XVIth Quark Confinement and the Hadron Spectrum Conference

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Argonne NATIONAL LABORATORY

Direct Measurement of QED Radiative Effects in PRad Experiment

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For the PRad Collaboration

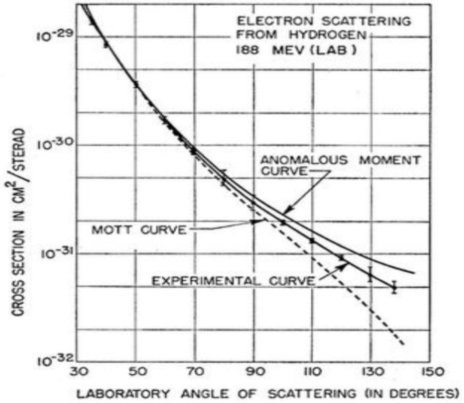
22 August 2024

Outline

- Electron Scattering and QED Radiative Effects
- PRad Experiment
- Direct Measurement of Radiative Photons in PRad
- Future Improvements from PRad-II

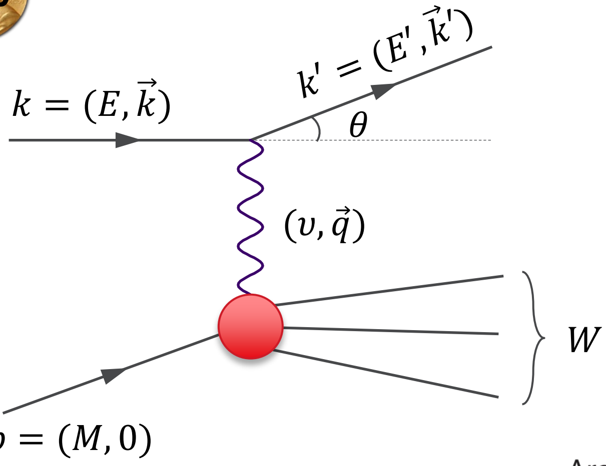
Electron Scattering Experiments

Hofstadter, McAllister,
Phys. Rev. 98, 217 (1955)



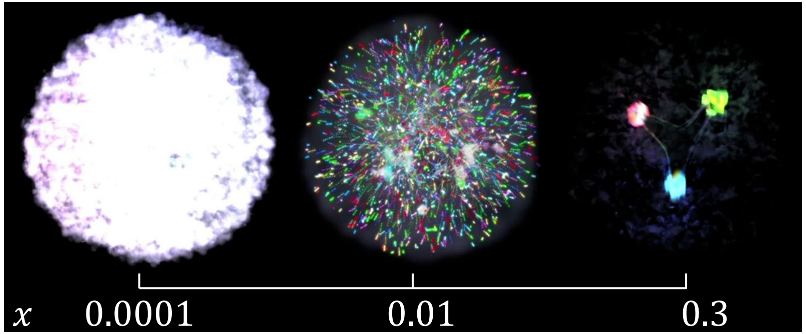
- Well developed experimental approach
  - *ep* elastic scattering measurements in 1950s by Hofstadter
  - Deep Inelastic Scattering (DIS) measurements in 1960-1970s at SLAC pioneered by Kendall, Friedman, and Taylor

- A "clean" way to probe the internal structure of the nucleon
  - Weighs in high precision QED calculations on the lepton vertex



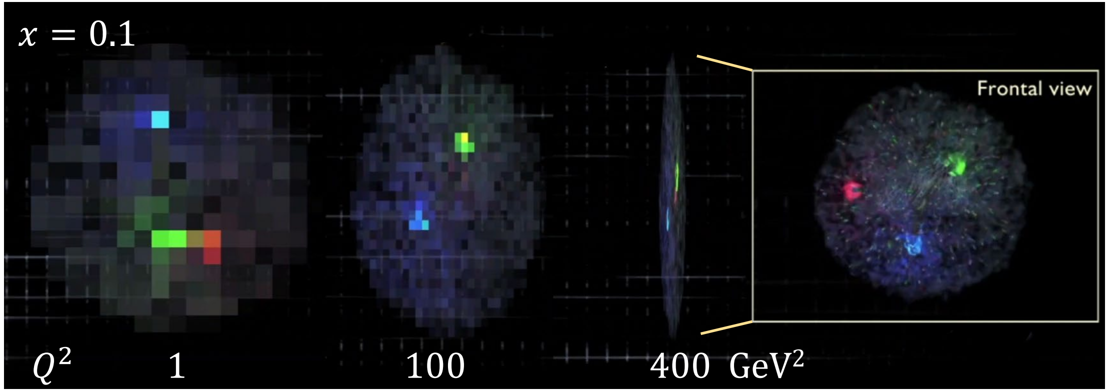
Study the Nucleon with the Electron Probe

https://arts.mit.edu/visualizing-the-proton/



- Probing the nucleon's internal structure
  - Q^2 ~ "resolution" of the probe
  - x ~ constituents the probe sees

- Elastic scattering $x = 1$
  - Probes the nucleon as a whole
  - EM Form factors

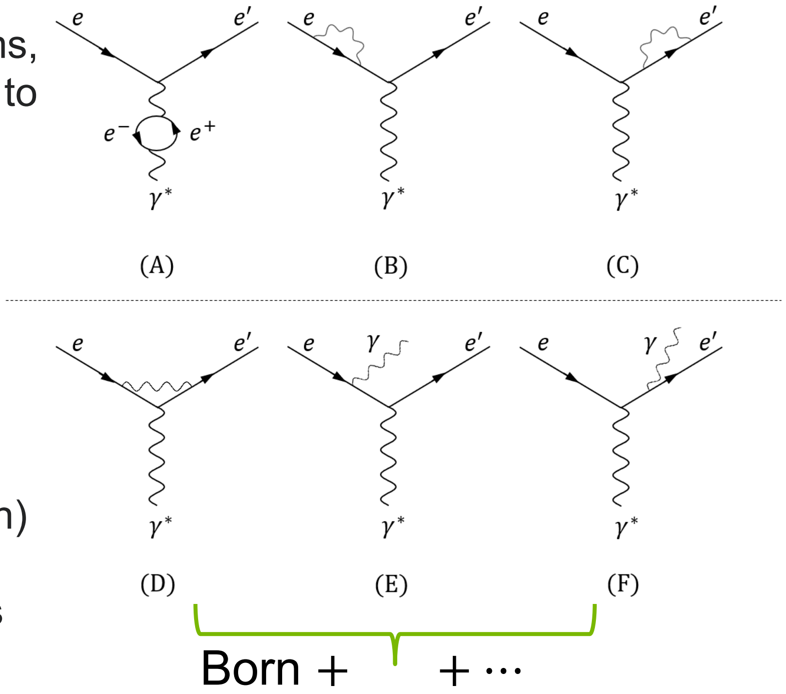


Radiative Effects

An unwanted “background” for all electron scattering measurements

- Lepton probe is not “clean”
  - **Higher order contributions** from loop diagrams, internal Bremsstrahlung, straggling effects due to external materials
  - Cross sections are obfuscated by the **radiative effects** in the measurements
  - **Unavoidable for all** electron scattering experiments

- Corrections to remove the radiative effects of measured observables
  - Internal corrections (mostly relied on calculation)
  - External energy loss (experimental setup)
  - Efforts from both theorists and experimentalists



QED Radiative Corrections

- The most famous recipe for radiative corrections - Mo&Tsai, Rev. Mod. Phys. 41,1969
- Key points in Mo&Tsai recipe
  - **Vacuum polarization and vertex correction** included in internal effects (QED)
  - **Internal Bremsstrahlung** is based on a **modified Bethe-Heitler** formula (not exact QED)
    - Approximation is often used to save computation time (at that time): equivalent radiator method (ERM) with the angle peaking approximation
  - **External Bremsstrahlung and ionization** due to particle traversing the materials (energy-loss effects)
- Discrepancy between Mo&Tsai and de Calan, Navelet, and Picard 1991

Status of the QED Radiative Corrections

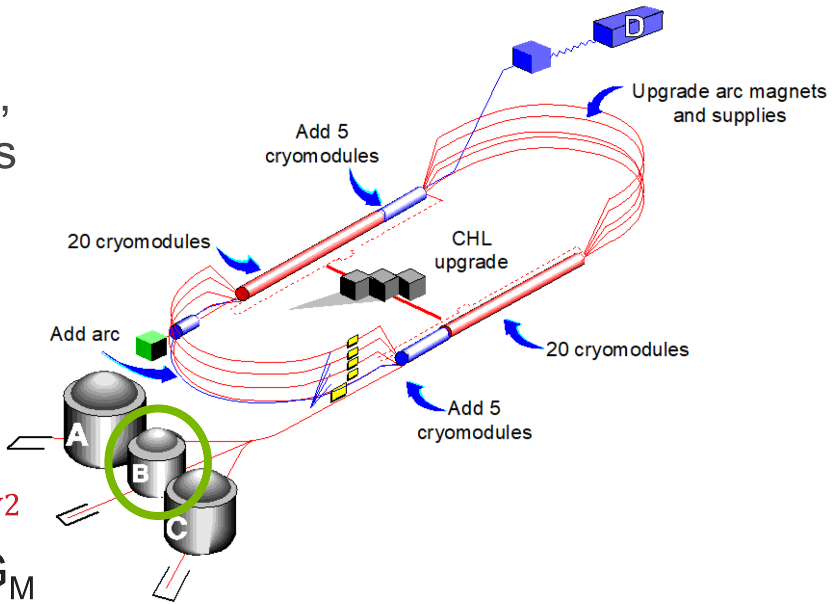
- Modern precision measurements require improvement of radiative corrections
  - NLO beyond URA for ep and ee (e.g., Akushvich et al. 2015)
  - Exact QED treatment for first-order Bremsstrahlung (e.g., ESEPP)
  - NNLO calculations (e.g., McMule)
  - Monte-Carlo simulation (GEANT4) with detailed geometry description for external effects

- Only **indirect** tests from experimental inputs
  - Unfolded data show “good agreements” with other predictions

- **PRad data** provide direct test to the calculations of radiative effects

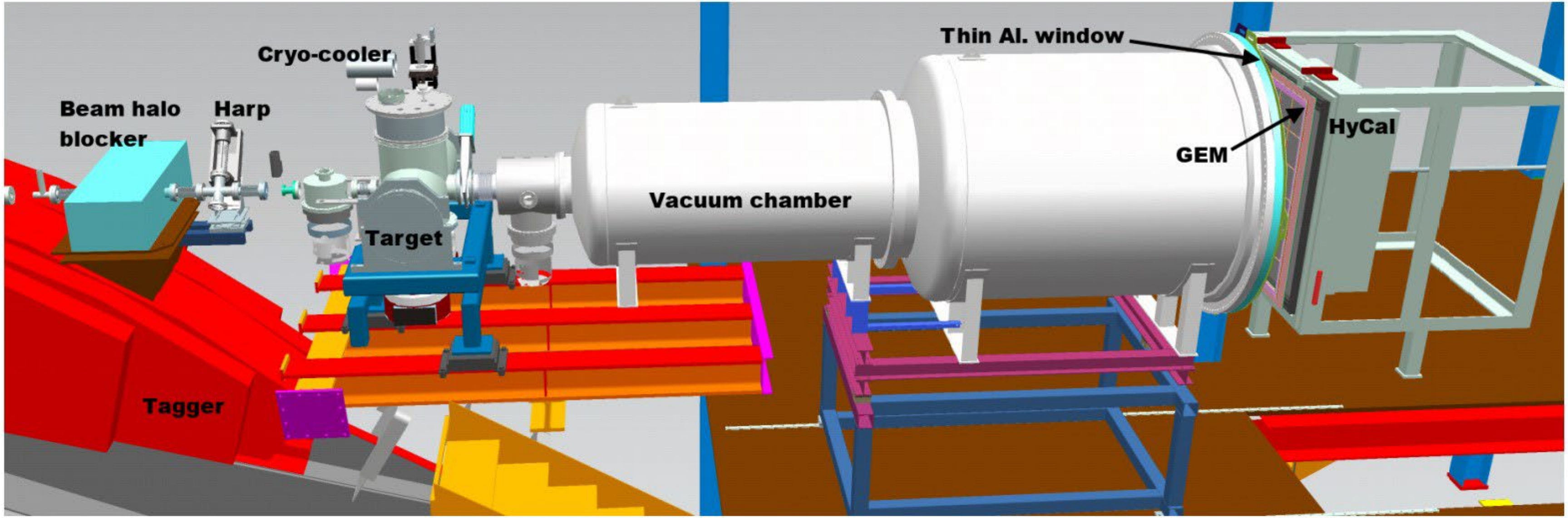
Proton Charge Radius Experiment

- Precision measurement of elastic *ep* and *ee* scatterings at low Q^2
- PRad data taking May/June 2016 at JLab, with 1.1 GeV and 2.2 GeV electron beams
- Uniqueness of PRad experiment
  - Magnetic-spectrometer-free , Large acceptance
  - Windowless gas flow target (normalization to Møller)
  - Unprecedented low-Q^2, $2 \times 10^{-4}\ \mathrm{GeV}^2$
  - Extreme forward angle -> minimize G_M



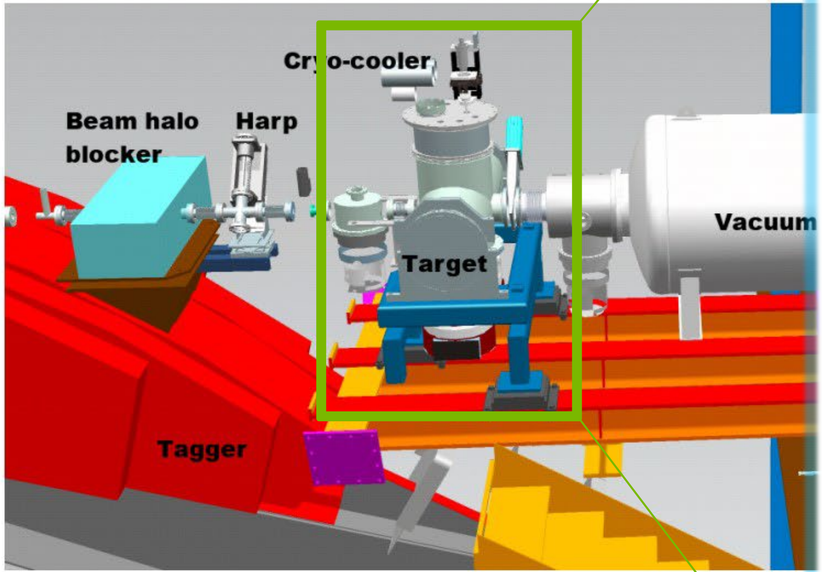
PRad Apparatus

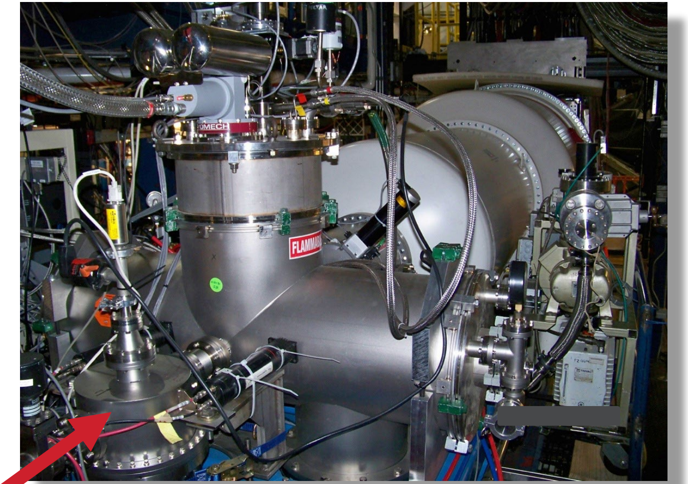
Large acceptance, small angle and non-magnetic apparatus

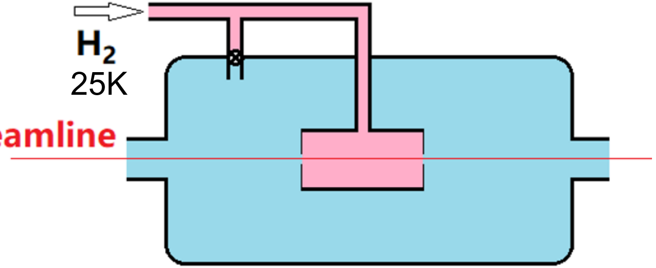


PRad Apparatus

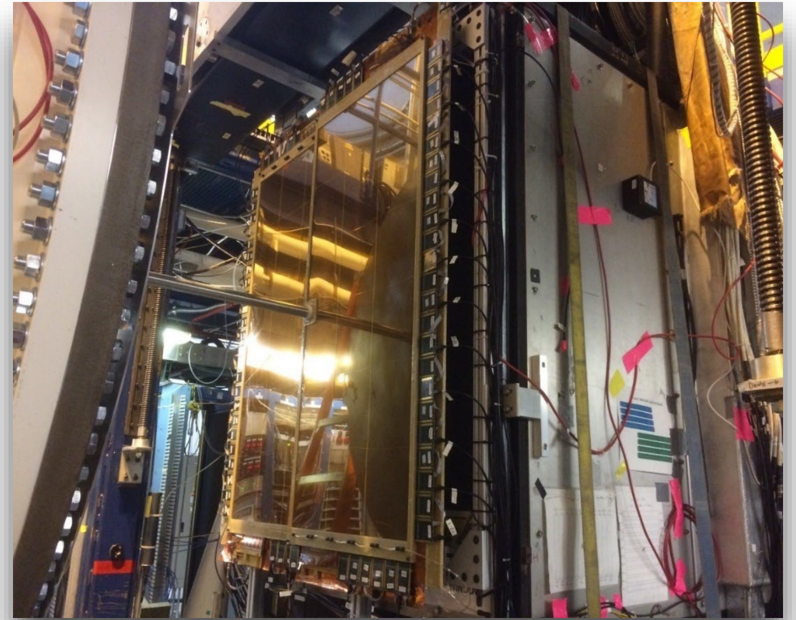
Large acceptance, small a



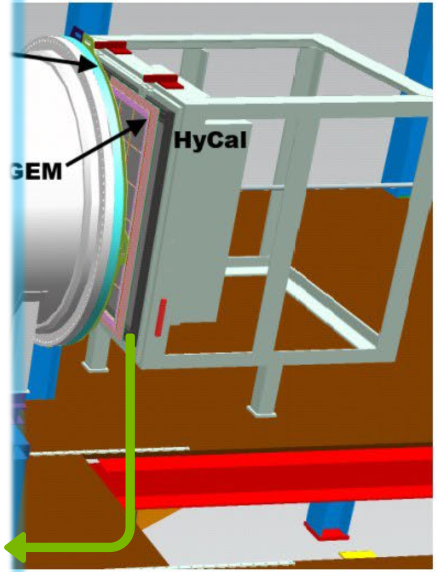




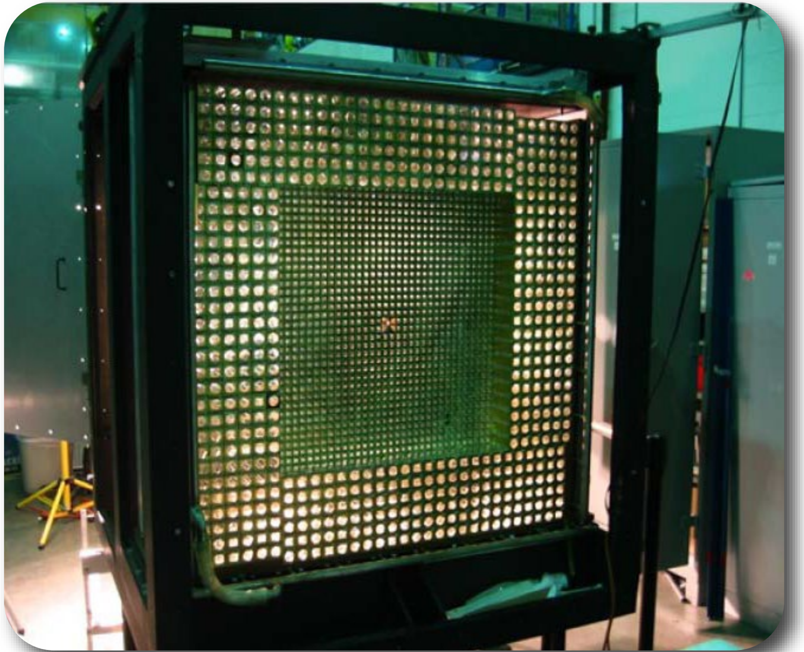
PRad Apparatus



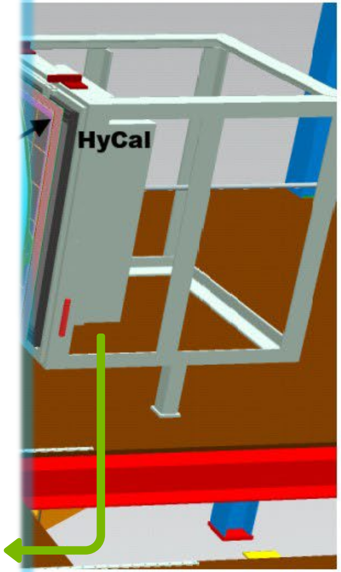
- Two large area GEM detectors
- Small overlap region in the middle
- Excellent position resolution (72 μm)



PRad Apparatus

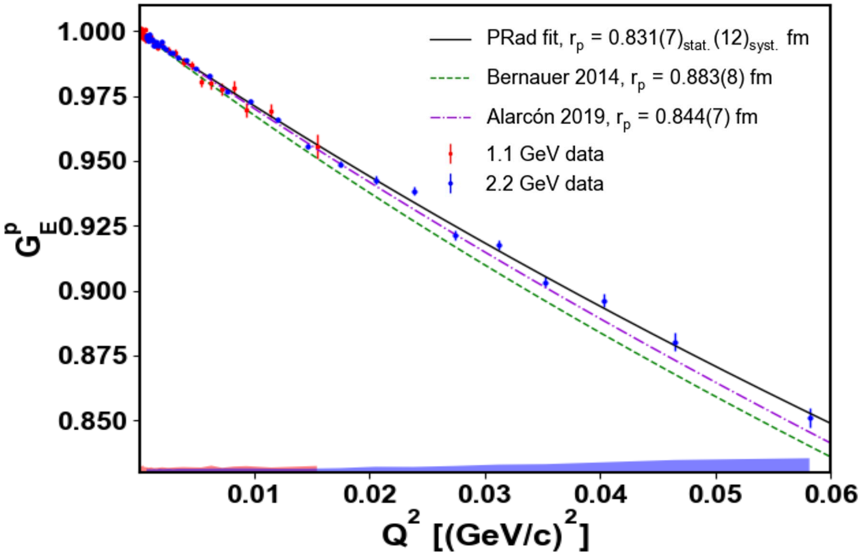


- Hybrid EM calorimeter (HyCal: Lead Tungstate + Lead Glass)
- Scattering angle coverage: ~ 0.7° to 7.0°
- Full azimuthal angle coverage
- High resolution and efficiency

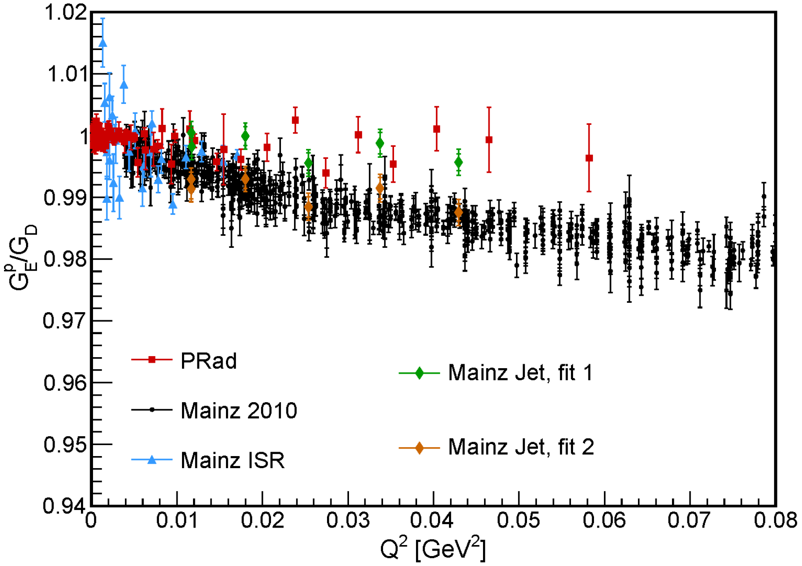


PRad Result and Data Tension

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



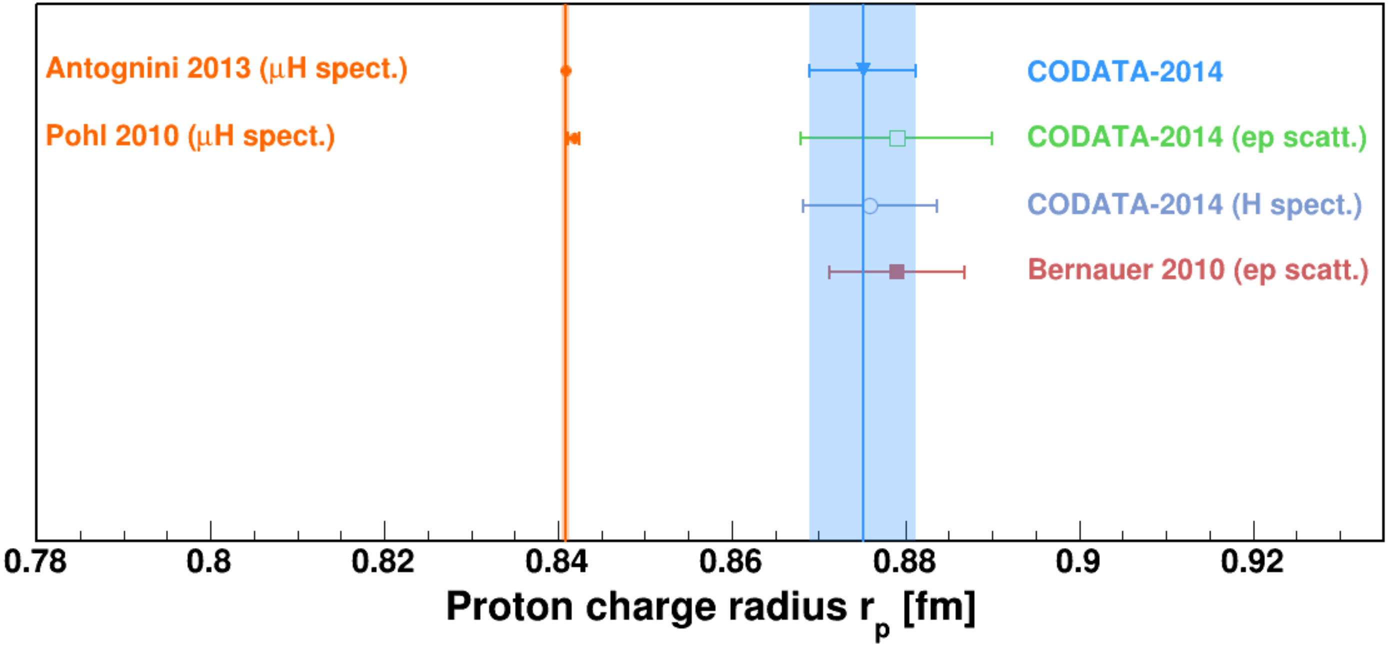
W. Xiong et al. Nature 575 (2019) 7781



W. Xiong and C. Peng, Universe 2023, 9(4), 182

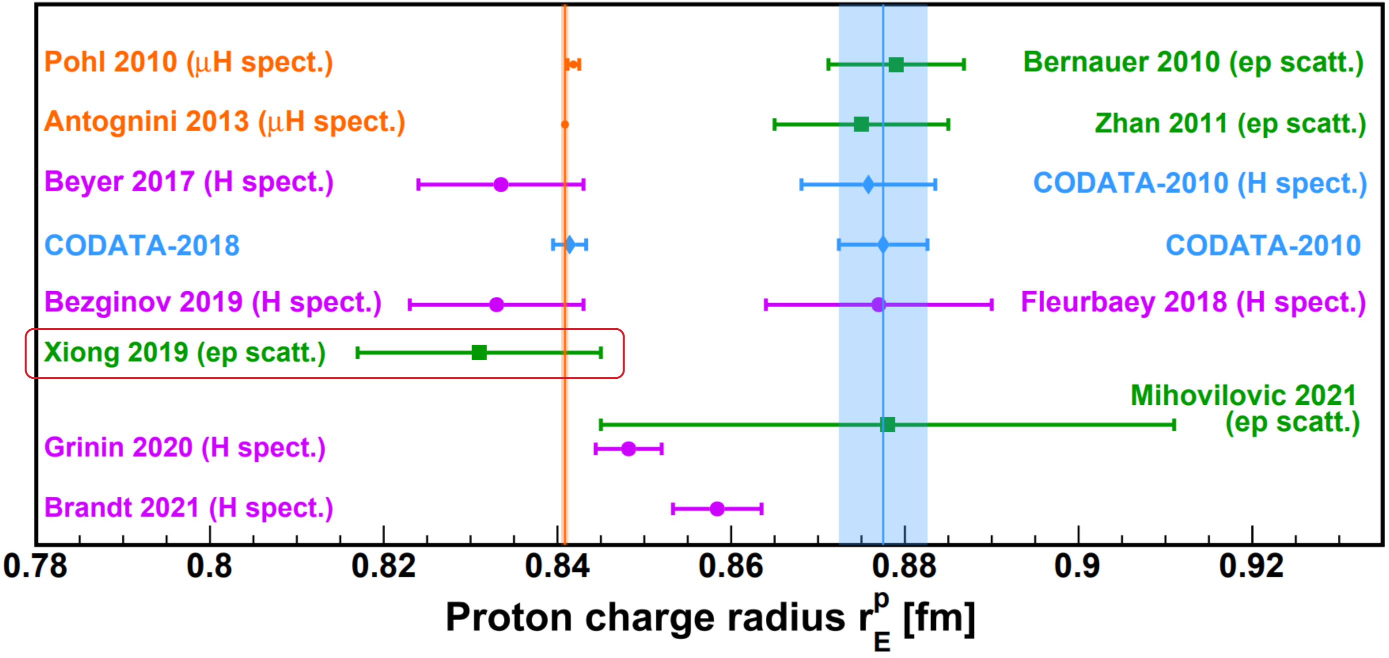
Proton Charge Radius “Puzzle”

What the puzzle looks like **10 years ago**



Proton Charge Radius "Puzzle"

As of today

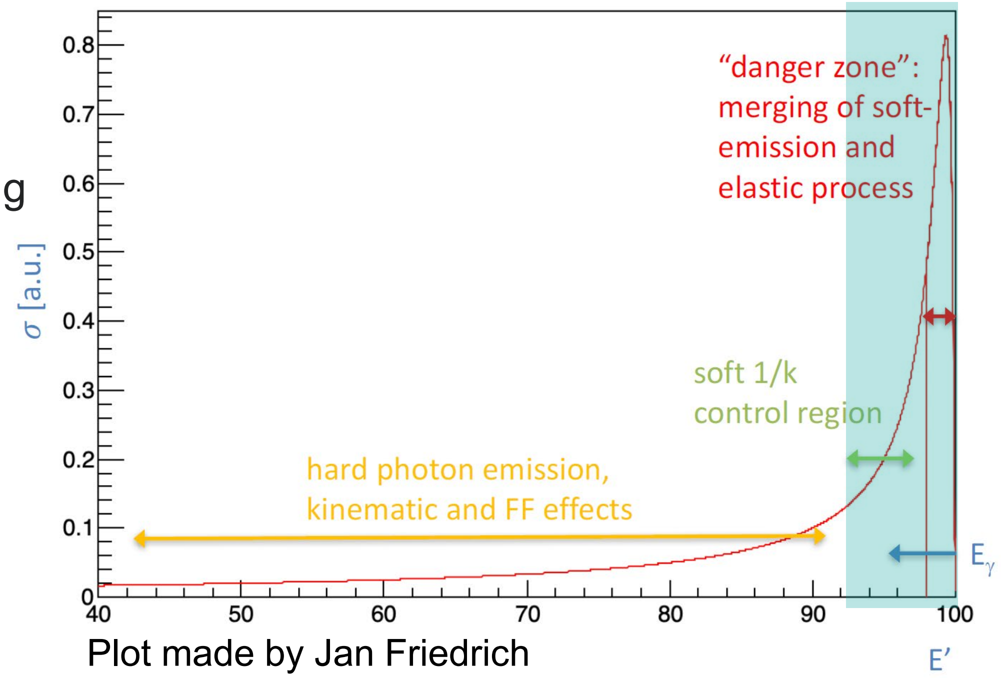


Radiative Photons "Under" Elastic Peak

- Finite energy resolution in the experiment -> "elastic peak" in experimental data is a merging peak of elastic process and Bremsstrahlung process

- Measured elastic peak
  - Convoluted with internal corrections and Bremsstrahlung
  - External energy loss shifts the measured kinematic variables

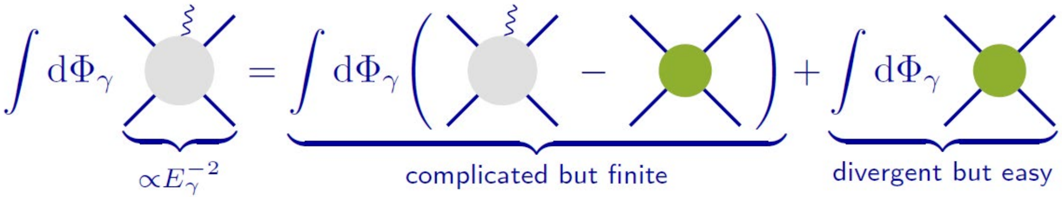
~Experimental ΔE Cut



Plot made by Jan Friedrich

“Tricky” Part in Bremsstrahlung

- Transformation to get infrared-divergent-free part of Bremsstrahlung
  - Cancellation happens between different correction terms
  - Small correction but not necessarily small uncertainty

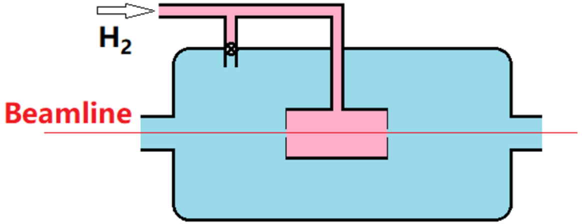


- An arbitrary energy scale ΔE is used to separate “soft” and “hard” Bremsstrahlung
  - Often chose to be smaller than detector resolution
  - “Soft” radiative photons absorbed into the elastic peak (similar to virtual corrections)
  - Multi-photon emission taken cared by exponentiation (difficult to calculate higher orders)

$$\sigma \cdot e^{\delta} = \sigma \left(1 + \delta + \frac{\delta^2}{2} + \cdots\right)$$

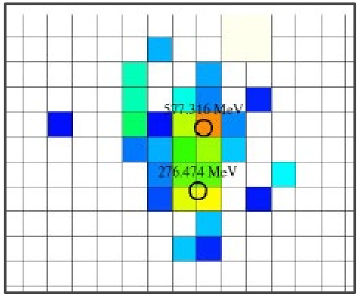
Measurement of Radiative Photons in PRad

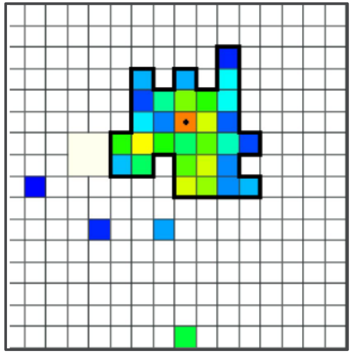
- HyCal to measure photon energy and information
  - Crystal part has a small merging distance for clusters (~ 3 cm)
  - Long distance between target and detector (~5.6 m)
  - Minimum opening angle of $0.3°$
  - Photon energy measurement down to 20 MeV
- GEM to identify photons from electrons
  - Sensitive to charged particles only
  - Contamination from other types of particles are small due to kinematics
- Negligible ISR from window-less target
  - Easy to correct external effects on scattered electron arm

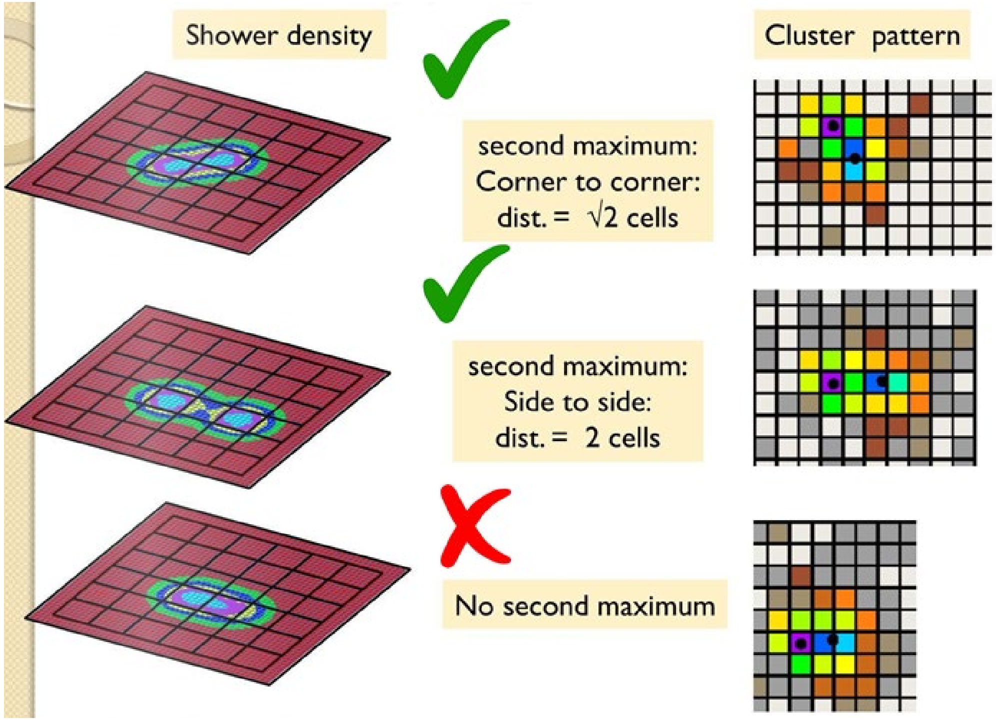


Separation of Radiative Photons

- Cluster splitting on HyCal
  - Minimum separation: corner to corner
  - Energy threshold on 20 MeV (choice based on resolution 2.6%/$\sqrt{E}$)





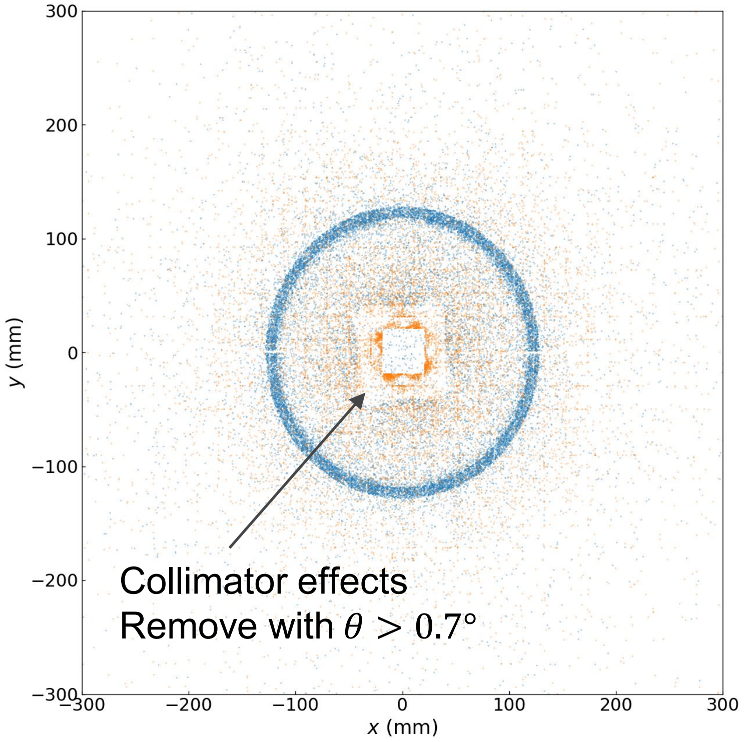


I. Larin, HyCal Clustering

Møller Ring with Radiative Photons

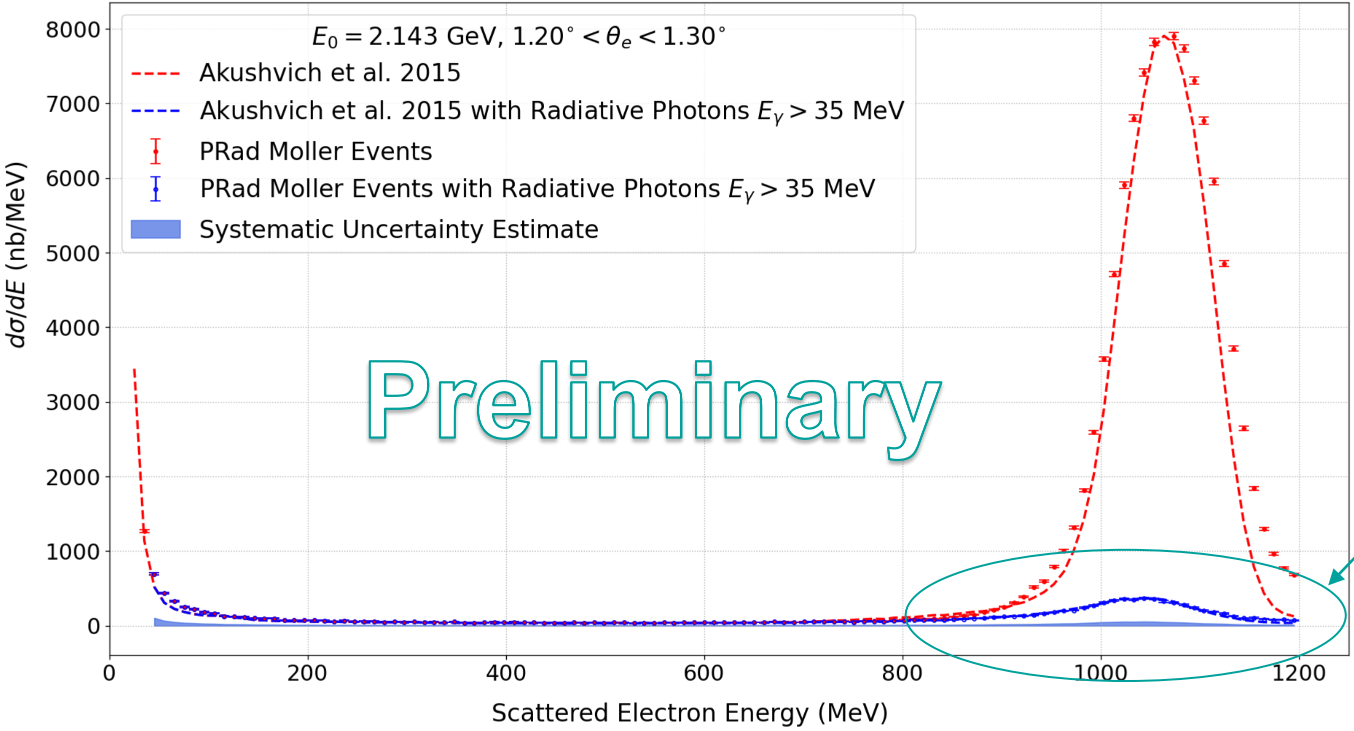
Geometrical distribution

- Radiative events selection
  - ep – coincidence of scattered electron and the radiative photon(s) + elasticity
  - ee – coincidence of two electrons and the radiative photon(s) + elasticity + coplanarity
- The symmetric Moller ring selection
  - Single-arm selection at $1.2° < \theta_e < 1.3°$
  - Elasticity cut with 3.5 σ_E
  - Co-planarity cut
  - Geometrical cut to remove collimator effects



Radiative Møller Events

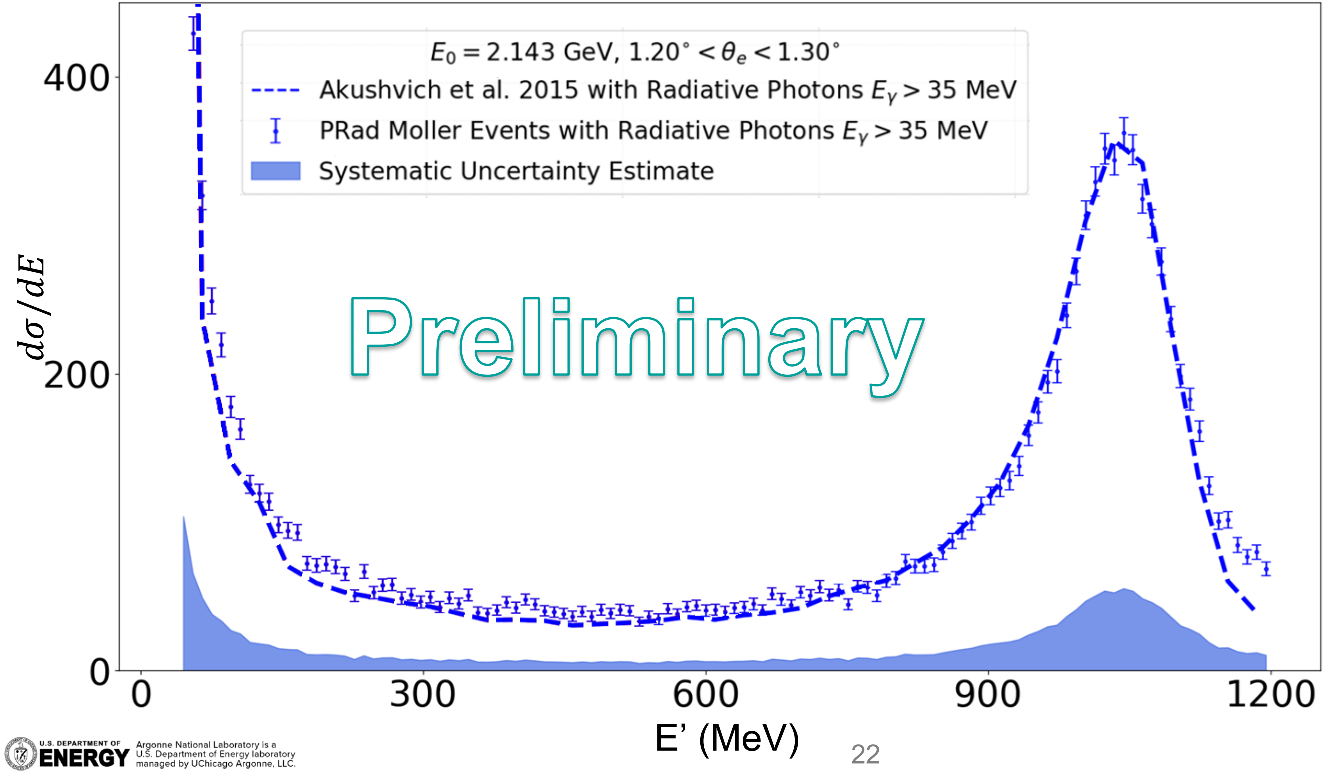
Scattered electron energy distribution



Bremsstrahlung buried under elastic (Moller) peak

Radiative Møller Events

Scattered electron energy distribution



Ongoing work for distributions over opening angle and photon energies

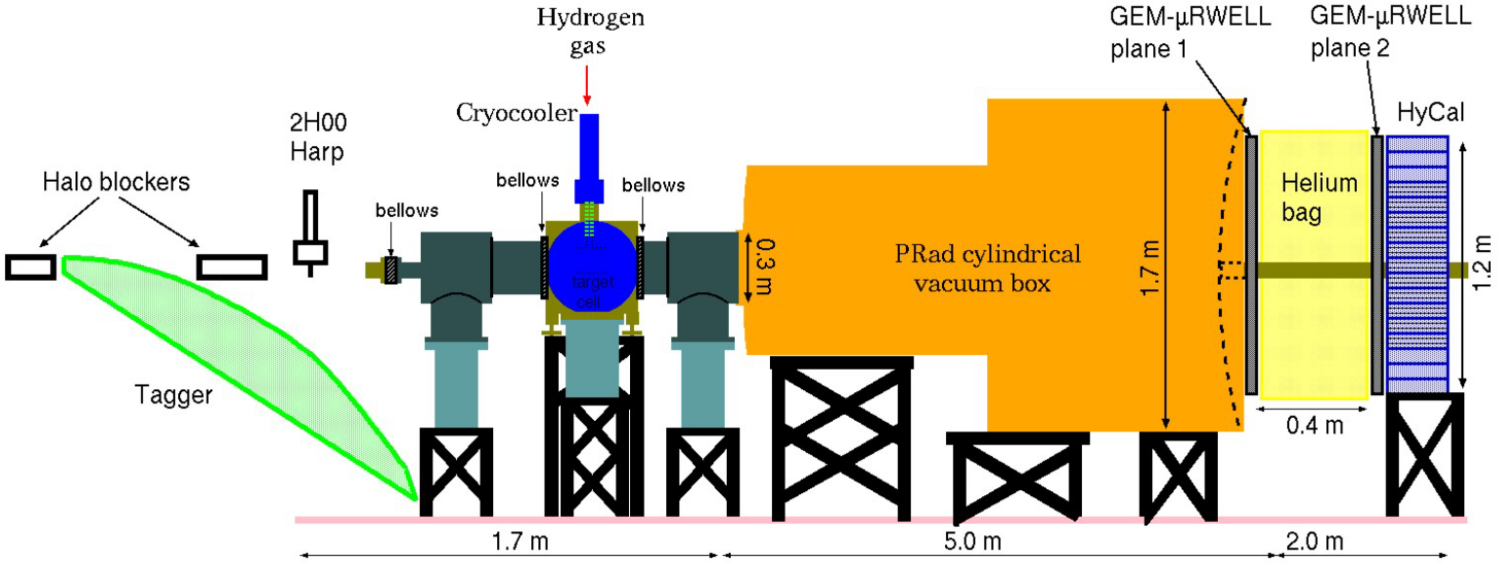
Future Results and Improvement from PRad-II

- Radiative photon distributions
  - Opening angle θ_γ and energy E_γ
  - All Møller events
  - Elastic *ep* events

- Improvement with PRad-II data
  - Higher statistics (critical for two-dimensional distribution of radiative photons)
  - Better PID efficiency with two GEM planes

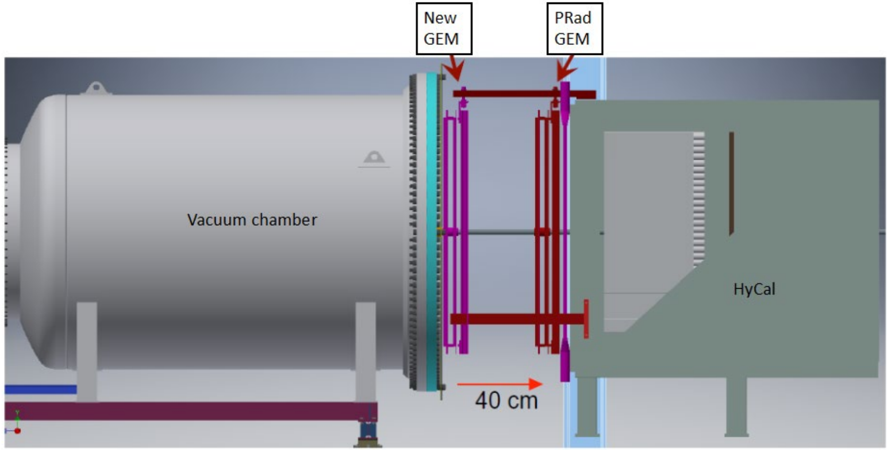
PRad-II Experiment

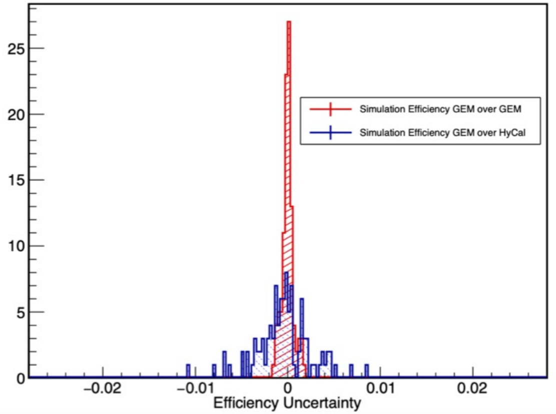
- JLab PAC 48 approved PRad-II (PR12-20-004) with the highest scientific rating “A”
- Goal: reach ultra-high precision (~4 times smaller total uncertainty), resolve tension between modern *e-p* scattering results

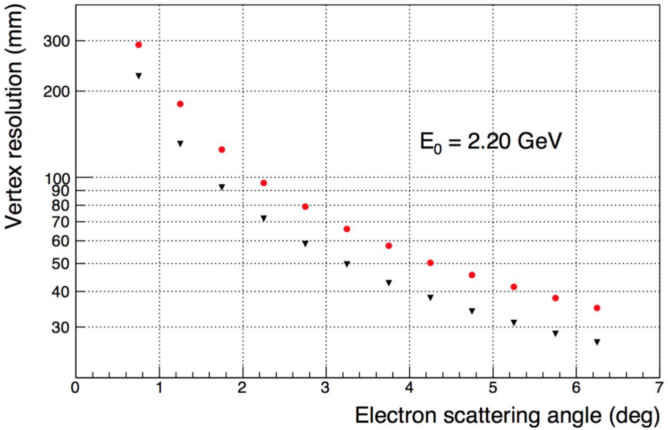


PRad-II Experiment

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

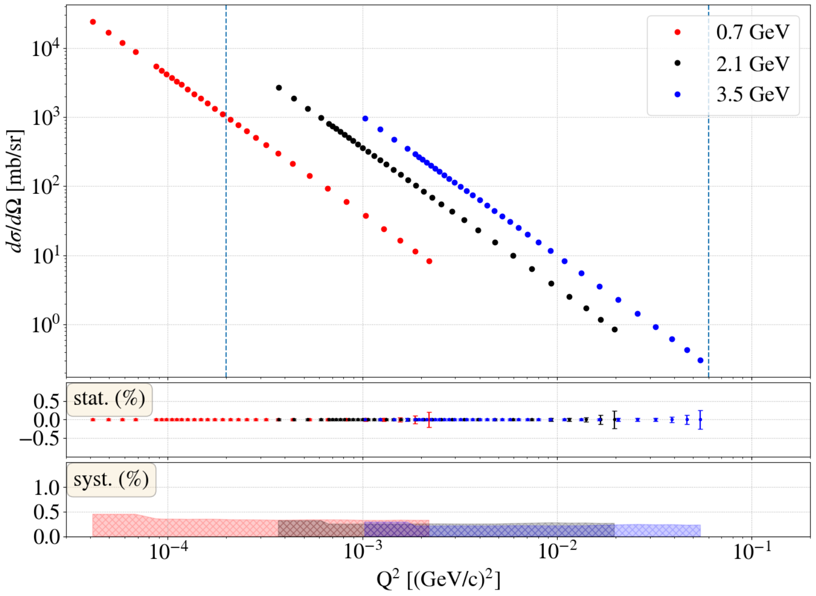


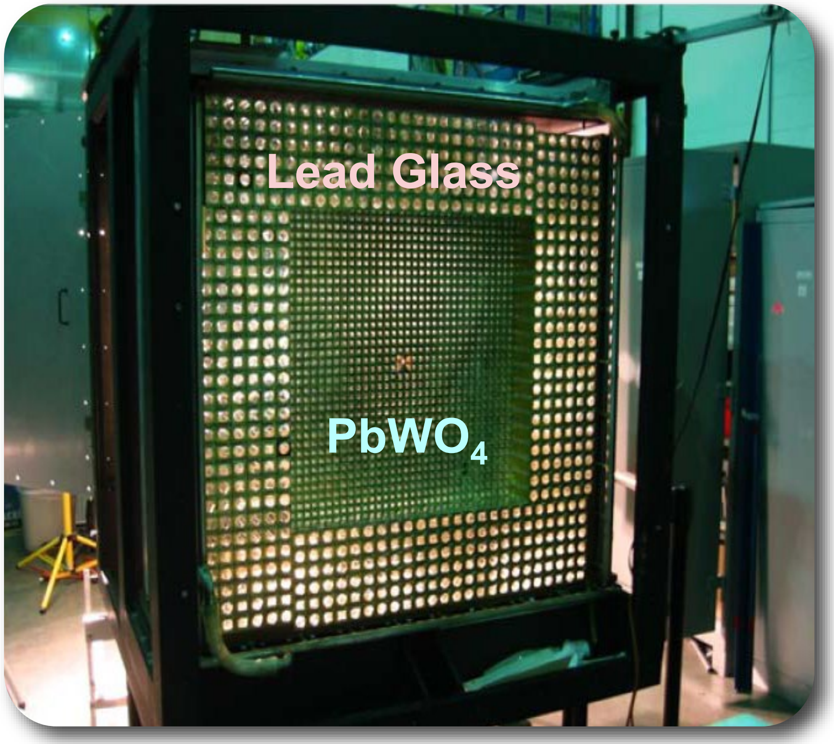




PRad-II Experiment

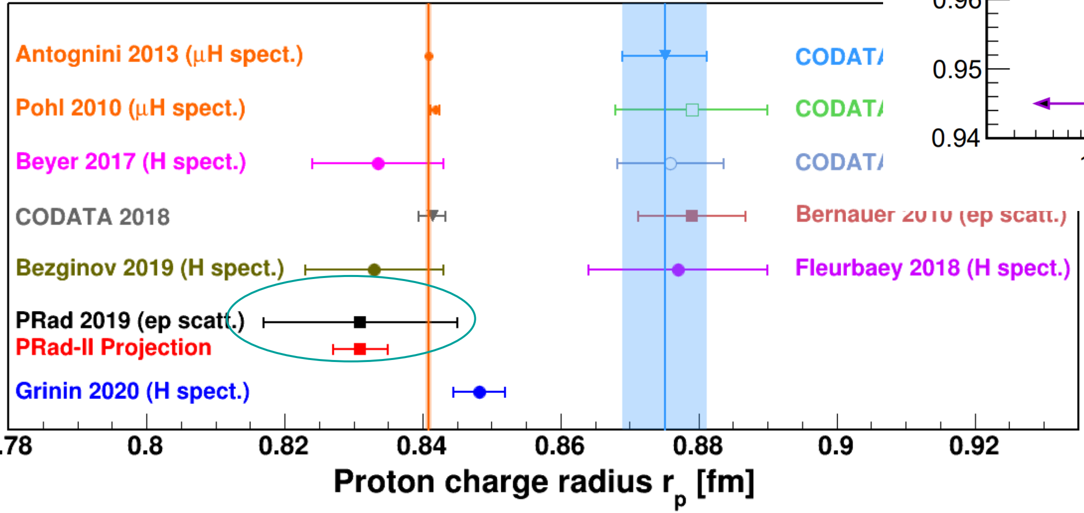
- More statistics, using high resolution $PbWO_4$ modules only

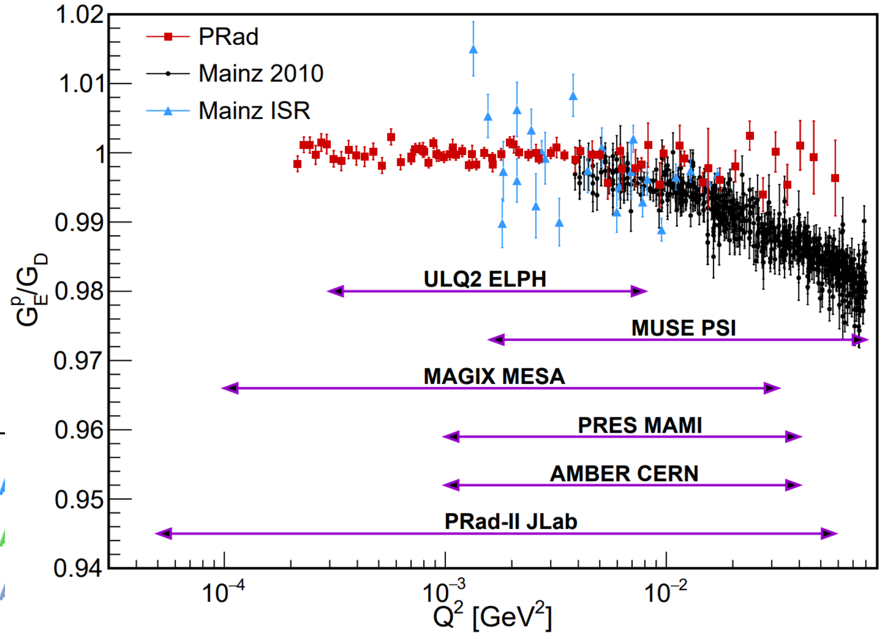




PRad-II Projections

- A factor of >3 improvement on extracted radius uncertainty
- More precise data to resolve G_E data tension





And better measurement of radiative photons!

Summary

- Direct measurement of radiative photons in PRad data
  - Experimental input to the direct test of radiative corrections for *ep* and *ee* scattering
  - Negligible effect on ISR due to window-less target
  - Measurement of radiative photon distributions
  - Limitation on the minimum photon energy and PID efficiency
- Expect a significant improvement from PRad-II
  - Wider kinematic coverage, higher statistics
  - Better PID and efficiency with two GEM detectors

THANK YOU

BAKCKUP SLIDES

Nucleons

- Nucleons (protons and neutrons) are the primary building blocks of the visible universe
- Composite of quarks (and anti-quarks), bound by exchange of gluons
  - Intensively interacting and highly correlated at low energy scale
  - Quantum Chromodynamics (QCD)
- Understand its emergent properties from QCD
  - Spin, mass, charge radius, etc…
  - Fundamental challenge lies in the non-perturbative regime