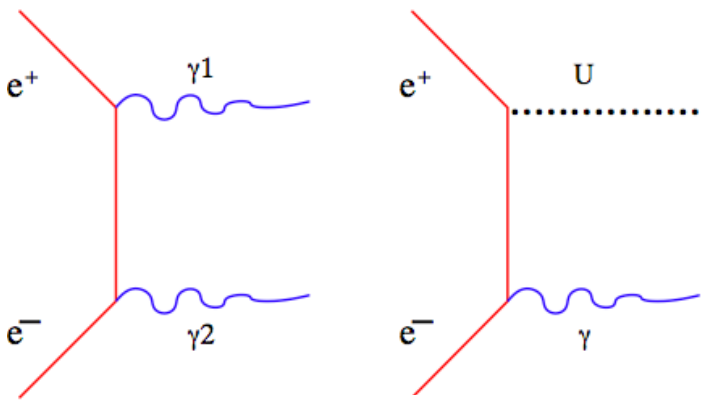
Proposal to do A' search with the positron beam in the missing mass approach

B. Wojtsekhowski and A. Gasparian

Dirac analysis of the process

$$\sigma = \frac{\pi r_e^2}{\gamma_+^2-1} \cdot \left[\frac{\gamma_+^2+4\gamma_++1}{\gamma_+^2-1} \ln(\gamma_+ + \sqrt{\gamma_+^2-1}) - \frac{\gamma_++3}{\sqrt{\gamma_+^2-1}}\right]$$



$$\sigma = \frac{\pi r_e^2}{\gamma_+} \cdot (\ln 2\gamma_+ - 1)$$

$$\frac{d\sigma}{d\cos\theta_\gamma^{cm}} = \frac{\pi r_e^2}{(\gamma_+^{cm})^2} \cdot \left[\frac{1}{\sin^2\theta_\gamma^{cm}} - \frac{1}{2}\right]$$

$$\frac{d\sigma}{dy} \approx \frac{\pi r_e^2}{2\gamma_+}\left[\frac{1-y}{y} + \frac{y}{1-y}\right]$$

$$\frac{d\sigma}{dy} \approx \varepsilon^2 \cdot \frac{\pi r_e^2}{y\gamma_+}\left[\frac{(1+\mu)^2}{1-(y+\mu)} - 2y\right]$$

$$y = \frac{E_\gamma}{E_{positron}}$$

$$\mu = m_{A'}^2/s$$

High resolution e-m calorimeters at JLab allow the design of an experiment for a sensitive search of the U-boson (A')

No assumption about the A' decay

Hall B – PRAD-II -1100 (2200) crystals $PbWO_4$ (need fADC)
Hall C – NPS - 1080 crystals (will run an experiment in 2023)
Hall D – 1600 crystals (will run an experiment in 2024)
Each calorimeter will use fADC-based DAQ
High energy and coordinate resolution, pulse width ~40 ns

Using 50-100 nA of 11-12 GeV positron beam in Hall B, or C, or D
U-boson search will cover mass range up to 100 MeV
The proposal for U-boson (A') search is under preparation for PAC51

Internal report on U boson search, summer, 2006

Search of U boson in electron-positron annihilation in flight

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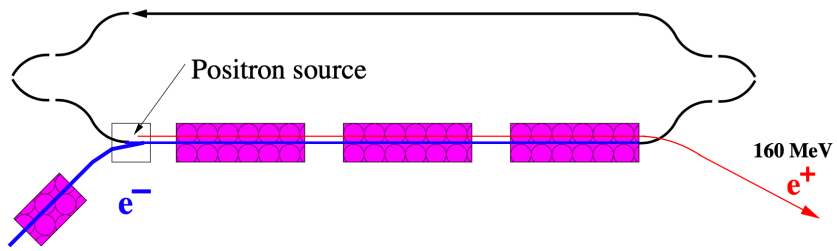
Abstract

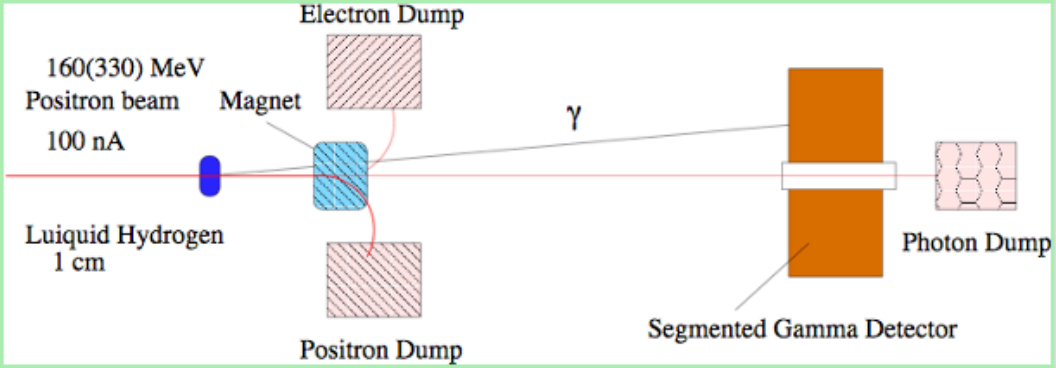
An experiment is proposed to search for a new gauge boson U in reaction $e^+e^- \to U\gamma$ in the mass range from 2 to 15 MeV. The data could determine the particle mass and the coupling constant f_e^2 (or its upper limit). The experiment could utilize a 160-330 MeV positron beam in JLab FEL. It needs a low-power liquid hydrogen target and a high-resolution gamma detector. With 240 hours of beam-time and full detector, this measurement will find the U boson or provide an upper limit for the coupling constant f_e^2 to the level of $\mathbf{10^{-8}}$ or **almost seven orders** smaller than the electromagnetic one e^2. Such a measurement will be a very important step in the investigation of the origin of the abundant 511 keV photons in Galactic Center.

U boson analyzed by P. Fayet, Phys. Lett. B 95, 285 (1980), Nucl. Phys. B 187184 (1981).



Schematic of the proposed experiment

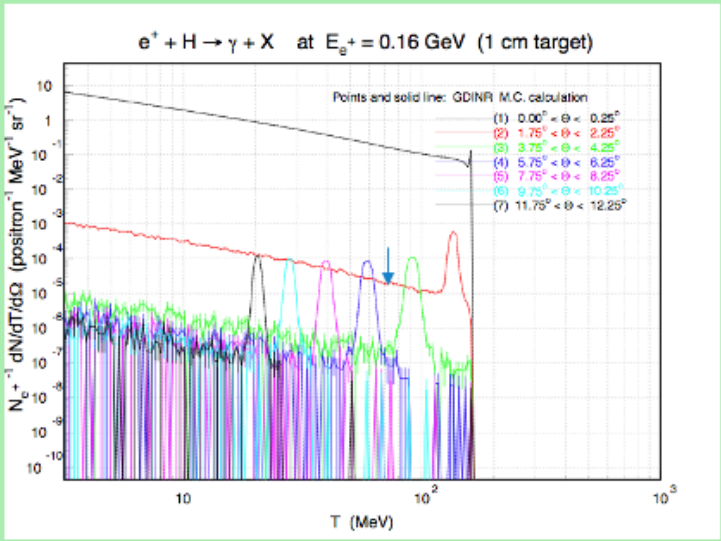
- Positron beam with 1-2 MeV spread
- Thin - 1 cm liquid hydrogen target
- Cleanup the rest of beam to the dumps



- Segmented photon detector ~ 1000 modules, ~2% energy resolution.
- Parallel DAQ for the total rate of ~50 MHz.

Makes use of high luminosity: 1000 parallel 1-d spectra.

Expected accuracy of the result



$$N_{U_\gamma} = 2\frac{f_e^2}{e^2} \cdot N_{\gamma\gamma}$$

$$N_{\gamma\gamma} = 63 \text{ MHz} \cdot 10^6 \text{ sec} = 6.3 \cdot 10^{13} \text{ events}$$

$$N_{background} = R \times N_{\gamma\gamma} \approx 6.3 \cdot 10^{11} \text{ events}$$

$f_e^2 < 0.3 \times 10^{-7}\, e^2$, which is "100+" improvement relative to the upper limit obtained from g-2 results

The photo-production processes

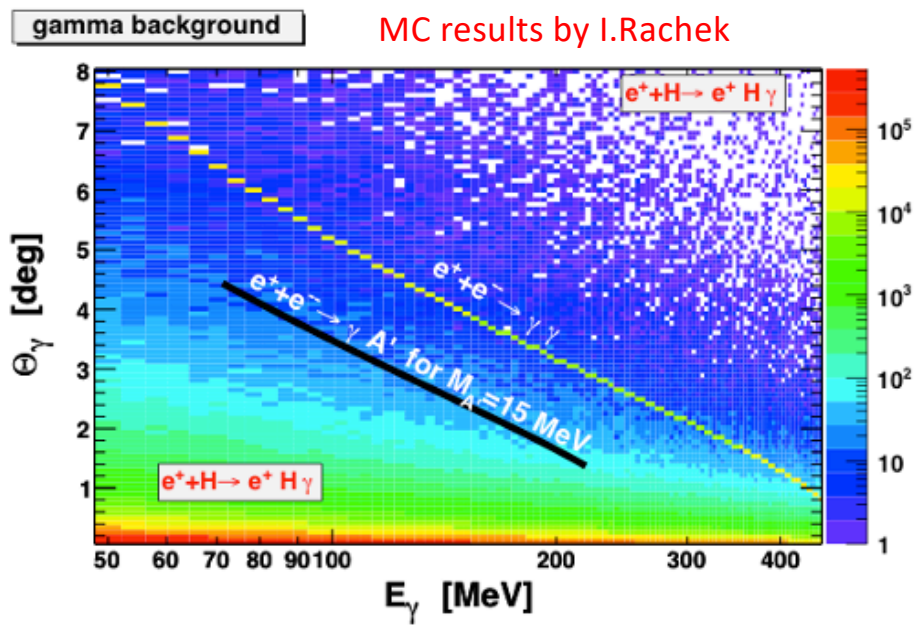
Basic QED: $e^+e^- \rightarrow \gamma\gamma$ (mono-energetic)
Search for : $e^+e^- \rightarrow \gamma U$ *(peak below main)*
Basic QED: $e^+Z \rightarrow \gamma$ (smooth brems.)

- Detect γ at fixed angle with the beam:

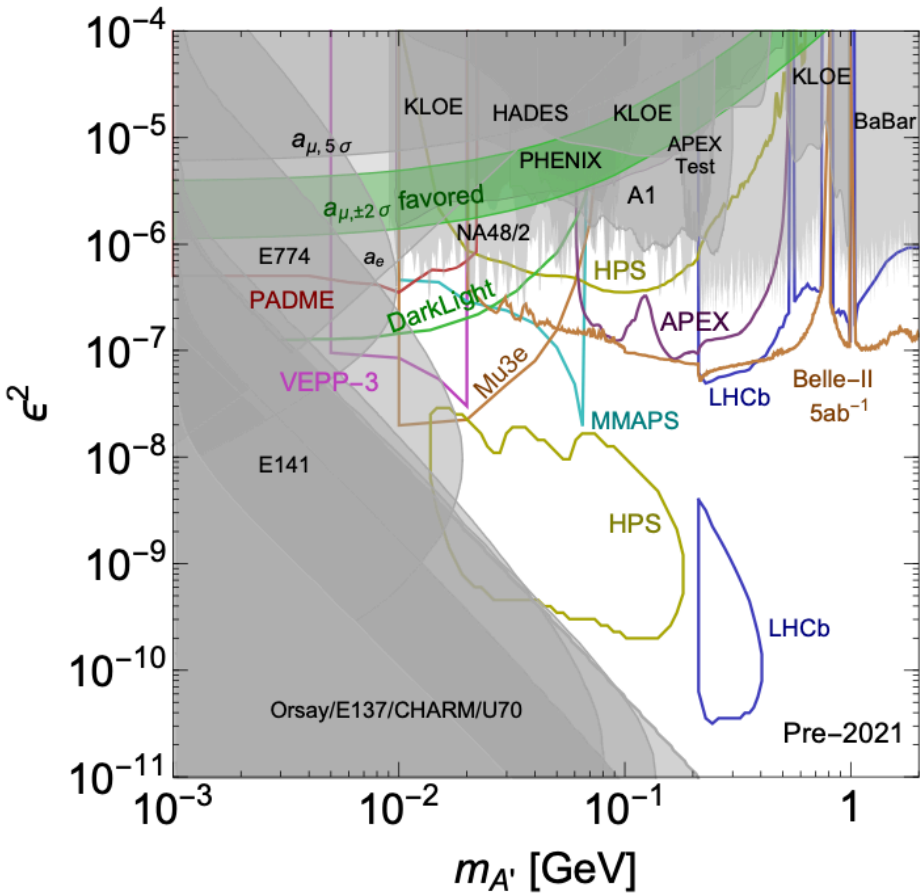
  reconstruct the mass
- Variation with the angle:

  control systematic
- Target Z

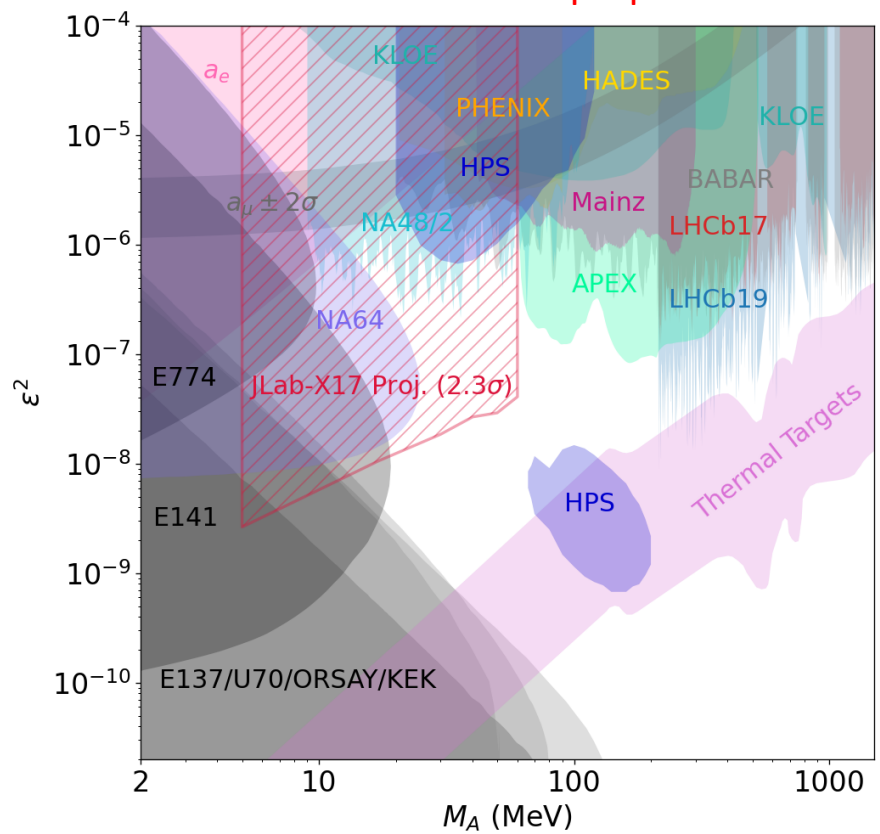
  Hydrogen vs. ^{12}C



World data on A' in all decay modes

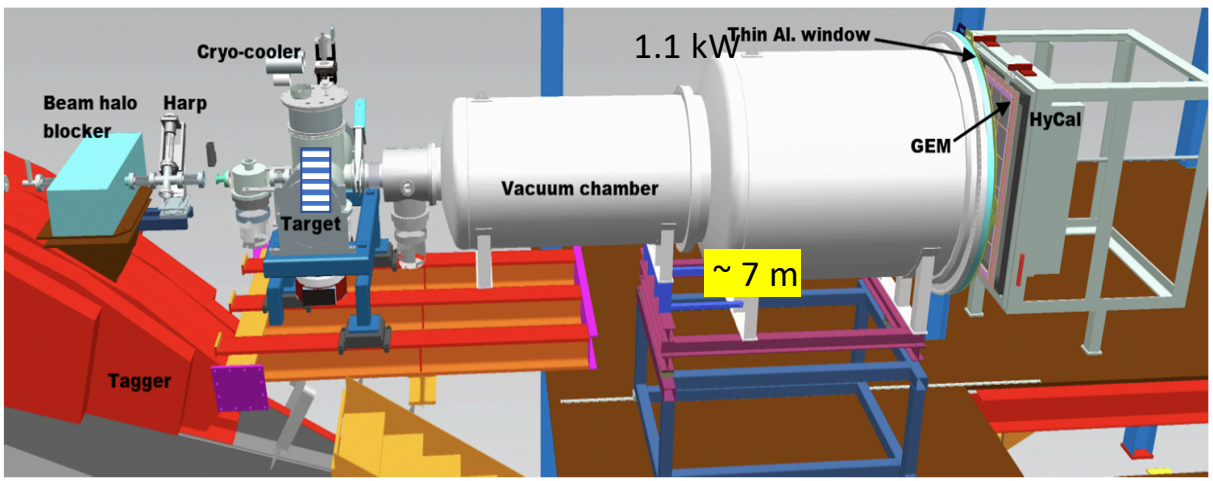


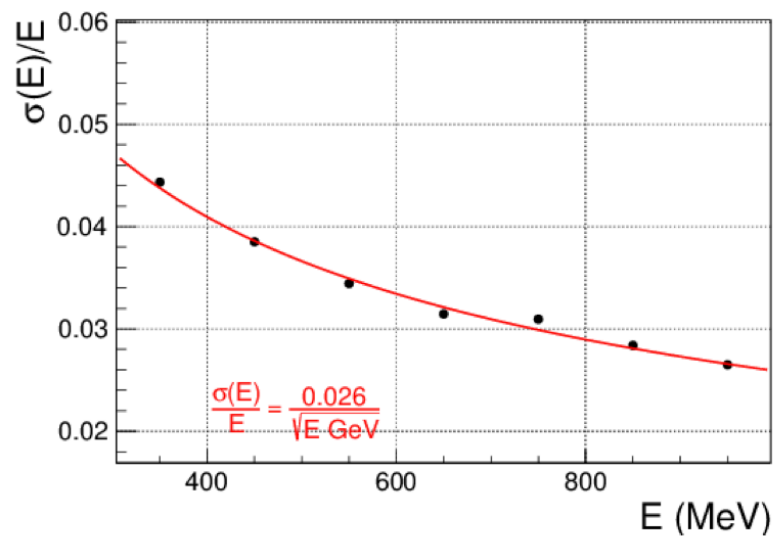
from X17 proposal



Positron beam with PRAD calorimeter in Hall B

No assumption about the A' decay





PrimEx Hybrid EM Calorimeter (HyCal)

- Combination of $PbWO_4$ and Pb-glass detectors (118x118 cm^2)

  $PbWO_4$ crystals → resolution
  Pb-glass → budget

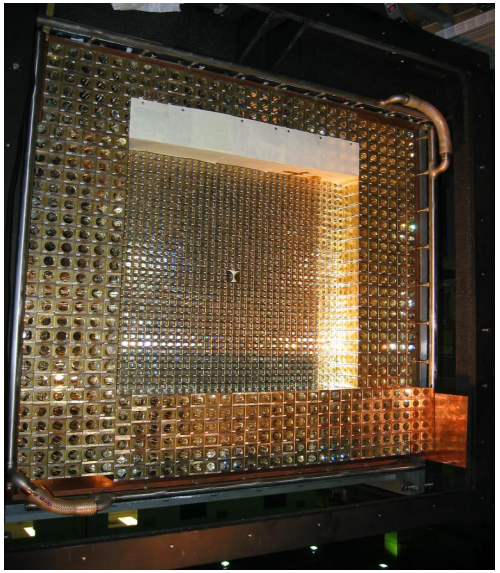
  - ✓ 34 x 34 matrix of 2.05 x 2.05 x 18 cm^3 $PbWO_4$ shower detectors (1152 $PbWO_4$ detectors)
  - ✓ 576 Pb-glass shower detectors (3.82x3.82x45.0 cm^3)
  - ✓ 2 x 2 $PbWO_4$ modules removed in middle for beam passage
  - ✓ ≈7.5 m from target

- Good energy and position resolutions:

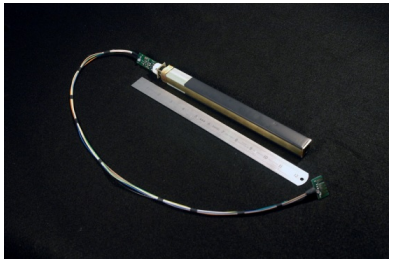
  - ✓ $\sigma_E / E = 2.6\% / \sqrt{E}$
  - ✓ $\sigma_{xy} / E = 2.7\ mm / \sqrt{E}$

- Good photon detection efficiency (≈100%)

- Served in 3 precision experiments!

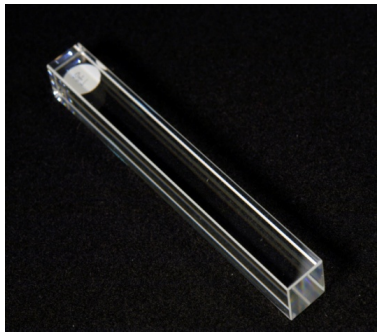


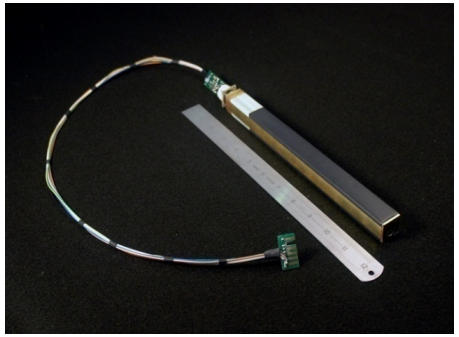
front view, before Light Monitoring System assembly

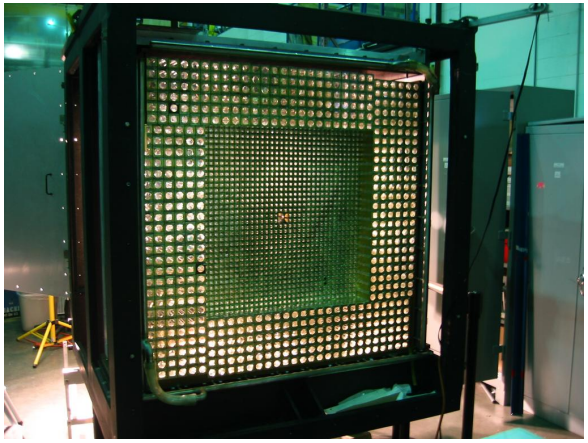


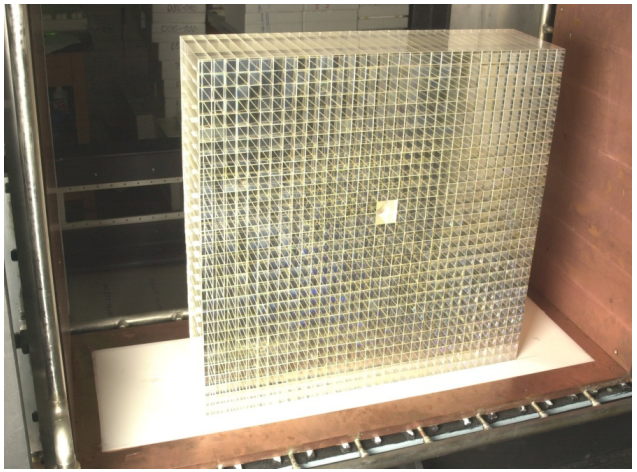
Single $PbWO_4$ detector

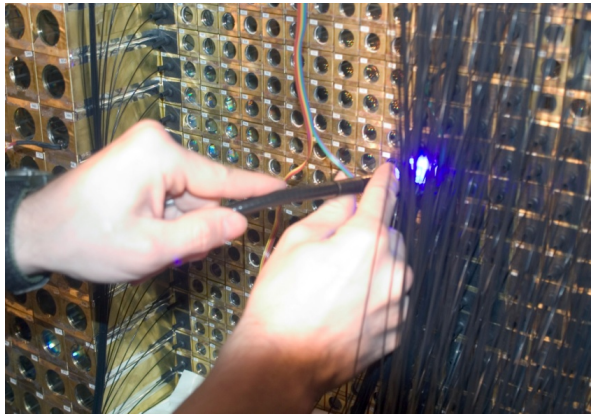
Electromagnetic Calorimeter (HyCal)



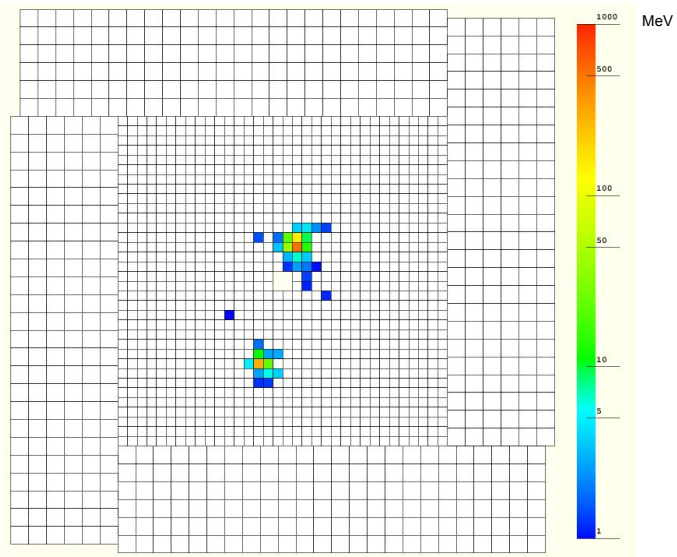


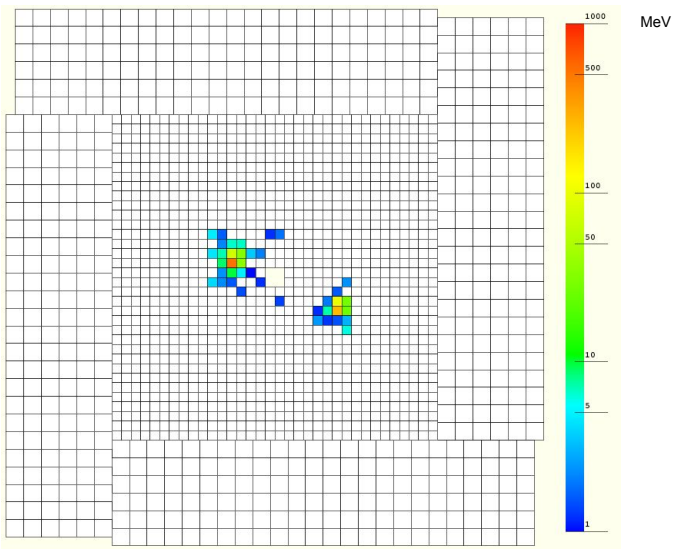






PRAD calorimeter events





Analysis made by X. Bai

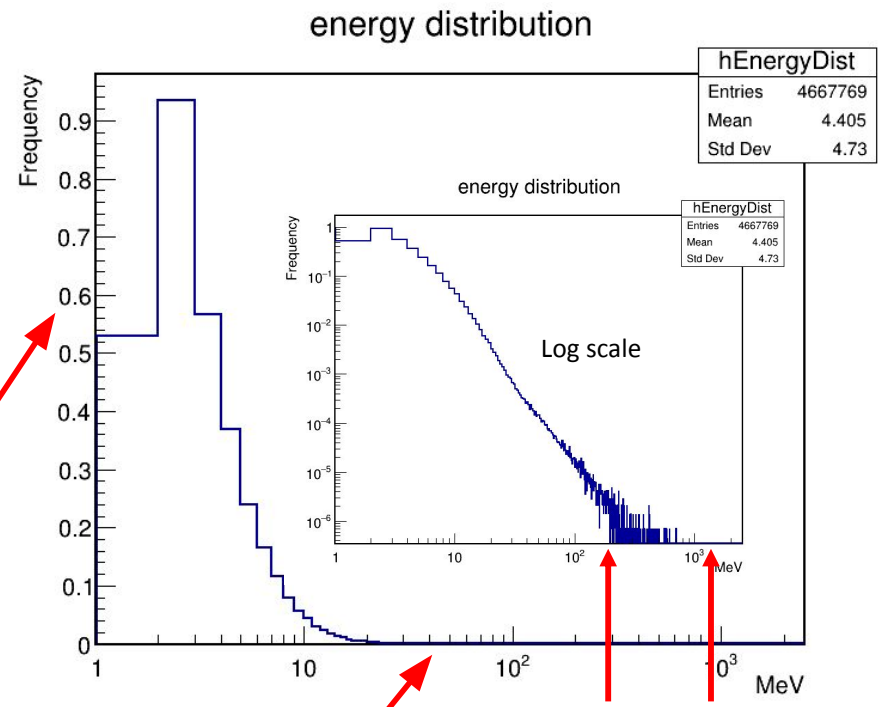
Number of crystals:
PRAD-I had 1156 -> plan to 2100

PRAD calorimeter rates

Energy distribution

- This is a sum of all modules - this plot does **NOT** represent how frequent it happens
- This is just to show energy situation
- Total Moller events: 1.4 M
- Entries are scaled by total Moller event count, so Y axis is "Frequency": (**dN/dE scaled by total counts**)

Bin_Count / Total_Moller_event_count



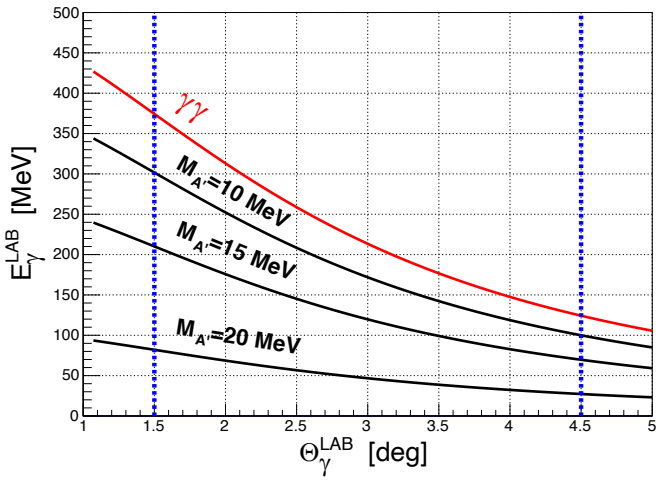
Luminosity ~ 3×10^{30}

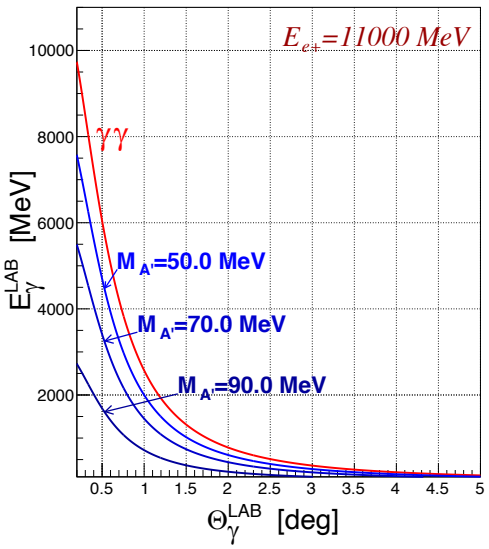
Analysis made by X. Bai

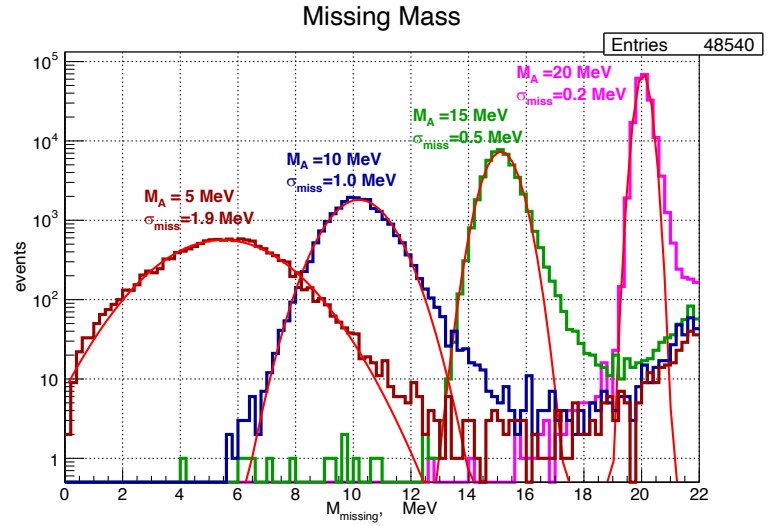
Each Bin is 1 MeV

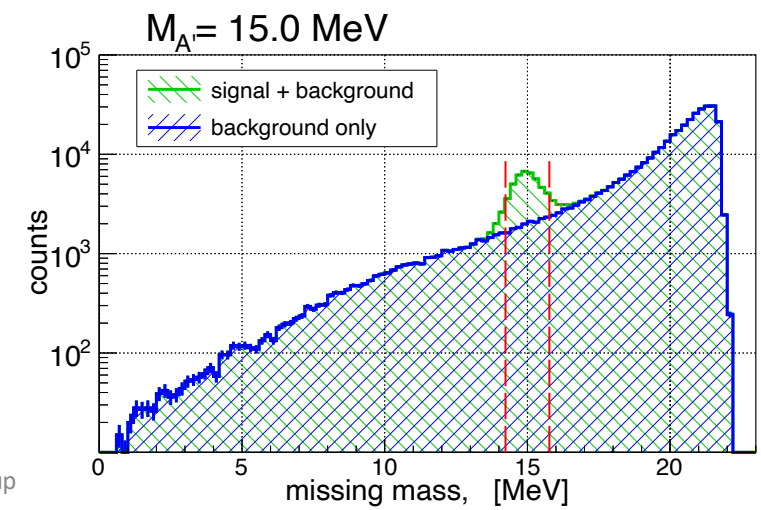
energy range of interest for 2.2 GeV beam

MC results by I.Rachek for 0.5 GeV and 11 GeV







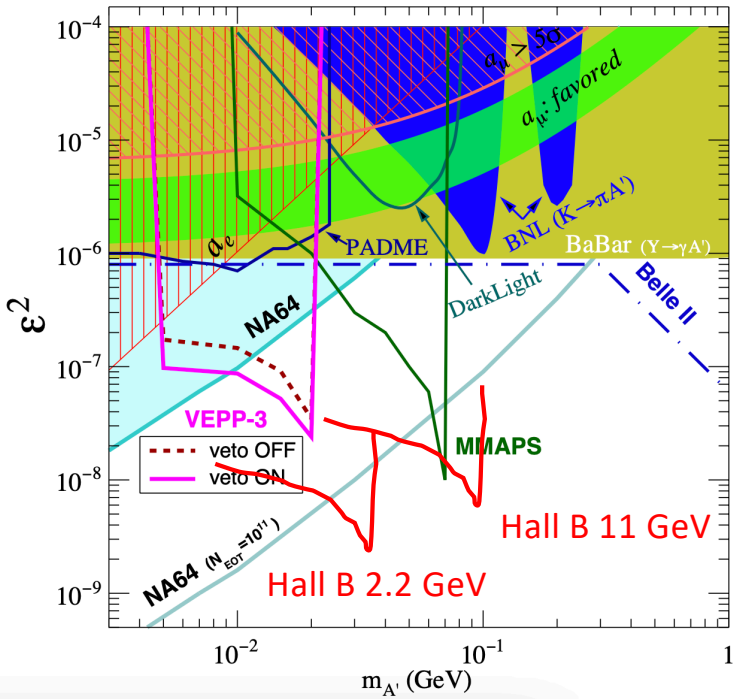


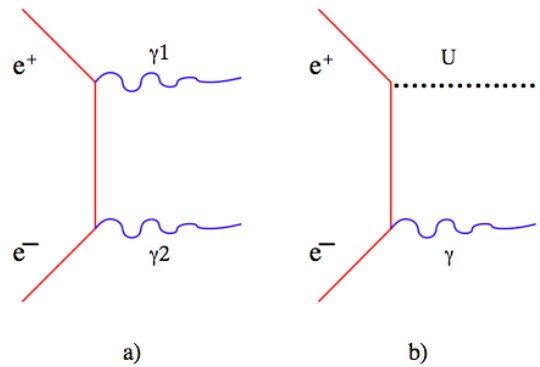
$$\frac{\delta m_A}{m_A} = \frac{E_\gamma}{E_+}\frac{\delta E_\gamma}{E_\gamma} \sim 0.5\%$$

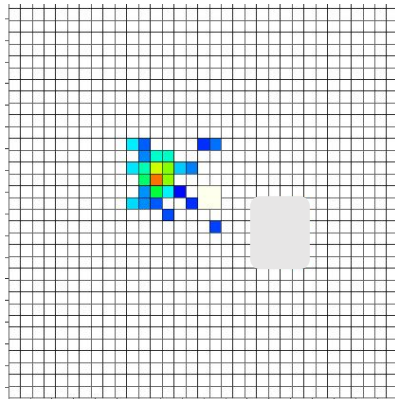
$$\frac{\delta m_A}{m_A} = \frac{E_\gamma}{m_e}\theta_\gamma \delta\theta_\gamma \sim 0.7\%$$

Positron beam with PRAD calorimeter in Hall B

No assumption about the A' decay







Luminosity: 50 nA x 5 cm LH2 ~ 0.7 x 10^{35} cm^{-2}/s

which is 70 times that of VEPP3, 10^6 of PADME, 10 times that of Cornell's

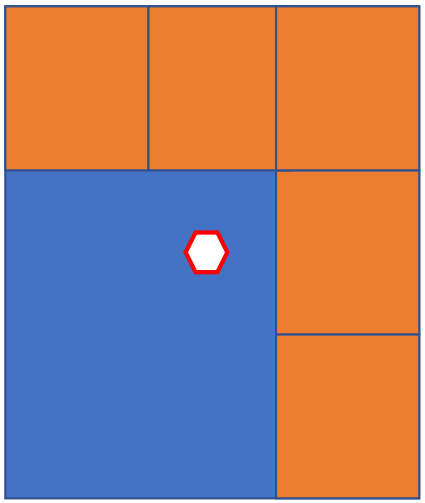
DAQ for clusters: 10 MHz of single high-energy hits distributed effectively in 1600 "analyzers"

Event rates and backgrounds

1. Positron beam intensity 50 nA on 5 cm long LH2 target: $L = 0.7 \times 10^{35}$
2. Brem photons in the angular range of interest: $(1-3) \times \sqrt{2\,m/E_+} = 0.6 - 2\ \mathrm{deg}$
   The hit rate is 5 MHz in this angular and energy range (result from MC)
3. Two-photon rate for 11 GeV beam is 2.5 MHz
4. U-boson rate for $\epsilon^2 = 10^{-7}$ will be 0.5 Hz
5. Elastic event rate is 1 MHz (above 0.6 deg)
6. Combined rate per crystal is below 100 kHz
7. In each 32 ns time window the number of high energy hits is 0.25 (in full detector)
8. Statistics are: 1.5×10^6 signal and 3×10^{11} background (for 1% missing mass resolution)
9. Two-three sigma sensitivity will be after a month of running

Concept of the DAQ for the A' experiment

34 x 34



1. Single photon data – Energy and angle => Output is a 2D matrix
2. Readout options:

a) Divide into 9 sections with modest loss (20%) of the area
One crate (16 fADC => 256 channels) with 1 MHz DAQ trigger which leads to data rate of 40 MBps << 20 GBps of the limit

b) Prospective way (already possible) is a streaming from six crates: using 12 streams each 10 GBps. With a 64 us time frame: Number of hits is 64/0.032*0.25/100 hits = 5 hits per channel, so the total data flow is 20 bytes x 1156 x 16 kHz = 0.5 GB/s

Conclusion: Projected 10 MHz events readout speed is a safe plan.

Summary

The JLab positron beam will allow a sensitive search for any decay mode and the potential discovery of a dark photon in the 100 MeV mass range