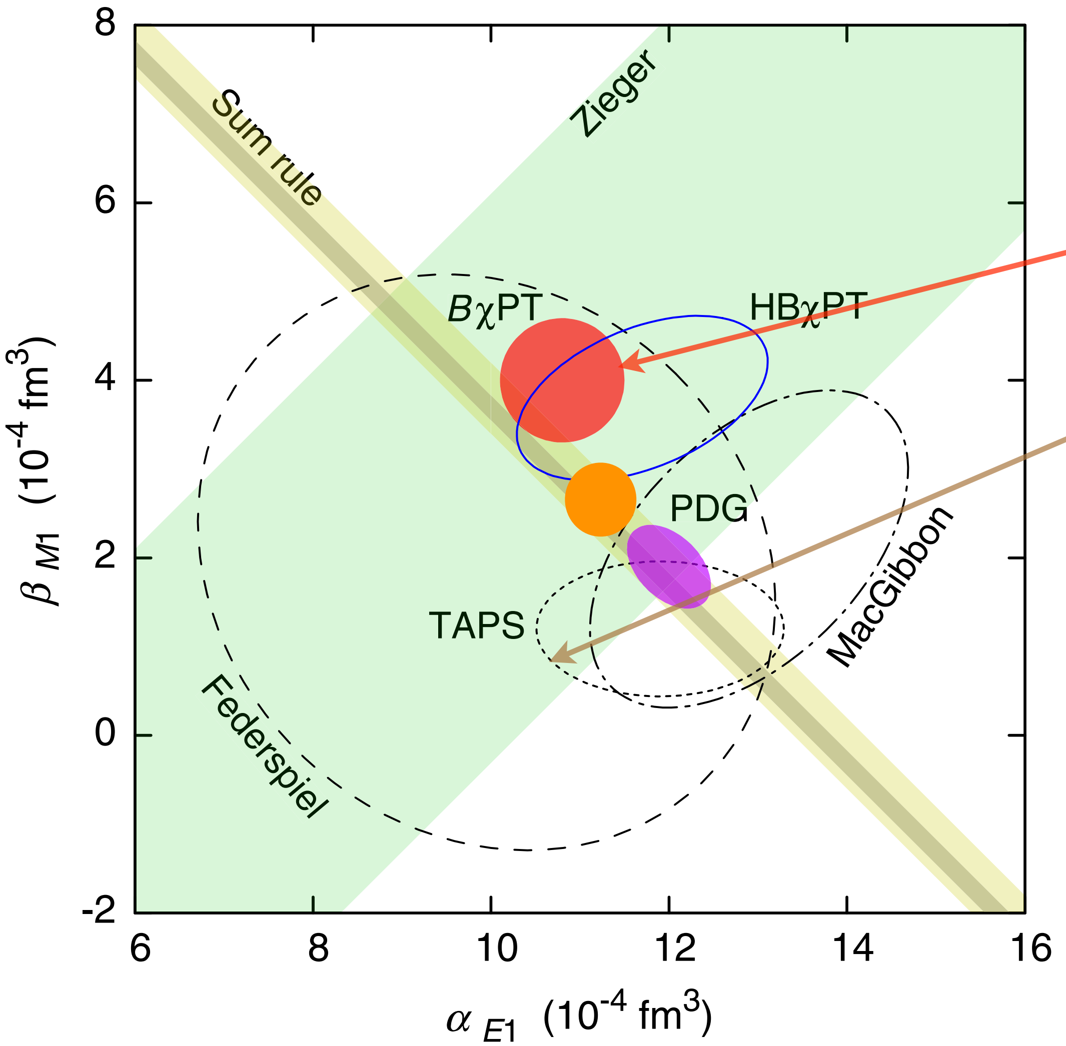
Proton polarizabilities from Compton scattering

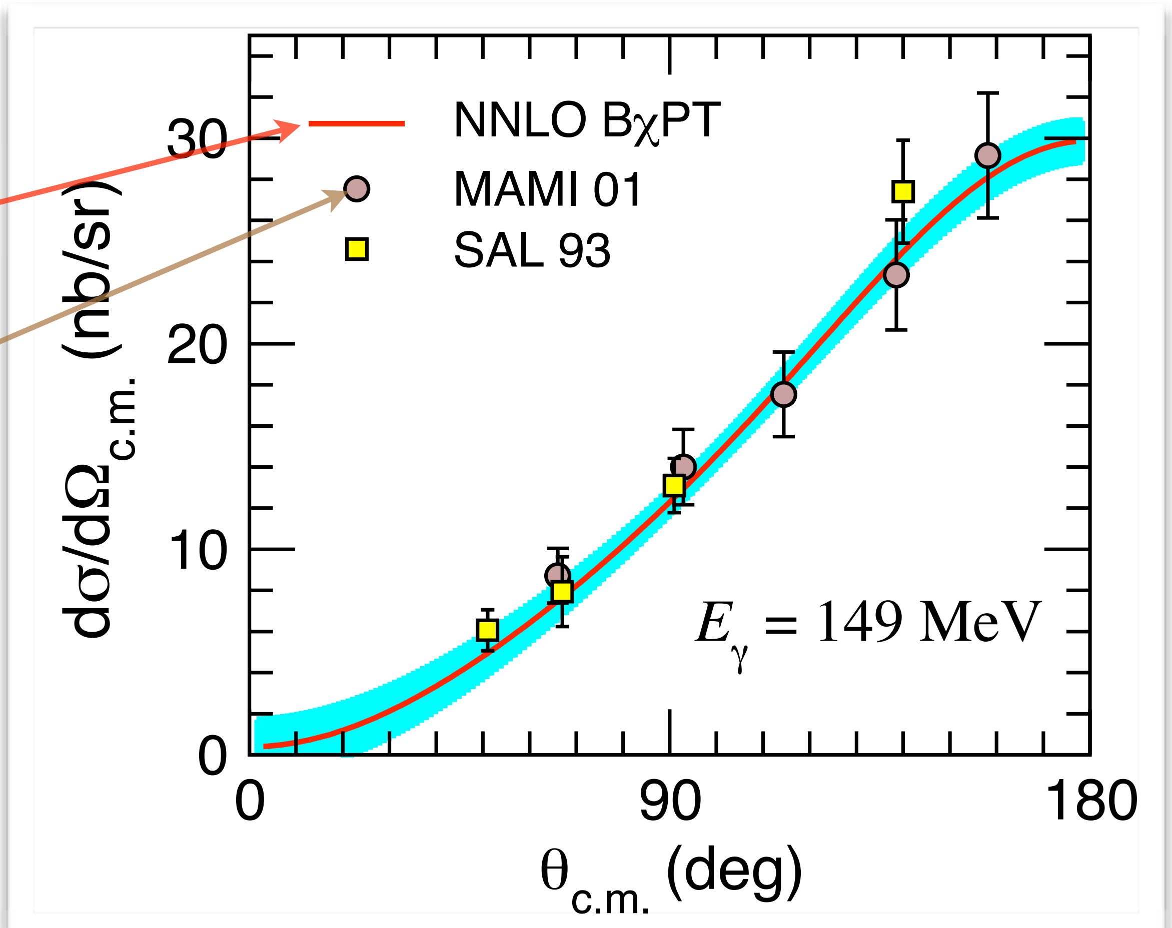


BChPT - Lensky & V.P., EPJC(2010)

HBChPT - Griesshammer, McGovern, Phillips, EPJA (2013)

Proton polarizabilities from Compton scattering





BChPT - Lensky & V.P., EPJC(2010)

HBChPT - Griesshammer, McGovern, Phillips, EPJA (2013)

$$\beta_{M1} = (1.9 \pm 0.5) \times 10^{-4}\,\mathrm{fm}^3 \ \text{[PDG]}$$

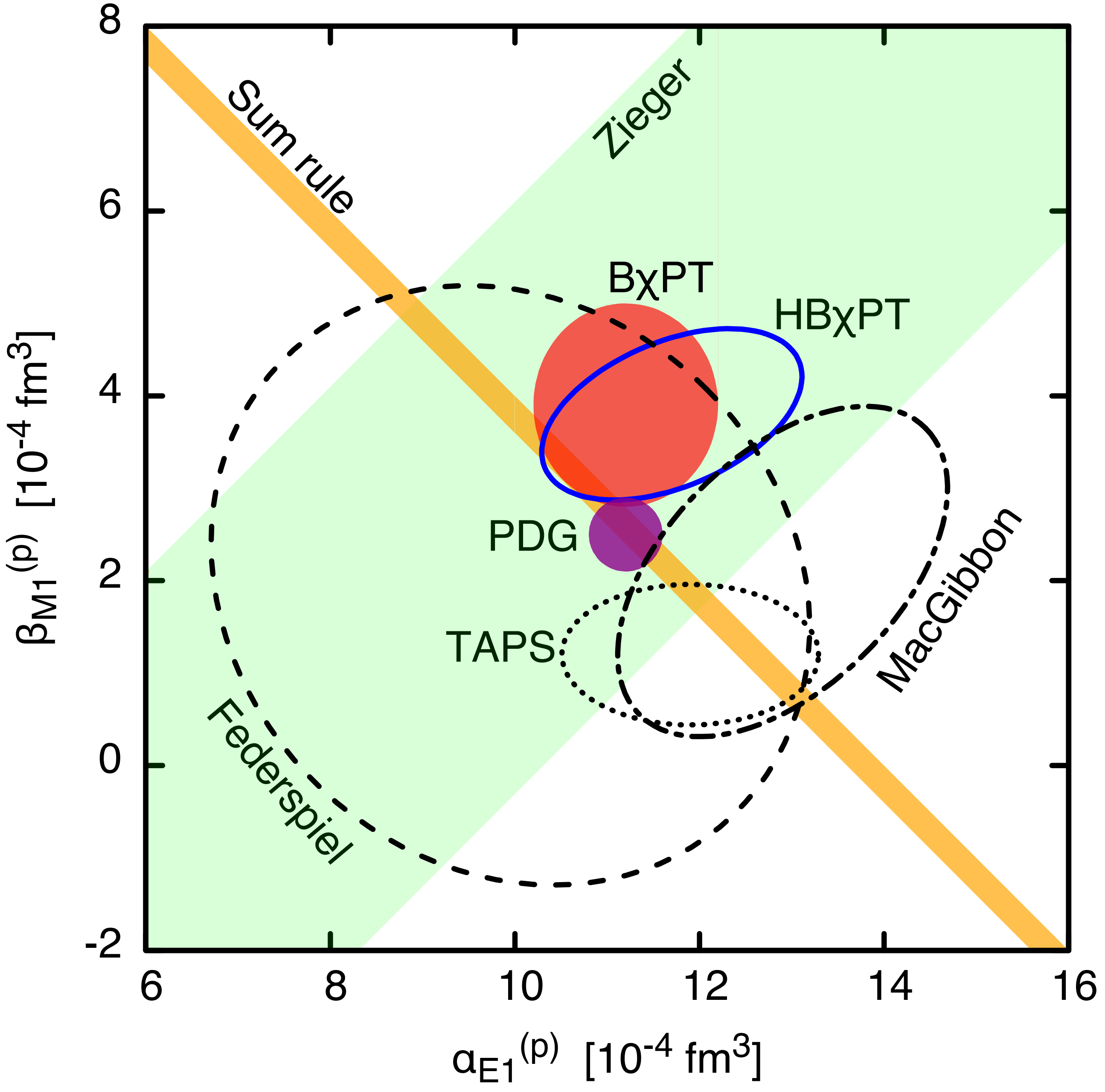
$$\beta_{M1} = (4.0 \pm 0.7) \times 10^{-4}\,\mathrm{fm}^3 \ \text{[BChPT@NNLO]}$$

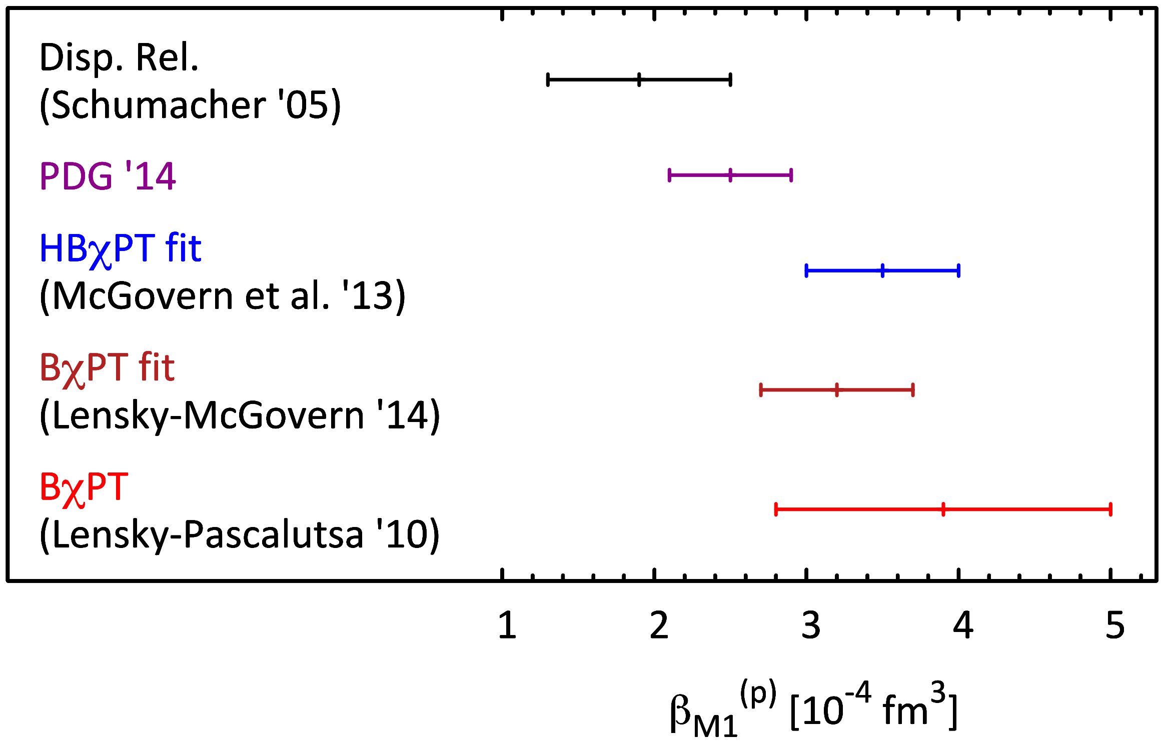
PDG adjusted values

from 2012 edition (purple) to

2013 on-line edition (orange)

Status of proton polarizabilities





Polarizability contribution in ChPT

Eur. Phys. J. C (2014) 74:2852
DOI 10.1140/epjc/s10052-014-2852-0

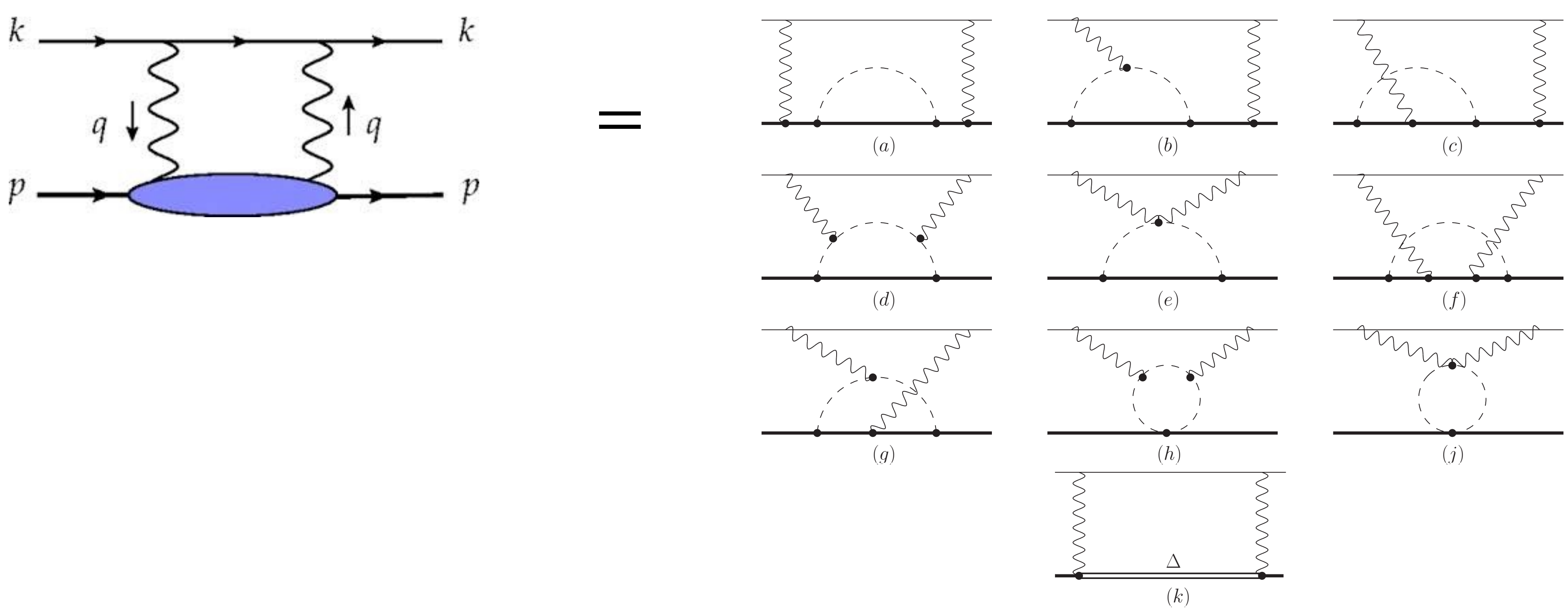
THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

Chiral perturbation theory of muonic-hydrogen Lamb shift: polarizability contribution

Jose Manuel Alarcón[1,a], **Vadim Lensky**[2,3], **Vladimir Pascalutsa**[1]

[1] Cluster of Excellence PRISMA Institut für Kernphysik, Johannes Gutenberg-Universität, Mainz 55099, Germany
[2] Theoretical Physics Group, School of Physics and Astronomy, University of Manchester, Manchester M13 9PL, UK
[3] Institute for Theoretical and Experimental Physics, Bol’shaya Cheremushkinskaya 25, 117218 Moscow, Russia



with corrections to elastic proton FFs subtracted, i.e. “polarizability” alone

Proton polarizability effect in mu-H

Heavy-Baryon (HB)ChPT

[Alarcon, Lensky & VP, EPJC (2014)]

(μeV)	Pachucki [9]	Martynenko [10]	Nevado and Pineda [11]	Carlson and Vanderhaeghen [12]	Birse and McGovern [13]	Gorchtein et al. [14]	LO-BχPT [this work]
$\Delta E^{(\text{subt})}_{2S}$	1.8	2.3	–	5.3 (1.9)	4.2 (1.0)	−2.3 (4.6)[a]	−3.0
$\Delta E^{(\text{inel})}_{2S}$	−13.9	−13.8	–	−12.7 (5)	−12.7 (5)[b]	−13.0 (6)	−5.2
$\Delta E^{(\text{pol})}_{2S}$	−12 (2)	−11.5	−18.5	−7.4 (2.4)	−8.5 (1.1)	−15.3 (5.6)	$-8.2(^{+1.2}_{-2.5})$

[a] Adjusted value; the original value of Ref. [14], +3.3, is based on a different decomposition into the 'elastic' and 'polarizability' contributions
[b] Taken from Ref. [12]

[9] K. Pachucki, Phys. Rev. A **60**, 3593 (1999).
[10] A. P. Martynenko, Phys. Atom. Nucl. **69**, 1309 (2006).
[11] D. Nevado and A. Pineda, Phys. Rev. C **77**, 035202 (2008).
[12] C. E. Carlson and M. Vanderhaeghen, Phys. Rev. A **84**, 020102 (2011).
[13] M. C. Birse and J. A. McGovern, Eur. Phys. J. A **48**, 120 (2012).
[14] M. Gorchtein, F. J. Llanes-Estrada and A. P. Szczepaniak, Phys. Rev. A 87, **052501** (2013).

Proton polarizability effect in mu-H

Heavy-Baryon (HB)ChPT

[Alarcon, Lensky & VP, EPJC (2014)]

(μeV)	Pachucki [9]	Martynenko [10]	Nevado and Pineda [11]	Carlson and Vanderhaeghen [12]	Birse and McGovern [13]	Gorchtein et al. [14]	LO-BχPT [this work]
$\Delta E_{2S}^{(\mathrm{subt})}$	1.8	2.3	–	5.3 (1.9)	4.2 (1.0)	−2.3 (4.6)[a]	−3.0
$\Delta E_{2S}^{(\mathrm{inel})}$	−13.9	−13.8	–	−12.7 (5)	−12.7 (5)[b]	−13.0 (6)	−5.2
$\Delta E_{2S}^{(\mathrm{pol})}$	−12 (2)	−11.5	−18.5	−7.4 (2.4)	−8.5 (1.1)	−15.3 (5.6)	$-8.2(^{+1.2}_{-2.5})$

[a] Adjusted value; the original value of Ref. [14], +3.3, is based on a different decomposition into the 'elastic' and 'polarizability' contributions
[b] Taken from Ref. [12]

[9] K. Pachucki, Phys. Rev. A **60**, 3593 (1999).
[10] A. P. Martynenko, Phys. Atom. Nucl. **69**, 1309 (2006).
[11] D. Nevado and A. Pineda, Phys. Rev. C **77**, 035202 (2008).
[12] C. E. Carlson and M. Vanderhaeghen, Phys. Rev. A **84**, 020102 (2011).
[13] M. C. Birse and J. A. McGovern, Eur. Phys. J. A **48**, 120 (2012).
[14] M. Gorchtein, F. J. Llanes-Estrada and A. P. Szczepaniak, Phys. Rev. A 87, **052501** (2013).

$$\Delta E_{2S}^{(\mathrm{pol})}(\text{LO-HB}\chi\text{PT}) \approx \frac{\alpha_{\mathrm{em}}^5 m_r^3 g_A^2}{4(4\pi f_\pi)^2}\frac{m_\mu}{m_\pi}(1-10G+6\log 2) = -16.1\ \mu\mathrm{eV},$$

Proton polarizability effect in mu-H

Heavy-Baryon (HB)ChPT

[Alarcon, Lensky & VP, EPJC (2014)]

(μeV)	Pachucki [9]	Martynenko [10]	Nevado and Pineda [11]	Carlson and Vanderhaeghen [12]	Birse and McGovern [13]	Gorchtein et al. [14]	LO-BχPT [this work]
$\Delta E_{2S}^{(\mathrm{subt})}$	1.8	2.3	–	5.3 (1.9)	4.2 (1.0)	−2.3 (4.6)[a]	−3.0
$\Delta E_{2S}^{(\mathrm{inel})}$	−13.9	−13.8	–	−12.7 (5)	−12.7 (5)[b]	−13.0 (6)	−5.2
$\Delta E_{2S}^{(\mathrm{pol})}$	−12 (2)	−11.5	−18.5	−7.4 (2.4)	−8.5 (1.1)	−15.3 (5.6)	$-8.2(^{+1.2}_{-2.5})$

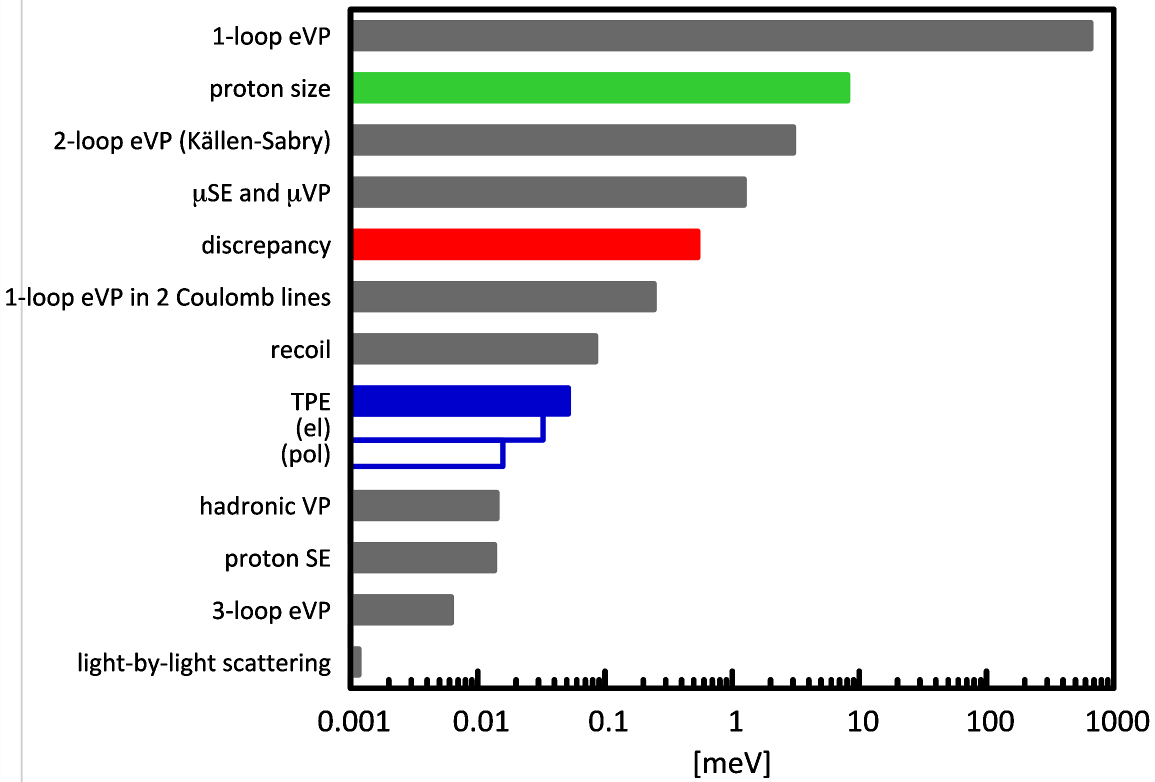
[a] Adjusted value; the original value of Ref. [14], +3.3, is based on a different decomposition into the 'elastic' and 'polarizability' contributions
[b] Taken from Ref. [12]

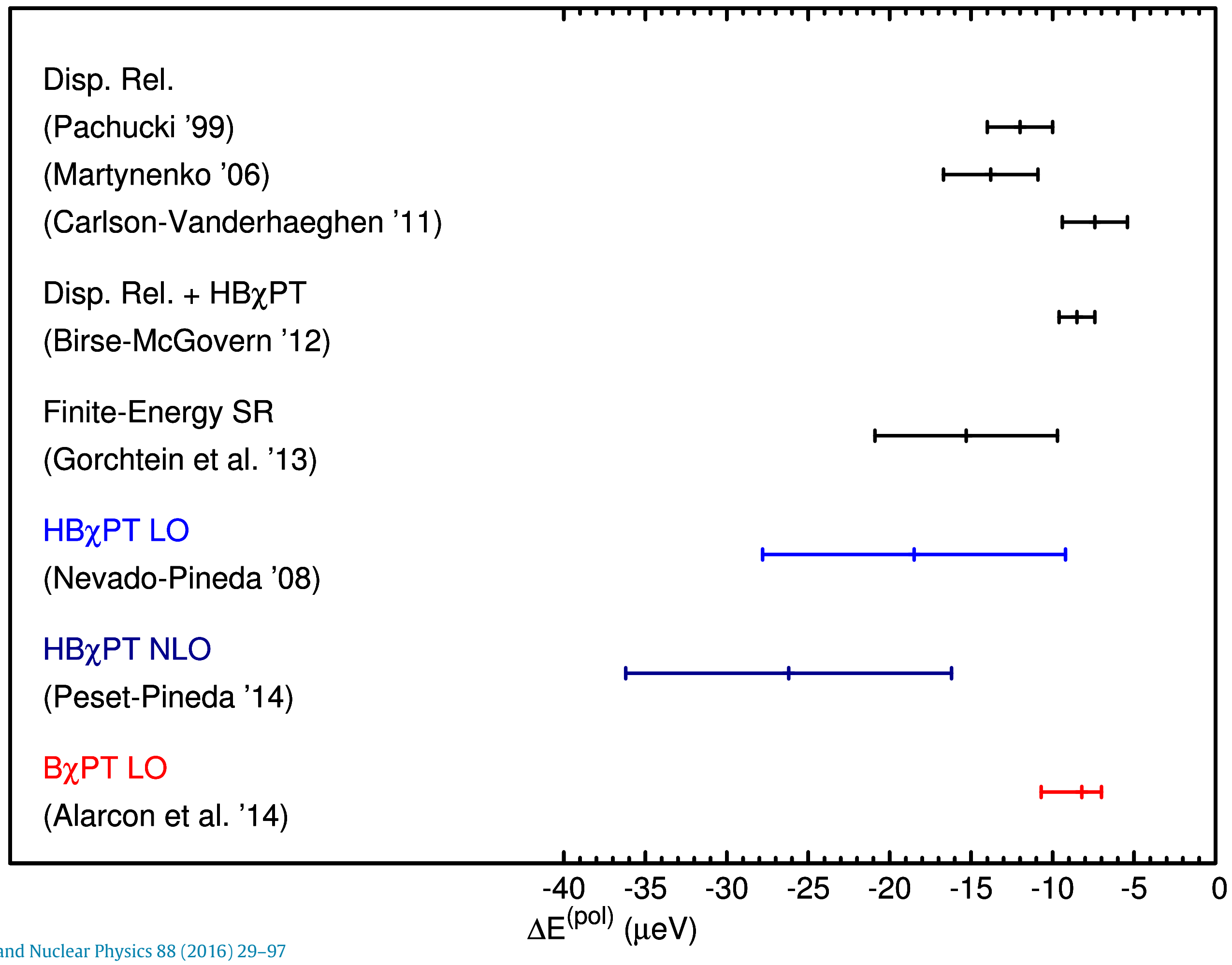
[9] K. Pachucki, Phys. Rev. A **60**, 3593 (1999).
[10] A. P. Martynenko, Phys. Atom. Nucl. **69**, 1309 (2006).
[11] D. Nevado and A. Pineda, Phys. Rev. C **77**, 035202 (2008).
[12] C. E. Carlson and M. Vanderhaeghen, Phys. Rev. A **84**, 020102 (2011).
[13] M. C. Birse and J. A. McGovern, Eur. Phys. J. A **48**, 120 (2012).
[14] M. Gorchtein, F. J. Llanes-Estrada and A. P. Szczepaniak, Phys. Rev. A 87, **052501** (2013).

$$\Delta E_{2S}^{(\mathrm{pol})}(\text{LO-HB}\chi\text{PT}) \approx \frac{\alpha_{\mathrm{em}}^5 m_r^3 g_A^2}{4(4\pi f_\pi)^2}\,\frac{m_\mu}{m_\pi}(1-10G+6\log 2) = -16.1\ \mu\mathrm{eV},$$

$G \simeq 0.9160$ is the Catalan constant.

Summary of polarizability contribution to mu-H Lamb shift





more in

Progress in Particle and Nuclear Physics 88 (2016) 29–97

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

ELSEVIER

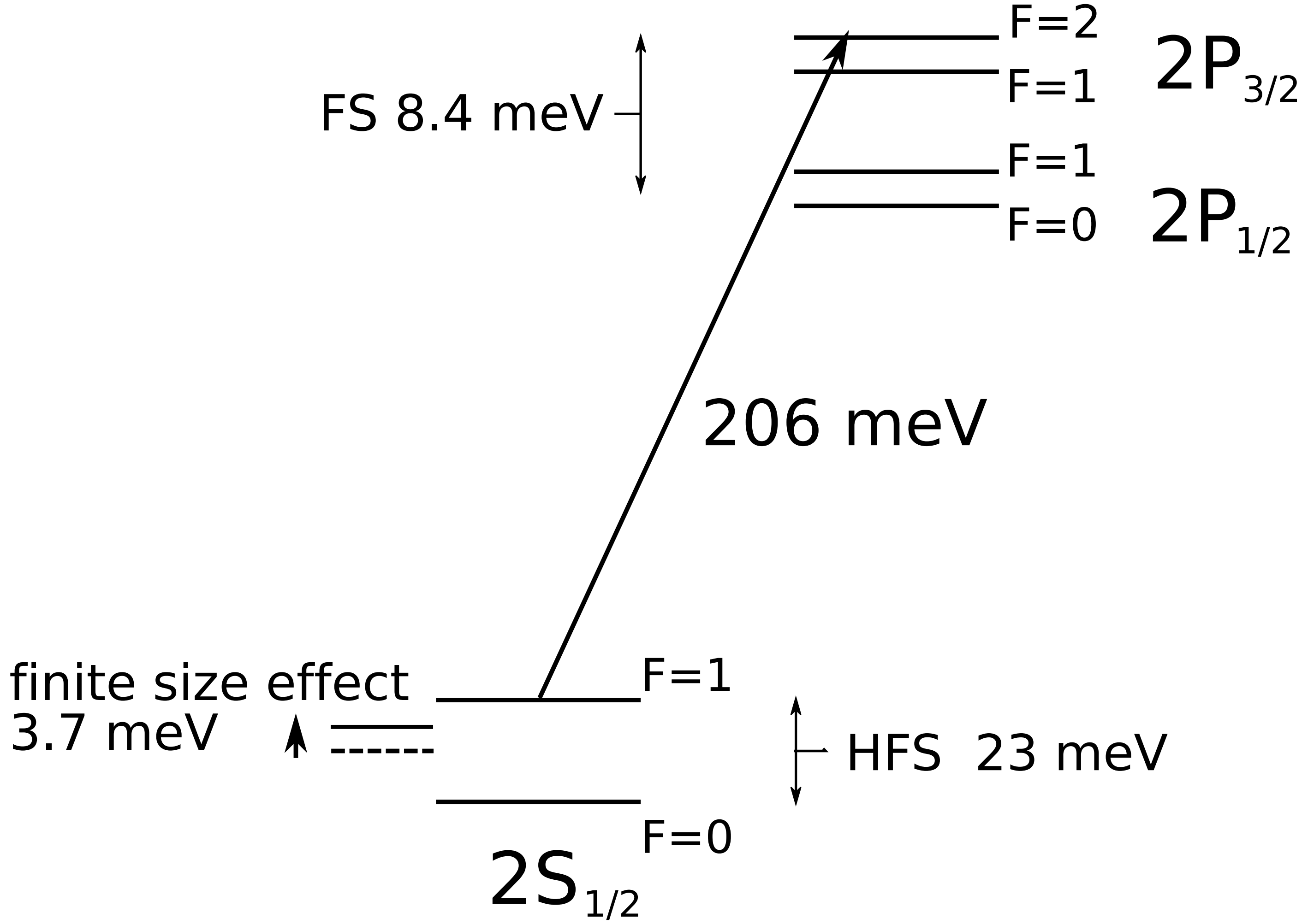
Review

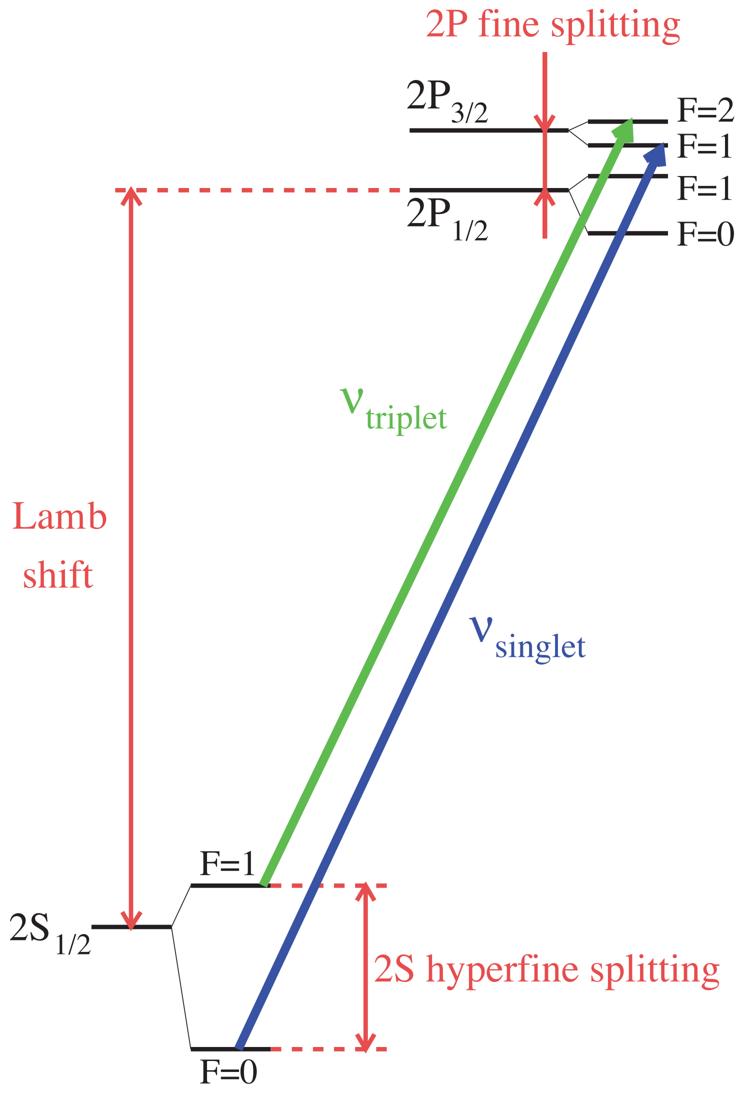
Nucleon polarizabilities: From Compton scattering to hydrogen atom

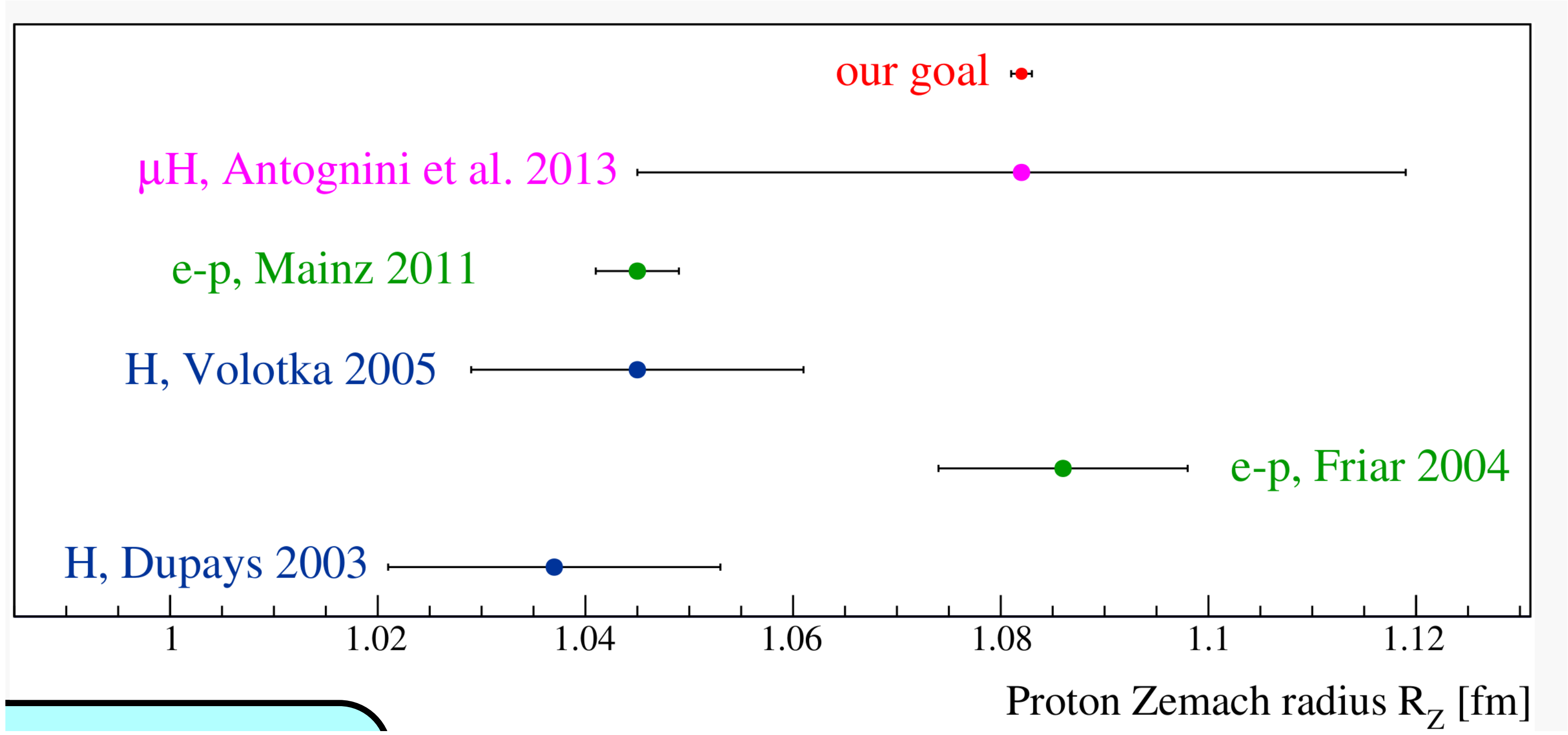
Franziska Hagelstein [a], Rory Miskimen [b], Vladimir Pascalutsa [a,*]

[a] *Institut für Kernphysik and PRISMA Excellence Cluster, Johannes Gutenberg-Universität Mainz, D-55128 Mainz, Germany*
[b] *Department of Physics, University of Massachusetts, Amherst, 01003 MA, USA*

CREMA Collaboration measured 2 transitions in muonic H:
Pohl et al., Nature (2010)
Antognini et al., Science (2013)





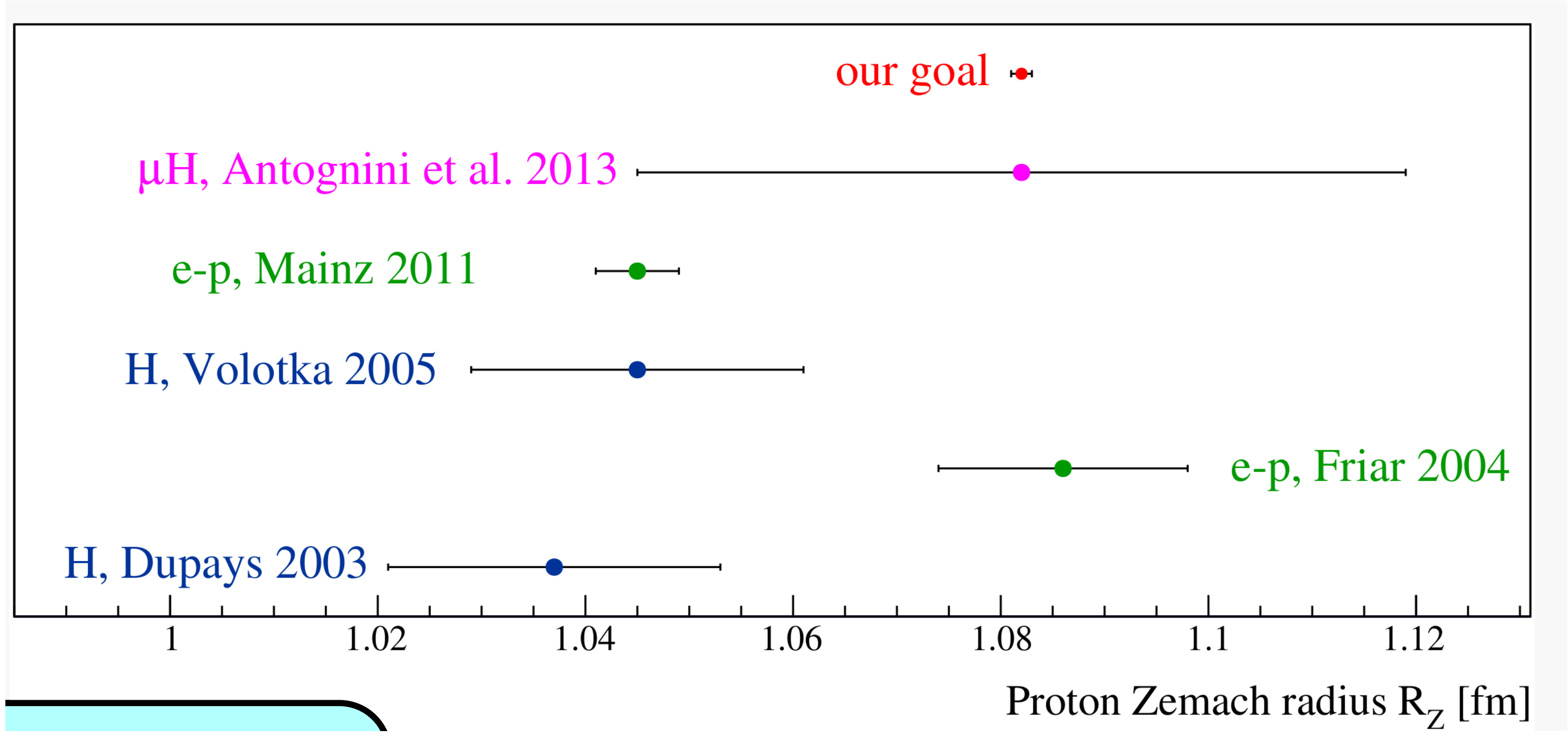

our goal
μH, Antognini et al. 2013
e-p, Mainz 2011
H, Volotka 2005
e-p, Friar 2004
H, Dupays 2003
1
1.02
1.04
1.06
1.08
1.1
1.12
Proton Zemach radius R_Z [fm]

$$\Delta E_{\mathrm{HFS}}^{\mathrm{exp}} = 22.8089(51)\,\mathrm{meV}$$

$$\Delta E_{\mathrm{HFS}}^{\mathrm{th}} = 22.9763(15) - 0.1621(10)\,(R_Z/\mathrm{fm}) + \Delta E_{\mathrm{HFS}}^{(\mathrm{pol})}$$

Zemach radius: $$R_Z = -\frac{4}{\pi}\int_0^\infty \frac{\mathrm{d}Q}{Q^2}\left[\frac{G_E(Q^2)G_M(Q^2)}{1+\varkappa} - 1\right]$$

from 2S HFS:
$1.082(37)$ [fm]



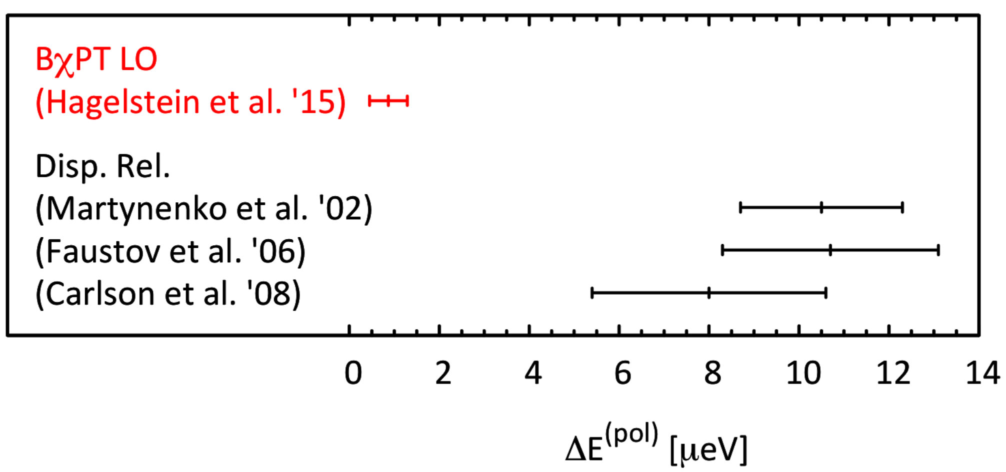
1S HFS: New experiment (approved)

HFS theory status

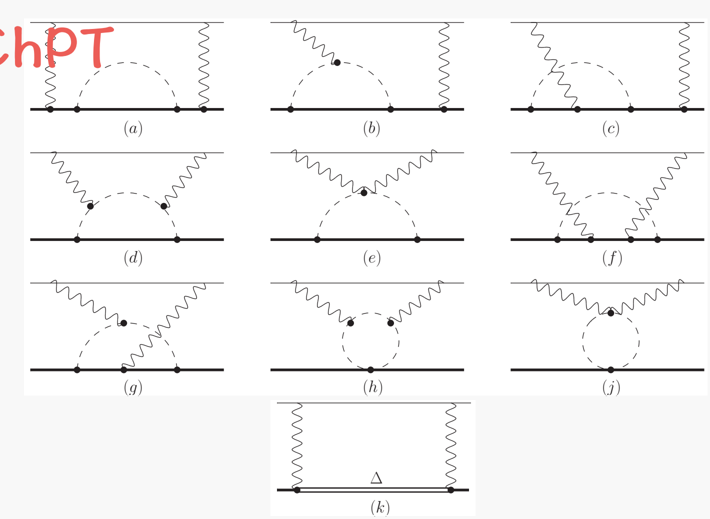
$$\Delta E_{\mathrm{HFS}}(1S) = [1 + \Delta_{\mathrm{QED}} + \Delta_{\mathrm{weak+hVP}} + \underbrace{\Delta_{\mathrm{Zemach}} + \Delta_{\mathrm{recoil}} + \Delta_{\mathrm{pol}}}_{\Delta_{\mathrm{TPE}}}]\Delta E_0^{\mathrm{HFS}}$$

Phys. Rev. A 68 052503, Phys. Rev. A 83, 042509, Phys. Rev. A 71, 022506

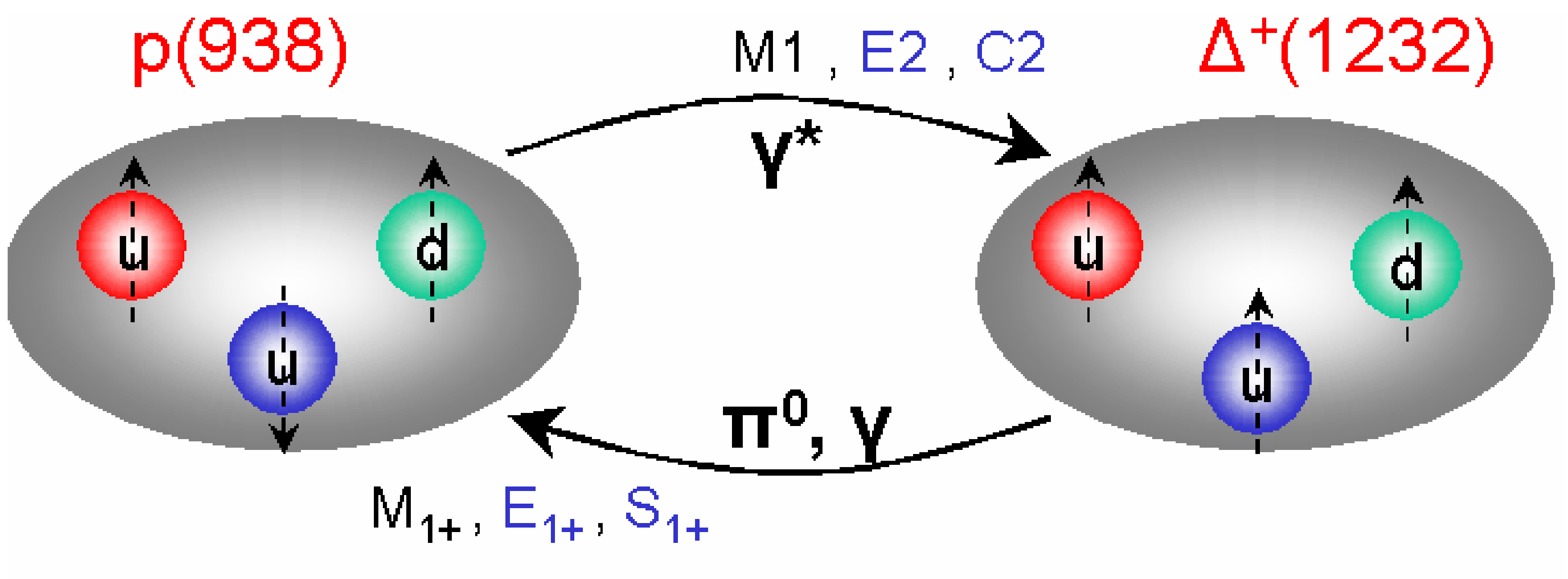
	μp		$\mu\,{}^3\mathrm{He}^+$		
	Magnitude	Uncertainty	Magnitude	Uncertainty	
$\Delta E_0^{\mathrm{HFS}}$	182.443 meV	0.1×10^{-6}	1370.725 meV	0.1×10^{-6}	
Δ_{QED}	1.1×10^{-3}	1×10^{-6}	1.2×10^{-3}	1×10^{-6}	
$\Delta_{\mathrm{weak+hVP}}$	2×10^{-5}	2×10^{-6}			
Δ_{Zemach}	7.5×10^{-3}	7.5×10^{-5}	3.5×10^{-2}	2.2×10^{-4}	$\leftarrow G_E(Q^2), G_M(Q^2)$
Δ_{recoil}	1.7×10^{-3}	10^{-6}	2×10^{-4}		$\leftarrow G_E, G_M, F_1, F_2$
Δ_{pol}	4.6×10^{-4}	8×10^{-5}	$(3.5 \times 10^{-3})^*$	$(2.5 \times 10^{-4})^*$	$\leftarrow g_1(x,Q^2), g_2(x,Q^2)$

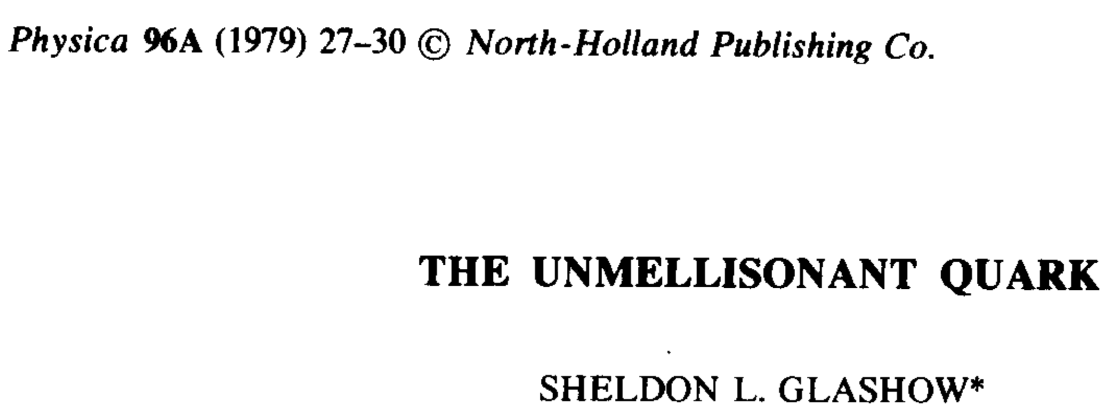


HFS calculation in ChPT



Delta(1232) and proton deformation




Physica 96A (1979) 27–30 © North-Holland Publishing Co.

THE UNMELLISONANT QUARK

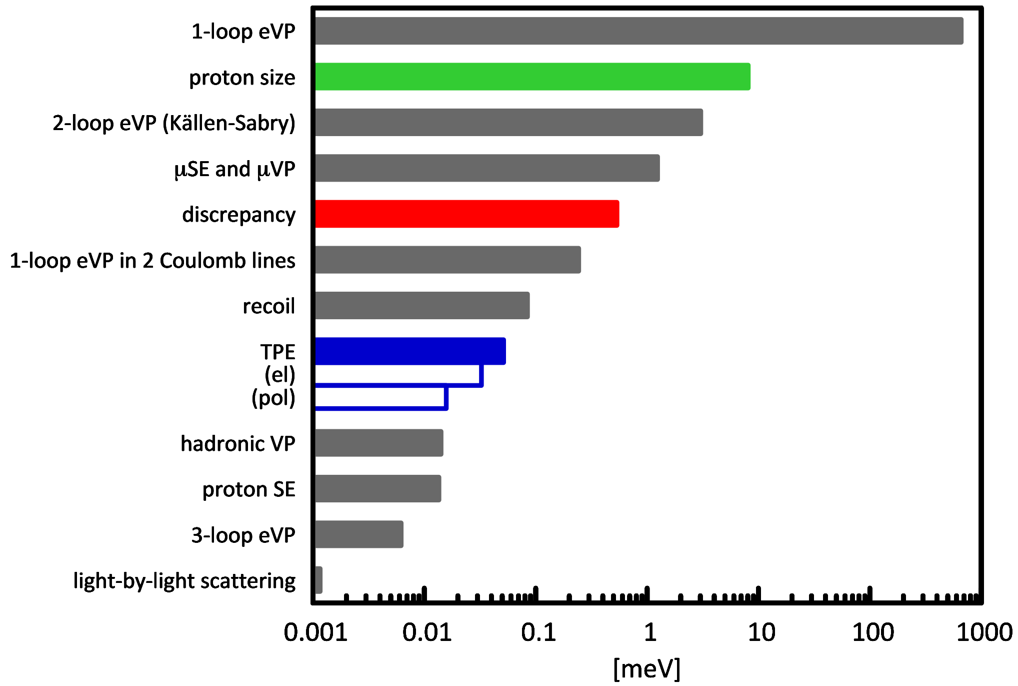
SHELDON L. GLASHOW*

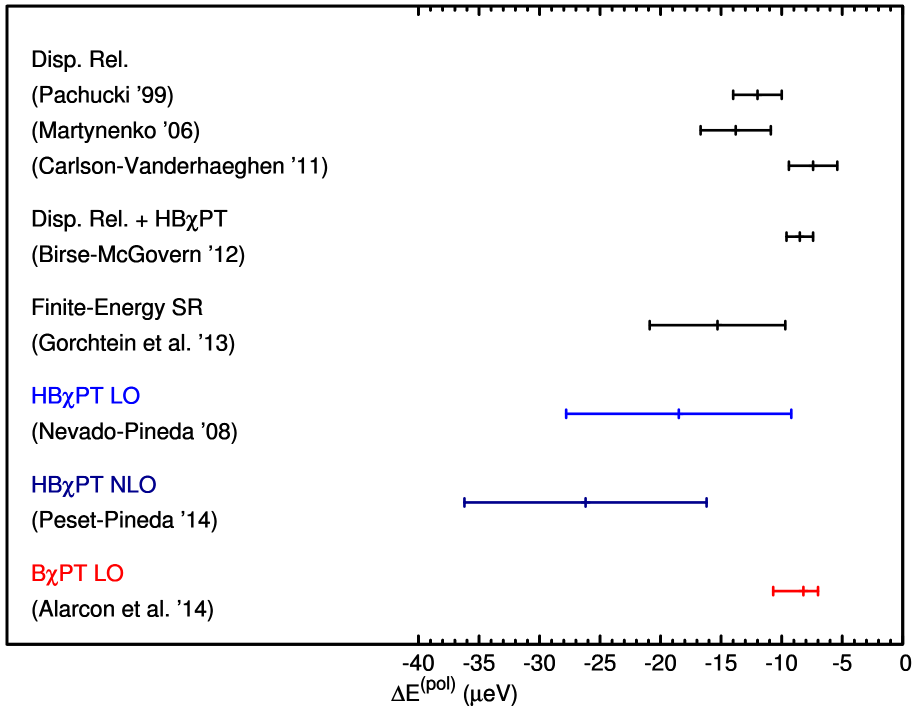
Quadrupole N-> Delta transitions signatures of nucleon deformation

Summary and outlook

Proton radius puzzle not solved…

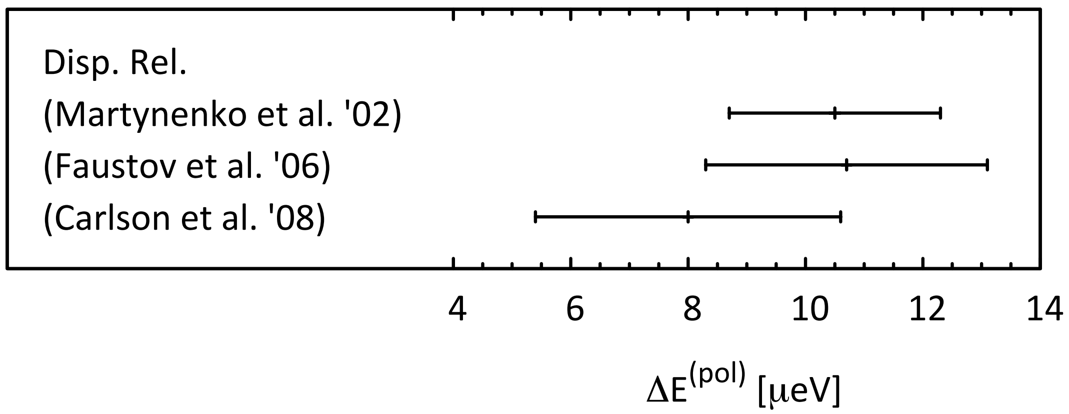
polarizability contribution to Lamb shift small but dominates the uncertainty in muH





Polarizability contribution to mu-H 2S HFS:

Order of magnitude in experimental precision from from the future 1S HFS experiment



need systematic theoretical understanding of proton Compton scattering to interpret the mu-H results, better than 1% understanding of proton structure effects

Collaborators

Oleksii Gryniuk (Mainz)

Franziska Hagelstein (Mainz)

Nadiia Krupina (Mainz)

Jose Alarcon (Bonn)

Vadim Lensky (Mainz)

Judith McGovern (Manchester)

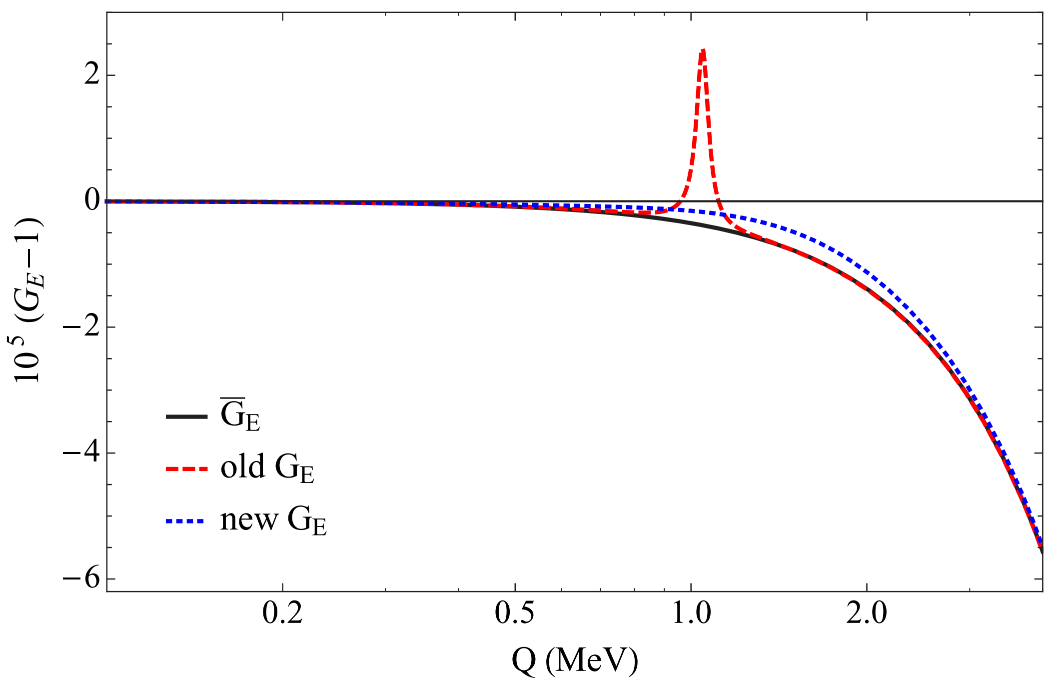
Rory Miskimen (Amherst)

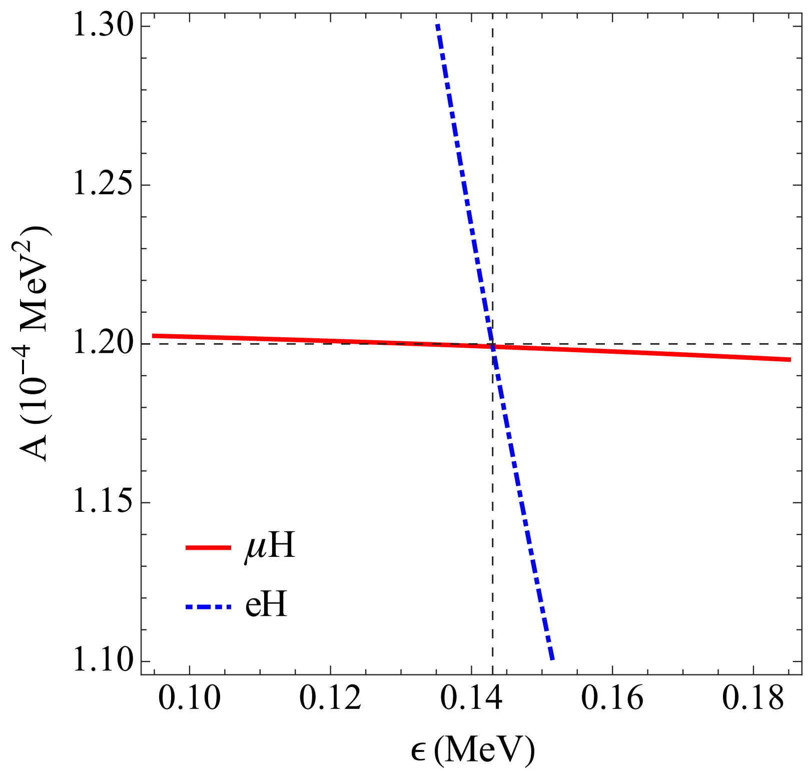
Marc Vanderhaeghen (Mainz)

Backup slides

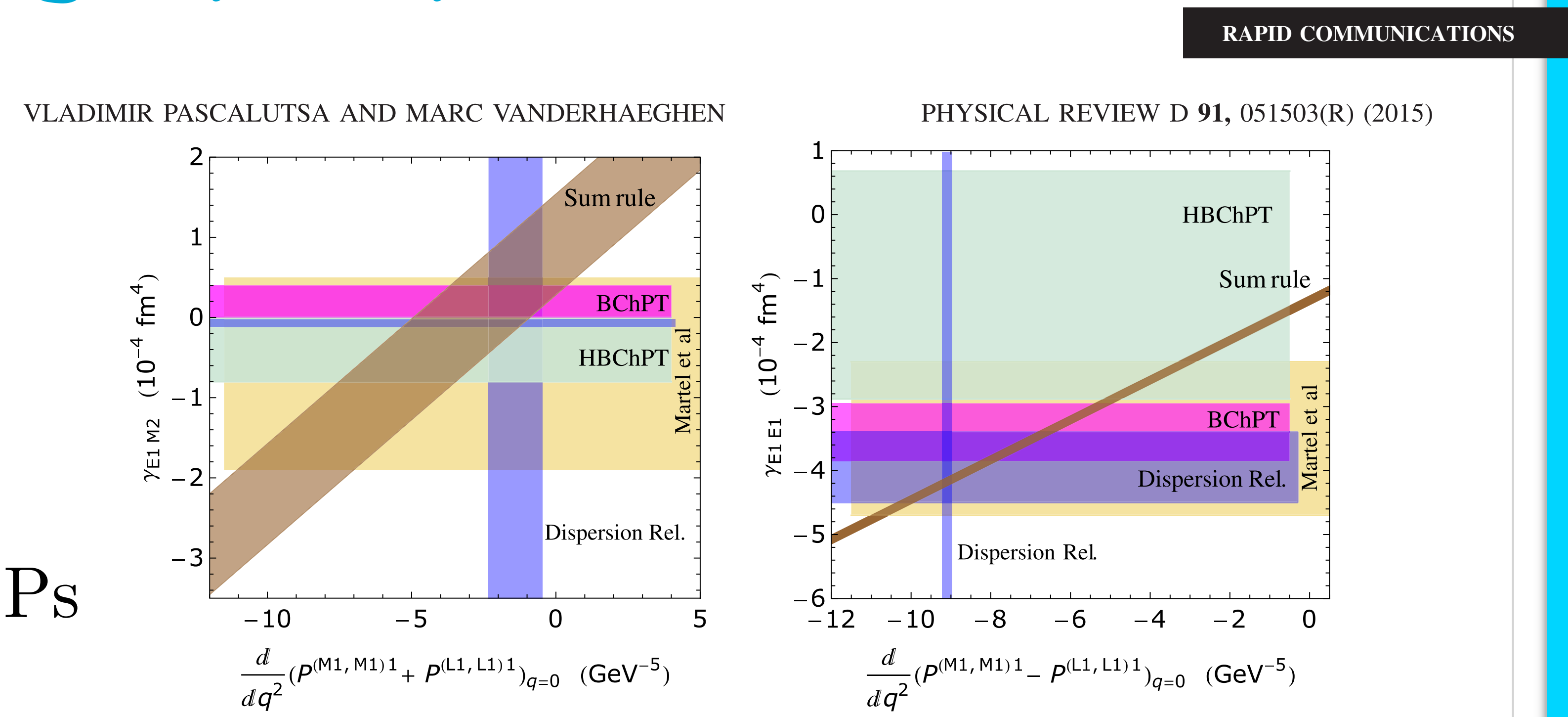
Soft effects in FFs

$$\widetilde{G}_E(Q^2) = \frac{A\, Q_0^2 Q^2 [Q^2+\epsilon^2]}{[Q_0^2+Q^2]^4}$$

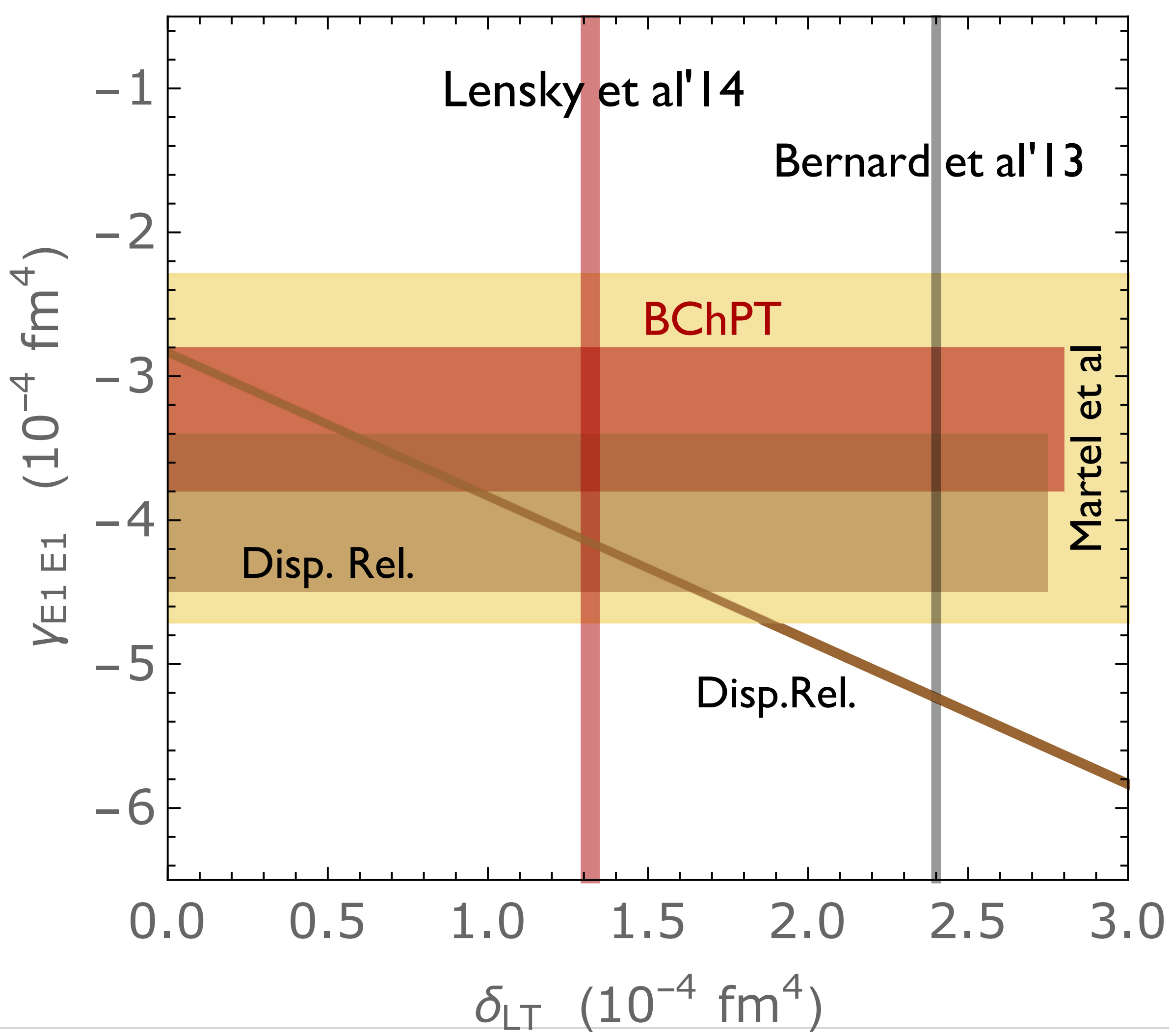




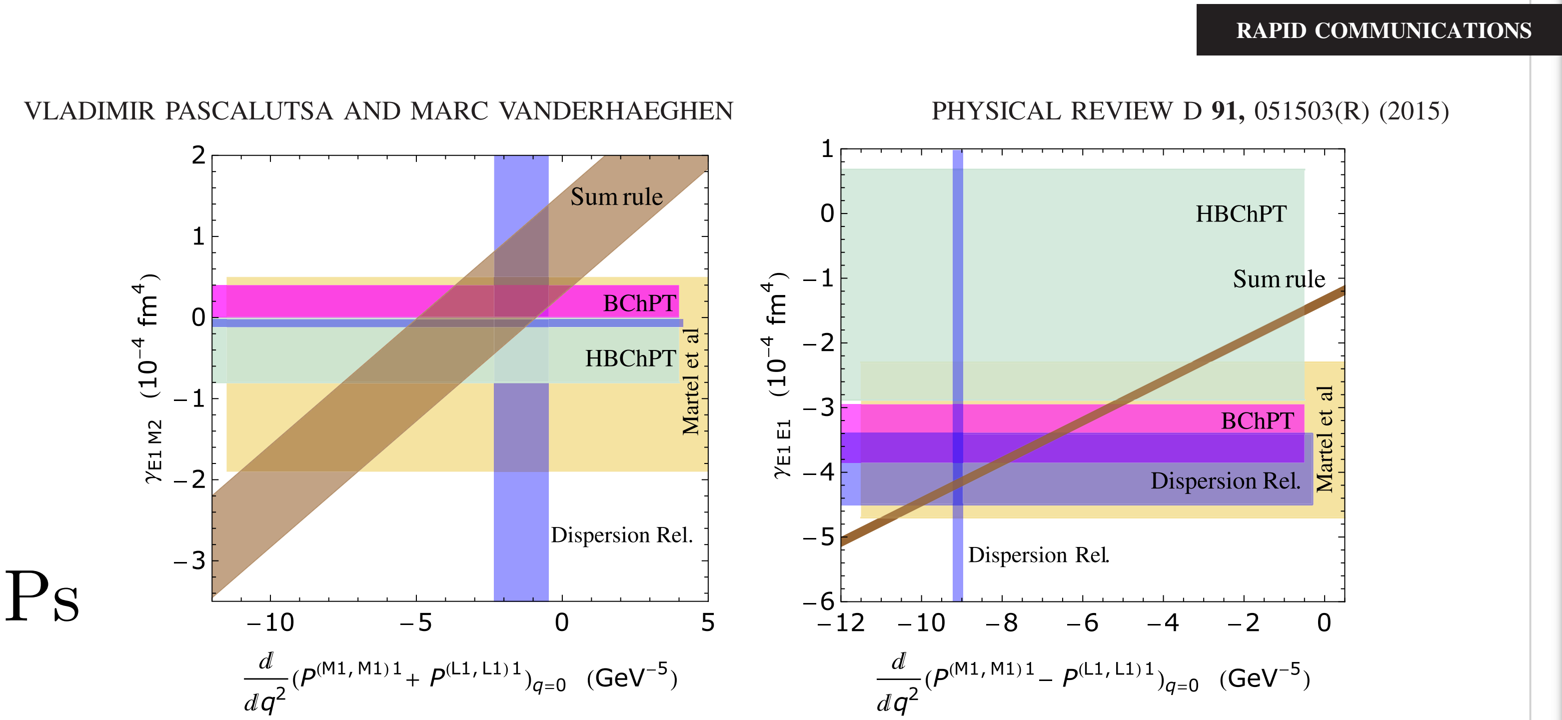
Relations among spin polarizabilities



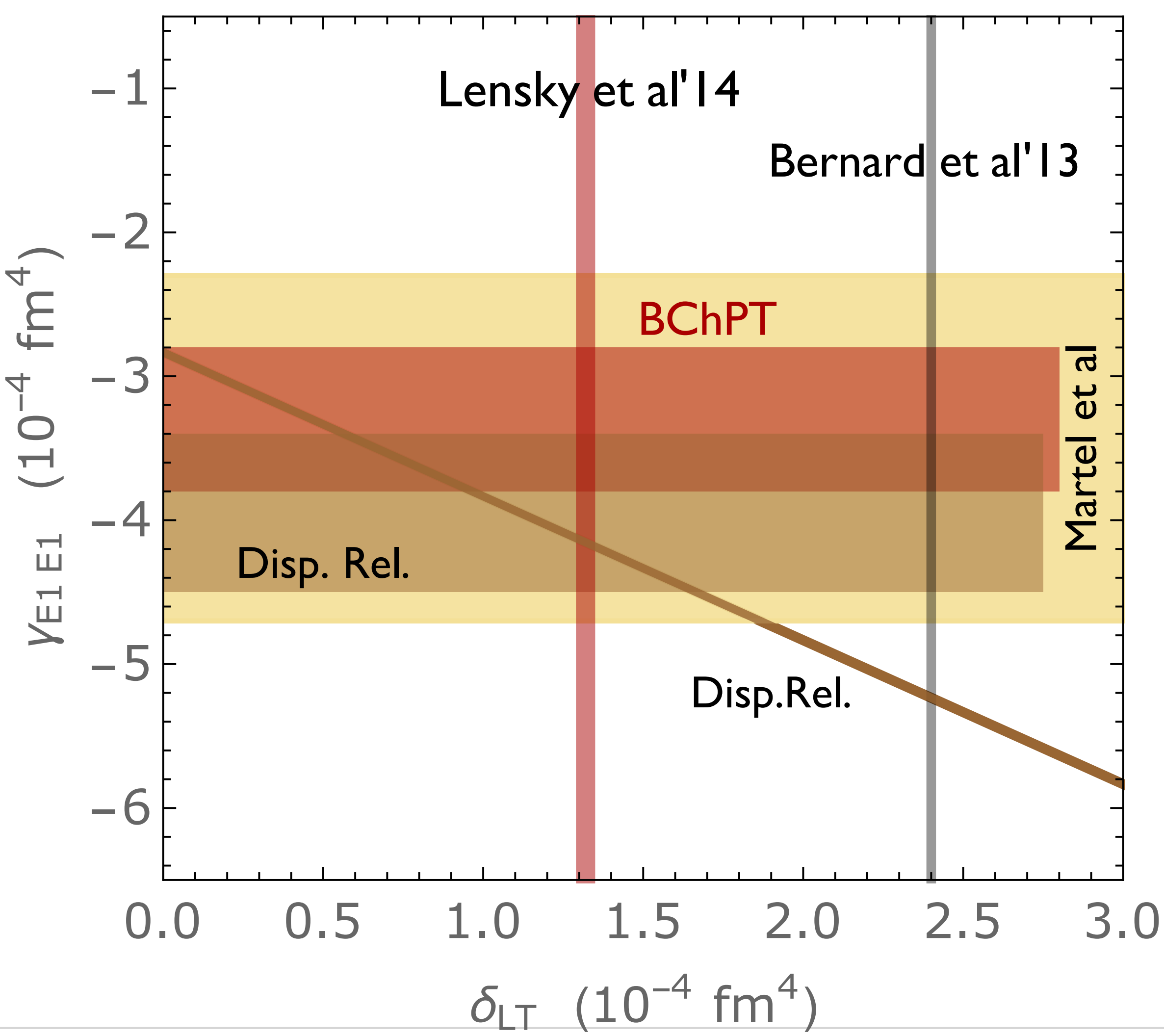
$$\delta_{LT} = -\gamma_{E1E1} + \text{VCS spin GPs}$$



Relations among spin polarizabilities



$$\delta_{LT} = -\gamma_{E1E1} + \text{VCS spin GPs}$$



1) Disp. Rel. (Pasquini et al) uses MAID as input for RCS and VCS and is consistent with MAID value of δ_{LT}

2) Lensky, Kao, Vanderhaeghen & V.P (in progress): verify the relation

$$\delta_{LT} = -\gamma_{E1E1} + \text{VCS spin GPs}$$

in baryon and heavy-baryon ChPT.

Spin polarizabilities

$$H_{\text{eff}}^{(2)} = -4\pi \left(\tfrac{1}{2}\alpha_{E1}\boldsymbol{E}^2 + \tfrac{1}{2}\beta_{M1}\boldsymbol{H}^2\right),$$

$$H_{\text{eff}}^{(3)} = -4\pi \left(\tfrac{1}{2}\gamma_{E1E1}\boldsymbol{\sigma}\cdot(\boldsymbol{E}\times\dot{\boldsymbol{E}}) + \tfrac{1}{2}\gamma_{M1M1}\boldsymbol{\sigma}\cdot(\boldsymbol{H}\times\dot{\boldsymbol{H}}) - \gamma_{M1E2}E_{ij}\sigma_i H_j + \gamma_{E1M2}H_{ij}\sigma_i E_j\right)$$

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

Spin polarizabilities

PRL **114,** 112501 (2015) PHYSICAL REVIEW LETTERS week ending 20 MARCH 2015

Measurements of Double-Polarized Compton Scattering Asymmetries and Extraction of the Proton Spin Polarizabilities

P. P. Martel,[1,2,3,*] R. Miskimen,[1,†] P. Aguar-Bartolome,[2] J. Ahrens,[2] C. S. Akondi,[4] J. R. M. Annand,[5] H. J. Arends,[2]

$$H_{\text{eff}}^{(2)} = -4\pi\left(\tfrac{1}{2}\alpha_{E1}\boldsymbol{E}^2 + \tfrac{1}{2}\beta_{M1}\boldsymbol{H}^2\right),$$

$$H_{\text{eff}}^{(3)} = -4\pi\left(\tfrac{1}{2}\gamma_{E1E1}\boldsymbol{\sigma}\cdot(\boldsymbol{E}\times\dot{\boldsymbol{E}}) + \tfrac{1}{2}\gamma_{M1M1}\boldsymbol{\sigma}\cdot(\boldsymbol{H}\times\dot{\boldsymbol{H}}) - \gamma_{M1E2}E_{ij}\sigma_i H_j + \gamma_{E1M2}H_{ij}\sigma_i E_j\right)$$

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

Spin polarizabilities

PRL **114,** 112501 (2015) PHYSICAL REVIEW LETTERS week ending 20 MARCH 2015

Measurements of Double-Polarized Compton Scattering Asymmetries and Extraction of the Proton Spin Polarizabilities

P. P. Martel,[1,2,3,*] R. Miskimen,[1,†] P. Aguar-Bartolome,[2] J. Ahrens,[2] C. S. Akondi,[4] J. R. M. Annand,[5] H. J. Arends,[2]

$$H^{(2)}_{\rm eff} = -4\pi \left(\tfrac{1}{2}\alpha_{E1}\boldsymbol{E}^2 + \tfrac{1}{2}\beta_{M1}\boldsymbol{H}^2\right),$$

$$H^{(3)}_{\rm eff} = -4\pi \left(\tfrac{1}{2}\gamma_{E1E1}\boldsymbol{\sigma}\cdot(\boldsymbol{E}\times\dot{\boldsymbol{E}}) + \tfrac{1}{2}\gamma_{M1M1}\boldsymbol{\sigma}\cdot(\boldsymbol{H}\times\dot{\boldsymbol{H}}) - \gamma_{M1E2}E_{ij}\sigma_i H_j + \gamma_{E1M2}H_{ij}\sigma_i E_j\right)$$

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

Forward spin polarizability: $\gamma_0 = -(\gamma_{E1E1} + \gamma_{M1M1} + \gamma_{E1M2} + \gamma_{M1E2})$

$$= \frac{1}{4\pi^2}\int_{\nu_0}^{\infty} d\nu\, \frac{\sigma_{1/2}(\nu) - \sigma_{3/2}(\nu)}{\nu^3}$$

$$= \lim_{Q^2\to 0} \frac{16\alpha M_N^2}{Q^6}\int_0^{x_0} dx\, x^2 \left[g_1(x,Q^2) - \frac{4M_N^2 x^2}{Q^2} g_2(x,Q^2)\right]$$

Spin polarizabilities

PRL **114,** 112501 (2015) PHYSICAL REVIEW LETTERS week ending 20 MARCH 2015

Measurements of Double-Polarized Compton Scattering Asymmetries and Extraction of the Proton Spin Polarizabilities

P. P. Martel,[1,2,3,*] R. Miskimen,[1,†] P. Aguar-Bartolome,[2] J. Ahrens,[2] C. S. Akondi,[4] J. R. M. Annand,[5] H. J. Arends,[2]

$$H_{\text{eff}}^{(2)} = -4\pi \left(\tfrac{1}{2}\alpha_{E1}\boldsymbol{E}^2 + \tfrac{1}{2}\beta_{M1}\boldsymbol{H}^2\right),$$

$$H_{\text{eff}}^{(3)} = -4\pi \left(\tfrac{1}{2}\gamma_{E1E1}\boldsymbol{\sigma}\cdot(\boldsymbol{E}\times\dot{\boldsymbol{E}}) + \tfrac{1}{2}\gamma_{M1M1}\boldsymbol{\sigma}\cdot(\boldsymbol{H}\times\dot{\boldsymbol{H}}) - \gamma_{M1E2}E_{ij}\sigma_i H_j + \gamma_{E1M2}H_{ij}\sigma_i E_j\right)$$

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

Forward spin polarizability: $\gamma_0 = -(\gamma_{E1E1} + \gamma_{M1M1} + \gamma_{E1M2} + \gamma_{M1E2})$

$$= \frac{1}{4\pi^2}\int_{\nu_0}^{\infty} d\nu\, \frac{\sigma_{1/2}(\nu) - \sigma_{3/2}(\nu)}{\nu^3}$$

$$= \lim_{Q^2\to 0}\frac{16\alpha M_N^2}{Q^6}\int_0^{x_0} dx\, x^2 \left[g_1(x,Q^2) - \frac{4M_N^2x^2}{Q^2}g_2(x,Q^2)\right]$$

$$\delta_{LT} = \gamma_0 + \lim_{Q^2\to 0}\frac{16\alpha M_N^2}{Q^6}\int_0^{x_0} dx\, x^2 g_2(x,Q^2)$$

From beam asymmetry

PRL **110,** 262001 (2013) PHYSICAL REVIEW LETTERS week ending 28 JUNE 2013

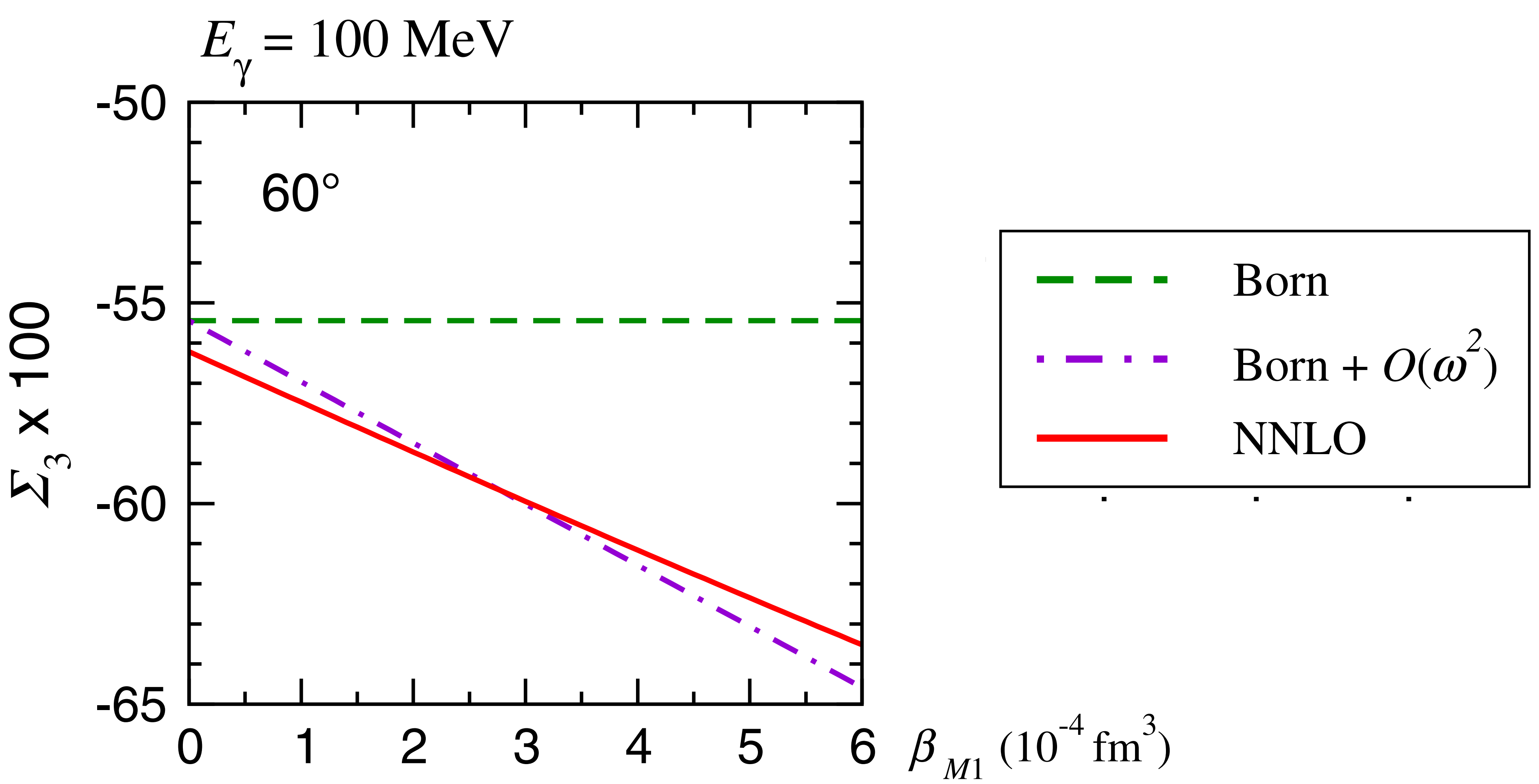
Separation of Proton Polarizabilities with the Beam Asymmetry of Compton Scattering

Nadiia Krupina and Vladimir Pascalutsa

PRISMA Cluster of Excellence Institut für Kernphysik, Johannes Gutenberg–Universität Mainz, 55128 Mainz, Germany

(Received 3 April 2013; published 25 June 2013)

$$\Sigma_3 \equiv \frac{d\sigma_{||} - d\sigma_\perp}{d\sigma_{||} + d\sigma_\perp} \stackrel{\text{LEX}}{=} \Sigma_3^{(\text{Born})} - \frac{4\beta_{M1}}{Z^2\alpha_{em}} \frac{\cos\theta \sin^2\theta}{(1+\cos^2\theta)^2}\,\omega^2 + O(\omega^4)$$

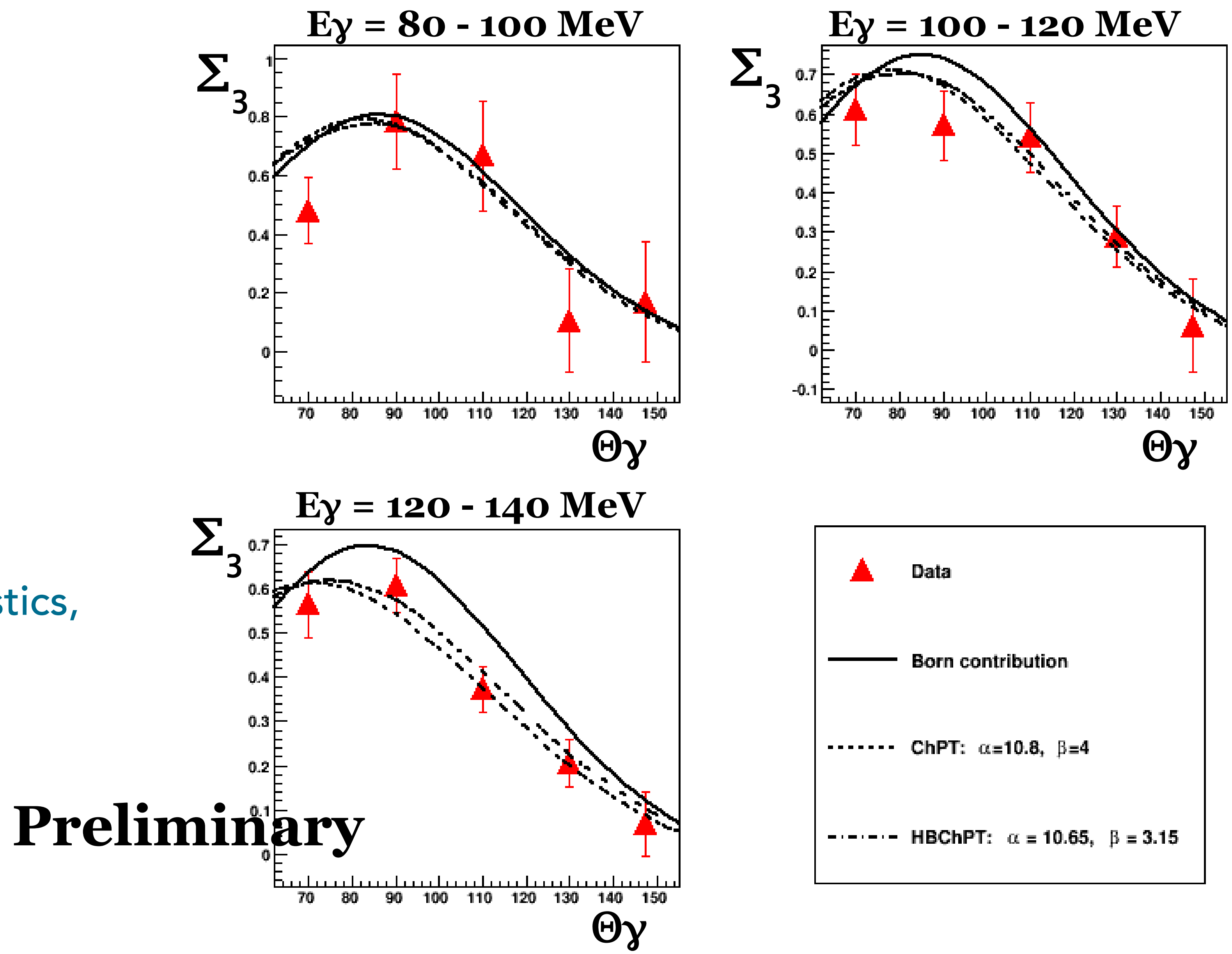


A2 MAMI (preliminary) data

Beam asymmetry Σ_3: Comparison with models

V. Sokhoyan et al., 2013 run

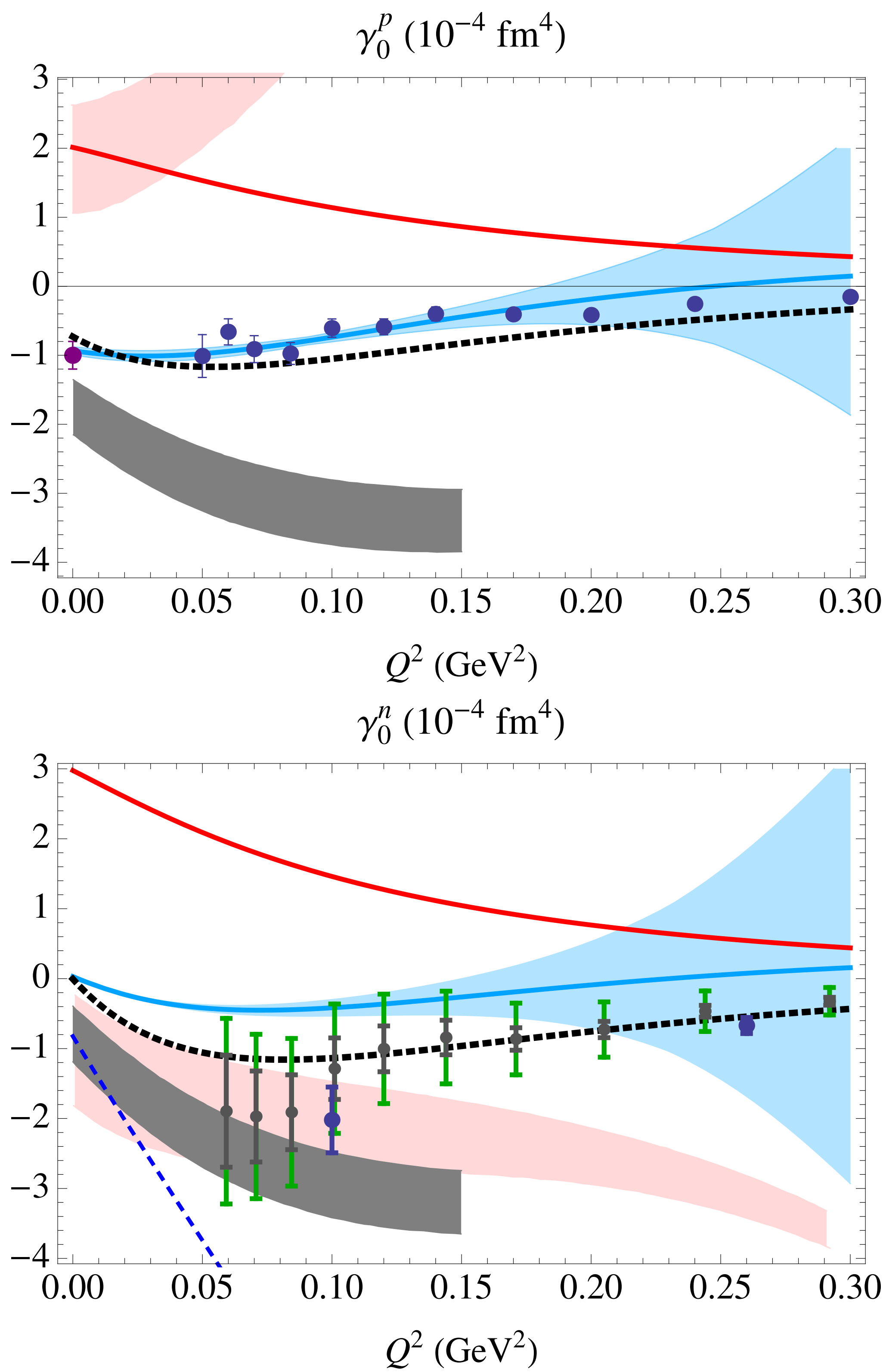
Need improvements in statistics, and systematics…



Curves: ***Krupina and Pascalutsa, PRL 110, 262001 (2013), J. McGovern, D. Phillips, H. Grießhammer, EPJA 49, 12 (2013)***

Forward spin polarizability at finite Q

figures from: Alarcon, Hagelstein, Lensky & V.P., in progress



Curves:

MAID (empir.)

LO-HBChPT

NLO-HBChPT

NLO- IRBChPT [Bernard et al (2006)]

LO-BChPT

NLO-BChPT [Lensky, Alarcon & V.P, PRC (2014)]

NLO-BChPT [Bernard et al (2013)]

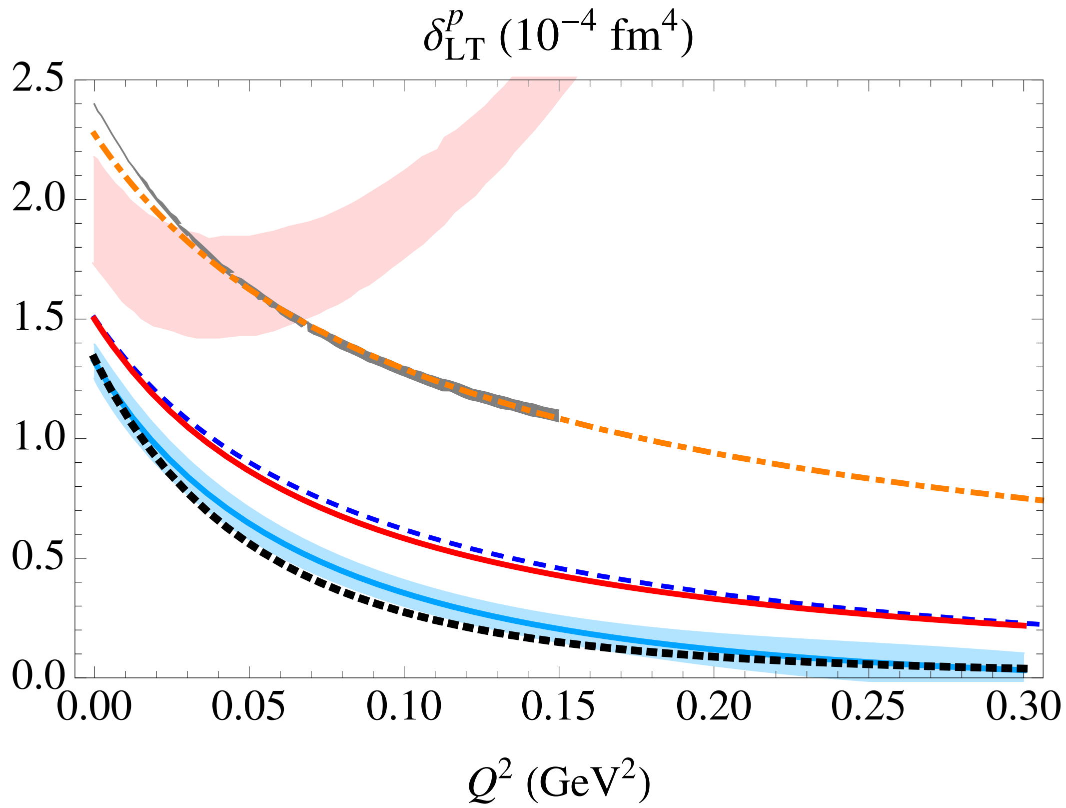
see talk by H. Krebs

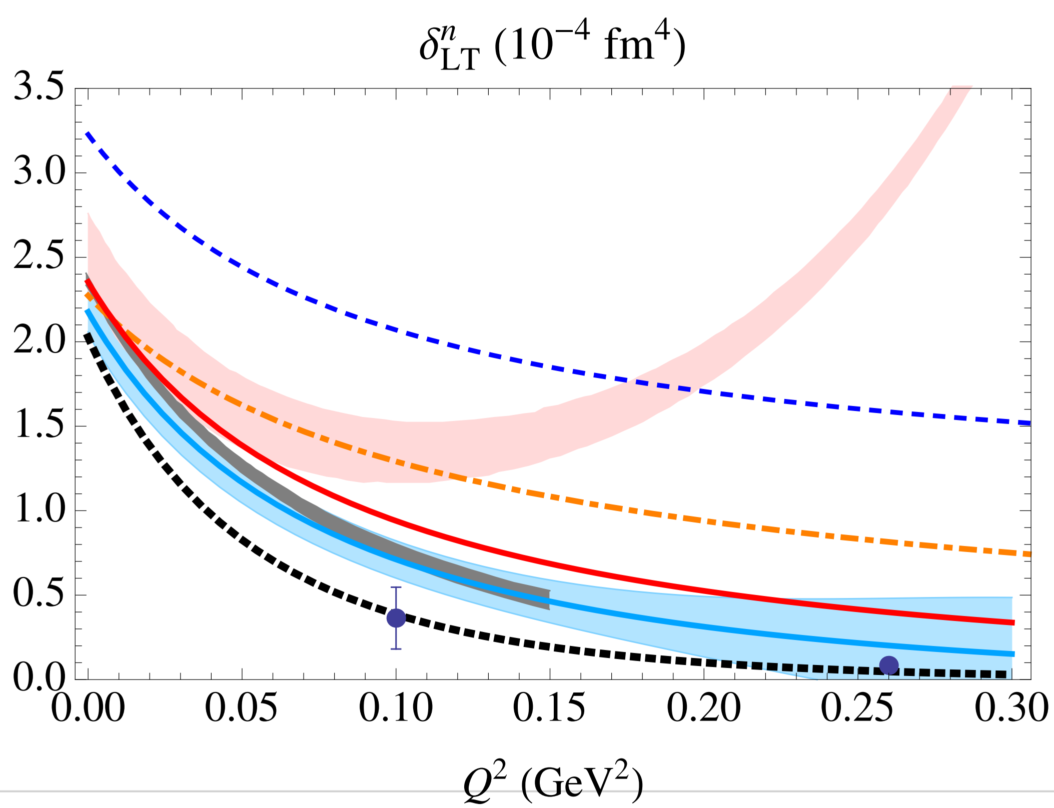
Data points:

K. Slifer, J.-P. Chen, S. Kuhn, et al

[Jefferson Lab spin program]

LT spin polarizability





Curves:

MAID (empir.)

LO-HBChPT

NLO-HBChPT

NLO- IRBChPT
[Bernard et al (2006)]

LO-BChPT

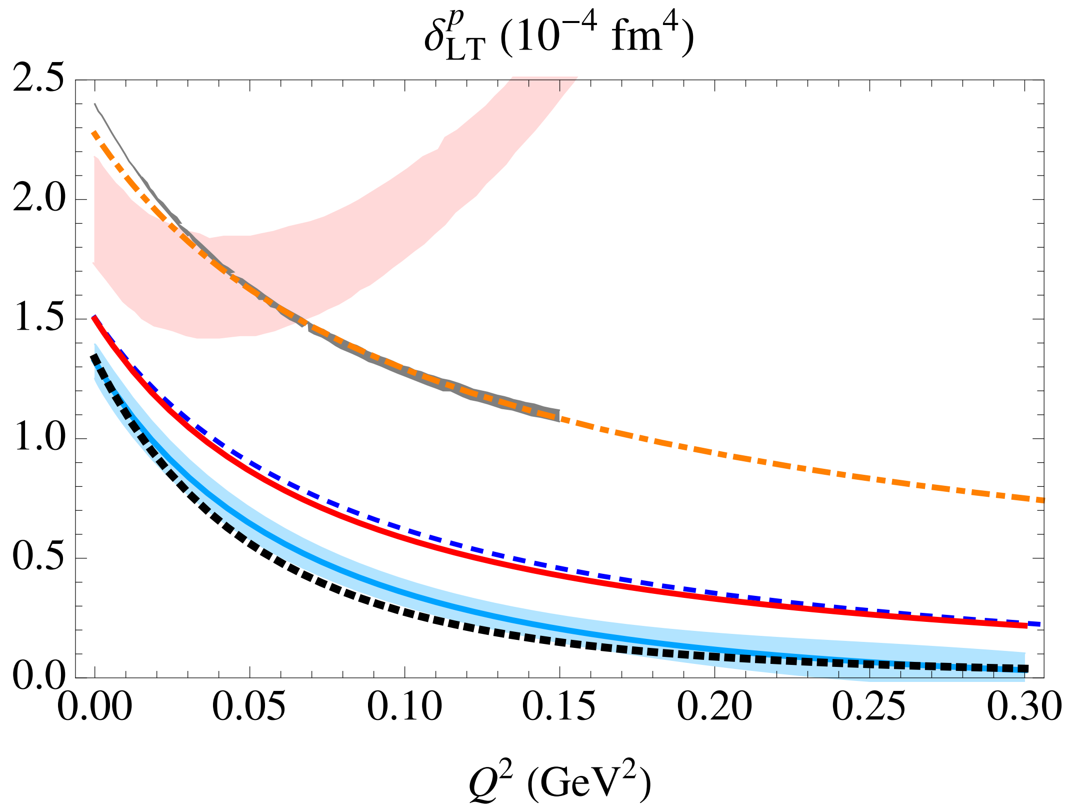
NLO-BChPT
[Lensky, Alarcon & V.P, PRC (2014)]

NLO-BChPT
[Bernard et al (2013)]

Data points:

K. Slifer, J.-P. Chen, S. Kuhn, et al
[Jefferson Lab spin program]

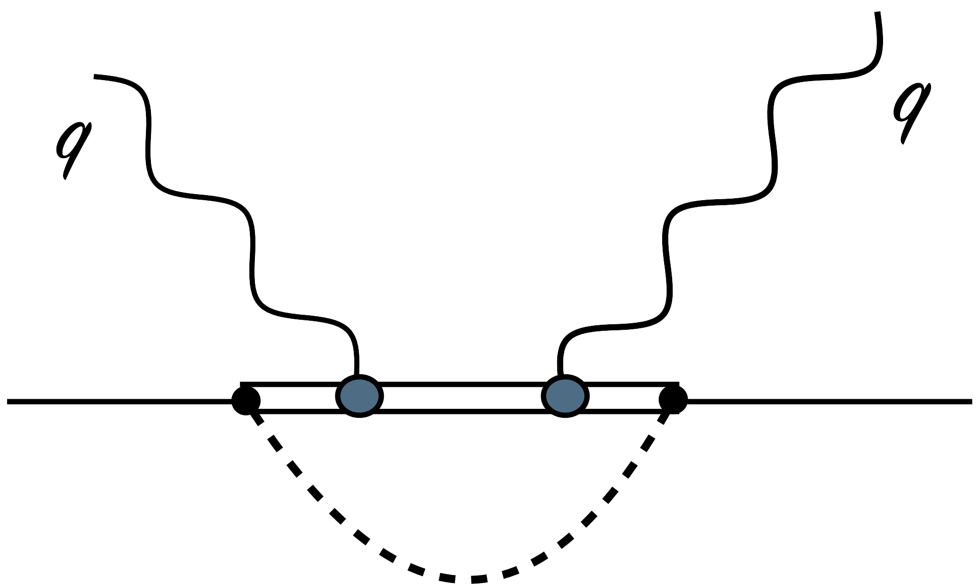
The difference



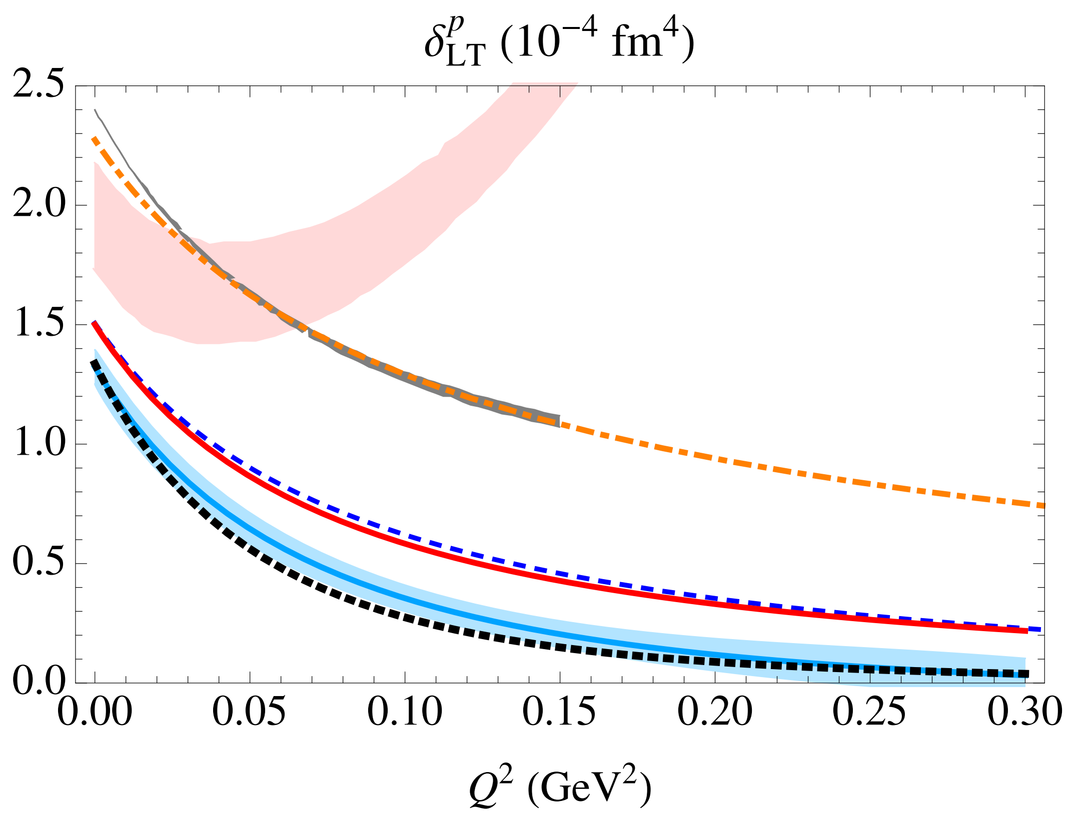
NLO-BChPT
[Bernard et al (2013)]

NLO-BChPT
[Lensky, Alarcon & V.P, PRC (2014)]

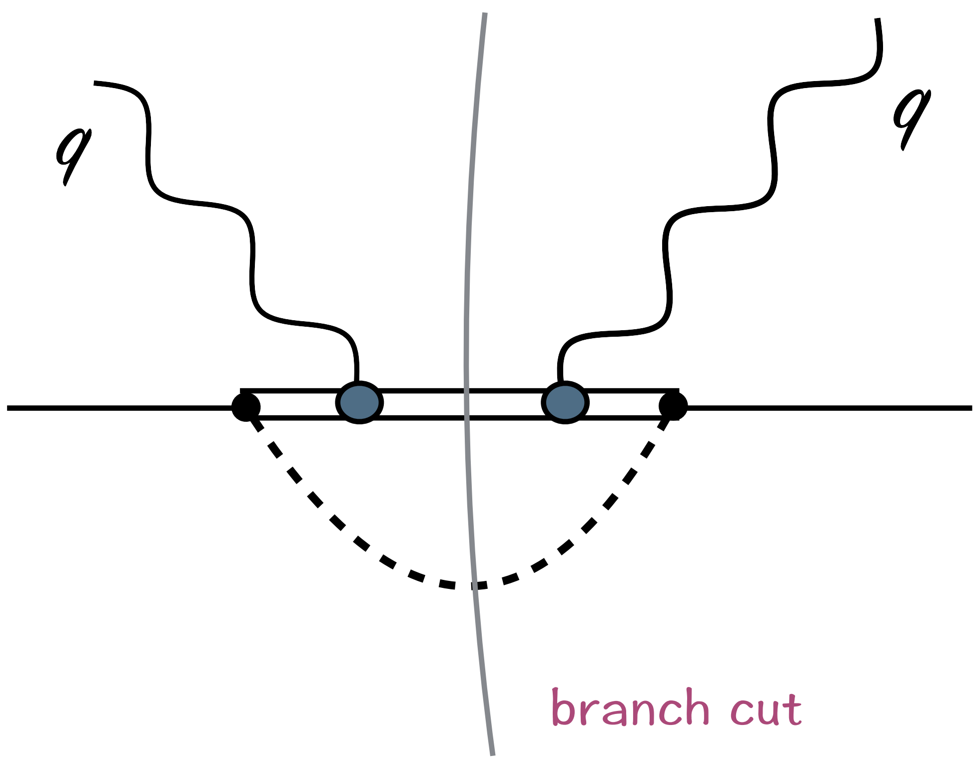
comes from



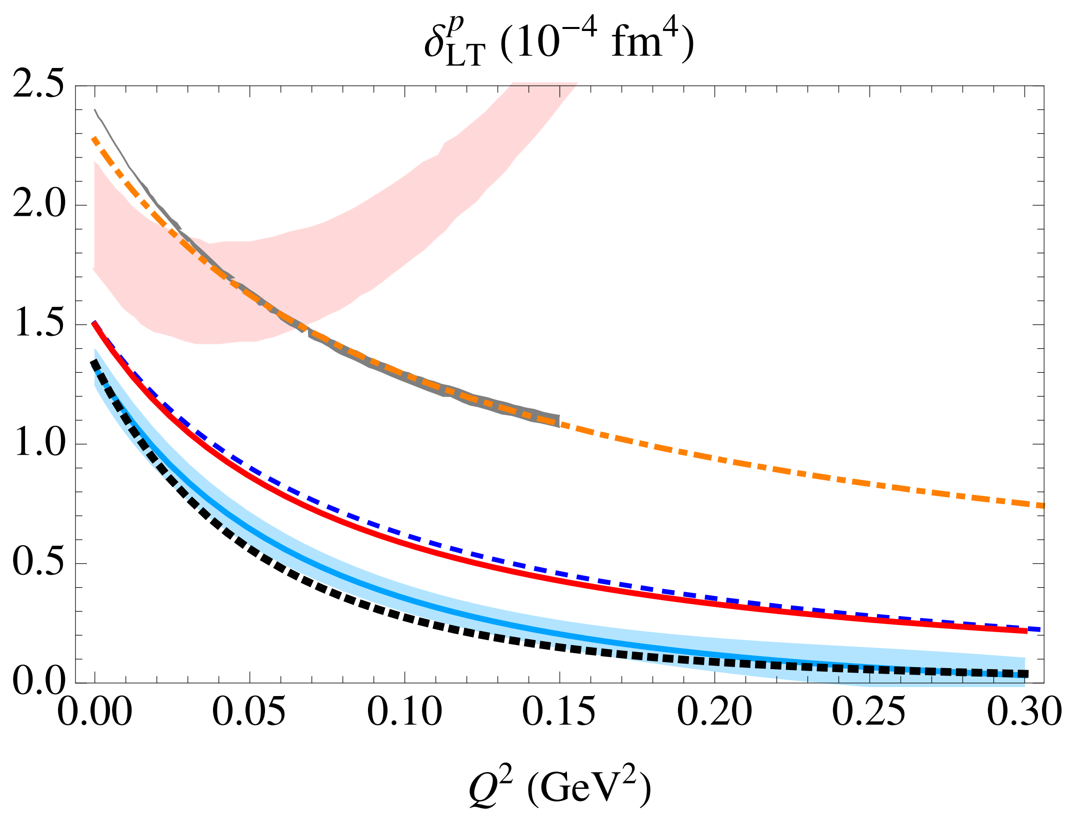
The difference



comes from



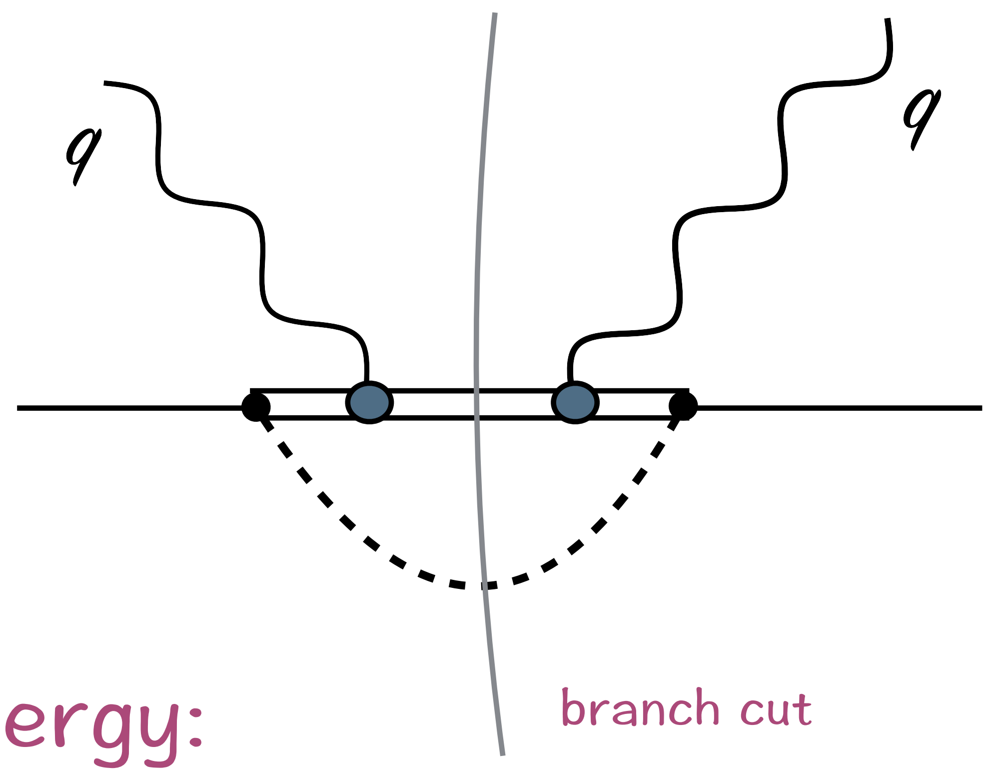
The difference



NLO-BChPT
[Bernard et al (2013)]

NLO-BChPT
[Lensky, Alarcon & V.P, PRC (2014)]

comes from

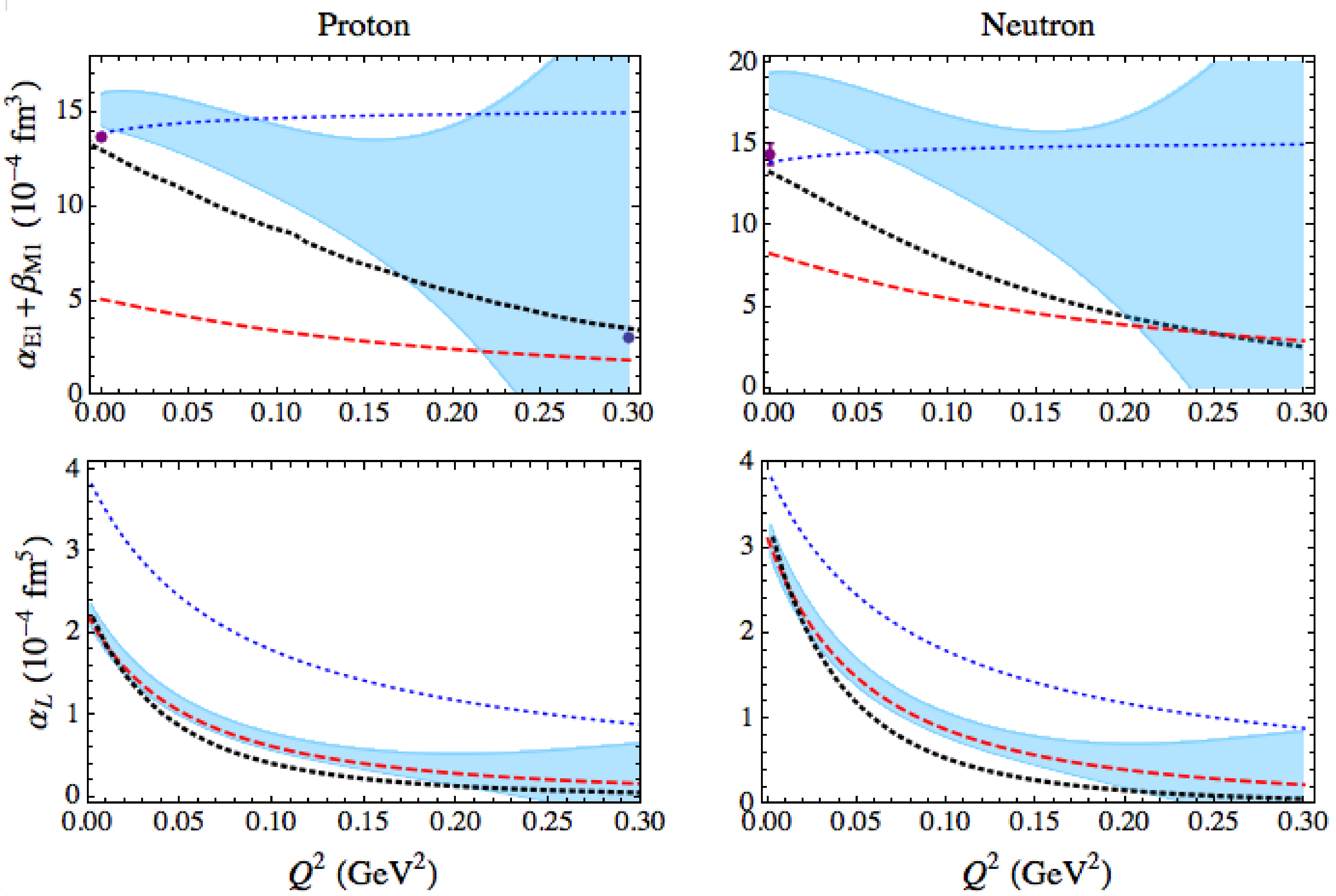


normally suppressed at low-energy:

pi-Delta production << pi-nucleon production

Predictions of BChPT for VVCS

Alarcon, Lensky & VP, PRC (2014)



Curves:

MAID (empir.)

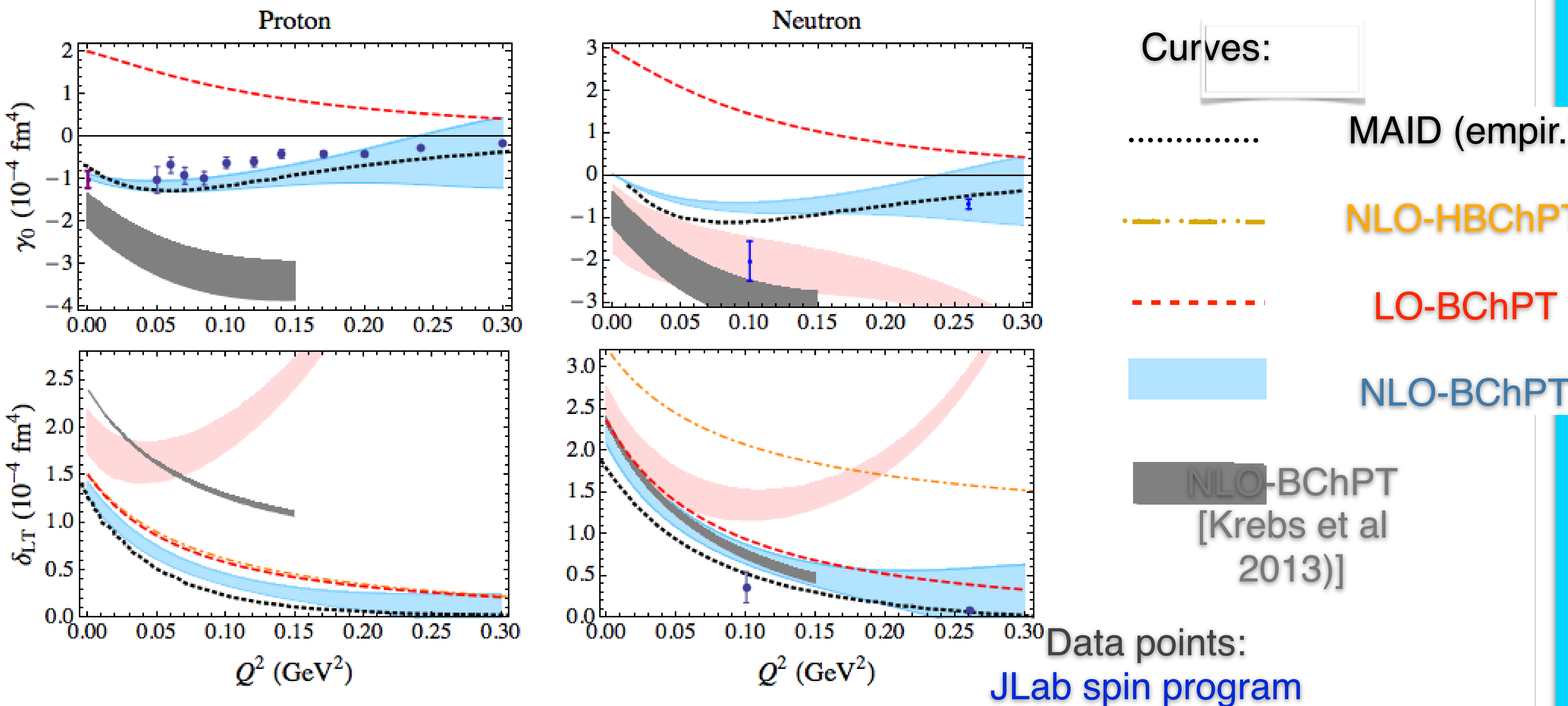
LO-HBChPT

LO-BChPT

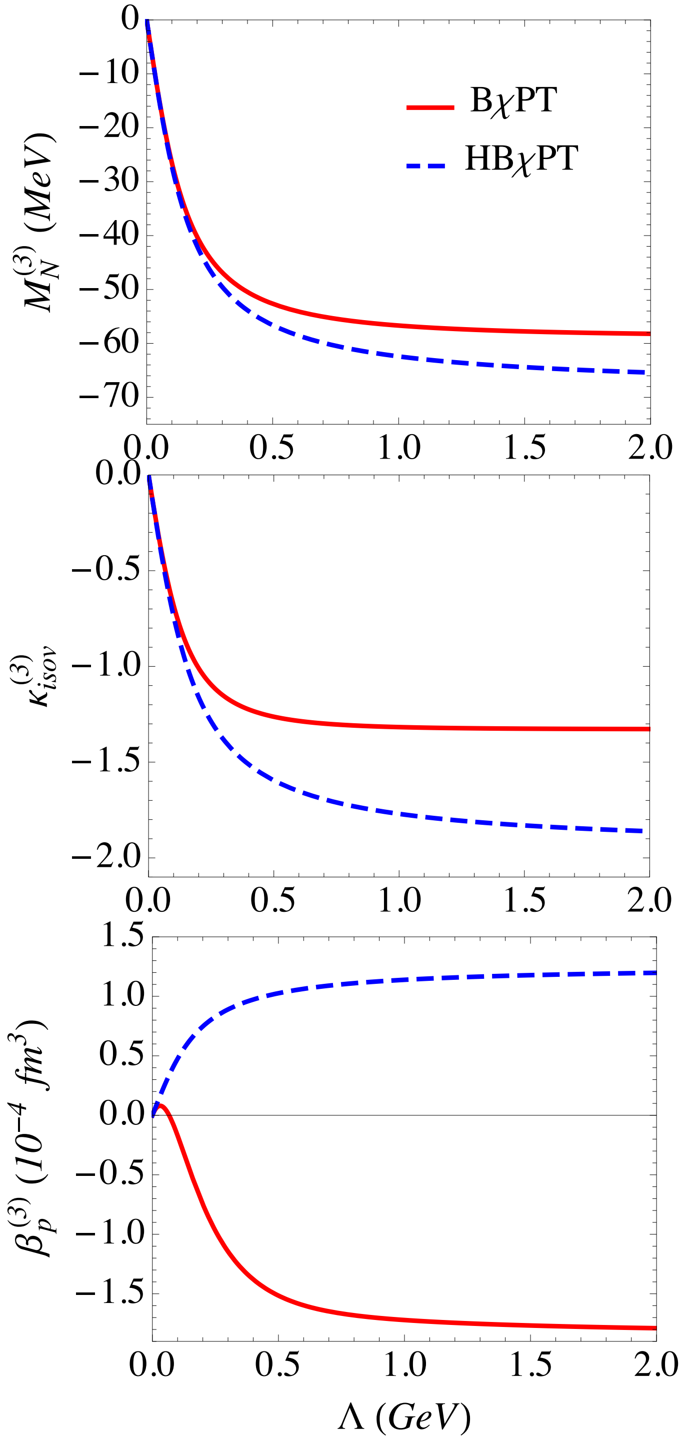
NLO-BChPT

BChPT for polarised VVCS (deltaLT puzzle)

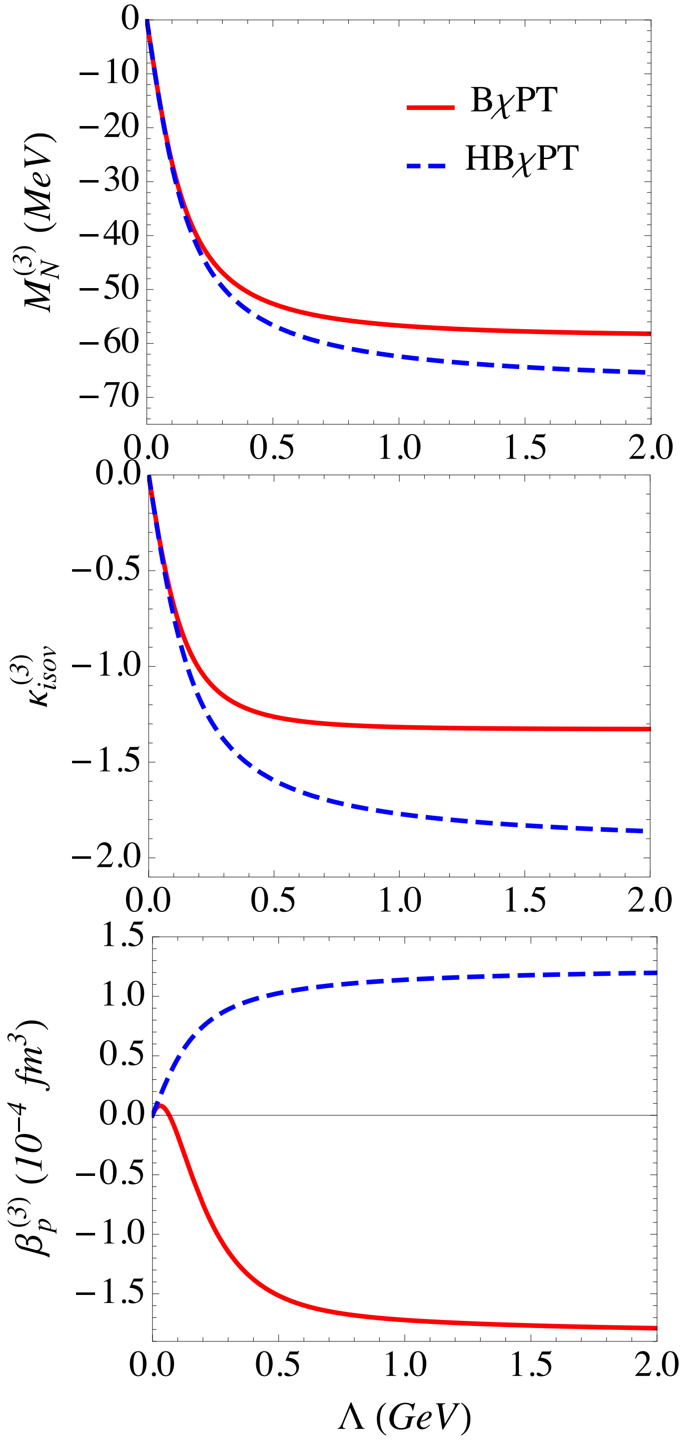
Alarcon, Lensky & VP, PRC (2014)



UV dependence in HB- vs B-ChPT



UV dependence in HB- vs B-ChPT

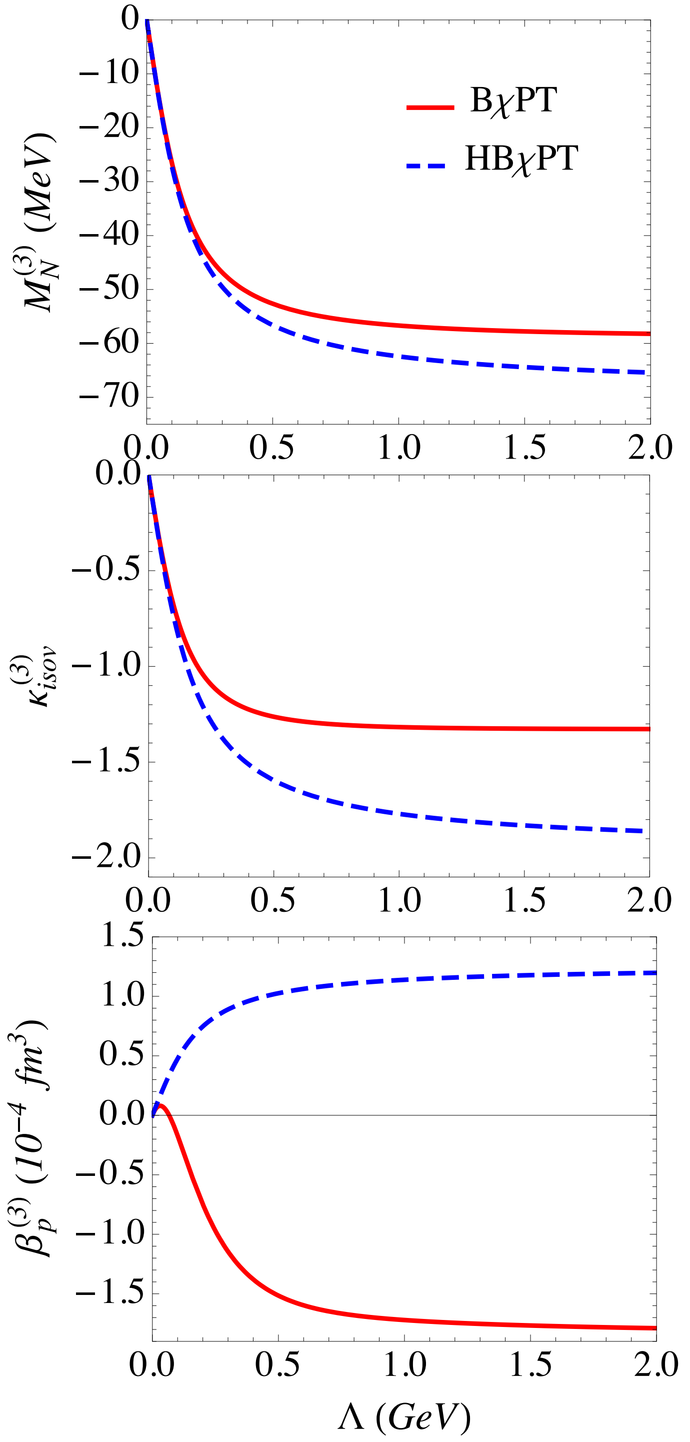


$$M_N \sim m_\pi^3$$

$$\kappa \sim m_\pi$$

$$\beta_M \sim \frac{1}{m_\pi}$$

UV dependence in HB- vs B-ChPT



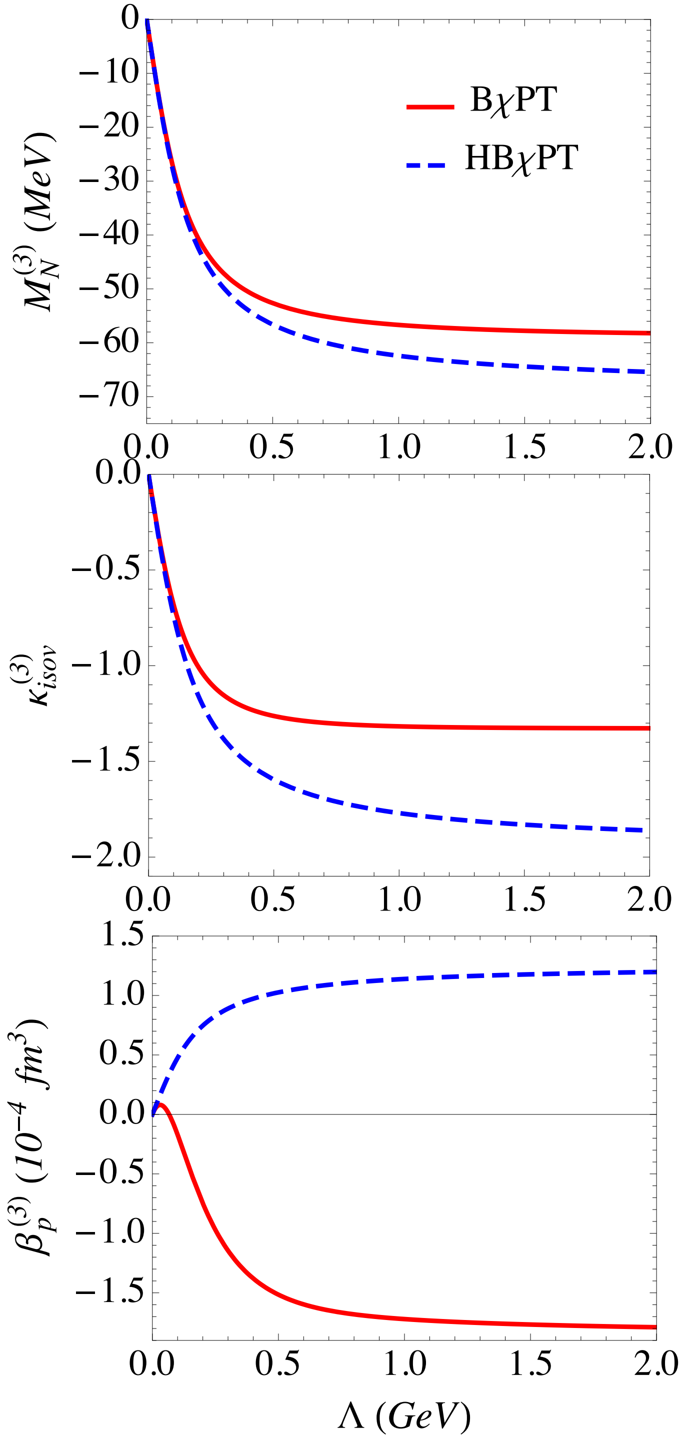
$$M_N \sim m_\pi^3$$

$$\kappa \sim m_\pi$$

$$\beta_M \sim \frac{1}{m_\pi}$$

Heavy-Baryon expansion fails for quantities where

UV dependence in HB- vs B-ChPT



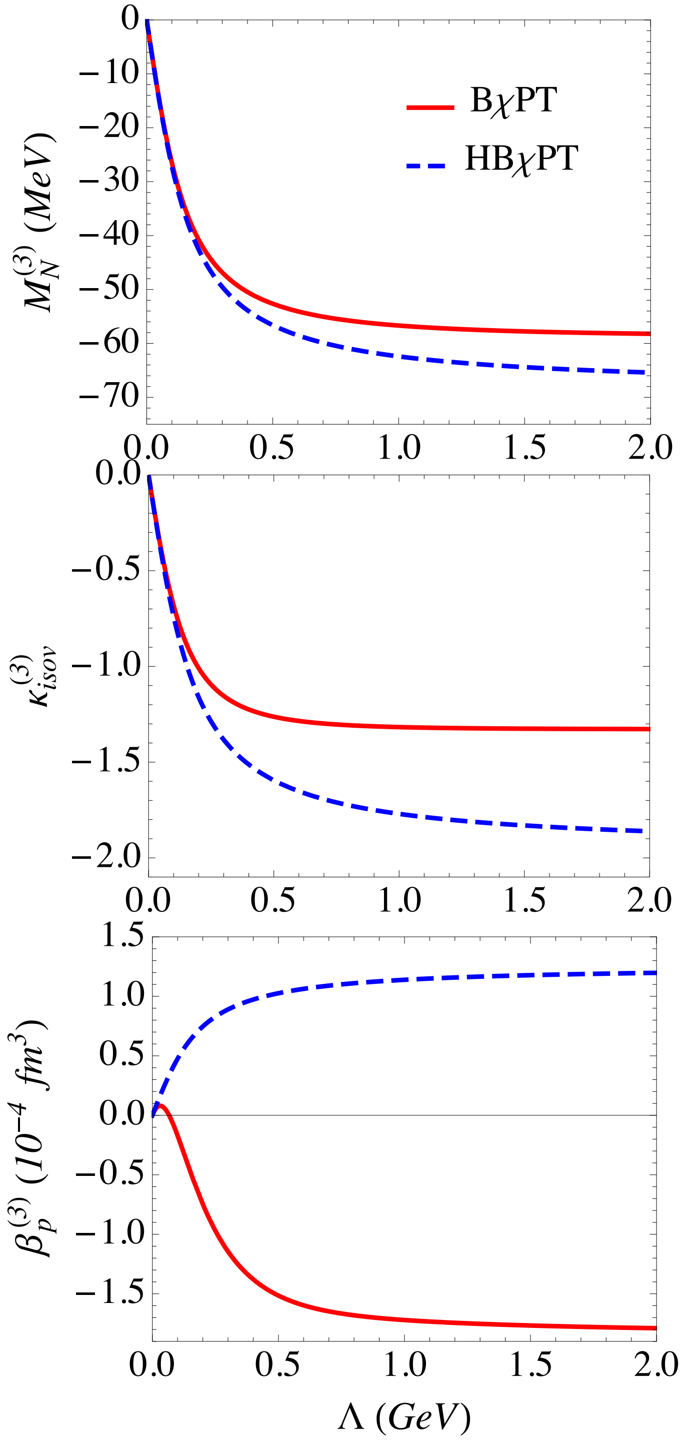
$$M_N \sim m_\pi^3$$

$$\kappa \sim m_\pi$$

$$\beta_M \sim \frac{1}{m_\pi}$$

Heavy-Baryon expansion fails for quantities where the leading chiral-loop effects scales with a negative

UV dependence in HB- vs B-ChPT



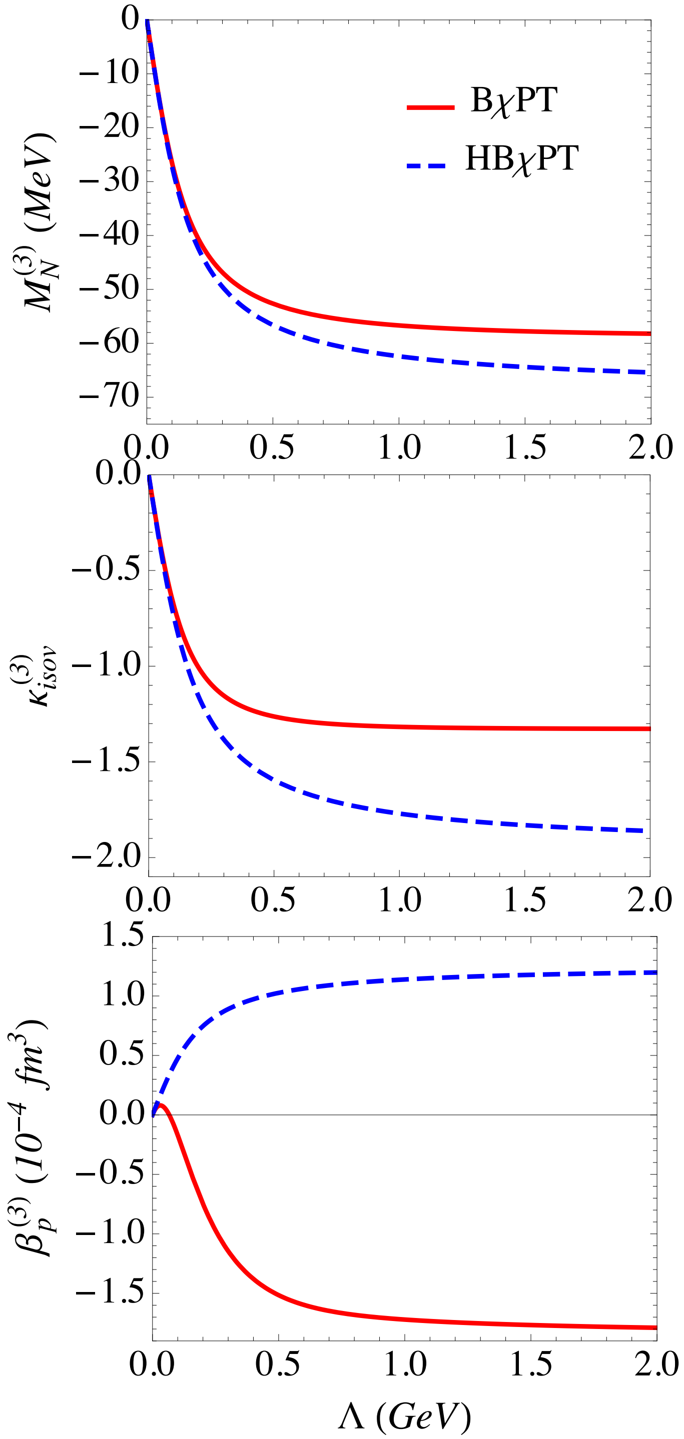
$$M_N \sim m_\pi^3$$

$$\kappa \sim m_\pi$$

$$\beta_M \sim \frac{1}{m_\pi}$$

Heavy-Baryon expansion fails for quantities where the leading chiral-loop effects scales with a negative power of pion mass

UV dependence in HB- vs B-ChPT



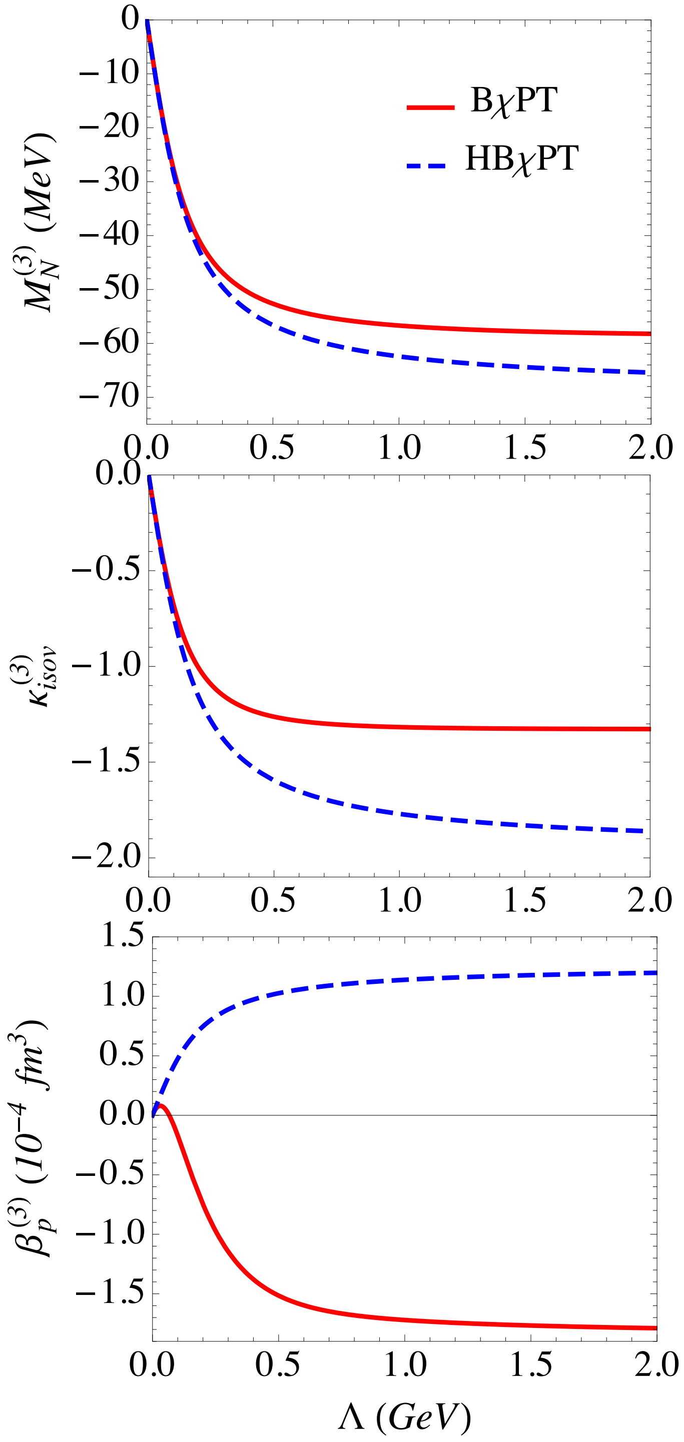
$$M_N \sim m_\pi^3$$

$$\kappa \sim m_\pi$$

$$\beta_M \sim \frac{1}{m_\pi}$$

Heavy-Baryon expansion fails for quantities where the leading chiral-loop effects scales with a negative power of pion mass

UV dependence in HB- vs B-ChPT



$$M_N \sim m_\pi^3$$

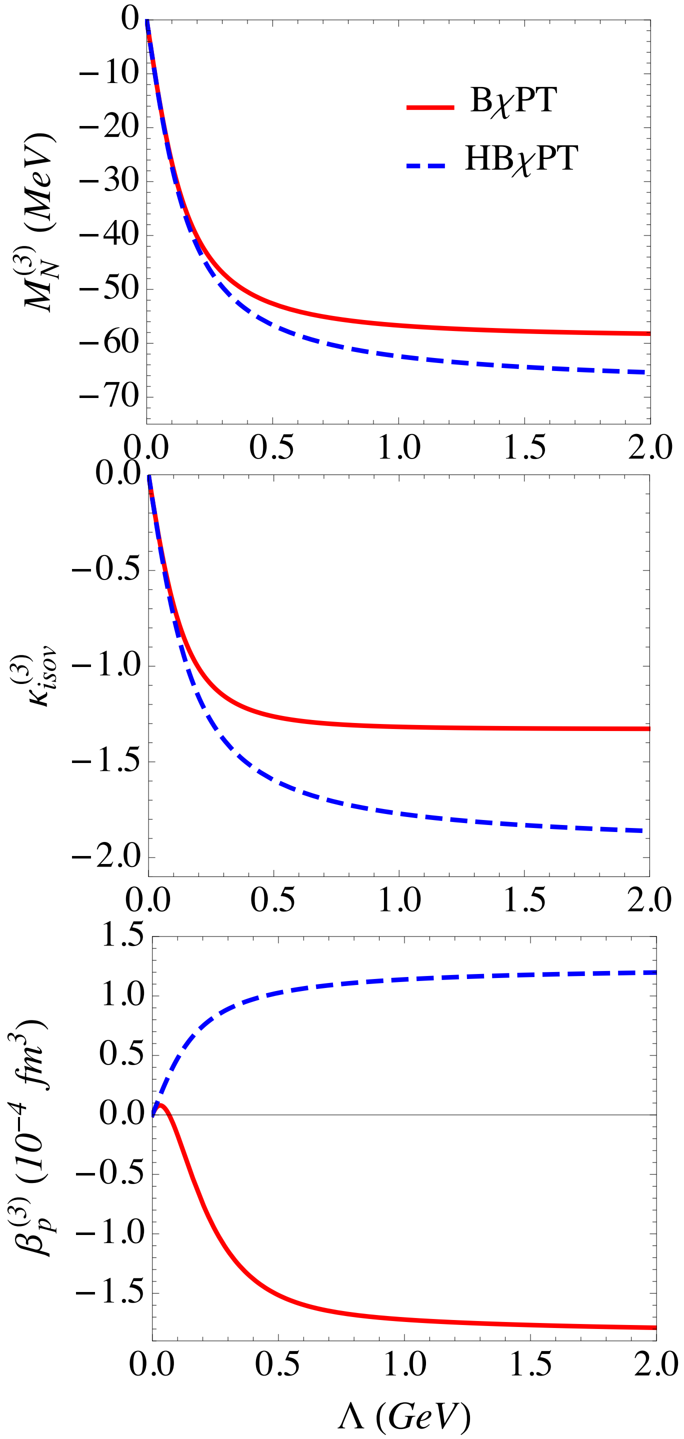
$$\kappa \sim m_\pi$$

$$\beta_M \sim \frac{1}{m_\pi}$$

Heavy-Baryon expansion fails for quantities where the leading chiral-loop effects scales with a negative power of pion mass

E.g.: the effective range parameters of the NN force

UV dependence in HB- vs B-ChPT



$$M_N \sim m_\pi^3$$

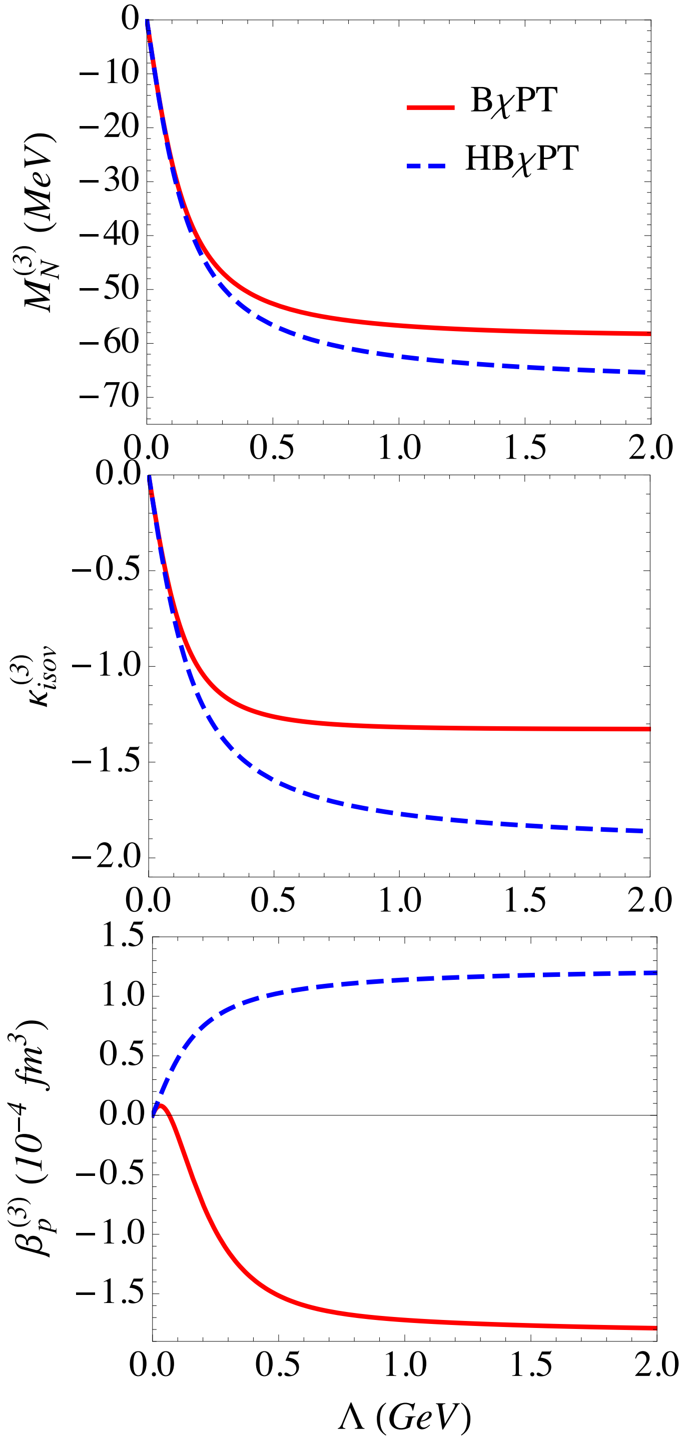
$$\kappa \sim m_\pi$$

$$\beta_M \sim \frac{1}{m_\pi}$$

Heavy-Baryon expansion fails for quantities where the leading chiral-loop effects scales with a negative power of pion mass

E.g.: the effective range parameters of the NN force are such quantities -- hope for “perturbative pions” (KSW)

UV dependence in HB- vs B-ChPT



$$M_N \sim m_\pi^3$$

$$\kappa \sim m_\pi$$

$$\beta_M \sim \frac{1}{m_\pi}$$

Heavy-Baryon expansion fails for quantities where the leading chiral-loop effects scales with a negative power of pion mass

E.g.: the effective range parameters of the NN force are such quantities -- hope for "perturbative pions" (KSW) in BChPT

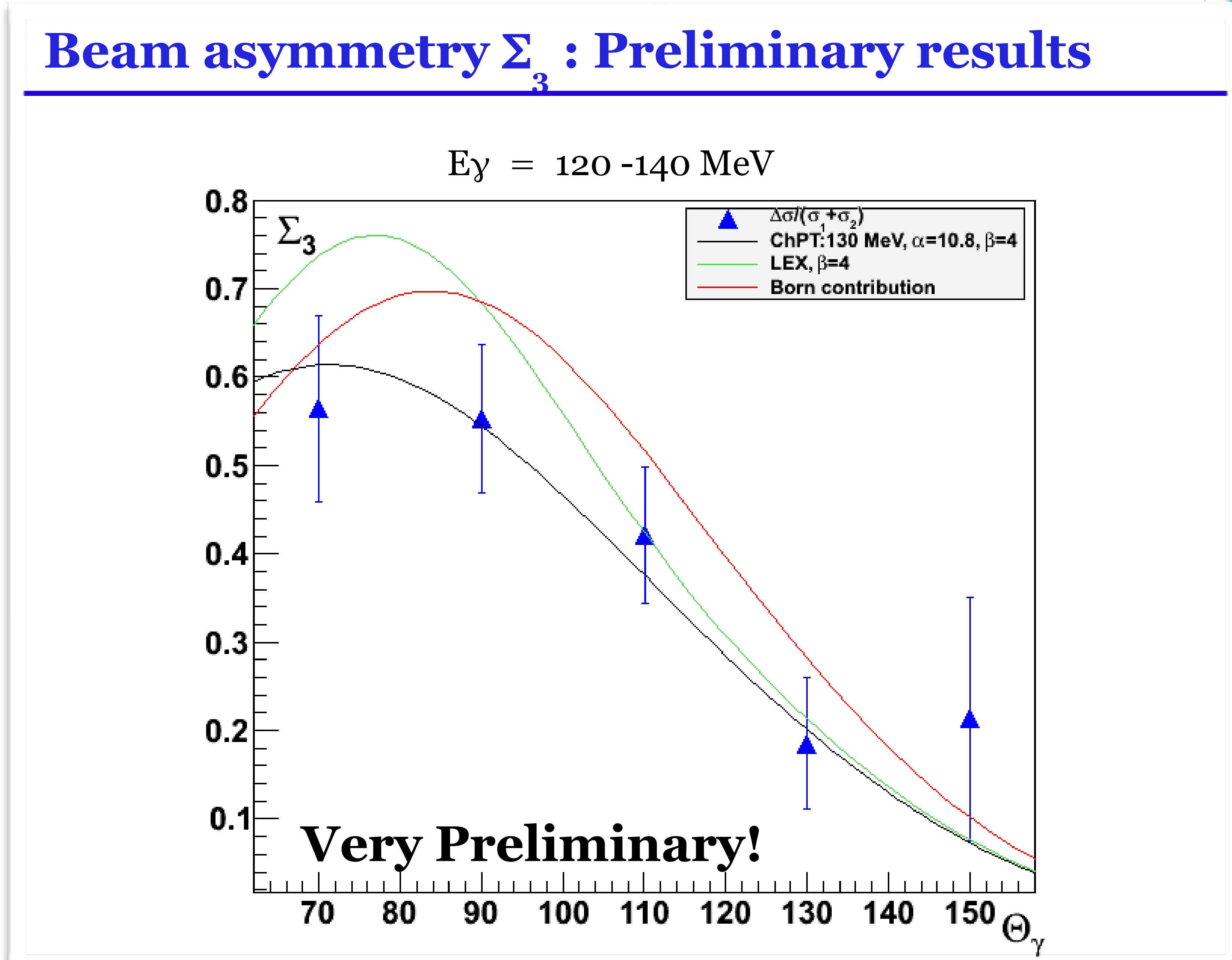
New Mainz data for Compton beam asymmetry

Data taken: 28.05. – 17.06.20

V. Sokhoyan, E. Downie et al.
[A2 Coll.]

first data on this observable below pion production threshold!

better precision needed!!



Predictions of HBChPT vs BChPT

HBChPT@LO

Bernard, Keiser, Meissner
Int J Mod Phys (1995)

$$\alpha_p = \alpha_n = \frac{5\pi\alpha}{6m_\pi}\left(\frac{g_A}{4\pi f_\pi}\right)^2 = 12.2\times 10^{-4}\ \ \mathrm{fm}^3,$$

$$\beta_p = \beta_n = \frac{\pi\alpha}{12m_\pi}\left(\frac{g_A}{4\pi f_\pi}\right)^2 = 1.2\times 10^{-4}\ \ \mathrm{fm}^3,$$

Predictions of HBChPT vs BChPT

HBChPT@LO

Bernard, Keiser, Meissner
Int J Mod Phys (1995)

$$\alpha_p = \alpha_n = \frac{5\pi\alpha}{6m_\pi}\left(\frac{g_A}{4\pi f_\pi}\right)^2 = 12.2\times 10^{-4}\ \text{fm}^3,$$

$$\beta_p = \beta_n = \frac{\pi\alpha}{12m_\pi}\left(\frac{g_A}{4\pi f_\pi}\right)^2 = 1.2\times 10^{-4}\ \text{fm}^3,$$

BChPT@NLO

Lensky & V.P., EPJC (2010)

$$\alpha = \underbrace{6.8}_{\mathcal{O}(p^3)} + \underbrace{(-0.1) + 4.1}_{\mathcal{O}(p^4/\Delta)} = 10.8\,,$$

$$\beta = \underbrace{-1.8}_{\mathcal{O}(p^3)} + \underbrace{7.1 - 1.3}_{\mathcal{O}(p^4/\Delta)} = 4.0\,.$$

Predictions of HBChPT vs BChPT

HBChPT@LO

Bernard, Keiser, Meissner
Int J Mod Phys (1995)

$$\alpha_p = \alpha_n = \frac{5\pi\alpha}{6m_\pi}\left(\frac{g_A}{4\pi f_\pi}\right)^2 = 12.2\times 10^{-4}\ \ \mathrm{fm}^3,$$

$$\beta_p = \beta_n = \frac{\pi\alpha}{12m_\pi}\left(\frac{g_A}{4\pi f_\pi}\right)^2 = 1.2\times 10^{-4}\ \ \mathrm{fm}^3,$$

BChPT@NLO

Lensky & V.P., EPJC (2010)

$$\alpha = \underbrace{6.8}_{\mathcal{O}(p^3)} + \underbrace{(-0.1) + 4.1}_{\mathcal{O}(p^4/\Delta)} = 10.8\,,$$

$$\beta = \underbrace{-1.8}_{\mathcal{O}(p^3)} + \underbrace{7.1 - 1.3}_{\mathcal{O}(p^4/\Delta)} = 4.0\,.$$

$\mu = m_\pi/M_N$

$$\boxed{\beta = \frac{e^2 g_A^2}{192\pi^3 F^2 M_N}\left[\frac{\pi}{4\mu} + 18\log\mu + \frac{63}{2} - \frac{981\pi\mu}{32} - (100\log\mu + \frac{121}{6})\mu^2 + \mathcal{O}(\mu^3)\right]}$$

Predictions of HBChPT vs BChPT

HBChPT@LO

Bernard, Keiser, Meissner
Int J Mod Phys (1995)

$$\alpha_p = \alpha_n = \frac{5\pi\alpha}{6m_\pi}\left(\frac{g_A}{4\pi f_\pi}\right)^2 = 12.2\times 10^{-4}\ \text{fm}^3,$$

$$\beta_p = \beta_n = \frac{\pi\alpha}{12m_\pi}\left(\frac{g_A}{4\pi f_\pi}\right)^2 = 1.2\times 10^{-4}\ \text{fm}^3,$$

BChPT@NLO

Lensky & V.P., EPJC (2010)

$$\alpha = \underbrace{6.8}_{\mathscr{O}(p^3)} + \underbrace{(-0.1) + 4.1}_{\mathscr{O}(p^4/\Delta)} = 10.8\,,$$

$$\beta = \underbrace{-1.8}_{\mathscr{O}(p^3)} + \underbrace{7.1 - 1.3}_{\mathscr{O}(p^4/\Delta)} = 4.0\,.$$

diamagnetic

$$\mu = m_\pi/M_N$$

$$\boxed{\beta = \frac{e^2 g_A^2}{192\pi^3 F^2 M_N}\left[\frac{\pi}{4\mu} + 18\log\mu + \frac{63}{2} - \frac{981\pi\mu}{32} - (100\log\mu + \frac{121}{6})\mu^2 + \mathcal{O}(\mu^3)\right]}$$

Predictions of HBChPT vs BChPT

HBChPT@LO

Bernard, Keiser, Meissner
Int J Mod Phys(1995)

$$\alpha_p = \alpha_n = \frac{5\pi\alpha}{6m_\pi}\left(\frac{g_A}{4\pi f_\pi}\right)^2 = 12.2\times 10^{-4}\ \ \text{fm}^3,$$

$$\beta_p = \beta_n = \frac{\pi\alpha}{12m_\pi}\left(\frac{g_A}{4\pi f_\pi}\right)^2 = 1.2\times 10^{-4}\ \ \text{fm}^3,$$

BChPT@NLO

Lensky & V.P., EPJC (2010)

$$\alpha = \underbrace{6.8}_{\mathscr{O}(p^3)} + \underbrace{(-0.1) + 4.1}_{\mathscr{O}(p^4/\Delta)} = 10.8\,,$$

$$\beta = \underbrace{-1.8}_{\mathscr{O}(p^3)} + \underbrace{7.1 - 1.3}_{\mathscr{O}(p^4/\Delta)} = 4.0\,.$$

paramagnetic

diamagnetic

$\mu = m_\pi / M_N$

$$\beta = \frac{e^2 g_A^2}{192\pi^3 F^2 M_N}\left[\frac{\pi}{4\mu} + 18\log\mu + \frac{63}{2} - \frac{981\pi\mu}{32} - (100\log\mu + \frac{121}{6})\mu^2 + \mathcal{O}(\mu^3)\right]$$

Predictions of HBChPT vs BChPT

HBChPT@LO

Bernard, Keiser, Meissner
Int J Mod Phys (1995)

$$\alpha_p = \alpha_n = \frac{5\pi\alpha}{6m_\pi}\left(\frac{g_A}{4\pi f_\pi}\right)^2 = 12.2\times 10^{-4}\ \text{fm}^3,$$

$$\beta_p = \beta_n = \frac{\pi\alpha}{12m_\pi}\left(\frac{g_A}{4\pi f_\pi}\right)^2 = 1.2\times 10^{-4}\ \text{fm}^3,$$

BChPT@NLO

Lensky & V.P., EPJC (2010)

$$\alpha = \underbrace{6.8}_{\mathscr{O}(p^3)} + \underbrace{(-0.1) + 4.1}_{\mathscr{O}(p^4/\Delta)} = 10.8\,,$$

$$\beta = \underbrace{-1.8}_{\mathscr{O}(p^3)} + \underbrace{7.1 - 1.3}_{\mathscr{O}(p^4/\Delta)} = 4.0\,.$$

paramagnetic

diamagnetic

$\mu = m_\pi / M_N$

$$\beta = \frac{e^2 g_A^2}{192\pi^3 F^2 M_N}\left[\frac{\pi}{4\mu} + 18\log\mu + \frac{63}{2} - \frac{981\pi\mu}{32} - (100\log\mu + \frac{121}{6})\mu^2 + \mathcal{O}(\mu^3)\right]$$

Bernard, Keiser, Meissner
PRL (1991)

Predictions of HBChPT vs BChPT

HBChPT@LO

Bernard, Keiser, Meissner
Int J Mod Phys (1995)

$$\alpha_p = \alpha_n = \frac{5\pi\alpha}{6m_\pi}\left(\frac{g_A}{4\pi f_\pi}\right)^2 = 12.2\times 10^{-4}\ \ \mathrm{fm}^3,$$

$$\beta_p = \beta_n = \frac{\pi\alpha}{12m_\pi}\left(\frac{g_A}{4\pi f_\pi}\right)^2 = 1.2\times 10^{-4}\ \ \mathrm{fm}^3,$$

BChPT@NLO

Lensky & V.P., EPJC (2010)

$$\alpha = \underbrace{6.8}_{\mathcal{O}(p^3)} + \underbrace{(-0.1) + 4.1}_{\mathcal{O}(p^4/\Delta)} = 10.8\,,$$

$$\beta = \underbrace{-1.8}_{\mathcal{O}(p^3)} + \underbrace{7.1 - 1.3}_{\mathcal{O}(p^4/\Delta)} = 4.0\,.$$

paramagnetic

diamagnetic

$\mu = m_\pi / M_N$

$$\beta = \frac{e^2 g_A^2}{192\pi^3 F^2 M_N}\left[\frac{\pi}{4\mu} + 18\log\mu + \frac{63}{2} - \frac{981\pi\mu}{32} - (100\log\mu + \frac{121}{6})\mu^2 + \mathcal{O}(\mu^3)\right]$$

Bernard, Keiser, Meissner
PRL (1991)

HBChPT@NLO:

mmer & Hemmert (2004)
McGovern, Phillips (2012)

The Delta contribution is
accompanied by “promoted” LECs,
hence not predictive

Predictions of HBChPT vs BChPT

HBChPT@LO

Bernard, Keiser, Meissner Int J Mod Phys(1995)

$$\alpha_p=\alpha_n=\frac{5\pi\alpha}{6m_\pi}\left(\frac{g_A}{4\pi f_\pi}\right)^2=12.2\times10^{-4}\ \ \mathrm{fm}^3,$$

$$\beta_p=\beta_n=\frac{\pi\alpha}{12m_\pi}\left(\frac{g_A}{4\pi f_\pi}\right)^2=1.2\times10^{-4}\ \ \mathrm{fm}^3,$$

BChPT@NLO

Lensky & V.P.

$$\alpha = \underbrace{6.8}_{\mathcal{O}(p^3)} + (\ldots$$

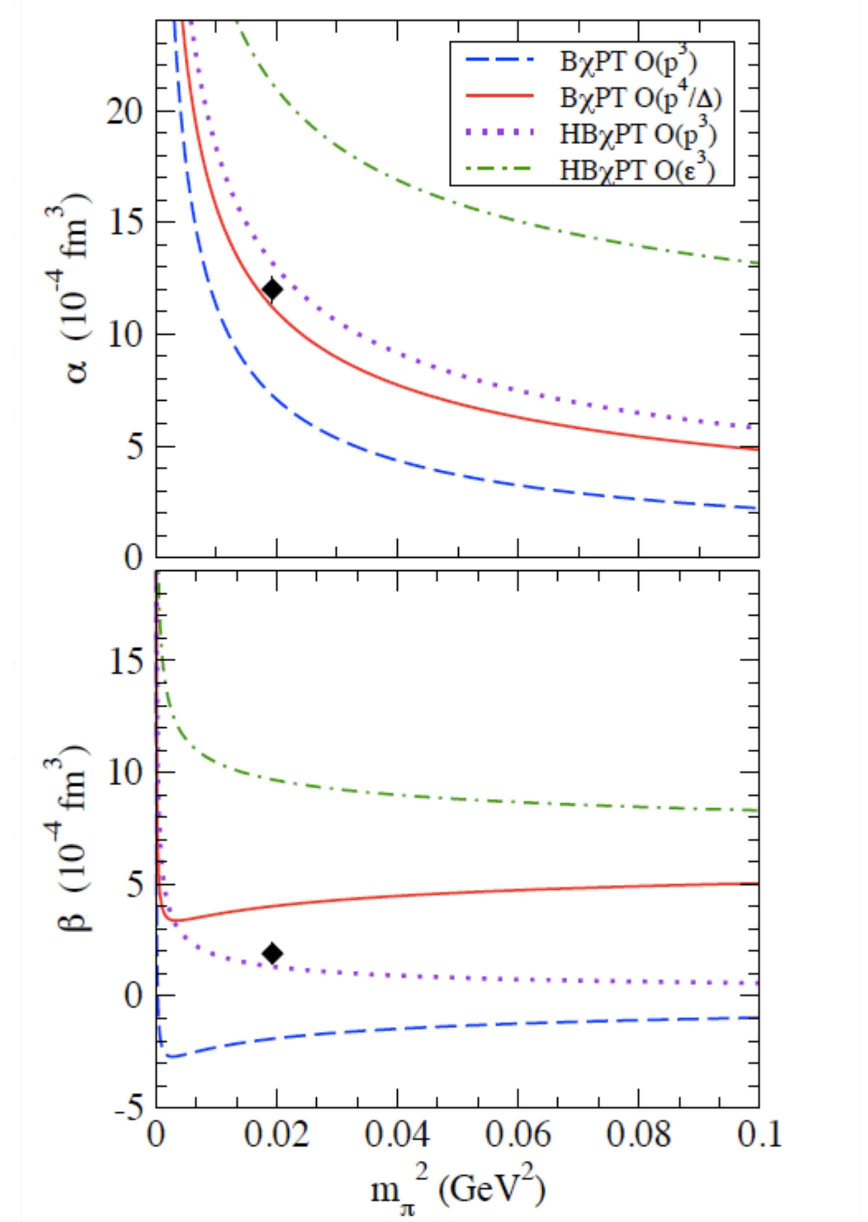
$$\beta = \underbrace{-1.8}_{\mathcal{O}(p^3)} + \ldots$$

paramagnetic

diamagnetic

$\mu = m_\pi/M_N$

$$\beta = \frac{e^2 g_A^2}{192\pi^3 F^2 M_N}\left[\frac{\pi}{4\mu} + 18\log\mu + \frac{63}{2} - \frac{981\pi\mu}{32} - (100\log\mu \ldots\right.$$



HBChPT@NLO:

mmer & Hemmert (2004)
McGovern, Phillips (2012)

The Delta contribution is accompanied by "promoted" LECs, hence not predictive

Lattice QCD data expected soon