# A dark photon search with JLab positron beam


Positron A' Collaboration

B.Raydo, B.Wojtsekhowski, P.Achenbach, S.Boyarinov, A.Camsonne, P.Degtiarenko, D.Gaskell, J.Grames, W.Henry, D.Higinbotham, I.Jaegle, D.Jones, M.Jones, D.Mack, D.Meekins, R.Michaels, E.Pasyuk, A.Somov, S.Stepanyan, H.Szumila-Vance, S.Taylor, A.S.Tadepalli, A.Gasparian, D.Bulumulla, N.Liyanage A.Ahmed, X.Bai, G.Cates, H.Nguyen, V.Nelyubin, D.Hamilton, I.Rachek, D.Nikolenko, E.King, J.Napolitano, S.Mayilyan, H.Mkrtchyan, A.Shahinyan, V.Tadevosyan, D.Dutta, C.Peng, I.Larin, R.Miskimen, T.Averett, L.Gan, M.Khandaker, B.Vlahovic and

**the PRAD collaboration and the Positron Working Group**

# A dark photon search with JLab positron beam

B.Raydo, A.Gasparian, N.Liyange, B.Wojtsekhowski

NASA Finds Direct Proof of Dark Matter in 2006

Motivation:

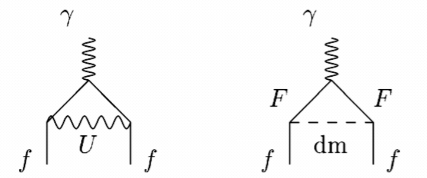
Credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

# The processes which could have a U-boson

C.Boehm, P.Fayet, Nuclear Physics B 683 (2004)

$g_e$-2, $g_\mu$-2
$\pi,\eta$ decays to $U\gamma$
$\pi,\varphi,\psi$ decays to $\gamma$ + invisible

*A.4. Constraints from g − 2*

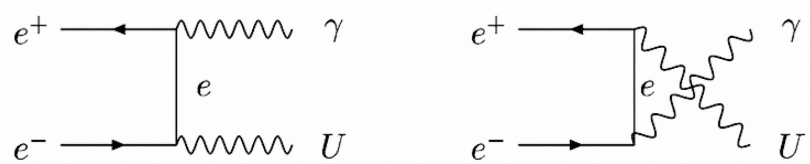



If the $U$ boson mainly decays into dark matter, then the $U$ production process turns out to be of the type $e^+e^- \to \gamma + \not{E}$, where $\not{E}$ is missing energy, which is of interest in experiments searching for single photon production events. But, in the case of a light dark matter candidate, such a process is likely to remain unobserved, owing to the large background associated with $e^+e^- \to \gamma\gamma$, in which one of the two photons escapes detection.

Upper limit for the coupling constant $|f_{eU}|^2 < 2\ 10^{-8}\,(m_U)^2$

$\varepsilon^2 < 10^{-4}$ at 10 MeV

*A.6.1. Direct U boson production*



# The process which could have a U-boson

P.Fayet, arXive:0607094 (2006) U-boson detectability, and LDM

$$\delta a_\mu \simeq \frac{f_{\mu V}^{\,2}}{4\,\pi^2} \int_0^1 \frac{m_\mu^{\,2}\, x^2\,(1-x)\,dx}{m_\mu^{\,2}\, x^2 + m_U^{\,2}\,(1-x)} \simeq \frac{f_{\mu V}^{\,2}}{8\,\pi^2}\, G(\frac{m_U}{m_\mu}) \longrightarrow |f_{\mu V}| \lesssim (.7 \text{ up to } 1.5)\ 10^{-3}$$

by searching for the decay $K^+ \to \pi^+ U$

$$|f_{sA}| \lesssim 2\, 10^{-7}\, m_U\,(\text{MeV}) \ .$$

$$|f_{eV}| \lesssim 1.3\, 10^{-4}\, m_U\,(\text{MeV})$$

Having $f_e^{\,2} \lesssim 10^{-5}\, e^2$ makes the detection of $U$ production in $e^+e^-$ colliders difficult. The prospects for actually producing and detecting such very weakly coupled $U$ bosons in $e^+e^- \to \gamma\, U$, as well as in other reactions, appear as challenging. Still efforts should be pursued in this direction.

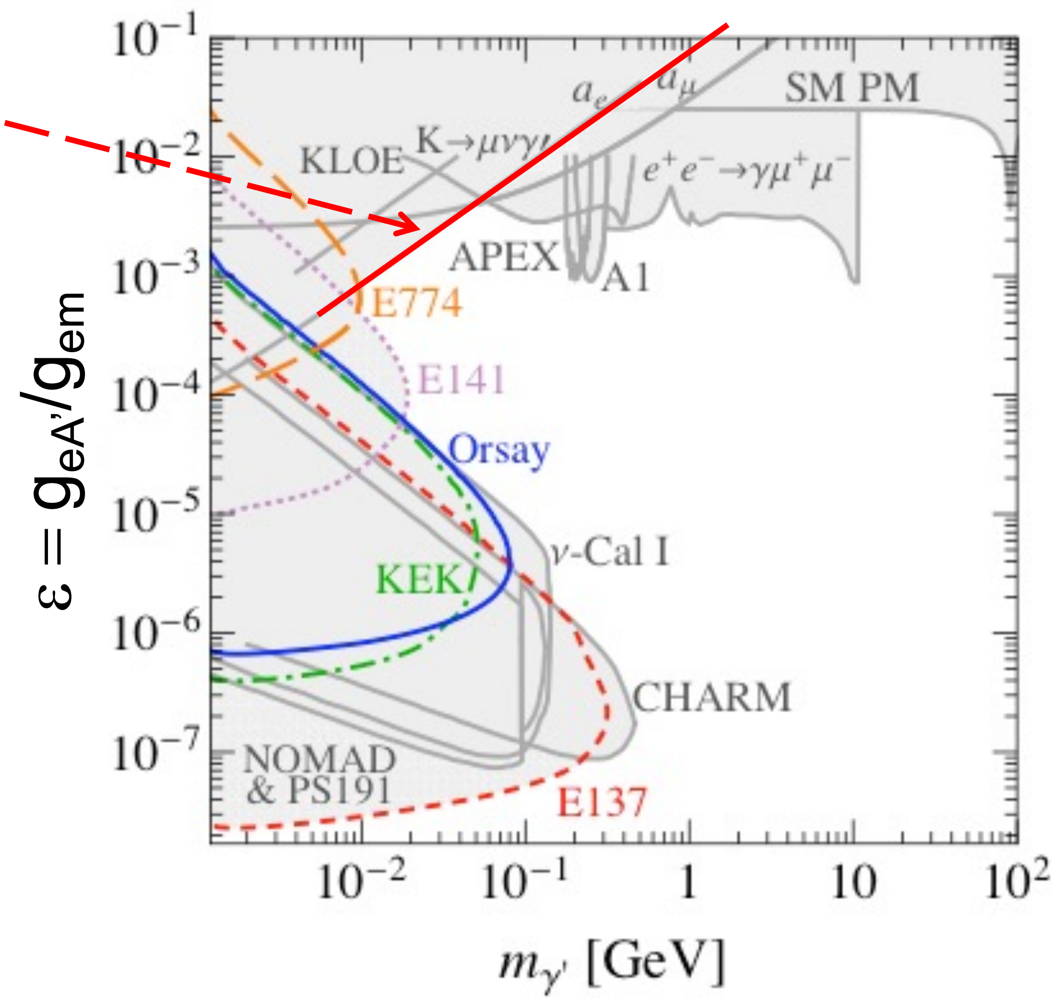
$$\frac{d\sigma}{d\cos\theta}\,(e^+e^- \to \gamma\, U) \simeq \frac{\alpha\, \epsilon^2}{s} \left( \frac{1}{\sin^2\theta} - \frac{1}{2} \right)$$

# “Old” summary of the searches

g-2 of muon and electron

Missing particle in e+e- to $\gamma$A’

Decay to SM (e+/e-) -
Beam Dump
Mass reconstruction




S. Andreas, C. Niebuhr, A. Ringwald, arXiv:1209.6083

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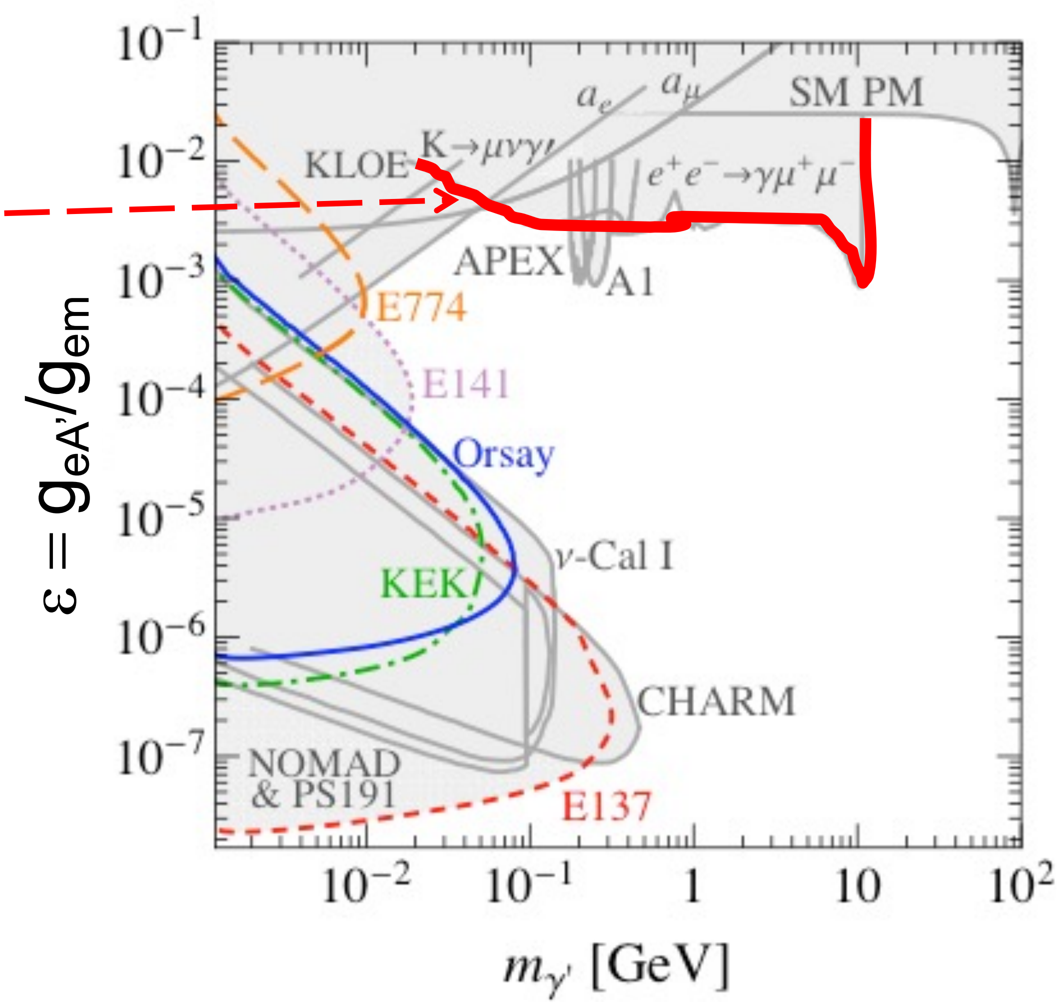
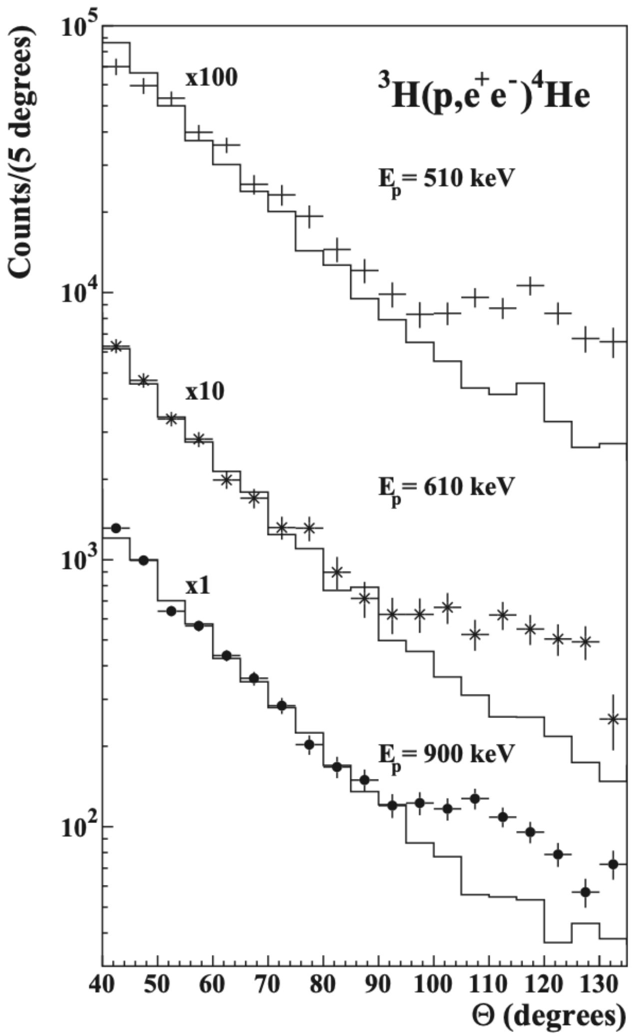



S. Andreas, C. Niebuhr, A. Ringwald, arXiv:1209.6083

# X17 signal in nuclear reactions




**New anomaly observed in $^{4}$He supports the existence of the hypothetical X17 particle**

A. J. Krasznahorkay,[1,*] M. Csatlós,[1] L. Csige,[1] J. Gulyás,[1] A. Krasznahorkay,[1,†] B. M. Nyakó,[1] I. Rajta,[1] J. Timár,[1] I. Vajda,[1] and N. J. Sas[2]
[1] *Institute for Nuclear Research (ATOMKI), P.O. Box 51, H-4001 Debrecen, Hungary*
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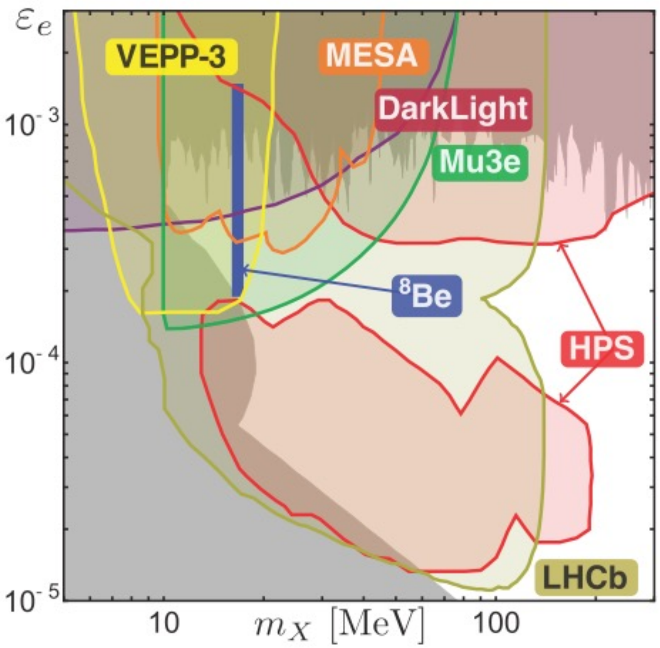
(Received 27 October 2019; revised 30 June 2021; accepted 6 October 2021; published 18 October 2021)

Angular correlation spectra of $e^+e^-$ pairs produced in the $^{3}H(p, e^+e^-)^{4}He$ nuclear reaction have been studied at $E_p = 510, 610$, and 900 keV proton energies. The main features of the spectra can be understood by taking into account the internal and external pair creations following the proton capture by $^{3}H$. However, these processes cannot account for an observed peak around 115° in the angular correlation spectra. This anomalous excess of $e^+e^-$ pairs can be described by the creation and subsequent decay of a light particle during the direct capture process. The derived mass of the particle is $m_X c^2 = 16.94 \pm 0.12(\text{stat}) \pm 0.21(\text{syst})$ MeV. According to the mass this is likely the same X17 particle, which we recently suggested [Phys. Rev. Lett. **116**, 042501 (2016)] for describing the anomaly observed in the decay of $^{8}$Be.

212 citations on 2016 paper according to PRL

# X17 signal and dark photon space




J.Feng etal., Phys. Rev. D **95**, 035017

Currently X17 is an urgent problem

Hopefully, it will be resolved, may be by PADME (beam energy scan) and/or by the X17/PRAD

The proposed A' experiment with 50 nA positron c.w. beam will be able to resolve the puzzle due to universal sensitivity, higher luminosity

| | Supporting | To be seen | Not supporting |
|---|---|---|---|
| Broadness of intermediate state | | | |
| Angular spectrum | | | |
| Kinematics | | | |
| Isospin | | | |
| Emission probability | | | |
| Conversion probability | | | |
| Complementary experimental evidence | | | |

ELSEVIER

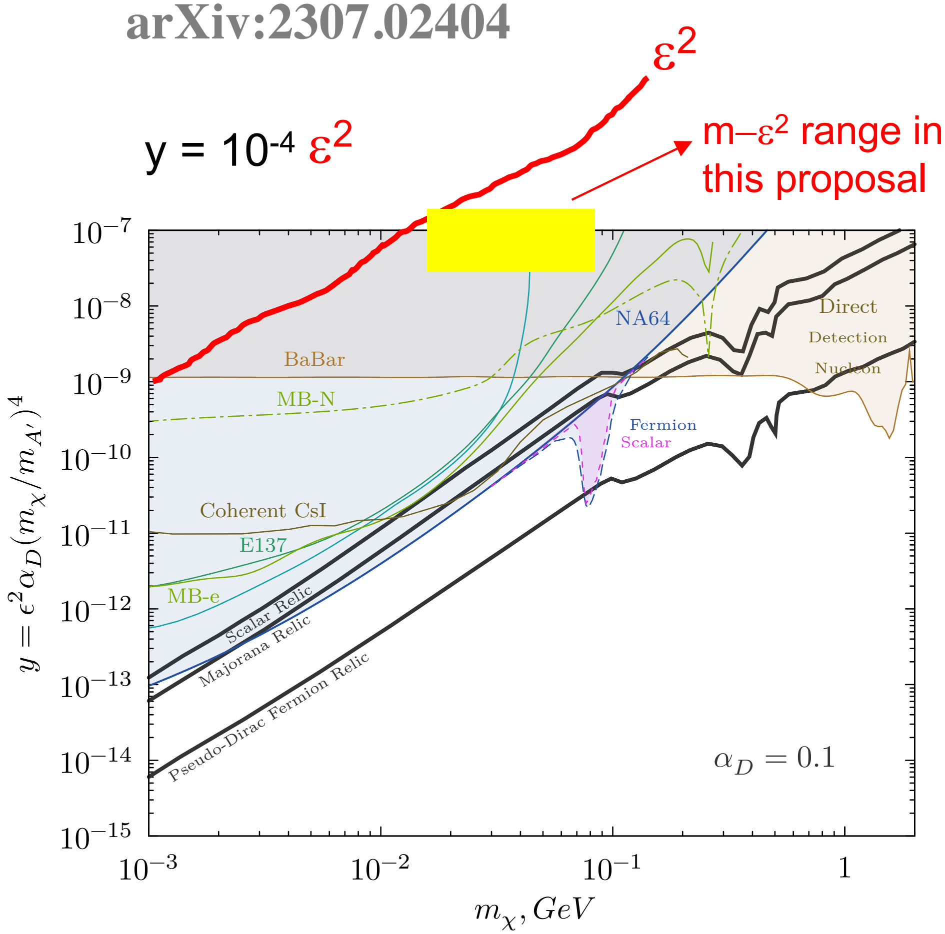
Nuclear Physics A
Volume 1008, April 2021, 122143

X17: A new force, or evidence for a hard $\gamma+\gamma$ process?

Benjamin Koch [a b]

# NA64 recent analysis

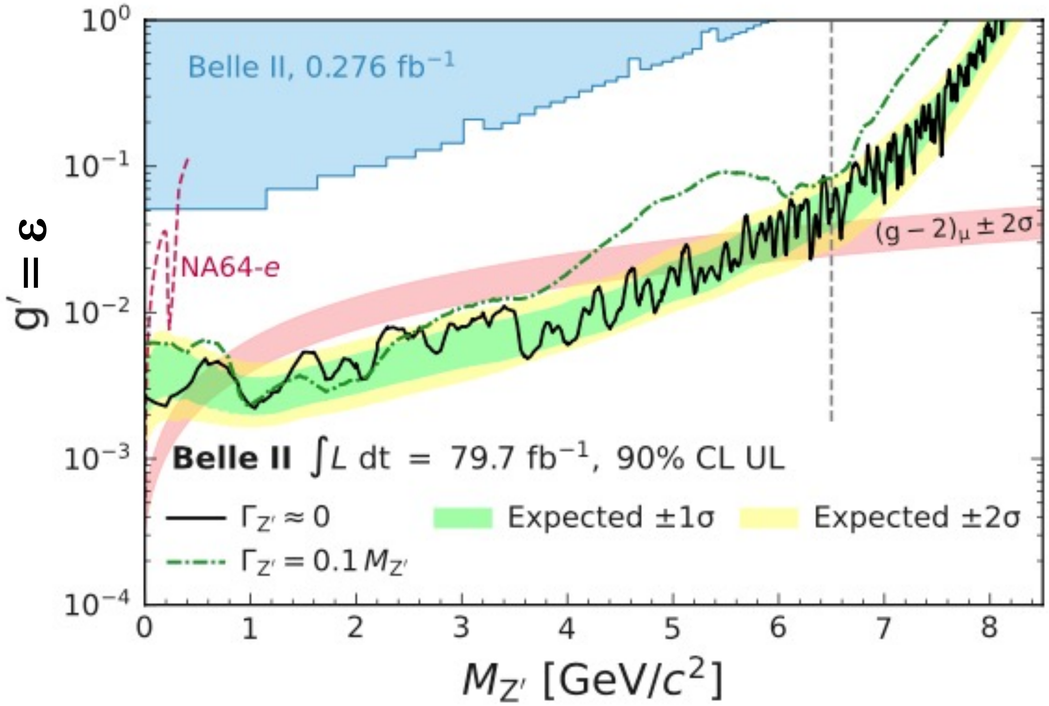
**arXiv:2307.02404**




100 GeV e on Z -> e Z A'
with active ECAL target

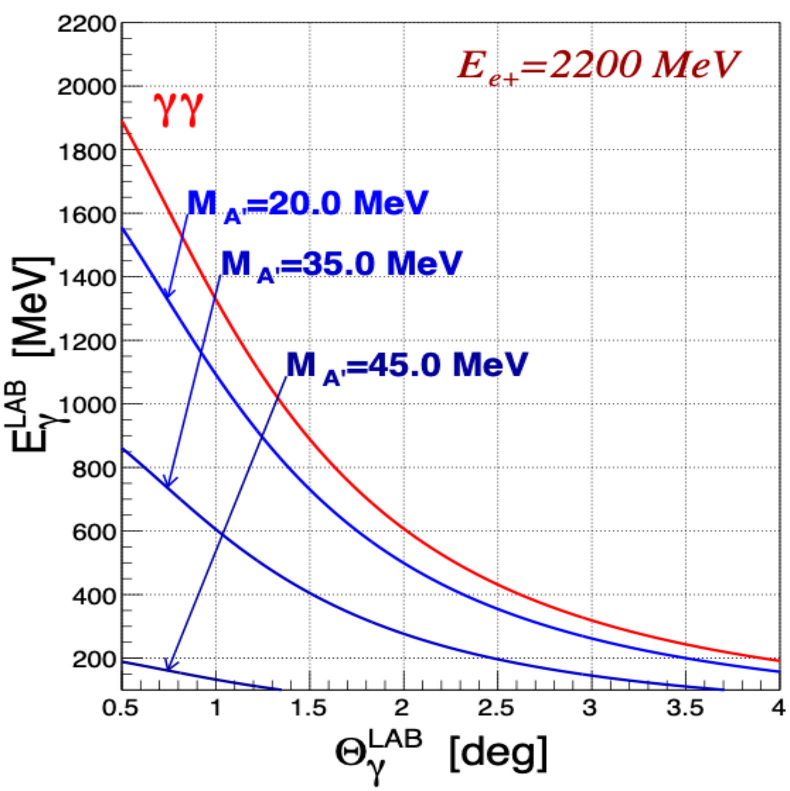
# Belle-II recent analysis

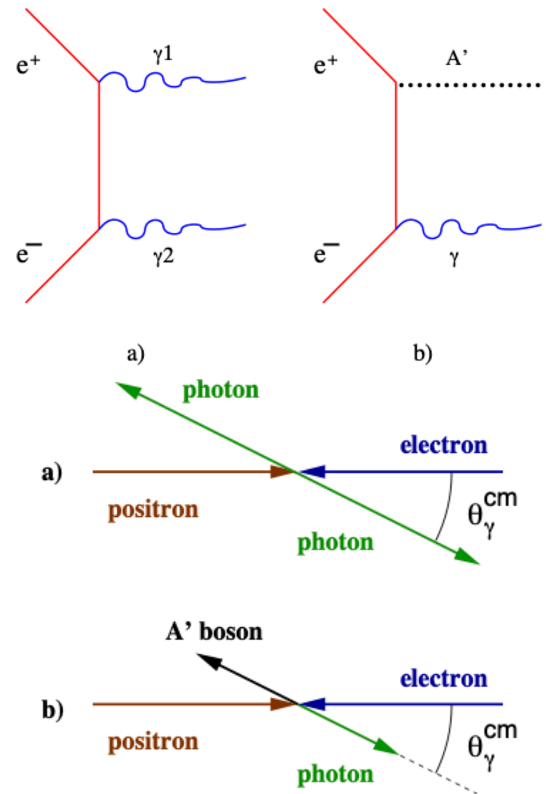
**arXiv:2212.03066v3**




e+e - -> γ + A' with
invisible decay of A'

# Experiment concept

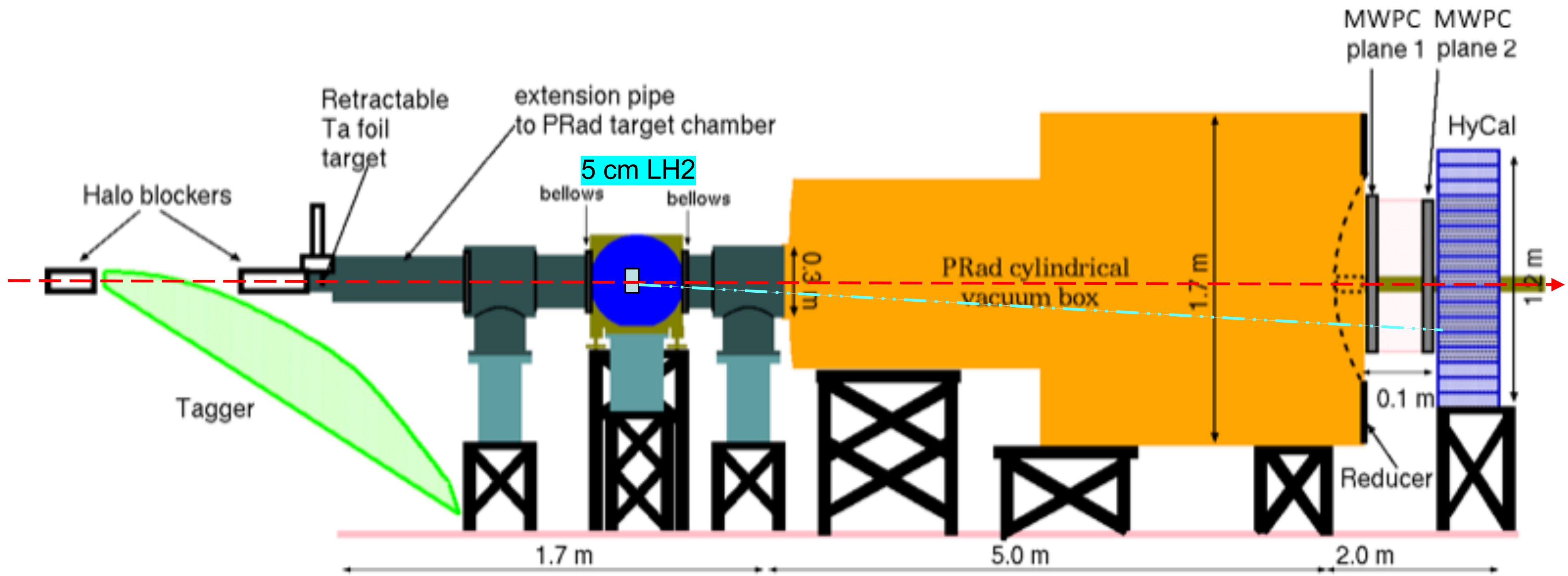



- A positron beam on a hydrogen target (e+e- annihilation)
- Selection of the one-photon final state events
- Search for a bump in the missing mass spectrum

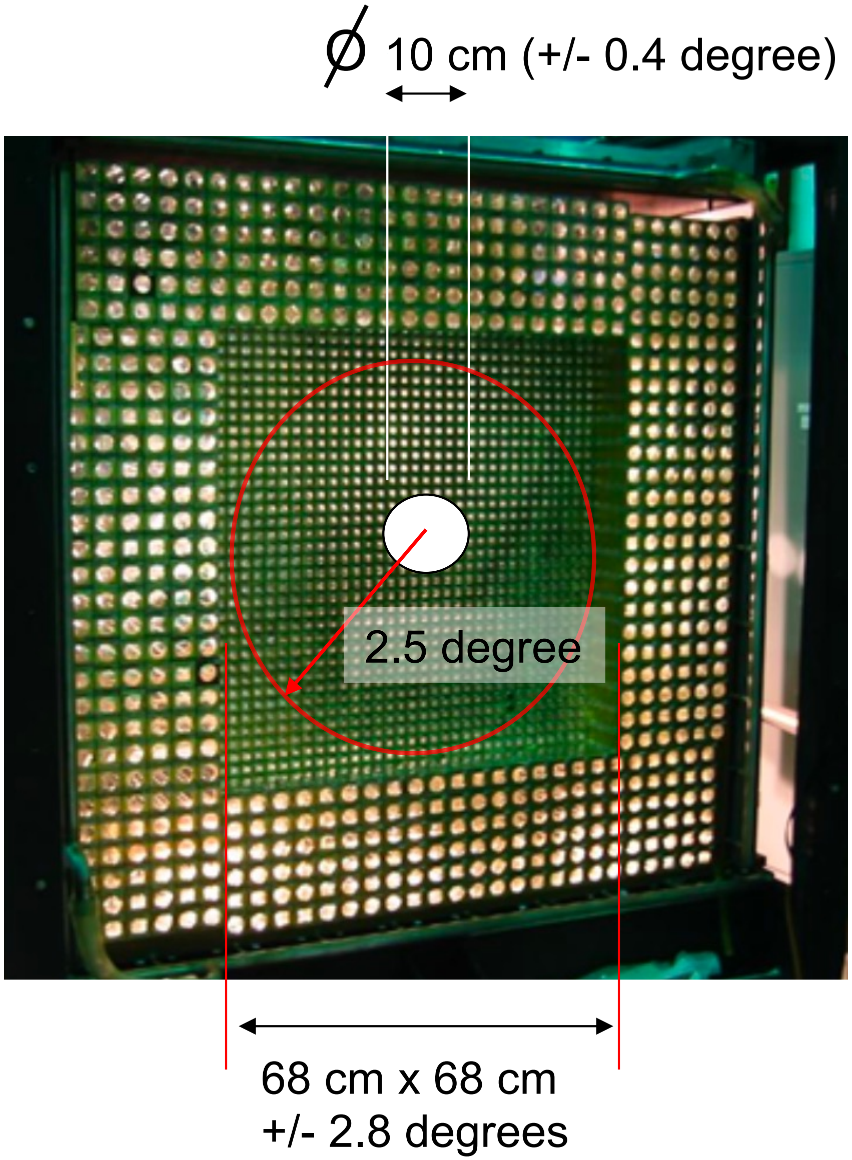
$$M_{A'}^2 = 2m_e^2 + 2m_e * (E_+ - E_\gamma) - 4E_+ * E_\gamma * \sin^2(\frac{\theta_\gamma}{2})$$

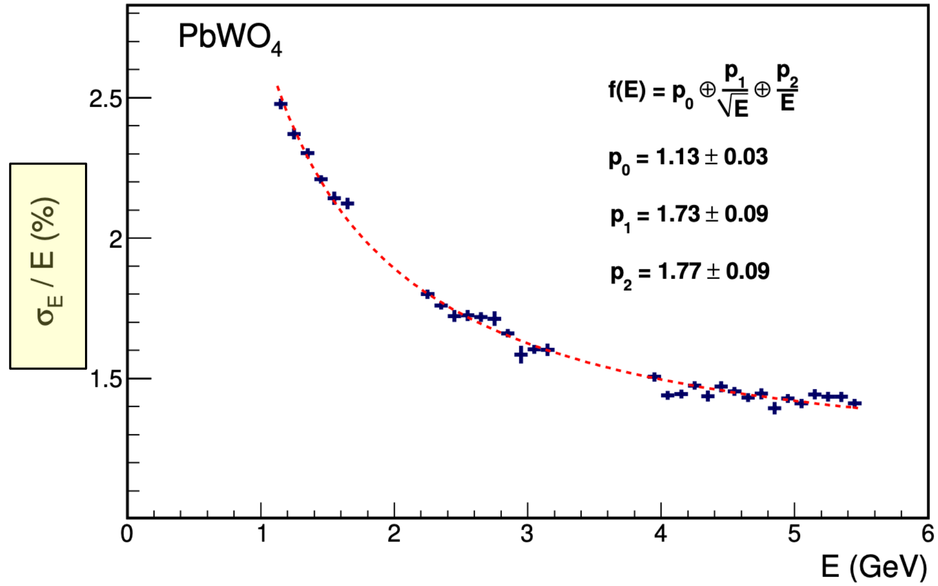
# Experiment layout

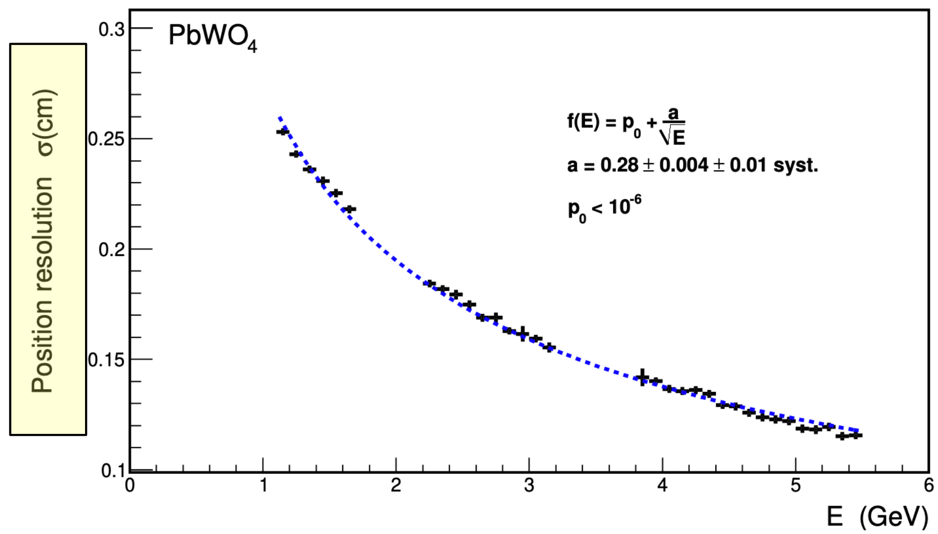



- 50 nA positron beam on 5 cm long LH2
- High resolution part of PRAD calorimeter
- fADC - based DAQ with programmable trigger

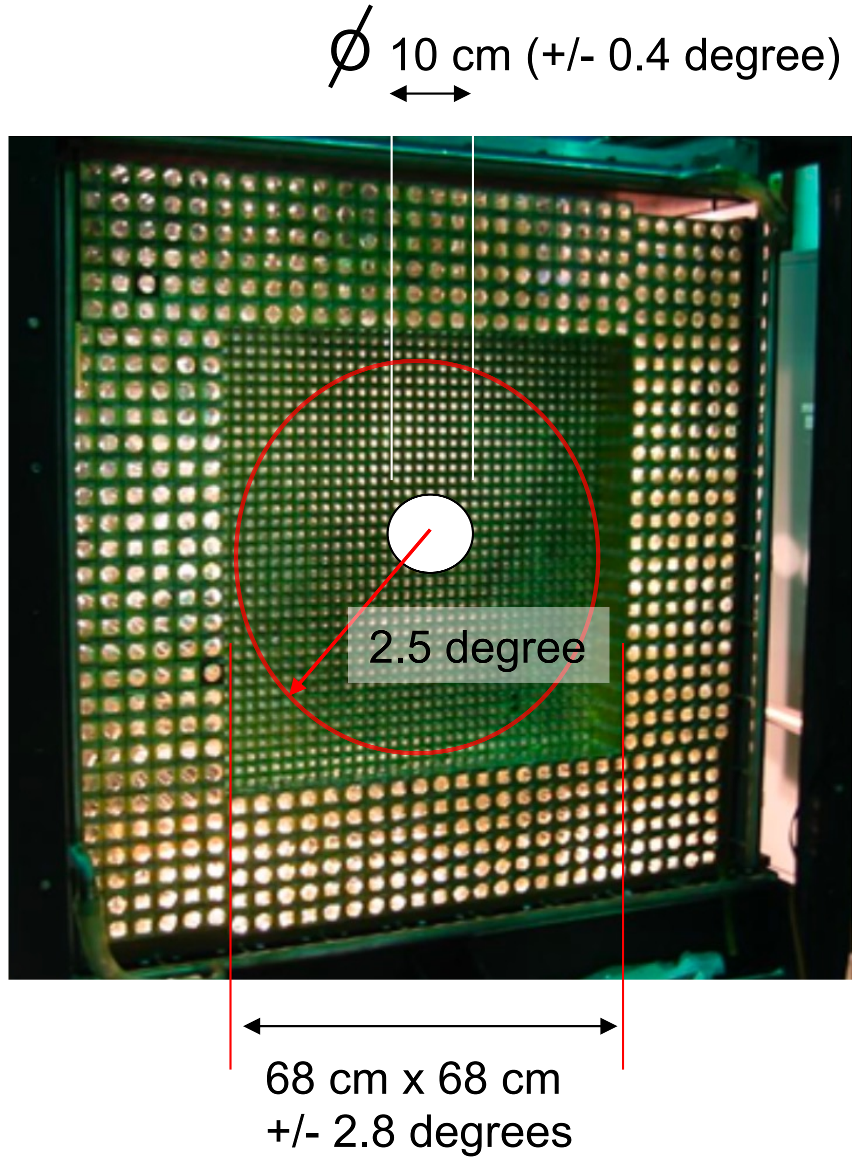
# Calorimeter parameters

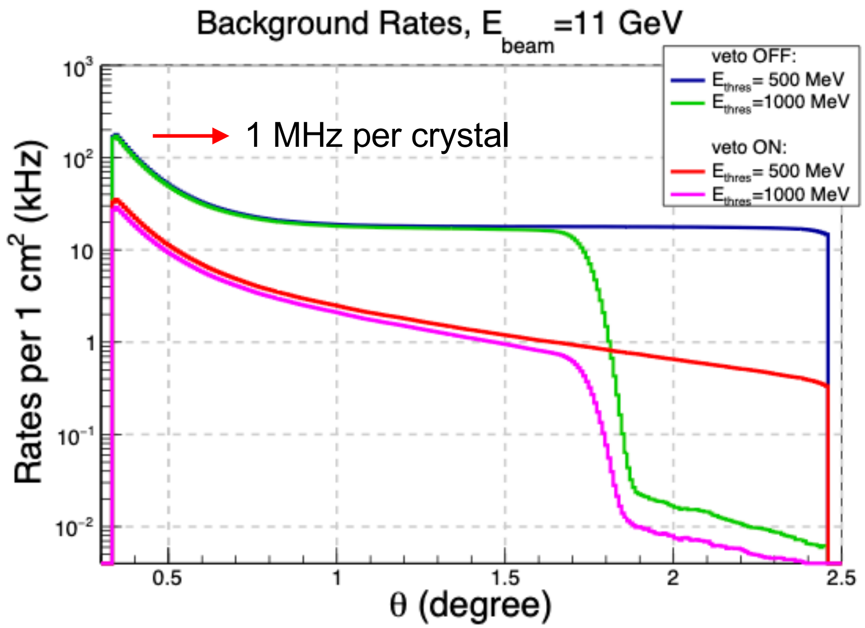


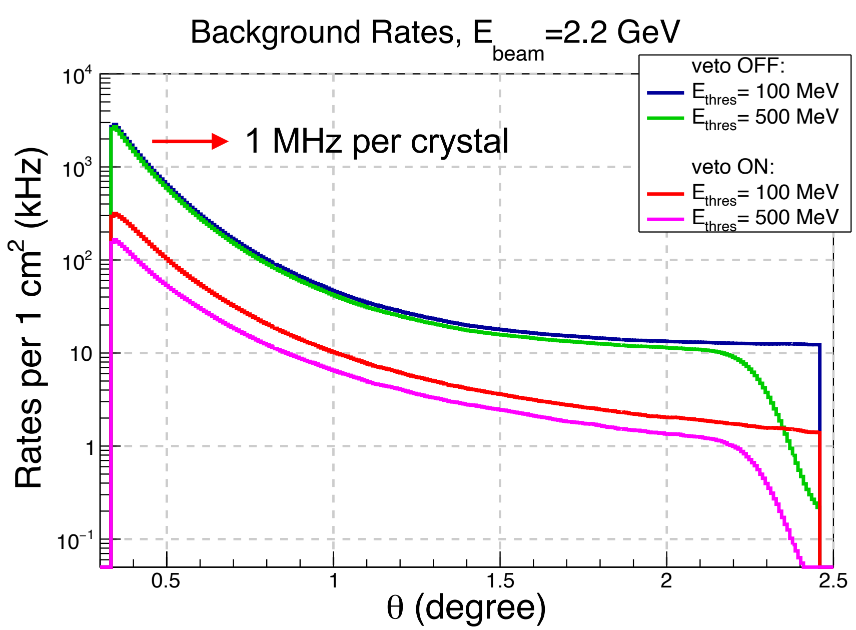



# Expected rate in the calorimeter



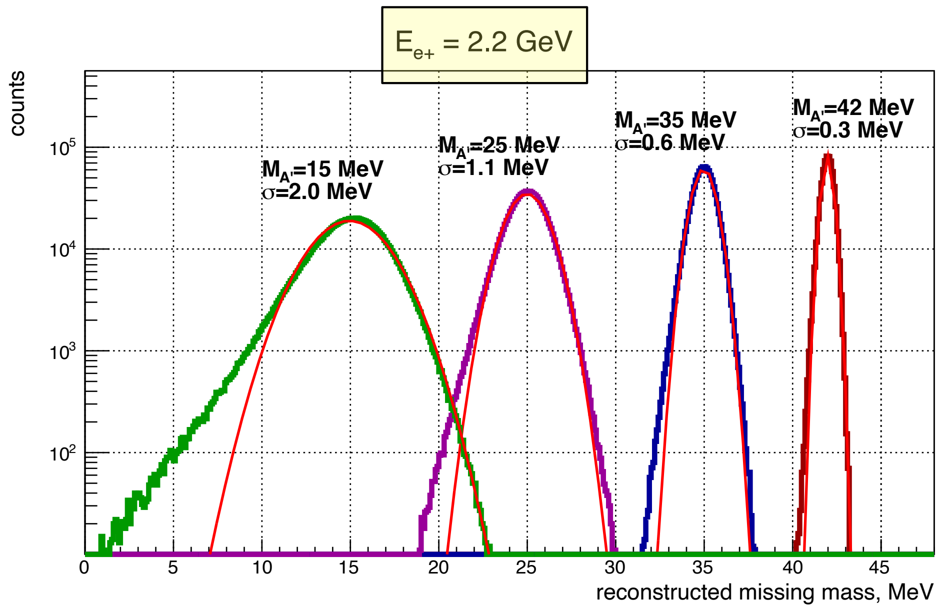



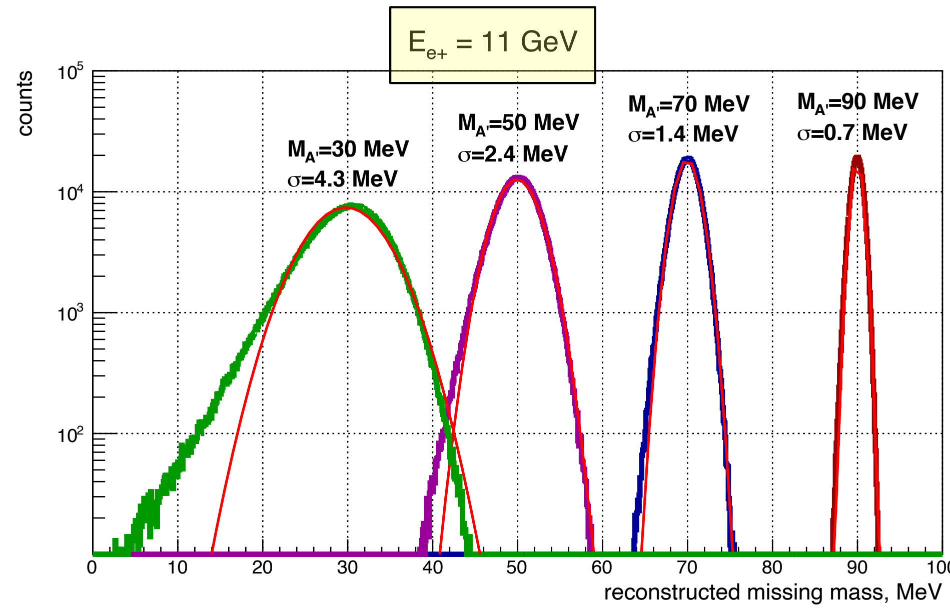



# Mass resolution

the photon energy and angle allow us to calculate
the missing mass:

$$M^2_{A'} = 2m_e^2 + 2m_e * (E_+ - E_\gamma) - 4E_+ * E_\gamma * \sin^2(\frac{\theta_\gamma}{2})$$



# Projected detector rates

Whole acceptance

| | brems. | $\gamma+\gamma$ | $\gamma+\gamma+\gamma$ | elastic $ep$ | Bhabha | $A'$ | Total Hz |
|---|---|---|---|---|---|---|---|
| No cuts | 1.57e+05 | 1.03e+06 | 3.12e+05 | 3.85e+05 | 1.48e+07 | 3.52e-01 | 1.67e+07 |
| Charge veto | 1.57e+05 | 1.03e+06 | 3.12e+05 | 0.00e+00 | 2.07e+05 | 3.52e-01 | 1.70e+06 |
| Single $\gamma$-cluster | 1.57e+05 | 8.87e+05 | 2.49e+05 | 0.00e+00 | 8.73e+04 | 3.48e-01 | 1.38e+06 |

Around $M_{mis} = 80 \pm 1.5$ MeV

$\varepsilon^2 = 1 \times 10^{-7}$

| | brems. | $\gamma+\gamma$ | $\gamma+\gamma+\gamma$ | elastic $ep$ | Bhabha | $A'$ | Total |
|---|---|---|---|---|---|---|---|
| No veto | 6.64e+03 | 0.00e+00 | 3.94e+03 | 0.00e+00 | 6.28e+04 | 3.04e-01 | 7.34e+04 |
| Charge veto | 6.64e+03 | 0.00e+00 | 3.94e+03 | 0.00e+00 | 1.38e+04 | 3.04e-01 | 2.44e+04 |
| Single $\gamma$-cluster | 6.64e+03 | 0.00e+00 | 3.18e+03 | 0.00e+00 | 3.63e+03 | 3.00e-01 | 1.34e+04 |

need $2\times10^9$ events ~ $2\times10^5$ sec

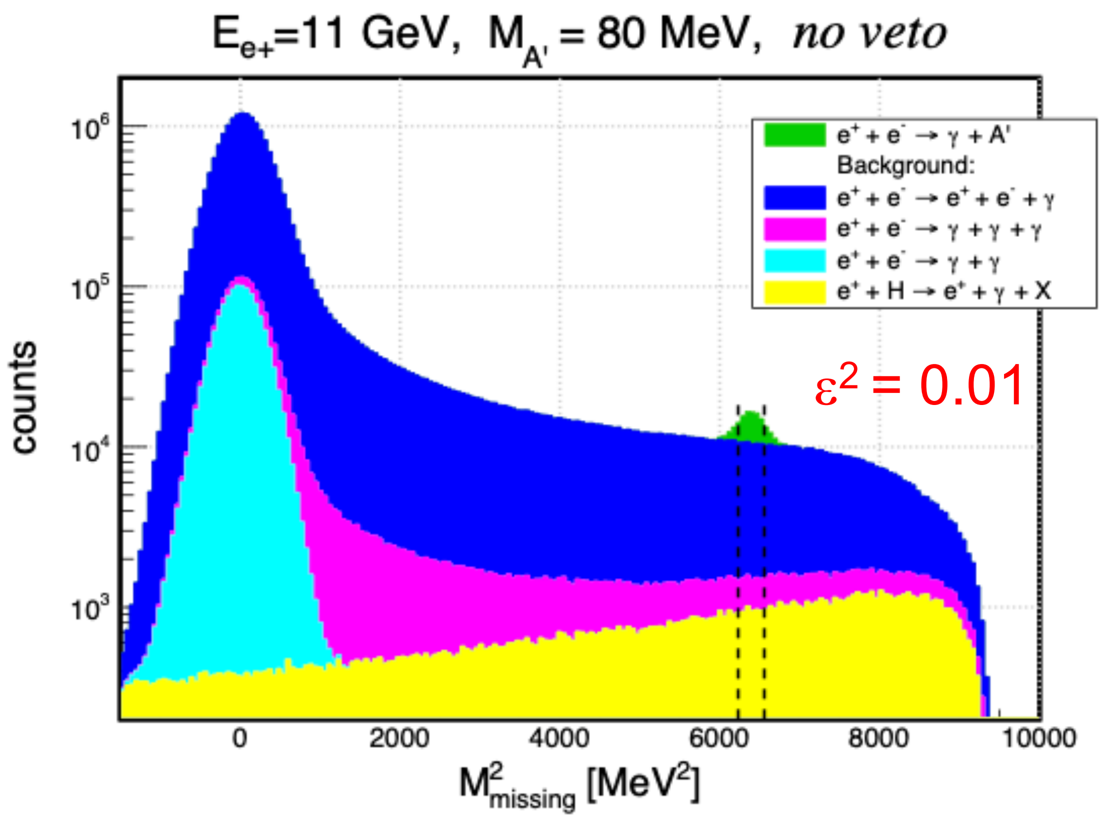
TABLE I. Cluster rates (Hz) for $E_{e+} = 11$ GeV, luminosity $= 7 \times 10^{34} cm^{-2} s^{-1}$, $E_{threshold} = 1$ GeV, $\theta = 0.5^\circ - 2.5^\circ$, $M_{A'} = 80$ MeV, $\epsilon^2 = 1 \times 10^{-7}$.

$$\frac{d\sigma}{d\cos\theta}(e^+e^- \to \gamma U) \simeq \frac{\alpha\,\epsilon^2}{s}\left(\frac{1}{\sin^2\theta} - \frac{1}{2}\right)$$

# Concept of this proposal

the photon energy and angle allow us to calculate the missing mass:

$$M^2_{A'} = 2m_e^2 + 2m_e * (E_+ - E_\gamma) - 4E_+ * E_\gamma * \sin^2(\frac{\theta_\gamma}{2})$$



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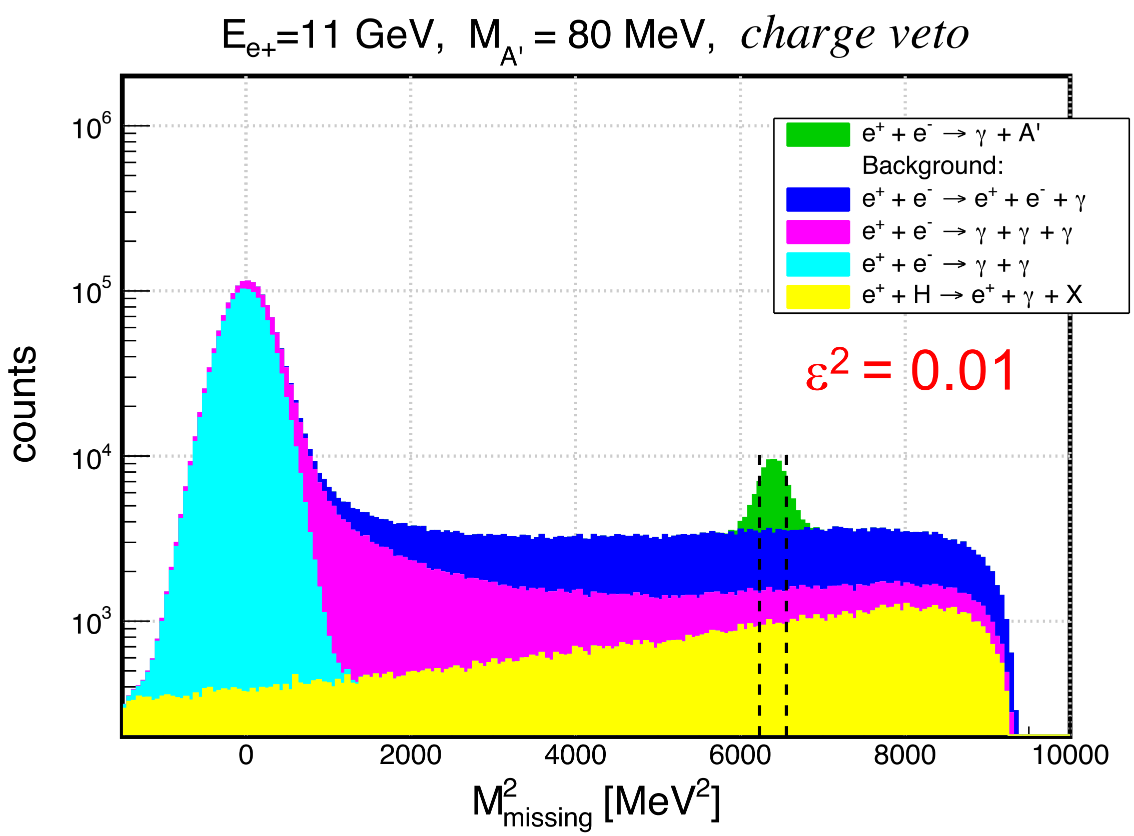

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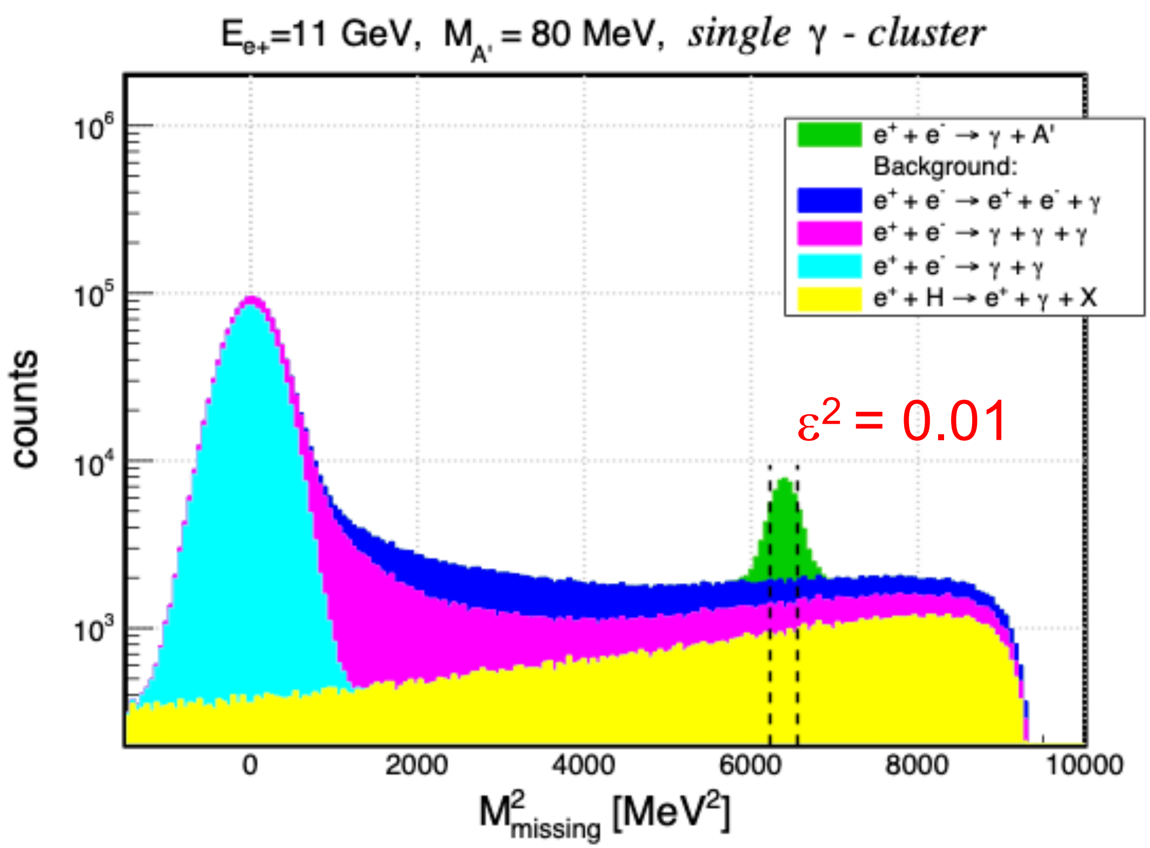
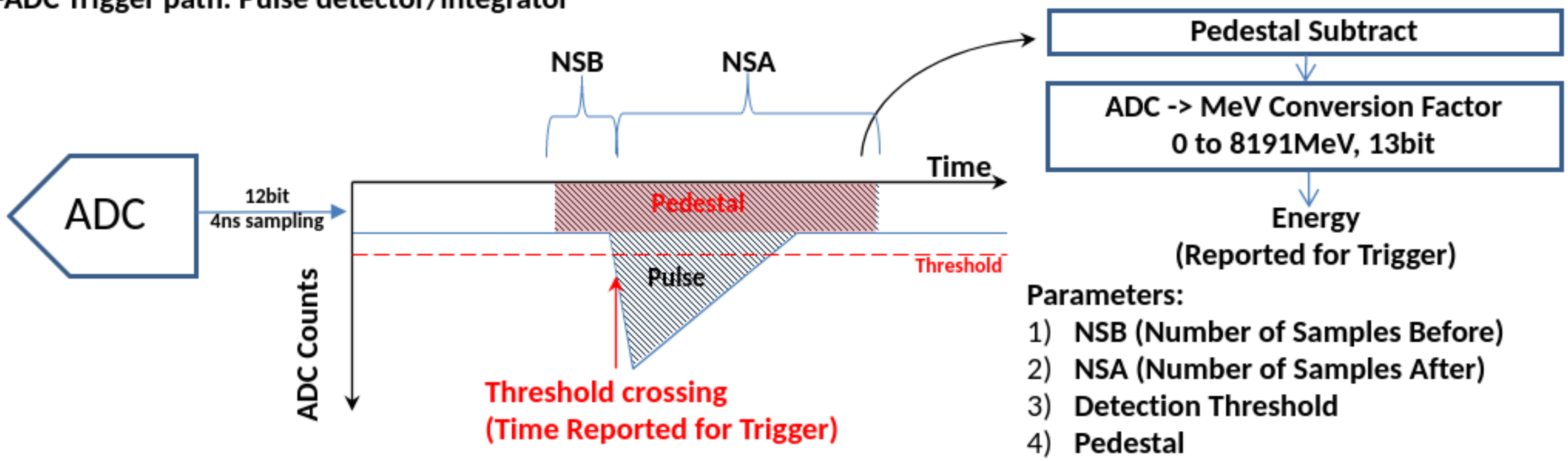


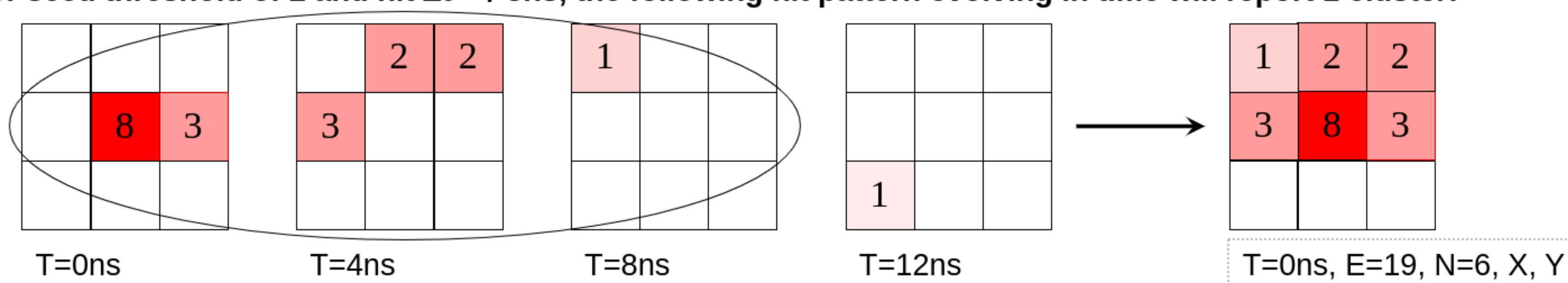
# High rate capability DAQ

FADC Trigger path: Pulse detector/integrator




Parameters:
1) NSB (Number of Samples Before)
2) NSA (Number of Samples After)
3) Detection Threshold
4) Pedestal
5) Gain

e.g. for seed threshold of 2 and hit Δt=+/-8ns, the following hit pattern evolving in time will report 1 cluster:



# High rate capability DAQ

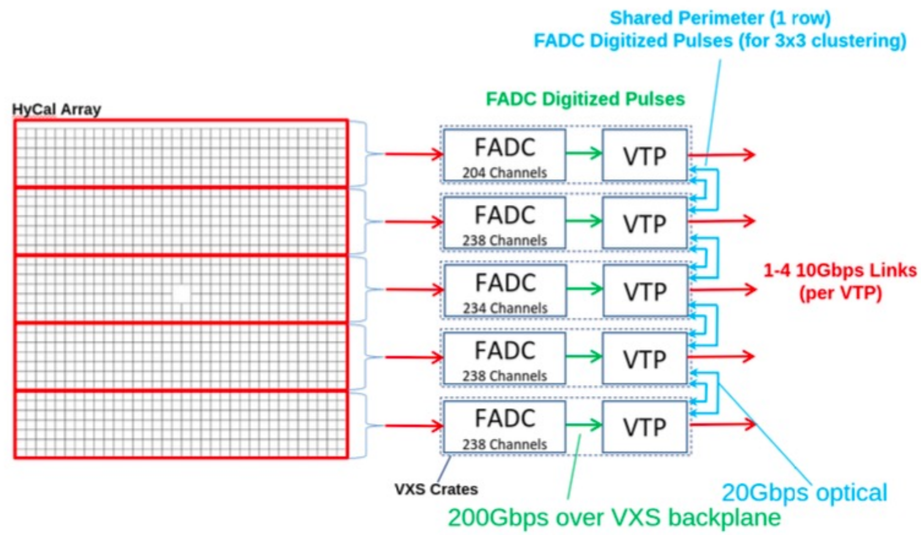
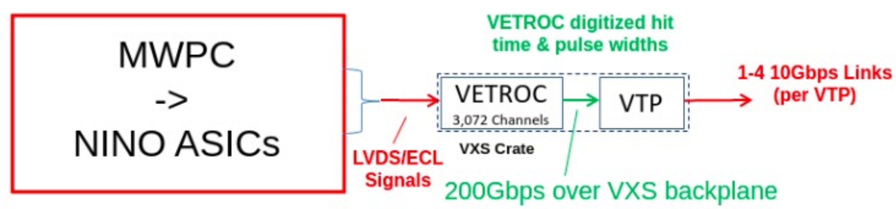


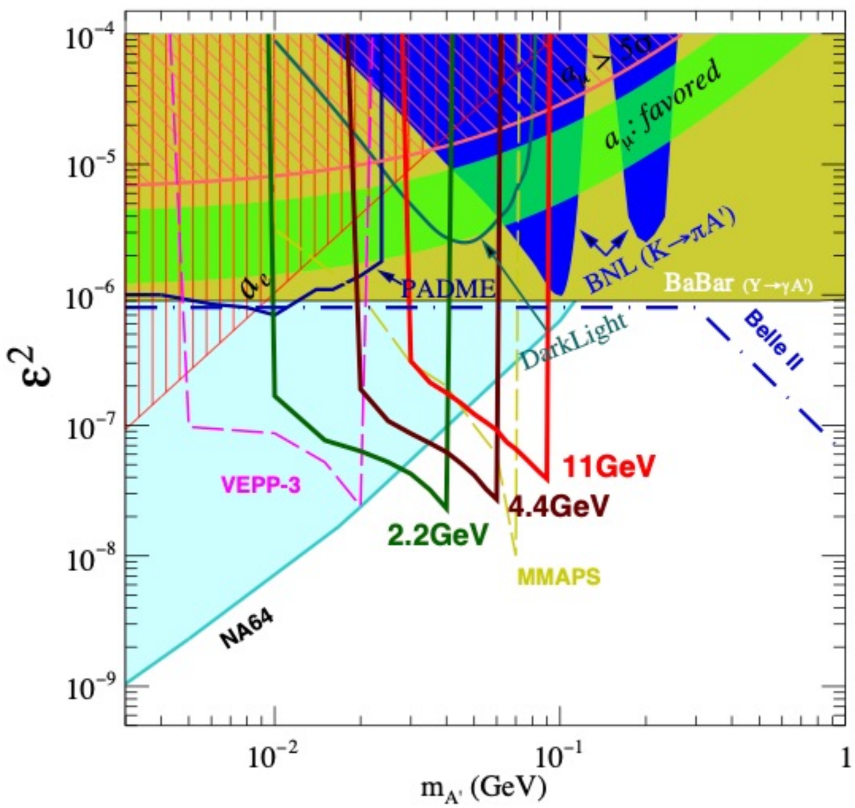

FIG. 17. HyCal DAQ Crate Layout.




The dominating data source is the HyCal streaming FADC hits, but with the hit stream filtering we expect no more than 20 MHz of clusters in the energy region of interest. The compact data packing of 58 bytes for the upper limit of 20 MHz of clusters, 1.16 GB/s, is well under the VTP streaming readout bandwidth (5 GB/s planned, with 20 GB/s capacity if ever needed).

# Projected sensitivity and beam time request

two-sigma level




## Uniqueness of the missing mass method

1. Sensitivity does not rely on specific decay mode of A' : e+e-, or hadrons, or semi-dark … 100 times more sensitive than ($g_\mu$-2)

2. Good mass resolution allows us to make a productive search for a signal with a 60-day run

3. Does not require new detector development (PRAD + two traditional MWPC)

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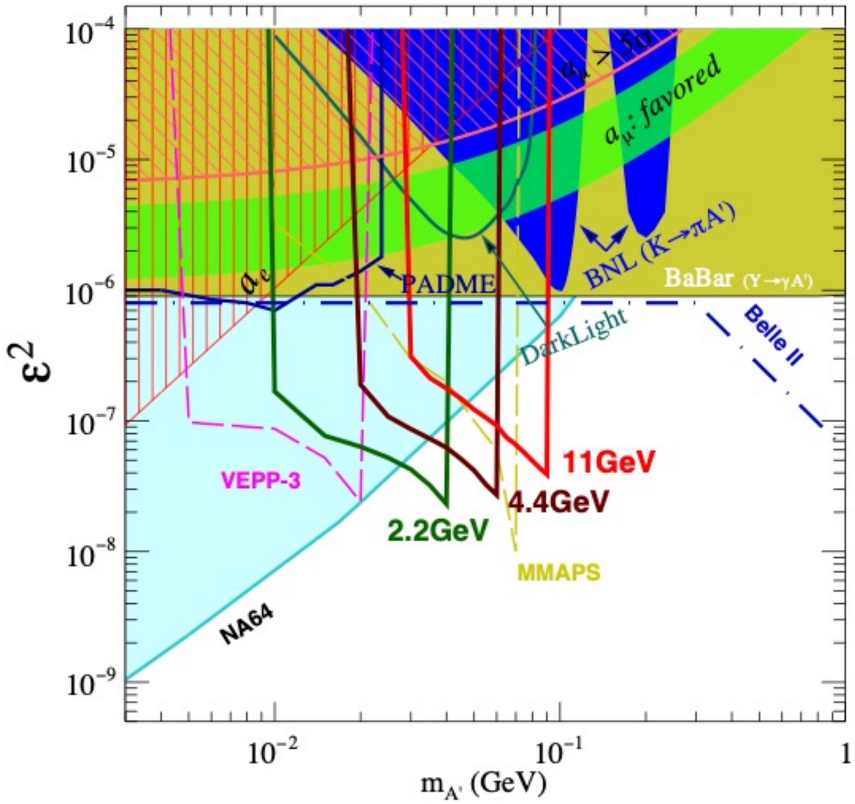


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| Kin. # | Beam energy, GeV | Beam, $\mu$A | Mass range, MeV | Time, days |
|---|---|---|---|---|
| C0 | 2.2 | 0.04 $e^-$ | DAQ code | 1/3 |
| C1 | 2.2 | 0.05 $e^+$ | 15-40 | 14 2/3 |
| C2 | 4.4 | 0.05 $e^+$ | 40-60 | 15 |
| C3 | 11 | 0.05 $e^+$ | 60-90 | 30 |
| | Total requested time | | | 60 |

beam time request

# Summary

- Proposed search for the A'-boson in the process of e+e- annihilation will use a missing mass reconstruction method which allows observation of A' independently of its decay mode(s).

- Experimental results will lead to an unambiguous conclusion about the coupling constant of the A'-boson and e+e- in a mass range 15-90 MeV.

- Key new item of this experiment is a 50 nA positron beam.

- Existing PRAD experimental setup is the main part of the required detector.

- Required DAQ high-rate capability is achievable using currently developed components. DAQ will be constructed for already approved PRad-II experiment.

# Backups

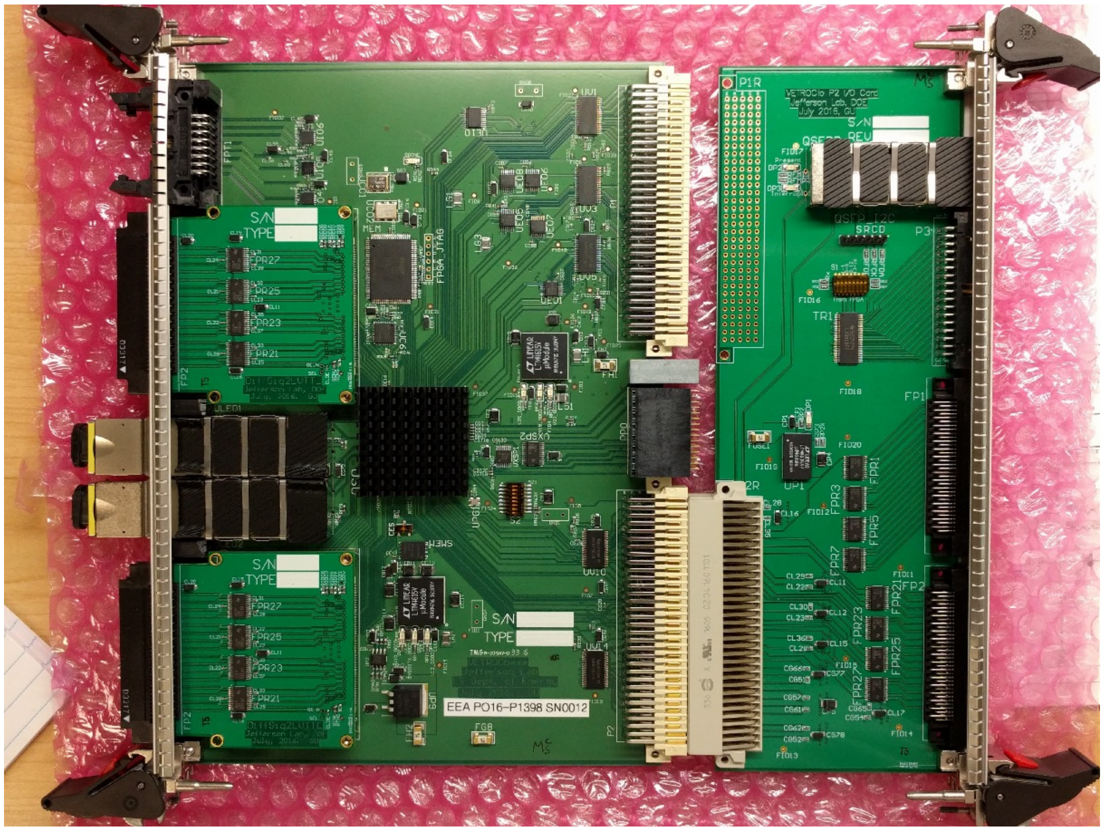
# Options for $e^+e^-$ experiment at low s

A "very" low energy $s^{1/2}$ ~ 100 MeV

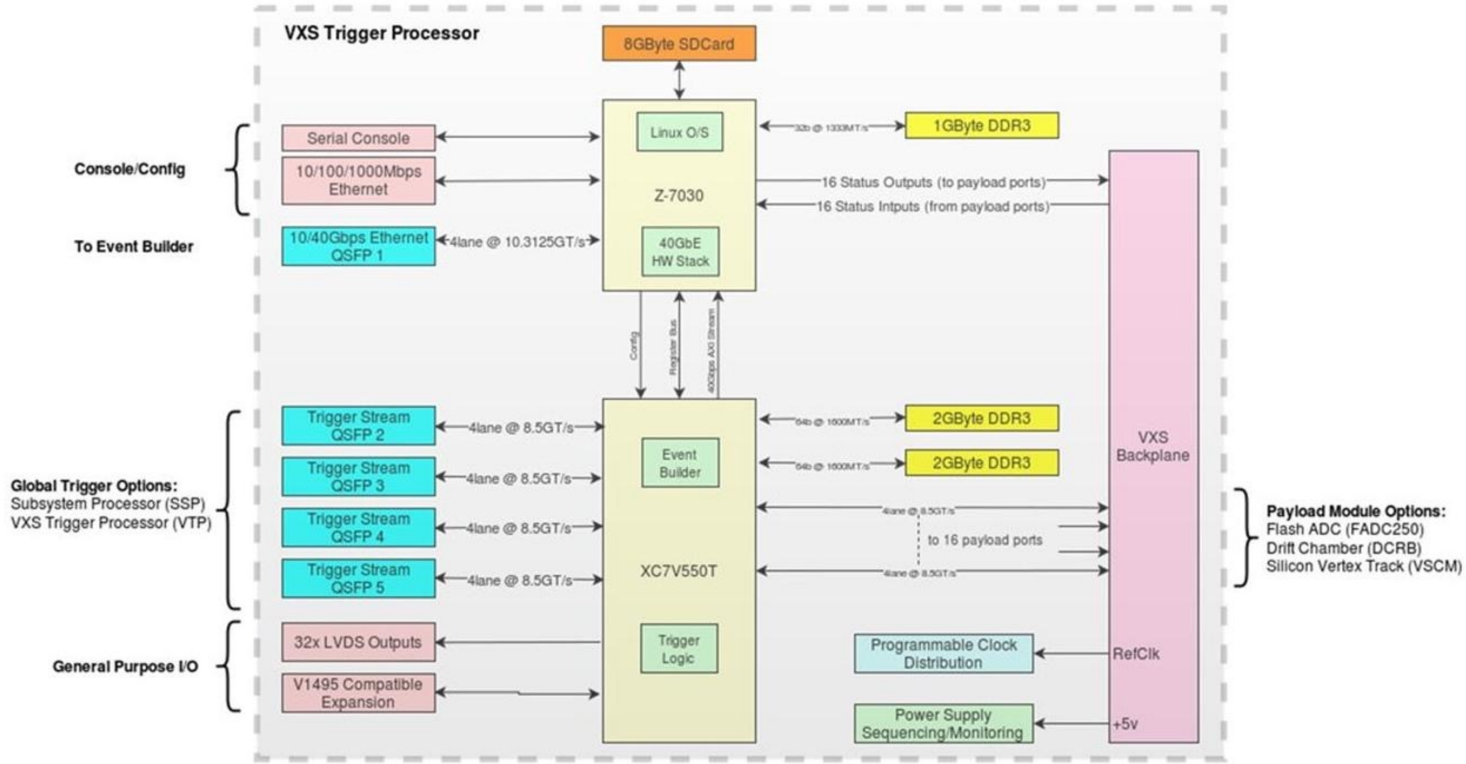
a) Search in existing data from good detector => problem with resolution at low s
b) 50 MeV x 50 MeV collider of e+e- => very low luminosity << $10^{30}$ $cm^{-2}/s$
c) Sliding beams of e+e- (200 MeV x 200 MeV)=> need specialized accelerator with two rings
d) Positron beam and atomic electrons

The focus is now on a positron beam of ~2-11 GeV incident on the hydrogen target

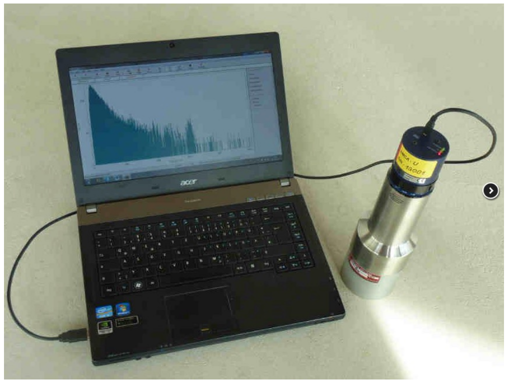
# High rate capability DAQ




# High rate capability DAQ and data flow

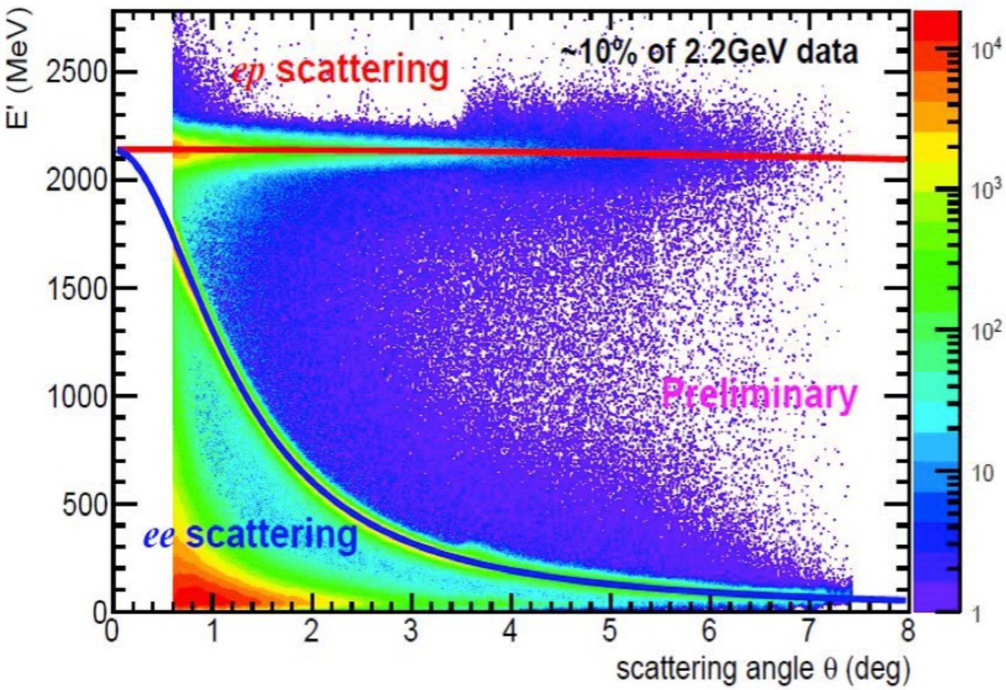



DAQ in this experiment operates as an advanced multi channel analyzer- and allows a high event collection rate

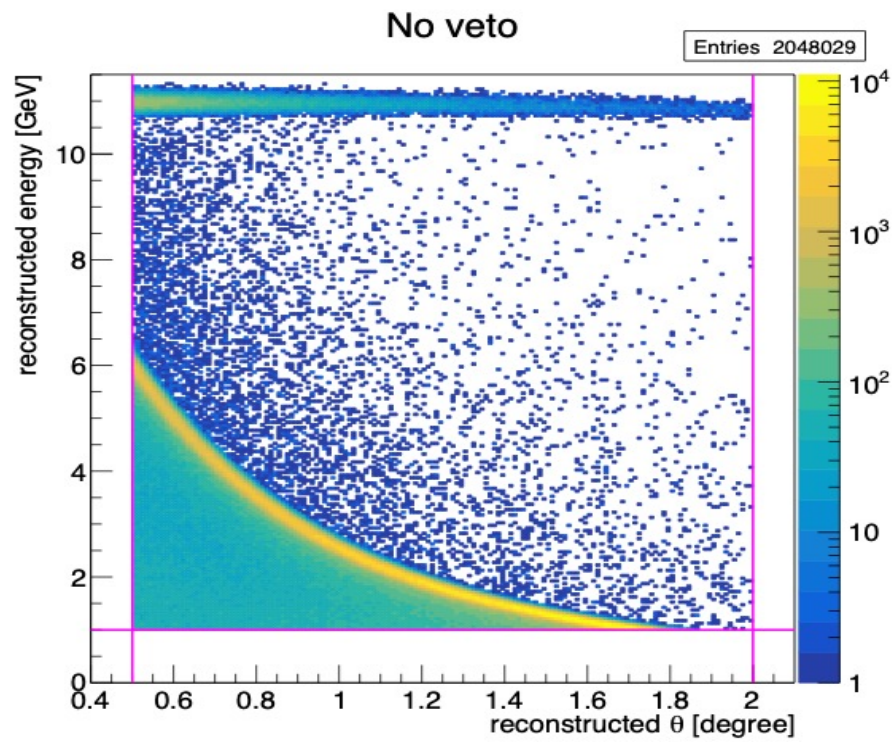


# Calorimeter data in PRAD vs. our MC

PRAD data




A' experiment simulation

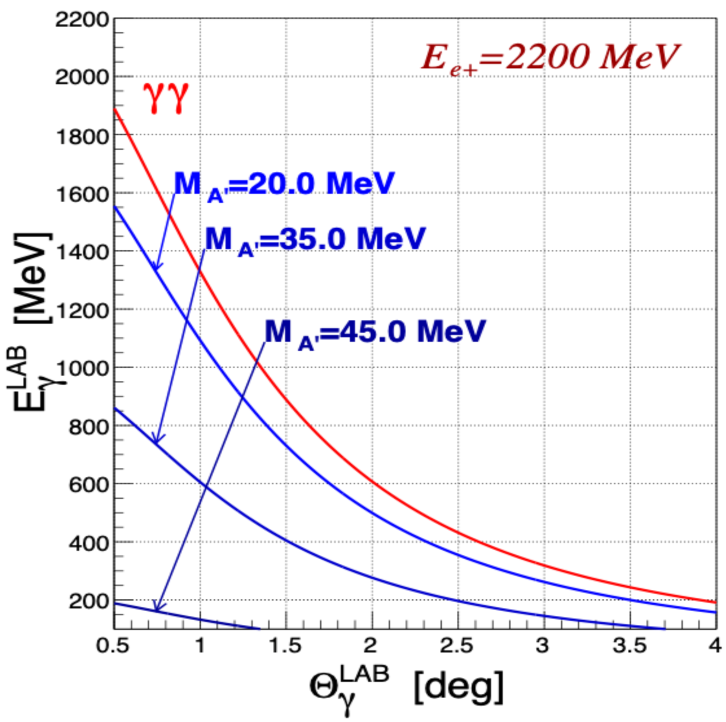


# Detector calibration

Most events are from the processes of $e^+e^-$ elastic scattering and two-gamma final state: ~$10^{14}$ of 1-hit and ~$10^{13}$ 2-hit events with exact energy-angle correlations.

These events will be used for energy calibration of the calorimeter blocks and for check/correction of the position related systematics.

Systematics is also suppressed due to the locus for events for given mass of A' mass: $M^2_{A'} = 2m_e^2 + 2m_e * (E_+ - E_\gamma) - 4E_+ * E_\gamma * \sin^2(\frac{\theta_\gamma}{2})$

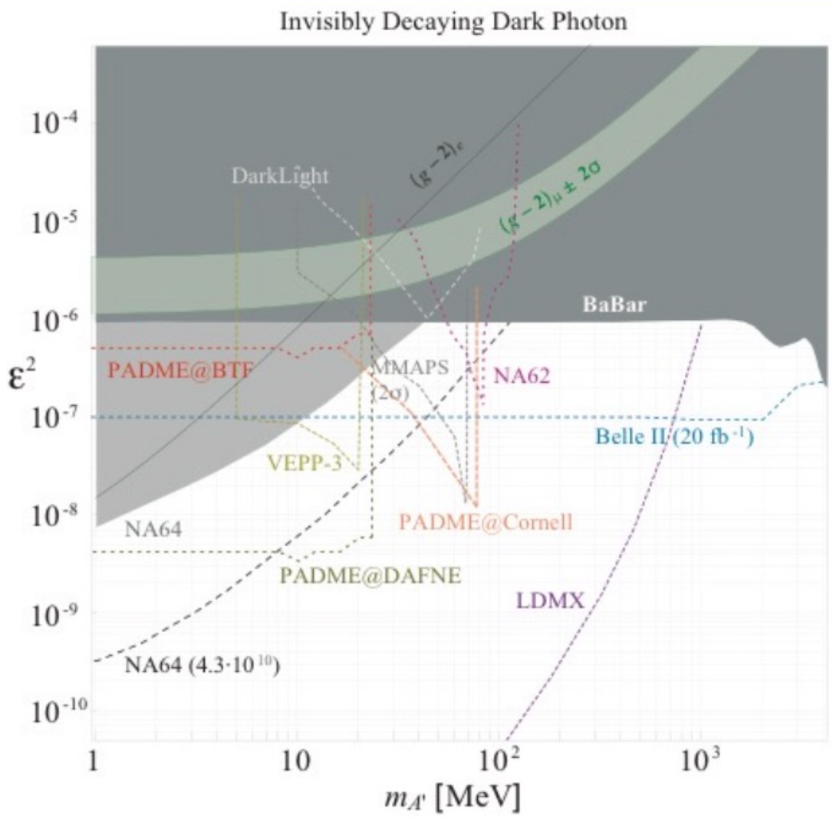


# PADME

Slide from the report by
P. Gianotti
for the PADME collaboration

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

## PADME prospects




**PADME sensitivity is limited by:**

- the Linac duty-cycle 50Hz x (40-250) ns/bunches
- Beam energy 550 MeV limits $M_{A'} < 23.7$MeV

**There are plans to move PADME to other positron beam line:**

- Cornell
- Jlab
- DAFNE extracted beam

**The Independent TAC review**

## PR12-23-005: Dark Photon Search with a JLab Positron Beam

This Hall B proposal aims to search for the dark matter candidate known as the A'-boson. This experiment only requires low current, unpolarized beam, making it a relatively simple positron experiment.

Primary Comments

1. This experiment requires a careful and controlled energy calibration of the HyCal for each beam energy setting yet there is no discussion of how this procedure is to be carried out. In particular, even with a refurbished tagger system, it can only go to 6 GeV, so how exactly will the calibrations be done with an 11 GeV beam? The proposal mentions using elastic scattering, but the details are sketchy.
**For energy calibration we plan to use Bhabha events and two-gamma (main annihilation process) events. Energy and angle for these events have exact correlation and the sum of hit energies equals the beam energy. As shown, for example in Fig. 6 of the proposal, energy-angle correlation for single hit (one cluster) events is a dominant feature in the plot. Two-hit events also have enormous statistics ($\sim 10^{13}$) events.**

8. Target windows are not explicitly included in the Monte Carlo. If they are not present they should be added.
**Yes, they will be added. The decision to use only a 5-cm long liquid hydrogen target in MC was made after a full analysis of the impact of the windows on experiment results. We found that impact of the windows is acceptably small: improvement of the $\epsilon^2$ sensitivity by 3% (due to extra electrons in the target) and increase of the events rate by 5-10%. The lH2 target is a better choice for this experiment but not dramatic. In fact, the Cornell's A' search proposal MMAPS had plan to use the Be target. The PADME experiment is also using the solid target.**

**We plan to use Be window in the target with a thickness of 5 mils (total 0.25 mm for both windows). The mass of the Be in the windows of liquid hydrogen target is 0.045 per cm$^2$, which is about 13% of the 5-cm long liquid hydrogen. The contribution to the number of electrons is about 5.6%, so the impact on the event rate (Bhabha and two-gamma) is small to be ignored in first MC. The contribution is larger ($\sim$ 10%) for the single-hit elastic events but they will be excluded on the trigger level because they correspond to a single-hit charged cluster. The bremsstrahlung from Be will add 13% to the rate of a similar process on hydrogen.**

**The TAC review**

## PR12-23-005: A Dark Photon Search with a JLab Positron Beam

The proposal aims to perform a search for a dark matter candidate, known as the A'-boson. The search will use the new JLab positron beam and study the process e+e-$\rightarrow \gamma$ X from an lH2 target triggered on single photon cluster events in the inner PbWO4 part of the HyCal calorimeter. The search will be sensitive to the production of A' bosons in the mass range from 15 - 90 MeV and with a sensitivity to couplings of the A' boson to the Standard Model electric charge $\epsilon^2 \sim 10^{-7}$. Due to the search in the missing mass spectrum, the experiment sensitivity is not connected with the specific decay mode of the boson candidate or its branching fraction into the different possible modes. The resolution of the HyCal allows for mass resolution at the level better than a few percent.

3. The high rates from low-angle positron-electron scattering are planned to be handled using streaming readout. However, only a proof of concept using the CLAS12 FT-Cal has been carried out. These tests are still a long way from full implementation in a production run with a large number of channels. Close collaboration with the JLab Fast Electronics Group and the Hall B DAQ and trigger experts is essential to realize this new mode of triggering and readout. The proposal also does not mention the need for an associated level-3 trigger or event filtering as part of the streaming mode. This should be considered to reduce background contributions.
**Experts from the JLab Fast Electronics Group and the Hall B DAQ are members of this collaboration. The expected streaming data rate is comparable/under what Hall B and Hall D currently write to tape so we certainly could plan to write everything without filtering (in this case you would just need enough computing/storage for a day or so of data). These details will have to be discussed with folks managing the tape storage system to make sure you can plan this. This is a lot simpler than dealing with event filters at the streaming level. What will be new in this experiment is the idea to self trigger FADC250 individual channels and readout over the VTP (we have readout the FADC250 with the VTP in SBS so the readout path through the VTP is also not new).**