The PRad-II and X17 Search Experiments at Jefferson Lab

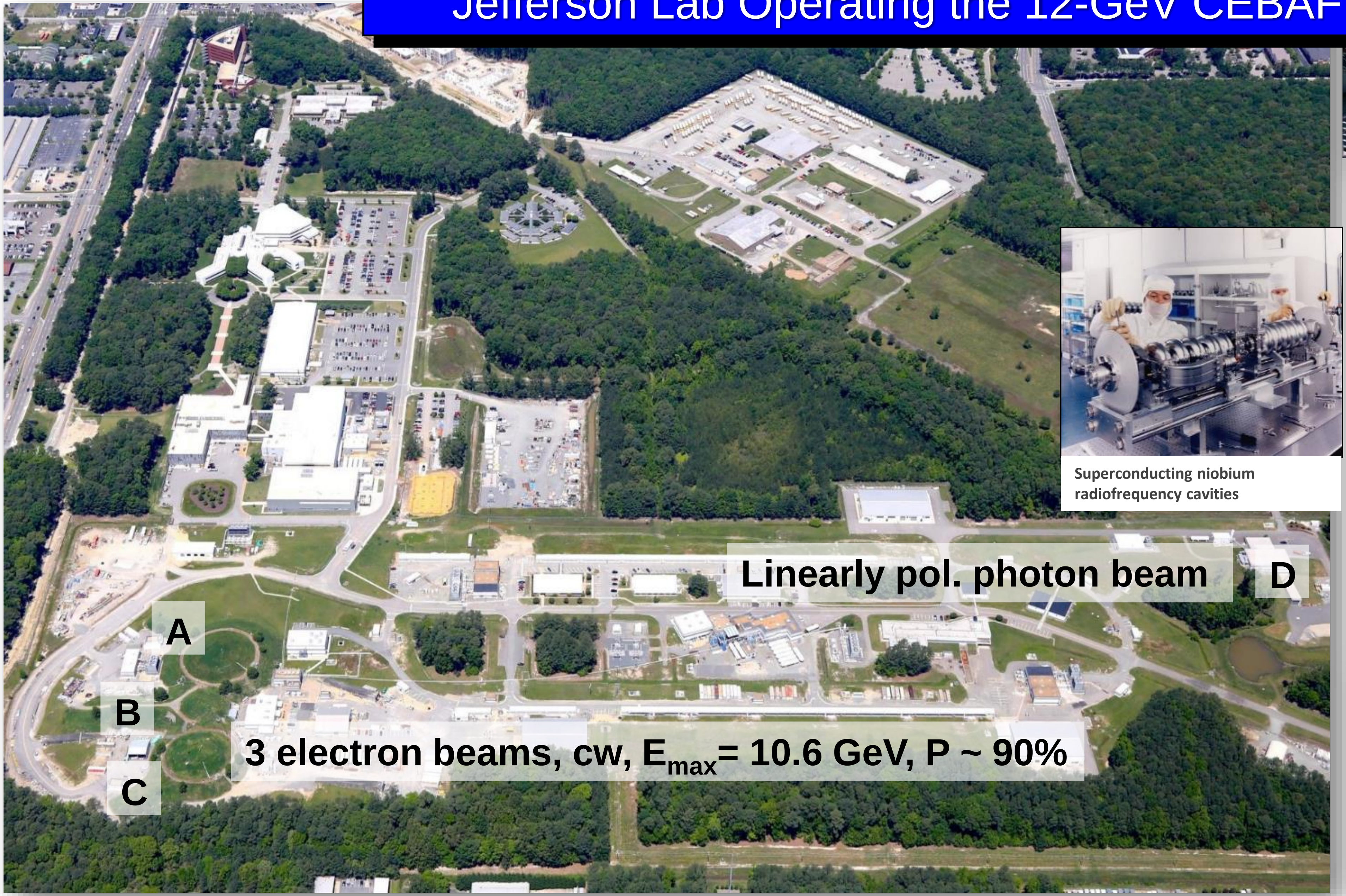
- X17 Search Experiment
- PRad-II Experiment
- PRad-II/X17 Hall B Run Group Status

Patrick Achenbach

Jefferson Lab

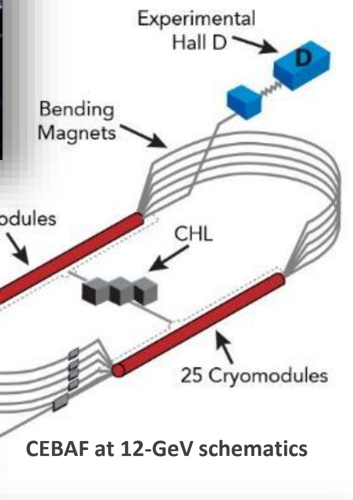
January 2o25

Jefferson Lab Operating the 12-GeV CEBAF



Superconducting niobium radiofrequency cavities


Cryogenic refrigeration plant



CEBAF at 12-GeV schematics


Cryomodules in the accelerator tunnel

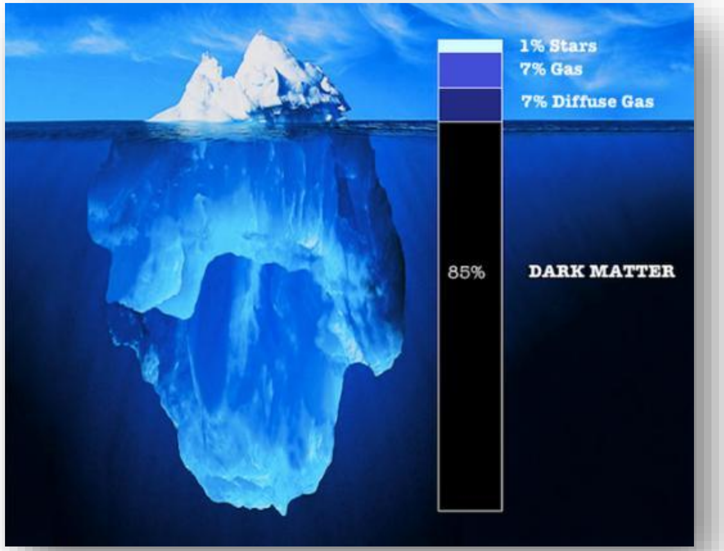

Recirculation arcs

X17 Search at Jefferson Lab

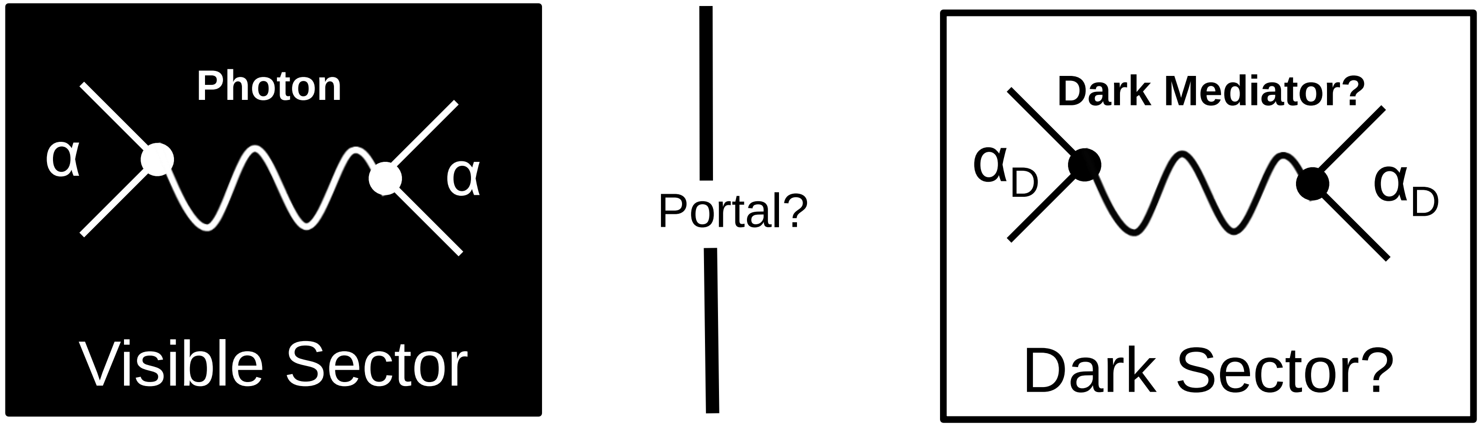
Physics Goals of X17 Search Experiment

- Most cosmological observations suggest
  $\approx$ 85% of the mass of the Universe consists of Dark Matter (DM):
- Assuming thermal origin, DM interacts with SM objects particles/fields
  - Either SM weakly (WIMPs) or feebly (new weak interaction)

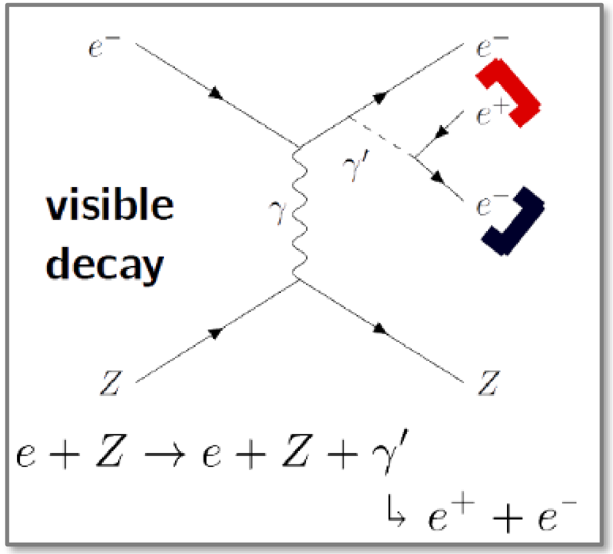
$$\langle \sigma_{\mathrm{annih}} v \rangle \sim \frac{g^4}{2\pi m^2} \simeq 6 \times 10^{-37} \mathrm{cm}^2 \left(\frac{g}{0.1}\right)^4 \left(\frac{m}{100\,\mathrm{GeV}}\right)^{-2}$$



- A simple theoretical SM extension model suggests a dark sector:
  - U(1) gauge boson (dark photon or X-particle)
  - Dark photon as portal between DM and SM through kinetic mixing



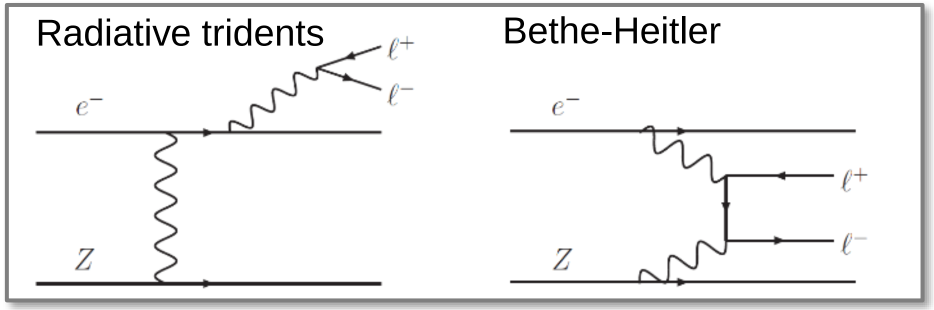
Dark Photon Visible Decay Searches

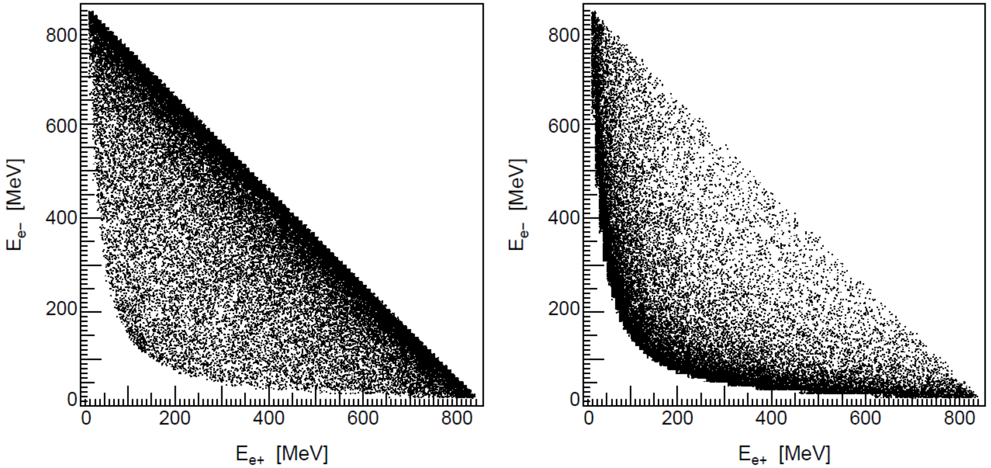


Concept of e+e- visible decay search experiments

- Coincidences reduce SM background
- High-precision determination of 4-vectors of e^+e^- pair
- Reconstruction of invariant mass spectrum

Back-grounds:



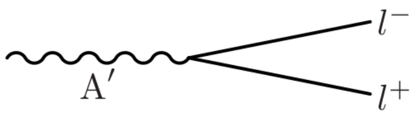


A' electro-production

- *A'* is emitted in forward cone → Detection symmetrically in forward detection
- *A'* carries away most of electron's energy → Energy sum near beam energy
- In any *A'* search unavoidable subtraction of continuous QED background

Dark Photon Exclusion Limits

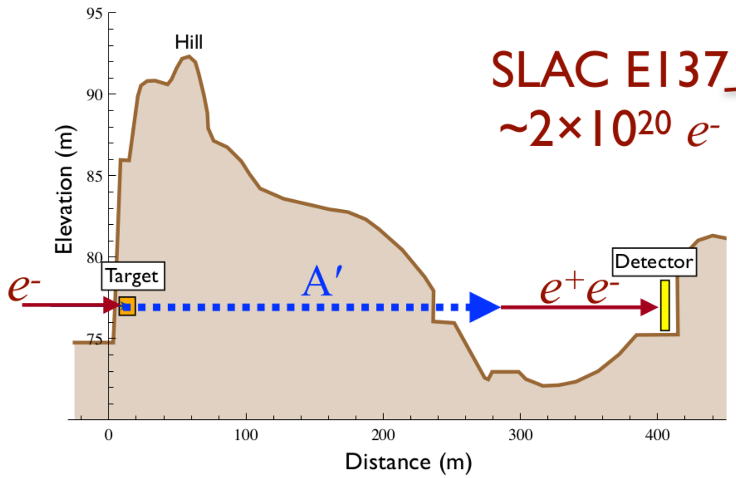
Generally, searches are "bump hunts" for $m(l^+l^-)$ resonances.



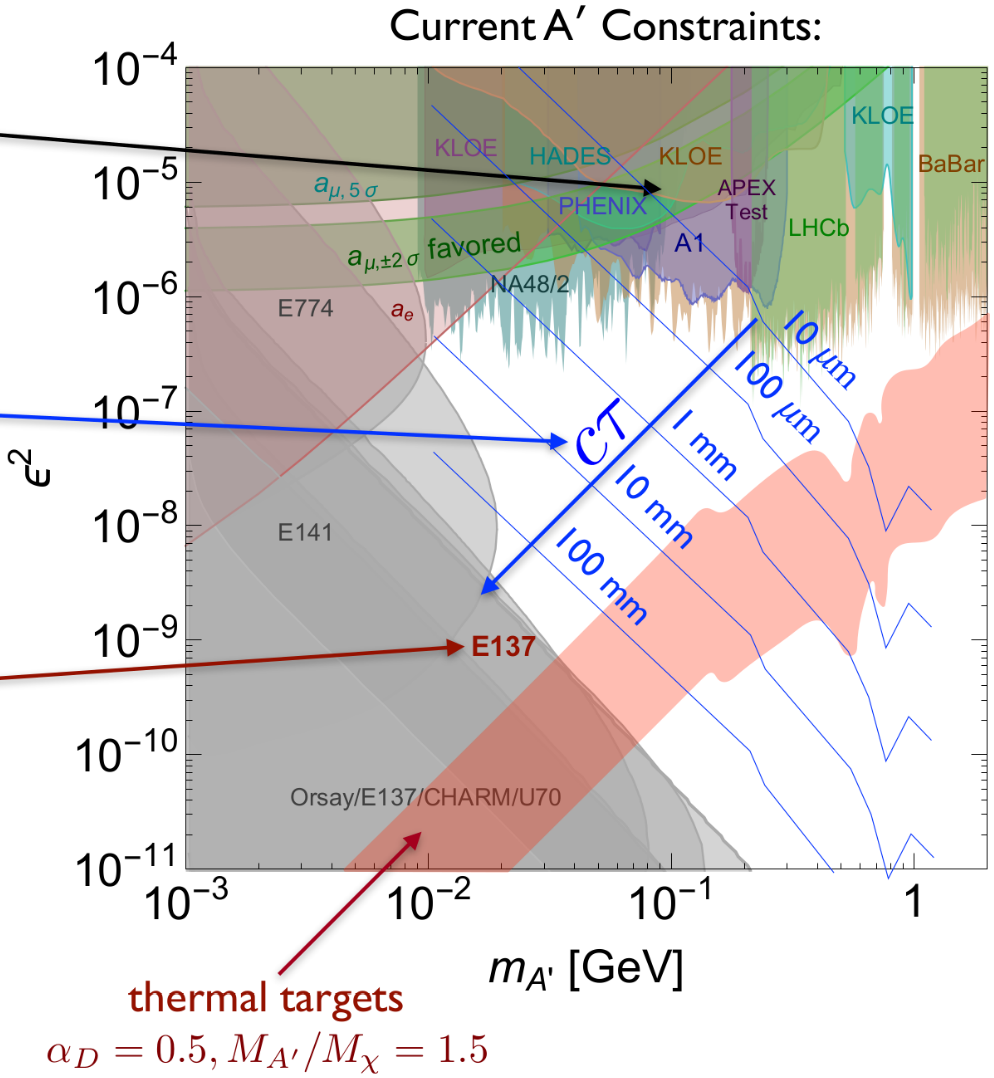
A′ becomes long lived at small couplings.

$$\gamma c\tau \propto \frac{1}{\epsilon^2 m_{A'}^2}$$

Leads to constraints from "beam dump experiments"



SLAC E137
~2×10^20 e^-

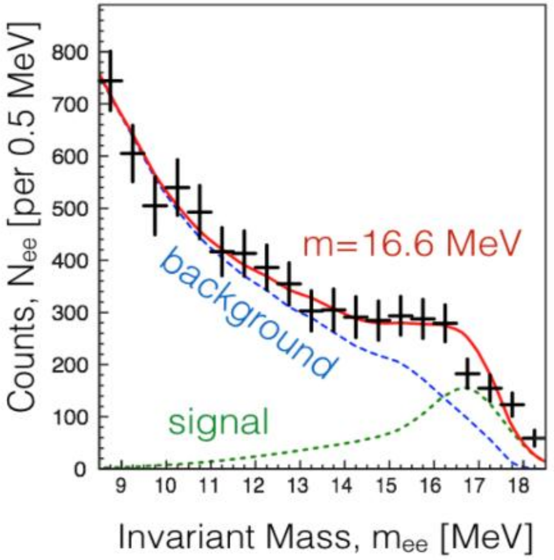


Physics Goals of X17 Search Experiment

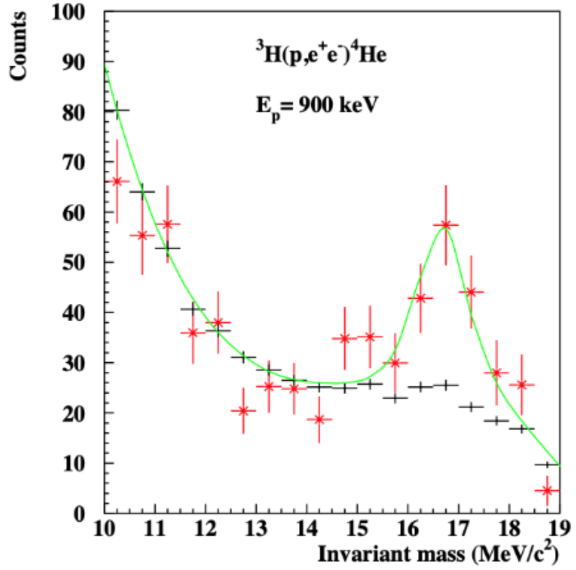
Observed anomaly: excess of e+e- pairs in $^{8}Be^{*}$, $^{4}He^{*}$ and $^{12}C^{*}$ decays

- Suggested explanation: hypothetical X17 particle
- Requires independent experimental verification

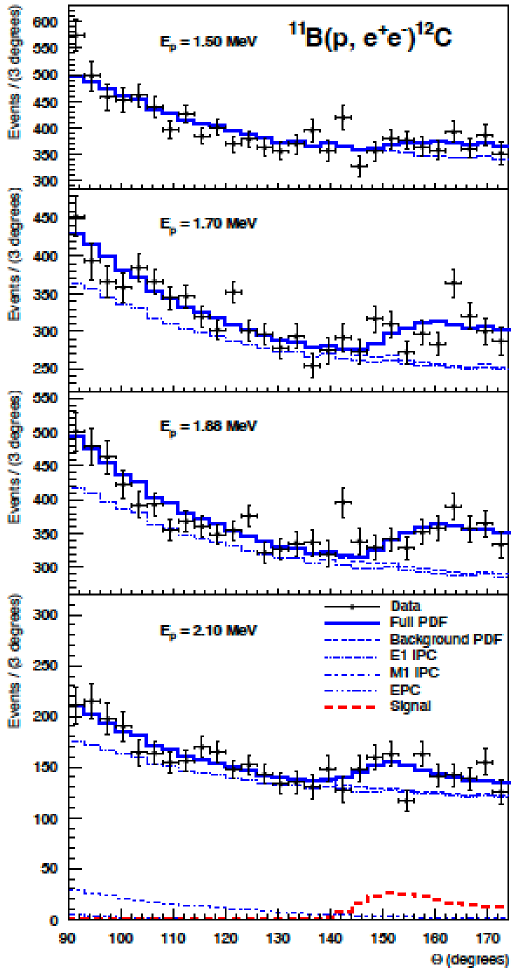
PRL 116, 042501 (2016)



PRC 104, 044003 (2021)



PRC 106, L061601 (2022)



Search with electron beams for hidden sector mediators in this mass range

Experimental Method and Detectors

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/c^2

- Detection of all final state particles (e', e+e- and/or $\gamma\gamma$)
  - Scattered electrons e' with 2 GEMs and $PbWO_4$ calorimeter
  - Decay e+ and e- with 2 GEMs and $PbWO_4$ calorimeter
  - Decay $\gamma\gamma$ pairs with $PbWO_4$ calorimeter and GEMs for veto

  → full control of kinematics

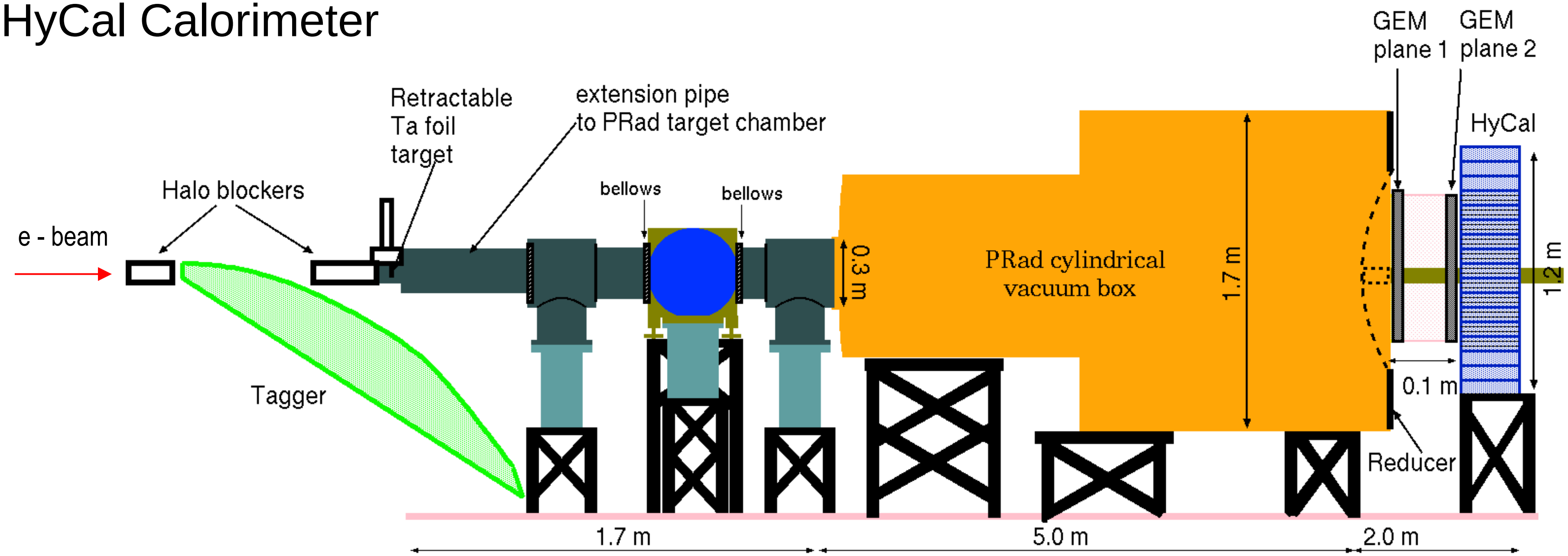
  → full control of background

- Bump hunting in invariant mass spectrum over SM background

X17 Search Setup in Hall B

Experimental setup based on PRad-II apparatus

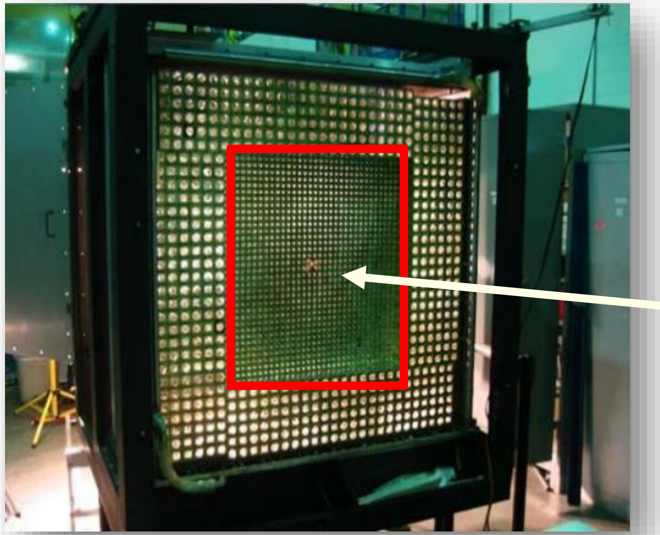
- Hall B Photon Tagger for $PbWO_4$ calorimeter calibration
- 1 µm Ta (2.4 x 10^{-4} X_0) thin foil targets
- Large vacuum box to minimize scattering
- Two planes of GEM detectors for tracking
- HyCal Calorimeter

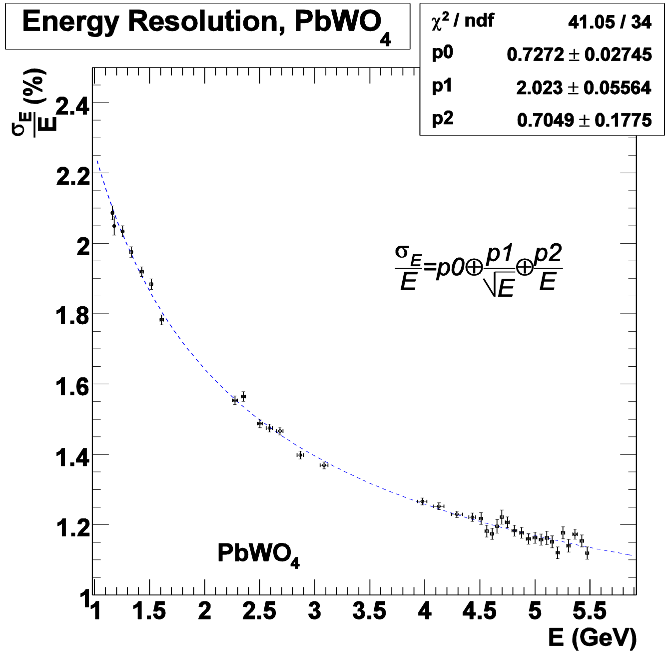


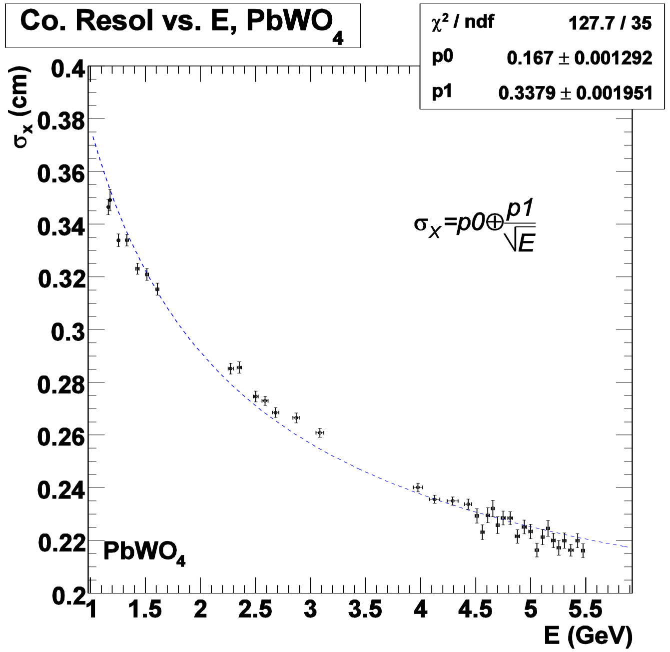
Electromagnetic Calorimeter

Hybrid Calorimeter HyCal from PrimEx

- 34 x 34 =1156 $PbWO_4$ modules, each 2 x 2 x 18 cm^3
- 68 x 68 cm^2 total detection area
- 2 x 2 or more crystals removed for beam passage
- New Flash-ADC readout electronics





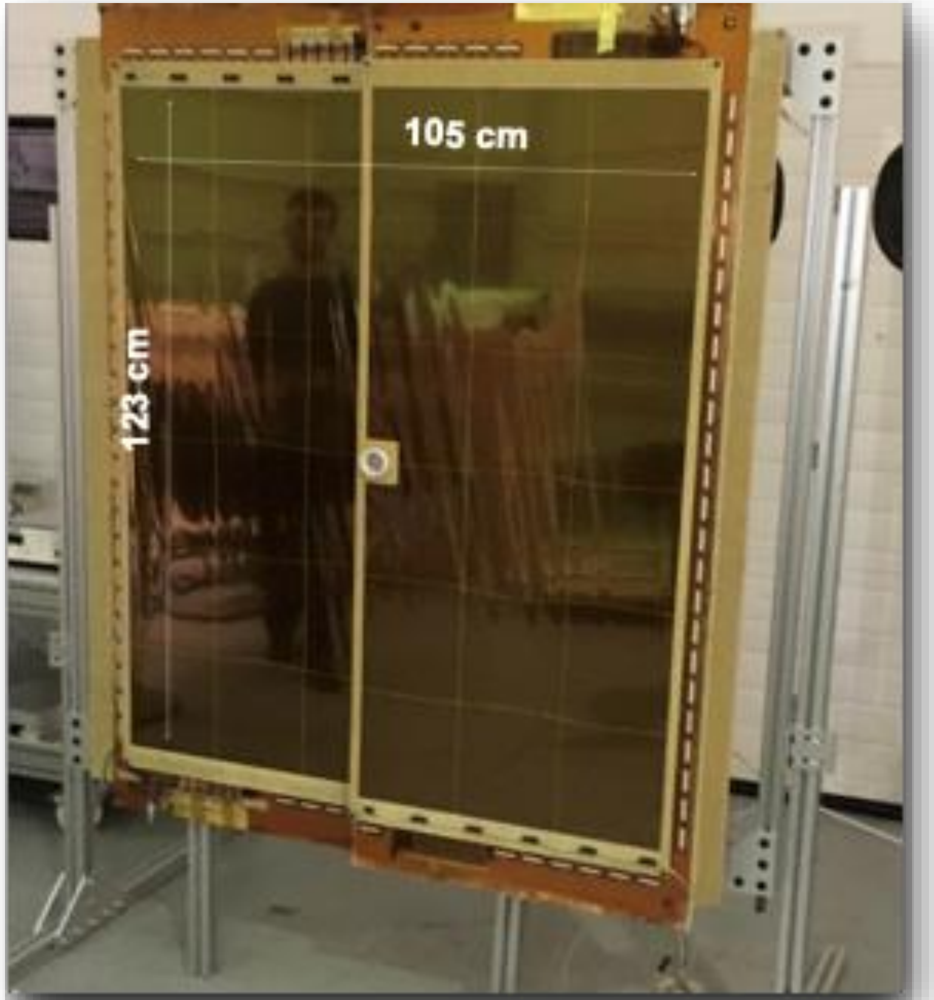


GEM Detector Tracking

Two planes (4 layers) of new GEMs

- Located in front of $PbWO_4$ behind vacuum window
- Optimized relative distance of 40 cm for resolution
- Good position resolution of $\sigma = 72\ \mu m$
- Veto of neutral particles for $X \rightarrow e^+e^-$ channel and veto of charged particles for $X \rightarrow \gamma\gamma$ channels
- New electronics based on APV-25 readout system

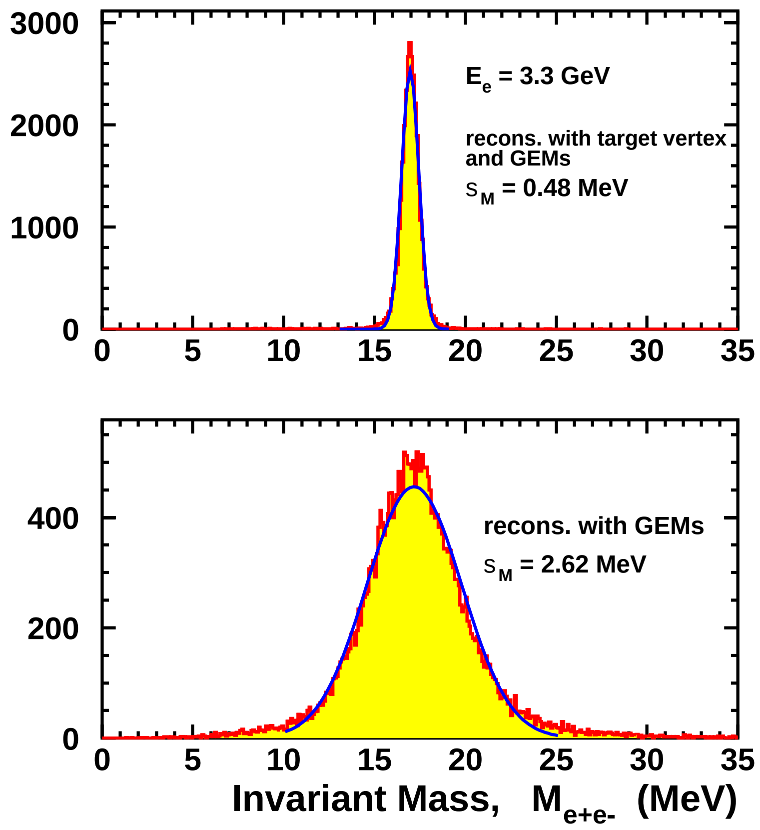
Under construction at University of Virginia
subcontracted by Jefferson Lab

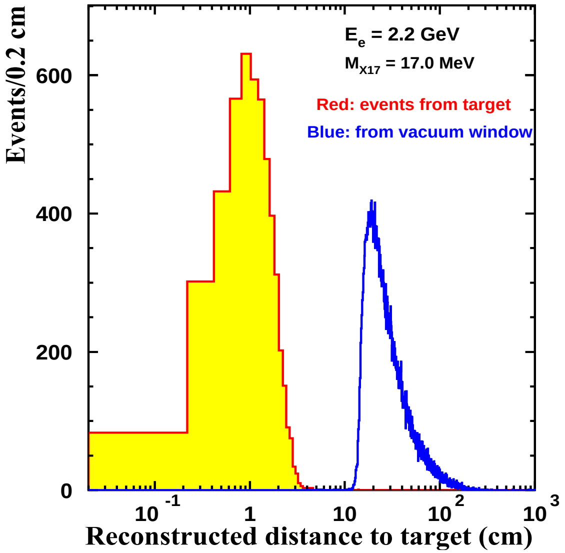


Invariant Mass and Vertex Resolutions

Invariant mass reconstruction

- Vertex, GEMs and $PbWO_4$ calorimeter provide σ_m = 0.48 MeV/c^2 for X17 particle
- GEMs and $PbWO_4$ calorimeter alone is worse
- GEM planes (with $PbWO_4$) discriminate events not originating from the target but do not to measure decay length, not a “displaced vertex” search experiment

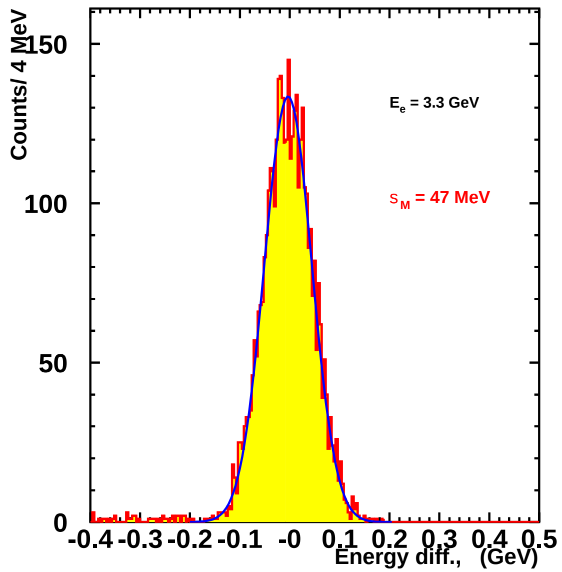




Energy Sum and Angular Resolutions

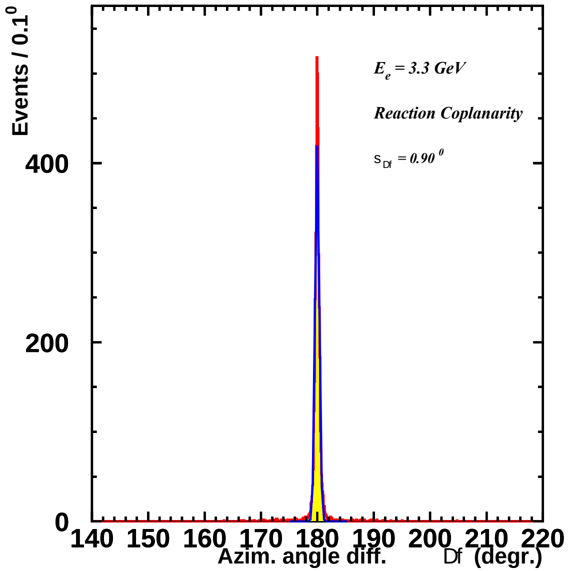
- Good energy resolution of $PbWO_4$ calorimeter (2.6% @ E = 1 GeV) and 1 μm thin target provide powerful energy selection cut:

  σ_E = 47 MeV @ 3.3 GeV beam



- GEMs excellent position resolution (σ = 72 μm) and 1 μm thin target provide further event selection criterion:

  Coplanarity between $\vec{p}_{e'}$ and $(\vec{p}_{e+} + \vec{p}_{e-})$ $\sigma_{\Delta\varphi} = 0.9°$

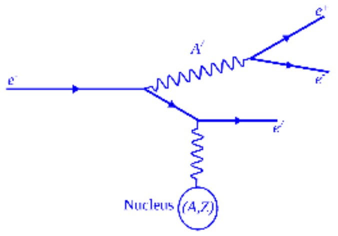


Physics Background Simulations

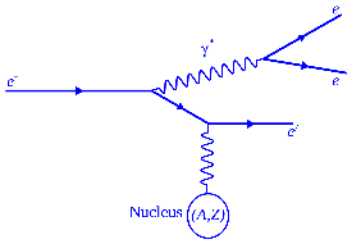
Physics background was simulated in two different ways:

1) GEANT4 based Monte Carlo background simulations
   - PRad experimental setup
   - Physics processes from GEANT package
   - Large statistics of beam electrons incident on target
   - Events with $N_{cluster} \geq 3$ analyzed in same way as signals

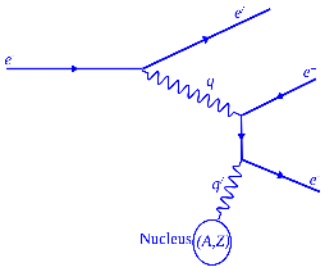
2) MadGraph5 EM event generator background simulations
   - Large statistics (~2M) of radiative trident events
   - Events were fed into the GEANT MC simulation
   - Same analysis procedure was applied for these events



X production channel



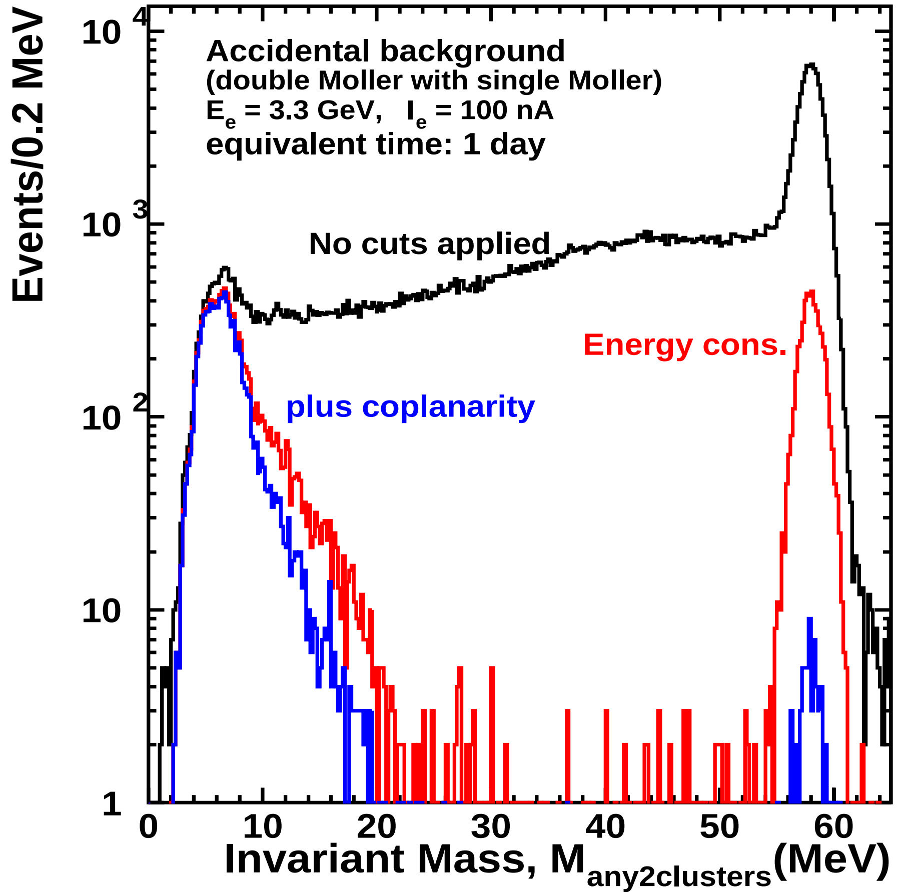
Radiative tridents



Bethe-Heitler

Trigger and Physics Background Rates

- Hardware trigger requires 3-cluster ($N_{cluster} \geq 3$) events:
  - Each one within 30 MeV < $E_{cluster}$ < 0.8 x E_{beam}
  - E_{total} > 0.7 x E_{beam}
- Two high-rate processes in this experiment:
  - Electron-nucleus elastic scattering: trigger will effectively suppress these events
  - Møller scattering: source of major accidentals
- Estimated rates for two main sources are:
  - Singles from Møller: Rate ≈ 107 kHz
  - Doubles from Møller: Rate ≈ 81.7 kHz
- Assuming 2 ns time resolution (bunch size):
  - Accidental coincidence rate: ≈17 Hz: not a significant background contribution



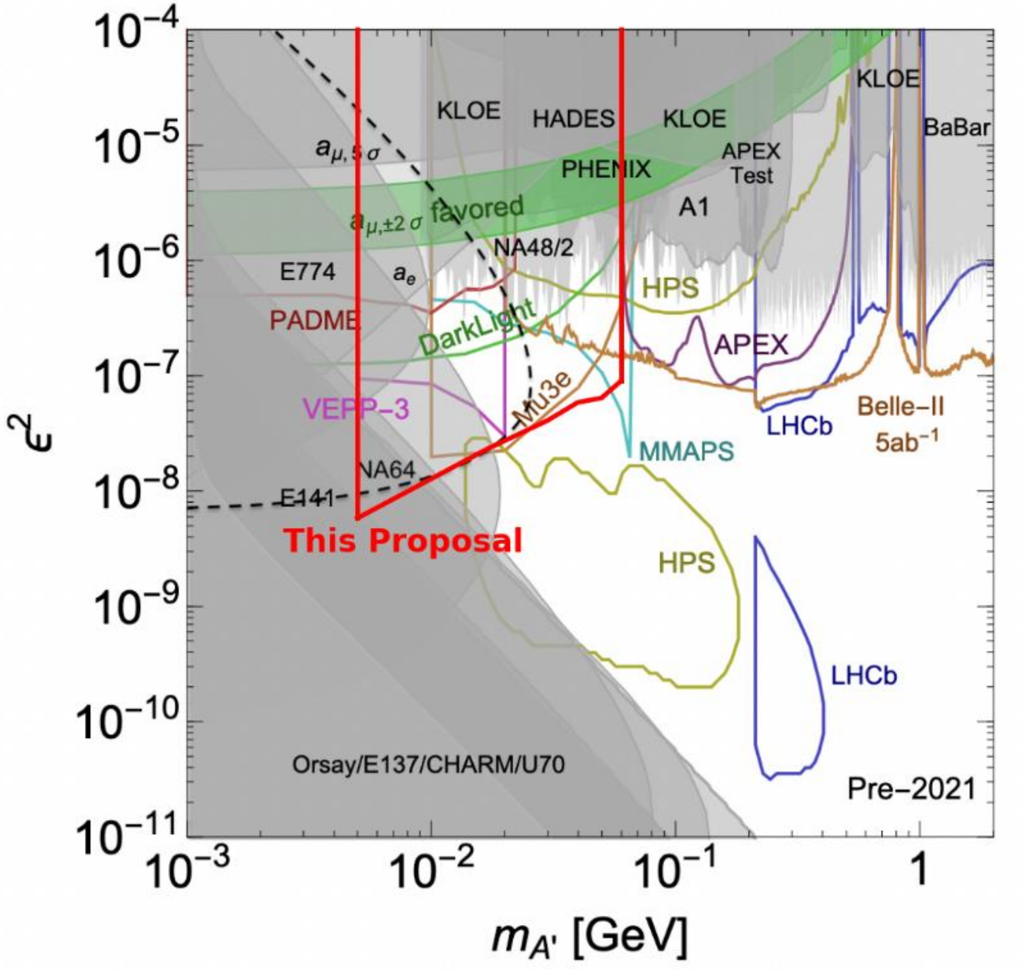
Reach Projection of X17 Search

Exclusion of relevant parameter space

- Based on Bjorken paper yield formula
- Assumes cross section averaging
- Invariant mass range: 3 – 60 MeV/c^2
- Coupling constant: $\varepsilon^2 \approx 10^{-8}$–$10^{-7}$
- Showing 5σ limits (discovery criterion)
- Event-by-event MC is being developed

Update of experimental reach is expected before experiment is performed

Reach from approved proposal:



PRad-II at Jefferson Lab

Nucleon Elastic Factor Factors

The cross section:

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

with:

$$\tau = \frac{Q^2}{4m_p^2}, \quad \varepsilon = \left(1 + 2\left(1+\tau\right)\tan^2\frac{\theta_e}{2}\right)^{-1}$$

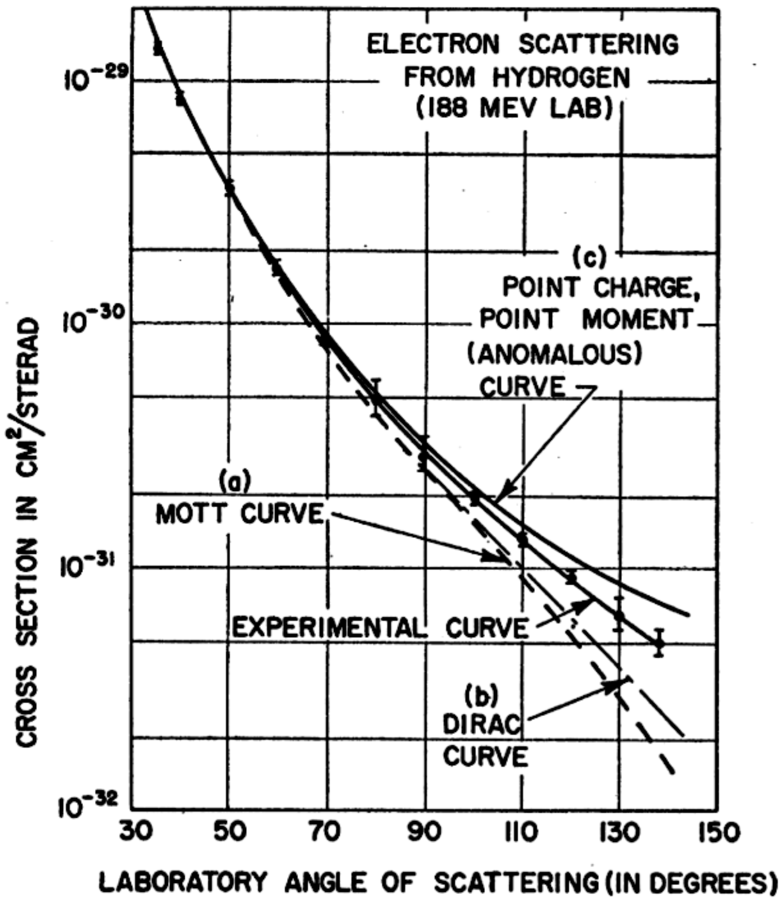
Fourier-transform of G_E, G_M $\rightarrow$ spatial distribution (Breit frame)

$$\left\langle r_E^2\right\rangle = -6\hbar^2\left.\frac{\mathrm{d}G_E}{\mathrm{d}Q^2}\right|_{Q^2=0} \qquad \left\langle r_M^2\right\rangle = -6\hbar^2\left.\frac{\mathrm{d}\left(G_M/\mu_p\right)}{\mathrm{d}Q^2}\right|_{Q^2=0}$$

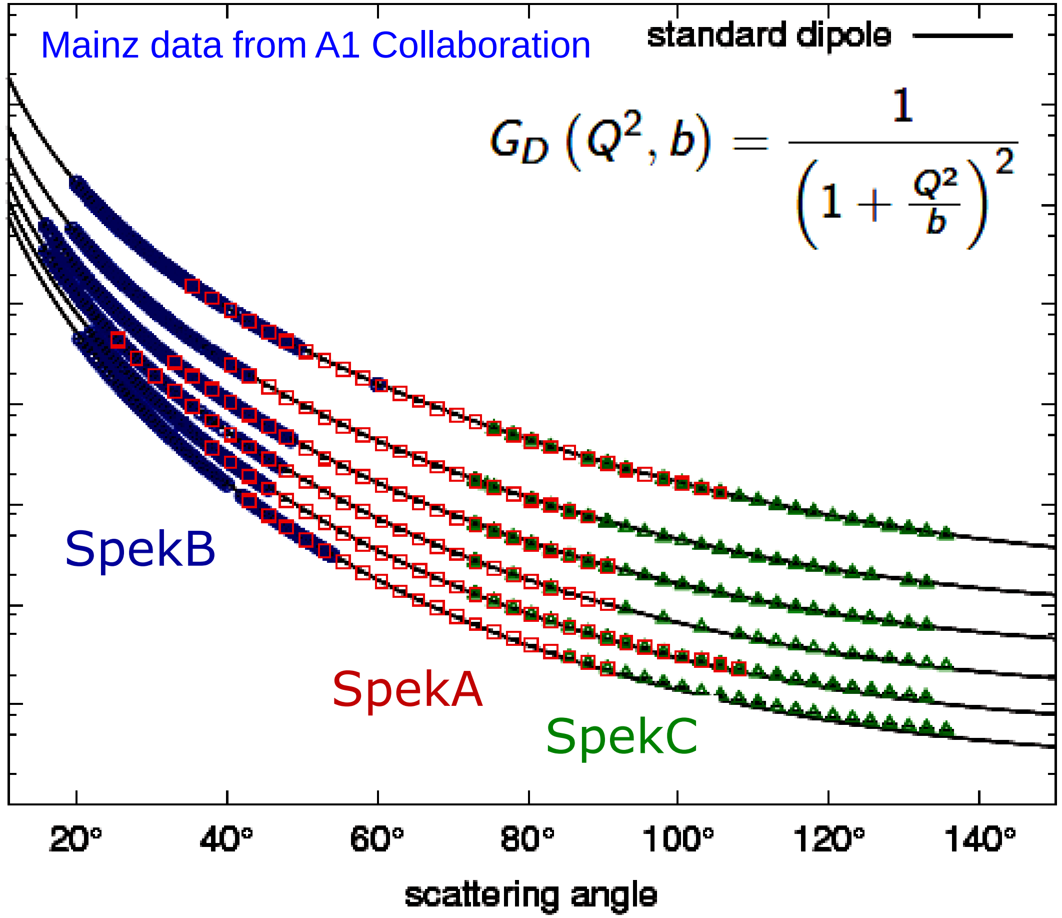
Mean squared radii determined from slope of corresponding form factors at $Q^2 = 0$

Measured Elastic Scattering Cross Sections

[Hofstadter, Phys. Rev. 102 (1956)]



E_0 = 855; 720; 585; 450; 315; 180 MeV



$$G_D\left(Q^2, b\right) = \frac{1}{\left(1 + \frac{Q^2}{b}\right)^2}$$

Dipole form factor as “classical” description of elastic cross sections

Q^2-Evolution of Form Factor Ratio

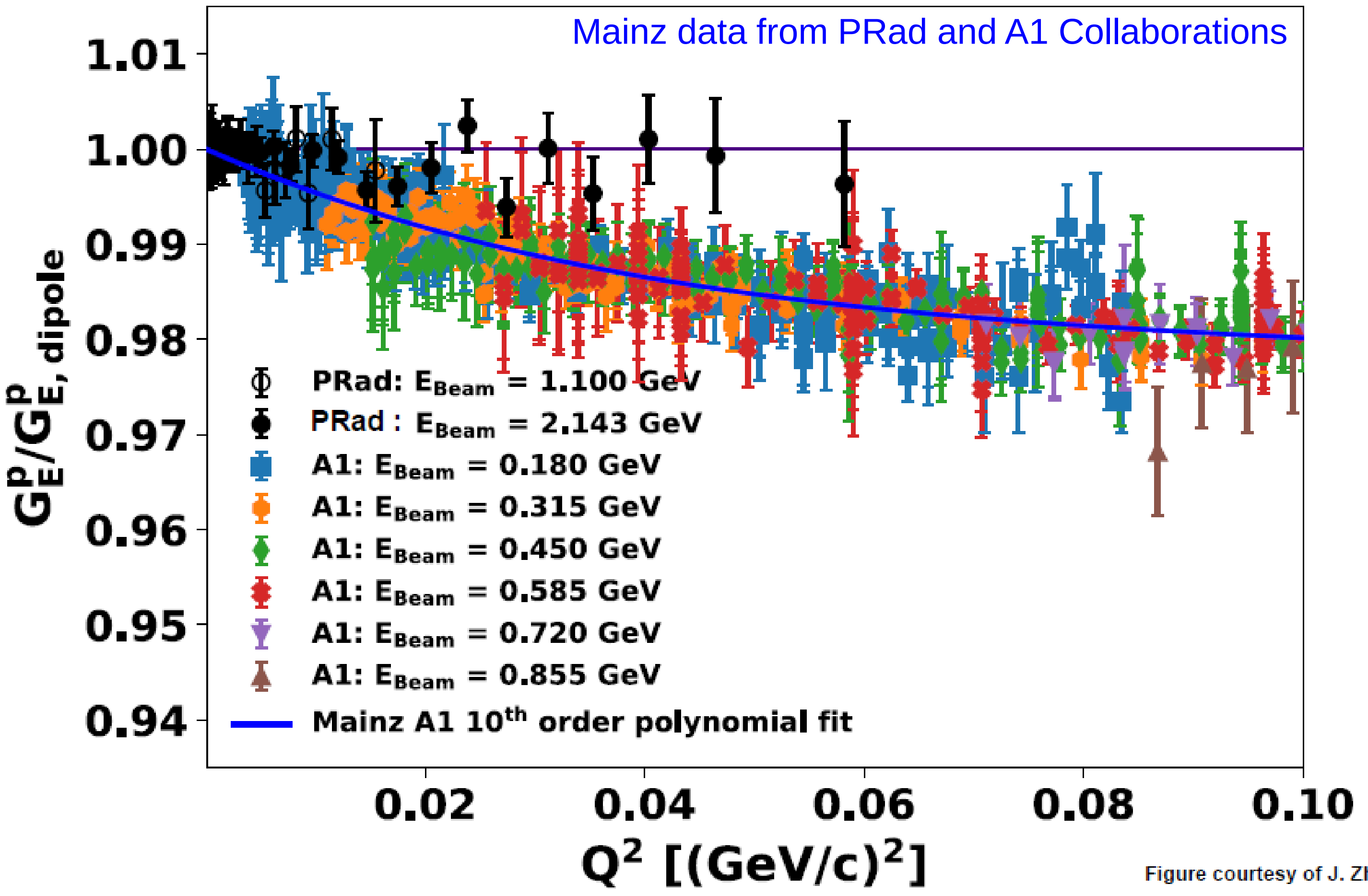
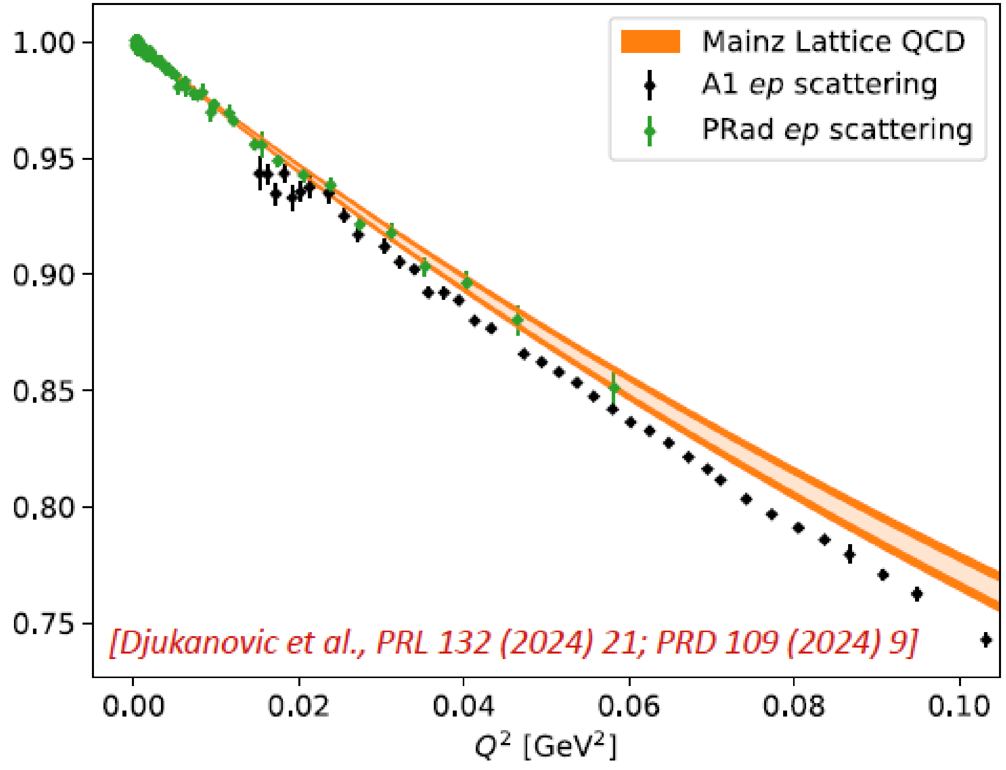


Figure courtesy of J. Zhou

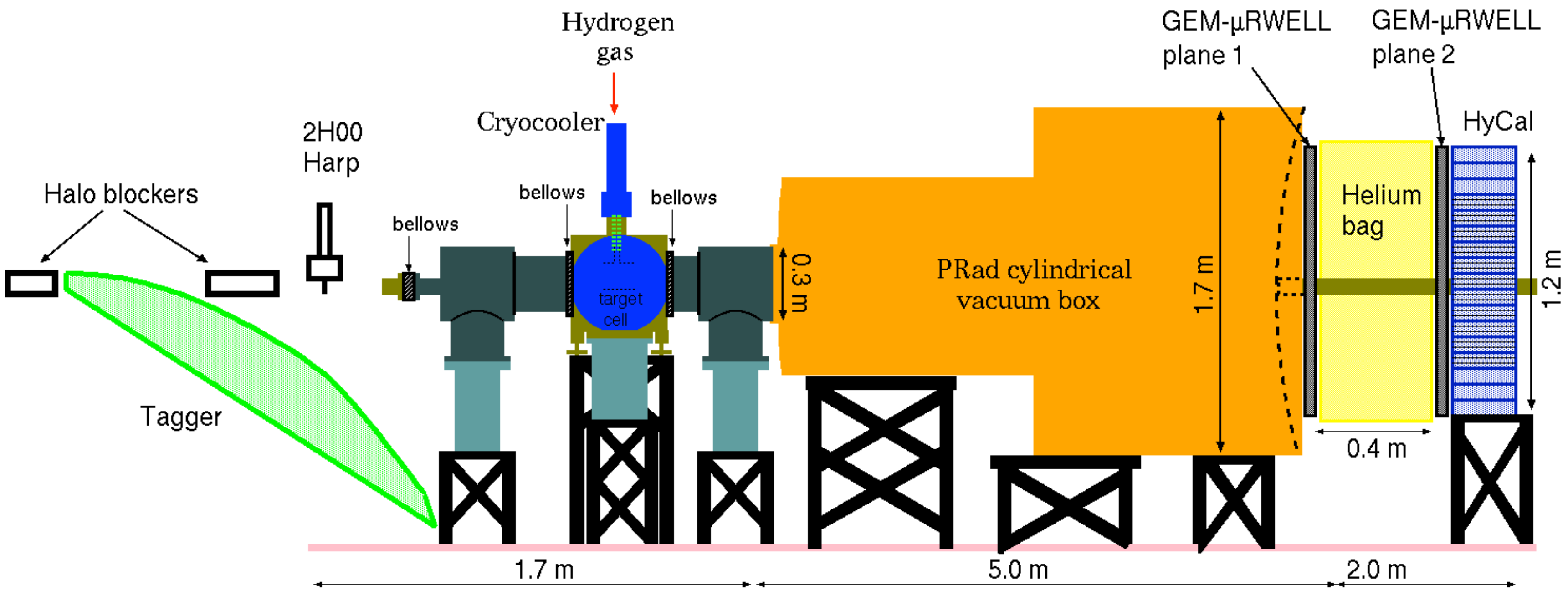
Comparison to Lattice QCD



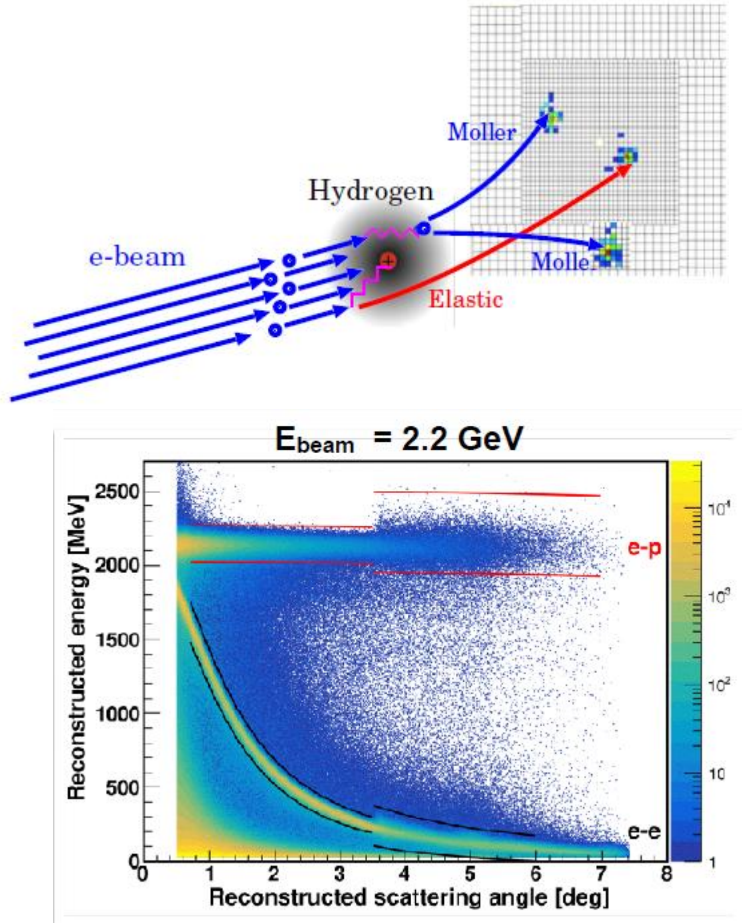
Discrepancies between data sets at Q^2 between 0.03 and 0.06 GeV^2/c^2

PRad-II Setup in Hall B

Background-minimized forward detection



Elastic to Møller scattering



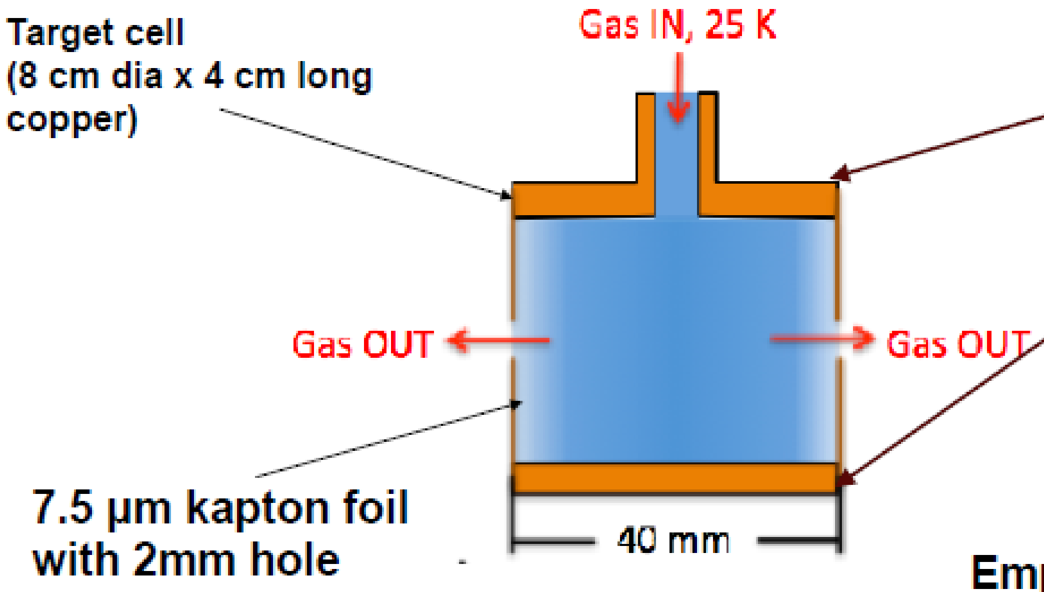
Data from PRad Collaboration

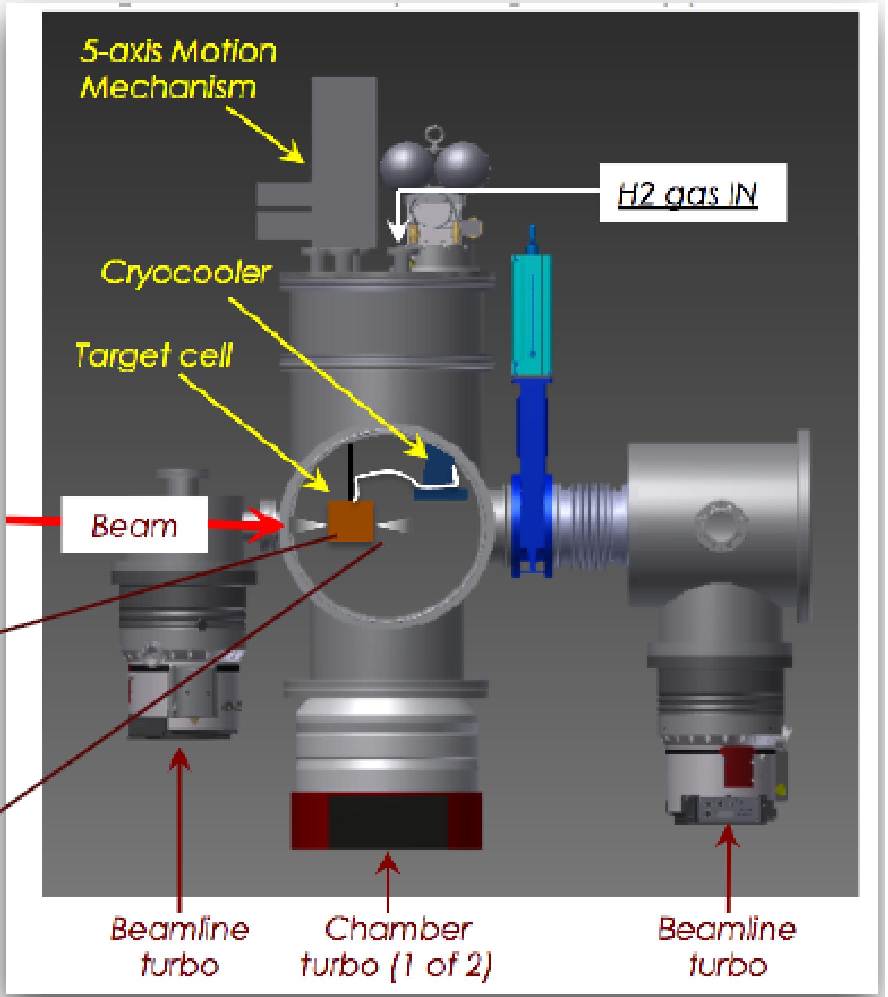
This particular experimental design:
- Allows control of systematics
- Eliminates need to monitor luminosity

Windowless Gas Flow Target

density:
~2x10^{18} atoms/cm^2

cell / chamber/ tank pressure:
470 / 2.3 / 0.3 mtorr

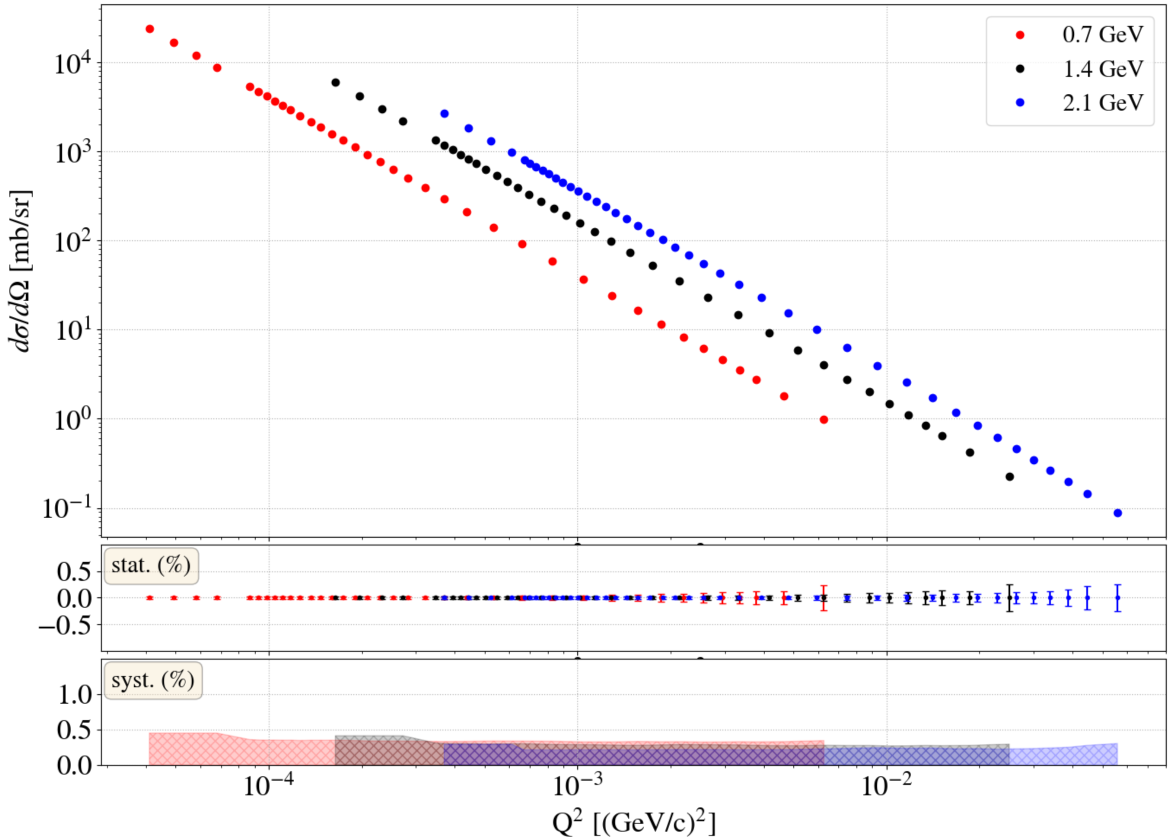




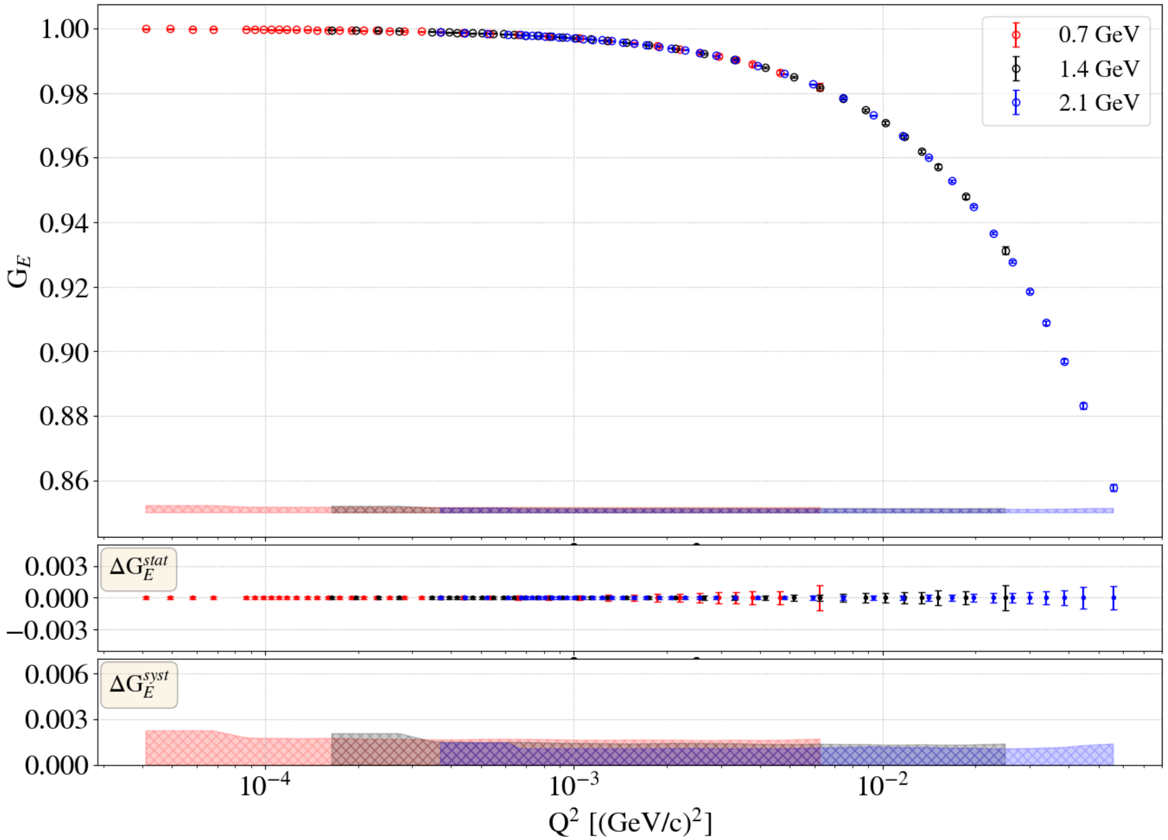
Empty target runs used to subtract background

Projections of Cross Section Precision

Cross sections

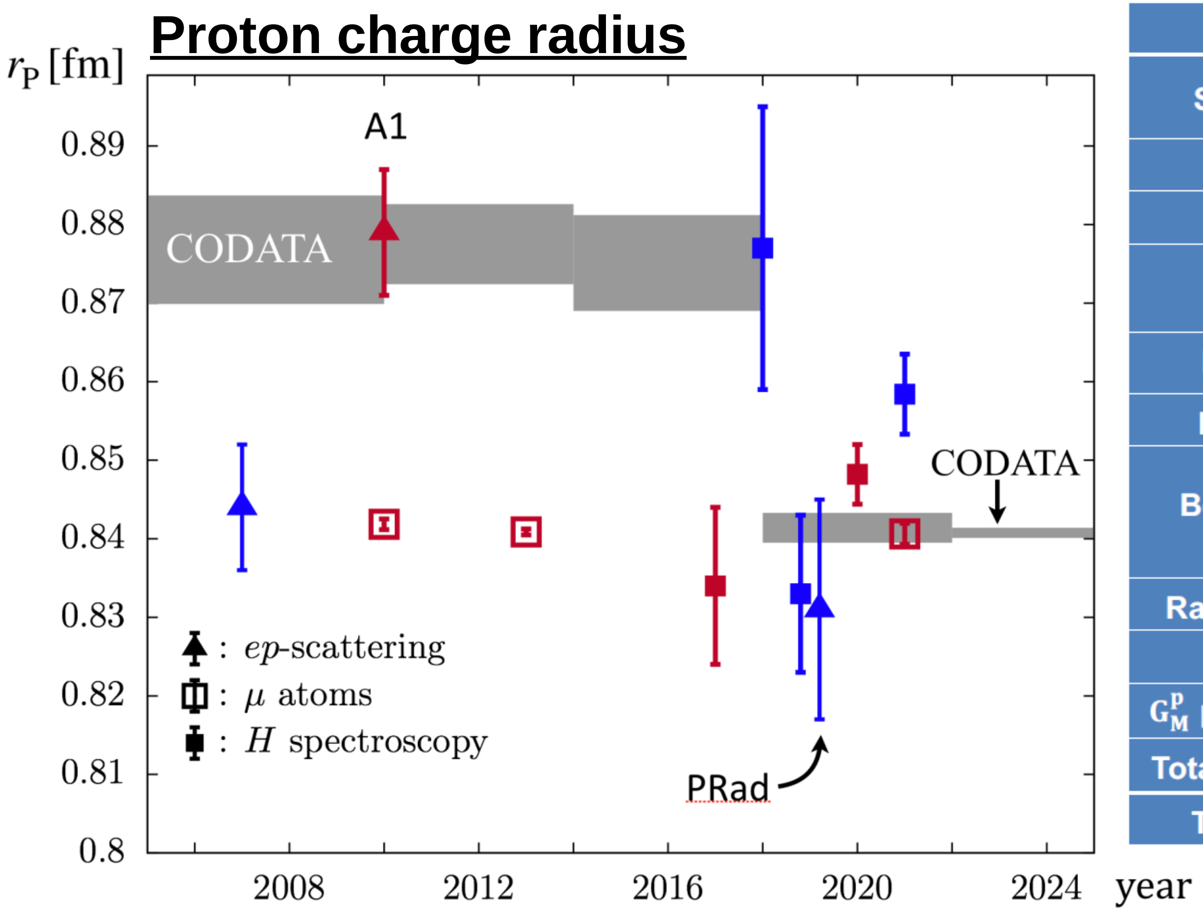


Proton electric form factor



Extremely low Q^2 coverage with overlap for different beam energies

Existing Data and Projected Radius Precision



Item	PRad δr_p [fm]	PRad-II δr_p [fm]	Result of
Stat. uncertainty	0.0075	0.0017	More beam time and higher DAQ rate
GEM efficiency	0.0042	0.0008	2nd tracking detector
Acceptance	0.0026	0.0002	2nd tracking detector
Beam energy related	0.0022	0.0002	2nd tracking detector
Event selection	0.0070	0.0027	2nd tracking + HyCal upgrade
HyCal response	0.0029	Negligible	HyCal upgrade
Beam background	0.0039	0.0016	Better vacuum 2nd halo blocker vertex res. (2nd tracking)
Radiative correction	0.0069	0.0004	Improved calc.
Inelastic ep	0.0009	Negligible	Upgraded HyCal
G_M^p parameterization	0.0006	0.0005	---
Total syst. uncertainty	0.0115	0.0032	
Total uncertainty	0.0137	0.0036	

PRad result: 0.831 ± 0.007 (stat.) ± 0.012 (syst.) fm
→ ± 0.002 (stat.) ± 0.003 (syst.) fm

PRad-II/X17 Run Group Status

Current Status of the Experiment Preparation

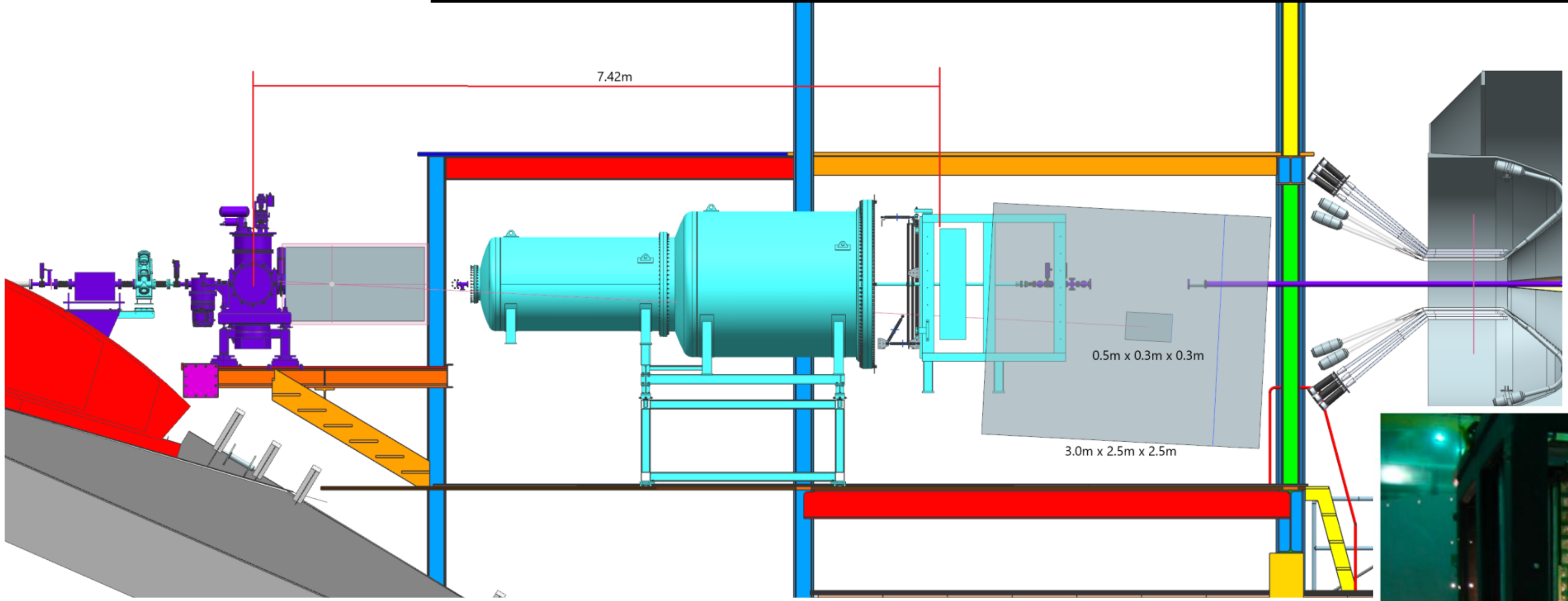
- Refurbishment and testing of HyCal calorimeter started last summer
- Construction of two GEM detectors is on track at University of Virginia; delivery to JLab and commissioning in Spring 2025
- DAQ electronics is procured (based on new fADC-250 modules); ready in Spring 2025
- PRad-II gas flow target has been set up and is tested in a lab
- Conceptual design of beamline finalized; engineering design in progress
- Work on new cabling and other experimental parts is underway in Hall B
- Experiments are tentatively and conditionally scheduled for Fall 2025

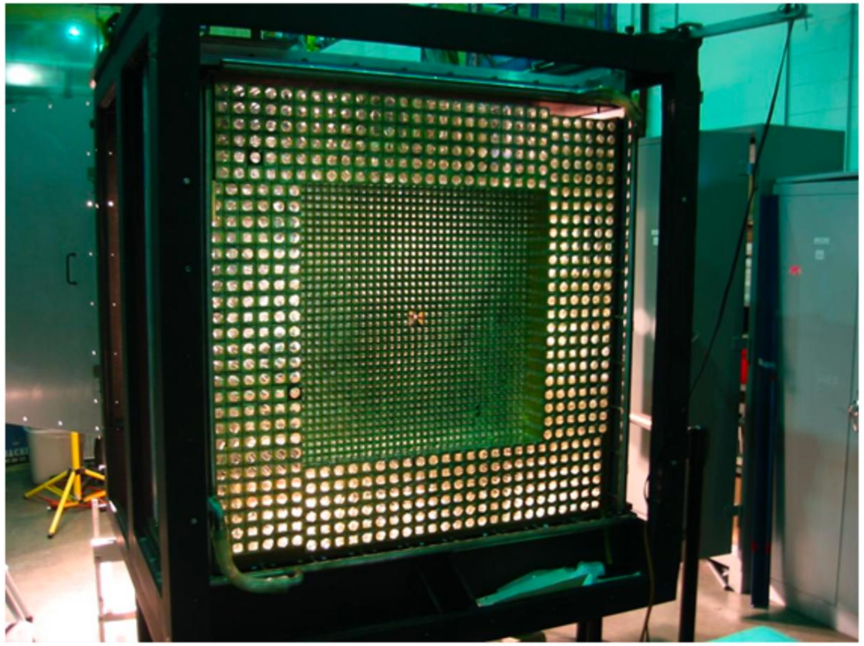
Conditional Schedule 2025-26

SAD or scheduled Run Group	Setup / Status	Target	Beam Energy	Start Date	End Date	Scheduled Calendar Days	Scheduled PAC Days = Cal.Days/2	Remaining PAC Days After Run
X17 search	HyCal/GEMs	Ta foil / Radiator	2.2	2025-11-10	2025-12-22	42	21	39
	winter break			2025-12-22	2026-01-12			
X17 search	HyCal/GEMs	Ta foil	2.2	2026-01-12	2026-03-02	49	25	15
	reconfigure	change		2026-03-02	2026-03-09	7		
PRad-II	HyCal/GEMs	H2 gas	2.1	2026-03-09	2026-04-07	29	15	26
	pass change			2026-04-07	2026-04-08	1		
PRad-II	HyCal/GEMs	H2 gas	0.7	2026-04-08	2026-04-21	13	7	19
	pass change			2026-04-21	2026-04-22	1		
PRad-II	HyCal/GEMs	H2 gas	1.4	2026-04-22	2026-05-25	33	17	2
Scheduled Accelerator Down 2026					**Total days:**	**175**	**84**	

- Assuming 24 weeks of physics running and successful Experimental Readiness Review

Invisible Decay Searches: Positron Annihilation





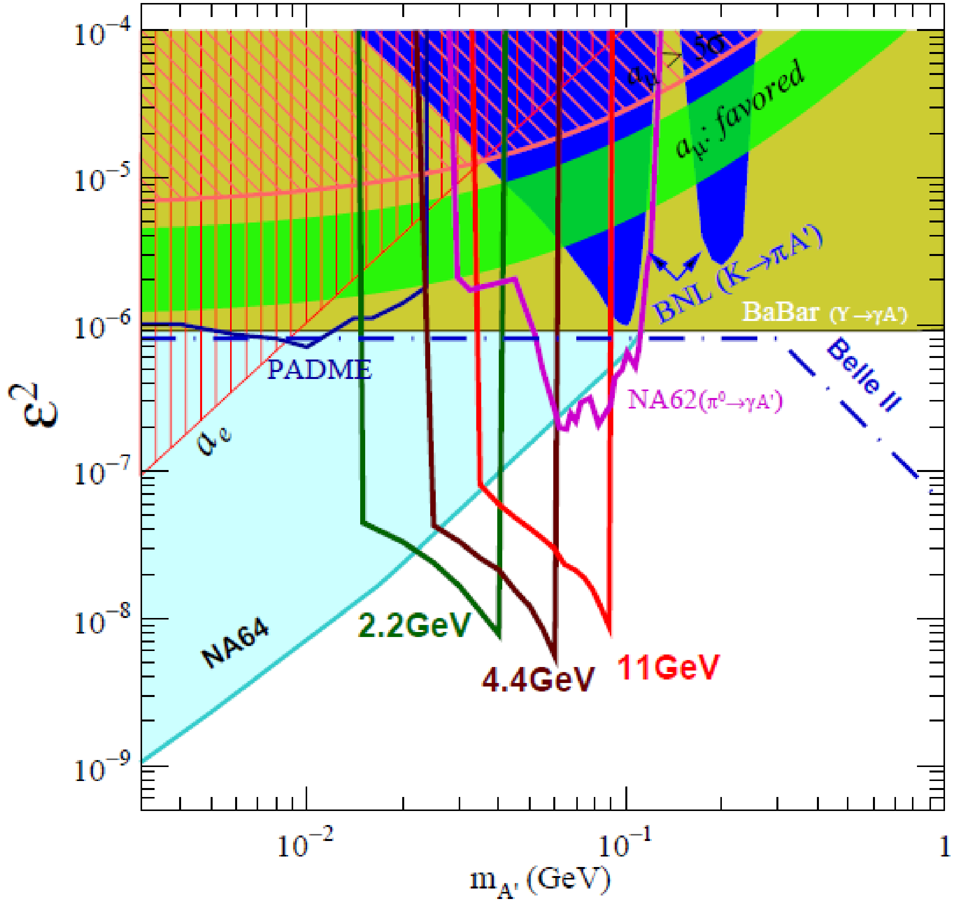
A' Search with Ce+BAF

- 50 nA positron beam, energy of 2.2, 4.4, and 11 GeV
- 5-cm-long target of liquid hydrogen
- Detection of photon from $e^+ + e^- \rightarrow A' + \gamma$
- Setup includes sweeper magnet and beam dump

Reach Projection for Invisible Decay Search

<u>A’ Search with Ce+BAF</u>

- Mass range from 15 to 90 MeV
- Sensitivity reaches $\varepsilon \geq 10^{-4}$
- Experimental sensitivity does not rely on coupling of A′-boson to quarks or possible semi-visible decay



PAC approved experiment that could possibly run in the 2030s

Summary

PRad-II and X17 Search are two cost-effective, mostly ready-to-run experiments:

- Validate existence or set an experimental upper limit on a search for X17
- Search for hidden sector particles in the [3 – 60] MeV mass range

- Validate existence or resolve discrepancy in proton form factor data
- Improve the precision on the proton charge raduis

Experiments could run as early as 2025/26