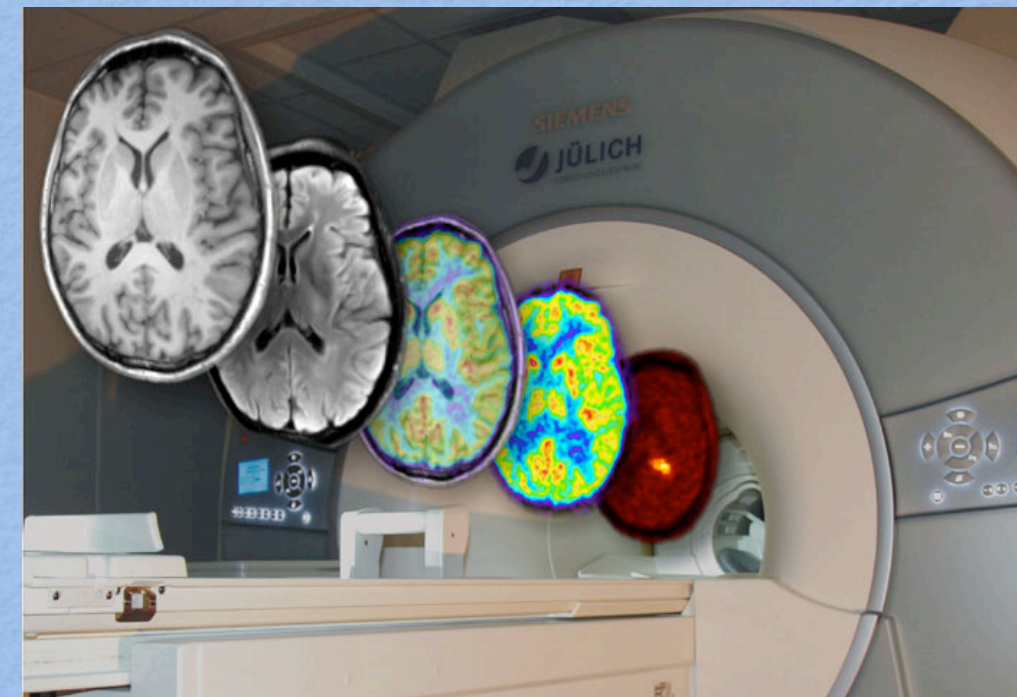




JOHANNES GUTENBERG
UNIVERSITÄT MAINZ



Modern topics in Precision Hadron Physics



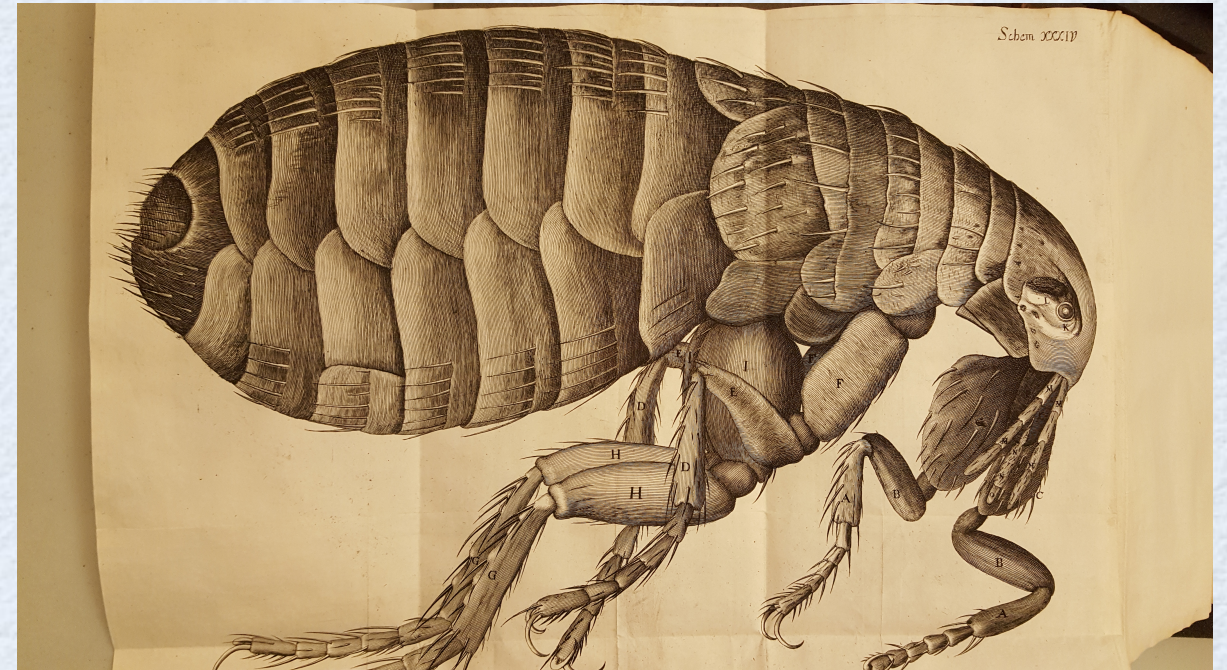
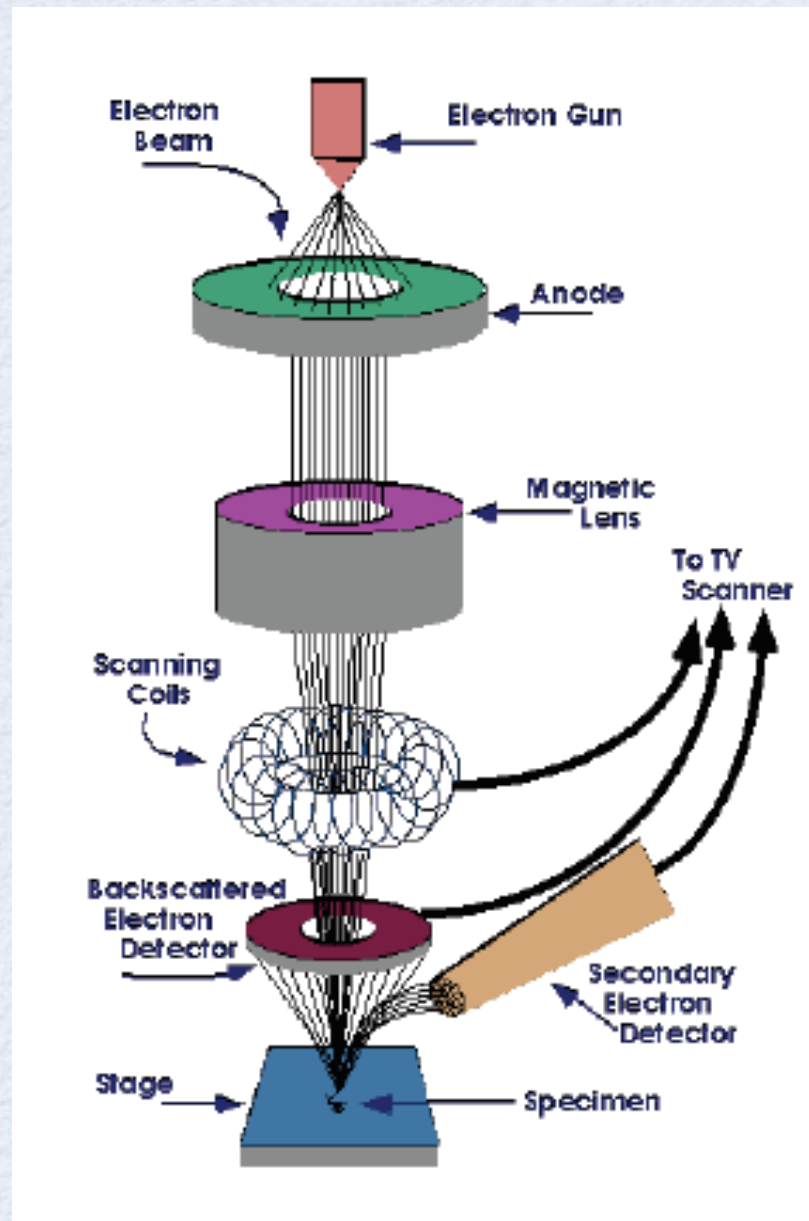
Marc Vanderhaeghen

*“The basic ideas and concepts behind the modern High-Energy Physics
and Cosmology”*

October 5 - 16, 2018, Truskavets, Ukraine

how to image a system

R.Hooke (Micrographia, 1665)

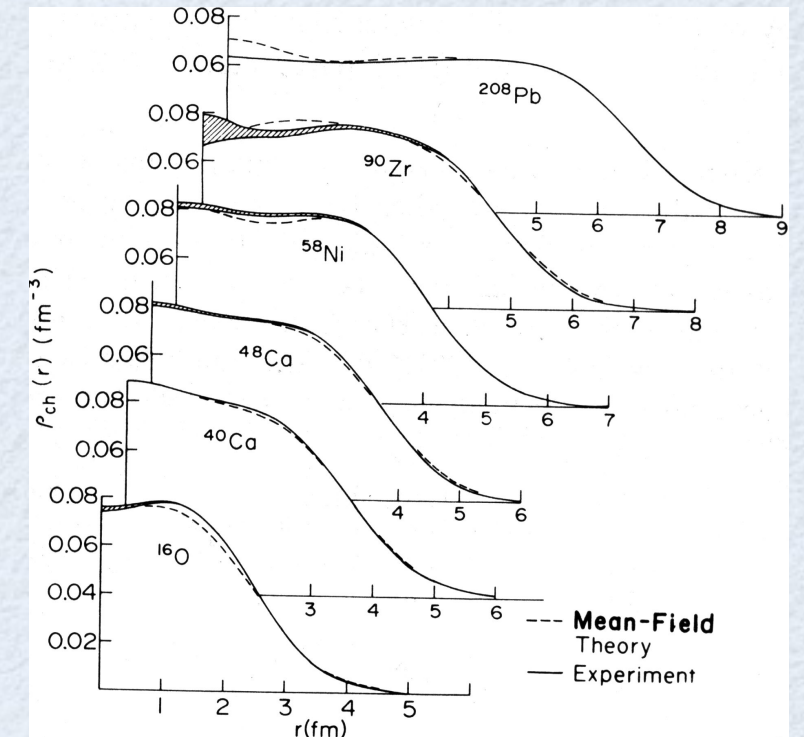
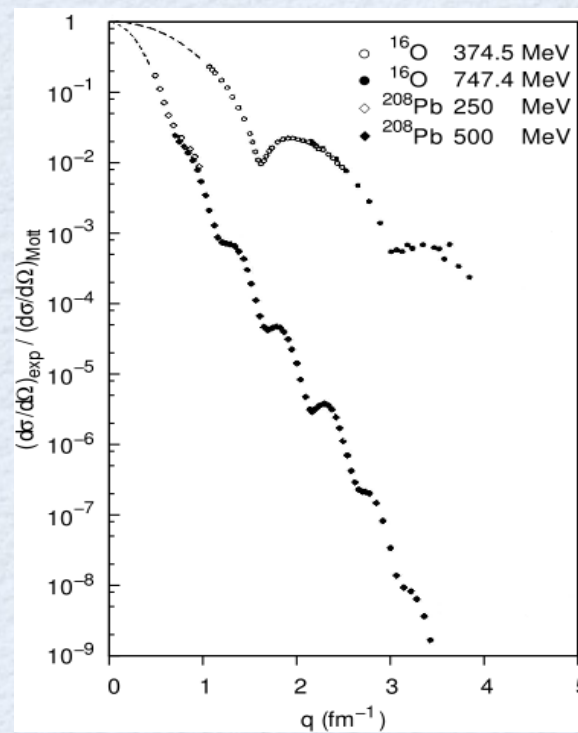


when target is static
($m_{\text{constituent}}, m_{\text{target}} \gg Q$)

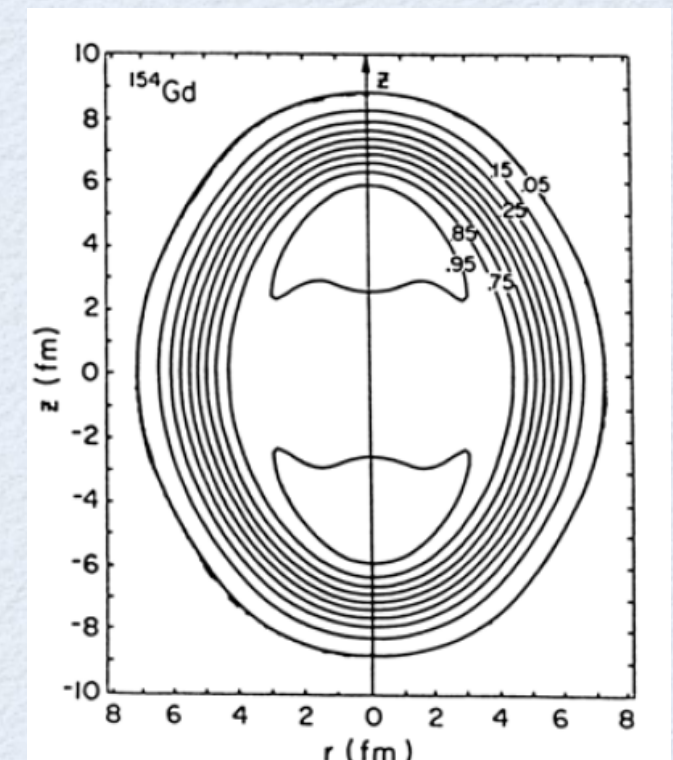
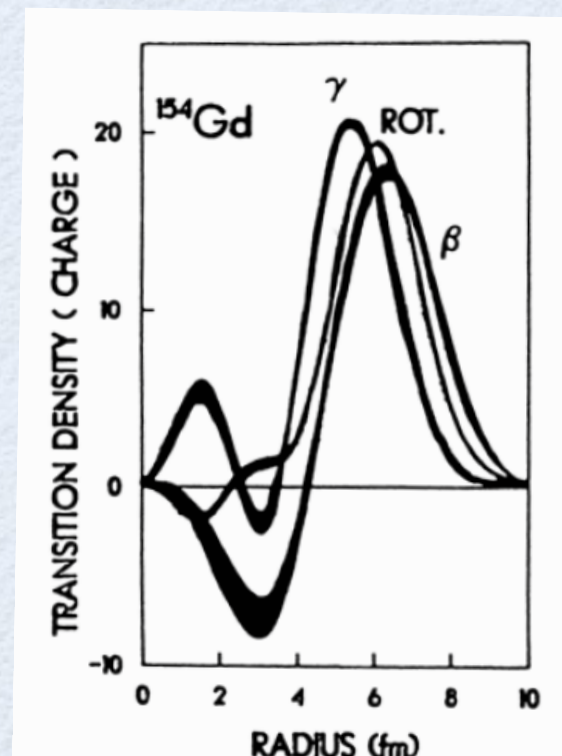
the 3D **Fourier transform** of **form factors**
gives the distribution of electric charge and magnetization

what do we know about spatial distributions of charges in nuclei?

sizes of nuclei:
as revealed through
elastic electron scattering

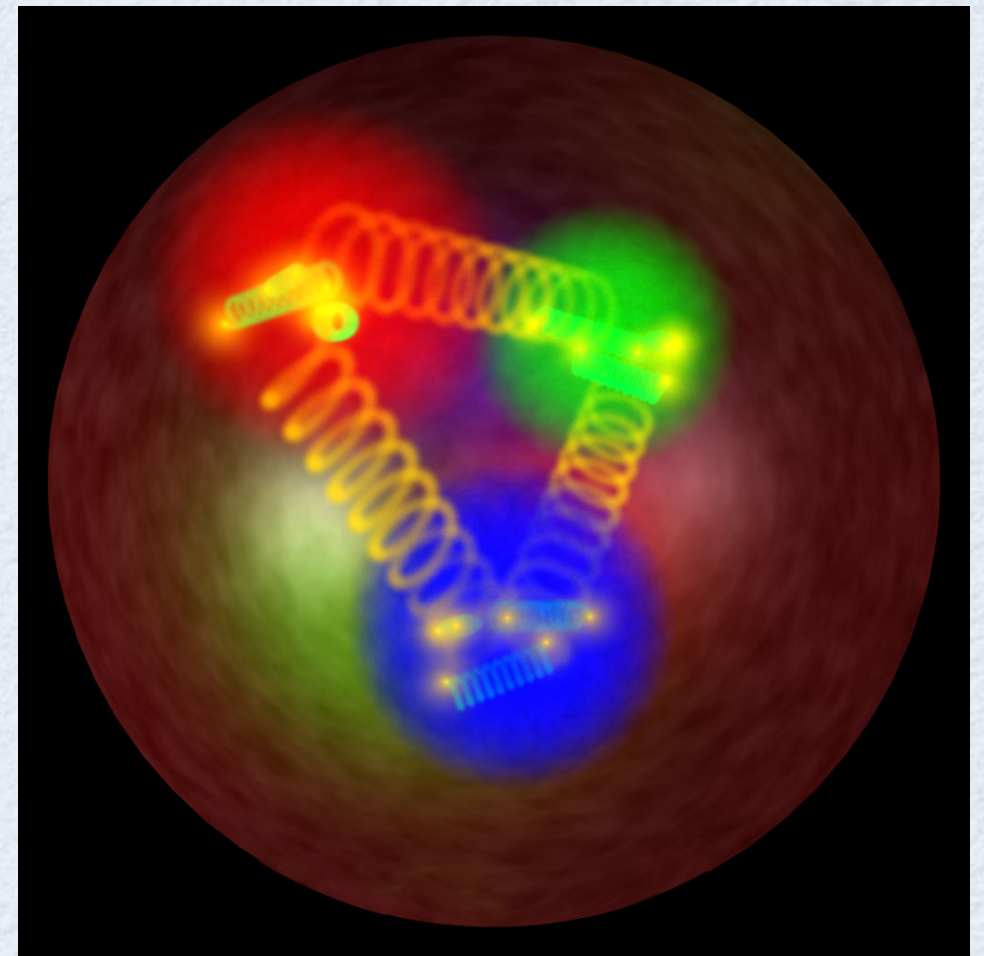


shapes of nuclei:
as revealed through
inelastic electron scattering

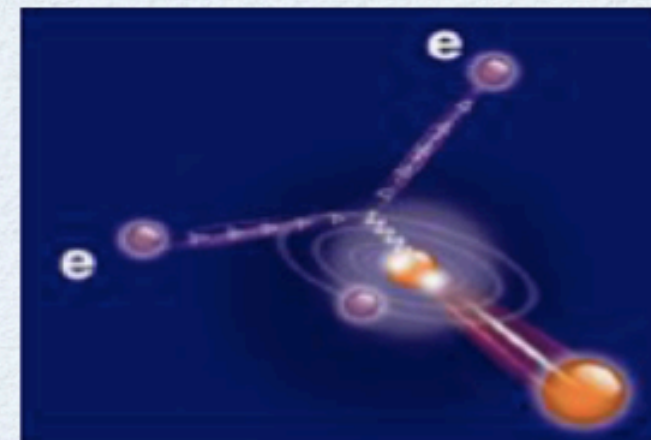
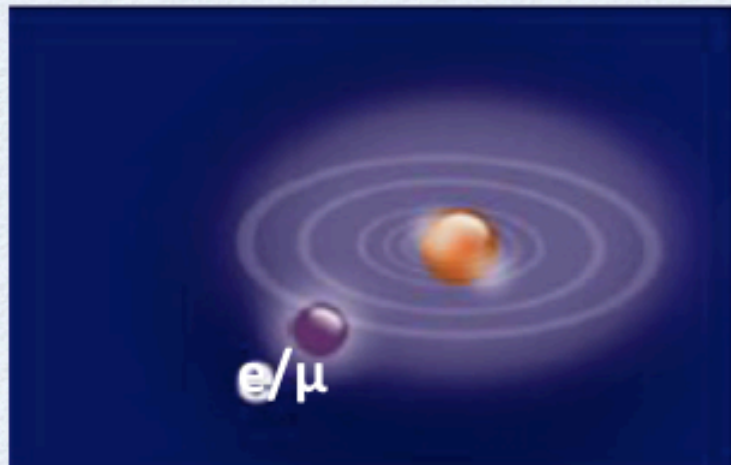


what do we know about the proton size and its charge distributions?

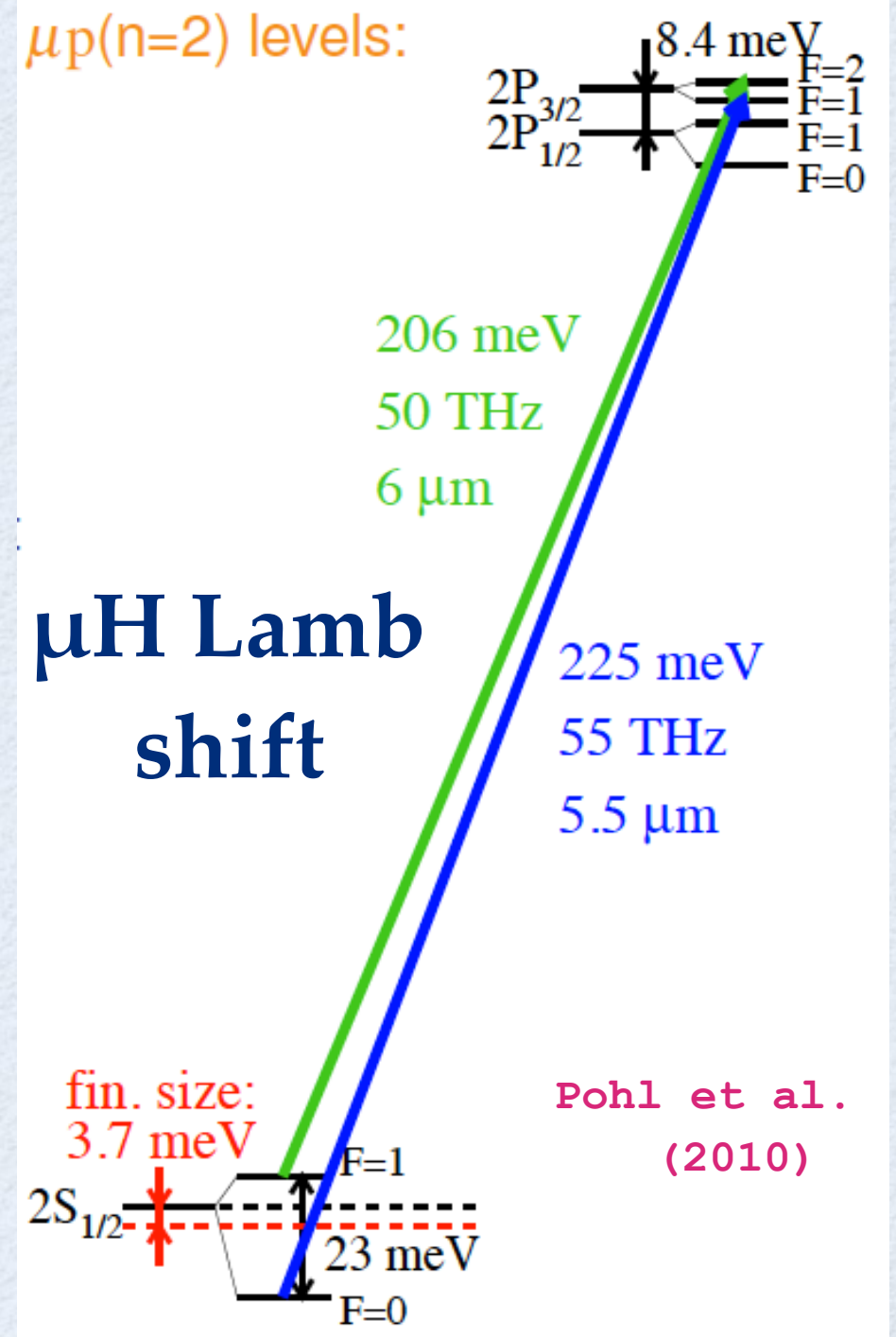
- ➔ proton **size**: charge radius R_E
very low Q^2 **elastic** electron scattering,
atomic spectroscopy (Lamb shift)
- ➔ proton **spatial (charge) distributions**
elastic electron scattering
e.m. FFs: $F_1(Q^2) \rightarrow \rho(\mathbf{b})$
- ➔ proton **3D transverse spatial/
longitudinal momentum distributions**
deeply virtual Compton scattering
GPDs $H(x, \xi, t) \rightarrow \rho(x, \mathbf{b})$ for $\xi=0$



proton radius puzzle



Proton radius from Hydrogen spectroscopy

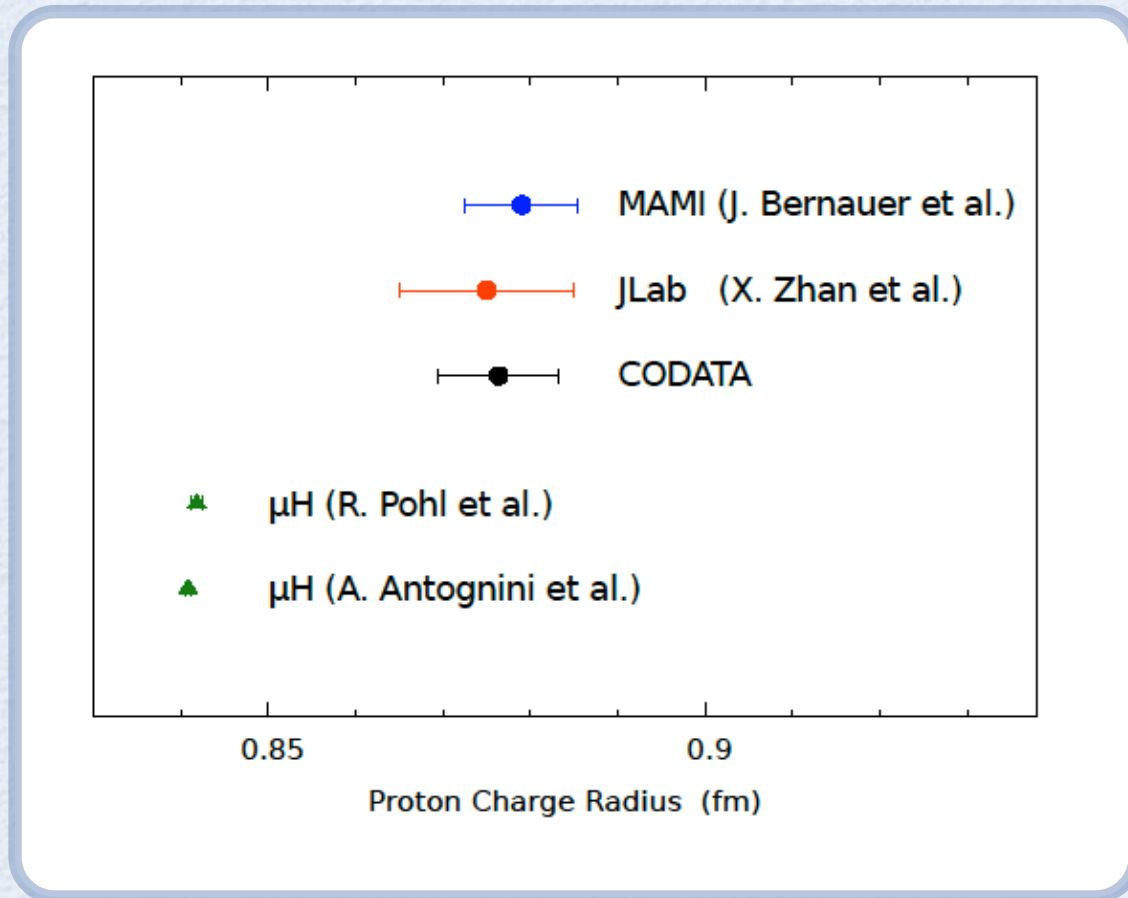


$$\Delta E_{LS} = 206.0336 (15) - 5.2275 (10) R_E^2 + \Delta E_{TPE} \quad \text{meV}$$

Antognini et al. (2013)

3.70 meV 0.0332 (20) meV $O(\alpha^5)$ correction

Proton radius puzzle



μH data:

$$R_E = 0.8409 \pm 0.0004 \text{ fm}$$

Pohl et al. (2010)

Antognini et al. (2013)

7σ difference !?

ep data:

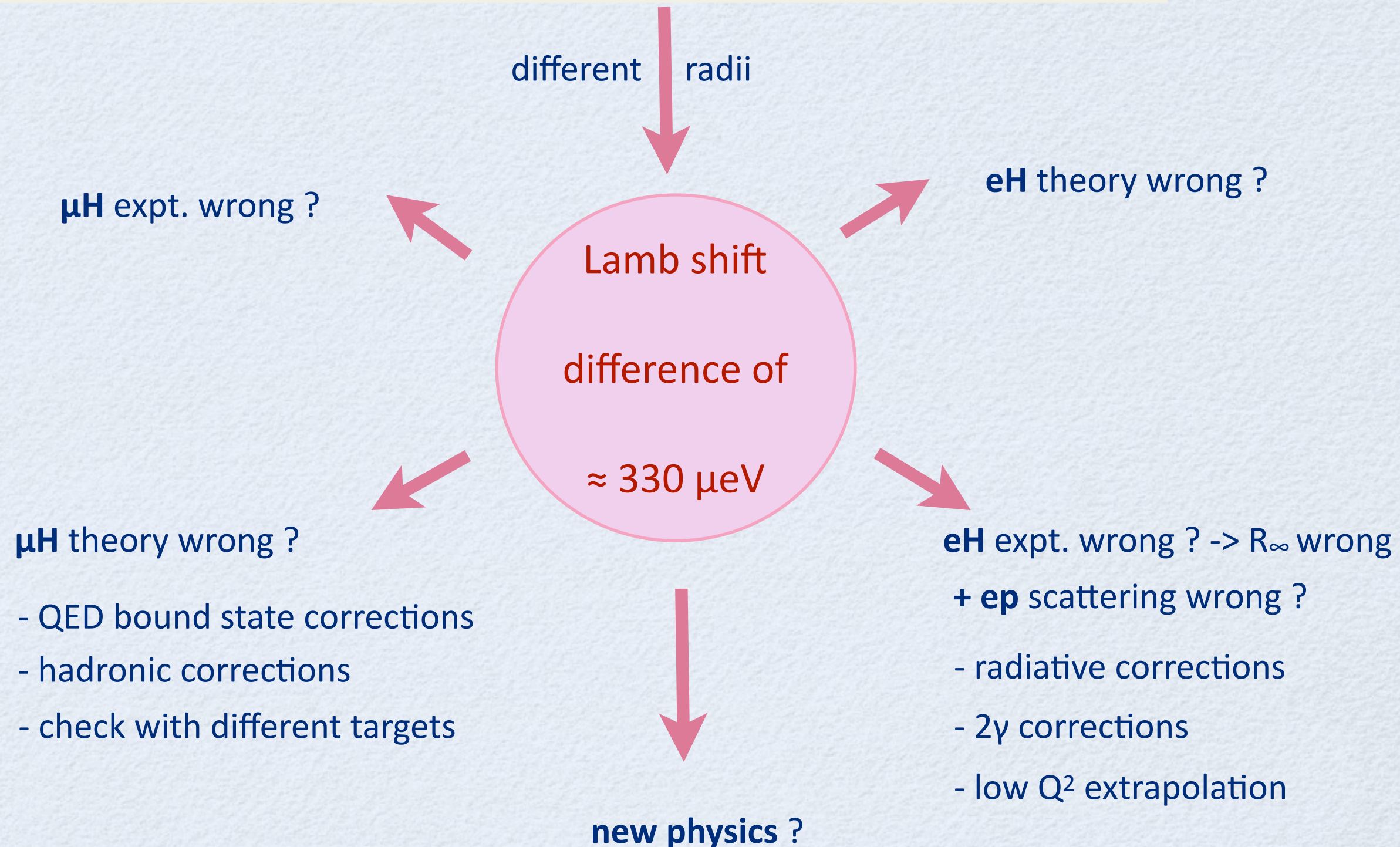
$$R_E = 0.8775 \pm 0.0051 \text{ fm}$$

CODATA (2012)



Proton radius puzzle: what could it mean ?

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



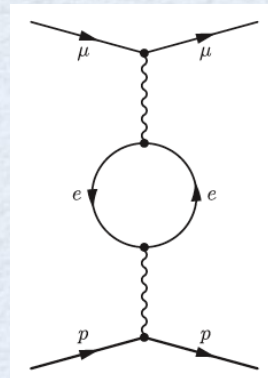
Lamb shift: QED corrections

➔ Calculated by several groups

Pachucki (1996, 1999)

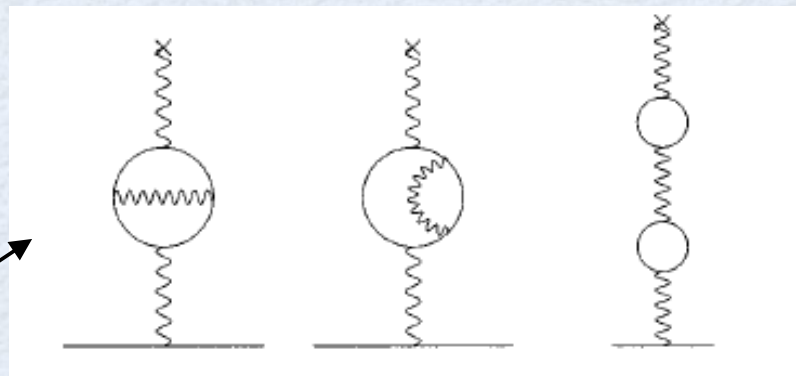
Borie (1976, 2005)

➔ 1 loop electron

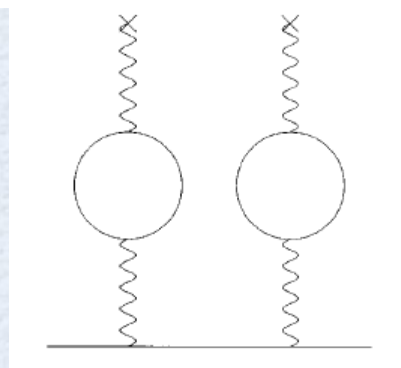


$$\Delta E = 205.0282 \text{ meV}$$

➔ 2 loop electron



$$\Delta E = 1.5081 \text{ meV}$$



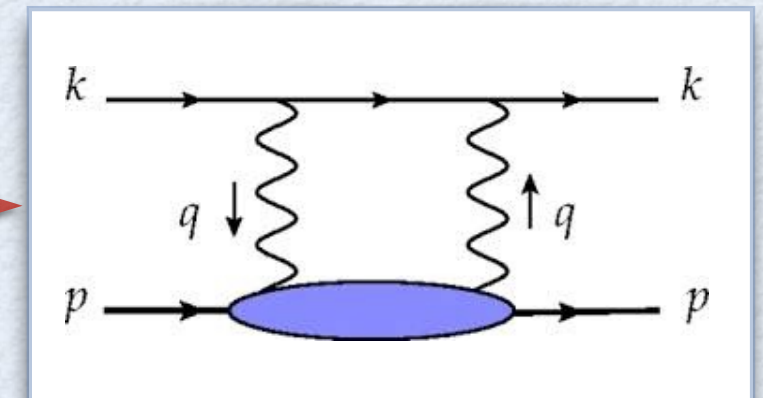
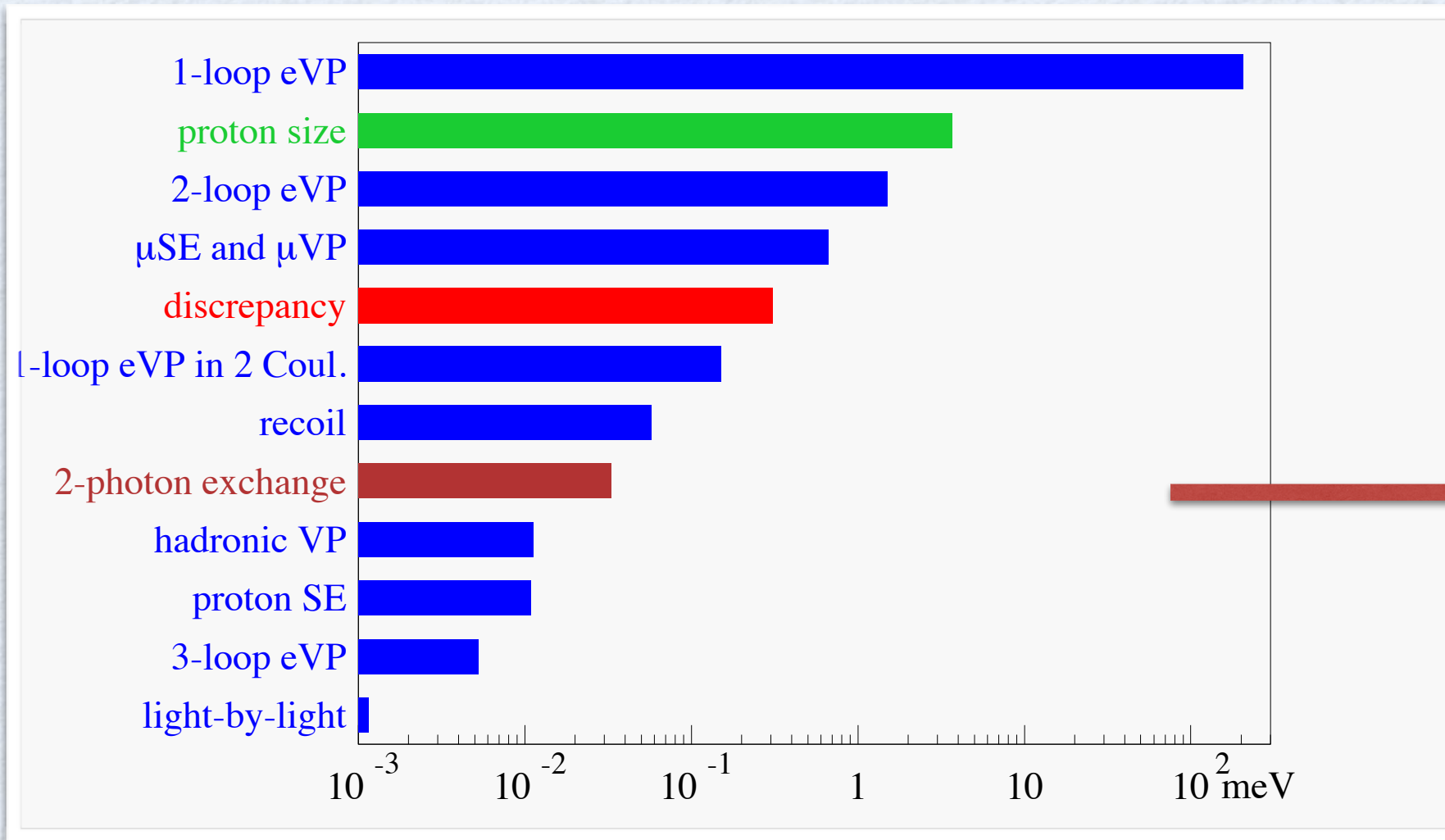
$$\Delta E = 0.1509 \text{ meV}$$

➔ Muon self-energy, vacuum polarization $\Delta E = -0.6677 \text{ meV}$

➔ other QED corrections calculated : all of size 0.005 meV or smaller $\ll 0.3 \text{ meV}$

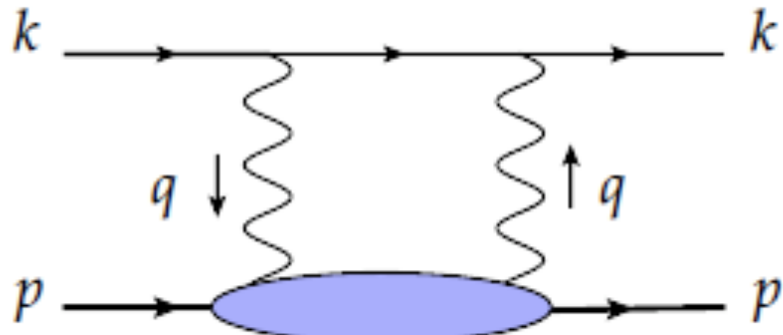
Lamb shift: status of known corrections

μH Lamb shift: summary of corrections



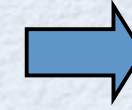
Two-photon exchange: largest theoretical uncertainty

Lamb shift: hadronic corrections



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

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



**Hadron physics
input required**

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

- 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

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

➔ 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: subtraction function

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

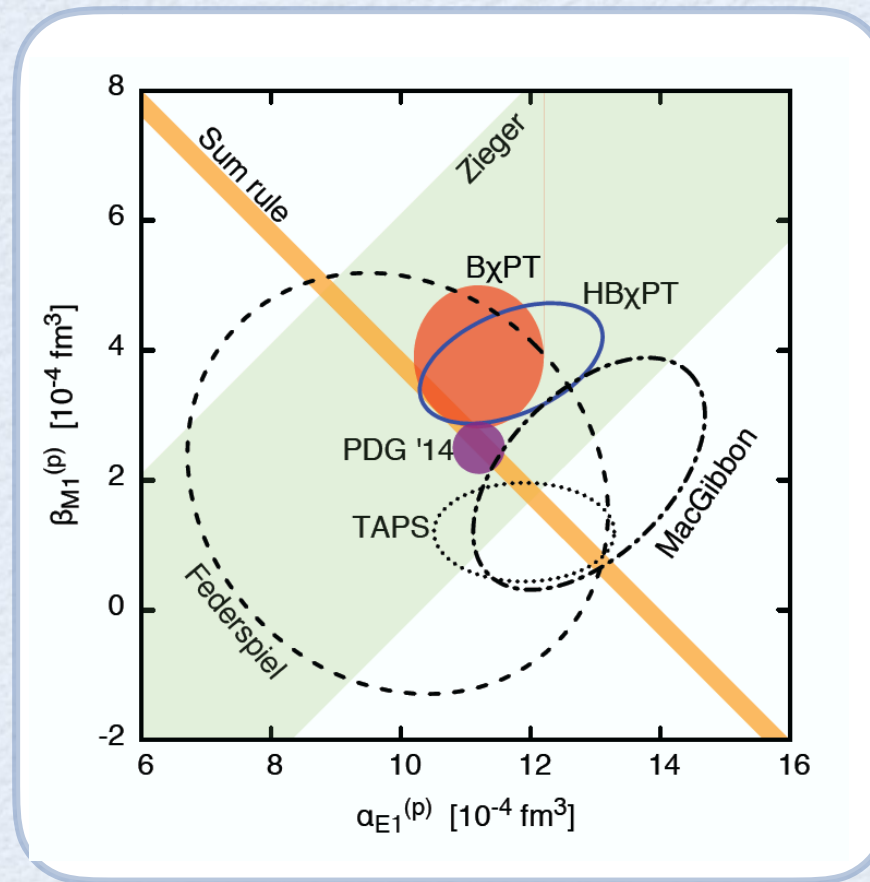
effective Hamiltonian:

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

electric

magnetic

polarizabilities



Theory analyses:

BChPT

Lensky, Pascalutsa (2010)

HBChPT

Griesshammer, McGovern, Phillips (2013)

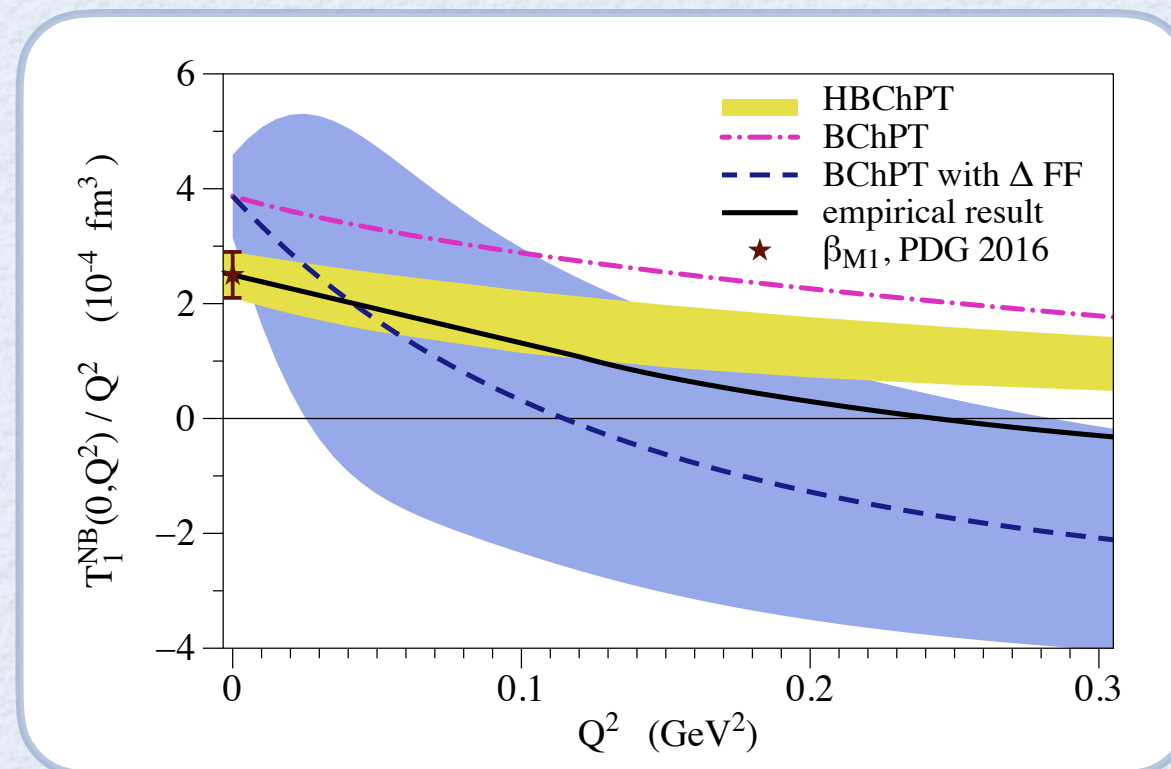
PDG '14 values:

$$\alpha_E = (11.2 \pm 0.2) \times 10^{-4} \text{ fm}^3$$

$$\beta_M = (2.5 \pm 0.4) \times 10^{-4} \text{ fm}^3$$

subtraction term

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



HBChPT

Birse, McGovern (2012)

BChPT

Lensky, Hagelstein, Pascalutsa, Vdh (2018)

Empirical result

(based on HERA data)

Tomalak, Vdh (2016)

Lamb shift: hadronic corrections summary

polarizability correction
on 2S level in μH in μeV

dispersive estimates



(μeV)	Pachucki [9]	Martynenko [10]	Nevado and Pineda [11]	Carlson and Vanderhaeghen [12]	Birse and McGovern [13]	Gorchtein et al. [14]	LO-B χ PT [this work]
$\Delta E_{2S}^{(\text{subt})}$	1.8	2.3	–	5.3 (1.9)	4.2 (1.0)	–2.3 (4.6) ^a	–3.0
$\Delta E_{2S}^{(\text{inel})}$	–13.9	–13.8	–	–12.7 (5)	–12.7 (5) ^b	–13.0 (6)	–5.2
$\Delta E_{2S}^{(\text{pol})}$	–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-B χ PT] Alarcon, Lensky, Pascalutsa, EPJC (2014) 74:2852

➡ elastic contribution on 2S level: $\Delta E_{2S} = -23 \mu\text{eV}$

total hadronic correction on Lamb shift

➡ inelastic contribution: Carlson, Vdh (2011) + Birse, McGovern (2012)

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

...or about 10% of needed correction

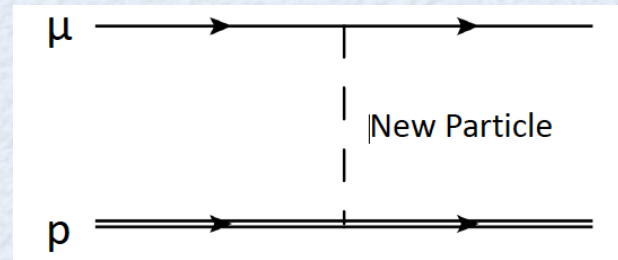
Proton radius puzzle: new physics ?



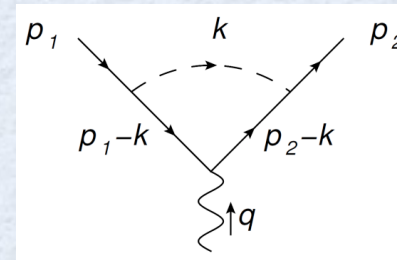
new muonic forces ?

lepton universality-violating models

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



invoking exchange of hypothetical light boson



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

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

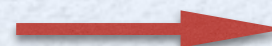
all leptons

V and A coupling to muons

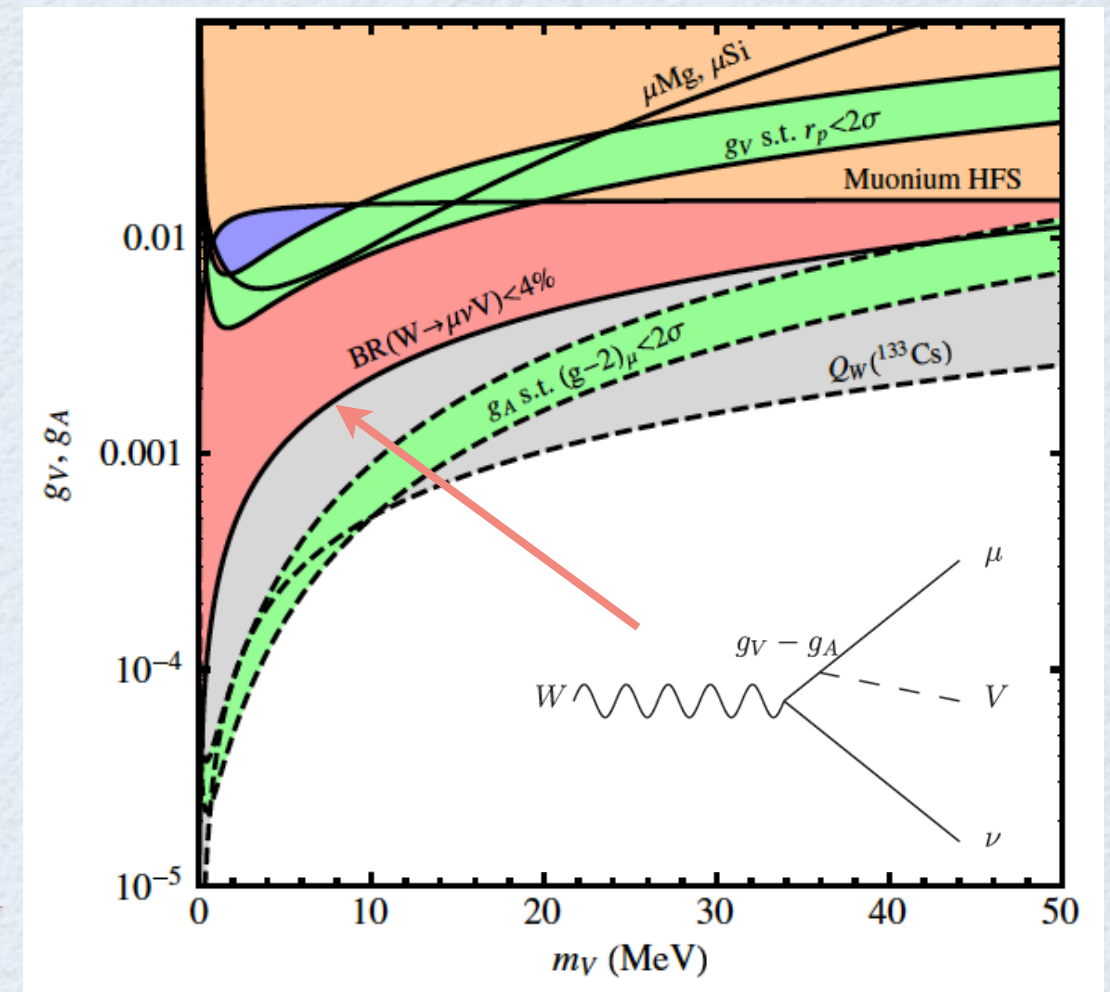
Batell, McKeen, Pospelov (2011)

Carlson, Rislow (2012)

Karshenboim, McKeen, Pospelov (2014)



strong constraint from leptonic W decay
embedding in a renormalizable theory required



Carlson, Freid (2015)

Proton radius puzzle: what's next ?

➔ μ atom Lamb shift: μ D, μ $^3\text{He}^+$, μ $^4\text{He}^+$ have been performed

➔ electronic H Lamb shift: higher accuracy measurements

➔ electron scattering analysis:

- radius extraction fits (use fits with correct analytical behavior: 2π cut)
 - radiative corrections, two-photon exchange corrections
- new fit $R_E = 0.904 (15) \text{ fm}$ (4σ from μH)

➔ electron scattering experiments:

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

- **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

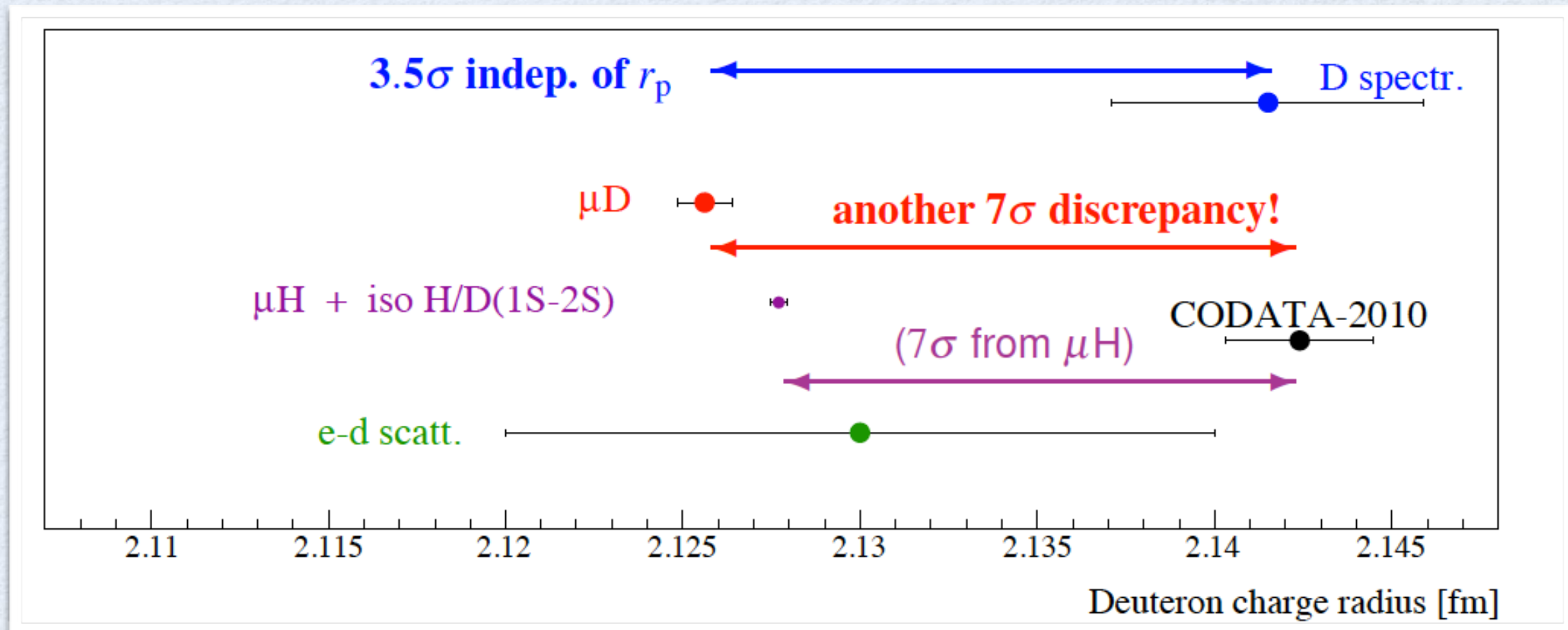
μD Lamb shift experiment

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

- CODATA 2010: $r_d = 2.14240 (210) \text{ fm}$

- r_p from μH + isotope shift : $r_d = 2.12771 (22) \text{ fm}$

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

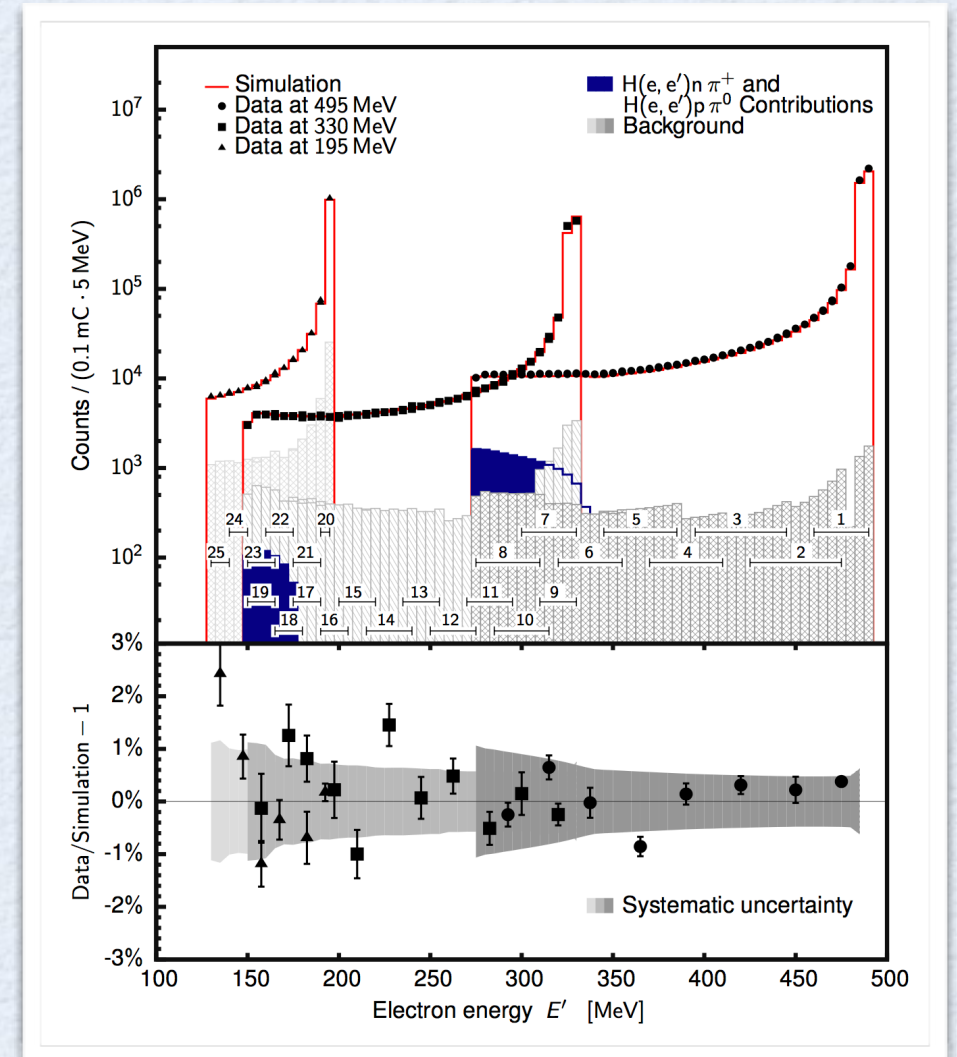
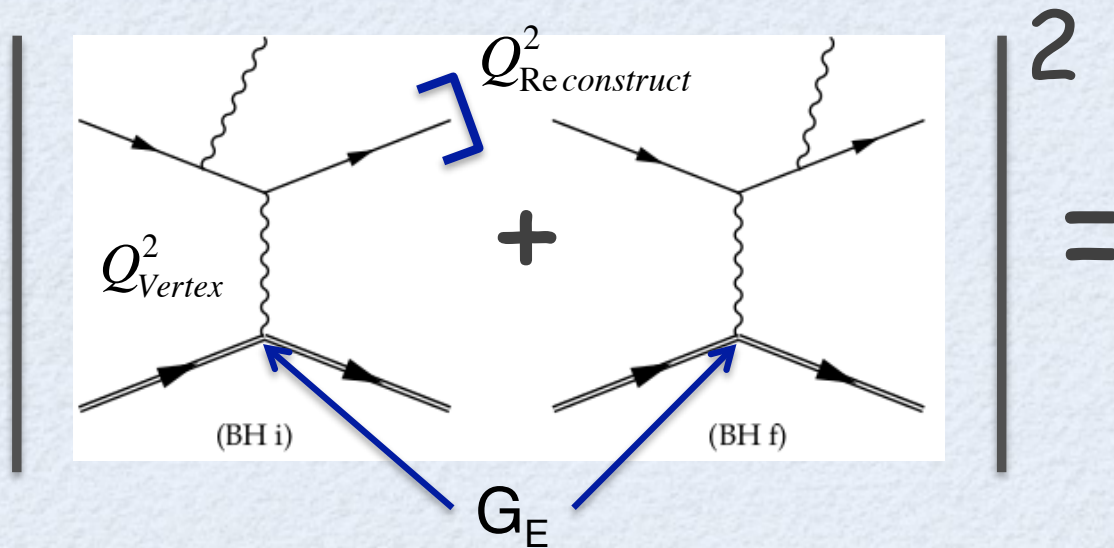


- electronic D (r_p indep.): $r_d = 2.14150 (450) \text{ fm}$ $\leftarrow 3.5 \sigma$ Pohl et al. (2016)

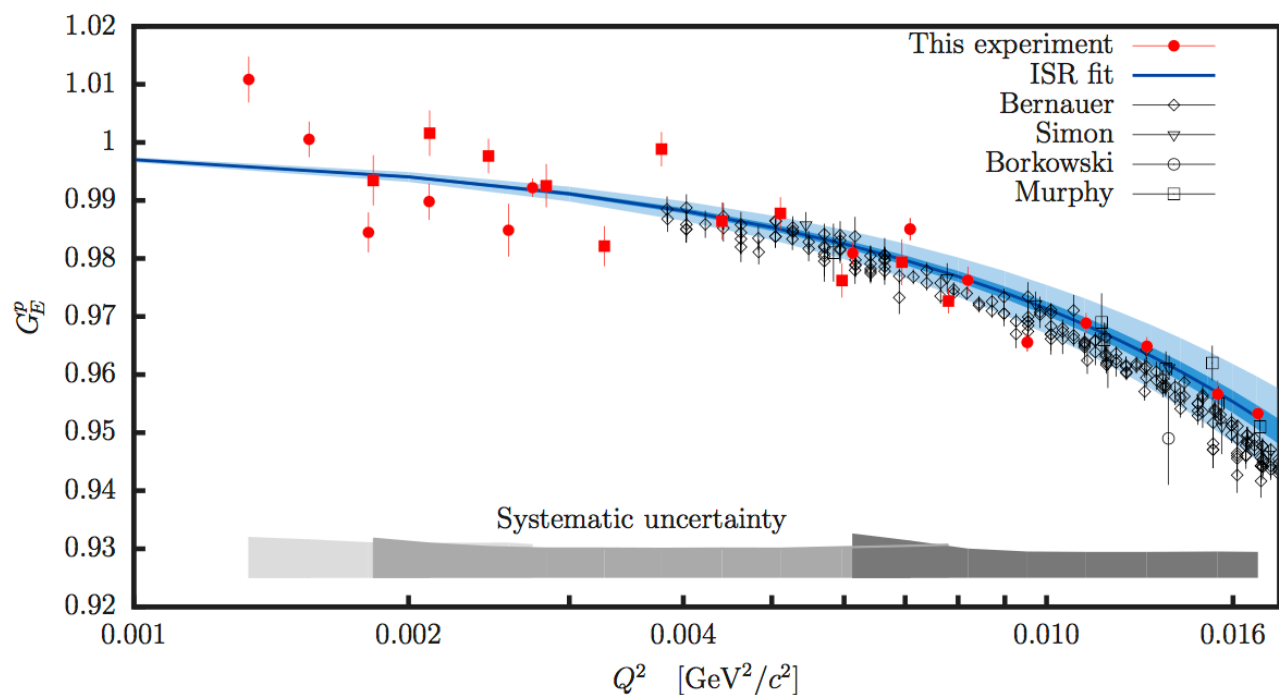
- improved radius measurement from e-d scattering was performed @ MAMI (2014)

ISR@MAMI experiment

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



Mihovilovic et al. (2017)



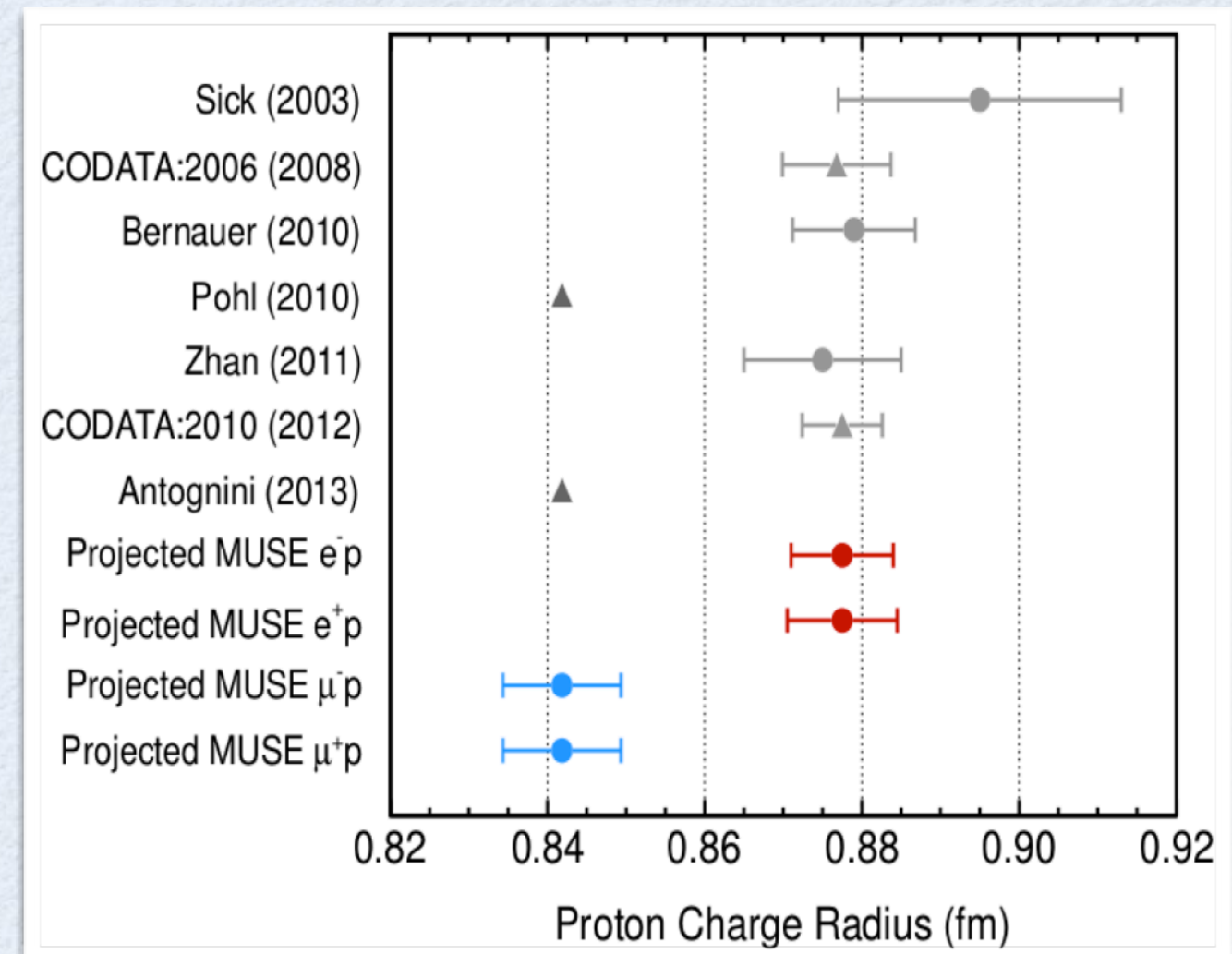
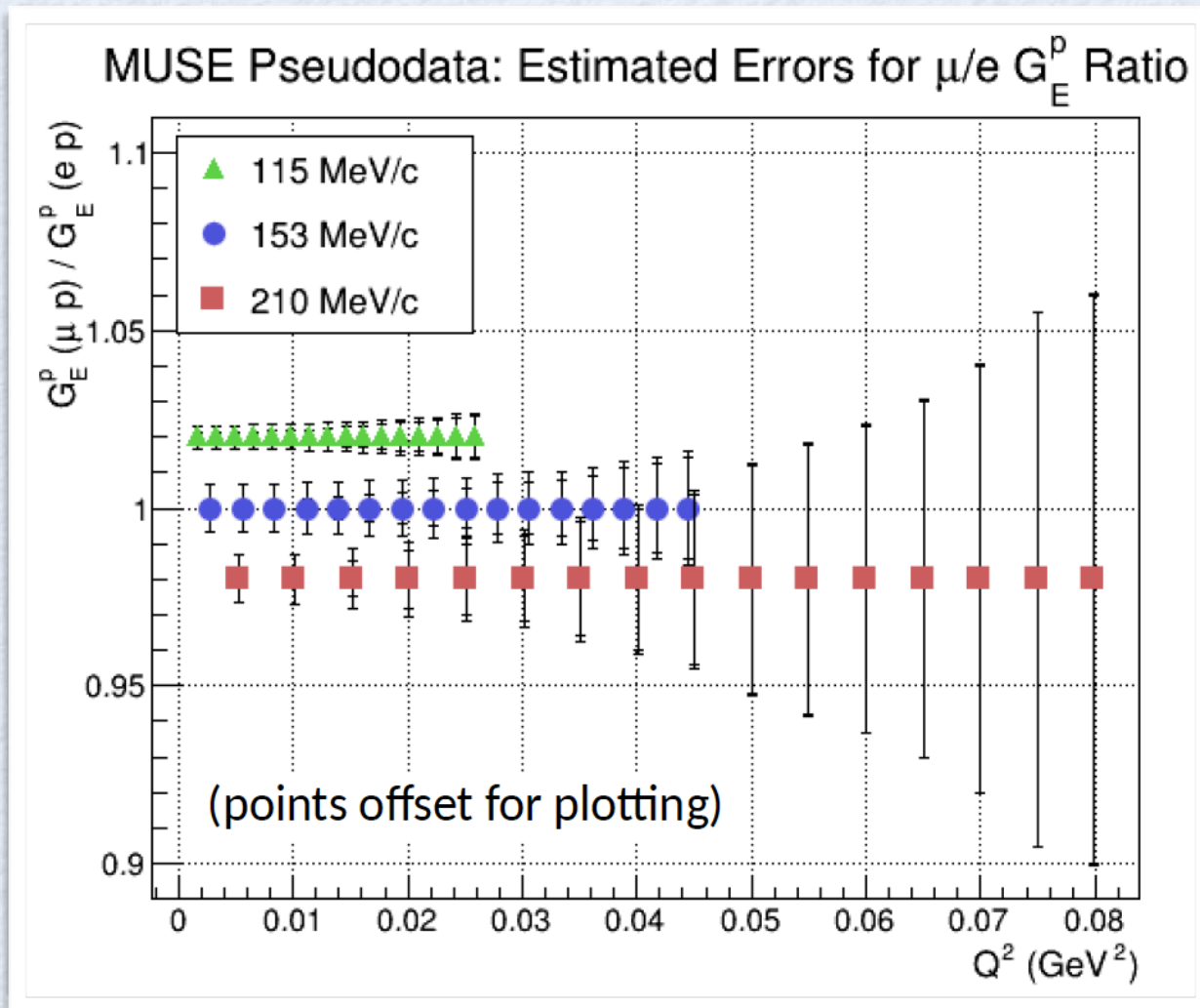
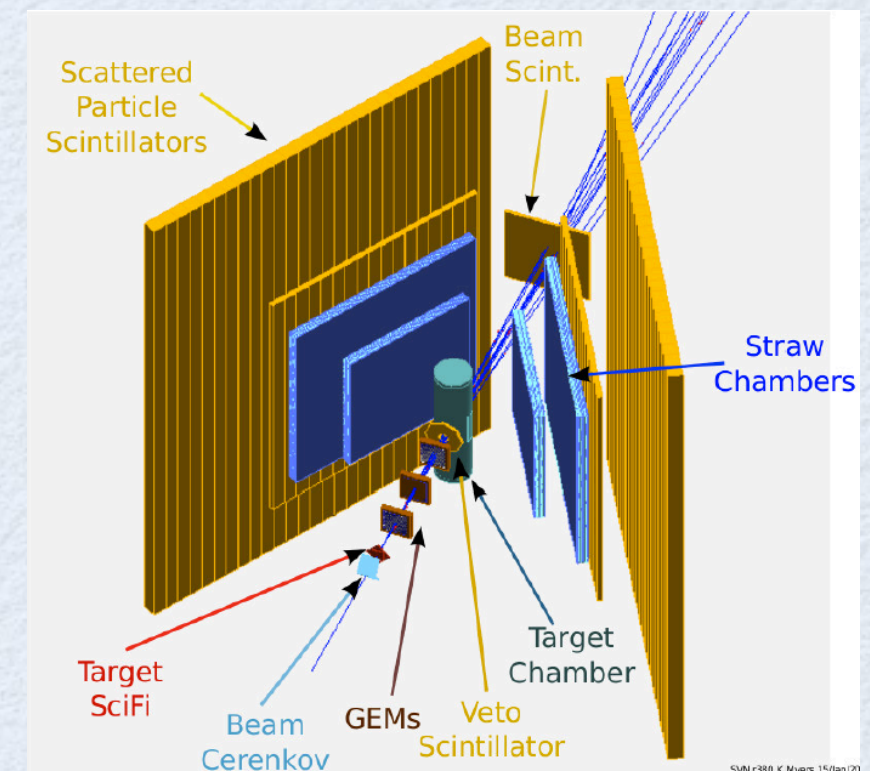
good understanding of radiative tail ($\sim 1\%$)

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

MUSE@PSI experiment

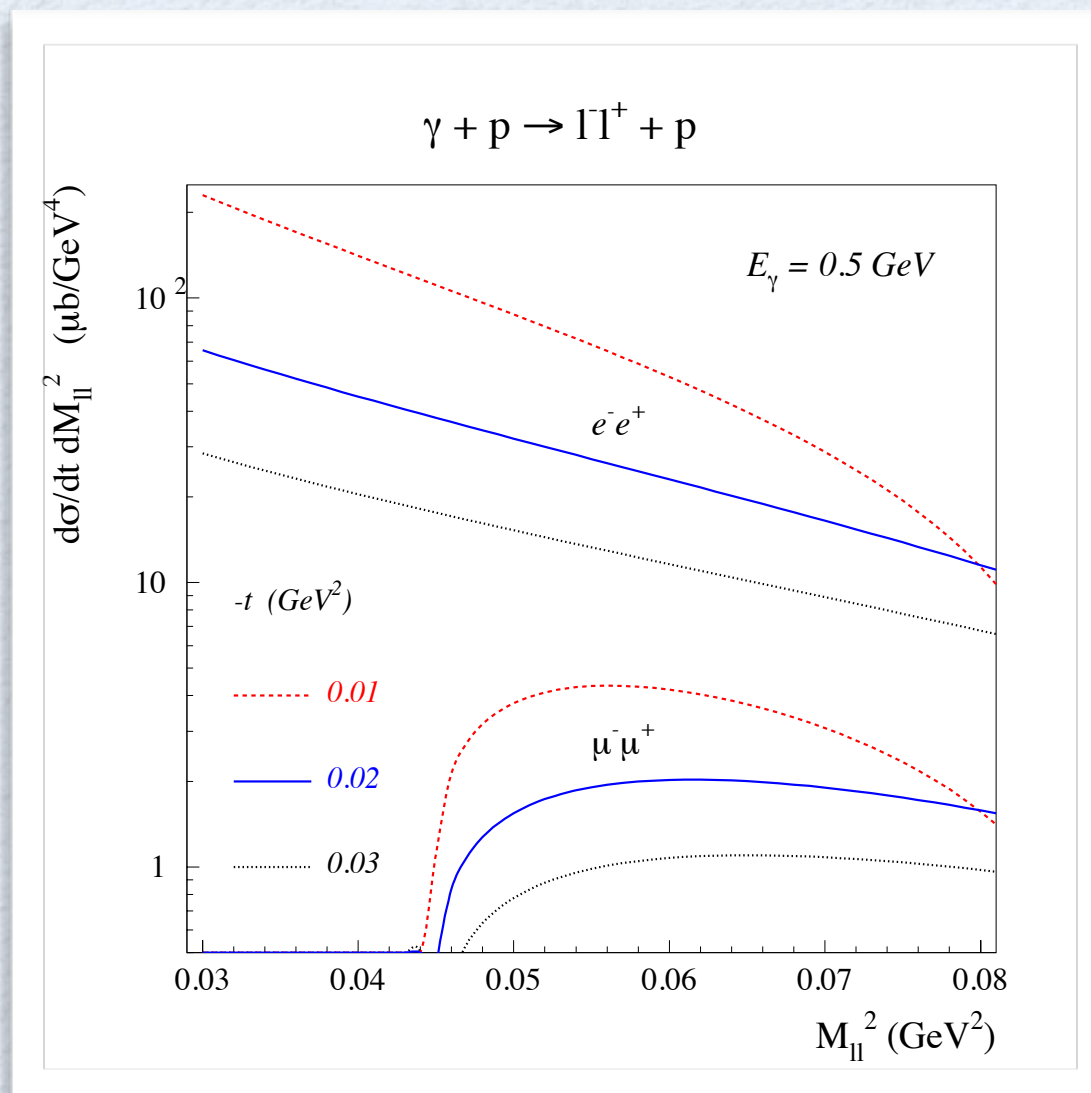
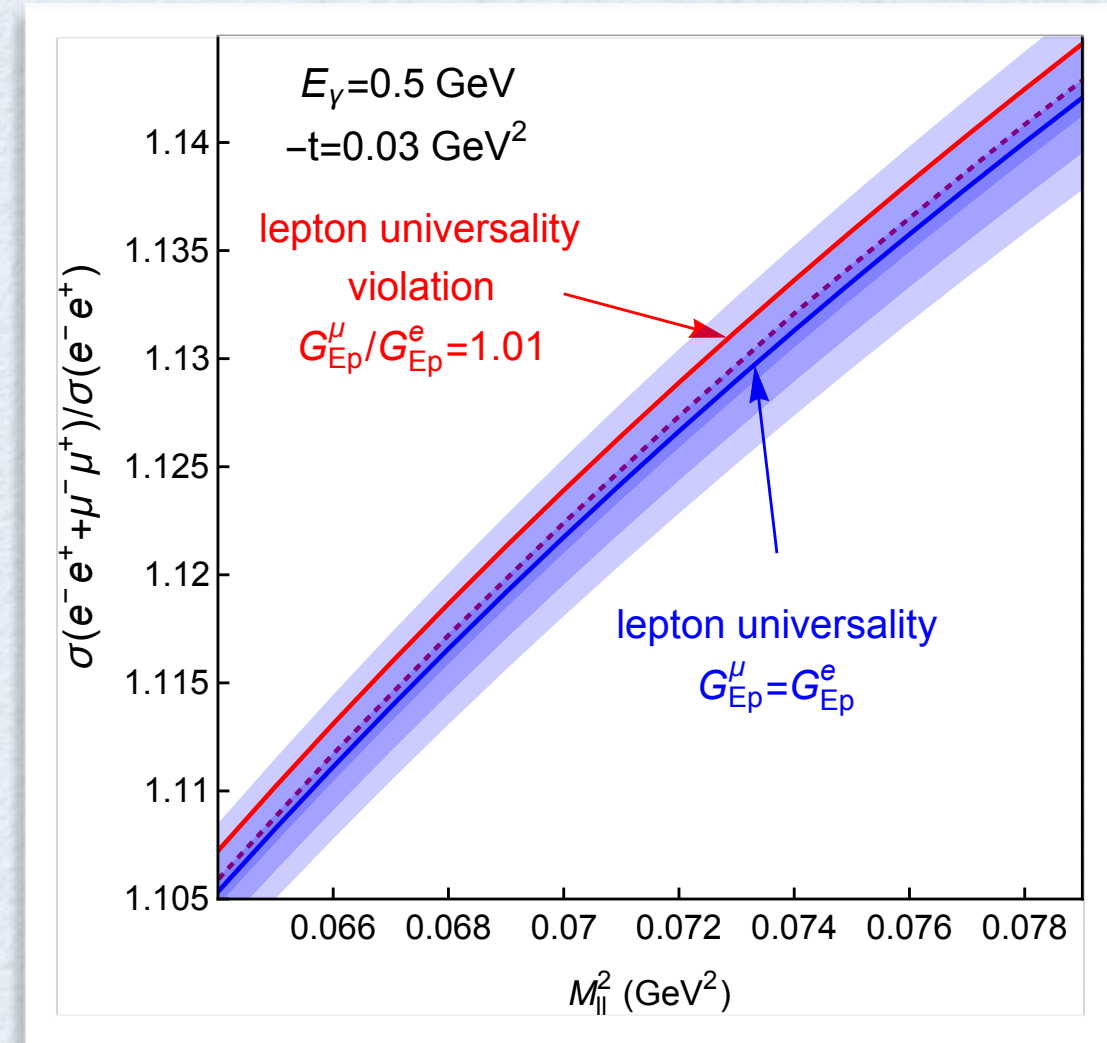
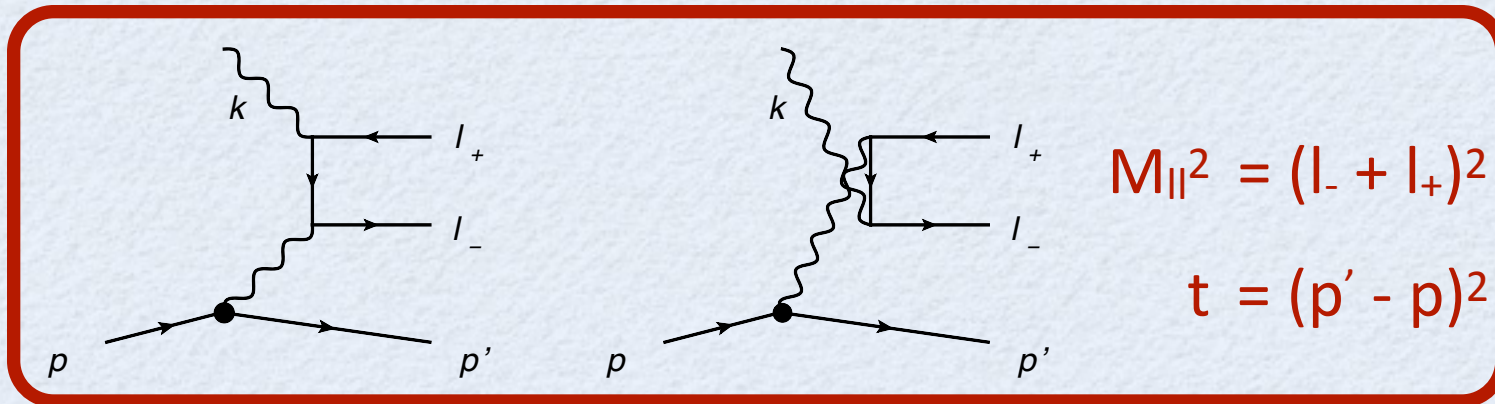
simultaneous measurement of e and μ

elastic scattering absolute cross sections



production run planned 2018 - 2019

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



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

New facility MESA

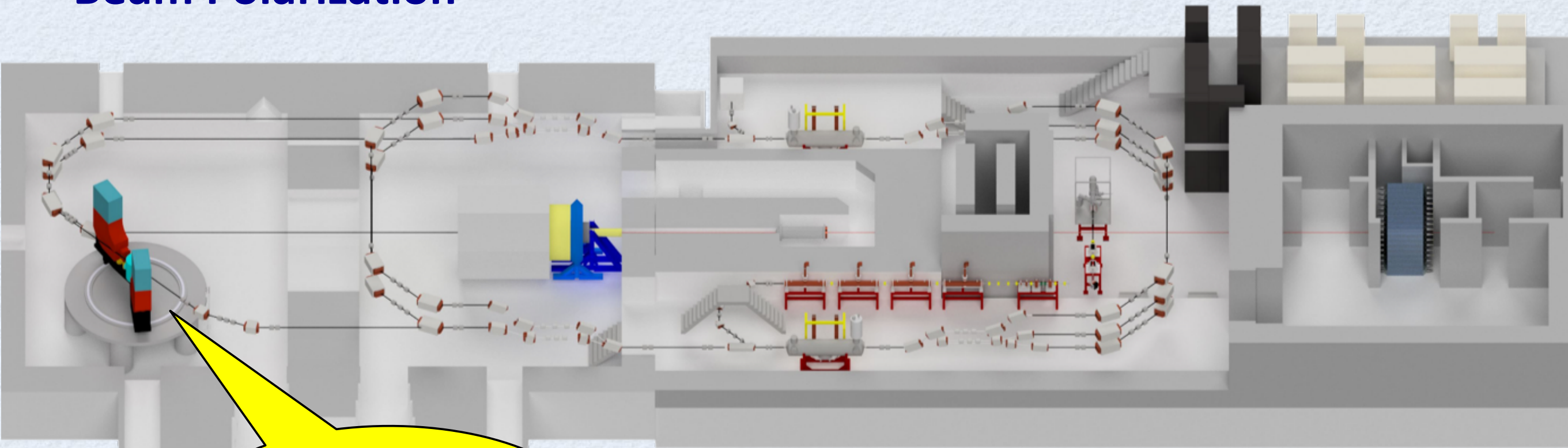
Mainz Energy-Recovering Superconducting Accelerator

Recirculating ERL Mode

$E_{\max} = 105 \text{ MeV}$

$I_{\max} > 1 \text{ mA}$

Beam Polarization



Mode 2: ERL
Internal Target
MAGIX Experiment

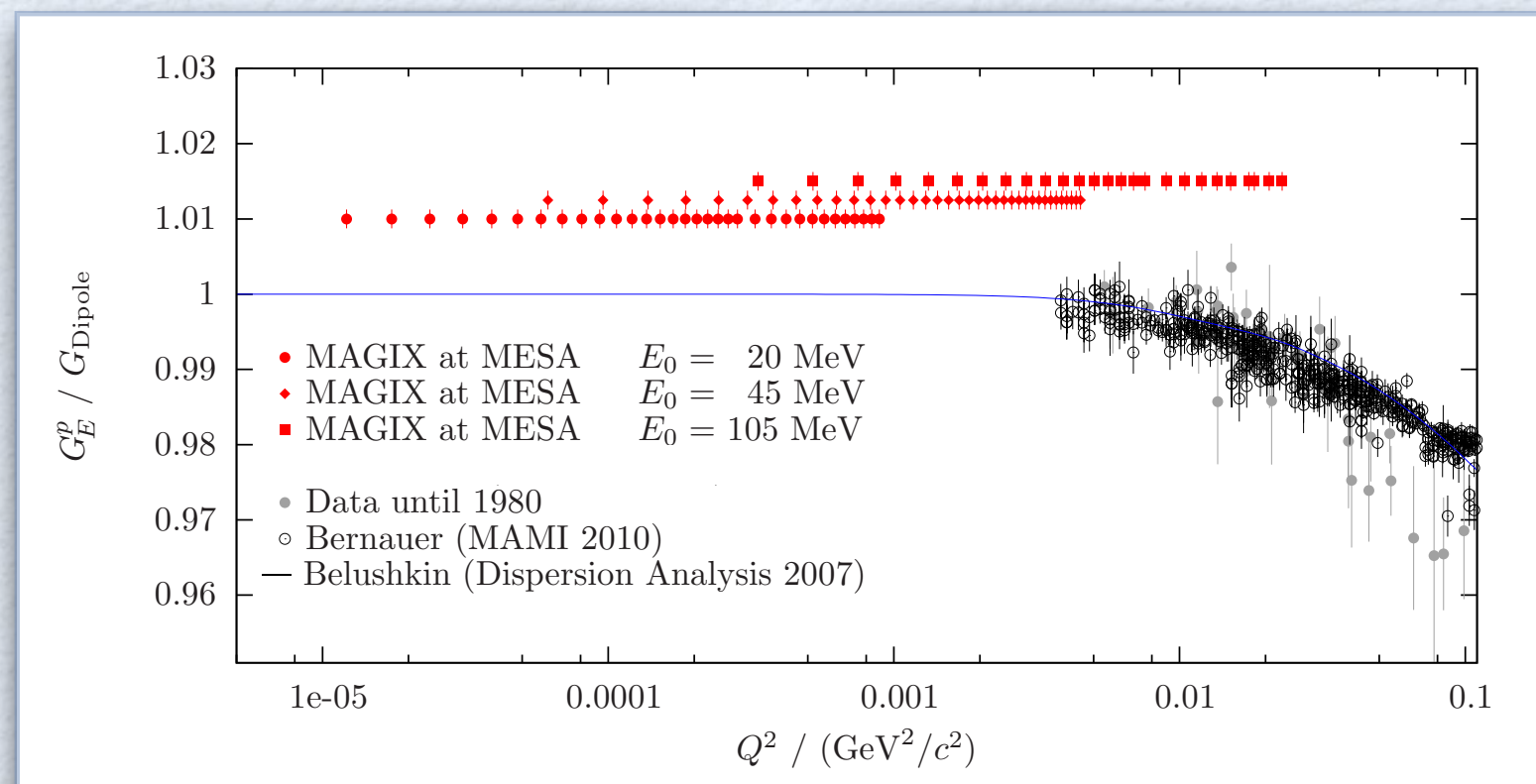
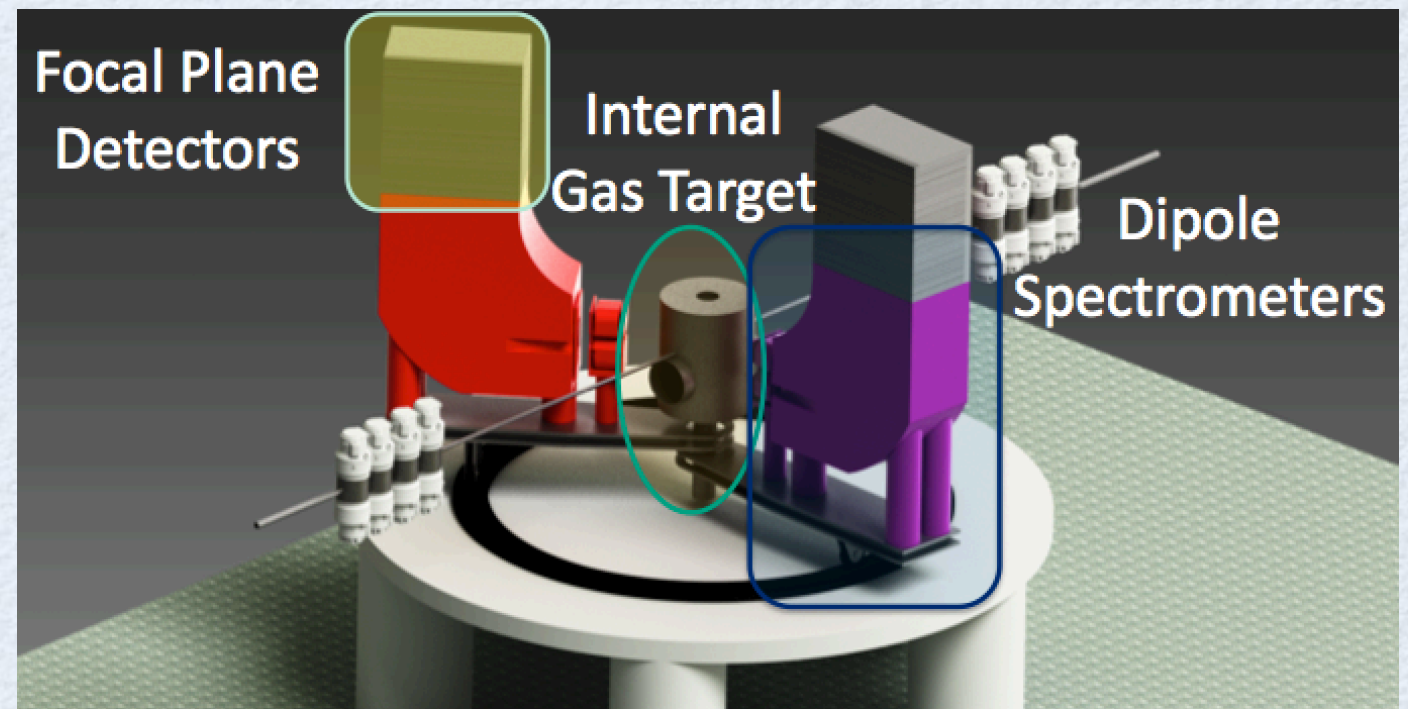
2 recirculations →
4 passes through SRF cavities

Low- Q^2 proton FF: MAGIX@MESA

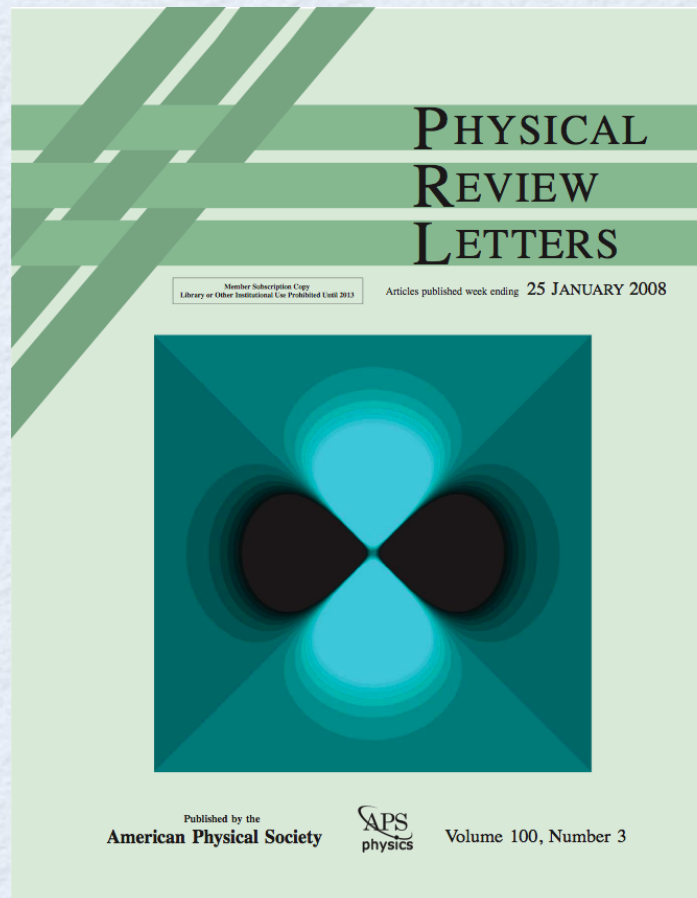
Operation of a high-intensity (polarized) ERL beam in conjunction with light internal target
→ a novel technique in nuclear and particle physics

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



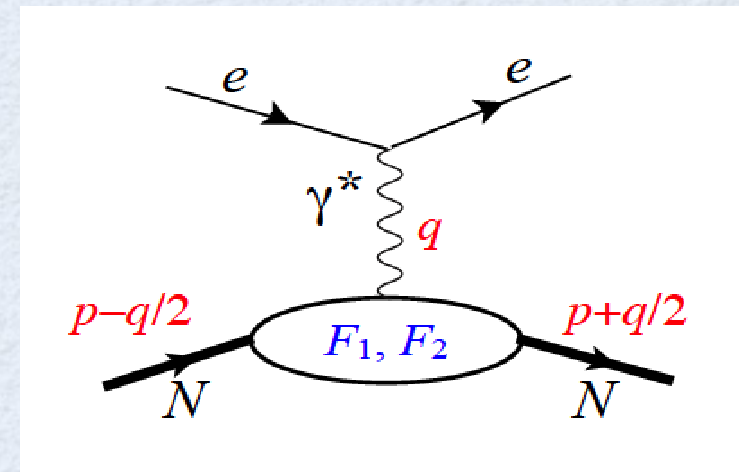
proton e.m. form factors, charge distributions



spin-1/2 electromagnetic form factors

➔ **(in)elastic electron scattering** is our microscope to investigate hadron structure

➔ in the **1-photon exchange approximation**:



nucleon (spin 1/2 target) structure is parameterized by 2 **form factors (FFs)**

$$\langle p + \frac{q}{2}, \lambda' | J^\mu(0) | p - \frac{q}{2}, \lambda \rangle = \bar{u}(p + \frac{q}{2}, \lambda') \left[F_1(Q^2) \gamma^\mu + F_2(Q^2) \frac{i}{2M} \sigma^{\mu\nu} q_\nu \right] u(p - \frac{q}{2}, \lambda)$$

↑
Dirac FF

↑
Pauli FF

for proton: $F_1(Q^2 = 0) = 1$ $F_2(Q^2 = 0) = \kappa_p = 1.79$

➔ equivalently: in experiment one often uses **Sachs FFs** with $\tau \equiv \frac{Q^2}{4M^2}$

$$\begin{aligned} G_M(Q^2) &= F_1(Q^2) + F_2(Q^2) && \longrightarrow \text{magnetic FF} \\ G_E(Q^2) &= F_1(Q^2) - \tau F_2(Q^2) && \longrightarrow \text{electric FF} \end{aligned}$$

$$G_E(Q^2) = 1 - \frac{1}{6} \langle r_E^2 \rangle Q^2 + \mathcal{O}(Q^4)$$

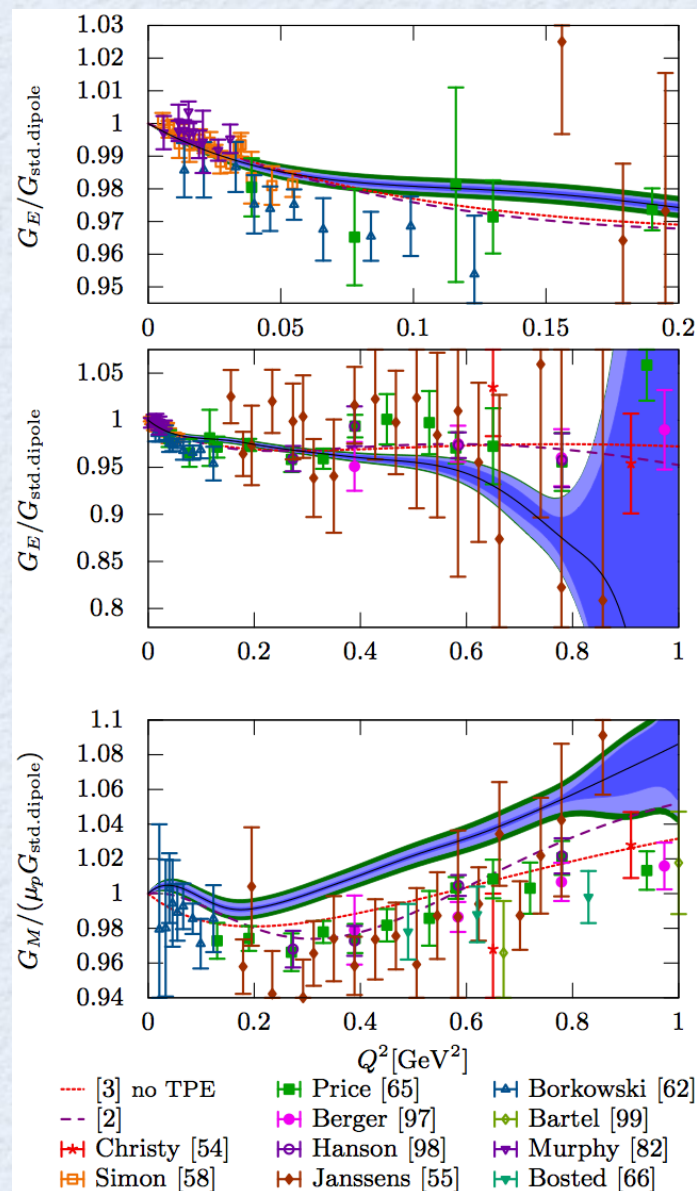
↑
charge radius

e⁻ scattering cross sections

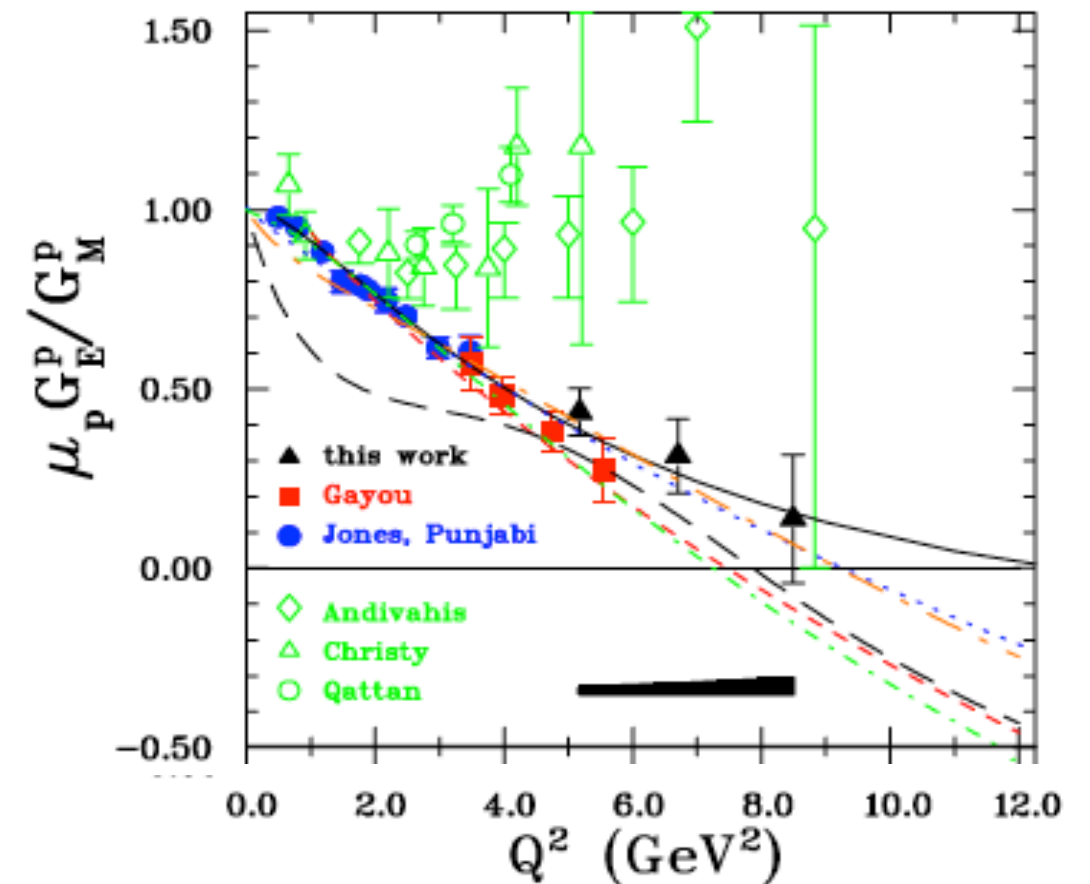
Electron scattering facilities JLab (12 GeV), MAMI (1.6 GeV):
uniquely positioned to deliver high precision data

MAMI/A1 achieved < 1% measurement
of proton charge radius R_E

JLab polarization transfer measurements:
 G_{Ep} / G_{Mp} difference with Rosenbluth



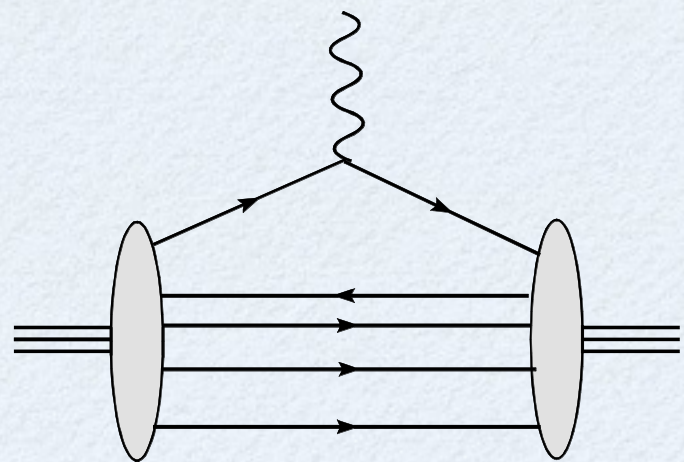
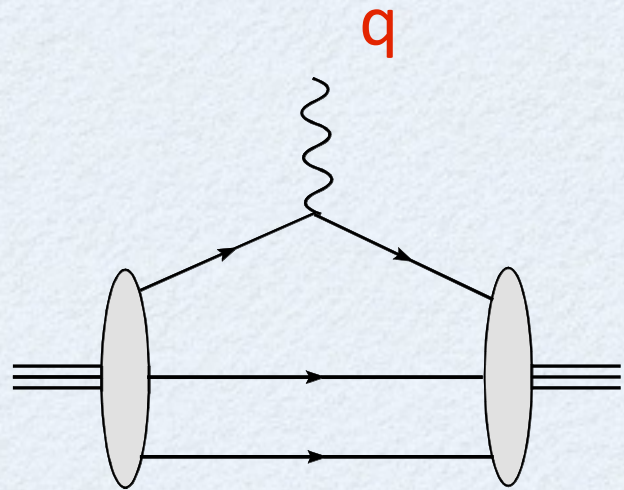
Bernaer et al. (2010, 2013)



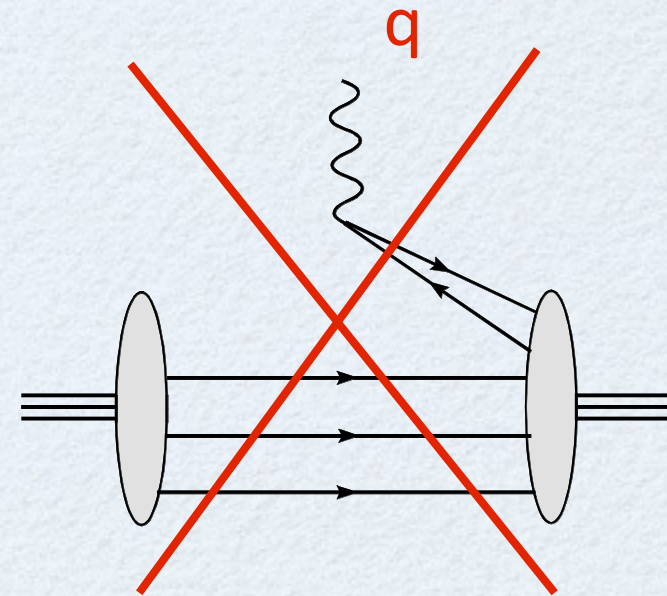
Jones et al. (2000) Punjabi et al. (2005)

Gayou et al. (2002) Puckett et al. (2010)

Interpretation of form factor as quark density



overlap of wave function
Fock components
with **same** number of quarks



overlap of wave function
Fock components
with **different** number of quarks
NO probability / charge density
interpretation

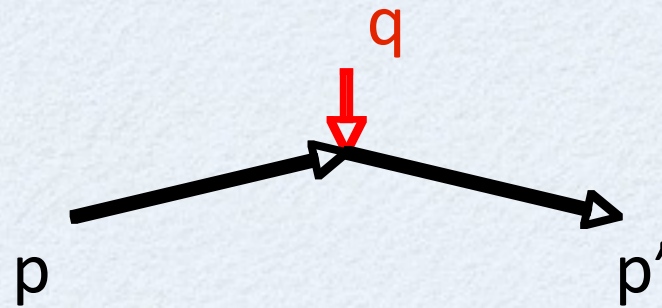
absent in a light-front frame!

$$q^+ = q^0 + q^3 = 0$$

quark transverse charge densities in nucleon (1)

→ light-front

$$q^+ = q^0 + q^3 = 0$$

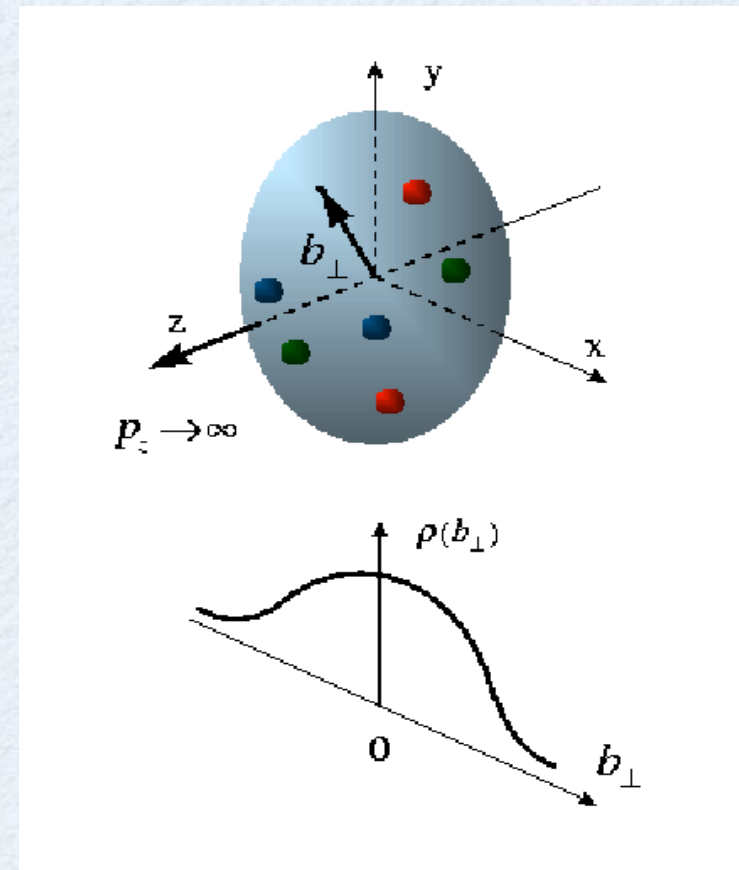


photon only couples to forward moving quarks

→ quark charge density operator

$$J^+ = J^0 + J^3 = \bar{q}\gamma^+q = 2q_+^\dagger q_+$$

with $q_+ \equiv \frac{1}{4}\gamma^-\gamma^+q$



→ longitudinally polarized nucleon

$$\begin{aligned} \rho_0^N(\vec{b}) &\equiv \int \frac{d^2\vec{q}_\perp}{(2\pi)^2} e^{-i\vec{q}_\perp \cdot \vec{b}} \frac{1}{2P^+} \langle P^+, \frac{\vec{q}_\perp}{2}, \lambda | J^+(0) | P^+, -\frac{\vec{q}_\perp}{2}, \lambda \rangle \\ &= \int_0^\infty \frac{dQ}{2\pi} Q J_0(bQ) F_1(Q^2) \end{aligned}$$

Soper (1997)

Burkardt (2000)

Miller (2007)

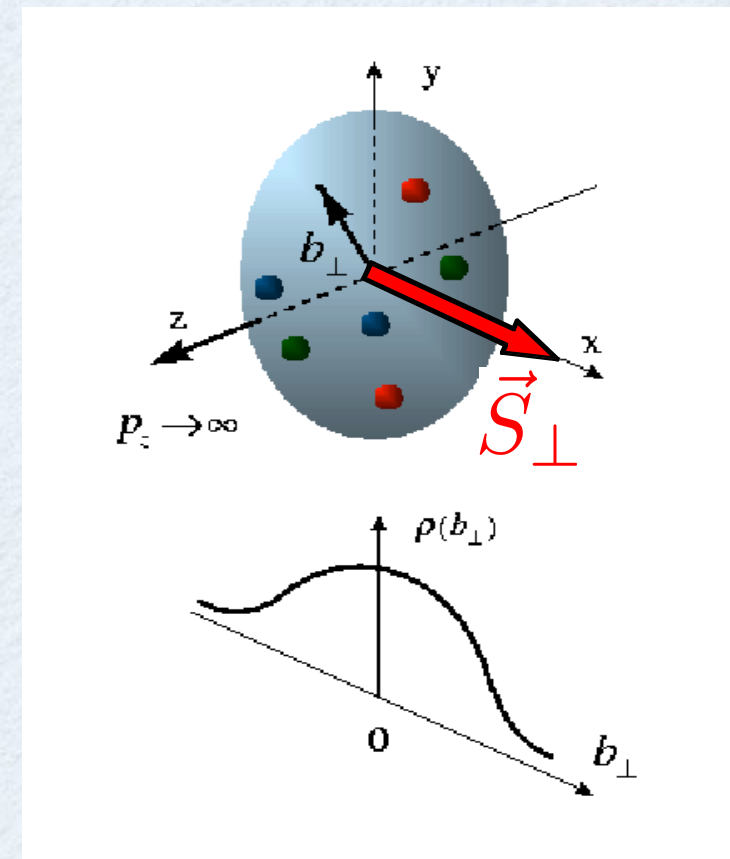
quark transverse charge densities in nucleon (2)

→ transversely polarized nucleon

transverse spin $\vec{S}_\perp = \cos \phi_S \hat{e}_x + \sin \phi_S \hat{e}_y$

e.g. along x-axis $\phi_S = 0$

$$\vec{b} = b(\cos \phi_b \hat{e}_x + \sin \phi_b \hat{e}_y)$$



→

$$\rho_T^N(\vec{b}) \equiv \int \frac{d^2 \vec{q}_\perp}{(2\pi)^2} e^{-i\vec{q}_\perp \cdot \vec{b}} \frac{1}{2P^+} \langle P^+, \frac{\vec{q}_\perp}{2}, s_\perp = +\frac{1}{2} | J^+(0) | P^+, -\frac{\vec{q}_\perp}{2}, s_\perp = +\frac{1}{2} \rangle$$

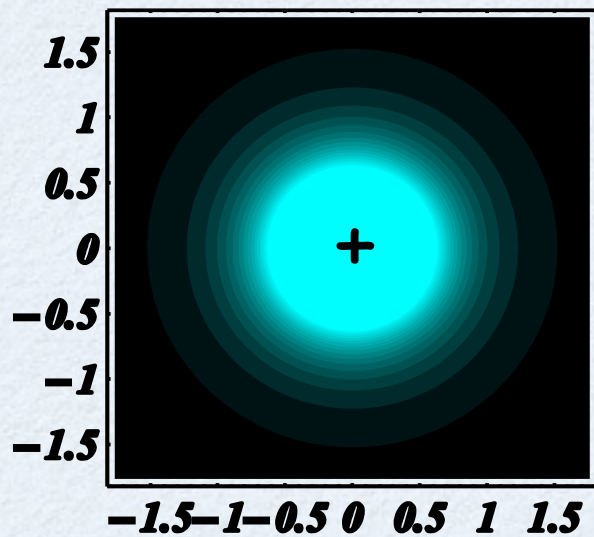
$$= \rho_0^N(b) + \sin(\phi_b - \phi_S) \int_0^\infty \frac{dQ}{2\pi} \frac{Q^2}{2M} J_1(bQ) F_2(Q^2)$$

↑
dipole field pattern

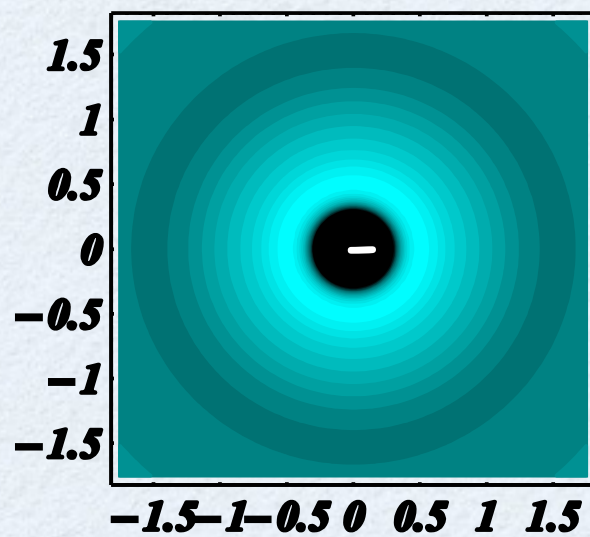
Carlson, Vdh (2007)

spatial imaging of hadrons

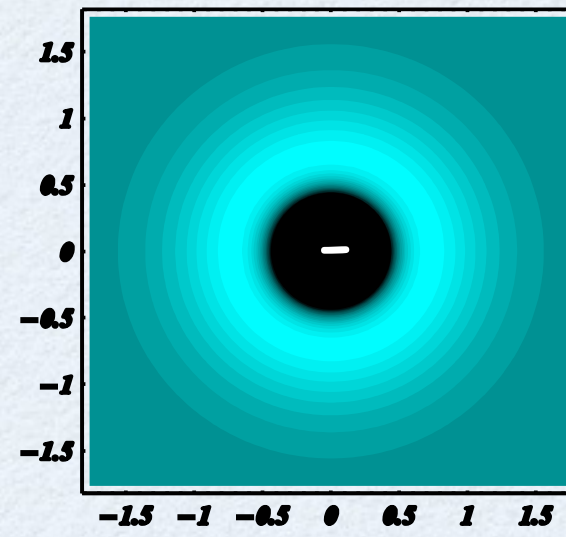
proton



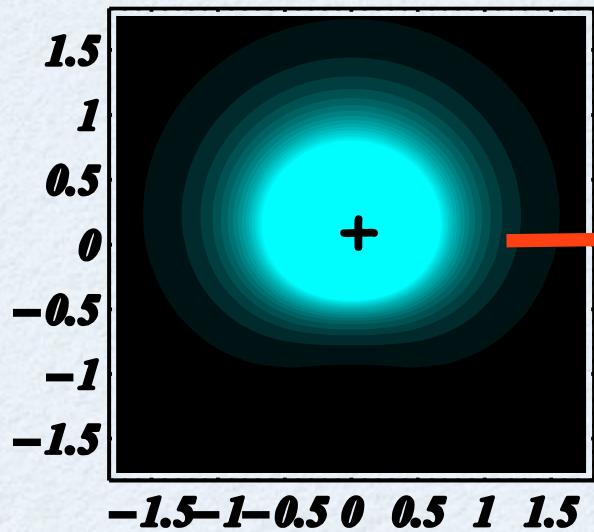
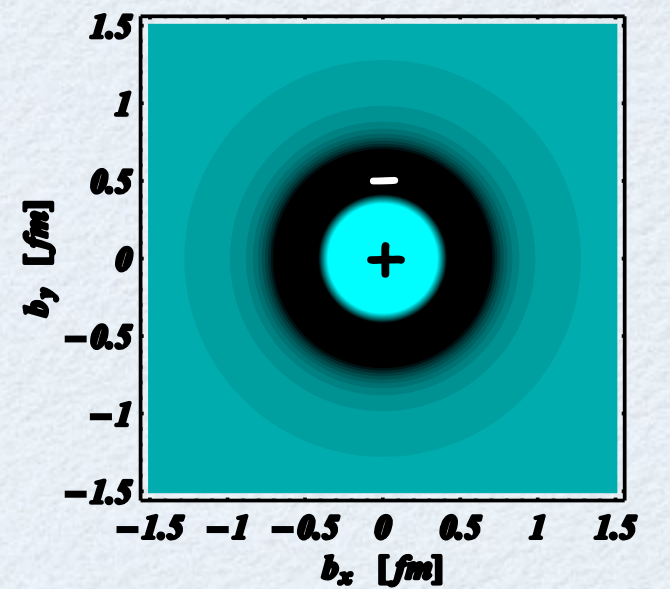
neutron



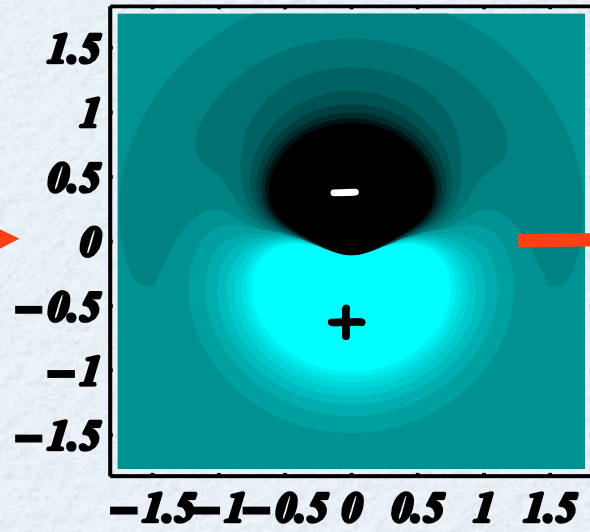
$p \rightarrow \Delta^+$



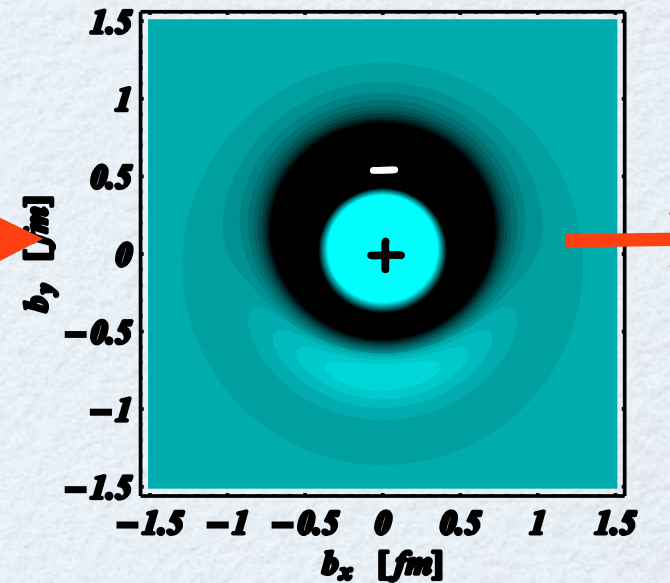
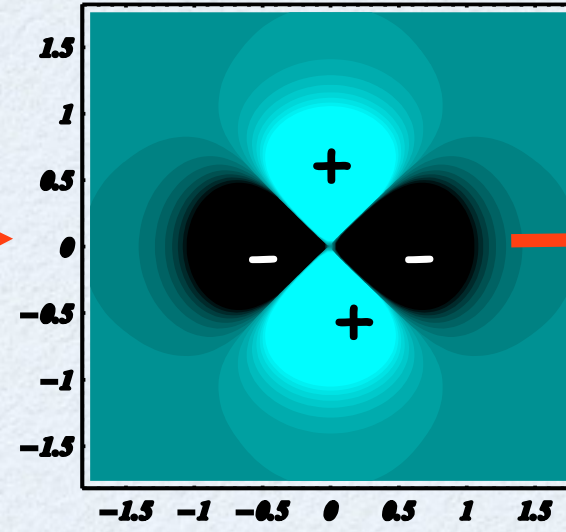
$p \rightarrow N^* (1440)$



Miller (2007)

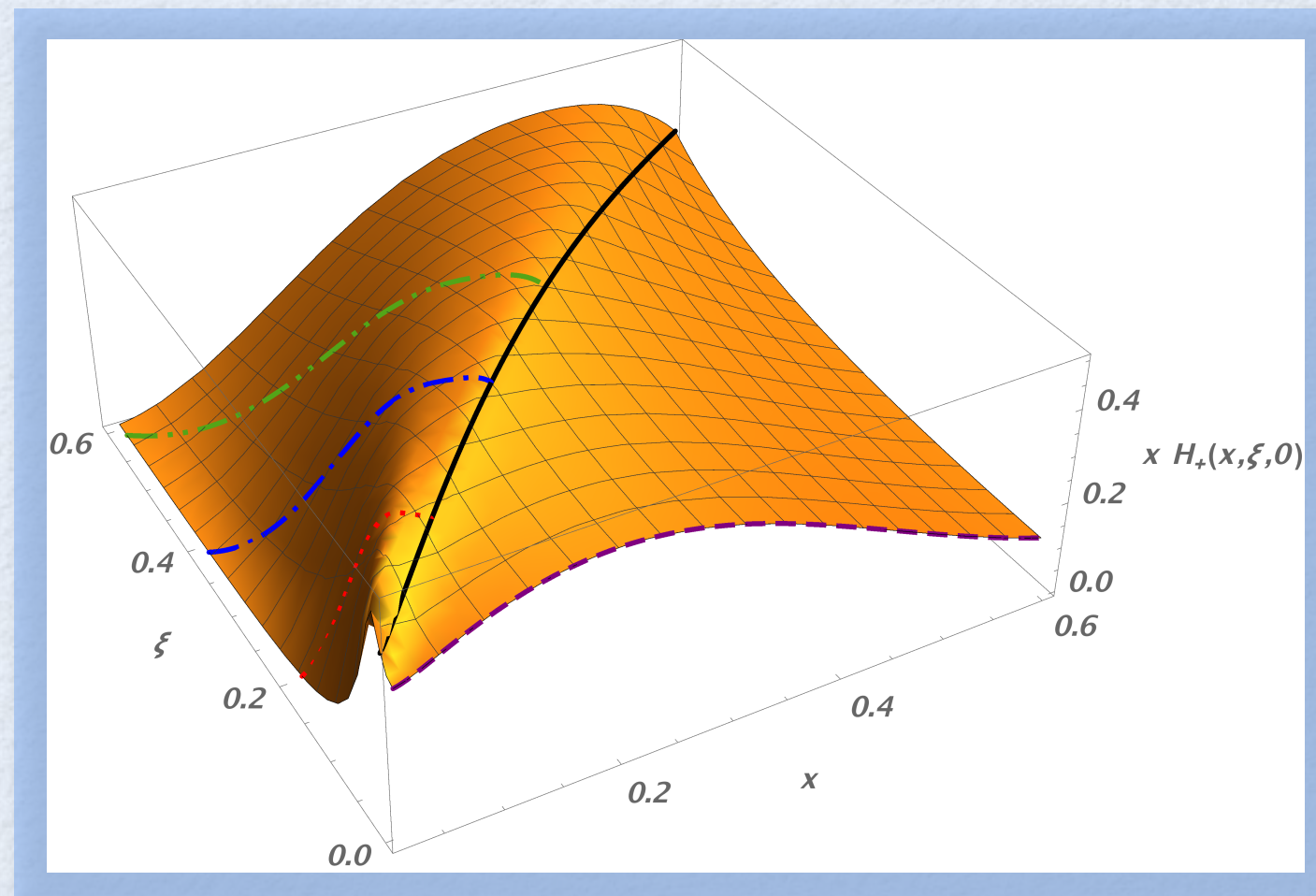


Carlson, Vdh (2007)



Tiator, Vdh (2007)

Generalised Parton Distributions



Correlations in transverse position/longitudinal momentum

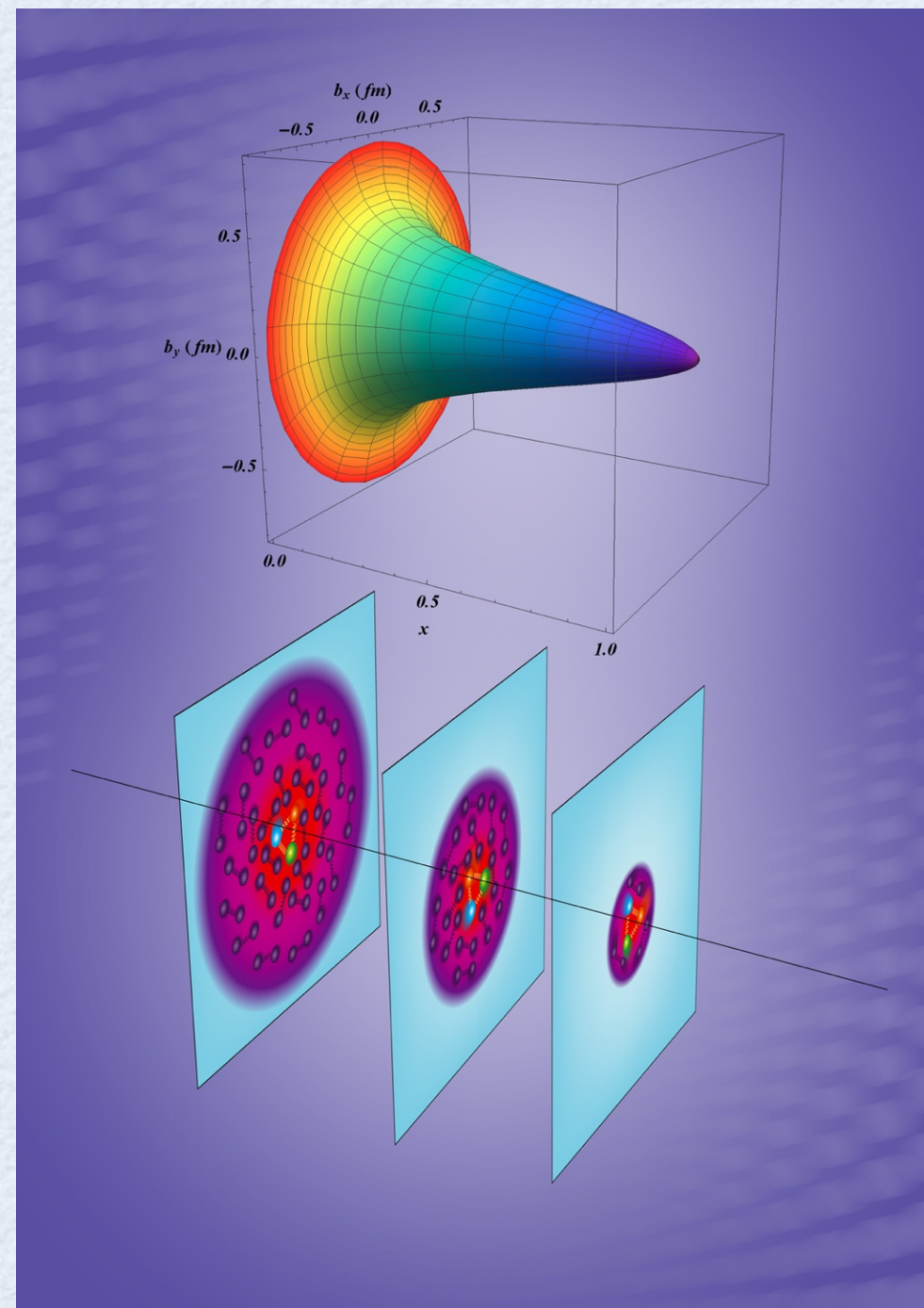
**elastic
scattering**



DIS

quark
distributions in
transverse
position space

quark
distributions in
longitudinal
momentum



proton
3D imaging

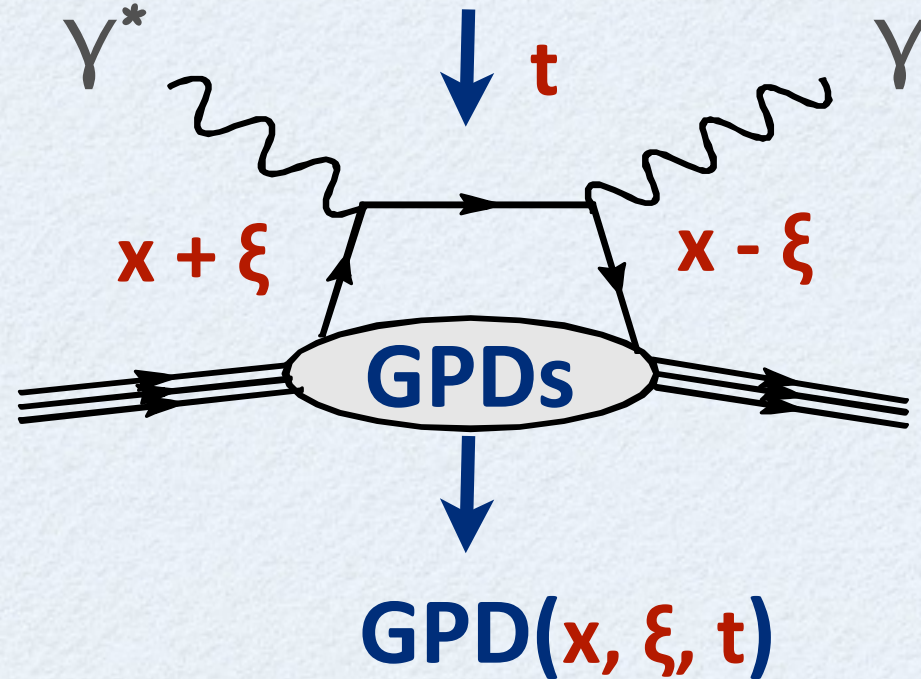
Burkardt (2000, 2003)

Belitsky, Ji, Yuan
(2004)

DVCS: tool to access GPDs

world data on proton F_2

$Q^2 \gg 1 \text{ GeV}^2$



➔ at large Q^2 : QCD factorization theorem

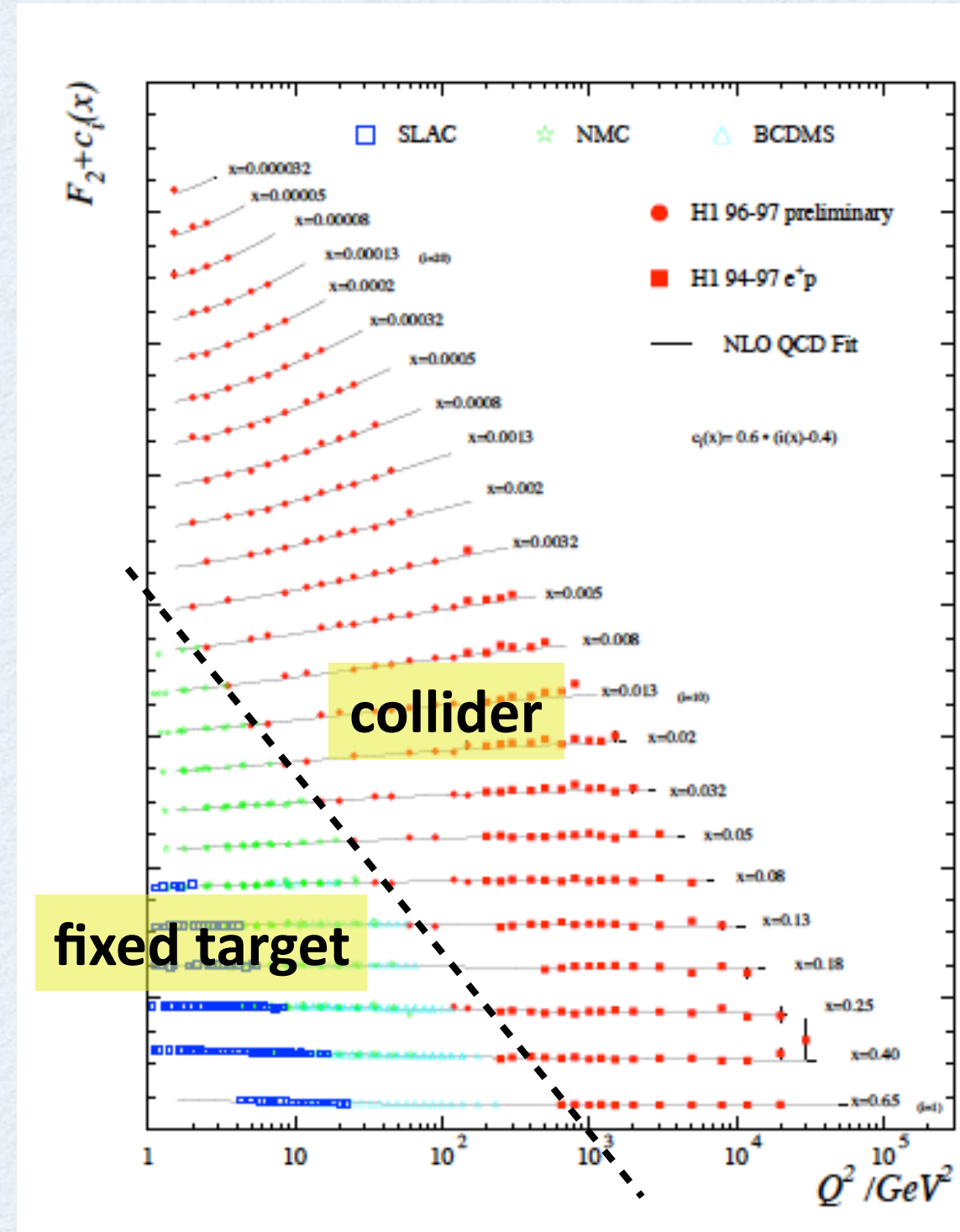
Müller et al (1994)

Ji (1995) Radyushkin (1996)

Collins, Frankfurt, Strikman (1996)

at twist-2: 4 quark helicity conserving GPDs

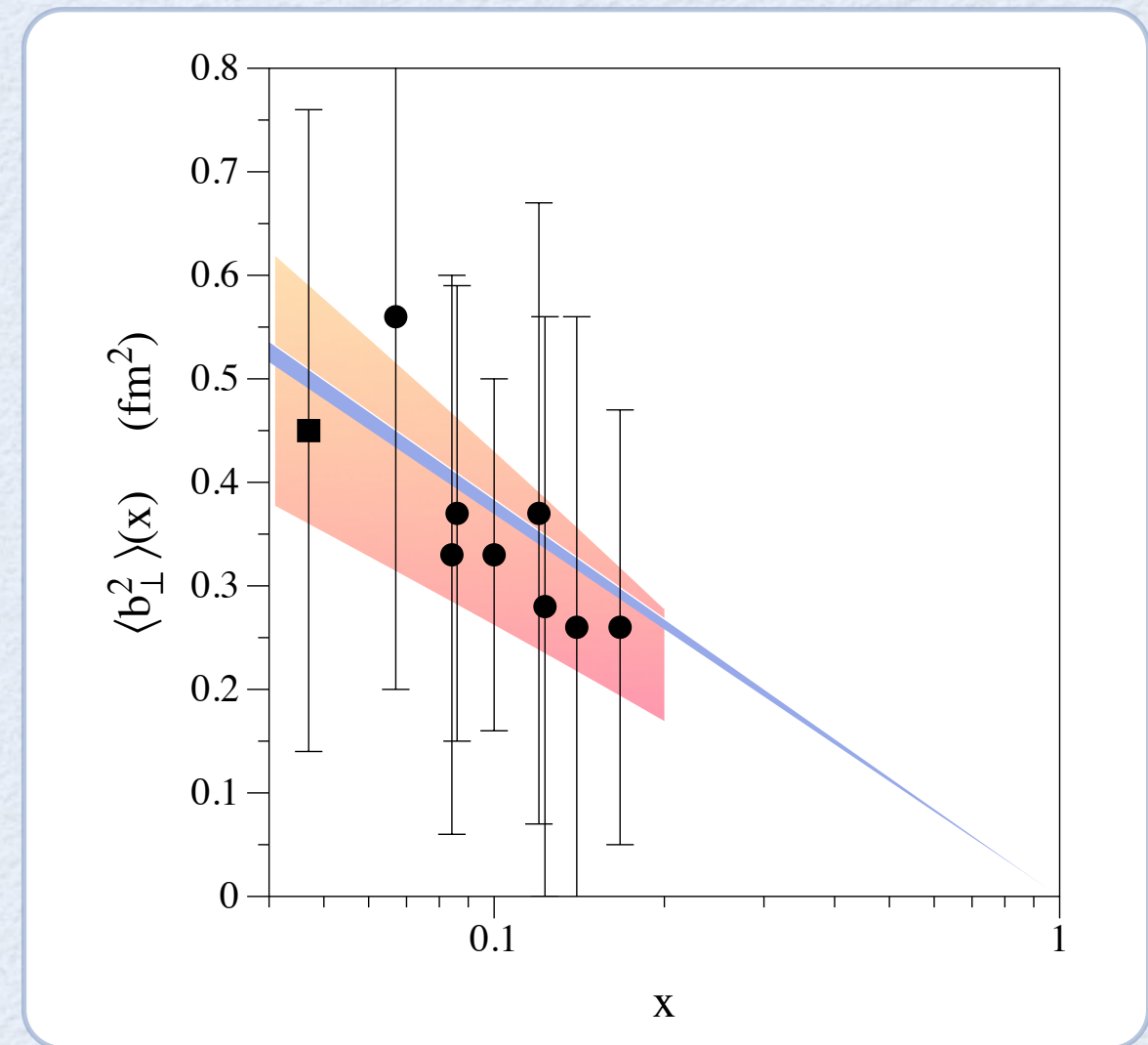
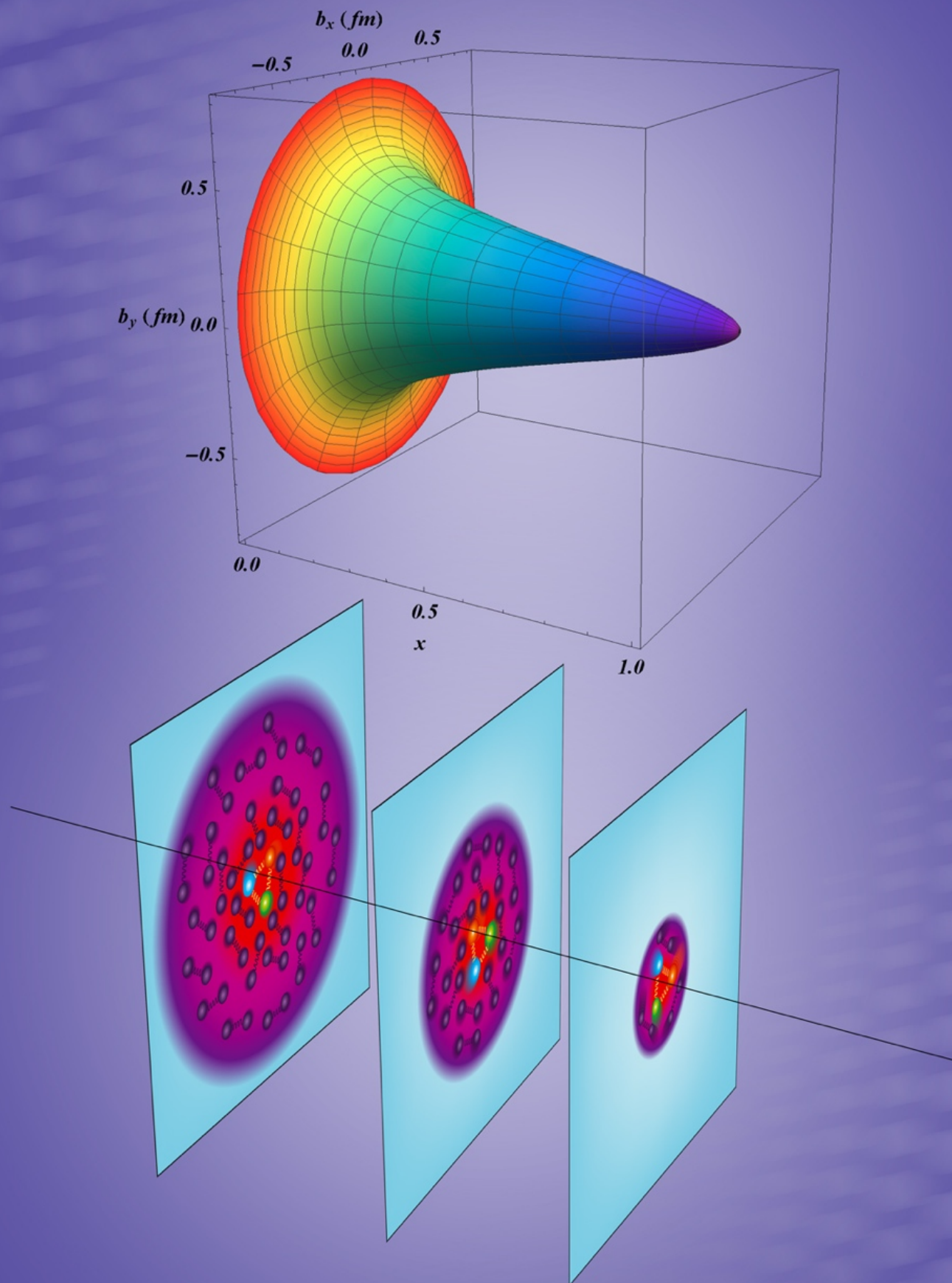
➔ key: Q^2 leverage needed to test QCD scaling



3D imaging of proton

black circles: CFF fit of JLab data

black squares: CFF fit of HERMES data

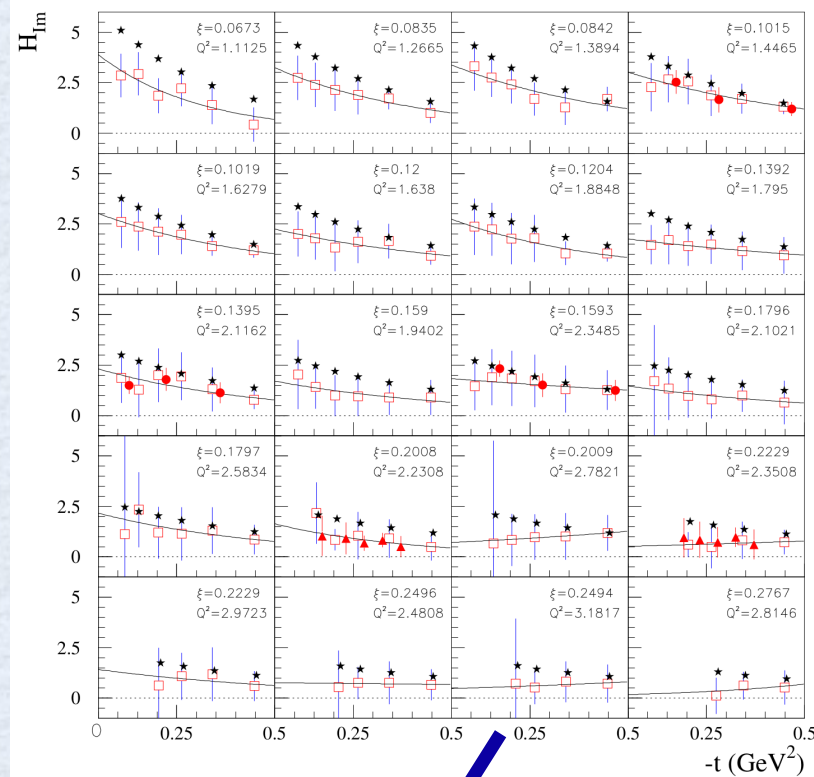


band: using $B_0(x) = a_{B_0} \ln(1/x)$

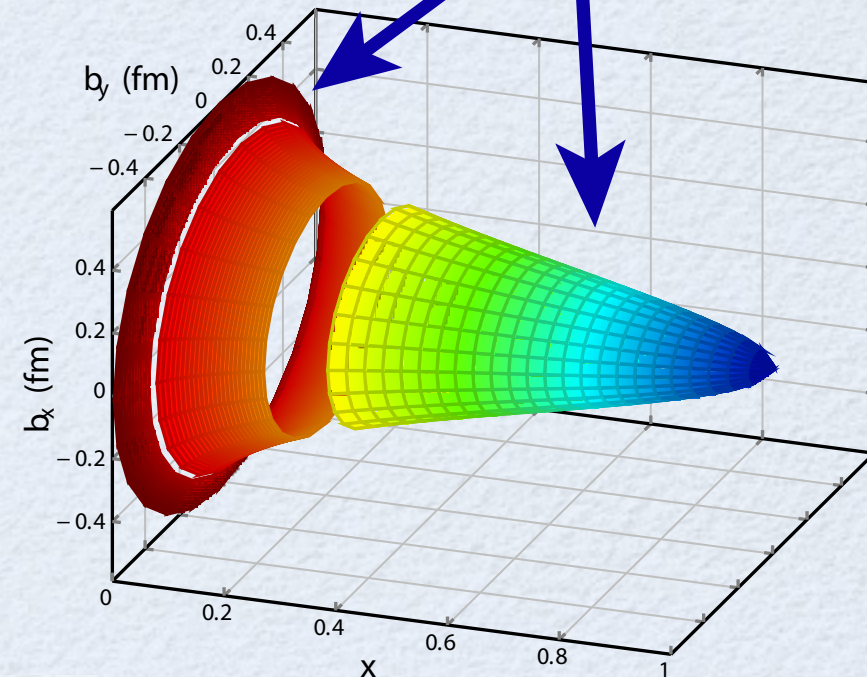
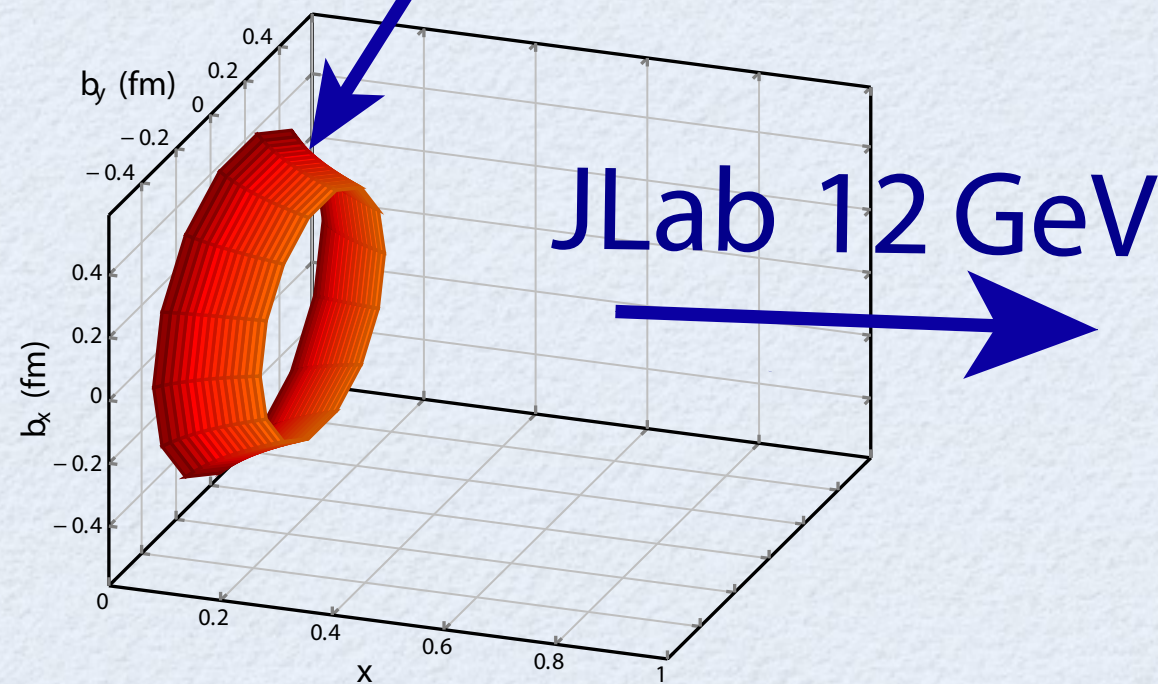
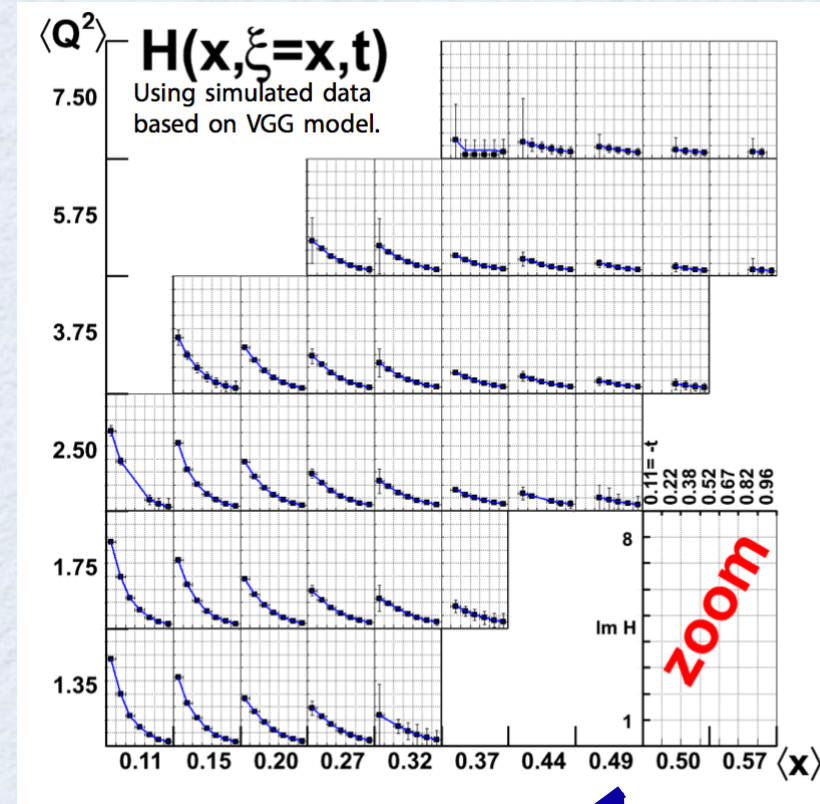
a_{B_0} fixed from elastic scattering

Projections for CFFs at JLab 12 GeV

Düpré-Guidal-Vanderhaeghen-PRD **95** 011501 (R) (2017)

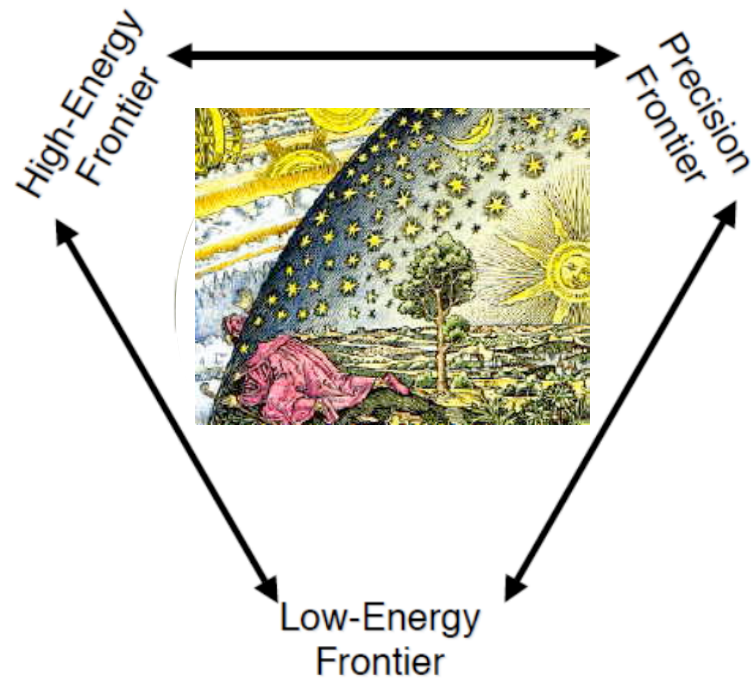
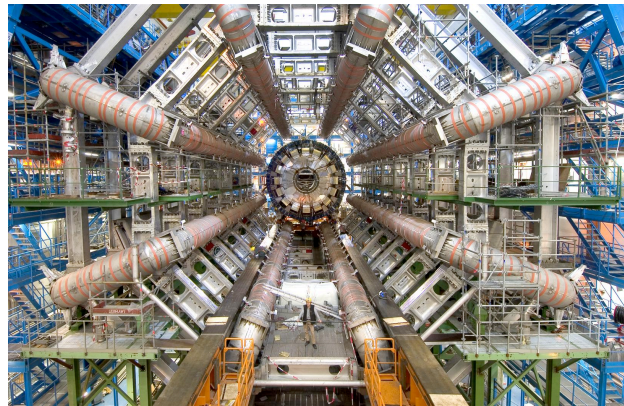


CLAS12 projections E12-06-119 with DVCS A_{UL} and A_{LU}



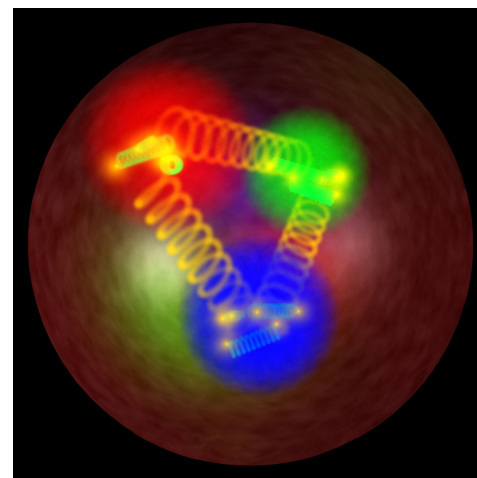
courtesy of Z.E. Meziani

Conclusions



Puzzles at low Energies ?!

- Proton Radius
- $(g-2)_\mu$
- Dark Photon



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

→ New tools: MESA