Status of the PRad Experiment
(E12-11-106)

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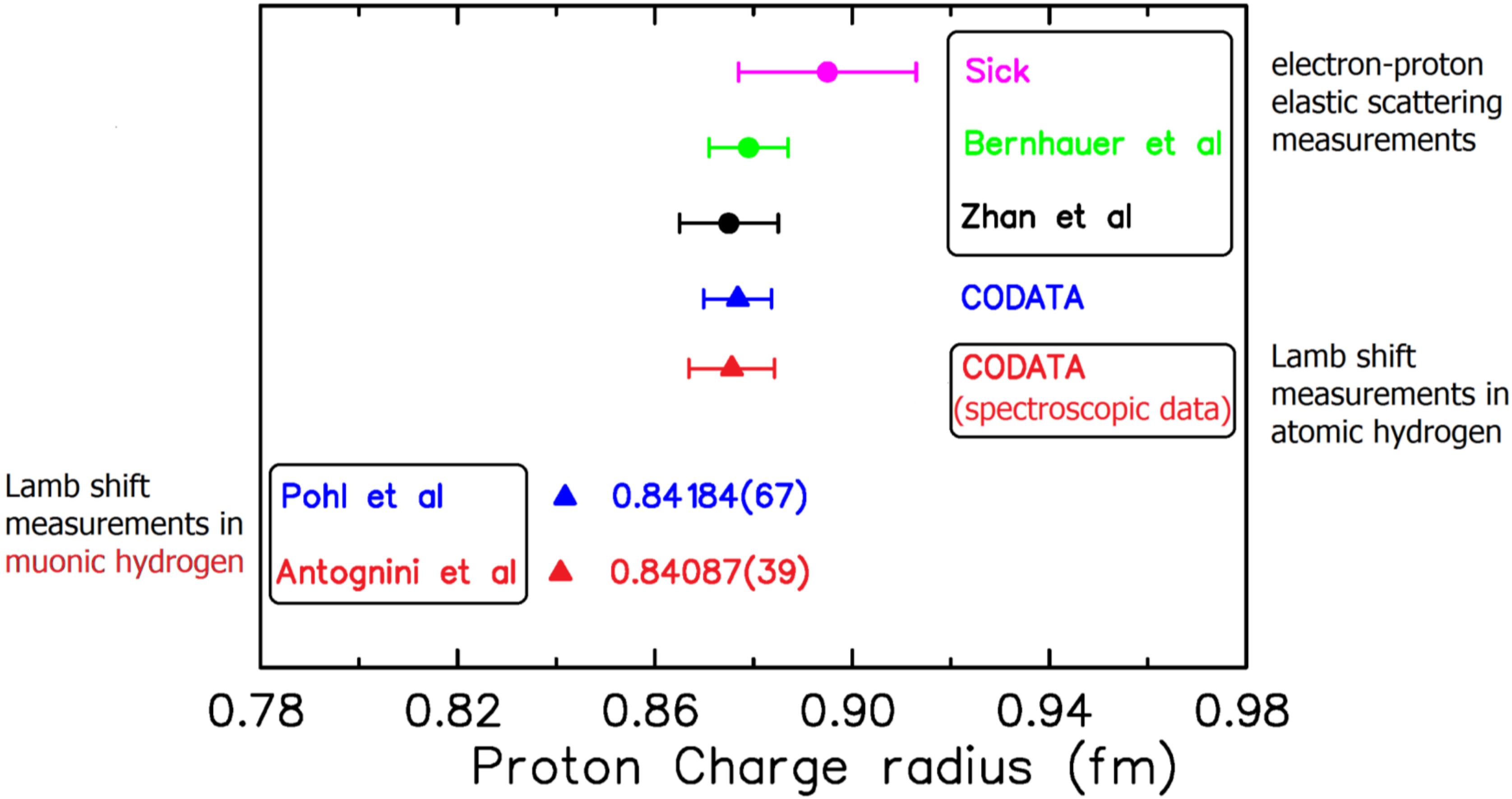
for the PRad collaboration

Outline

- PRad Physics goals
- ep-scattering and the proton radius
- PRad experiment
  - experimental setup
  - development of apparatus
  - current status
- Summary

The Proton Charge Radius Puzzle



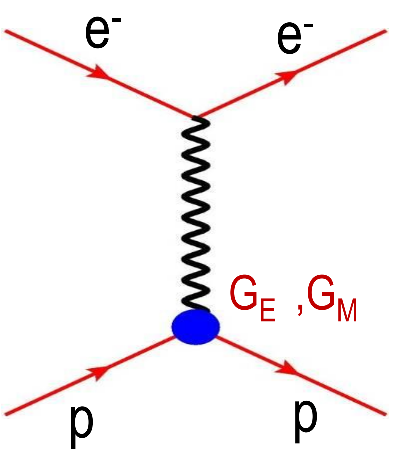
- **New high precision experiments are needed to solve this 7σ discrepancy**

The Proton Charge Radius from $ep \to ep$ Scattering Experiments

- In the limit of first Born approximation the elastic *ep* scattering (one photon exchange):

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

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



- Structureless proton:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} = \frac{\alpha^2\left[1 - \beta^2 \sin^2\frac{\theta}{2}\right]}{4k^2 \sin^4\frac{\theta}{2}}$$

- G_E and G_M were extracted using Rosenbluth separation (or at extremely low Q^2 the G_M can be ignored, like in the PRad experiment)

- The Taylor expansion at low Q^2:

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

✓ Definition of the Proton Radius:

$$< r^2 > = \int \rho(r) r^2 dr$$

✓ Extraction of the Proton Radius:

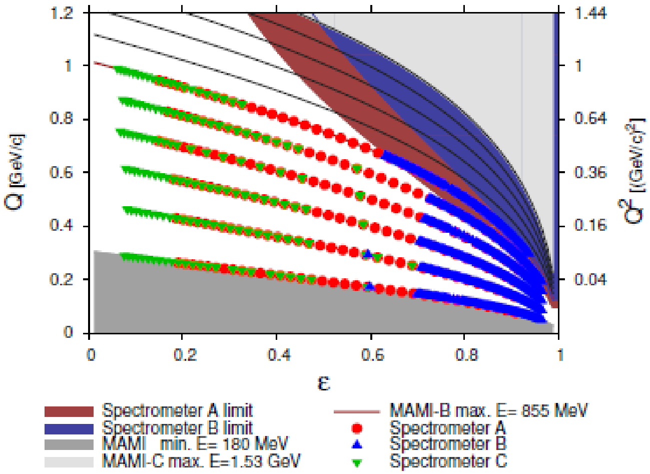
(r.m.s. charge radius given by the slope):

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

An Example: Recent Mainz ep-Experiment (2010)

Three spectrometer facility of the A1 collaboration:

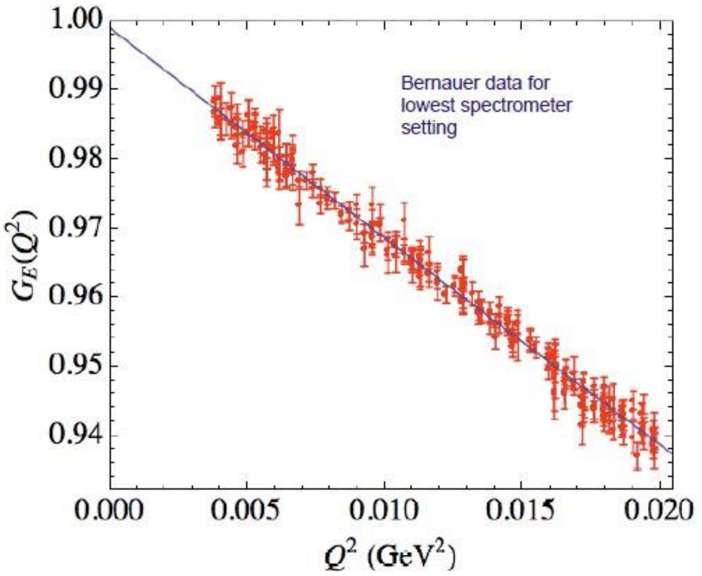
J. Bernauer, PRL 105,242001, 2010



- ✓ Q^2 = [0.004 – 1.0] $(GeV/c)^2$ range
- ✓ Large amount of overlapping data sets (~1400)
- ✓ Statistical error ≤ 0.2%
- ✓ Luminosity monitoring with spectrometer
- ✓ Additional beam current measurements

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

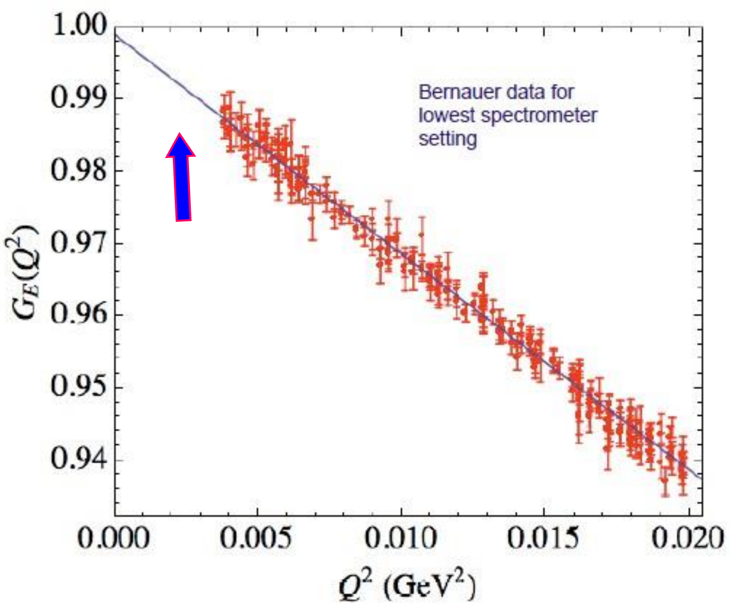
- ✓ Confirms the previous results from *ep→ep* scattering;
- ✓ Consistent with CODATA06 value: (r_p=0.8768(69) fm)



The PRad Experiment (E12-11-106)

- Experimental goals:
  - reach very low Q^2 range (~ 10 times less than the Mainz experiment)
  - reach sub-percent precision in r_p extraction

- Suggested solutions:
  1) Non-magnetic-spectrometer method: use high resolution high acceptance crystal calorimeter
     - reach smaller scattering angles: ($\Theta = 0.7^0 - 3.8^0$) ($Q^2 = 2\text{x}10^{-4} - 8\text{x}10^{-2}$) GeV/c^2
     - essentially, model independent r_p extraction
  2) Simultaneous detection of *ee* → *ee* Moller scattering
     - (best known control of systematics)
  3) Use high density windowless H2 gas flow target:
     - beam background fully under control with high quality CEBAF beam
     - minimize experimental background

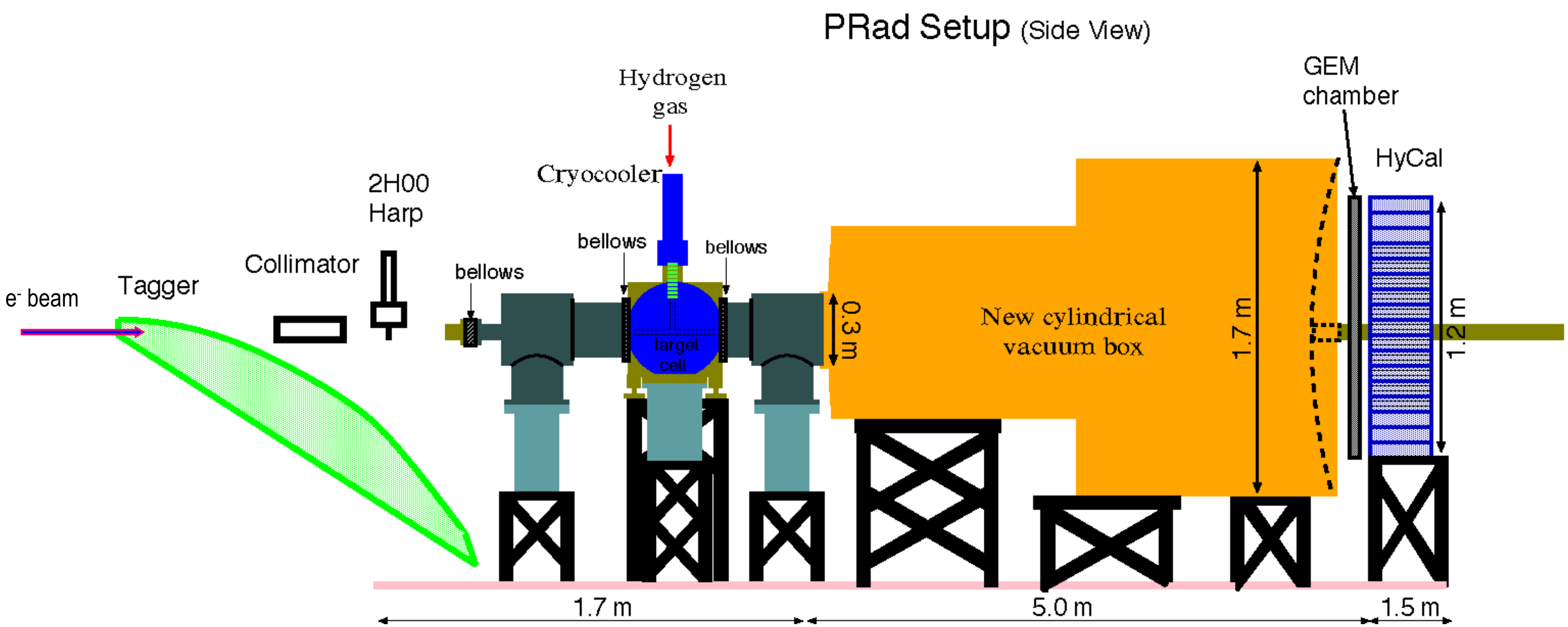


Mainz low Q^2 data set

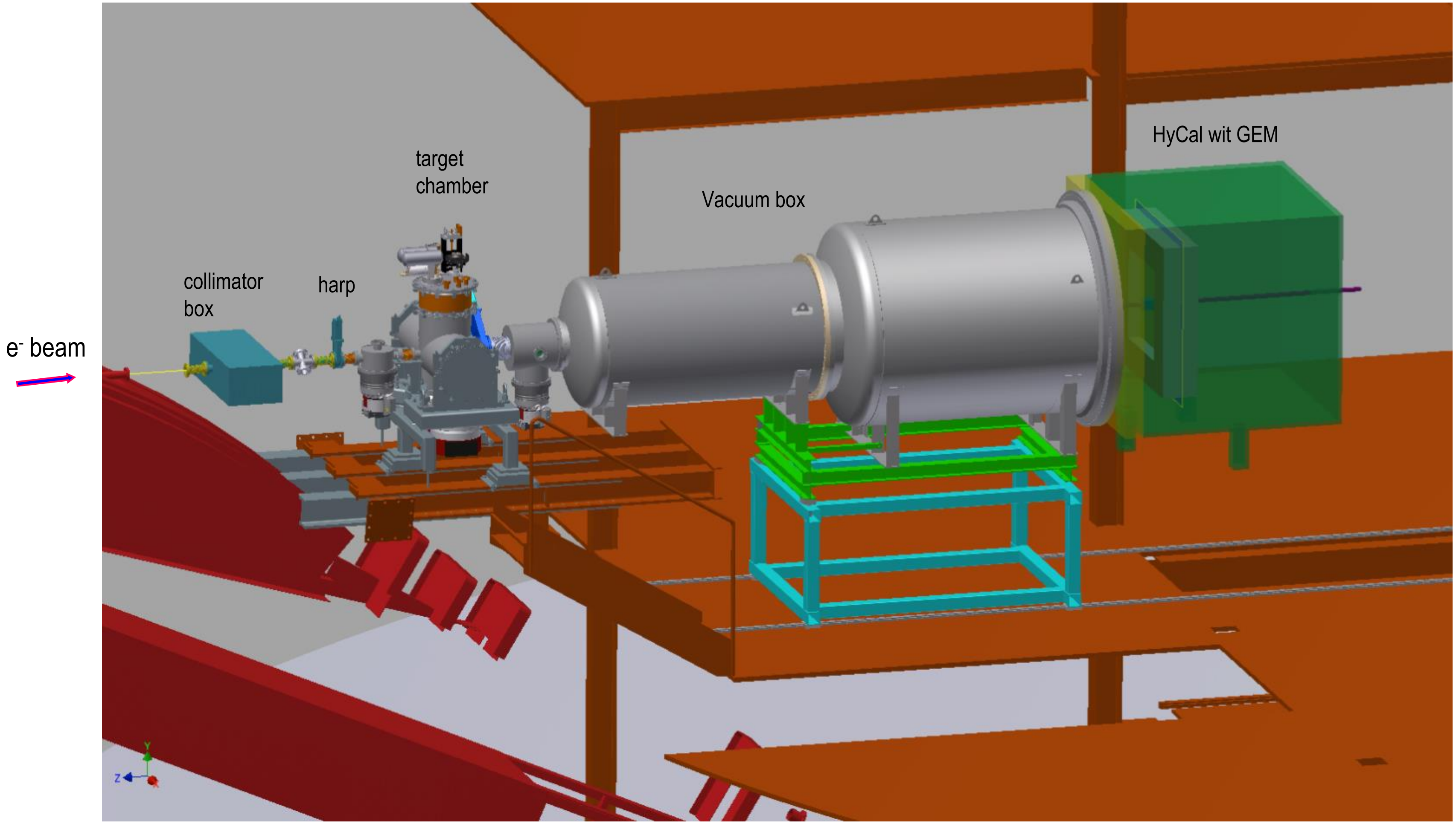
- Two beam energies: E_0 = 1.1 GeV and 2.2 GeV to increase Q^2 range: ($2\text{x}10^{-4} - 8\text{x}10^{-2}$) GeV/c^2
- Will reach sub-percent precision in r_p extraction (0.6% total)
- Approved by PAC39 (June, 2012) with high “A” scientific rating

PRad Experimental Setup (schematics)

- Main detectors and elements:
  - windowless H_2 gas flow target
  - PrimEx HyCal calorimeter
  - vacuum box with one thin window at HyCal end
  - X,Y – GEM detector on front of HyCal
- Beam line equipment:
  - standard beam line elements (0.1 – 10 nA)
  - photon tagger for HyCal calibration
  - collimator box (6.4 mm collimator for photon beam, 12.7 mm for e^- beam halo "clean-up")
  - Harp 2H00
  - pipe connecting Vacuum Window through HyCal



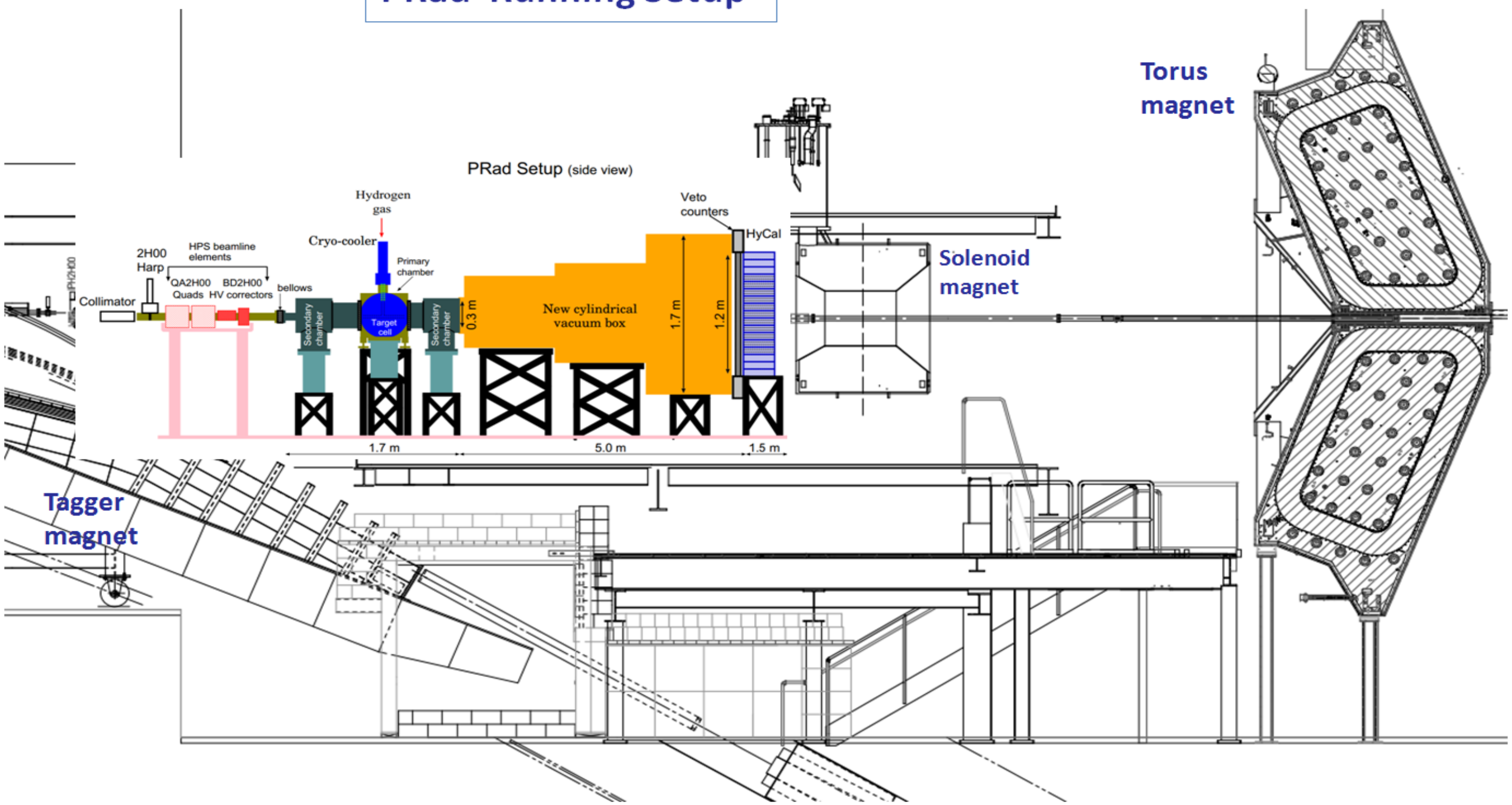
PRad Experimental Setup (3D view)



PRad Running Configuration in Hall B (suggested)

- Footprint of PRad setup: ~ 8.2 x 1.7 m^2
- Installation in parallel with CLAS12 work/assembly in Hall B
- Engineering and Physics runs during evenings/nights and over weekends

PRad Running Setup

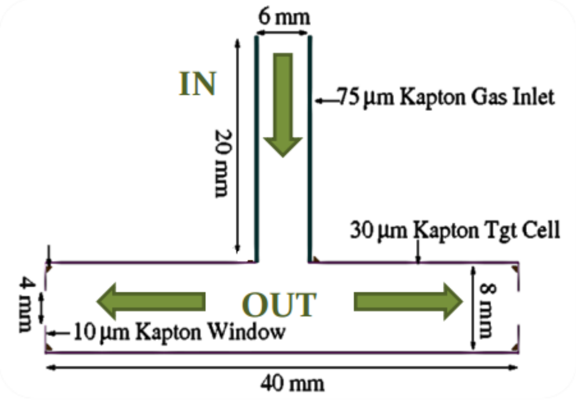


Distance between the HPS Quads' girder and the center of the Hall is ~10.5 m

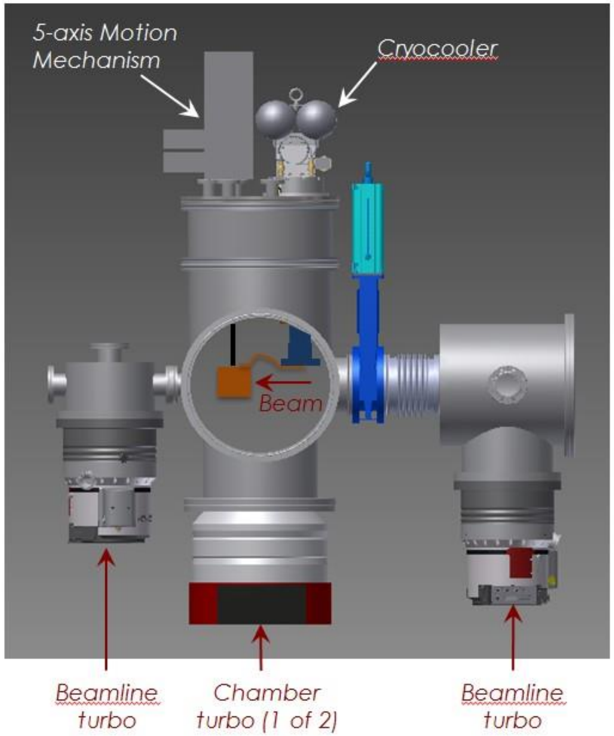
Windowless H_2 Gas Flow Target

- Target proposal specs:

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
Cell pressure	0.6 torr
Vacuum in target chamber	$\sim 5 \times 10^{-3}$ torr



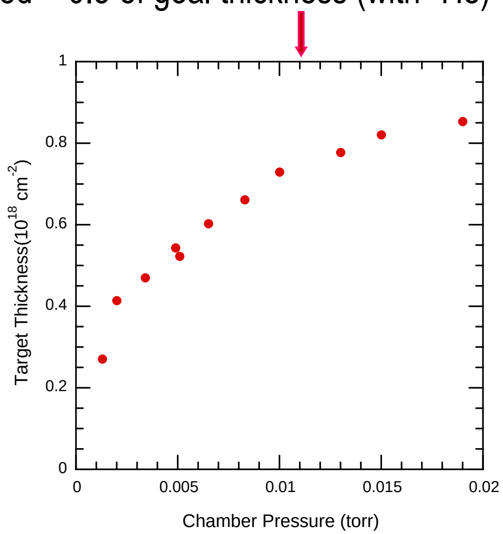
e^- beam



- NSF MRI award in 2012 (#PHY-1229153) to develop and construct this target (~0.4M)

Target Status

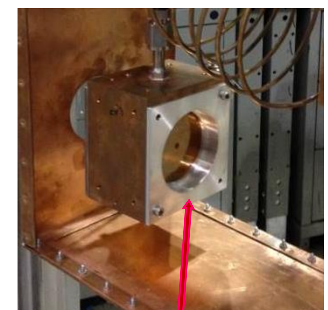
- All parts and elements are at JLab:
  - Target system has been built
  - Chamber support stands are built
  - Assembled and tested in January 2015
  - Entire pumping system assembled and tested (at room T, with He, only 1 chamber turbo, not 2, no beam line turbos)
  - Achieved ~0.5 of goal thickness (with ^{4}He)



from Ch. Keith

Target chamber

Target head

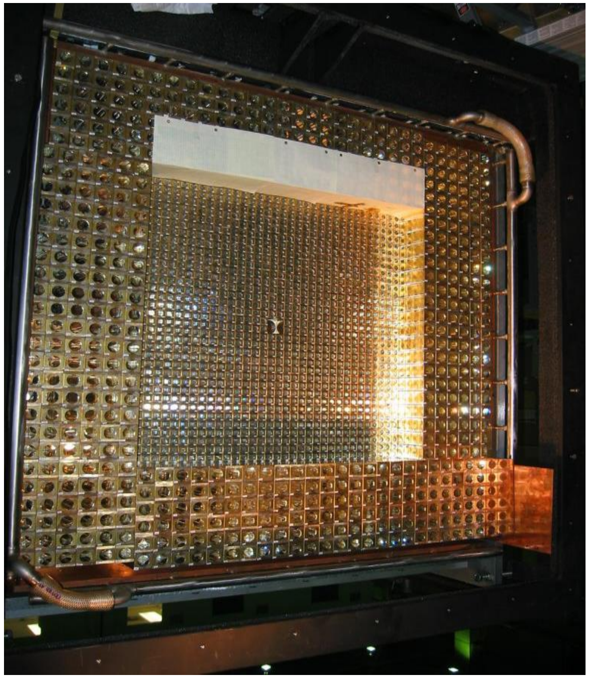


Target cell

- Full system test with He gas is underway (Oct. 2015)
- Target will be ready for installation in the Hall B beam line (estimated time: 8-10 days)

Electromagnetic Calorimeter (PrimEx HyCal)

- Combination of $PbWO_4$ and Pb-glass detectors (118x118 cm^2)
- 34 x 34 matrix of 2.05 x 2.05 x 18 cm^3 $PbWO_4$ shower detectors
- 576 Pb-glass shower detectors (3.82x3.82x45.0 cm^3)
- 2 x 2 $PbWO_4$ modules removed in middle for beam passage
- 5.5 m from H_2 target (~0.5 sr acceptance)

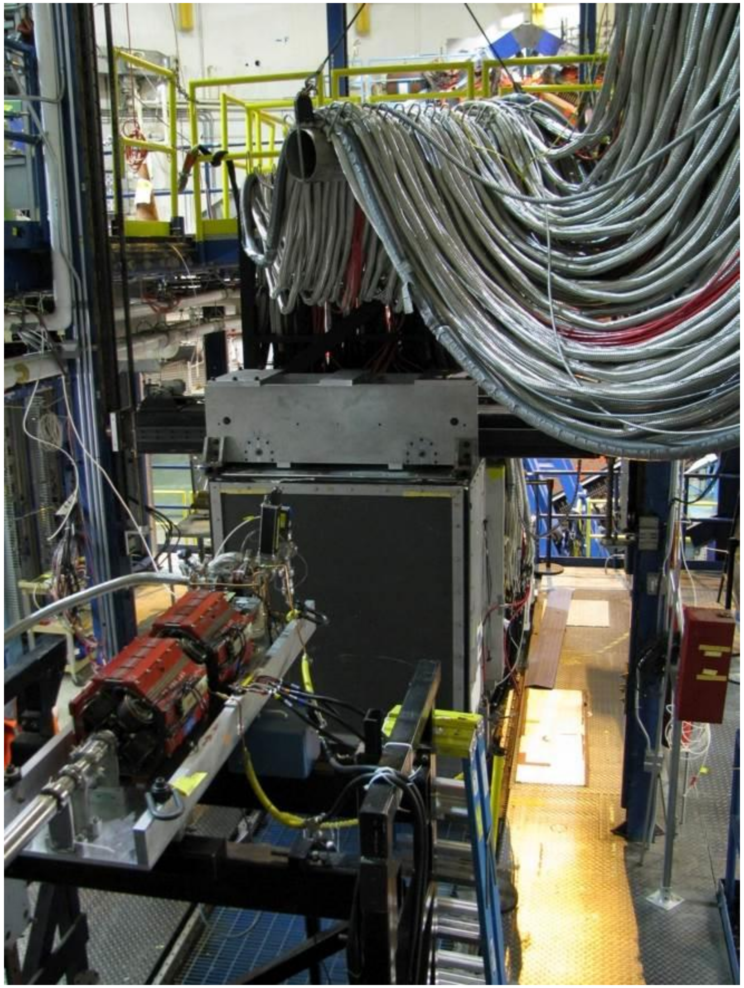


- Resolutions:
  - for $PbWO_4$ shower detectors:
    - ✓ energy: $\sigma/E = 2.6\,\%/\sqrt{E}$
    - ✓ position: $\sigma_{xy} = 2.5\text{ mm}/\sqrt{E}$
  - for Pb-glass shower detectors factor of ~2.5 worse

HyCal Current Operational Status

- Moved back to Hall B in June, 2014:
  (thanks to Technical Group (D. Tilles and All)
  - Cabling system with infrastructure reassembled
  - Trigger, analog and HV electronics are reinstalled
  - Cooling system is operational
  - LMS checked and repaired
  - All individual detectors checked and repaired
  - DAQ is operational (HyCal readout part)
  - Transporter is reinstalled/repaired and operational

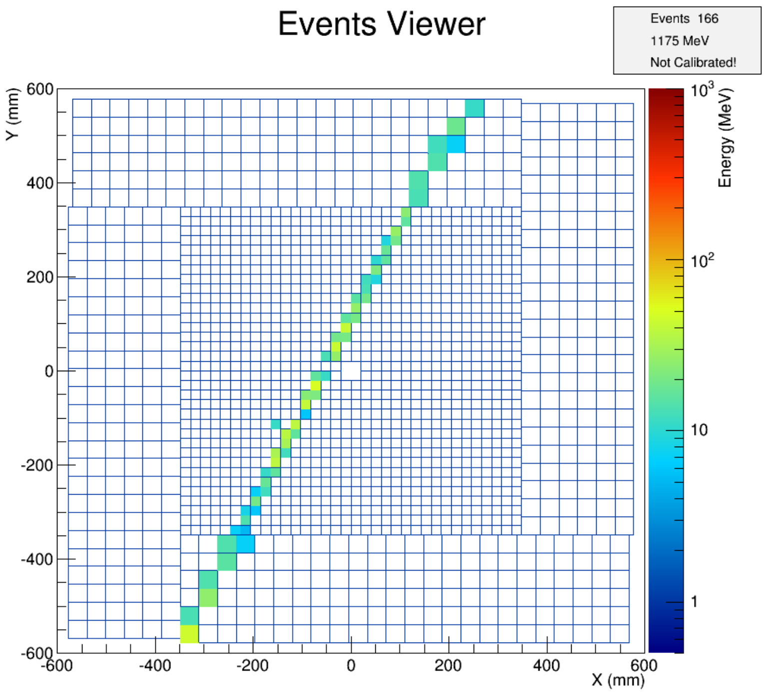
✓ **HyCal is ready for experiment**



HyCal in Hall B beam line (Nov., 2014)

HyCal Current Status

- HyCal is currently up in Transporter for cosmic ray tests



Cosmic event in HyCal

✓ **HyCal is fully repaired and ready for the experiment.**

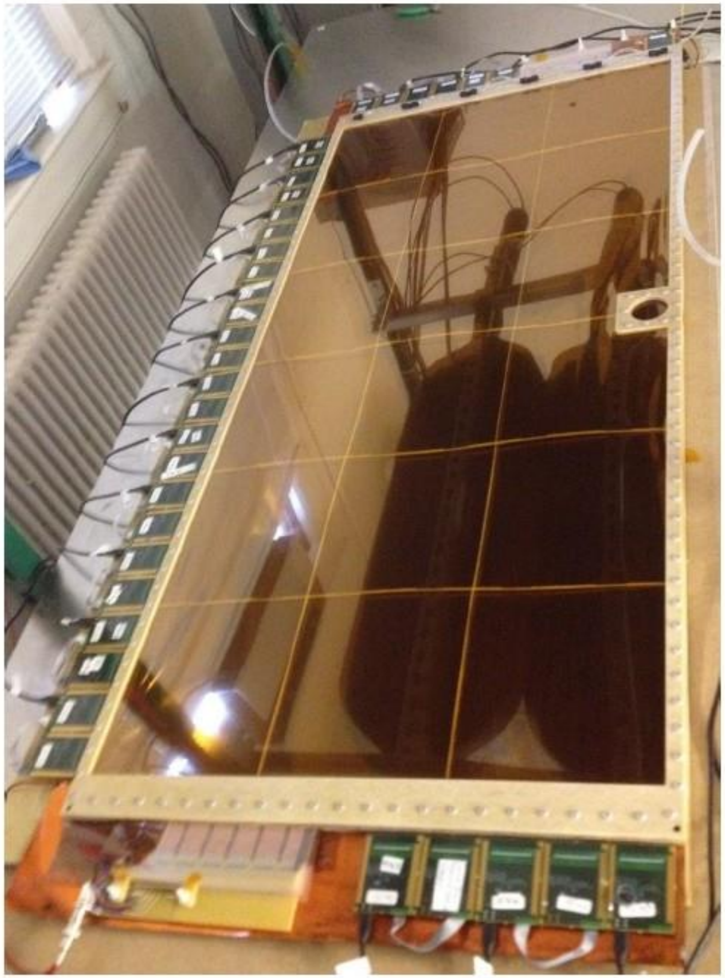
HyCal in Hall B beam line (Oct, 2015)

GEM Chambers

- Tasks for GEM:
  - factor of >10 improvements in coordinate resolutions
  - similar improvements in Q^2 resolution (very important)
  - unbiased coordinate reconstruction (including transition region)
  - increase Q^2 range by including Pb-glass part

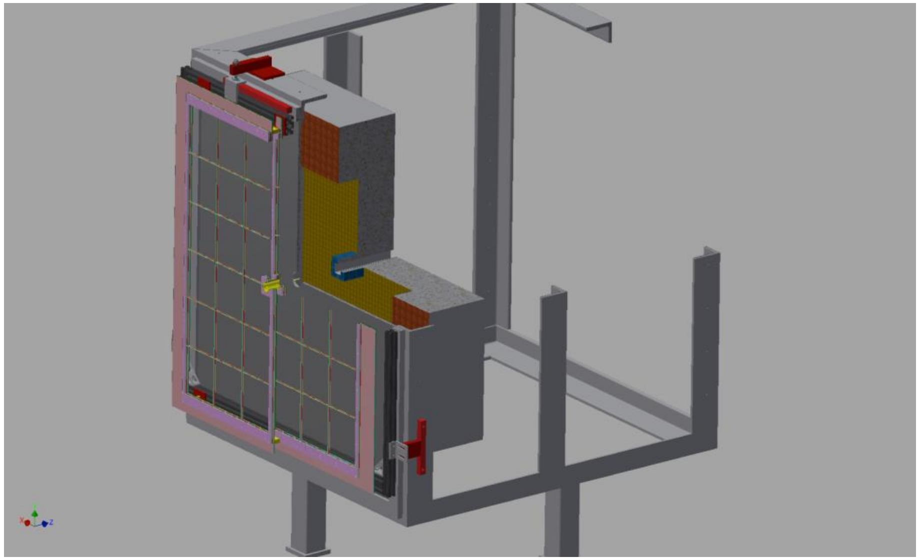
- Designed at UVa
- All components are built at CERN/RESARM and received at UVa
- 1st GEM chamber is completed in Sep. 2015, cosmic tests are underway (UVa)
- 2nd chamber is planned for Nov. 2015 (UVa)
- GEM DAQ is ported into CODA (MSU/UVa)
- Delivery to JLab: Jan. 2016

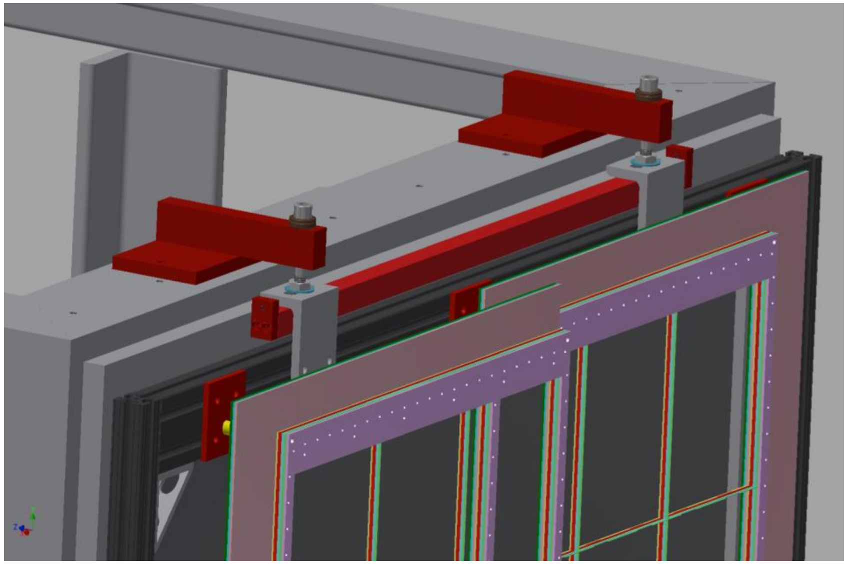
- GEM will be ready for installation in Feb. 2016
  (estimated installation time: 3 days)

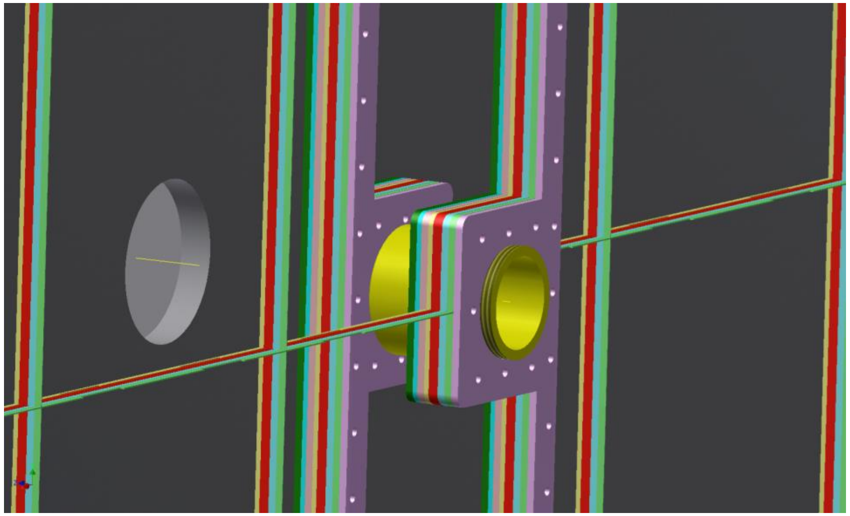


GEM chambers at UVa, Aug. 2015

GEM Mount on HyCal







- Conceptual design is done by Duke/Jlab
- Remaining work:
  - ✓ engineering design in progress
  - ✓ construction (in local shop)
  - ✓ ready by Jan. 2016

Vacuum Box

- Engineering design is done by Duke/Jlab
- Construction is done (March 2015)
- Tested with window by vendor (March 2015)
- Delivered to JLab (March 2015)

- Remaining work:
  - stands for vacuum box:
    - ✓ conceptual design done;
    - ✓ engineering design in progress
    - ✓ ready by Jan. 2016

Smaller chamber at JLab

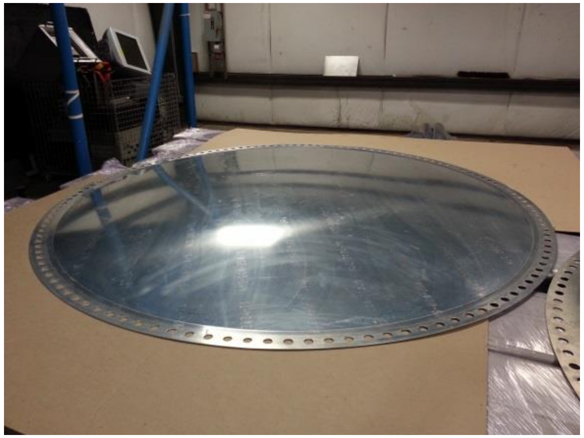
- ready for installation:
  Jan. 2016
  (estimated time: 2 days)

Larger chamber at shop

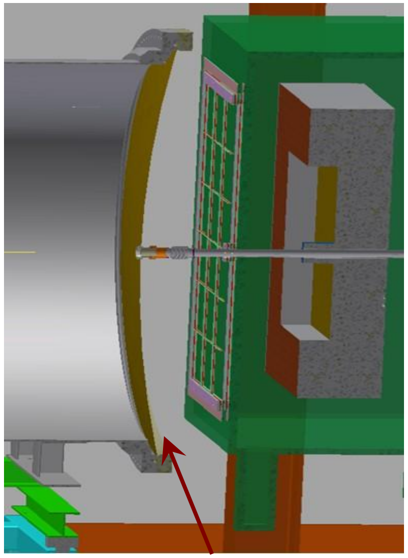
Larger chamber at JLab

Vacuum Window

- Thin Al-window on Vacuum Box at the HyCal end
  - thickness: ~2 mm
  - diameter : 1.7 m
  - connected to the beam vacuum pipe in center
- Design and construction done
- Vacuum tests are done
- Remaining work:
  - connection to the vacuum pipe
  - ✓ design in progress
  - ✓ ready by Feb. 2016



e^- beam

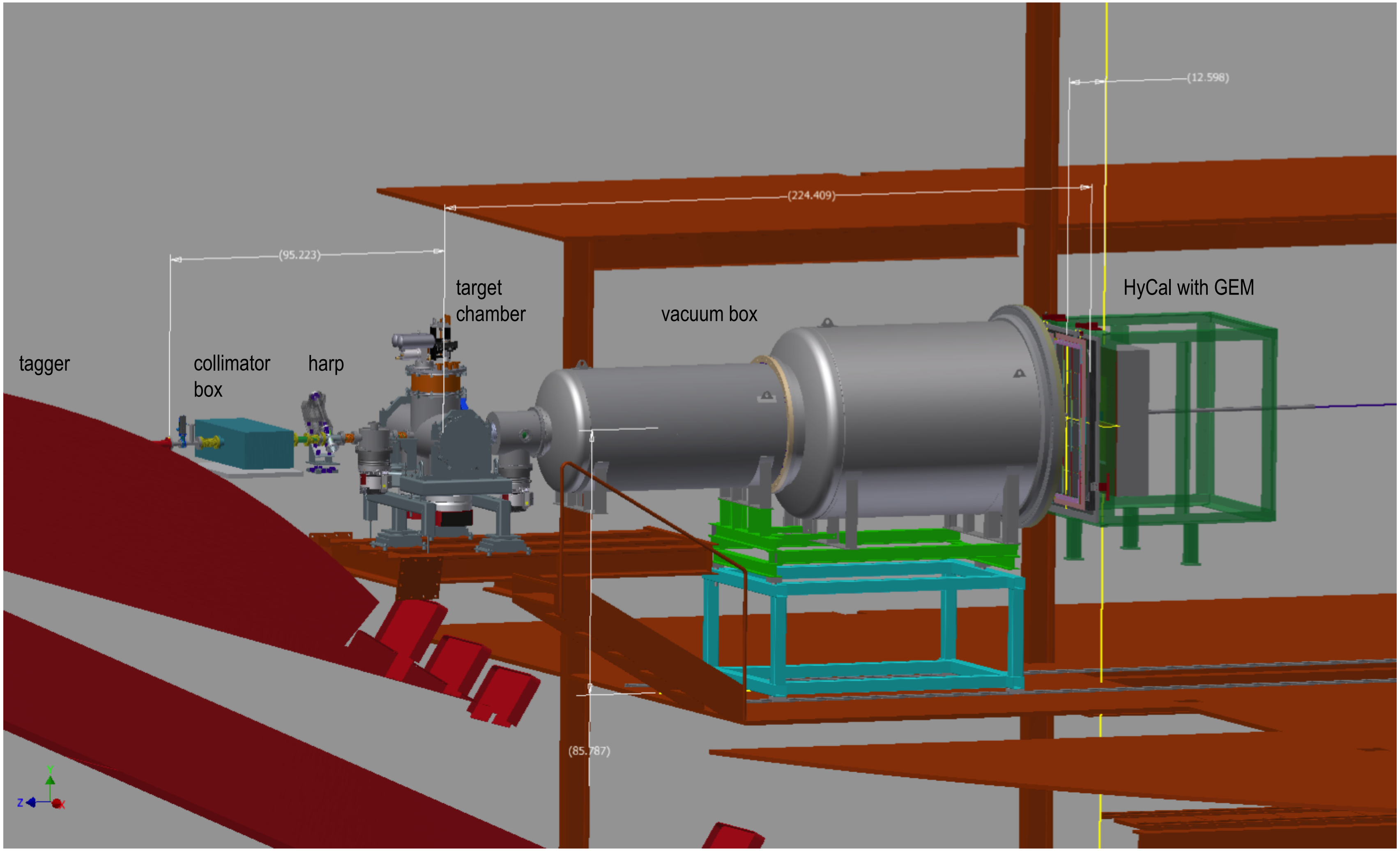


Vacuum Window

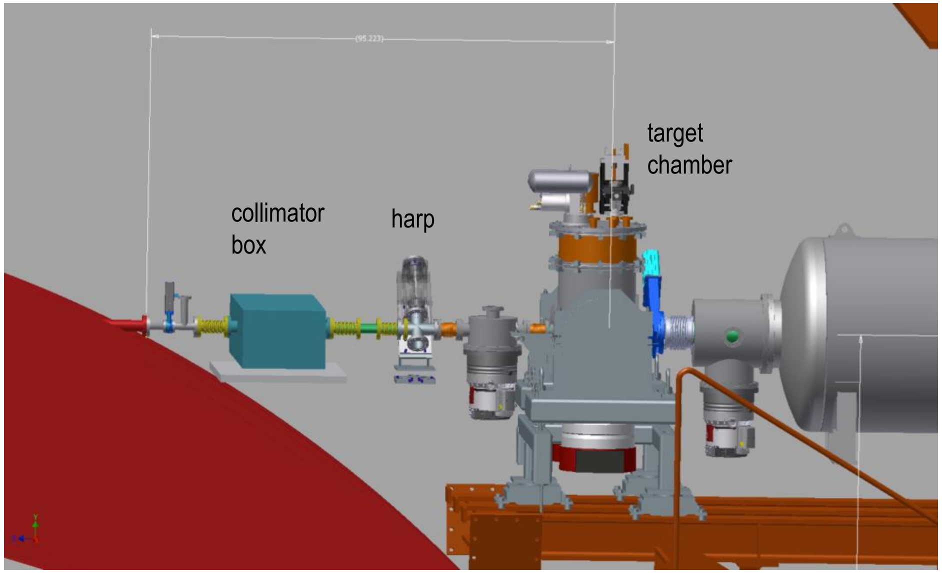
Preparation of the Vacuum Window at JLab

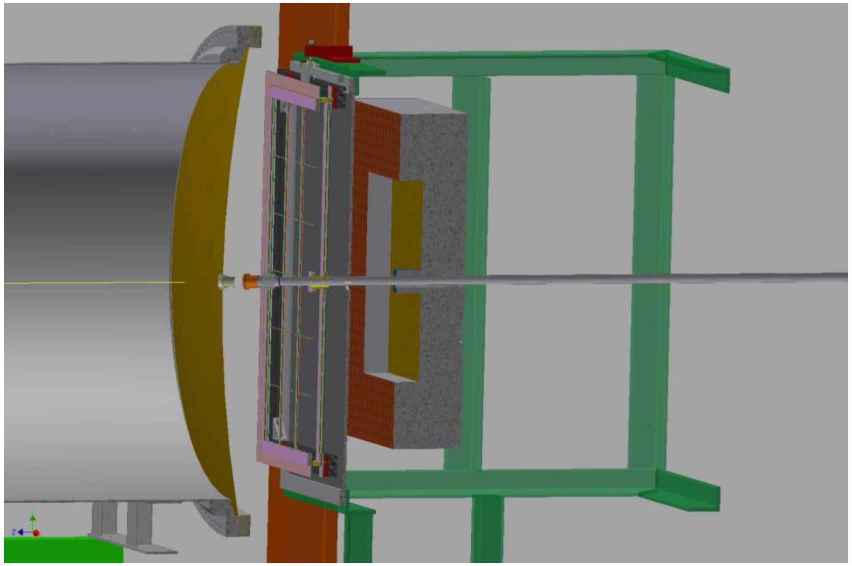
- Vacuum Window will be ready for installation: Feb. 2016 (estimated time: 2 days)

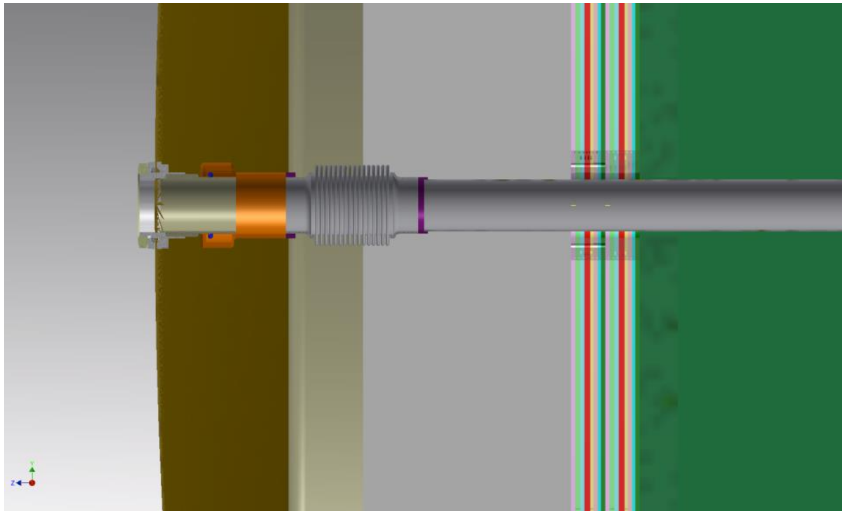
PRad Beam Line



Beam Line Elements

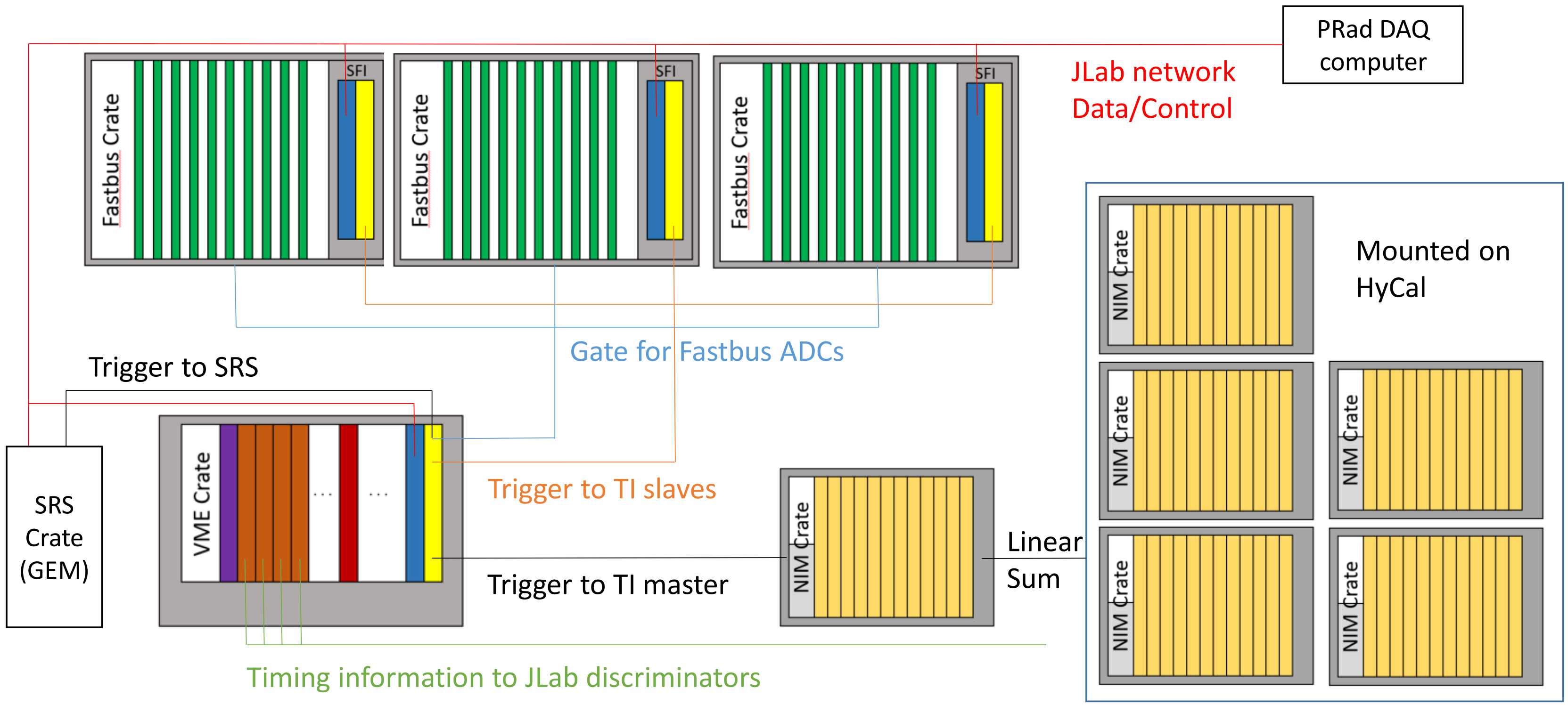






- Remaining work on Beam Line:
  - vacuum box stands (design in progress)
  - beam line from Vacuum Window through HyCal (design in progress)
  - collimator box (installation)
  - Harp 2H00 (installation)
- Beam line ready for installation: Jan 2016
- Beam line change from HPS to PRad: ~ 20 days (including target)

DAQ and Electronics



- PrimEx FASTBUS-based electronics and UVa linear sum modules for trigger
- Ready, taking cosmic data

PRad Collaboration Institutional List

- Currently 16 collaborating universities and institutions

  Jefferson Laboratory
  NC A&T State University
  Duke University
  Idaho State University
  Mississippi State University
  Norfolk State University
  University of Virginia
  Argonne National Laboratory
  University of North Carolina at Wilmington
  University of Kentucky
  Hampton University
  College of William & Mary
  Tsinghua University, China
  Old Dominion University
  ITEP, Moscow, Russia
  Budker Institute of Nuclear Physics , Novosibirsk, Russia

- Open for new collaborators and institutional groups !!!

Summary

- *"Proton radius puzzle"* is still unsolved after 5 years.
- PRad is uniquely designed to address this *puzzle*.

- PRad experimental setup, in most part, is ready for the experiment.
  - ✓ few remaining work on beam line elements
- The experimental setup will be ready for installation in Feb. 2016.

- Readiness Review is scheduled for Nov. 12, 2015.

- PRad will be ready for any "opportunistic" run for this spring.

  - ✓ open for new collaborators and institutional groups !!!

✓ PRad is supported in part by NSF MRI award #PHY-1229153
✓ my research work is supported in part by NSF awards: PHY-1506388 and PHY-0855543

Buck up slides

Estimated Errors

- Extraction of proton charge radius was always limited by systematics and fitting uncertainties

- High rates will provide good statistical errors (~0.2% for all Q^2 bins)

- Simultaneous detection of two processes:
  - $ep \longrightarrow ep$
  - $ee \longrightarrow ee$ Moller scattering
- and windowless H_2 gas target

  - will significantly reduce major systematic errors typical for all previous *ep*-scattering experiments

Contributions	Estimated Error (%)
Statistical error	0.2
Acceptance (including Q^2 determination)	0.4
Detection efficiency	0.1
Radiative corrections	0.3
Background and PID	0.1
Fitting error	0.2
Total Error	0.6%

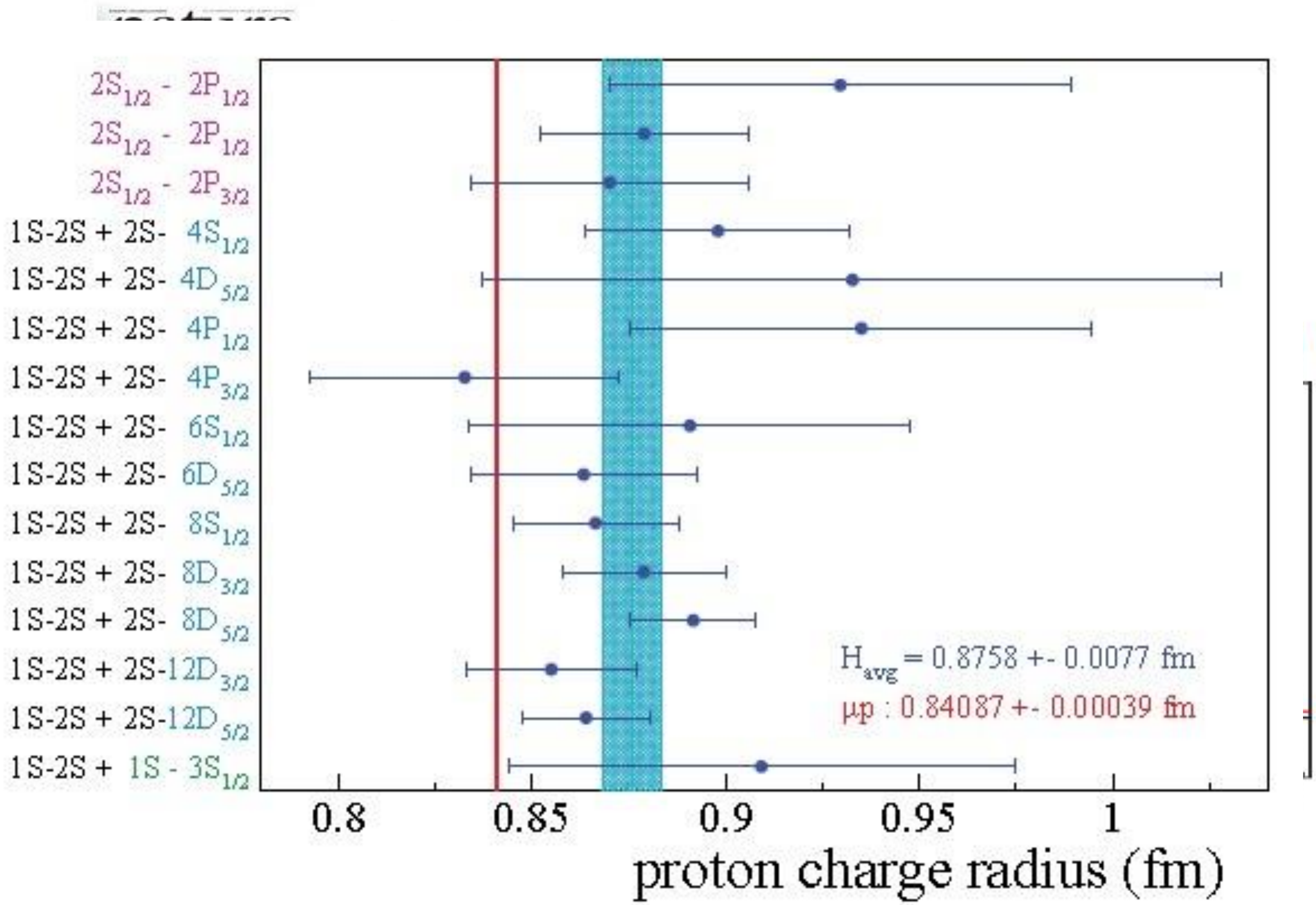
- Estimated error budget (added quadratically)

Beam Quality Requirements

Quality	Value
Energy	1.1 and 2.2 GeV
Beam current	0.1 – 10 nA
Luminosity	~ 10^{28} $cm^{-2}s^{-1}$
σ_x, σ_y	~ 100 μm
Position stability	~ 100 μm
Beam halo	< $(1x10^{-7})^*$
Divergence	< mrad
Emittance (ε_x, ε_y)	$8x10^{-10}$ m-rad

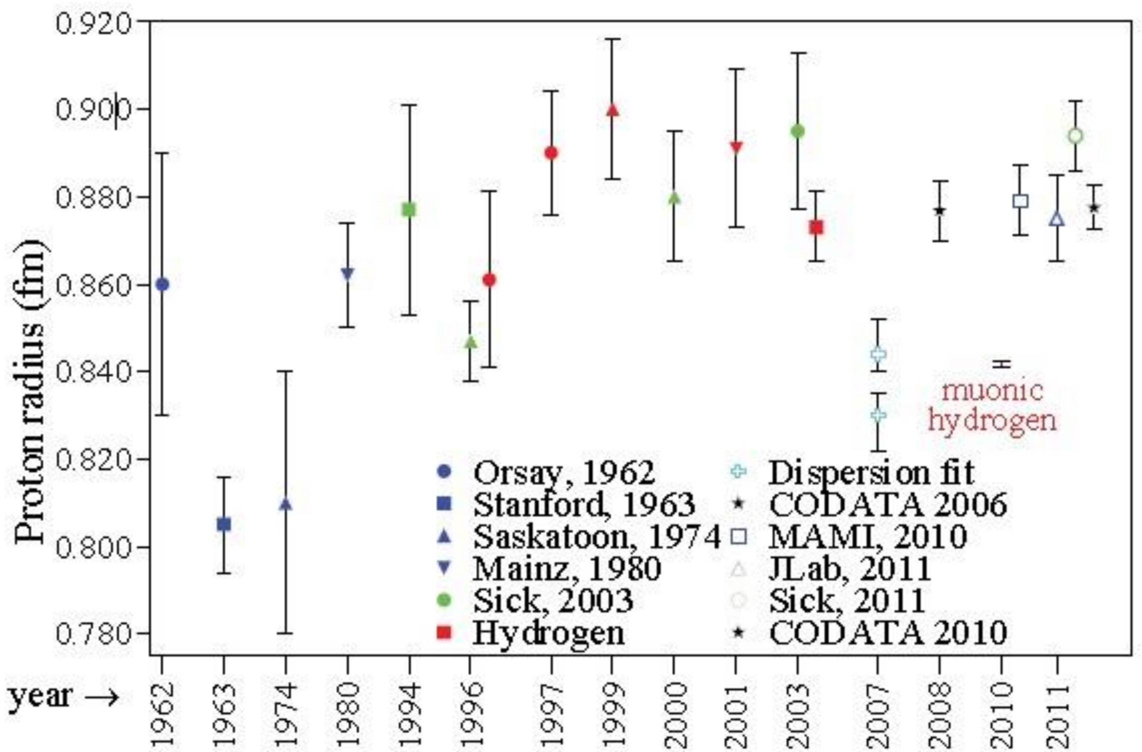
* for R > 3 mm from the beam center

New Results from Muonic Hydrogen Experiments (2010, 2013)

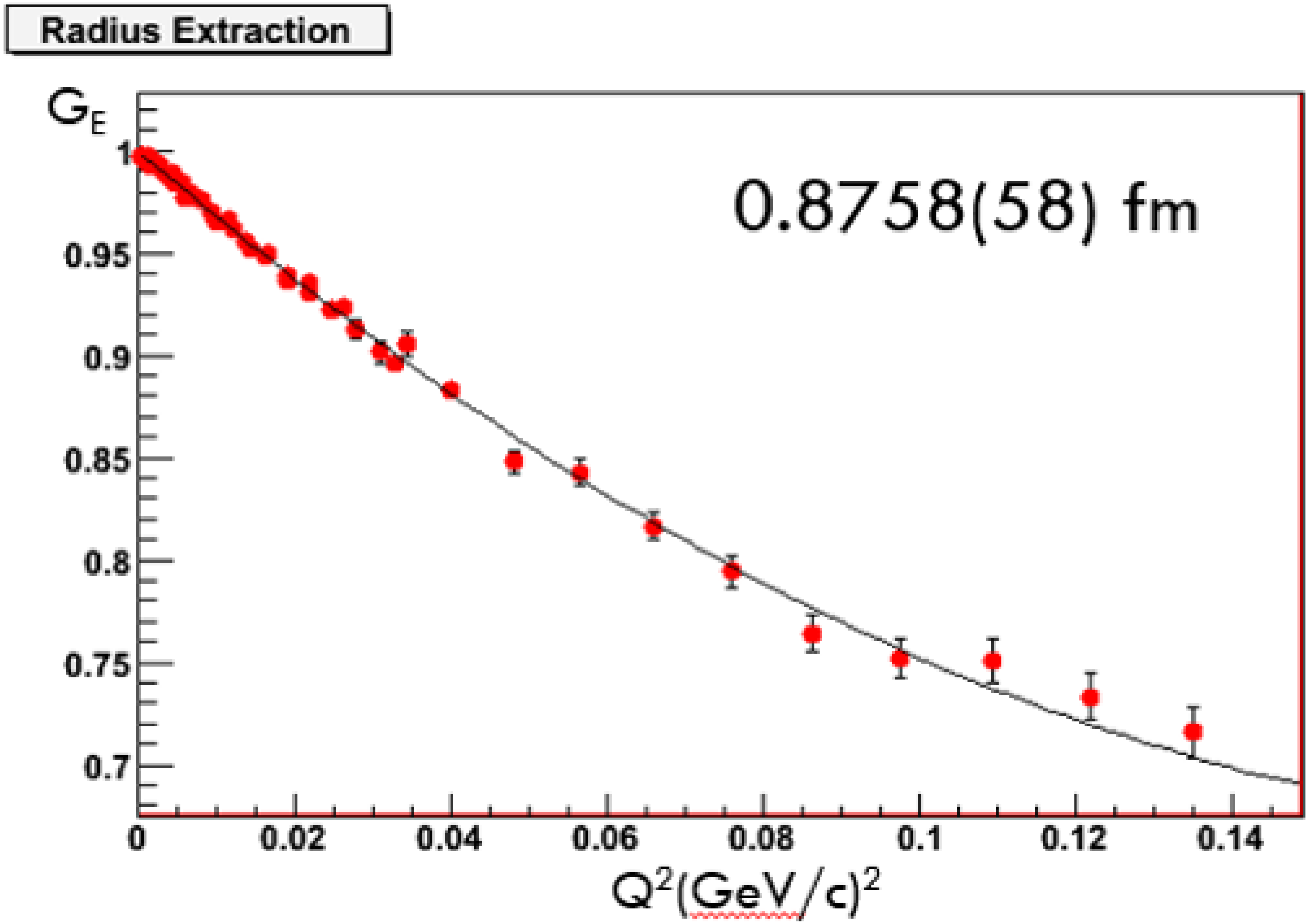


- r_p = 0.84184(67) fm ➡ Unprecedented less than 0.1% precision
- Different from most of previous experimental results and analyses

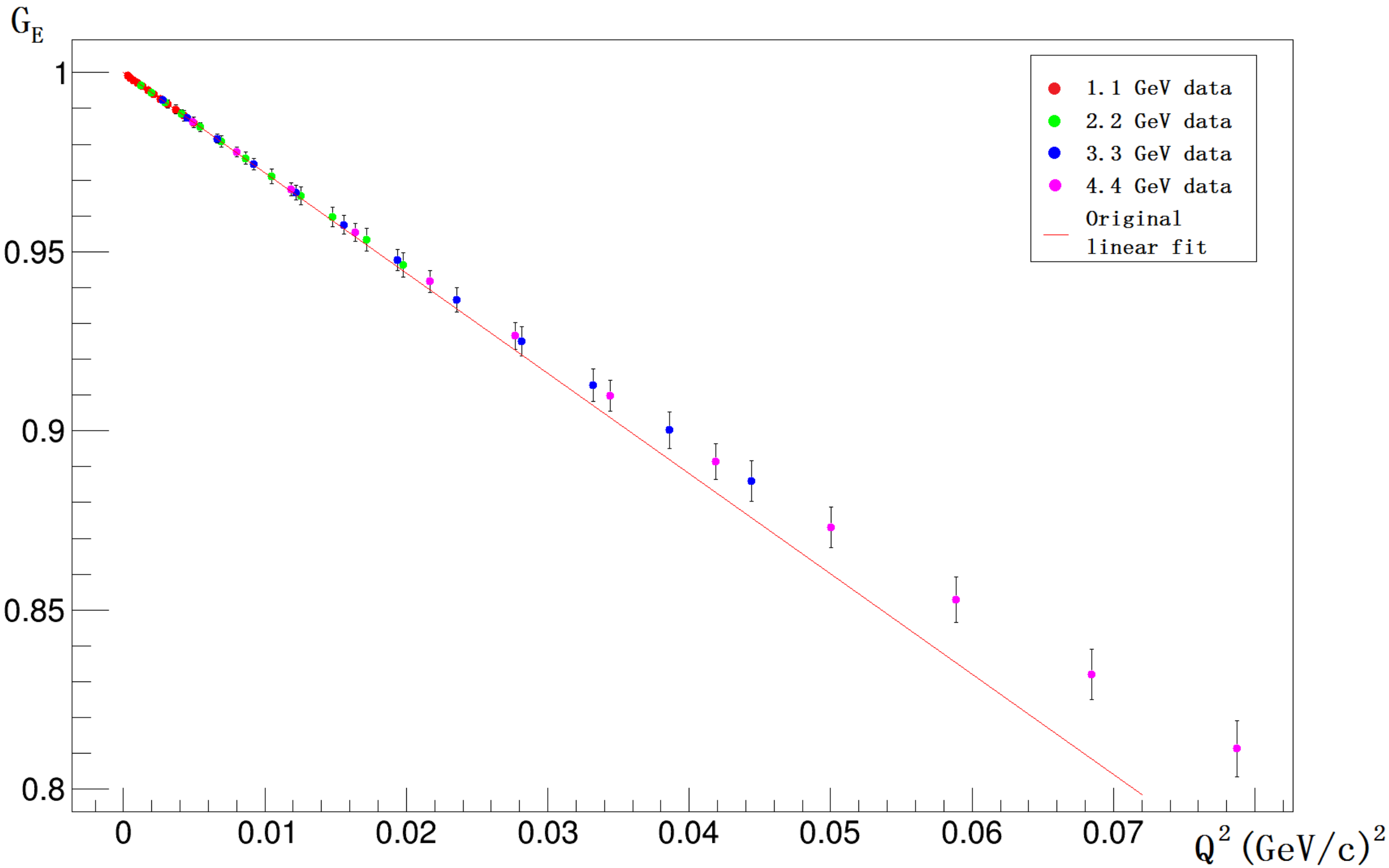
Proton Radius Extracted From e-p Scattering Experiments



- More different analysis results than actual experiments
- Started with: $r_p \approx$ 0.81 fm in 1963
- Reached to: $r_p \approx$ 0.88 fm by 2011



Radius Extraction
G_E
0.8758(58) fm
1
0.95
0.9
0.85
0.8
0.75
0.7
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
$Q^2 (GeV/c)^2$



G_E
1
0.95
0.9
0.85
0.8
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
$Q^2\ (GeV/c)^2$
1.1 GeV data
2.2 GeV data
3.3 GeV data
4.4 GeV data
Original linear fit