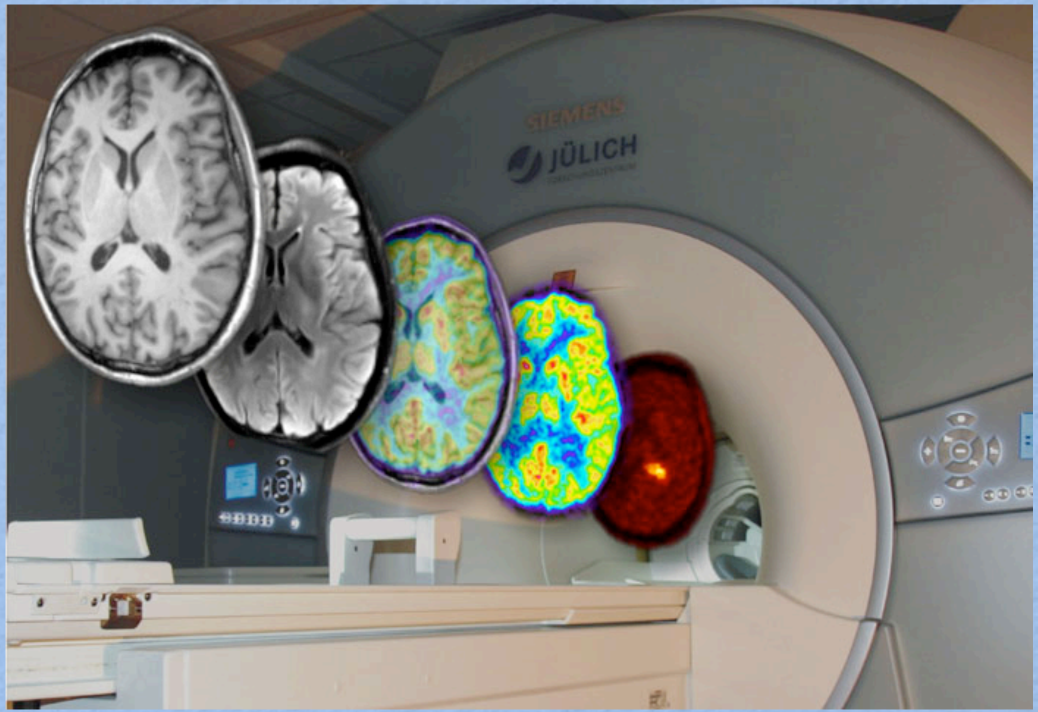
Electromagnetic structure of hadrons



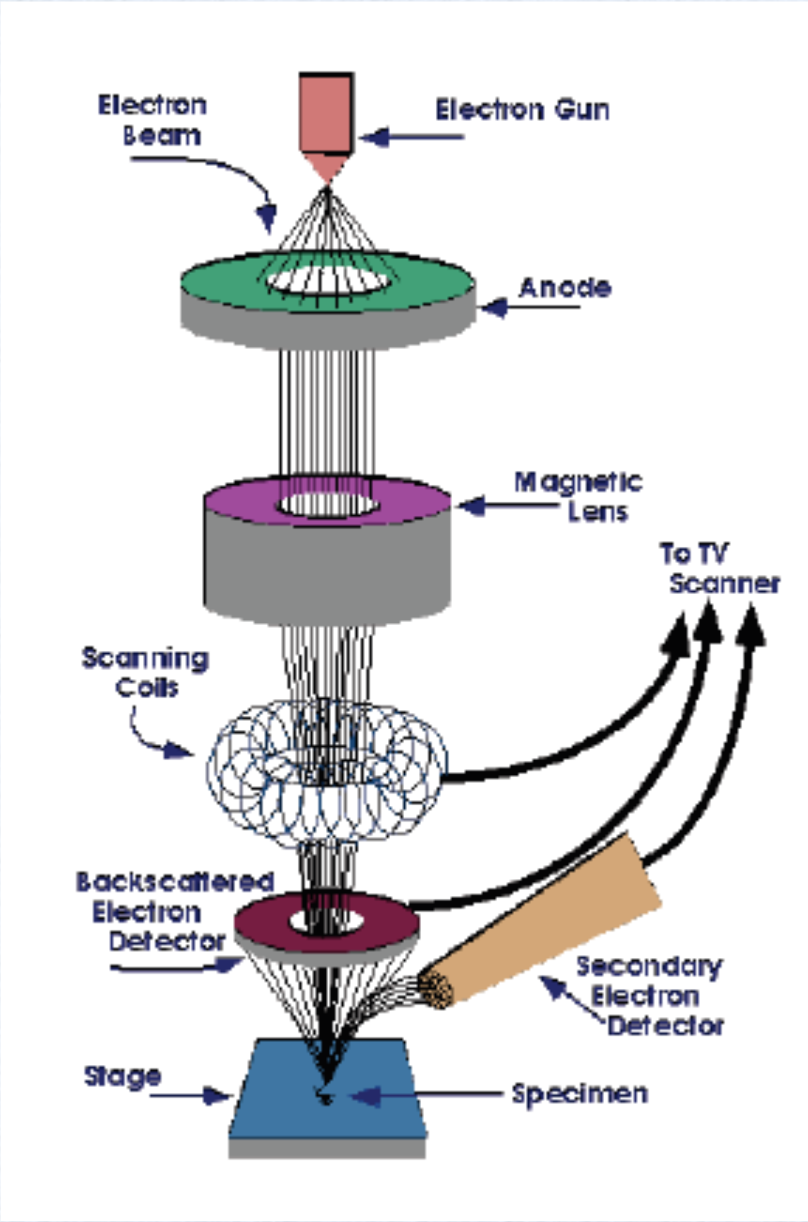
Marc Vanderhaeghen

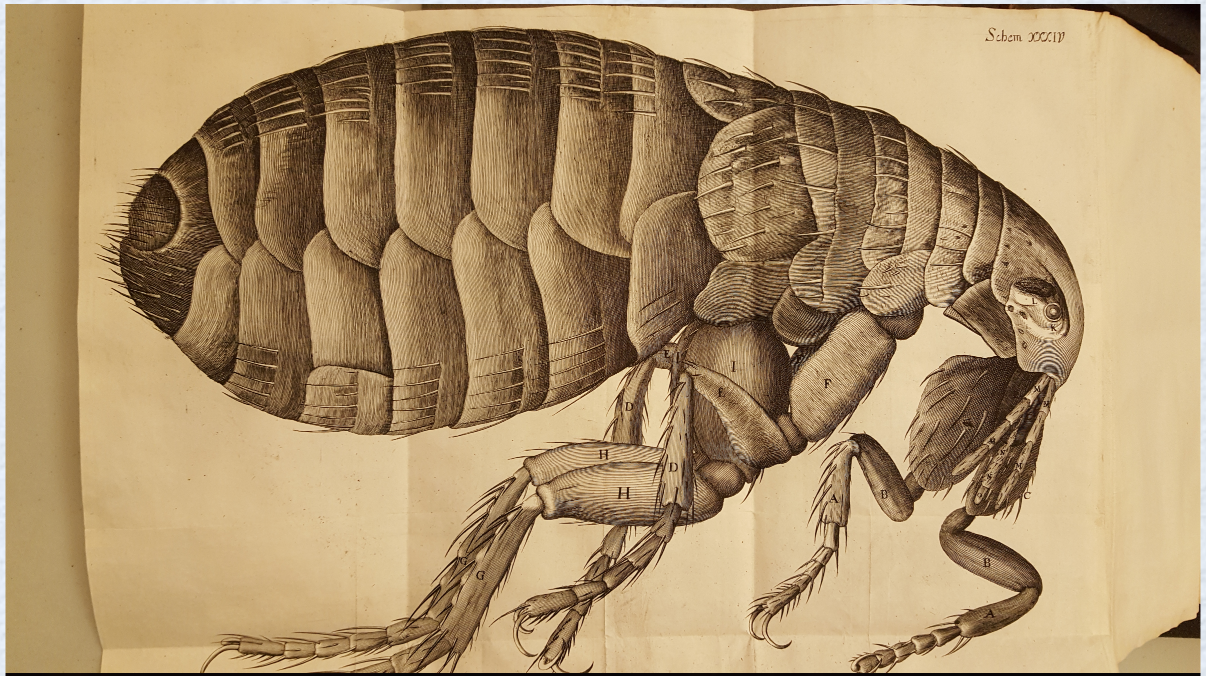
2017 Intl. Summer Workshop on Reaction Theory

June 12 - 22, 2017, Bloomington, Indiana

how to image a system

R.Hooke (Micrographia, 1665)





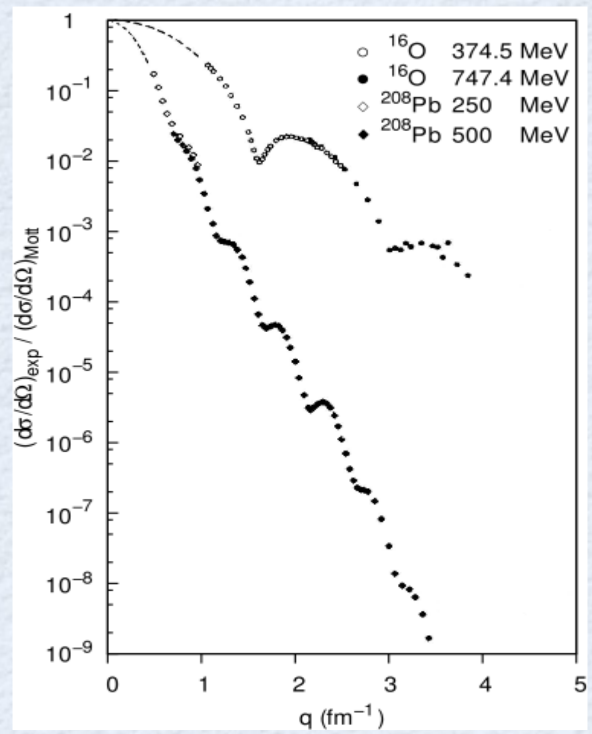
when target is static

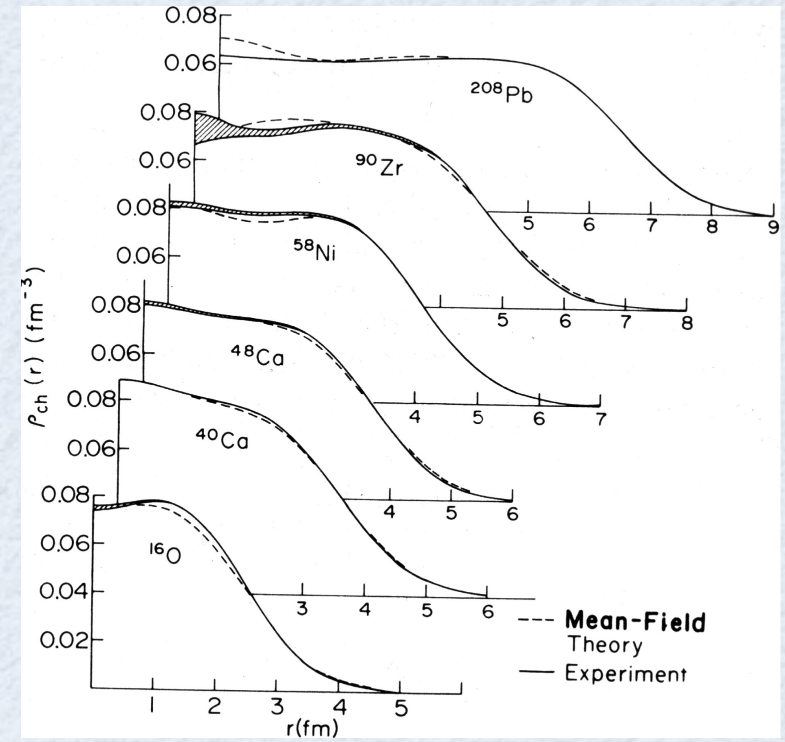
($m_{constituent}$, m_{target} >> Q)

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

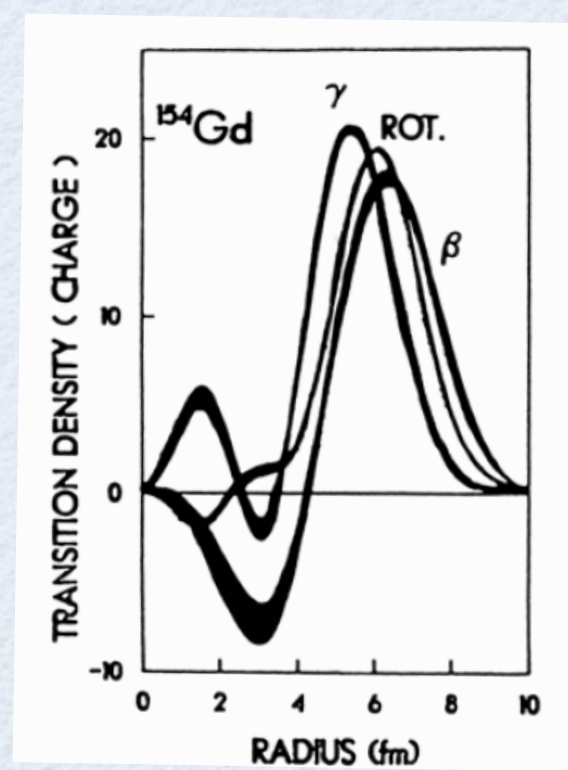
what do we know about spatial distributions of charges in nuclei?

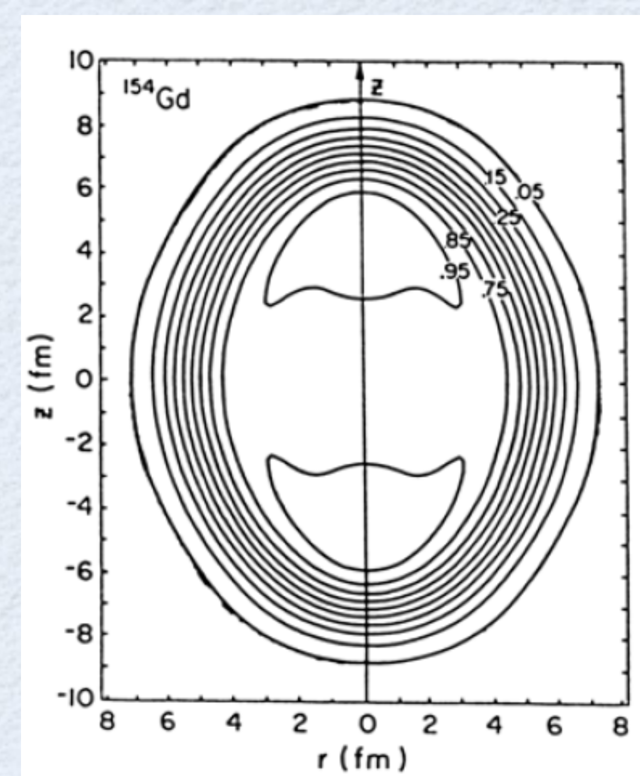
sizes of nuclei:
as revealed through
elastic electron scattering





shapes of nuclei:
as revealed through
inelastic electron scattering



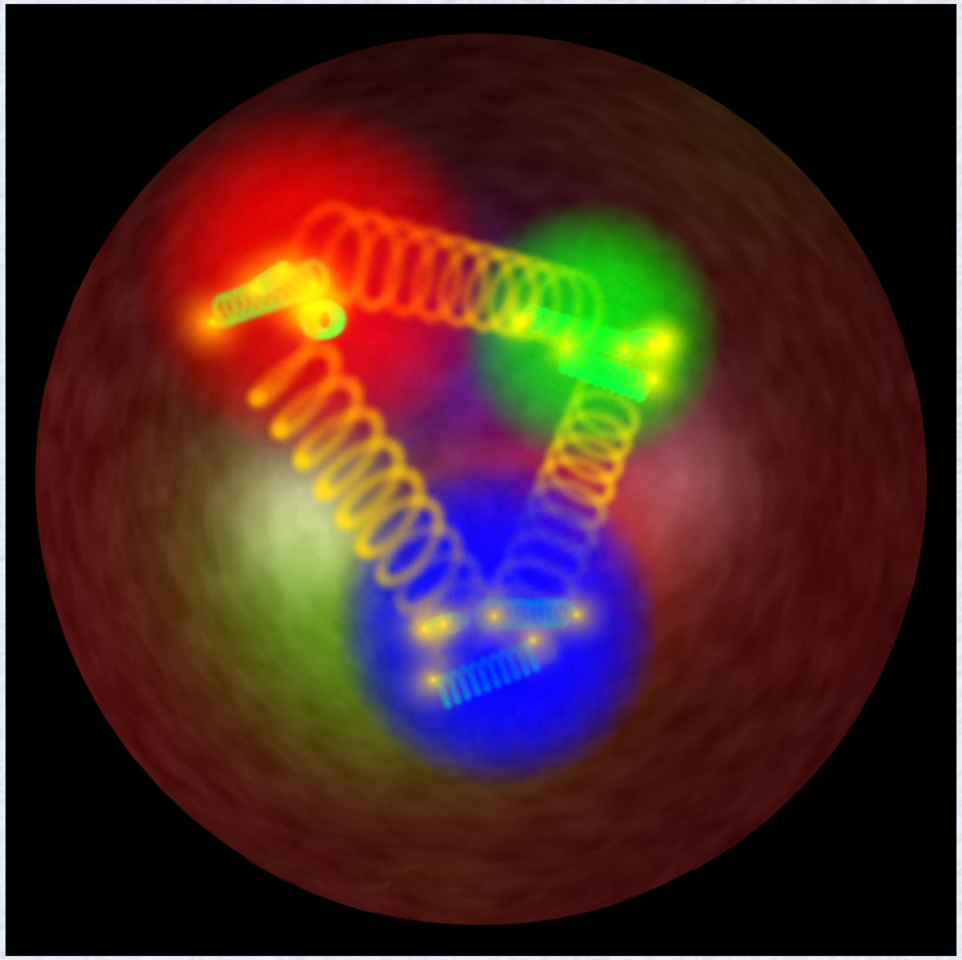


what do we know about the proton size and its charge distributions?

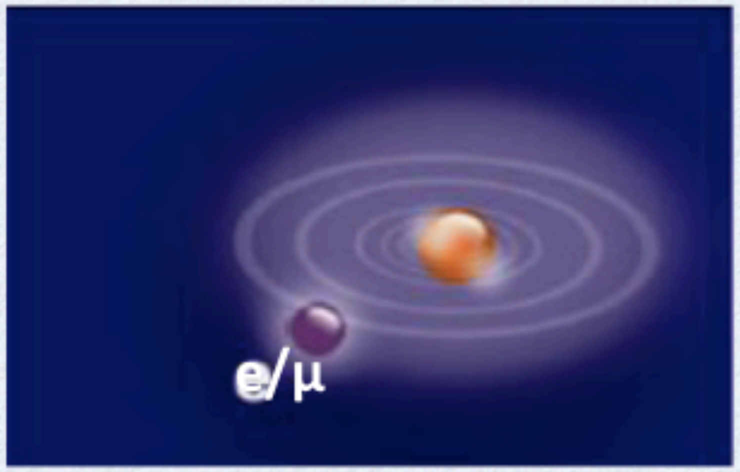
- proton **size**: charge radius R_E
  very low Q^2 **elastic** electron scattering,
  atomic spectroscopy (Lamb shift)

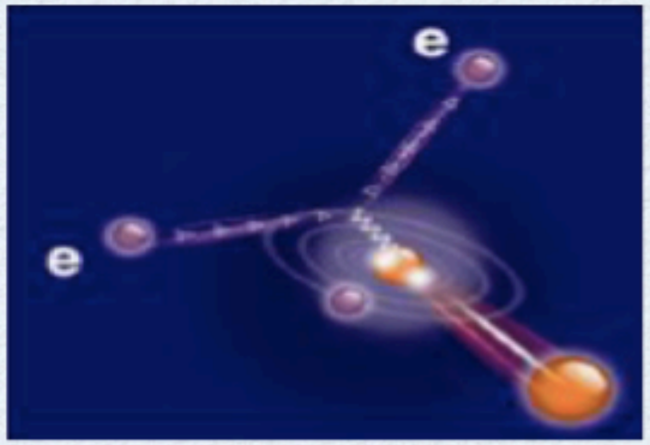
- proton **spatial (charge) distributions**
  elastic electron scattering
  e.m. FFs: $F_1(Q^2) \rightarrow \rho(\mathbf{b})$

- proton **3D transverse spatial/ longitudinal momentum distributions**
  deeply virtual Compton scattering
  GPDs $H(x, \xi, t) \rightarrow \rho(x, \mathbf{b})$ for $\xi=0$

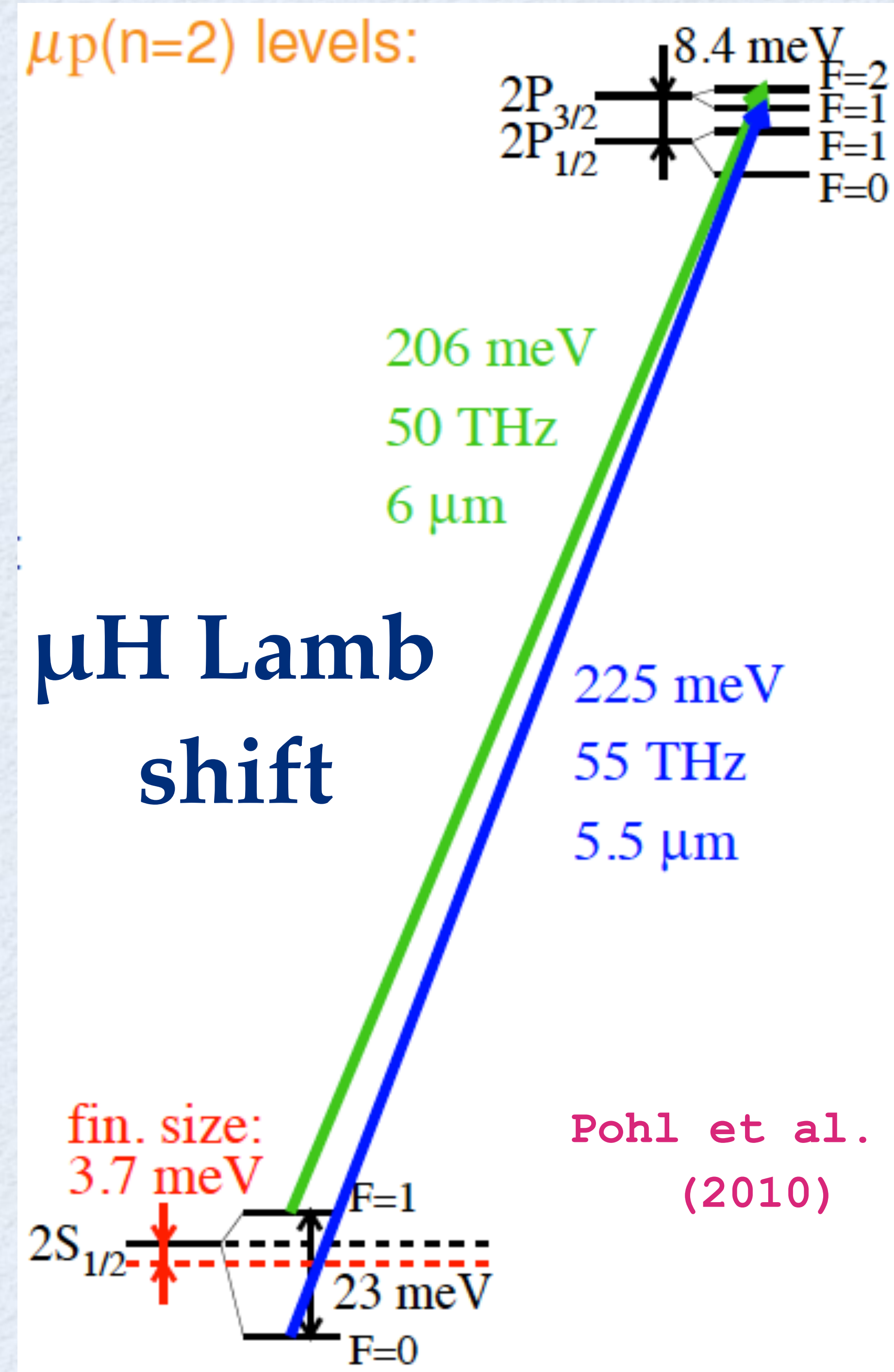


proton radius puzzle





Proton radius from Hydrogen spectroscopy



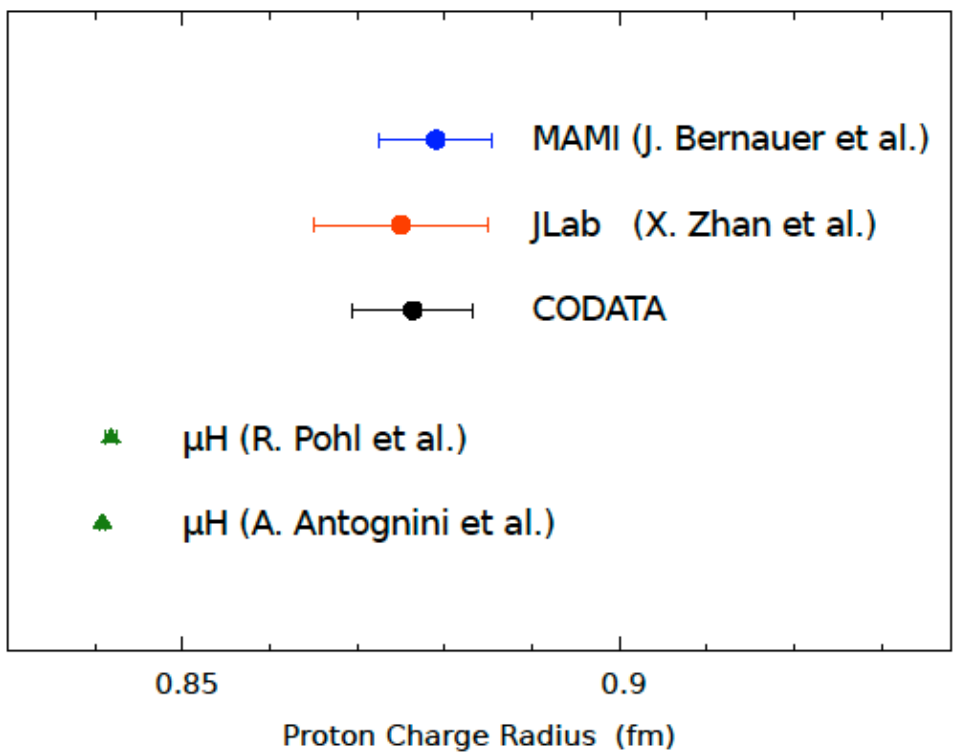
$$\Delta E_{LS} = 206.0336\ (15)\ -\ 5.2275\ (10)\ R_E^2\ +\ \Delta E_{TPE} \quad \text{meV}$$

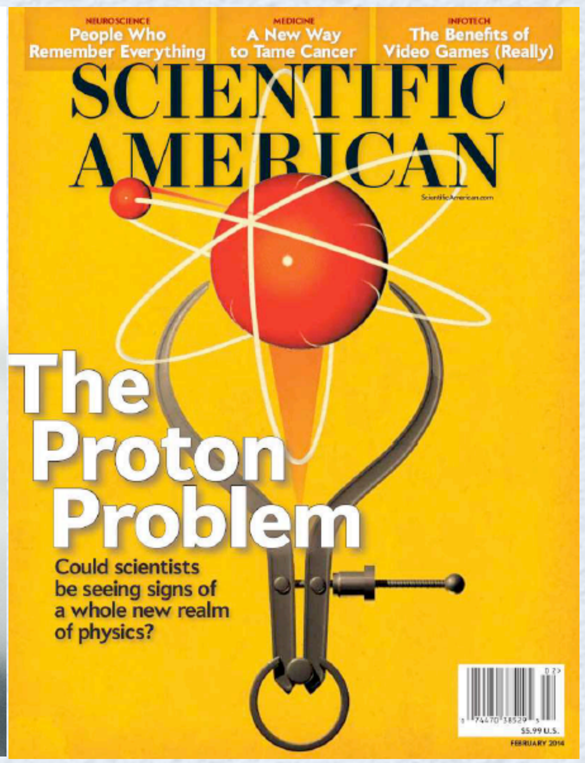
Antognini et al.(2013)

R_E^2 term ↓ 3.70 meV

ΔE_{TPE} ↓ O(α^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)

Proton radius puzzle: what could it mean ?

ΔE_{LS} = 206.0336 (15) - 5.2275 (10) R_E^2 + ΔE_{TPE} 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 ?

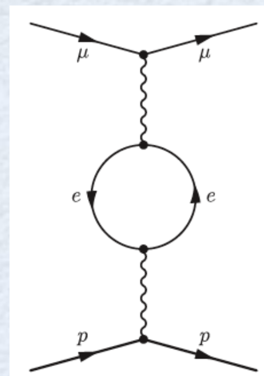
Lamb shift: QED corrections

- Calculated by several groups

Pachucki (1996, 1999)

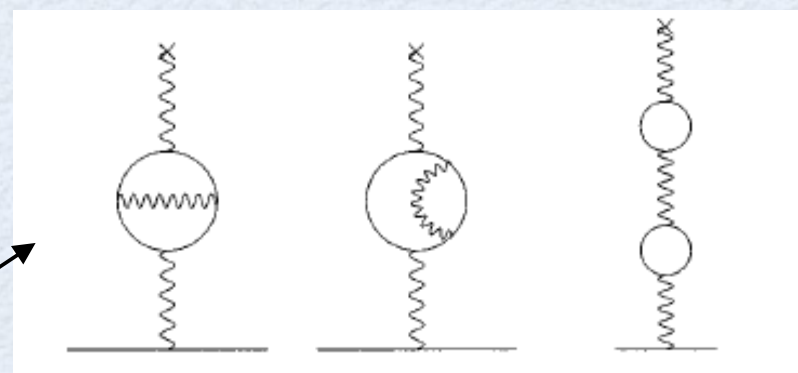
Borie (1976, 2005)

- 1 loop electron

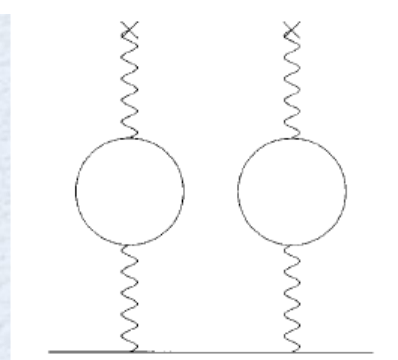


ΔE = 205.0282 meV

- 2 loop electron



ΔE = 1.5081 meV

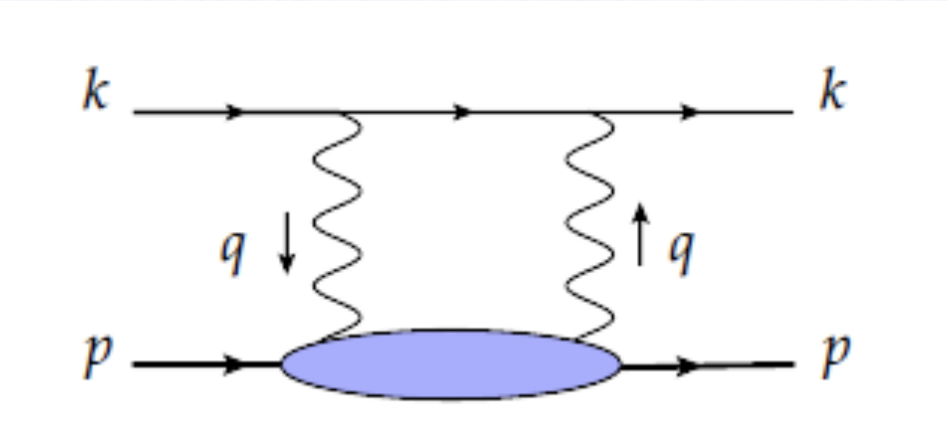


ΔE = 0.1509 meV

- 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)



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

- 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

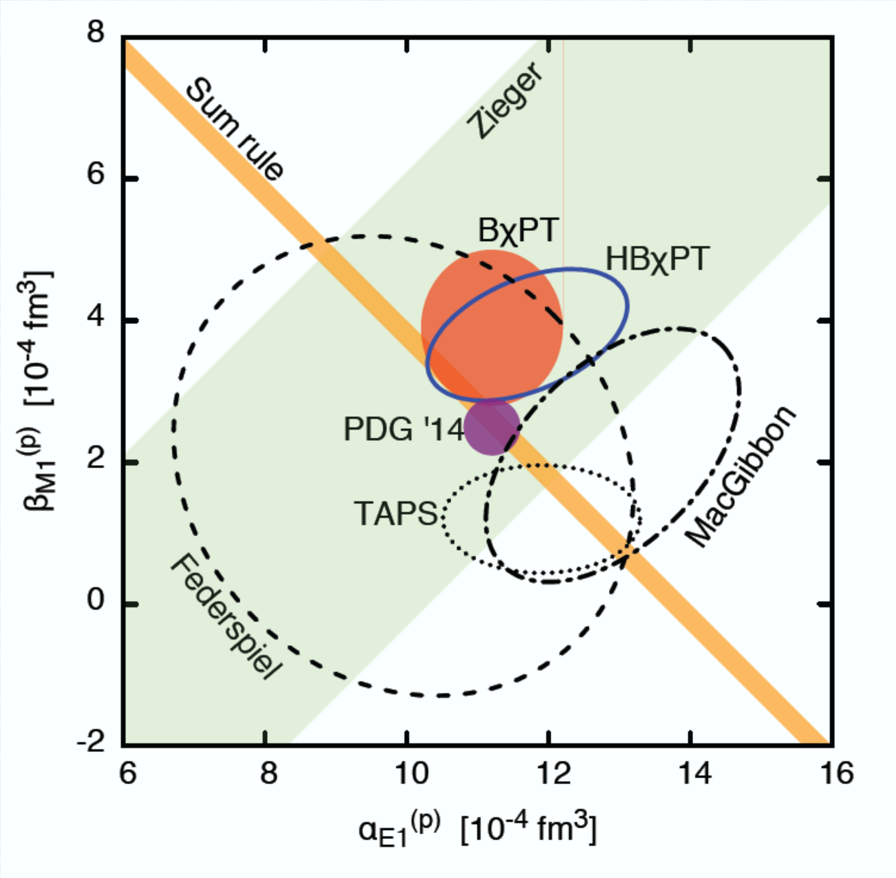
contains a subtraction term $T_1(0,Q^2)$

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:

α_E = (11.2 ± 0.2) × 10^{-4} fm^3

β_M = (2.5 ± 0.4) × 10^{-4} fm^3

➡ subtraction term $T_1(0,Q^2)$

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

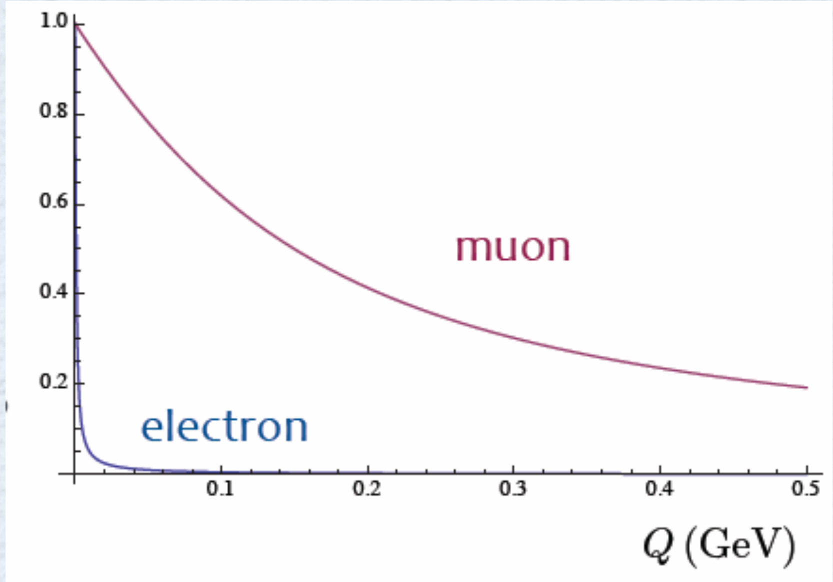
$$T_2^{\mathrm{non-Born}}(0,Q^2) = \frac{Q^2}{e^2}(\alpha_E + \beta_M) + \mathcal{O}(Q^4)$$

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).

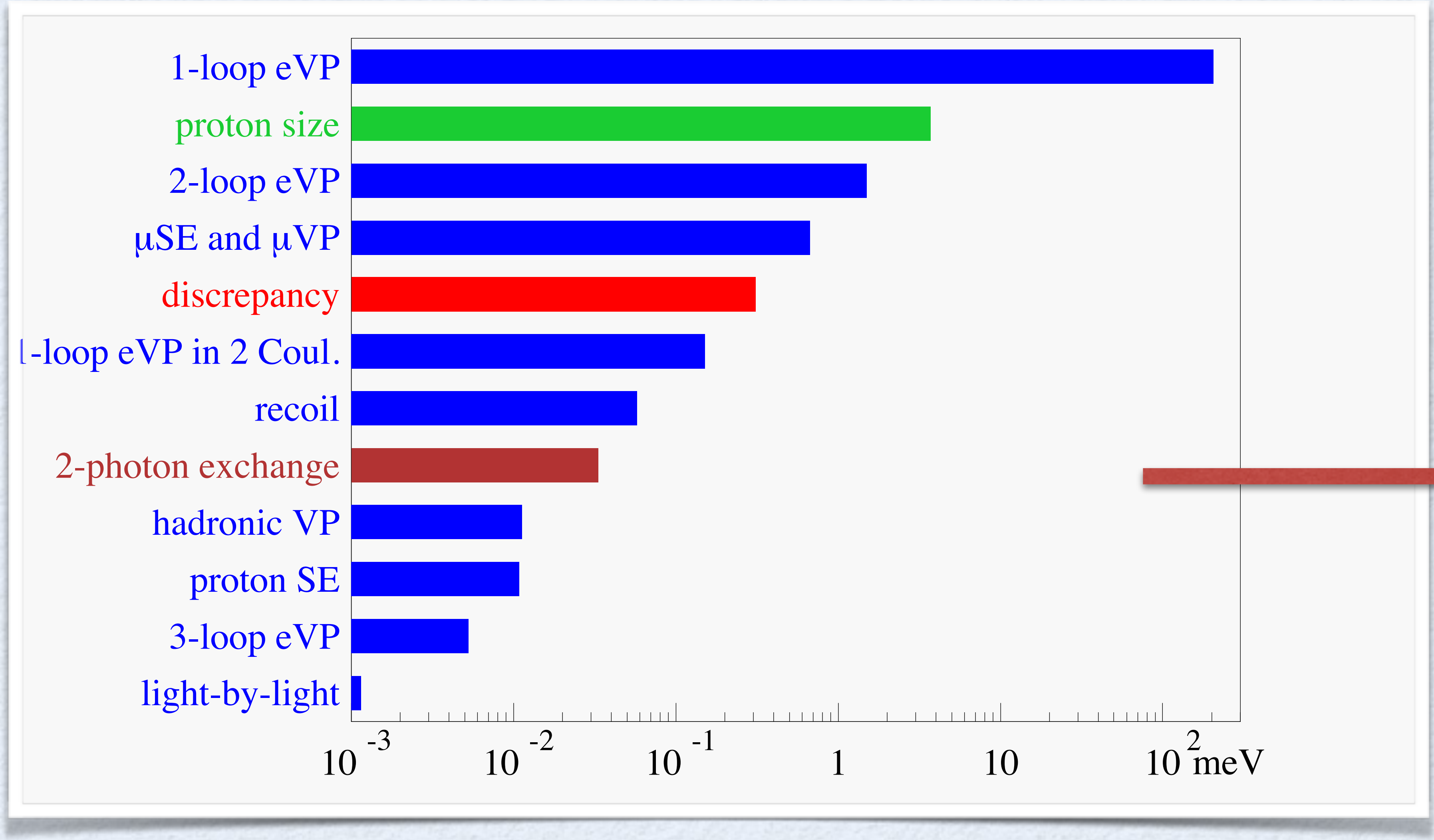
[LO-BχPT] Alarcon, Lensky, Pascalutsa, EPJC (2014) 74:2852

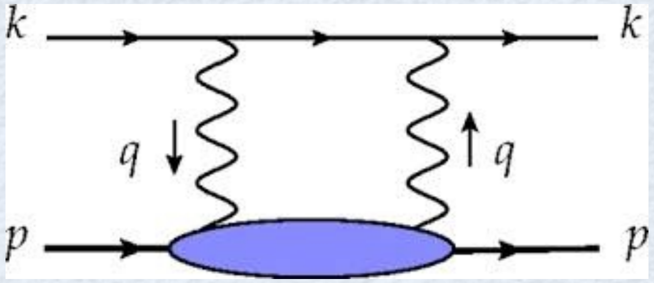
total hadronic correction on Lamb shift

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

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

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

...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:

- 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

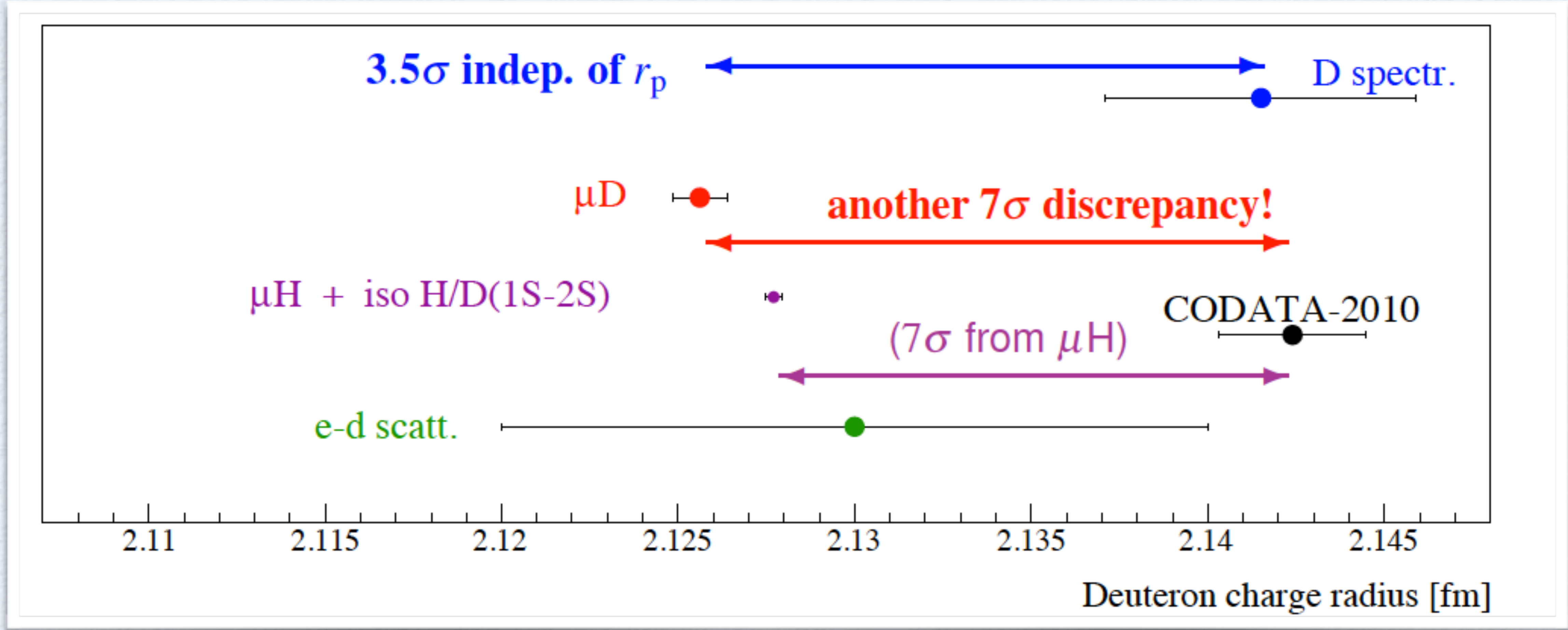
μD Lamb shift experiment

- 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, $\mu\ {}^3He^+$, $\mu\ {}^4He^+$, ...

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)

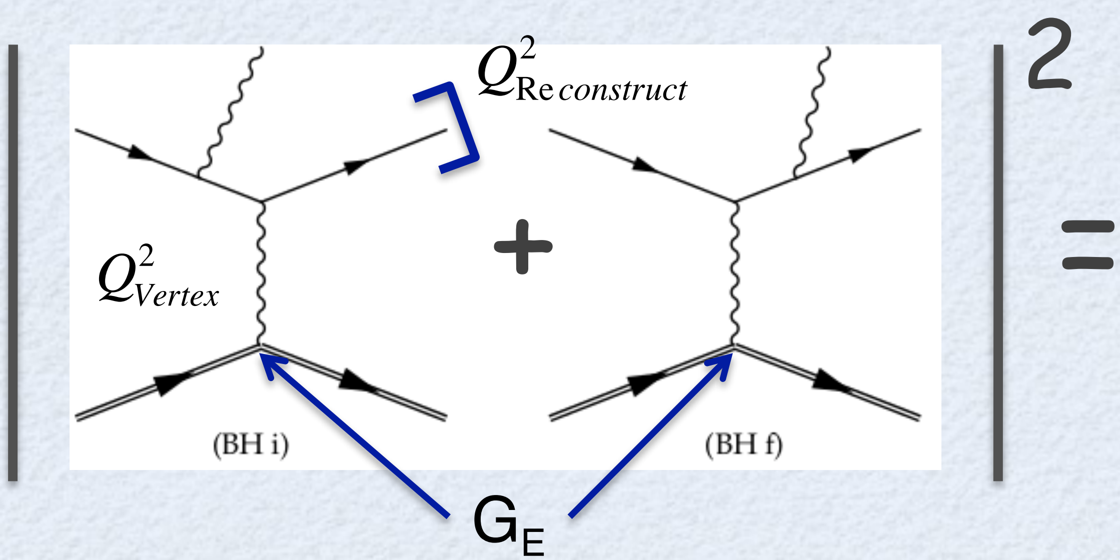
present accuracy factor 5 worse than experimental precision: $\delta_{exp}(\Delta E_{LS})$ = 3.4 μeV

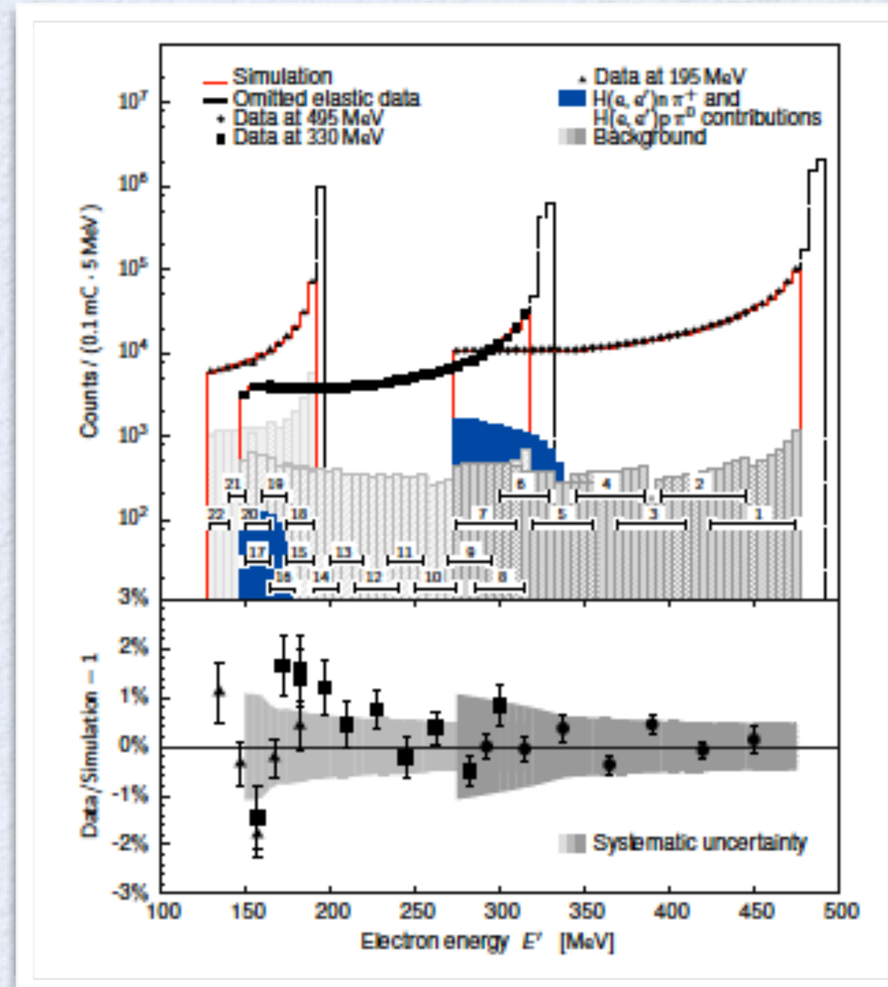
$\mu\ {}^3He^+$: ΔE_{TPE} = (15.46 ± 0.39) meV nucleon potentials form chiral EFT
Nevo Dinur, Ji, Bacca, Barnea (2016)

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

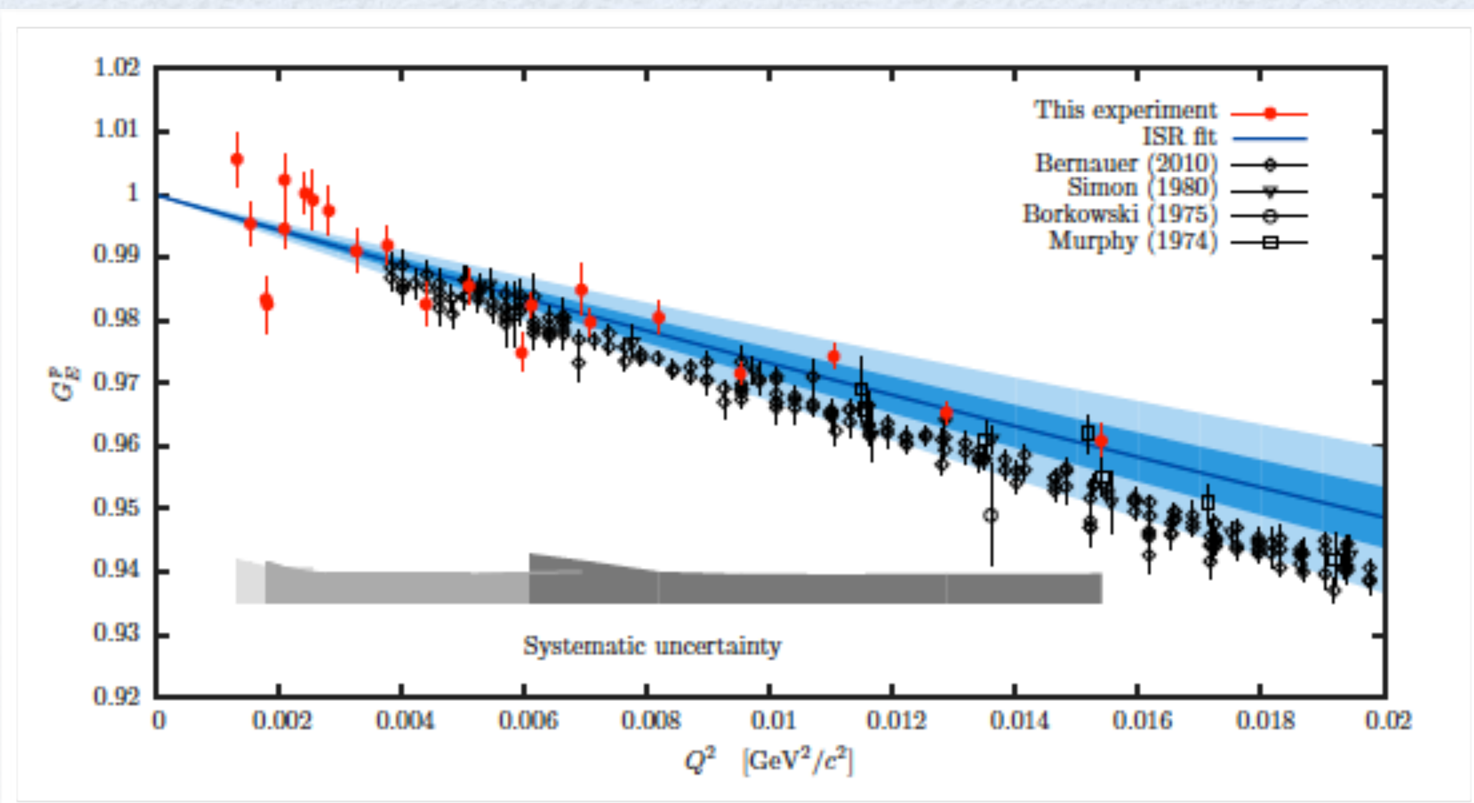
ISR@MAMI experiment

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





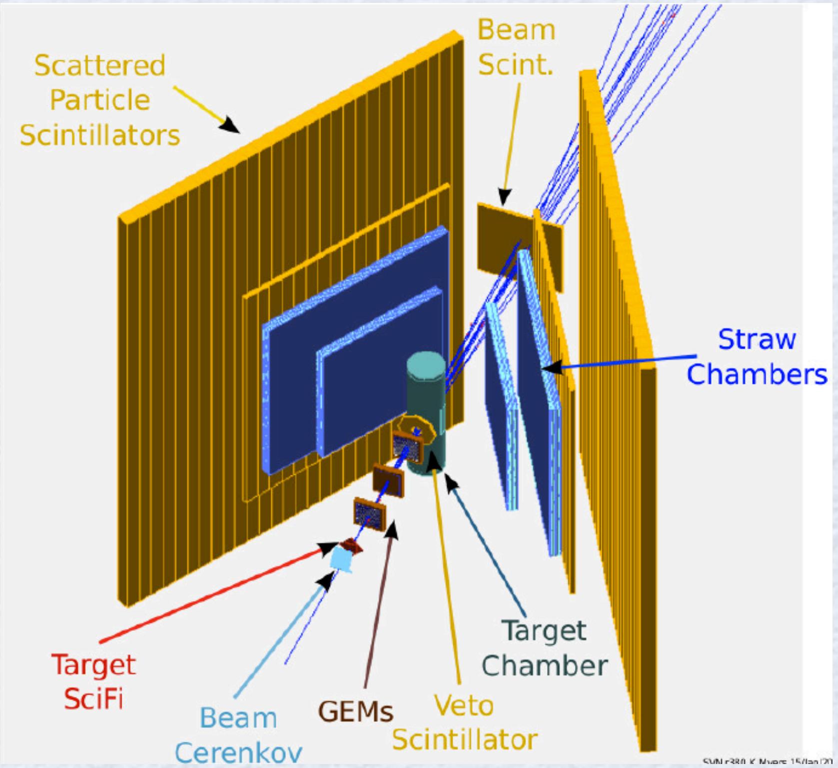
Mihovilovic et al.(2016)



good understanding of radiative tail (~ 1%)

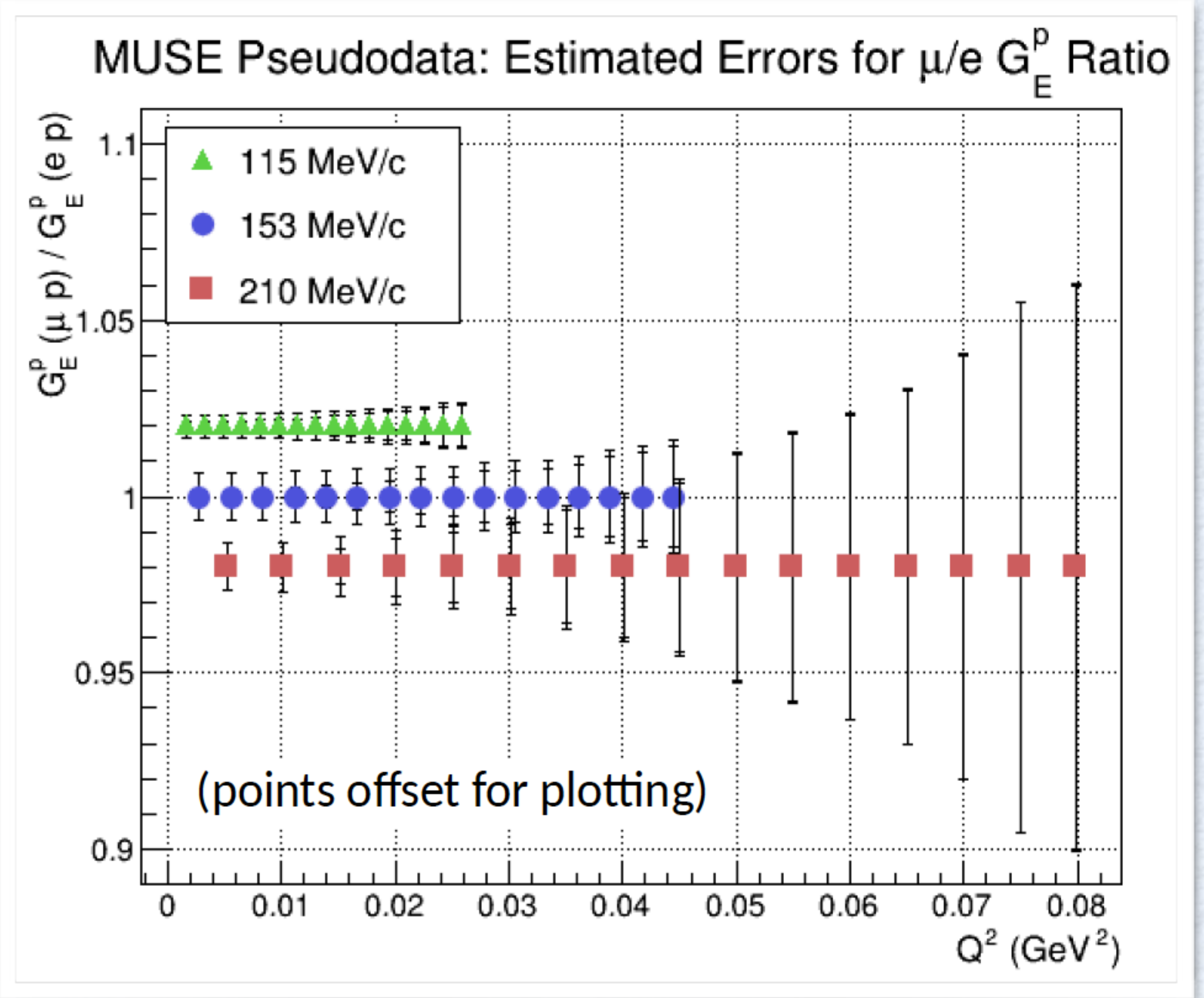
follow up experiment:
down to $Q^2 \approx 2 \times 10^{-4}$ GeV^2

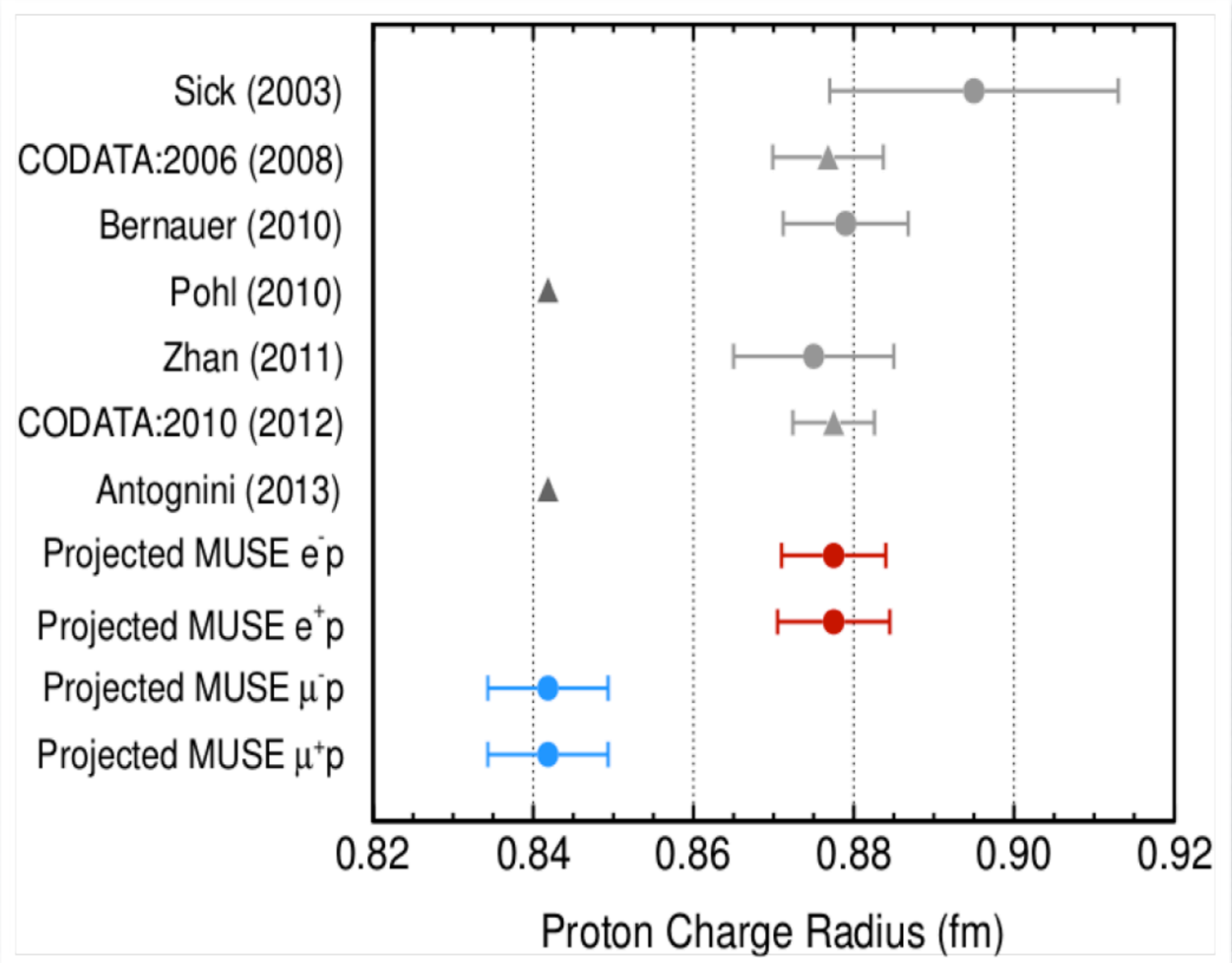
MUSE@PSI experiment



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

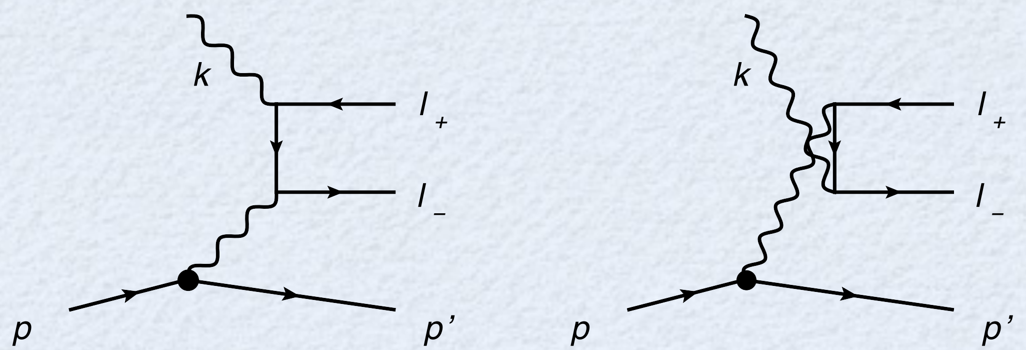
elastic scattering absolute cross sections





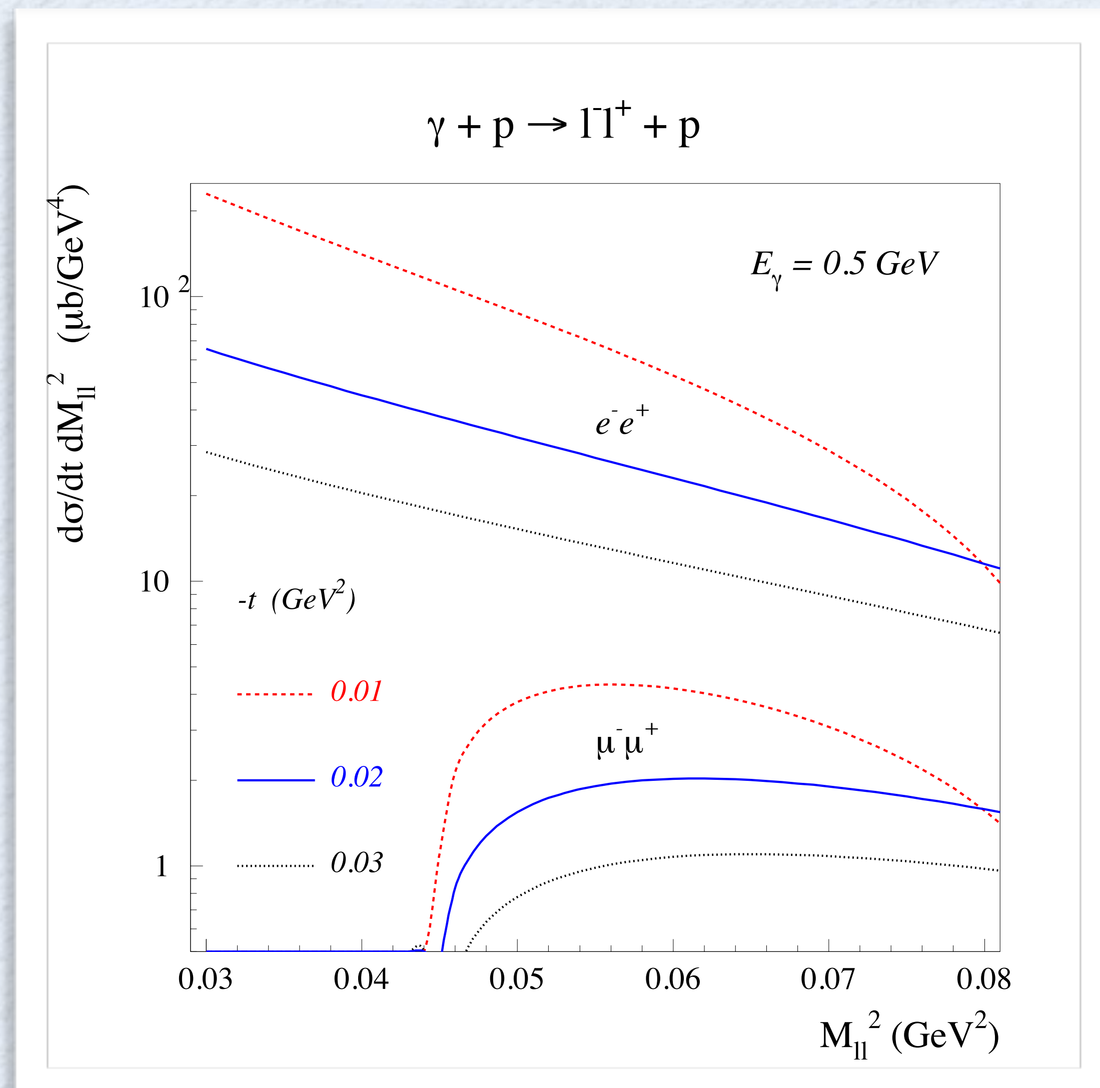
production run planned 2018 - 2019

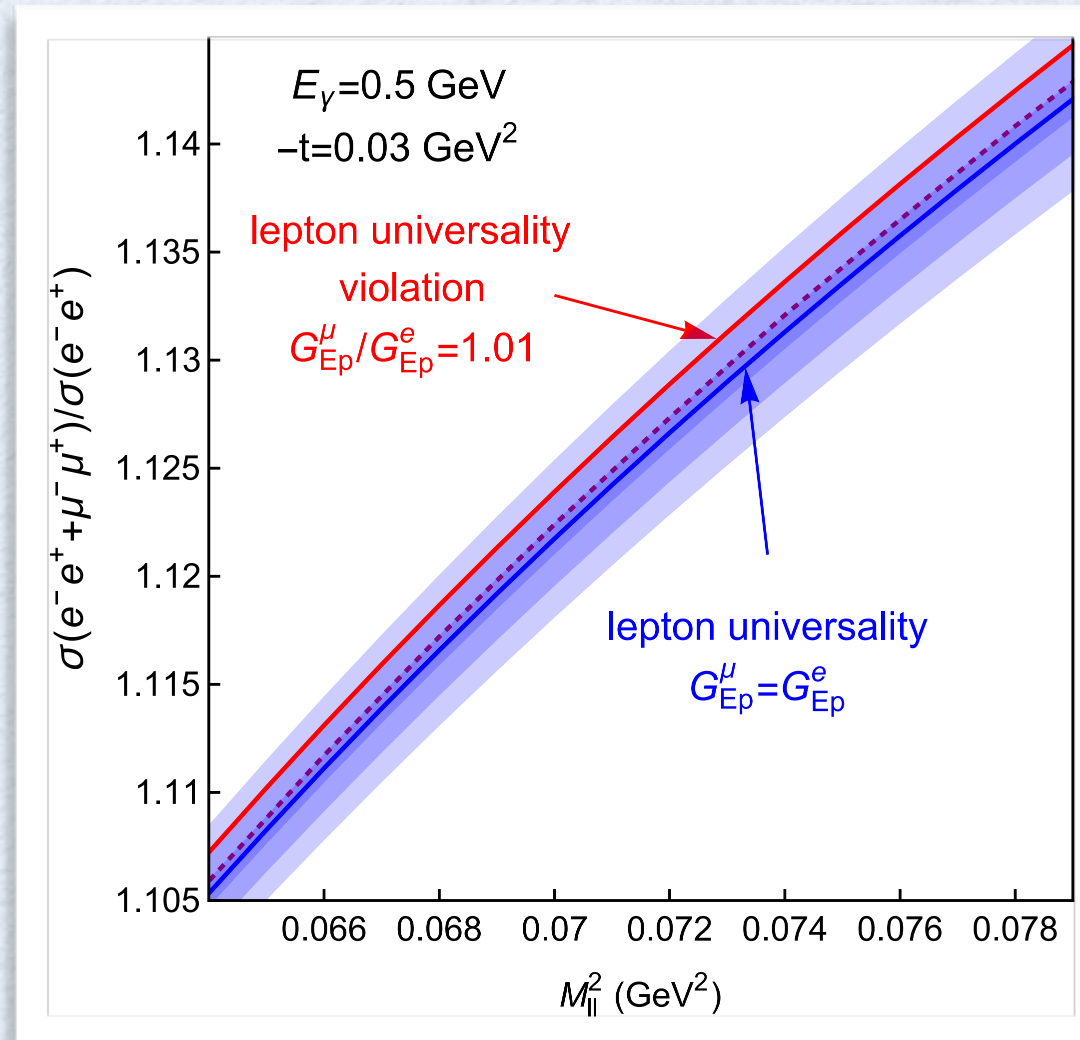
Lepton universality test in $\gamma p \rightarrow e^- e^+ p$ vs $\gamma p \rightarrow \mu^- \mu^+ p$



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

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





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

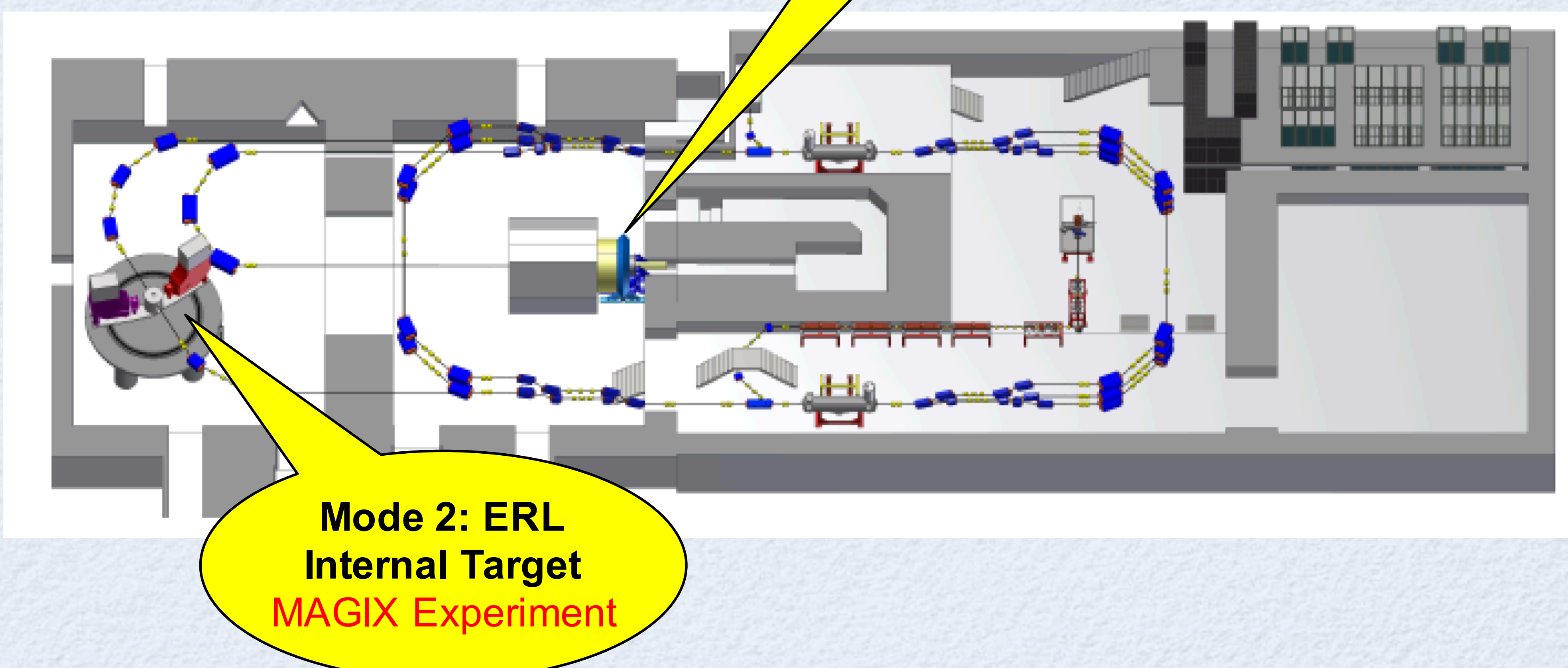
Recirculating ERL

E_{max} = 155 MeV

I_{max} > 1 mA (ERL)

commissioning 2020

Cluster of Excellence Precision Physics, Fundamental Interactions and Structure of Matter
PRISMA

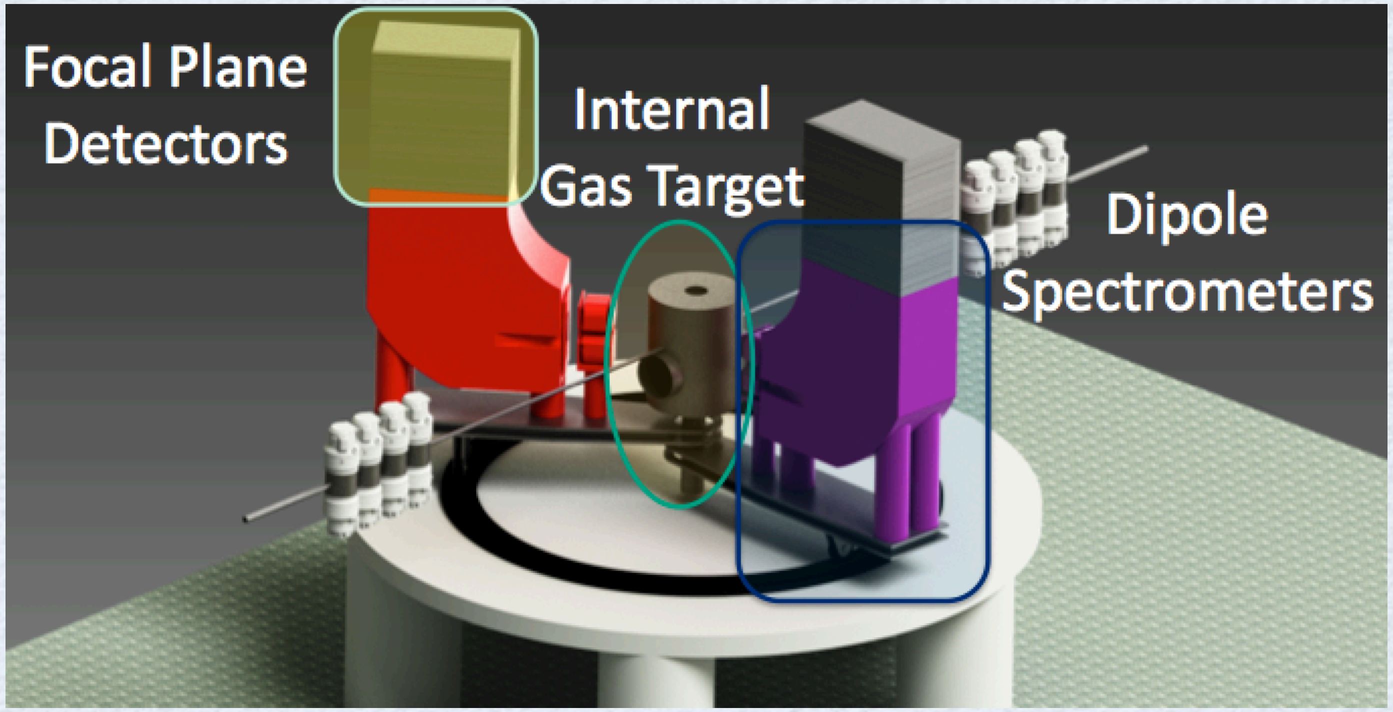


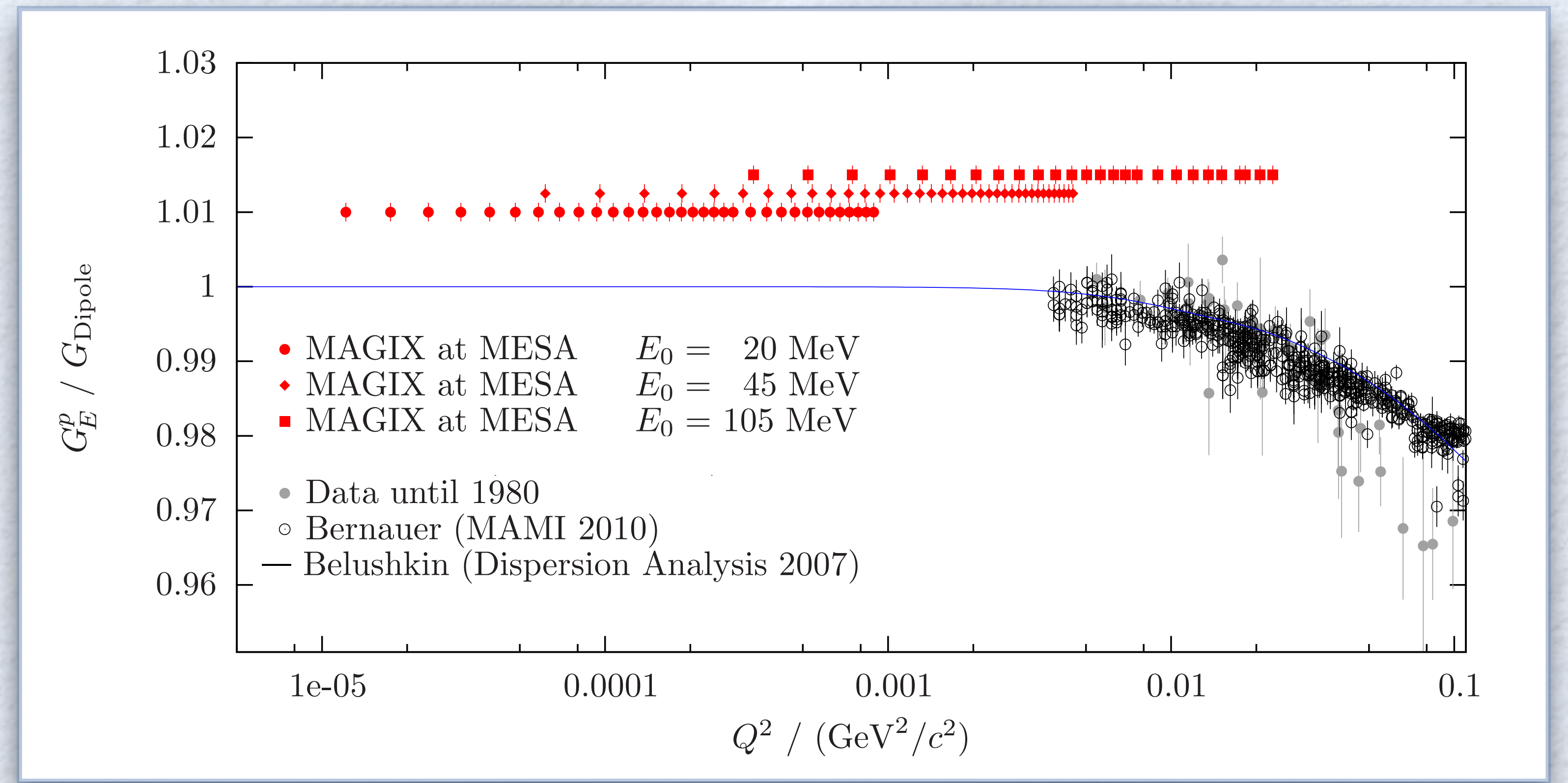
Low-Q^2 proton FF: MAGIX@MESA

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

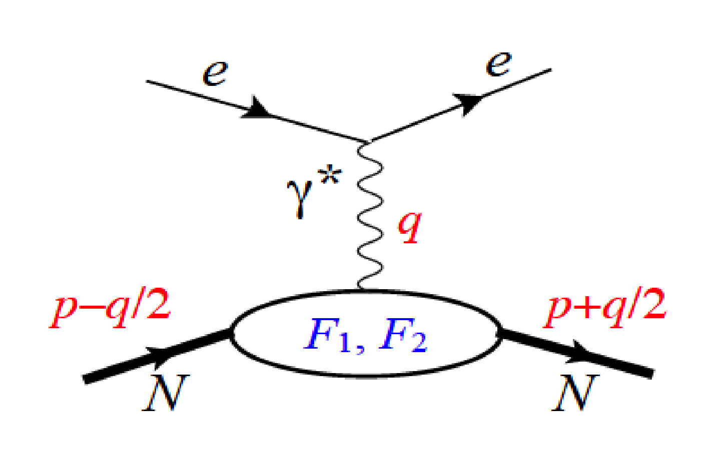




proton e.m. form factors, charge distributions

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 (F_1) **Pauli FF** (F_2)

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 $\tau \equiv \frac{Q^2}{4M^2}$

$$G_M(Q^2) = F_1(Q^2) + F_2(Q^2) \longrightarrow \text{magnetic FF}$$

$$G_E(Q^2) = F_1(Q^2) - \tau F_2(Q^2) \longrightarrow \text{electric FF}$$

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

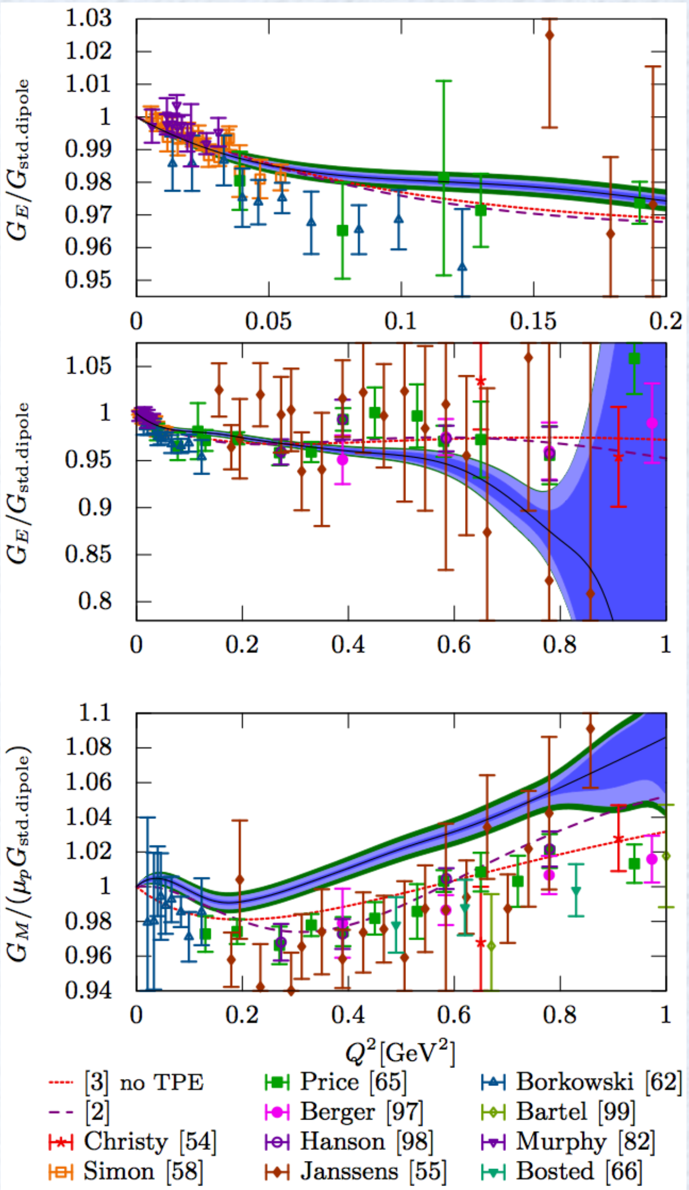
charge radius ($\langle r_E^2\rangle$)

e^- scattering cross sections

Electron scattering facilities JLab (12 GeV), MAMI (1.6 GeV):

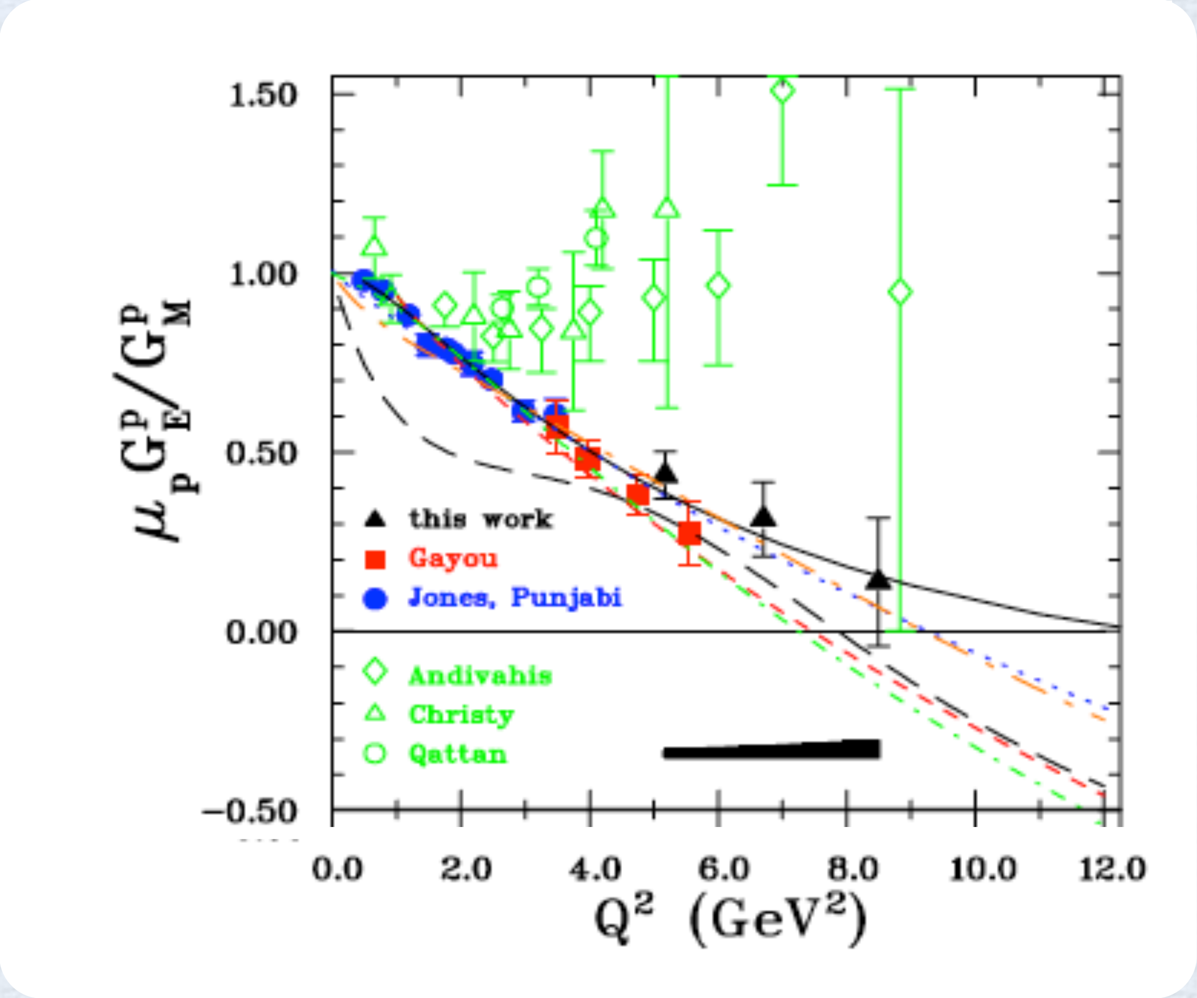
uniquely positioned to deliver high precision data

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



Bernauer et al.(2010, 2013)

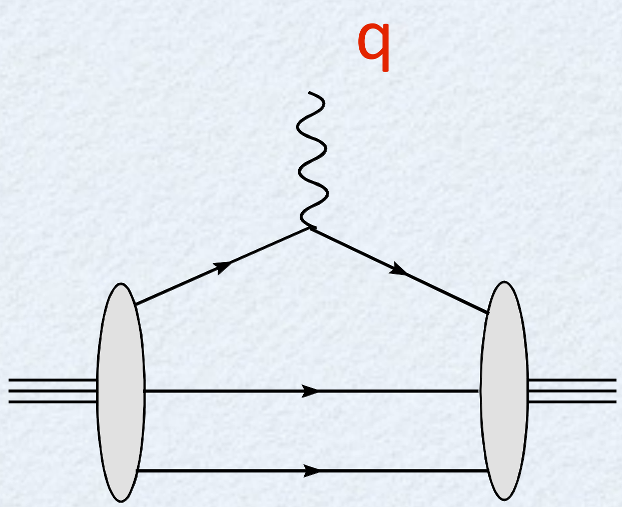
JLab polarization transfer measurements: G_{Ep} / G_{Mp} difference with Rosenbluth

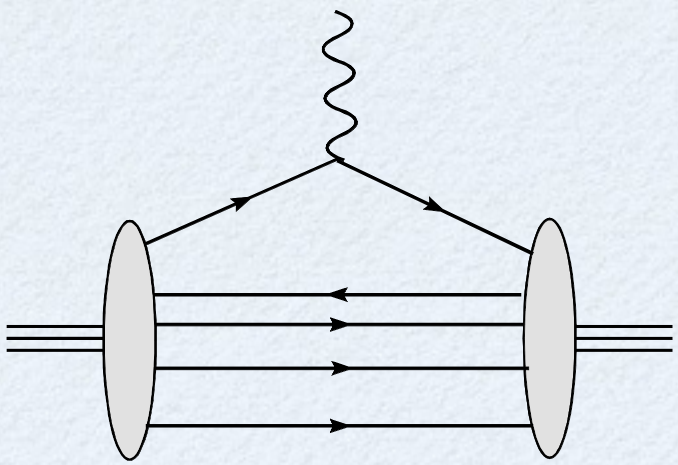


Jones et al.(2000) Punjabi et al.(2005)

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

Interpretation of form factor as quark density

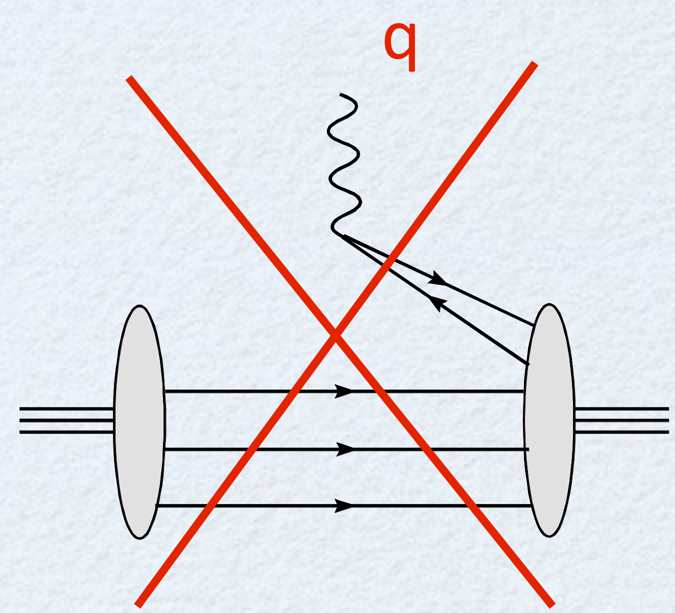




overlap of wave function

Fock components

with same number of quarks



overlap of wave function
Fock components

with different number of quarks

NO probability / charge density

interpretation

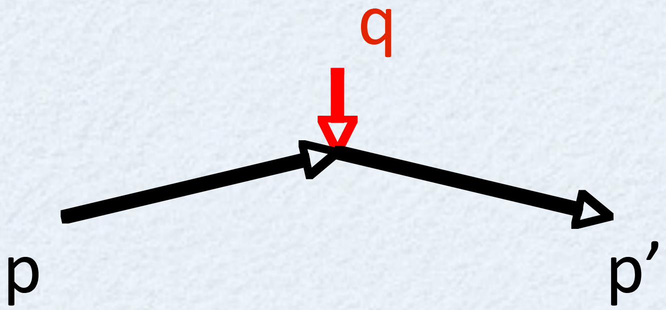
absent in a light-front frame!

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

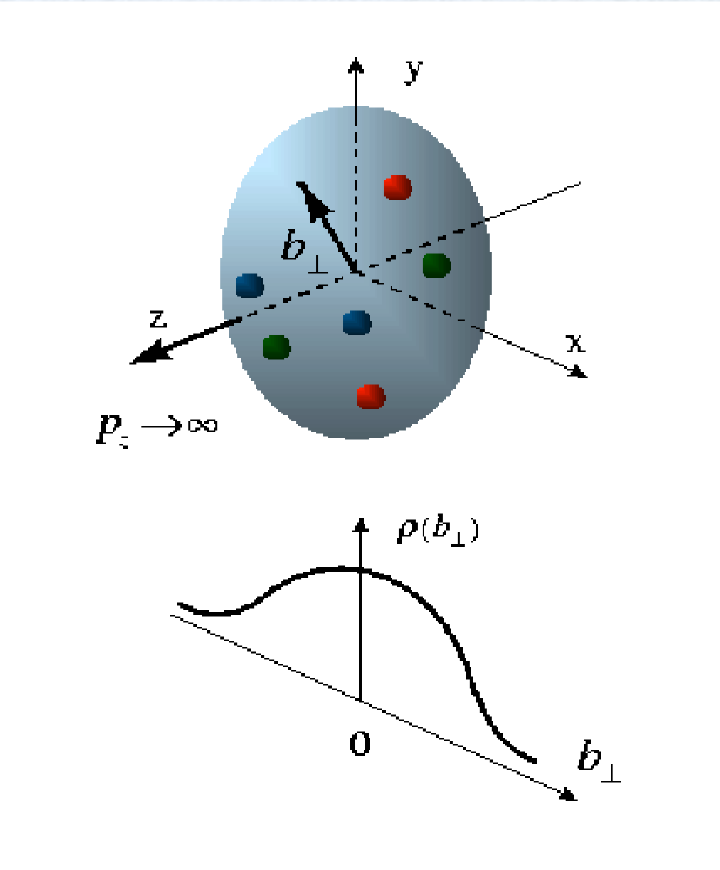
quark transverse charge densities in nucleon (1)

- light-front

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



photon only couples to forward moving quarks



- quark charge density operator

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

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

- longitudinally polarized nucleon

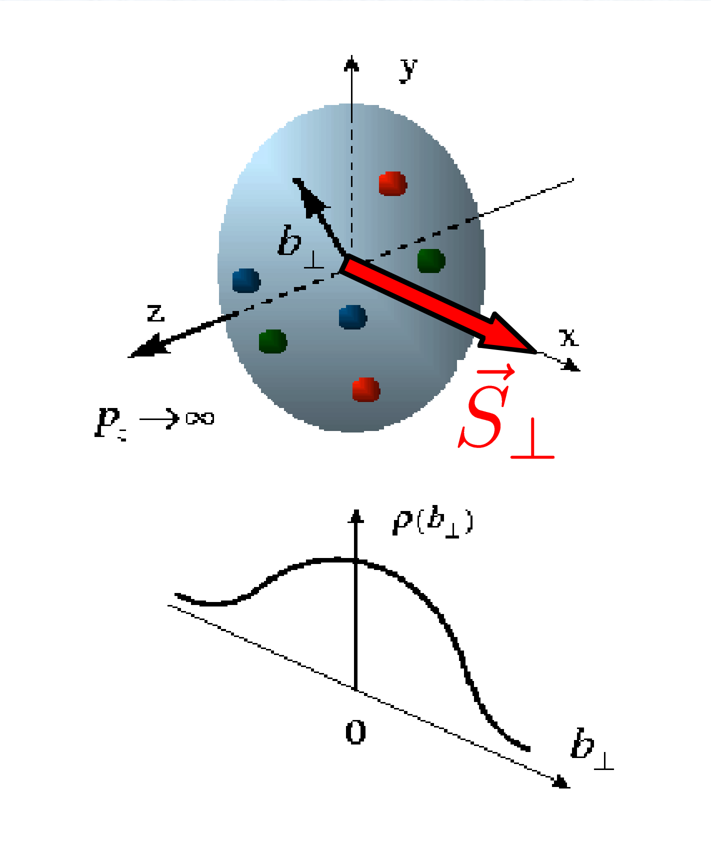
$$\rho_0^N(\vec{b}) \equiv \int \frac{d^2\vec{q}_\perp}{(2\pi)^2}\, e^{-i\vec{q}_\perp\cdot\vec{b}}\, \frac{1}{2P^+} \langle P^+, \frac{\vec{q}_\perp}{2}, \lambda | J^+(0) | P^+, -\frac{\vec{q}_\perp}{2}, \lambda \rangle$$
$$= \int_0^\infty \frac{dQ}{2\pi}\, Q J_0(bQ) F_1(Q^2)$$

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 $\phi_S = 0$

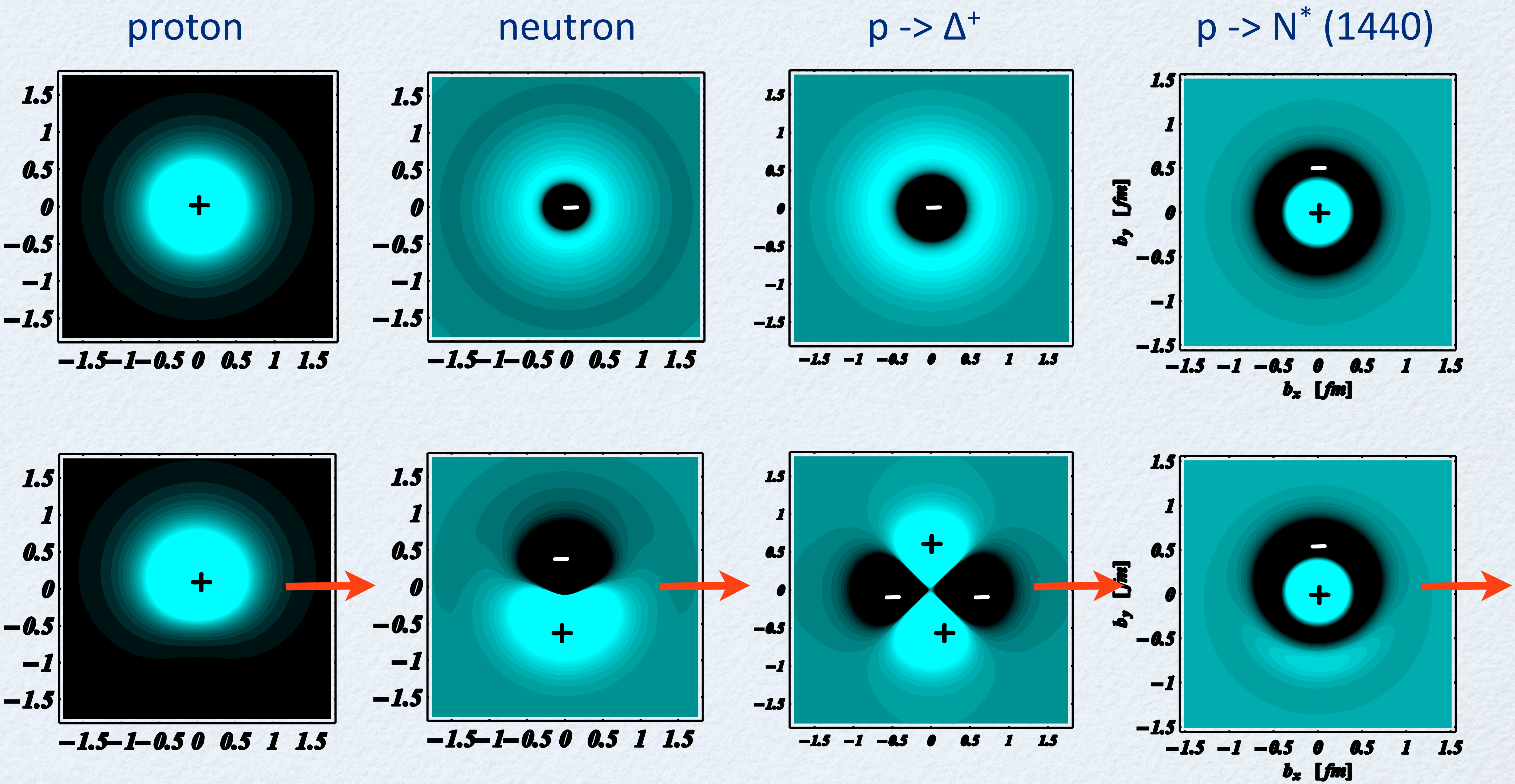
$$\vec{b} = b(\cos\phi_b\, \hat{e}_x + \sin\phi_b\, \hat{e}_y)$$

- $$\rho_T^N(\vec{b}) \equiv \int \frac{d^2\vec{q}_\perp}{(2\pi)^2}\, e^{-i\vec{q}_\perp\cdot\vec{b}}\, \frac{1}{2P^+} \langle P^+, \frac{\vec{q}_\perp}{2}, s_\perp = +\frac{1}{2}|J^+(0)|P^+, -\frac{\vec{q}_\perp}{2}, s_\perp = +\frac{1}{2}\rangle$$
$$= \rho_0^N(b) + \sin(\phi_b - \phi_S) \int_0^\infty \frac{dQ}{2\pi}\, \frac{Q^2}{2M}\, J_1(bQ)\, F_2(Q^2)$$

dipole field pattern

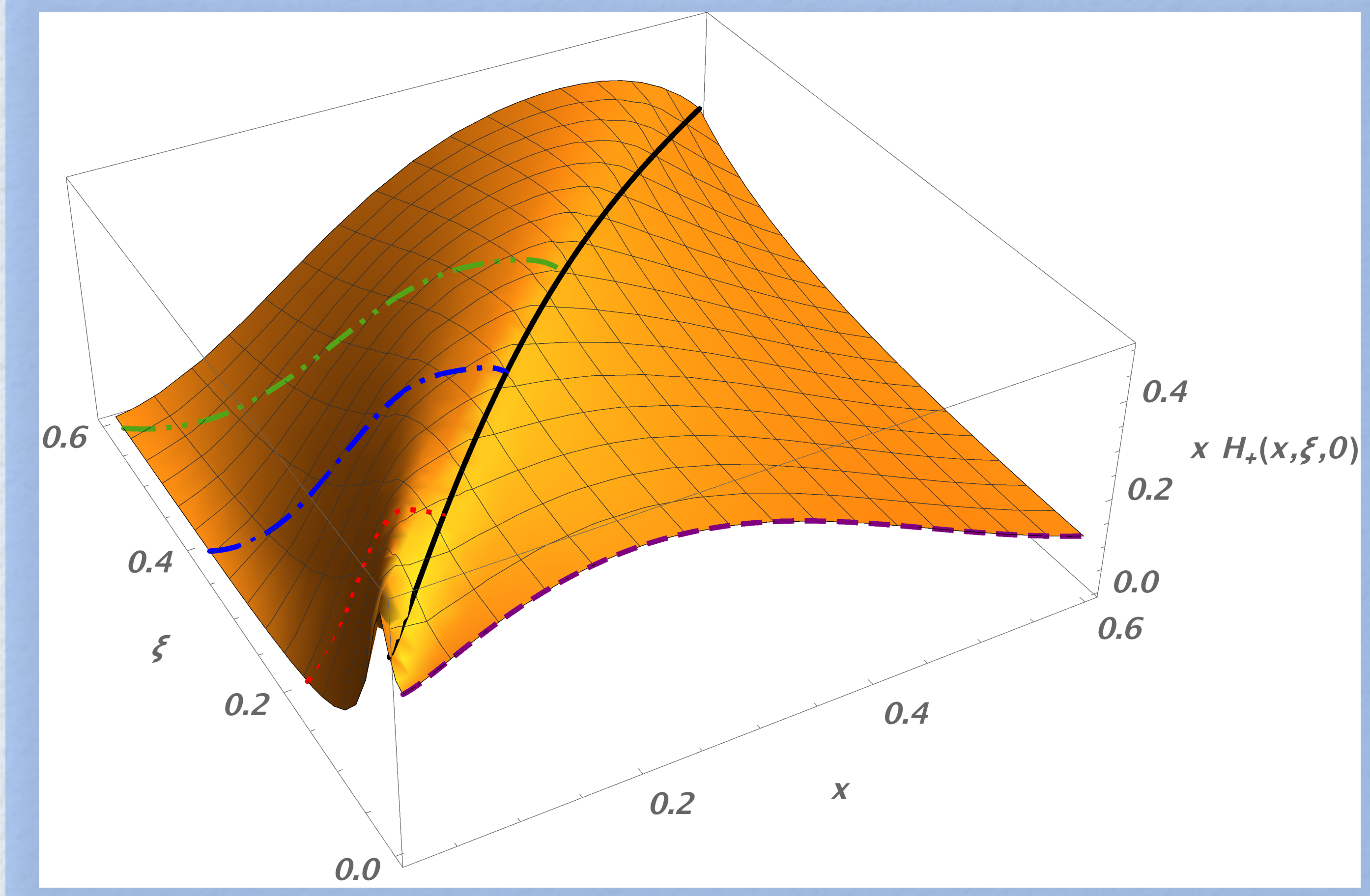
Carlson, Vdh (2007)

spatial imaging of hadrons



Miller(2007)   Carlson, Vdh(2007)   Tiator, Vdh(2007)

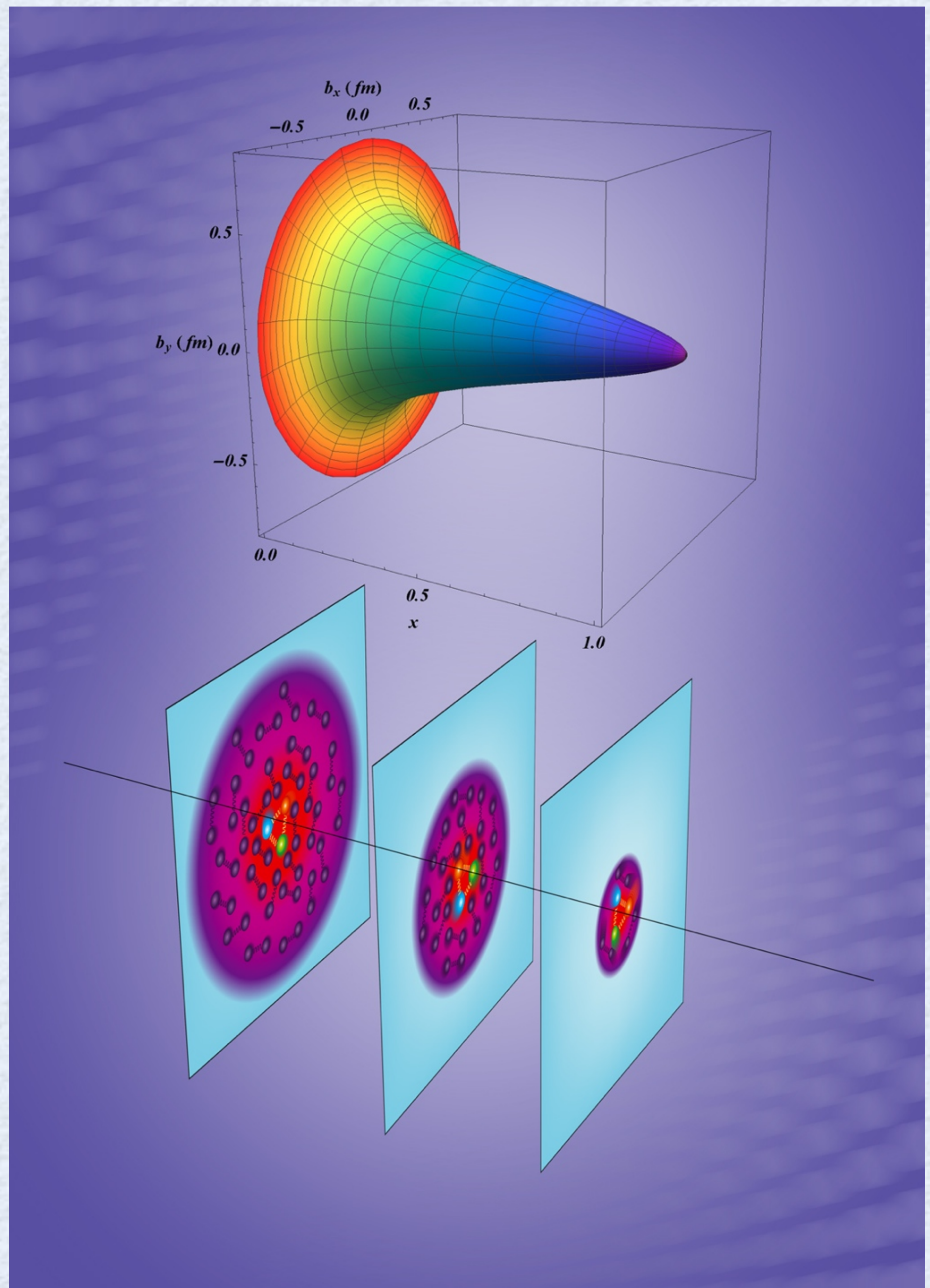
Generalised Parton Distributions



Correlations in transverse position/longitudinal momentum

elastic scattering → **GPDs** ← **DIS**

quark distributions in **transverse position space**



quark distributions in **longitudinal momentum**

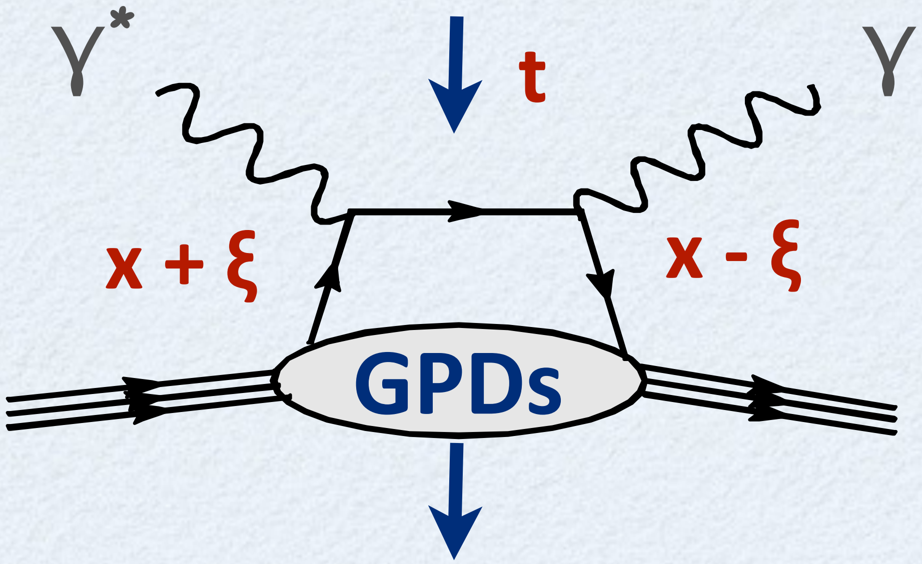
proton
3D imaging

Burkardt(2000, 2003)

Belitsky, Ji, Yuan (2004)

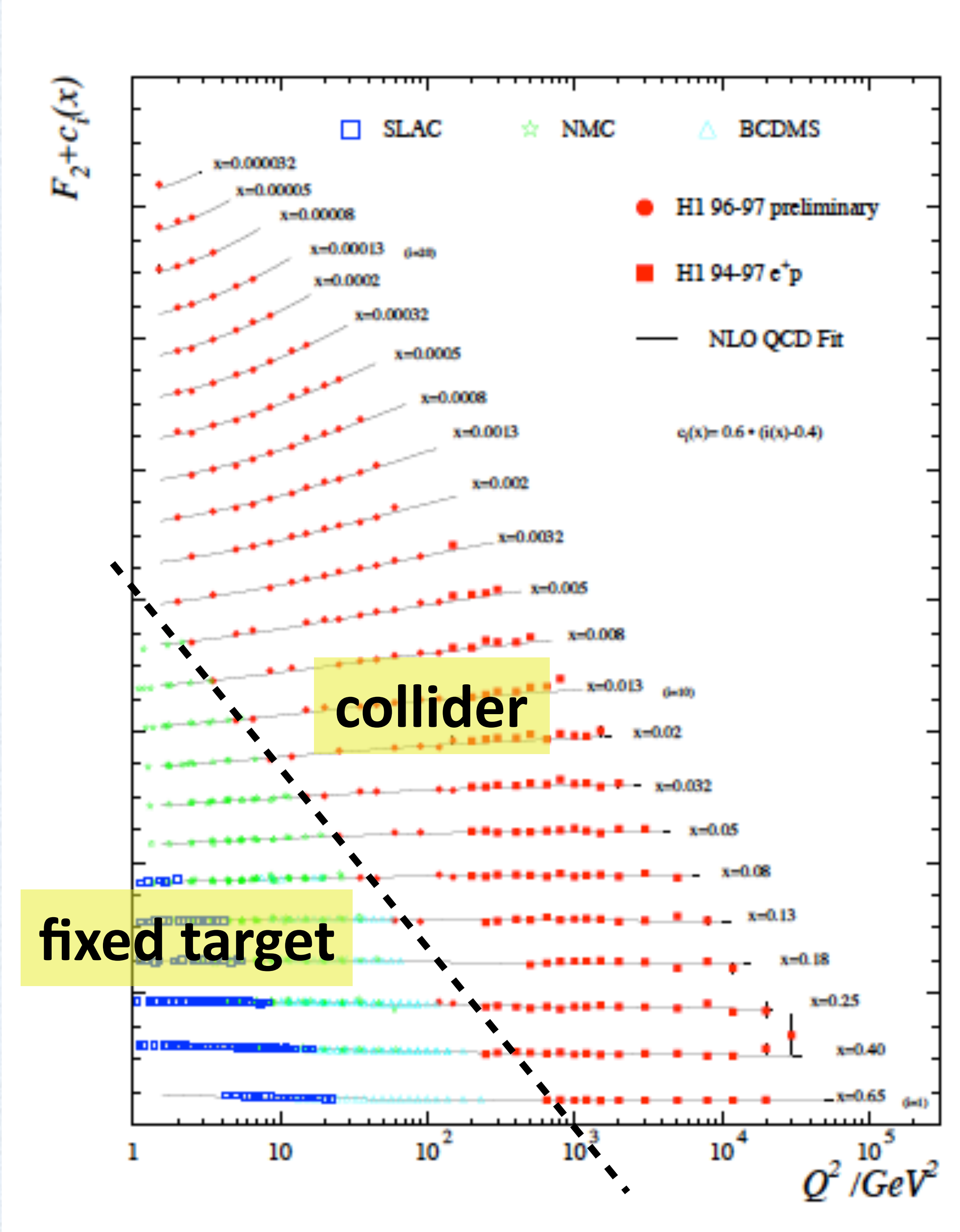
DVCS: tool to access GPDs

$Q^2 >> 1\ GeV^2$



GPD(x, ξ, t)

world data on proton F_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**

GPDs: known limits

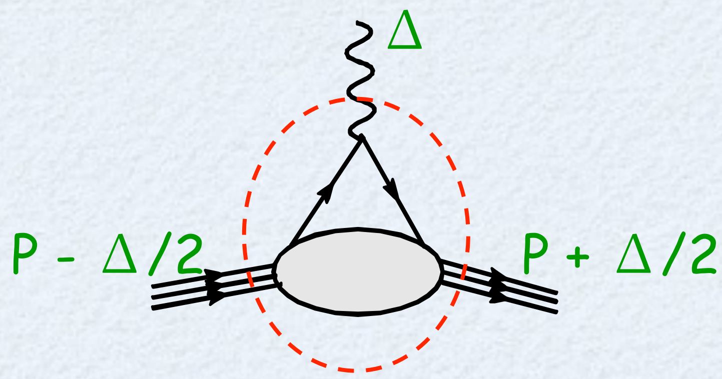
- in forward kinematics (ξ=0, t = 0) : **PDF limit**

$$H^q(x, \xi = 0, t = 0) = q(x)$$

$$\tilde{H}^q(x, \xi = 0, t = 0) = \Delta q(x)$$

$E, \tilde{E}^q$ do not appear in forward kinematics (DIS) ➡ **new information**

- first moments of GPDs : **elastic form factor limit**



t = Δ^2

$$\int_{-1}^{+1} dx H^q(x, \xi, t) = F_1^q(t)$$ → Dirac FF

$$\int_{-1}^{+1} dx E^q(x, \xi, t) = F_2^q(t)$$ → Pauli FF

$$\int_{-1}^{+1} dx \tilde{H}^q(x, \xi, t) = G_A^q(t)$$ → axial FF

$$\int_{-1}^{+1} dx \tilde{E}^q(x, \xi, t) = G_P^q(t)$$ → pseudoscalar FF

GPDs: higher moments, total quark angular momentum

$$\int_{-1}^{+1} dx x H^q(x,\xi,t) = A(t) + \xi^2 C(t)$$

$$\int_{-1}^{+1} dx x E^q(x,\xi,t) = B(t) - \xi^2 C(t)$$

→ form factors of energy-momentum tensor

Polyakov, Weiss(1999)

Polyakov(2003)

Goeke, Schweitzer et al.(2007)

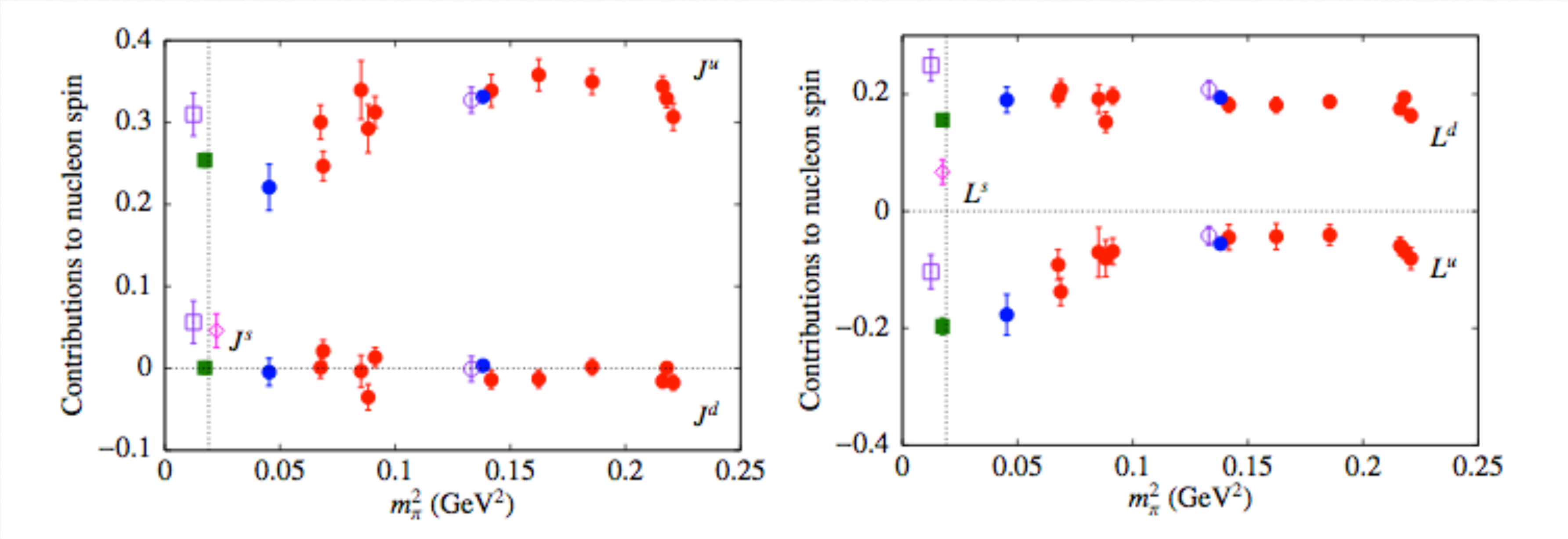
Ji's angular momentum sum rule

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

lattice QCD calculations at the physical point

e.g. twisted mass fermions

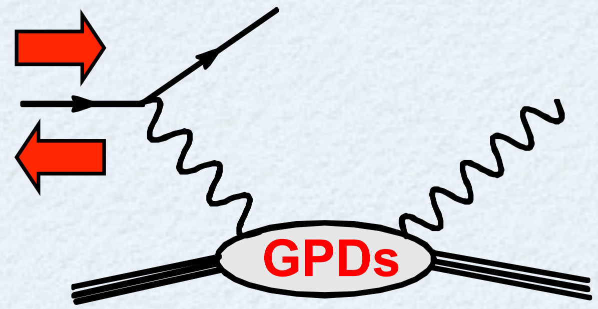
Alexandrou et al.(2016)



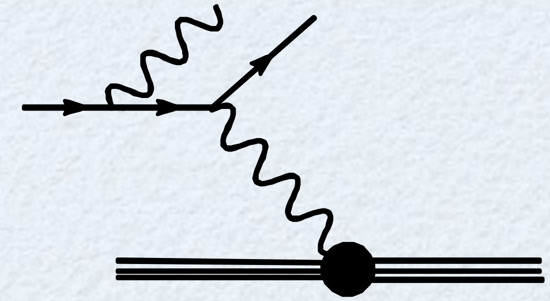
d, s-quarks carry very small total angular momentum, u-quark carries around 50%

DVCS beam spin asymmetries: first observations around 2000

$$A_{LU} = \frac{(BH) * Im(DVCS) * \sin\Phi}{(BH^2+DVCS^2)}$$



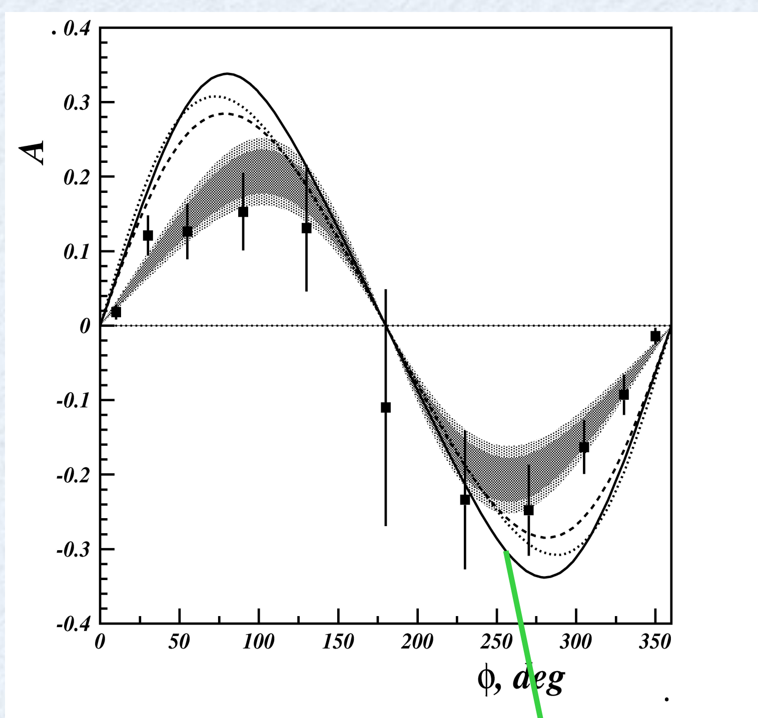
DVCS



Bethe-Heitler

CLAS

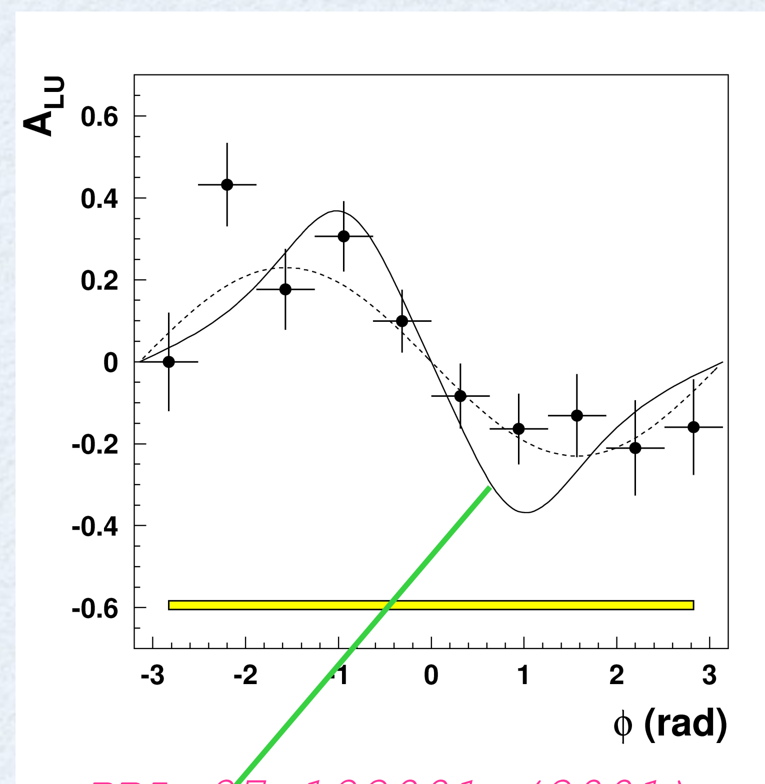
Q^2 = 1.25 GeV^2 ,
x_B = 0.19,
$-t$ = 0.19 GeV^2



PRL 87:182002 (2001)

HERMES

Q^2 = 2.6 GeV^2 ,
x_B = 0.11,
$-t$ = 0.27 GeV^2



PRL 87:182001 (2001)

twist-2 + twist-3

Vdh, Guichon, Guidal (1999)
Kivel, Polyakov, Vdh (2000)

DVCS accesses Compton Form Factors: 8 CFFs at twist-2

$$\mathcal{H}_{Re}(\xi,t) \equiv \mathcal{P}\int_0^1 dx \left\{ \frac{1}{x-\xi} + \frac{1}{x+\xi} \right\} H_+(x,\xi,t)$$

$$\mathcal{H}_{Im}(\xi,t) \equiv H_+(\xi,\xi,t)$$

$$\tilde{\mathcal{H}}_{Re}(\xi,t) \equiv \mathcal{P}\int_0^1 dx \left\{ \frac{1}{x-\xi} - \frac{1}{x+\xi} \right\} \tilde{H}_+(x,\xi,t)$$

$$\tilde{\mathcal{H}}_{Im}(\xi,t) \equiv \tilde{H}_+(\xi,\xi,t)$$

and analogous formulas for GPDs $E, \tilde{E}^q$ respectively

with singlet GPD combinations (quark + anti-quark):

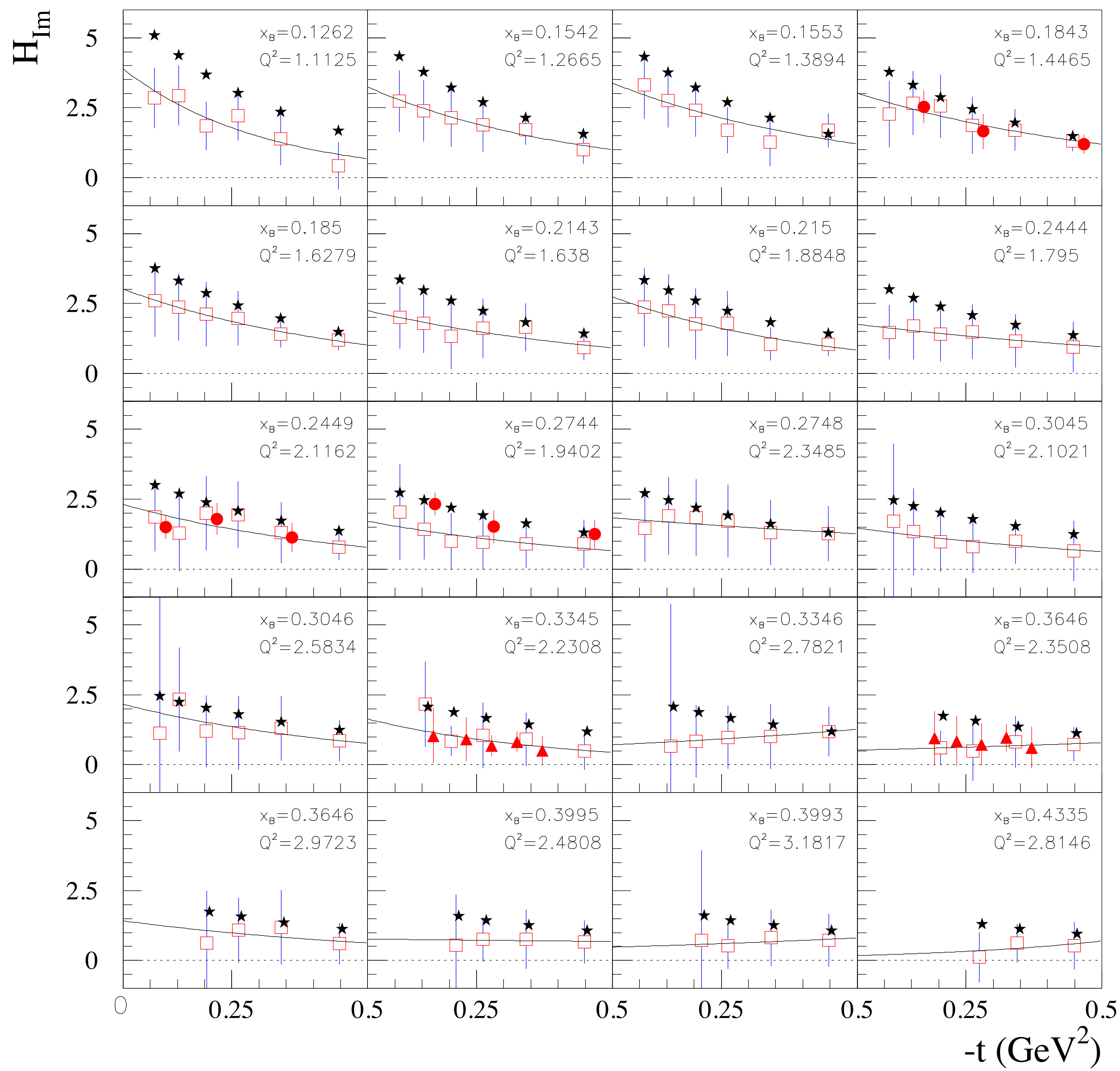
$$H_+(x,\xi,t) \equiv H(x,\xi,t) - H(-x,\xi,t)$$

$$\tilde{H}_+(x,\xi,t) \equiv \tilde{H}(x,\xi,t) + \tilde{H}(-x,\xi,t)$$

CFF fit extractions from data: Guidal(2008,...) Guidal, Moutarde(2009,...)

Kumericki, Mueller, Passek-Kumericki(2008,...)

global analysis of JLab 6 GeV data



$\mathcal{H}_{Im}(\xi, t)$

red solid circles:
CLAS: σ, A_{LU}, A_{UL}, A_{LL}

red open squares:
CLAS: σ, A_{LU}

red triangles:
Hall A: σ, A_{LU}

black stars
VGG model values

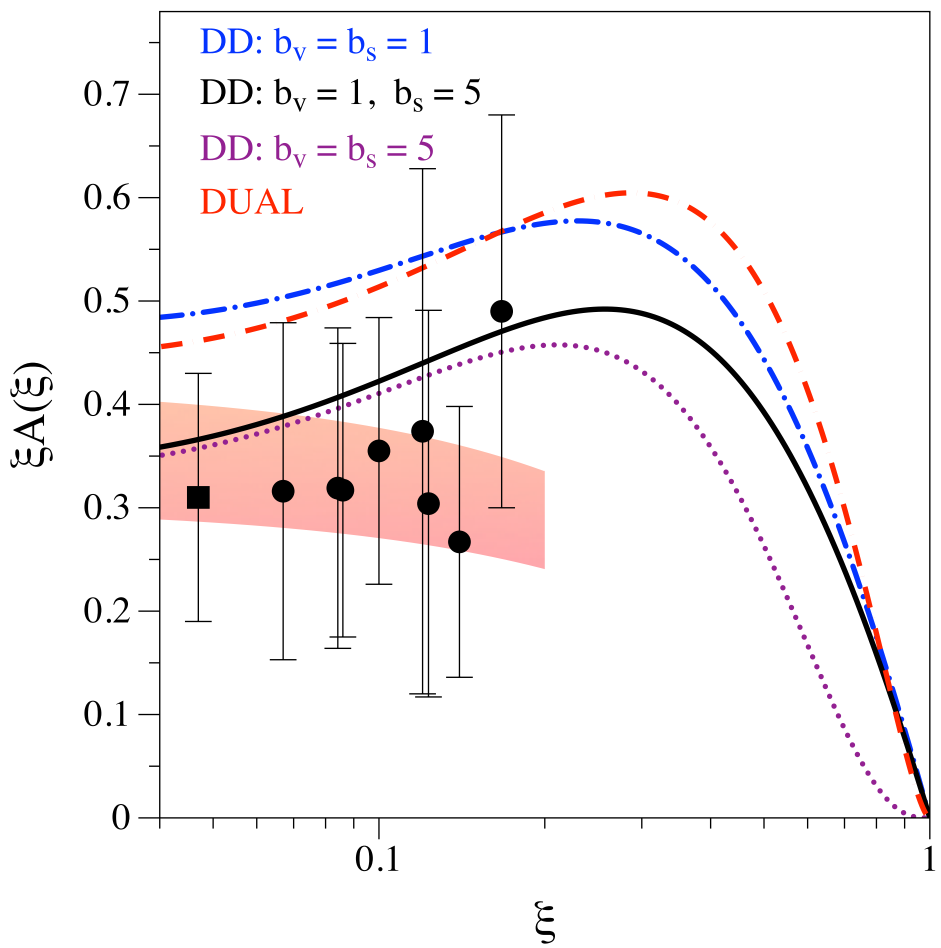
Dupré, Guidal, Vdh(2017)

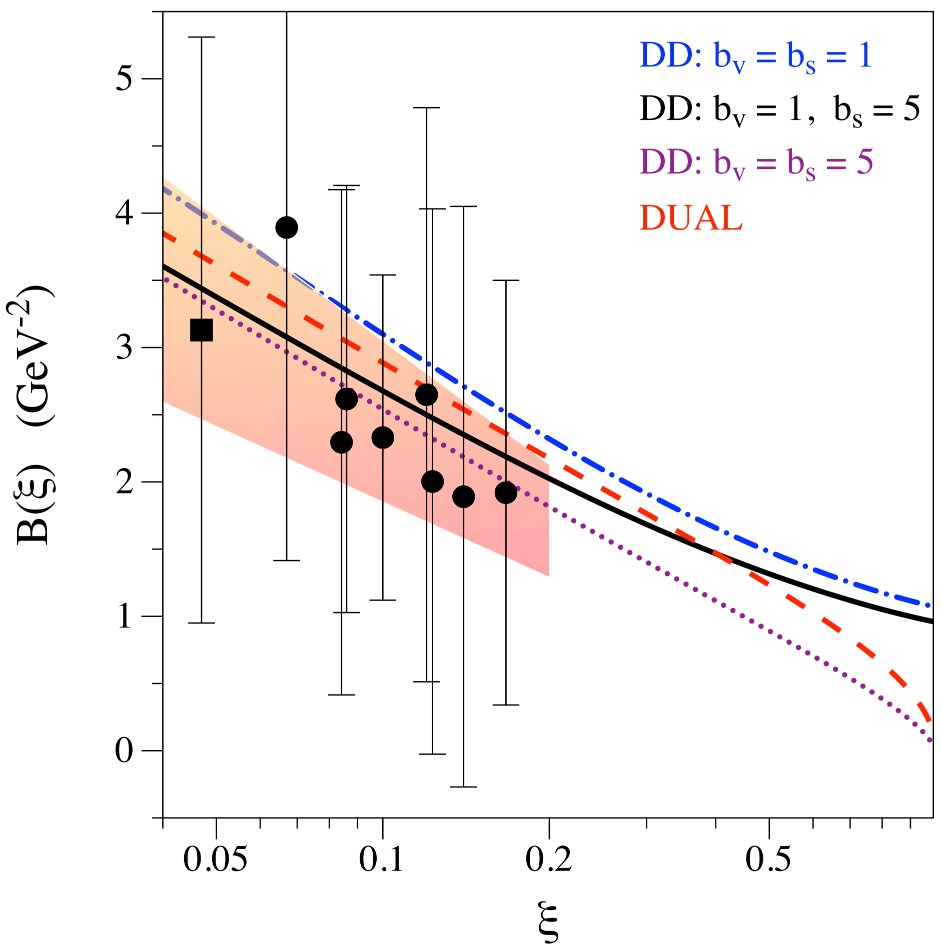
CFF $\mathcal{H}_{\rm Im}$:

$$\mathcal{H}_{Im}(\xi, t) = A(\xi)e^{B(\xi)t}$$

black circles: CFF fit of JLab data — Dupré, Guidal, Vdh(2017)

black squares: CFF fit of HERMES data — Guidal, Moutarde(2009)



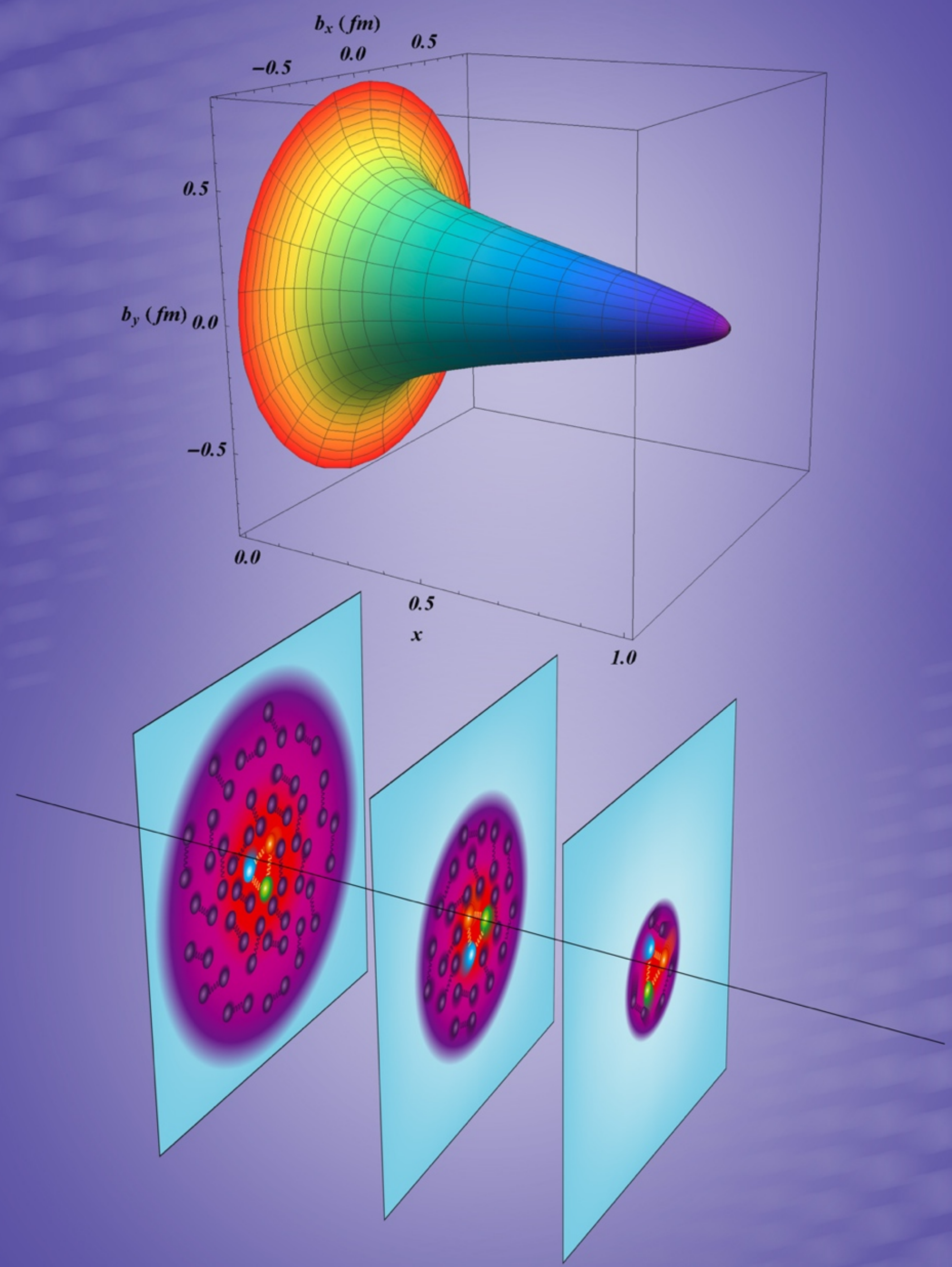


$$A(\xi) = a_A(1-\xi)/\xi$$

red bands:
1- parameter
fits of data

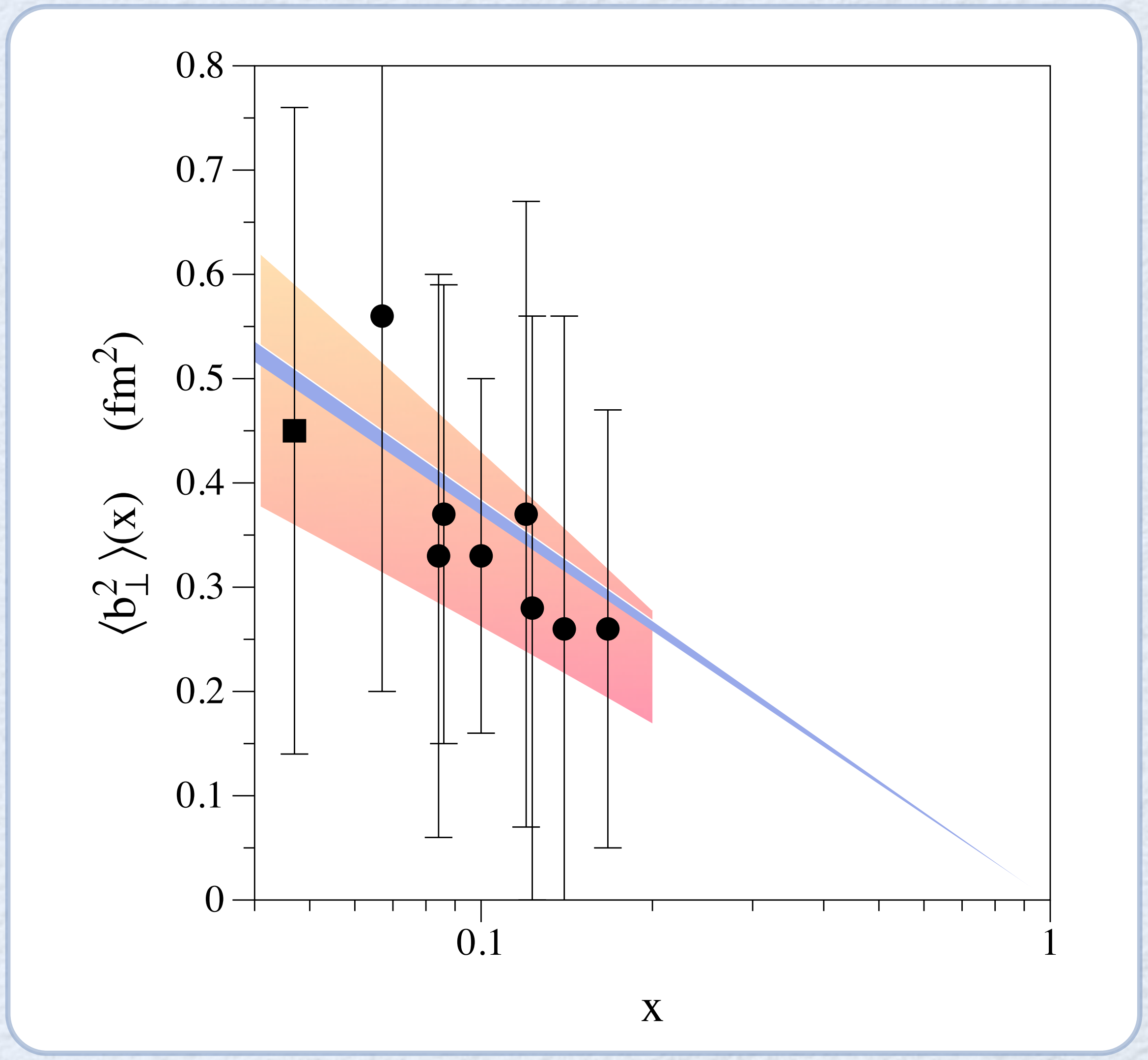
$$B(\xi) = a_B \ln(1/\xi)$$

3D imaging of proton



black circles: CFF fit of JLab data

black squares: CFF fit of HERMES data



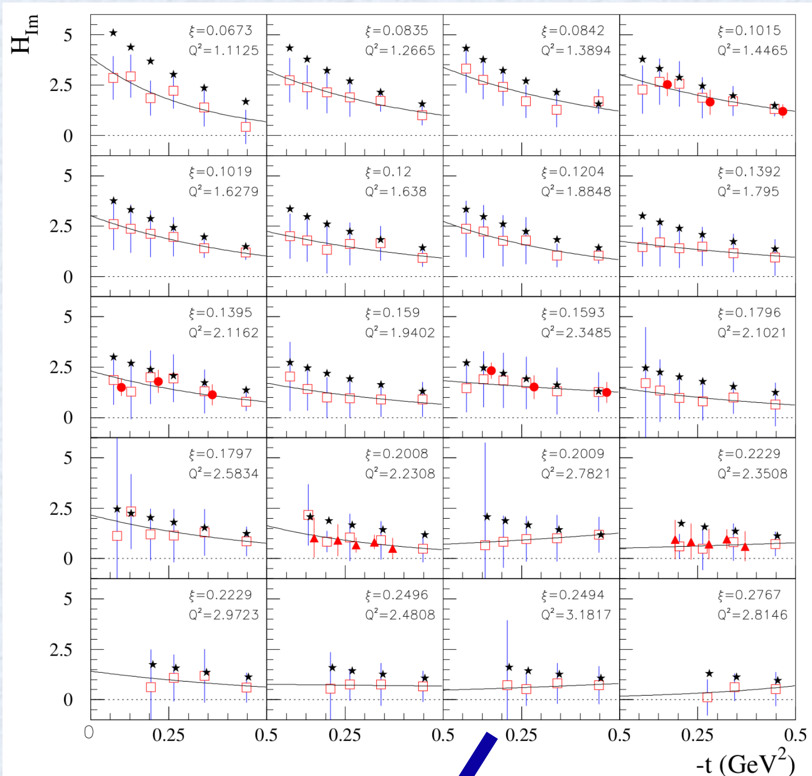
band: using $B_0(x) = a_{B_0} \ln(1/x)$

a_{B_0} fixed from elastic scattering

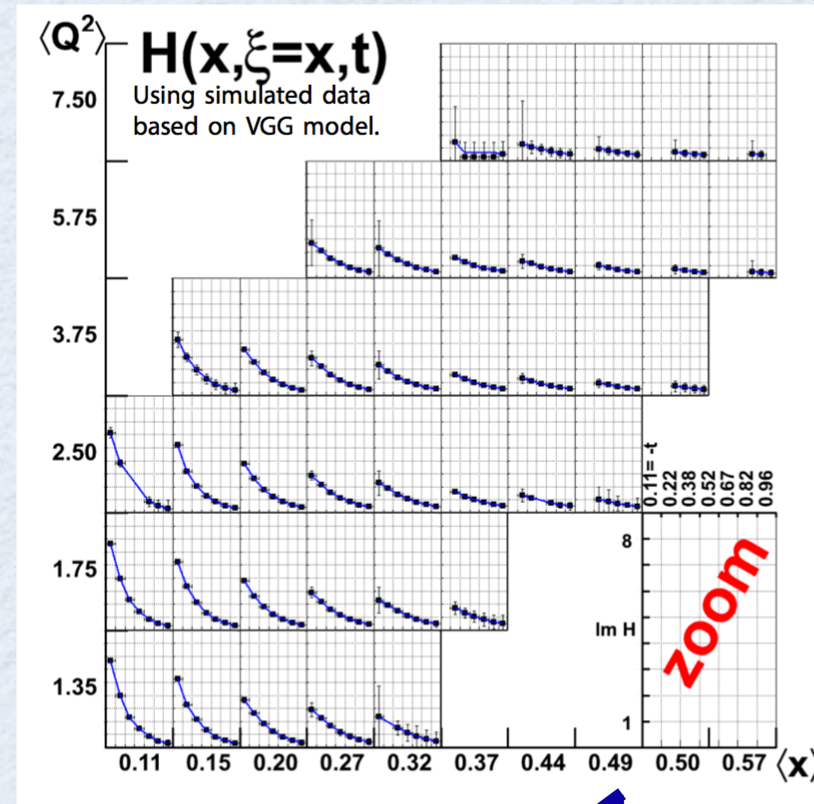
Dupré, Guidal, Vdh(2017)

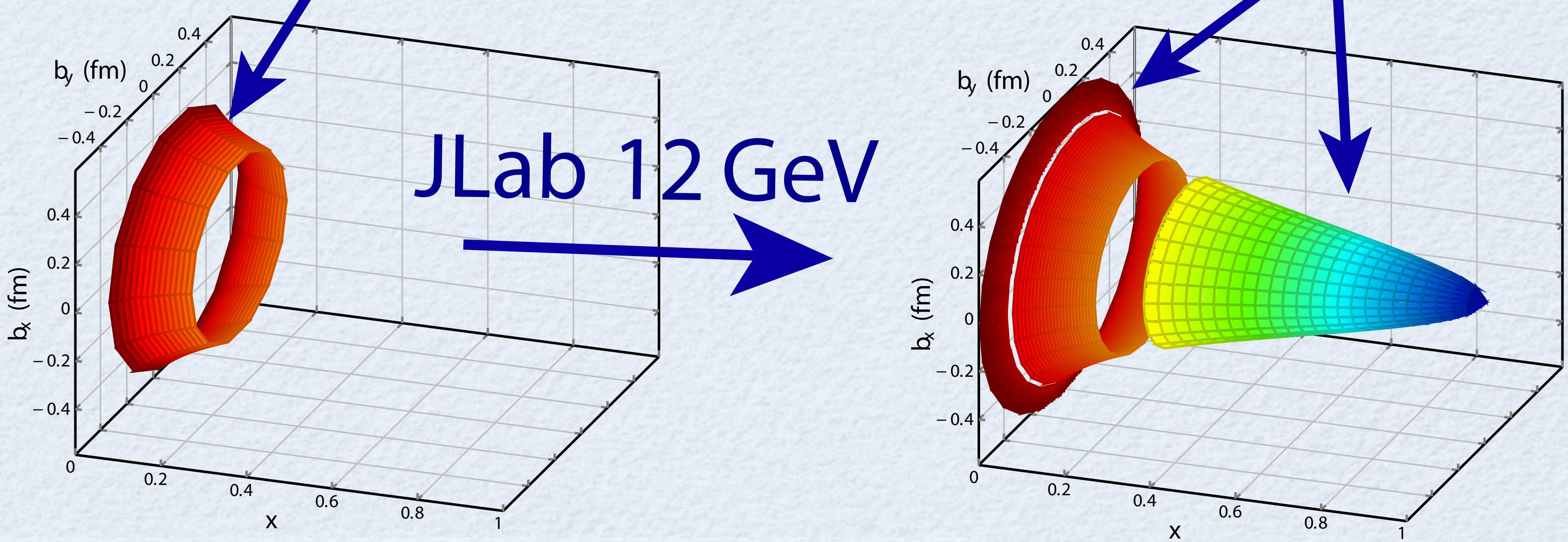
Projections for CFFs at JLab 12 GeV

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



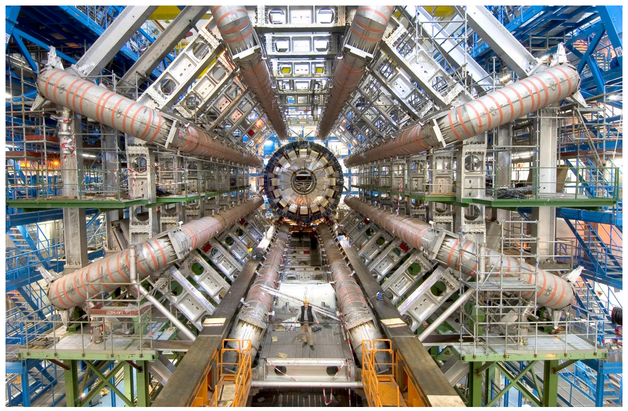
CLAS12 projections E12-06-119 with DVCS A_{UL} and A_{LU}

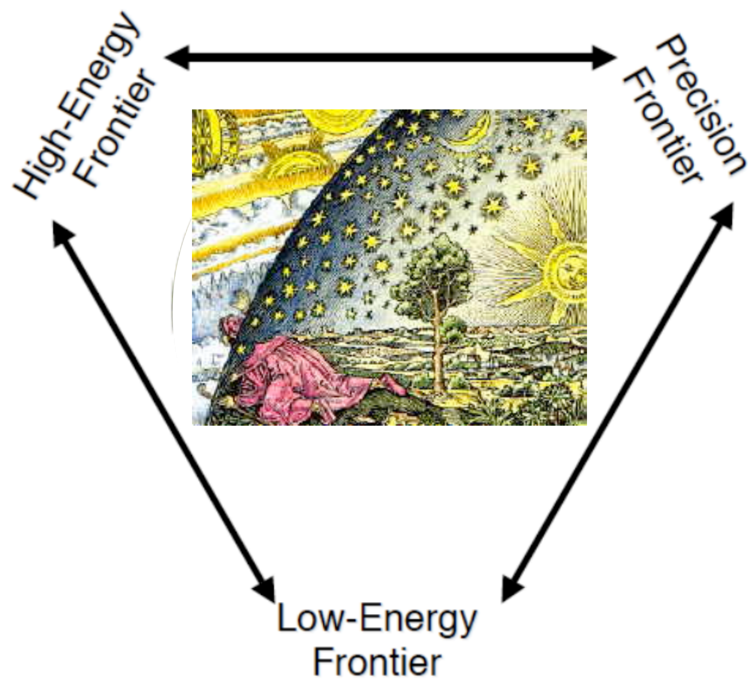


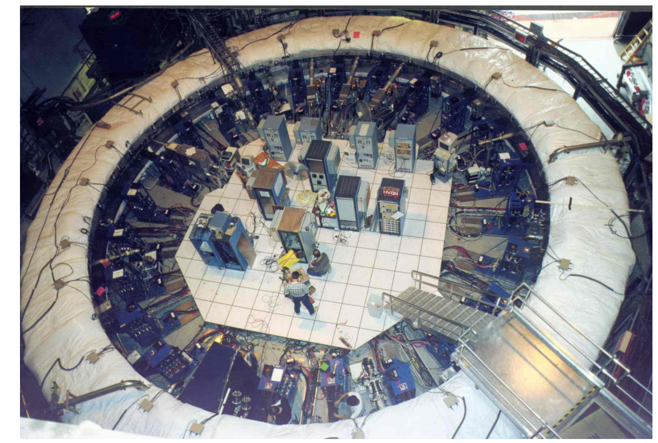


courtesy of Z.E. Meziani

Conclusions

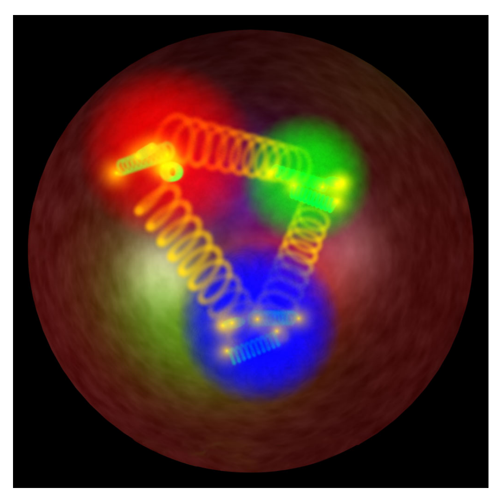






Puzzles at low Energies ?!

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



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

→ New tools: MESA