Search for a dark force mediator

Bogdan Wojtsekhowski, JLab

Outline of the talk

- Approved proposal
- PRL 2006 on e^+e^- and NASA 2006 galaxy event
- Positron beam on an atomic electron at JLab
- Original experiments for axions at SLAC +
- BEST paper, APEX, HPS, X17
- The experiment in Hall B with HyCal
- DAQ rate capability
- Projected results

A dark photon search with JLab positron beam

Positron A' collaboration

P.Achenbach, A.Gasparian, N.Liyanage, B.Raydo, B.Wojtsekhowski, W.Xiong

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. Ahmidouch, 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

- We propose an experiment to search for a new particle, the U/A′-boson, by measuring the missing mass spectra in the positron annihilation in flight with an atomic electron with one final particle (photon) detected.

- The missing mass reconstructed from the energy and angle of the detected photon will provide the means for the search for any type of secondary particle produced in the reaction -“production experiment”.

- The projected statistical sensitivity for the reduced coupling constant $\varepsilon^2 = f_e^2/e^2$ reaches 2×10^{-8} with 55 days of run at a positron beam current of 50 nA.

- The experiment is in the same physics category which at Jefferson Lab includes several related approved experiments – HPS, APEX, DarkLight, X17. The important complementarity of this proposal is due to the ability to observe A’ which decays dominantly to the invisible particles.

PR12+24-005

PAC52 review

Scientific Rating: A-

Recommendation: Conditionally approved (C1) for 55 PAC days in Hall B

Title: A Dark Photon Search with a JLab Positron Beam

Spokespersons: B. Wojtsekhowski (contact), P. Achenbach, A. Gasparian, B. Raydo, N. Liyanage, W. Xiong

Motivation: The proposal is to search for the A′ boson in the annihilation of a high energy positron with an atomic electron ($e^+ + e^- \rightarrow A' + \gamma$) using the missing mass method. The A' boson in this reaction would be a new particle that exists in a manner beyond the standard model (BSM) of nuclear and particle physics. Strong constraints on the light A′ boson parameters have been obtained from electron and muon anomalous magnetic moments ($g - 2$) and other particle decay modes. There are also other JLab experiments with similar physics goals that are either approved, conditionally approved, and/or deferred (PR12+23-005, E12-10-009, E12-11-006, E12-21-003), but what makes this proposal different is that it is independent of decay modes. In this way, the experiment is sensitive to invisible decay modes of the A', so it is a broader and more generic search.

Measurement and Feasibility: The observed variables are the photon energy and its angle relative to the direction of the incident beam. The projected sensitivity to the coupling constant of the A′-boson (relative to the electromagnetic coupling) is at the 2×10^{-8} level (2σ sensitivity) in the mass range of 15 to 90 MeV. The experiment will use PRAD detector components in Hall B at a luminosity of 7×10^{34} Hz/cm^2, and a positron beam with a current of 50 nA at beam energies of 2.2, 4.4 and 11.0 GeV, along with a 5-cm-long liquid hydrogen target. The request is for 55 PAC days of running.

Issues: In the future, the proponents should plot their sensitivity reach at a significance level that is consistent with the experimental limits being compared to. The TAC report has raised a number of technical issues that need to be addressed in setting up the experiment.

Summary: This proposed experiment provides an important search for dark photons that does not rely on specific decay modes of the A′, with a reach beyond existing invisible decay limits from NA64, PADME, and Belle-II. As this dark photon search experiment is within a highly competitive nuclear physics environment, its competitiveness may likely change in the period of time that will be required until a running positron beam is available at CEBAF. Future jeopardy reviews of the experiment should pay particular attention to this issue.

The PAC conditionally approves the proposal for 55 PAC days. A C1 review by the Lab should be conducted at an appropriate time and verify that positron beams will be available with the parameters required for the experiment.

Theory review

PR12-24-005: *A Dark Photon Search...*

Y.-T. Chien, D. Richards

This is a resubmission of the proposal last year with additional simulations requested by PAC51. In that sense, there are no additional theory comments other than to note that the updated simulations leading to increased sensitivities for the dark photon coupling for a slightly decreased runtime request. We reiterate the "discovery" potential of this proposal, and its advantage as a "missing energy" experiment that does not rely on the details of the dark-photon decay. We list the theory report of last year, by Kostas Orginos and Ian Balitsky, below:

> This proposal aims to utilize a possible positron beam at JLab to search for dark gauge bosons using positron anihilation on atomic electrons. The proposal describes well the state- of-the-art in this area and makes the case that this project fits well with current and future activities in the searches for dark gauge bosons. The discovery potential of this project is significant, in the sense that a non-zero signal will have profound implications to our understanding of particle physics. However, the risk of a null result is also very high. It is a high-risk/high-gain project and perhaps one should carefully weigh the risk of failure with the potential discoveries. Certainly, if a positron beam becomes available at JLab this project may be an interesting addition to the physics JLab can do.

Dark matter is an elephant in the room

1E 0657-56:
NASA Finds Direct Proof of Dark Matter

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.

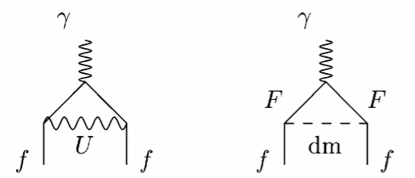
This composite image shows the galaxy cluster 1E 0657-56, also known as the "bullet cluster." This cluster was formed after the collision of two large clusters of galaxies, the most energetic event known in the universe since the Big Bang.

The processes which could have a U-boson

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

g_e-2, g_μ-2
π,η decays to Uγ
π,φ,ψ decays to γ + invisible

A.4. Constraints from g − 2

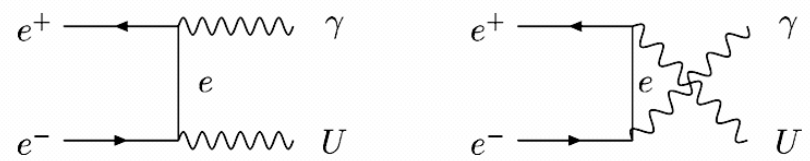


If the U boson mainly decays into dark matter, then the U production process turns out to be of the type $e^+e^- \to \gamma + \not{E}$, where $\not{E}$ is missing energy, which is of interest in experiments searching for single photon production events. But, in the case of a light dark matter candidate, 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 $|f_{eU}|^2 < 2\ 10^{-8}\,(m_U)^2$

A.6.1. Direct U boson production

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



The $e^+ + e^-$ to $U+\gamma$ can find a new particle

PRL **96,** 141802 (2006) PHYSICAL REVIEW LETTERS week ending 14 APRIL 2006

Probing MeV Dark Matter at Low-Energy e^+e^- Colliders

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(Received 12 October 2005; published 14 April 2006)

It has been suggested that the pair annihilation of dark matter particles χ with mass between 0.5 and 20 MeV into e^+e^- pairs could be responsible for the excess flux (detected by the INTEGRAL satellite) of 511 keV photons coming from the central region of our Galaxy. The simplest way to achieve the required cross section while respecting existing constraints is to introduce a new vector boson U with mass M_U below a few hundred MeV. We point out that over most of the allowed parameter space, the process $e^+e^- \to U\gamma$, followed by the decay of U into either an e^+e^- pair or an invisible ($\nu\bar{\nu}$ or $\chi\bar{\chi}$) channel, should lead to signals detectable by current B-factory experiments. A smaller, but still substantial, region of parameter space can also be probed at the Φ factory DAΦNE.

As always, the luminosity and
the photon energy resolution
are the key factors

The $e^+ + e^-$ to $U+\gamma$ can find a new particle

Search of U boson in electron-positron annihilation in flight

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Abstract

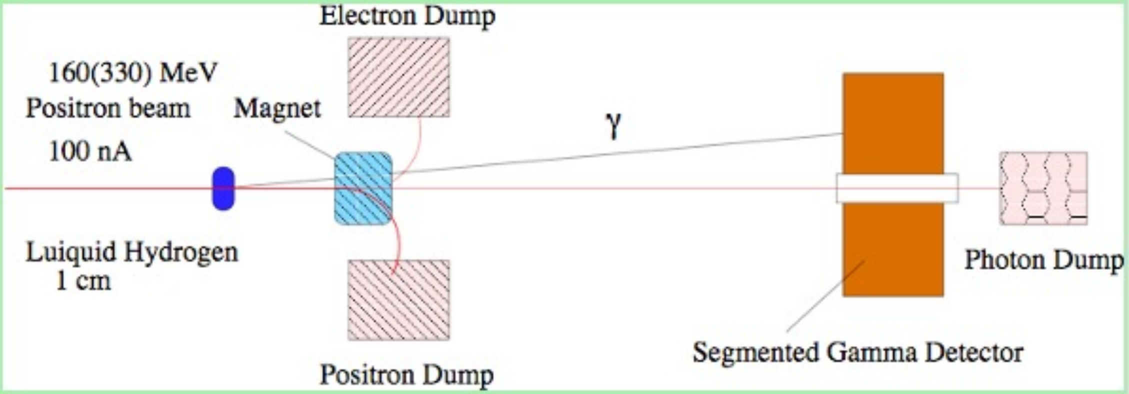
An experiment is proposed to search for a new gauge boson U in reaction $e^+e^- \to U\gamma$ in the mass range from 2 to 15 MeV. The data could determine the particle mass and the coupling constant f_e^2 (or its upper limit). The experiment could utilize a 160-330 MeV positron beam in JLab FEL. It needs 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.

As always, the luminosity and
the photon energy resolution
are the key factors

The $e^+ + e^-$ at JLab FEL

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.

Oct. 27, 2006 DNP APS Nashville

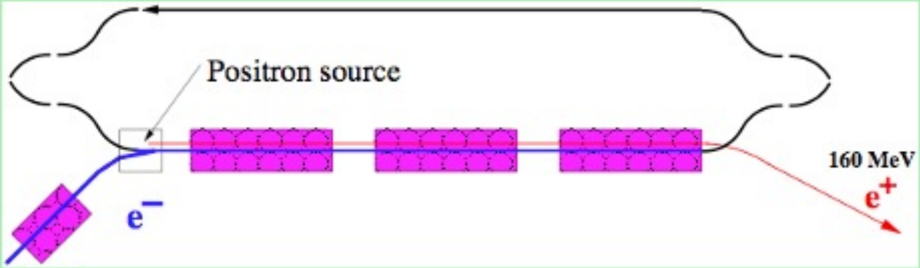
The e^++e^- at JLab FEL

Positron Beam

A beam of 25 nA 400 MeV was produced at Saclay in 1980

Beam of 1 μA was used for SLC (120 Hz), we need d.f. 100%

At Jlab FEL:



Production: **~ 10^{-6}** positrons per each 160 MeV electron into acceptance of the SC linac for acceleration.

Use of 160 kW 1 mA beam allows for 60 nA positrons
There are several alternative schemes with different energy and intensity of electron beam.

Oct. 27, 2006 DNP APS Nashville

The $e^+ + e^-$ at JLab FEL

Summary

- Observation of a U boson signal on the level of 5 sigma (statistical), assuming $f_e^2 = 0.3*10^{-8}$, requires 10 days of production running (total~ 20 days experiment).
- In M_U in range 2-15 MeV, this experiment has unique sensitivity, which about 2+ orders higher than (g-2).
- Experiment will explore exciting explanation of the 511 keV signal, light dark matter and search for particle beyond Standard Model.
- Development of the positron beam capability has other important physics and technological applications in JLab.

Oct. 27, 2006 DNP APS Nashville

PHYSICAL REVIEW D VOLUME 38, NUMBER 11 1 DECEMBER 1988

Search for neutral metastable penetrating particles produced in the SLAC beam dump

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(Received 6 May 1988)

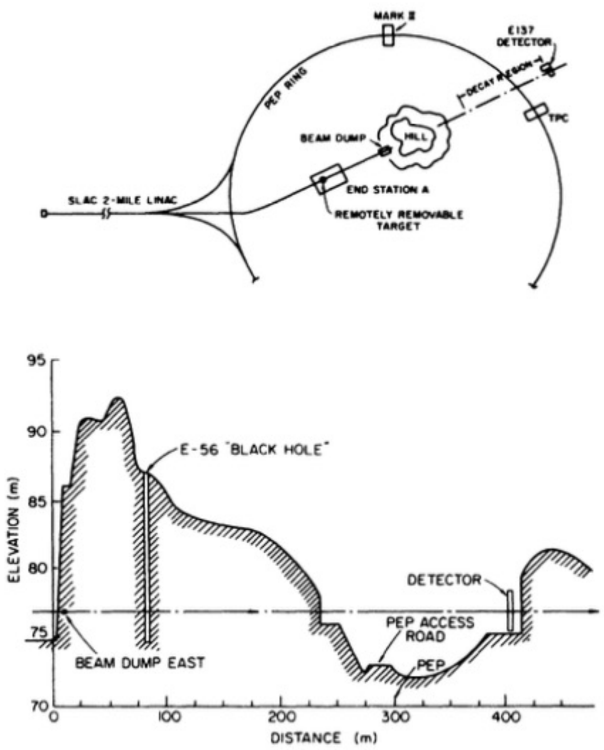
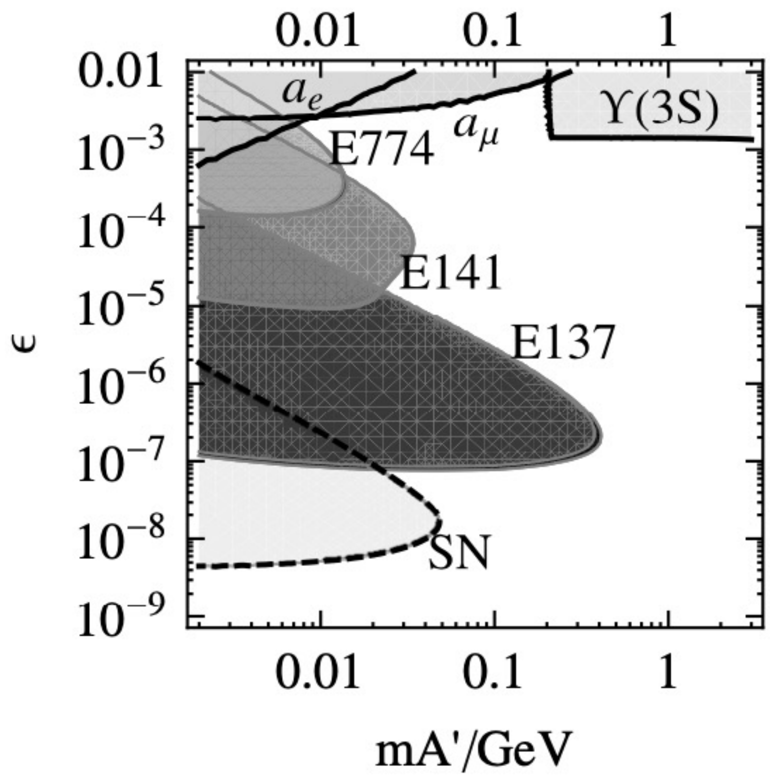


FIG. 2. Layout of SLAC experiment E137.



PHYSICAL REVIEW D **80,** 075018 (2009)

New fixed-target experiments to search for dark gauge forces

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(Received 20 July 2009; published 28 October 2009)

Fixed-target experiments are ideally suited for discovering new MeV–GeV mass $U(1)$ gauge bosons through their kinetic mixing with the photon. In this paper, we identify the production and decay properties of new light gauge bosons that dictate fixed-target search strategies. We summarize existing limits and suggest five new experimental approaches that we anticipate can cover most of the natural parameter space, using currently operating GeV-energy beams and well-established detection methods. Such experiments are particularly timely in light of recent terrestrial and astrophysical anomalies (PAMELA, Fermi, DAMA/LIBRA, etc.) consistent with dark matter charged under a new gauge force.

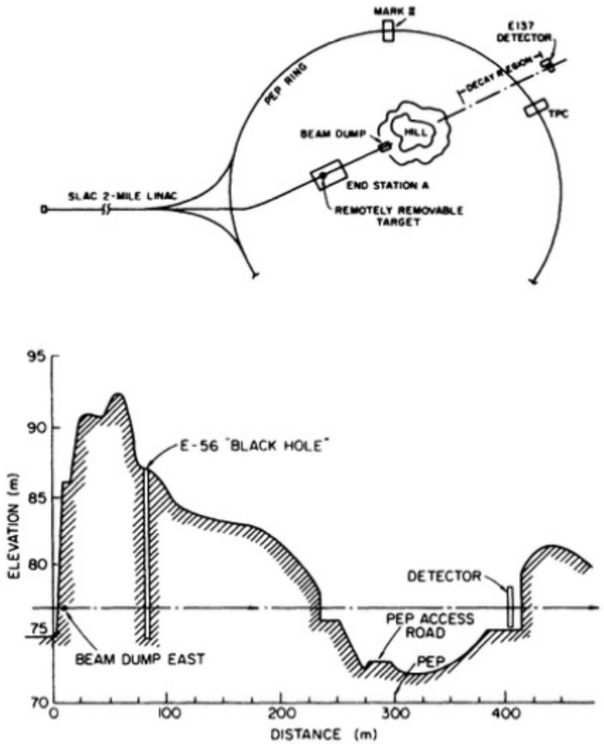
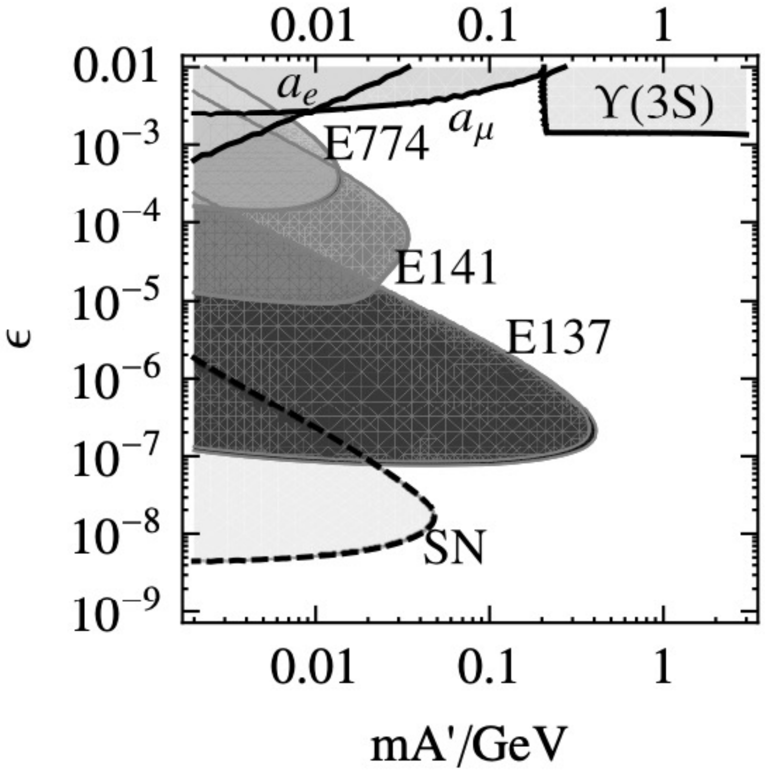
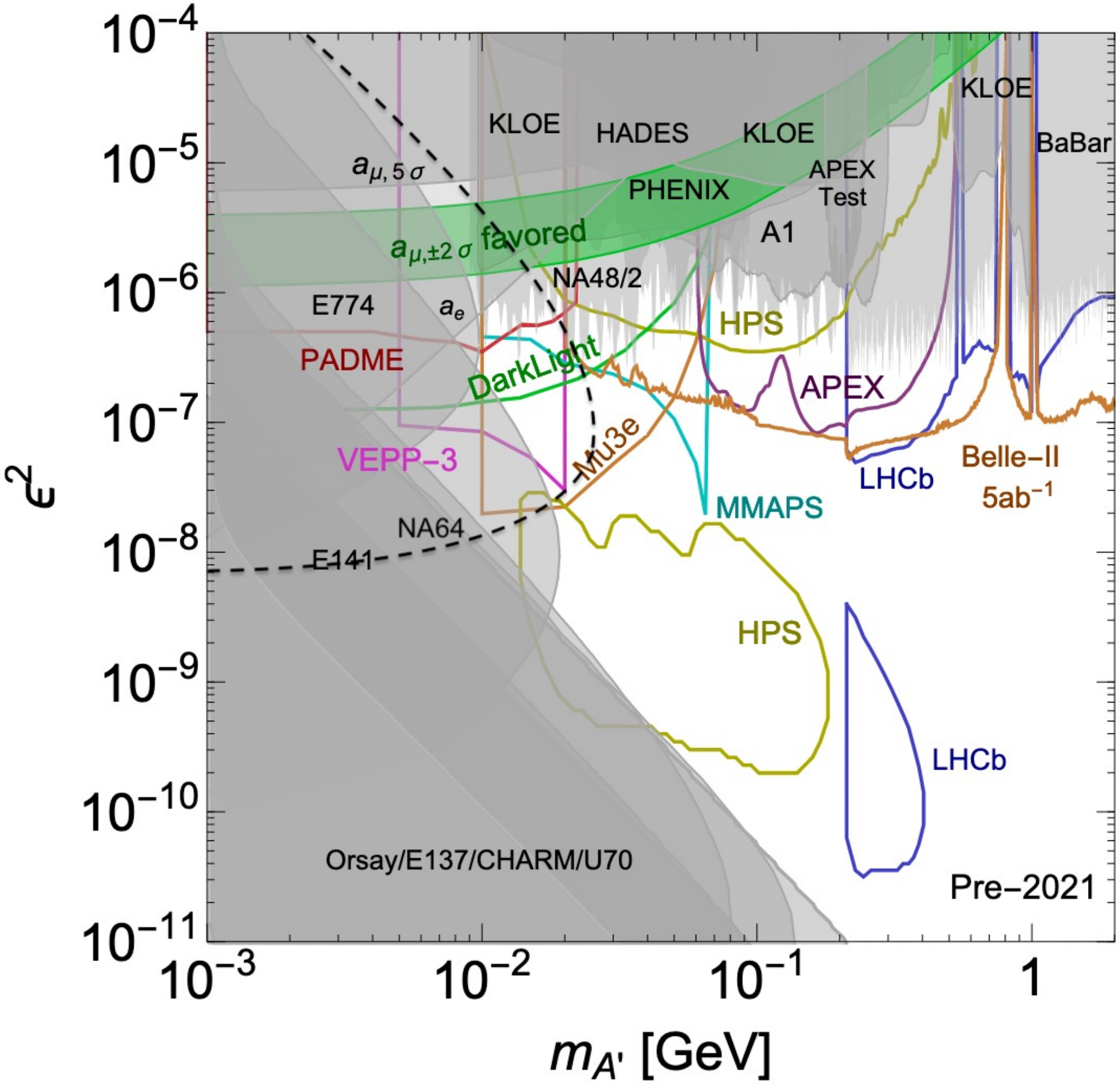


FIG. 2. Layout of SLAC experiment E137.



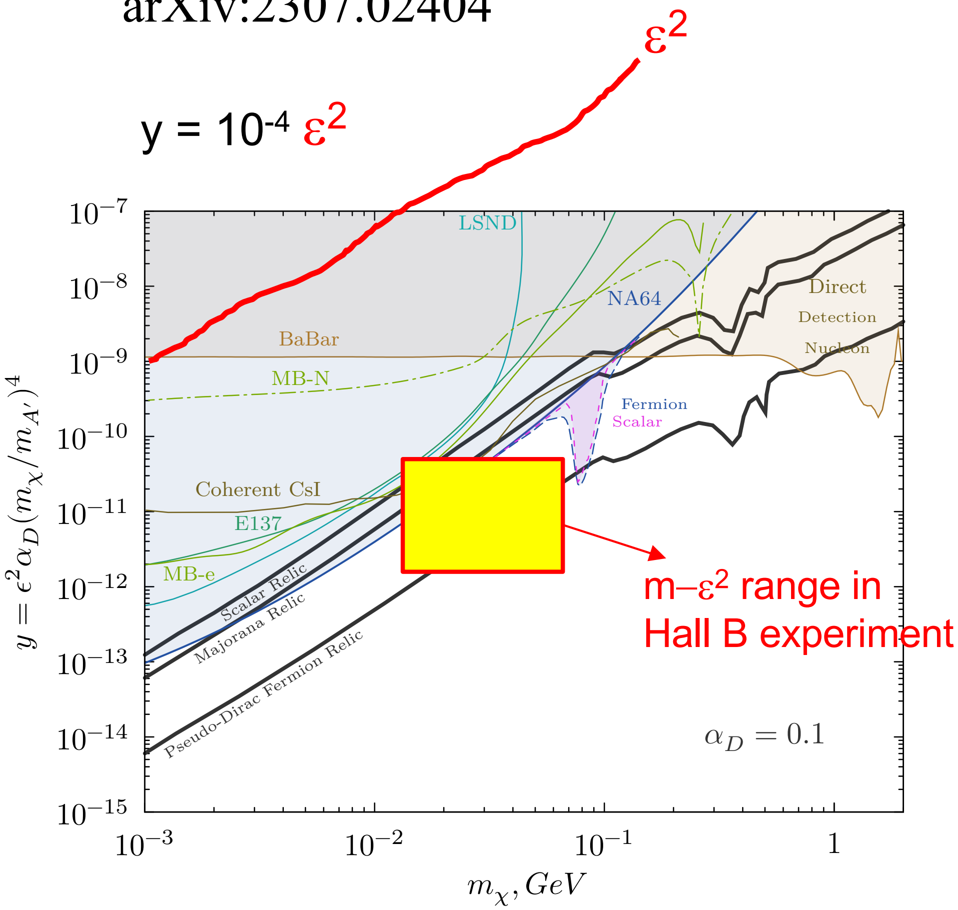
A' parameter space summary in 2017

US Cosmic Visions ... : arXiv:1707.04591



NA64 recent analysis

arXiv:2307.02404



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

NA-64 more analysis

Eur. Phys. J. C (2021) 81:959

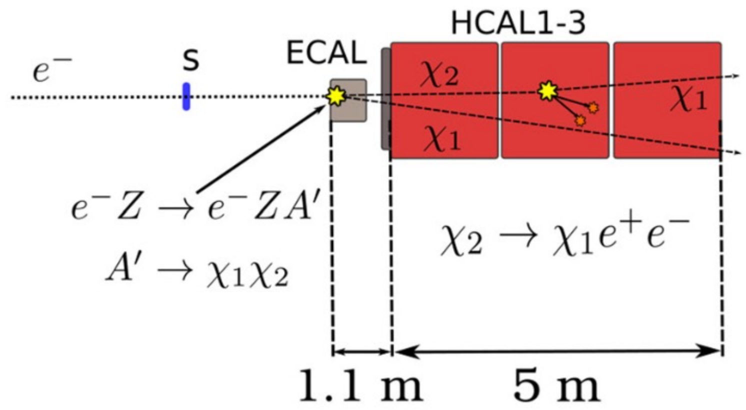


Fig. 3 A schematic view of an event $A' \to \chi_1\chi_2(\chi_2 \to \chi_1 e^+ e^-)$ from a A' produced after a 100 GeV e^- scatters off in the active dump, $e^- Z \to e^- Z A'$. The χ_2 particle decaying within HCAL2 corresponds to the S1 signature (see text for more details)

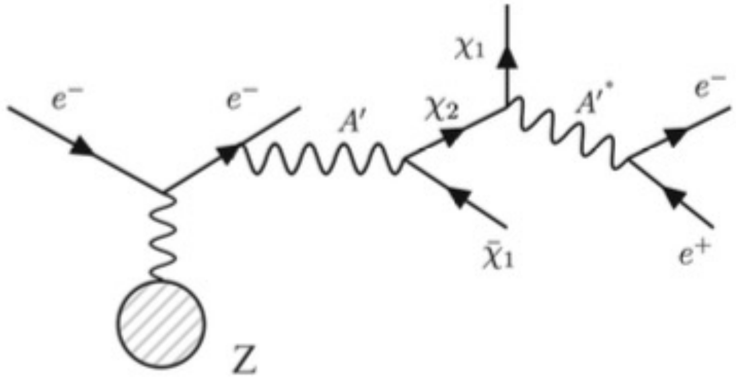
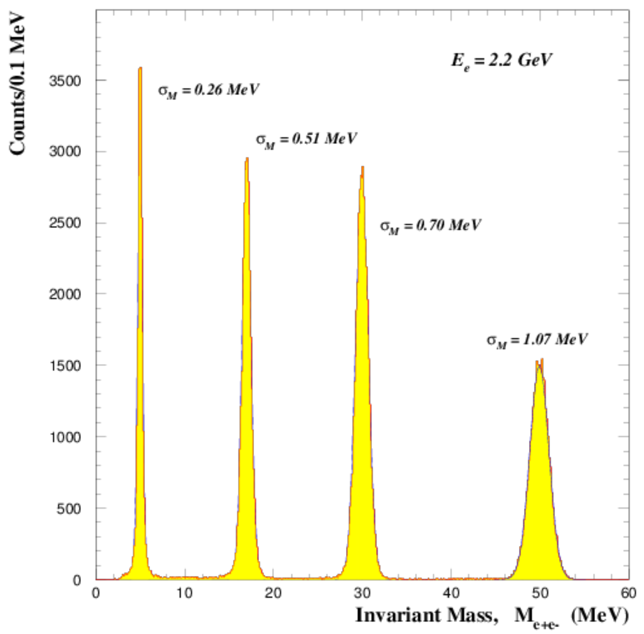


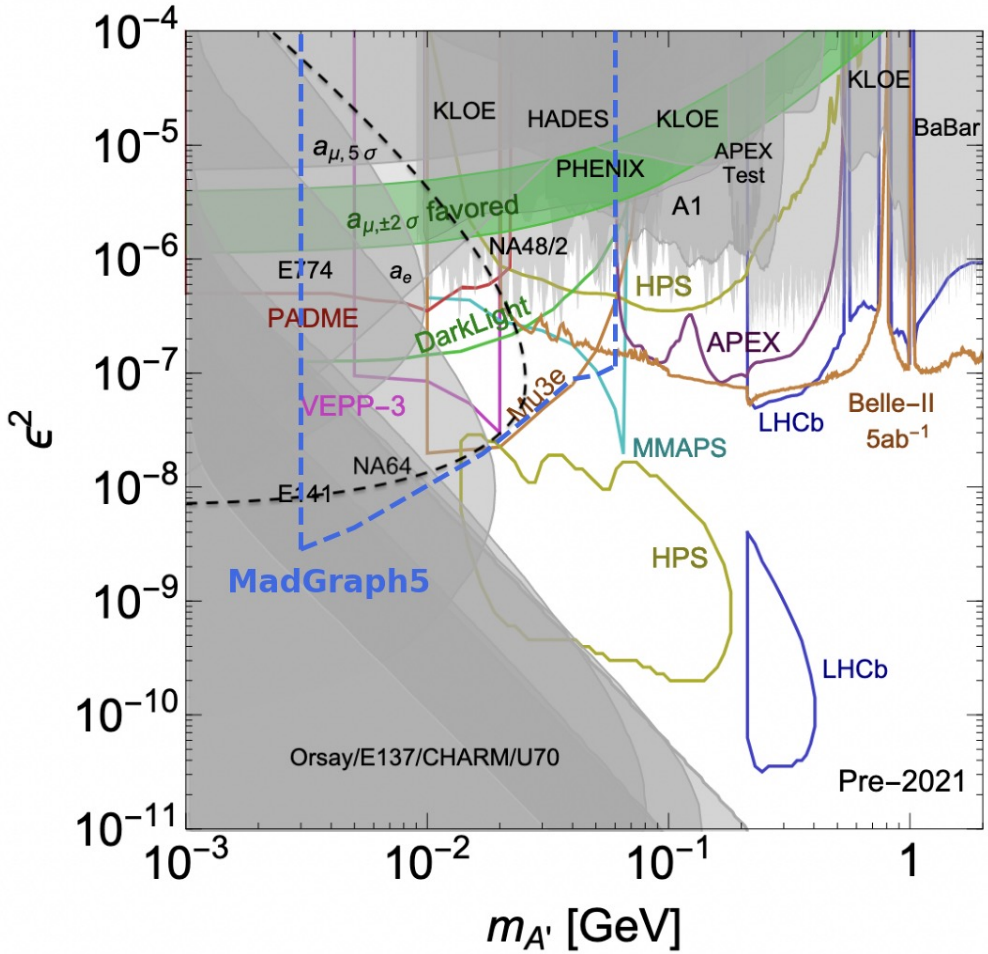
Fig. 1 Production of A' and subsequent semi-visible decay chain of a Dark Photon, $e^- Z \to e^- Z A'$; $A' \to \chi_1\chi_2(\chi_2 \to \chi_1 e^+ e^-)$

A Direct Detection Search for Hidden Sector New Particles in the 3-60 MeV Mass Range , X17

E12-21-003

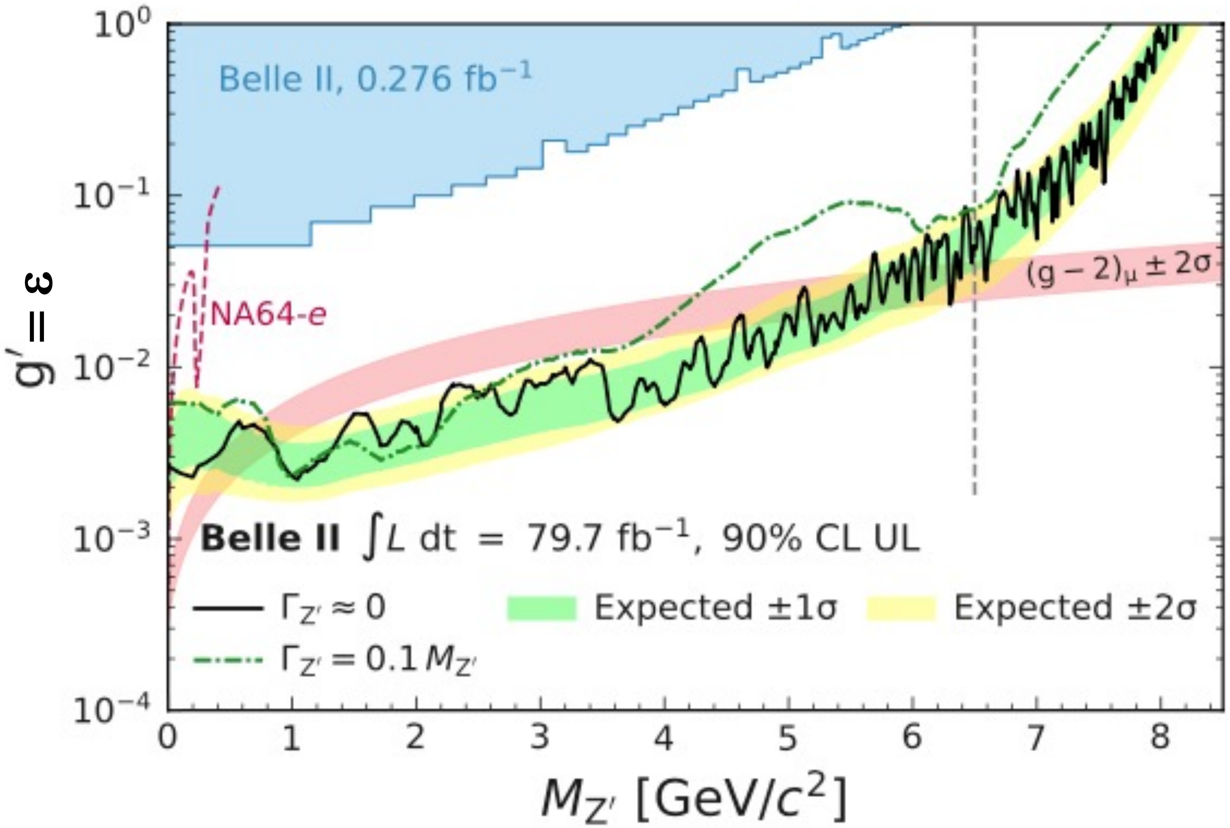
visible decay mode





Belle-II recent analysis invisible decay

arXiv:2212.03066v3   e+e- --> $\gamma *$ + Z' with invisible decay of Z'



Good mass resolution for $m_{Z'} < 0.1$ GeV is hard to get

Very recent summary of the A' experiments

https://indico.ijclab.in2p3.fr/event/10641/contributions/
35523/attachments/24178/35270/Achenbach-HP2030-2024.pdf

Multi-GeV, Multi-μA, not-CERN Lepton Beams

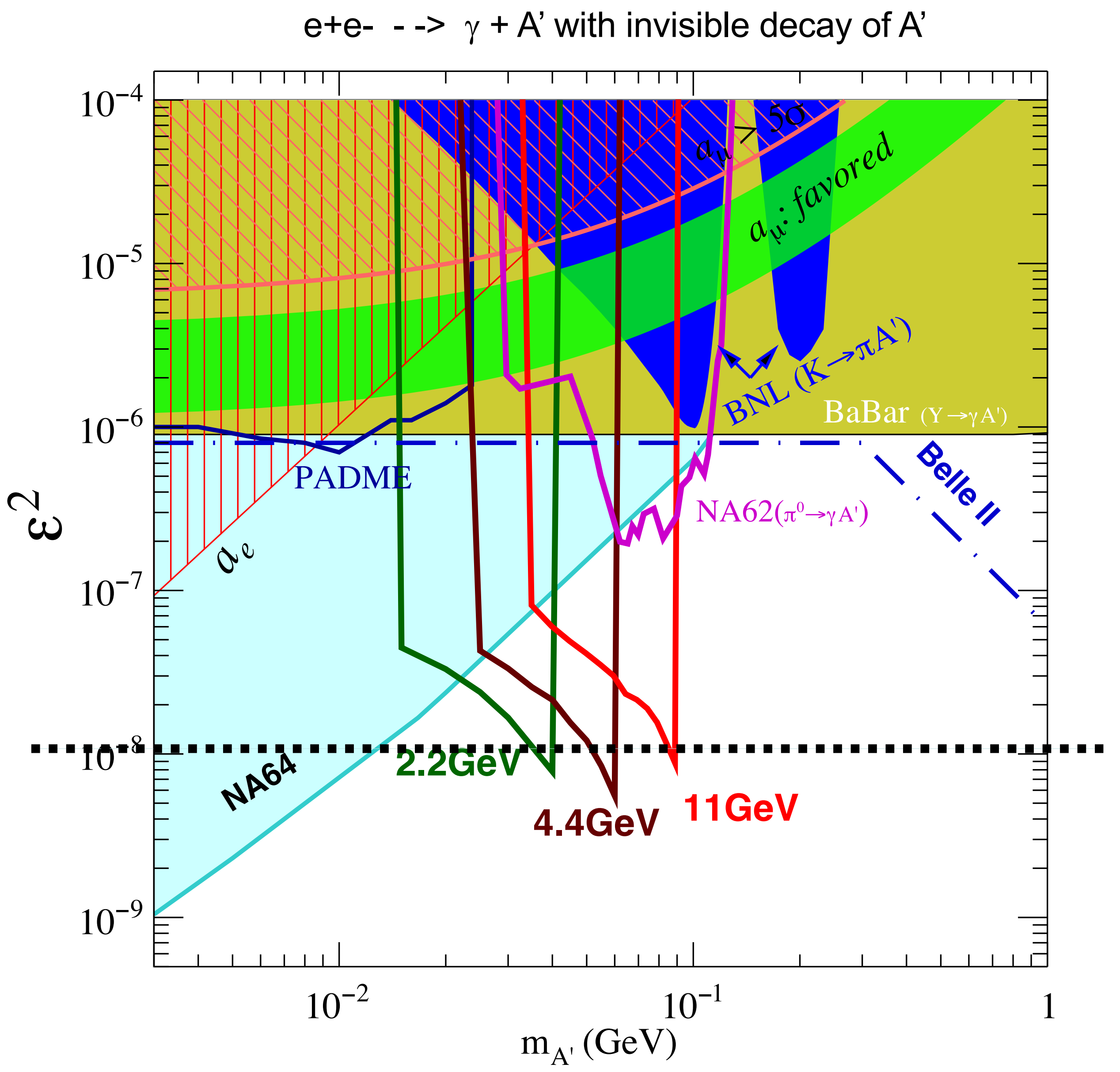
Experiments…	***Beams…***
Recent:	
▪ APEX (completed)	e- at Jefferson Lab
▪ A1 (completed)	e- at MAMI
▪ BDX-Mini (completed)	e- at Jefferson Lab
▪ HPS (part. completed)	.
▪ PADME (running)	e+ at Frascati
Near Future:	
▪ X17 Search (cond. scheduled)	e- at Jefferson Lab
▪ More HPS (to be scheduled)	.
▪ BDX (potentially)	.
▪ MAGIX (under construction)	e- at MESA
▪ DarkMESA (under preparation)	.
Far Future:	
▪ A' Search with positrons (C1)	e+ at Jefferson Lab
▪ LDMX-like (under preparation)	e- at ELSA
▪ LDMX (under preparation)	e- at SLAC
… and more	

I will focus on what I am a little more familiar with

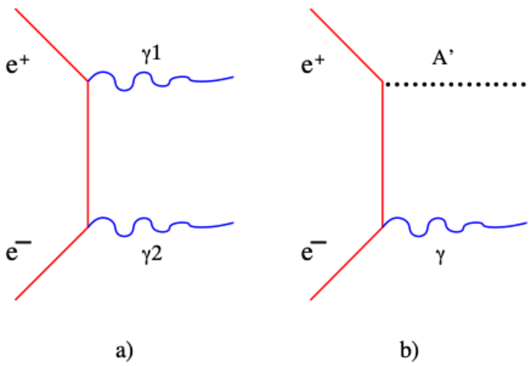
Dark Matter and Dark Sector Searches with High-Intensity Lepton Beams

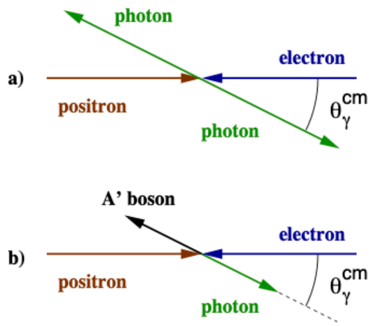
Oct. 2o24
P Achenbach, JLab

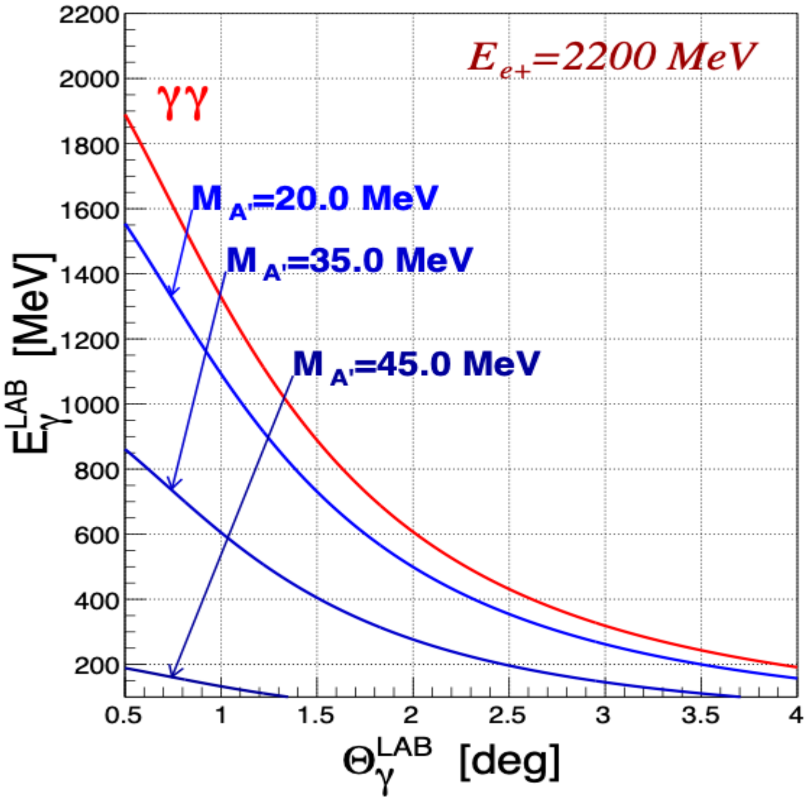
Current summary of A' invisible decay



The experimental method



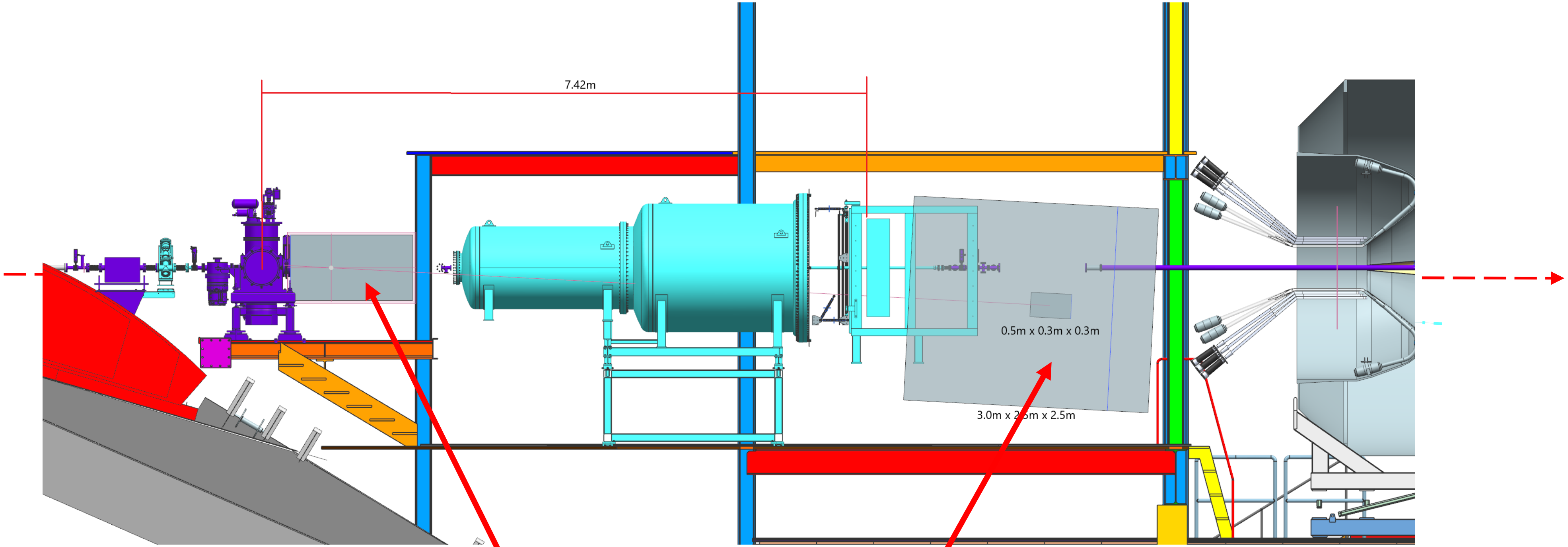


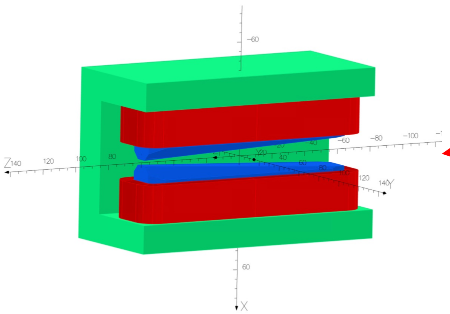


- A positron beam on a hydrogen target (e^+e^- annihilation)
- Selection of tone-photon final state events
- Search for a bump in the missing mass spectrum
- Connection between A' and dark matter is not essential for the proposed study

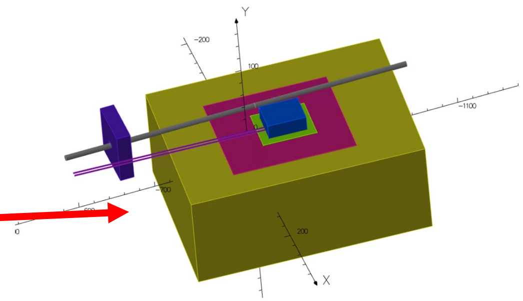
$$M_{A'}^2 = 2m_e^2 + 2m_e * (E_+ - E_\gamma) - 4E_+ * E_\gamma * \sin^2(\frac{\theta_\gamma}{2})$$

Layout of the experiment in Hall B

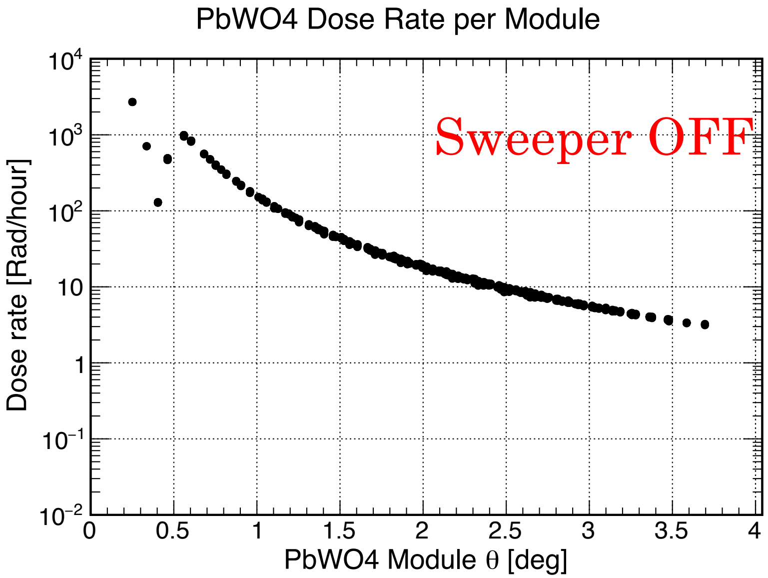


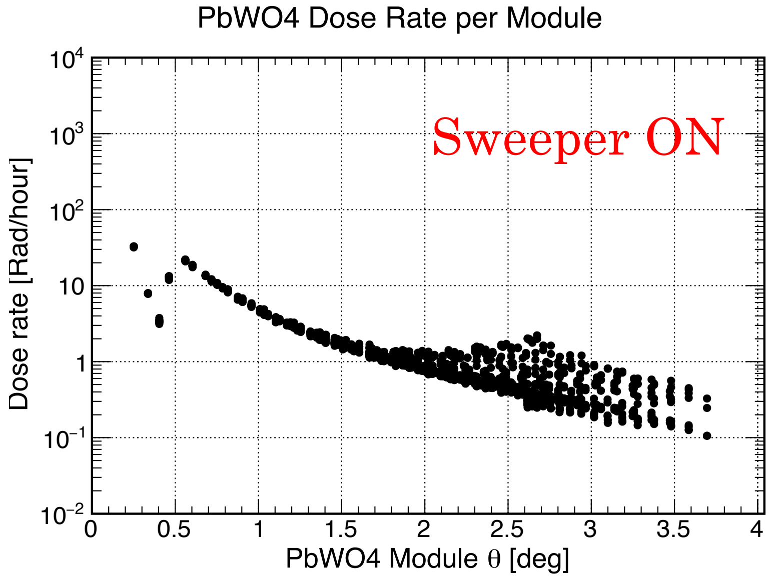


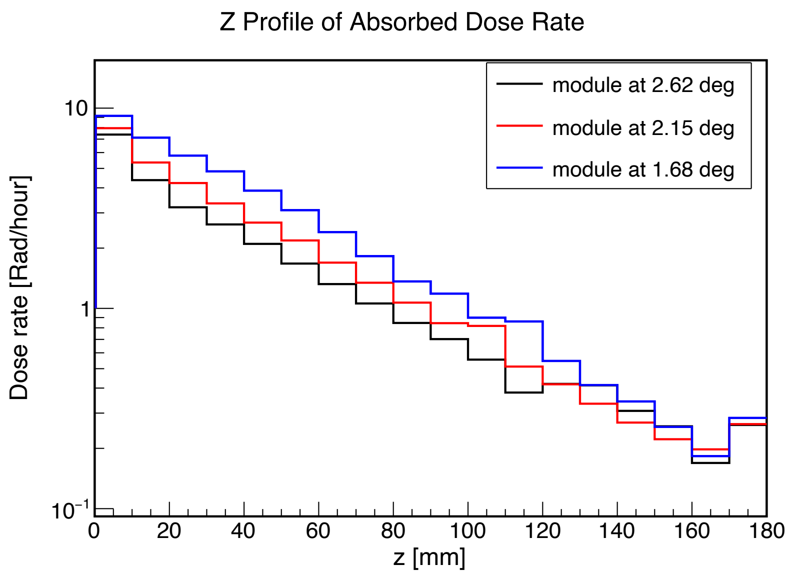
- NEW for PAC52 –
  - Geant4-based MC
  - sweeper
  - dump
- 50 nA positron beam on 5 cm long LH2
- High resolution part of PRIMEX HyCal calorimeter
- fADC - based DAQ with programmable trigger, 20 MHz

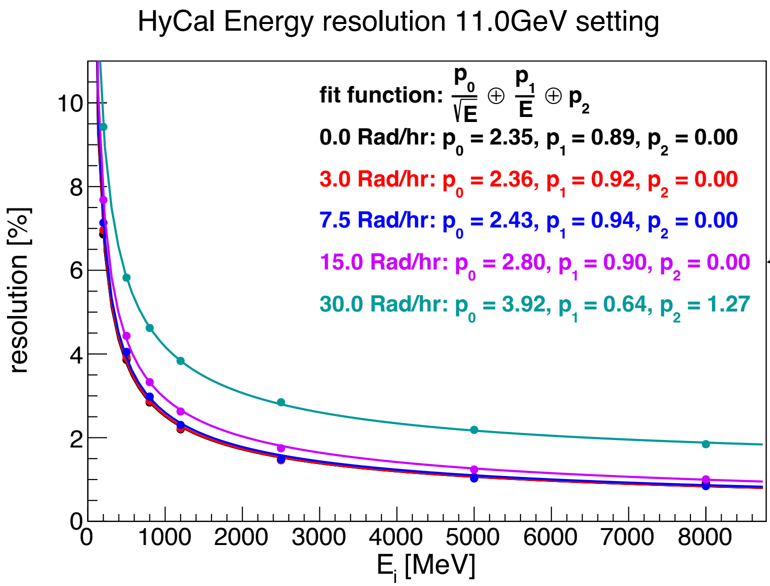


Calorimeter radiation load and resolution



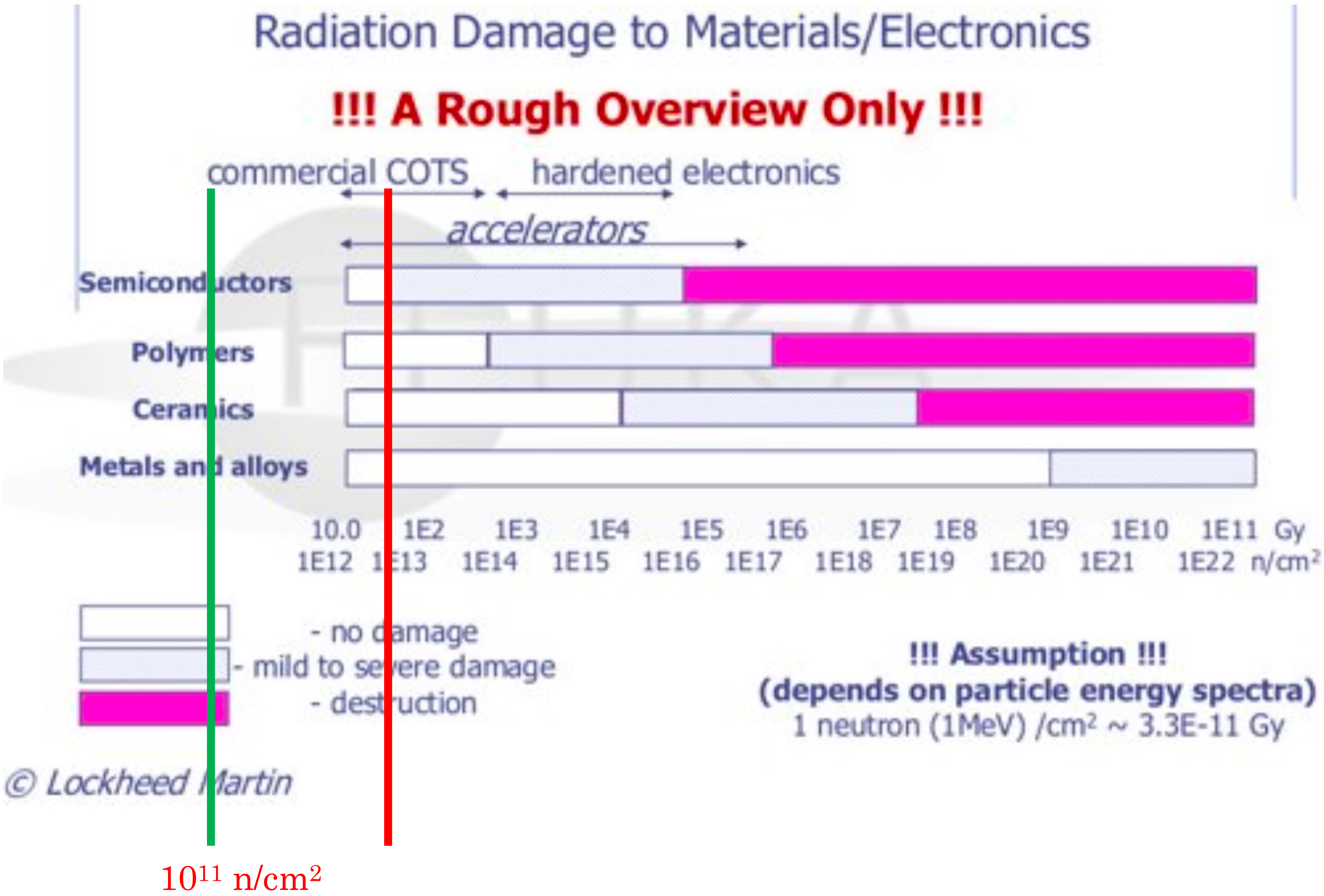






11 GeV
15 days

Neutron radiation impact



Typical neutron radiation in Hall B

Another estimate was made by using a calculation made for the recent experiment, see Fig. 35. The fluence at the entrance of the solenoid was found to be close to 3×10^9 n/cm^2, so at a distance

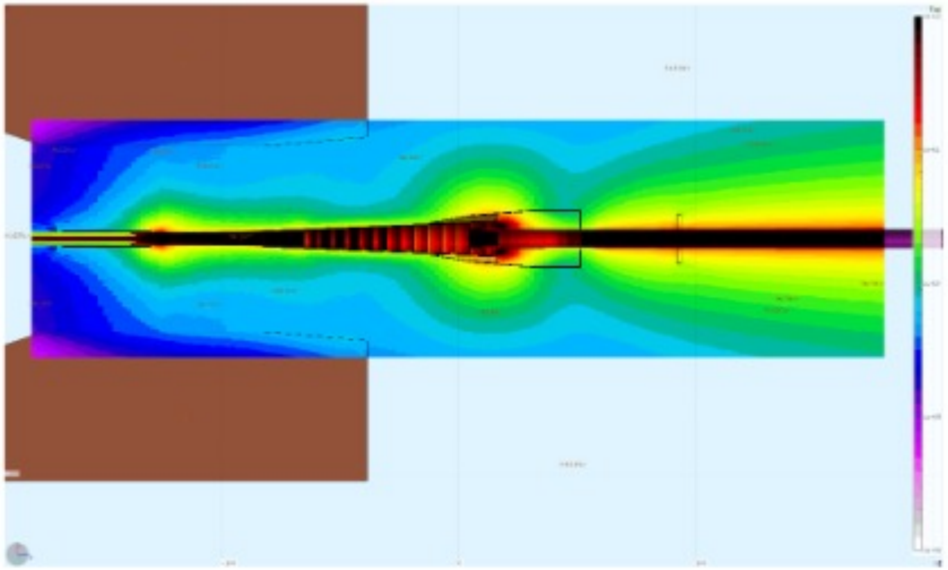


FIG. 35. Neutron dose after the recent experiment in Hall B according to calculations by L. Zana.

of 5 meters the estimated level is $10^7 - 10^8$ n/cm^2. The upper value (10^8 n/cm^2) is 2000 times below the value reported in Ref. [67].

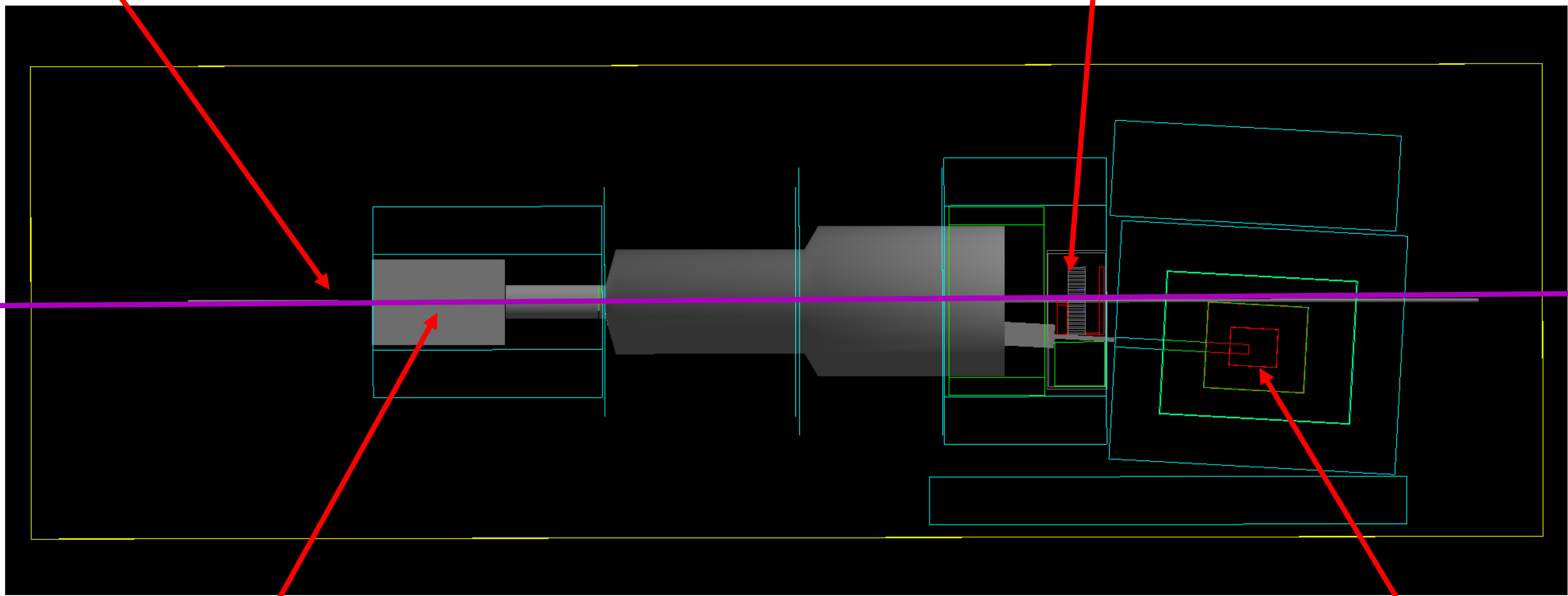
Using the value 10^8 n/cm^2 as a benchmark, we come to the first level of design/calculation of the beam dump for the proposed experiment, see Figs. 18 and 32.

Geant4 model of A’ experiment

5 cm LH2 target

Detector

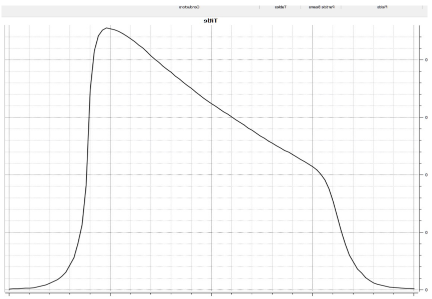
Beam
50 nA



Sweeper, Bdl ~ 2 T-m

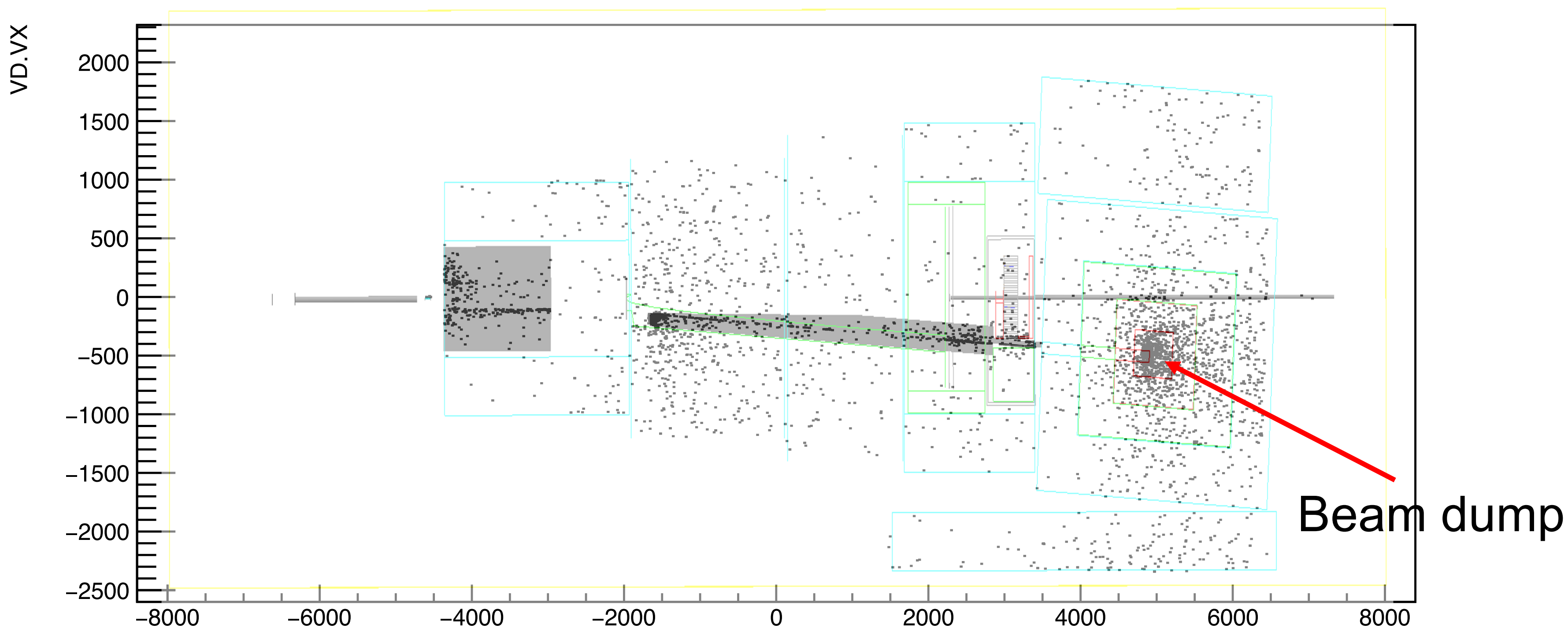
Beam dump
power < 550 W

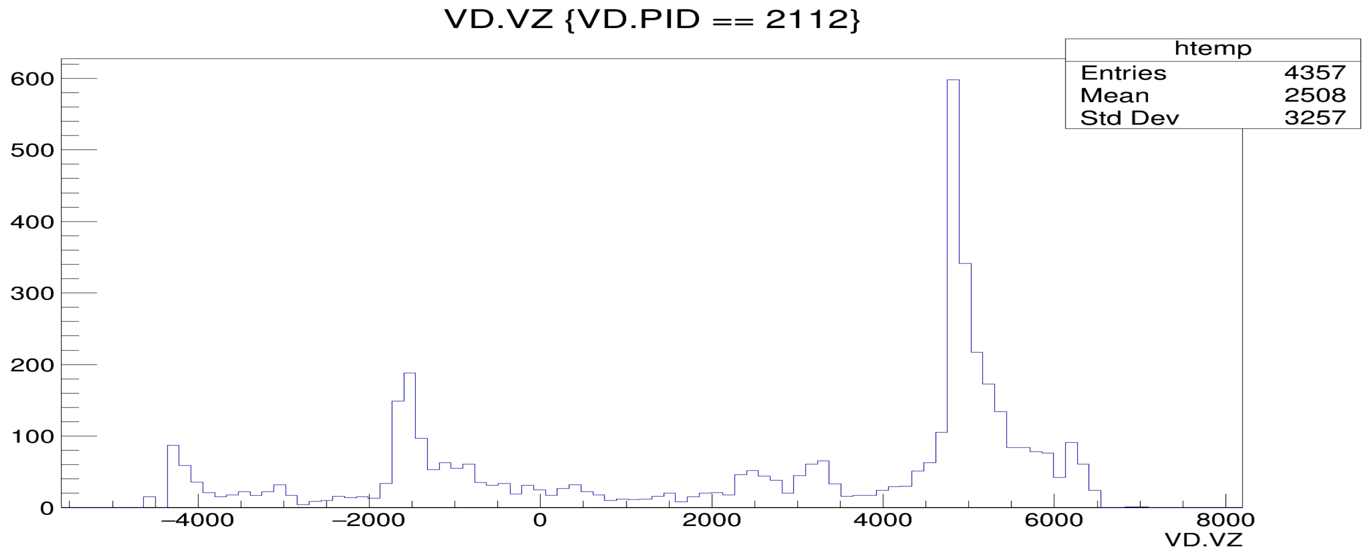
B



z

Neutron sources locations





Neutron radiation expectation

The Geant4-based radiation analysis was found to be consistent with the FLUKA-based calculation performed by the Radcon group (Fig. 36). At a distance of 5 m, after an 11-GeV 50-nA 15-day run, the dose is below 0.7×10^8 n/cm^2, so it is below the benchmark level. Additional contributions from 2.2 and 4.4 GeV runs will increase the budget to 0.9×10^8 n/cm^2.

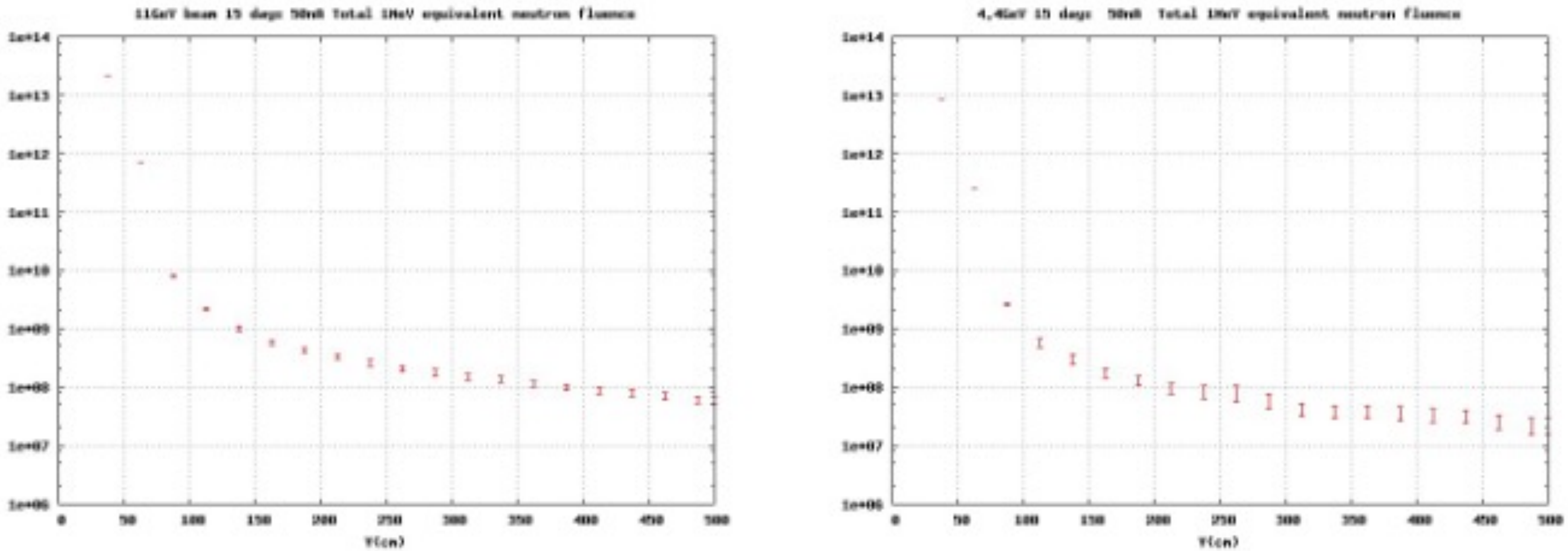
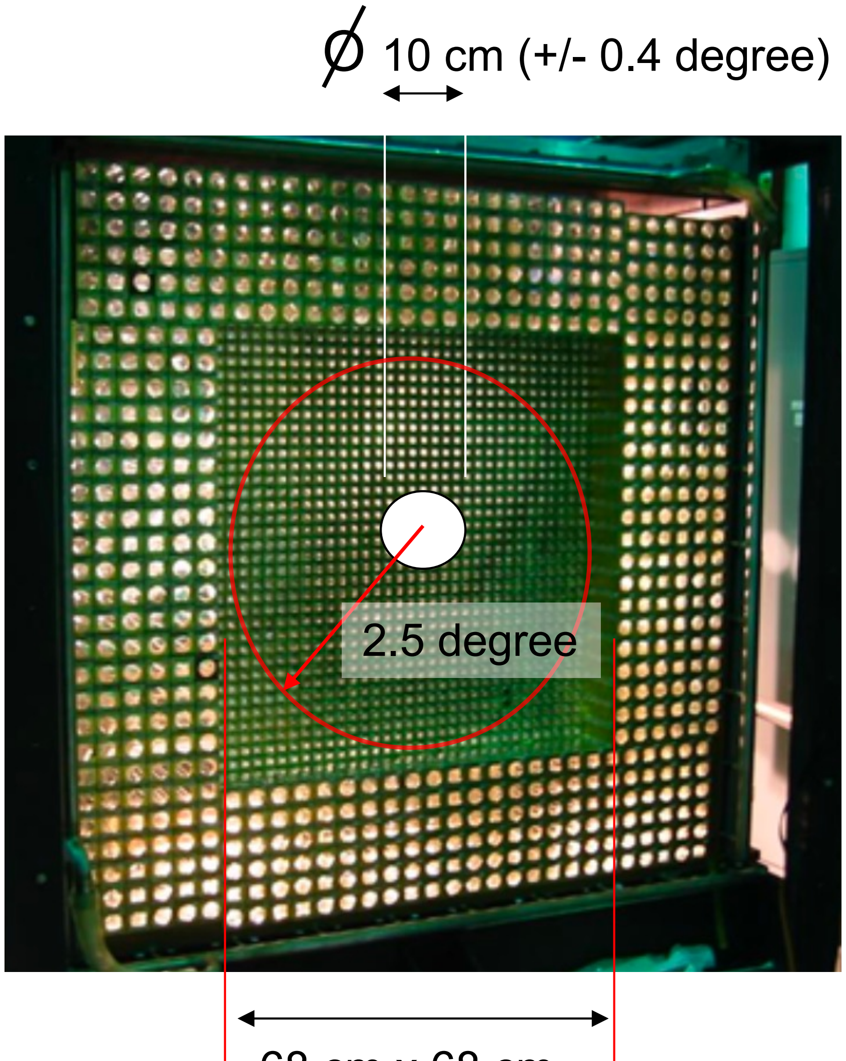
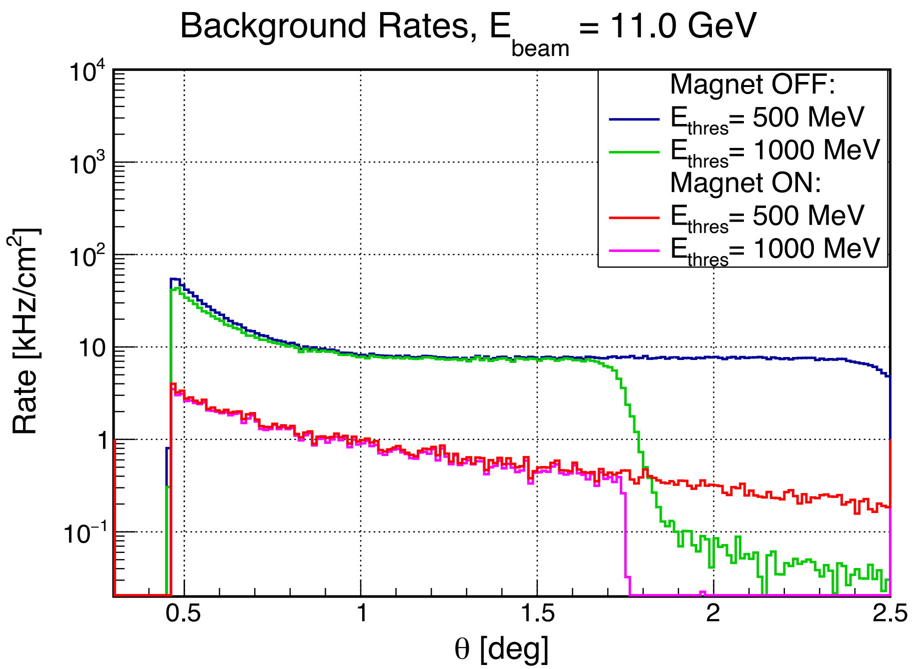


FIG. 36. Neutron radiation dose around the local beam dump vs. distance from dump center according to L. Zana in 4.4 GeV and 11 GeV parts of this experiment.

The value (10^8 n/cm^2) is 2000 times below the value recommended in the published studies of the radiation impact on the electronics.

Expected rate in the calorimeter

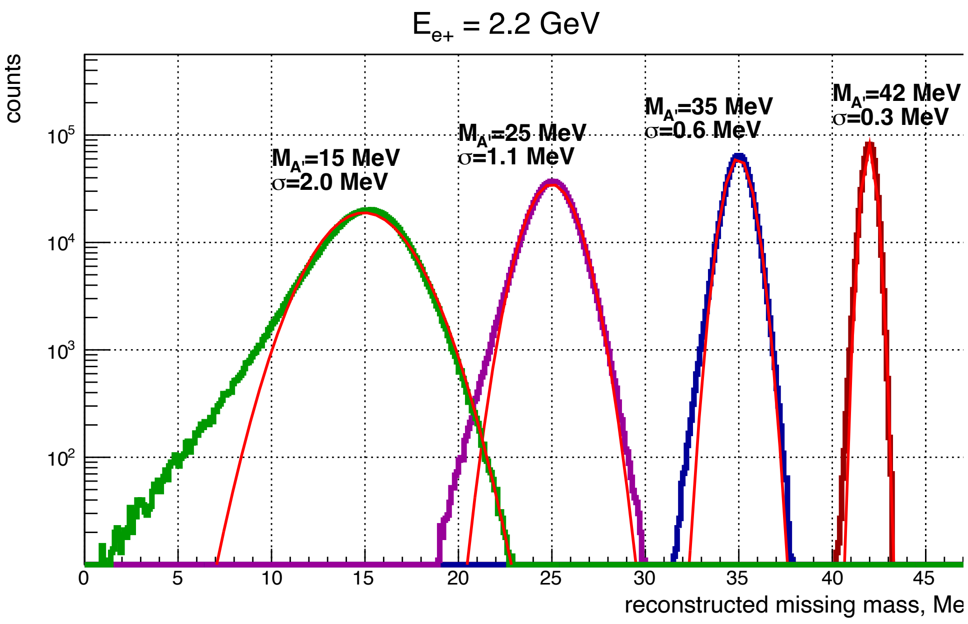


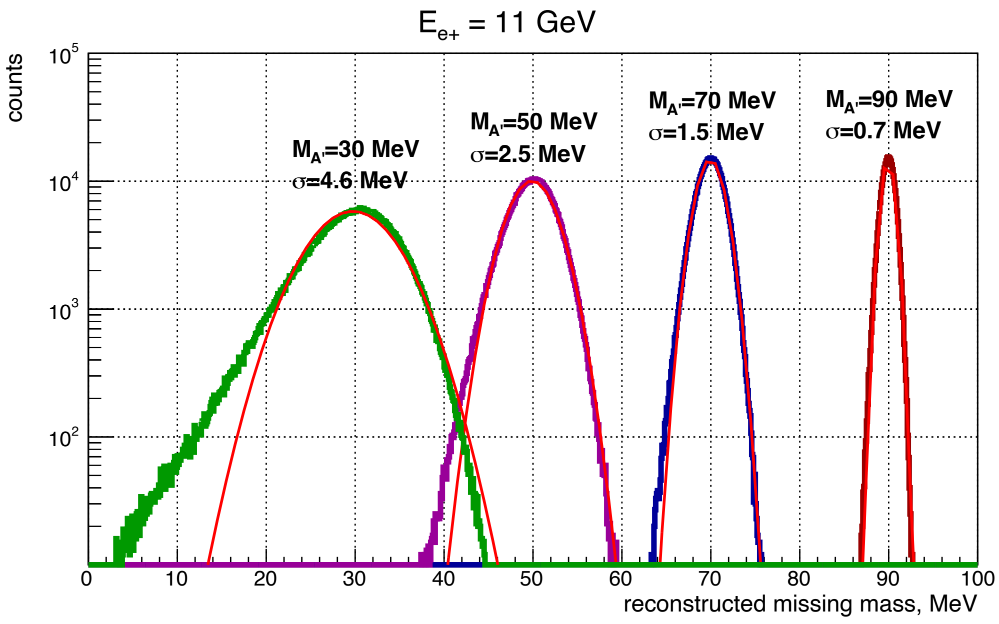


Mass resolution

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

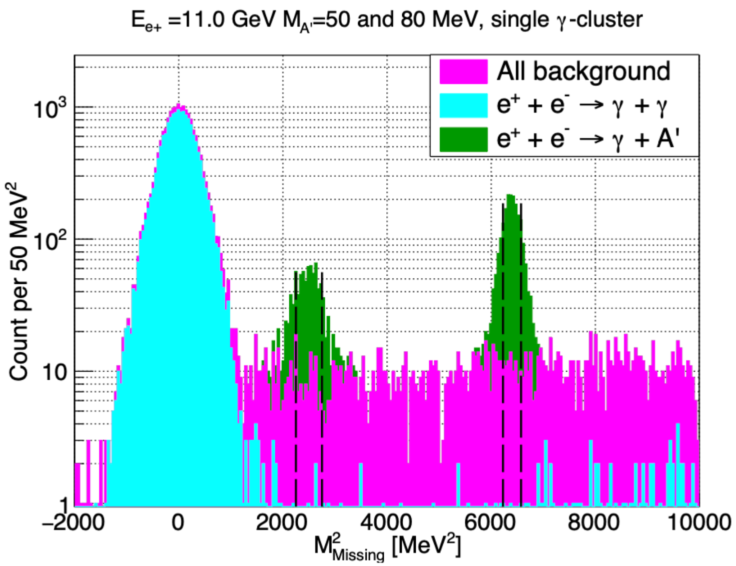
TABLE I. Statistics for $E_{e+} = 11$ GeV, $\mathcal{L} = 7 \times 10^{34} cm^{-2}/s$, 15 days, $E_\gamma > 0.5$ GeV, $\theta = 0.5^\circ - 2.5^\circ$, $\epsilon^2 = 1 \times 10^{-7}$.

Whole M_{miss} acceptance, Total rate [Hz]

	Physics MC	Geant4-based MC
Sweeper OFF	1.9e+07	2.6e+07
Sweeper ON	1.8e+06	1.5e+06
Single γ-cluster	1.3e+06	1.4e+06

in the interval $M_{miss} = 80 \pm 1\sigma$, Events in 15 days

	Background	A'	$Signal/\sqrt{Background}$
Sweeper OFF	4.3e+10	1.3e+06	6.1 (resol. corrected)
Sweeper ON	1.1e+10	1.3e+06	11.9
Single γ-cluster	0.9e+10	1.3e+06	13.2



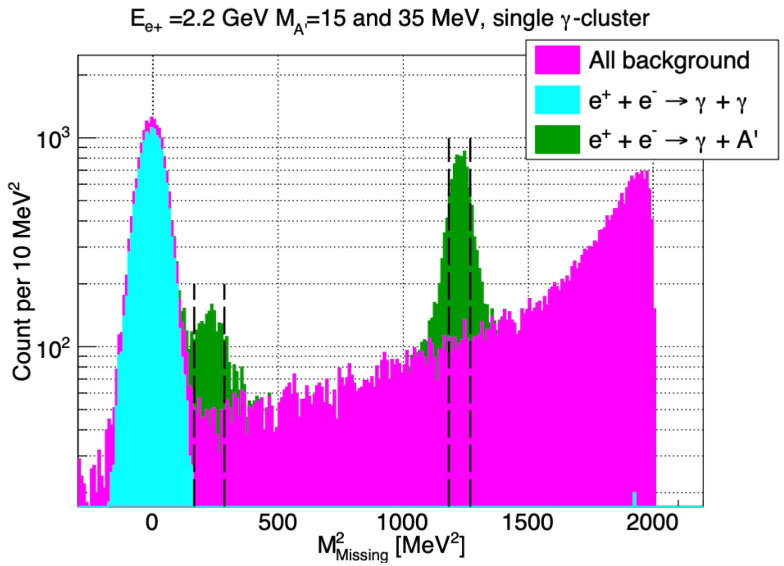
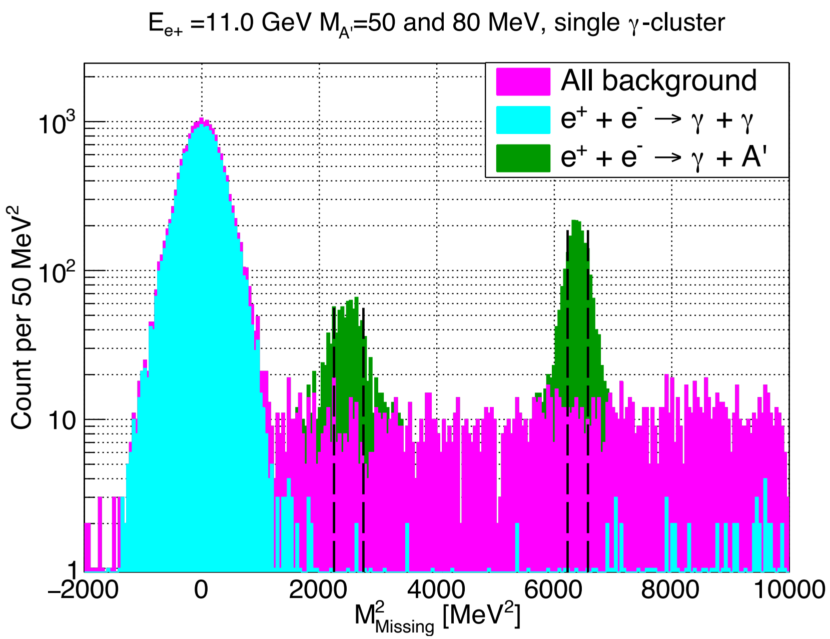
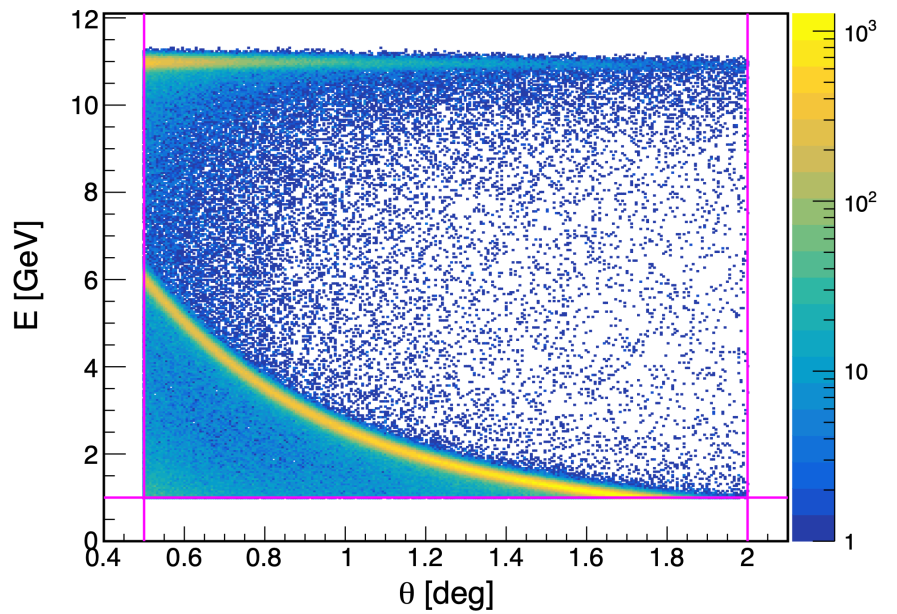


FIG. 16. Results of the Monte Carlo simulation for the missing mass distribution. The mixing constant is taken to be $\epsilon^2 = 10^{-2}$ to simplify visualization on the plot. Left – for $E_{e+} = 11$ GeV beam energy, $M_{A'} = 50$ and $M_{A'} = 80$ MeV. Right – for $E_{e+} = 2.2$ GeV beam energy, $M_{A'} = 15$ and $M_{A'} = 35$ MeV. Vertical dashed lines indicate the width of a sliding search window ($\pm 1\sigma_{M^2}$). Each spectrum corresponds to data taking for 13 milli seconds with a luminosity of 7×10^{34} cm^{-2}s^{-1}.

Detector non-uniformity estimation-I



13 milli seconds with a luminosity of 7×10^{34} cm^{-2}s^{-1}.



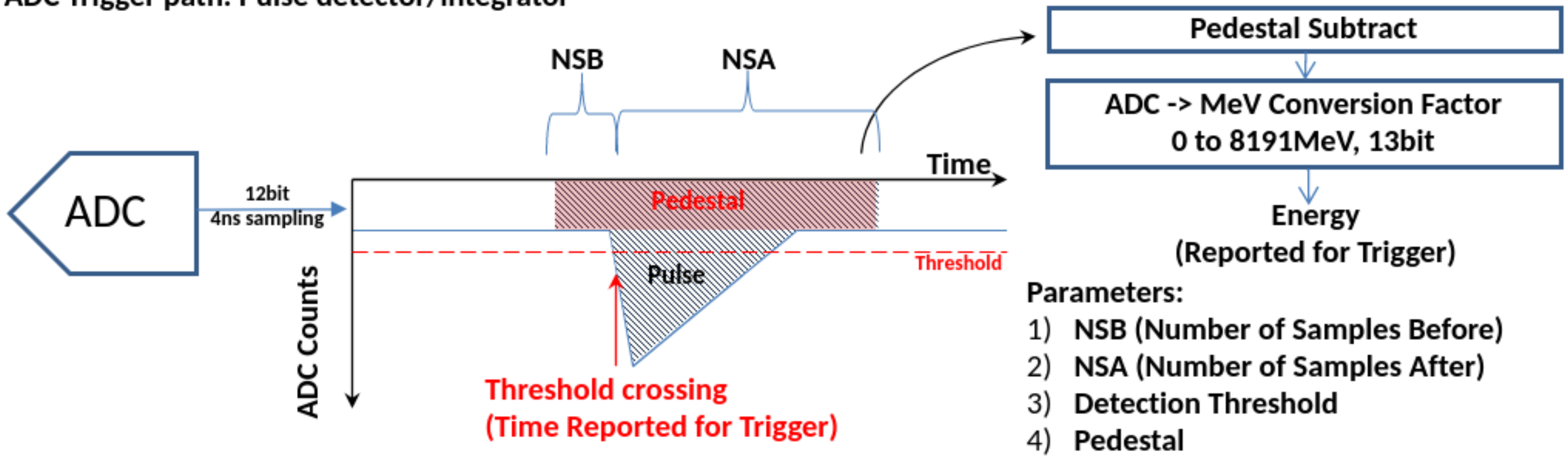
$$M^2_{A'} = 2m_e^2 + 2m_e * (E_+ - E_\gamma) - 4E_+ * E_\gamma * \sin^2(\frac{\theta_\gamma}{2})$$

Mass spectrum quality contributions:

- Photon angle, θ - calibrated using GEM chamber with 1x10^{-6} radian steps
- Detector efficiency - calibrated using e^+-e^- rate and the photon angle, 10^{-6}
- Photon energy - calibrated using e^+-p and e^+-e^- elastic locus/band and θ

High rate capability DAQ

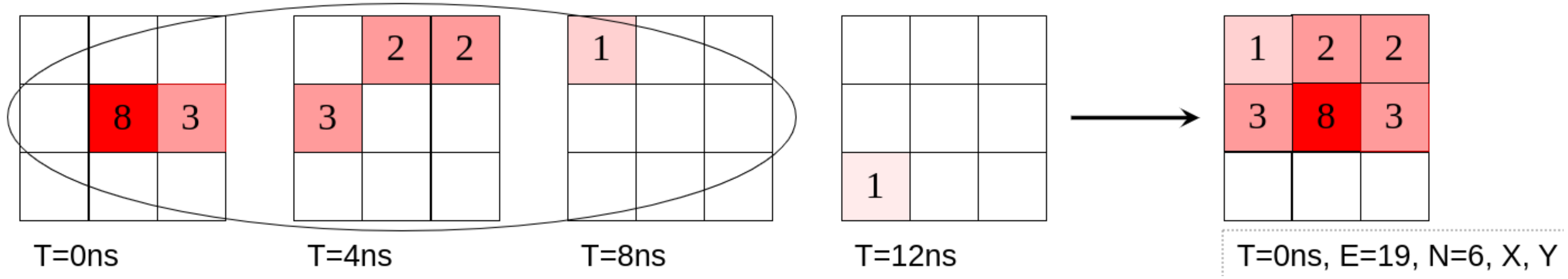
FADC Trigger path: Pulse detector/integrator



Parameters:

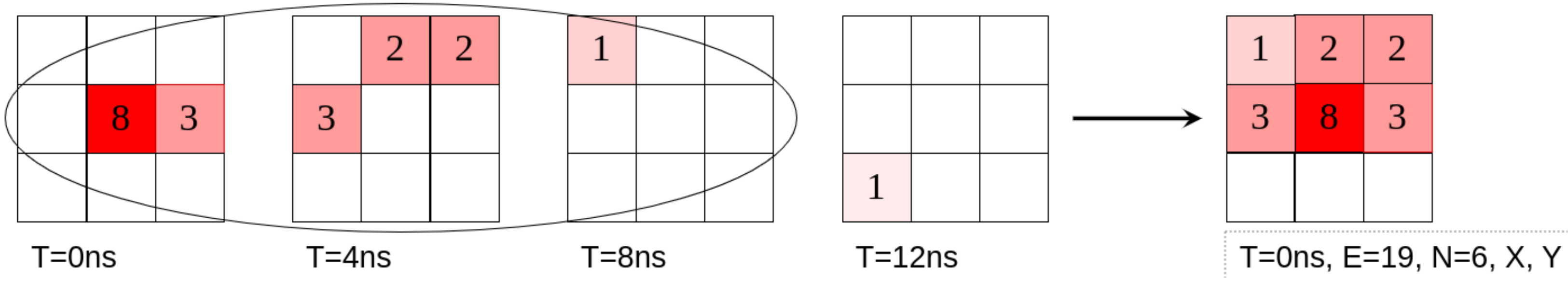
1) NSB (Number of Samples Before)
2) NSA (Number of Samples After)
3) Detection Threshold
4) Pedestal
5) Gain

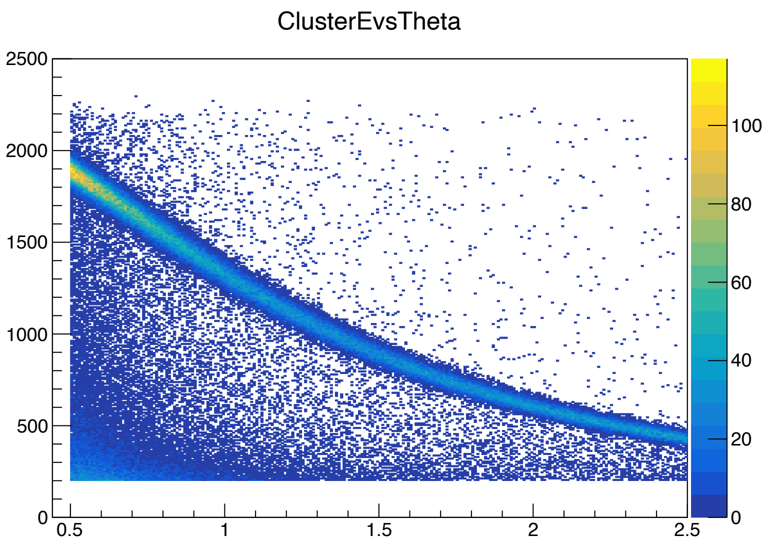
e.g. for seed threshold of 2 and hit Δt=+/-8ns, the following hit pattern evolving in time will report 1 cluster:

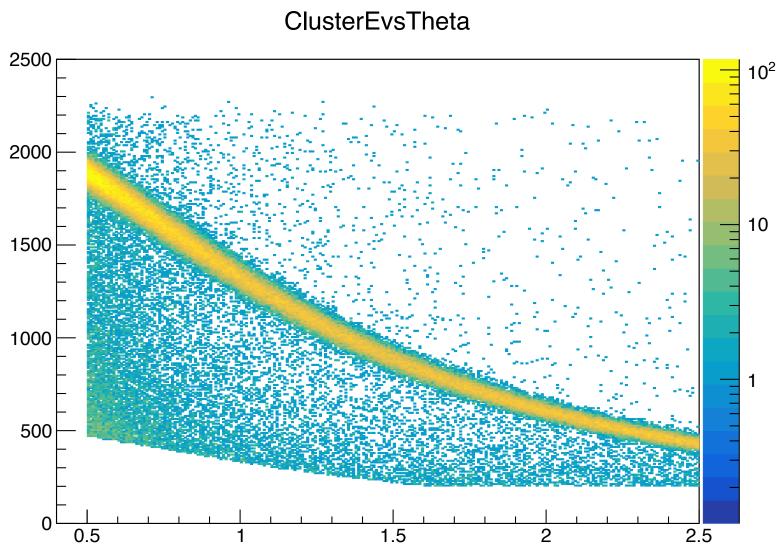


High rate capability DAQ

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







- Calculated DAQ capability for single cluster events is certainly above 20 MHz.
- Expected event rate is 1.5 MHz for 11 GeV run and 10 MHz at 2.2 GeV run.

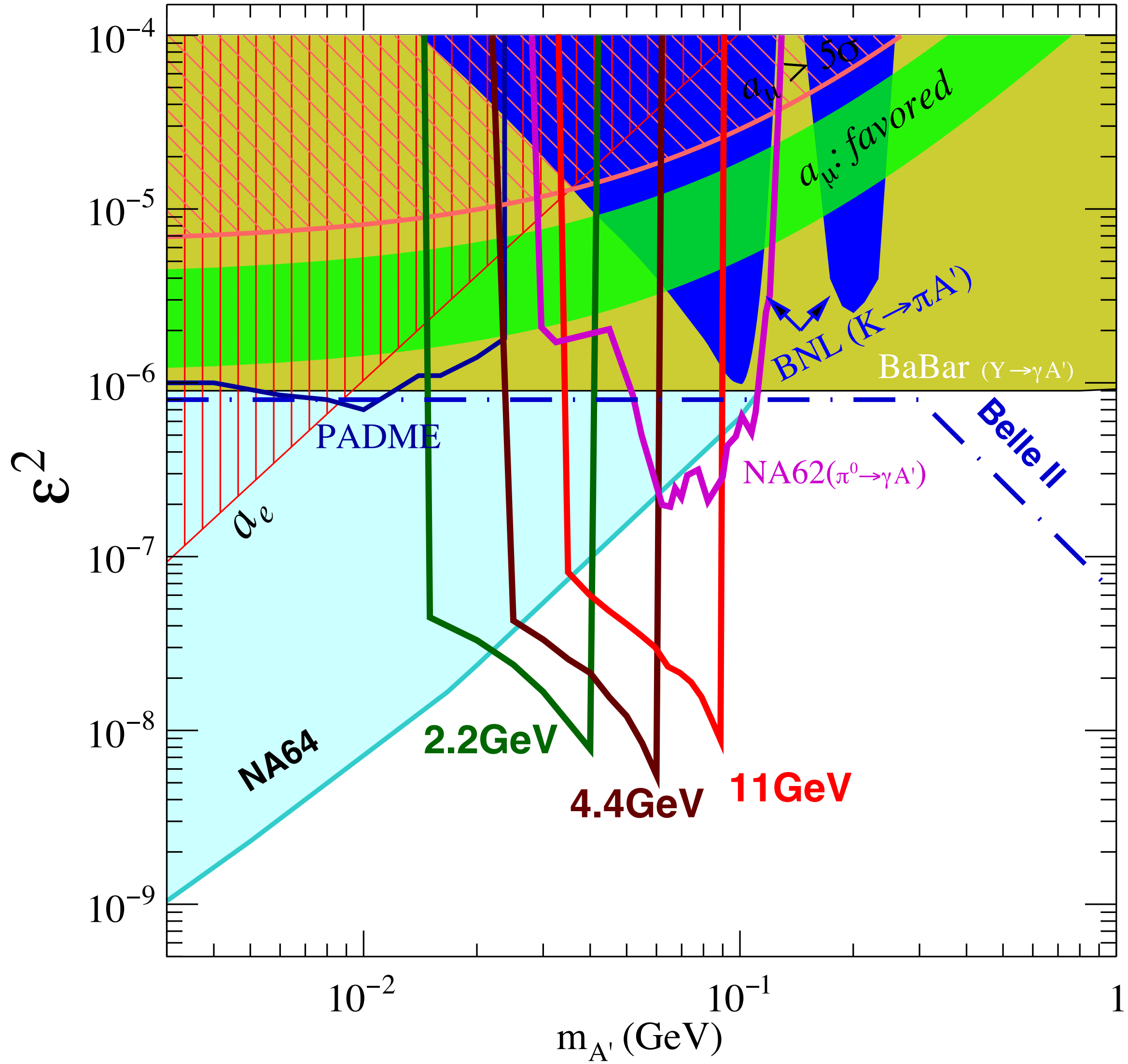
Projected sensitivity of this experiment

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_μ-2)

2. Good mass resolution allows us to make a productive search for a signal with a 55-day run in mass range 15-90 MeV.

two-sigma level limit



Summary

1. We propose a search for the A'-boson in the process of e+e- annihilation using the upcoming JLab positron beam.

2. This experiment will be sensitive to the A' coupling constant ε^2 on the level of $2x10^{-8}$ in the 15-90 MeV mass range.

3. The experiment will be based on the existing PRAD experimental setup in Hall B. Required beam line development is well understood.

4. Experiment approved for 55 days of beam time.