Improved description of the nucleon polarizabilities with relativistic Chiral Effective Field Theory

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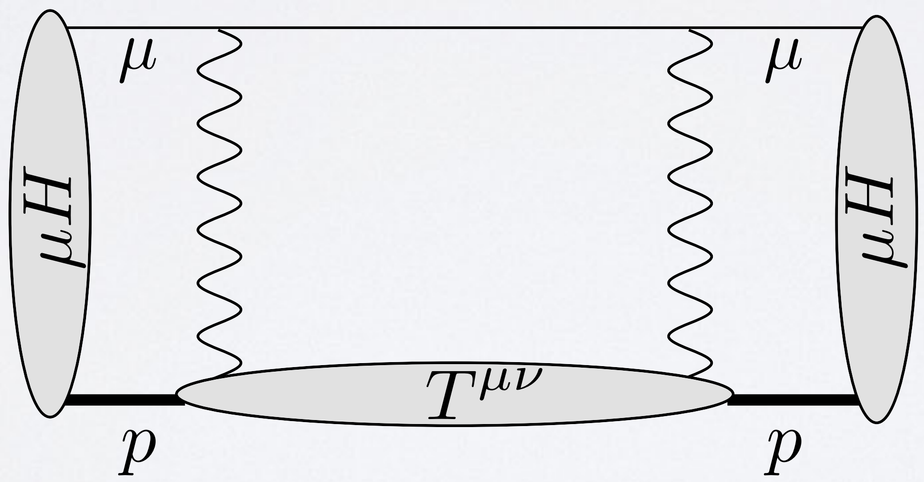

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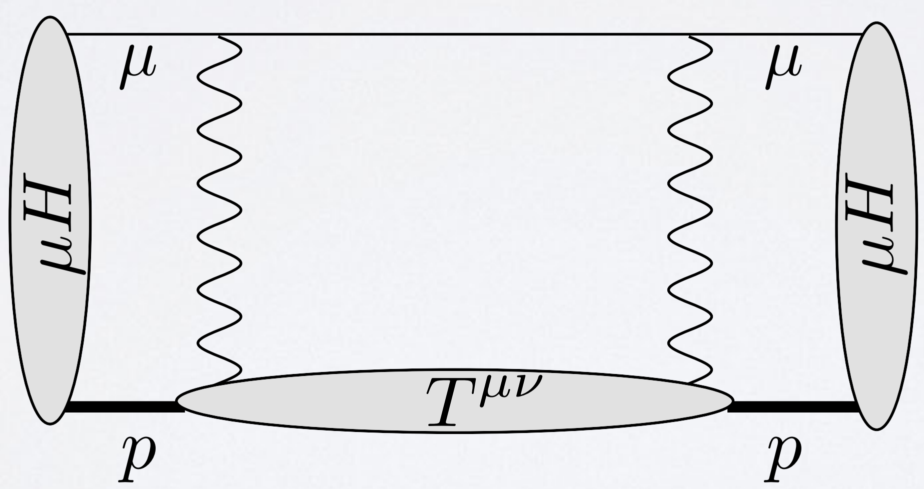

- They have the potential to solve the "Proton radius Puzzle".

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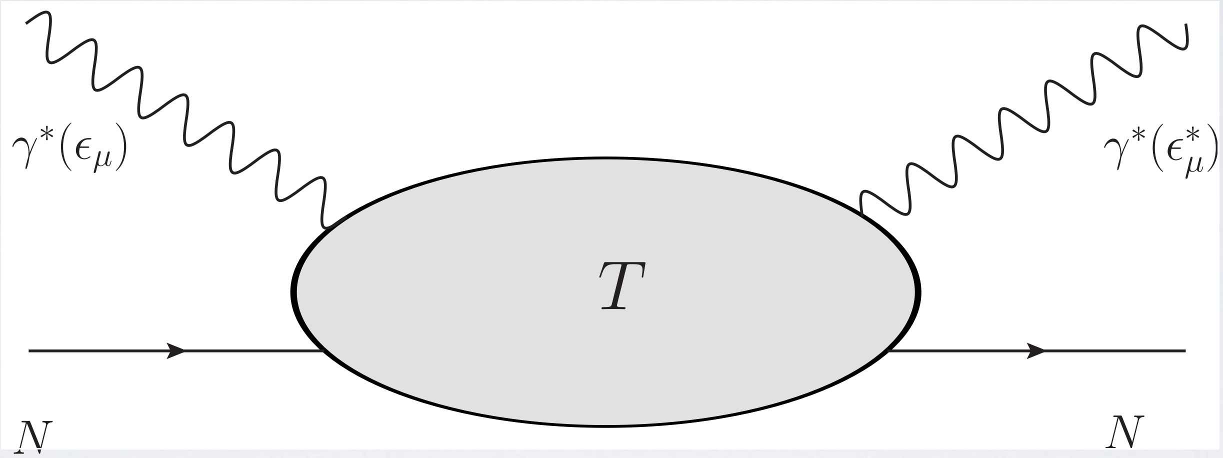

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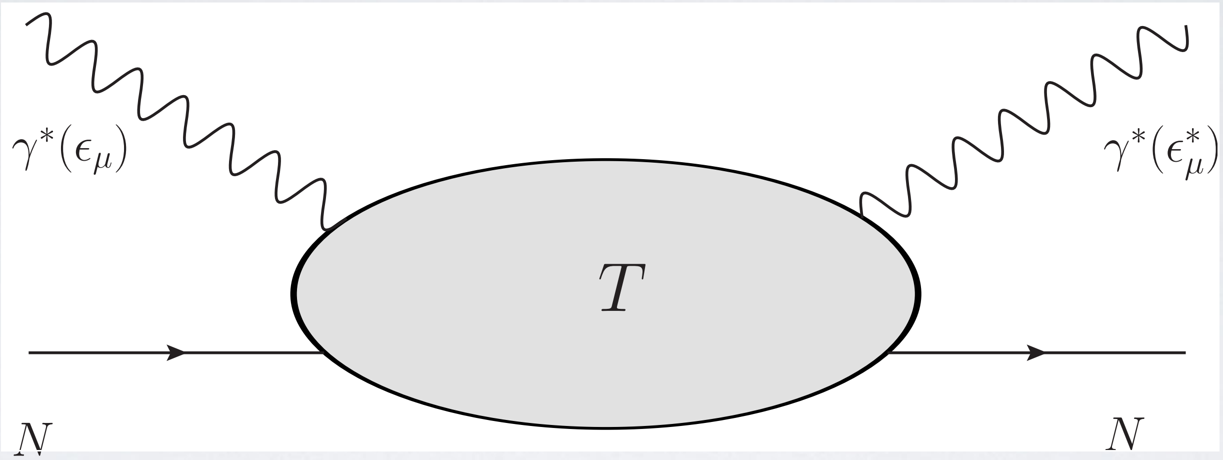

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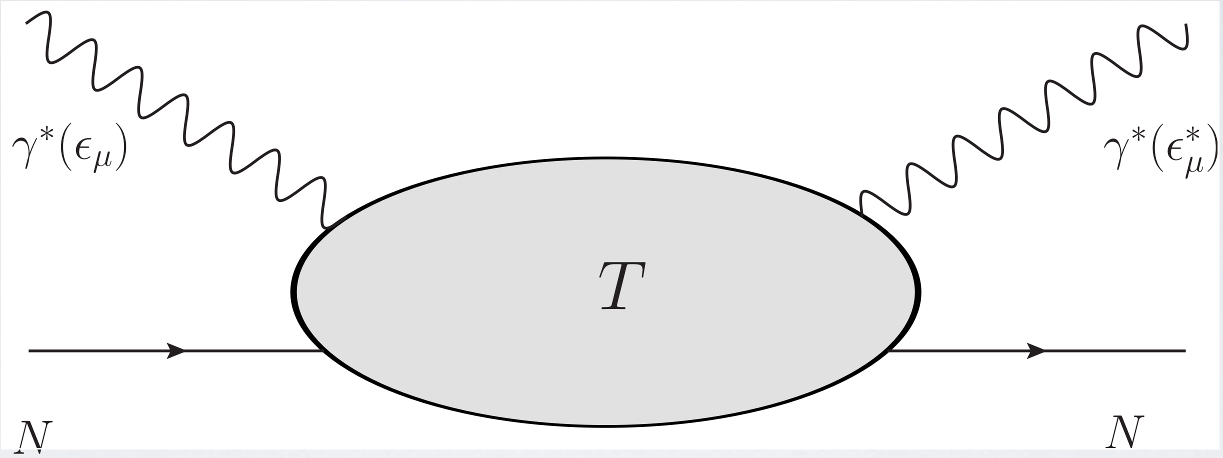

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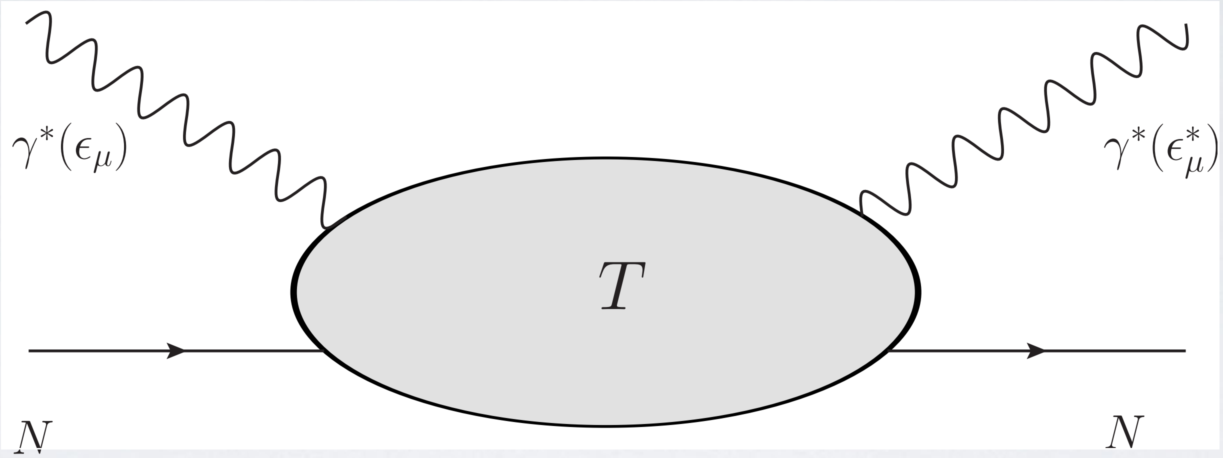

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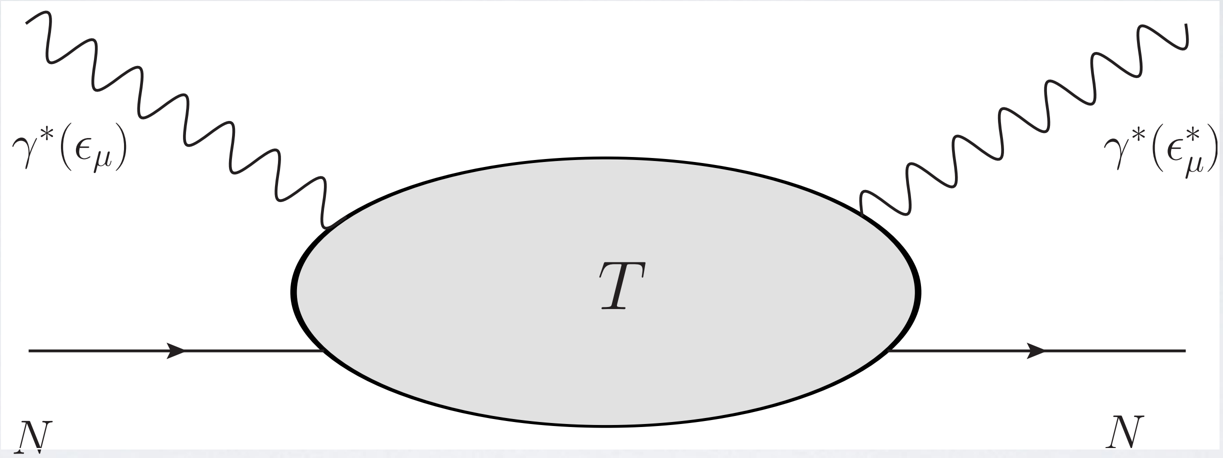

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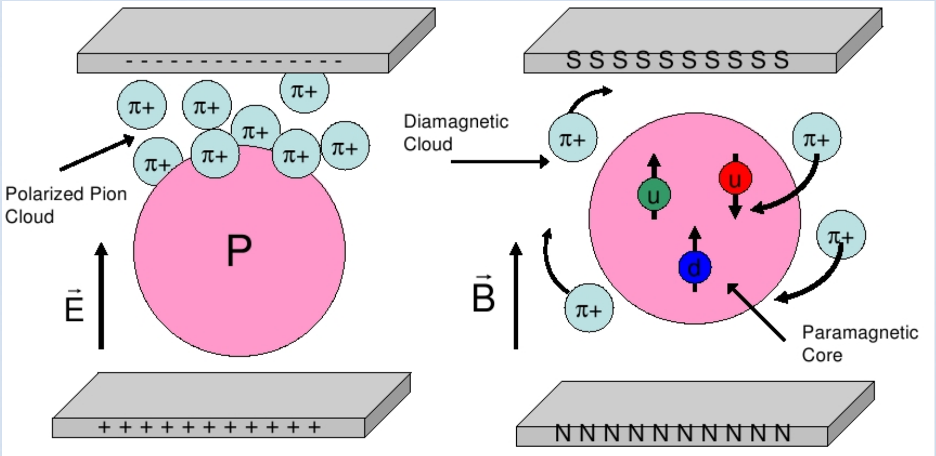

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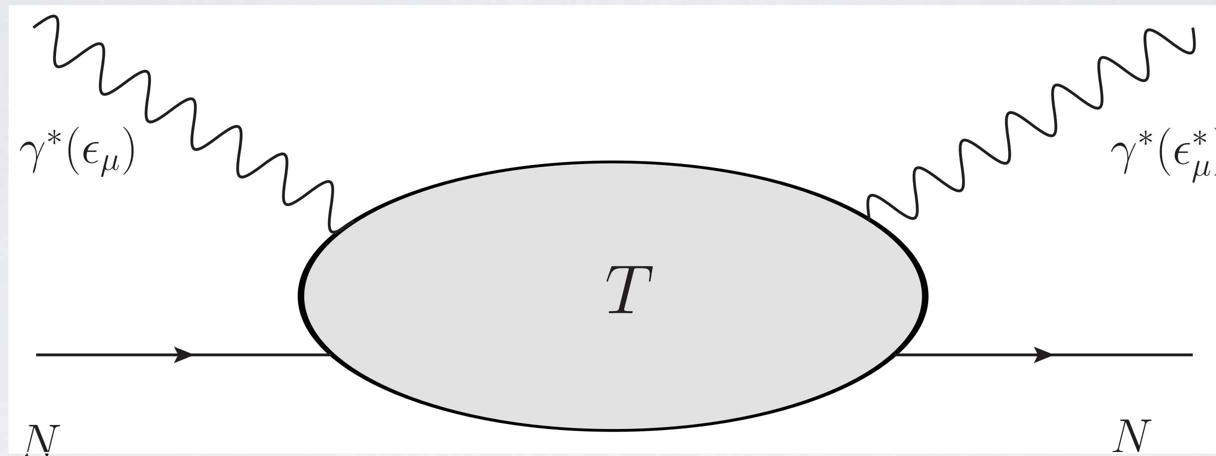

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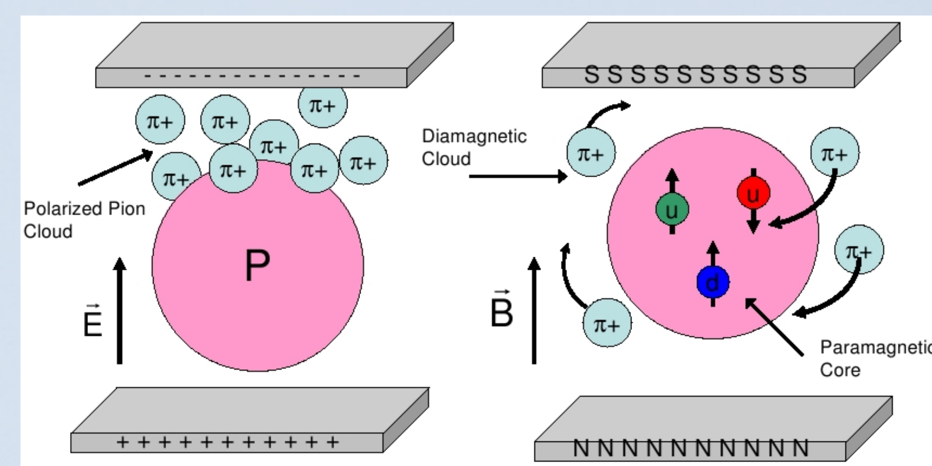

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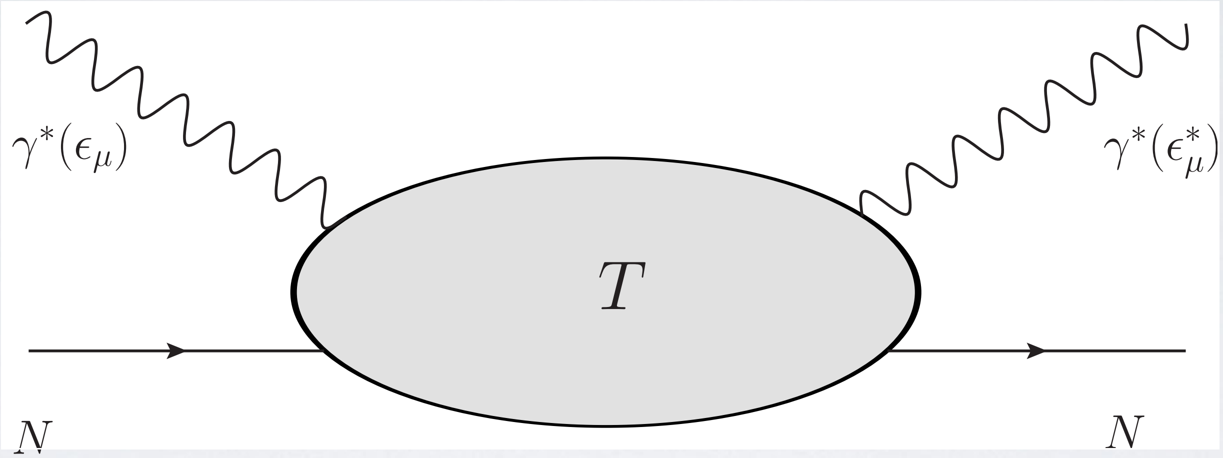

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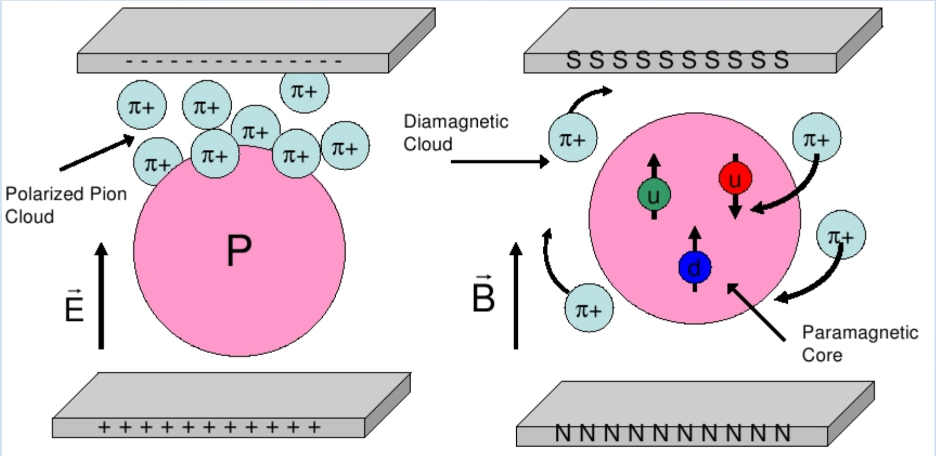

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- Relativistic corrections are very important for some polarizabilities

[Bernard, Kaiser and Meißner, PRL 67 (1991)], *[Kao, Spitzenberg and Vanderhaeghen, PRD 67 (2003)]*.

Theoretical Approach

- We calculate the Compton scattering with relativistic Chiral EFT including the $\Delta(1232)$ up to $\mathcal{O}(p^4/\Delta)$ in the δ-counting.

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- We decompose the Compton amplitude in the relativistic form:

$$T(\nu,Q^2) = \epsilon'^{*}_{\mu}\epsilon_{\nu}\Big\{\Big(-g^{\mu\nu}+\frac{q^\mu q^\nu}{q^2}\Big)T_1(\nu,Q^2)+\frac{1}{m_N^2}\Big(p^\mu-\frac{p\cdot q}{q^2}q^\mu\Big)\Big(p^\nu-\frac{p\cdot q}{q^2}q^\nu\Big)T_2(\nu,Q^2)$$
$$+\frac{i}{m_N}\epsilon^{\mu\nu\alpha\beta}q_\alpha s_\beta S_1(\nu,Q^2)+\frac{i}{m_N^3}\epsilon^{\mu\nu\alpha\beta}q_\alpha(p\cdot q s_\beta - s\cdot q p_\beta)S_2(\nu,Q^2)\Big\}$$

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$$+\frac{i}{m_N}\epsilon^{\mu\nu\alpha\beta}q_{\alpha}s_{\beta}S_1(\nu,Q^2)+\frac{i}{m_N^3}\epsilon^{\mu\nu\alpha\beta}q_{\alpha}(p\cdot q s_{\beta}-s\cdot q p_{\beta})S_2(\nu,Q^2)\Big\}$$

- In order to extract the polarizabilities, we relate T_1, T_2, S_1 and S_2 to f_T, f_L, g_{TT}, g_{LT}.

$$f_T(\nu,Q^2) = T_1(\nu,Q^2)$$

$$f_L(\nu,Q^2) = -T_1(\nu,Q^2)+\frac{\nu^2+Q^2}{Q^2}T_2(\nu,Q^2)$$

$$g_{TT}(\nu,Q^2) = \frac{\nu}{m_N}\Big(S_1(\nu,Q^2)-\frac{Q^2}{m_N\,\nu}S_2(\nu,Q^2)\Big)$$

$$g_{LT}(\nu,Q^2) = \frac{Q}{m_N}\Big(S_1(\nu,Q^2)+\frac{\nu}{m_N}S_2(\nu,Q^2)\Big)$$

Results

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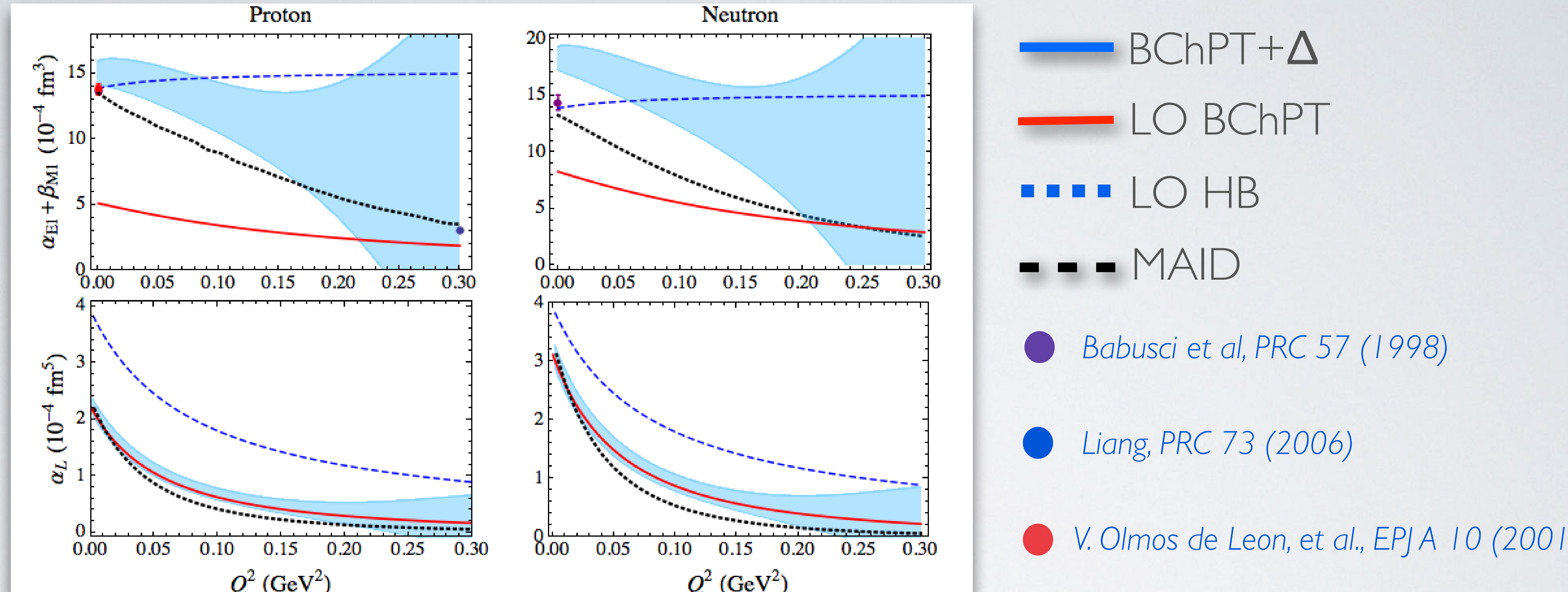
- For the Scalar Polarizabilities:



	Proton		Neutron	
	This work	Empirical	This work	Empirical
$\alpha_{E1}+\beta_{M1}$ (10^{-4} fm^3)	15.12(82) [1]	13.8(4) [2]	18.30(99)	14.40(66) [3]
α_L (10^{-4} fm^5)	2.31(12) [1]	2.32 [4]	3.21(17)	3.32 [4]

[1] Lensky, Alarcón and Pascalutsa, PRC 90 (2014).
[2] Olmos de León, et al., EPJ A 10, 207 (2001).
[3] Babusci, et al. PRC 57, 291 (1998).
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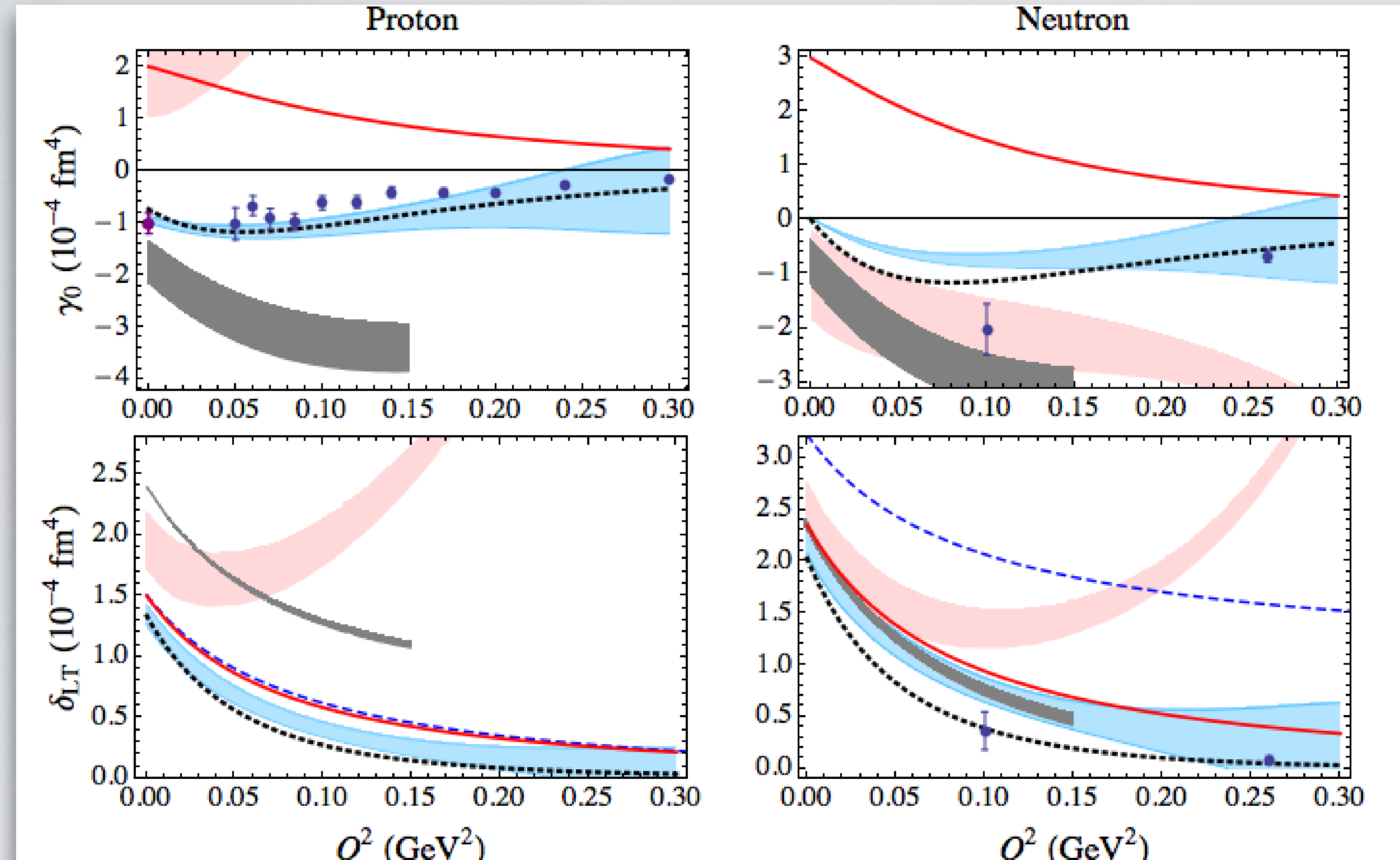
- For the Spin Polarizabilities:



BChPT+Δ

LO BChPT

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γ_0 (10^{-4} fm^4)	$-0.93(5)$ [1]	$-1.00(8)(12)$ [2]	$0.05(1)$	-0.005 [3]
δ_{LT} (10^{-4} fm^4)	$1.35(7)$ [1]	1.34 [3]	$2.20(12)$	2.03 [3]

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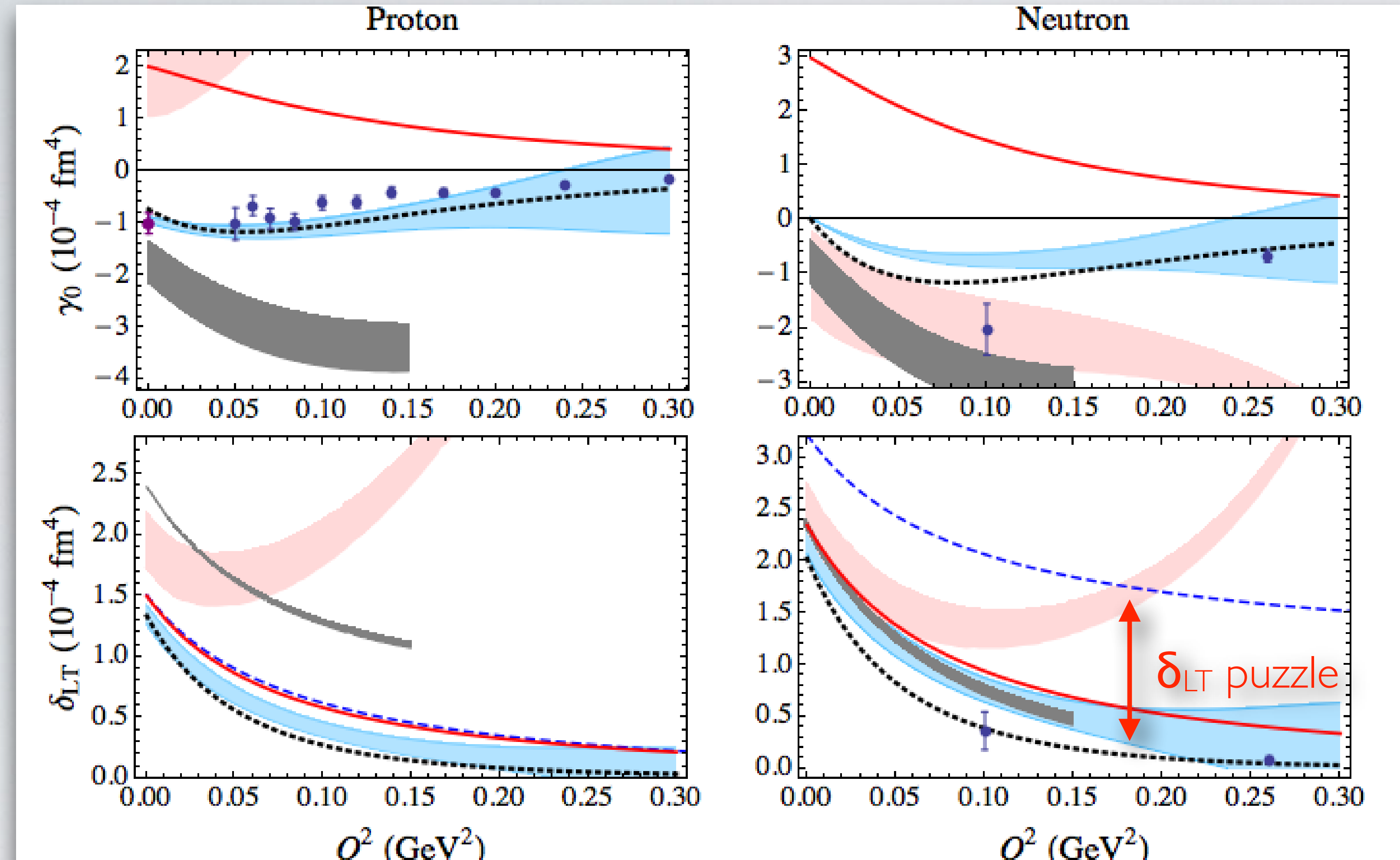

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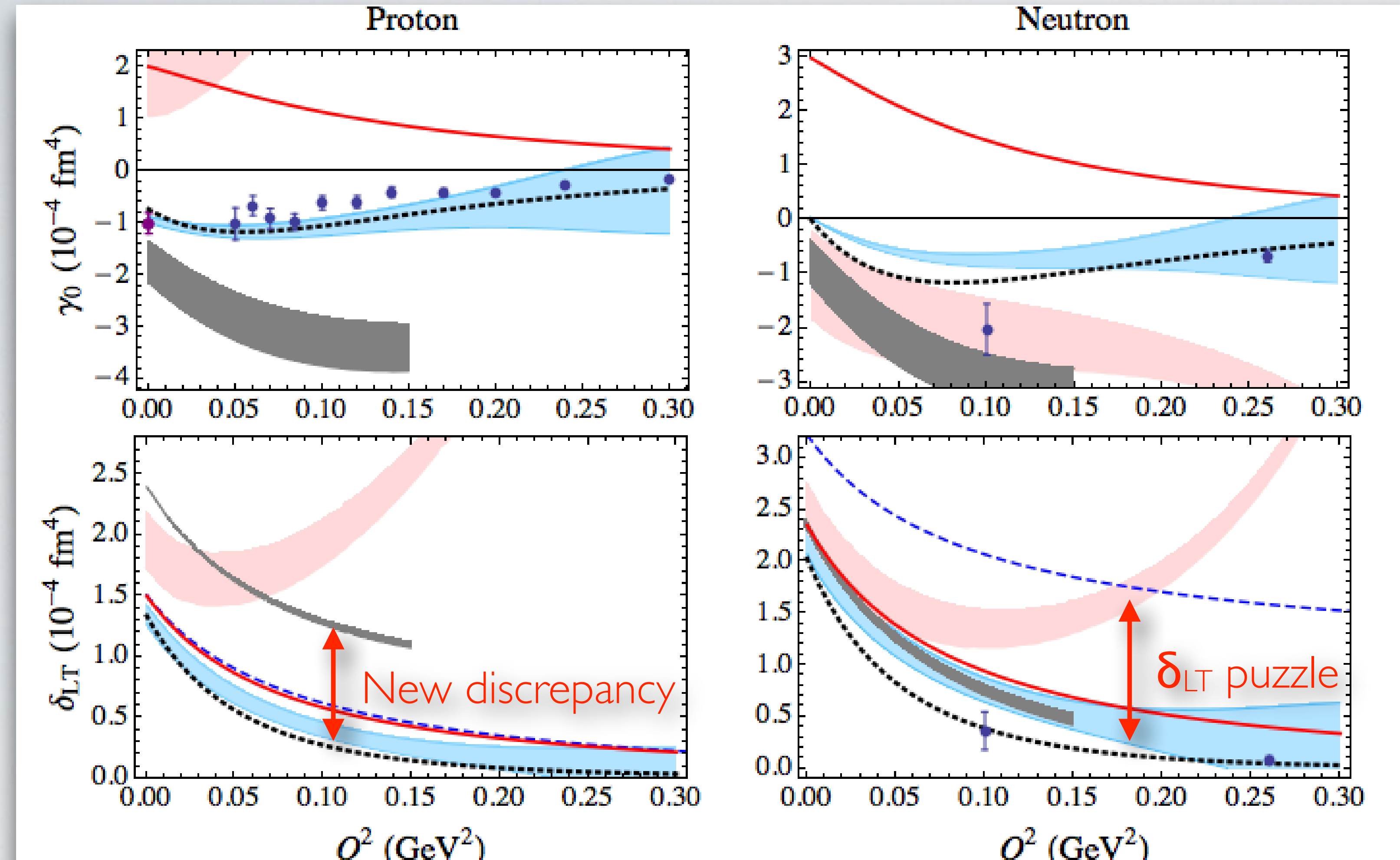

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- They have the potential to solve "Proton Radius Puzzle":

$$\Delta E_{2P-2S}^{exp} - \Delta E_{2P-2S}^{th}(r_E^{\rm CODATA}) = 0.31 \text{ meV} = 310 \ \mu\text{eV}$$

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- They have the potential to solve "Proton Radius Puzzle":

$$\Delta E^{exp}_{2P-2S} - \Delta E^{th}_{2P-2S}(r_E^{\mathrm{CODATA}}) = 0.31 \text{ meV} = 310 \ \mu\text{eV}$$

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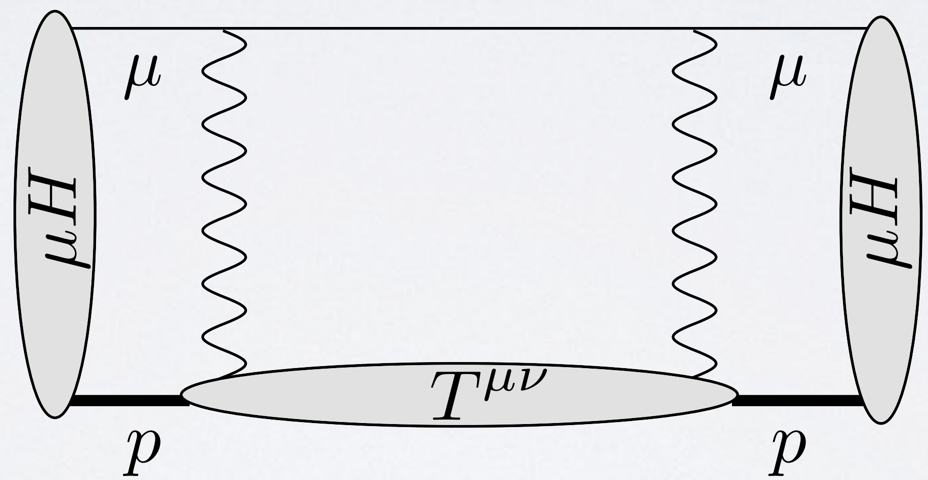

$$T^{\mu\nu}(P,q) = -\left(g^{\mu\nu} + \frac{q^\mu q^\nu}{q^2}\right) T_1(\nu^2, Q^2) + \frac{1}{M_p^2}\left(P^\mu - \frac{P\cdot q}{q^2}q^\mu\right)\left(P^\nu - \frac{P\cdot q}{q^2}q^\nu\right) T_2(\nu^2, Q^2)$$

$$\Delta E_{2S}^{(pol)} \approx \frac{\alpha_{em}}{\pi}\phi^2_{n=2}\int_0^\infty \frac{dQ}{Q^2} w(\tau_\ell)\left[T_1^{(NB)}(0,Q^2) - T_2^{(NB)}(0,Q^2)\right]$$

$$T_1^{(NB)} = 4\pi Q^2 \beta_{M1}(Q^2) + \ldots$$

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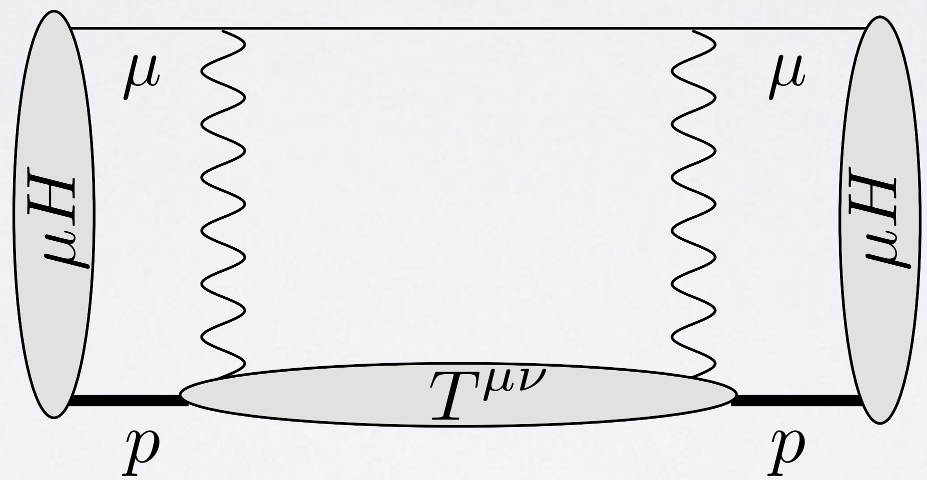

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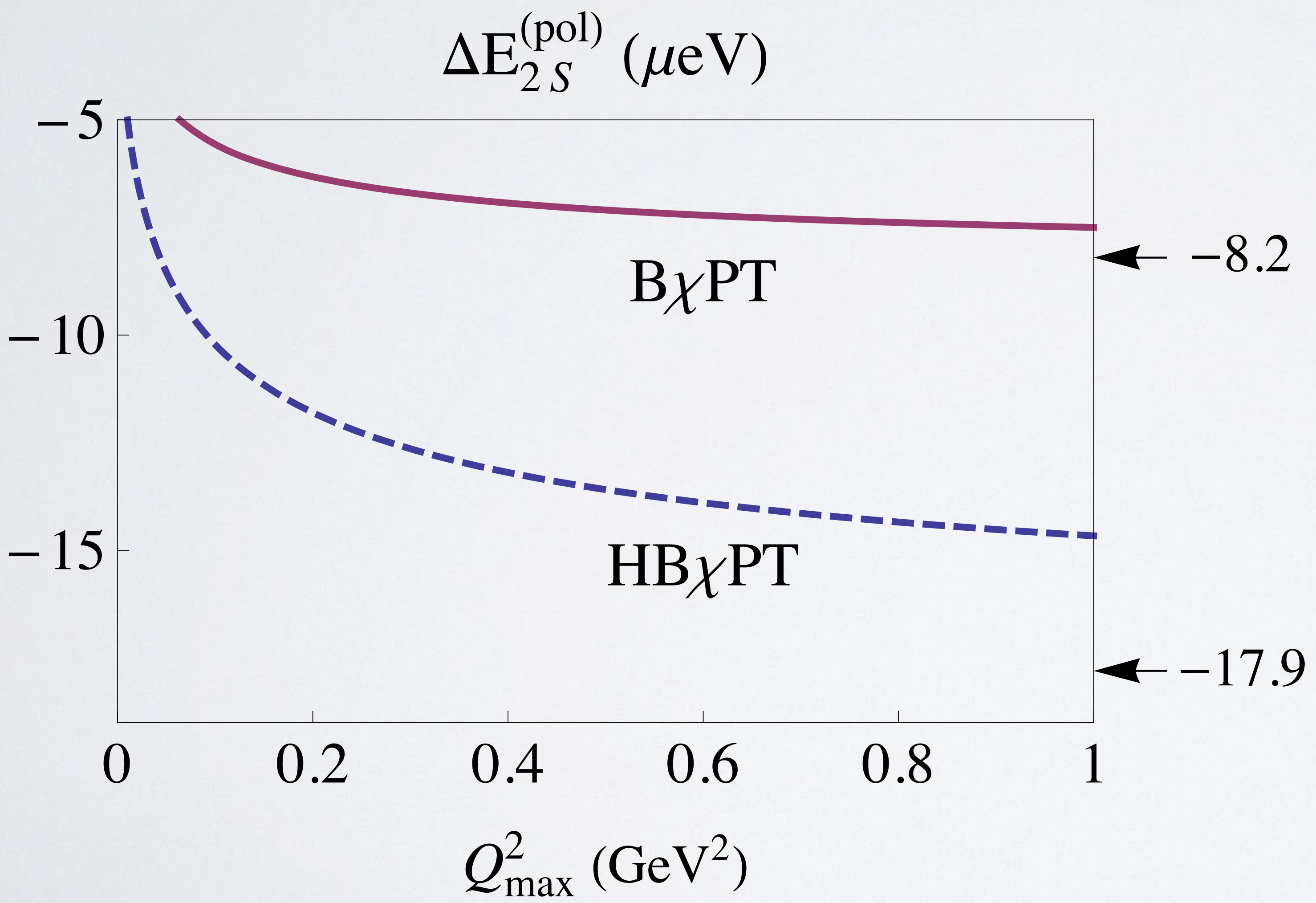

[Alarcón, Lensky, Pascalutsa, EPJ C 74 (2014).]

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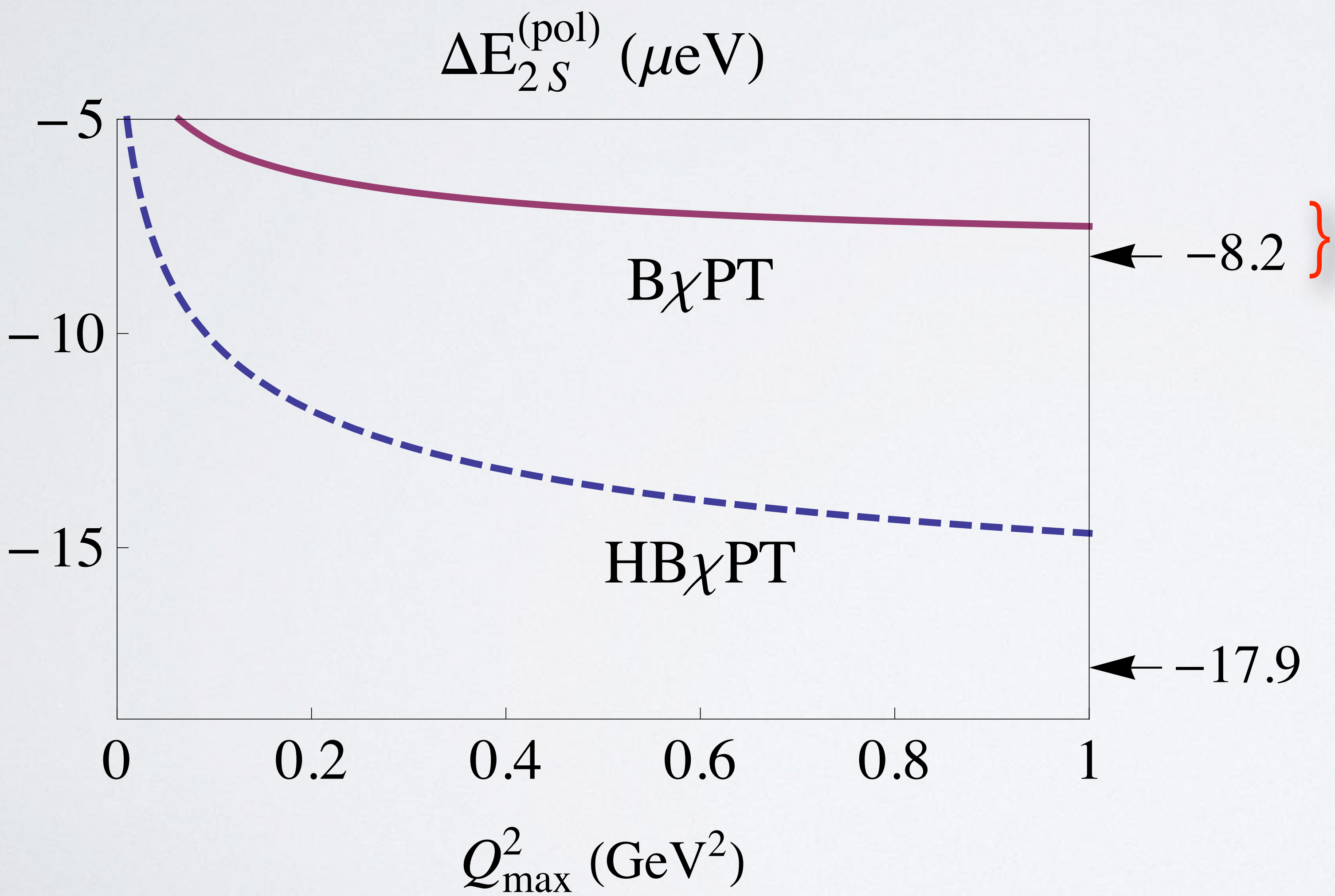

} ~10% → Within the uncertainty of the calculation

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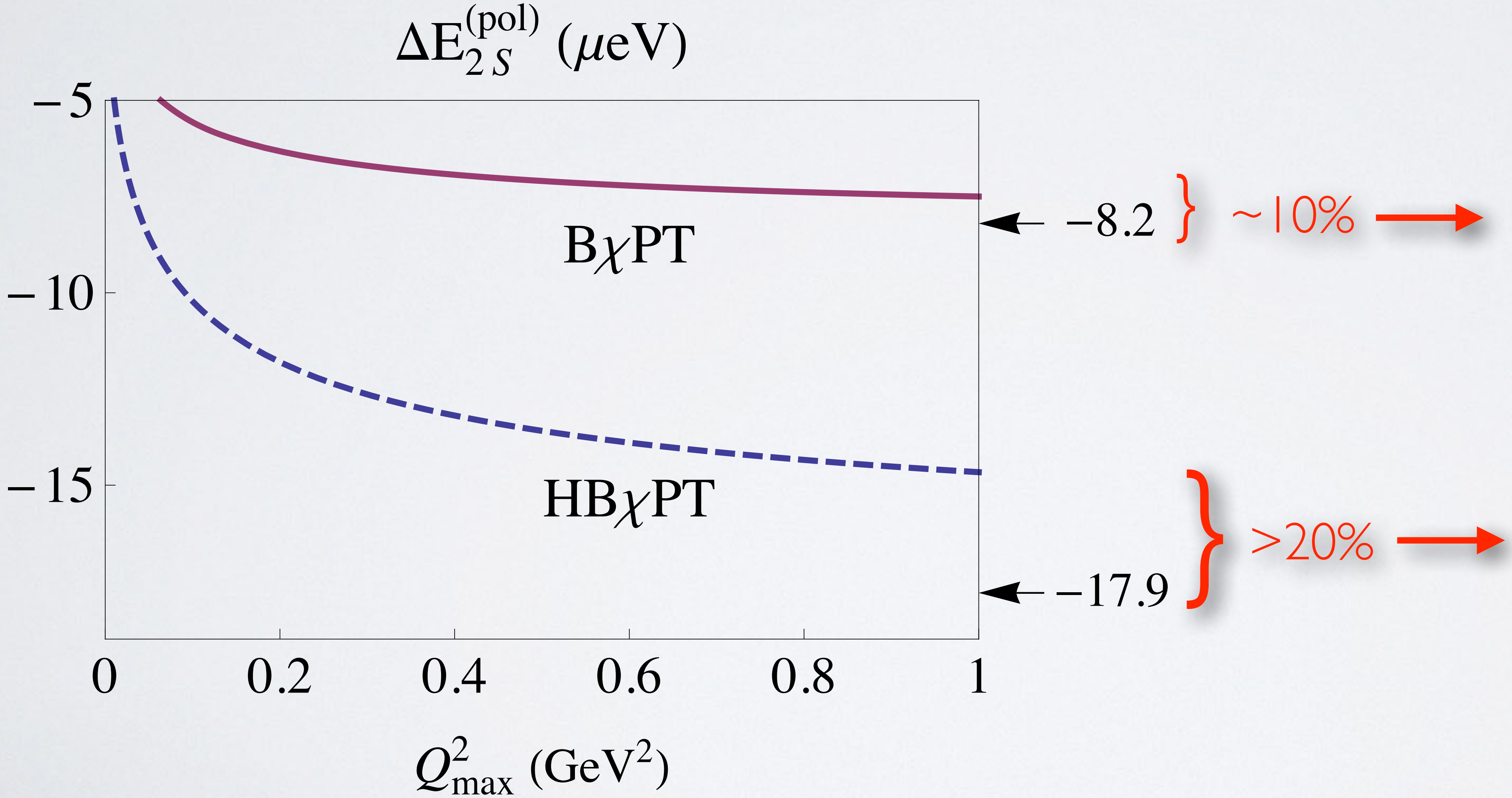

Within the uncertainty of the calculation

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[Alarcón, Lensky, Pascalutsa, EPJ C 74 (2014).]

Lamb shift

- The relativistic structure is important to agree with phenomenological determinations of $\Delta E_{2S}^{(\mathrm{pol})}$.

(μeV)	Pachucki [1]	Martynenko [2]	Nevado & Pineda [3]	Carlson & Vanderhaeghen [4]	Birse & McGovern [5]	Gorchtein Llanes-Estrada & Szczepaniak [6]	Alarcón, Lensky & Pascalutsa [7]	Peset & Pineda [8]
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Chiral EFT calculations (light blue)

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- Relativistic chiral EFT agrees with dispersive determinations!

Summary and Conclusions

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- We calculate the VVCS amplitude in covariant BChPT + **Δ** up to O(p^4/**Δ**) in the **δ**-counting.
- We included a dipole structure to the magnetic coupling of the **Δ**(1232) → Important to reproduce electroproduction data.
- The calculation is ***predictive***.
- Our predictions are in good agreement with experimental data and the MAID model.
- We improve the Chiral EFT results for the polarizabilities, specially the in spin-dependent case.
- The Compton amplitude can be employed to calculate the leading proton-structure corrections to the **μ**H Lamb shift.
- Our prediction agrees with dispersive calculations:

	Alarcón, Lensky & Pascalutsa	Birse & McGovern
$\Delta E_{2S}^{(\mathrm{pol})}$	$-8.2^{+2.0}_{-2.5}$	-8.5(1.1)

FIN

Spares

Dependence on the dipole form factor

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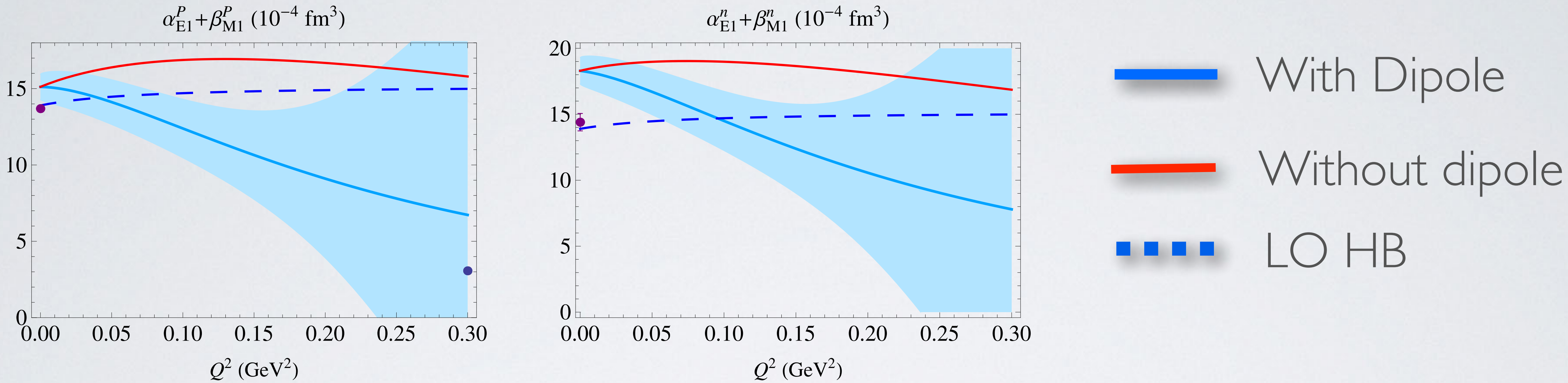
- For the Scalar Polarizabilities



Dependence on the dipole form factor

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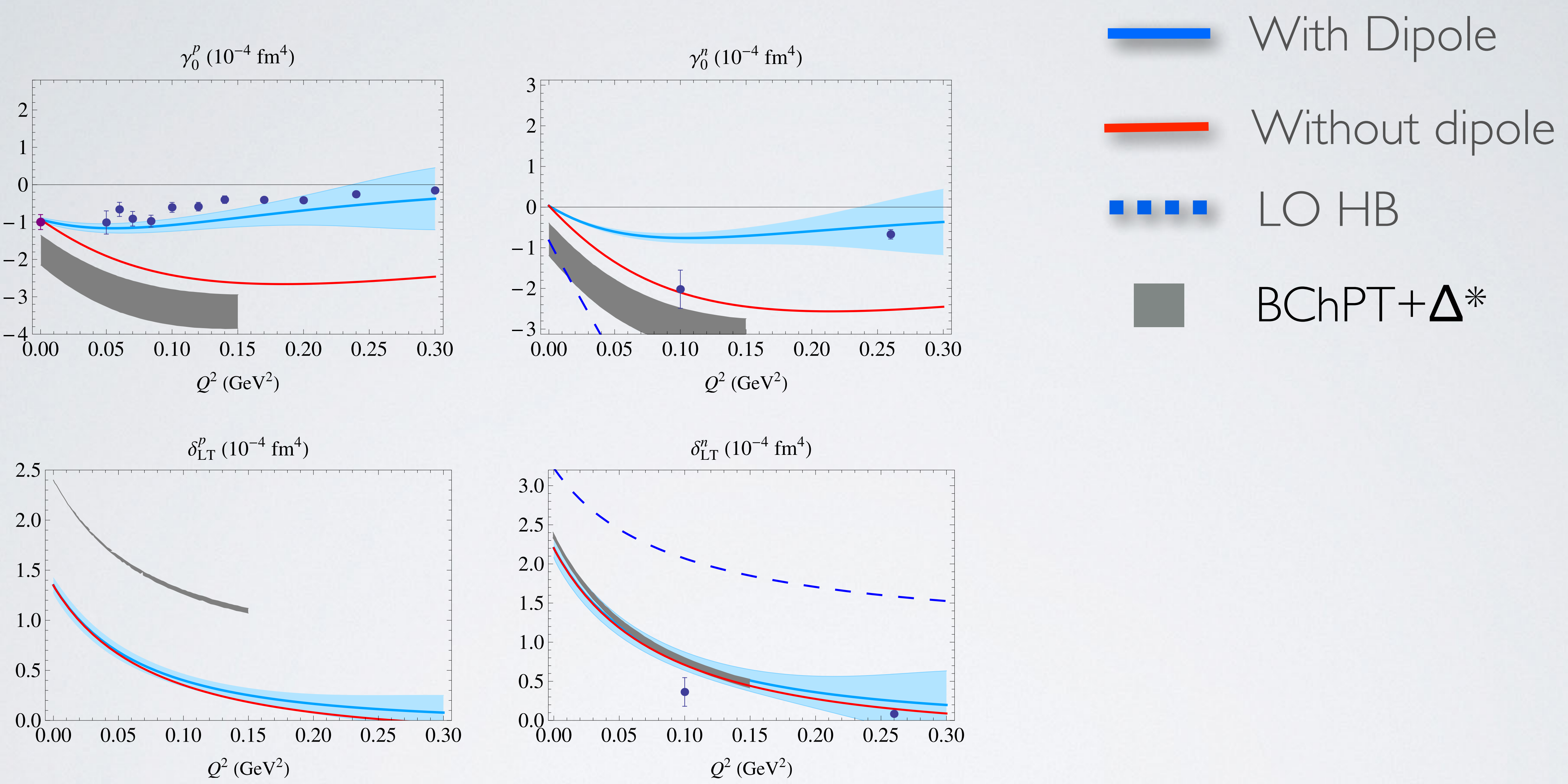


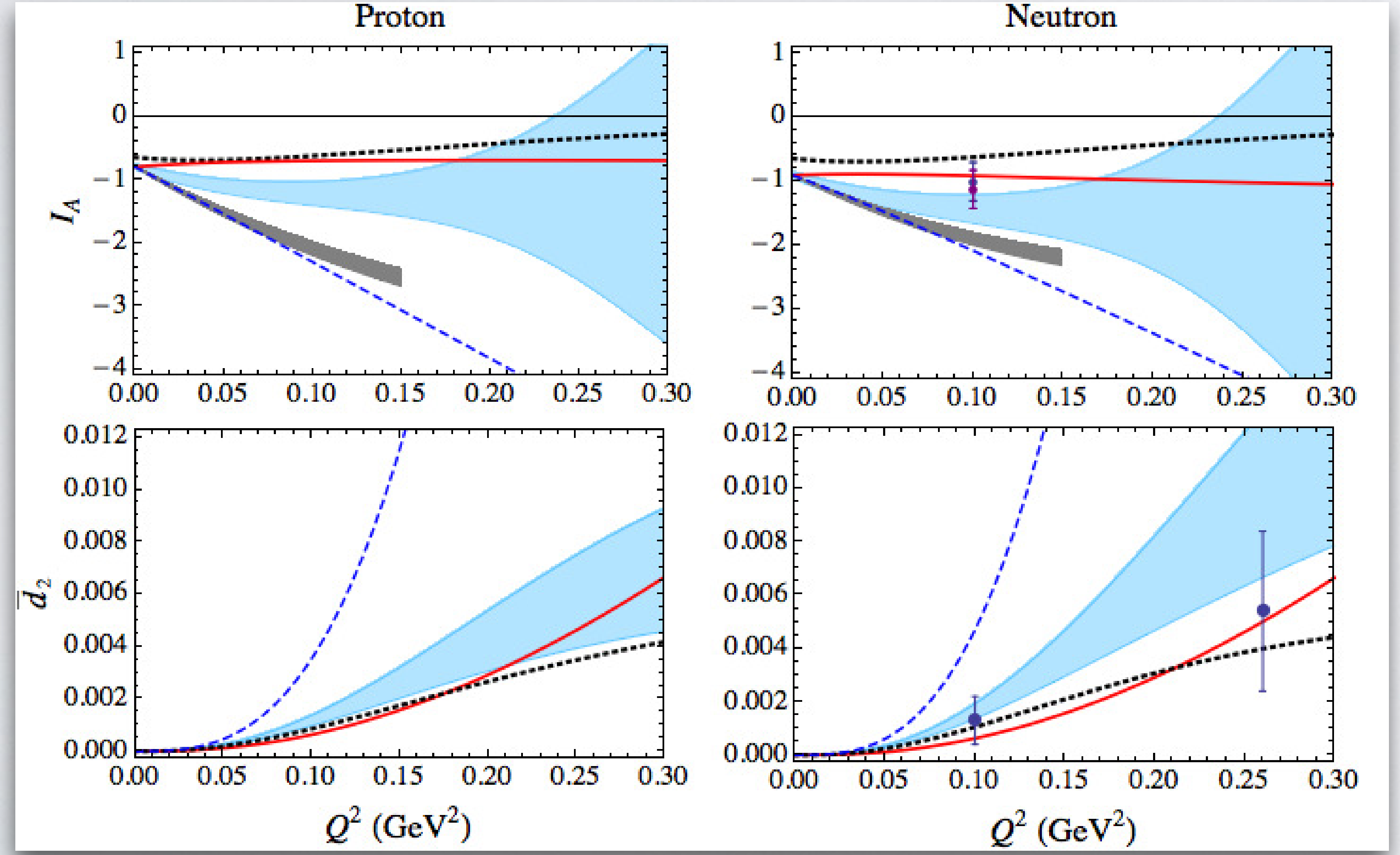
Some other interesting moments

Results

- For some interesting moments:

$$\bar{d}_2(Q^2) = \int_0^{x_0} dx\, x^2[2g_1(x,Q^2) + 3g_2(x,Q^2)]$$ → Structure corrections to HFS

$$I_A(Q^2) = \frac{2M_N^2}{Q^2}\int_0^{x_0} dx\, g_{TT}(x,Q^2)$$ → GDH Sum Rule



BChPT+Δ

LO BChPT

LO HB

[Kao et al., PRD 67 (2003)]

MAID

BChPT+Δ*

[Bernard et al., PRD 87 (2013)]

(I_A) Amarian et al. PRL 89 (2002)

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(d_2) Amarian et al. PRL 92 (2004)