

Some ideas  
about

# Forward physics and BSM in $e^+e^-$ collisions

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with F. Acanfora, A. Mastroddi, D. Redigolo 2307.06369, 2406.14614

# New physics dark(er) side

## How large should a coupling be?

- Heavy new physics has been searched for at many colliders of the “energy frontier” of each time (sub-100 GeV @LEP, 100s of GeV @TeVatron, TeV at @LHC)
- The idea relies on the existence of couplings of order 1 between SM states and new physics. This is observed in a significant fraction of the interactions we know, most notably gauge interactions  
 $(g_1 \simeq \frac{1}{3}, g_2 \simeq \frac{2}{3}, g_3 \simeq 1)$
- Still lots of (puzzlingly) small couplings exist in nature, e.g. the Yukawa couplings (as small as  $10^{-5}$  for electron Yukawa)
- And “intermediate” small couplings, e.g. the Higgs boson quartic  $\lambda \simeq \frac{1}{10}$  or the loop level gluon-Higgs  $g_{Hgg} \simeq \frac{1}{40}$

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**A counter perspective has taken shape in the last 10+ years: new physics might be coupled**

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**very weakly to our familiar SM states**

- And “intermediate” small couplings, e.g. the Higgs boson quartic  $\lambda \simeq \frac{1}{10}$  or the loop level gluon-

$$\text{Higgs } g_{Hgg} \simeq \frac{1}{40}$$

[The Mission](#)[Life in the Abyss](#)[The Last Frontier](#)[Dispatches](#)[E-mail](#)[Resources](#)[Table of Contents](#)

## Discoveries in the Deep

A Chronology of Undersea Exploration

**1818**

Sir John Ross lowers a line more than a mile into the North Atlantic and hauls up worms and a large sea star.

**1843**

Edward Forbes proposes that no substantial life can exist below three hundred fathoms.

**1858**

The first transatlantic telegraph cable comes to life, its laying preceded by deep seabed surveys.

**1859**

Darwin's Origin of Species implies that the deep is a sanctuary for living fossils.

**1864**

Norwegians haul up from the deep a sea lily, a living fossil previously found only in rocks 120 million years old.

**1870**

Jules Verne's Twenty Thousand Leagues Under the Sea depicts no life in the ocean's deepest regions.

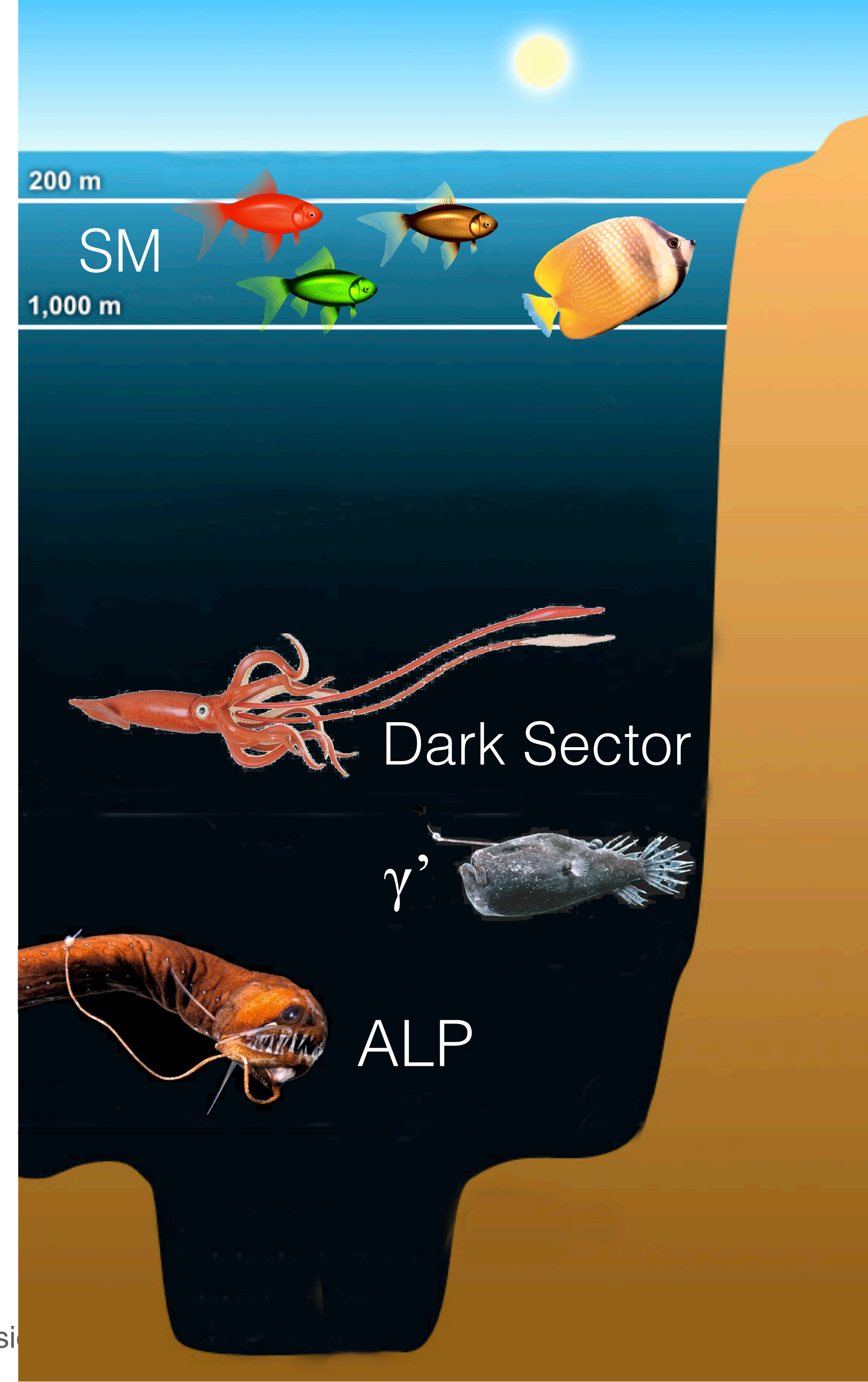
**1872-76**

British ship Challenger sails the globe while lowering dredges and other gear into the deep, finding long mountain chains, puzzling nodules, and hundreds of animals previously unknown to science.



Pacific Ocean above Juan de Fuca Ridge.

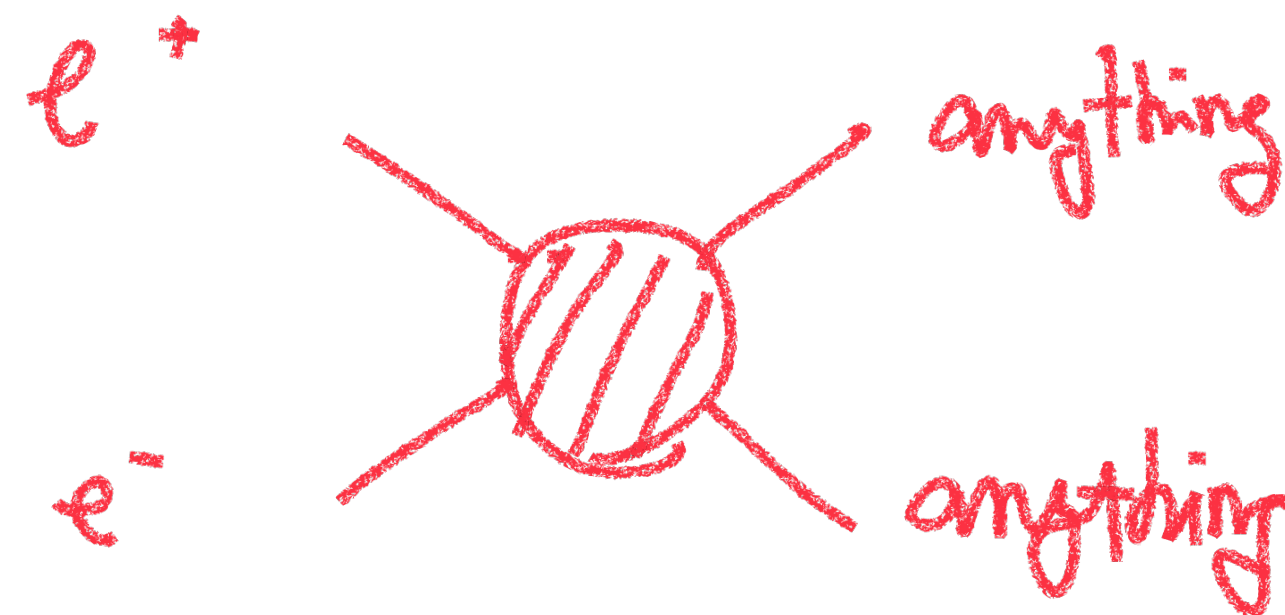
The deeper you look ...  
the larger lumi you need



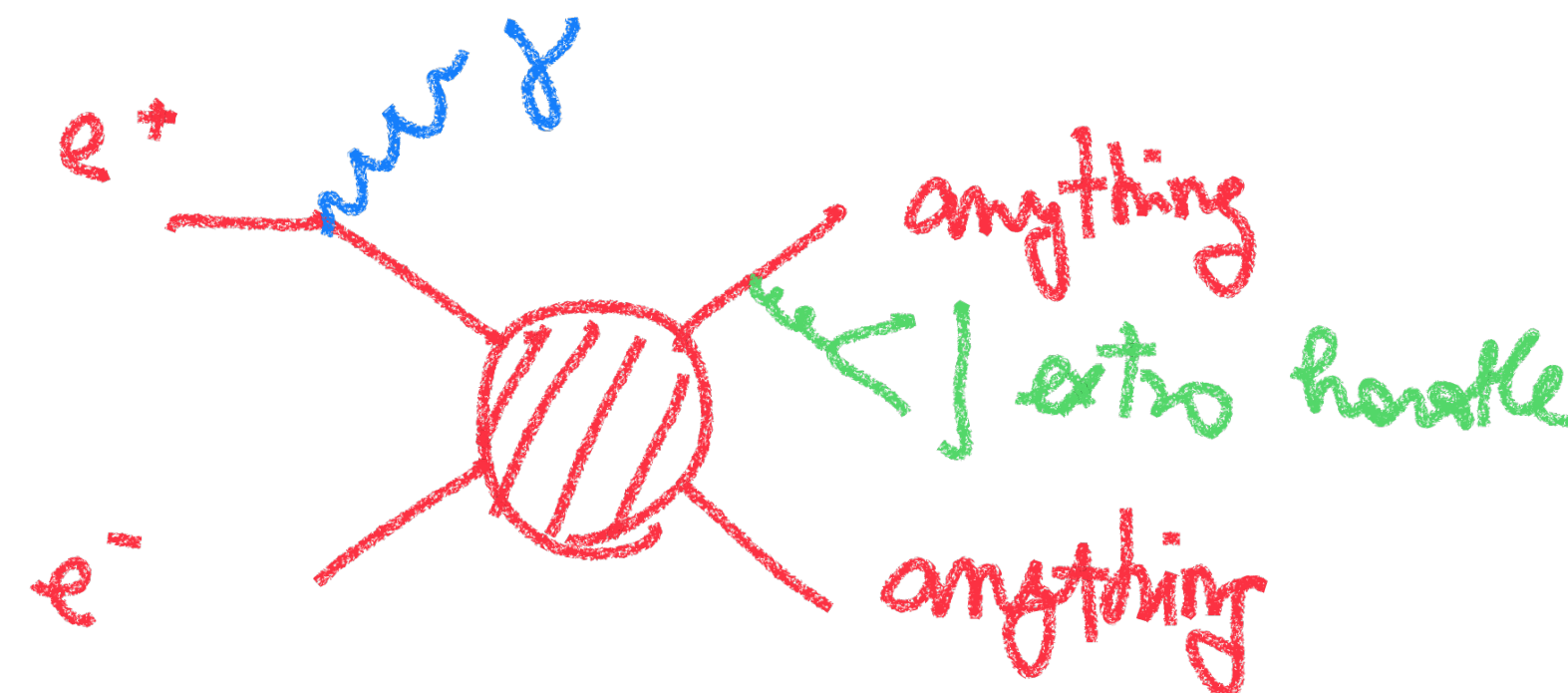
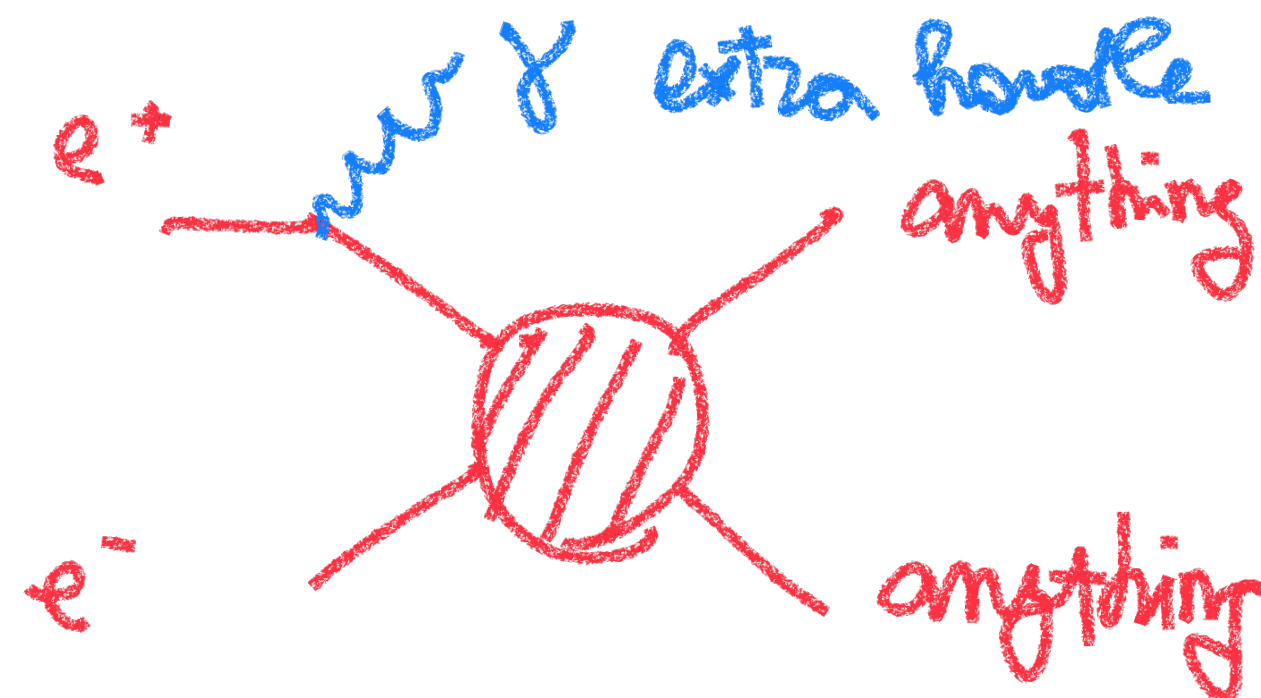
# Weakly coupled new physics production mechanisms

less is more?

- Most copious production mechanism is a clear candidate for the search of new physics



- Other production mechanism can have more “handles” to remove background and should be considered as well.



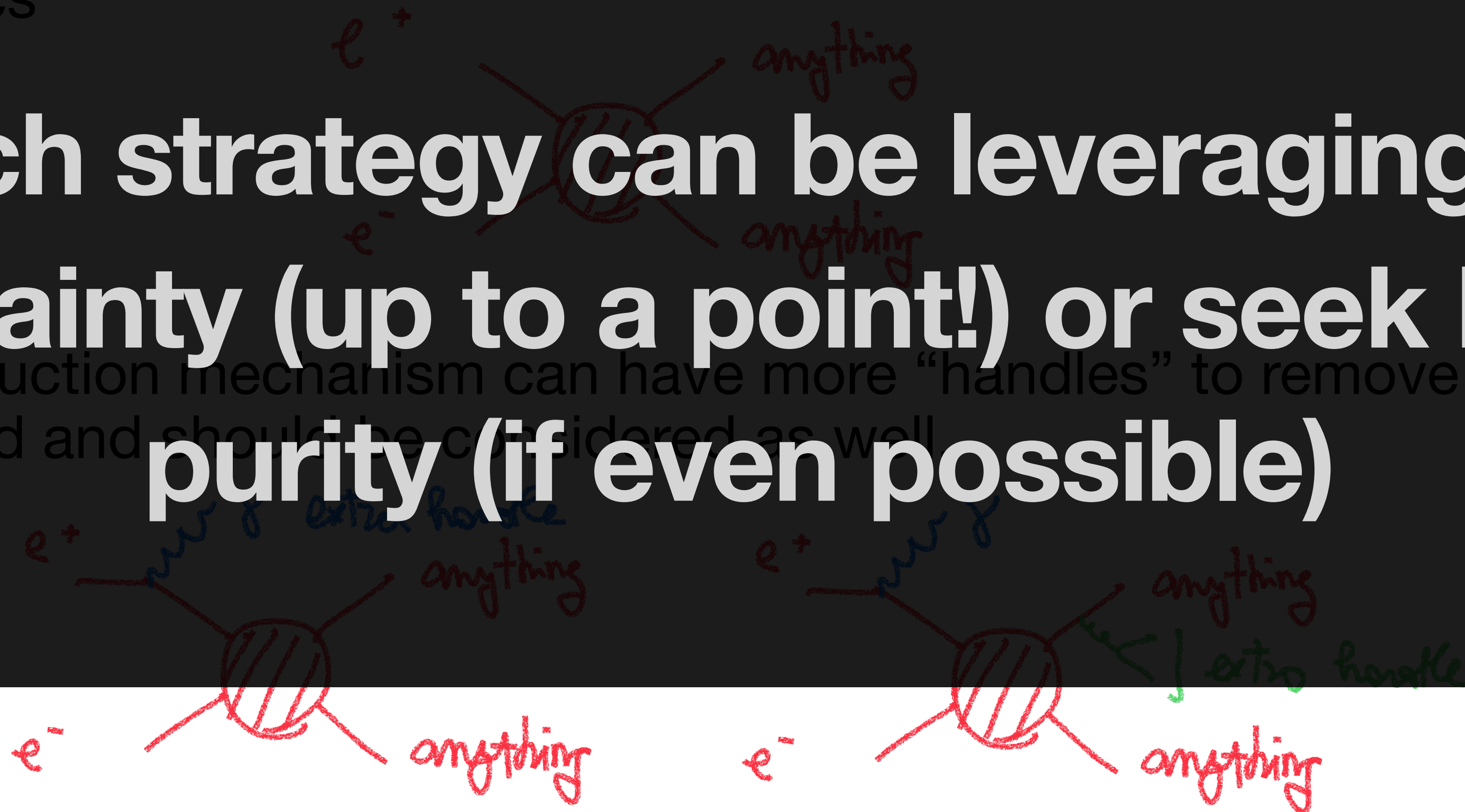
# Weakly coupled new physics production mechanisms

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**Search strategy can be leveraging stat-uncertainty (up to a point!) or seek higher-purity (if even possible)**

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# Weakly coupled new physics production mechanisms

$$\mathcal{L}_{\text{ALP}} \propto \frac{1}{2} (\partial_\mu a)^2 + \frac{m_a^2}{2} a^2$$

FREE SCALAR MASSIVE PARTICLE

$$+ \#_{\text{eff}} a F_{\mu\nu} \tilde{F}^{\mu\nu} +$$

$$+ \#_{\text{eff}} a \bar{\psi} \psi +$$

dimension-full coupling  $\sim \text{GeV}^{-1}$   
 $10^{-3} \text{GeV}^{-1} \sim M_{\text{NP}} \simeq \text{GeV}$



$$\frac{g_{\text{SH}}^2}{16\pi^2} \frac{\#_{\text{UV}}}{M_{\text{NP}}} = \#_{\text{eff}}$$

Much smaller couplings than  $10^{-3} \text{ GeV}^{-1}$  should be pursued, until we find a good way to hide GeV New Physics

# Weakly coupled new physics production mechanisms

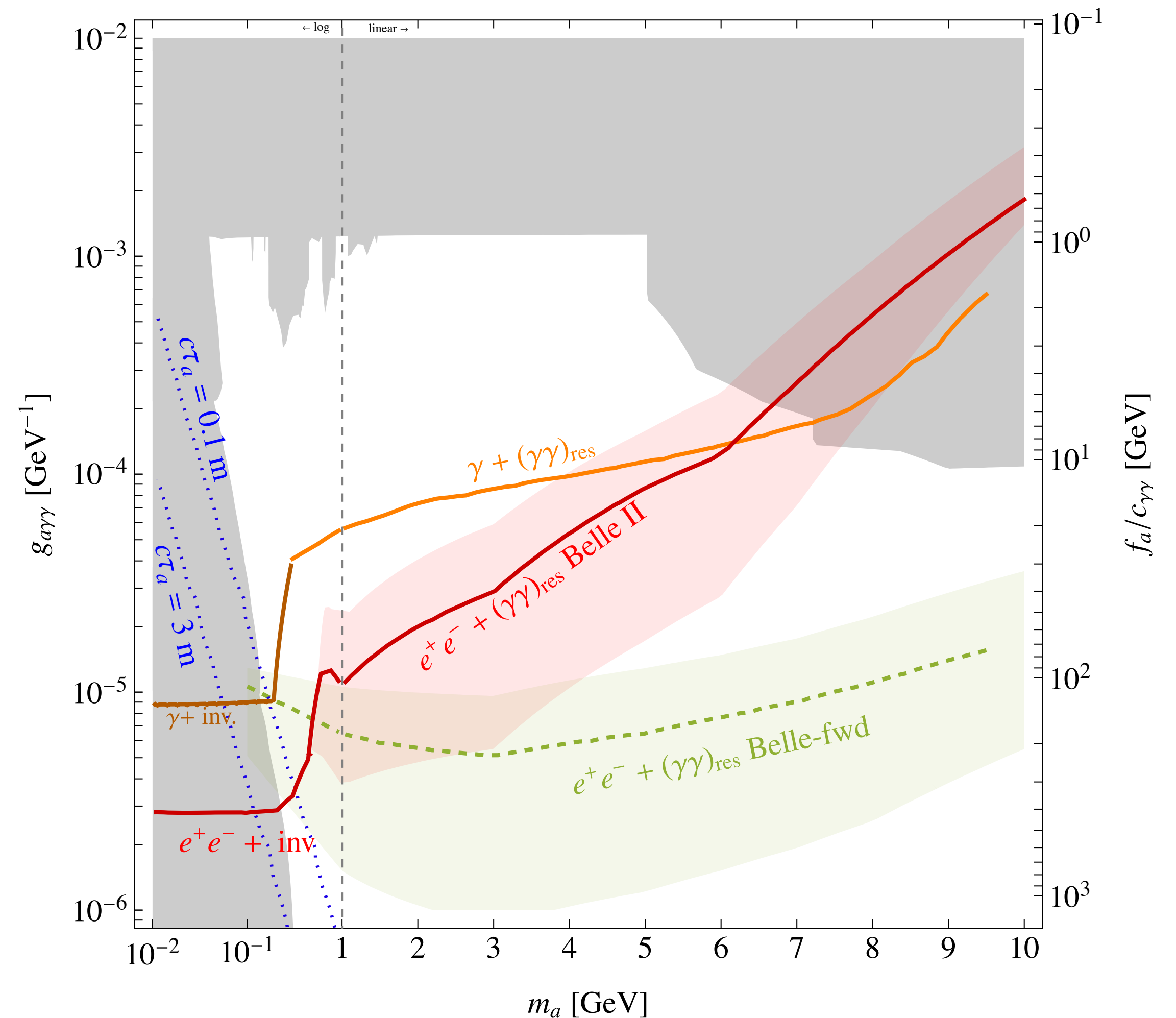
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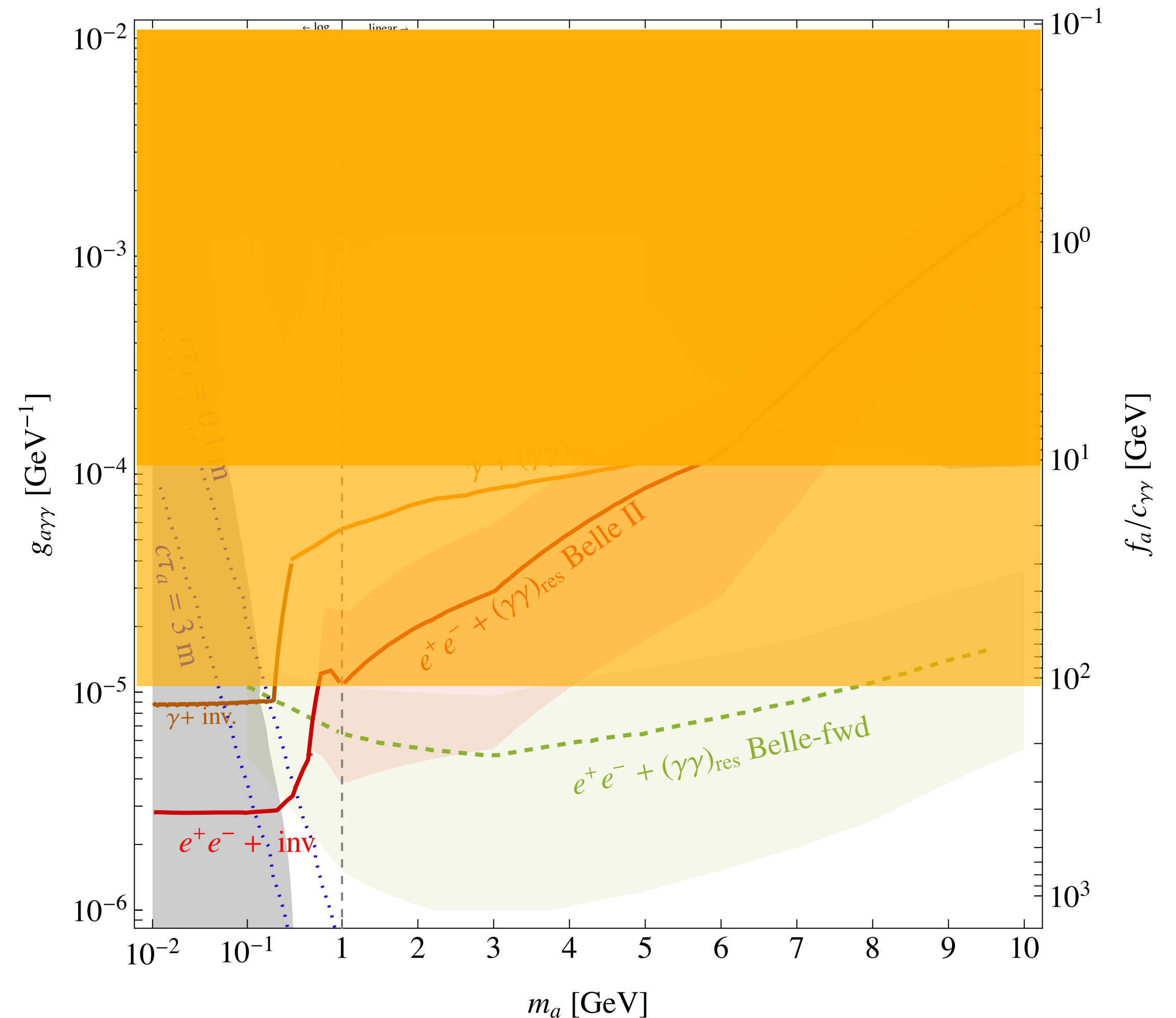
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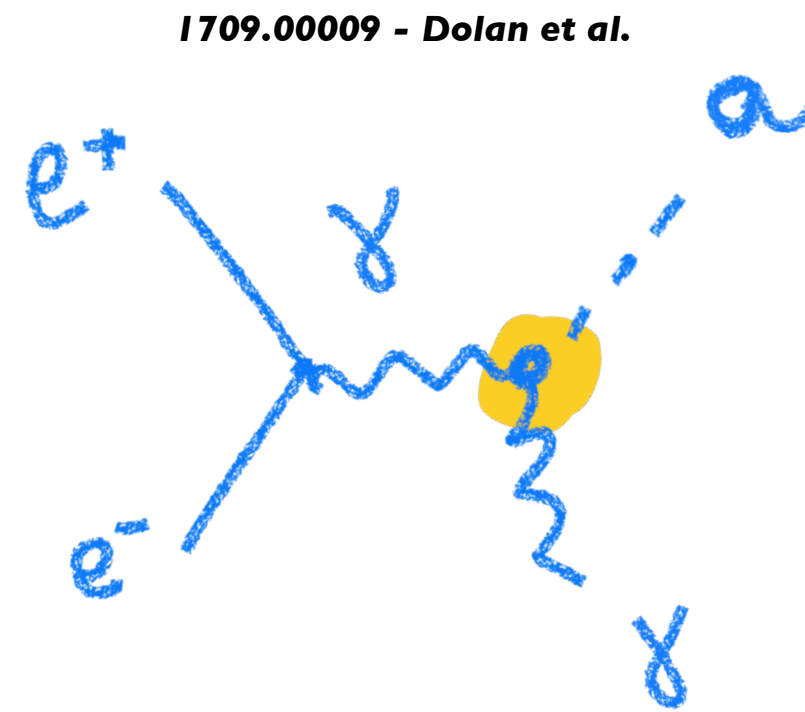
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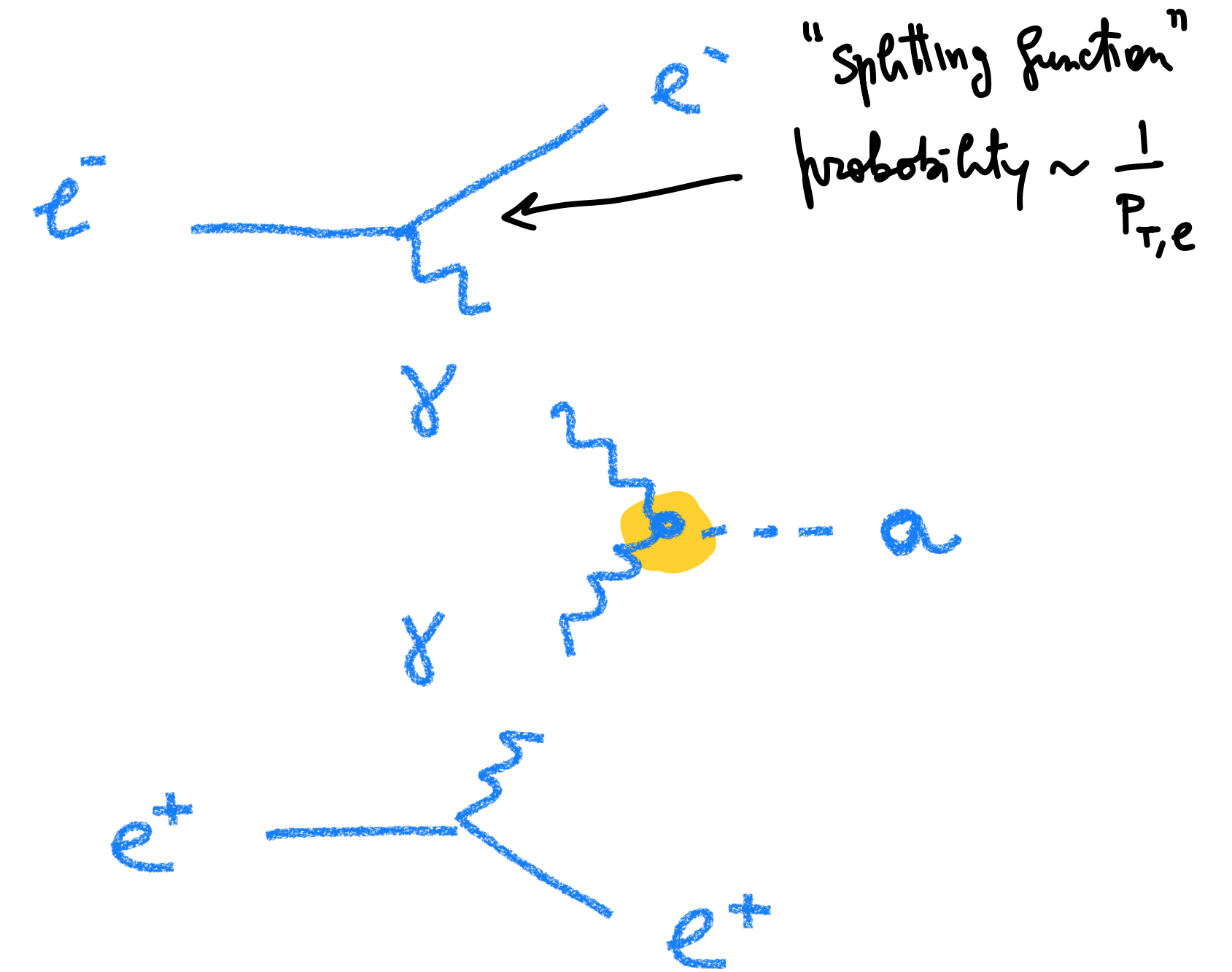
# Weakly coupled new physics production mechanisms



2-to-2 production mechanism with  $a$  and  $\gamma$  back-to-back (in the CoM frame)

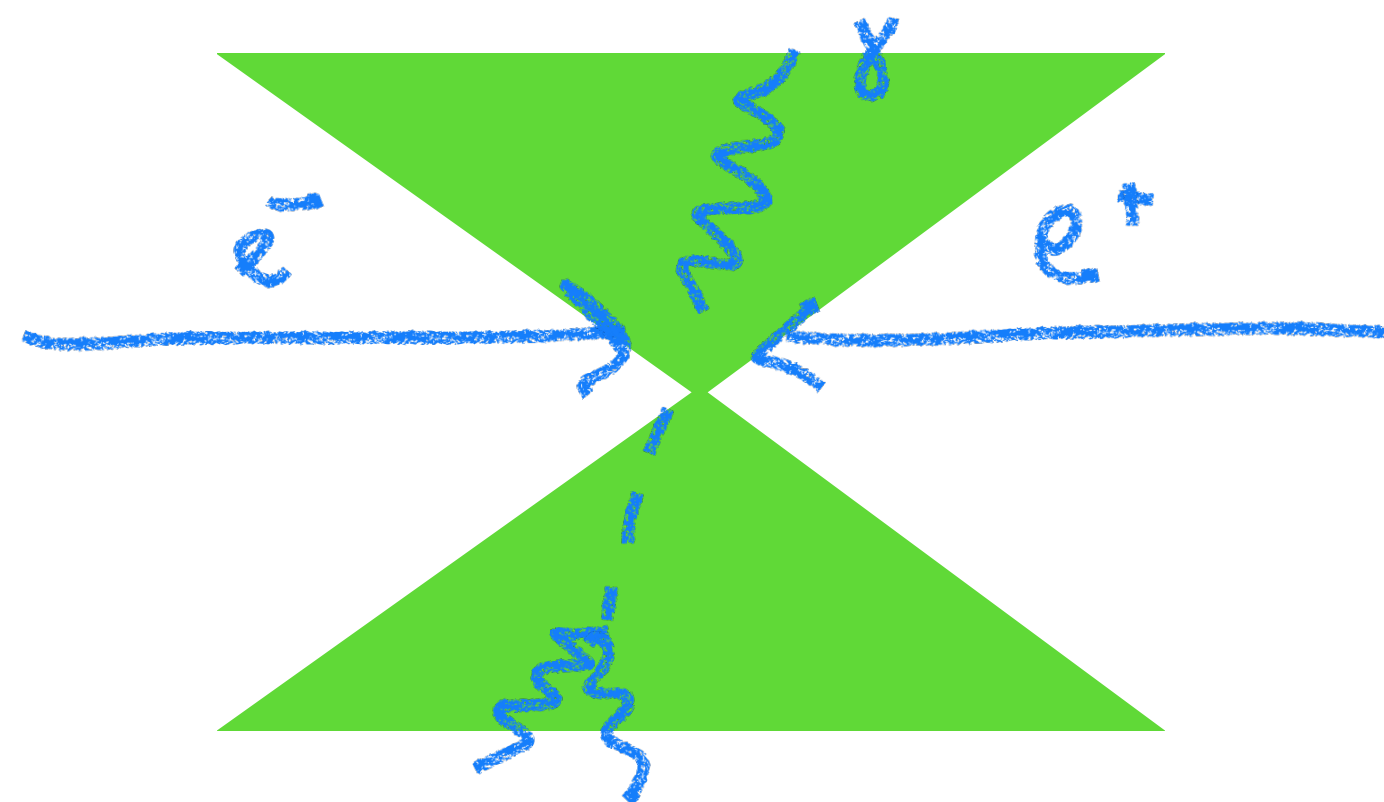
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2-to-2 kinematics is very restrictive, only the polar scattering angle is significant

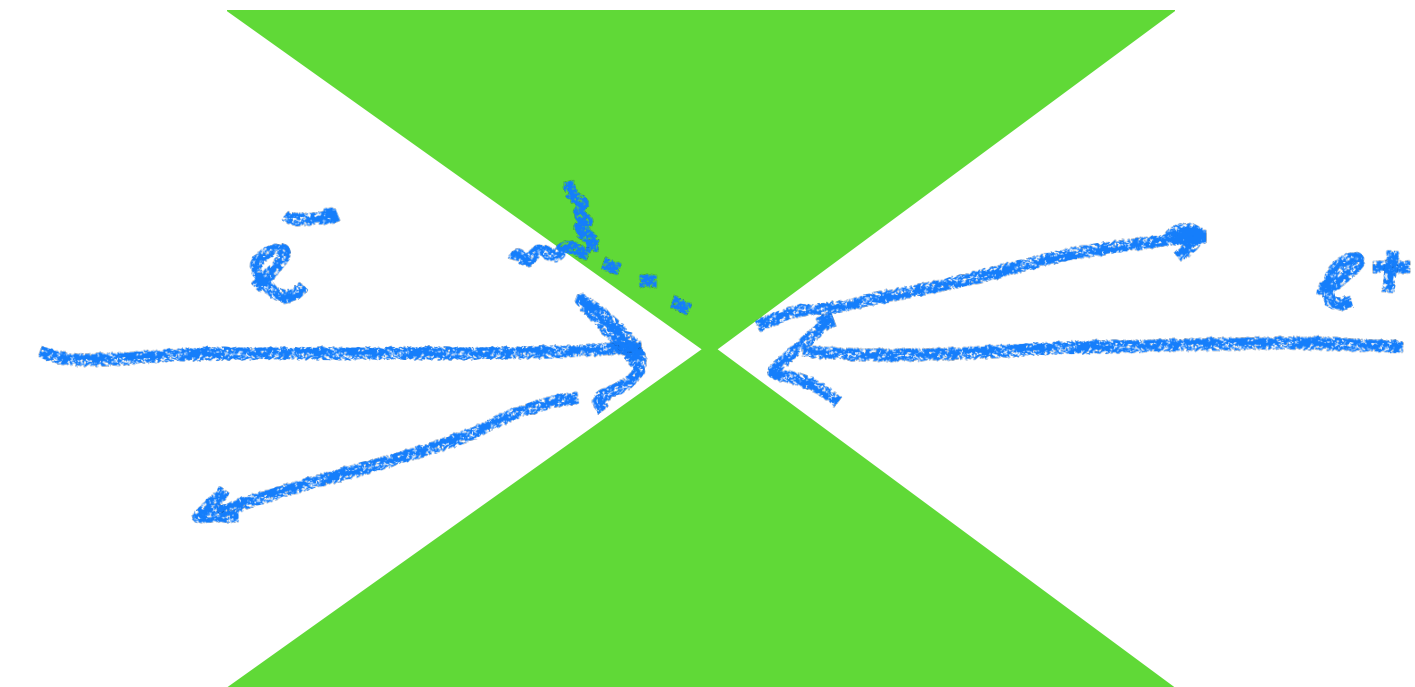


2-to-3 production mechanism with richer phase-space than 2-to-2)  $\rightarrow$  more handles!

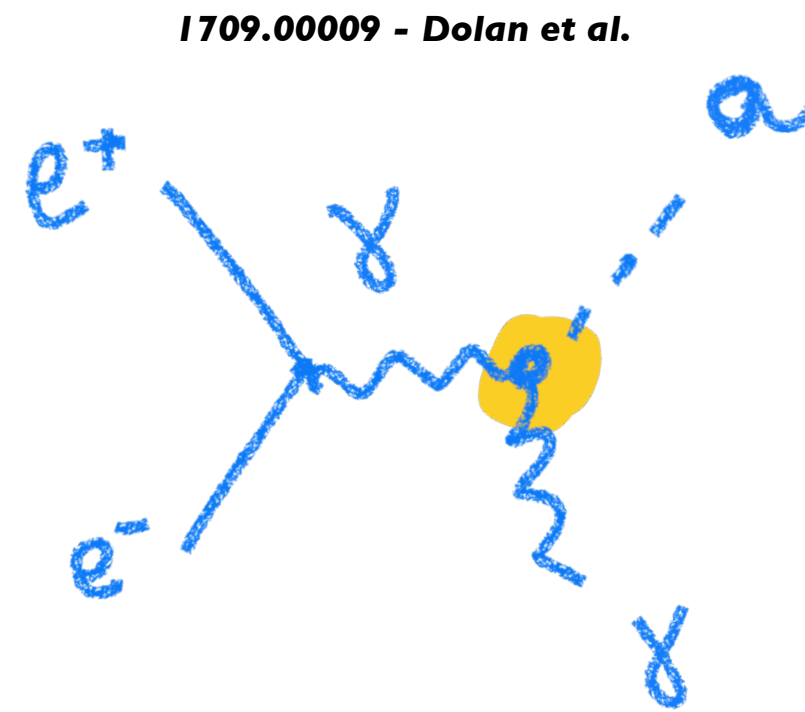
minor acceptance gain from forward coverage



huge acceptance gain from forward coverage



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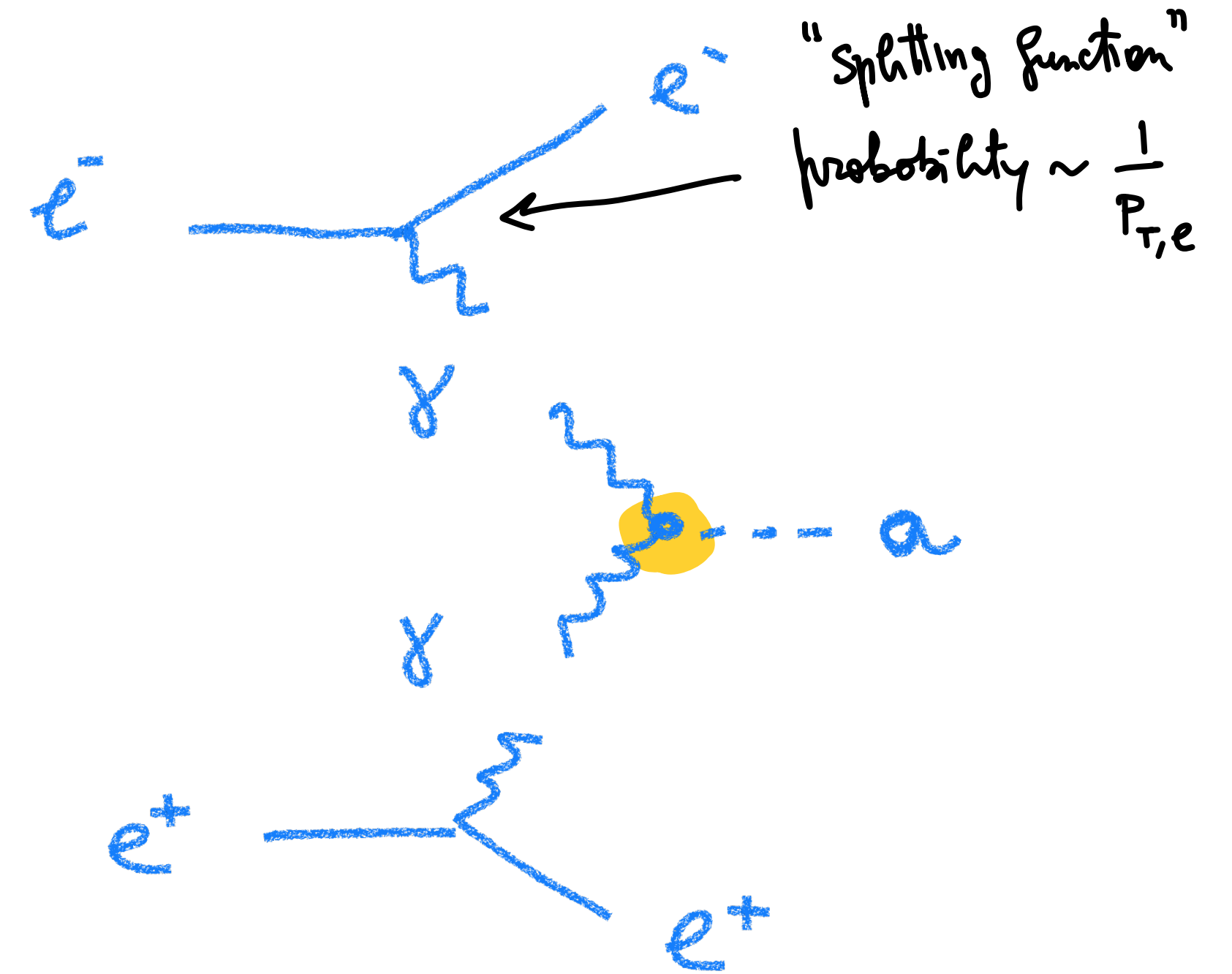
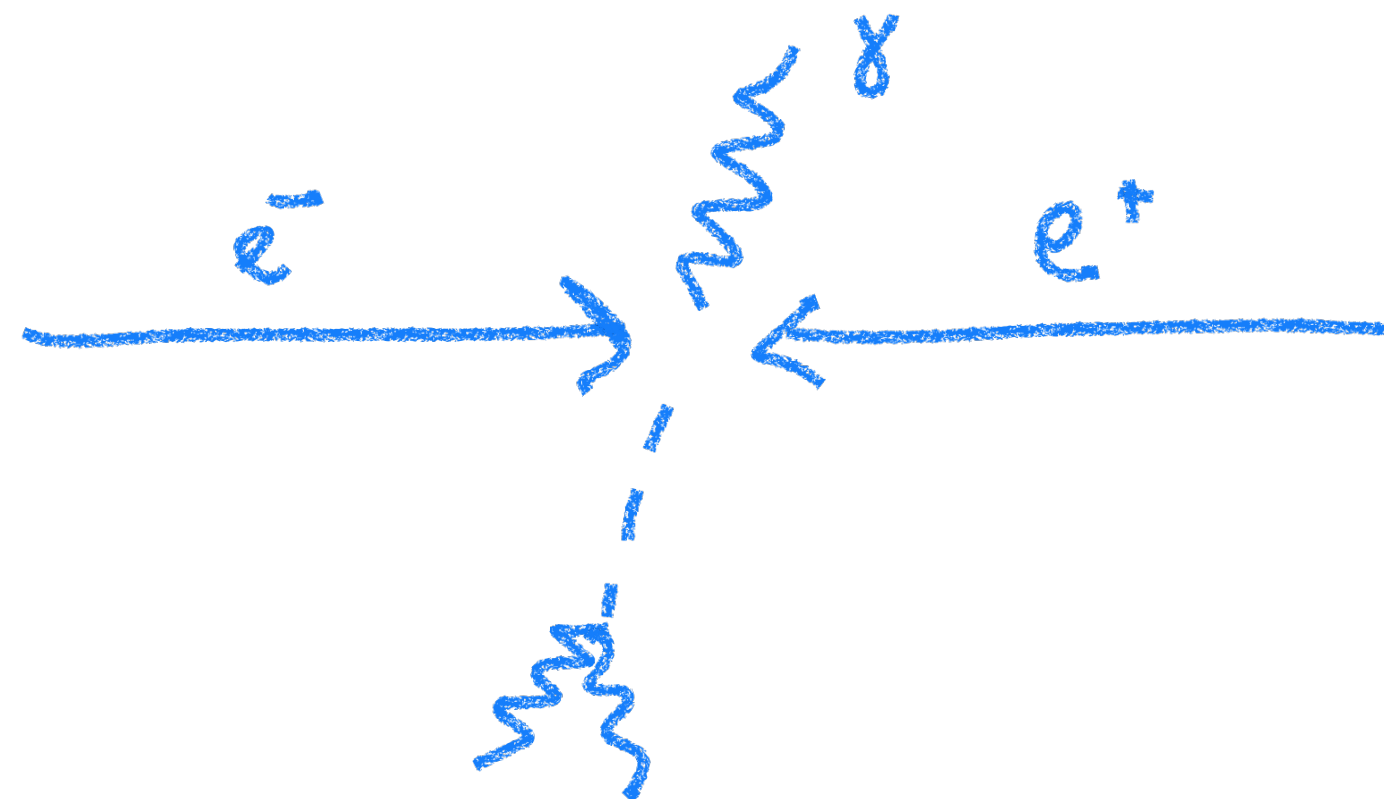


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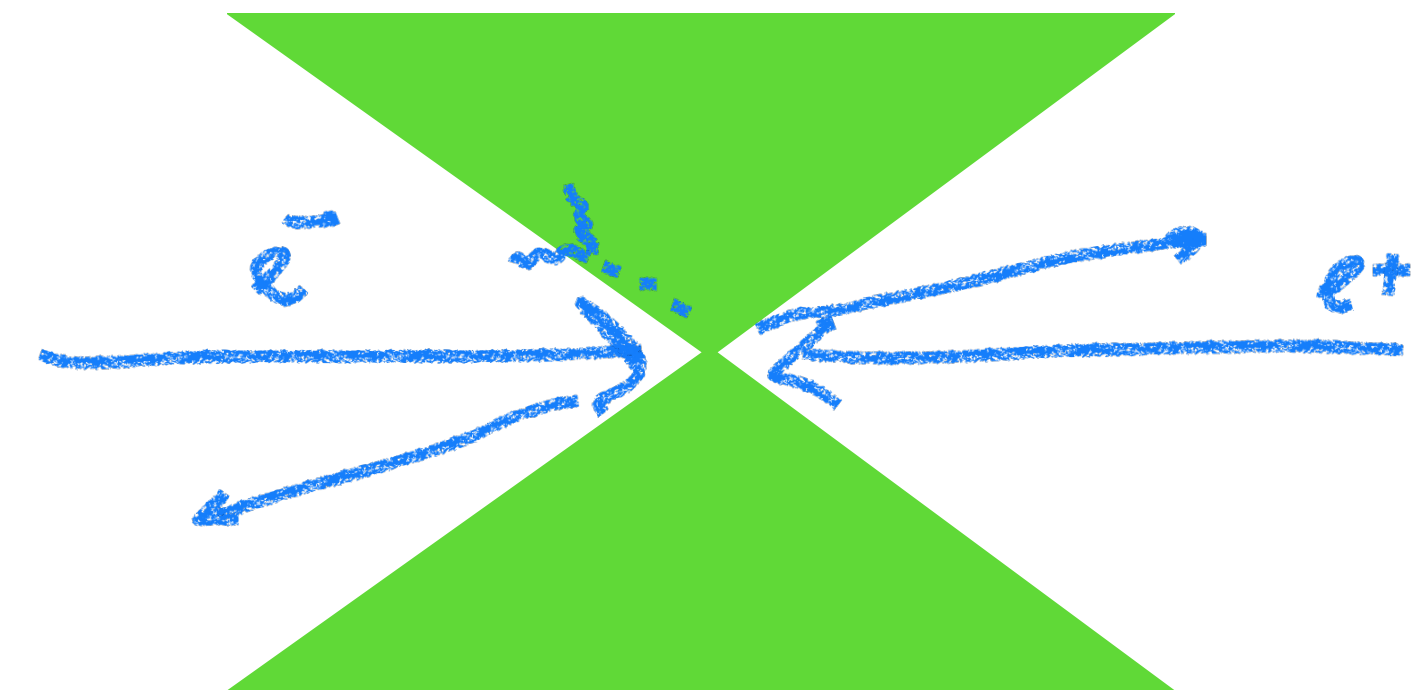
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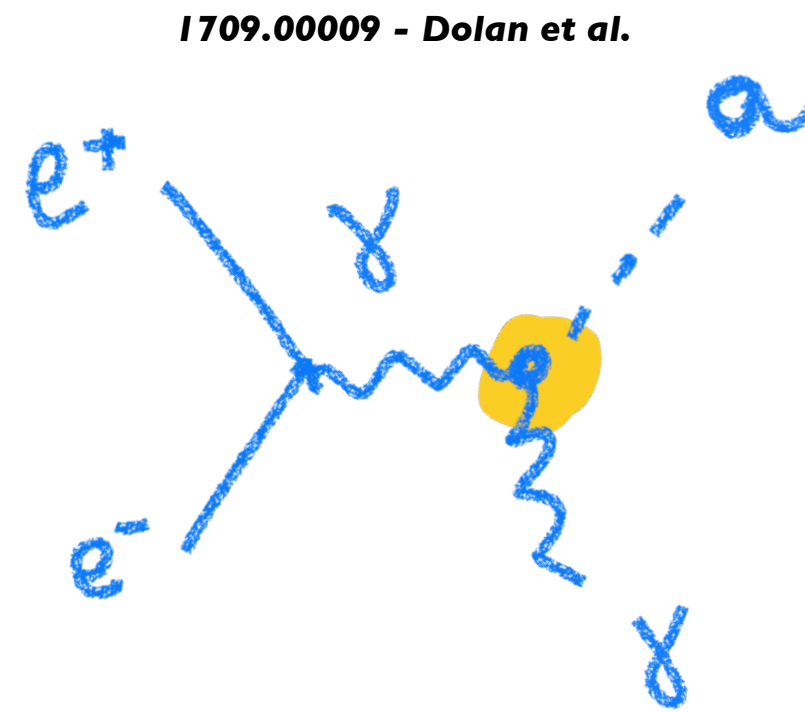


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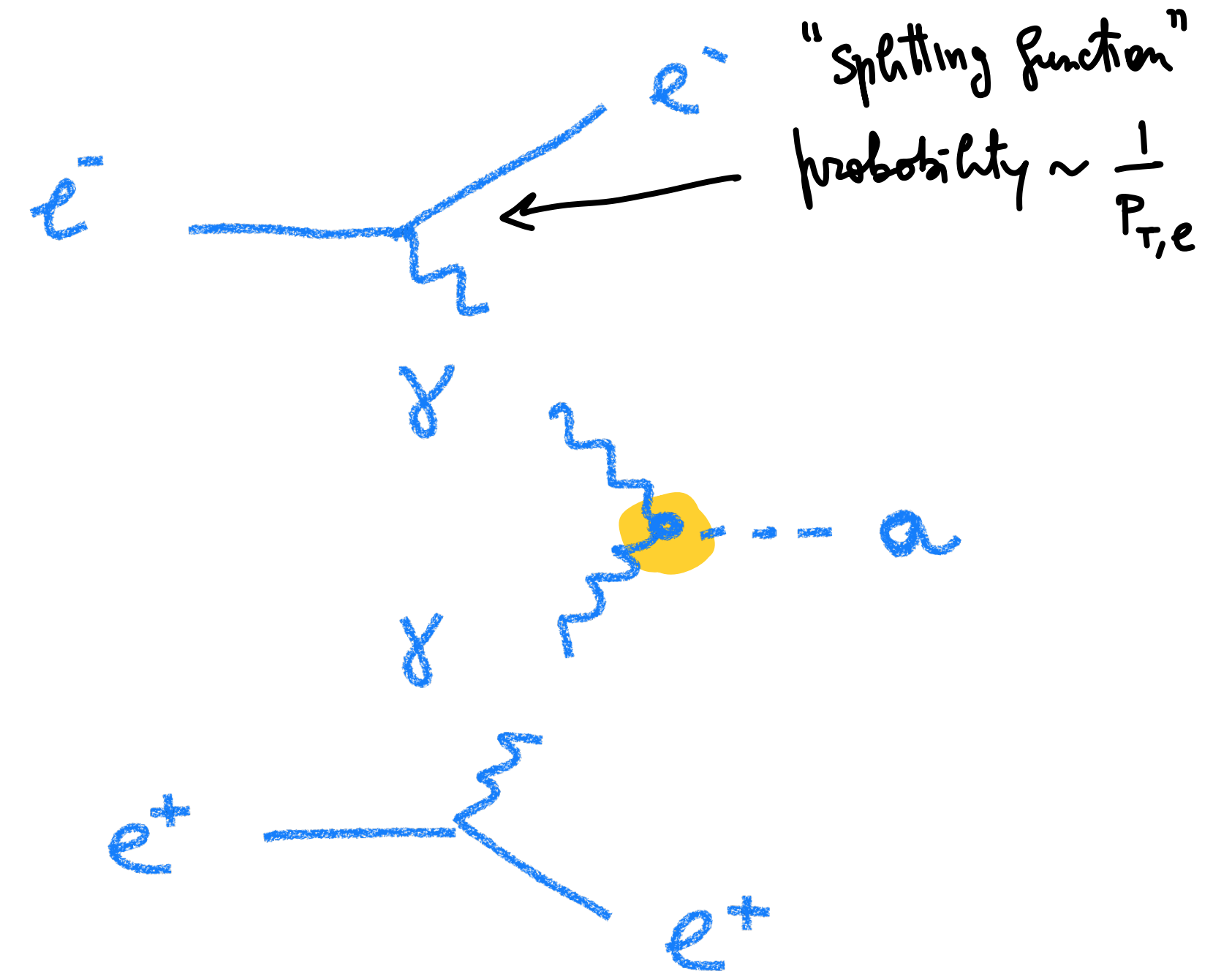
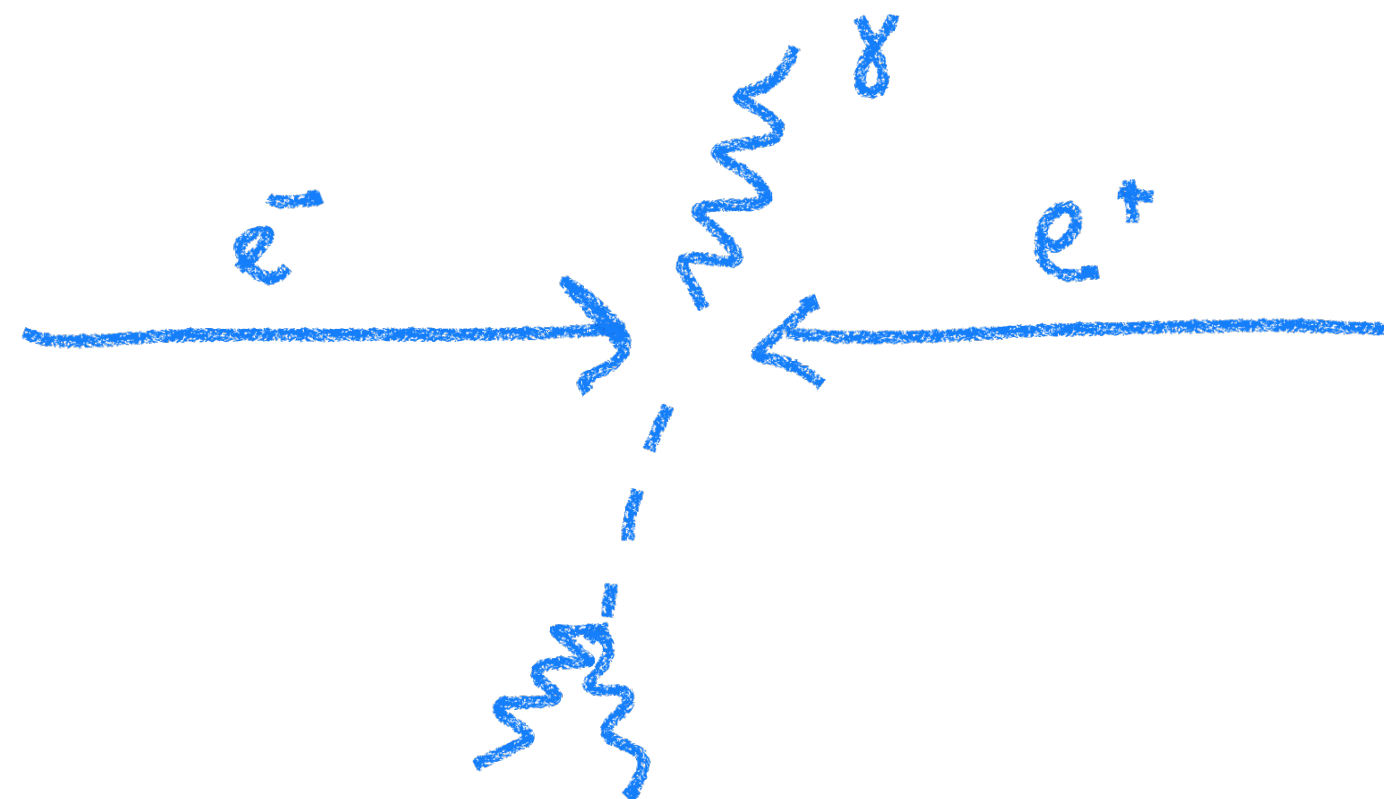


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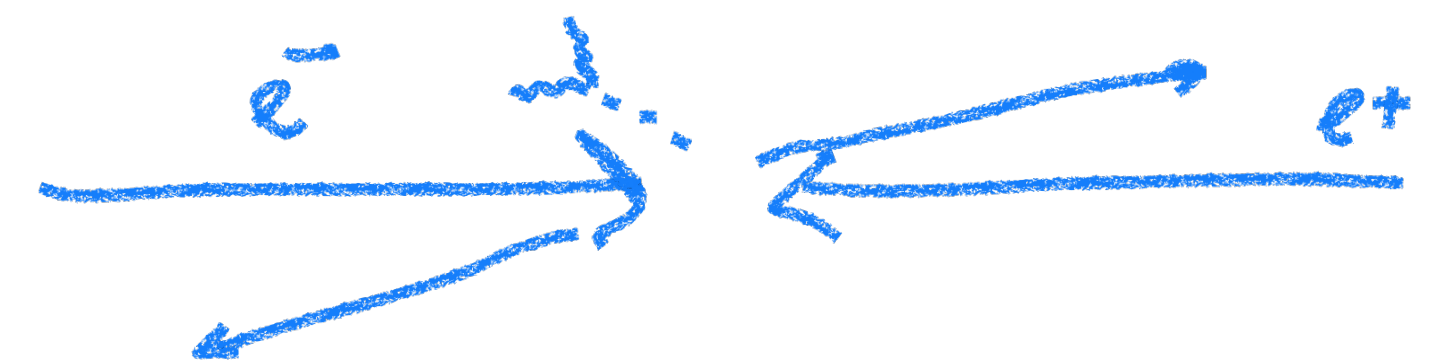
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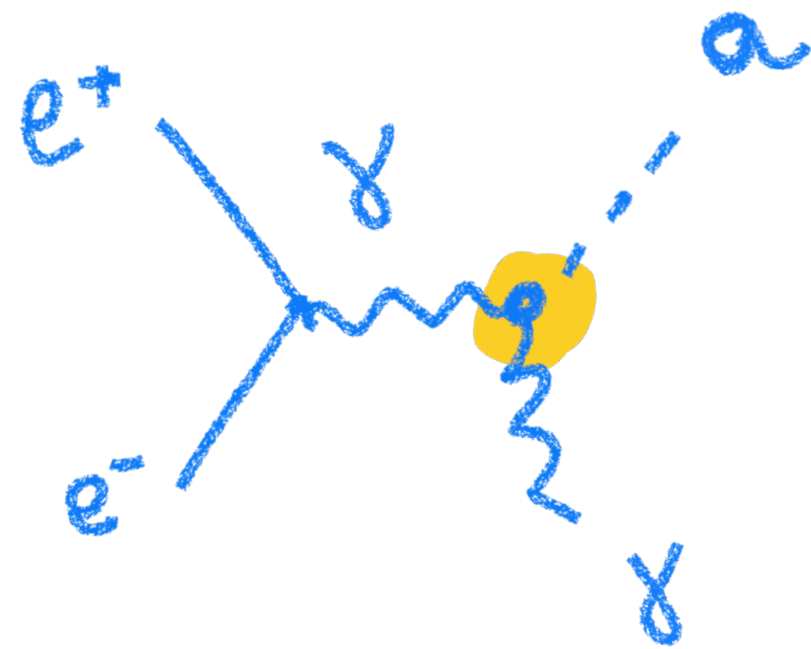
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1709.00009 - Dolan et al.

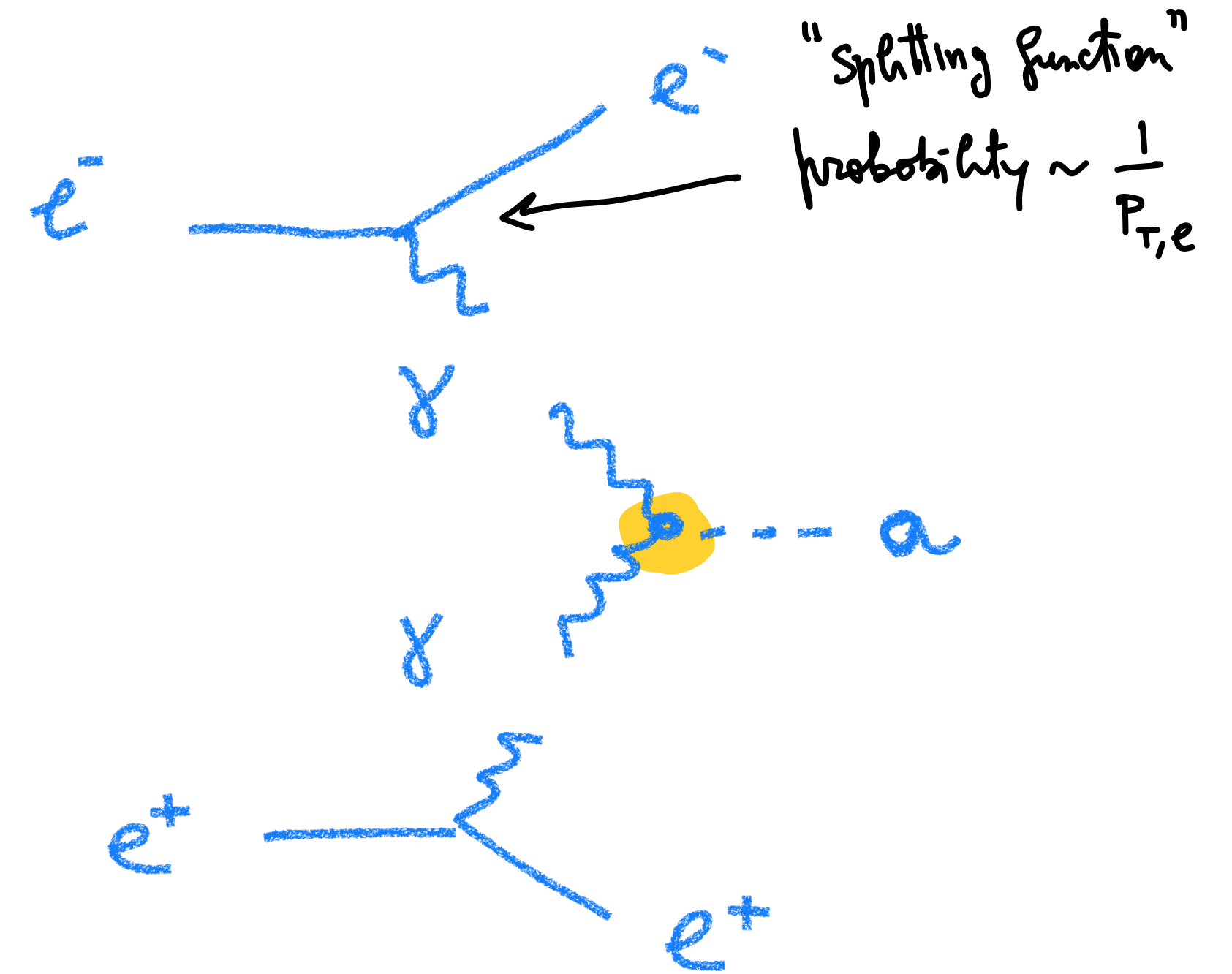
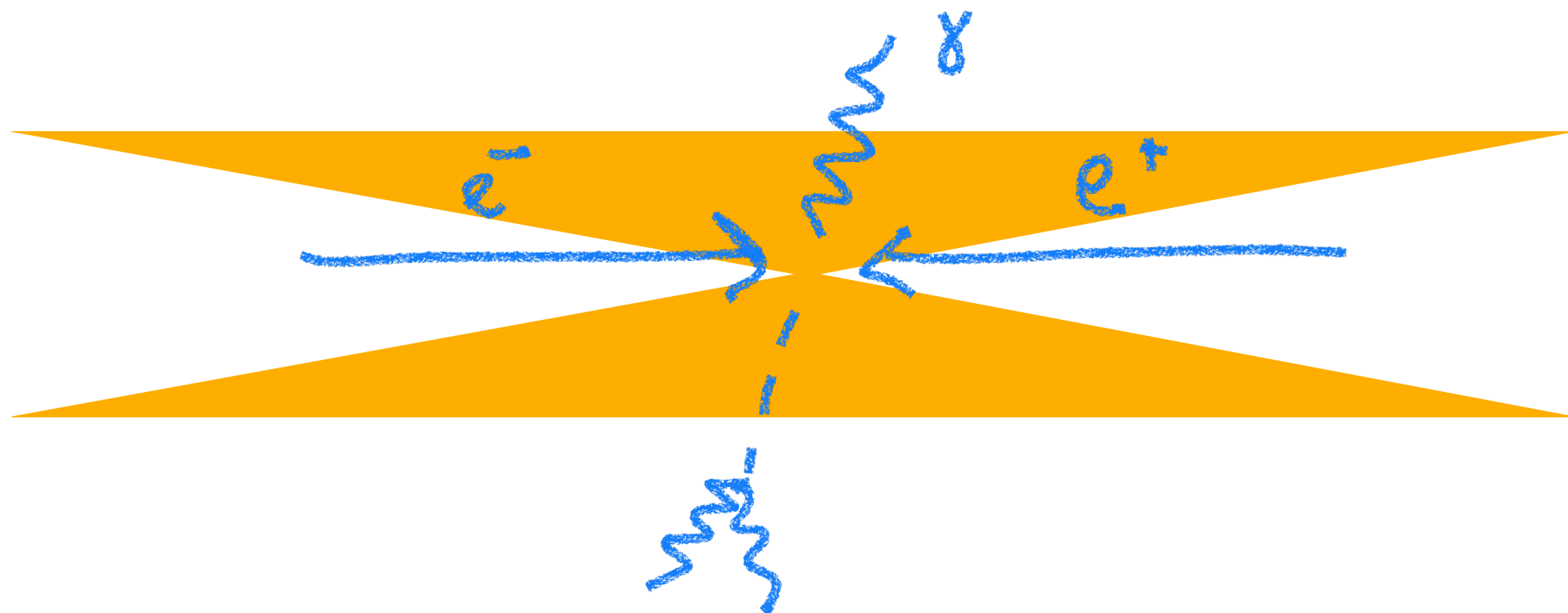


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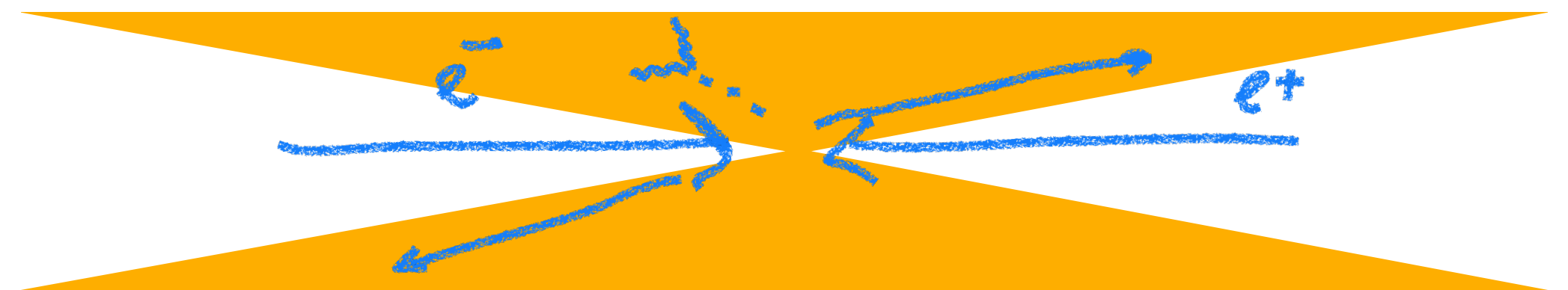
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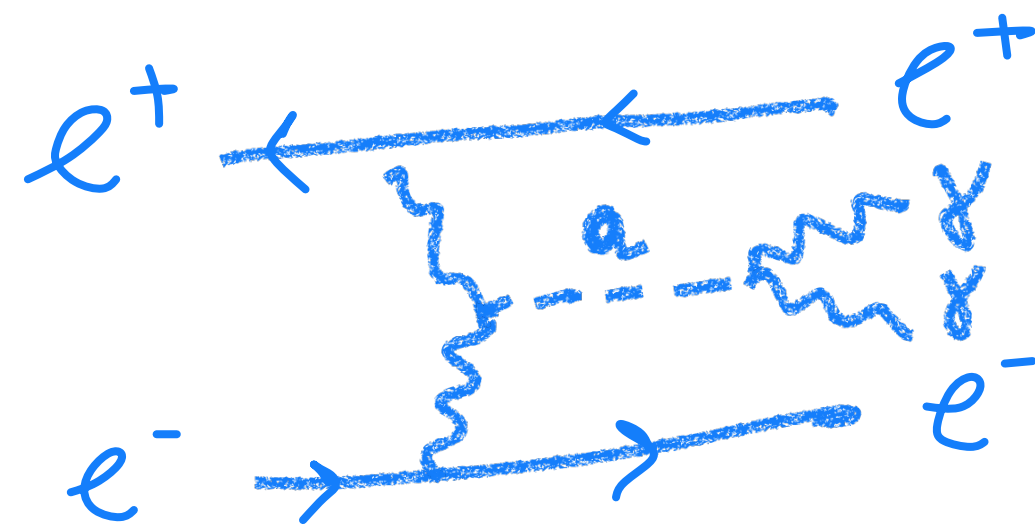
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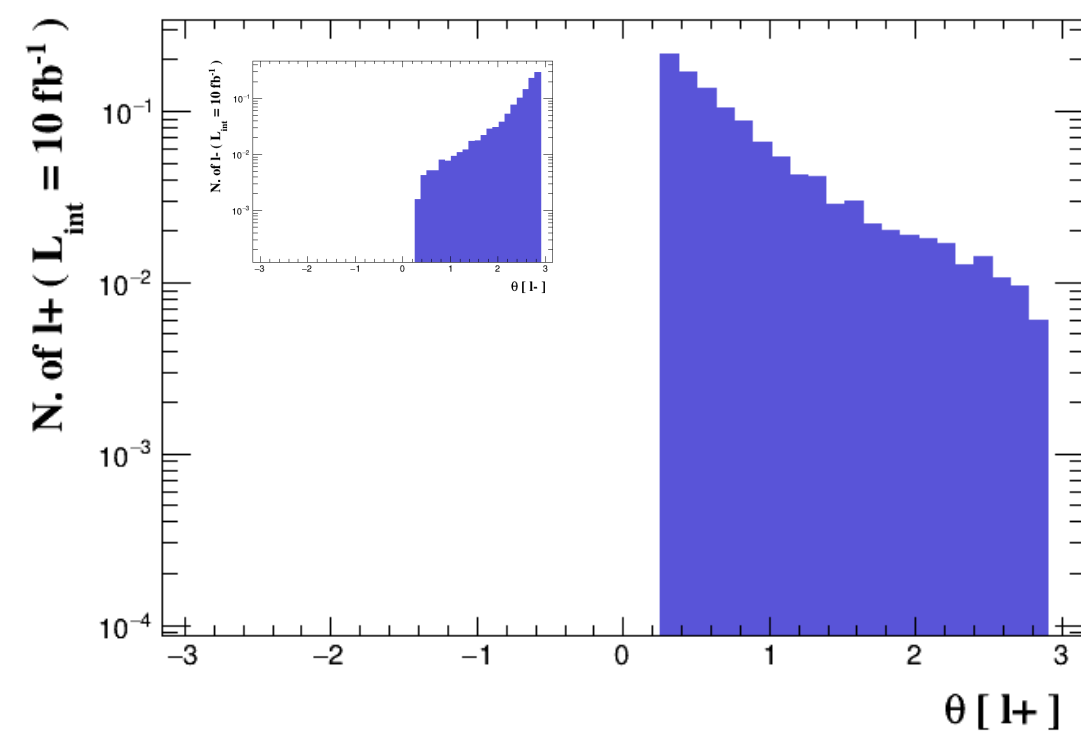
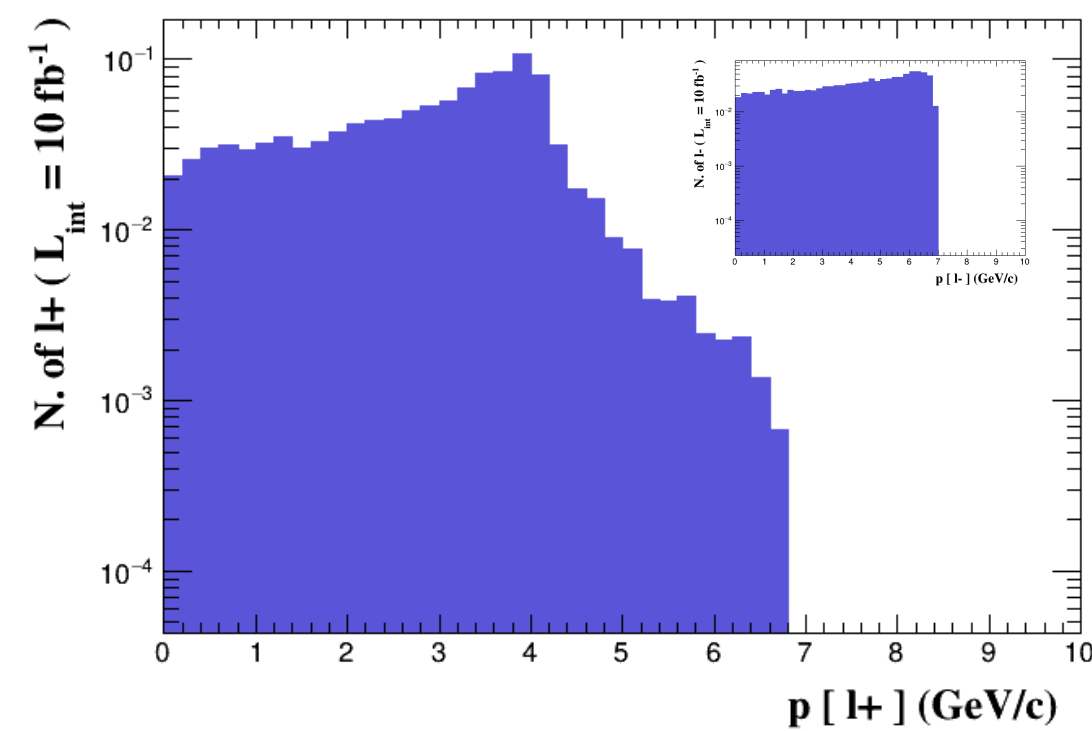
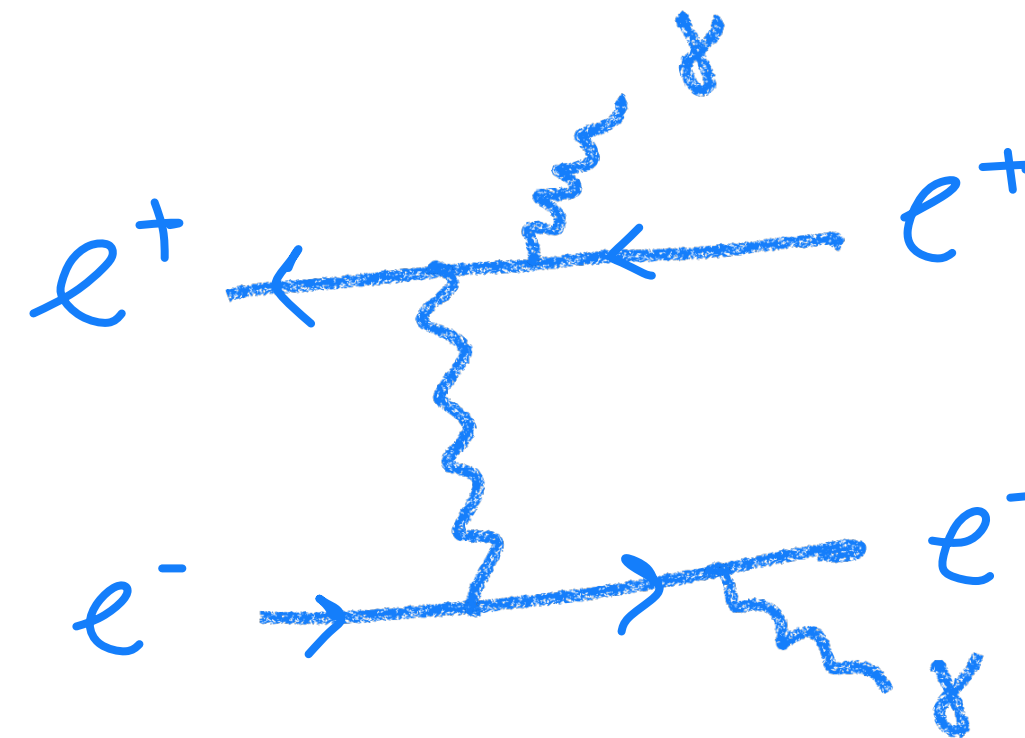


# Background and new physics production mechanisms

signal is  $e^+e^- \rightarrow e^+e^-(\gamma\gamma)_a$



main background is  $e^+e^- \rightarrow e^+e^-\gamma\gamma$  from Bhabha

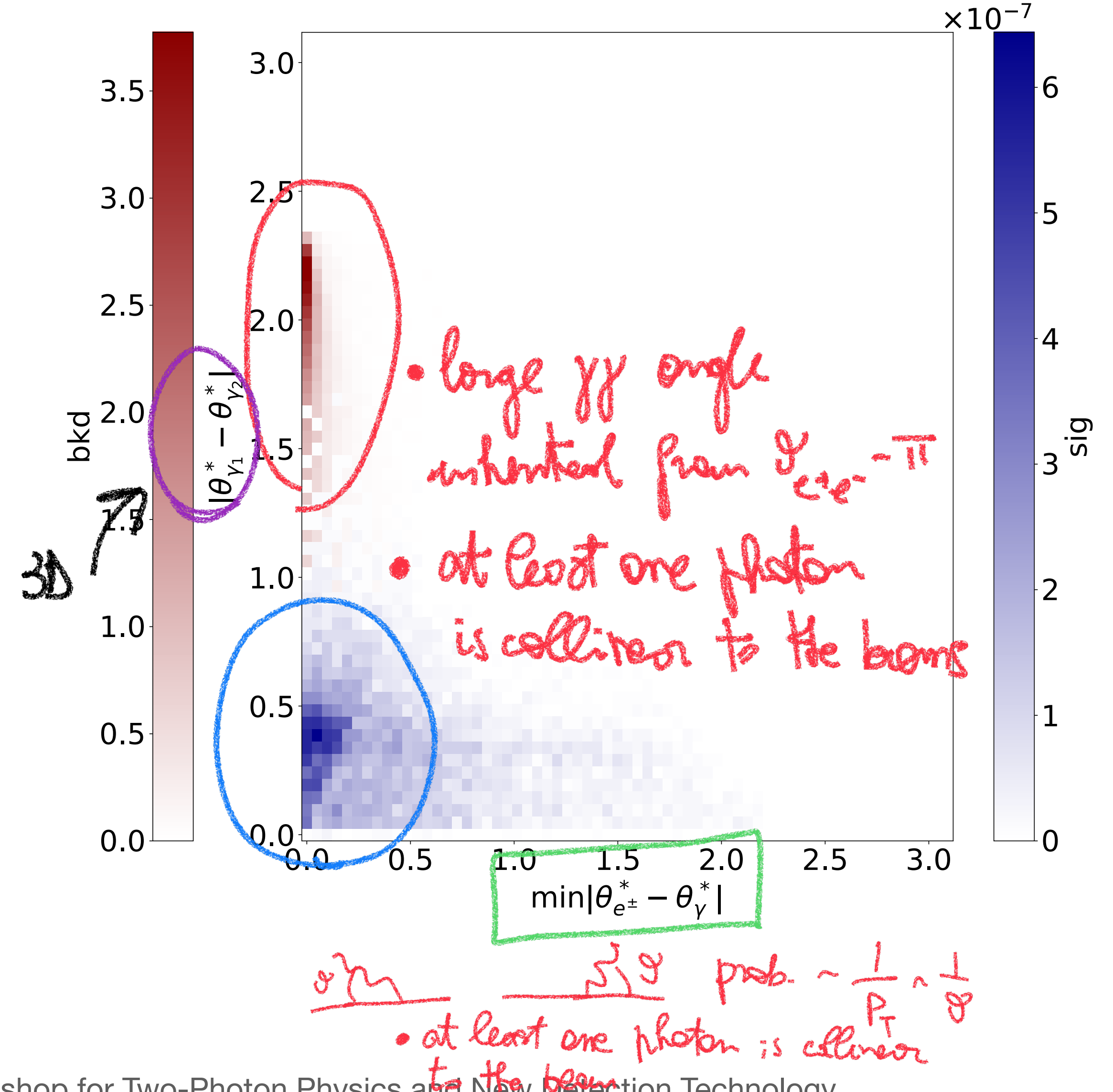
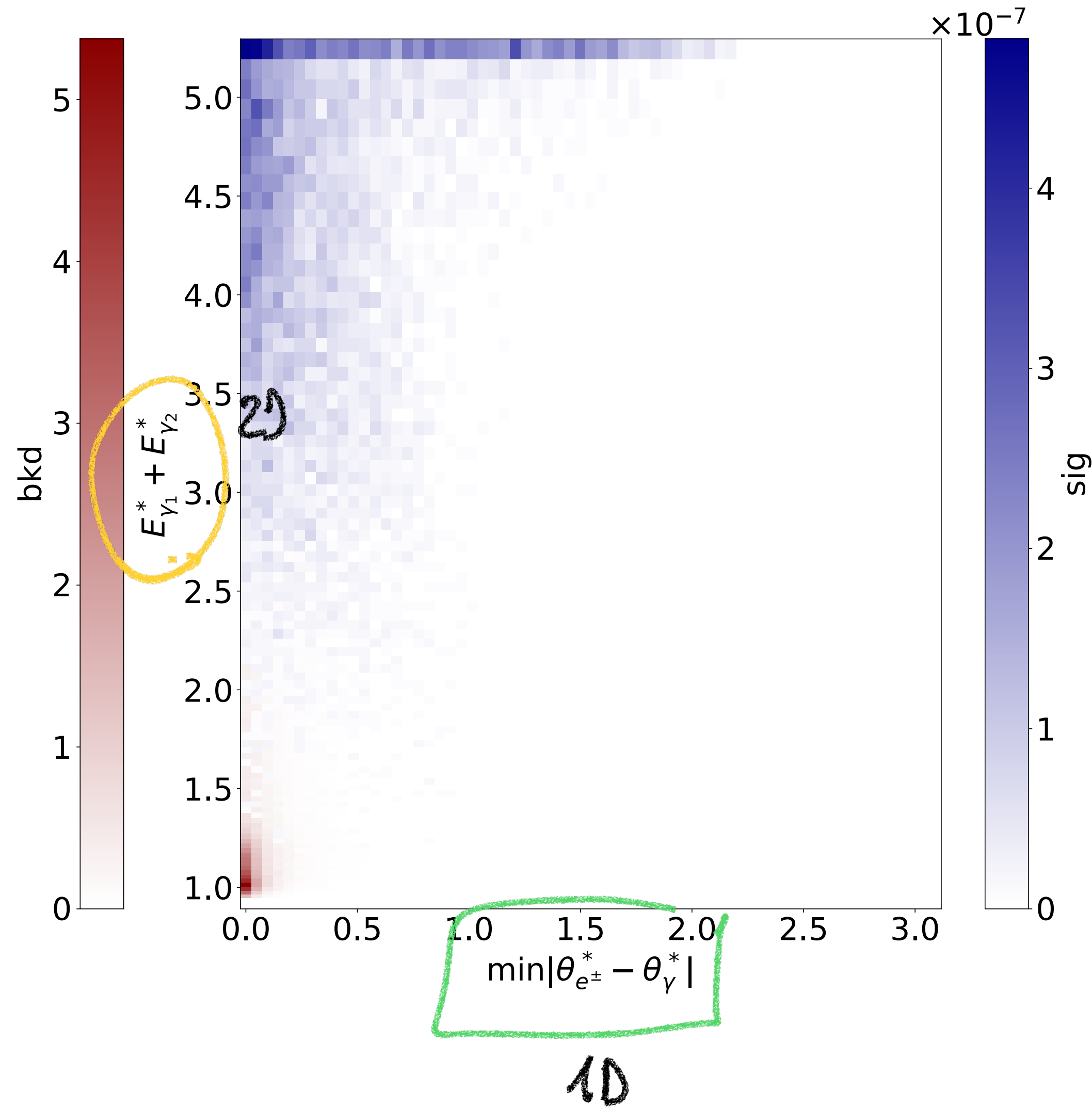


single variable distributions are very similar for the BG

**a multi-dimension analysis is necessary**

# Background and new physics production mechanisms

the multi-dimension analysis



# Reach for new physics with a highly differential analysis

$$\sigma_{sig} \cdot \mathcal{A}_{geom} = 5.3 \cdot 10^{-5} \text{pb} \left( \frac{g_{a\gamma\gamma}}{10^{-4} \text{GeV}^{-1}} \right)$$

$$\sigma_{bg} \cdot \mathcal{A}_{geom} = 13 \text{ pb}$$

## 4D differential analysis

$$t_+ = \left( p_{e_{in}^+} - p_{e_{out}^+} \right)^2 ,$$

$$t_- = \left( p_{e_{in}^-} - p_{e_{out}^-} \right)^2 ,$$

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$$m_{\gamma\gamma} - m_a \in [-3, 1.5] \cdot \sigma_{m_a} ,$$

$$E^* > 0.25 \text{ GeV}, \quad \theta^* \in [22, 158]^\circ ,$$

$$\Delta\theta_{\gamma\gamma} > 0.048 \quad \text{or} \quad \Delta\phi_{\gamma\gamma} > 0.048 ,$$

$$\Delta\theta_{\gamma e^\pm} > 0.048 \quad \text{or} \quad \Delta\phi_{\gamma e^\pm} > 0.048 .$$

Very demanding to generate enough statistics for  $50 \text{ ab}^{-1}$  in 4D

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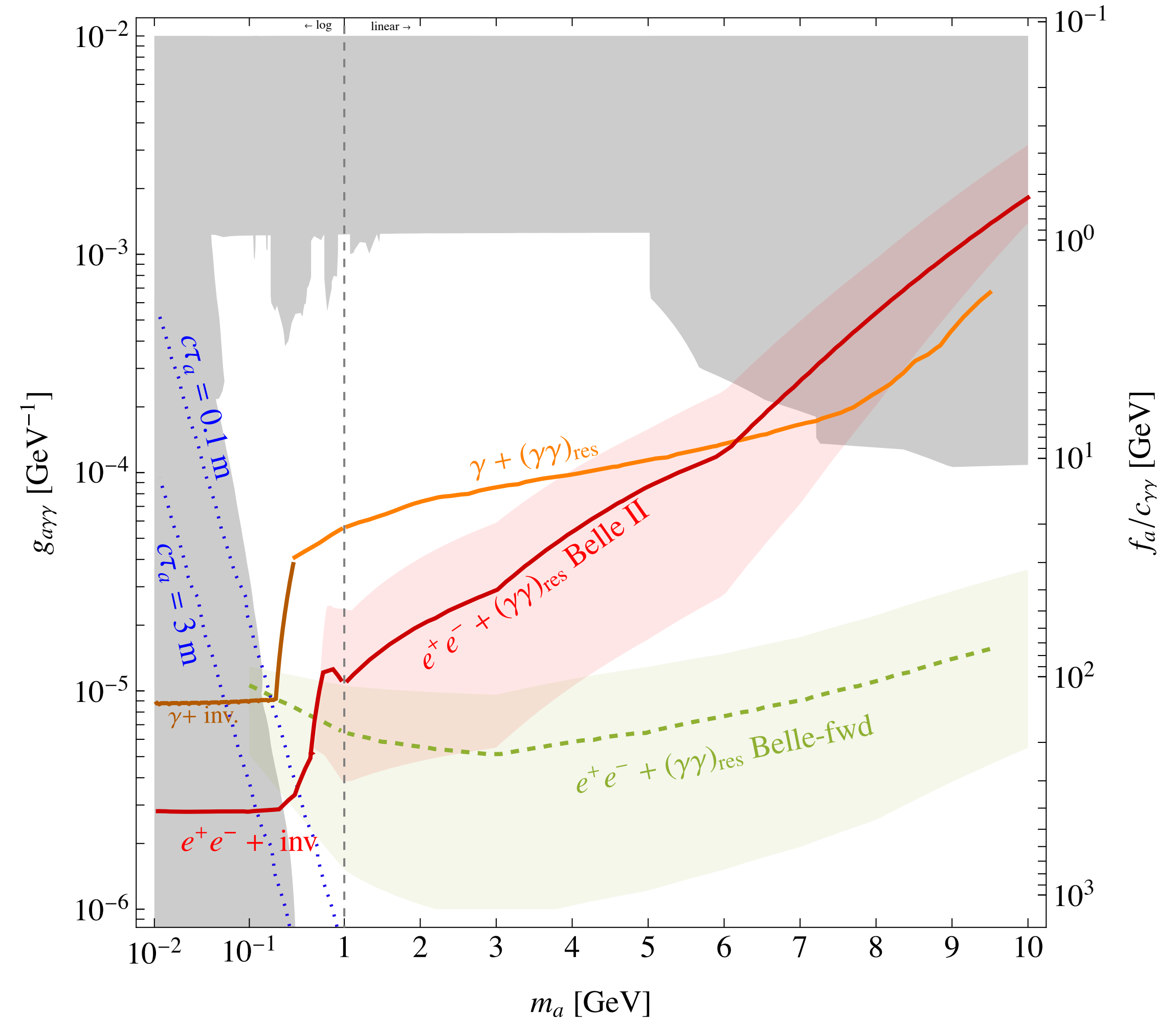
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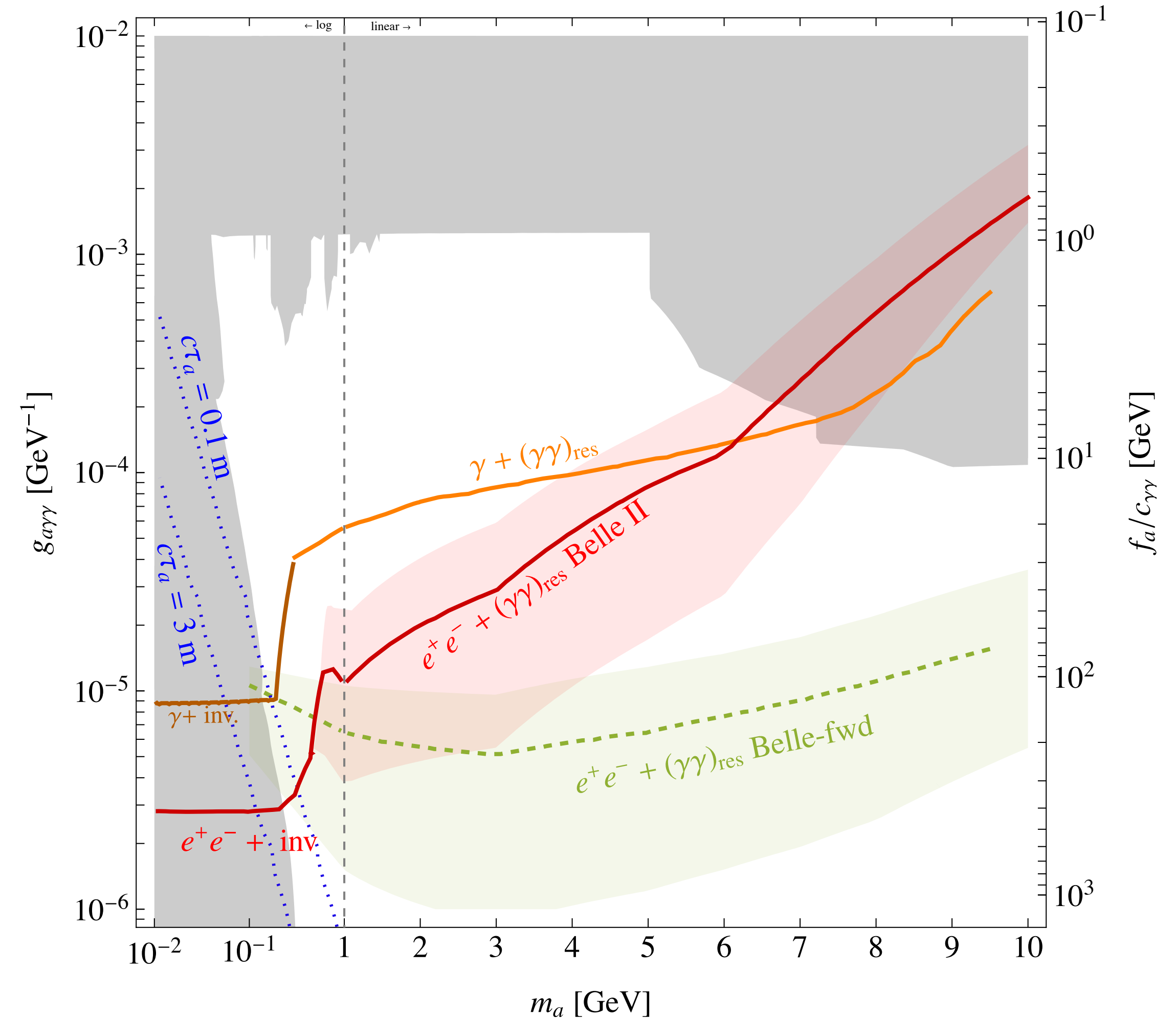
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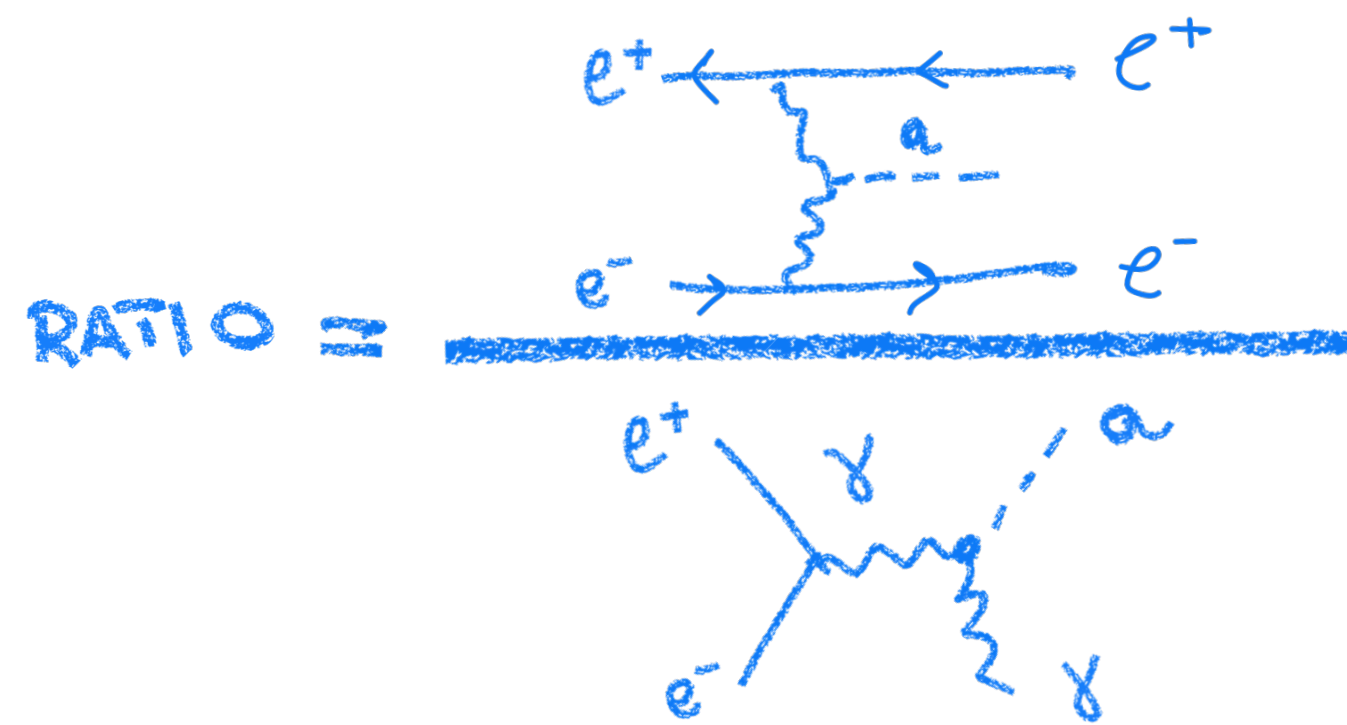
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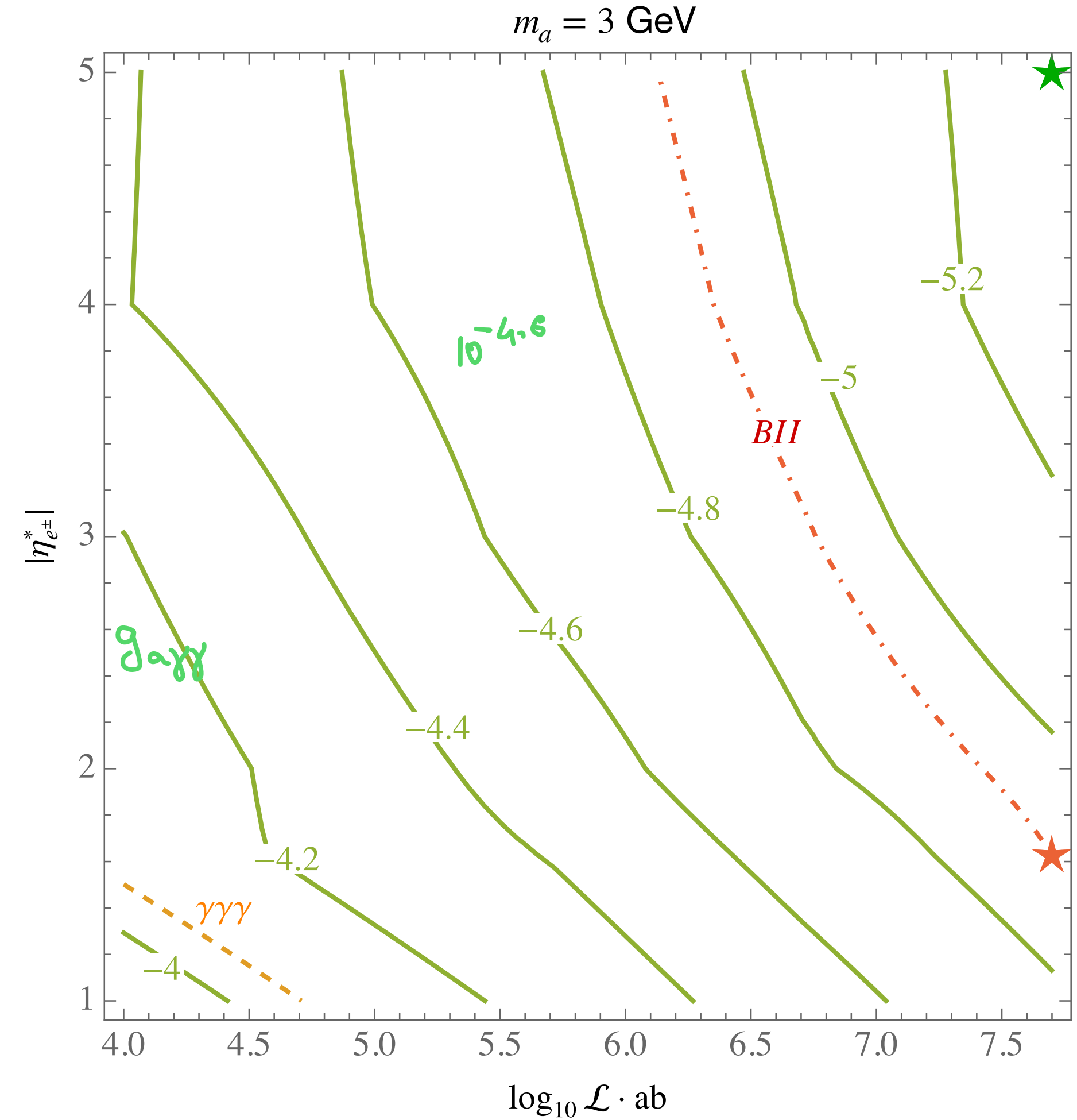
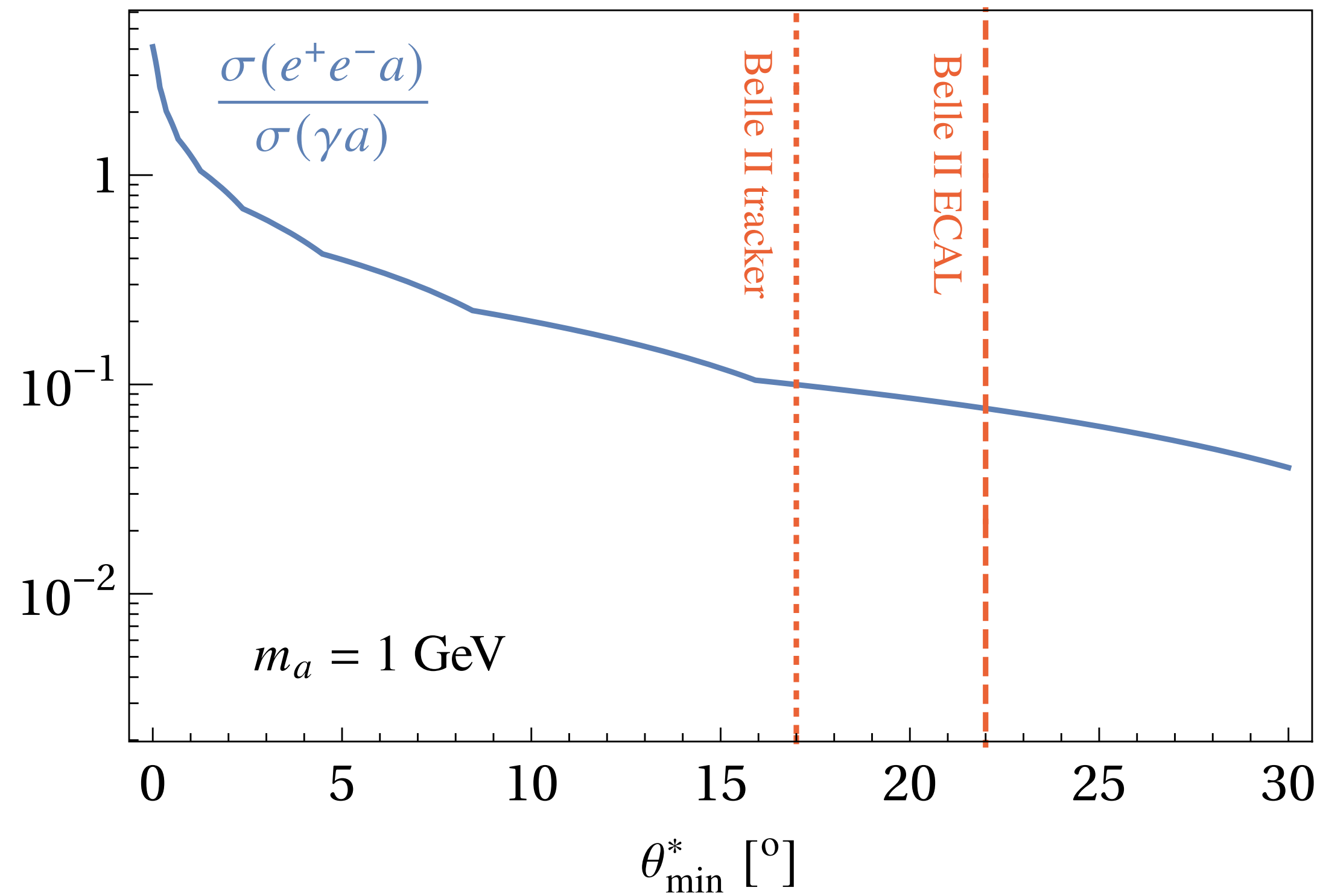
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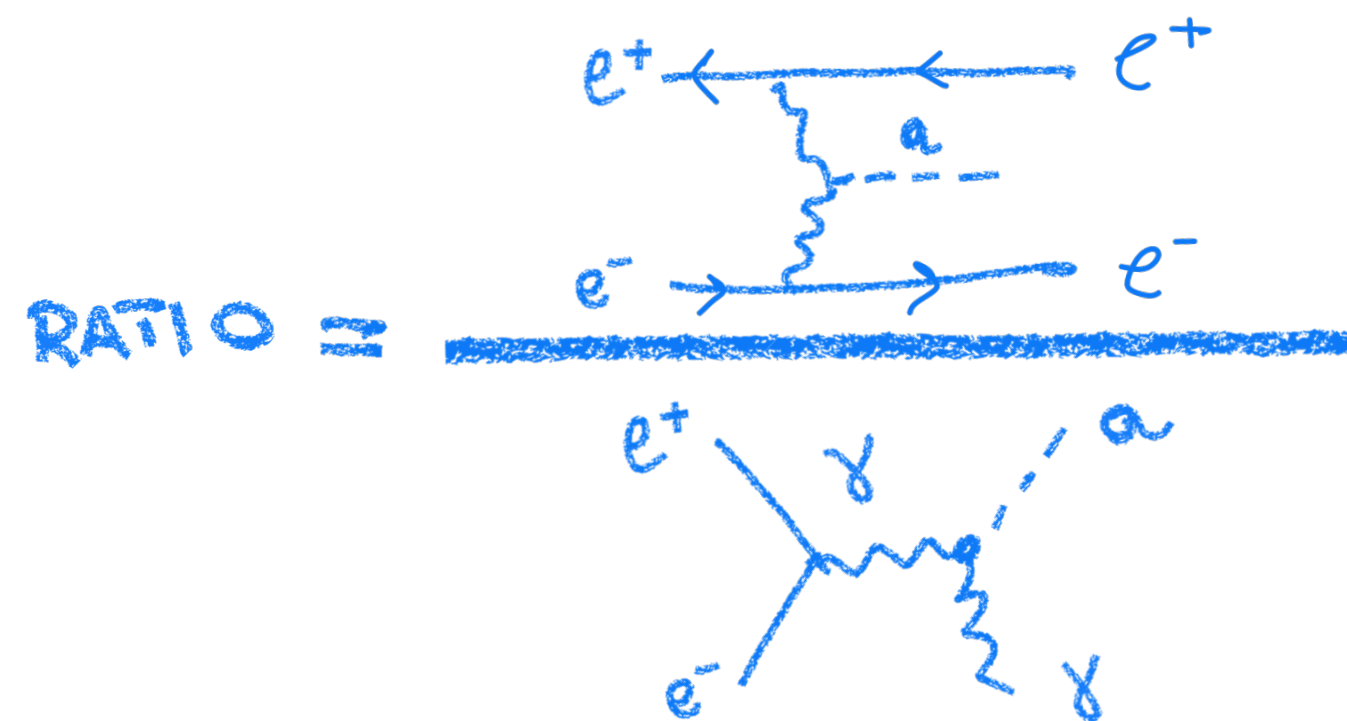
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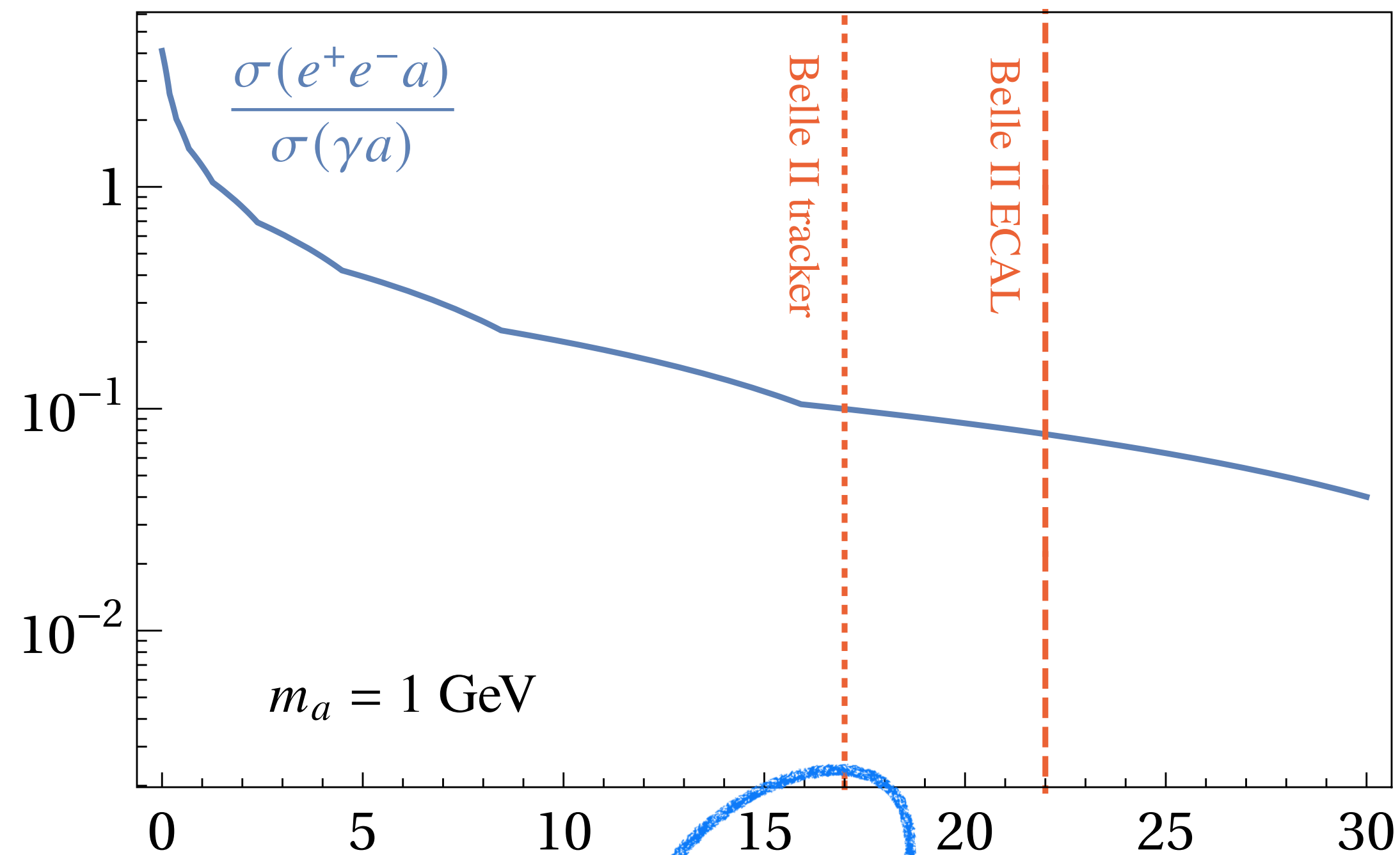
ALP cross section vs Belle II coverage



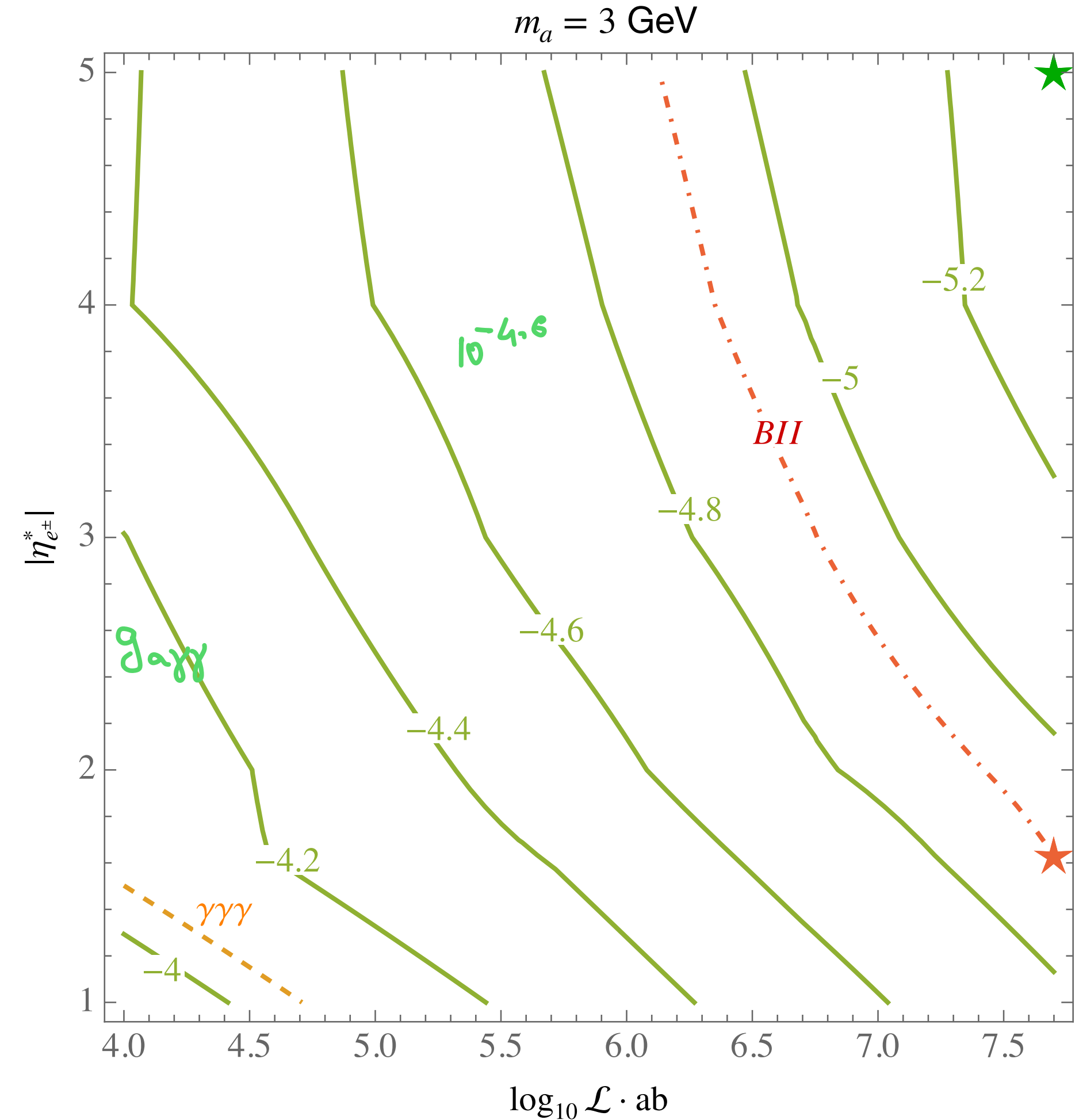
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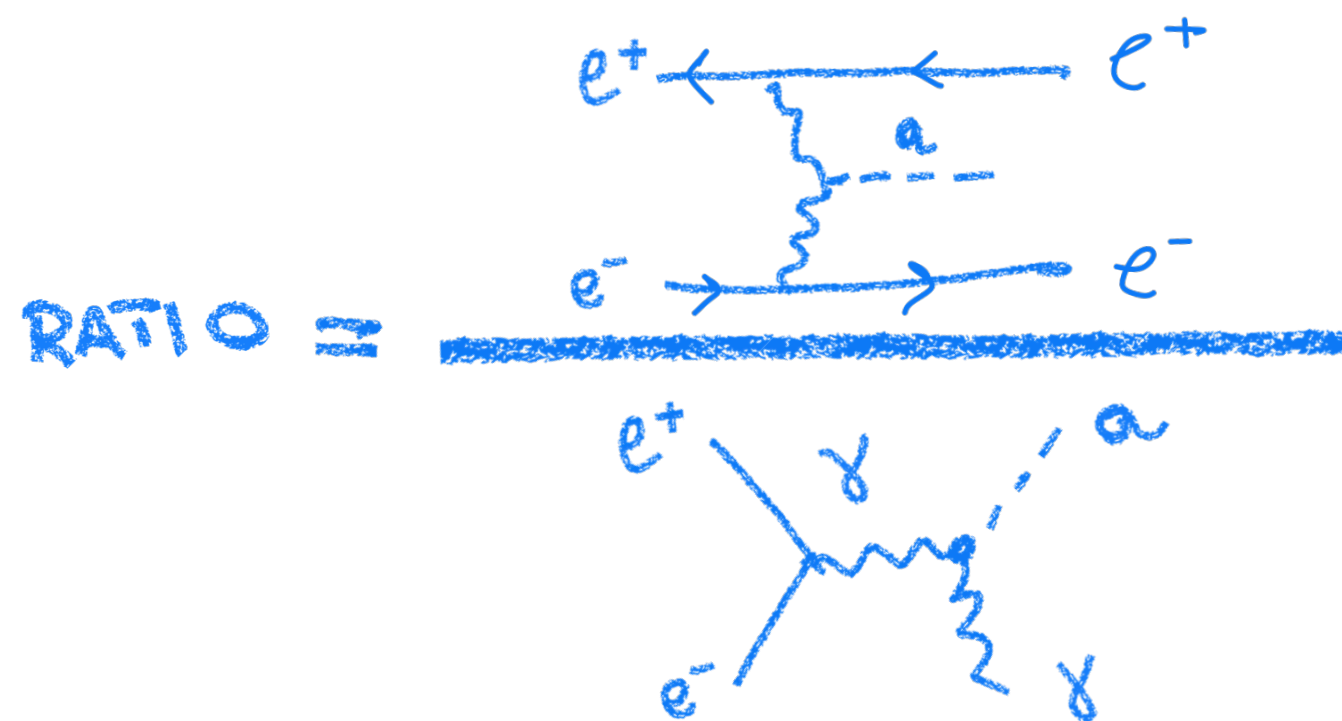
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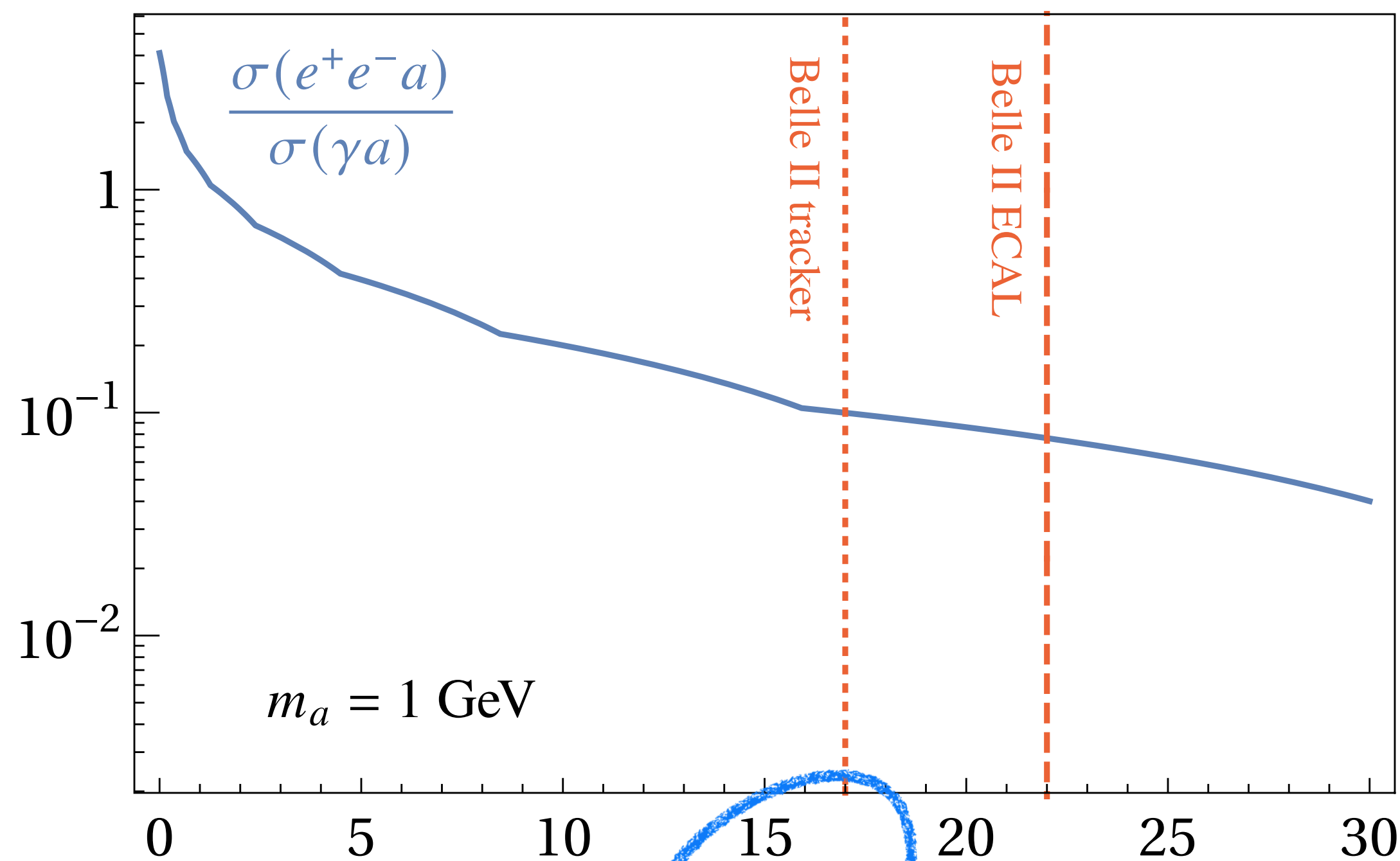
FWD TAGGER  $\theta_{\min}^* [^\circ]$  COVERAGE



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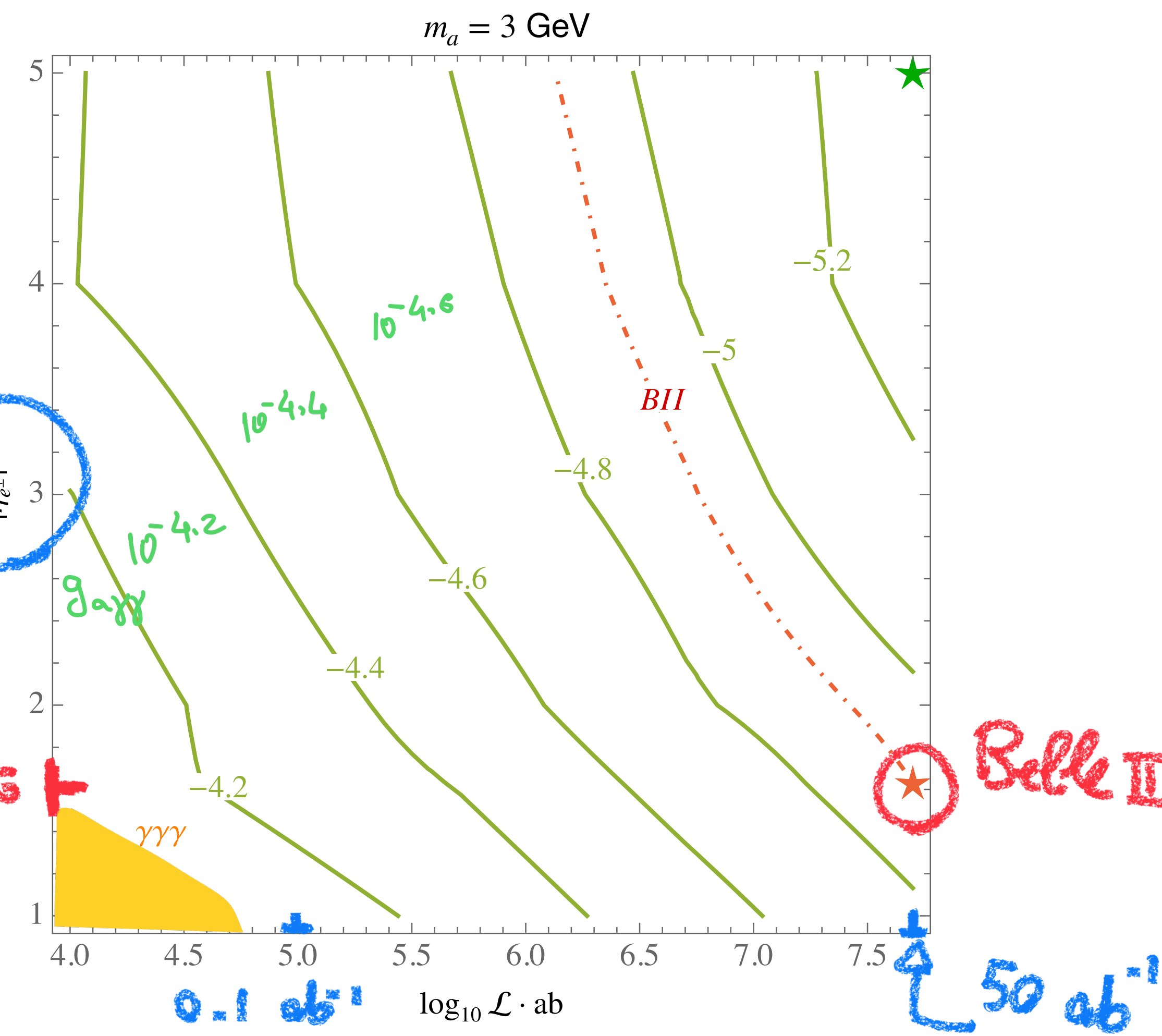


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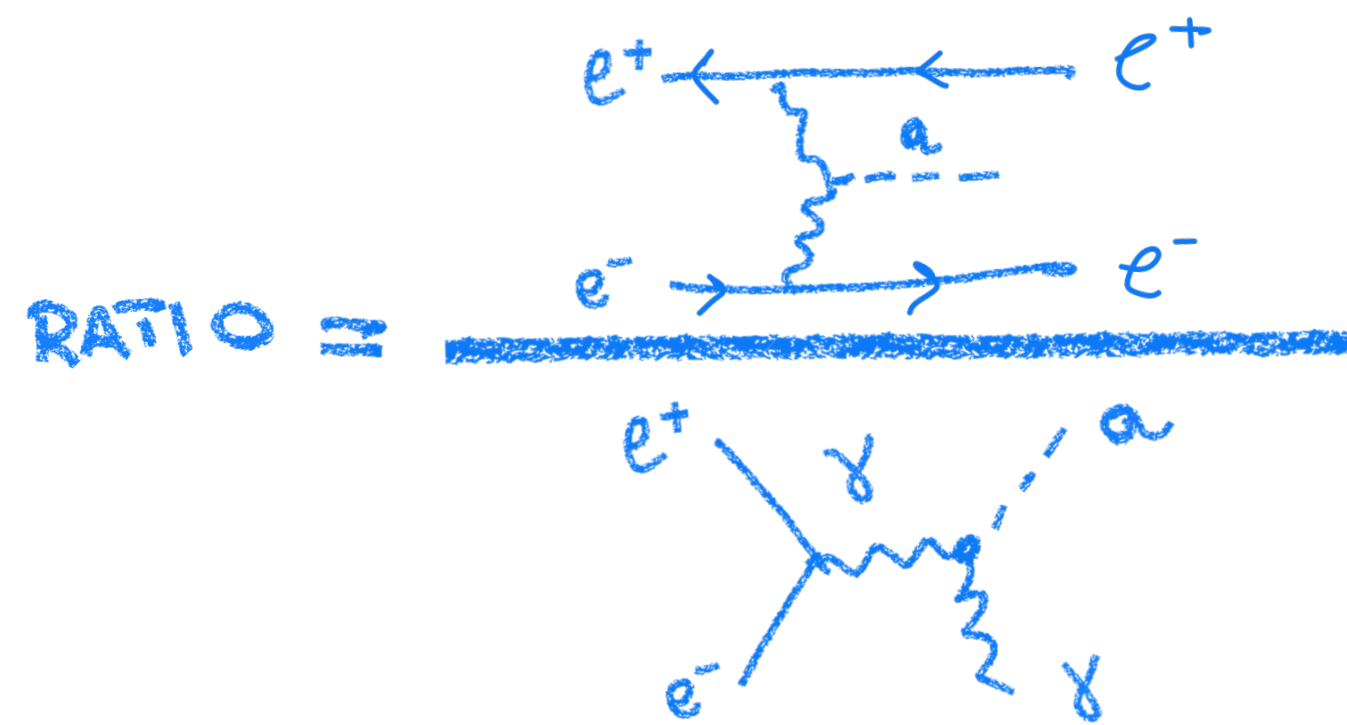
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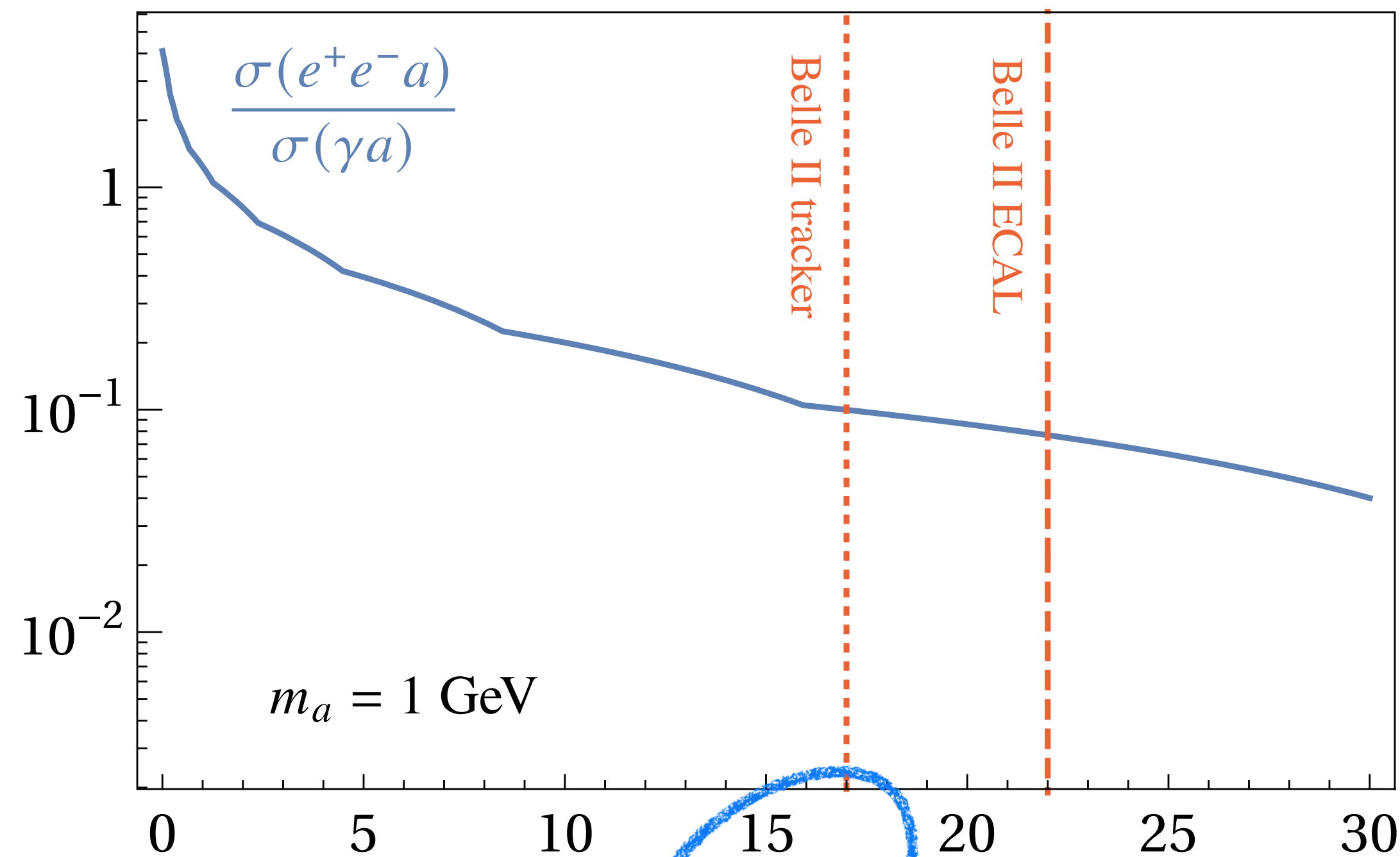


Improvement over the "standard"  $3\gamma$  search possible for a wide choice of acceptance angle vs. luminosity choices

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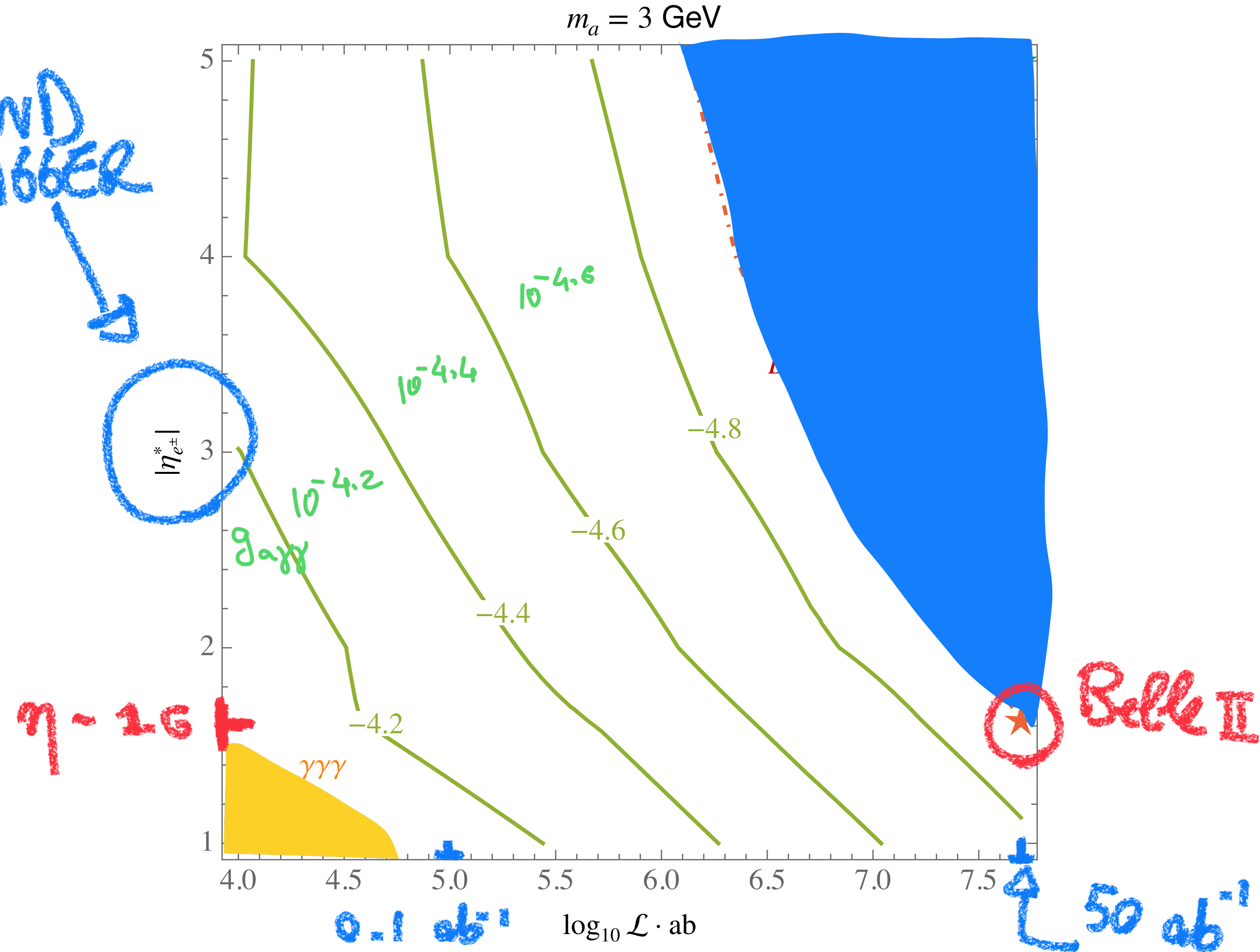


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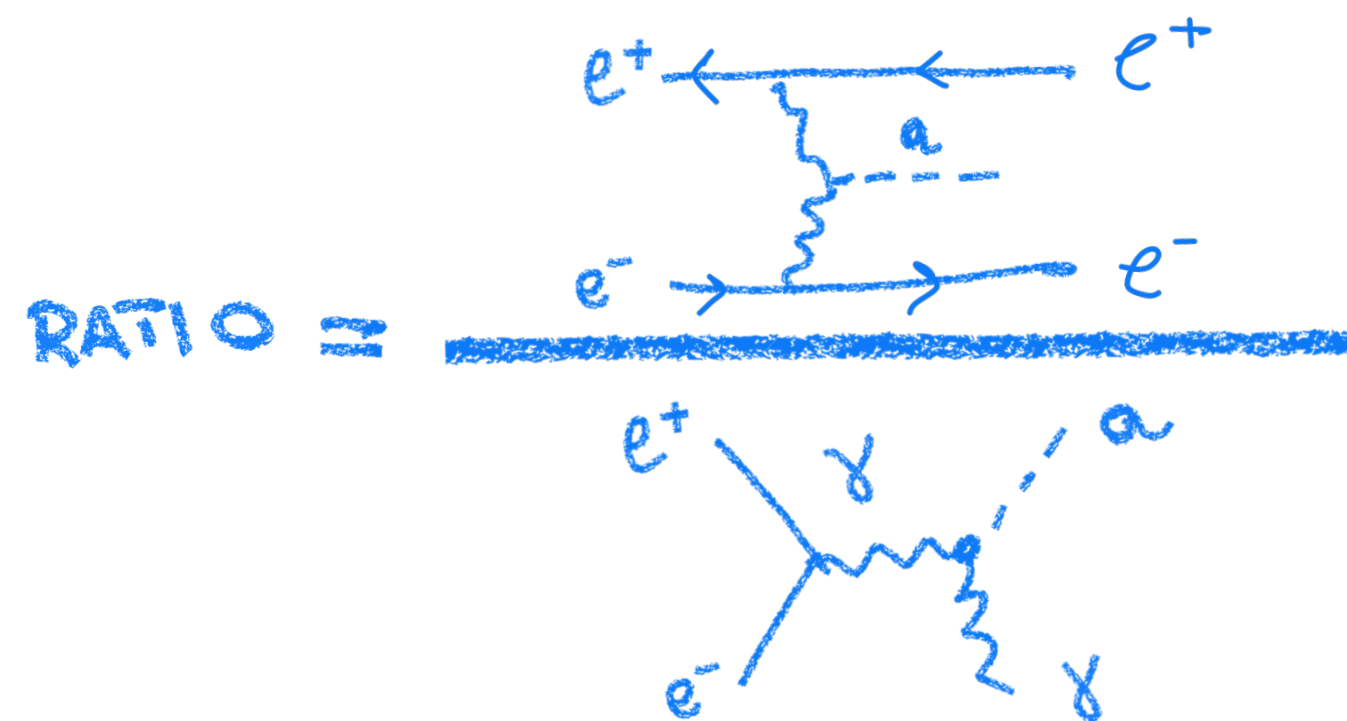
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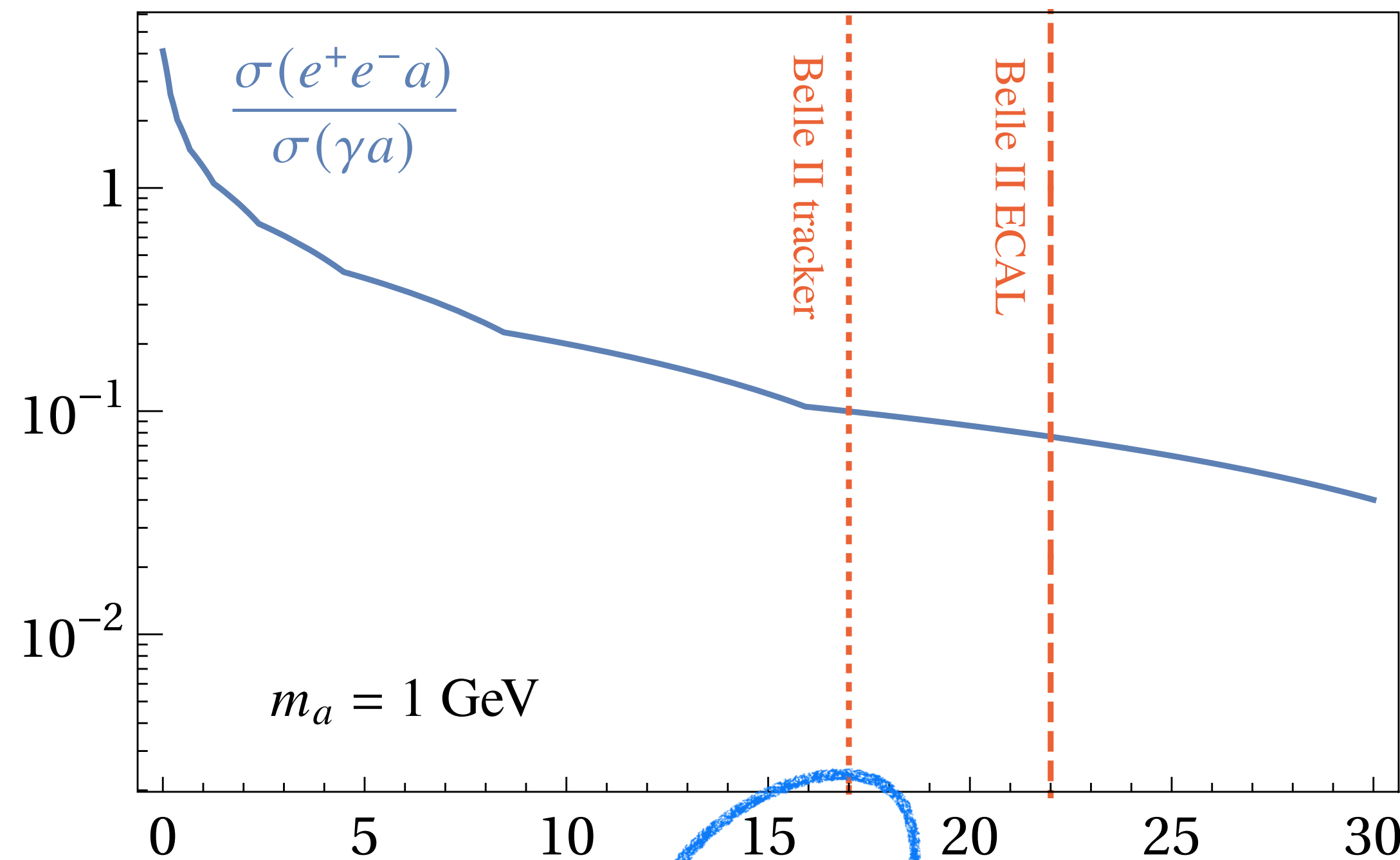


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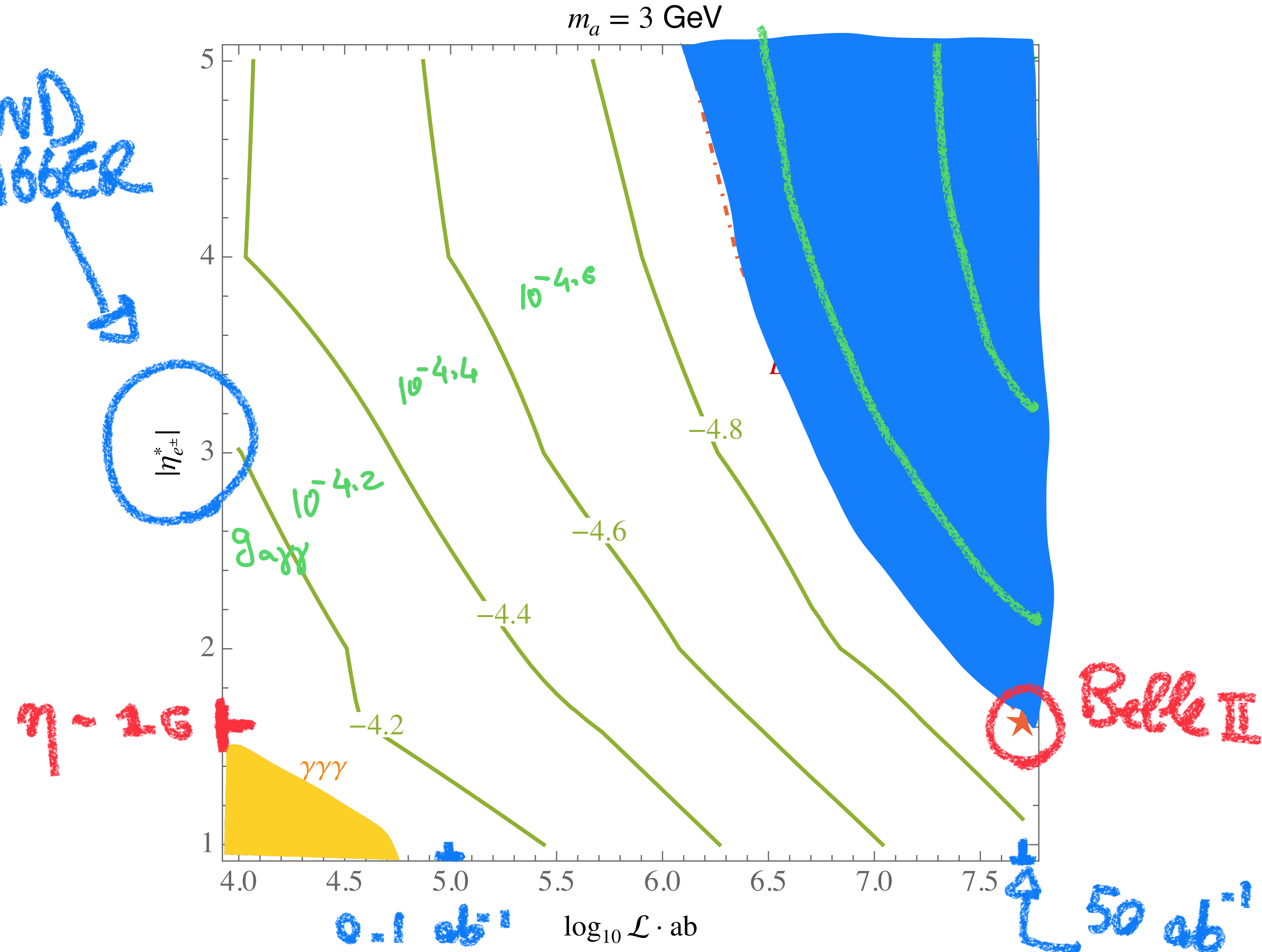


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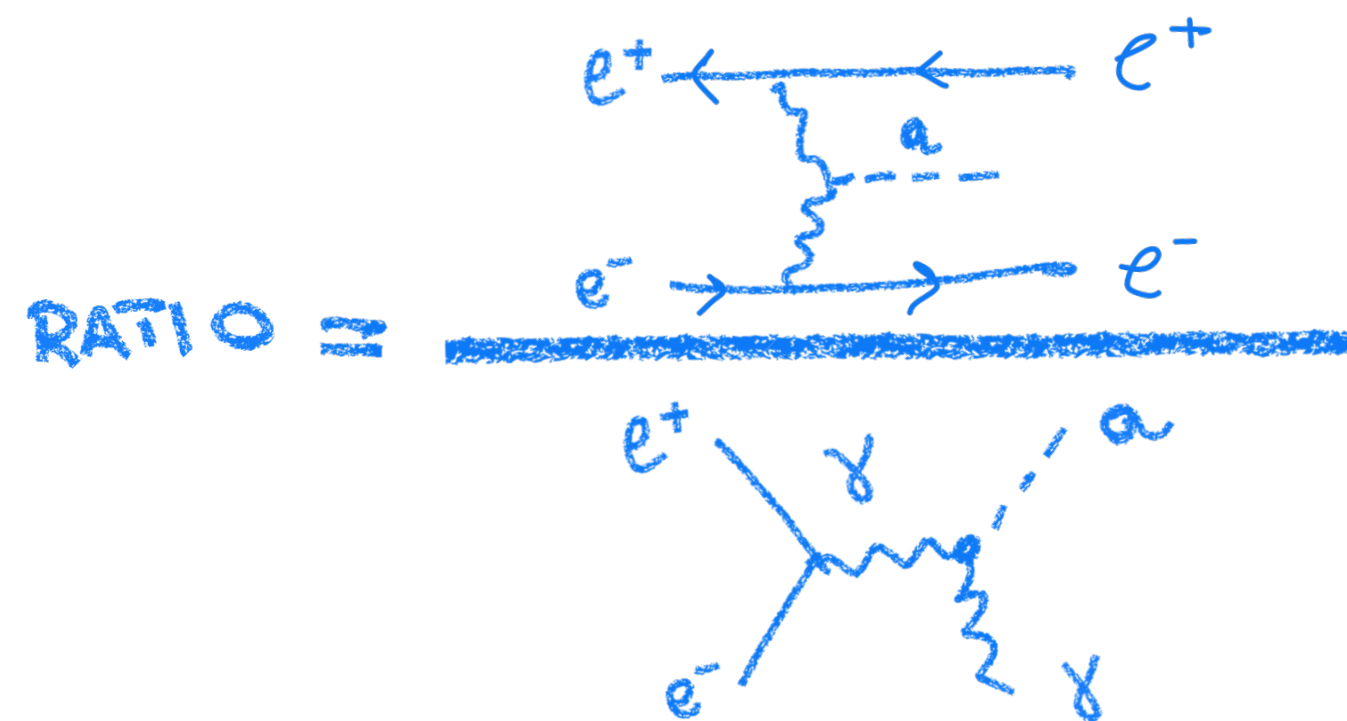
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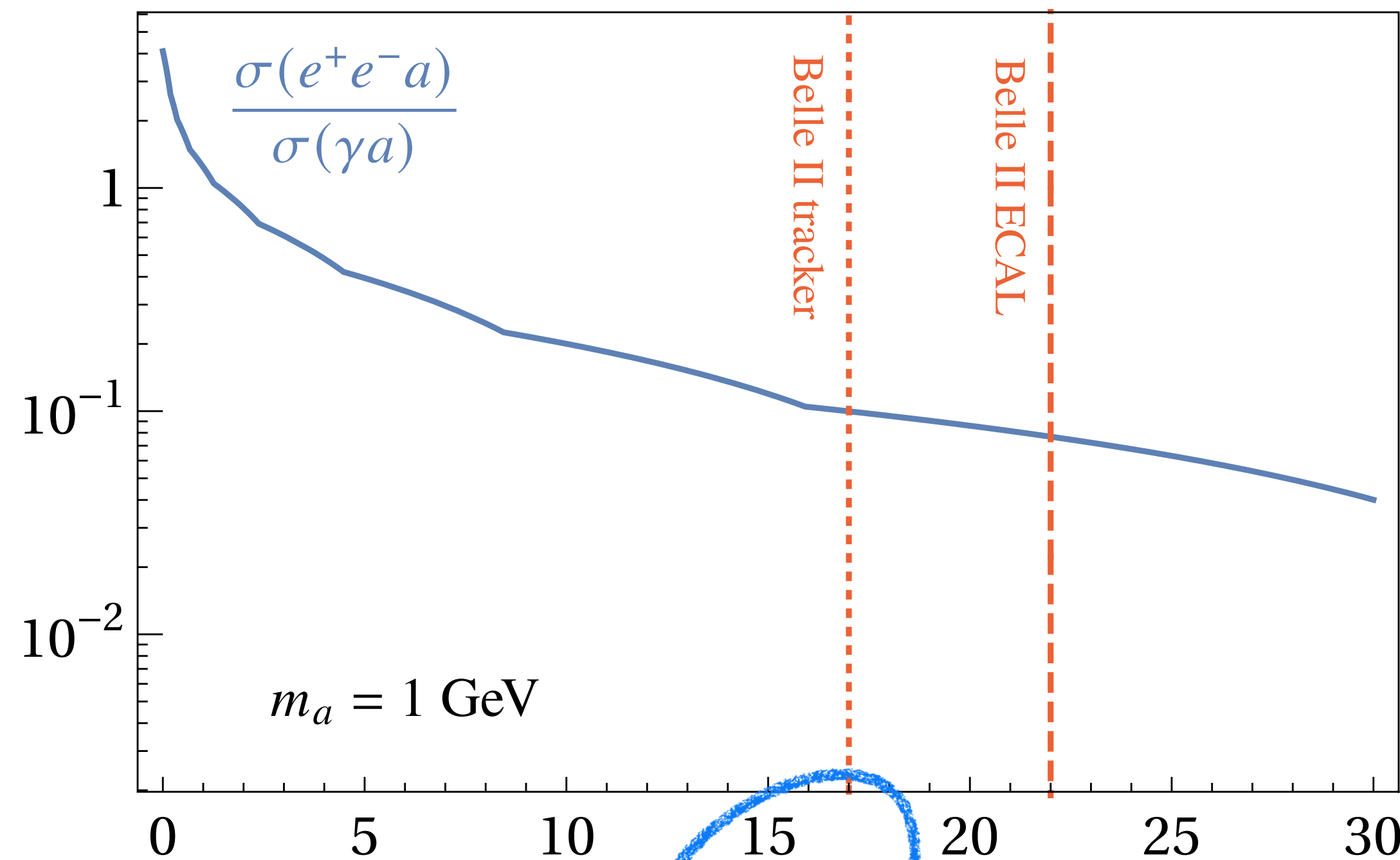


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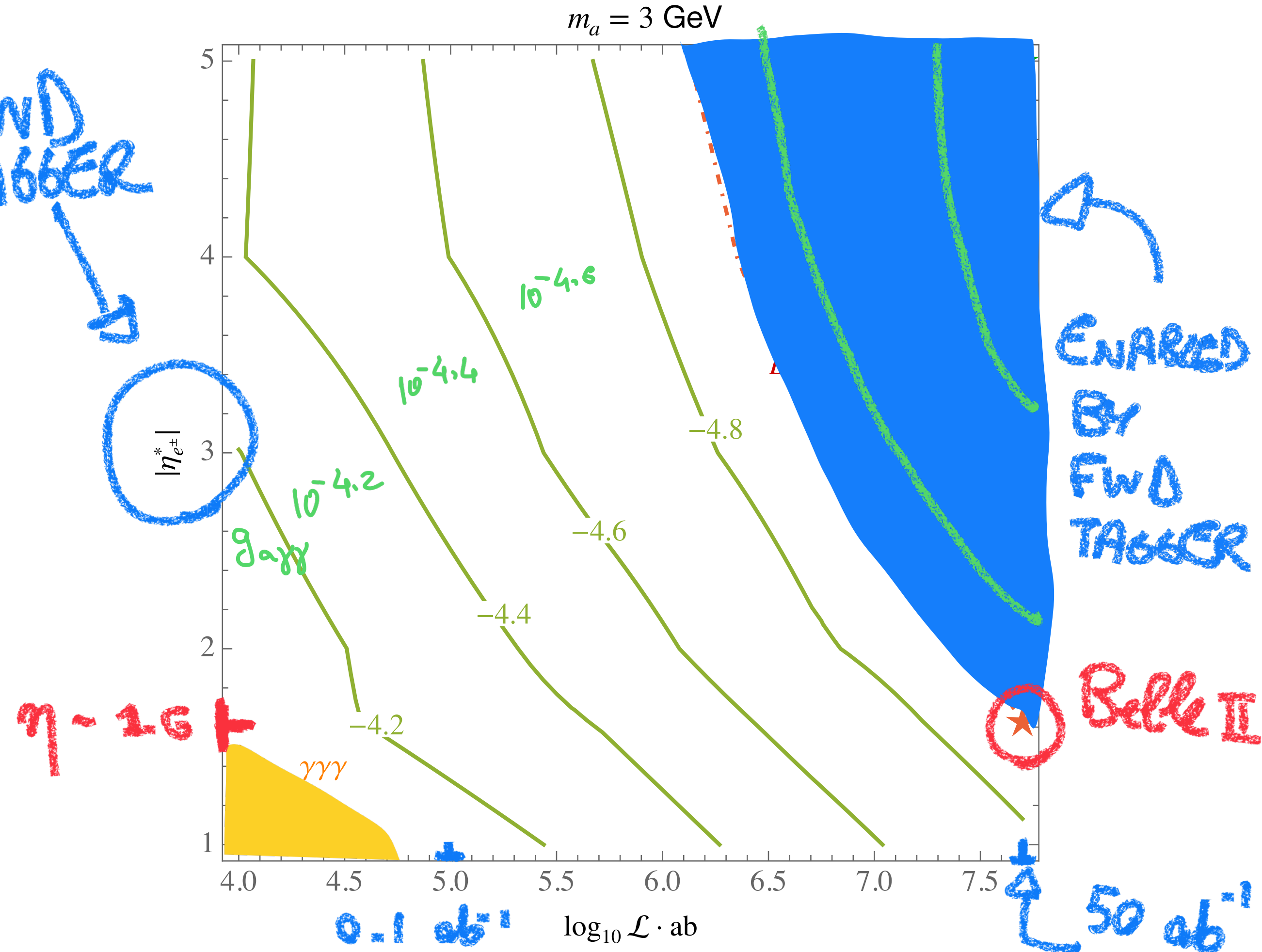


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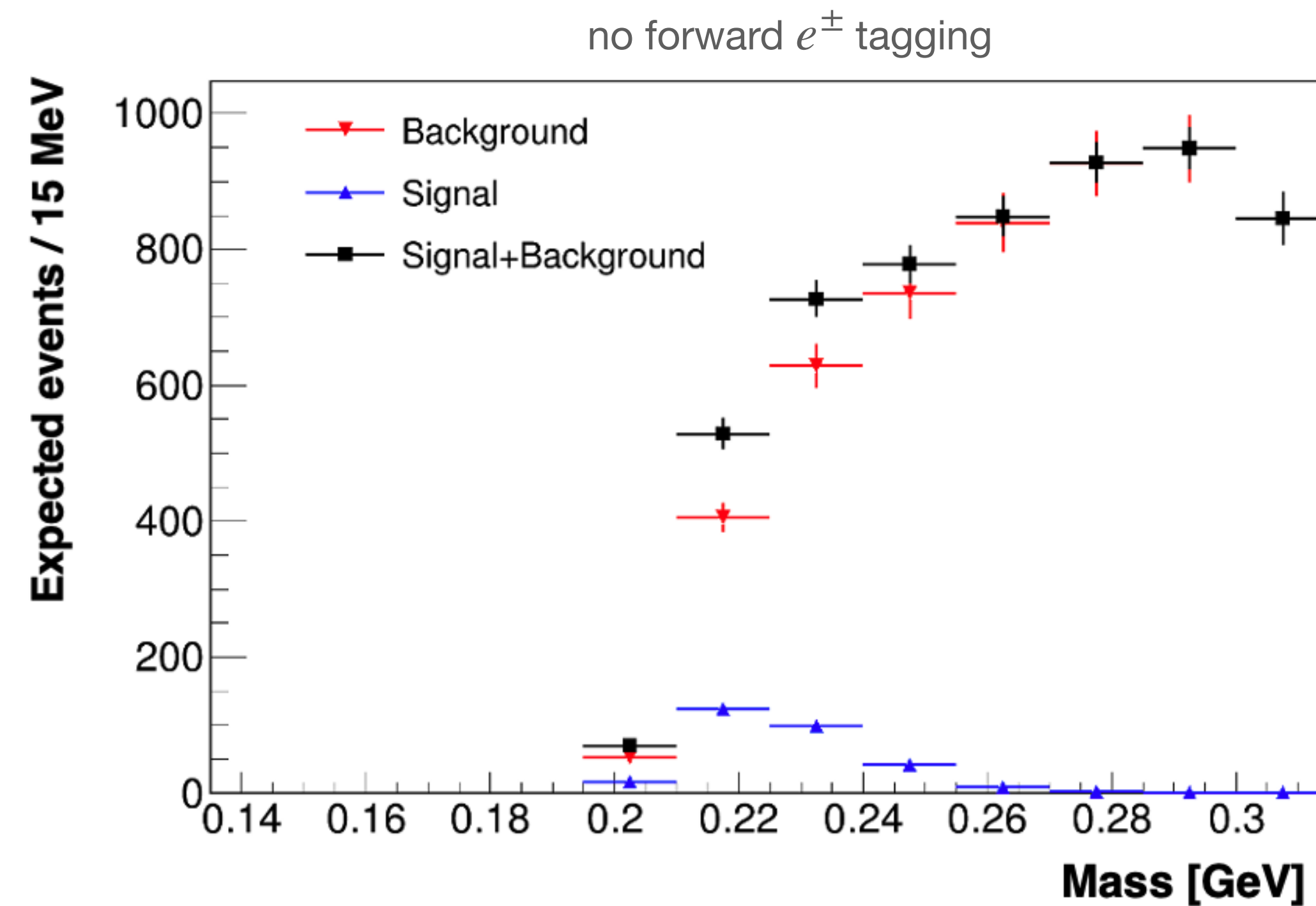
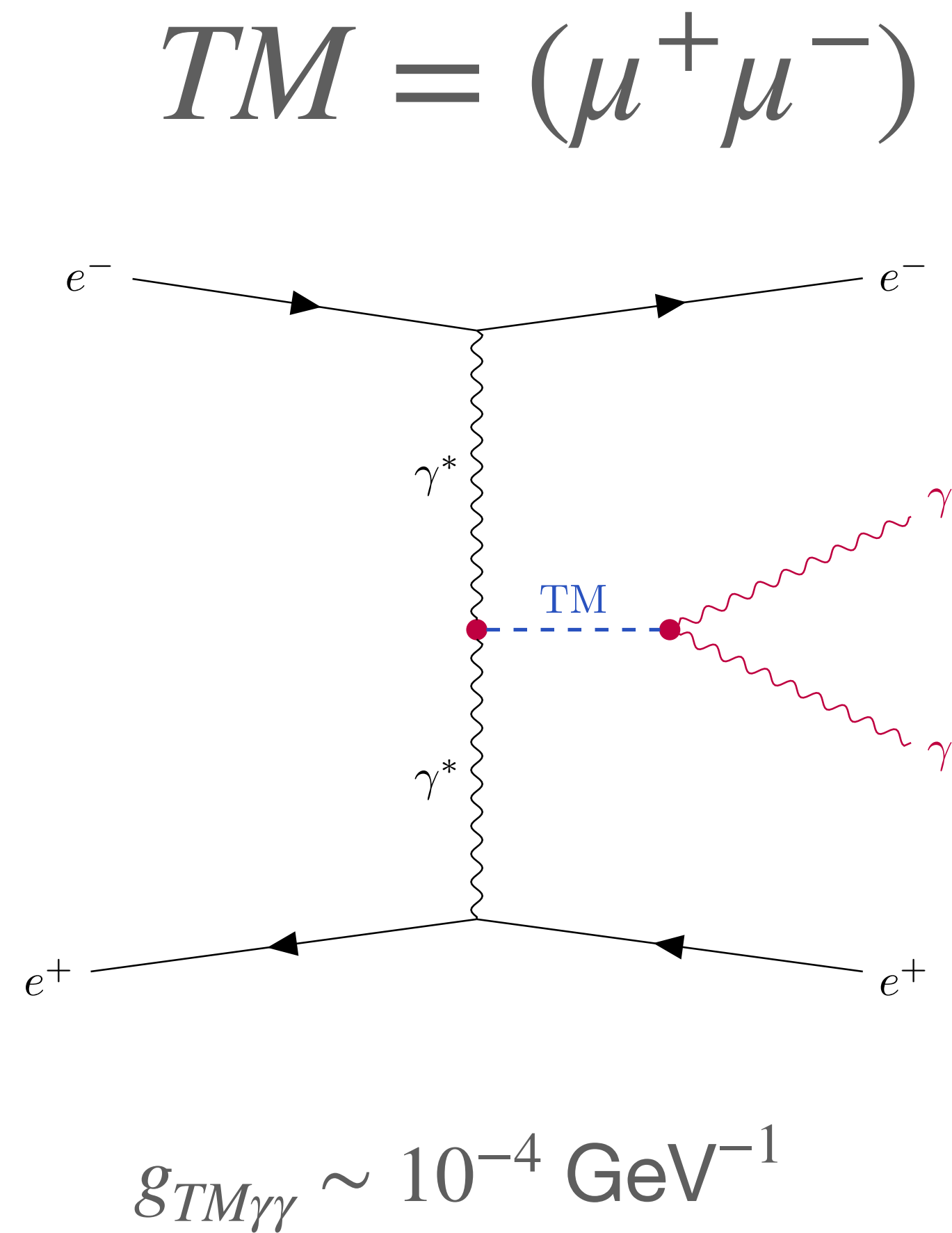
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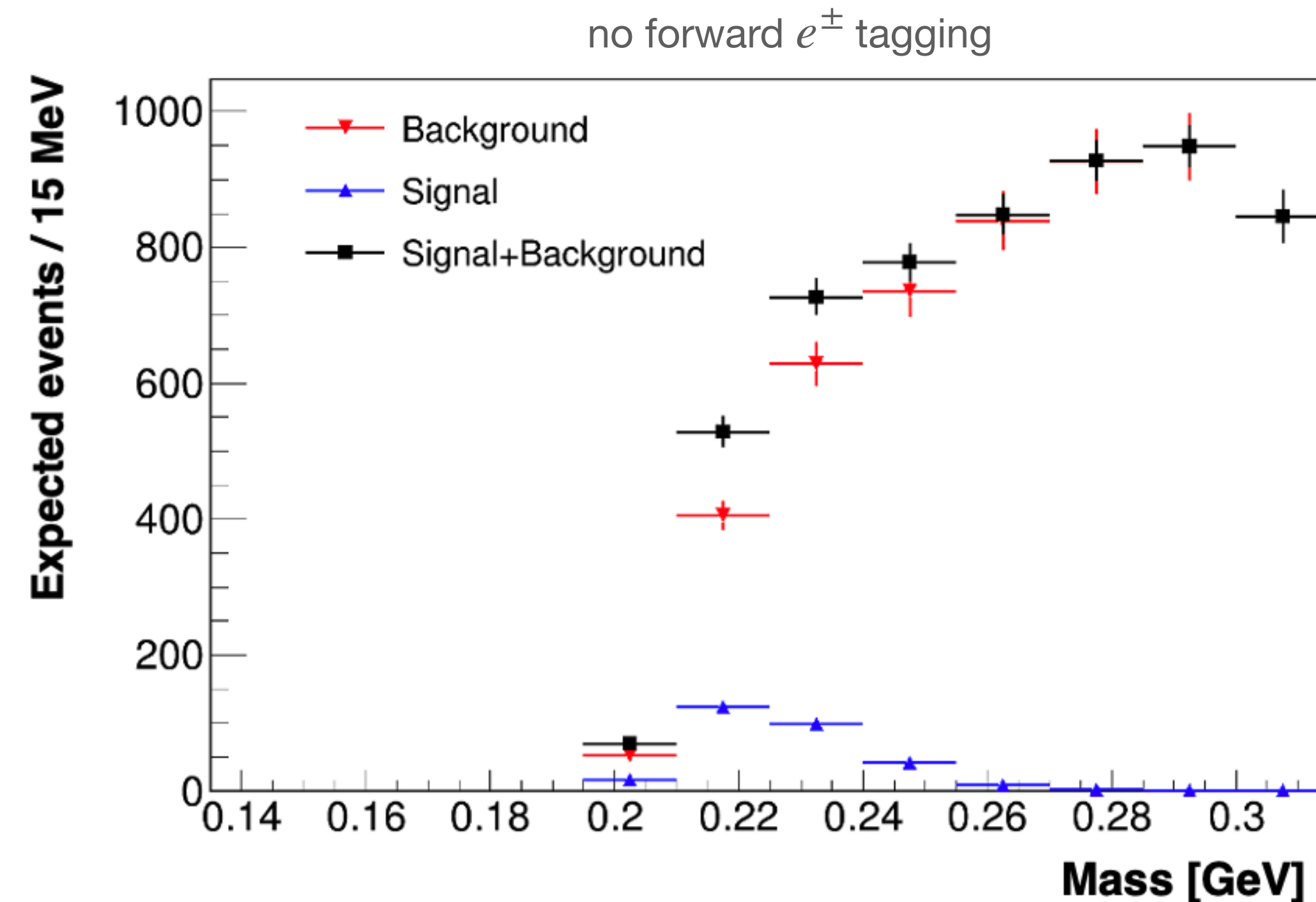
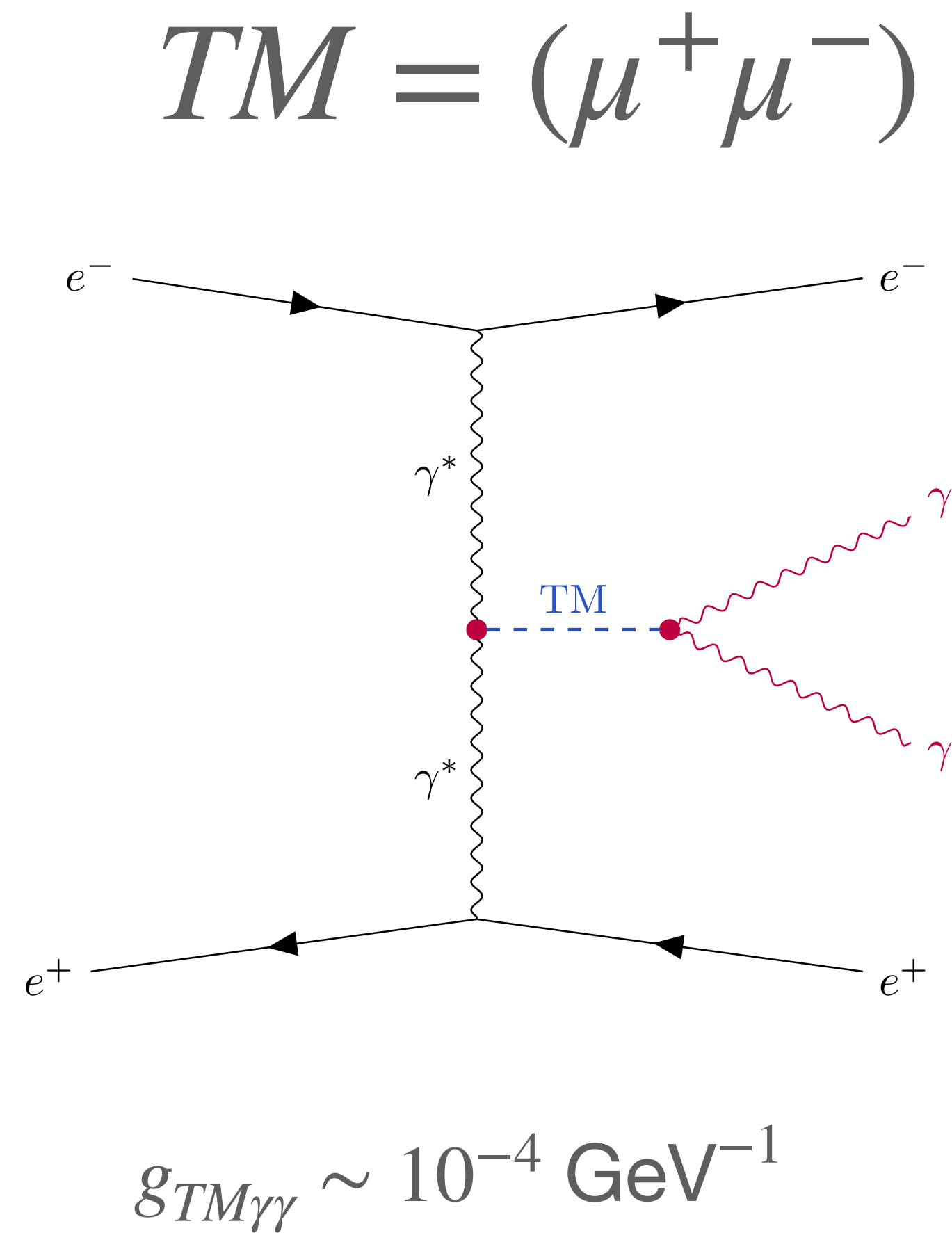
# A SM target: true muonium

2501.17753 - Gargiulo, Ruben and Di Meco, Elisa and Palmisano, Stefano - Feasibility of true muonium observation in Belle-II existing dataset



# A SM target: true muonium

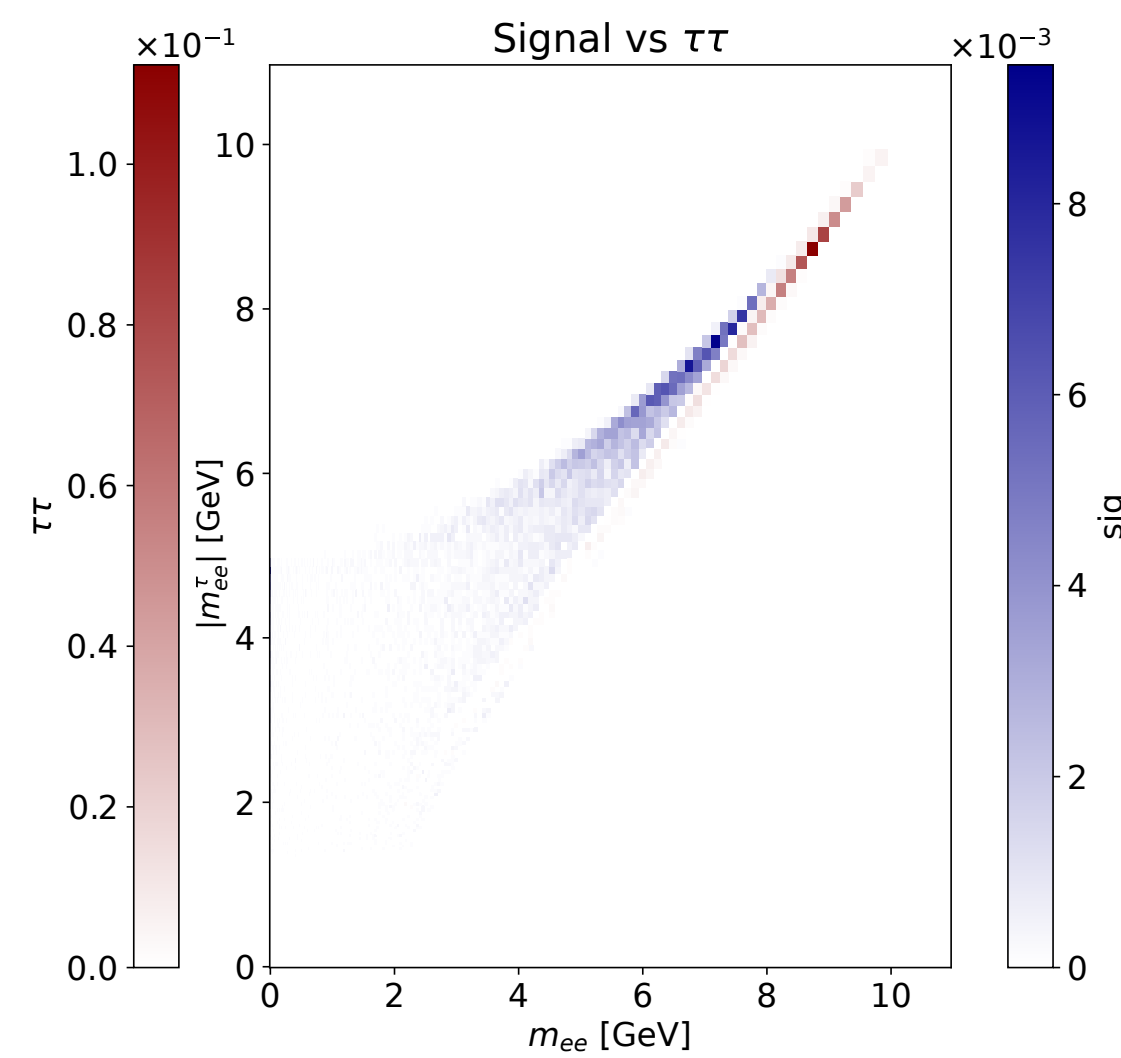
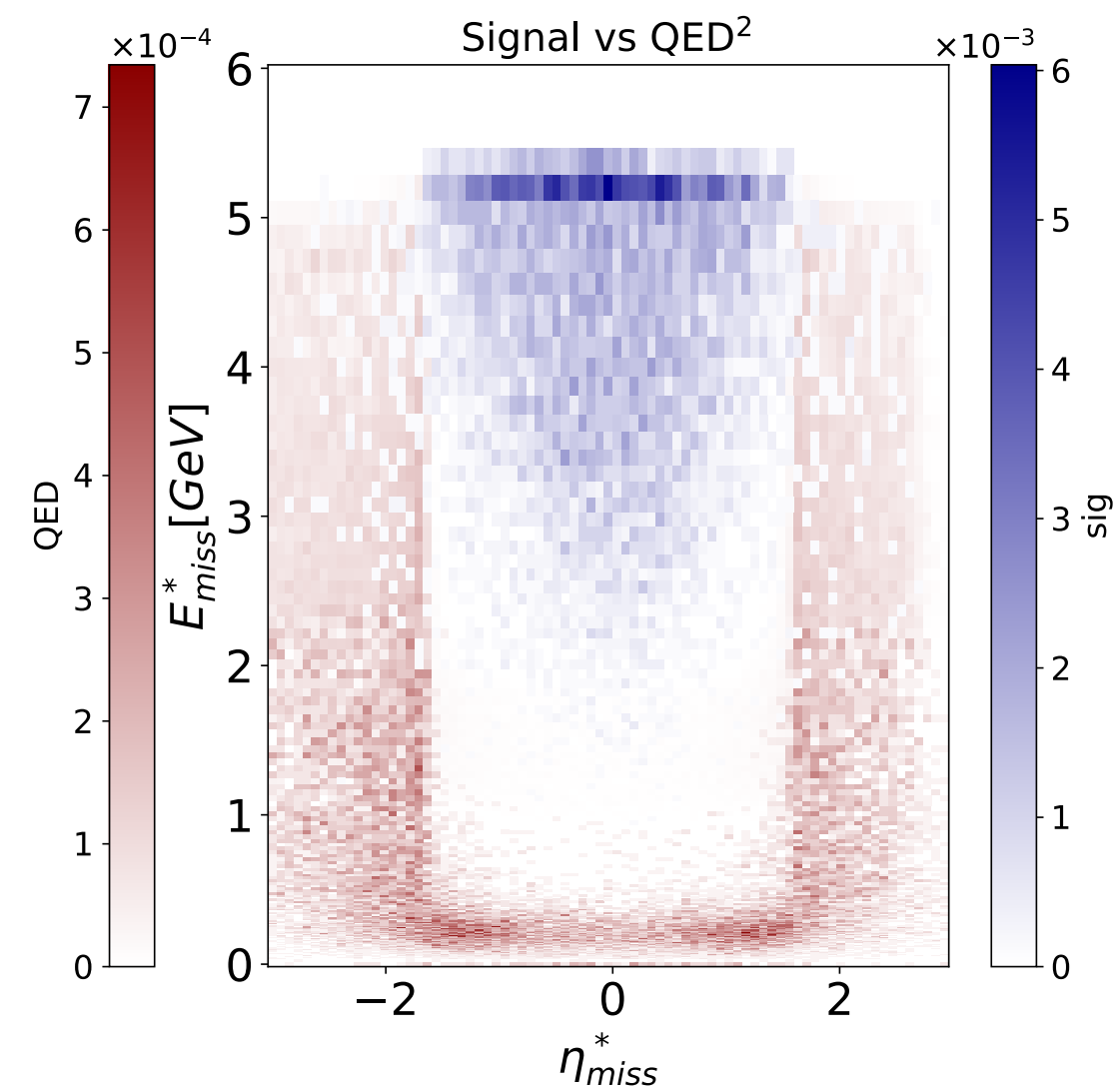
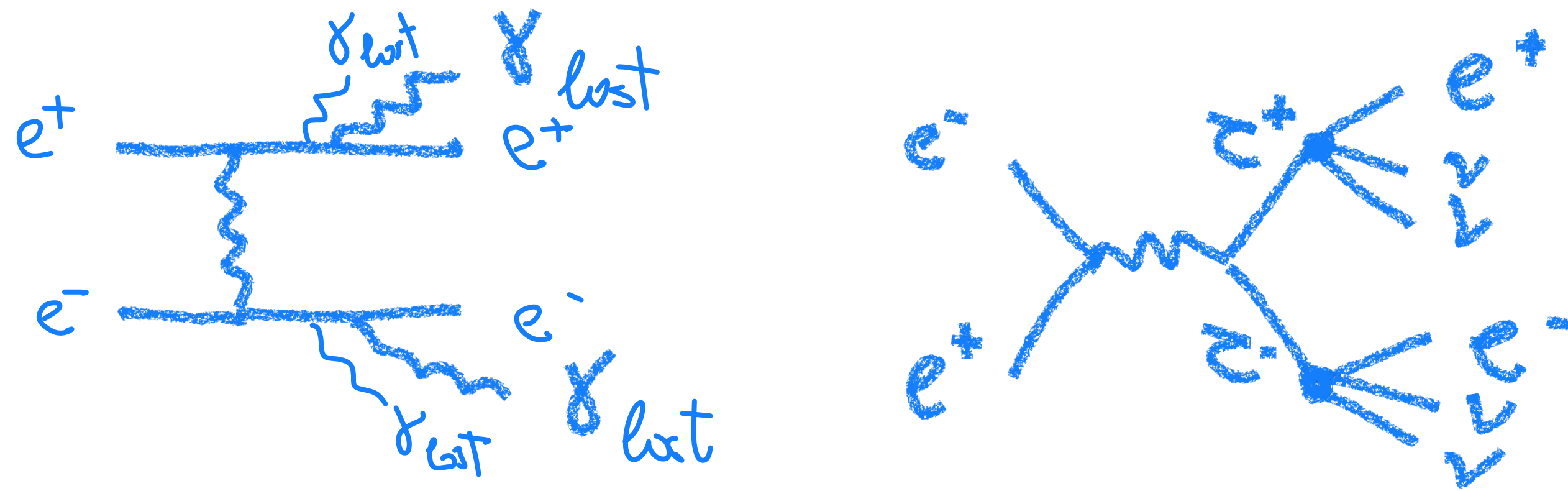
2501.17753 - Gargiulo, Ruben and Di Meco, Elisa and Palmisano, Stefano - Feasibility of true muonium observation in Belle-II existing dataset



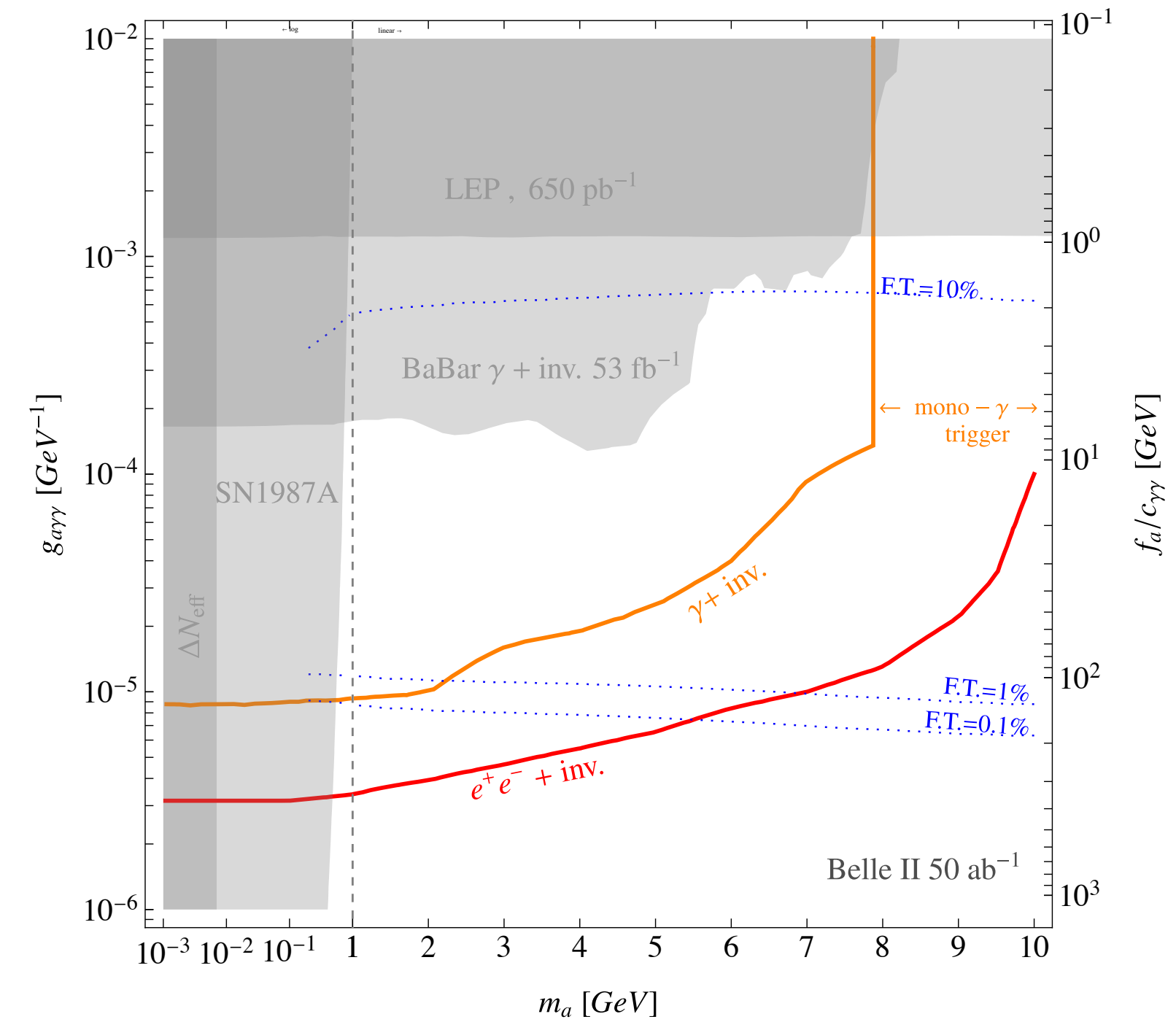
subject to improvements with forward  $e^\pm$  tagging

# Another BSM target: $a \rightarrow$ dark matter

2307.06369 - Acanfora, Francesca and Franceschini, Roberto and Mastroddi, Alessio and Redigolo, Diego - Fusing photons into nothing, a new search for invisible ALPs and Dark Matter at Belle II

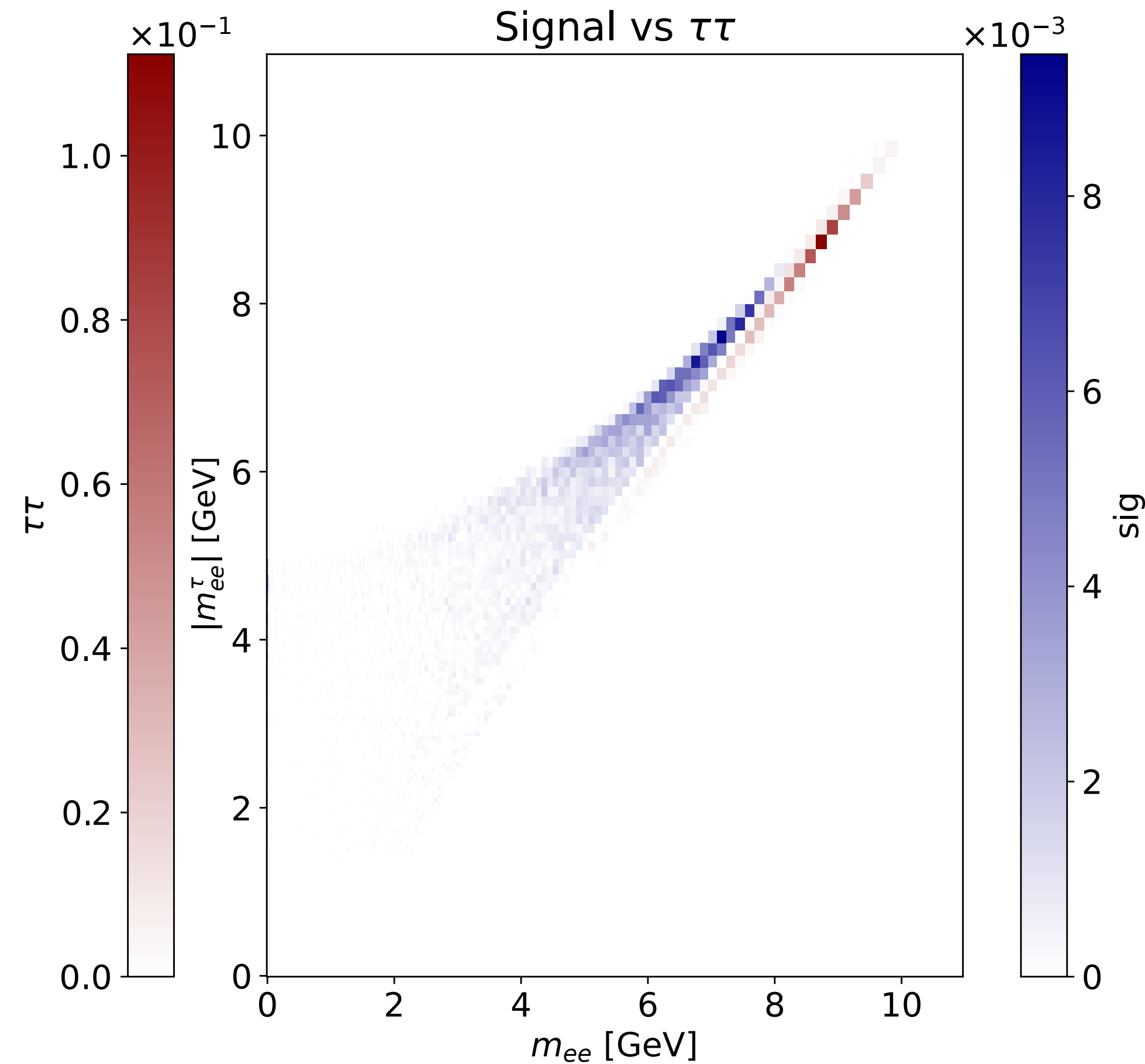


no forward  $e^\pm$  tagging  
 $\theta_{\min}^* = 22^\circ$ ,  $E_{\min}^* = 0.25$  GeV,  
 benefit from forward  $e^\pm$  tagging to be studied closely



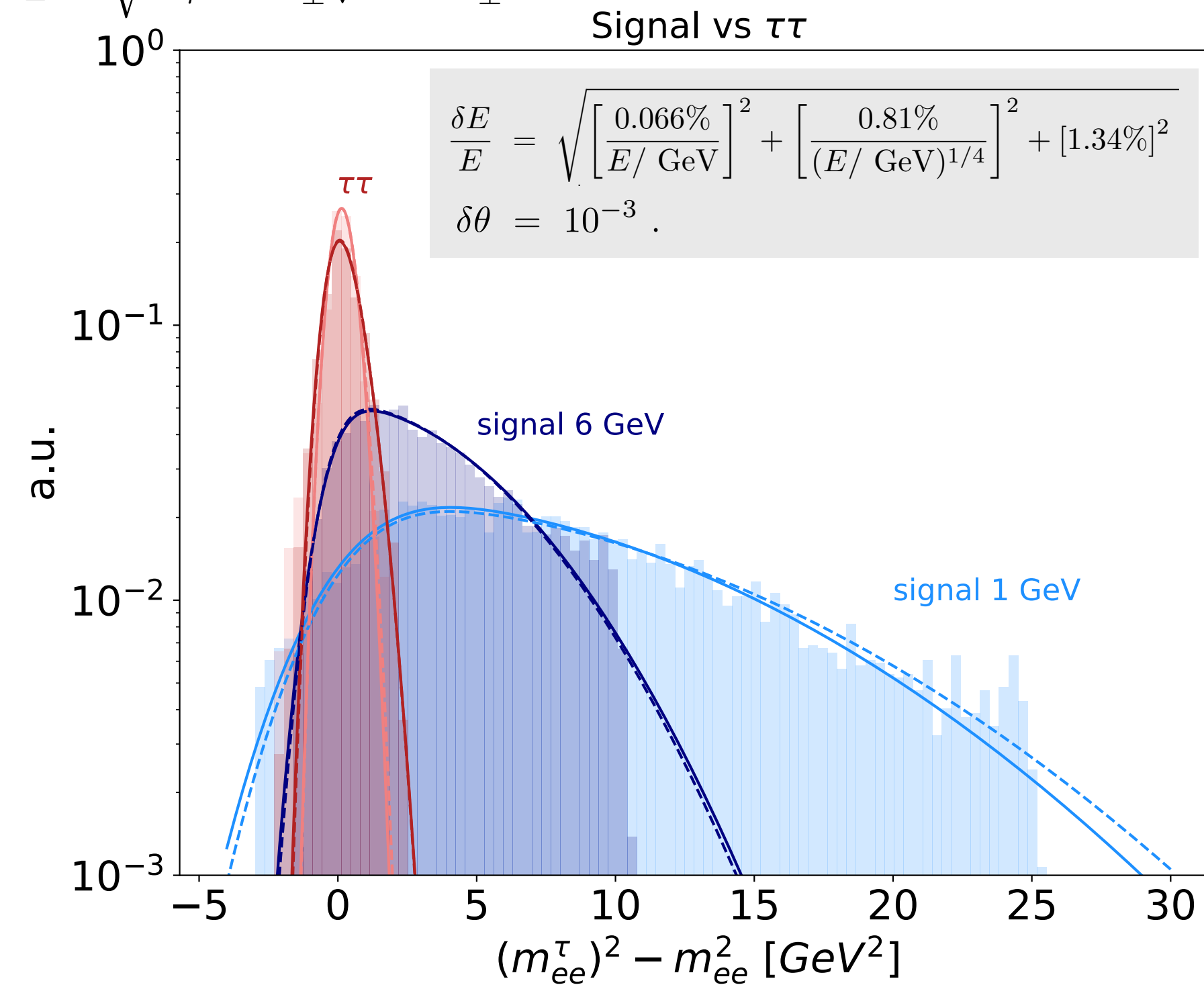
# Another BSM target: dark matter

2307.06369 - Acanfora, Francesca and Franceschini, Roberto and Mastroddi, Alessio and Redigolo, Diego - Fusing photons into nothing, a new search for invisible ALPs and Dark Matter at Belle II



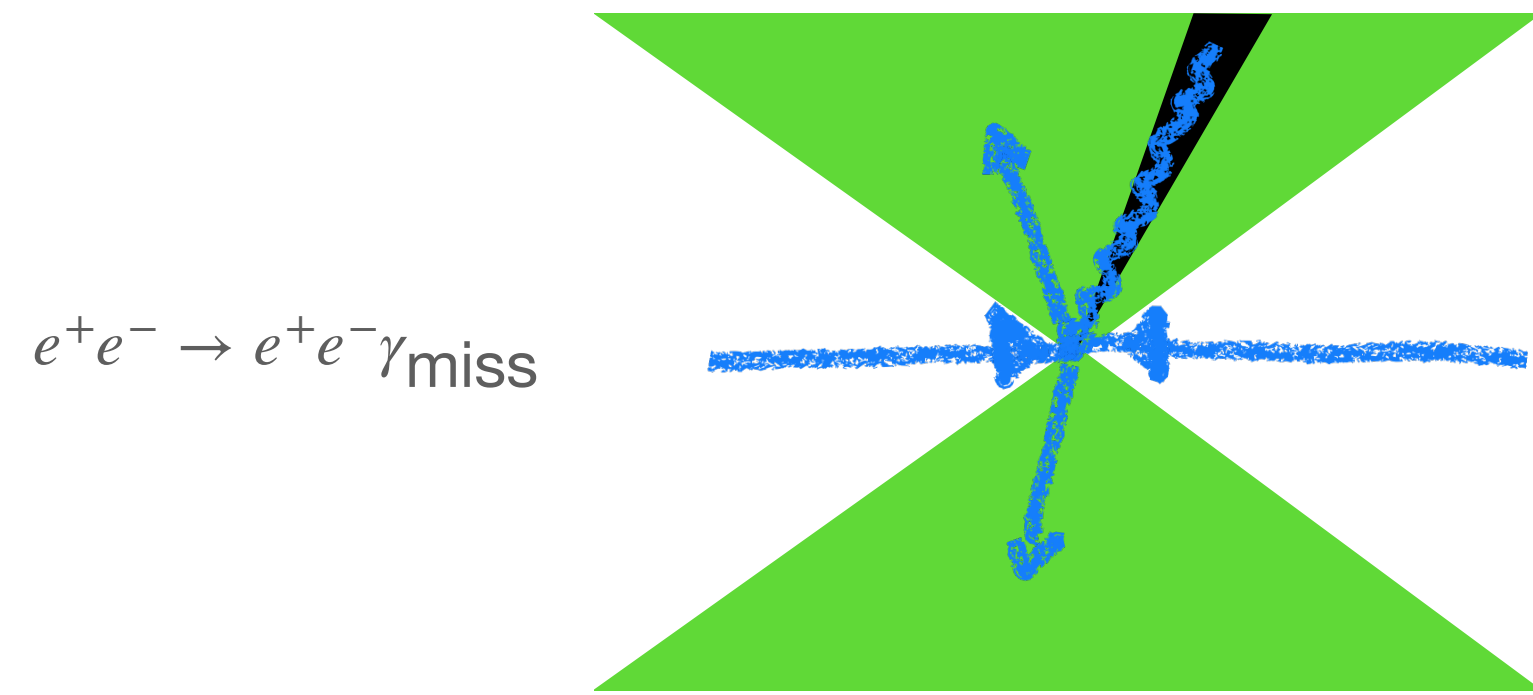
$$(m_{ee}^\tau)^2 = \frac{2}{s - 4m_\tau^2} \left[ m_\tau^4 - \sqrt{s} m_\tau^2 (E_+^* + E_-^*) + 2E_-^* E_+^* (s - 2m_\tau^2) + m_\tau^2 c_\phi \mathcal{M}_- \mathcal{M}_+ \right],$$

$$\mathcal{M}_\pm = \sqrt{m_\tau^2 - 2E_\pm^* \sqrt{s} + 4E_\pm^{*2}}.$$



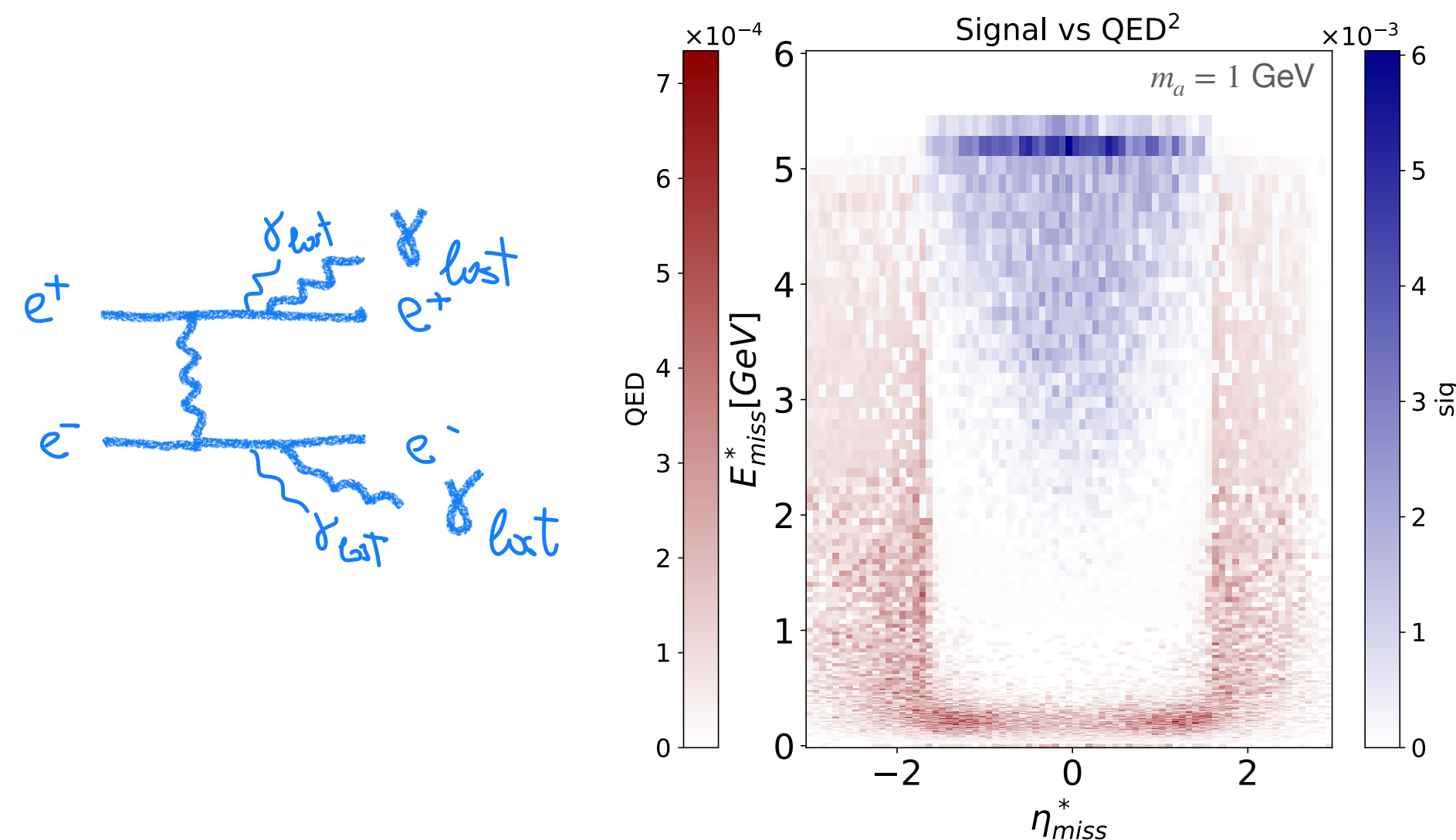
# Another BSM target: dark matter

2307.06369 - Acanfora, Francesca and Franceschini, Roberto and Mastroddi, Alessio and Redigolo, Diego - Fusing photons into nothing, a new search for invisible ALPs and Dark Matter at Belle II



detector acceptance gaps needs to be mapped carefully, as backgrounds  $e^+e^- \rightarrow e^+e^-\gamma_{\text{miss}}$  come back

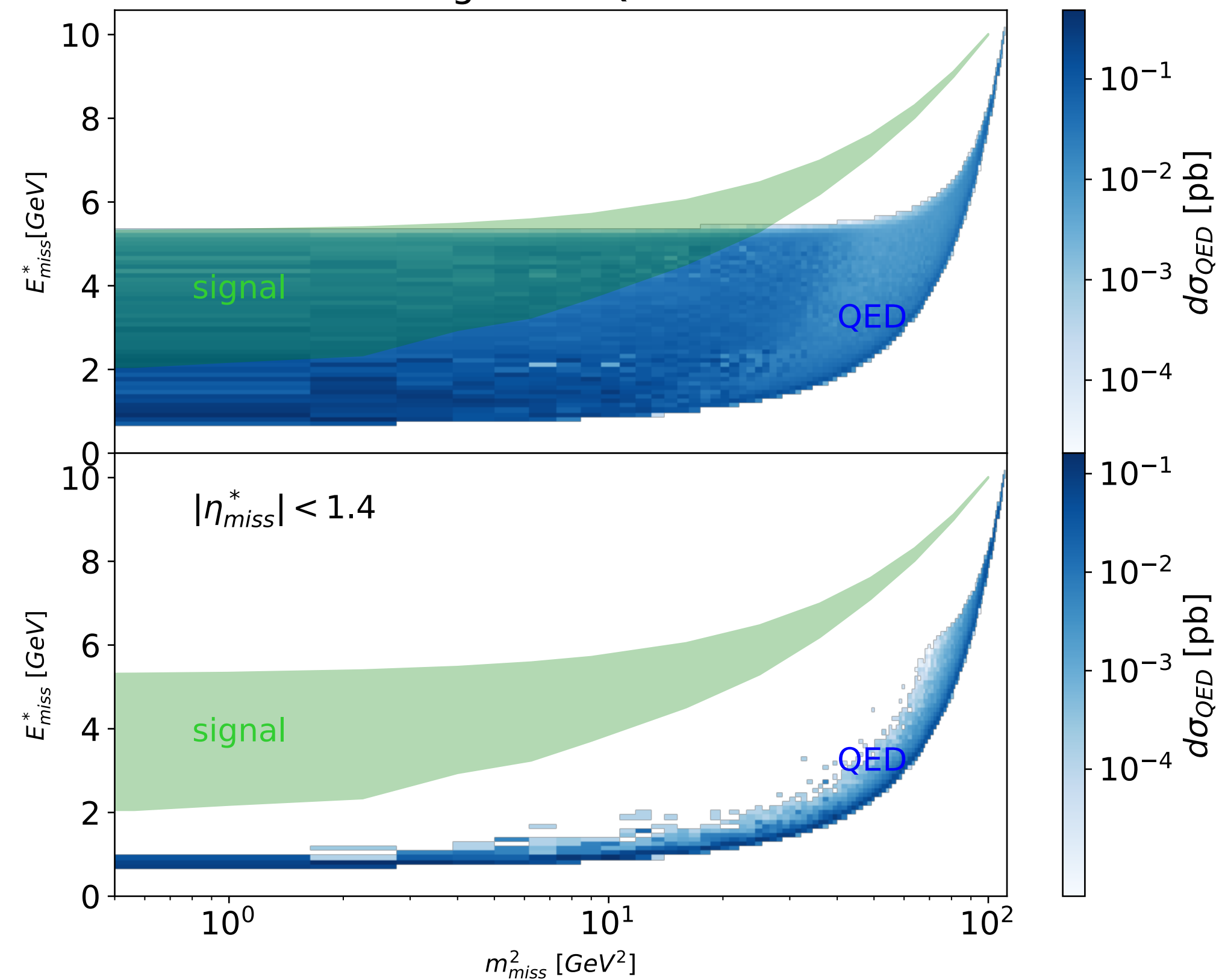
$$\delta m_{\text{miss}}^2 \simeq \left[ 1 - \left( \frac{m_{\text{miss}}}{10 \text{ GeV}} \right)^4 \right] \text{GeV}^2.$$



missing photons from Bhabha have a typical direction around the beam pipe, so they are usually nearly back-to-back

$$\Rightarrow m_{\text{miss}} \simeq 2E_{\gamma_{\text{miss}}} \simeq E_{\text{miss}}$$

Signal vs QED<sup>2</sup>



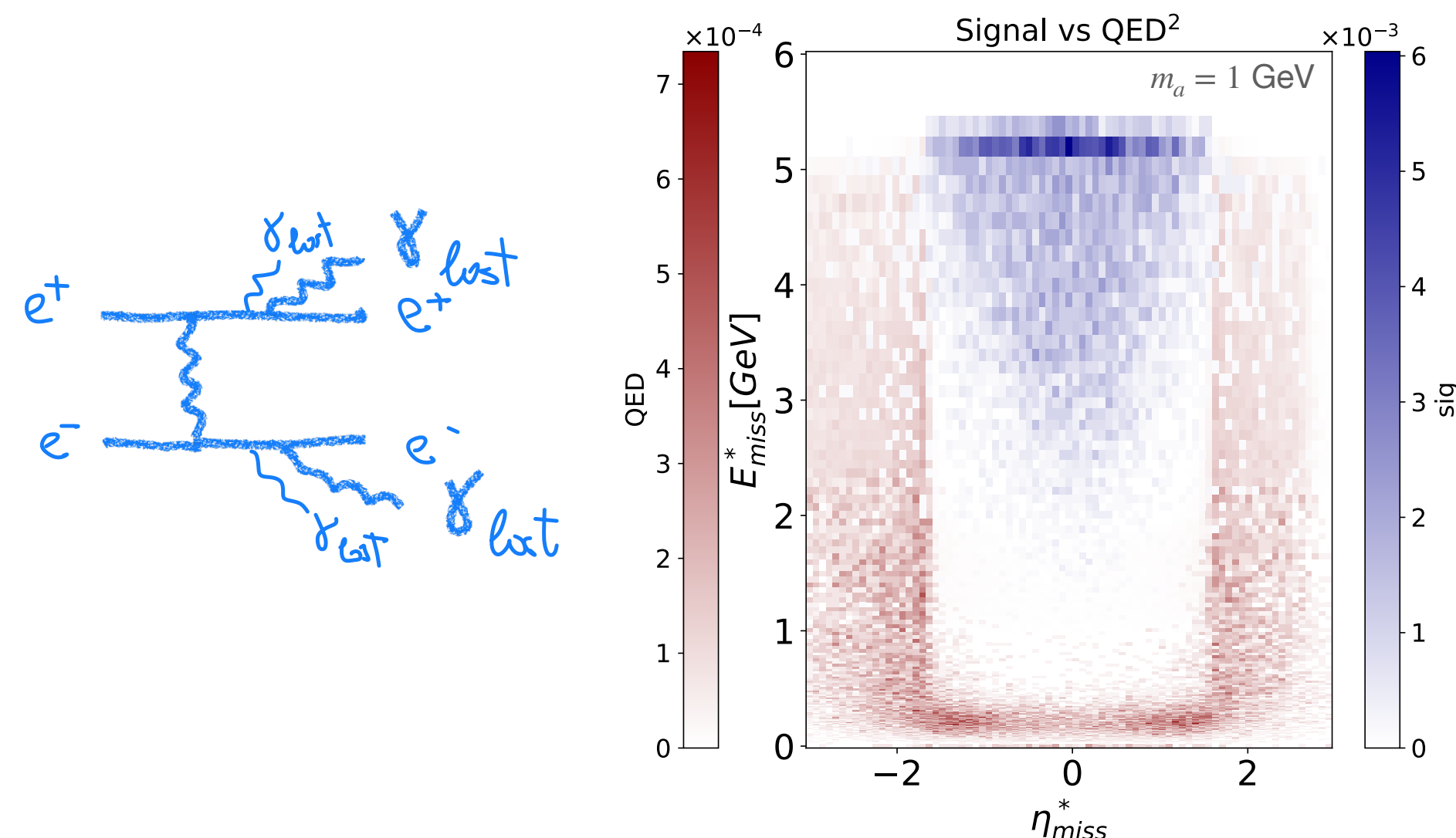
# Another BSM target: dark matter

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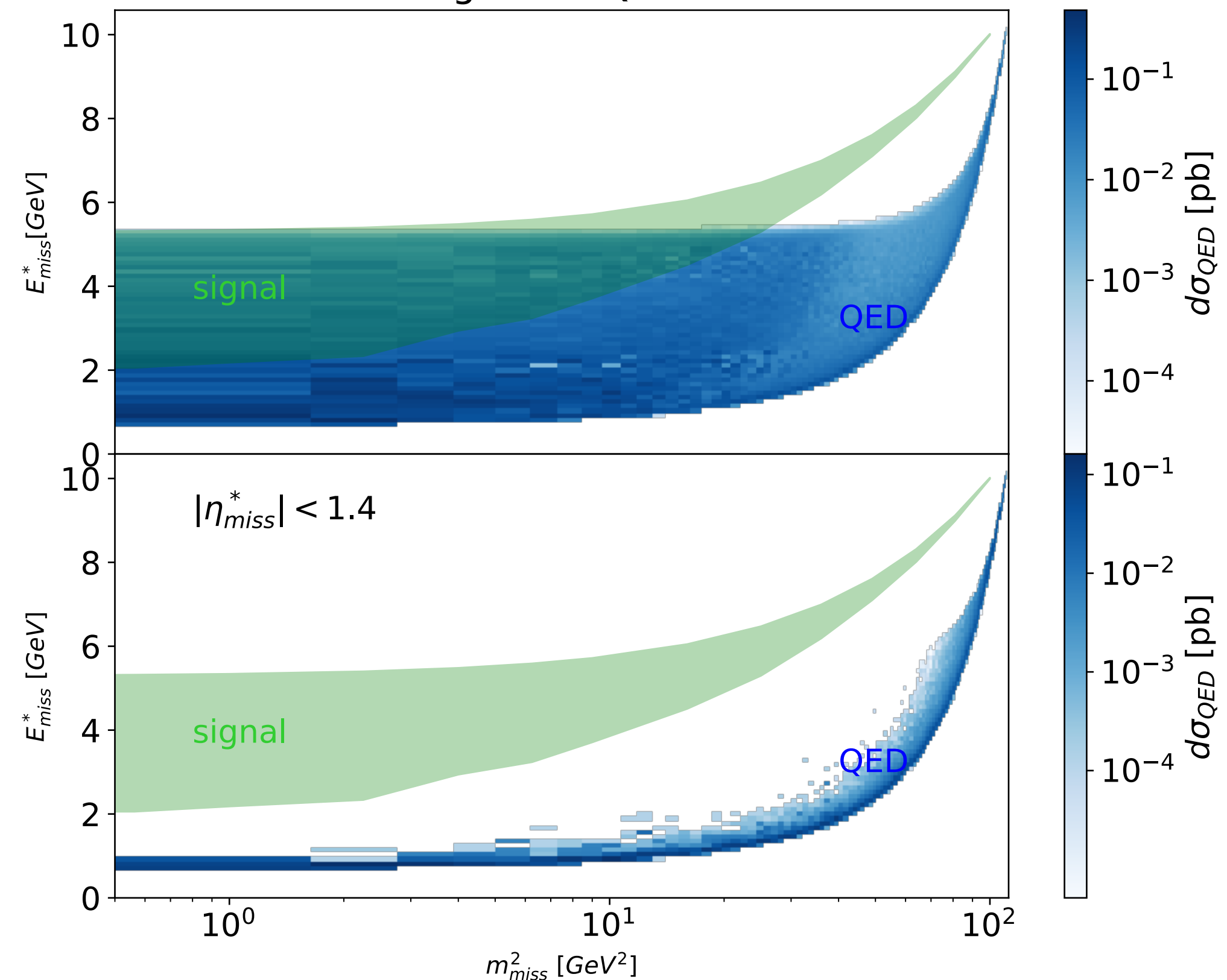
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Signal vs QED<sup>2</sup>



# Once upon a time physics was all forward ...

## A SEARCH FOR NARROW RESONANCES IN PROTON-PROTON COLLISIONS AT 53 GeV CENTRE-OF-MASS ENERGY

M.G. ALBROW, B. ALPER, J. ARMITAGE, D. ASTON, P. BENZ, G.J. BOBBINK, B. BOŠNJAKOVIĆ<sup>1)</sup>, A.G. CLARK, F.C. ERNE, W.M. EVANS, C.N.P. GEE, E.S. GROVES<sup>2)</sup>, L.E. HOLLOWAY<sup>3)</sup>, J.N. JACKSON, G. JARLSKOG, H. JENSEN, P. KOOIJMAN, D. KORDER, F.K. LOEBINGER, A.A. MACBETH, N.A. McCUBBIN, H.E. MONTGOMERY, J.V. MORRIS, P.G. MURPHY, H. OGREN<sup>4)</sup>, R.J. OTT, D. RADOJICIC<sup>5)</sup>, S. ROCK, A. RUDGE, J.C. SENS, A.L. SESSOMS<sup>6)</sup>, J. SINGH, D. STORK, P. STROLIN<sup>7)</sup>, J. TIMMER and W.A. WENZEL<sup>2)</sup>

*CERN, Geneva, Switzerland  
Daresbury Laboratory, UK*

*Foundation for Fundamental Research on Matter (FOM), The Netherlands*

*University of Lancaster, UK*

*University of Liverpool, UK*

*University of Manchester, UK*

*Rutherford Laboratory, UK*

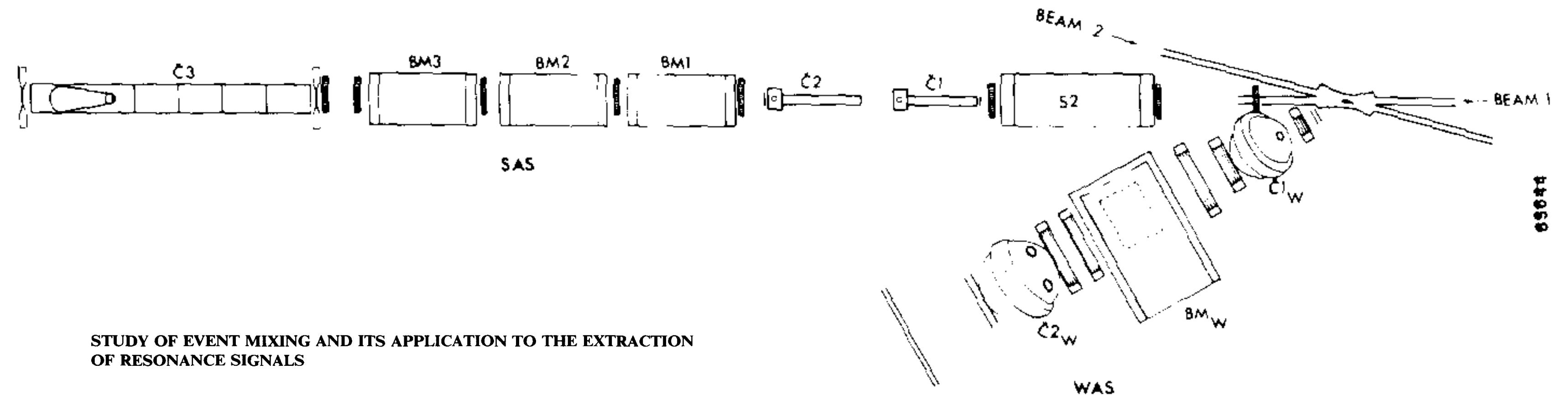
*University of Utrecht, The Netherlands*

*University of Lund, Sweden*

Received 6 July 1976

A search for narrow resonances produced in pp collisions at the CERN ISR has been carried out using two magnetic spectrometers to measure and identify two final-state charged hadrons. The resultant two-particle invariant mass spectra show no strong structure suggesting any new narrow resonance. The statistical significance of various enhancements seen in the data is discussed, and upper limits on the cross section times branching ratio for new particle production are presented.

1976



## STUDY OF EVENT MIXING AND ITS APPLICATION TO THE EXTRACTION OF RESONANCE SIGNALS

D. DRIJARD and H.G. FISCHER

*CERN, Geneva, Switzerland*

T. NAKADA \*

*Institut für Hochenergiephysik, Heidelberg, Germany*

Received 27 February 1984

The features of the invariant mass distribution obtained from combinations of particles from different events, i.e. event mixing, is studied in detail. It is shown that special care is needed in order to reproduce the shape of the uncorrelated invariant mass distribution. A way to determine the number of resonances and its statistical error using an event mixing technique is described.

1984

## Using Energy Peaks to Count Dark Matter Particles in Decays

Kaustubh Agashe<sup>a</sup>, Roberto Franceschini<sup>a</sup>, Doojin Kim<sup>a</sup>, and Kyle Wardlow<sup>a</sup>

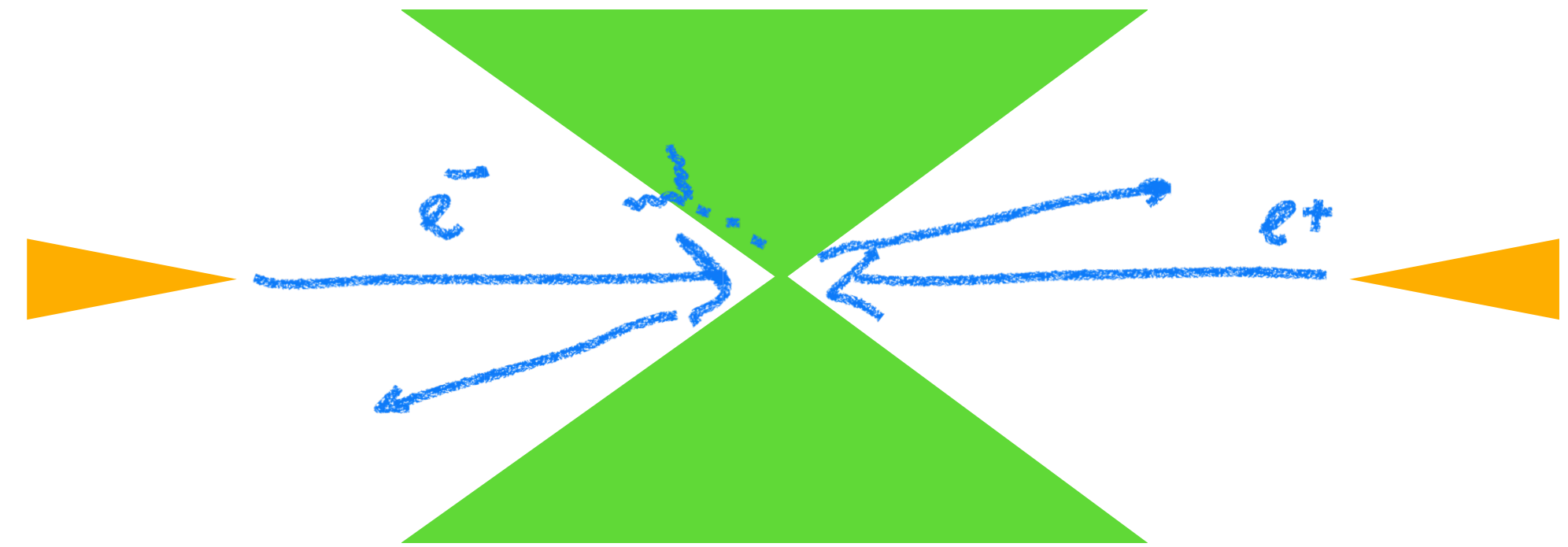
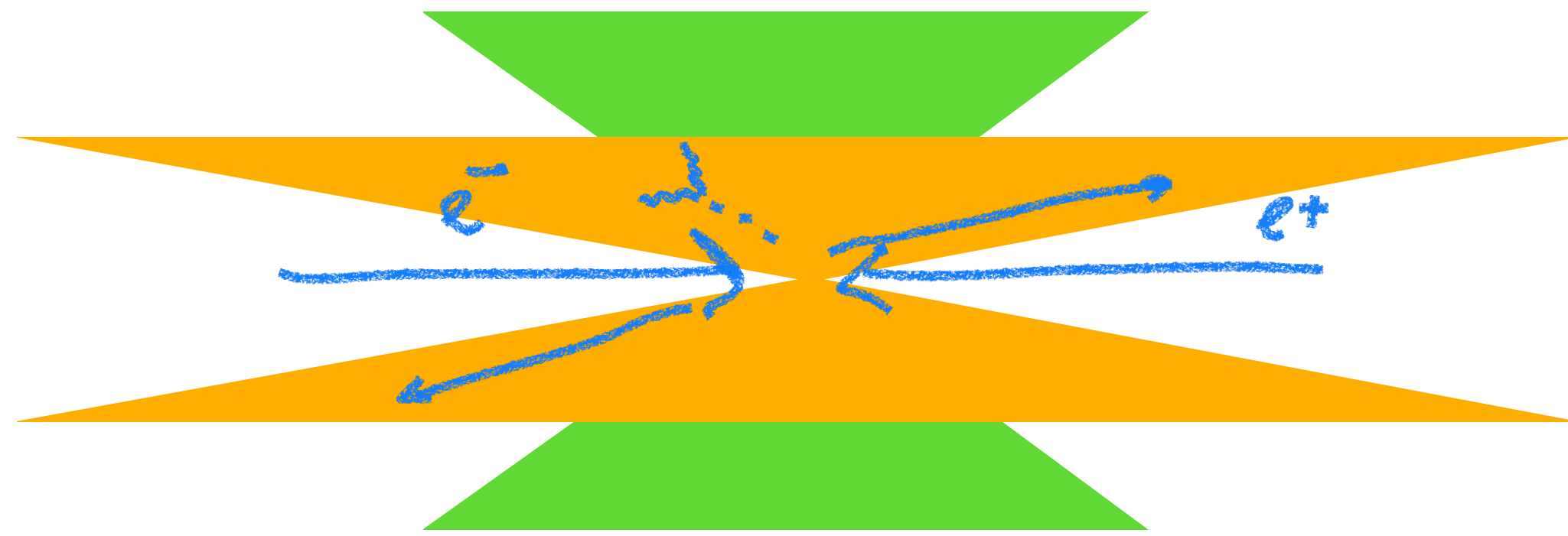
<sup>a</sup>Maryland Center for Fundamental Physics, Department of Physics, University of Maryland, College Park, MD 20742, U.S.A.

2012

- then came the barrel ...

# Forward is back!

(never went out fashion)

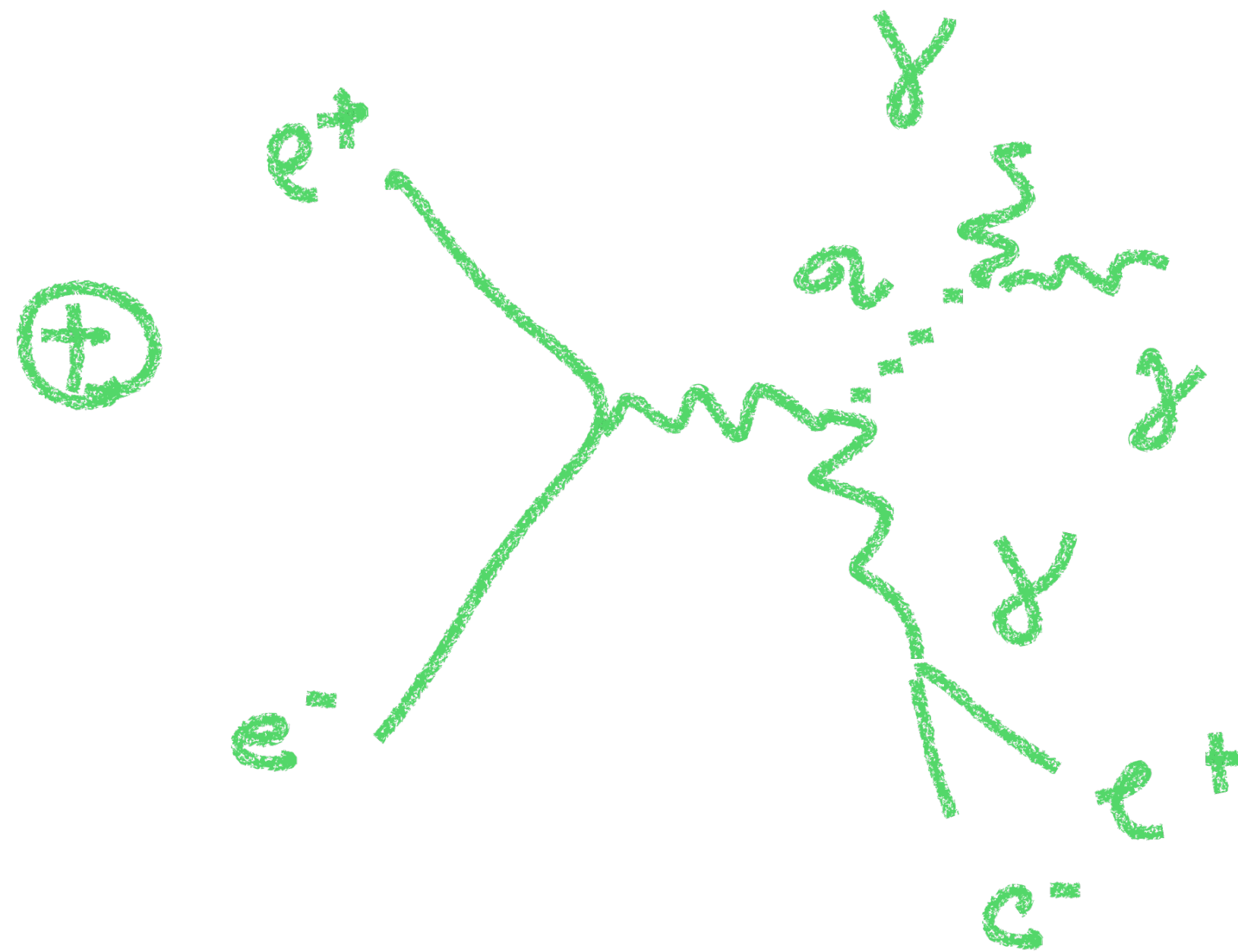
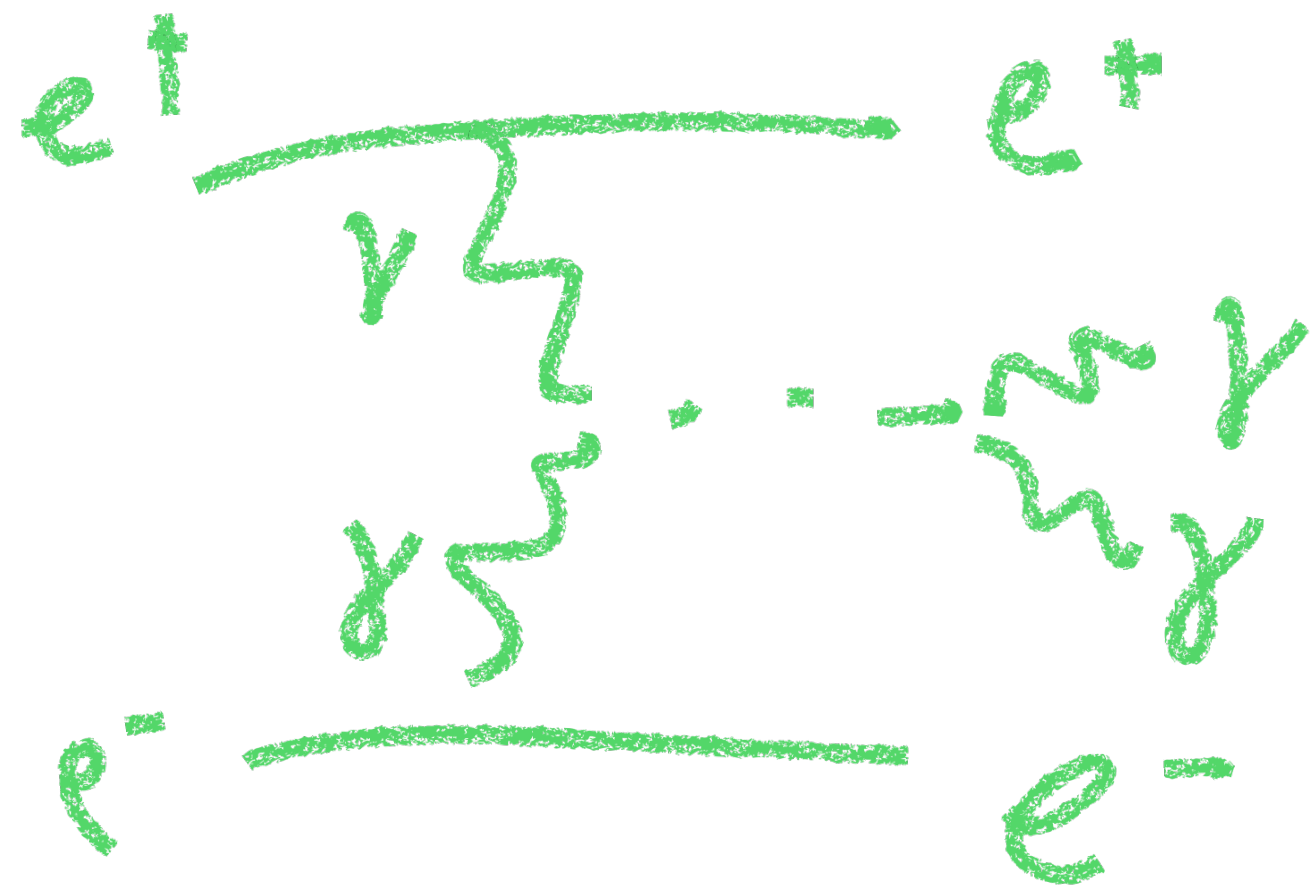


lots of opportunities from angular coverage of the region around the beam pipe at Belle II

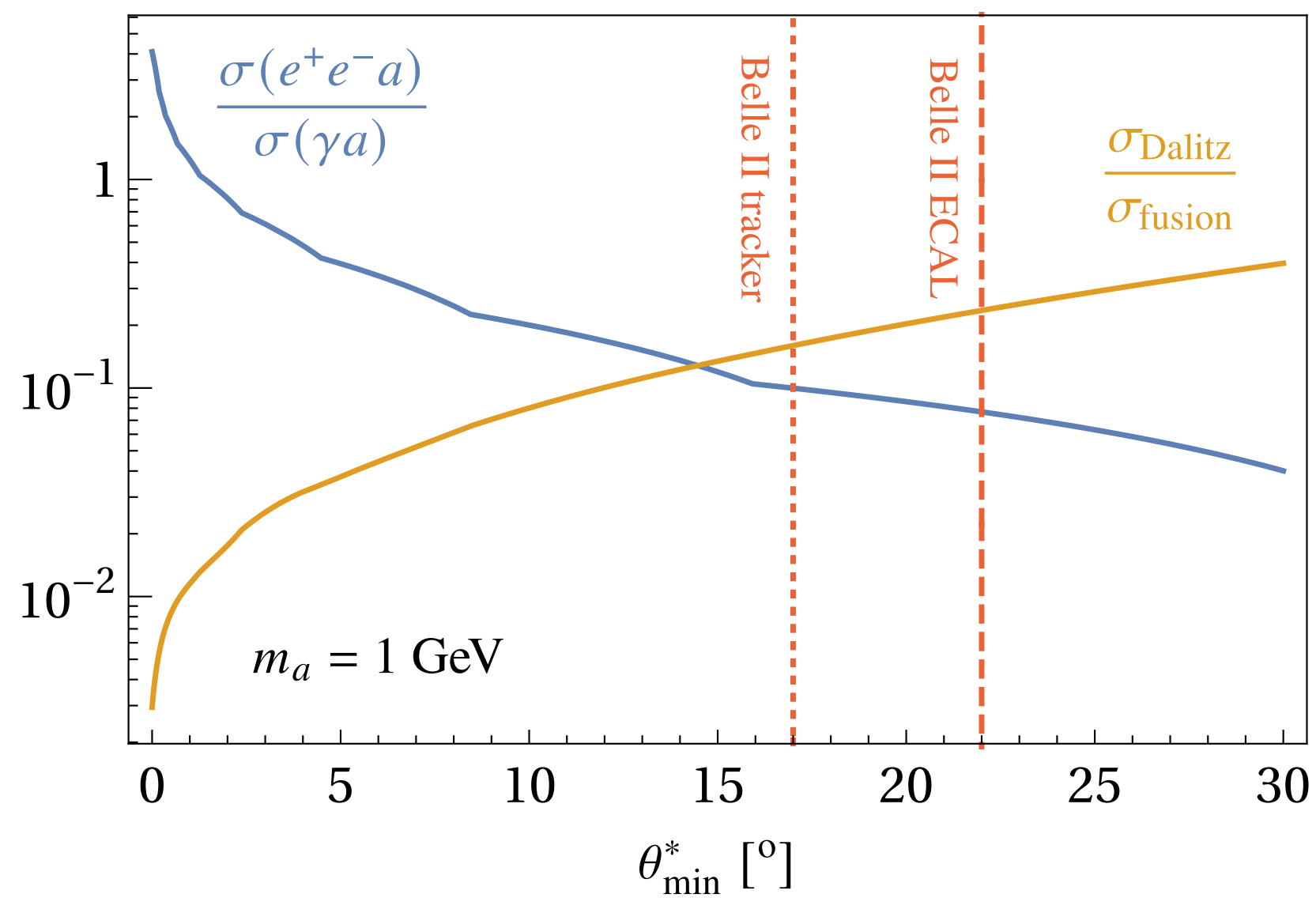
- axion like particles from BSM physics (decay to photons [2406.14614](#), decay to DM [2307.06369](#))
- true muonium (yet unobserved SM state which can be observed and studied in detail at Belle II, [2501.17753](#))
- ...

possible long lasting effect as this type of detectors is in demand for muon colliders, which have a blind region “the nozzle” that stops muon decay products in thick tungsten

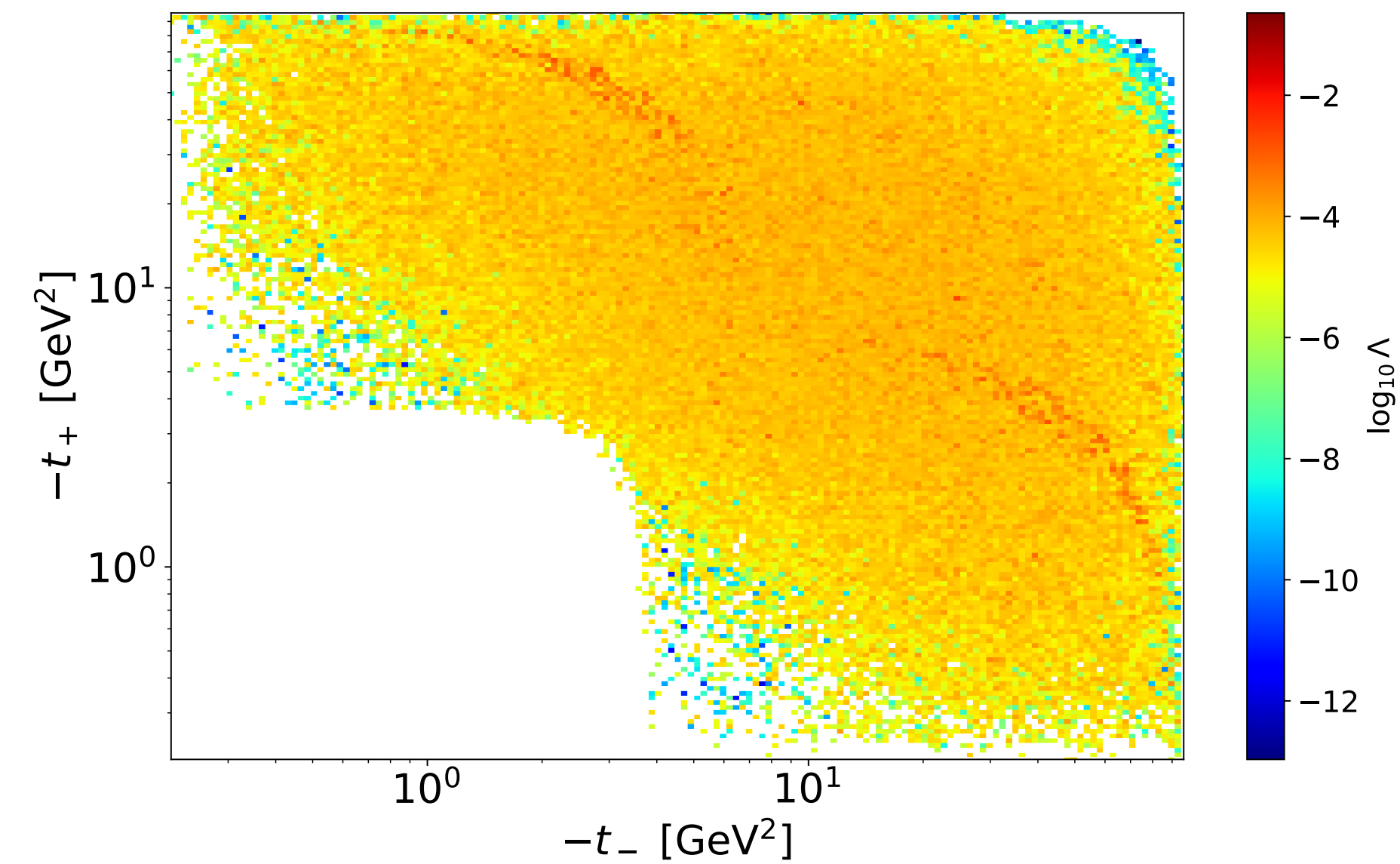
**Thank you**



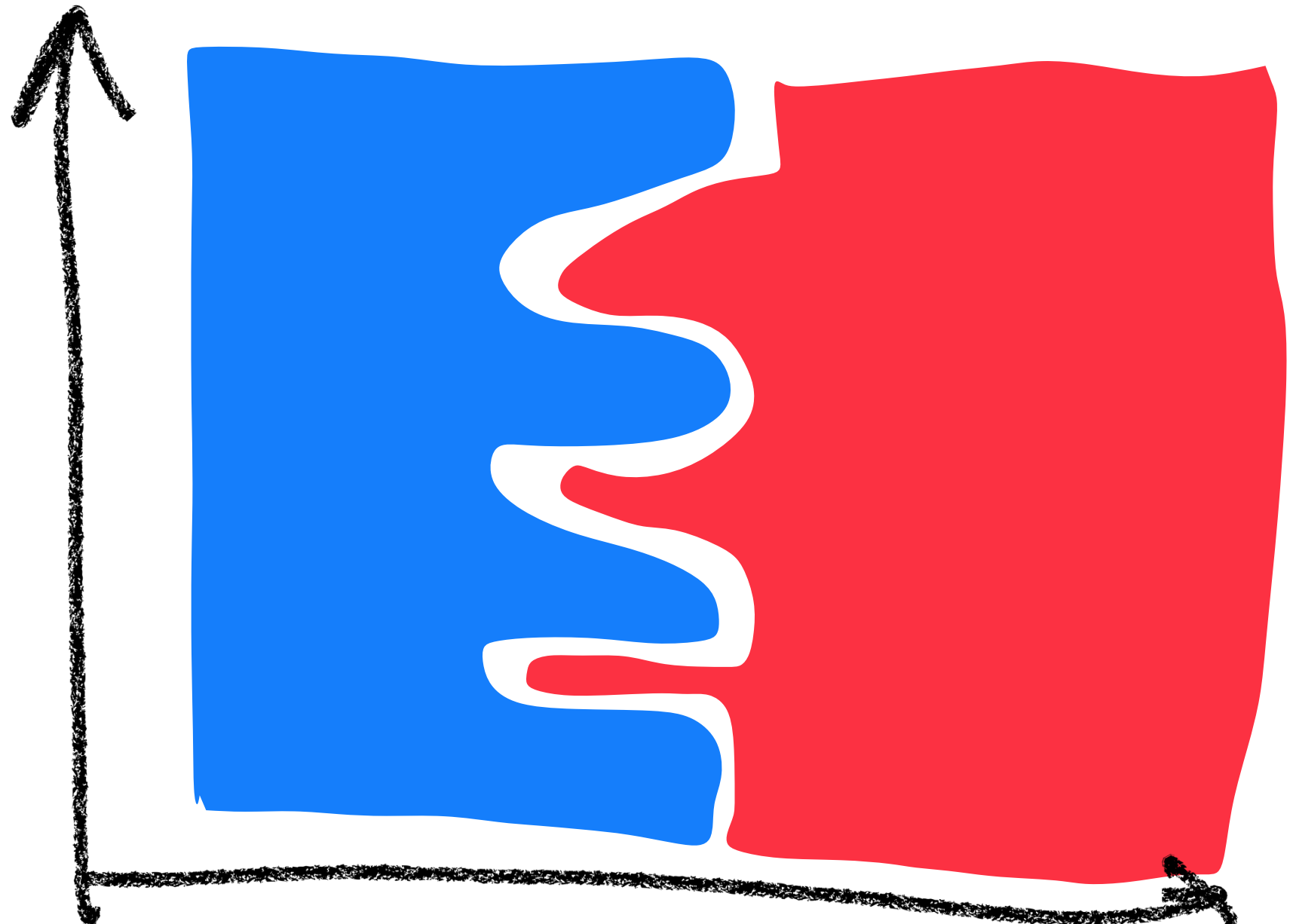
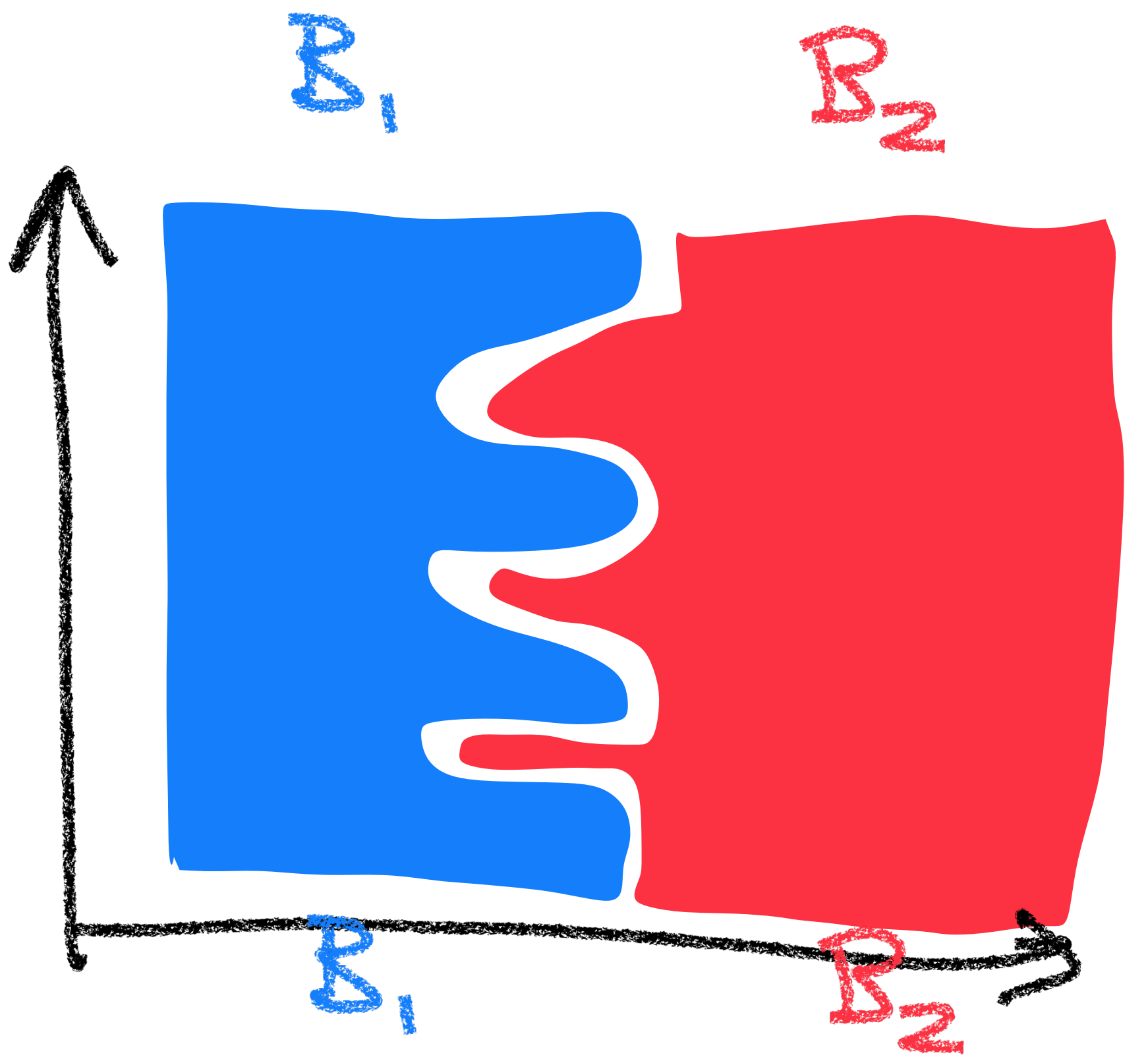
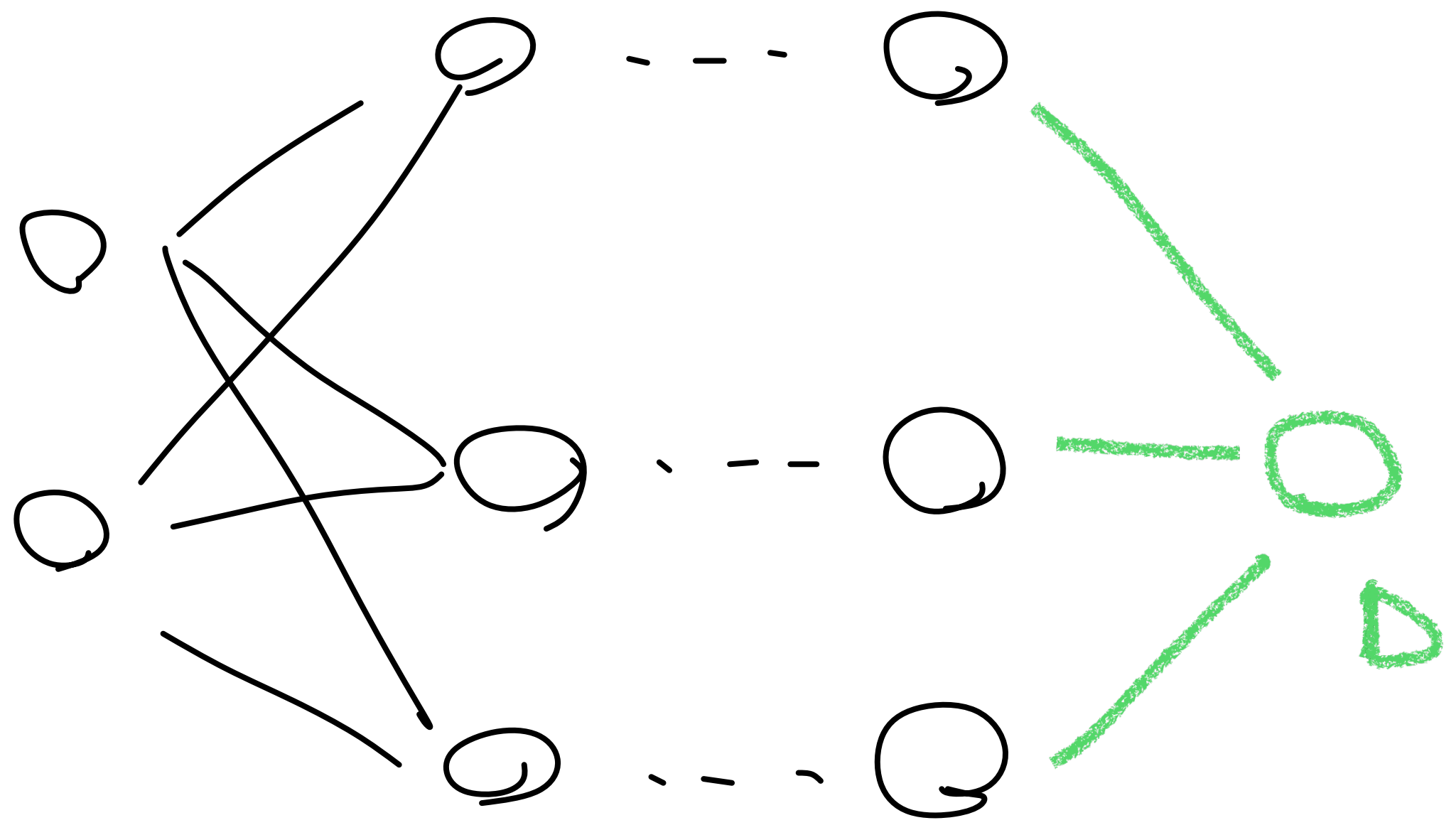
ALP cross section vs Belle II coverage



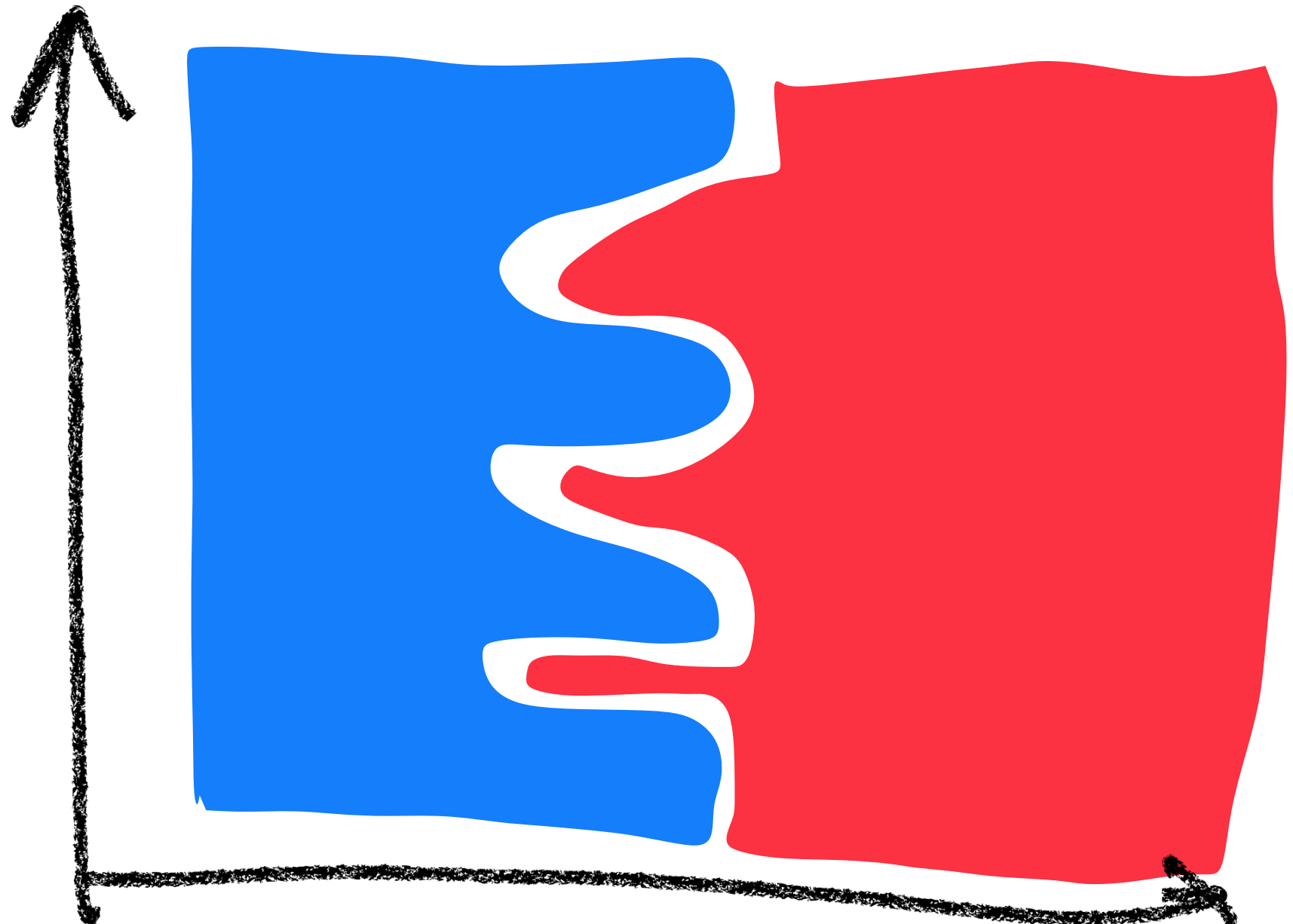
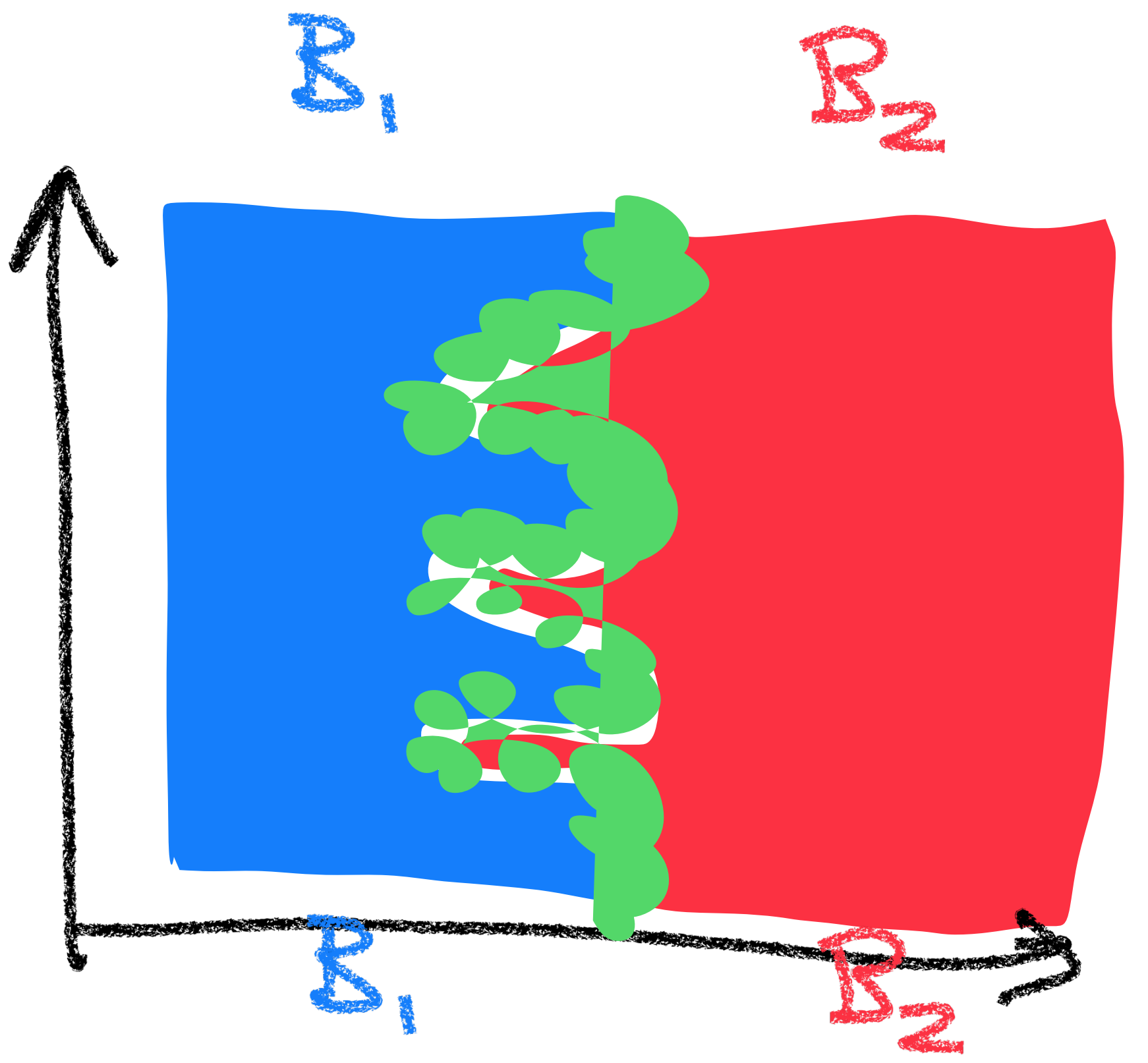
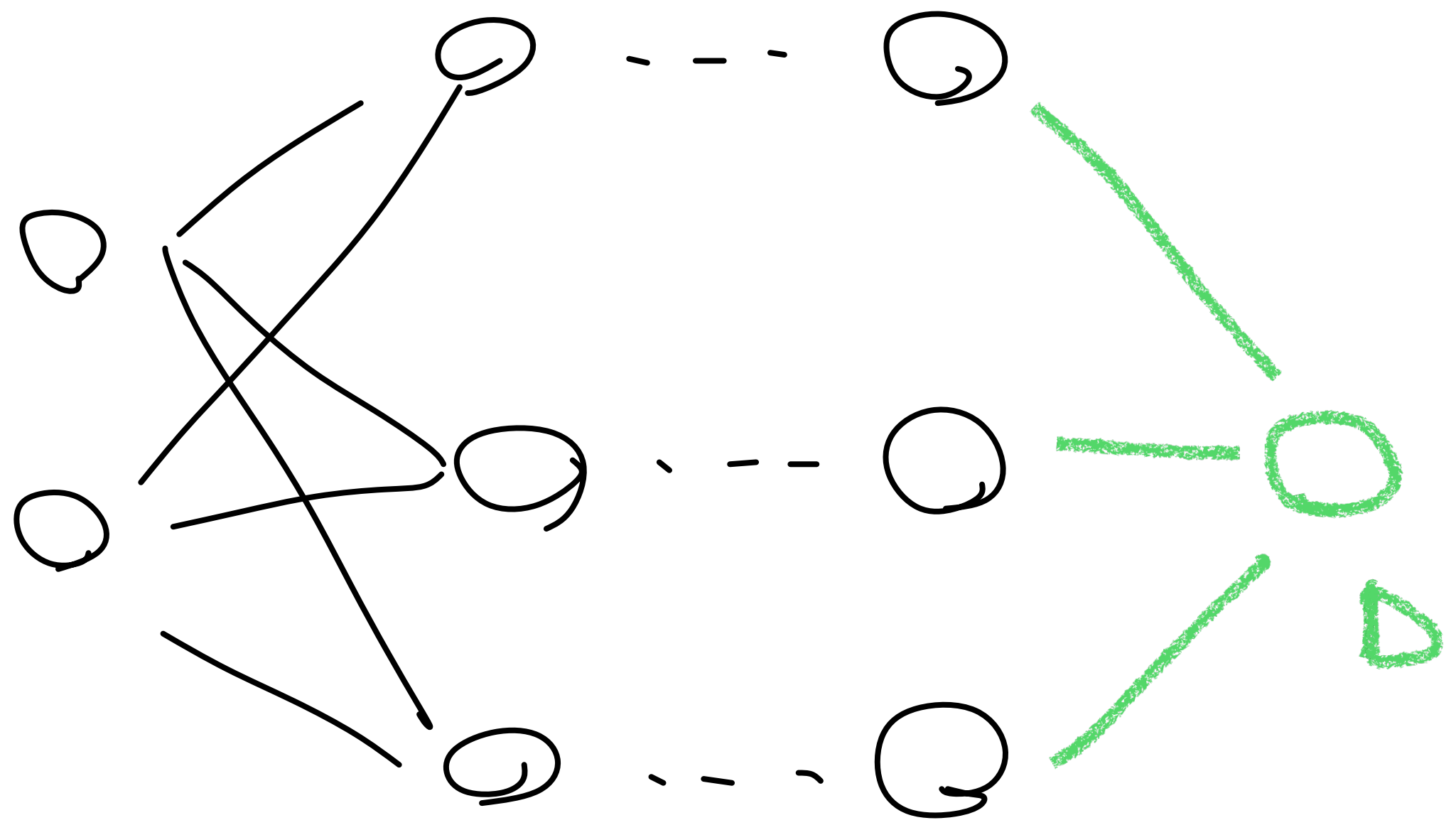
$$\begin{aligned}
 t_+ &= \left( p_{e_{in}^+} - p_{e_{out}^+} \right)^2, \\
 t_- &= \left( p_{e_{in}^-} - p_{e_{out}^-} \right)^2, \\
 s_- &= \left( p_{e_{in}^+} + p_{e_{in}^-} - p_{e_{out}^+} \right)^2, \\
 s_+ &= \left( p_{e_{in}^+} + p_{e_{in}^-} - p_{e_{out}^-} \right)^2,
 \end{aligned}$$



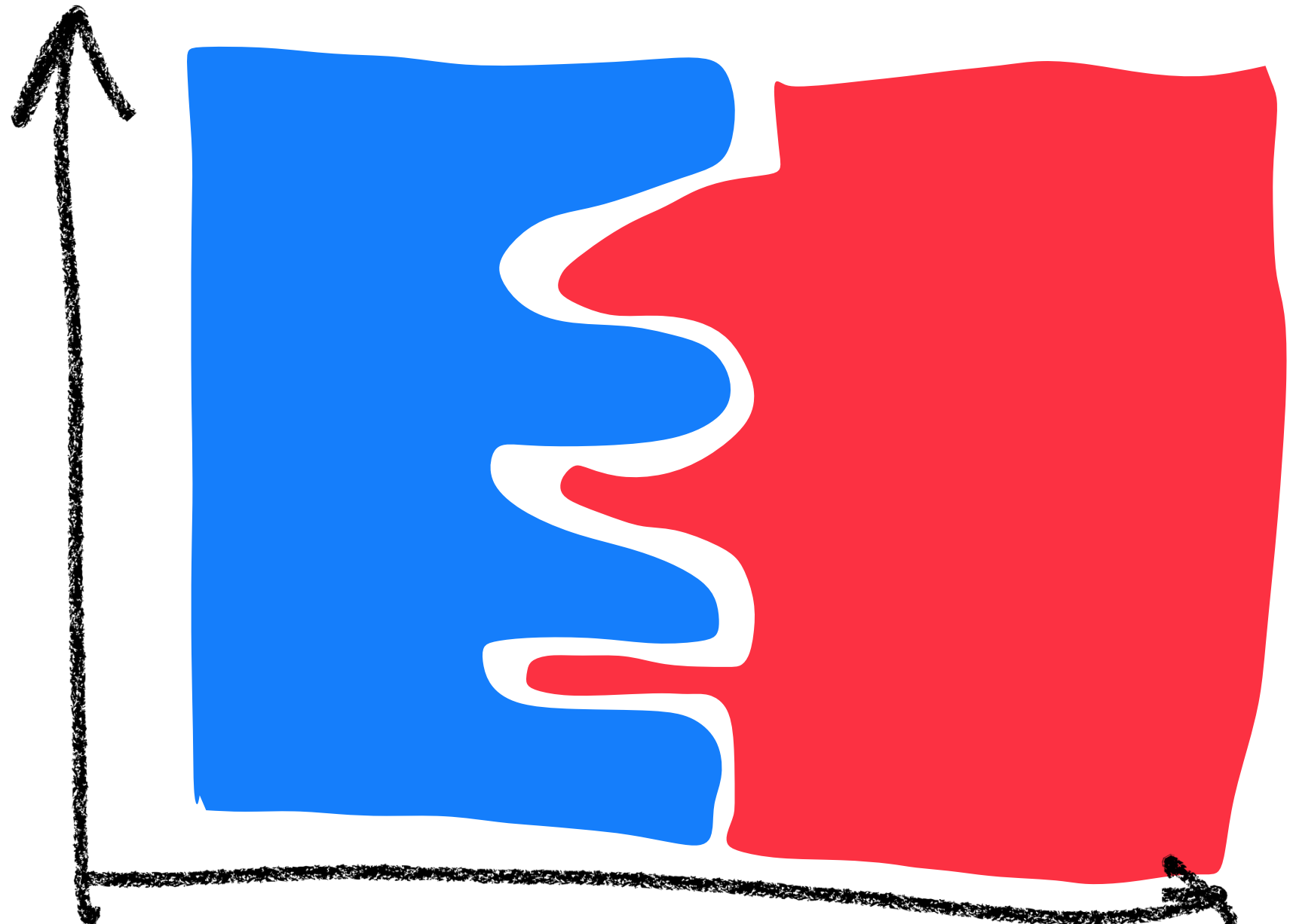
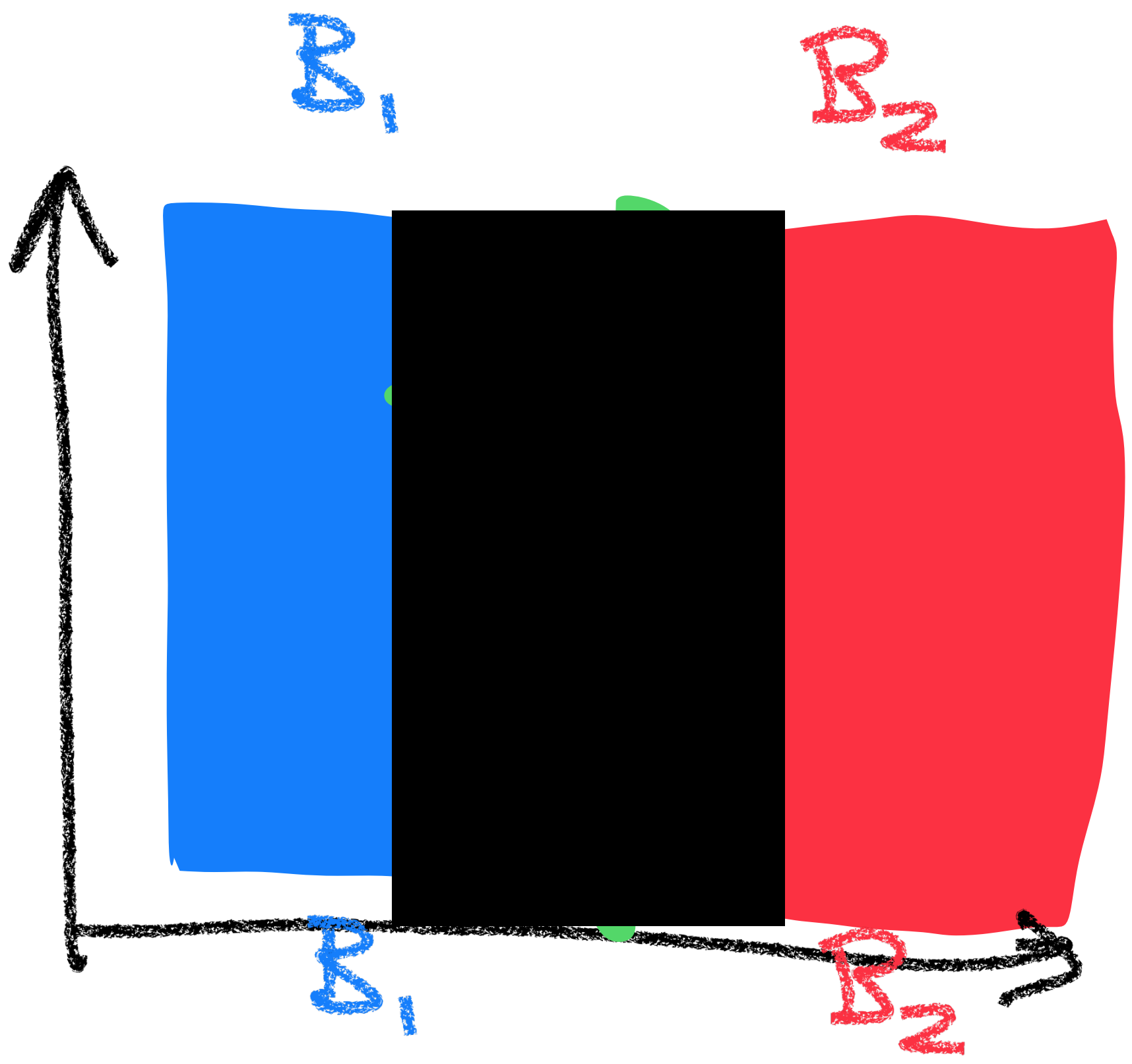
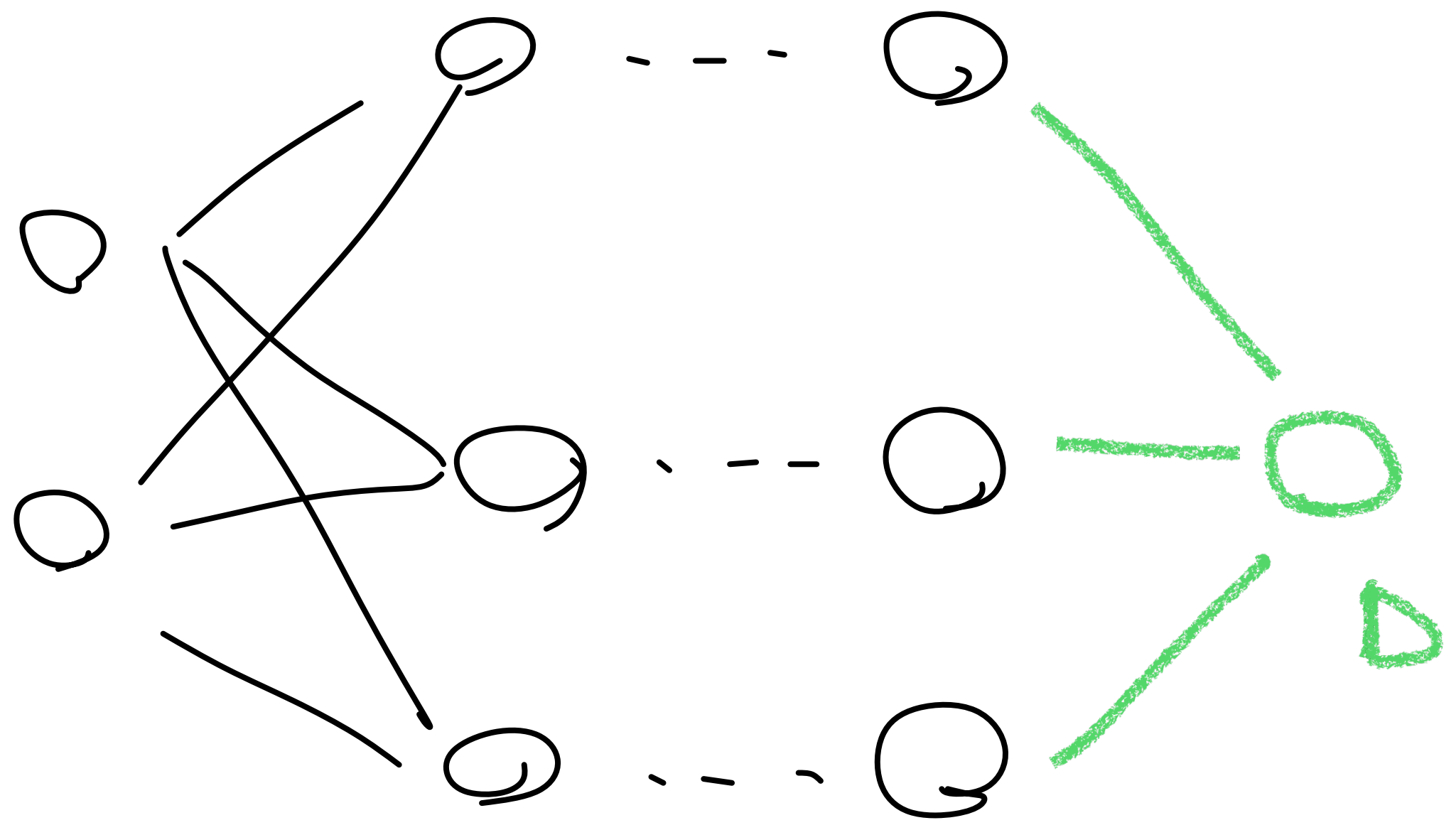
$$S(y): y \rightarrow A \sin(y) + B$$



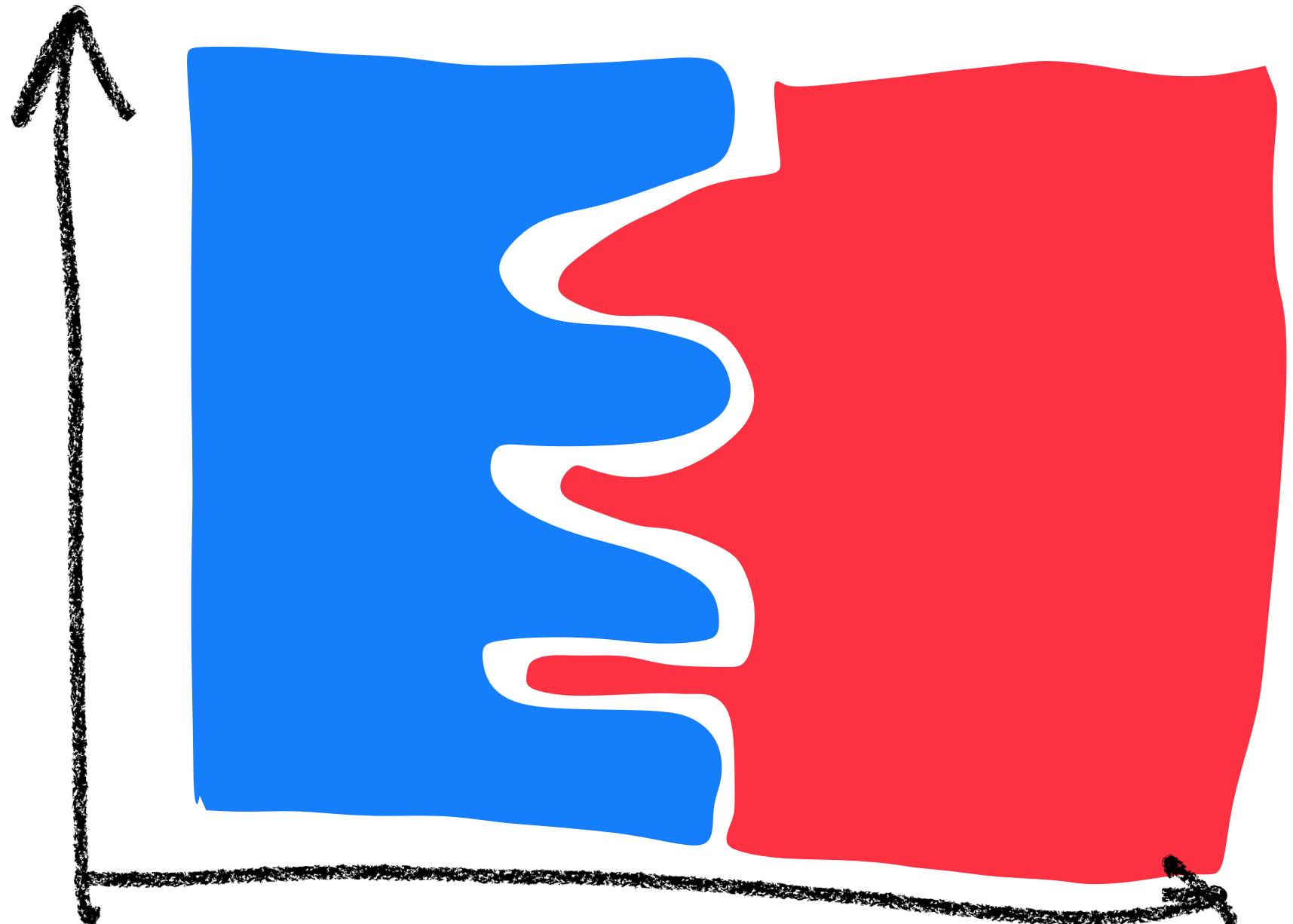
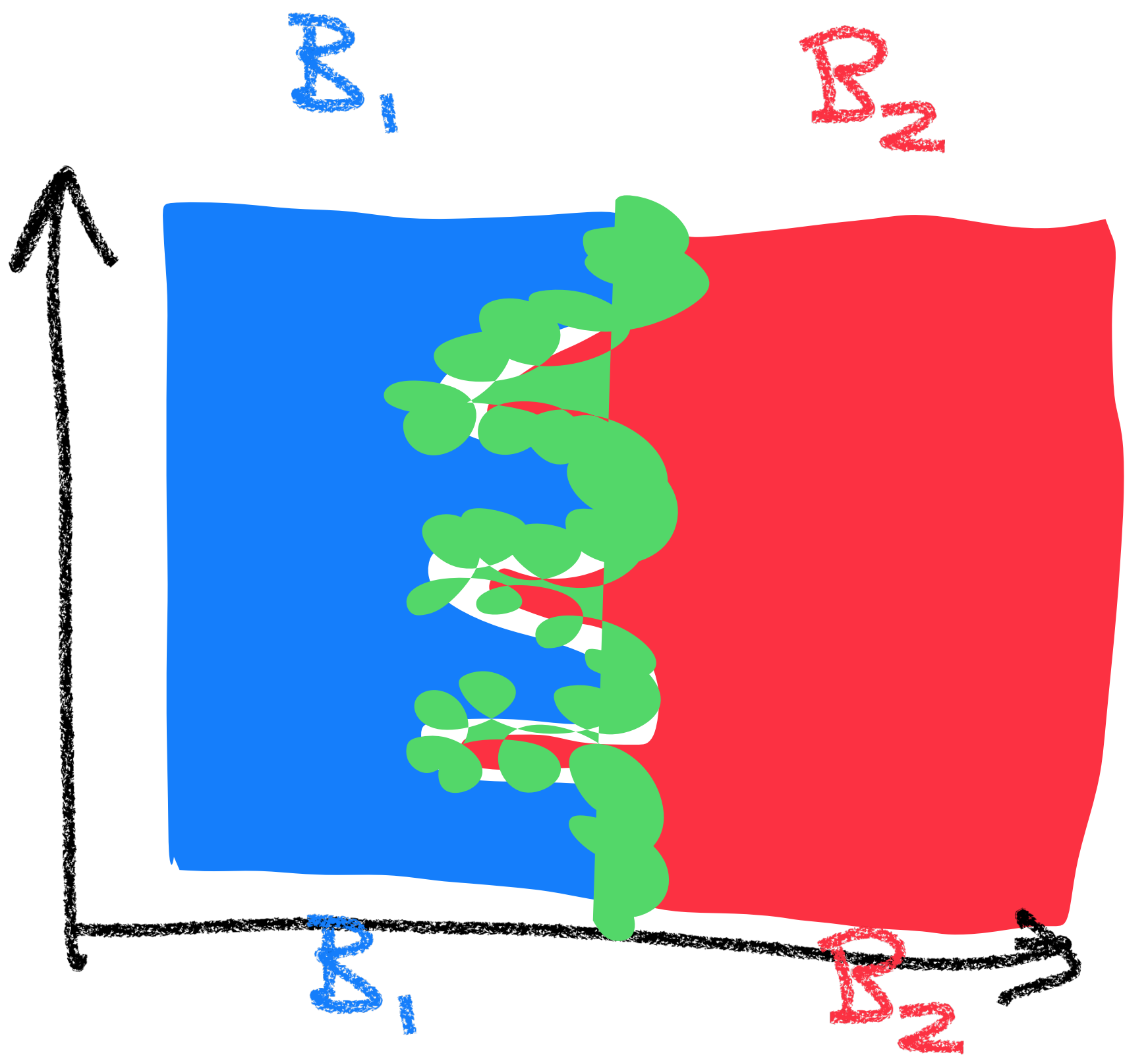
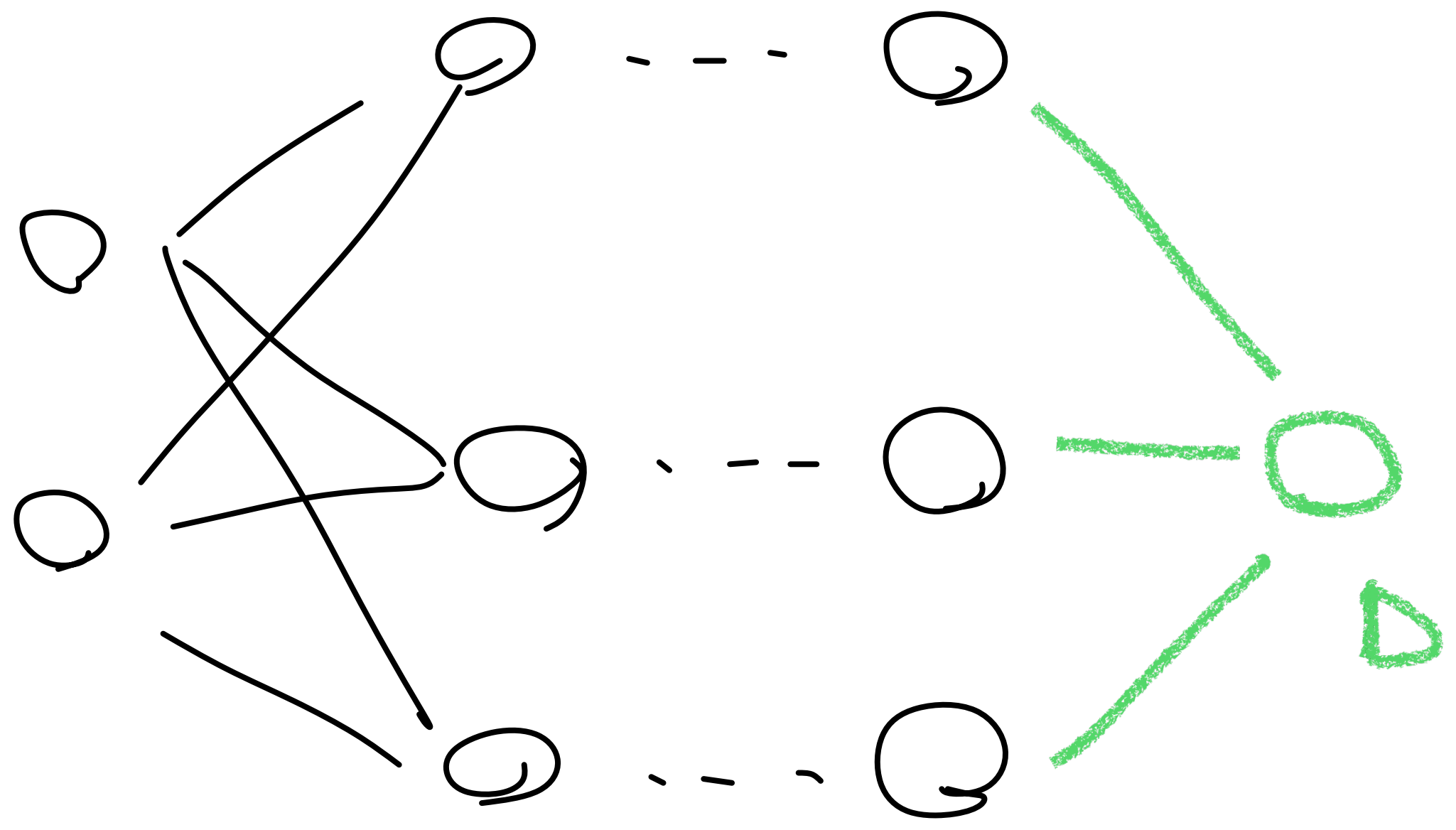
$$S(y) : y \rightarrow A \sin(y) + B$$



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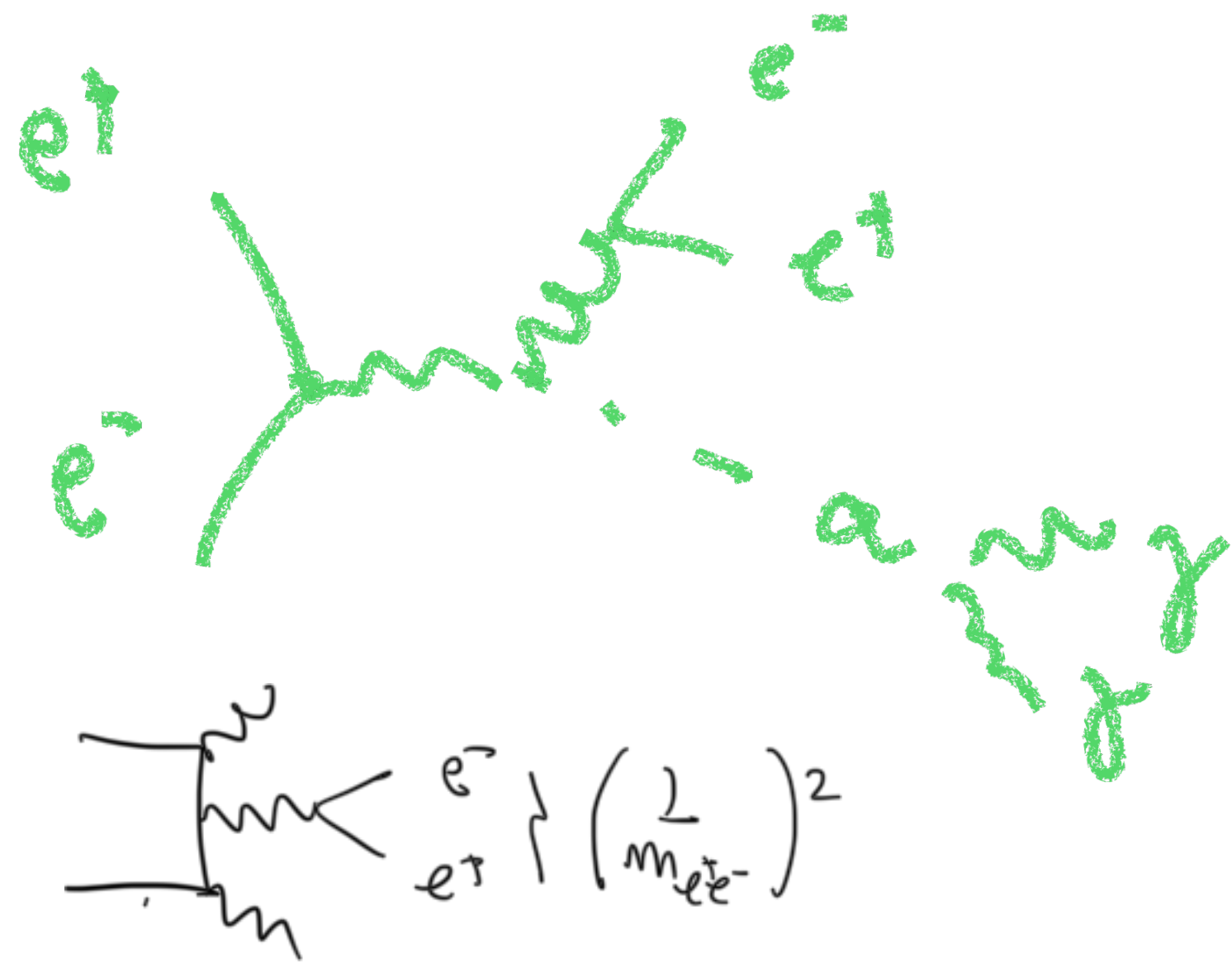


Table 3.1.: Overview of the centrally produced background processes used in the analysis. The number of streams represents the amount of background that is simulated compared to the actual recorded data. All histograms and event counts given will compensate for this. For a better visualization, the subdominant leptonic and  $B$ -event backgrounds will be grouped in most histograms. The dashed lines indicate the used grouping.

Name	No. of Streams	Processes
$\gamma\gamma$	2.0	$e^+e^- \rightarrow \gamma\gamma(\gamma)$
$e^+e^-$	0.1	$e^+e^- \rightarrow e^+e^-(\gamma)$
$e^+e^-e^+e^-$	1.0	$e^+e^- \rightarrow e^+e^-e^+e^-$
$e^+e^-\mu^+\mu^-$	1.0	$e^+e^- \rightarrow e^+e^-\mu^+\mu^-$
$llXX$	1.0	$e^+e^- \rightarrow e^+e^-X^+X^-$ , $X \in \{\tau, \pi, K, p\}$ ; $\mu^+\mu^-X^+X^-$ , $X \in \{\mu, \tau\}$ ; $e^+e^- \rightarrow \tau^+\tau^-\tau^+\tau^-$
$\mu^+\mu^-$	1.0	$e^+e^- \rightarrow \mu^+\mu^-(\gamma)$
$\tau^+\tau^-$	4.0	$e^+e^- \rightarrow \tau^+\tau^-(\gamma)$
$q\bar{q}$	4.0	$e^+e^- \rightarrow q\bar{q}$ , $q \in \{u, d, s, c\}$
$hhISR$	1.0	$e^+e^- \rightarrow hh\gamma$ , $hh \in \{\pi^+\pi^-, \pi^+\pi^-\pi^0, K^+K^-, K_S^0K_L^0\}$
$B^0\bar{B}^0$	4.0	$e^+e^- \rightarrow \Upsilon(4s) \rightarrow B^0\bar{B}^0$
$B^+\bar{B}^-$	4.0	$e^+e^- \rightarrow \Upsilon(4s) \rightarrow B^+\bar{B}^-$

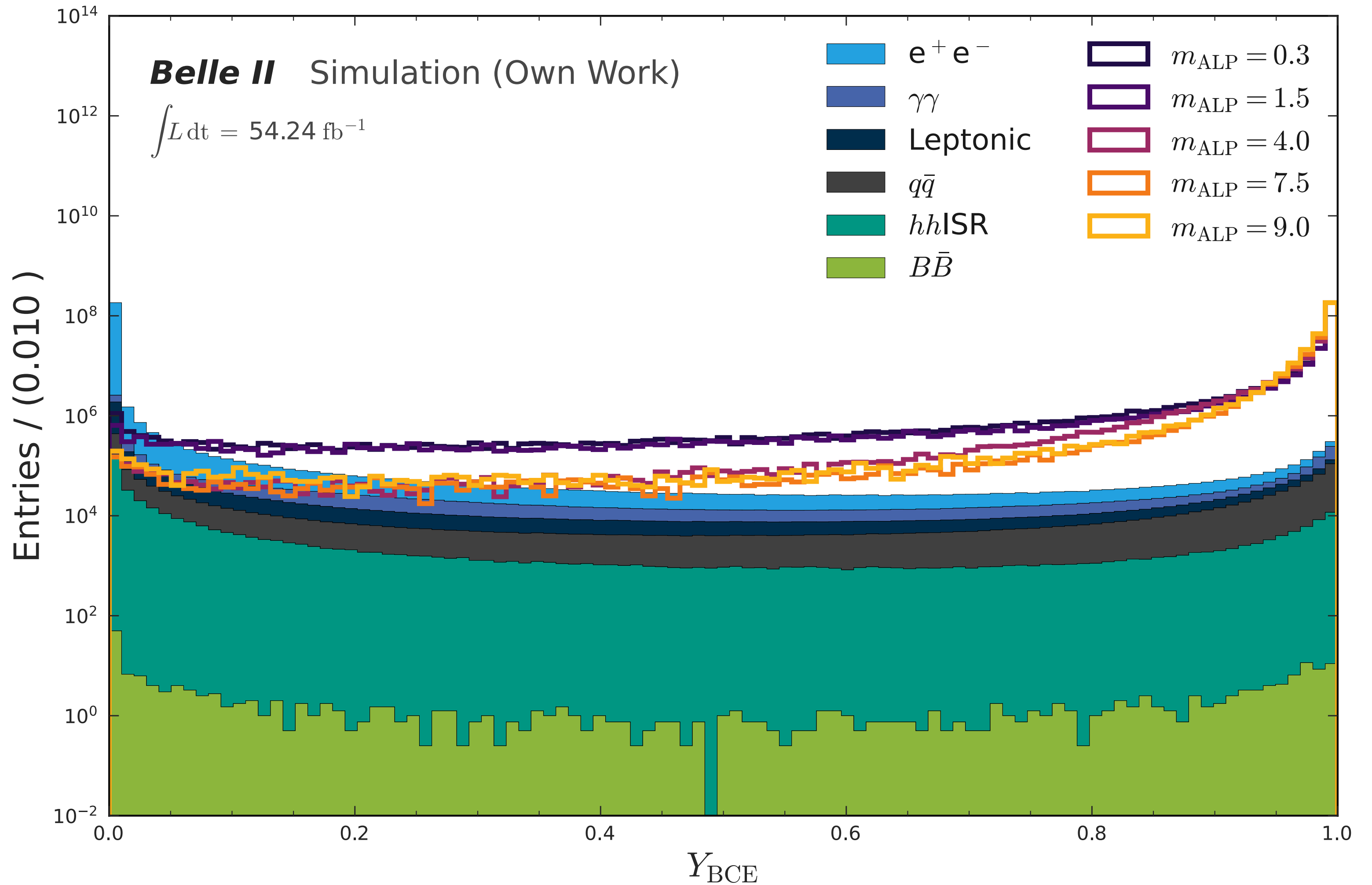
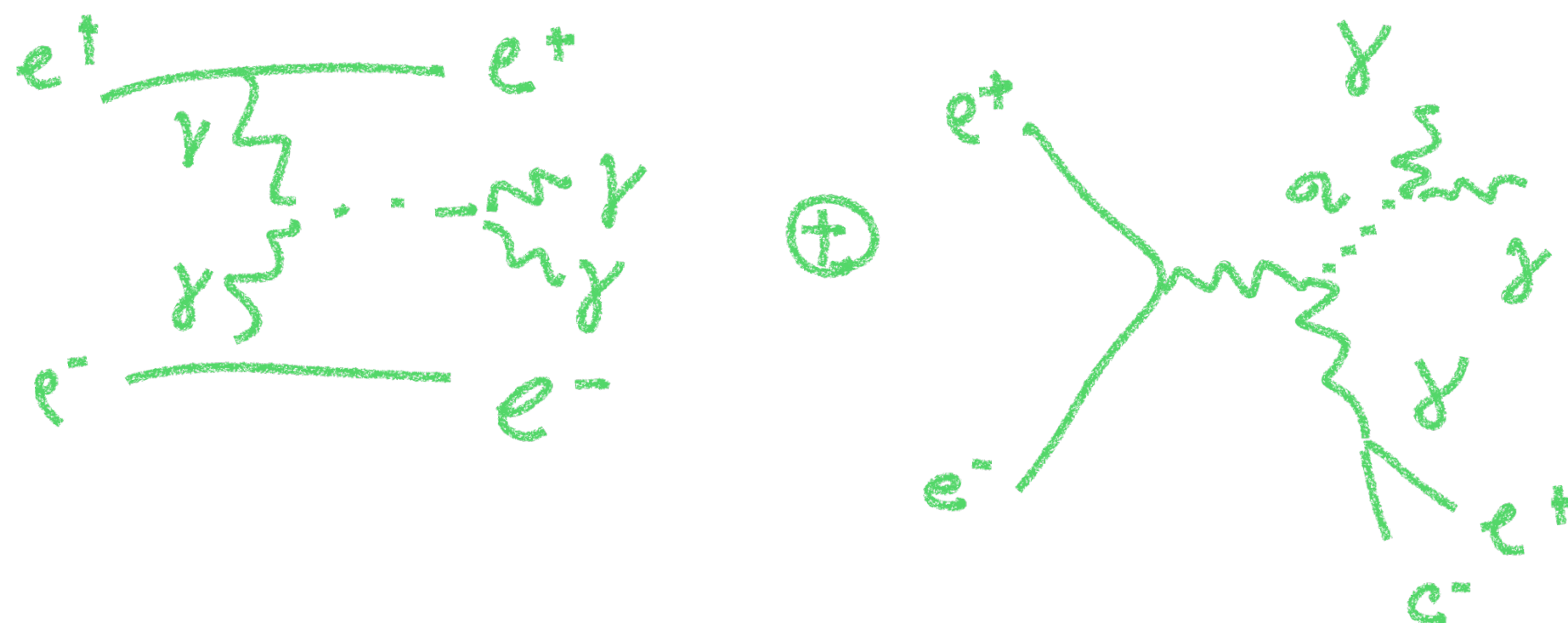


Figure 7.4.: Output value of the neural network classifier for the full available background dataset of  $54.24 \text{ fb}^{-1}$  and a five signal masses throughout the mass range. Most of the signal (background) events are classified correctly with values close to 1 (0). To better visualize the intermediate regions, the y-axis is logarithmically scaled.

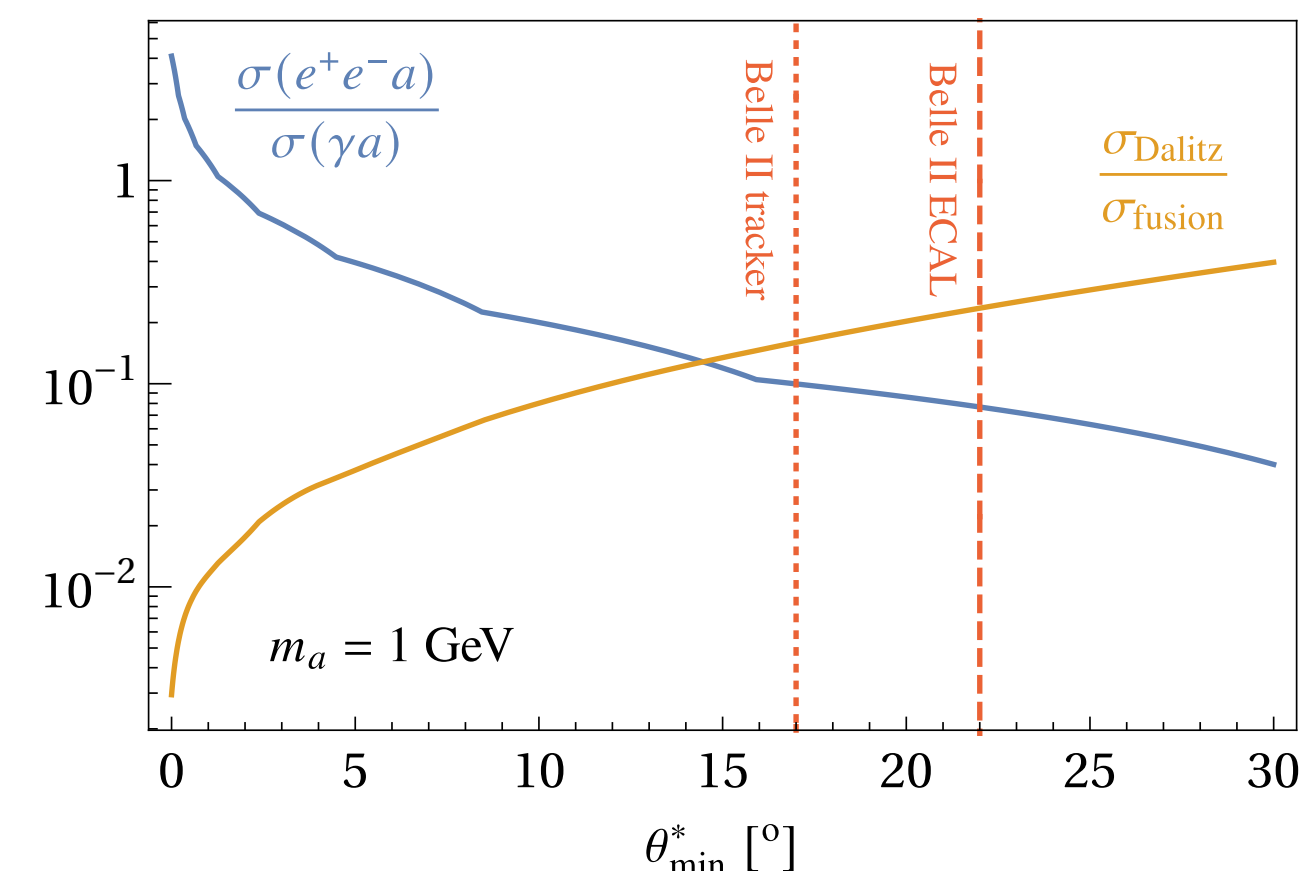
In general it is not possible to make a one-to-one comparison between the result in the thesis and that in the paper. The analysis methodology is different:

- thesis used a neural-network classifier (sensitive to background mistagging)
- paper used a completely differential analysis in 4D with a binned likelihood ratio (protected from background mistagging, but requires more precise background predictions)
- There is agreement that Bhabha scattering is the main background.
- It would be necessary to compare the detailed predictions of the Belle II Monte Carlo (Babayaga) and MG5\_aMC@NLO in the region of phase space that is of interest, especially because the selection inevitably pushes toward the sparsely populated tail of phase space, which is therefore harder to model. Possible, but not a short term goal.

# Two signals in the same final state



ALP cross section vs Belle II coverage



- Since the signal has a component with peak at  $m_{ee} \simeq 0$  (Dalitz-like with  $\gamma \rightarrow e^+e^-$ ) and a component with peak at  $m_{ee} \simeq \sqrt{s} - m_A$  (true fusion), it could already be very useful to know whether the neural network has identified one region or the other. The point of the paper was that “true-fusion” region can be purified, whereas no such statement is available for the Dalitz-like region. On the contrary we conjecture the Dalitz-like region cannot be purified beyond a certain point.
- The fact that the network is learning to discriminate several signals of different mass from the background remains somewhat unclear, especially it is unclear if the signal isolation strategy learnt is truly optimal for each mass or it’s a generic strategy valid, but not optimal, for all masses