Proton remains puzzling

Proton mass, spin, charge radius and even new physics

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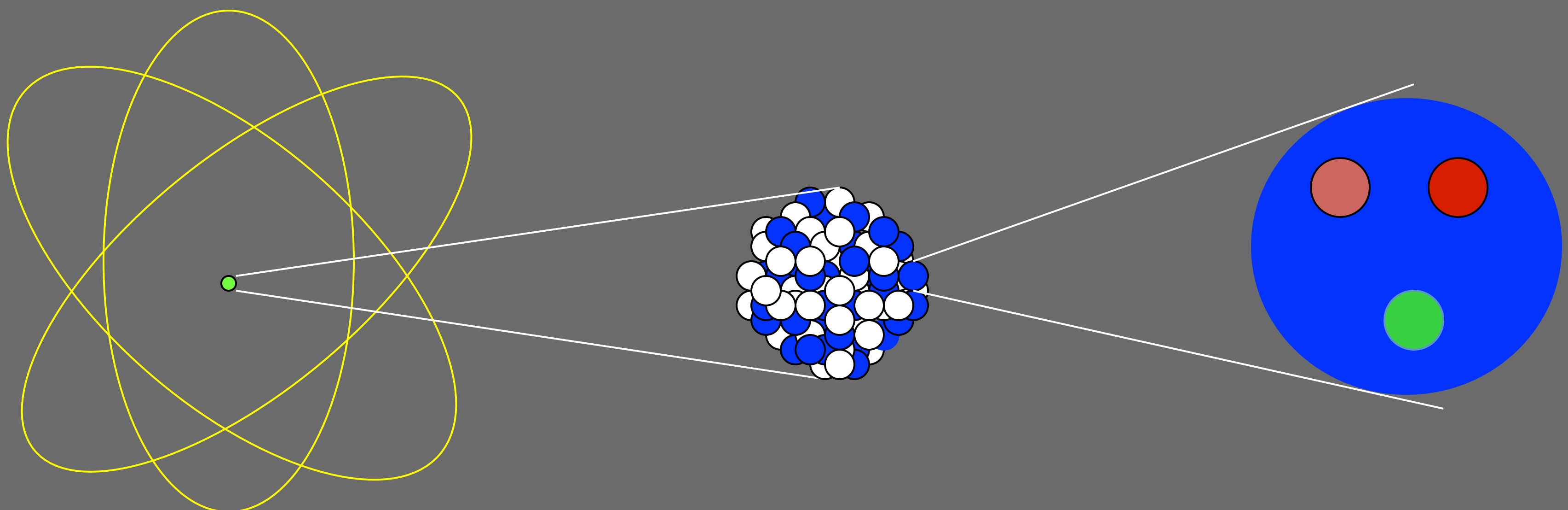
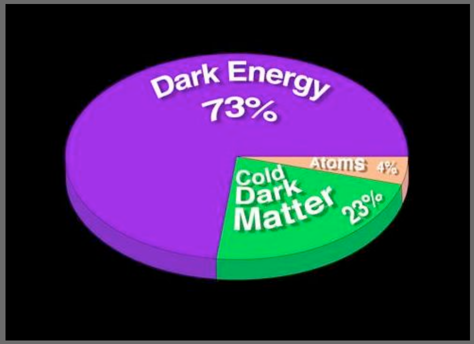
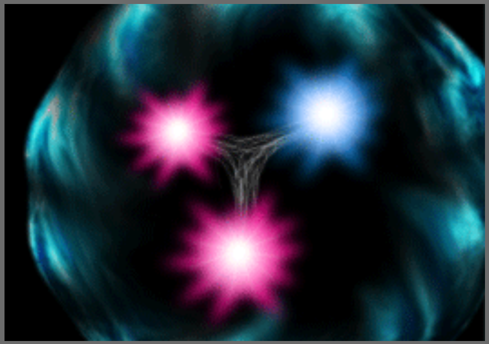
Nuclear physics is the study of the structure of matter

- **Most of the visible 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, and of course gravity).**



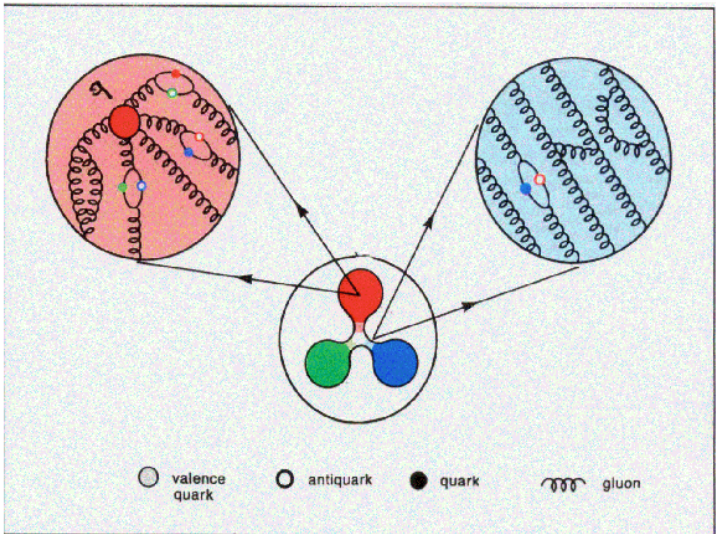
atom: **10^{-10} m** nucleus: **10^{-14} m** nucleon: **10^{-15} m**

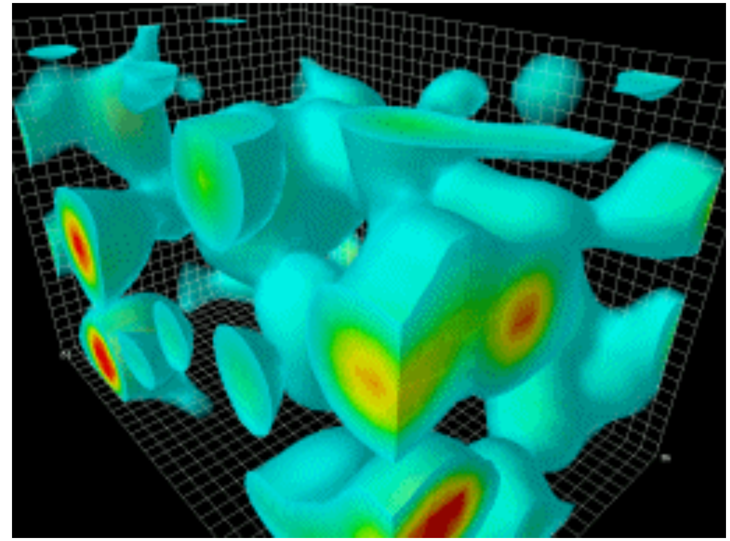




Proton: a fascinating many-body relativistic system

Higgs discovery almost irrelevant to proton mass





$$H_{QCD} = H_q + H_m + Hg + H_a$$

$H_q =$ Quark energy $\int d^3x \, \psi^\dagger \left(-i\mathbf{D}\cdot\alpha\right) \psi$

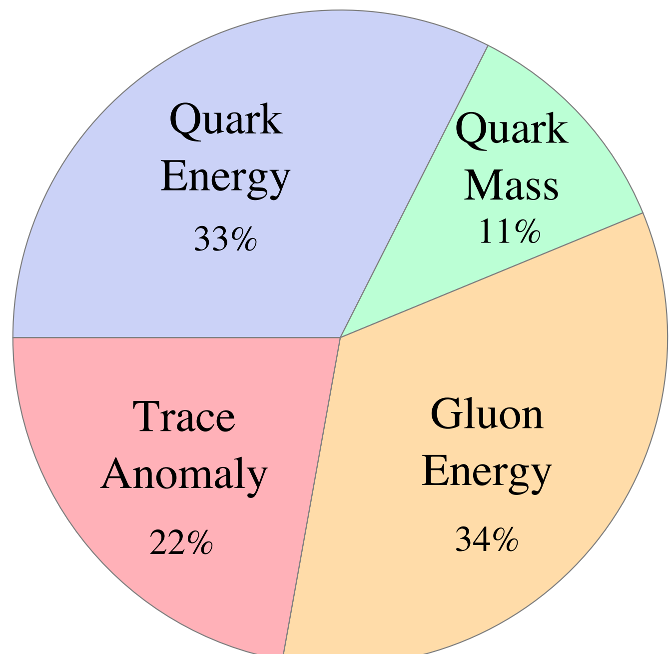
$H_m =$ Quark mass $\int d^3x \, \bar{\psi} m \psi$

$H_g =$ Gluon energy $\int d^3x \, \frac{1}{2} \left(\mathbf{E}^2 + \mathbf{B}^2\right)$

$H_a =$ Trace anomaly $\int d^3x \, \frac{9\alpha_s}{16\pi} \left(\mathbf{E}^2 - \mathbf{B}^2\right)$

Sets the scale for the Hadron mass!

X. Ji PRL 74 1071 (1995)



Spin Milestones and Proton Spin Puzzle

- Spin Milestones: (Nature)
  - 1896: Zeeman effect (milestone 1)
  - 1922: Stern-Gerlach experiment (2)
  - 1925: Spinning electron (Uhlenbeck/Goudsmit)(3)
  - 1928: Dirac equation (4)
  - Quantum magnetism (5)
  - 1932: Isospin(6)
  - 1935: Proton anomalous magnetic moment
  - 1940: Spin–statistics connection(7)
  - 1946: Nuclear magnetic resonance (NMR)(8)
  - 1971: Supersymmetry(13)
  - 1973: Magnetic resonance imaging(15)
  - **1980s: "Proton spin crisis" (now puzzle)**
  - 1990: Functional MRI (19)
  - 1997: Semiconductor spintronics (23)
  - 2000s: "New breakthrough in spin physics"?

topological insulator, quantum anomalous Hall effect, etc..

Pauli and Bohr watch a spinning top

Proton spin taken for granted for coming from the spin of the quarks!!

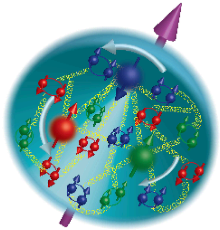
Nature: http://www.nature.com/milestones/milespin/index.html

Impressive experimental progress in QCD spin physics in the last 25 years

- **Inclusive spin-dependent DIS**
  - CERN: EMC, SMC, COMPASS
  - SLAC: E80, E142, E143, E154, E155
  - DESY: HERMES
  - JLab: Hall A, B and C
- **Semi-inclusive DIS**
  - SMC, COMPASS
  - HERMES, JLab
- **Polarized pp collisions**
  - BNL: PHENIX & STAR
- **Polarized e+e- collisions**
  - KEK: Belle

Z. Meziani

Nucleon Spin Decomposition



Proton spin puzzle

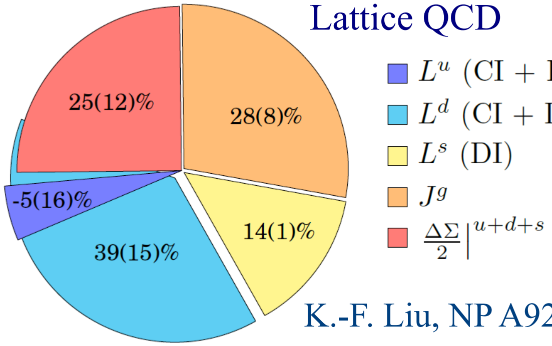
$$\Delta\Sigma = \Delta u + \Delta d + \Delta s \sim 0.3$$

Quark spin only contributes a small fraction to nucleon spin.

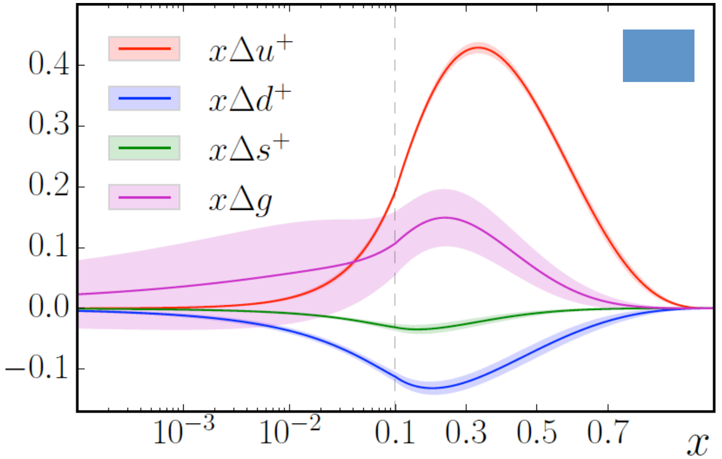
J. Ashman et al., PLB 206, 364 (1988); NP B328, 1 (1989).

Spin decomposition

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



K.-F. Liu, NP A928, 99 (2014).



JAM Collaboration, to appear in PRD (2016).

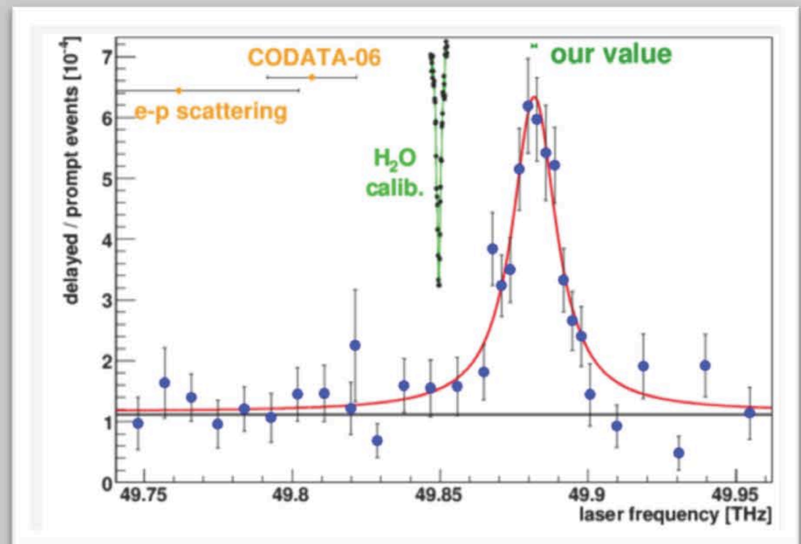
Access to $L_{q/g}$

It is necessary to have transverse information.

Coordinate space: GPDs
Momentum space: TMDs

3D imaging of the nucleon.

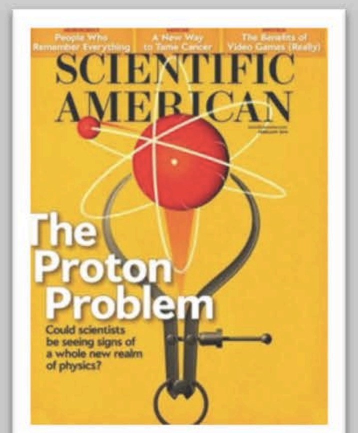
The Proton Size Puzzle



The New York Times

Süddeutsche Zeitung

DIE ZEIT



SPIEGEL ONLINE

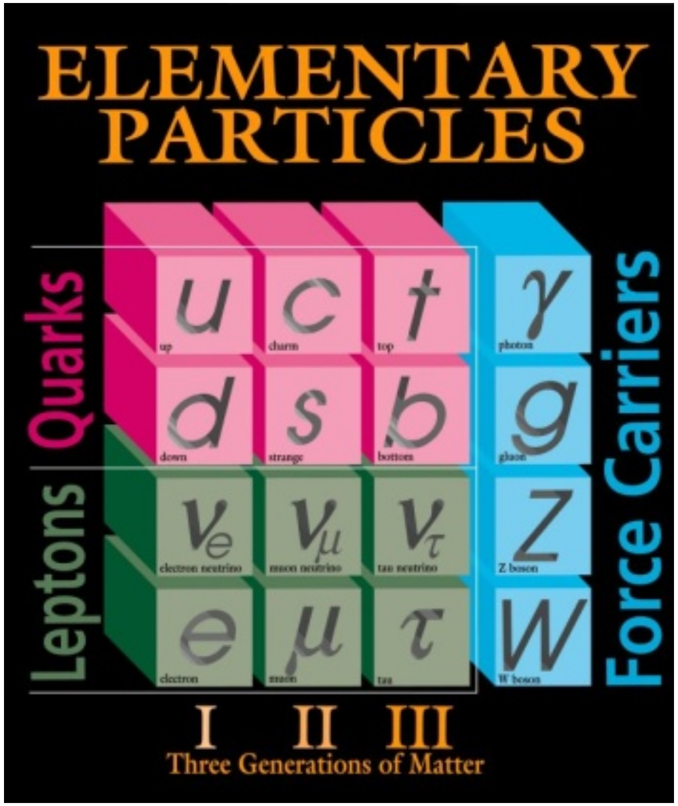
la Repubblica

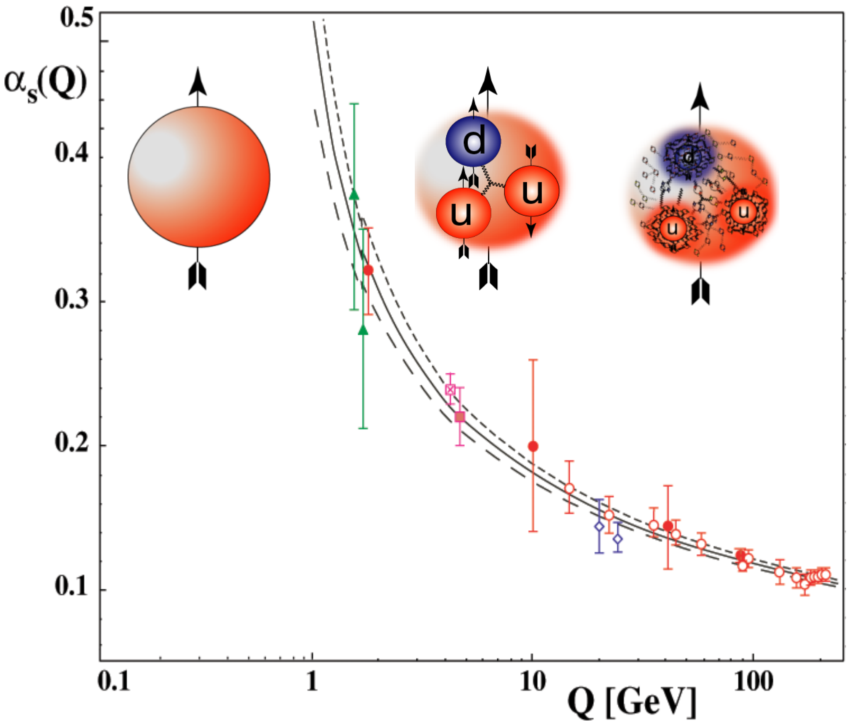
Neue Zürcher Zeitung

NATIONAL GEOGRAPHIC

Los Angeles Times

QCD: still unsolved in non-perturbative region



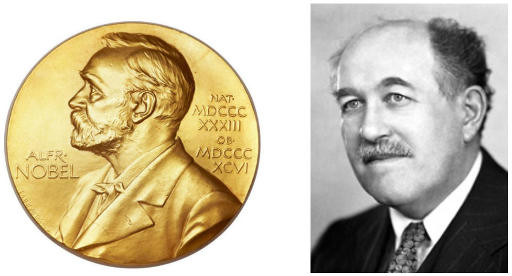


Gauge bosons: gluons (8)

- *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*

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 magnetic moment of the proton".

$g \neq 2$

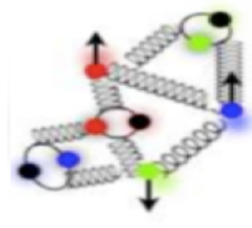
1960: Elastic e-p scattering

Nobel Prize
In Physics 1961

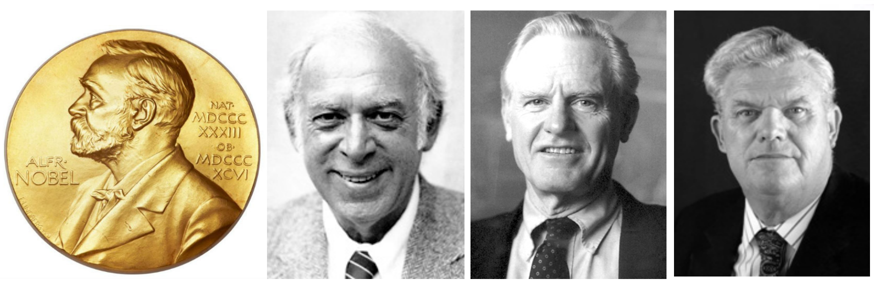
Robert Hofstadter

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

Form factors $\rightarrow$ Charge distributions



1969: Deep inelastic e-p scattering



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 Freedom

Nobel Prize in Physics 2004

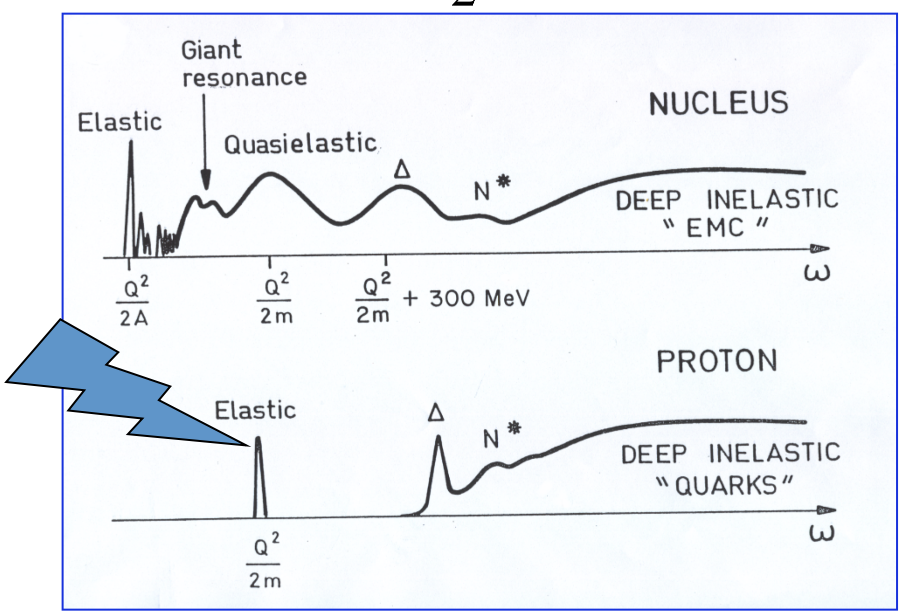
David J. Gross, H. David Politzer, Frank Wilczek

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

Lepton scattering: powerful microscope!

- Clean probe of hadron structure
- Electron (lepton) vertex is well-known from QED
- One-photon exchange dominates, ***higher-order exchange diagrams are suppressed (two-photon physics)***
- ***Vary the wave-length of the probe to view deeper inside***

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4E^2 \sin^4 \frac{\theta}{2}} \frac{E'}{E} \left(\frac{G_E^2 + \tau G_M^2}{1+\tau} \cos^2 \frac{\theta}{2} + 2\tau G_M^2 \sin^2 \frac{\theta}{2} \right) \qquad \tau = -q^2 / 4M^2$$

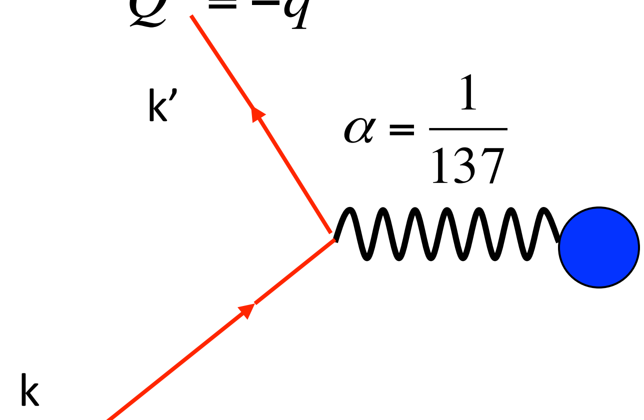


Virtual photon 4-momentum

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

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

$$\alpha = \frac{1}{137}$$



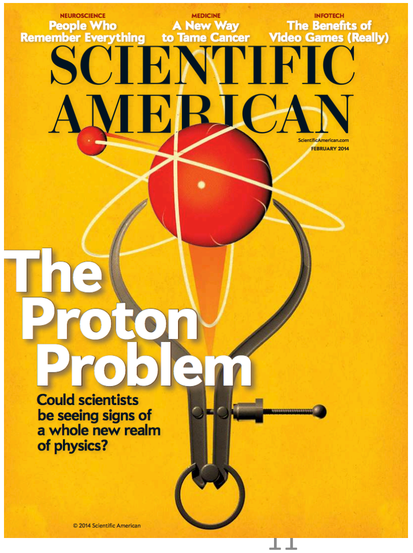
Proton Charge Radius

- An important property of the nucleon
  - Important for understanding how QCD works
  - Challenge to Lattice QCD (exciting new results, Alexandrou et al.)
  - An important physics input to the bound state QED calculations, affects muonic H Lamb shift ($2S_{1/2} - 2P_{1/2}$) by as much as 2%

- Electron-proton elastic scattering to determine electric form factor (Nuclear Physics)

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

- Spectroscopy (Atomic physics)
  - Hydrogen Lamb shift
  - Muonic Hydrogen Lamb shift

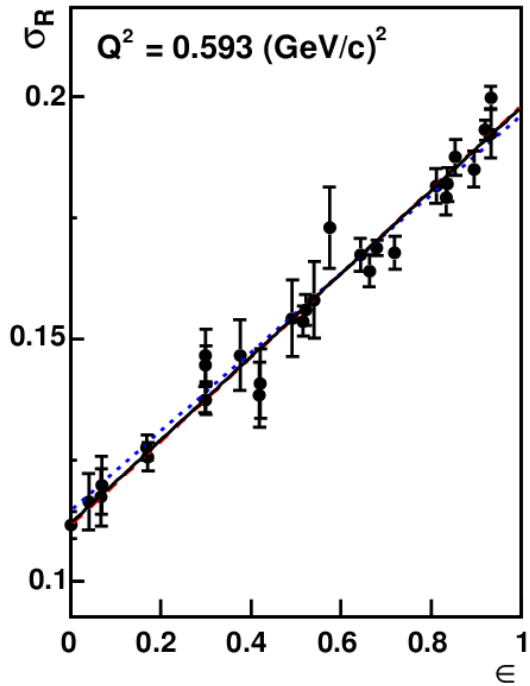


Unpolarized electron-nucleon scattering

(Rosenbluth Separation)

- Elastic e-p cross section

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



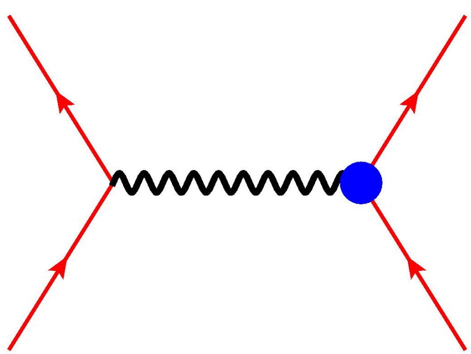
$$\sigma_R = \tau G_M^2 + \epsilon G_E^2$$

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

$$\varepsilon = (1 + 2(1+\tau)\tan^2\frac{\theta}{2})^{-1}$$

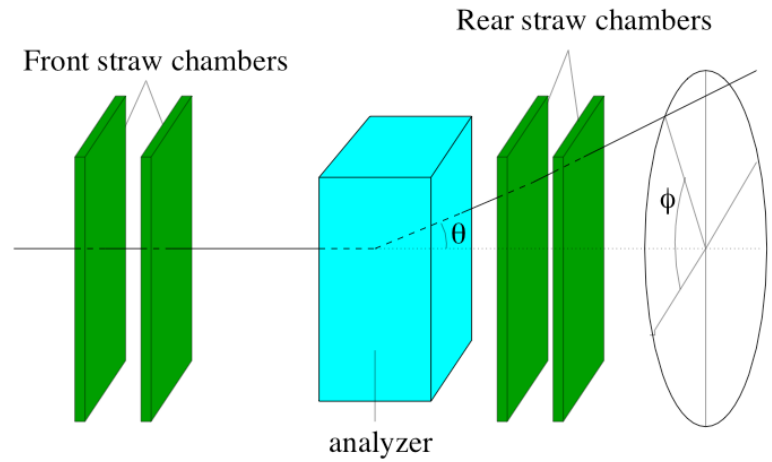
- At fixed Q^2, fit $d\sigma/d\Omega$ vs. $\tan^2(\theta/2)$
  - Measurement of absolute cross section
  - ***Dominated by either G_E or G_M***
    - Low Q^2 by G_E
    - High Q^2 by G_M

G_E or G_M



Electron-proton elastic scattering with longitudinally polarized electron beam and recoil proton polarization measurement

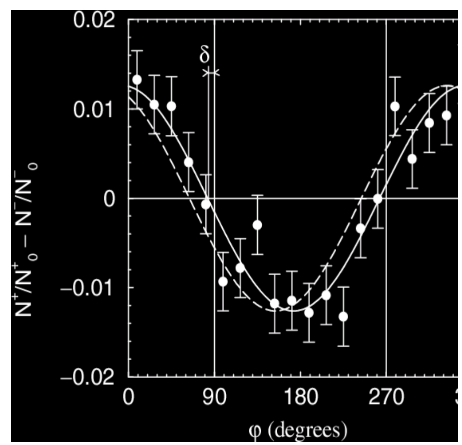
Polarization Transfer → $\dfrac{G_E^p}{G_M^p}$

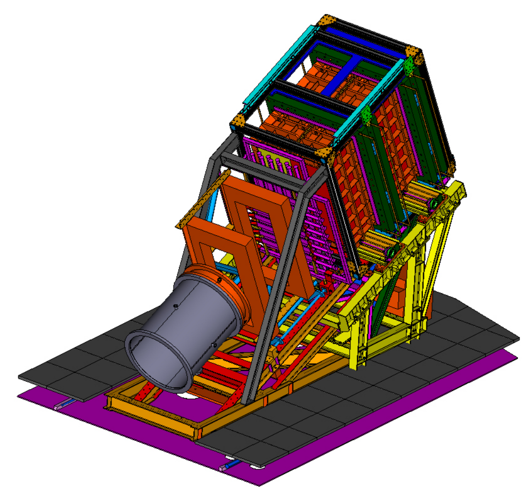


- Recoil proton polarization

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

- Focal Plane Polarimeter
  - recoil proton scatters off secondary ^{12}C target
  - P_t, P_l measured from φ distribution
  - P_b, and analyzing power cancel out in ratio





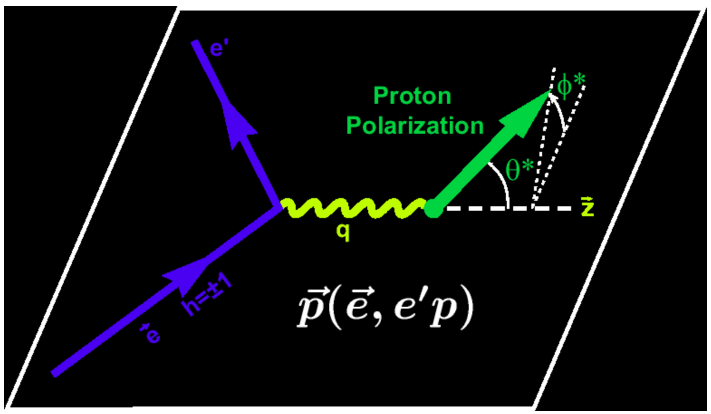
Focal-plane polarimeter

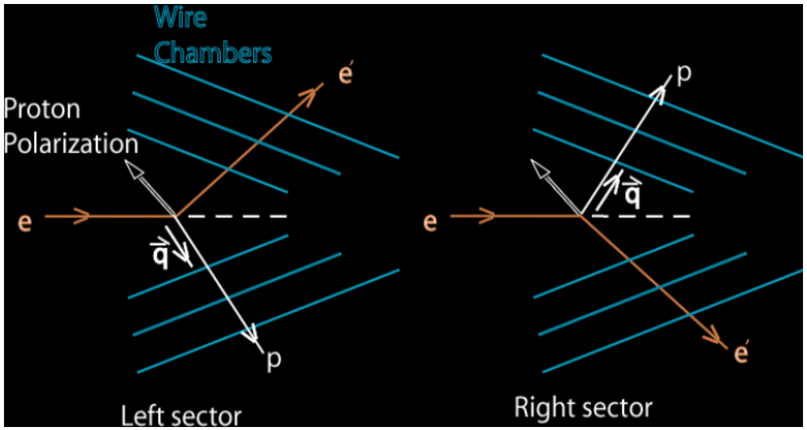
Asymmetry Super-ratio Method

Polarized electron-polarized proton elastic scattering

- Polarized beam-target asymmetry

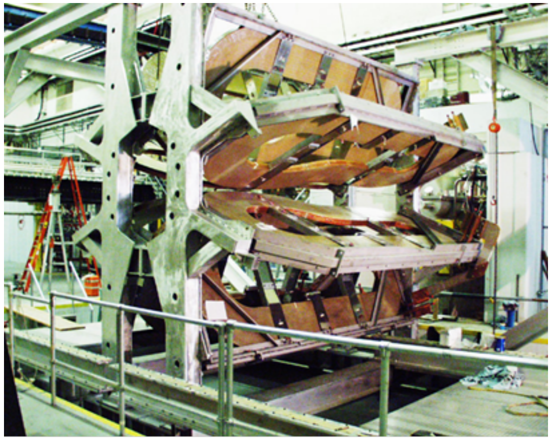
$$A_{exp} = P_b P_t \frac{-2\tau v_{T'} \cos\theta^* {G_M^p}^2 + 2\sqrt{2\tau(1+\tau)} v_{TL'} \sin\theta^* \cos\phi^* G_M^p G_E^p}{(1+\tau) v_L {G_E^p}^2 + 2\tau v_T {G_M^p}^2}$$





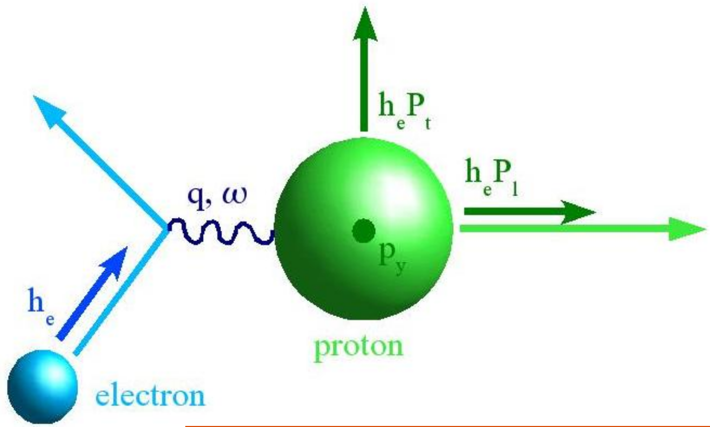
- Super-ratio

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



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

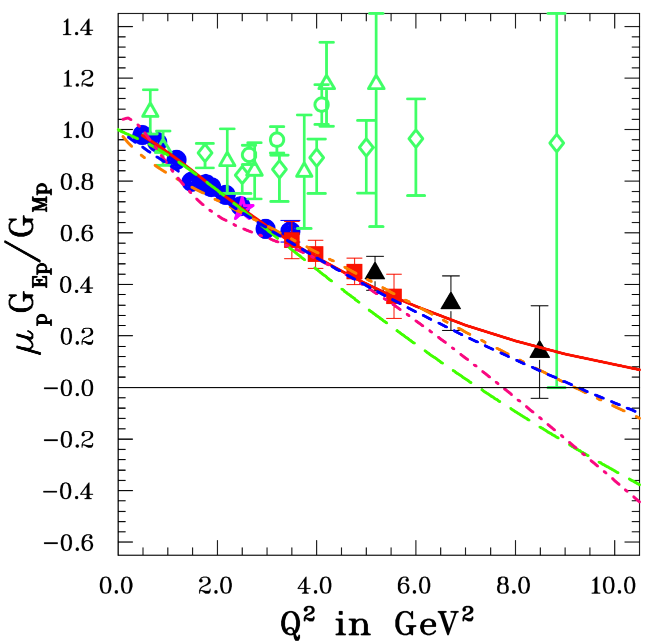
Tremendous advances in electron scattering



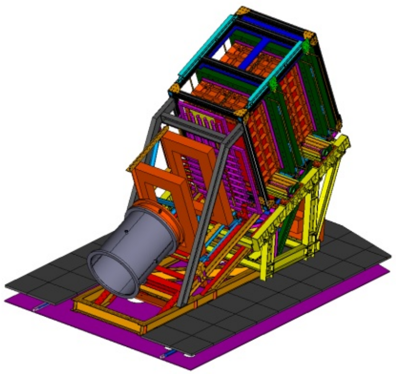
Unprecedented capabilities:

- High Intensity
- High Duty Factor
- High Polarization
- Parity Quality Beams
- Large acceptance detectors
- State-of-the-art polarimetry, polarized targets

$$\frac{G_{Ep}}{G_{Mp}} = -\frac{P_t}{P_\ell}\frac{(E_e + E_{e'})}{2M}\tan\left(\frac{\theta_e}{2}\right)$$

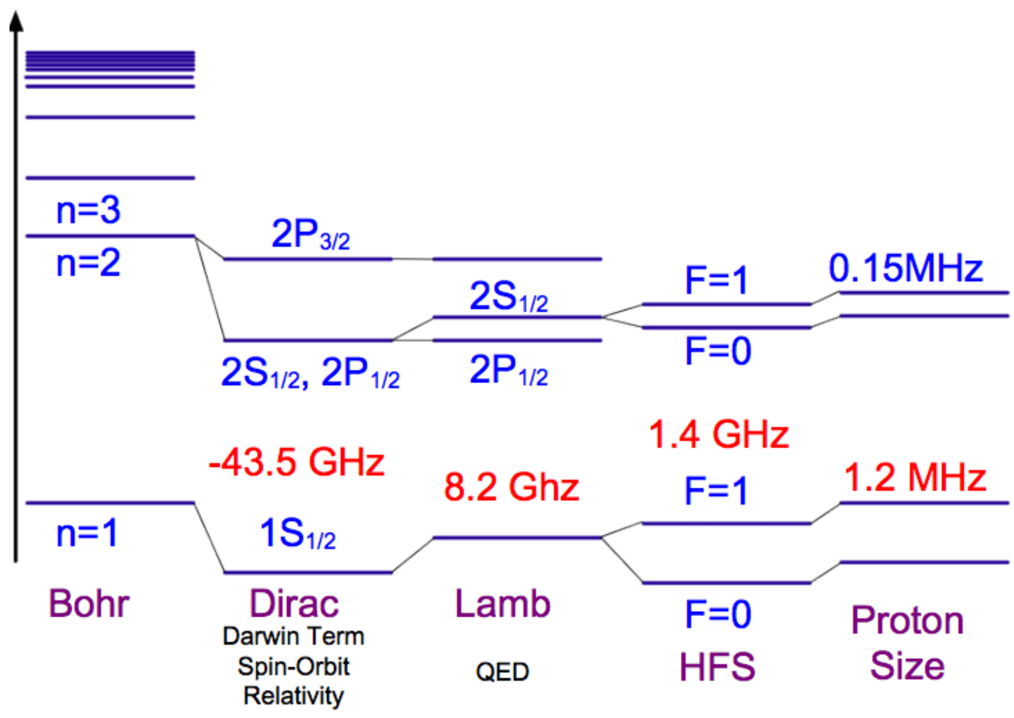


Polarized ^3He target



Focal plane polarimeter – Jefferson Lab

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.

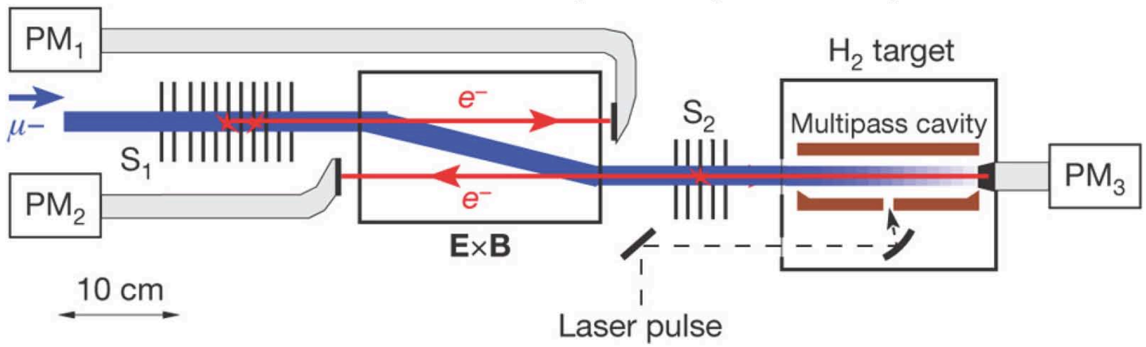
Yields R_∞ (the most precisely known constant)

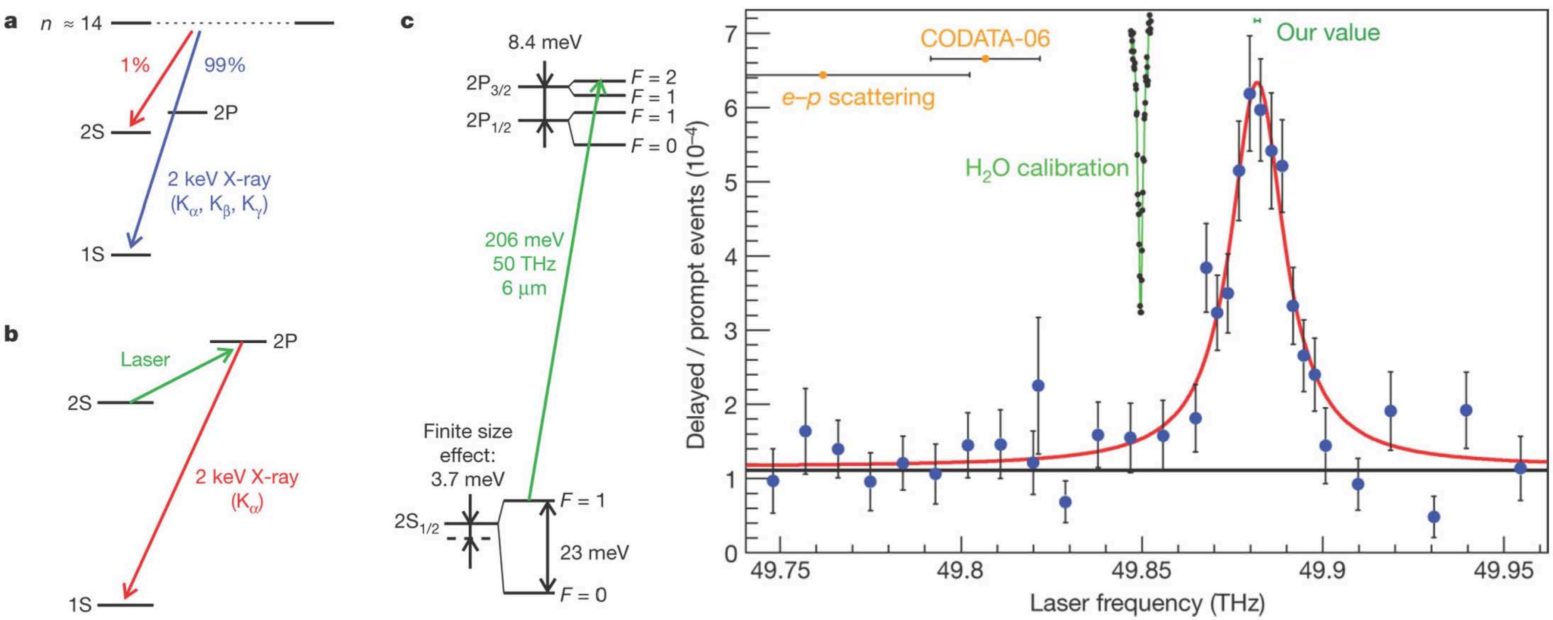
Comparing measurements to QED calculations that include corrections for the finite size of the proton provide an indirect but very precise value of the rms proton charge radius

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

Muonic hydrogen Lamb shift at PSI (2010, 2013)

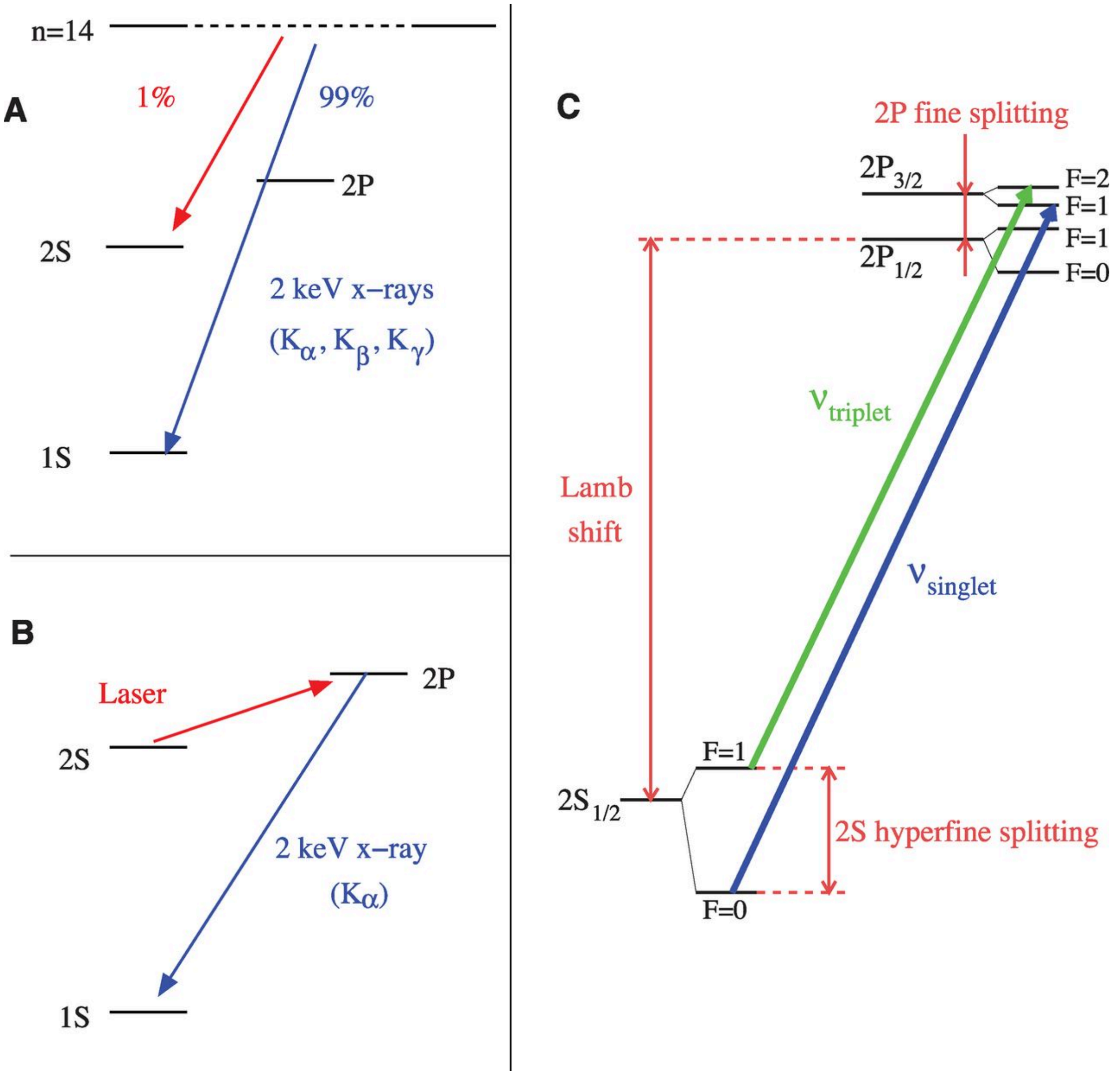
Nature **466**, 213-216 (8 July 2010)





2010: new value is r_p = 0.84184(67) fm

New PSI results reported in Science 2013

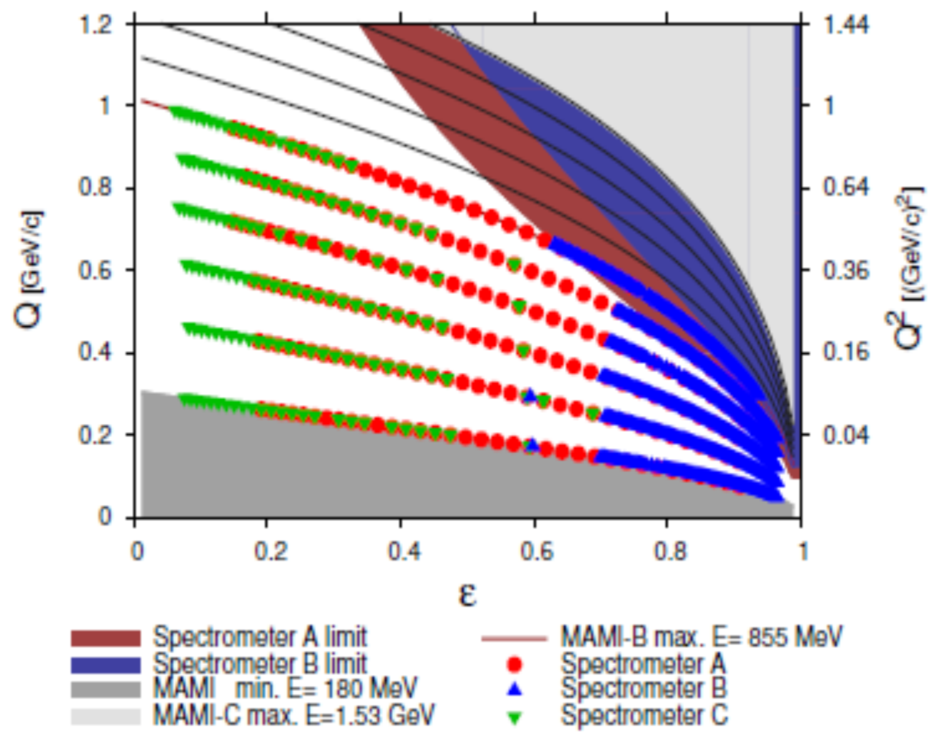


2013: r_p = 0.84087(39) fm, A. Antognini *et al.*, Science 339, 417 (2013)

Recent ep Scattering Experiments

Three spectrometer facility of the A1 collaboration:

Measurements @ Mainz



– Large amount of overlapping data sets

– Statistical error ≤ 0.2%

– Luminosity monitoring with spectrometer

- $Q^2 = 0.004 - 1.0\ (\text{GeV/c})^2$

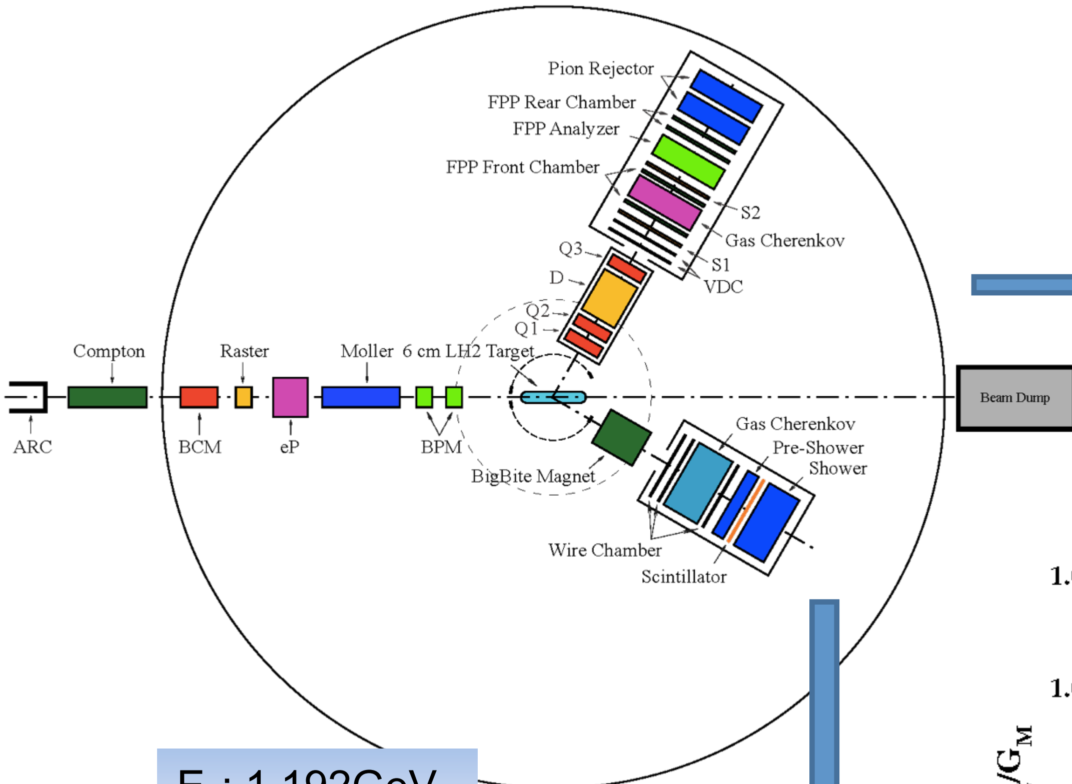
result: $r_p = 0.879(5)_{stat}(4)_{sys}(2)_{mod}(4)_{group}$

J. Bernauer, PRL 105,242001, 2010

5-7σ higher than muonic hydrogen result !

(J. Bernauer)

JLab Recoil Proton Polarization Experimental



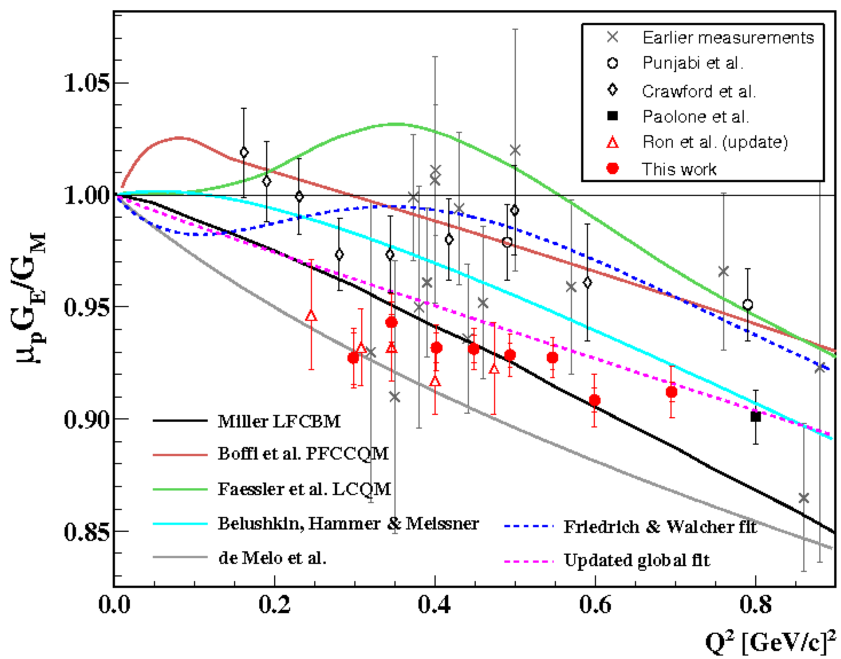
LHRS

- $\Delta p/p0$: ± 4.5% ,
- out-of-plane: ± 60 mrad
- in-plane: ± 30 mrad
- $\Delta\Omega$: 6.7msr
- QQDQ
- Dipole bending angle 45^o
- VDC+FPP
- P_p : 0.55 ~ 0.93 GeV/c

E_e: 1.192GeV
P_b: ~83%

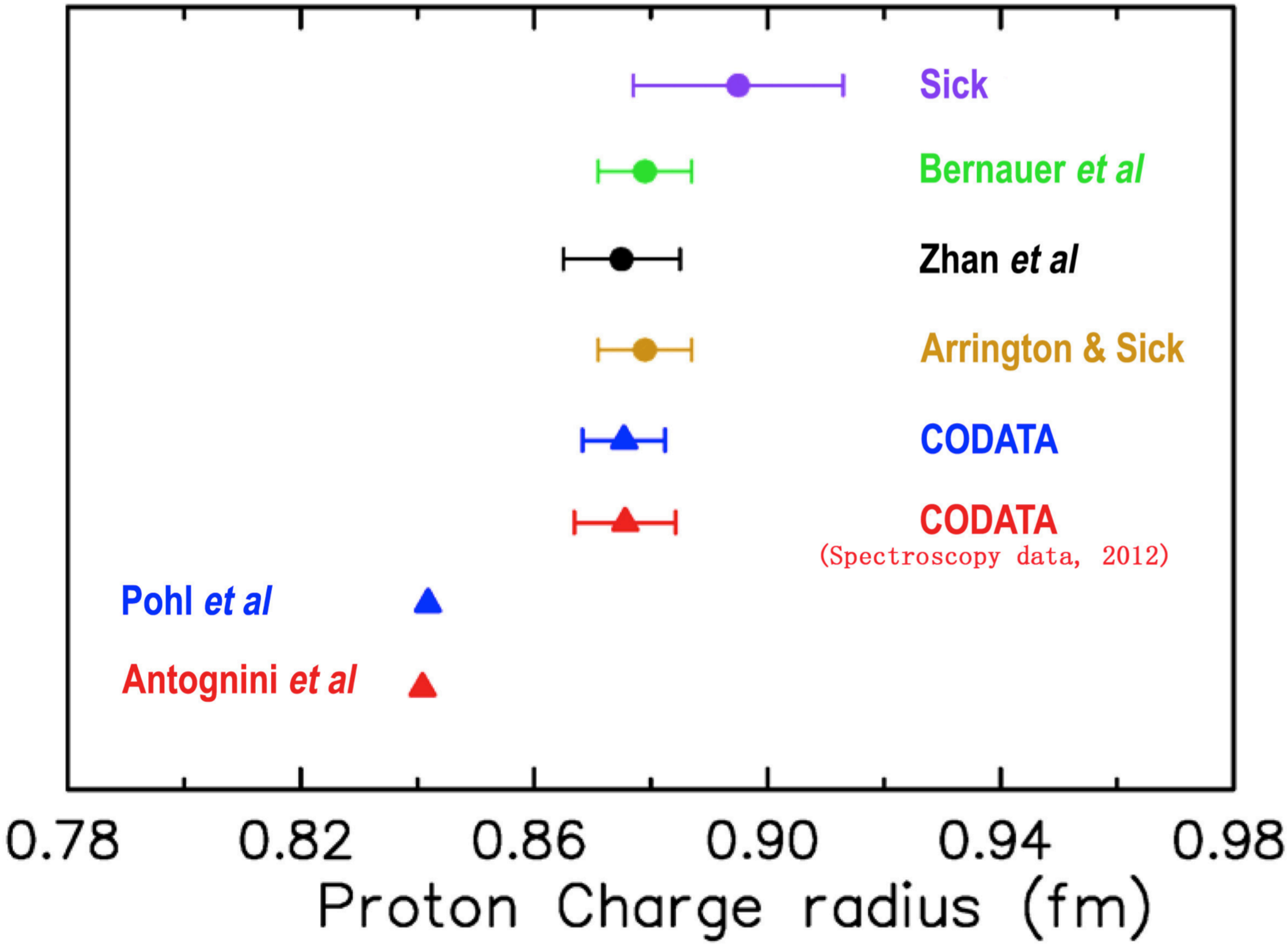
BigBite

- Non-focusing Dipole
- Big acceptance.
  - Δp: 200-900MeV
  - $\Delta\Omega$: 96msr
- PS + Scint. + SH



X. Zhan et al. Phys. Lett. B 705 (2011) 59-64
C. Crawford et al. PRL98, 052301 (2007)

Proton Charge Radius from recent experiments and analyses



Revisits QED Calculations….

An additional 0.31 meV to match CODATA value

Contribution		Value [meV]	Uncertainty [10^{-4} meV]
Uehling		205.0282	
Källen–Sabry		1.5081	
VP iteration		0.151	
Mixed $\mu - e$ VP		0.00007	
Hadronic VP [21,23]		0.011	20
Sixth order VP [24]		0.00761	
Whichmann–Kroll		−0.00103	
Virtual Delbrück		0.00135	
Light–by–light		–	10
Muon self–energy and muonic VP (2^{nd} order)		−0.66788	
Fourth order electron loops		−0.00169	
VP insertion in self energy [17]		−0.0055	10
Proton self–energy [18]		−0.0099	
Recoil [17,43]		0.0575	
Recoil correction to VP (one–photon)		−0.0041	
Recoil (two–photon) [19]		−0.04497	
Recoil higher order [19]		−0.0096	
Recoil finite size [32]		0.013	10
Finite size of order $(Z\alpha)^4$ [32]	$-5.1975(1)\, r_{\mathrm{p}}^2$	−3.979	(620)
Finite size of order $(Z\alpha)^5$	$0.0347(30)\, r_{\mathrm{p}}^3$	0.0232	(20)
Finite size of order $(Z\alpha)^6$		−0.0005	
Correction to VP	$-0.0109\, r_{\mathrm{p}}^2$	−0.0083	
Additional size for VP [19]	$-0.0164\, r_{\mathrm{p}}^2$	−0.0128	
Proton polarizability [18,33]		0.015	40
Fine structure $\Delta E(2P_{3/2} - 2P_{1/2})$		8.352	10
$2P_{3/2}^{F=2}$ hyperfine splitting		1.2724	
$2S_{1/2}^{F=1}$ hyperfine splitting [42], (−22.8148/4)		−5.7037	20

Evaluation by Jentschura, Annals Phys. 326, 500 (2011)
Recent summary by A. Antognini et al., arXiv:1208.2637

Birse and McGovern, arXiv:1206.3030
0.015(4) meV (proton polarizability)

J.M. Alarcon, et al. 1312.1219
0.008 meV

G.A. Miller, arXiv:1209.4667

New experiments at HIGS and Mainz on proton polarizabilities

Revisits of e-p scattering data (just 2015)

- Re-analysis of existing proton form factor data
  - D. W. Higinbotham, arXiv:1510.01293: two parameter dipole form fit describes the data at both low Q^2 and high Q^2 well, and the result is consistent with PSI value
  - K. Griffioen, C. Carson, S. Maddox, arXiv:1509.06676: re-analysis of Mainz data, focusing on the low Q^2 part with a polynomial form fit.
  - M. Horbatsch and E. A. Hessels, arXiv:1509.05644: re-analysis of Mainz data, simple fits (one-parameter model, dipole model, linear model) for low Q2 data, and spline extension to high Q2 data, these fits can all describe data well, but the extracted radius varies from 0.84 ~ 0.89 fm. So current data is not able to resolve the puzzle.
  - J. Arrington, arXiv:1506.00873: re-analysis of world data, found the previous scattering results might underestimate the uncertainty.
  - **Distler, Walcher, and Bernauer, arXiv1511.00479**

All these studies emphasize even more the importance of low Q^2 e-p scattering data

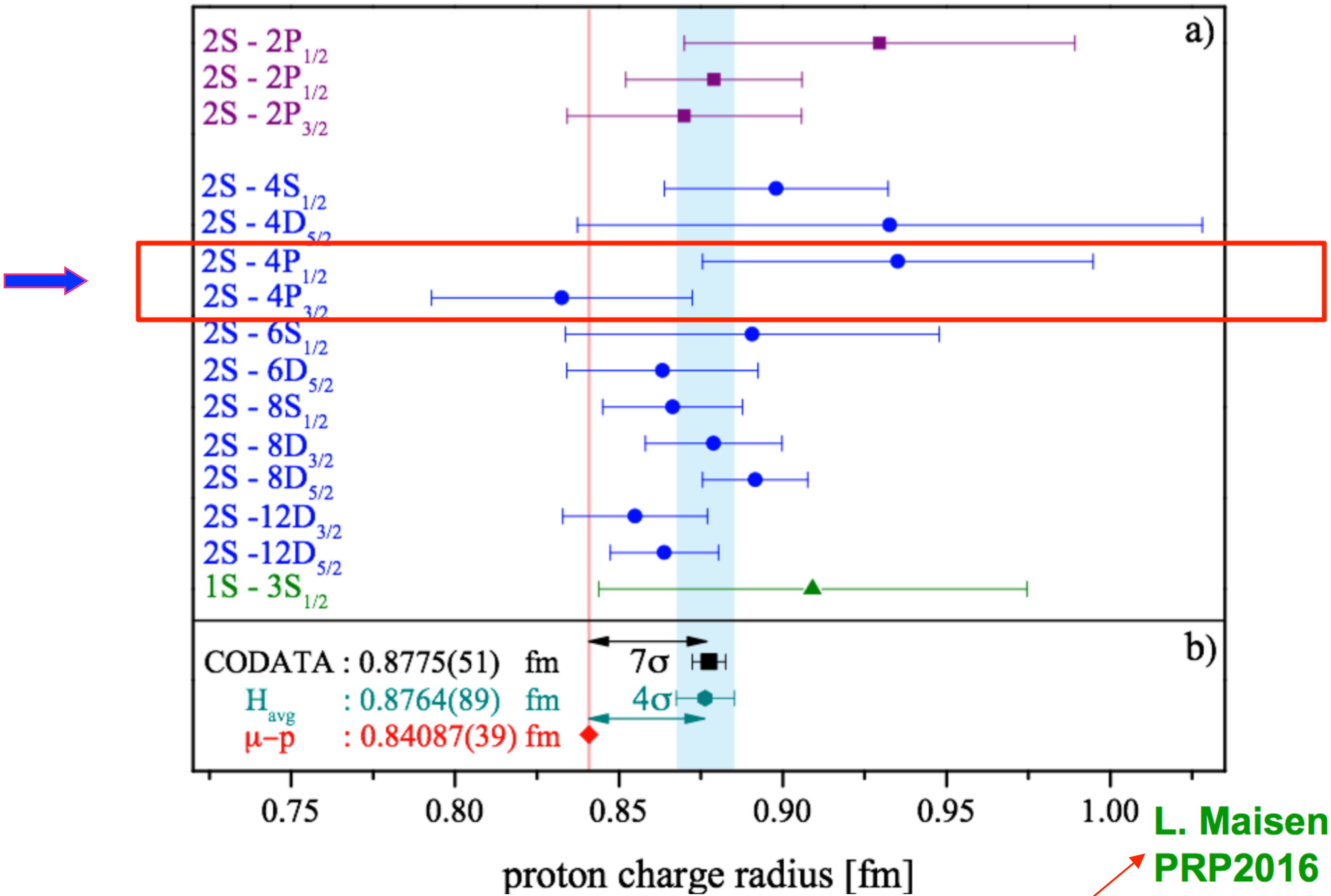
New Physics or what? - Incomplete list

- New physics: new particles, Barger et al., Carlson and Rislow; Liu and Miller,….New PV muonic force, Batell et al.; Carlson and Freid; Extra dimension: Dahia and Lemos; Quantum gravity at the Fermi scale R. Onofrio;…….
- Contributions to the muonic H Lamb shift: Carlson and Vanderhaeghen,; Jentschura, Borie, Carroll et al, Hill and Paz, Birse and McGovern, G.A. Miller, J.M. Alarcon, Ji, Peset and Pineda….
- Higher moments of the charge distribution and Zemach radii, Distler, Bernauer and Walcher,…..
- J.A. Arrington, G. Lee, J. R. Arrington, R. J. Hill discuss systematics in extraction from ep data, no resolution on discrepancy
- Donnelly, Milner and Hasell discuss interpretation of ep data,………

Discrepancy explained by some but others disagree

- Dispersion relations: Lorentz et al.
- Frame transformation: D. Robson
- **New experiments: Mainz (e-d, ISR), JLab (PRad), PSI (Lamb shift, and MUSE), H Lamb shift**

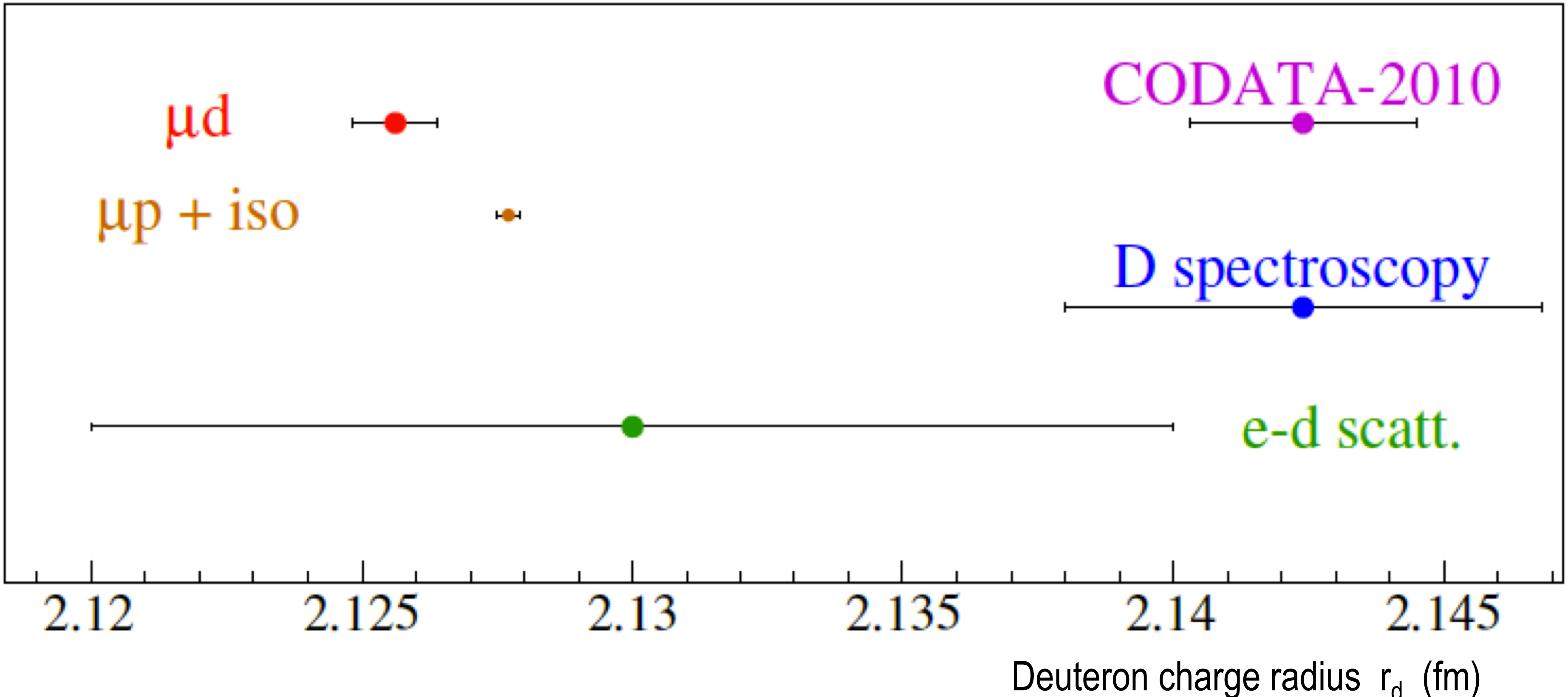
The Proton Radius Puzzle (June 2016)



L. Maisenbacher, PRP2016 (Trento)

- New, preliminary value for r_p was reported in PRP-2016 Workshop (Trento, Italy) from ordinary hydrogen
- Consistent with the muonic-hydrogen result !
- Is the Puzzle solved? No, new measurements are needed (spectroscopy, ep-scattering)

Muonic Deuterium: A New Puzzle?



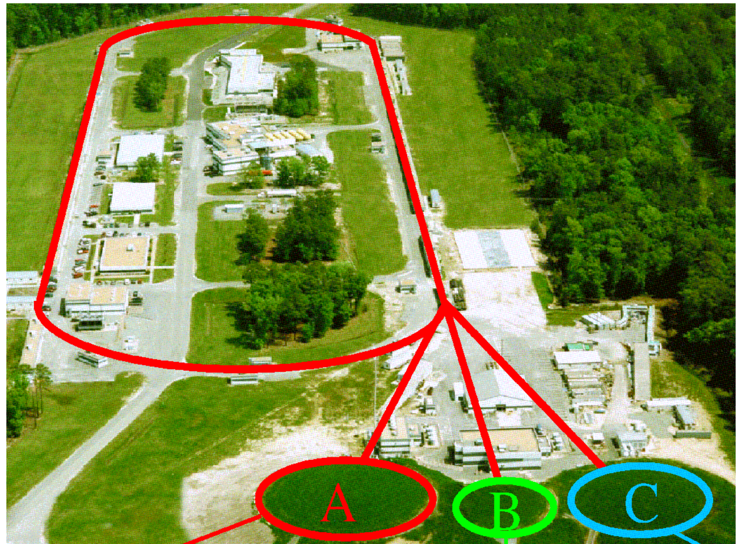
from M. Kohl

- ✓ Presented by J. Krauth at PSAS-2016 (Jerusalem) and PRP-2016 (Trento)
- ➢ Reported in Workshop only, unpublished yet!

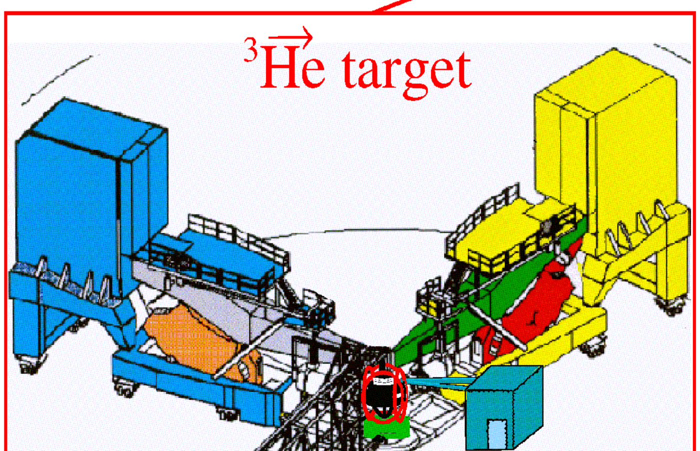
➢ New high precision experiments are needed (both in spectroscopy and scattering)

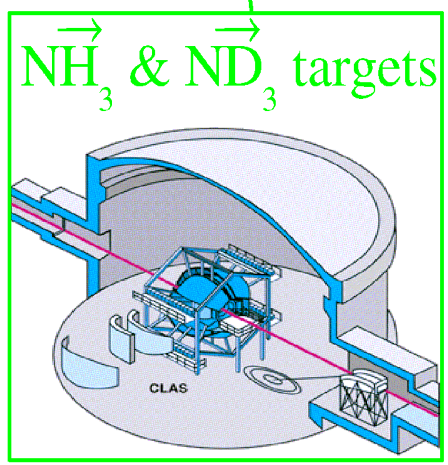
Jefferson Lab Experimental Halls

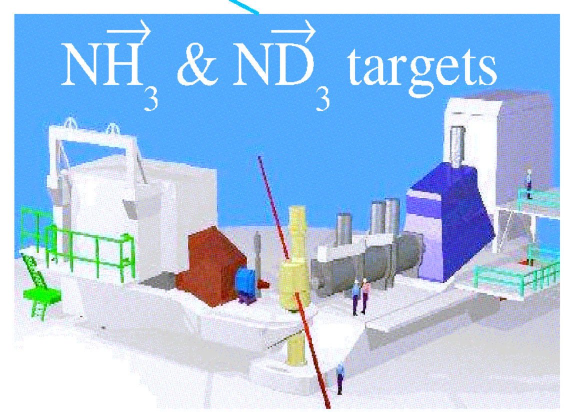
6 GeV polarized
CW electron beam
Pol=85%, 180μA



Upgraded to 12 GeV with a new Hall D







HallA: two HRS’

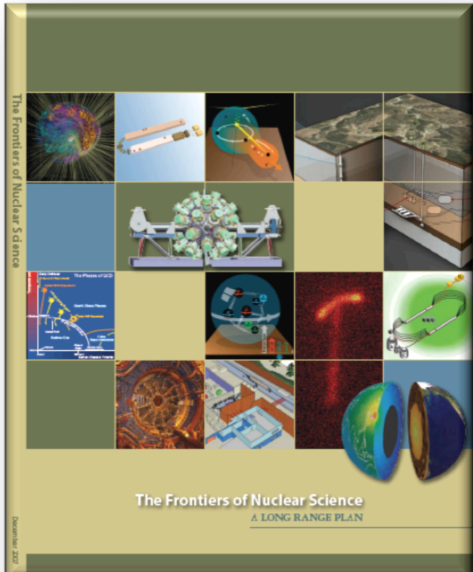
Hall B:CLAS

Hall C: HMS+SOS

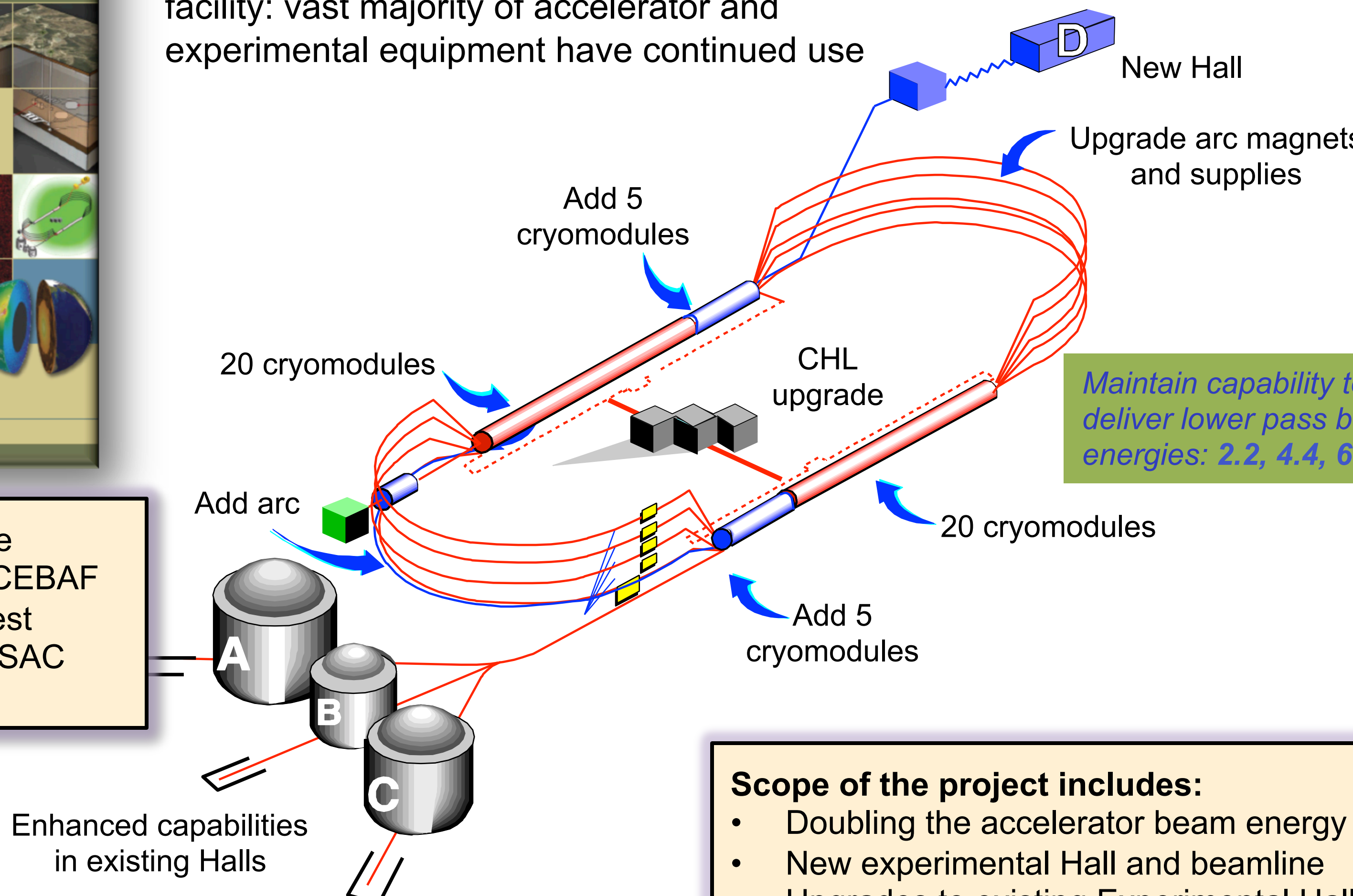
Recoil polarimeter

Recoil polarimeters

12 GeV Upgrade at JLab



Upgrade is designed to build on existing facility: vast majority of accelerator and experimental equipment have continued use



*Maintain capability to deliver lower pass beam energies: **2.2, 4.4, 6.6….***

The completion of the 12 GeV Upgrade of CEBAF was ranked the highest priority in the 2007 NSAC Long Range Plan.

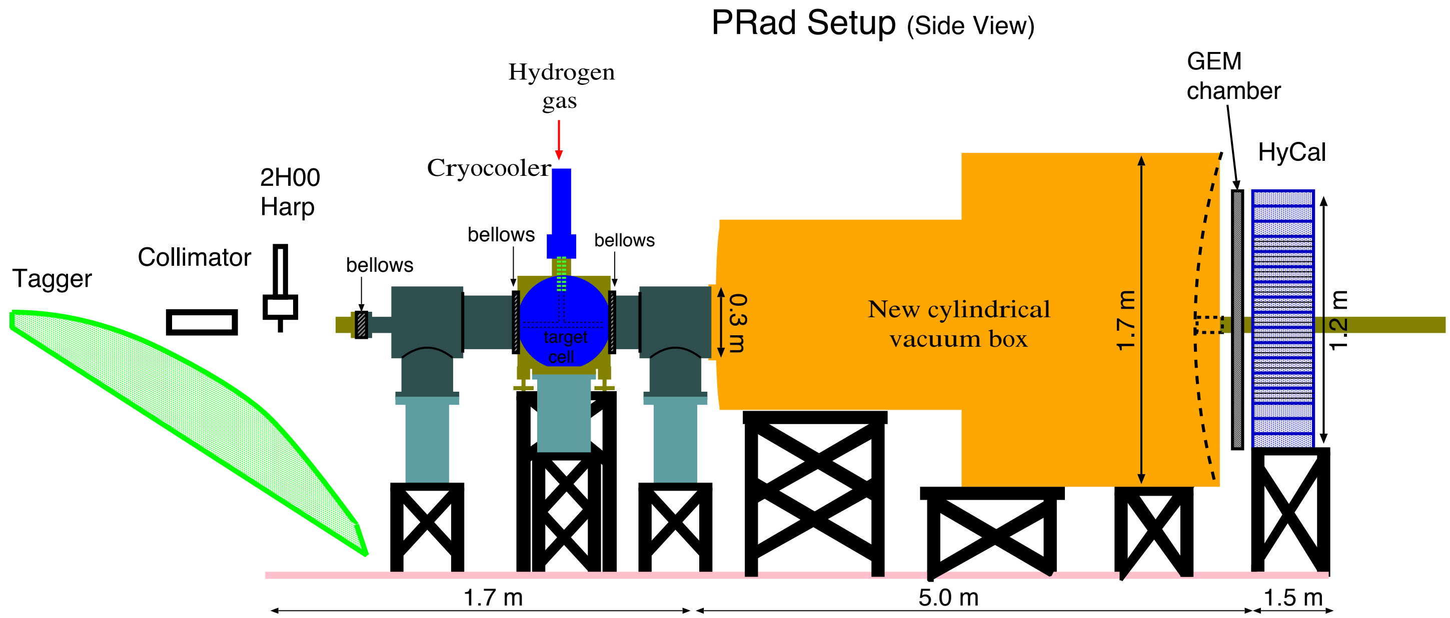
Scope of the project includes:

- Doubling the accelerator beam energy
- New experimental Hall and beamline
- Upgrades to existing Experimental Halls

Solenoidal Large Intensity Device (SoLID) proposed for Hall A

Allison Lung's presentation

PRad Experimental Setup in Hall B at JLab



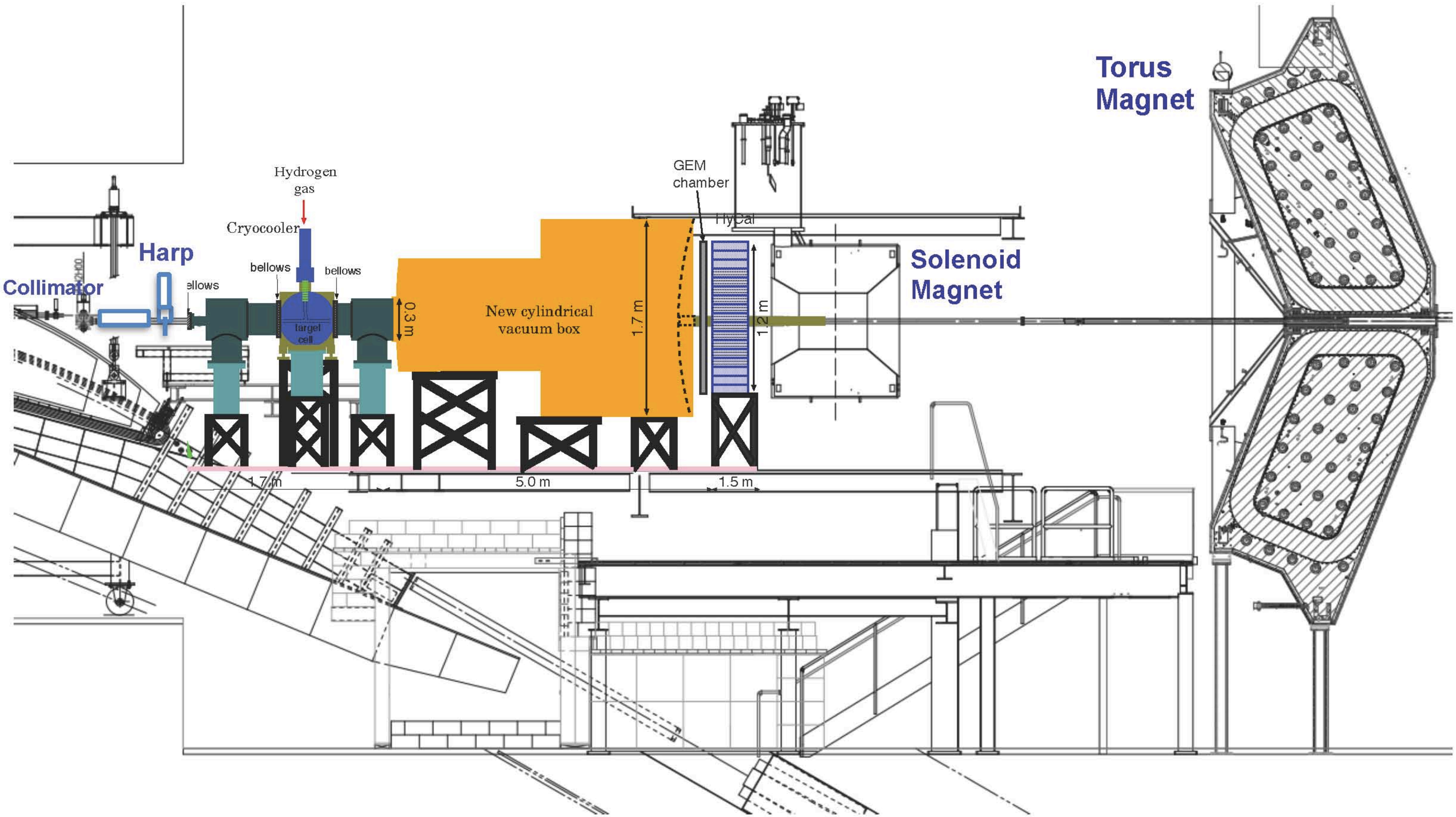
- **High resolution, large acceptance, hybrid HyCal calorimeter (PbWO$_4$ and Pb-Glass)**
- **Windowless H_2 gas flow target**
- **Simultaneous detection of elastic and Moller electrons**
- **Q^2 range of $2\text{x}10^{-4}$ – 0.14 GeV^2**
- **XY – veto counters replaced by GEM detector**
- **Vacuum box**

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

Future sub 1% measurements:
(1) ep elastic scattering at Jlab (PRad)
(2) μp elastic scattering at PSI - 16 U.S. institutions! (MUSE)
(3) ISR experiments at Mainz

Ongoing H spectroscopy experiments

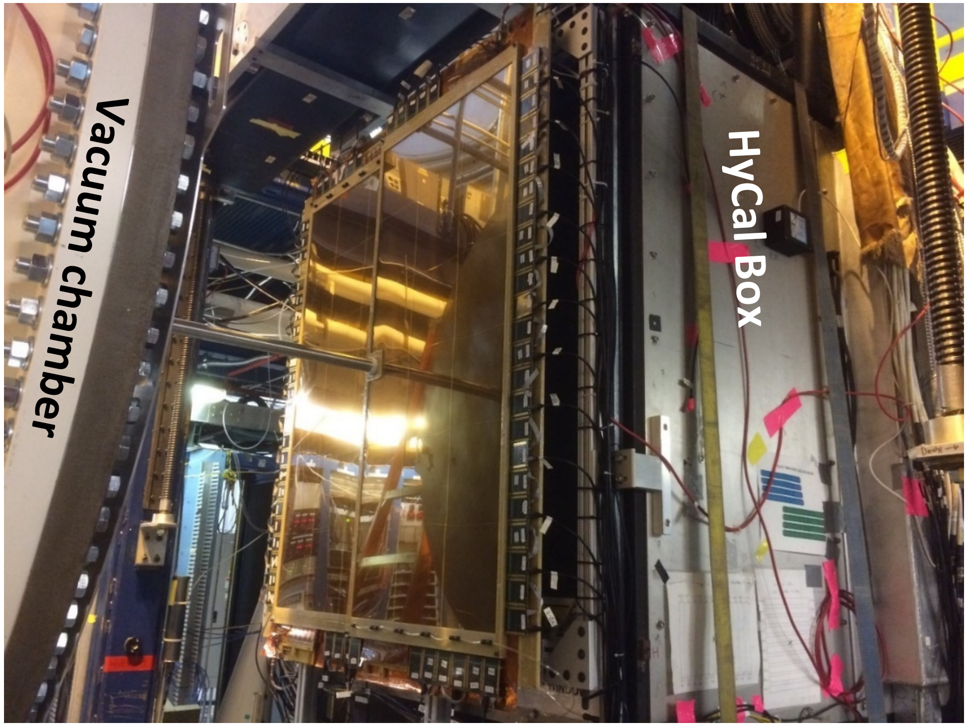
PRad Running Setup

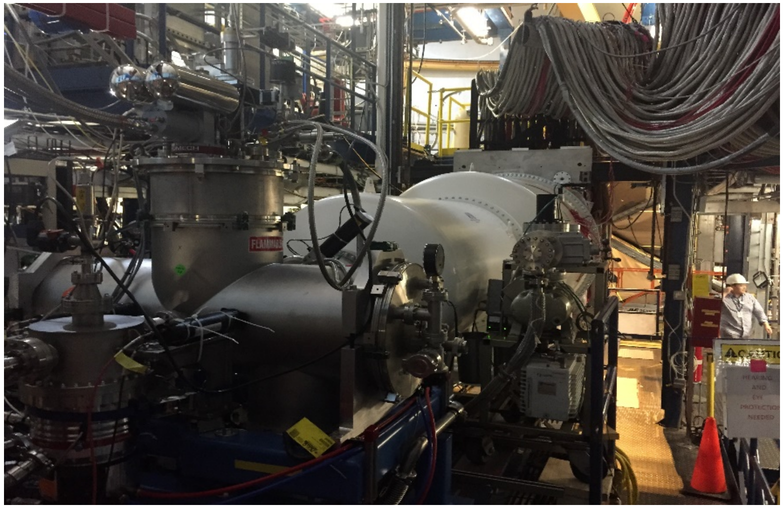


Distance: 2H00 wire harp to Solenoid support frame ~13.7 m

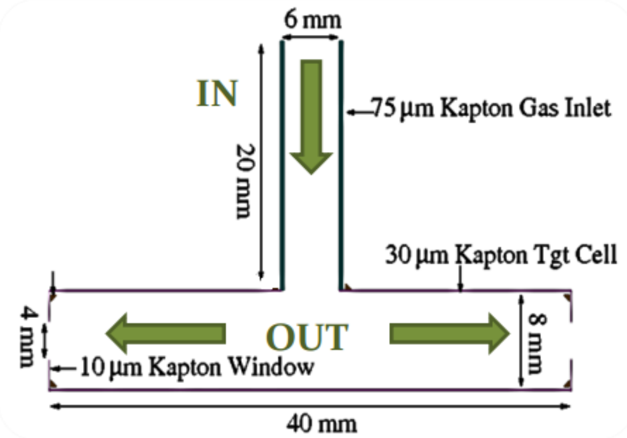
Installation completed on May 11, 2016

(Thanks to Hall B Technical Group (D. Tilles and All))

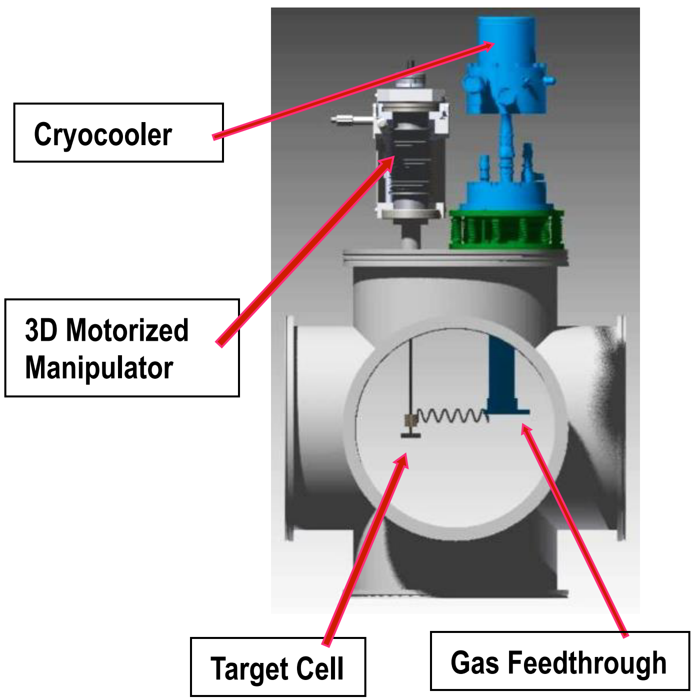




Windowless H_2 Gas Flow Target



- **Target cell (original design):**
  - cell length 4.0 cm
  - cell diameter 8.0 mm
  - cell material 30 µm Kapton
  - input gas temp. 25 K
  - target thickness 1×10^{18} H/cm^2
  - average density 2.5×10^{17} H/cm^3
  - gas mass-flow rate 6.3 Torr-l/s ≈ 430 sccm



- **Target components:**
  - pumping system
  - cryocooler
  - motorized Manipulator
  - chillers for pumps and cryocooler
  - Target and secondary chambers

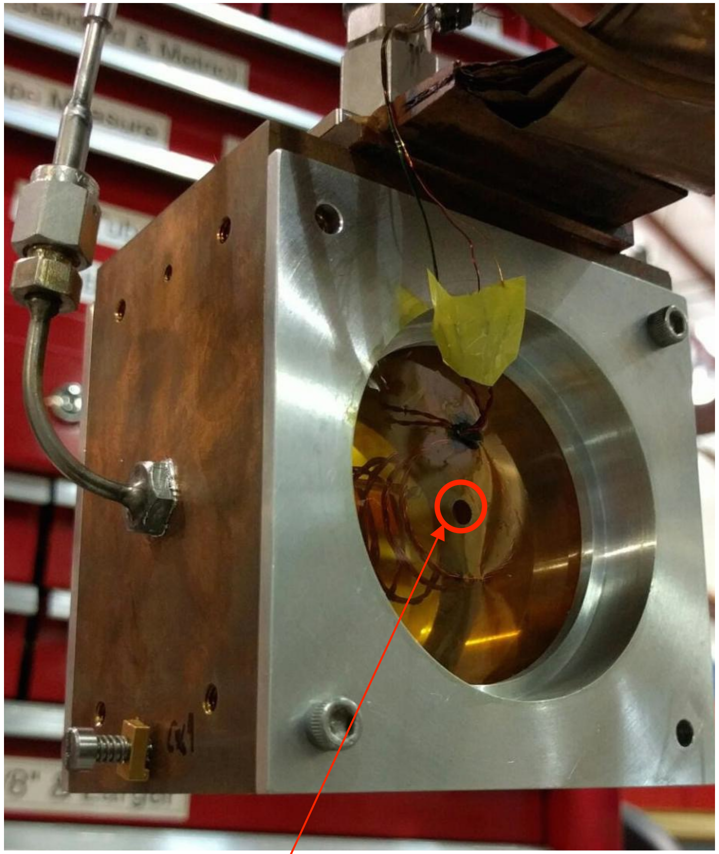
- **Kapton cell**

Target supported by NSF - MRI grant

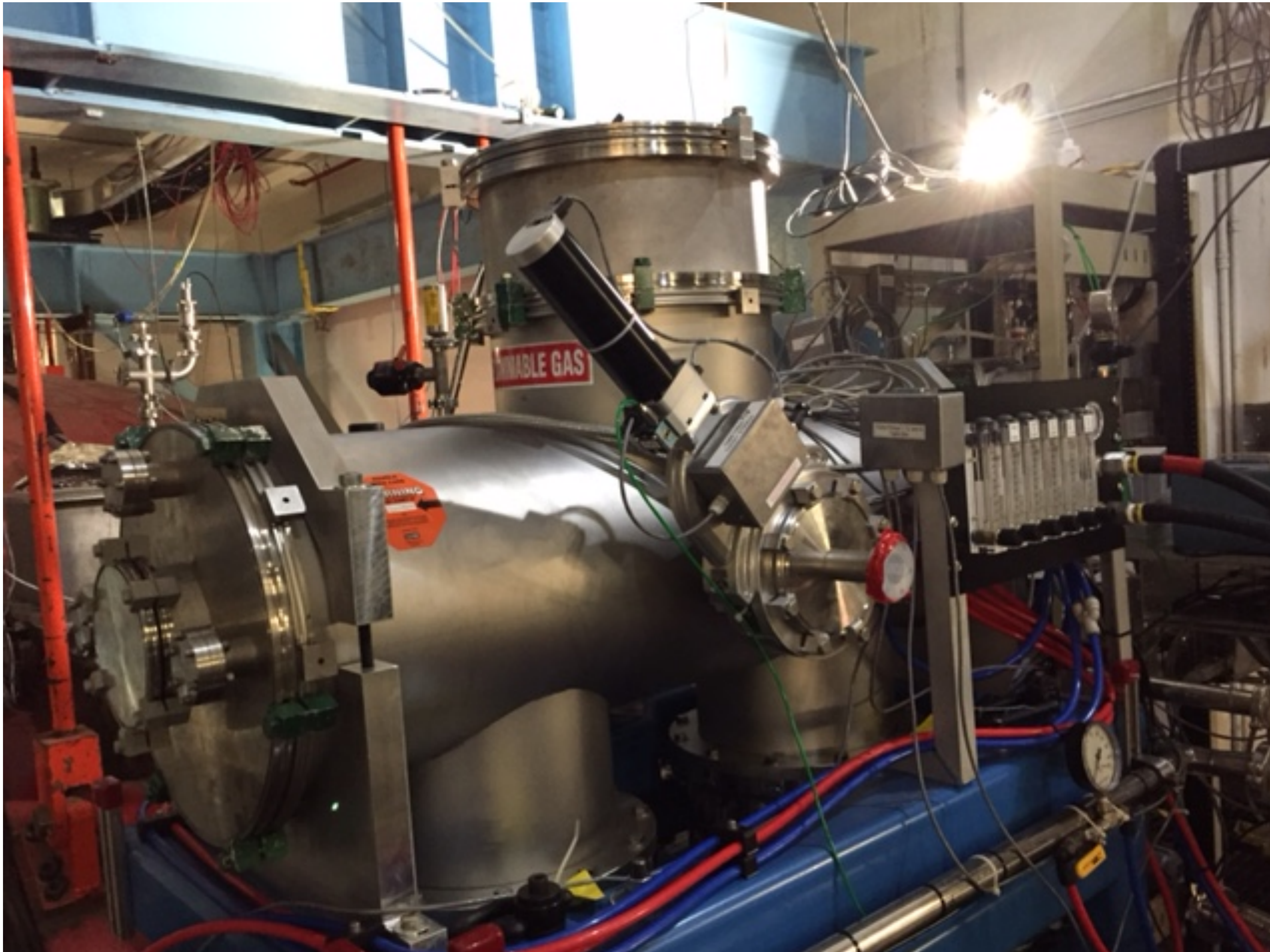
Windowless Gas Flow Target

- Target chamber is differentially pumped with four high speed turbo pumps.
- Cell orifices up- and down-stream
- Four-axis motion system to position the target cell, ~10 m accuracy

- 20 K, 0.5 torr Hydrogen gas inside the cell.
  - Cell pressure vs. chamber pressure
    ~ 200 : 1

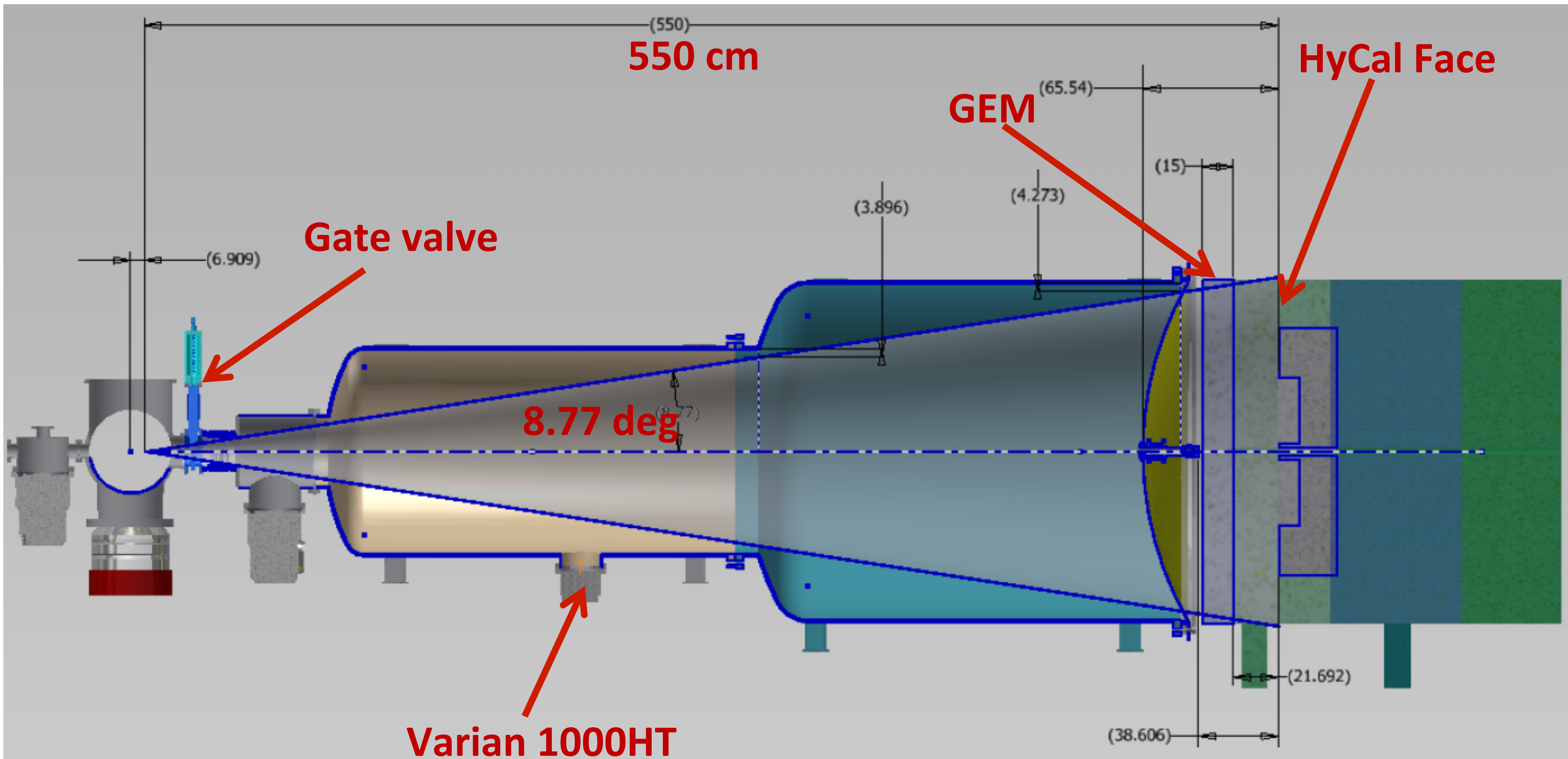


Cell orifice


MABLE GAS

Vacuum Box and GEM

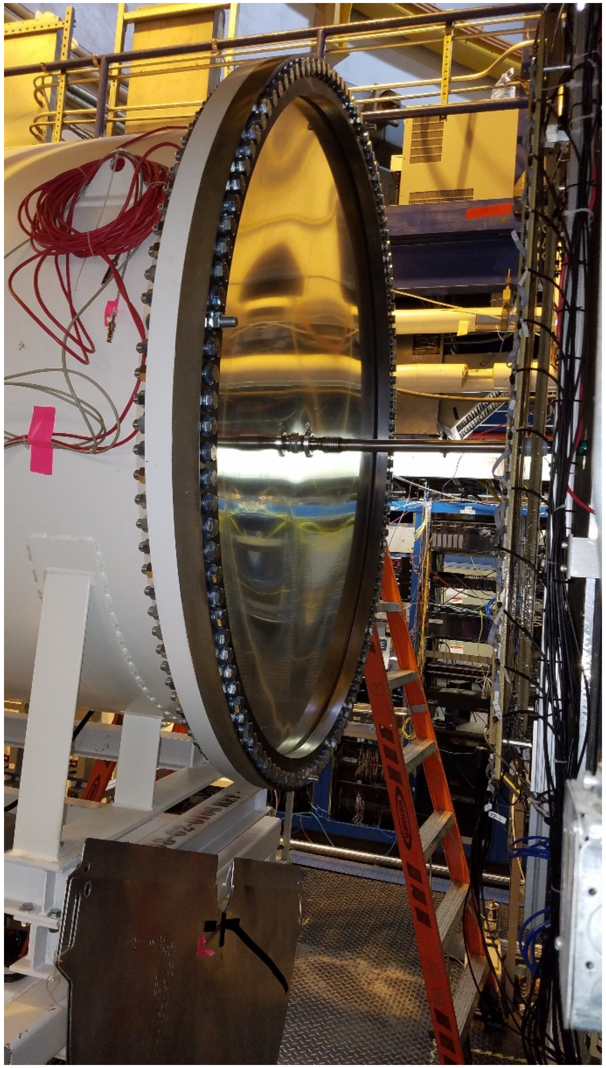
Two-cylinder design for vacuum box
GEM detector to replace veto counter to improve Q2 resolution (particularly with using lead blocks)



▪ **GEM detector funded by DOE**

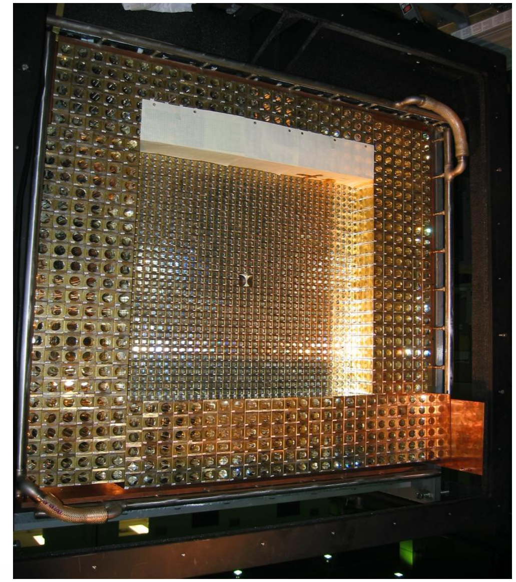
Vacuum Box

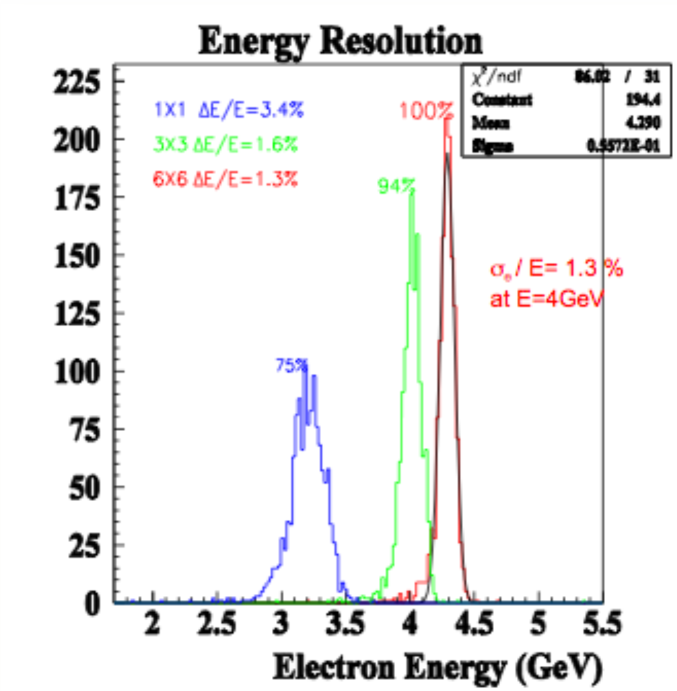
– Engineering design done by Duke/JLab
– Installed in May, 2016
– Connect to beam pipe at the end, no material on the beamline

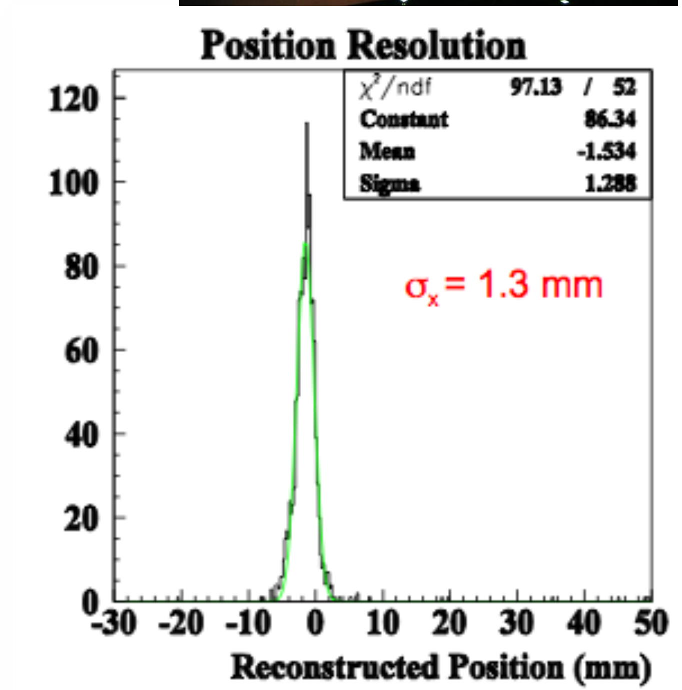


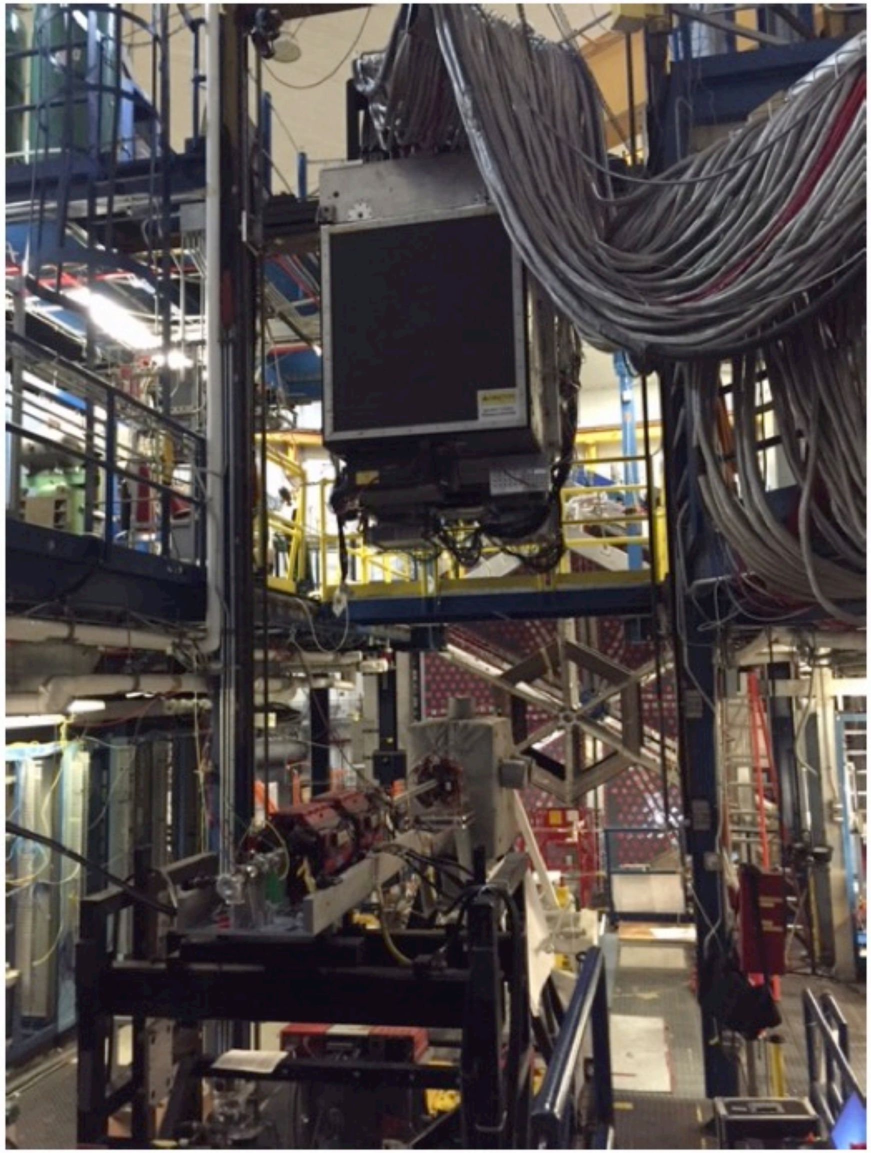
High Resolution Calorimeter

- HyCal calorimeter: 1152 $PbWO_4$ modules arranged in 34x34 matrix in the center, 576 outer Pb-glass modules
- 2.05 x 2.05 cm^2 x18 cm (20 rad. Length)
- ~5.5 m from the target,
- 0.5 sr acceptance





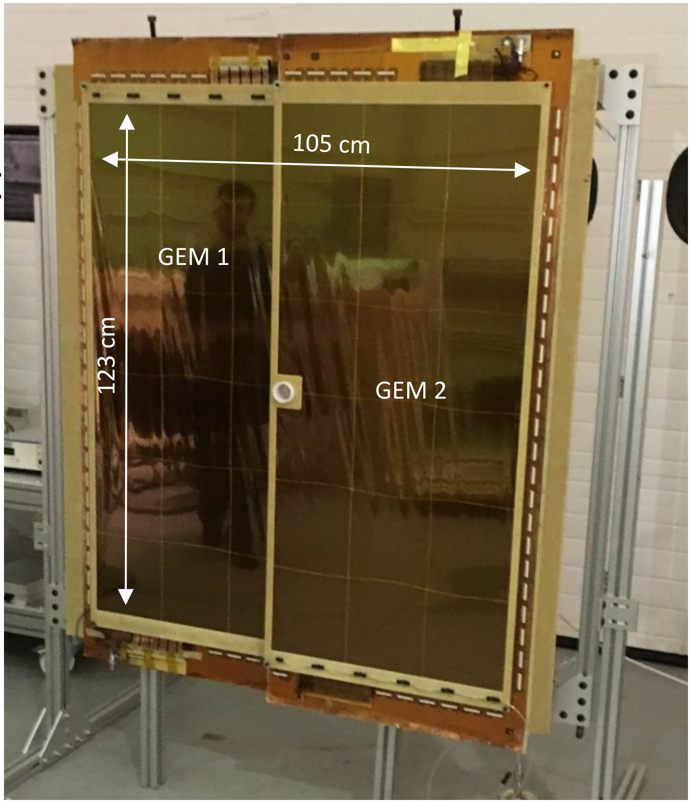




GEM Detectors

- Largest GEM detector ever built in the world. Two chambers to cover the entire region of HyCal
- Two modules overlap in the central part opening for beam pipe
- COMPASS-like strip readout (1.3 m long vertical strips, acceptable capacitance noise level)

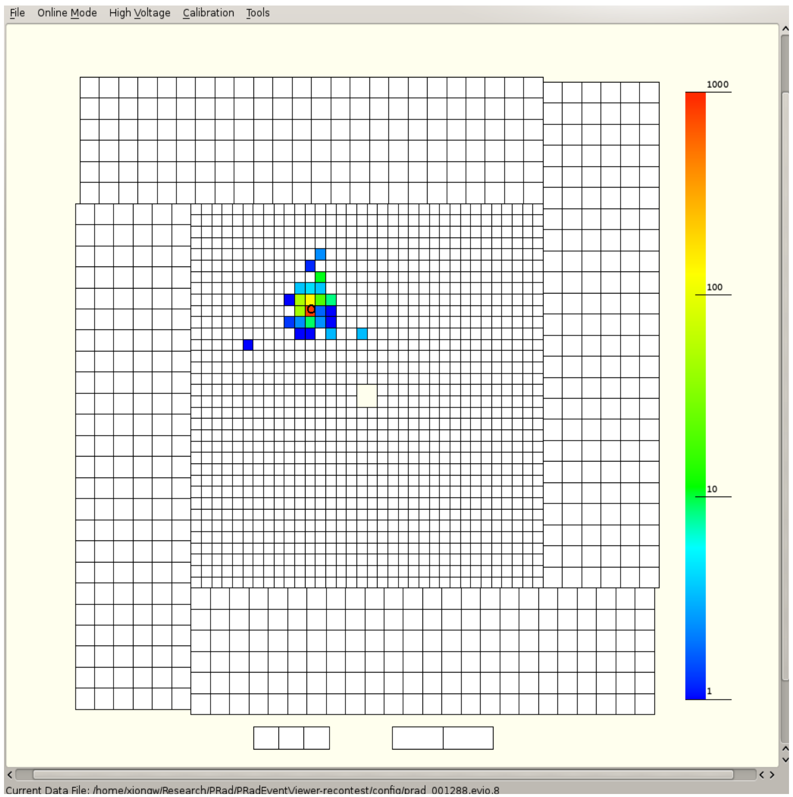
• Mounted on HyCal box

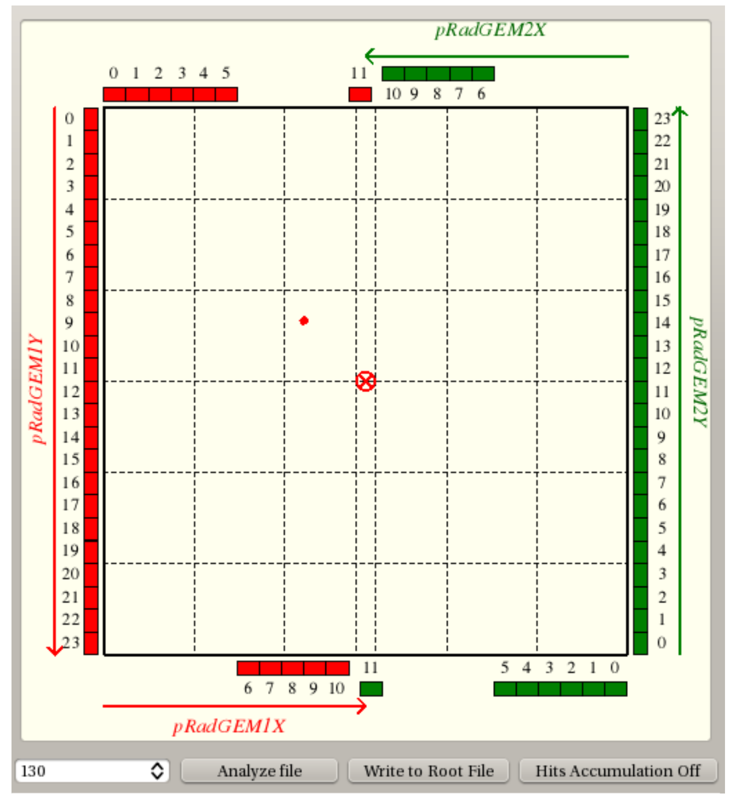


Two modules mounted on the holding frame in PRad GEM configuration before the cosmic run in EEL (March 2016)

HyCal – GEM Matching

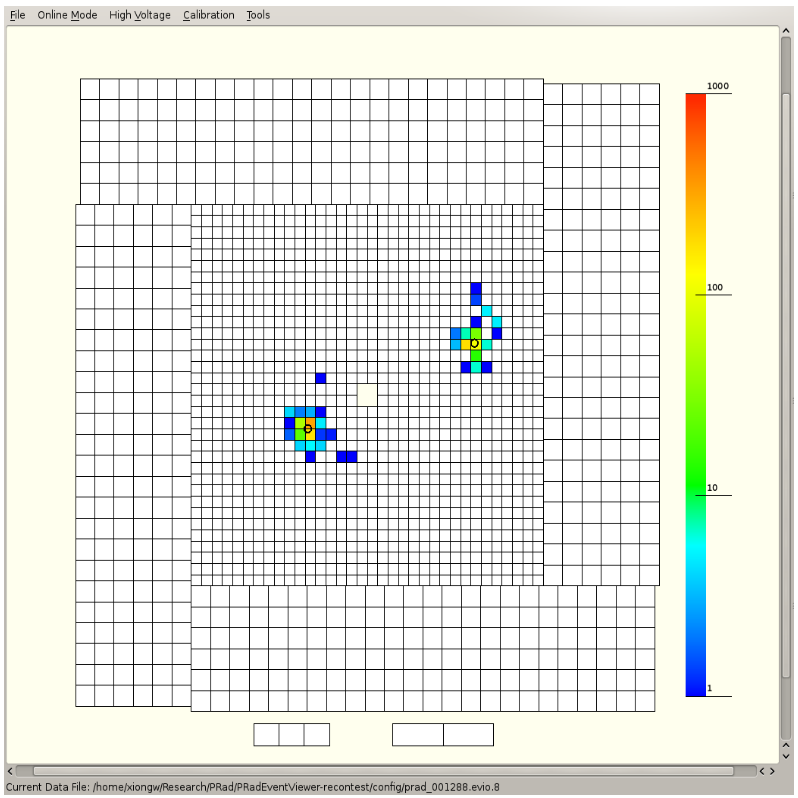
– Online matching, e-p elastic scattering event candidate

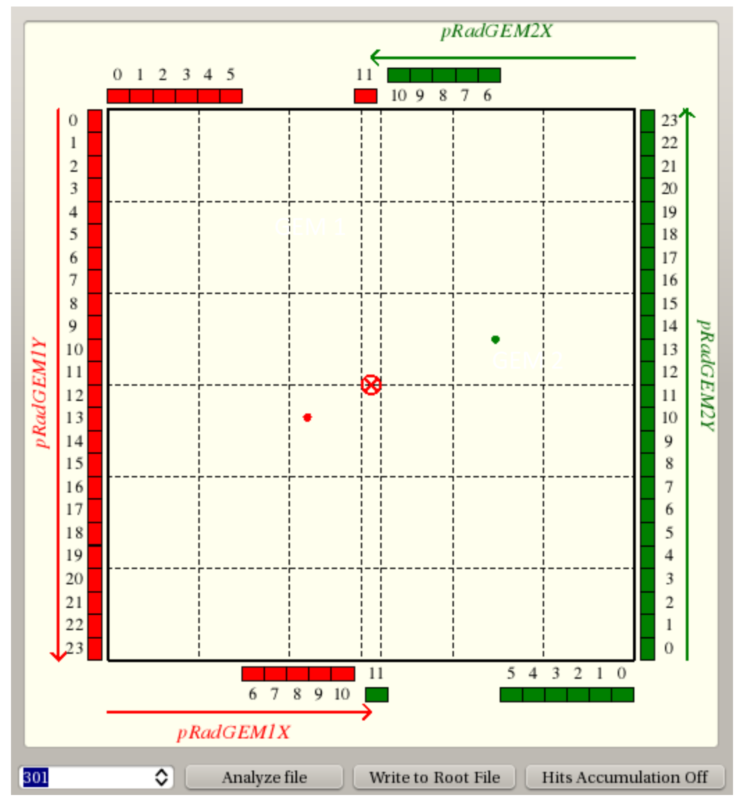




HyCal – GEM Matching

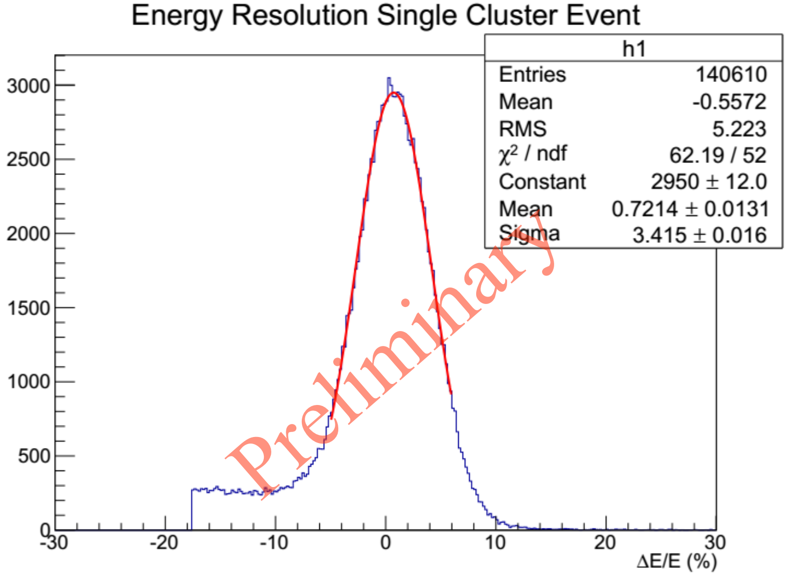
– Online matching, Møller event candidate

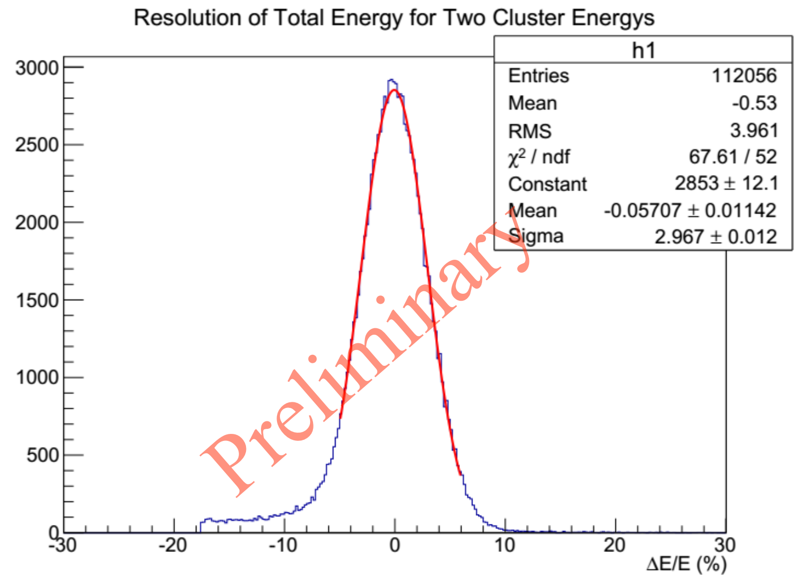




Preliminary analysis

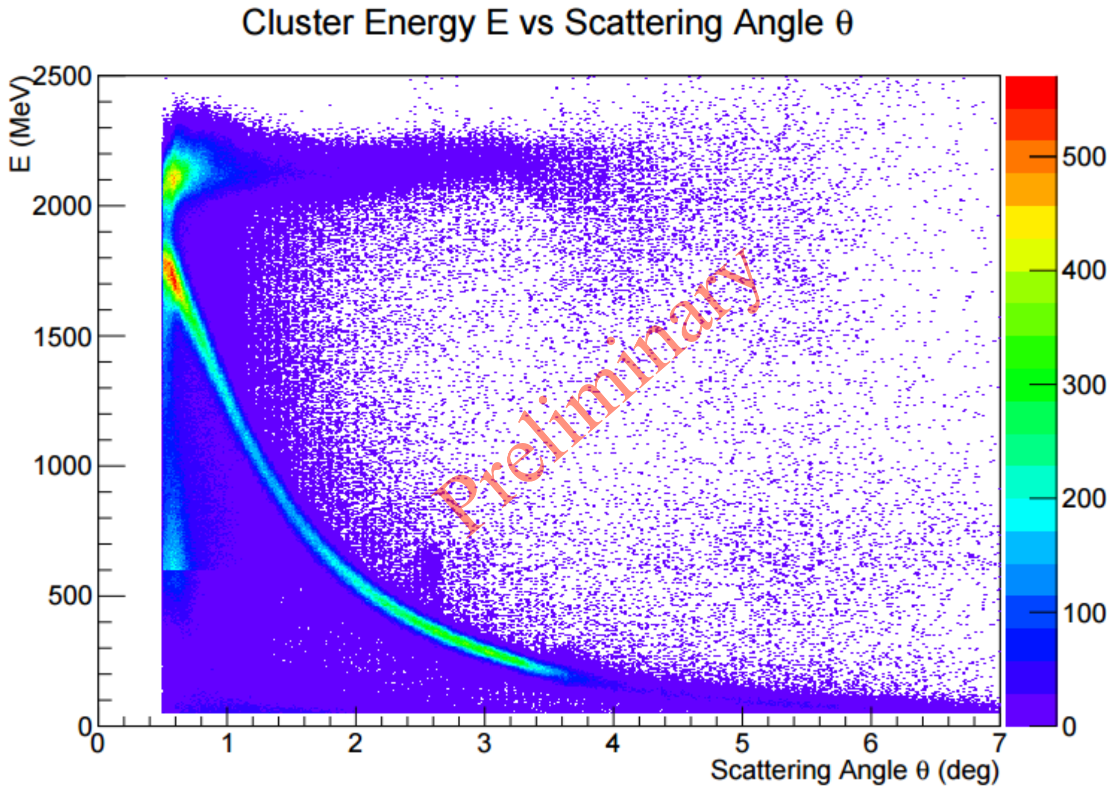
- Energy resolution from 1st iteration of calibration
  - Single cluster event (e-p elastic scat. candidate) ~





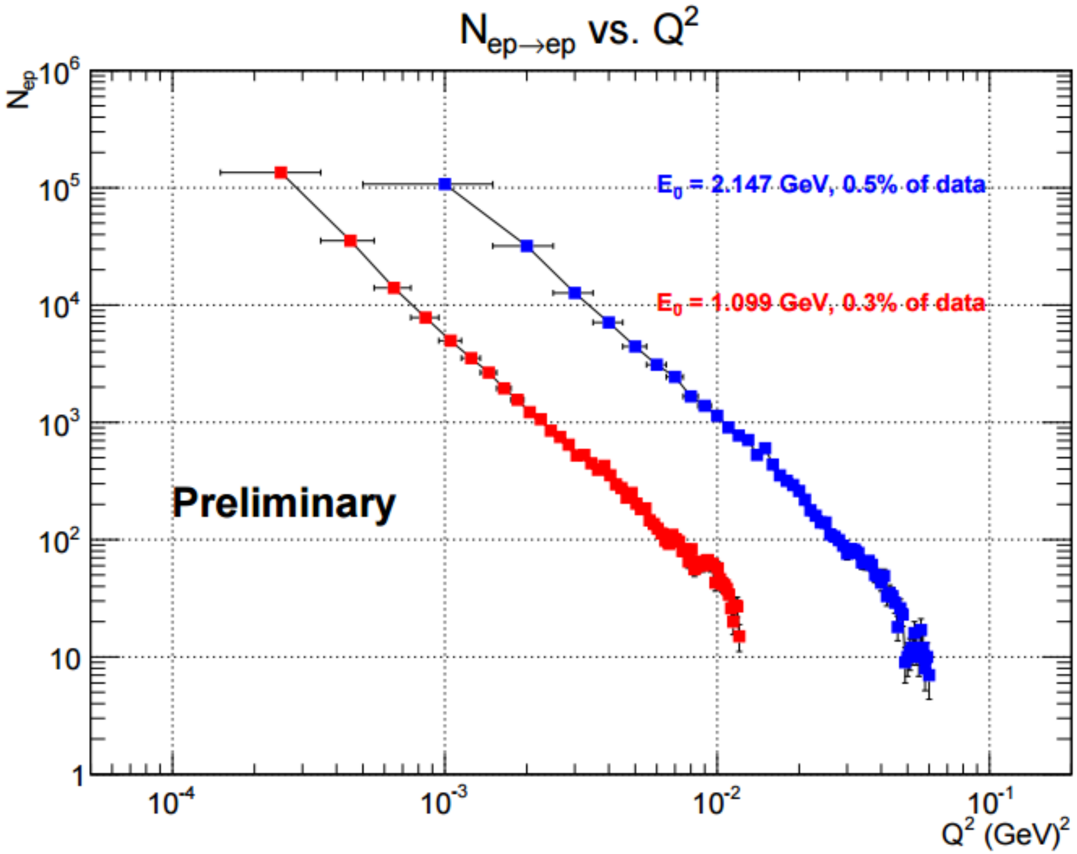
Preliminary analysis

- 2D-map of cluster energy vs. theta (from latest 2.2 GeV data)

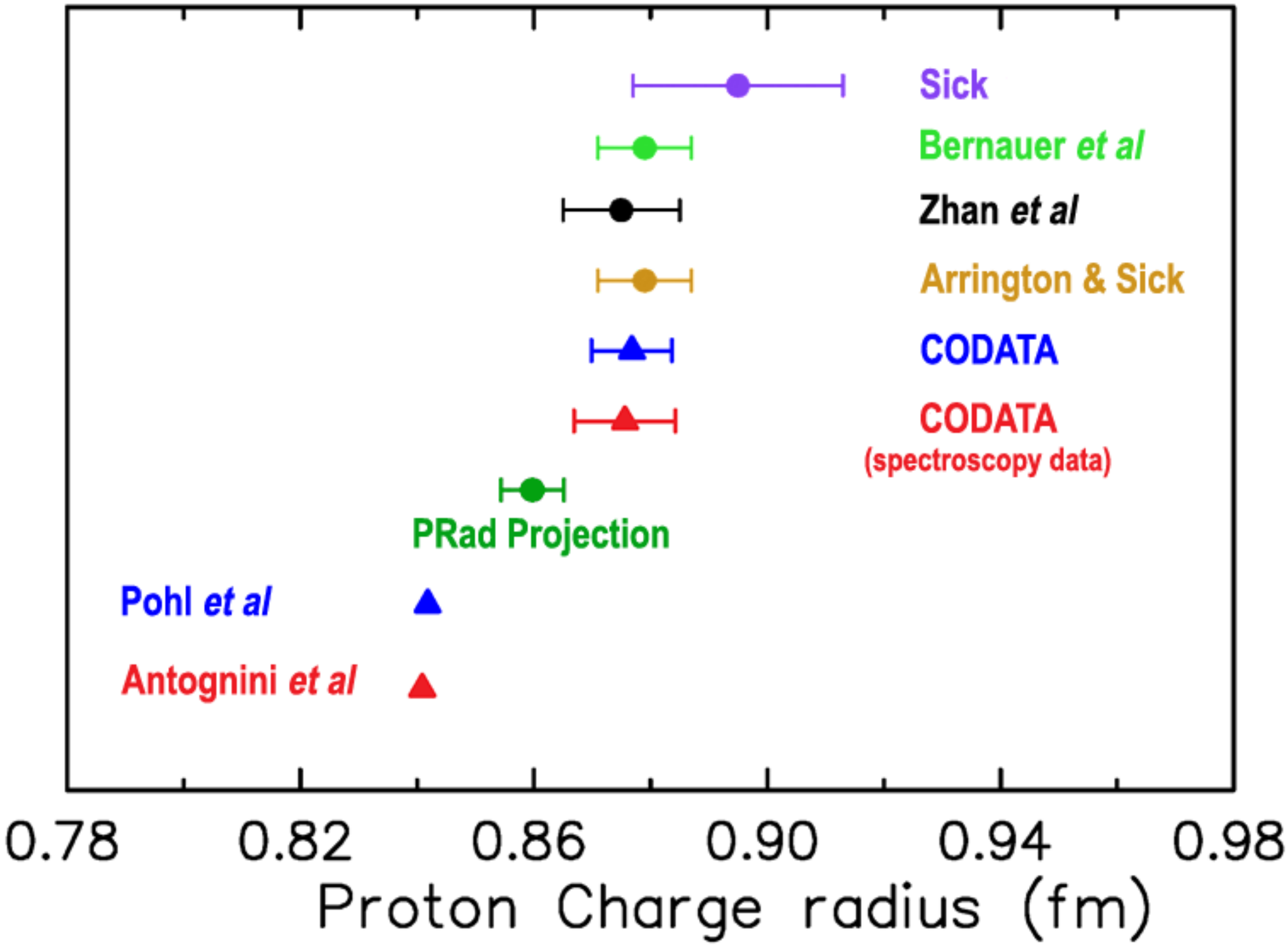


Preliminary analysis

- Q^2 distribution of e-p elastic scattering event candi



PRad Projected Result with world data



Summary and outlook

- Proton charge radius: fundamental quantity important to atomic, nuclear, and particle physics
- Proton charge radius puzzle triggered by muonic hydrogen atom Lamb shift measurements motivated extensive theoretical and experimental activities
- New precision measurement from electron scattering at low Q^2 is **a MUST**
- **PRad: new experiment on e-p elastic scattering uses novel experimental techniques** – completed **data taking in June 2016**
- Stay tuned for more news about proton charge radius

Acknowledgement: the PRad Collaboration
Supported in part by U.S. Department of Energy under contract number DE-FG02-03ER41231, NSF MRI PHY-1229153

Kunshan 昆山

- Population 1.647 million (by 2010)
- Household population is 730,000
- 6,500 foreign companies in the city and 4,200 of them belong to Taiwanese owners
- More than 100,000 Taiwaneses live and work in the city
- GDP in 2013 of 292 billion yuan (US$47.45 billion)
- capital of the world's notebook and tablet sector

Located in Jiangsu Province between Shanghai and Suzhou

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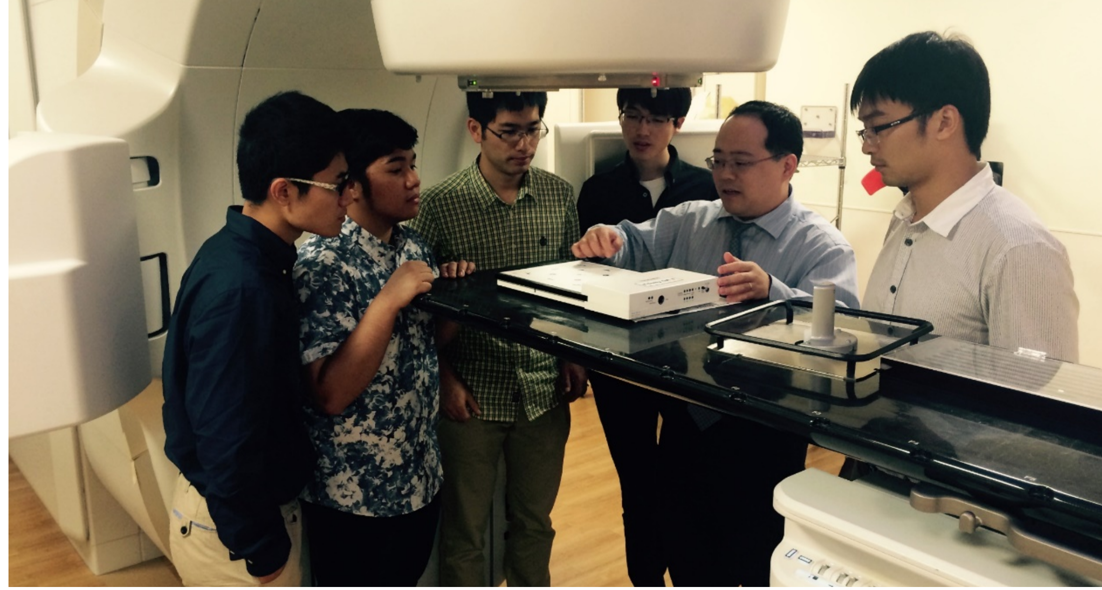
2 years in 2 countries



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