Future projects with electromagnetic probes

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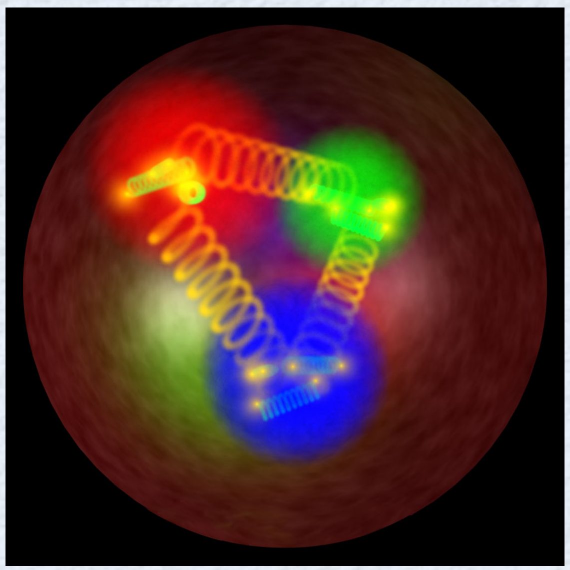
The Future of Non-Collider Physics

Mainz, April 27-28, 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

$sin^2\theta_W$

$(g-2)_\mu$

R_E Proton charge radius

Dark Photon

Strong interactions
Hadron structure
Hadron spectroscopy

↔

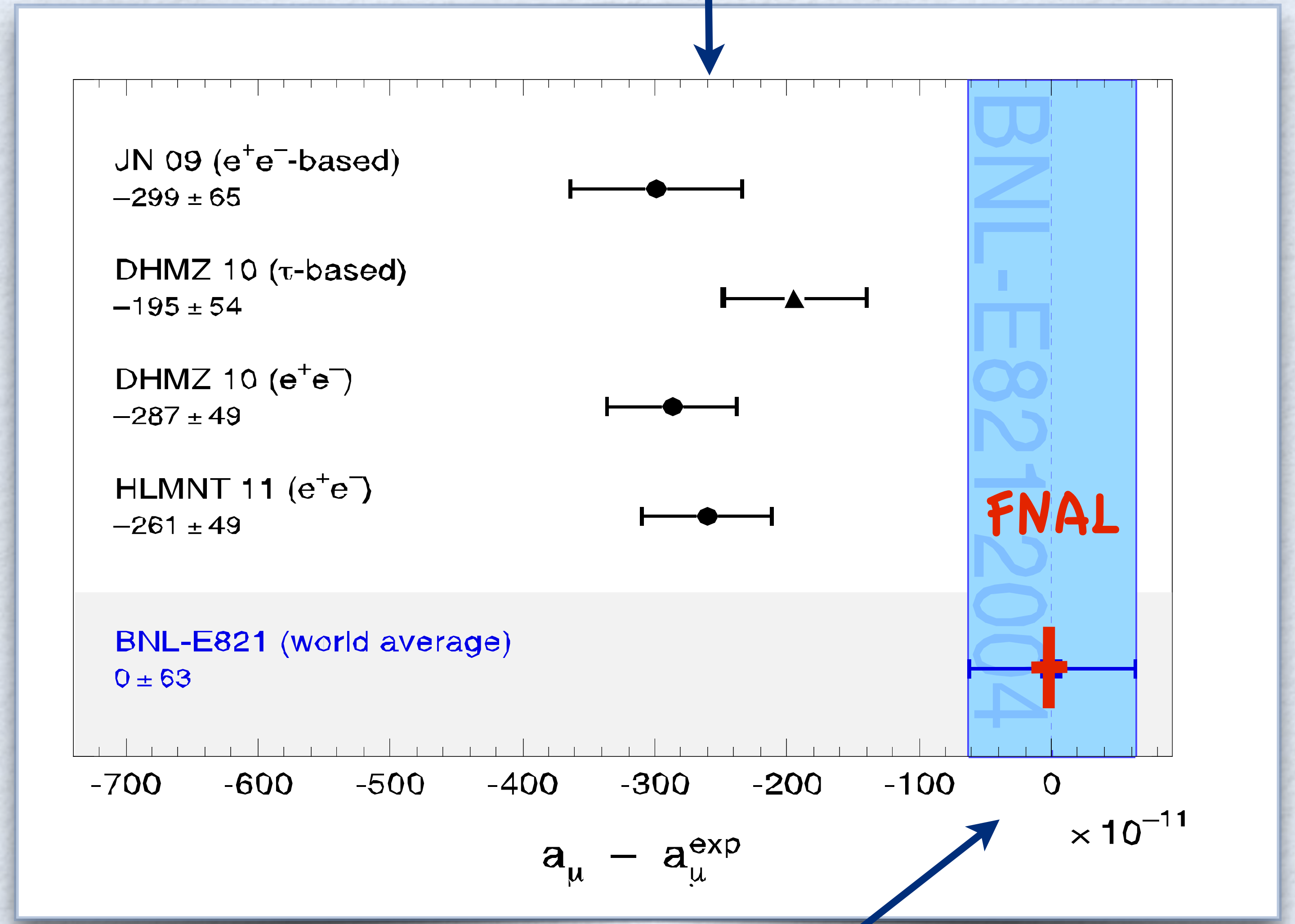
Particle physics
Atomic physics
Astro(particle) physics

Anomalous Magnetic Moment of the Muon

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

$(g-2)_\mu$: theory vs experiment

SM predictions for a_μ



BNL-E821 measurement of a_μ

$a_\mu^{exp} = (11\ 659\ 208.9 \pm 6.3) \times 10^{-10}$

$a_\mu^{exp} - a_\mu^{SM} =$

$(26.1 \pm 5.0_{\,th} \pm 6.3_{\,exp}) \times 10^{-10}$

Hagiwara et al. (2011)

3 - 4 σ deviation from SM value !

Errors or new physics ?

New FNAL, J-PARC experiments

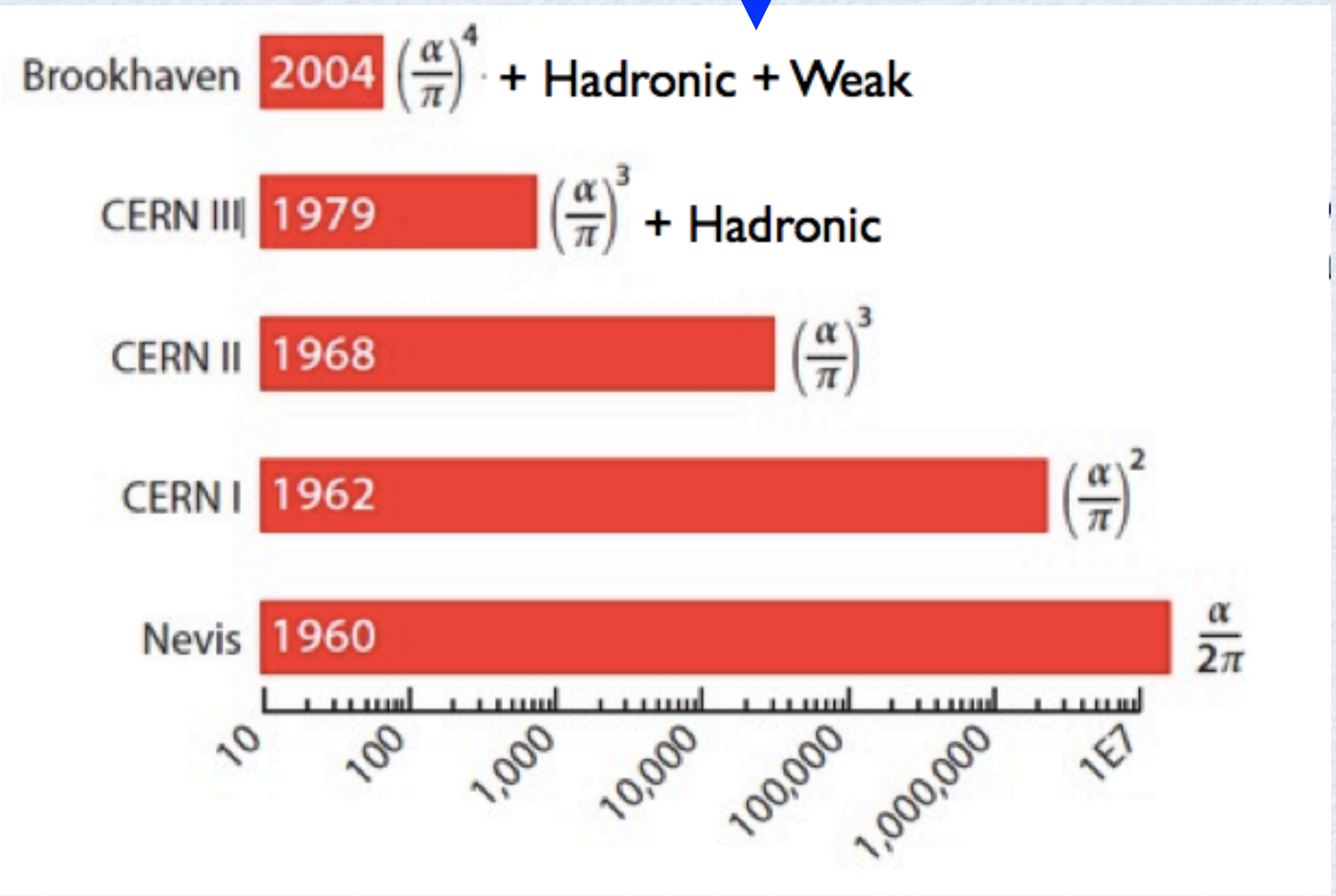
$\delta a_\mu^{FNAL} = 1.6 \times 10^{-10}$

factor 4 improvement in exp. error

-> Improve theory !

$(g-2)_\mu$: history of relevant corrections

Contribution (theory) resolved

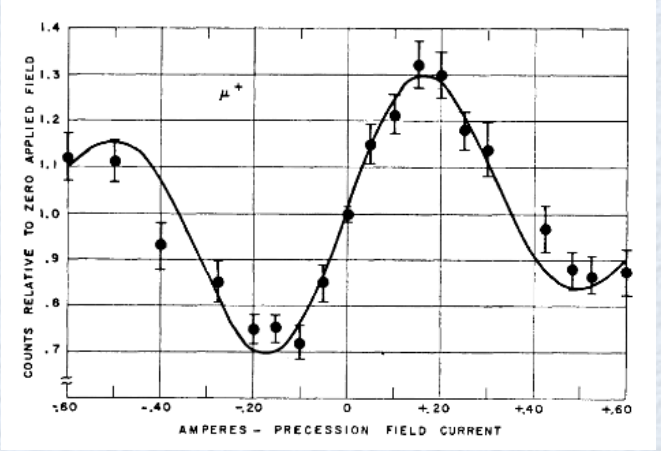


Uncertainty of measurement in 10^{-11}

Brookhaven

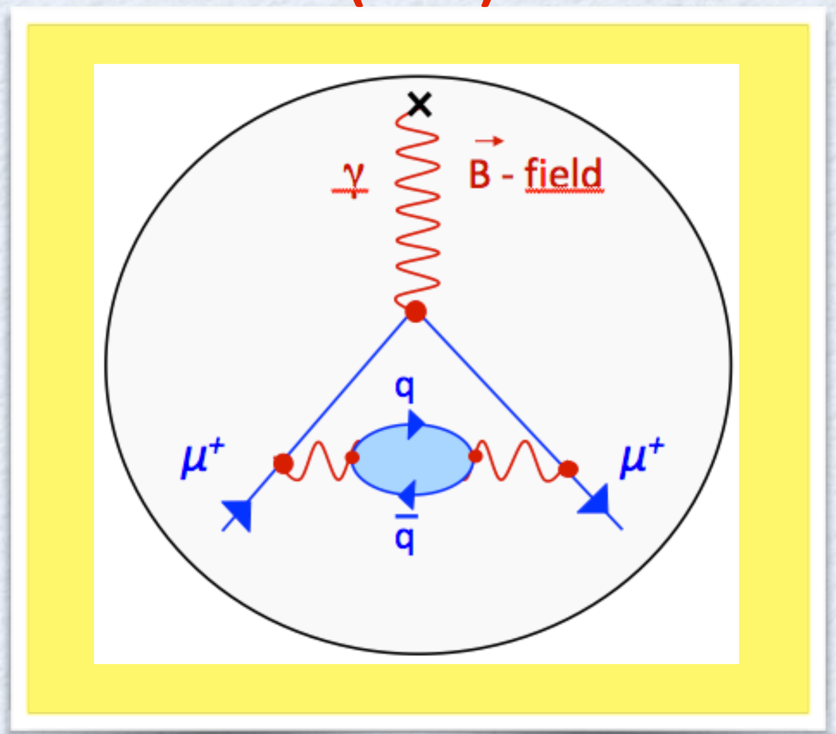
CERN I

Nevis



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

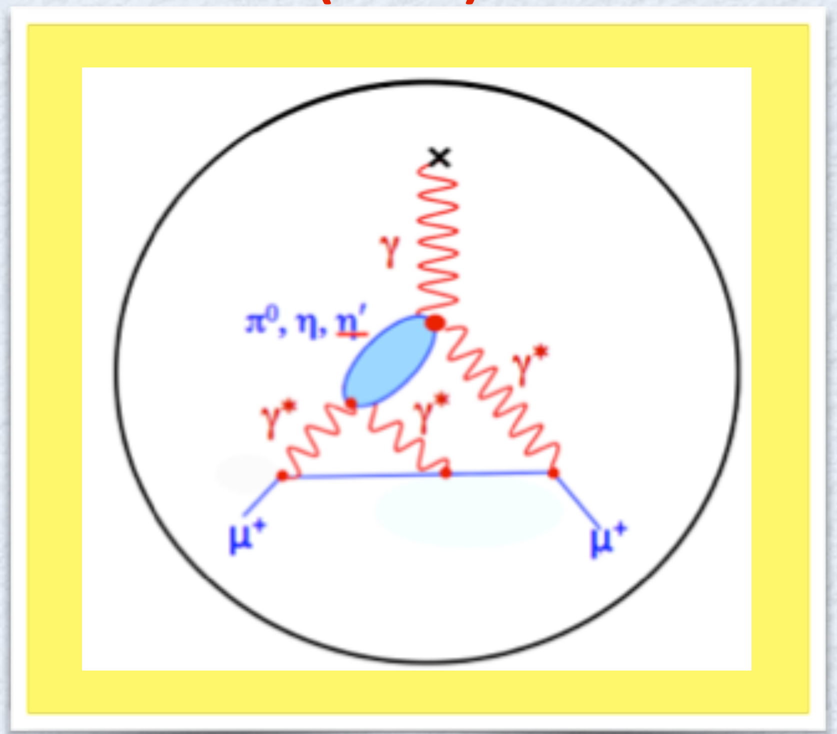
hadronic vacuum polarization (HVP)



$a_\mu^{\text{l.o. had, VP}} = (692.3 \pm 4.2) \times 10^{-10}$

Teubner et al. (2011)

hadronic light-by-light scattering (HLbL)



$a_\mu^{\text{had, LbL}} = (10.5 \pm 2.6) \times 10^{-10}$ (I)

$= (10.2 \pm 3.9) \times 10^{-10}$ (II)

(I) Prades,de Rafael, Vainshtein(2009)

(II) Jegerlehner(2015)

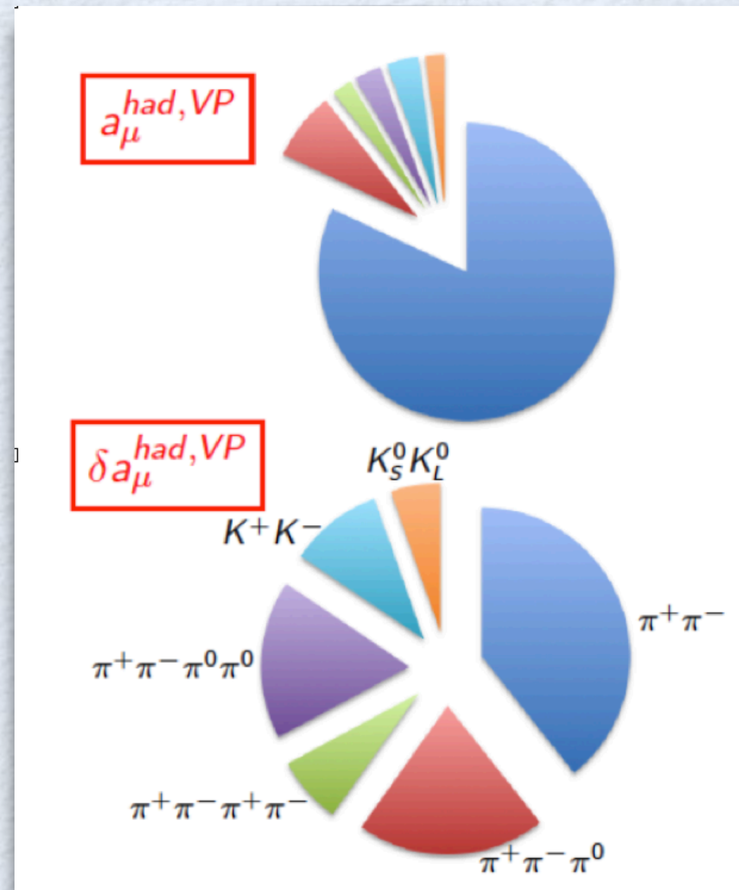
New FNAL and J-Parc $(g\text{-}2)_\mu$ expt. : $\delta a_\mu^{exp} = 1.6 \times 10^{-10}$

HVP determined by cross section measurements of e^+e^- -> hadrons

measurements of meson transition form factors required as input to reduce uncertainty

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

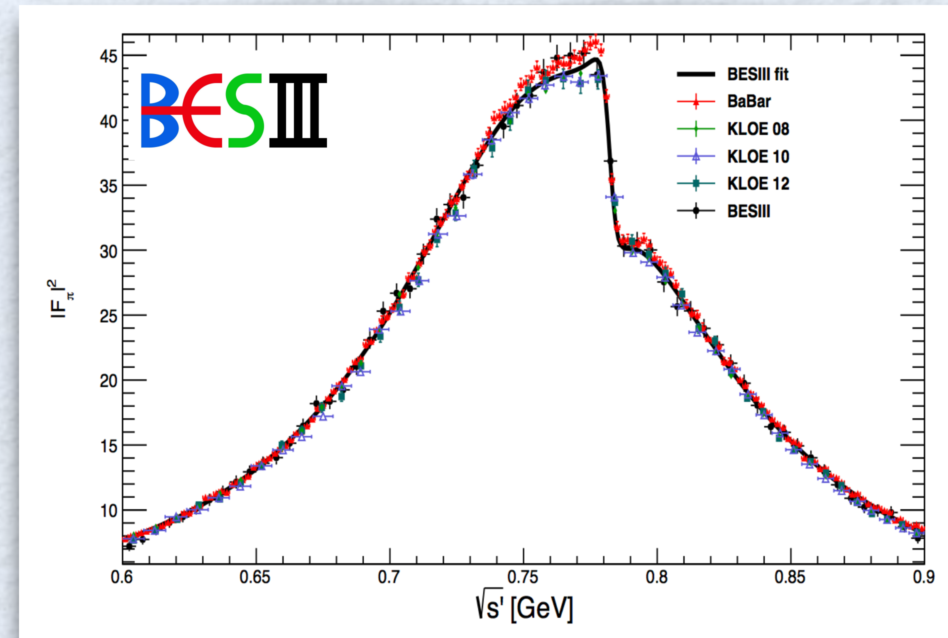
➡ **data:** optical theorem and analyticity allow to relate HVP correction with $\sigma(e^+e^- \rightarrow \text{hadrons})$

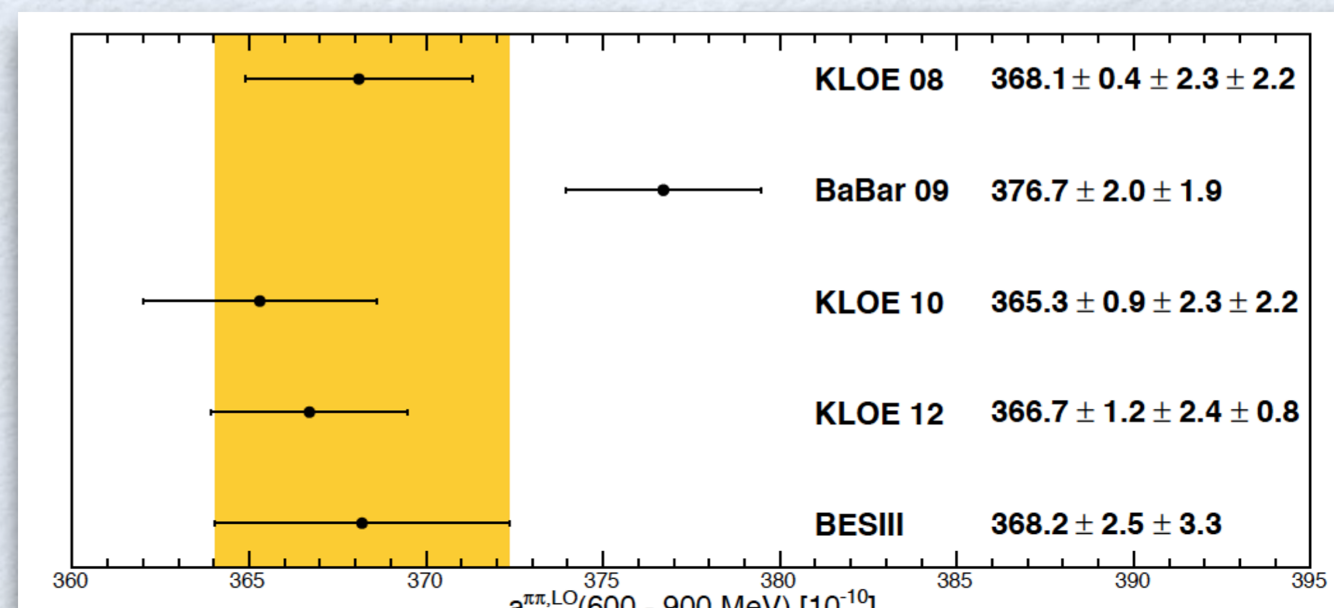


New BESIII data for $\pi^+\pi^-$ channel

PLB 753 (2016) 629

0.9% systematic uncertainty achieved



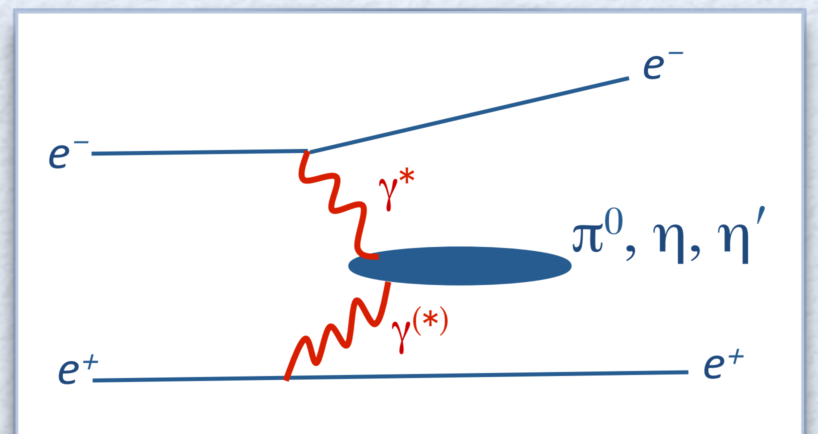


➡ **theory developments:**
dispersion theory, lattice QCD

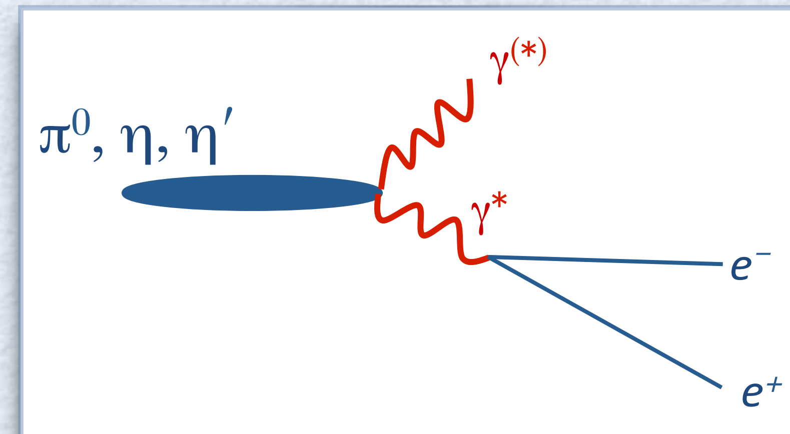
aim: reduction of current error by factor of 2

hadronic LbL corrections to $(g\text{-}2)_\mu$

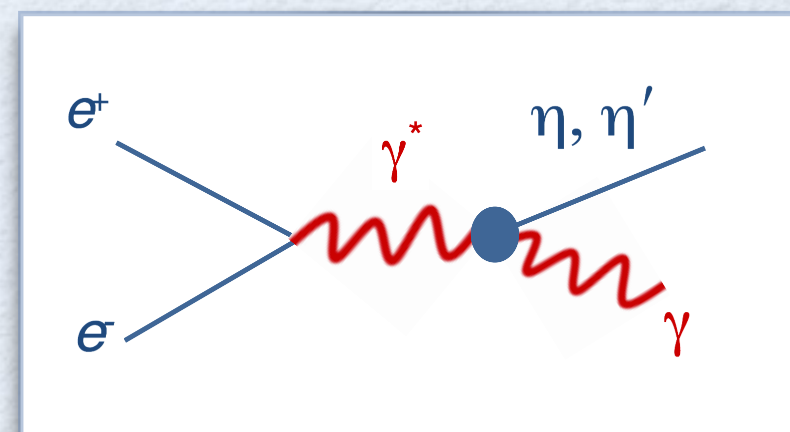
experimental input: meson transition FFs, $\gamma^* \gamma^*$ -> multi-meson states, meson Dalitz decays



CLEO, BaBar, Belle, BESIII, ...



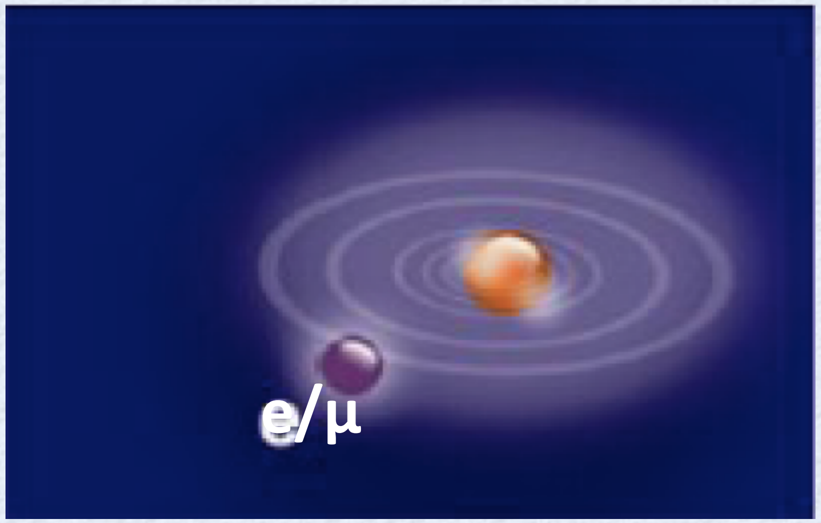
KLOE, MAMI/A2, BESIII, ...

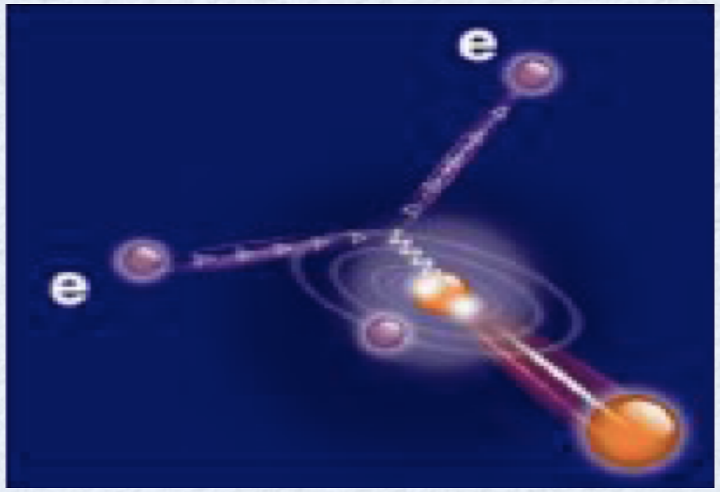


SND, CMD-2, BESIII, ...

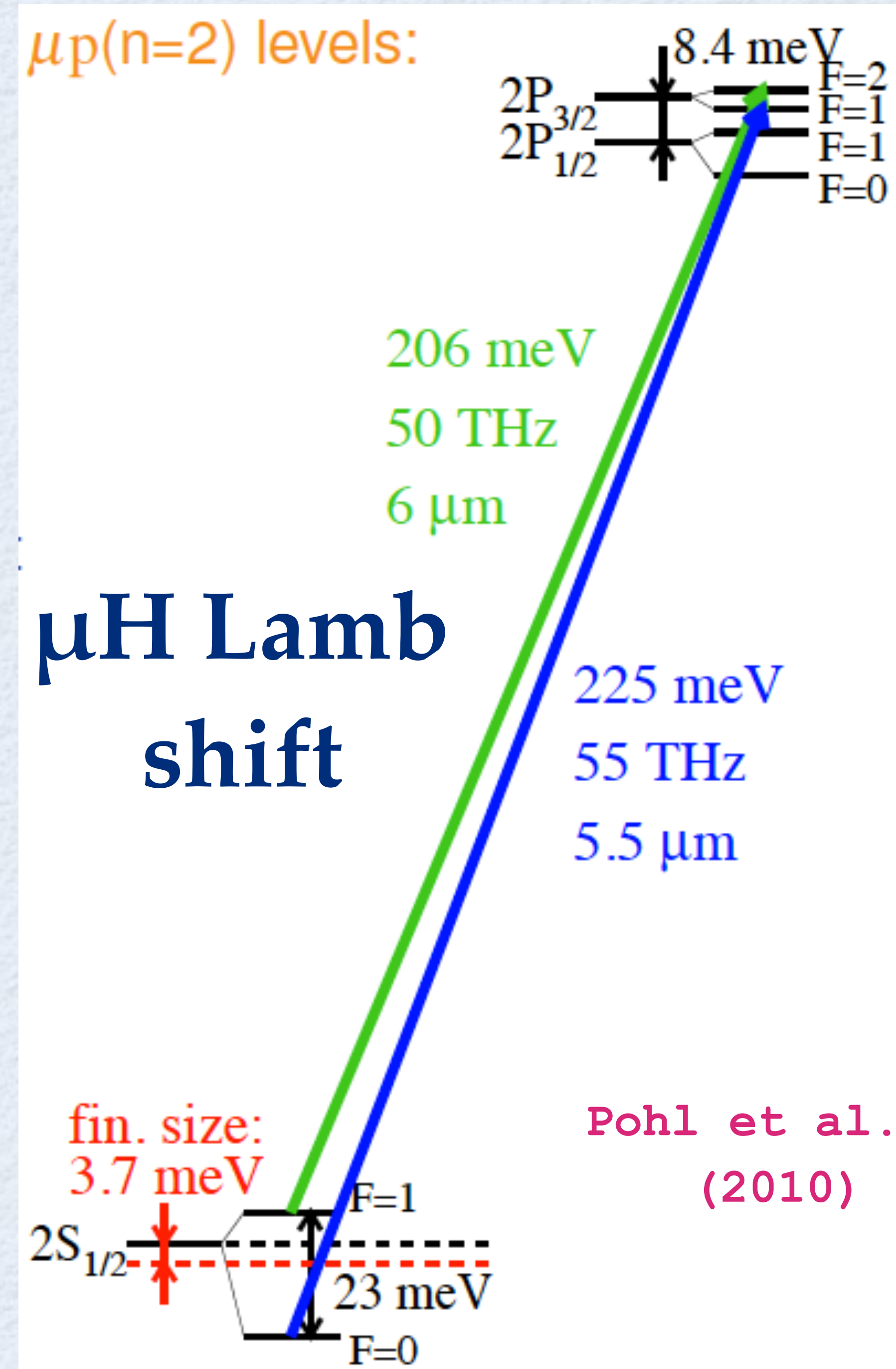
theory deveolpments: - sum rules, dispersion relations
- lattice QCD
- Dyson-Schwinger
- phenomenology, modeling

Proton Radius Puzzle





Proton radius from Hydrogen spectroscopy



$$\Delta E_{LS} = 206.0336\,(15)\; - \;5.2275\,(10)\; R_E^2 \; + \; \Delta E_{TPE} \qquad \text{meV}$$

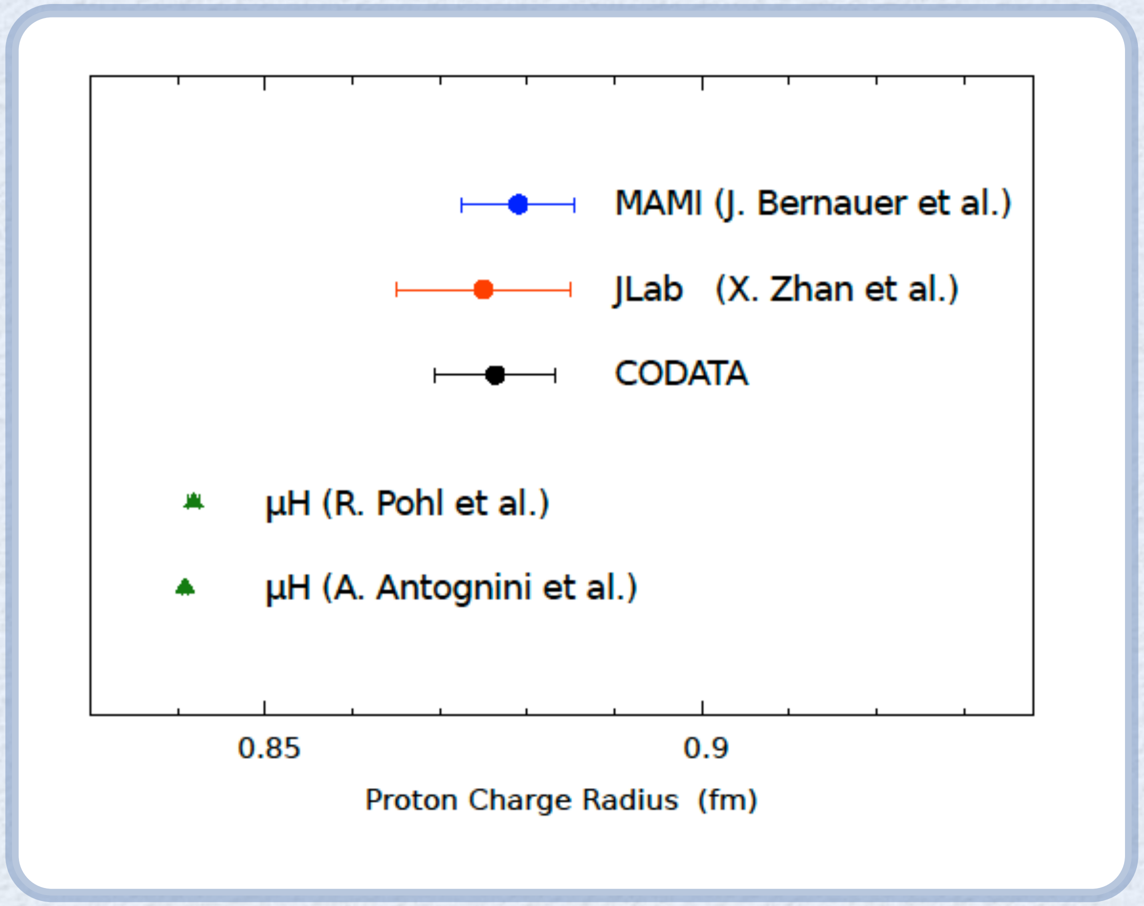
Antognini et al.(2013)

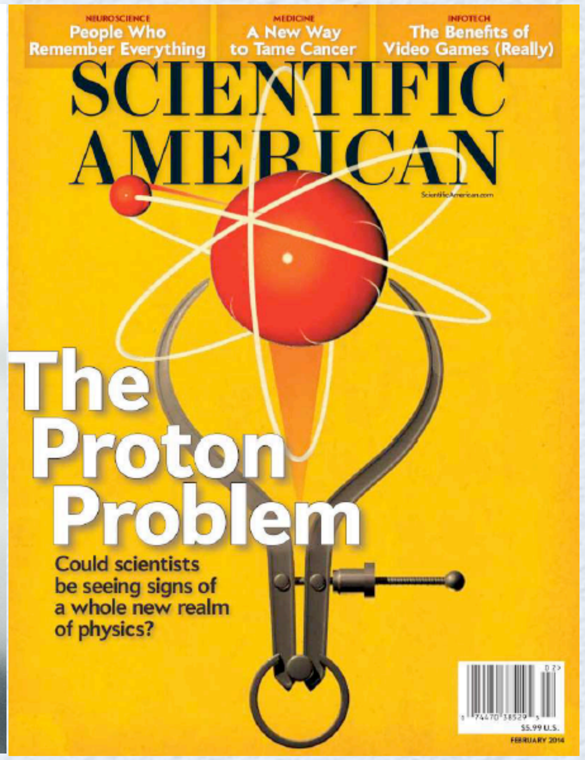
3.70 meV

$O(\alpha^5)$ correction

0.0332 (20) meV

Proton radius puzzle





μH data: $R_E = 0.8409 \pm 0.0004$ fm

Pohl et al. (2010)

Antognini et al. (2013)

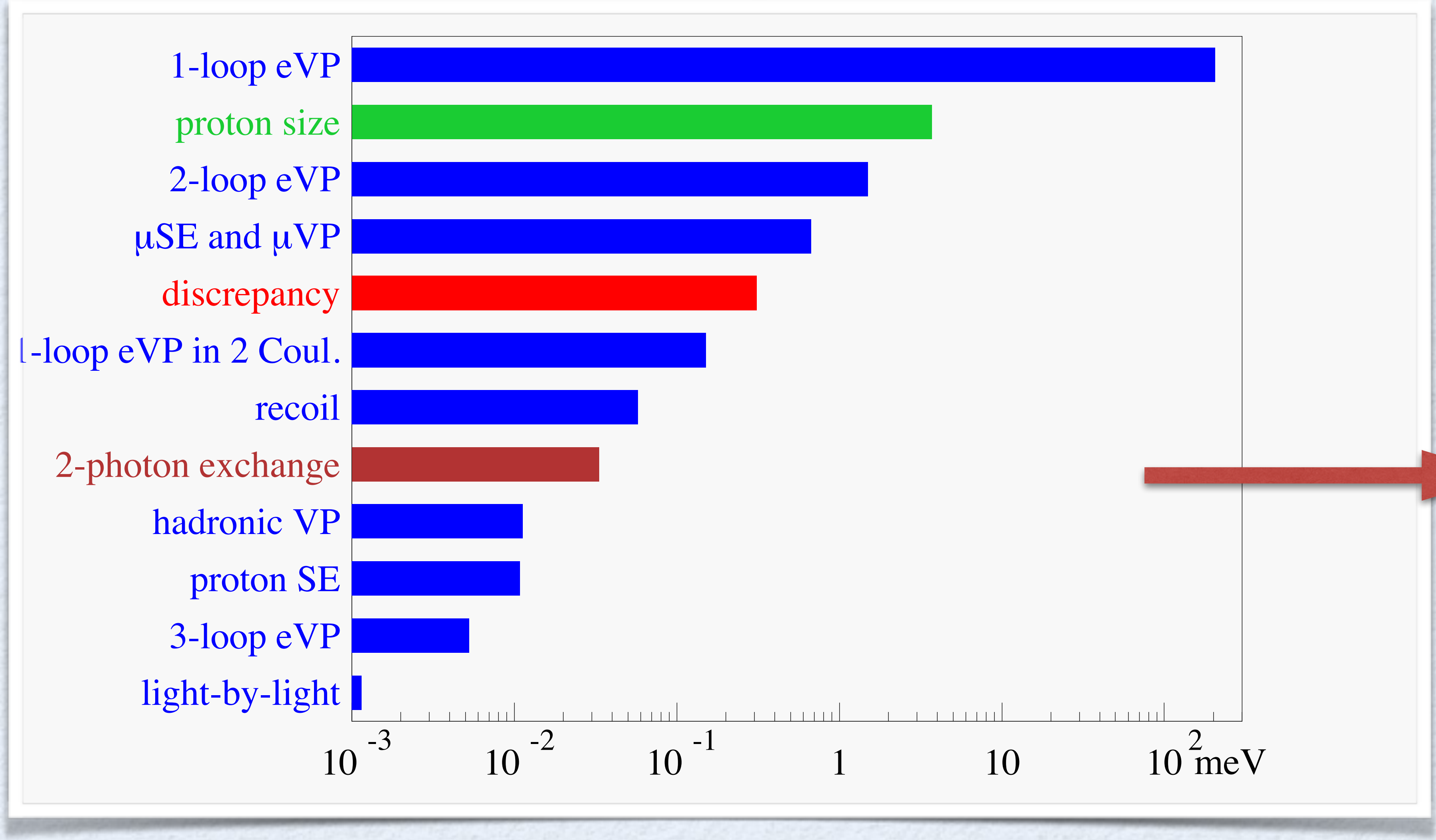
7 σ difference !?

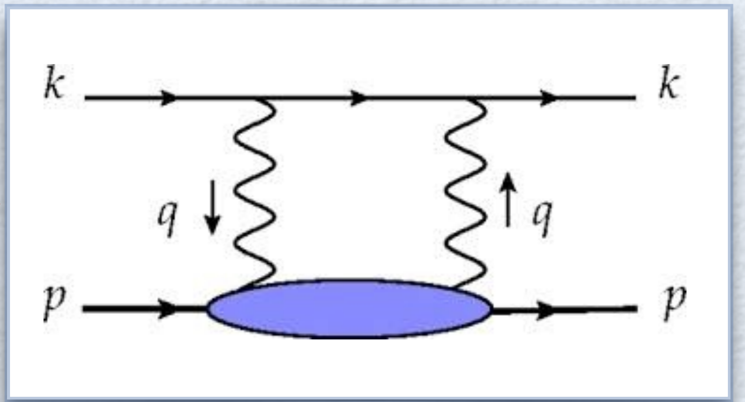
ep data: $R_E = 0.8775 \pm 0.0051$ fm

CODATA (2012)

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

ΔE_{TPE} = (33 ± 2) μeV

...or about 10% of needed correction

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)

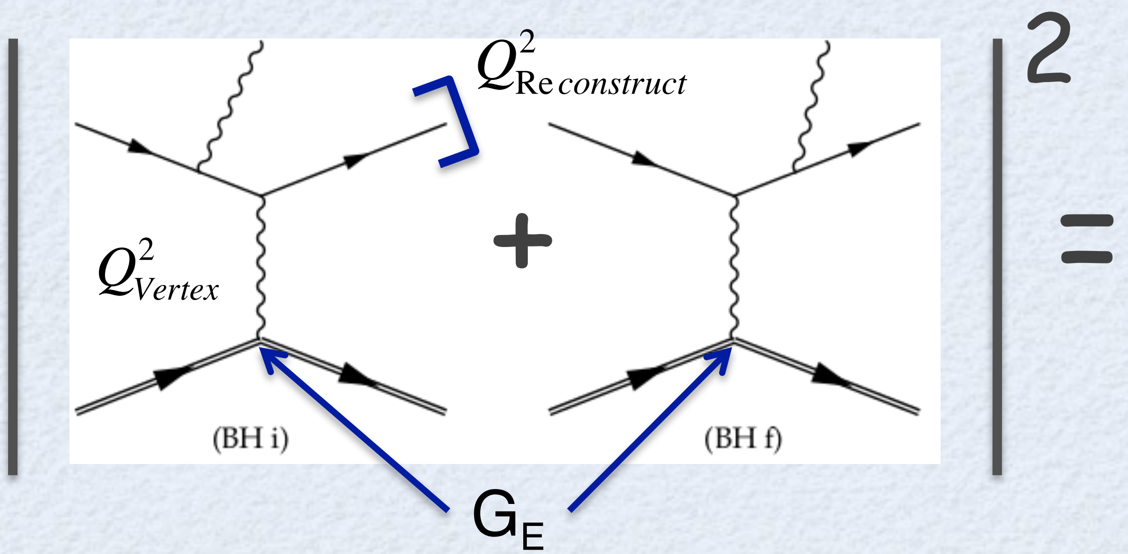
  - MESA: low-energy, high resolution spectrometers

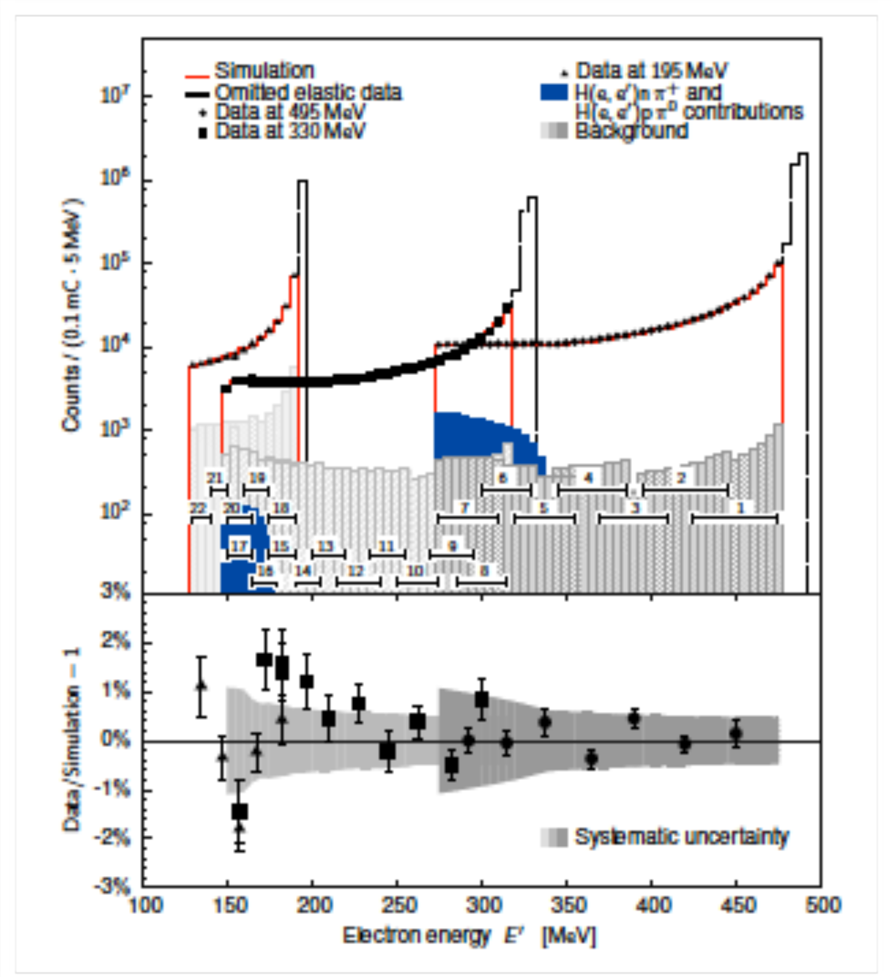
- muon scattering experiments: MUSE@PSI (2018/9)

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

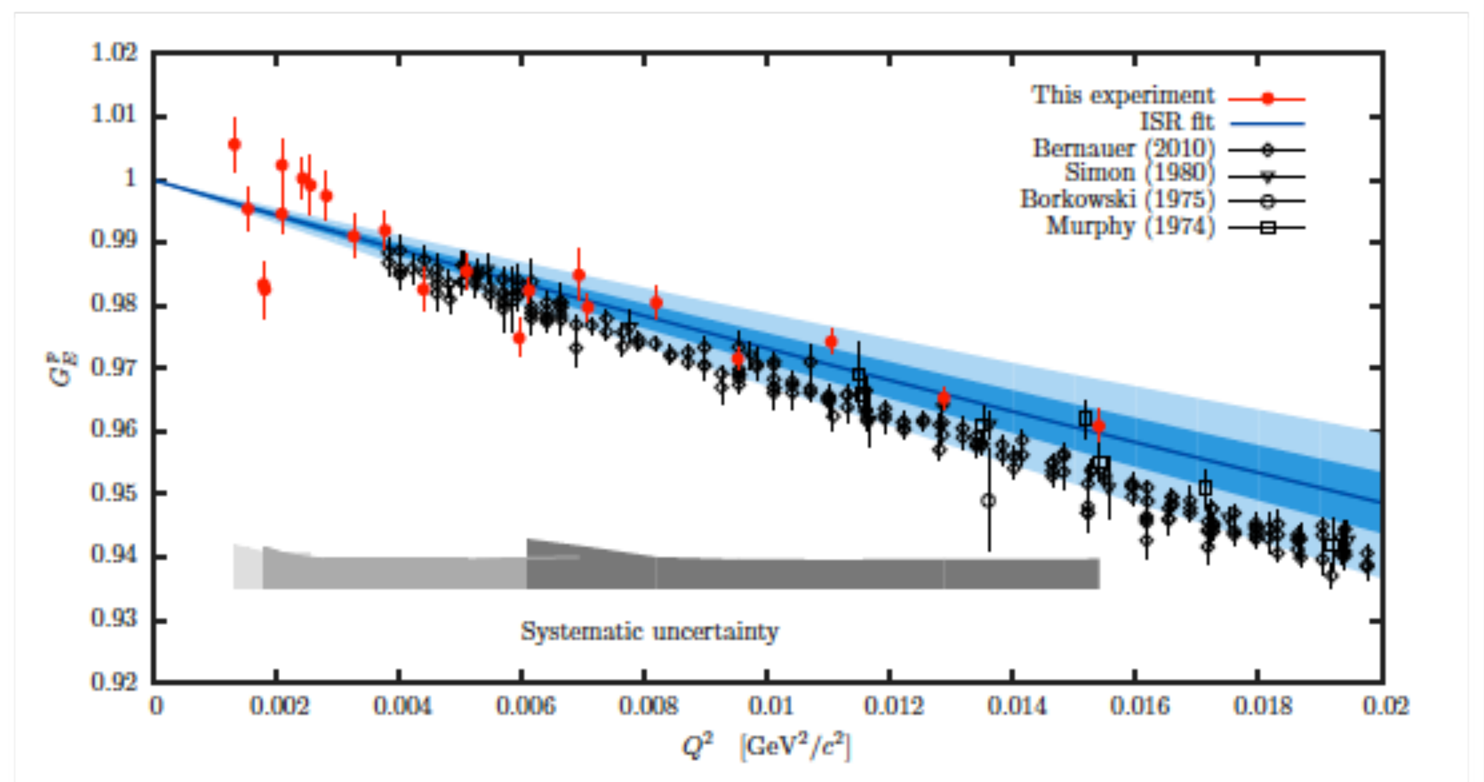
ISR@MAMI experiment

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





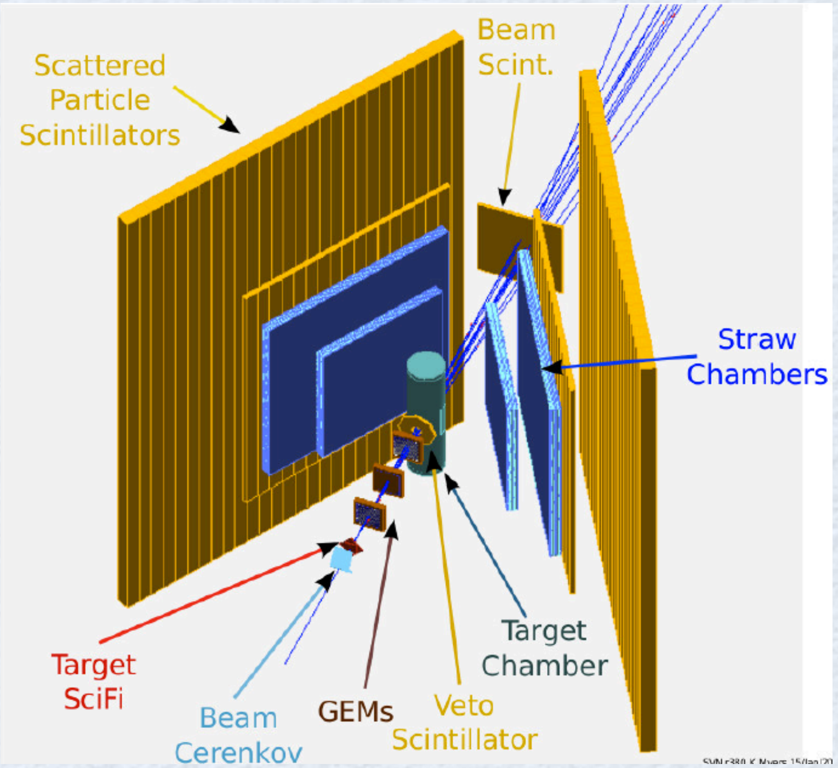
Mihovilovic et al.(2016)



good understanding of radiative tail (~ 1%)

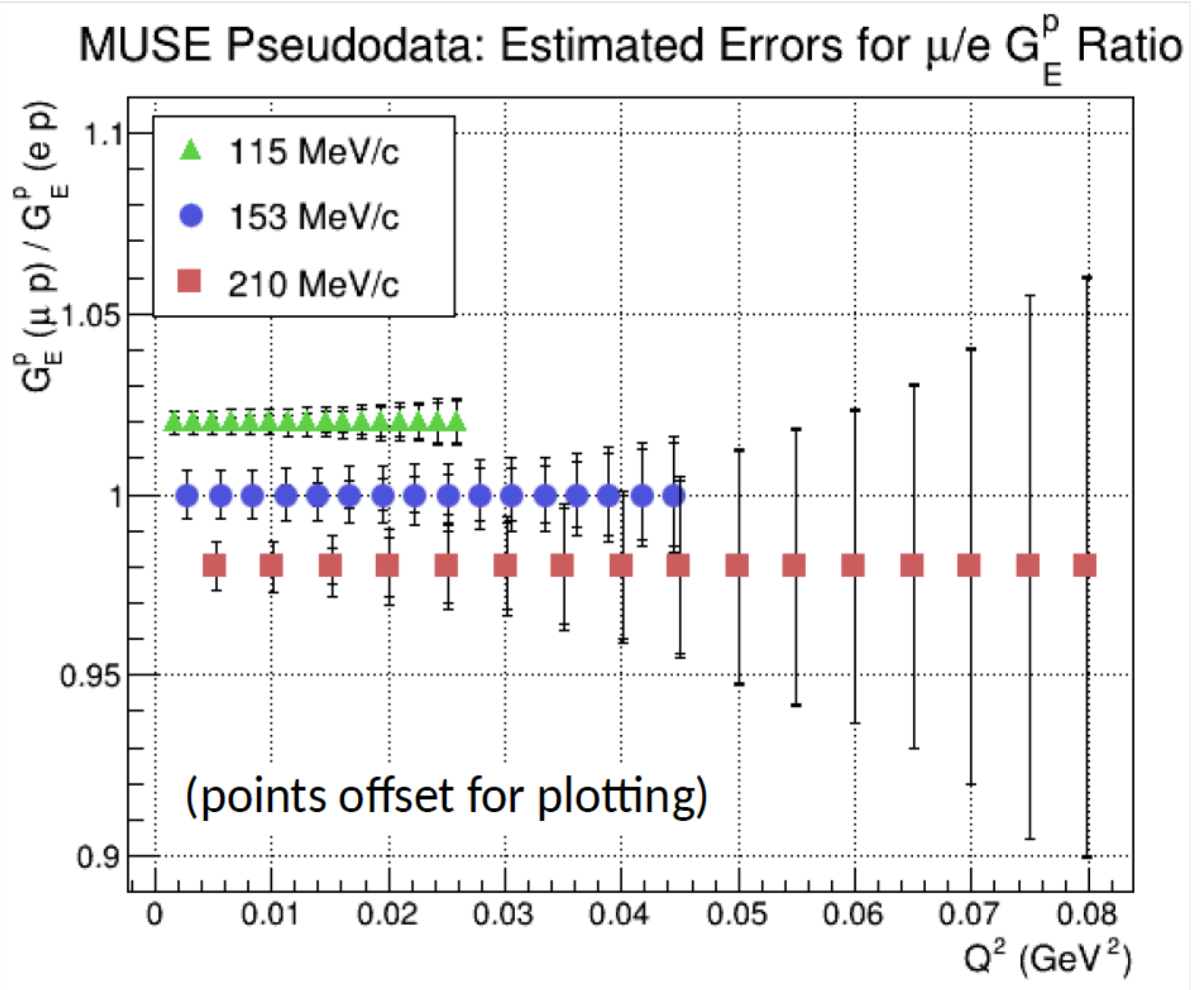
follow up experiment: down to $Q^2 \approx 2 \times 10^{-4}$ GeV^2

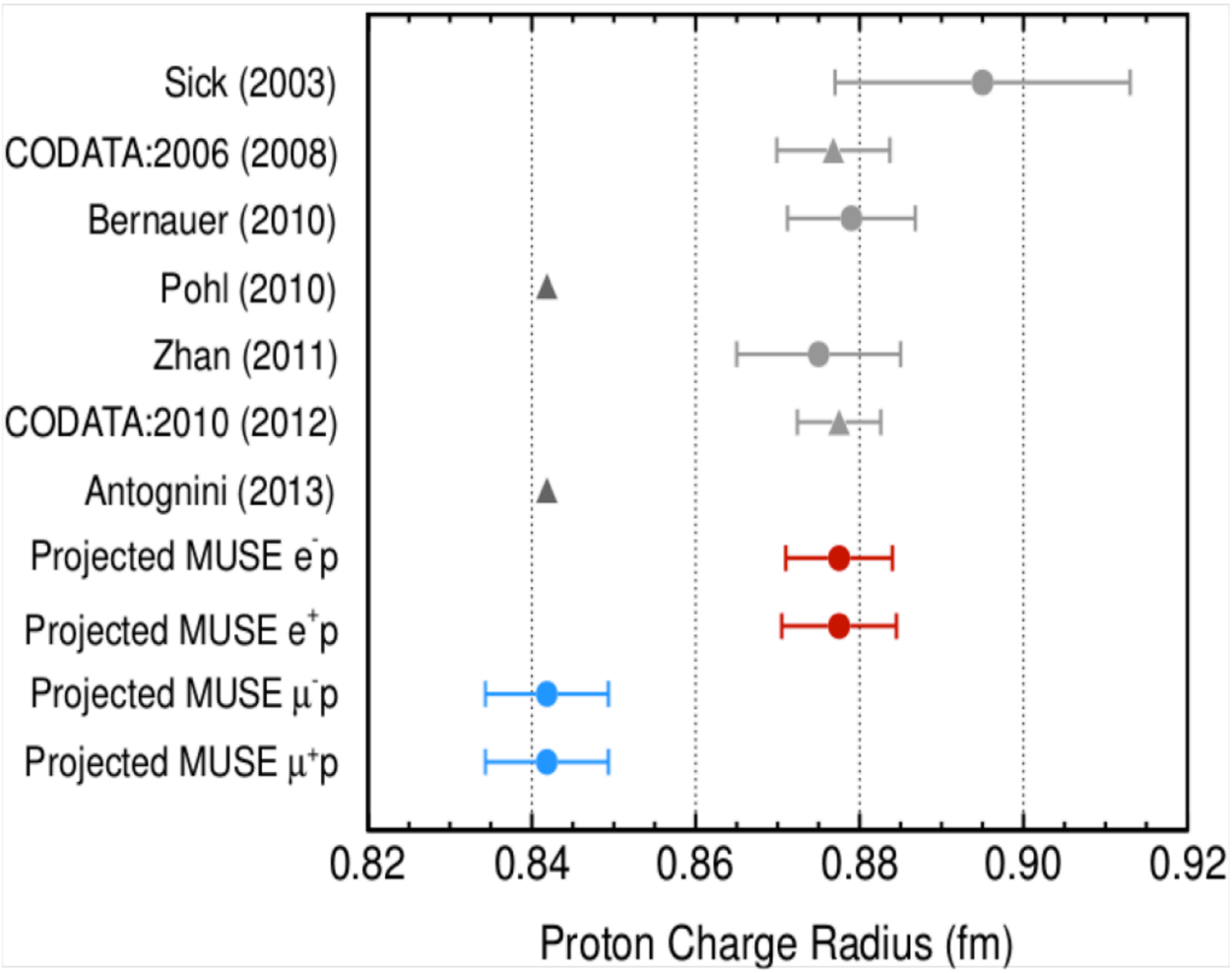
MUSE@PSI experiment



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

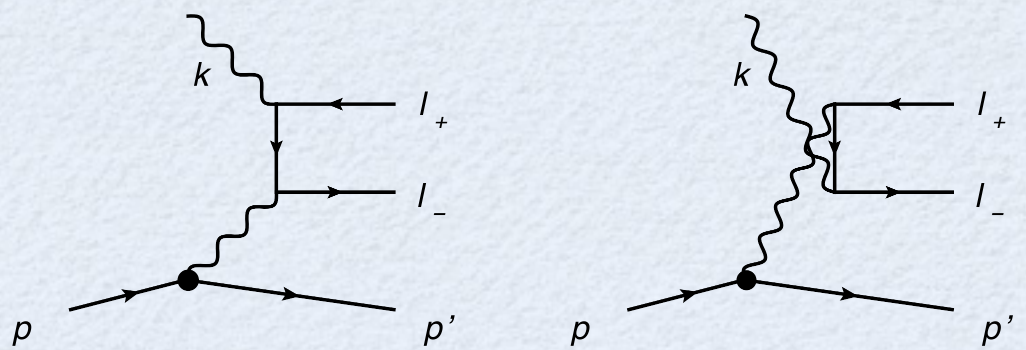
elastic scattering absolute cross sections





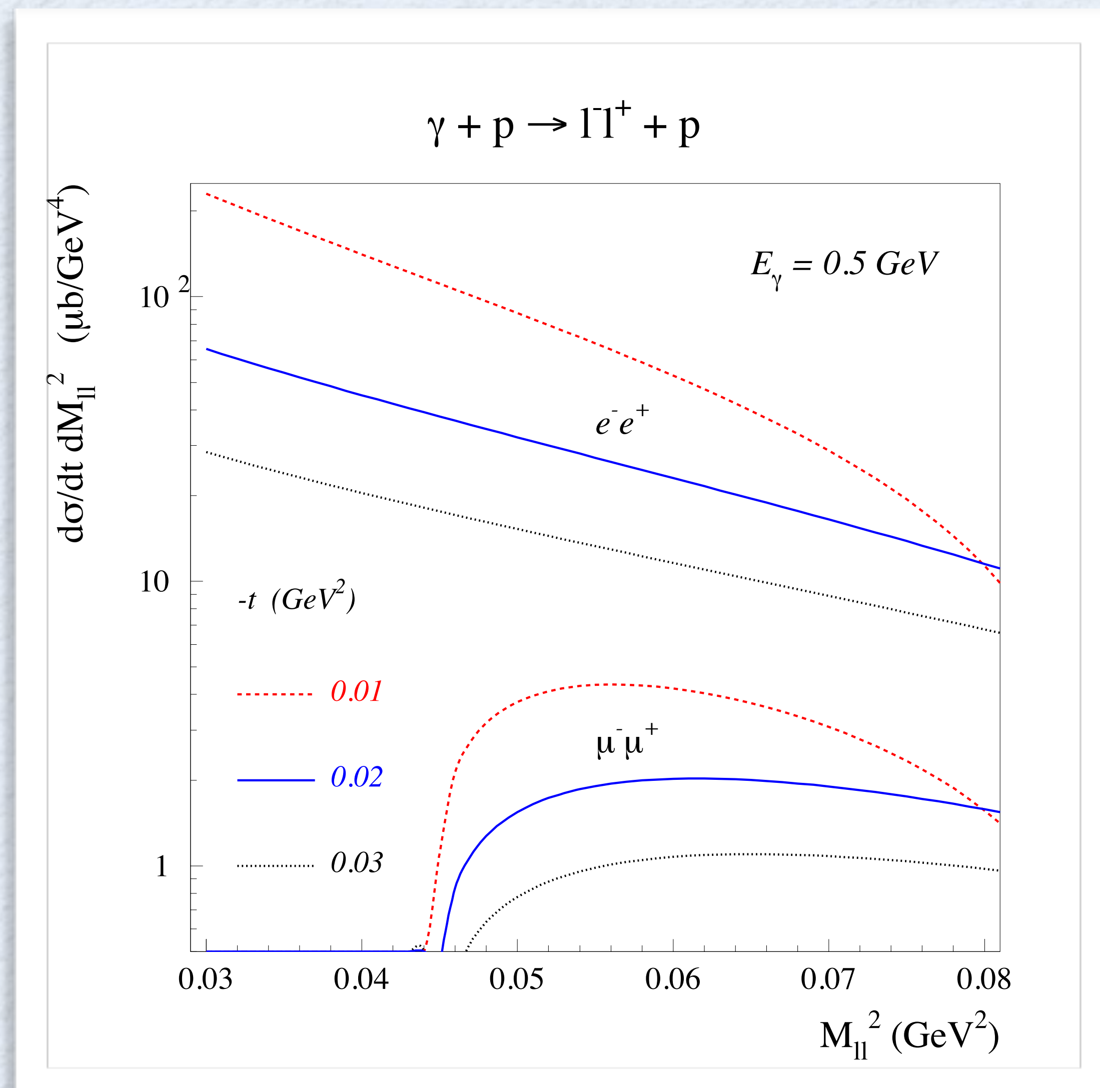
production run planned 2018 - 2019

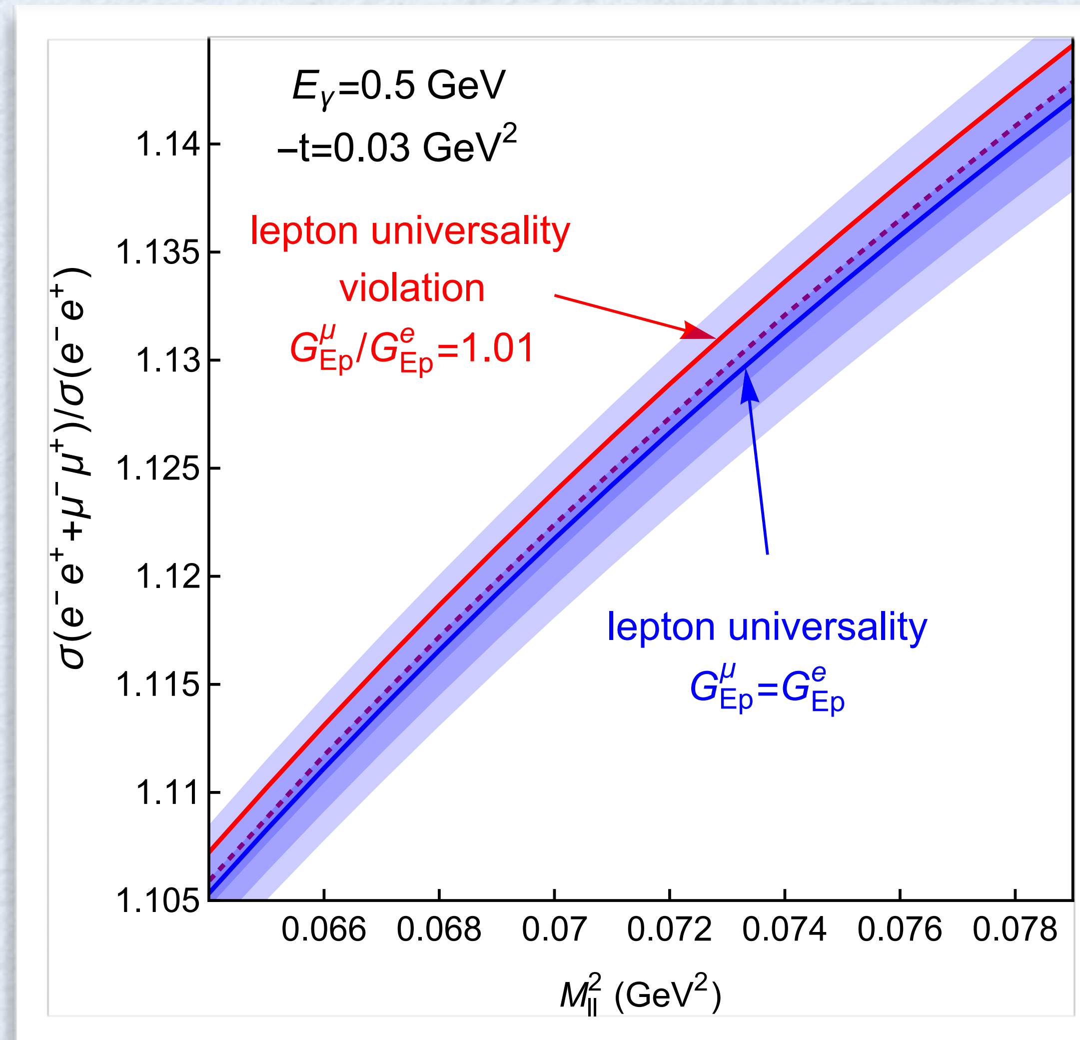
Lepton universality test in
$\gamma p \rightarrow e^- e^+ p$ vs $\gamma p \rightarrow \mu^- \mu^+ p$



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

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





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)

New facility MESA

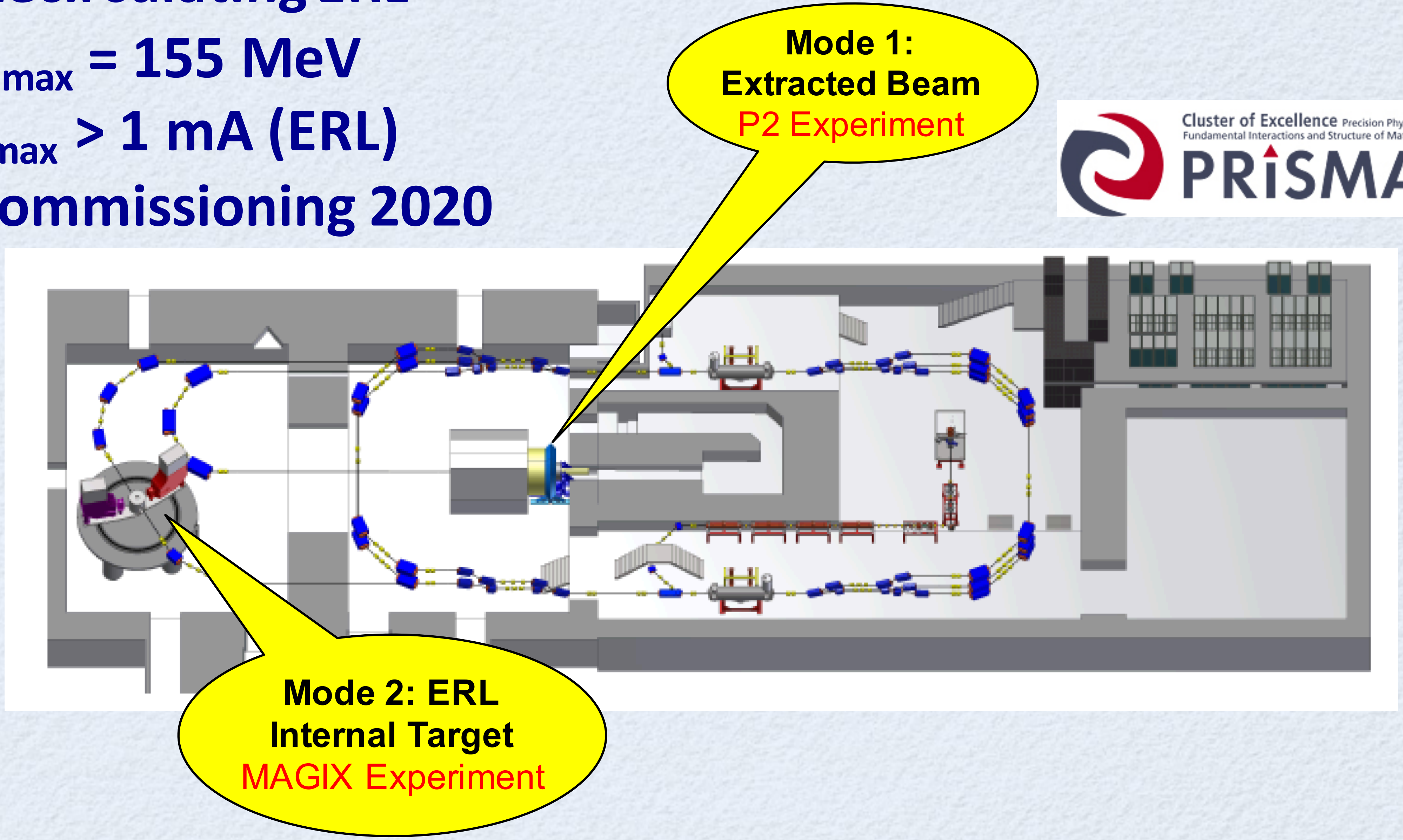
Mainz Energy-Recovering Superconducting Accelerator

Recirculating ERL

E_{max} = 155 MeV

I_{max} > 1 mA (ERL)

commissioning 2020

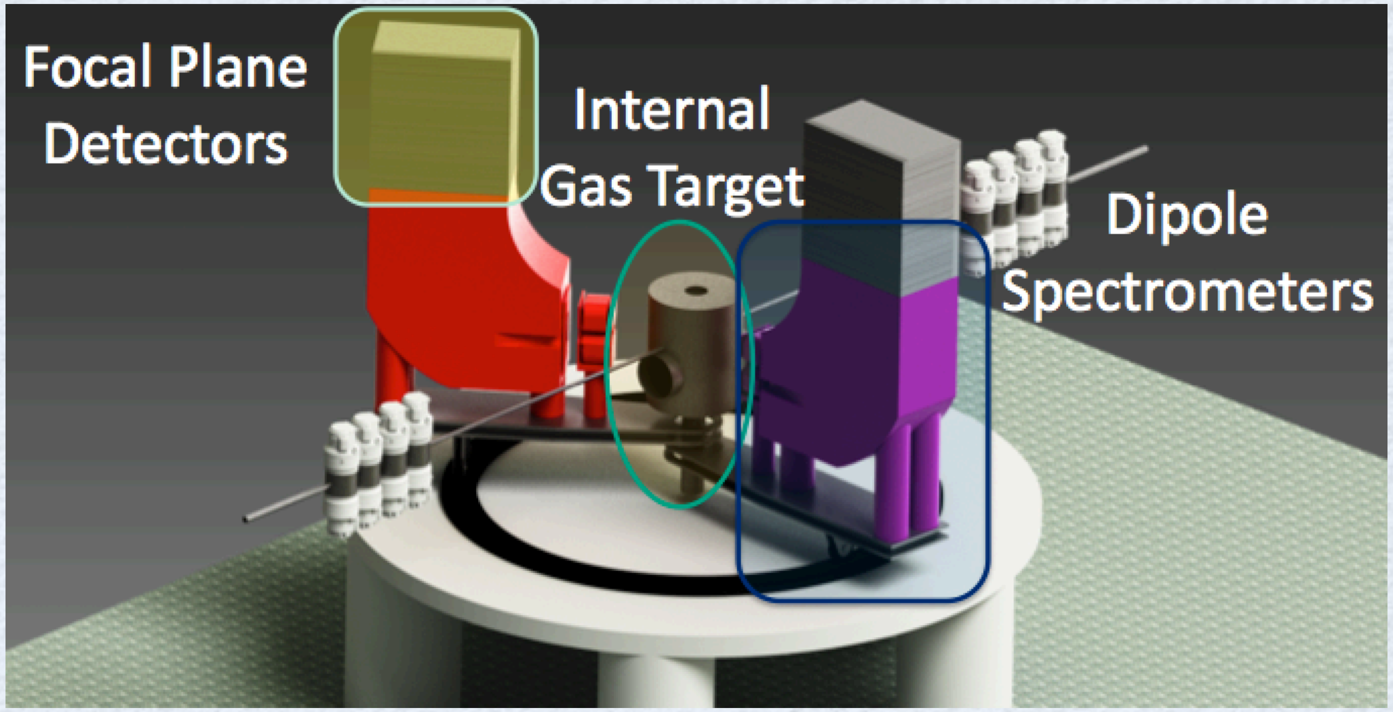


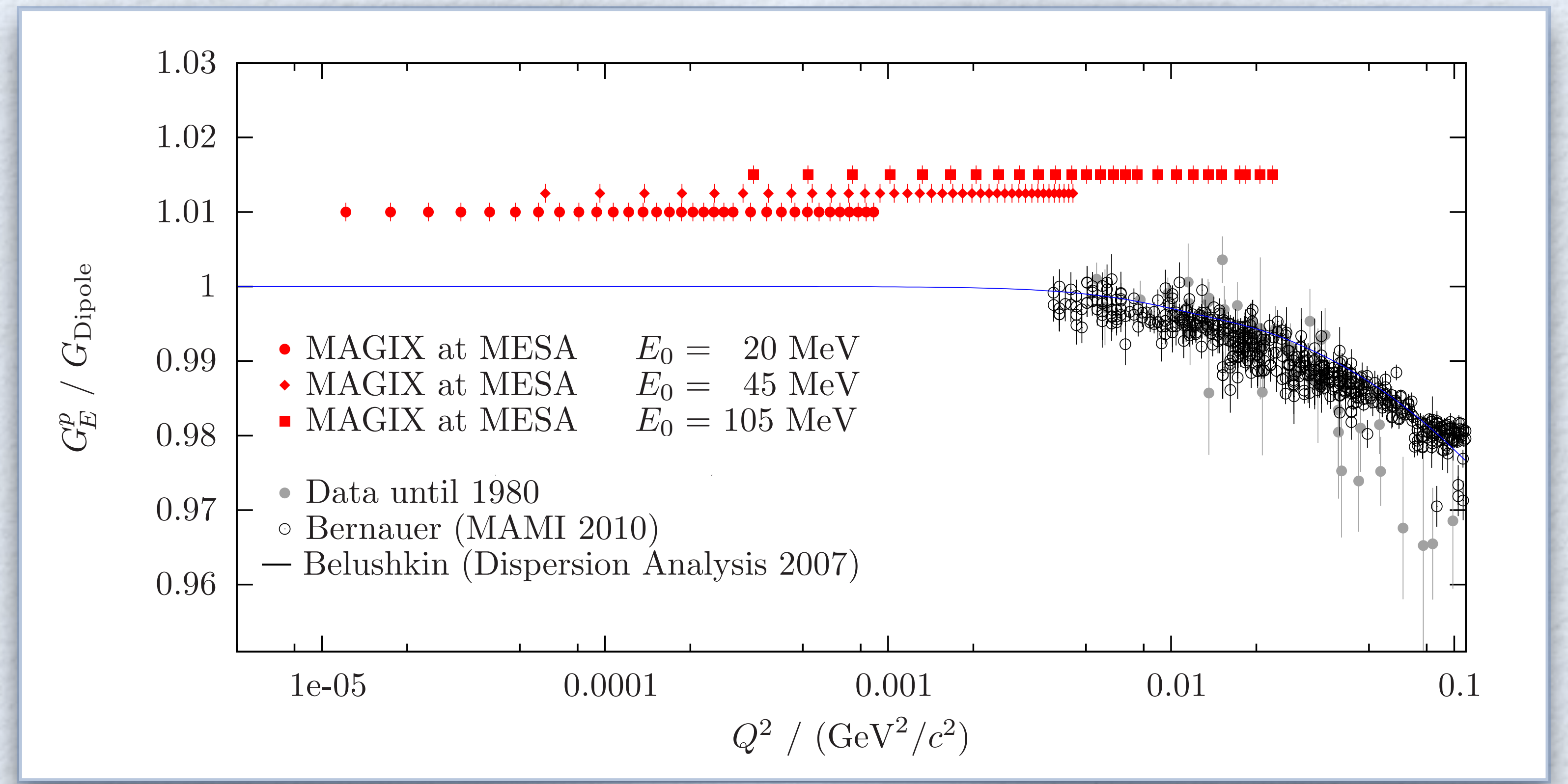
Low-Q^2 proton FF: MAGIX@MESA

Operation of a high-intensity (polarized) ERL beam in conjunction with light internal target
→ a novel technique in nuclear and particle physics

High resolution spectrometers MAGIX:

- double arm, compact design
- momentum resolution: $\Delta p/p < 10^{-4}$
- acceptance: ±50 mrad
- GEM-based focal plane detectors
- Gas Jet or polarized T-shaped target

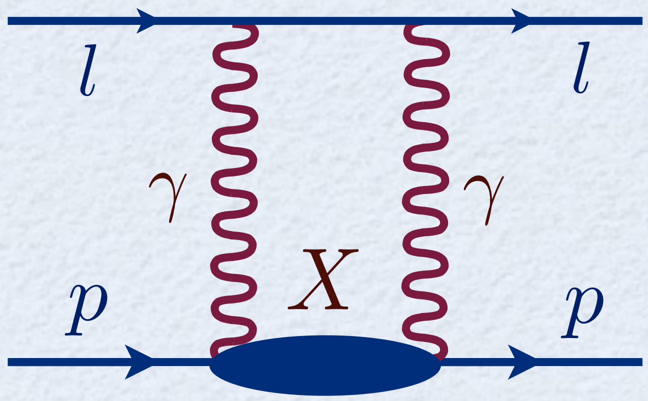




Hyperfine splitting: TPE for proton spin dependent amplitude

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

Antognini (2016)



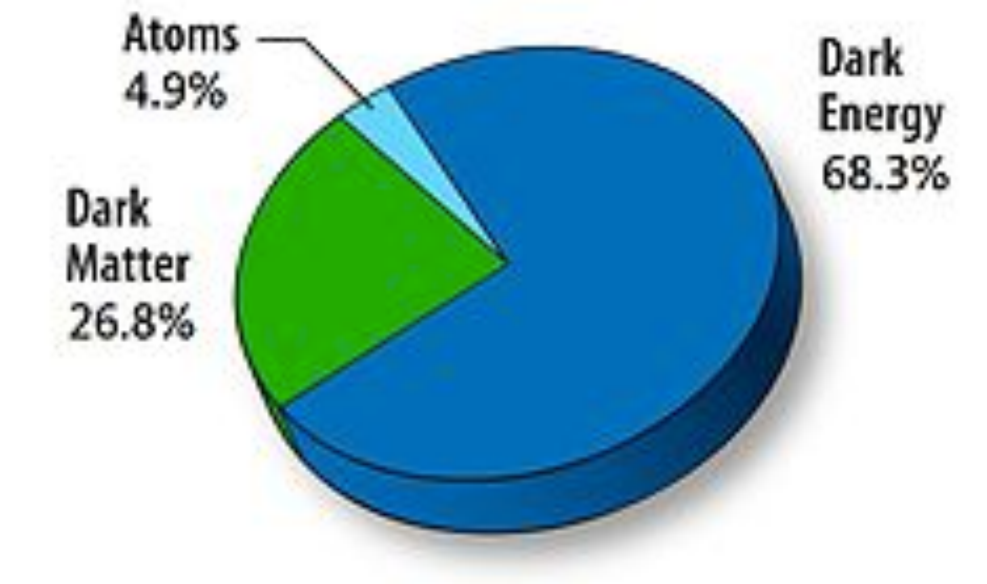
	relative contribution ($\times 10^{-3}$)	relative uncertainty
X=p (Zemach)	-7,36	140 ppm
X=p (recoil)	0,8476	0.8 ppm
X=p, πN,…(polarizability)	0,363	86 ppm
total	-6,149	164 ppm

Carlson, Nazaryan, Griffioen (2011); Tomalak et al. (2016)

Impressive 1 ppm accuracy requires improvement on 2ɣ

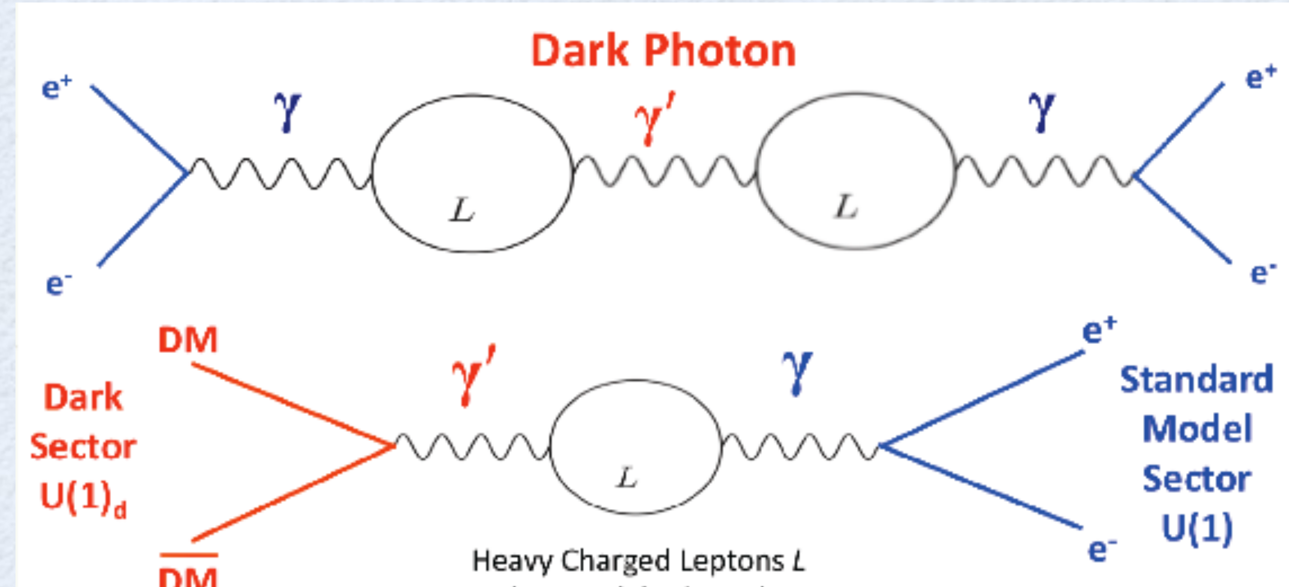
The Dark Photon

as a possible Extension of the Standard Model

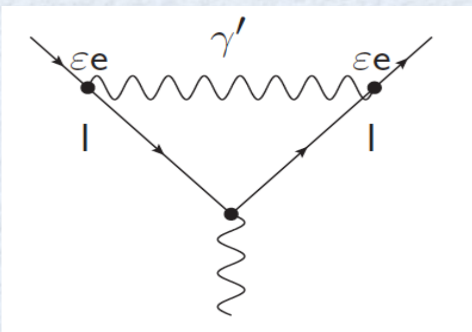


- **light dark sector**: could explain astrophysical anomalies:
  e^+ excess in cosmic ray flux
- **possible explanation for $(g-2)_\mu$**

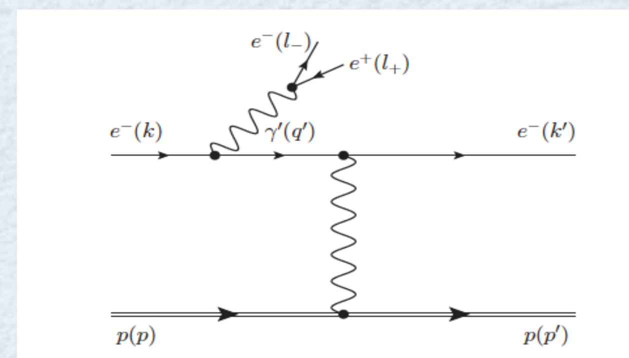
A way to relate the dark sector to the SM (coupling ~ ε^2)



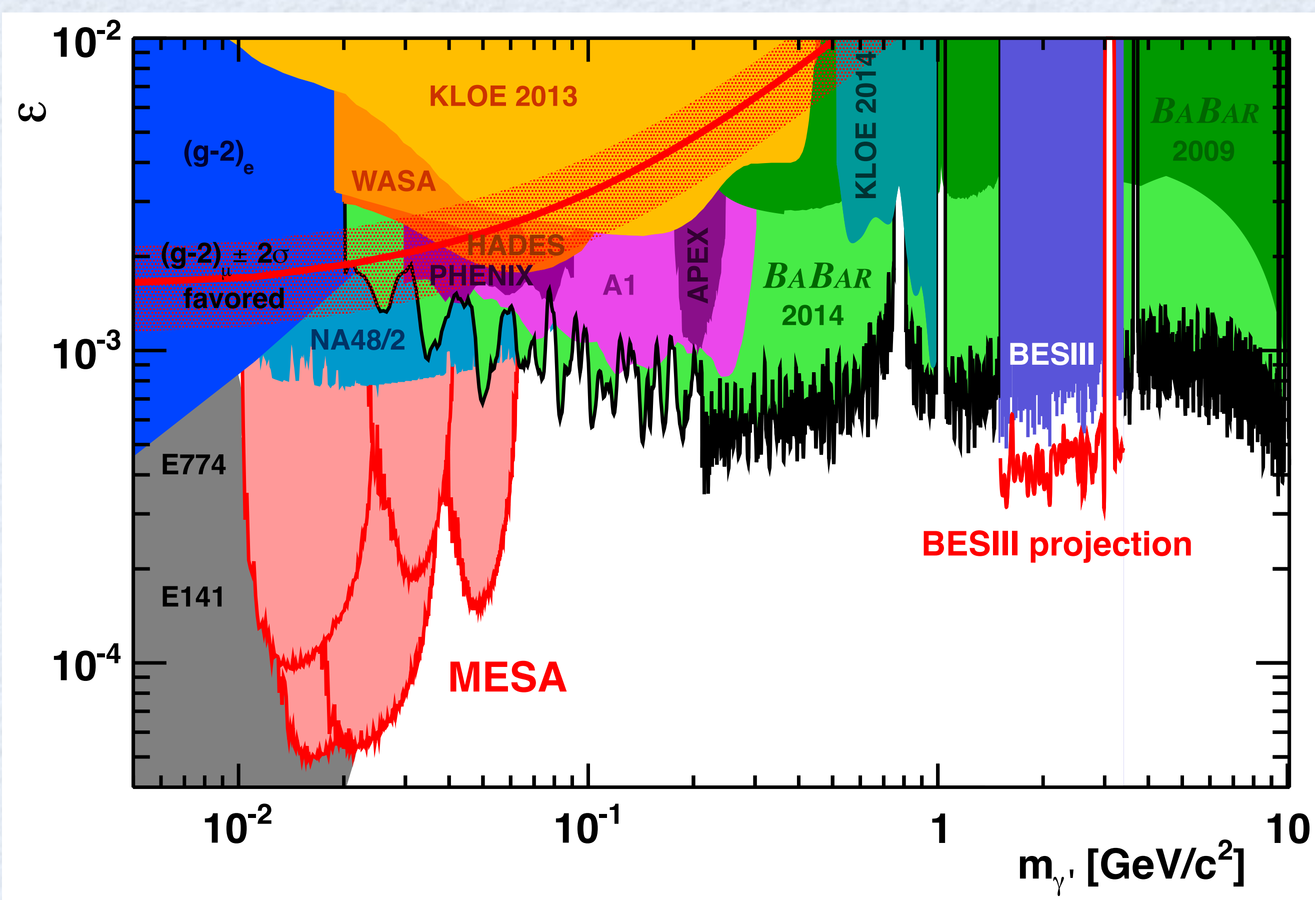
Holdom (1986), . . .



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



Bjorken et al. (2009)



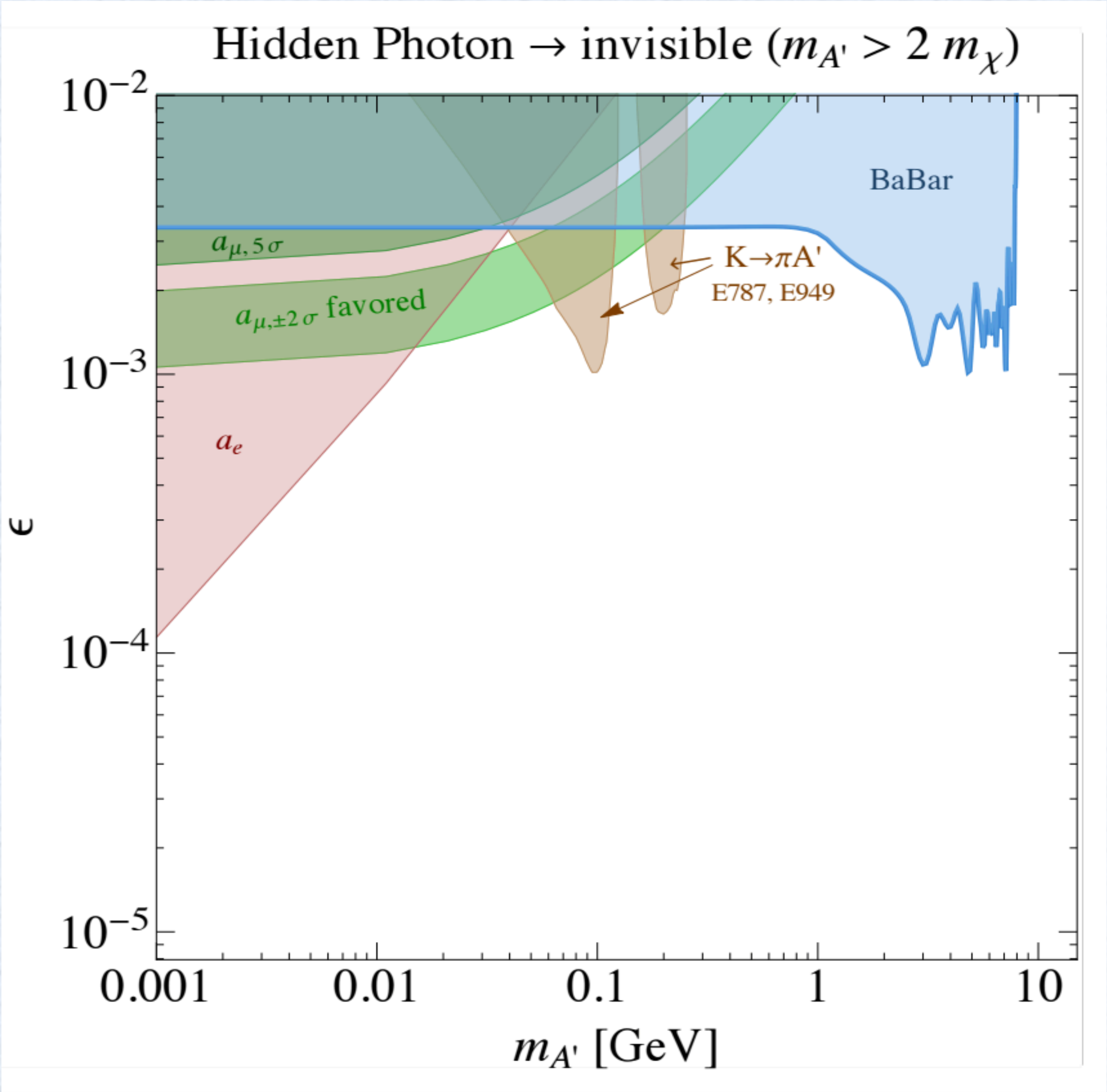
Dark Photon as explanation for $(g-2)_\mu$ (almost) ruled out !

… at least in most straight-forward model

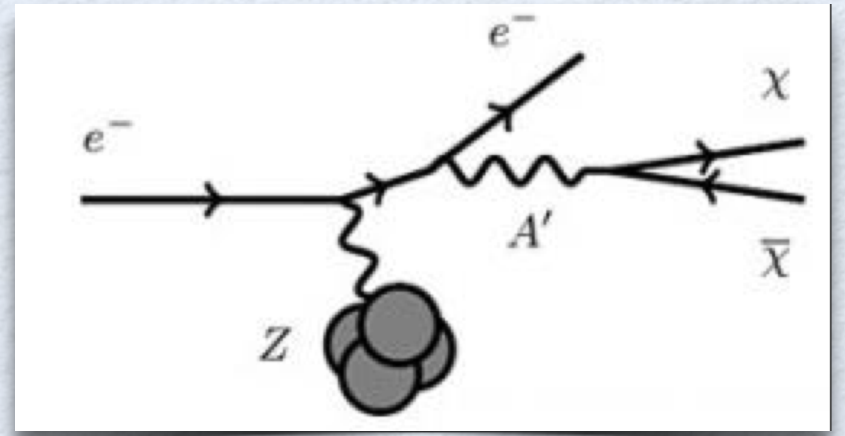
Low-mass/low-coupling range will be covered by JLab, MESA,… expts.

Model 2: Dark Photon coupling to light Dark Matter (invisible decay!)

$$m_{\gamma'} > 2m_{\mathrm{DM}}$$



Marciano, Davoudiasl



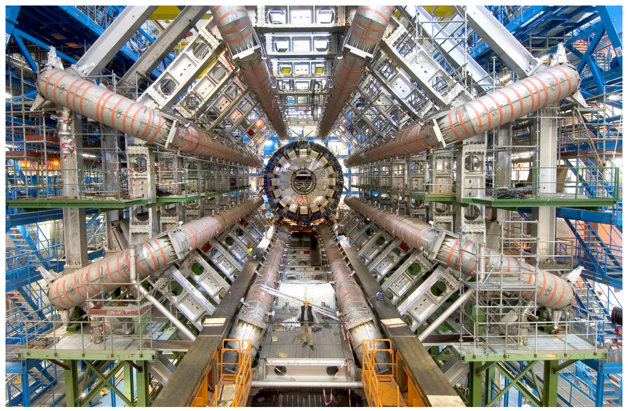
- Dark Matter particle not seen
- Few constraints
- Could again explain $(g-2)_\mu$

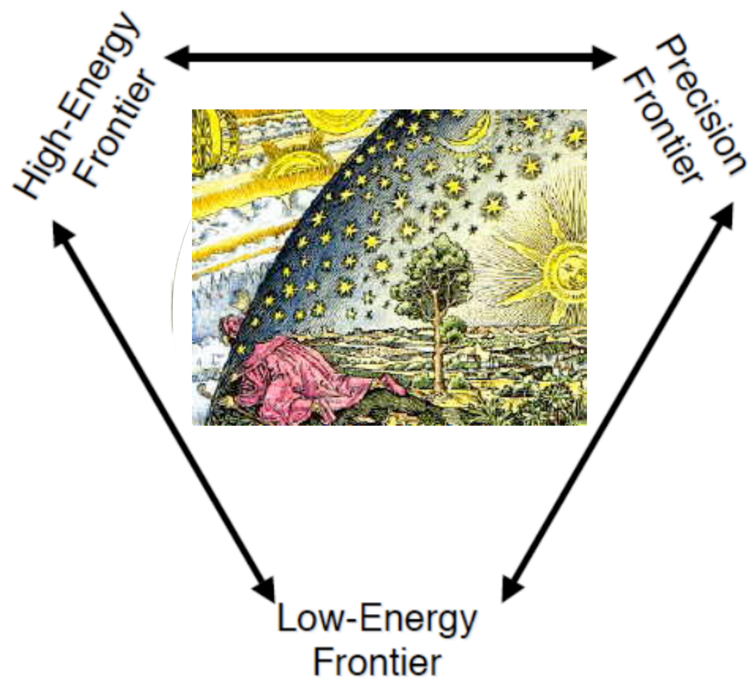
→ Missing energy / mass

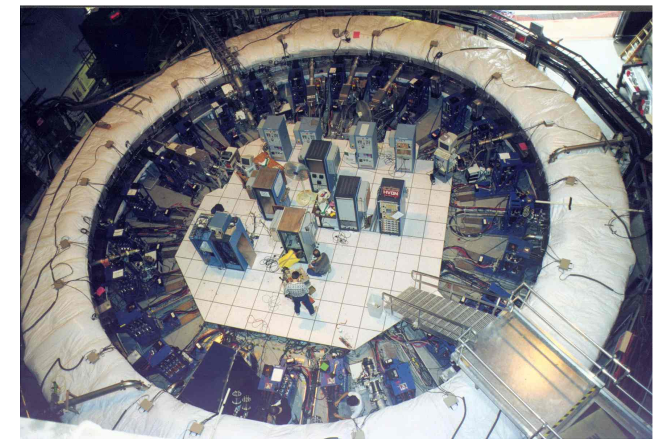
→ Search for Dark Matter particle directly using dedicated low-background detectors

$$e + p \rightarrow e' + p + \mathrm{X}$$
$$\hookrightarrow \textit{invisible}$$

Conclusions

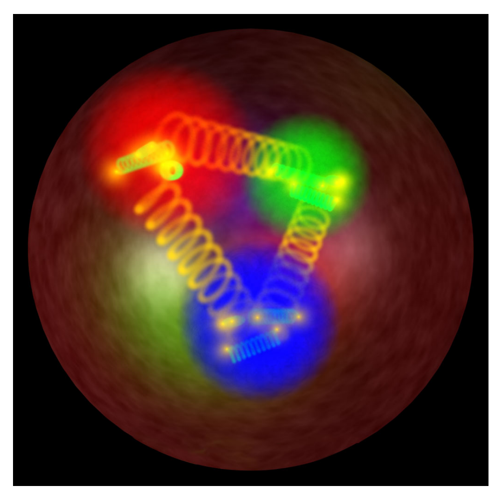






Puzzles at low Energies ?!

- *Proton Radius*
- *$(g\text{-}2)_\mu$*
- *Dark Photon*



Low Energy experiments study the structure of particles and more than that !

→ New tools: MESA