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

Bauer & Erner [arXiv:2308.09746]

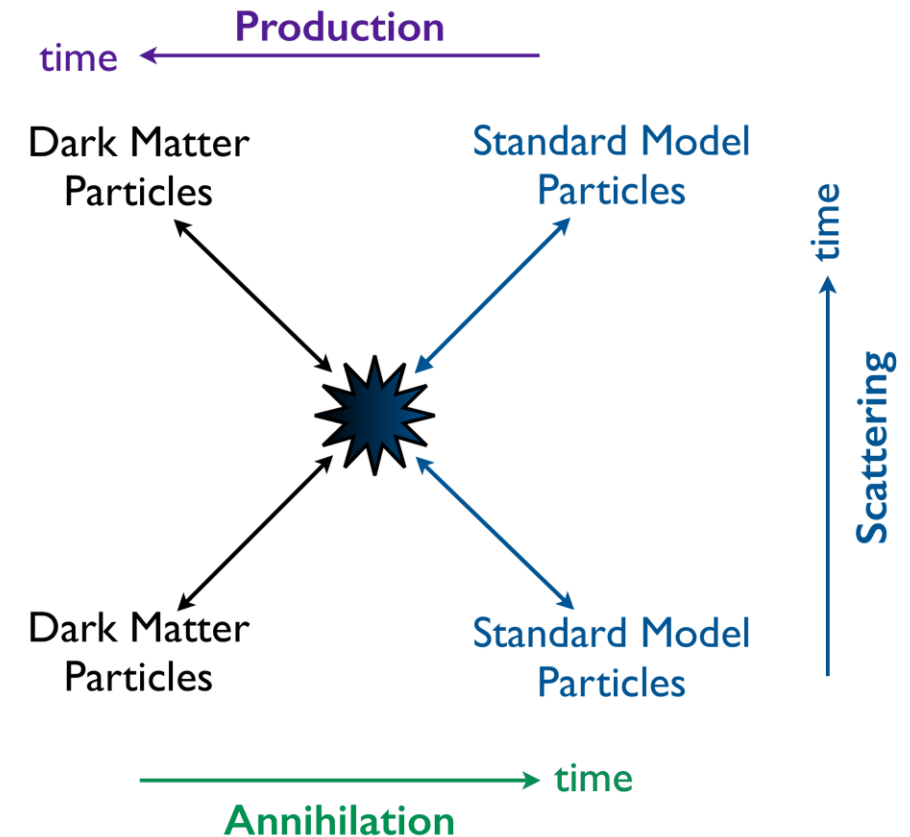Sofie Nordahl Erner

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Introduction

With current experiments

- Can determine mass and coupling strength

- Cannot determine quantum numbers such as spin

$\Rightarrow$ 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

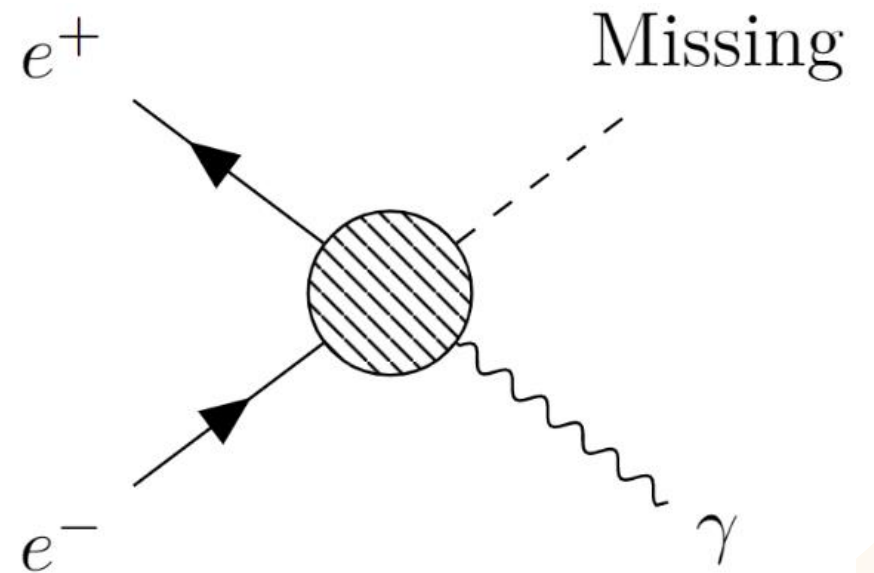Currently in Detectors

Polarised Beams
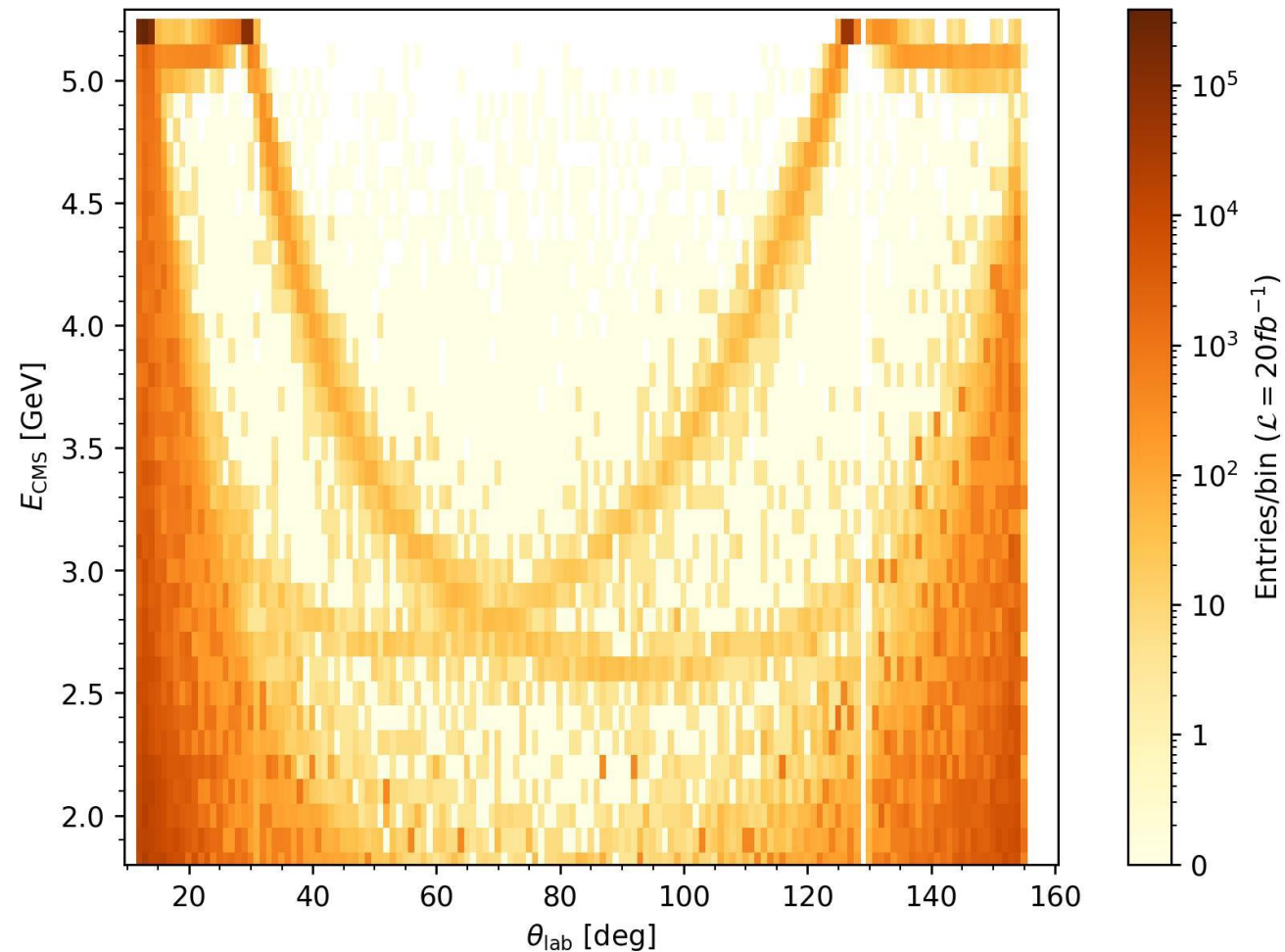
Photon Polarisation

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
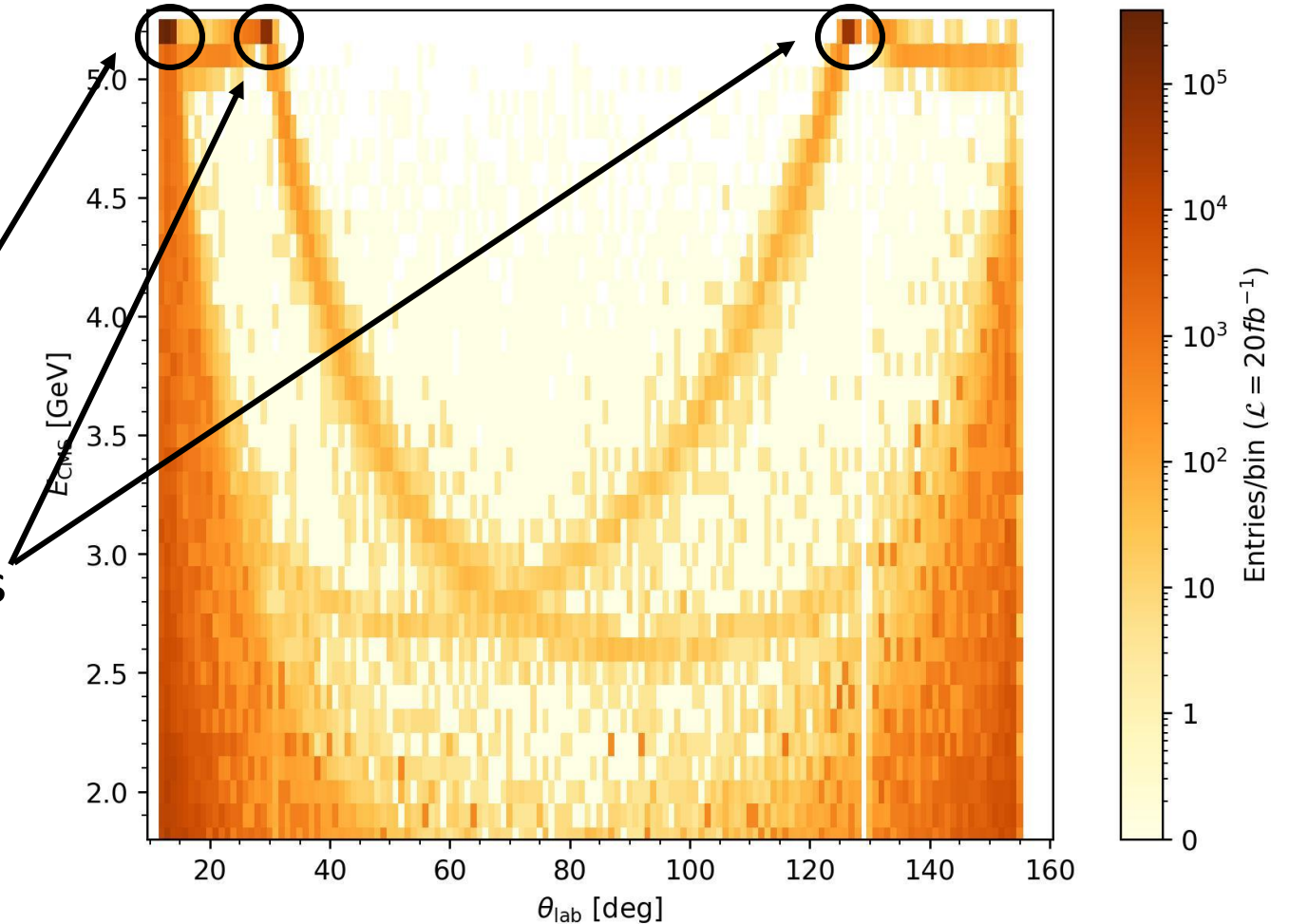   - Asymmetric angular coverage
    - Gaps between barrel and endcaps

Standard Model Background

Processes:

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

- Asymmetric angular coverage
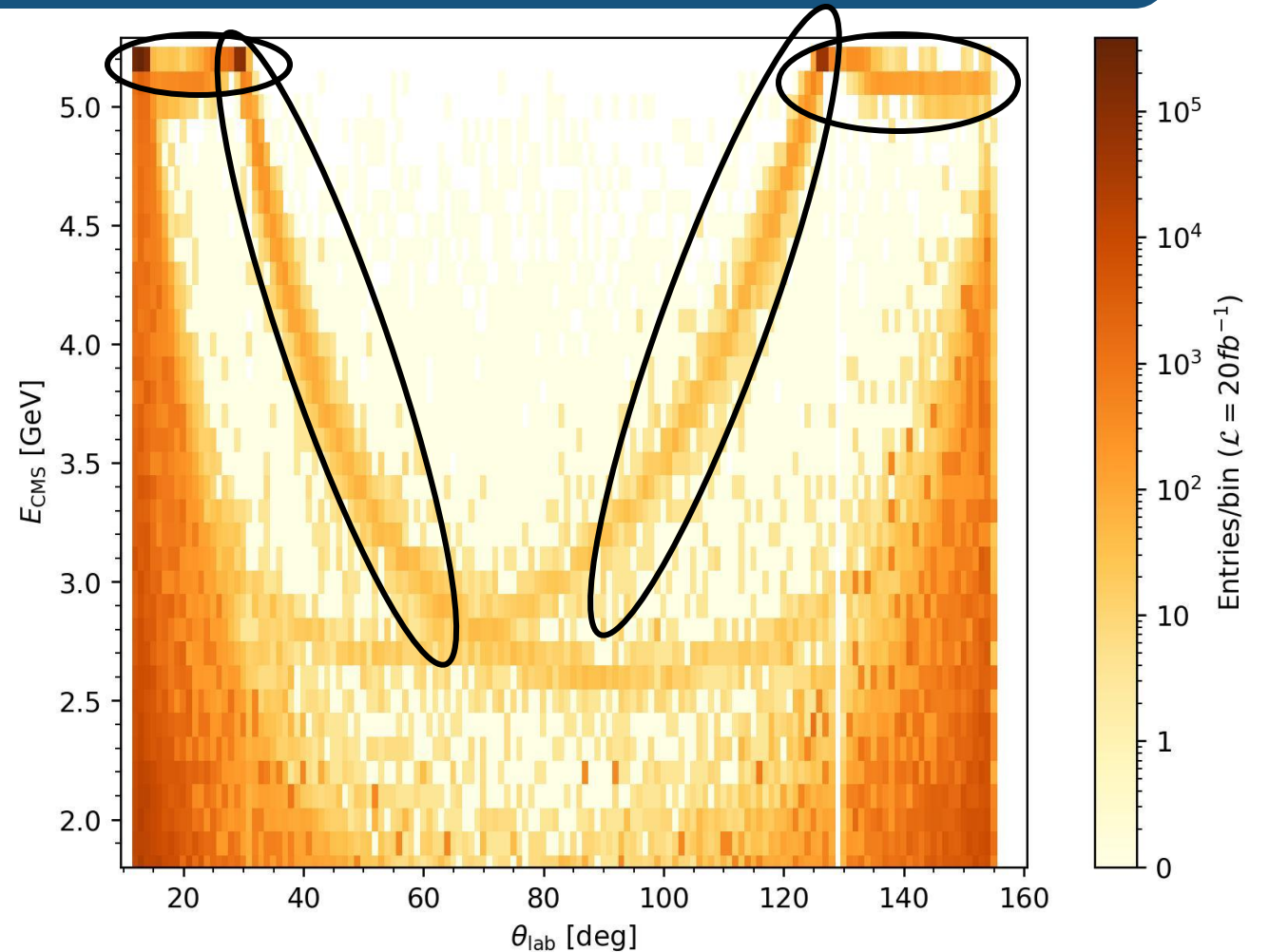
- Gaps between barrel and endcaps

Standard Model Background

Processes:

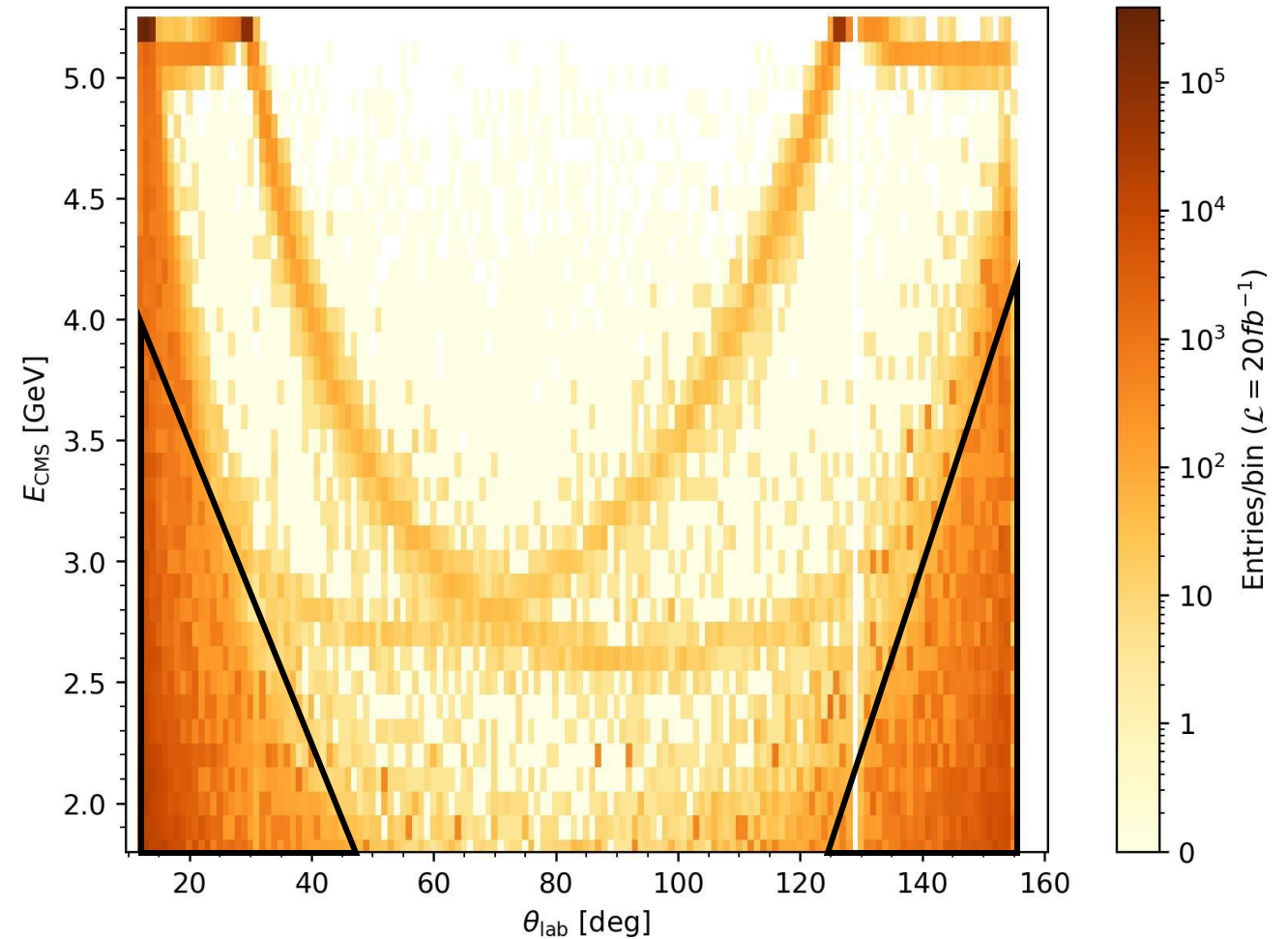- $e^+ e^- \rightarrow$
  - $\gamma\gamma(\gamma)$

Gaps between barrel and endcaps
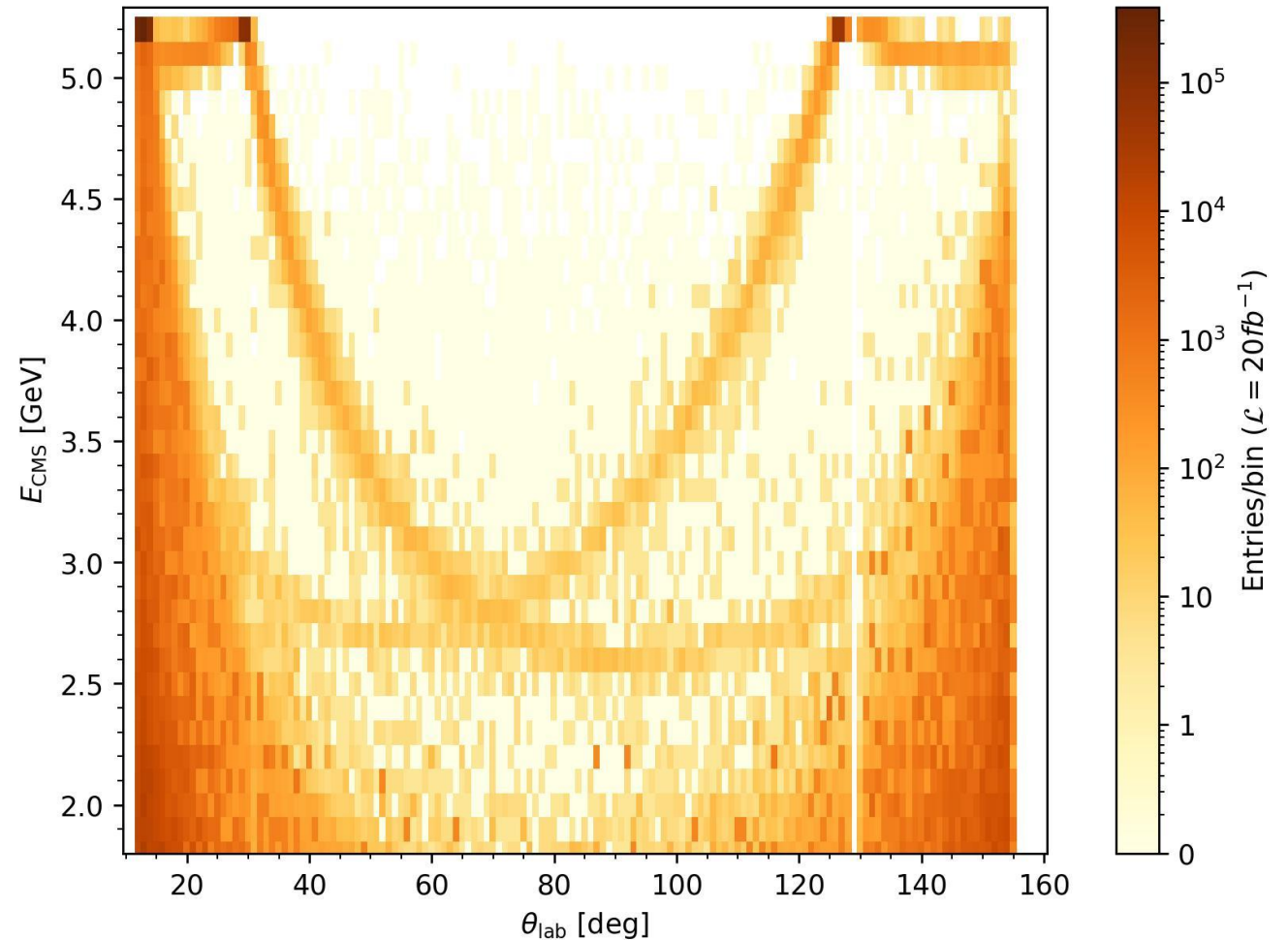
Standard Model Background

Processes:

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

Standard Model Background

Processes:

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

- Irreducible & everywhere
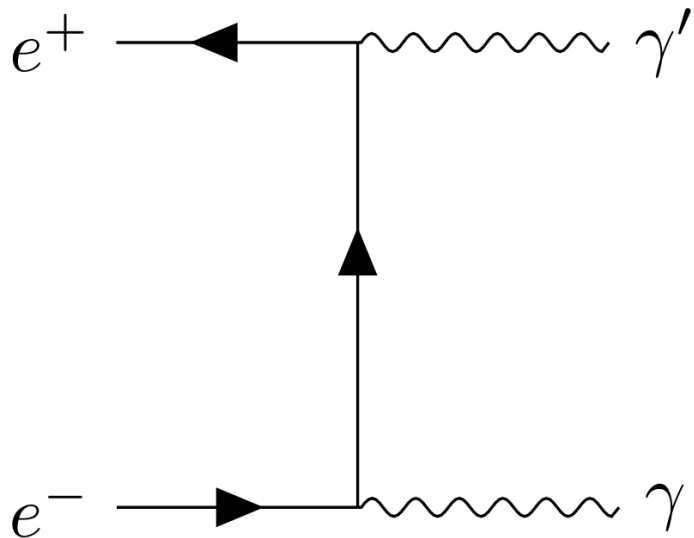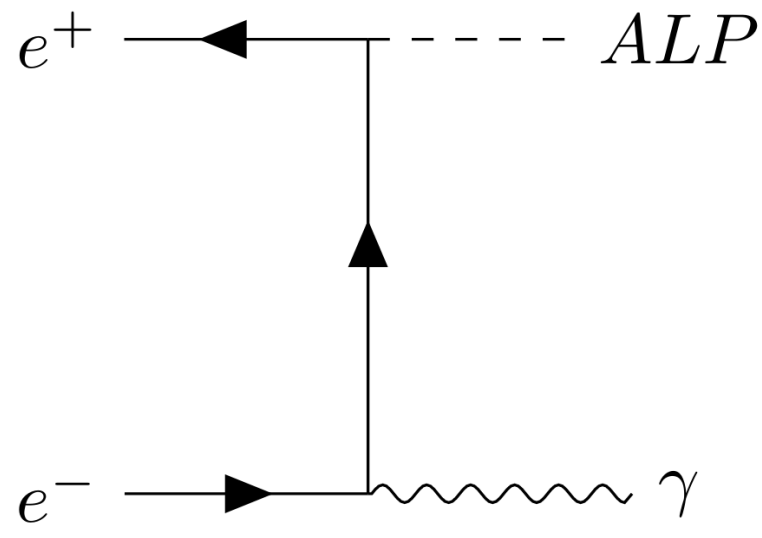- Decrease for increasing E_{CMS}

Dark Matter Models

Sofie Nordahl Erner

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 Matter Contributions
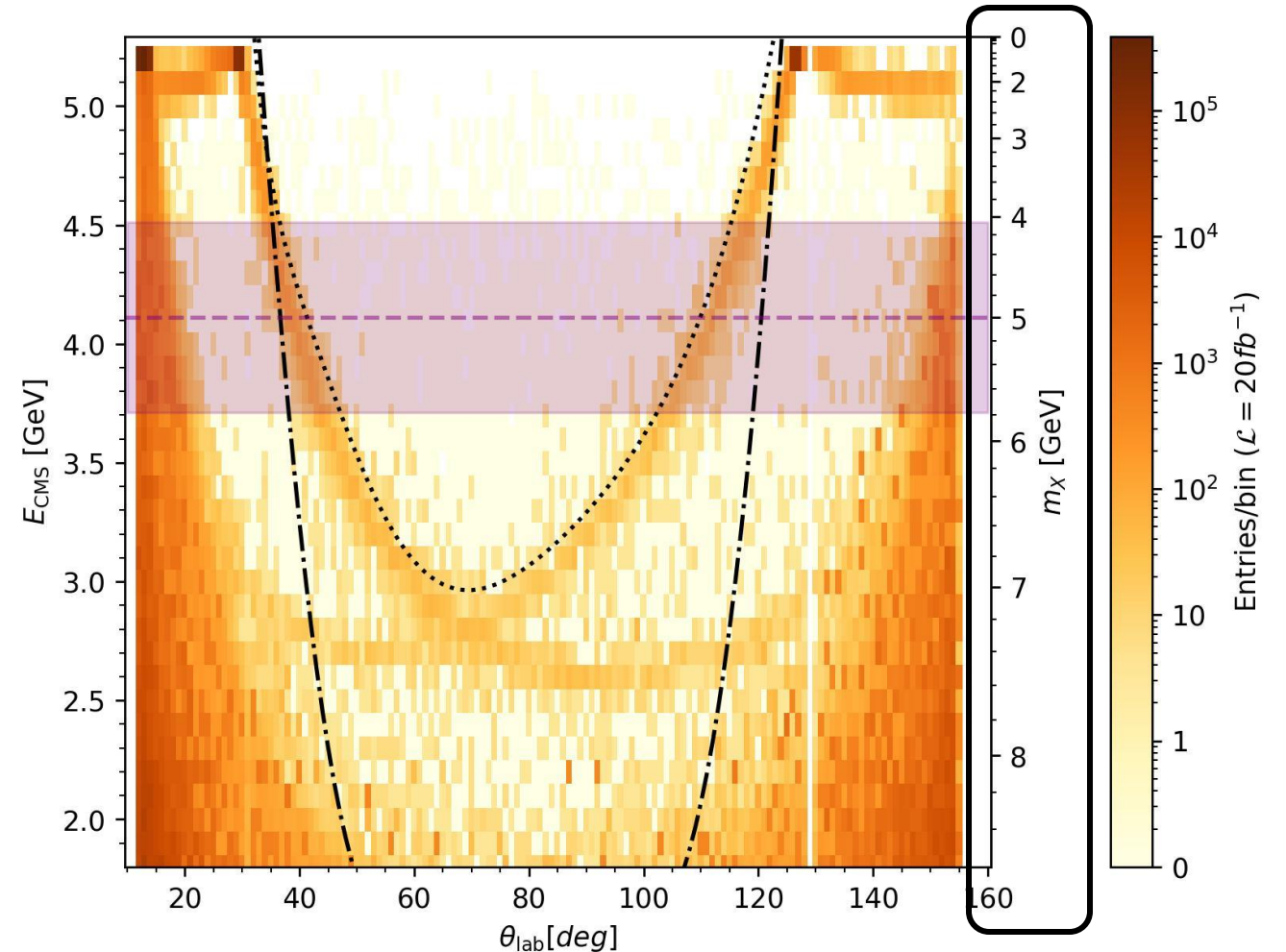
Signal

Dark Matter Model

Dark Photon

ALP-fermion

ALP-photon
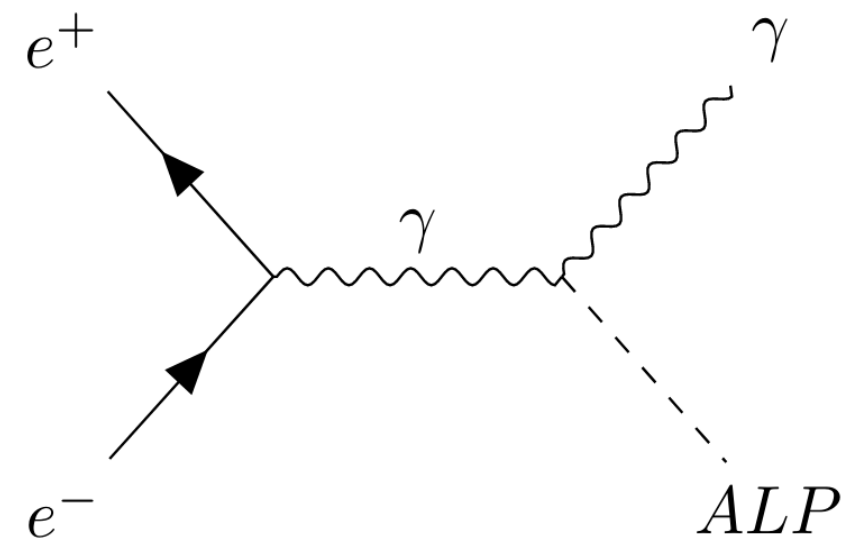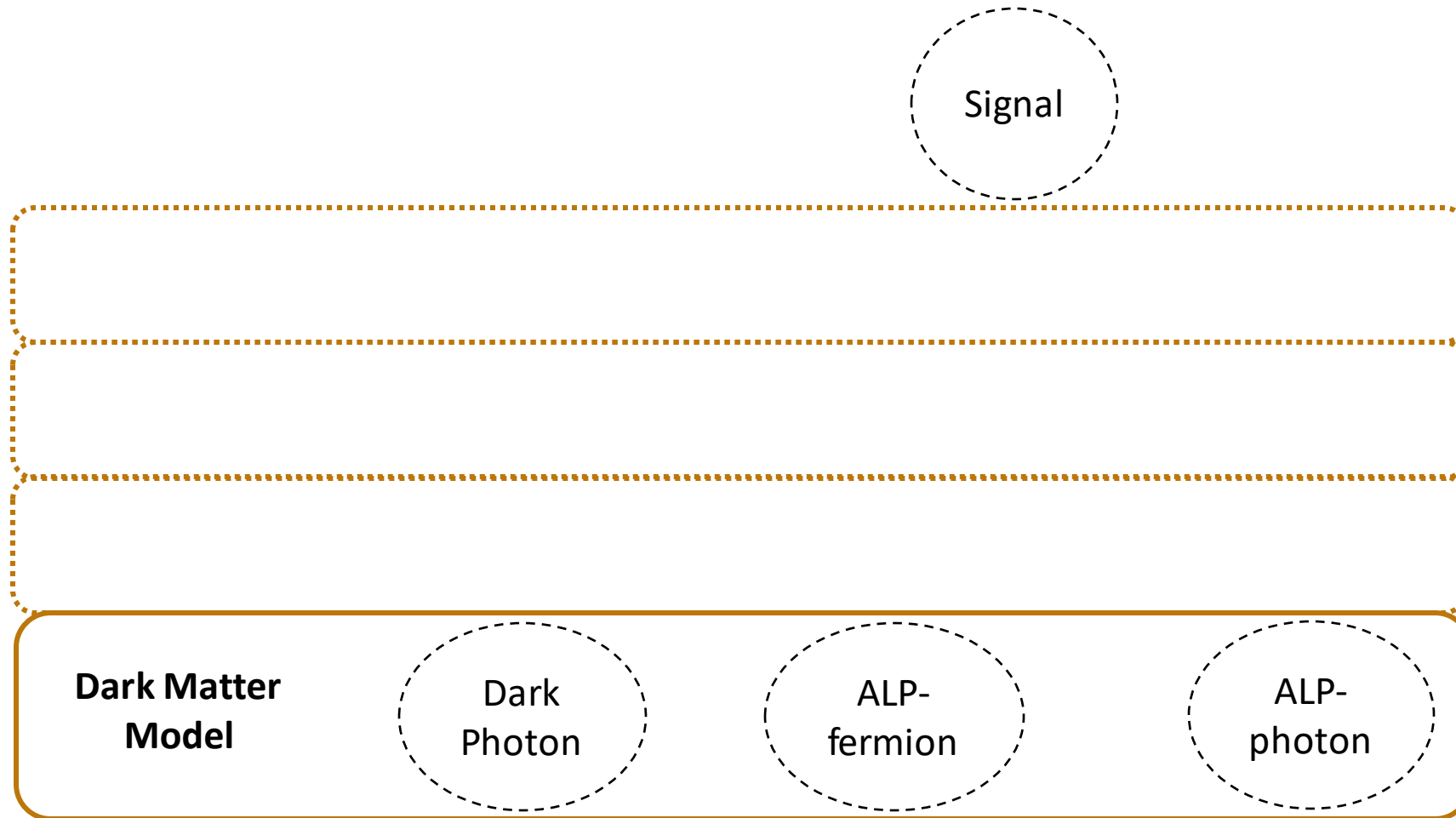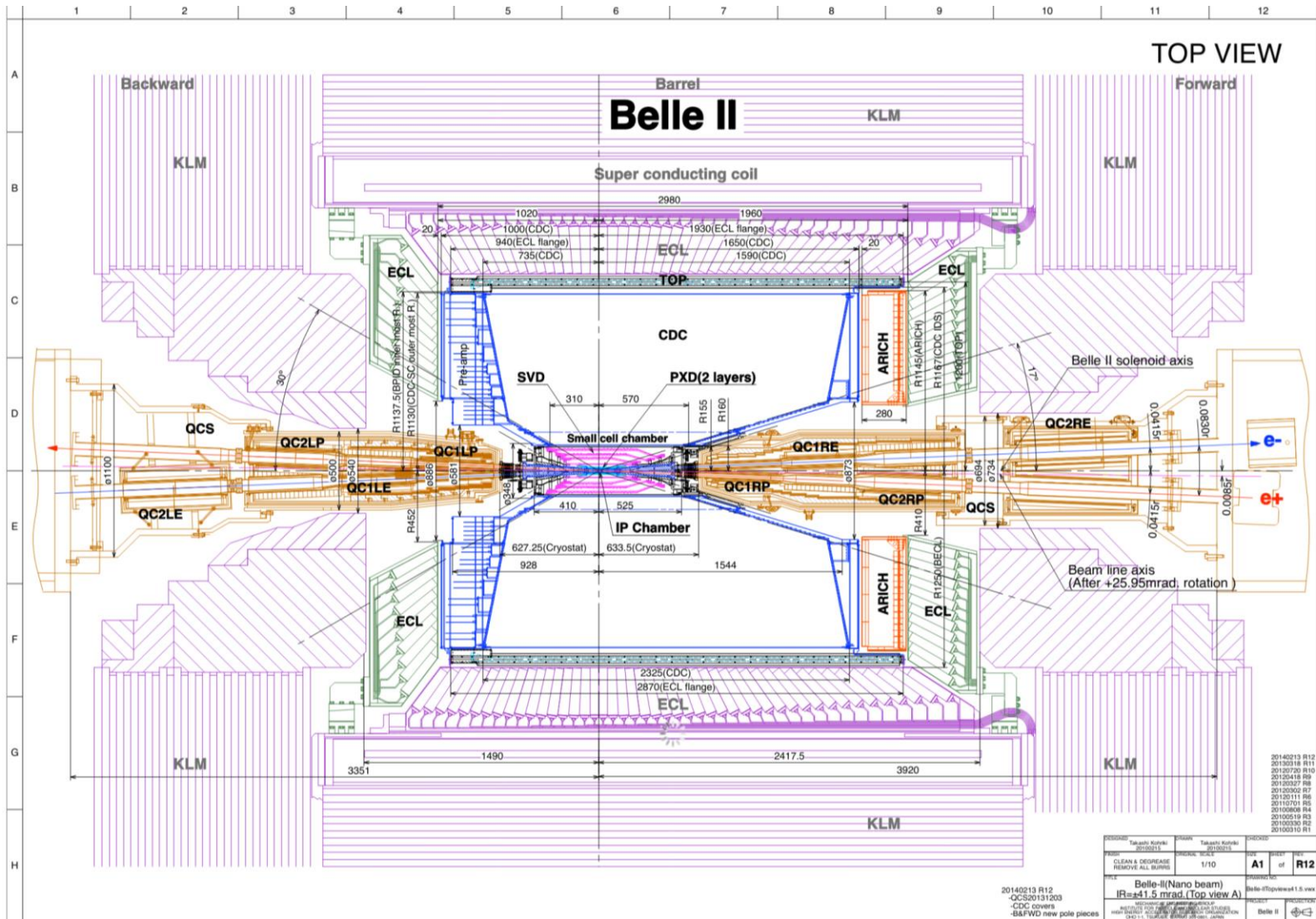
Currently in Detectors

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
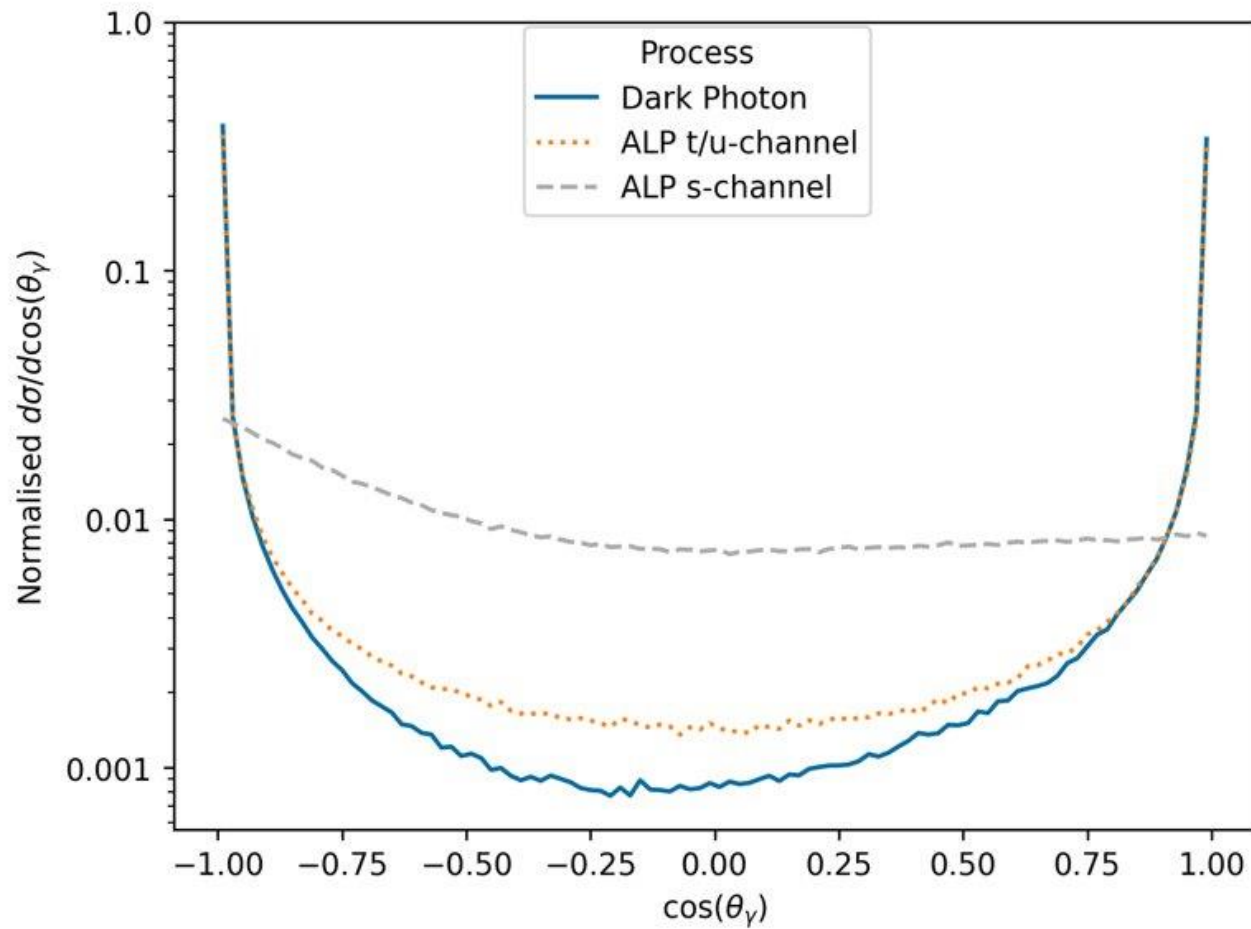
- **Difference between s- and t/u-channel contributions**
  - Distinguish between ALP contributions

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

Polarised Beams

Planned: 70% electron beam polarisation at Belle II
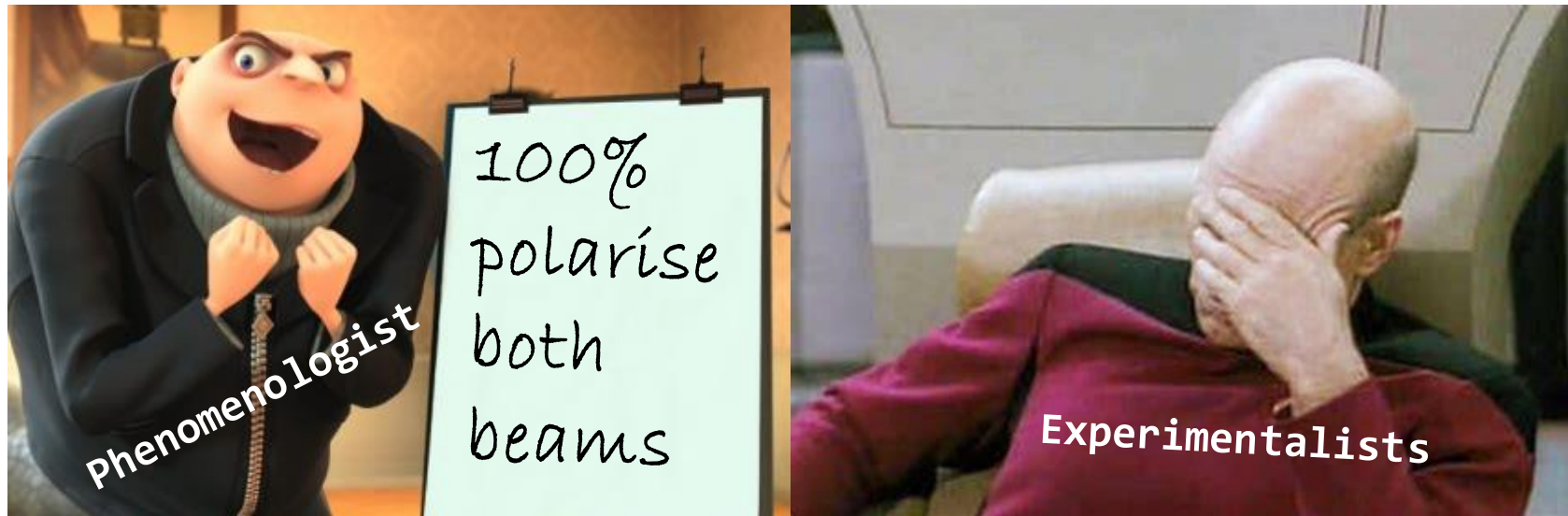
Polarised Beams

Planned: 70% electron beam polarisation at Belle II

Polarised Beams

Planned: 70% electron beam polarisation at Belle II
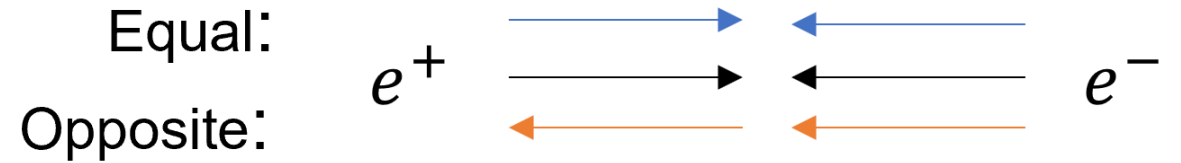
Polarised Beams

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

Equal:

Opposite:

e^+ e^-

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

Distinguish t/u-channel Dark Photon and ALPs contributions

Currently in Detectors
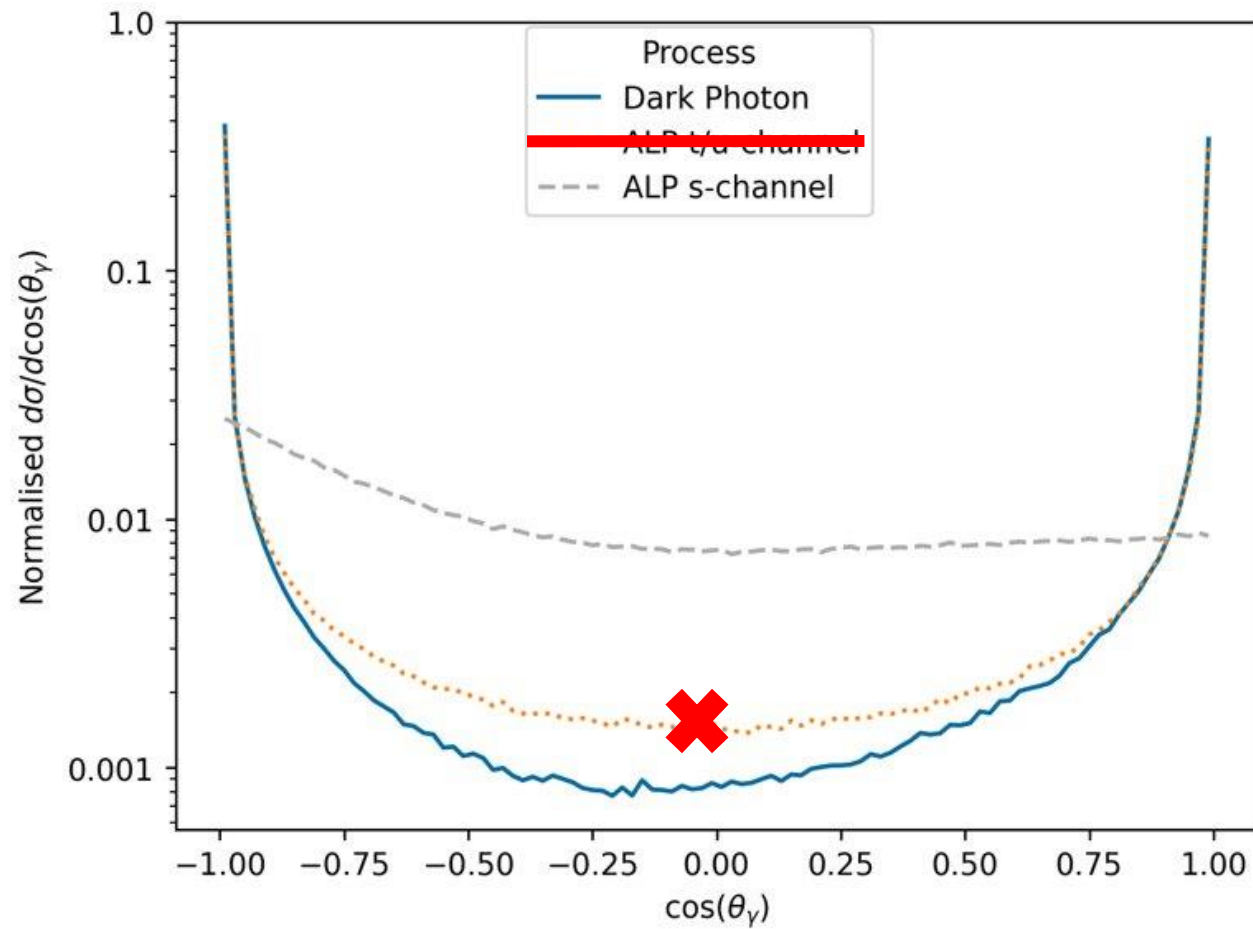
Oppositie Beam Helicities

Currently in Detectors

Equal Beam Helicities

Conclusion

Signal

Angular Distribution

t/u - channel

s – channel

Polarised Beams

Opposite

Equal

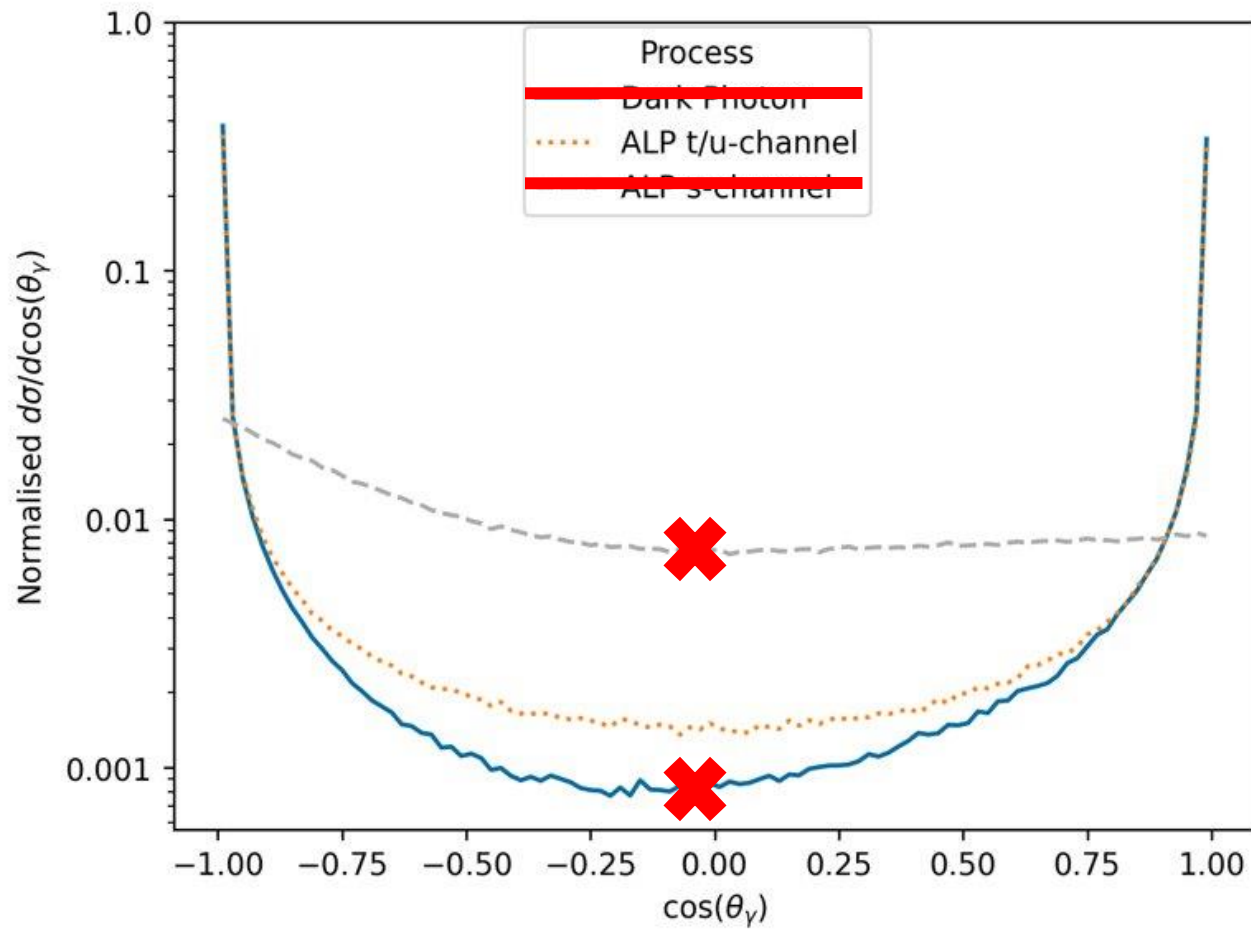Opposite

Dark Matter Model

Dark Photon

ALP- fermion

ALP- photon
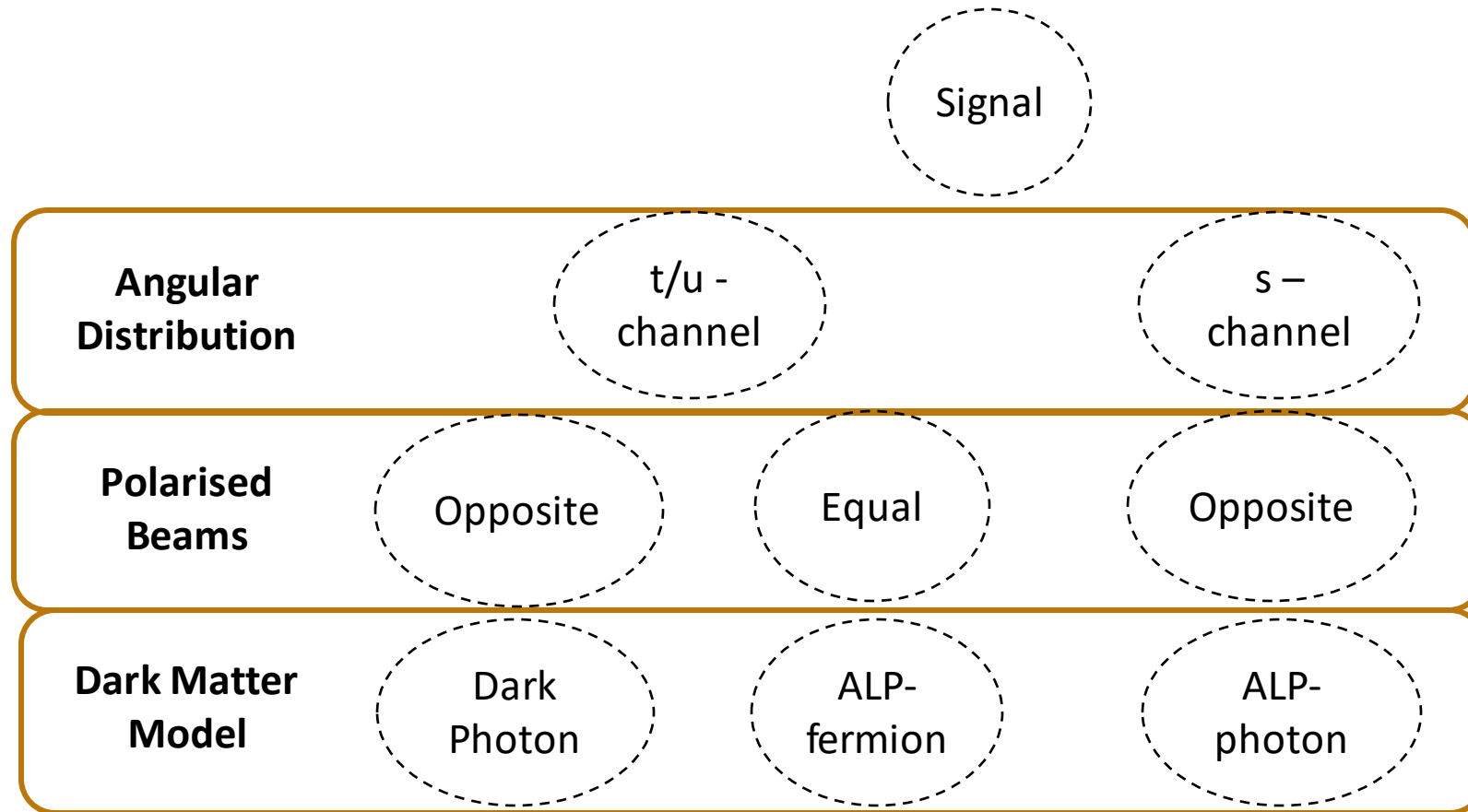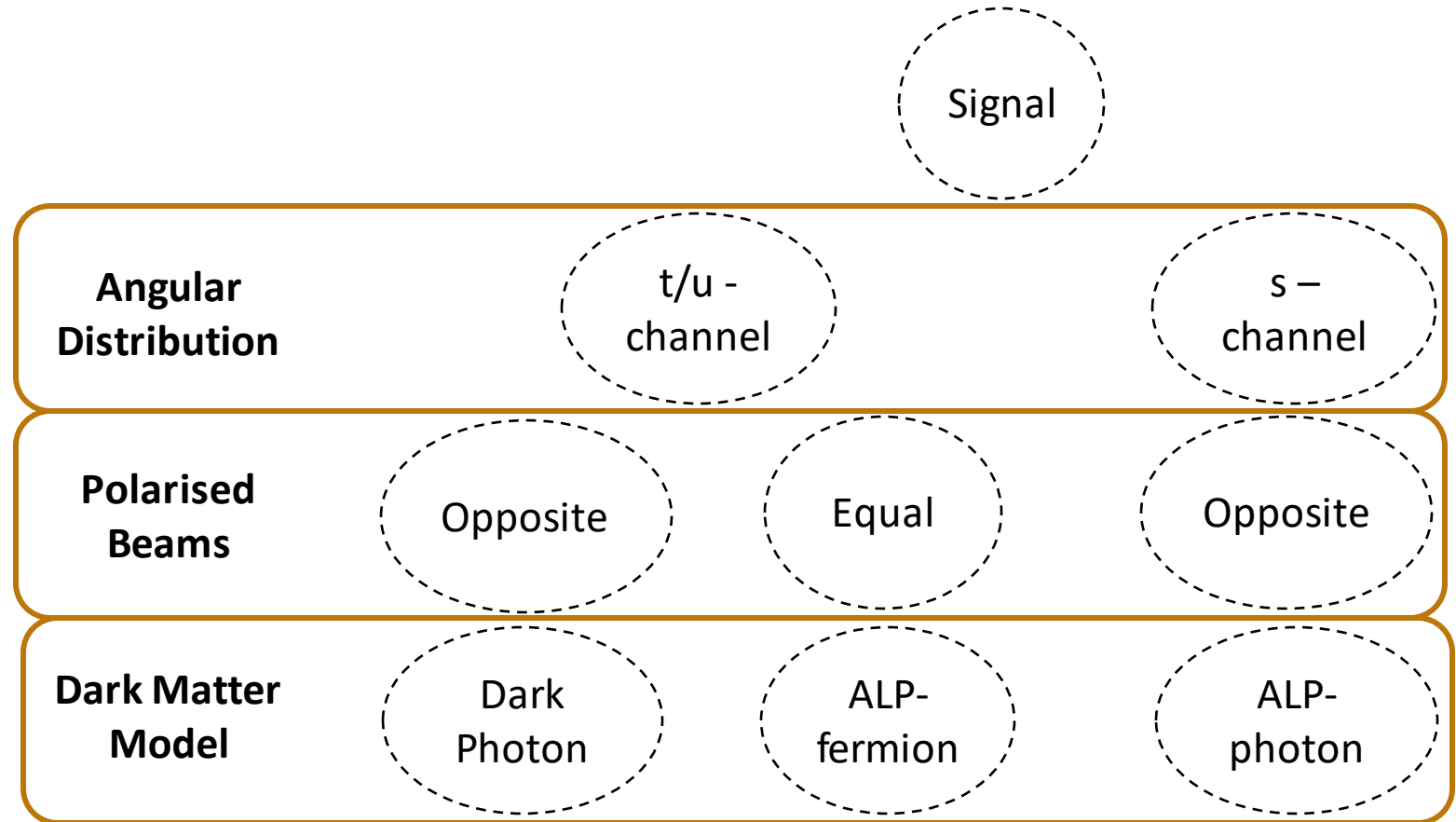
Not Yet Done

Conclusion

- Separate the dark matter contributions

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

⇒ **Measure the Spin of Dark Matter**

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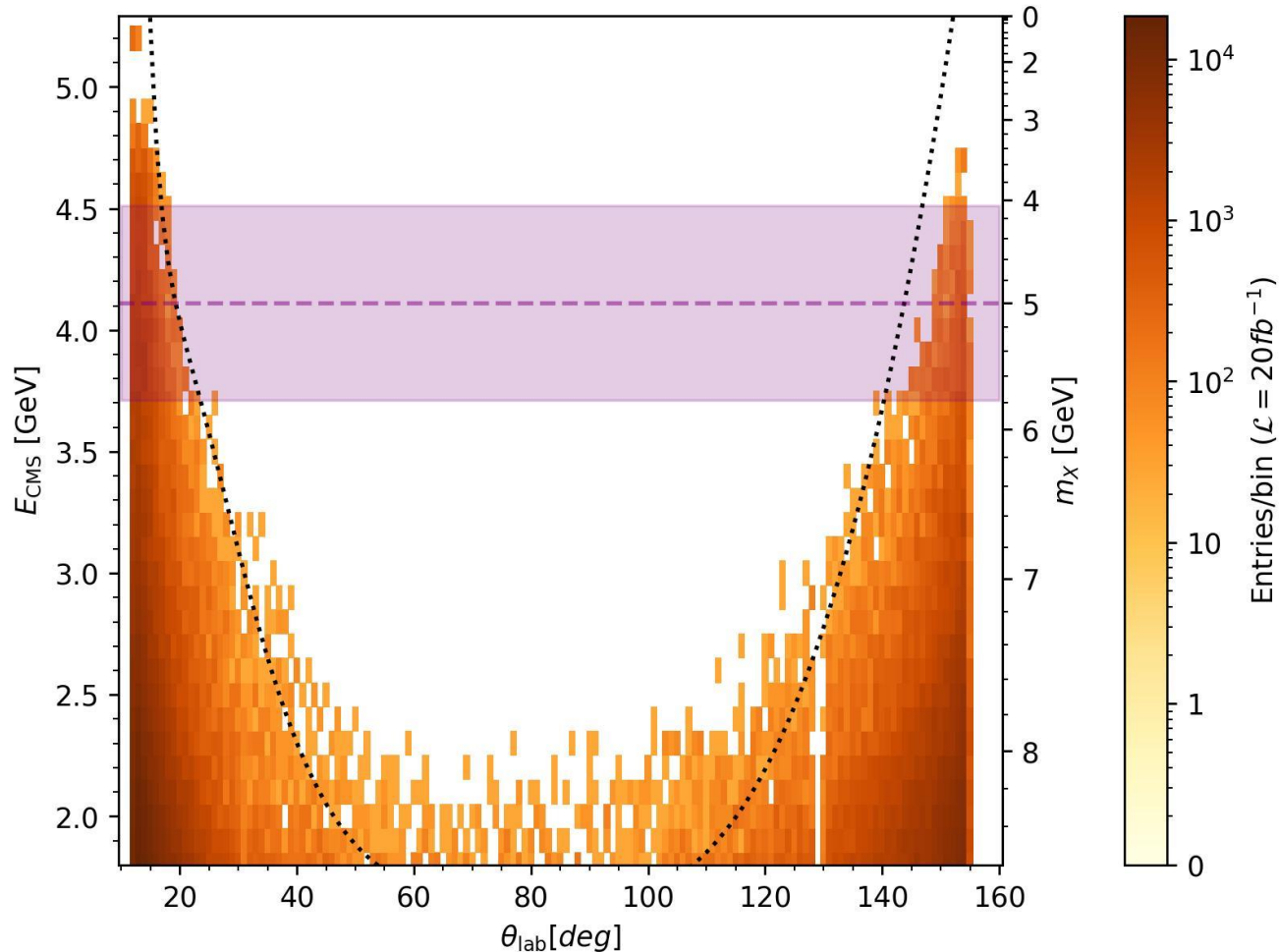
Polarised Beams

Reduced SM background for equally polarised beams
  ○ Photon-only final states drop out

⇒ Provide significantly better exclusion limits on ALP-fermion coupling

Polarised Beams

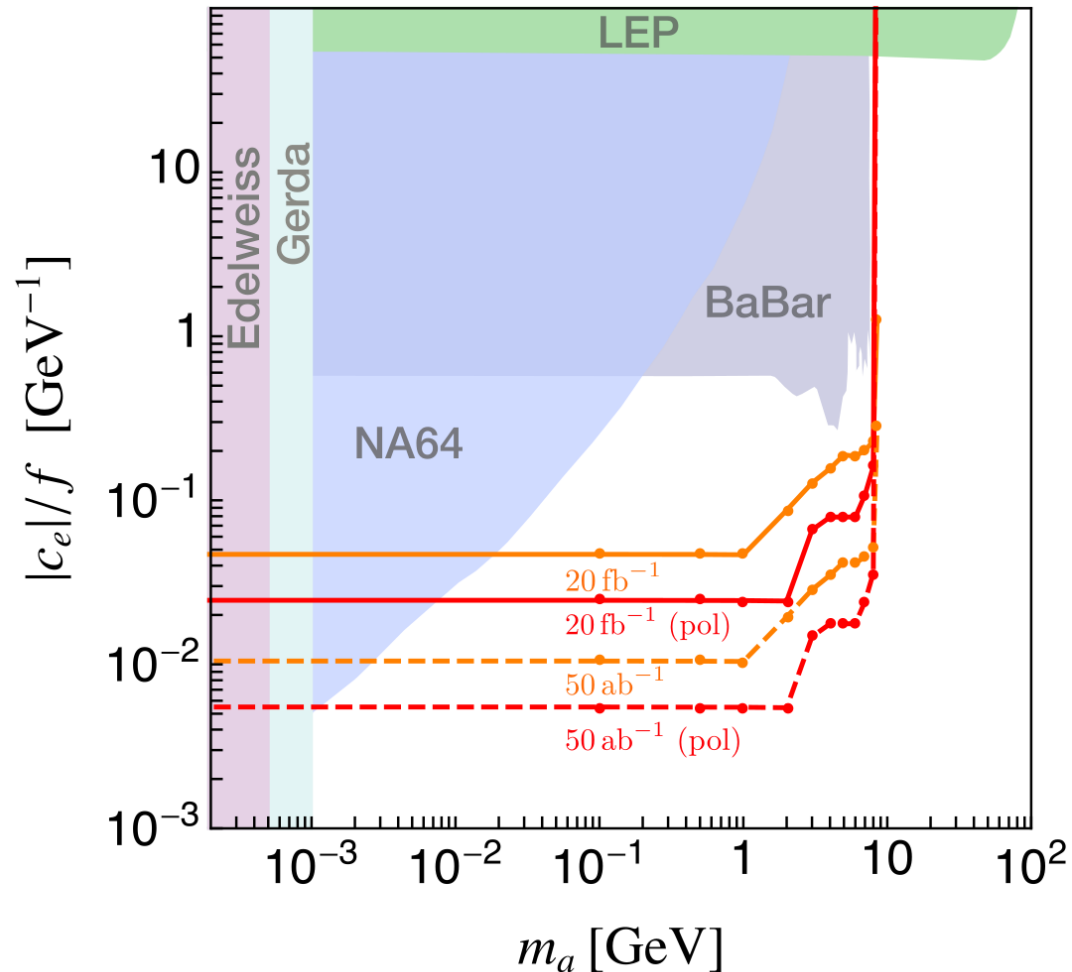Reduced SM background for equally polarised beams

$\Rightarrow$ Provide significantly better exclusion limits on ALP-fermion coupling

Orange: Unpolarised beams

Red: Beams with equal polarisation

Polarised Beams

Reduced SM background for equally polarised beams

$\Rightarrow$ Provide significantly better exclusion limits on ALP-fermion coupling

Effectively the same SM background for opposite polarised beams

? Can we get better limits on dark photon and ALP-photon couplings **?**
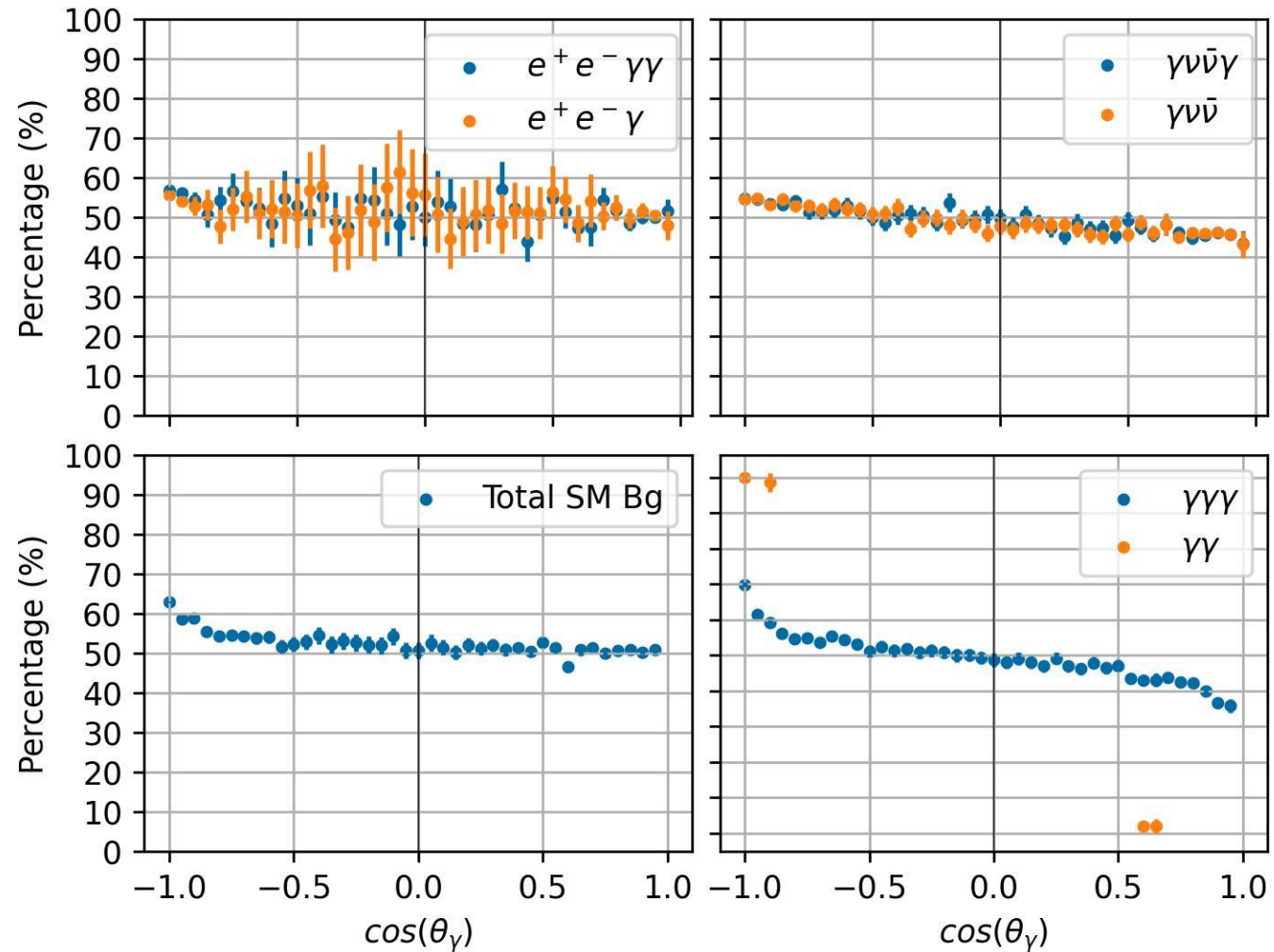
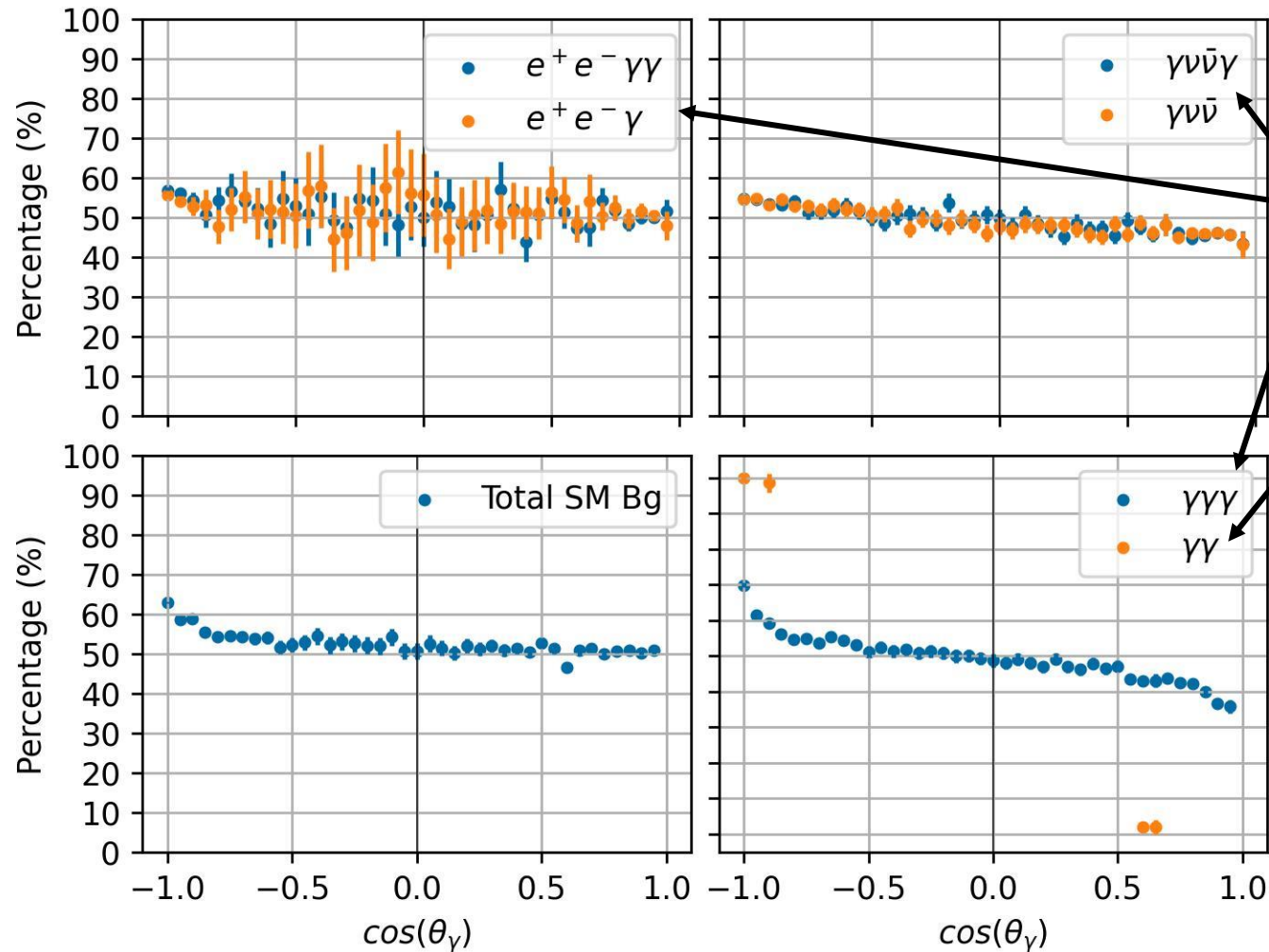# Polarisation of the Photon

Polarisation of the Photon

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

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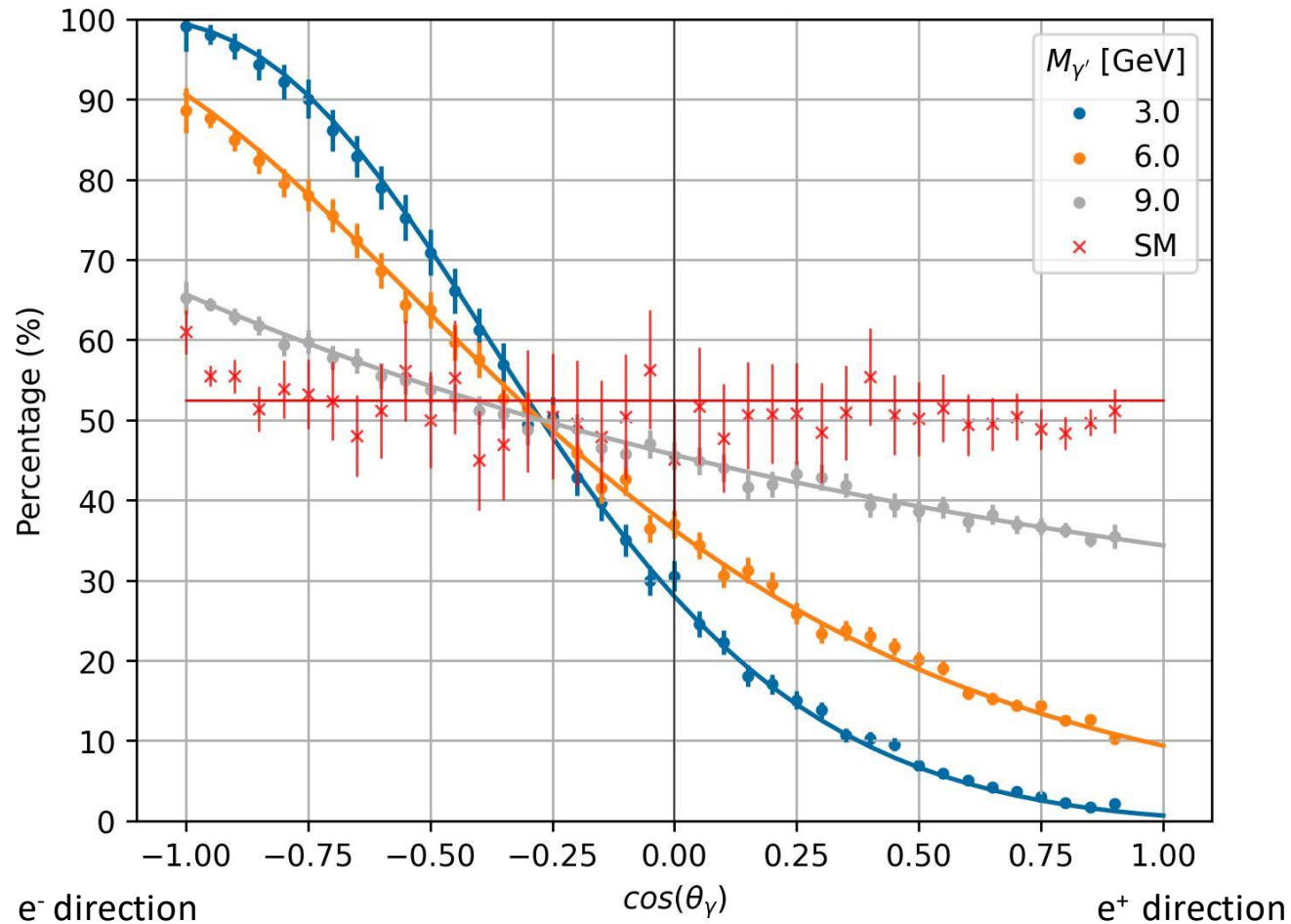
Polarisation of the Photon

Sofie Nordahl Erner

Polarisation of the Photon

SM Background

- Mostly random
  - Several contributions

- Restricted by mono-photon signal
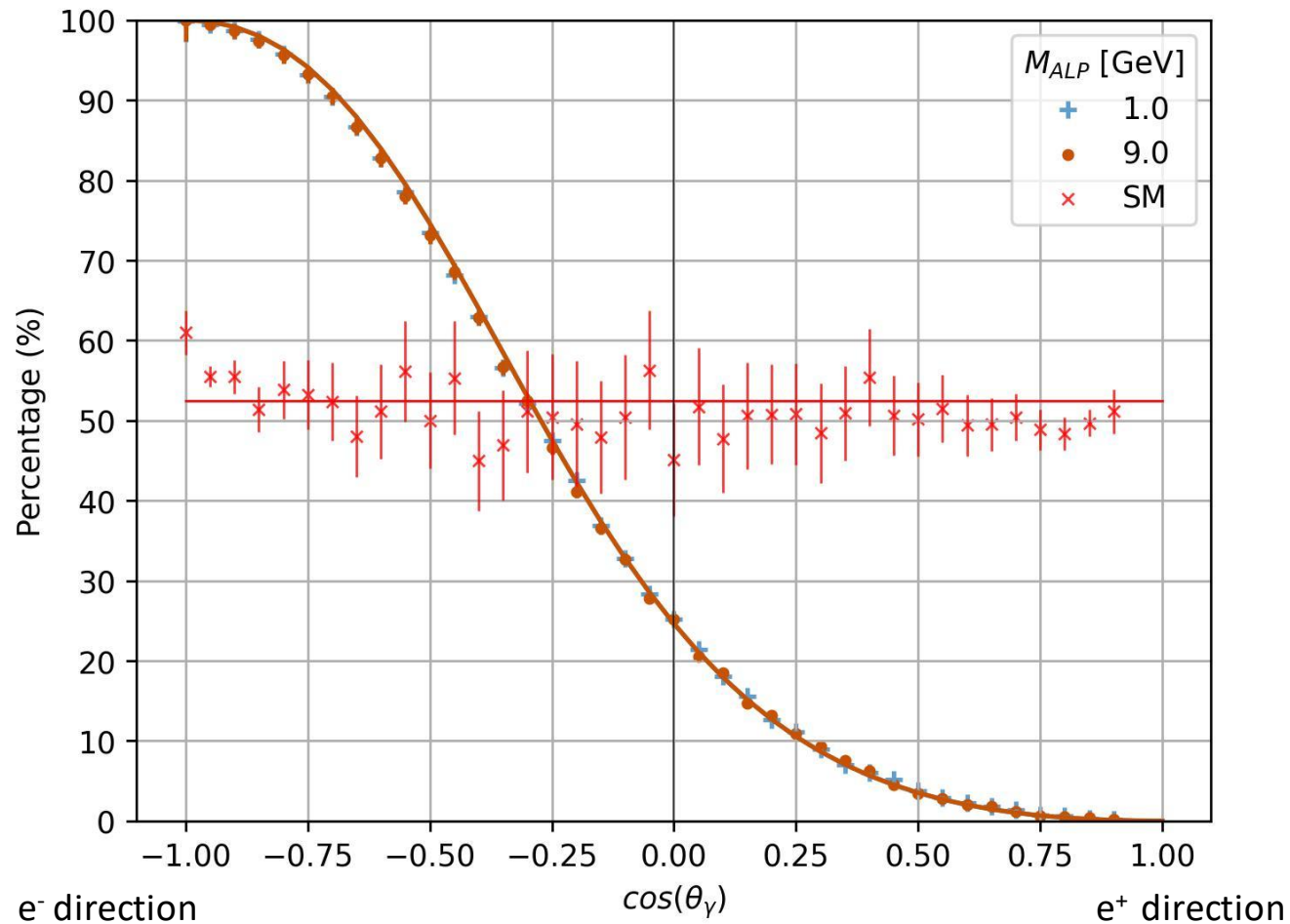
- Total SM background around 50%

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
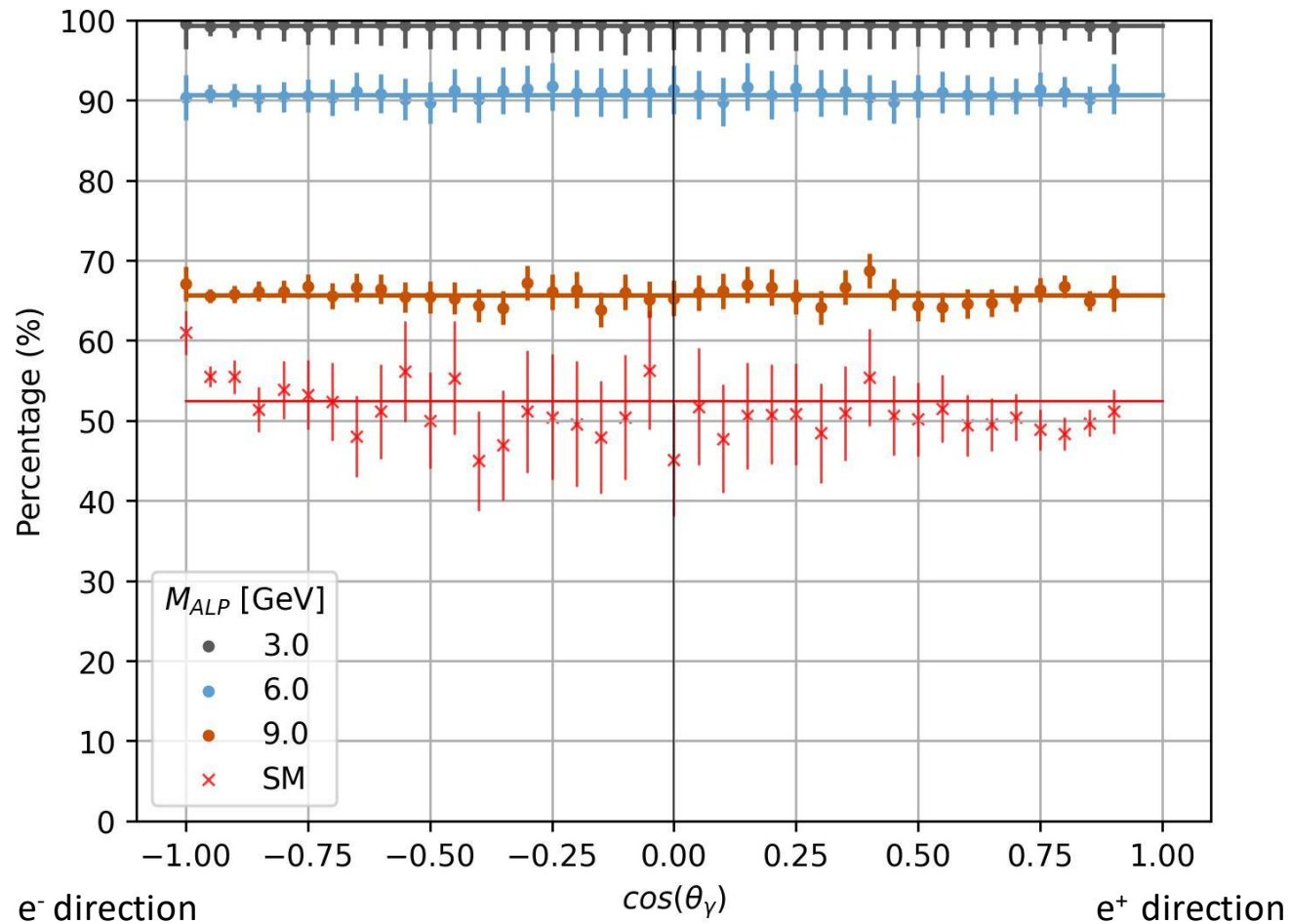
Polarisation of the Photon

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

⇒ Helicity match both incoming beams

⇒ No angular dependence

- Same shape as SM Background

Different from dark photon and ALP-photon coupling
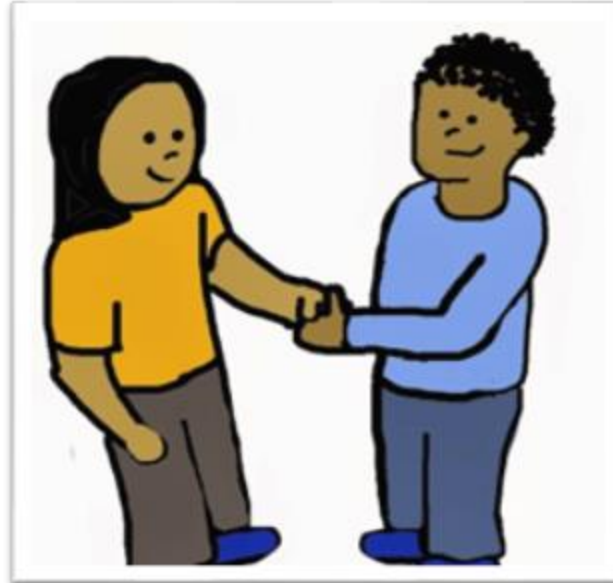
Polarisation of the Photon

Not Planned! This was speculative

- Do not know how it would be implemented
$\Rightarrow$ Not going to try and provide exclusion limits

Outlook

- What is realistic?

- How to measure the polarisation of the outgoing photon?

- What degree of beam polarisation is needed to distinguish contributions?

Phenomenologist **Experimentalists**

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

- Shape of photon helicity fraction distribution

⇒ Provide better exclusion limits on dark photon and ALP-photon couplings

Thanks for listening!

Backup Slides

Dark Photon

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

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

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)

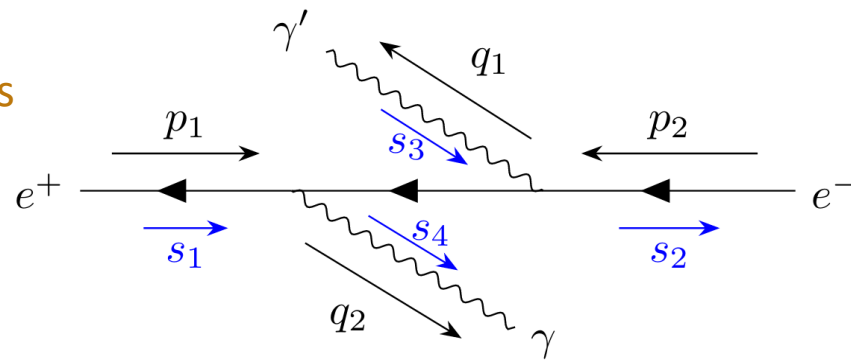Pseudo-scalar particle with linear effective Lagrangian

$$\mathcal{L}_{\text{eff}} = \frac{1}{2} \left(\partial_\mu a \right) \left(\partial^\mu a \right) - \frac{m_a^2}{2} a^2 + \sum_f \frac{c_{ff}}{2} \frac{\partial^\mu a}{f_a} \bar{f} \gamma_\mu \gamma_5 f$$

$$+ g_s^2 C_{GG} \frac{a}{f_a} G_{\mu\nu}^A \tilde{G}^{\mu\nu,A} + g^2 C_{WW} \frac{a}{f_a} W_{\mu\nu}^A \tilde{W}^{\mu\nu,A} + g'^2 C_{BB} \frac{a}{f_a} B_{\mu\nu} \tilde{B}^{\mu\nu}$$

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

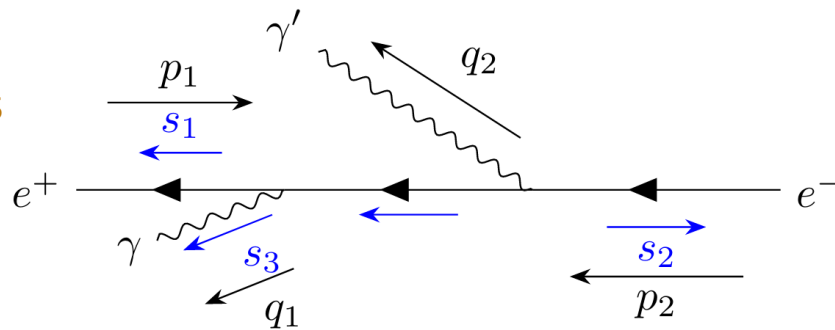# Spin Structure Diagrams