SEARCHING FOR DARK PHOTONS WITH POSITRONS AT JEFFERSON LAB

Luca Marsicano
INFN Genova,Università Di Genova

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Dark Matter Search

- Dark Matter (DM) existence is highly motivated by various astrophysical observations (Galaxy Rotation Curves, CMBR fluctuations, collisions between galaxy clusters...)
- DM properties remain to date unknown (interactions with Standard Model, mass..)

DM Thermalization hypothesis: thermal equilibrium with primordial Universe and decoupling due to Universe cooling

→ Present DM density depends on DM-SM interaction properties

→ DM mass and interaction cross section are bound

If $m_{DM} \sim 100$ GeV → typical Weak Interaction cross section: “WIMP Miracle”

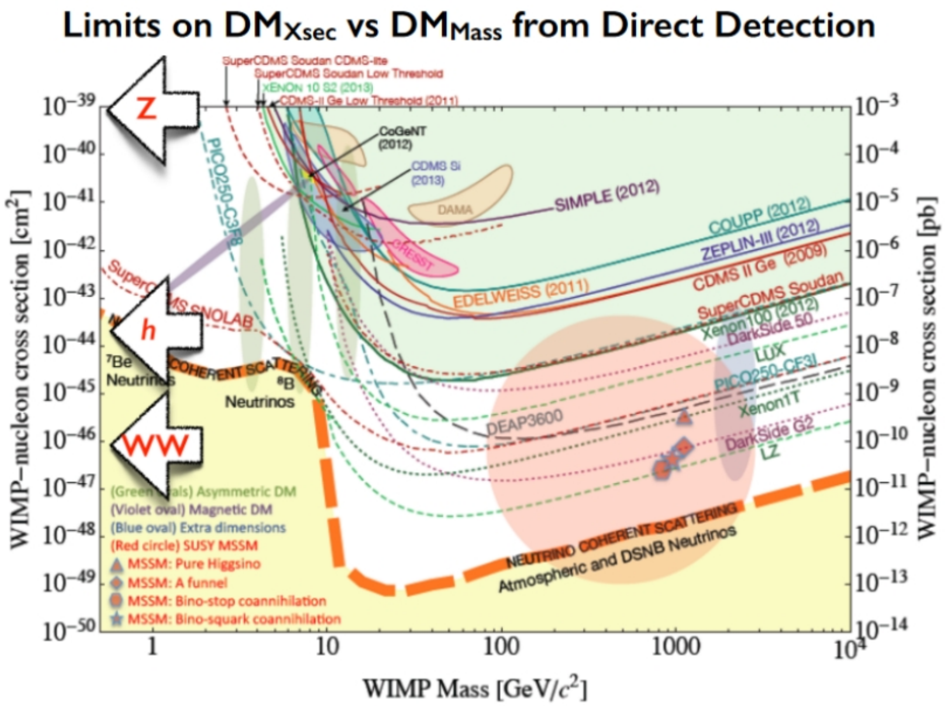
From WIMPs to Dark Sector

- WIMPs search: detectors made of large volumes of active materials to detect cosmogenic DM scattering over nuclei

  -low sensitivity to light DM candidates (<10 GeV)

- NO evidence of WIMP to date

  → Search for lower mass candidates



- To preserve DM thermalization: lower DM mass→higher interaction cross section → new force necessary

- Simplest Model: Dark Sector of χ (MeV-GeV mass range) particles coupled to SM through a U(1) massive gauge boson, the Dark Photon (A',U), kinetically mixed with SM photon:

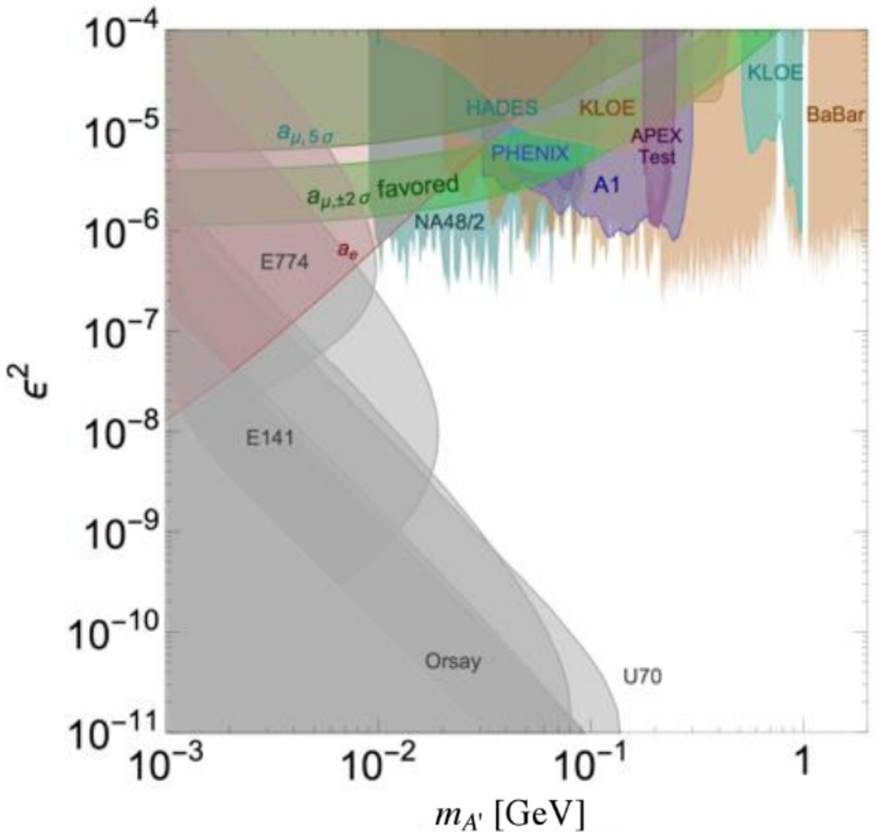
$$L_{kin.mix} = \varepsilon F^{\mu\nu} F'_{\mu\nu}$$

A' Invisible VS Visible Decay

A' decay depends on the $m_{A'}/m_\chi$ ratio:

- If $m_{A'} < 2m_\chi$, main decay:

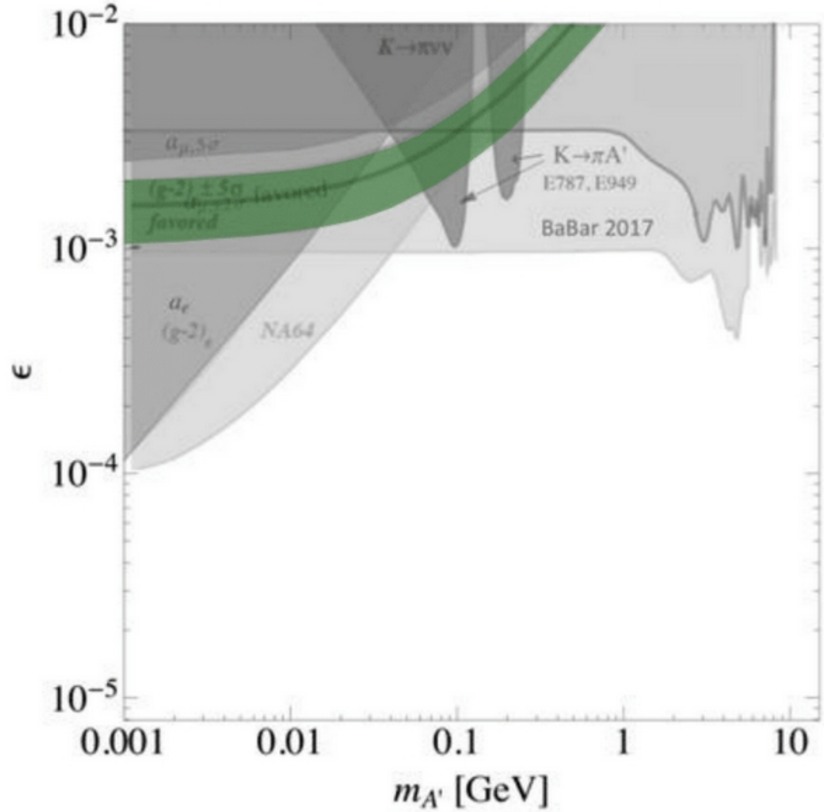
  Visible: $A' \rightarrow ll$



- If $m_{A'} > 2m_\chi$, main decay:

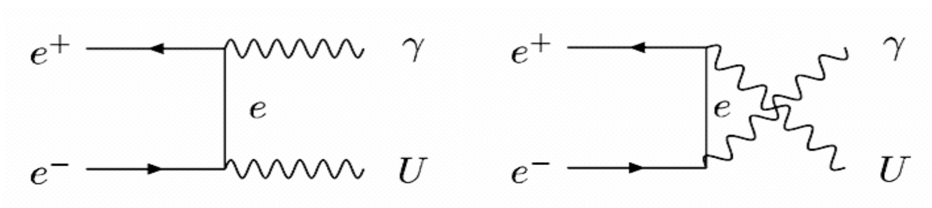
  Invisible: $A' \rightarrow \chi\chi$

The paradigm addressed in this work



Searching for A' with positrons

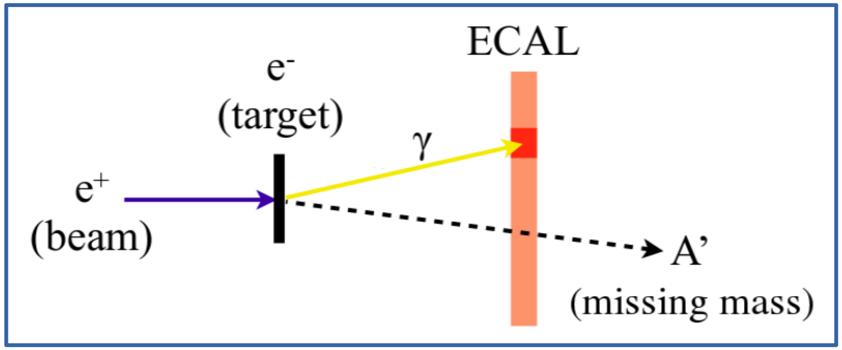
- A' production from e^+e^- annihilation:



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

- A' can be probed with e^+-on target experiments (e.g. PADME at LNF, *High Energy Phys.* 2014:959802; VEPP-3, arXiv:1207.5089 [hep-ex])
- Produced A' exit the detector volume without interacting
- Detect recoiling γ with EM calorimeter and compute the Missing Mass:

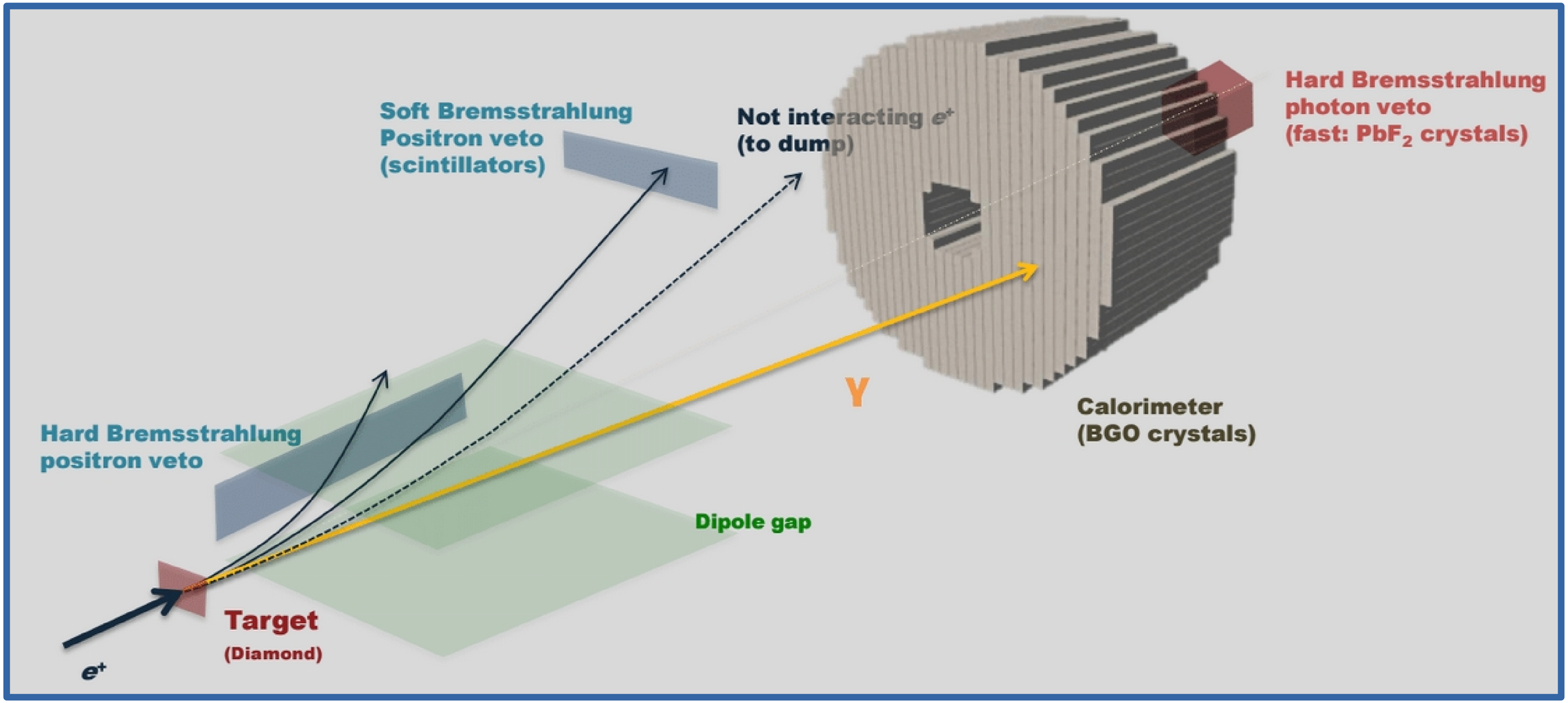
$$M^2_{MISS} = (P_e + P - P_\gamma)^2$$



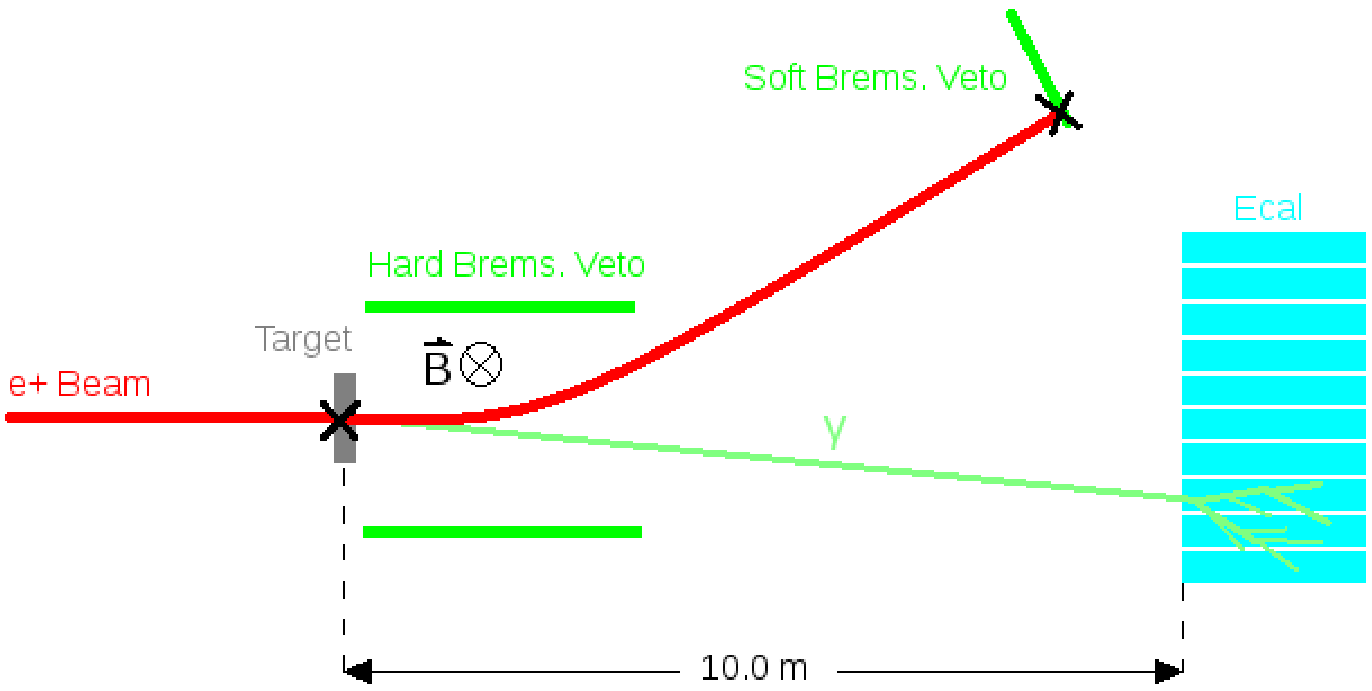
- Sensitivity of proposed experiments is limited by available energy in CM, going as $\sqrt{E_{BEAM}}$.
- 11 GeV e^+ beam @JLab would allow to exceed this limit

The PADME Experiment

- PADME is the first e+ on target experiment searching for Dark Photon
- 500 MeV DAΦNE-LINAC e^+ beam (search for A' masses up to ~ 22.5 MeV)
- 15 cm radius BGO calorimeter placed ~2 m downstream the target
- Magnet and Veto system to bend charged particles and reduce background from Bremsstrahlung events.



A' Experiment With e^+ @JLab



Required Beam Parameters:

- Current: 10 nA – 100 nA
- Energy: 11 GeV (Max $m_{A'}$ ~ 106 MeV)
- Momentum Dispersion <1%
- Angular Dispersion: <0.1 mrad

Target:

- Thickness: 100 μm (Possible to use thicker target, at the cost of a higher multiple scattering rate)
- Material: Carbon (compromise between density and low A/Z ratio)

Calorimeter Parameters

Cylindrical shape:

- Radius: 500 mm
- Inner hole: 20 mm radius
- 1x1x20 cm^3 crystals (indicative)
- Angular acceptance at a distance of 10 m from the target: ε ~ 50 mrad

Performance:

- Energy Resolution:

  σ(E)/E = 0.02/sqrt(E(GeV))
- Angular resolution:

  5mm/10m = 0.5 mrad
- Rate: ~20 kHz per crystal

Parameter:	ρ	MP	X_0^*	R_M^*	dE^*/dx	λ_I^*	τ_{decay}	λ_{max}	$n^\natural$	Relative output†	Hygro-scopic?	$d(LY)/dT$
Units:	g/cm^3	°C	cm	cm	MeV/cm	cm	ns	nm				%/°C‡
NaI(Tl)	3.67	651	2.59	4.13	4.8	42.9	245	410	1.85	100	yes	−0.2
BGO	7.13	1050	1.12	2.23	9.0	22.8	300	480	2.15	21	no	−0.9
BaF_2	4.89	1280	2.03	3.10	6.5	30.7	650^s	300^s	1.50	36^s	no	-1.9^s
							0.9^f	220^f		4.1^f		0.1^f
CsI(Tl)	4.51	621	1.86	3.57	5.6	39.3	1220	550	1.79	165	slight	0.4
CsI(pure)	4.51	621	1.86	3.57	5.6	39.3	30^s	420^s	1.95	3.6^s	slight	−1.4
							6^f	310^f		1.1^f		
$PbWO_4$	8.3	1123	0.89	2.00	10.1	20.7	30^s	425^s	2.20	0.3^s	no	−2.5
							10^f	420^f		0.077^f		
LSO(Ce)	7.40	2050	1.14	2.07	9.6	20.9	40	402	1.82	85	no	−0.2
$LaBr_3$(Ce)	5.29	788	1.88	2.85	6.9	30.4	20	356	1.9	130	yes	0.2

Materials:

- PbWO4, LSO(Ce) best options: high light yield and density, small R_M and X_0, fast decay (good for timing and pile up)
- BGO,BSO slower, lower light yield, but still valuable options

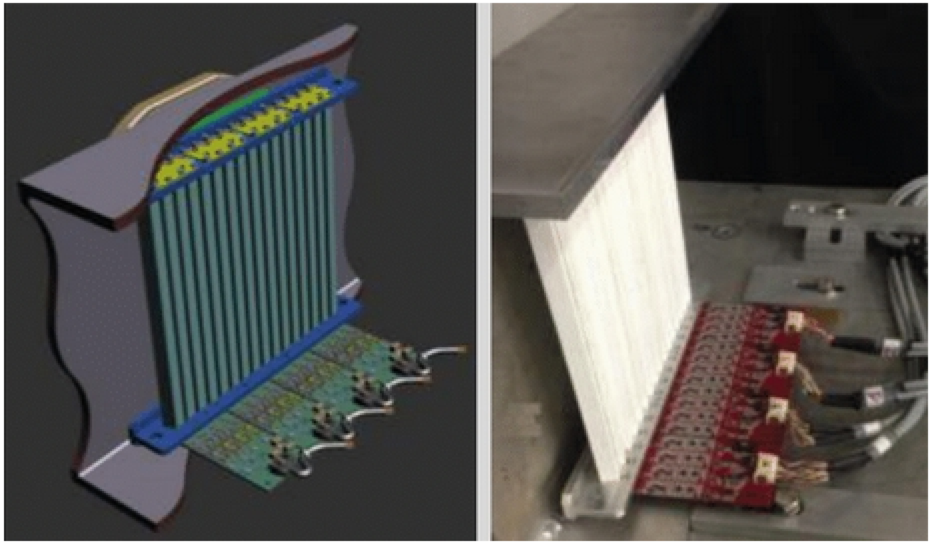
Magnet And Veto System

- Magnetic field in the target region is necessary to bend away the beam and other charged particles from the ECal trajectory
- A constant field of 2 T over a 2 m region is required (easily achievable)
- e^+ losing energy via Bremsstrahlung in the target hit the veto detectors
- An efficiency $\varepsilon = 99.5\%$ is assumed for the veto system; (efficiency achieved by PADME detector)

  → A $5X10^{-3}$ reduction of Brem. background is assumed

PADME Veto System

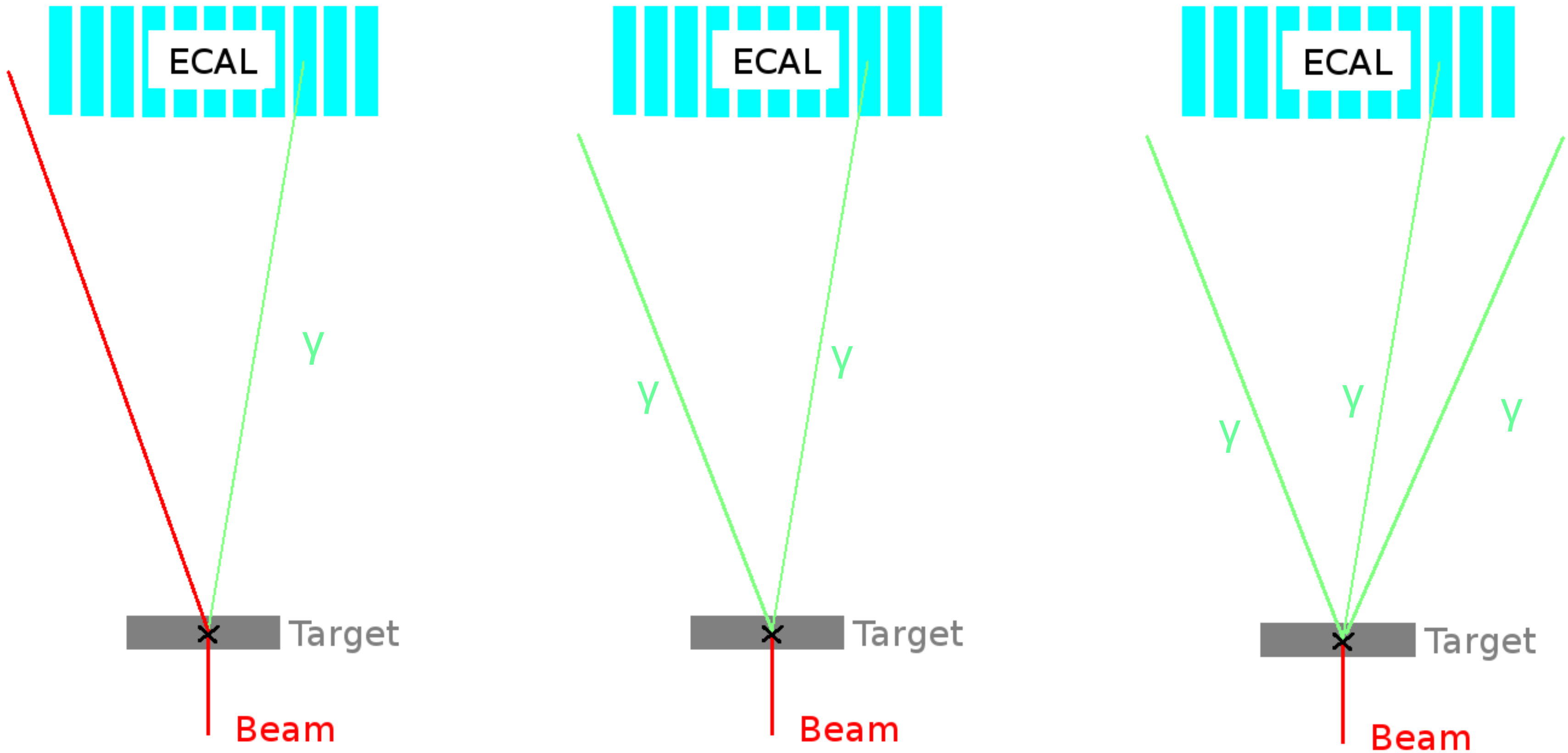
-Time resolution better than 500 ps
-Efficiency better than 99.5% for MIPs
-10X10X180 mm^3 plastic scintillator bars



Main Background Processes

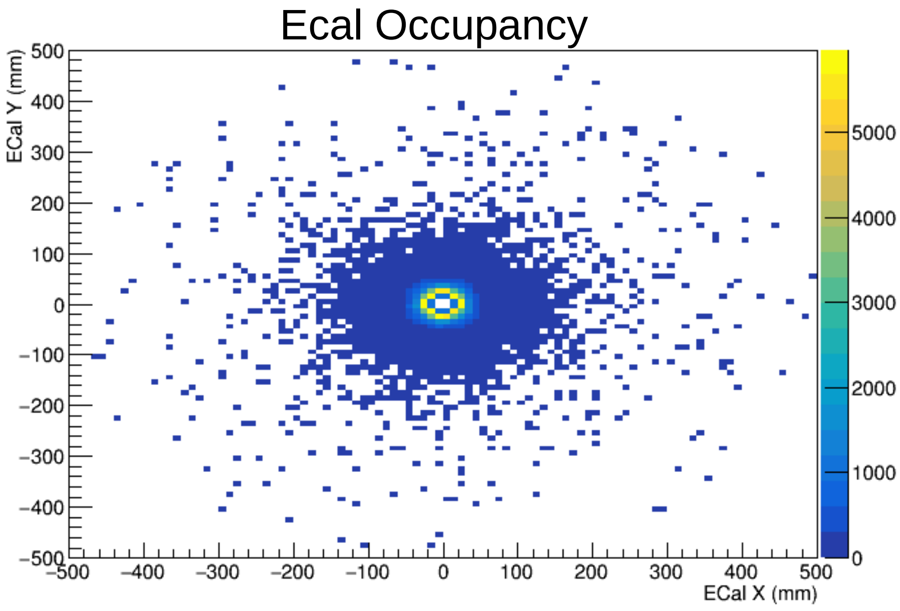
Main processes that result in a single gamma hitting the ECal:

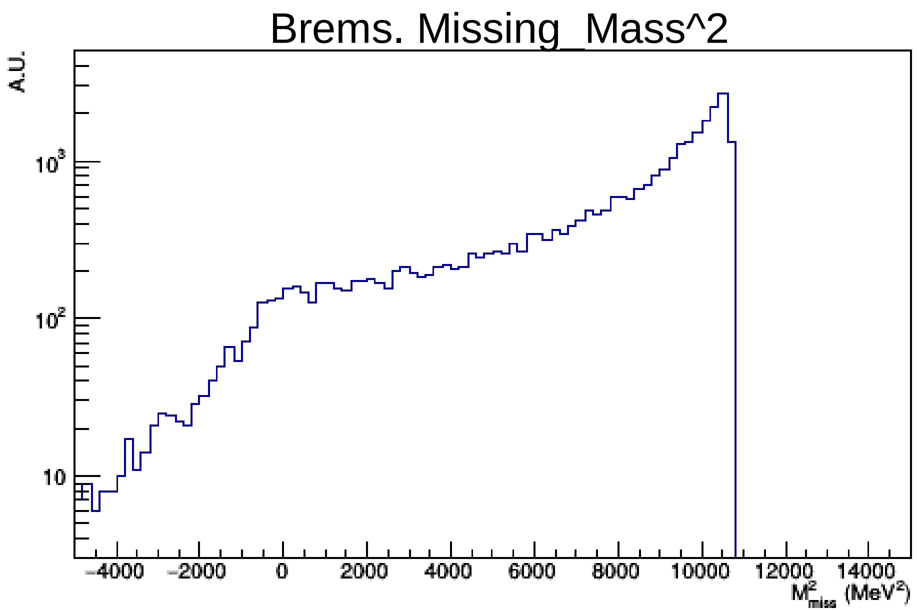
Bremsstrhalung | **2-γ Annihilation** | **3-γ Annihilation**



Bremsstrahlung Background

- Brems. background estimated using GEANT4
- Simulation of $2X10^{10}$ 11 GeV positrons impinging on the carbon target
- Missing mass spectrum computed for γs reaching the volume of the ECal
- The majority of γ from Brems. process falls into the Ecal central hole
- Still, Brems. is the biggest contribution to the γ rate on the Ecal (20 Khz per crystal with I=10 nA and 100 μm target)





2-γ Annihilation

- 2-γ ann. background evaluated using *CALCHEP* (arXiv:1207.6082 [hep-ph])
- 10^6 annihilations are generated and the topology of events is studied:

  - In the ~75% of simulated events no γ hits in the Ecal volume

  - In the ~24% both γ hit the ECal (event can be rejected)

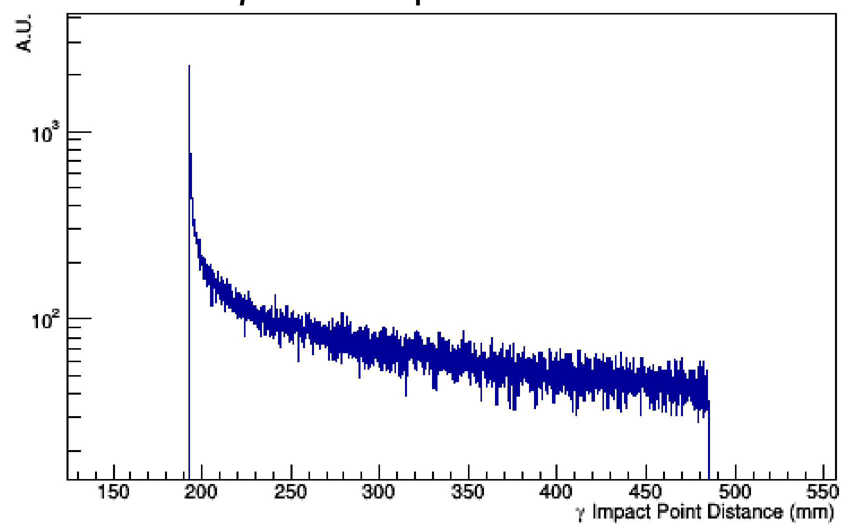
  -In the ~1.4% one γ hits the ECal

- The energy for single γ hits is centered at ~ 420 MeV

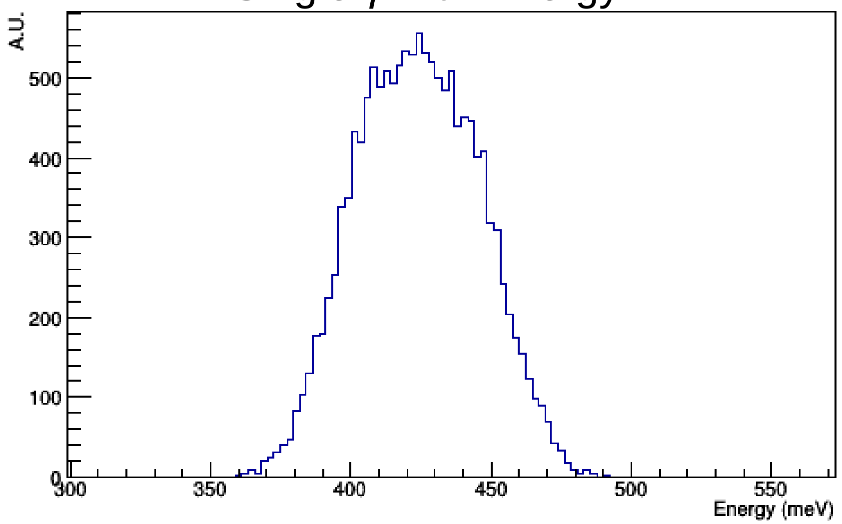
  with energy cut E_{cut} = 500 MeV →

  10^{-4} reduction → 2-γ ann. background is negligible

Double γ Hit – Impact Point Distance



Single γ Hit - Energy

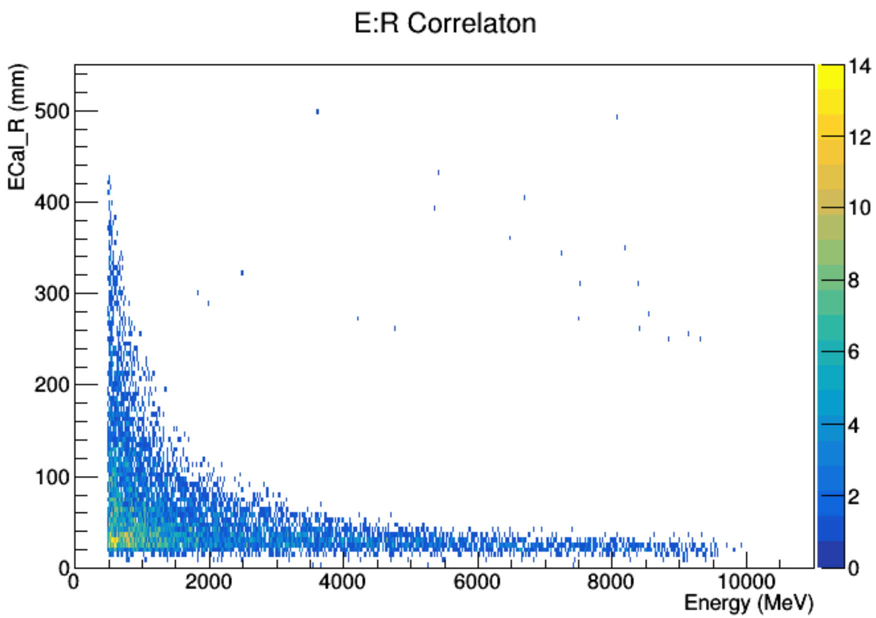


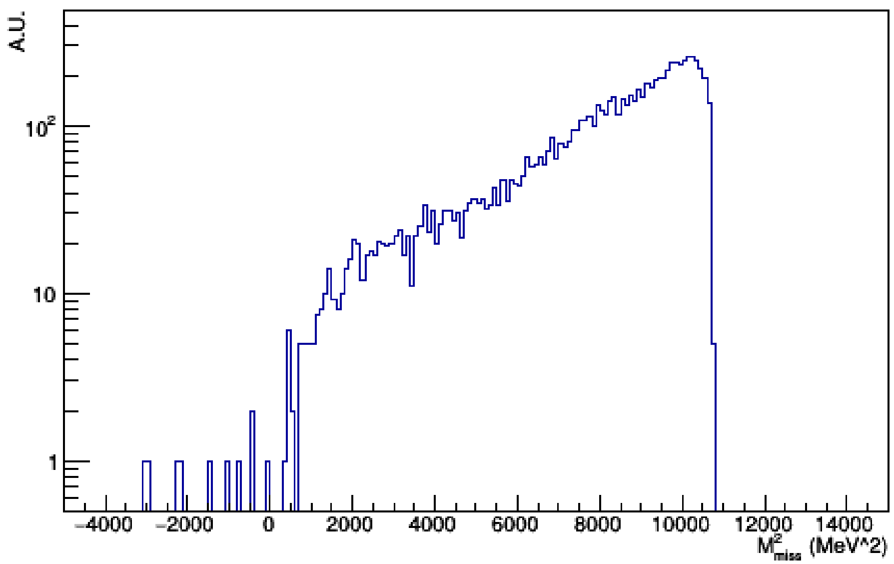
3-γ Annihilation

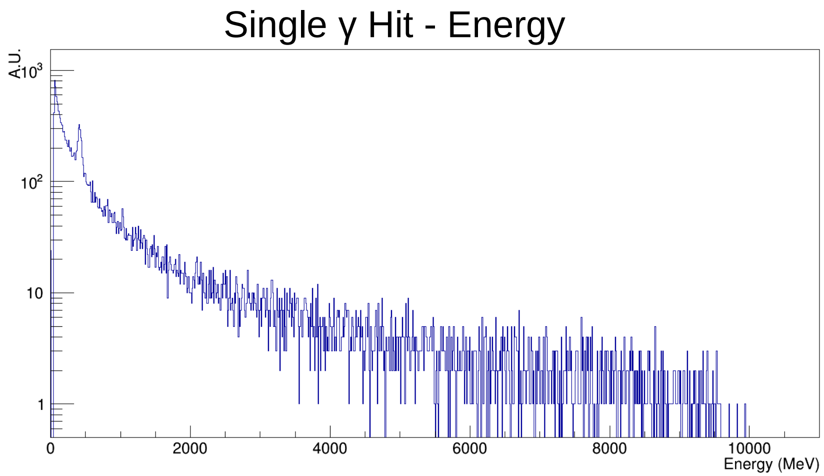
- Same procedure used for 2-γ ann. background
- Total 3-γ ann. cross section:

$$\sigma_{e+e-\rightarrow\gamma\gamma\gamma} \sim 0.16\,\sigma_{e+e-\rightarrow\gamma\gamma}$$

- In the ~17% of events a single γ hits Ecal
- Background from 3-γ ann. can't be neglected





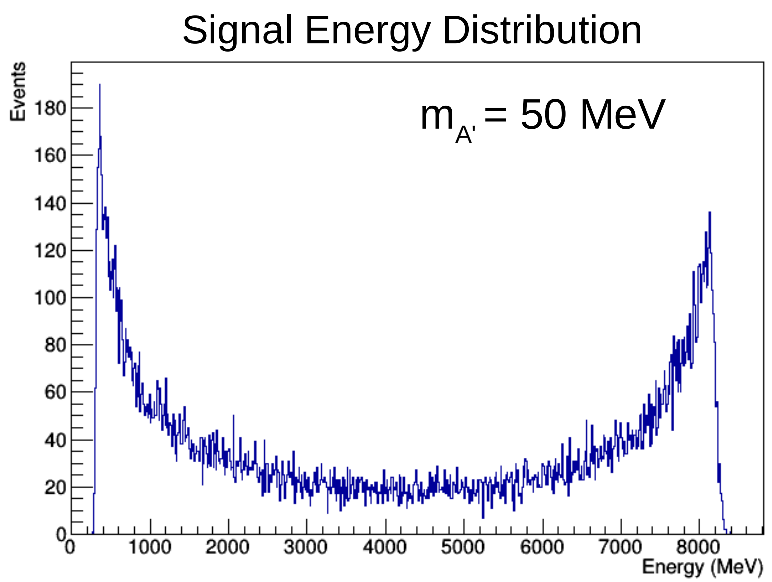


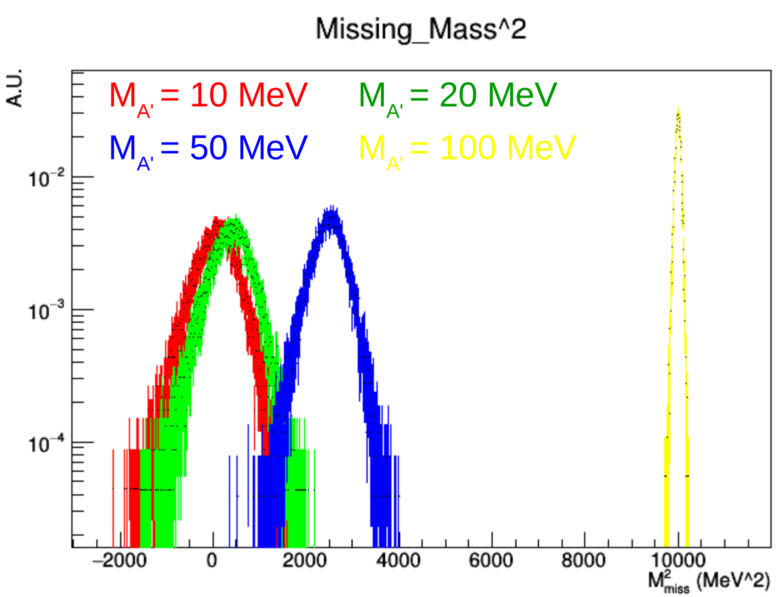
Signal

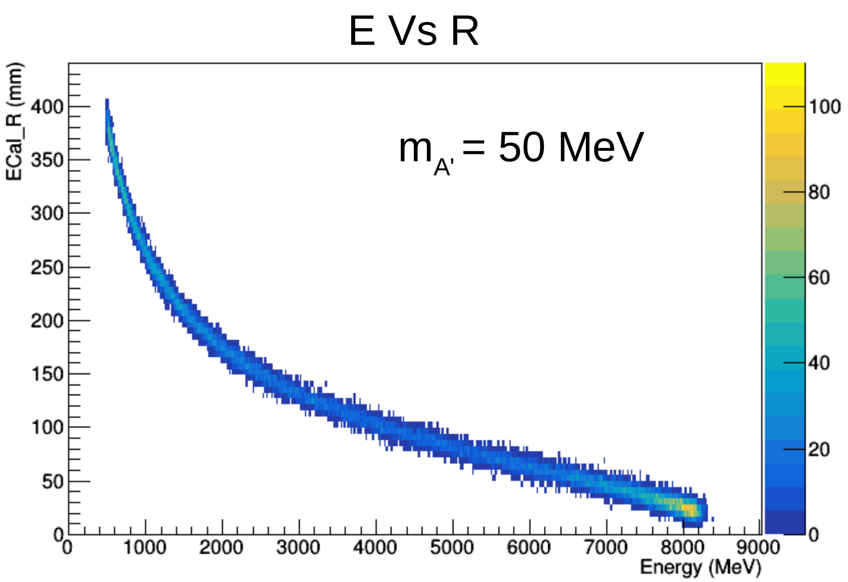
- Signal events generated with *CALCHEP* for 6 different values of $m_{A'}$ in the 1-103 MeV range
- Total cross section (outside resonance region):

$$\sigma_{e+e- \to \gamma A'} \sim 2\, \varepsilon^2\, \sigma_{e+e- \to \gamma\gamma}$$

- Estimated signal acceptance with E_{cut} = 500 MeV: $\varepsilon(m_{A'})$ ~0.2 (roughly independent of $m_{A'}$)
- Missing Mass spectrum computed for different A' masses; measured M_{miss}^2 resolution $\sigma(m_{A'}^2)$







Reach Calculation

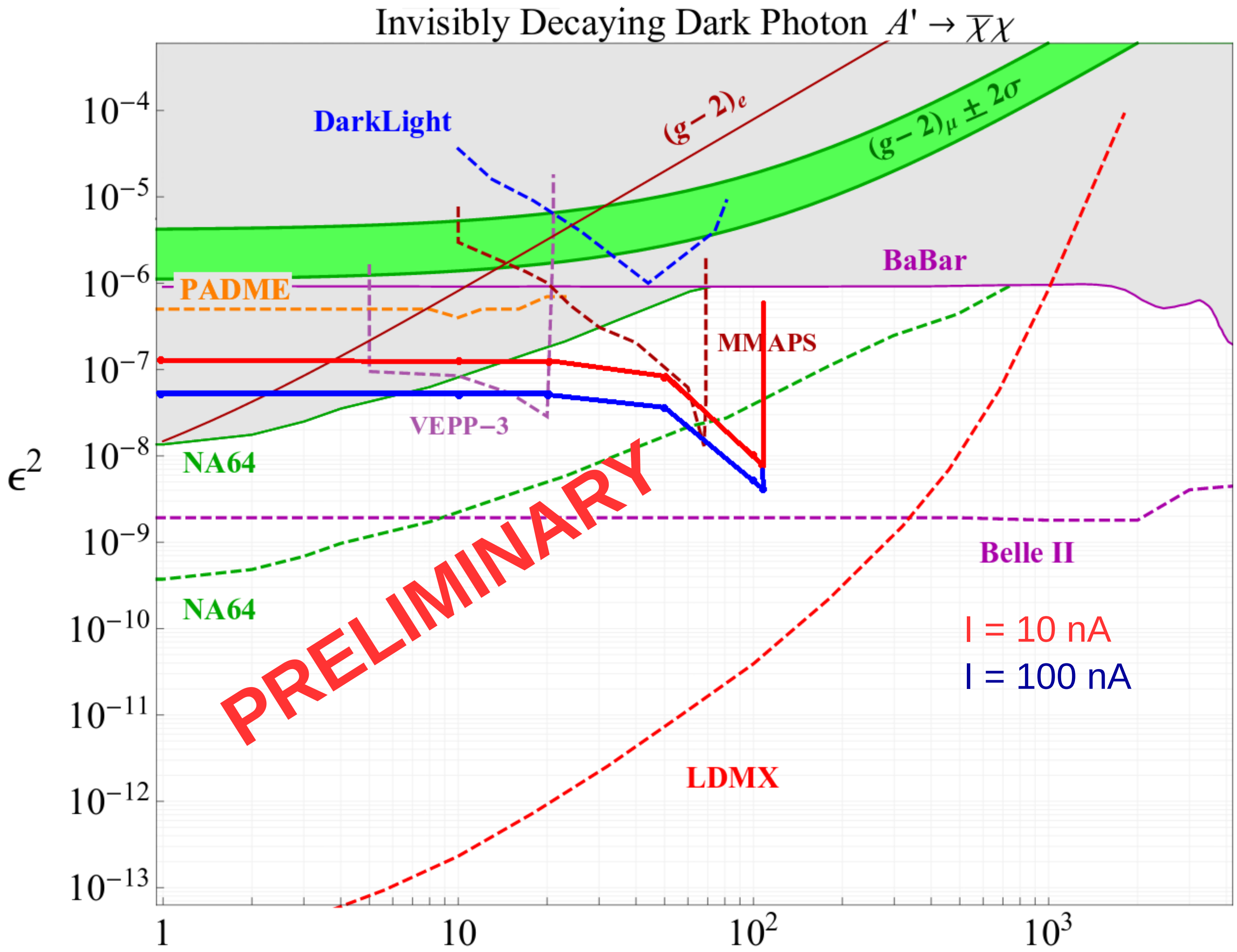
- Measurement run of 1 year, with 50% beam on time.
- $N_s(m_A)$: number of expected signal events for a given $m_{A'}$; mixing parameter value fixed to $\varepsilon = 1$
- $N_B(m_A)$: number of expected background events (from both brems. and 3γ-ann.) with computed M_{miss}^2 in the interval:

$$[m_{A'}^2 - 2\,\sigma(m_{A'}^2)\,,\, m_{A'}^2 - 2\,\sigma(m_{A'}^2)\,]$$

- Minimum measurable value of ε^2:

$$\varepsilon^2_{min}(m_{A'}) = 2\,\frac{\sqrt{N_B(m_{A'})}}{N_S(m_{A'})}$$

Reach



Invisibly Decaying Dark Photon $A' \to \overline{\chi}\chi$
DarkLight
$(g-2)_e$
$(g-2)_\mu \pm 2\sigma$
BaBar
PADME
MMAPS
VEPP−3
NA64
NA64
PRELIMINARY
Belle II
I = 10 nA
I = 100 nA
LDMX
ϵ^2
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
1
10
10^2
10^3

Conclusions

- A preliminary study of the achievable sensitivity for a Dark Photon experiment with a 11 GeV e+ beam at Jefferson Lab was carried out
- The assumptions made on the detector performance (electromagnetic calorimeter resolution, veto system efficiency) are consistent with existing detectors
- This experiment would probe unexplored regions of the A' parameter space, exceeding in sensitivity other Missing Mass experiments
- The unique features of a positron beam at JLab (high energy, continuous structure, capability to switch between different energy values) would make it the best option for this class of experiments