Status of the Prad-II and X17 Search Experiments in Hall B

Ashot Gasparian

NC A&T SU

For the PRad-II/X17 collaboration

CLAS collaboration meeting, June 25-28, 2024, CNU, Newport News VA

Outline

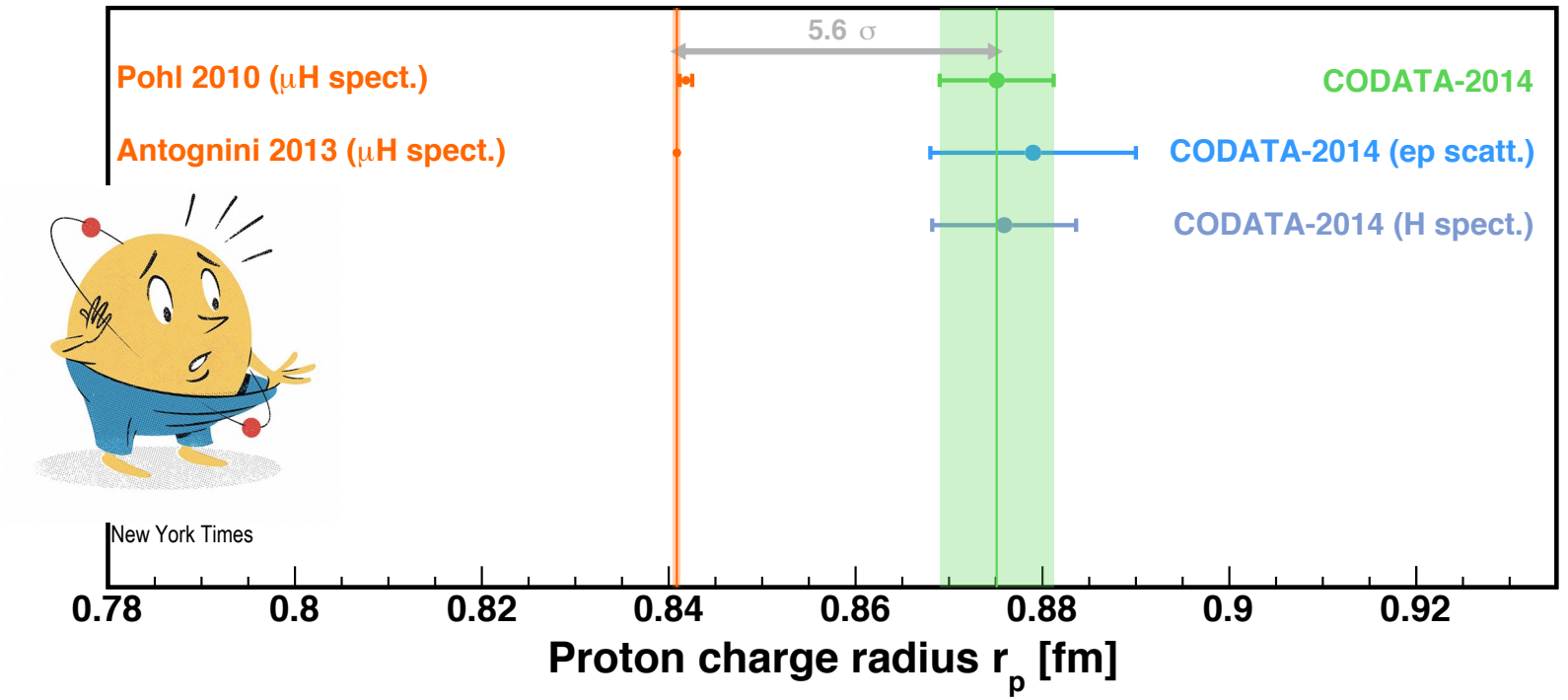
- PRad-II, physics goals
- upgrades to PRad experimental setup
- status of the setup preparation work
- X17 Search experiment, the goals
- additions to PRad-II setup and the status
- summary and outlook

The PRad Experiment in Hall B

(Performed in May-June 2016)

- PRad goals:
  - ✓ measurement of G_{EP} at very low Q^2 range;
  - ✓ critical input to the "Proton Radius Puzzle" resolution.

- PRad experimental method:
  - ✓ ep → ep elastic scattering experiment;
  - ✓ not a magnetic spectrometer experiment;
  - ✓ use HyCal and GEM for detection part;
  - ✓ measure all angles in one experimental setting ($\vartheta_e = 0.6^0 – 7.0^0$) ($Q^2 = 2x10^{-4} \div 6x10^{-2}$) GeV/c^2 ;
  - ✓ calibrate with a well-known QED process: simultaneous detection of ee → ee Moller scattering;
  - ✓ use windowless H_2 gas flow target



Regular hydrogen average (CODATA): 0.8751 ± 0.0061 fm

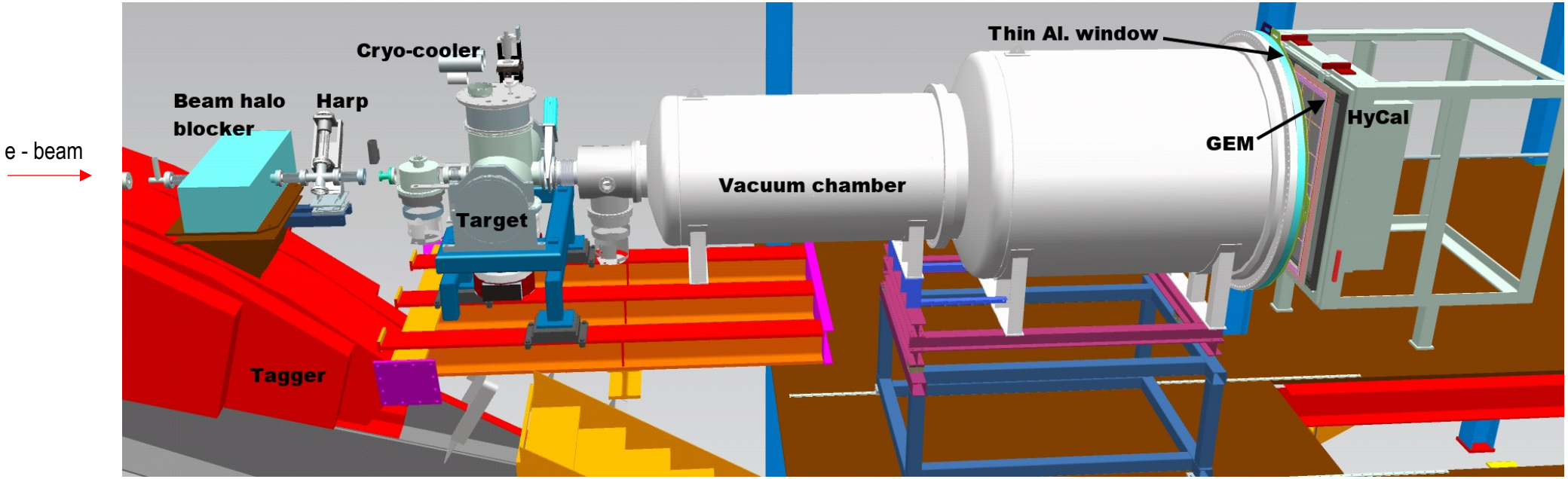
Muonic hydrogen (CREMA coll. 2013): 0.8409 ± 0.0004 fm

Muonic hydrogen (CREMA coll. 2010): 0.84184 ± 0.00067 fm

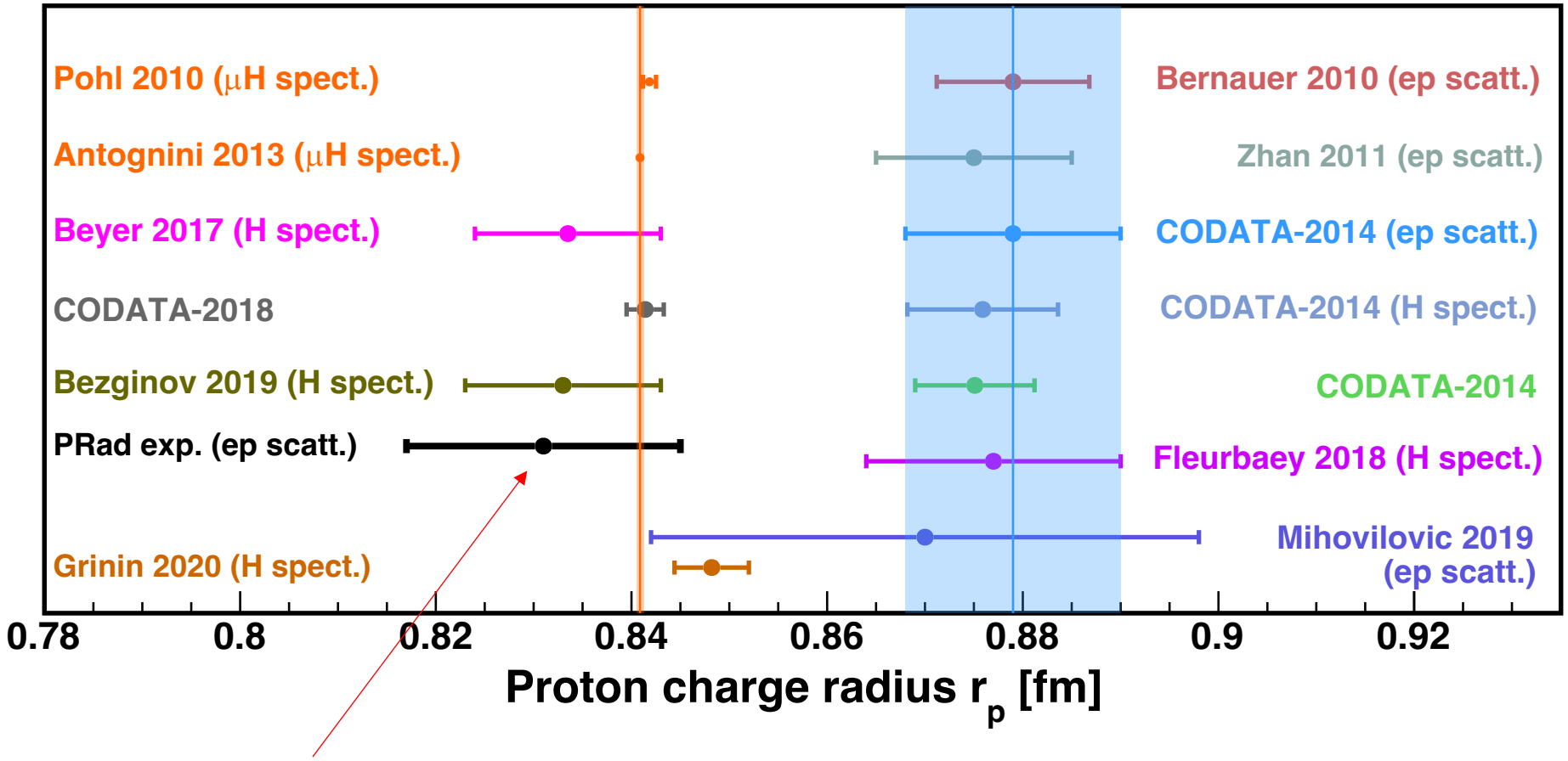
PRad Experimental Setup Used

- Main detector elements:
  - windowless H_2 gas flow target
  - PrimEx HyCal calorimeter
  - vacuum box with one thin window at HyCal end
  - X,Y – GEM detectors on front of HyCal

- Beam line equipment:
  - standard beam line elements (0.1 – 50 nA)
  - photon tagger for HyCal calibration
  - collimator box (6.4 mm collimator for photon beam, 12.7 mm for e^- beam halo “cleanup”)
  - Harp 2H00 I



PRad Result on Proton Charge Radius



PRad final result: $R_p = 0.831 \pm 0.007$ (stat.) ± 0.012 (syst.) fm (± 1.67%)

published in: Nature 575, 145–150 (2019)

Goals for the PRad-II Experiment (E12-20-004)

- There is certain discrepancy between two very recent FF precision measurements.
- The "Puzzle" is still not fully resolved!.

- New high accuracy ep-scattering measurements are needed.

- PRad-II goals:
  - High accuracy Gep measurement in a wide Q^2 range (Q^2 = 10^{-5} – 10^{-2} GeV^2);
  - a factor of 4 improvement on Rp

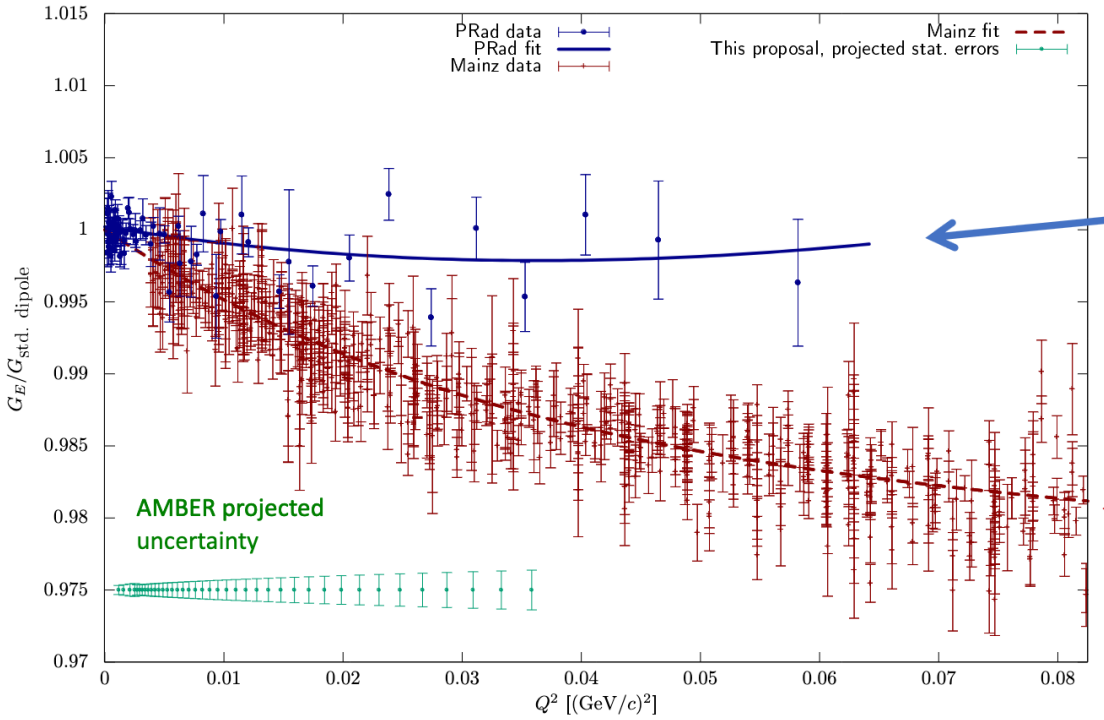


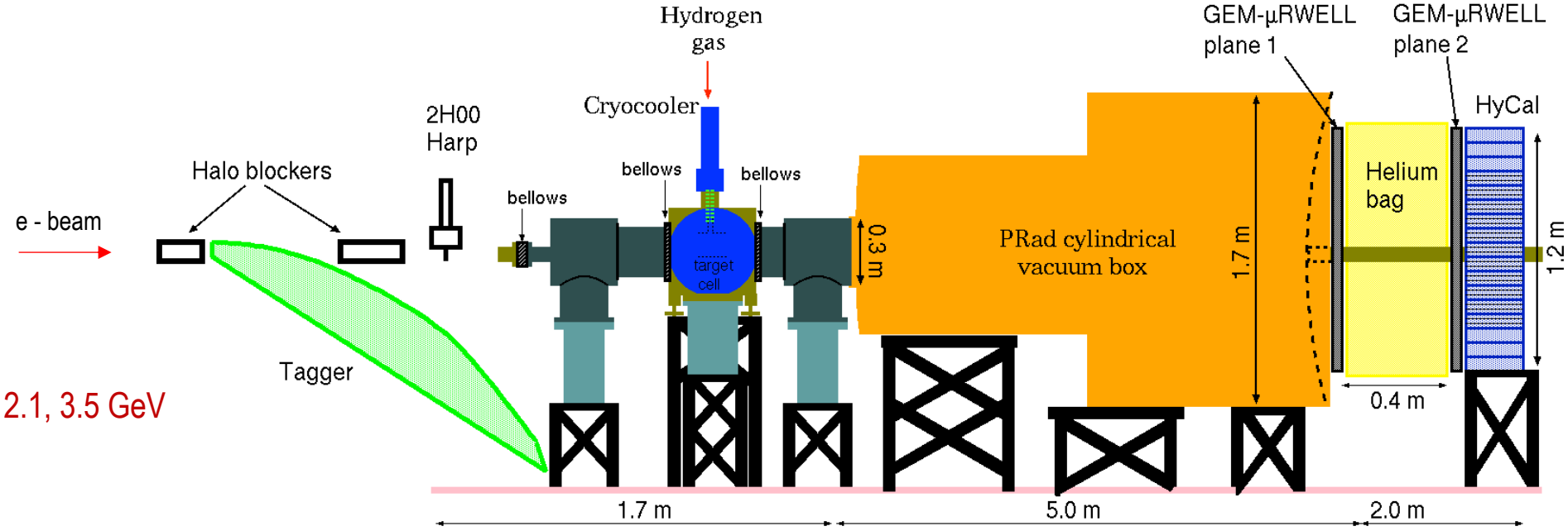
figure: J. Bernauer

PRad-II Experimental Setup and Experimental Goals

- Significantly improved statistics (4 times less statistical uncertainties, also helps systematics uncertainties).

- Upgrade PRad experimental setup (improving the systematics):
  - adding full tracking capability (second plane of GEM detectors).
  - upgrade DAQ/electronics to fADC based system (new trigger and readout).
  - small-size scintillator detectors just downstream the target to veto Moller electrons to reach the 10^{-5} GeV^2 Q^2 range.
  - adding new "beam halo blacker" just before the Tagger for less beam background.
  - use the $PbWO_4$ crystal part only (high energy resolution).

PRad-II Experimental Setup (Side View)

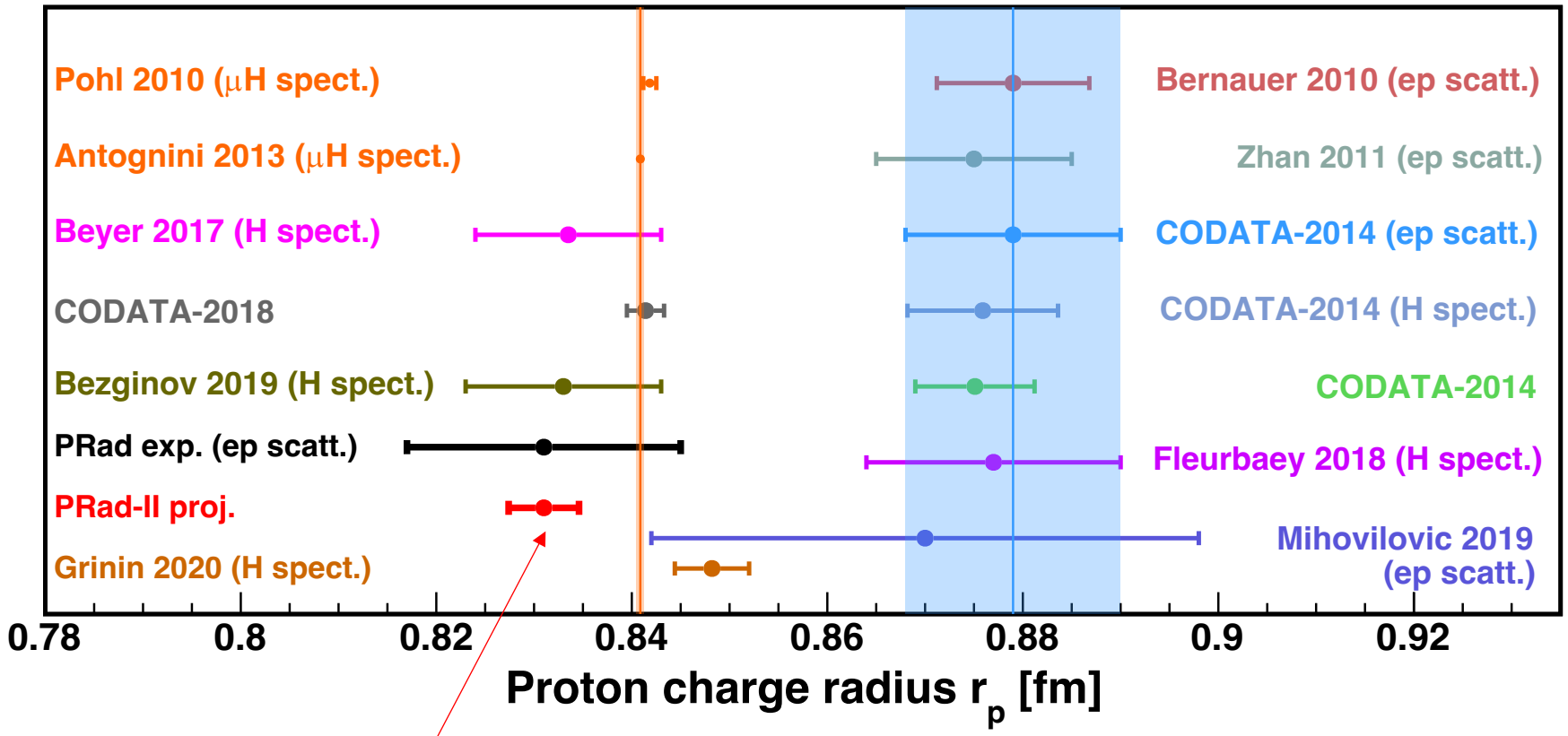


- Beam energies: Ee = 0.7, 2.1, 3.5 GeV

- Total beam time: 40 days

PRad-II Expected Result on the Proton Radius

(PAC48, 2020, E12-20-004)



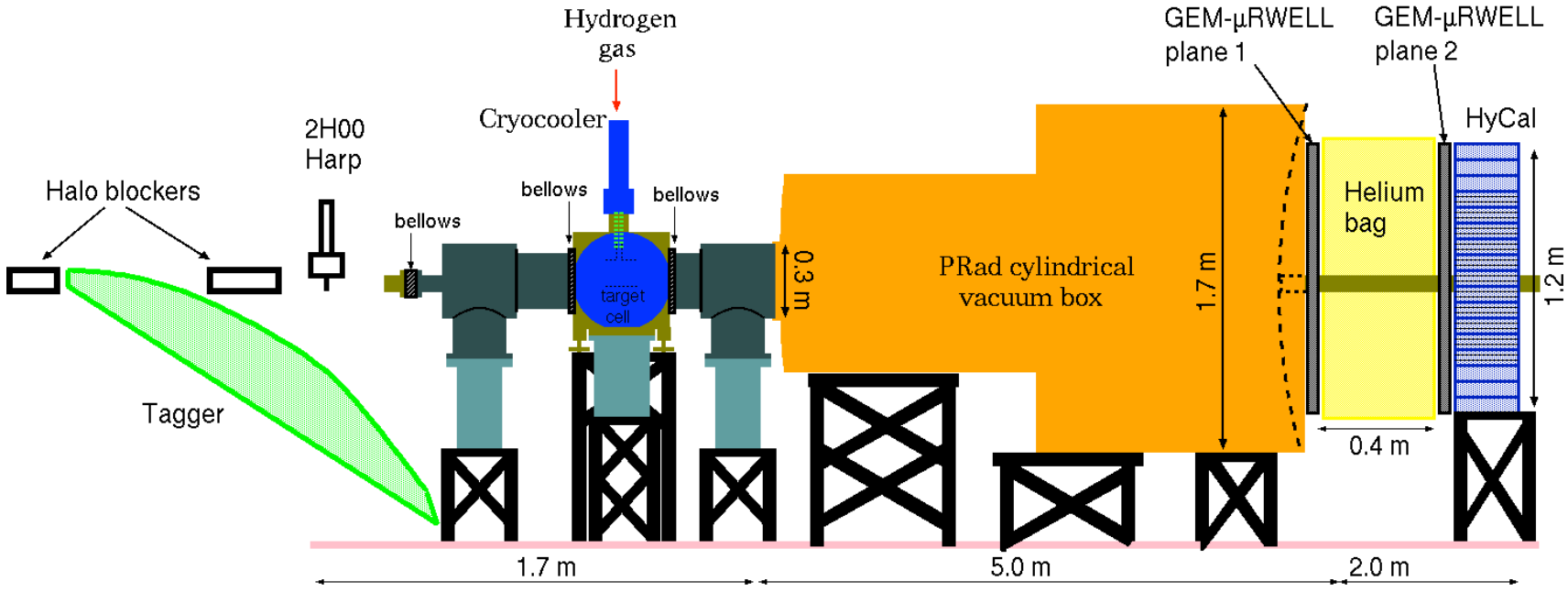
PRad-II projected result: $R_p = 0.831 \pm 0.0014$ (stat.) ± 0.0041 (syst.) fm ($\pm$ 0.43%)

Experimental Setup Preparation Status:
Beam Line Elements

- All new beam line elements for both PRad-II and X17 Search experiments are identified, optimized conceptual design part is completed.
- Engineering design is in progress.

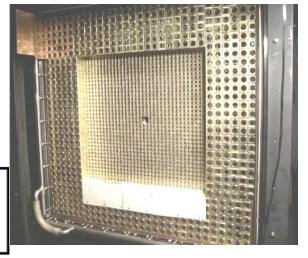
- **See upcoming slide for "X17 Beam Line Elements"**

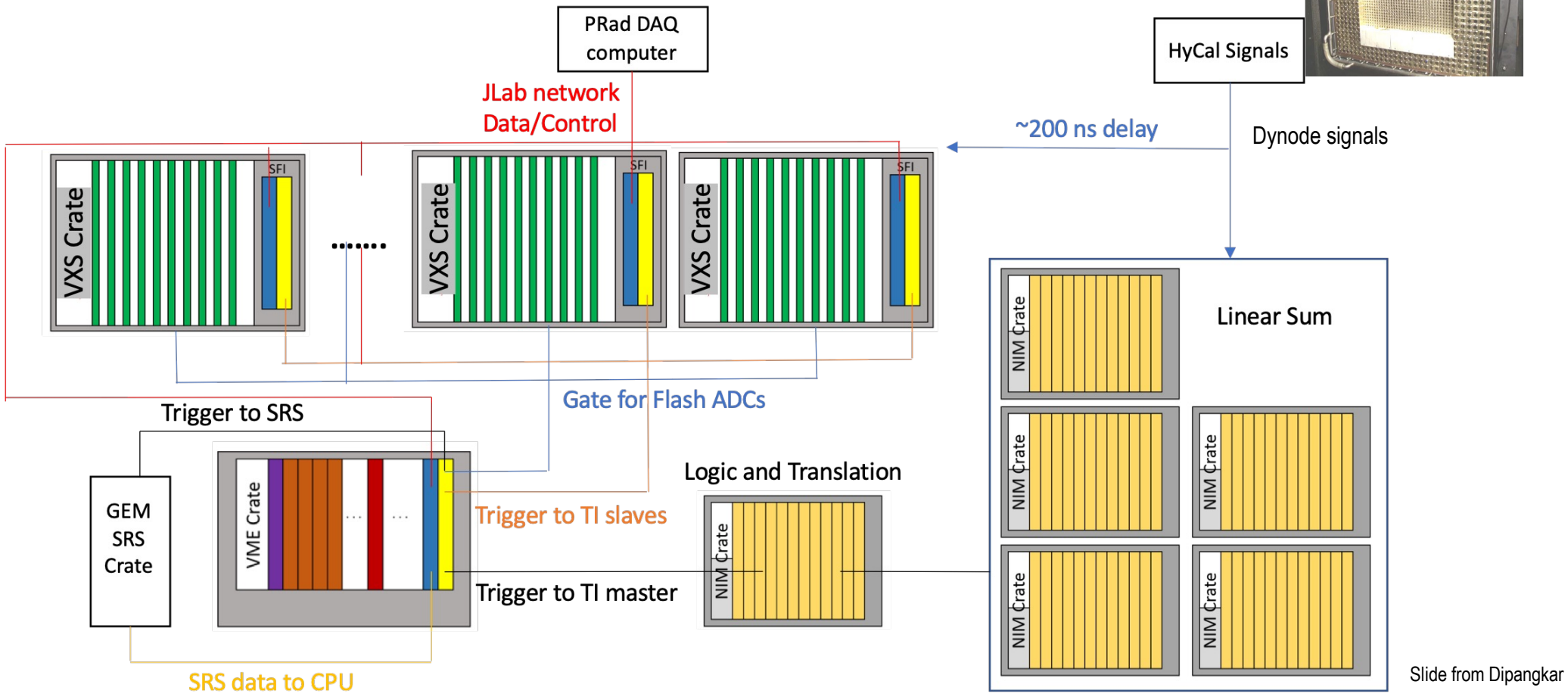
PRad-II Experimental Setup (Side View)



PRad-II Experimental Setup Preparation Status: DAQ and Readout Electronics

- 72 fADC250 modules (1152 channels), 5 VXS crates is in procurement. ($PbWO_4$ part only).
- Modern flash ADC-based pipelined DAQ with robust trigger efficiency monitoring.





Slide from Dipangkar

PRad-II Experimental Setup Preparation Status: DAQ and Readout Electronics, procurement status

- 85 fADC250 are already ordered from JLab: we hope to use (from Patrick Achenbach)
- Hope to use 72 of them for our experiments. (will cover the $PbWO_4$ part only) (from Patrick Achenbach)
- 3 fADC250 are already in the Lab for testing (from Chris Cuevas)
- All 5 VXS crates are delivered to the Lab (from Chris Cuevas)
- Installation of all 5 VXS crates in Hall B is planned for the next few weeks (from Chris Cuevas)

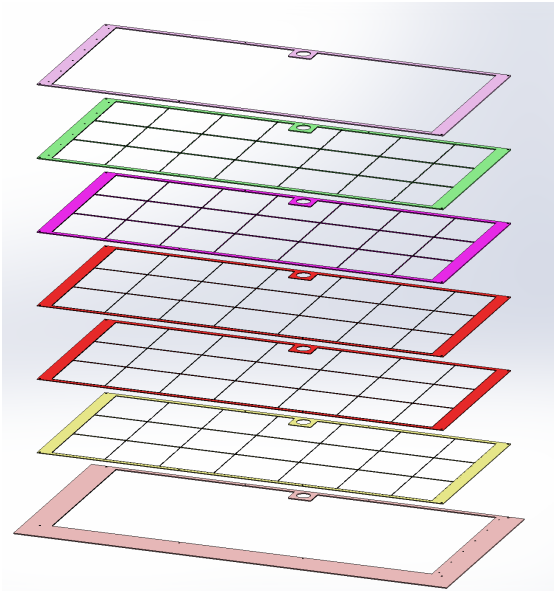
- This will allow to run experiments using the inner $PbWO_4$ part only: PRad-II and X17 Search experiments.

PRad-II Experimental Setup Preparation Status:
Two Planes of New GEM Detectors

- 4 new GEM modules to assemble 2 tracking layers.
- Size: 120 x 55 cm2, similar to PRad GEMs.
- GEM and readout foils: design updated, currently under fabrication at CERN.
- GEM holding frames: design optimized, order being placed.
- All GEM parts expected by September/October, expect to complete the detector fabrication by March 2025.
- All readout electronics ordered, expected by this November.

- Will be ready for installation and testing by mid-spring, 2025.

PRad GEM on front of HyCal



Optimized and updated GEM frame design for PRad-II

Slide is from Nilanga

PRad-II Experimental Setup Preparation Status:
DAQ and Readout Electronics, re-cabling and installation

- All FASTBUS crates with power supplies are removed from electronics rocks.
- Re-termination of HyCal signal cables (RG58) with Lemo connectors in progress.
- Channel-by-channel testing is in progress.
- New 5 VXS crates is planned to install in next few weeks.

PRad-II Experimental Setup Preparation Status:
HyCal Tests in ECB Building

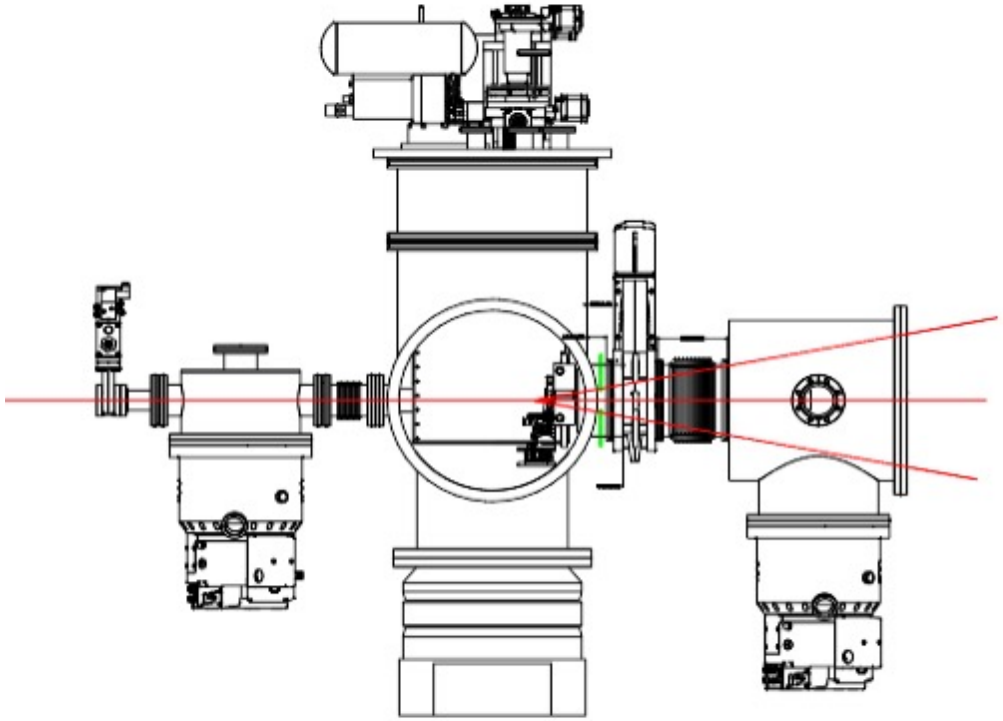
- We plan to test and repair all HyCal channels (~1600) in ECB building:
  - with cosmic rays;
  - with Light Monitoring System (LMS)
  - check optical contacts

- HyCal was recently re-positioned (in last week), the area was cleared, and ready to start the work.

- Planned to finish all tests during this summer/fall period.

PRad-II Experimental Setup Preparation Status:
4 New Scintillator Detectors to Reach the $Q^2=10^{-5}$ GeV^2 Range

- 4 small scintillator detectors placed next to the H2 gas flow target chamber.
- Size: 4 x 6 x 0.3 cm^3
- Remotely movable perpendicular to the beam direction.
- Conceptual design by Y. Sharabian: completed.
- Engineering design by C. Guthrie: in progress.
- Manufacturing: by Spring, 2025
- Estimated time for test in beamline: Summer, 2025.



X17 Search Experiment, Physics Goals

(Approved by PAC50 in 2022, E12-21-003)

- 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 (or fields) in [3 – 60] MeV mass range produced in electron-nucleus collisions and detected in e^+e^- or $\gamma\gamma$ channels.

X17 Search Experiment: Experimental Method

- The method:
  - ✓ "bump hunting" in the invariant mass spectrum over the beam background.
  - ✓ detection of all final state particles (e', e^+e^- and/or $\gamma\gamma$) → full control of kinematics

- Electroproduction on heavy nucleus in forward directions:

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

in mass range of: [3 - 60] MeV
Target: Tantalum, ($_{73}Ta^{181}$), 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 for veto).

- Will provide a tight control of experimental background.

X17 Search Experiment: Beam Time and Statistics

- Target: Ta; thickness: 1 μm (t = 2.4x10^{-4} r.l.), N_{tgt} = 0.56x10^{19} atoms/cm^2
  for E_e = 3.3 GeV and I_e = 100 nA (N_e = 6.25x10^{11} e$^-$/s),

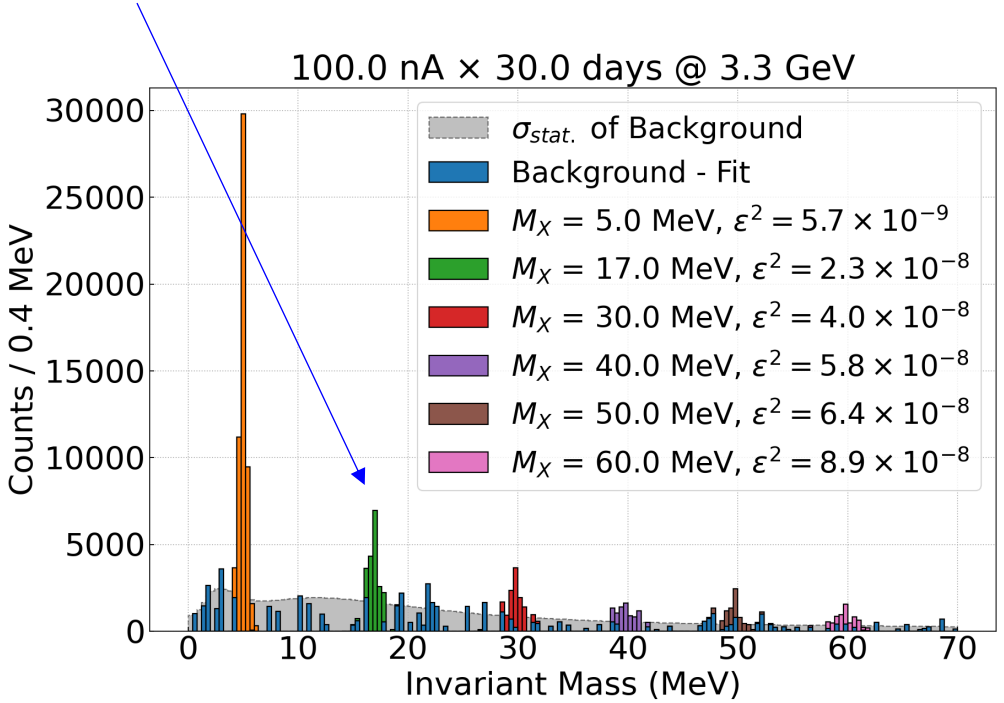
Example: the estimated X17 production rate (Eq. 14, J. D. Bjorken, et al. Phys. Rev. D, 80:075018. 2009):

$N_{X17} \sim N_C * N_e * t * \varepsilon^2 * (m_e/m_x)^2$

$$\epsilon^2 = \frac{N_X}{5 \times N_e T \frac{m_e^2}{m_X^2}}$$

≈ 32 K produced events per 30 days for ε^2 = 2.3x10^{-8} ($N_C = 5$)

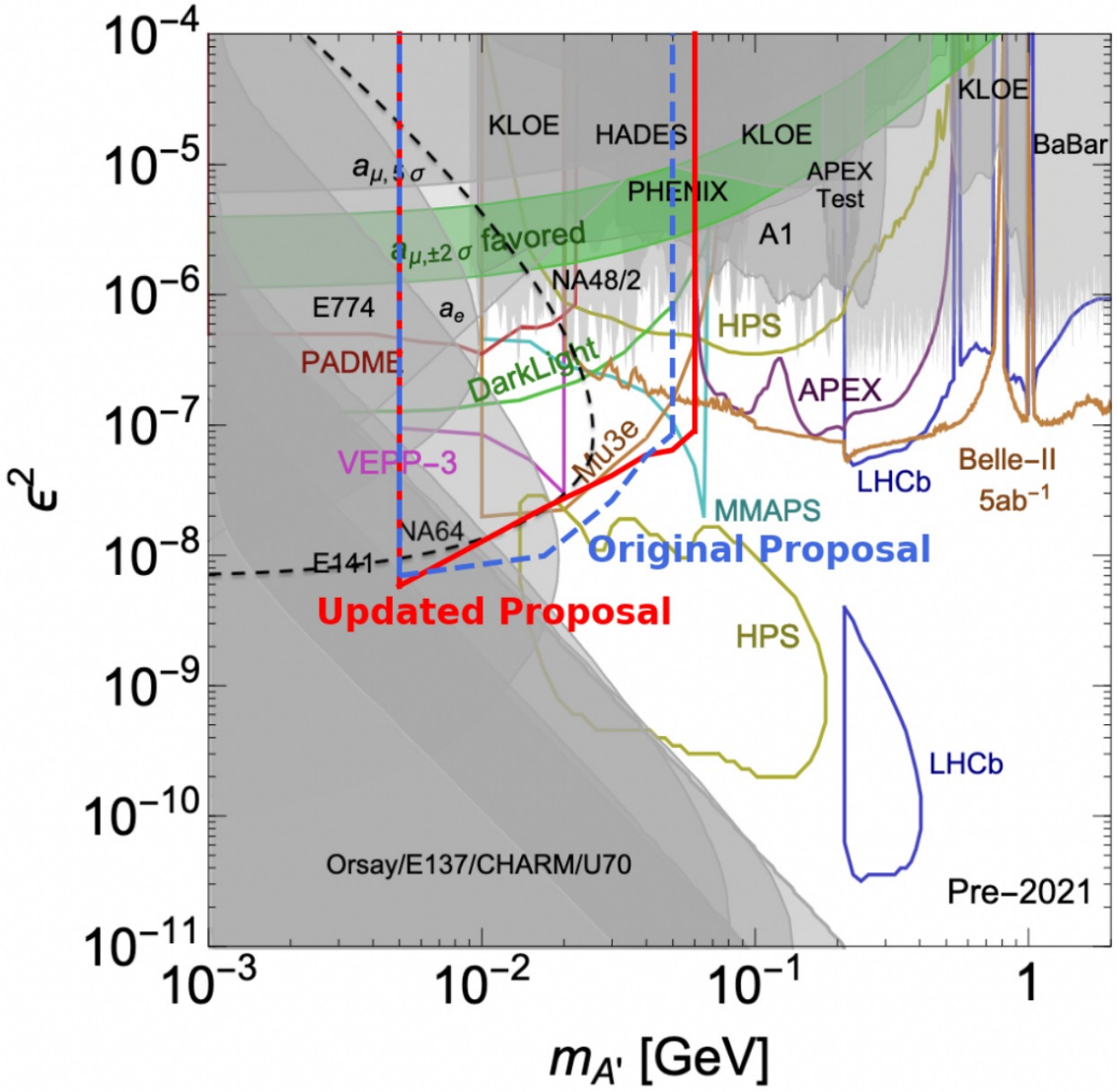
	Time (days)
Setup checkout, calibration	4.0
Production at 2.2 GeV, 50 nA	20.0
Production at 3.3 GeV, 100 nA	30.0
Energy change	0.5
Empty target runs	5.5
Total	60



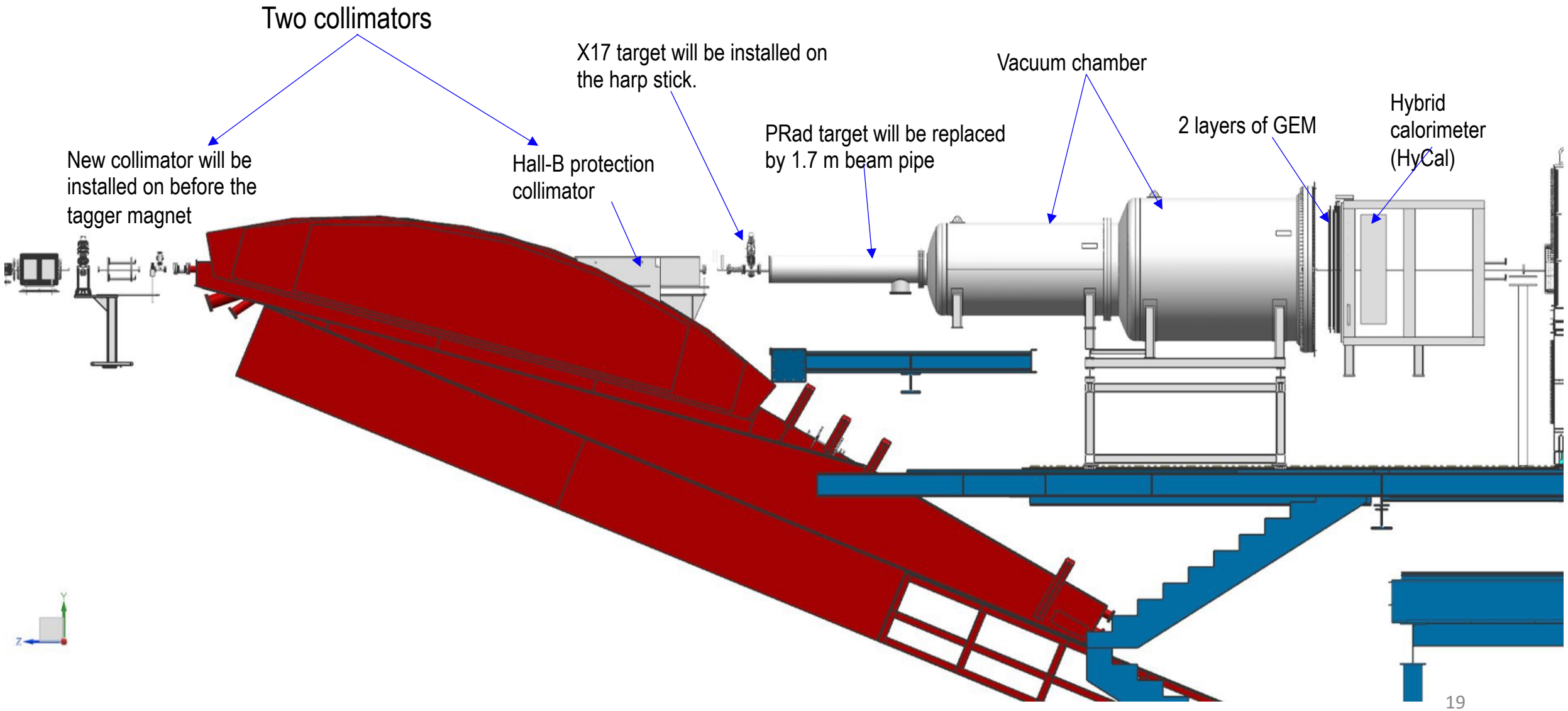
Parameter Space (ε^2 *vs.* Mass), Physics Reach

- Invariant mass range: [3 -- 60] MeV
- Coupling constant: $\varepsilon^2 \approx [10^{-8} — 10^{-7}]$
- This proposal uses 5σ limits (discovery criterion as per PDG), while the 2 - 2.4 σ limit is commonly used in many other experiments.

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



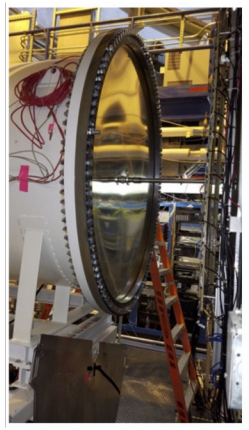
X17 Experimental Setup:
(change of the target only)

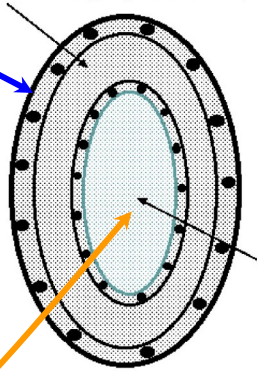


X17 Search Experiment: Beam Line Elements

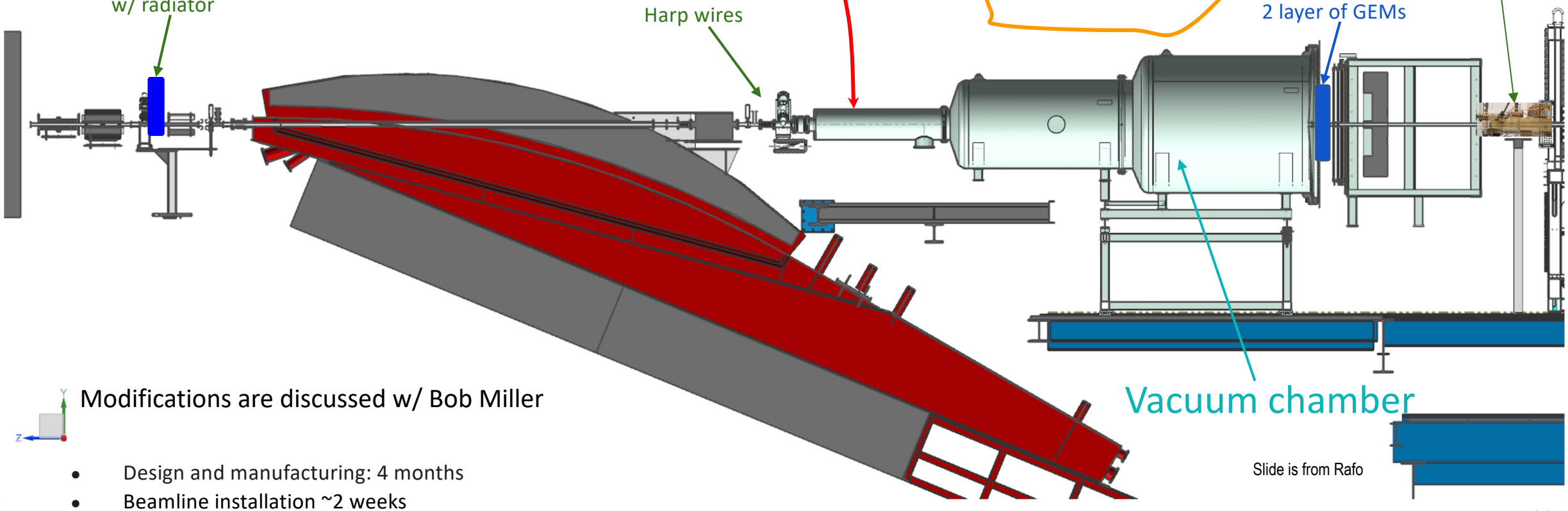
New parts to be manufactured

- New tube: 30 cm dia., 1.7m long
- New reducer flange
- 1 m dia Aluminum window





2H01 girder to be placed after the HyCal



Modifications are discussed w/ Bob Miller

- Design and manufacturing: 4 months
- Beamline installation ~2 weeks

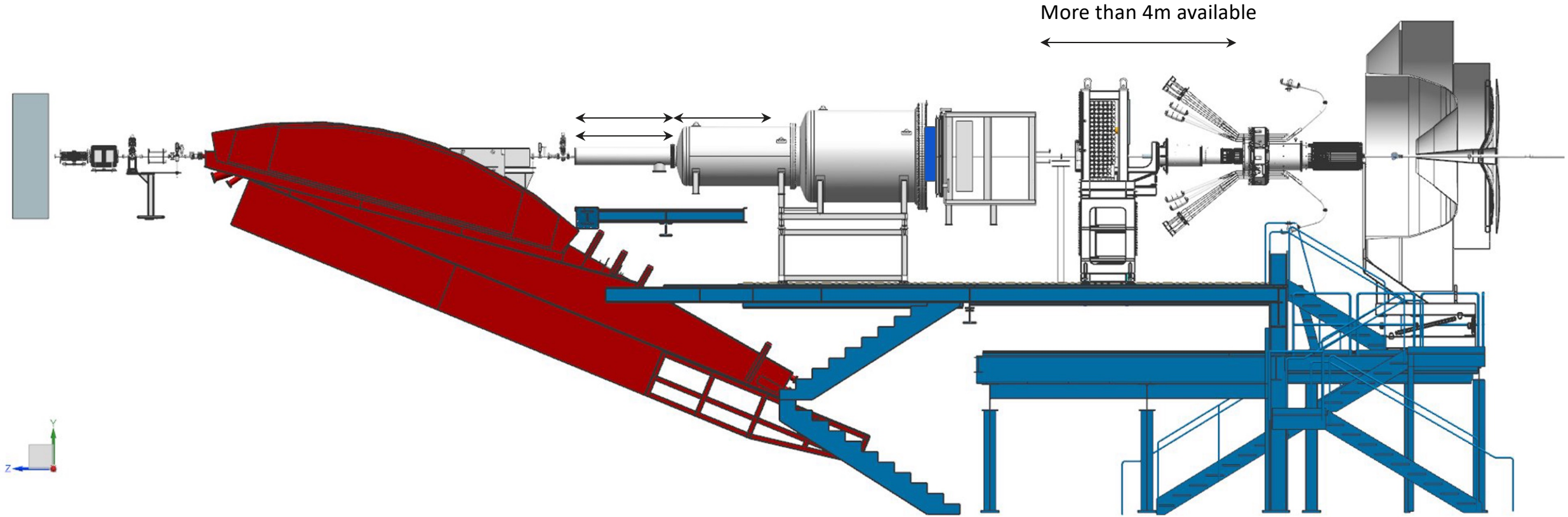
Slide is from Rafo

Summary and Outlook

- Conceptual design of all beamline elements for both PRad-II and X17 Search experiments is finalized. Engineering design is in progress.
- Construction of four GEM detectors is on track to be ready by mid-spring 2025 (UVA group)
  - cosmic ray tests in Hall B beam line, starting from summer of 2025
- All t2 fADC250 modules with 5 VXS crates are procured for the $PbWO_4$ part of HyCal.
- Work on cables is underway in Hall B.
- Preparation for HyCal test started in the Environmentally Controlled Building, complete in Fall of 2024.
- Ready for ERR review this Fall.
- Experiments ready for run from Fall, 2025.

- Thanks to Hall B administration, engineering group, technicians and Fast Electronics Group for their strong support and help.

Backup Slides


More than 4m available
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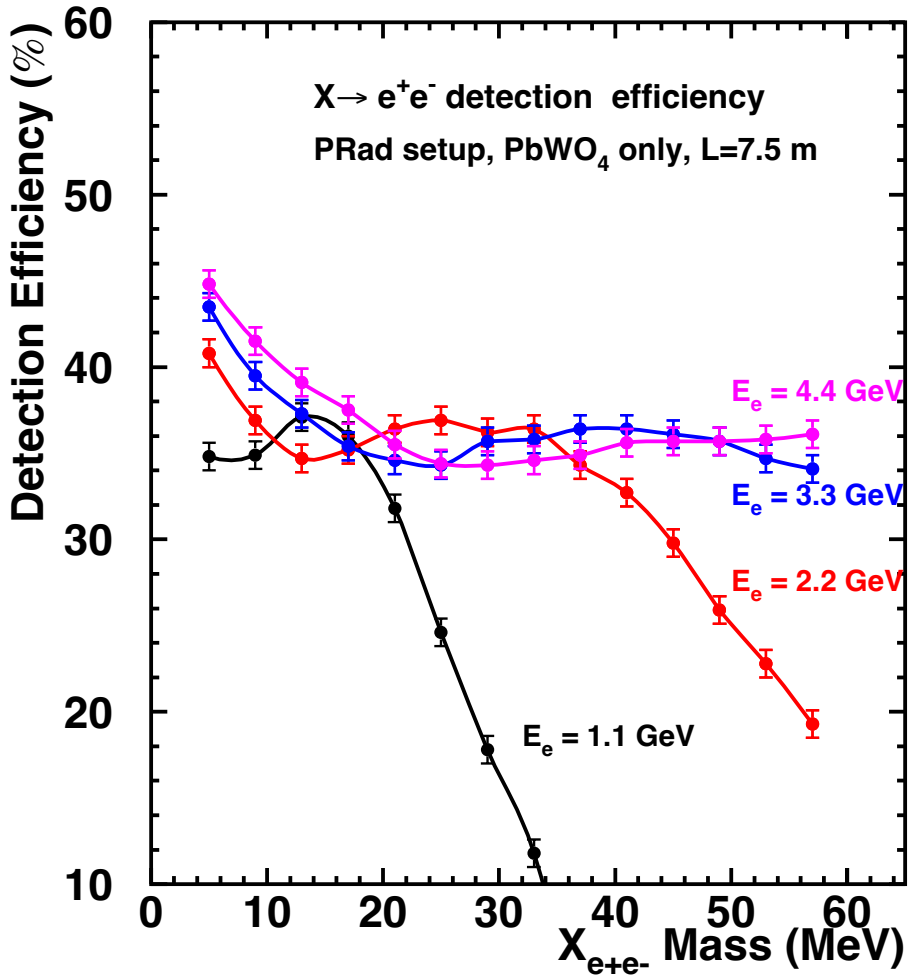
Detection Efficiency (Geometrical Acceptance)

- Trigger configuration:
  - ✓ total energy sum in calorimeter: $\Sigma E_{clust} > 0.7 \times E_{beam}$
  - ✓ 3 clusters in $PbWO_4$ calorimeter;
  - ✓ each cluster energy: 30 MeV $< E_{clust} < 0.8 \times E_{beam}$ (rejects the elastic scattered electrons)
- Large phase space for virtual photon, γ^*:
  - ✓ energy interval: $E_{\gamma^*} \approx [0.2 - 0.8]\ E_{beam}$;
  - ✓ $\vartheta_{e'} \approx [0.4^0 -- 3.7^0]$ angular range.
  - ✓ provides X-particle production in wide energy spectrum and in forward solid angle
- Target to detector distance: L = 7.5 m provides good (integrated) detection efficiency in [3 - 60] MeV mass range for E_e = 2.2, 3.3 and 4.4 GeV.
- E_e = 2.2 and 3.3 GeV were chosen for relative ease of scheduling during CEBAF low-energy runs.

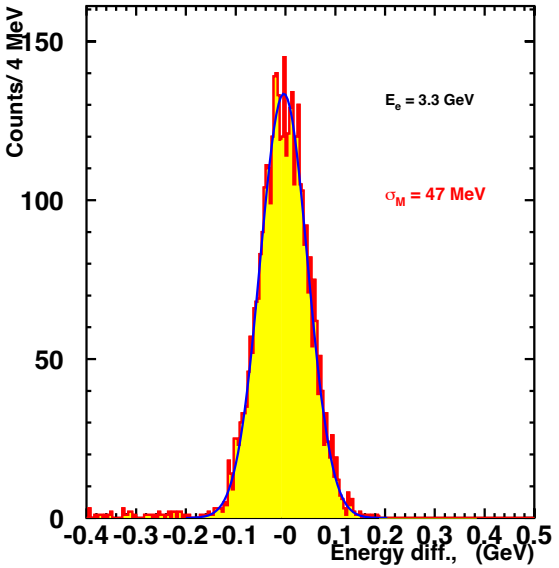


Experimental Resolutions

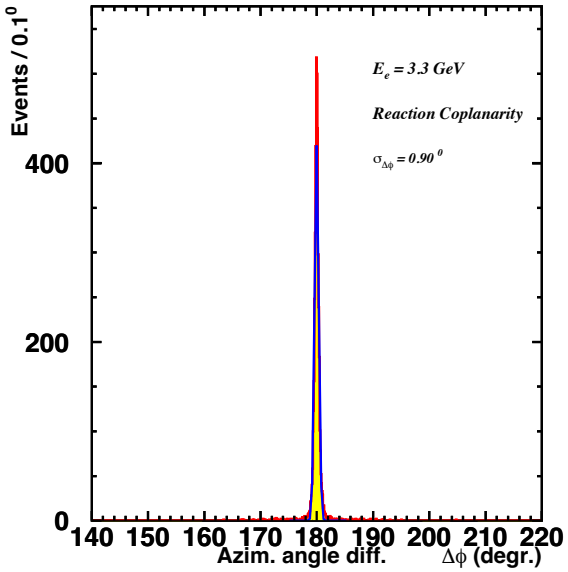
- Good energy resolution of $PbWO_4$ calorimeter (2.6% @ E=1 GeV) and 1 μm thin target provides powerful energy selection cut in this experiment (ΔE = 47 MeV @ 3.3 GeV beam).

  - ✓ important selection criterion for multi-channel and; accidental events;

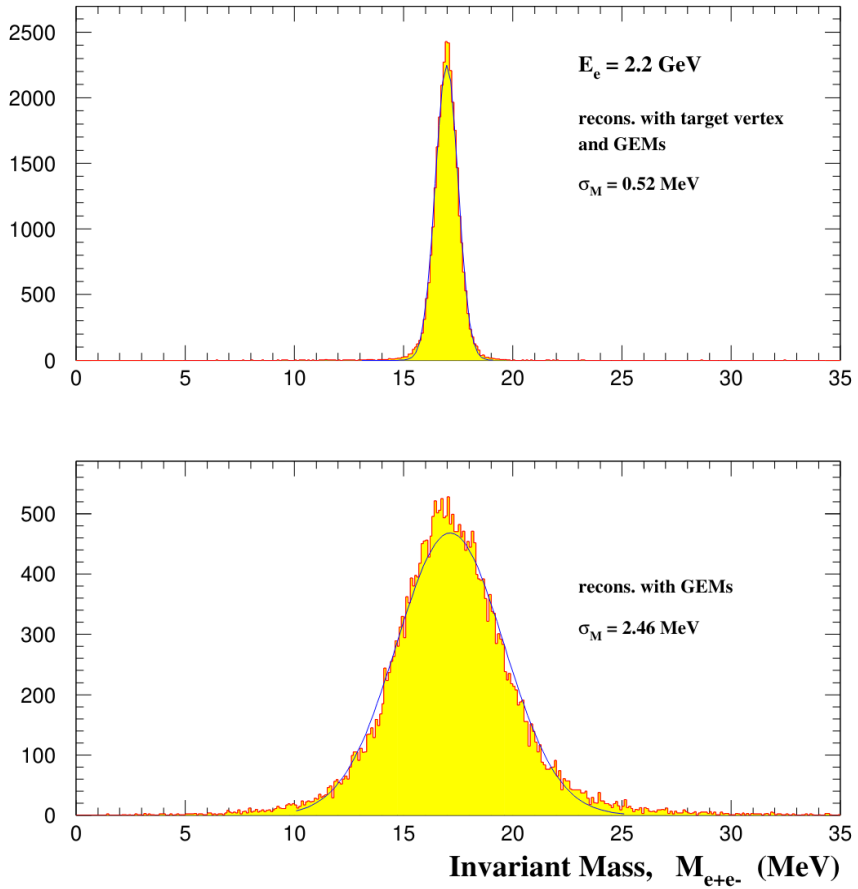
  - ✓ critical cut at low-mass range (see next slides).

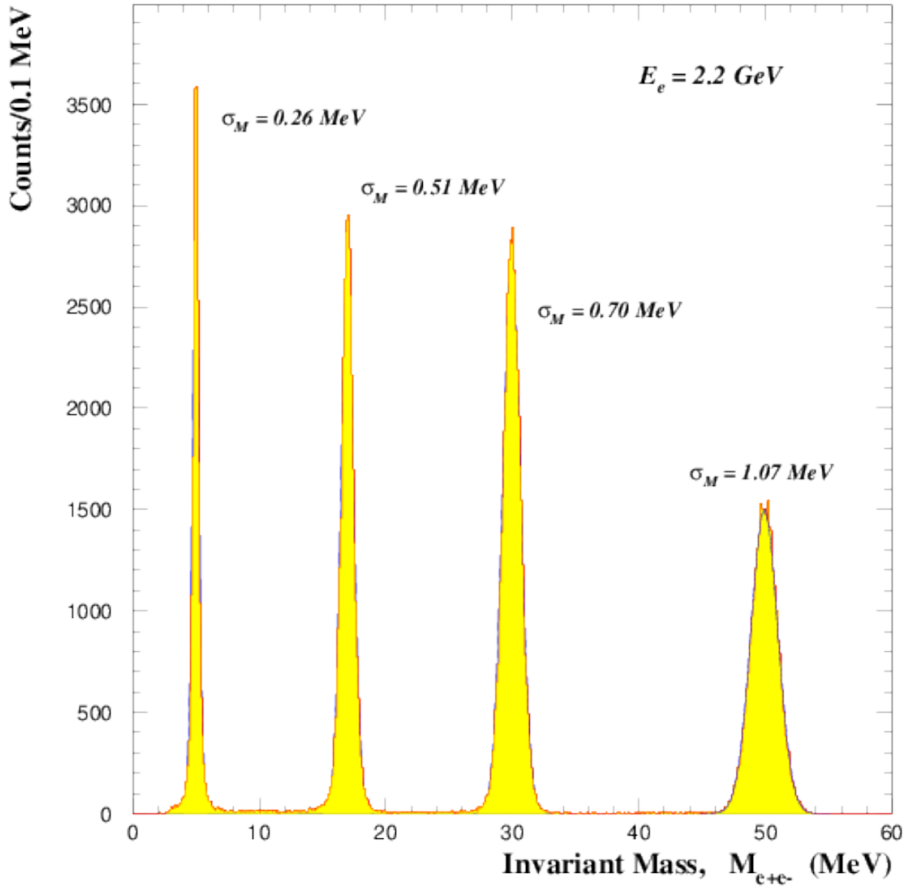


- Coplanarity (between $\overrightarrow{P_{e'}}$ and ($\vec{P}_{e+}$ + $\vec{P}_{e-}$) vectors): ($\vartheta_{\Delta\varphi}$ = 0.9^0)
  GEMs' excellent position resolution (σ = 72 μm), together with very thin 1 μm target ($2.4x10^{-4}$ r.l.) provides event selection criterion ($\vartheta_{\Delta\varphi}$ = 0.9^0), important for:
  - ✓ multi-particle and;
  - ✓ accidental coincidence events.



Invariant Mass resolution (more plots)





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	

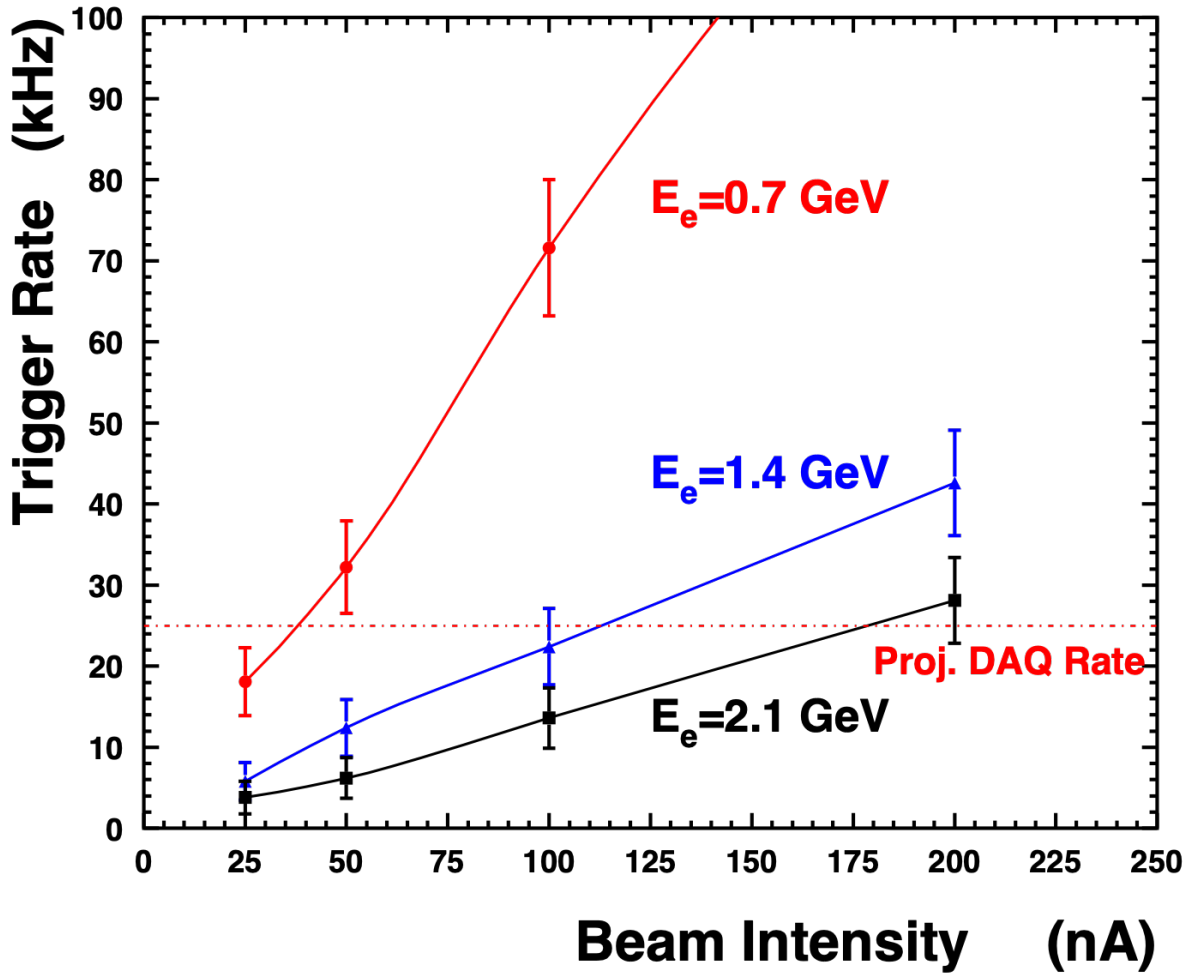
Suggested Run:

0.7	20	4
2.1	150	5
3.5	150	15

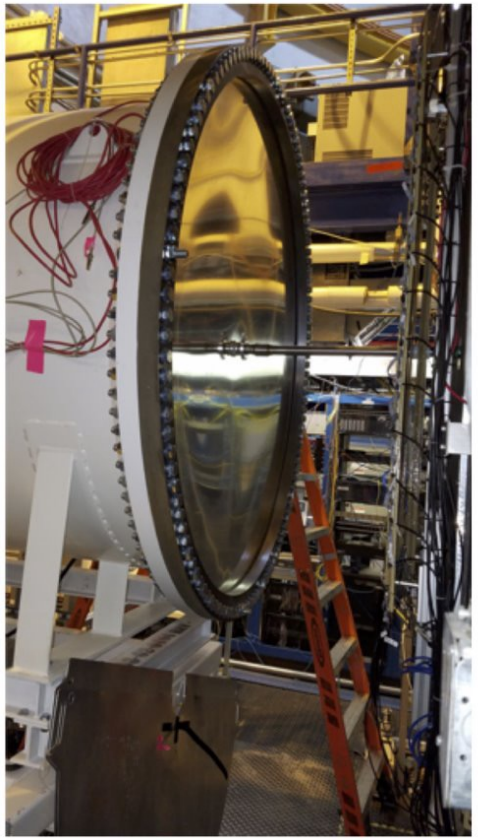
Setup checkout, tests and calibration	7 days	(Intensity is limited by central crystals)
Beam energy change	1 day	
Empty target runs	8 days	
Total:	40 days (no change)	

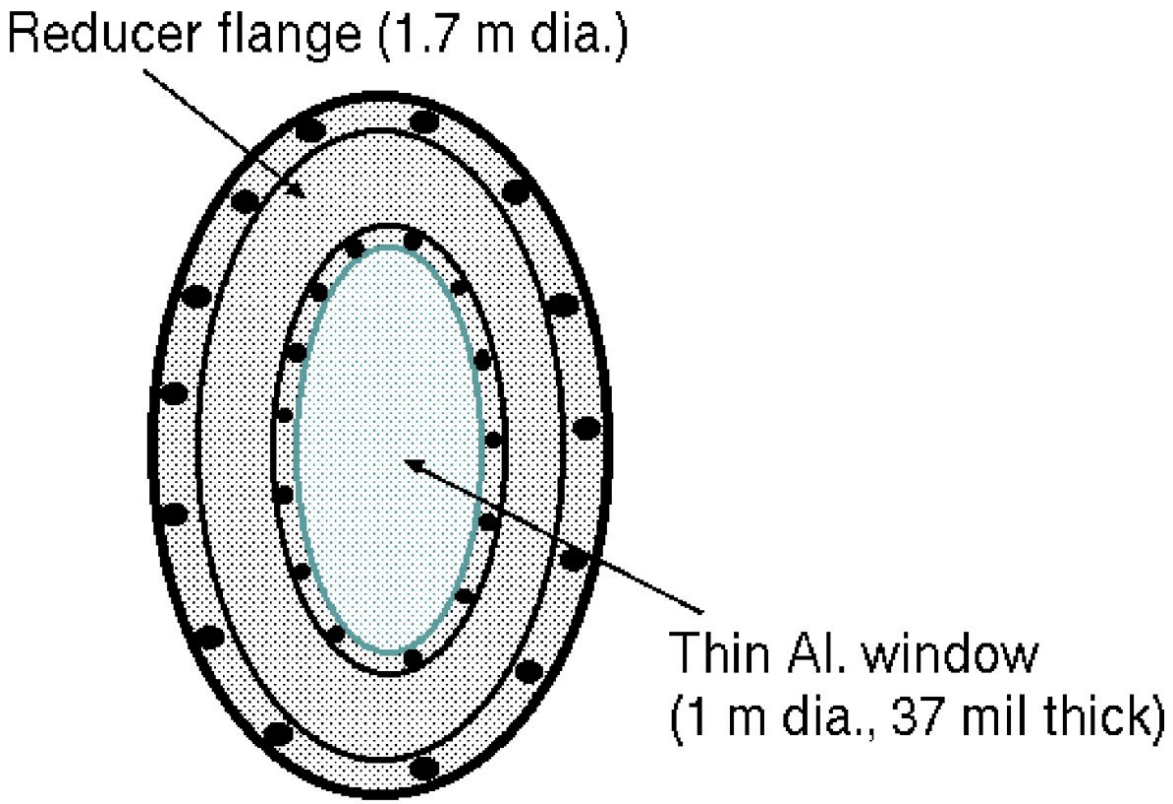
The upgraded DAQ enables 7-fold improved rate

Critical for the factor of ~4 reduction in the statistical uncertainty of PRad-II

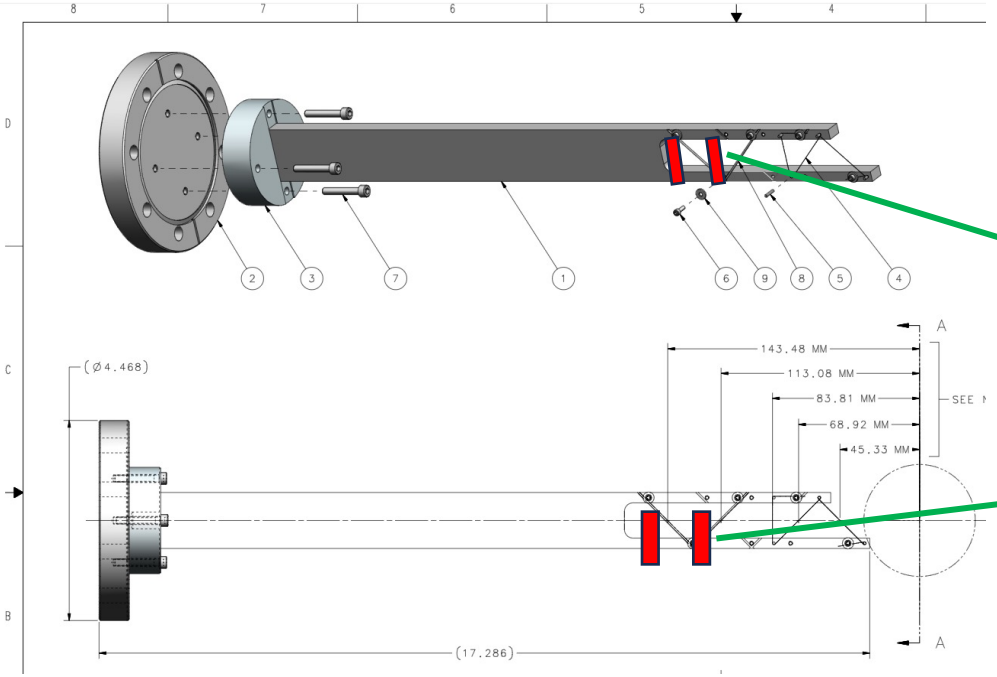


Vacuum Window Reducer
(to use tinner window material)

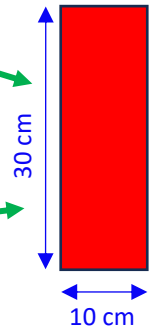




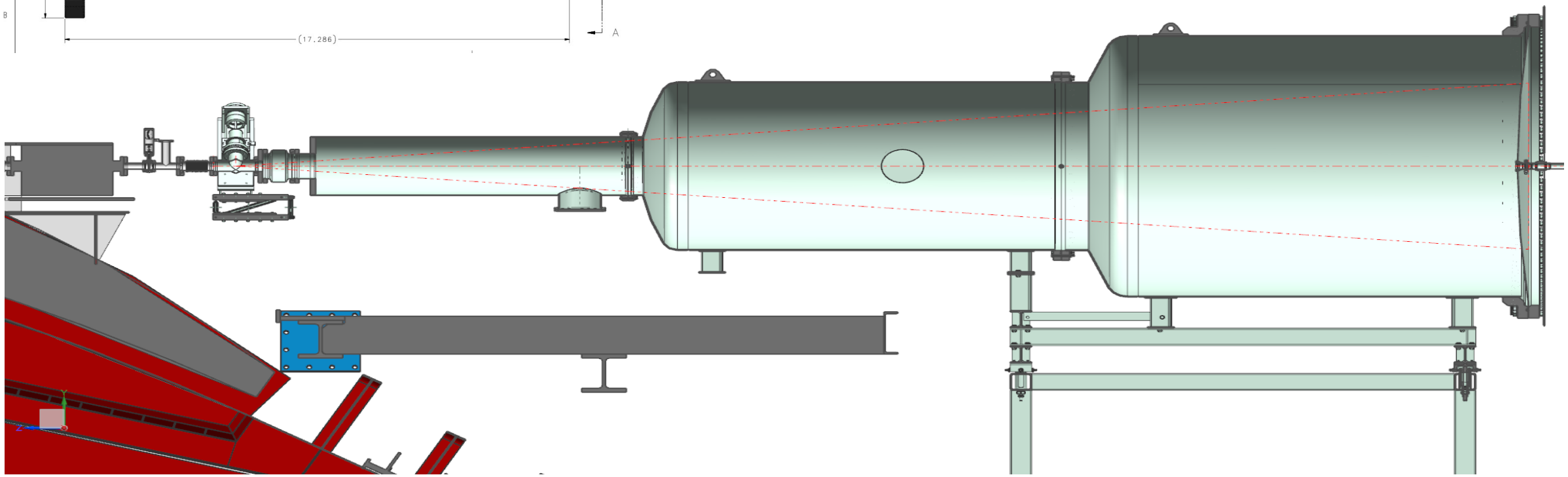
X17 Search Experiment: New Target Ladder



The target will be placed on the 2H02A harp stick.



Two 1 μm “Ta” target foils will be placed in the place of thick wires of the harp.
“Ta” foils are commercially available.



Upstream collimator and the radiator

The collimator along with the radiator will be placed in between the tagger harp and the tagger.