

Update on Ongoing PRad-II and X17 Search Experiments (run group “O”)

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NC A&T SU

for the PRad-II/X17 collaboration

CLAS collaboration meeting, June 29, 2026

Outline

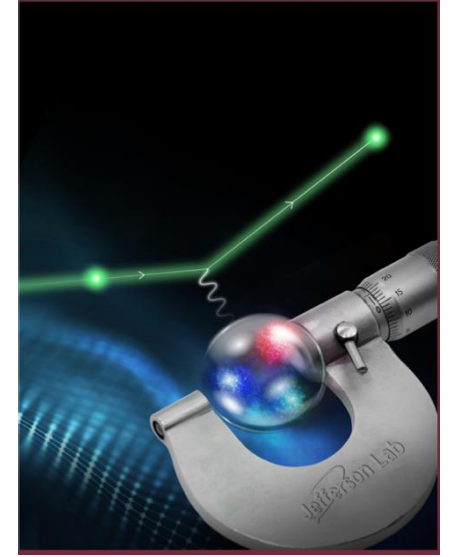
- what the PRad-II is going to improve
- experimental improvements and preliminary results
- the second experiment: X17 Search
- current experimental status
- summary and outlook

The Goals of Current Runs

1) PRad-II experiment:

Measure ep-elastic diff. cross sections at extreme forward angles ($\vartheta_e = 0.4^\circ - 3.5^\circ$) to extract:

- proton **electric form factor** at $Q^2 = 2 \times 10^{-5} \div 6 \times 10^{-2} \text{ GeV}^2/c^2$
- proton **charge radius** with a factor of 3 better accuracy than PRad-I



2) X17 Search experiment:

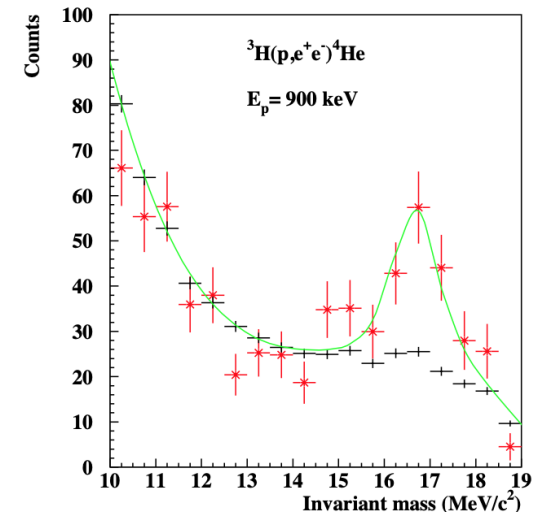
Electroproduction of yet unknown hypothetical particles on heavy nucleus in forward directions:

$$e^- + \text{Ta} \rightarrow e' + \gamma^* + \text{Ta} \rightarrow e' + X + \text{Ta}, \quad \text{with} \quad X \rightarrow e^+e^- \text{ (with tracking)}$$
$$\text{and} \quad X \rightarrow \gamma\gamma \text{ (without tracking)}$$

in [3 - 60] MeV mass range.

With two experimental objectives:

- validate **existence or establish an experimental upper limit** on the electroproduction of the hypothetical X17 particle;
- Search for “**hidden sector**” intermediate particles in [3 – 60] MeV mass range.



The PRad (and PRad-II) Experimental Approach

- PRad developed a novel experimental approach for the **radius measurement** including:

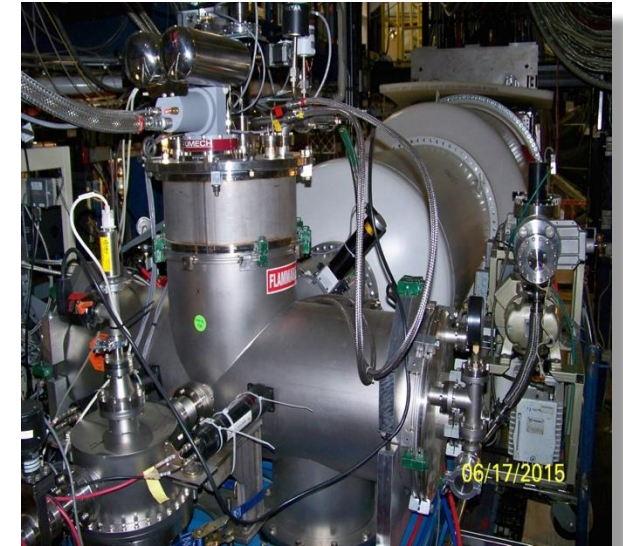
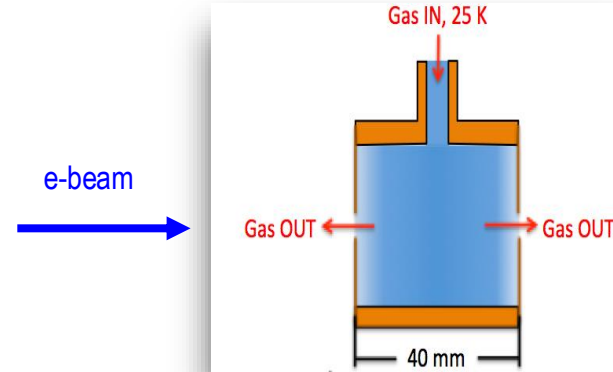
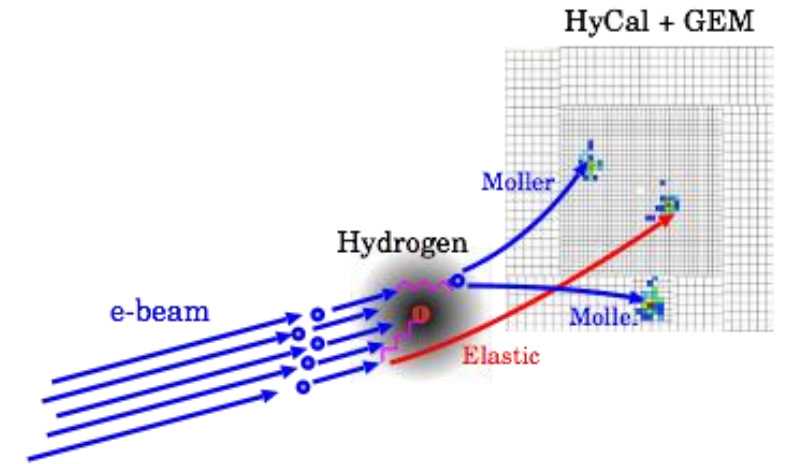
- 1) Use large acceptance, high resolution electromagnetic **calorimeter** (HyCal) and **two plains of large GEM** coordinate detectors for **tracking** providing access to:

- ✓ **measure all angles in one experimental setting** ($\vartheta_e = 0.4^\circ - 7.0^\circ$) ($Q^2 = 2 \times 10^{-5} \div 6 \times 10^{-2}$) GeV^2/c^2 ;
- ✓ **access to smaller angles** ($\vartheta_e \approx 0.5^\circ$);
- ✓ **azimuthal symmetry of the setup provides simultaneous detection of $ee \rightarrow ee$ Moller events**, providing a robust calibration of ep-cross sections with a **well-known QED process**;

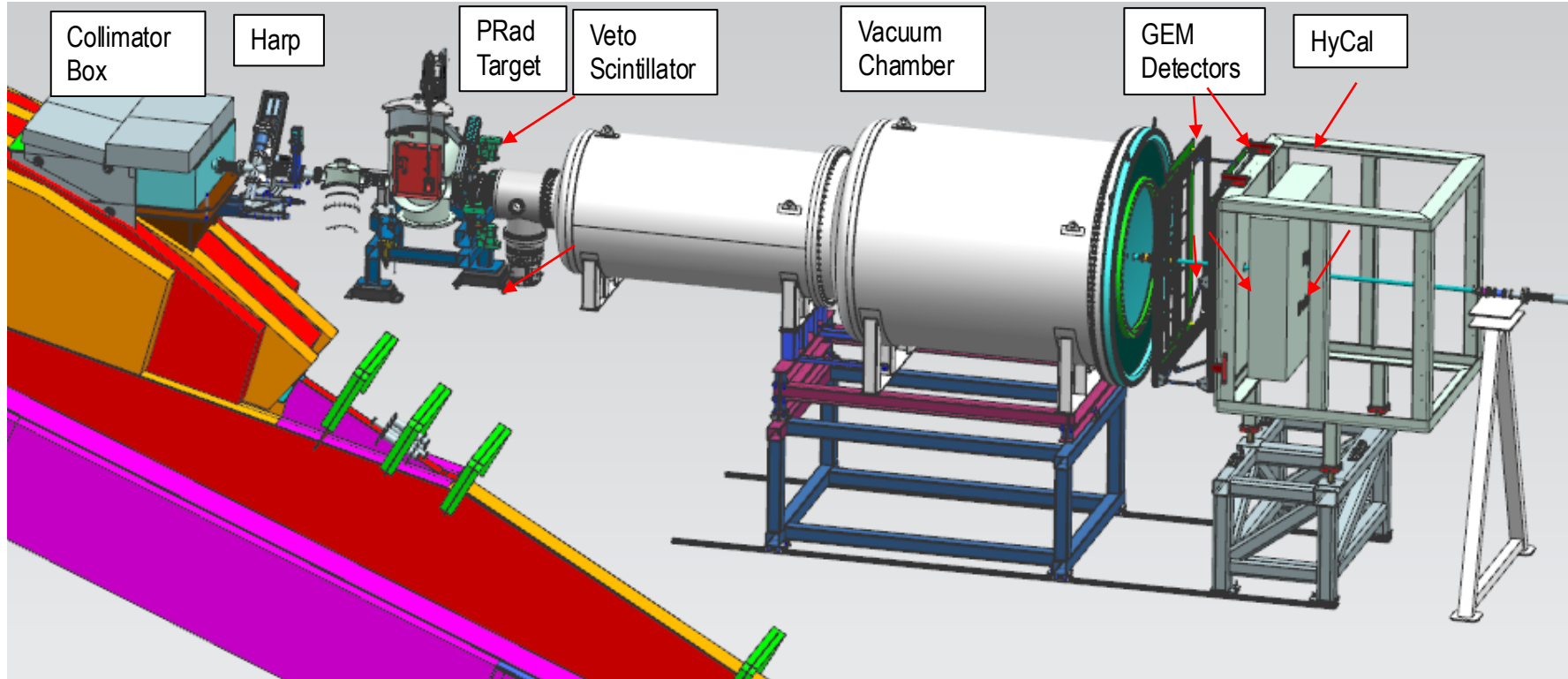
- ✓ **best known control of systematics.**

- 2) Use **windowless H_2 gas flow target**:

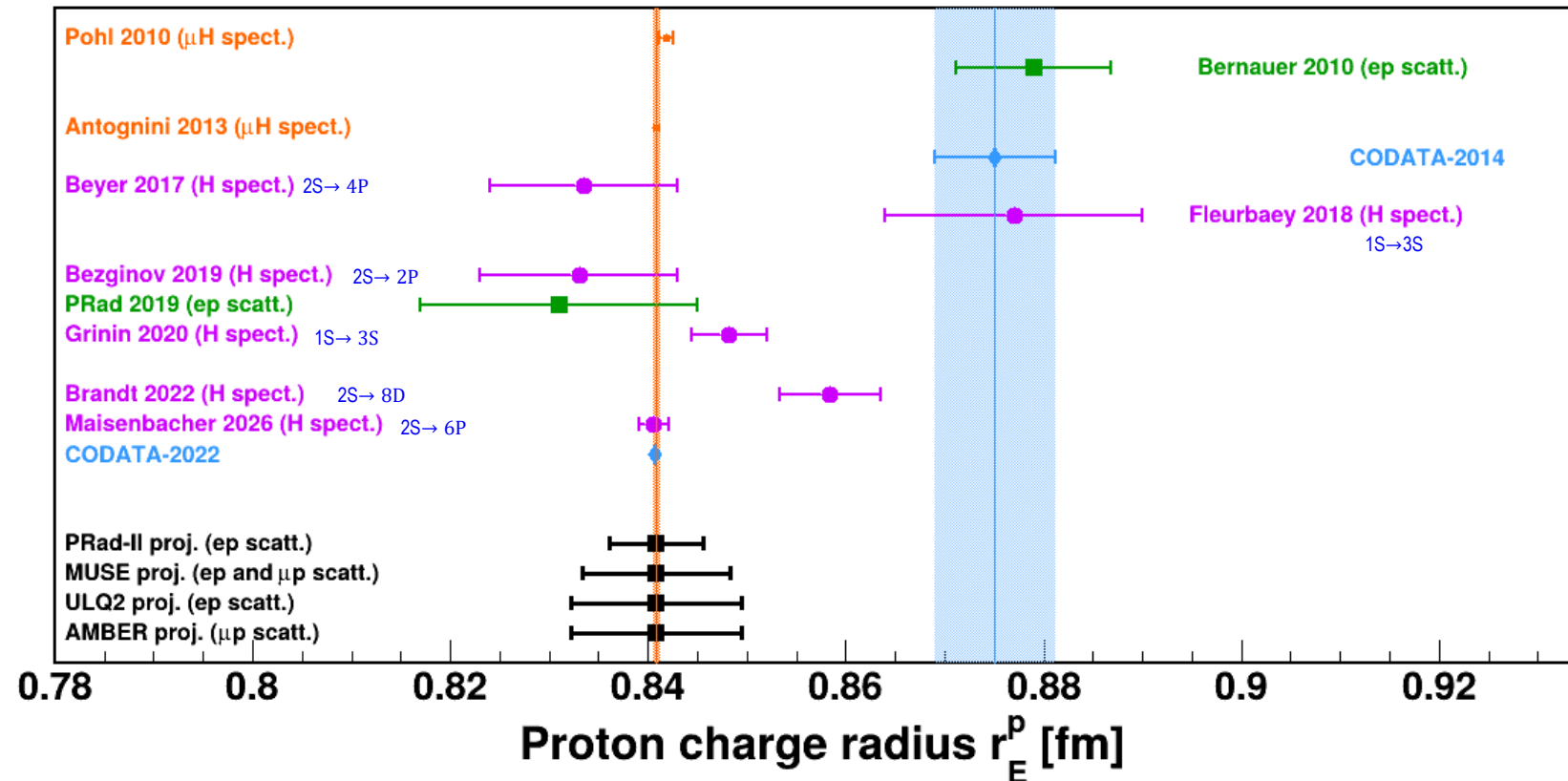
- ✓ **minimize experimental background.**



Schematics of the PRad-II Experiment (E12-20-004)



Why New PRad-II Experiment: Today's Status of the Proton Radius Puzzle



- With the recent atomic spectroscopy experiment ([Nature, 2026, Garching, Germany](#)), the **Puzzle**, on the spectroscopy level, is considered to be resolved.
- For the scattering sector: **difference** between PRad and all other ep- scattering experiments is on 3σ level only. New **high accuracy ep- or μp - scattering experiments are needed.**

Why New PRad-II Experiment: Today's Status of the G_E^P at Small Q^2 Range

- There is certain **discrepancy** between two very recent G_E^P **form factor** precision measurements: PRad-I and A1 MAMI at Mainz.
- New **high accuracy ep-scattering experiments** are needed to address these differences.
- PRad-II experimental goals:
 - high accuracy G_E^P measurement in a wide Q^2 range: $Q^2 = 10^{-5} - 10^{-2}$ GeV^2 ;
 - reach the $Q^2 = 10^{-5}$ GeV^2 range
 - a factor of **3 improvement on Rp**

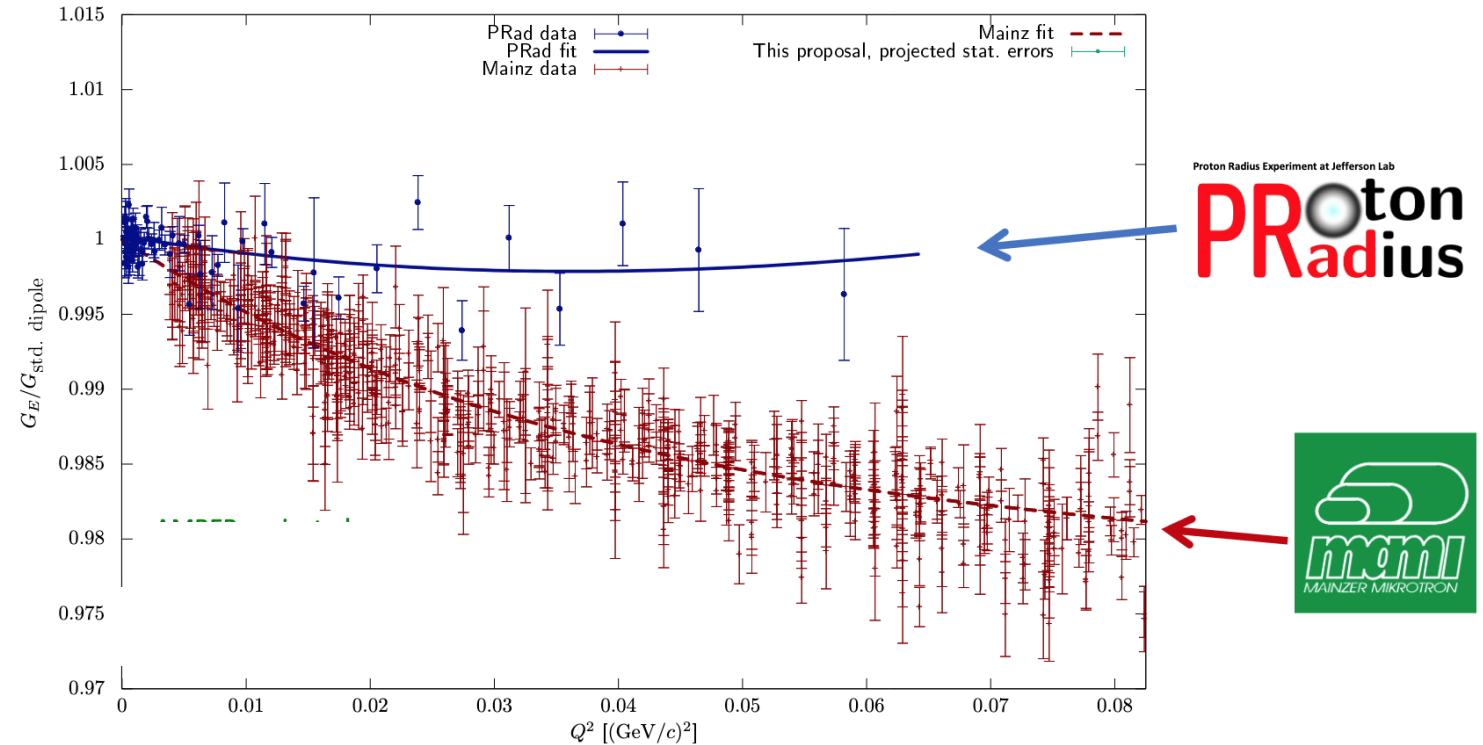


figure: J. Bernauer

The PRad-II Improvements over the PRad Experiment

1) Order of magnitude improvement on statistics \Rightarrow reaching to 4 times less statistical uncertainties:

- ✓ upgrade the DAQ rate to 25 kHz by implementing new fADC based system;
- ✓ increase the H₂ gas flow target density by a factor of 2 (by gas flow rate and temperature);
- ✓ slightly more beam time.

1) Improve the systematics by upgrading the PRad experimental setup:

- ✓ adding full tracking capability (second plane of GEM detectors);
- ✓ significantly improving the beamline vacuum, including the scattering chamber;
- ✓ upgrade DAQ electronics to fADC based system (new trigger and fast readout);
- ✓ small-size scintillator detectors downstream the target to veto Moller electrons to reach the 10^{-5} GeV² Q² range;
- ✓ adding new “beam halo blacker” just before the Tagger for less beam background;
- ✓ use the PbWO₄ crystal part only (high energy and position resolutions).

Improvements on Prad-II: DAQ and Readout Electronics

- New **fADC-250** readout electronics has been implemented for all **1200 channel** PbWO_4 crystals
 - ✓ upgrade the **DAQ rate to 25 kHz** by implementing **new fADC based system**;
- New **DAQ system**, combining the new **fADC** and **GEM electronics** has been developed and implemented for this experiment capable of close to 25 kHz readout rate.
- We have been running with about 21 kHz trigger rate and with about 91% life-time

✓

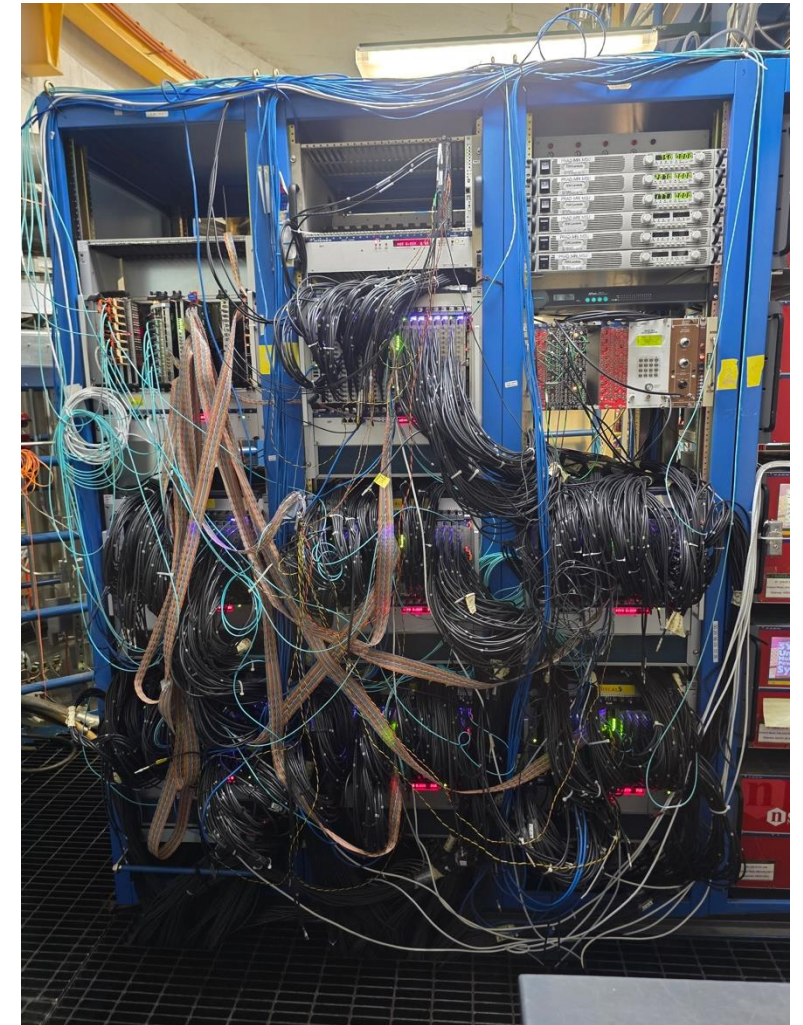
RC-D Trigger

Branch Current	LiveTime	DAQ Rate	
330 Hz	93.7 %	25439 Hz	238 MHz

Physics Triggers	Description	Rate (Hz)	Precedence (Hz)	Preced
0	None-Spec	23888.0	23888.0	0
1	1_Cluster_750	28800.0	28800.0	1
2	2_Cluster_750	34800.0	34800.0	1
3	3_Cluster_750	4488.0	4488.0	1
4	1_Cluster_1400	23376.0	23376.0	1
5	1_Cluster_300	35904.0	35904.0	1
6	1_Cluster_300	23547.0	23547.0	1
7	None	99.0	99.0	1

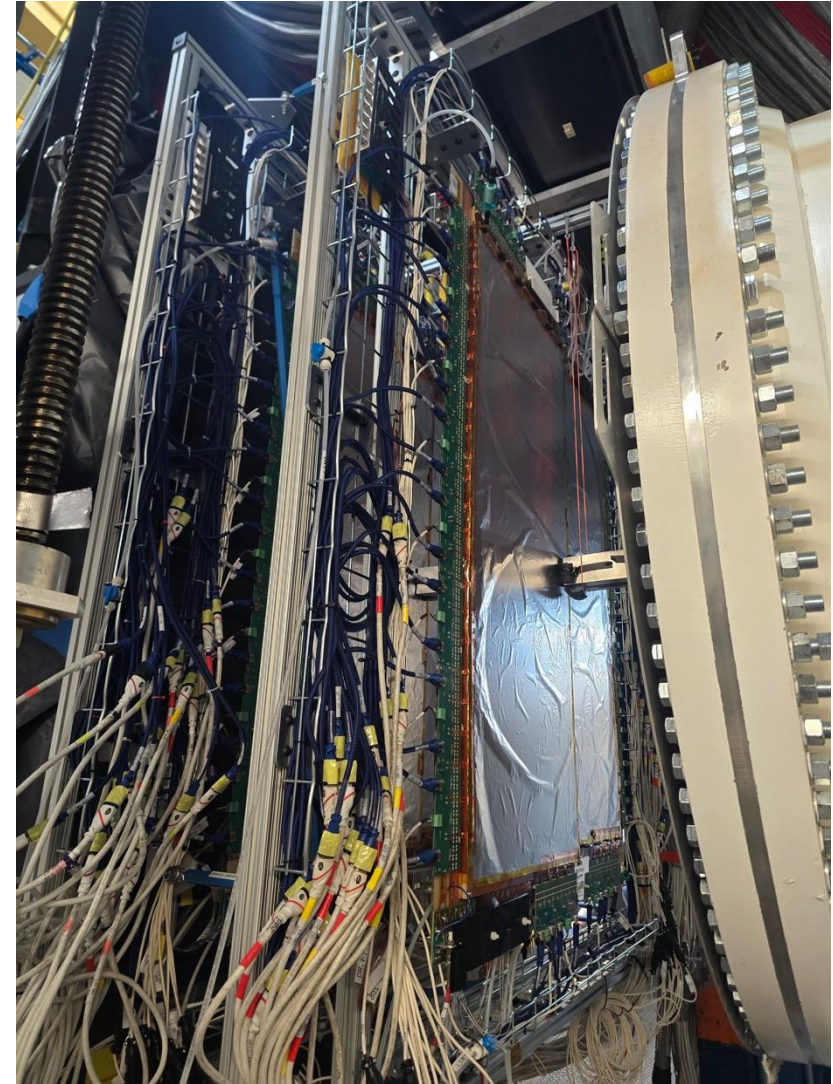
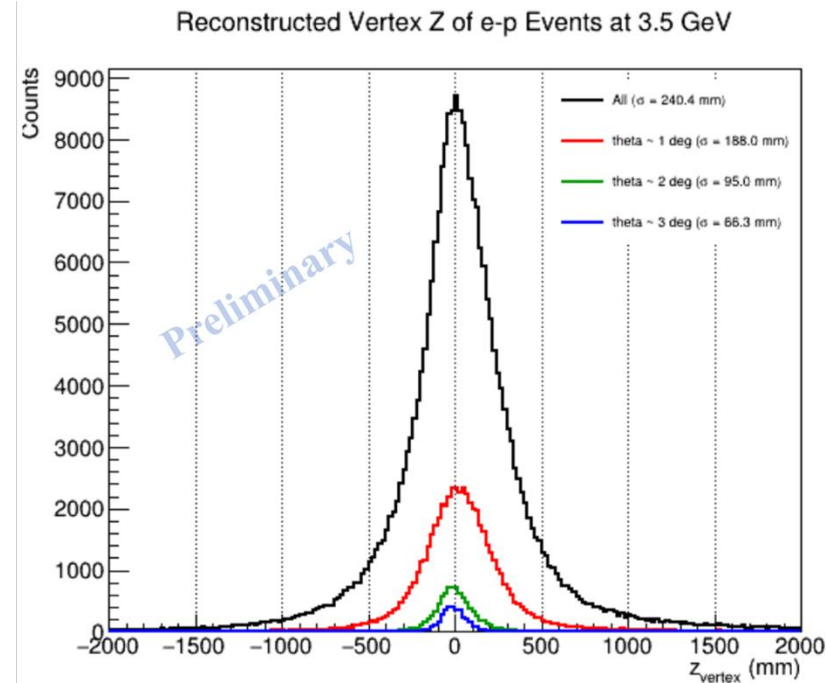
Trig TS Front Panel	Description	Rate (Hz)	Precedence (Hz)	Preced
18	None	20.0	20.0	0
23	None	147.0	147.0	9
24	None	147.0	147.0	9
25	None	147.0	147.0	9
26	None	147.0	147.0	9
27	None	147.0	147.0	9

ROCs	Modules (%)	Rates (MHz)	Errors
1	achtyr02	0.0	achtyr02 0.0%
2	achtyr03	0.0	achtyr03 0.0%
3	achtyr04	0.0	achtyr04 0.0%
4	achtyr05	0.0	achtyr05 0.0%
5	achtyr06	0.0	achtyr06 0.0%
6	achtyr07	0.0	achtyr07 0.0%
7	achtyr08	0.0	achtyr08 0.0%
8	achtyr09	0.0	achtyr09 0.0%
9	achtyr10	0.0	achtyr10 0.0%
10	achtyr11	0.0	achtyr11 0.0%
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98	achtyr99	0.0	achtyr99 0.0%
99	achtyr100	0.0	achtyr100 0.0%



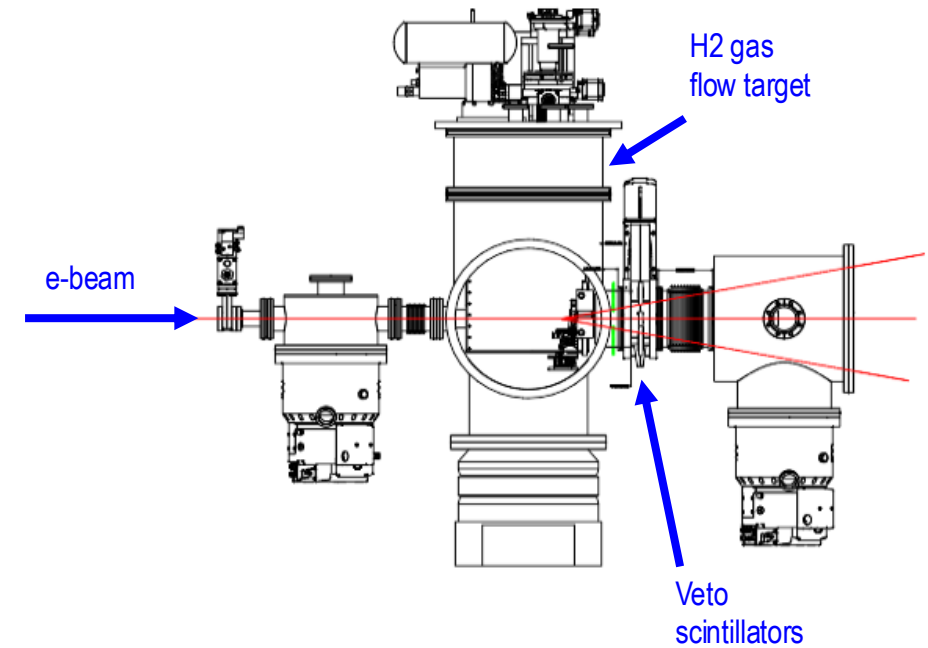
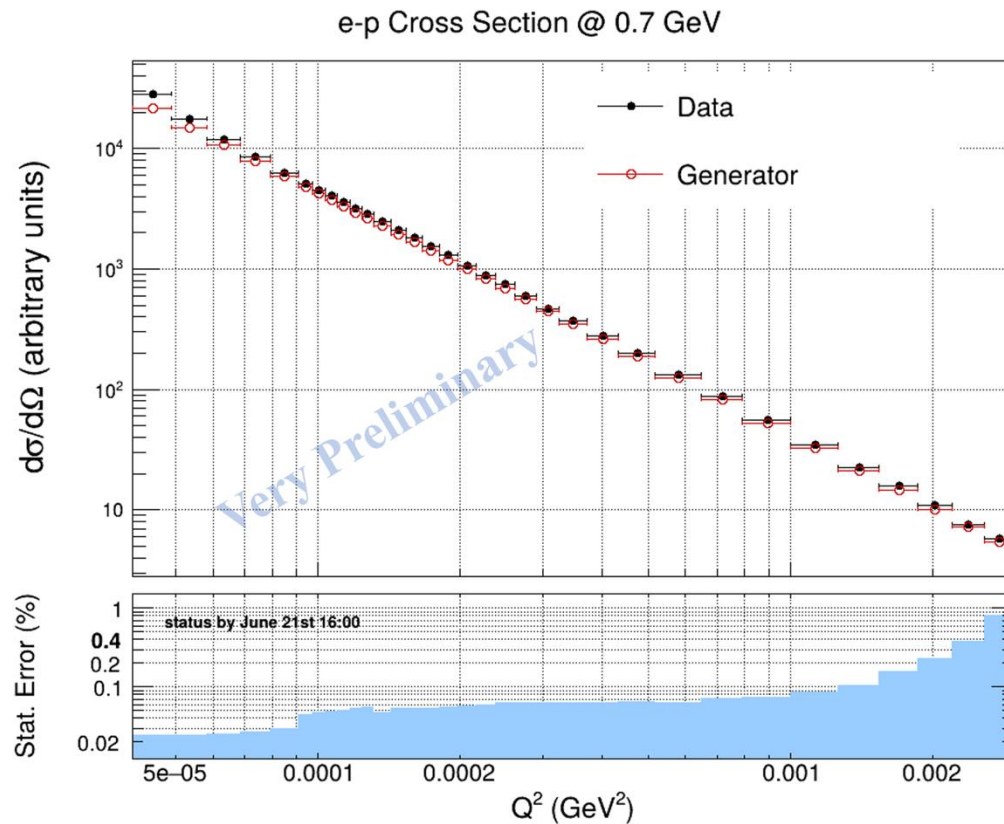
Improvements on Prad-II: 2 GEM Planes, Tracking

- Two planes of four GEMs developed and successfully implemented in this experiment to provide better tracking capability.
- 25 kHz DAQ rate achieved with standard GEM electronics.
- Provided a moderate vertex reconstruction (about 18 cm at 1 degrees).
- Critical for beam background.



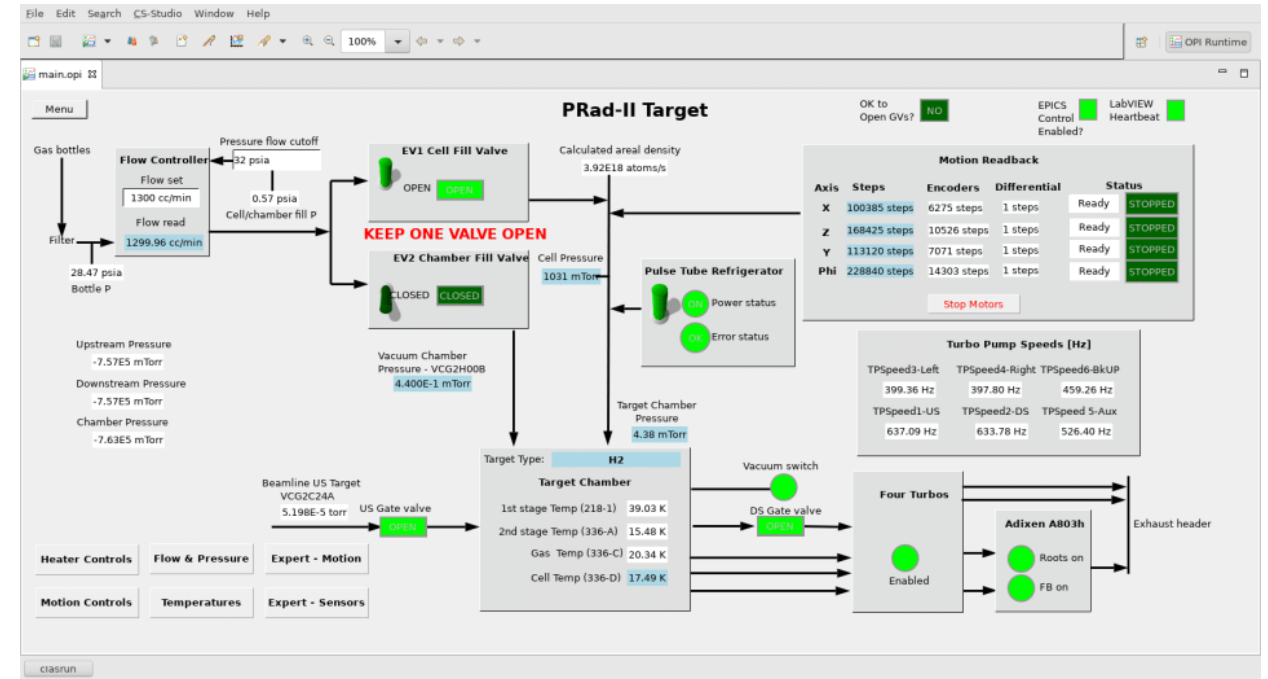
Improvements on Prad-II: Small-sized 4 Veto Scintillators

- New scintillator detectors to Reach the $Q^2=10^{-5}$ GeV² Range:
 - ✓ 4 small scintillator detectors placed next to the H2 gas flow target chamber.
 - ✓ size: $4 \times 6 \times 0.3$ cm³
 - ✓ remotely movable perpendicular to the beam direction.



Improvements on Prad-II: more gas density in H2 target

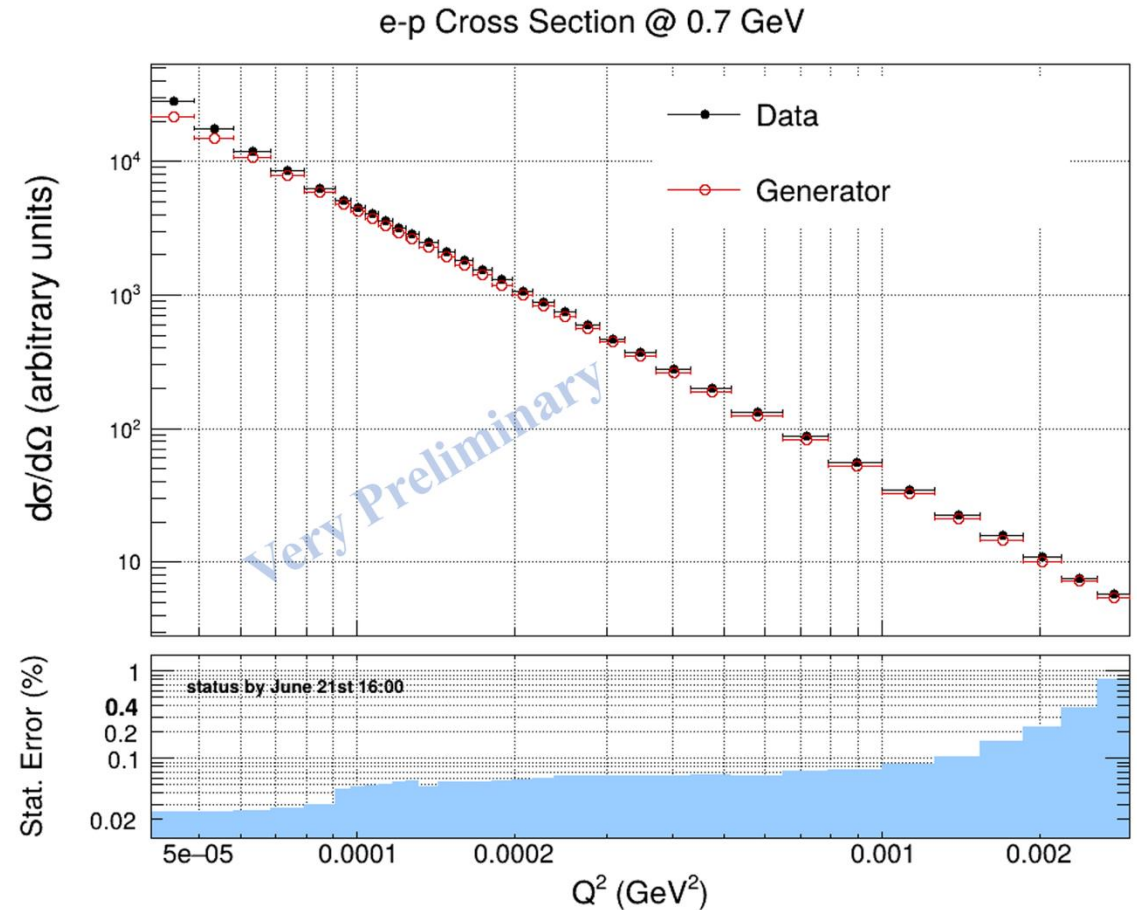
- factor of **2 more density** in H2 gas flow target:
 - ~ 4×10^{18} H/cm²
 - ✓ increasing the gas flow to 1300 cc/min vs. 600 cc/min
 - ✓ lowering H2 temperature to 16 K



H2 gas flow target on-line screen

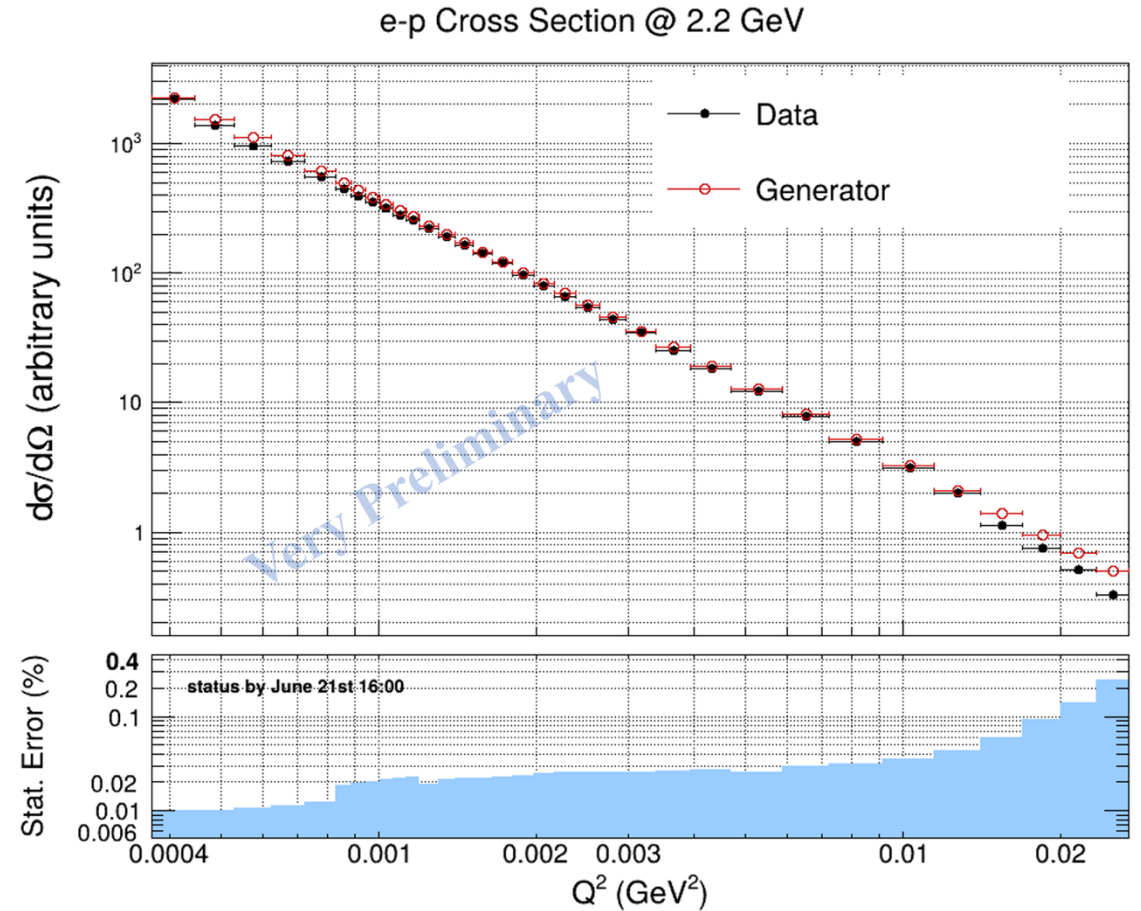
Prad-II Collected Data: 0.7 GeV Beam Energy

- $E_e = 0.7 \text{ GeV}$, one-pass at low-energy machine setting:
 - ✓ 4-5 days of run for statistics;
 - ✓ beam intensity: $I_e = 50 \text{ nA}$;
 - ✓ providing about 0.8% stat error at highest $Q^2 \approx 3 \times 10^{-3} \text{ GeV}^2$ bin
 - ✓ reached the 10^{-5} GeV^2 Q^2 range



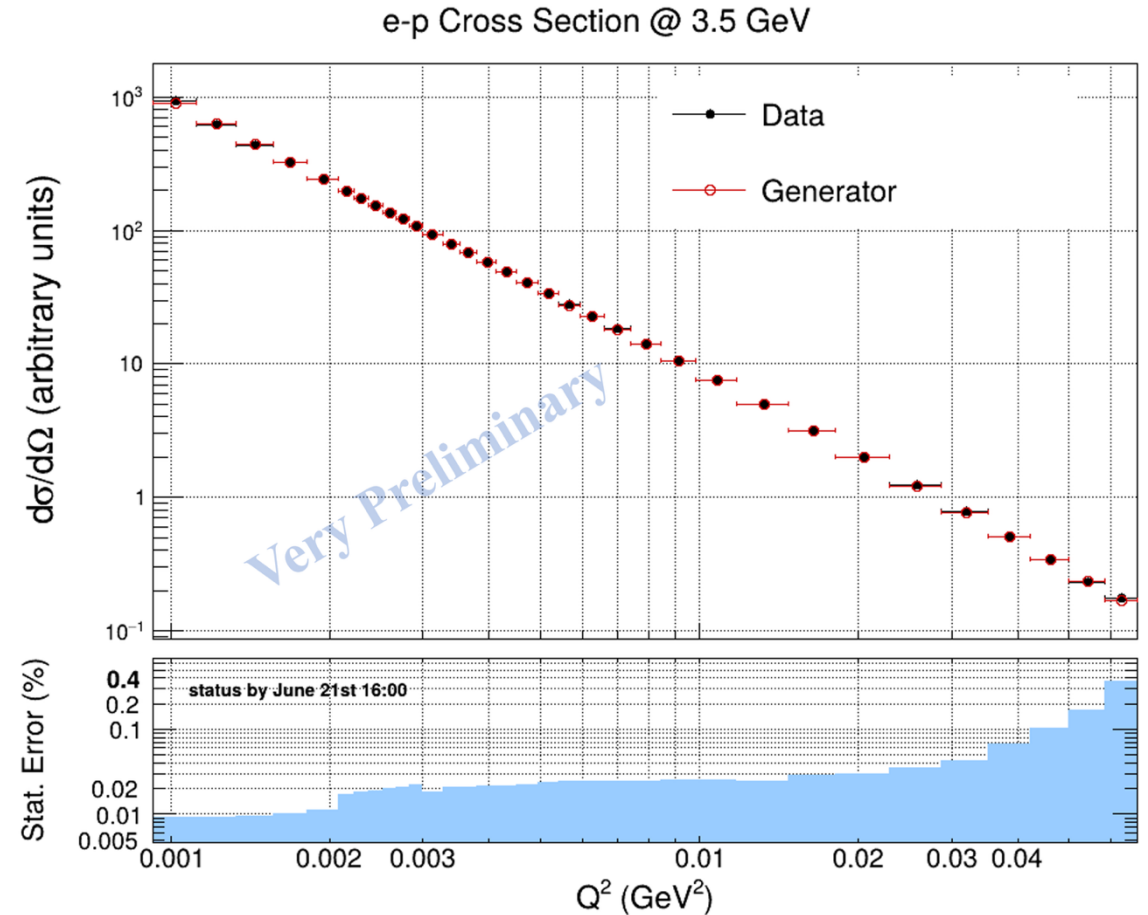
Prad-II Collected Data: 2.2 GeV Beam Energy

- $E_e = 2.2 \text{ GeV}$, one-pass at high-energy machine setting:
 - ✓ 8 days of run for statistics;
 - ✓ beam intensity: $I_e = 320 \text{ nA}$;
 - ✓ providing about 0.2% stat error at highest $Q^2 \approx 3 \times 10^{-2} \text{ GeV}^2$ bin



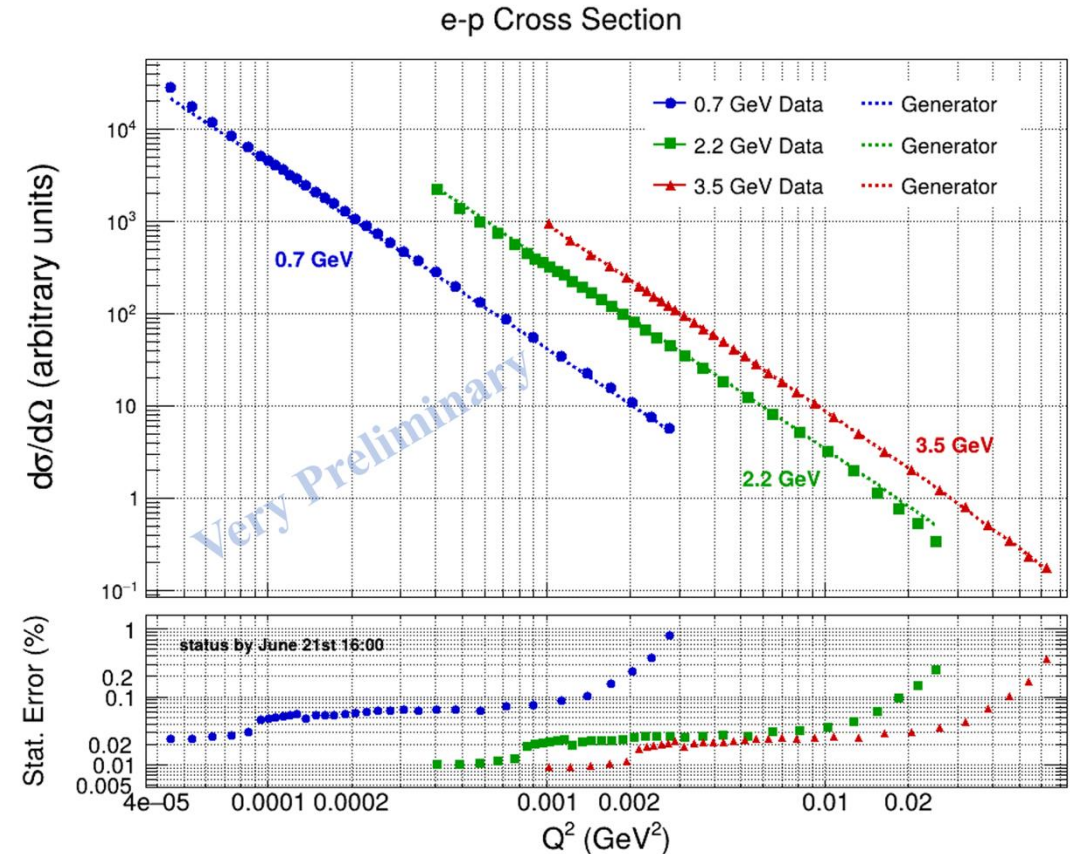
Prad-II Collected Data: 3.5 GeV Beam Energy

- $E_e = 3.5 \text{ GeV}$, fifth-pass at low-energy machine setting:
 - ✓ 8 days of run for statistics;
 - ✓ beam intensity: $I_e = 750 \text{ nA}$;
 - ✓ providing about 0.2% stat error at highest $Q^2 \approx 3 \times 10^{-2} \text{ GeV}^2$ bin



Conclusions on PRad-II Experiment

- Data taking process for the PRad-II experiment is completed.
- Good experimental data set is collected for all 3 energies:
 $E_e = 0.7, 2.2, \text{ and } 3.5 \text{ GeV}$.
- Preliminary on-line analysis results showing that the goals of the PRad-II will be reached.
- Data analysis process already started.
- First results are expected by next summer.
- Many thanks to:
 - ✓ the CLAS collaboration;
 - ✓ Hall B staff and administration;
 - ✓ Hall B engineers and technicians;
 - ✓ Fast electronics Group;
 - ✓ Physics Division administration.

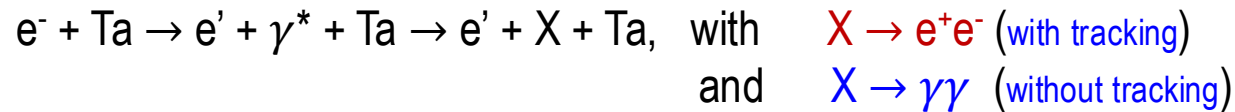


Upcoming X17 Search Experiment: Physics Goals

- Two experimental objectives:

- 1) **Validate existence or establish an experimental upper limit** on the electroproduction of the hypothetical **X17 particle** claimed in several ATOMKI low-energy proton-nucleus experiments.
- 2) **Search for “hidden sector” intermediate particles in [3 – 60] low MeV** mass range.

- Electroproduction on heavy nucleus in forward directions:



in mass range of: **[3 - 60] MeV**

Target: Tantalum, ($_{73}\text{Ta}^{181}$), 1 μm (2.4×10^{-4} r.l.) thick foil.

- All 3 final state particles will be detected in this experiment:**

- ✓ scattered electrons, e' , with 2 GEMs and PbWO_4 calorimeter;
- ✓ decay e^+ and e^- particles, with 2 GEMs and PbWO_4 calorimeter;
- ✓ or decay $\gamma\gamma$ pairs, with PbWO_4 calorimeter (and GEMs as veto).

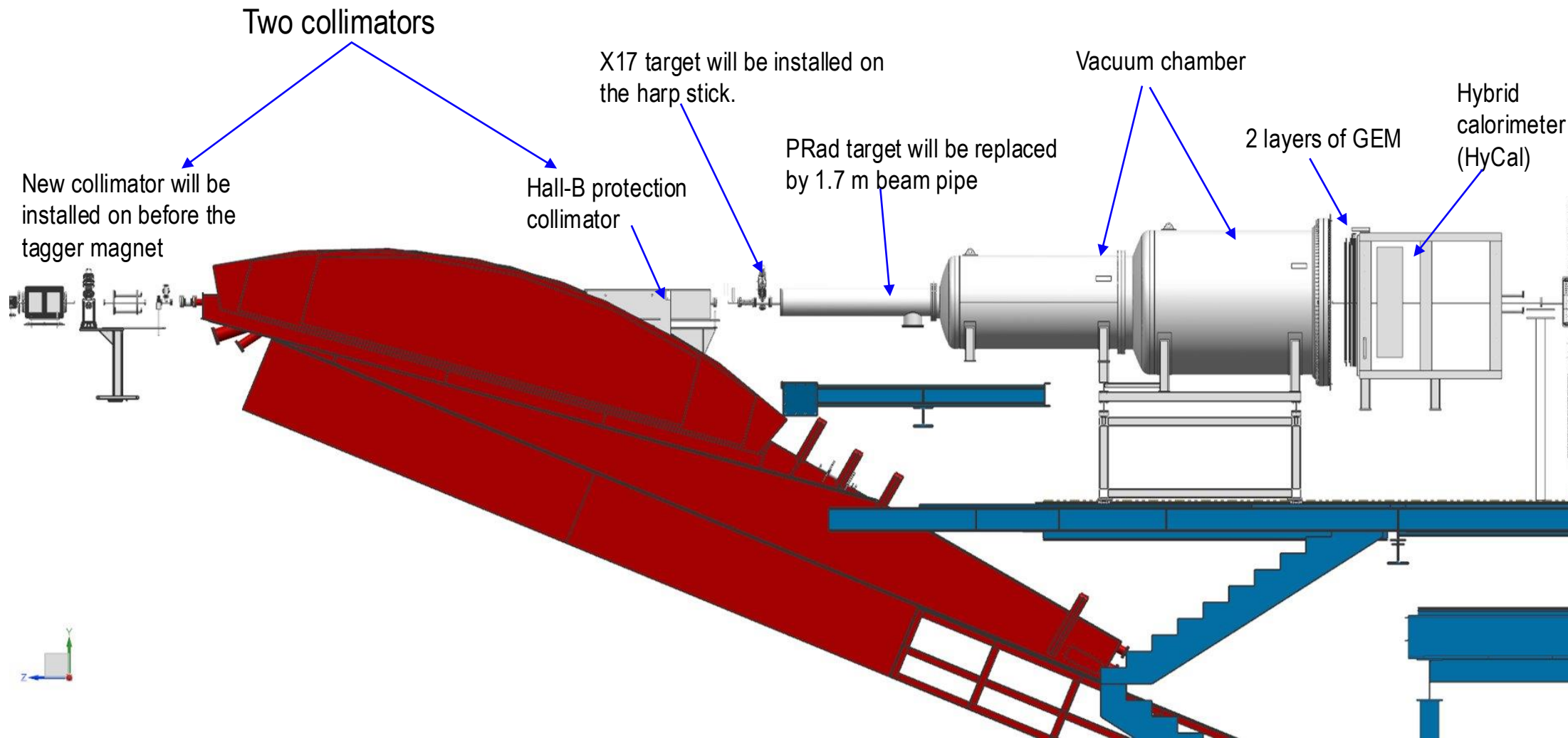
- Arguably, best know **control of experimental background**.

- approved by PAC50 in 2022, E12-21-003

	Time (days)
Setup checkout, calibration	4.0
Production at 2.2 GeV, 50 nA	20.0
Production at 3.3 GeV, 100 nA	30.0
Energy change	0.5
Empty target runs	5.5
Total	60

Sketch of the X17 Experimental Setup:

(change of the H2 target, in most part)

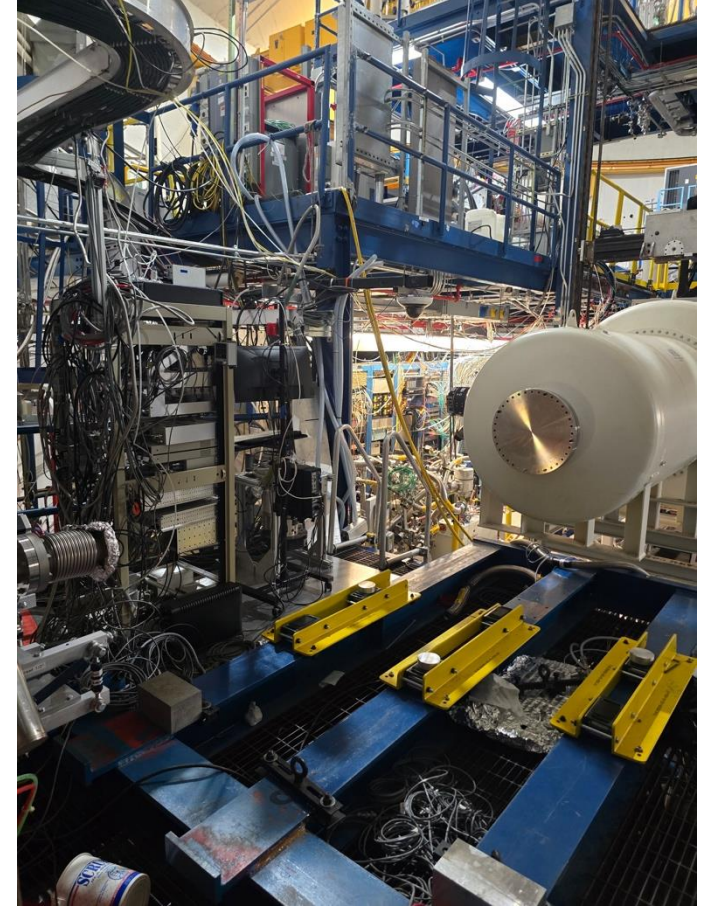
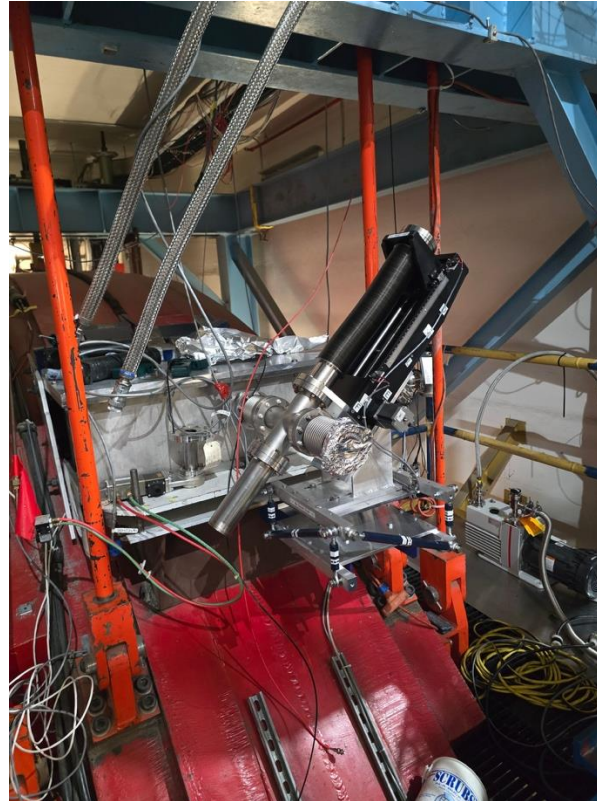


Organization of the On-line Trigger for X17 Experiment

- Control of the experimental background is the most important part of any fix target experiment.
- The X17 experiment will have a full control of kinematics by measuring:
All 3 final state particles will be detected in this experiment:
 - ✓ scattered electrons, e' , with 2 GEMs and PbWO_4 calorimeter;
 - ✓ decay e^+ and e^- particles, with 2 GEMs and PbWO_4 calorimeter;
 - ✓ or decay $\gamma\gamma$ pairs, with PbWO_4 calorimeter (and GEMs as veto).
- That will allow implementing a strong on-line trigger:
 - ✓ **3 or more clusters** with each energies:
 $0.1 \text{ GeV} < E_{cluster} < 0.7 \times E_{beam}$
 - ✓ Total energy of calorimeter $> 0.7 \times E_{beam}$
- That will reject the **ep-Mott and ee-Moller events**, leaving only the coincidence between these two high cross section processes.
- This trigger is already tested a week ago.

Current Status of the X17 Experimental Setup

- Transition from PRad-II to X17 started on June 24
- It is planned to complete by Wednesday, July 1
- X17 experiment will start from Wednesday, July 1, with $E_e = 2.2$ GeV (one-pass) and up to the end of August.
- It will use 30 out of 60 PAC approved days.
- Hoping to run the rest of days in near future.



Plot is from Rafo

Summary for the X17 experiment

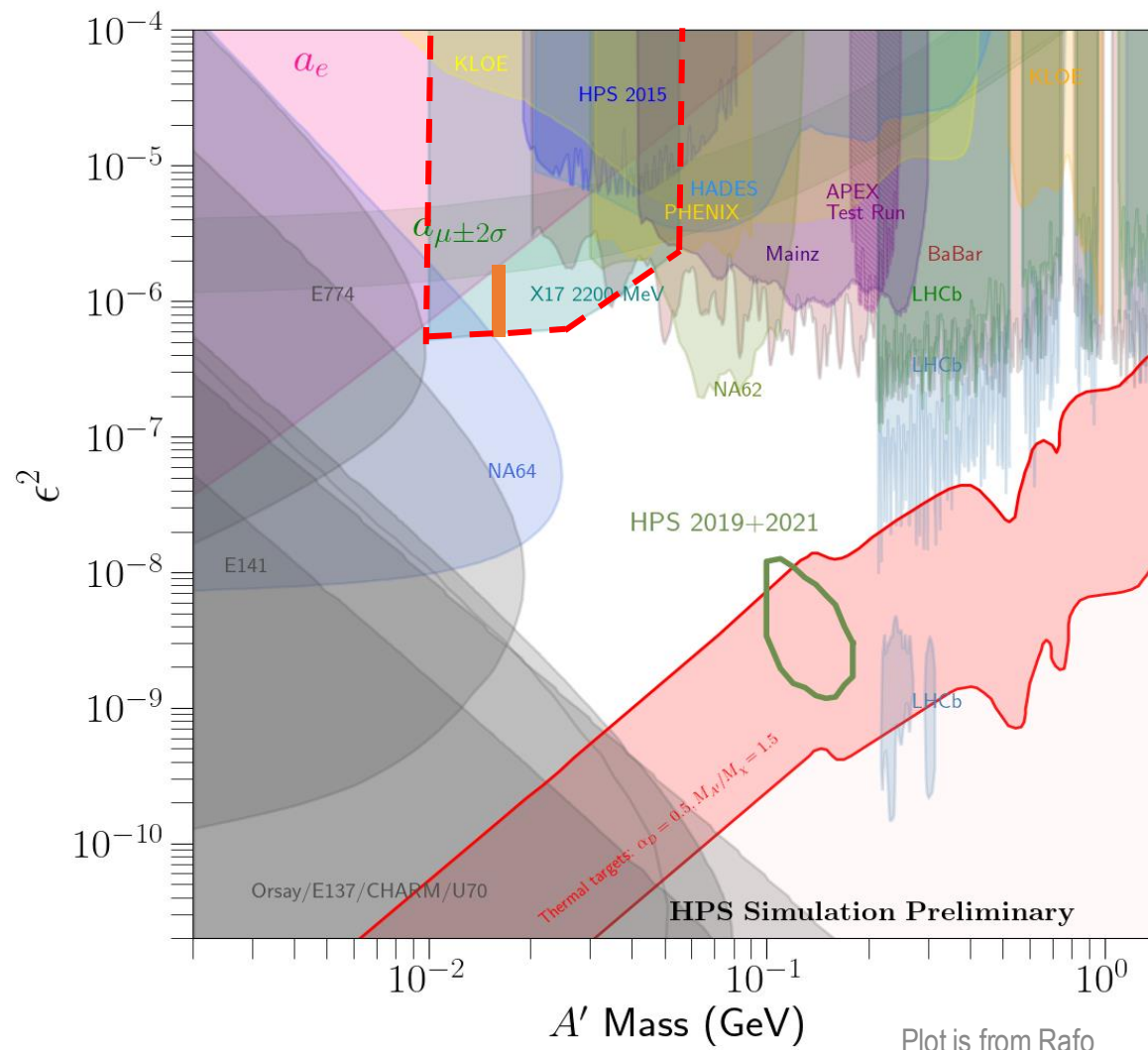
- Major parts of the experimental setup for X17 are already installed, tested and successfully used in the PRad-II experiment.
- Few remaining parts (like some pipes and engineering survey) will be finished by Wednesday, July 1.
- Experiment will start from **July 1, and up to the end of August.**
- **CLAS collaboration** support and active participation in the PRad-II experiment was **highly appreciated.** Expecting a similar **collaboration for the X17 experiment.**
- **Many thanks to:**
 - ✓ the CLAS collaboration;
 - ✓ Hall B staff and administration;
 - ✓ Hall B engineers and technicians;
 - ✓ Fast electronics Group;
 - ✓ Physics Division administration.

Backup Slides

Expected Physics Reach (ϵ^2 vs. mass parameter space)

- For:
 - $E_e = 2.2$ GeV, $I_e = 50$ nA, **40 days of run**
- ✓ **MADGRAPH5** event generator used for the signal, background from GEANT4
- Invariant mass range: **[3 -- 60] MeV**
- Coupling constant range: $\epsilon^2 \approx [10^{-7} - 10^{-6}]$
- with **5 σ** limits:

$$\frac{N_{\text{signal}}}{\sqrt{N_{\text{signal}} + N_{\text{bgd}}}} \geq 5$$



PRad: Proton Charge Radius from $ep \rightarrow ep$ Scattering Experiments

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

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

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

- Structureless proton:

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

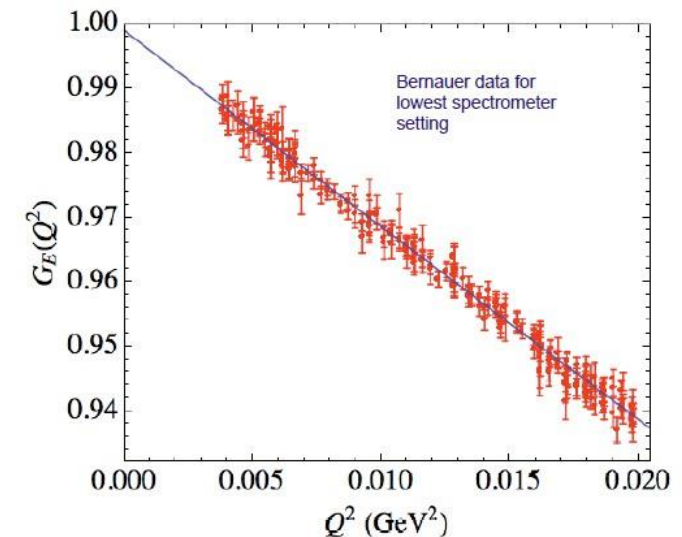
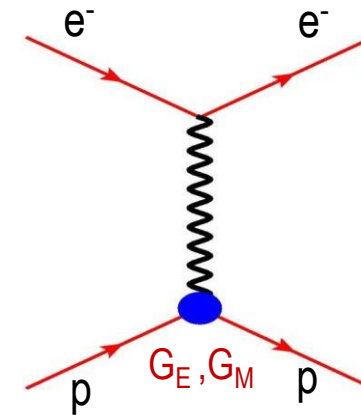
- G_E and G_M can be extracted using Rosenbluth separation
- for extremely low Q^2 , the cross section is dominated by G_E
- Taylor expansion of G_E at low Q^2

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

definition of the **proton rms charge radius** \rightarrow

derivative at $Q^2 = 0$:

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



Mainz low Q^2 data set
Phys. Rev. C 93, 065207, 2016

Extraction of the $ep \rightarrow ep$ Elastic Scattering Cross Section

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

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

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

✓ **Luminosity cancelled for both methods**

- Radiative effects corrected by Monte Carlo method:
 - ✓ GEANT4 based simulation package with full geometry setup
 - ✓ event generators with complete calculations of radiative corrections^{1),2)}
 - ✓ iterative procedure applied for radiative corrections

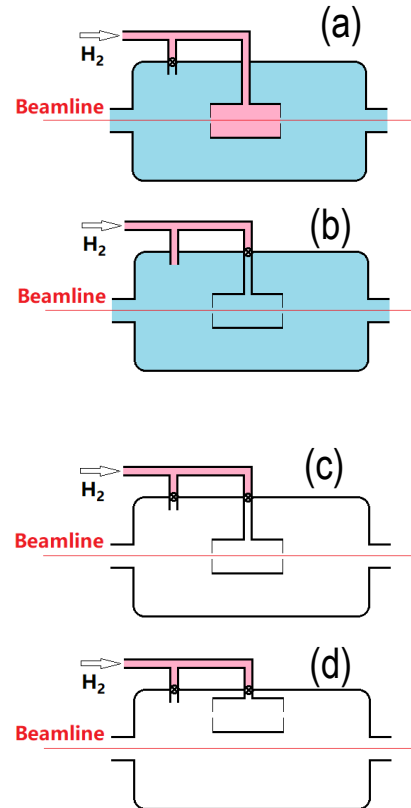
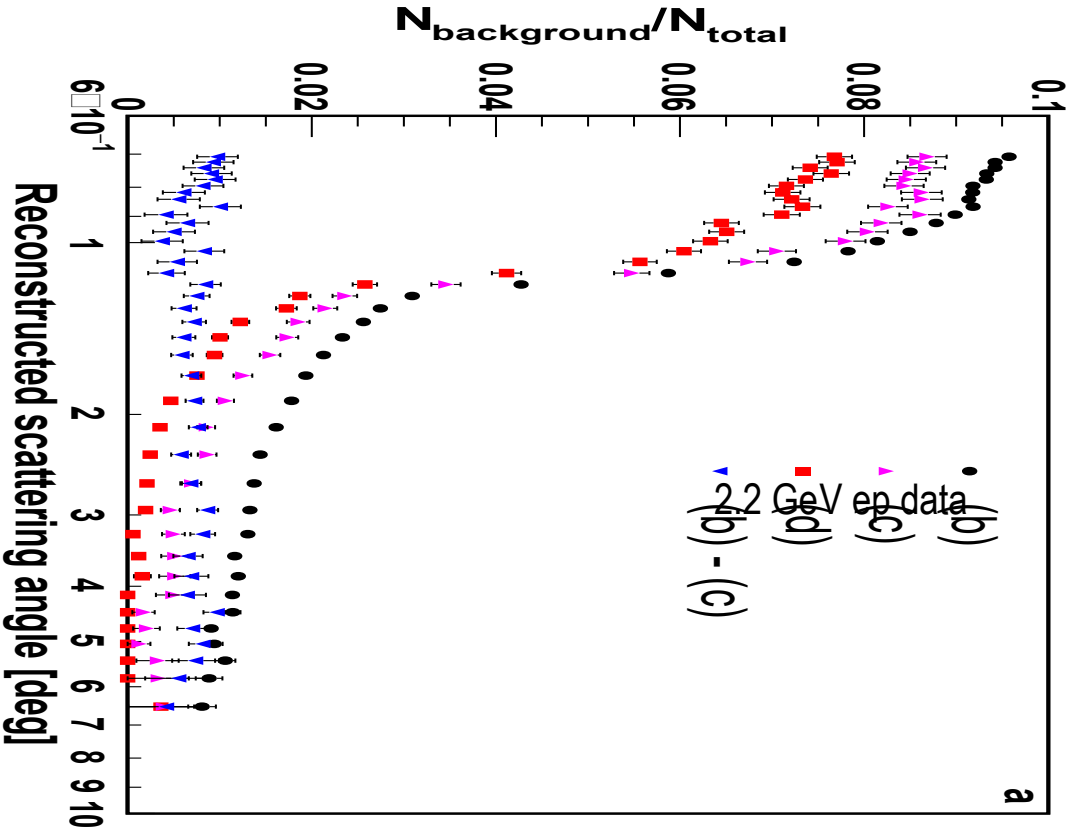
$$\sigma_{ep}^{\text{Born}(exp)} = \left(\frac{\sigma_{ep}}{\sigma_{ee}}\right)^{\text{exp}} / \left(\frac{\sigma_{ep}}{\sigma_{ee}}\right)^{\text{sim}} \cdot \left(\frac{\sigma_{ep}}{\sigma_{ee}}\right)^{\text{Born}(model)} \cdot \sigma_{ee}^{\text{Born}(model)}$$

1) A. V. Gramolin et al., *J. Phys. G Nucl. Part. Phys.* 41(2014)115001;

2) I. Akushevich et al., *Eur. Phys. J. A* 51(2015)1 (fully beyond ultra relativistic approximation).

Data Analysis: Empty Target Runs for Background Subtraction

- 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

Suggested New Beam Time Distribution:

Original proposal:

E (GeV)	Inten. (nA)	Time (days)	
0.7	20	4	(Intensity was limited by DAQ)
1.4	70	5	
2.1	70	15	

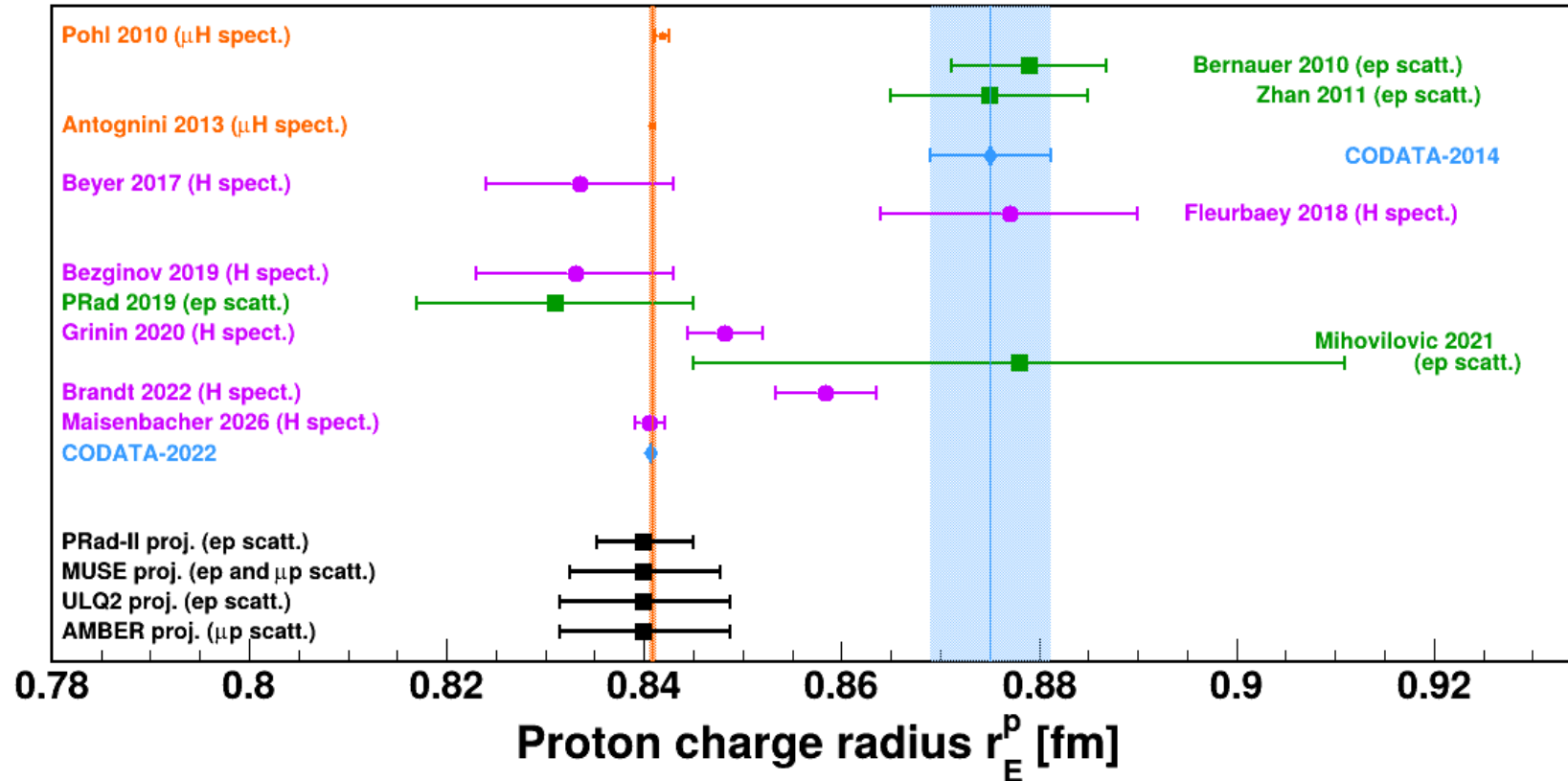
Suggested Run:

0.7	20	4
2.2	150	5
3.5	150	15

Setup checkout, tests and calibration	7 days	(Intensity is limited by central crystals)
Beam energy change	1 day	
Empty target runs	8 days	

Total: 40 days (no change)

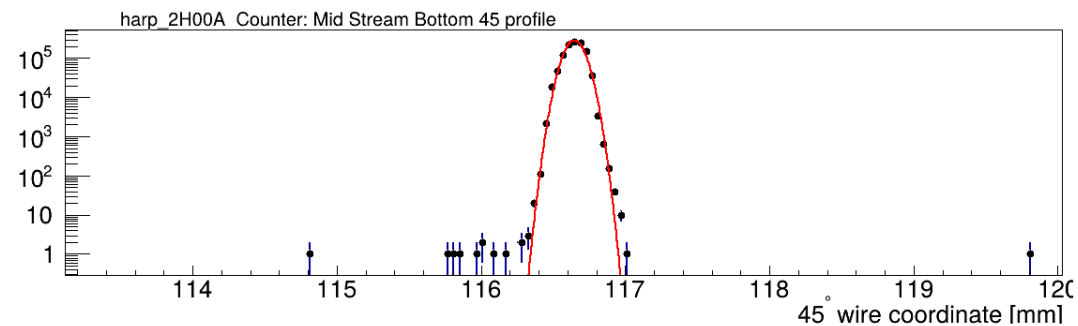
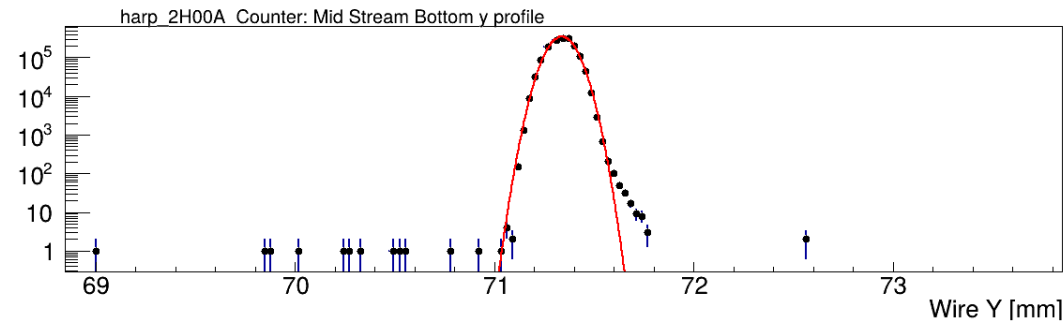
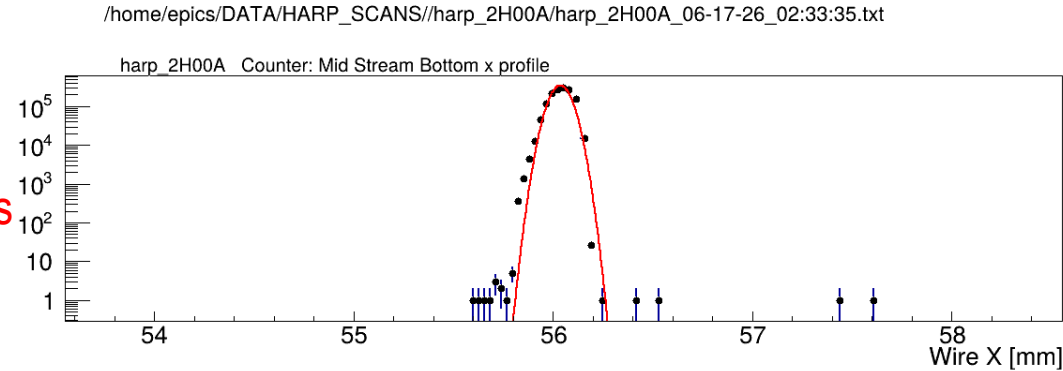
Today's Status of the Proton Radius Puzzle



- With the recent atomic spectroscopy experiment ([Nature, 2026, Garching](#)), the **Puzzle on the spectroscopy level is resolved.**
- For the scattering sector: **difference** between PRad and all other ep scattering experiments **is on 3σ level only.**

PRad-I Results on the Form Factor (G_E) at Small Q^2 Range

- There is certain **discrepancy** between two very recent **Form Factor** precision measurements: PRad-I and A1 MAMI at Mainz.
- New **high accuracy ep-scattering measurements** are needed to address these differences.



PRad-II: Improvements on G_E^p Form Factor Measurement

- To address the **differences** between A1 MAMI, Mainz (2010) and PRad, JLab (2019) results.
- statistical uncertainties only, with:
 - ✓ 6 days with 0.7 GeV, 20nA
 - ✓ 6 days with 2.1 GeV 150nA
 - ✓ 12 days with 3.5 GeV, 150nA
- Total beam time: **40 PAC days**
- Only PbWO_4 part of HyCal used.

