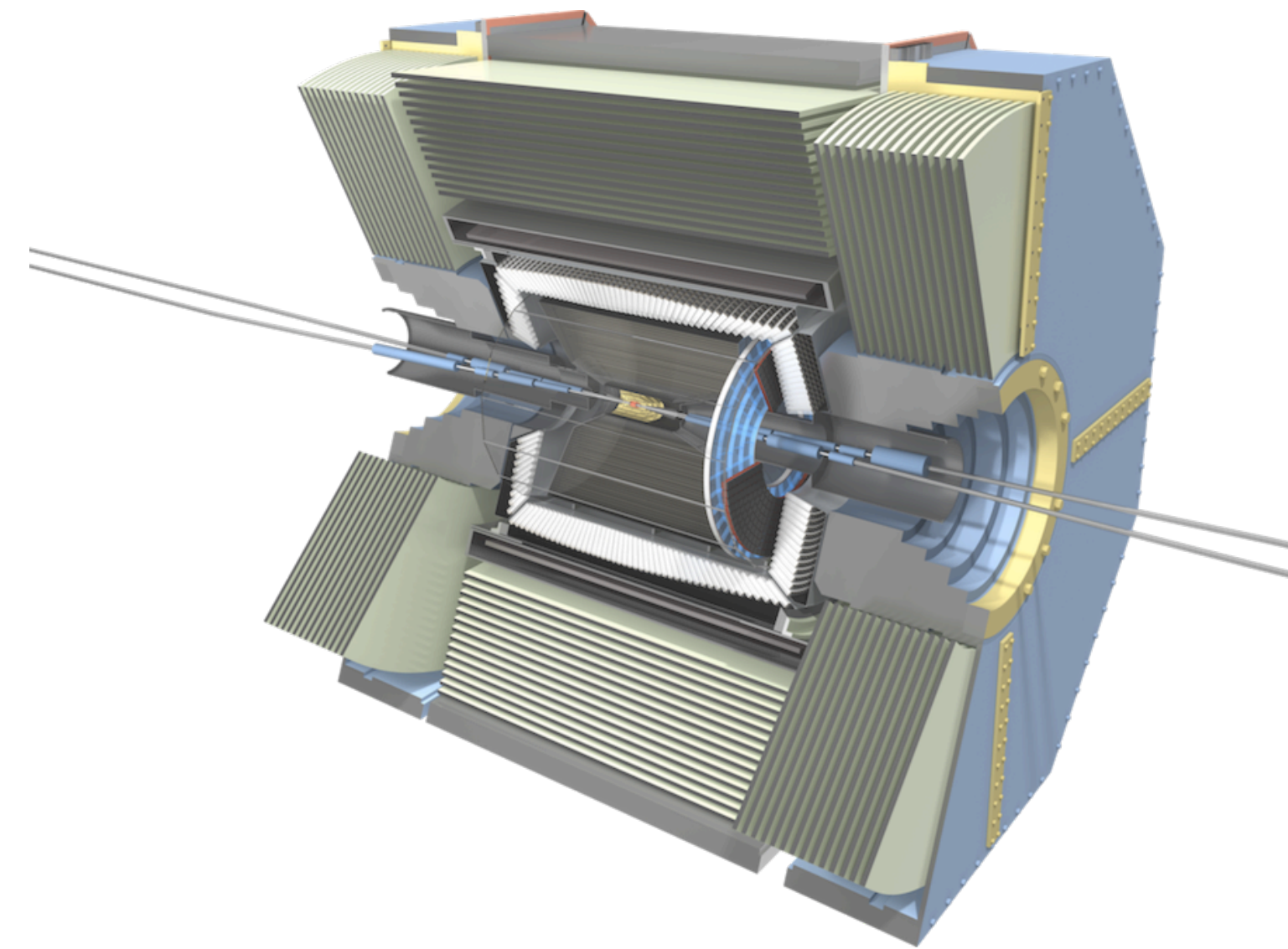


# Dark searches



2022 August 3, *Belle II Summer Workshop*

Michael De Nuccio [they/them]

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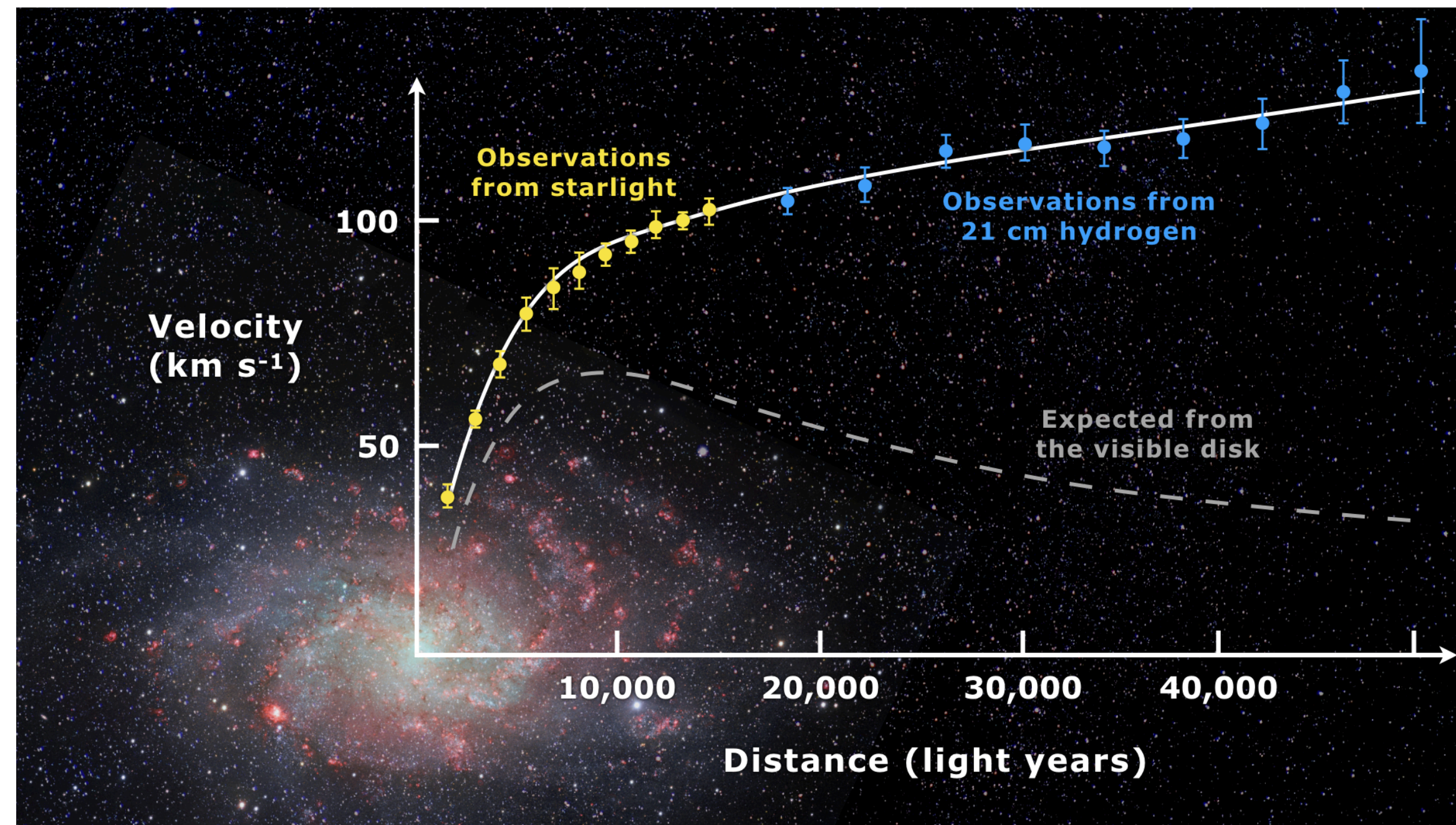
# Overview

- Dark Matter @ **Belle II**
- **Dark analyses**
  - Axion-like particles
  - Dark photon
  - And more!

# Introduction

# Compulsory slides about Dark Matter

- *Hints* from astrophysics & cosmology
- Modified gravity or **new particles**  $\Rightarrow$  **Dark Matter (DM)**
- Interacts with Standard Model (SM) particles via **gravity**  
hopefully also **somehow else** so we can detect it

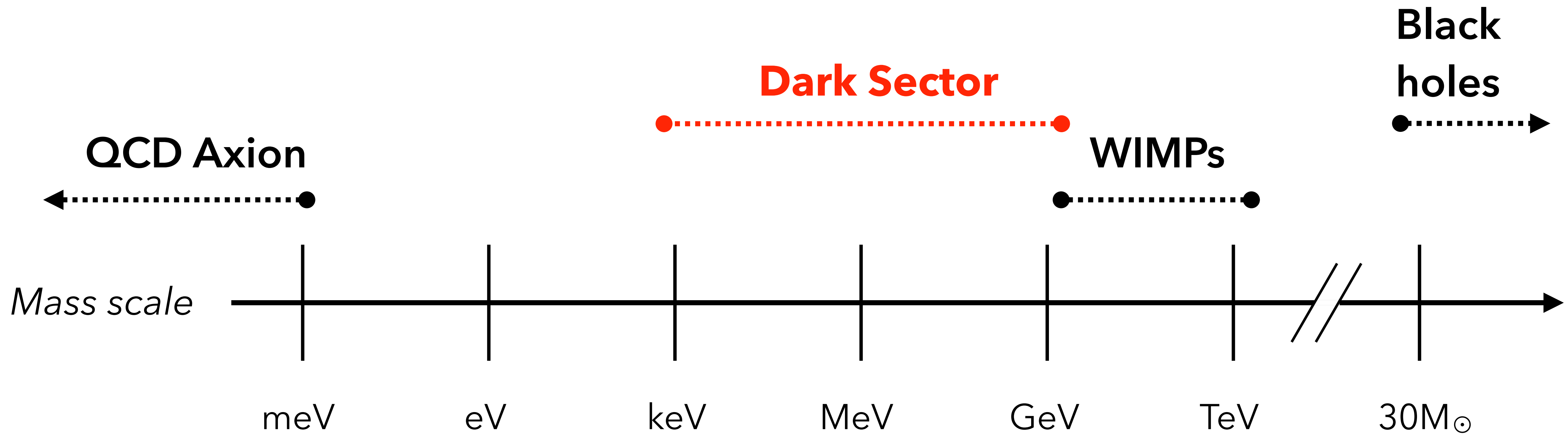


# Compulsory slides about Dark Matter

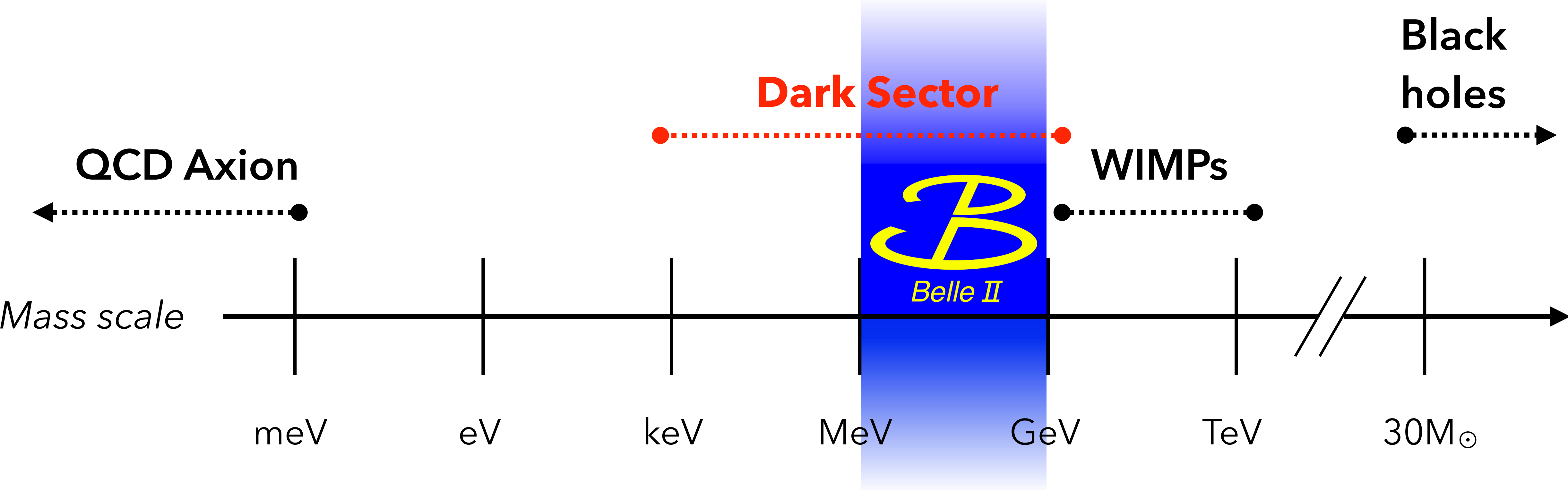
- **Dark Sector**

- DM and SM were in thermal equilibrium in early universe:  $\chi\bar{\chi}\leftrightarrow M\bar{M}$
- Cool down  $\Rightarrow$  DM production & annihilation stop (freeze-out)  $\Rightarrow$  **relic density**
- Low-mass DM, new feeble interaction: **Dark Sector**
  - SM and DM coupled via a **dark mediator**

# Compulsory slides about Dark Matter

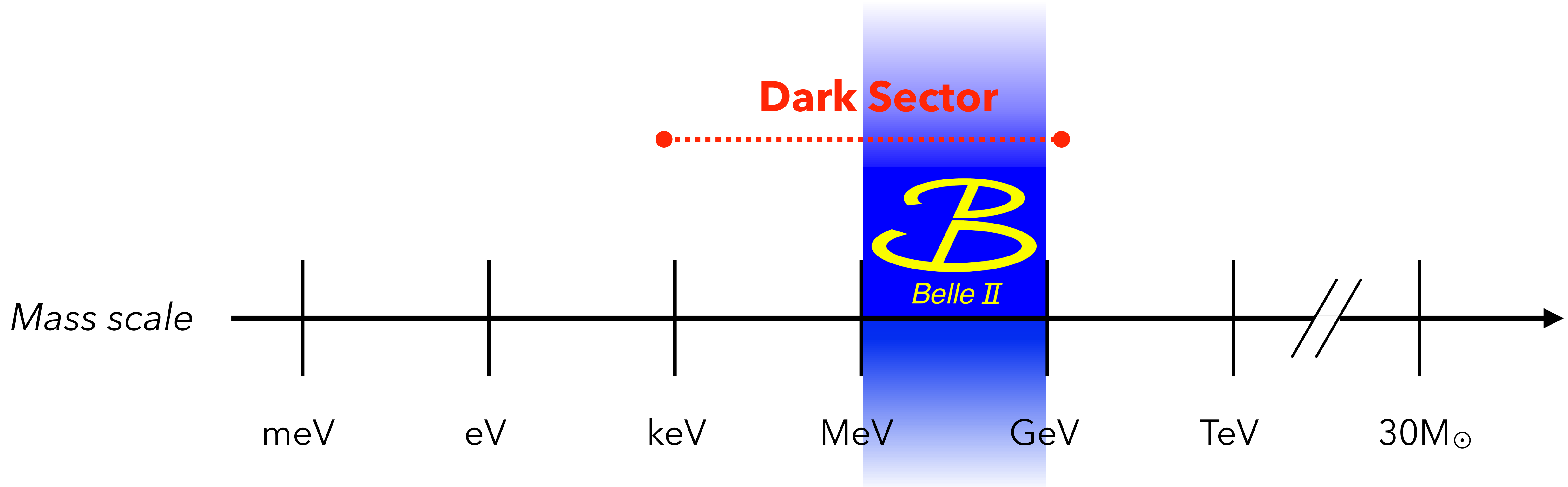


# Belle II can explore the Dark Sector



# Belle II is good at exploring the Dark Sector

- **Hermetic detector** (90% of solid angle)
- **Clean environment** ( $e^+e^-$  collider)
  - Known initial state
  - Low-multiplicity events (few particles)
- **Dedicated triggers for low-multiplicity** events

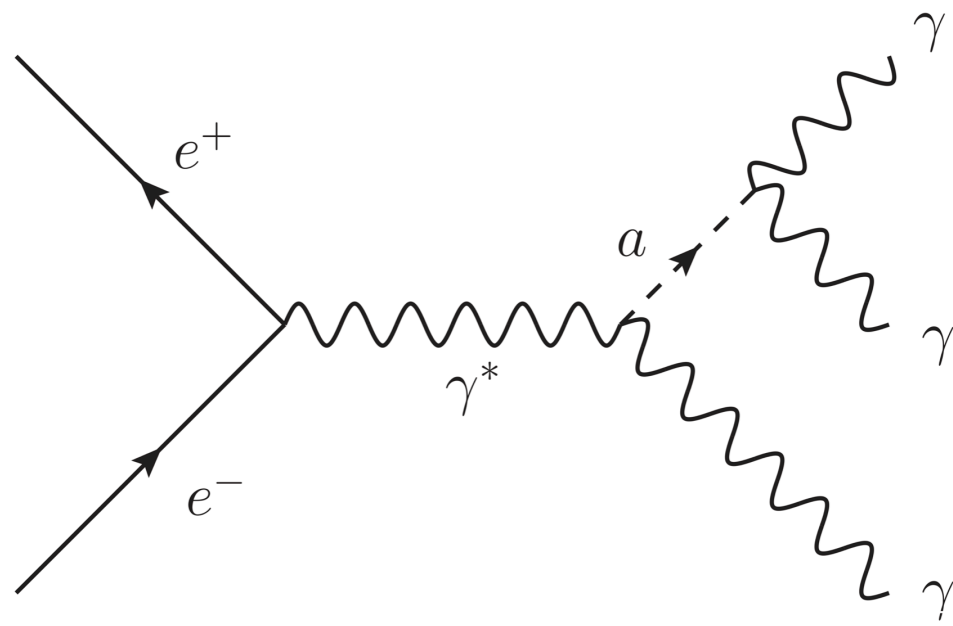




# How to search for Dark Matter (Kurzgesagt)

## Physical process

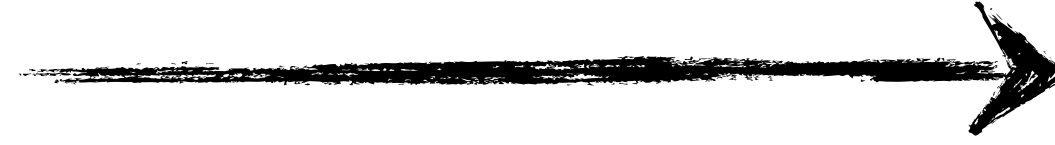
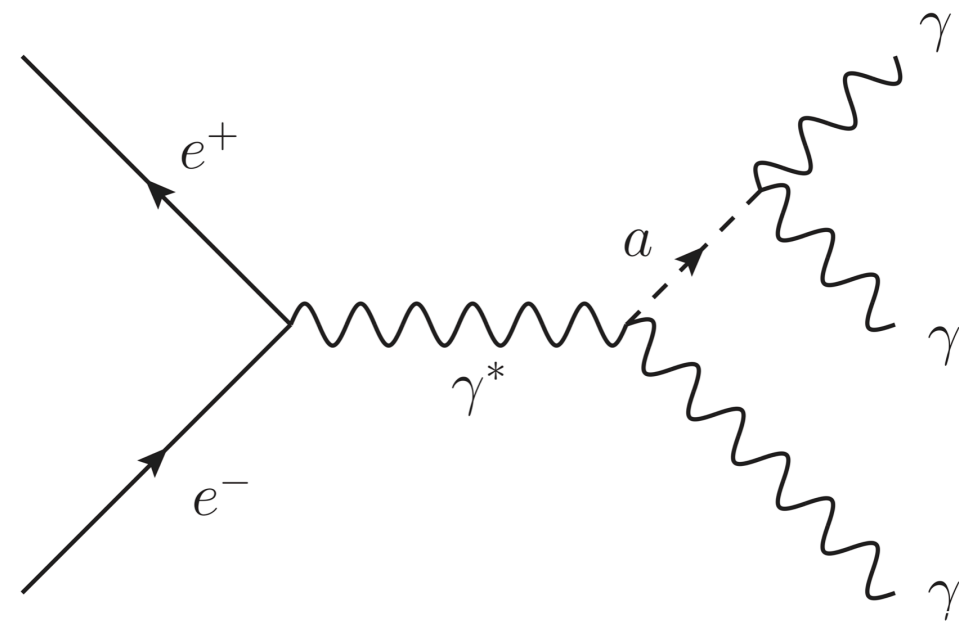
- "Doesn't exist"  $\Rightarrow$   
MC simulation driven by theory



# How to search for Dark Matter (Kurzgesagt)

## Physical process

- "Doesn't exist"  $\Rightarrow$   
MC simulation driven by theory



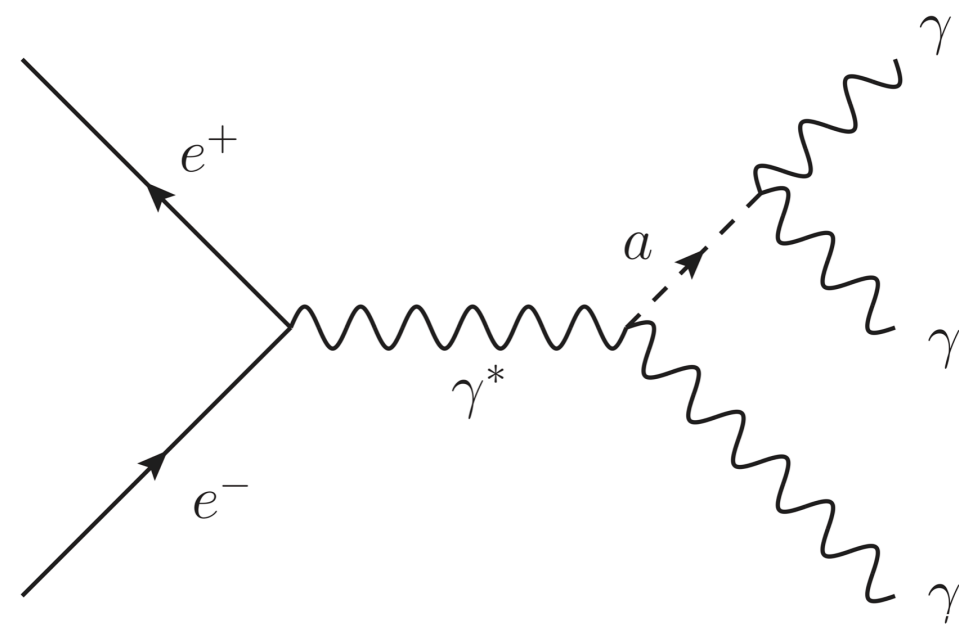
## Selection on variables

- Kill background
- Save signal

# How to search for Dark Matter (Kurzgesagt)

## Physical process

- "Doesn't exist"  $\Rightarrow$   
MC simulation driven by theory

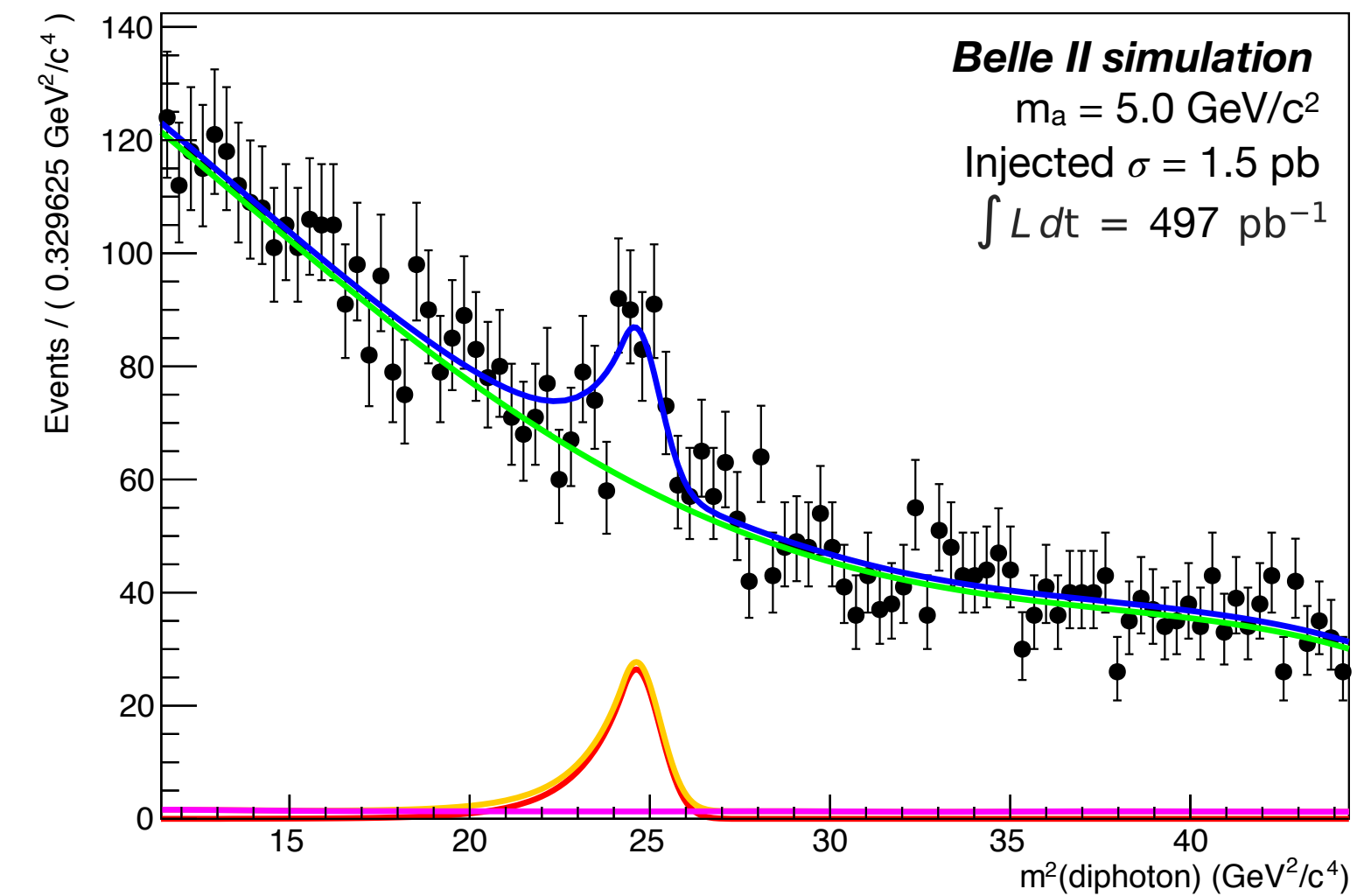


## Selection on variables

- Kill background
- Save signal



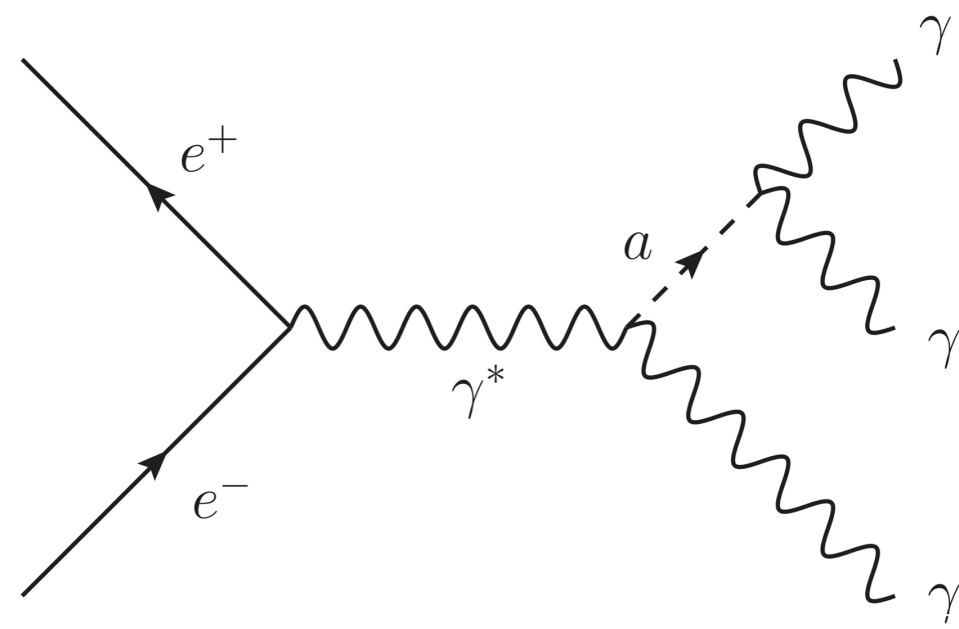
## Signal & background modeling



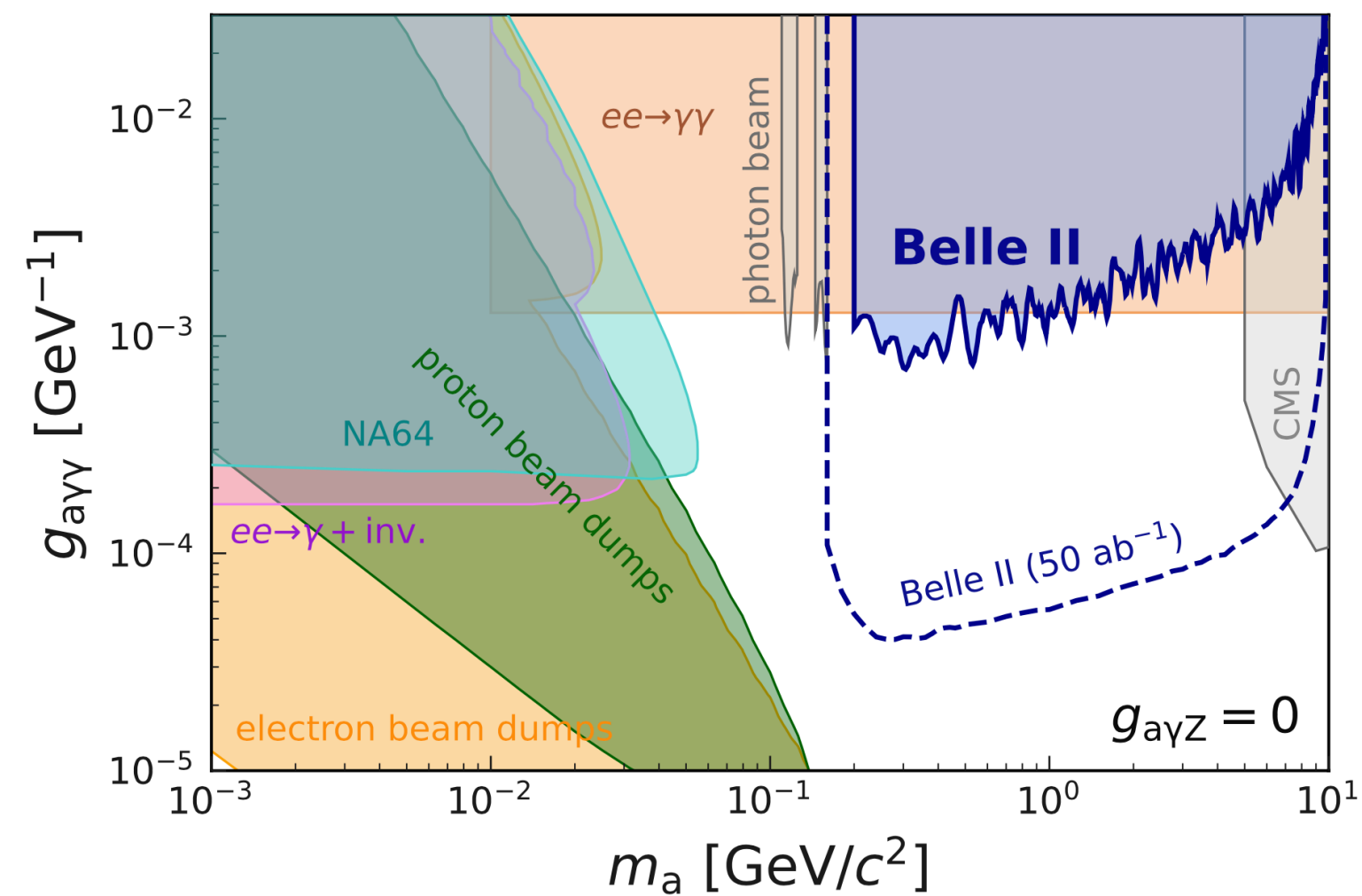
# How to search for Dark Matter (Kurzgesagt)

## Physical process

- "Doesn't exist"  $\Rightarrow$  MC simulation driven by theory



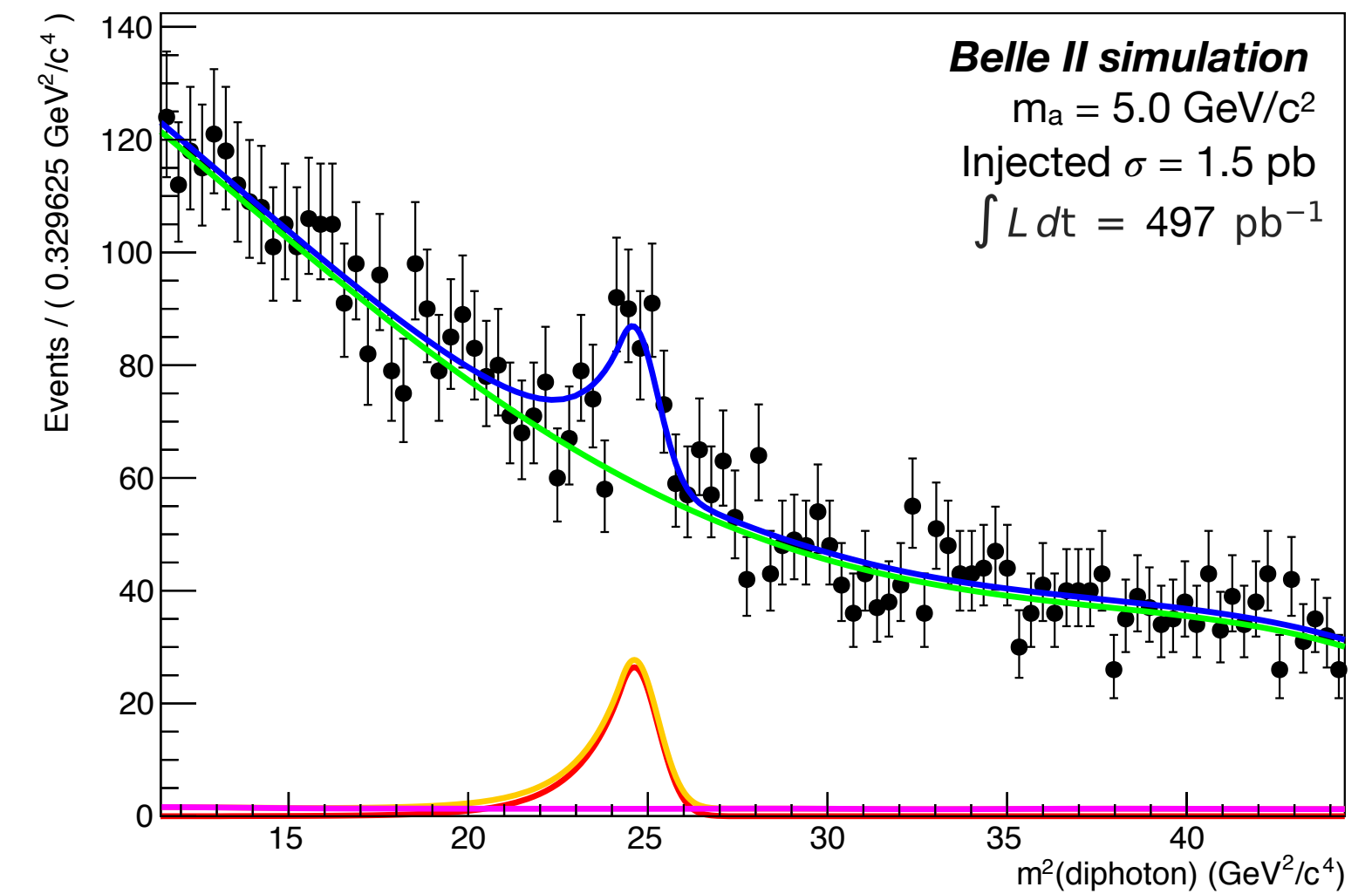
## Upper limits



## Selection on variables

- Kill background
- Save signal

## Signal & background modeling



# Analyses

# Overview

From the **Belle II Snowmass White Paper:**

<b>10 Direct searches for light non-SM physics and Dark Sector studies</b>	<b>32</b>
10.1 Axion-like particles . . . . .	33
10.2 Dark photon . . . . .	34
10.2.1 Minimal dark photon model . . . . .	34
10.2.2 Extended dark photon models . . . . .	34
10.3 $Z'$ in an $L_\mu - L_\tau$ model . . . . .	35
10.4 Long-lived signatures . . . . .	36
10.4.1 Inelastic Dark Matter . . . . .	36
10.4.2 Dark scalar . . . . .	37

# Overview

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**Don't panic!**

Only **two** in "detail"

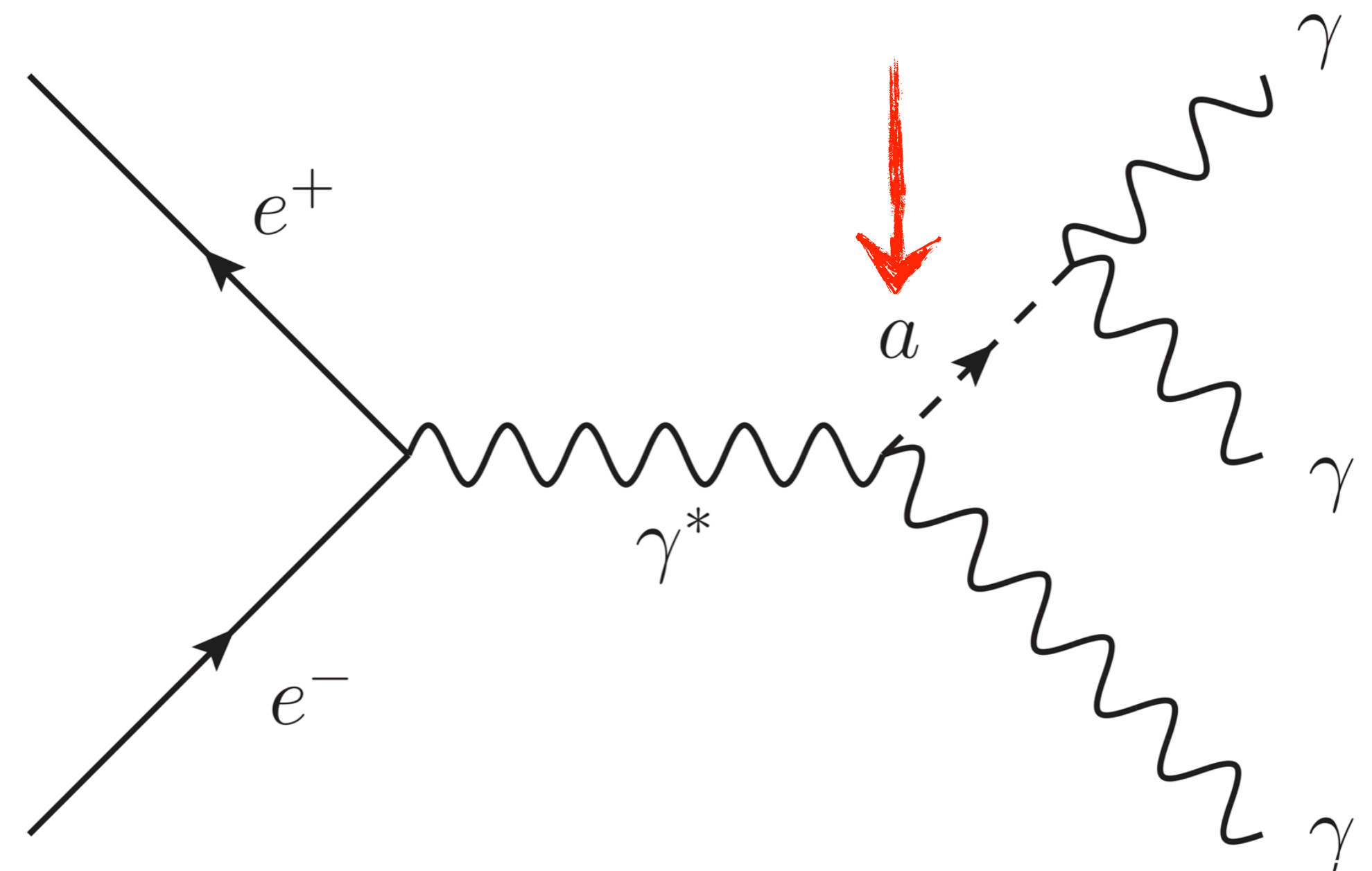
Just mention the others

<https://arxiv.org/pdf/2207.06307.pdf>

# Axion-like particles (ALPs)

- **ALPs**: cousins of axion; massive, neutral, pseudoscalar; dark mediators
- $e^+e^- \rightarrow a\gamma$ ,  $a \rightarrow \gamma\gamma$
- **3-photon final state, no missing E**
- Parameters: mass  $m_a$  and coupling  $g_{a\gamma\gamma}$
- **Backgrounds:**
  - $e^+e^- \rightarrow \gamma\gamma(\gamma)$
  - $e^+e^- \rightarrow e^+e^-(\gamma)$  - if tracks are mis-reconstructed
  - $e^+e^- \rightarrow \pi^0/\eta/\eta' \gamma$  - peaking backgrounds
- Pushing to **low masses is difficult**
  - $\gamma\gamma$  from ALP merge (tough to distinguish them)
  - $\pi^0$  is nearby
  - First iteration: not done

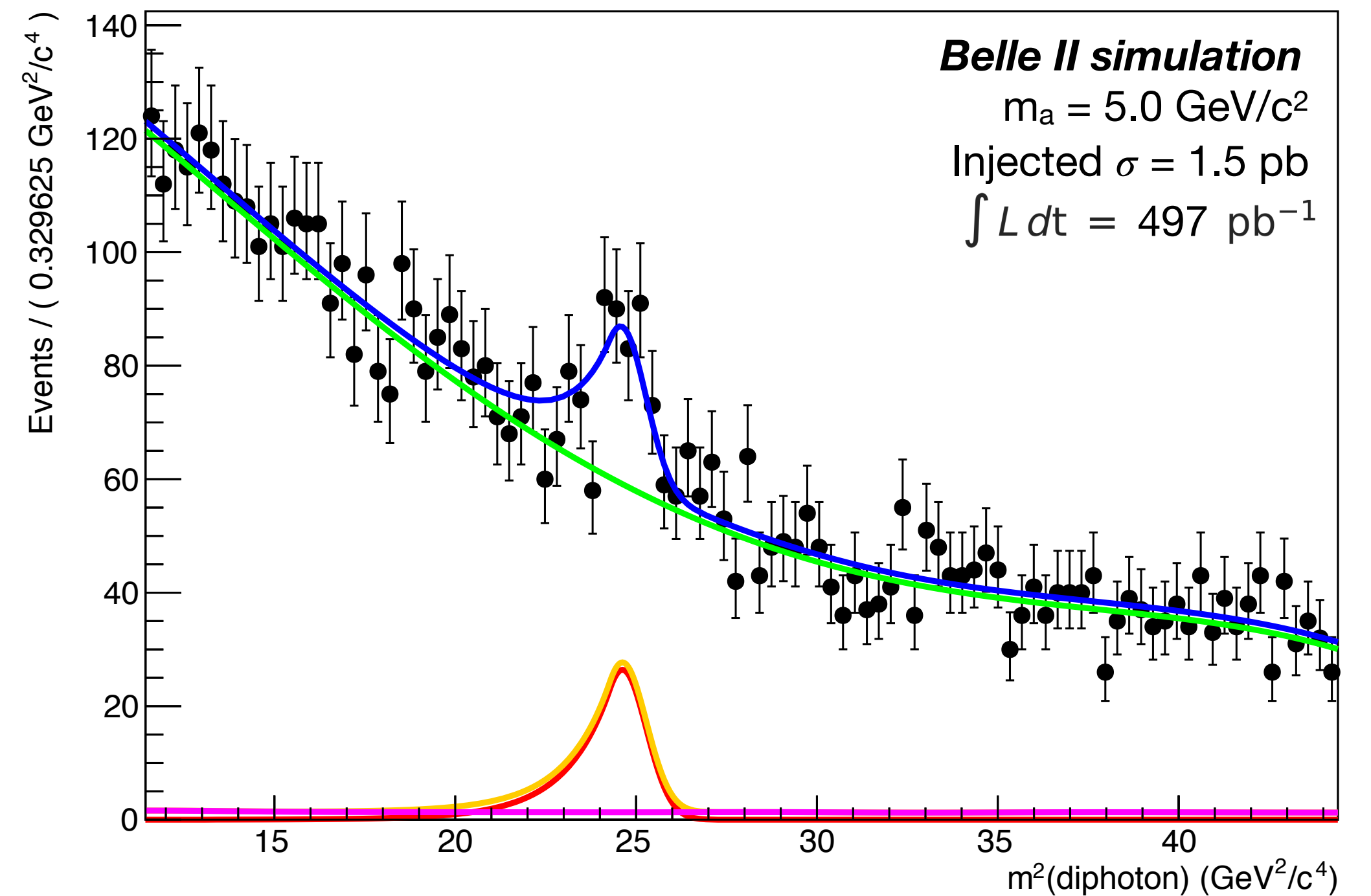
*My previous analysis*





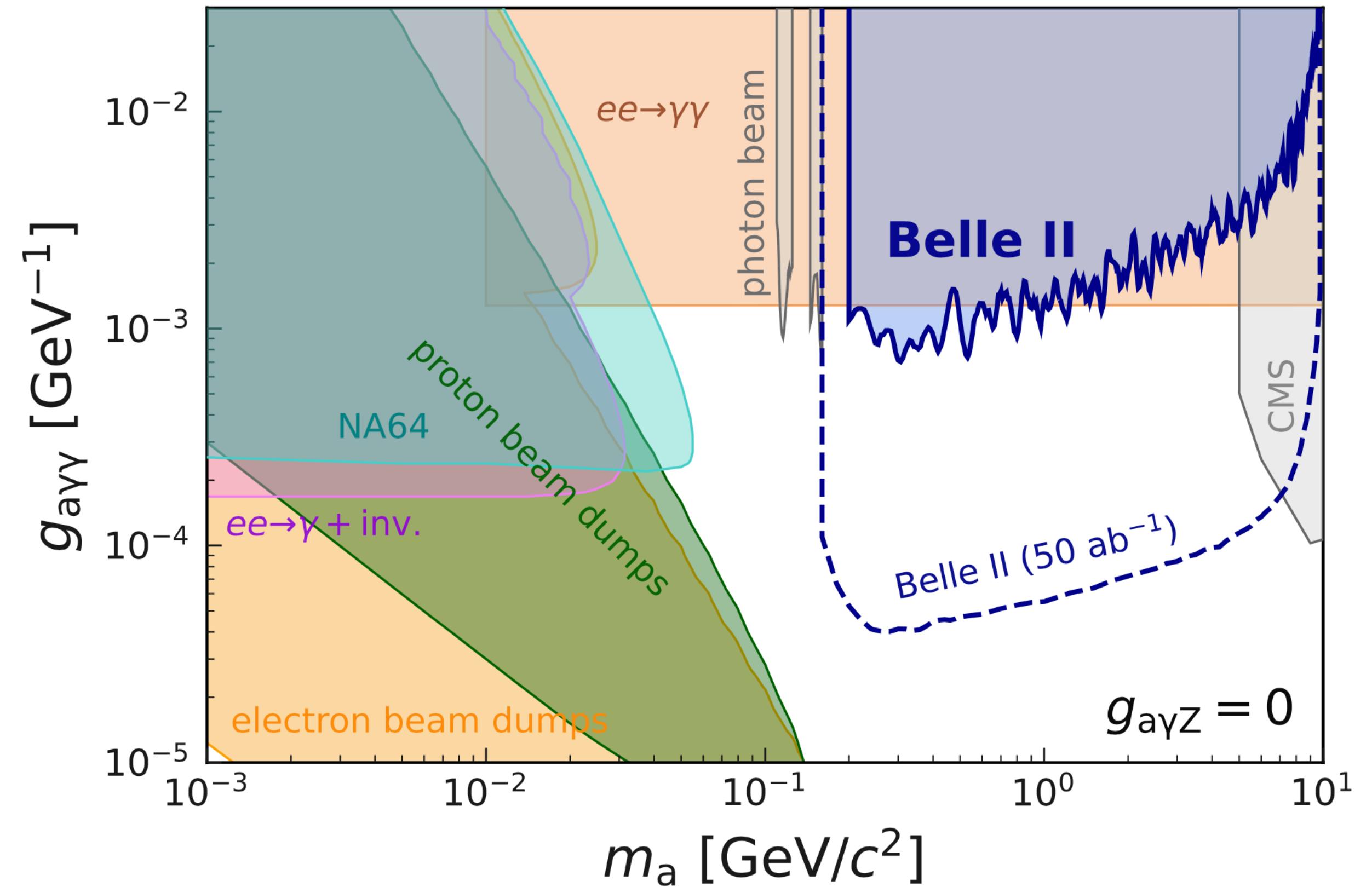
# Axion-like particles (ALPs)

- **Selection:** multi-dimensional **rectangular cut(s)**
  - In the **future: MVA** (Multi-Variate Analysis = Neural Network) particularly for low mass (merging photons and  $\pi^0$ )
- Mass scan: **search a peaking signal over smooth background**



# Axion-like particles (ALPs)

- **Found nothing**  $\Rightarrow$  **upper limits**
  - The money plots that make your supervisors happy :)
- Already competitive with preliminary data
- Belle II has a **unique area of sensitivity**

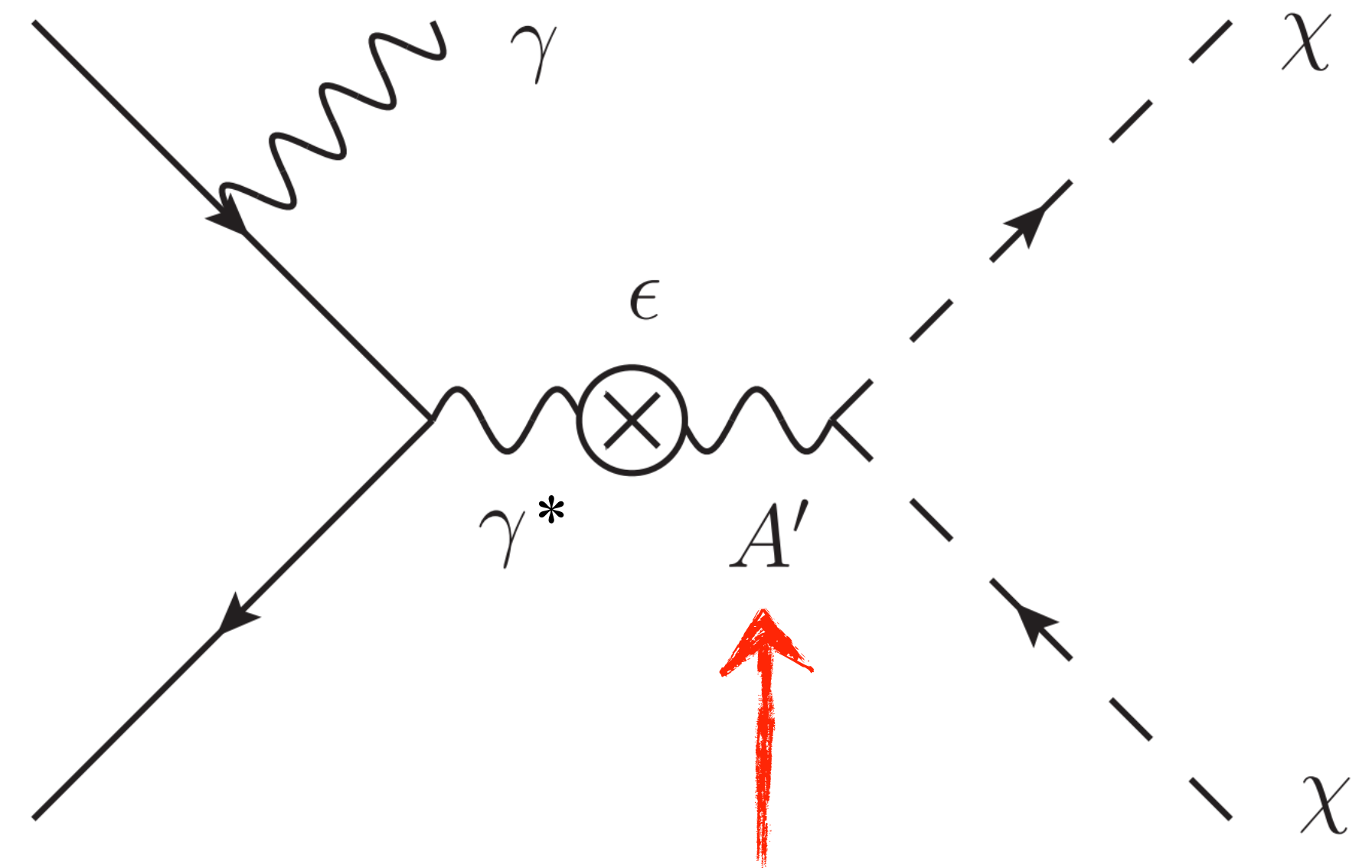


<https://arxiv.org/pdf/2007.13071.pdf>

# Dark photon

- Dark mediator (mixes with SM photons and with DM)
- $e^+e^- \rightarrow \gamma A', A' \rightarrow \chi\chi$
- **Search for 1 single  $\gamma$  and missing E**
  - Works also for long-lived particles
- Parameters: mass  $m_{A'}$  and coupling  $\epsilon$
- **Backgrounds:**
  - $e^+e^- \rightarrow \gamma\gamma(\gamma)$  with **missed** photons
  - Cosmics
- Detector inefficiencies: what if we **miss a  $\gamma$** ?
  - Measure and correct **photon inefficiencies** in data & MC

*My current analysis*



# Dark photon

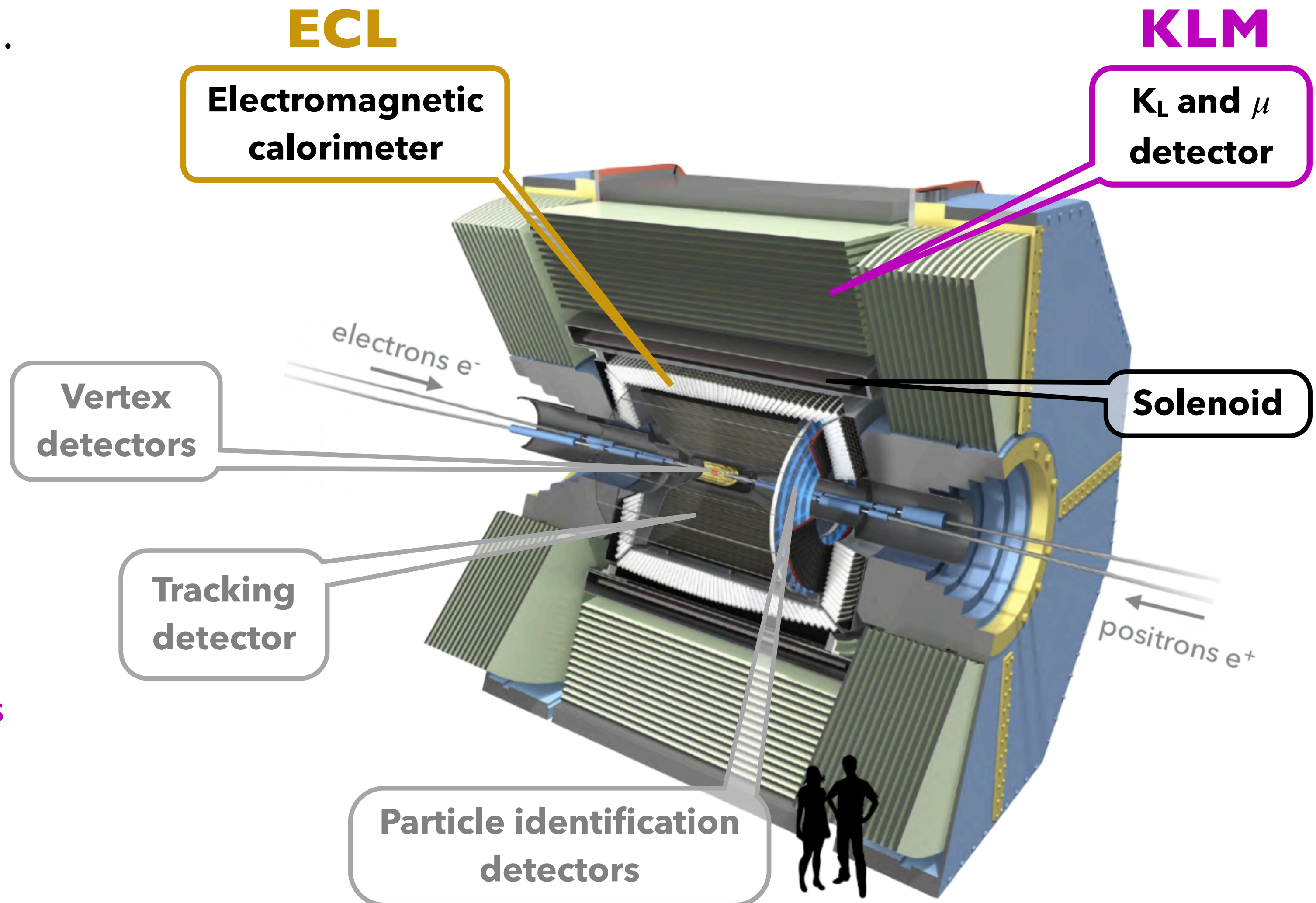
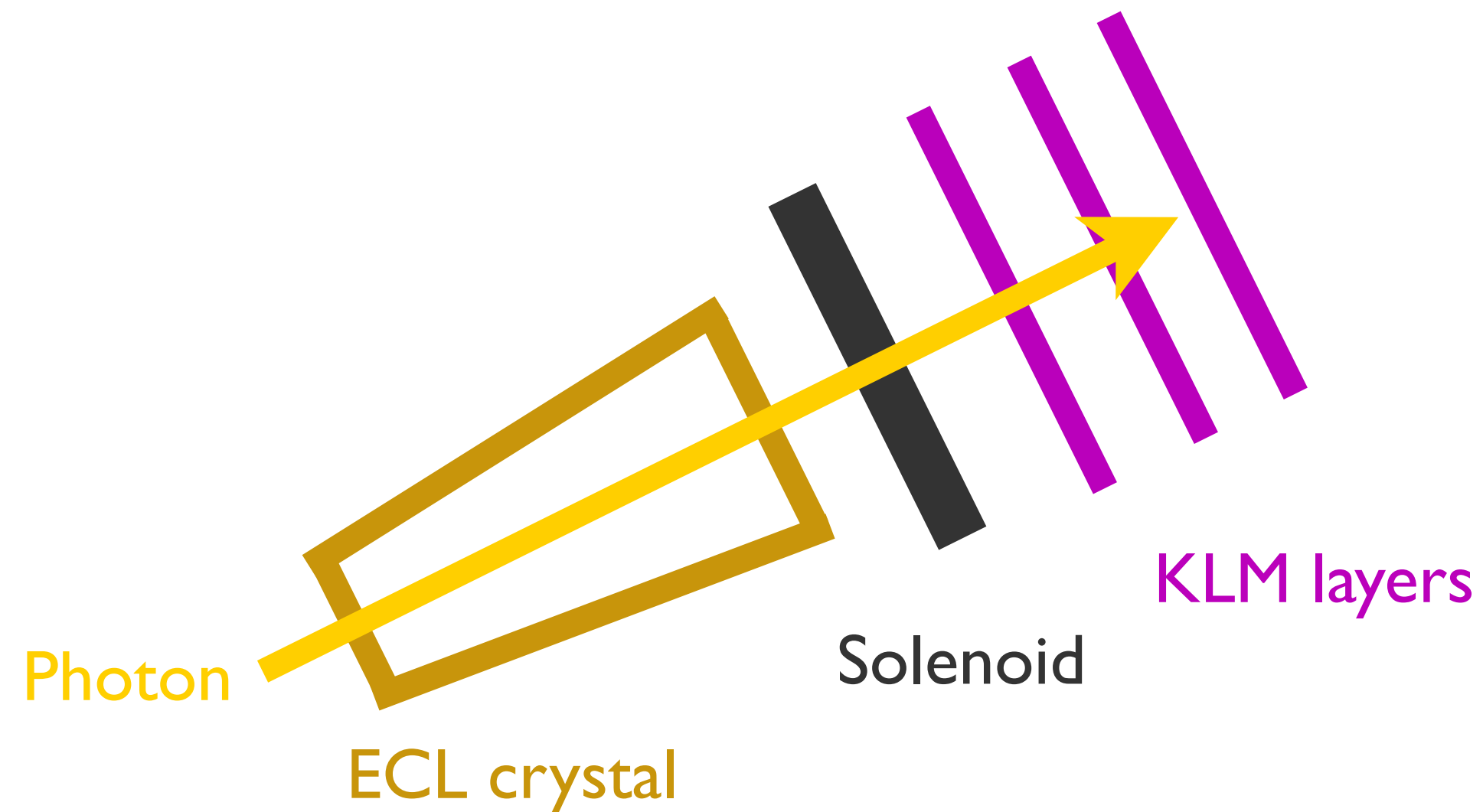
Selection:

- **Define what photon we accept**
  - $E, \theta, t$ , shower shape variables, ...
- **Define what we reject**
  - Other photons
  - **KLM clusters**
  - Tracks

# Dark photon

Selection:

- Define what **photon** we accept
  - $E, \theta, t$ , shower shape variables, ...
- Define what we reject
  - Other **photons**
  - **KLM clusters**
  - Tracks

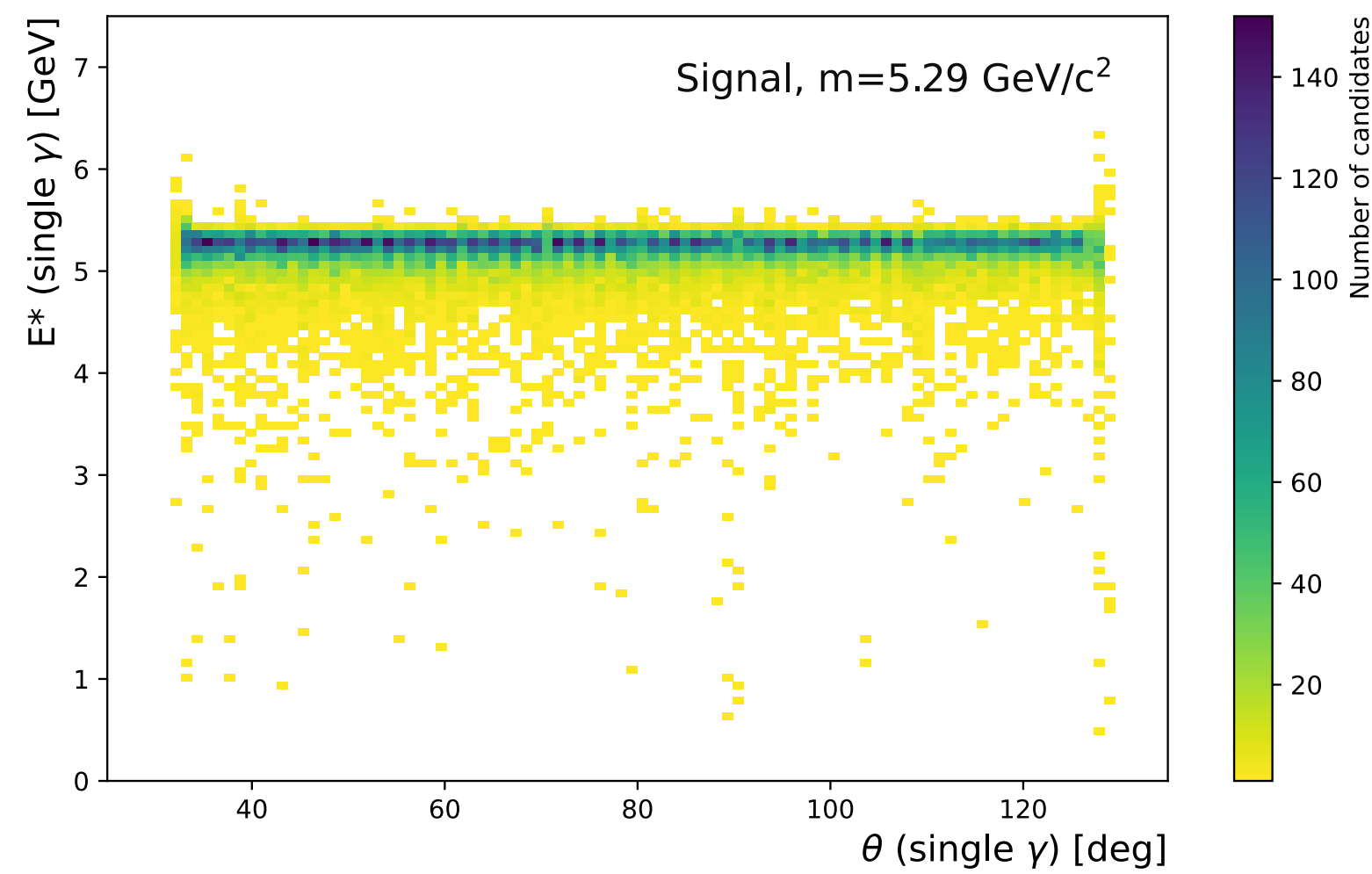


# Dark photon

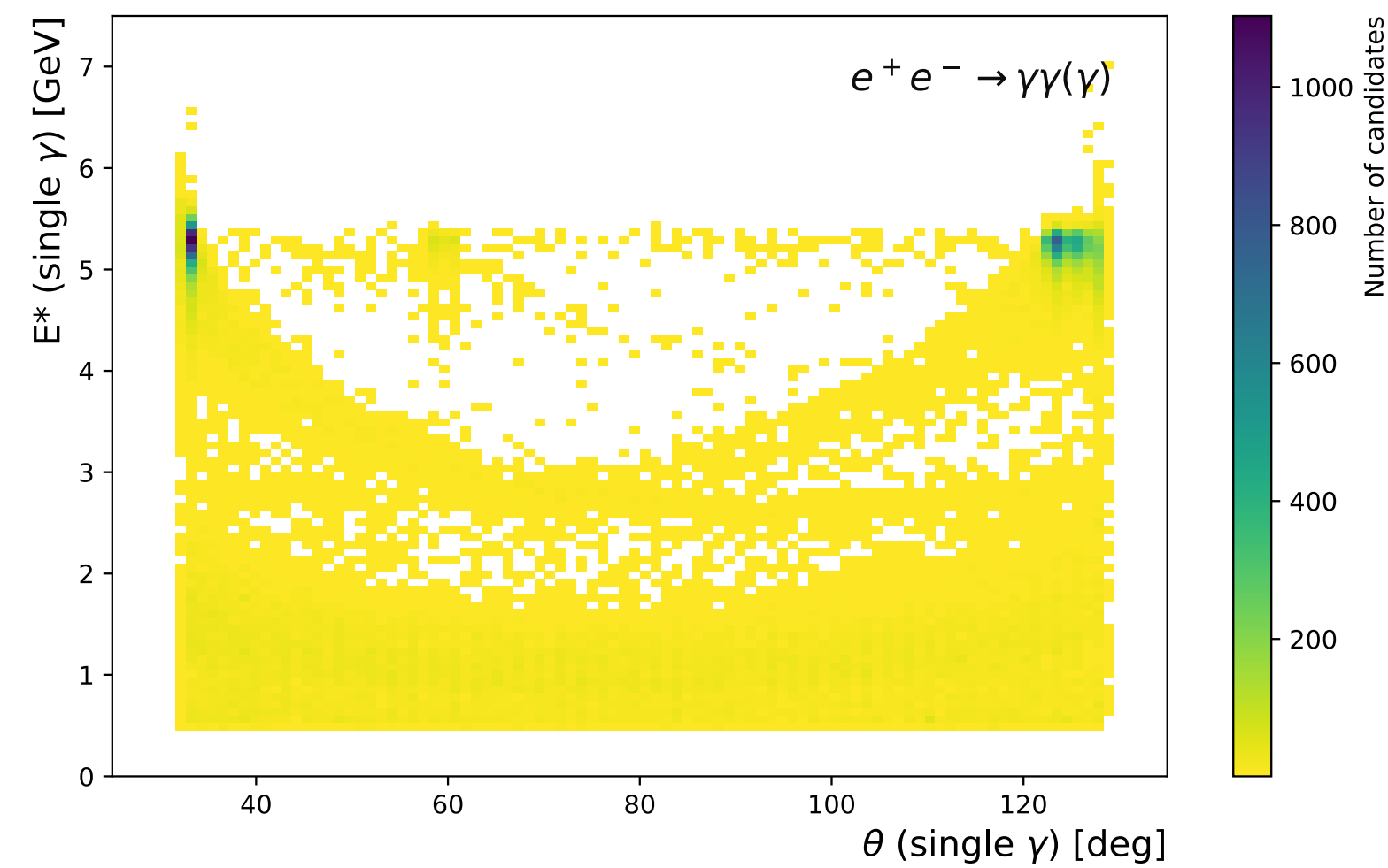
- Signal vs background
  - $E^*(\gamma)$  vs  $\theta(\gamma)$
  - Signal: **horizontal strips**
  - Background ( $ee \rightarrow \gamma\gamma(\gamma)$ , cosmics): **blobs**

*Brutally preliminary!*

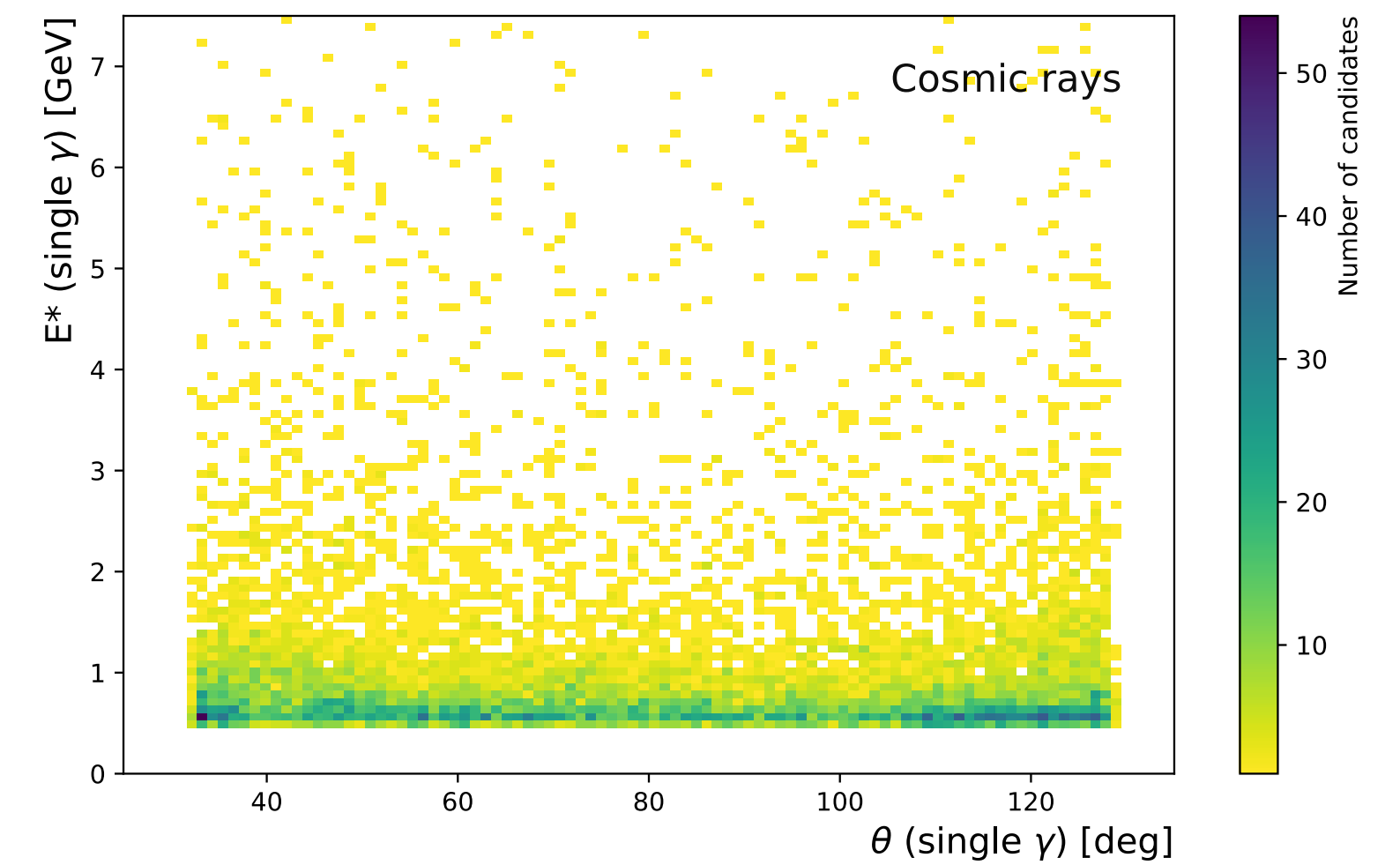
Signal



$ee \rightarrow \gamma\gamma(\gamma)$

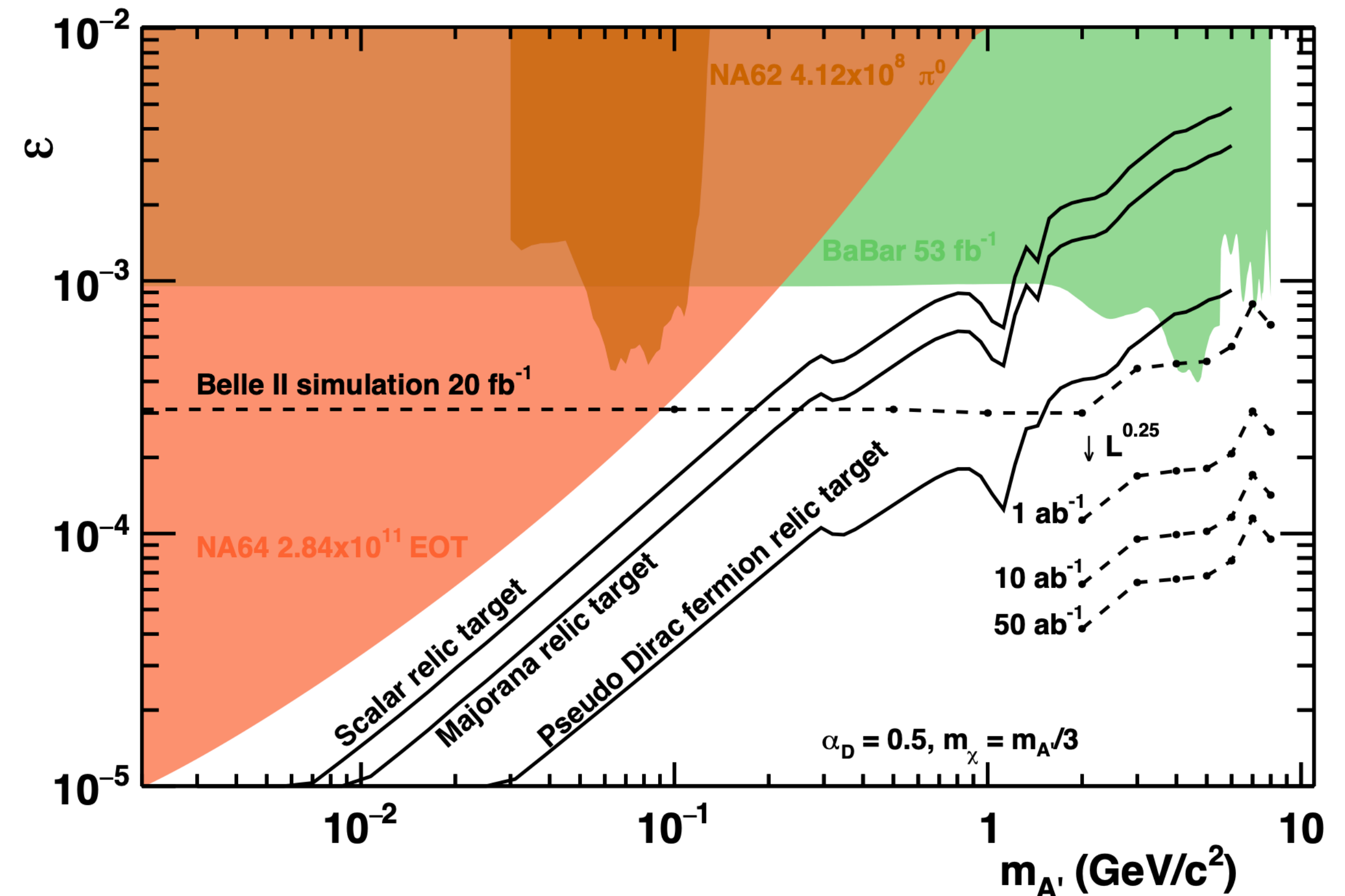


Cosmics



# Dark photon

- Belle II has **unique reach**
- Sensitivity to see a signal where it could explain relic Dark Matter



# Other dark searches

- Z' to (in)visible

- Dark photon + dark Higgs

- Inelastic dark matter

- Dark scalar

$\mu\bar{\mu} + \text{missing E}$

**Displaced** vertexes

**Known initial state &  
low multiplicity**

very important for these analyses



**Belle II excels  
Unique sensitivities**



# Summary

# Summary

- **Dark Sector** is cool
- More than few **dark searches** @ Belle II
  - Axion-like particles
  - Dark photon
- Belle II has **unique sensitivity** in these areas!

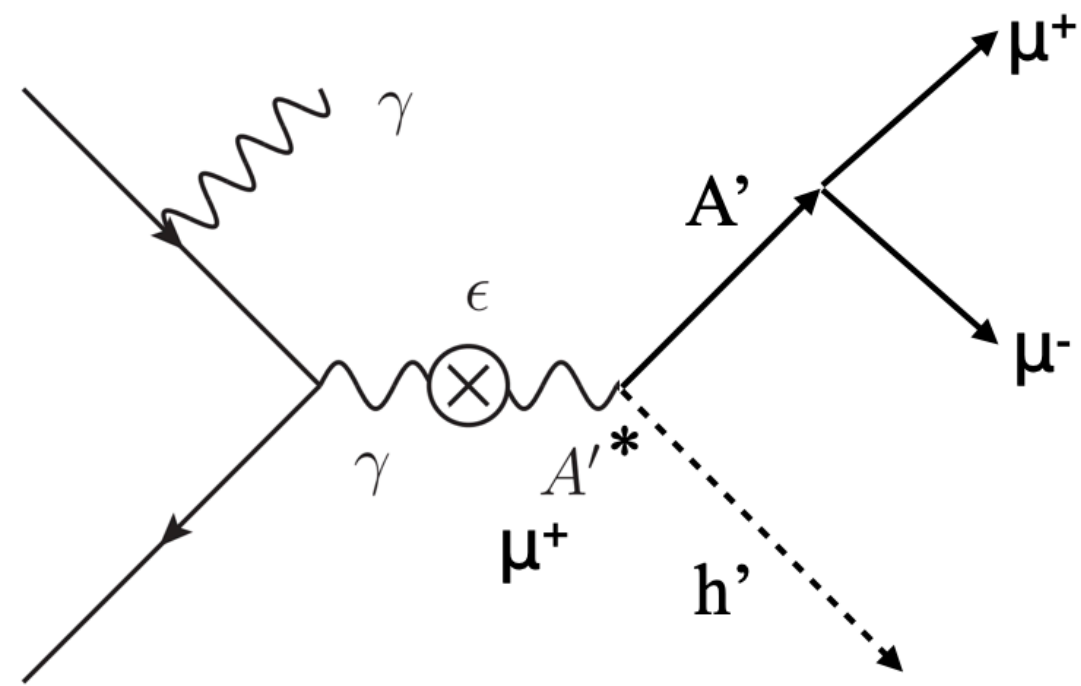
# Backup

# Useful links

- Snowmass page  
[https://snowmass21.org/submissions/rf?s\[\]=belle](https://snowmass21.org/submissions/rf?s[]=belle)
- Snowmass White Paper: Belle II physics reach and plans for the next decade and beyond  
<https://arxiv.org/abs/2207.06307>
- Belle II Executive Summary  
<https://arxiv.org/pdf/2203.10203.pdf>
- Physics reach of a long-lived particle detector at Belle II  
<https://arxiv.org/pdf/2105.12962.pdf>

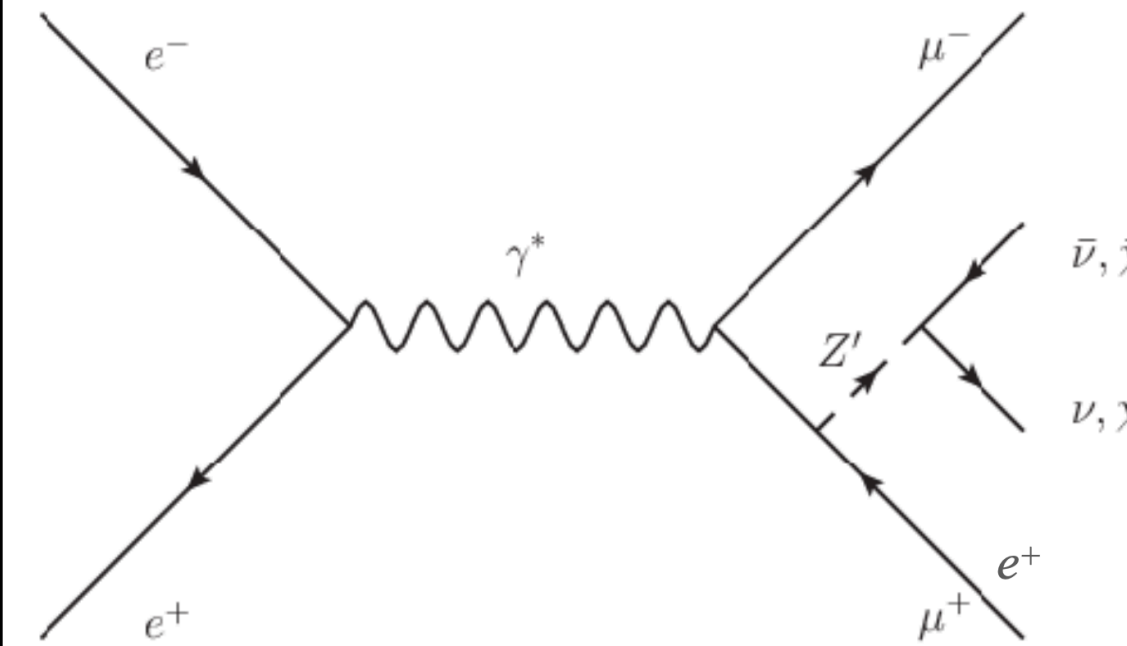
# Other dark searches

## Dark photon + dark Higgs



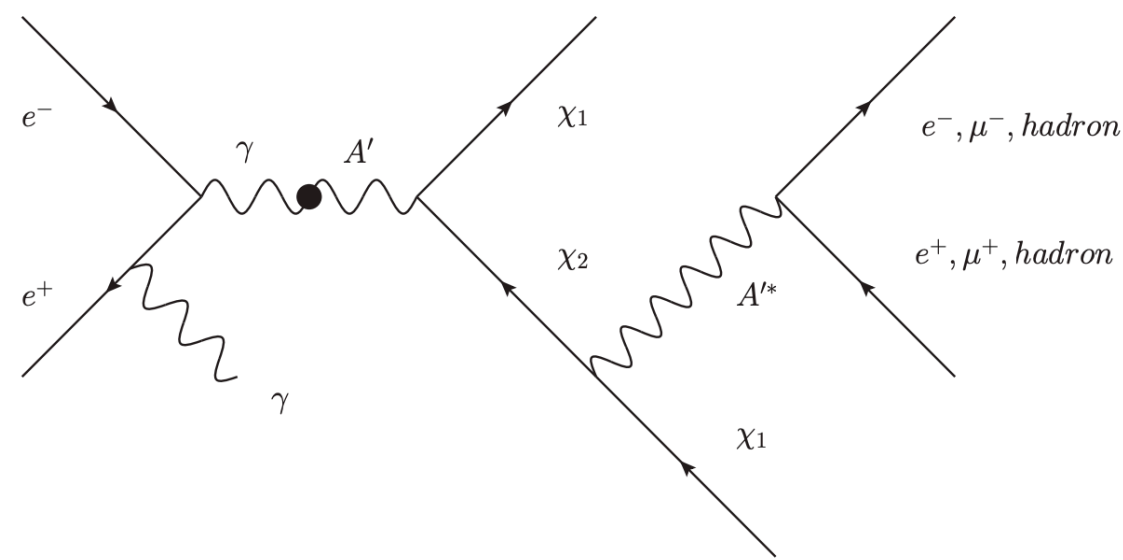
- $\mu\bar{\mu}$  + missing E
- Unique sensitivity

## Z' to (in)visible



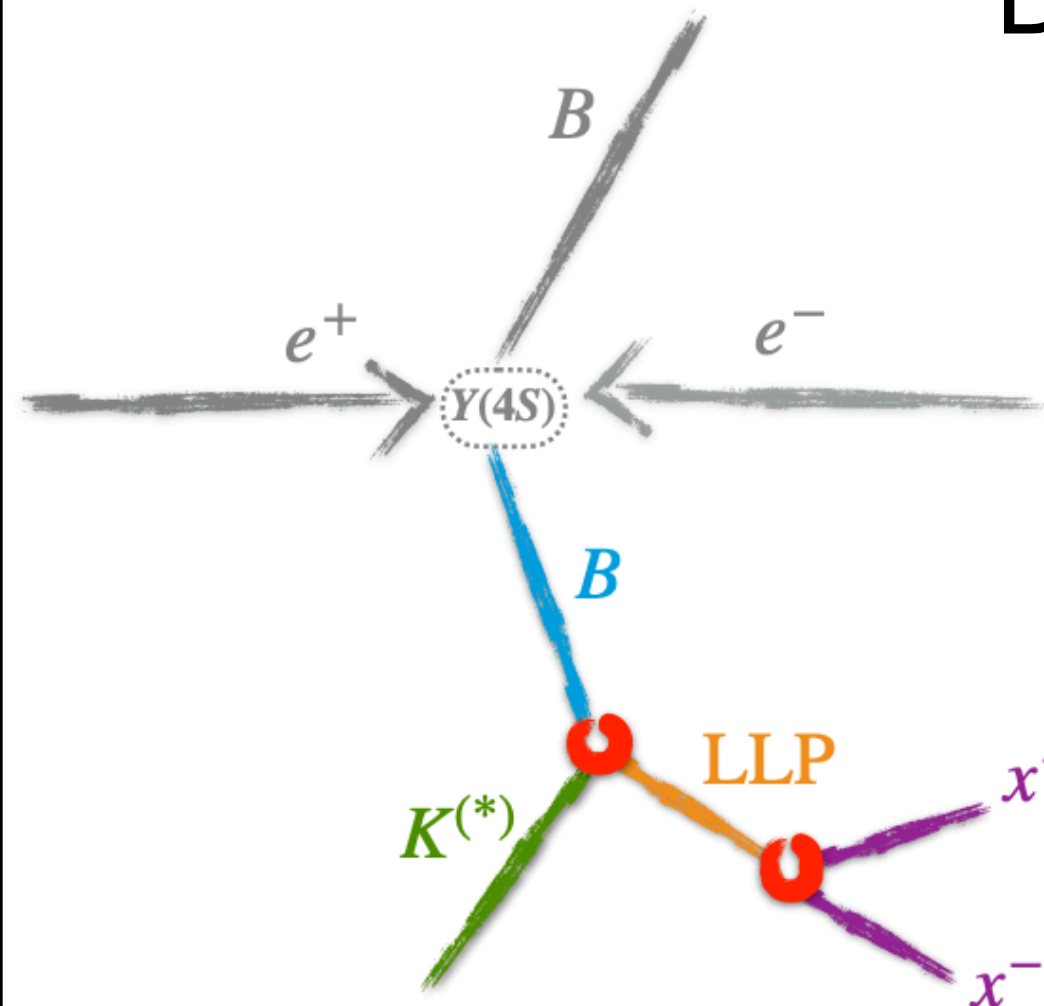
- Addresses g-2 anomaly
- $\mu\bar{\mu}$  + missing E
- Probe g-2 with  $50 \text{ ab}^{-1}$

## Inelastic dark matter



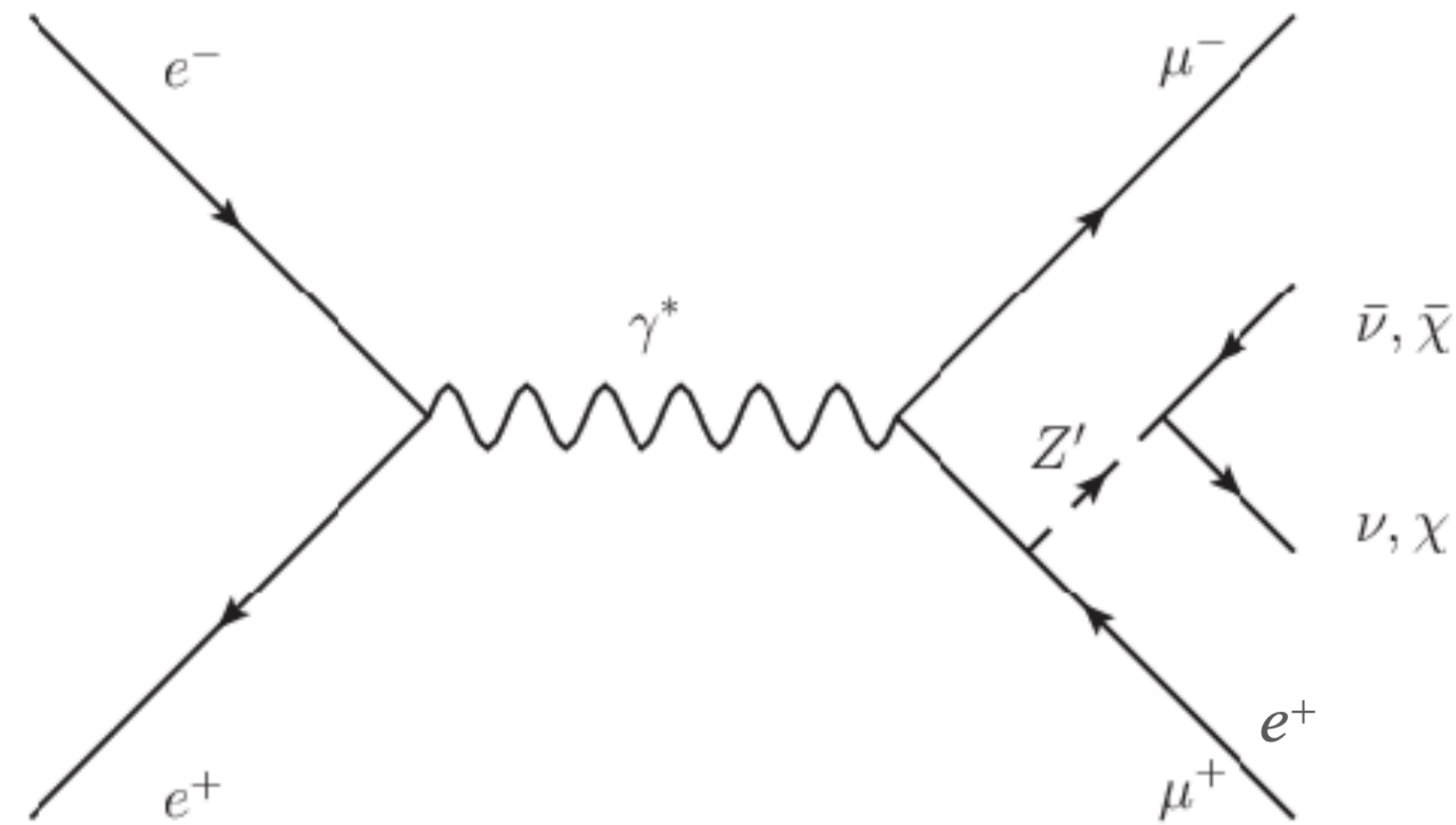
- 3 new particles:  $\chi_1, \chi_2, A$
- $\gamma$  + displaced  $e\bar{e}/\mu\bar{\mu}/h\bar{h}$  + missing E
- Bkg:  $K_S^0, \Lambda^0$ , continuum
- Displaced vertexing

## Dark scalar



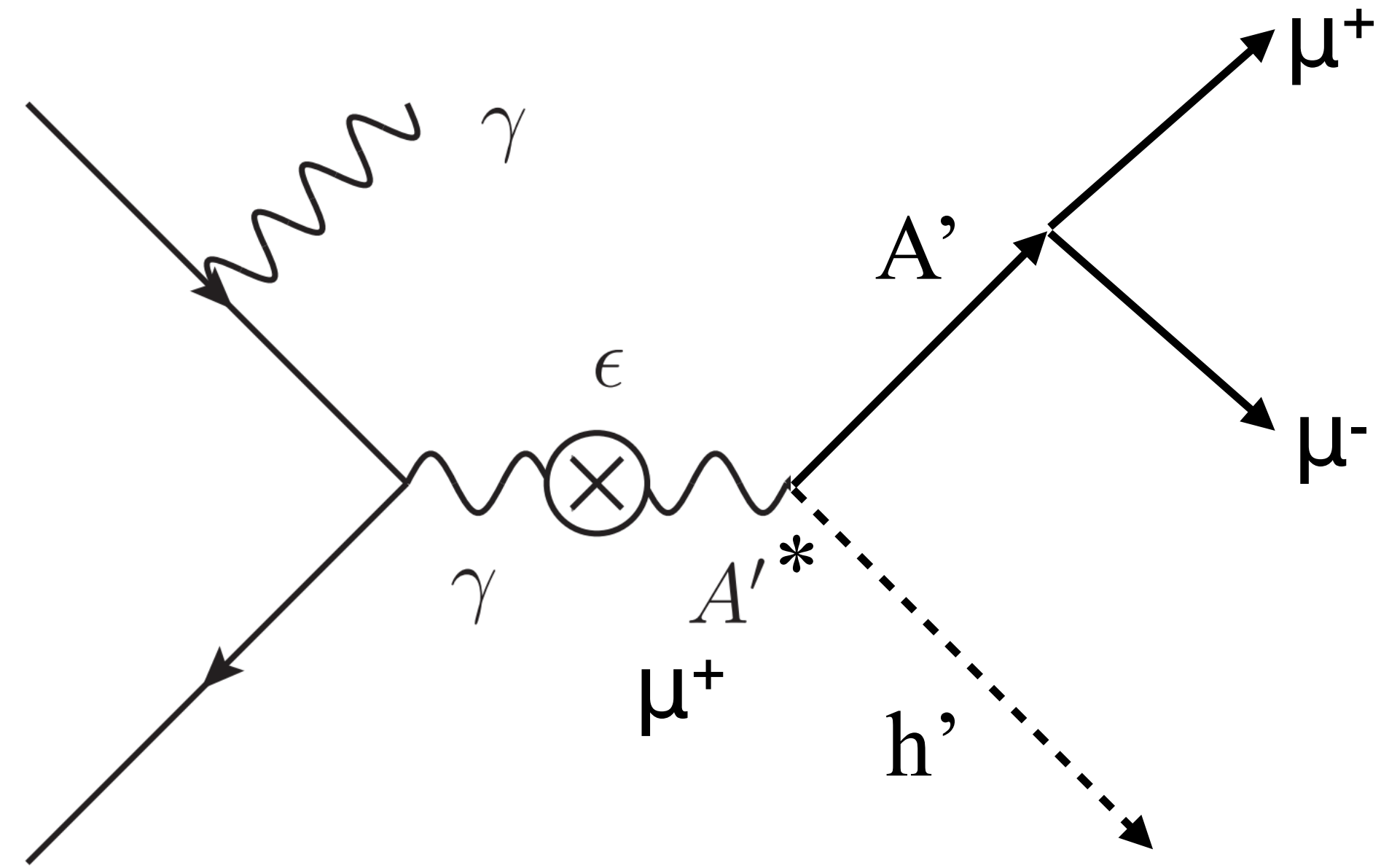
- K + displaced  $x\bar{x}$
- Bkg:  $K_S^0, \Lambda^0$ , continuum
- Displaced vertexing, multiple channels, multiple lifetimes

# (In)visible $Z'$



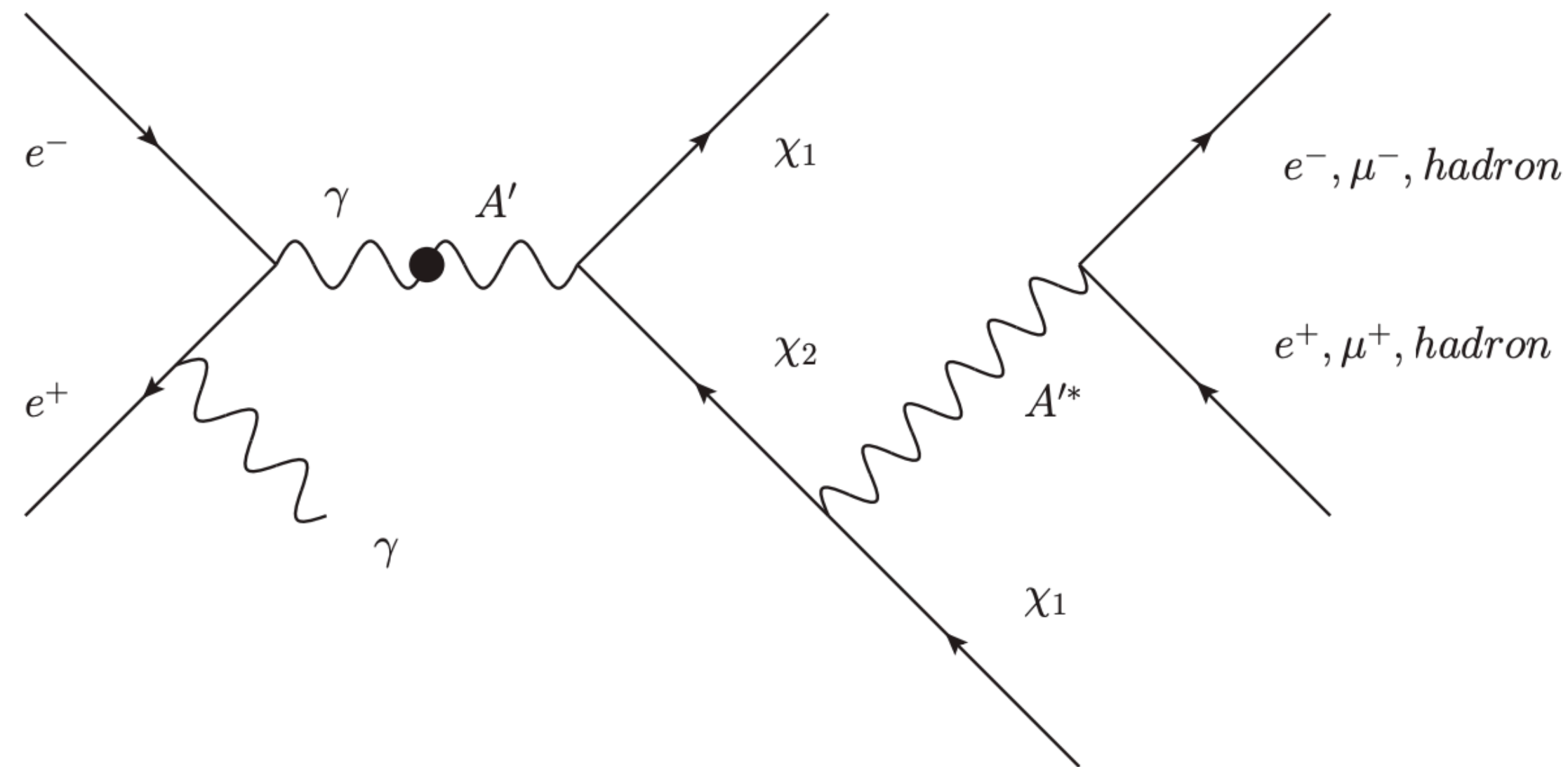
- $Z'$  interacts only with mu and taus
- $ee \rightarrow \mu\mu Z', Z'$  undetected so missing energy
- Could explain the  $g-2$  anomaly
- $Z' \rightarrow \mu\mu$  are relevant if  $m(Z') > 2m(\mu)$  (another analysis)

# Dark photon + dark Higgs



- Looks exactly like (in)visible  $Z'$ ,  $\mu\mu$
- $ee \rightarrow \text{gamma}^* \text{-(epsilon)} \rightarrow A'^* \rightarrow A' h', A' \rightarrow \mu\mu$
- Final state:  $\mu\mu + \text{missing energy (from the undetected } h')$

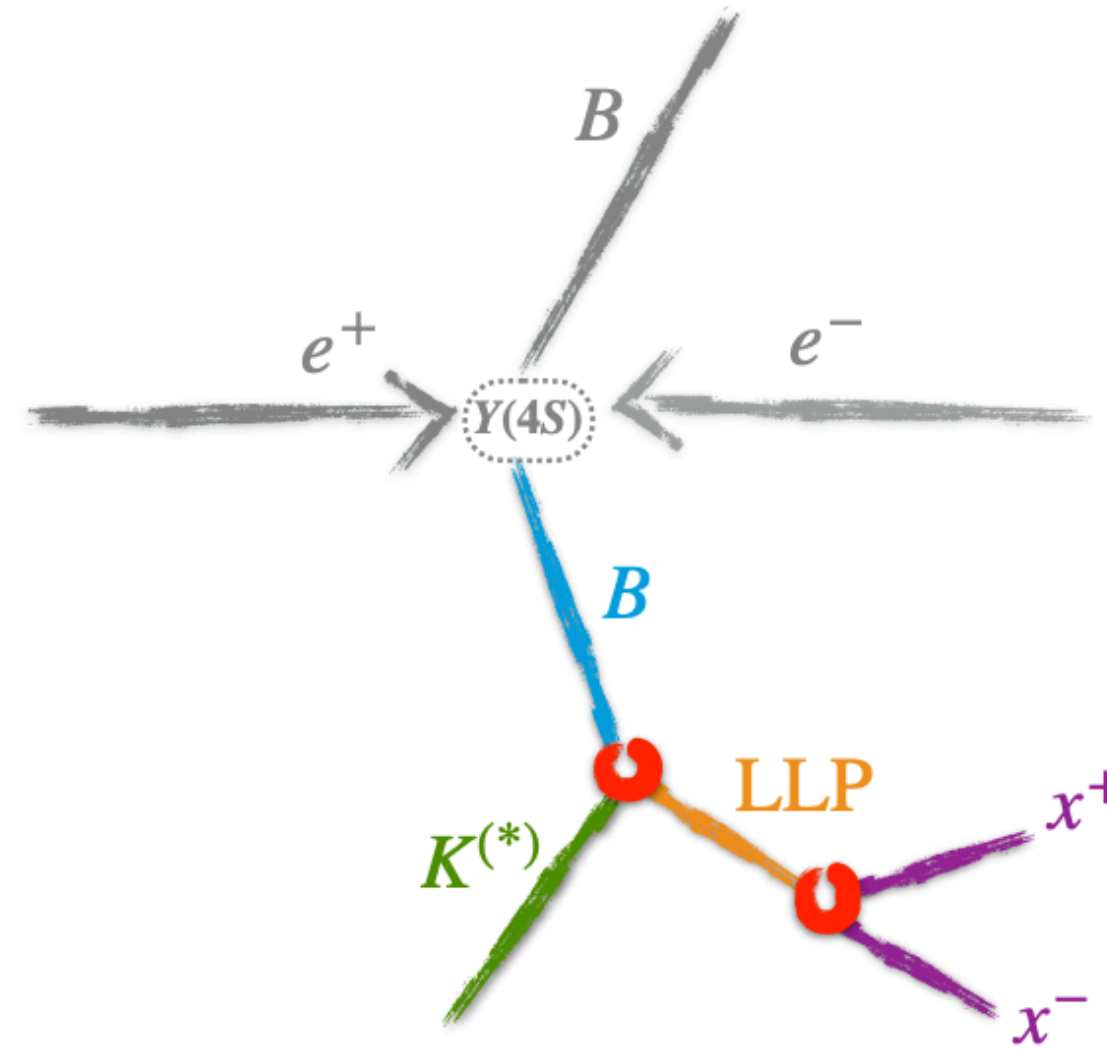
# Inelastic dark matter



- 5 parameters, 3 new DM particles, off-shell DM- $\rightarrow$ DM decay
- satisfies relic density with thermal freeze-out and is compatible with constraints from direct detection experiments
- $ee \rightarrow \gamma A' \rightarrow \gamma \chi_1 \chi_2, \chi_2 \rightarrow \chi_1 ee$
- Displaced vertex
- Bkg-free even with  $50 \text{ ab}^{-1}$ , so sensitivity scales w lumi and not  $\text{lumi}^{1/2}$



# Dark scalar



- Dark scalar  $S$  and dark fermion  $x$  ( $\chi$ )
- If  $m(S) > 2m(x)$ : invisible decay of  $S$
- If  $m(S) < 2m(x)$ :  $S \rightarrow ff$ ,  $S$  long lived if small mixing angle
- Search both