Search for a **Dark Photon:** proposal for the experiment at VEPP–3.

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IEBWorkshop
Cornell University
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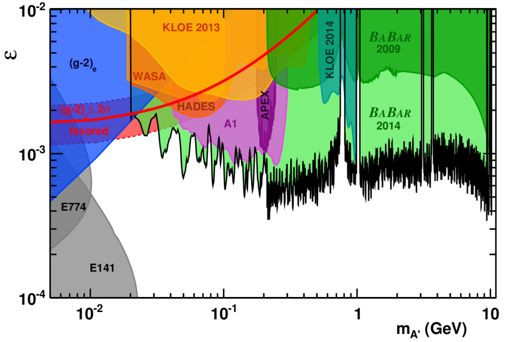
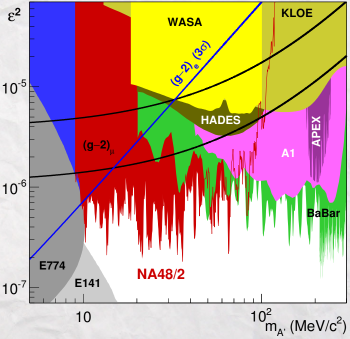
Latest results of dark photon searches

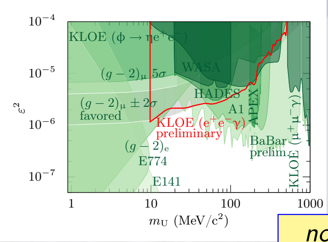
BABAR (2014): $e^+e^- \to \gamma A'$, $A' \to e^+e^-, \mu^+\mu^-$



NA48/2: $\pi^0 \to \gamma e^+e^-$



KLOE 2015 $e^+e^- \to \gamma(e^+e^-)$



results of 2013-2015

WASA 2013	$\pi^0 \to \gamma(e^+e^-)$	PLB 726 (2013) 187
KLOE 2013	$\phi \to \eta(e^+e^-)$	PLB 720 (2013) 111
KLOE 2014	$e^+e^- \to \gamma(\mu^+\mu^-)$	arXiv:1404.7772
MAMI-A1 2014	$e^-N \to e^-N(e^+e^-)$	PRL 112 (2014) 221802
PHENIX 2014	$\pi^0, \eta \to \gamma(e^+e^-)$	arXiv:1409.0851
HADES 2014	$pN \to X(e^+e^-)$	PLB 731 (2014) 265
KLOE 2015	$e^+e^- \to \gamma(e^+e^-)$	arXiv:1501.05173
NA48/2 2015	$\pi^0 \to \gamma(e^+e^-)$	arXiv:1504.00607

no A' signal observed to date

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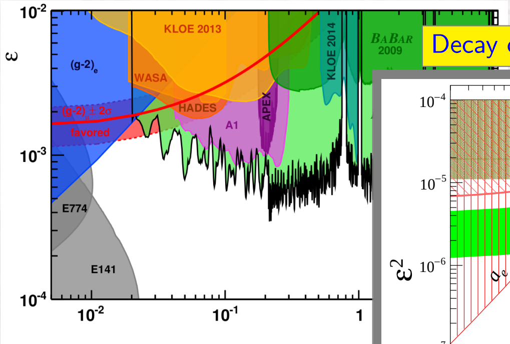

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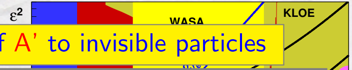
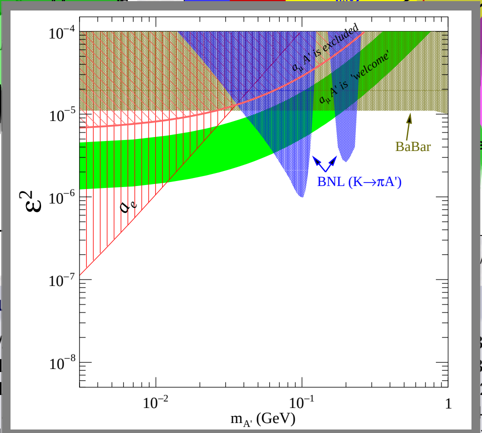
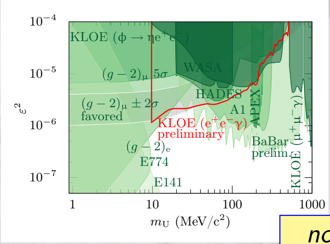


Decay of A' to invisible particles



KLOE 2015 $e^+e^- \to \gamma(e^+e^-)$



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W…		…) 187
Kl…		…) 111
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M…		…) 221802
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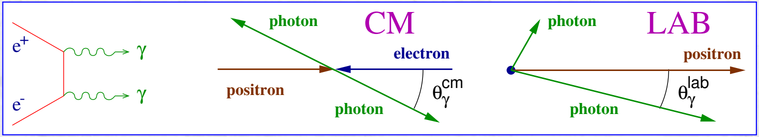
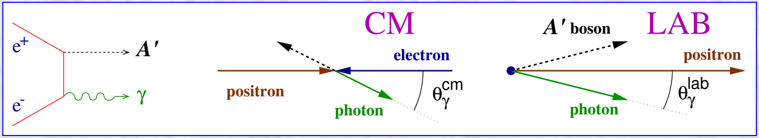
instead of standard two-photon annihilation $e^+e^- \to \gamma + \gamma$



. . . annihilation with the production of dark photon $e^+e^- \to \mathrm{A}' + \gamma$:

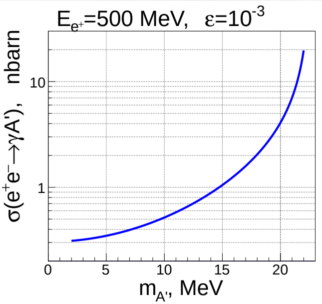


differential cross section (in Lab System):

$$\frac{d\sigma}{dy} \approx \varepsilon^2 \cdot \frac{\pi r_0^2}{y\gamma_+} \left[\frac{(1+\mu)^2}{1-(y+\mu)} - 2y \right]$$

where

$y = E_\gamma^{lab} / E_+$, $\mu = M_A^2 / s$

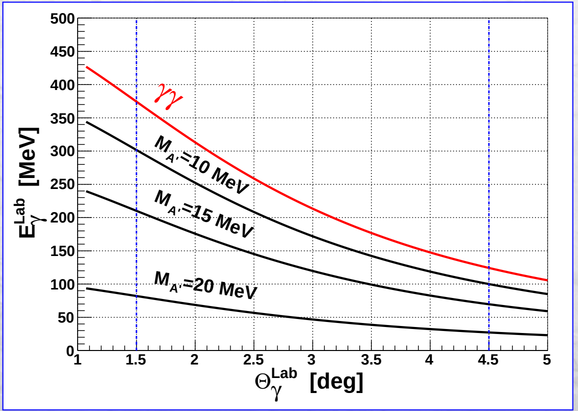


Kinematic correlations in annihilation

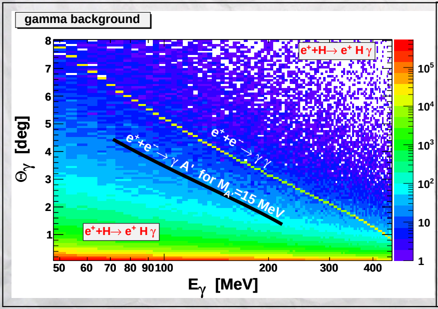
Photon energy depends on its emission angle and the mass of the 2nd particle:

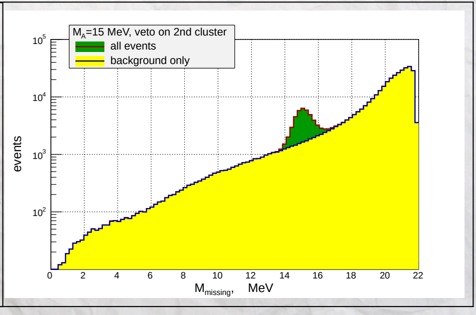
$$E_\gamma \approx E_+ \cdot \frac{1 - M_A^2/s}{1 + \gamma_+(1 - \cos\theta_\gamma)}, \qquad s = 2m_e(E_+ + m_e)$$

for $E_+ = 500$ MeV $\rightarrow \sqrt{s} = 22.6$ MeV :



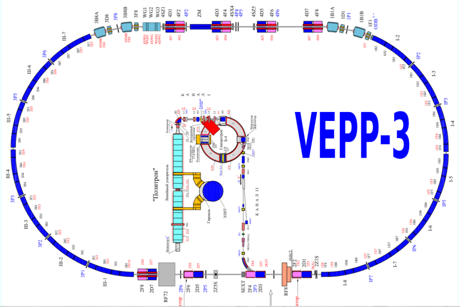
- measure energy and emission angle of γ-quantum
- search for a "bump" on top of QED background
- A'-boson should appear in a missing mass spectrum as a peak above QED background:
- peak width is defined by energy and angular resolutions of the γ-detector



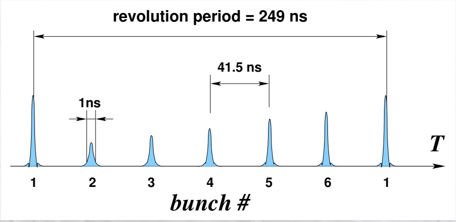


VEPP–3 approach

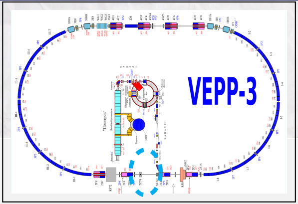
- *positron* beam repeatedly crosses the *internal* hydrogen gas target
- working with the new injector complex, which provides $2 \cdot 10^9\ e^+$ per second;
- staying at injector energy $E_{e^+} = 500$ MeV – no energy ramping in VEPP–3
- 6 bunches in VEPP–3; every 10 seconds the oldest bunch is replaced by a new one with up to $2 \cdot 10^{10}$ positrons, stored in the injector's *cooler* ring;
- designed luminosity of the experiment: $10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- special magnetic system providing free flight for γ–quanta from target to detector is needed
- using a segmented EM-calorimeter placed at a distance of $\sim$ 8 m from the target
- searching for a peak in a missing mass distribution.



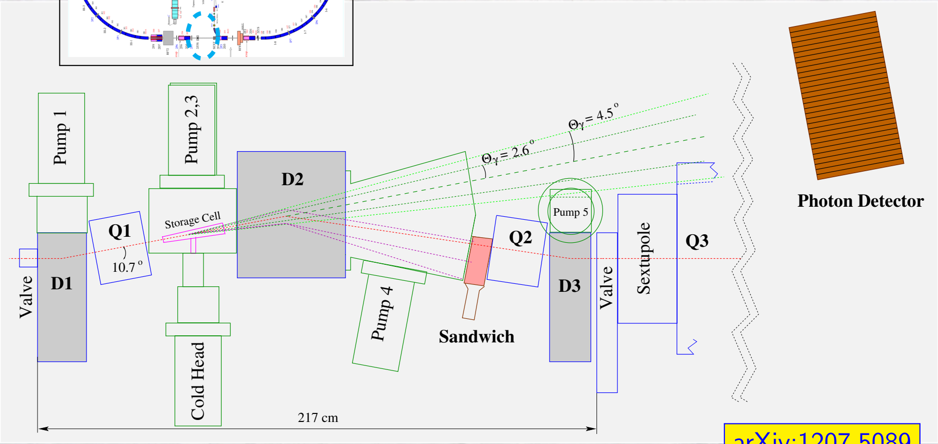
VEPP-3 beam microstructure:
6-bunches mode



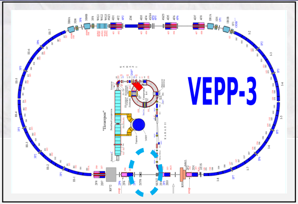
1st configuration for the experiment at VEPP–3



Three dipole magnets in the 2nd straight section of VEPP-3



arXiv:1207.5089



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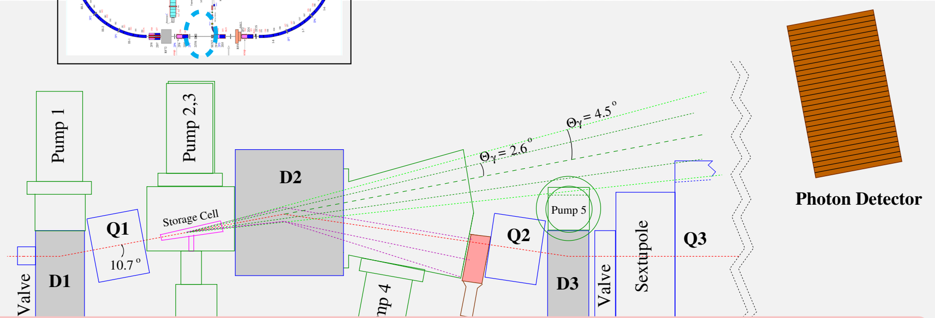
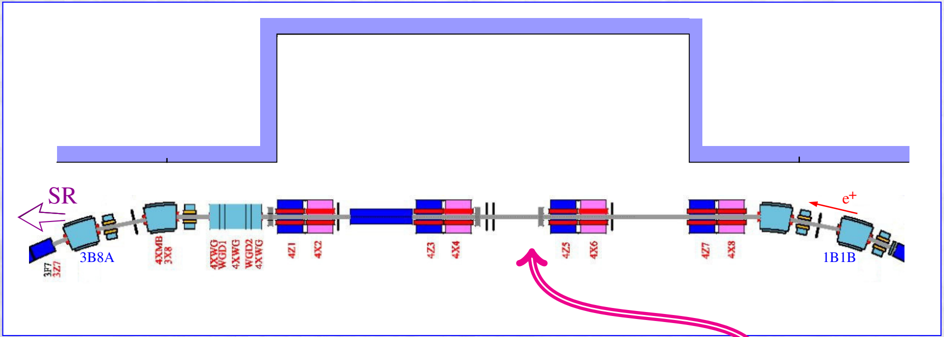
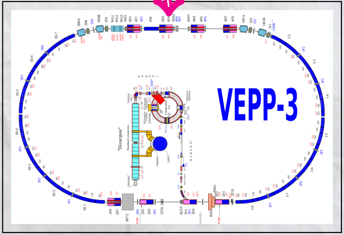


obvious drawbacks

- very busy space – difficult to clean-up the path from the target to the calorimeter
- VEPP–3 becomes completely unavailable for other programs (SR,KEDR,VEPP-4) when the dipoles are installed

2nd configuration: The ByPass at VEPP–3





BYPASS along the 4th straight section of VEPP–3 – *where the FEL was previously situated*

- vacuum chamber with pumping system
- 3 dipole magnets
- 6 quadrupoles
- elements of beam diagnostics

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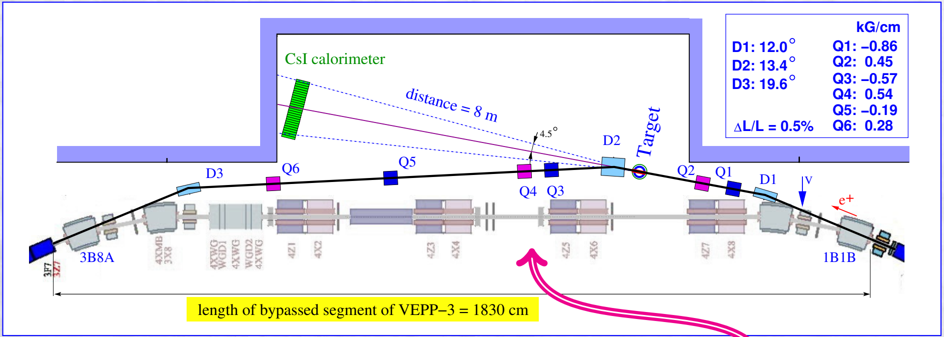

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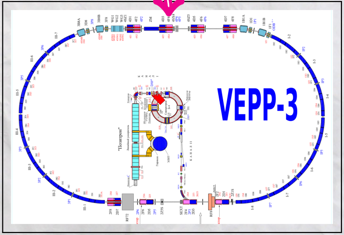

Photon detector

The desired specifications:

- energy resolution $\sigma_E/E \leq 5\%$ in the range $E_\gamma = 50 \div 500$ MeV
- angular resolution $\Delta\theta \sim 0.1^\circ$
- angular acceptance in θ^{lab}: $1.5^\circ \div 4.5^\circ$ – corresponds to $\theta^{CM} = 90^\circ \pm 30^\circ$
- angular acceptance in ϕ: 360°

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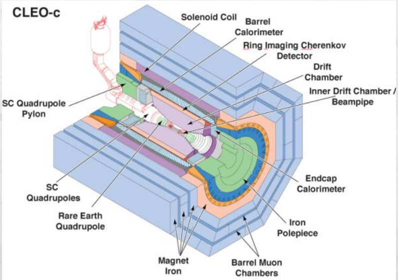
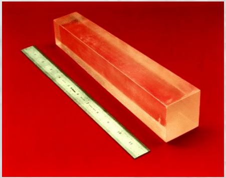
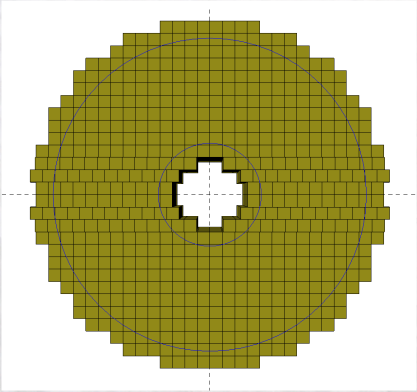
Considering an option of using the crystals from the CLEO EM–calorimeter



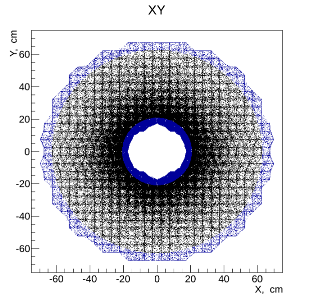


CsI(Tl) crystals
1650 rectangular crystals in endcaps
crystal size: $5 \times 5 \times 30 cm^3$ ($16.2 X_0$)
4 Hamamatsu S1790 photodiodes per crystal

Calorimeter based on CsI(Tl) crystals from CLEO



- 608 crystals are assembled in a "ring"
- calorimeter is placed at a distance of 8 m from the target
- based on CLEO measurements with 180 MeV positrons:
  - energy resolution $\sigma_E = 3.8\%$
  - spatial resolution $\sigma_x = 12$ mm $\Rightarrow$ angular resolution: $\sigma_\theta = 0.09^\circ$



event rate at threshold 25 MeV and luminosity 10^{33}:

- total background rate: 850 kHz
- maximum per a crystal < 20 kHz

Main background processes

background QED processes

1. positron bremmstrahlung on hydrogen $e^+ + H \rightarrow e^+ + X + \gamma$
2. Bhabha scattering with bremsstrahlung $e^+ + e^- \rightarrow e^+ + e^- + \gamma$
3. 2-photon annihilation $e^+ + e^- \rightarrow \gamma + \gamma$
4. 3-photon annihilation $e^+ + e^- \rightarrow \gamma + \gamma + \gamma$

– Part of background events can be identified and rejected.
– The rest form a smooth "substrate"; their fluctuations define a search sensitivity.
– For realistic background estimation a Monte Carlo simulation is required.
– Such simulation was performed using GEANT4 toolkit and a set of dedicated event generators.

Event generators

1. $e^+ + H \to e^+ + X + \gamma$

   root class *TFoam*, dif. cross section $\frac{d\sigma_\gamma}{dE_\gamma d\Omega_\gamma}$ from "classic" paper

   Y-S. Tsai, Rev. Mod. Phys **46** 815 (1974), Rev. Mod. Phys **49** 421 (1977).

2. $e^+ + e^- \to e^+ + e^- + \gamma$

   adapted event generator from CMD–3

   A.B.Arbuzov, G.V.Fedotovich, F.V.Ignatov, E.A.Kuraev, A.L.Sibidanov, **BINP preprint 2004-70**

3. $e^+ + e^- \to \gamma + \gamma$ $e^+ + e^- \to \gamma + \gamma + \gamma$

   event generator based on an aproach from:

   F. A. Berends and R. Kleiss, "Distributions for electron-positron annihilation into two and three photons", Nucl. Phys. **B186** (1981) 22

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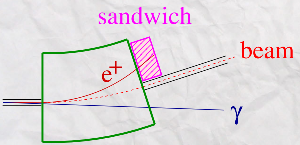
4. $e^+ + e^- \to \gamma + A'$

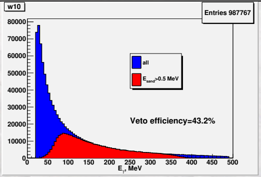
   root class *TFoam*, dif. cross section $\frac{d\sigma}{dy} \approx \varepsilon^2 \cdot \frac{\pi r_0^2}{y\gamma_+} \left[\frac{(1+\mu)^2}{1-(y+\mu)} - 2y \right]$

   derived from P. Fayet, Phys.Rev. **D 75** (2007) 115017, *Eq.55*

Identification of background events

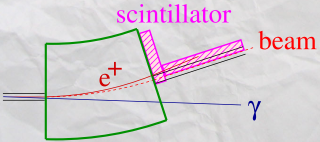
- more than one γ-quantum in calorimeter
  - a symmetrical (around $\theta^{CM} = 90^\circ$) calorimeter acceptance is required
  - then events of 2-photon annihilation (and partially of 3-photon one) can be identified
- veto-counter for positrons
  - bremsstrahlung is partially rejected
  - rejection efficiency depends on configuration of veto-counter

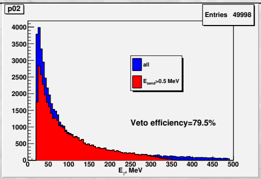




$\epsilon = 43\%$

$f = 2.4$ MHz



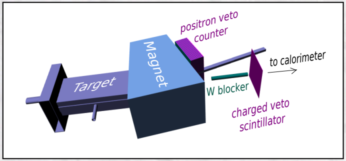


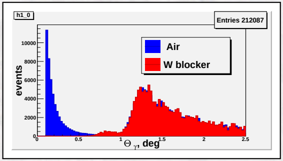
$\epsilon = 80\%$

$f = 17$ MHz

Secondary sources of background events

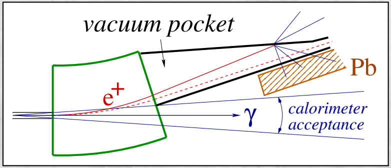
- large flux of bremsstrahlung photons, emitted at small angle:
  miss the calorimeter, but are able to produce a shower, passing 8m of air ($0.026X_0$)
  can be dumped by a blocker: 20cm-long tungsten rod at the exit of the dipole



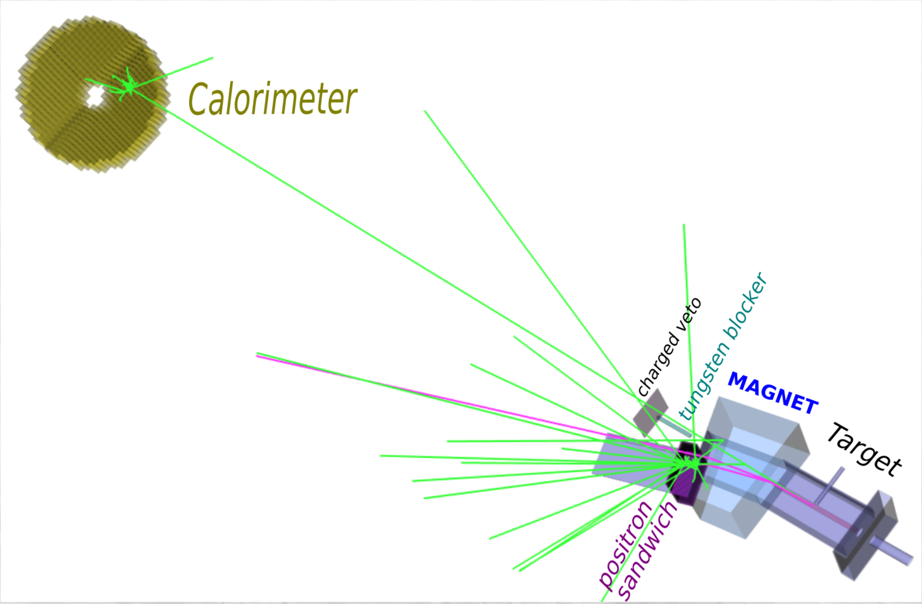


- positrons that lost a small fraction of energy in the target are bent in the dipole magent and hit the vacuum chamber wall, producing showers.

  ⇒ *Install:*
  - Pb shields wherever it is possilble;
  - vacuum pocket close to magnet exit (where there is no room for Pb-shield) guiding positrons to shielded area



The configuration accepted for Monte Carlo simulation



Monte Carlo: energy and angular resolution

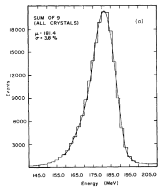
cluster 3×3 crystals is analyzed; threshold $= 10$ MeV

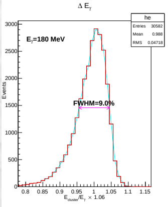
Signal = energy depositon + noise; noise = coherent + individual

noise parameters from CLEO paper [NIM A265(1988)258]: $\sigma_{coh} = 0.3$ MeV, $\sigma_{ind} = 0.6$ MeV

Energy resolution

measured simulated

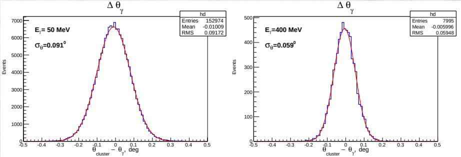




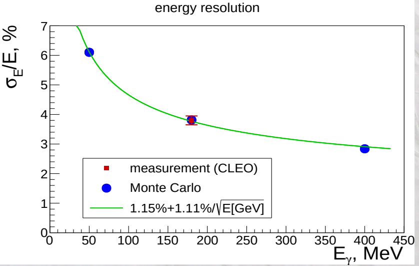
$E_{e^+} = 180$ MeV $E_{e^+} = 180$ MeV

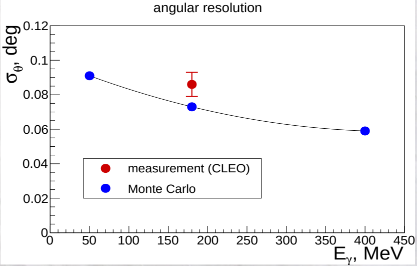
Angular resolution

simulated



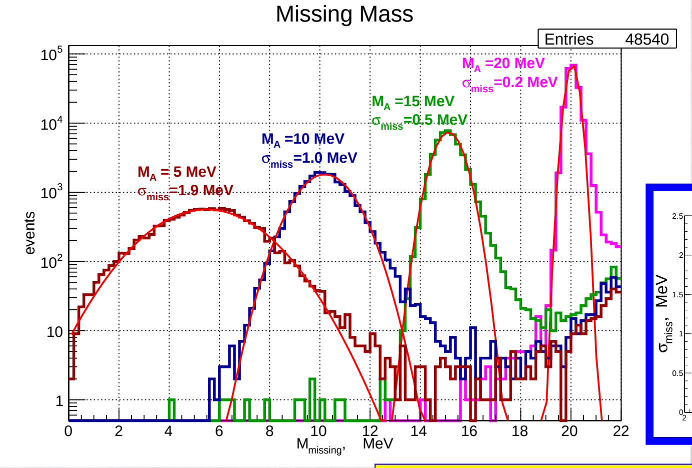
$E_{e^+} = 50$ MeV $E_{e^+} = 400$ MeV

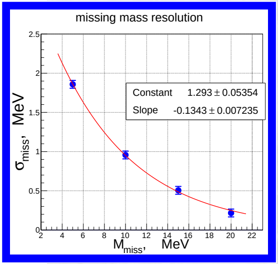




Data analysis is aimed at selecting events with a single cluster in the calorimeter and searching for a peak in the missing mass distribution

Results for 4 values of A'-boson mass: m_{miss} =5,10,15,20 MeV



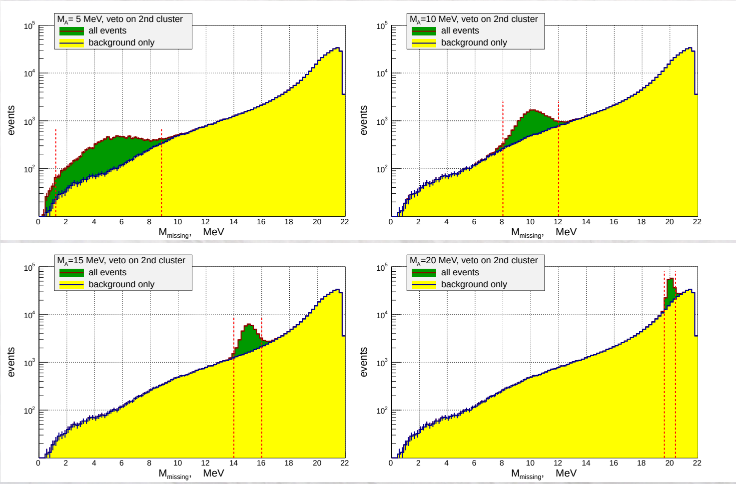


resolution is fitted by a function: $\sigma_{miss}(M_A) = 3.6 \cdot e^{-0.13 \cdot M_A}$ [MeV]

Monte Carlo: missing mass distributions

Event selection:

$E_{cluster} > 25$ MeV; $1.5^\circ < \theta_{cluster} < 4.5^\circ$; $N_{cluster} == 1$;
veto on signal in positron sandwich;
veot on charged particle in the calorimeter aperture;

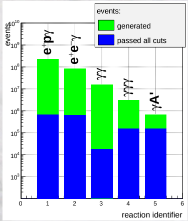


set:

$\varepsilon = \mathbf{0.1}$

Cross sections, mBarn

$e^+p\gamma$	21.0
$e^+e^-\gamma$	7.7
$\gamma\gamma$	1.4
$\gamma\gamma\gamma$	0.27



Monte Carlo: search sensitivity

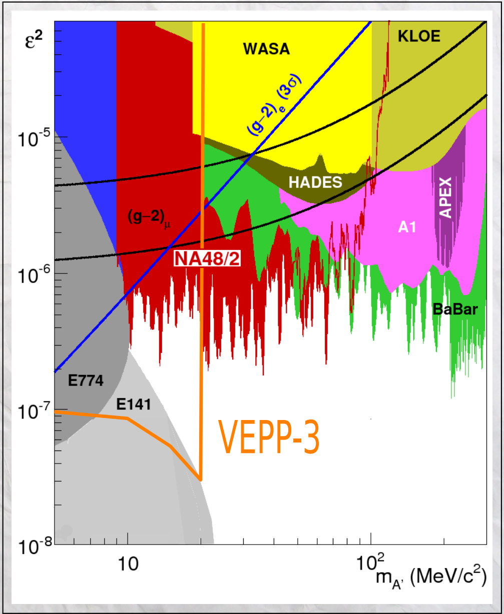
search conditions

- Beam energy $E_{e^+} = 500$ MeV
- luminosity $\mathcal{L} = 10^{33}$ cm^{-2}s^{-1} →
  - beam current 30 mA +
  - target thickness 5×10^{15} at/cm^2
- Run time $T = 10^7$ seconds →
  half-year with 65% time utilization
- width of search window: $\pm 2\sigma_{mis}$

MC results

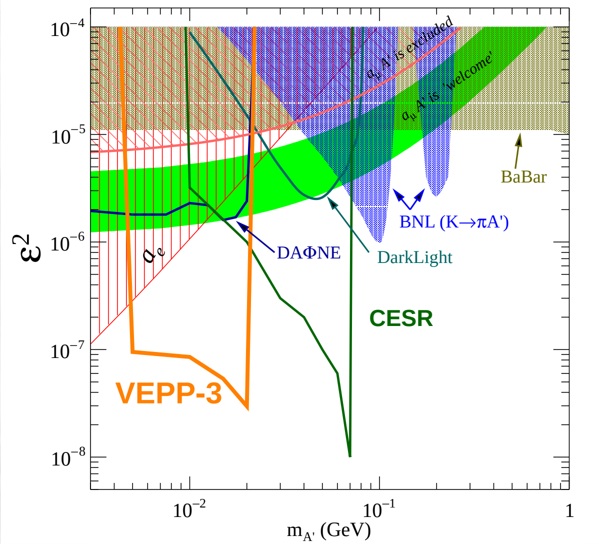
M'_A MeV	M_{miss} window MeV	ε^2 (95% CL)
5	±3.8	9.5×10^{-8}
10	±2.0	8.5×10^{-8}
15	±1.0	5.4×10^{-8}
20	±0.4	3.0×10^{-8}

A' decays to e^+e^-



Search sensitivity: decay mode-independent search of A'

Invisible decay of A'



Existing constraints

decay mode-independent:

- muon $(g_\mu - 2)$
- electron $(g_e - 2)$

invisible:

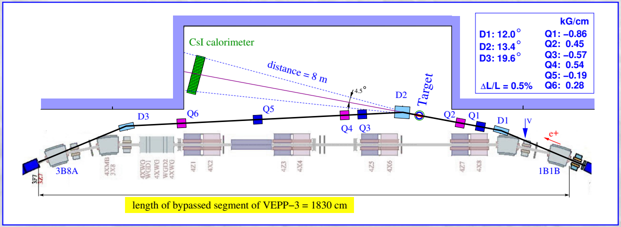
- BaBar $\Upsilon(1S) \to \gamma A'$
- BNL: $K \to \pi A'$

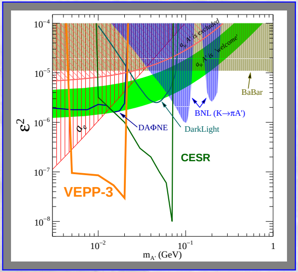
Proposed measurements

	$\mathcal{L}$	duration, s
VEPP-3:	10^{33},	10^7
CESR:	10^{34},	10^7
DAΦNE:	10^{28},	$2 \cdot 10^7$
DarkLight	$6 \cdot 10^{35}$	$2 \cdot 10^6$

Conclusion

- A decay mode independent search for a dark photon is effective in a setup with an intense positron beam and an internal hydrogen gas target.
- Crystals from the CLEO endcap EM-calorimeter would be a good choice for the photon-detector.
- If the proposal is accepted the measurement at the ByPass at VEPP-3 can be prepared and performed in 3-4 years.
- Budker Institute has a good opportunity to contribute to the worldwide hunt for a dark photon.





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THANK YOU!