

# **Fusing photons into nothing, a new search for invisible ALPs and Dark Matter at Belle II**

**Francesca Acanfora - 2307.06369**

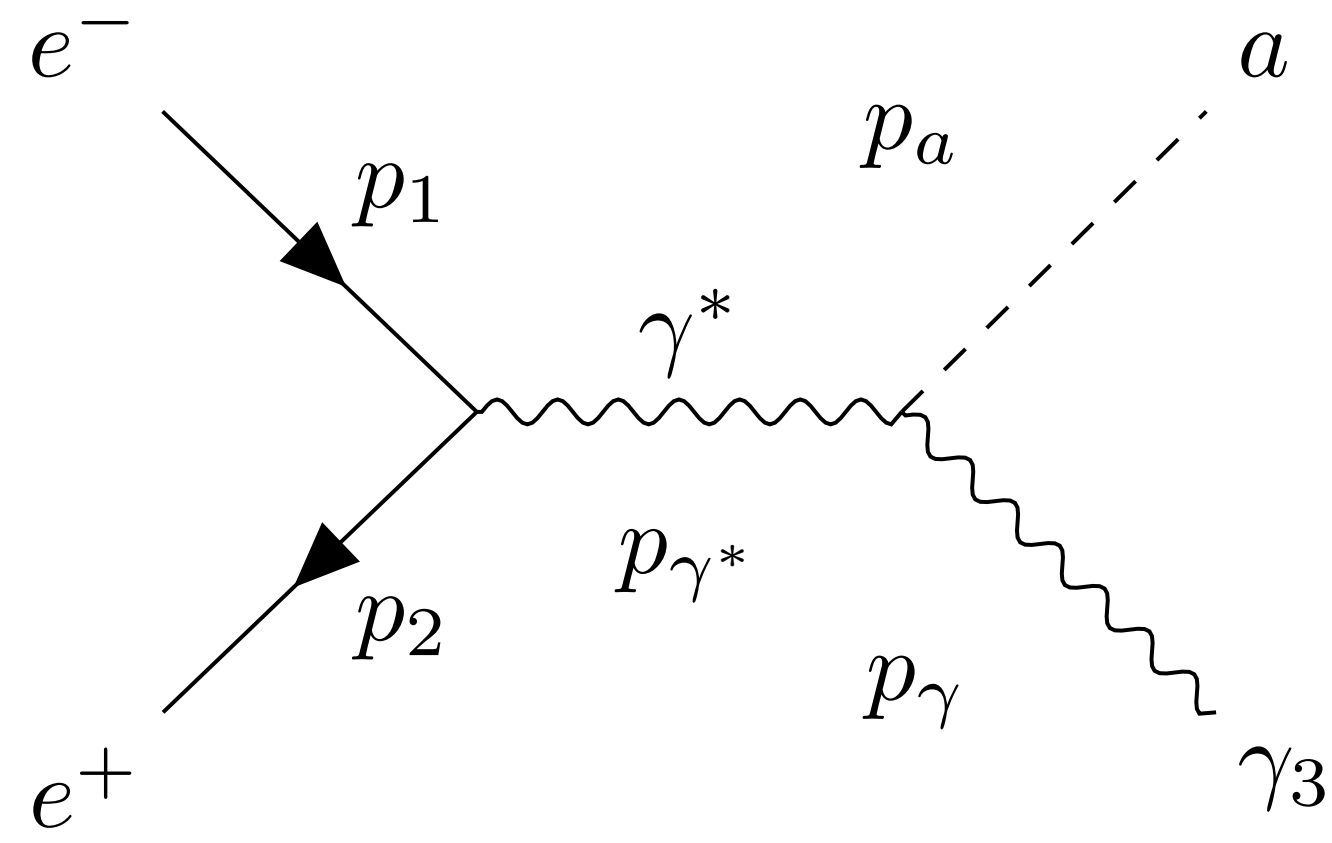
**In collaboration with R. Franceschini, A. Mastroddi, D. Redigolo**



Francesca Acanfora, 04-07-2024, Karlsruhe Institute of Technology, TTP

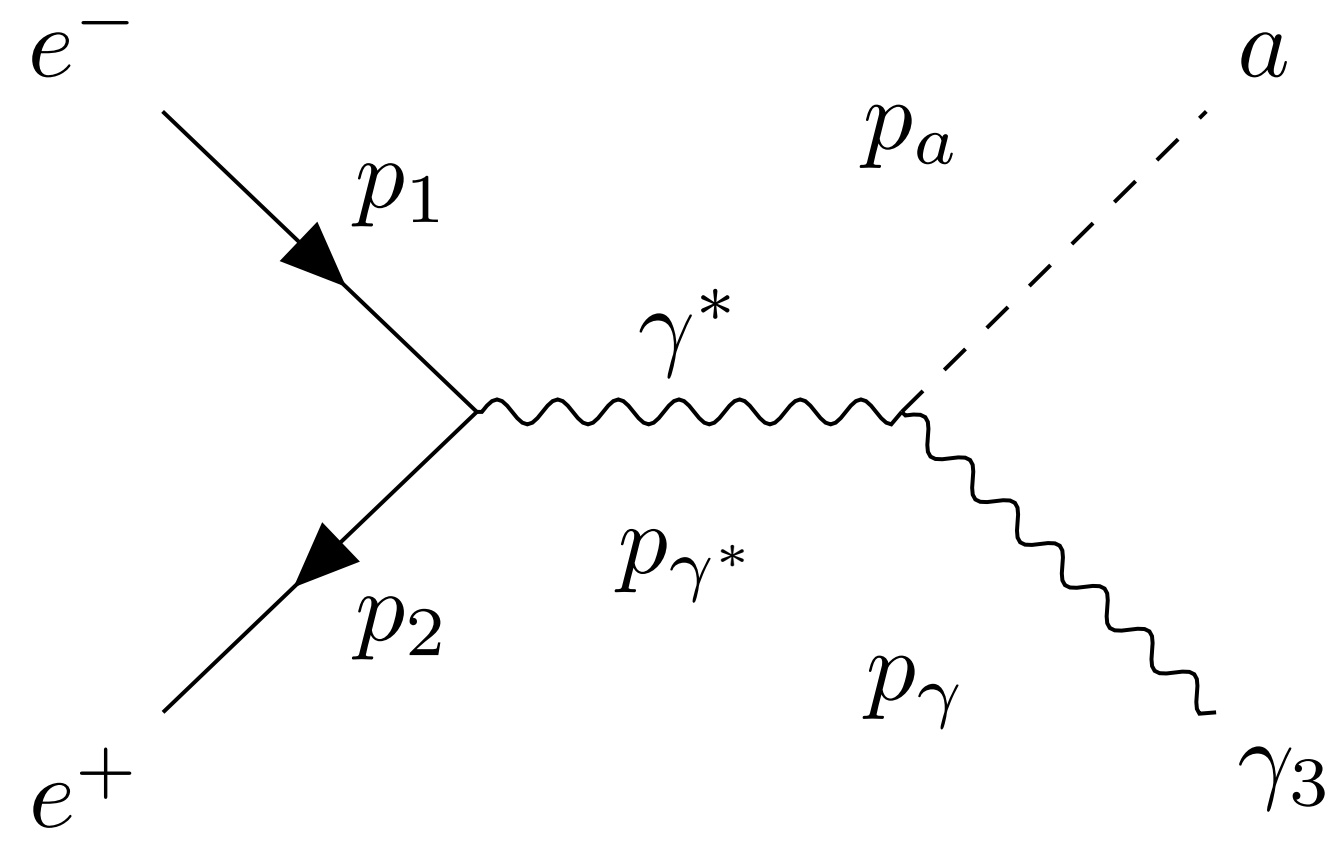


$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 - \frac{m_a^2}{2}a^2 - \frac{g_{a\gamma\gamma}}{4}aF_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{i}{2}\bar{\chi}\gamma^\mu\partial_\mu\chi + \frac{M_\chi}{2}\bar{\chi}\chi + \frac{g_{a\chi\chi}}{2}M_\chi a\bar{\chi}\gamma_5\chi$$



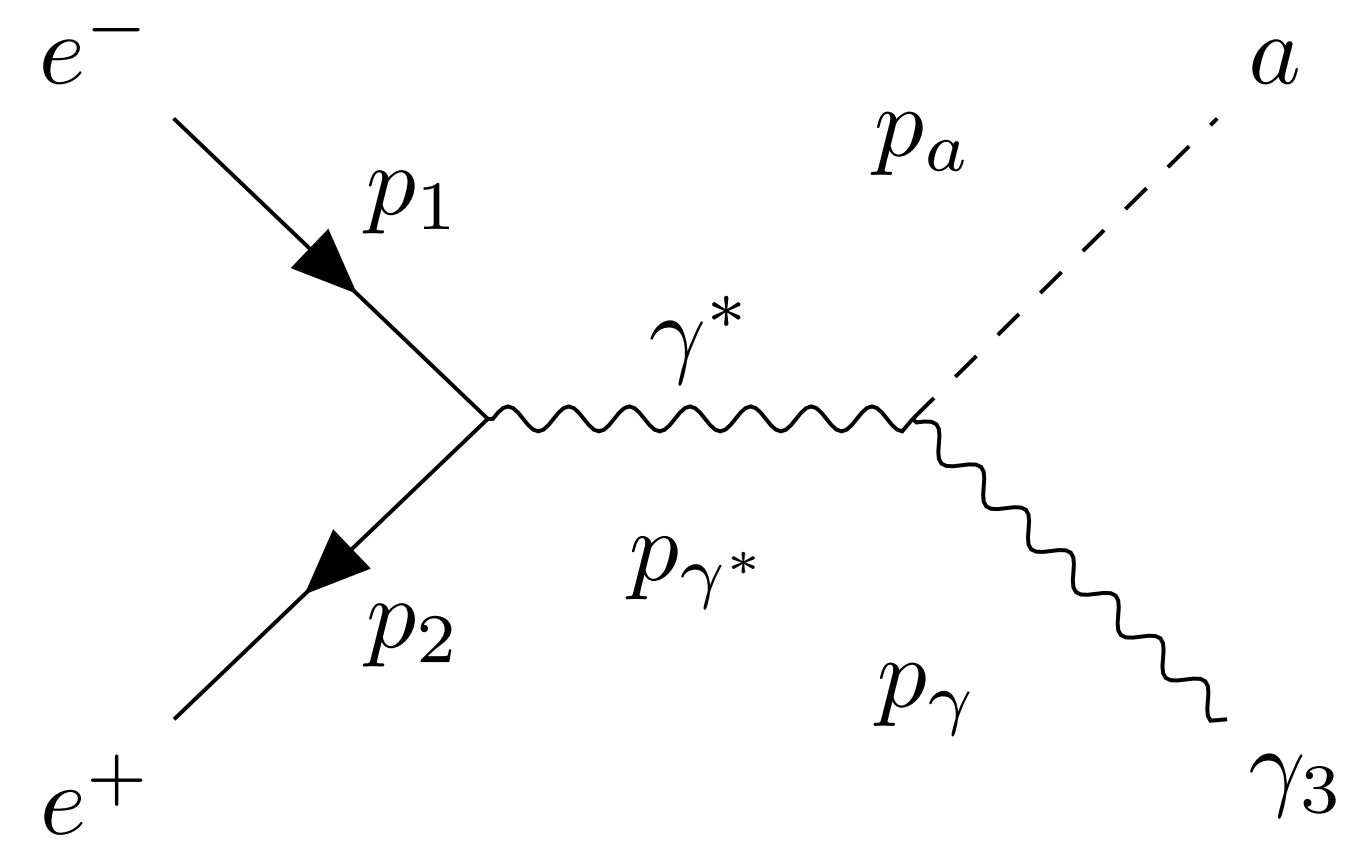
ALP-strahlung

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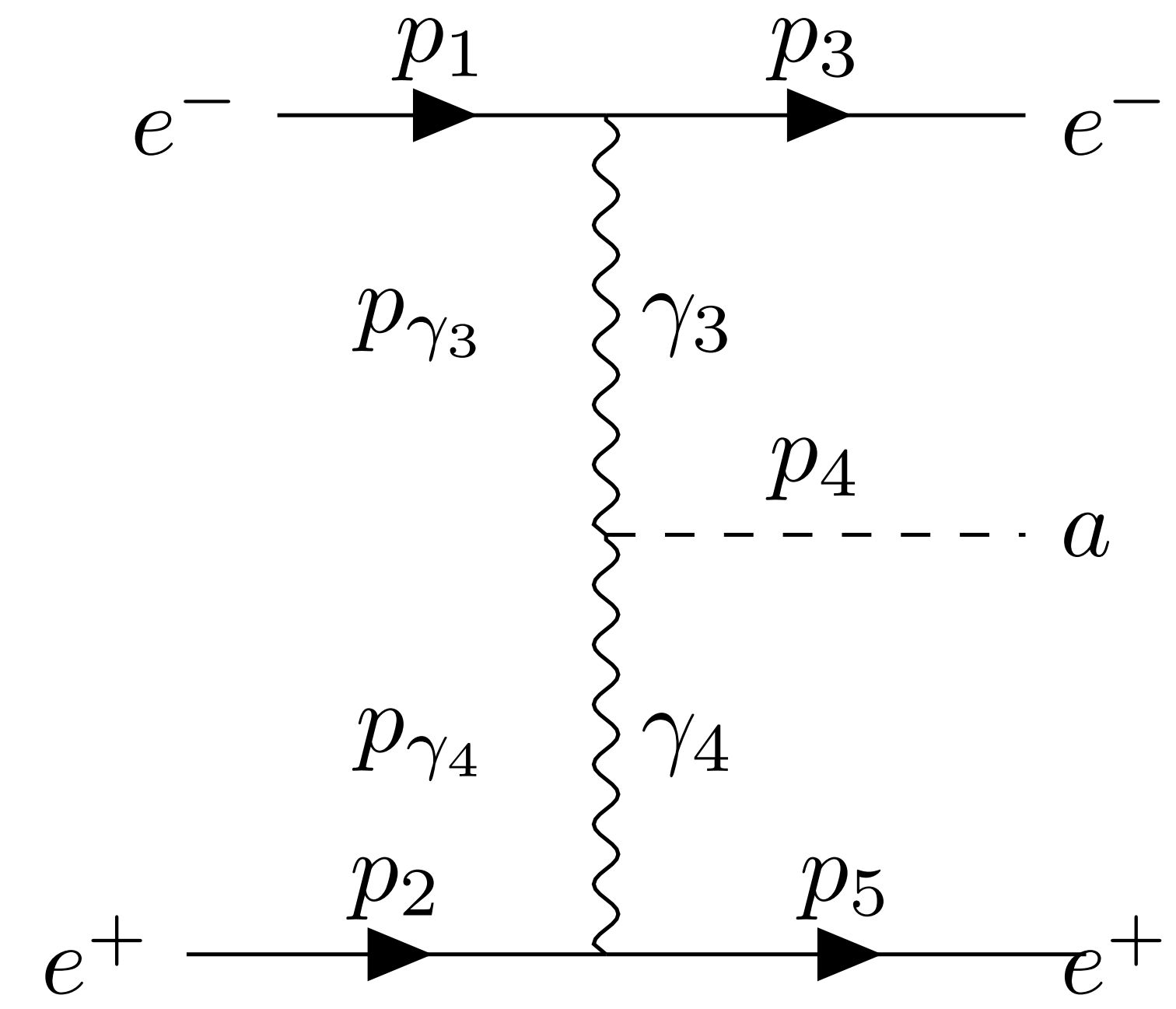


ALP-strahlung

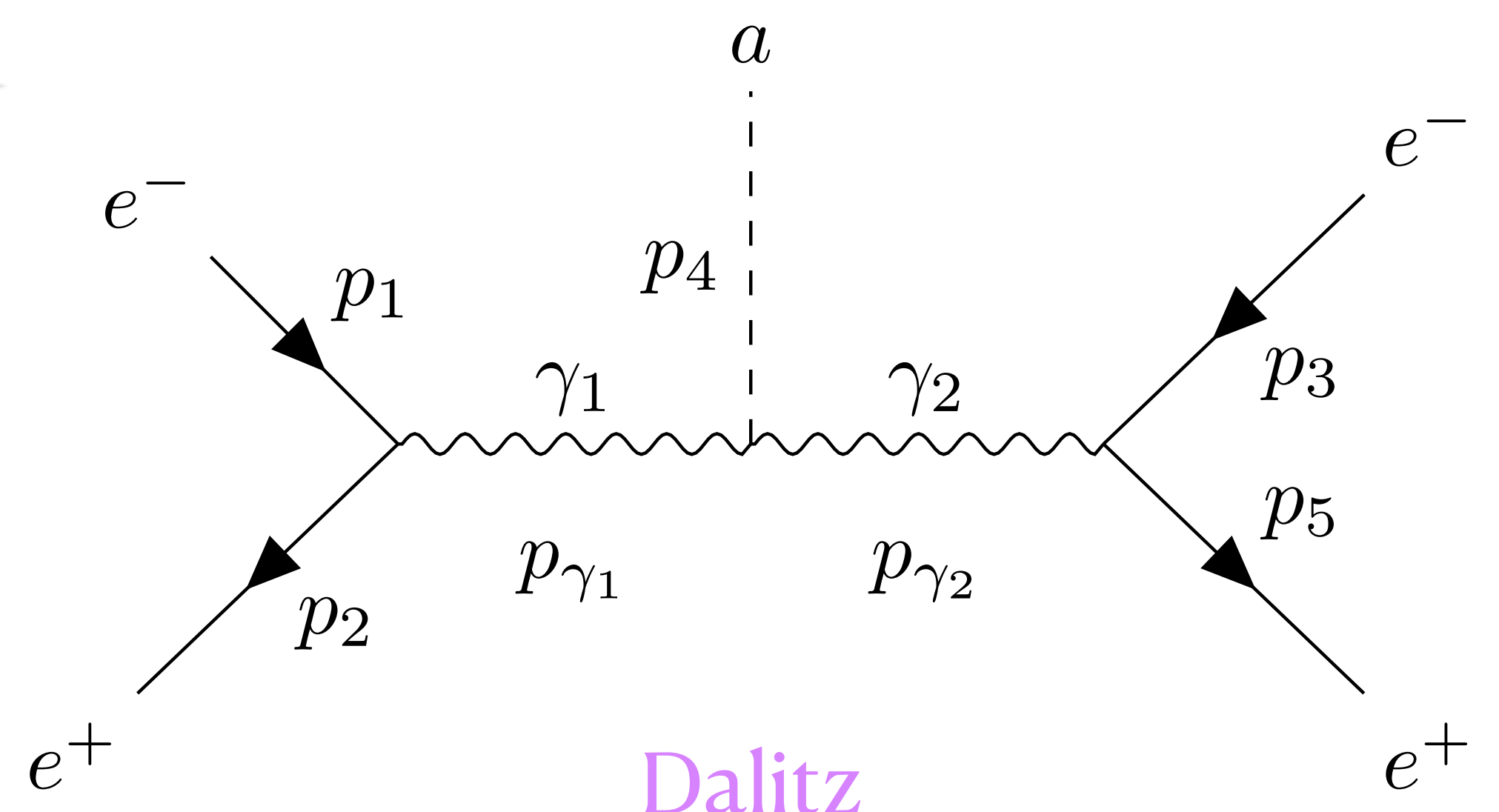
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ALP-strahlung



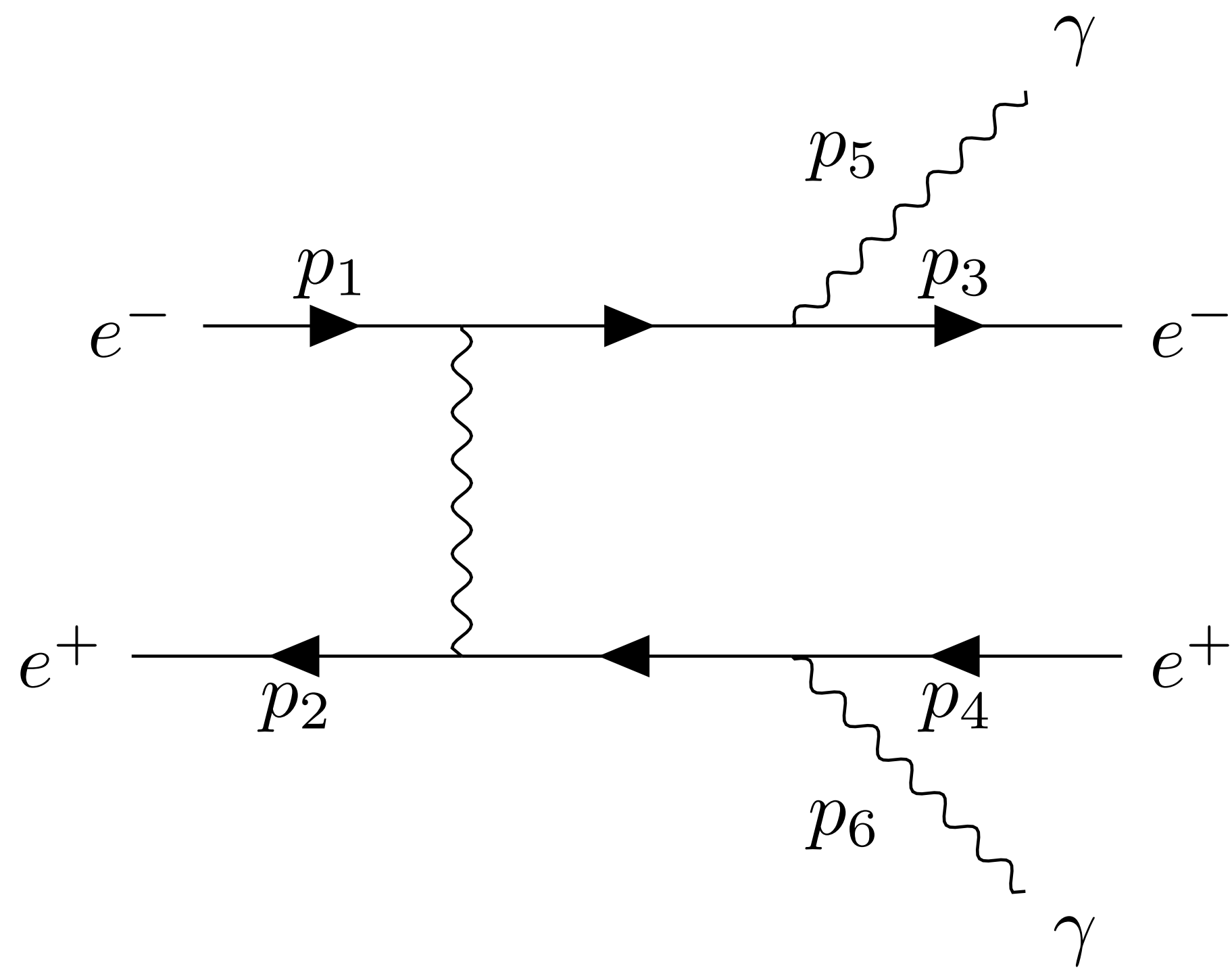
VBF



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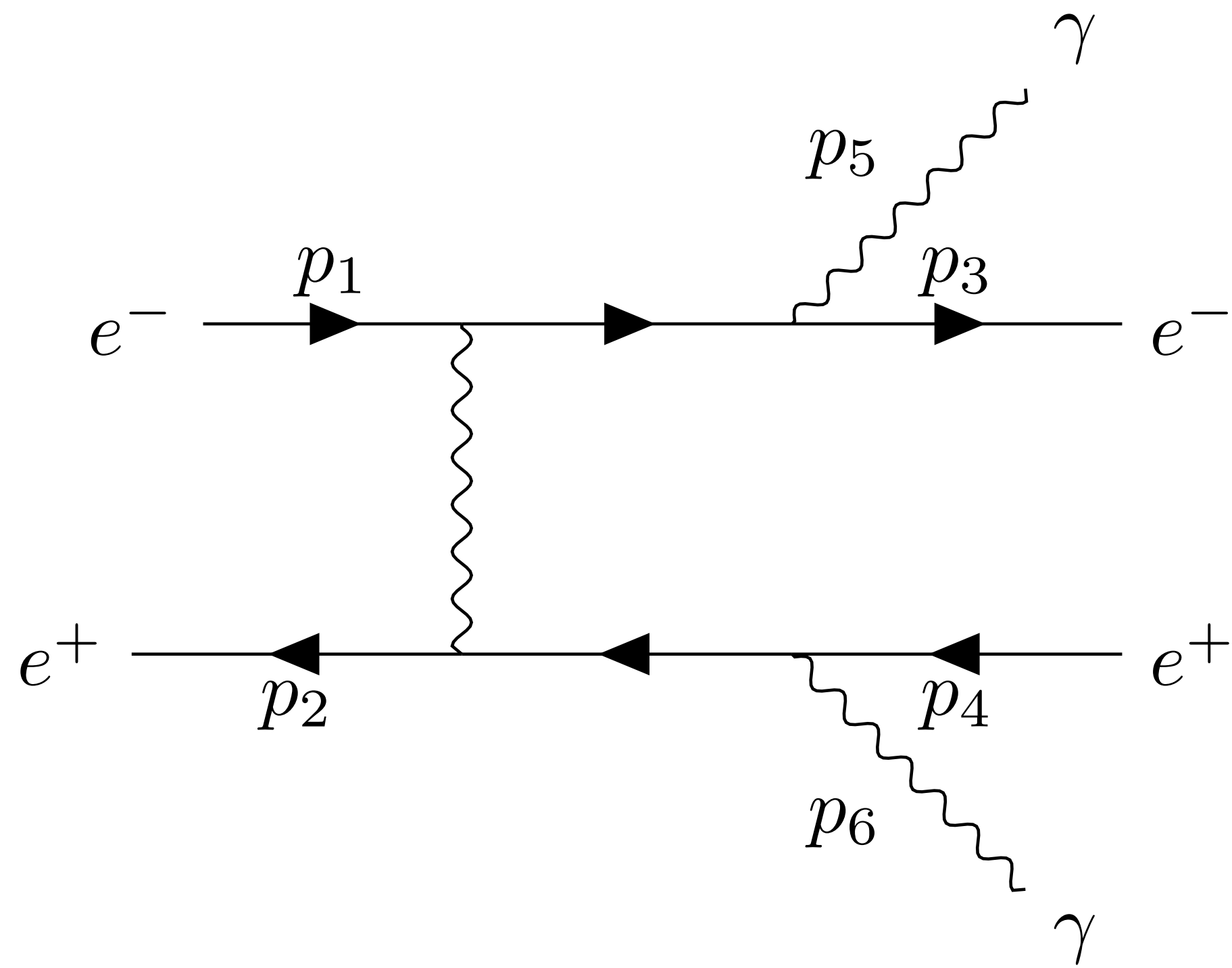
# Backgrounds

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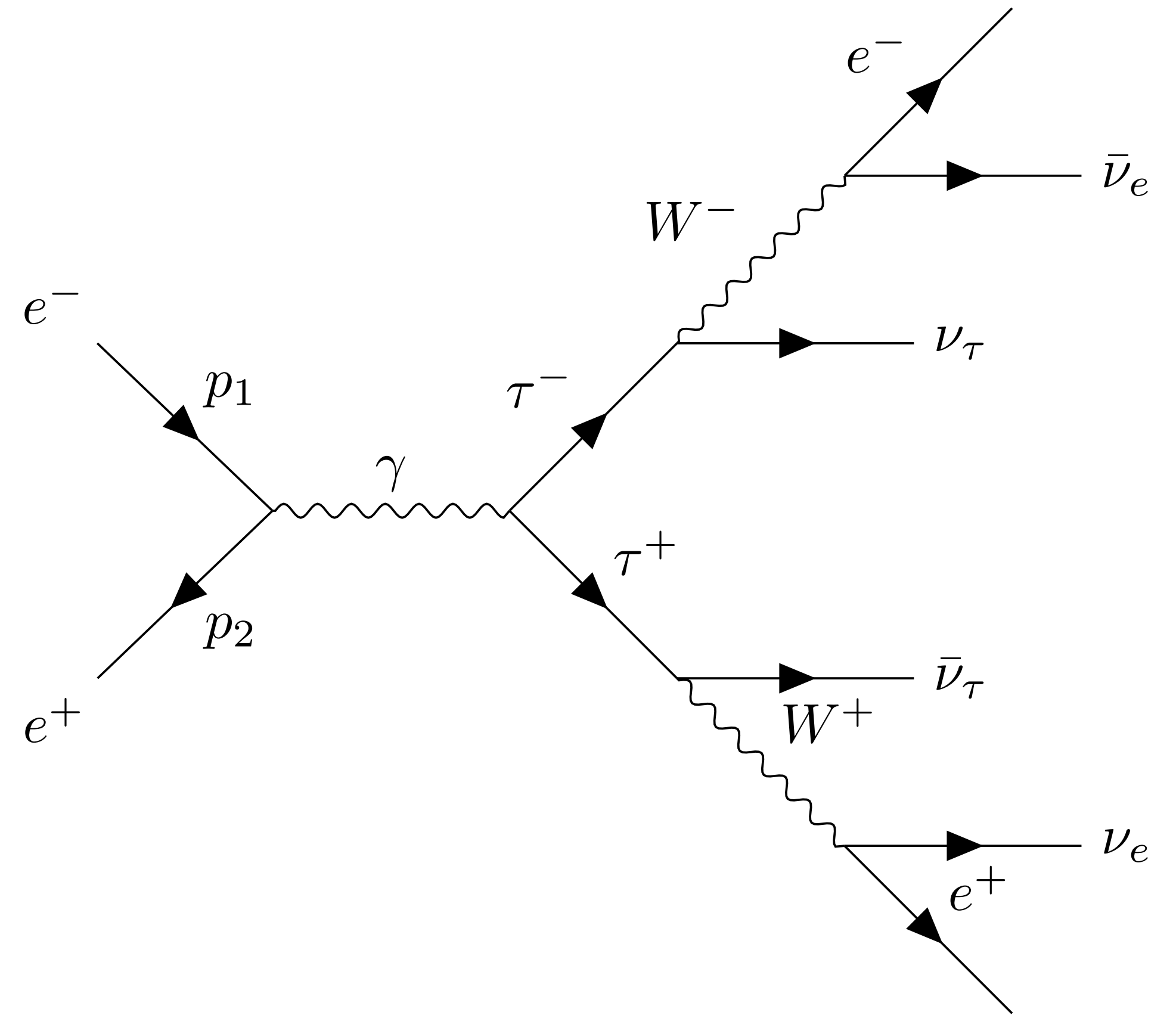


QED<sup>2</sup>

# Backgrounds

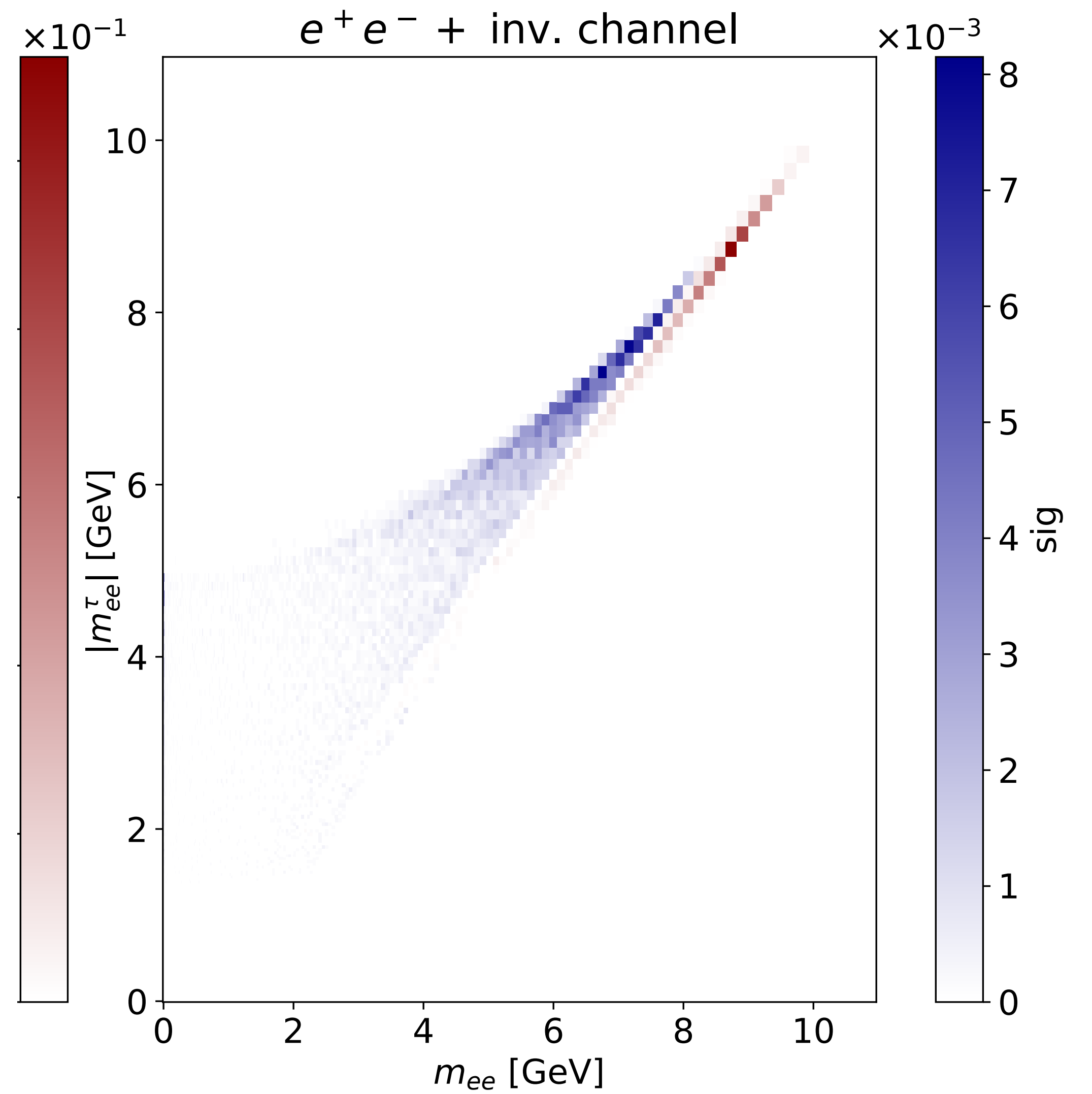
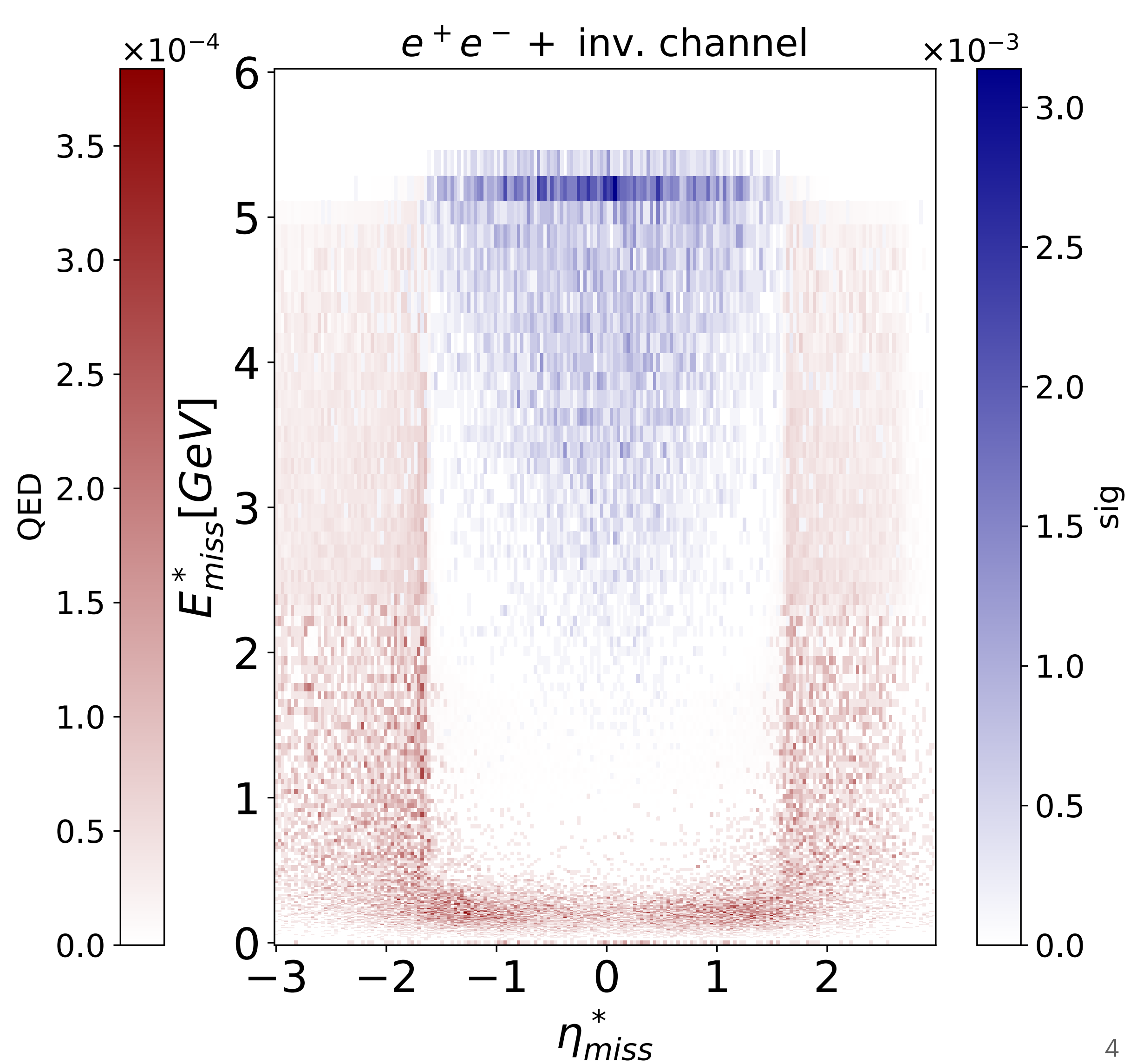


QED<sup>2</sup>

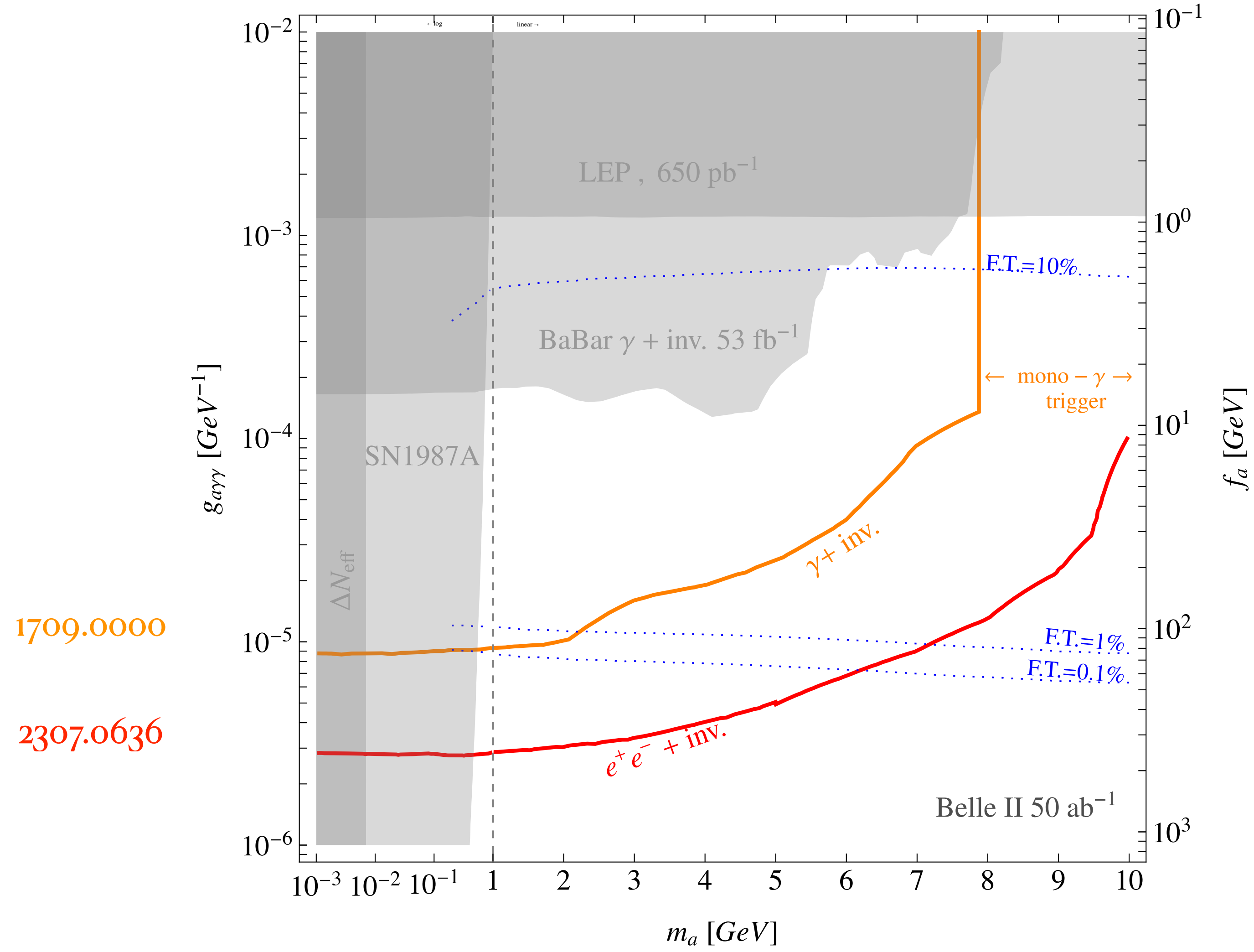


$\tau\tau$

# Background killing

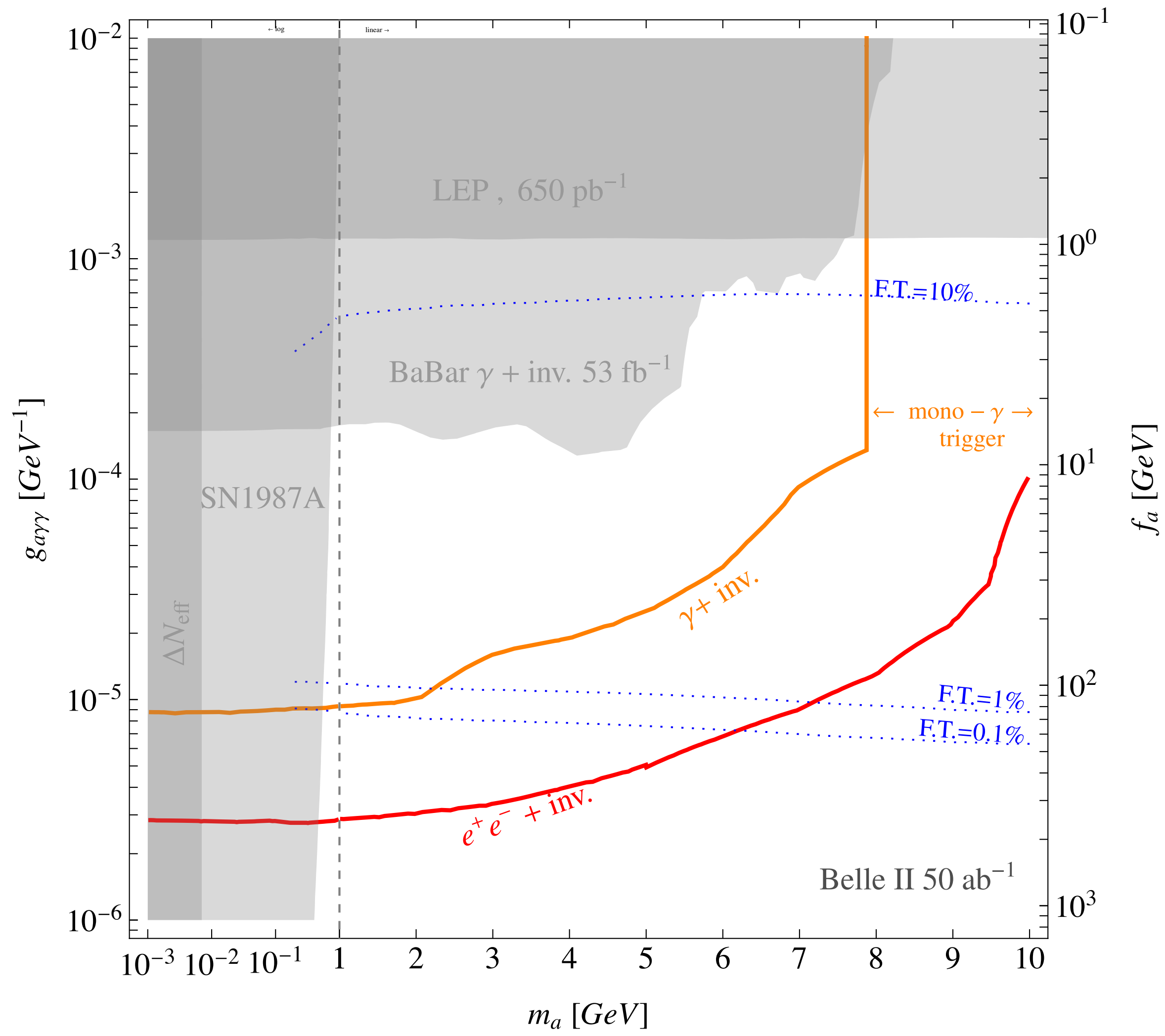






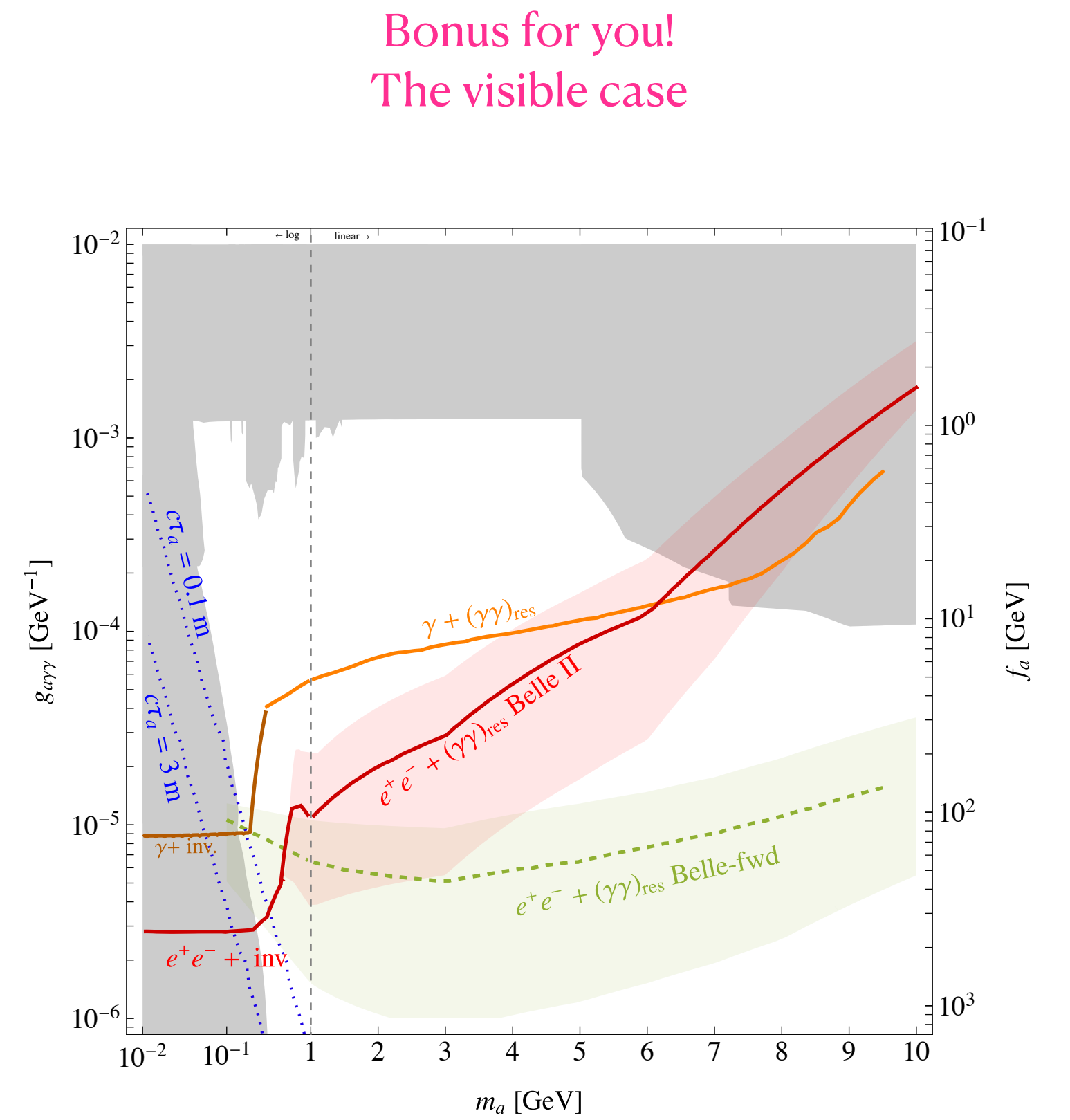
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2406.14614

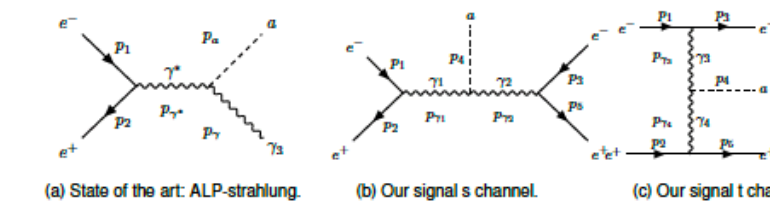
# Fusing photons into nothing, a new search for invisible ALPs and DM at Belle II

## THE SETUP

A massive pseudoscalar coupled to photons and the Dark Sector:

$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 - \frac{m_a^2}{2}a^2 - \frac{g_{a\gamma\gamma}}{4}F_{\mu\nu}F^{\mu\nu} + \frac{i}{2}\bar{\chi}\gamma^\mu\partial_\mu\chi + \frac{M_X}{2}\bar{\chi}\chi + \frac{g_{a\chi\chi}}{2}M_X a\bar{\chi}\gamma_5\chi, \quad (1)$$

- **Belle II: High intensity** to test directly extremely feebly interactions of DM.
- **Light DM** (in the MeV – GeV range) production in the early Universe through thermal freeze-out [2].
- **Collider searches** support (in)direct observations in testing the allowed parameter space of thermal DM freeze-out.



Backgrounds

$$\text{QED}^n := e^-e^+ \rightarrow e^\pm e^\mp + n\gamma_{inv} \quad (2)$$

$$\tau\tau := e^-e^+ \rightarrow \tau^+\tau^-, \tau \rightarrow e\nu\bar{\nu} \quad (3)$$

## METHODS

Both channels have  $bg \approx O(nb)$  while

$$\sigma(e^+e^- \rightarrow \gamma a) \approx 10^{-3} \text{ pb} \left[ \frac{g_{a\gamma\gamma}}{10^{-4} \text{ GeV}^{-1}} \right]^2, \quad (4)$$

$$\sigma(e^+e^- \rightarrow e^+e^- a) \approx 7 \times 10^{-5} \text{ pb} \left[ \frac{g_{a\gamma\gamma}}{10^{-4} \text{ GeV}^{-1}} \right]^2.$$

Our life looks hard but we can perform a high purity search!

## The QED background phase space has a prohibited region

To be invisible,  $e^\pm$  and  $\gamma$  must not satisfy Belle II acceptance

$$\theta_{\min}^* = 22^\circ, \quad E_{\min}^* = 0.25 \text{ GeV}, \quad (5)$$

Given large missing energy, you can not get small missing mass and a small  $|\eta_{\text{miss}}^*|$  (see fig. 2 left).

- The most dangerous configuration is the one with **two hard photons**.
- With  $E_{\text{miss}}$  lower bound and  $\eta_{\text{miss}}^* = 0$  they can only be **hard** and flying in opposite directions
- The smallest possible mass is achieved by photons along opposite blind edges

$$m_{\text{miss}}^*|_{\text{QED}^2} = E_{\text{miss}}^* \cos \theta_{\min}^*, \quad (6)$$

## $\tau\tau$ kinematics is peculiar

- **On shell**, back to back  $\tau$ s
- $\nu\bar{\nu}$  make one massless body N
- The simplified process only has **3 dot**:  $E(e^\pm)$  and one azimuthal angle  $\phi$
- Compute  $e^\pm$  **invariant mass** in this system:

$$(m_{ee}^*)^2 = \frac{2}{s - 4m_\tau^2} \left[ m_\tau^4 - \sqrt{s}m_\tau^2(E_\tau^* + E_{\tau'}^*) + 2E_\tau^*E_{\tau'}^*(s - 2m_\tau^2) + m_\tau^2c_\phi M_- M_+ \right], \quad (7)$$

- Compare it to the real  $m_{ee}$ . The  $\tau\tau$  lives on a **stripe** (see fig. 2 right).

## Event selection

Optimize  $S/\sqrt{B}$  in the cut-and-count scheme while keeping at least 90% of the signal:

$$|m_{\text{miss}}^* - m_a^*| \leq \kappa \cdot \delta m_{\text{miss}}^*, \quad E_{\text{miss}}^* \in \left[ \frac{E_{\text{low}}}{m_{\text{miss}}^*}, \frac{s + m_a^2}{2\sqrt{s}} \right], \quad |\eta_{\text{miss}}^*| \leq \eta_{\text{miss}}^{\text{high}} \quad (8)$$

Then, to get rid of the  $\tau\tau$ , 2d Log-Likelihood on  $(m_{ee}, m_{ee}^*)$ :

$$\Lambda = -2 \sum_{i,j} \ln \frac{L(S_{ij}, B_{ij})}{L(0, B_{ij})}, \quad L(S, B) = \frac{(S+B)^B}{B!} e^{-(S+B)} \quad (9)$$

where  $i$  and  $j$  run on the bins of the plane  $(m_{ee}, |m_{ee}^*|)$ . The sensitivity shown in Fig. 2 corresponds to 95% C.L. and it is distributed by requiring  $\Lambda < 4$ .

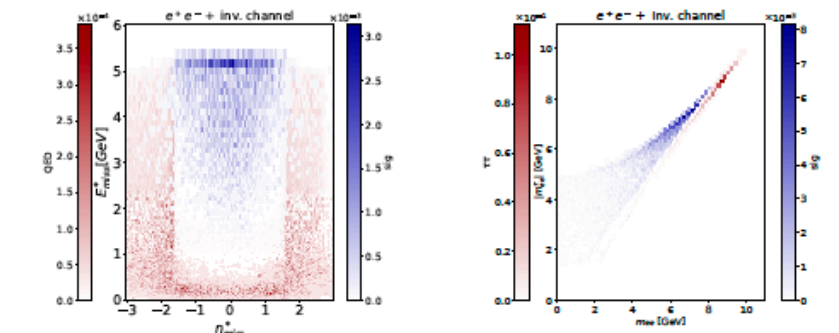
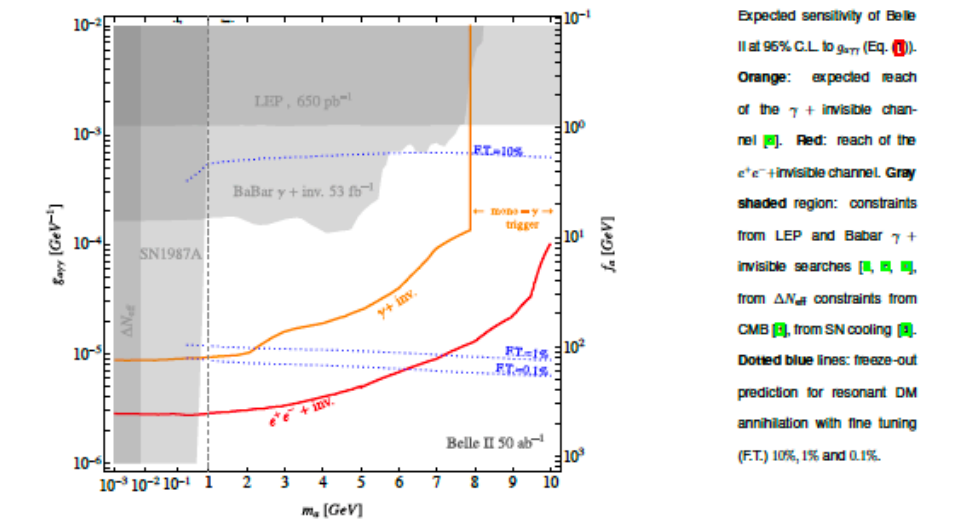


Figure 2: Signal (blue) and background (red) onto  $m_a = 1 \text{ GeV}$ . **Left**: distribution of signal and QED bg with respect to  $m_{\text{miss}}^*$  and  $E_{\text{miss}}^*$  with uniform binning. **Right**: distribution with respect to  $m_{ee}$  and  $|m_{ee}^*|$  of signal and  $\tau\tau$  bg. The binning is such that  $\delta E_{\text{miss}}^*/E_{\text{miss}}^* = 2\%$ ,  $\delta m_{ee}/m_{ee} = 2\%$  and  $\delta \eta_{\text{miss}}^* = 0.075$ .

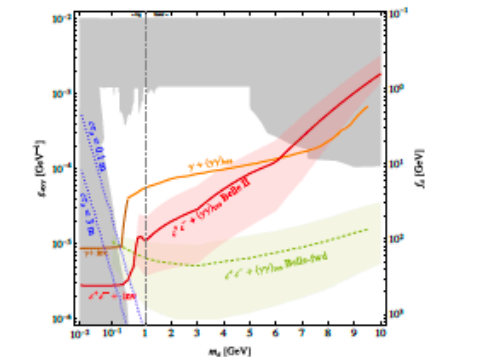
## TAKE HOME



- State of the art Belle II sensitivity comes from the  $\gamma +$  invisible final state [2].
- We derived that the expected sensitivity on an ALP decaying invisibly at Belle II with  $50 \text{ ab}^{-1}$  of data in the channel  $e^+e^- +$  invisible is a **significant improvement** over the **whole phase space** (Fig. 2).
- The **signal kinematics** is easily **distinguishable** from the SM background due to the interplay between low **missing mass** and large central **missing energy**.

## What next?

- ALP **off-shell** production [2];
- Other experimental setups, i.e. other high-intensity  $e^+e^-$  colliders as well as **future colliders**;
- The **visible case** (2406.14614):  $e^+e^- \rightarrow \gamma a, a \rightarrow \gamma\gamma$ .



## References

[1] J. Alshabih et al. Search for new large extra dimensions with the DELPHI detector at LEP. *Eur. Phys. J. C*, 60:17–23, 2000.  
 [2] W. Altmannshofer et al. The Belle II Physics Book. *PTEP*, 2019(10):120201, 2019. [Erratum: PTEP, 2020, 02001 (2020)].  
 [3] Gidon Barak, Matthew J. Dolan, and Christopher McCabe. A Lower Bound on the Mass of Cold Thermal Dark Matter from Planck. *JCAP*, 08(04):018, 2017.  
 [4] Matthew J. Dolan, Tobias Fuchs, Christopher Henry, Fab. Kahlhoefer, and Kai Schrek. History. Revised constraints on dark matter annihilation into photons. *JHEP*, 12(04):120, 2017. [Erratum: JHEP, 19(10):193, 2019].  
 [5] Florian Engel, Jeremy Mardon, Mikhalo Papait, Tomer Volansky, and Yi-Ming Zhong. Constraining Light Dark Matter with Low Energy  $e^+e^-$  Collisions. *JHEP*, 11(10):193, 2015.  
 [6] Patrick J. Fox, Fred Herrig, Jonathan Kopp, and Yuhai Tang. LEP Shows Light on Dark Matter. *Phys. Rev. D*, 94(10):102001, 2017.  
 [7] G. Krnjačić et al. A Stochastic Whitepaper: Dark Matter Production at Intensity Frontier Experiments. 7 2022.  
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# Thank you :)

**Backup slides**

# What will ALP decay into?

$$\frac{\Gamma(a \rightarrow \gamma\gamma)}{\Gamma(a \rightarrow \chi\chi)} \sim \left( \frac{\alpha_{\text{em}}}{4\pi} \right)^2 \frac{1}{r^2 \sqrt{1 - 4r^2}} \sim \mathcal{O}(10^{-7} - 10^{-6}) \rightarrow r \sim 0 \text{ or } r \sim \frac{1}{2}$$

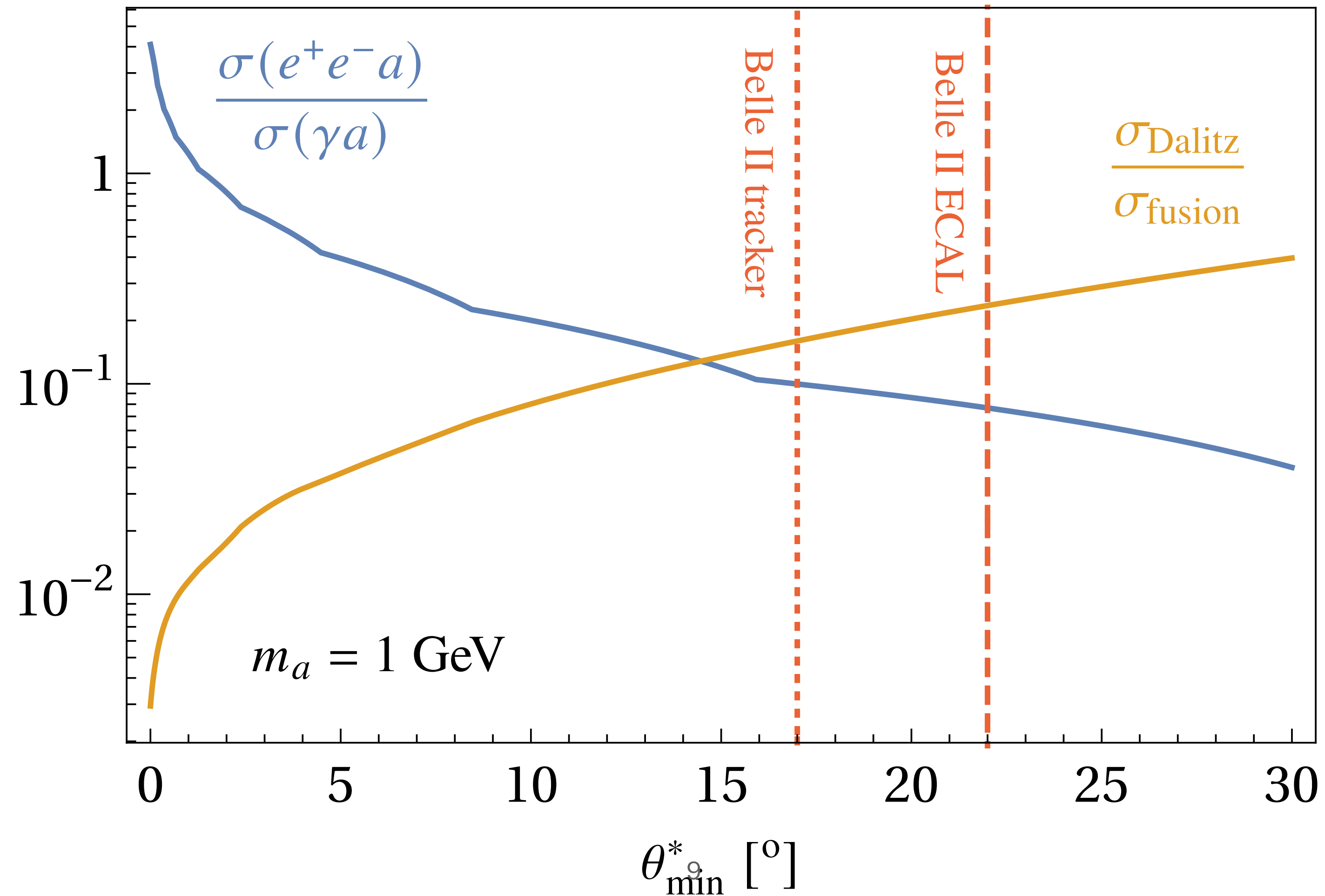
$$r \equiv M_\chi / m_a \lesssim 1/2, \quad g_{a\gamma\gamma} = \frac{\alpha_{\text{em}} c_{\gamma\gamma}}{2\pi f_a} \quad c_{\gamma\gamma} \sim \mathcal{O}(1) \quad g_{a\chi\chi} \sim 1/f_a$$

$\frac{1}{r^2}$  comes from the scale dependence of the partial width

$\sqrt{1 - 4r^2} \rightarrow$  phase space suppression of the invisible channel.

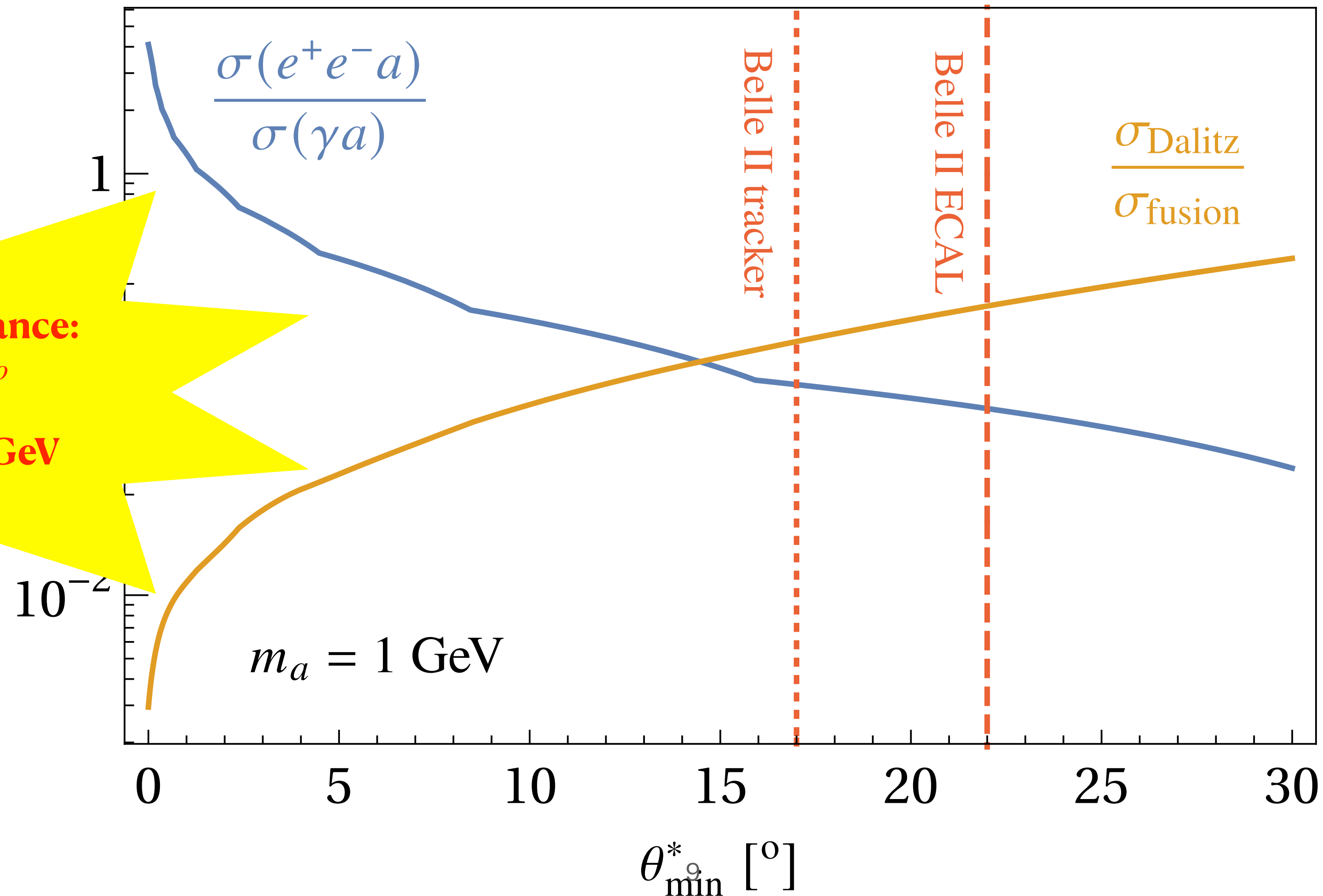
# Angular acceptance controls processes hierarchies

ALP cross section vs Belle II coverage

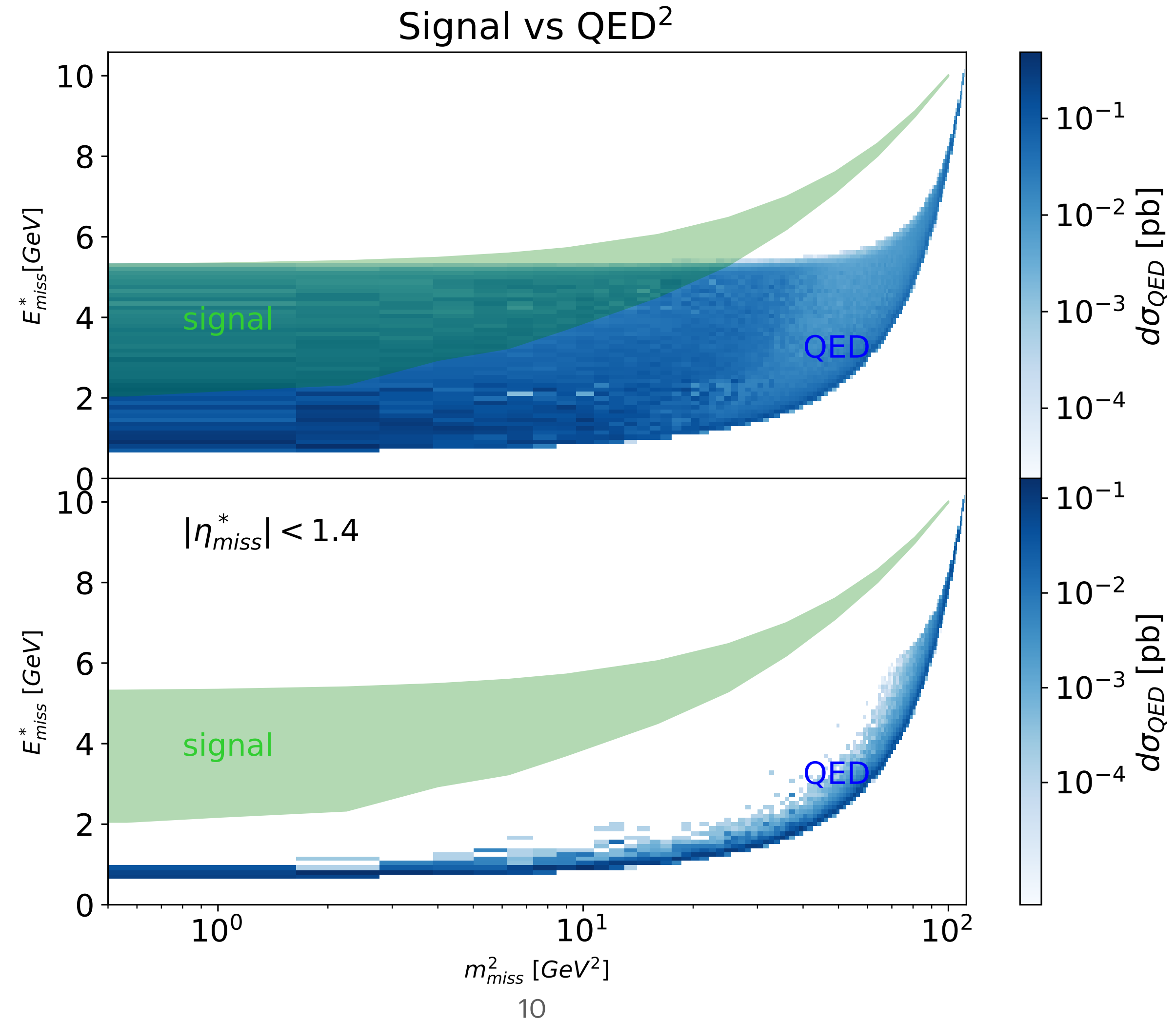


# Angular acceptance controls processes hierarchies

ALP cross section vs Belle II coverage



# Effect of selections on QED background





# Signal - $\tau\tau$ separation depends on ALP mass

