SFB 1044
THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

PRISMA

HIM

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JG|U

# Overview on Nucleon Form Factors

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7th Workshop on Hadron Physics in China and Opportunities Worldwide

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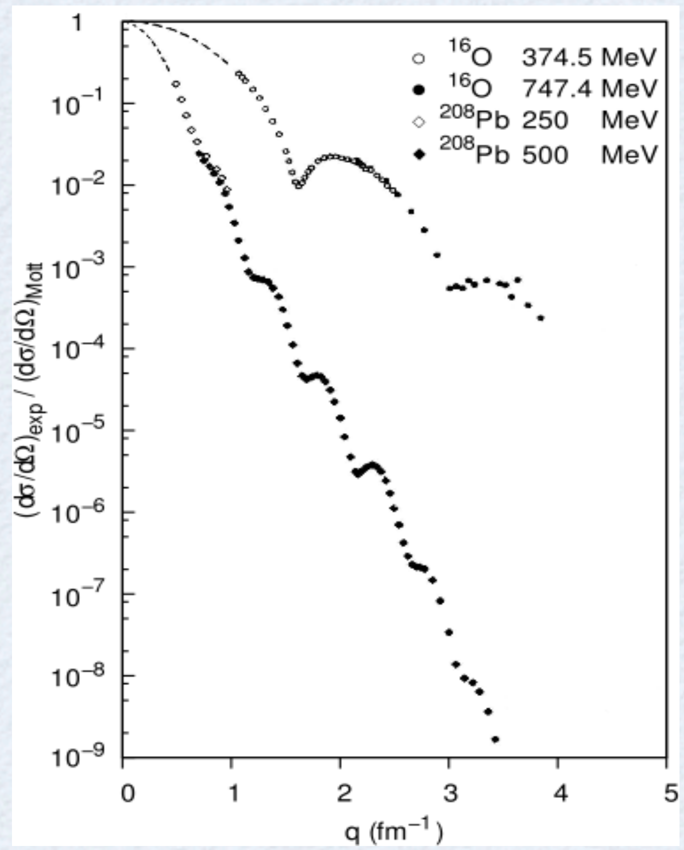
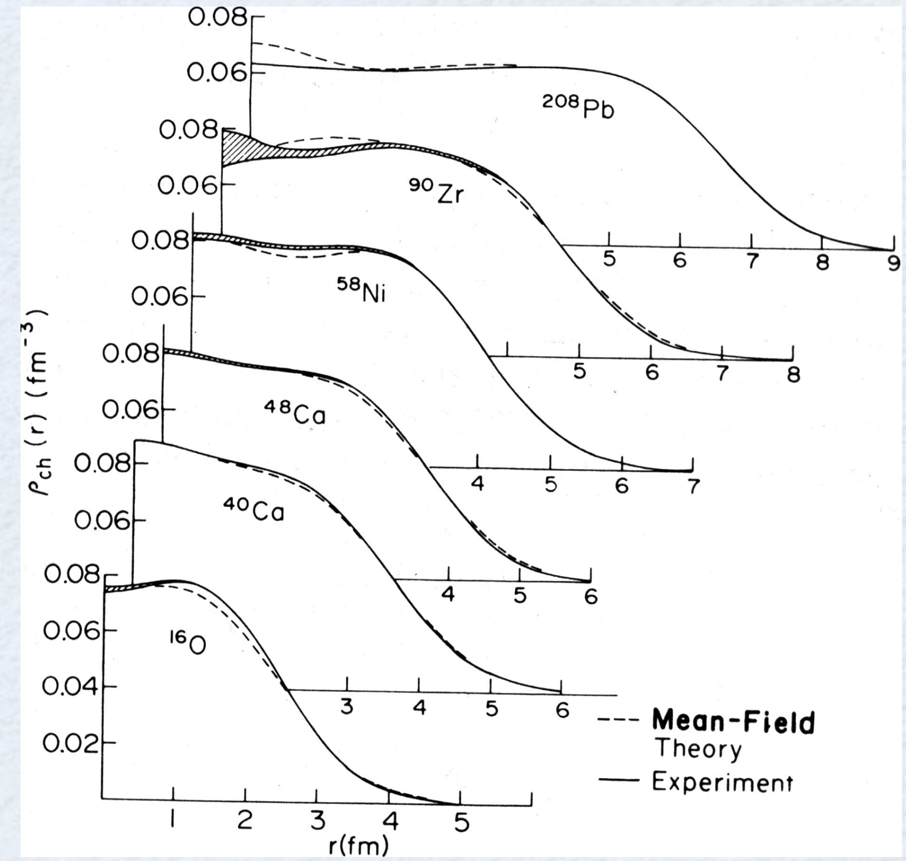
Duke Kunshan University, China

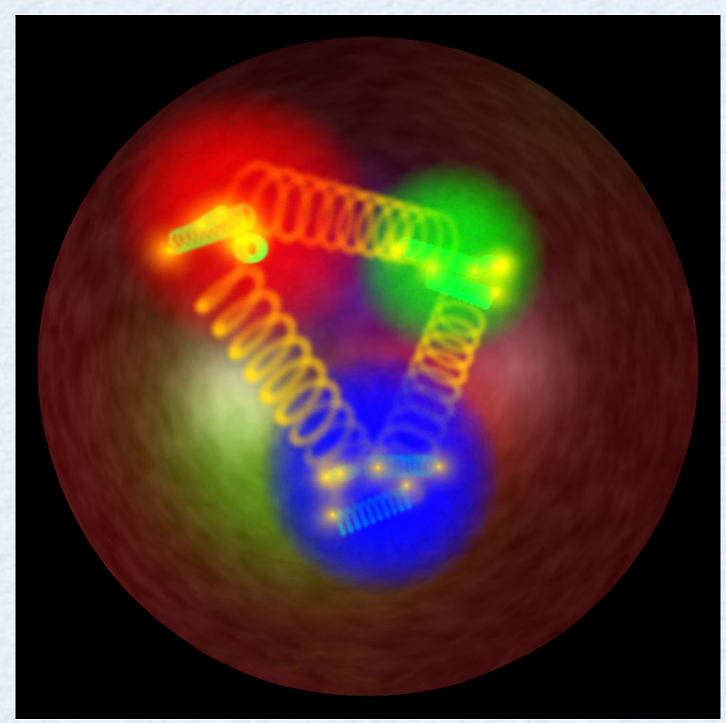
# Part 1: Proton size

time honored tool:
electroweak probe

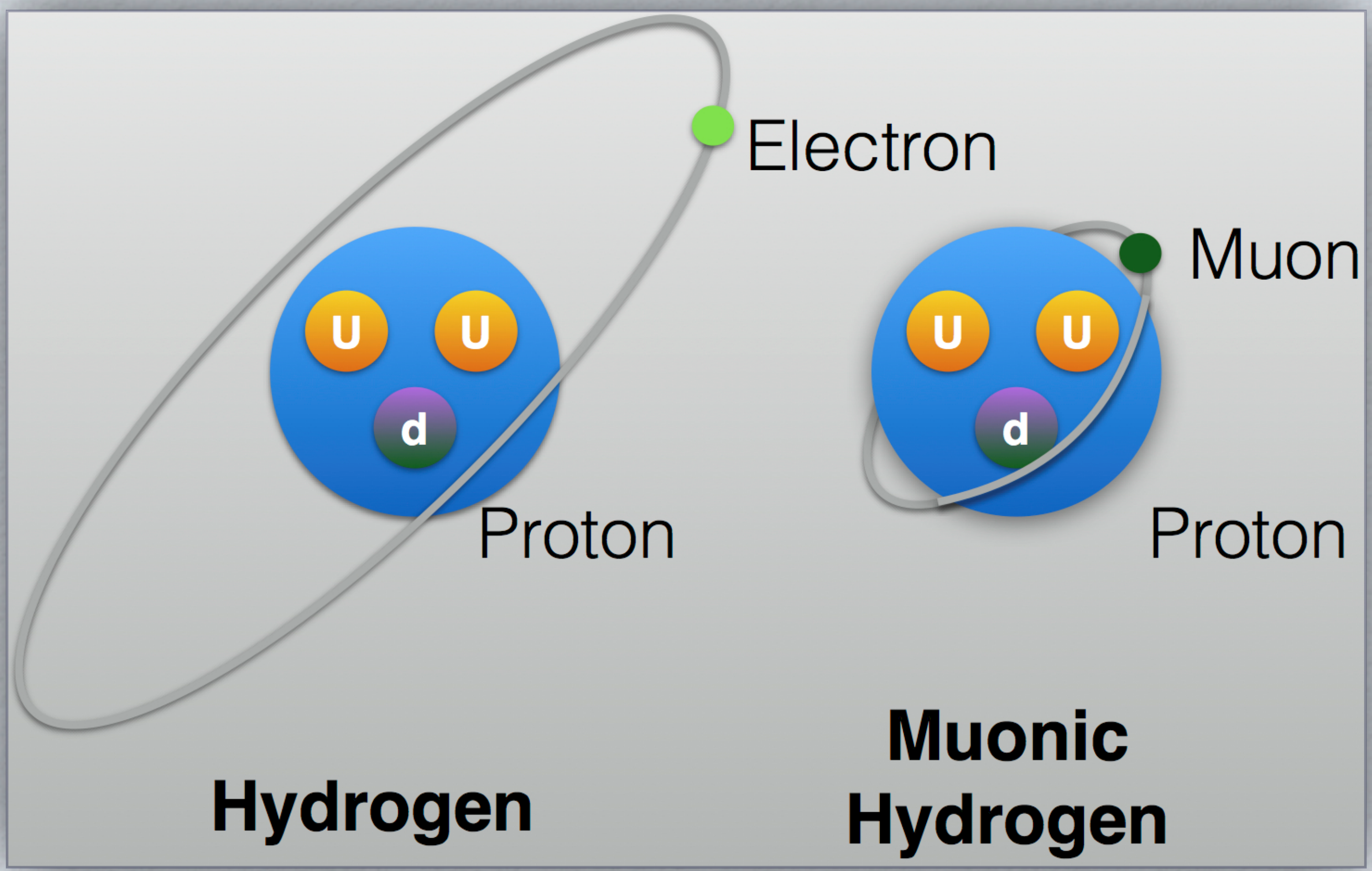


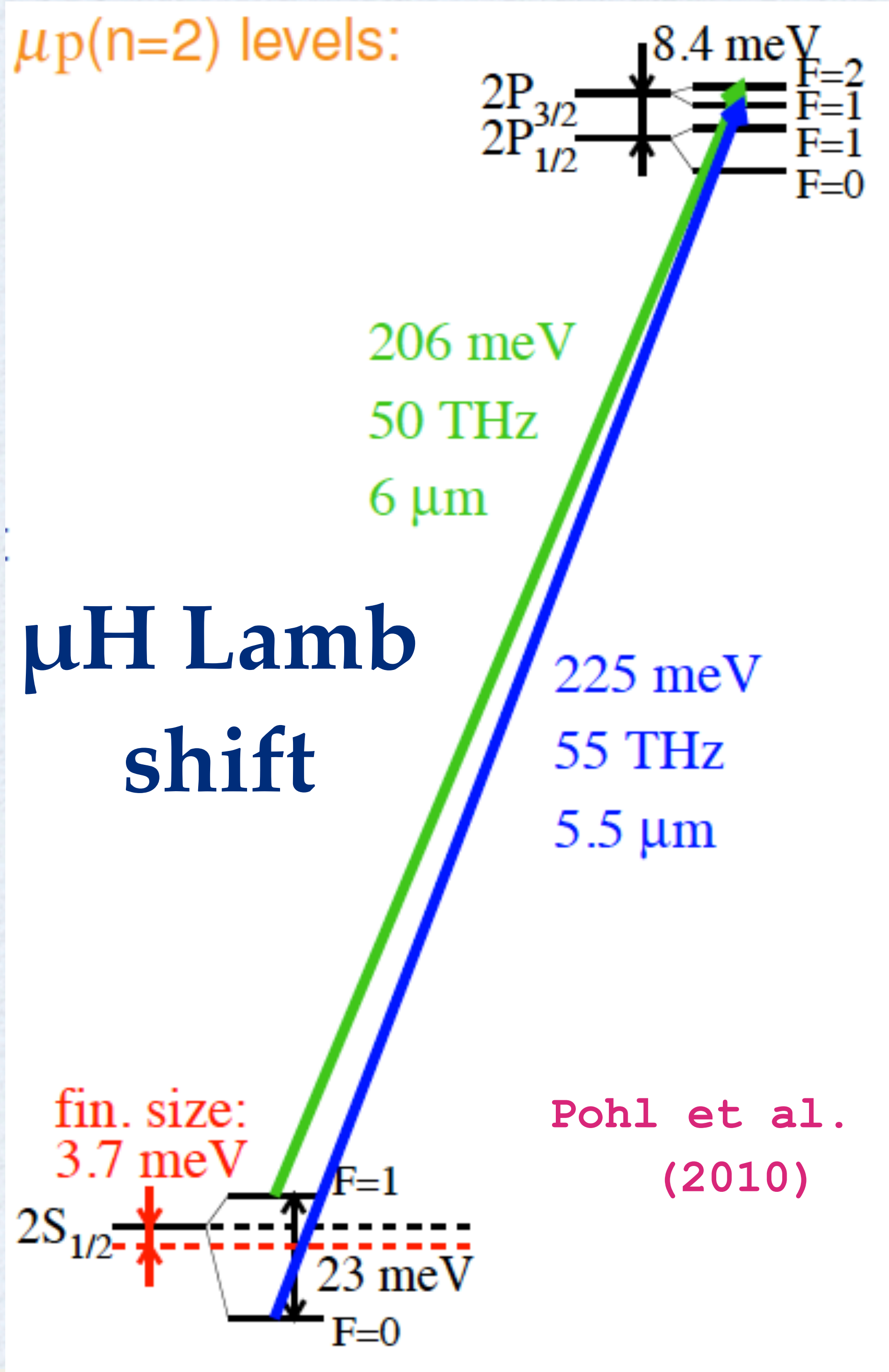




how accurate do we
know the proton size ?



# Proton radius from Hydrogen spectroscopy



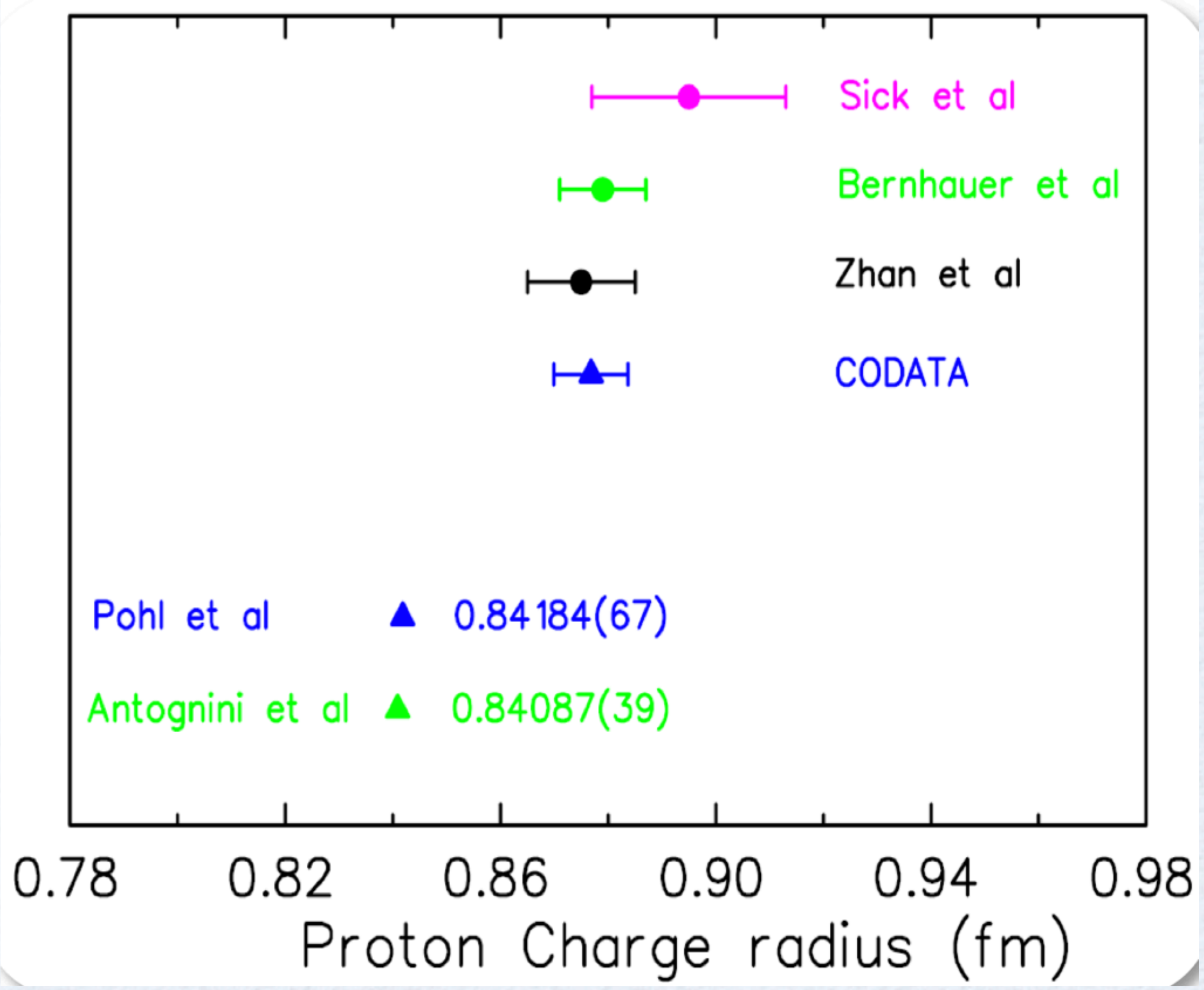

$$\Delta E_{LS} = 209.9779\,(49) - 5.2262\ R_E^2 + 0.00913\ R^3_{(2)}\ \text{meV}$$

3.70 meV

0.026 meV

O($\alpha^5$) correction

# Proton radius puzzle





**μH data:** $R_E = 0.8409 \pm 0.0004$ fm

Pohl et al.(2010)

Antognini et al.(2013)

**7 σ difference !?**

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

CODATA(2012)

# Proton radius puzzle: what could it mean ?

$$\Delta E_{LS} = 209.9779\,(49) - 5.2262\ R_E^{\,2} + 0.00913\ R^3_{(2)}\ \text{meV}$$

different radii

**μH** expt. wrong ?

**eH** theory wrong ?

Lamb shift

difference of

≈ 320 μeV

**μH** theory wrong ?

- QED bound state corrections
- hadronic corrections
- check with different targets

**eH** expt. wrong ? -> $R_\infty$ wrong

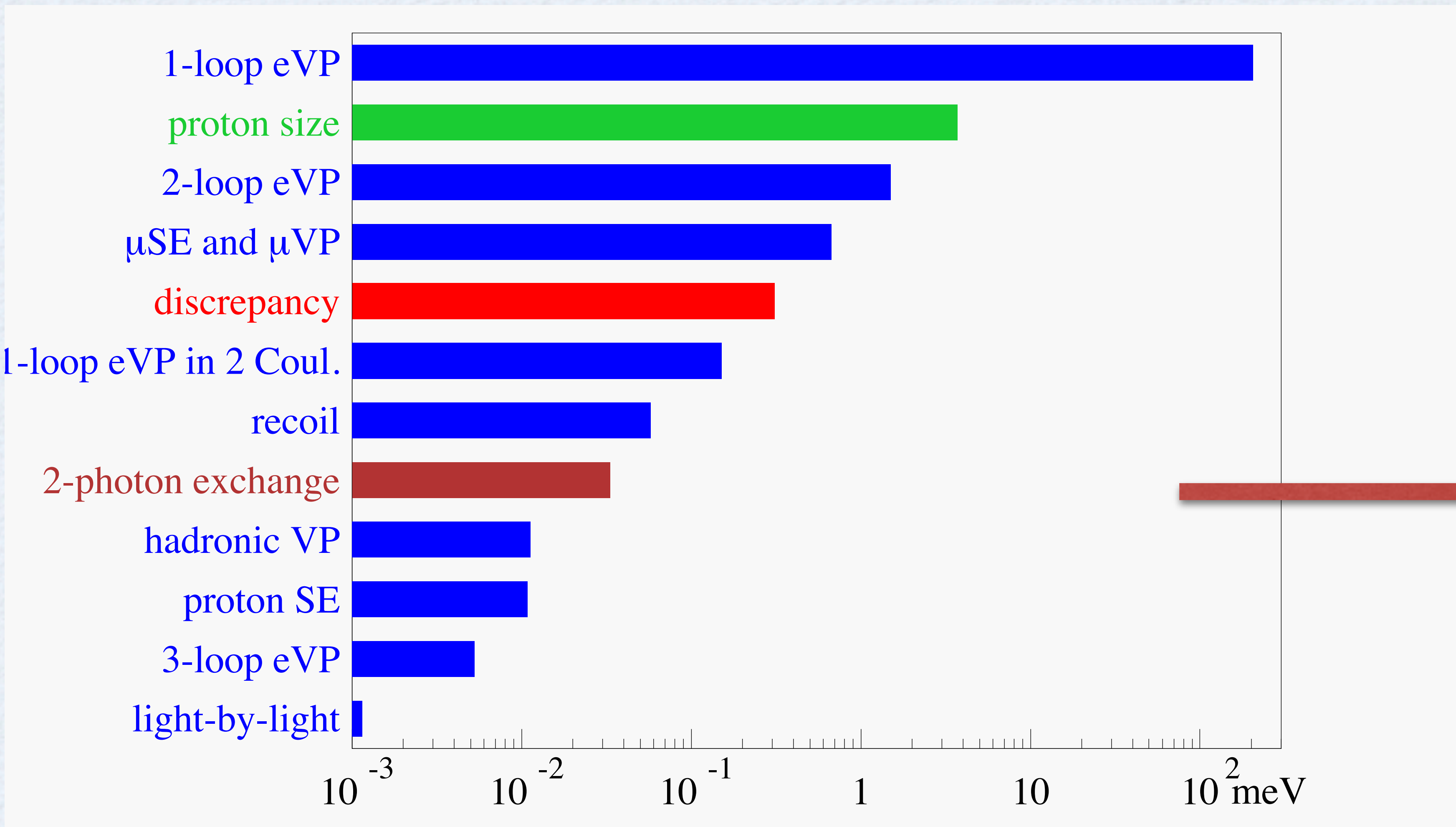
**+ ep** scattering wrong ?

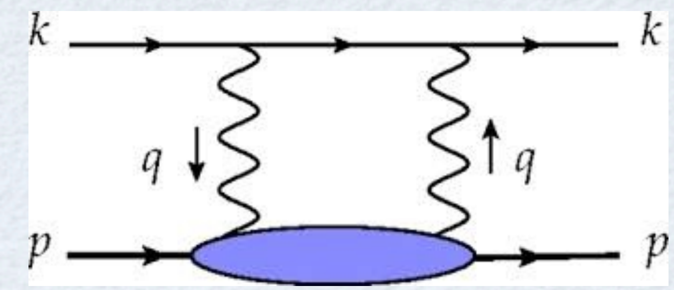
- radiative corrections
- 2γ corrections
- low $Q^2$ extrapolation

**standard model** wrong ?

# Lamb shift: status of known corrections

**μH Lamb shift: summary of corrections**




largest theoretical uncertainty

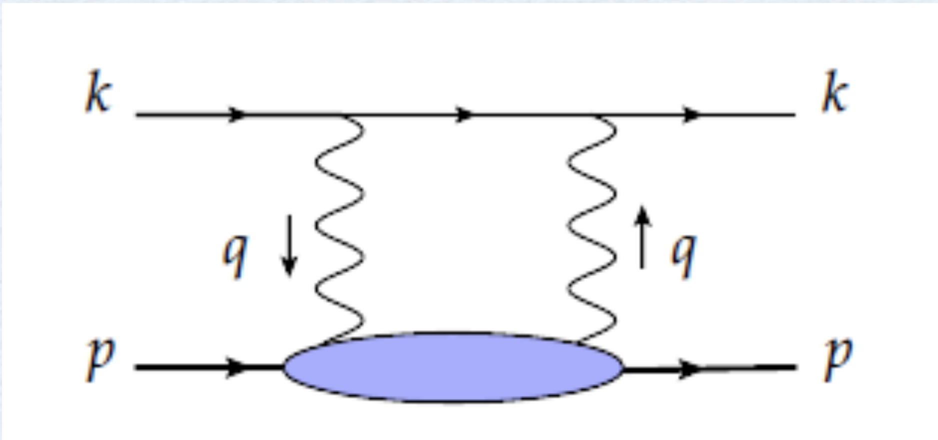
- elastic contribution on 2S level: $\Delta E_{2S}$ = -23 μeV
- inelastic contribution: Carlson, Vdh (2011) + Birse, McGovern (2012)

**total hadronic correction on Lamb shift**

$\Delta E_{(2P-2S)} = (33 \pm 2)$ μeV

...or about 11% of needed correction

# Lamb shift: hadronic corrections (I)




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

- Lower blob contains both elastic (nucleon) and in-elastic states

  Information contained in **forward, double virtual Compton scattering**

**Hadron physics input required**

- Described by two amplitudes T1 and T2: function of energy ν and virtuality $Q^2$

- Imaginary parts of T1 , T2: unpolarized structure functions of proton

$$
\begin{aligned}
\mathrm{Im}\, T_1(\nu, Q^2) &= \frac{1}{4M} F_1(\nu, Q^2) \\
\mathrm{Im}\, T_2(\nu, Q^2) &= \frac{1}{4\nu} F_2(\nu, Q^2)
\end{aligned}
$$

- ΔE evaluated through an integral over $Q^2$ and ν

$$
\begin{aligned}
\Delta E &= \Delta E^{el} \\
&+ \Delta E^{subtr} \\
&+ \Delta E^{inel}
\end{aligned}
$$

→ Elastic state: involves **nucleon form factors**

→ Subtraction: involves **nucleon polarizabilities**

→ Inelastic, dispersion integrals: involves **structure functions F1, F2**

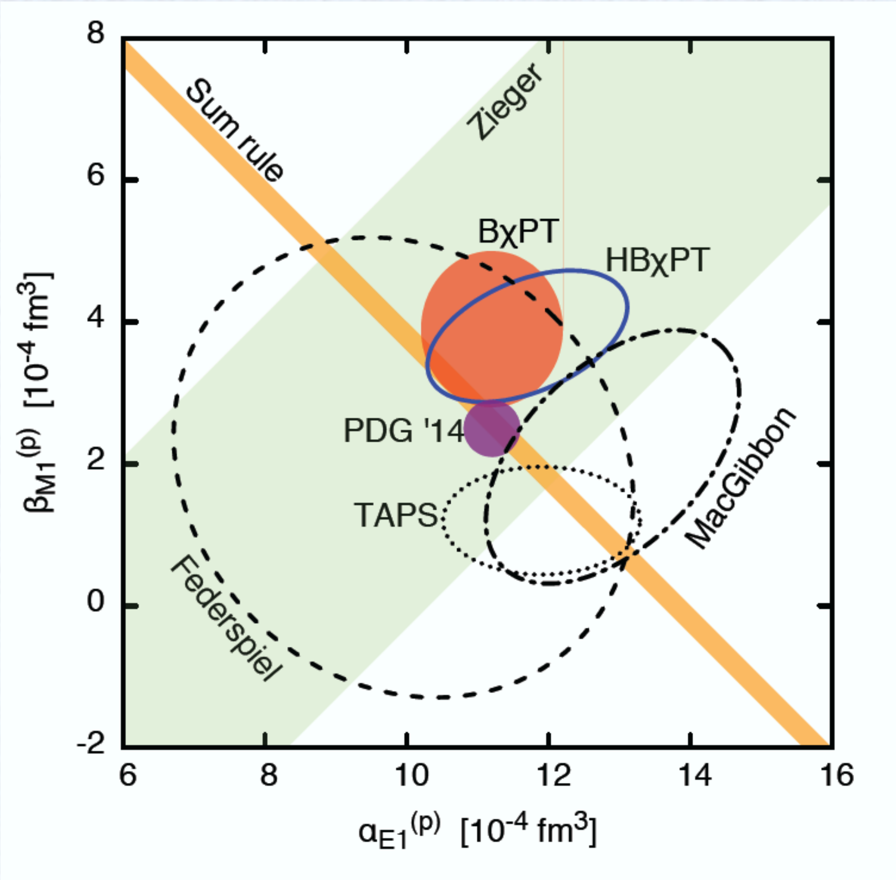
# Lamb shift: hadronic corrections (II)

- low-energy expansion of forward, doubly virtual Compton scattering contains a subtraction term $T_1(0,Q^2)$

effective Hamiltonian:

$$\mathcal{H} = -\frac{1}{2} 4\pi\alpha_E \vec{E}^{\,2} - \frac{1}{2} 4\pi\beta_M \vec{B}^{\,2}$$

electric, magnetic polarizabilities




Theory analyses:

**BChPT**
Lensky, Pascalutsa (2010)

**HBChPT**
Griesshammer, McGovern, Phillips (2013)

**PDG '14 values:**

$\alpha_E$ = (11.2 ± 0.2) × $10^{-4}$ fm$^3$

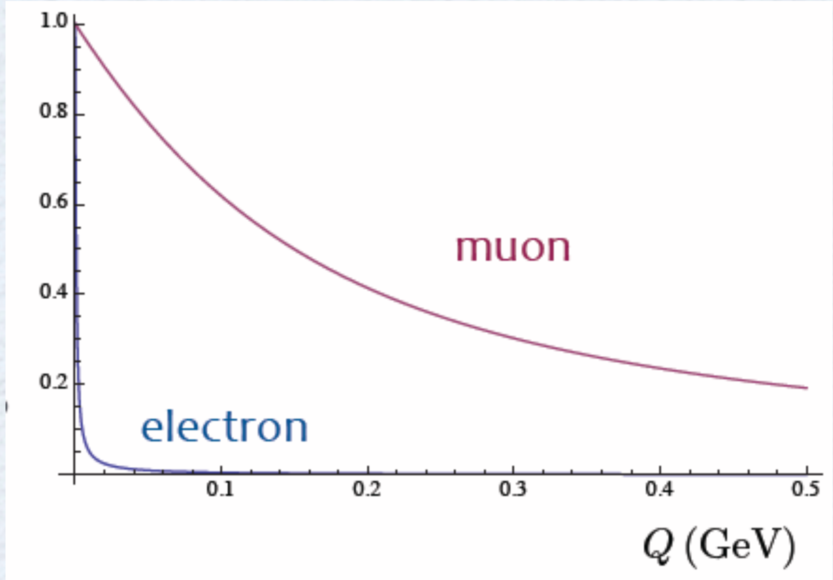
$\beta_M$ = ( 2.5 ± 0.4) × $10^{-4}$ fm$^3$

- subtraction term $T_1(0,Q^2)$

$$T_1^{\mathrm{non-Born}}(0,Q^2) = \frac{Q^2}{e^2}\beta_M + \mathcal{O}(Q^4)$$

$$T_2^{\mathrm{non-Born}}(0,Q^2) = \frac{Q^2}{e^2}(\alpha_E + \beta_M) + \mathcal{O}(Q^4)$$

weighting function in Lamb shift




next order terms: calculable in chiral perturbation theory

Nevado, Pineda (2008) ; Birse, McGovern (2012); Alarcon, Lensky, Pascalutsa (2014)

# Lamb shift: hadronic corrections summary

polarizability correction on 2S level in μH

dispersive estimates

HBChPT

HBChPT + dispersive

BChPT

| (μeV) | Pachucki [9] | Martynenko [10] | Nevado and Pineda [11] | Carlson and Vanderhaeghen [12] | Birse and McGovern [13] | Gorchtein et al. [14] | LO-B$\chi$PT [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).

[LO-BχPT] Alarcon, Lensky, Pascalutsa, EPJC (2014) 74:2852


**total hadronic correction on Lamb shift**

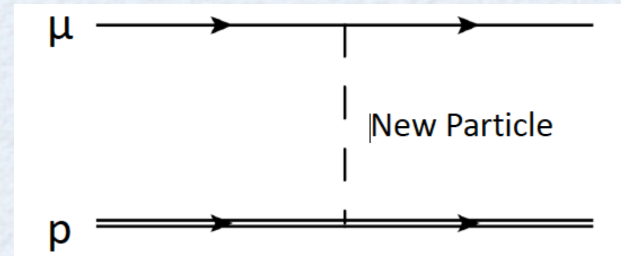
$\Delta E_{(2P-2S)} = (33 \pm 2)\ \mu\mathrm{eV}$

...or about 11% of needed correction

# Proton radius puzzle: new physics ?

➡ new **muonic forces** ?

lepton universality-violating models

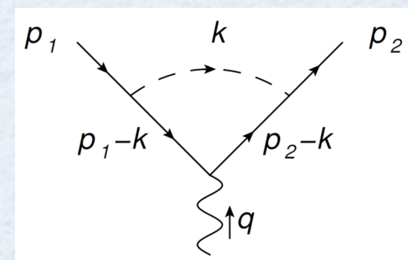



invoking exchange of

hypothetical light boson

**challenge**: new physics must also

respect $(g-2)_\mu$ discrepancy




simultaneously explain 1 ppm

and $10^4$ ppm discrepancies !!!

Tucker-Smith Yavin (2010)

Barger,Chiang, Keung, Marfiata (2011)

➡ parity-violating muonic forces (V and A)

fine tuning between V and A coupling to muon

$$\mathcal{L}_{\rm int} = -V_\nu[\kappa J_\nu^{\rm em} - \bar{\psi}_\mu(g_V\gamma_\nu + g_A\gamma_\nu\gamma_5)\psi_\mu]$$

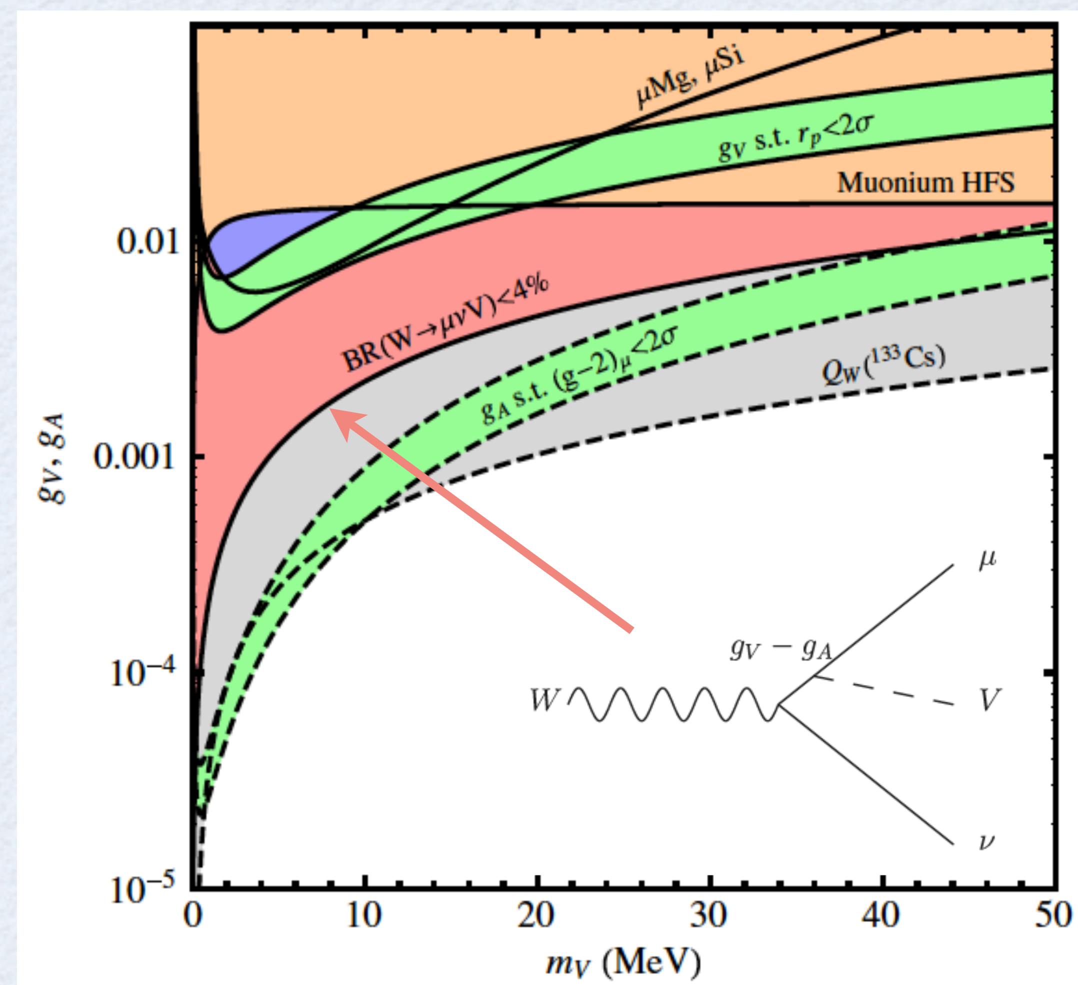
all leptons

V and A coupling to muons

Batell, McKeen, Pospelov (2011)

Carlson, Rislow (2012)

Karshenboim, McKeen, Pospelov (2014)




strong constraint from leptonic W decay

embedding in a renormalizable theory required

Carlson, Freid (in progress)

# Proton radius puzzle: what's next ?

- $\mu H$ Lamb shift: muonic D, muonic $^3He$, $^4He$ have been performed
- electronic H Lamb shift: higher accuracy measurements underway
- electron scattering analysis: Lorenz et al.
  - radius extraction fits (use fits with correct analytical behavior: $2\pi$ cut)
  - radiative corrections, two-photon exchange corrections

  new fit $R_E = 0.904\ (15)$ fm ($4\sigma$ from $\mu H$) Lee, Arrington, Hill (2015)
- electron scattering experiments:

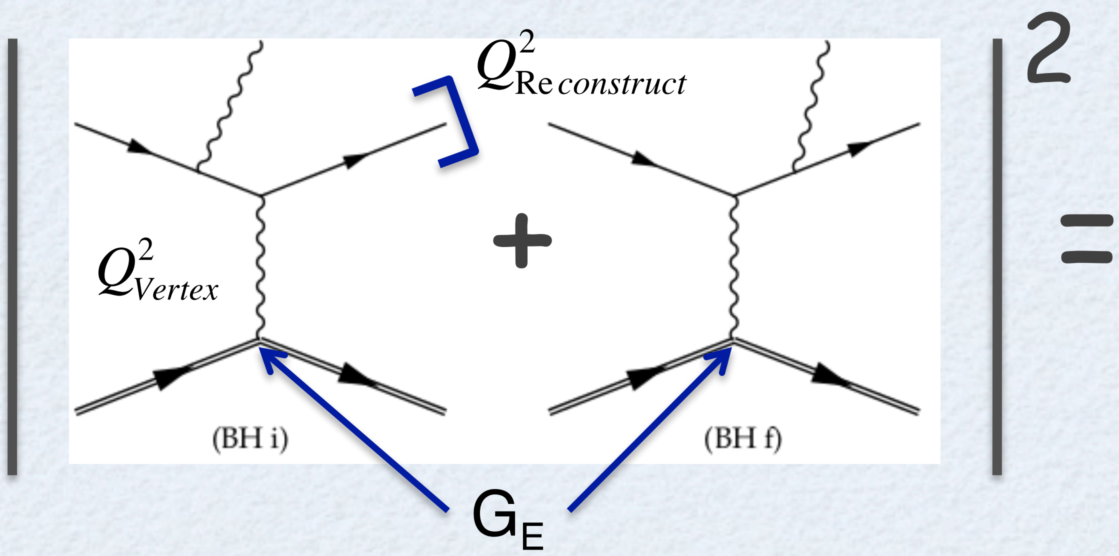
  new $G_{Ep}$ experiments down to $Q^2 \approx 2 \times 10^{-4}$ GeV$^2$

  - MAMI/A1: Initial State Radiation (2013/4)
  - JLab/Hall B: HyCal, magnetic spectrometer-free experiment, norm to Møller (2016/7)

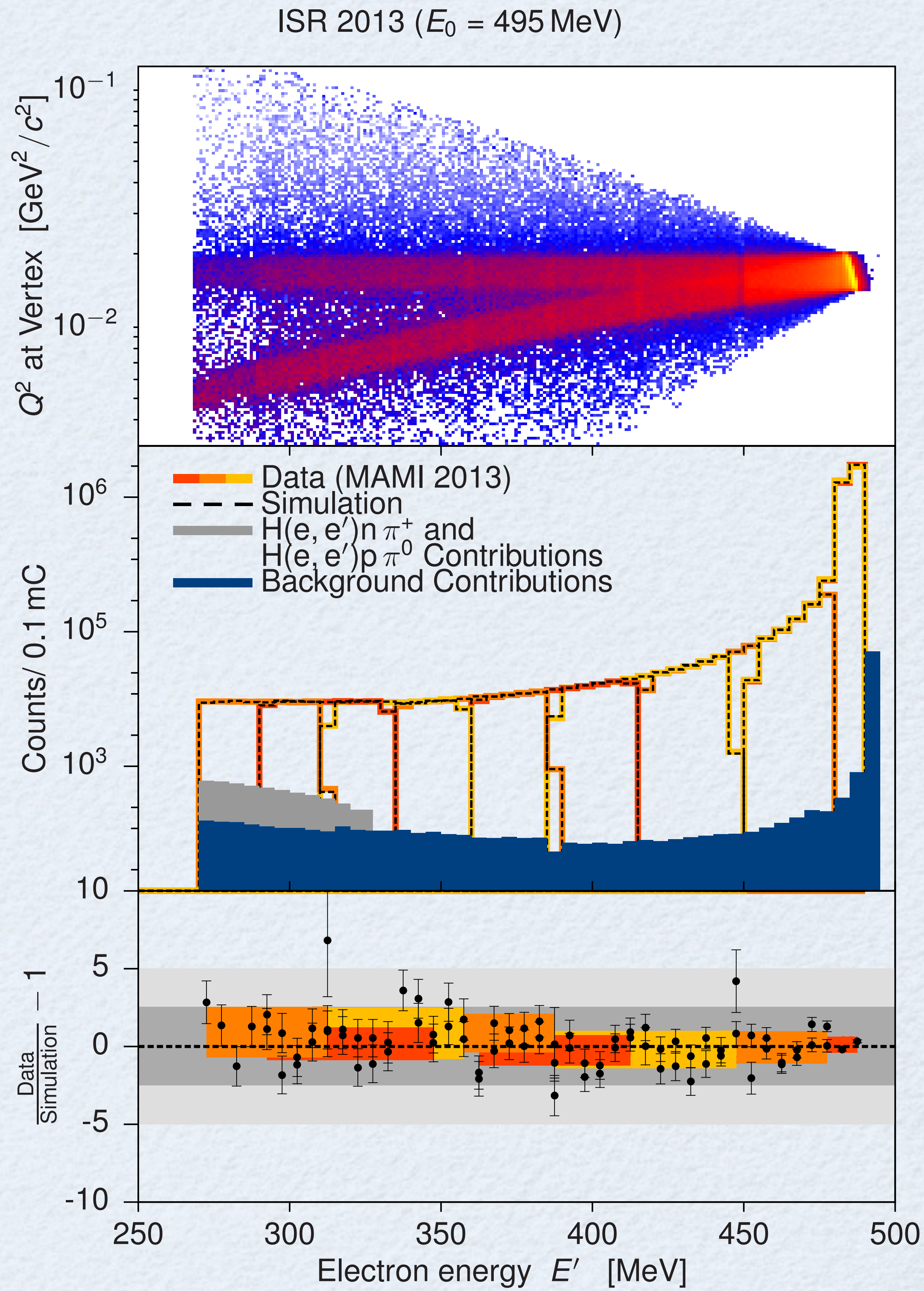
    see talk: H. Gao
  - MESA: low-energy, high resolution spectrometers (2019)
- muon scattering experiments: MUSE@PSI (2017/8)
- $e^-e^+$ versus $\mu^-\mu^+$ photoproduction: lepton universality test

# ISR@MAMI experiment

- **Extracting FFs from the radiative tail.**
- Radiative tail dominated by coherent sum of two Bethe-Heitler diagrams.




- In data ISR can not be distinguished from FSR. **Combining data with the simulation, $G_e^p$ at $Q^2 \sim 10^{-4}$ (GeV/c)$^2$ reached**.
- Experiment performed in 2013.
- Preliminary results at high $Q^2$ demonstrate <u>2% agreement</u> in a region with known FFs.




Mihovilovic et al.(2015)

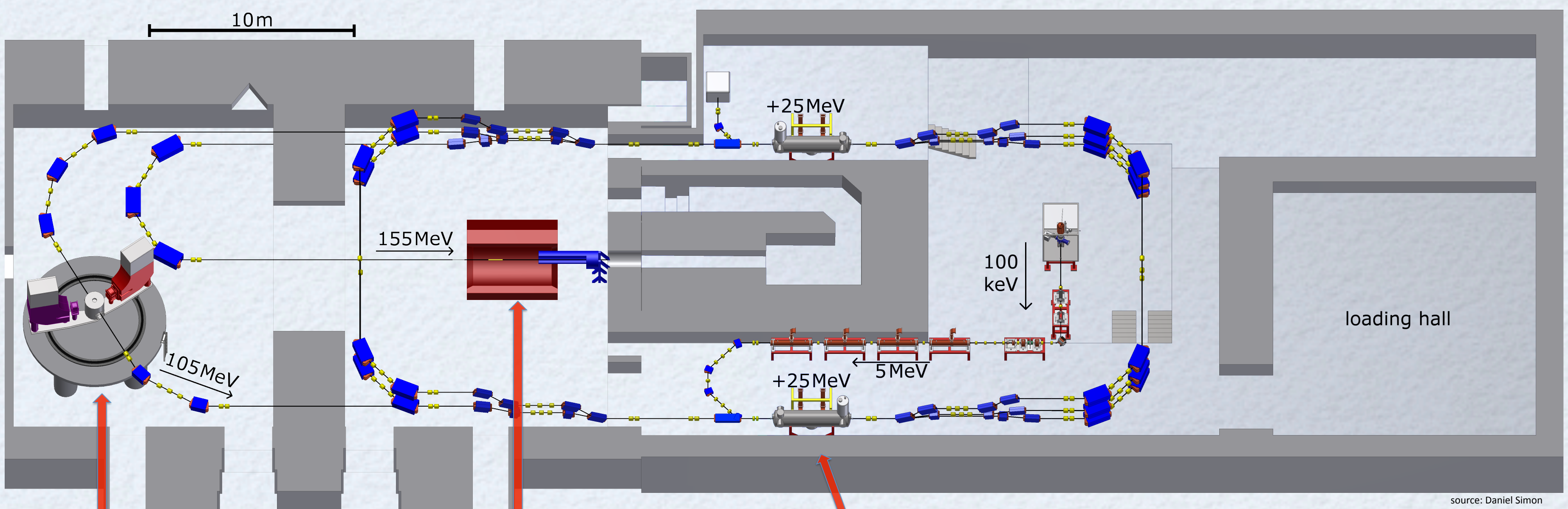
# MESA: Mainz Energy Recovering Superconducting Accelearator

## Key data

- polarized beam: 150 µA & 155 MeV for external target in non energy recovery mode (EB)
- unpolarized beam: 10 mA & 105 MeV for internal target in energy recovery mode (ER)
- normalized emittance < 1 mm
- 2 cryomodules, 2 superconducting 9-cell cavities each
- expected commissioning: 2018

## Current status

- cryomodules ordered and under construction
- lattice design advancing
- most architectural challenges solved
- radiation protection simulations finished
- preparing tender for magnets, power supplies, vacuum system, etc.

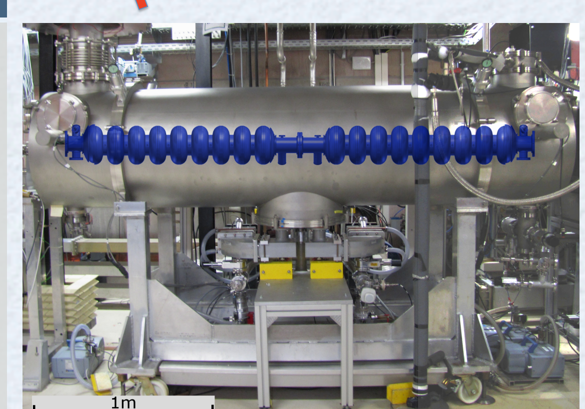



## Internal target *MAGIX*

- search for the dark photon, proton radius, polarizabilities, few-body physics program
- hydrogen gas target
- luminosity ~ $10^{34}\,cm^{-2}s^{-1}$
- works in ER mode

## External target *P2*

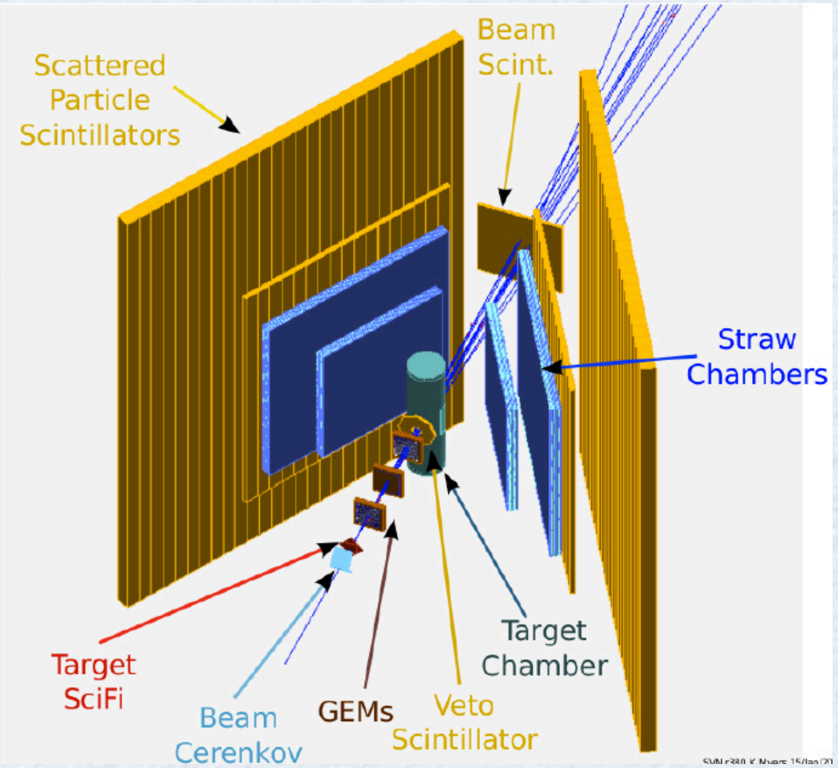
- precise measurement of Weinberg angle
- measurement of lead neutron skin
- liquid hydrogen / lead target
- luminosity ~ $10^{39}\,cm^{-2}s^{-1}$
- works in EB mode




## Modified ELBE-type

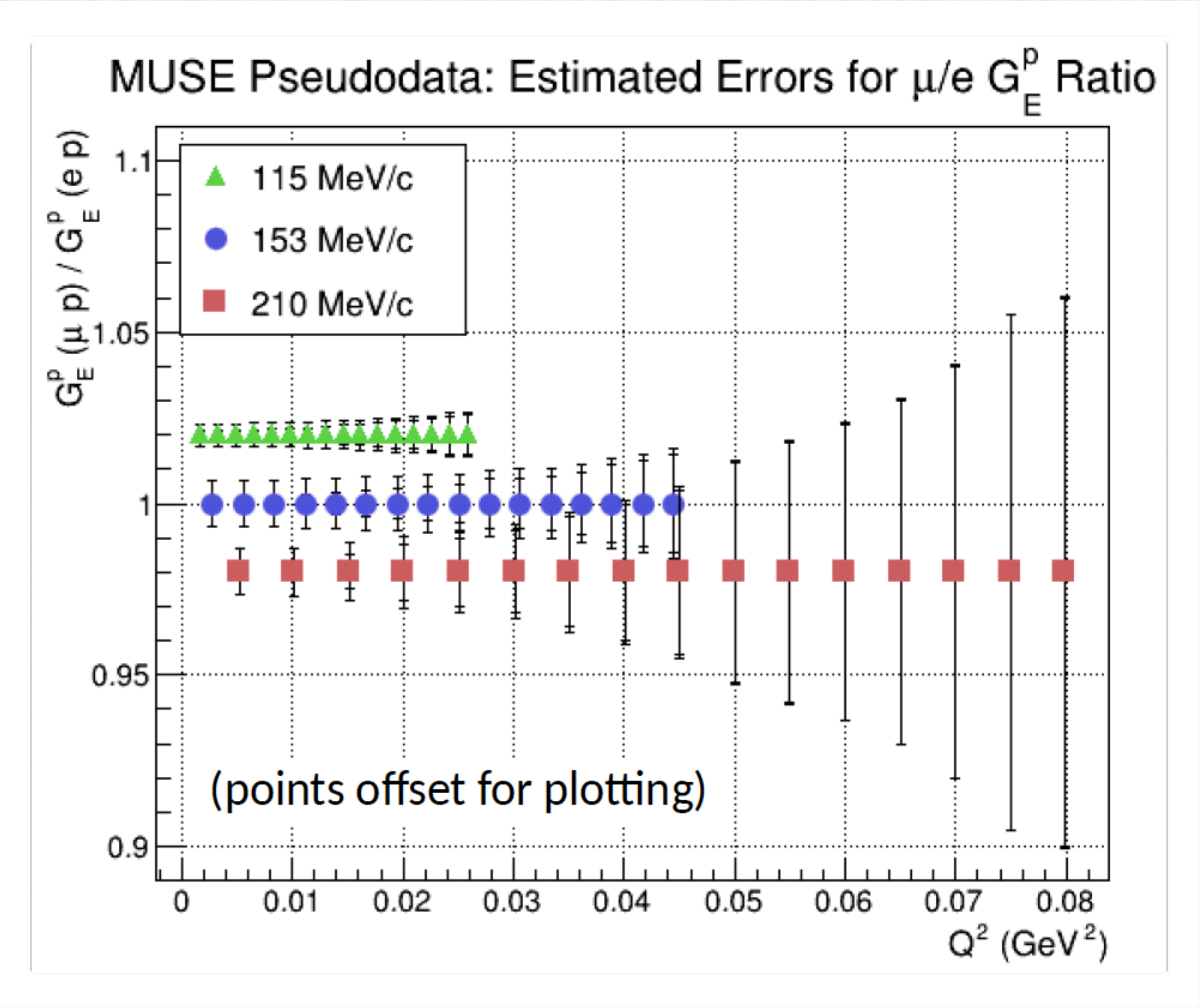
- TESLA/XFEL cavities
- 25 MeV energy gain per cryomodule
- cryogenic loss: 40 W at 4 K
- 3 passes in EB mode
- 2x2 passes in ER mode

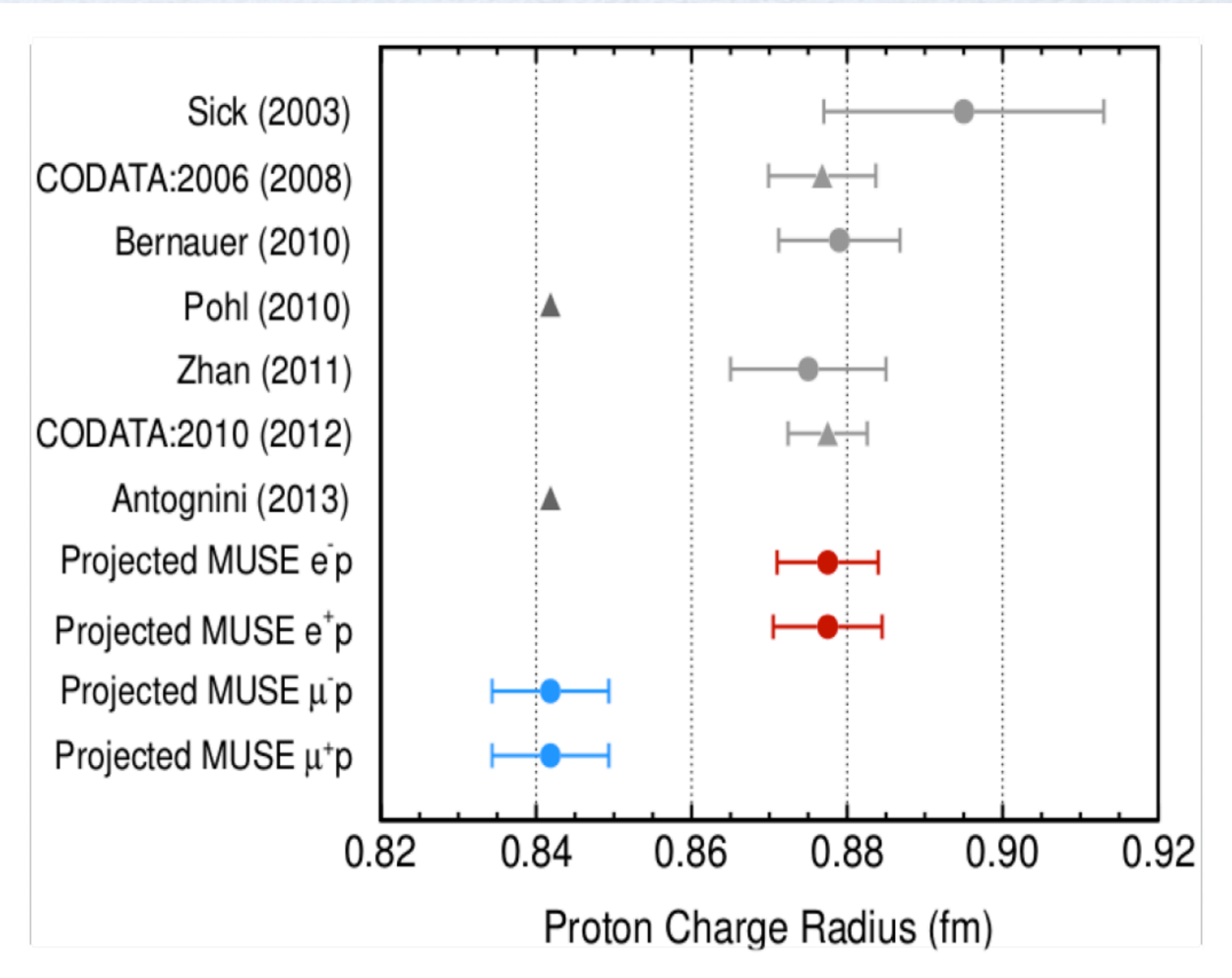
# MUSE@PSI experiment




simultaneous measurement of ***e*** and **μ**

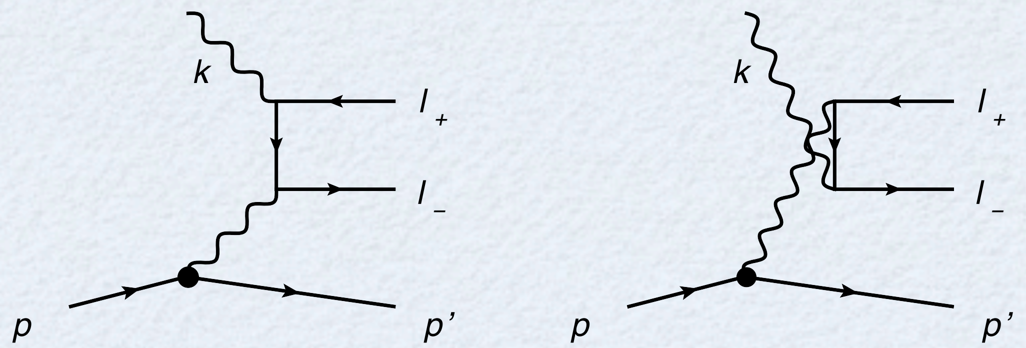
elastic scattering absolute cross sections



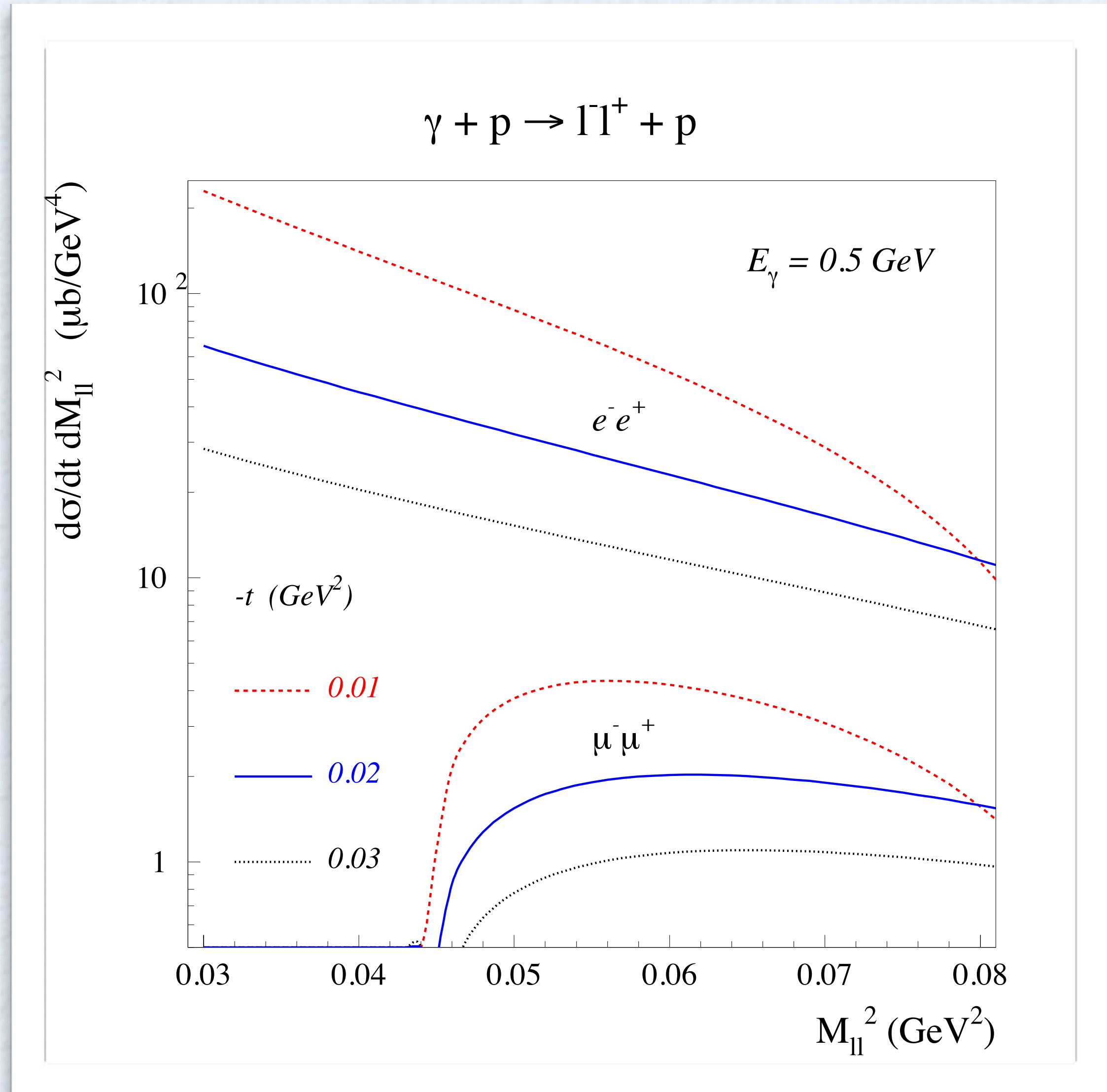

production run planned 2017 - 2018

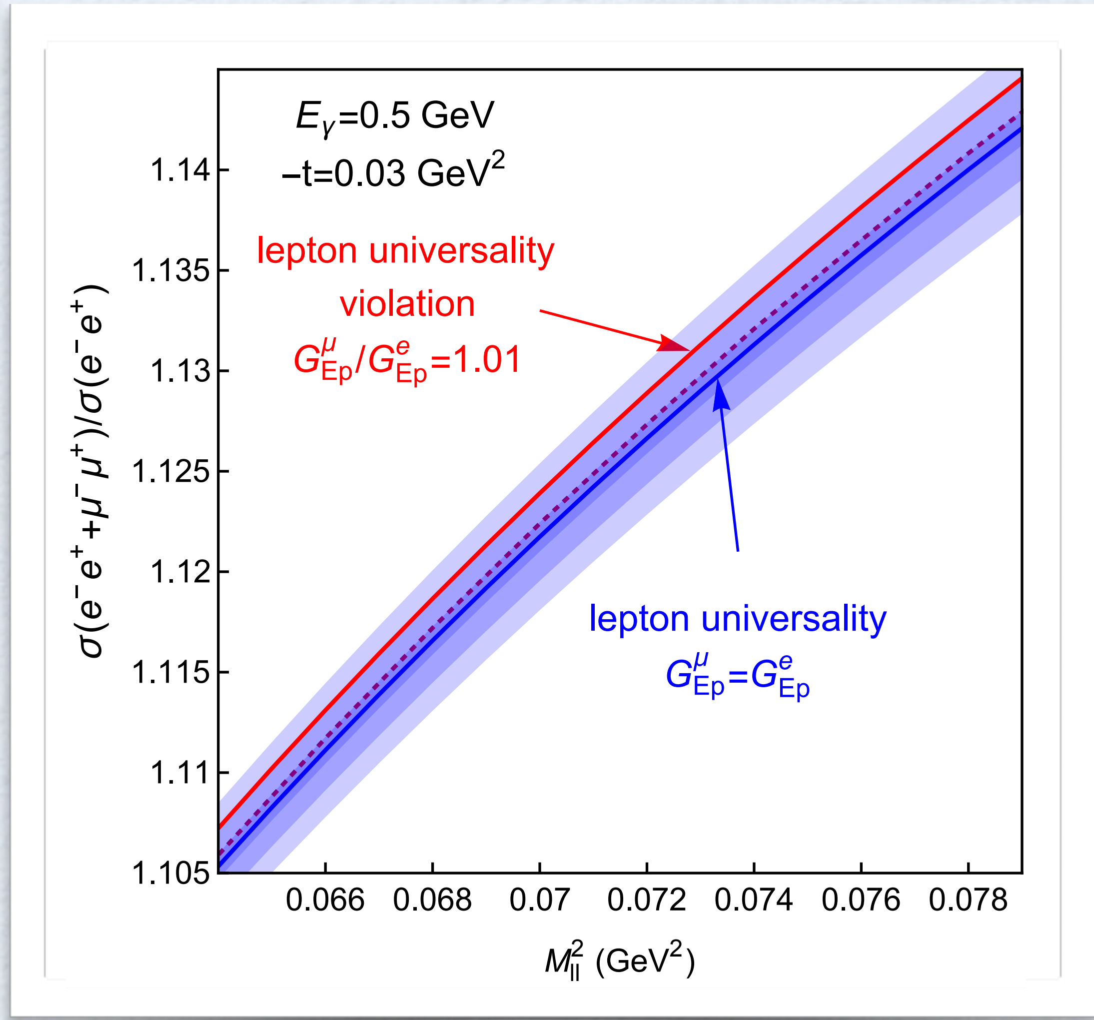
# Lepton universality test in $\gamma p \to e^- e^+ p$ vs $\gamma p \to \mu^- \mu^+ p$




$M_{ll}^2 = (l_- + l_+)^2$

$t = (p' - p)^2$



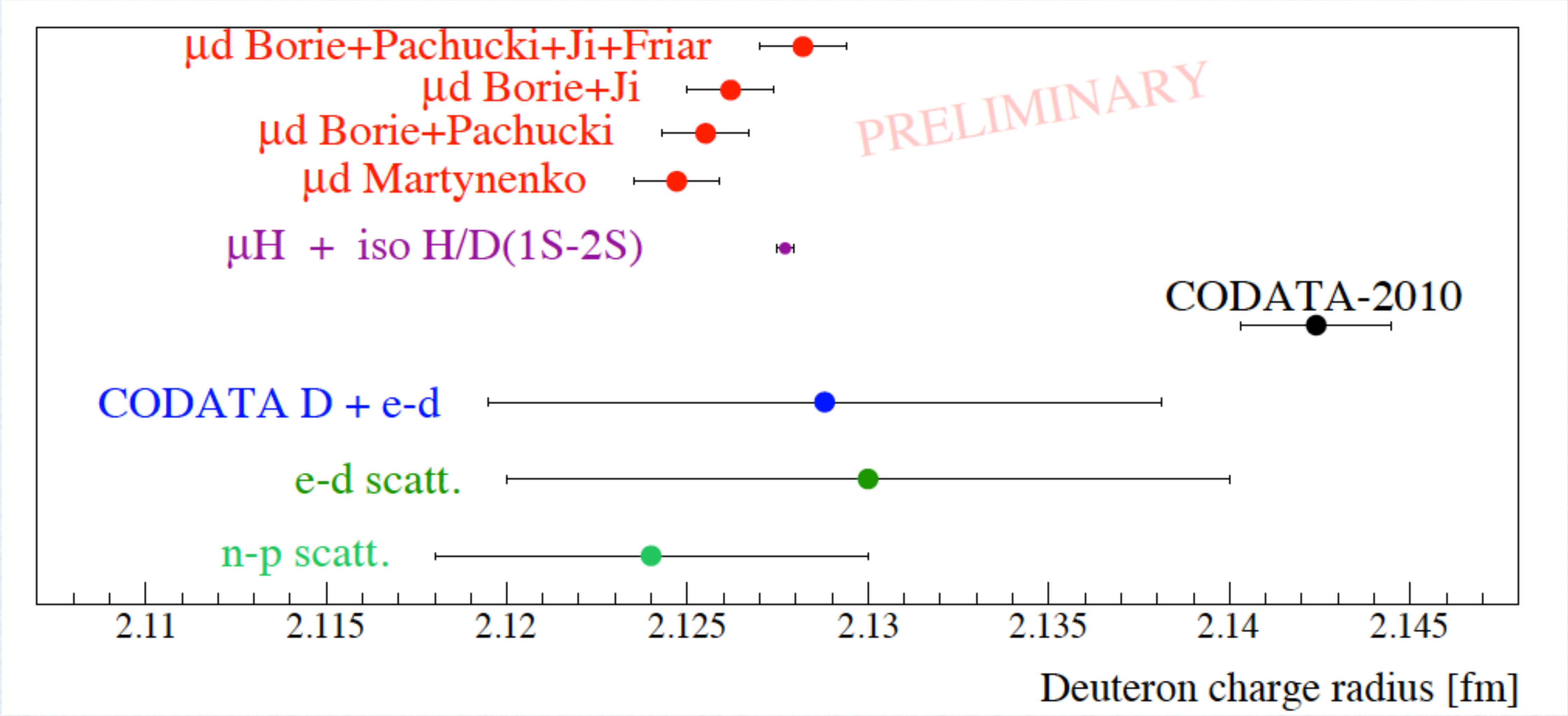

difference in measured proton charge FF in electron vs muon observables leads to a **0.2% absolute effect** in $(e^-e^+ + \mu^-\mu^+)$ vs $\mu^-\mu^+$ ratio

Pauk,Vdh(2015)

# μD Lamb shift experiment

- H/D isotope shift (1S - 2S): $r_d^2 - r_p^2 = 3.82007 \pm 0.00065\ fm^2$ Parthey et al. (2010)

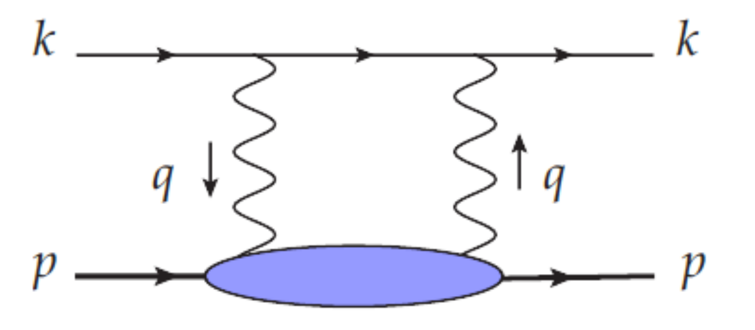
- new μD Lamb shift experiment performed @ PSI




- caveat: error bar for μD does not include polarization correction
- new radius measurement from e-d scattering was performed @ MAMI (2014)
  factor 2 improvement expected

# Polarization correction for μD Lamb shift

- **polarization correction needs to be controlled to extract deuteron charge radius**




| Ref. | $\Delta E^{(\text{structure})}_{2P-2S}$ (meV) |
|---|---|
| Pachucki (AV18) (2011) | 1.680(16) |
| Friar (zero range approximation) (2013) | 1.697(19) |
| Hernandez et al. (AV18, $N^3LO$) (2014) | 1.709(20) |
| Pachucki, Wienczek (2015) | 1.707(20) |
| Krauth et al. (2015) | 1.709(15) |
| Gorchtein et al. (2014) | 1.748(740) |

potential models

compilation of potential models

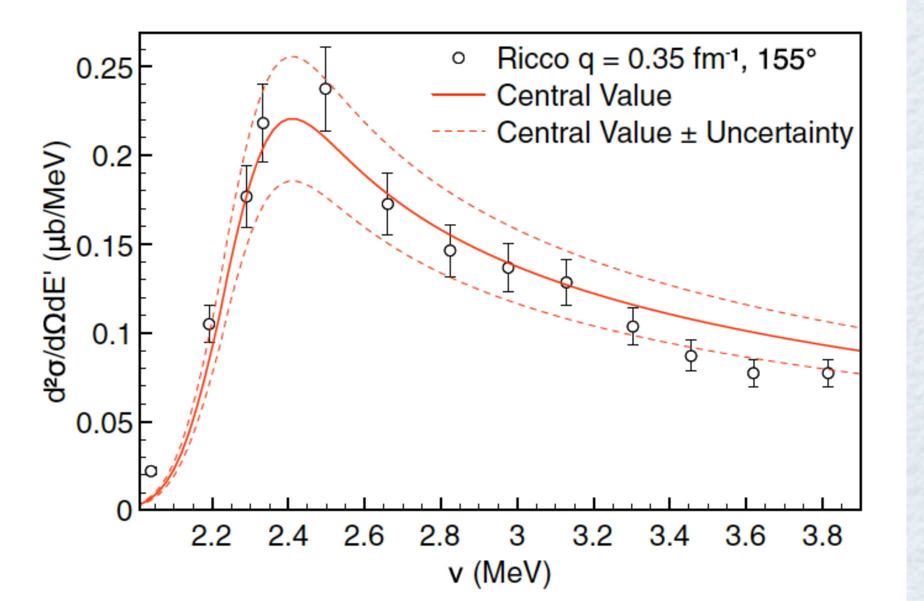
data based: dispersive analysis

- **Experimental check of polarization correction:**

$$e + d \to e + p + n$$

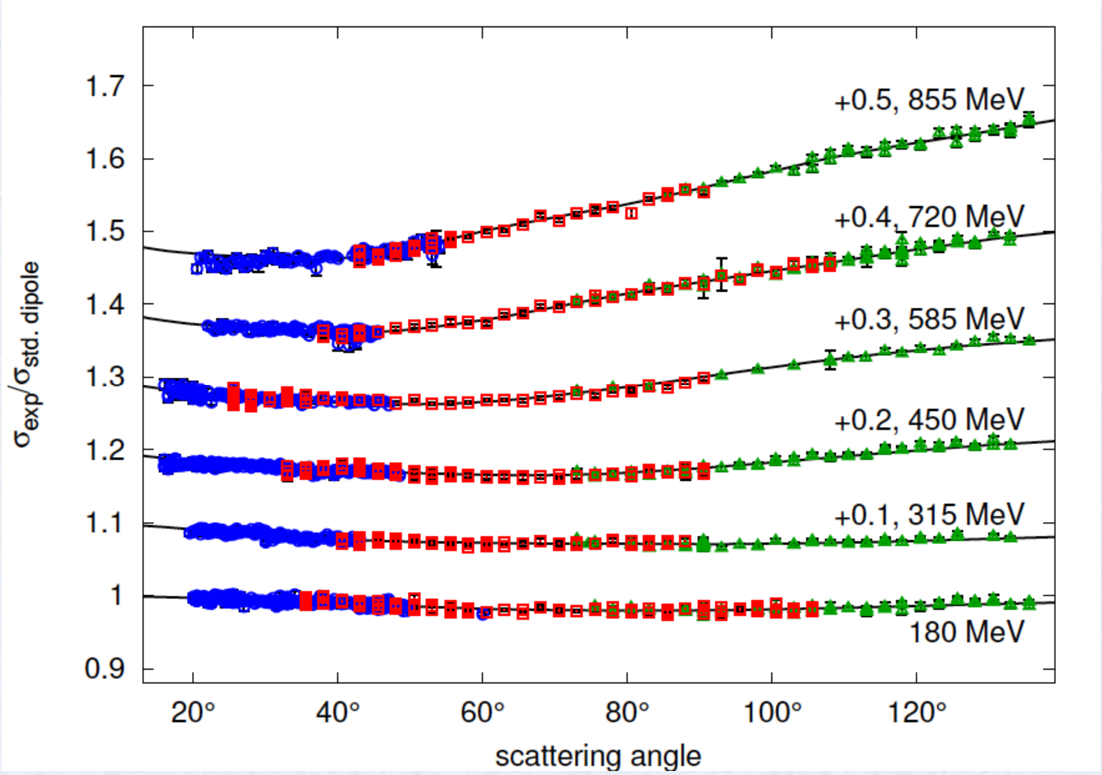
- can be related using a dispersive analysis to deuteron FFs, unpolarized structure functions, polarizabilities
- present fit to world data yields large uncertainty (740 μeV)
- nearly all uncertainty at present arises from deuteron threshold disintegration region

$$\langle Q^2 \rangle = 0.003 - 0.006 \ (\text{GeV/c})^2$$
$$\langle \nu \rangle = 6 - 10 \ \text{MeV}$$

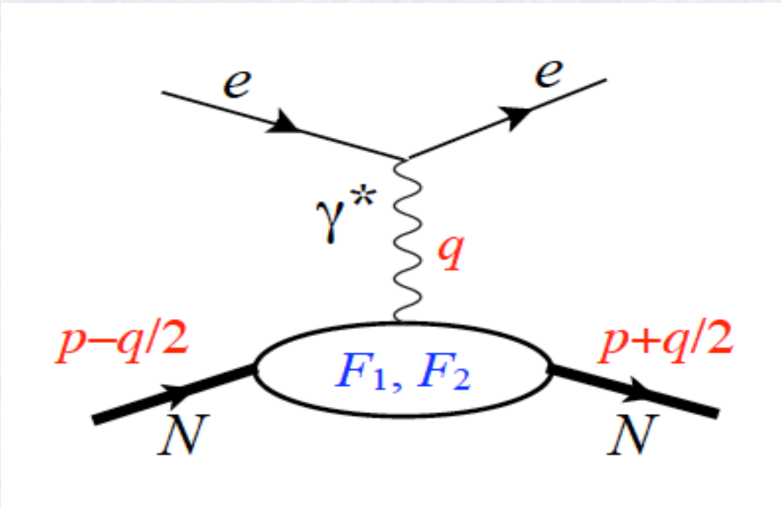



**data needed !**

# Part 2: Proton / Baryon spatial structure




# e⁻ scattering: unpolarized cross sections



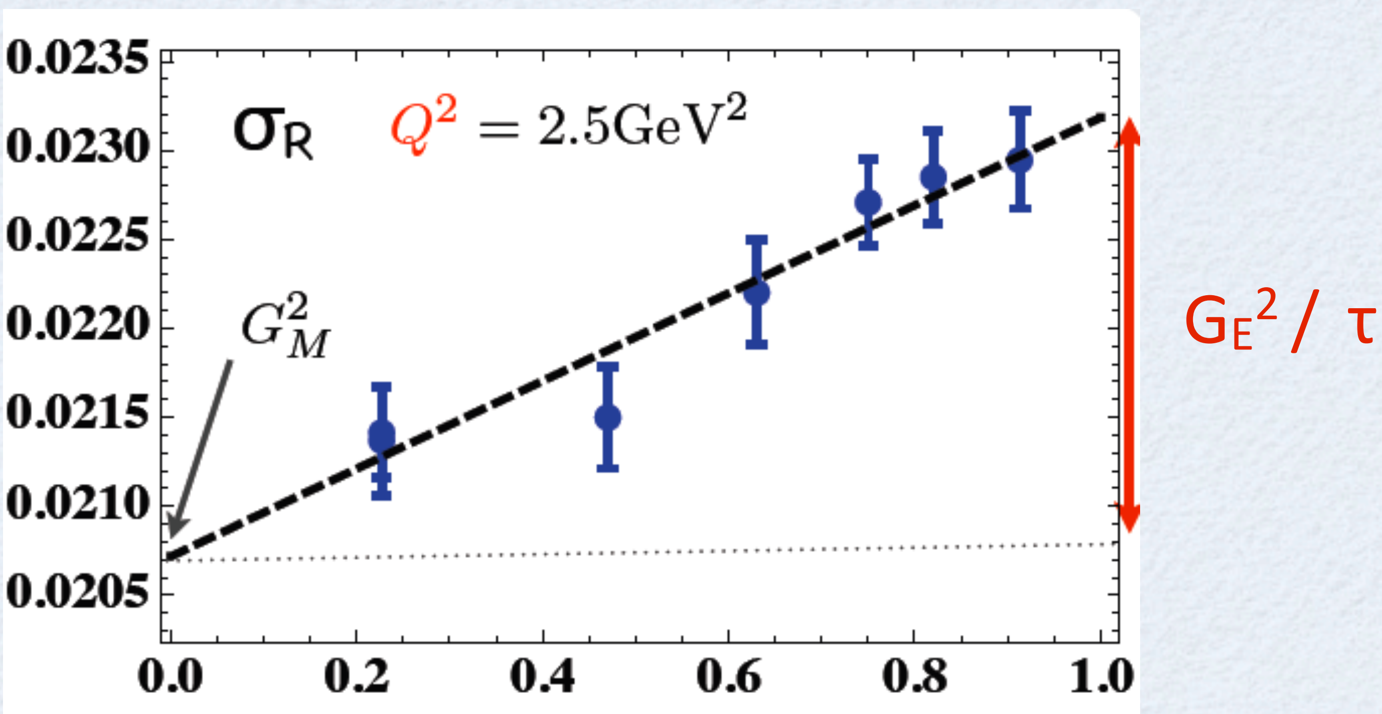

$G_M = F_1 + F_2$

$G_E = F_1 - \tau F_2$

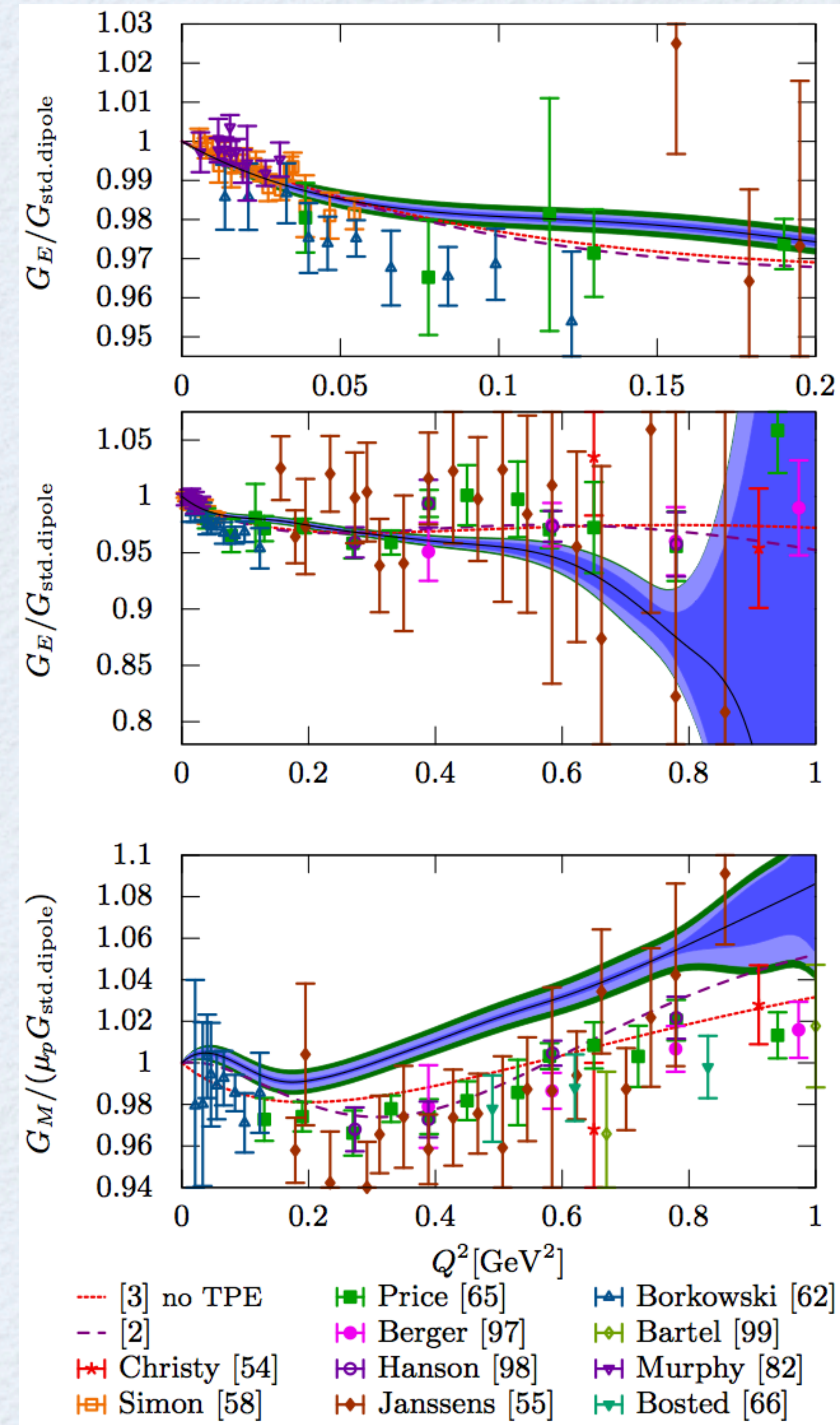
$$\tau \equiv \frac{Q^2}{4M^2} \qquad \frac{1}{\varepsilon} \equiv 1 + 2(1+\tau)\tan^2\frac{\theta}{2}$$

$$\sigma_{\mathrm{R}} = G_M^2 + \frac{\varepsilon}{\tau} G_E^2$$

Rosenbluth separation technique




ε




Andivahis et al.(1994)

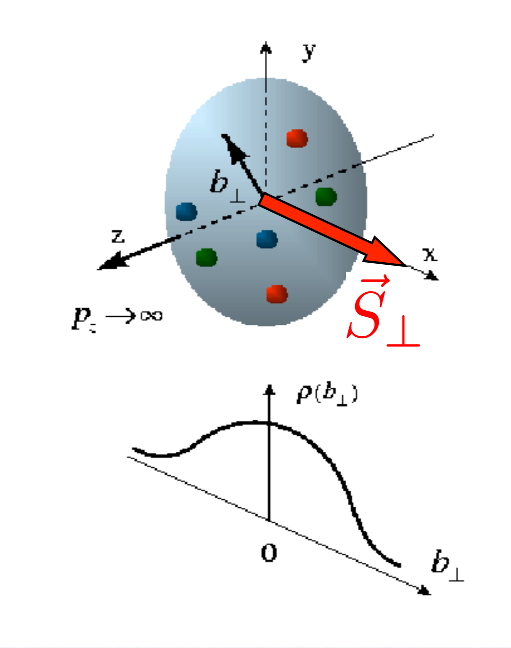
Bernauer et al.(2010, 2013)

# Form factors: 2D light-front densities of hadrons

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

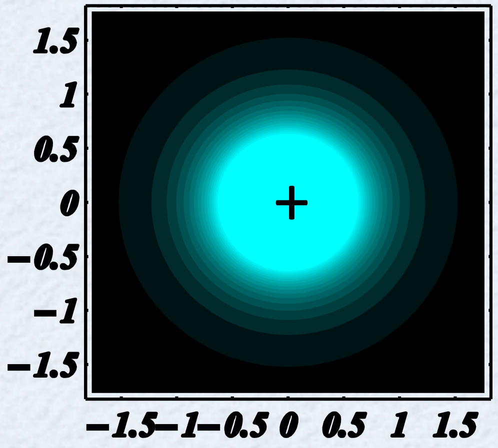
→ unpolarized Dirac FF $F_1$

→ transverse polarization Pauli FF $F_2$

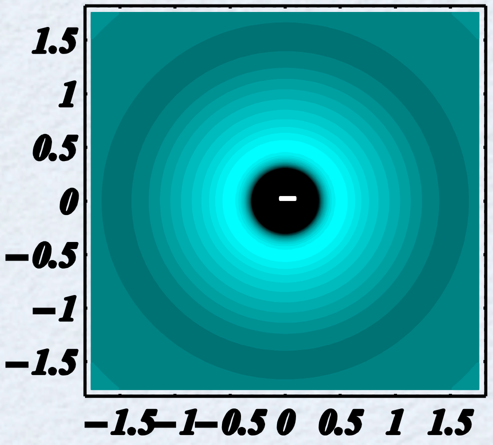



proton | neutron

unpolarized charge density




b (fm)

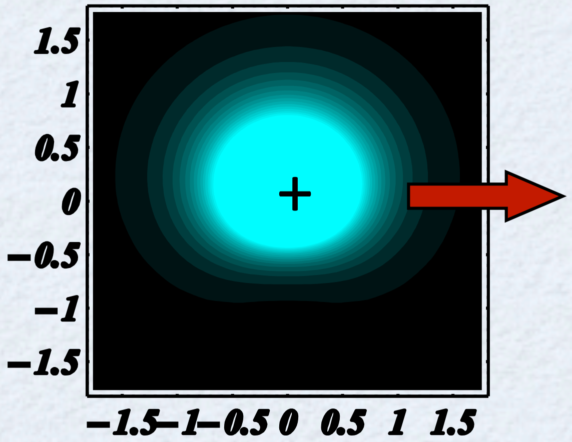


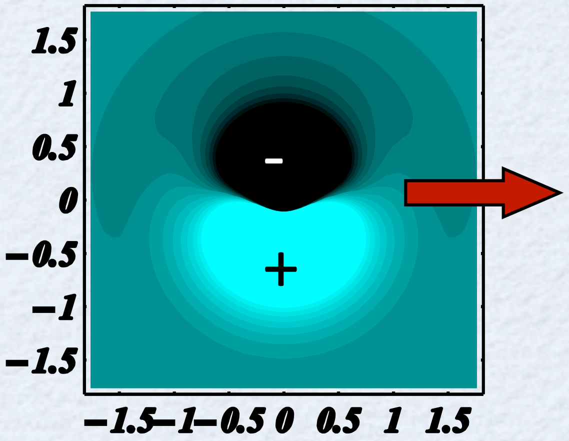

b (fm)

Burkardt (2000,2003)

Miller(2007)

density for transverse polarization



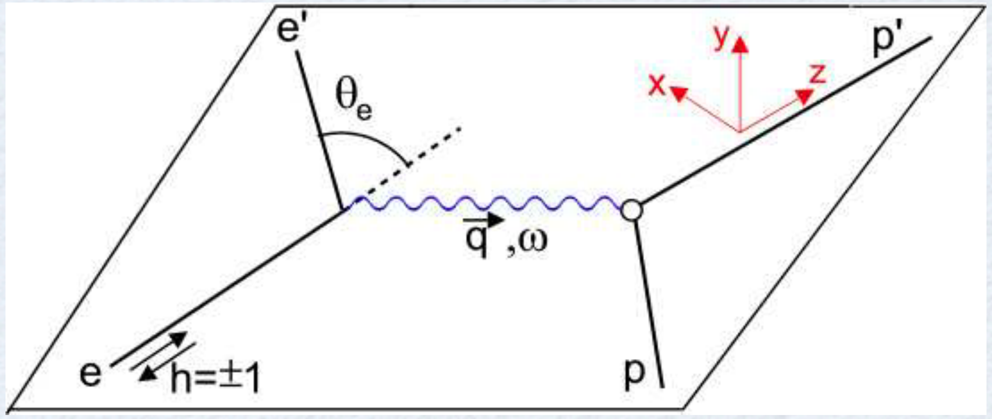




Carlson, Vdh(2008)

# e⁻ scattering: double polarization

$$\vec{e} + p \rightarrow e + \vec{p}$$

Akhiezer, Rekalo (1974)




$$d\sigma_{pol} = d\sigma_{unpol}(1 + h\,S_x\,P_t \;+\; h\,S_z P_l)$$

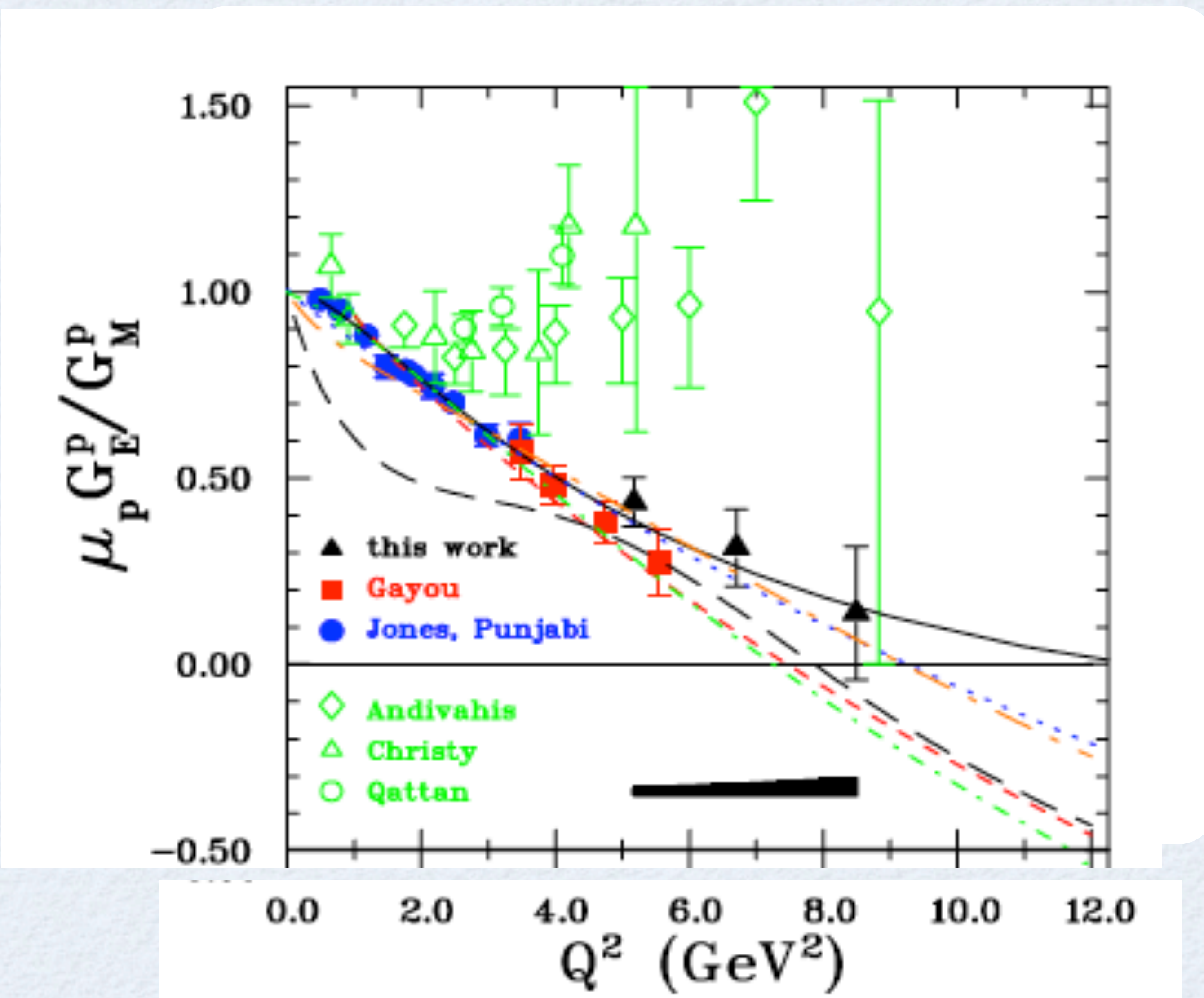
$$P_t = -\sqrt{\frac{2\varepsilon(1-\varepsilon)}{\tau}}\,\frac{G_E G_M}{\tau\,\sigma_{\mathrm{R}}}$$

$$P_l = \sqrt{1-\varepsilon^2}\,\frac{G_M^2}{\tau\,\sigma_{\mathrm{R}}}$$

→

$$\frac{P_t}{P_l} = -\sqrt{\frac{2\varepsilon}{\tau(1+\varepsilon)}}\,\frac{G_E}{G_M}$$

# Rosenbluth vs polarization transfer measurements of $G_E/G_M$ of proton




**Rosenbluth data**

SLAC, JLab (Hall A, C)

**Polarization data**

JLab (Hall A, C)

| | |
|---|---|
| GEpI | Jones et al.(2000) |
| | Punjabi et al.(2005) |
| GEpII | Gayou et al.(2002) |
| GEpIII | Puckett et al.(2010) |

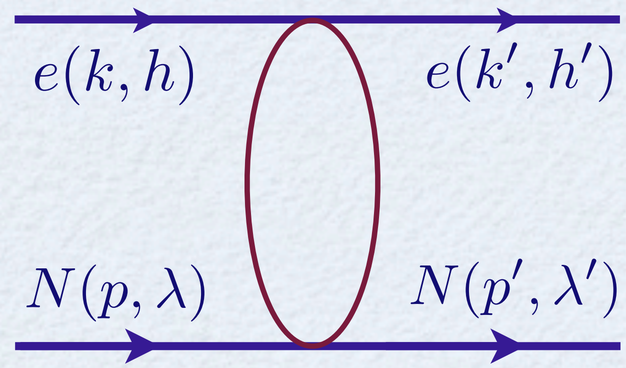
Two methods: two different results

most likely: 2γ-exchange correction

# 2γ-exchange in e⁻ scattering: general

$$P = \frac{p + p'}{2}$$

$$K = \frac{k + k'}{2}$$




$$t = (k - k')^2 \qquad u = (k - p')^2$$

$$s = (p + k)^2 \qquad \nu = \frac{s - u}{4}$$

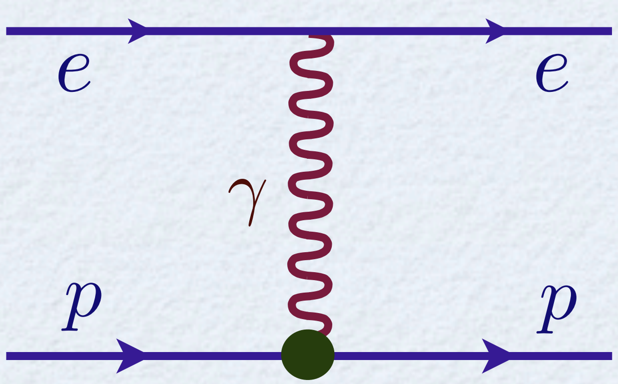
discrete symmetries + $m_e = 0$ → 3 structure amplitudes

$$T = \frac{e^2}{Q^2} \bar{e}(k', h') \gamma_\mu e(k, h) . \bar{N}(p', \lambda') [\mathcal{G}_M(\nu, t) \gamma^\mu - \mathcal{F}_2(\nu, t) \frac{P^\mu}{M} + \mathcal{F}_3(\nu, t) \frac{\hat{K} P^\mu}{M^2}] N(p, \lambda)$$

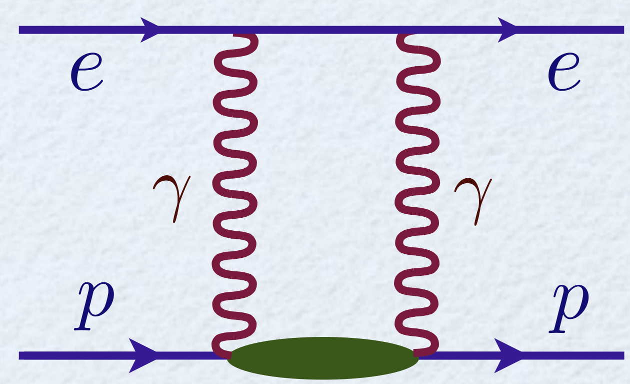
Guichon, Vdh (2003)

Leading contribution to cross section - interference term

1 photon diagram




2 photon exchange diagram




$$\delta_{TPE} \sim \Re \mathcal{G}_M, \Re \mathcal{F}_2, \Re \mathcal{F}_3$$

# observables including 2γ-exchange

$$\tilde{G}_M(\nu, Q^2) = G_M(Q^2) + \delta\tilde{G}_M$$
$$\tilde{F}_2(\nu, Q^2) = F_2(Q^2) + \delta\tilde{F}_2$$
$$\tilde{F}_3(\nu, Q^2) = 0 + \delta\tilde{F}_3$$

for real part:

3 independent observables

$$Y_{2\gamma}^M(\nu, Q^2) \equiv \mathcal{R}\left(\frac{\delta\tilde{G}_M}{G_M}\right)$$
$$Y_{2\gamma}^E(\nu, Q^2) \equiv \mathcal{R}\left(\frac{\delta\tilde{G}_E}{G_M}\right)$$
$$Y_{2\gamma}^3(\nu, Q^2) \equiv \frac{\nu}{M^2}\mathcal{R}\left(\frac{\tilde{F}_3}{G_M}\right)$$

$$\tilde{G}_E \equiv \tilde{G}_M - (1+\tau)\tilde{F}_2$$
$$\tilde{G}_E(\nu, Q^2) = G_E(Q^2) + \delta\tilde{G}_E$$

$$\frac{\sigma_R}{G_M^2} = 1 + \frac{\varepsilon}{\tau}\frac{G_E^2}{G_M^2} + 2\,Y_{2\gamma}^M + 2\varepsilon\frac{G_E}{\tau G_M}\,Y_{2\gamma}^E + 2\varepsilon\left(1 + \frac{G_E}{\tau G_M}\right)Y_{2\gamma}^3 + \mathcal{O}(e^4)$$

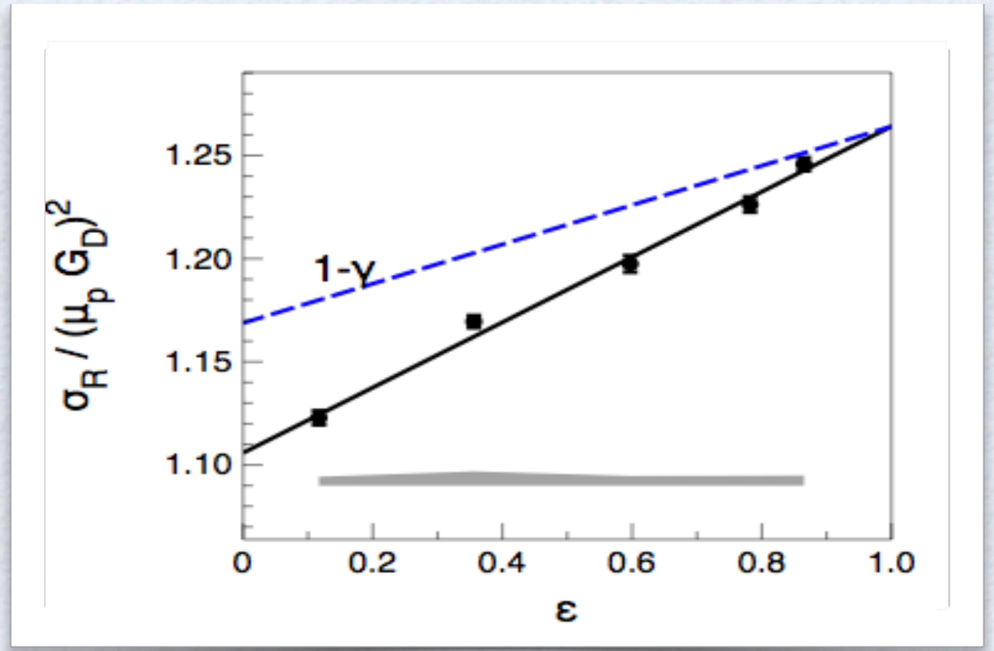
$$-\sqrt{\frac{\tau(1+\varepsilon)}{2\varepsilon}}\frac{P_t}{P_l} = \frac{G_E}{G_M} + Y_{2\gamma}^E - \frac{G_E}{G_M}\,Y_{2\gamma}^M + \left(1 - \frac{2\varepsilon}{1+\varepsilon}\frac{G_E}{G_M}\right)Y_{2\gamma}^3 + \mathcal{O}(e^4)$$

$$\frac{P_l}{P_l^{Born}} = 1 - 2\varepsilon\left(1 + \frac{\varepsilon}{\tau}\frac{G_E^2}{G_M^2}\right)^{-1}\left\{\left[\frac{\varepsilon}{1+\varepsilon}\left(1 - \frac{G_E^2}{\tau G_M^2}\right) + \frac{G_E}{\tau G_M}\right]Y_{2\gamma}^3 + \frac{G_E}{\tau G_M}\left[Y_{2\gamma}^E - \frac{G_E}{G_M}Y_{2\gamma}^M\right]\right\} + \mathcal{O}(e^4)$$

# extraction of 2γ-amplitudes: data

Rosenbluth data: JLab (Hall A)

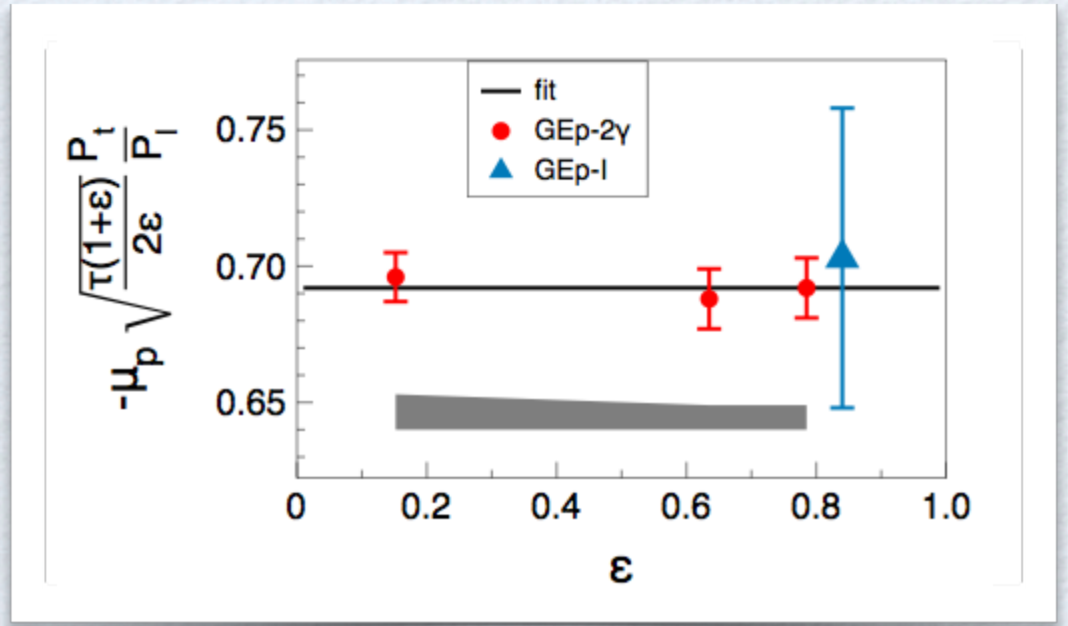
$Q^2 = 2.64\ \mathrm{GeV}^2$

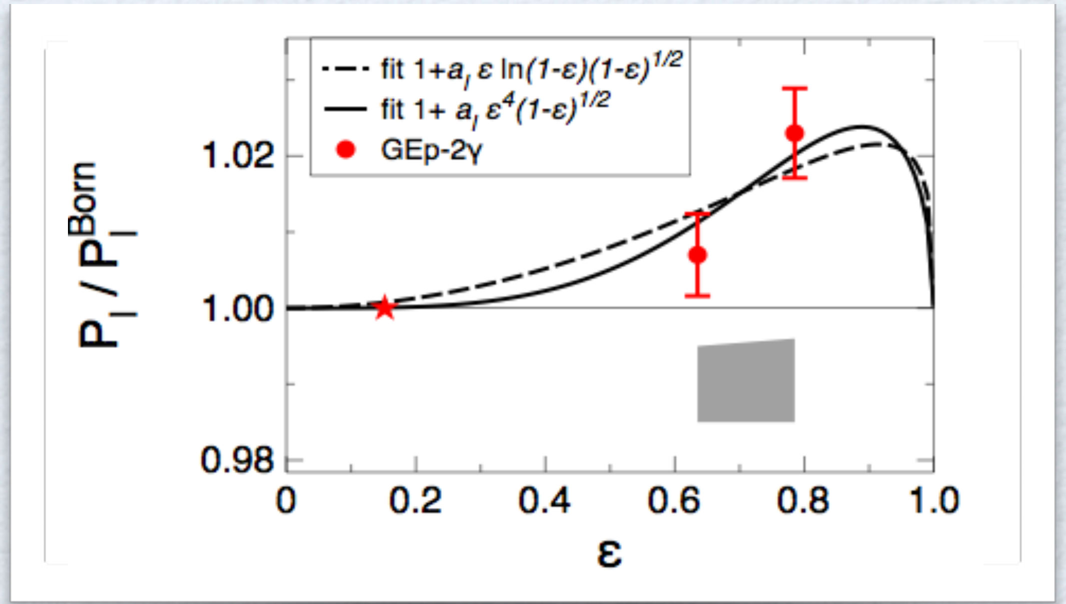



Qattan et al. (2005)

Polarization data: JLab (Hall C)

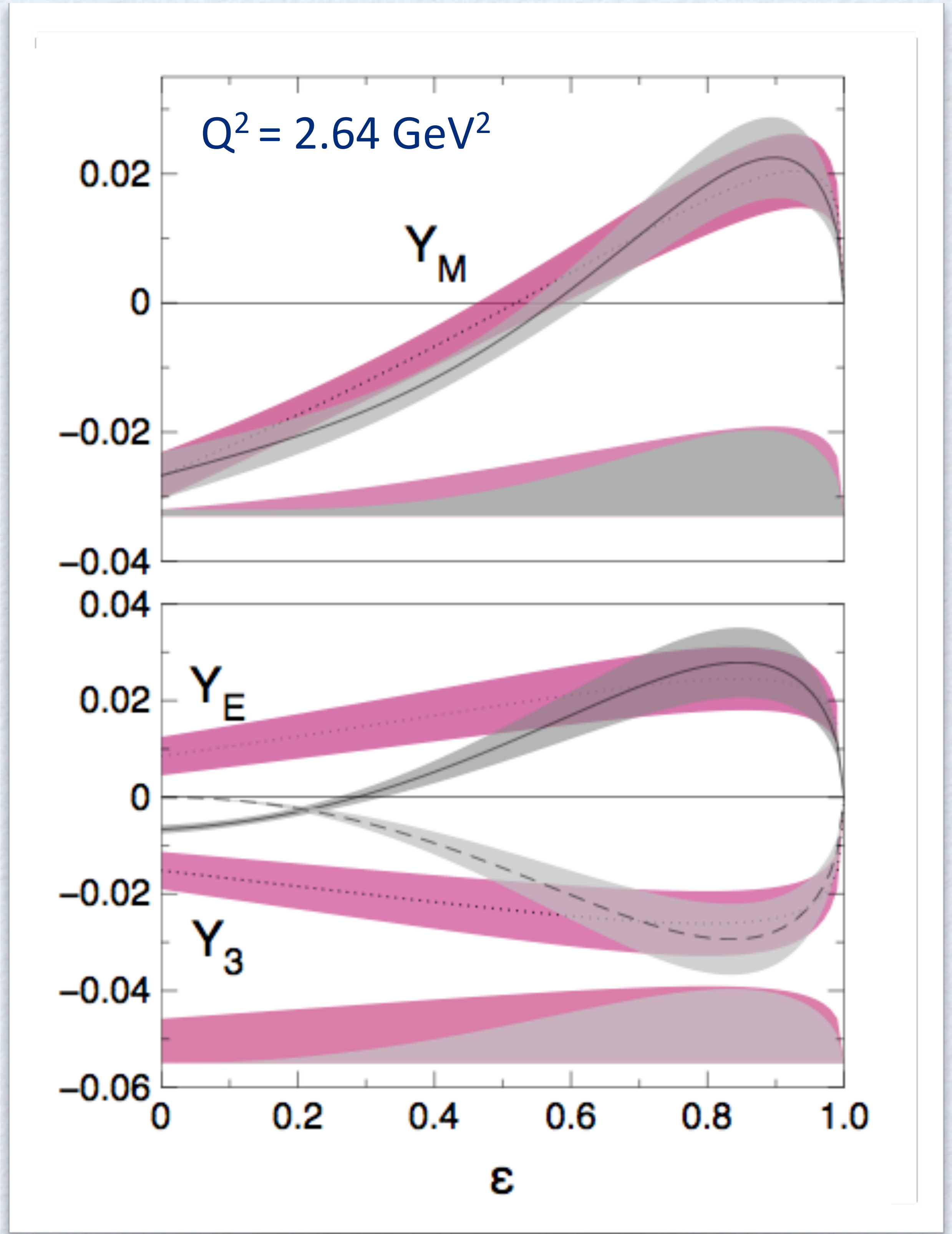
$Q^2 = 2.5\ \mathrm{GeV}^2$

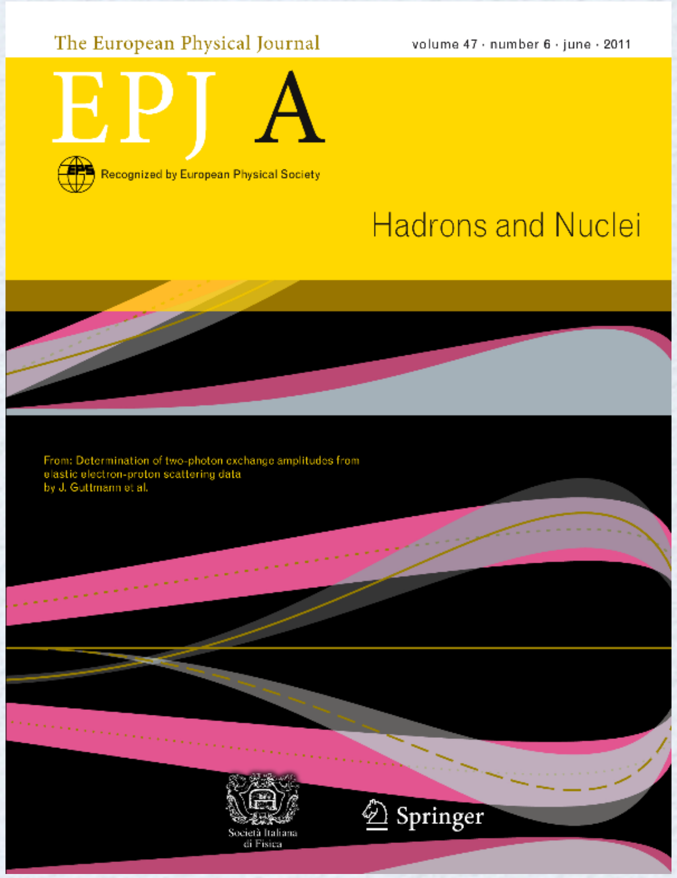



Meziane et al. (2011)

# extraction of 2γ-amplitudes: fit

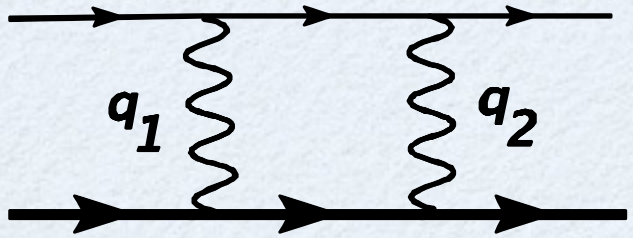



Guttmann, Kivel, Meziane, Vdh (2011)

→ extracted 2γ amplitudes are in the (expected) 2-3 % range

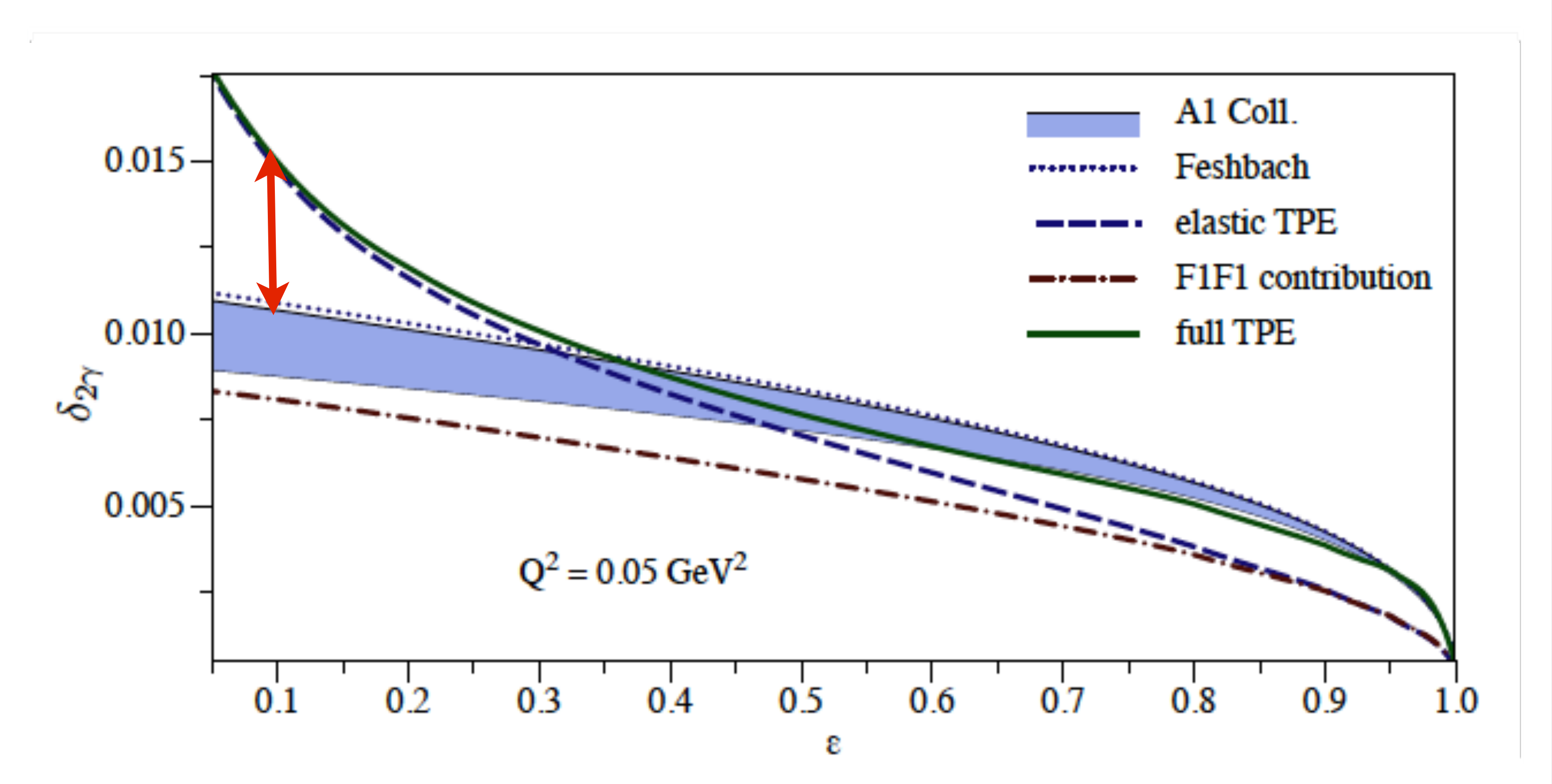
# 2γ-exchange in e⁻p elastic scattering




N, πN,...

- box graph model (on-shell vertices) Blunden, Melnitchouk, Tjon (2003, 2005)
- unsubtracted DR formalism Borisyuk, Kobushkin (2008)
- subtracted DR formalism, inelastic states Tomalak, Vdh (2014), ...

present deviation relevant for a precise extraction of magnetic radius

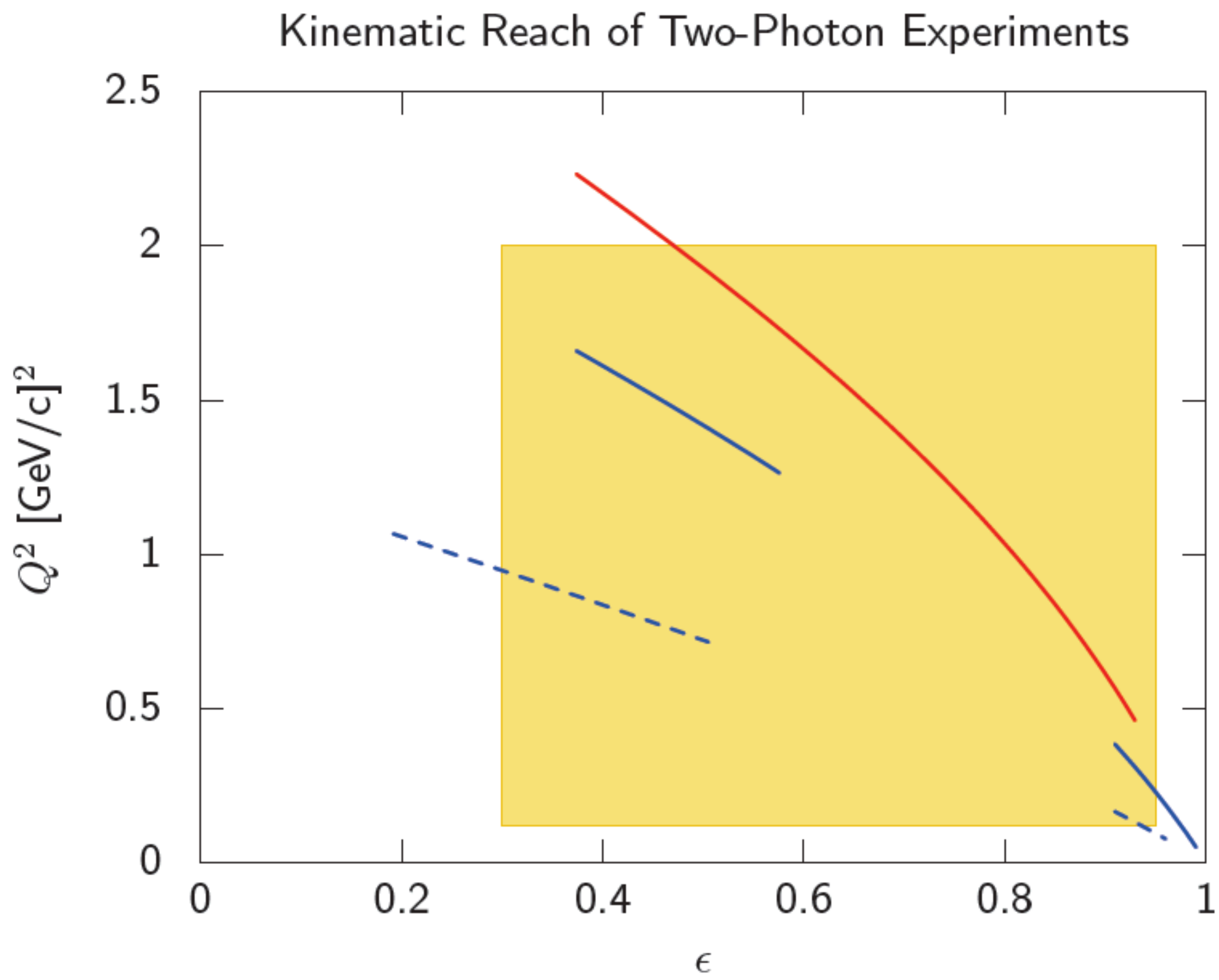


# recent TPE experiments measuring $e^+/e^-$

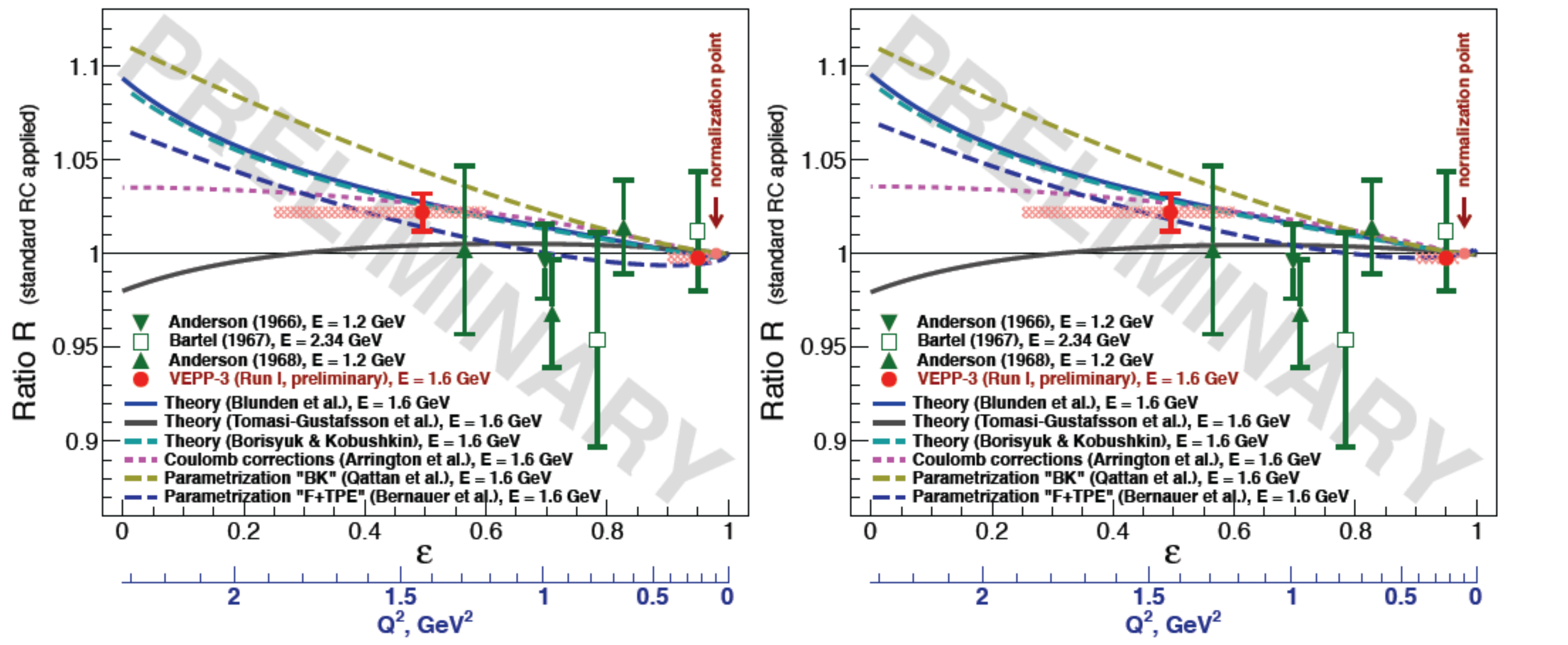
**CLAS**
- $e^-$ to $\gamma$ to $e^{+/-}$ -beam

**VEPP-3**
- 1.6/1 GeV beam
- no field
- preliminary results

**OLYMPUS**
- DORIS @ DESY
- 2 GeV beam
- data taking finished 01/2013
- no results yet :(



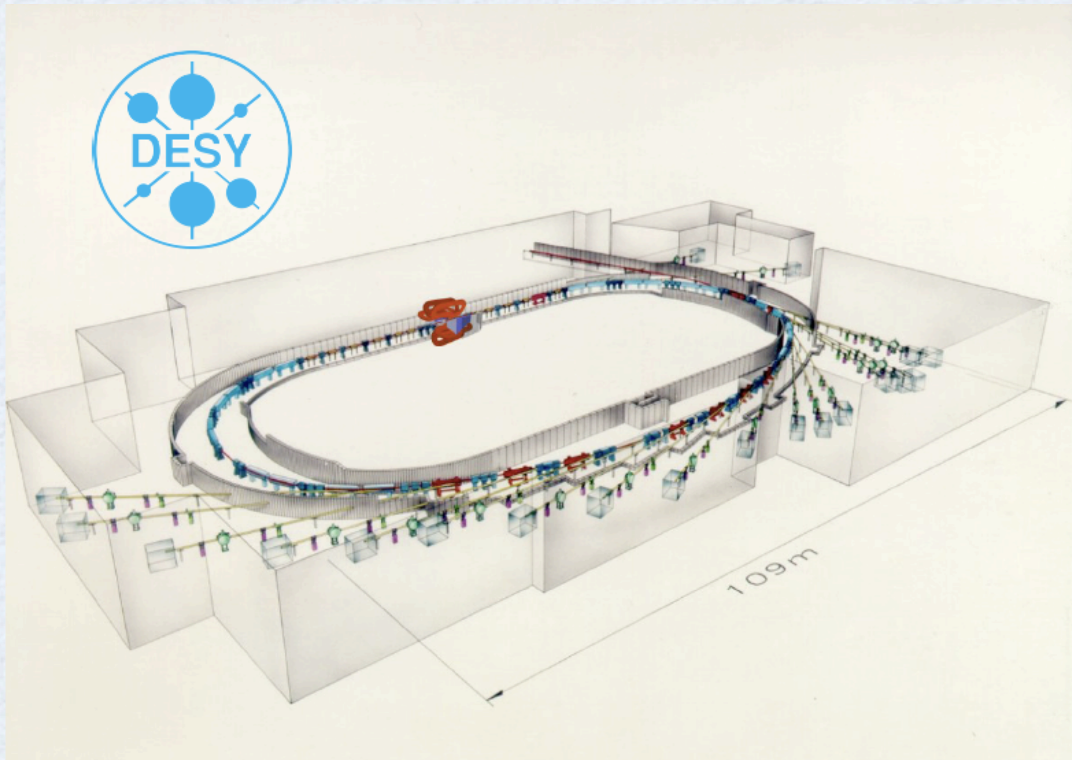
# VEPP-3 results for $e^+/e^-$ ratio

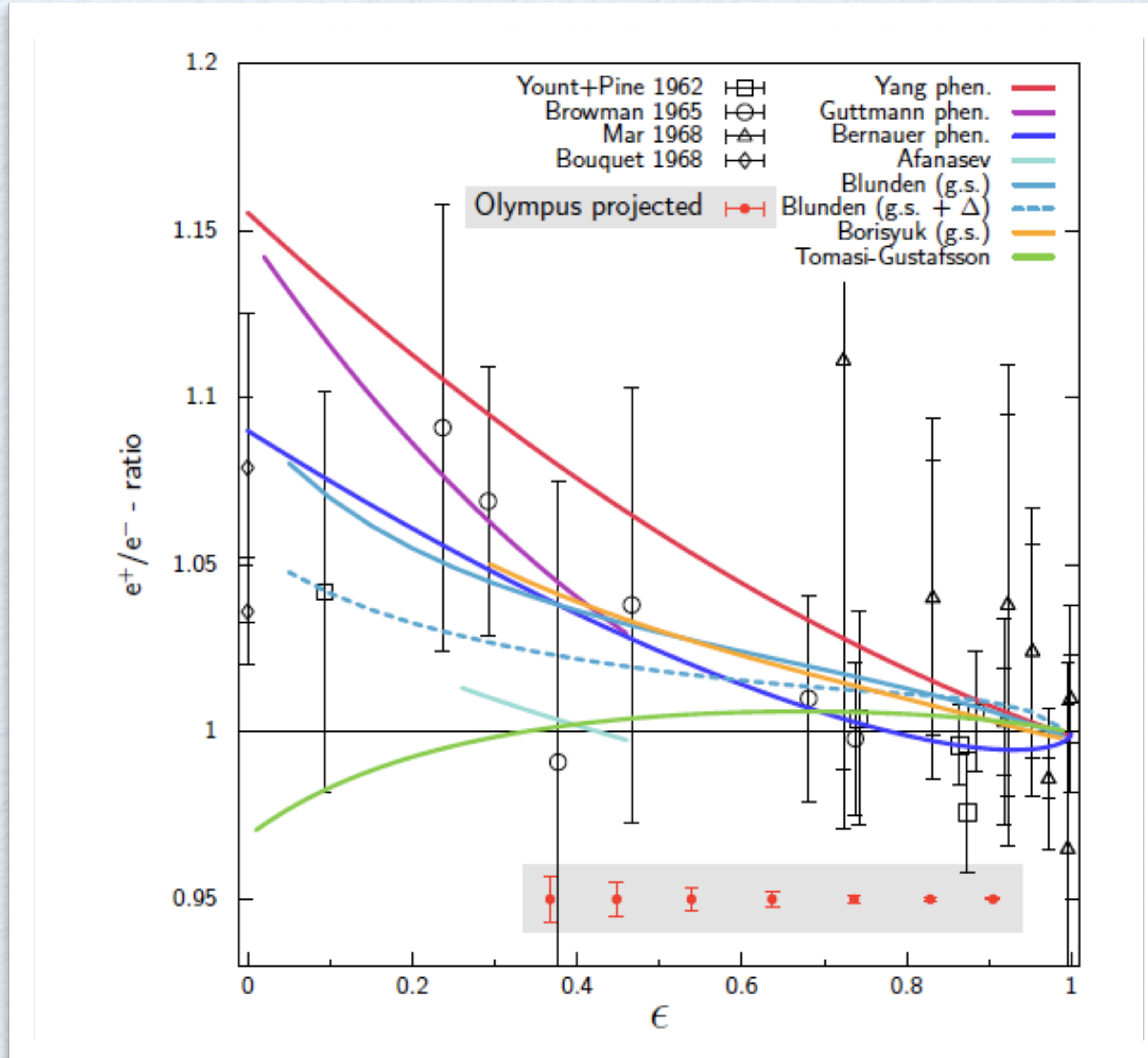


# Olympus experiment of $e^+/e^-$ ratio

experiment: DORIS@DESY

$E_e$ = 2 GeV, $Q^2$ in range 0.6 - 2.2 GeV$^2$




data taking in 2012,

analysis ongoing,

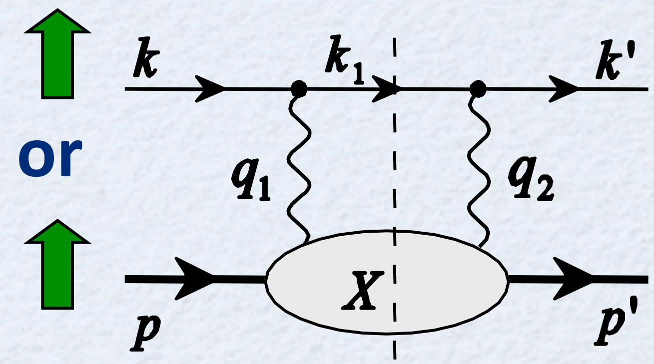
first results end 2014

# normal spin asymmetries in elastic $e^-N$ scattering

➡ directly proportional to imaginary part of 2-photon amplitudes

spin of beam **or** target

normal to scattering plane




on-shell intermediate state

measures the absorptive part of

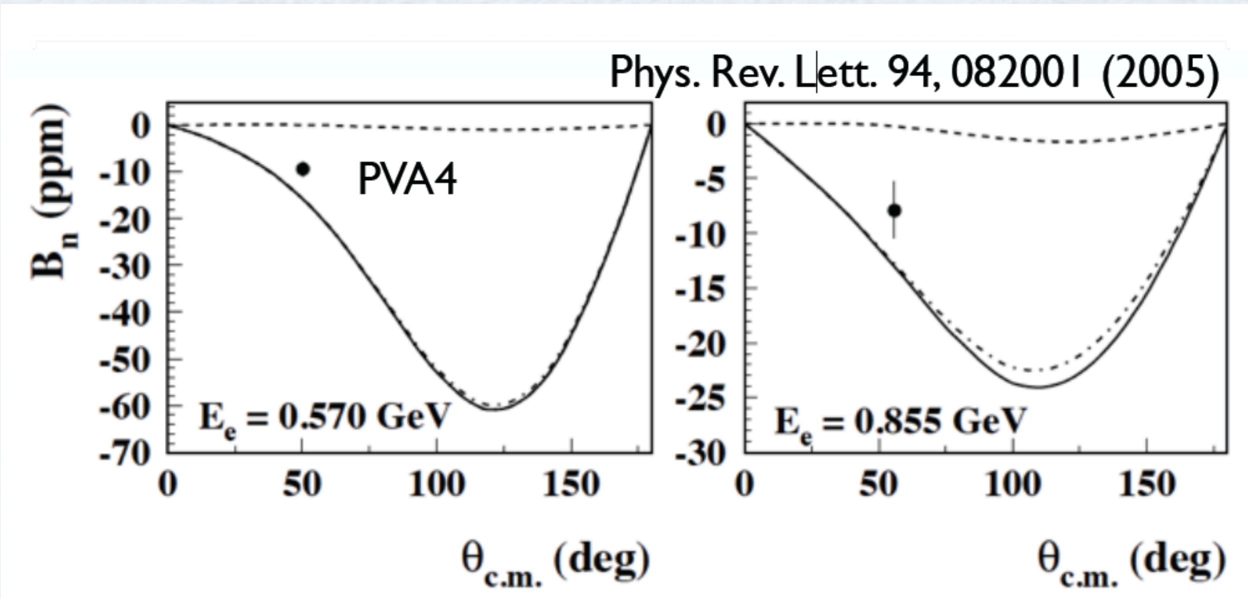
double virtual Compton scattering

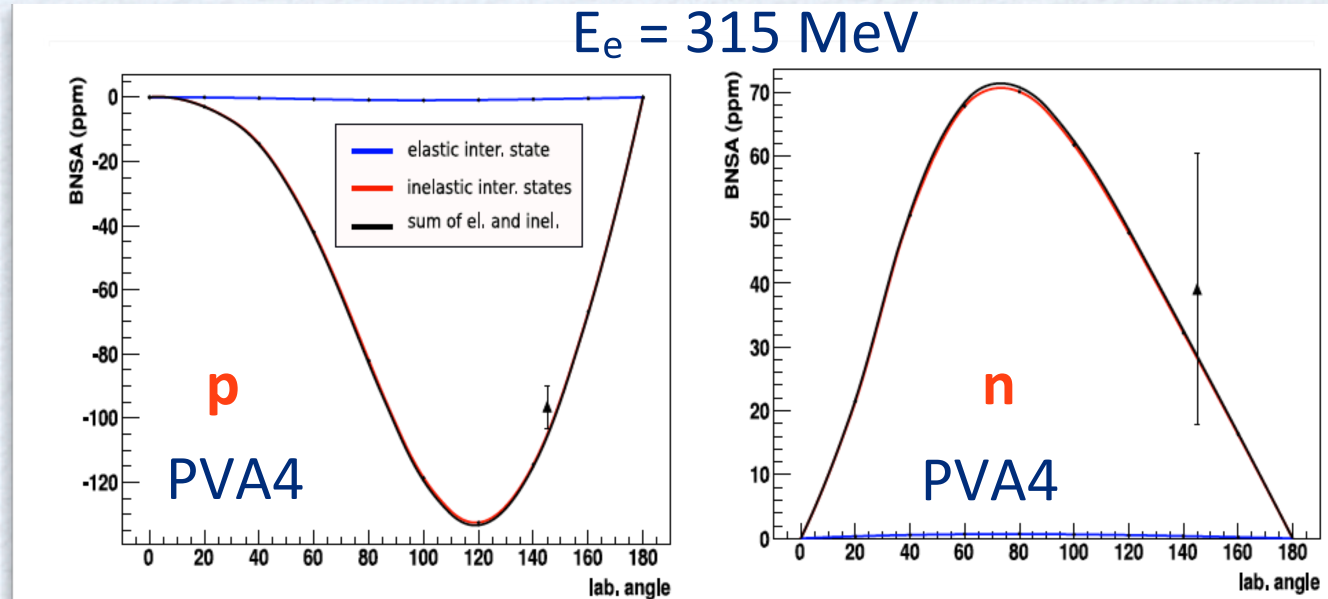
➡ order of magnitude estimates:

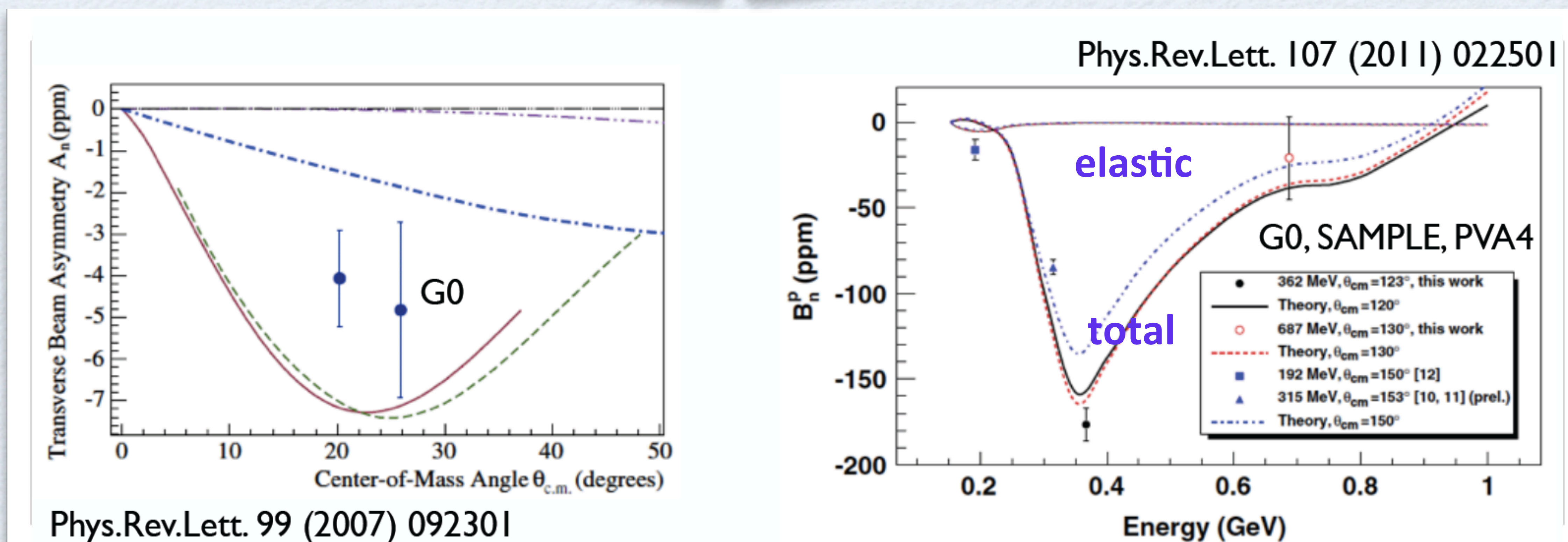
target: $A_n \sim \alpha_{em} \sim 10^{-2}$

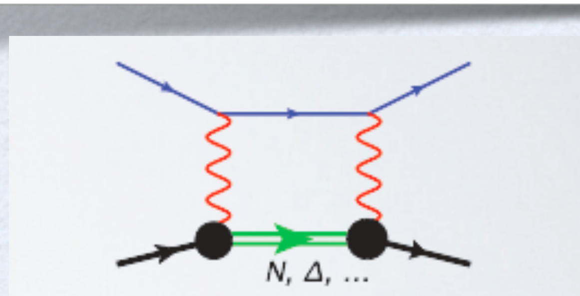
beam: $B_n \sim \alpha_{em} \dfrac{m_e}{E_e} \sim 10^{-6} - 10^{-5}$

# beam normal spin asymmetry in e⁻N elastic



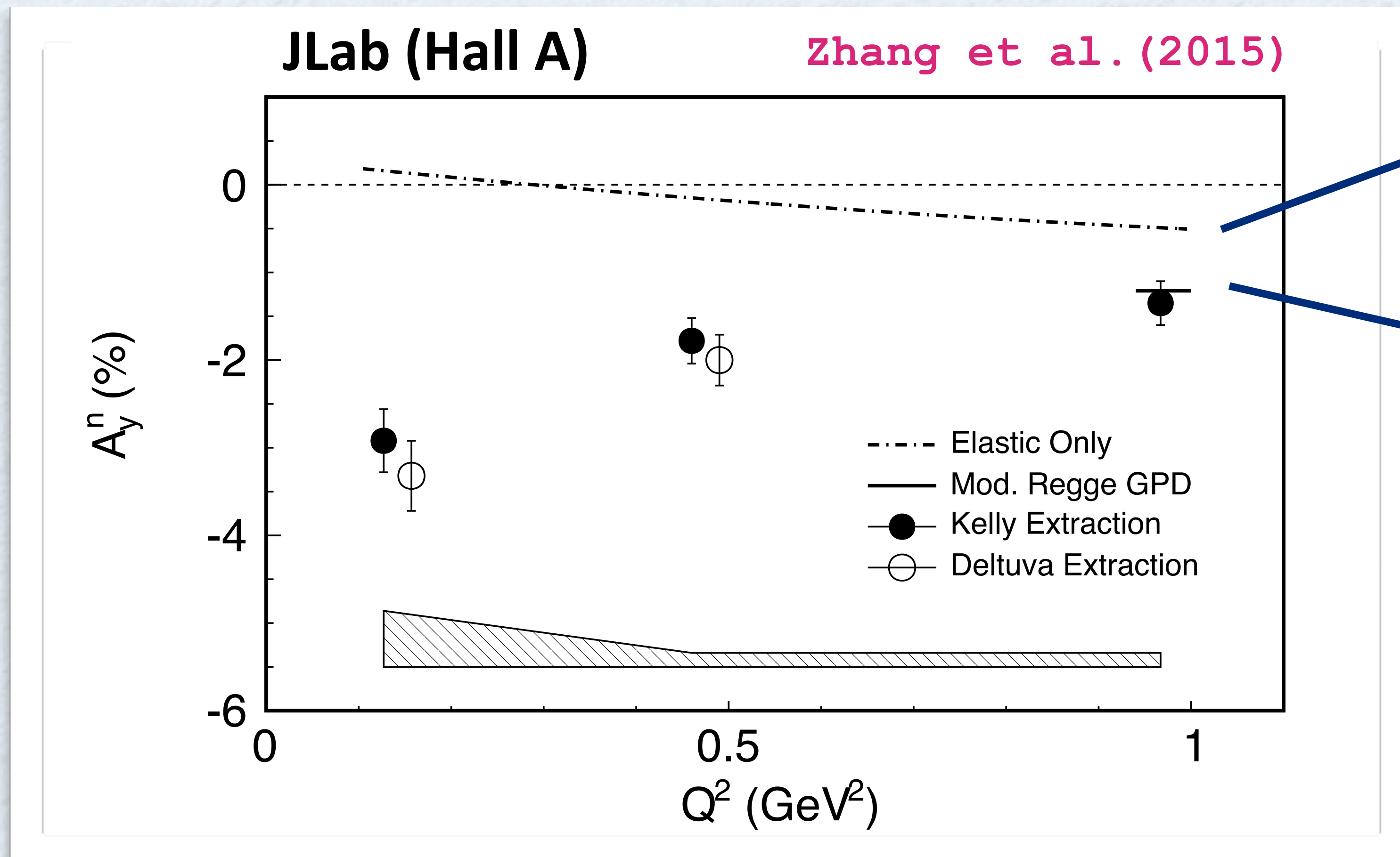

calculations: elastic (very small)

elastic + inelastic: Pasquini, Vdh (2004)

# target normal spin asymmetry in e⁻N elastic

$$
\begin{aligned}
A_n &= \sqrt{\frac{2\,\varepsilon\,(1+\varepsilon)}{\tau}}\,\left(G_M^2 + \varepsilon/\tau G_E^2\right)^{-1} \\
&\times \left\{-G_M\,\mathcal{I}\left(\delta\tilde{G}_E + \frac{\nu}{M^2}\tilde{F}_3\right) + G_E\,\mathcal{I}\left(\delta\tilde{G}_M + \left(\frac{2\varepsilon}{1+\varepsilon}\right)\frac{\nu}{M^2}\tilde{F}_3\right)\right\}
\end{aligned}
$$

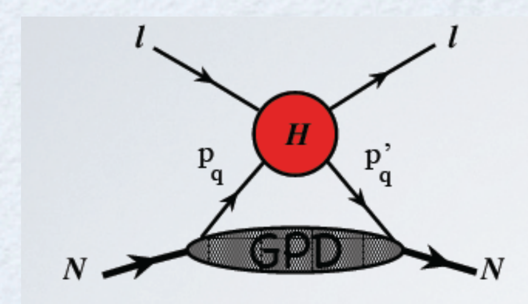
$^3He^{\uparrow}(e,e')$ quasi-elastic scattering on **neutron**




elastic contribution

De Rujula, Kaplan, De Rafael (1971)

GPD model calculation




Chen, Afanasev, Brodsky, Carlson, Vdh (2004)

at present: no proton data exist

# Summary/Outlook


## 1) Proton radius puzzle:

- precision muonic atom spectroscopy
  has shaken textbook knowledge
- generated a large activity to scrutinize result
- what can be expected (timescale) ?

  eH Lamb shift (~ 1/2 - 1 year)

  new $e^-$ scattering (~ 1-2 years)

  $\mu^-$ scattering (~ 3 years)
- new expt: $\mu^-\mu^+$ vs $e^-e^+$ pair production as lepton universality test

## 2) Proton spatial structure: form factors, two-photon processes

- deuteron, $^3$He, $^4$He, light nuclei e.m. obsevables:
  impact on precision atomic physics, connect with ab initio EFT
- two-photon exchange observables ($e^-$ / $e^+$ ratio, asymmetries):
  precise understanding needed to use electron scattering as a precision tool
  input in polarizability corrections in atomic spectroscopy
- many new opportunities for precision measurements

# Thank you!