Preparation of the PRad-II Experiment

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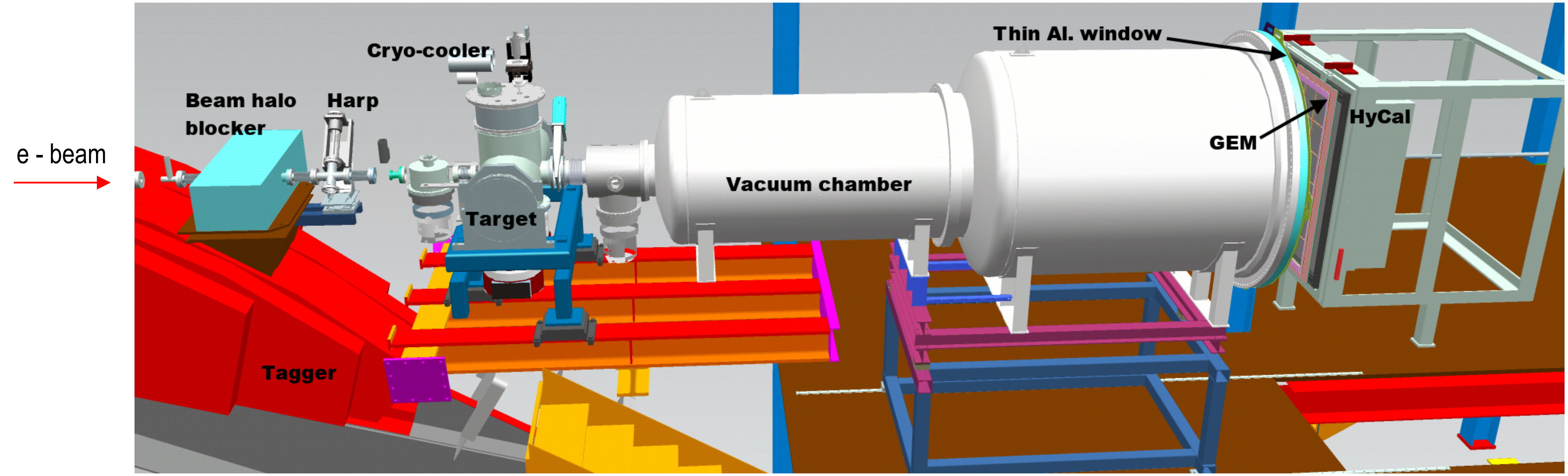
for the PRad collaboration

Items to be discussed

- PRad Basic concepts
- Improvements for PRad-II:
  - ✓ more statistics;
  - ✓ new beam halo blocker;
  - ✓ new scintillator veto counters;
  - ✓ second GEM plane for tracking;
  - ✓ upgraded HyCal;
  - ✓ improved radiative corrections

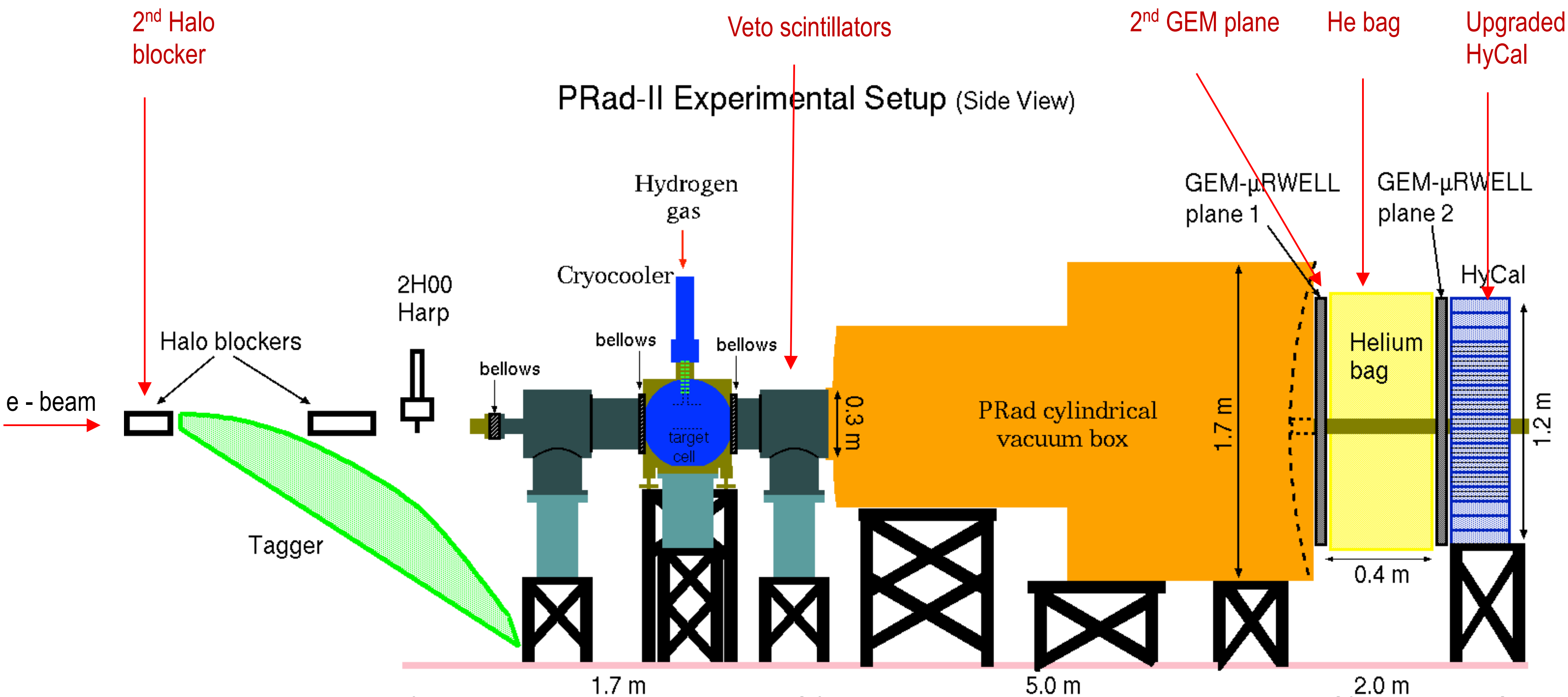
PRad Basic Concepts

1) Measure the ep-elastic cross section in relatively large Q^2 range with one experimental setting ($Q^2 = 2x10^{-4} \div 6x10^{-2}$ GeV/c^2)
2) Access to smaller Q^2 range, $Q^2 = 2x10^{-4}$ GeV/c^2
3) Normalize the diff. cross sections to a well-known QED processes: simultaneous detection of $ee \rightarrow ee$ Moller scattering.



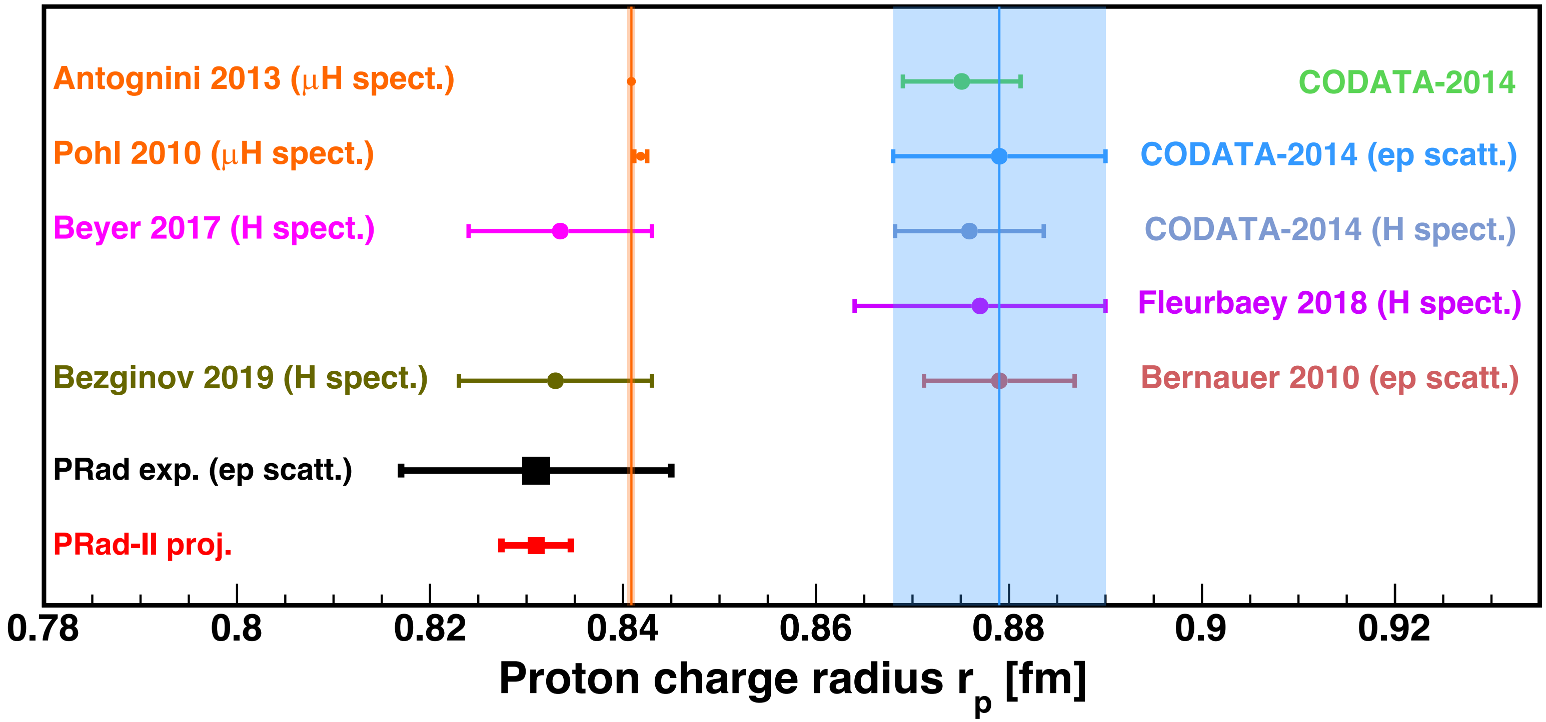
PRad-II Concepts

1) Based on PRad, design a new experiment to measure the Proton Radius (and the form factor) with the best possible precision and accuracy in ep-scattering experiments.
2) Access to one more order of magnitude less Q^2 range ($Q^2 = 2x10^{-5}$ GeV/c^2)



PRad-II Expected Accuracy

- Approved by Jlab's PAC-48 in August, 2020 (with C1 condition)
- Expected total uncertainty: 0.43% (a factor of 4 improvement over PRad)



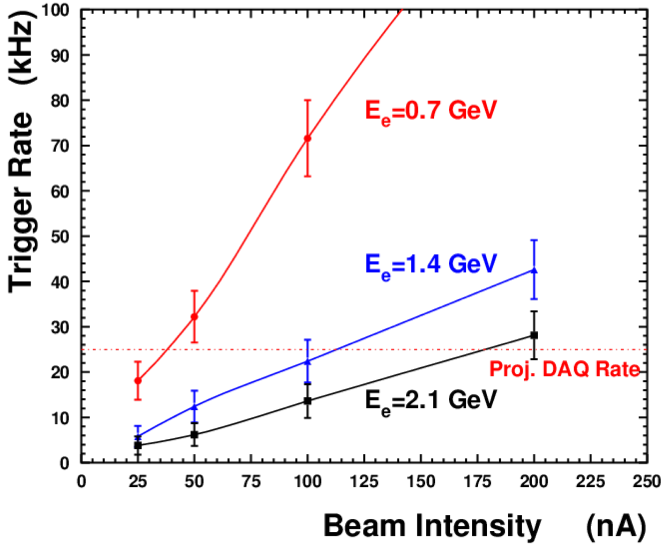
Improvements in Uncertainties

Sources	PRad δr_p [fm]	PRad-II δr_p [fm]	PRad-II δr_p [fm] w/o HyCal upgrade and with 2 new GEM planes
Stat. uncertainty	0.0075	0.0017	0.0017
HyCal non-uniform response	0.0029	0.0001	0.0013
Inelastic *ep*	0.0009	0.0001	0.0009
Event selection	0.0070	0.0027	0.0034
GEM efficiency	0.0042	0.0008	0.0027
Acceptance & beam energy related	0.0034	0.0003	0.0003
Beam background	0.0039	0.0016	0.0016
Radiative correction	0.0069	0.0004	0.0004
G_M^p parameterization	0.0006	0.0005	0.0005
Total systematic	0.0115	0.0032	0.0049
Total uncertainty	0.0137	0.0036	0.0052

Statistics

- Planning to take ~ 16 times more statistics, 4 times better statistical uncertainty.

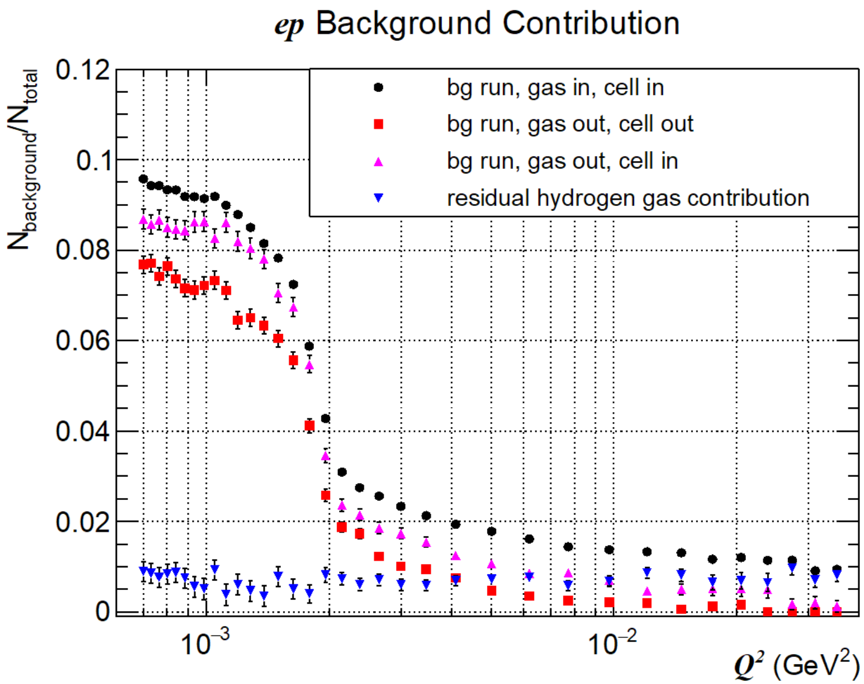
- How?
  - ✓ PRad-II is approved for 40 PAC days (with C1 condition)
  - ✓ run with higher beam current
  - ✓ implement new fADC based DAQ
    - ➢ need 240 fADC250 housed in 15 VXS crates, each with CPU, TP, Interface board and signal distribution card

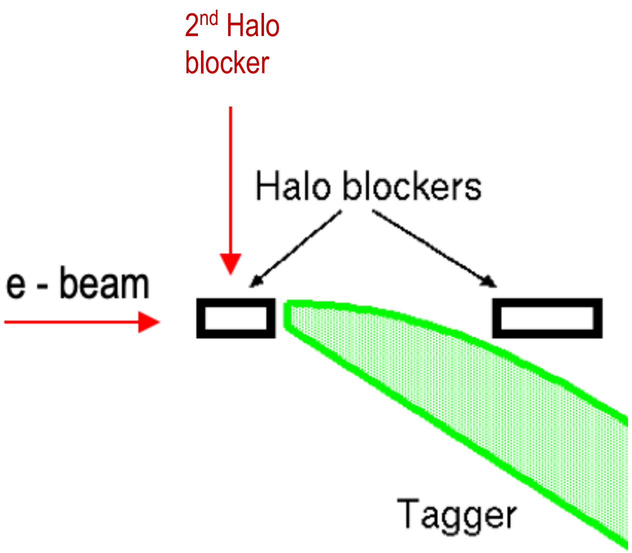


Equipment	Cost per unit ($)	Number of units	Total cost ($)
FADC250	6,000	240	1,440,000
VXS Crate	16,000	15	240,000
CPU	5,500	15	82,500
Trigger processor	9,000	15	135,000
Trigger interface	1,500	15	22,500
Signal distribution card	2,000	15	30,000
Total		15	1,950,000

New Beam halo Blocker

- 2^{nd} beam halo blocker
  - can be a copy of the existing "photon beam collimator" with 3 positions:
    - ✓ "open"
    - ✓ ½" hole
    - ✓ ¼" hole

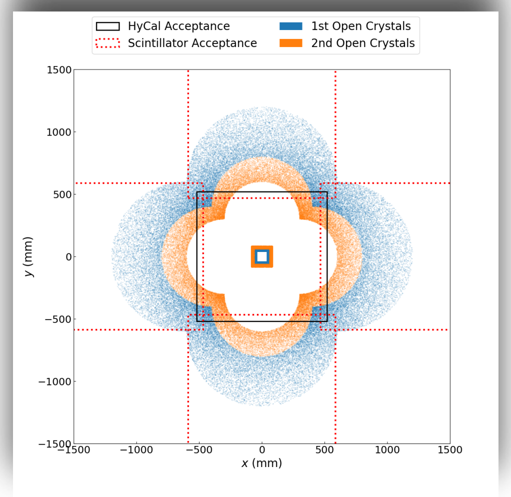




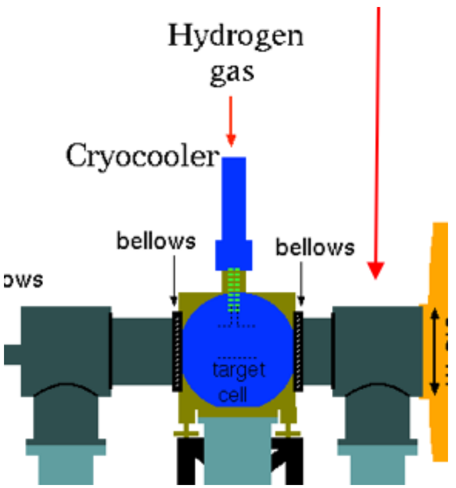
Moller Veto scintillator Counters

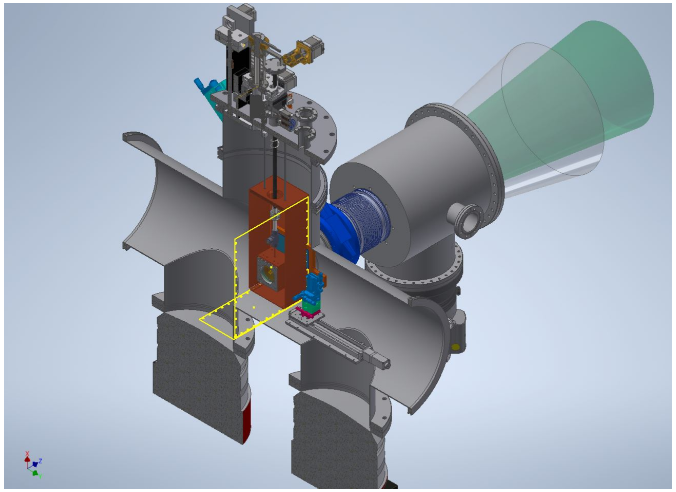
- To reach the $Q^2 = 2x10^{-5}$ GeV/c^2 range, we need to veto the Moller events at very small angles (~0.5^0) and take E_e = 0.7 GeV electron beam
- 4 small scintillator detectors (~ 4x15 cm size) will be placed inside the main target chamber and will be retractable.

- Conceptual design work is completed with the Target group



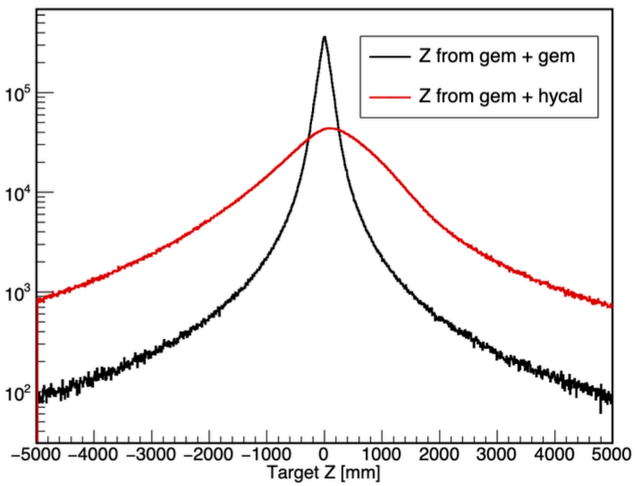
4 veto scintillators

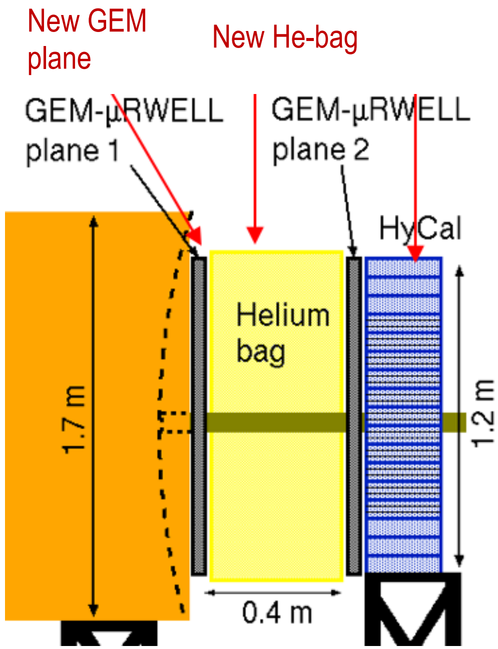




Second GEM Plane for Tracking

- The 2^{nd} GEM plane will add tracking capabilities in the experiment, providing:
  - ✓ reducing the beam-line background by improving the z-vertex reconstruction (critical);
  - ✓ critical improvements in GEM detection efficiencies (very important).
- The 2^{nd} plane will be based on the same GEM, included new, tested technologies.
- New He-bag for background reduction.

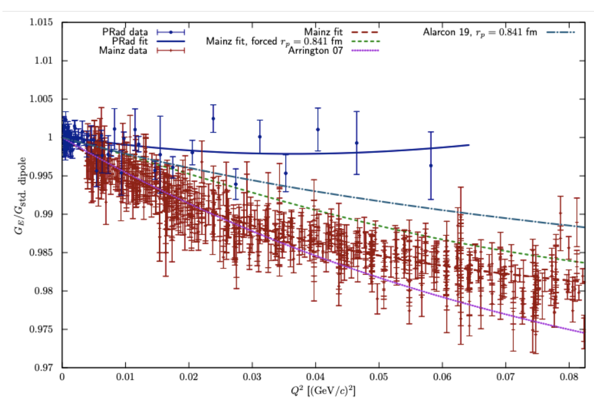


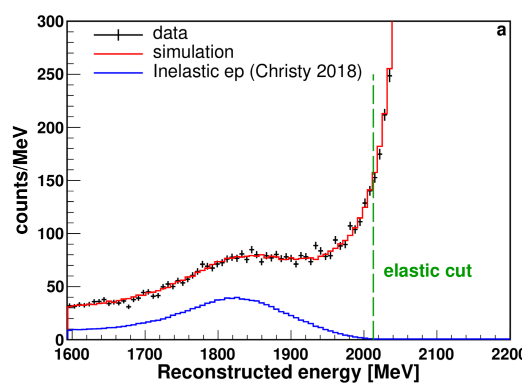


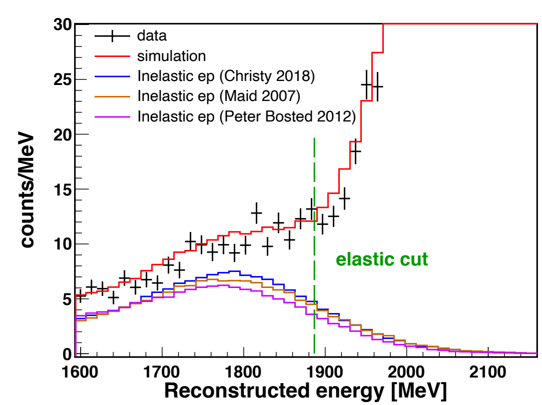
HyCal Upgrade

- HyCal upgrade (change all Pb-glass to PbWO4 based detectors) will provide:
  - ✓ ~3 times better position and energy resolutions at higher Q^2 range. Critical for the ep-inelastic background subtraction.
  - ✓ make uniform detector response for entire Q^2 range. Critical for the proton radius extraction with this method.
  - ✓ Improvements in GEM detection efficiency measurements. Critical item for this method.
  - ✓ improvements in event selection process. Very important.
  - ✓ will help in experimental test of radiative corrections.

- PRad form factor difference from other best ep-experiments is ~ 1.5 -2 % at larger Q^2 range.
- the ep-inelastic contributions in PRad at this Q^2 range (Pb-glass part) is also ~ 2%



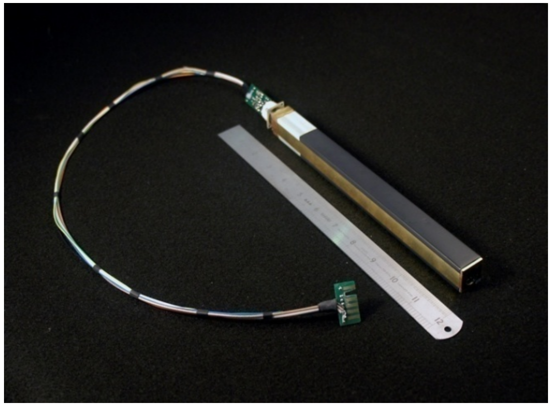


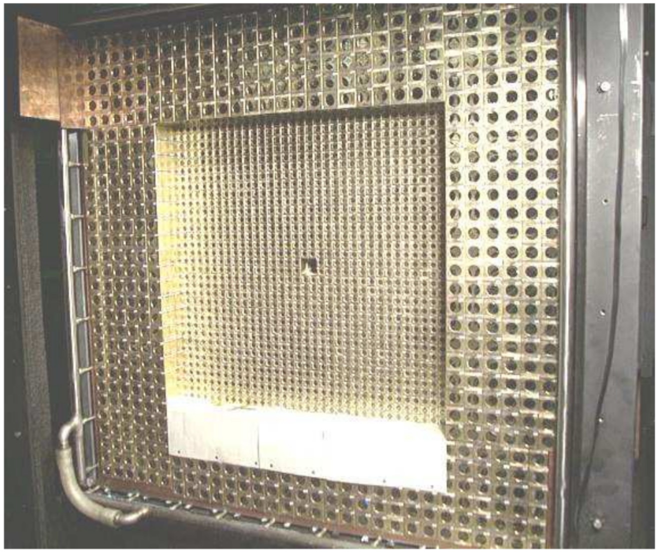


HyCal Upgrade

- HyCal upgrade will include :
  - ✓ ~ 1500 new $PbWO_4$ detector modules to replace the ~ 600 Pb-glass detectors;
  - ✓ HyCal Frame will stay with the same cooling system;
  - ✓ HyCal transporter with the cable holding structure will stay;
  - ✓ HyCal stand table will stay;

- NSF RI-1 pre-proposal is submitted in January, 2021 (includes ~$4.M for the HyCal upgrade, total: $7.1M)





Uncertainties with and without HyCal Upgrade

Selected Items	PRad δr_p [fm]	PRad-II δr_p [fm]	PRad-II δr_p [fm] w/o HyCal upgrade and with 2 new GEM planes
Inelastic ep	0.0009	0.0001	0.0009
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Event selection	0.0070	0.0027	0.0034
Total uncertainty	0.0137	0.0036	0.0052

Studies of Radiative corrections (RCs) for PRad-II

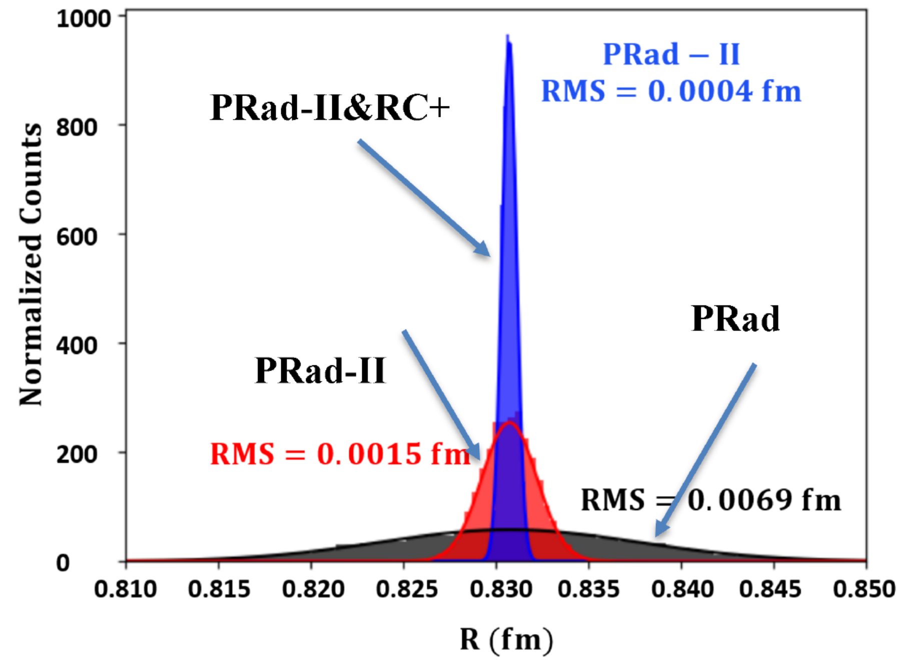
- RCs one of the largest syst. uncertainty sources of r_p in PRad
  - Total syst. uncertainty due to the higher order RCs -- δr_p = 0.0069 fm
  - Syst. uncertainties correlated and Q^2 dependent for e-p and MØller scatterings

- Aiming at a significantly better precision by PRad-II compared with PRad
  - Employ two planes of coordinate detectors in PRad-II to better determine efficiency
  - Use the integrated MØller method for all angular bins
  - Suppress the Q^2 dependent syst. uncertainties
  - Turn all the MØller syst. uncertainties into cross section normalization uncertainties

- Better testing for various calculations of radiative effects with PRad-II
  - Precise photon/electron PID with upgraded coordinate detectors and HyCal
  - Simultaneous detection of the scattered electrons and radiative photons from the "hard" radiative process

- Aiming at total systematic uncertainty of 0.0032 fm with PRad-II
  - Plans in place for improved RC calculations at the NNLO level by our theory colleagues
  - Focus on the elastic e-p and MØller scatterings beyond ultrarelativistic limit
  - All RC calculations based on new methods to be finished up by the end of 2024

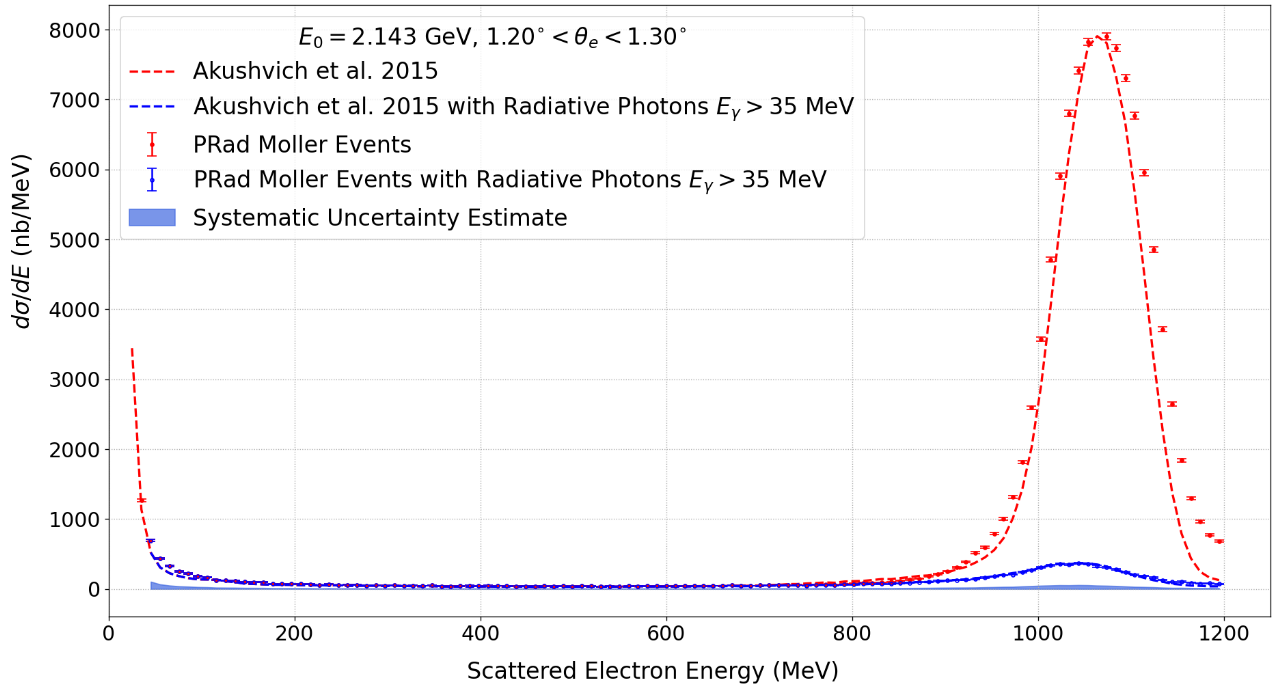
- Improvement of the RC associated syst. uncertainty on r_p
  - Black spectrum -> the RC syst. for PRad
  - Red spectrum -> projected RC syst. with two planes of coordinate detectors plus current RC calculations
  - Blue spectrum -> projected RC syst. with two planes of coordinate detectors plus improved RC calculations at NNLO



- Outline of the current project presented in the Whitepaper on Radiative Corrections: *A. Afanasev, et al. arXiv:2012.09970 [nucl-th]*
  - Planned with other current RC-related studies for the JLab SoLID SIDIS and proposed DRad experiment
  - Collaborations with different groups at PSI and Mainz on RC topics underway

- Carry out further studies of the r_p robust extraction in PRad-II
  - Including also a blind analysis to reduce possible bias stemming from the normalization and the Q^2-dependence of the form factor

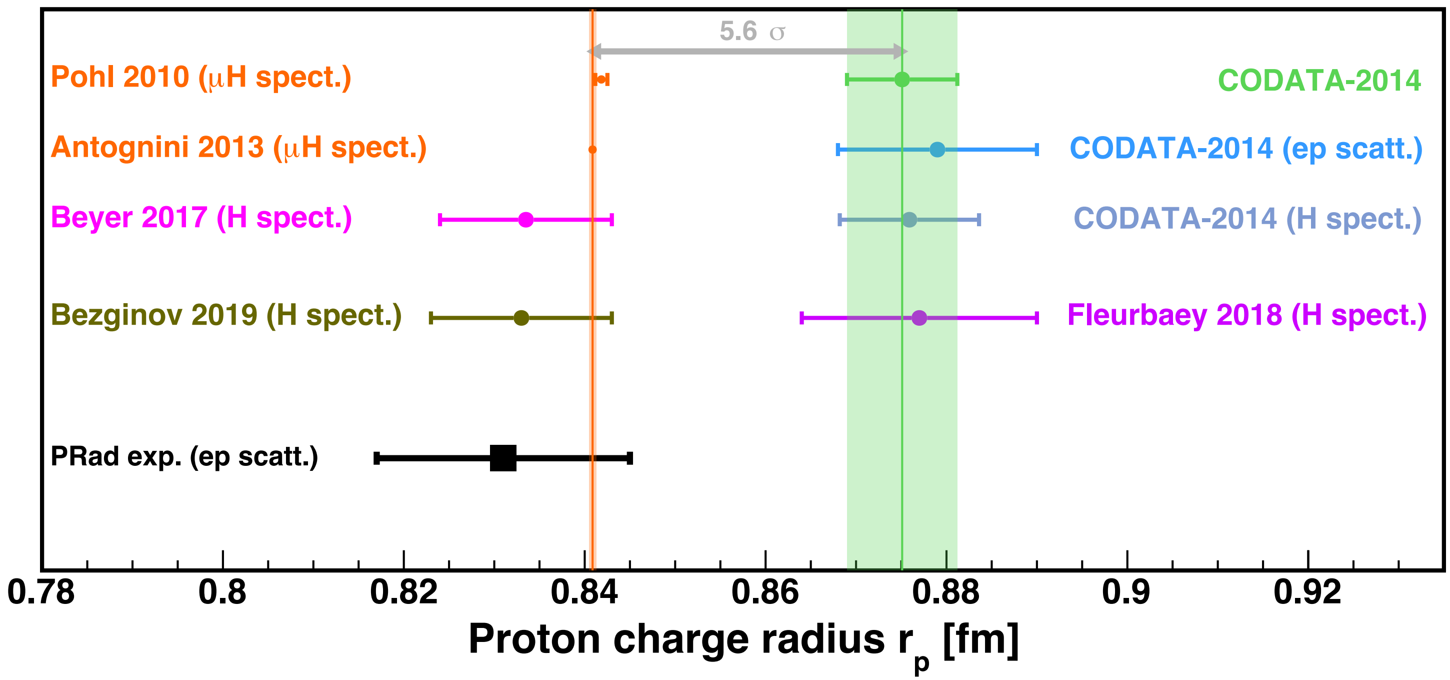
- Experimental validation of the radiative correction recipes
  - Symmetric single-arm Møller events from PRad 2.2 GeV data
  - Select "hard" radiative photon with $E_\gamma > 35$ MeV (limited by HyCal resolution)



- PRad-II will significantly reduce the uncertainties
  - Improved PID with two GEMs
  - Better resolution on low energy photons with all crystal HyCal
  - Higher statistics to check radiative photon distributions vs. their opening angles and energies

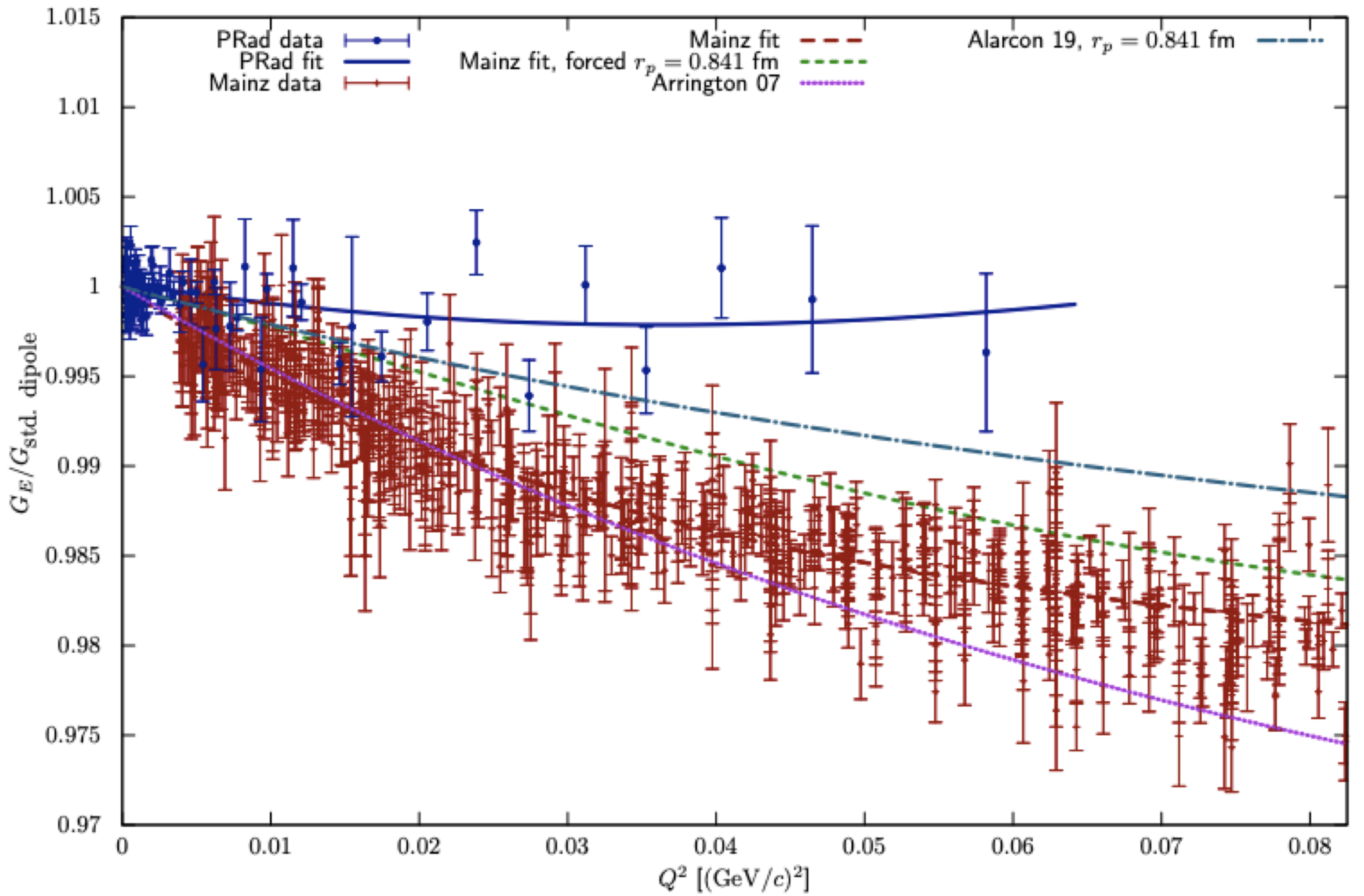
Thank you!

PRad Result and Uncertainties

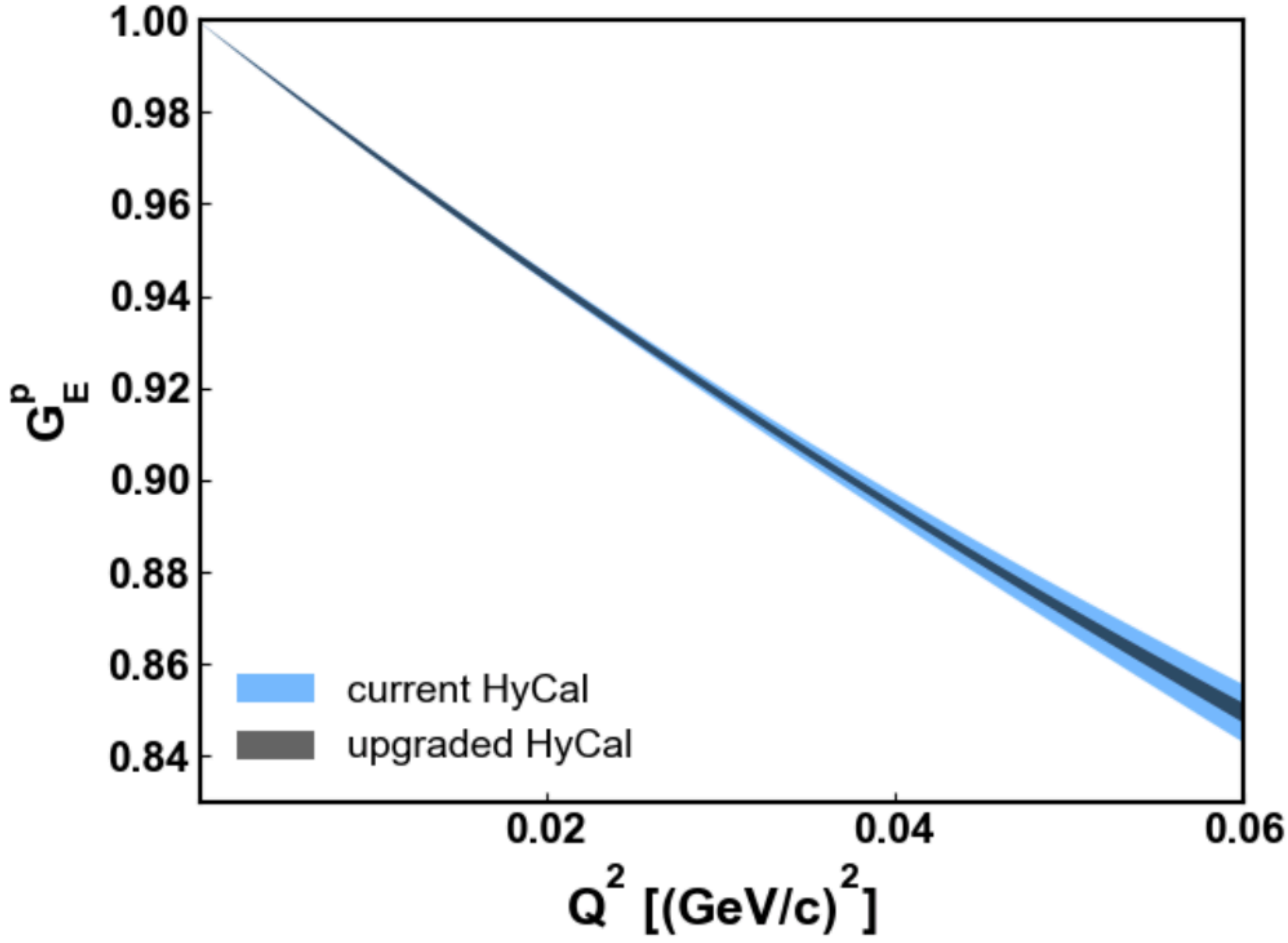


PRad final result: $R_p = 0.831 \pm 0.007$ (stat.) $\pm$ 0.012 (syst.) fm

HyCal Upgrade



Improvements in Form Factor



NSF RI-1 Summary Budget

Table 2: *Subsystems and responsible institutions for the upgraded PRad-II detector system*

Subsystem	Institution	Cost ($ Million)
$PbWO_4$ detector modules HV supply, cables and assembly	North Carolina A&T State University	4.1
fADC based readout electronics	Duke University Mississippi State University	1.95
Gain monitoring system Front end patch panel	Mississippi State University	0.1
Two planes of GEM detectors and readout electronics	University of Virginia	0.95
Total cost		7.1