A Dark Photon Search with a JLab positron beam

Bogdan Wojtsekhowski

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".
This experiment has the potential to discover a dark matter particle and
has a unique feature: The search sensitivity has no impact from the uncertainty
in the boson decay mode and branching value.
The proposed search for a narrow peak in the missing mass spectrum will
allow us to find or put an upper limit on the new particle coupling with
normal matter (electron/positron).
The projected statistical sensitivity for the reduced coupling constant
f2/e2 reaches 2×10^{-8} with 55 days of run at a positron beam current of 50 nA.
The result will be very important in dark matter parameter analysis.

PAC51 review

PR12+23-005

Scientific Rating: N/A

Recommendation: Deferred

Title: A Dark Photon Search with a JLab positron beam

Spokespersons: A. Gasparian, N. Liyanage, B. Raydo, B. Wojtsekhowski (contact)

Motivation: The proposal aims at a search for the A′-boson in the mass range from 15 to 90 MeV using the missing mass method. The A′-boson is the kinetically mixed dark photon. Knowledge of the A' boson mass and its coupling to an electron (or an upper limit on this coupling) is of large interest to the dark matter research field. The proposed sensitivity might allow the collaboration to resolve the question whether there is a connection between the hypothetical X17 particle and the A'-boson.

Measurement and Feasibility: The proposed experiment is to be carried out in Hall B using detectors and equipment that have been employed with success in the PRAD experiment E12-11-106. A positron beam with energies of 2.2, 4.4 and 11 GeV and a current of 50 nA will impinge on the atomic electrons of the target material. The signal process is $e^+ e^- \rightarrow \gamma A'$ and the main background comes from $e^+ e^- \rightarrow \gamma \gamma$. The experiment will detect a single photon and search for the A' in the missing mass spectrum.

Issues: While some physics background has been simulated for the proposal, the committee feels that a full Geant4 simulation of the measurement is needed to assess the sensitivity of the experiment. This should include a study of how the foreseen veto will exclude possible signal events. In addition, a more detailed discussion of the reach in comparison to competing experiments is needed.

Summary: The PAC finds that the proposal presents an exciting and important search experiment. It encourages the proponents to resubmit this proposal after addressing the issues noted above.

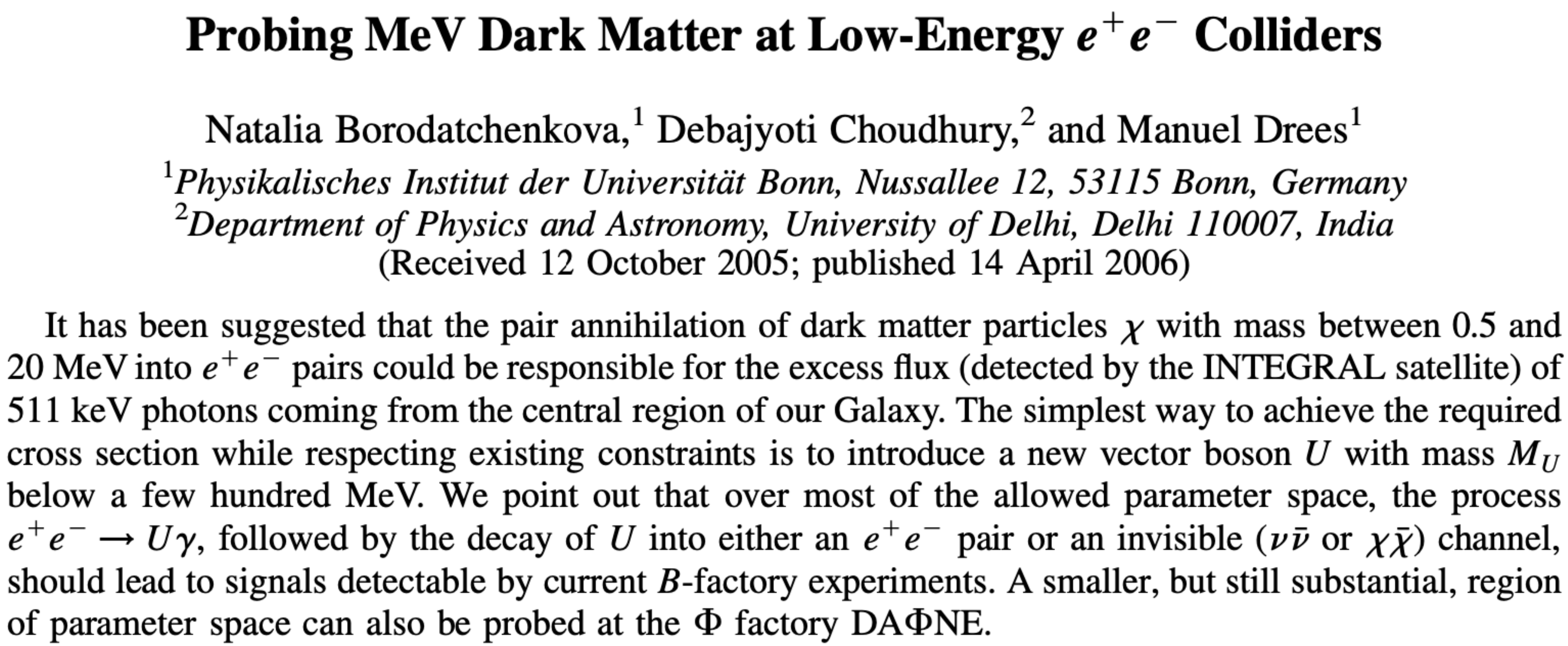
A dark photon search with JLab positron beam

Positron A' collaboration

P.Achenbach, B.Raydo, B.Wojtsekhowski, 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, A. Ahmidouch,
N.Liyanage, A.Ahmed, X.Bai, G.Cates, H.Nguyen, V.Nelyubin,
W.Xiong,
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



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

Natalia Borodatchenkova,[1] Debajyoti Choudhury,[2] and Manuel Drees[1]

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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.

A dark photon search with JLab positron beam

NASA Finds Direct Proof of Dark Matter

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.

Search of U boson in electron-positron annihilation in flight

B. Wojtsekhowski, P. Degtiarenko, A. Freyberger, L. Merminga
Thomas Jefferson National Accelerator Facility, Newport News, VA 23606

2006 tech note

Abstract

An experiment is proposed to search for a new gauge boson U in reaction $e^+e^- \rightarrow U\gamma$ 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.

The configuration of FEL allows for an alternative scheme of positron production and acceleration, which is nicely use ideas of the energy recovery linac already realized at FEL. In this case the 10 mA electron beam circulated at FEL as usual will incident into the W radiator just before entering for de-acceleration, see Fig. 4. The produced positrons

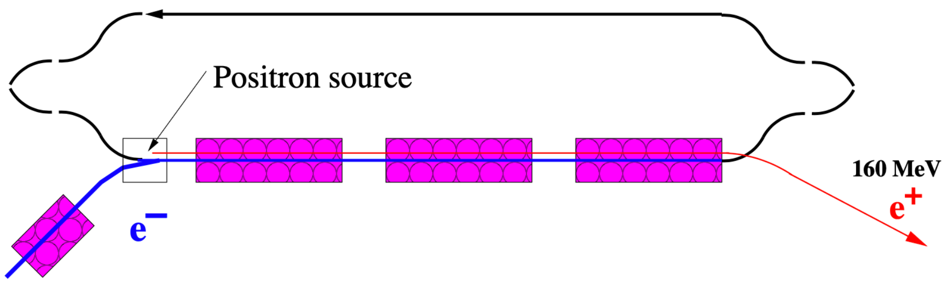


Figure 4: The layout for positron production at 160 MeV.

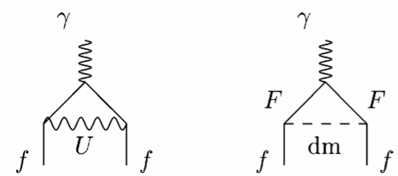
will be in correct phase to be accelerated. For the 50 μm W radiator tilted to 5.74° and 160 MeV incident electron energy the total yield of the positrons is 5×10^{-3} per incident electron. These positrons have much less angular spread than in the 10 MeV case, however

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 $U\gamma$
π,φ,ψ decays to γ + invisible

A.4. Constraints from g − 2

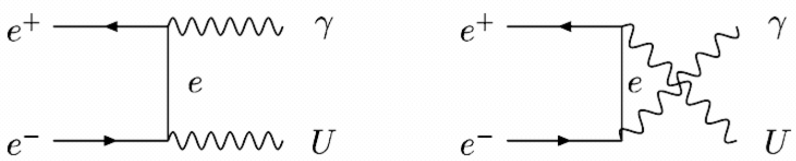


If the U boson mainly decays into dark matter, then the U production process turns out to be of the type $e^+e^- \to \gamma + \not{E}$, where $\not{E}$ is missing energy, which is of interest in experiments searching for single photon production events. But, in the case of a light dark matter candidate,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

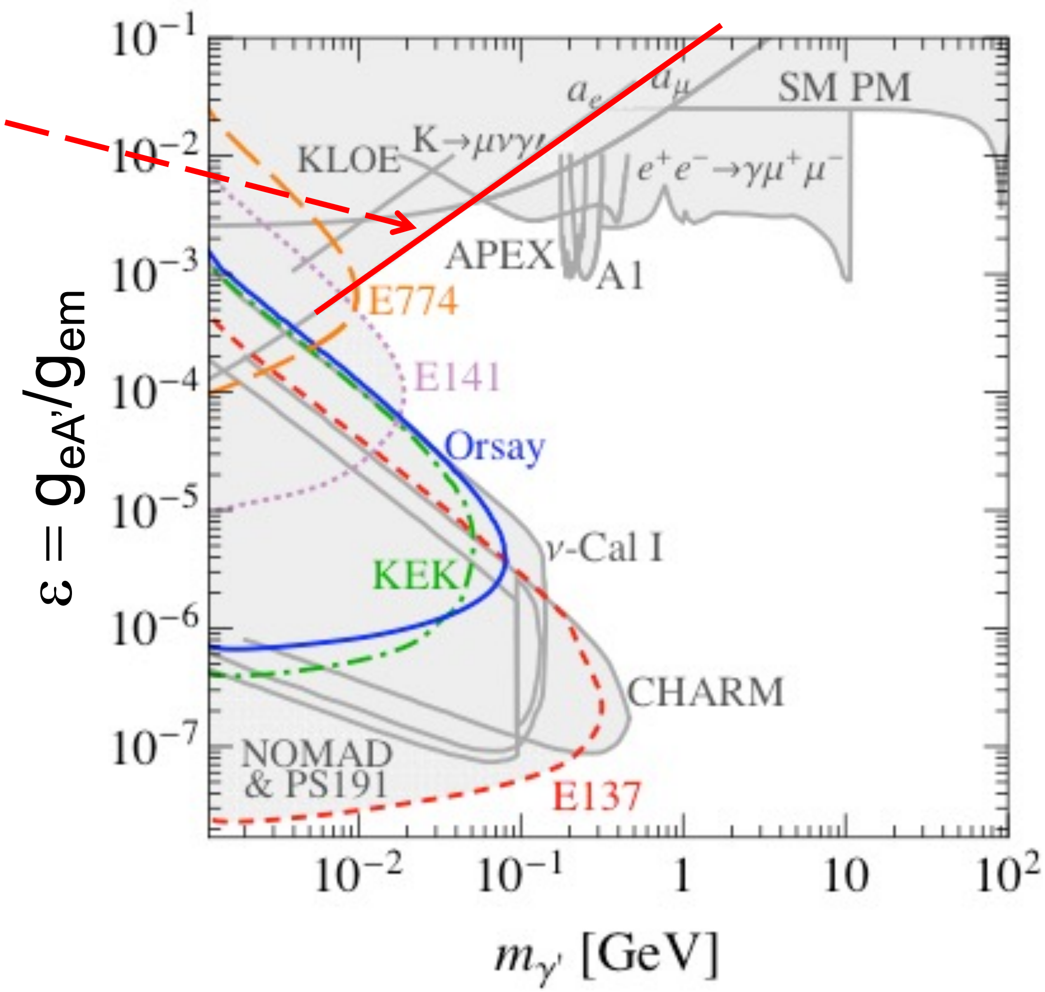


2013 summary of the searches

g-2 of muon and electron

Missing particle in e+e- to γA'

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



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

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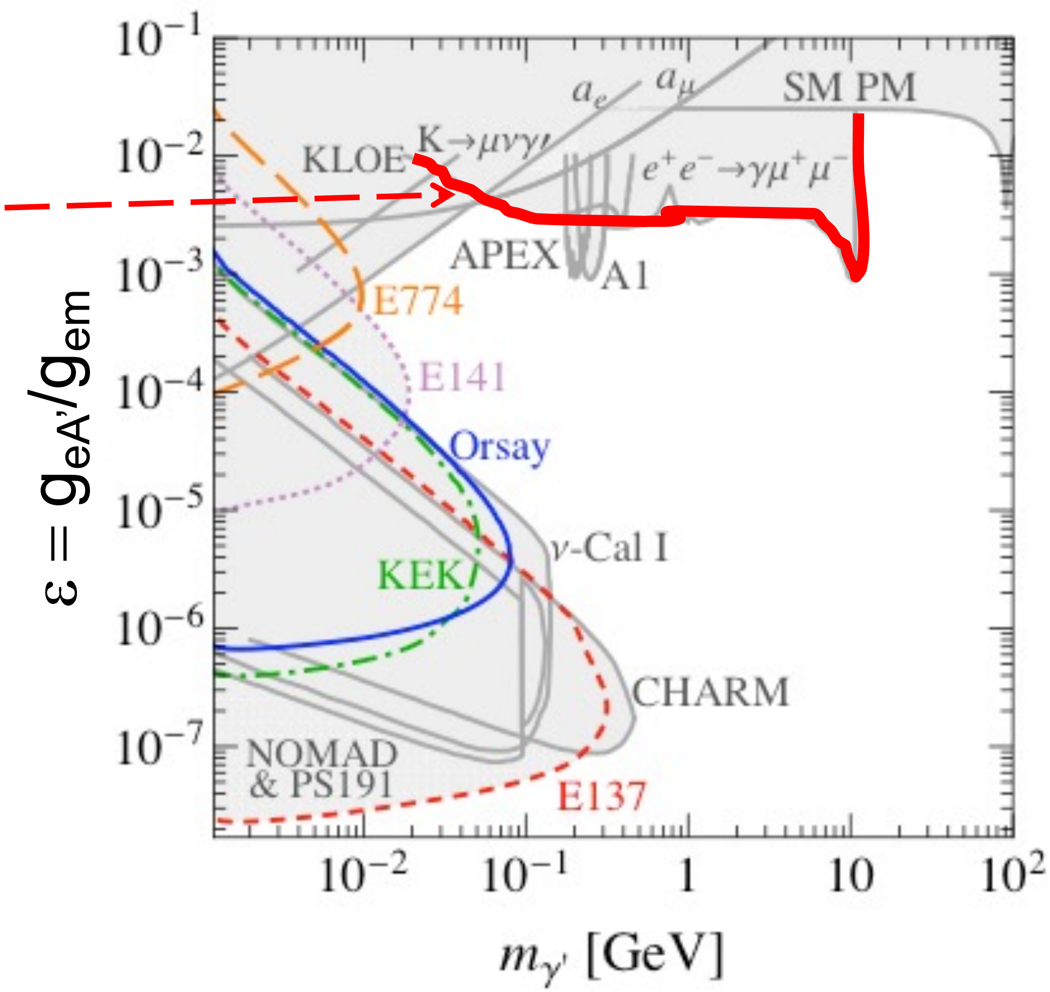


S. Andreas, C. Niebuhr, A. Ringwald, arXiv:1209.6083

From the NA64 review

arXiv:2003.07257v1 [hep-ph] 16 Mar 2020

5.1 NA64e

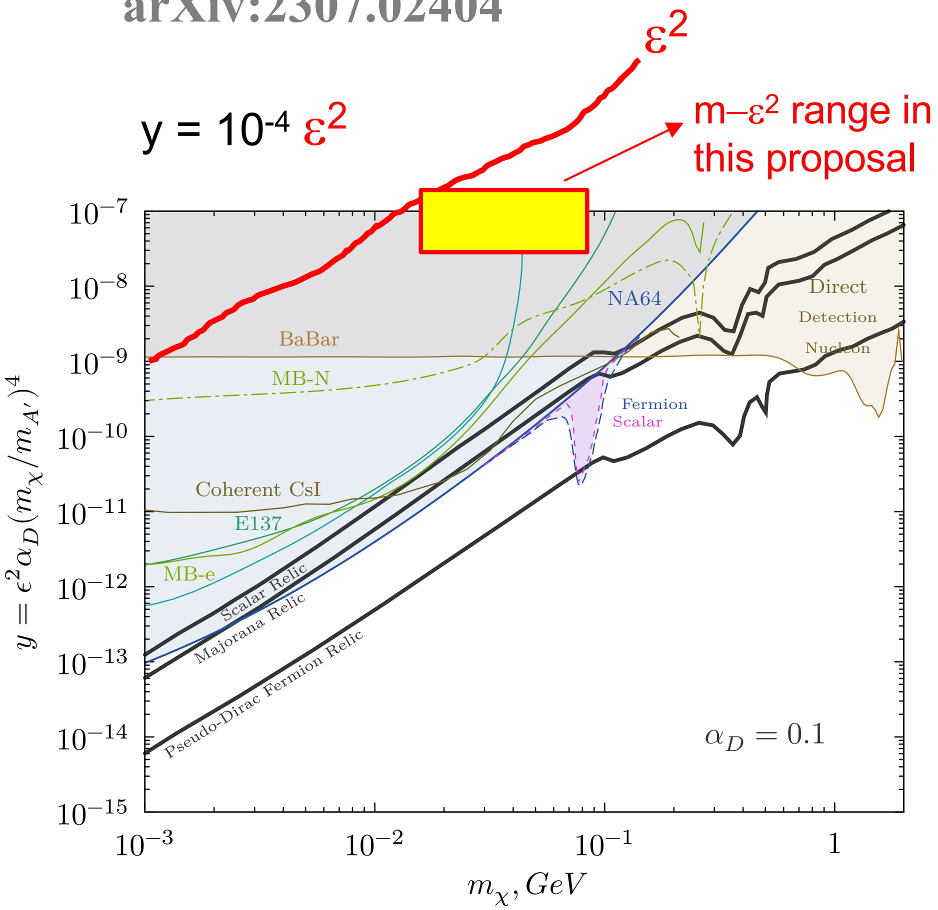
5.1.1 Invisible mode. Dark photon bounds

The NA64 collected $NEOT = 2.84 \cdot 10^{11}$ statistics in the 2016-2018 years. Recently NA64 collaboration [34] has been analyzed these data and obtained new bounds on ϵ parameter[9] by factor ~ 2.5 stronger the previous bound [32], see the upper l.h.s. panel in Fig.6. After the long shutdown (LS2) at CERN the NA64 experiment plans to accumulate $NEOT \gtrsim 5 \times 10^{12}$. The NA64e future expected limits on mixing strength ϵ after the LS2 period assuming the zero-background case are shown in the upper l.h.s. panel in Fig.6.

To estimate NA64 LDM discovery potential we have used the formulae of Appendix A to calculate the predicted value of ϵ^2 as a function of α_D, m_χ and $m_{A'}$ in the assumption that in the early Universe LDM was in thermo equilibrium. We used the values $\alpha_D = 0.02,\ 0.05,\ 0.1$ and $\frac{m_{A'}}{m_\chi} = 2.5,\ 3$. We have made the calculations for the case of scalar, Majorana and pseudo-Dirac LDM with ($\delta \ll 1$). Our results [91] are presented in Fig.6. The upper r.h.s plot and lower plots in Fig.6 show the required number of EOT for the 90% C.L. exclusion of the A' with a given mass $m_{A'}$ in the ($m_{A'}, n_{EOT} \times 10^{-12}$) plane for pseudo-Dirac with $\delta \ll 1$ (the upper r.h.s panel), Majorana (the lower l.h.s. panel), and scalar (the lower r.h.s. panel) LDM models for $\frac{m_{A'}}{m_\chi} = 2.5$ (solid), and $= 3$ (dashed), and $\alpha_D = 0.1$ (red), 0.05 (blue), and 0.02 (green). We see that NA64 experiment has already excluded scalar LDM model with $\alpha_D \le 0.1$, $\frac{m_{A'}}{m_\chi} \ge 3$ and Majorana LDM with $\alpha_D = 0.02$, $\frac{m_{A'}}{m_\chi} \ge 2.5$. As one can see from Fig.6 with $n_{EOT} = 5 \times 10^{12}$ NA64e will be able to exclude the most interesting and natural LDM scenarios in the A' mass range $1\ MeV \le m_{A'} \le 150$ MeV except the most difficult case of pseudo-Dirac LDM with $\alpha_D = 0.1$, $\alpha_D = 0.05$ and $\frac{m_{A'}}{m_\chi} = 2.5$.

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

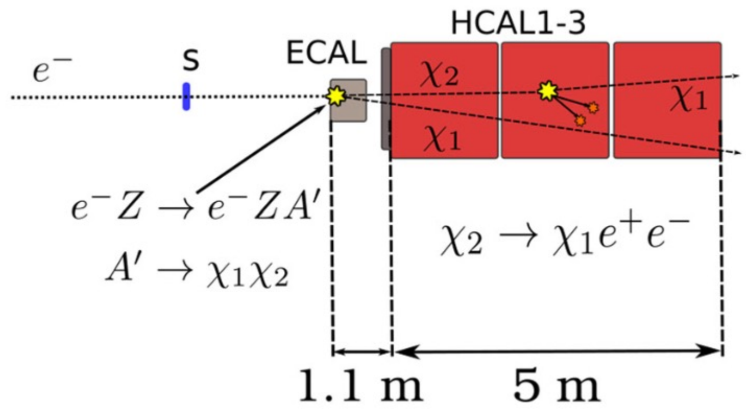


Fig. 3 A schematic view of an event $A' \to \chi_1\chi_2(\chi_2 \to \chi_1 e^+ e^-)$ from a A' produced after a 100 GeV e^- scatters off in the active dump, $e^- Z \to e^- Z A'$. The χ_2 particle decaying within HCAL2 corresponds to the S1 signature (see text for more details)

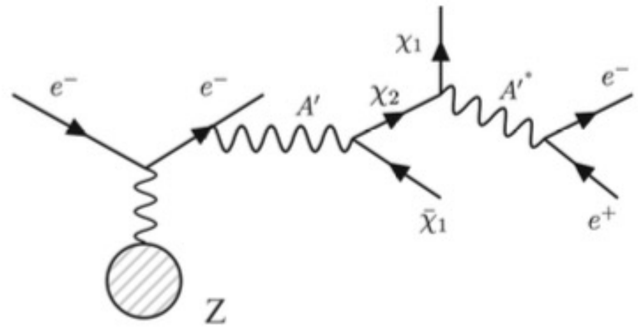
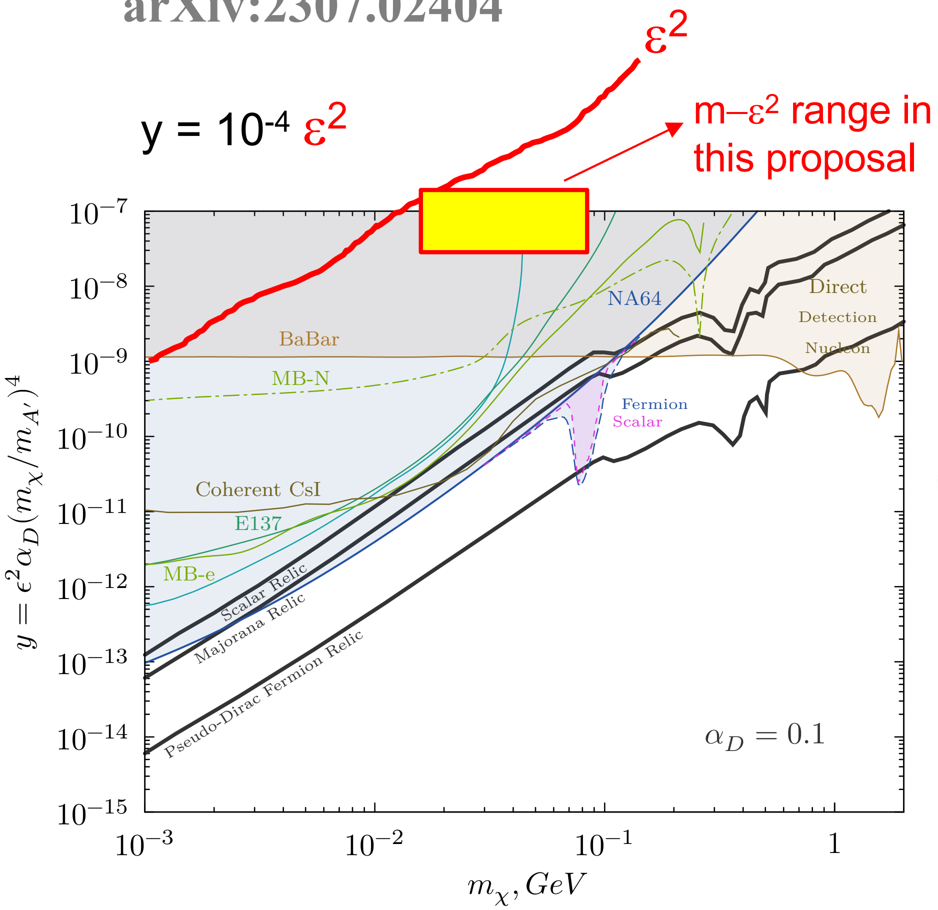


Fig. 1 Production of A' and subsequent semi-visible decay chain of a Dark Photon, $e^- Z \to e^- Z A'$; $A' \to \chi_1\chi_2(\chi_2 \to \chi_1 e^+ e^-)$

NA64 recent analysis

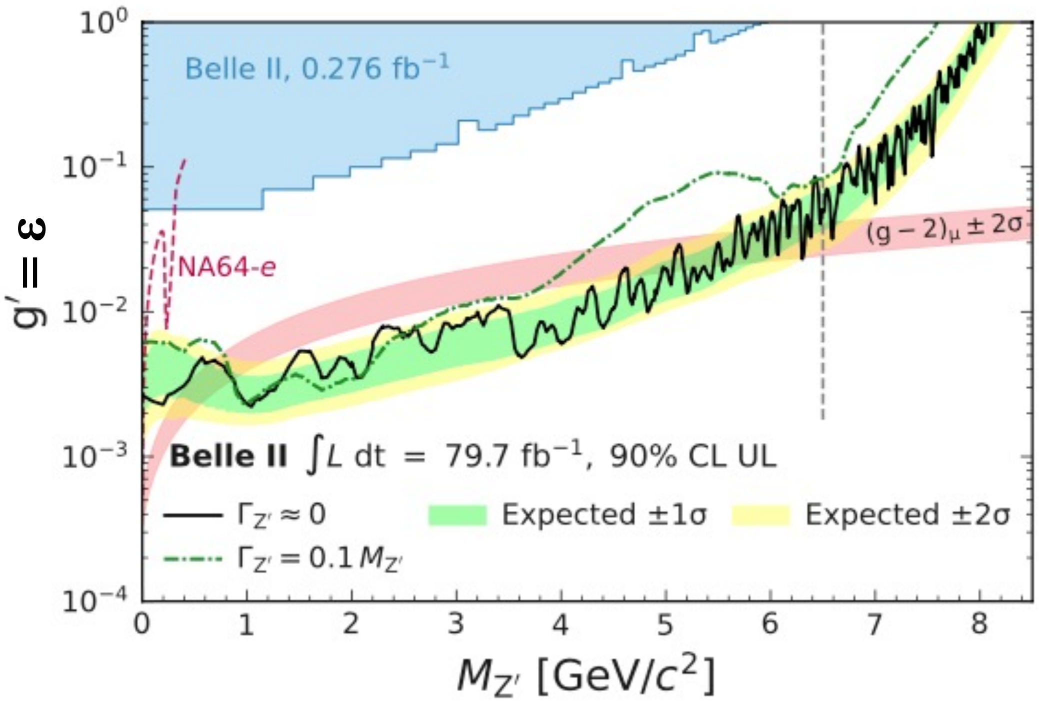
Belle-II recent analysis

arXiv:2307.02404



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

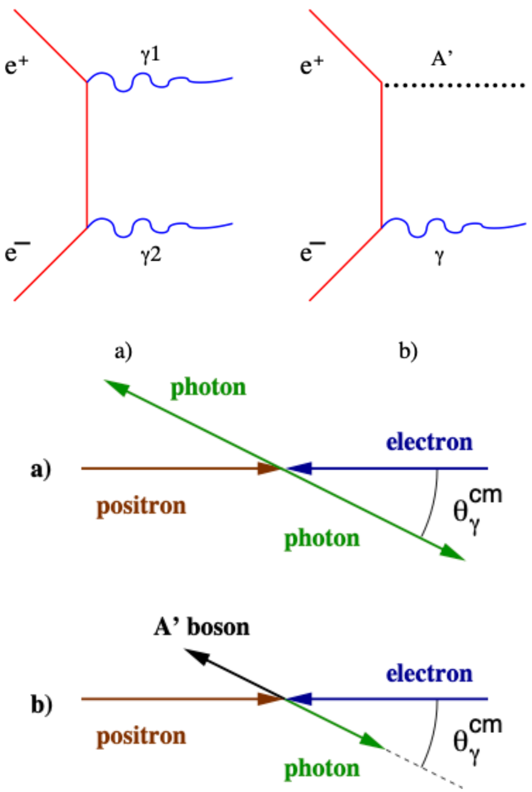
arXiv:2212.03066v3

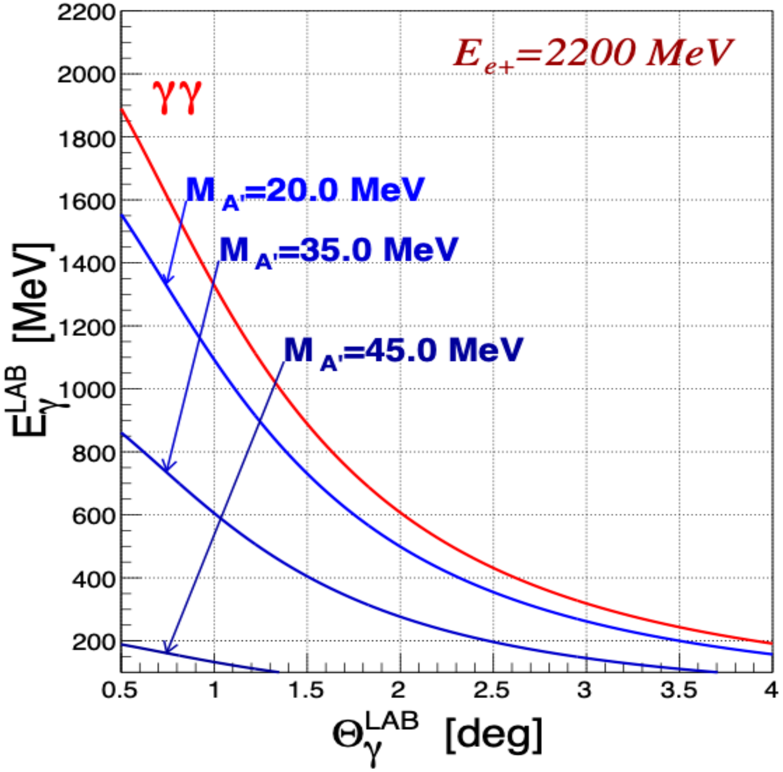


e+e --> γ + A' with
invisible decay of A'

Mass resolution for m_A < 0.1 GeV is hard to get

This experiment concept

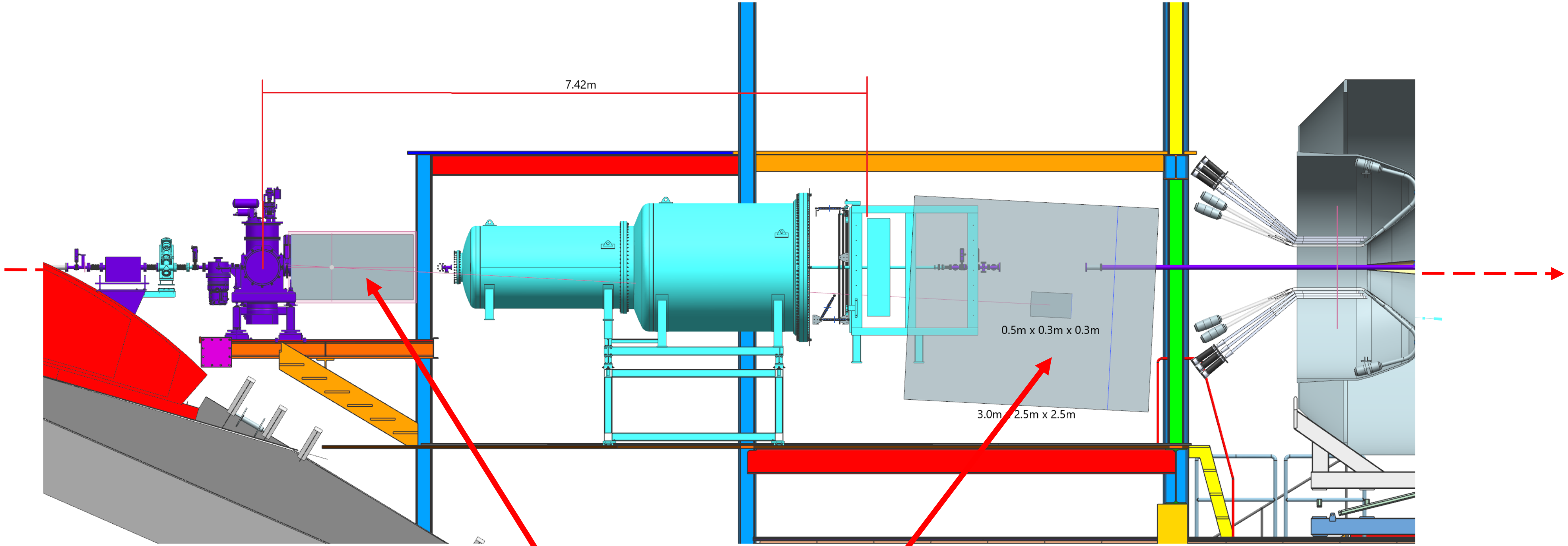




- A positron beam on a hydrogen target (e+e- annihilation)
- Selection of the one-photon final state events
- Search for a bump in the missing mass spectrum

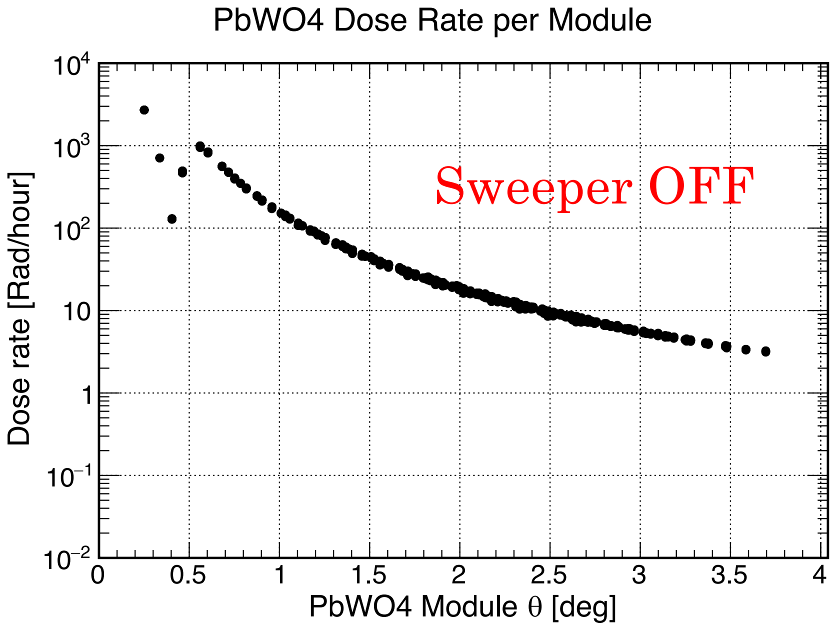
$$M_{A'}^2 = 2m_e^2 + 2m_e * (E_+ - E_\gamma) - 4E_+ * E_\gamma * \sin^2(\frac{\theta_\gamma}{2})$$

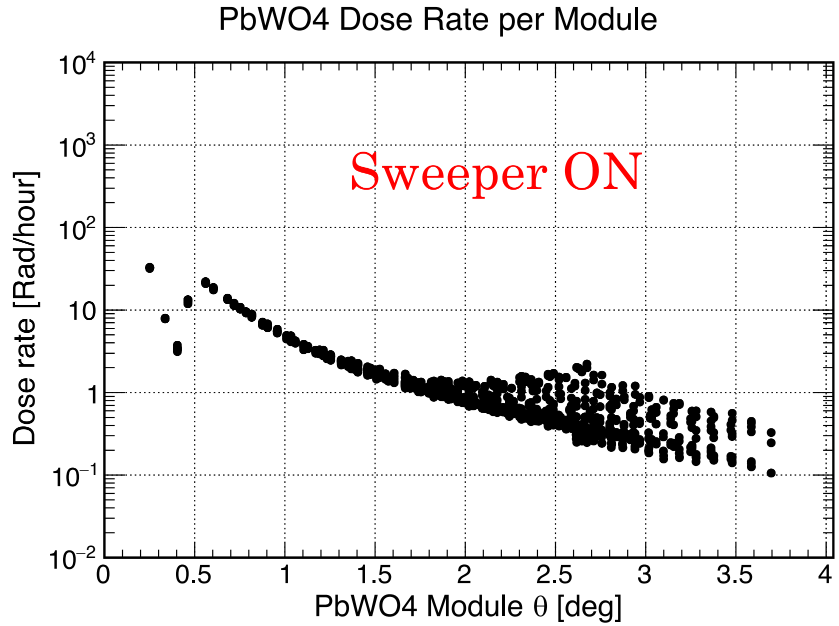
Hall B positron beam experiment

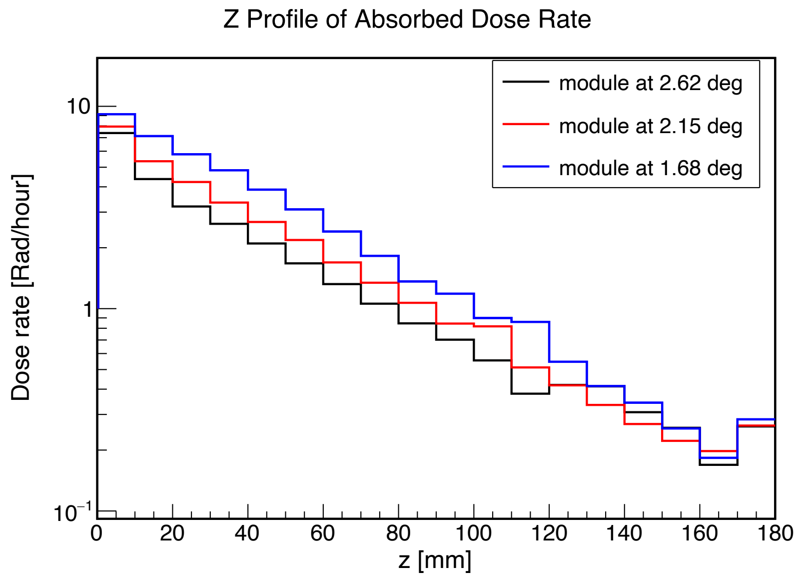


- NEW for PAC52 –
  - sweeper
  - dump
  - Geant4 MC
- 50 nA positron beam on 5 cm long LH2
- High resolution part of PRAD calorimeter
- fADC - based DAQ with programmable trigger

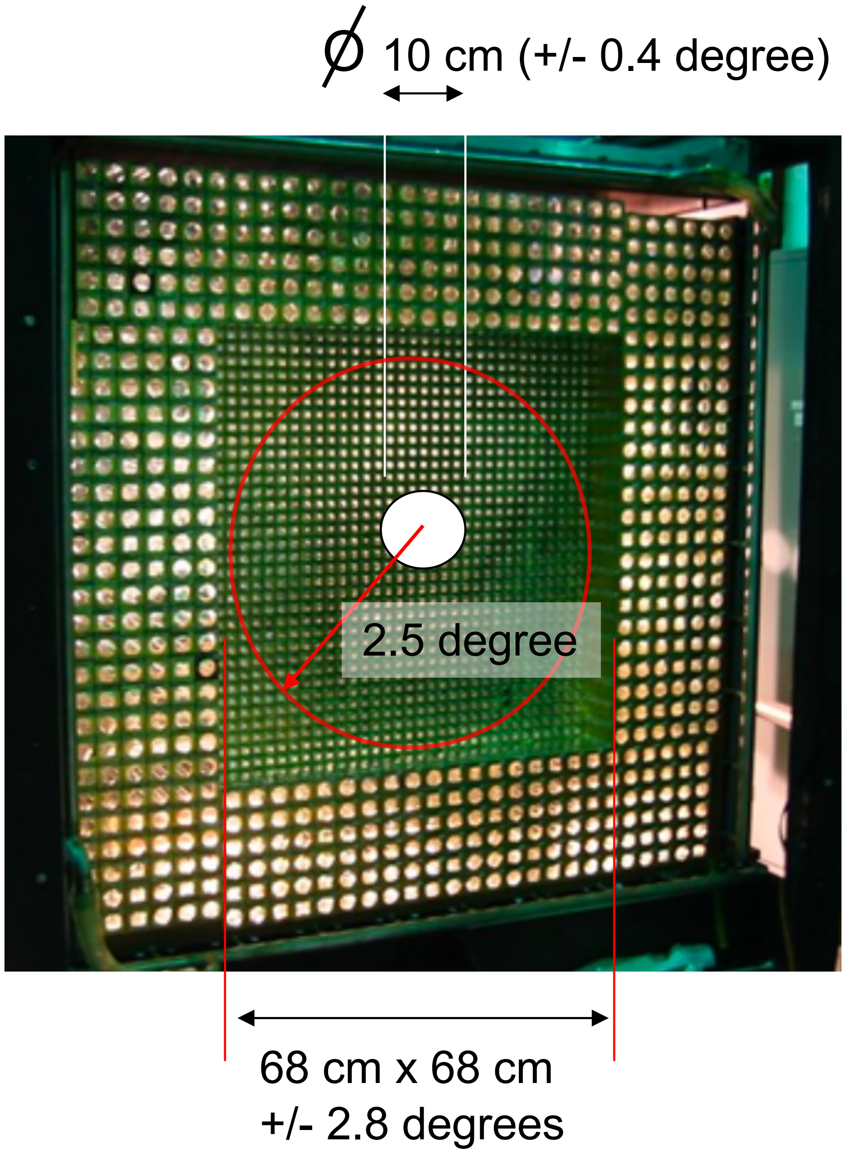
Calorimeter radiation load

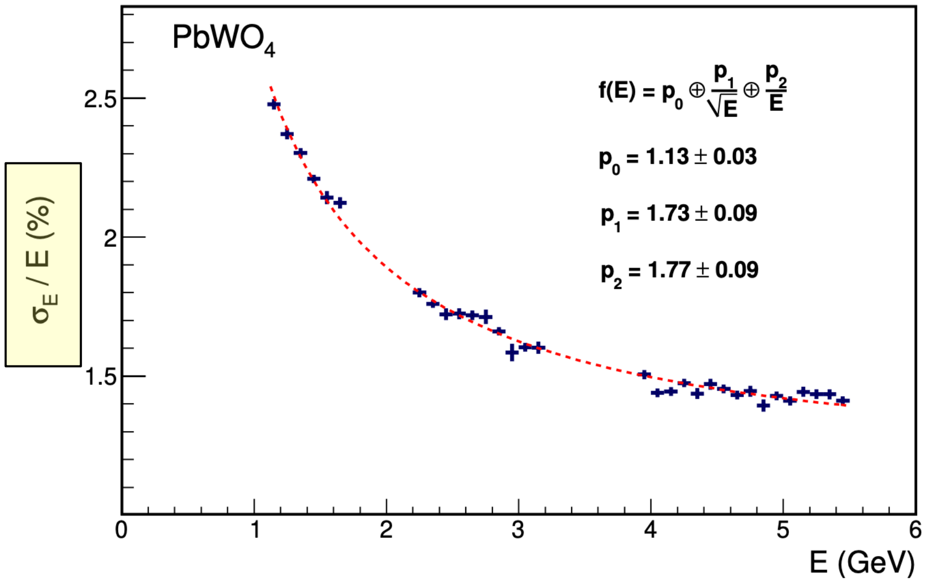


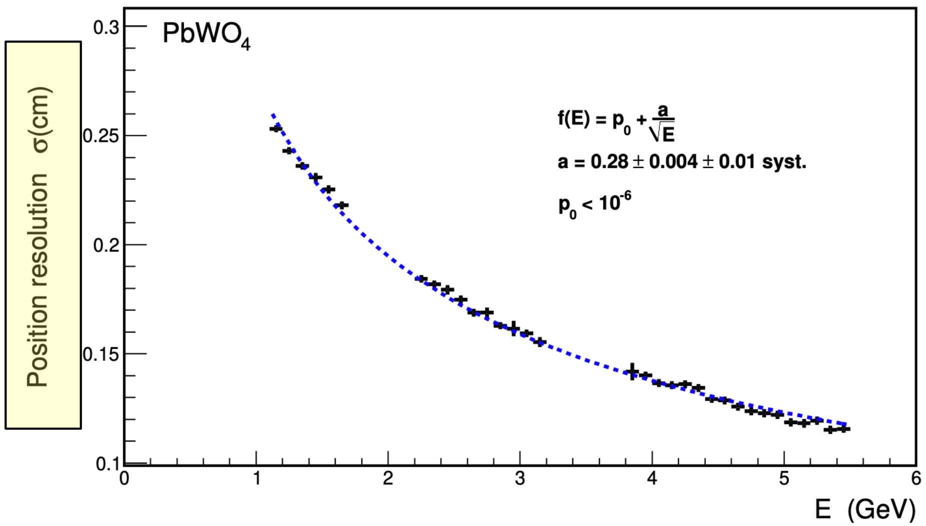




Calorimeter parameters



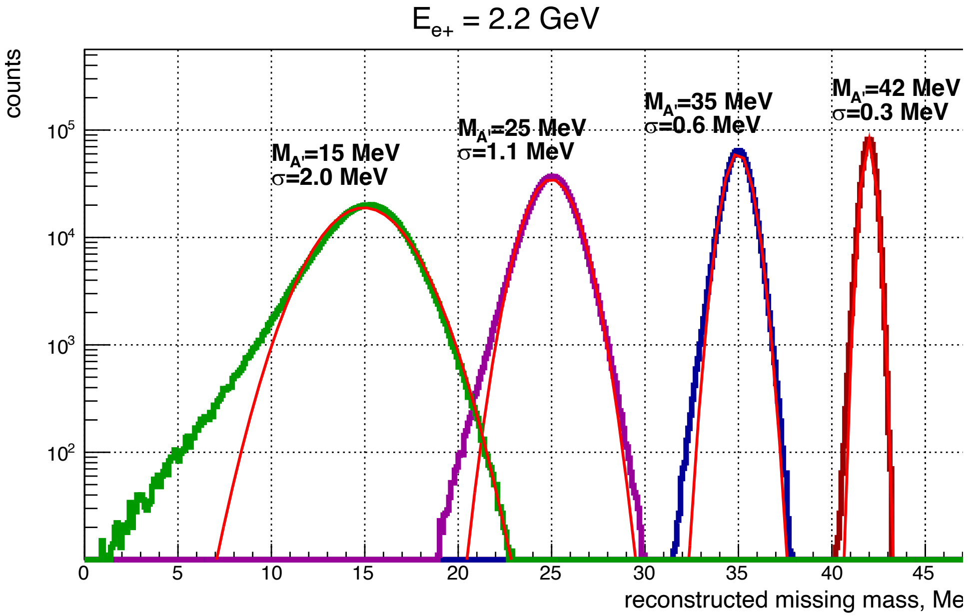


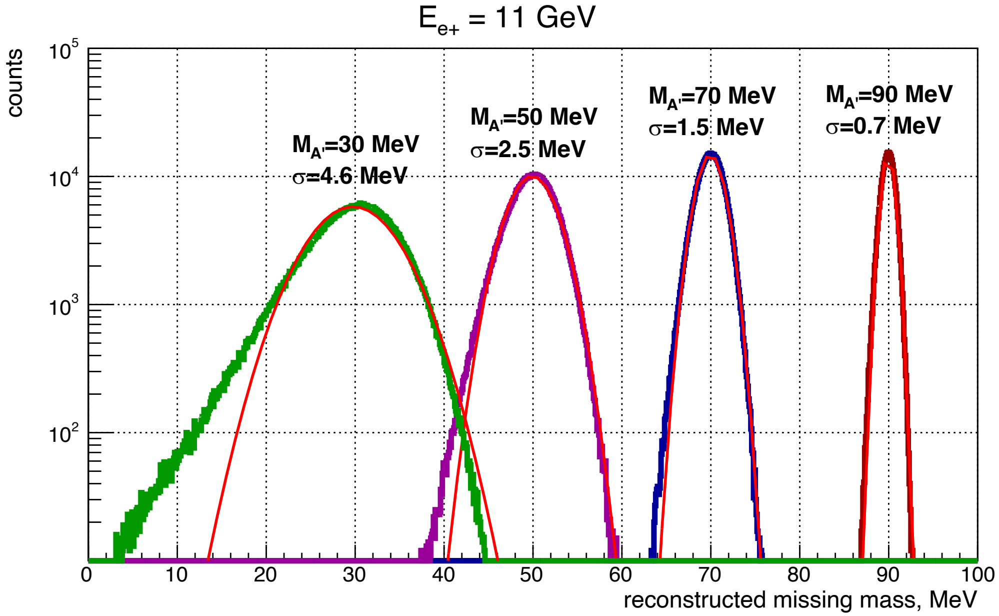


Mass resolution

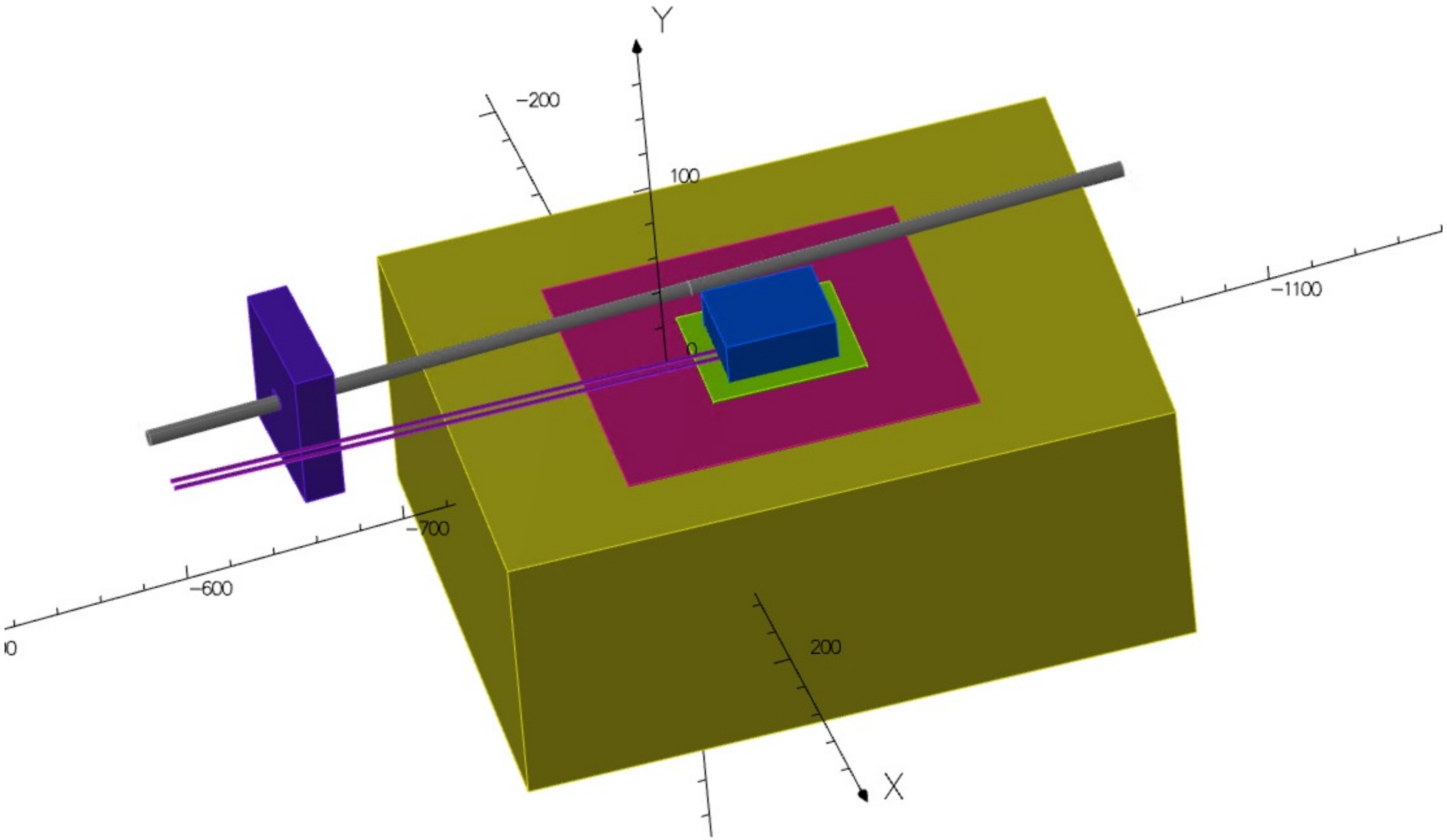
the photon energy and angle allow us to calculate
the missing mass:

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

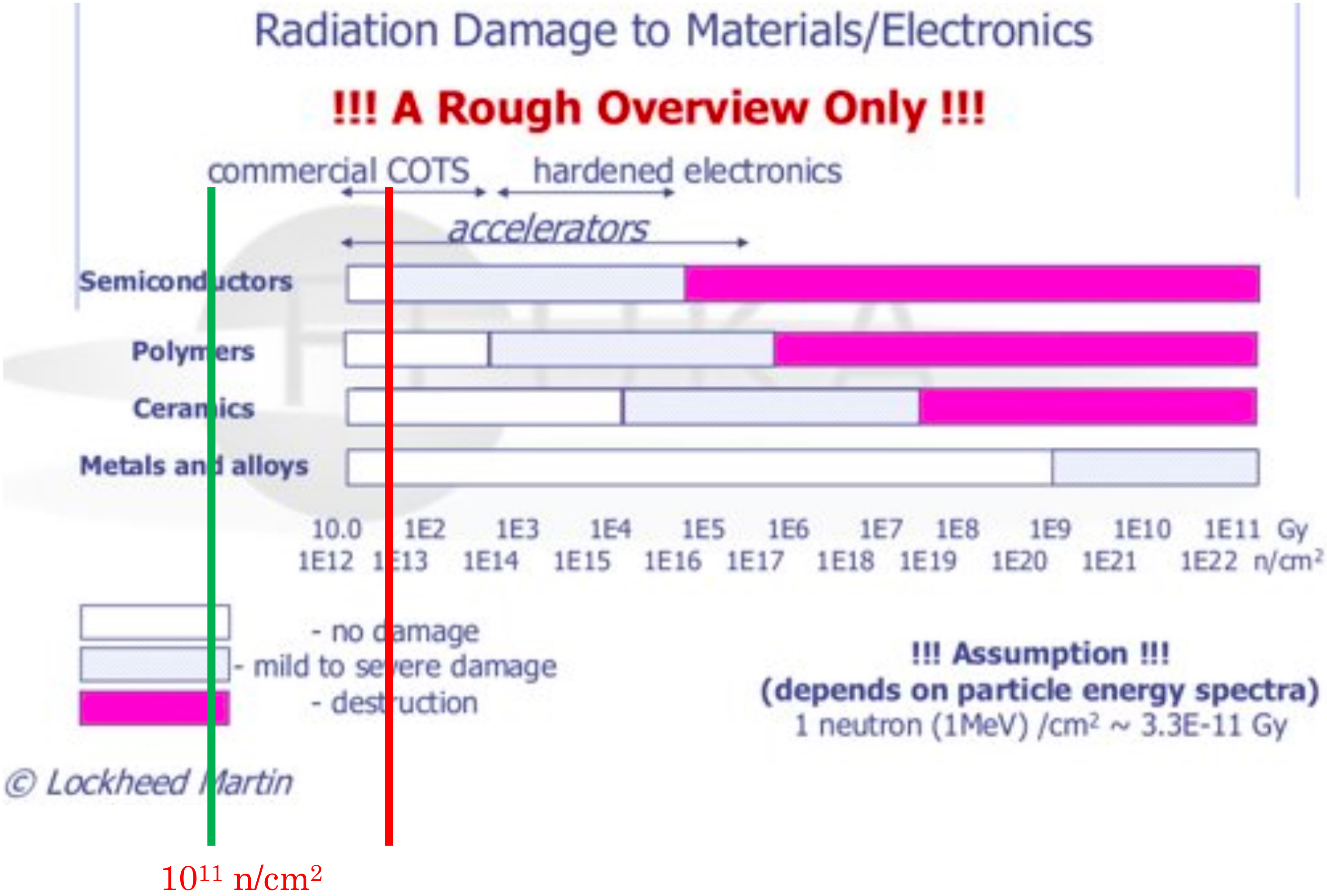




Beam dump



Neutron radiation impact



Neutron radiation in Hall B

An 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

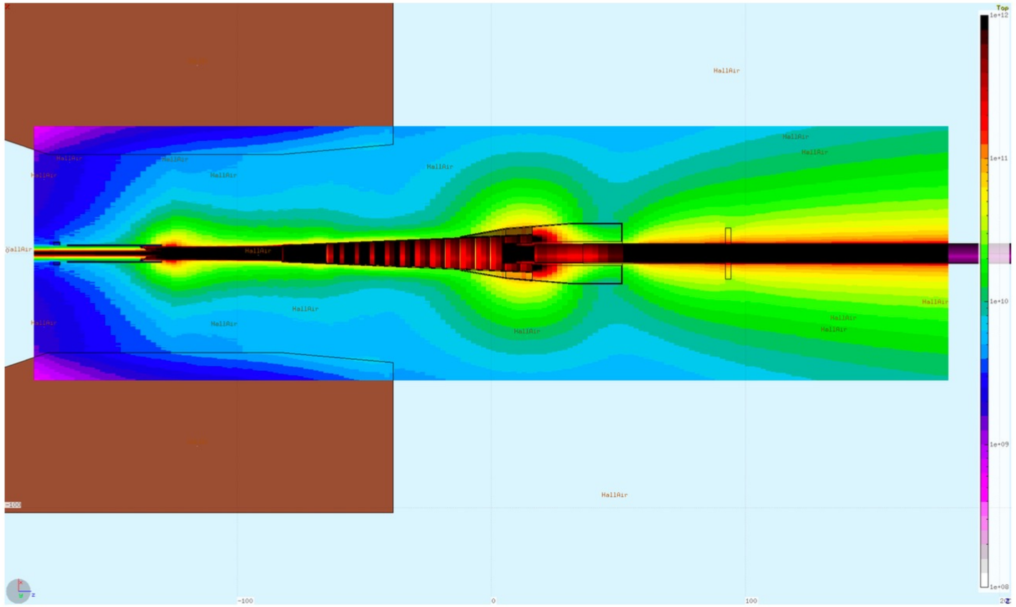


FIG. 35. Neutron dose after the recent experiment in Hall B according to calculations by L. Zana.

5 meter 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 with the first level design/calculation of the beam dump for the proposed experiment, see Figs. 18 and 32.

Neutron radiation prediction

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 11-GeV 50-nA 15-days run the dose is below 0.7×10^8 n/cm^2, so it is below to 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.

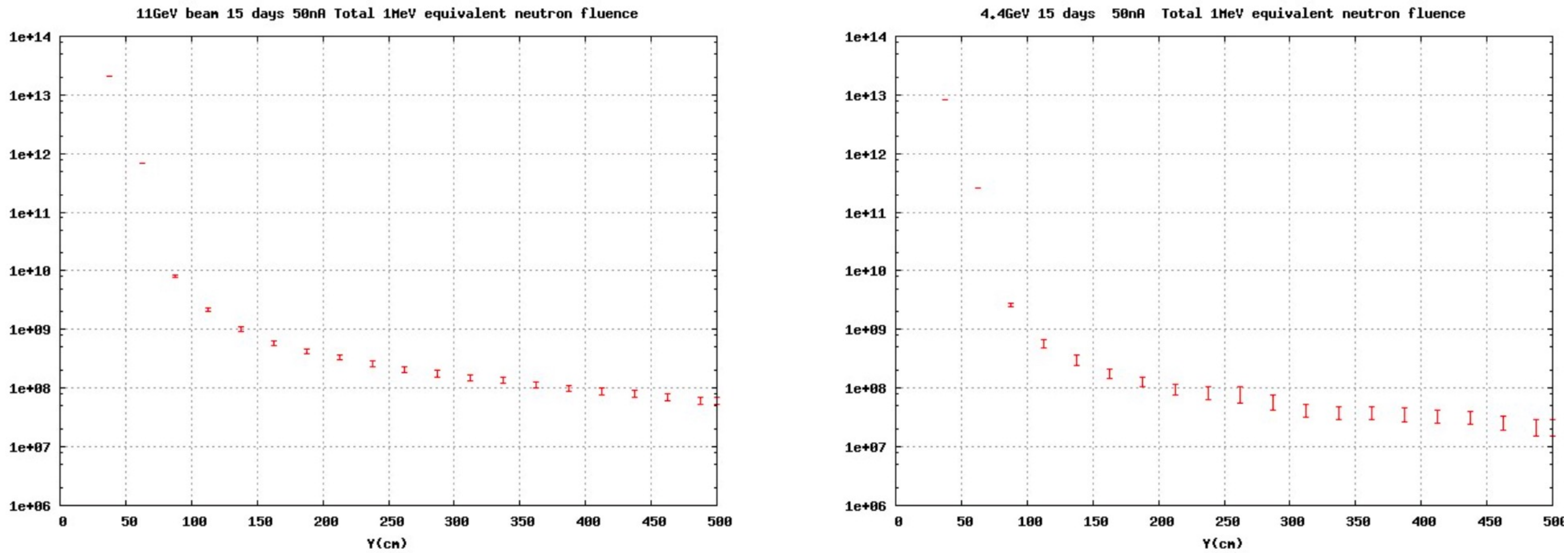
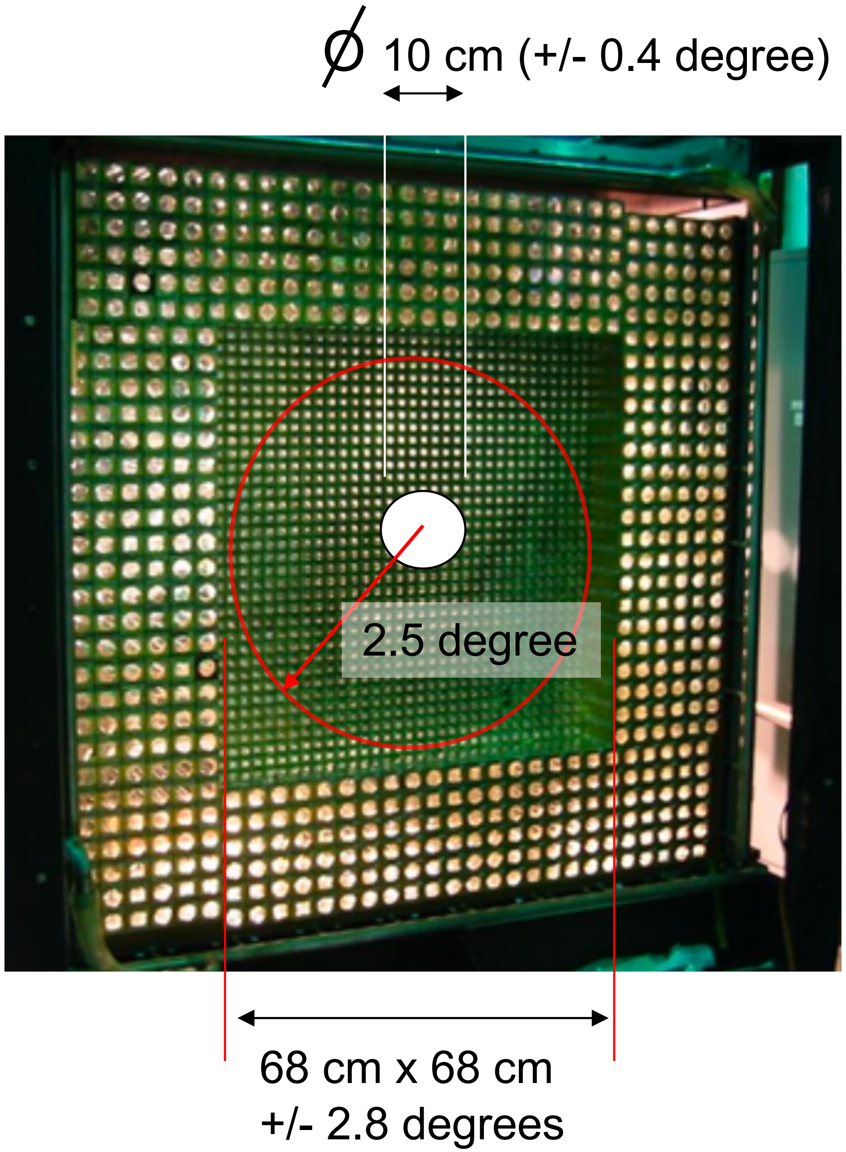
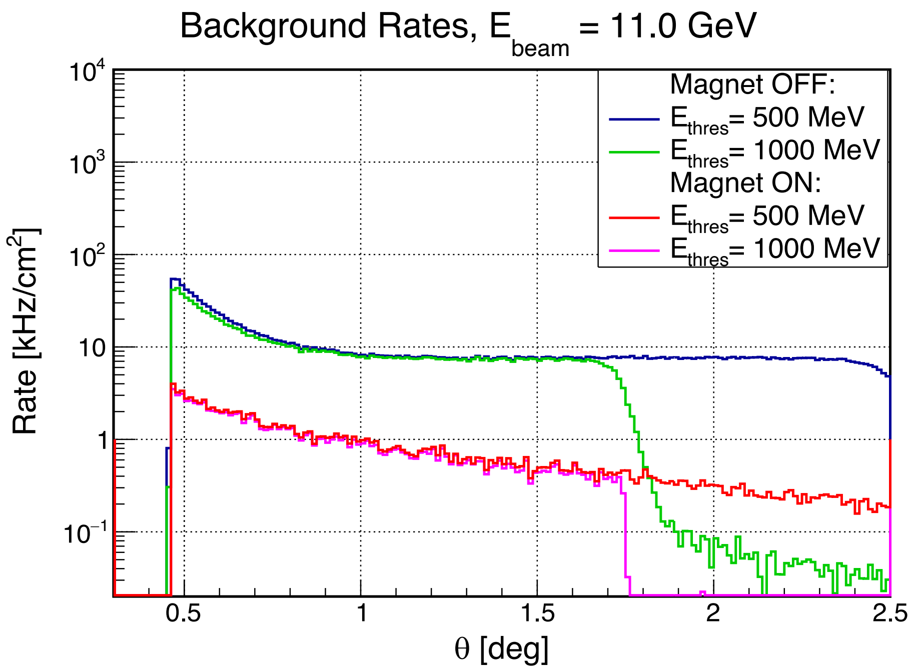


FIG. 36. Neutron radiation dose around the local beam dump vs. distance from dump center according to L. Zana in 4.4 GeV and 11 GeV parts of this experiment.

Expected rate in the calorimeter





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

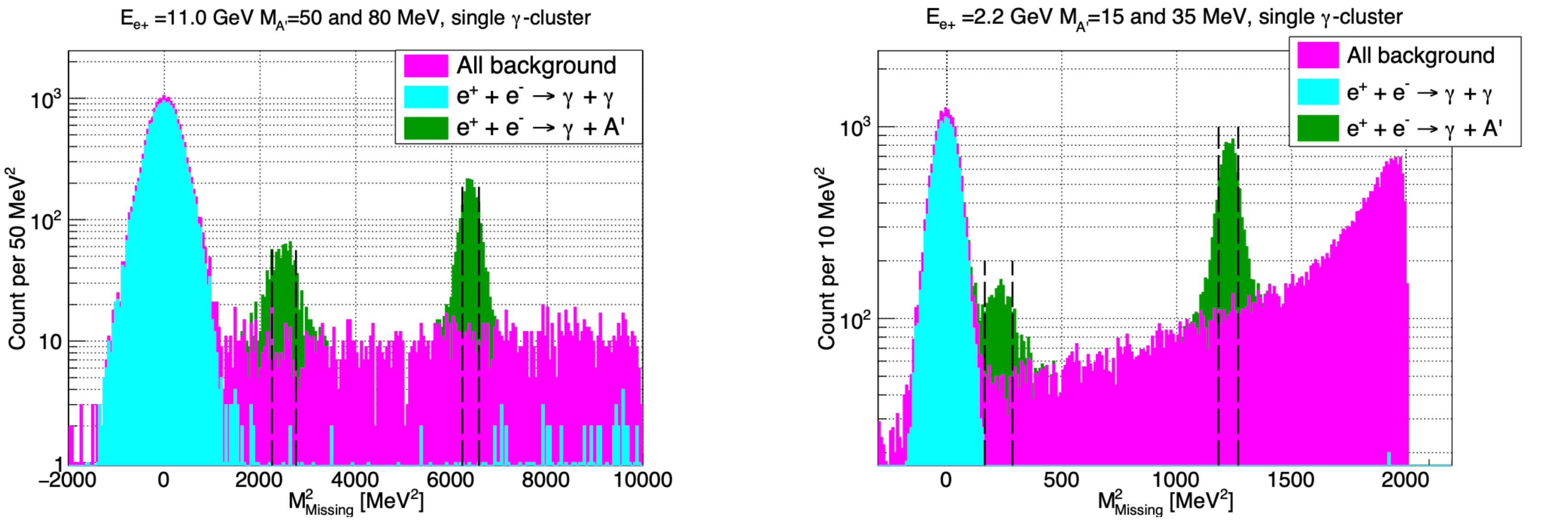
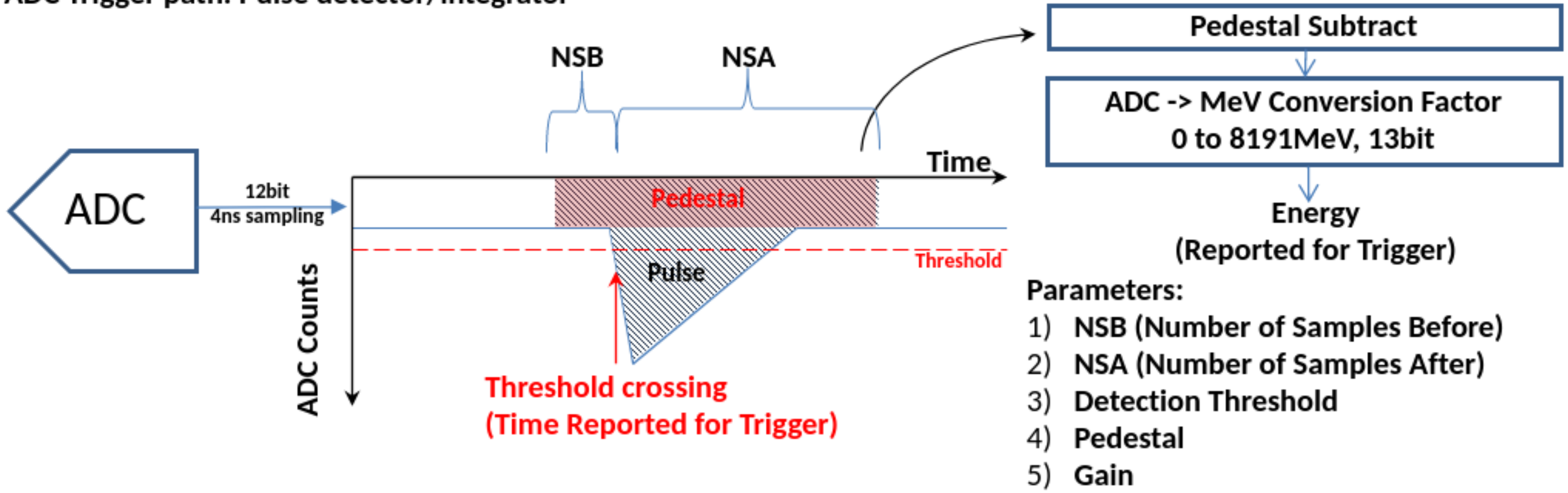


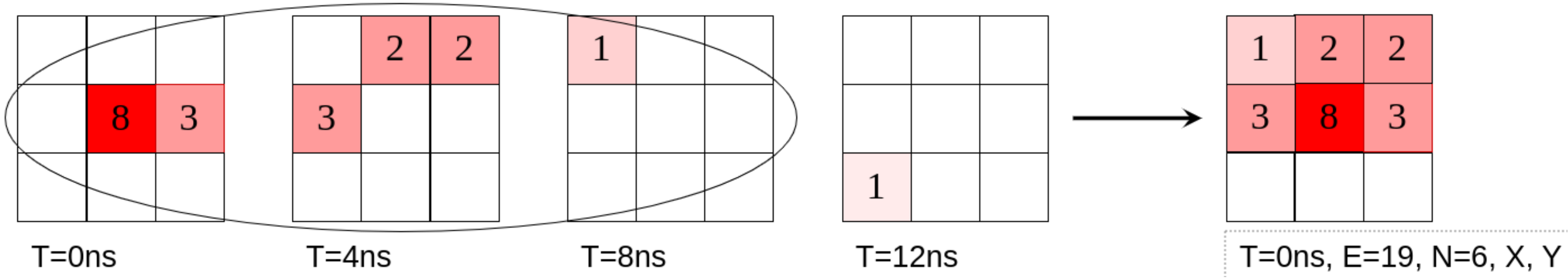
FIG. 16. Results of the Monte Carlo simulation for the missing mass distribution. The mixing constant is taken to be $\epsilon^2 = 10^{-2}$ to simplify visualization on the plot. Left – for $E_{e+} = 11$ GeV beam energy, $M_{A'} = 50$ and $M_{A'} = 80$ MeV. Right – for $E_{e+} = 2.2$ GeV beam energy, $M_{A'} = 15$ 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} $cm^{-2}s^{-1}$.

High rate capability DAQ

FADC Trigger path: Pulse detector/integrator

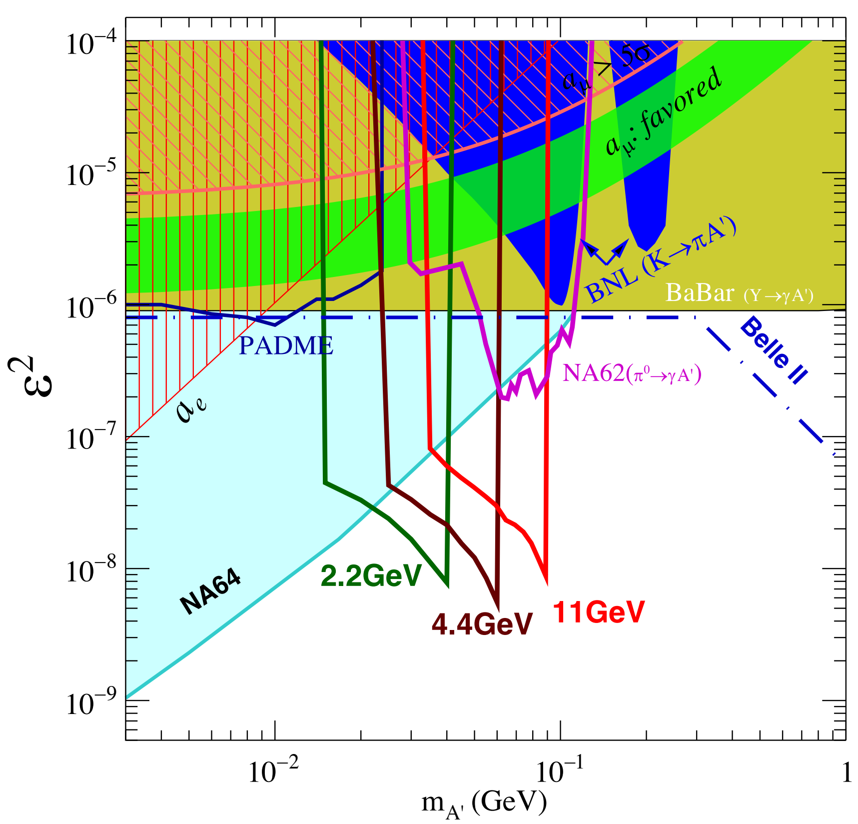


e.g. for seed threshold of 2 and hit Δt=+/-8ns, the following hit pattern evolving in time will report 1 cluster:



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_μ-2)

2. Good mass resolution allows us to make a productive search for a signal with a 55-day run

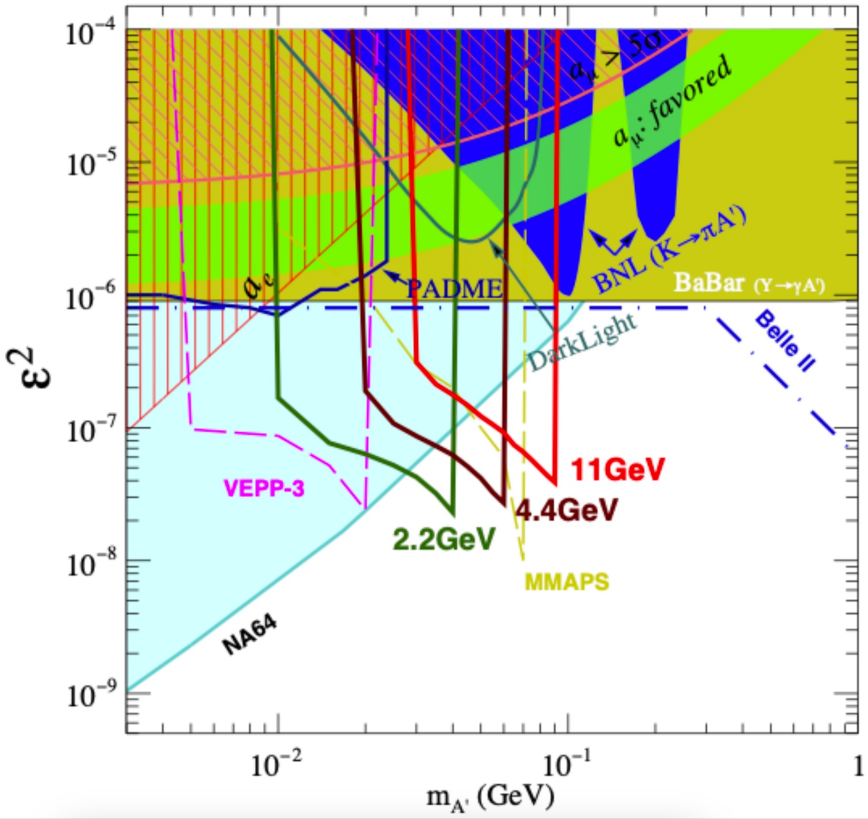
3. Does not require new detector development

4. The sweeper dipole designed (copy from CPS)

5. The beam dump calculated in FLUKA and Geant4

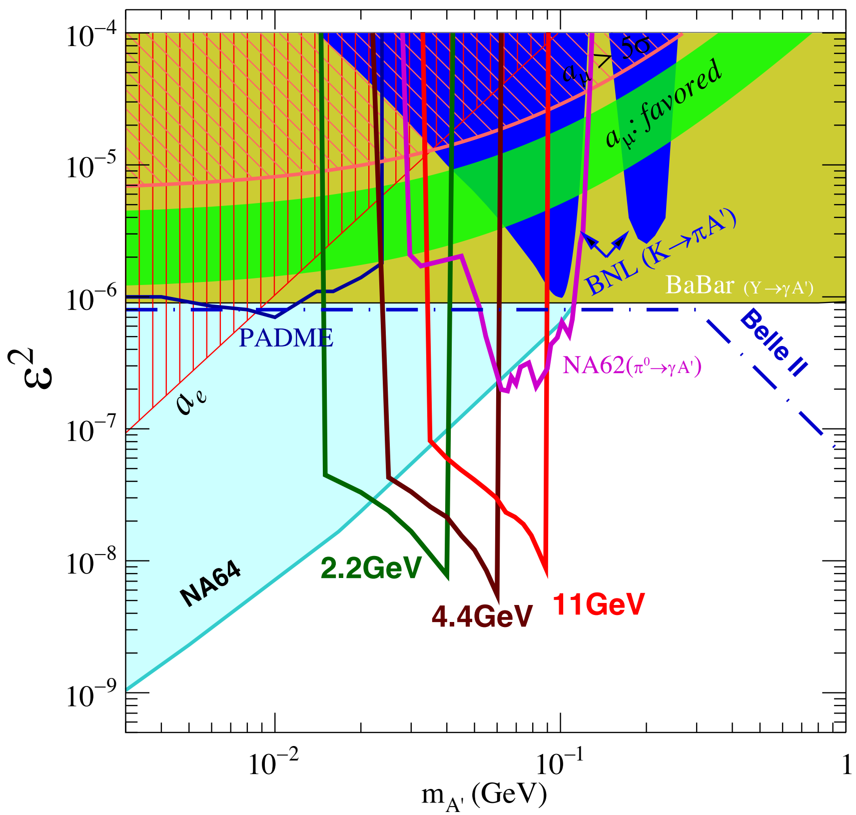
Compare with the previous proposal

two-sigma level



Projected sensitivity and beam time request

two-sigma level



Uniqueness of the missing mass method

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5. The beam dump calculated in FLUKA and Geant4

Kin. #	Beam energy, GeV	Beam, μA	Mass range, MeV	Time, days
C1	2.2	0.050 e^+	15-40	15 + 1
C2	4.4	0.050 e^+	40-60	15 + 1
C3	11	0.050 e^+	60-90	15 + 1 +7
	Total requested time			55

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) and its mass accurate measurement.

- 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.