PRISMA

SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

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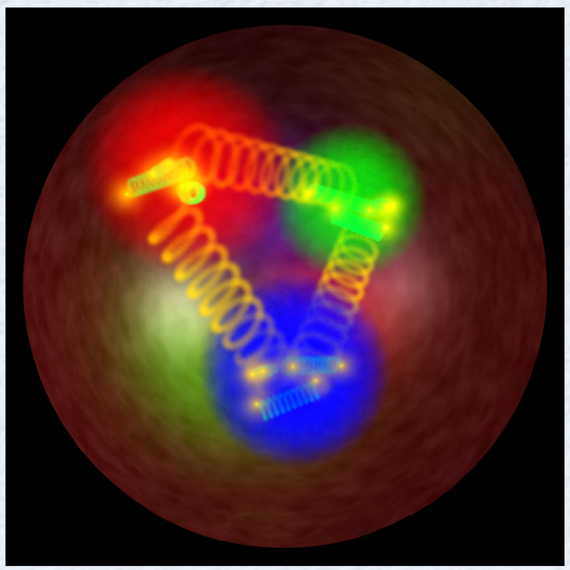
MAGIX Collaboration Meeting, Mainz, February 15-17, 2017

Hadron physics (= The Low-Energy Frontier of the Standard Model)

plays a central and connecting role in interpretation of measurements at the precision frontier of the Standard Model



Hadrons and Nuclei

$sin^2\theta_W$

$(g\text{-}2)_\mu$

R_E Proton charge radius

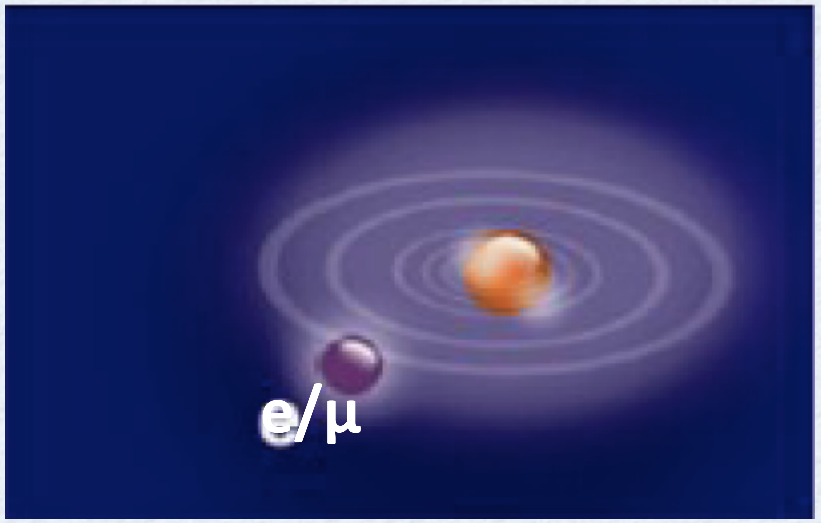
Dark Photon

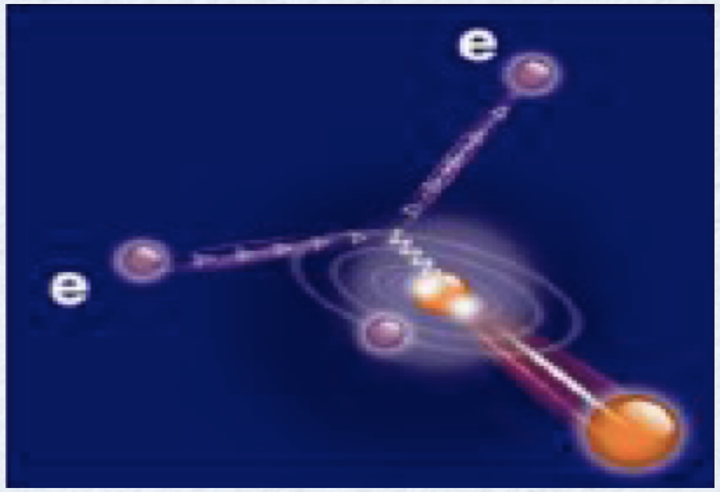
Strong interactions
Hadron structure
Hadron spectroscopy

↔

Particle physics
Atomic physics
Astro(particle) physics

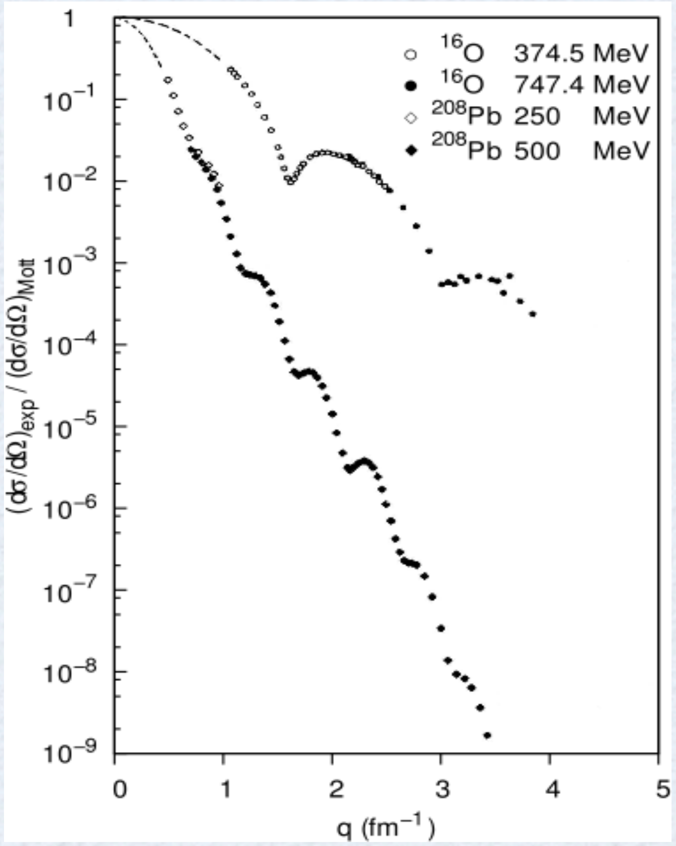
Proton Radius Puzzle

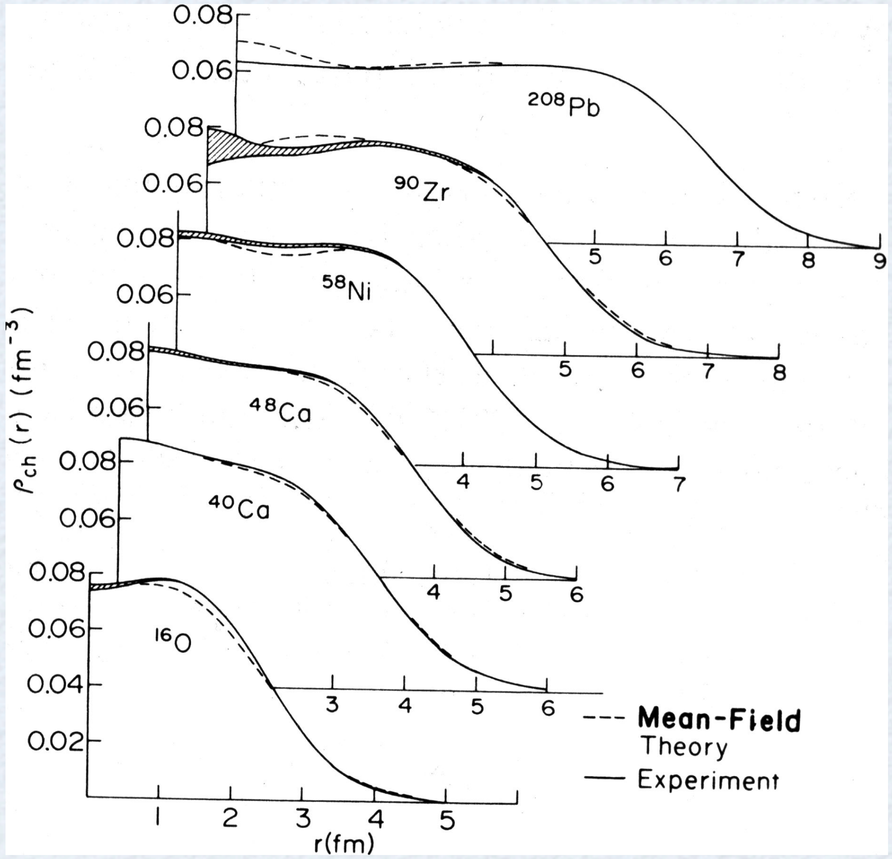




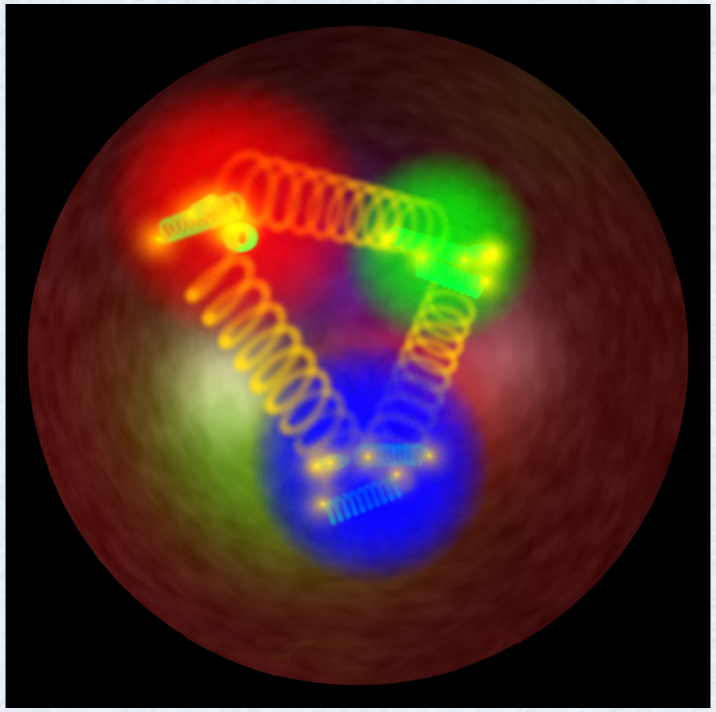
how to measure sizes of hadronic systems

time honored tool:
electroweak probe

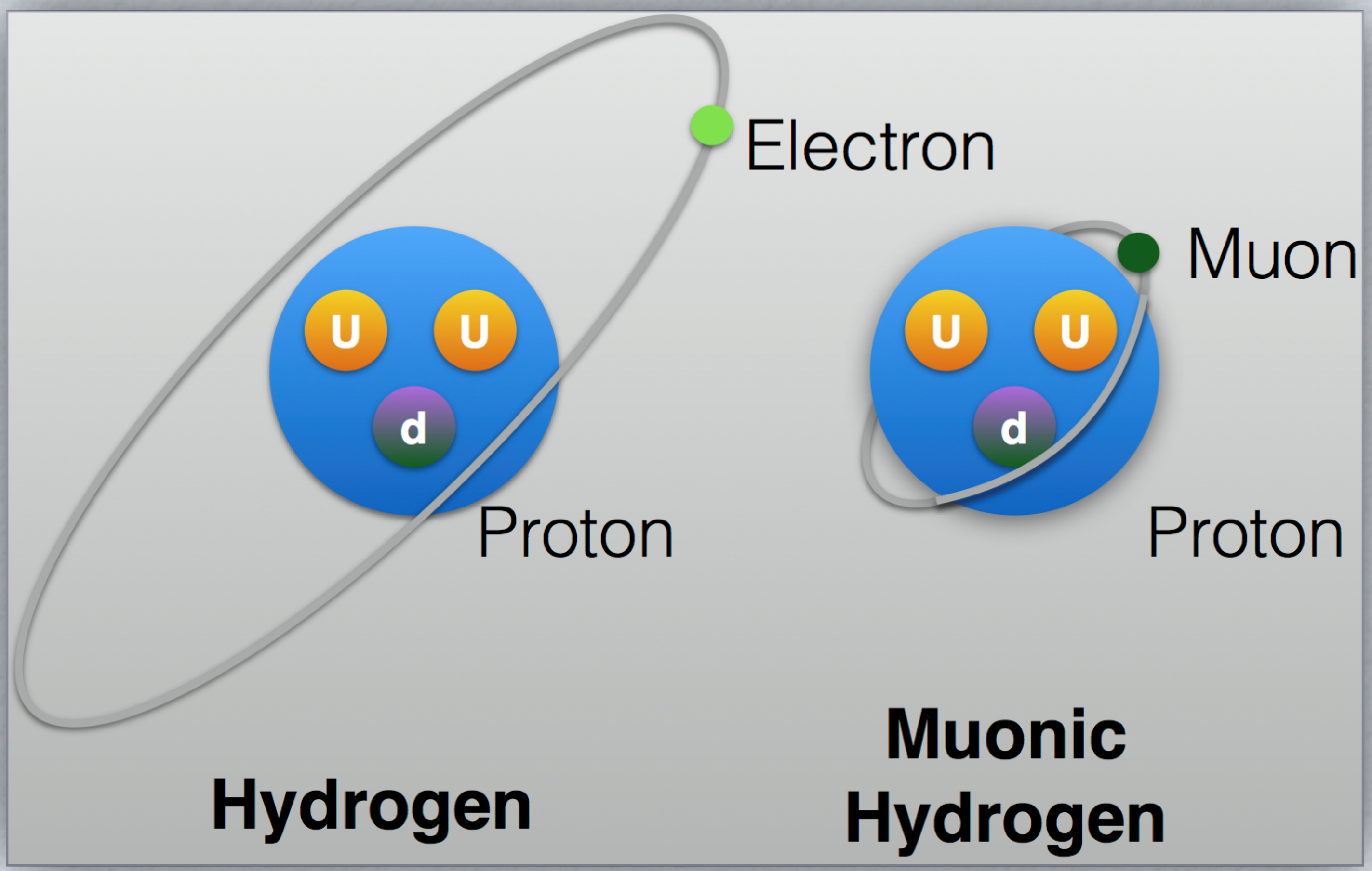


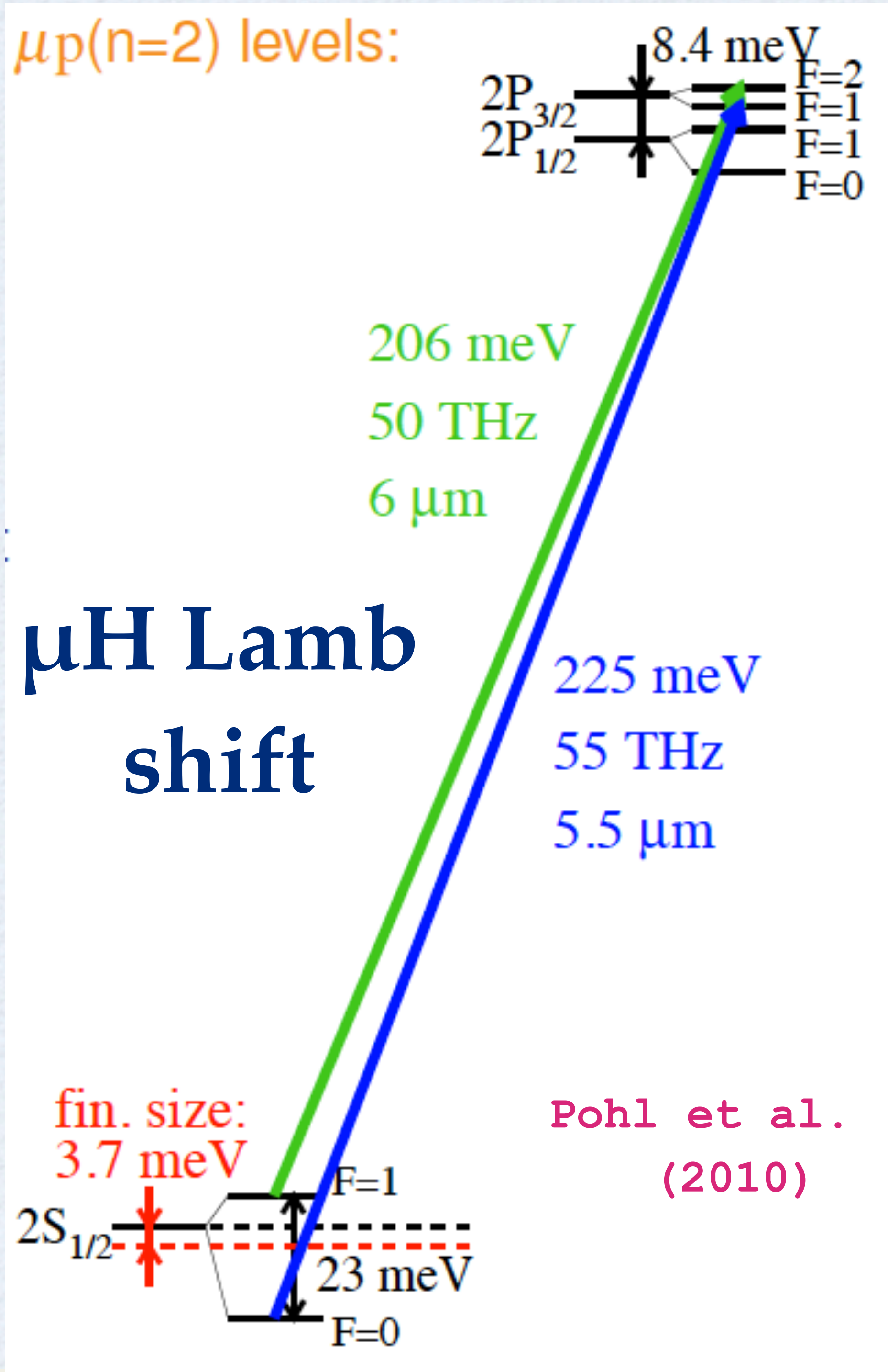


how accurate do we
know the proton size ?



Proton radius from Hydrogen spectroscopy





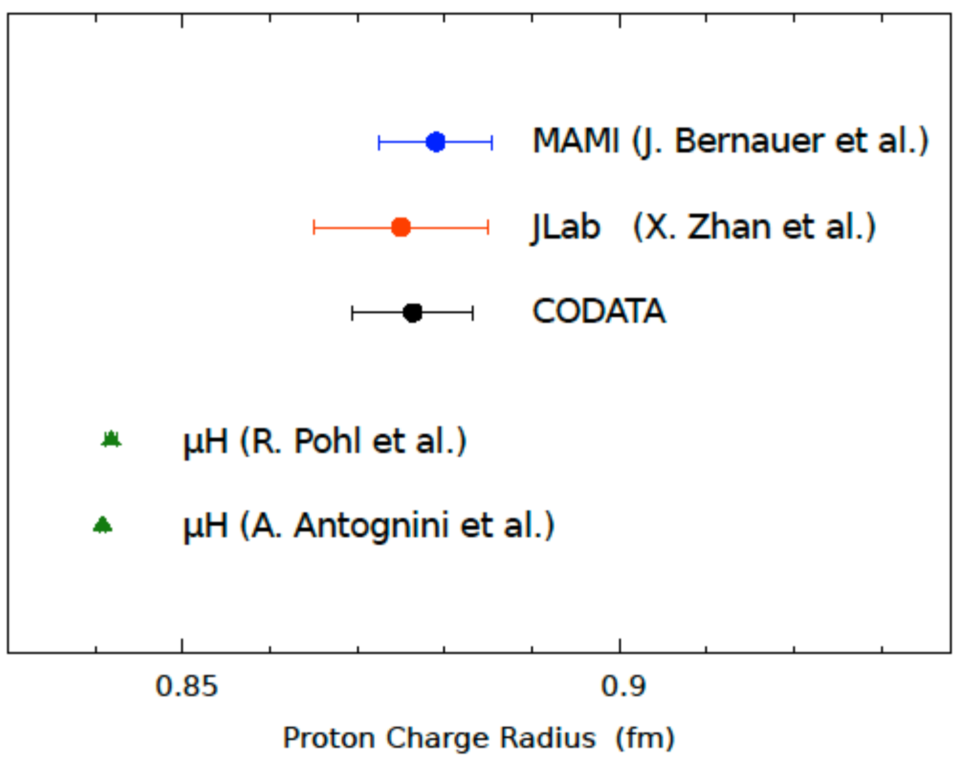
$$\Delta E_{LS} = 209.9779\,(49) - 5.2262\;R_E^{\,2} + 0.00913\;R^3_{(2)}\ \text{meV}$$

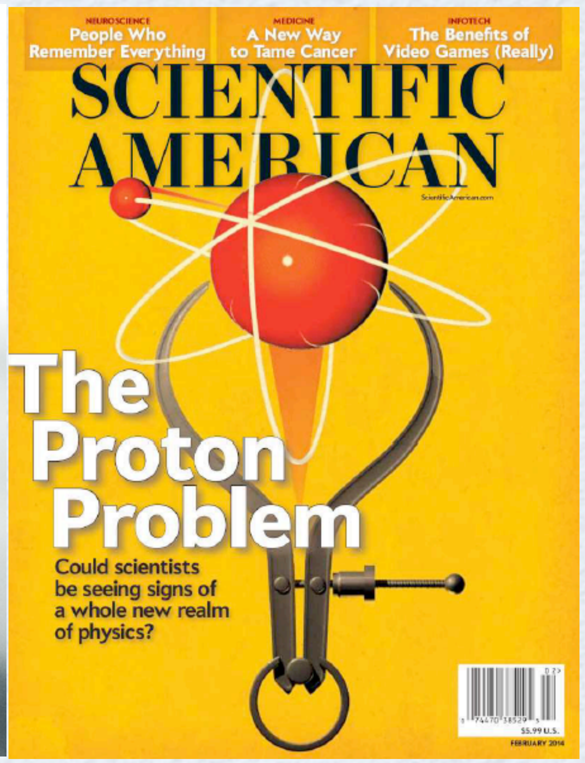
↓ 3.70 meV

↓ 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

Lamb shift

difference of

≈ 330 μeV

μH expt. wrong ?

eH theory wrong ?

μH theory wrong ?

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

eH expt. wrong ? -> R_∞ wrong

+ ep scattering wrong ?

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

new physics ?

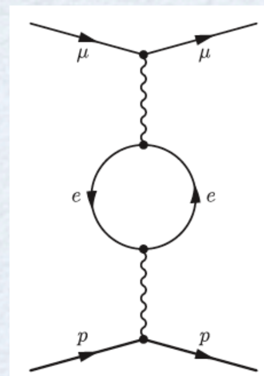
Lamb shift: QED corrections

- Calculated by several groups

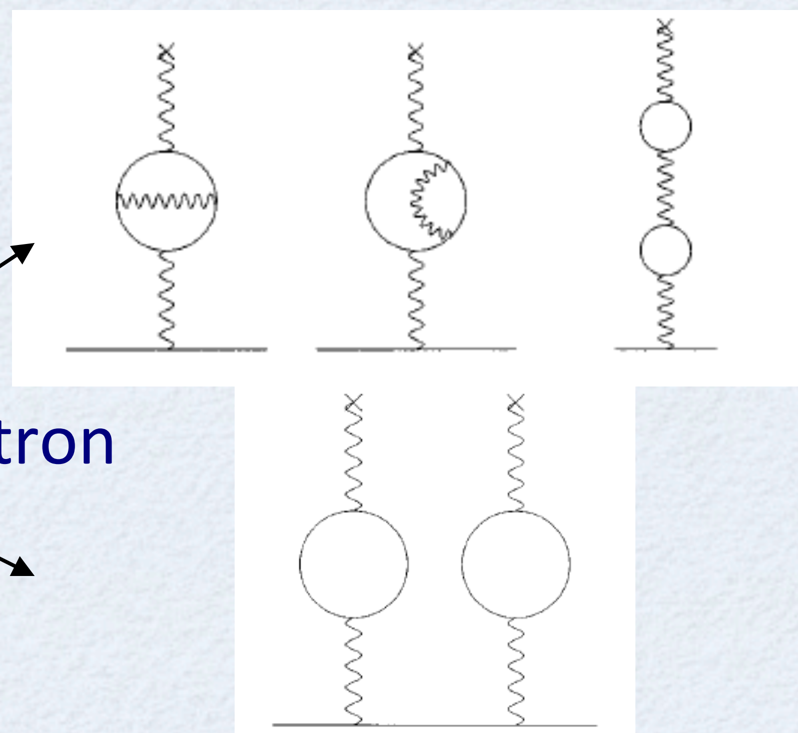
Pachucki (1996, 1999)

Borie (1976, 2005)

- 1 loop electron



ΔE = 205.0282 meV



- 2 loop electron

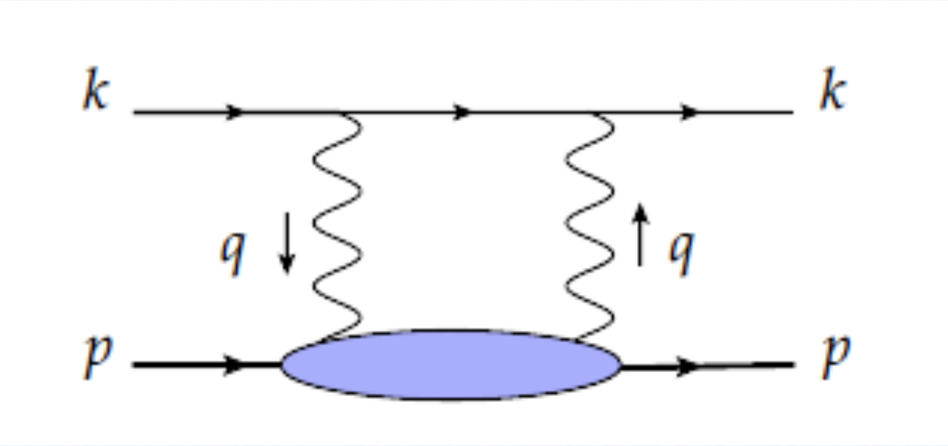
ΔE = 1.5081 meV

ΔE = 0.1509 meV

- Muon self-energy, vacuum polarization ΔE = -0.6677 meV

- other QED corrections calculated : all of size 0.005 meV or smaller << 0.3 meV

Lamb shift: hadronic corrections (I)



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

- 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

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

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

$$\Delta E = \Delta E^{el} + \Delta E^{subtr} + \Delta E^{inel}$$

- ΔE^{el} → Elastic state: involves **nucleon form factors**
- ΔE^{subtr} → Subtraction: involves **nucleon polarizabilities**
- ΔE^{inel} → Inelastic, dispersion integrals: involves **structure functions F1, F2**

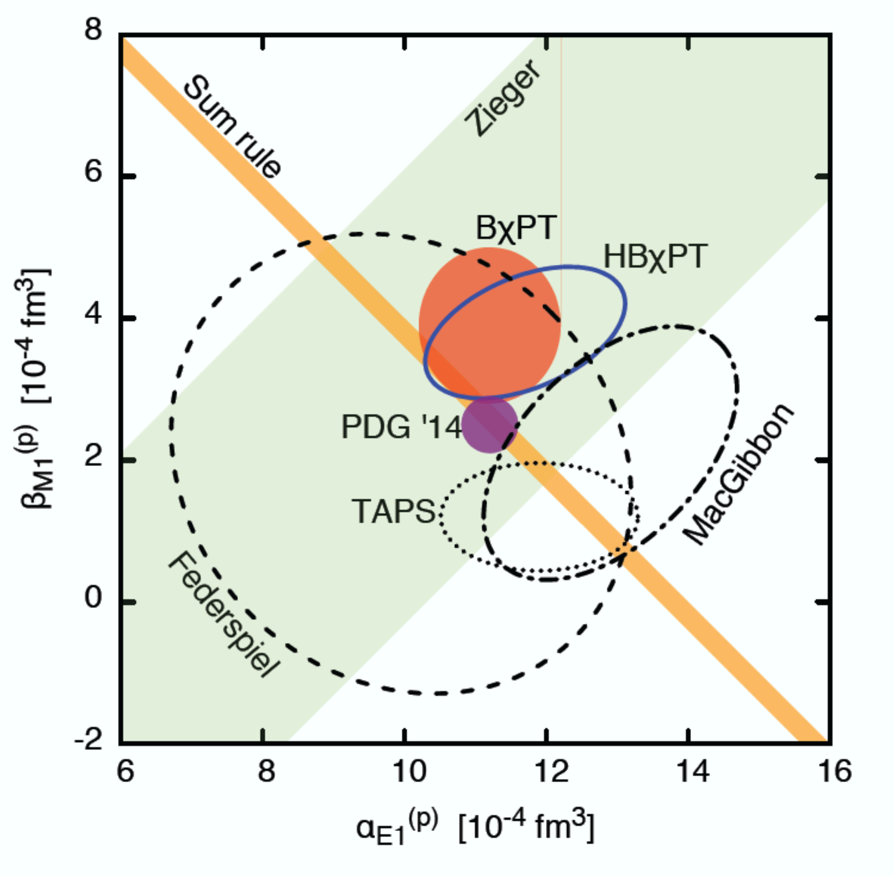
Lamb shift: hadronic corrections (II)

- 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:

α_E = (11.2 ± 0.2) × 10^{-4} fm^3

β_M = (2.5 ± 0.4) × 10^{-4} fm^3

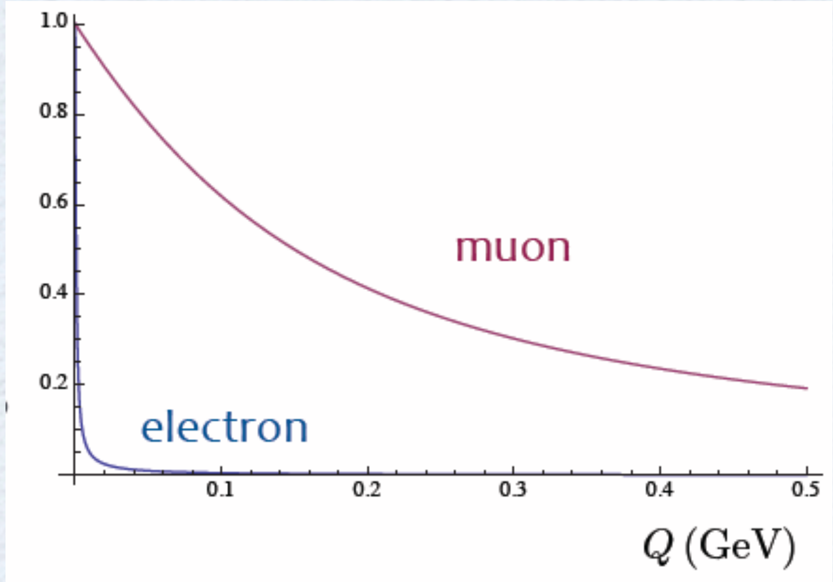
- subtraction term $T_1(0,Q^2)$

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

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

next order terms: calculable in chiral perturbation theory
Nevado, Pineda(2008) ; Birse, McGovern(2012);
Alarcon, Lensky, Pascalutsa(2014)

weighting function in Lamb shift



Lamb shift: hadronic corrections summary

polarizability correction on 2S level in μH in μeV

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-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).

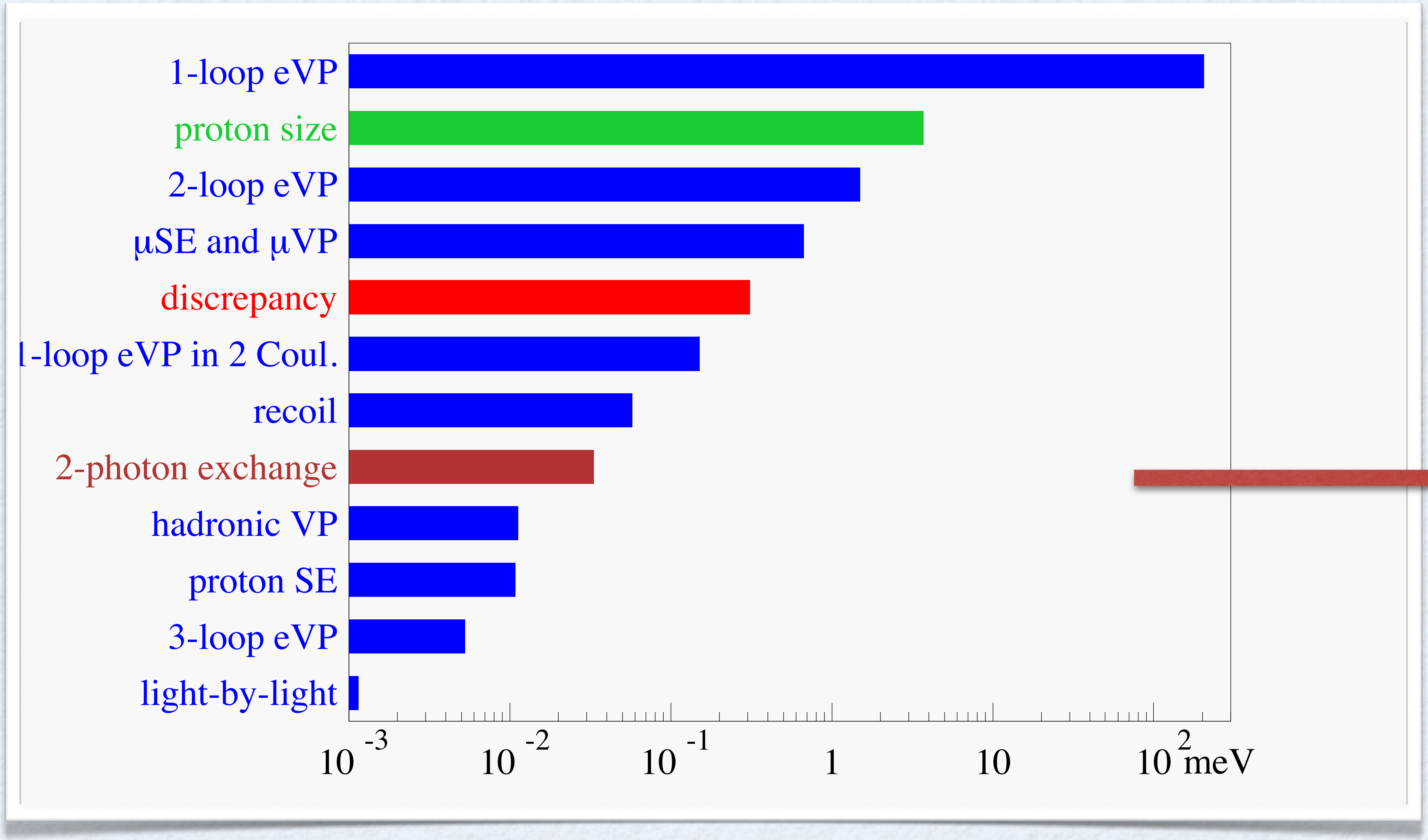
[LO-BχPT] Alarcon, Lensky, Pascalutsa, EPJC (2014) 74:2852

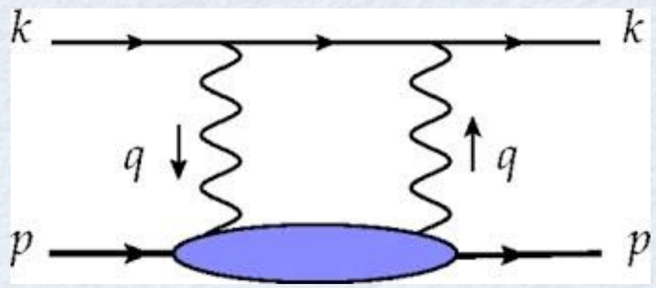
total hadronic correction on Lamb shift

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

Lamb shift: status of known corrections

μH Lamb shift: summary of corrections





largest theoretical uncertainty

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

total hadronic correction on Lamb shift

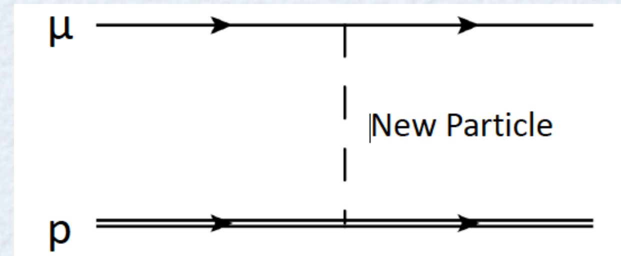
$\Delta E_{(2P - 2S)} = (33 \pm 2)$ μeV

...or about 10% of needed correction

Proton radius puzzle: new physics ?

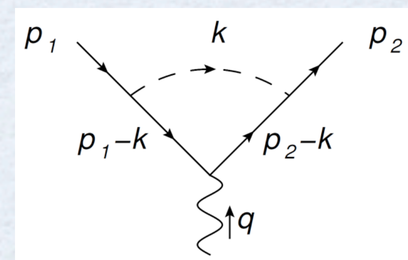
- new **muonic forces** ?

lepton universality-violating models



invoking exchange of hypothetical light boson

challenge: new physics must also respect $(g\text{-}2)_\mu$ 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

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

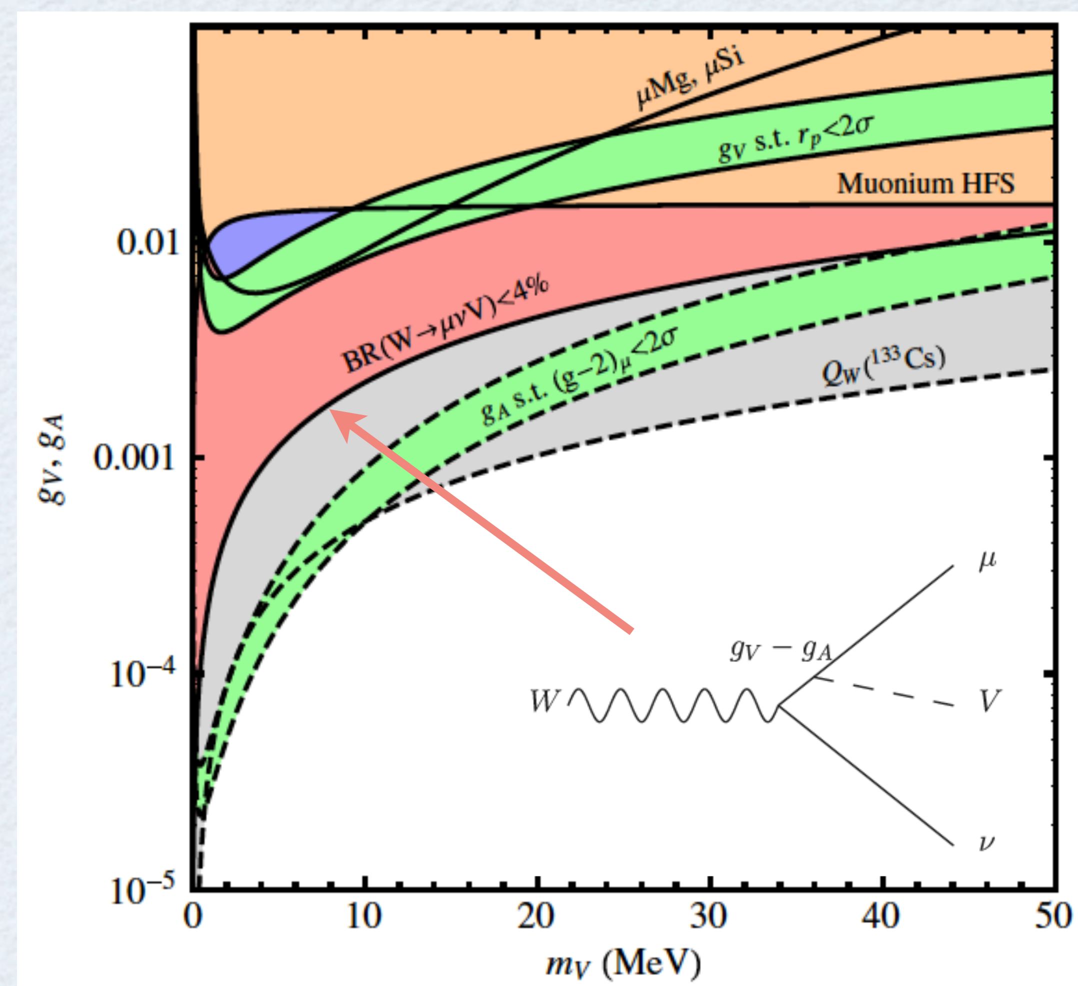
all leptons

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 (2015)

Proton radius puzzle: what's next ?

- μ atom Lamb shift: μ D, μ $^3He^+$, μ $^4He^+$ have been performed

- electronic H Lamb shift: higher accuracy measurements

- electron scattering analysis: Lorenz et al.; Hill, Lee, Paz

  - radius extraction fits (use fits with correct analytical behavior: 2π cut)
  - radiative corrections, two-photon exchange corrections

  new fit $R_E = 0.904\ (15)$ fm (4σ from μH)

- 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)
  - MESA: low-energy, high resolution spectrometers

- muon scattering experiments: MUSE@PSI (2018/9)

- e^-e^+ versus $\mu^-\mu^+$ photoproduction: lepton universality test

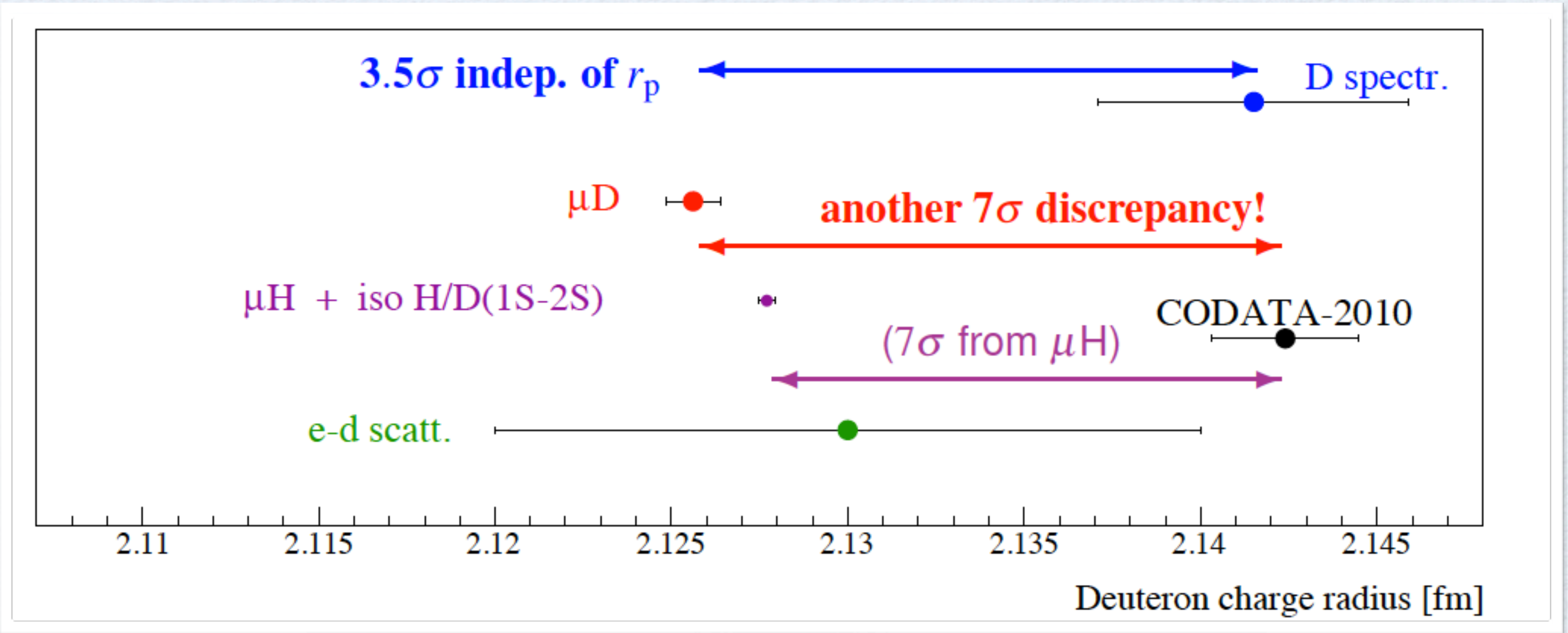
μD Lamb shift experiment

- H/D isotope shift (1S - 2S): $r_d{}^2 - r_p{}^2 =$ 3.82007 (65) fm^2 Parthey et al. (2010)

- CODATA 2010: r_d = 2.14240 (210) fm

- r_p from μH + isotope shift : r_d = 2.12771 (22) fm

- new μD Lamb shift @ PSI: $r_d = 2.12562\ (13)_{theo}\ (77)_{theo}$ fm Pohl et al., Science 353,417 (2016)



- electronic D (r_p indep.): r_d = 2.14150 (450) fm ← 3.5 σ Pohl et al. (2016)

- improved radius measurement from e-d scattering was performed @ MAMI (2014)

Polarization corrections for μD, μ ^{3}He$^+$, μ ^{4}He$^+$, ...

μH: ΔE^{TPE} (2P - 2S) = (33 ± 2) μeV   Carlson, Vdh (2011) + Birse, McGovern (2012)

present accuracy comparable with experimental precision: $\delta_{exp}(\Delta E_{LS})$ = 2.3 μeV

μD: ΔE^{TPE} = (1727 ± 20) μeV   nucleon potentials form chiral EFT   Hernandez et al. (2014)

ΔE^{TPE} = (1748 ± 740) μeV   dispersive analysis   Carlson, Gorchtein, Vdh (2014)

ΔE^{TPE} = (1710 ± 15) μeV   theory average used in exp.   Krauth (2016)

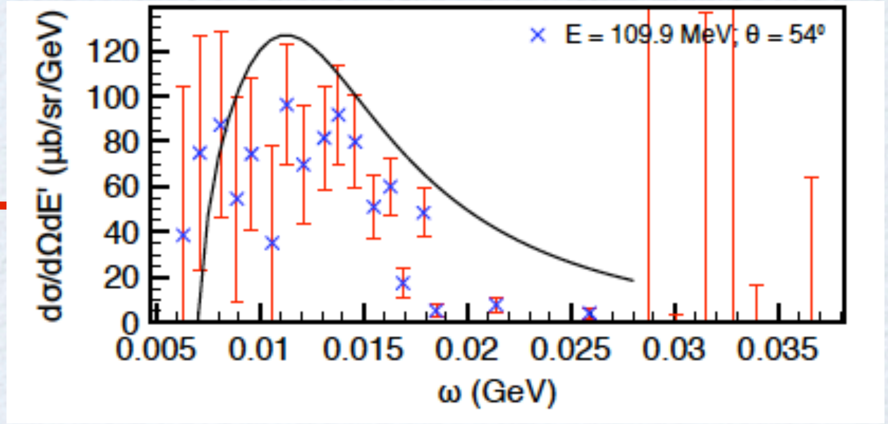
present accuracy factor 5 worse than experimental precision: $\delta_{exp}(\Delta E_{LS})$ = 3.4 μeV

μ ^{3}He$^+$: ΔE^{TPE} = (15.46 ± 0.39) meV   nucleon potentials form chiral EFT
Nevo Dinur, Ji, Bacca, Barnea (2016)

ΔE^{TPE} = (15.14 ± 0.49) meV   dispersive analysis   Carlson, Gorchtein, Vdh (2016)

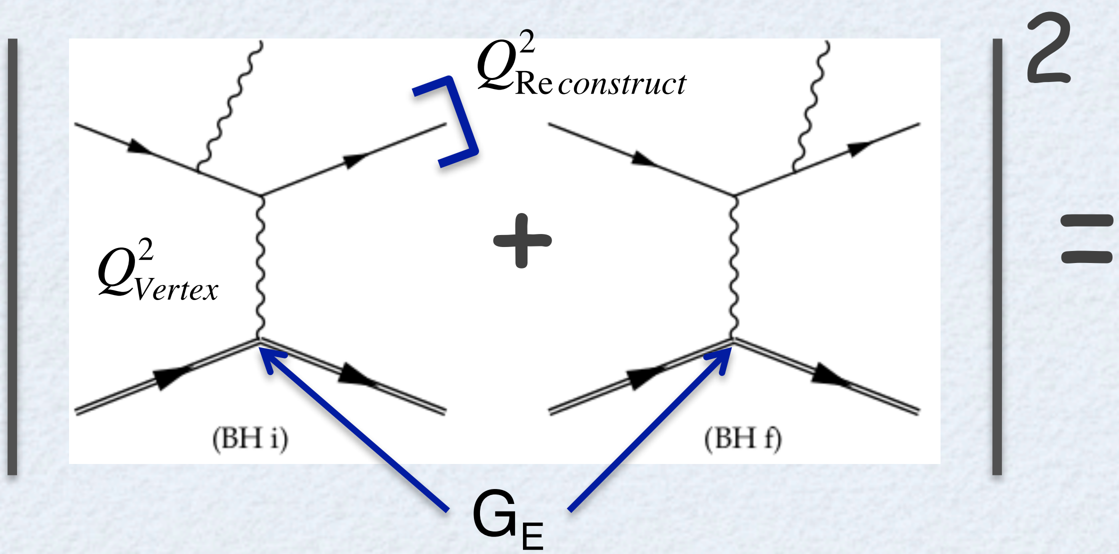
impact of a 5% measurement at MESA

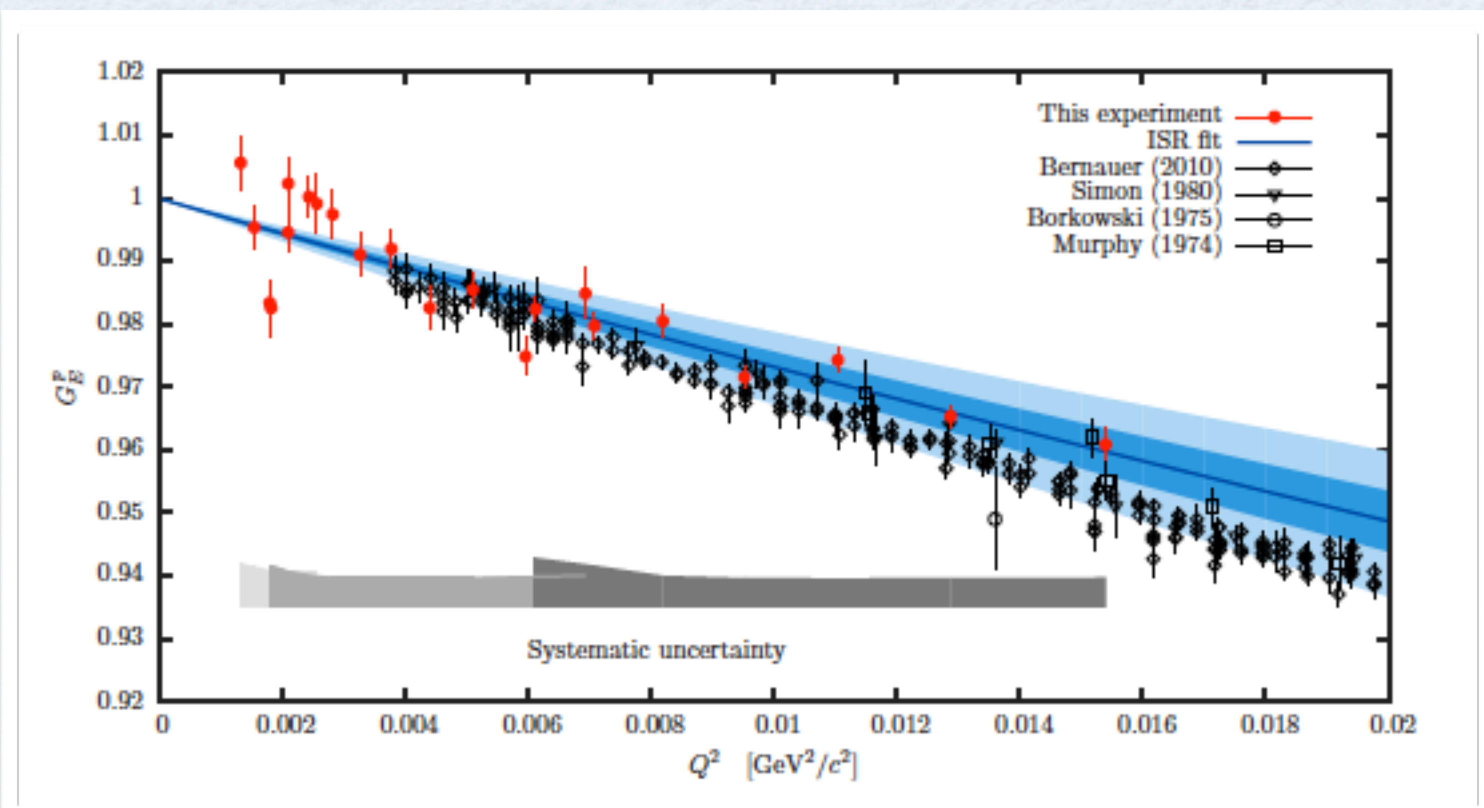
Kinematics	δa_2	$\delta(\Delta E_{2S}^{\text{nuclear}})$	$\delta(\Delta E_{2S}^{\text{TPE}})$
$E = 110$ MeV			
$\theta = 54°$	±0.014	0.40 meV	0.49 meV
$\theta = 30°$	±0.0075	0.21 meV	0.35 meV
$\theta = 25°$	±0.0055	0.16 meV	0.33 meV
$\theta = 20°$	±0.0040	0.11 meV	0.30 meV

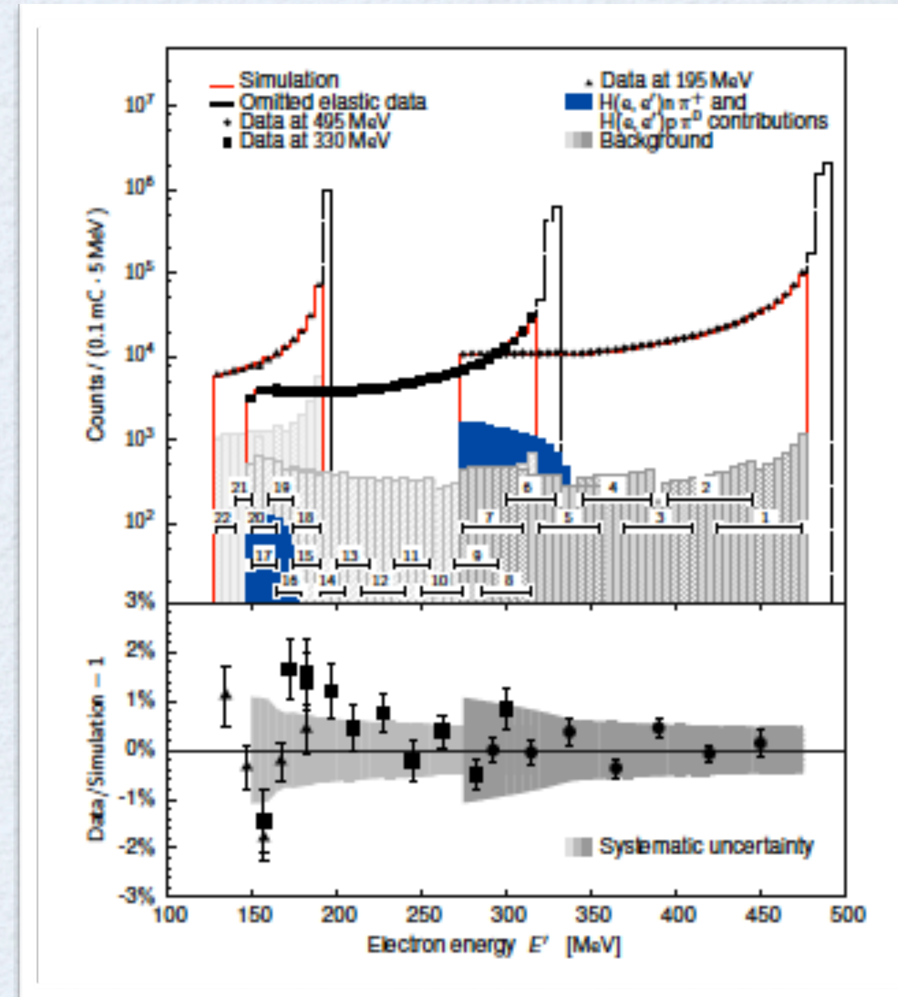


ISR@MAMI experiment

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







Mihovilovic et al. (2016)

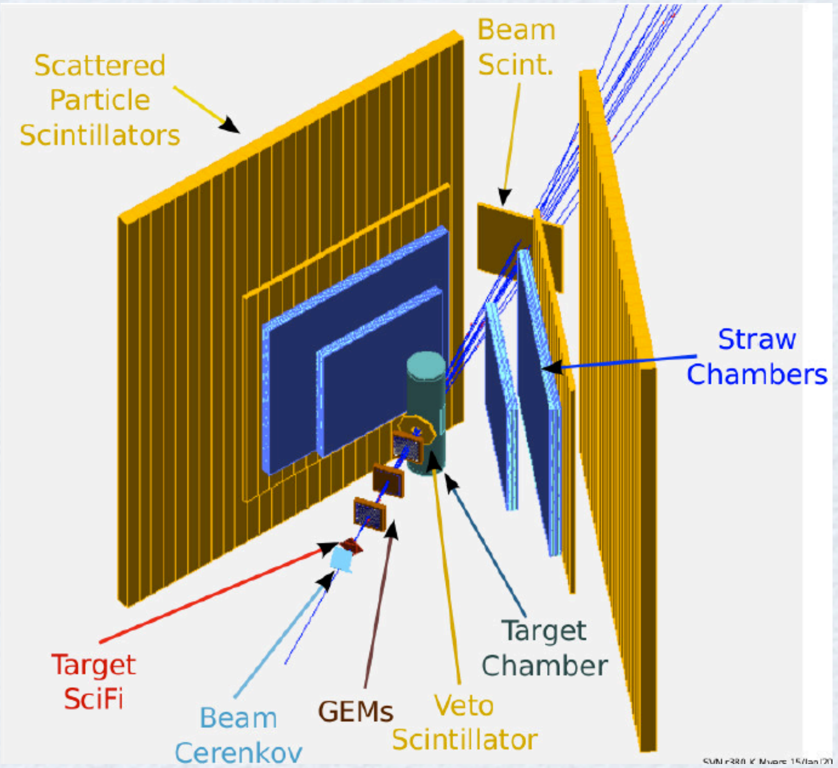
good understanding of radiative tail (~ 1%)

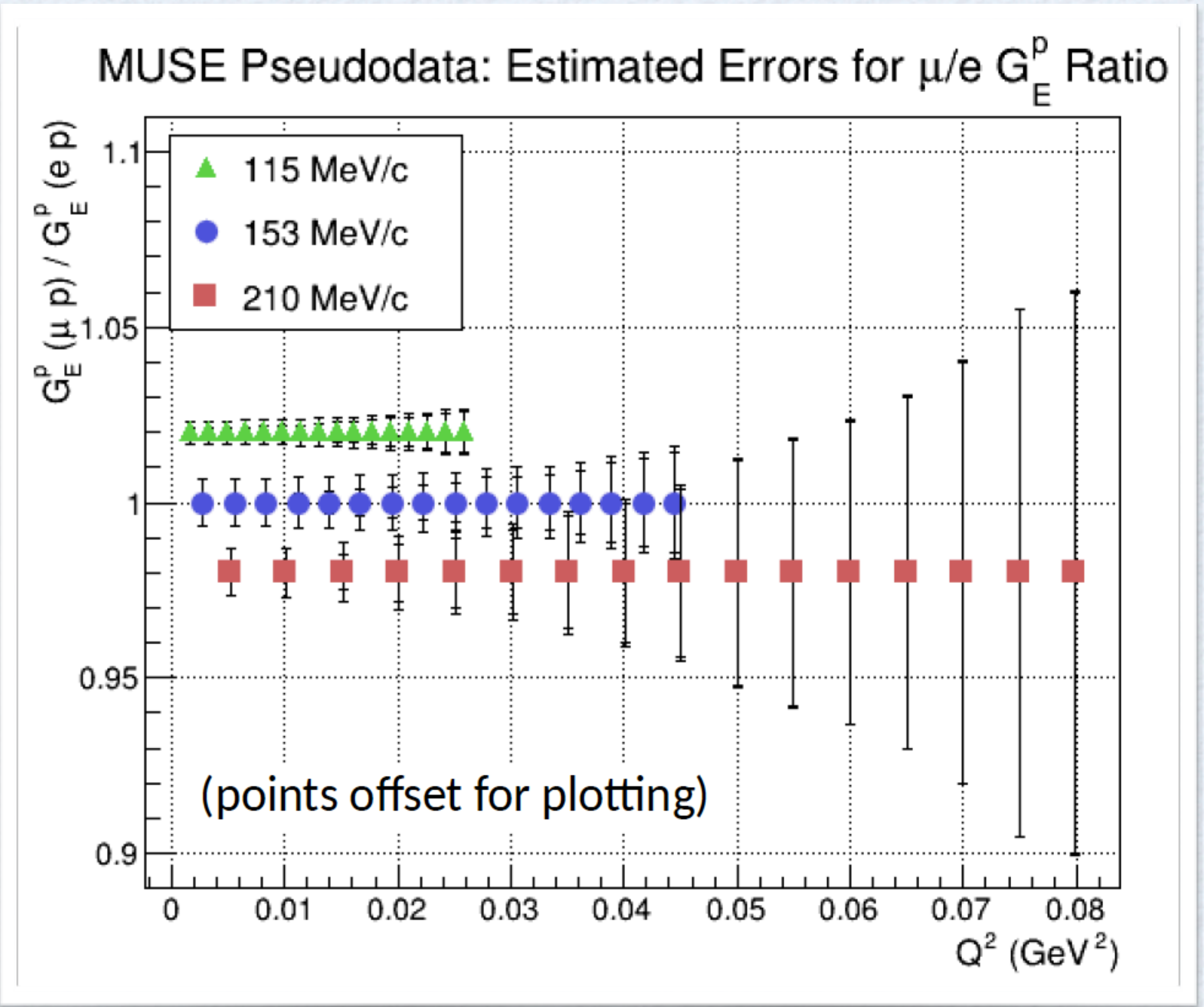
follow up experiment: down to $Q^2 \approx 2 \times 10^{-4}$ GeV^2

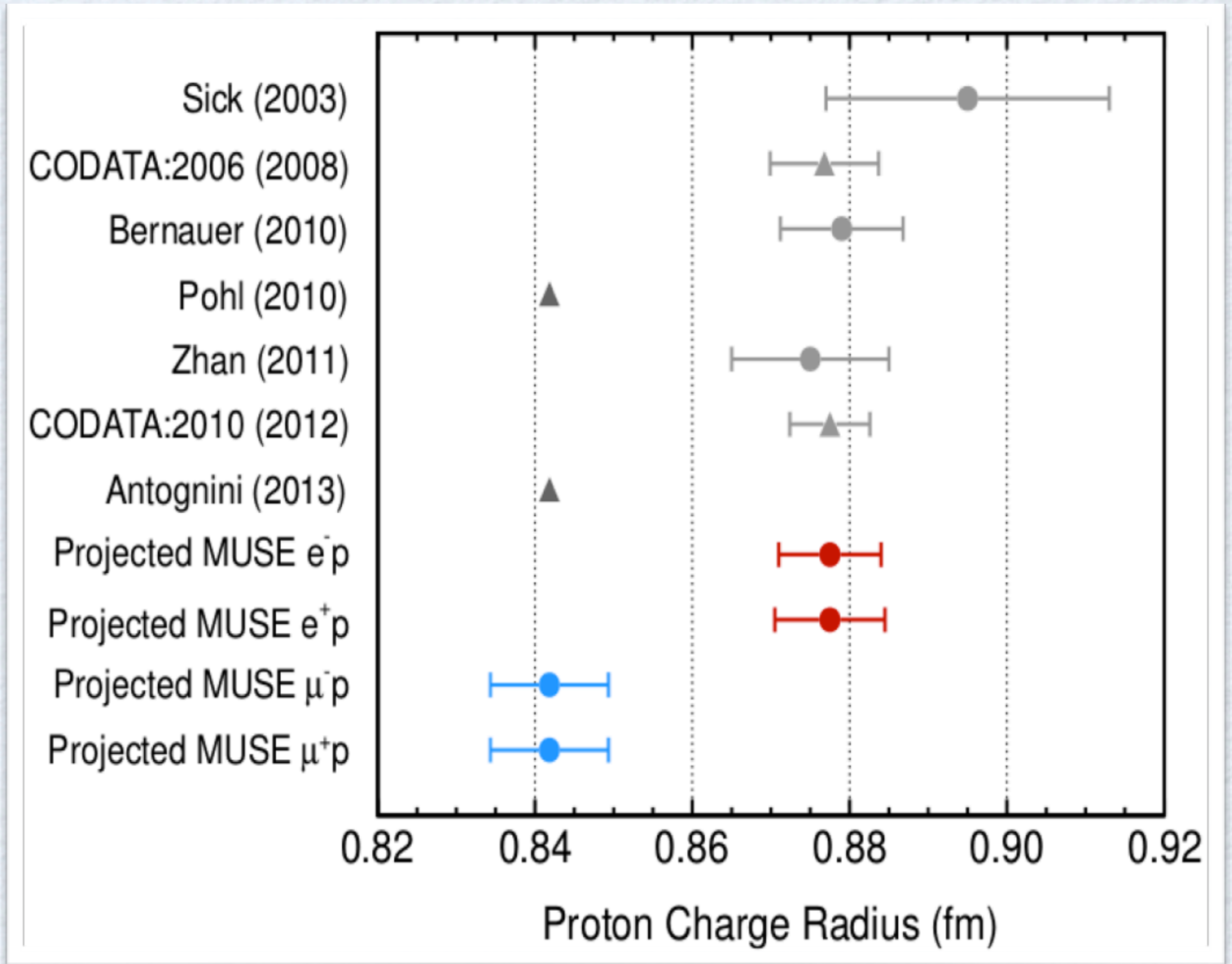
MUSE@PSI experiment

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

elastic scattering absolute cross sections

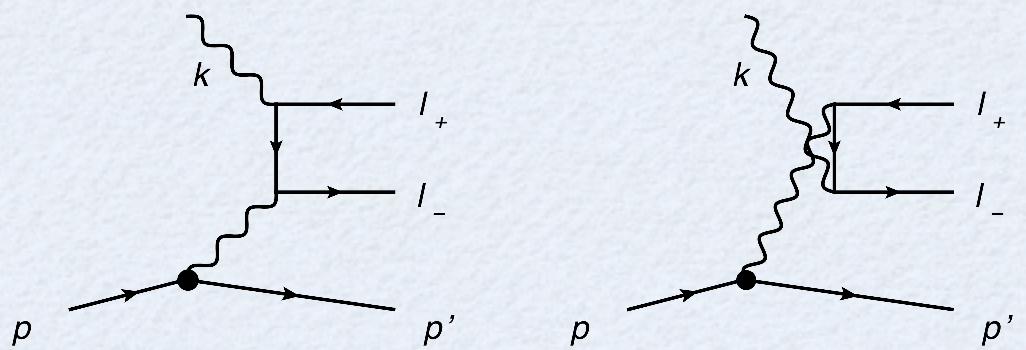






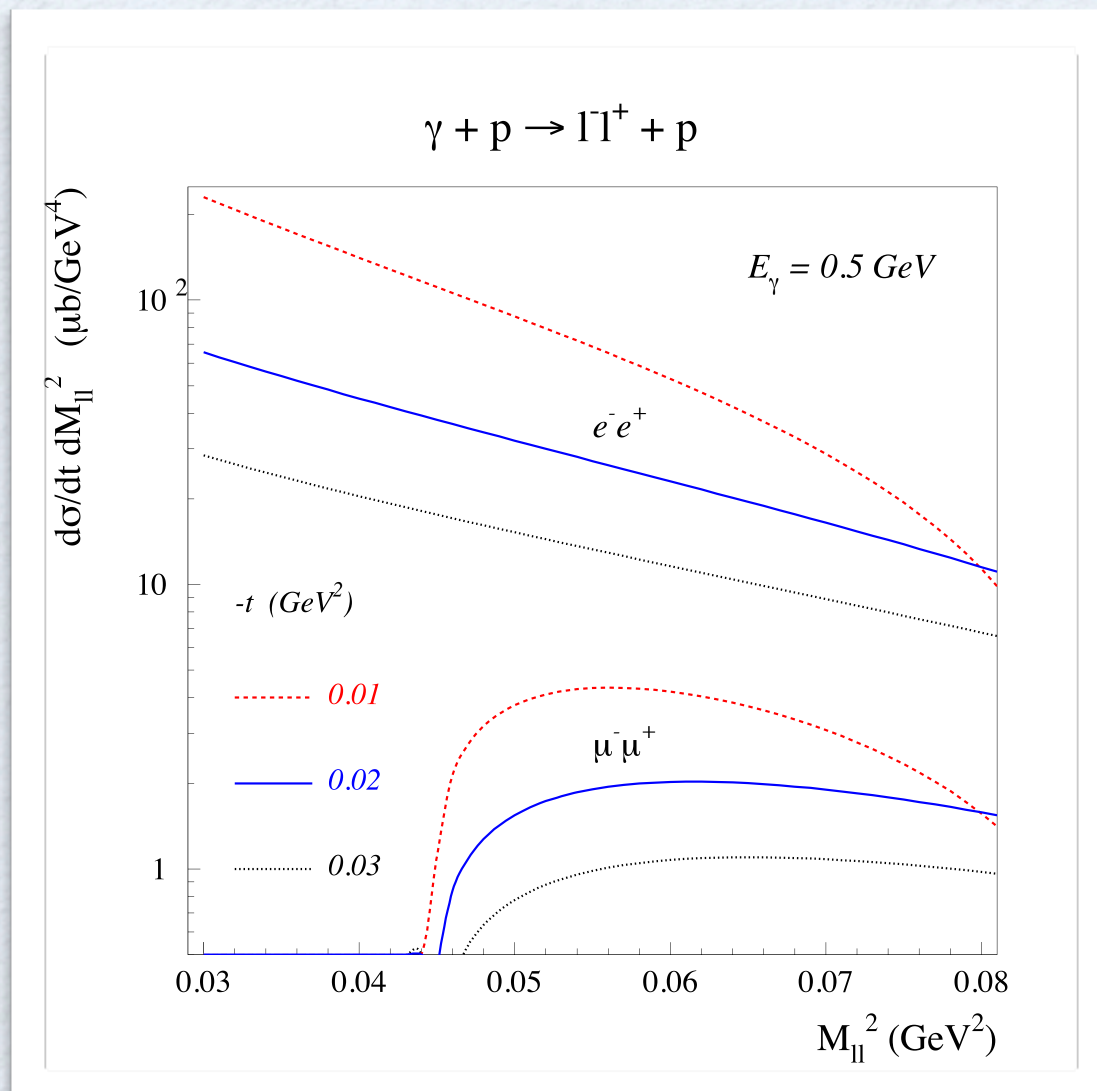
production run planned 2018 - 2019

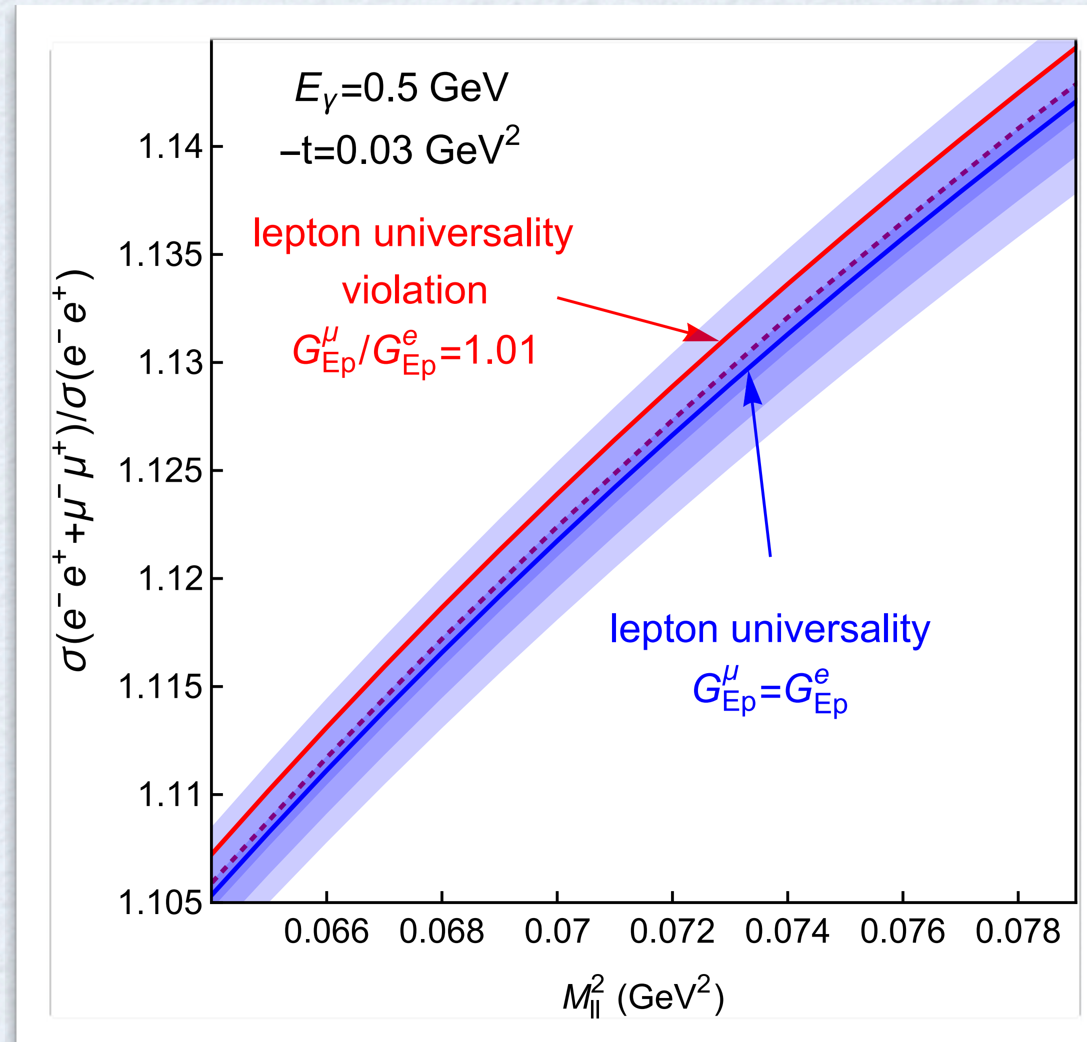
Lepton universality test in $\gamma p \to e^- e^+ p$ vs $\gamma p \to \mu^- \mu^+ p$



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

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





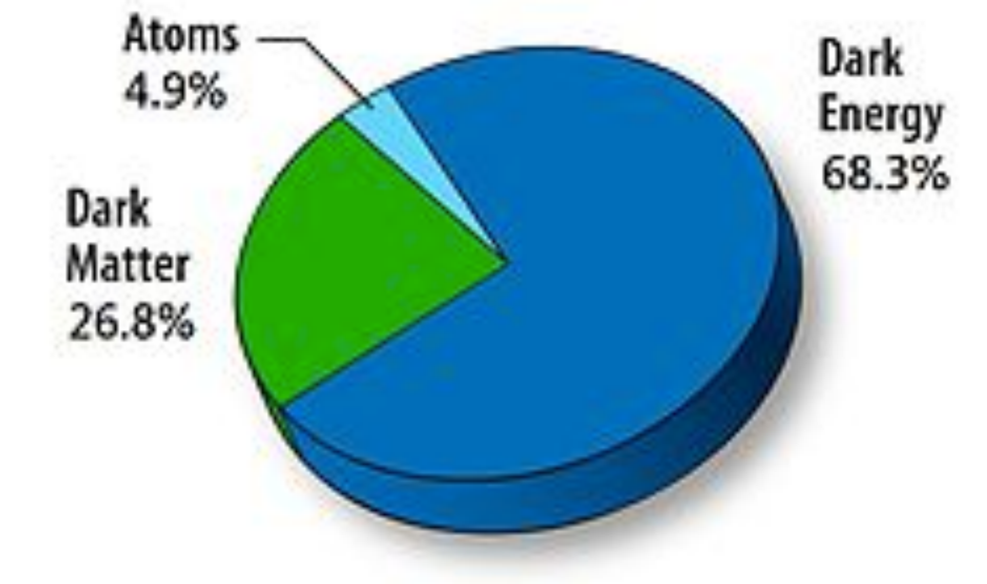
difference in measured proton charge FF
in electron vs muon observables
leads to a **0.2% absolute effect**
in $(e^- e^+ + \mu^- \mu^+)$ vs $\mu^- \mu^+$ ratio

Pauk,Vdh(2015)

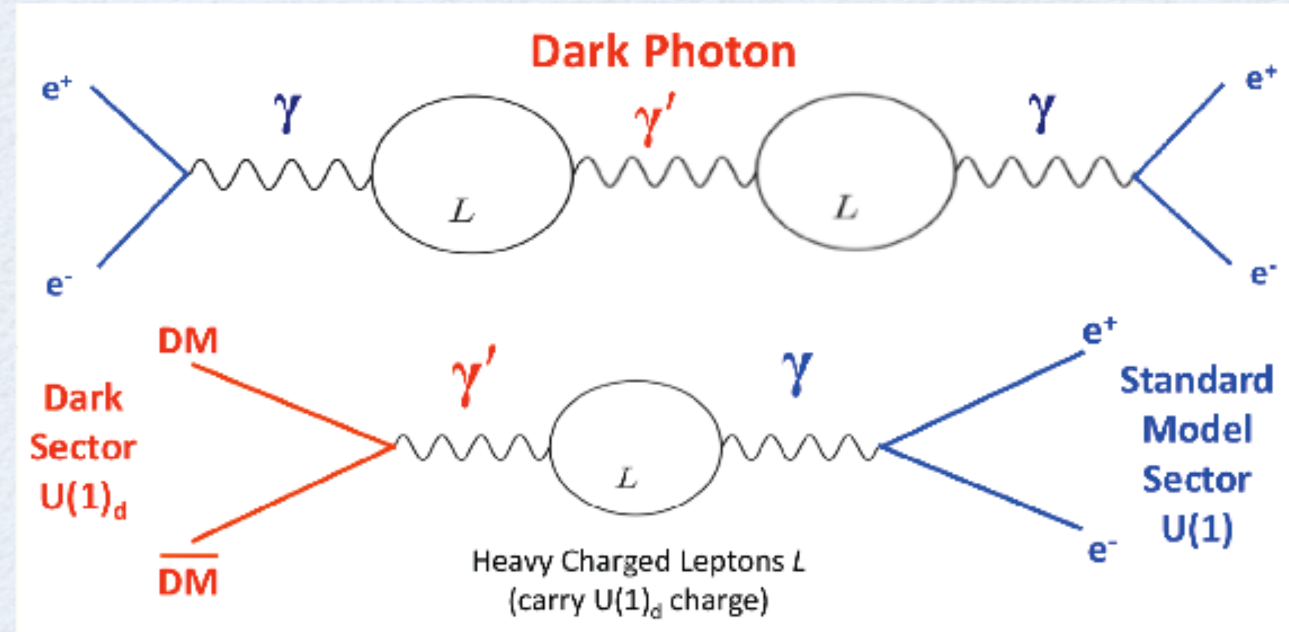
The Dark Photon

as a possible Extension of the

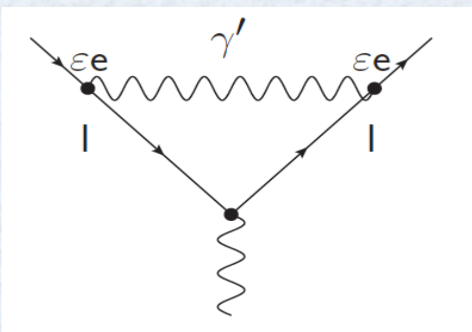
Standard Model



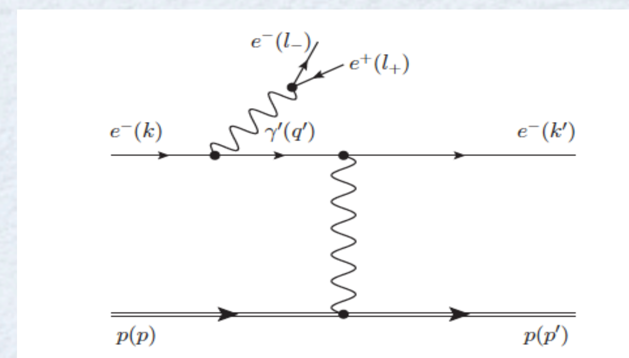
Holdom(1986),...



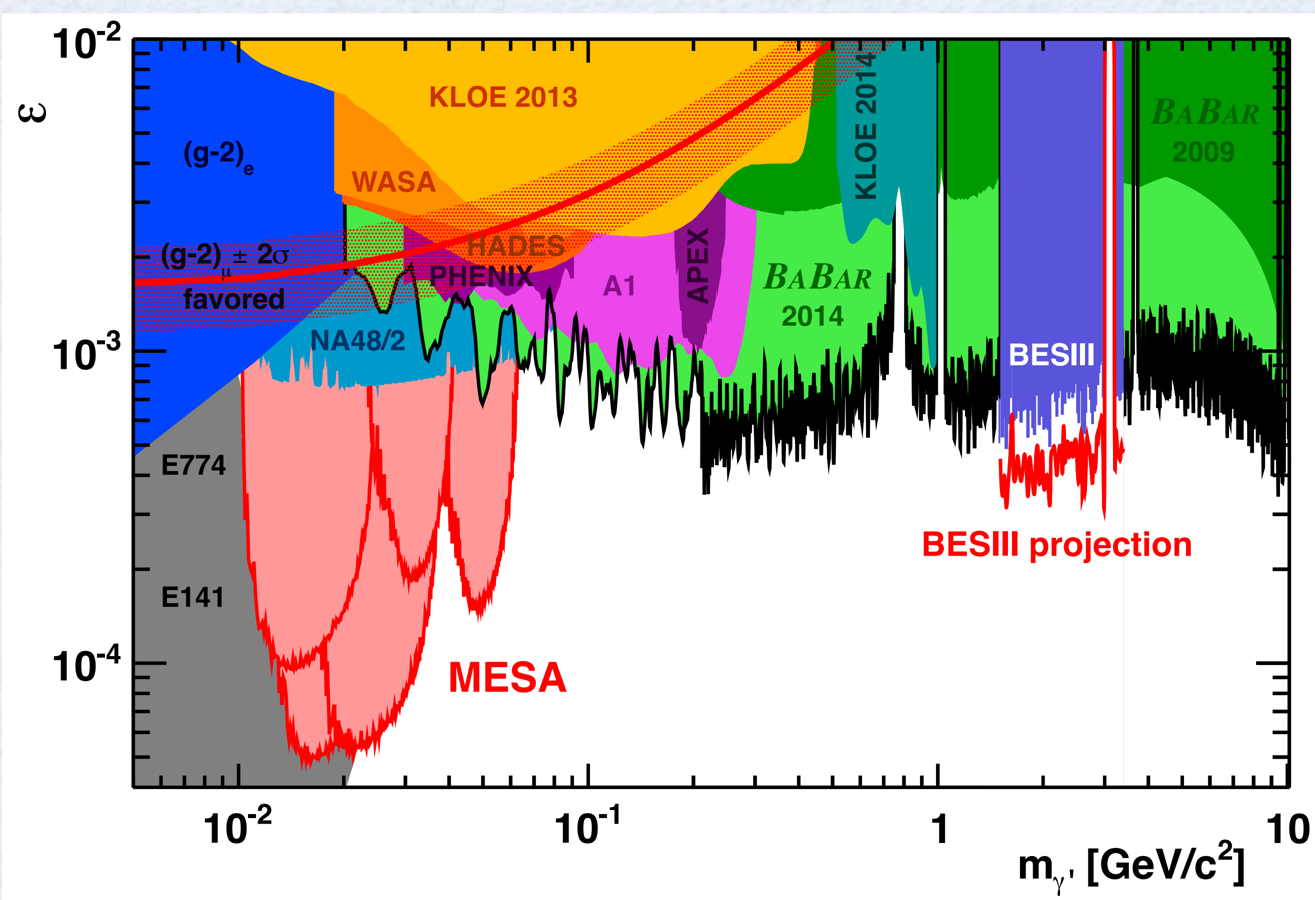
- **light dark sector**: could explain astrophysical anomalies:
  e$^+$ excess in cosmic ray flux
- **possible explanation for $(g\text{-}2)_\mu$**



red band: $(g\text{-}2)_\mu$



Bjorken et al. (2009)



Dark Photon as explanation for $(g\text{-}2)_\mu$ (almost) ruled out !

... at least in most straight-forward model

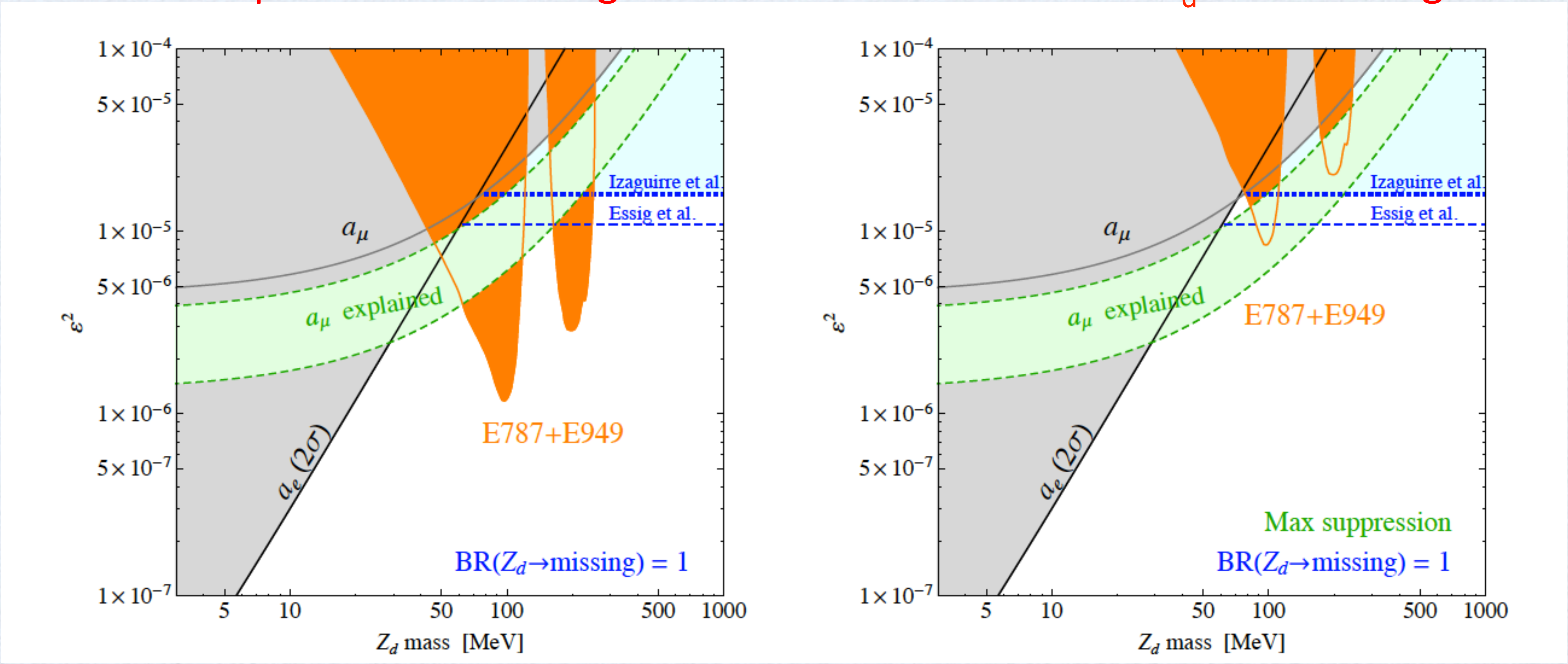
Low-mass/low-coupling range will be covered by JLab, MESA,... expts.

K➔$\pi^+\gamma_d$ Constraints for BR(Z_d➔*invisible*)~1
m_{Z_d}=100, 200MeV ruled out?

Marciano, Davoudiasl

implies dark matter X with mass $m_X < m_{Z_d}/2$

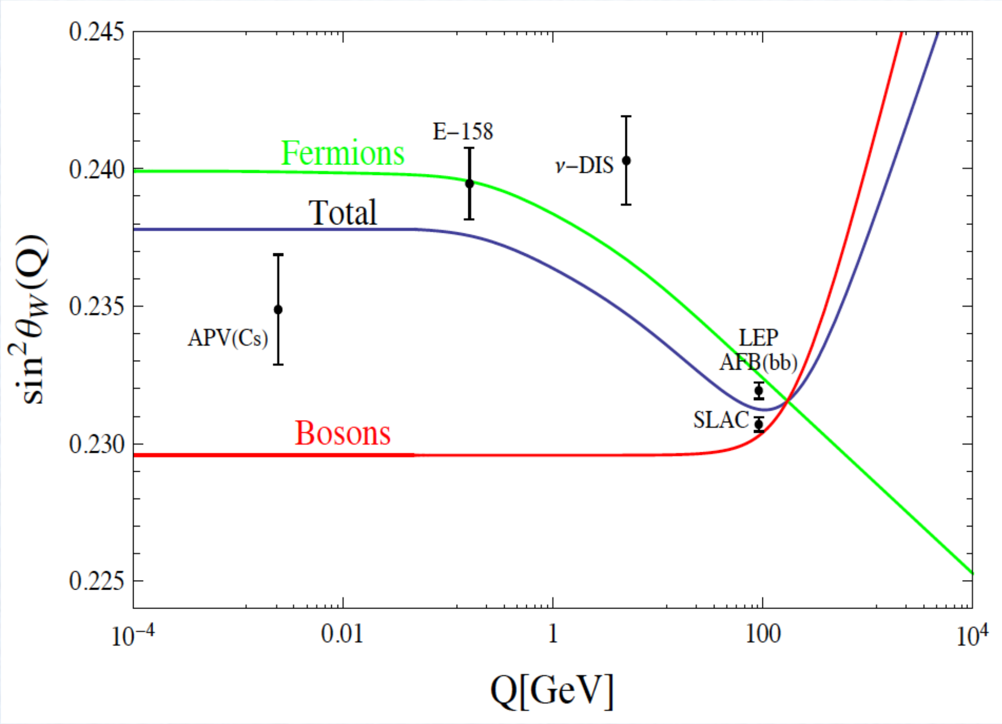
pure kinetic mixing | with Z-Z_d mass mixing

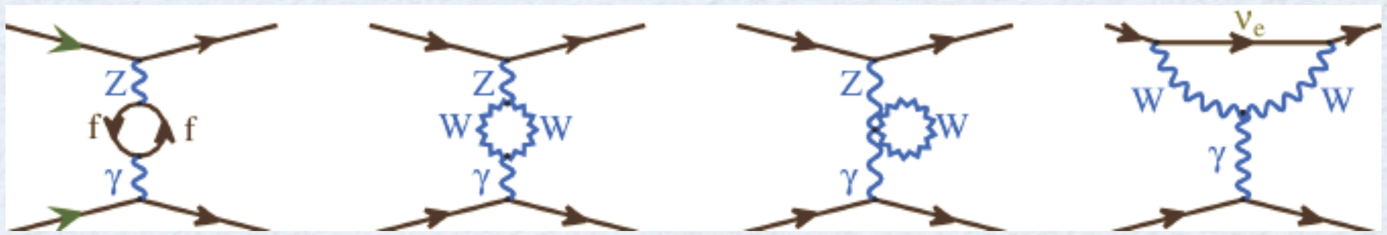


Orange: rare K decay constraints from BNL E787+E949
Blue: e^+e^- -> γ + invisible constraint from BABAR

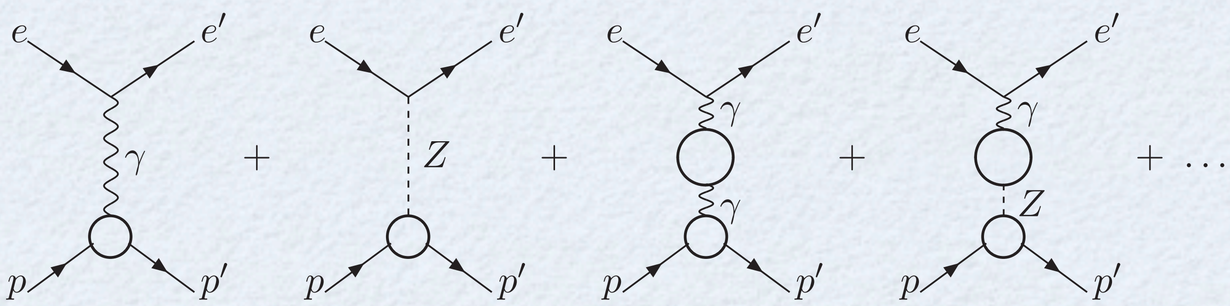
Parity Violating

Electron Scattering

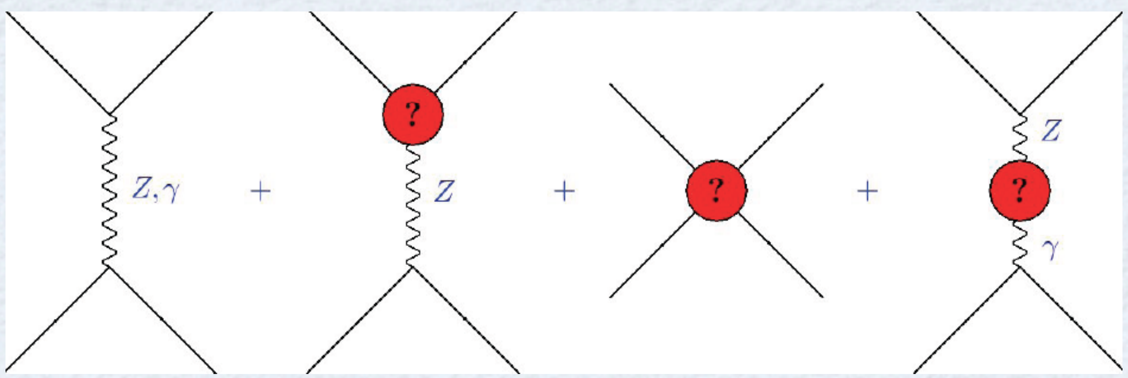




SM: universal quantum corrections leads to a scale dependent, „running“ $\sin^2\theta_W(Q)$

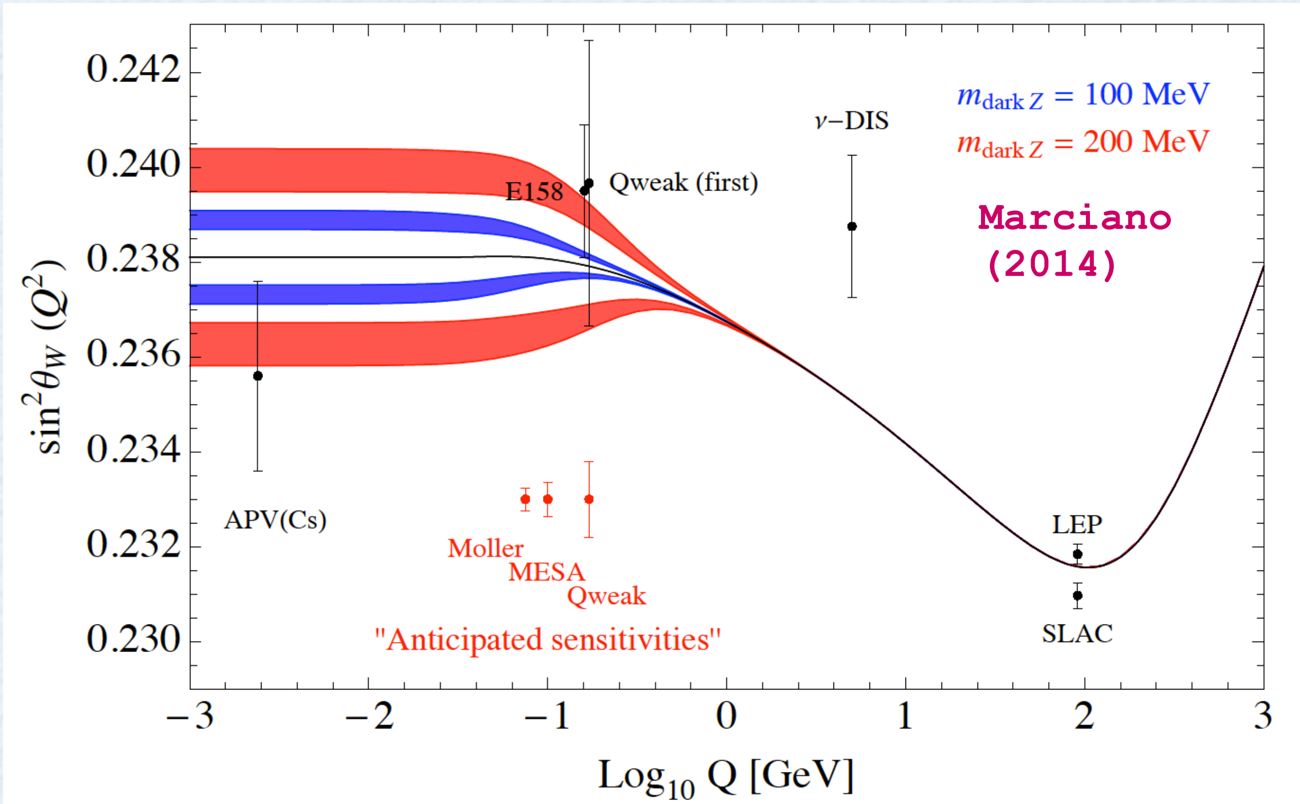


Sensitivity to new beyond SM physics:



extra Z | mixing with dark Z | contact interactions | new fermions

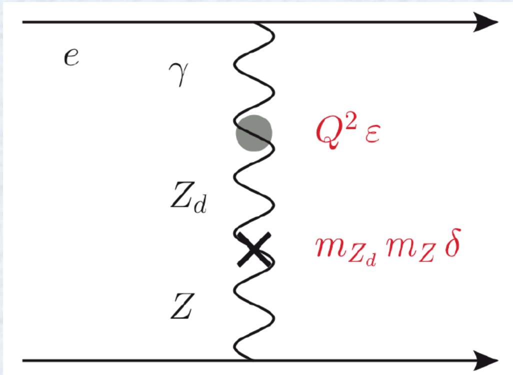
contact int: Λ_{new} ≈ 17 TeV (E158@SLAC)



➡ Project **P2**:
exceeding scale accessible in direct LHC searches, complementarity with precision searches @ LHC

P2@MESA: 0.13 % measurement of $\sin^2\theta_W$
Λ_{new} ≈ **49 TeV**

Marciano, Davoudiasl



Outlook

- proton radius puzzle had motivated to sharpen focus at the precision frontier

- generated a large exp/theo activity:

  - new measurements: srutinize results, complementarity
  - theory: improve on accuracy of hadronic corrections
    polarizability program, few-body physics (ab initio calculations) program

- new faciltiy at the precision frontier will enable
  to search for new physics (dark photons, dark matter, new parity violating interactions...)

wish you a productive meeting