Nuclear Physics – The Structure of the Nucleon

Haiyan Gao
Nuclear and Particle Physics, BNL &
Duke University

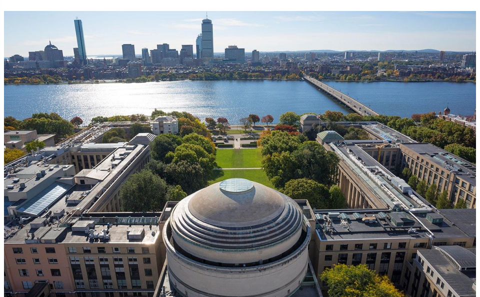
African School of Physics, December 5th, 2022

@BrookhavenLab

Brief Introduction of myself




Tsinghua University (84-88) (BS)
California Institute of Technology (89-94) (Ph.D.)
Univ. of Illinois, Urbana-Champaign (94-96) (postdoc)
Argonne National Lab (96-97) (staff)
Massachusetts Institute of Technology (97-04) (faculty)
Duke Univ. (02-present) (faculty)
Duke Kunshan University (Jan 2015 – June 2019) Vice Chancellor for Academic Affairs
Brookhaven National Laboratory (June 2021 –) Associate Laboratory Director, NPP

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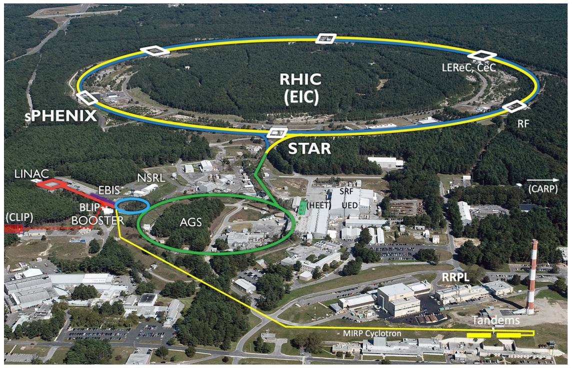
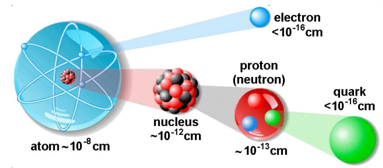
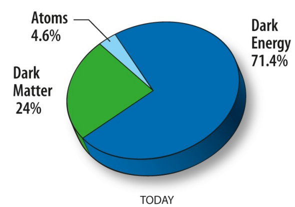
Nuclear & Particle Physics at BNL

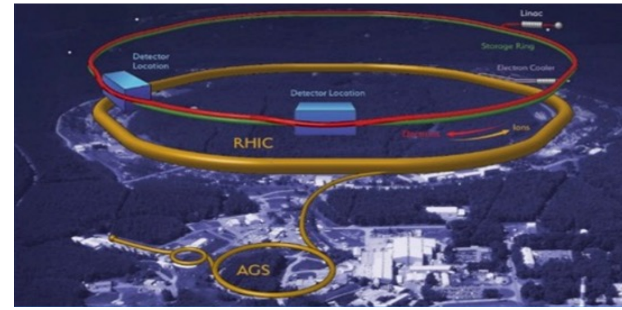


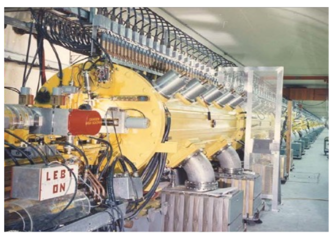
To understand sub-atomic world deeper and deeper





Electron-Ion Collider

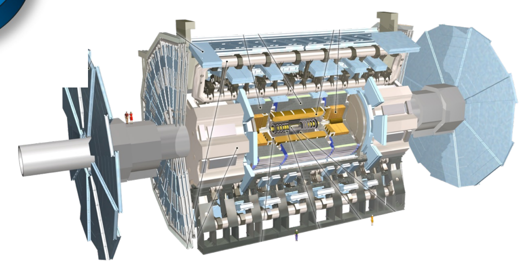




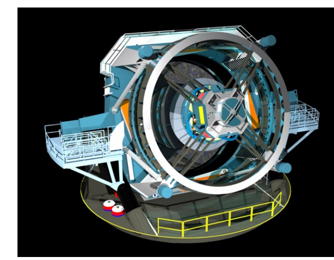
BLIP: Medical Isotopes

NASA Space Radiation Lab

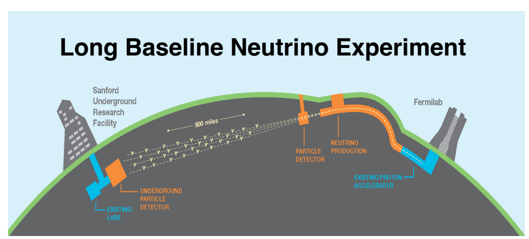
Develop unique technologies to answer fundamental questions in nature and applications of societal benefits

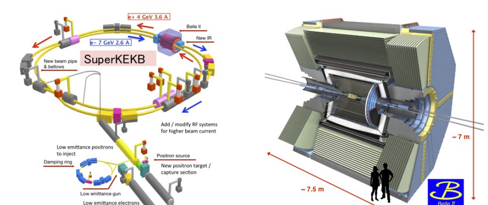


ATLAS @ LHC



Rubin Observatory





Belle II at SuperKEKB

High-Energy Theory, Nuclear Physics Theory
Center for Fundamental Nuclear Science
RIKEN-BNL Research Center

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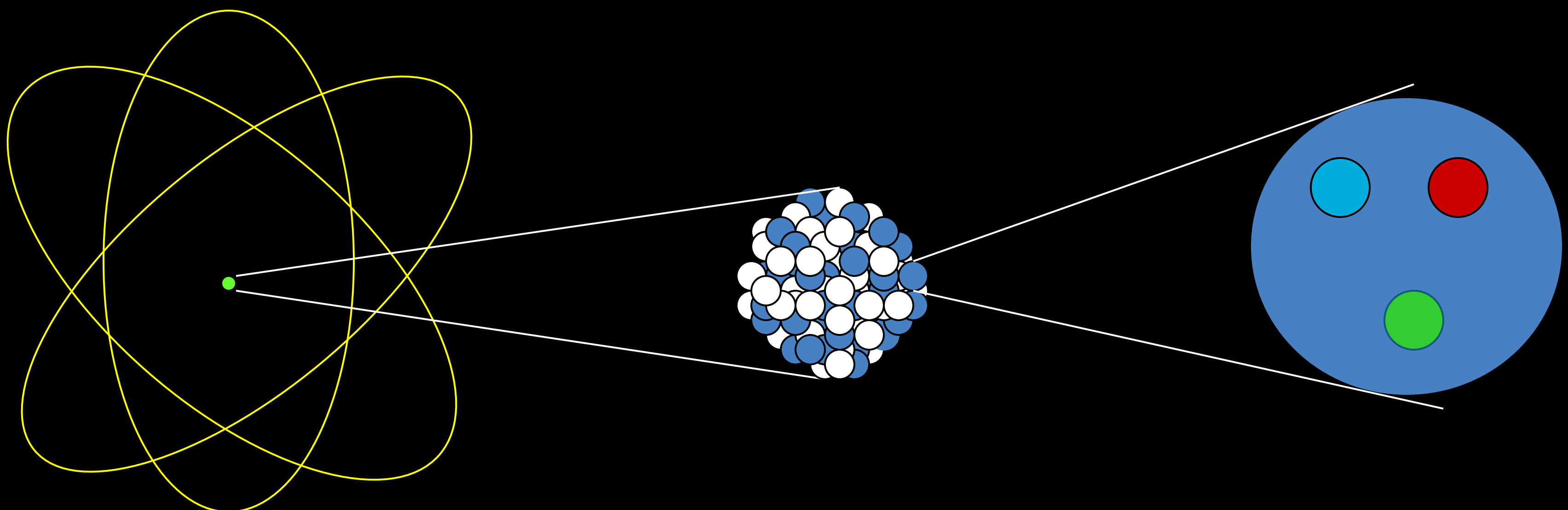
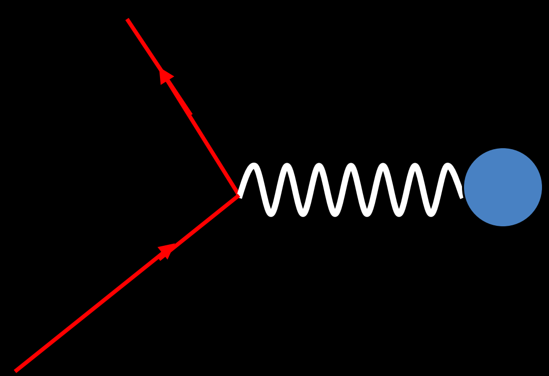
Nuclear physics is the study of the structure of matter

- Most of the mass and energy in the universe around us comes from nuclei and nuclear reactions.
- The nucleus is a unique form of matter in that all the forces of nature are present : (strong, electromagnetic, weak).

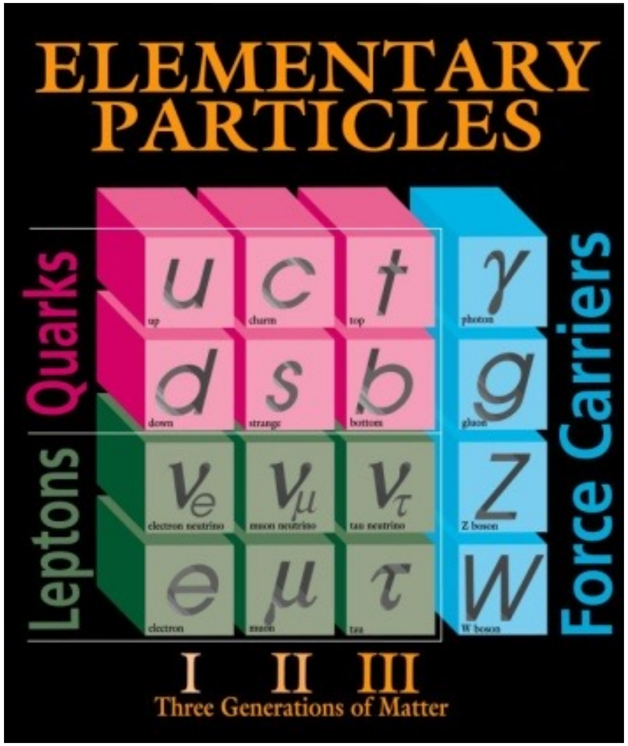


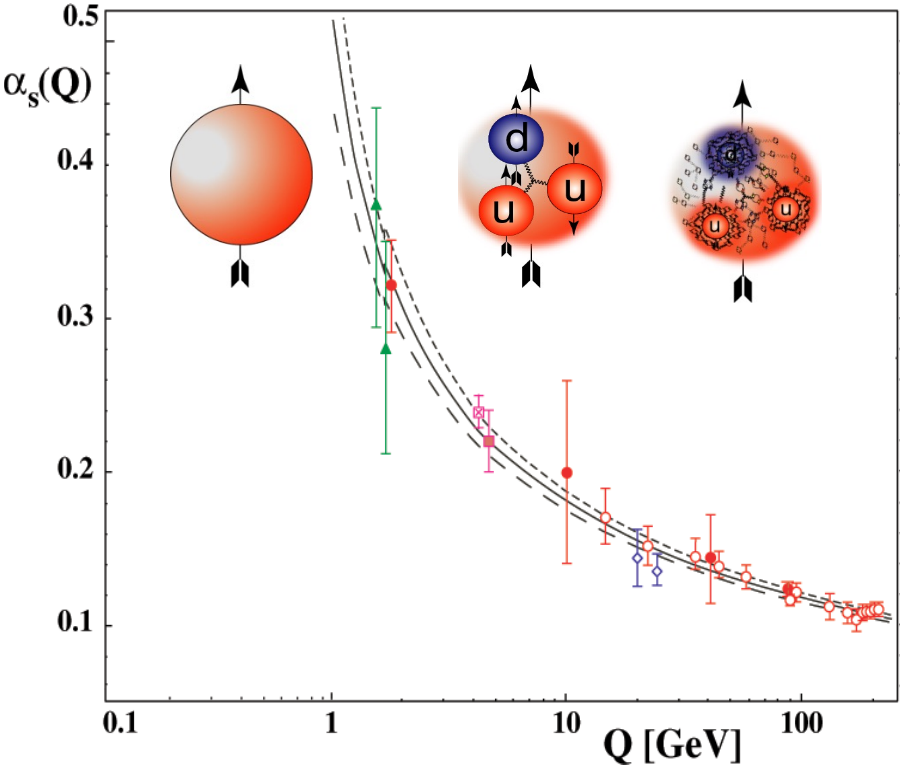
atom: 10^{-10} m   nucleus: 10^{-14} m   nucleon: 10^{-15} m



$$\lambda \approx \frac{h}{p}$$

QCD: still unsolved in non-perturbative region





Gauge bosons: gluons (8)

- *2004 Nobel prize for ``asymptotic freedom"*
- *non-perturbative regime QCD ?????*
- *One of the top 10 challenges for physics!*
- *QCD: Important for discovering new physics beyond SM*
- *Nucleon structure is one of the most active areas*

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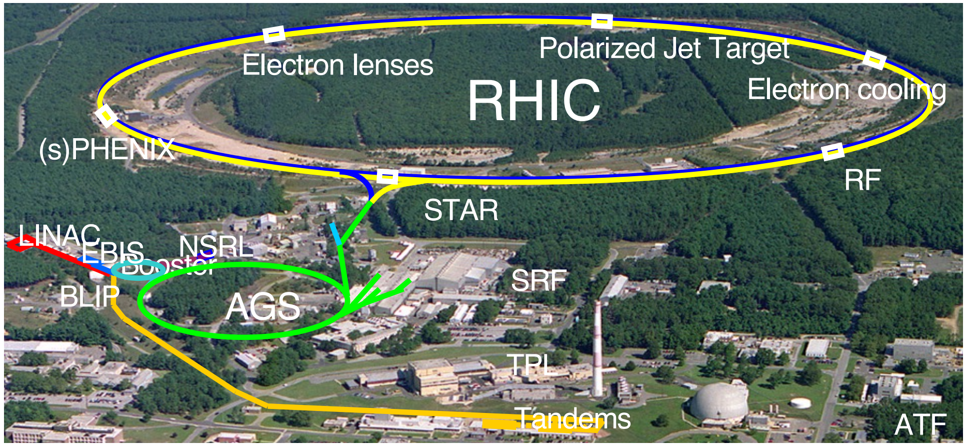
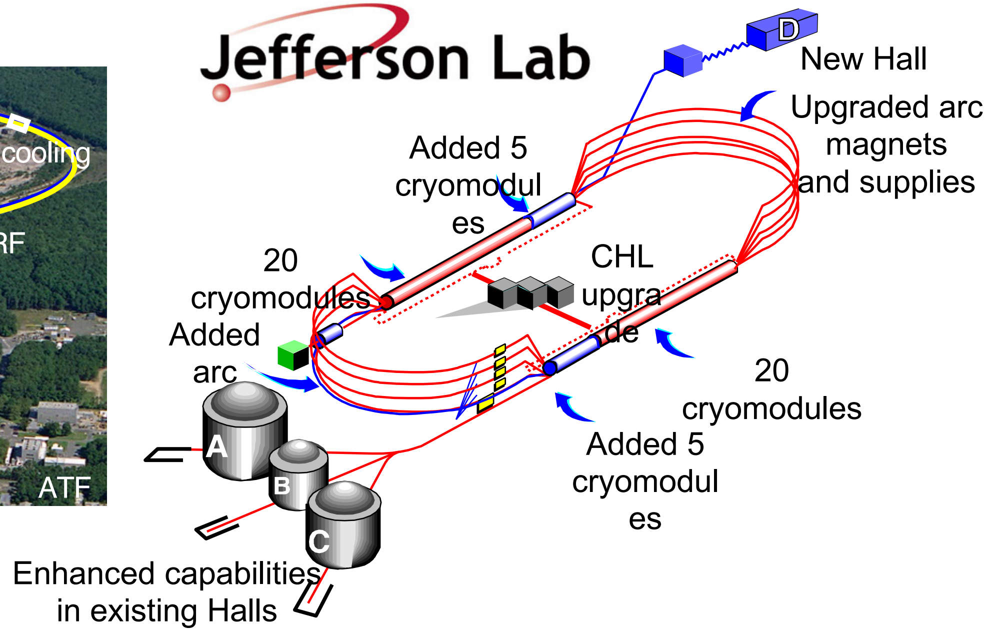
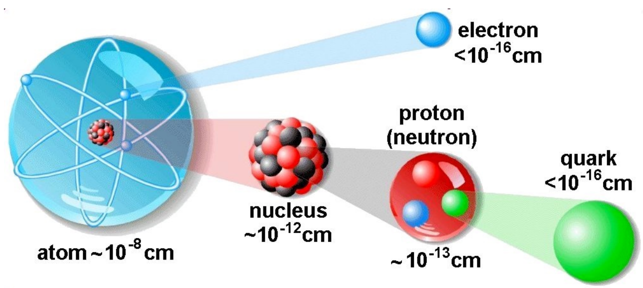
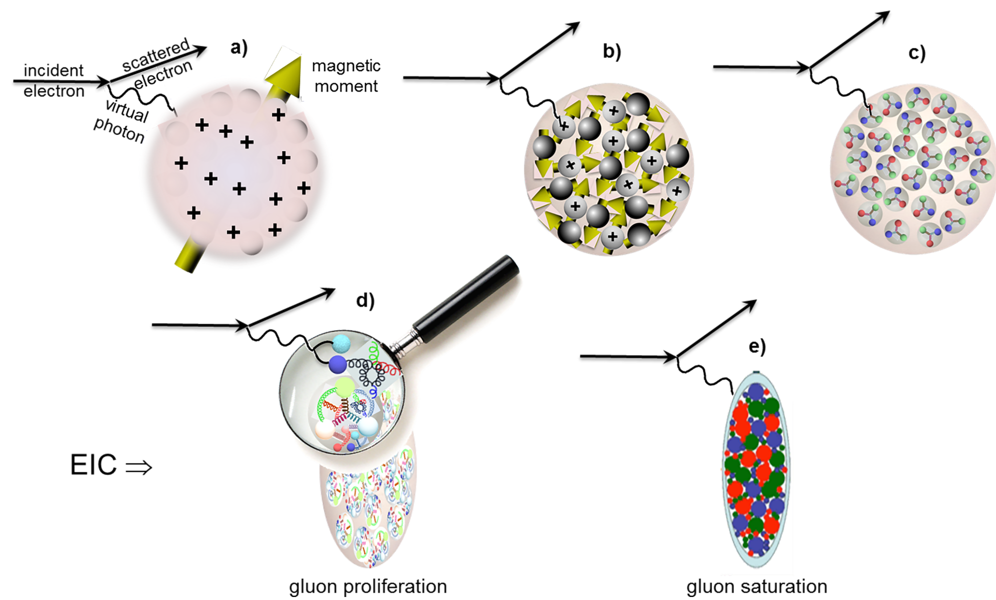
Structure of visible matter probed at existing DOE (QCD) facilities

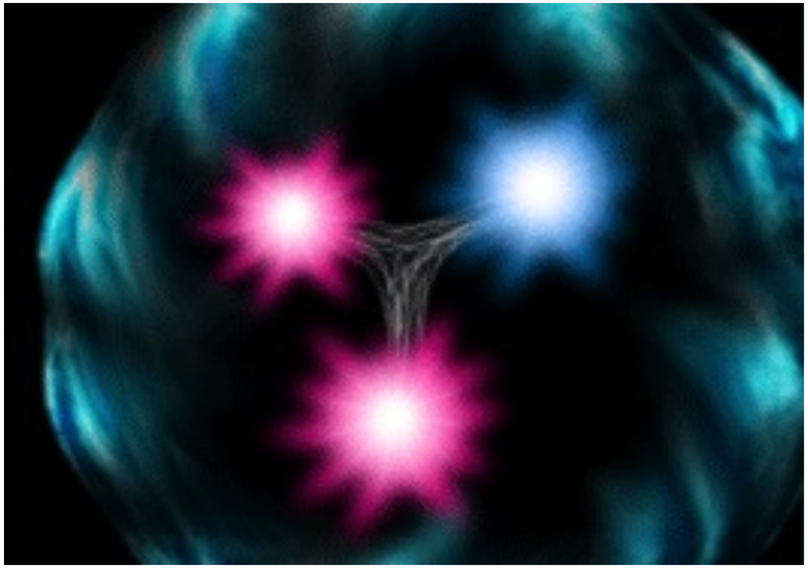


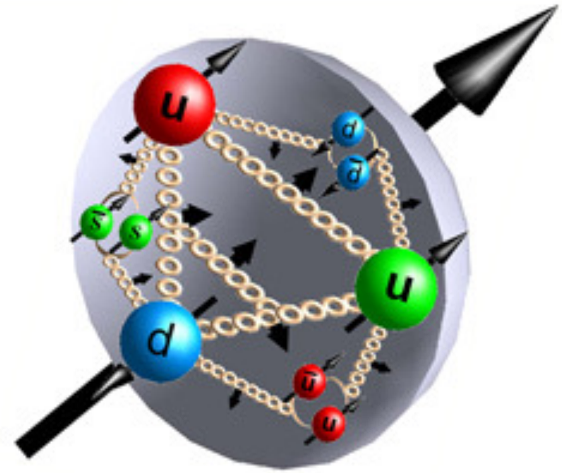






Nucleon Structure

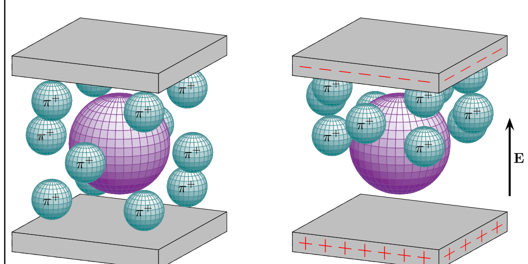




- *Charge and magnetism (current) distribution*
- *Spin distribution*
- *Quark momentum and flavor distribution*
- *Polarizabilities*
- *Strangeness content*
- *Three-dimensional structure*
- *……*

Electric polarizability (α_E)

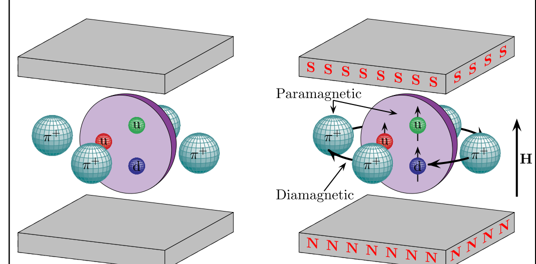
$$\vec{P} = \alpha_E \vec{E}$$



"Stretchability"

Magnetic polarizability (β_M)

$$\vec{M} = \beta_M \vec{H}$$



"Alignability"

Image credit: P. Martel

Lepton scattering: powerful microscope!

Clean probe of hadron structure

Electron point-like particle, electron vertex is well-known from quantum electrodynamics

One-photon exchange dominates, ***higher-order exchange diagrams are suppressed***

One can vary the wave-length of the probe to view deeper inside the hadron

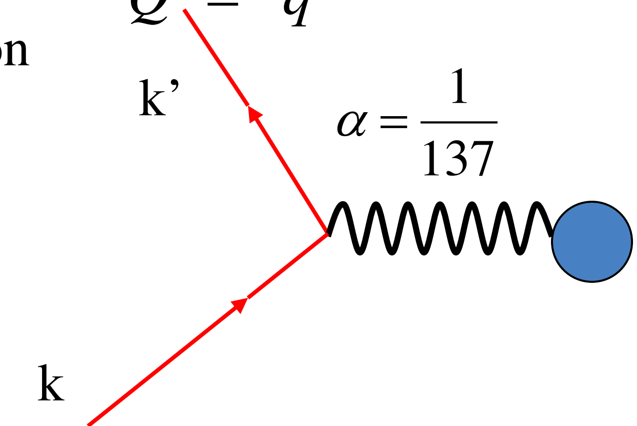
Resolution $\propto h/Q$

- $Q \approx 20$ MeV $\lambda \approx 10$ fm nucleus
- $Q \approx 200$ MeV $\lambda \approx 1$ fm nucleon
- $Q \approx 2$ GeV $\lambda \approx 0.1$ fm inside nucleon
- $Q \approx 20$ GeV $\lambda \approx 0.01$ fm quark

Virtual photon 4-momentum

$$q = k - k' = (\vec{q}, \omega)$$

$$Q^2 = -q^2$$



Using electron scattering as example

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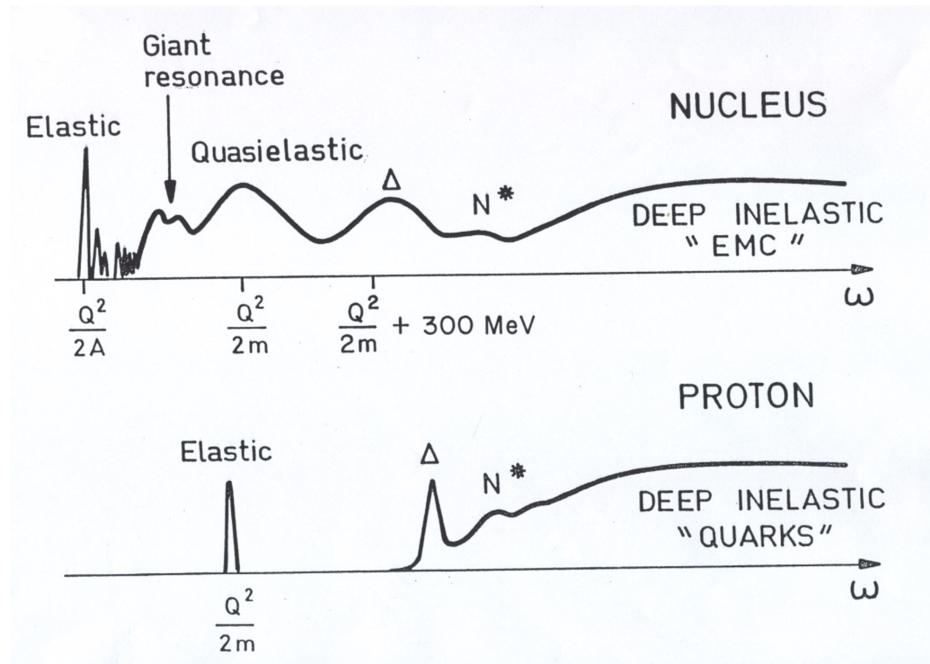
Electron-nucleon (Nucleus) scattering

m: mass of the nucleon

Low Q^2 elastic scattering, $x=1=Q^2/2m\omega$

As Q^2 increases inelastic effects dominates

As Q^2 further increases, deep-inelastic scattering off quarks inside



Electron energy transfer

What is inside the proton/neutron?

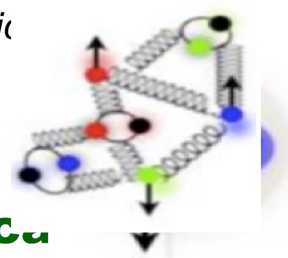
1933: Proton's magnetic moment


Nobel Prize In Physics 1943

Otto Stern

"for … and for his discovery of the magneti moment of the proton".

$g \neq 2$



1960: Elastic e-p scattering

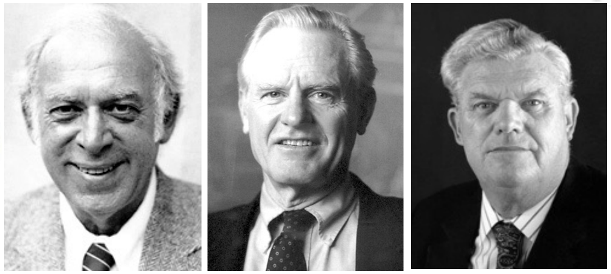

Nobel Prize In Physics 1961

Robert Hofstadter

"for … and for his thereby achieved discoveries concerning the structure of the nucleons"

$\text{Form factors} \rightarrow \text{Charge distributions}$

1969: Deep inelastic e-p sca

Nobel Prize in Physics 1990

Jerome I. Friedman, Henry W. Kendall, Richard E. Taylor

"for their pioneering investigations concerning deep inelastic scattering of electrons on protons …".

1974: QCD Asymptotic Freedo


Nobel Prize in Physics 2004

David J. Gross, H. David Politzer, Frank Wilczek

"for the discovery of asymptotic freedom in the theory of the strong interaction".

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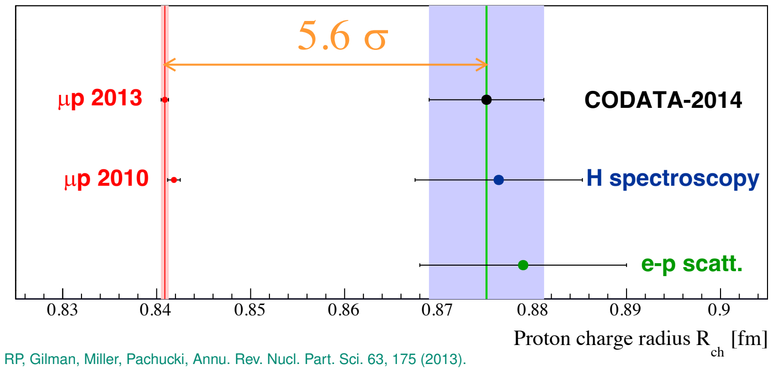
slide credit: Jian-Wei Qiu

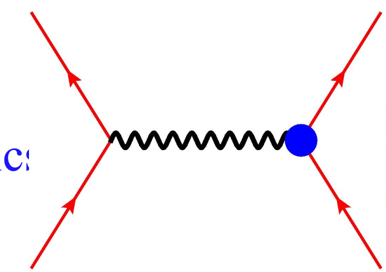
Proton Charge Radius and the puzzle

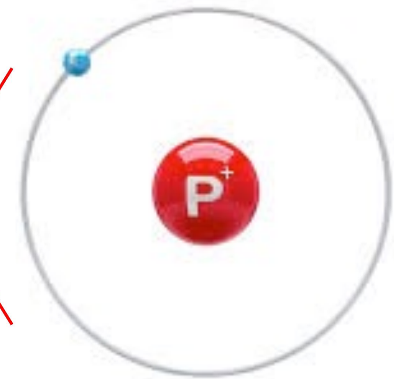
- Proton charge radius:
  1. A fundamental quantity for proton
  2. Important for understanding how QCD works
  3. An important physics input to the bound state QED calculation, affects muonic H Lamb shift ($2S_{1/2} - 2P_{1/2}$) by as much as 2%, and critical in determining the Rydberg constant



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

- Methods to measure the proton charge radius:
  1. Hydrogen spectroscopy (atomic physics)
     - Ordinary hydrogen
     - Muonic hydrogen
  2. Lepton-proton elastic scattering (nuclear physics
     - *ep* elastic scattering (like PRad)
     - ***μ**p* elastic scattering (like MUSE, COMPASS++/AMBER)





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

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

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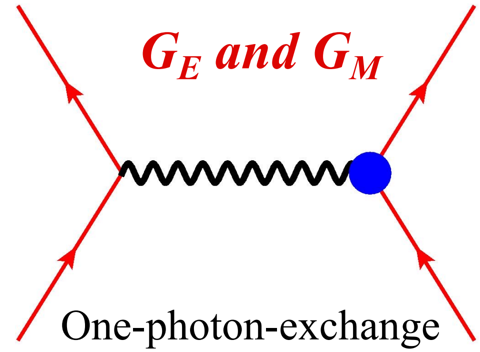
Electron-proton elastic scattering

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

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

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



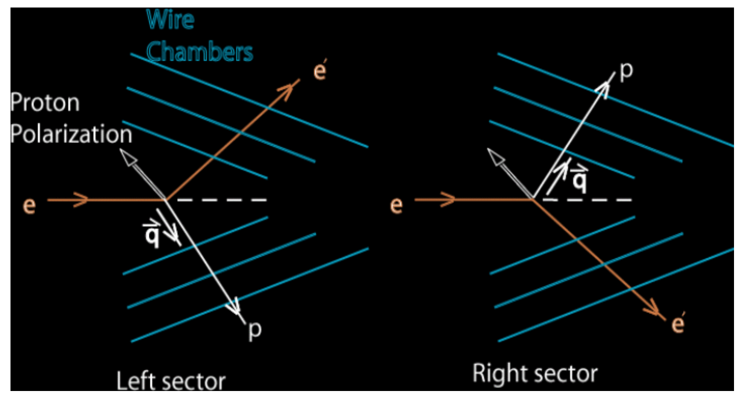
- **Recoil proton polarization measurement *(pol beam only)***

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

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

(pol beam and pol target)

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



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

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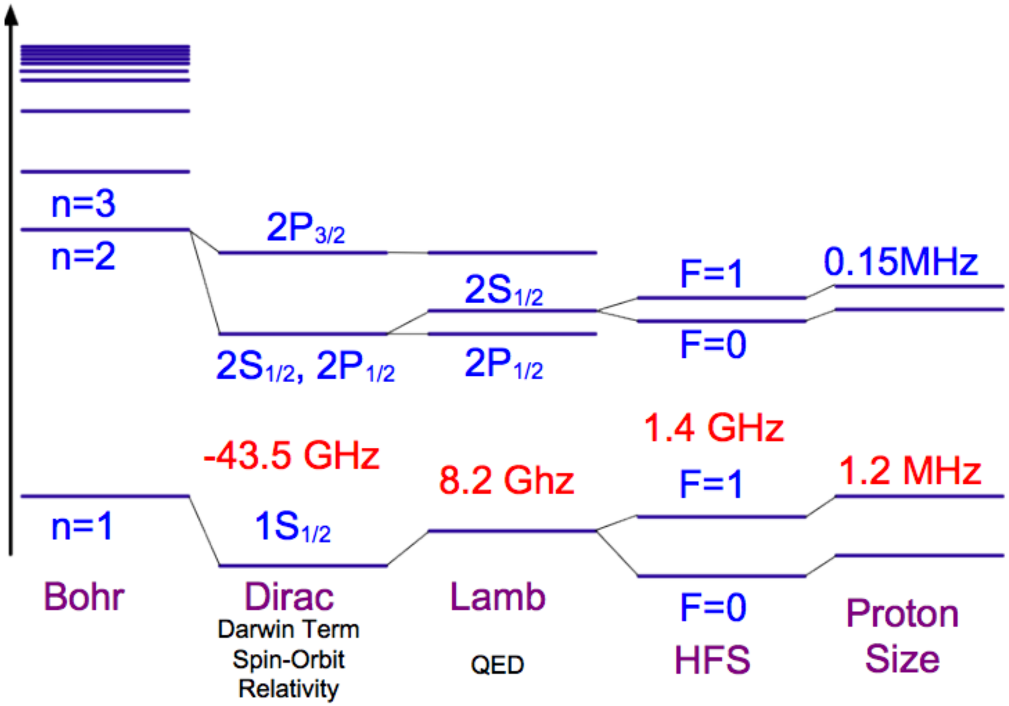
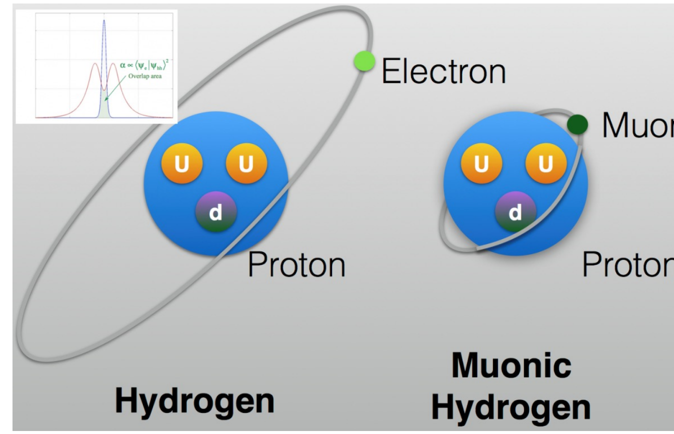
C. Crawford et al. PRL98, 052301 (2007)

Hydrogen Spectroscopy





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%

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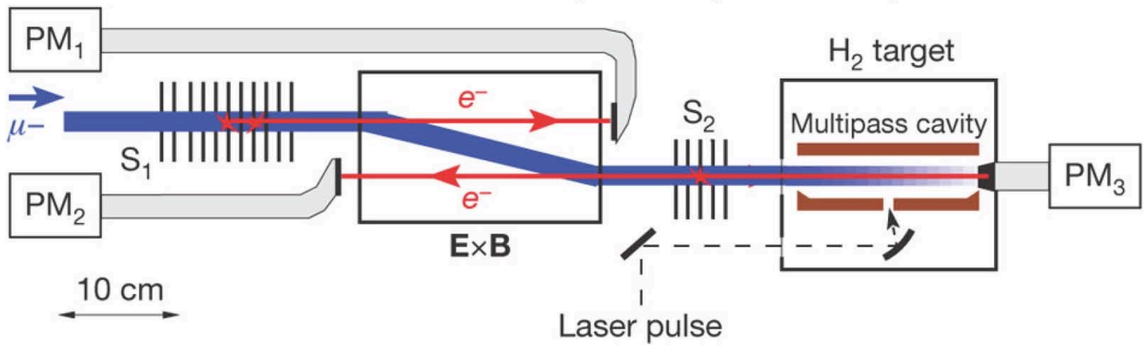
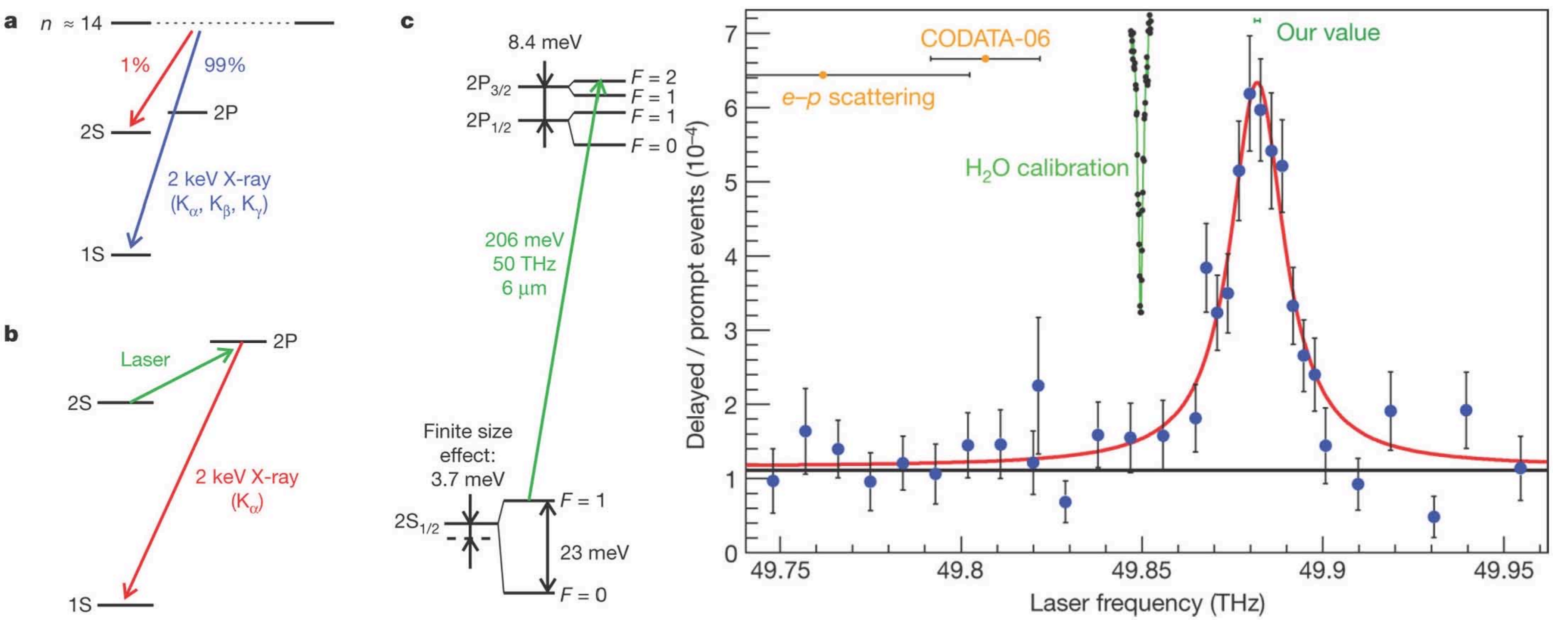
Muonic hydrogen Lamb shift at PSI (2010, 2013)

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





2010 value is r_p = 0.84184(67) fm

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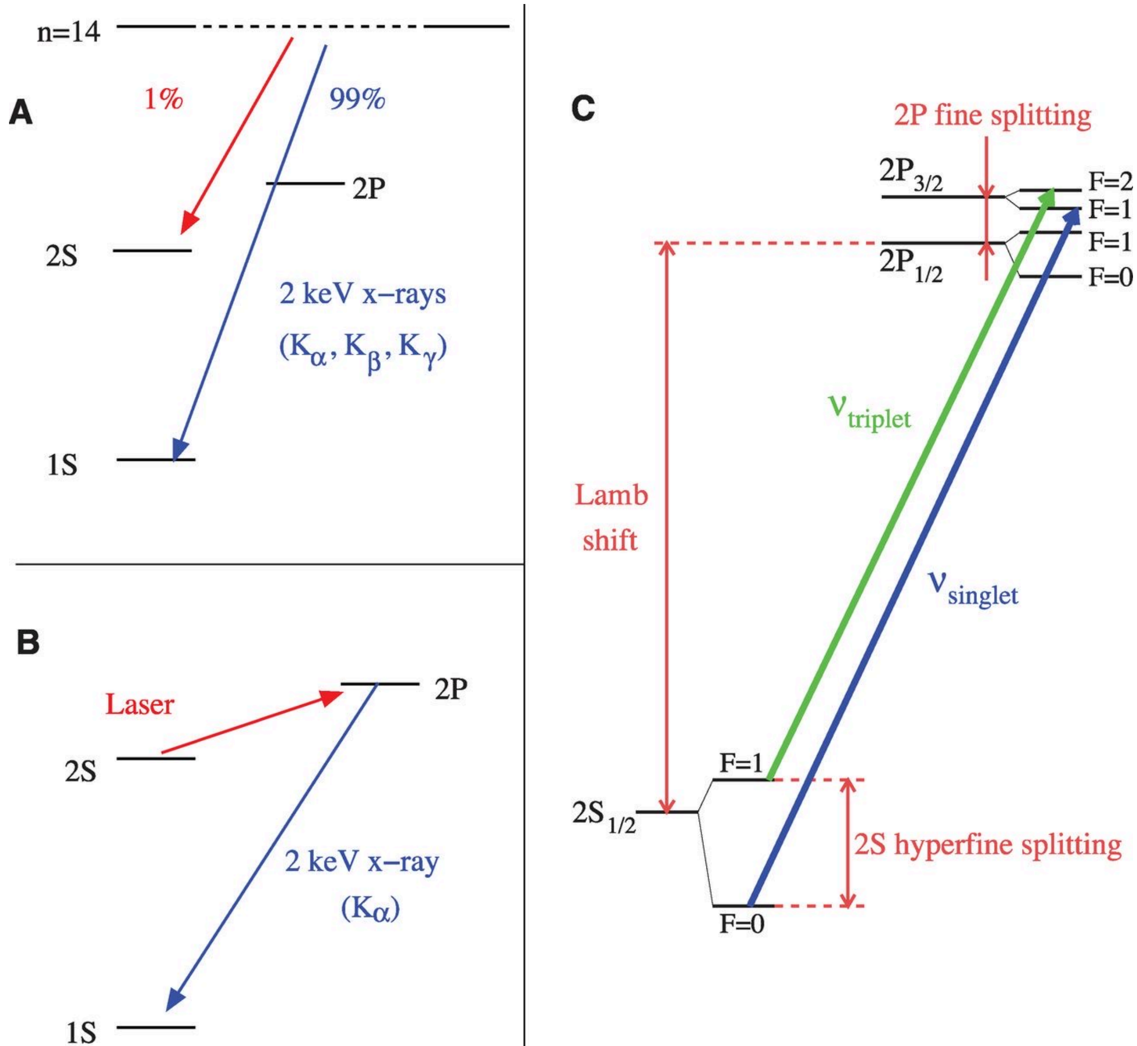
2013 PSI results reported in Science



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

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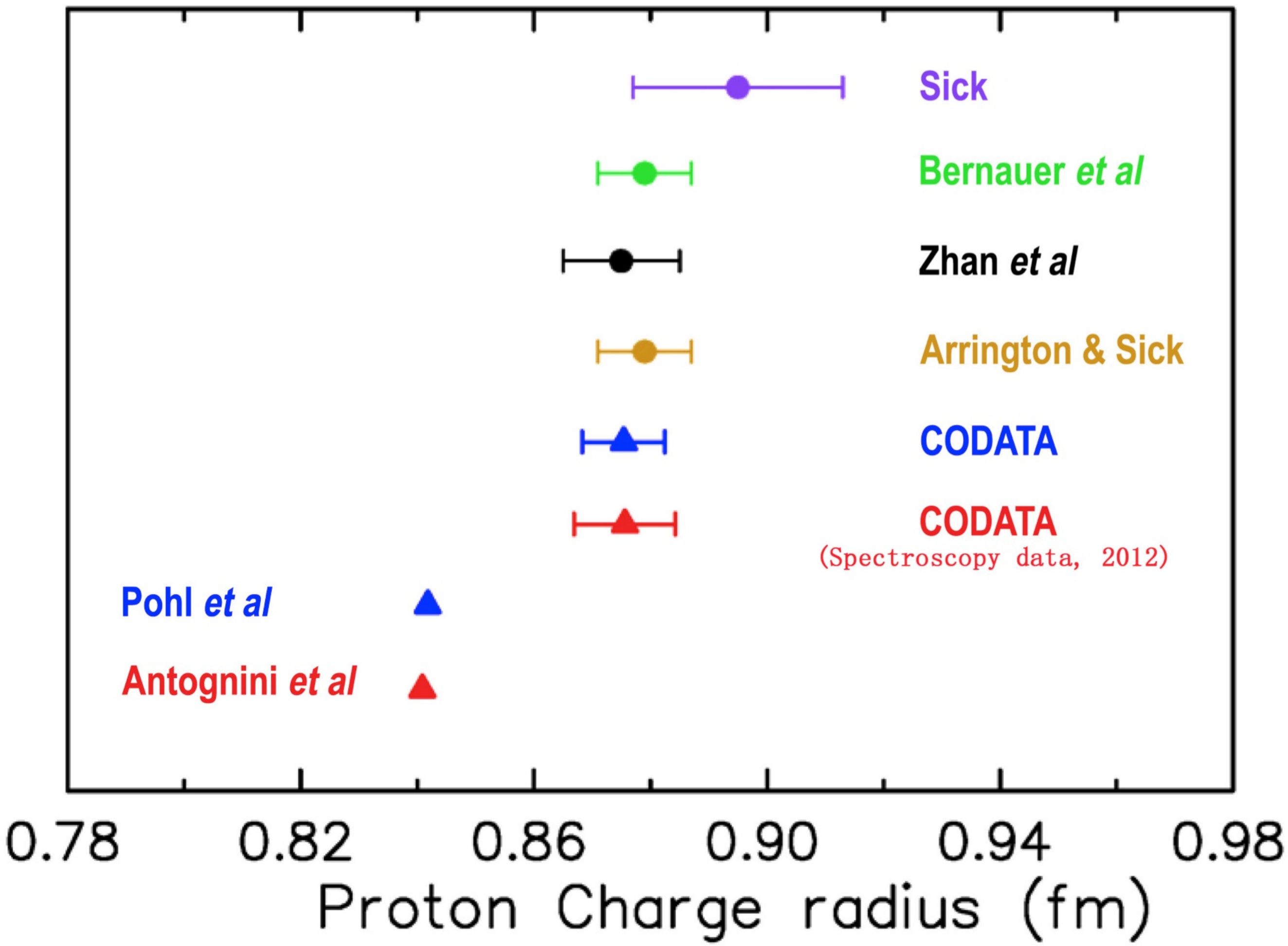
The situation on the Proton Charge Radius in 2013



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

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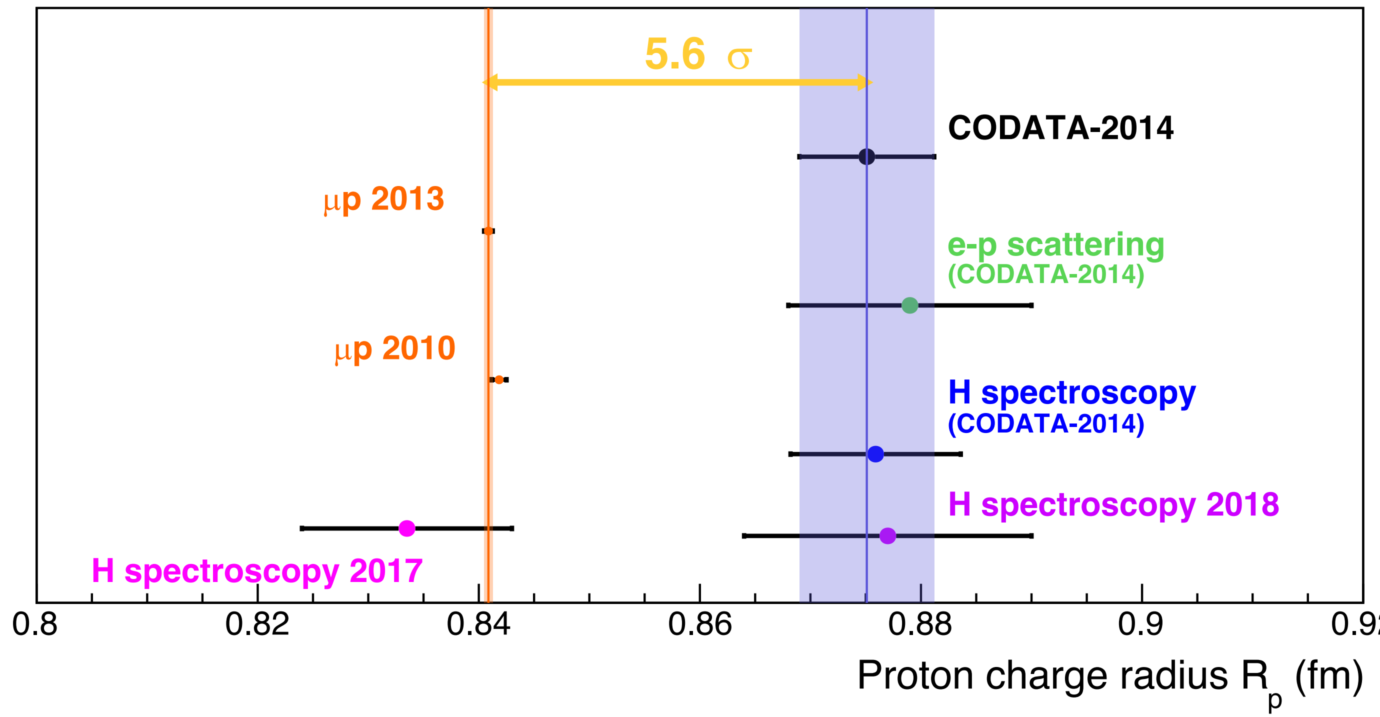
The Proton Charge Radius Puzzle in 2018



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): $0.810 \pm 0.035_{stat.} \pm 0.074_{syst.} \pm 0.003$ (delta_a, delta_b) (Mihovilovic PLB 771 (2017); $0.870 \pm 0.014_{stat.} \pm 0.024_{syst.} \pm 0.003_{mod.}$ (Mihovilovic 2019)

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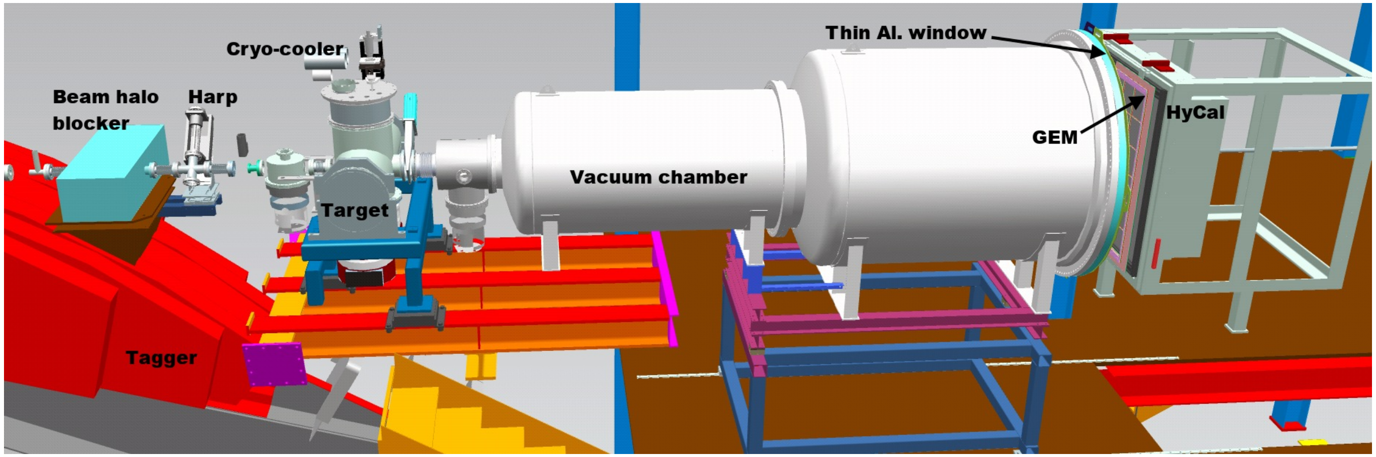
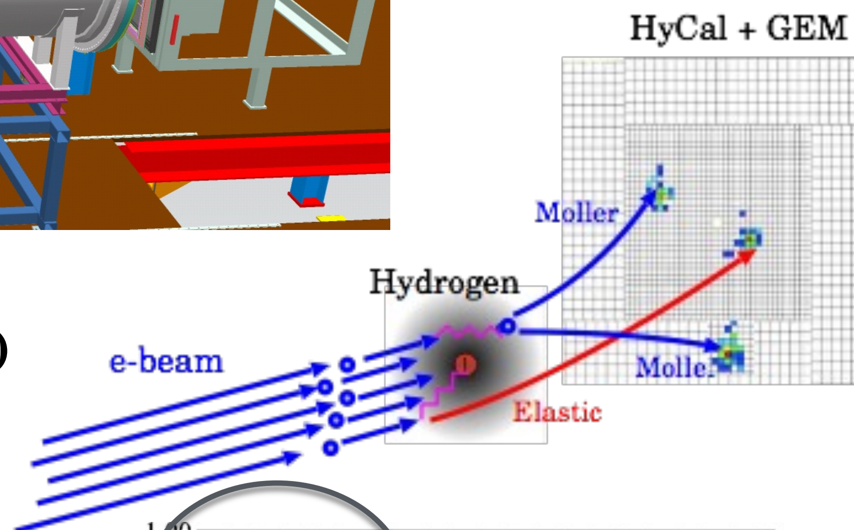
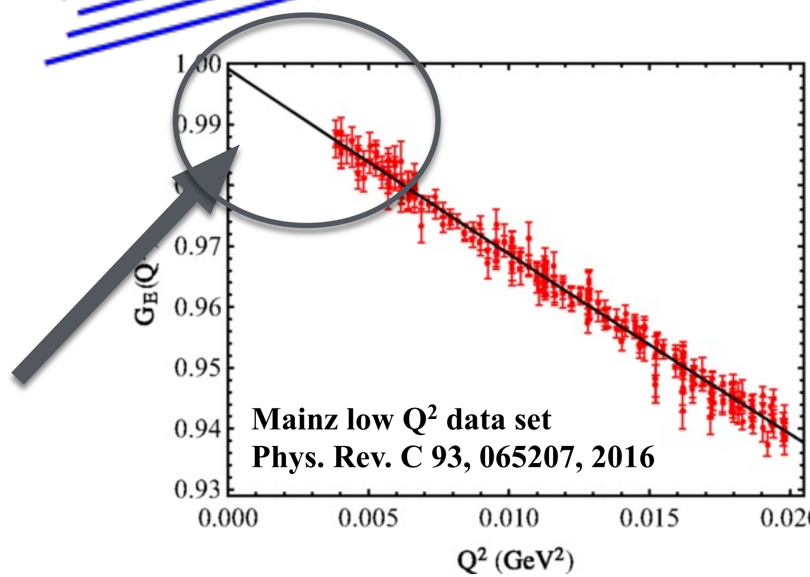
The *PRad Experiment in Hall B at JLab*



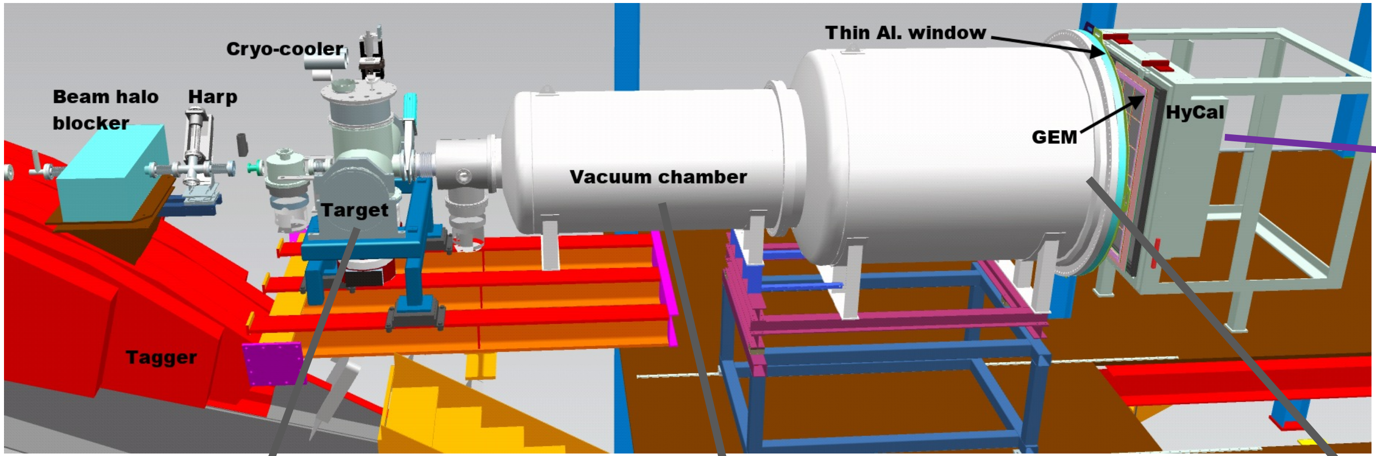
- **High resolution, large acceptance, hybrid HyCal calorimeter (PbWO$_4$ and Pb-Glass)**
- **Windowless H_2 gas flow target**
- **Simultaneous detection of elastic and Moller electrons**
- **Q^2 range of 2×10^{-4} – 0.06 GeV^2**
- **XY – veto counters replaced by GEM detector**
- **Vacuum chamber**

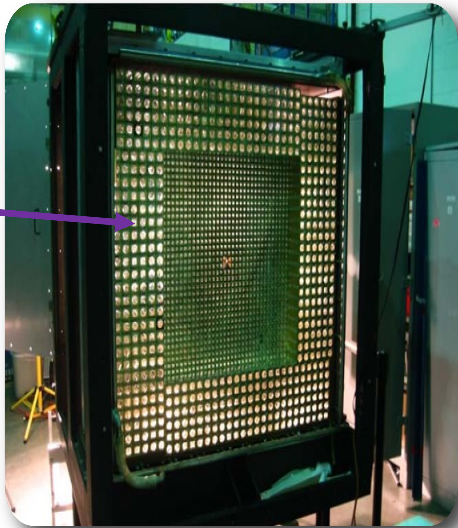
Spokespersons: A. Gasparian (contact), H. Gao, D. Dutta, M. Khandaker



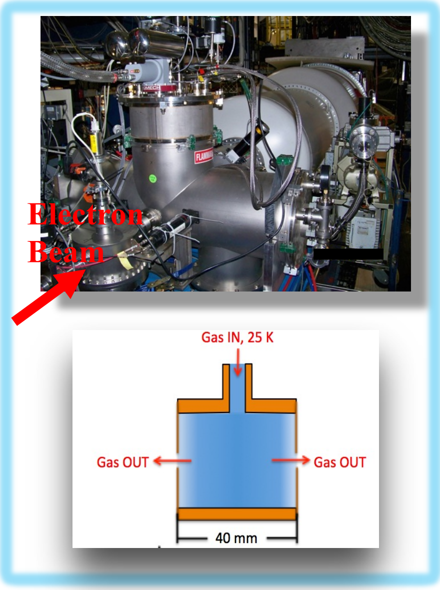


The *PRad Experimental setup*





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



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J. Pierce *et al.,* NIMA **1003**, 165300 (2021)

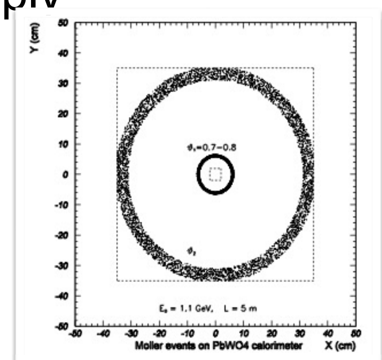
Analysis – Event Selection

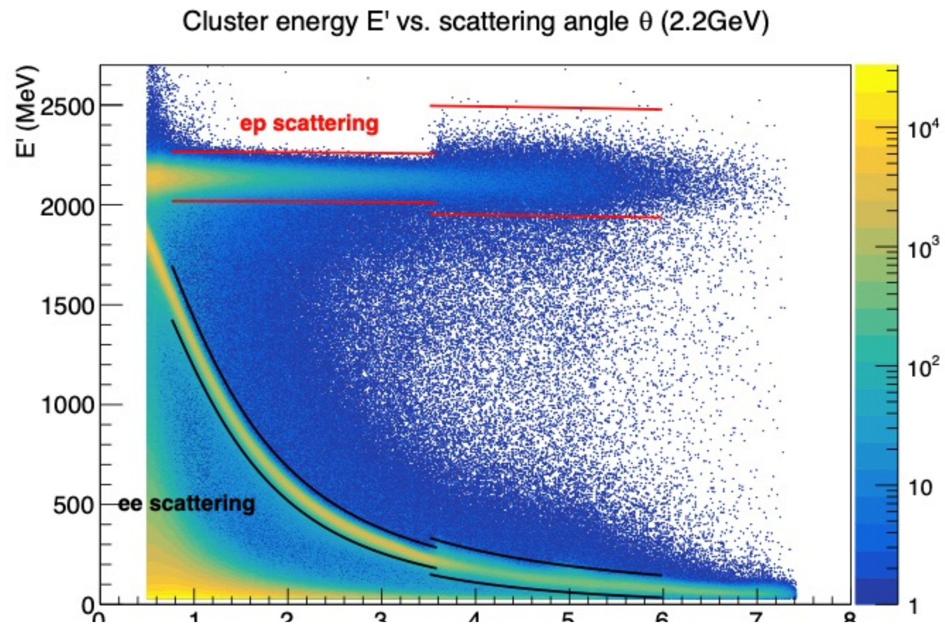
Event selection method

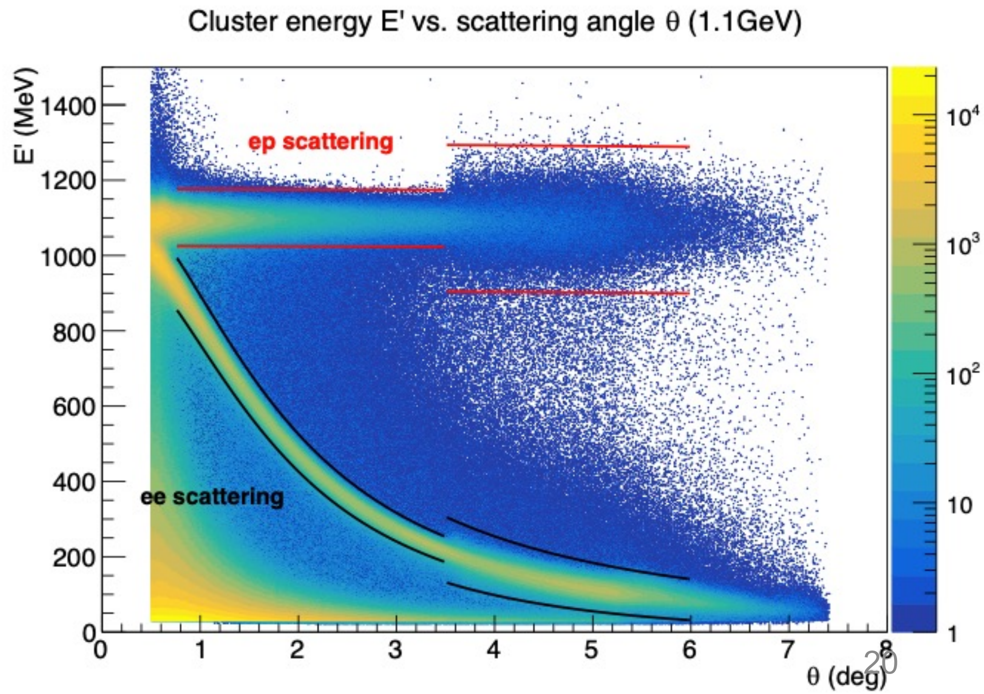
1. For all events, require hit matching between GEMs and HyCal

2. For *ep* and *ee* events, apply angle-dependent energy cut based on kinematics
   1. Cut size depend on local detector resolution

3. For *ee*, if requiring double-arm events, apply additional cuts
   1. Elasticity
   2. Co-planarity
   3. Vertex z







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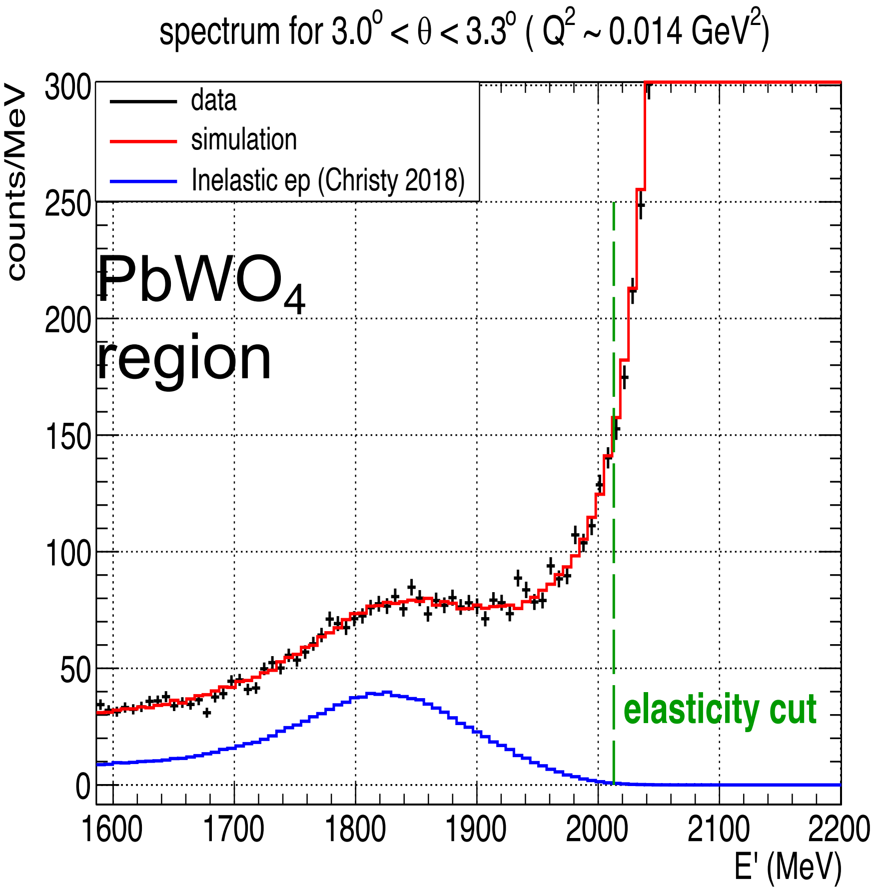
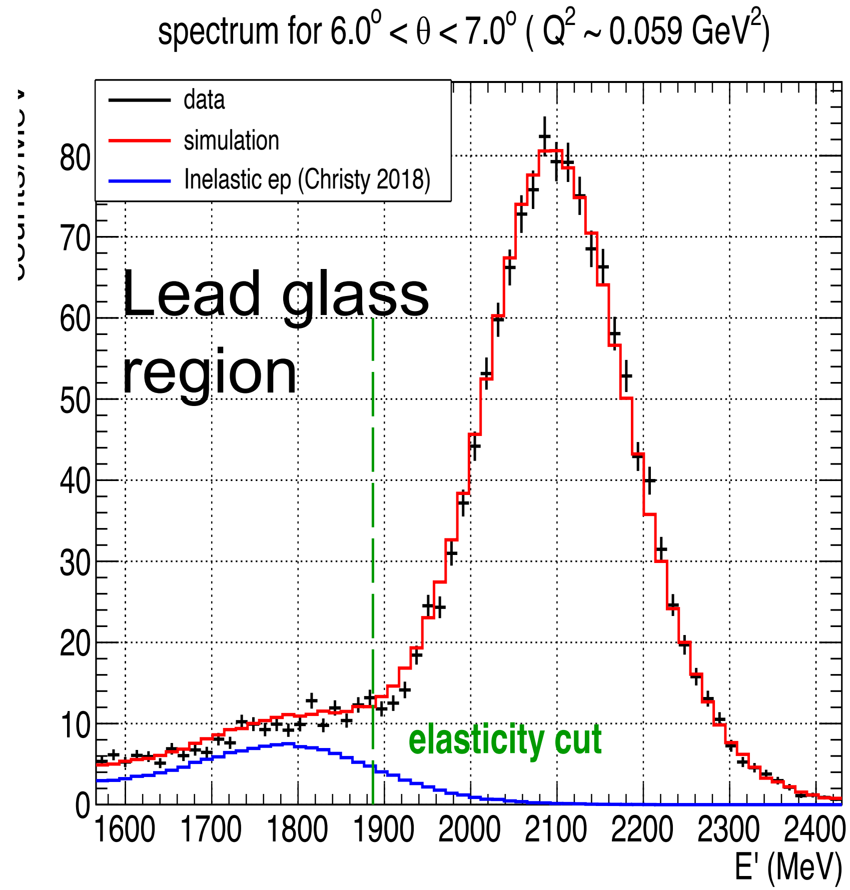
Analysis – elastic cut and inelastic contribution

- Using Christy 2018 empirical fit to study inelastic ep contribution
- Good agreement between data and simulation
- Negligible for the $PbWO_4$ region (<3.5°), less than 0.2%(2.0%) for 1.1GeV(2.2GeV) in the Lead glass region





M.E. Christy and P.E. Bosted. PRC 81, 055213 (2010)

Extraction of ep Elastic Scattering Cross Section

- To reduce the systematic uncertainty, the ep cross section is normalized to the Møller cross section:

$$\left(\frac{d\sigma}{d\Omega}\right)_{ep} = \left[\frac{N_{\exp}(ep \to ep \text{ in } \theta_i \pm \Delta\theta_i)}{N_{\exp}(ee \to ee)} \cdot \frac{\varepsilon^{ee}_{\text{geom}}}{\varepsilon^{ep}_{\text{geom}}} \cdot \frac{\varepsilon^{ee}_{\text{det}}}{\varepsilon^{ep}_{\text{det}}}\right] \left(\frac{d\sigma}{d\Omega}\right)_{ee}$$

- Method 1: bin-by-bin method – taking *ep/ee* counts from the same angular bin
  - Cancellation of energy independent part of the efficiency and acceptance
  - Limited coverage due to double-arm Møller acceptance
- Method 2: integrated Møller method – integrate Møller in a fixed angular range and use it as common normalization for all angular bins
  - Needs to know the GEM efficiency well
- Luminosity cancelled from both methods
- PRad: Bin-by-bin range: 0.7° to 1.6° for 2.2 GeV, 0.75° to 3.0° for 1.1 GeV. Larger angles use integrated Møller method (3.0° to 7.0° for 1.1 GeV; 1.6° to 7.0° for 2.2 GeV)
- PRad-II: two planes of GEM/μRwell allow for ***integrated Møller method*** for the entire experiment
- Event generators for unpolarized elastic ep and Møller scatterings have been developed based on complete calculations of radiative corrections – ***PRad-II with NNL for RC***
  1. A. V. Gramolin et al., J. Phys. G Nucl. Part. Phys. 41(2014)115001
  2. I. Akushevich et al., Eur. Phys. J. A 51(2015)1 (beyond ultra relativistic approximation)
- A Geant4 simulation package is used to study the radiative effects, and an iterative procedure applied

$$\sigma_{ep}^{Born(exp)} = \left(\frac{\sigma_{ep}}{\sigma_{ee}}\right)^{exp} / \left(\frac{\sigma_{ep}}{\sigma_{ee}}\right)^{sim} \cdot \left(\frac{\sigma_{ep}}{\sigma_{ee}}\right)^{Born(model)} \cdot \sigma_{ee}^{Born(model)}$$

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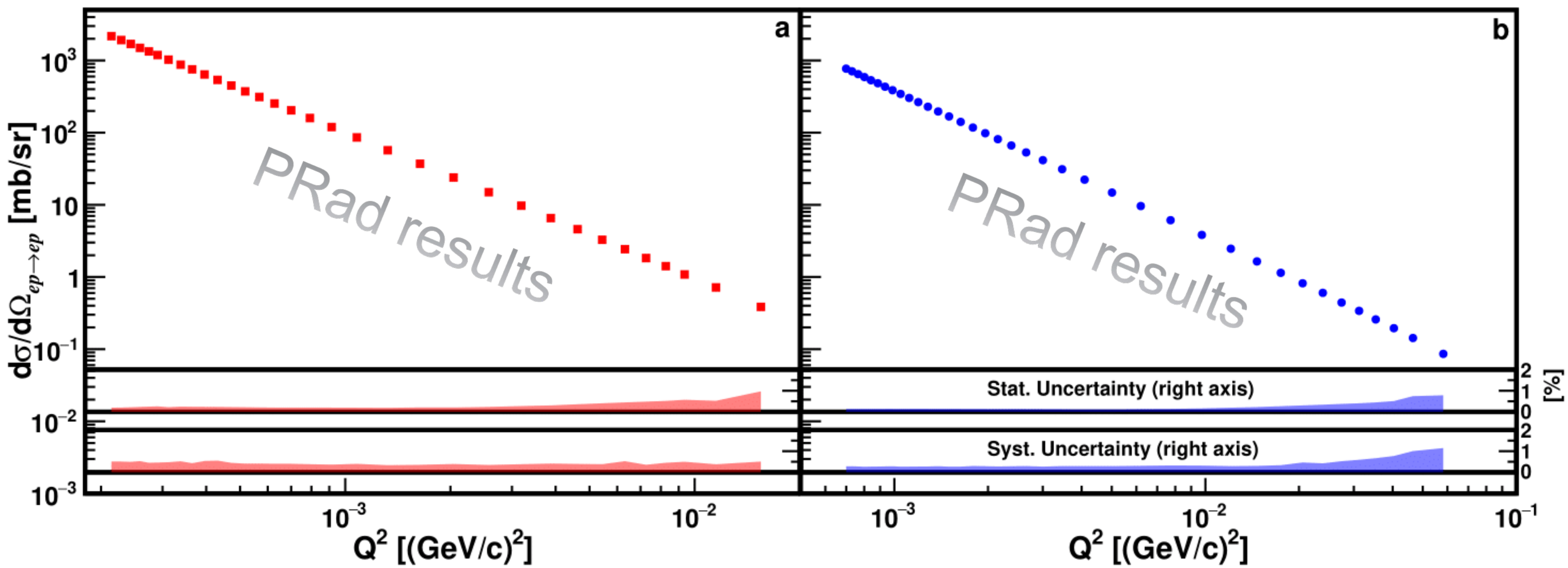
Elastic ep Cross Sections

- 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

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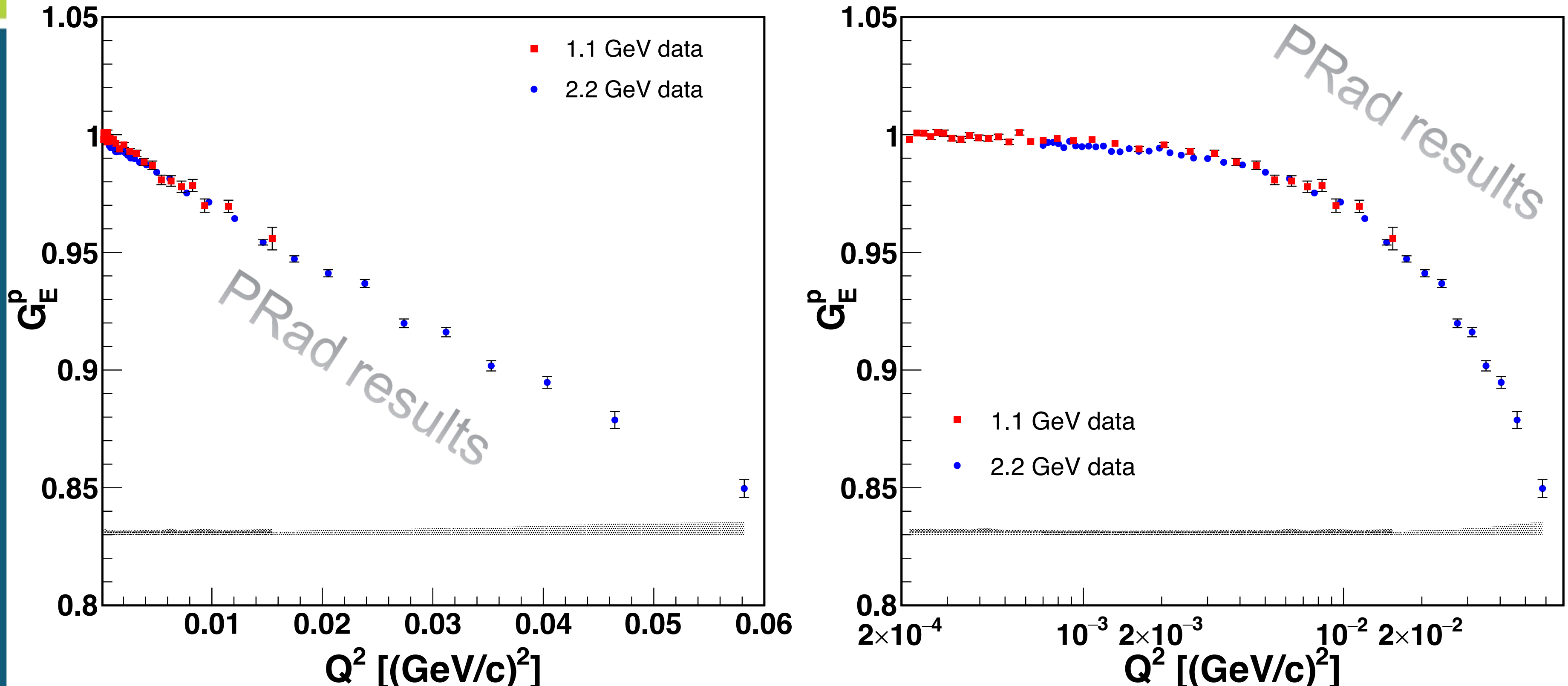
Proton Electric Form Factor G_E



Proton Electric Form Factor G'_E (Normalized)

- n_1 and n_2 obtained by fitting PRad G_E to $\begin{cases} n_1 f(Q^2), & \text{for 1GeV data} \\ n_2 f(Q^2), & \text{for 2GeV data} \end{cases}$

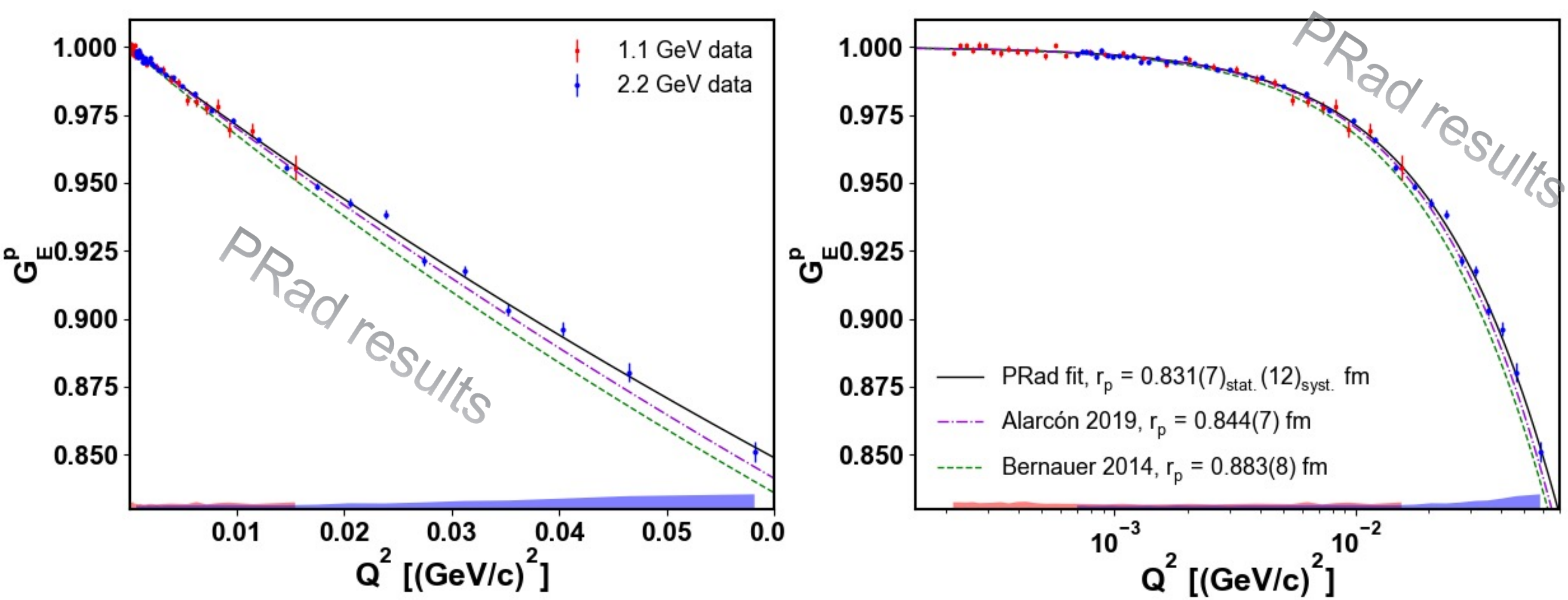
Using rational (1,1)

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

- 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*. PRC98,025204 (2018)

- PRad fit shown as $f(Q^2)$ $r_p =$ 0.831 +/- 0.007 (stat.) +/- 0.012 (syst.) fm



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

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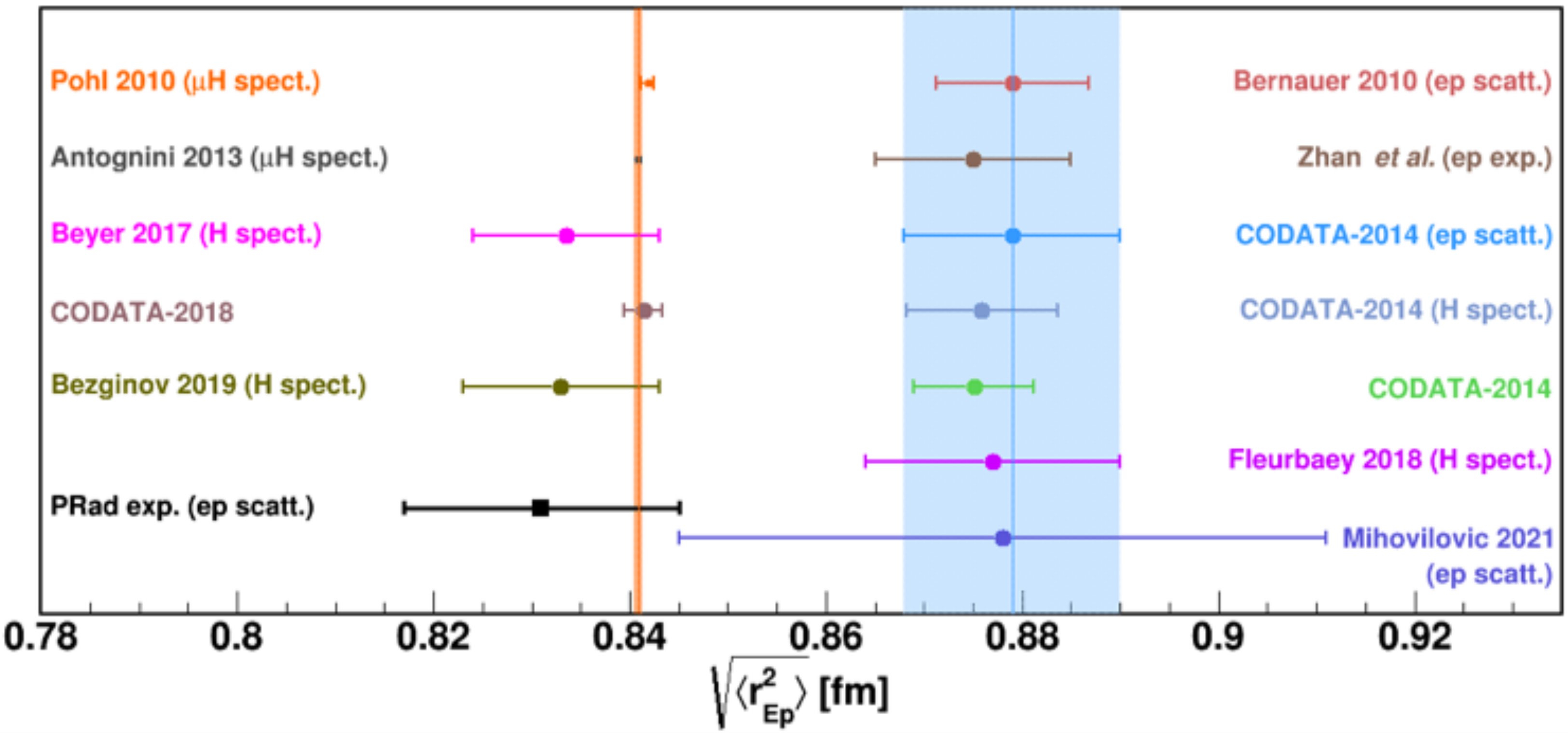
Proton radius at the time of PRad publication

- 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.

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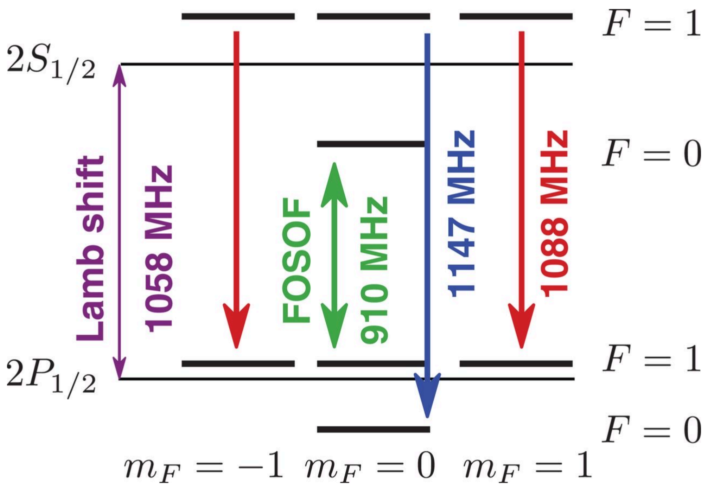
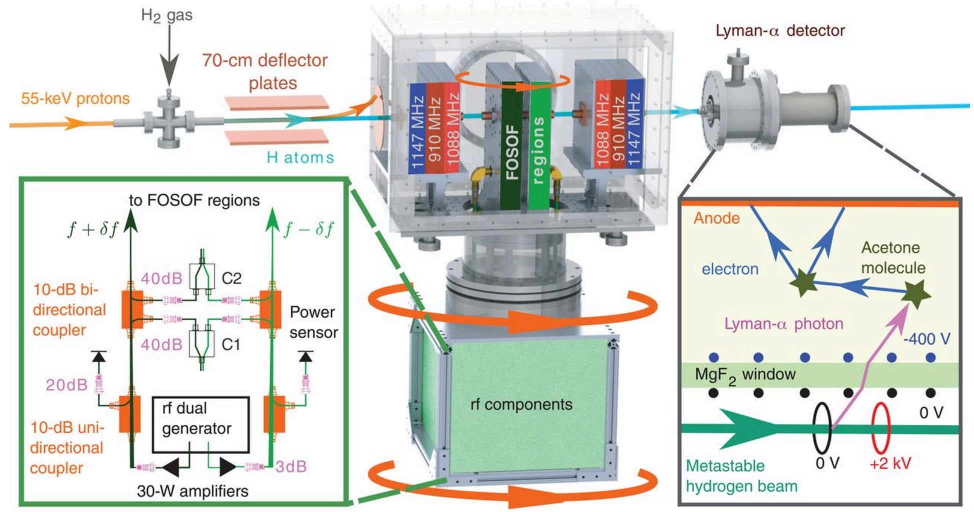
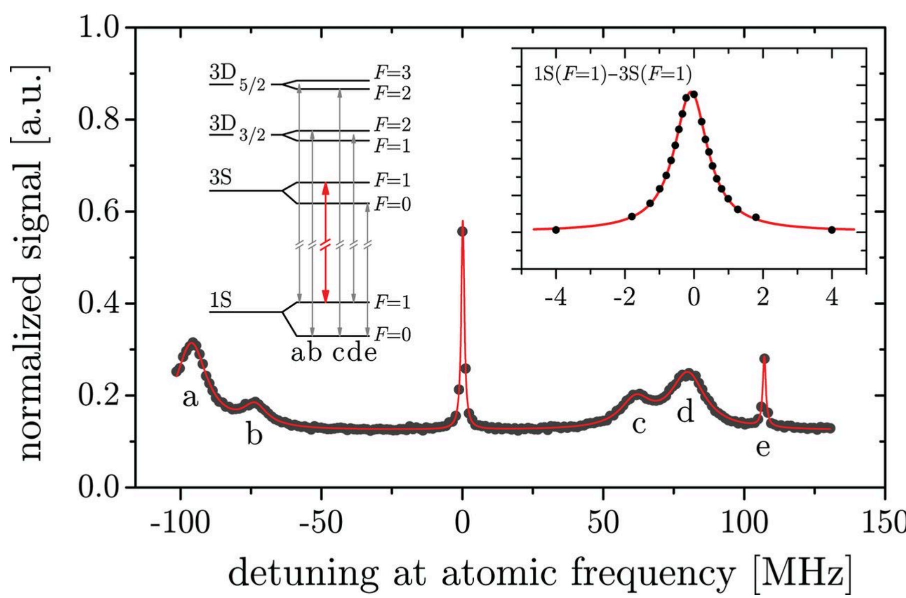
More from ordinary hydrogen spectroscopy

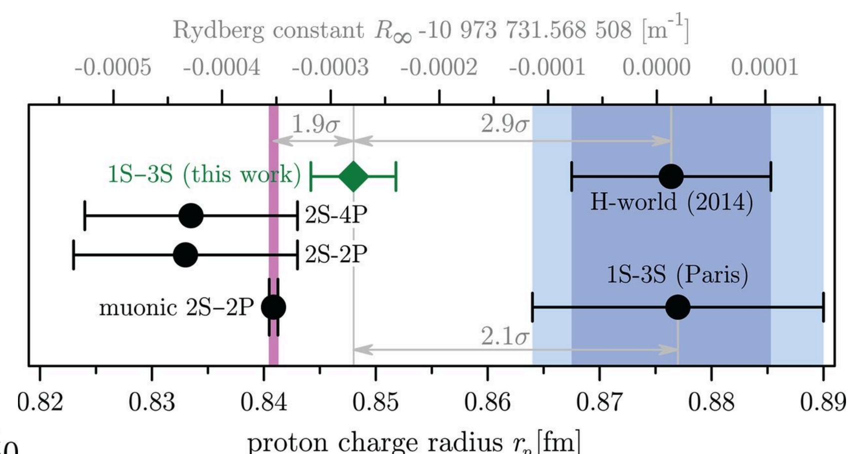




Bezginov *et al.*, Science 365, 1007 (2019)

r_p = 0.833(10) fm





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

r_p = 0.8482(38) fm

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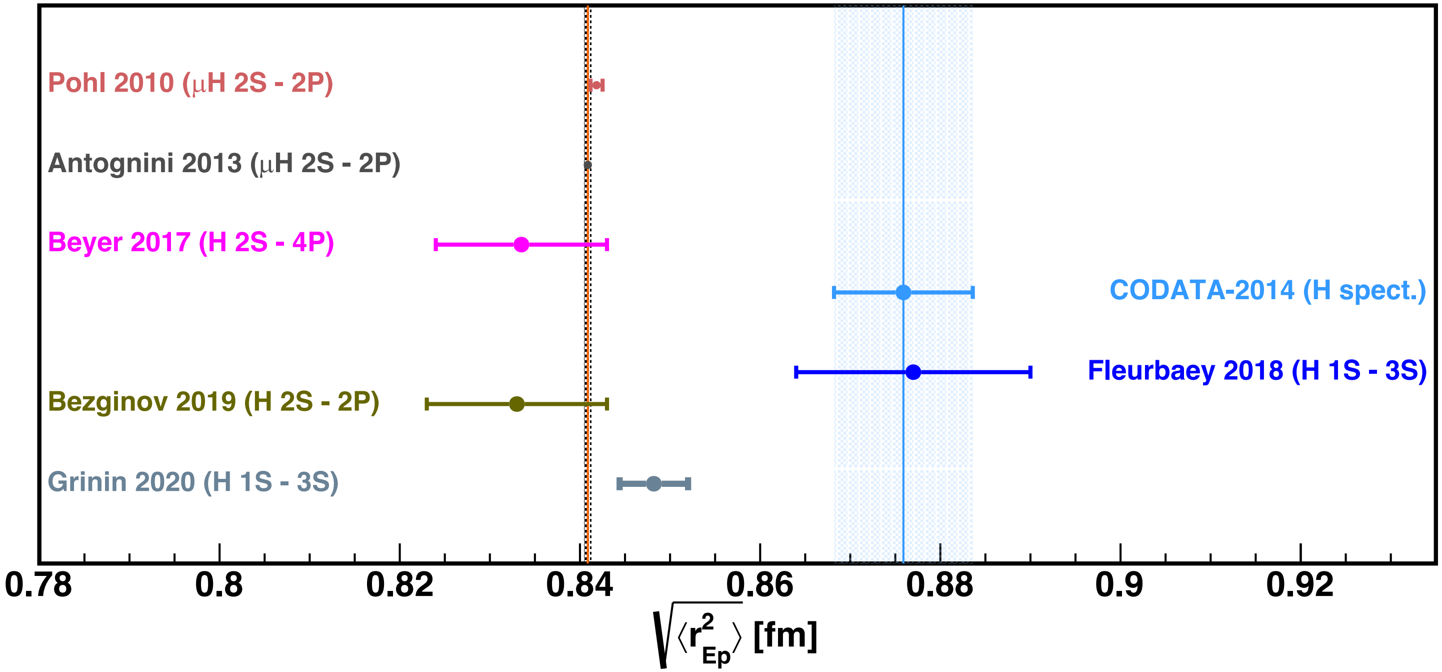
Proton radius from ordinary and muonic H spectroscopy



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	$2S^{F=1}_{1/2} - 2P^{F=2}_{3/2}$ $2S^{F=0}_{1/2} - 2P^{F=1}_{3/2}$	0.84087(39)	
Beyer 2017	H	$2S - 4P$ with $(1S - 2S)$	0.8335(95)	10 973 731.568 076 (96)
Fleurbaey 2018	H	$1S - 3S$ with $(1S - 2S)$	0.877(13)	10 973 731.568 53(14)
Bezginov 2019	H	$2S_{1/2} - 2P_{1/2}$	0.833(10)	
Grinin 2020	H	$1S - 3S$ with $(1S - 2S)$	0.8482(38)	10 973 731.568 226(38)

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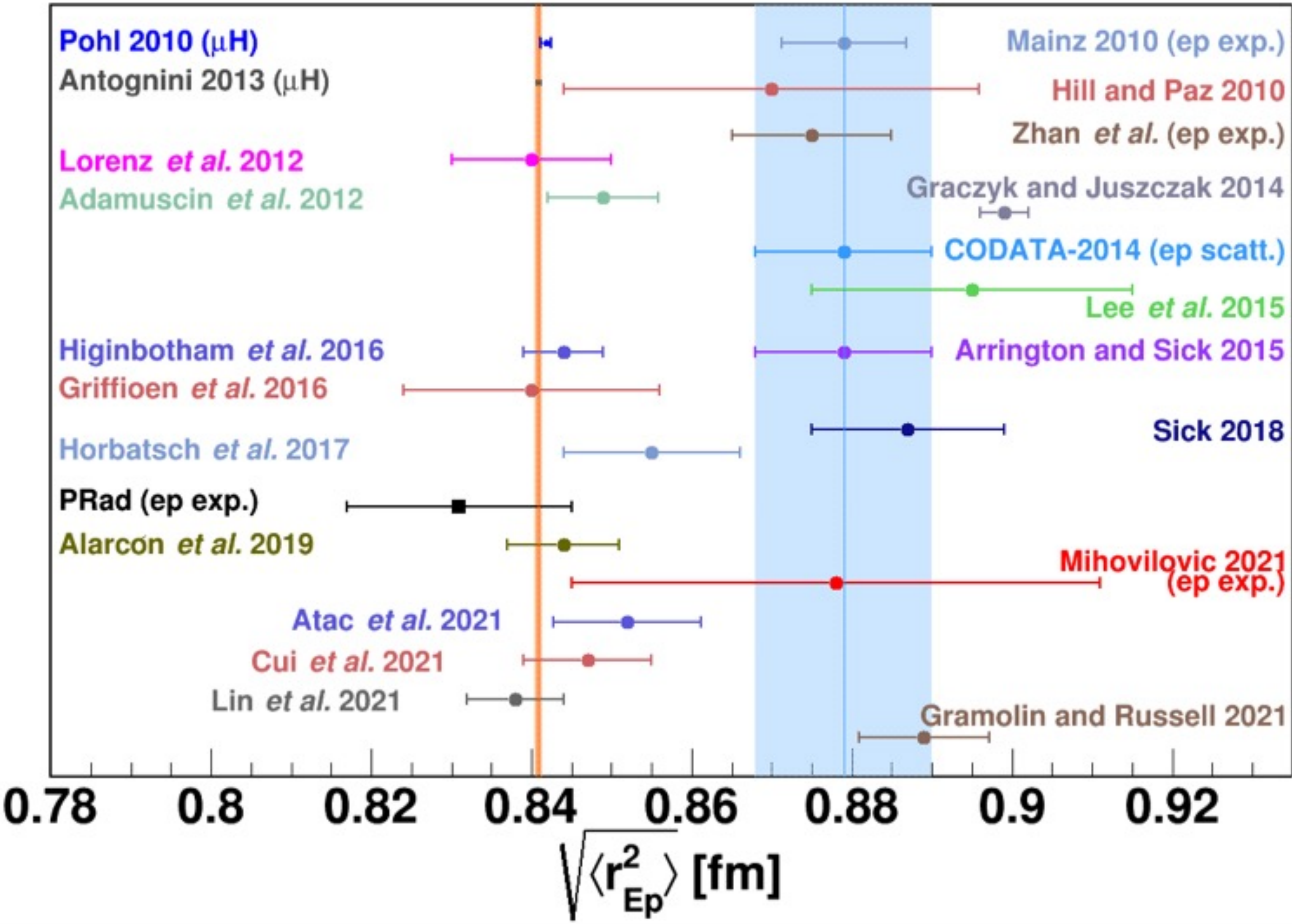
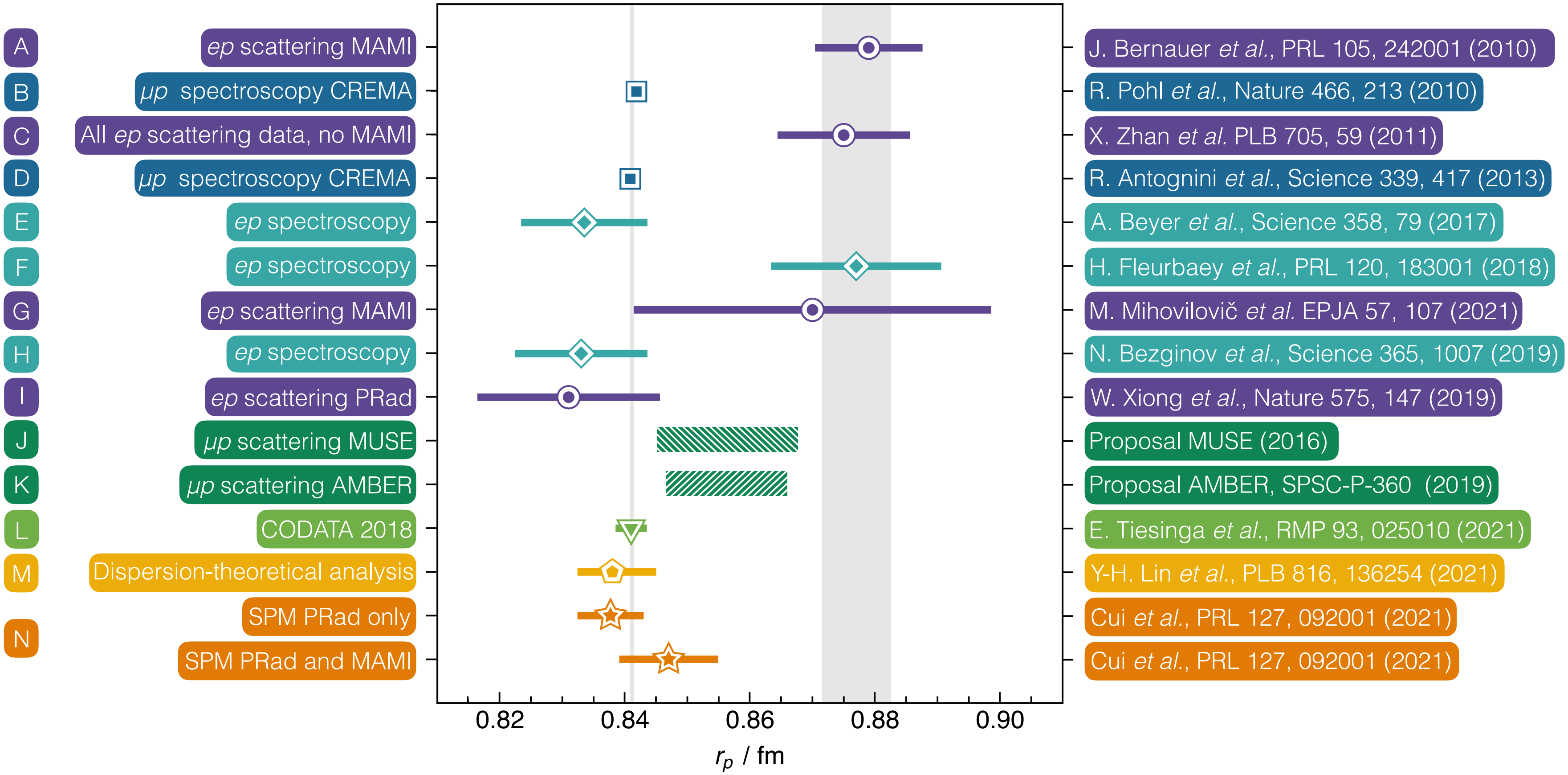
(Re)analyses of e-p scattering data



Gao and Vanderhaeghen, Rev. Mod. Phys. 94, 015002 (2022)



More recent review by Zhu-Fang Cui *et al* 2022
Chinese Phys. C **46** 122001

statistical Schlessinger point method (SPM)

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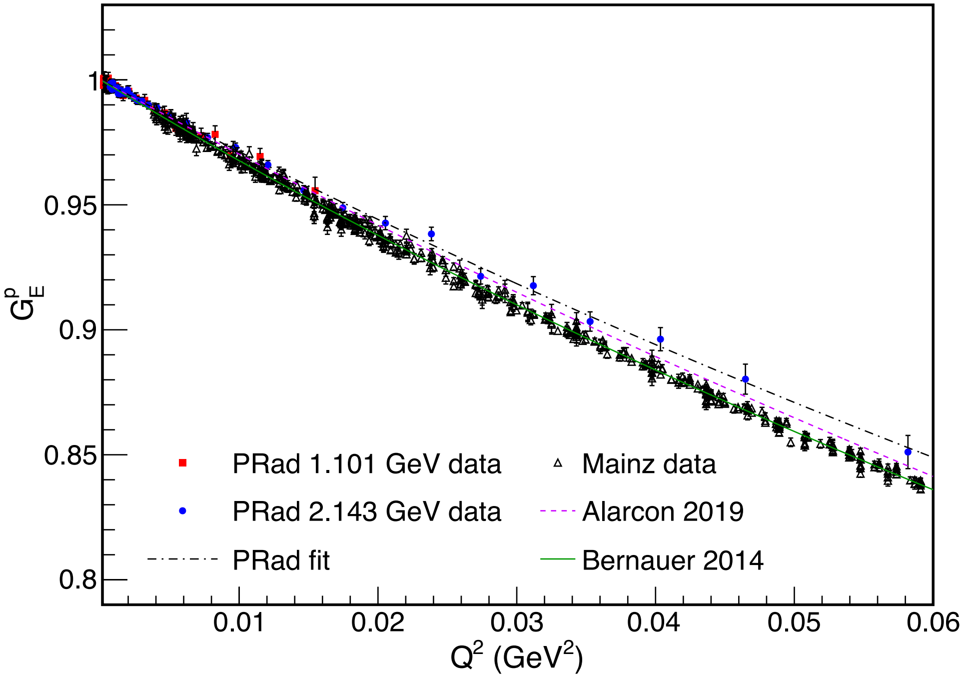
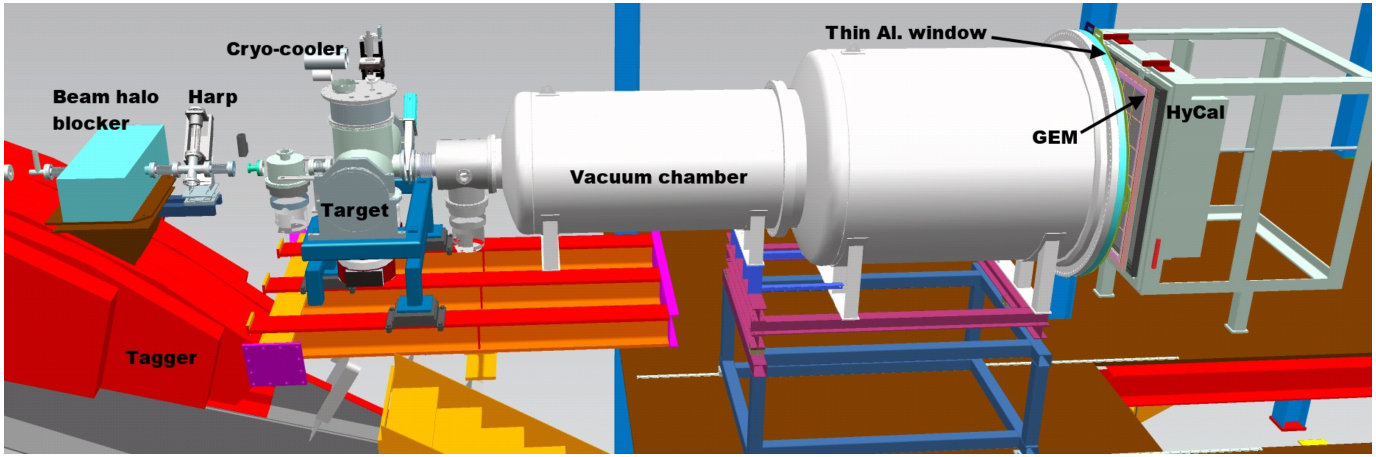
e-p scattering: magnetic spectrometer and calorimetric method





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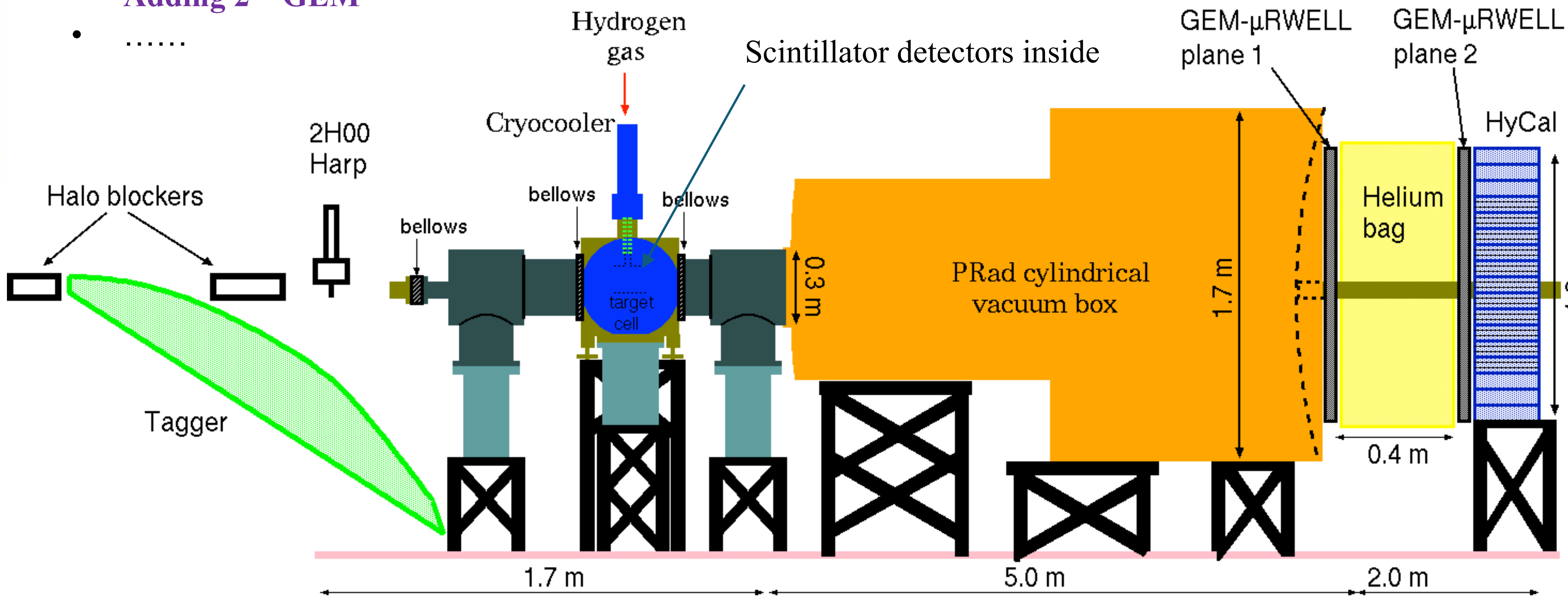
PRad-II: goals and approaches

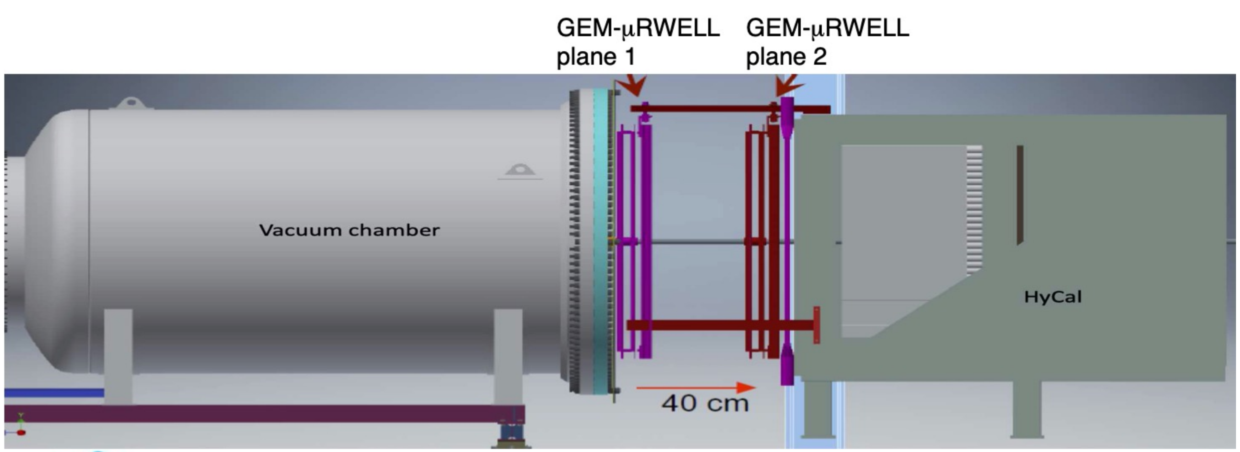
- Reduce the uncertainty of the r_p measurement by a factor of **3.8!**
- Reach an unprecedented low values of Q^2 : 4×10^{-5} $(GeV/c)^2$
- How?
  - Improving tracking capability by adding a second plane of tracking detector
  - Adding new rectangular cross shaped scintillator detectors to separate Moller from ep electrons in scattering angular range of 0.5^0- 0.8^0
  - Upgrading HyCal and electronics for readout
    - Replacing lead glass blocks by $PbWO_4$ modules (uniformity, resolutions, inelastic channel)
    - Converting to FADC based readout
  - Suppressing beamline background
    - Improving vacuum
    - Adding second beam halo blocker upstream of the tagger
  - Reducing statistical uncertainties by a factor of 4 compared with PRad
  - Three beam energies: 0.7, 1.4 and 2.1 GeV – ***0.7 GeV is critical to reach the lowest Q^2 (4×10^{-5} $(GeV/c)^2$)***
  - Improve radiative correction calculations by going to NNL order
  - Potential target improvement (***not used in projection***)

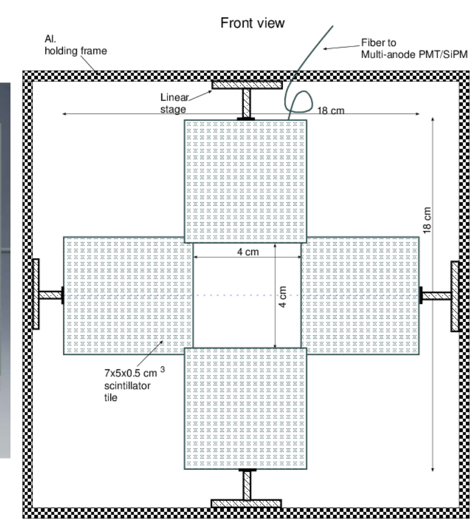
Approved with the highest rating by the JLab Program Advisory Committee in summer 2020

PRad-II Experimental Setup (Side View)

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

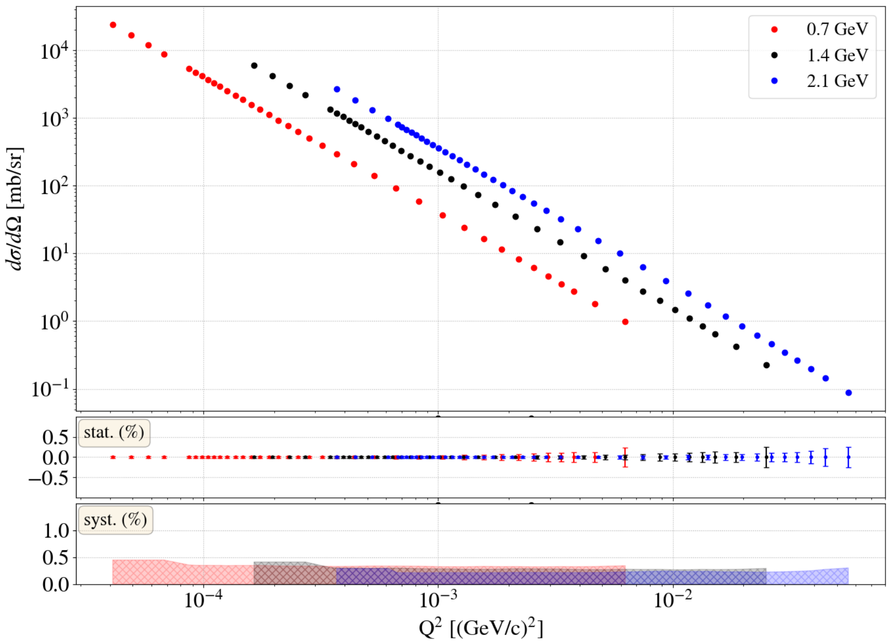




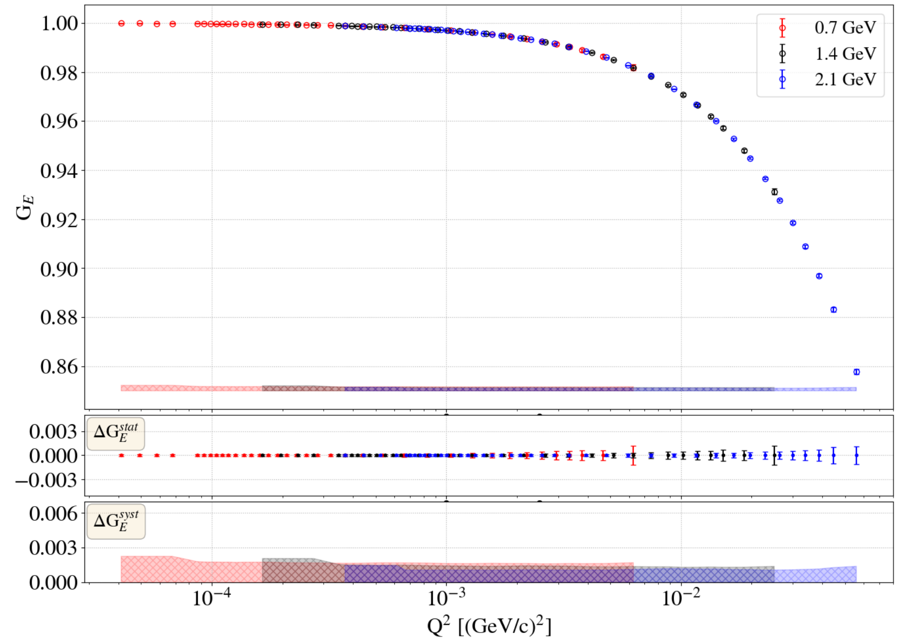


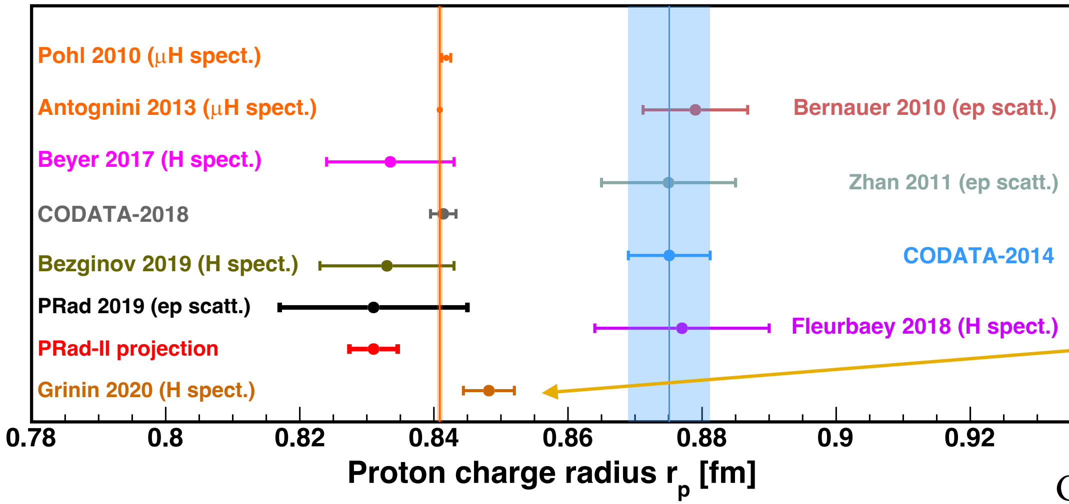
Projections for PRad-II

Differential Cross section



Electric form factor



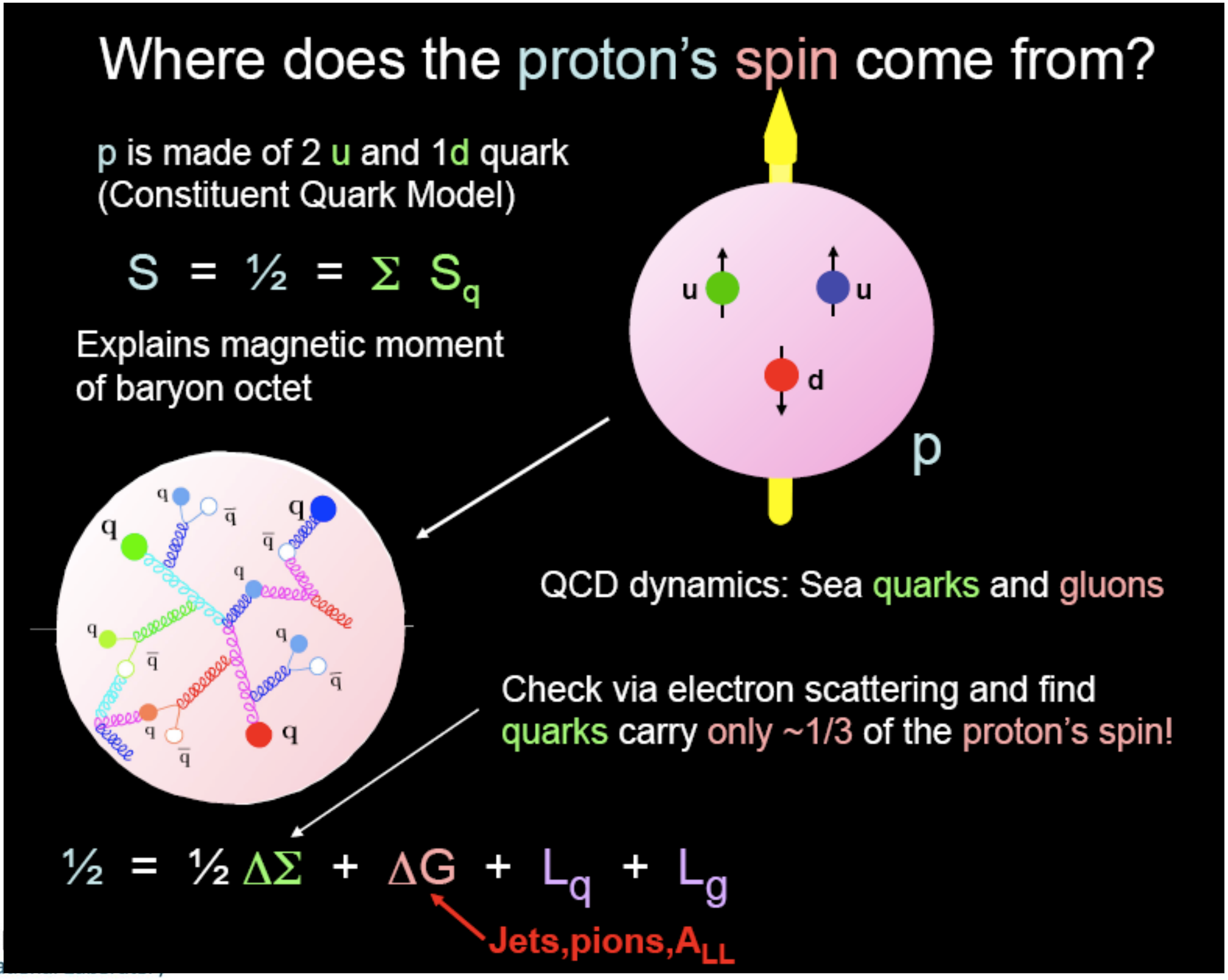


- Nuclear deformation effects, Lin and Zou, arxiv:1910.13916
- New physics?
  - **Latest result from ordinary hydrogen Lamb shift:** $r_p = 0.8482 \pm 0.0038$ fm Grinin *et al*., Science **370**, 1061 (2020)
  - **PRad-II: total uncertainty 0.0036 fm**

Gasparian *et al.* arXiv:2009.10510

Spin structure of the nucleon

- 1980s: "Proton spin crisis" (original EMC result from CERN)



The Electron-Ion Collider

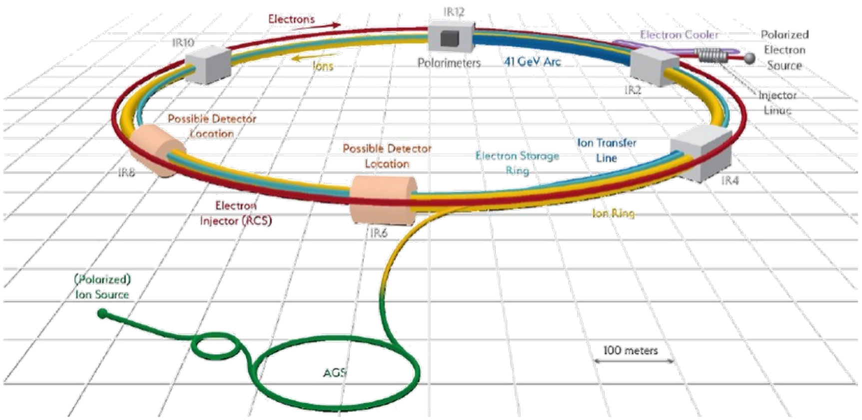
2015 NSAC LRP

“We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB."

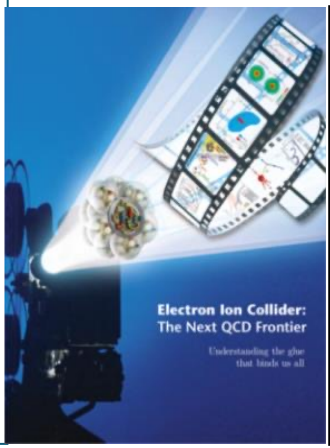
Project Design Goals

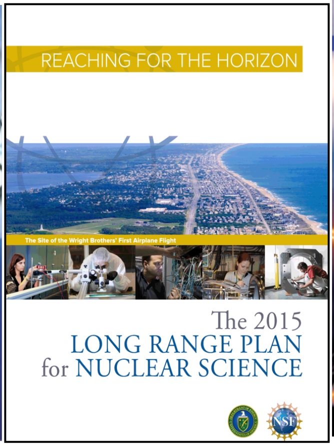
- High Luminosity: L= 10^{33}–10^{34} $cm^{-2}sec^{-1}$, 10–100 fb^{-1}/year
- Highly Polarized Beams: ~70%
- Large Center of Mass Energy Range: E_{cm} = 20–140 GeV
- Large Ion Species Range: protons – Uranium
- Large Detector Acceptance and Good Background Conditions
- Accommodate a Second Interaction Region (IR)

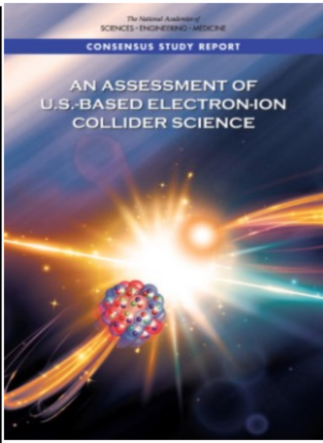
Conceptual design scope and expected performance meet or exceed NSAC Long Range Plan (2015) and the EIC White Paper requirements endorsed by NAS (2018)

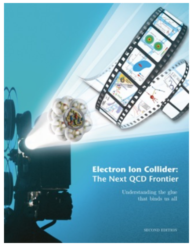


Double Ring Design Based on Existing RHIC Facility

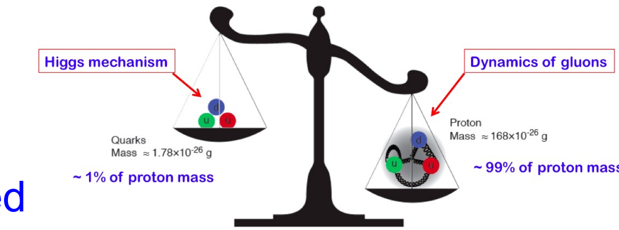






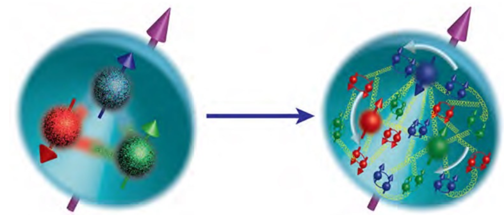


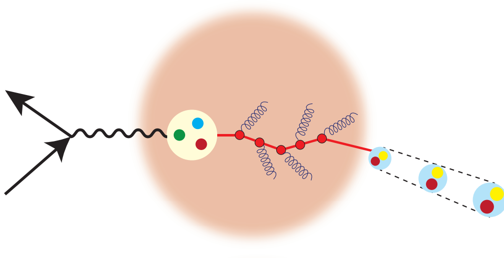
EIC Physics at-a-Glance



How are the sea quarks and gluons, and their spins, distributed space and momentum inside the nucleon?

How do the nucleon properties (mass & spin) emerge from their interactions?

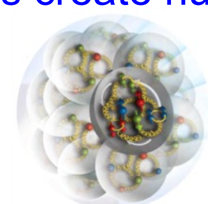




How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

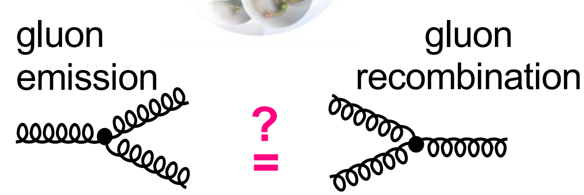
How do the confined hadronic states emerge from these quarks and gluons?

How do the quark-gluon interactions create nuclear binding?



How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?



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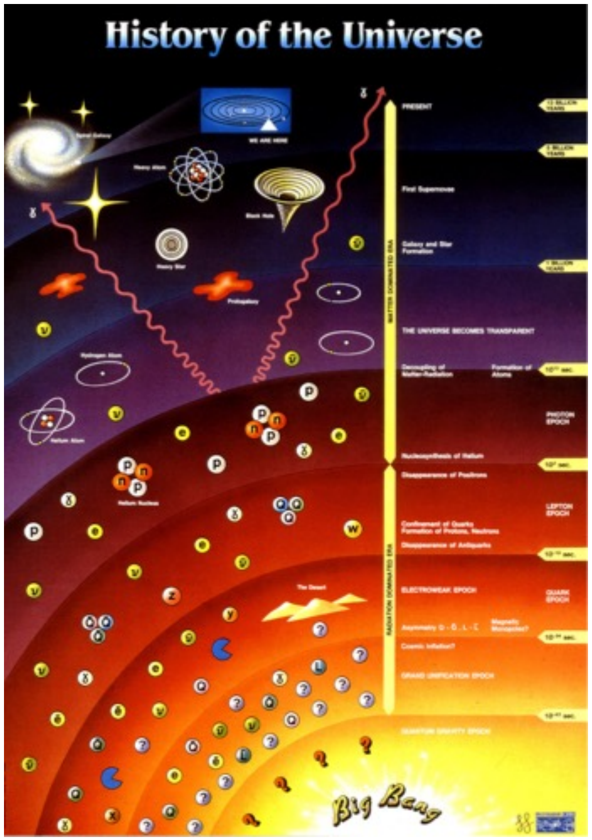
Nuclear physics – study of structure of matter in all its forms

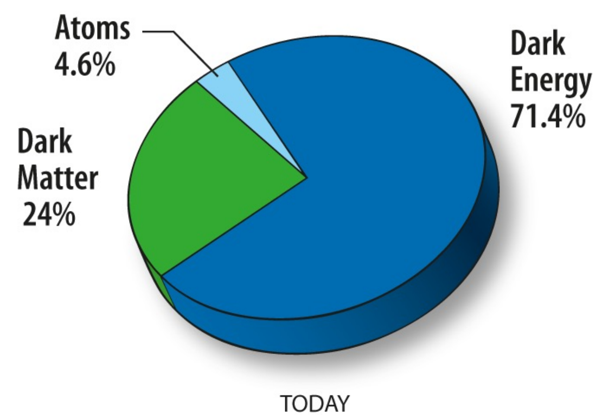
– **Most of the mass and energy in the universe around us comes from nuclei and nuclear reactions.**

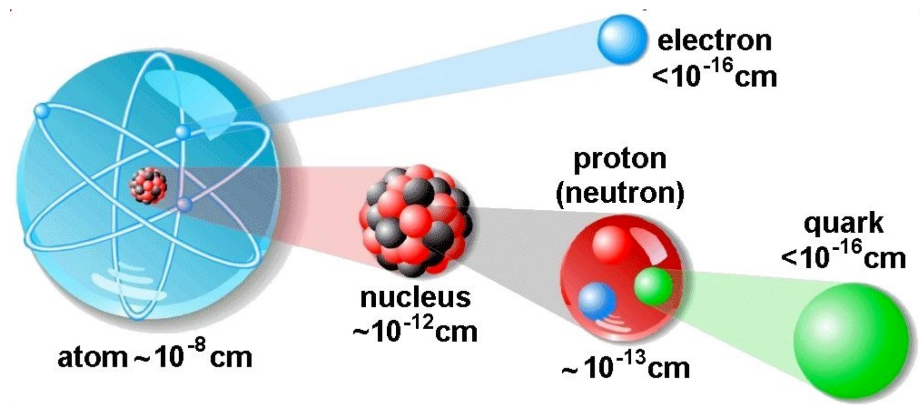
– **The nucleus is a unique form of matter in that all the forces of nature are present : (strong, electromagnetic, weak).**



About 1 second after the Big Bang, protons and neutrons were formed

In today's universe, 99% visible matter are atomic nuclei (protons and neutrons).





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