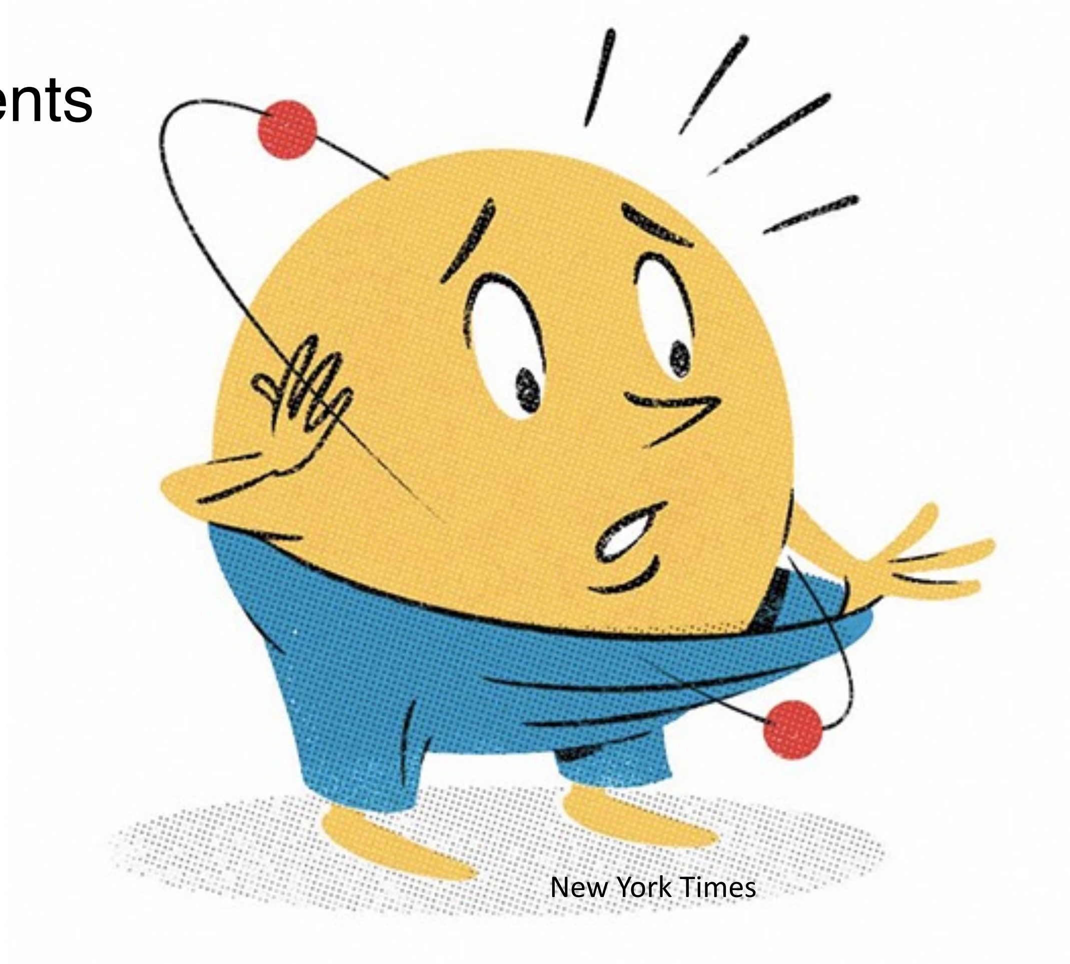
Current Status and Future of Proton Charge Radius Puzzle

- Weizhi Xiong (熊伟志)
- 山东大学

- Seminar @ 中国科学技术大学
- June 28th 2023

Outline

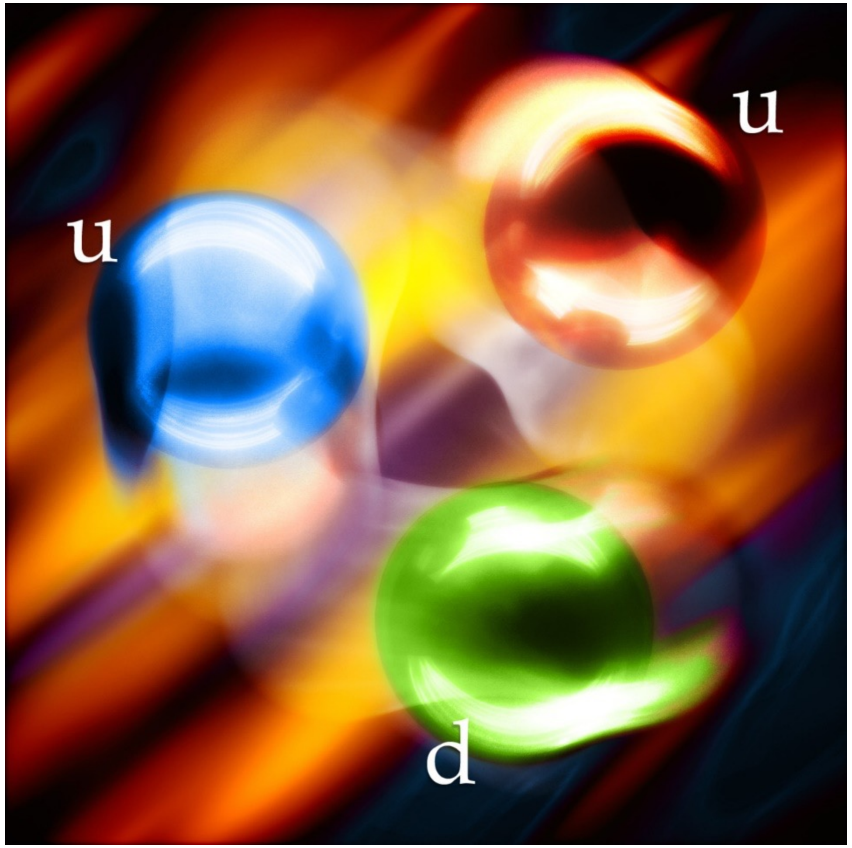
- ➢Intro to Proton Charge Radius Puzzle
- ➢Recent Progress from *ep* Scattering Experiments
- ➢Remaining Issues for Lepton Scattering
- ➢Future Lepton Scattering Experiments
- ➢Summary


New York Times

General Info on r_p

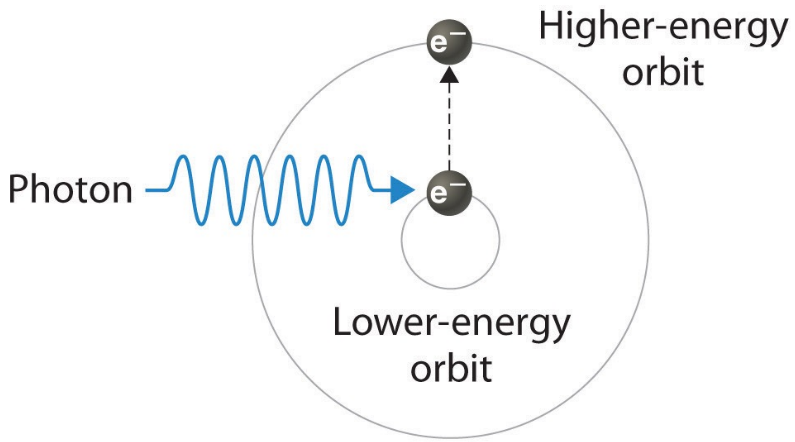
- Nucleons (protons and neutrons) make up over 99% of the mass of visible universe

- Proton charge radius (r_p):
  1. Related to spacial distribution of proton's charge
  2. Important for understanding how QCD works
  3. Critical in determining Rydberg constant (R_∞)
  4. Input to the bound state QED calculation for atomic hydrogen energy levels

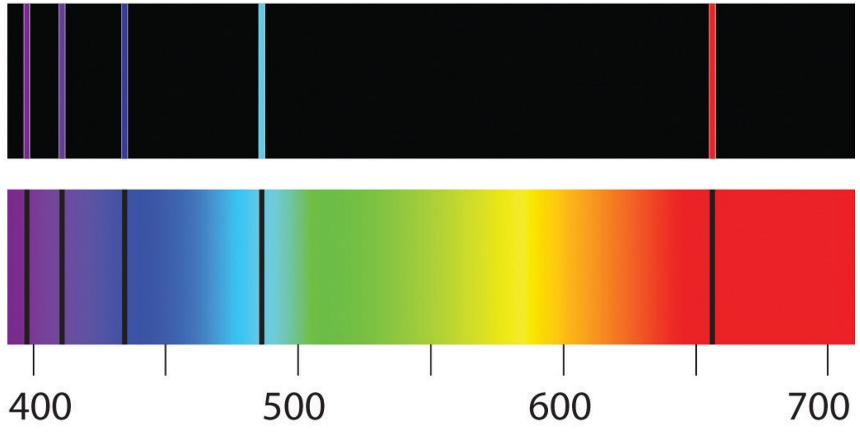


How to Measure

- Two different methods for measuring r_p
  1. Hydrogen spectroscopy (atomic physics)
     - ➢ Ordinary hydrogen
     - ➢ Muonic hydrogen



(a) Electronic absorption transition



(b) H_2 emission spectrum (top), H_2 absorption spectrum (bottom)

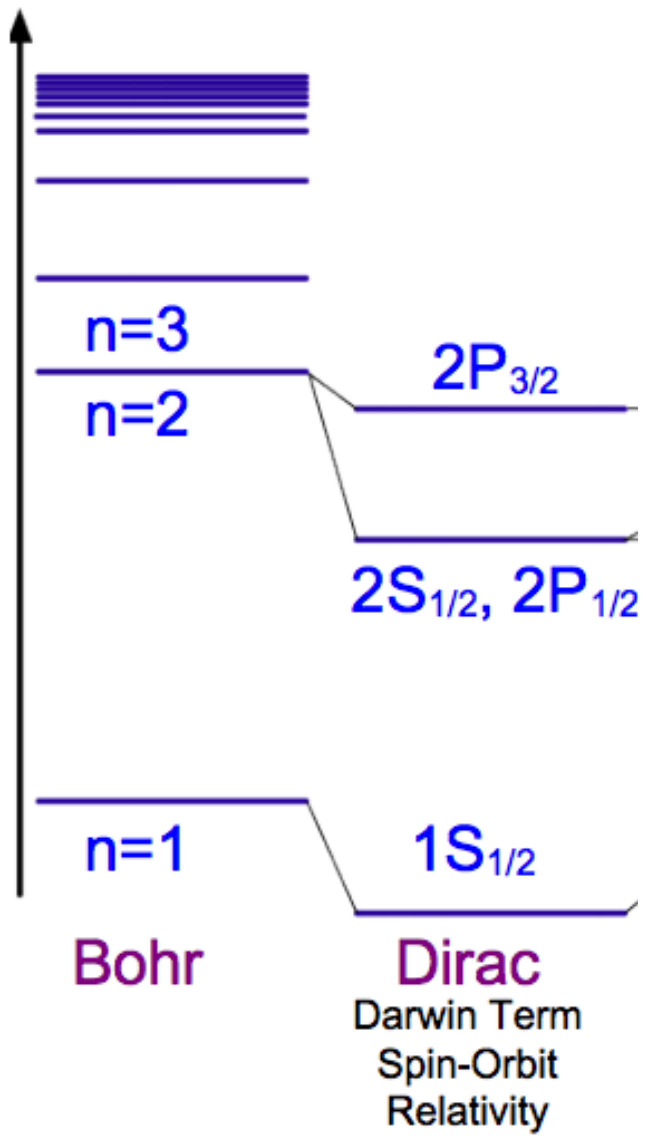
How to Measure

- Two different methods for measuring r_p

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

2. Lepton-proton elastic scattering (nuclear physics)
   - *ep* elastic scattering (like PRad)
   - *μp* elastic scattering (like MUSE)

Hydrogen Spectroscopy



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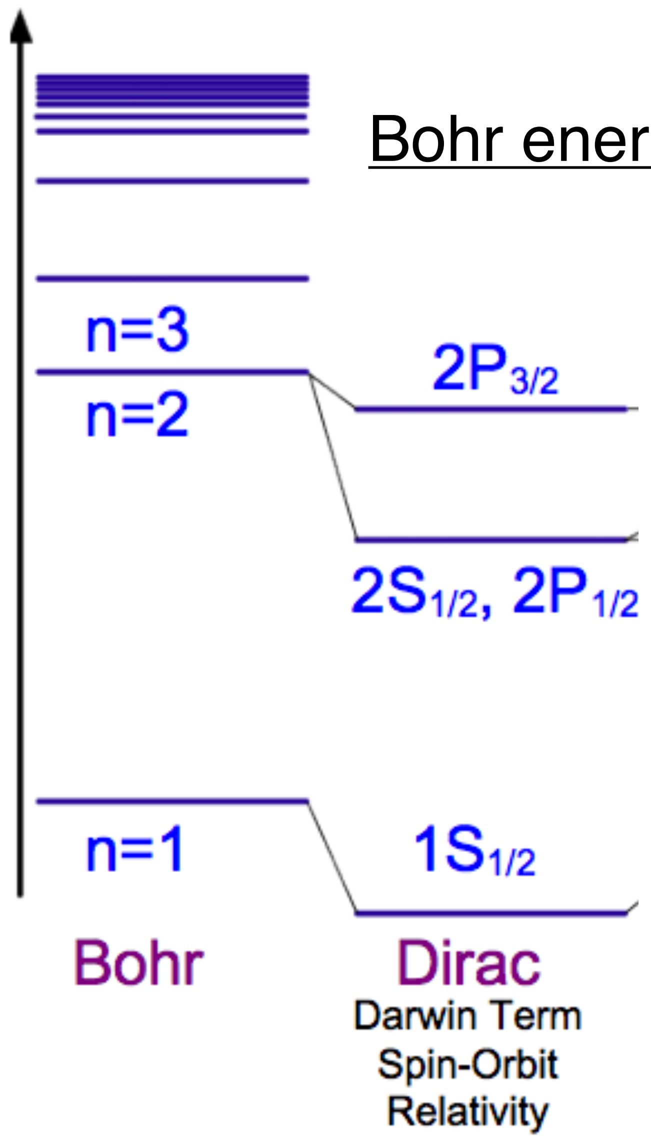
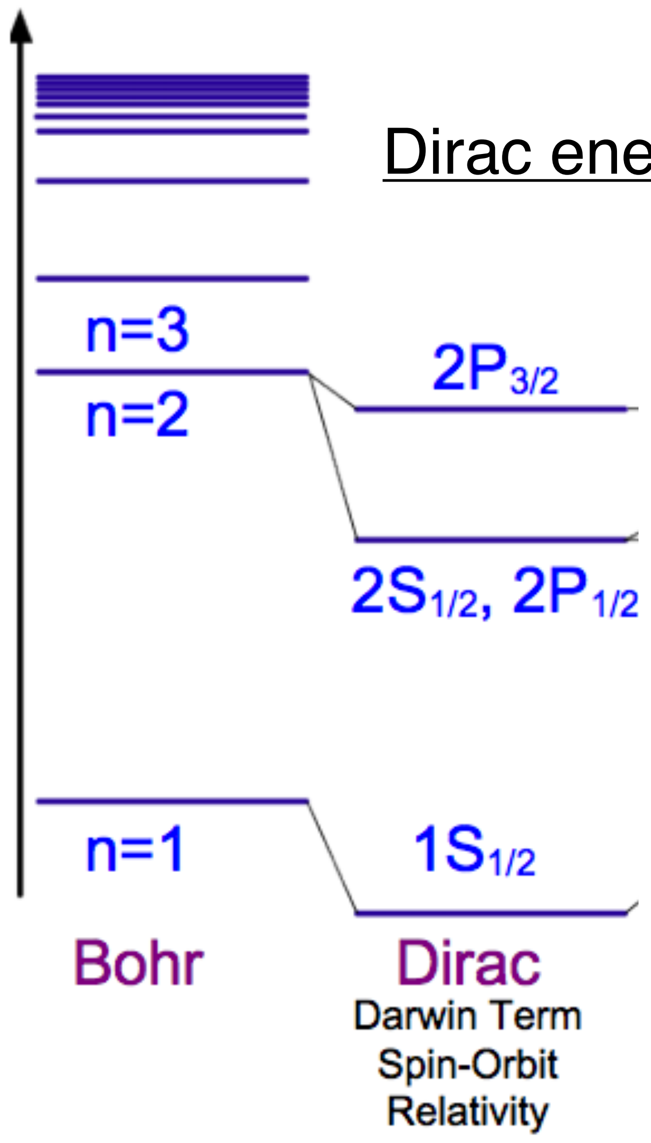


Bohr energy level: $$E_n = -m\frac{(Z\alpha)^2}{2n^2} = -2\pi R_\infty \frac{Z^2}{n^2},$$

Hydrogen Spectroscopy

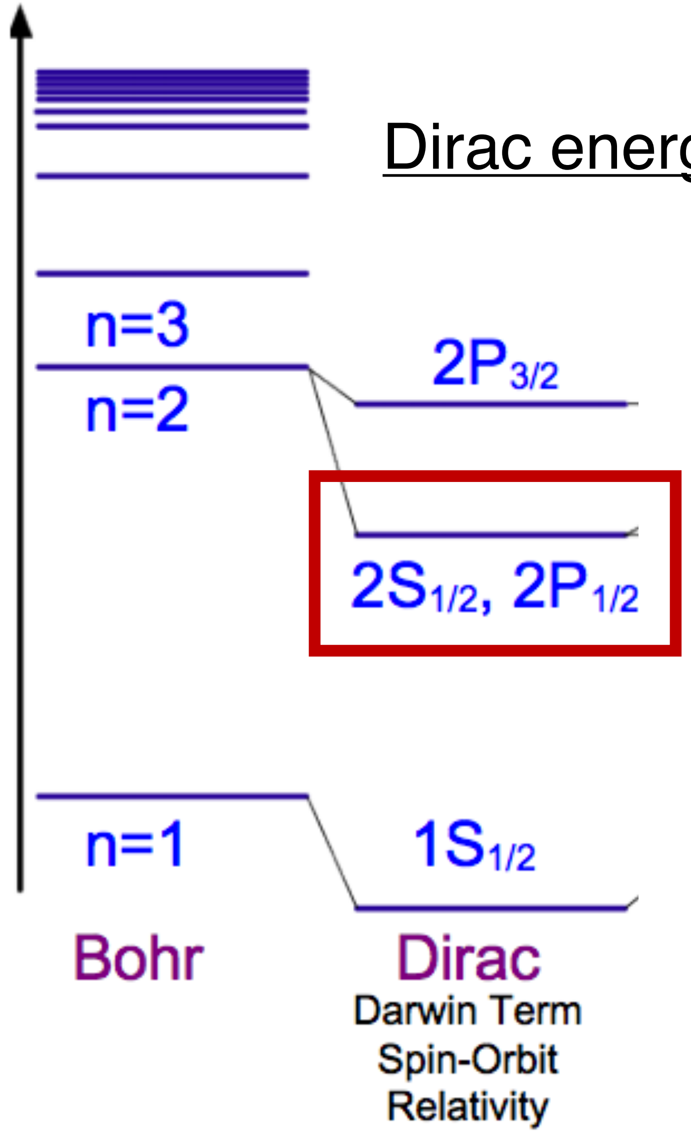


Dirac energy level:

$$E_{nj} = mc^2 \, f(n,j)\,,$$

$$f(n,j) = \left[1 + \frac{(Z\alpha)^2}{\left(n - j - \frac{1}{2} + \sqrt{\left(j+\frac{1}{2}\right)^2 - (Z\alpha)^2}\right)^2}\right]^{-\frac{1}{2}}$$

Hydrogen Spectroscopy



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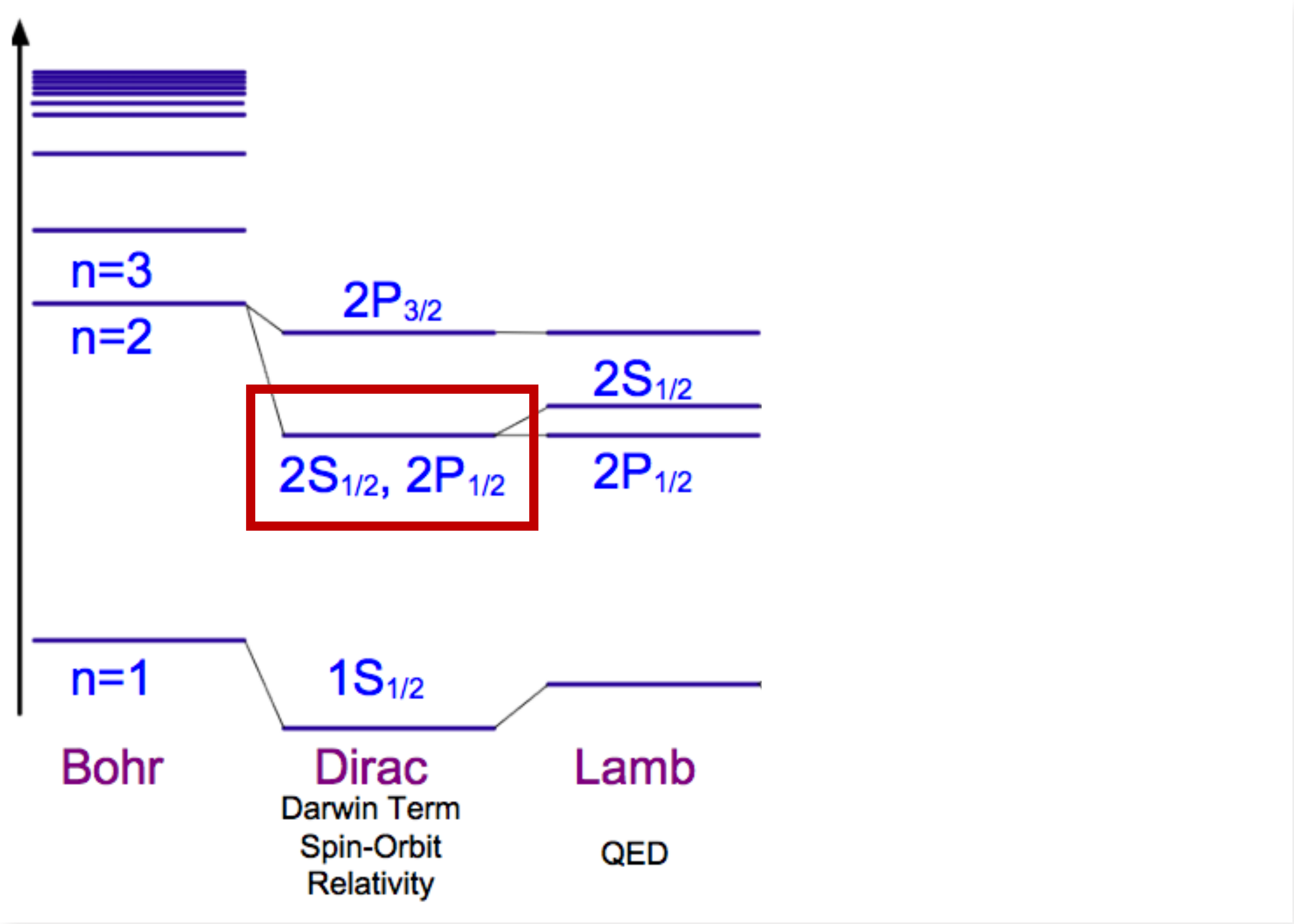
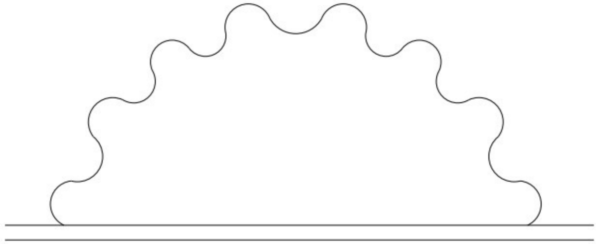


- Lamb shift measured in 1947
- Transition frequency about 1 GHz
- Largely dominated by electron self-energy



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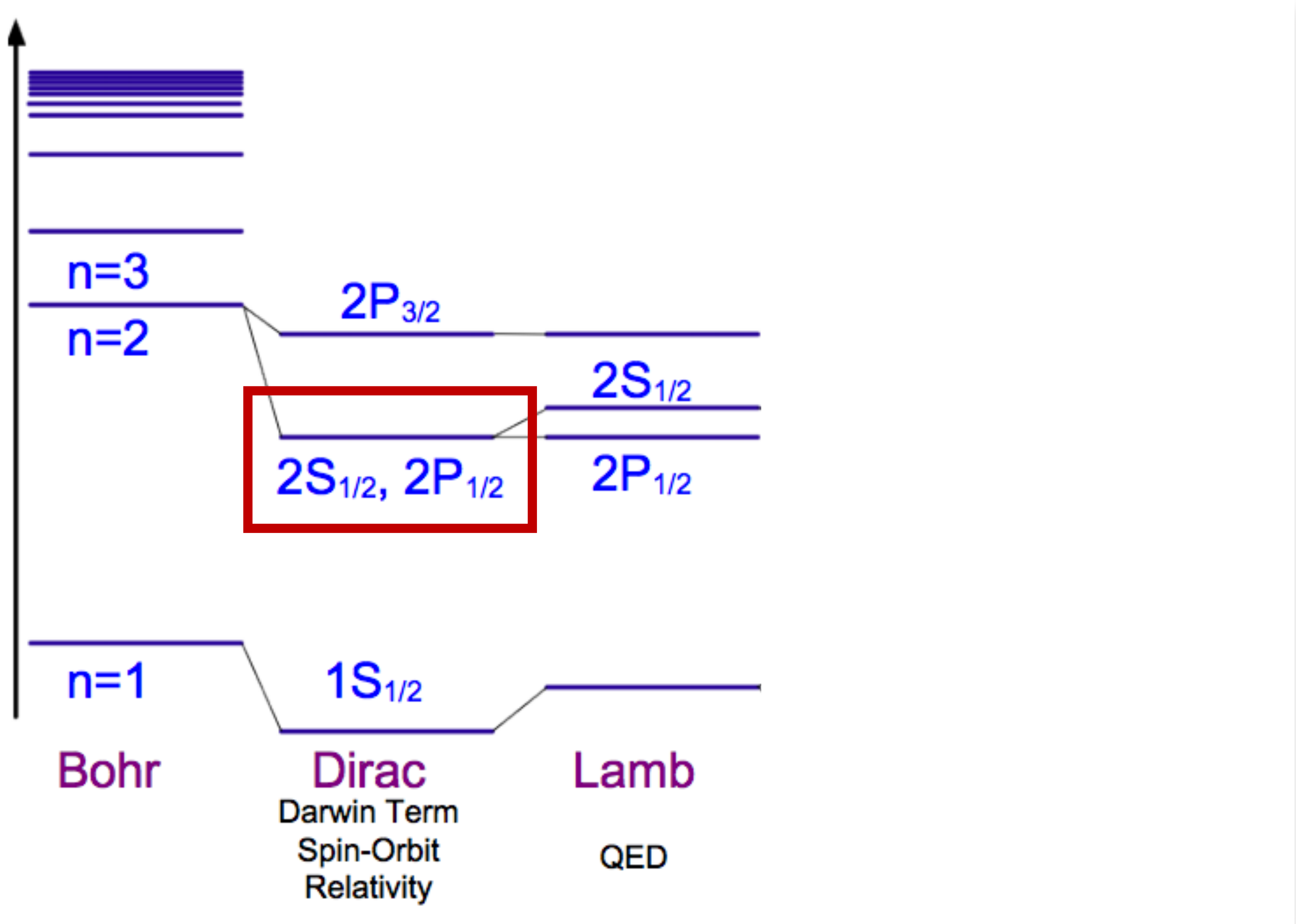
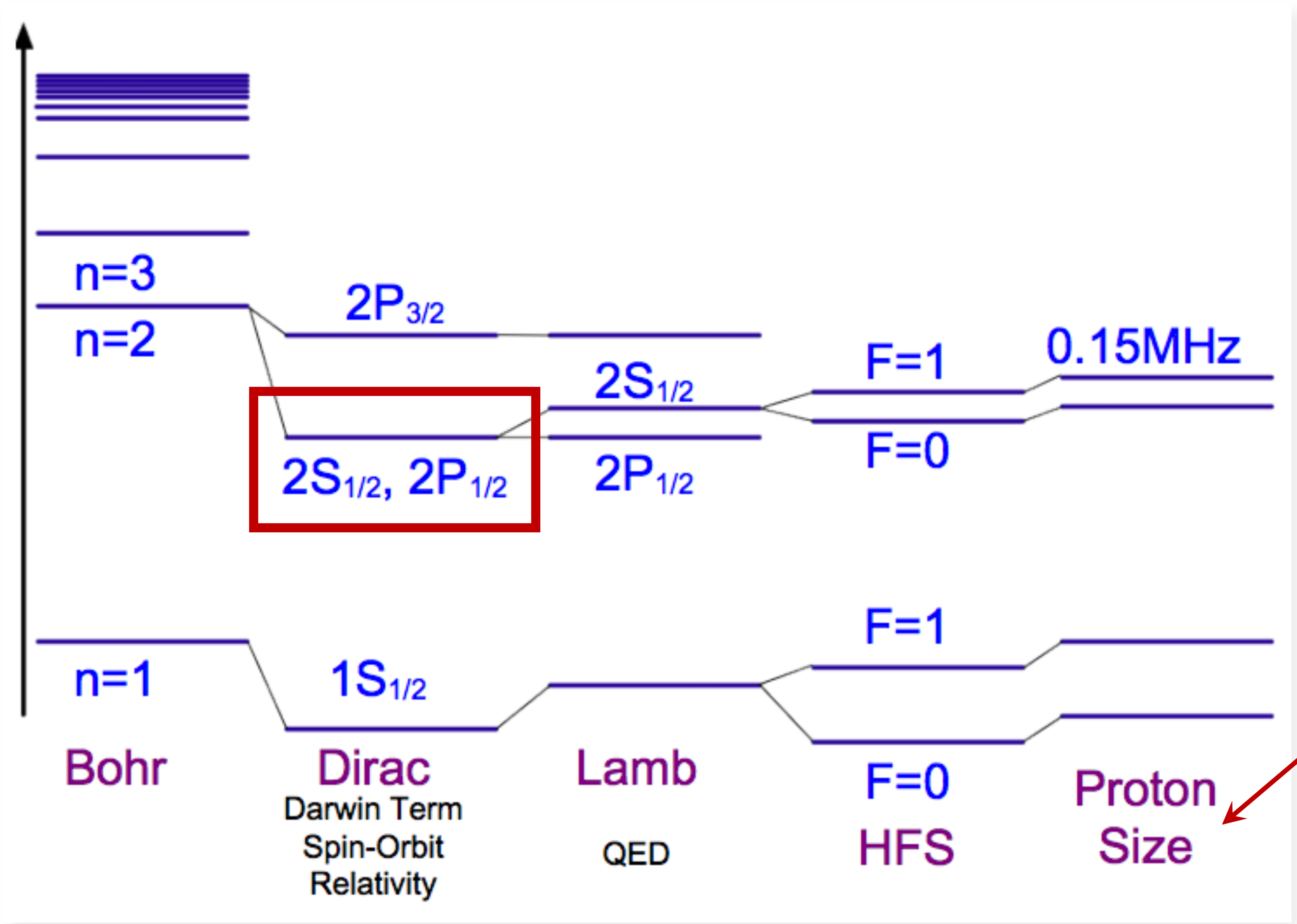


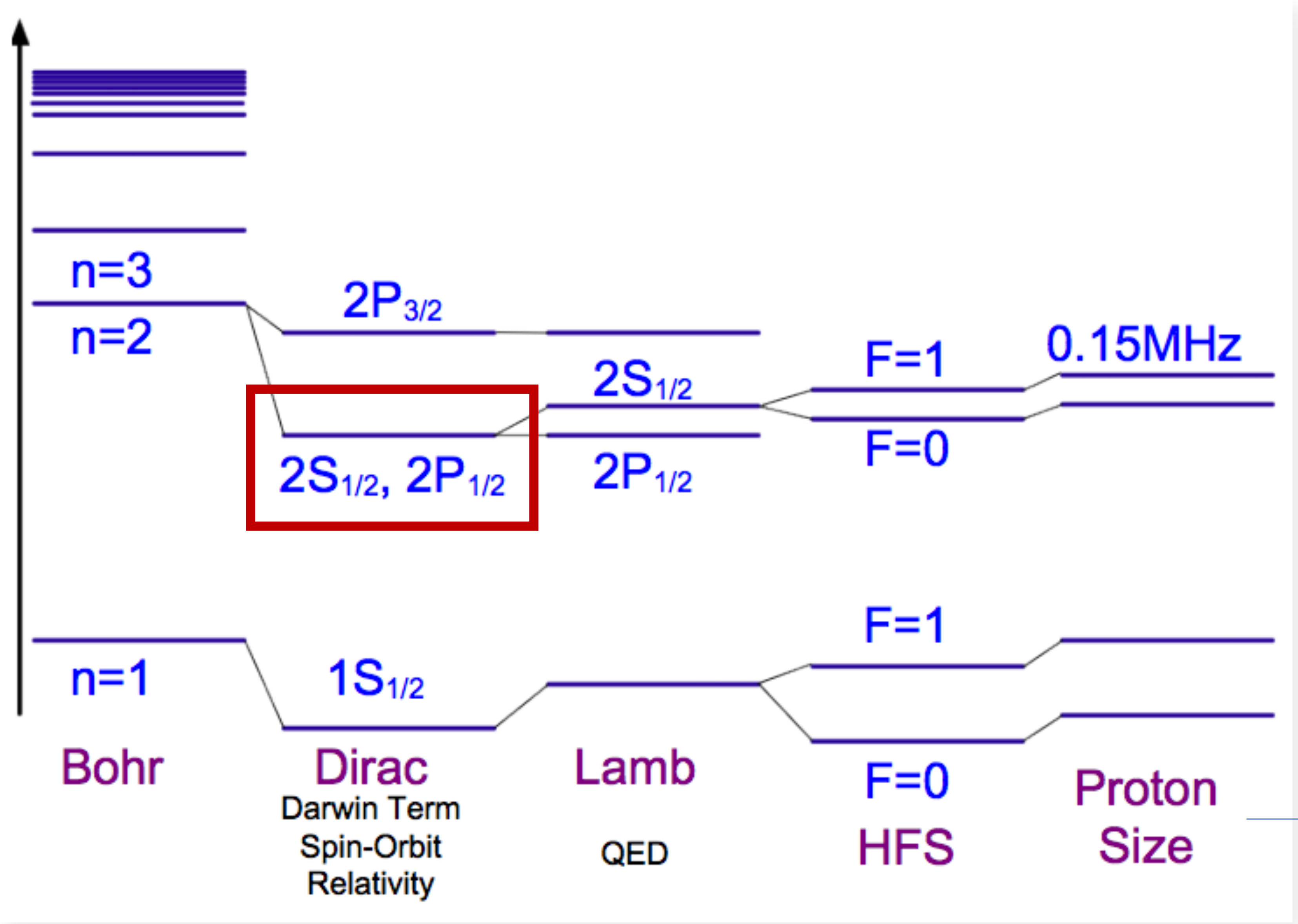
- Lamb shift contains
  1. Radiative correction (RC)
  2. Recoil term
  3. RC-recoil mixing term

Hydrogen Spectroscopy



- Lamb shift contains
  1. Radiative correction (RC)
  2. Recoil term
  3. RC-recoil mixing term
  4. Proton finite size term

Hydrogen Spectroscopy



- Physics origin of the proton finite size effect:
  - S-state wavefunction has overlap with the proton

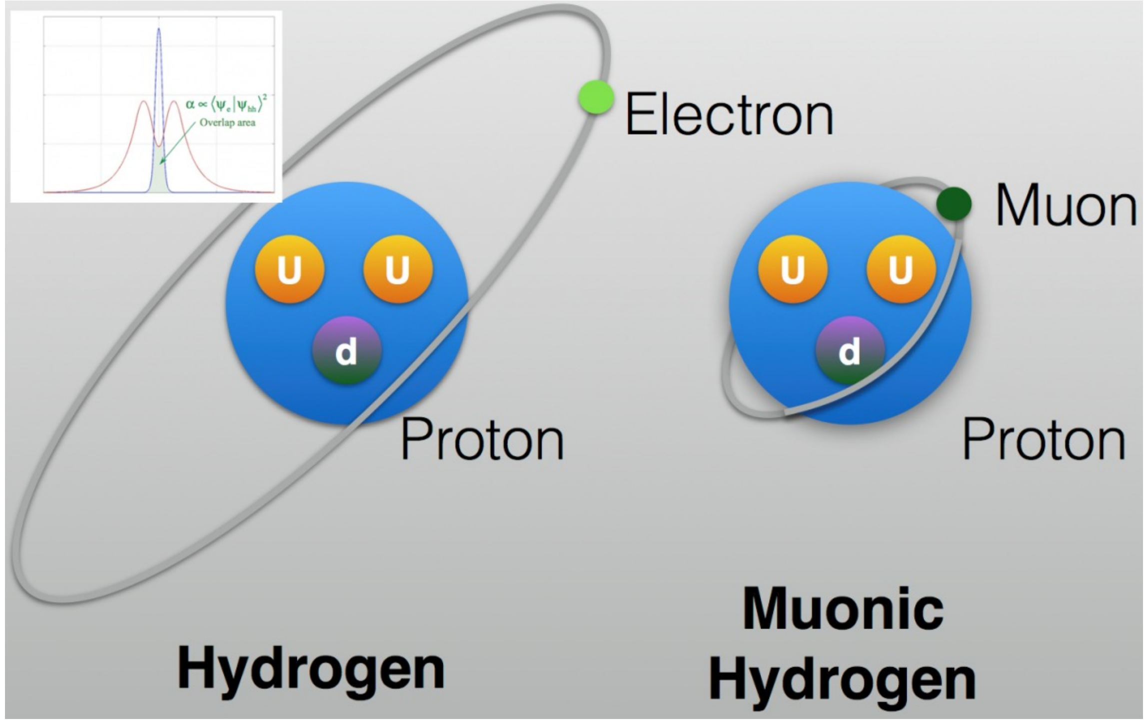
G. Miller PRC 99 035202 (2019)

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

Ordinary Hydrogen v.s. Muonic Hydrogen

- One can do this with ordinary hydrogen or muonic hydrogen
- Muon is ~200 times heavier than electron
- Orbit much closer to proton, more sensitive to proton size

$$\langle r^{\text{orbit}} \rangle \simeq \frac{\hbar}{Z\alpha\, m_r c} n^2$$



Proton finite size effect in 2S-2P: 2% in μH, 0.015% in H

Unpolarized *ep* Elastic Scattering

- Elastic ep scattering, in the limit of Born approximation (one photon exchange):

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \left(\frac{E'}{E}\right) \frac{1}{1+\tau} \left(G_E^{p\,2}(Q^2) + \frac{\tau}{\varepsilon} G_M^{p\,2}(Q^2)\right)$$

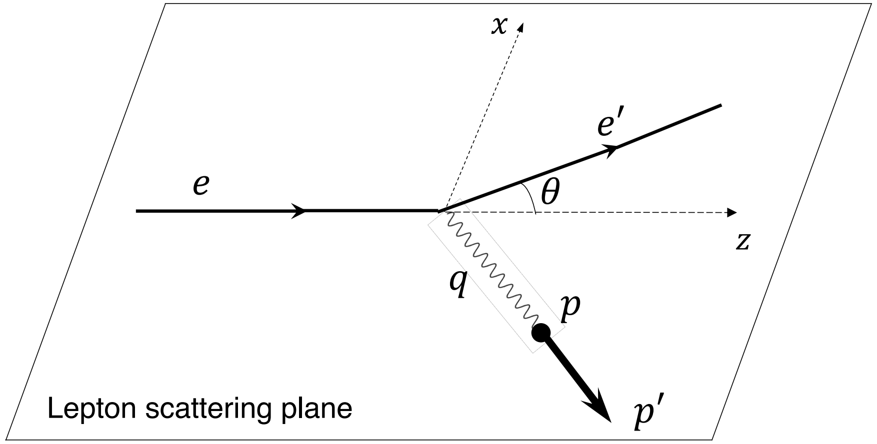
$$Q^2 = 4EE' \sin^2\frac{\theta}{2} \qquad \tau = \frac{Q^2}{4M_p^2} \qquad \varepsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right]^{-1}$$

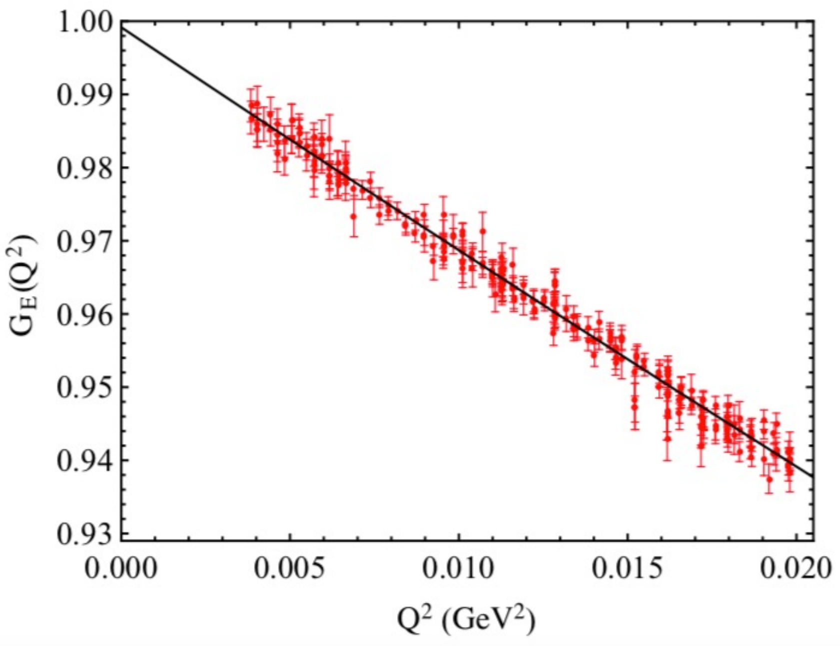
Taylor expansion of G_E at low Q^2

$$G_E^p(Q^2) = 1 - \frac{Q^2}{6}\langle r^2\rangle + \frac{Q^4}{120}\langle r^4\rangle + \ldots$$

Derivative at low Q^2 limit

$$\langle r^2\rangle = -6 \frac{dG_E^p(Q^2)}{dQ^2}\bigg|_{Q^2=0}$$

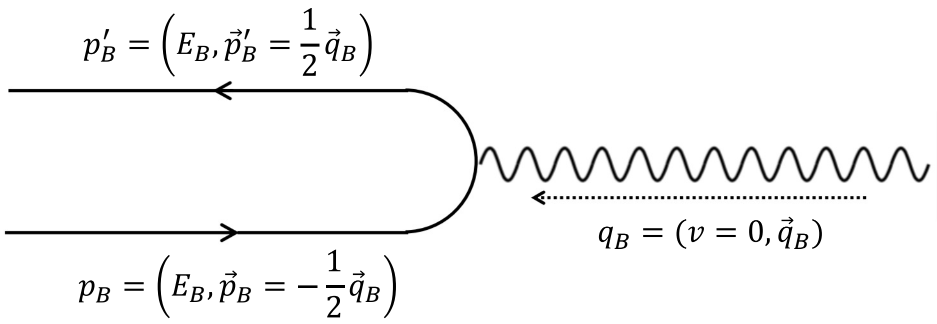




Physical Interpretation of G_E

- Classical interpretation: in Breit frame and non-relativistic static system

$$
\begin{aligned}
G_{E,M}(Q^2) &= \int \rho(\vec{r}) e^{i\vec{q}\cdot\vec{r}} d^3\vec{r} \\
&= \int \rho(\vec{r}) d^3\vec{r} - \frac{\vec{q}^2}{6} \int \rho(\vec{r}) \vec{r}^2 d^3\vec{r} + \ldots
\end{aligned}
$$



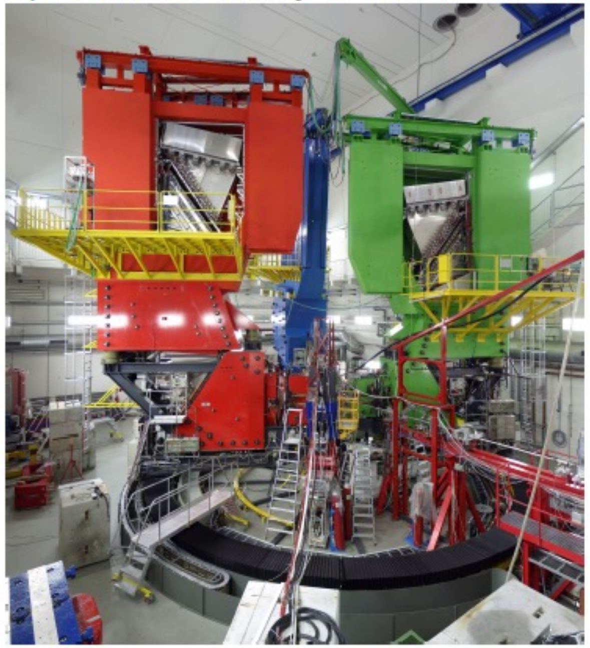
- Not rigorous, lots of research activities to refine the interpretation:
  - Y. Chen (陈毅) and C. Lorcé, *PRD* 106 (2022) 11, 116024
  - E. Epelbaum *et al. PRL* 129 (2022) 1, 012001
  - R. L. Jaffe *PRD* 103 (2021) 1, 016017
  - …
  - Y. Li (李阳)*et al. PLB* 838 (2023) 137676
  - C. Lorcé *PRL* 125 (2020) 23, 232002
  - G. A. Miller, *PRC* 99 (2019) 3, 035202

- Charge radius is defined for FF slope
- For both scattering and hydrogen spectroscopy, we are going after $G'_E(0)$

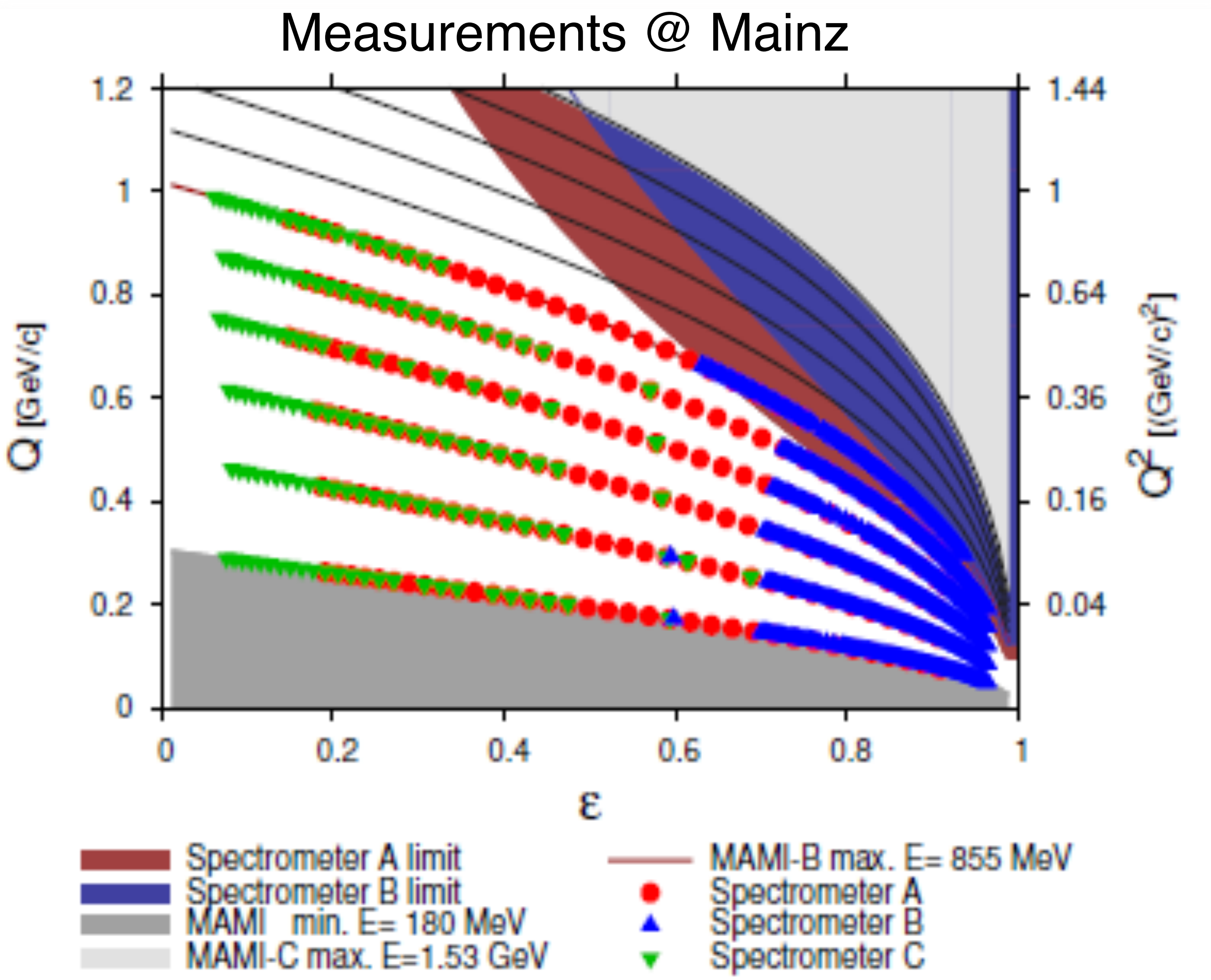
More info: H. Gao and M. Vanderhaeghen, RMP 94, no.1, 015002 (2022)

Unpolarized *ep* Elastic Scattering

Three spectrometer facility of the A1 collaboration:

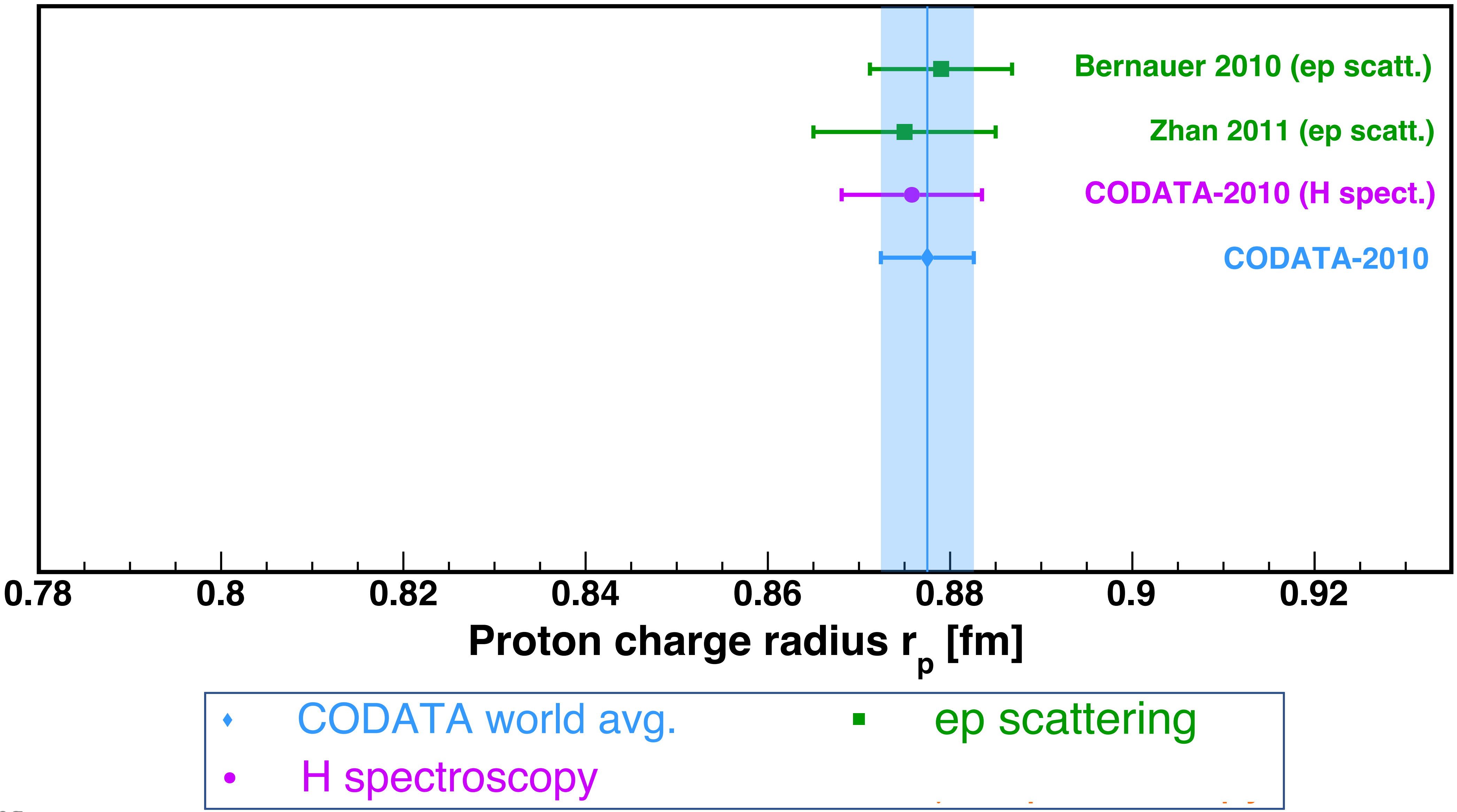


J.C. Bernauer *et al.* PRL. 105 (2010) 242001

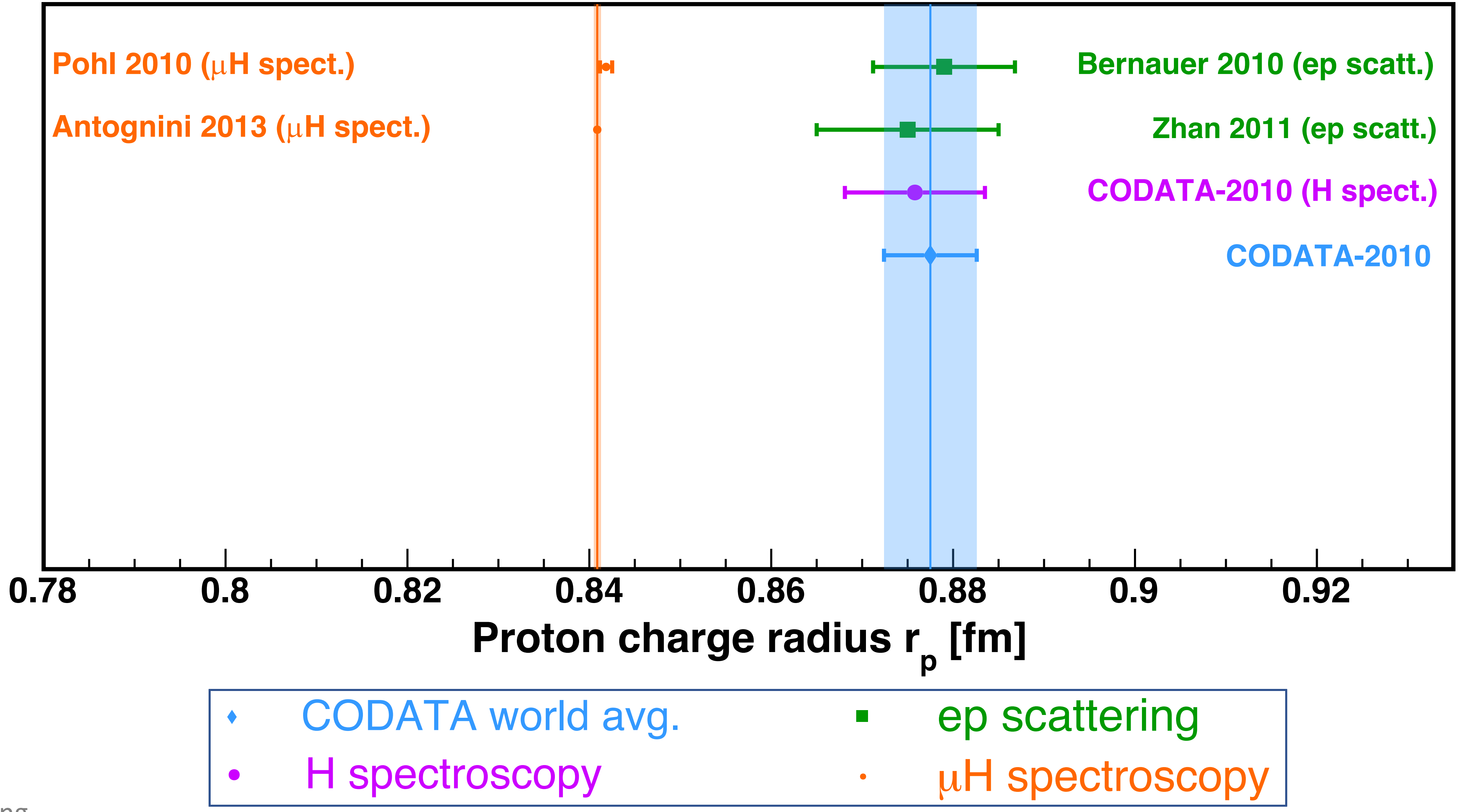


- Large amount of overlapping data sets
- Statistical error $\leq 0.2\%$
- Luminosity monitoring with spectrometer
- $Q^2 = 0.004 - 1.0\ (\mathrm{GeV}/c)^2$
- result: $r_p = 0.8791(79)$ fm

Proton Charge Radius



Proton Charge Radius Puzzle



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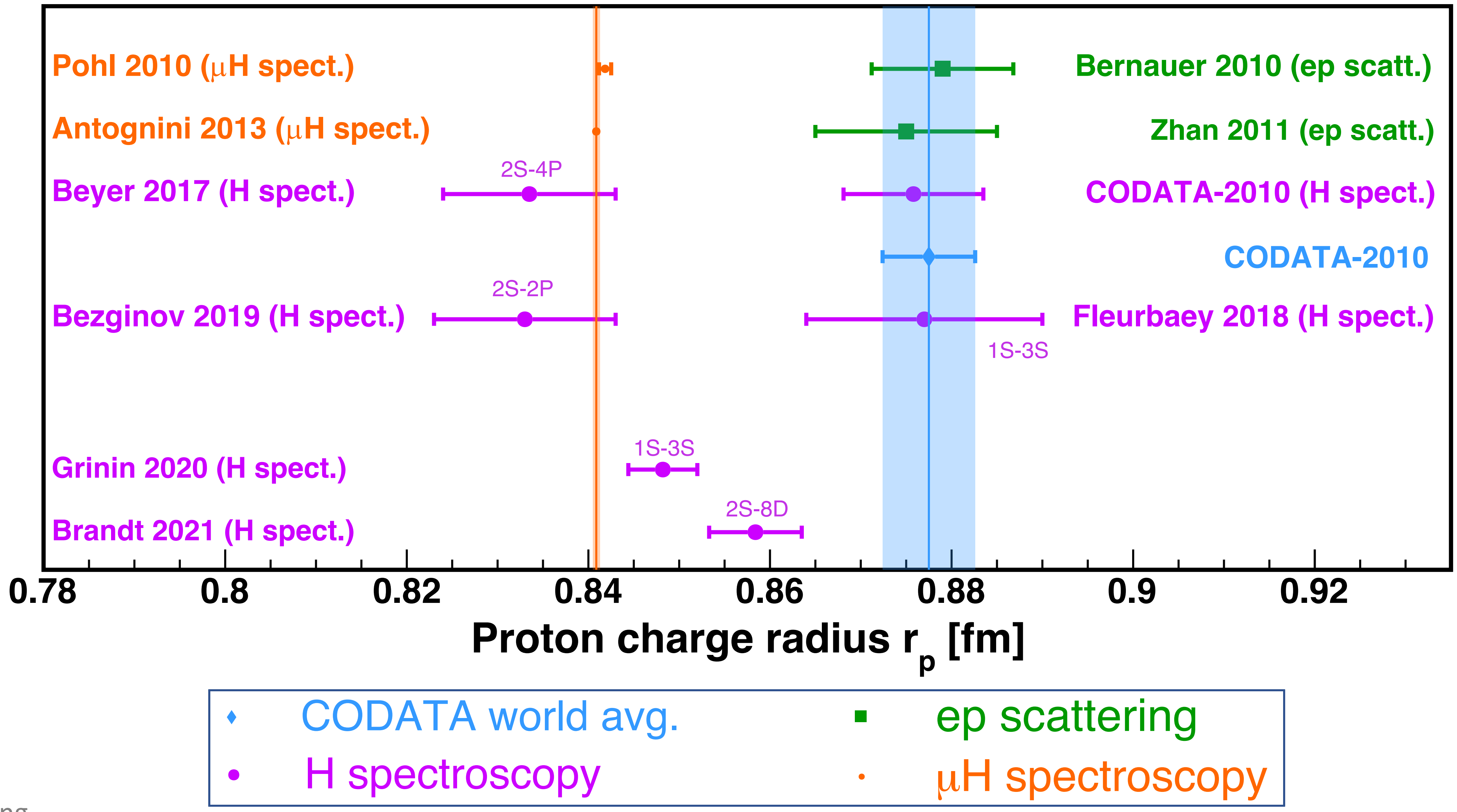

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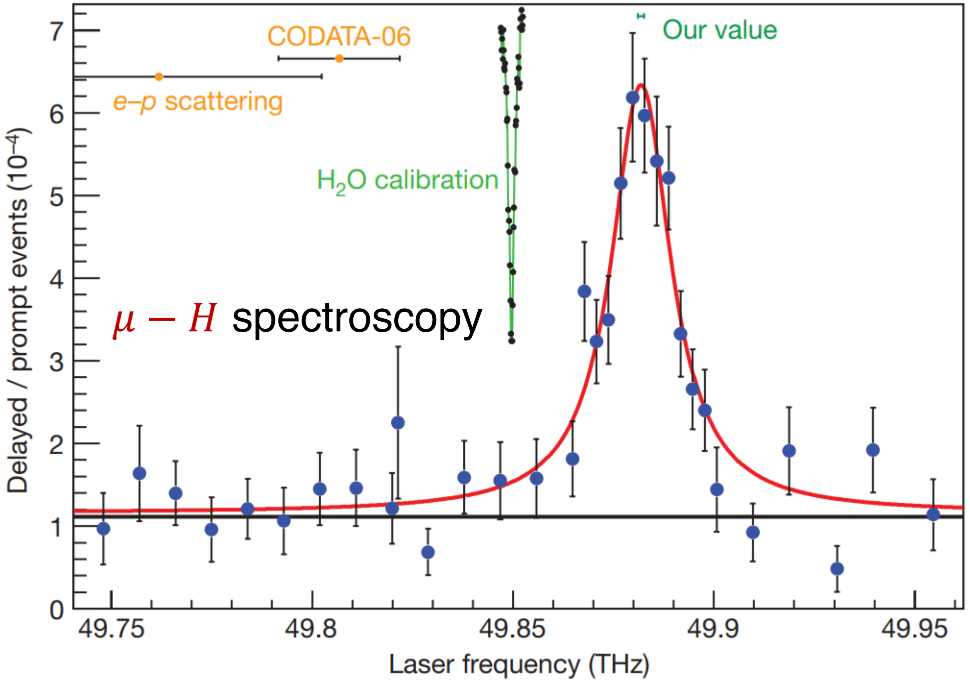
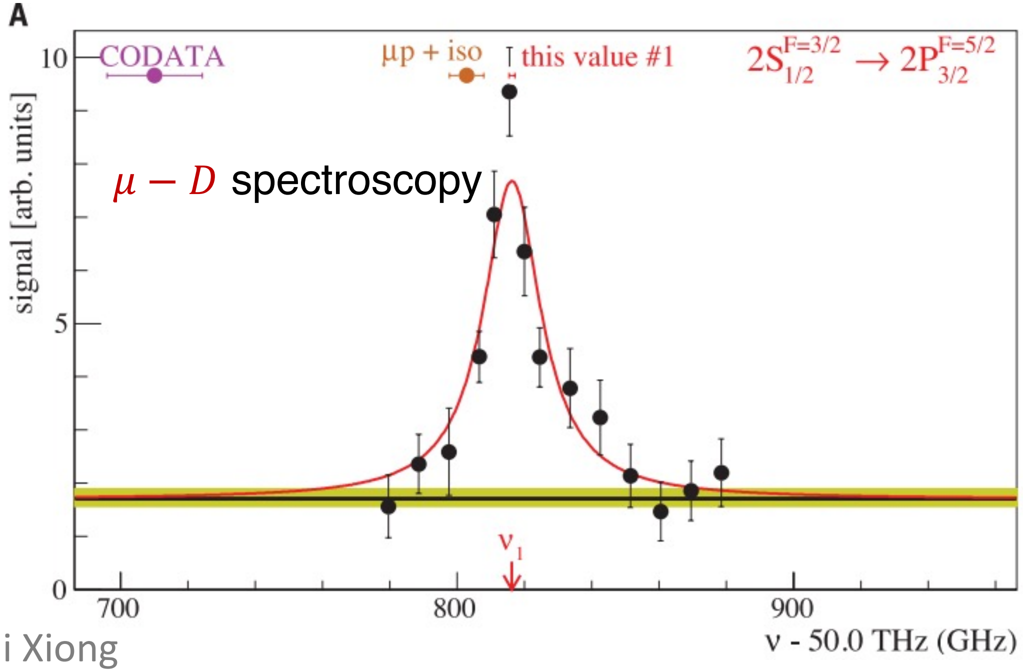
The “Z=1” Puzzle





- similar discrepancies exist for both proton and deuteron charge radius
  - *Nature 466 (2010) 213-216*
  - *Science 339 (2013) 417-420*
  - *Science* 353 (2016) 6300, 669-673

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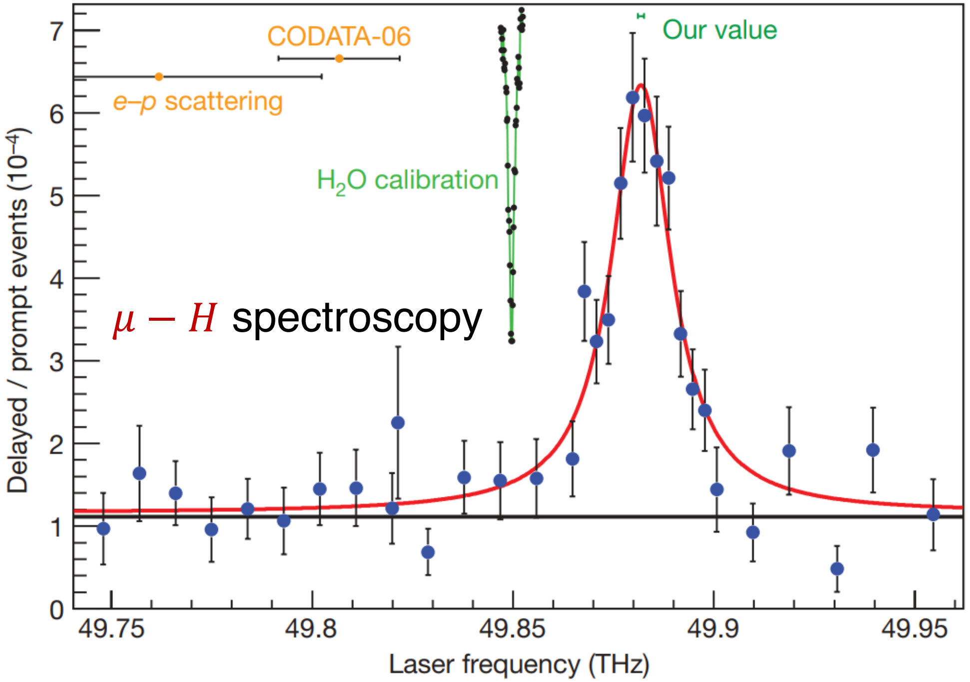

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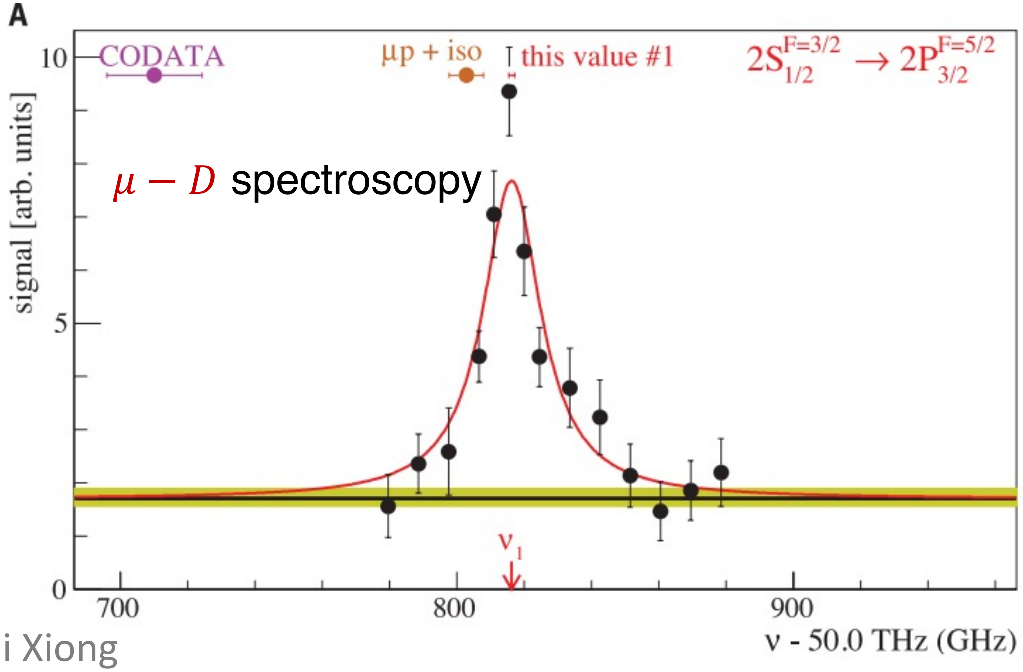
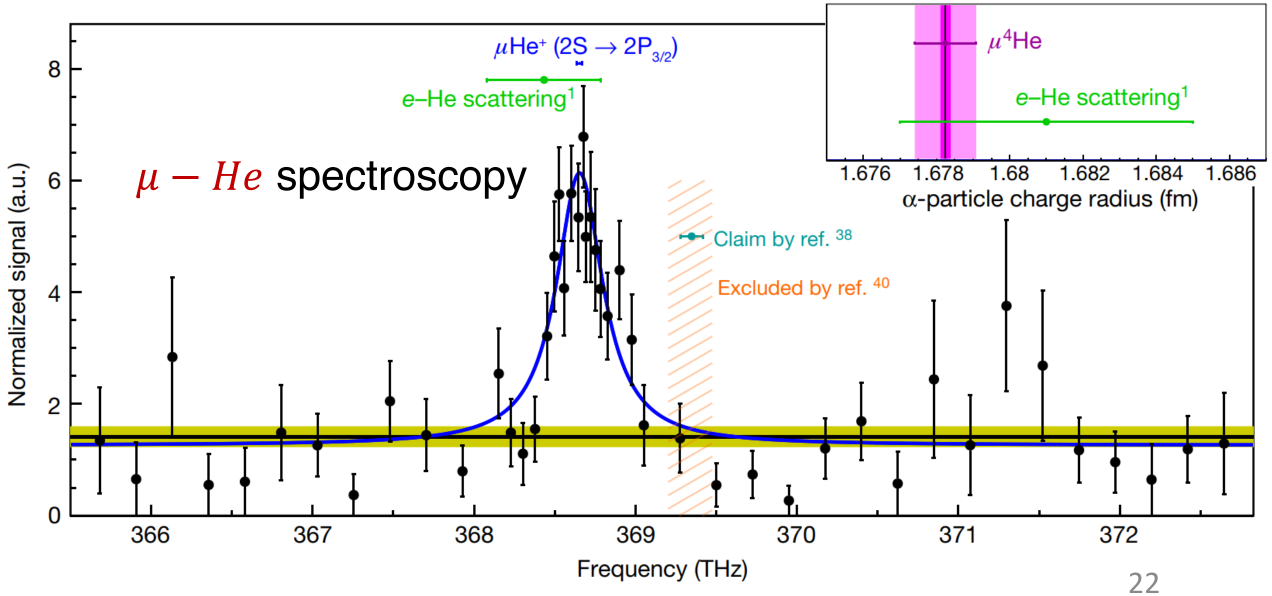
- yet $\mu - He$ measurement consistent with *e-He* scattering result
  - *Nature* 589 (2021) 7843, 527-531





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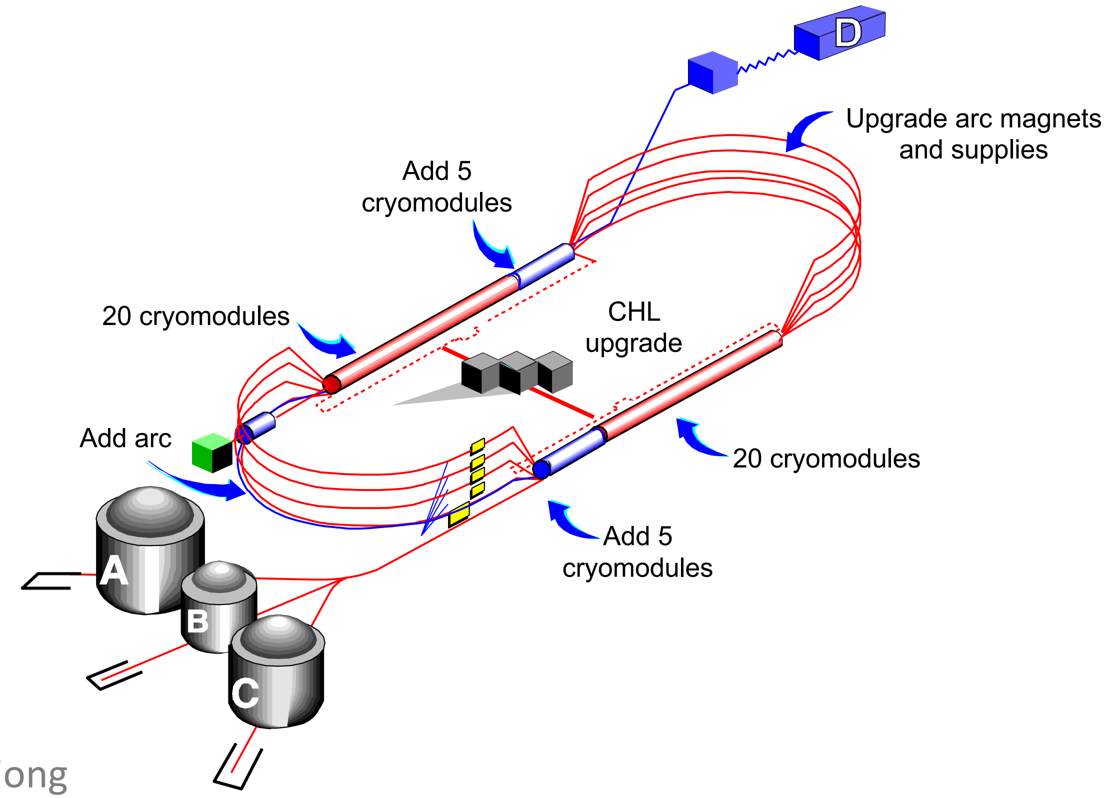
New York Times

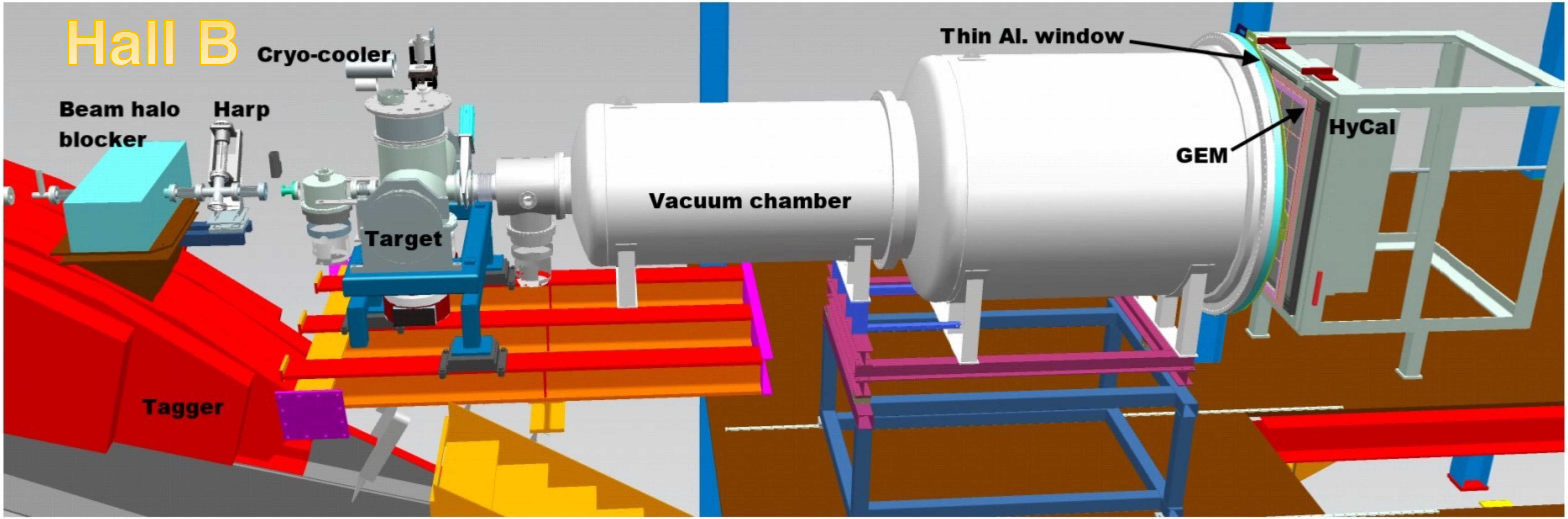
Jefferson Lab

- Thomas Jefferson National Accelerator Facility (JLab), Newport News, VA
- Completed 6 GeV to 12 GeV upgrade in 2015
- 4 experimental Halls
- PRad data taking May/June 2016, with 1.1 GeV and 2.2 GeV electron beams



PRad Experimental Apparatus

Large acceptance, small angle and non-spectrometer apparatus



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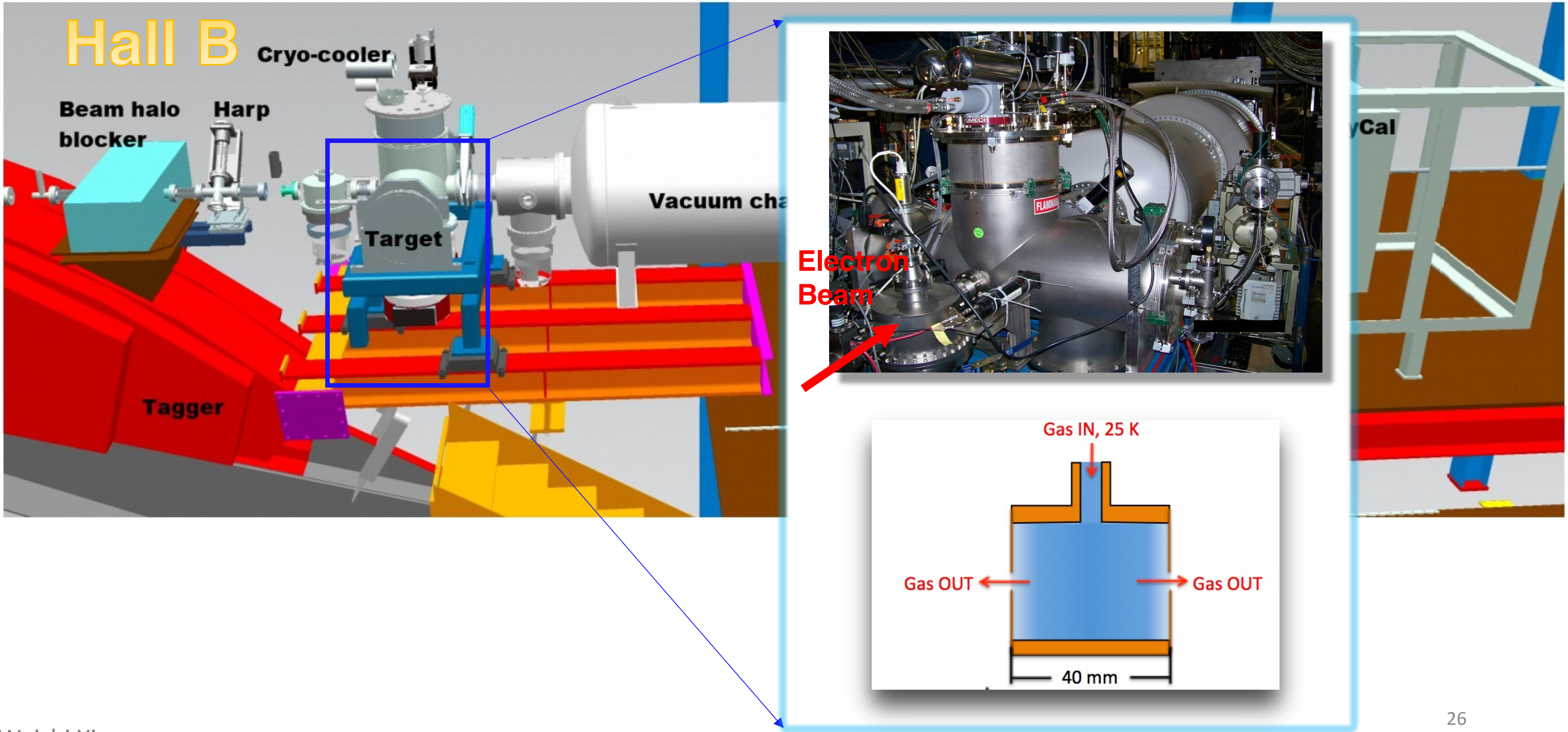

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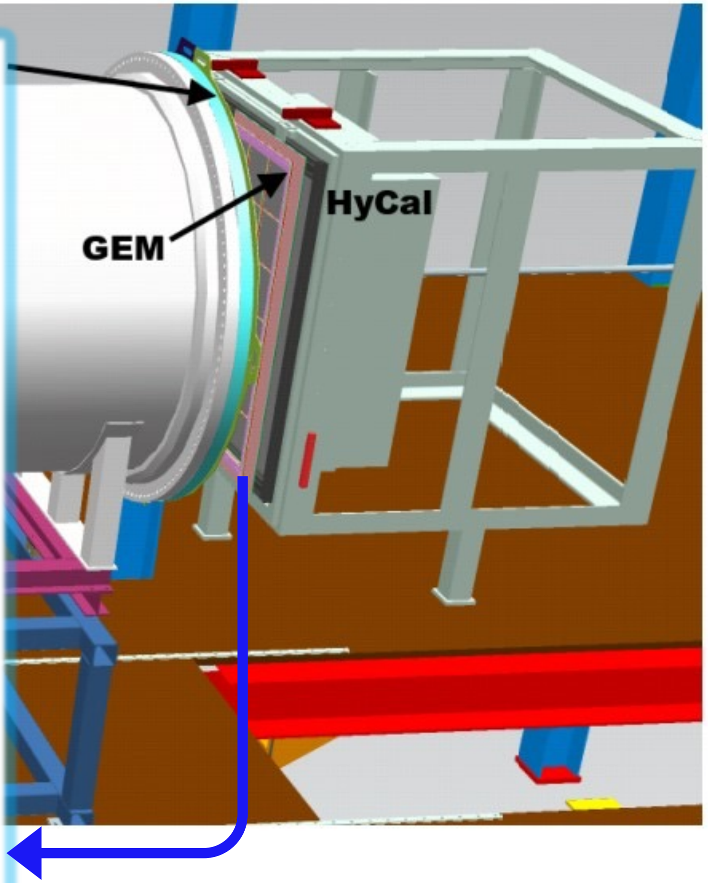

- Two large area GEM detectors
- Small overlap region in the middle
- Excellent position resolution (72 μm)

PRad Experimental Apparatus

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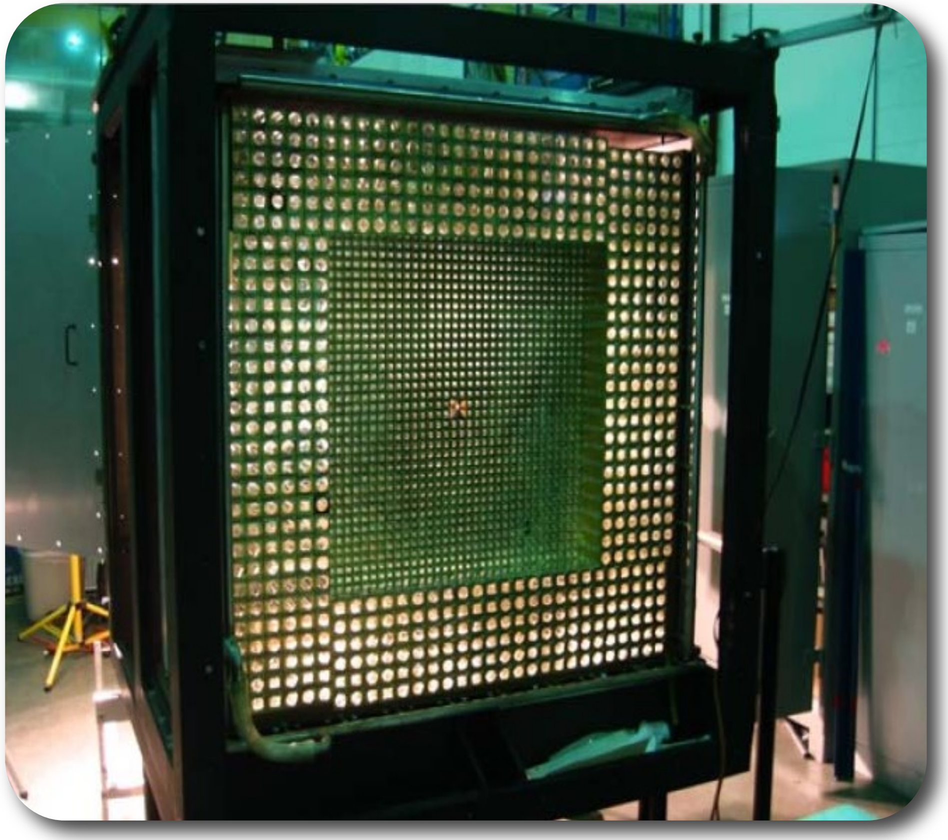
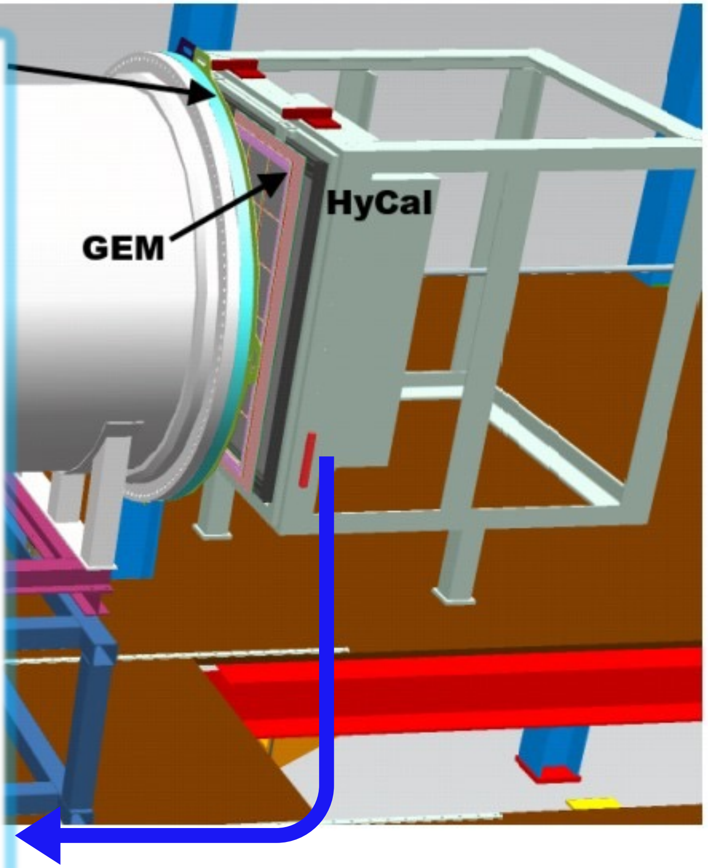
Hall B



- Hybrid EM calorimeter (HyCal)
  - Inner 1156 $PbWO_4$ modules
  - Outer 576 lead glass modules
- Scattering angle coverage: ~ 0.7° to 7.0°
- Full azimuthal angle coverage
- High resolution and efficiency



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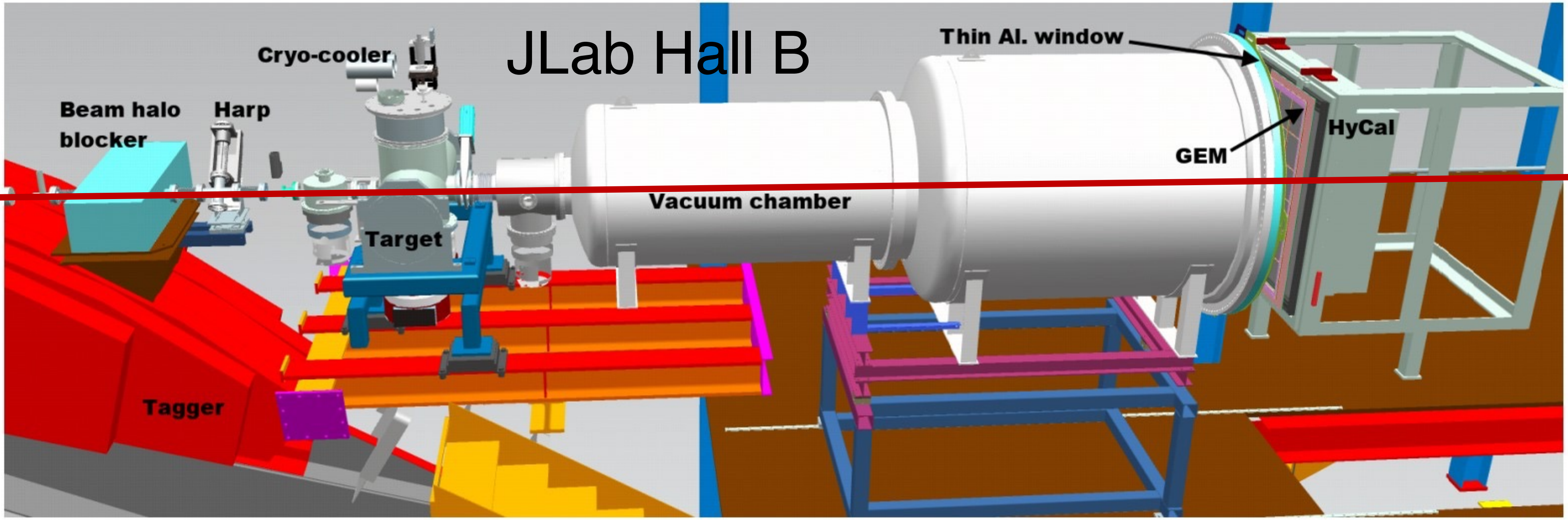
PRad Experiment Overview

Large acceptance, small angle and non-spectrometer apparatus

- At each beam energy, different Q^2 data collected at the same time
- Covers two orders of magnitude in low Q^2 with the same detector setting
  - ~$2x10^{-4}$ - $6x10^{-2}$ GeV^2

e Beam dir.



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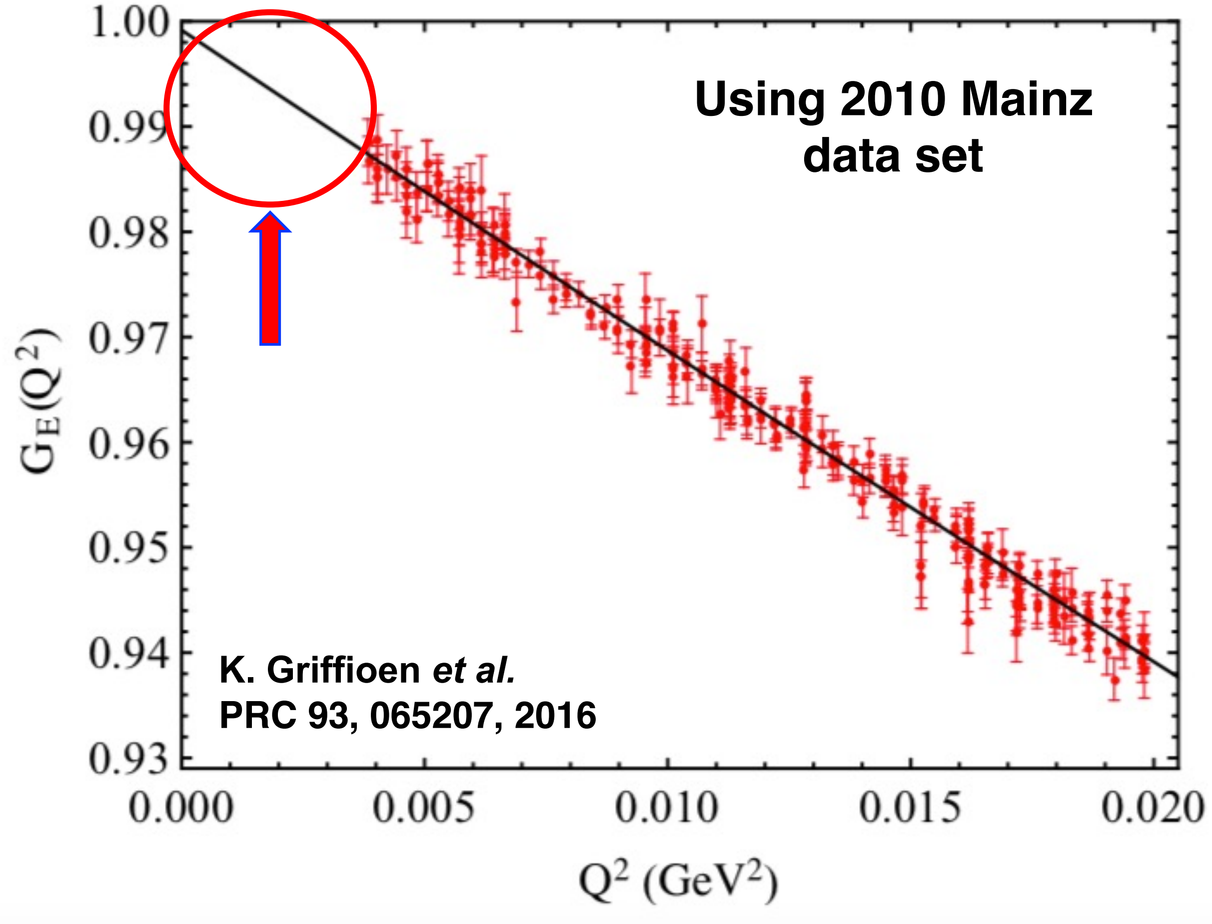

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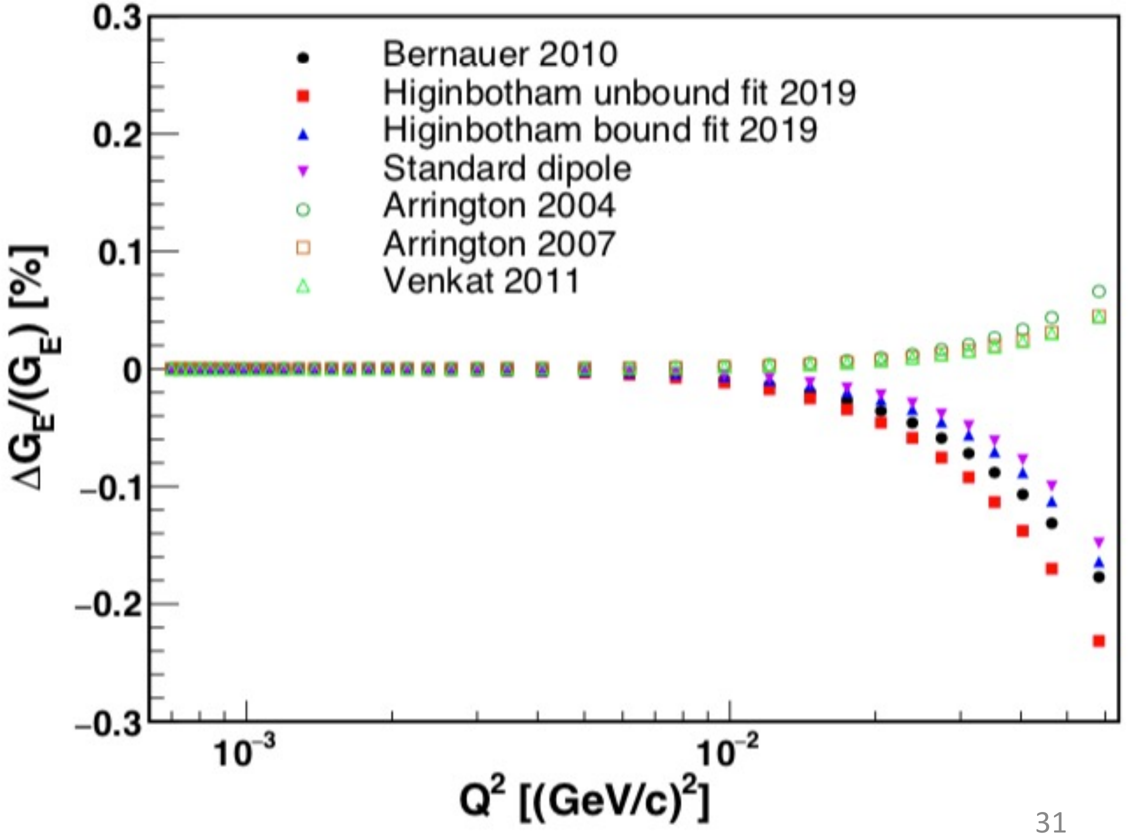

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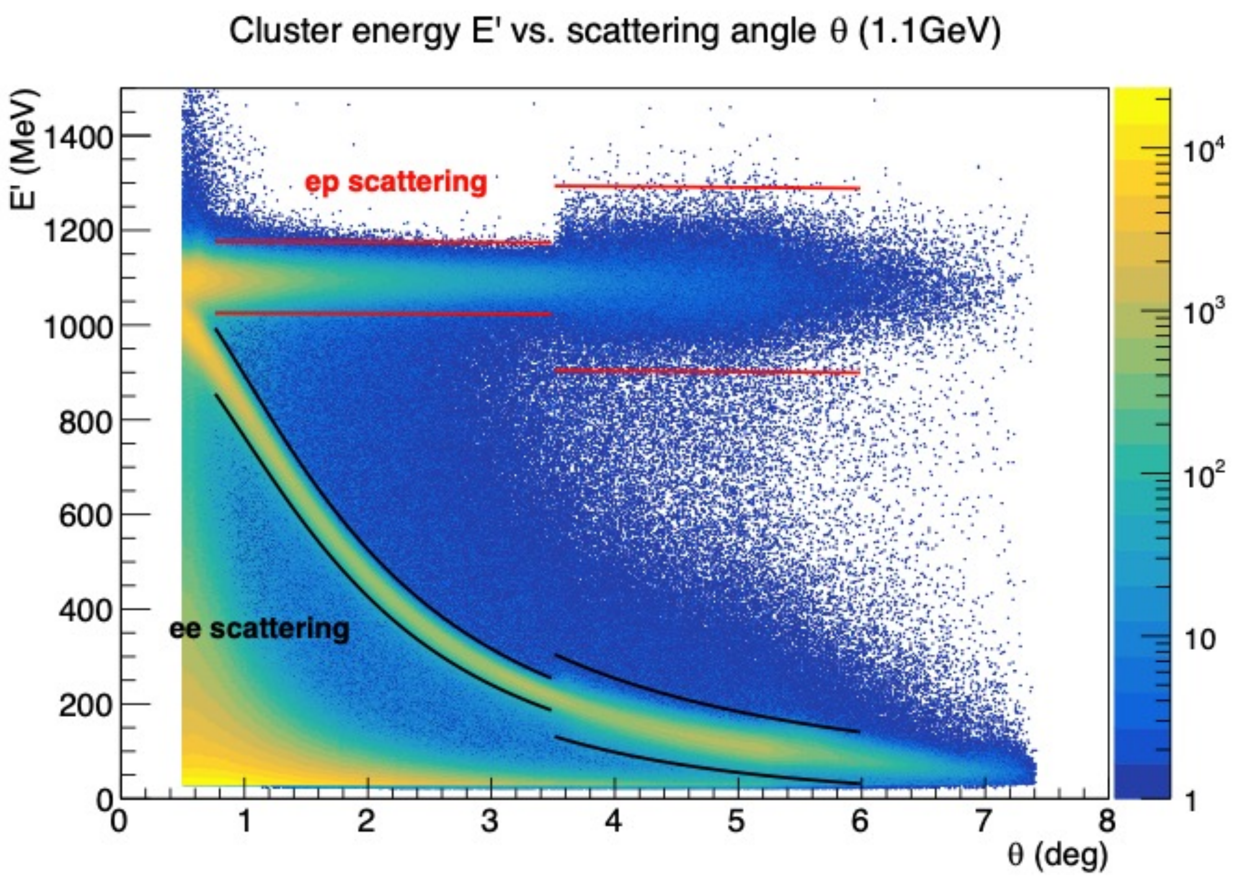
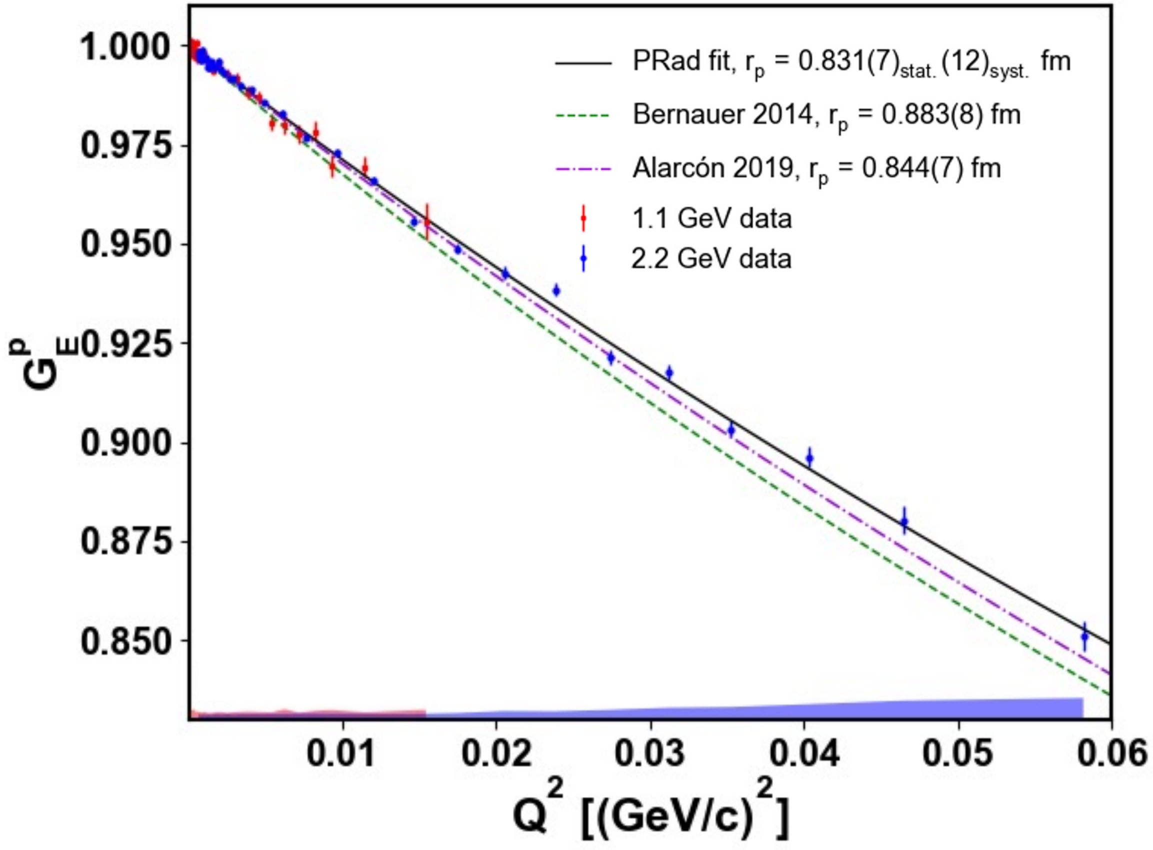
- Normalize to the simultaneously measured Møller scattering process

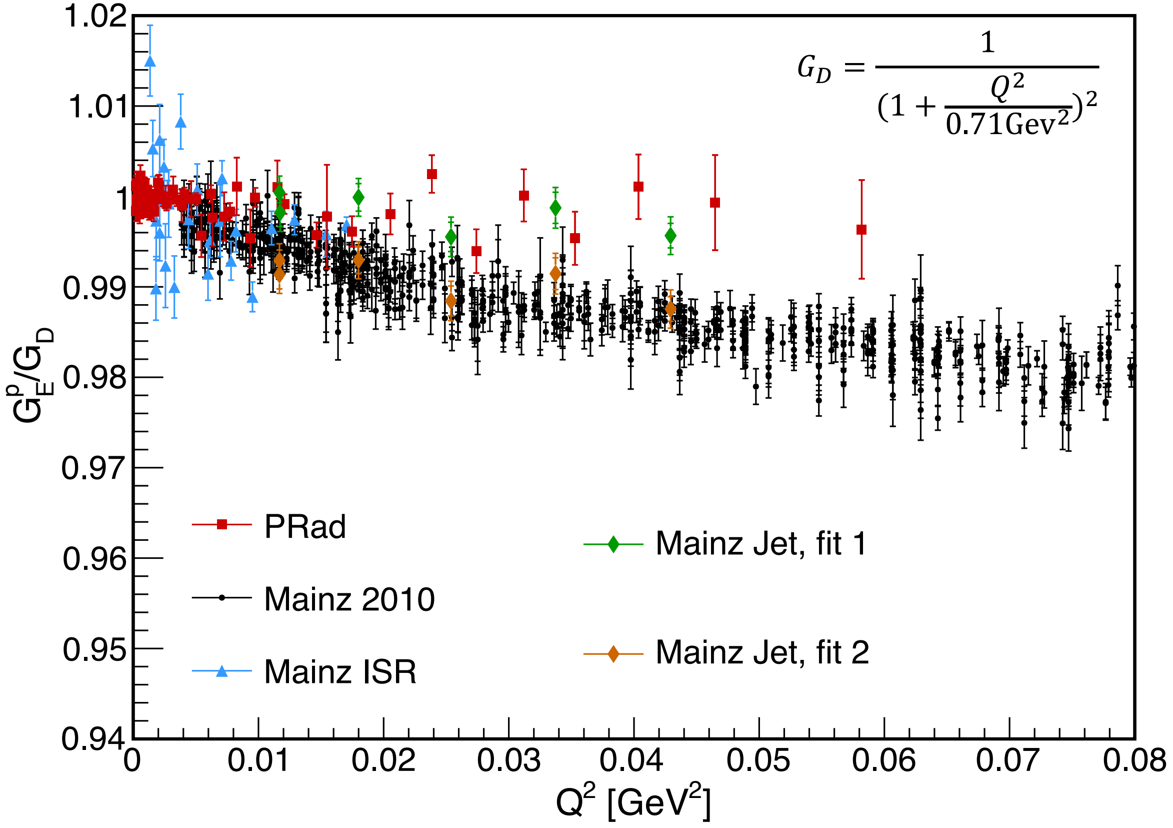


PRad Result

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

W. Xiong *et al. Nature* 575 (2019) 7781





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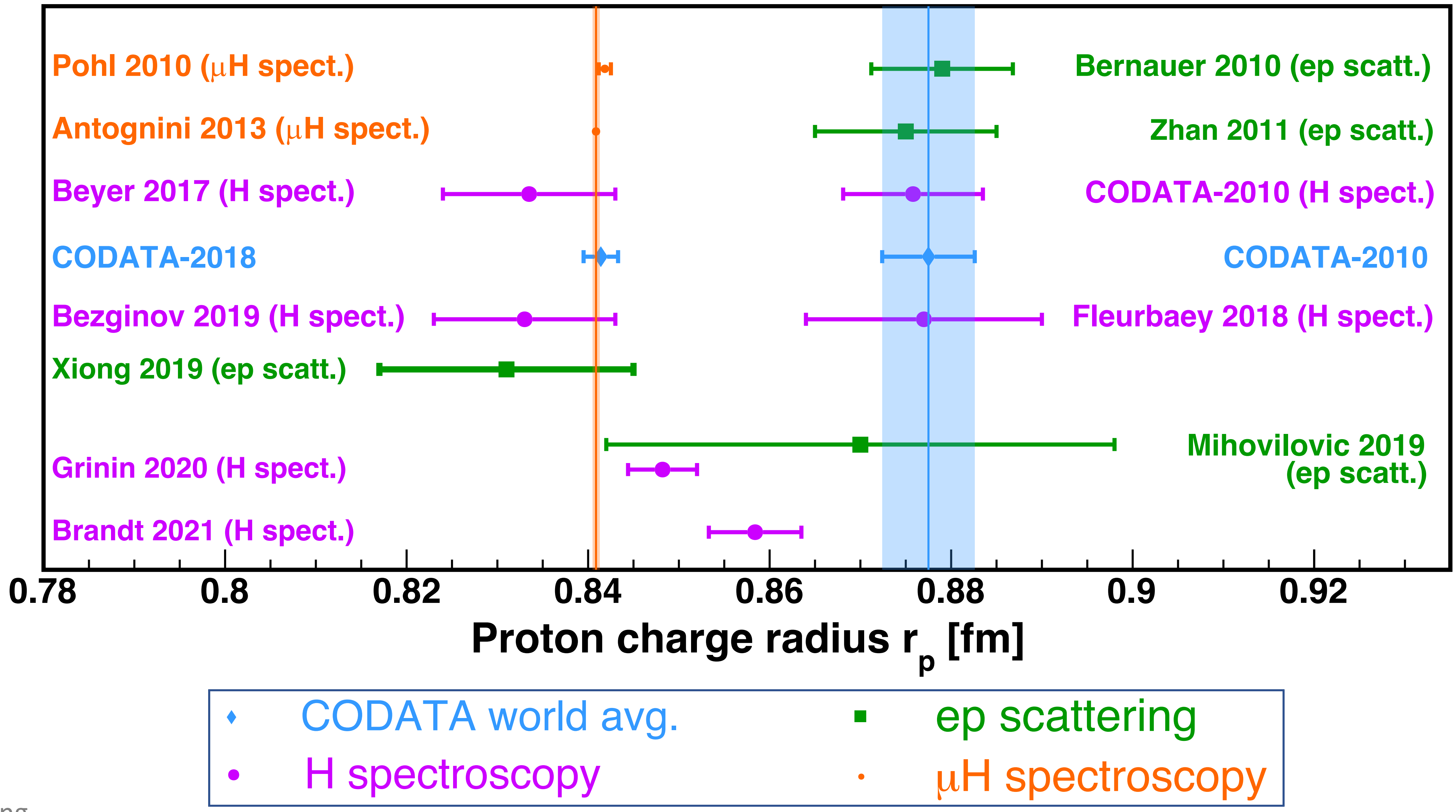
Current Status on Proton Charge Radius



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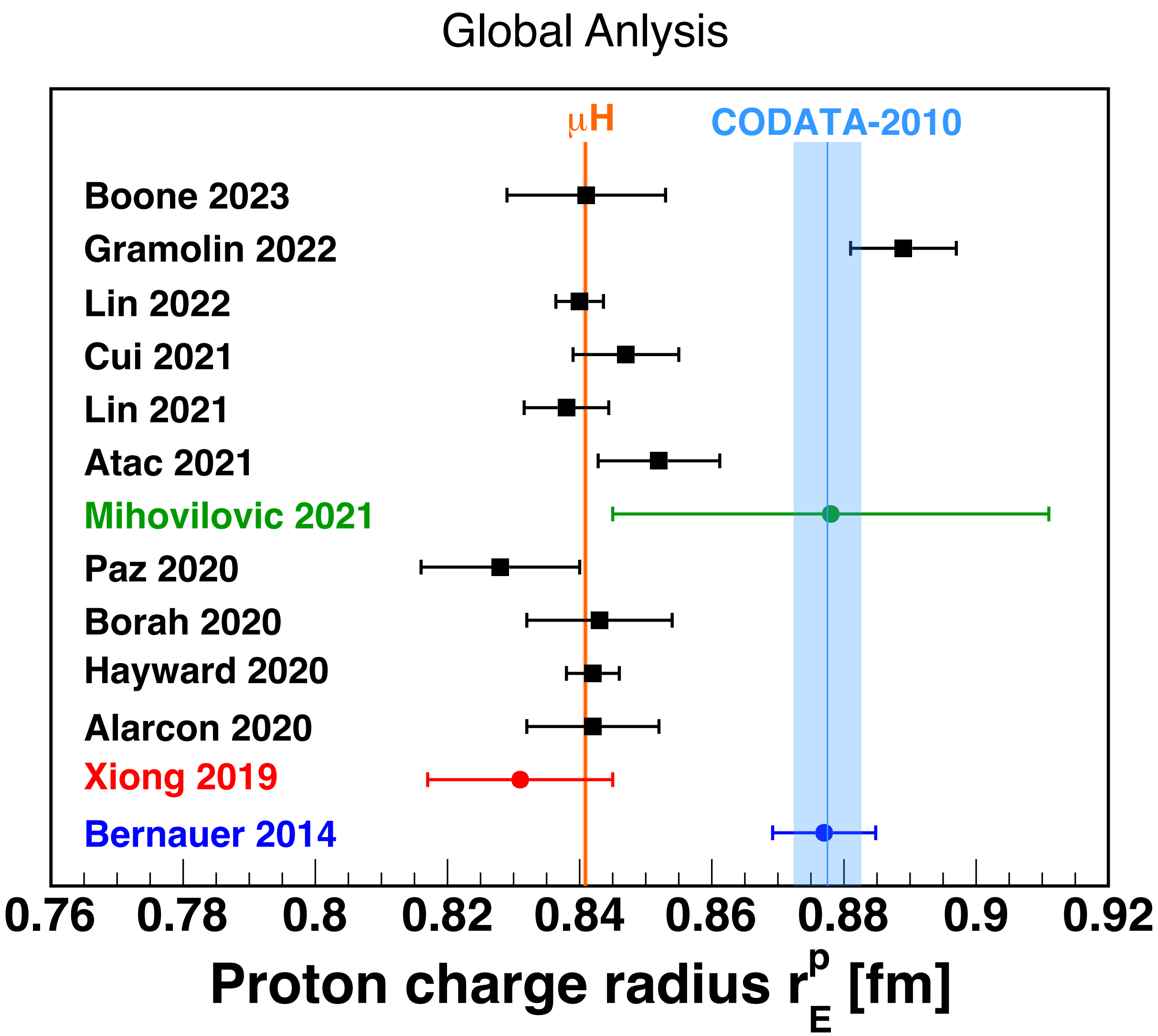
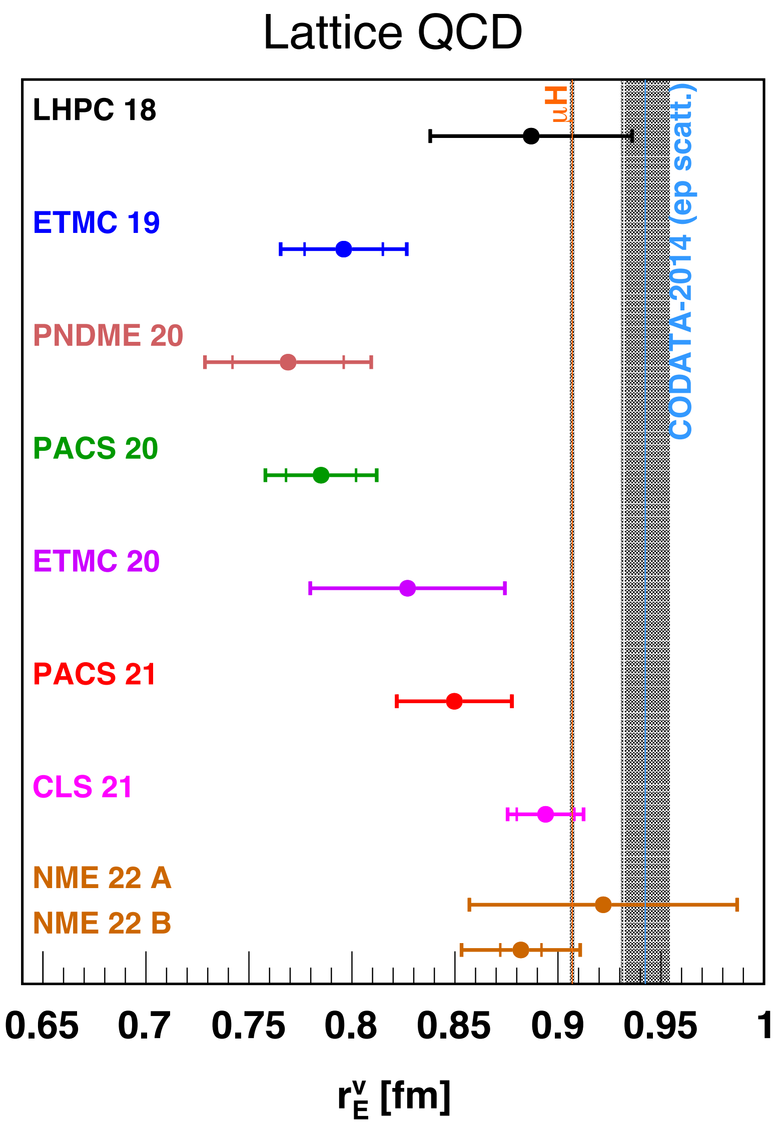
Other Results from Global Analysis and Lattice QCD





WX and Chao Peng (彭潮) arXiv:2302.13818

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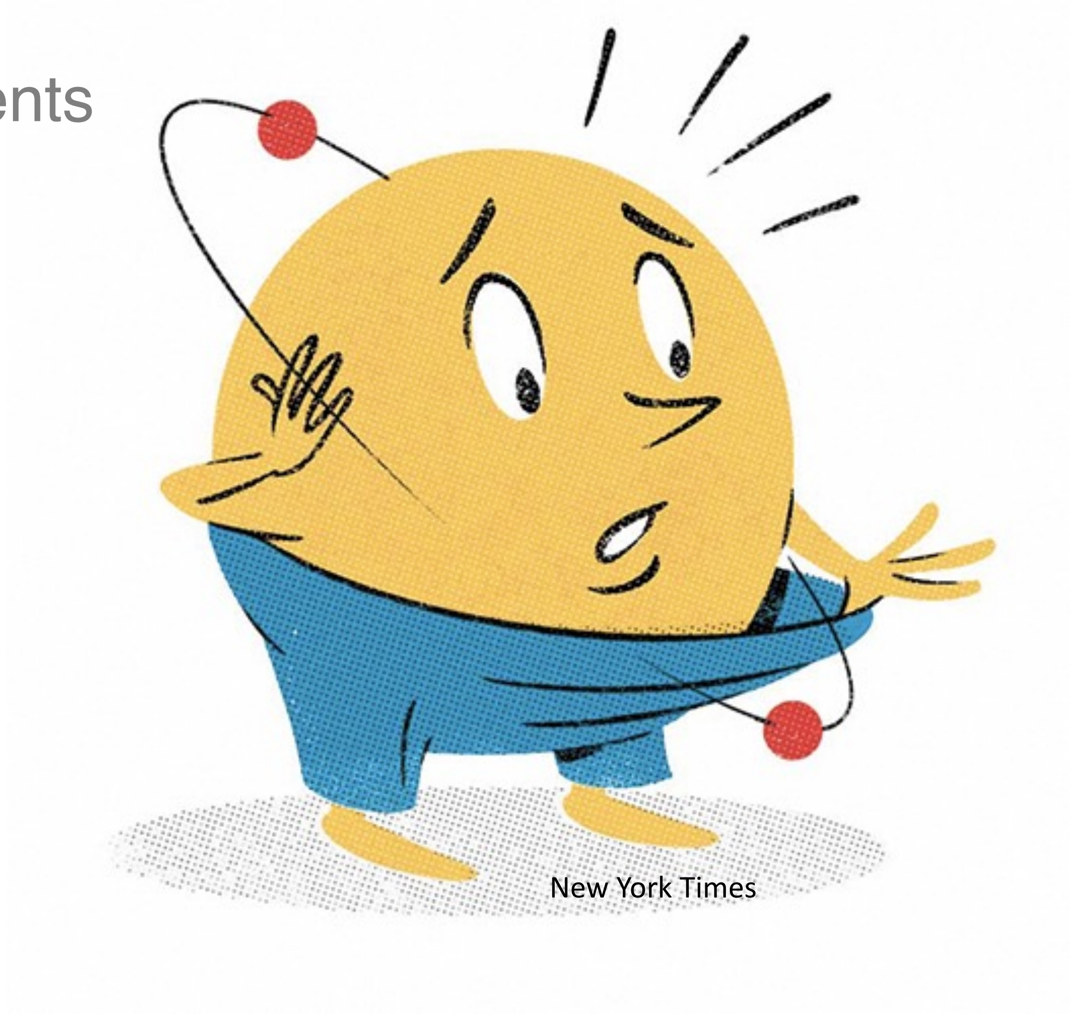

New York Times

Remaining Issues for Lepton Scattering

- Need other experiments to confirm/reject PRad result
- Is r_p the same in lepton scattering and spectroscopy?
  - C. Peset *et al. Prog. Part. Nucl. Phys.* 121 (2021) 103901

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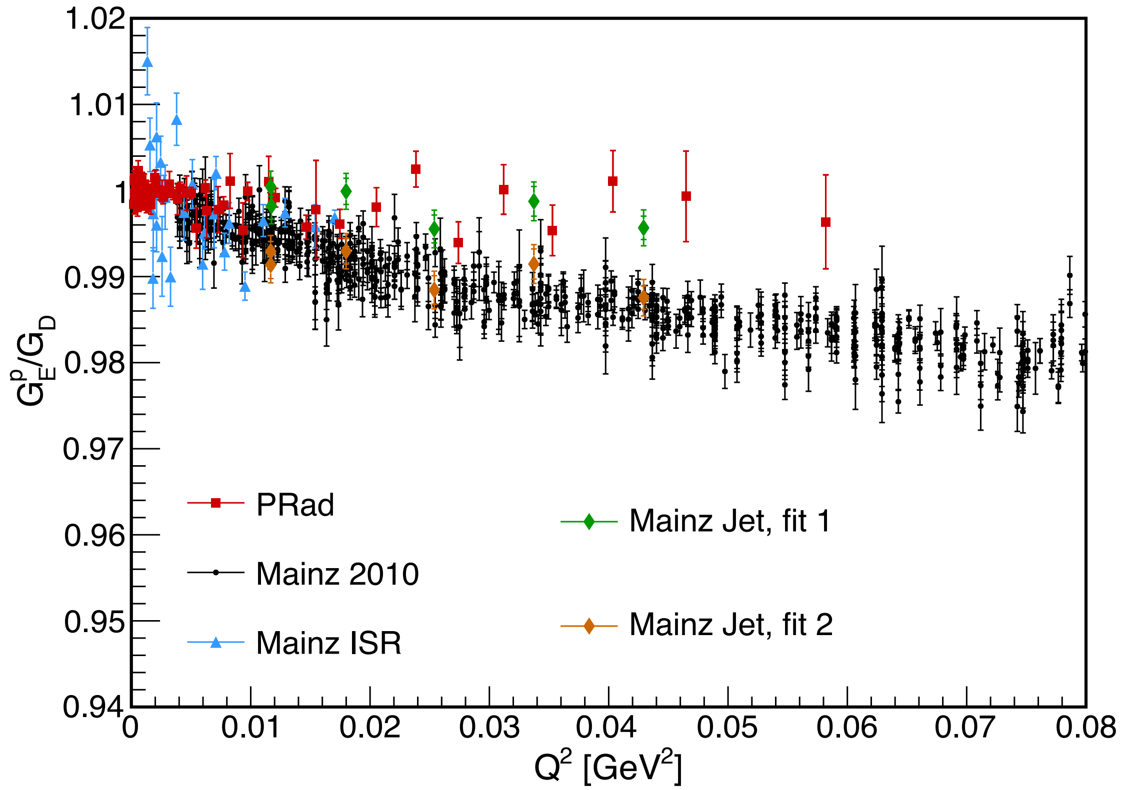

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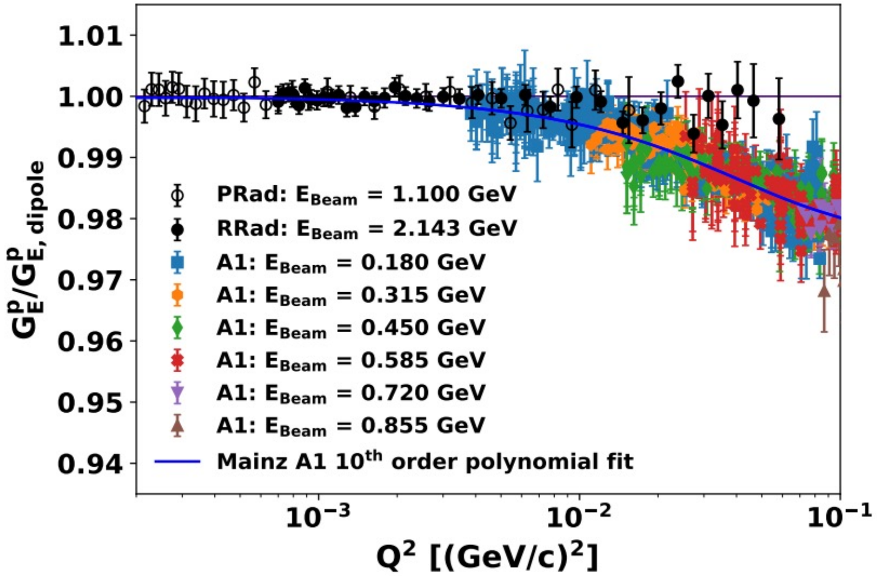
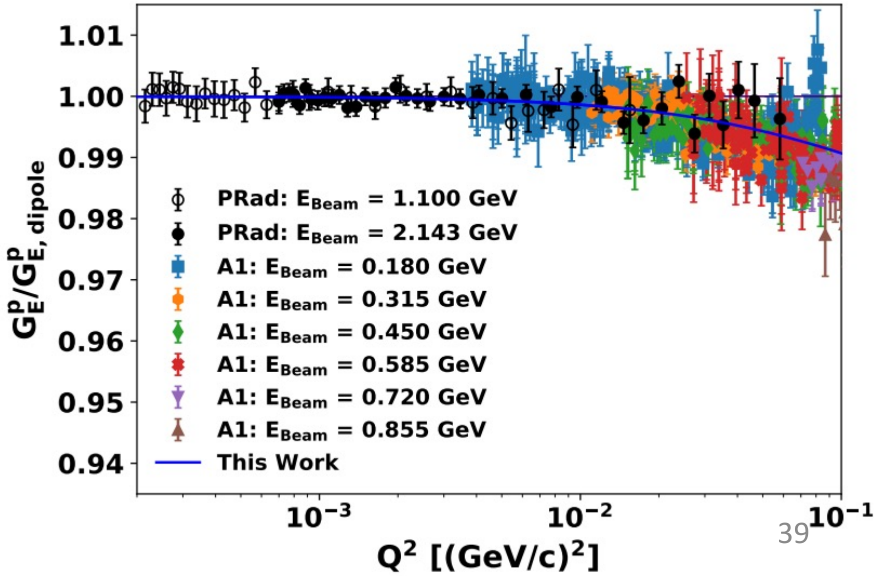
  3. Problem with fitting procedure?

- J. Zhou (周璟怡) *et al.* PRC 106 (2022) 6, 065505
- Use rational (1, 1) to fit Mainz data up to Q^2~0.5GeV^2

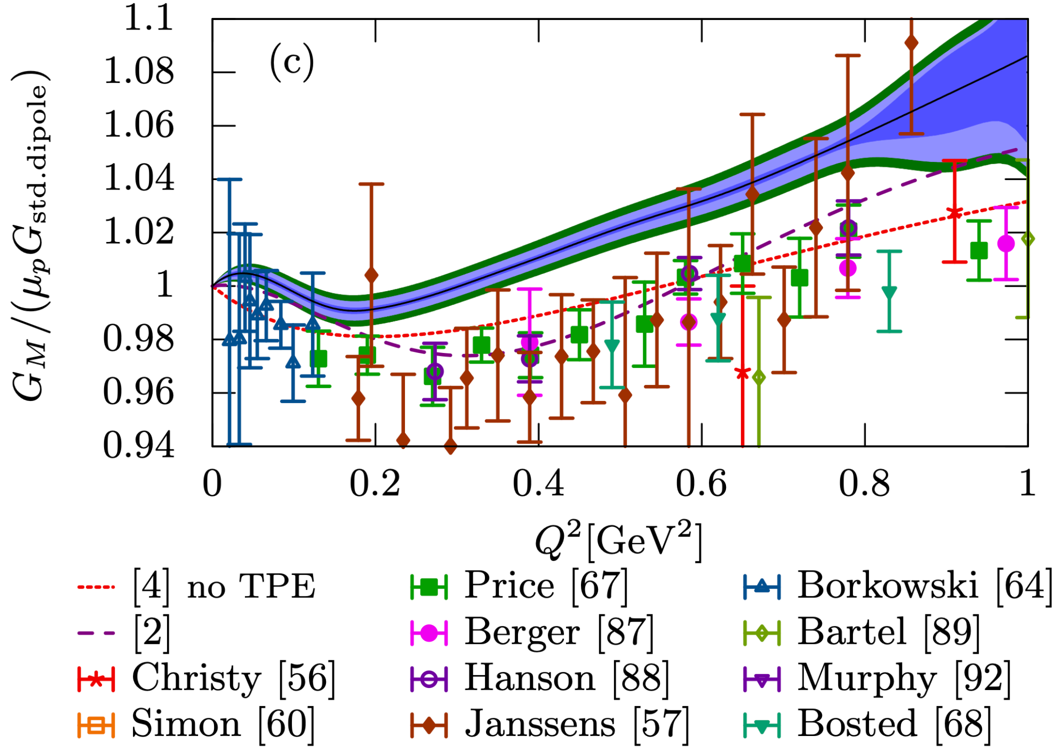




Remaining Issues for Lepton Scattering

- Need other experiments to confirm/reject PRad result
- Is r_p the same in lepton scattering and spectroscopy?
  - ➢ C. Peset *et al. Prog. Part. Nucl. Phys.* 121 (2021) 103901
- Why $\mathrm{G_E}$ data are different?
  1. Problem with RC?
  2. Unknown systematics?
  3. Problem with fitting procedure?
  4. Problem with G_M and r_M?
  5. ...

J. Bernauer et al. *PRC* 90 (2014) 1, 015206



➢ G. Lee *et al.* PRD 92 013013:
- 0.776(38) fm for Mainz data
- 0.914(35) fm for world data excluding Mainz

Remaining Issues for Lepton Scattering

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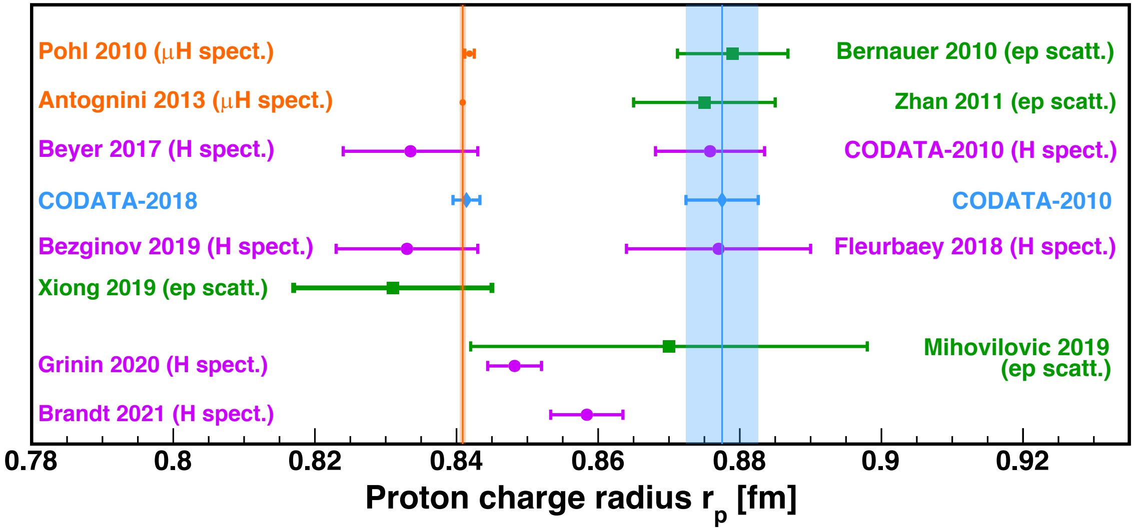

Remaining Issues for Lepton Scattering

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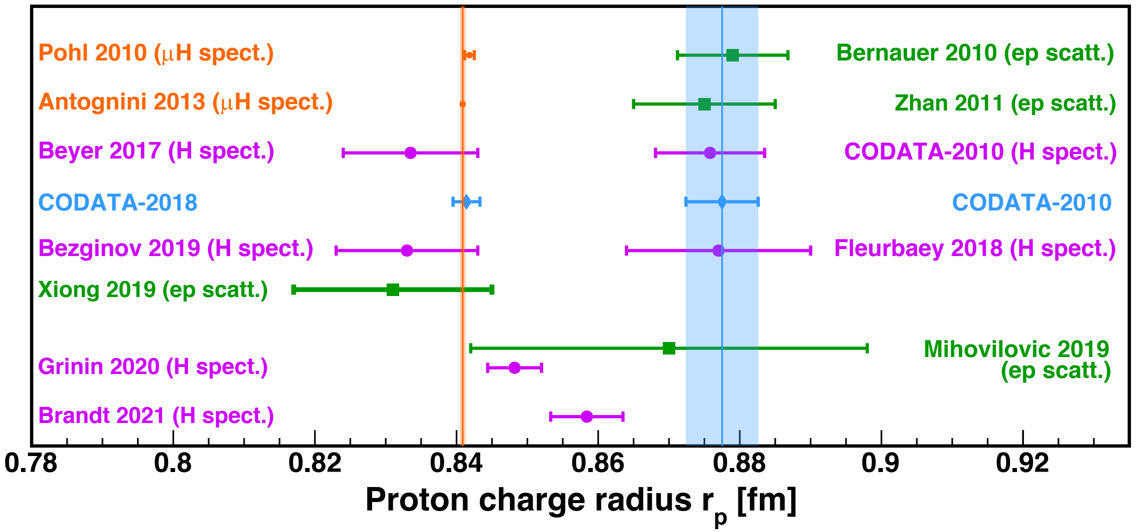
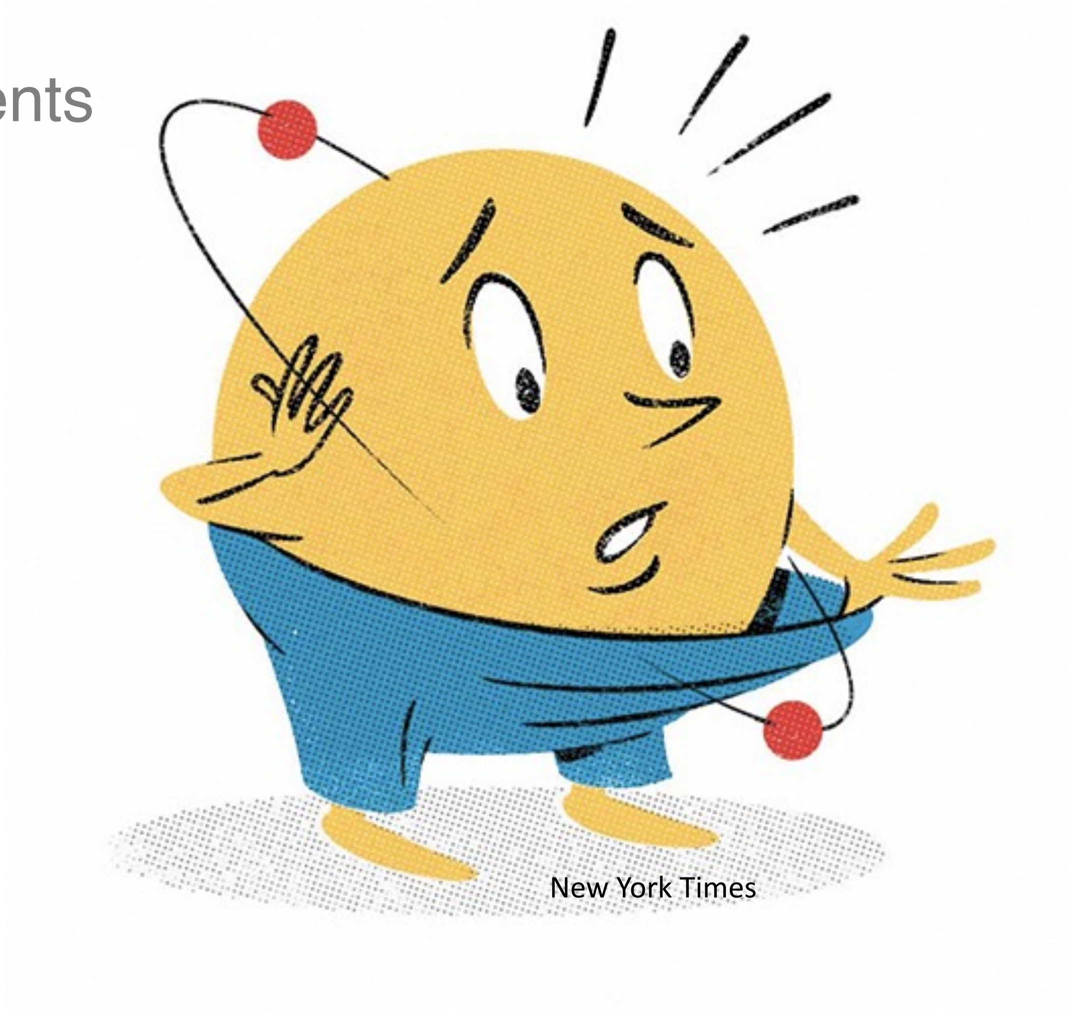


Need future lepton scattering experiments with higher precision!

Outline

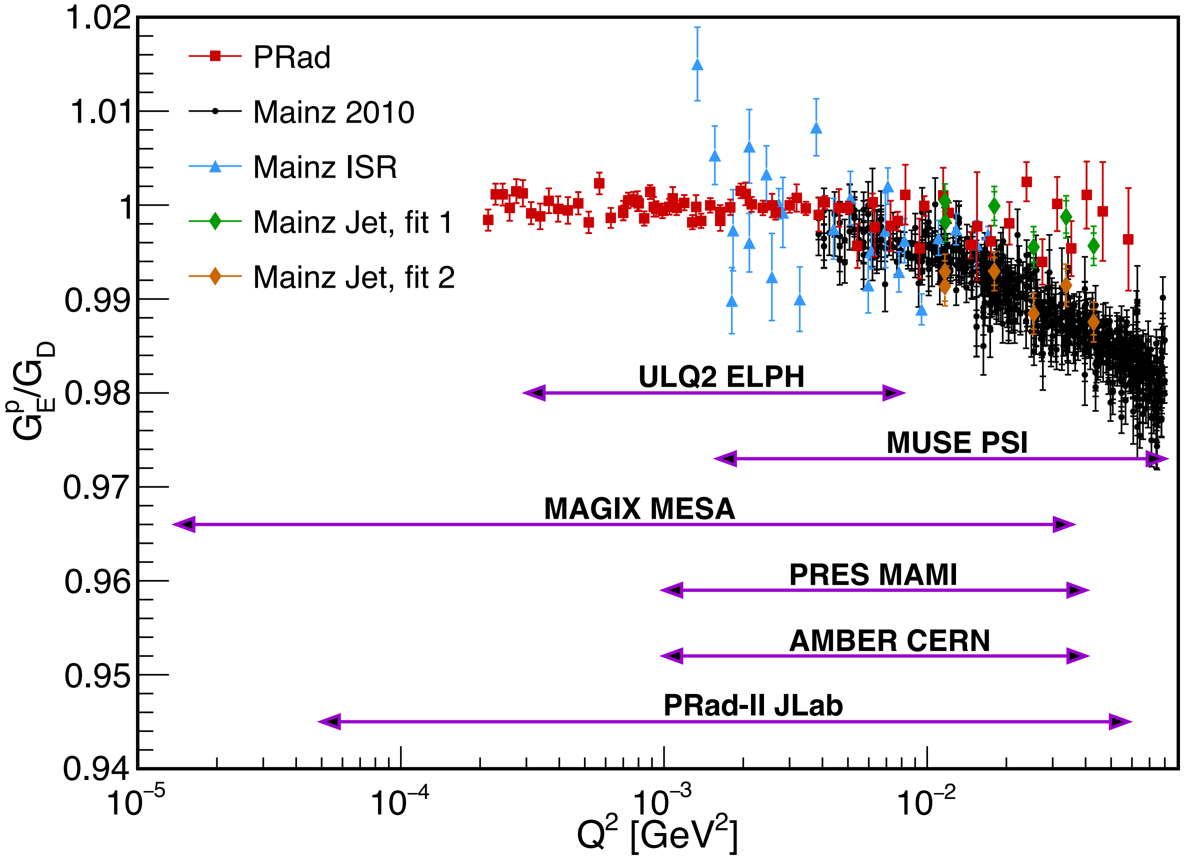
- ➢Intro to Proton Charge Radius Puzzle
- ➢Recent Progress from *ep* Scattering Experiments
- ➢Remaining Issues for Lepton Scattering
- ➢Future Lepton Scattering Experiments
- ➢Summary



Highlights of Future Lepton Scattering Experiments

- MUSE experiment at PSI
  - First r_p measurement using muon
  - 4 types of incident leptons: $e^{\pm}$ and $\mu^{\pm}$
- AMBER experiment at CERN
  - 100 GeV muon beam, detecting scattered muon and recoiled proton
  - Ultra-small scattering angle, minimize G_M
  - Smaller RC for muon
- PRES experiment at Mainz
  - detecting both scattered electron and recoiled proton
  - Q2 reconstructed using proton, suppress RC
- MAGIX experiment at Mainz
  - Using jet target
  - Strong sensitivity on both G_E and G_M
- ULQ2 experiment at Tohoku University, Japan
  - Normalize to the well-known *e-*^{12}*C* cross section
  - Strong sensitivity on both G_E and G_M

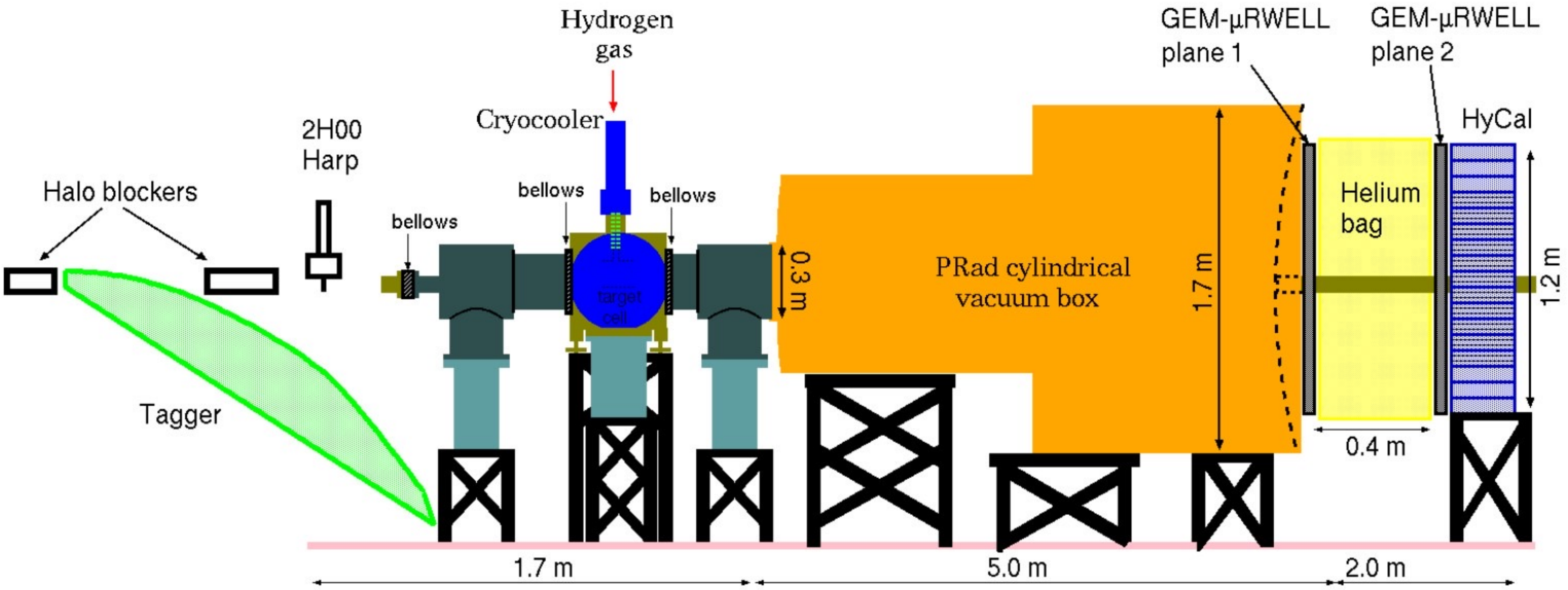
Projected Q^2 coverage



WX and Chao Peng (彭潮) arXiv:2302.13818

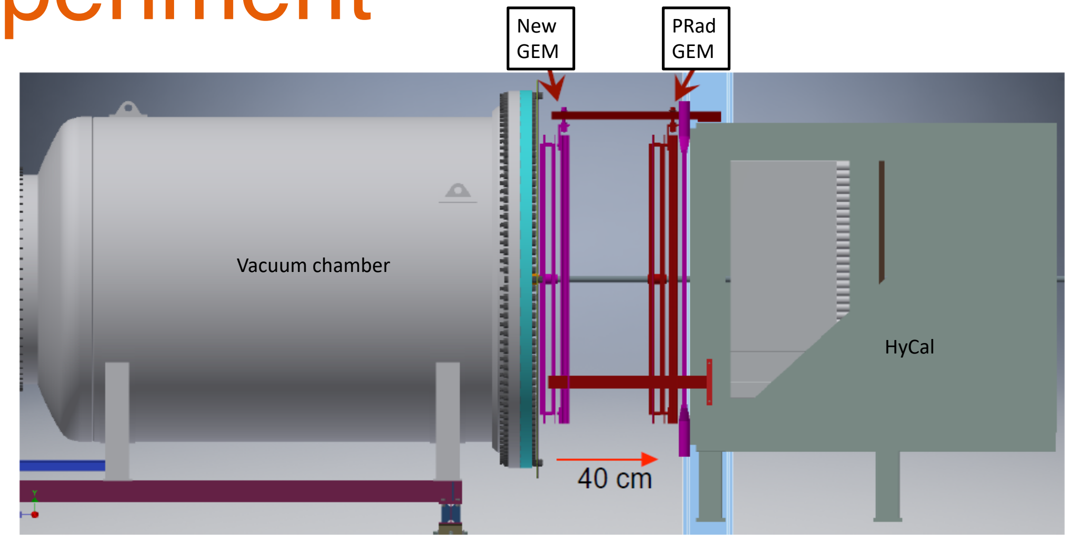
PRad-II Experiment

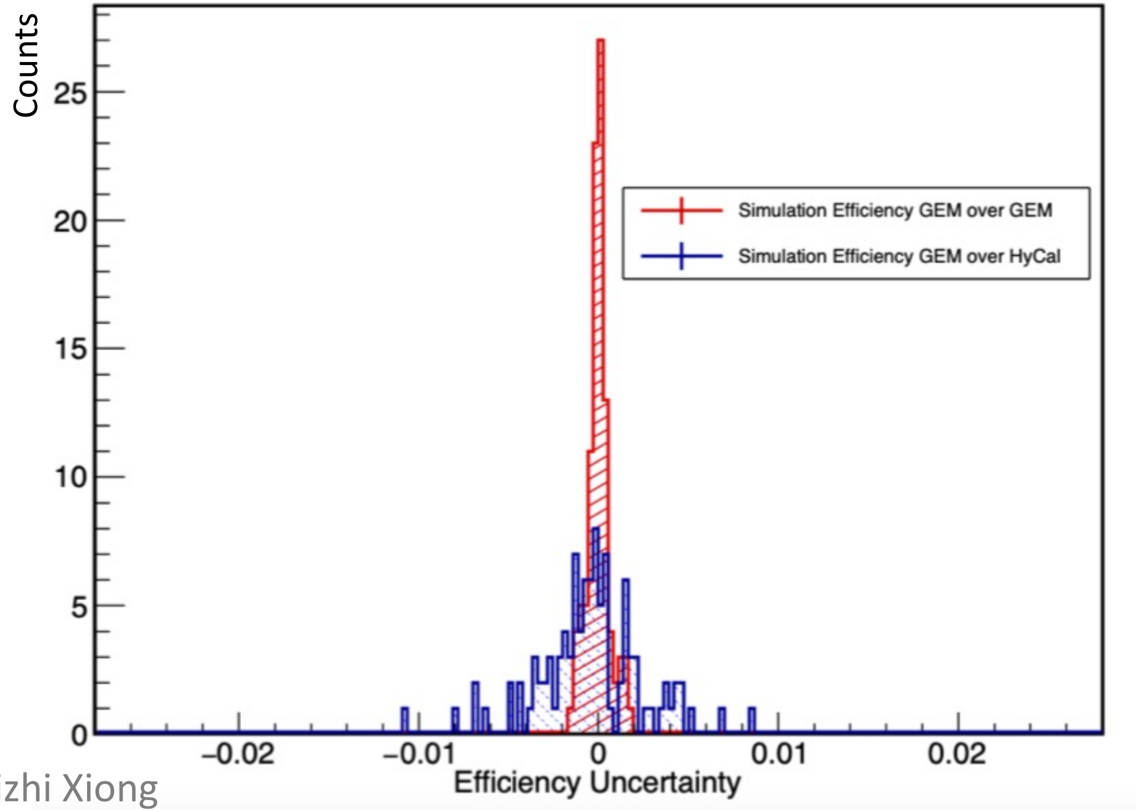
- JLab PAC 48 approved PRad-II (PR12-20-004) with the highest scientific rating “A”
- Goal: reach ultra-high precision (~4 times smaller total uncertainty), resolve tension between modern *e-p* scattering results

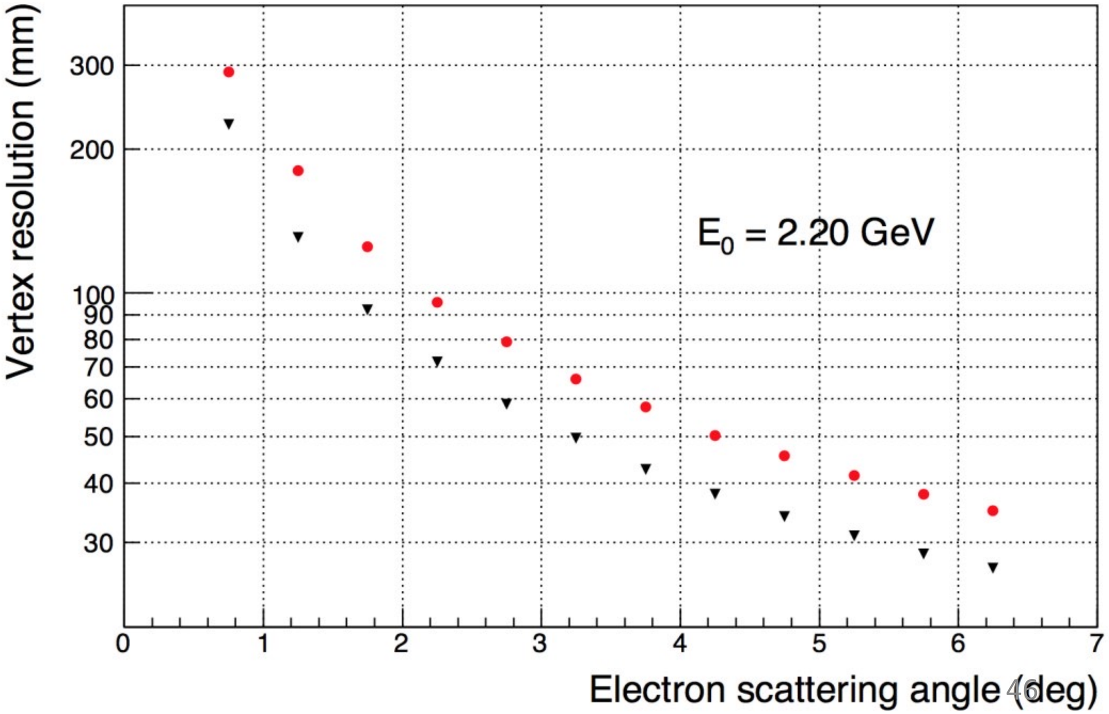


PRad-II Experiment

- Adding tracking capacity (second GEM plane)
  - ➢ Improve GEM efficiency measurement
  - ➢ Vertex-z reconstruction for *ep* to reject upstream background

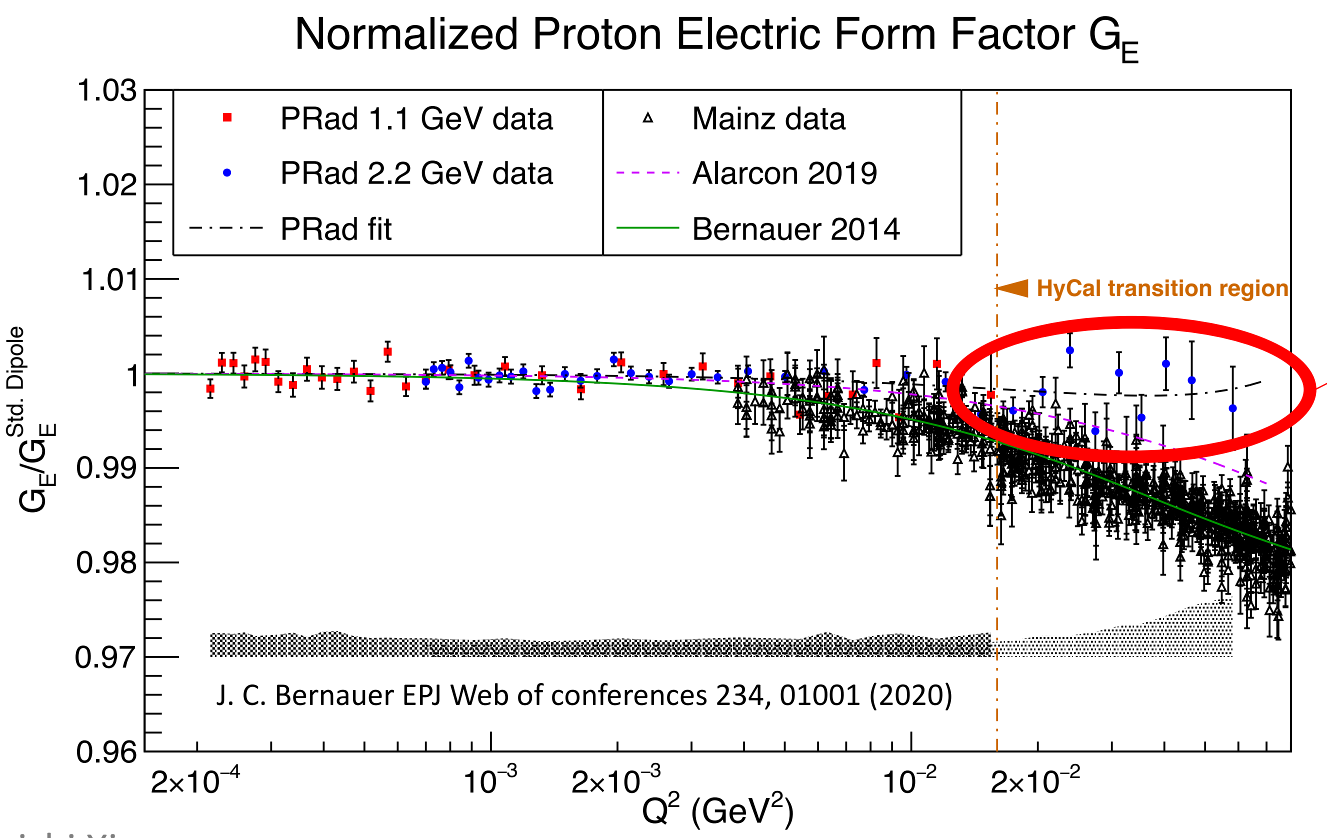


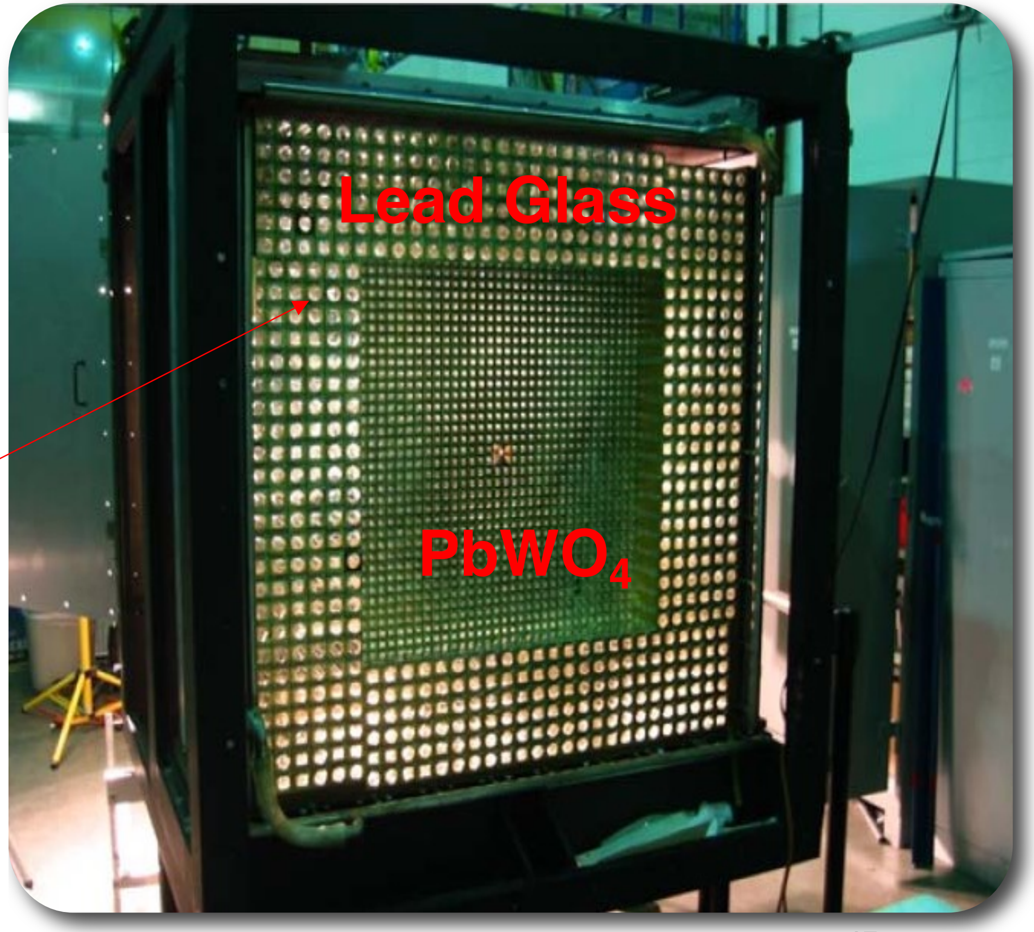




PRad-II Experiment – Cont.

- Upgraded HyCal with all high resolution $PbWO_4$ modules
  - ➢ Better energy resolution: 2.4% v.s. 6.0% from LG
  - ➢ Better position resolution
  - ➢ Better non-linearity response





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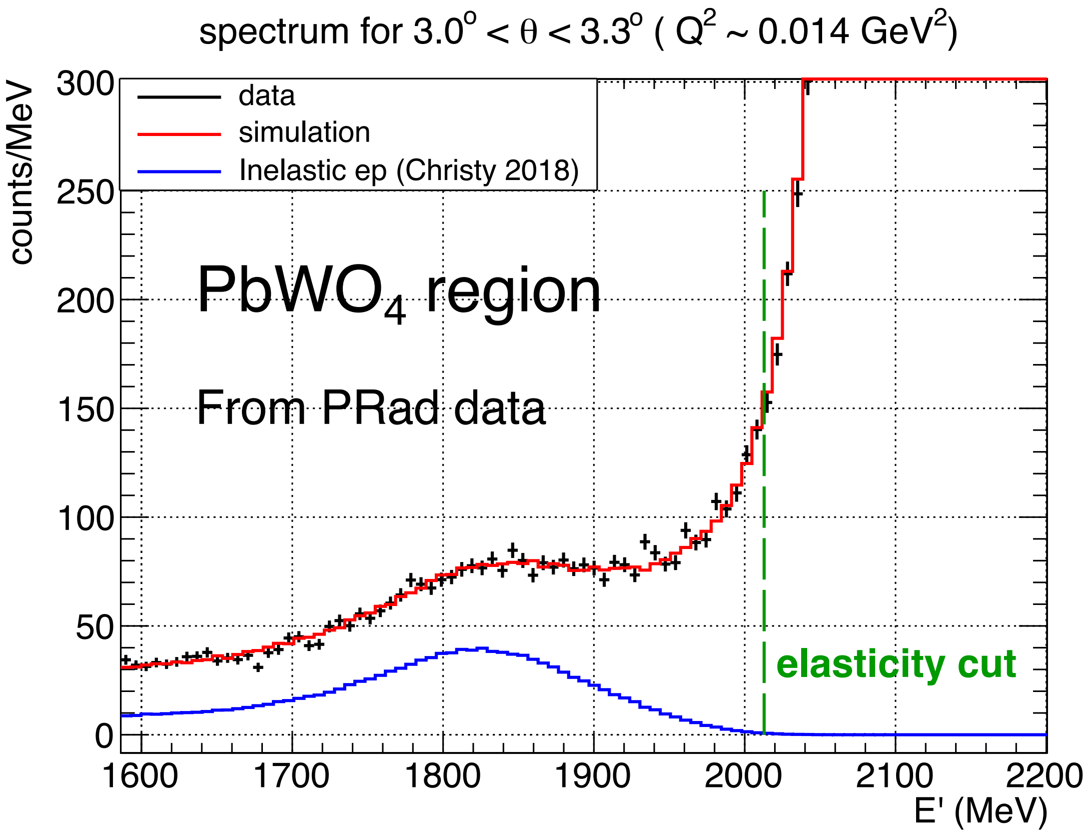

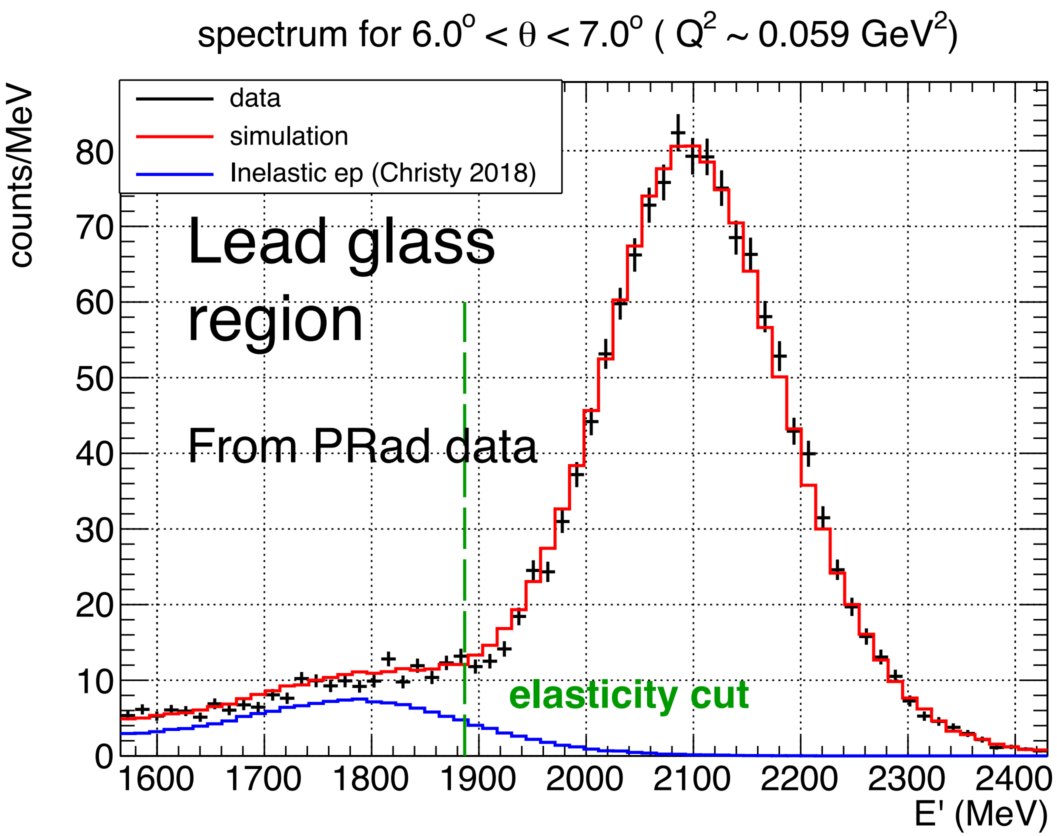

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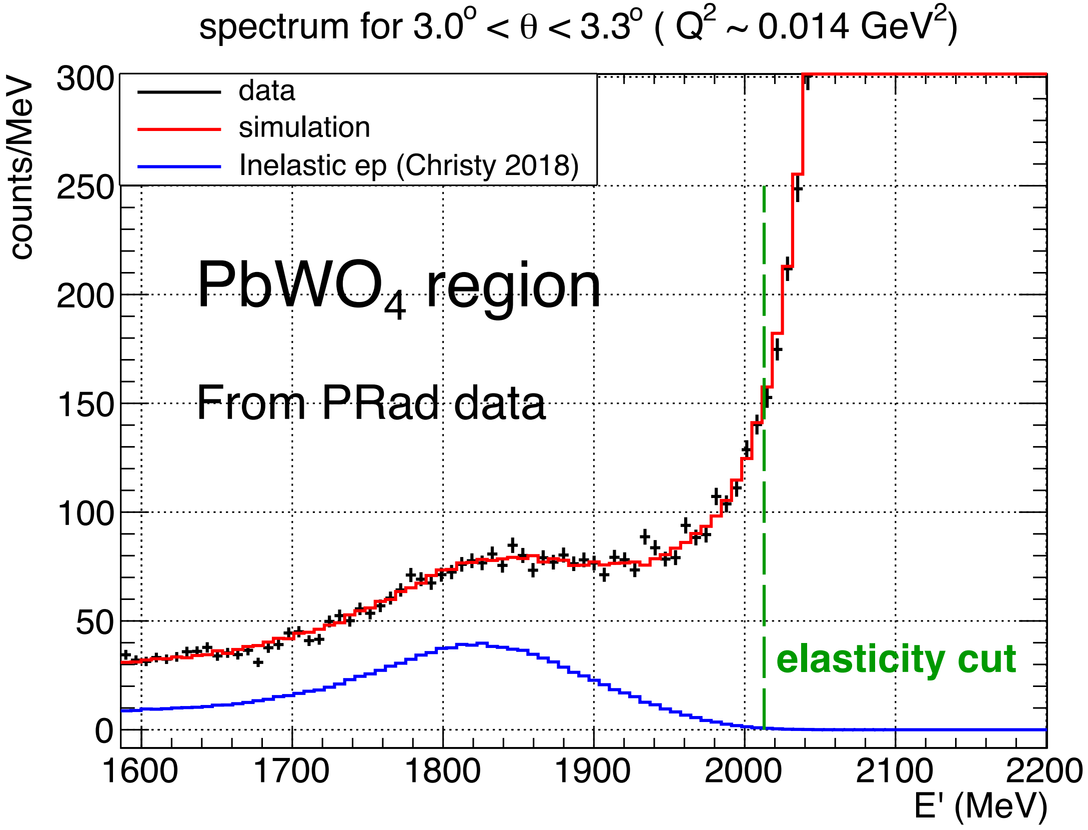
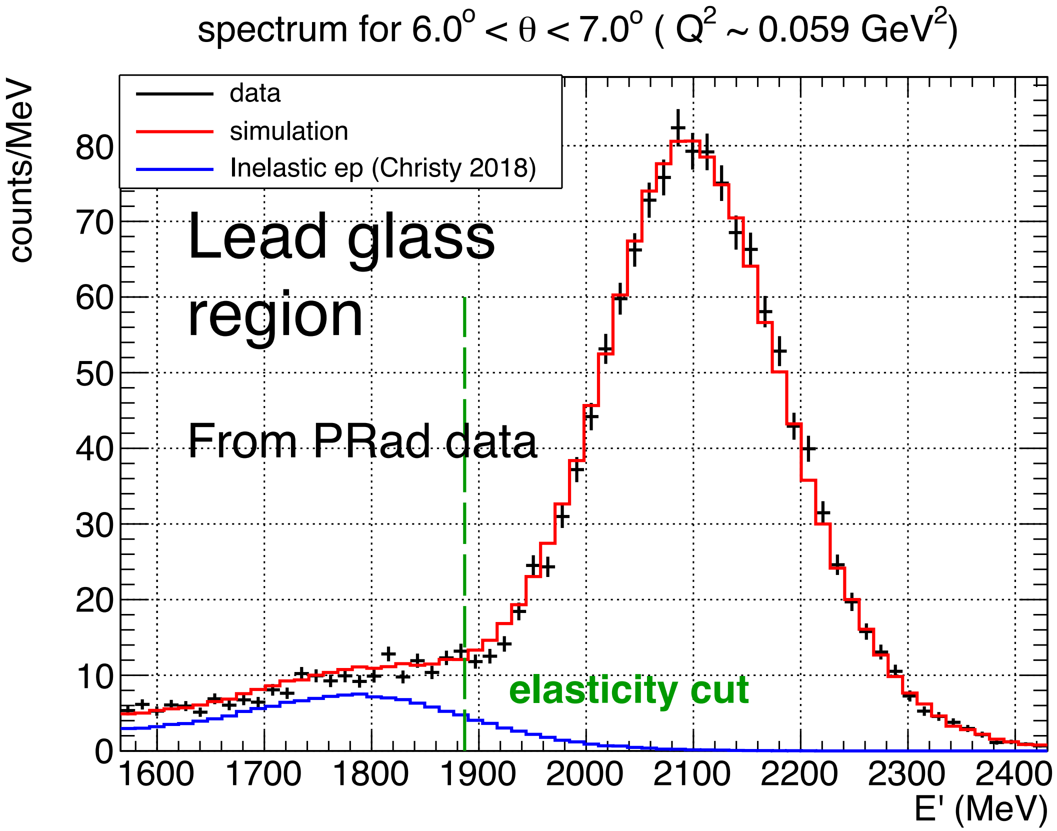
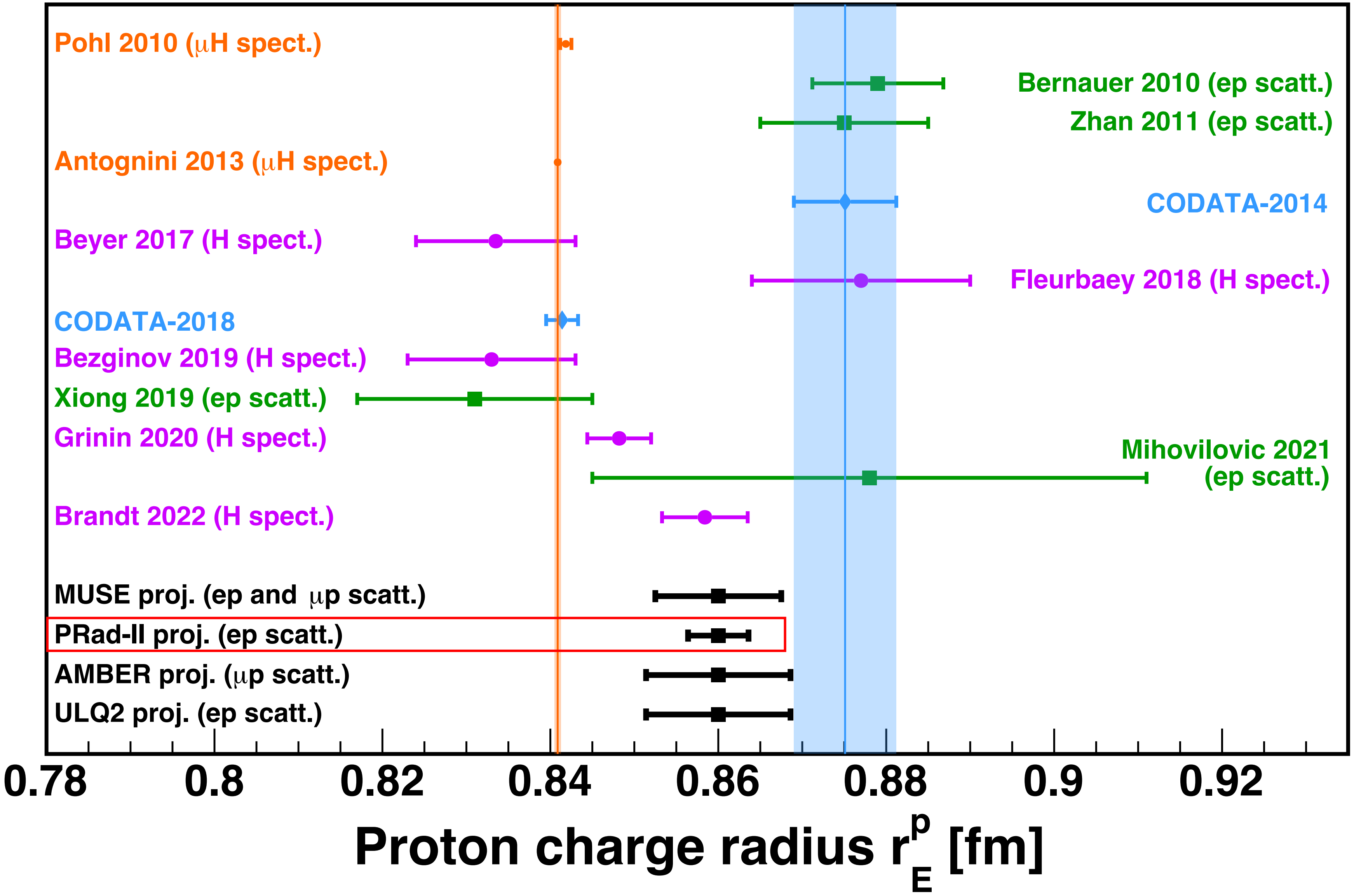
  - ➢ Better position resolution
  - ➢ Better non-linearity response
- Currently seeking funding or used modules for the upgrade



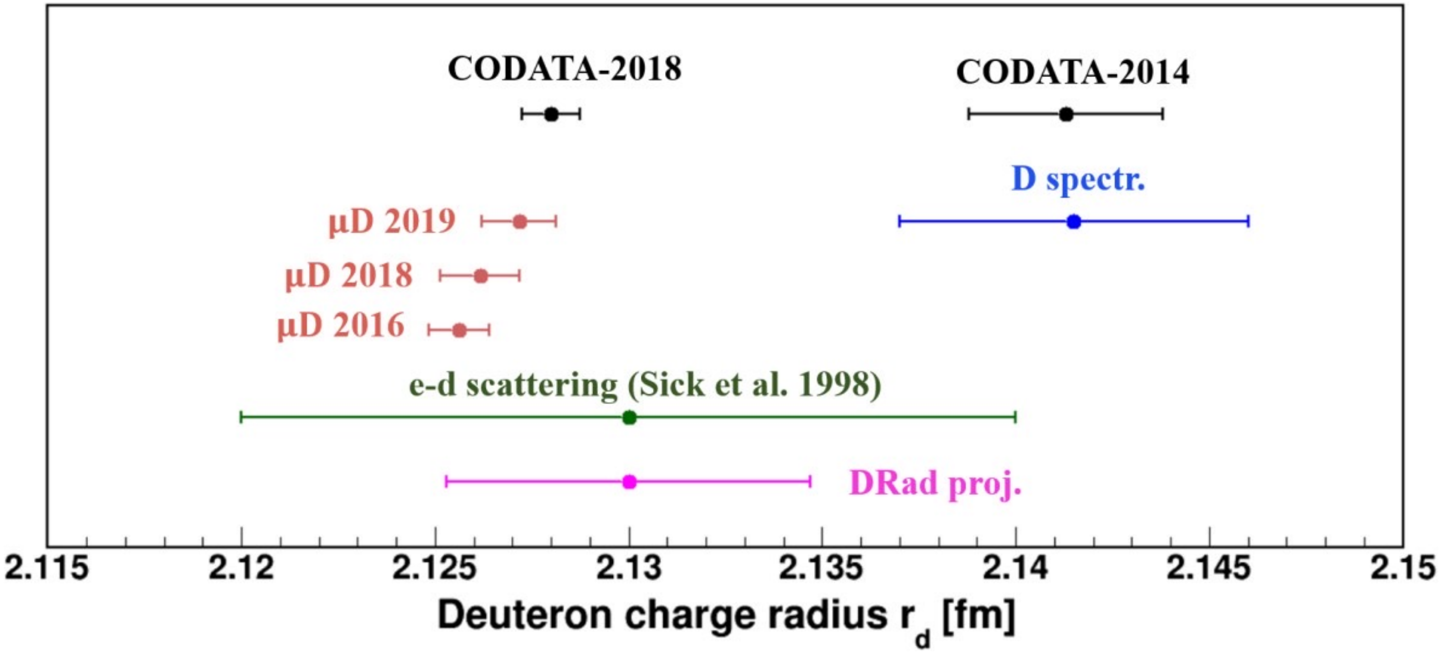


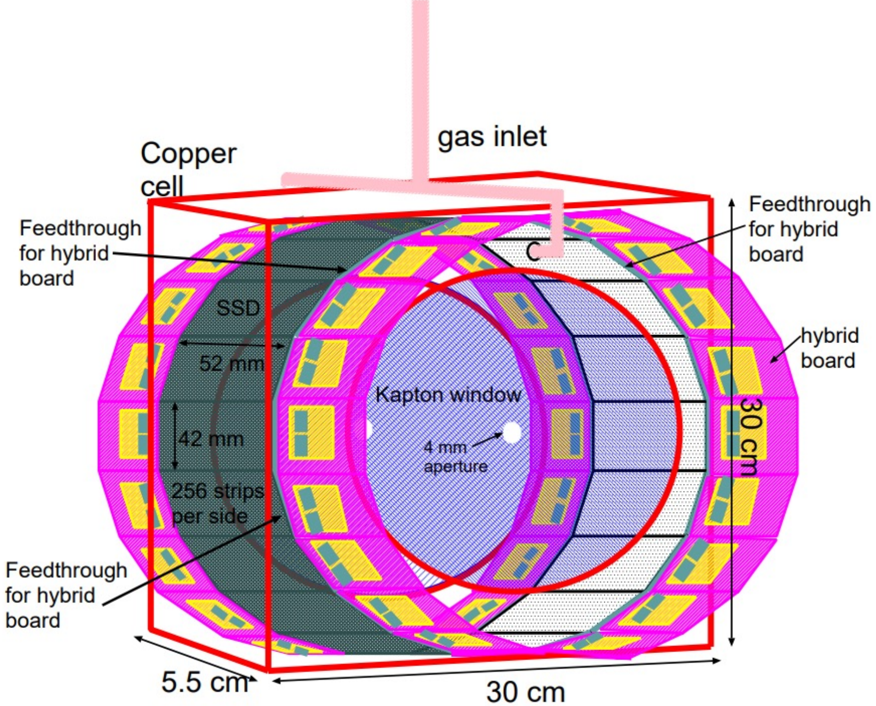
Projected Results



Deuteron Charge Radius Puzzle and DRad Experiment

- Similar 7σ discrepancy exists between μD and D spectroscopy ("deuteron charge radius puzzle")
- Previous *ed* scattering precision not good enough, need better data
- Use mostly PRad setup with additional recoil detector for deuteron detection
- Plan to submit proposal this year to JLab





Weizhi Xiong

Summary

- PRad measured r_p using novel scattering technique:
  - ➢ r_p = 0.831 +/- 0.007 (stat.) +/- 0.012 (syst.) fm (*Nature* 575 (2019) 7781)
- Puzzle considered partially resolved, but many problems remain, particularly in lepton scattering
  - ➢ r_p definition between scattering and spectroscopy
  - ➢ Form factor difference between PRad and Mainz data
- Many future lepton scattering experiments will help address these issues, and push precision frontier
  - PRad-II experiment with $\delta_r \sim 0.0036$ fm, will be most precise scattering result, new search for lepton-universality violation

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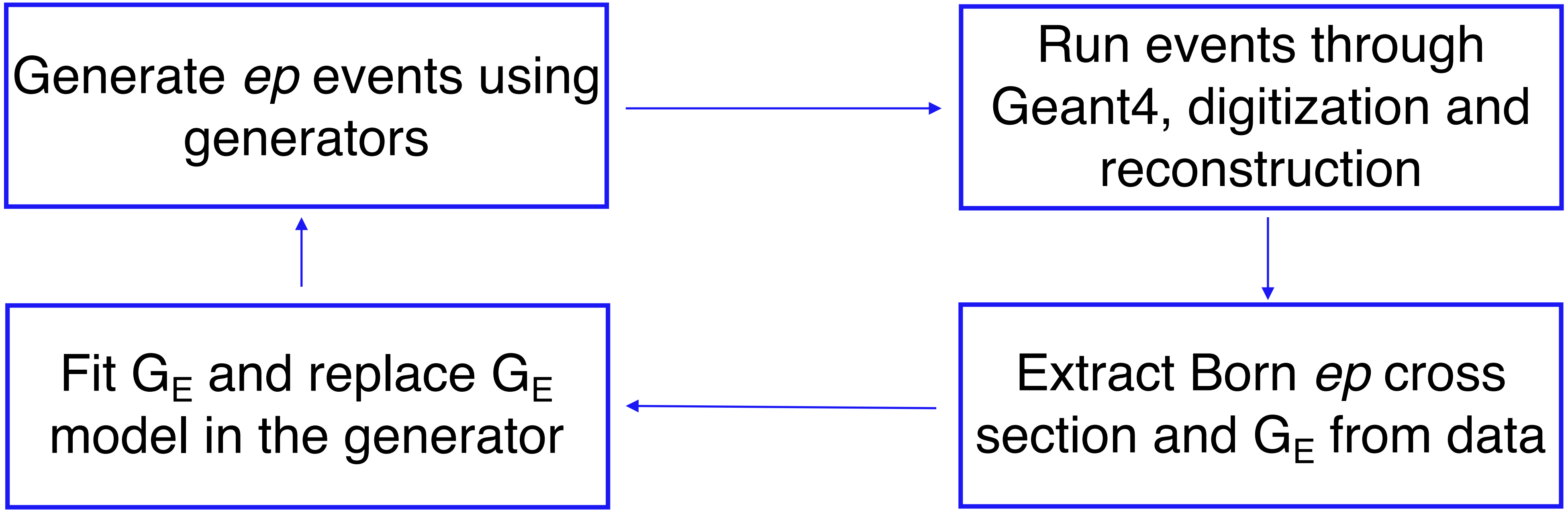
Thank you for your attention and we welcome all physics ideas

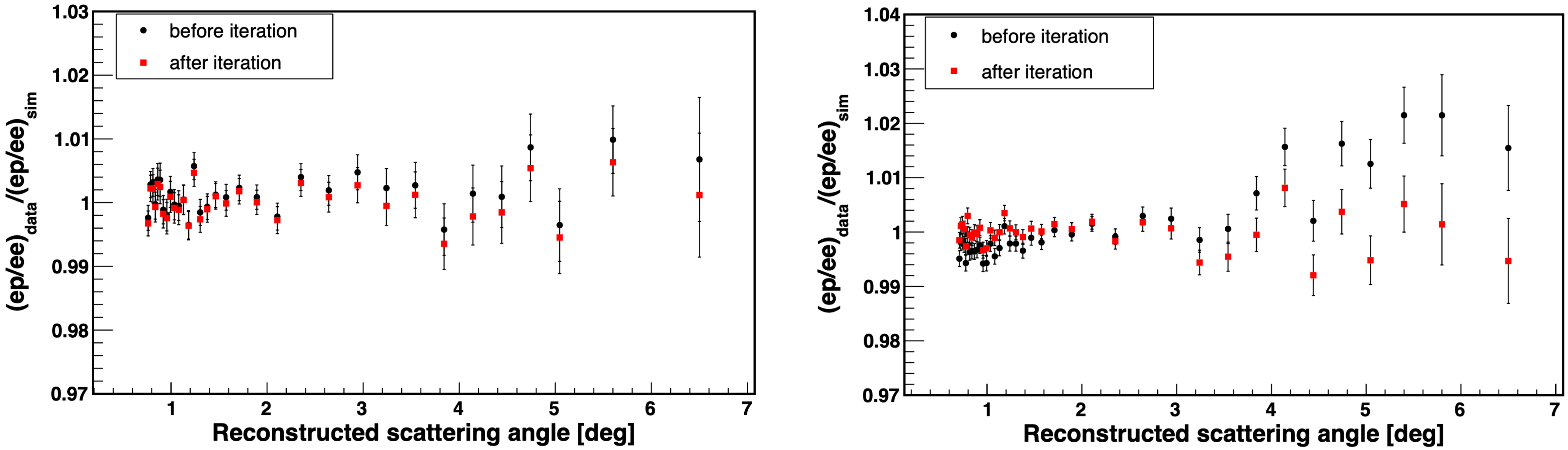
Backup

Iterative Procedure



- Iteration stopped when the super-ratio $(\sigma_{ep}/\sigma_{ee})^{exp}/(\sigma_{ep}/\sigma_{ee})^{sim}$ converges to 1
- Covergence speed quite fast (# of iteration needed < 5)
- final result independent of the initial G_E model, and # of iteration

Iterative Procedure



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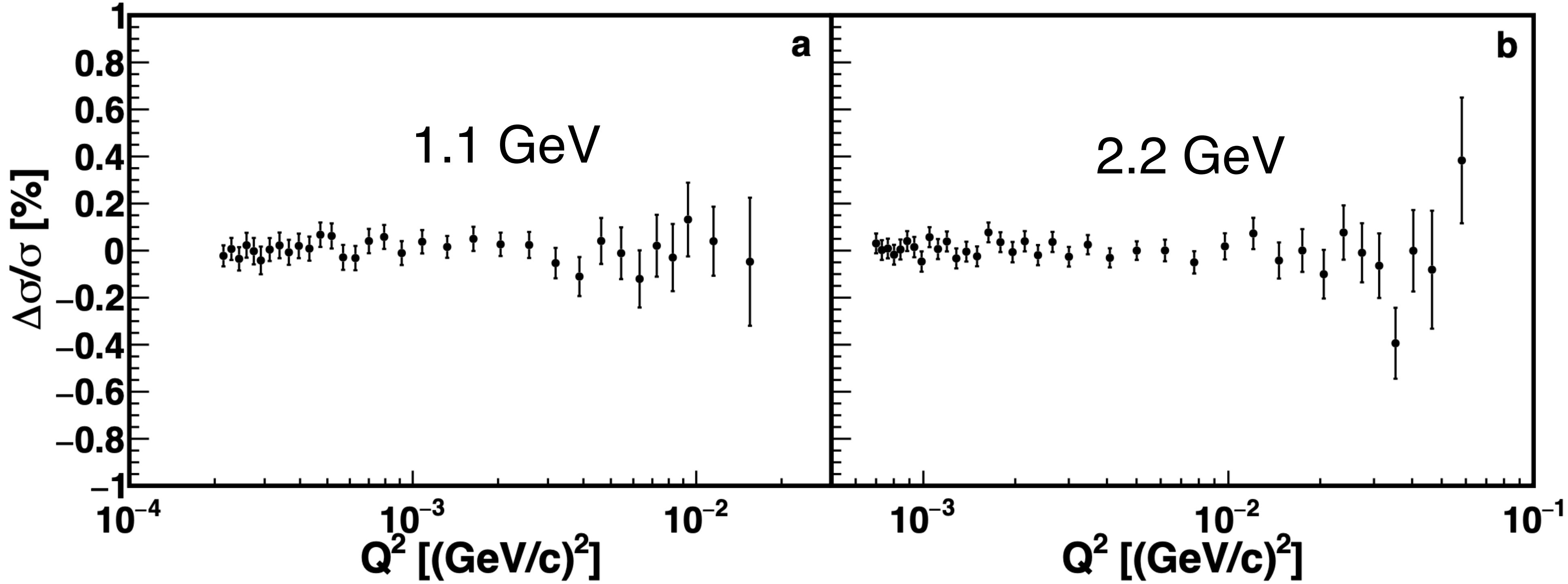
Iterative Procedure

Relative difference of cross section before and after iteration



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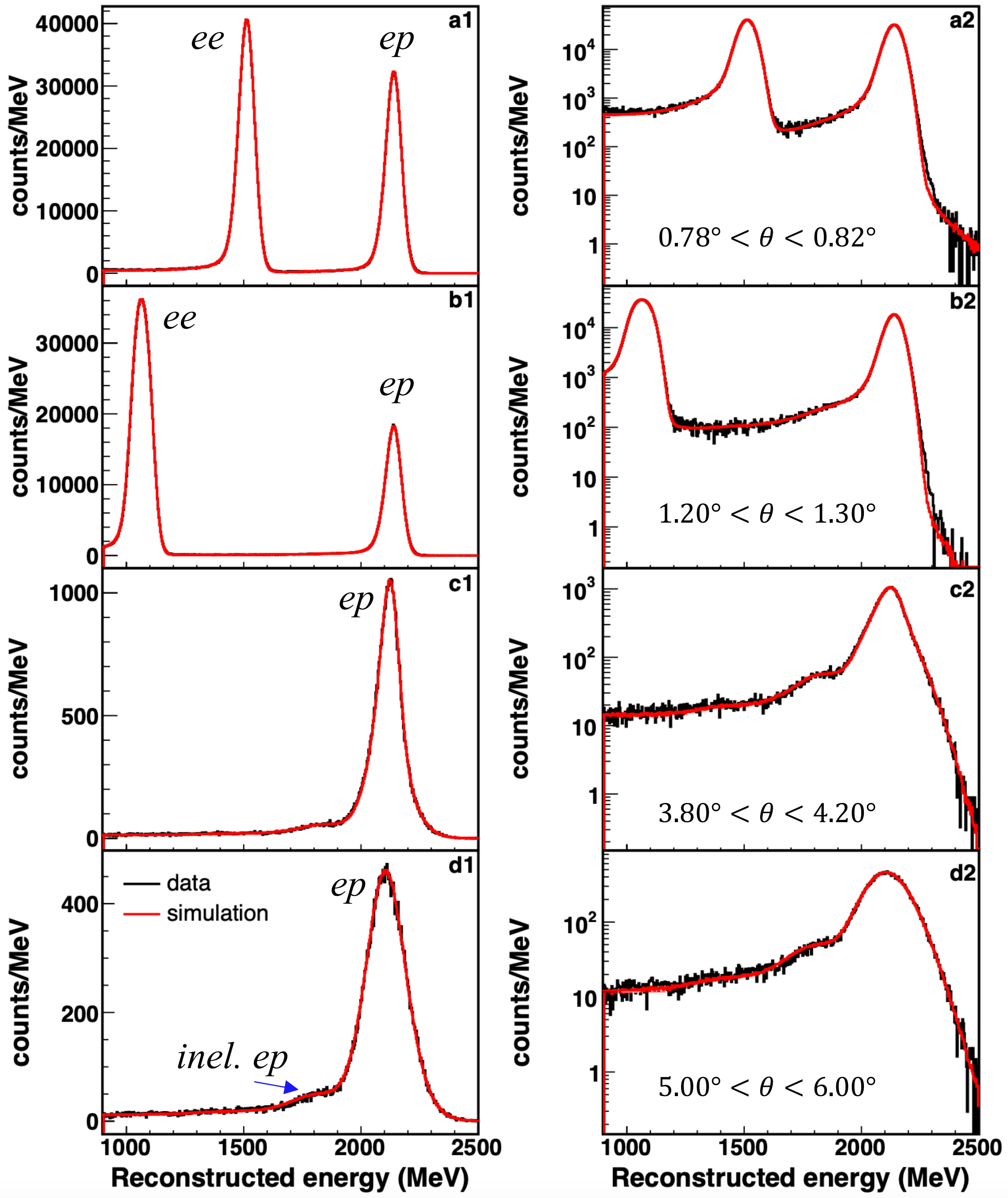
Data v.s. Simulation

- Reasonable agreement for e' energy spectra between data and simulation at all angles

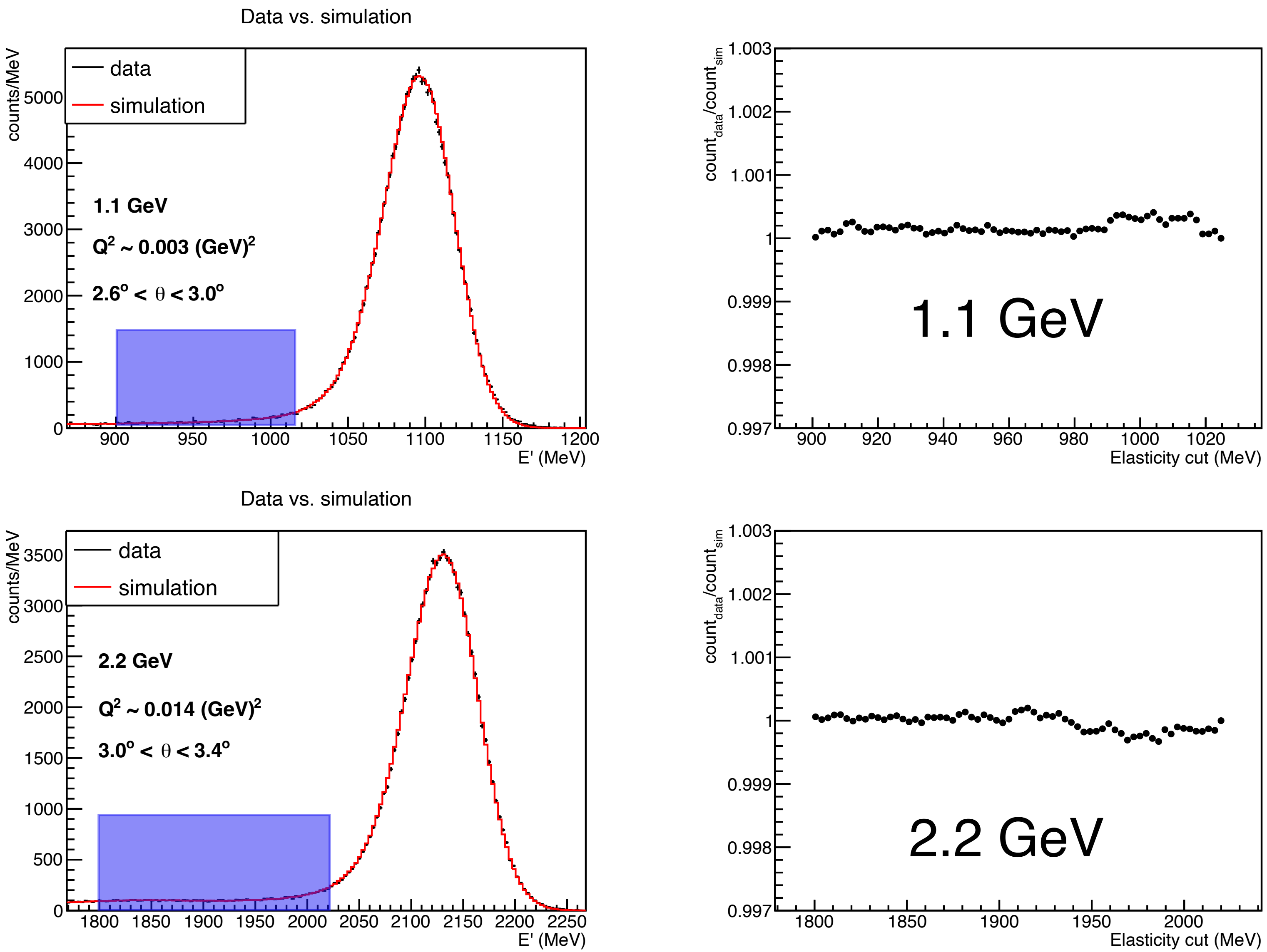
- Geant4 Simulation includes:

  1. *ep* elastic events with rad. effect
     - I. Akushevich et al., Eur. Phys. J. A 51(2015)1
     - A. V. Gramolin et al., J. Phys. G Nucl. Part. Phys. 41(2014)115001
  2. *ee* elastic events with rad. effect
     - I. Akushevich et al., Eur. Phys. J. A 51(2015)1
  1. inelastic ep with rad. effect
     - M. E. Christy and P. E. Bosted, PRC 81, 055213 (2010)
  2. Detector response and pile-up effect



Radiative Tails

- Changing elasticity cut at the radiative tail and obtain different sets of cross section results
- Sensitivity on cross section: typically within +/- 0.15%
- Mostly due to non-uniformity of HyCal modules



PRad-II Uncertainty Budget

Item	PRad δr_p [fm]	PRad-II δr_p [fm]	Reason
Stat. uncertainty	0.0075	0.0017	more beam time
GEM efficiency	0.0042	0.0008	2nd GEM detector
Acceptance	0.0026	0.0002	2nd GEM detector
Beam energy related	0.0022	0.0002	2nd GEM detector
Event selection	0.0070	0.0027	2nd GEM + HyCal upgrade
HyCal response	0.0029	negligible	HyCal upgrade
Beam background	0.0039	0.0016	better vacuum 2nd halo blocker vertex res. (2nd GEM)
Radiative correction	0.0069	0.0004	improved calc.
Inelastic *ep*	0.0009	negligible	-
G_M^p parameterization	0.0006	0.0005	HyCal upgrade
Total syst. uncertainty	0.0115	0.0032	
Total uncertainty	0.0137	0.0036	

Extracting Form Factors

- One of the methods for form factor extraction is the well know Rosenbluth separation:

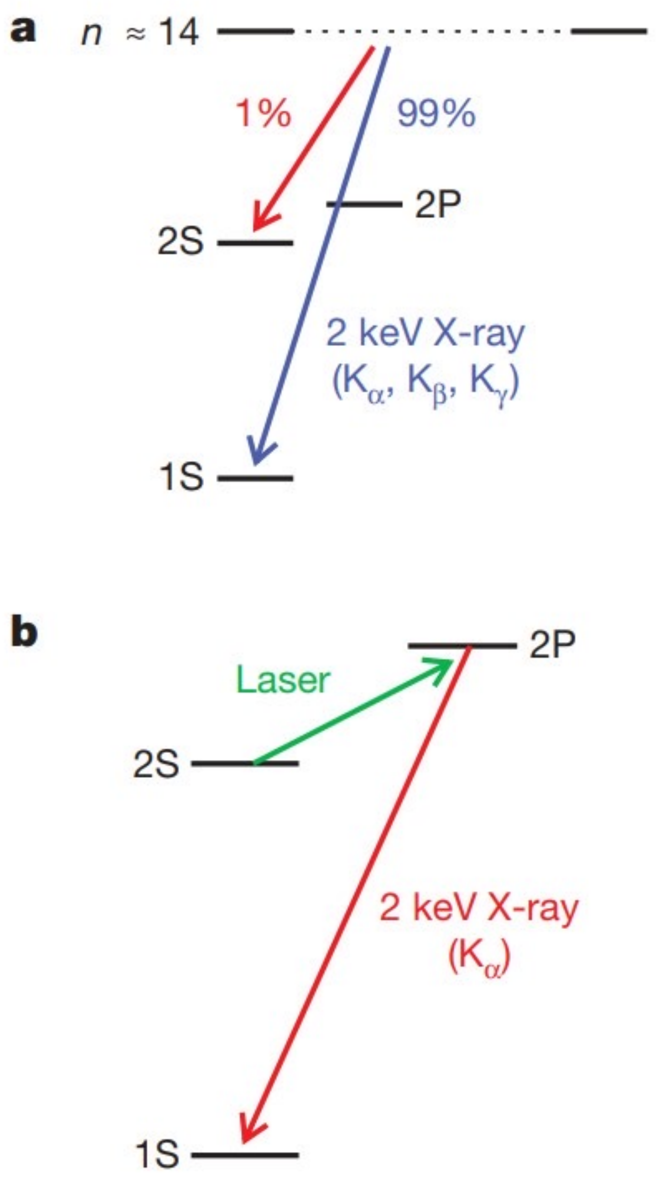
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Mott}} \left(\frac{E'}{E}\right) \frac{1}{1+\tau} \left({G_E^p}^2(Q^2) + \frac{\tau}{\varepsilon} {G_M^p}^2(Q^2) \right)$$

$$\Downarrow$$

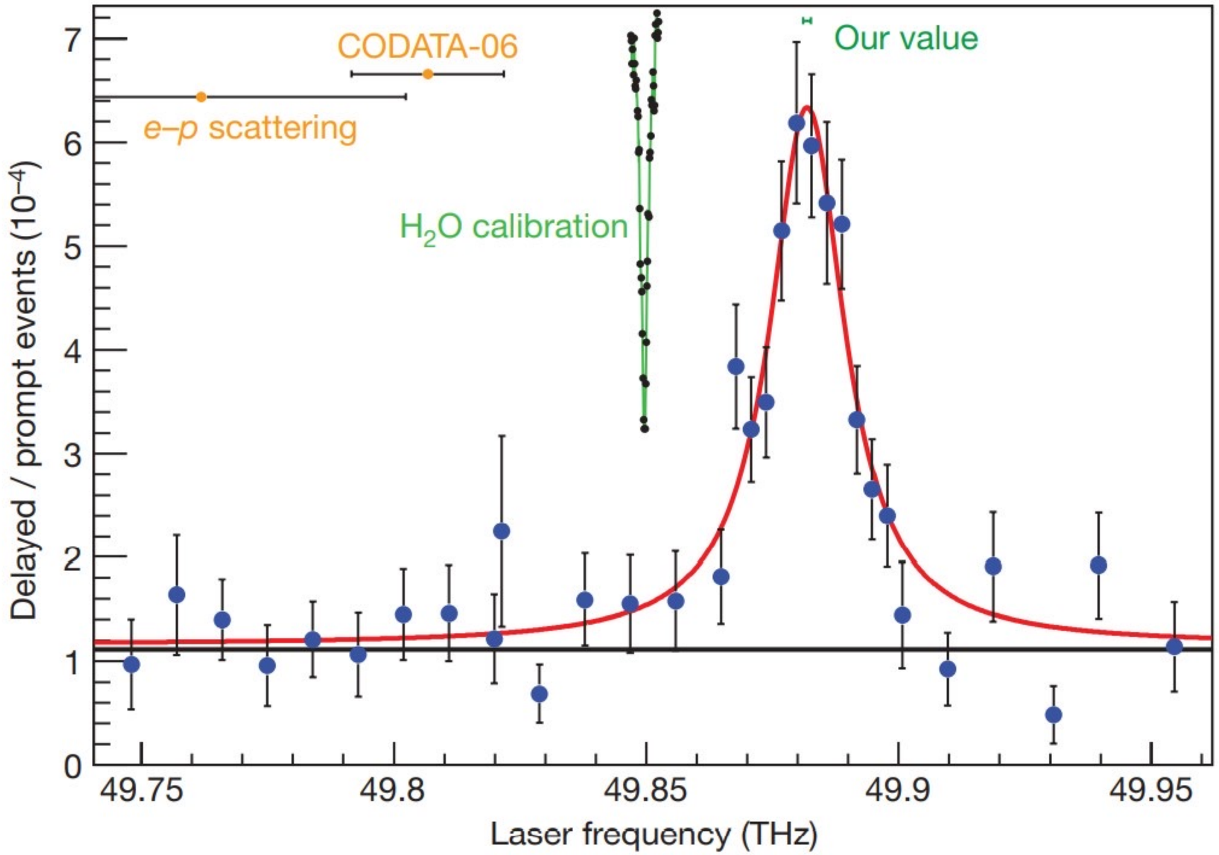
$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{reduced}} = {G_M^p}^2(Q^2) + \frac{\epsilon}{\tau} {G_E^p}^2(Q^2)$$

$$\tau = \frac{Q^2}{4M_p^2} \qquad \varepsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right]^{-1}$$

Muonic Hydrogen Measurement

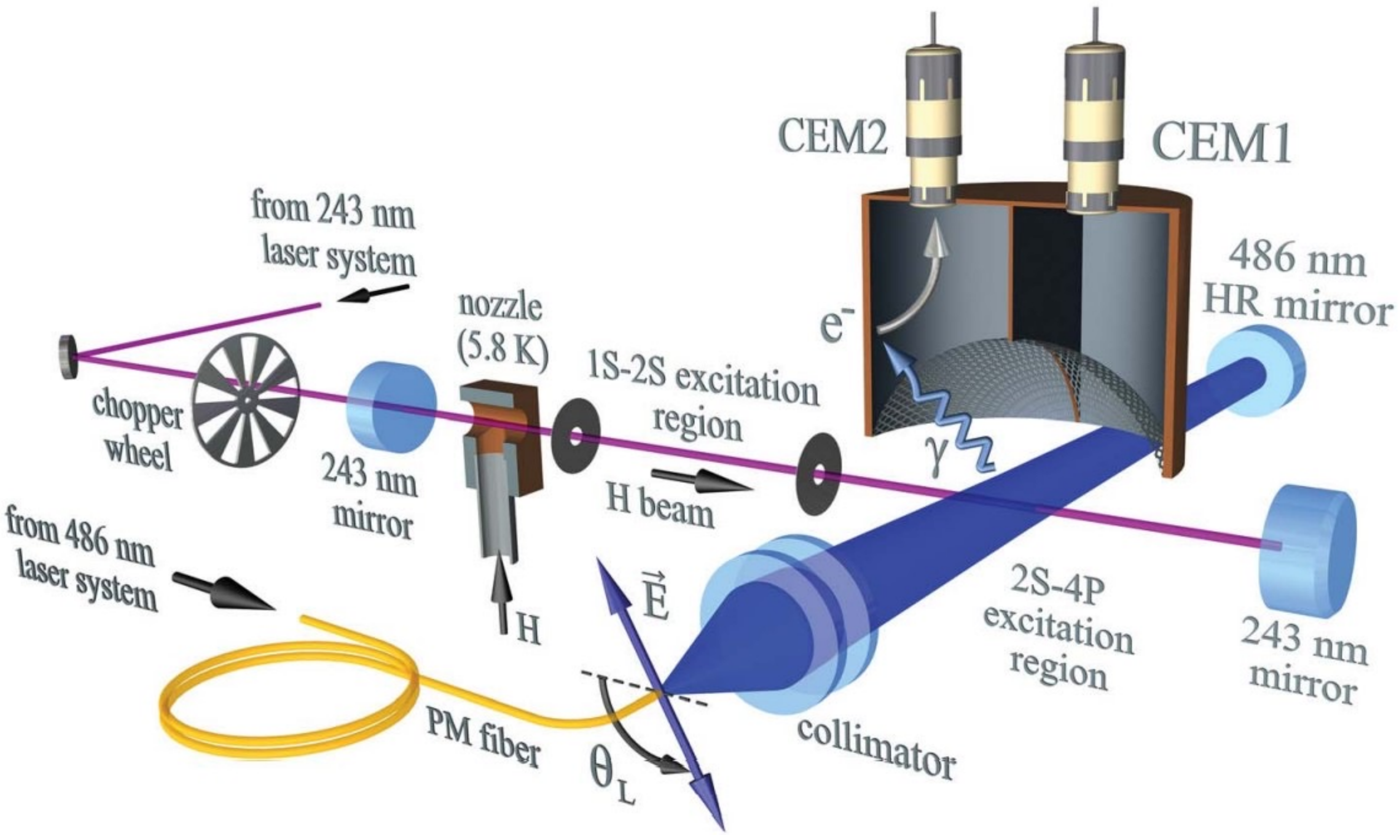


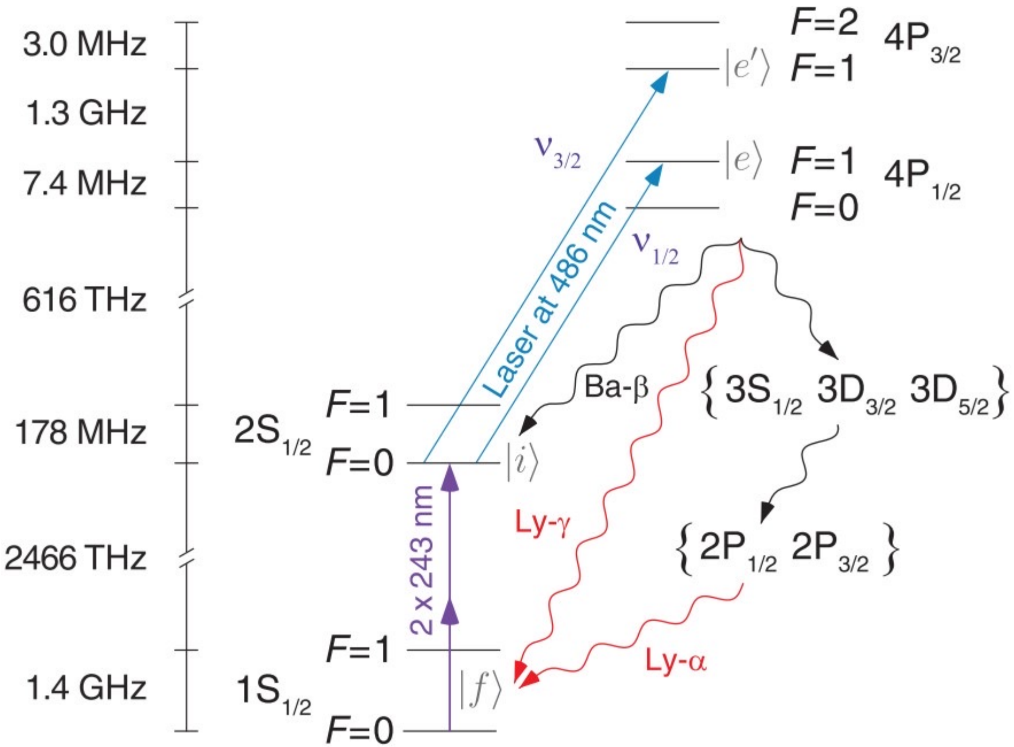
- Steps in muonic hydrogen 2S-2P Lamb shift measurement (R. Pohl, *et al. Nature* 466 213-216 (2010))



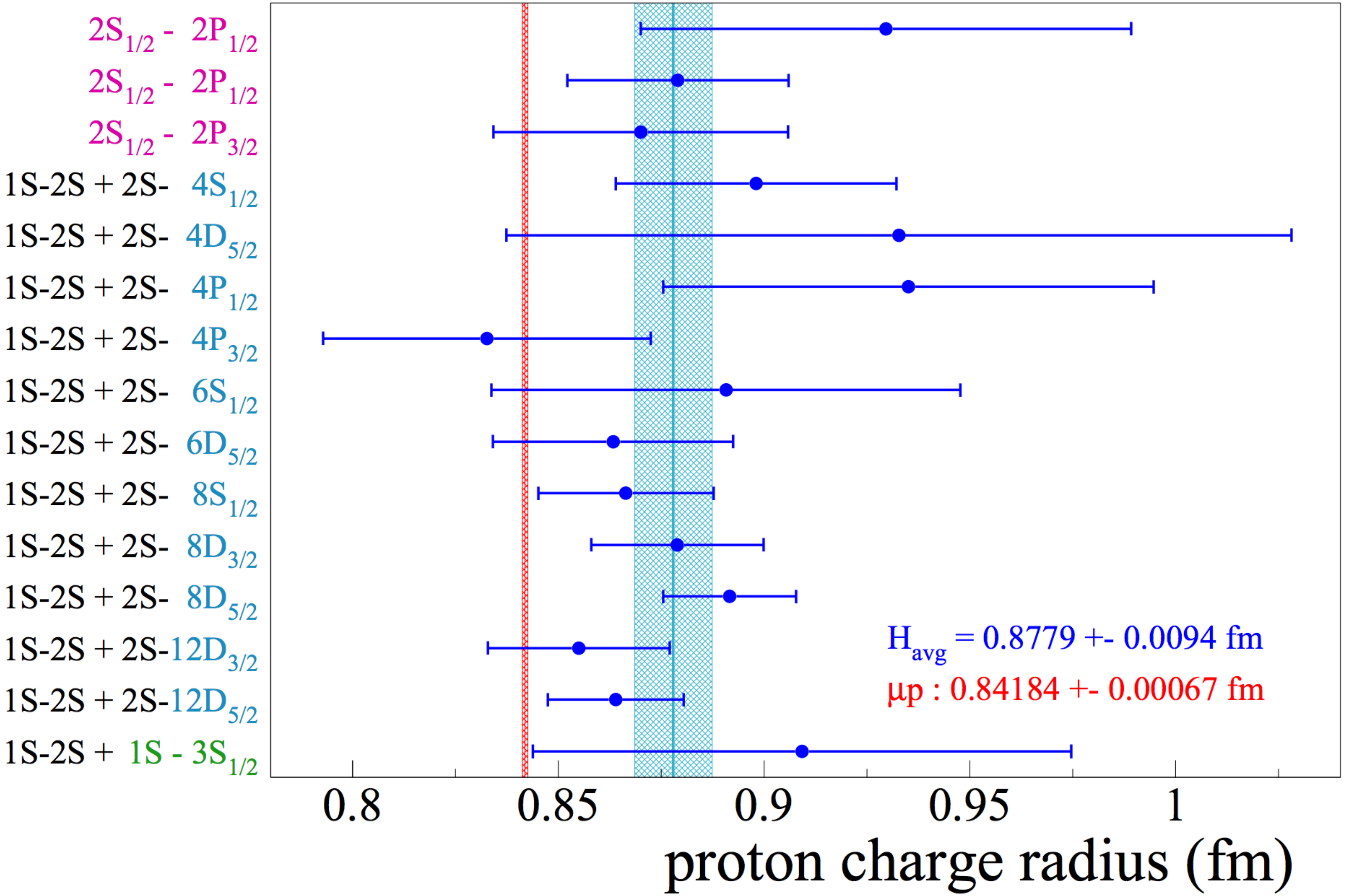
Ordinary Hydrogen Measurement

- Ordinary hydrogen 2S-4P transition measurement (A. Beyer *et al.* *Science* 358, 79-86 (2017))





Ordinary Hydrogen v.s. Muonic Hydrogen

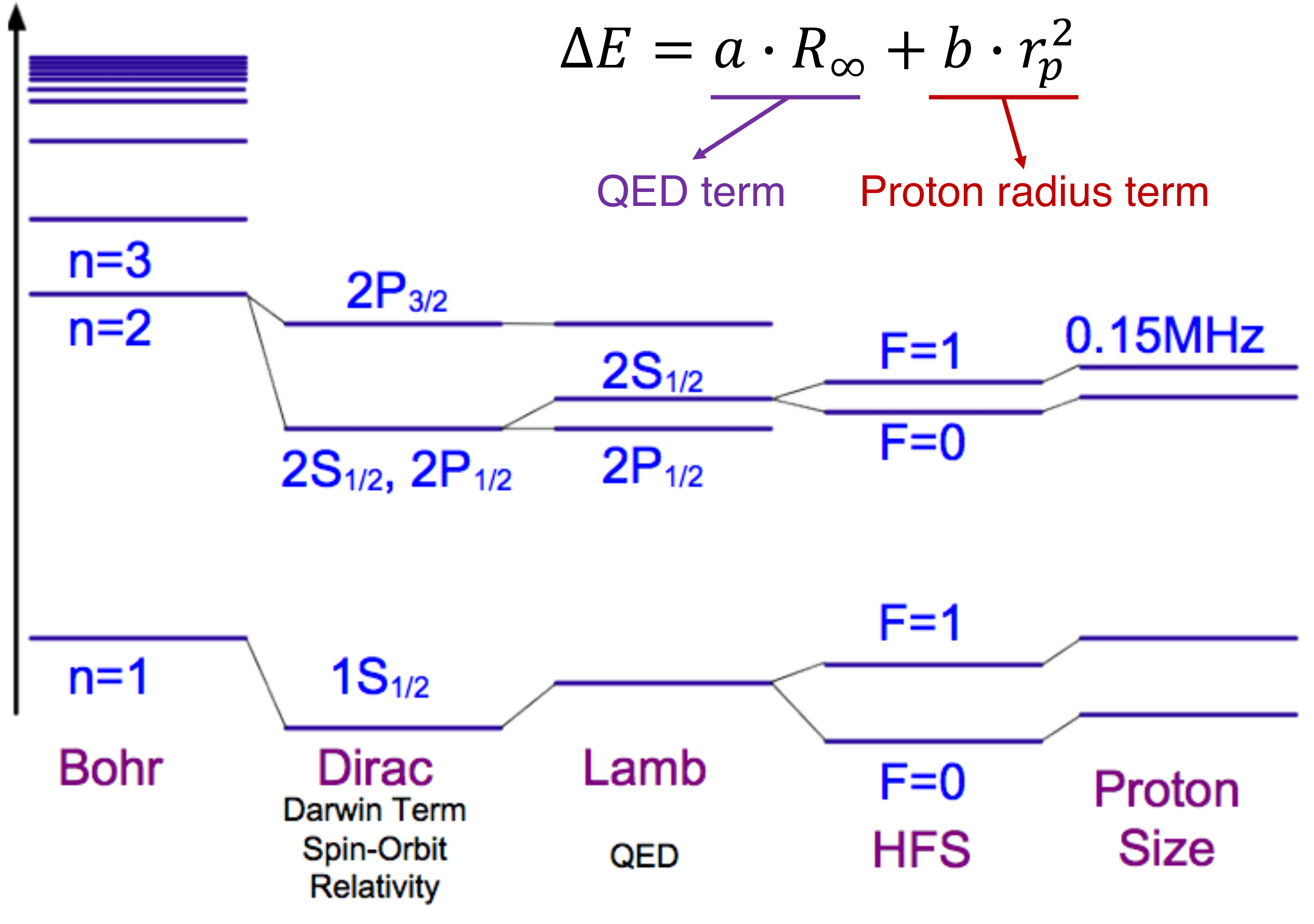


Hydrogen Spectroscopy

$$\Delta E = a \cdot R_\infty + b \cdot r_p^2$$

QED term

Proton radius term



1. Small splitting measurements:
   - ➢ States with the same n
   - ➢ Precise knowledge of R_∞ not required
   - ➢ Independent measurement on r_p

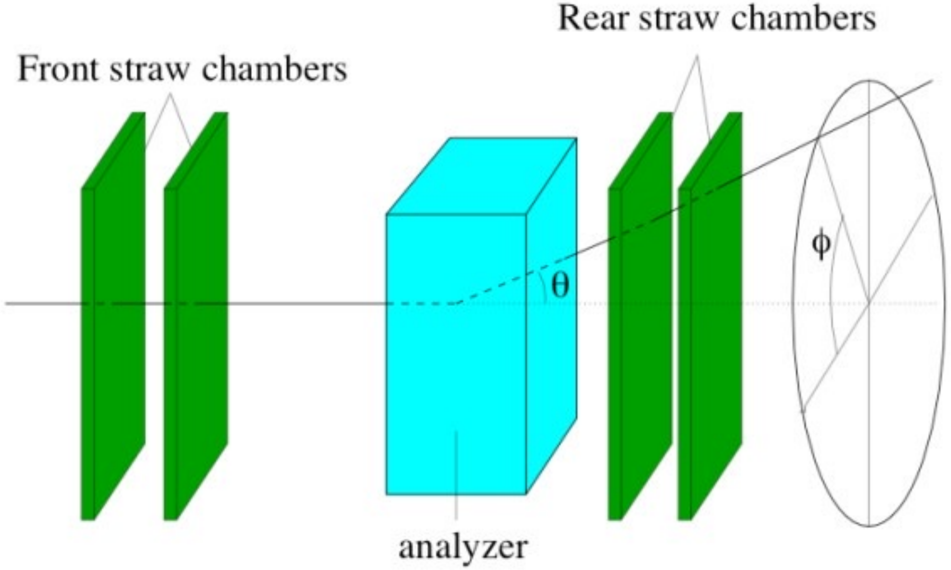
2. Large splitting measurements:
   - ➢ States with different n
   - ➢ Precision on R_∞ not good enough
   - ➢ At least need two different transition
   - ➢ Solve for r_p and R_∞ at the same time

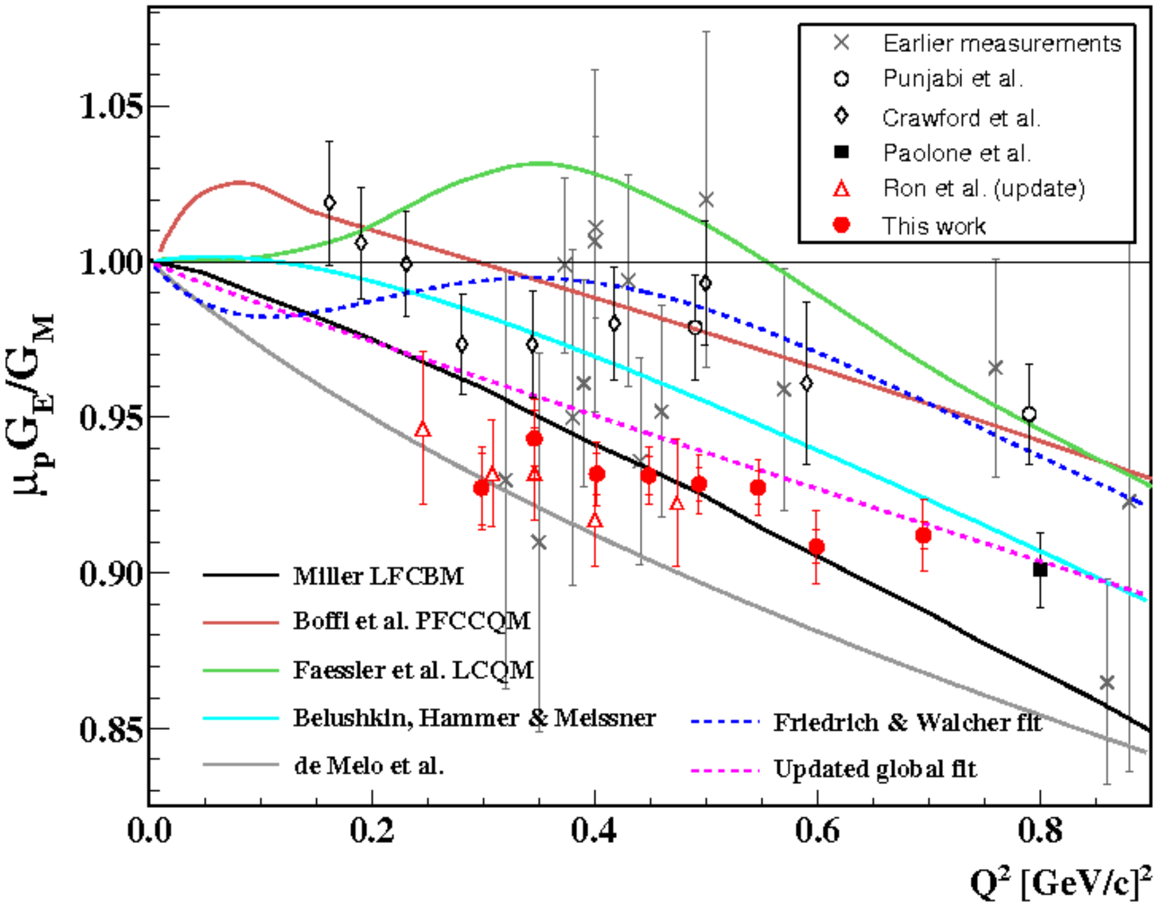
Polarized *ep* Elastic Scattering
(longitudinally polarized electron beam and recoil proton polarization measurement)

- Extract form factor ratio by measuring polarization of recoil proton:

$$\frac{G_E}{G_M} = -\frac{P_y}{P_z}\frac{E+E'}{2m}\tan\frac{\theta_e}{2}.$$

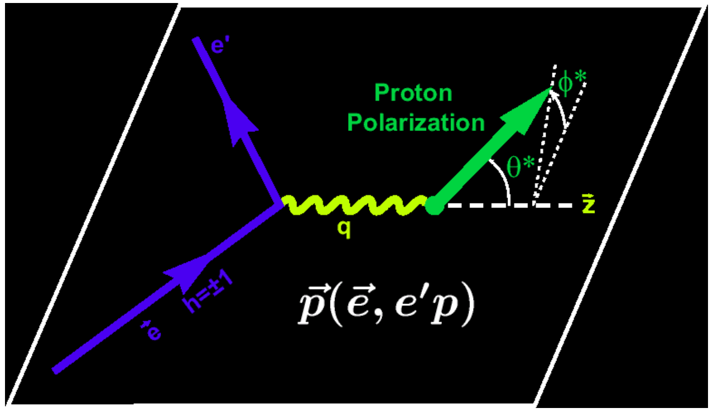
- Couple with cross section measurement to separate form factors
- Reduce many typical systematics for RS

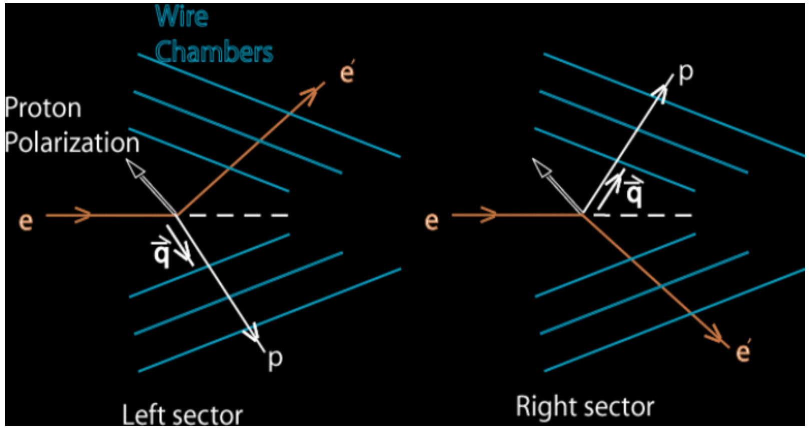




X. Zhan et al. Phys. Lett. B 705 (2011) 59-64

Polarized *ep* Elastic Scattering
(Polarized electron – polarized proton measurement)

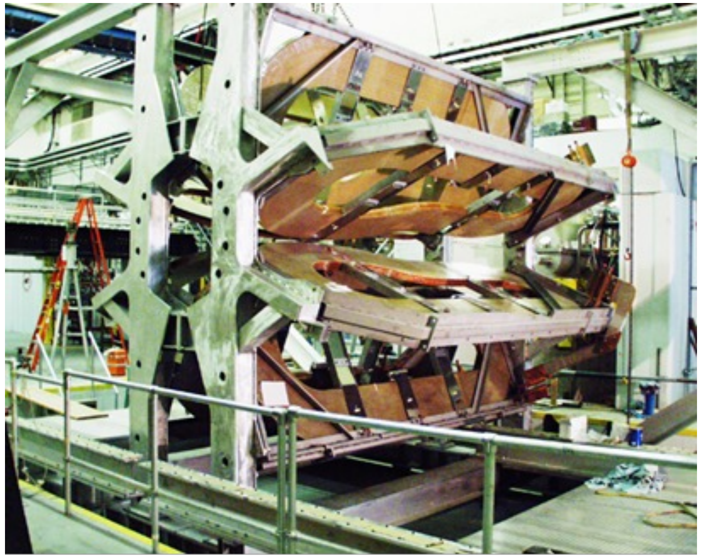




- Elastic scattering asymmetry (longitudinally polarized beam, polarized target):

$$A_{phys} = \frac{v_z \cos\theta^* {G_M^p}^2 + v_x \sin\theta^* \cos\phi^* G_M^p G_E^p}{(\tau {G_M^p}^2 + \epsilon {G_E^p}^2)\ /\ [\epsilon(1+\tau)]},$$

$$A_{exp} = P_b P_t\, A_{phys}$$

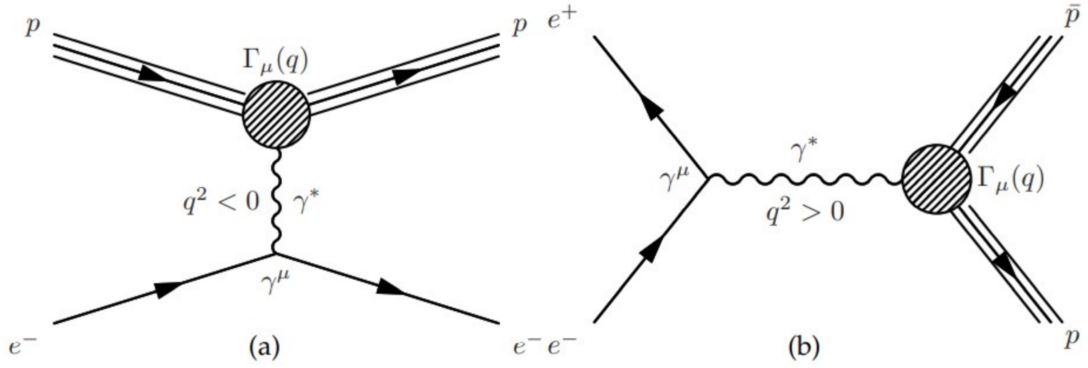


- Form factor ratio can be obtained from two experimental asymmetries (A_l and A_r), at same Q^2 but with different target spin orientations

BLAST pioneered the technique, later also used in Jlab Hall A experiment

Timelike Form Factor

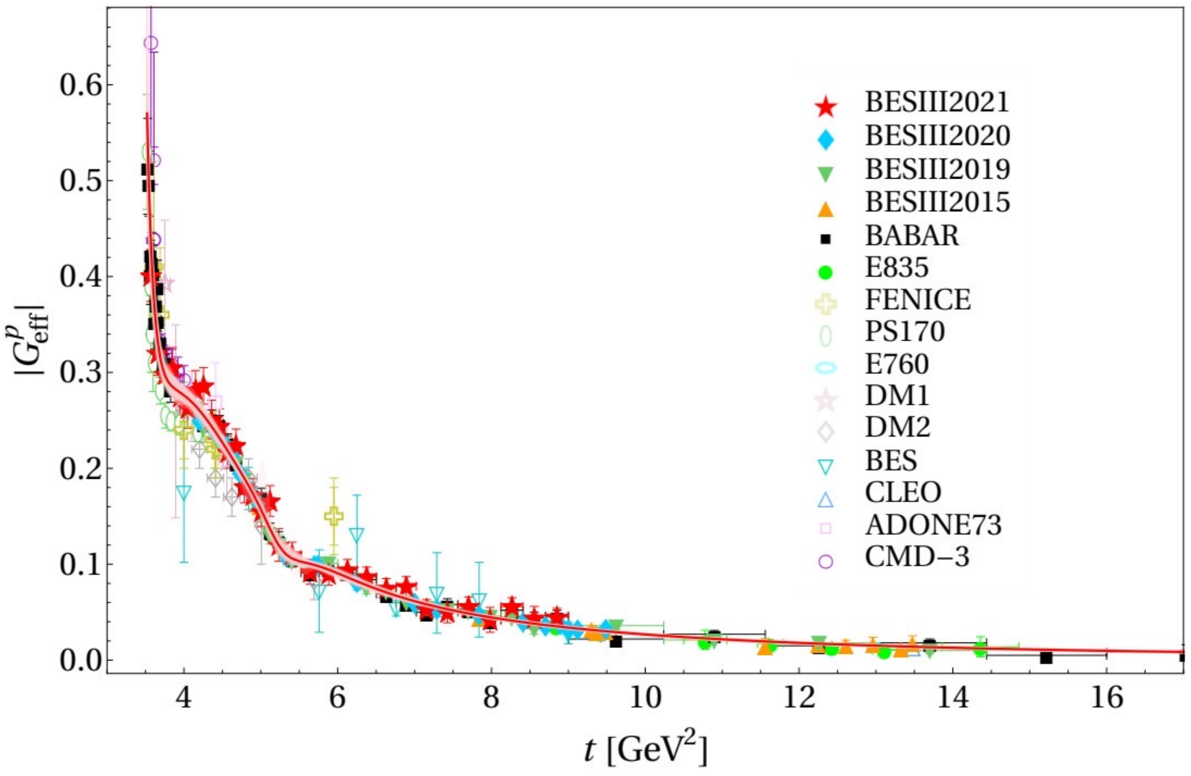
- EM form factor can also be measured in e+e- annihilation:



$$\sigma_{e^+e^-\to p\bar{p}}(t) = \frac{4\pi\alpha^2\beta}{3t}C(t)\left[|G_M(t)|^2 + \frac{2m_p^2}{t}|G_E(t)|^2\right]$$

$$\equiv \frac{4\pi\alpha^2\beta}{3t}C(q^2)\left(1 + \frac{2m_p^2}{t}\right)|G_{\rm eff}^p(t)|^2.$$

arXiv.2211.05419

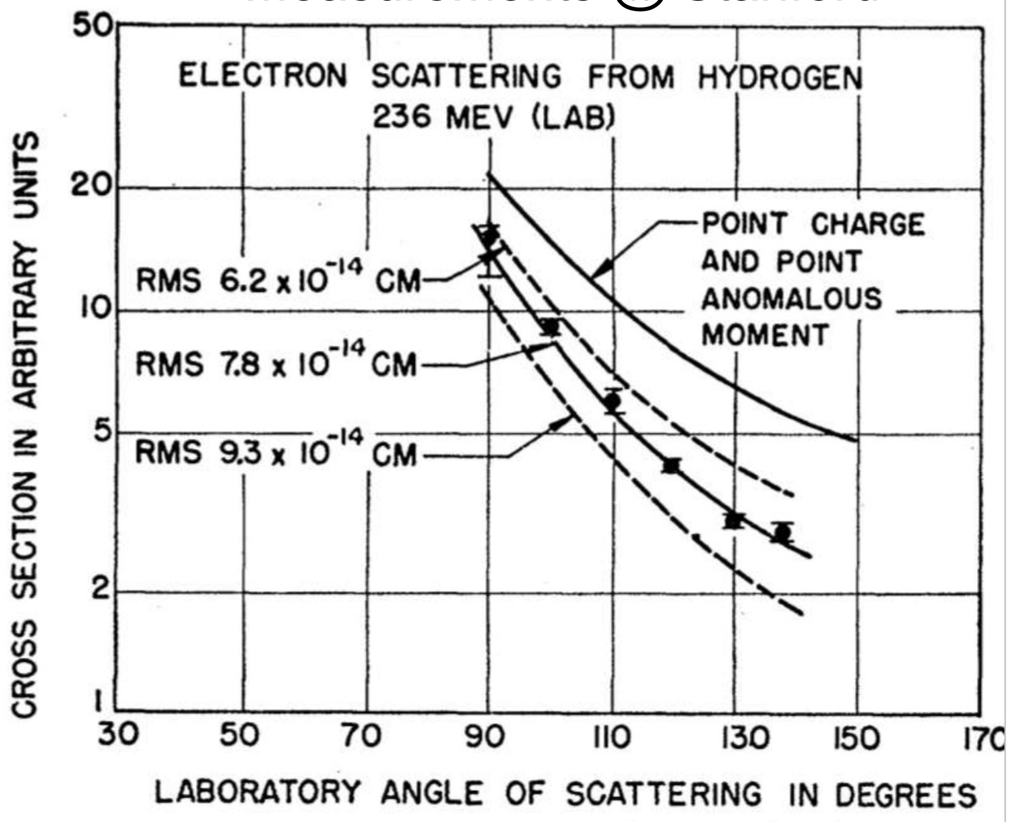


$$|G_{\rm eff}| \equiv \sqrt{\frac{|G_E|^2 + \xi|G_M|^2}{1+\xi}}$$

Unpolarized *ep* Elastic Scattering
(First measurement of proton charge radius)

- started with Robert Hofstadter
  - Nobel prize in physics (1961): … for his pioneering studies of electron scattering in atomic nuclei and for his consequent discoveries concerning the structure of nucleons …"

Measurements @ Stanford



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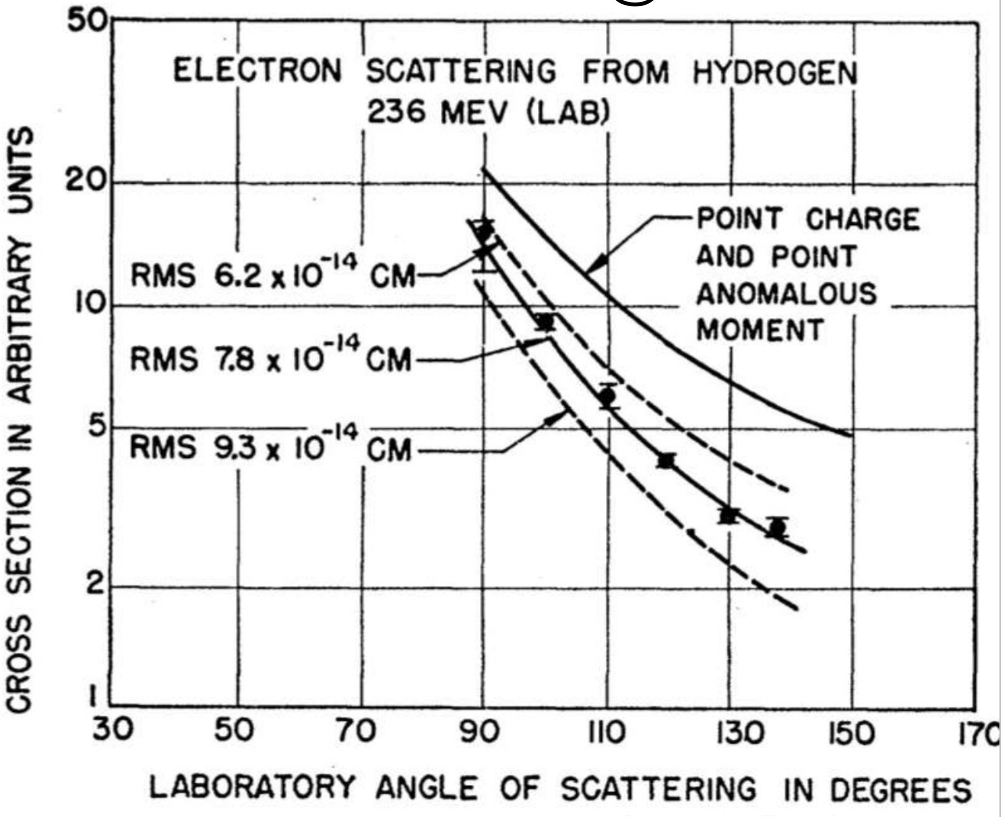
- started with Robert Hofstadter
  - Nobel prize in physics (1961): … for his pioneering studies of electron scattering in atomic nuclei and for his consequent discoveries concerning the structure of nucleons …"
- The Proton rms charge radius in 1956 was measured to be:
  - 7.8 10^{-14} cm (0.78 fm)

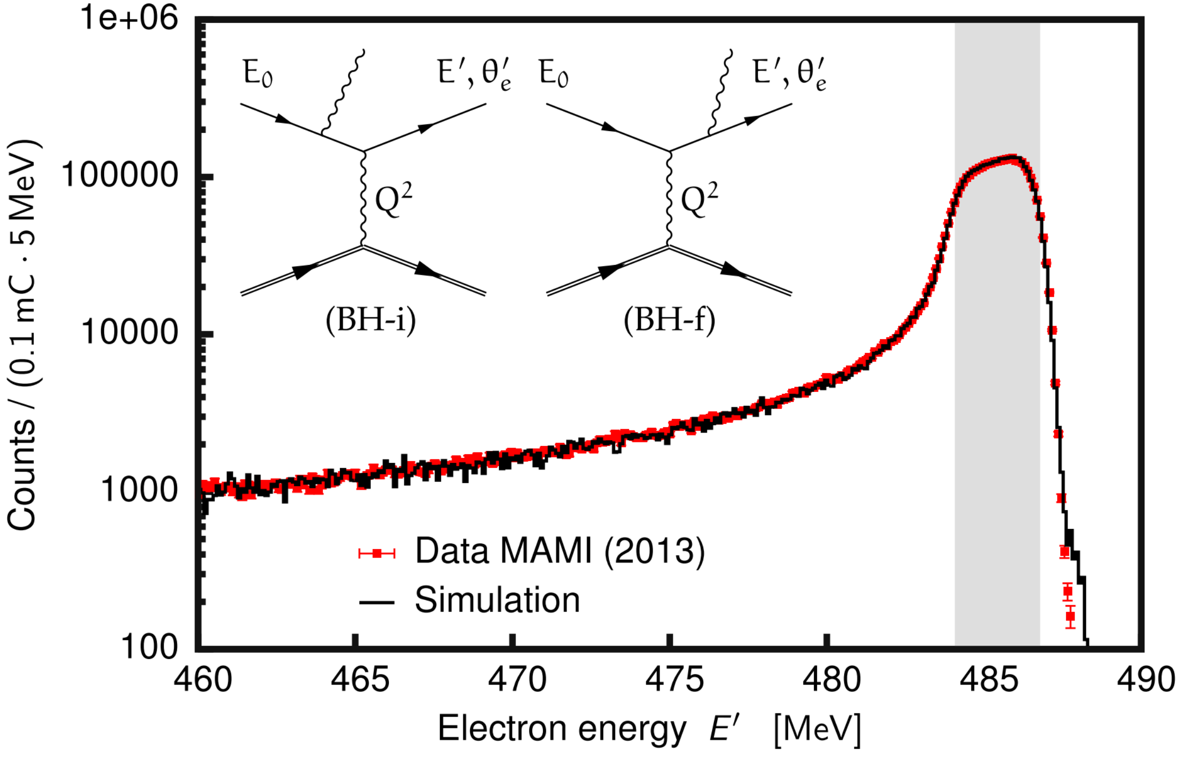
    Hofstadter, McAllister, Phys. Rev. 102, 851 (1956).
- Over 60 years of experimentation

Measurements @ Stanford



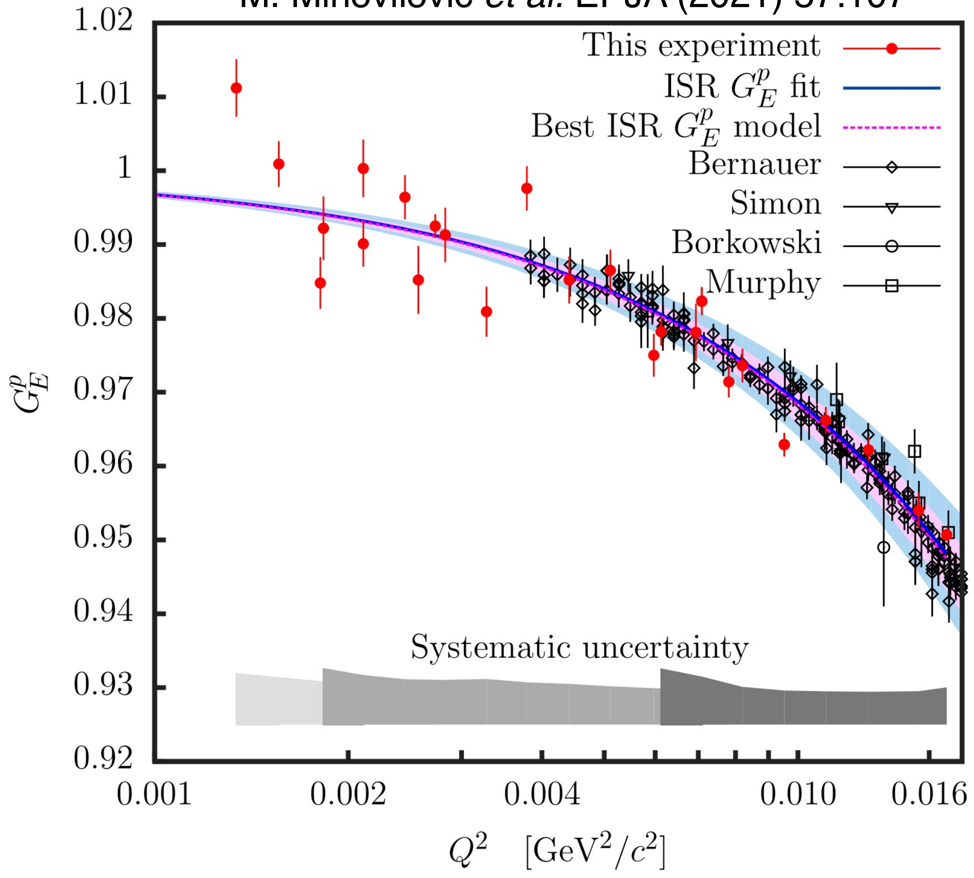
Mainz Initial State Radiation (ISR) Experiment

- Using ISR technique to reach lower Q^2: 0.001 to 0.016 GeV^2
- Final result: $r_p = 0.878 \pm 0.011_{stat.} \pm 0.031_{syst.} \pm 0.002_{mod.}$ fm



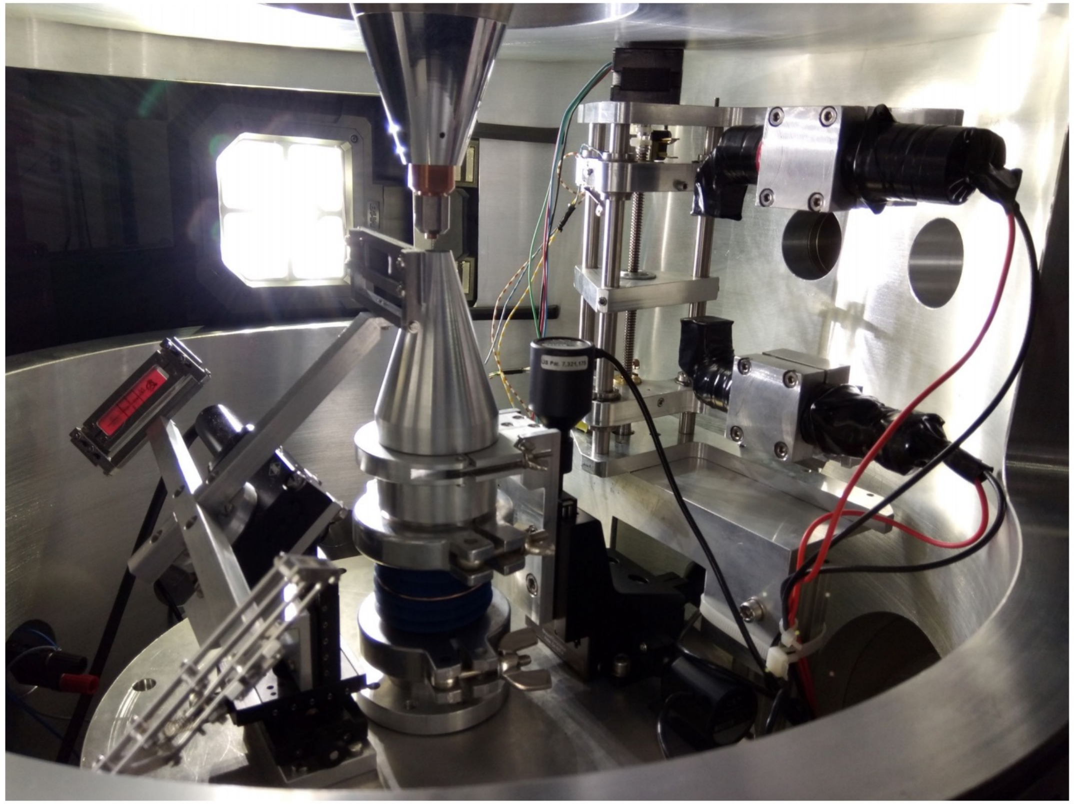
M. Mihovilovic *et al.* arXiv.1905.11182

M. Mihovilovic *et al.* EPJA (2021) 57:107

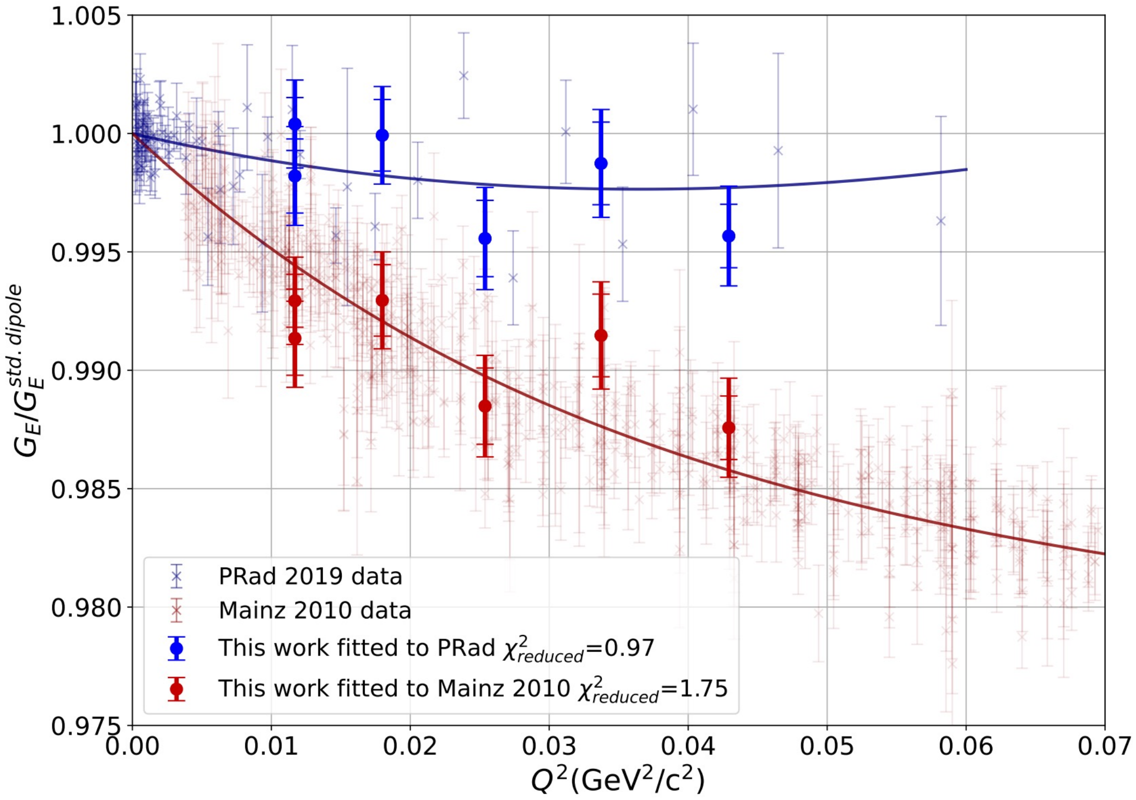


Mainz Jet Target Experiment

- Using novel gas-jet target, but limited by statistics
- Fit to PRad: $\chi^2_{reduced} = 0.97$, fit to Mainz $\chi^2_{reduced} = 1.75$

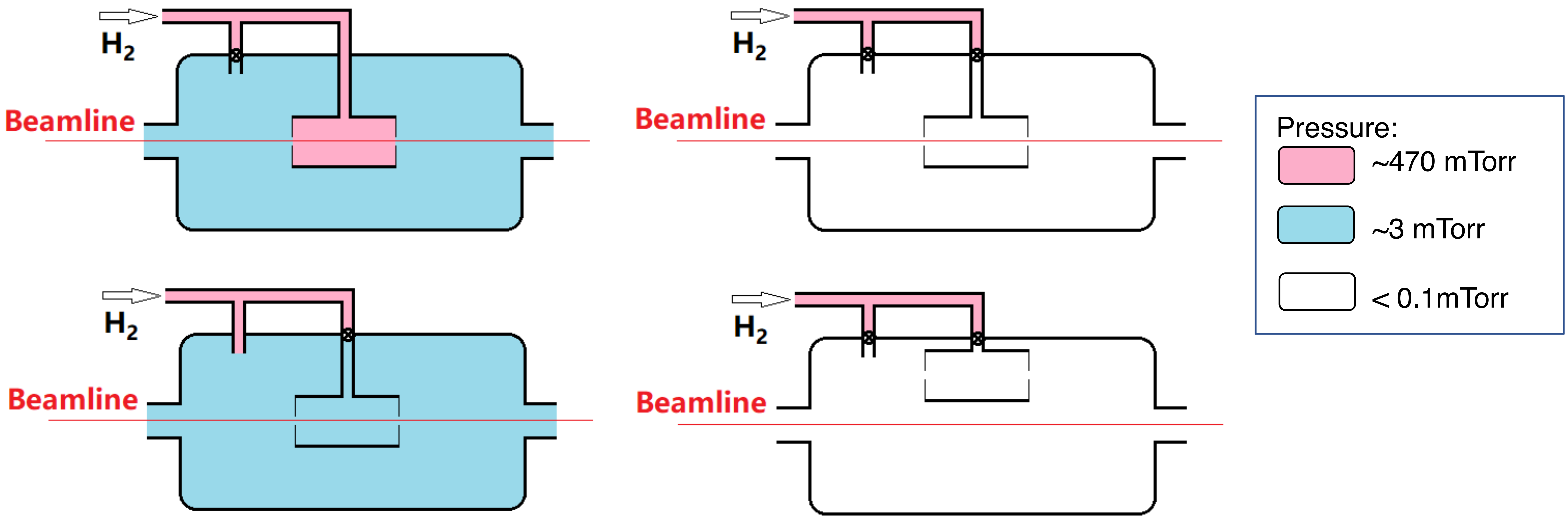


Y. Wang et al. PRC 106 (2022) 4, 044610



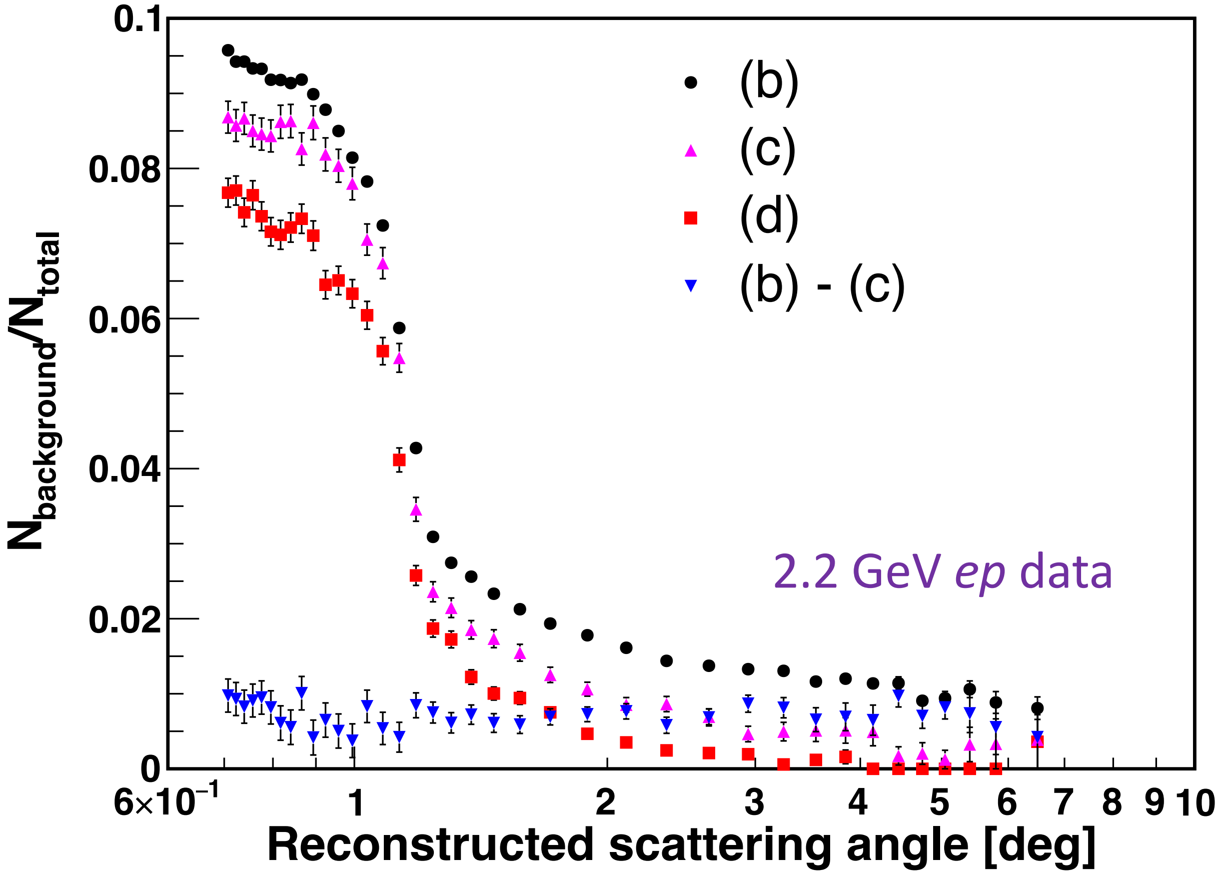
Analysis – Background Subtraction

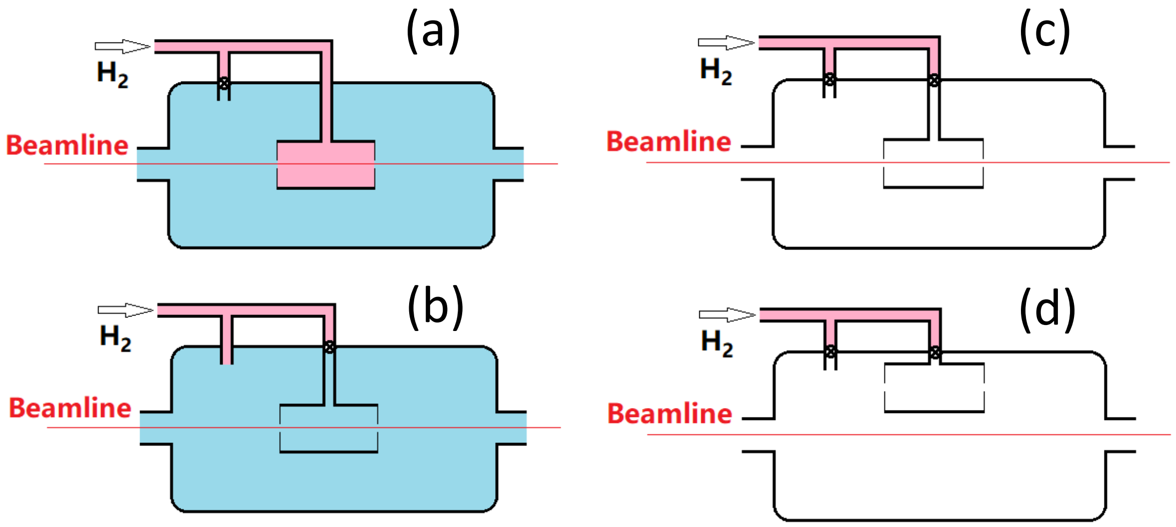
- Runs with different target condition taken for background subtraction and studies for the systematic uncertainty
- Developed simulation program for target density (COMSOL finite element analysis)



Analysis – Background Subtraction (2.2 GeV)

- *ep* background rate ~ 10% at forward angle (<1.1 deg, dominated by upstream beam halo blocker), less than 2% otherwise
- ee background rate ~ 0.8% at all angles





Residual hydrogen gas: hydrogen gas filled during background runs

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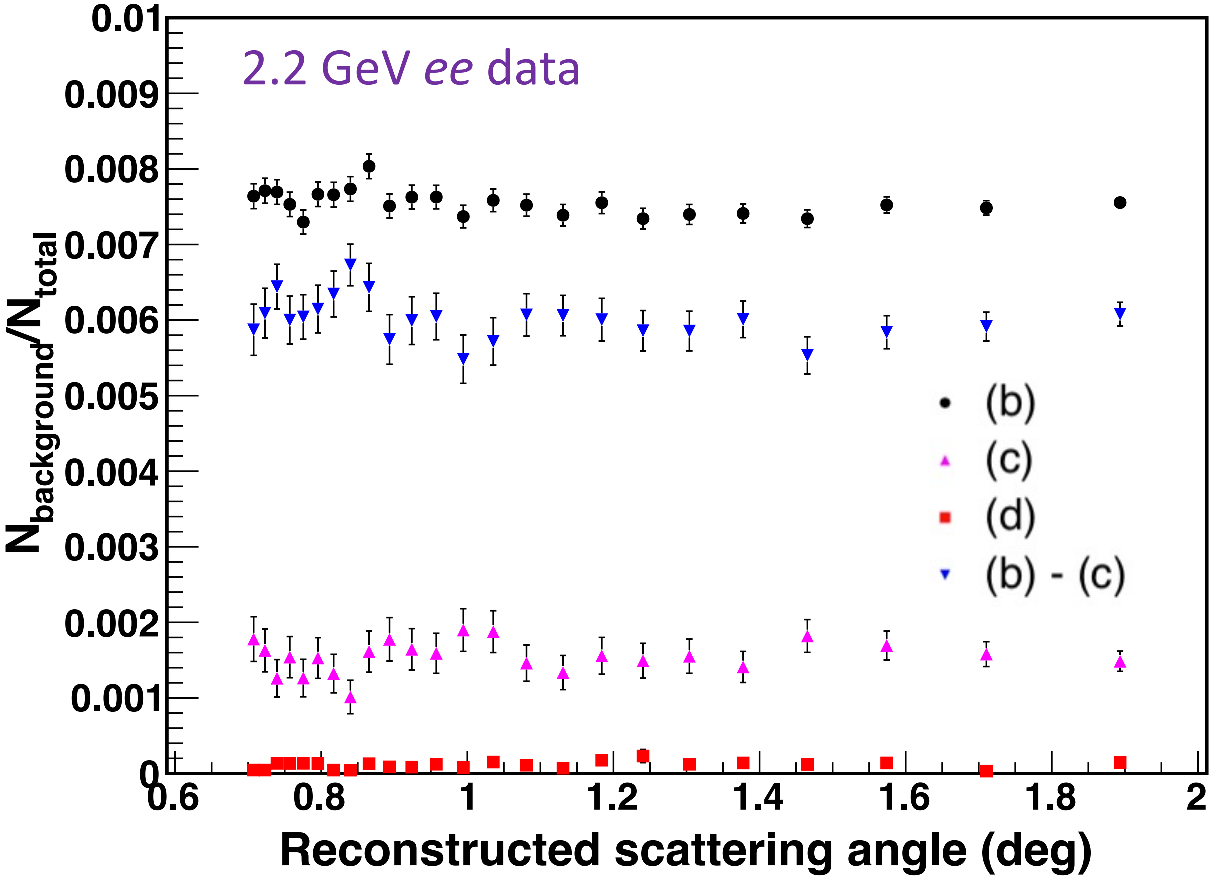
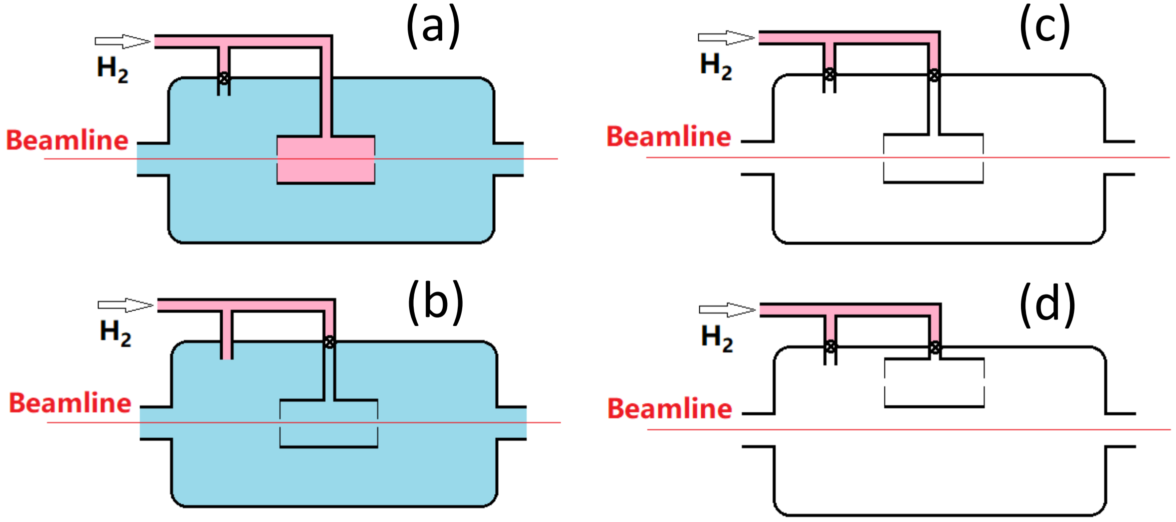


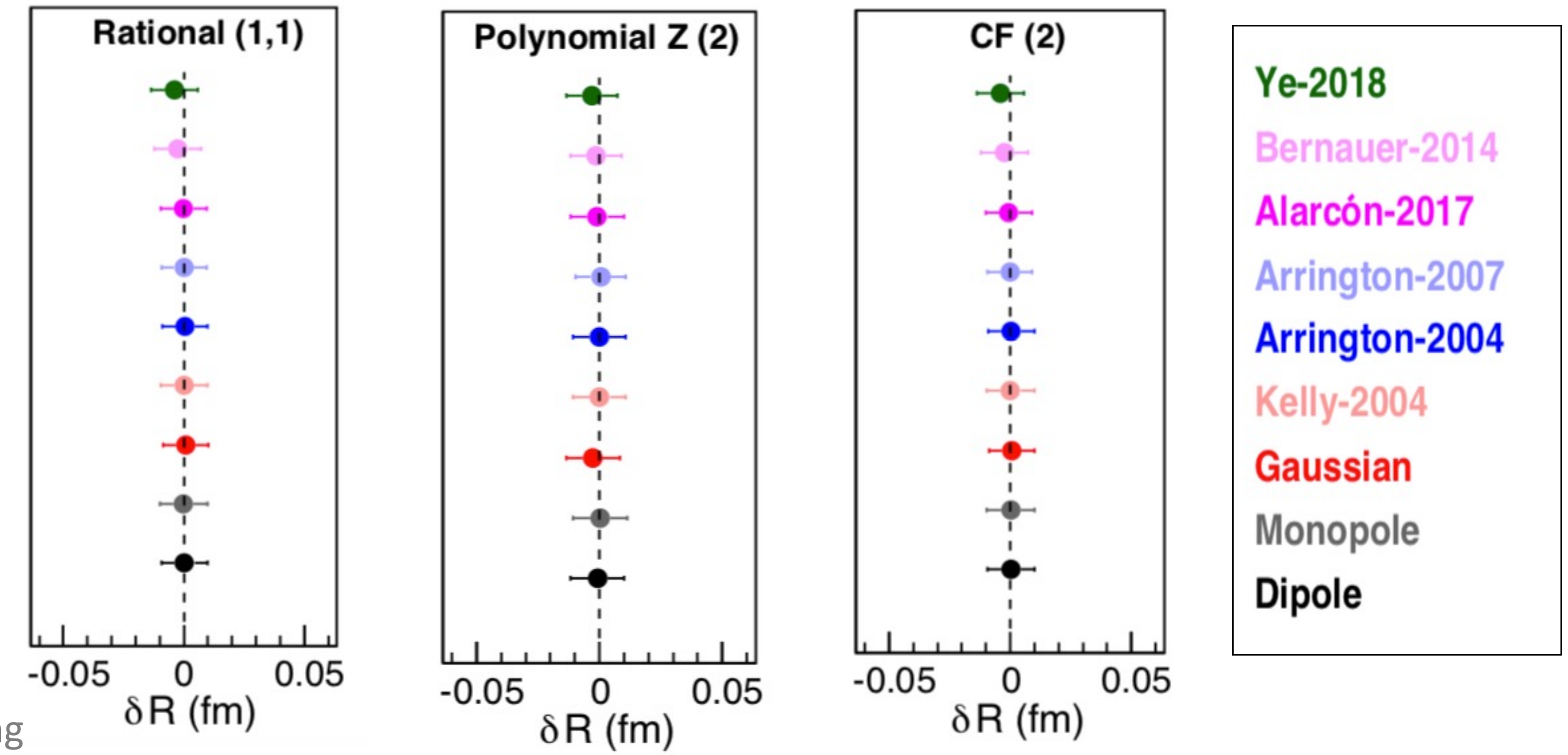


Residual hydrogen gas: hydrogen gas filled during background runs

Searching the Robust Fitters

- Various fitters tested with a wide range of G_E parameterizations, using PRad kinematic range and uncertainties (X. Yan (严雪飞) *et al.* PRC 98, 025204 (2018))
- Rational (1,1), 2nd order z transformation and 2nd order continuous fraction are identified as robust fitters with also reasonable uncertainties
- Typically a floating parameter n is included to take care normalization uncertainties

$$f(Q^2) = n\, G_E^p(Q^2)$$



Rational (1,1)

$$\frac{1+p_1Q^2}{1+p_2Q^2}$$

2nd order z transformation

$$1+p_1z+p_2z^2,$$

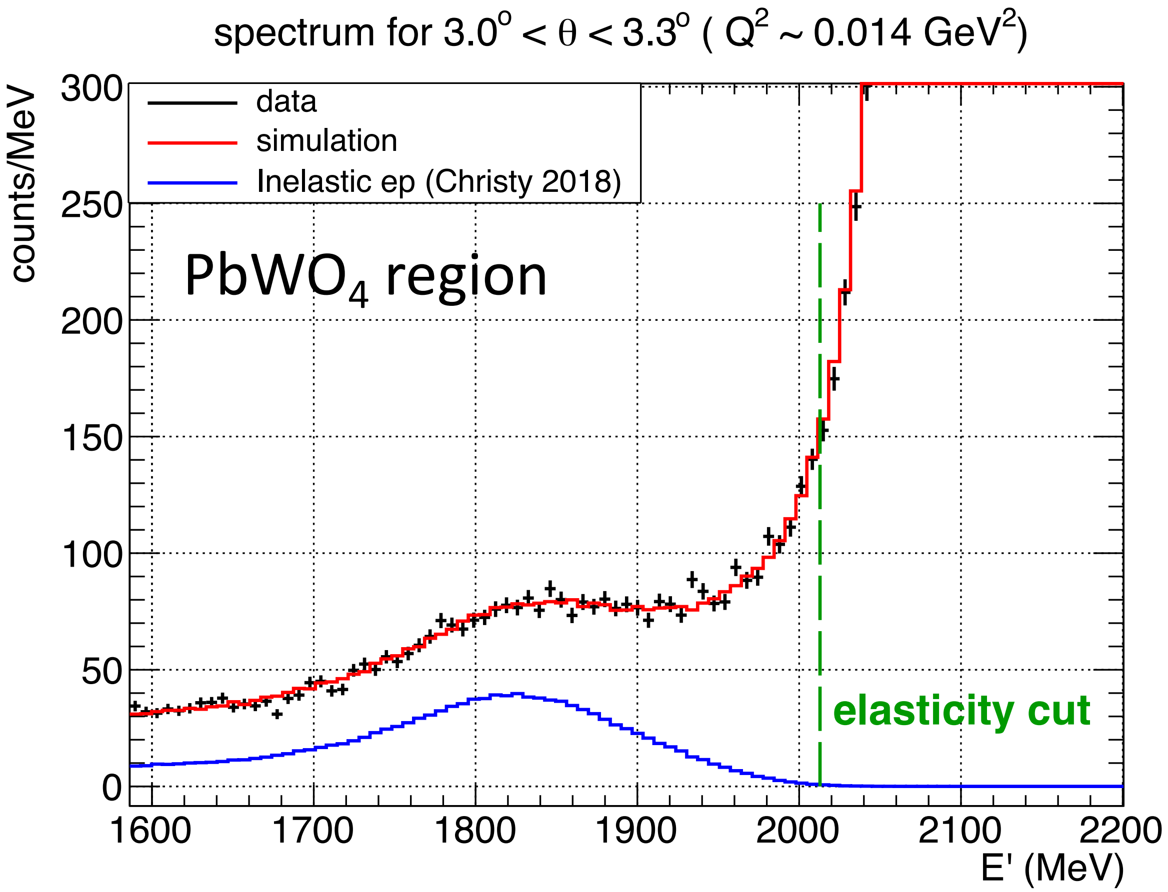
$$z=\frac{\sqrt{T_c+Q^2}-\sqrt{T_c-T_0}}{\sqrt{T_c+Q^2}+\sqrt{T_c-T_0}}$$

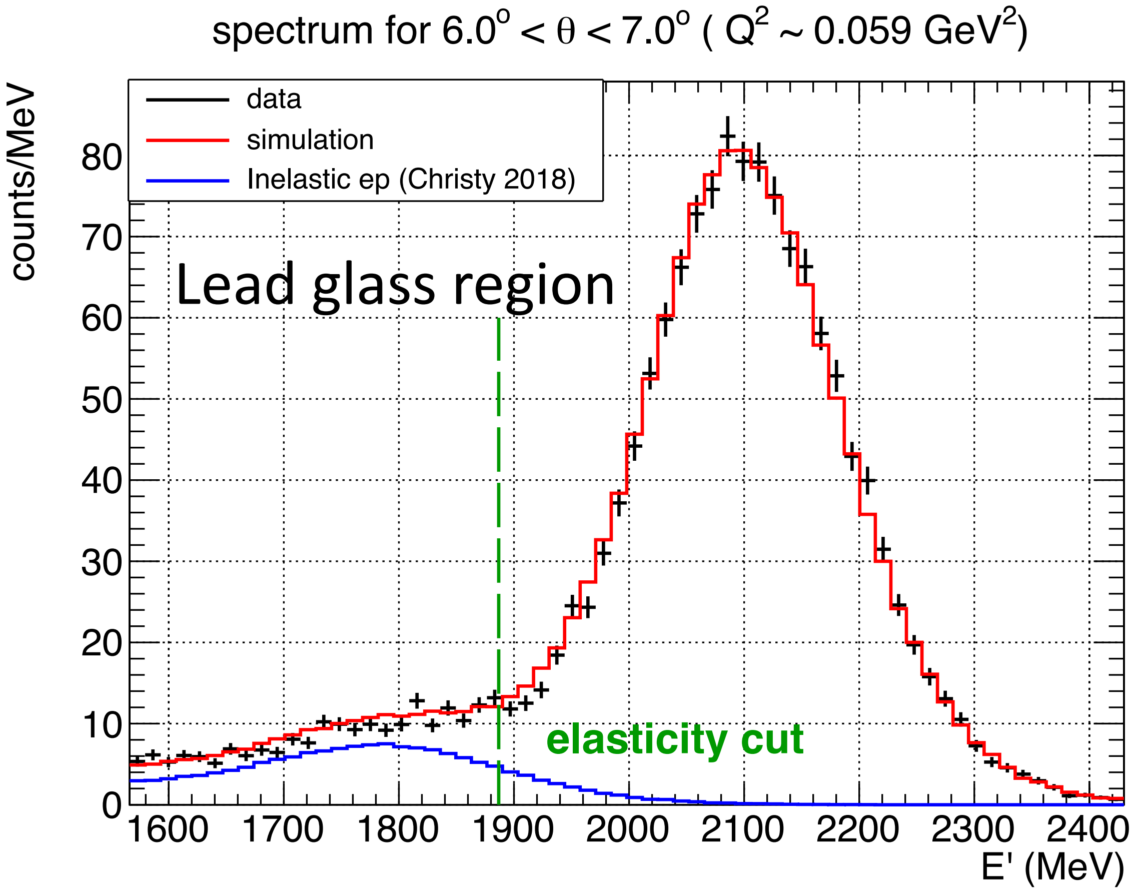
2nd order continuous fraction

$$\frac{1}{1+\frac{p_1Q^2}{1+p_2Q^2}}$$

Analysis – Inelastic ep Contribution

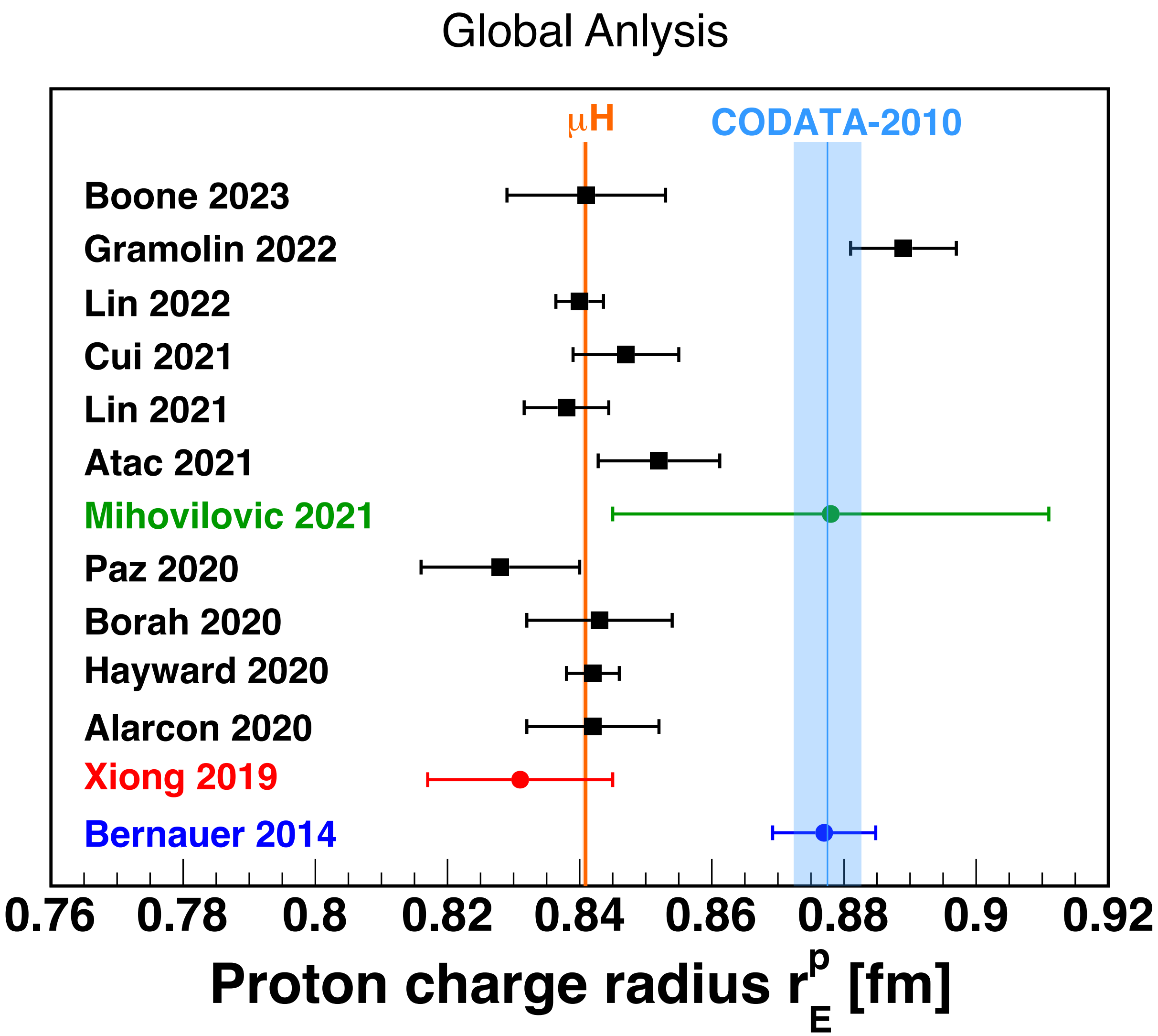
- Using Christy 2018 empirical fit to study inelastic ep contribution
- Good agreement between data and simulation
- Negligible for the $PbWO_4$ region (<3.5°), less than 0.2%(2.0%) for 1.1GeV(2.2GeV) in the Lead glass region

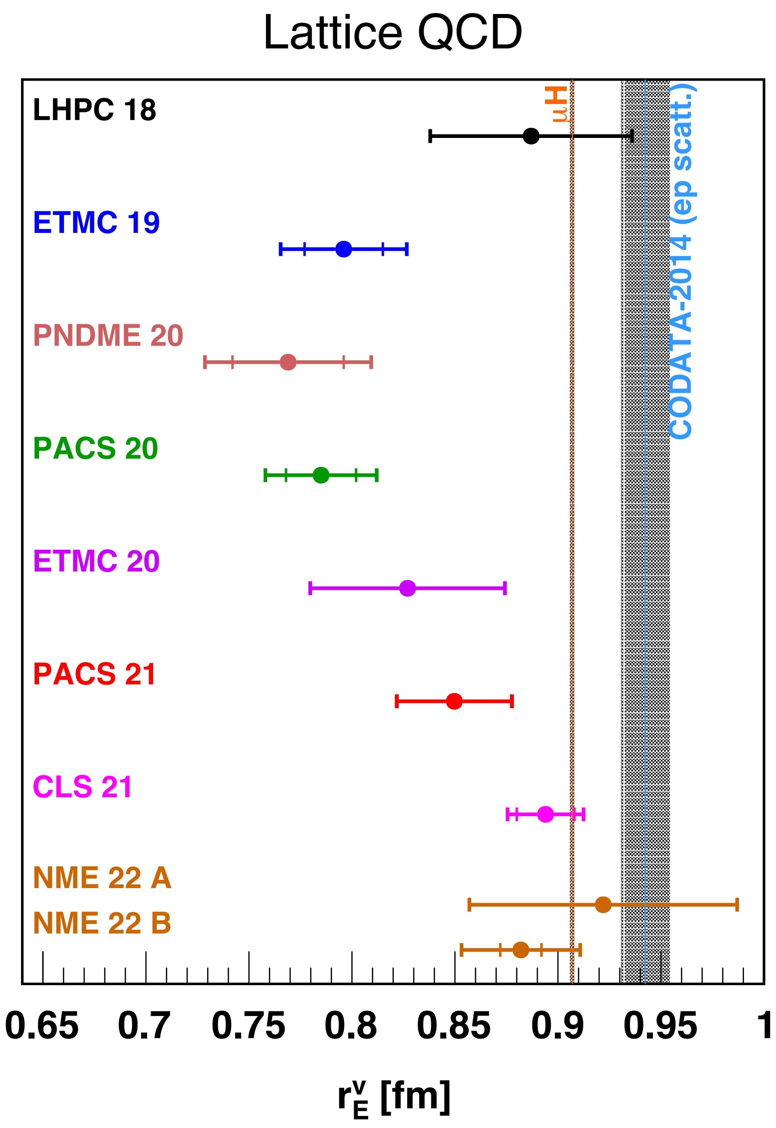




M. E. Christy and P. E. Bosted, PRC 81, 055213 (2010)

Other Results from Global Analysis and Lattice QCD

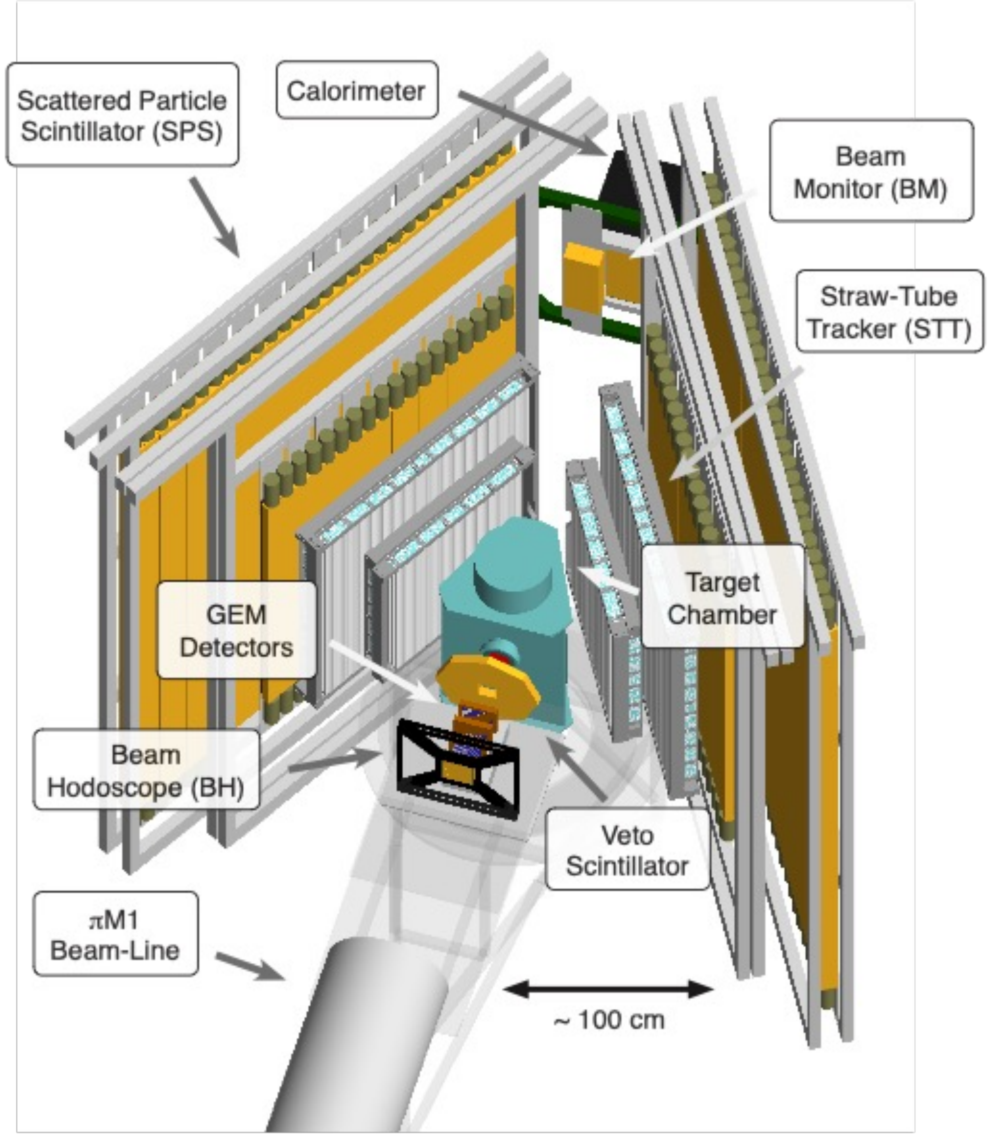




WX and Chao Peng (彭潮) arXiv:2302.13818

MUSE Experiment

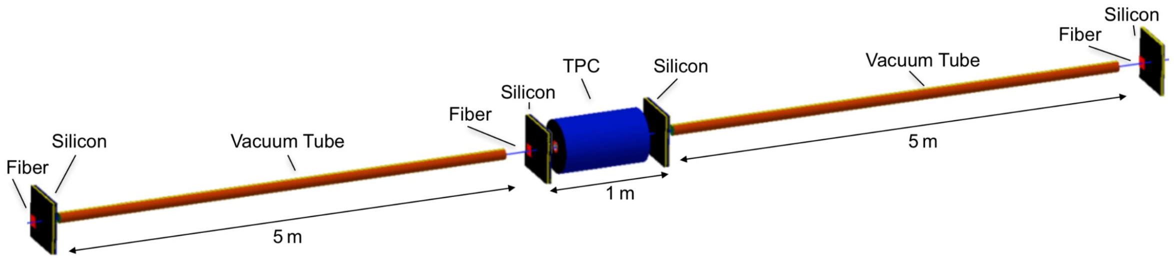
- First r_p measurement using muon
  - 4 types of incident leptons: $e^{\pm}$ and $\mu^{\pm}$
- Direct test for lepton-universality violation
- Different beam polarity can constrain two-photon exchange
- Currently taking data at PSI



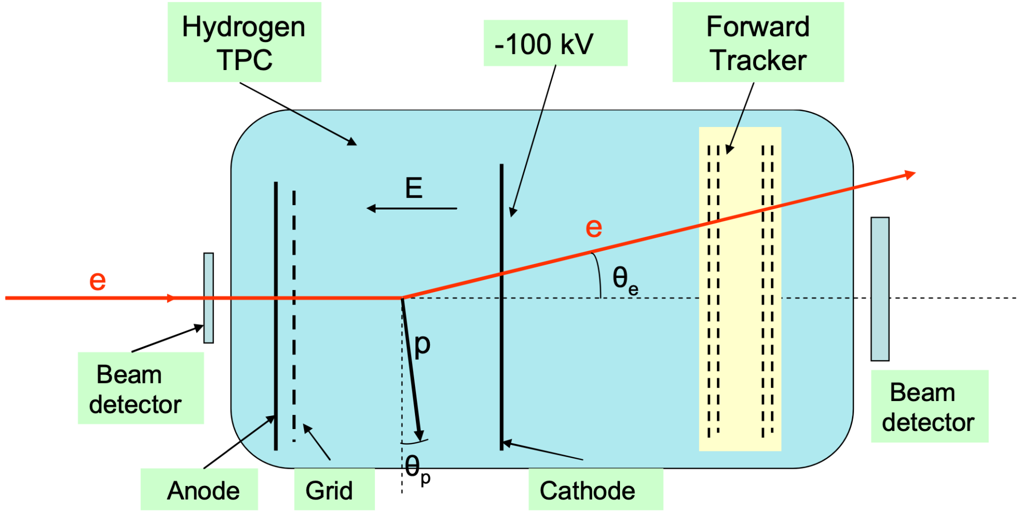
AMBER and PRES Experiments

- AMBER@CERN uses high energy (~100 GeV) muon beam
- PRES@Mainz uses 720 MeV electron beam
- Both use time-projection chamber as active target, detecting both scattered electron and recoil proton
- Q^2 can be reconstructed by recoil proton, largely suppress radiative effect

AMBER@CERN

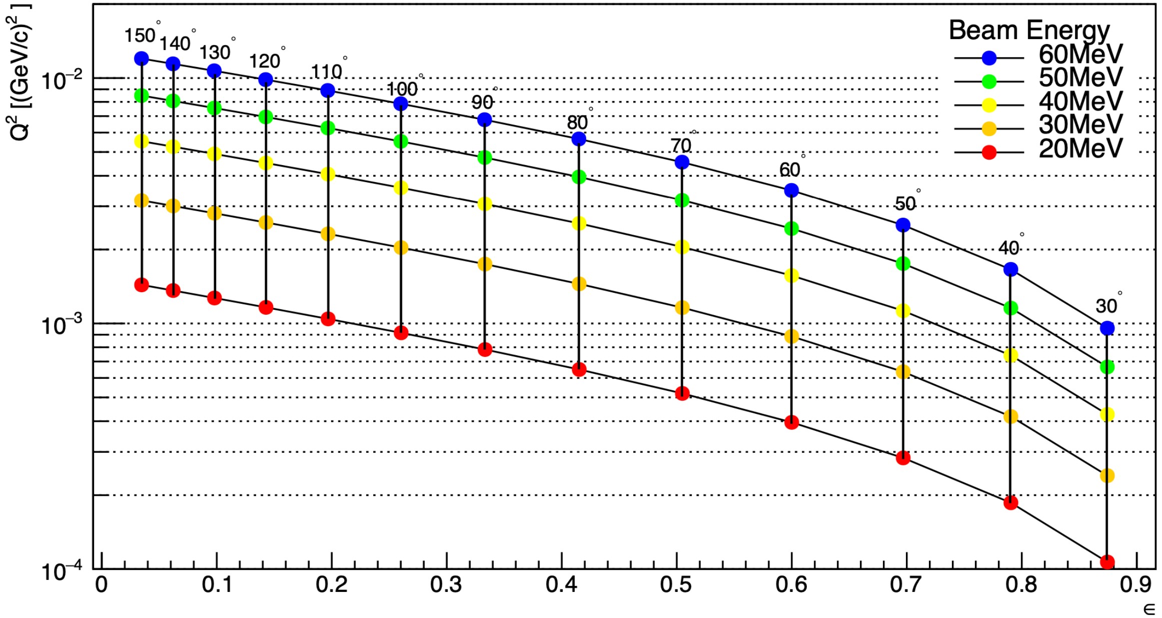


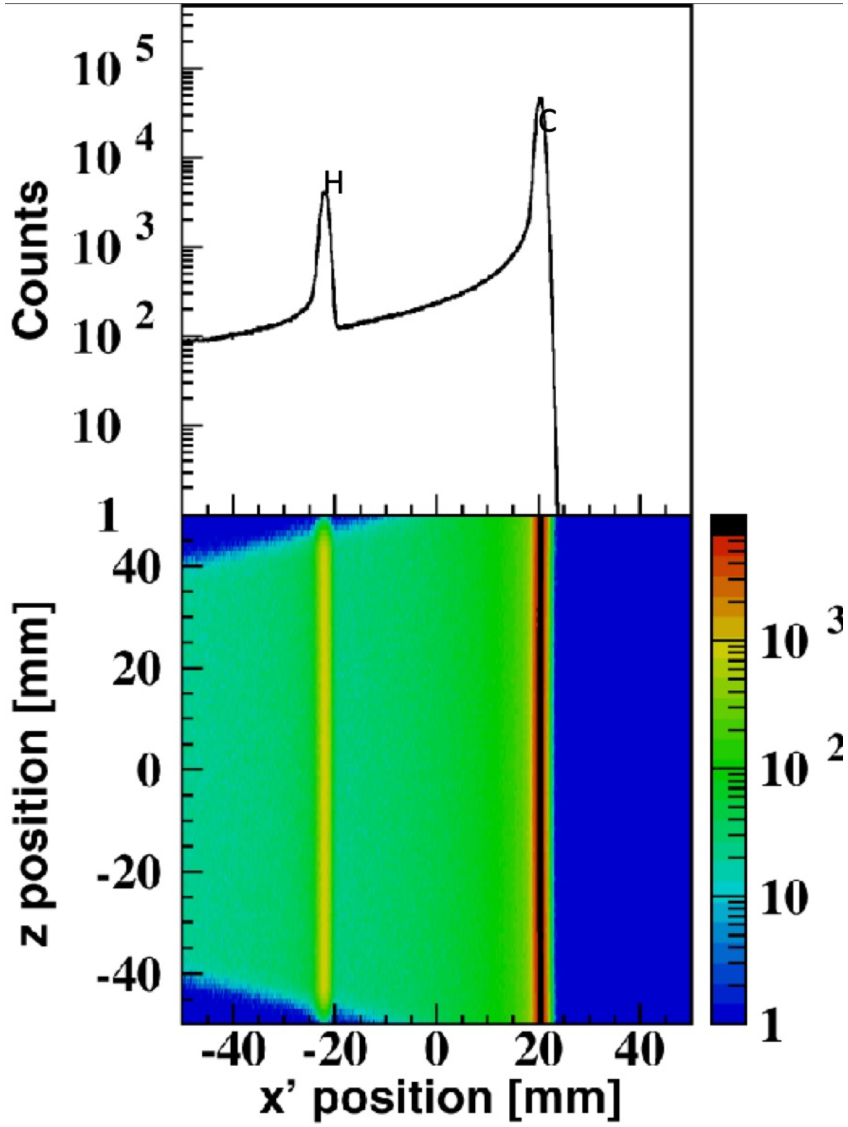
PRES@Mainz



ULQ2 Experiment

- ULQ2 experiment at Tohoku University, Japan
- 20-60 MeV electron beam
- Normalize to the well-established *e-*^{12}*C* cross section
- Rosenbluth separation to measure both G_E and G_M
- Projected uncertainty for G_E ~0.1%
- Q^2: 3 x 10^{-4} ~ 8 x 10^{-3} GeV^2

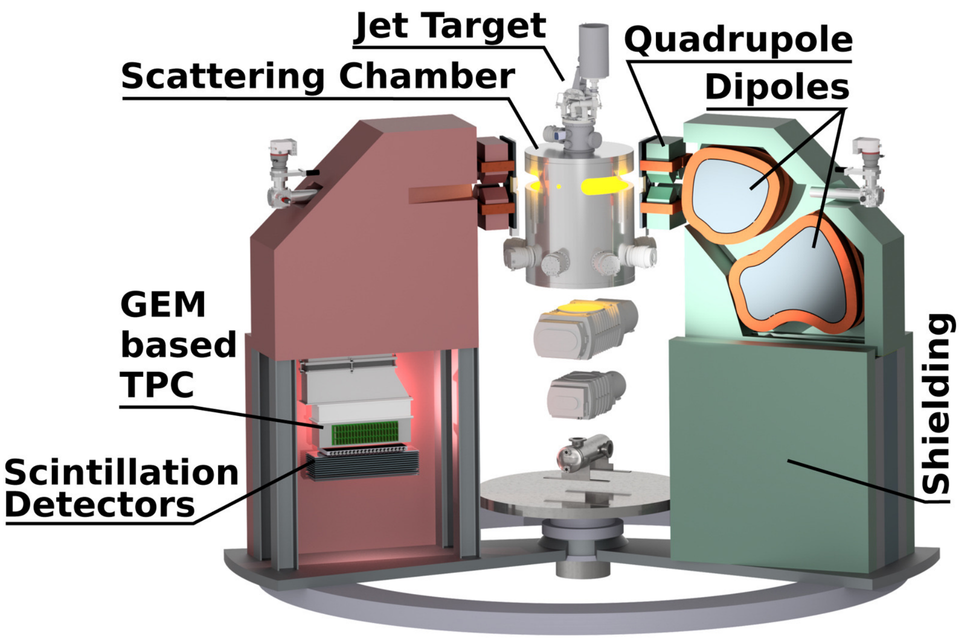


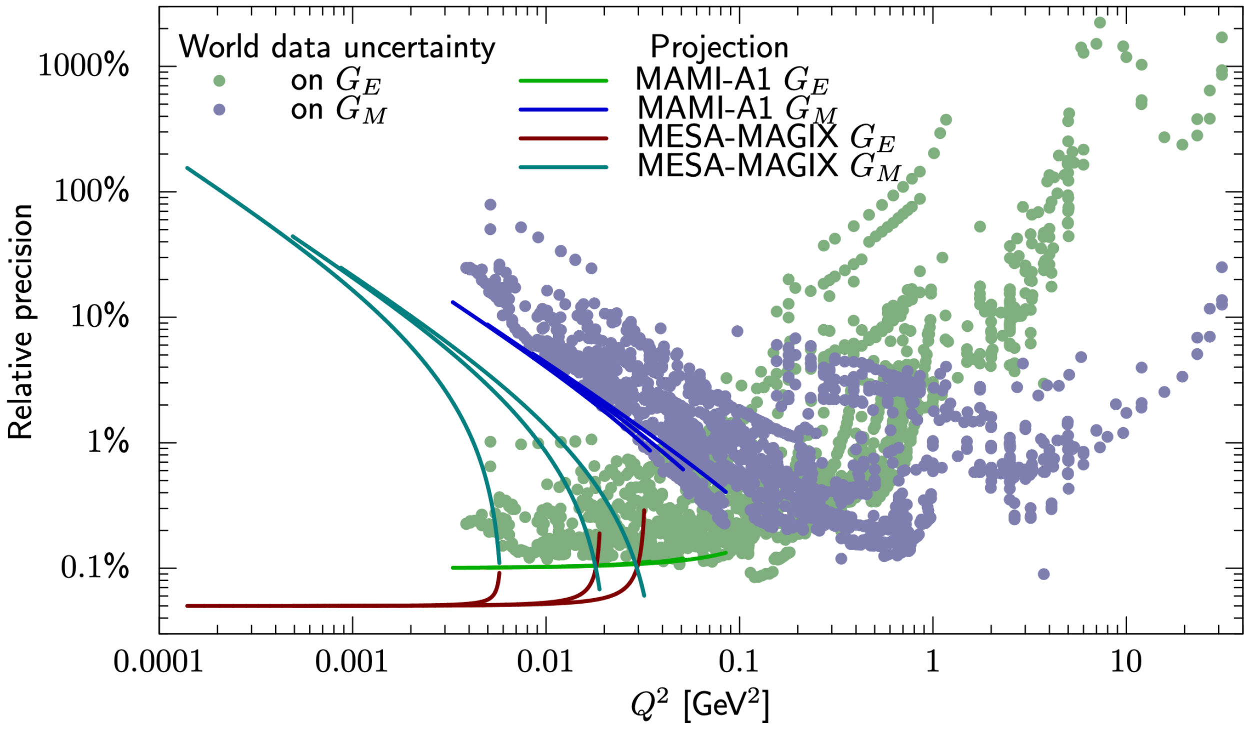


https://indico.mitp.uni-mainz.de/event/132/contributions/552/attachments/420/451/24_1_Suda_PRP_2018.pdf

MAGIX Experiment

- Will use the new MESA accelerator at Mainz (under construction), 20-105 MeV electron beam up to 1 mA
- Will use the fully tested jet target and two new multi-purpose spectrometers
- Strong sensitivity on both G_E and G_M, can achieve an order of magnitude better precision for low Q^2 G_M

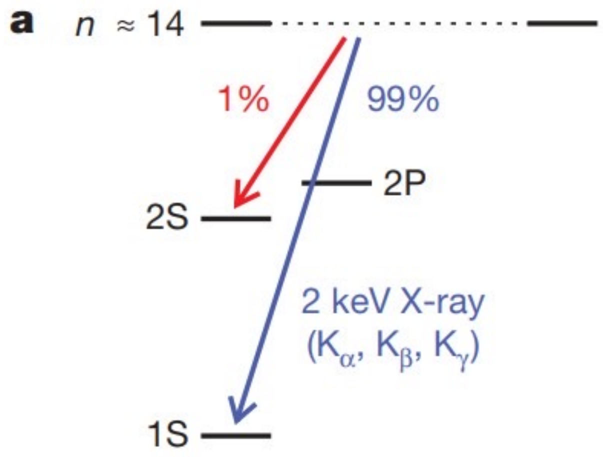




Muonic Hydrogen Measurement

- Steps in muonic hydrogen 2S-2P Lamb shift measurement (R. Pohl, *et al. Nature* 466 213-216 (2010))

1. Slow muon (~keV) captured and replace a electron
2. 99% muons decay to ground state right away, 1% decay to meta-stable 2S state (τ~1μs)



Weizhi Xiong

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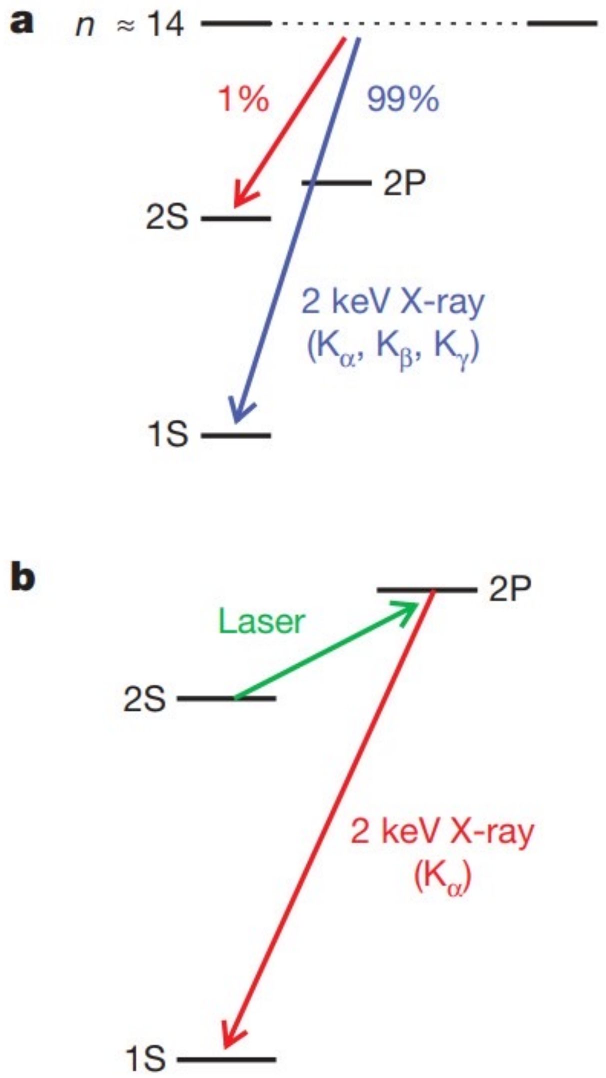
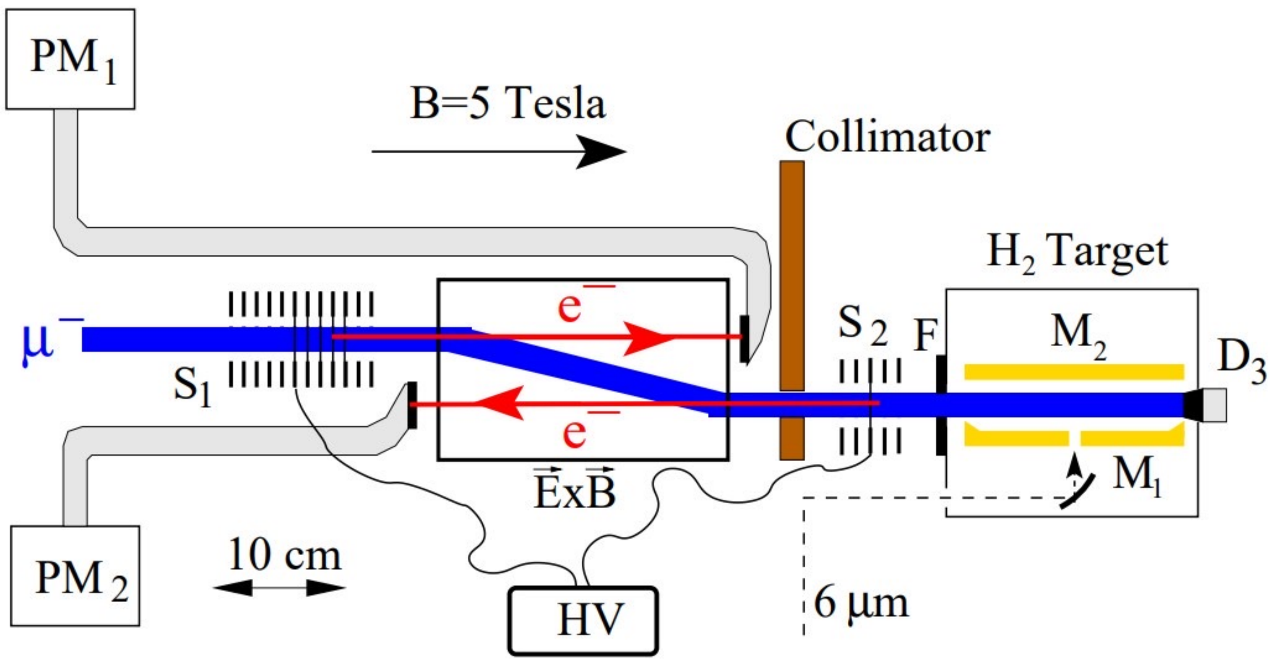
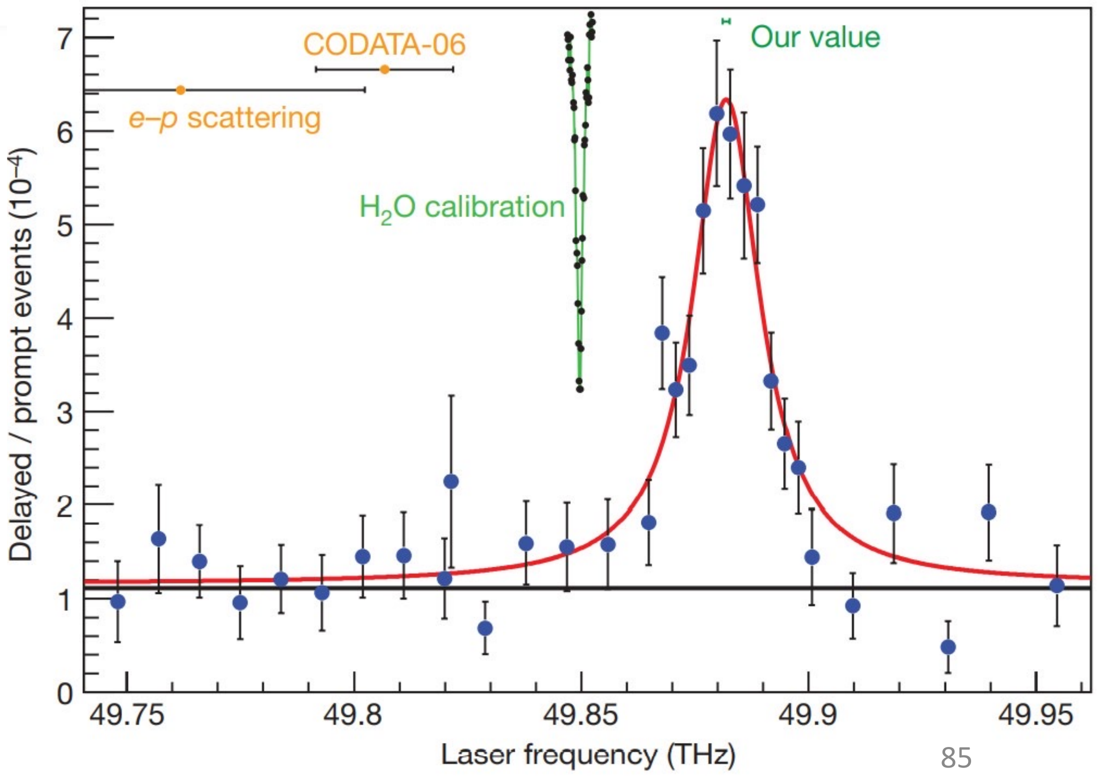
1. Slow muon (~keV) captured and replace a electron
2. 99% muons decay to ground state right away, 1% decay to meta-stable 2S state (τ~1μs)
3. Use tunable laser to drives muons from 2S to 2P
4. 2P muons decay right away (~ps) to 1S, emitting a 2keV X-ray
5. Events selected by the 2keV X-ray signal and a delayed electron signal from muon decay



Muonic Hydrogen Measurement

1. DAQ and laser system triggered by muon signal from PM1 and PM2
2. Anti-trigger provided by muons hitting D3
3. Laser activated to drive muon from 2S to 2P
4. 2keV photon and delayed signal from muon decay detected

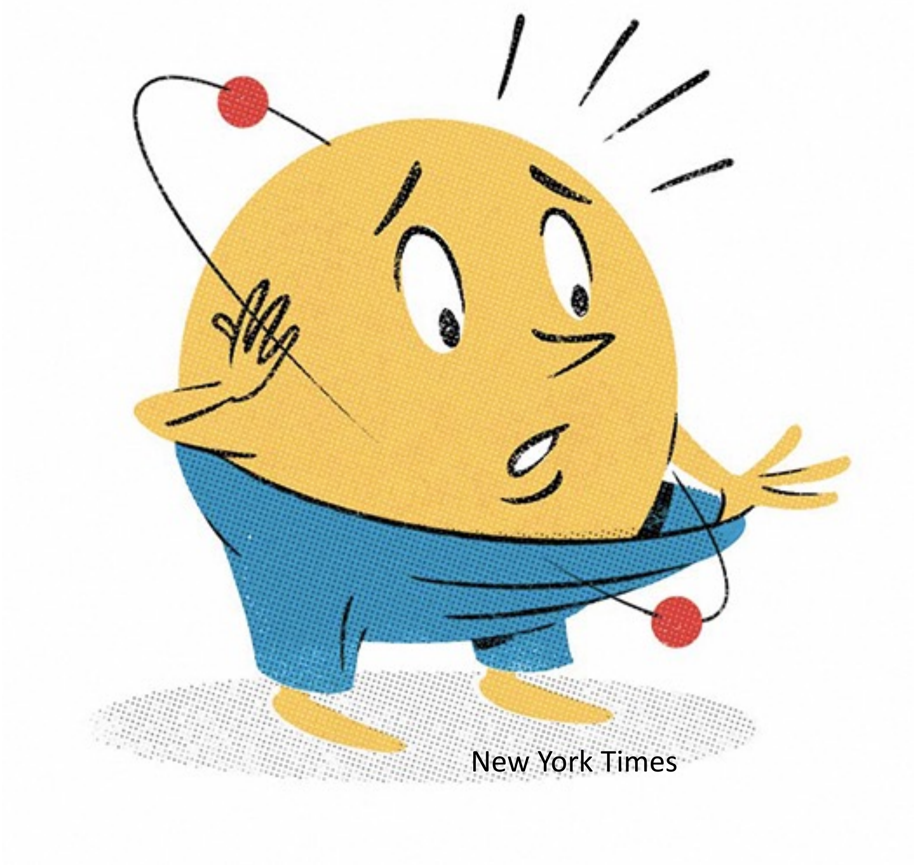




Weizhi Xiong

Proton Charge Radius Puzzle

- Possible solution to the puzzle:
  1. The ep scattering results are wrong
     - ➢ Fit procedure not good enough
     - ➢ Q^2 not low enough, structures in the form factors
     - ➢ Proton magnetic radius



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     - ➢ Rydberg constant could be off by ~5σ


New York Times

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  3. μH spectroscopy results are wrong
     - ➢ Laser calibration, two photon exchange…?
  4. New physics beyond the standard model
     - ➢ Lepton universality violation


New York Times

Extraction of *ep* Elastic Scattering Cross Section

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

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

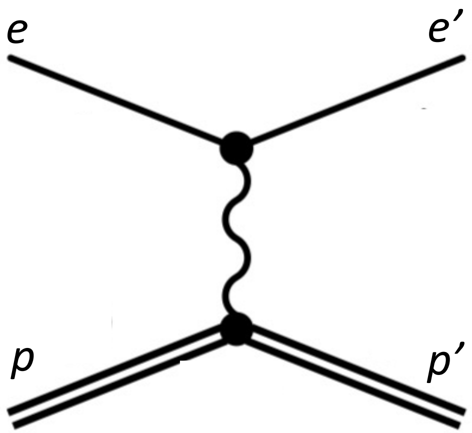
- Method 1: bin-by-bin method – taking *ep/ee* counts from the same angular bin
  - ➢ Cancellation of energy independent part of the efficiency and acceptance
  - ➢ Limited converge due to double arm Møller acceptance
- Method 2: integrated Møller method – integrate Møller in a fixed angular range and use it as common normalization for all angular bins
- Luminosity cancelled from both methods

- Bin-by-bin range: 0.7^o to 1.6^o for 2.2 GeV, 0.75^o to 3.0^o for 1.1 GeV. Larger angles use integrated Møller method

Radiative Correction

Leading order

- From experiment, we look for $ep \rightarrow ep$ process and want to measure the Born level *ep* elastic scattering cross section



- Described by the Rosenbluth formula:

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \left(\frac{E'}{E}\right) \frac{1}{1+\tau} \left(G_E^{p\,2}(Q^2) + \frac{\tau}{\varepsilon} G_M^{p\,2}(Q^2)\right)$$

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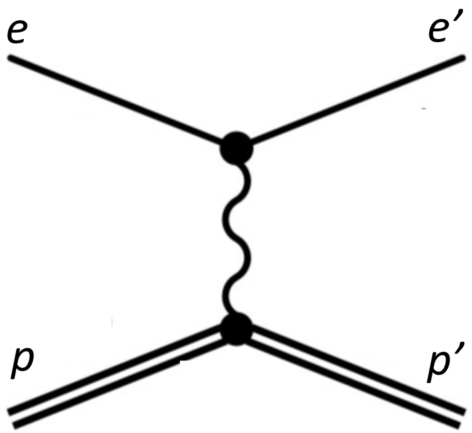

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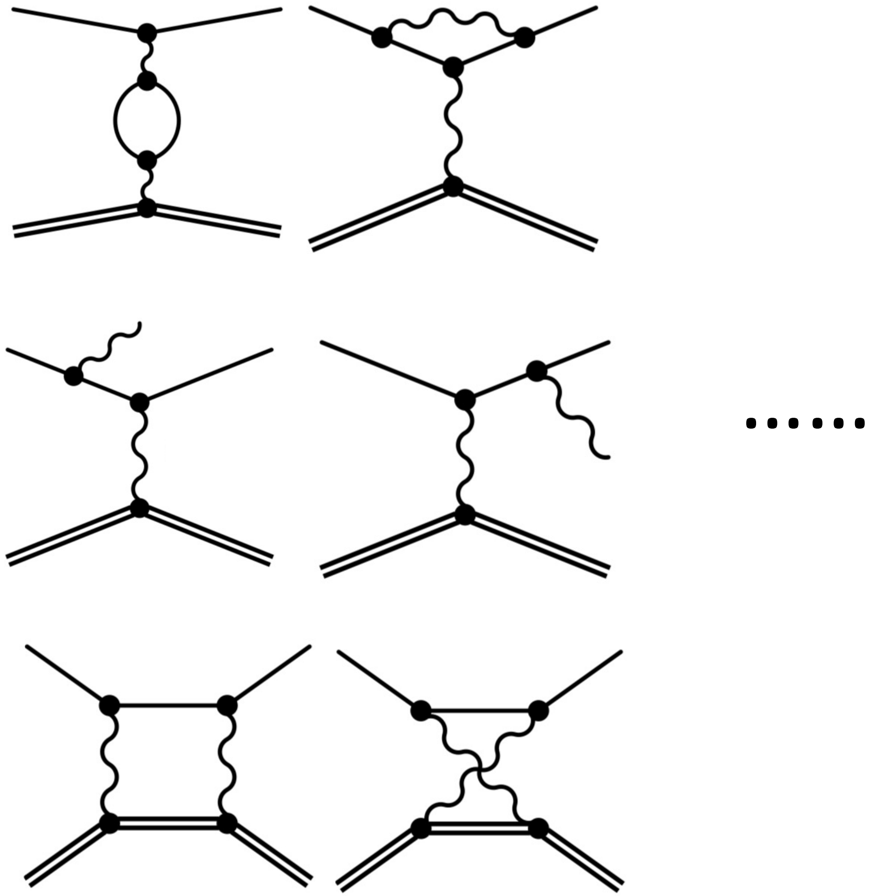
Next-to-Leading order

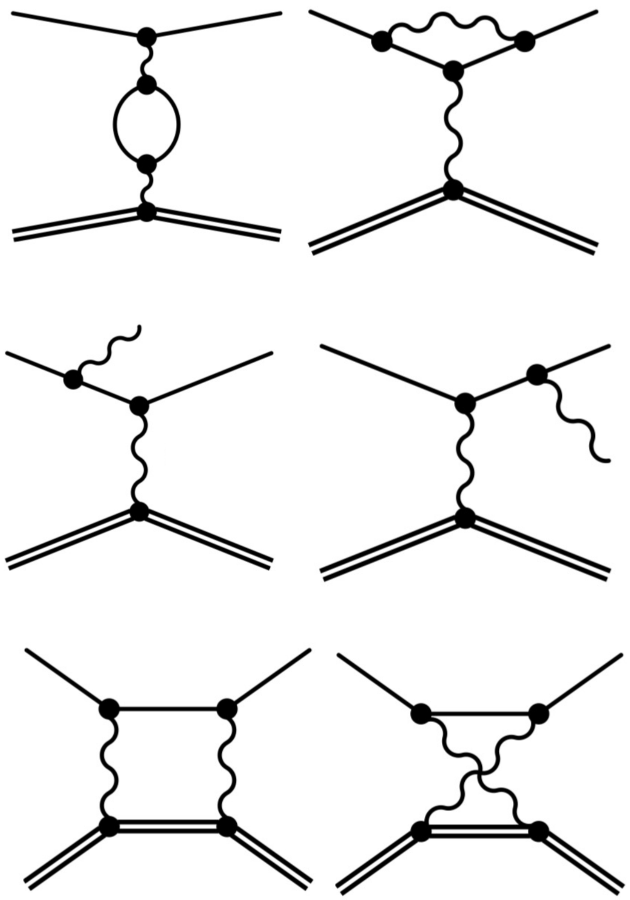


Radiative Correction

- Radiative effects corrected by Monte-Carlo method:
  1. Geant4 simulation package with full geometry setup
  2. event generators with complete calculations of radiative corrections[1,2] beyond ultra relativistic approximation
  3. Include emission of radiative photons beyond peaking approximation
  4. Include Two Photon Exchange effect[3], less than 0.2% for *ep* in PRad kinematic range
  5. Iterative procedure applied for radiative correction

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

Diagrams for *ep* elastic scattering



1. I. Akushevich et al., Eur. Phys. J. A 51(2015)1 (fully beyond ultra relativistic approximation)
2. A. V. Gramolin et al., J. Phys. G Nucl. Part. Phys. 41(2014)115001
3. O. Tomalak, Few Body Syst. **59**, no. 5, 87 (2018)

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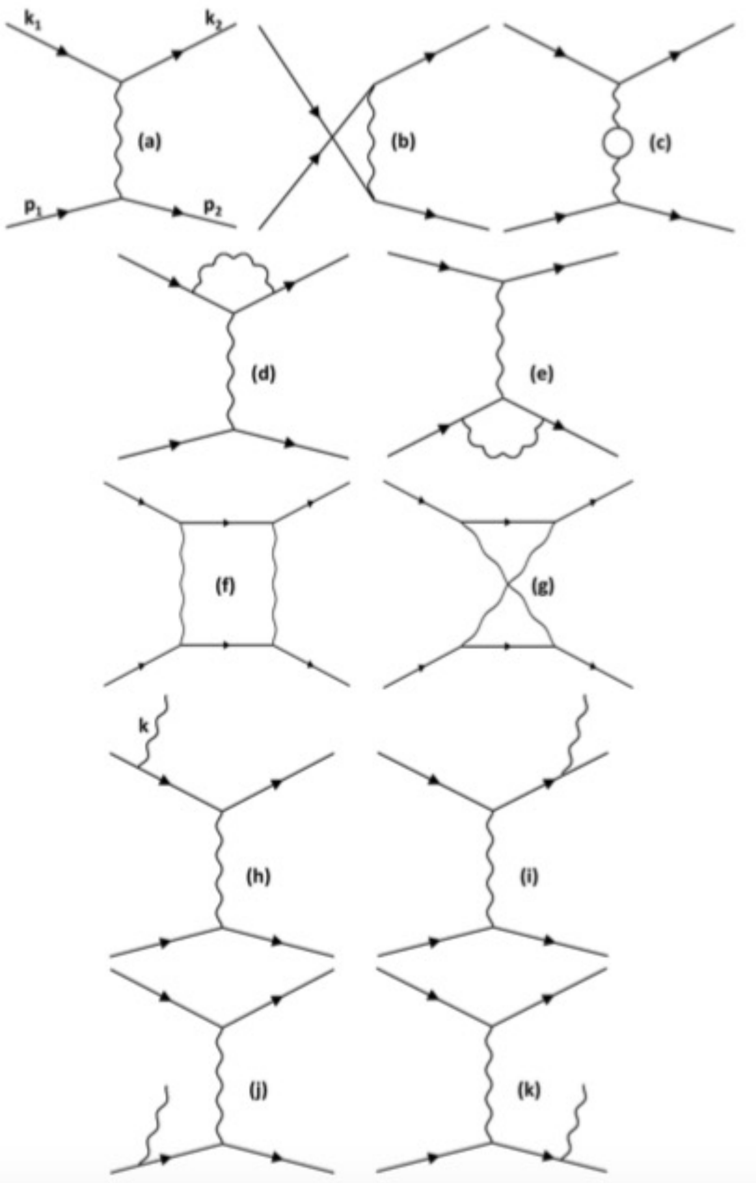
Diagrams for *ee* elastic scattering



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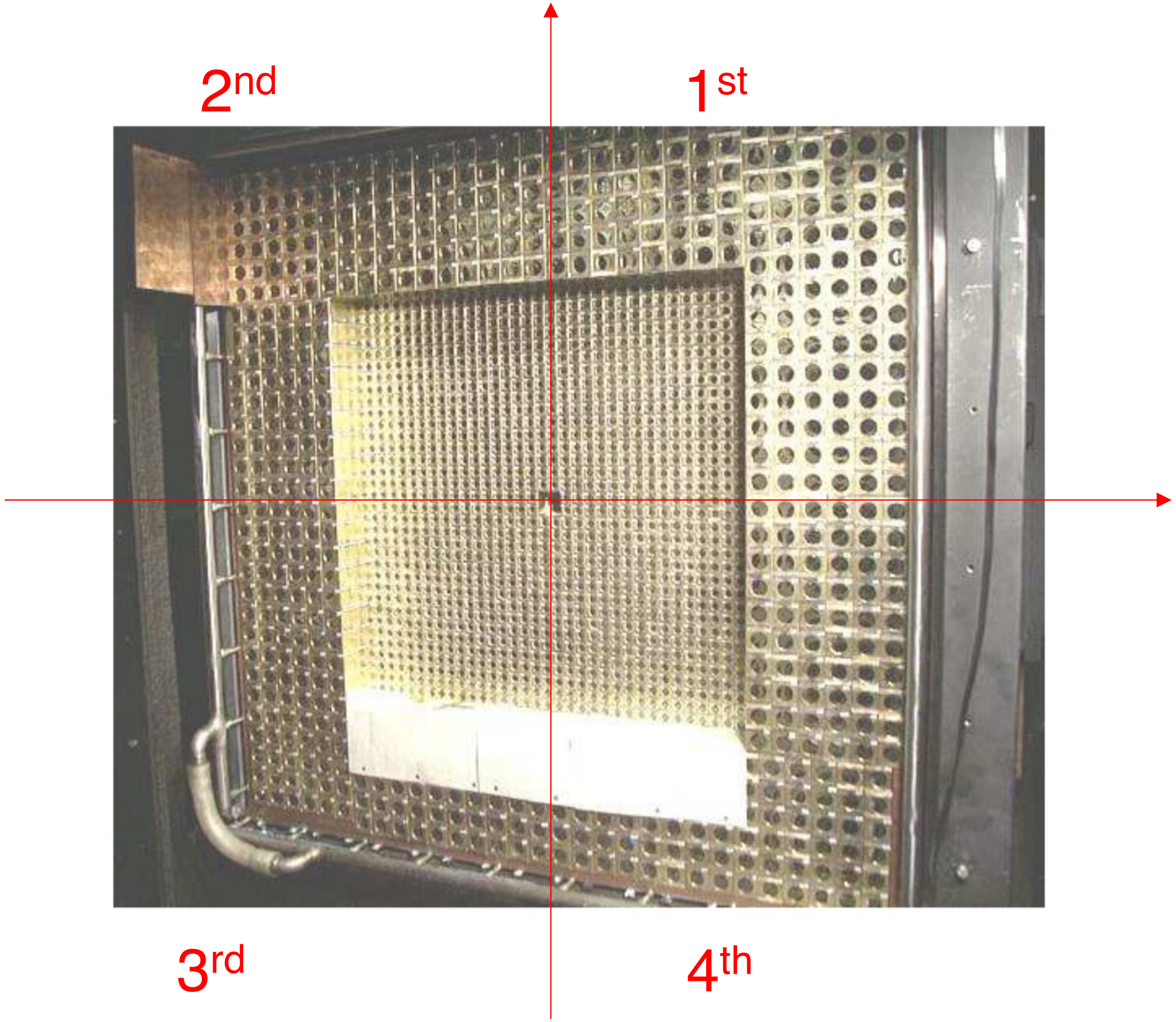
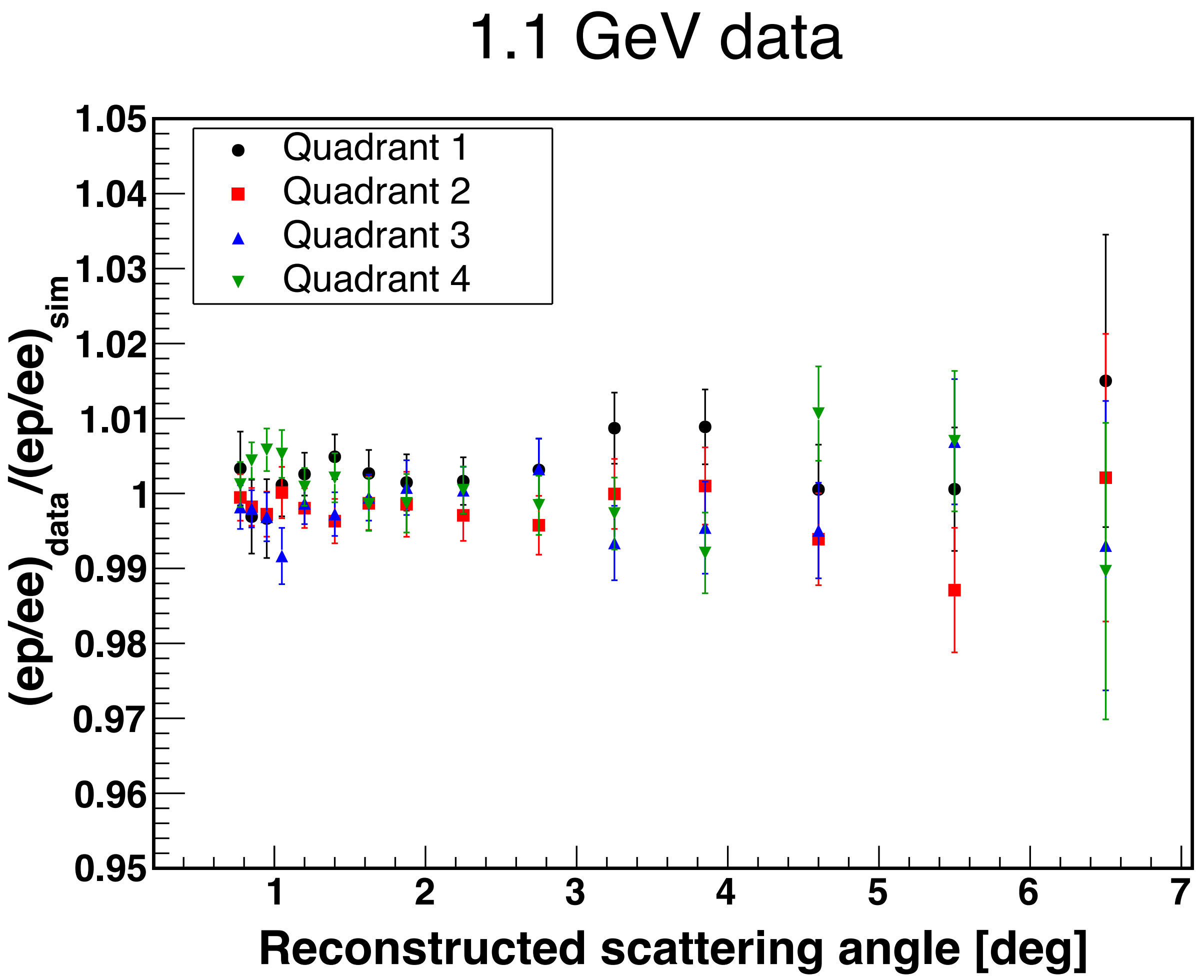
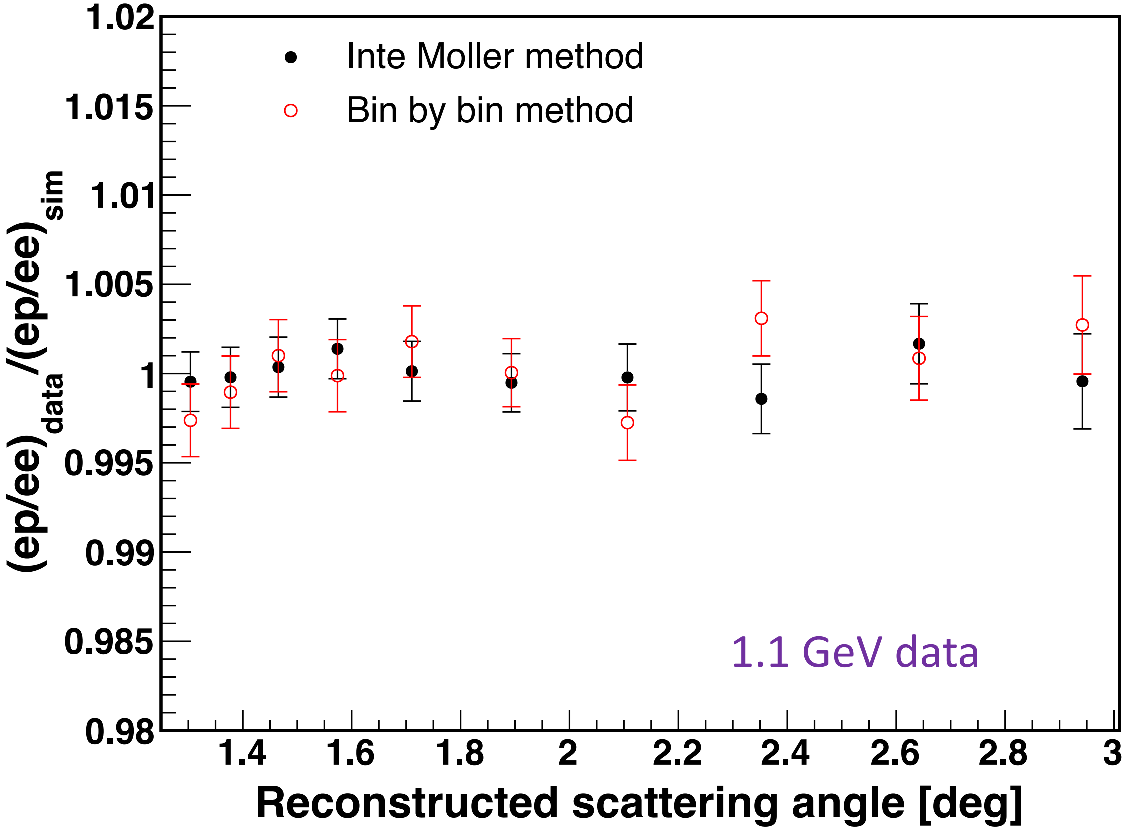
Checking Systematics – Azimuthal Symmetry

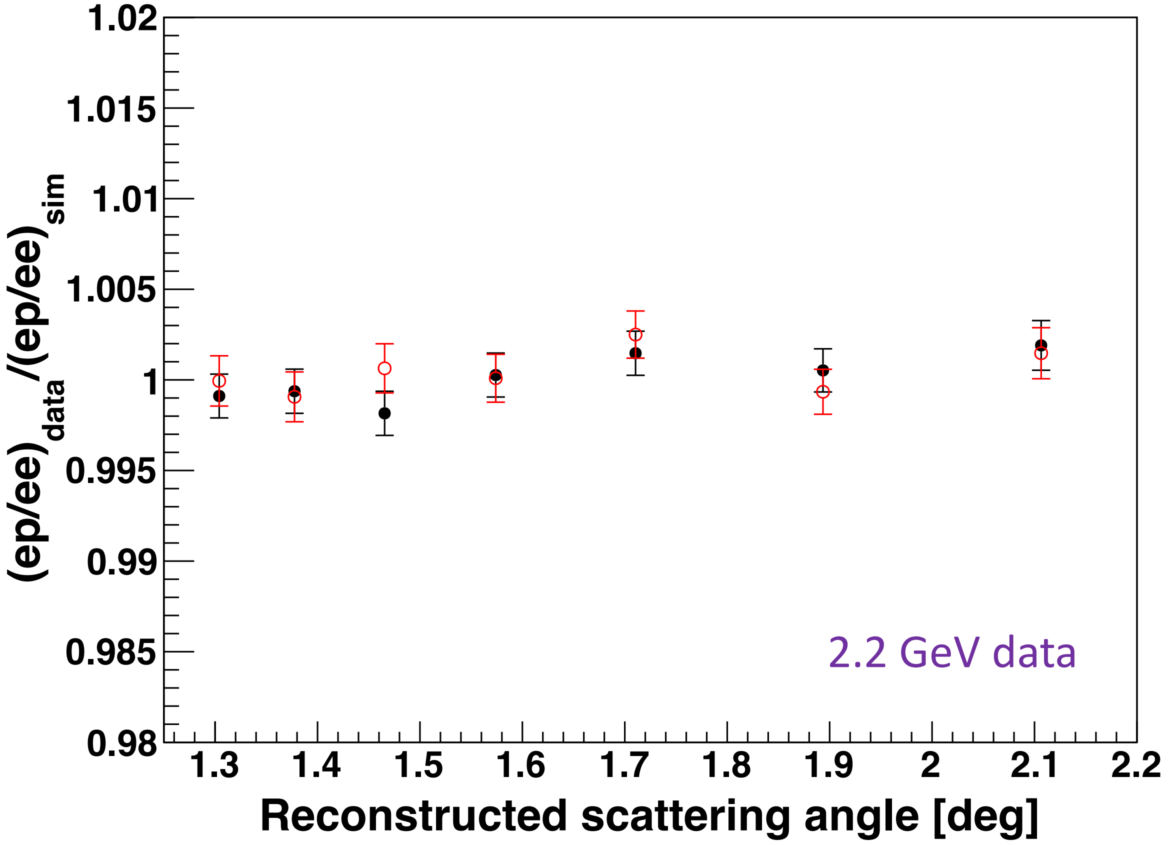




Checking Systematics – Different methods of Forming *ep/ee* ratio

- Method 1: bin-by-bin method – taking *ep/ee* counts from the same angular bin
- Method 2: integrated Møller method – integrate Møller in a fixed angular range and use it as common normalization for all angle bins
- Luminosity cancelled in both methods

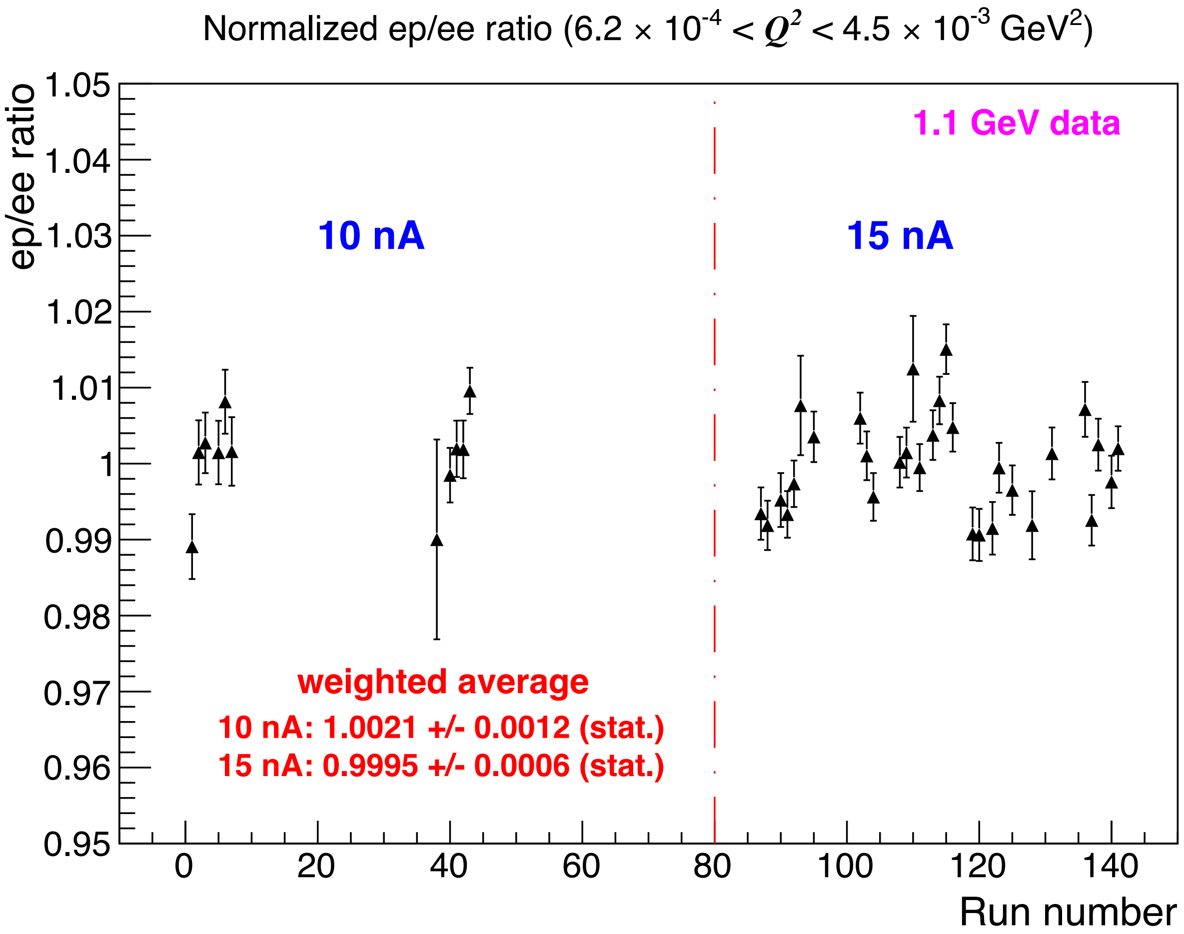


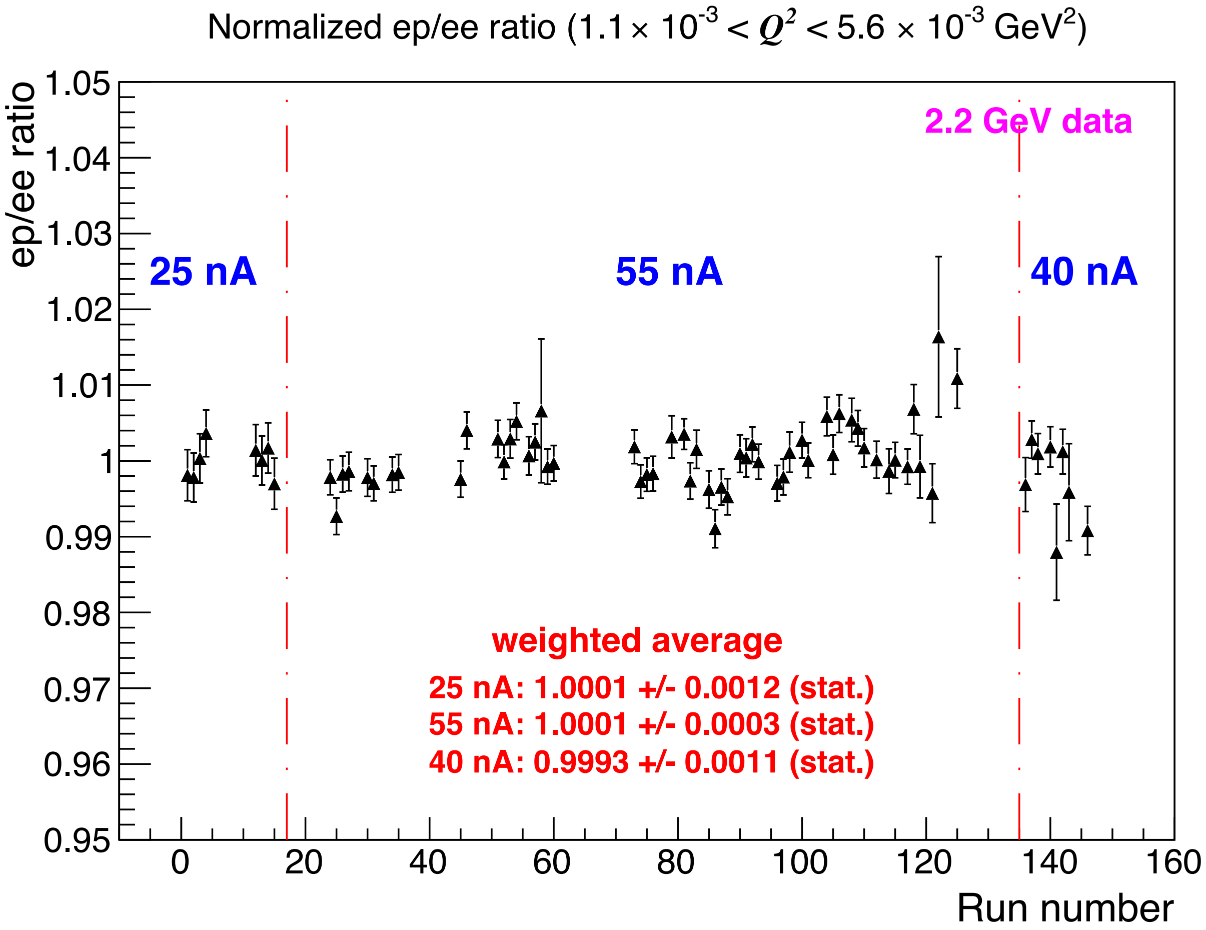


Systematic Uncertainties

Item	r_p uncertainty [fm]	n_1 uncertainty	n_2 uncertainty
Event selection	0.0070	0.0002	0.0006
Radiative correction	0.0069	0.0010	0.0011
Detector efficiency	0.0042	0.0000	0.0001
Beam background	0.0039	0.0017	0.0003
HyCal response	0.0029	0.0000	0.0000
Acceptance	0.0026	0.0001	0.0001
Beam energy	0.0022	0.0001	0.0002
Inelastic *ep*	0.0009	0.0000	0.0000
G_M^p parameterization	0.0006	0.0000	0.0000
Total	0.0115	0.0020	0.0013

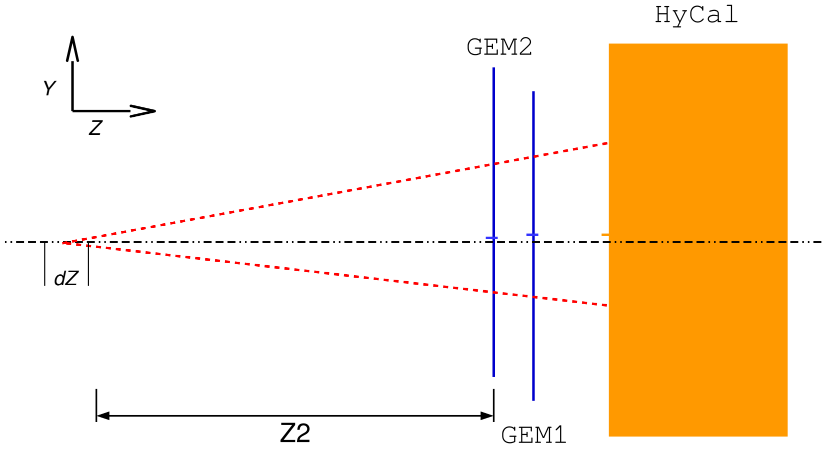
Checking Systematics – Stability vs. Runs

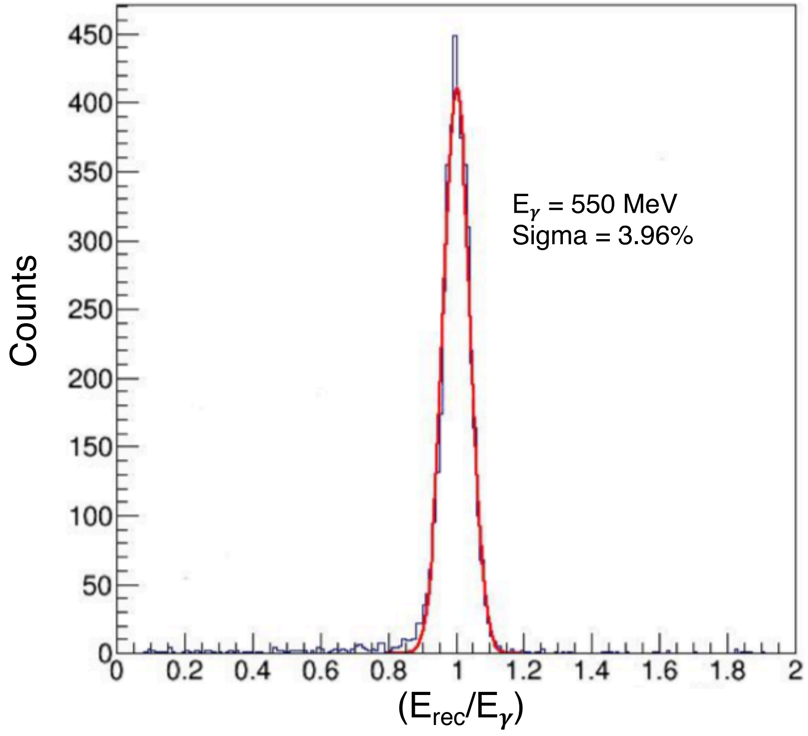


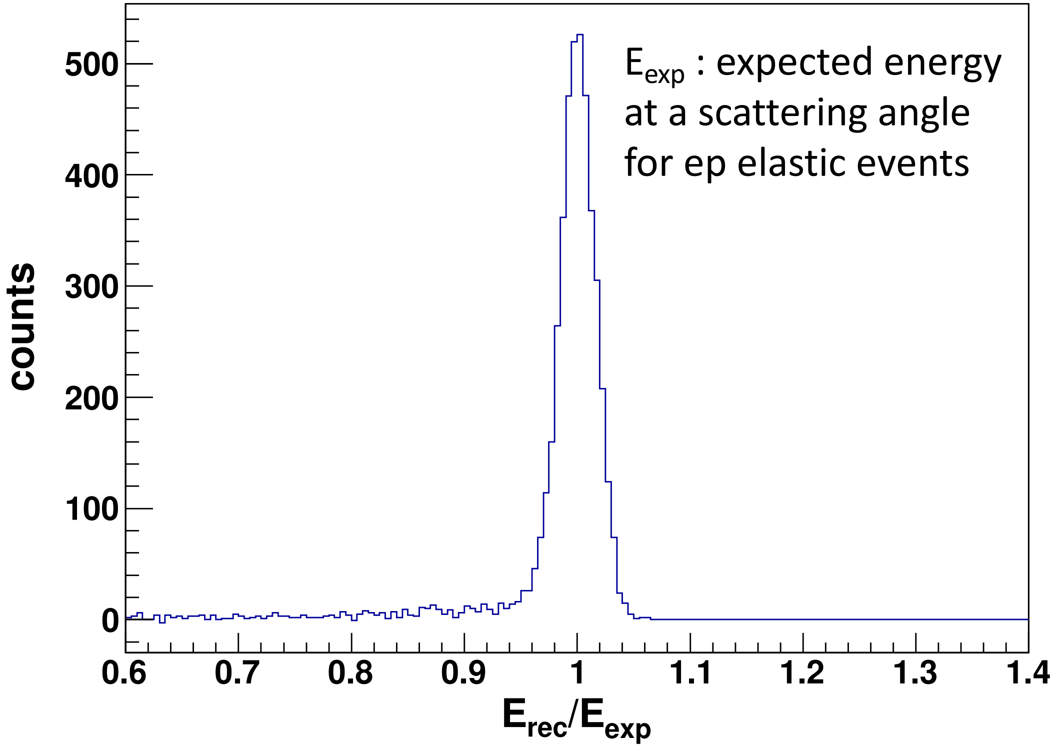


Detector Calibration

- HyCal energy calibration:
  1. Tagged photon beam calibration
  2. Calibration using elastic *ep* and *ee* events
- Detector position calibration
  1. Detector position surveyed by JLab survey group
  2. Using double arm Møller events

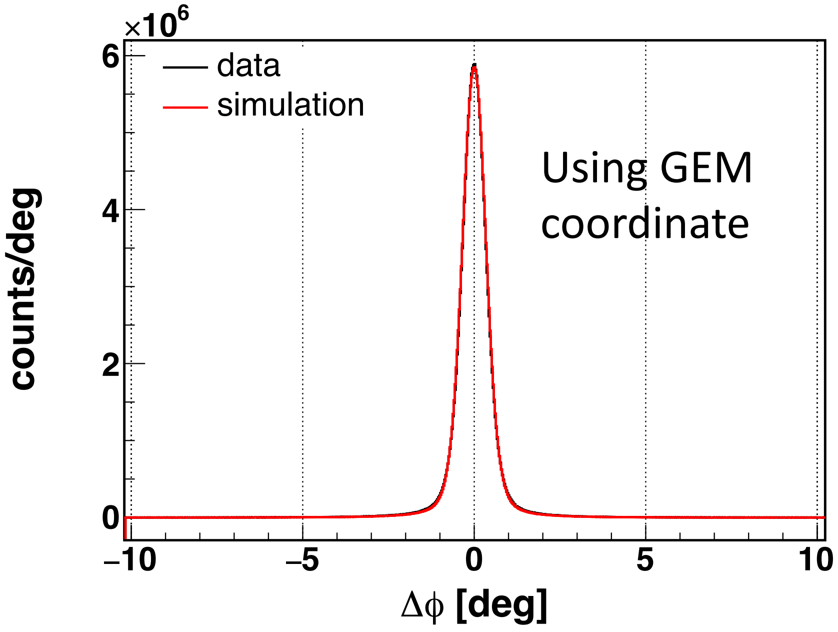


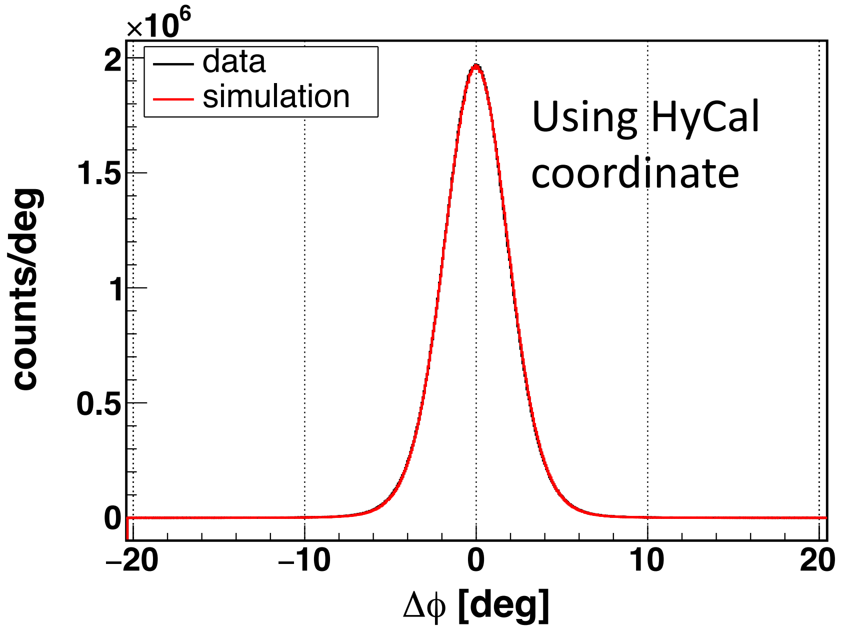




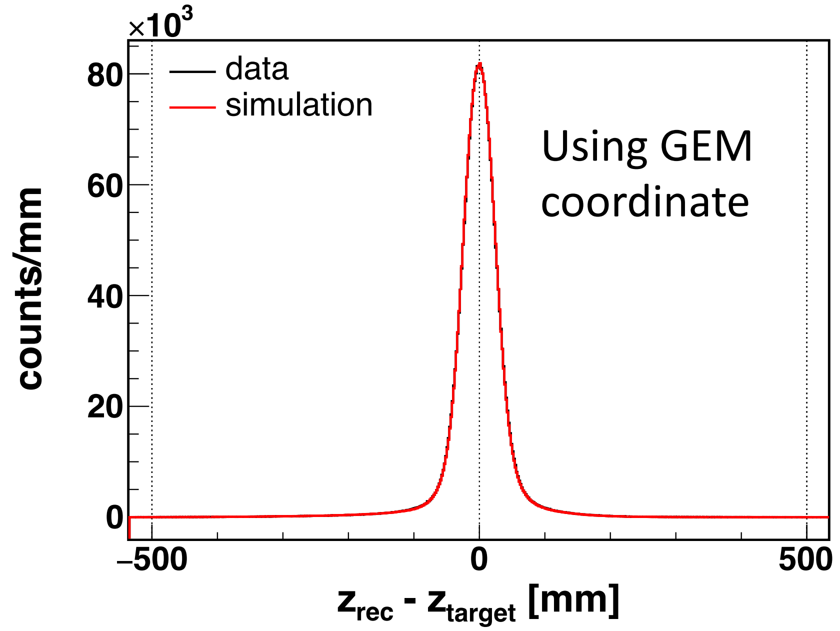
Detector Calibration

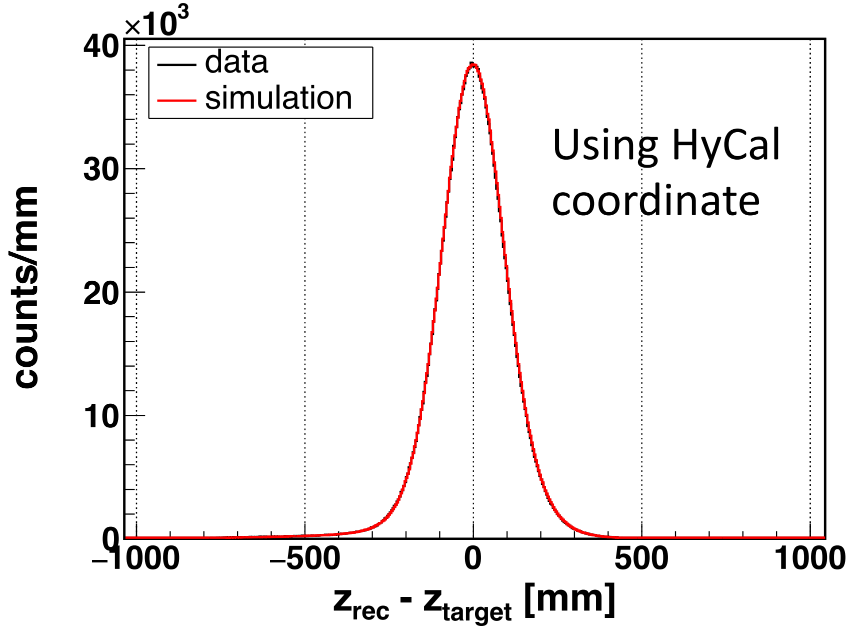
Co-planarity





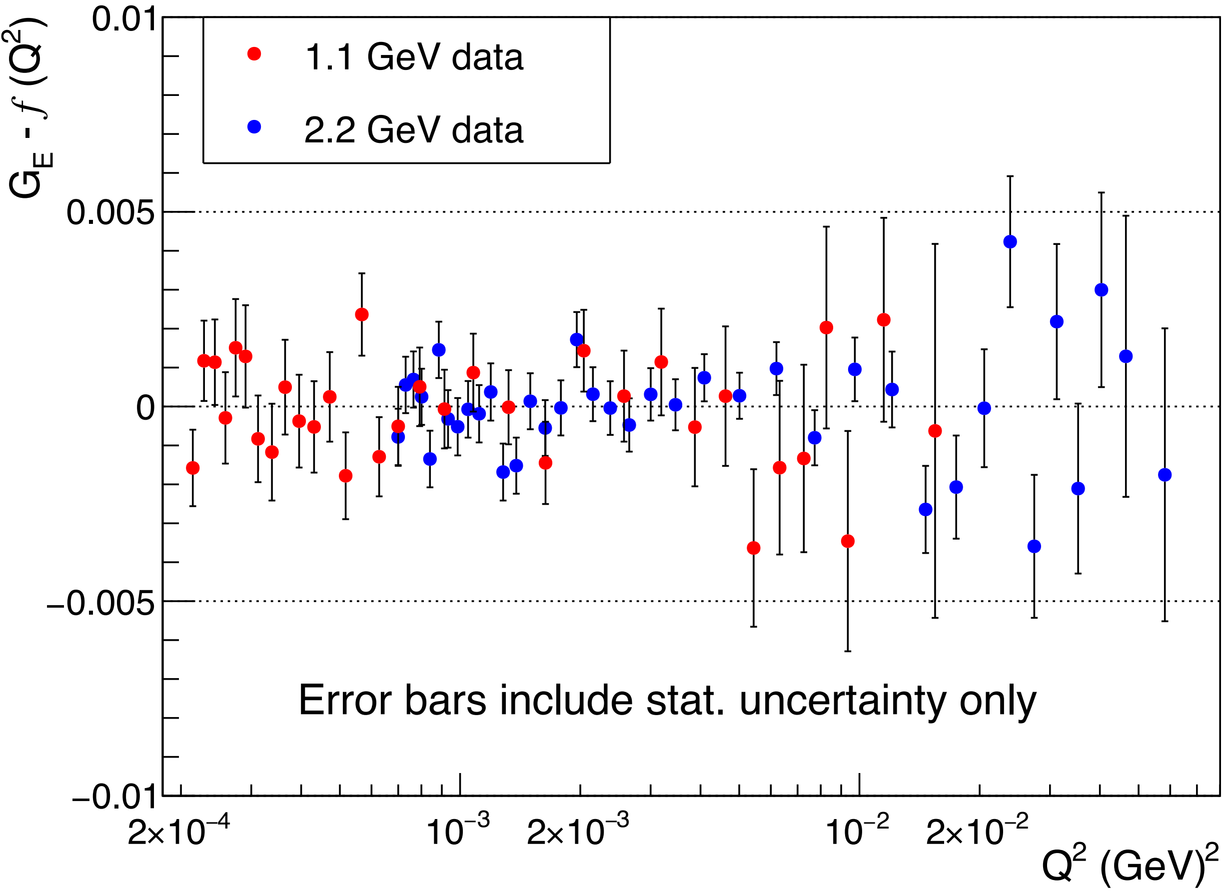
Vertex-z

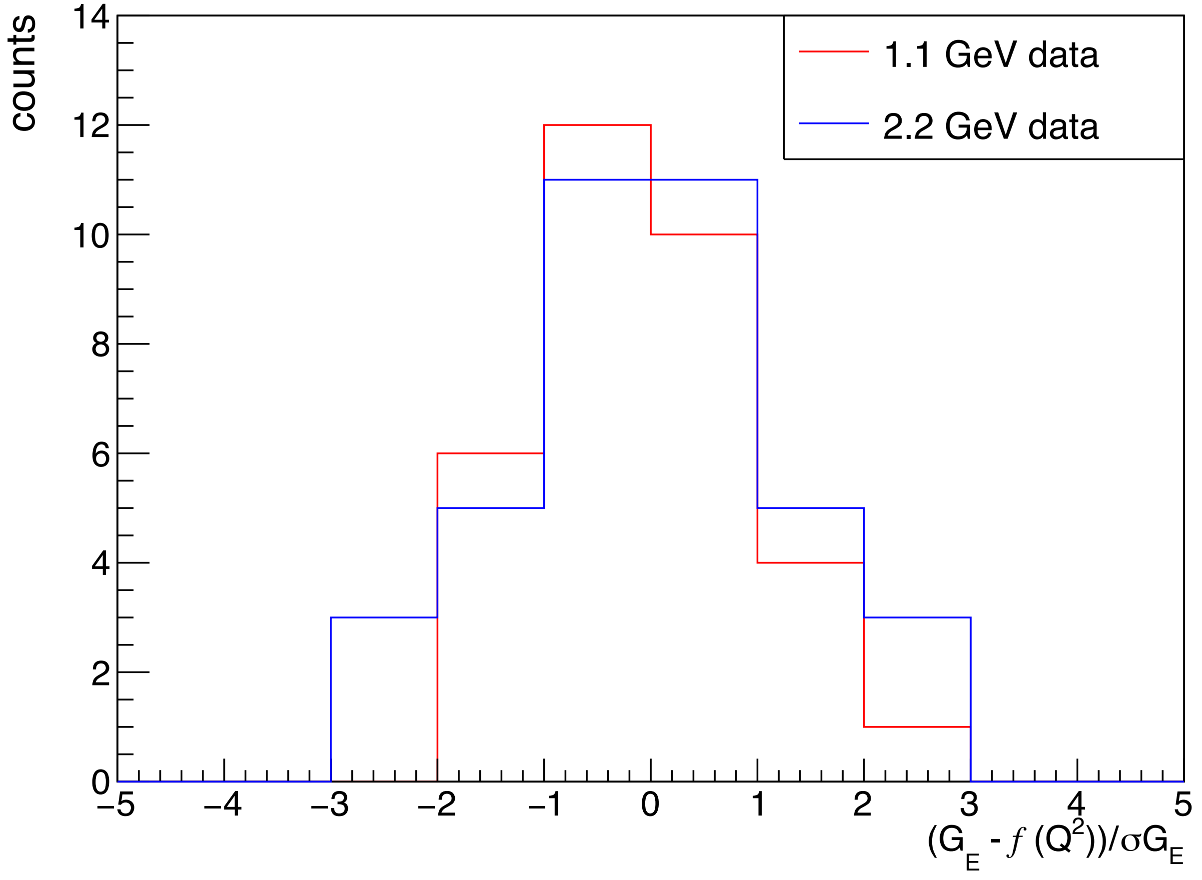




Quality of the Fit

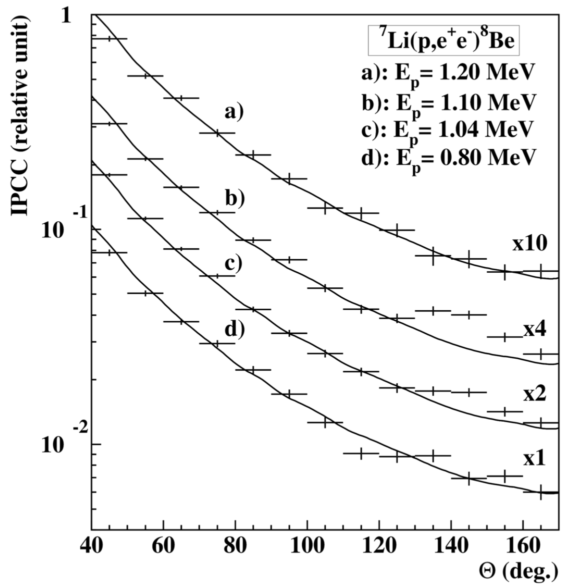
- χ^2/ndf ~ 1.3 (statistical uncertainty only, 33 data points from 1.1 GeV, 38 data points from 2.2 GeV)
- Furthermost outlier about 2.5σ from the fit
- 67% and 58% data points within 1σ for 1.1 and 2.2 GeV data respectively

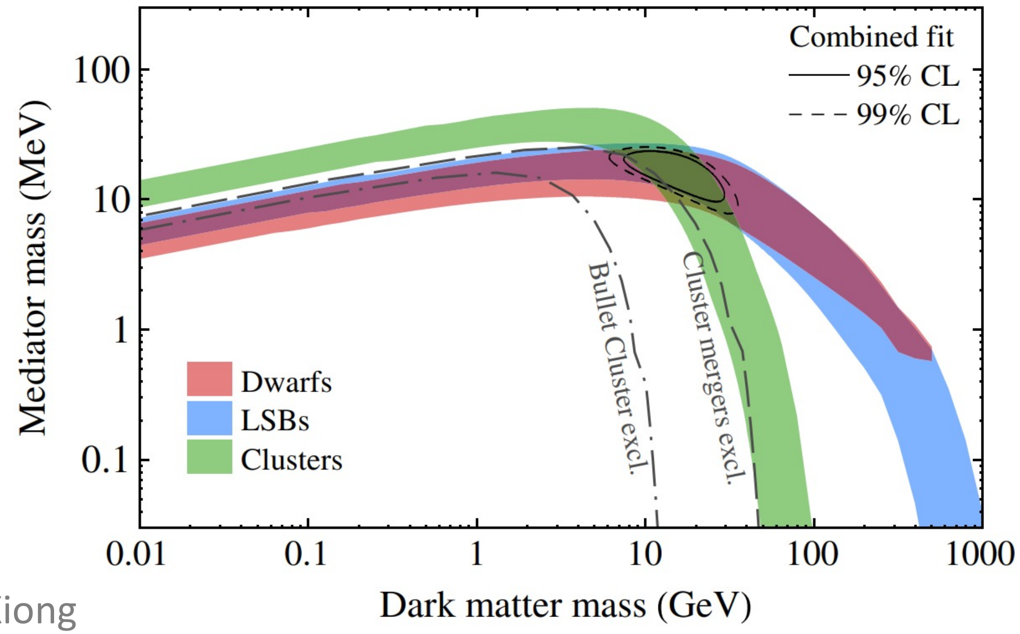


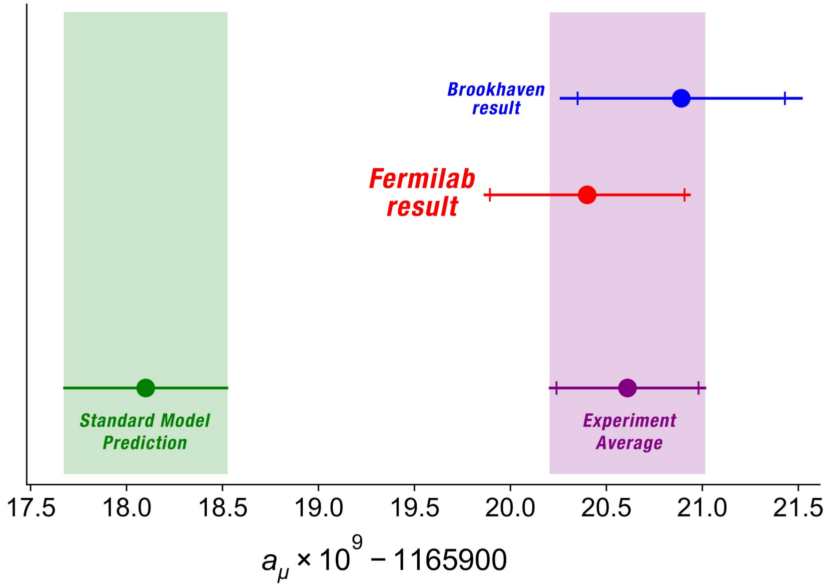


X17 Particle Search Experiment

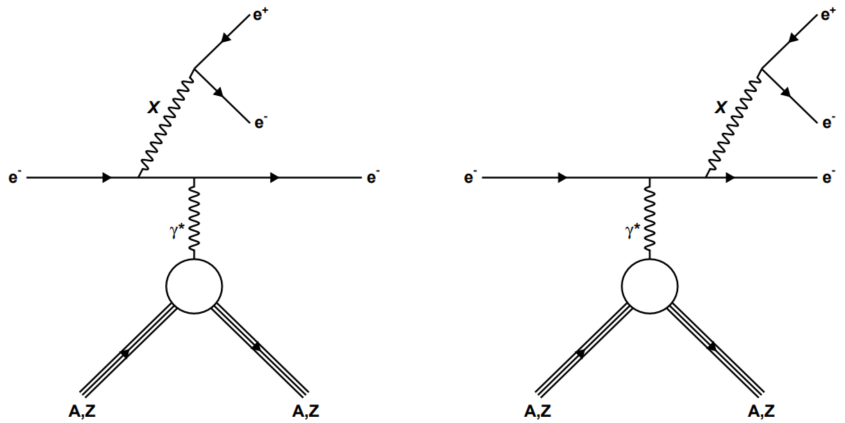
- Search for new 3-60 MeV dark hidden sector particle using PRad setup
- Currently approved with highest scientific rating “A”
- Motivated by multiple recent anomalies:
  1. ^{8}Be anomaly and the X17 particle
  2. Astronomical small structure
  3. muon g-2

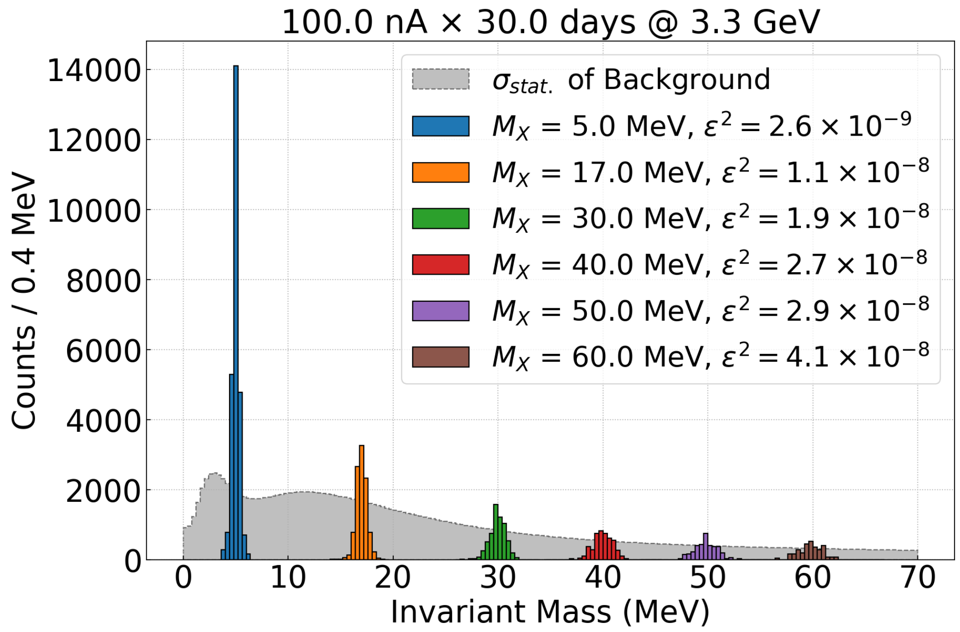




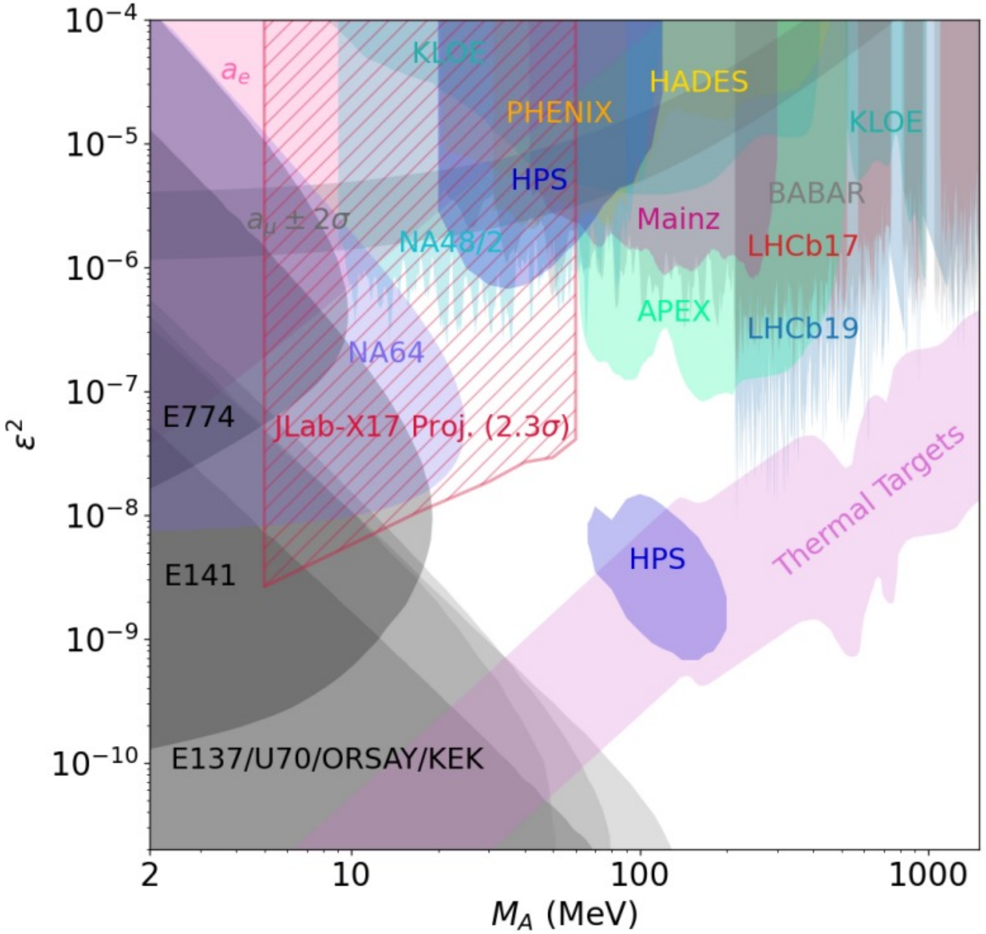


X17 Particle Search Experiment





Projected Search Range



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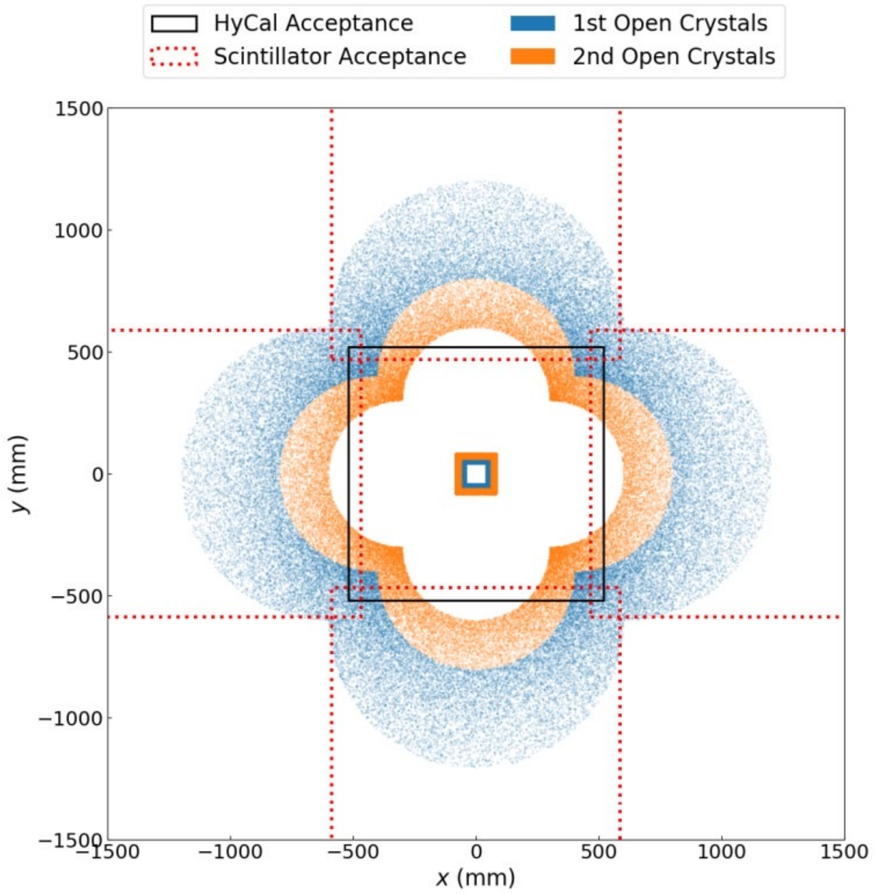
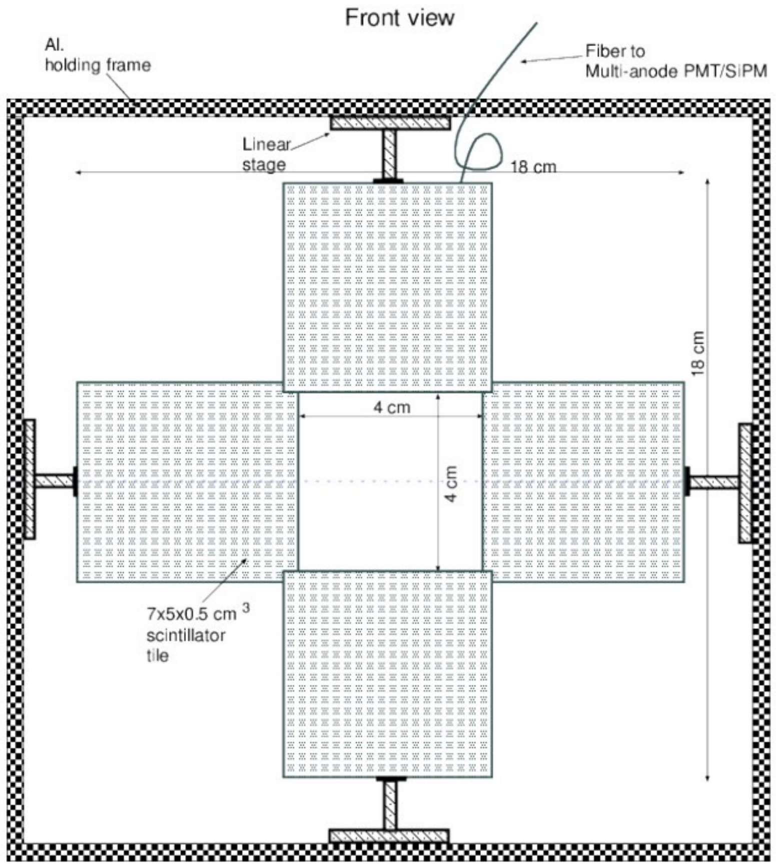
PRad-II Experiment – Cont.

- Convert to FADC based readout for HyCal
- Four times smaller stat. uncertainty
- Better RC calculating including NNLO diagrams
- New scintillating detectors, help reaching $Q^2 \sim 10^{-5}$ GeV^2





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