Recent developments in hadron structure: from electron scattering to atomic physics

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Unraveling the structure of mesons and baryons

- **Basic question: unraveling strong QCD**

Origin of mass, spin, imaging of hadrons

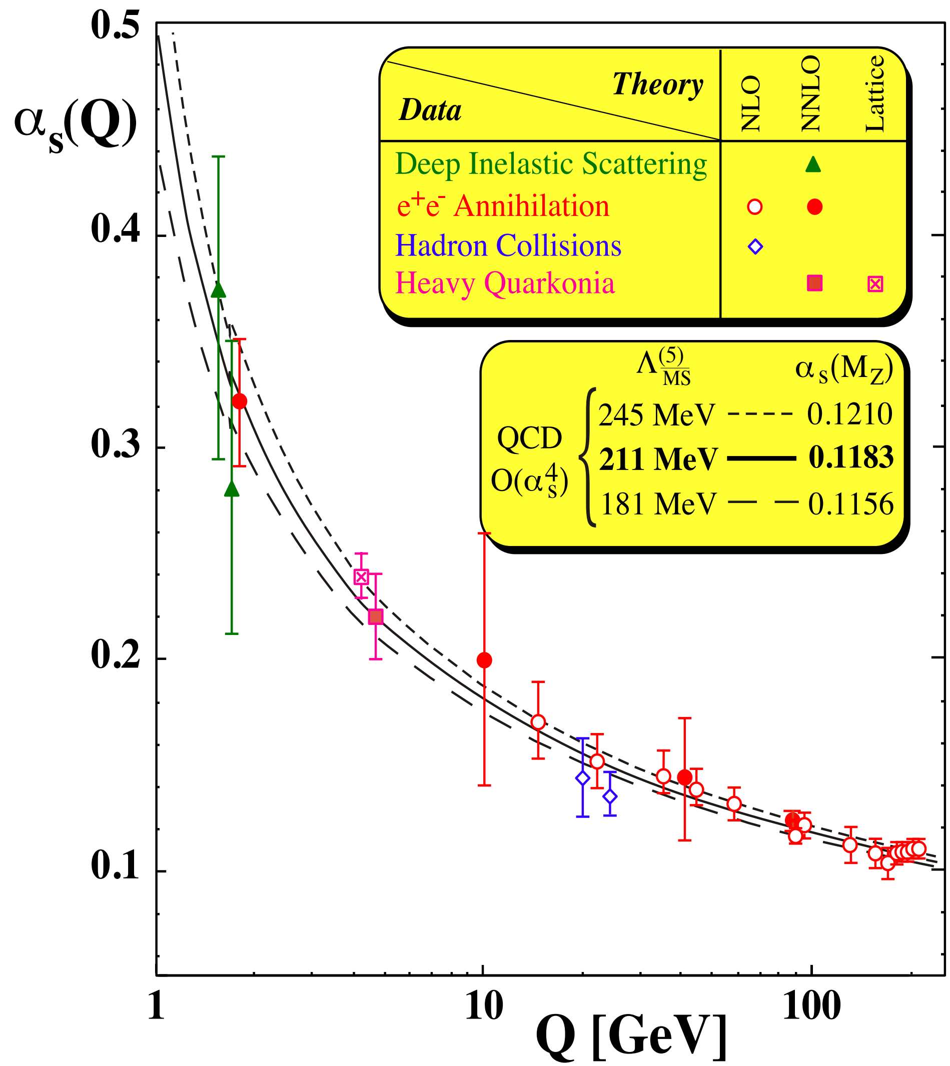
- **Precision hadron physics**

Impact on new physics searches: $(g\text{-}2)_\mu$,dark photon search, proton radius puzzle, weak mixing angle

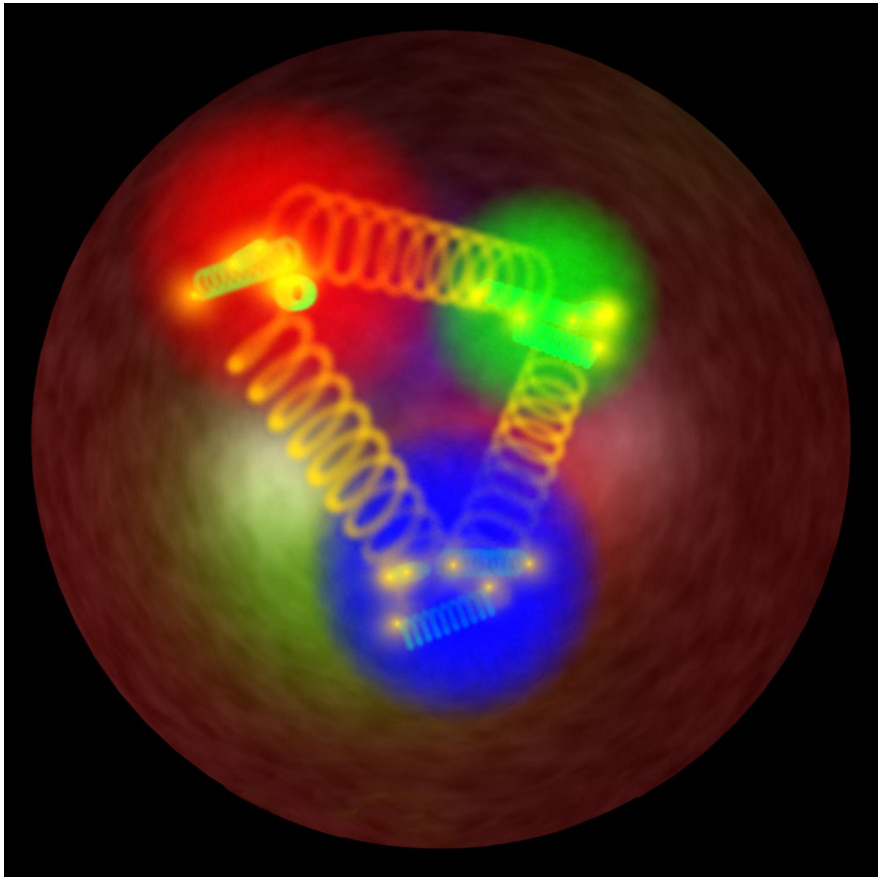
- **Theory tools**

lattice QCD: ab initio

EFT/phenomenology: interplay with precision hadron data



What is the size of the proton?

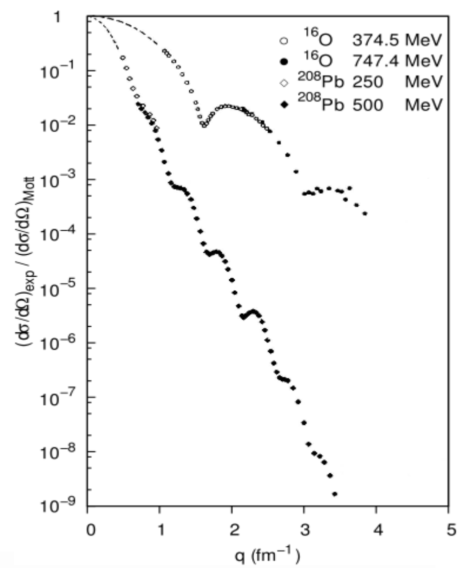


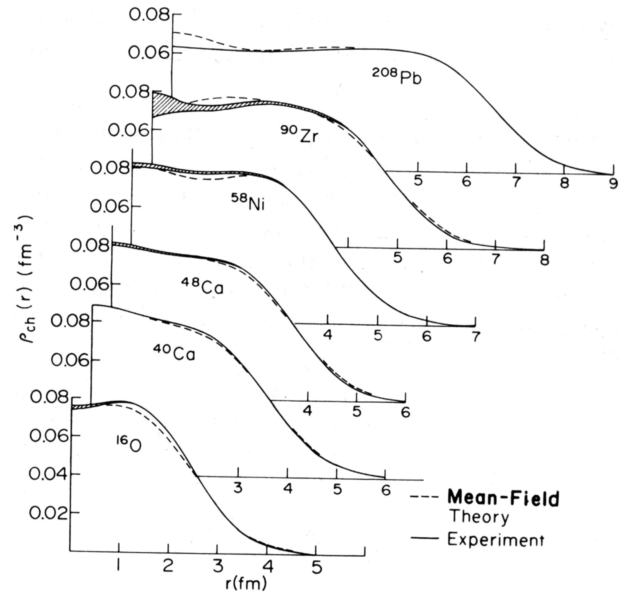
Sizes and shapes of non-relativistic many-body systems

Sizes of nuclei

as revealed through

elastic electron scattering

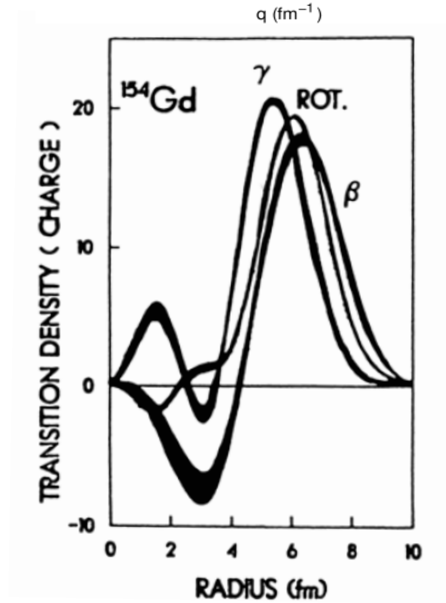


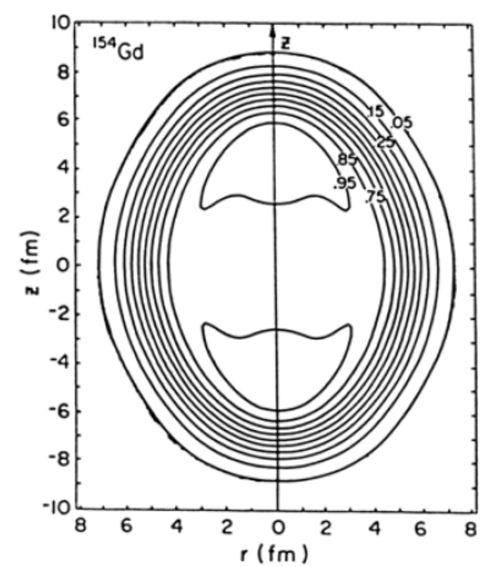


Shapes of deformed nuclei

as revealed through

inelastic electron scattering





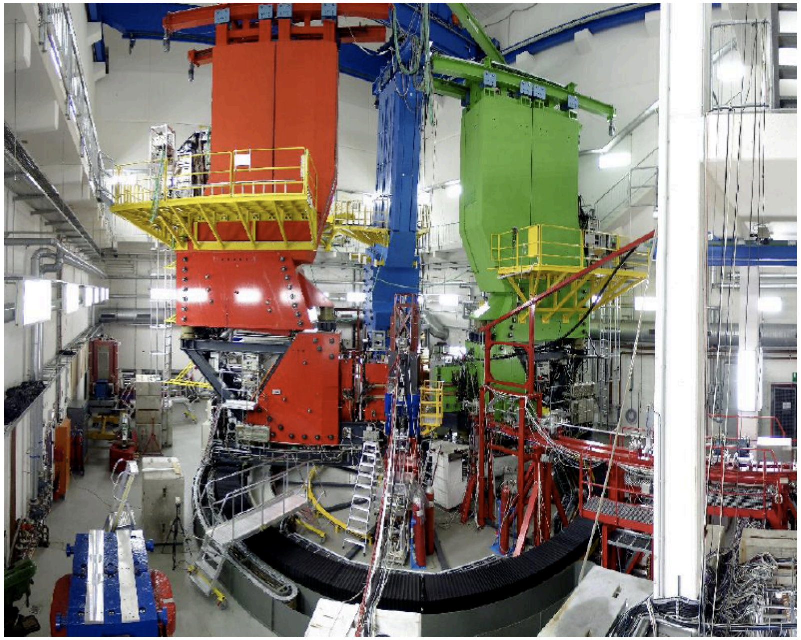
Perspective on shape of hadrons: Alexandrou, Papanicolas, Vdh (2011)

Electron scattering facilities MAMI, JLab:

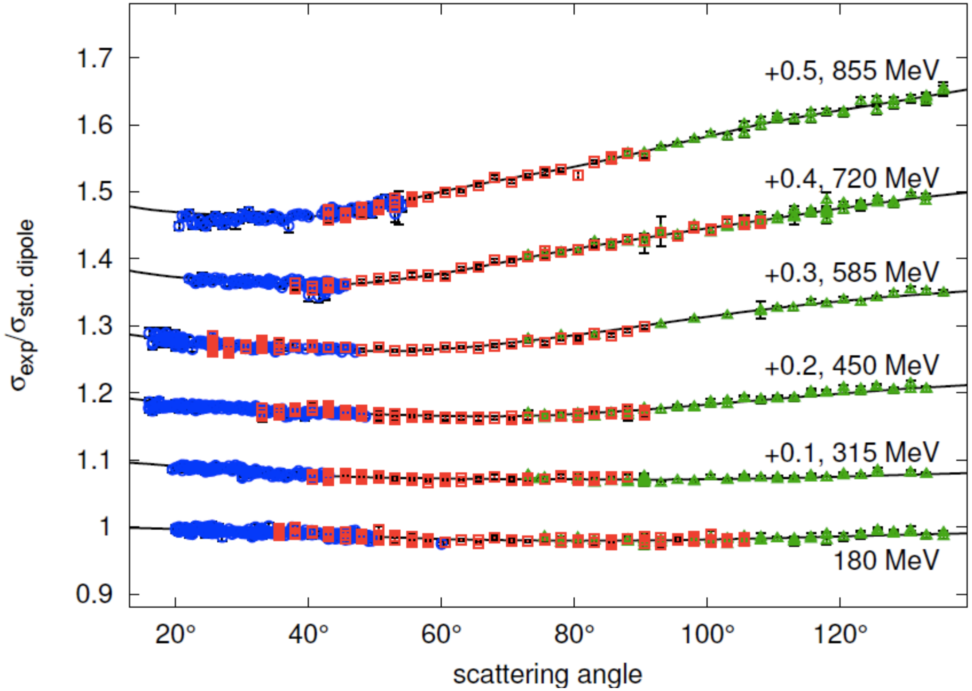
uniquely positioned to deliver high-precision hadron data

recent cross section data A1@MAMI

High momentum resolution ~ 10^{-4}

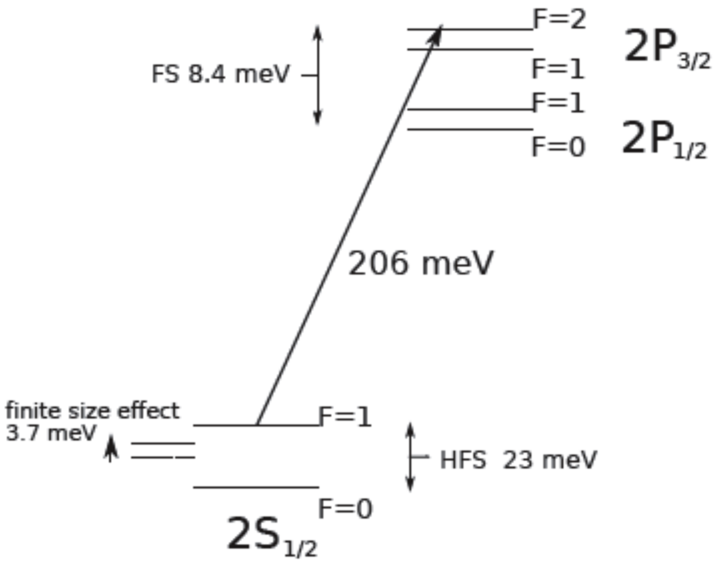


MAMI achieved 1% measurement of R_E



Bernauer et al. (2010)

extraction of R_E from μH Lamb shift



- Lamb shift is dominated by vacuum polarization : drops 2S state by a lot
- Experiment measures 2S F=1 to 2P3/2 F = 2 state

  (F is total angular momentum)
- Finite size effect on s-wave states (l = 0)

  Non-relativistic 1γ-exchange calculation

$$\Delta E = \frac{2\pi\alpha}{3} R_E^2 \, \phi_n^2(0)$$

Karplus, Klein, Schwinger (1952)

- Leading term of order O(α^4) : $\phi_n^2(0) = m_r^3 \alpha^3 / (\pi n^3)$

Lamb Shift

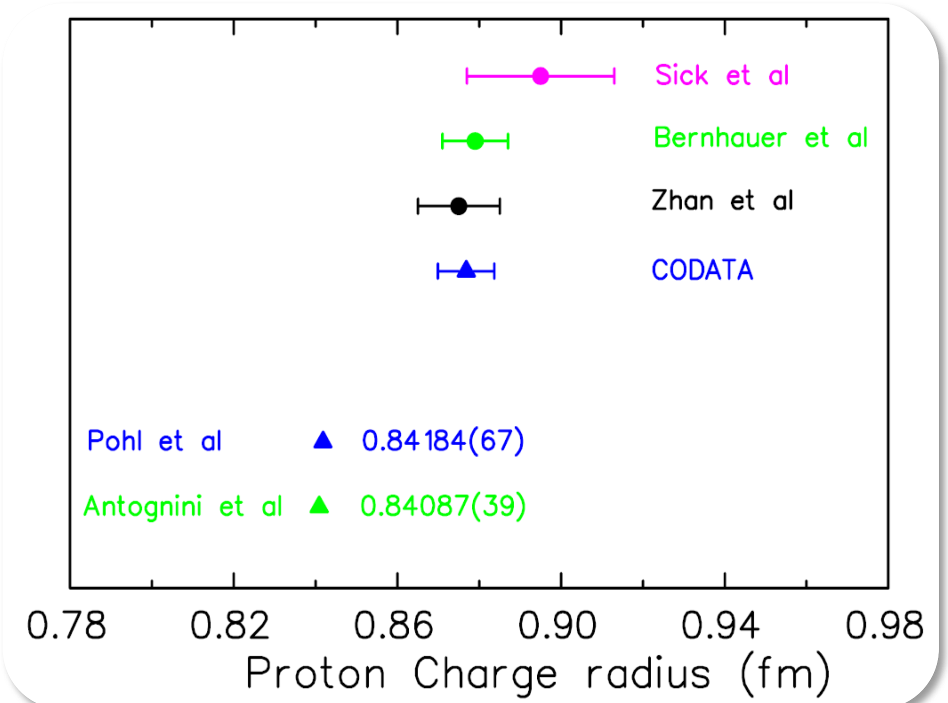
ΔE_{LS} = 209.9779 (49) - 5.2262 R_E^2 + 0.00913 $R^3_{(2)}$ meV

3.70 meV

0.026 meV

$R^3(2)$: O(α^5) correction term

Proton radius puzzle ?



μH data:

$R_E = 0.8409 \pm 0.0004$ fm

Pohl et al.(2010)

Antognini et al.(2013)

7.7σ difference !?

ep-data :

CODATA

$R_E = 0.8772 \pm 0.0046$ fm

Bernauer et al. (2010)

Zhan et al.(2011)

Experimental precision ≈ 2 μeV

Energy shift ascribed to finite proton size is 310 μeV less than expected !!!

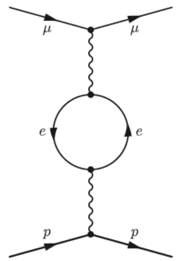
Lamb shift: QED corrections

- Calculated by several groups

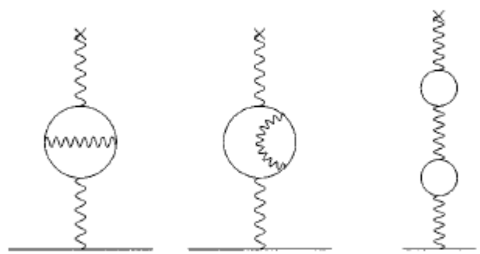
Pachucki (1996, 1999)

Borie (1976, 2005)

- 1 loop electron

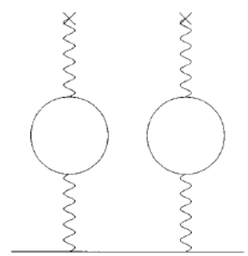


ΔE = 205.0282 meV



ΔE = 1.5081 meV

- 2 loop electron

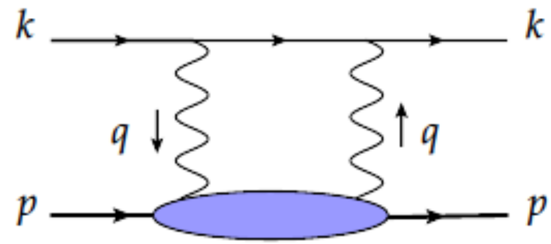


ΔE = 0.1509 meV

- 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)



- **Finite-size** correction:

  γγ box diagram

- "3rd Zemach moment"

  non-rel. calculation

  Friar(1979)

$$R^3_{(2)} = \int d^3\vec{r}_1\, d^3\vec{r}_2\, |\vec{r}_1 - \vec{r}_2|^3\, \rho_E(r_1)\, \rho_E(r_2)$$

$$= \frac{48}{\pi} \int_0^\infty \frac{dQ}{Q^4} \left[G_E^2(Q) - 1 - 2Q^2 G_E(0) \frac{dG_E}{dQ^2}(0) \right]$$

  recent evaluation

  Distler, Bernauer, Walcher(2011)

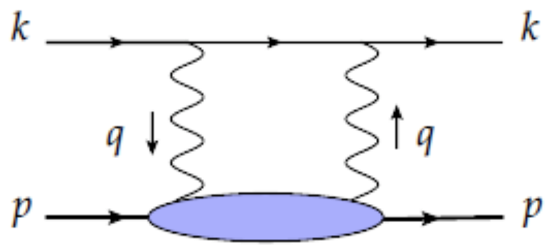
  $R^3_{(2)} = 2.85\ (8)\ \mathrm{fm}^3 \longrightarrow \Delta E \approx -0.026$ meV

- What do we know model independently ?

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

  Information is contained in forward, double virtual Compton scattering

Lamb shift: hadronic corrections (II)



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

- 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

$$\Delta E = \Delta E^{el} \rightarrow \text{Elastic state: involves } \textbf{nucleon form factors}$$
$$+ \Delta E^{subtr} \rightarrow \text{Subtraction: involves } \textbf{nucleon polarizabilities}$$
$$+ \Delta E^{inel} \rightarrow \text{Inelastic, dispersion integrals: involves } \textbf{structure functions F1, F2}$$

Lamb shift: hadronic corrections (III)

- Low-energy expansion of forward, doubly virtual Compton scattering constrains 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

$$\lim_{\nu^2, Q^2 \to 0} T_1^{\mathrm{non-Born}}(\nu, Q^2) = \frac{\nu^2}{e^2}(\alpha_E + \beta_M) + \frac{Q^2}{e^2}\beta_M$$

$$\lim_{\nu^2, Q^2 \to 0} T_2^{\mathrm{non-Born}}(\nu, Q^2) = \frac{Q^2}{e^2}(\alpha_E + \beta_M)$$

subtraction term for T_1

- Numerical evaluations :

(μeV)	Carlson,Vdh (2011)	Pachucki (1999)	Martynenko (2006)
ΔE^{subt}	5.3 ± 1.9	1.8	2.3
ΔE^{inel}	-12.7 ± 0.5	-13.9	-13.8
ΔE^{el}	-29.5 ± 1.3	-23.0	-23.0
ΔE	-36.9 ± 2.4	-35.1	-34.5

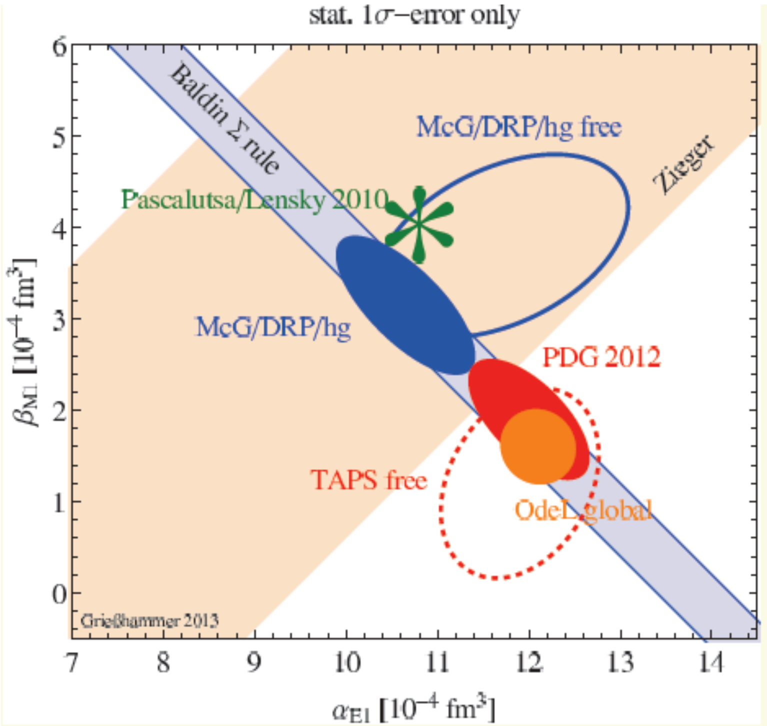
Carlson,Vdh (2011)
+ Birse, McGovern (2012)

$\Delta E = (-33 \pm 2)\ \mu\text{eV}$

or about 12% of the needed correction …

present **experimental precision**: **2 μeV**

Static Polarizability Status



Theory analyses:

BChPT: Lensky,Pascalutsa (2010)

HBChPT: Griesshammer, McGovern, Phillips (2013)

Disp. Rel.: Olmos de Leon (2001)

New (2013) PDG values:

$\alpha = (11.2 \pm 0.4) \times 10^{-4}$ fm^3

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

Dispersion based and chiral extractions of α_E - β_M disagree at about 2σ

In the low-energy range: linear photon beam asymmetry in Compton scattering is purely dependent on β_M

Krupina,Pascalutsa (PRL 110, 2013)

More precise measurement of β_M underway at A2@MAMI using linearly polarized photons

Proton radius puzzle: what could it mean ?

- unknown correction ? …after known constraints have been built in !
- Change in Rydberg constant ?

In absence of further (sizeable) corrections, use of muonic extraction of R_E plugged into electron H Lamb shift yields R_∞ which is 4.9σ away from CODATA value   (and factor 4.6 more precise)

Pohl et al. (2010)

- New physics ?

- explain 3σ $(g-2)_\mu$ discrepancy AND 7σ R_E discrepancy from μH Lamb shift simultaneously invoking a correction by a hypothetical light boson ?
- $(g-2)_e$ puts strong limit on coupling to e -> much smaller,

Non-universality e – μ ?

- New parity violating muonic forces ?
- Can rare Kaon decay data help ?

Tucker, Smith (2010)   Barger, Chiang, Keung, Marfatia (2011)

Batell, McKeen, Pospelov (2011)   Brax, Burrage (2011)   Rislow, Carlson (2012)

Proton radius puzzle: what‘s next ?

- Muonic Lamb shift : muonic D, muonic ^{3}He measurements planned

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

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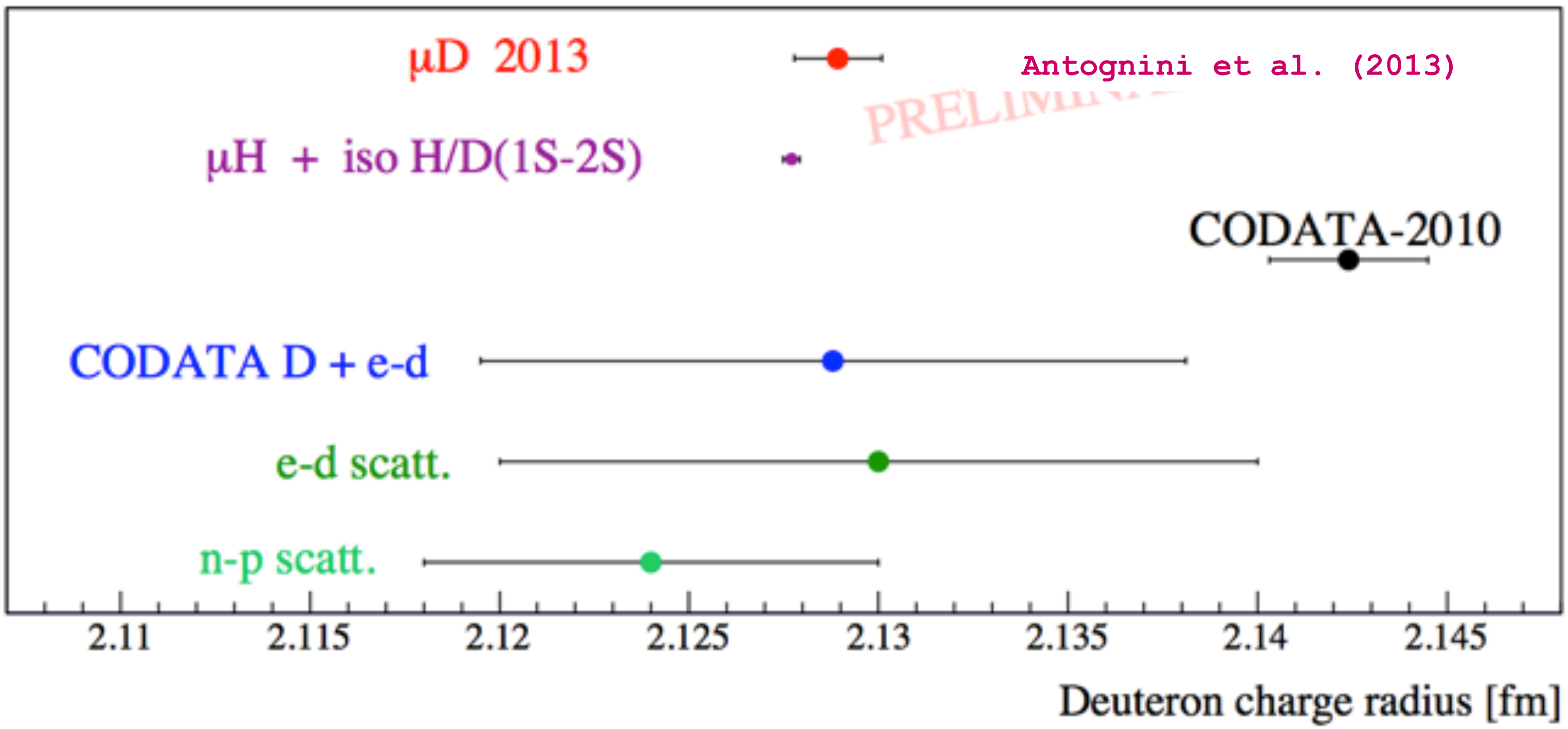


New radius measurement from e-d scattering planned at MAMI (2014)

Caveat: error bar for μD does not include polarization correction

Polarization correction for μD Lamb shift

Data based dispersion relation analysis: Carlson, Gorchtein, Vdh (2013)

Elastic	$\Delta \bar{E}^{el}$	-0.417(2) meV
Nuclear (QE)	ΔE^{PWBA}	-1.616(739) meV
	ΔE^{FSI}	-0.391(44) meV
	$\Delta E^{\perp}$	-0.322(3) meV
Hadronic	ΔE^{hadr}	-0.028(2) meV
Subtraction	ΔE^{subt}	0.740(40) meV
	$\Delta E^{Thomson}$	0.023(1) meV
	ΔE_{total}	-2.011(740) meV

largest uncertainty

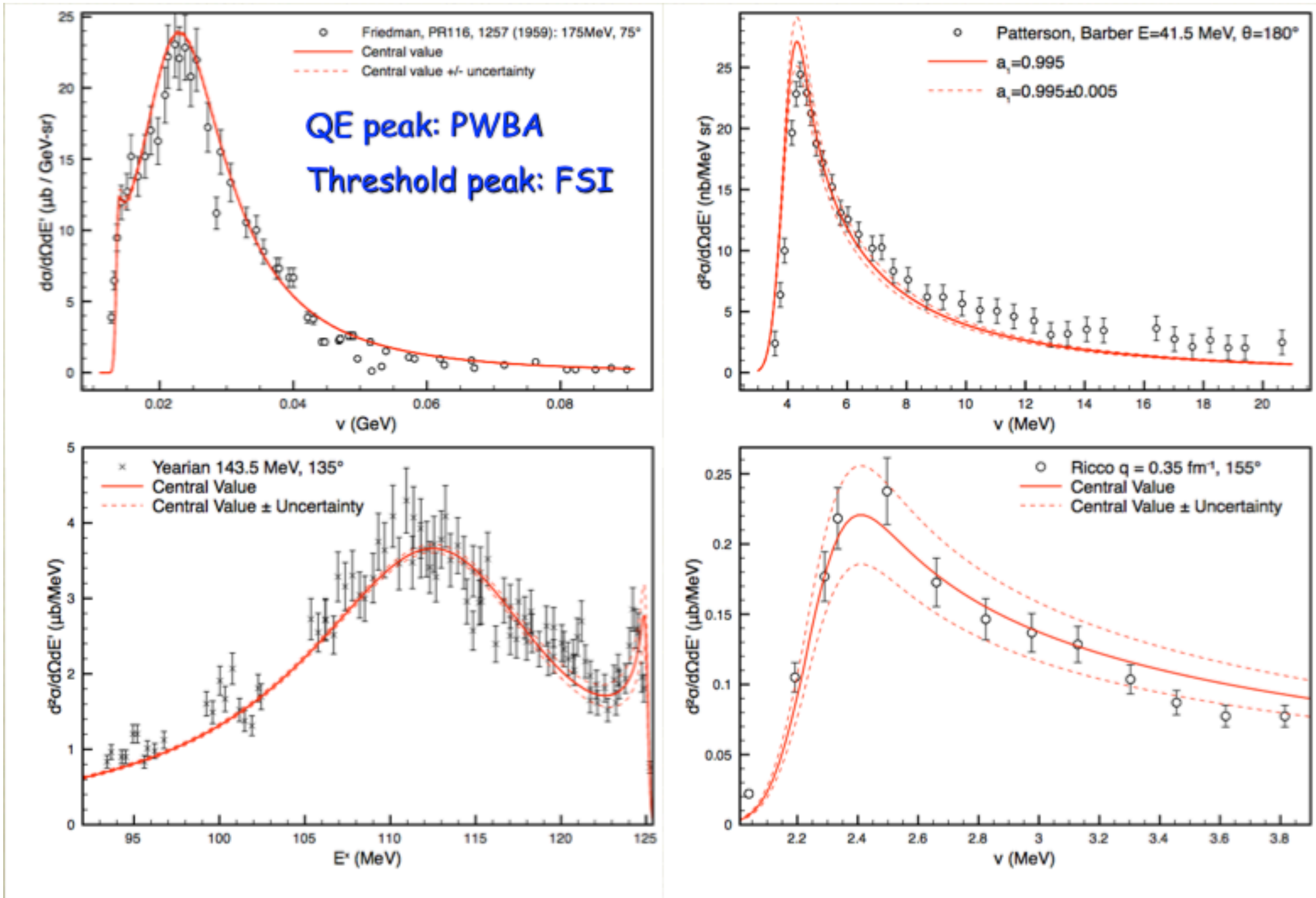
Polarization correction to $2S_{1/2}$ level

Compared to NR calculation: ΔE_{total} = -1.680 (16) meV Pachucki (2011)

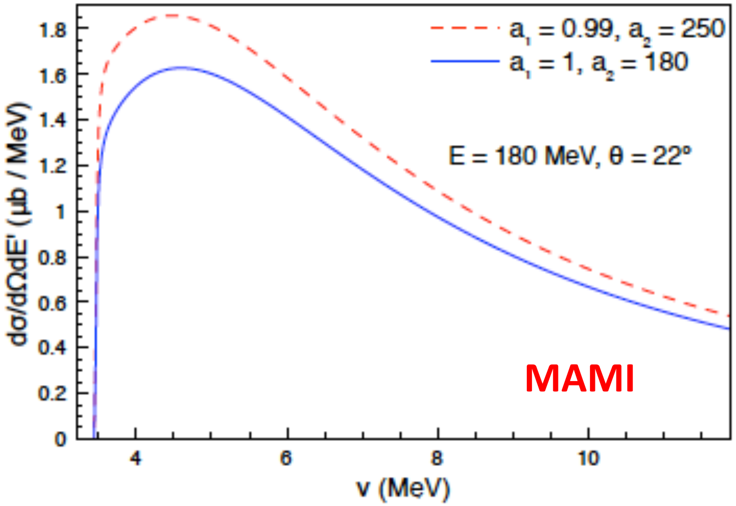
The bulk of the uncertainty in DR approach comes from a very limited kinematic region

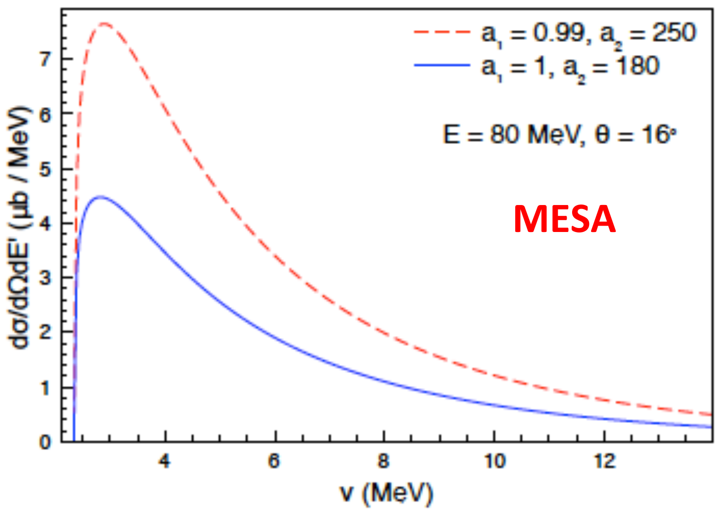
$$\boxed{\begin{aligned} \langle Q^2 \rangle &= 0.003 - 0.006\ (\mathrm{GeV/c})^2 \\ \langle \nu \rangle &= 6 - 10\ \mathrm{MeV} \end{aligned}}$$

Fit of Quasi-elastic e-D scattering data: 0.005 GeV^2 < Q^2 < 3 GeV^2



New low Q^2 (forward angle) data needed to constrain F_2 for D





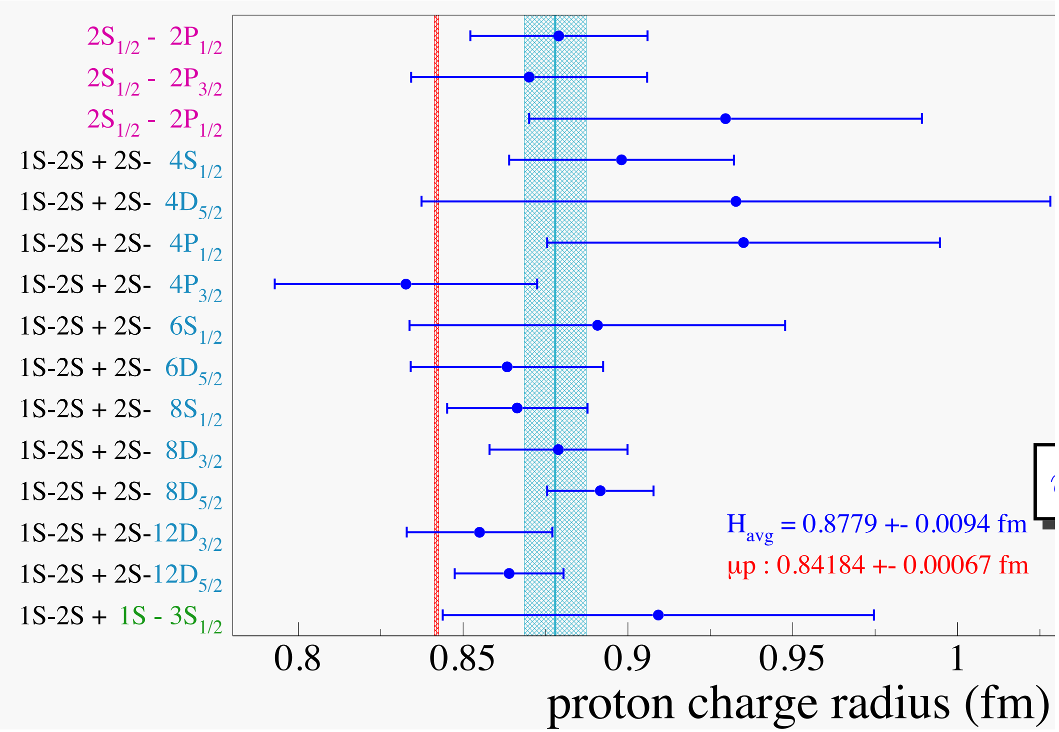
E_{lab}, θ_{lab}	Exp. precision	$\delta(\Delta E^{\mu D}_{2S-2P})$	$\delta(\Delta E^{eD}_{1S-2S})$
180 MeV, 30°	2%	740 μeV	12 kHz
	1%	370 μeV	6 kHz
180 MeV, 22°	2%	390 μeV	6.32 kHz
	1%	195 μeV	3.16 kHz
180 MeV, 16°	2%	211 μeV	3.36 kHz
	1%	110 μeV	1.68 kHz
80 MeV, 16°	2%	67 μeV	1.078 kHz
	1%	48 μeV	0.780 kHz

Proton radius puzzle: what's next ?

- Muonic Lamb shift : muonic D, muonic ^{3}He measurements planned

- Electronic H Lamb shift : higher accuracy measurement very timely

  New proposal (York Univ, Canada) : R_E to 0.7%



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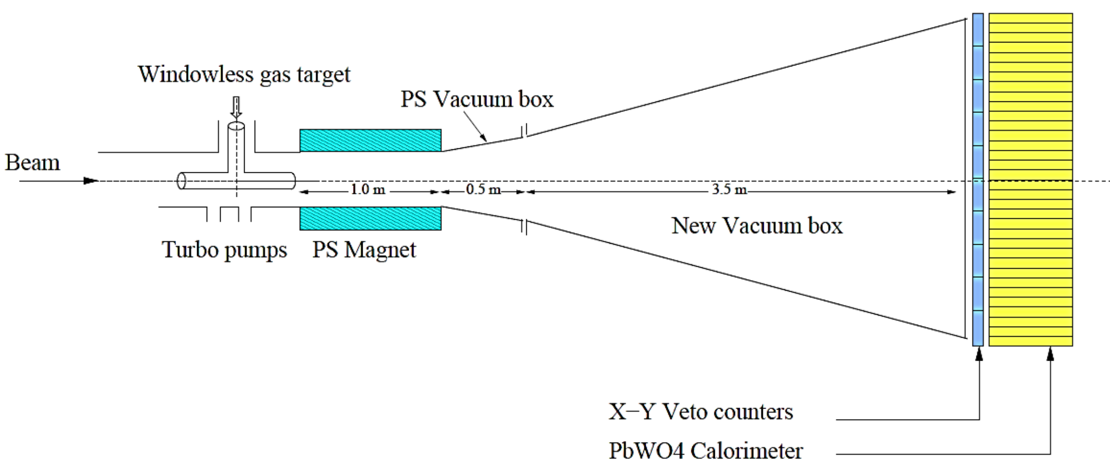
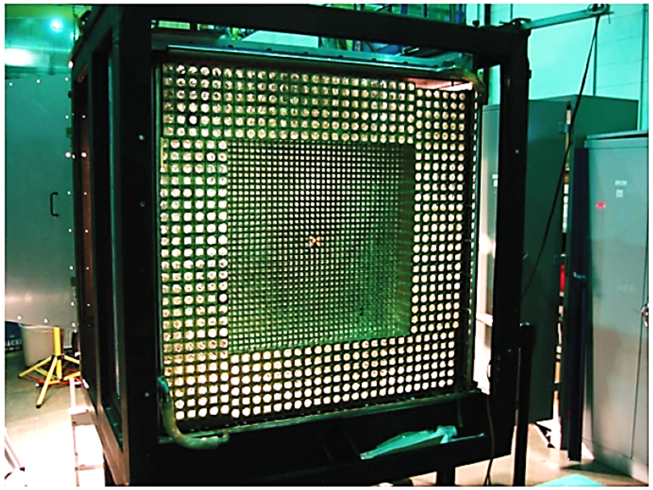
- new G_{Ep} measurements at very low Q^2 down to $Q^2 \approx 2\text{x}10^{-4}$ GeV^2

  JLAB/Hall B approved expt : magnetic-spectrometer-free experiment (HyCal)
  $Q^2 = 2\text{x}10^{-4} - 2\text{x}10^{-2}$ GeV^2
  ep→ep cross sections normalized to Moller scattering





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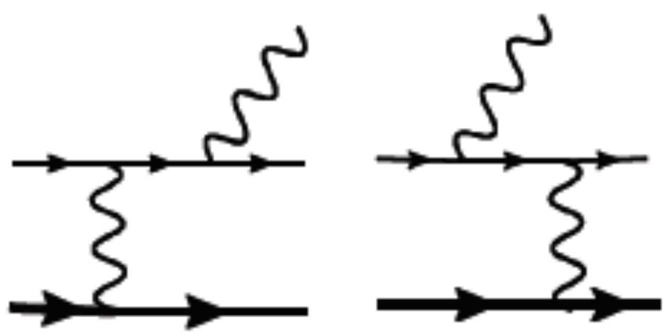

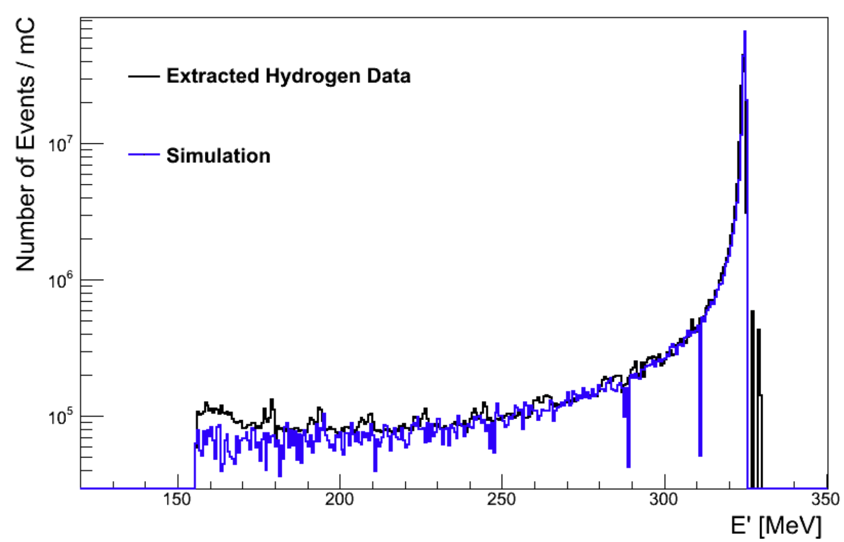

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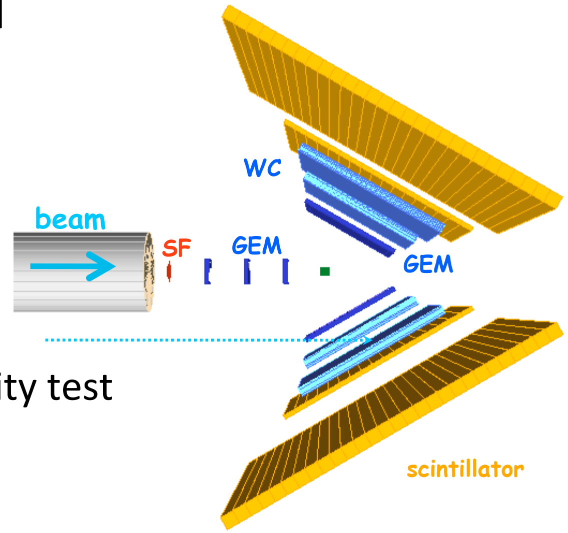
  MAMI/A1 : using initial state radiation (2013)
  MESA : low-energy, high resolution spectrometers

- μ – p scattering (MUSE) at low Q^2 at PSI: (2015 – 2017)

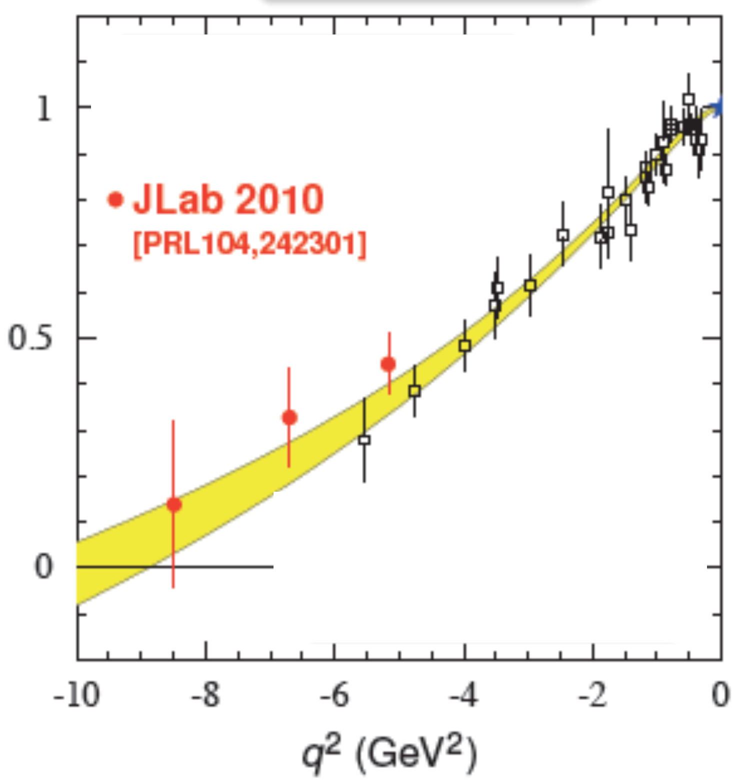


  simulataneous measurement of $\mu^\pm$ p and $e^\pm$ p: lepton universality test
  $0.002\ \text{GeV}^2 < Q^2 < 0.07\ \text{GeV}^2$
  2 beam polarities give 2γ exchange test

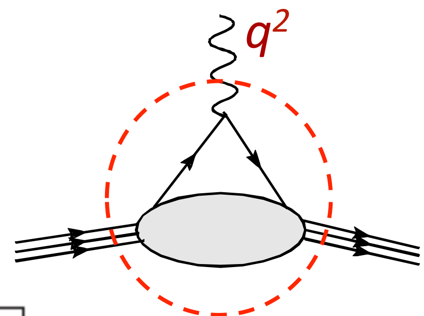
Complementing hadron structure in space- and timelike regions

Proton spacelike form factors

e- p → e- p



JLab, MAMI

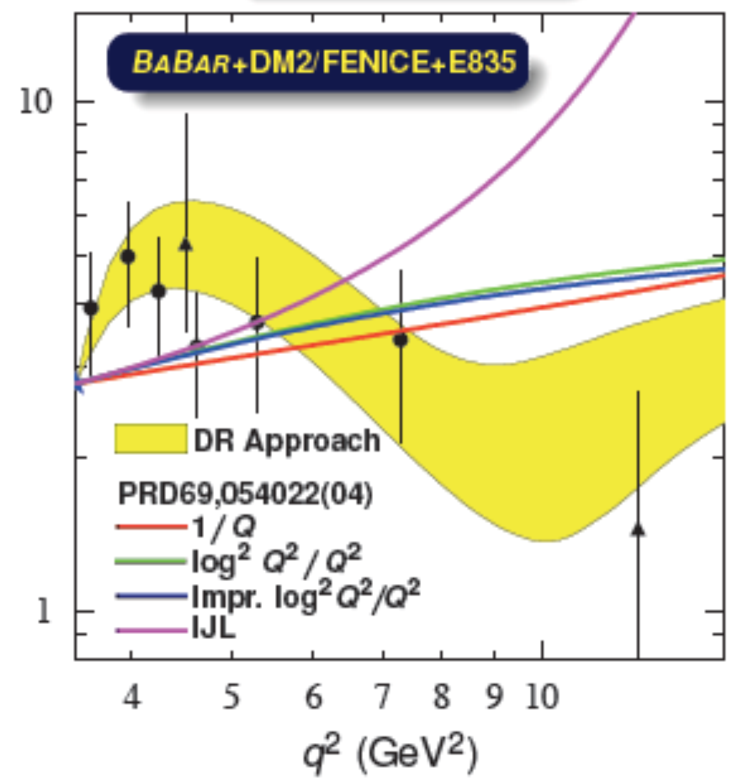


y-axis:

$\mu_P\, G_E / G_M$

Proton timelike form factors

$e^+ e^- \rightarrow p\, \bar{p}$

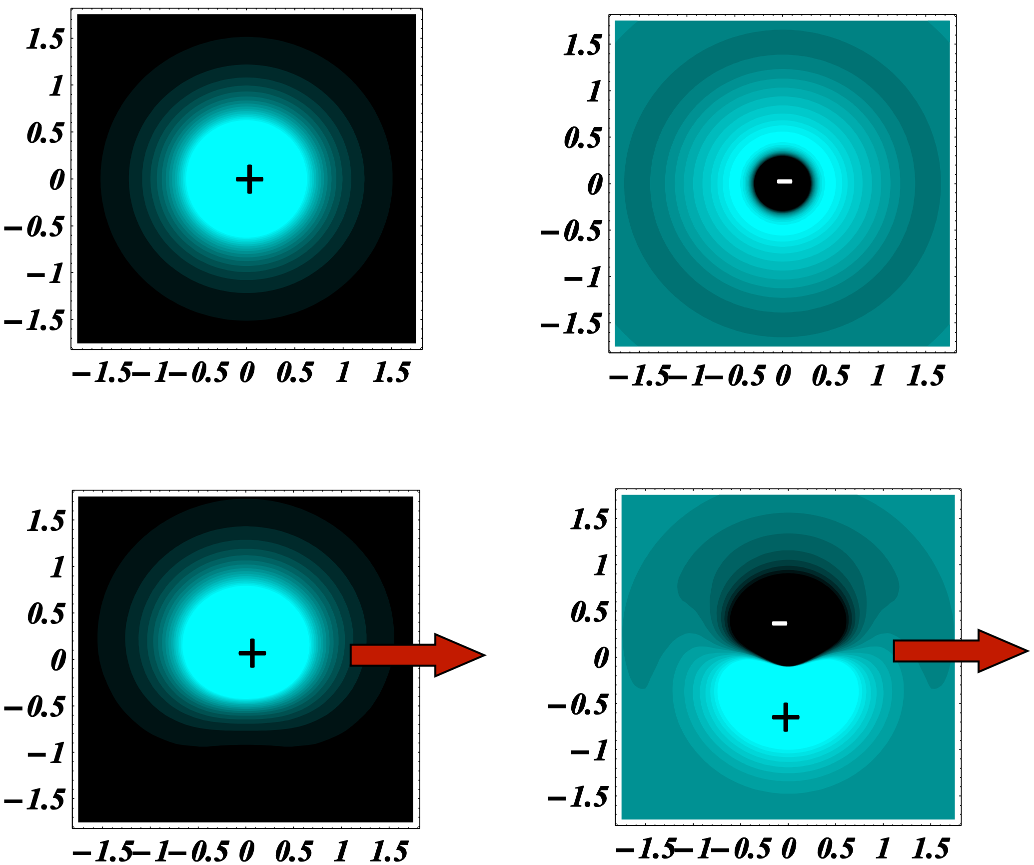


BES-III, PANDA

Spatial imaging of hadrons

Charge, mass, spin densities of quarks in a hadron

proton neutron



Miller (2007) Carlson, Vdh (2008)

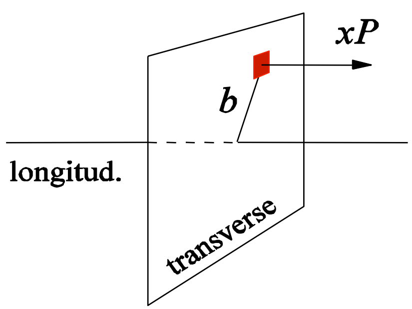
p -> Δ^+ (1232)

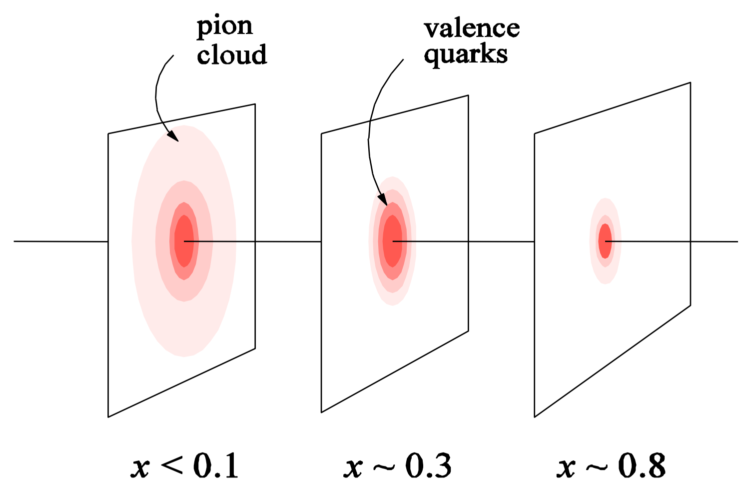
Generalized Parton Distributions (GPDs): 3D image of hadrons

Deep-Inelastic Scattering
longitudinal
quark distribution
in momentum space

Unifying concept
GPDs
fully-correlated
quark distributions in both
coordinate and momentum space

Elastic Scattering
transverse quark
distribution in
coordinate space





Burkardt (2000, 2003),
Belitsky, Ji, Yuan (2004)

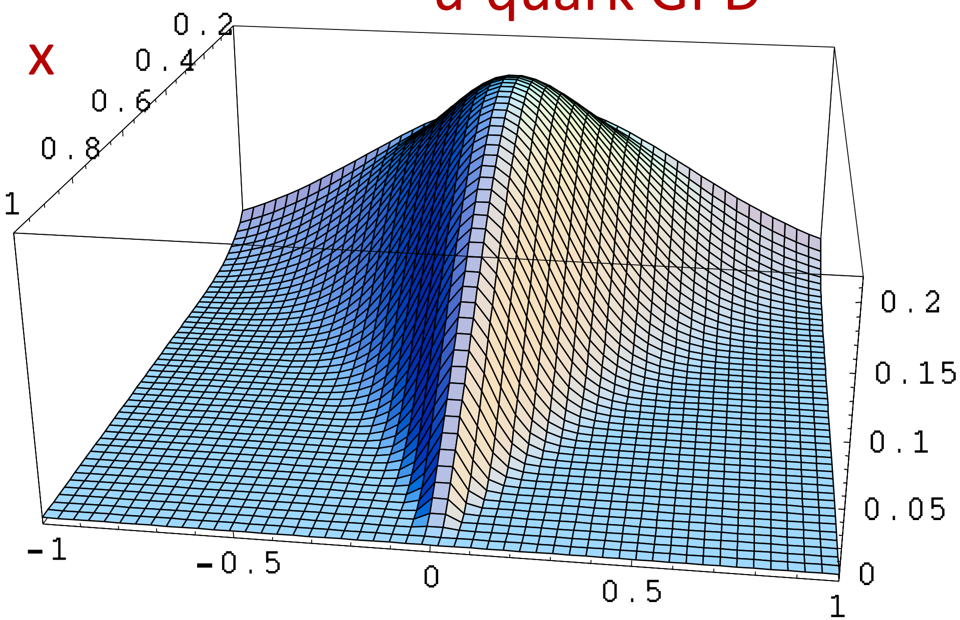
GPDs: transverse image of hadrons

GPDs: quark distributions w.r.t. longitudinal momentum x and transverse position $b_\perp$

lattice QCD: moments of GPDs

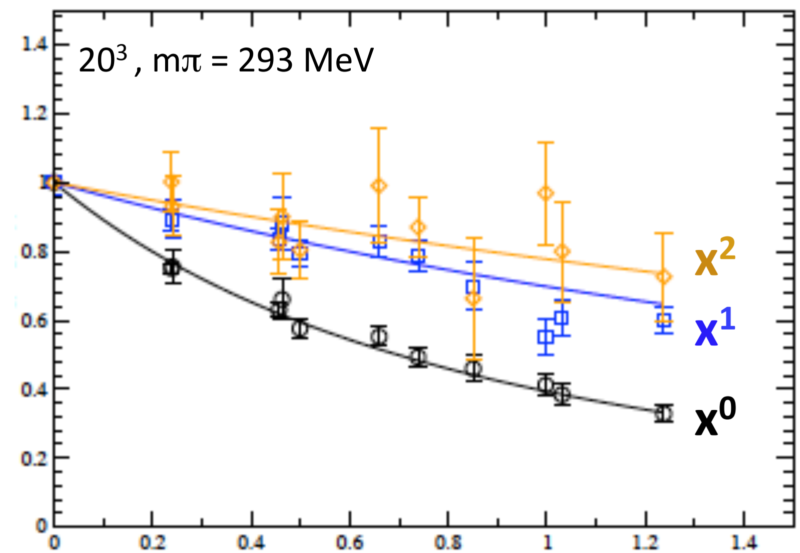
u-quark GPD

x



$b_\perp$ (fm)

x^n moment of u-d GPD



-t (GeV^2)

Fourier transform

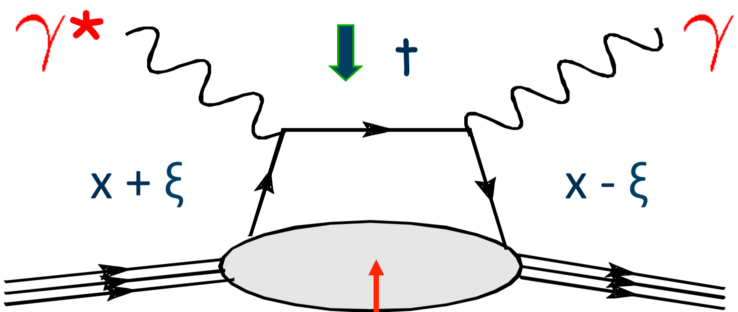
Guidal, Polyakov, Radyushkin, Vdh (2005)

Diehl, Feldmann, Jakob, Kroll (2005)

LHPC Coll.

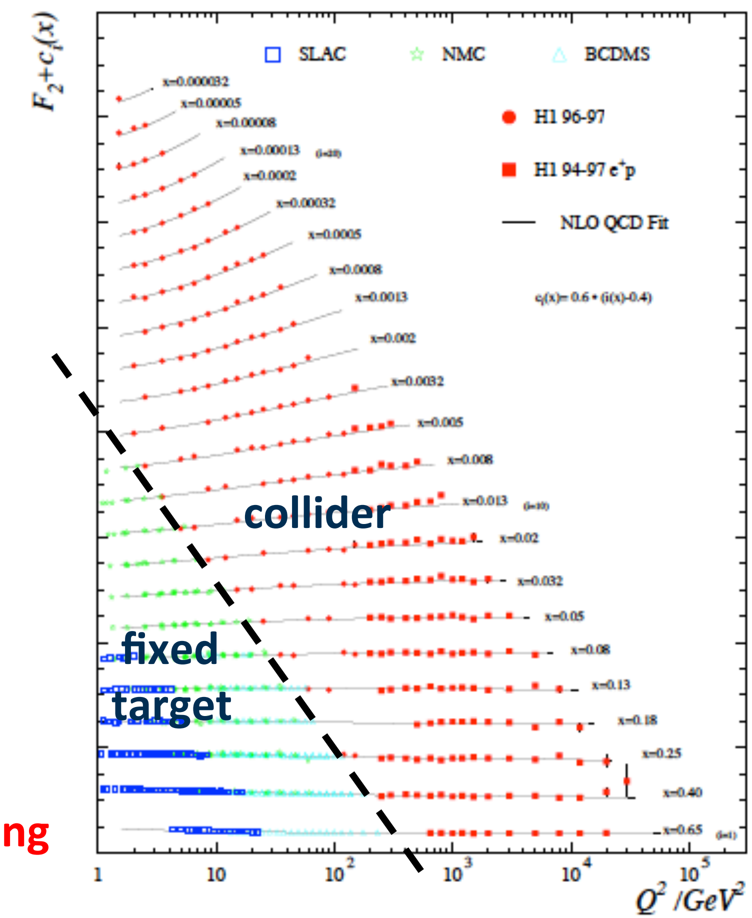
QCD factorization: tool to access GPDs

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



GPD (x, ξ ,t)

world data on proton **F2**



➡ at large Q^2 : **QCD factorization theorem** :
hard exclusive process described by GPDs
model independent !

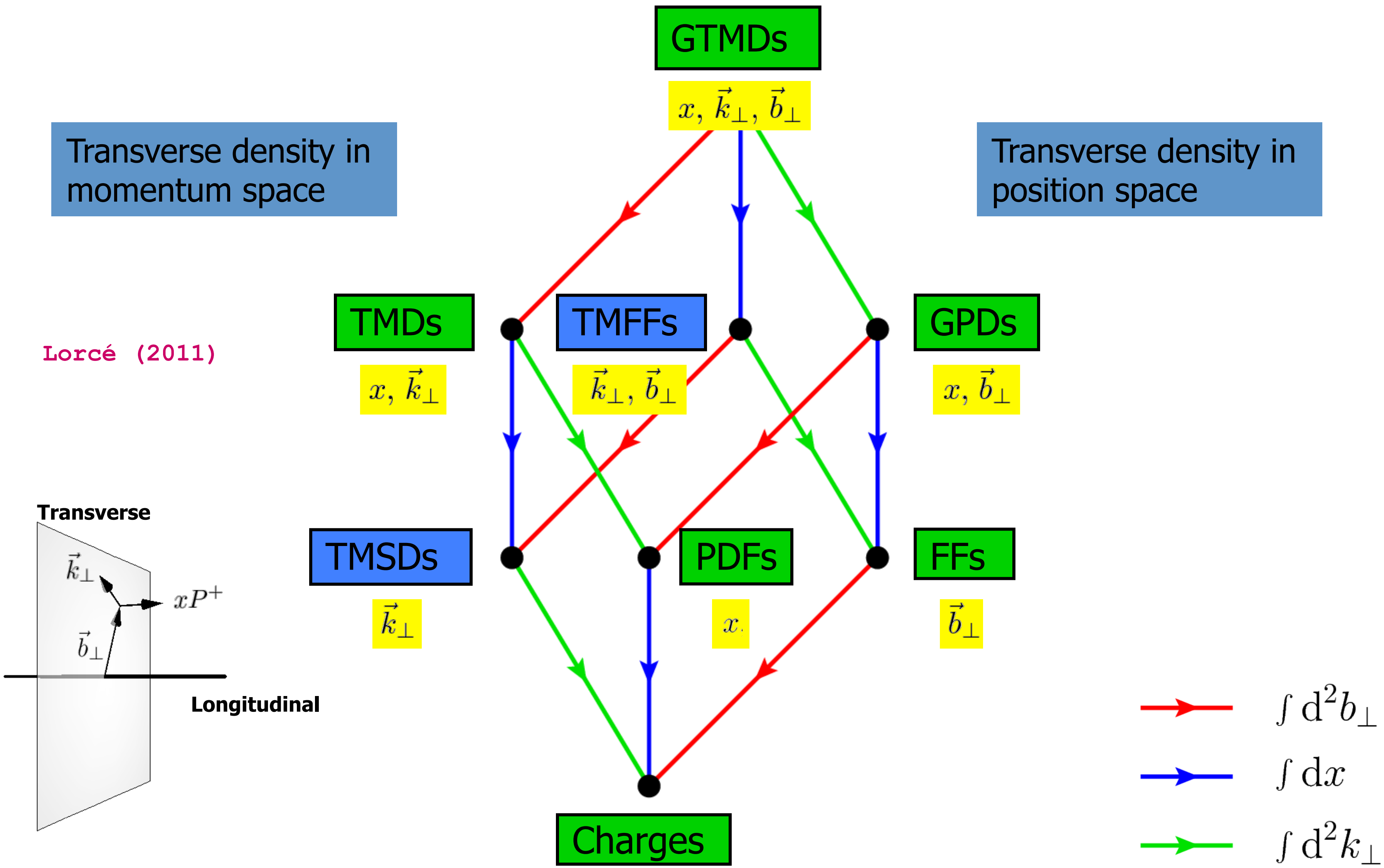
Müller et al.(1994), Ji(1995), Radyushkin(1995), Collins, Frankfurt, Strikman (1996)

➡ **KEY** Q^2 leverage required to test **QCD scaling**

„complete“ picture of nucleon

$\xi = 0$

Momentum space	$\vec{k}_\perp \leftrightarrow \vec{z}_\perp$ $\vec{\Delta}_\perp \leftrightarrow \vec{b}_\perp$	Position space

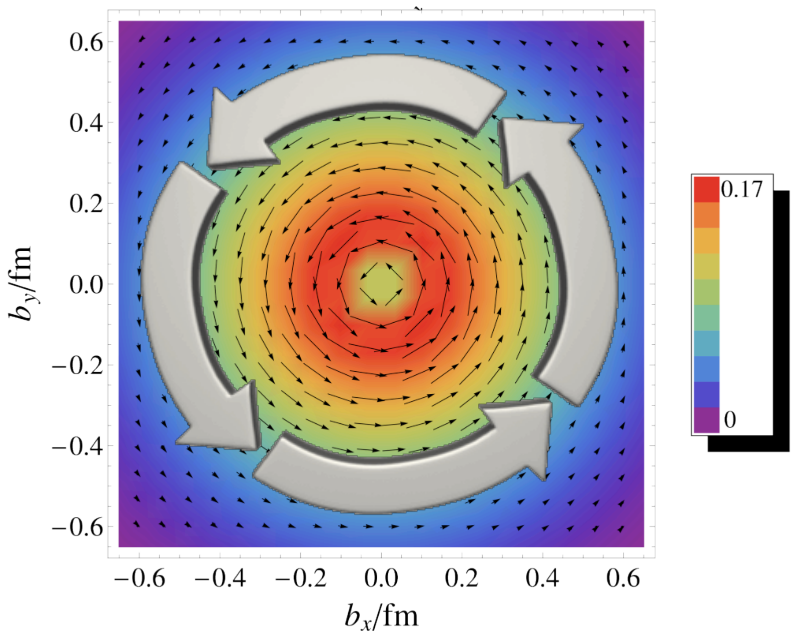


Quark orbital angular momentum in proton

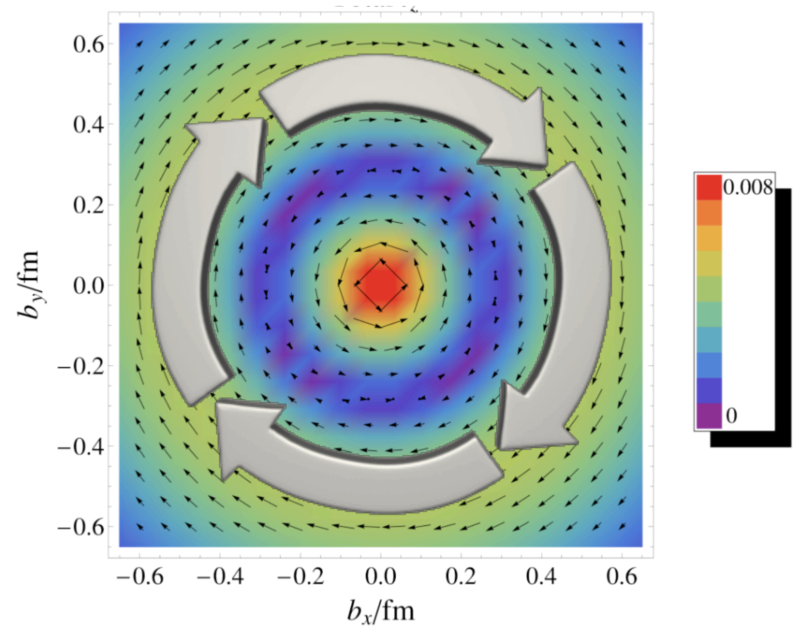
$$\ell_z^q = \int \mathrm{d}^2\vec{b}_\perp \, (\vec{b}_\perp \times \langle \vec{k}_\perp^q \rangle)_z$$

$$\langle \vec{k}_\perp^q \rangle = \int \mathrm{d}x \, \mathrm{d}^2\vec{k}_\perp \, \vec{k}_\perp \, \rho_{LU}^q(x, \vec{b}_\perp, \vec{k}_\perp)$$

$\langle \vec{k}_\perp^u \rangle \; [GeV/fm^2]$



$\langle \vec{k}_\perp^d \rangle \; [GeV/fm^2]$



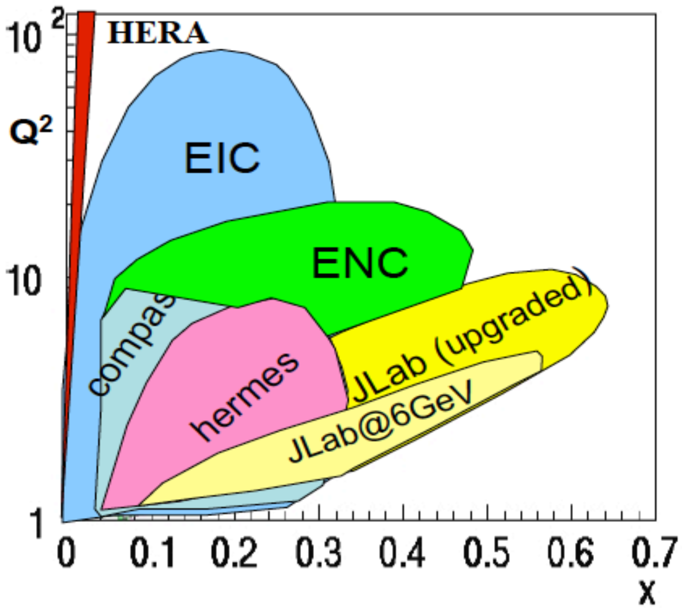
Proton spin

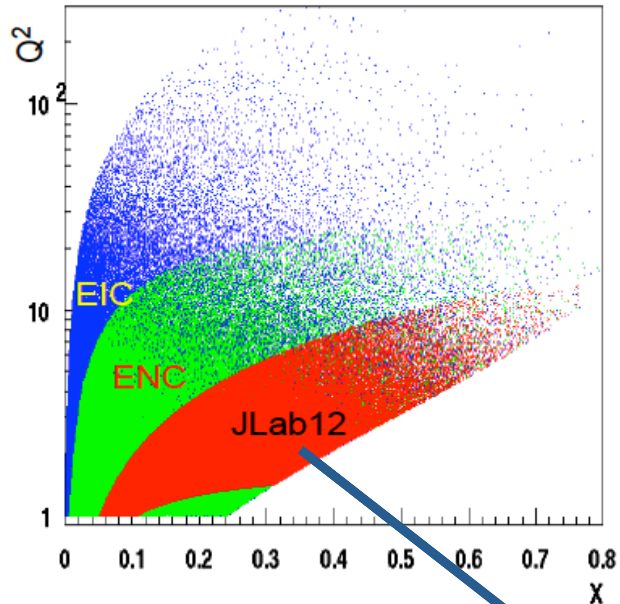
u-quark OAM

d-quark OAM

Results in a light-front constituent quark model:
Lorce', BP, Xiong, Yuan, PRD85 (2012)

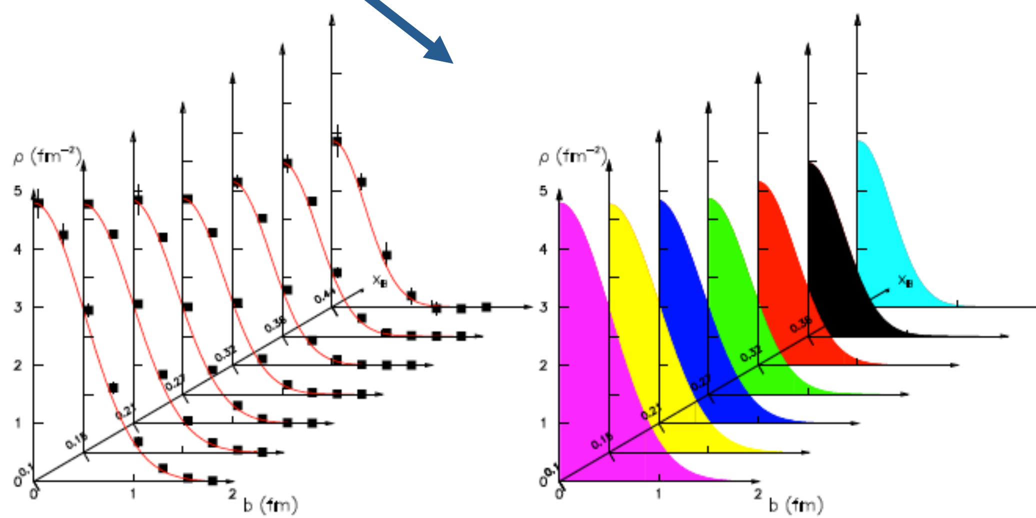
Energy-luminosity frontier in lepton-nucleon physics





JLab 11 GeV projections:

Guidal, Moutarde, Vdh (2013)



- **High-energy, high-luminosity facilities: Compass, JLab@11 GeV, collider projects (EIC, ENC, ...)**
- **Global nucleon structure analysis effort required**

CONCLUSIONS

- **Strong interplay between**
  high-energy $\longleftrightarrow$ precision $\longleftrightarrow$ low-energy frontiers

- **Impact of hadron physics on new physics searches:**
  $(g\text{-}2)_\mu$, Q_{weak} , new dark photon searches

- **Unraveling hadron structure in strong QCD:**
  - proton radius puzzle has shaken textbook beliefs

  - combination of new experiments + theory opens perspectives for an imaging of hadrons to an unprecedented level of detail