How to Measure the Spin of Dark Matter in $e^+e^- \to \gamma + X$

Bauer & Erner [arXiv:2308.09746]

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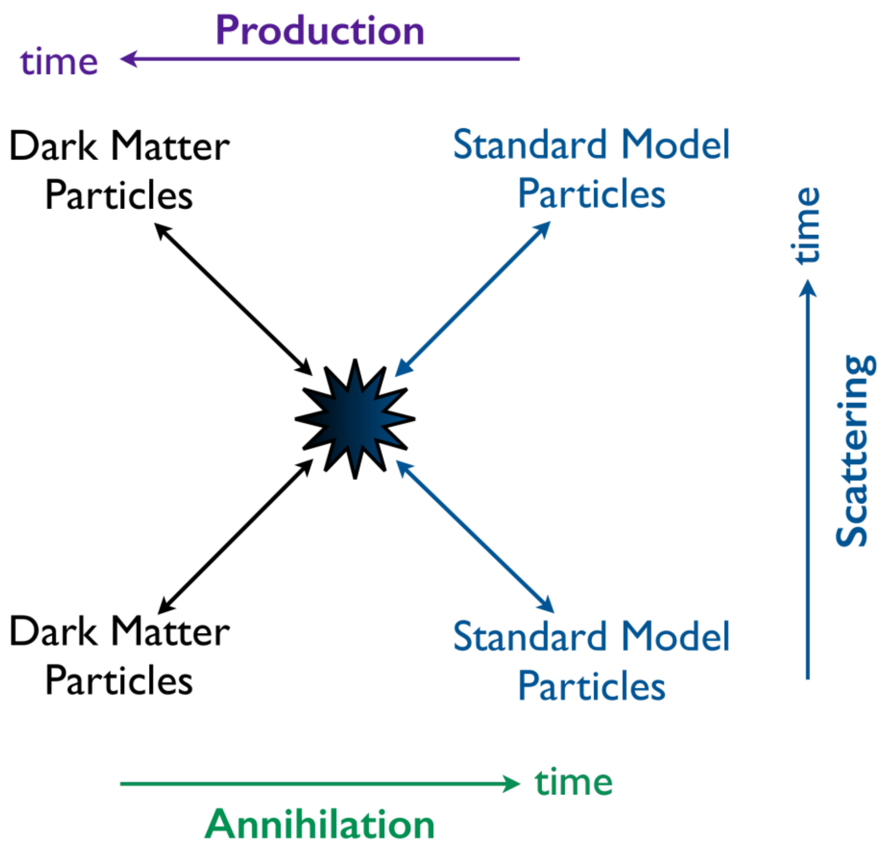
Introduction

With current collider experiments

- Can determine mass and coupling strength
- Cannot determine quantum numbers such as spin

⇒ Dark matter models are indistinguishable



https://particleastro.brown.edu/dark-matter/

Outline

Goal

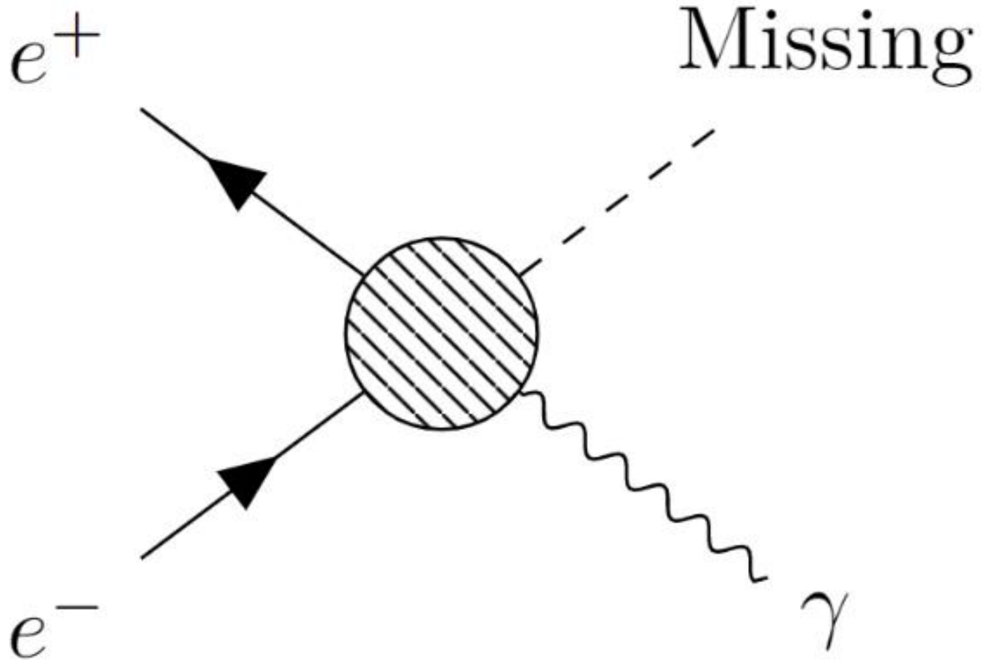
Measure the Spin of Dark Matter

- Process
- Standard Model Background
- Dark Matter Models
- Currently in Detectors
- Polarised Beams
- Conclusion

Process

- Mono-photon signal with missing energy

- Collider: Belle II
  - Beam Energies: 4 & 7 GeV
  - Asymmetric Angular Coverage

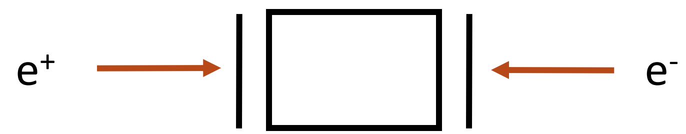


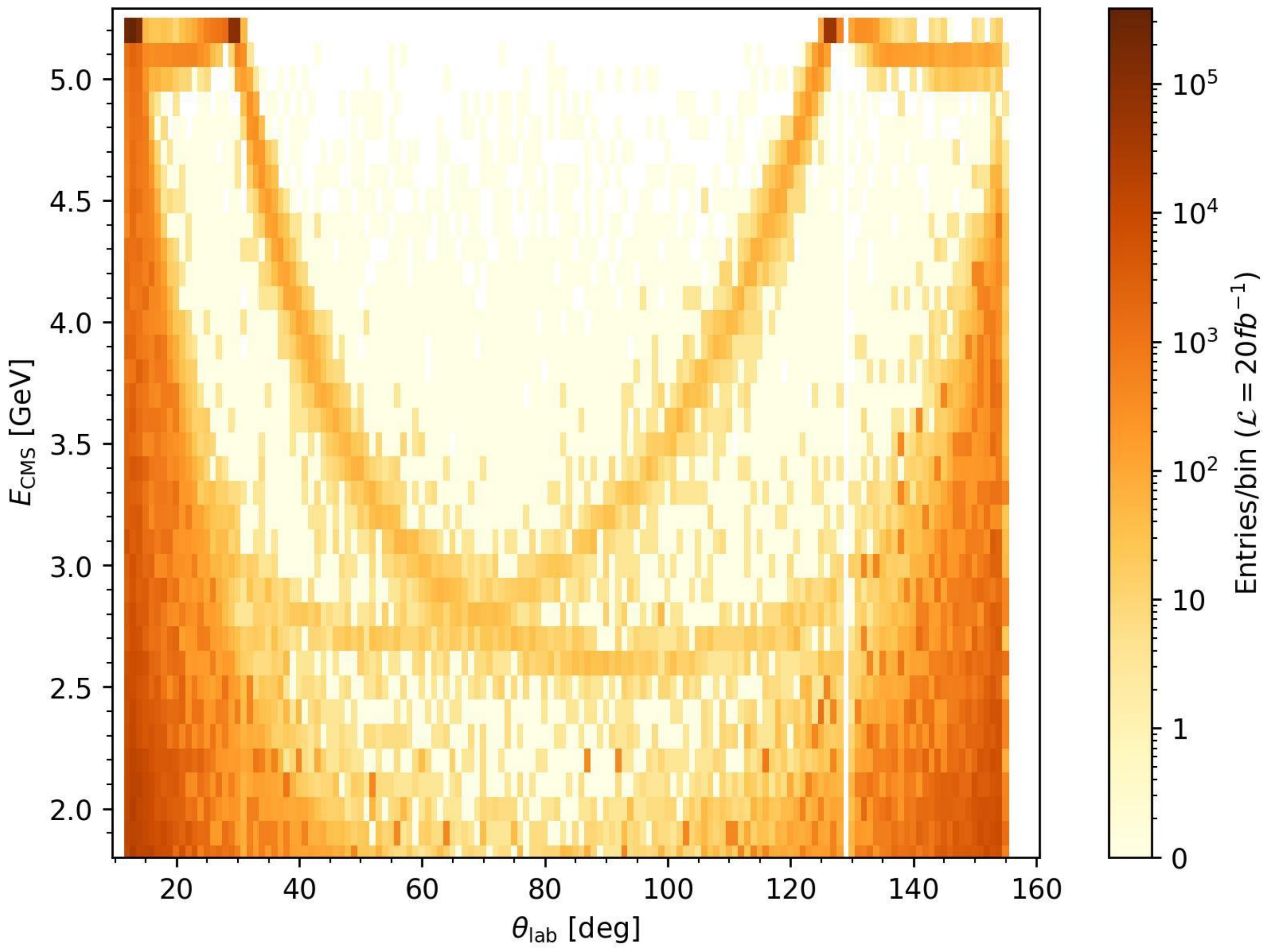
Standard Model Background

Processes:

- $e^+ e^- \rightarrow$
  - $\gamma \gamma (\gamma)$
  - $e^+ e^- \gamma (\gamma)$
  - $\bar{\nu} \nu \gamma (\gamma)$

- All particles but one photon undetected
  - Asymmetric angular coverage
  - Gaps between barrel and endcaps





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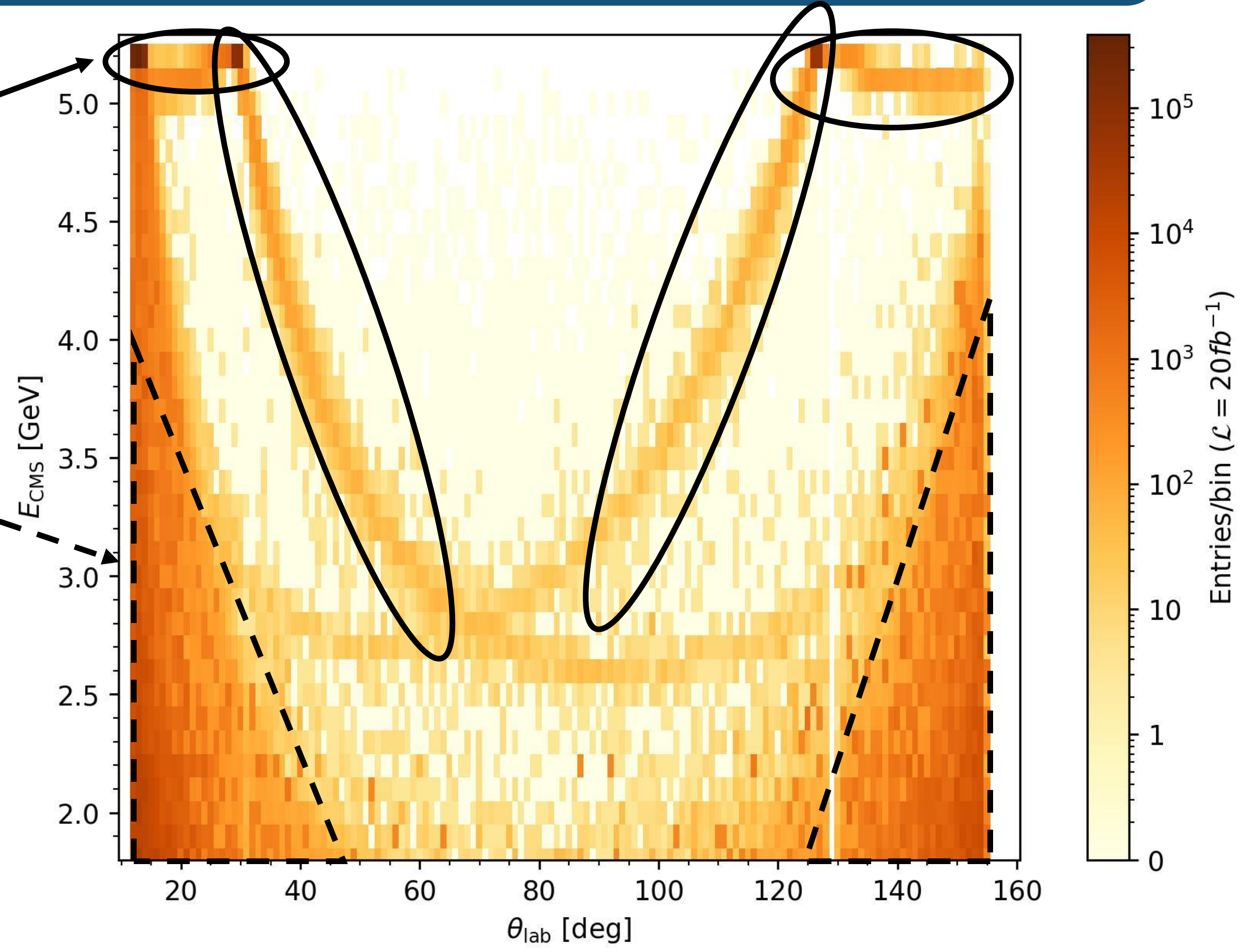


- All particles but one photon undetected
  - Asymmetric angular coverage
  - Gaps between barrel and endcaps

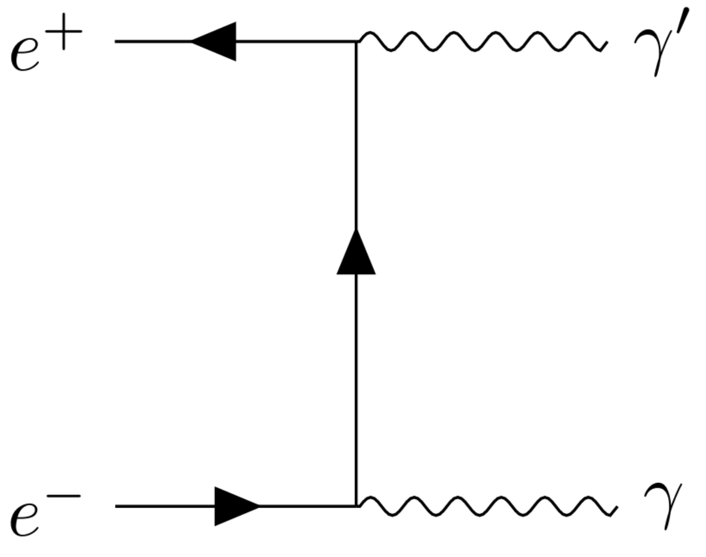
- Neutrino background irreducible & everywhere

Dark Matter Models

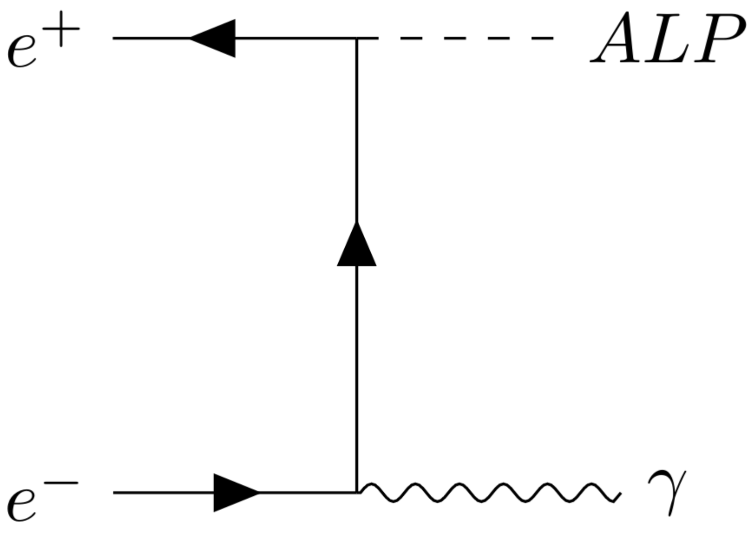
Type & Spin	Fermion Coupling	Photon Coupling
Axion-Like-Particles (ALPs)		
Pseudo-Scalar spin-0	$-\frac{c_{ff}}{f_a} a \sum_\psi m_\psi \bar{\psi}\gamma^5\psi$	$-\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu}$ $g_{a\gamma\gamma} = {}^4/_{f_a}\left(C_{BB} c_\theta^2 + C_{WW} s_\theta^2\right)$
Dark Photon		
Vector spin-1	$-g_X X_\mu \sum_{e,\mu,\tau}\left(\bar{L}\gamma^\mu L + \bar{l}\gamma^\mu l\right)$	NA

Dark Matter Models

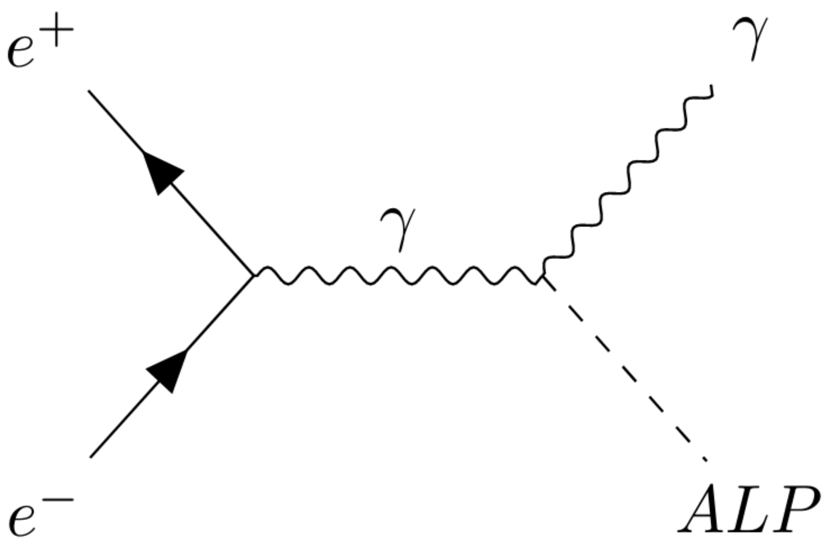
Dark Photon



ALP t/u-channel



ALP s-channel



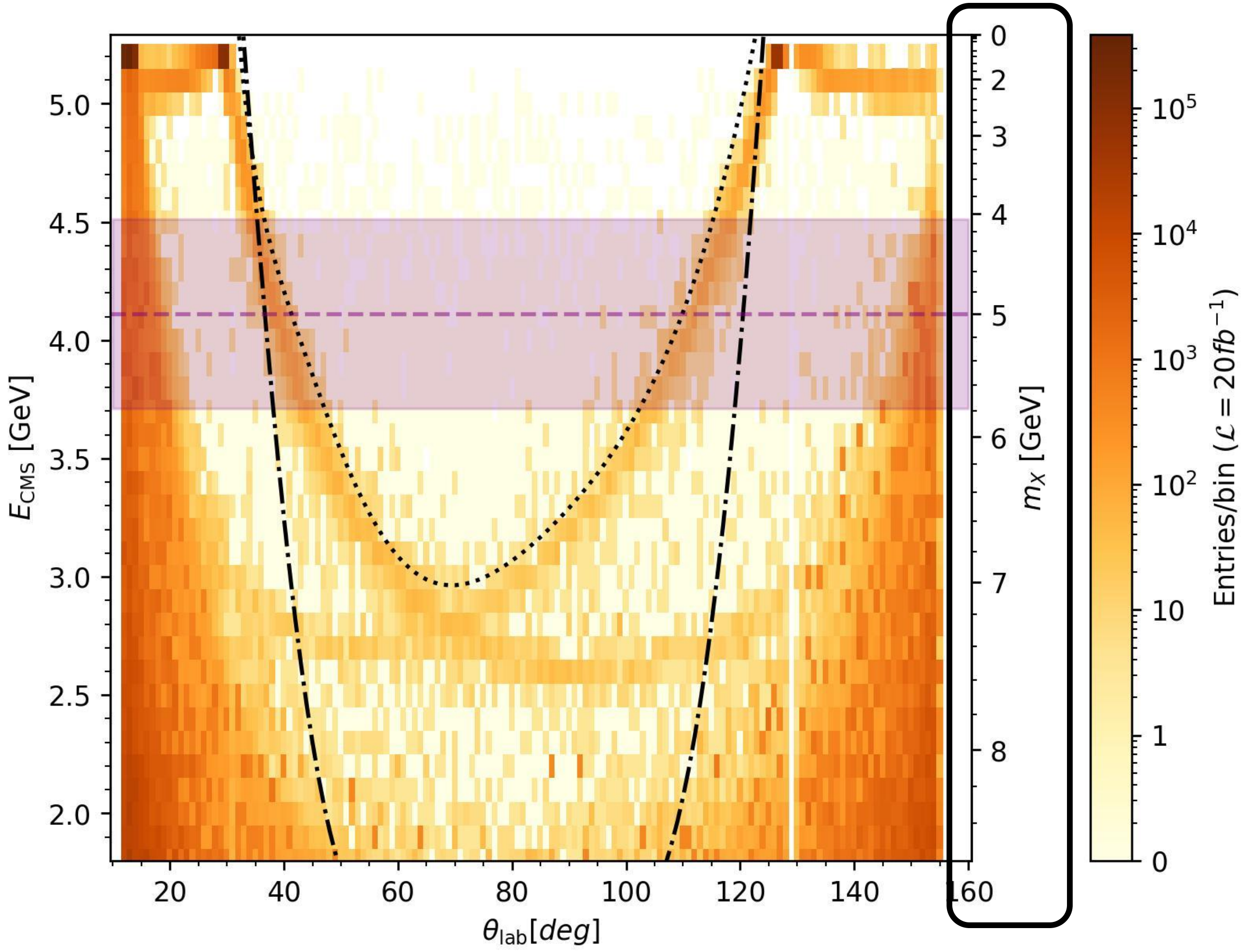
Currently in Detectors

- 2 → 2 scattering

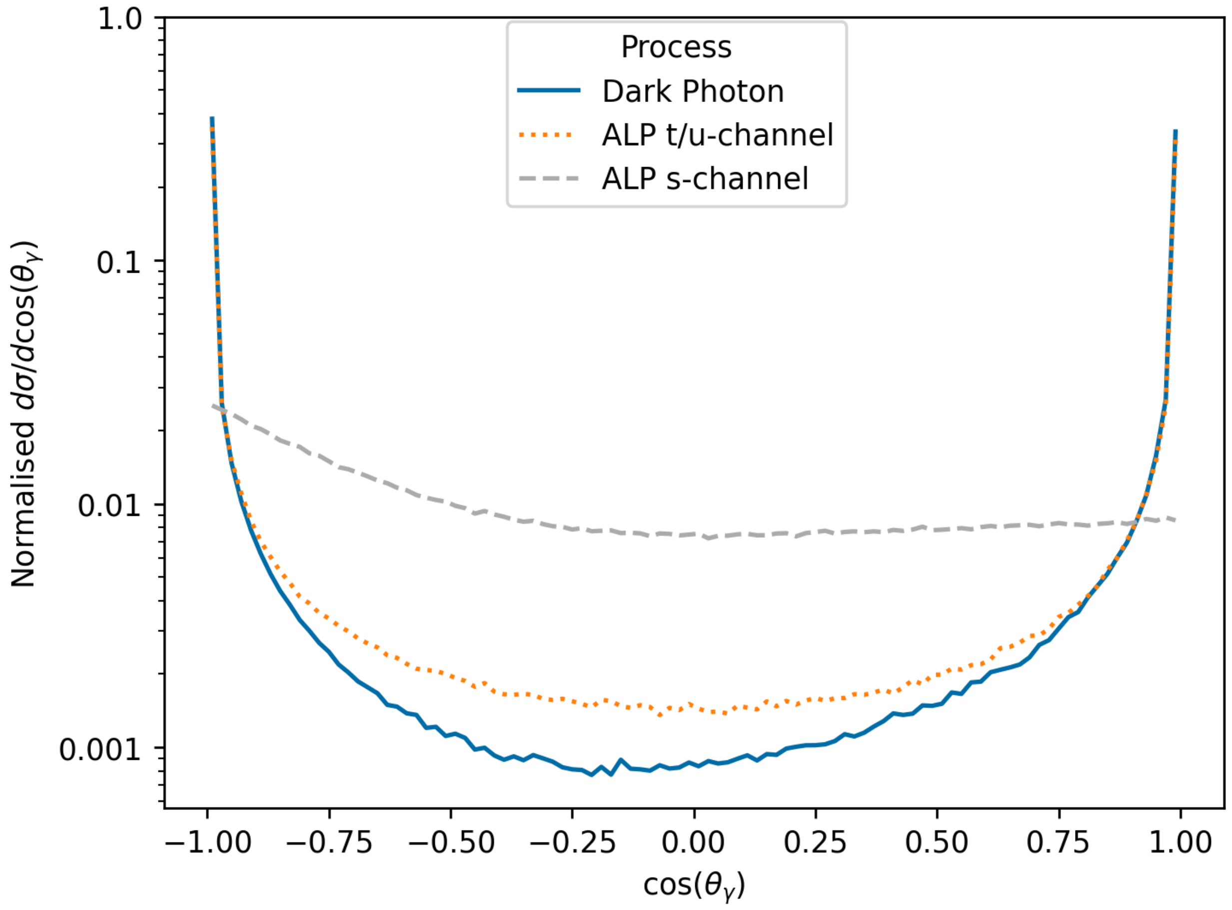
⇒ Final photon E_{CMS} function of dark matter mass

  - Not including initial-state-radiation (ISR)

- Same for all DM contributions



Currently in Detectors



Angular Distribution

- Difference between s- and t/u-channel contributions
  - Distinguish between ALP contributions
  - Cannot distinguish between ALP and Dark Photon t/u-channel contributions

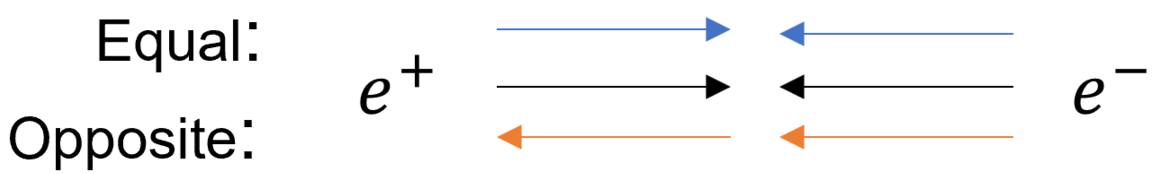
Polarised Beams

Planned: 70% electron beam polarisation at Belle II

Interest: 100% polarise both beams

Polarised Beams

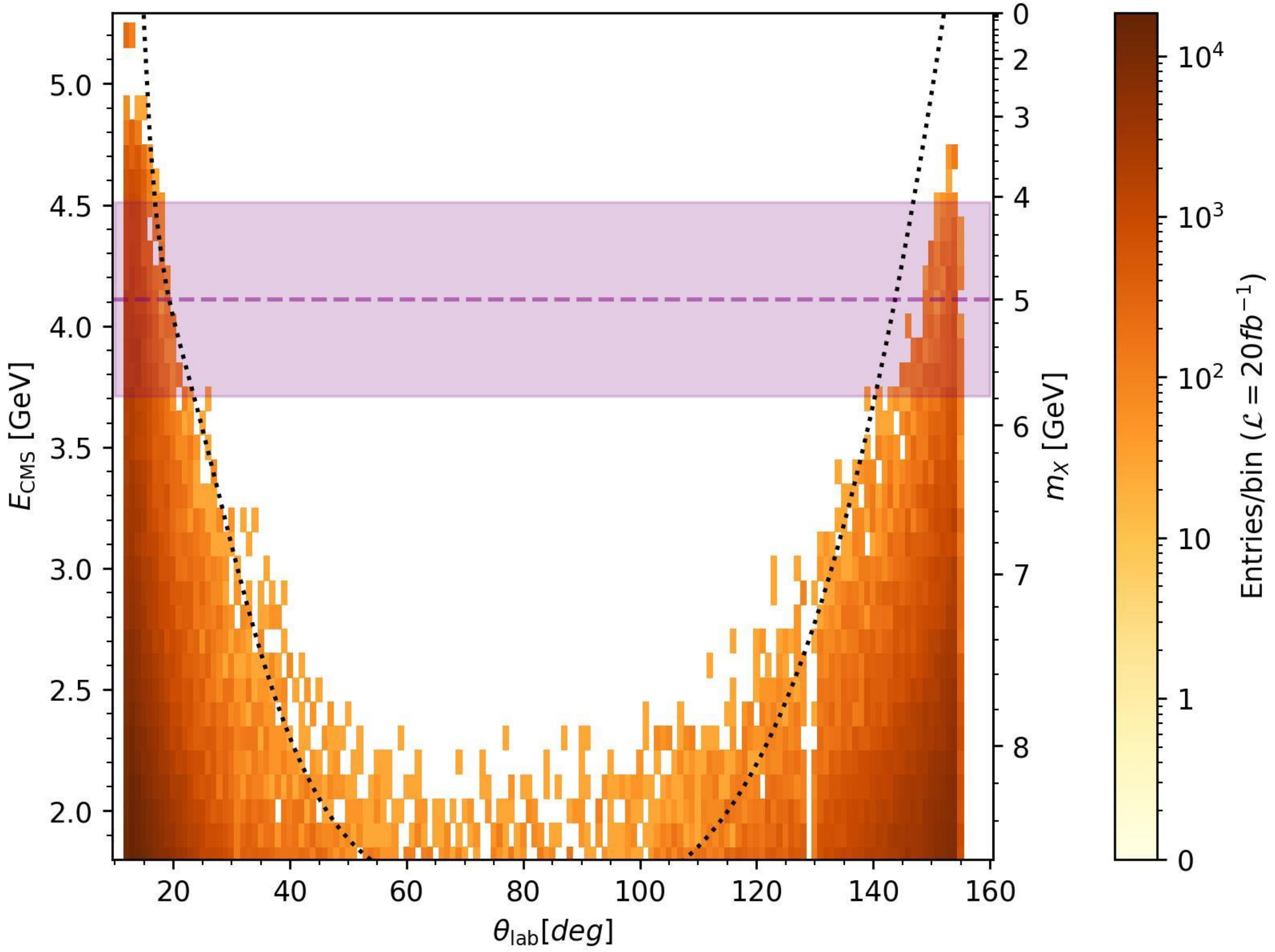
Allows for "selection" of processes as they require specific spin structures



Polarisation	Opposite	Equal
DM Signal present	Dark photon & ALP s-channel	ALP t/u-channel

Distinguish t/u-channel Dark Photon and ALPs contributions

Polarised Beams

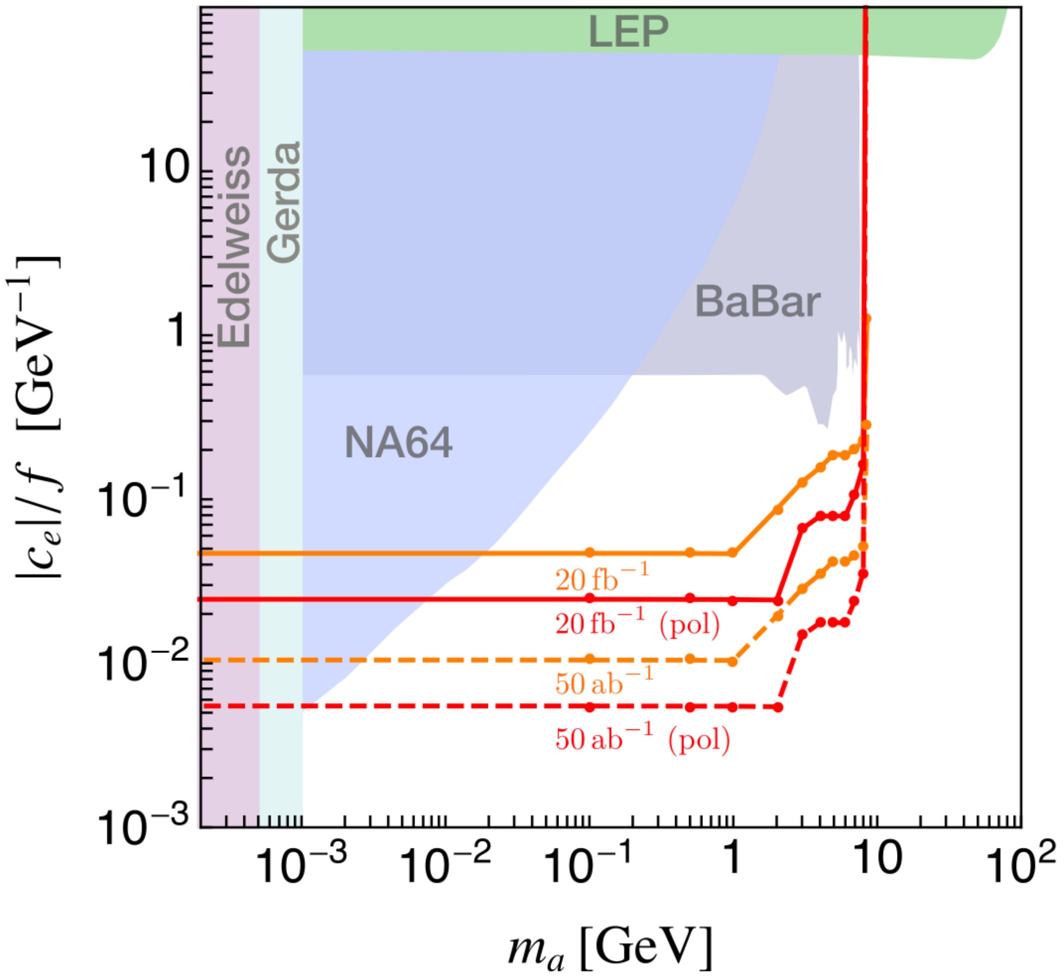


Reduced SM background for equally polarised beams

- Photon-only final states drop out

⇒ Provide significantly better exclusion limits on ALP-fermion coupling

Polarised Beams



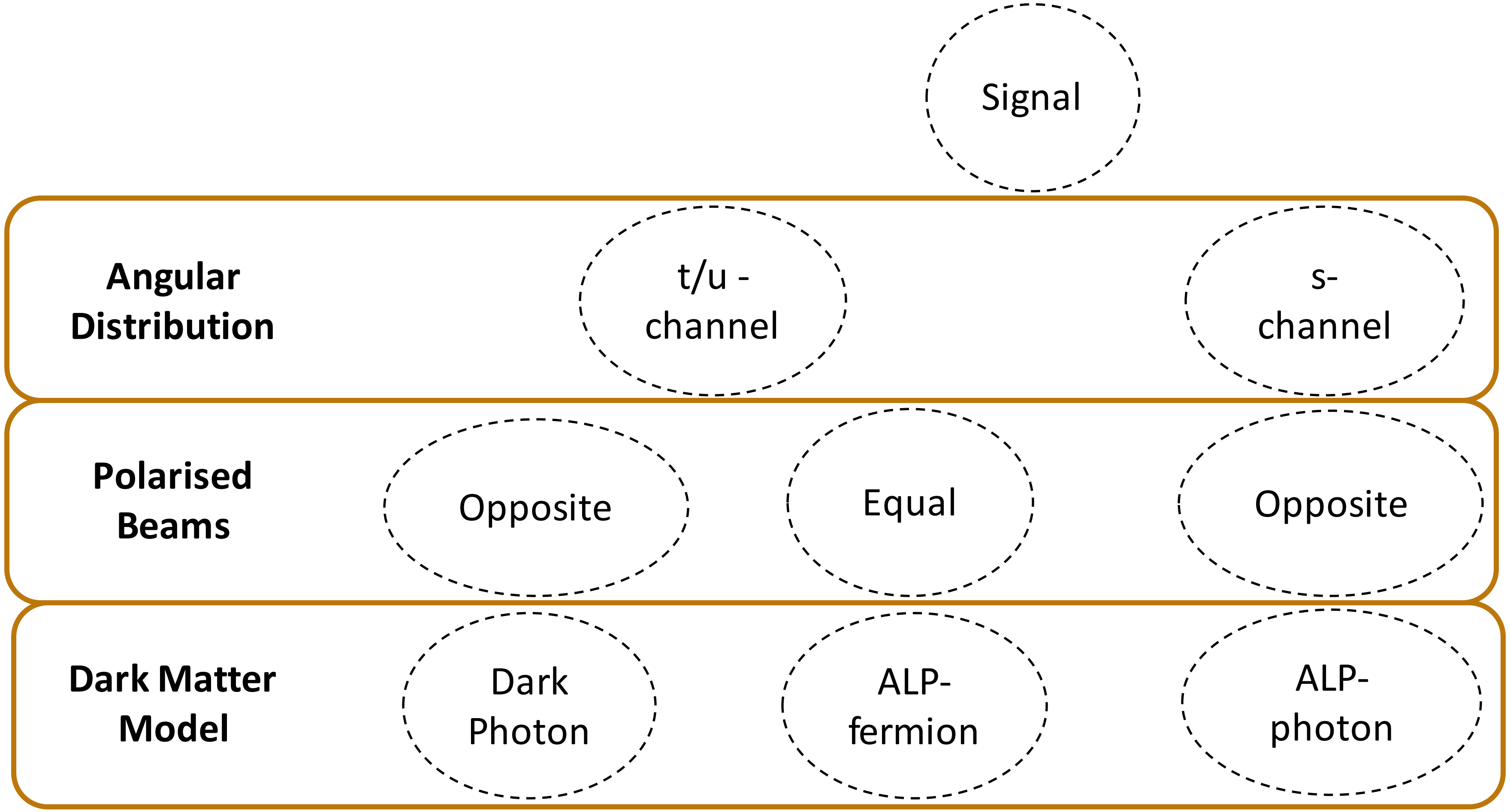
Reduced SM background for equally polarised beams

⇒ Provide significantly better exclusion limits on ALP-fermion coupling

Orange: Unpolarised beams

Red: Beams with equal polarisation

Conclusion


Signal
Angular Distribution
t/u - channel
s- channel
Polarised Beams
Opposite
Equal
Opposite
Dark Matter Model
Dark Photon
ALP- fermion
ALP- photon

Conclusion

- Separate the dark matter contributions

⇒ Distinguish between spin-0 ALP and spin-1 Dark Photon

⇒ **Measure the Spin of Dark Matter**

- Reduced SM background for equally polarised beams

⇒ Provide significantly better exclusion limits on ALP-fermion coupling

Thanks for listening!

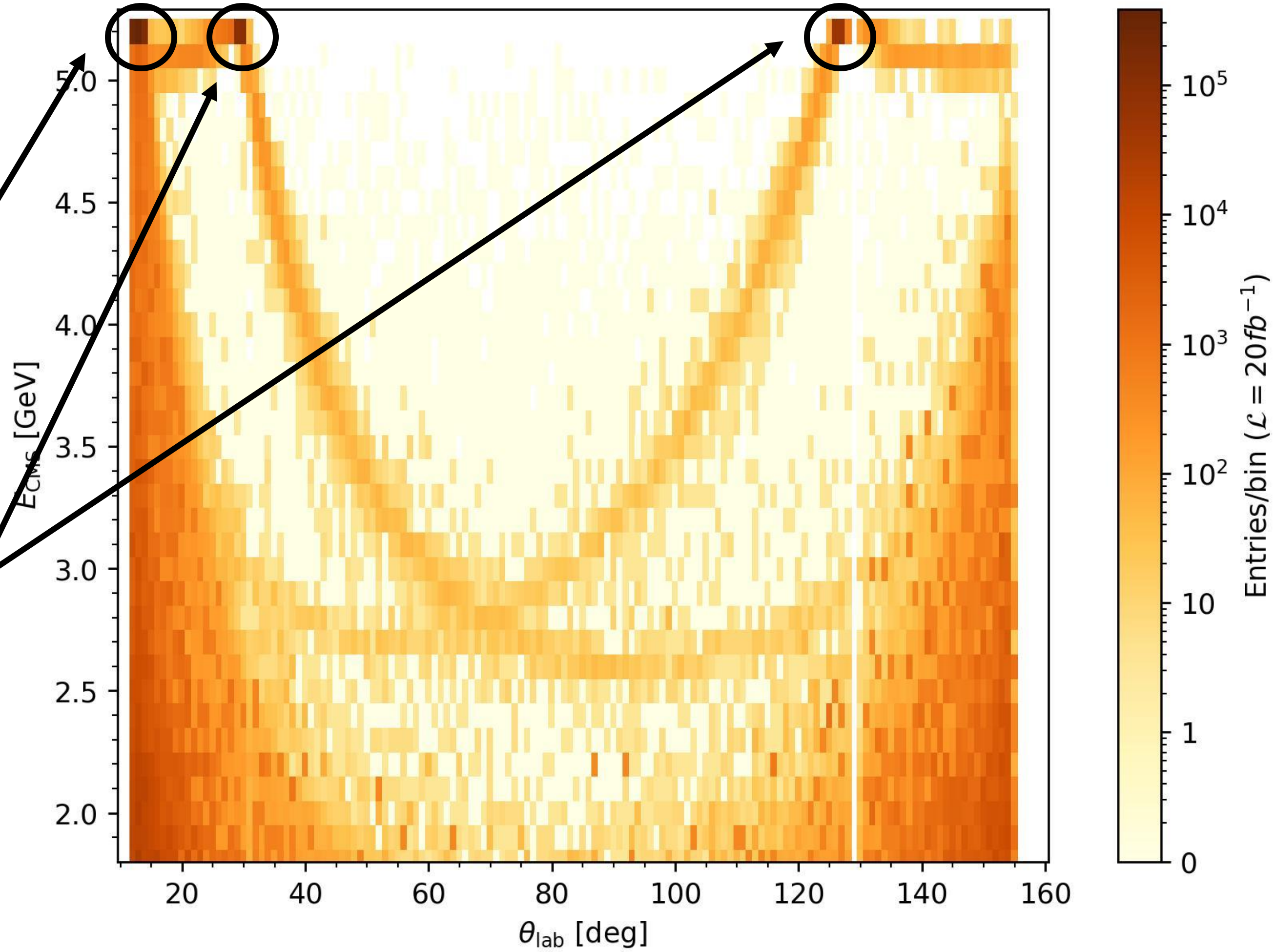
Backup Slides

Standard Model Background

Processes:

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

- Asymmetric angular coverage
- Gaps between barrel and endcaps



Standard Model Background

Processes:

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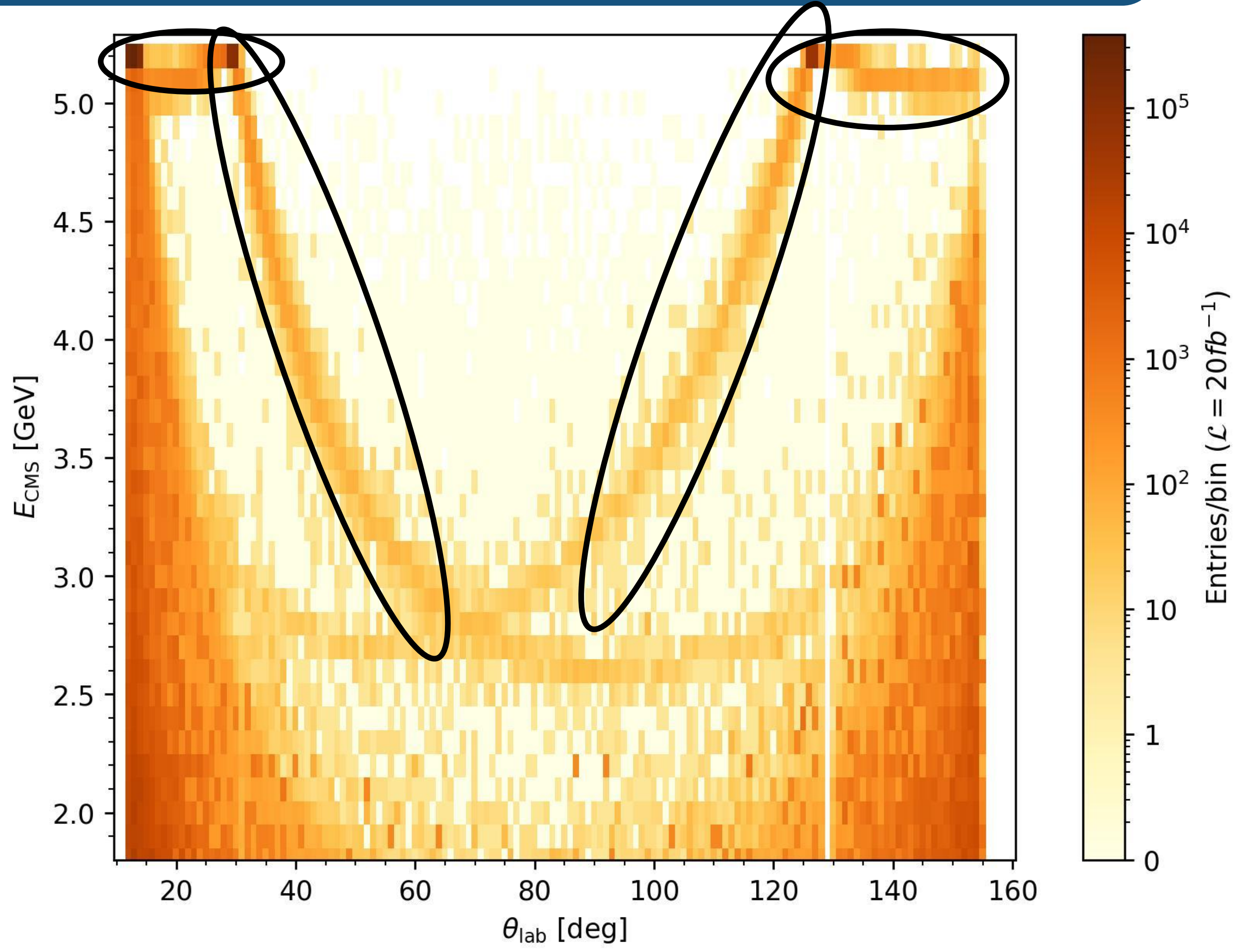
Gaps between barrel and endcaps



Standard Model Background

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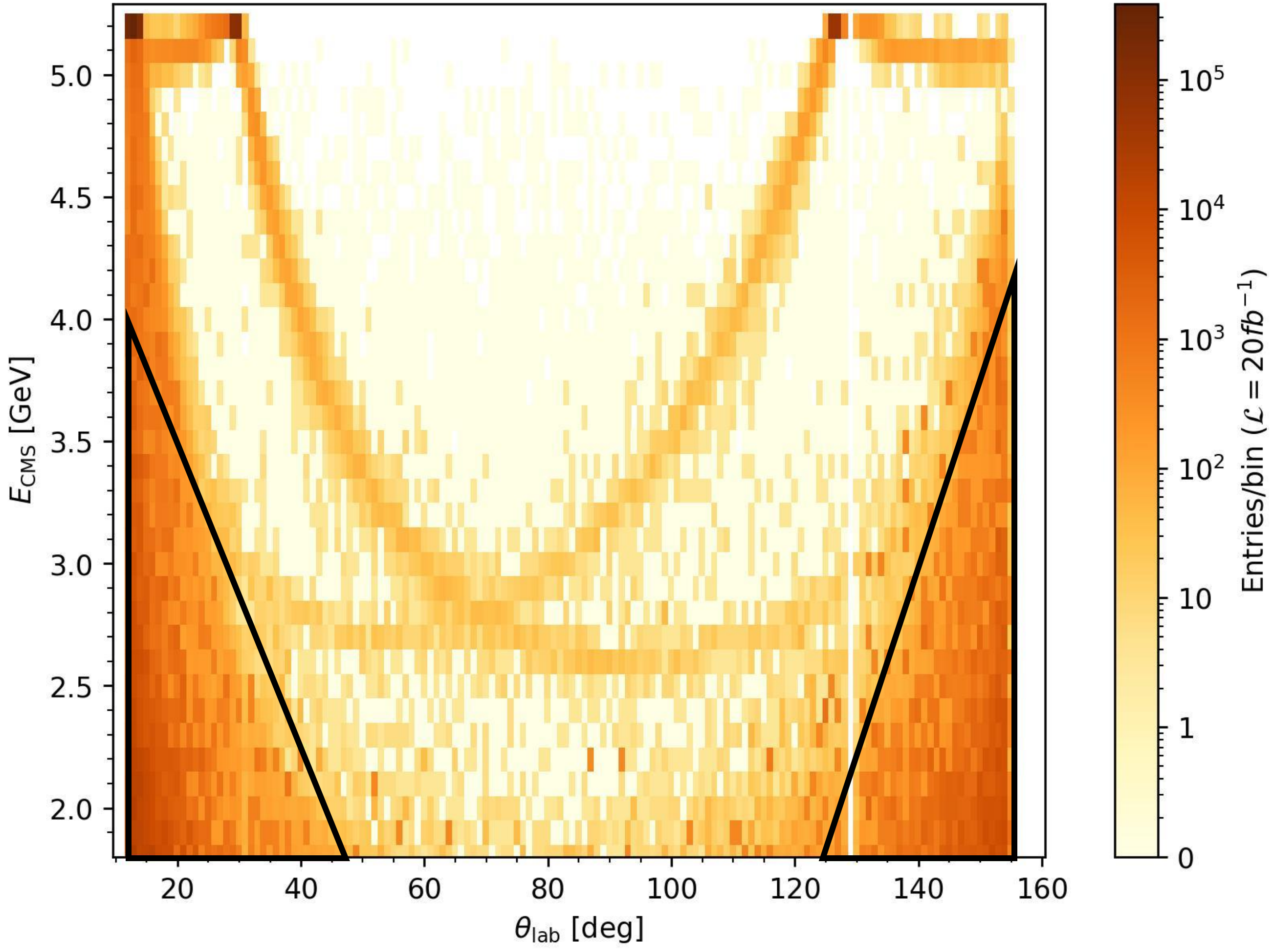
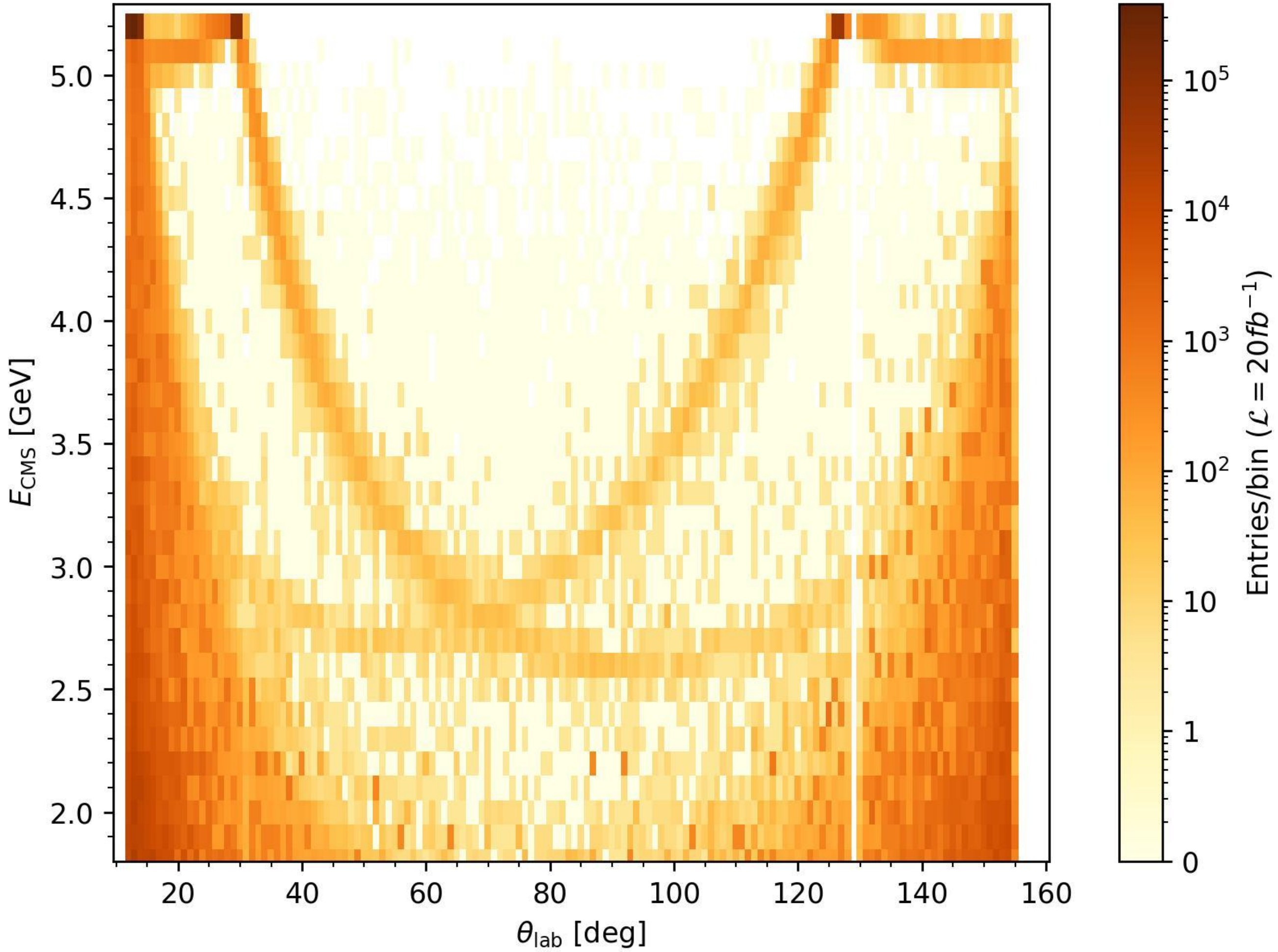


Standard Model Background

Processes:

- $e^+ e^- \rightarrow$
    - $\gamma \gamma (\gamma)$
    - $e^+ e^- \gamma (\gamma)$
    - $\bar{\nu} \nu \gamma (\gamma)$

Irreducible & everywhere



Dark Photon

Introduce a new $U(1)_X$ gauge symmetry with vector boson X_μ which kinetically mixes with the hypercharge boson B_μ.

$$\mathcal{L} = -\frac{1}{4}\hat{F}_{\mu\nu}\hat{F}^{\mu\nu} - \frac{\epsilon'}{2}\hat{F}_{\mu\nu}\hat{X}_{\mu\nu} - \frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} - g' j^Y_\mu \hat{B}_\mu$$
$$- g_X j^X_\mu \hat{X}_\mu - \frac{1}{2}\hat{M}_X^2 \hat{X}_\mu \hat{X}^\mu$$

Other options are gauging a global symmetry of SM:

- $U(1)_{L_i - L_j}$ lepton number difference
- $U(1)_{B-L}$ baryon - lepton number difference (Used)

[Bauer, Foldenauer, and Jaeckel arXiv:1803.05466]

Axion-Like-Particles (ALPs)

Pseudo-scalar particle with linear effective Lagrangian

$$\mathcal{L}_{\text{eff}} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_a^2}{2}a^2 + \sum_f \frac{c_{ff}}{2}\frac{\partial^\mu a}{f_a}\bar{f}\gamma_\mu\gamma_5 f$$
$$+ g_s^2 C_{GG}\frac{a}{f_a}G^A_{\mu\nu}\tilde{G}^{\mu\nu,A} + g^2 C_{WW}\frac{a}{f_a}W^A_{\mu\nu}\tilde{W}^{\mu\nu,A} + g'^2 C_{BB}\frac{a}{f_a}B_{\mu\nu}\tilde{B}^{\mu\nu}$$

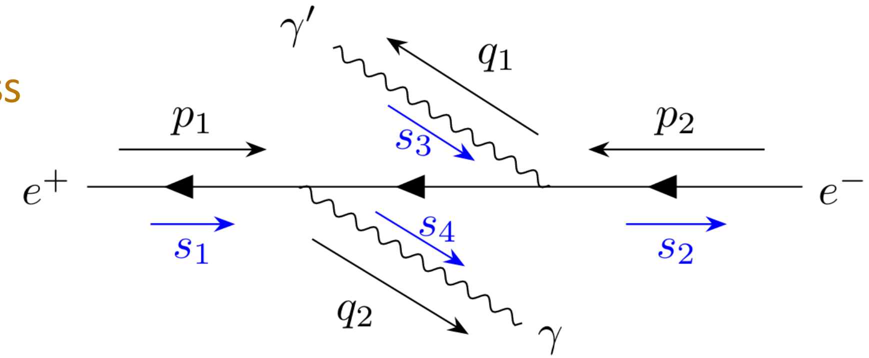
[I. Brivio et al arXiv:1701.05379 & Bauer et al arXiv:1808.10323]

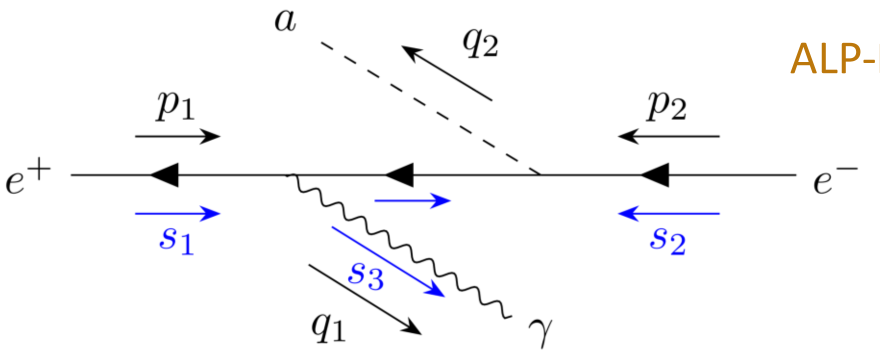
Spin Structure Diagrams

Dark Photon

Axion-Like-Particles

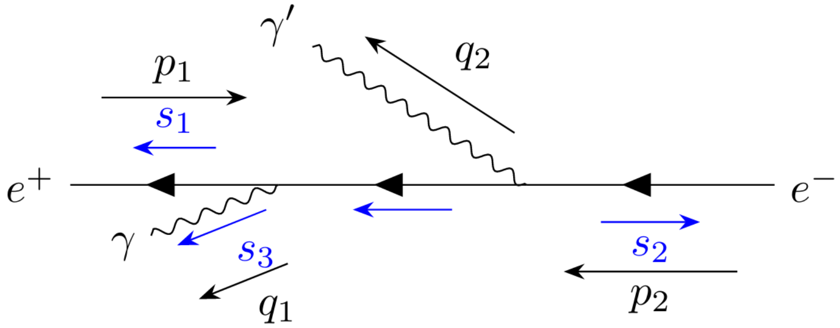
Small DM mass

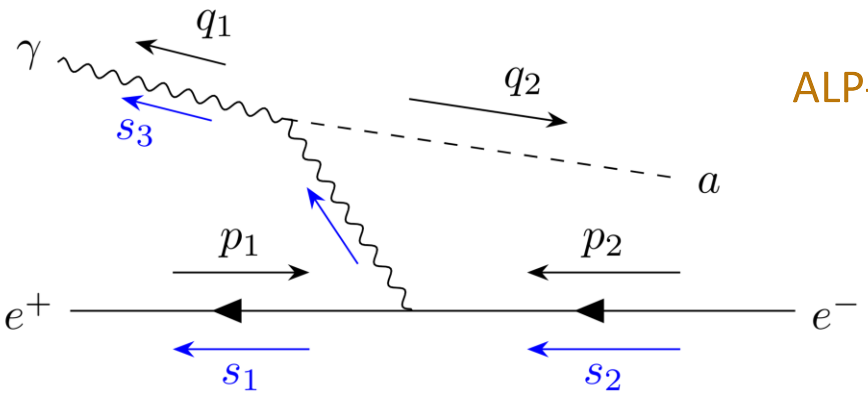




ALP-Fermion

Large DM mass





ALP-Photon

Polarisation of the Photon

Not Planned!

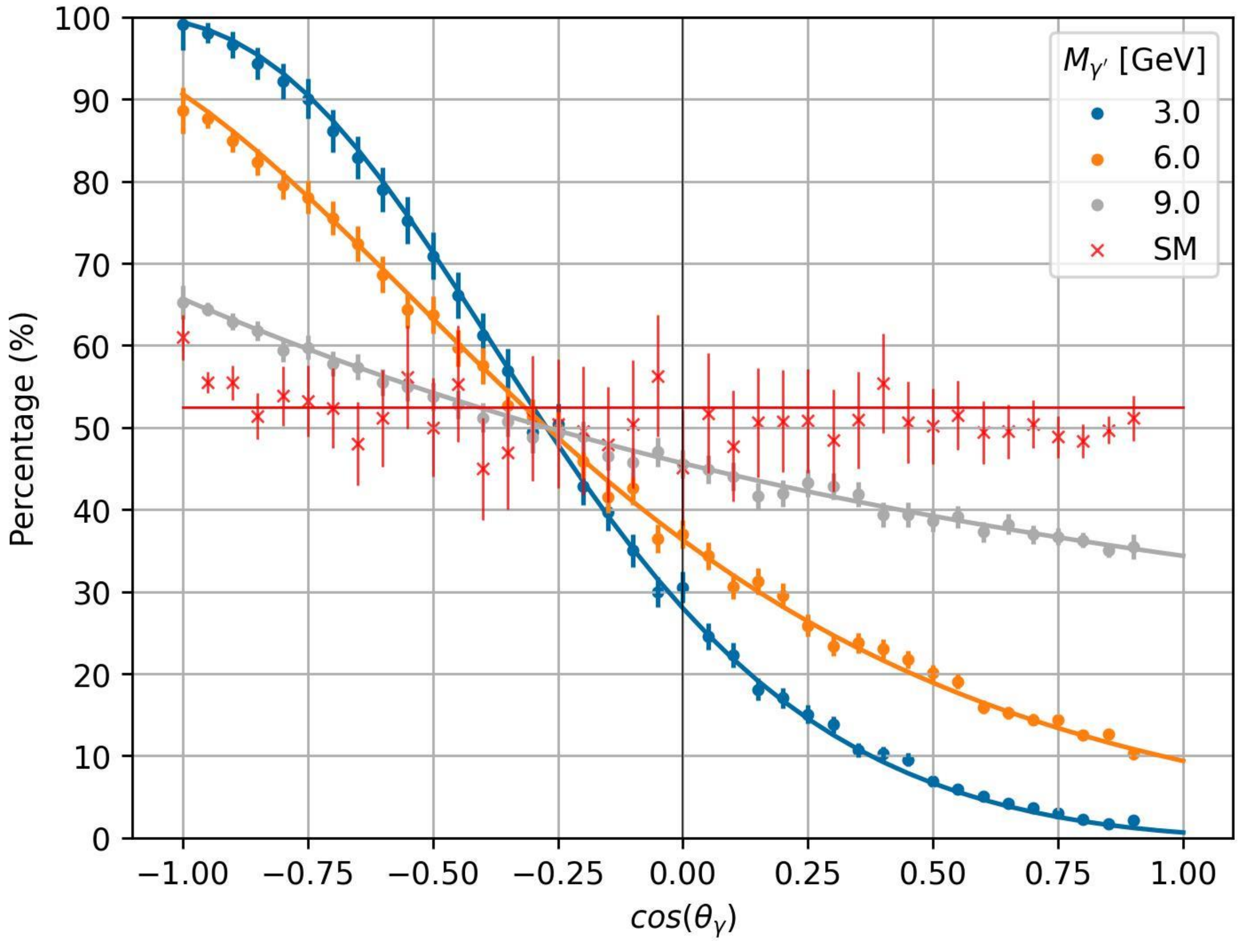
Speculative

Polarisation of the Photon

Percentage of the photon helicity being equal to the incoming electron for 100% polarised beams

$$\text{Percentage} = \frac{|\mathcal{M}|^2(2\lambda_{e^-} = \lambda_\gamma = 1)}{|\mathcal{M}|^2(\lambda_{e^\pm} = \lambda_\gamma = 0)}$$

Polarisation of the Photon



Dark Photon

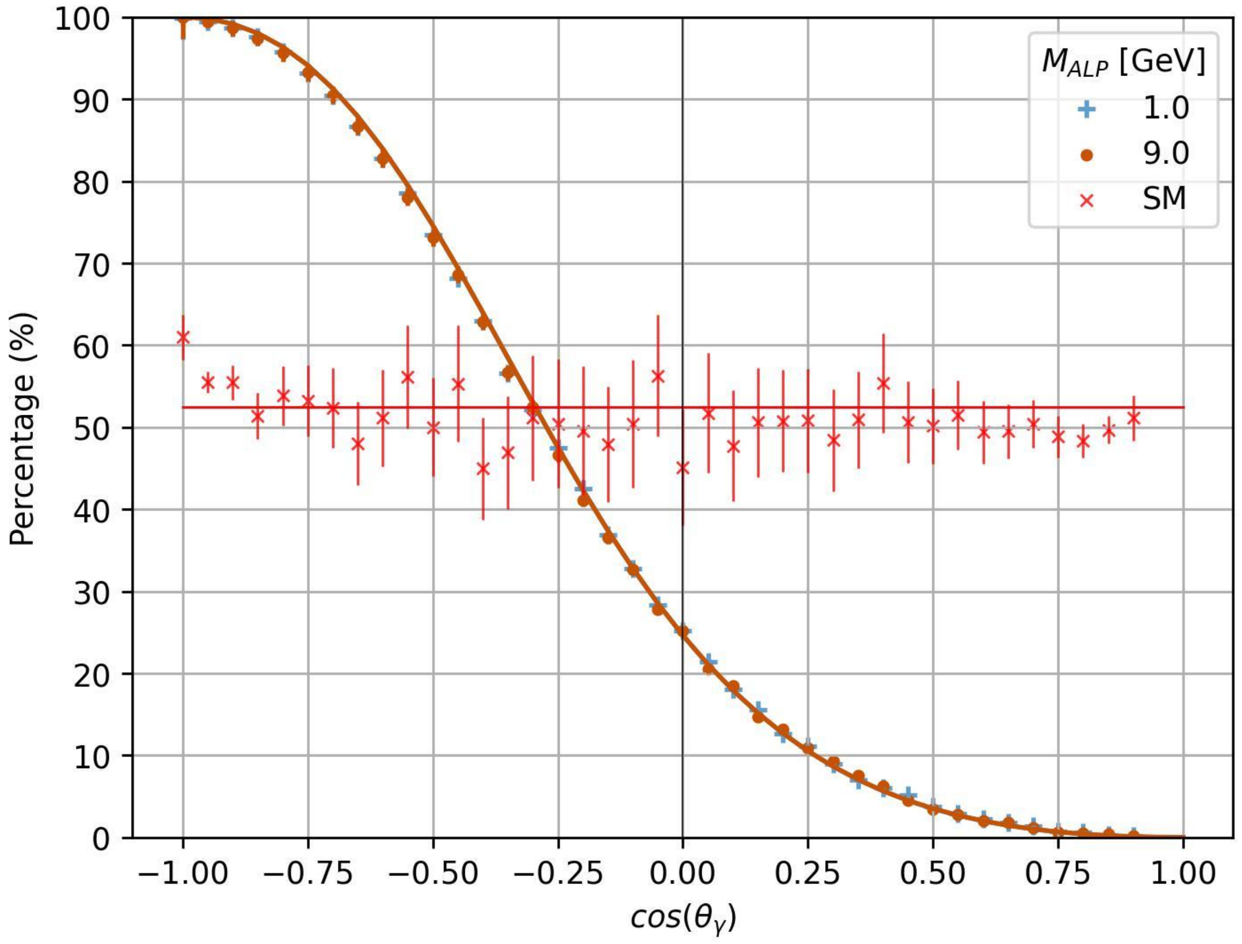
- Angular correlation
  - Follows incoming beams

- As mass increases, direction of final photon becomes more random

⇒Percentage tends towards 50 %

- Skew from unequal beam energies

Polarisation of the Photon



ALP-Photon Coupling

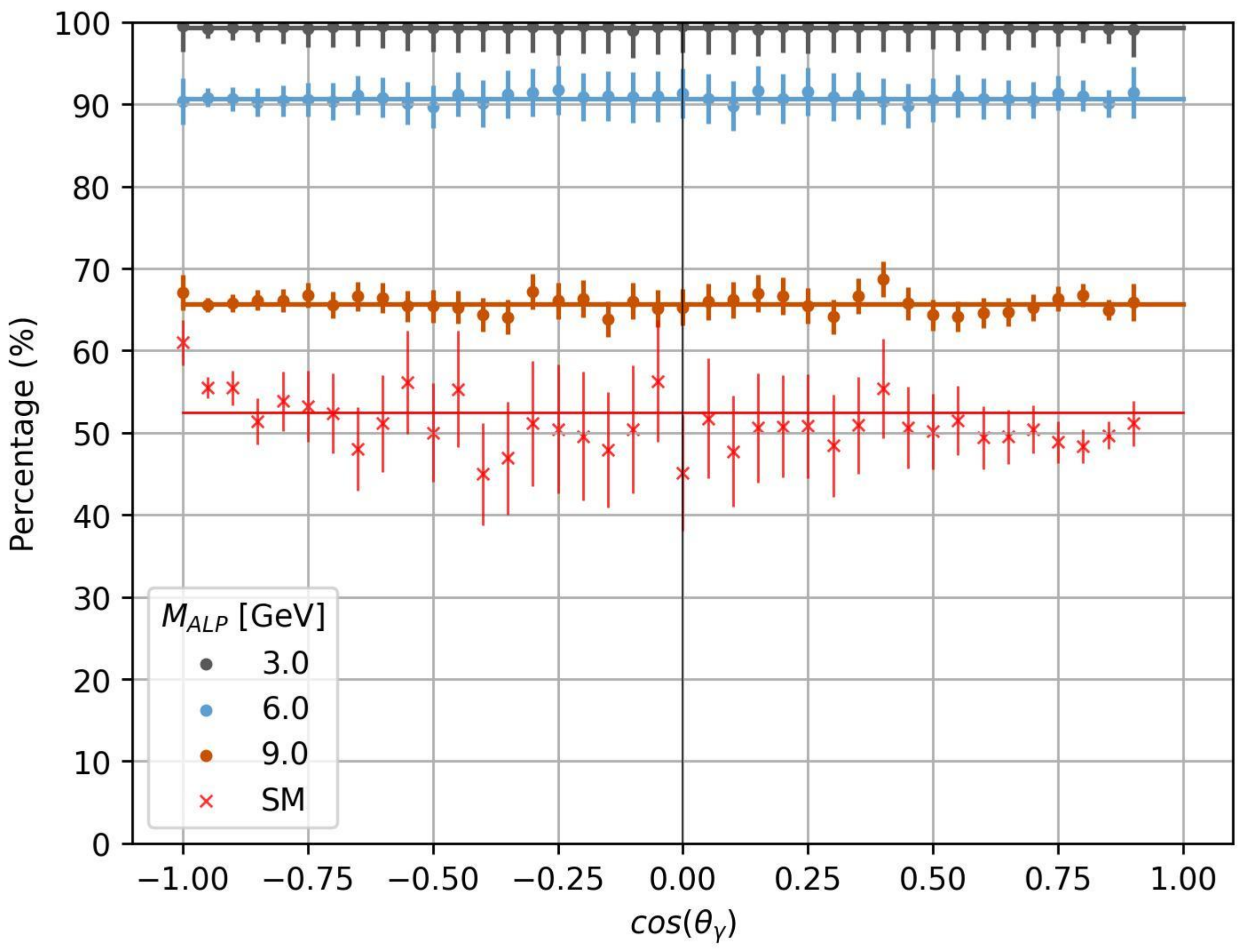
- Same shape as Dark Photon
- ALP emission independent of incoming beams

⇒ ALP mass factors out and has no influence

Significantly different to SM Background

⇒ Better exclusion limits

Polarisation of the Photon



ALP-Fermion Coupling

- ALP-fermion interaction causes helicity flip

$\Rightarrow$ Helicity match both incoming beams

$\Rightarrow$ No angular dependence

- Same shape as SM Background

Different from dark photon and ALP-photon coupling

Polarisation of the Photon

Not Planned! This was speculative

- Do not know how it would be implemented

$\Rightarrow$ Not going to try and provide exclusion limits