Selected topics in hadronic and nuclear physics

October 10, 2021

Symposium on QCD and Nuclei

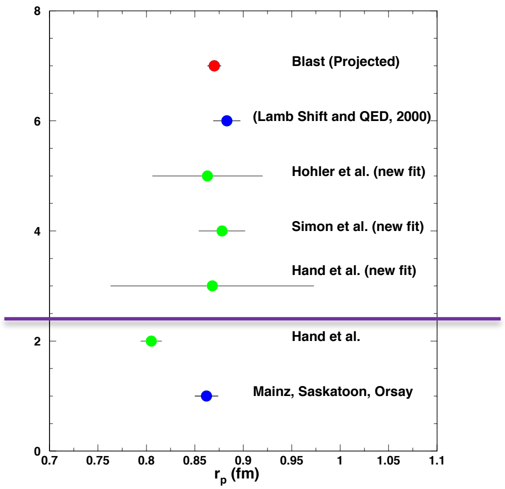
Haiyan Gao
Duke University

Duke UNIVERSITY

Outline

- Introduction
- Proton charge radius
- SIDIS@SoLID, tensor charge, and EDM
- Double polarized photodisintegration of ^{3}He and Gerasimov-Drell-Hearn (GDH) sum rule
- Summary

r_p ex
Proton charge Radius EXperiment



Home
[Pictures]
[Projects]
[Reports]
[Software]
[Target]
[Nucleon Form Factors]

Collaboration

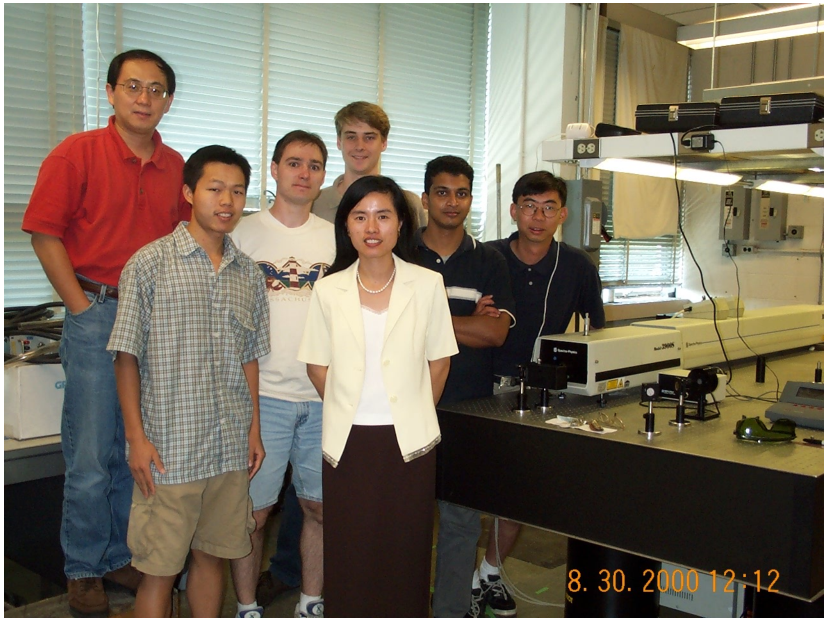
Spokespersons: Haiyan Gao, John R. Calarco
Students: Benjamin Clasie, Chris Crawford, Jason Seely
And the BLAST collaboration.

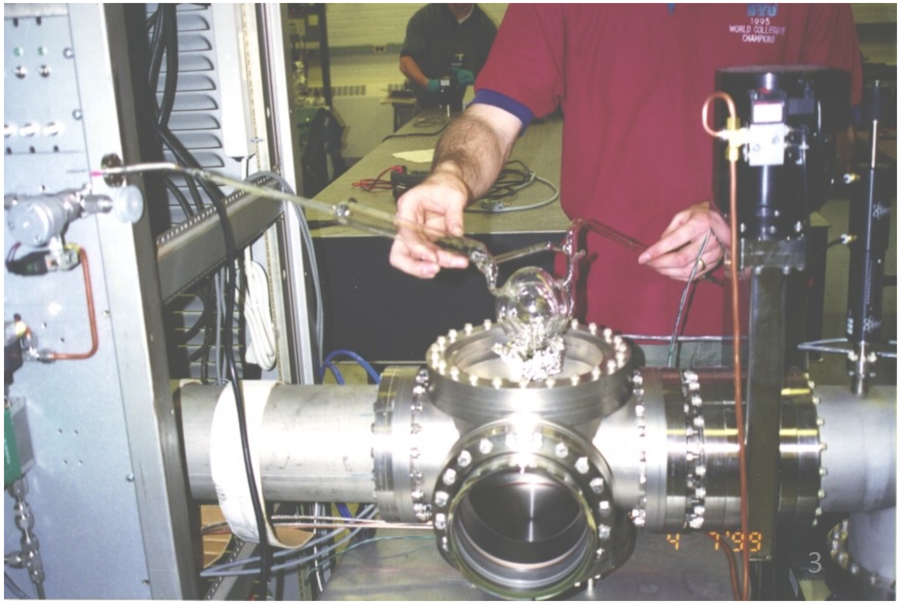
Abstract

The proton charge and current radii are fundamental quantities in physics. Precise determination of the proton charge radius is extremely important to the understanding of the proton structure in terms of quark and gluon degrees of freedom of Quantum Chromodynamics. It is also essential for high-precision tests of Quantum Electrodynamics using the hydrogen Lamb shift measurements. We propose a new precision measurement of the proton charge radius using a laser-driven polarized hydrogen internal gas target and the BLAST detector in the South Hall Ring at the MIT-Bates Laboratory. This measurement will fully utilize the unique features of the polarized internal target, polarized electron beam in the storage ring, and the BLAST large acceptance spectrometer. This measurement is expected to provide the most precise information on the proton charge radius from electron scattering, which will have significant impact on tests of QCD and QED.

The Proton Radius Experiment has been conditionally approved to run at the BATES Linear Accelerator. See the full proposal (also in Postscript).

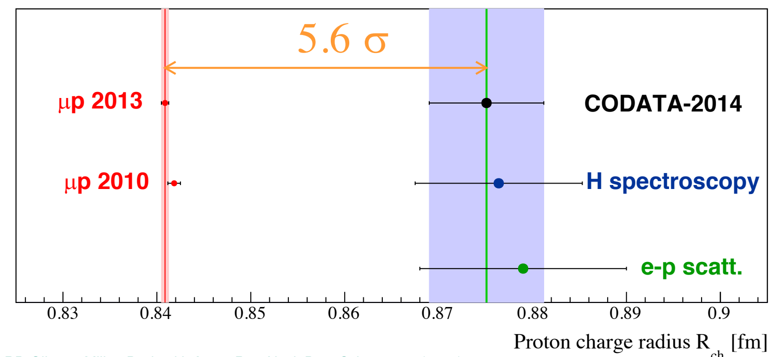
maintainer: Chris Crawford 617-253-6734
last modified: 2001 April 23





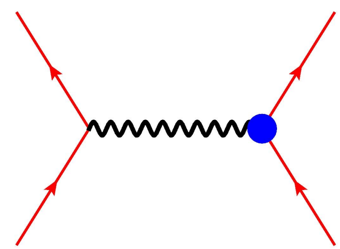
Proton Charge Radius and the puzzle

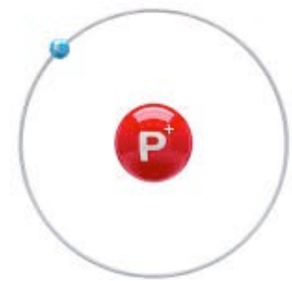
- Proton charge radius:
  1. An important quantity for proton
  2. Important for understanding how QCD works
  3. An important physics input to the bound state QED calculation, affects muonic H Lamb shift ($2S_{1/2} - 2P_{1/2}$) by as much as 2%, and critical in determining the Rydberg constant



RP, Gilman, Miller, Pachucki, Annu. Rev. Nucl. Part. Sci. 63, 175 (2013).

- Methods to measure the proton charge radius:
  1. Lepton-proton elastic scattering (nuclear physics)
     - *ep* elastic scattering (Mainz-A1, PRad,..)
     - ***μ**p* elastic scattering (MUSE, AMBER)





  2. Hydrogen spectroscopy (atomic physics)
     - Ordinary hydrogen
     - Muonic hydrogen

$$\sqrt{< r^2 >} = \sqrt{-6\frac{dG(q^2)}{dq^2}|_{q^2=0}}$$

- Important point: the proton radius measured in lepton scattering defined the same as in atomic spectroscopy (G.A. Miller, 2019)

$$\Delta E = -4\pi\alpha G'^{p}_{E}(0)|\psi_{n0}(0)|^2\delta_{l0}$$

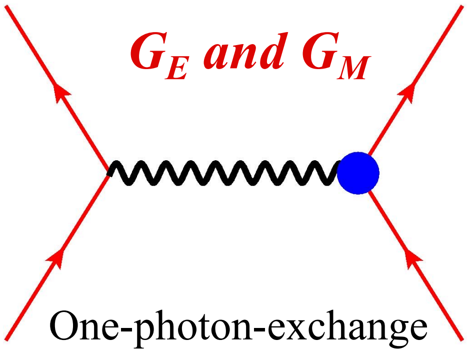
$$= 4\pi\alpha\frac{r_p^2}{6}|\psi_{n0}(0)|^2\delta_{l0}.$$

Electron-proton elastic scattering

- **Unpolarized elastic e-p cross section** ***(Rosenbluth separation)***

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \cos^2\frac{\theta}{2}}{4E^2 \sin^4\frac{\theta}{2}} \frac{E'}{E} \left(\frac{{G_E^p}^2 + \tau {G_M^p}^2}{1+\tau} + 2\tau {G_M^p}^2 \tan^2\frac{\theta}{2} \right)$$

$$= \sigma_M f_{rec}^{-1} \left(A + B \tan^2\frac{\theta}{2} \right) \qquad \tau = \frac{Q^2}{4M^2}$$

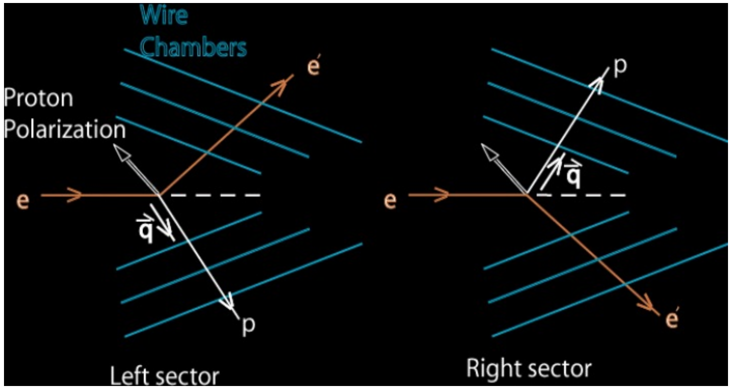


- **Recoil proton polarization measurement** ***(pol beam only)***

$$\frac{G_E^p}{G_M^p} = -\frac{P_t}{P_l} \frac{E+E'}{2M} \tan\frac{\theta}{2}$$

- **Asymmetry (super-ratio) measurement**

(pol beam and pol target)

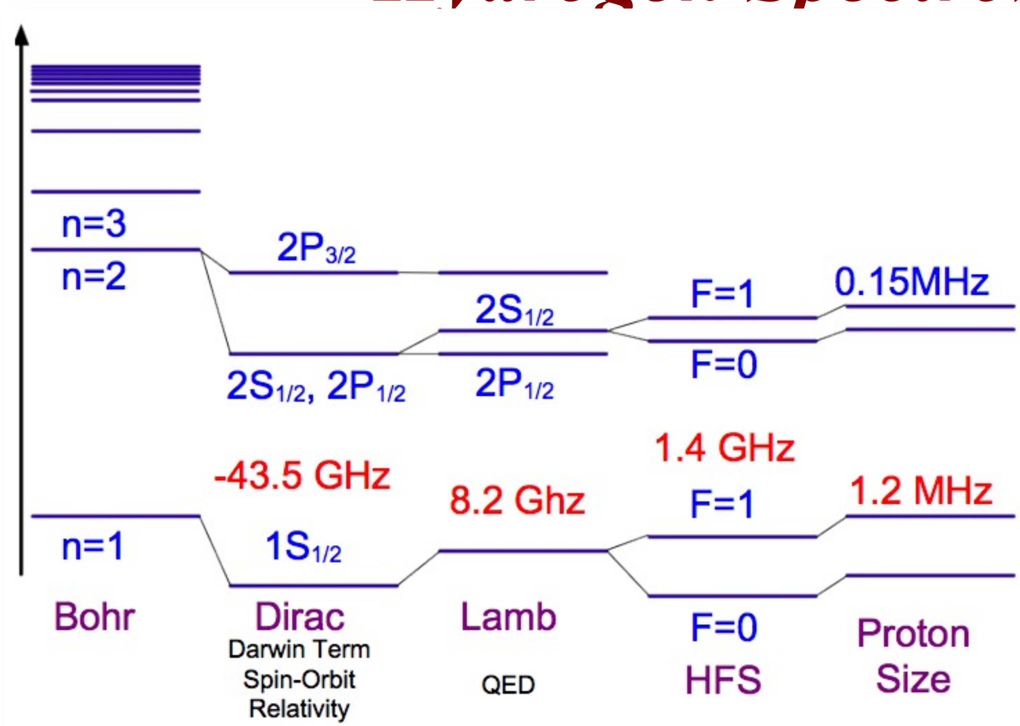


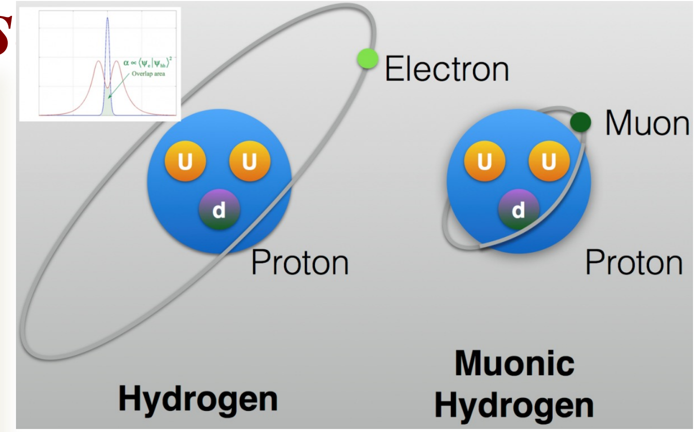
$$R_A = \frac{A_1}{A_2} = \frac{a_1 - b_1 \cdot G_E^p/G_M^p}{a_2 - b_2 \cdot G_E^p/G_M^p}$$

$$A_{exp} = P_b P_t \frac{-2\tau v_{T'} \cos\theta^* {G_M^p}^2 + 2\sqrt{2\tau(1+\tau)} v_{TL'} \sin\theta^* \cos\phi^* G_M^p G_E^p}{(1+\tau) v_L {G_E^p}^2 + 2\tau v_T {G_M^p}^2}$$

C. Crawford et al, PRL98, 052301 (2007)

Hydrogen Spectros





$$\Delta E = -4\pi\alpha G'^{p}_{E}(0)|\psi_{n0}(0)|^2\delta_{l0}$$
$$= 4\pi\alpha\frac{r_p^2}{6}|\psi_{n0}(0)|^2\delta_{l0}.$$

The absolute frequency of H energy levels has been measured with an accuracy of 1.4 part in 10^{14} via comparison with an atomic cesium fountain clock as a primary frequency standard.

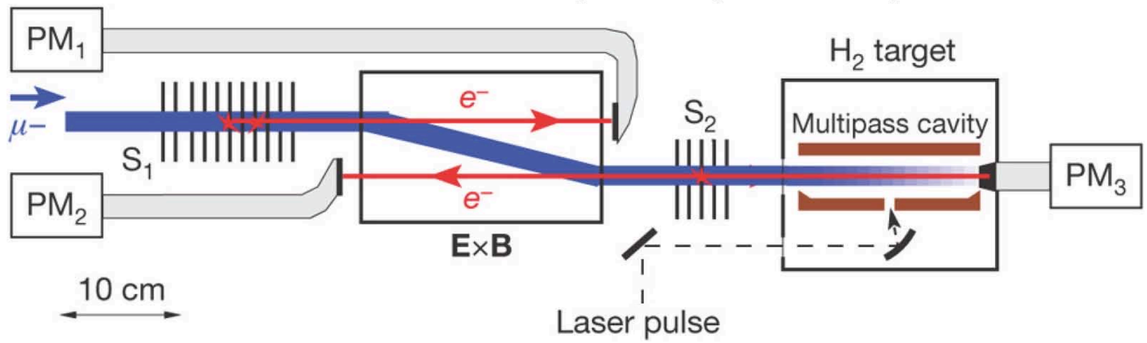
Yields Rydberg constant R_∞ (one of the most precisely known constants)

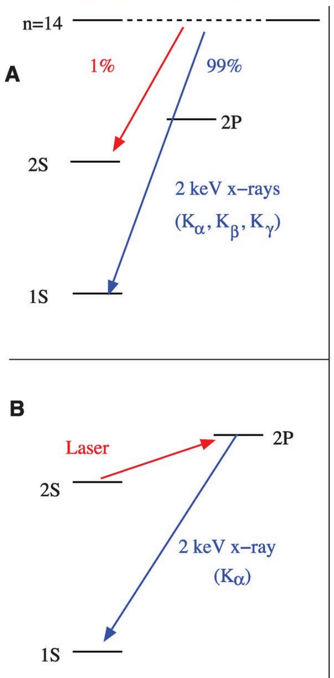
Comparing measurements to QED calculations that include corrections for the finite size of the proton can provide very precise value of the rms proton charge radius

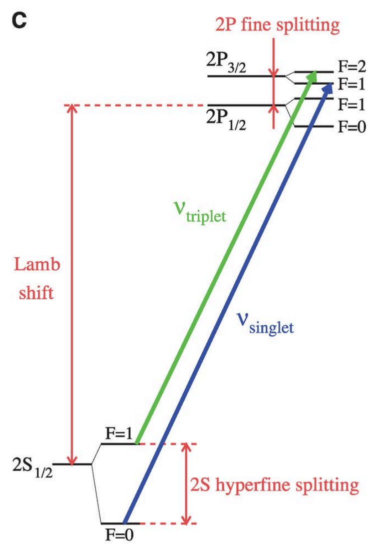
Proton charge radius effect on the muonic hydrogen Lamb shift is 2%

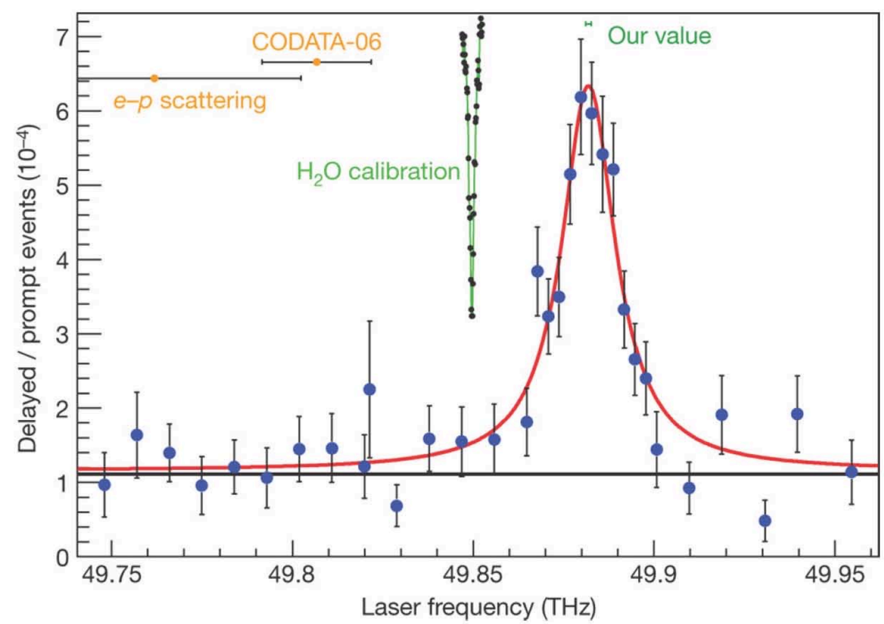
Muonic hydrogen Lamb shift at PSI (2010, 2013)

Nature **466**, 213-216 (8 July 2010)







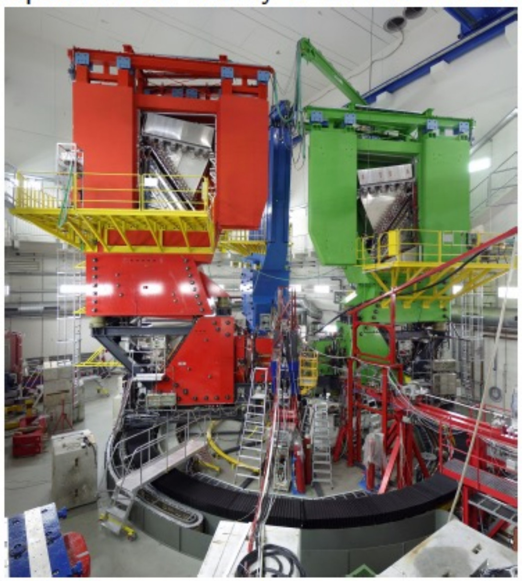


2013: $r_p = 0.84087(39)$ fm,
A. Antognini *et al*., Science 339, 417 (2013)

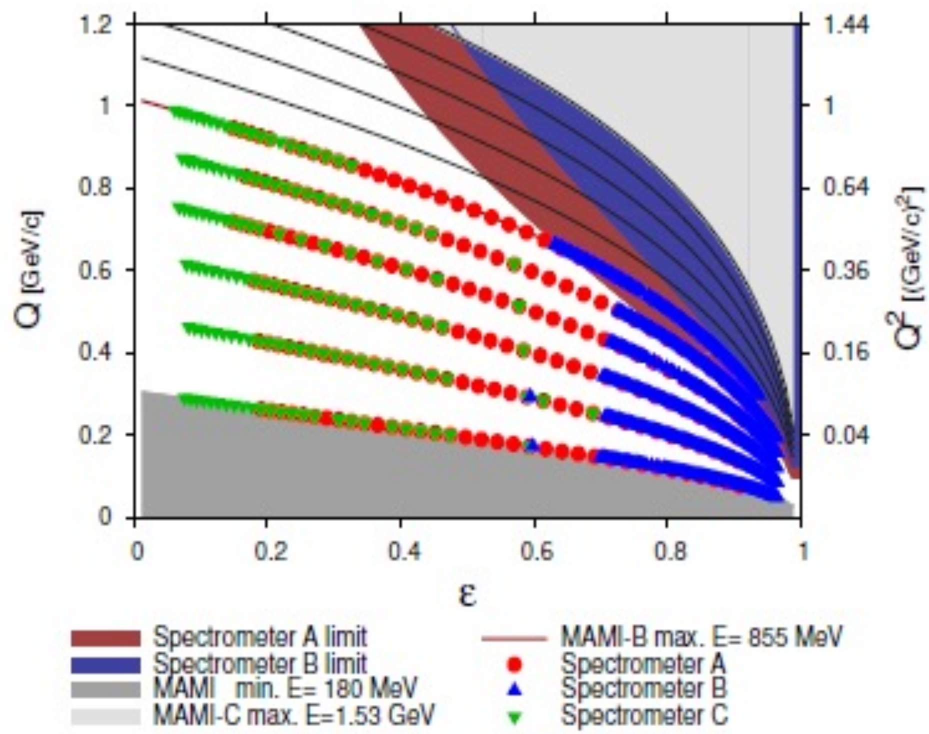
2010 value is $r_p = 0.84184(67)$ fm
R. Pohl *et al*., Nature 466, 213 (2010)

Electron-proton Scattering – Mainz A1 experiment

Three spectrometer facility of the A1 collaboration:



Measurements @ Mainz



- **Large amount of overlapping data sets**
- **Cross section measurement**
- **Statistical error ≤ 0.2%**
- **Luminosity monitoring with spectrometer**

- **$Q^2 = 0.004 – 1.0\ (GeV/c)^2$**

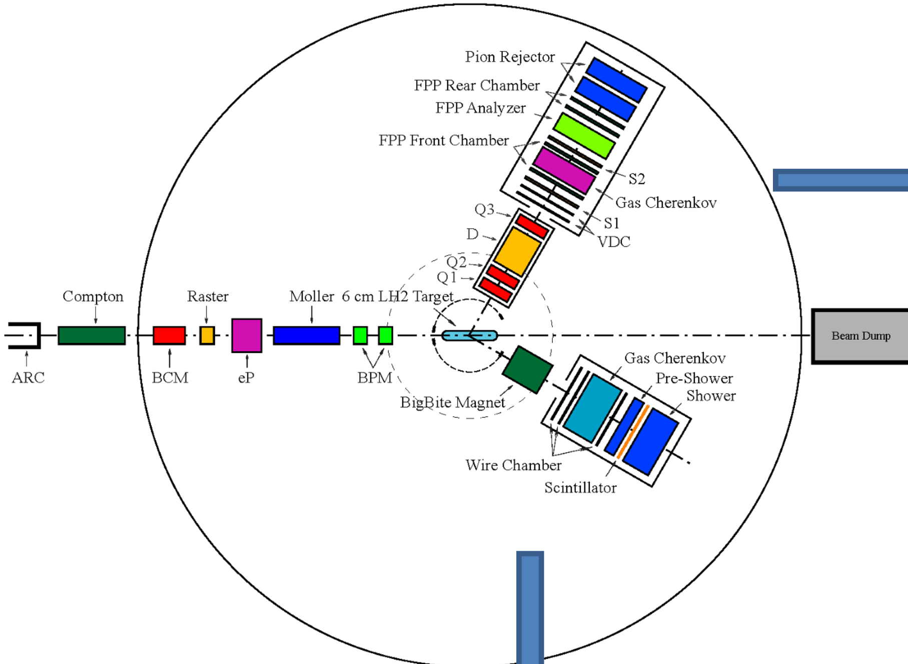
result: $r_p = 0.879(5)_{stat}(4)_{sys}(2)_{mod}(4)_{group}$

J. Bernauer, PRL 105, 242001 (2010)

5-7σ higher than muonic hydrogen result !

(J. Bernauer)

JLab Recoil Proton Polarization Experiment



LHRS

- Δp/p0: ± 4.5% ,
- out-of-plane: ± 60 mrad
- in-plane: ± 30 mrad
- ΔΩ: 6.7msr
- QQDQ
- Dipole bending angle 45°
- VDC+FPP
- P_p : 0.55 ~ 0.93 GeV/c

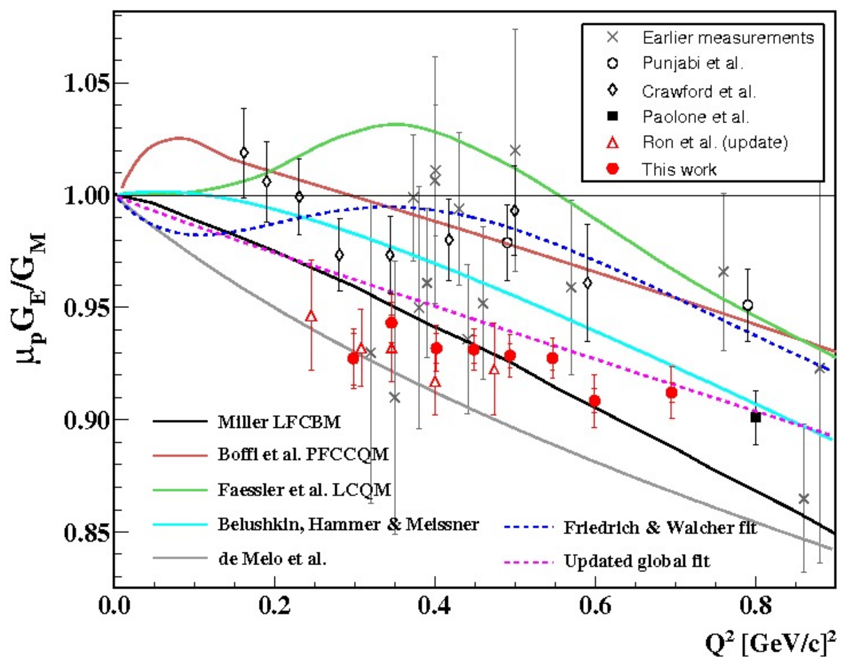
- **$Q^2 = 0.3 – 0.7\ (GeV/c)^2$**
- **$r_p = 0.875 \pm 0.010$ fm**

(global analysis not including Mainz A1)

BigBite

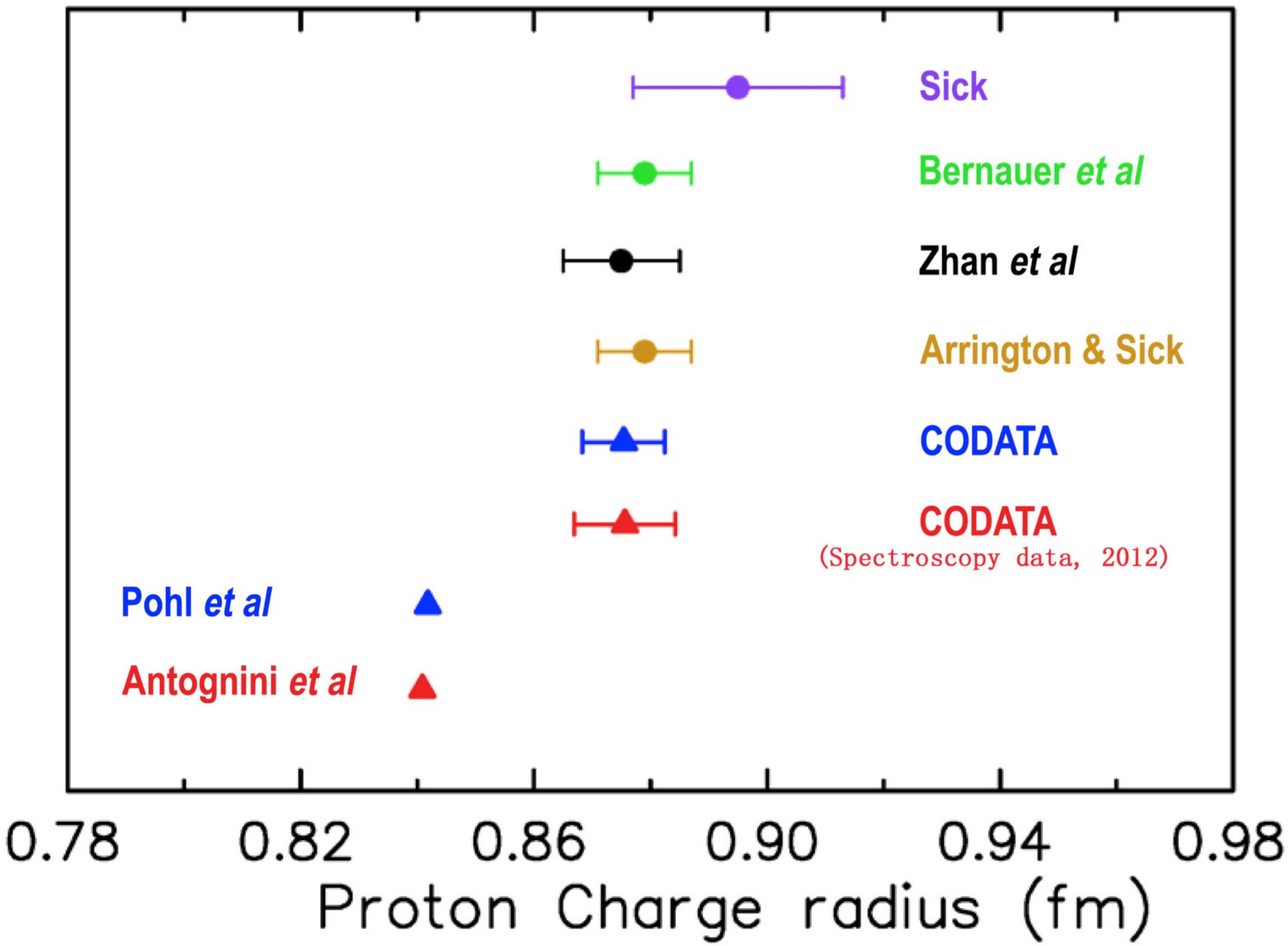
- Non-focusing Dipole
- Big acceptance.
  - Δp: 200-900MeV
  - ΔΩ: 96msr
- PS + Scint. + SH

E_e: 1.192GeV
P_b: ~83%



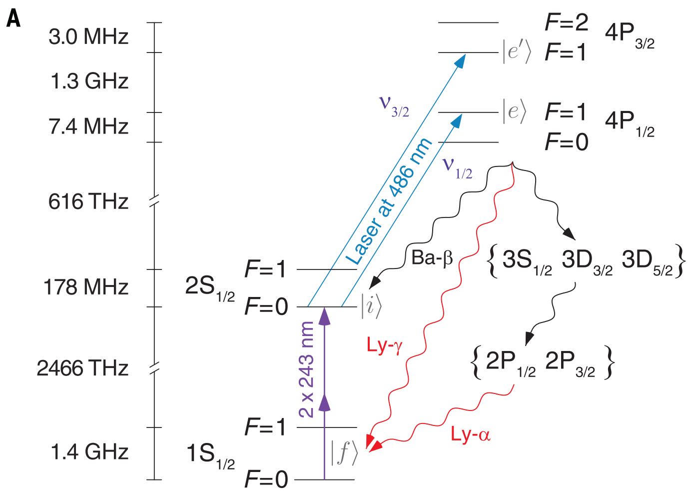
X. Zhan et al. Phys. Lett. B 705 (2011) 59-64

The situation on the Proton Charge Radius in 2013

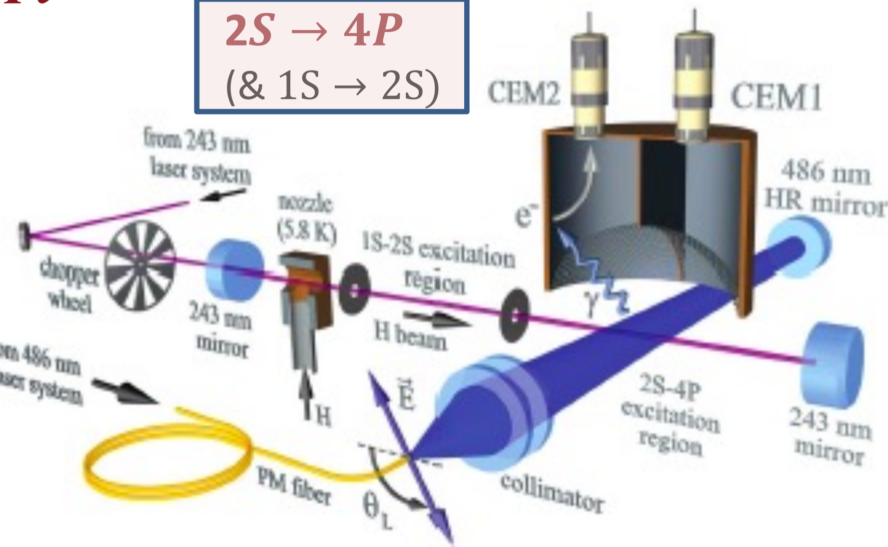


This proton charge radius puzzle triggered intensive experimental and theoretical efforts worldwide in the last decade or so

Ordinary hydrogen spectroscopy



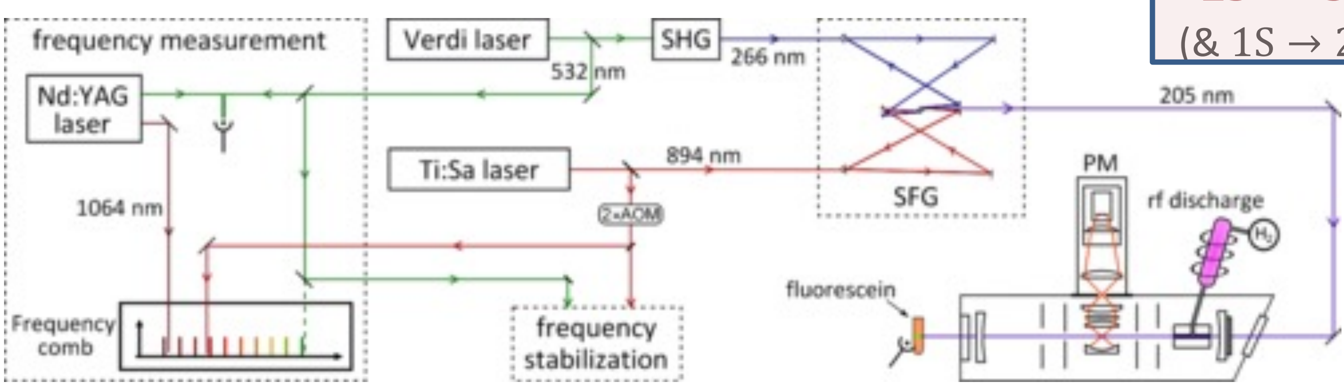
2S → 4P
(& 1S → 2S)



$R_\infty = 10\,973\,731.568\,076(96)\ \mathrm{m}^{-1}, r_p = 0.8335(95)$ fm

Beyer *et al.*, Science 358, 79 (2017)

1S → 3S
(& 1S → 2S)

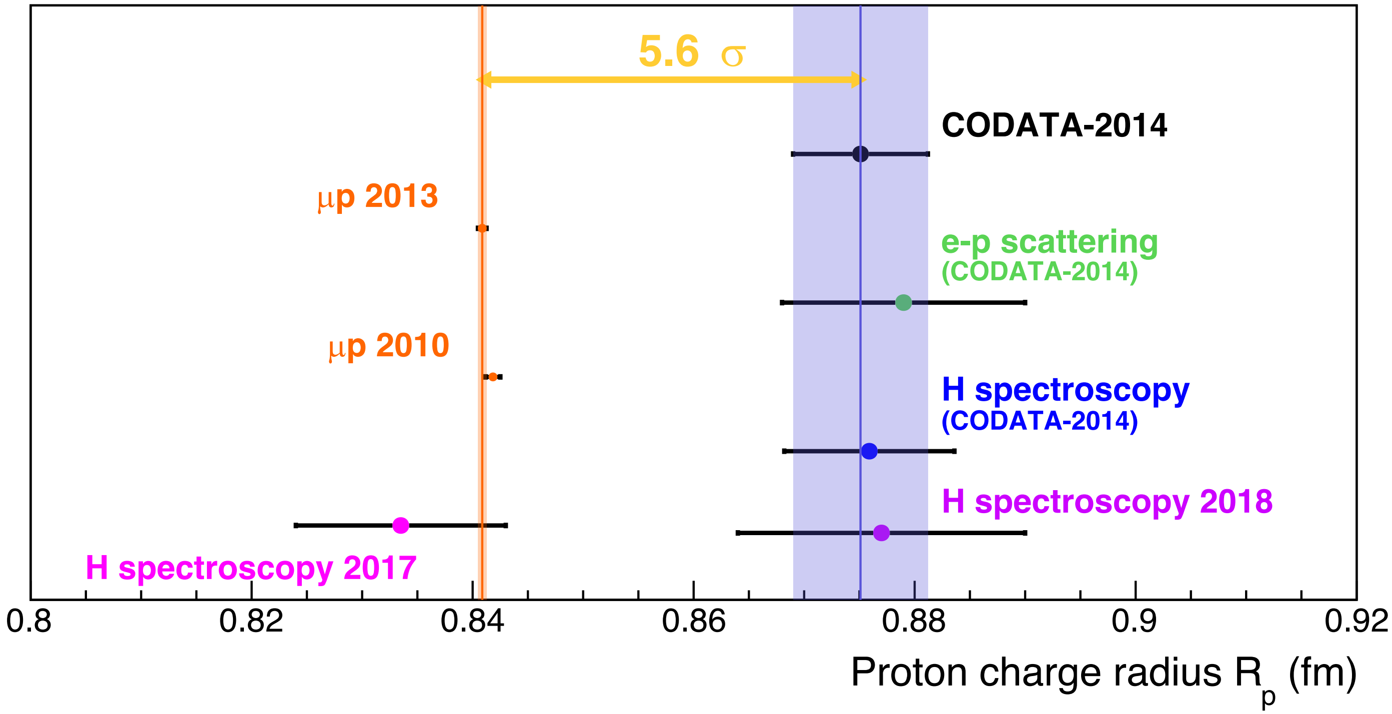


$R_\infty = 10\,973\,731.568\,53(14)\ \mathrm{m}^{-1}, r_p = 0.877(13)$ fm

Fleurbaey *et al.* PRL 120, 183001 (2018)

Parthey *et al.*, PRL 107, 203001 (2011)
Matveev *et al.* PRL 110, 230801 (2013)

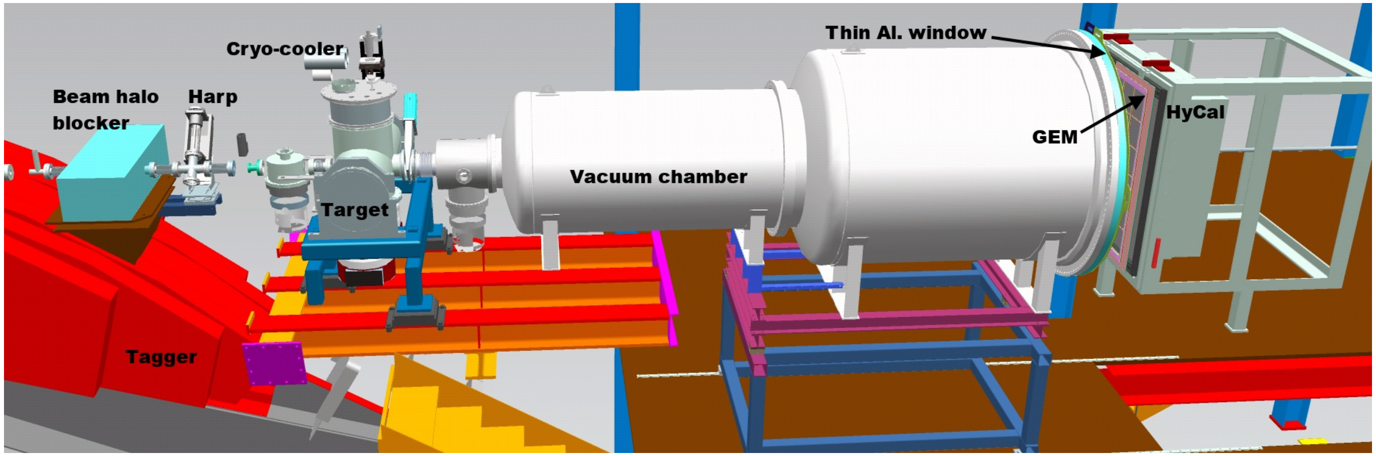
The Proton Charge Radius Puzzle in 2018

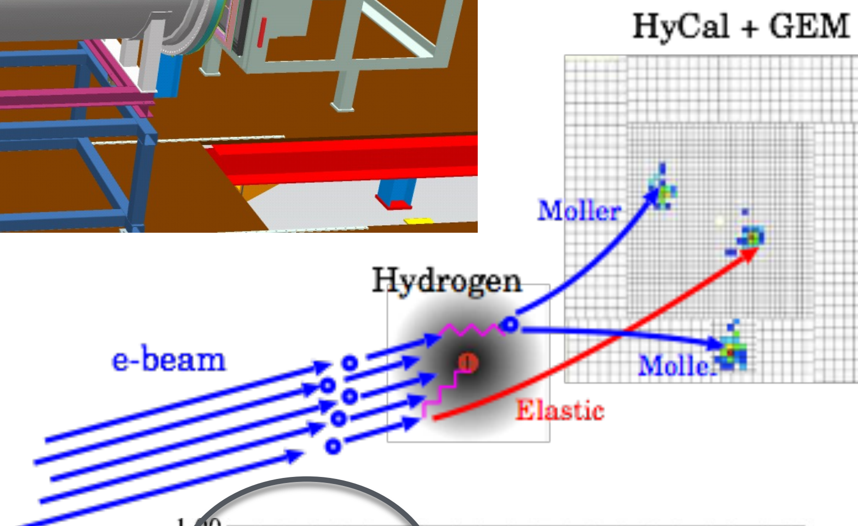


Electron scattering: 0.879 ± 0.011 fm (CODATA 2014)
Muon spectroscopy: 0.8409 ± 0.0004 fm (CREMA 2010, 2013)
H spectroscopy (2017): 0.8335 ± 0.0095 fm (A. Beyer et al. Science 358(2017) 6359)
H spectroscopy (2018): 0.877 ± 0.013 fm (H. Fleurbaey et al. PRL.120(2018) 183001)

Not shown: ep scattering (ISR, 2017): 0.810 ± $0.035_{stat.}$ $\pm 0.074_{syst.}$ ±0.003 (delta_a, delta_b) (Mihovilovic PLB 771 (2017); 0.878 ± $0.011_{stat.}$ $\pm 0.031_{syst.}$ $\pm 0.002_{mod}$. (Mihovilovic 2021))

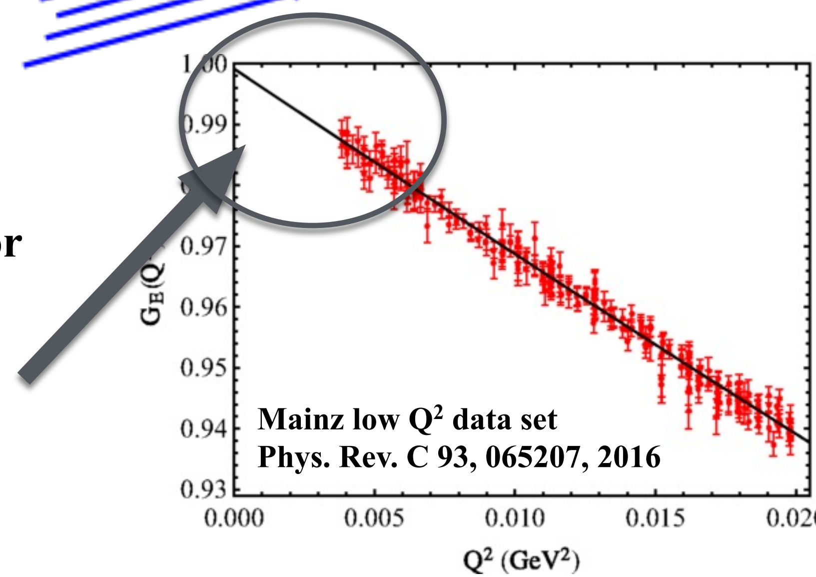
The *PRad Experiment in Hall B at JLab*





- High resolution, large acceptance, hybrid HyCal calorimeter (PbWO$_4$ and Pb-Glass)
- Windowless H_2 gas flow target
- Simultaneous detection of elastic and Moller electrons
- Q^2 range of $2x10^{-4}$ – 0.06 GeV^2
- XY – veto counters replaced by GEM detector
- Vacuum chamber

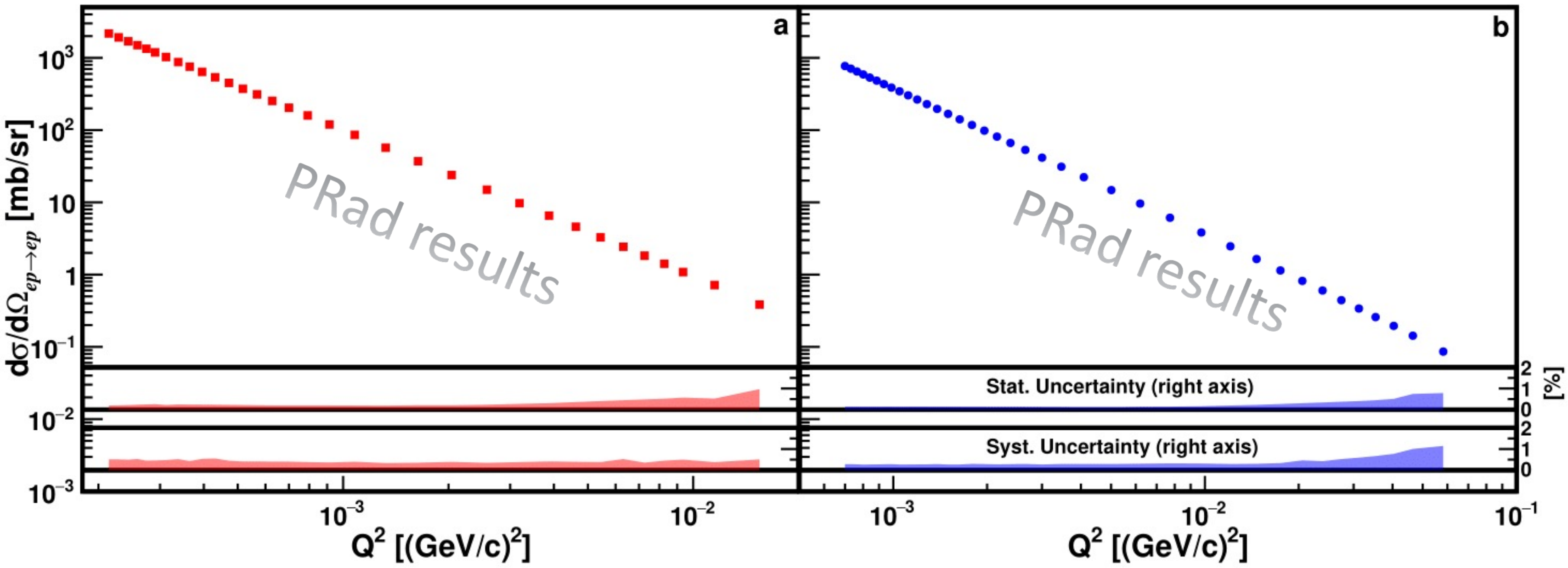
Spokespersons: A. Gasparian (contact), H. Gao, D. Dutta, M. Khandaker



I. Larin, Y. Zhang *et al.*, Science 6490, 506 (2020)

Elastic ep Cross Sections

- Differential cross section v.s. Q^2, with 2.2 and 1.1 GeV data
- Statistical uncertainties: ~0.15% for 2.2 GeV, ~0.2% for 1.1 GeV per point
- Systematic uncertainties: 0.3%~1.1% for 2.2 GeV, 0.3%~0.5% for 1.1 GeV (shown as shadow area)



Systematic uncertainties shown as bands

Xiong et al., Nature 575, 147–150 (2019)

Proton Electric Form Factor G'_E (Normalized)

- n_1 and n_2 obtained by fitting PRad G_E to

$$\begin{cases} n_1 f(Q^2), & \text{for 1GeV data} \\ n_2 f(Q^2), & \text{for 2GeV data} \end{cases}$$

Using rational (1,1)

$$f(Q^2) = \frac{1 + p_1 Q^2}{1 + p_2 Q^2}$$

- G'_E as normalized electric Form factor:

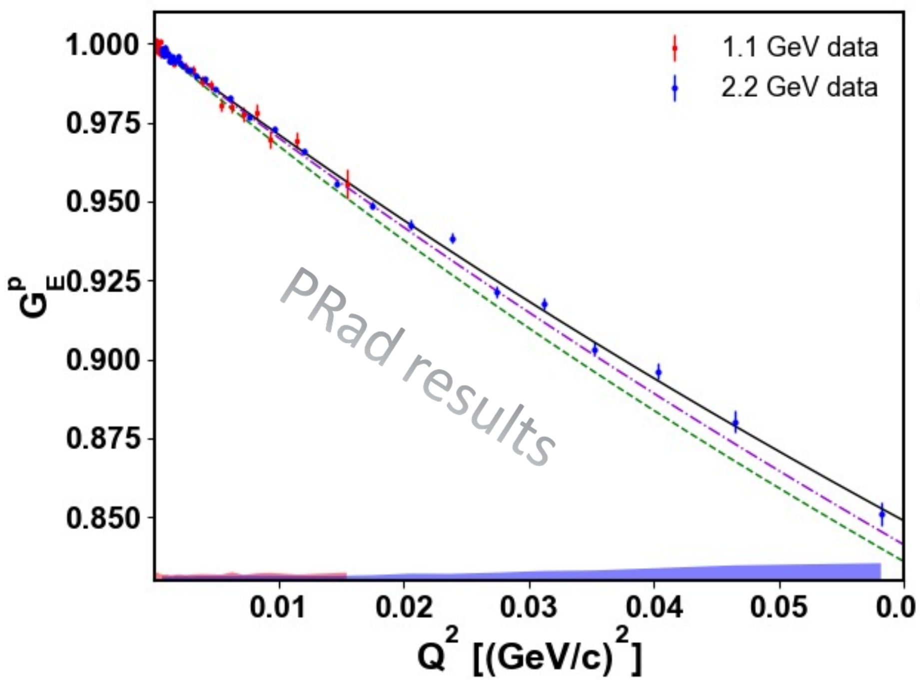
$$\begin{cases} G_E/n_1, & \text{for 1GeV data} \\ G_E/n_2, & \text{for 2GeV data} \end{cases}$$

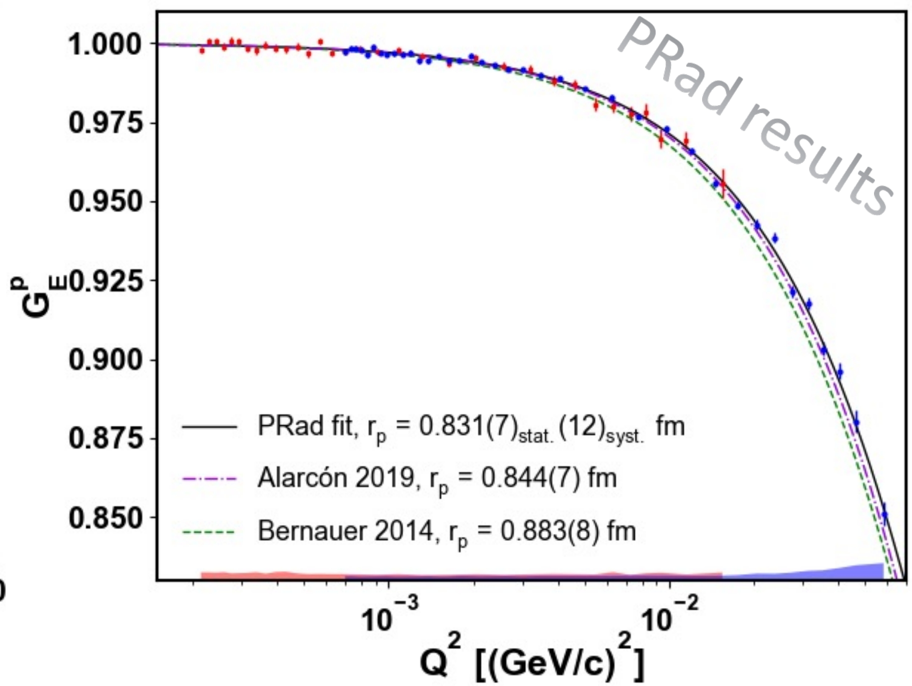
Yan et al., PRC 98, 025204 (2018)

- PRad fit shown as $f(Q^2)$

r_p = 0.831 +/- 0.007 (stat.) +/- 0.012 (syst.) fm

Xiong et al., Nature 575, 147–150 (2019)

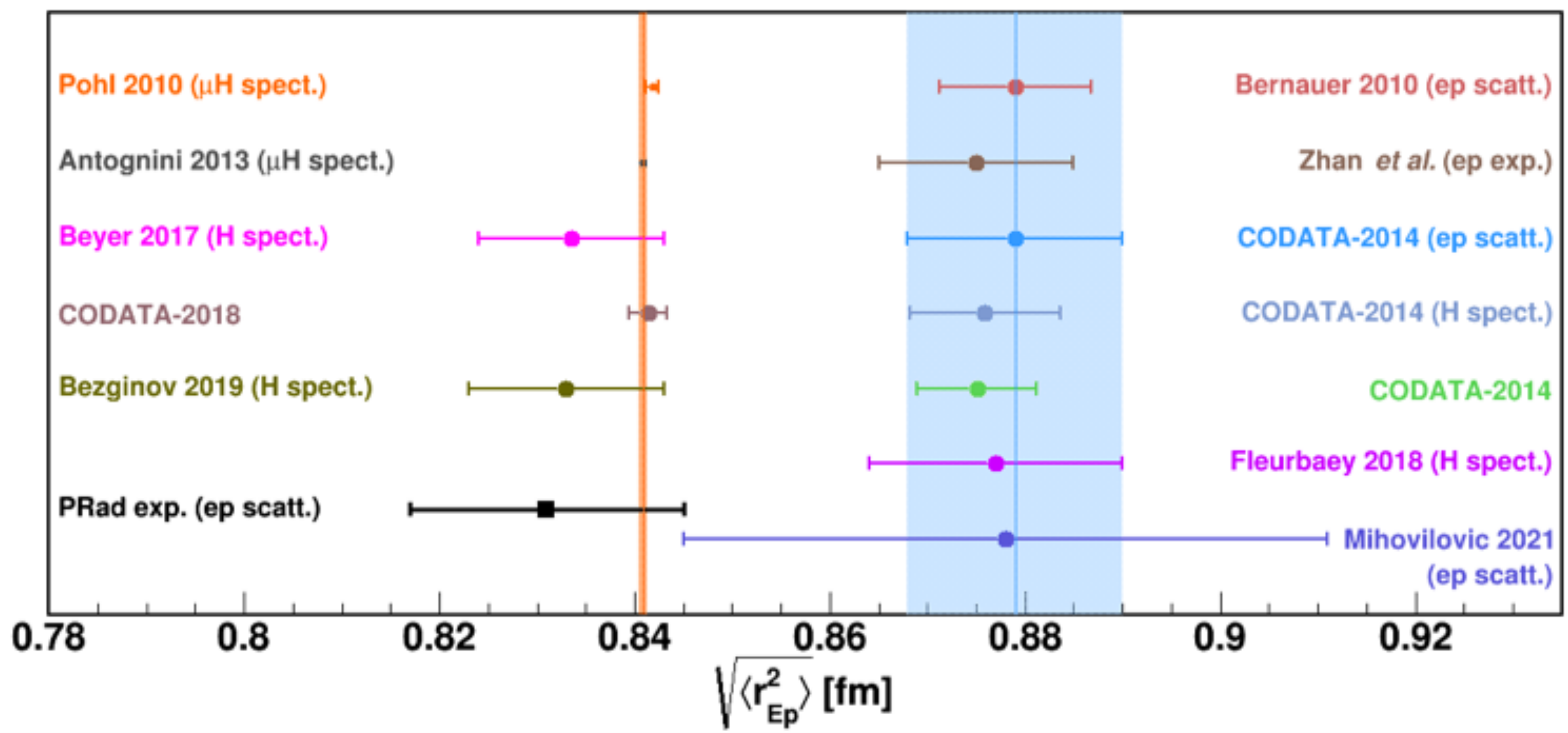




n_1 = 1.0002 +/- 0.0002(stat.) +/- 0.0020 (syst.),
n_2 = 0.9983 +/- 0.0002(stat.) +/- 0.0013 (syst.)

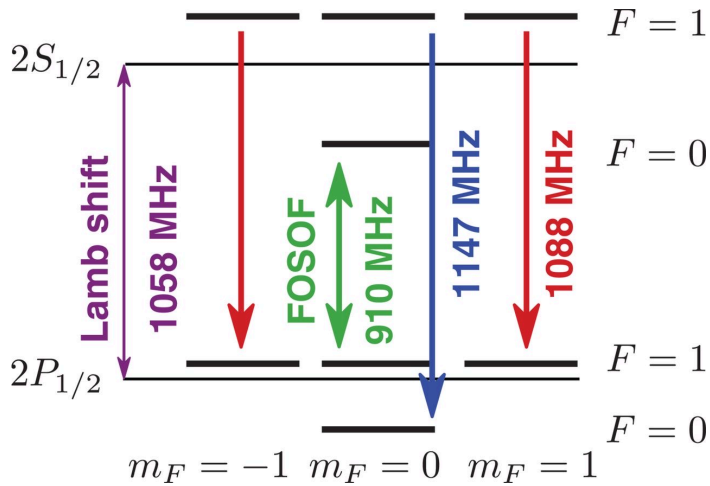
Proton radius at the time of PRad publication

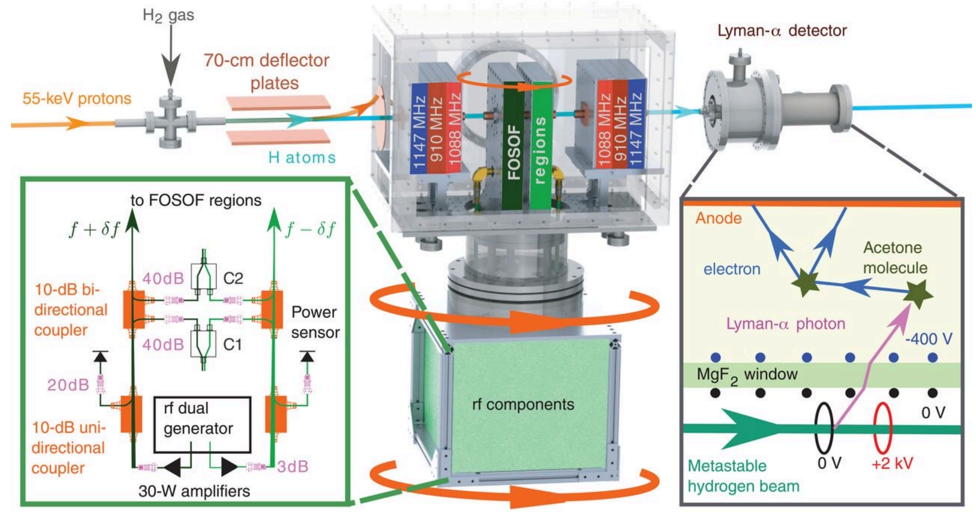
- PRad result r_p : 0.831 +/- 0.0127 fm, *Xiong et al., Nature 575, 147–150 (2019)*
- H Lamb Shift: 0.833 +/- 0.010 fm, Bezginov *et al., Science* **365**, 1007-1012 (2019)
- CODATA 2018 value of r_p: 0.8414 +/- 0.0019 fm, *E. Tiesinga et al., RMP 93, 025010(2021)*



CODATA has also shifted the value of the Rydberg constant.

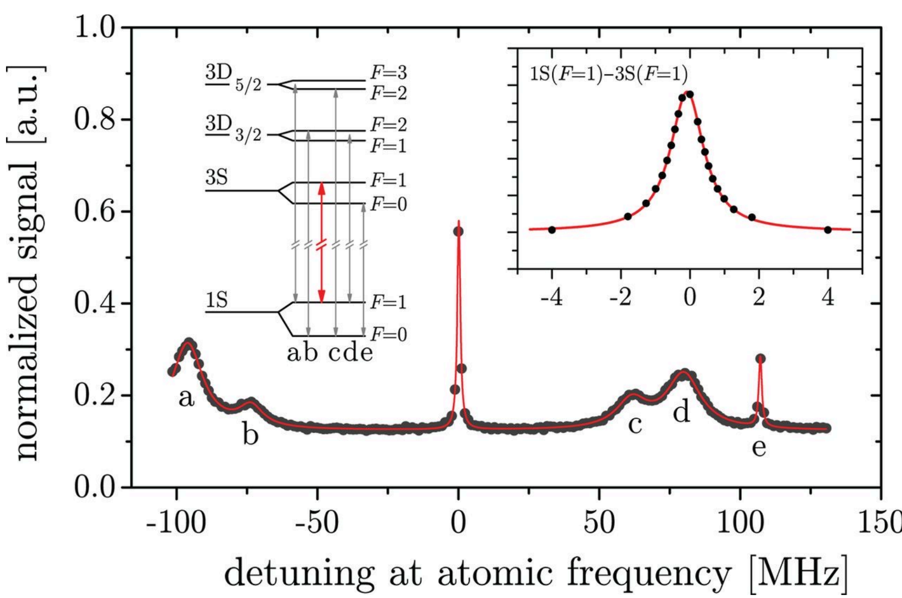
More from ordinary hydrogen spectroscopy

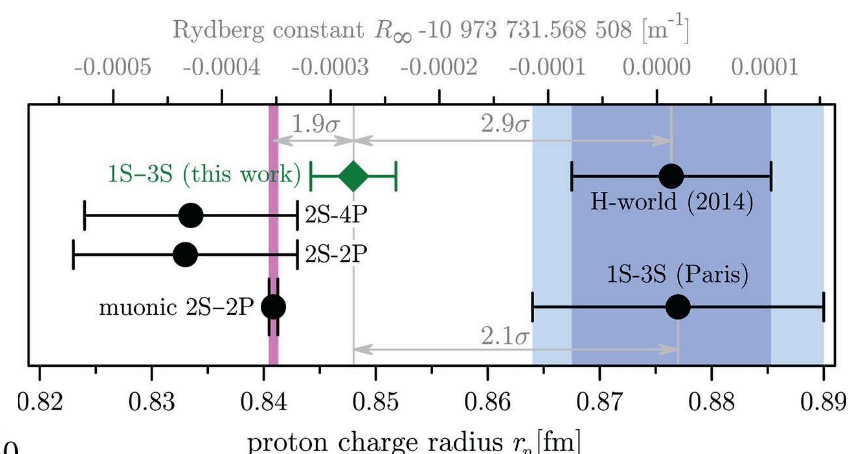




Bezginov *et al*., Science 365, 1007 (2019)

r_p = 0.833(10) fm

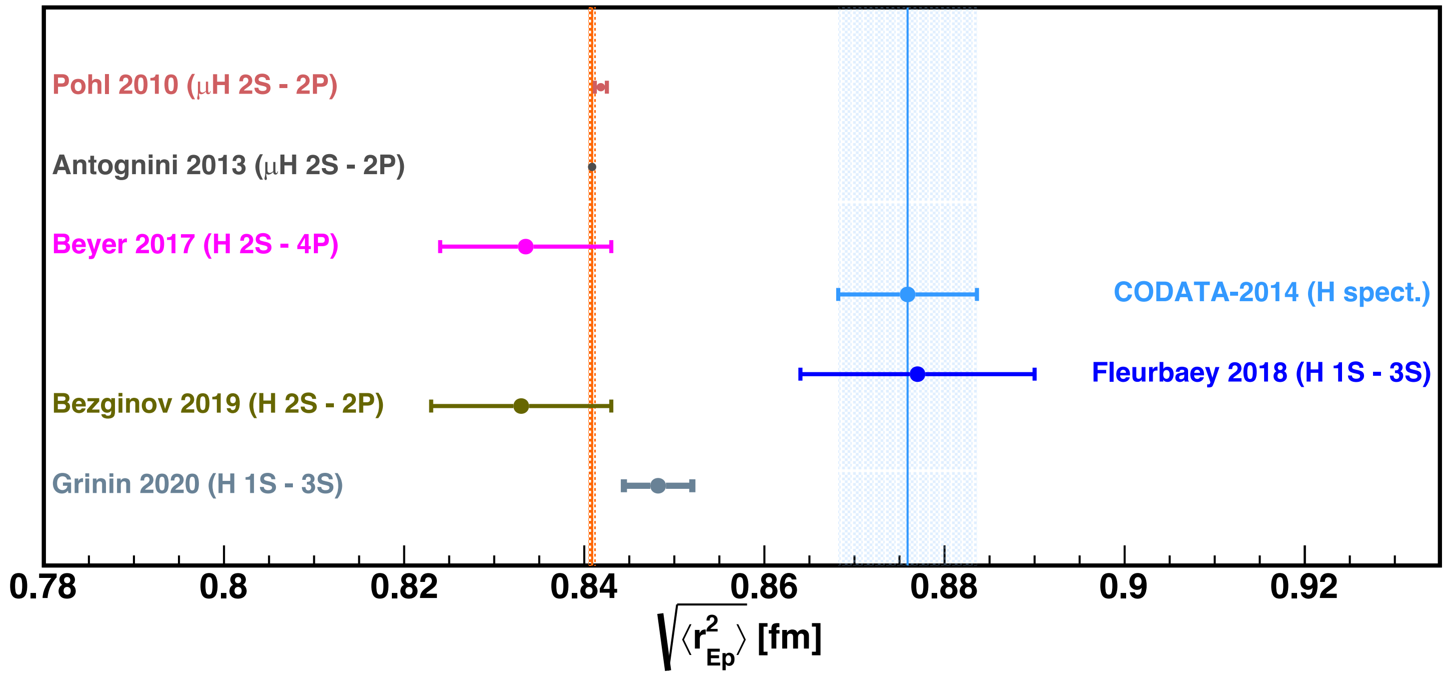




Grinin *et al*., Science 370, 1061 (2020)

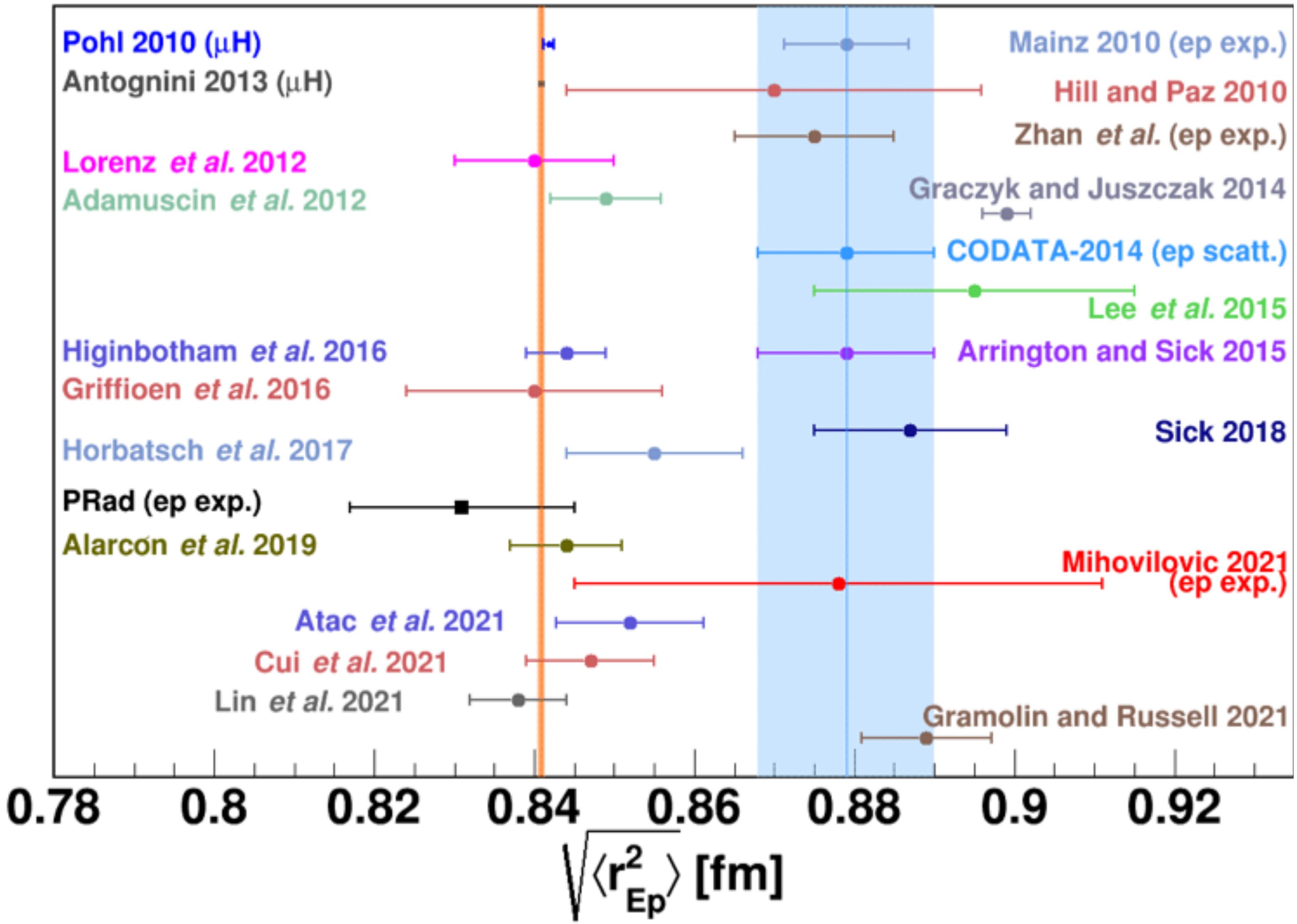
r_p = 0.8482(38) fm

Proton radius from ordinary and muonic H spectroscopy



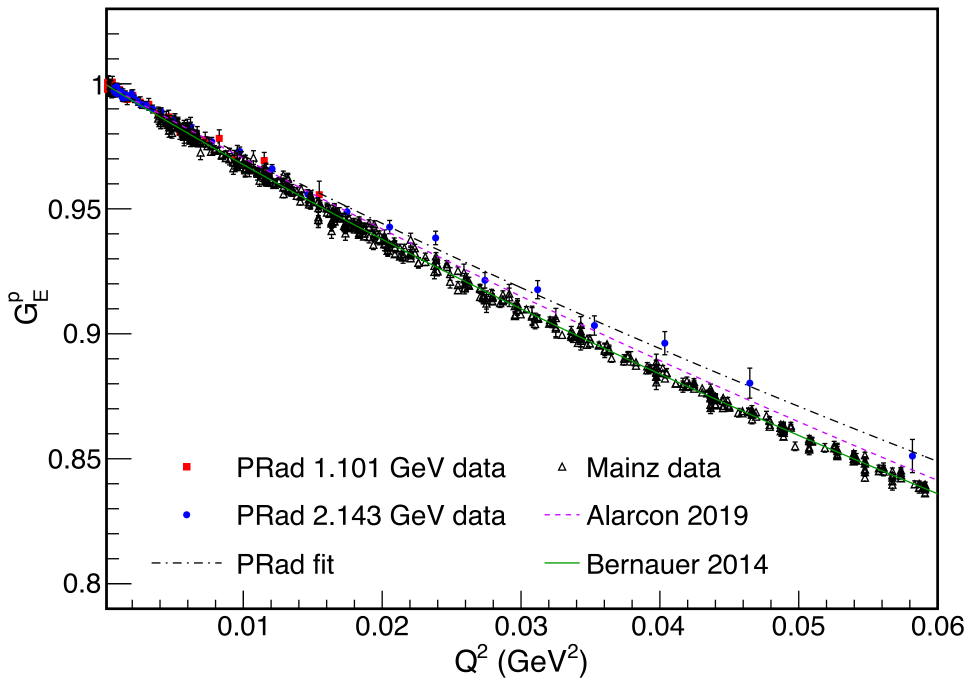
Experiment	Type	Transition(s)	$\sqrt{< r^2_{Ep} >}$ (fm)	r_∞ (m^{-1})
Pohl 2010	μH	$2S^{F=1}_{1/2} - 2P^{F=2}_{3/2}$	0.84184(67)	
Antognini 2013	μH	$2S^{F=1}_{1/2} - 2P^{F=2}_{3/2}$	0.84087(39)	
		$2S^{F=0}_{1/2} - 2P^{F=1}_{3/2}$		
Beyer 2017	H	$2S - 4P$	0.8335(95)	10 973 731.568 076 (96)
		with $(1S - 2S)$		
Fleurbaey 2018	H	$1S - 3S$	0.877(13)	10 973 731.568 53(14)
		with $(1S - 2S)$		
Bezginov 2019	H	$2S_{1/2} - 2P_{1/2}$	0.833(10)	
Grinin 2020	H	$1S - 3S$	0.8482(38)	10 973 731.568 226(38)
		with $(1S - 2S)$		

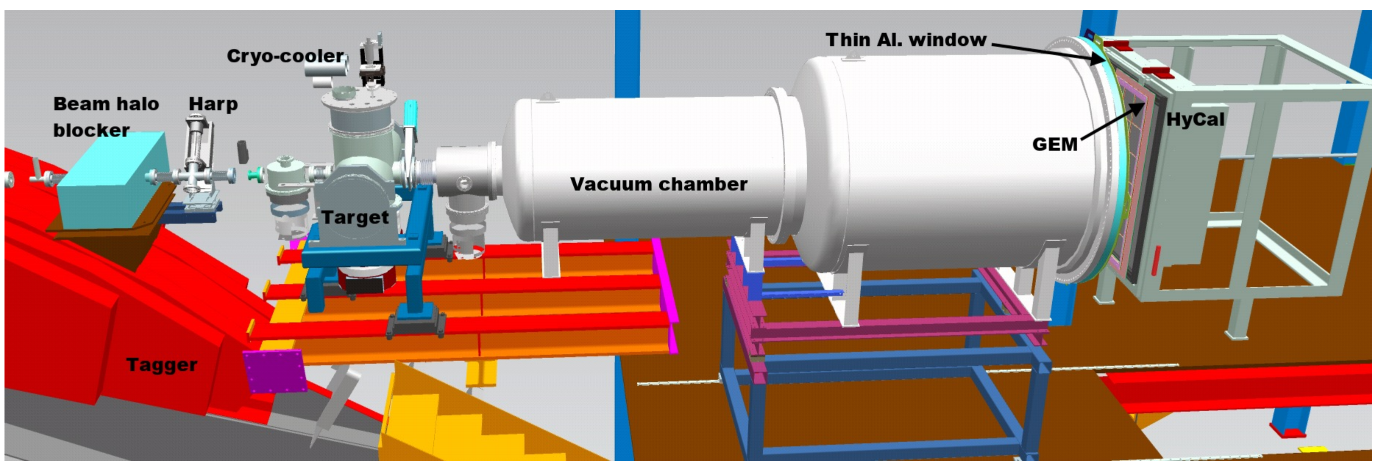
(Re)analyses of e-p scattering data



Gao and Vanderhaeghen, arXiv:2105.00571
(to appear in RMP)

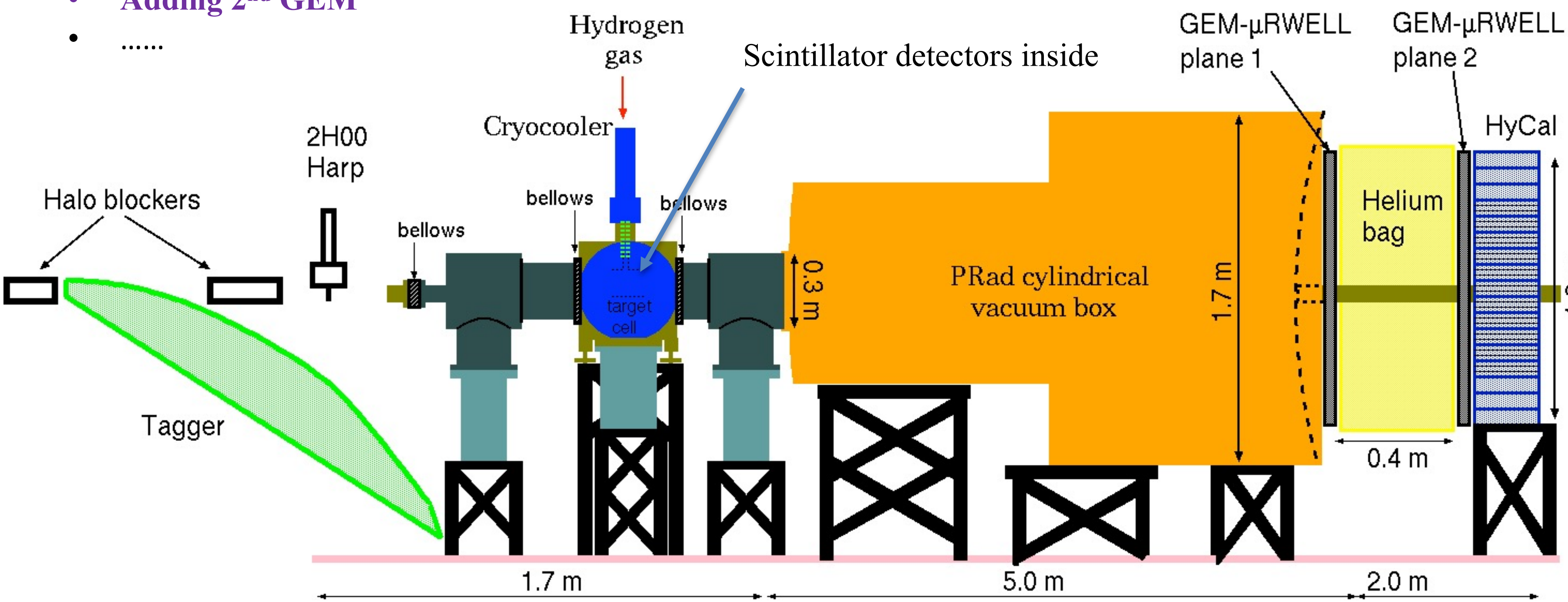
e-p scattering: magnetic spectrometer and calorimetric method

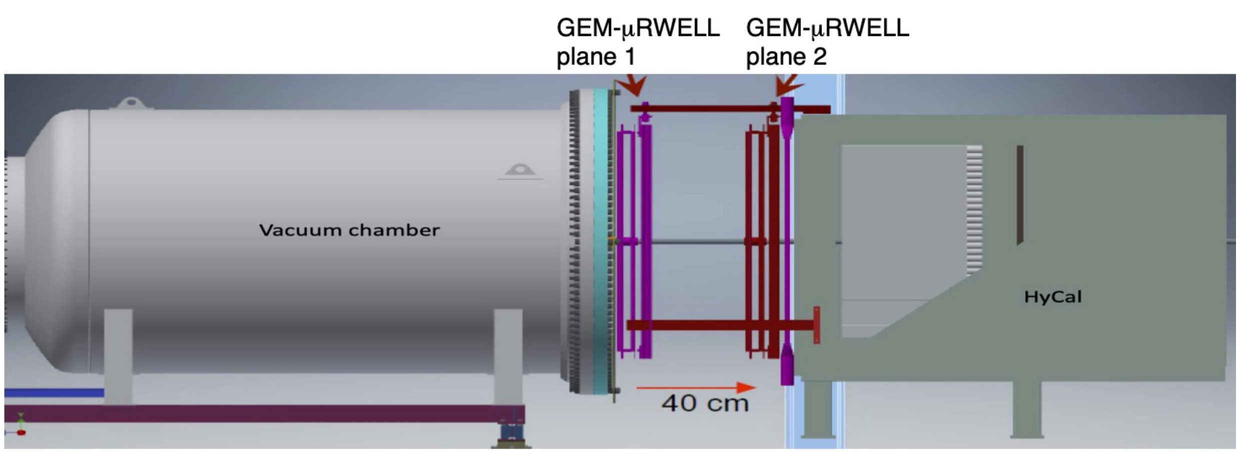


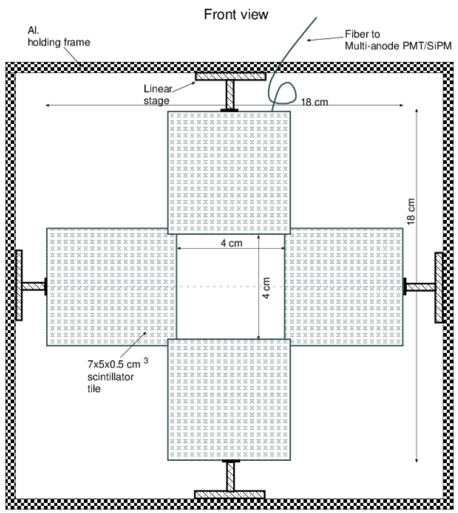


PRad-II Experimental Setup (Side View)

- **Upgrade HyCal**
- **Adding 2nd GEM**
- ……

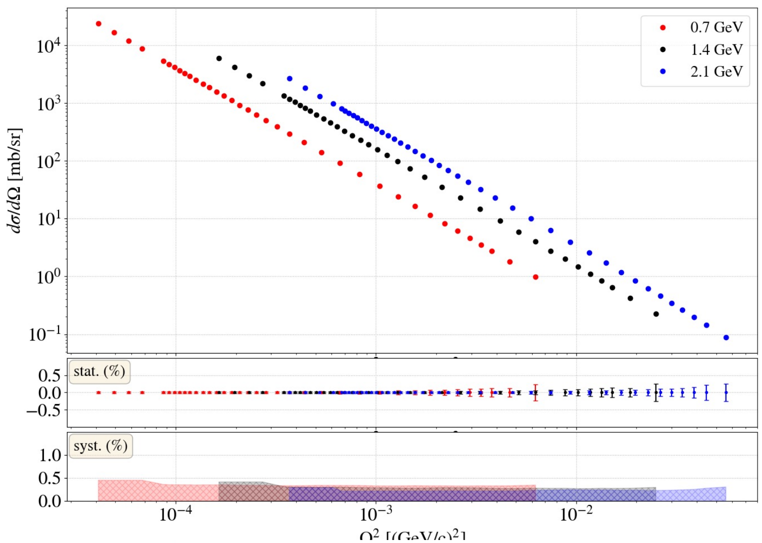




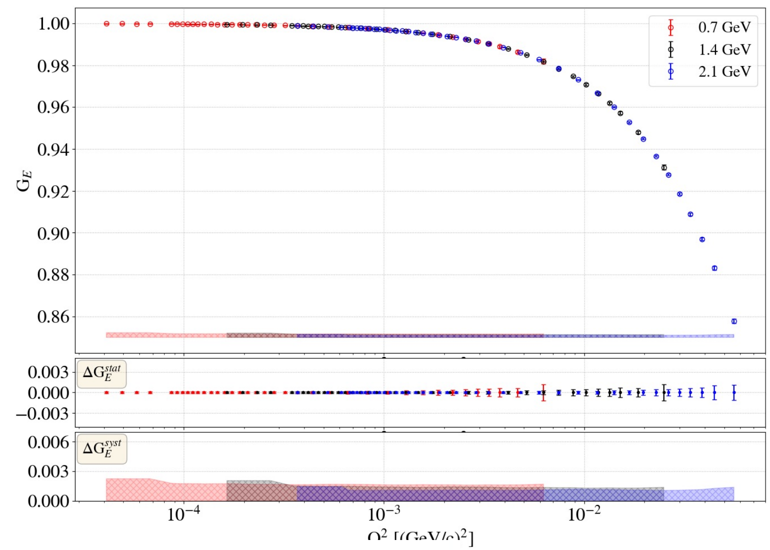


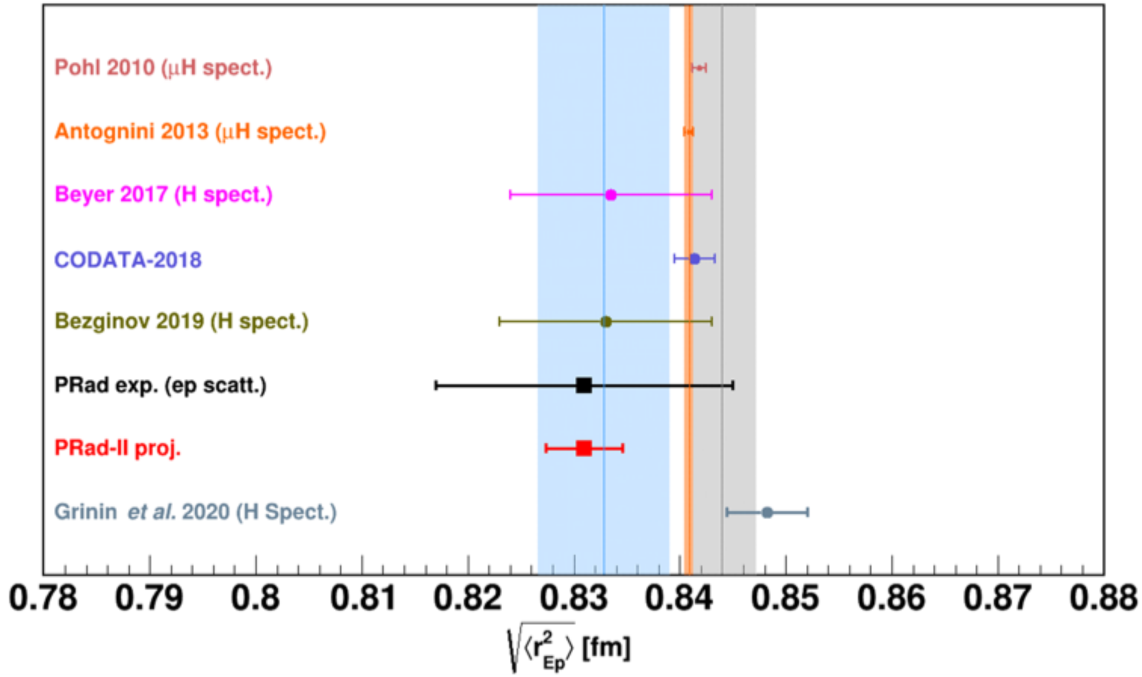
Projections for PRad-II

Differential Cross section



Electric form factor

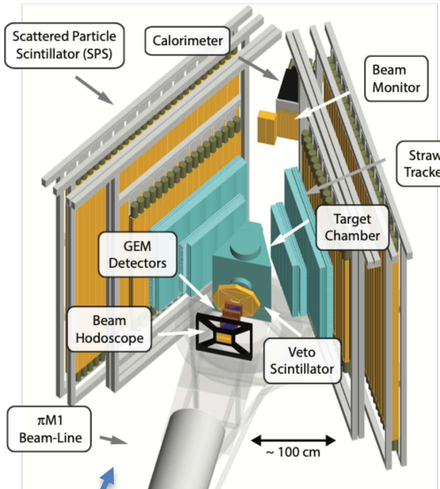


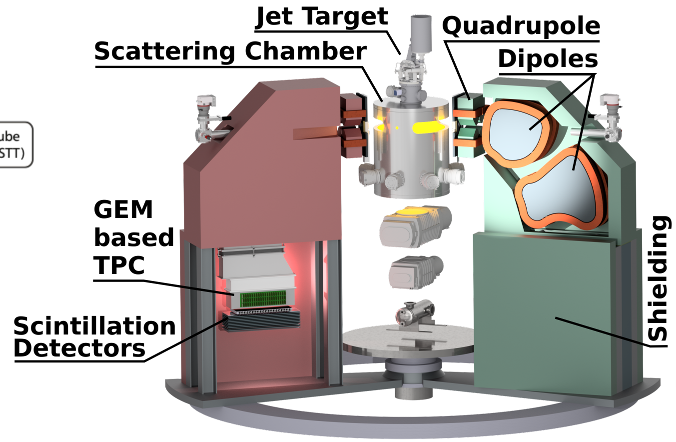


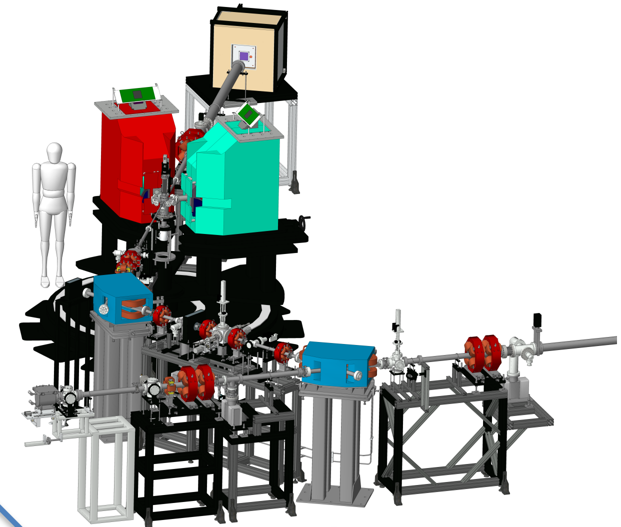
PRad-II goal: 0.0036 fm

Gasparian *et al.* arXiv:2009.10510

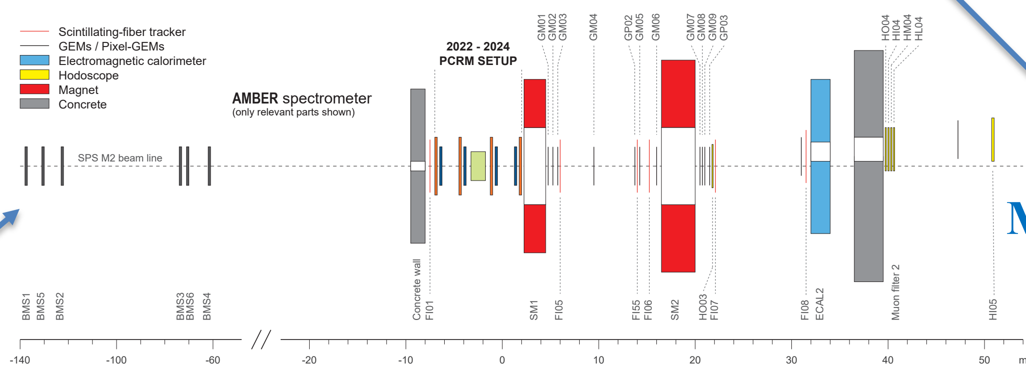
Ongoing and Future Experiments







MUSE

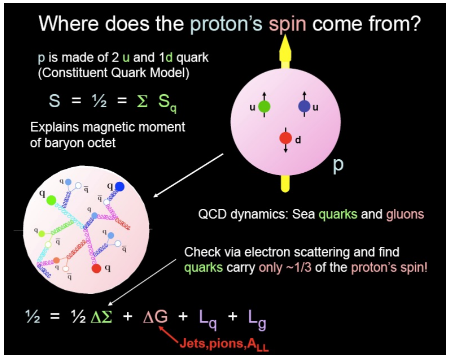


MAGIX@MESA

ULQ²

AMBER

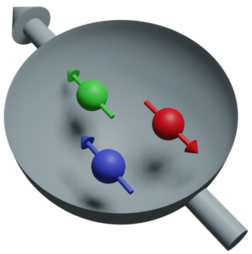
Experiment	Beam	Laboratory	Q^2 $(\mathrm{GeV/c})^2$	δr_p (fm)	Status
MUSE	$e^{\pm}$, $\mu^{\pm}$	PSI	0.0015 - 0.08	0.01	Ongoing
AMBER	$\mu^{\pm}$	CERN	0.001 - 0.04	0.01	Future
PRad-II	e^-	Jefferson Lab	4×10^{-5} - 6×10^{-2}	0.0036	Future
PRES	e^-	Mainz	0.001 - 0.04	0.6% (rel.)	Future
A1@MAMI (jet target)	e^-	Mainz	0.004 - 0.085		Ongoing
MAGIX@MESA	e^-	Mainz	$\geq 10^{-4} - 0.085$		Future
ULQ²	e^-	Tohoku University	3×10^{-4} - 8×10^{-3}	$\sim 1\%$ (rel.)	Future

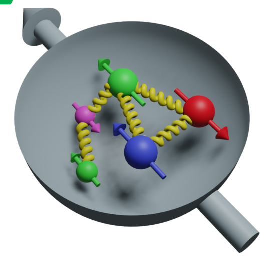


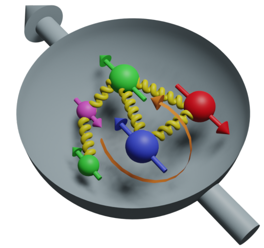
The nucleon spin puzzle

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + (L_q + L_g)$$

Jaffe-Manohar, 90
Ji, 96
Chen et al., 08
Wakamatsu, 11, …







Quark helicity
Best known

$$\frac{1}{2}\int dx\,(\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s})$$

$$\sim 30\%$$

Gluon helicity
Start to know

$$\Delta G = \int dx \Delta g(x)$$

~40% -- RHIC Spin data at Q^2 = 10 GeV^2

Orbital Angular Momentum of quarks and gluons
Little known

Net effect of partons' transverse motion?

With larger uncertainty →

Lattice QCD →

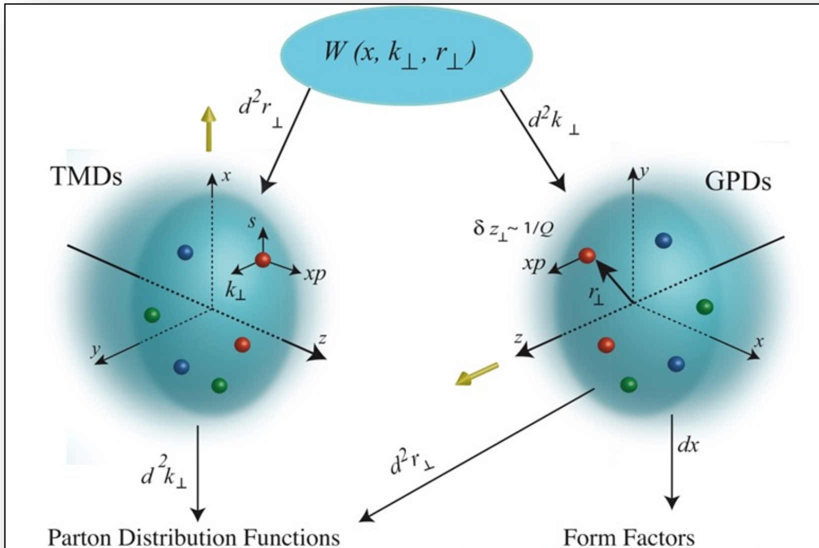
$$L_{u+d+s} = 0.207(64)_{stat}(45)_{syst}$$
$$J_{u+d+s} = 0.408(61)_{stat}(48)_{syst}$$
$$J_g = 0.133(11)_{stat}(14)_{syst}$$

$$J_N = 0.54(6)_{stat}(5)_{syst}$$
(MS = 2 GeV)

C. Alexandrou et al., PRL 119, 142002 (2017).

Orbital motion - Nucleon Structure from 1D to 3D

→ Nucleon Spin
→ Quark Spin



Nucleon Polarization	Quark polarization: Un-Polarized	Quark polarization: Longitudinally Polarized	Quark polarization: Transversely Polarized
U	$f_1 =$		$h_1^\perp =$ − Boer-Mulder
L		$g_1 =$ − Helicity	$h_{1L}^\perp =$ −
T	$f_{1T}^\perp =$ − Sivers	$g_{1T}^\perp =$ −	$h_{1T} =$ − Transversity $h_{1T}^\perp =$ − Pretzelosity

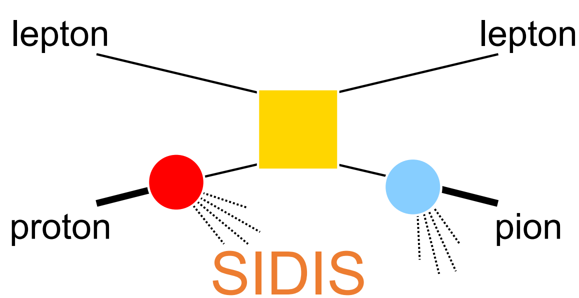
Corresponding fragmentation functions

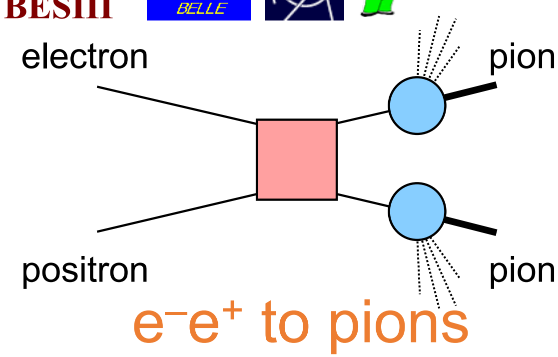
Generalized parton distribution (GPD)

Transverse momentum dependent parton distributions (TMD-PDFs)

Connected via 5-D Wigner distributio

Transverse momentum dependent Fragmentation functions (TMD-FFs)

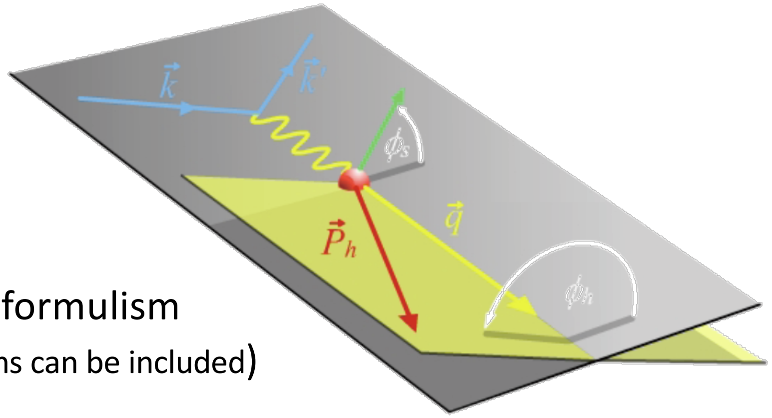




Separation of Collins, Sivers and Pretzelosity through angular dependence

SIDIS SSAs depend on 4-D variables (x, Q^2, z, P_T) and small asymmetries demand **large acceptance** + **high luminosity** allowing for measuring symmetries in 4-D binning with precision!

(2π azimuthal coverage)



$$A_{UT}(\phi_h, \phi_S) = \frac{1}{P_{t,pol}} \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

Leading twist formulism
(higher-twist terms can be included)

$$= A_{UT}^{Collins} \sin(\phi_h + \phi_S) + A_{UT}^{Pretzelosity} \sin(3\phi_h - \phi_S) + A_{UT}^{Sivers} \sin(\phi_h - \phi_S)$$

$$A_{UT}^{Collins} \propto \langle \sin(\phi_h + \phi_S) \rangle_{UT} \propto h_1 \otimes H_1^{\perp}$$

$$A_{UT}^{Pretzelosity} \propto \langle \sin(3\phi_h - \phi_S) \rangle_{UT} \propto h_{1T}^{\perp} \otimes H_1^{\perp}$$

Collins fragmentation function from e^+e^- collisions

$$A_{UT}^{Sivers} \propto \langle \sin(\phi_h - \phi_S) \rangle_{UT} \propto f_{1T}^{\perp} \otimes D_1$$

Unpolarized fragmentation function

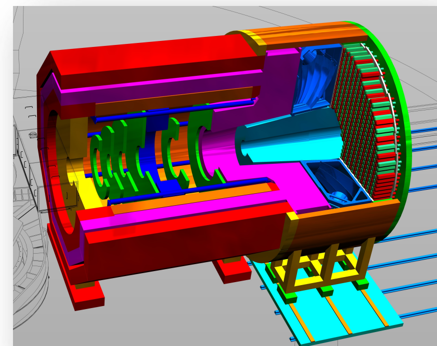
SoLID@12-GeV JLab: QCD at the intensity frontier

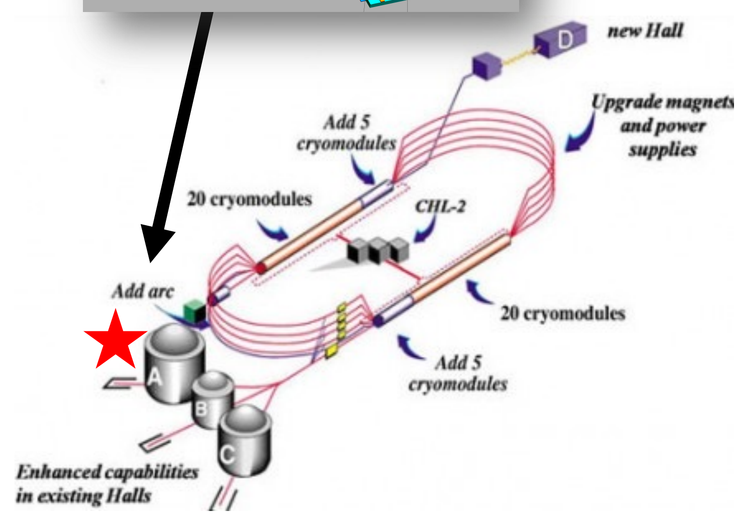
SoLID will ***maximize*** the science return of the 12-GeV CEBAF upgrade by **combining...**

High Luminosity	+	Large Acceptance
$10^{37\text{-}39}$ /cm^2/s [>100x CLAS12][>1000x EIC]		Full azimuthal ϕ coverage

Research at **SoLID** will have the ***unique*** capability to **explore** the QCD landscape while **complementing** the research of other key facilities

- Pushing the phase space in the search of new physics and of hadronic physics
- 3D momentum imaging of a relativistic strongly interacting confined system (nucleon spin)
- Superior sensitivity to the differential electro- and photo-production cross section of J/ψ near threshold (proton mass)

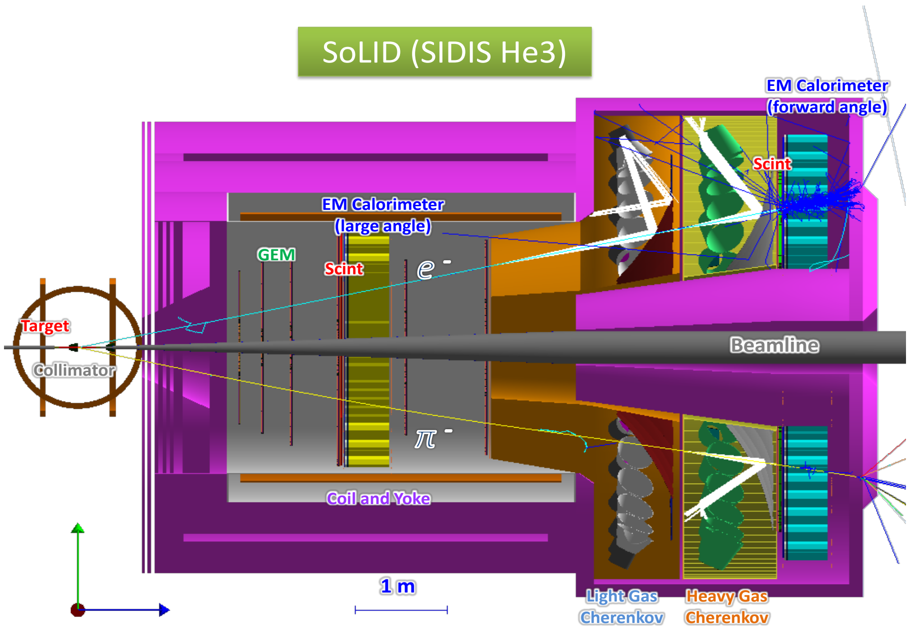


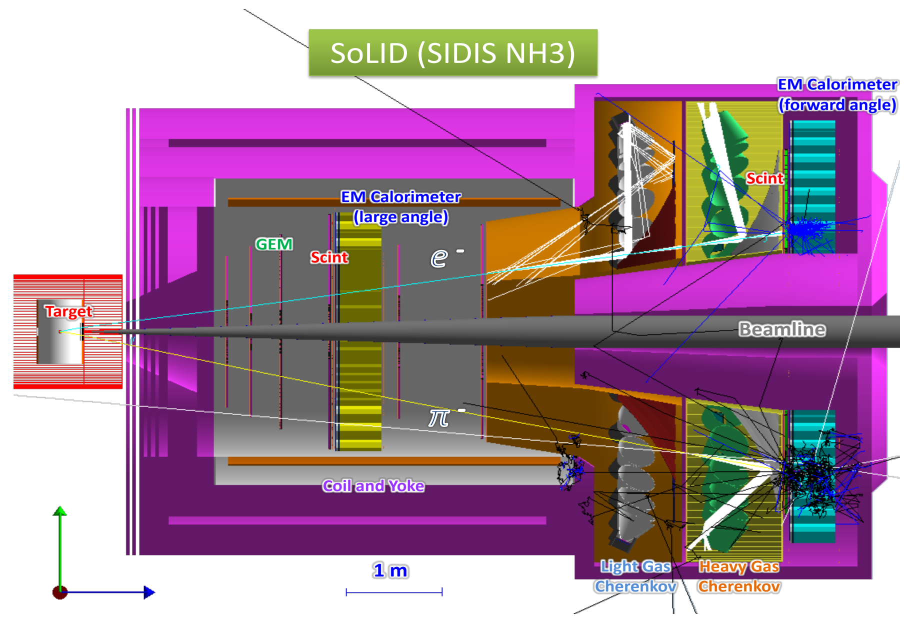


Synergizing with the pillars of EIC science (proton spin and mass) through high-luminosity valence quark tomography and precision J/ψ production near threshold

Haiyan Gao

SIDIS with polarized "neutron" and proton @ SoLID





E12-10-006: Single Spin Asymmetries on Transversely Polarized ^{3}He @ 90 days
Rating A Spokespersons: J.P. Chen, H. Gao (contact), J.C. Peng, X. Qian

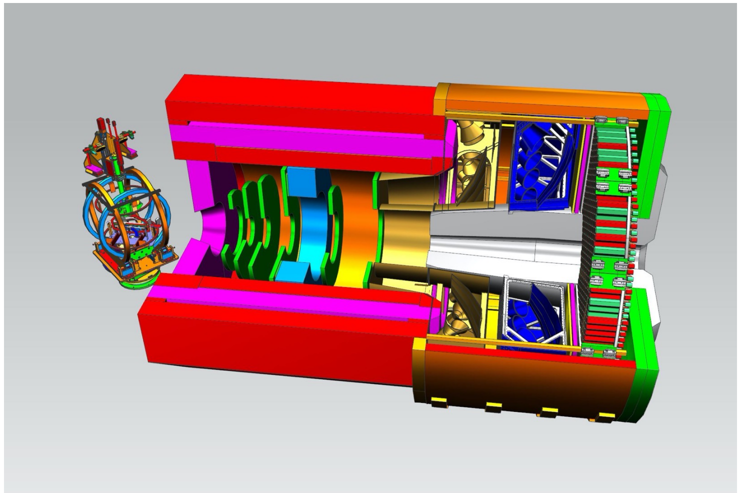
E12-11-007: Single and Double Spin Asymmetries on Longitudinally Polarized ^{3}He @ 35 days
Rating A Spokespersons: J.P. Chen (contact), J. Huang, W.B. Yan

E12-11-108: Single Spin Asymmetries on Transversely Polarized Proton @ 120 days
Rating A Spokespersons: J.P. Chen, H. Gao (contact), X.M. Li, Z.-E. Meziani

Run group experiments approved for TMDs, GPDs, and spin

Haiyan Gao

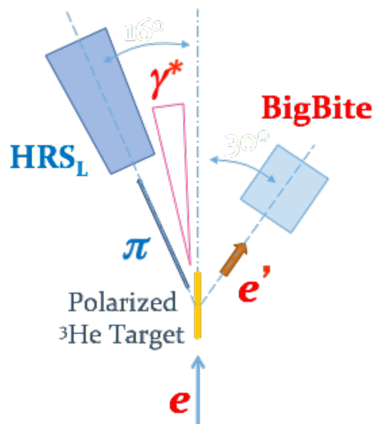
QCD intensity frontier with SoLID: large-acceptance & high luminosity

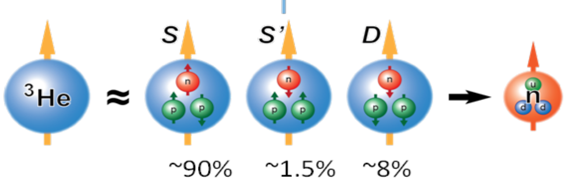


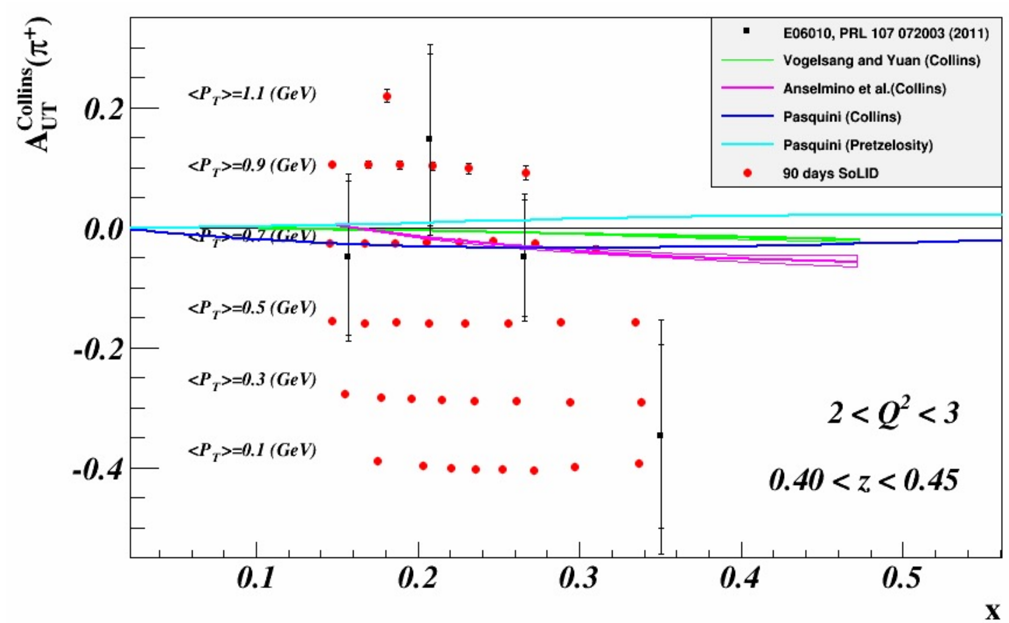
Quantum leap: 4-D binning for the first time!

SoLID-SIDIS program: Large acceptance, Full azimuthal coverage + High luminosity

- 4-D mapping of asymmetries with precision
  $\Delta z = 0.05$, $\Delta P_T = 0.2$ GeV, $\Delta Q^2 = 1$ GeV^2, x bin sizes vary with median bin size 0.02 (statistical uncertainty for each bin: $\delta A \leq 0.02$)
- Constrain models and forms of TMDs, Tensor charge, …
- Lattice QCD, QCD dynamics, models







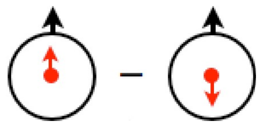
X. Qian et al., PRL107, 072003(2011)

- **More than 1400 bins in x, Q^2, P_T and z for 11/8.8 GeV beam.**

Haiyan Gao

Transversity and Tensor Charge

Transversity distribution

h_1  (Collinear & TMD)

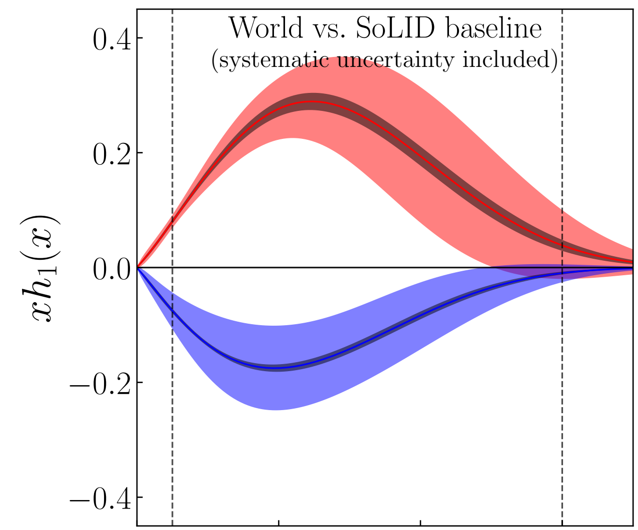
- Chiral-odd, unique for the quarks
- No mixing with gluons, simpler evolution effect
- A transverse counterpart to longitudinal spin g_1, difference shows the relativistic effect
- Zeroth moment gives tensor charge:

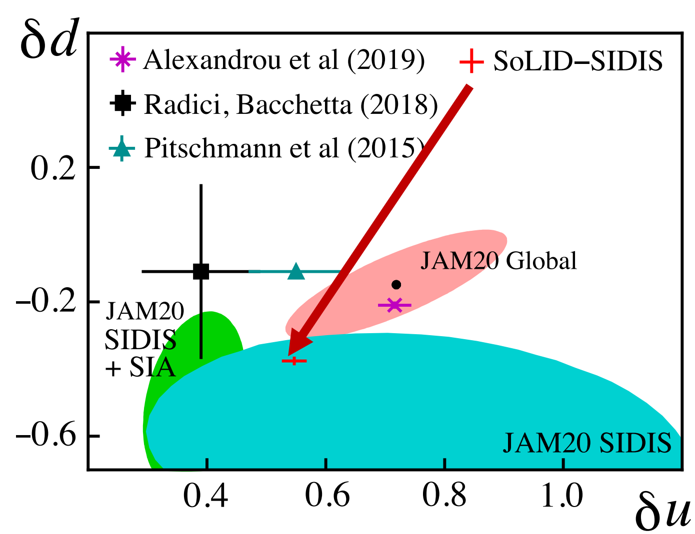
$$\langle \mathrm{P,S} | \overline{\psi}_q i\sigma^{\mu\nu} \psi_q | \mathrm{P,S} \rangle = g_T^q \overline{u}(\mathrm{P,S}) i\sigma^{\mu\nu} u(\mathrm{P,S})$$

$$g_T^q = \int_0^1 \left[h_1^q(x) - h_1^{\overline{q}}(x) \right] dx$$

- A fundamental QCD quantity, valence quarks dominate
- Precisely calculated on the lattice
- Difference from nucleon axial charge is due to relativity
- High luminosity-large acceptance allows for high-precision test of LQCD predictions

FLAG review 2019: 1902.08191
Relative uncertainty 4% (u), 7% (d)

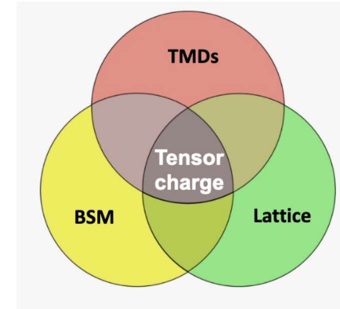




JAM20: arxiv:2002.08384

Constraint on Quark EDMs

$$d_n = g_T^d\, d_u + g_T^u\, d_d + g_T^s\, d_s$$



Constraint on quark EDMs with combined proton and neutron EDMs

	d_u upper limit	d_d upper limit
Current g_T + current EDMs	$1.27\times10^{-24} e$ cm	$1.17\times10^{-24} e$ cm
SoLID g_T + current EDMs	$6.72\times10^{-25} e$ cm	$1.07\times10^{-24} e$ cm
SoLID g_T + future EDMs	$1.20\times10^{-27} e$ cm	$7.18\times10^{-28} e$ cm

Include 10% isospin symmetry breaking uncertainty

Sensitivity to new physics

$$d_q \sim e m_q/(4\pi\Lambda^2)$$

Three orders of magnitude improvement on quark EDM limit → Probe to 30 ~ 40 times higher scale

Current quark EDM limit: $10^{-24} e$ cm → ~ 1 TeV

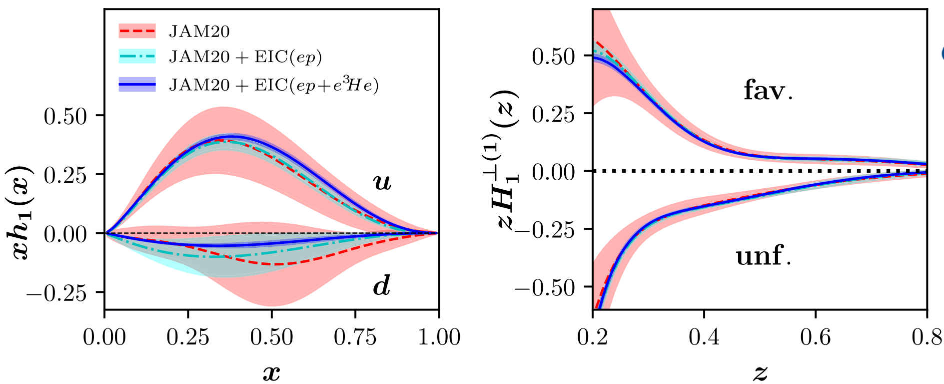
Future quark EDM limit: $10^{-27} e$ cm → 30 ~ 40 TeV

Image credit: D. Pitonyak

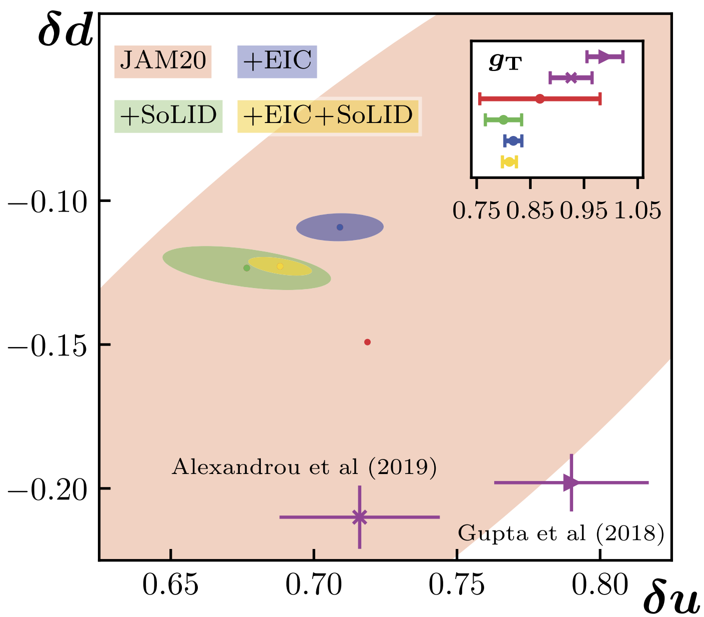
H. Gao, T. Liu, Z. Zhao, PRD 97, 074018 (2018)

TENSOR CHARGE AT THE EIC AND JLAB

L. Gamberg, Z. Kang, D. Pitonyak, A. Prokudin, N. Sato Phys.Lett.B 816 (2021)



JAM20: Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato, Phys.Rev.D 102 (2020)



- EIC data will allow to have g_T extraction at the precision at the level of lattice QCD calculations

- JLab 12 data will allow to have complementary information on tensor charge to test the consistency of the extraction and expand the kinematical region

A. Prokudin@PANIC 2021

Thank you for your attention!

Acknowledgement: The JLab PRad collaboration, SoLID collaboration and collaborators @ HIGS; Stephan Paul for the AMBER experiment, Jan Bernauer for Mainz experiments, Ron Gilman and Steffen Strauch for the MUSE experiment, Toshimi Suda for the ULQ^2 experiment.

Supported in part by NSF MRI PHY-1229153 and the U.S. Department of Energy under contract number DE-FG02-03ER41231