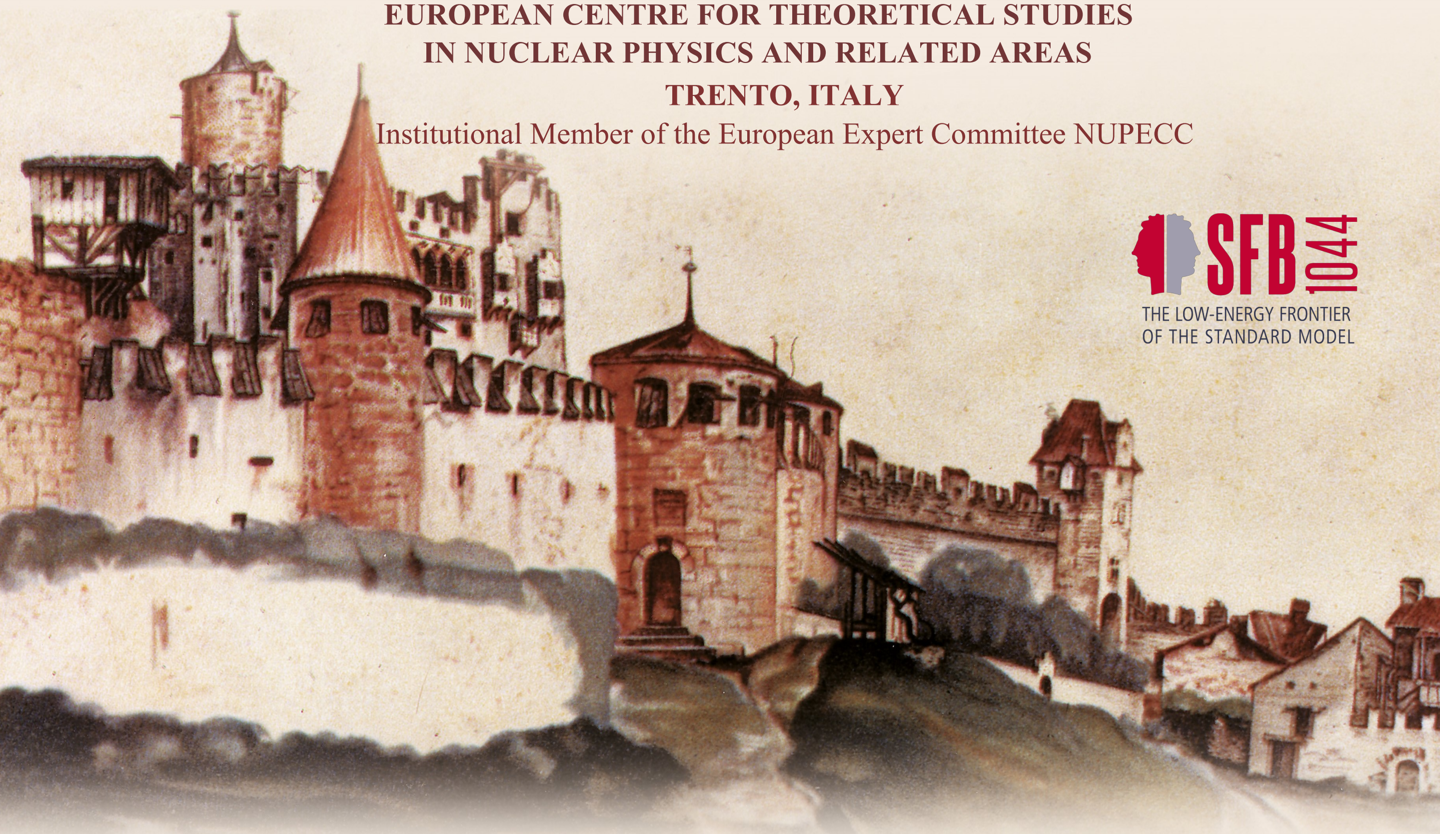
ECT*

EUROPEAN CENTRE FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS
TRENTO, ITALY
Institutional Member of the European Expert Committee NUPECC

SFB 1044
THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL



Castello di Trento ("Trint"), watercolor 19.8 x 27.7, painted by A. Dürer on his way back from Venice (1495). British Museum,

Nucleon Spin Structure at Low Q: A Hyperfine View

Trento, July 2 - 6, 2018

Main Topics

- New measurements of spin structure functions, polarizabilities and form factors
- Sum rules, dispersion relations and empirical parametrizations
- Chiral perturbation theory of nucleon spin polarizabilities
- Progress in lattice QCD of the nucleon spin structure
- Hyperfine structure of muonic hydrogen

Confirmed Speakers

M.W. Ahmed (*Duke University,* USA), J. M. Alarcon (*JLab,* USA), C. Alexandrou (*University of Cyprus, Nicosia*, Cyprus), F. Hagelstein (*Universität Bern,* Switzerland), C. Carlson (*College of William and Mary,* USA), S. Kanda (*Riken,* Japan), S. Kuhn (*Old Dominion University,* USA), V. Lensky (*Universität Mainz,* Germany), P. Martel (*Universität Mainz,* Germany), H.W. Lin (*Michigan State University,* USA), K. Ottnad (*Universität Mainz,* Germany), E. Pace (*University of Rome Tor Vergata and INFN,* Italy), K. Pachucki (*University of Warsaw,* Poland), A. Pineda (*IFAE, Barcelona,* Spain), Jan Rijneveen (*University of Bochum*, Germany), Nora Rijneveen (*University of Bochum*, Germany), M. Ripani (*INFN Genoa,* Italy), S. Sconfietti (*INFN Pavia,* Italy), K. Slifer (*University of New Hampshire,* USA), N. Sparveris (*Temple University,* USA), L. Tiator (*Universität Mainz,* Germany), A. Vacchi (*INFN Trieste,* Italy).

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SFB 1044
THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

Nucleon spin structure: highlights and workshop goals

Marc Vanderhaeghen

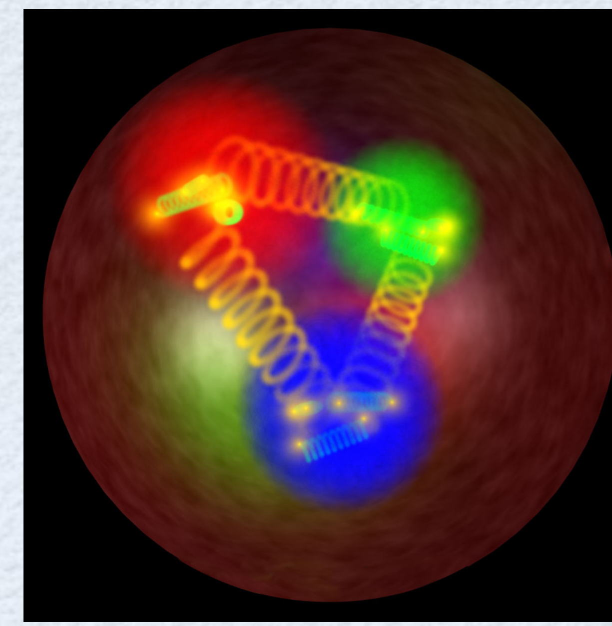
JOHANNES GUTENBERG UNIVERSITÄT MAINZ
JG|U

Nucleon spin structure at low Q : dawn of hadron physics

Otto Stern's measurement of the g-factor of the proton (1932-33):

$g_{proton} = 5.586$

Deviation from point particle value (g=2) indicates that proton has internal structure



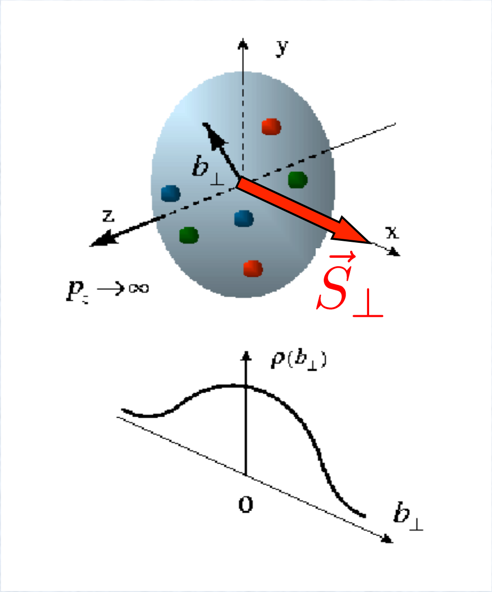
Nobel Prize Physics (1943):
"for his contribution to the development of the molecular ray method and his discovery of the magnetic moment of the proton"

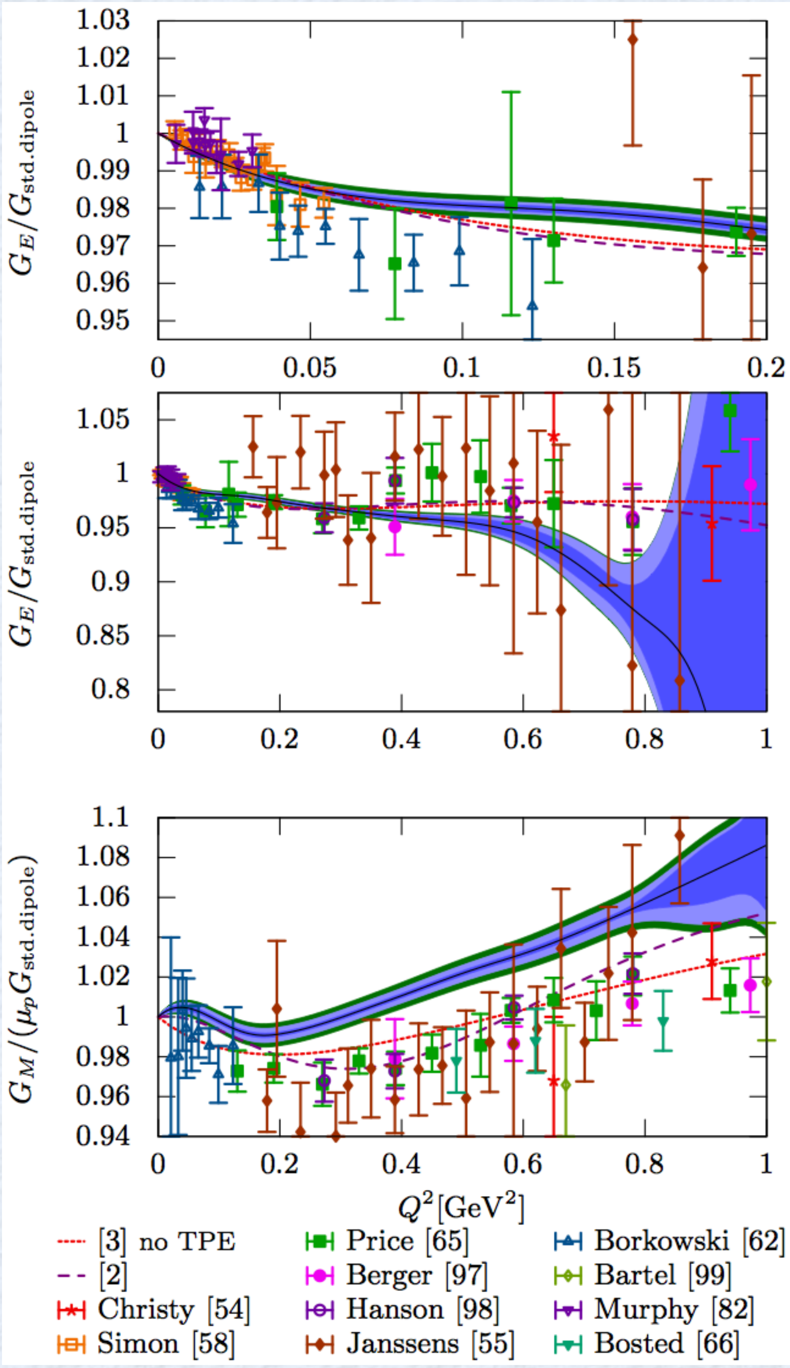
Form factors: 2D densities of hadrons

$$\rho^N(\vec{b}) = \int_0^\infty \frac{dQ}{2\pi} Q\, J_0(b\,Q) F_1(Q^2)$$
$$+ \sin(\phi_b - \phi_S) \int_0^\infty \frac{dQ}{2\pi} \frac{Q^2}{2M_N} J_1(b\,Q) F_2(Q^2)$$

→ unpolarized Dirac FF F_1

→ transverse polarization Pauli FF F_2





blue bands:

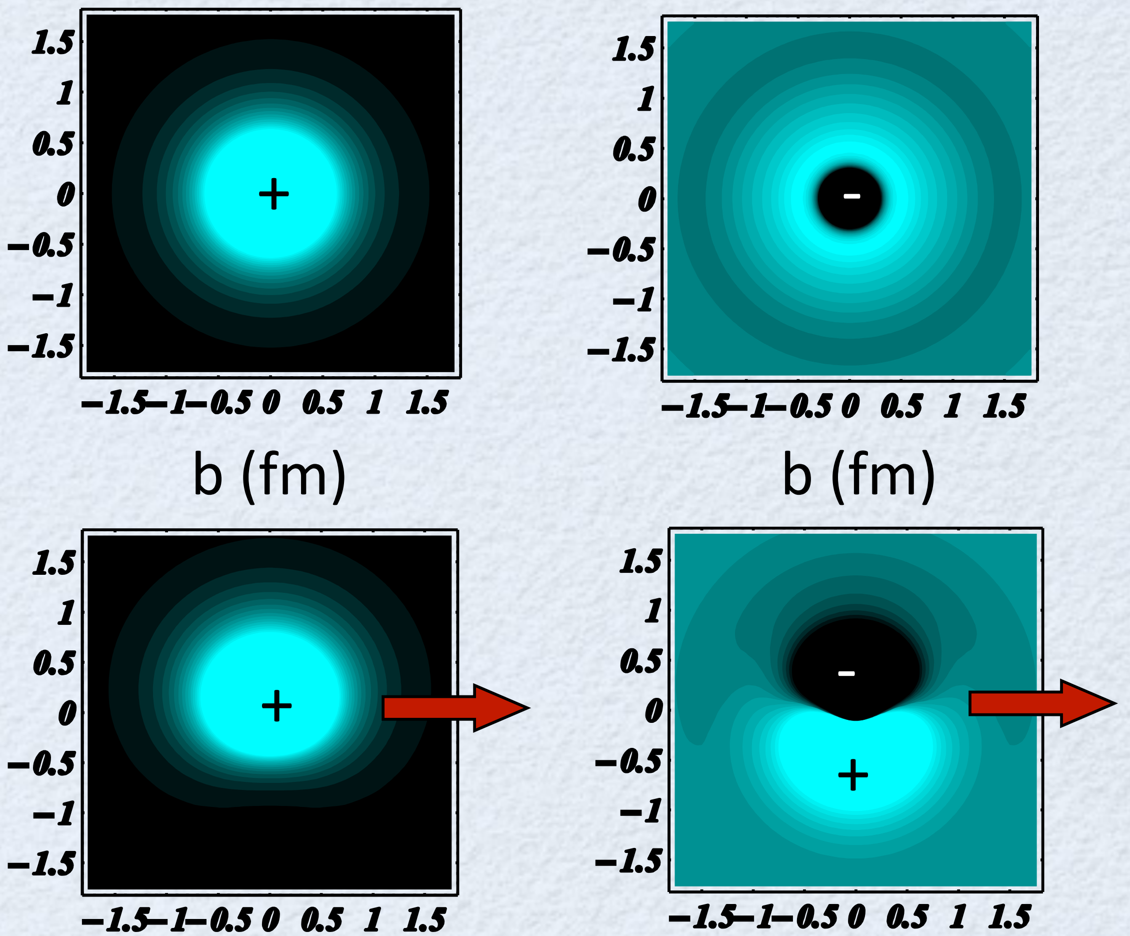
Bernauer et al. (2010,2013)

proton

neutron

unpolarized charge density

density for transverse polarization

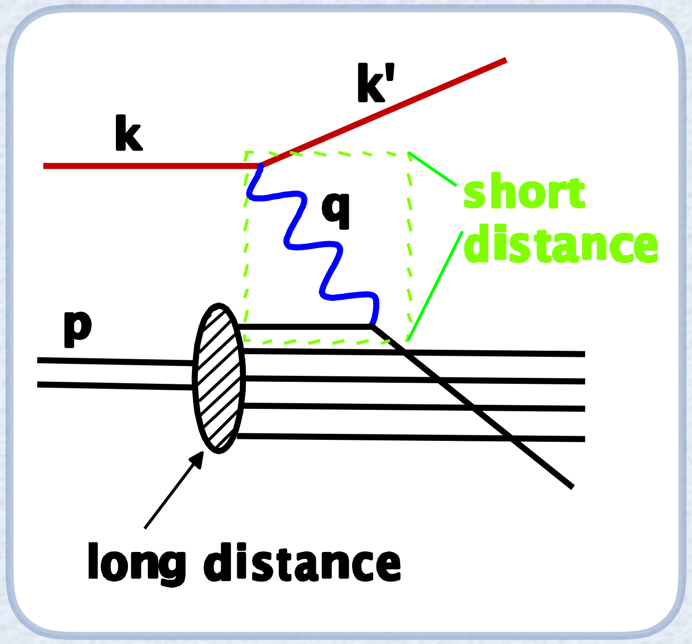


Burkardt (2000,2003)

Miller(2007)

Carlson, Vdh(2008)

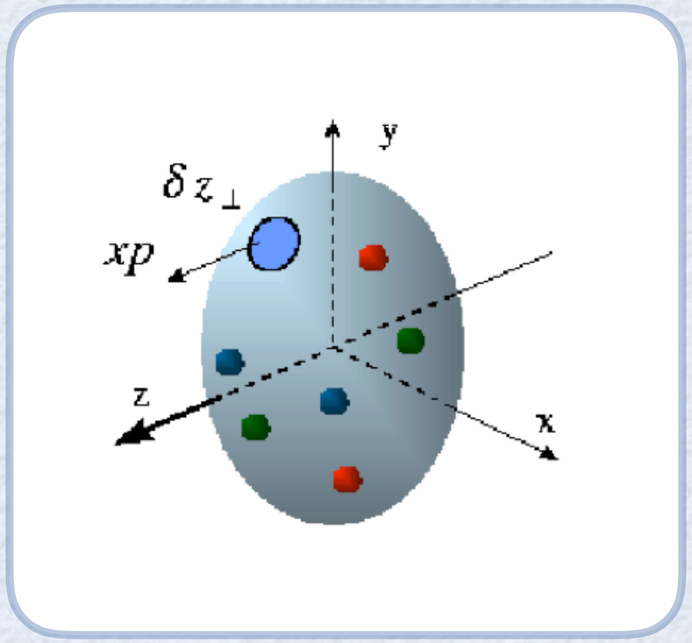
Nucleon spin structure at large Q : Quark-gluon structure

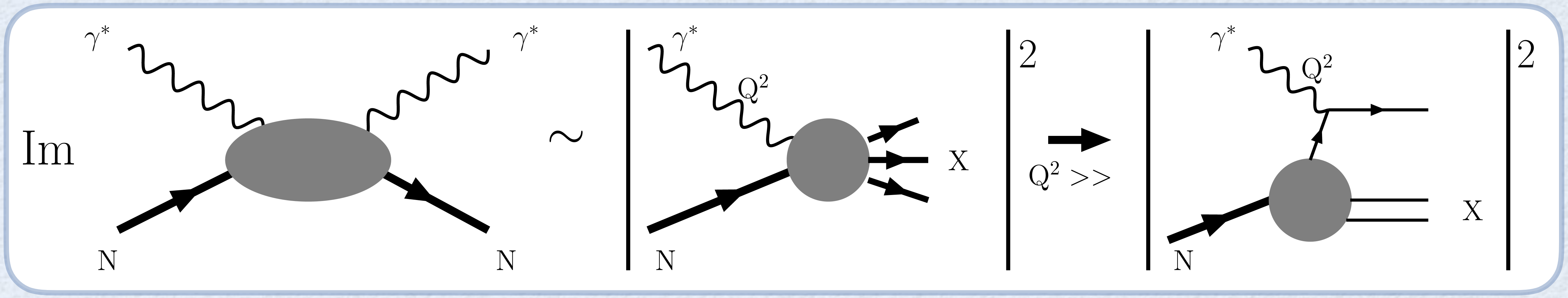


Deep-inelastic scattering

$Q^2 >> 1$ GeV^2

At fixed $x_B = \dfrac{Q^2}{2p \cdot q}$





$$d\sigma \sim L_{\mu\nu} W^{\mu\nu}$$

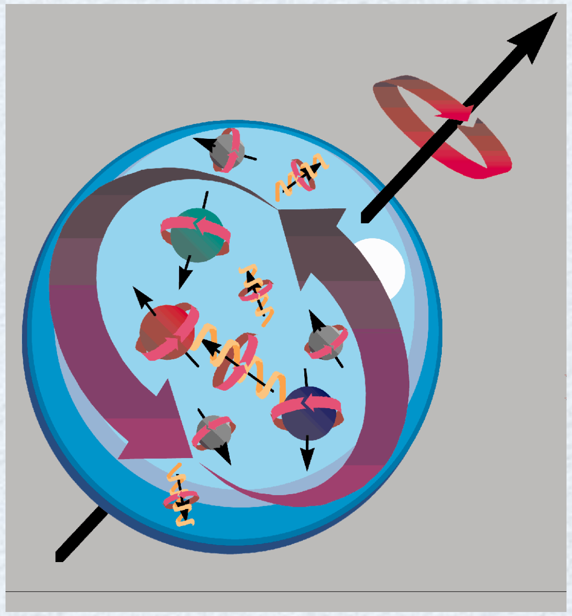
$$W_a^{\mu\nu} = \frac{2M_N}{p \cdot q} i\varepsilon^{\mu\nu\alpha\beta} q_\alpha \left\{ S_\beta \; g_1(x_B, Q^2) + \left[S_\beta - \frac{S \cdot q}{p \cdot q} p_\beta \right] \; g_2(x_B, Q^2) \right\}$$

g_1, g_2 : Spin dependent structure functions

Nucleon spin and orbital angular momentum

- Deep-inelastic experiments:

$$\Delta q \sim 30\% \quad (SIDIS/DIS)$$
$$\Delta G \sim 40\% \quad (RHIC)$$



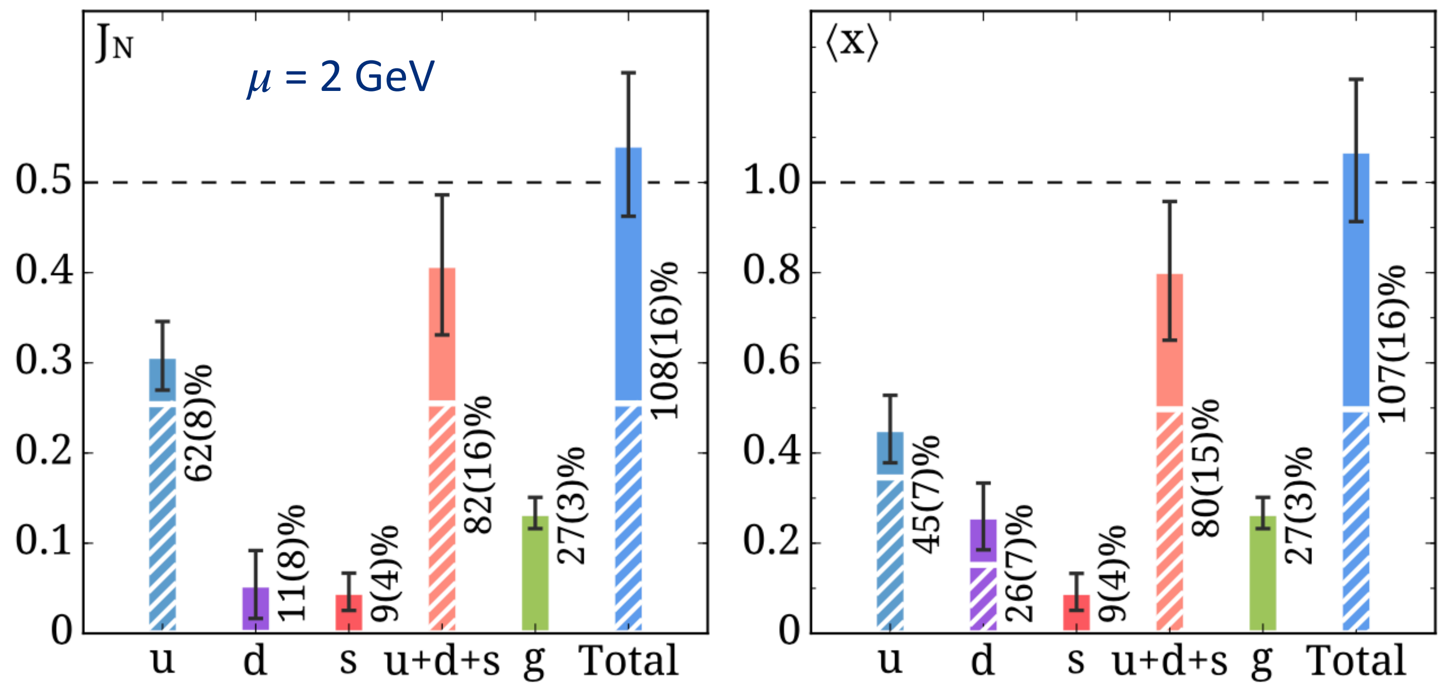
- Ji's angular momentum sum rule   Ji (1995)

$$\int_{-1}^{+1} dx\, x\, \{H^q(x,\xi,0) + E^q(x,\xi,0)\} = A(0) + B(0) = 2J^q$$

H, E: generalized parton distributions (GPDs)

- lattice QCD calculations at the physical point

see talks: Alexandrou, Lin, Ottnad



Alexandrou et al. (2017)

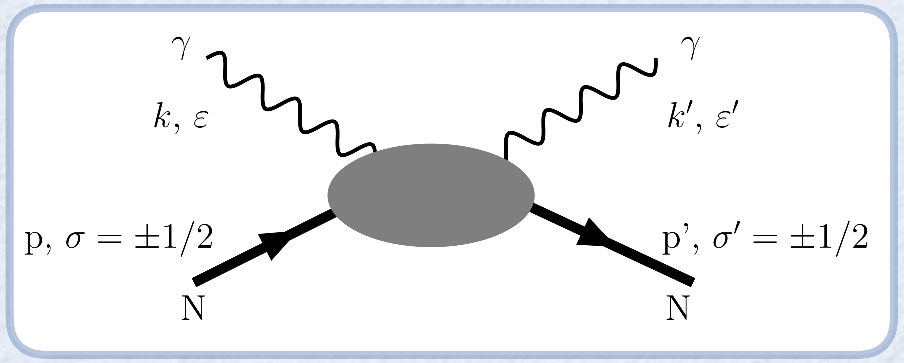
d, s-quarks carry very small total J in proton, u-quark carries around 60%, gluons around 30%

Sharing of momentum and total angular momentum between quarks and gluons identical in proton !

Nucleon spin structure with real photons

- forward real Compton scattering

$$T(\nu, \theta = 0) = \vec{\varepsilon}'^{*} \cdot \vec{\varepsilon}\, f(\nu) + i\vec{\sigma} \cdot (\vec{\varepsilon}'^{*} \times \vec{\varepsilon})\, g(\nu)$$



$$k = k', p = p'$$

low-energy expansion

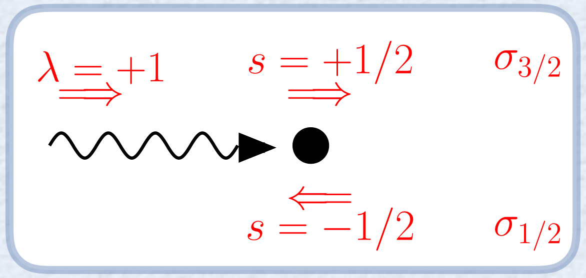
$$f(\nu) = \frac{-e^2}{4\pi M} + (\alpha_E + \beta_M)\,\nu^2 + \mathcal{O}(\nu^4)$$

$$g(\nu) = \frac{-e^2\kappa^2}{8\pi M^2}\,\nu + \gamma_0\,\nu^3 + \mathcal{O}(\nu^5)$$

LET polarizabilities

- term in ν : GDH **sum rule**

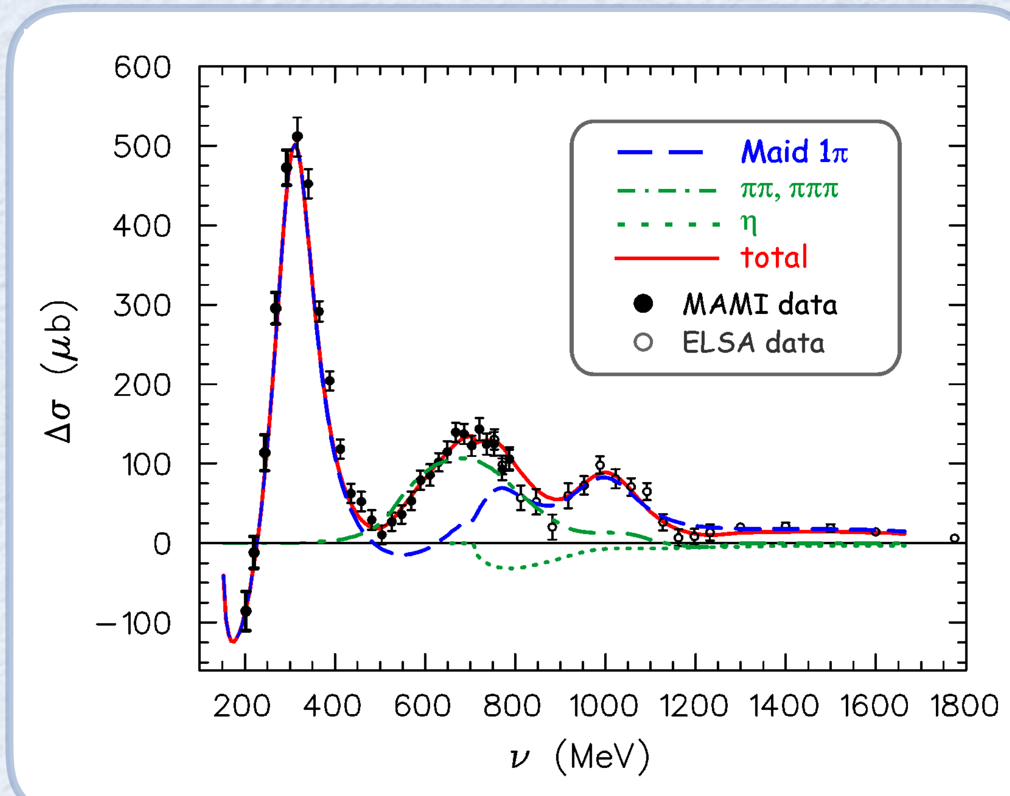
$$\frac{e^2\pi\kappa^2}{2M^2} = \int_{\nu_0}^{\infty} d\nu' \frac{\sigma_{3/2} - \sigma_{1/2}}{\nu'}$$



Gerasimov(1966); Drell,Hearn(1966)

lhs SR: **204 µb** rhs SR: **(211 ±15) µb** ✔

$$\Delta\sigma = \sigma_{3/2} - \sigma_{1/2} \qquad \vec{\gamma}\vec{p} \to X$$



Drechsel,Tiator(2004)

- term in ν³ : forward spin polarizability sum rule

$$\gamma_0 = -\frac{1}{4\pi^2} \int_{\nu_0}^{\infty} d\nu' \frac{\sigma_{3/2} - \sigma_{1/2}}{\nu'^{\,3}}$$

proton: $\gamma_0 = -(1.01 \pm 0.08 \pm 0.10) \times 10^{-4}\ \mathrm{fm}^4$

Proton spin polarizabilities

effective Hamiltonian (3rd order): nucleon spin polarizabilities

$$H_{\rm eff}^{(3)} = -4\pi\Big[\frac{1}{2}\gamma_{E1E1}\vec{\sigma}\cdot(\vec{E}\times\dot{\vec{E}}) + \frac{1}{2}\gamma_{M1M1}\vec{\sigma}\cdot(\vec{H}\times\dot{\vec{H}}) - \gamma_{M1E2}E_{ij}\sigma_i H_j + \gamma_{E1M2}H_{ij}\sigma_i E_j\Big]$$

forward spin polarizability

$$\gamma_0 = -\gamma_{E1E1} - \gamma_{E1M2} - \gamma_{M1E2} - \gamma_{M1M1}$$

theory predictions (units $10^{-4} \times \mathrm{fm}^4$): dispersion theory Drechsel, Pasquini, Vdh (2000)

chiral EFT McGovern, Phillips, Griesshammer (2013)

Lensky, McGovern, Pascalutsa (2015)

Pasquini, Vdh: Ann.Rev.Nucl.Part.Sci.68(2018)75-103

	Σ_{2x} and $\Sigma_3^{\rm LEGS}$	Σ_{2x} and $\Sigma_3^{\rm MAMI}$	DRs	HBChPT	BChPT	L_χ
γ_{E1E1}	-3.5 ± 1.2	-5.0 ± 1.5	-4.5	-1.1 ± 1.8	-3.3 ± 0.8	-3.7
γ_{M1M1}	3.16 ± 0.85	3.13 ± 0.88	3.0	2.2 ± 0.7[a]	2.9 ± 1.5	2.5
γ_{E1M2}	-0.7 ± 1.2	1.7 ± 1.7	-0.08	-0.4 ± 0.4	0.2 ± 0.2	1.2
γ_{M1E2}	1.99 ± 0.29	1.26 ± 0.43	2.3	1.9 ± 0.4	1.1 ± 0.3	1.2

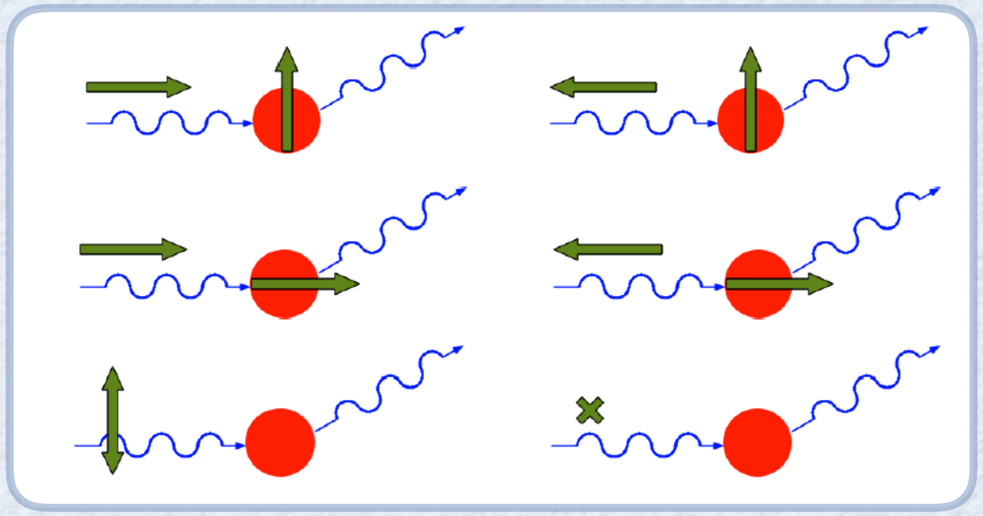
MAMI/A2 data Martel et al. (2015)

polarized Compton scattering

measure angular dependence of asymmetries

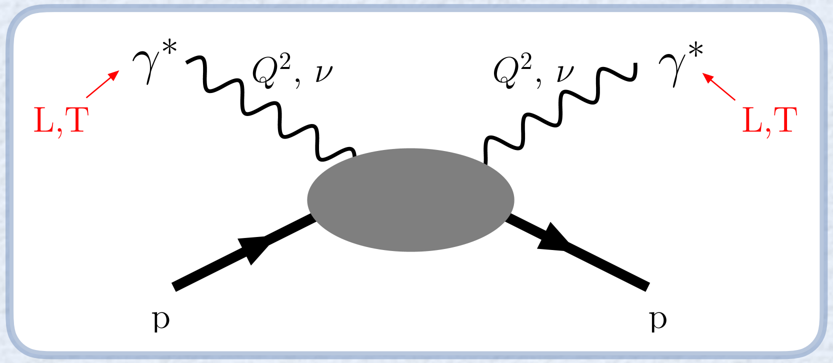
see talks: Ahmed, Martel (exp);

Pascalutsa, Sconfietti (th)



Nucleon spin structure with virtual photons

- forward, virtual Compton scattering



$$T^{\mu\nu}_{spin} = \frac{i}{M}\,\epsilon^{\nu\mu\alpha\beta}\,q_\alpha s_\beta\,S_1(\nu,Q^2) + \frac{i}{M^3}\,\epsilon^{\nu\mu\alpha\beta}\,q_\alpha(p\cdot q\;s_\beta - s\cdot q\;p_\beta)\,S_2(\nu,Q^2)$$

$$\mathrm{Im}\;S_1(\nu,\,Q^2) = \frac{e^2}{4M}\,\frac{M}{\nu}\,g_1(x,\,Q^2), \qquad \mathrm{Im}\;S_2(\nu,\,Q^2) = \frac{e^2}{4M}\,\frac{M^2}{\nu^2}\,g_2(x,\,Q^2)$$

spin structure functions

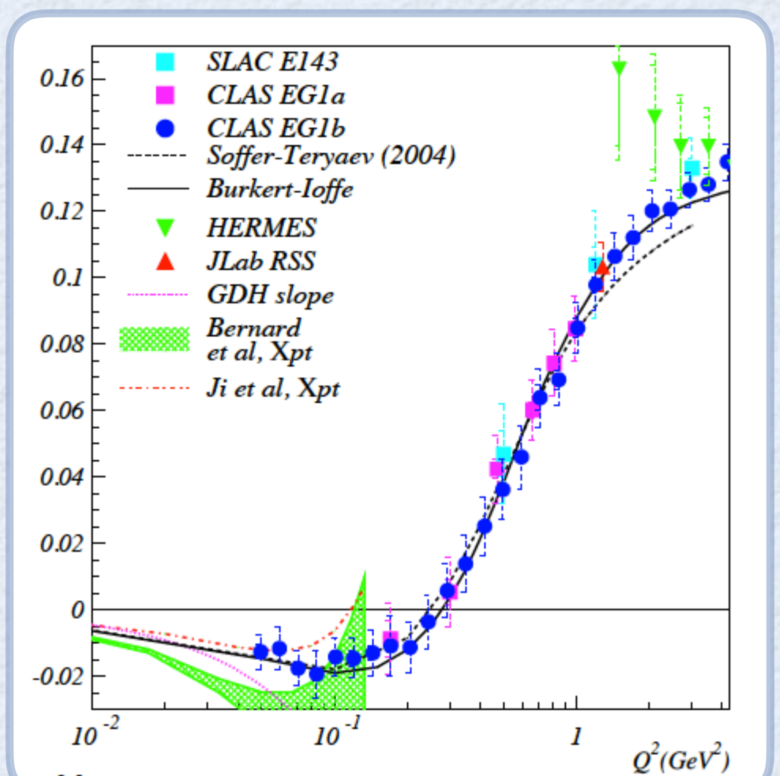
- moments of spin structure functions (x_0 : inelastic threshold)

$$\Gamma_1(Q^2) = \int_0^{x_0} dx\, g_1(x,Q^2)$$

$$\frac{Q^2}{2M^2}\left(-\frac{\kappa^2}{4}\right), \quad Q^2 \to 0$$ GDH sum rule

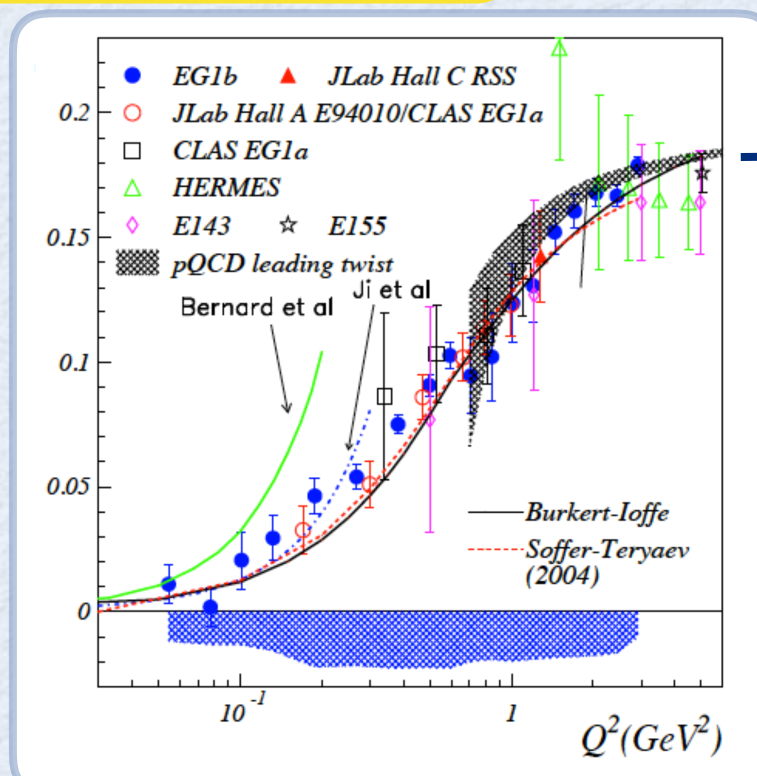
$$\Gamma_1(Q^2)|_{scaling}, \quad Q^2 \to \infty$$ parton helicity structure (DIS)

$\Gamma_1{}^p$



Chen (2010)

$\Gamma_1{}^{p-n}$



$$\frac{1}{6}g_A\left\{1 - \frac{\alpha_s}{\pi} + \ldots\right\}$$

Bjorken sum rule

see talks:

Kuhn, Chen, Ripani, Slifer

Nucleon spin polarizabilities with virtual photons

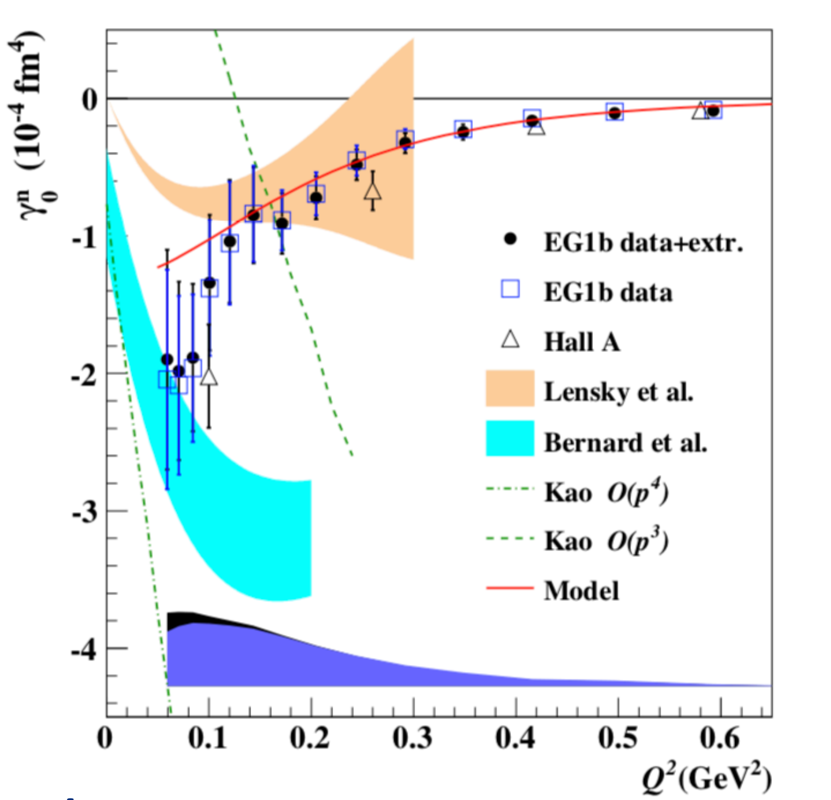
- higher moments of spin structure functions: spin polarizabilities

$$\gamma_0(Q^2) = \frac{4M^2e^2}{\pi Q^6}\int_0^{x_0} dx\, x^2 \left\{ g_1(x,Q^2) - \frac{4M^2}{Q^2}x^2\, g_2(x,Q^2)\right\} \longrightarrow \gamma_0, \quad Q^2 \to 0$$

$$\delta_{LT}(Q^2) = \frac{4e^2M^2}{\pi Q^6}\int_0^{x_0} dx\, x^2\, \{g_1(x,Q^2) + g_2(x,Q^2)\}$$

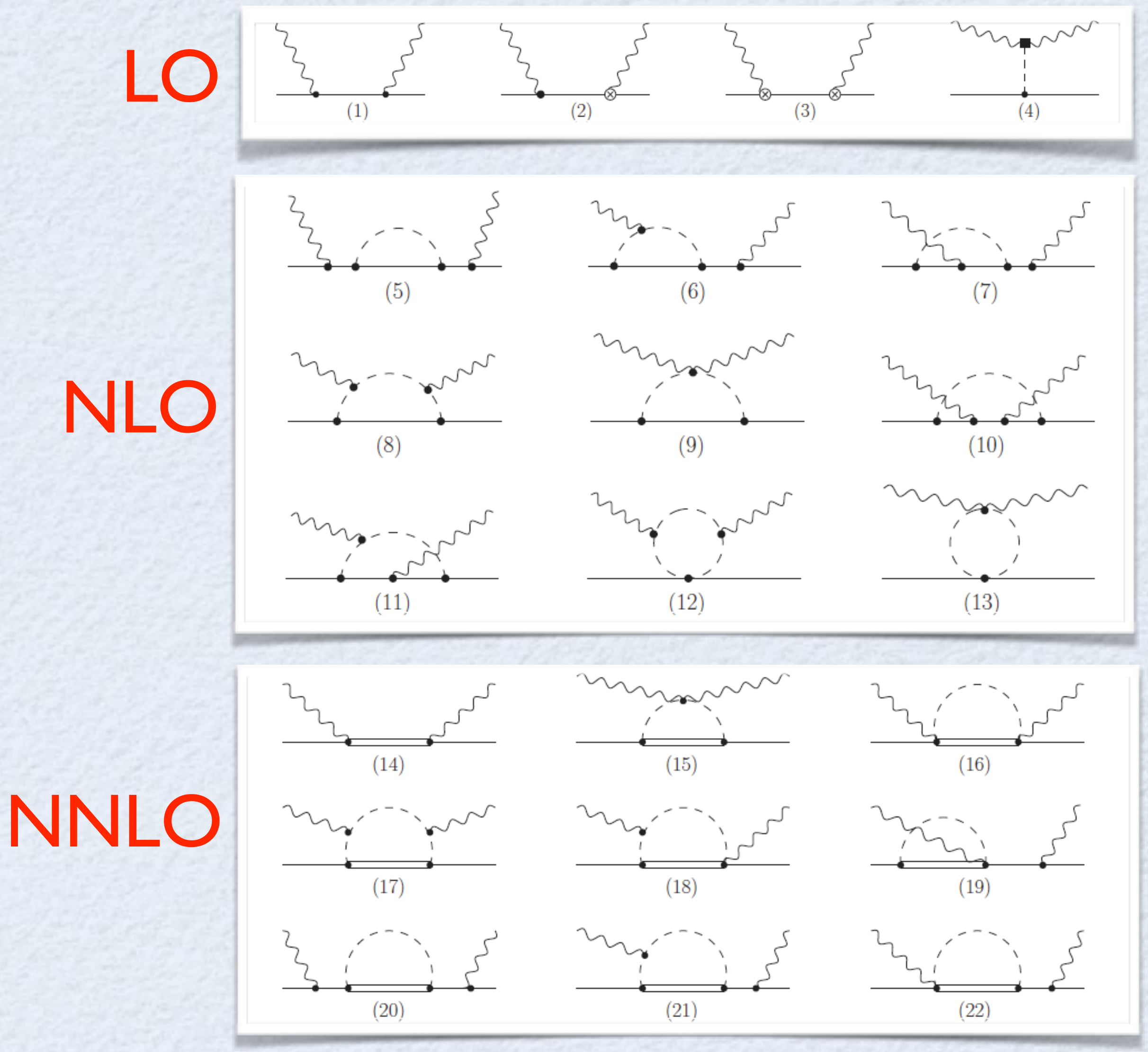
- provide strong test for theory:

chiral EFT calculations / lattice QCD



JLab/CLAS data Guller et al.(2015)

Lensky, Alarcon, Pascalutsa(2014)



see talks: Pascalutsa, Lensky, Rijneveen

New spin sum rules with virtual photons at low Q

Can we formulate sum rules relating observables to observables for virtual photons as is the case for real photons (GDH, FSP) ?

low-energy expansion for virtual photons

$$(S_1 - S_1^{\rm pole})(\nu, Q^2) = -\frac{e^2}{8\pi M}\kappa^2 + M\gamma_0\,\nu^2 + M\gamma_L\,Q^2 + \mathcal{O}(Q^4, \nu^4, Q^2\nu^2)$$

$$\gamma_L = \frac{e^2}{24\pi M^2}\kappa^2\,\langle r_2^2\rangle + \gamma_{E1M2} - 3M\frac{e^2}{4\pi}\left[P'^{(M1,M1)1}(0) + P'^{(L1,L1)1}(0)\right]$$

$P^{(M1,M1)1}(Q^2)$, $P^{(L1,L1)1}(Q^2)$ Generalized Polarizabilities

-> measured in **V**irtual **C**ompton **S**cattering

sum rule for I_1

$$(S_1 - S_1^{\rm pole})(\nu = 0, Q^2) = \frac{e^2}{2\pi M} I_1(Q^2)$$

with

$$I_1(Q^2) = \frac{2M^2}{Q^2}\int_0^{x_0} dx\, g_1(x, Q^2)$$

$$I_1'(0) = \frac{\kappa^2}{12}\langle r_2^2\rangle + \frac{2\pi M^2}{e^2}\gamma_{E1M2} - \frac{3M^3}{2}\left[P'^{(M1,M1)1}(0) + P'^{(L1,L1)1}(0)\right]$$

Sum rules relating RCS, VCS, VVCS
Can be tested by experiment !

Pascalutsa, Vdh (2015)

New spin sum rules with virtual photons

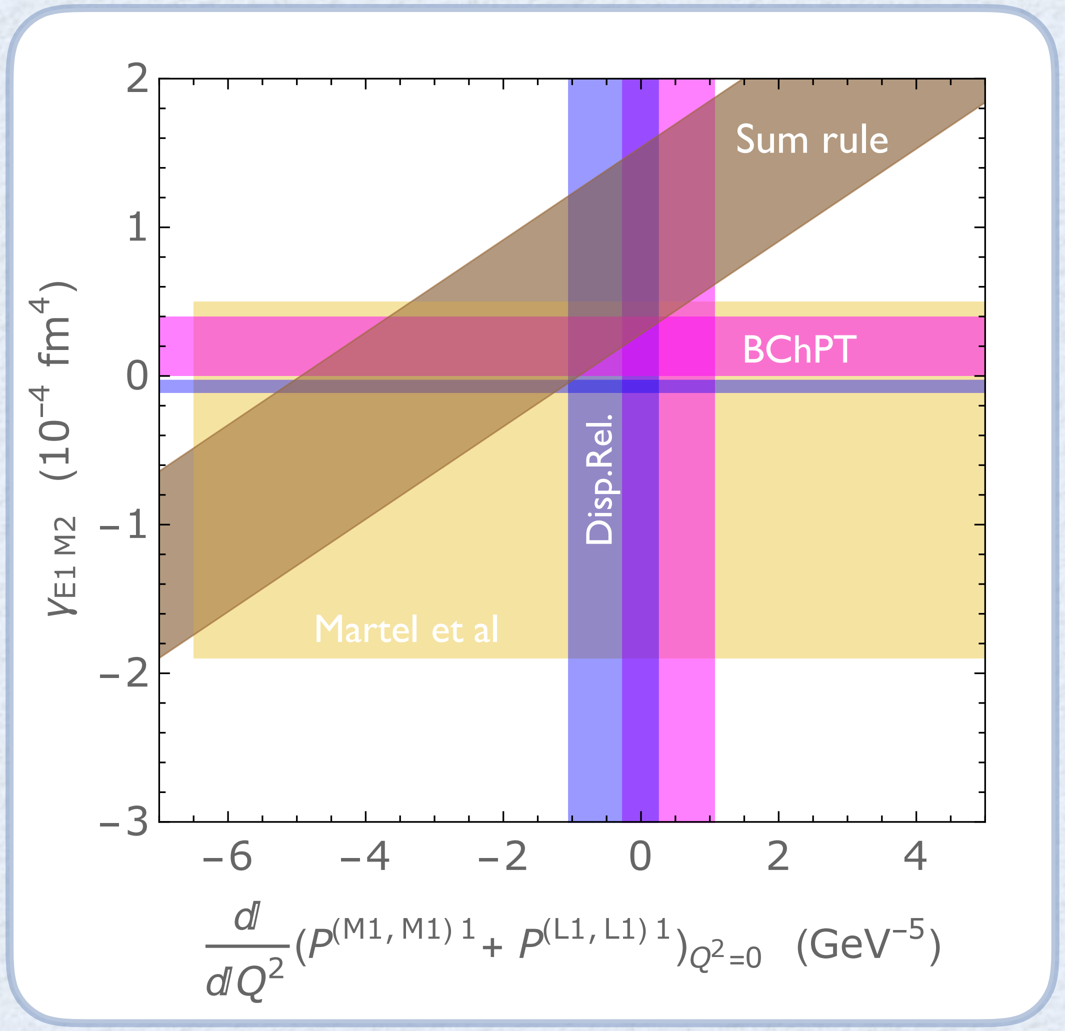
$$I_1(Q^2) = \frac{2M^2}{Q^2}\int_0^{x_0} dx\, g_1(x, Q^2)$$

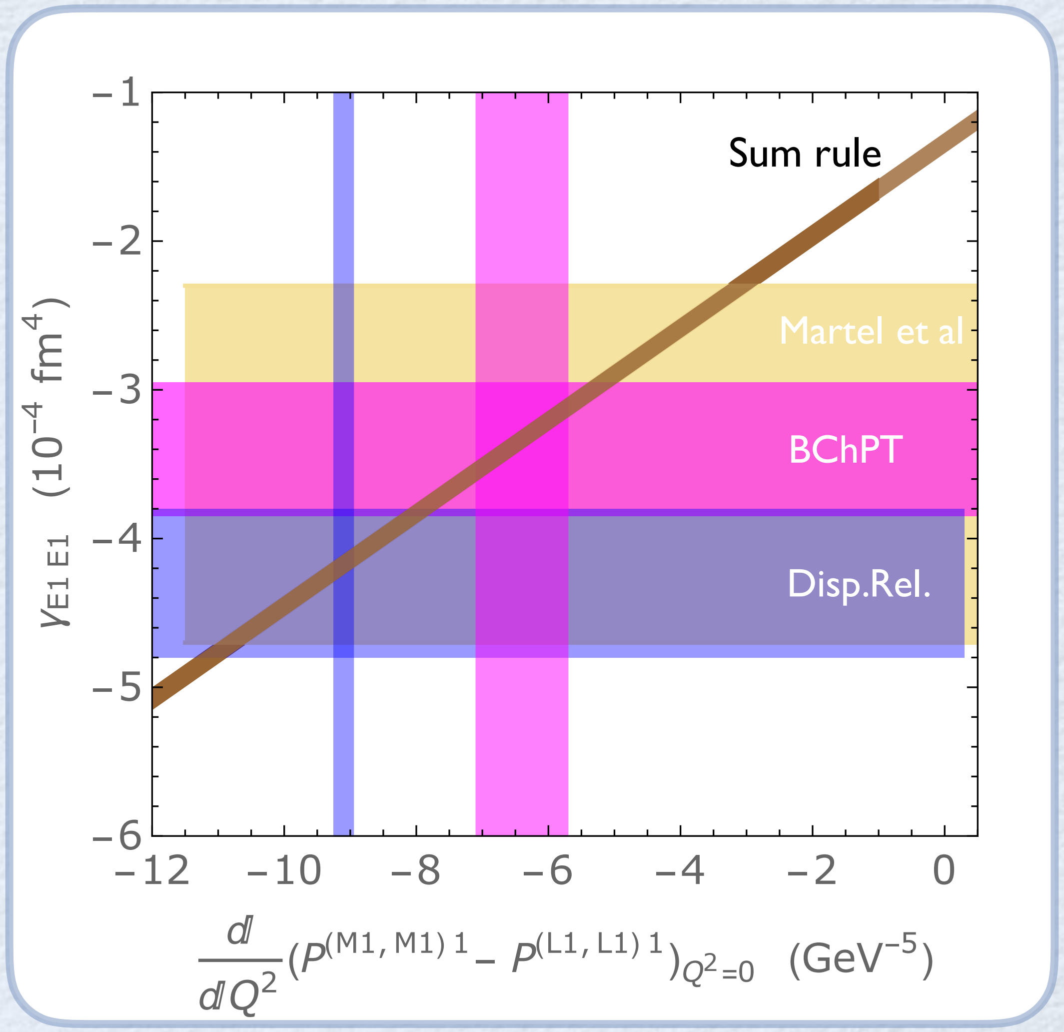
$$\delta_{LT}(Q^2) = \frac{16\alpha M^2}{Q^6}\int_0^{x_0} dx\, x^2 [g_1 + g_2](x, Q^2)$$

$$I_1'(0) = \frac{\kappa^2}{12}\langle r_2^2\rangle + \frac{2\pi M^2}{e^2}\gamma_{E1M2} - \frac{3M^3}{2}\left[P'^{(M1,M1)1}(0) + P'^{(L1,L1)1}(0)\right]$$

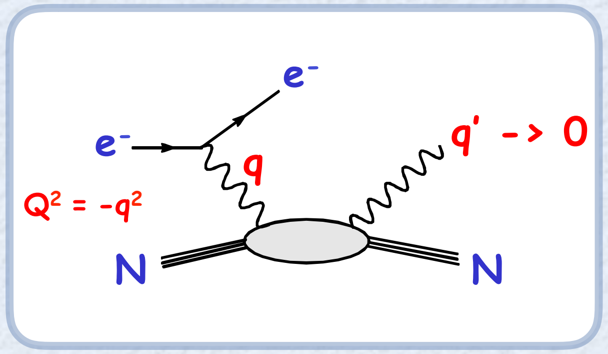
$$\delta_{LT}(0) = -\gamma_{E1E1} + 3M\frac{e^2}{4\pi}\left[P'^{(M1,M1)1}(0) - P'^{(L1,L1)1}(0)\right]$$

Pascalutsa, Vdh (2015)



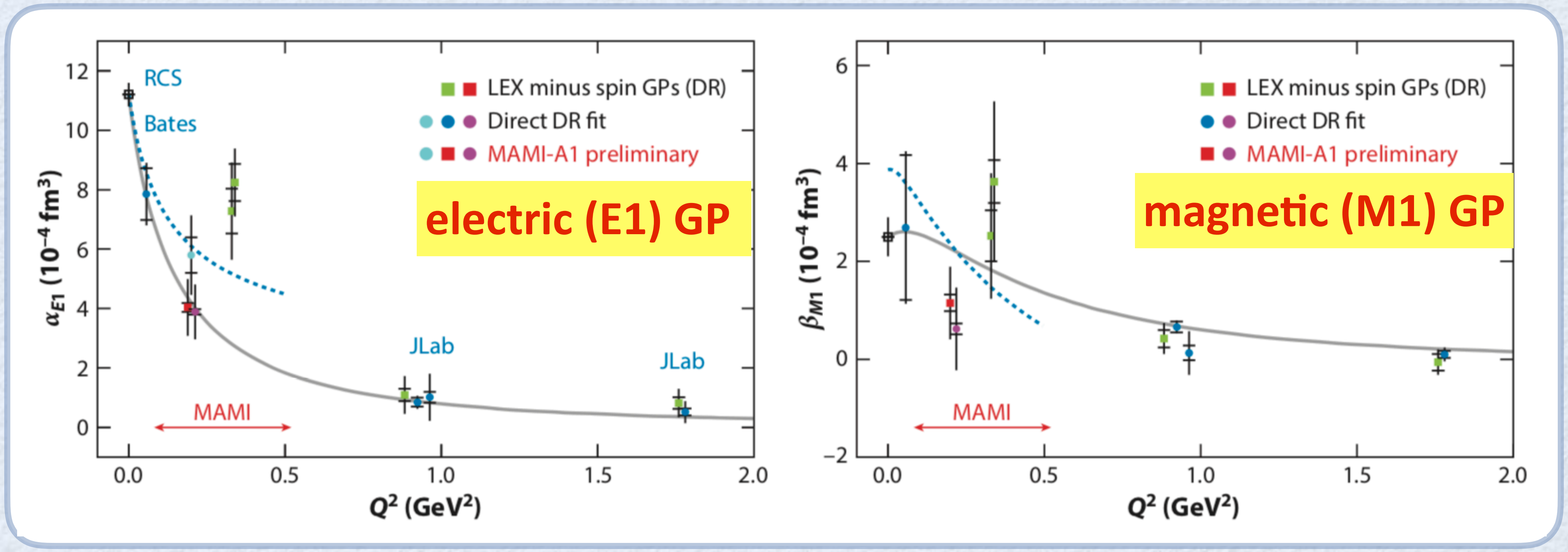


Generalized Polarizabilities of nucleon



new **MAMI** data
Correa (2016)
Blomberg(2016)

see talk: Sparveris



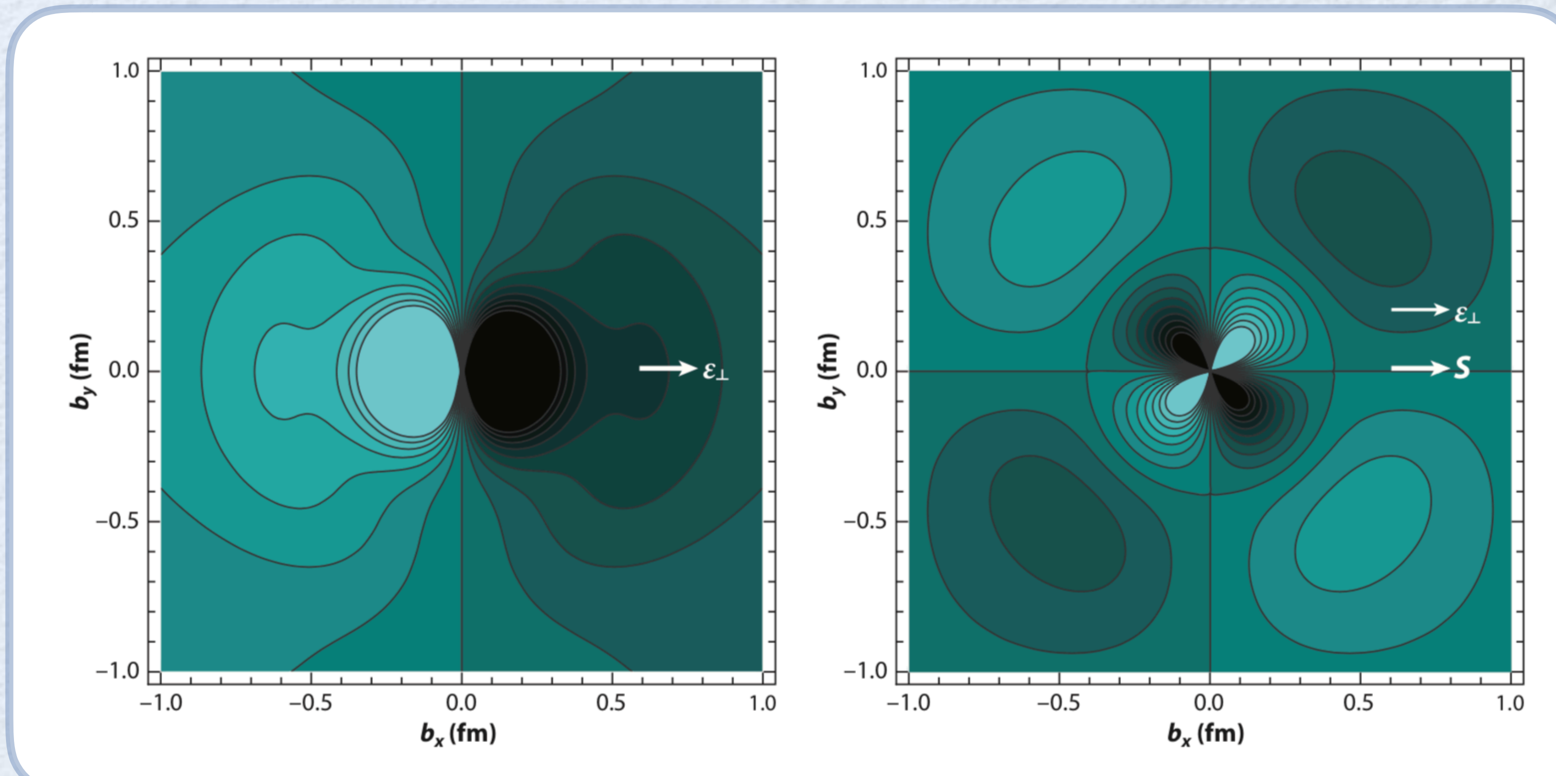
energy shift: $\delta E = -\vec{E} \cdot \vec{P}_0$

induced polarization

$$\vec{P}_0(\vec{b}) = \int \frac{d^2\vec{q}_\perp}{(2\pi)^2} e^{-i\vec{q}_\perp \cdot \vec{b}} \vec{P}_0(\vec{q}_\perp)$$

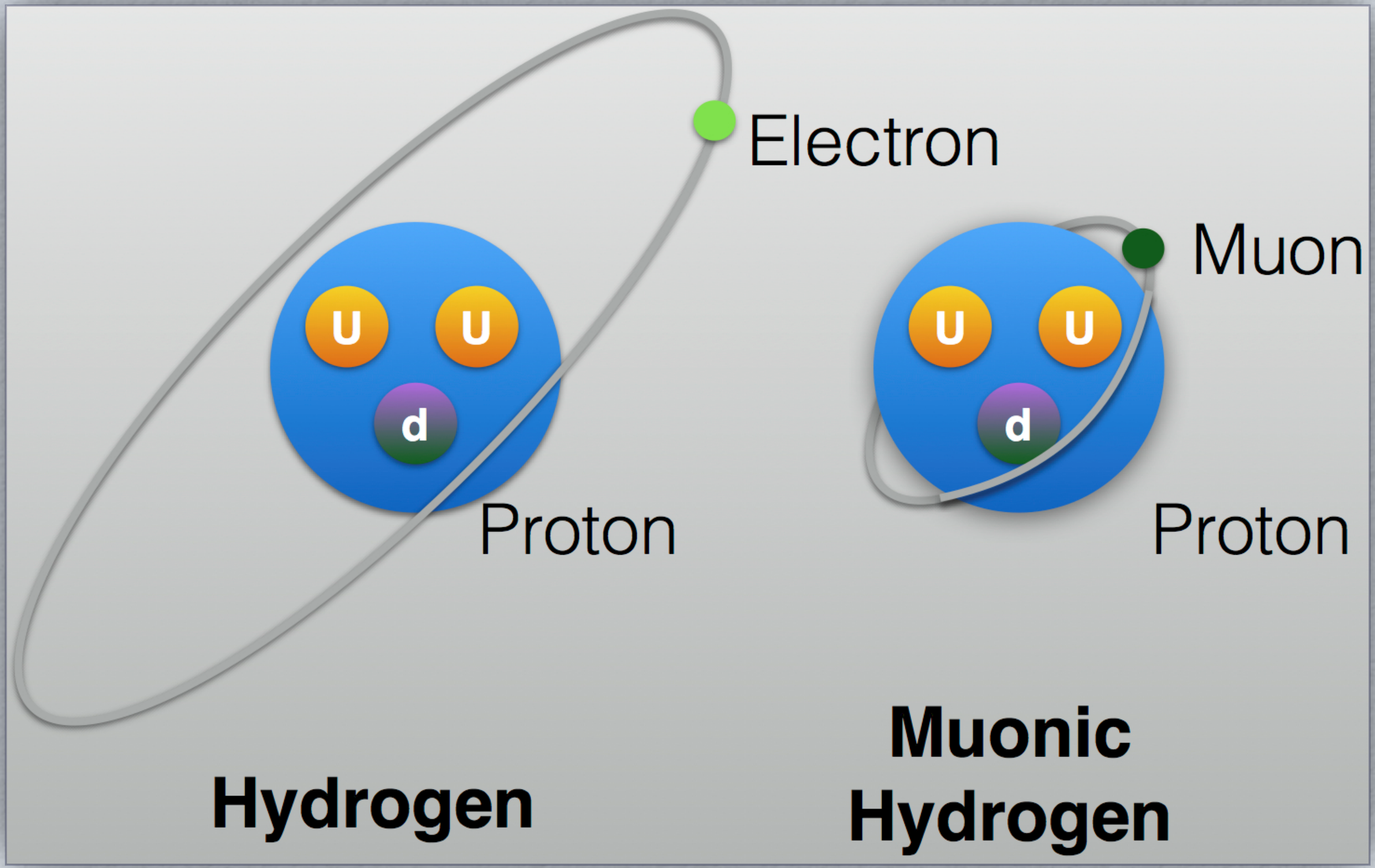
$$= \hat{b} \int_0^\infty \frac{dQ}{(2\pi)} Q J_1(b Q) A(Q^2)$$

combination of nucleon
generalized polarizabilities



Gorchtein,Lorcé,Pasquini,Vdh(2009); Pasquini,Vdh(2018)

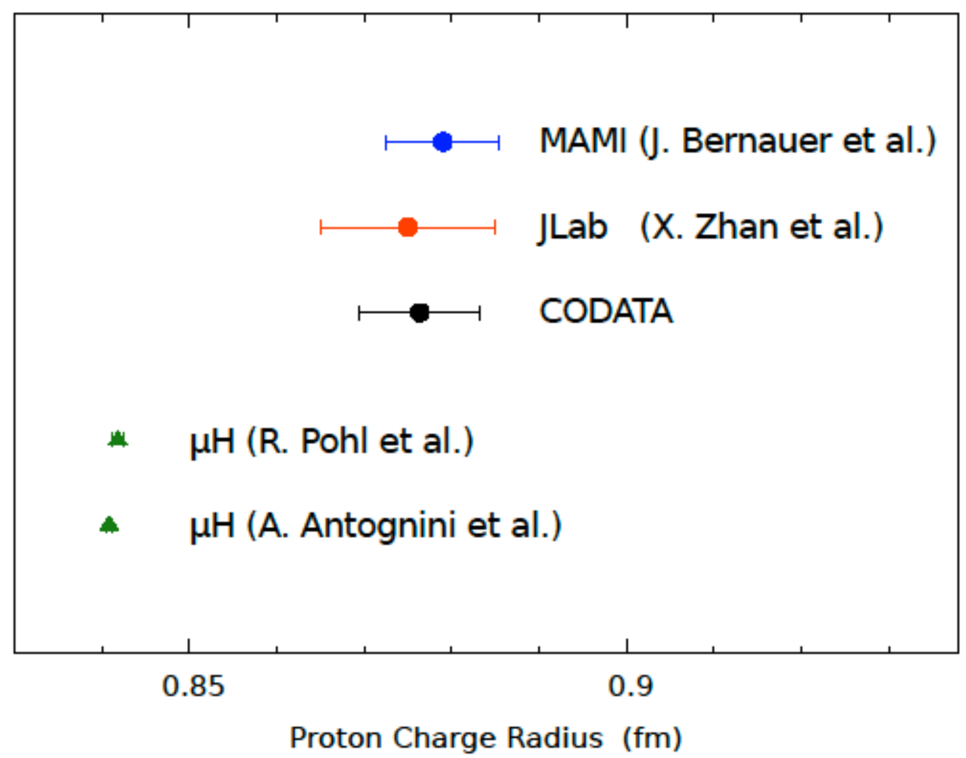
Proton structure in Hydrogen spectroscopy

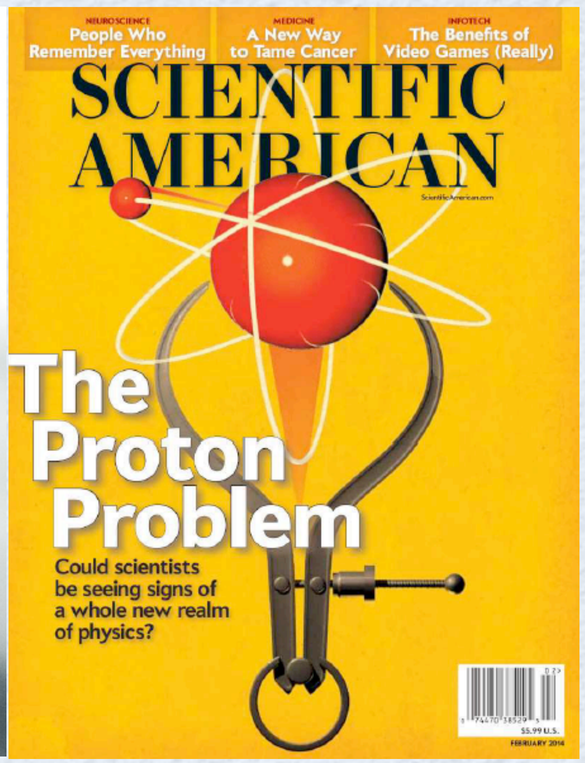


s-wave leptons have a finite probability to be found at the origin of the proton:

-> sensitivity to the charge/magnetization distribution of the proton

Lamb shift: Proton charge radius puzzle





μH data: $R_E = 0.8409 \pm 0.0004$ fm

Pohl et al. (2010)

Antognini et al. (2013)

5.6 σ difference !?

ep data: $R_E = 0.8775 \pm 0.0051$ fm

CODATA (2012)

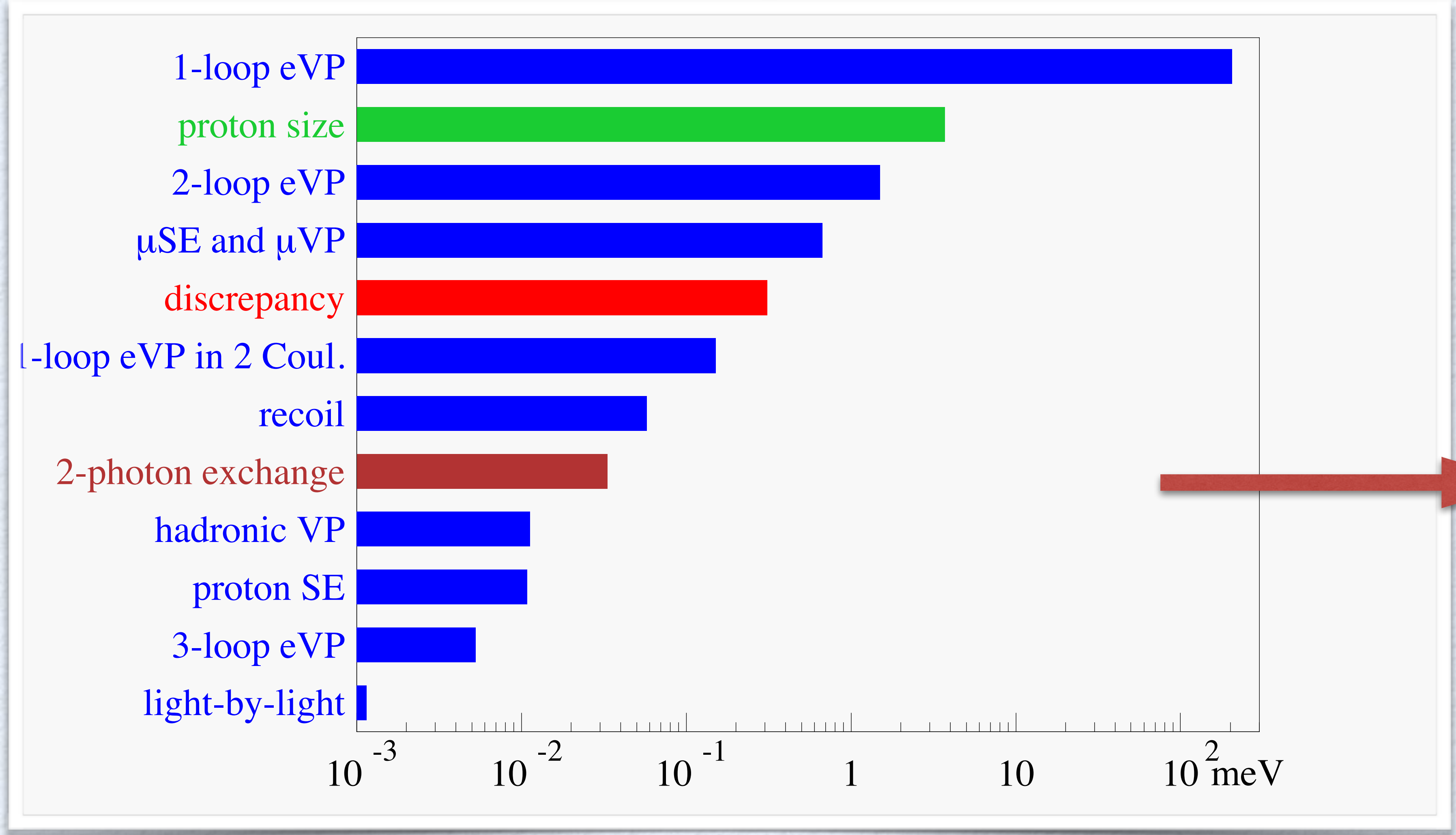
see talks:

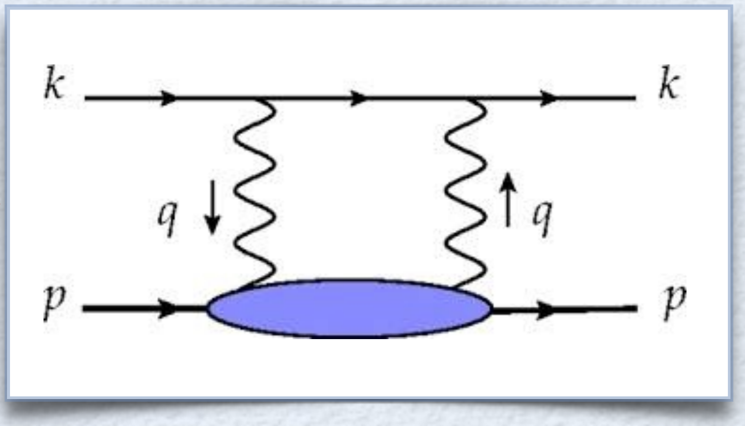
Gasparian (exp)

Alarcon (th)

Lamb shift: status of known corrections

µH Lamb shift: summary of corrections



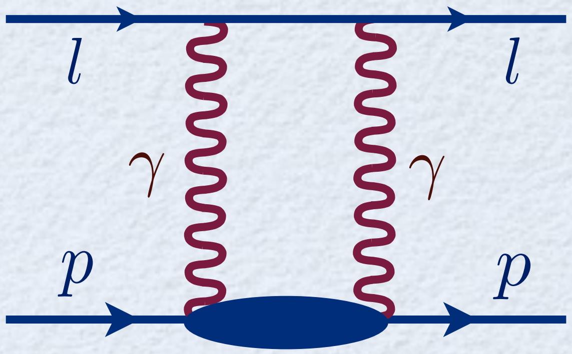


Two-photon exchange: largest theoretical uncertainty

Muonic hydrogen hyperfine splitting: TPE for proton spin dependent amplitude

forthcoming PSI
1S-HFS measurement in μH
with 1 ppm accuracy

see talks: Antognini, Kanda



see talks:

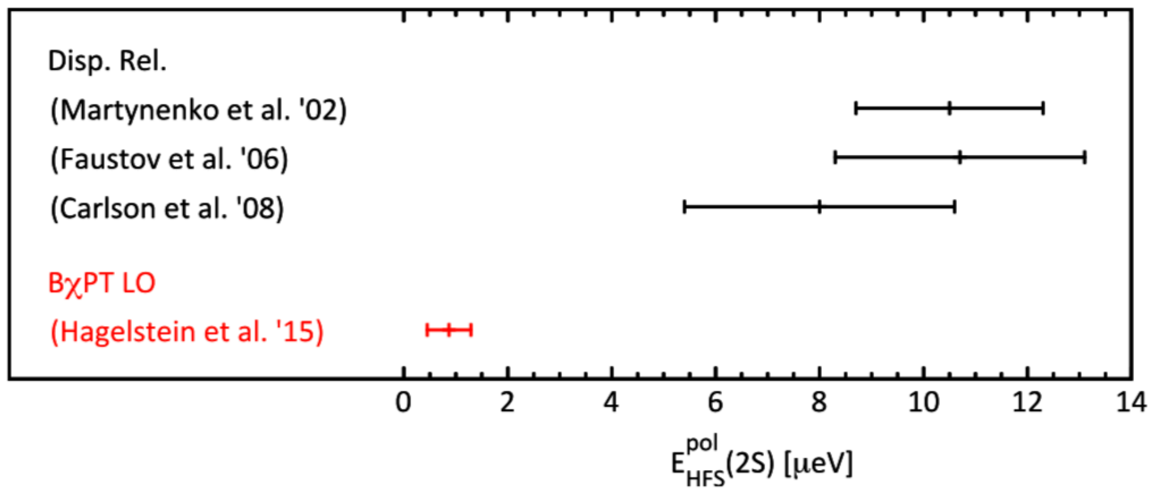
Carlson, Distler, Hagelstein, Pachucki, Pineda

1S-HFS in μH

	relative contribution (×10^{-3})	relative uncertainty
X=p (Zemach)	-7,36	140 ppm
X=p (recoil)	0,8476	0.8 ppm
X=p, πN,… (polarizability)	0,363	86 ppm
total	-6,149	164 ppm

Carlson,Nazaryan,Griffioen(2011);

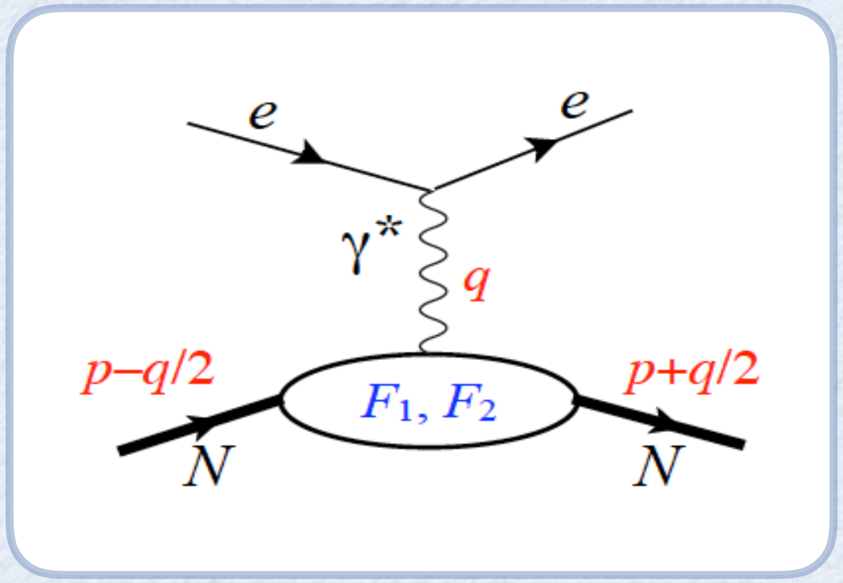
Tomalak et al.(2016)



Hagelstein,Miskimen,Pascalutsa
Prog.Part.Nucl.Phys.88(2016)29-97

Impressive 1 ppm accuracy requires improvement on 2γ !!

Precise G_M at low Q^2 needed

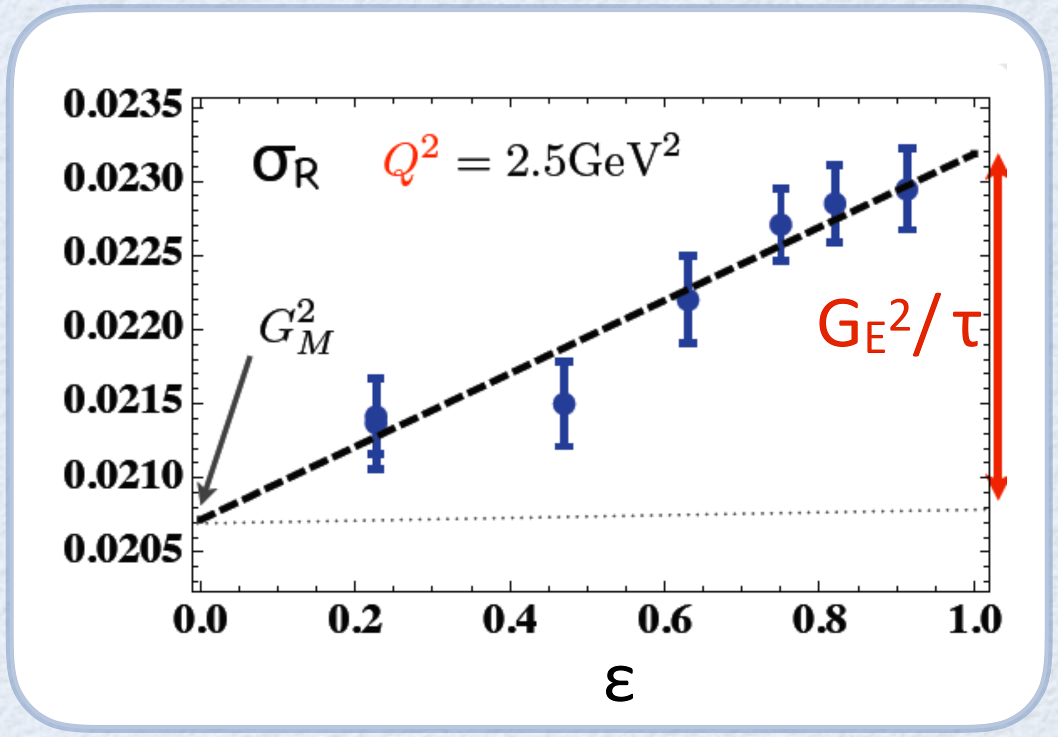


$G_M = F_1 + F_2$

$G_E = F_1 - \tau F_2$

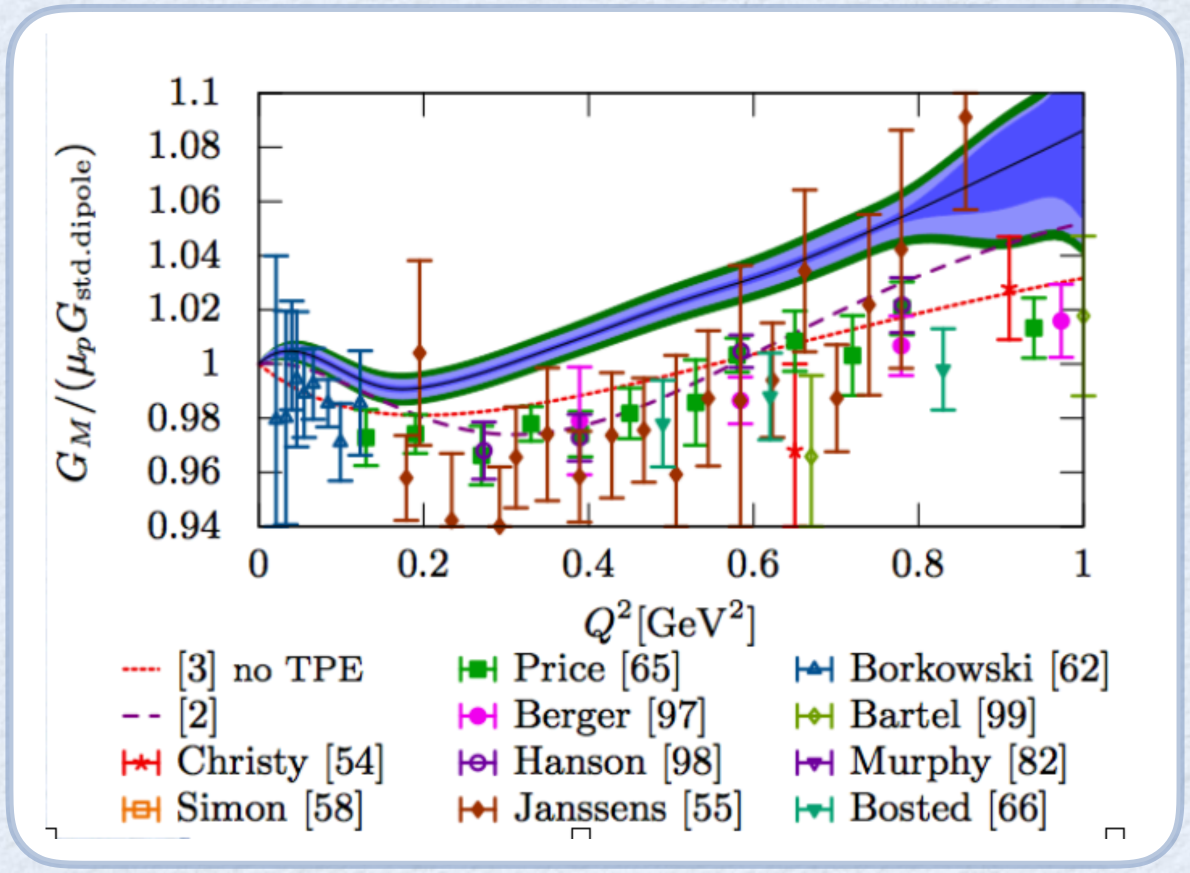
$\tau \equiv \frac{Q^2}{4M^2}$ $\frac{1}{\varepsilon} \equiv 1 + 2(1+\tau)\tan^2\frac{\theta}{2}$

$$\sigma_R = G_M^2 + \frac{\varepsilon}{\tau} G_E^2$$



Rosenbluth separation technique

Andivahis et al.(1994)



Bernauer et al.(2010, 2013)

see talk:

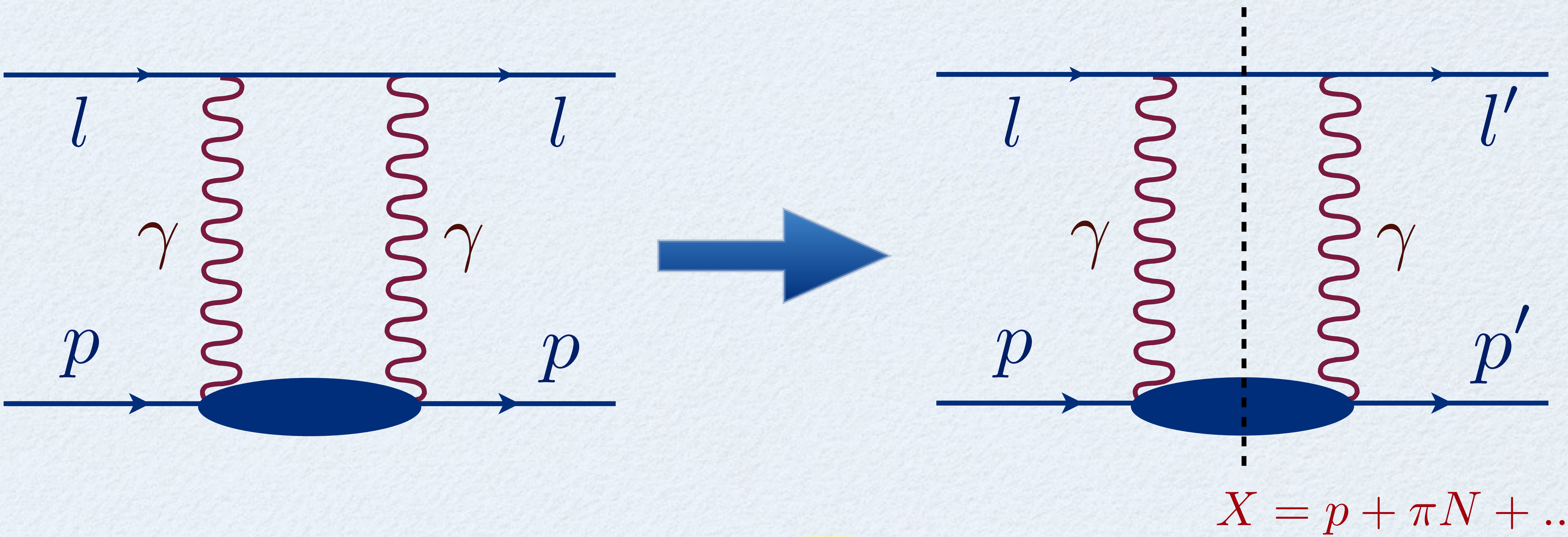
Bernauer

TPE in dispersive framework

forward scattering

non-forward scattering

account for all inelastic 2γ



dispersion relations

based on on-shell information

Borisyuk, Kobushkin (2008)

Tomalak, Vdh (2014, 2015, 2016)

Pasquini, Tomalak, Vdh (2017)

2γ-exchange at low Q²

Feshbach inelastic elastic

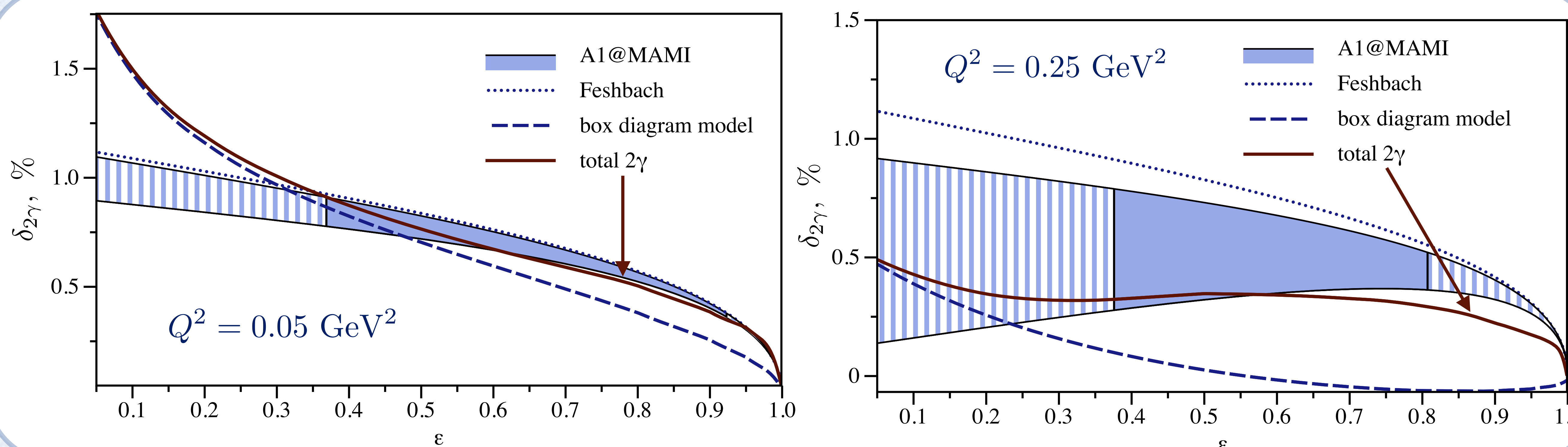
$$\delta_{2\gamma} \sim a\,\sqrt{Q^2} + b\,Q^2 \ln Q^2 + c\,Q^2 \ln^2 Q^2$$

McKinley, Feshbach (1948)
R.W.Brown (1970)
M. Gorchtein (2013)

unpolarized proton structure

Tomalak, Vdh (2016)

$$\delta_{2\gamma} = \int \mathrm{d}\nu_\gamma \mathrm{d}\tilde{Q}^2 (\omega_1(\nu_\gamma, \tilde{Q}^2) \cdot F_1(\nu_\gamma, \tilde{Q}^2) + \omega_2(\nu_\gamma, \tilde{Q}^2) \cdot F_2(\nu_\gamma, \tilde{Q}^2))$$



- 2γ at large ε agrees with empirical fit: G_E extraction ✓
- deviations from empirical fit seen at low ε: G_M extraction sensitive

Workshop goals

Hadronic corrections to hyperfine splitting in **muonic H**

- crucial input: G_M, spin polarizabilities, polarized structure functions, …

Elastic electron scattering has reached level of precision where TPE effects are clearly visible

- high precision data forthcoming: PRad@JLab, MAGIX@MESA
- full assessment of TPE corrections needed

Spin structure functions at low Q^2 : experiment

- several JLab 6 GeV analysis completed or near completed
- polarizability program: RCS, VCS
- what are next experimental steps?

Theoretical understanding of low Q^2 spin structure:

- new sum rules relating RCS, VCS, and VVCS can be tested in exp. in a model independent way
- what is the state of ChEFT in describing the low Q^2 spin structure
- test for theory used for calculating the proton spin structure in hyperfine splitting in muonic H

wish you a productive meeting