NUCLEON STRUCTURE AT LOW-ENERGY / PRECISION FRONTIER

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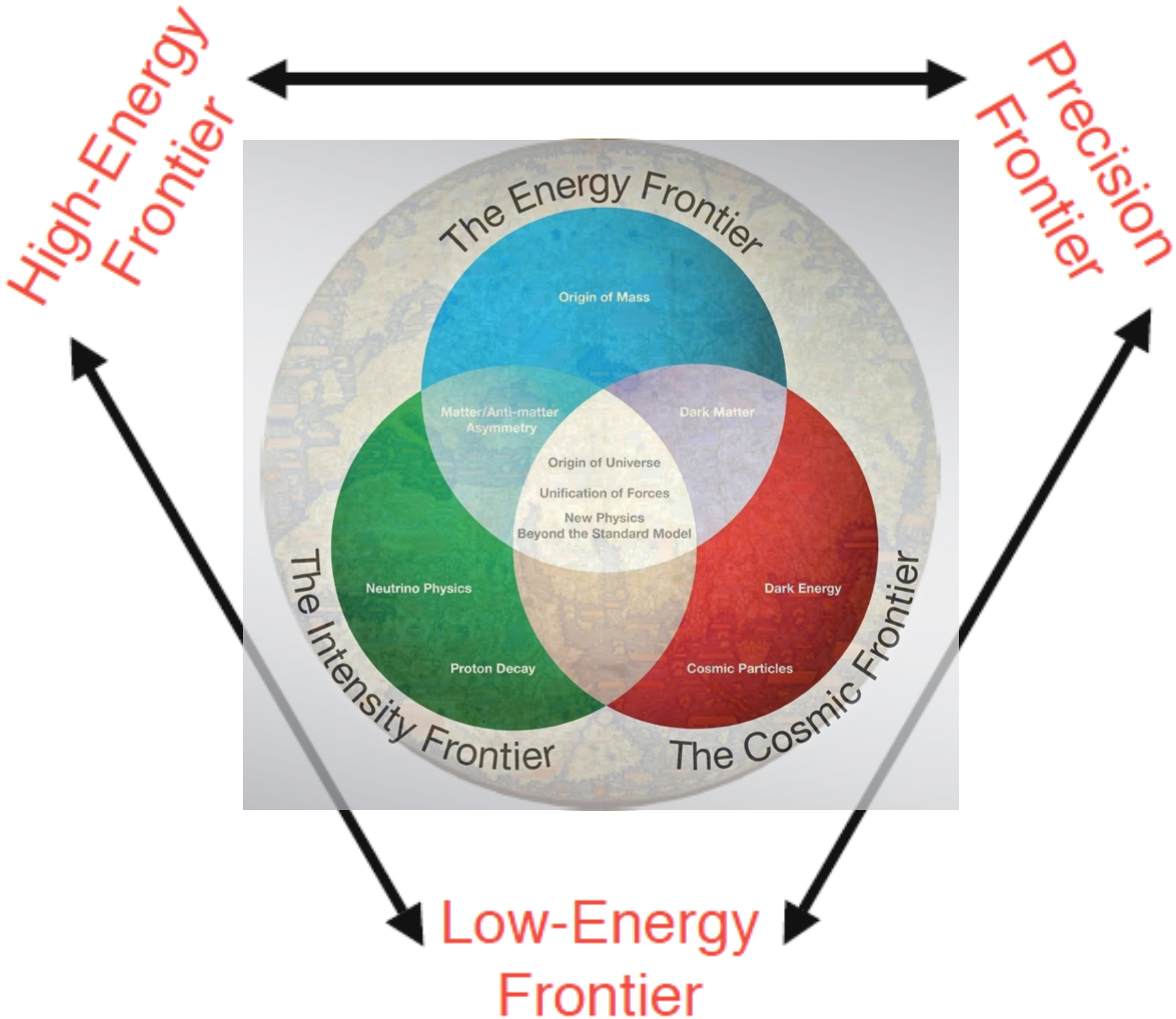
Frontiers of subatomic physics

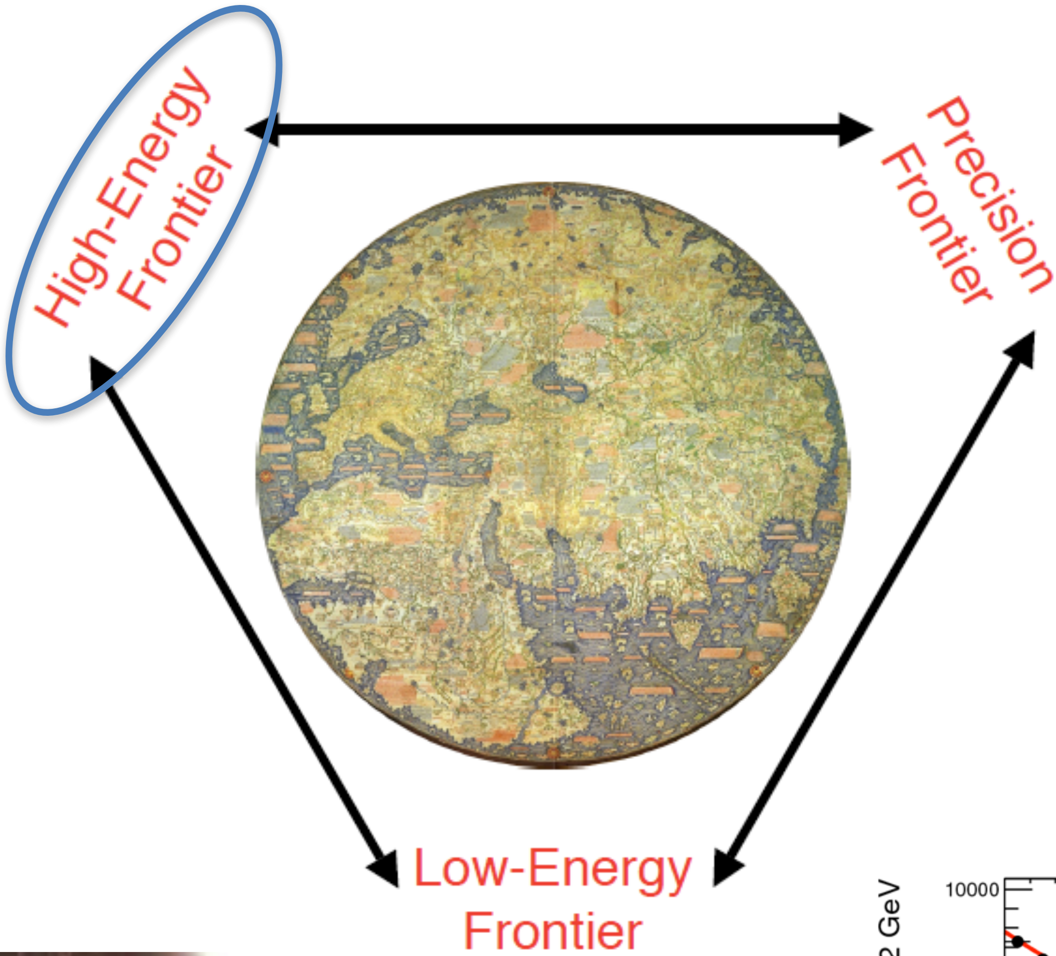


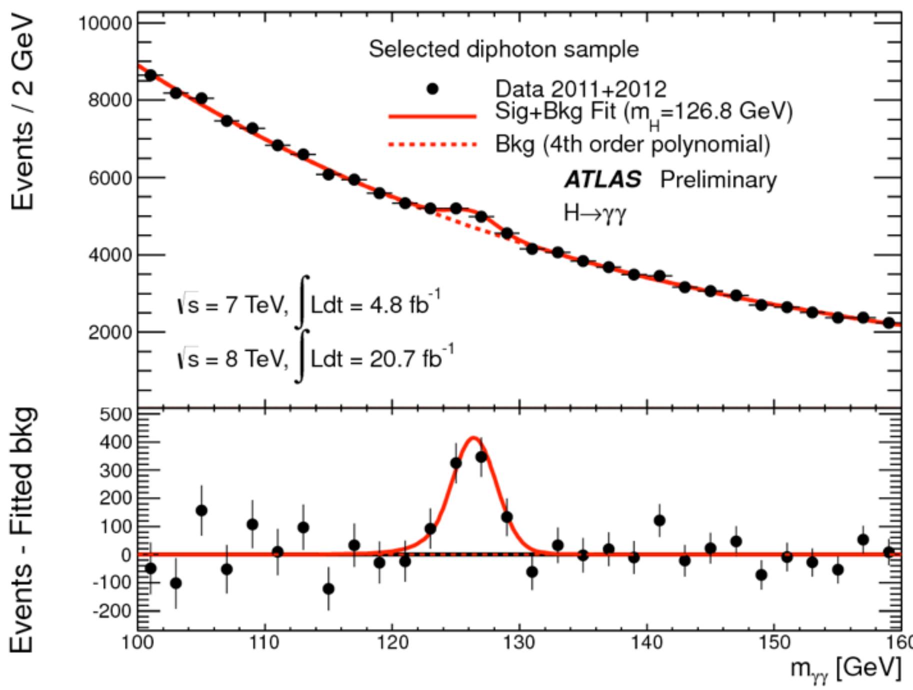
High energy easy to identify

LHC

Higgs boson discovery
Production of new particles and stuff

Next: **ILC**



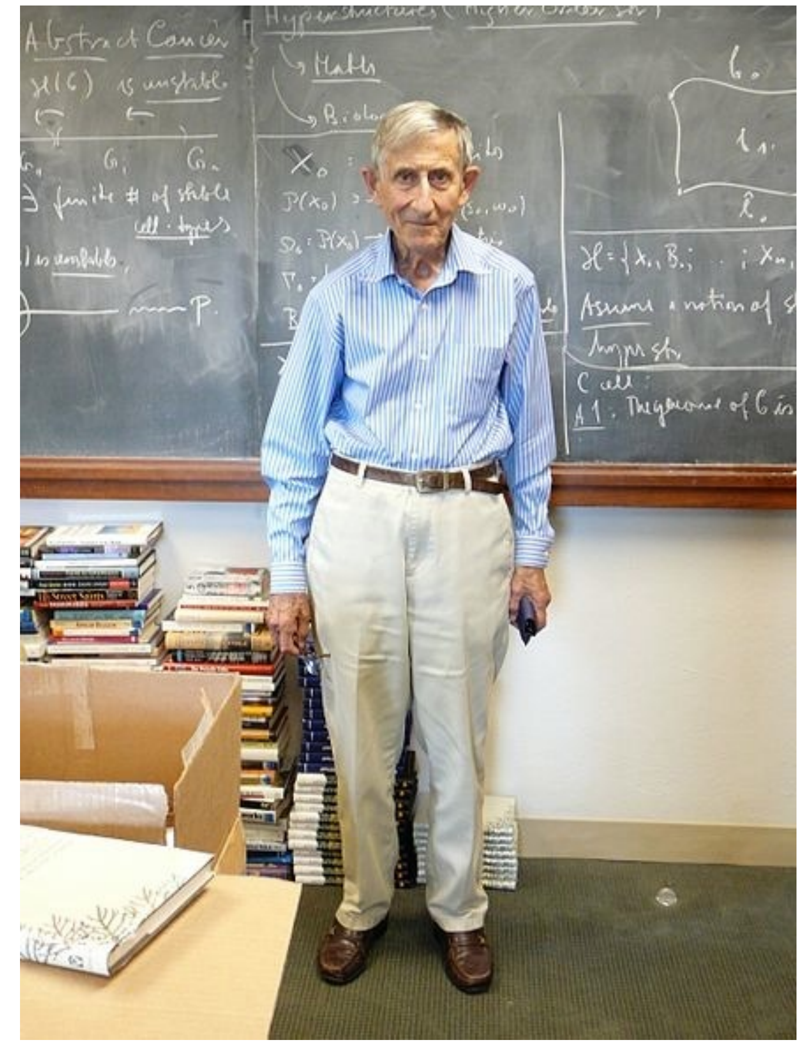


Breaking through frontiers

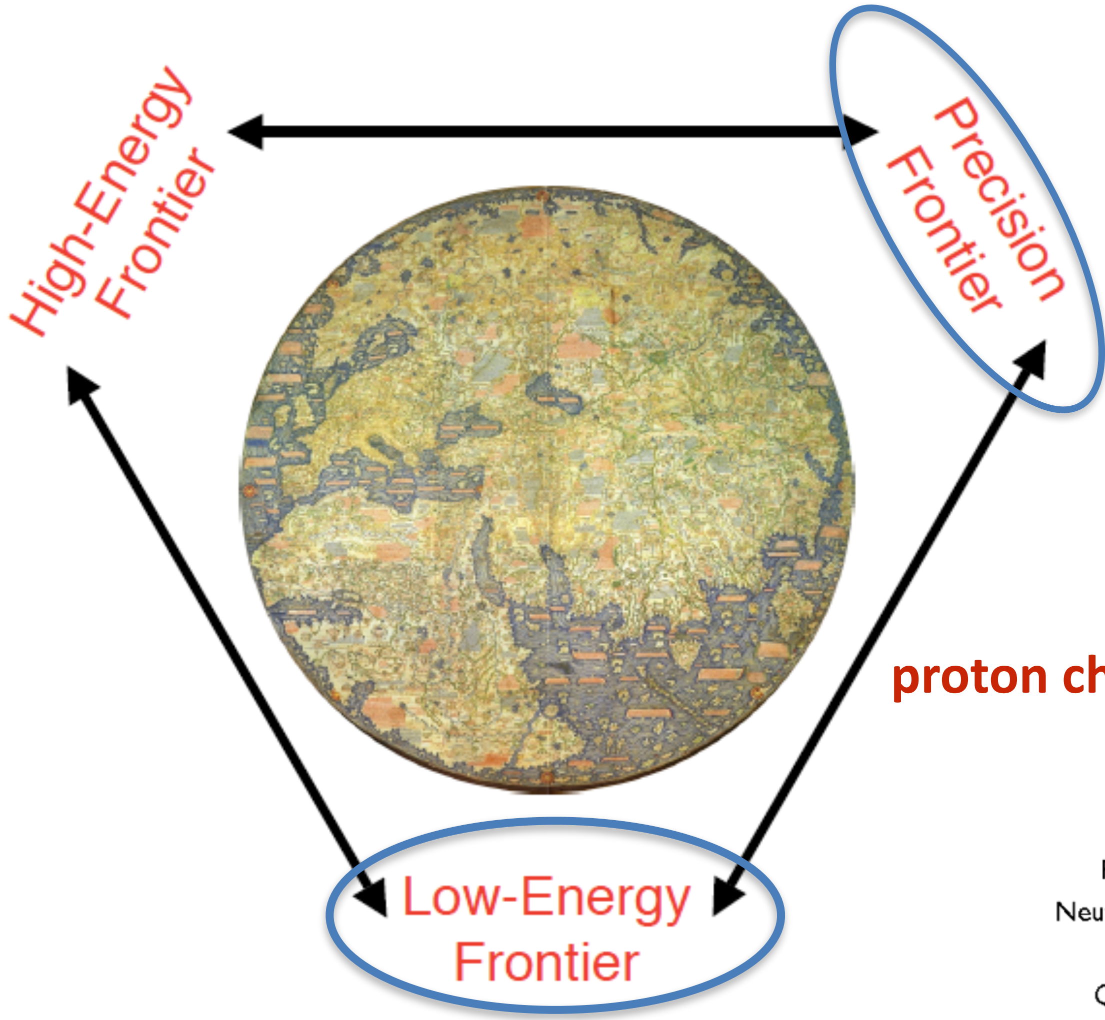
Freeman Dyson on 16 discoveries awarded the Nobel Prize between 1945 and 2008:

"*four discoveries on the* energy frontier, *four on the* rarity frontier, *eight on the* accuracy frontier. *Only a quarter of the discoveries were made on the energy frontier, while half of them were made on the accuracy frontier.* ***For making important discoveries, high accuracy was more useful than high energy.***"

(Freeman Dyson, review of The Lightness of Being, F. Wilczek, The New York Review of Books, April 2009)



Precision frontier and the stumbling stone



Testing SM at low energies, quantum loop corrections

$\sin^2\theta_W$

EDM

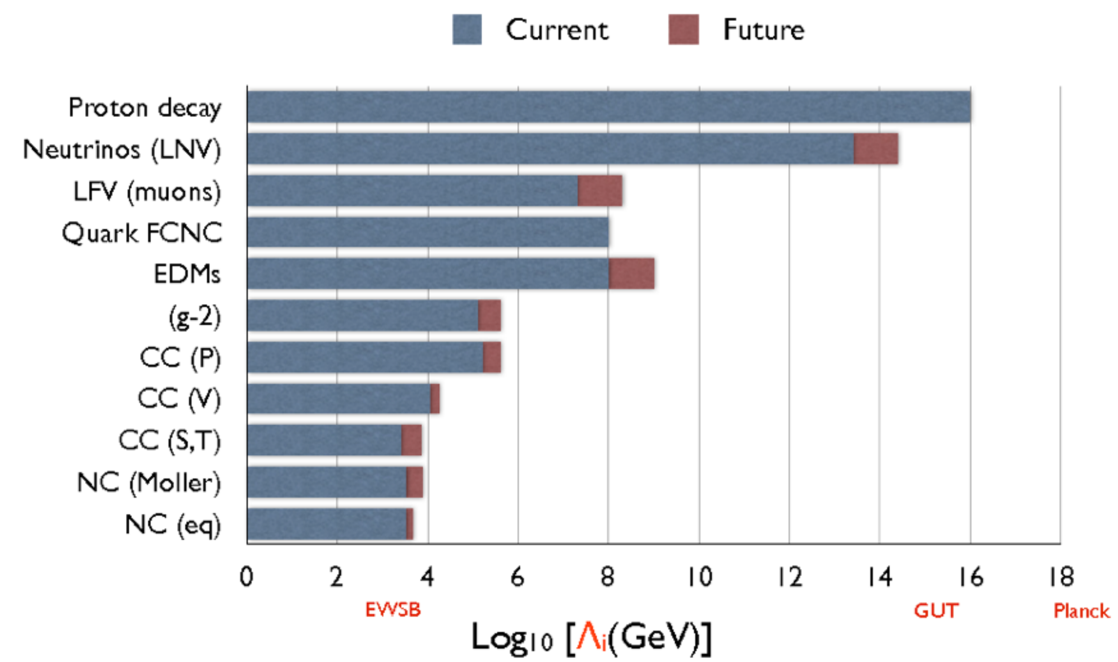
Flavor physics

Atomic tests

(g-2)μ

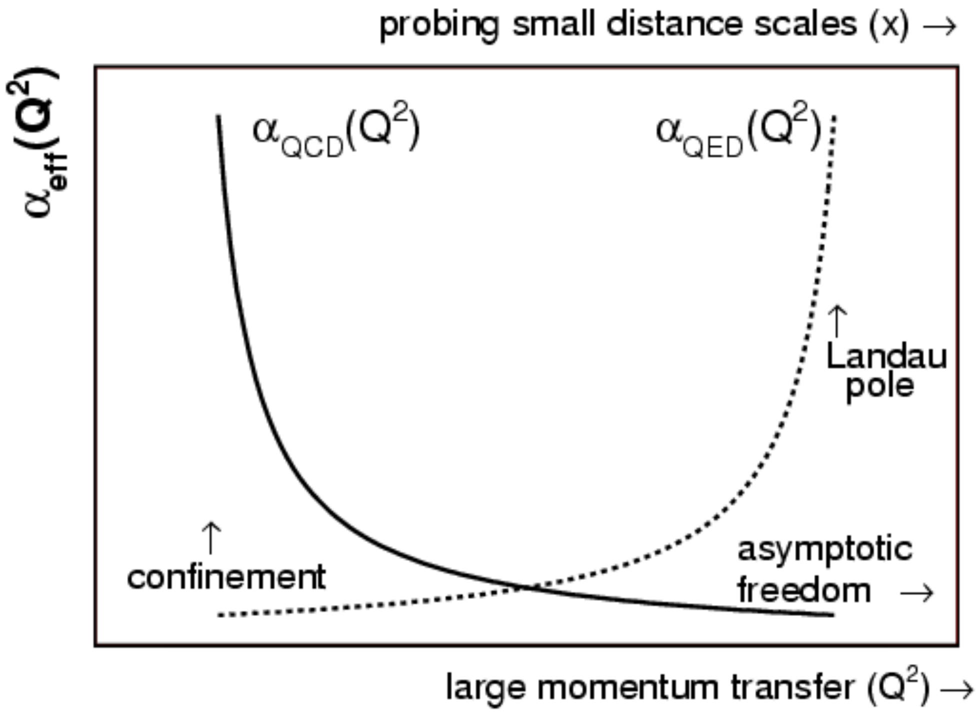
proton charge radius puzzle

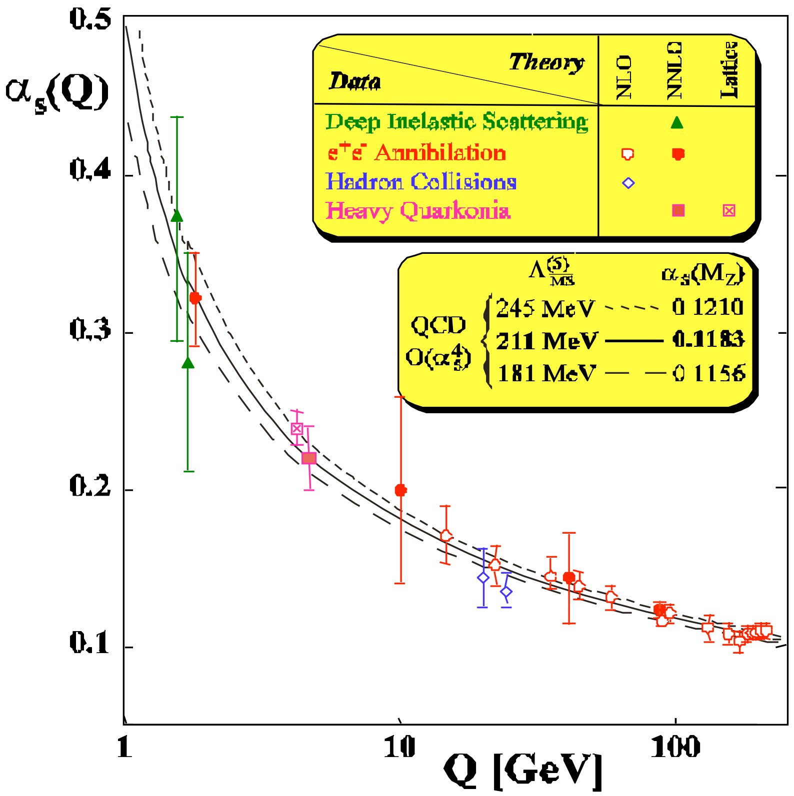
Low-Energy Strong Interaction:
non-perturbative QCD
structure info (FFs, GPDs, PDFs)



[from Cigriliano & Ramsey-Musolf, Ann.Rev.Mod.Sci(2013)]

QCD coupling





For $Q^2 \to \infty,\ \alpha_s \to 0$: **asymptotic freedom**

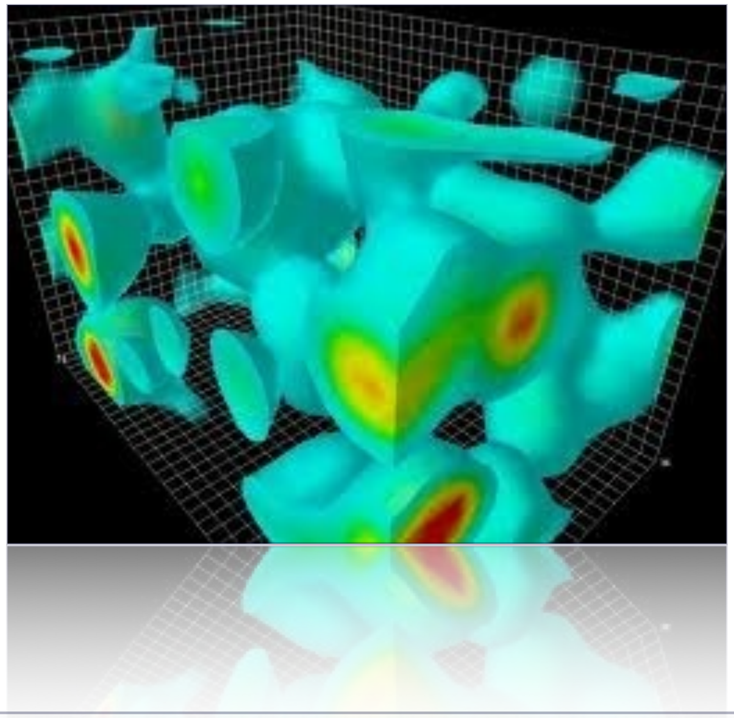
For $Q \sim \Lambda_{QCD}$ non-perturbative phenomena:

color confinement,
spontaneous chiral symmetry breaking,
generation of nucleon mass, ...

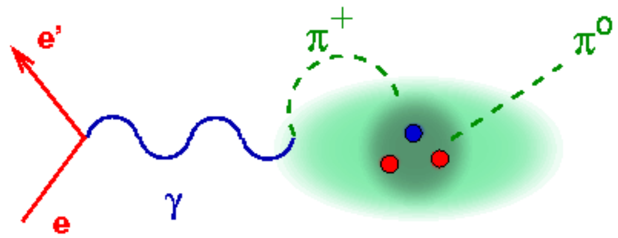
QFTs of low-energy strong interaction

… turning the tumble stone into stepping stones

Lattice QCD



Chiral perturbation theory (ChPT), a.k.a Chiral Effective-Field Theory (ChEFT)



ChPT basic facts

✦ **S. Weinberg, *Phenomenological Lagrangians,* Physica (1979):**
aimed to obtain quantum corrections to PCAC (LETs + chiral symmetry), derived the **Effective Field Theory** framework

✦ **Gasser & Leutwyler (1984, 1985) worked out ChPT in the meson sector.**

✦ **'Chiral' and 'Perturbative' go together:**
pions are Goldstone bosons of spontaneous ChSB,
interaction goes with powers of energy, vanishes at E=0 in the chiral limit.
perturbative expansion in energy and pion mass (but not a series expansion!)

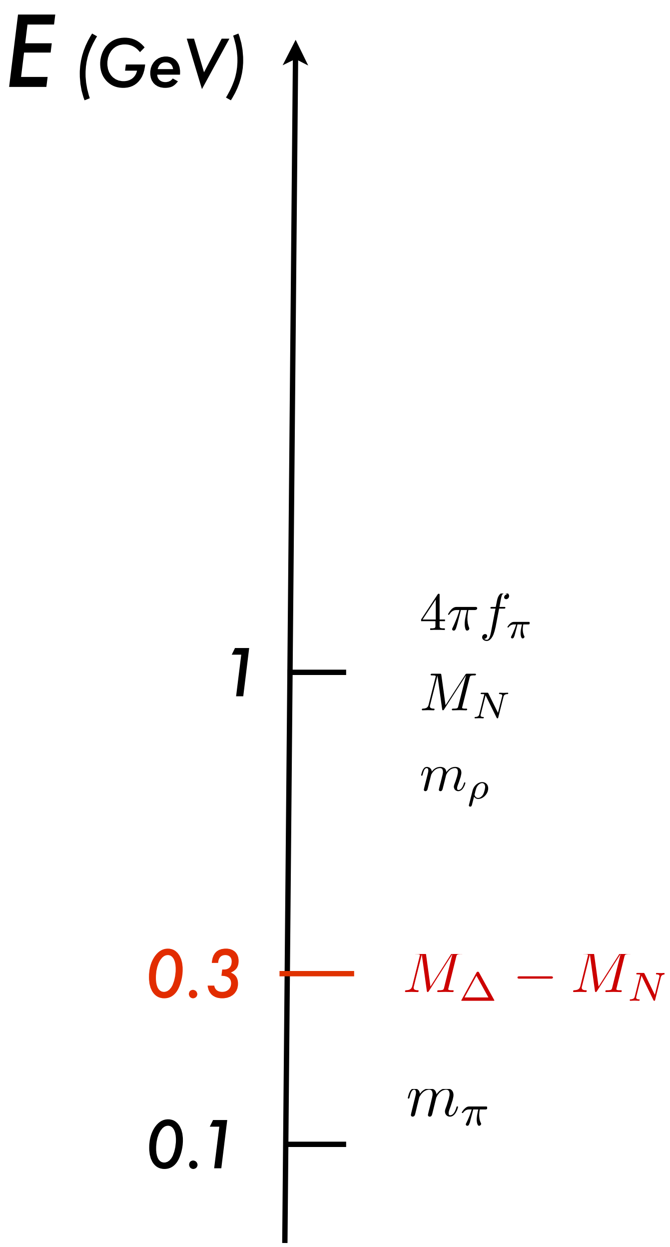
✦ **Most general Lagrangian (allowed by symmetries), hence infinitely many constants (LECs) parametrising the short-range physics.**

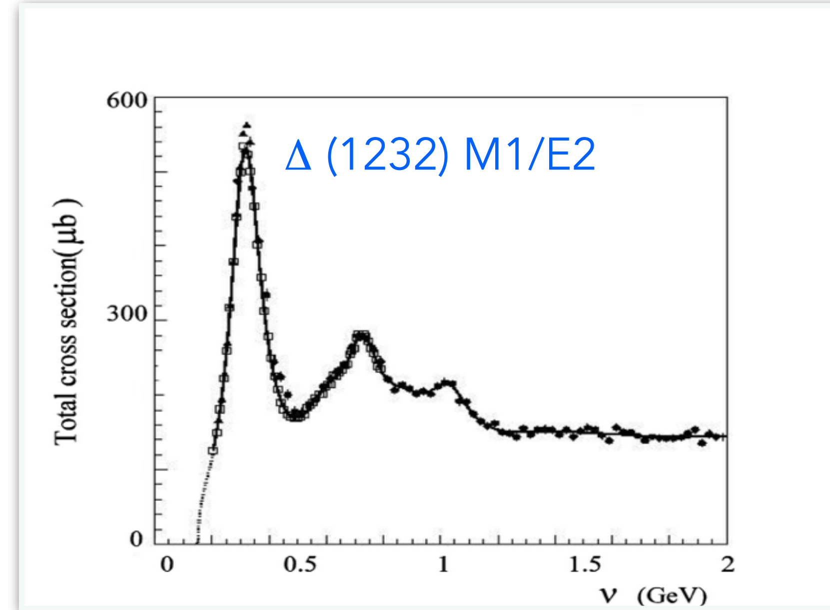
✦ **Predictive provided: *Hierarchy of scales and Naturalness***

Baryon ChPT

Not just the pion cloud: Delta(1232) excitation

Jenkins & Manohar, PLB (1991)
Hemmert, Holstein, Kambor, JPhysG (1998)
V.P. & Phillips, PRC (2003)





- The 1st nucleon excitation — Delta(1232) is within reach of chiral perturbation theory (293 MeV excitation energy is a light scale)
- Include into the chiral effective Lagrangian as explicit dof
- Power-counting for Delta contributions (SSE, ``delta-counting") depends on what chiral order is assigned to the excitation scale.

Example: Nucleon mass

$$\mathcal{L} = \sum_k \mathcal{L}^{(k)}, \qquad k = \#\text{ of pion derivatives and masses}$$

$$\mathcal{L}^{(1)}_{\pi N} = \bar{N}(i\not{D} - \mathring{M}_N + \mathring{g}_A\, a_\mu \gamma^\mu \gamma_5)N$$

$$= \bar{N}\Big(i\not{\partial} - \mathring{M}_N + \frac{\mathring{g}_A}{2f_\pi}(\partial_\mu \pi)\gamma^\mu\gamma_5\Big)N + O(\pi^2)$$

$$\mathcal{L}^{(2)}_{\pi N} = 4\,\mathring{c}_{1N}\, m_\pi^2\, \bar{N}\, N + \ldots$$

Power-counting:

$$n = \textstyle\sum_k k V_k + 4L - 2N_\pi - N_N$$

V_k	# of vertices from $\mathcal{L}^{(k)}$
L	# of Loops
N_π	# of internal pions
N_N	# of internal nucleons

LECs

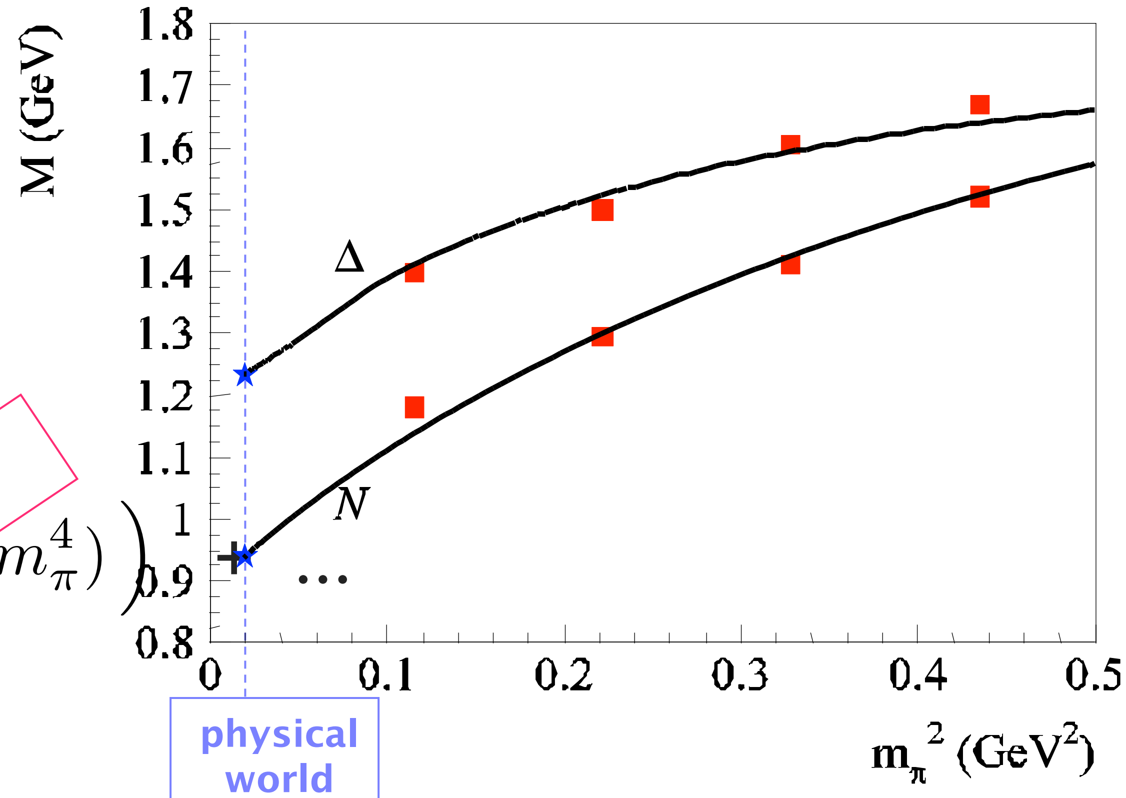
$k = 1,\ V_k = 2,\ L = 1,\ N_\pi = 1,\ N_N = 1$

$$M_N = \mathring{M}_N - 4\,\mathring{c}_{1N}\, m_\pi^2 - $$  $$+ \ \ldots$$

$O(p^3)$

$$M_N = \mathring{M}_N - 4\,\mathring{c}_{1N}\, m_\pi^2 - \frac{g_A^2}{(4\pi f_\pi)^2}\left(\frac{3\pi}{2} m_\pi^3 + O(m_\pi^4)\right)$$

prediction of ChPT



[V.P. & Vanderhaeghen, PLB (2006)]

Heavy-baryon ChPT? No!

LECs

$$M_N = \overset{\circ}{M}_N - 4\,\overset{\circ}{c}_{1N}\, m_\pi^2 \; - $$  + ...

$O(p^3)$

 $$= \frac{3g_A^2}{2(4\pi f_\pi)^2}\Big\{ - M_N^3\, L + M_N\,(1-L)\, m_\pi^2 - m_\pi^3 \Big(\sqrt{1 - m_\pi^2/4M_N^2}\; \arccos\frac{m_\pi}{2M_N} + \frac{m_\pi^4}{4M_N}\,\ln\frac{m_\pi^2}{M_N^2}\Big)\Big\}$$

where $L = \frac{1}{\epsilon} + \dots$ contains the UV-divergence, removed in MS-bar: $L = 0$
remaining m_π^2 "complicates life a lot" [GSS88]. Violation of power counting?!!

Gasser, Sainio & Svarc, NPB (1988); ...

Led to **Heavy-Baryon ChPT** [Jenkins & Manohar, PLB (1991)] which for a decade was considered as the only consistent formulation.

Drawback: not working — 1. removes m_π^2 in dimreg but not in cutoff schemes,
2. demotes important contributions to "higher-orders"

Fortunately, HB not needed: m_π^2 term removed by renormalization of the LEC.

Japaridze & Gegelia (1999), published in (2003)!

Relevance to low-energy/precision frontiers

ChPT gives predictions*, i.e. free-parameter free results, for:

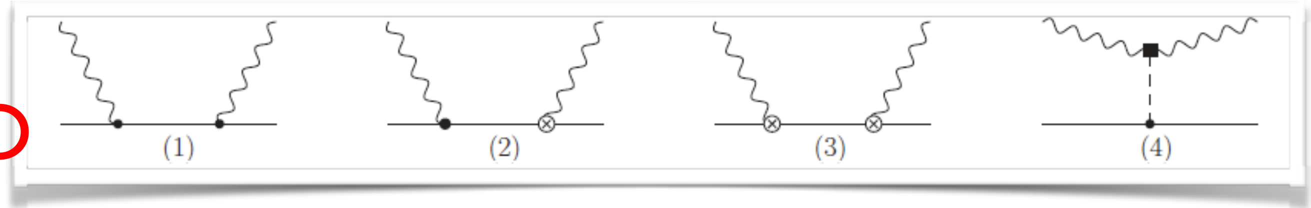
1. **Nucleon polarizabilities**

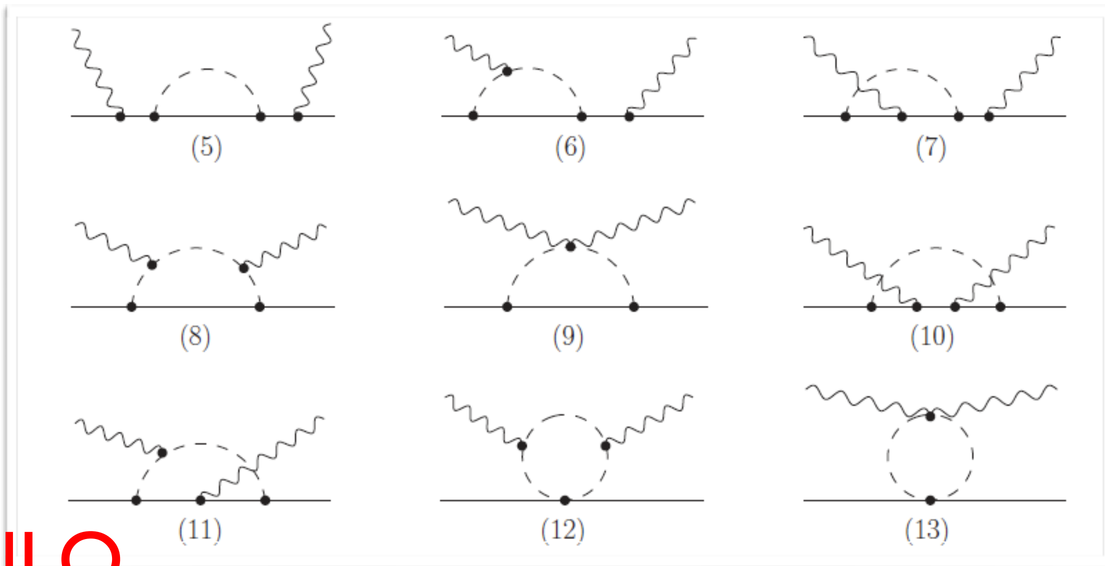
2. **Nucleon structure effects in hydrogen Lamb shift beyond the charge radius**

*Predictions of HBChPT differ from BChPT

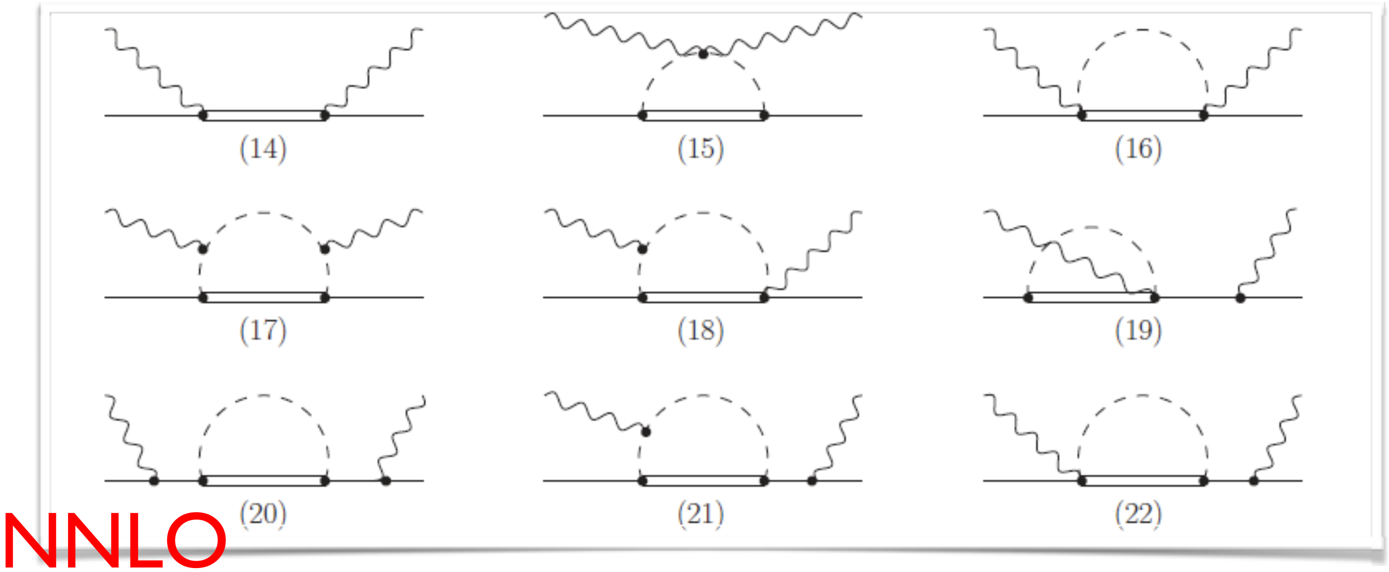
ChPT of Compton scattering off protons

LO



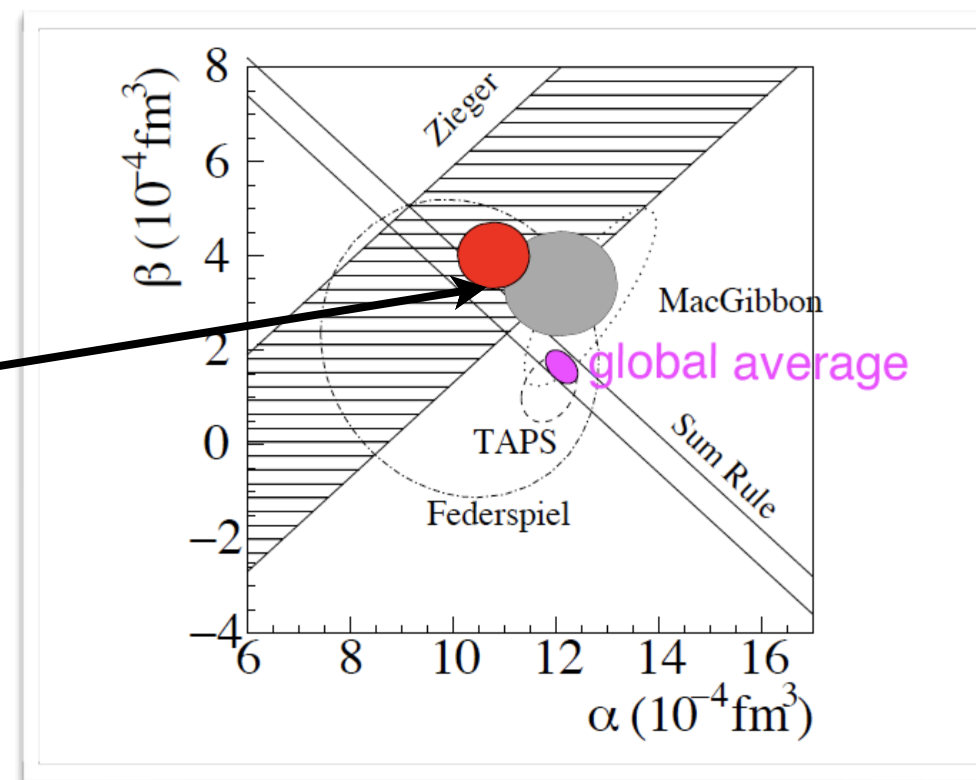


NLO



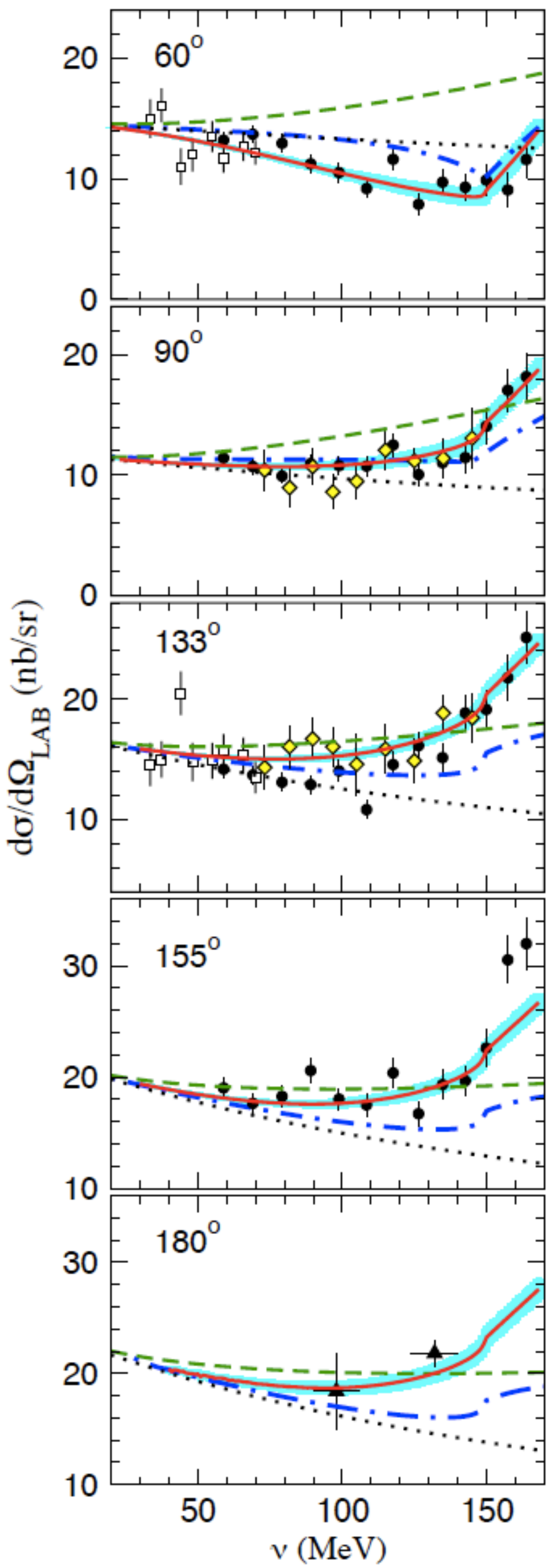
NNLO

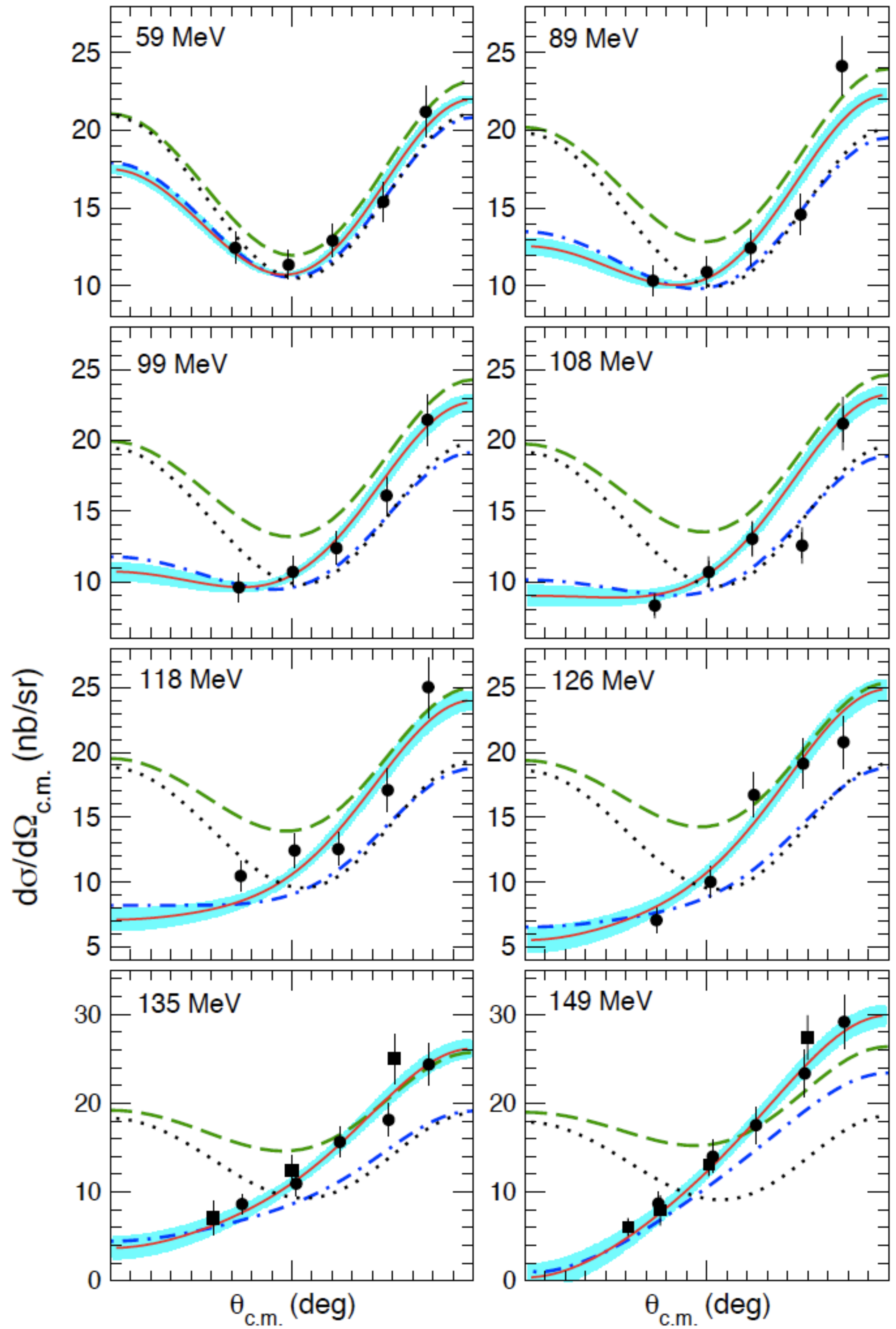
$\mathcal{O}(p^2)$	$\frac{e^2}{4\pi} = \frac{1}{137}$, $M_N = 938.3$ MeV, $\hbar c = 197$ MeV$\cdot$ fm
$\mathcal{O}(p^3)$	$g_A = 1.267$, $f_\pi = 92.4$ MeV, $m_\pi = 139$ MeV, $m_{\pi^0} = 136$ MeV, $\kappa_p = 1.79$
$\mathcal{O}(p^4/\Delta)$	$M_\Delta = 1232$ MeV, $h_A = 2.85$, $g_M = 2.97$, $g_E =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



Lensky & V.P., EPJC (2010)

Unpolarized cross sections





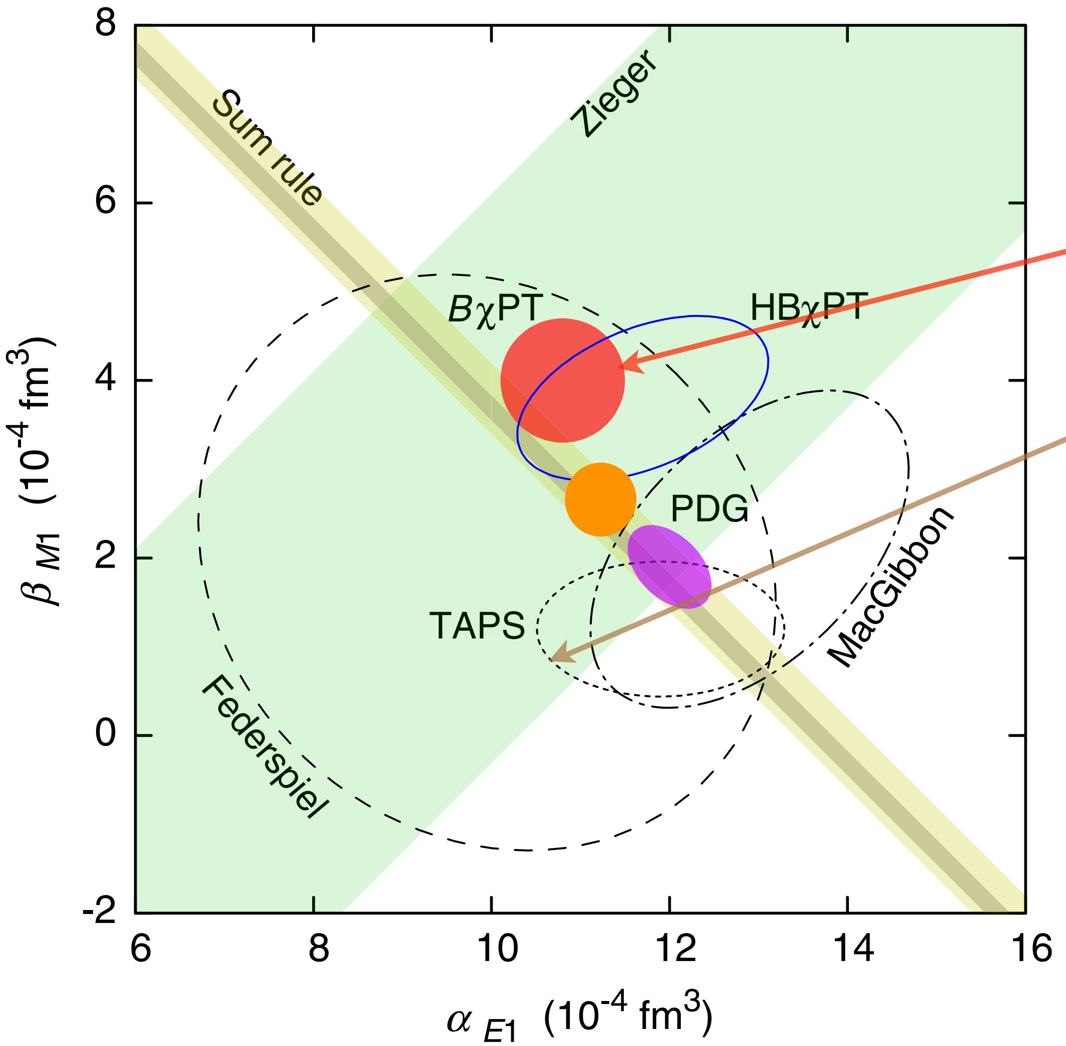
Data points:
MAMI/TAPS (2001)
SAL (1993)
Illinois (1991)

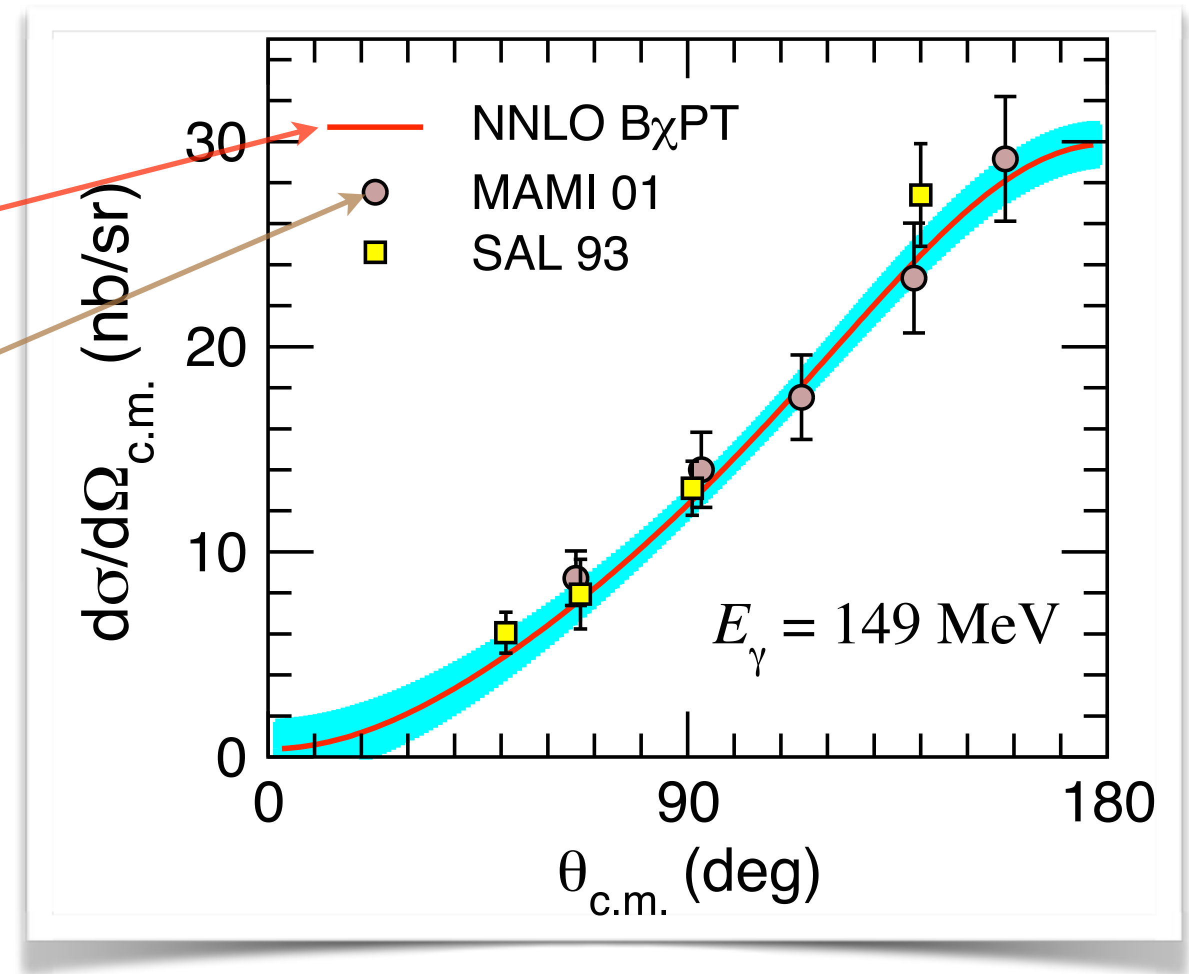
Curves:

- Klein-Nishina
- Born + WZW
- + p-qube
- Total NNLO

Lensky & V.P.,EPJC (2010)]

Proton polarizabilities





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

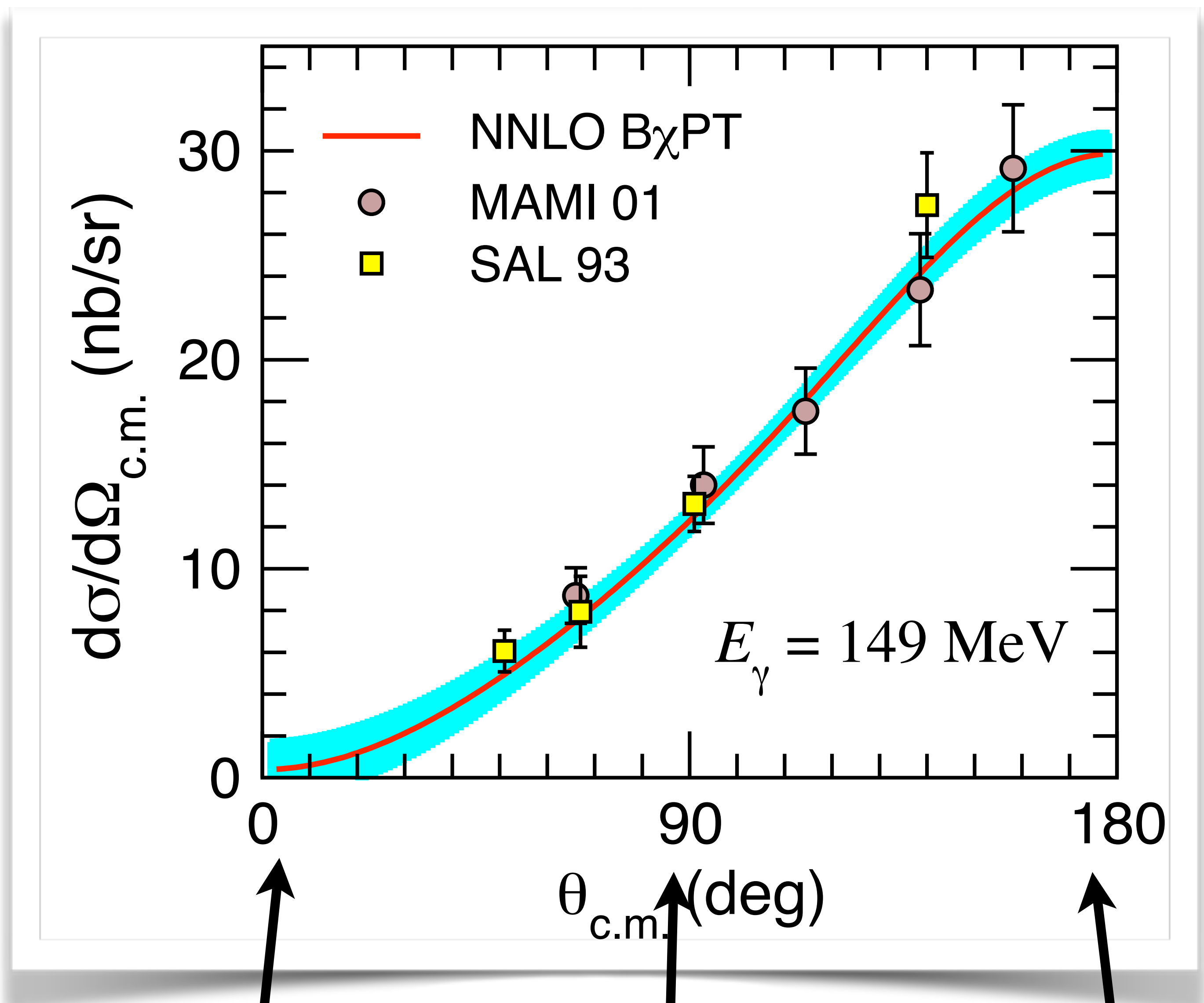
$$\beta_{M1} = (4.0 \pm 0.7) \times 10^{-4}\,\mathrm{fm}^3\ \text{[BChPT@NNLO]}$$

BChPT - Lensky & V.P., EPJC(2010)
HBChPT - Griesshammer, McGovern, Phillips, EPJA (2013)

PDG adjusted values
from 2012 edition (**purple**) to
2013 on-line edition (**orange**)

Extracting polarizabilities from angular dep.

$$\frac{d\sigma^{(\mathrm{NB})}}{d\Omega} = -2\pi Z^2 \frac{\alpha}{M}\left(\frac{\nu'}{\nu}\right)^2 \nu\nu' \left[2\alpha_{E1}\left(1+\cos^2\theta\right) + 4\beta_{M1}\cos\theta\right] + O(\nu^4)$$

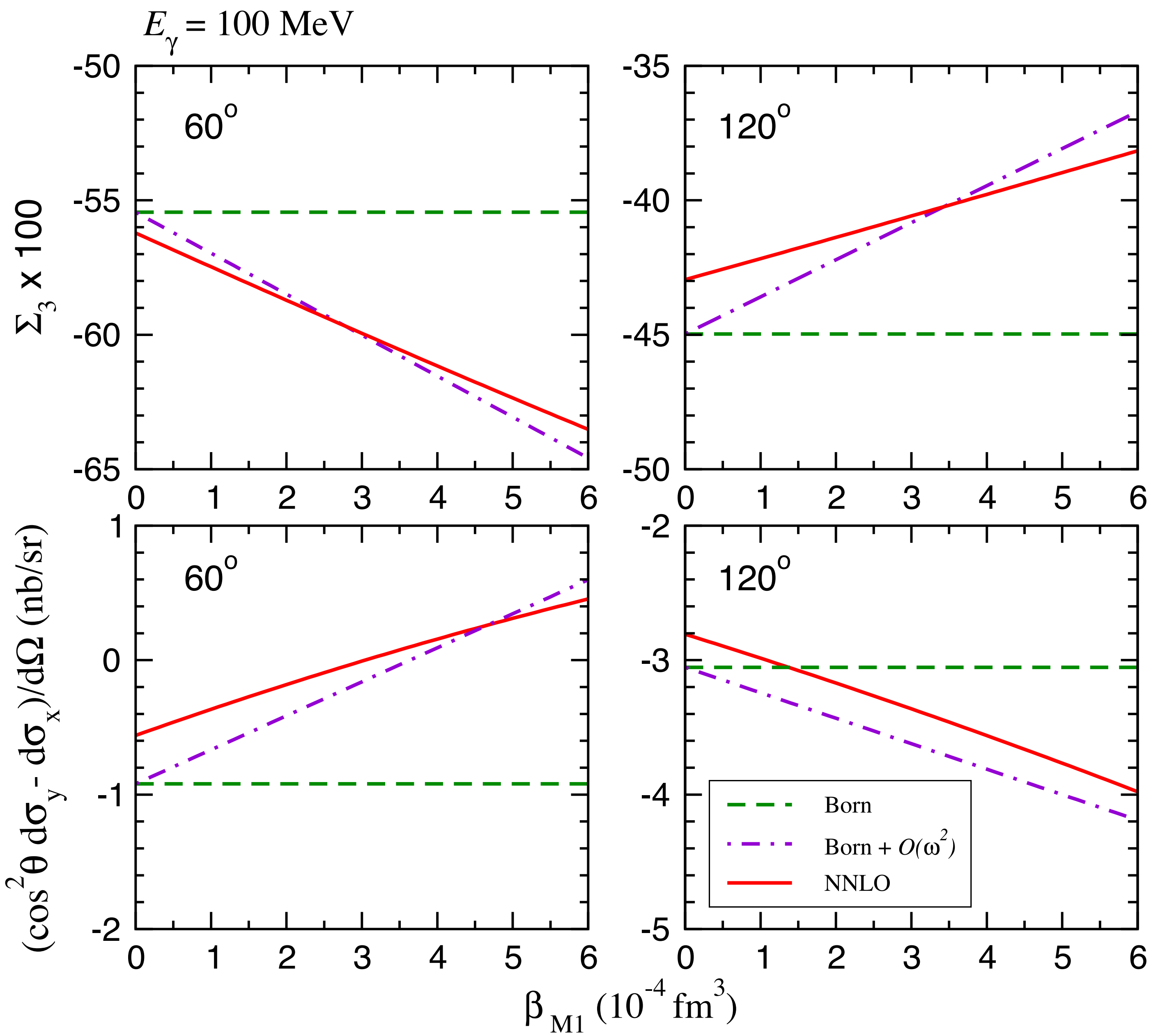


$\alpha + \beta$ α $\alpha - \beta$

From linear beam asymmetry

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

Krupina & V.P, PRL (2013)



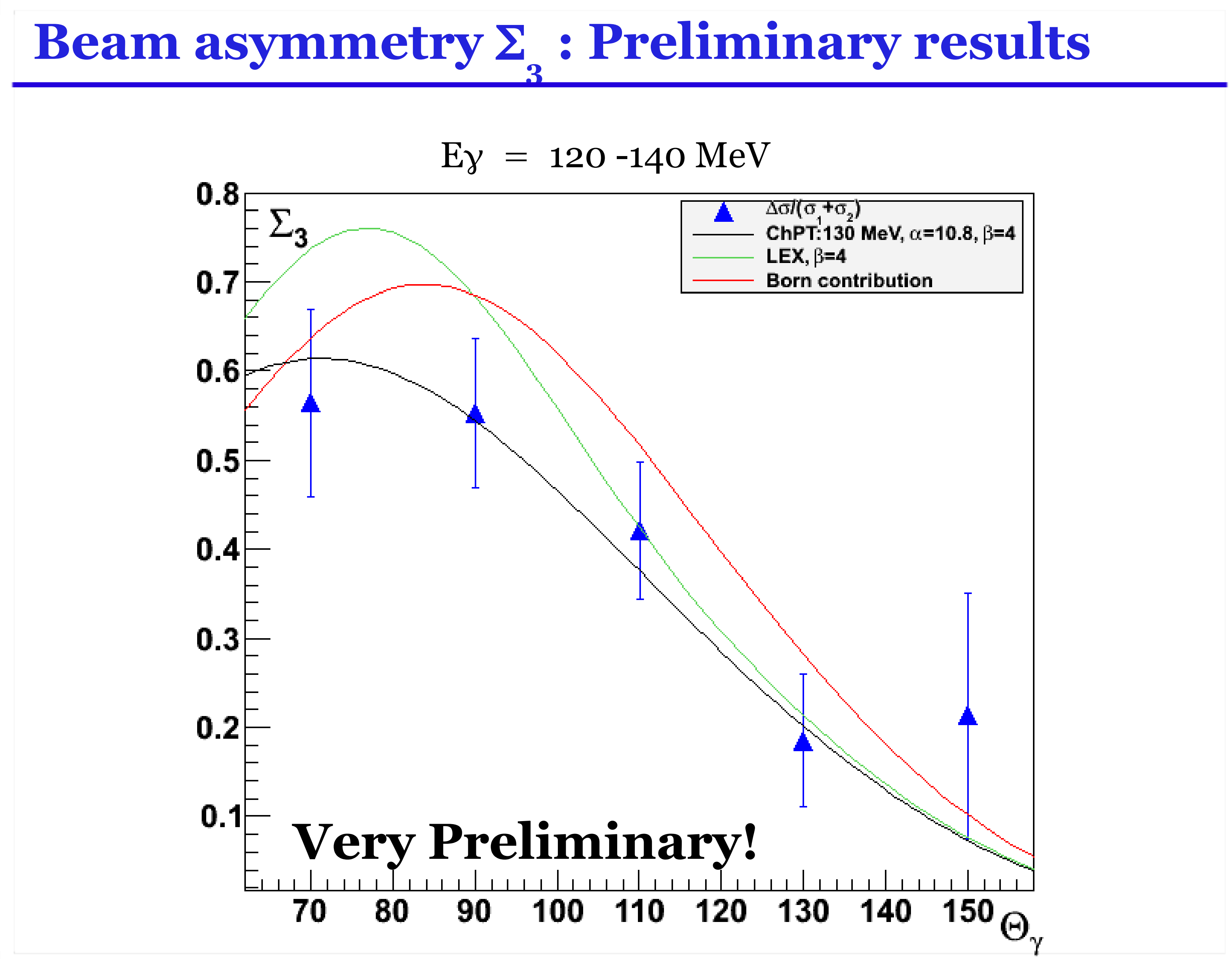
New Mainz data for Compton beam asymmetry

Data taken: 28.05. – 17.06.2013, 327 h

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)

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

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

BChPT@NLO

Lensky & V.P.

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

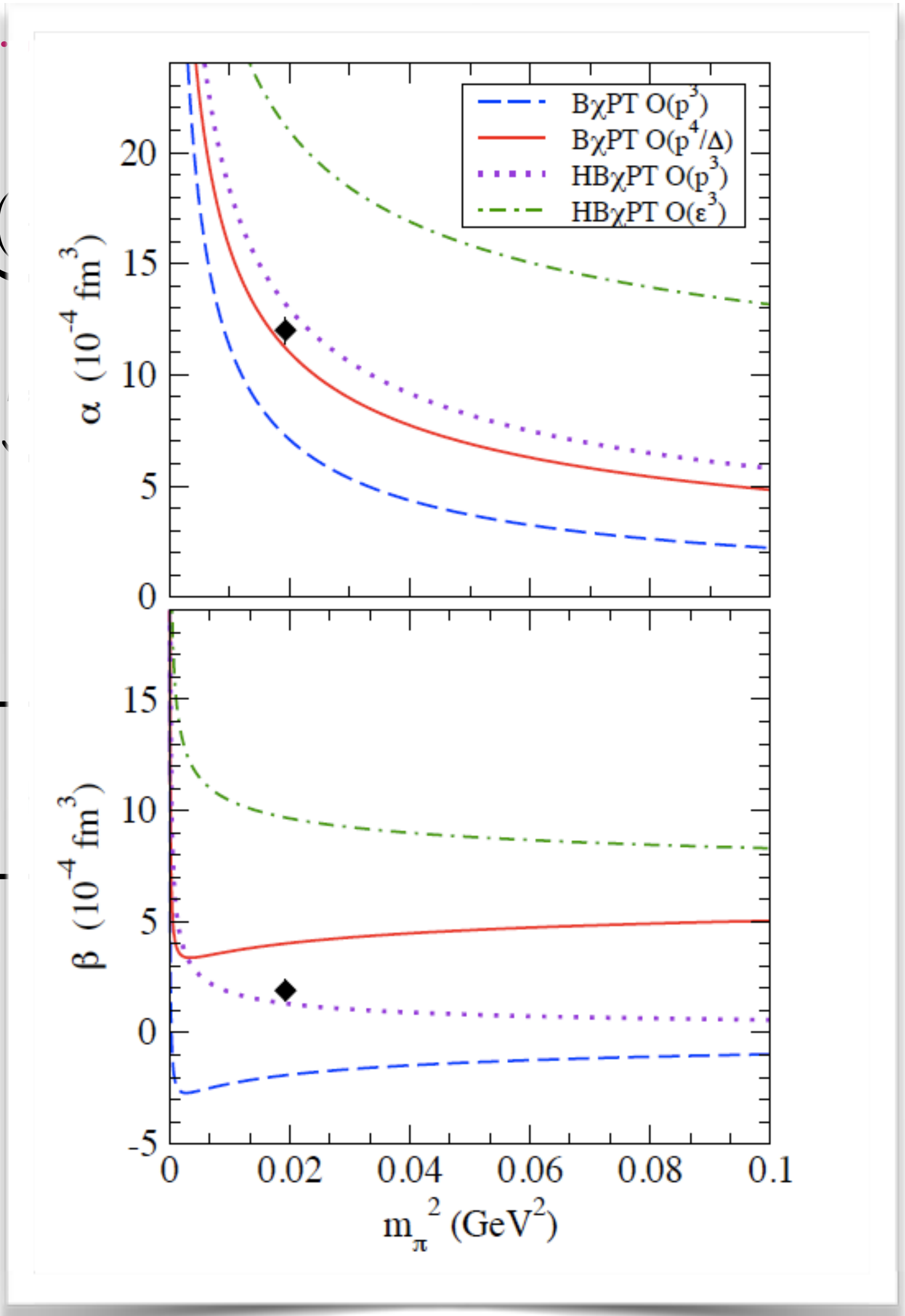
$$\beta = \underbrace{-1.8}_{\mathscr{O}(p^3)} + \ \dots$$

paramagnetic

diamagnetic

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

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



HBChPT@NLO:
Griesshammer & Hemmert (2004)
Griesshammer, McGovern, Phillips (2012)

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

Lattice QCD data expected soon

Discoveries relevant to modern precision frontier

The Nobel Prize in Physics 1955

Willis Eugene Lamb

"for his discoveries concerning the fine structure of the hydrogen spectrum"

Polykarp Kusch

"for his precision determination of the magnetic moment of the electron"

The Nobel Prize in Physics 1961

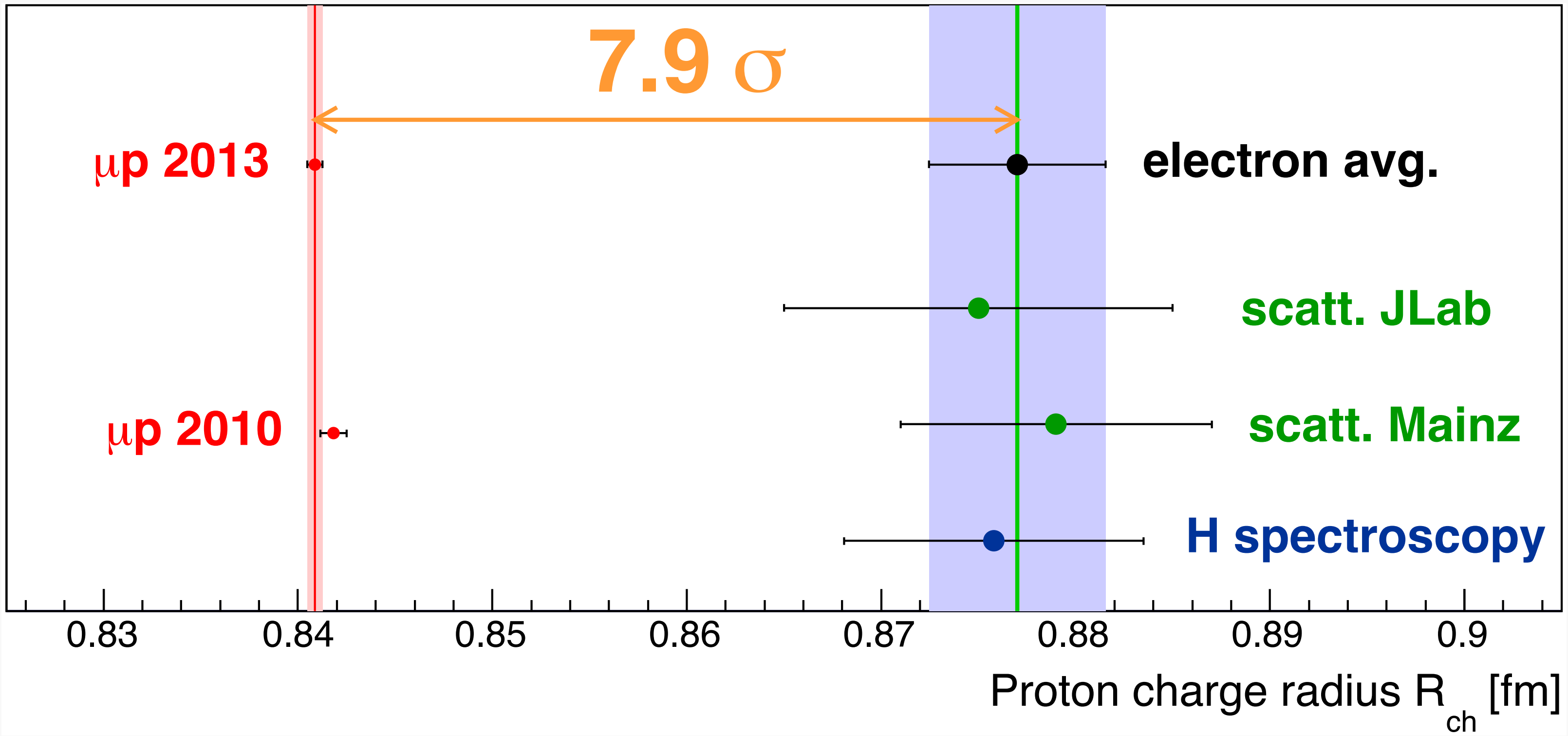
Robert Hofstadter

"for his pioneering studies of electron scattering in atomic nuclei and for his thereby achieved discoveries concerning the structure of the nucleons"

The proton radii puzzle

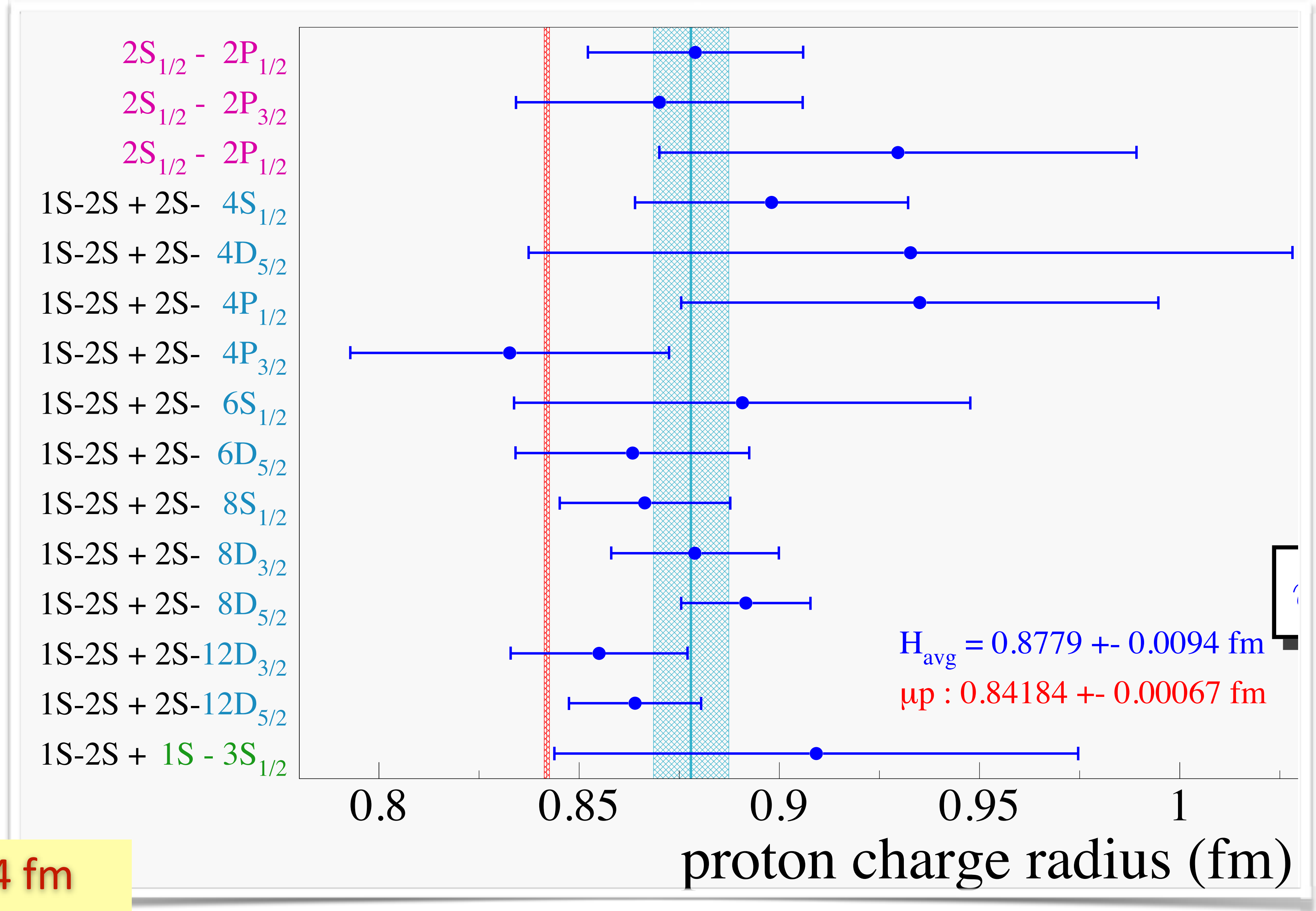
3 ways to the proton radius

e-p scattering
H precision laser spectroscopy
μp laser spectroscopy



Pohl *et al.*, Nature 466, 213 (2010)
Antognini *et al.*, Science 339, 417 (2013)

Proton size



Pohl et al. (2010)
Antognini et al. (2013)

μH: $r_E = 0.8409 \pm 0.0004$ fm

8σ discrepancy

ep-data :
CODATA 2010 $r_E = 0.8772 \pm 0.0046$ fm
Bernauer et al. (2010), (2013)
Zhan et al. (2011)

The discrepancy translates into
310 micro-eV deficit
in the Lamb shift of muonic hydrogen

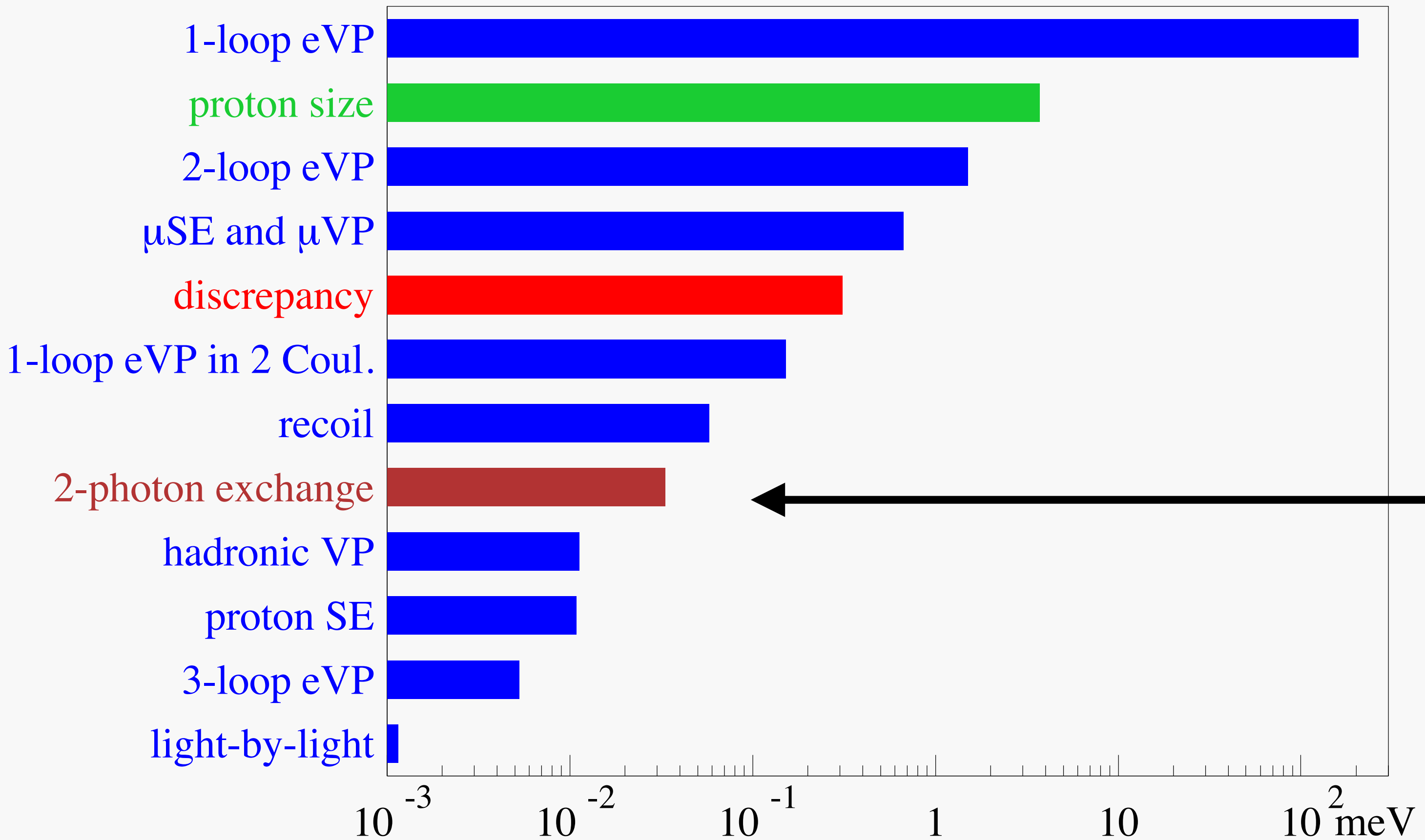
Theory of muonic hydrogen Lamb shift

Discrepancy = 0.31 meV

Theory uncertainty = 0.0025 meV

$\Rightarrow$ 120δ(theory) deviation?

$$\Delta E^{\rm th} = 206.0668(25) - 5.2275(10)\, r_{\rm p}^2 \quad [\rm meV]$$

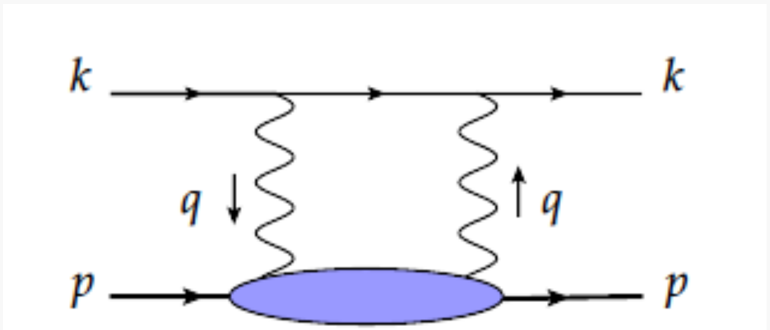


Pachucki, PRA 60, 3593 (1999)

Borie, arXiv: 1103.1772-v6

Jentschura, Ann. Phys. 326, 500 (2011)

Karshenboim *et al.*, PRA 85, 032509 (2012)



proposed to resolve the puzzle

De Rujula, PLB (2011)

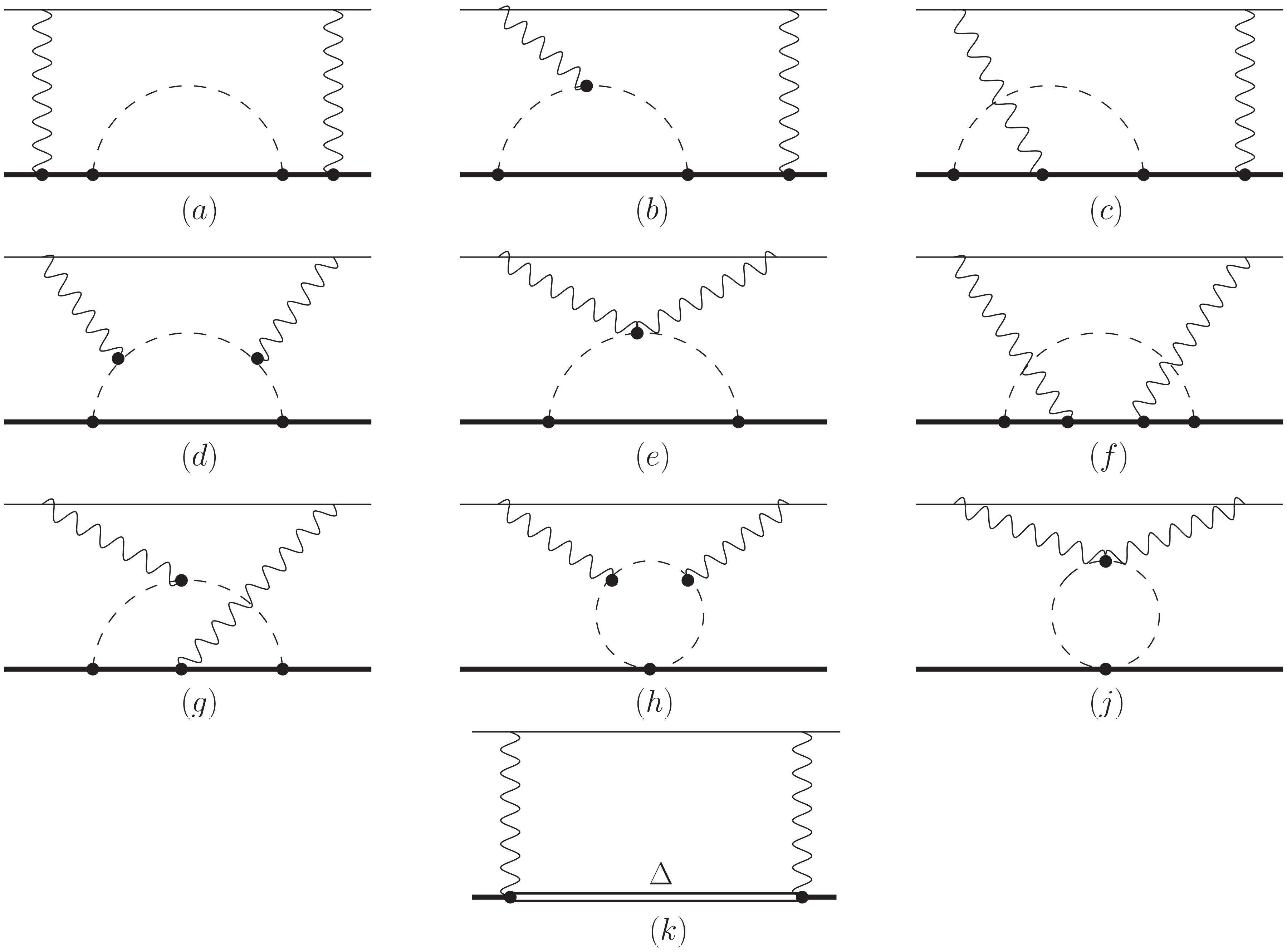
Miller, PLB (2013)

calculable in ChPT

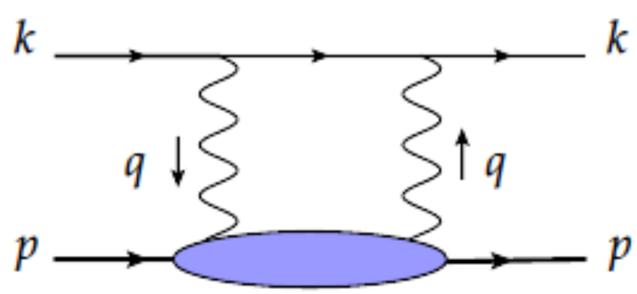
HB ChPT: **Nevado & Pineda (2008)**

BChPT: **Alarcon, Lensky & V.P.**

Lamb shift in ChPT



Lamb shift in terms of VVCS amplitudes



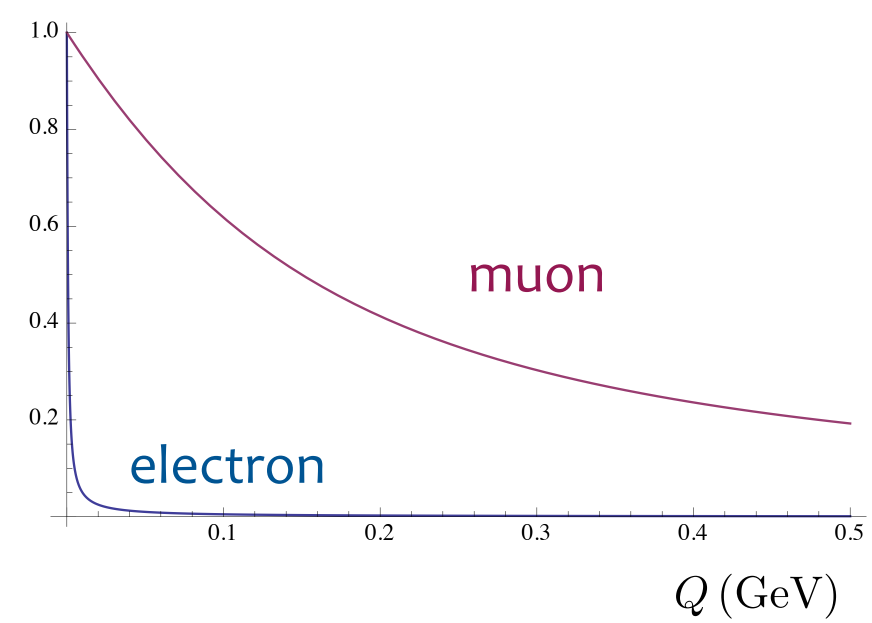
$$\Delta E_{nS}^{(\mathrm{pol})} = -4\alpha_{em}\phi_n^2 \int_0^\infty \frac{dQ}{Q^2}\, w\big(Q^2/4m_\ell^2\big)\, \Big[T_2^{(\mathrm{NB})}(0,Q^2) - T_1^{(\mathrm{NB})}(0,Q^2)\Big]$$

where unpolarized, forward Doubly-Virtual Compton scattering (VVCS) amplitude:

$$\phi_n^2(0) = m_r^3\alpha^3/(\pi n^3)$$

$$\begin{aligned} T^{\mu\nu}(p,q) &= \frac{i}{8\pi M}\int d^4x\, e^{iqx}\langle p|Tj^\mu(x)j^\nu(0)|p\rangle \\ &= \left(-g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\right) T_1(\nu,Q^2) \\ &+ \frac{1}{M^2}\left(p^\mu - \frac{p\cdot q}{q^2}q^\mu\right)\left(p^\nu - \frac{p\cdot q}{q^2}q^\nu\right) T_2(\nu,Q^2) \end{aligned}$$

$$w_\ell(Q) = \sqrt{1+\frac{Q^2}{4m_\ell^2}} - \frac{Q}{2m_\ell}$$



$$\begin{aligned} T_1^{(\mathrm{NB})}(0,Q^2) &\simeq Q^2\beta_{M1} \\ T_2^{(\mathrm{NB})}(0,Q^2) &\simeq Q^2(\alpha_{E1}+\beta_{M1}), \quad \text{for low } Q \end{aligned}$$

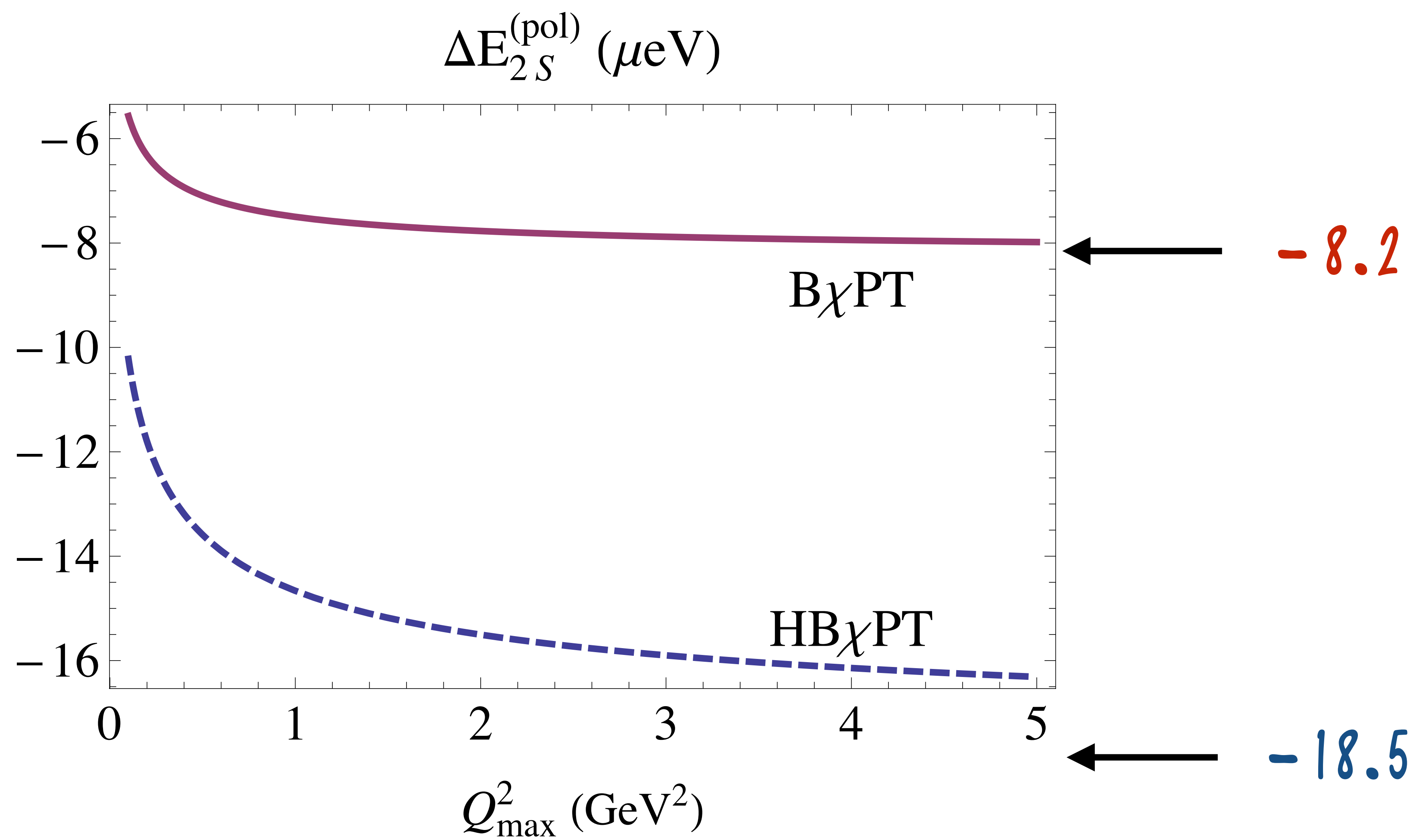
Proton polarizability effect in mu-H

			HBChPT				Alarcon, Lensky, V.P.
(μeV)	Pachucki [9]	Marty-nenko [10]	Nevado & Pineda [11]	Carlson & Vanderhaeghen [12]	Birse & 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)	3.3(4.6)	−3.0
$\Delta E_{2S}^{(\mathrm{inel})}$	−13.9	−13.8	−−	−12.7(5)	−12.7(5)*	−13.0(6)	−5.2
$\Delta E_{2S}^{(\mathrm{pol})}$	−12(2)	−11.5	−18.5	−7.4(2.4)	−8.5	−9.7(5.6)	$-8.2(^{+1.2}_{-2.8})$

[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).

Polarizability effect in mu-H Lam shift

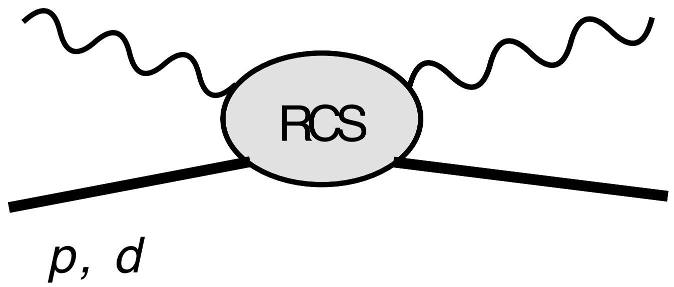
$$\Delta E_{nS}^{(\mathrm{pol})} = -4\alpha_{em}\phi_n^2 \int_0^\infty \frac{dQ}{Q^2}\, w\big(Q^2/4m_\ell^2\big)\ \Big[T_2^{(\mathrm{NB})}(0,Q^2) - T_1^{(\mathrm{NB})}(0,Q^2)\Big]$$

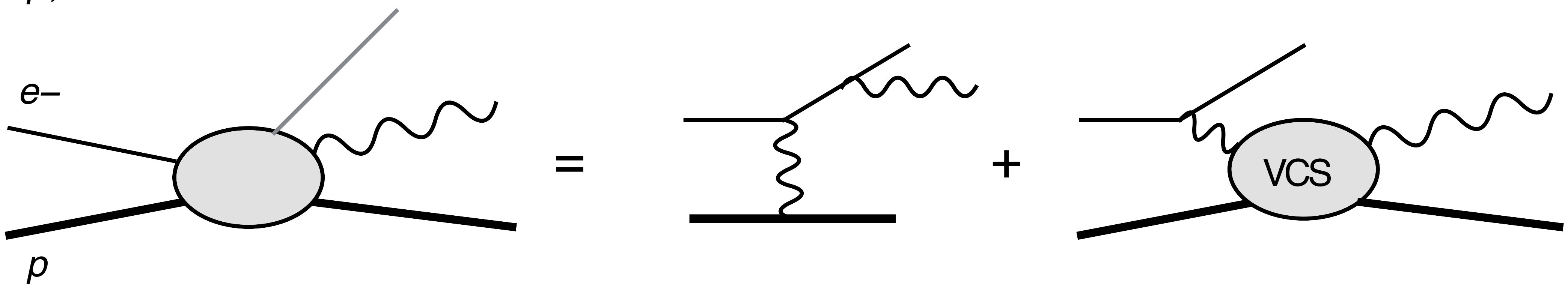


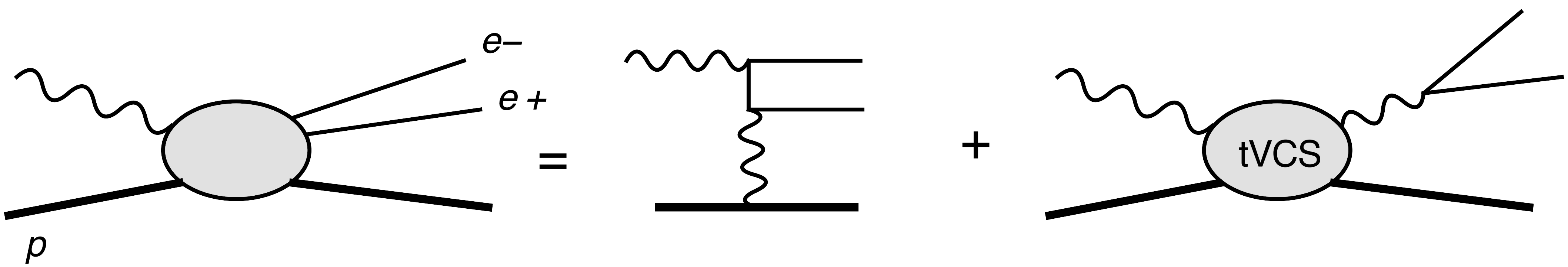
Heavy-Baryon and Baryon ChPT yield different predictions.. again
this time for proton structure corrections to Lamb shift

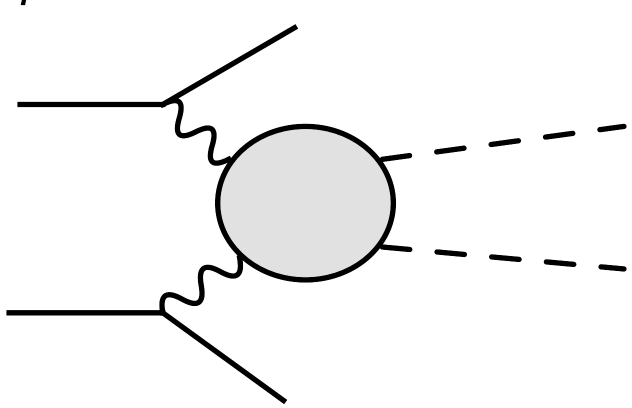
but neither of them predicts the effect to be nearly enough to resolve the puzzle

More of two-photon processes



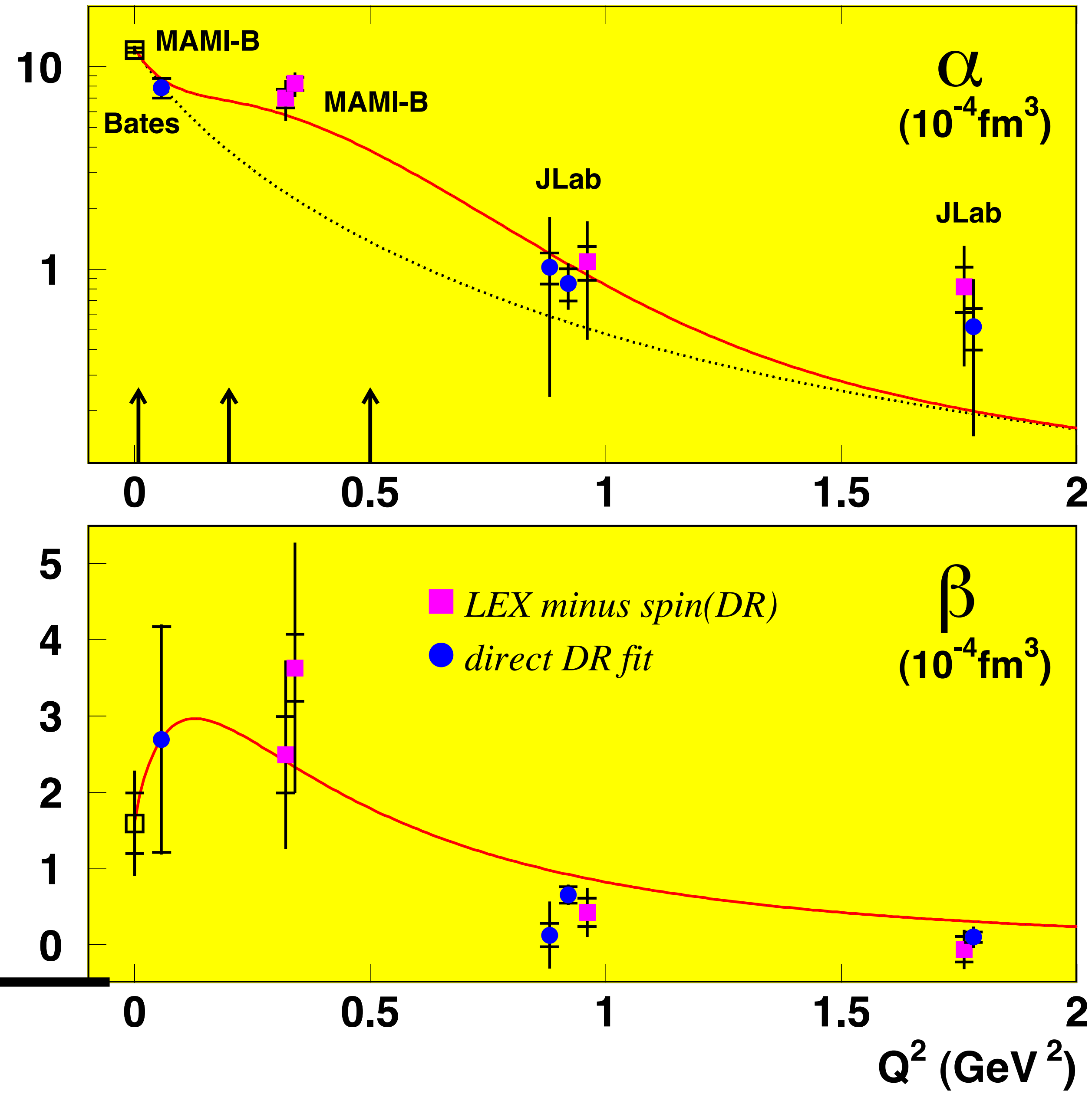






Virtual Compton scattering (VCS)

H. Fonvieille, H. Merkel et al.



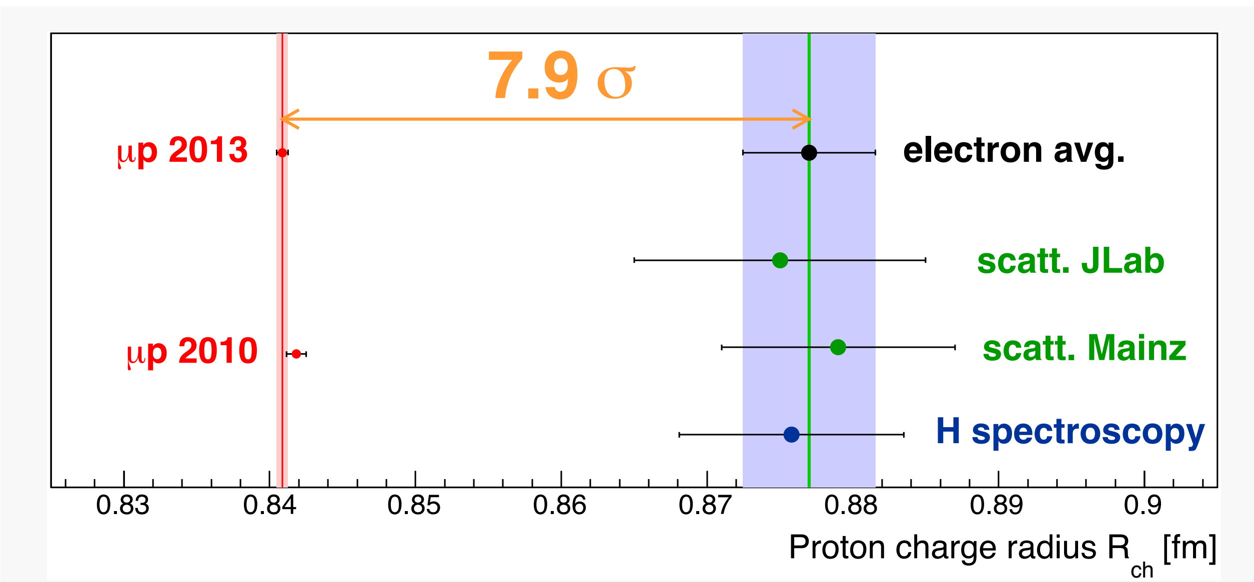
"terra incognita"

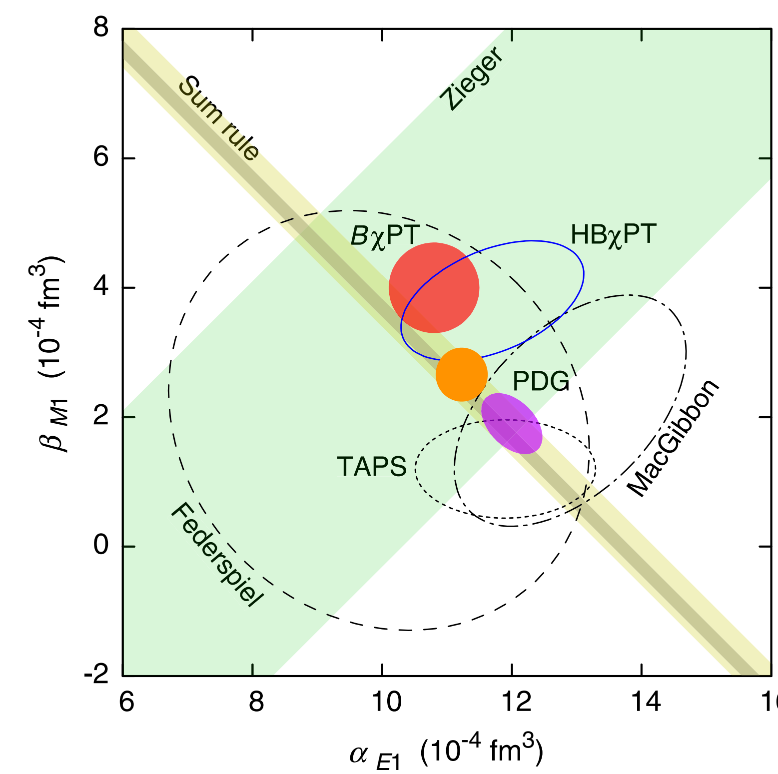
Time-like region

$$(\gamma N \to N e^+ e^-)$$

Summary and outlook

- Nucleon structure on intersection of low-energy and precision frontiers: *proton charge radius, polarizabilities*.





Chiral PT predictions, tested in polarizabilities, *rule against scenarios* where the charge radius puzzle is explained by proton structure (beyond the radius itself)

- Stay tuned for Compton scattering (RCS, VCS, tVCS, VVCS) ongoing experiments at MAMI, HIGS, JLab and muon scattering at PSI !