Dark Matter & Flavor Factories

DMNet International Symposium “Dark Matter Studies in Accelerator Physics”

Diego Redigolo
INFN Florence

New search strategies to explore dark sector targets

NA62

@ kaon factories

see arXiv 2201.07805

New Physics Searches at Kaon and Hyperon Factories

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@ muon factories

see arXiv 2006.04795

with L. Calibbi, J. Zupan, R. Ziegler

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@ B meson factories

see arXiv 2307.06369 + to appear

with F. Acanfora, R. Franceschini, A. Mastroddi

Why is this important?

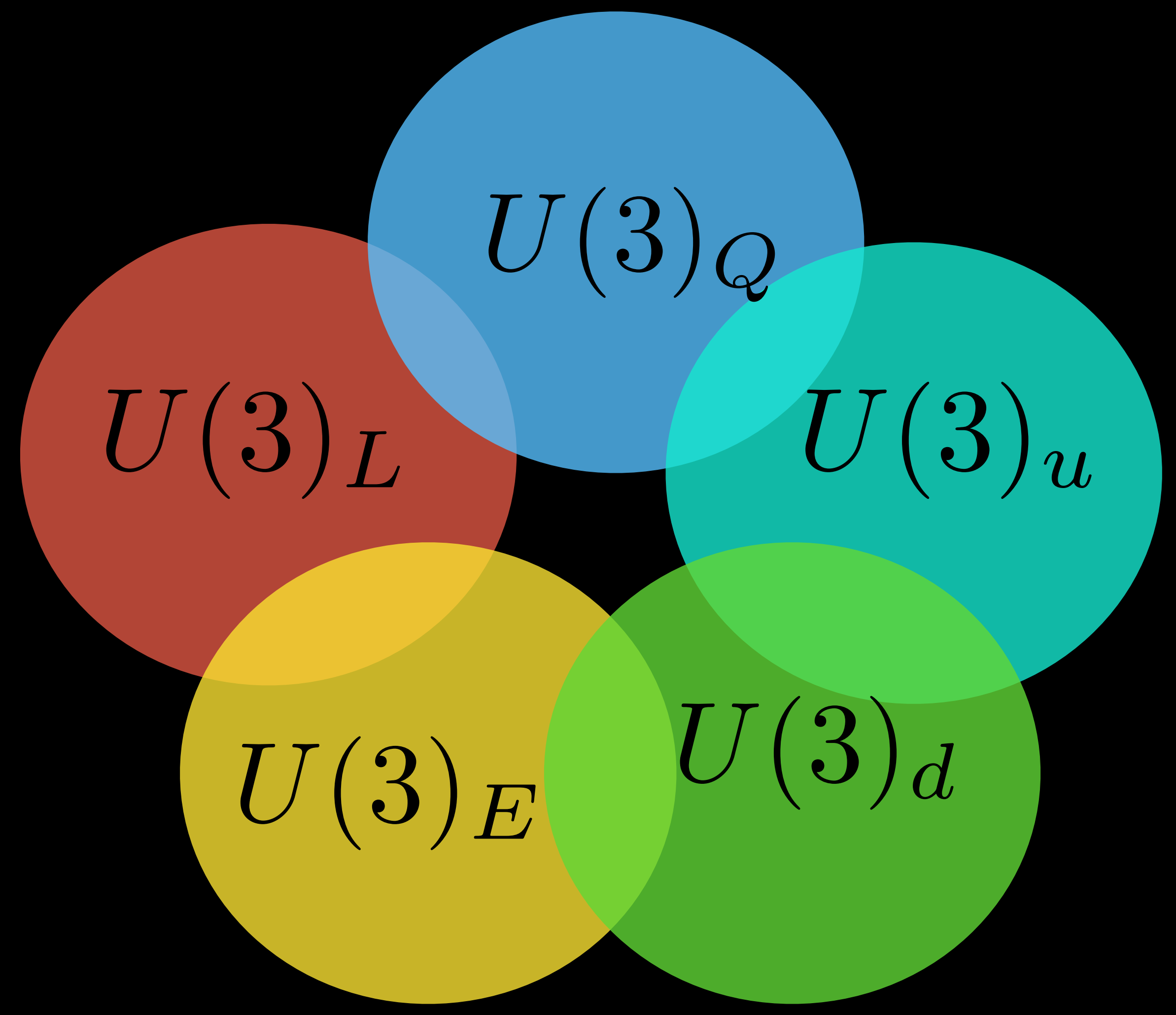
Triggering data that would otherwise get lost

Example @ MEG II

Squeezing the data as much as we can

Example @ Belle II

Where is the theory?



Peccei-Quinn charges can be flavor dependent

$$Q_i, u_i, d_i, E_i, L_i$$

Calibbi-Goertz-Redigolo-Ziegler-Zupan 2016

Ema-Hamaguchi-Moroi-Nakayama 2016

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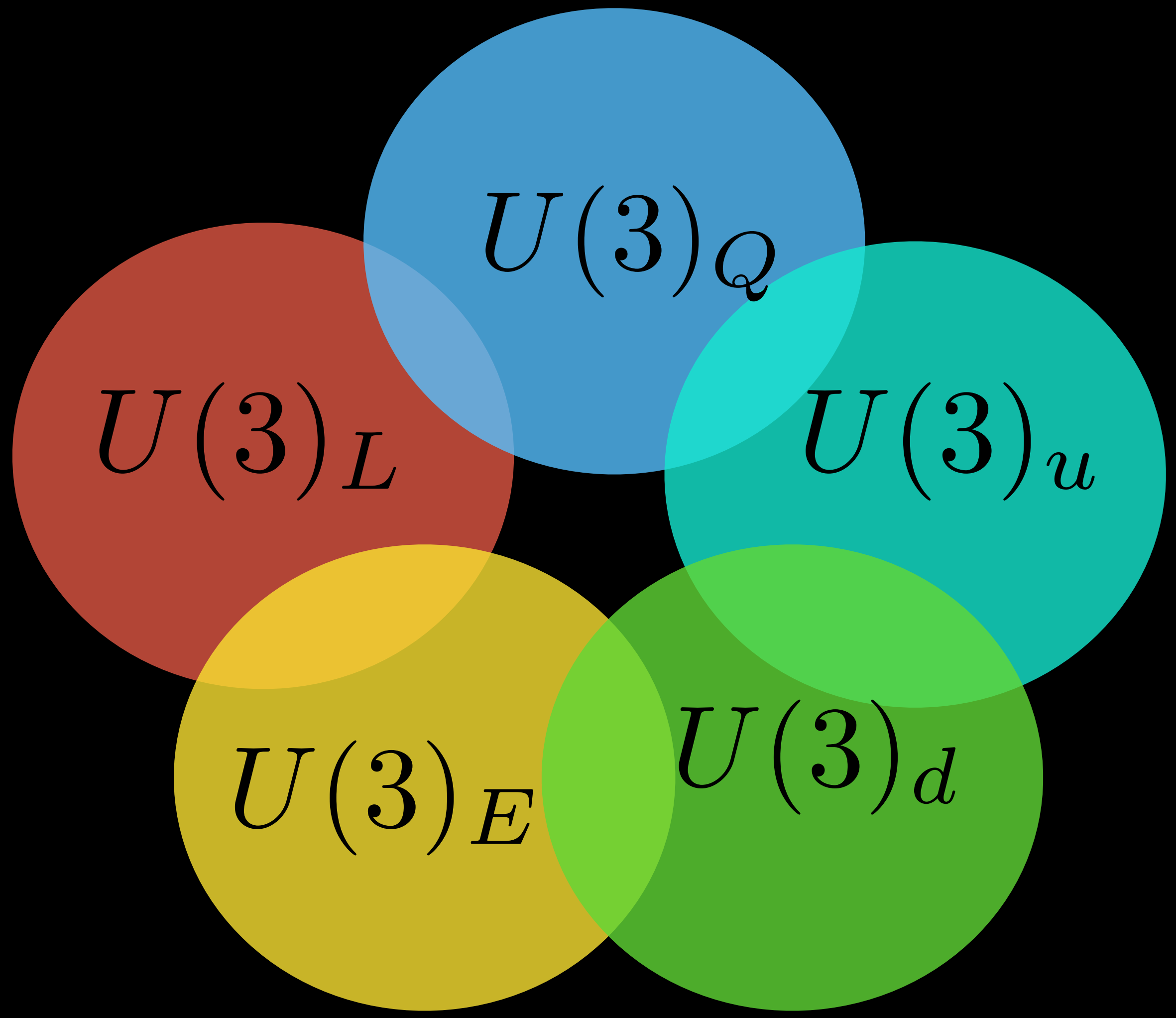

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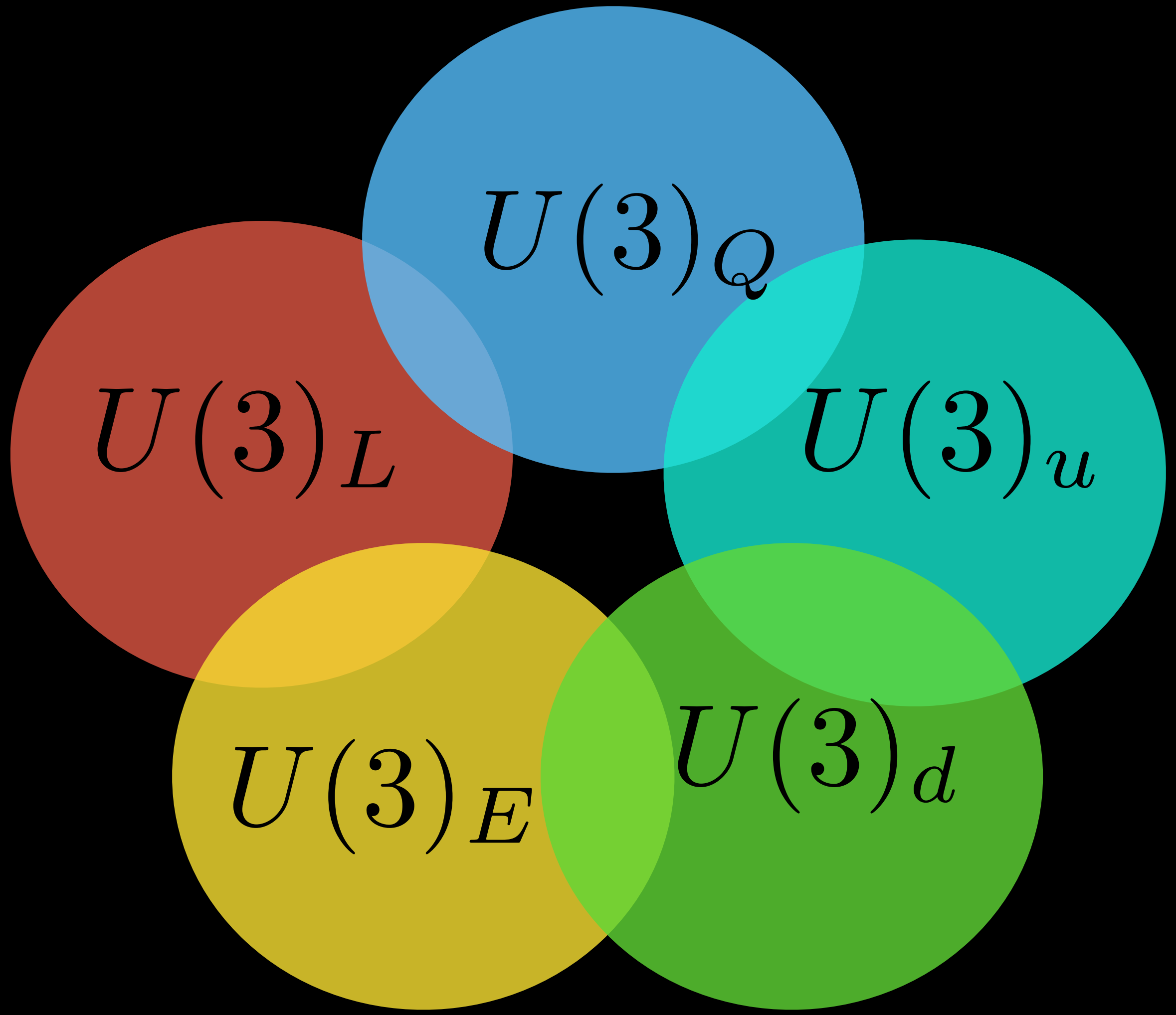

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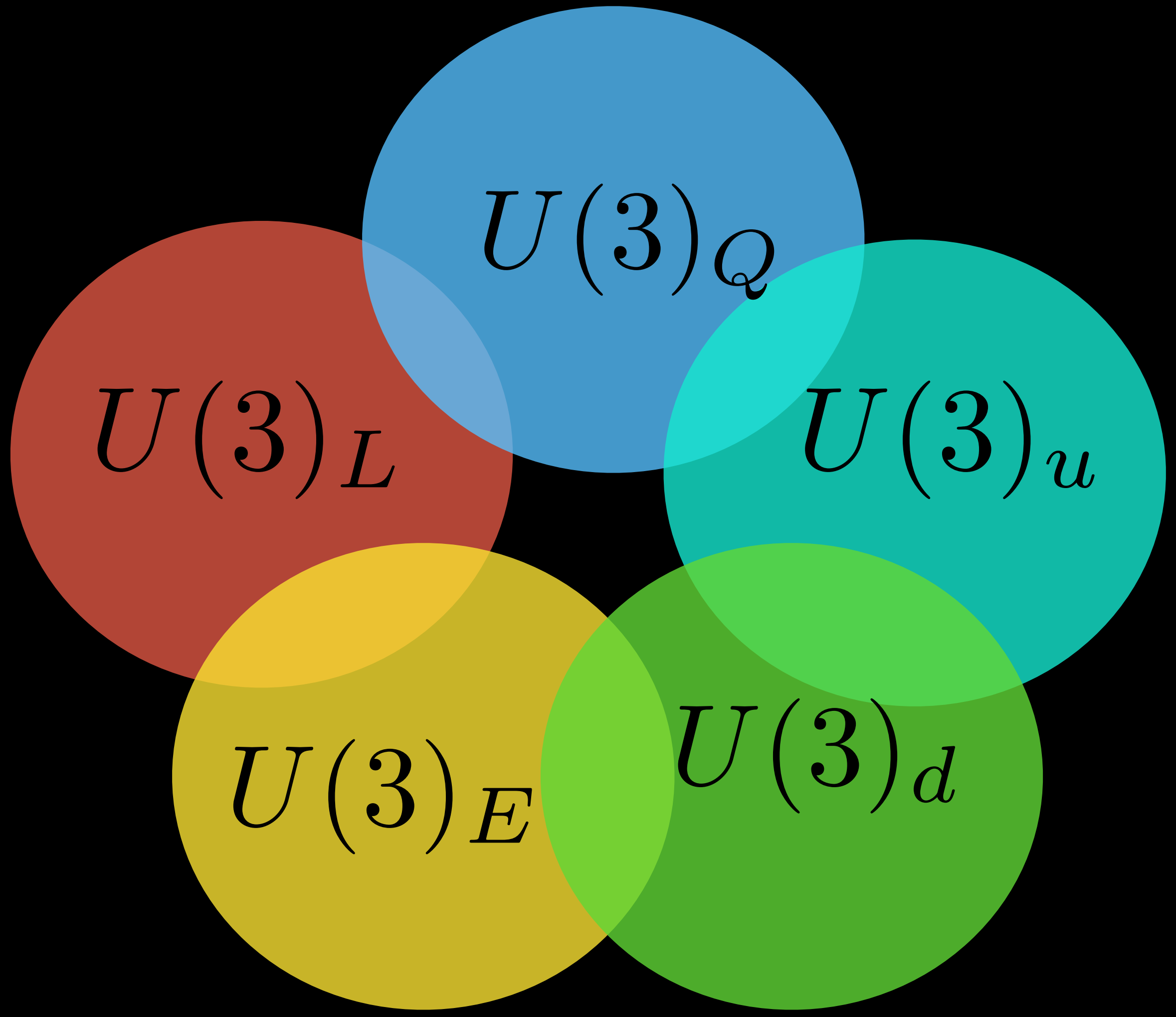

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The hierarchy FLAVOR-DIAGONAL vs FLAVOR-VIOLATING depends on the UV flavor theory

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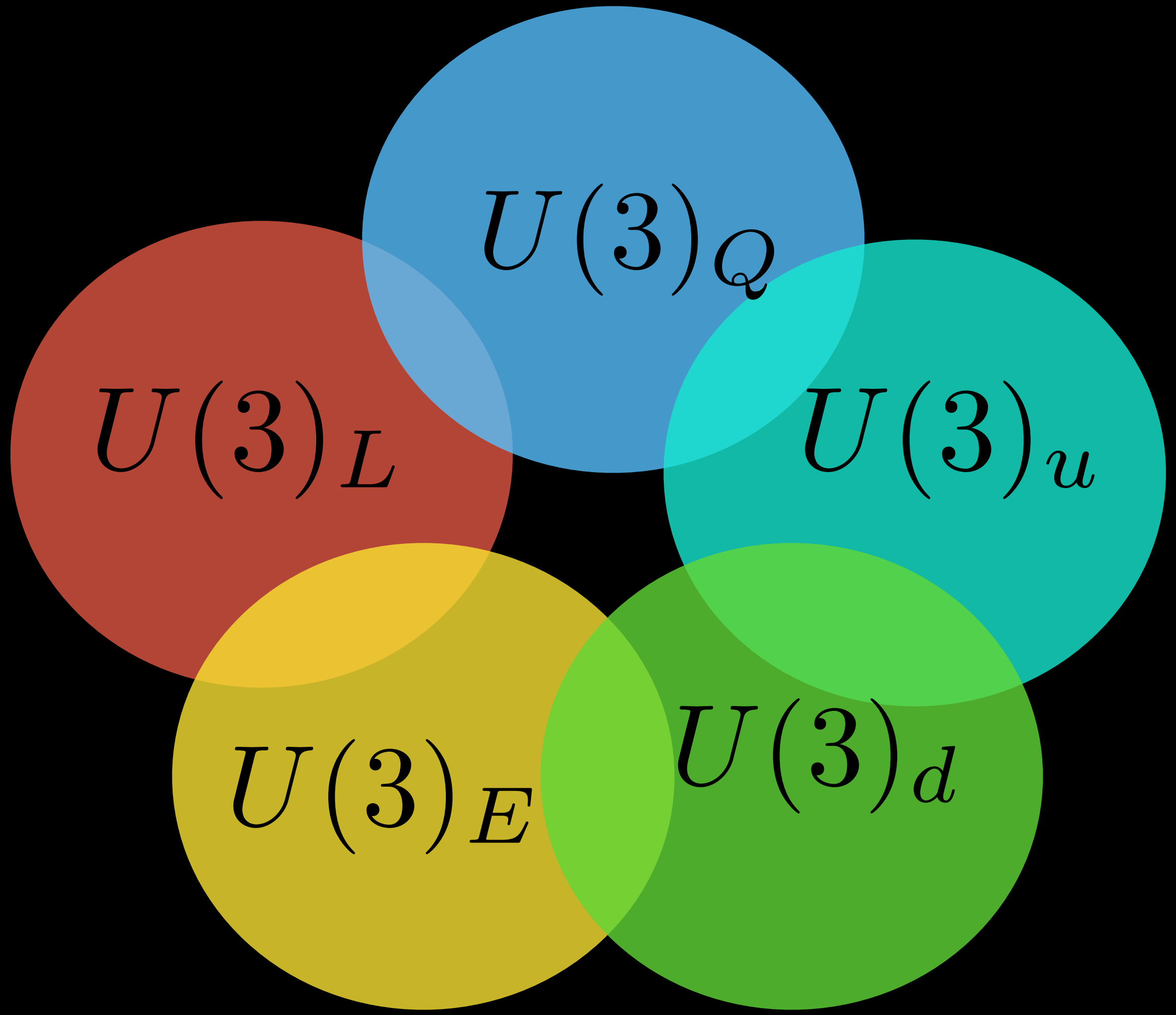

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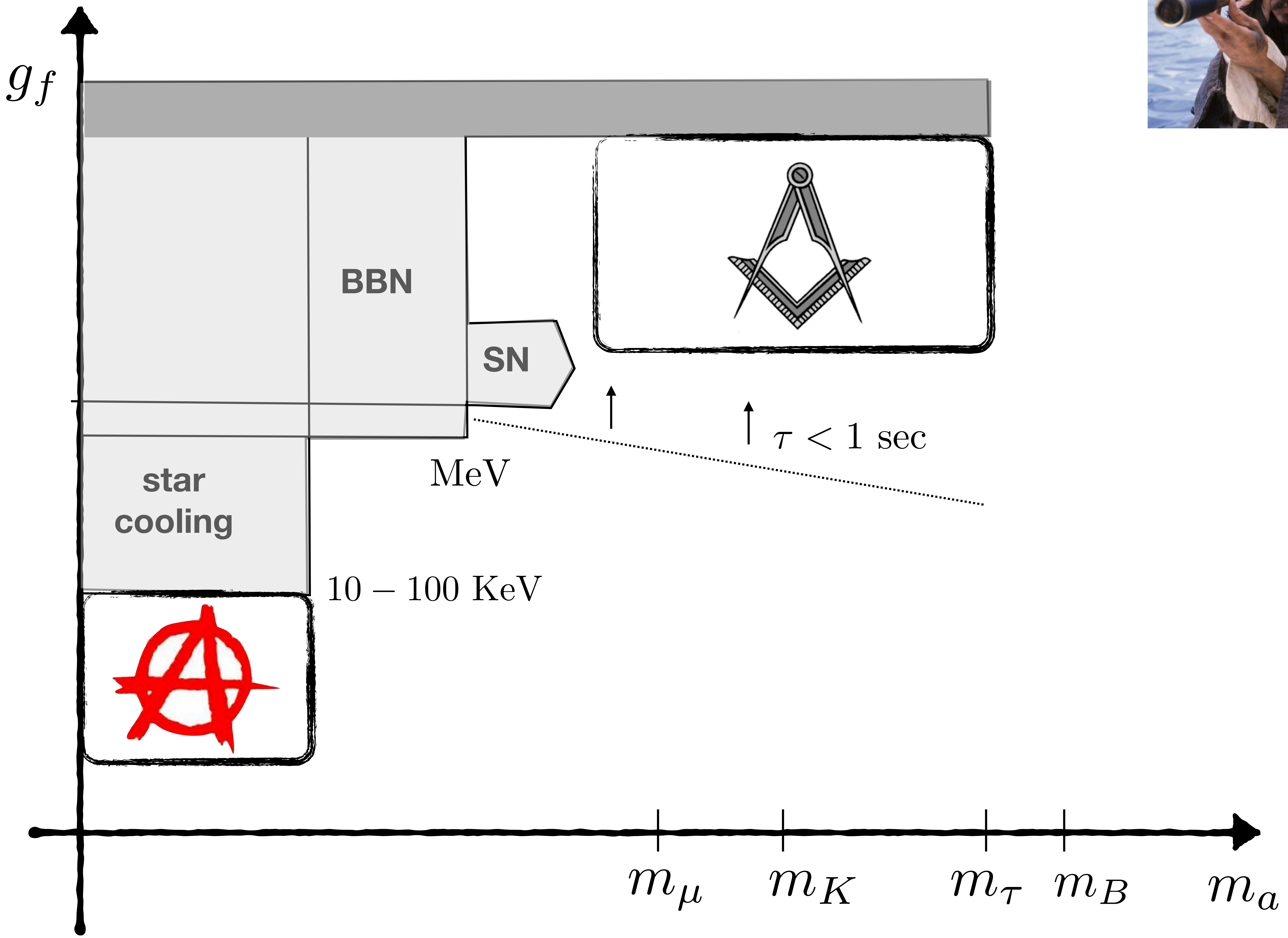
The hierarchy FLAVOR-DIAGONAL vs FLAVOR-VIOLATING depends on the UV flavor theory

Flavor Anarchy: $C^{A,V}_{ij}(\Lambda_{\rm UV}) \sim \mathcal{O}(1)$

Minimal Flavor Violation: $C^{A,V}_{ij}(\Lambda_{\rm UV}) = 0$

Theory landscape



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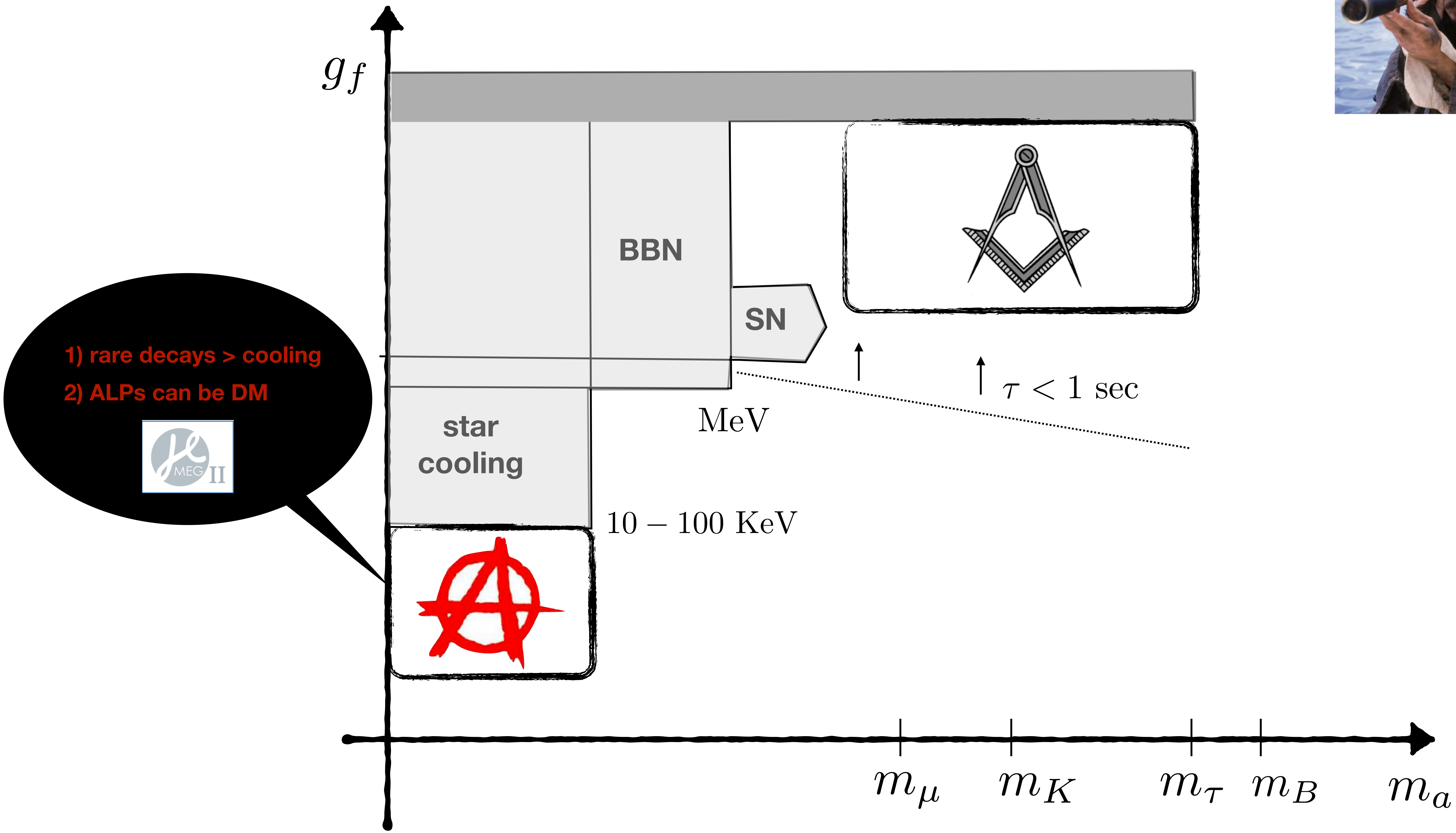

Theory landscape

Triggers

Enormous luminosities poses trigger challenges

We need to know what to look for in advance

MEG II as an example

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MEG II as an example

see arXiv 2006.04795
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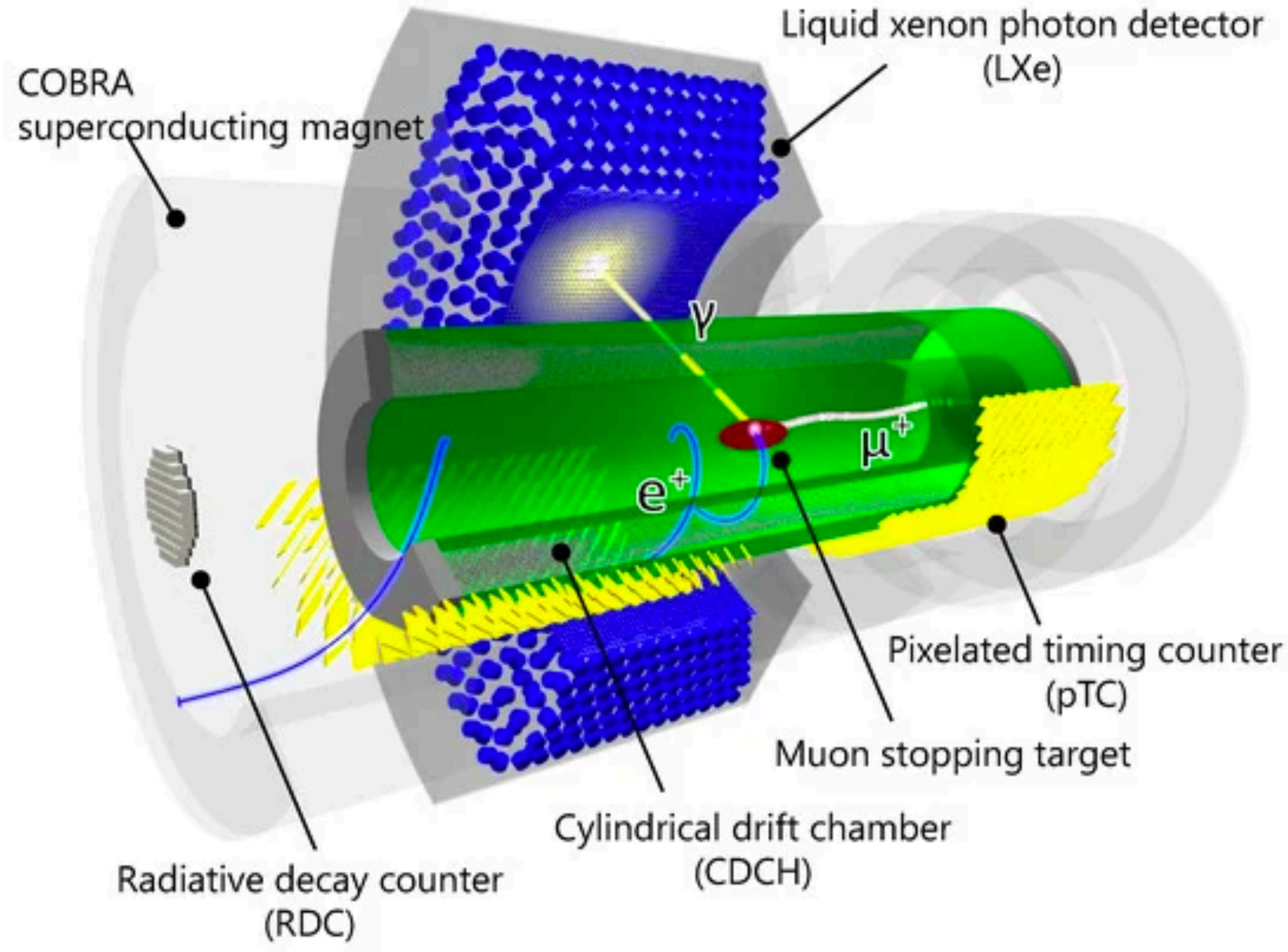
MEG II

$\mathrm{BR}(\mu \to e\gamma) < 4.2 \times 10^{-13}$ MEG 2016



Trigger level info:

1) Photon energy by liquid Xenon scintillator

2) hit on the timing counter

Offline:

3) full mesure of the positron momentum

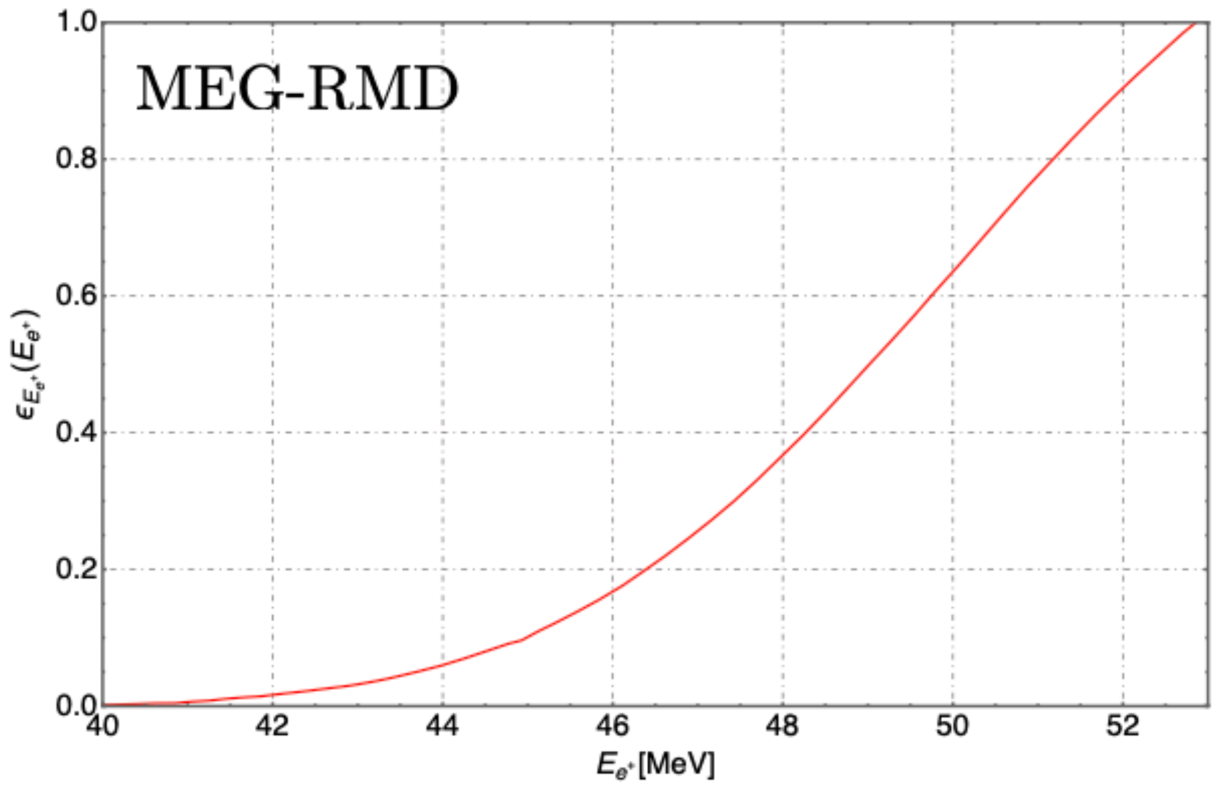
Trigger Selection

$\mathrm{BR}(\mu \to e\gamma) < 4.2 \times 10^{-13}$ MEG 2016 $\longleftrightarrow$ 1) very high intensity
2) very exclusive trigger targeted at $\mu \to e\gamma$

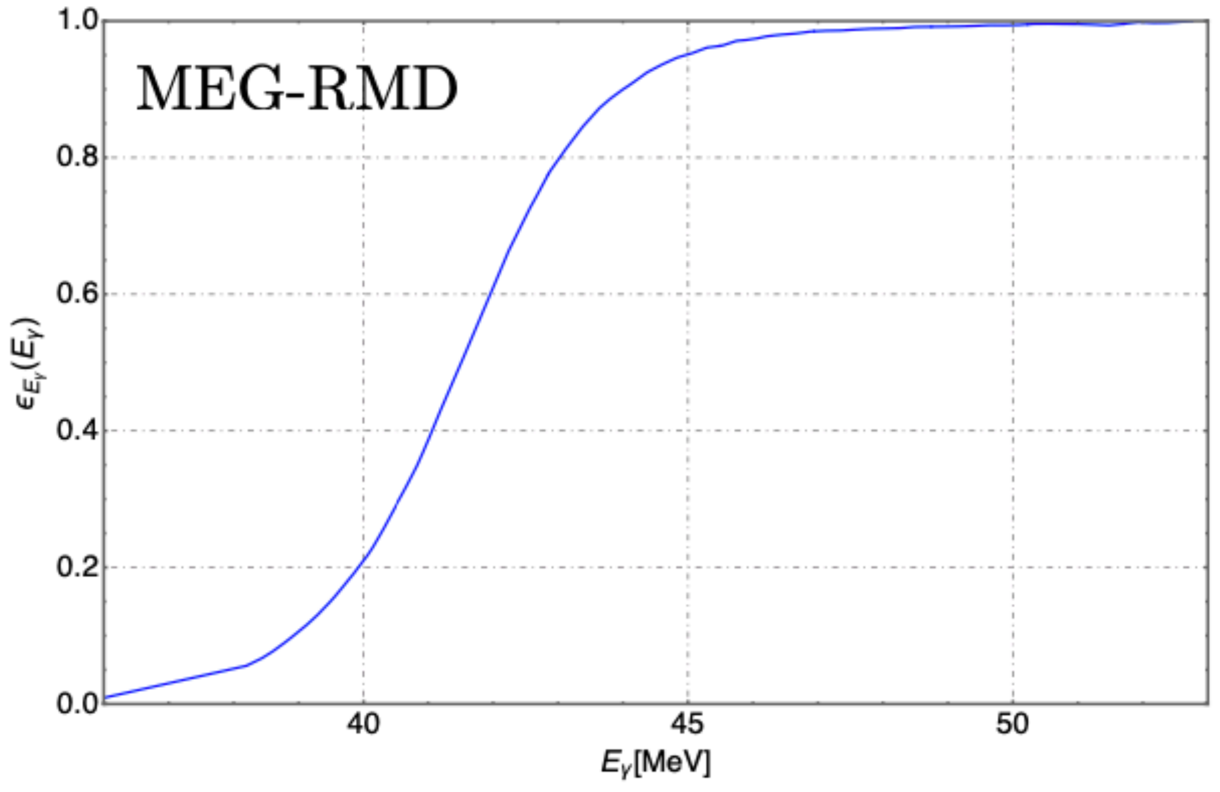
The trigger maximize the efficiency to back to back positron-photon of $E = m_\mu/2$

See Galli et al. *JINST 9 (2014)*

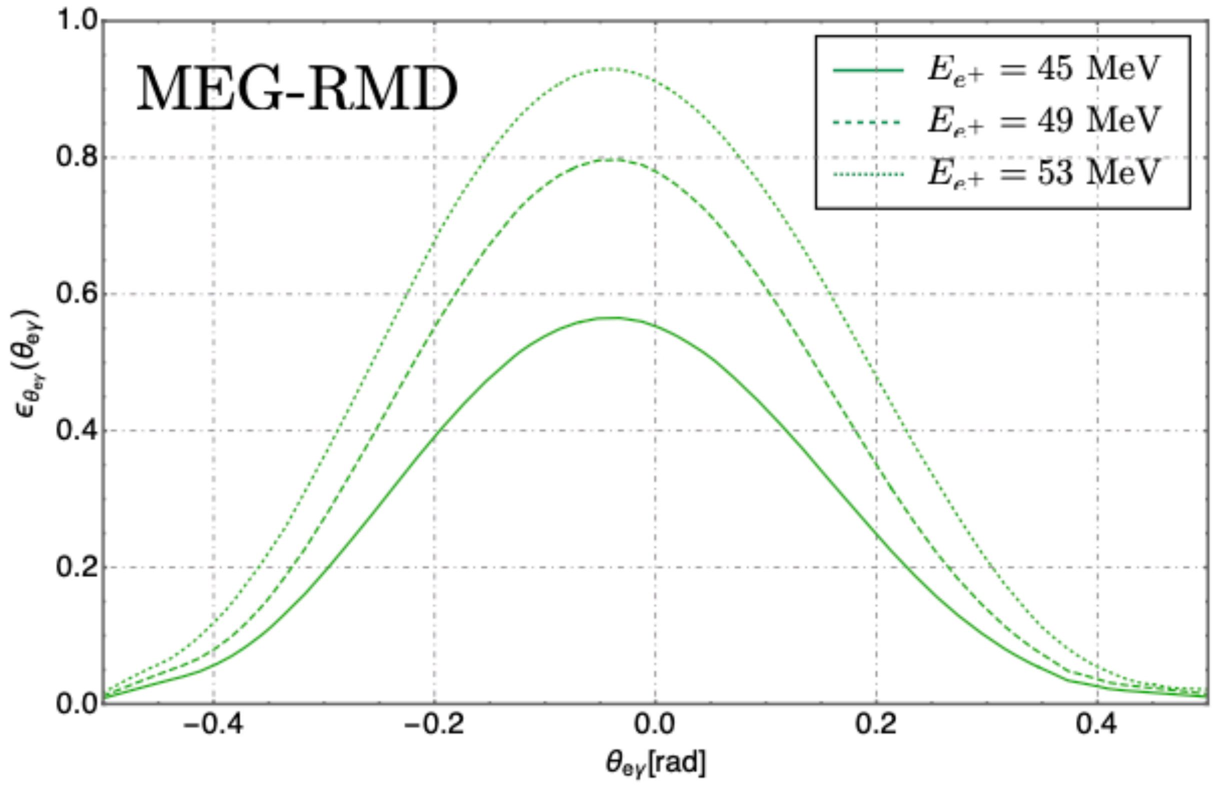
Positron energy >45 MeV hardware



Photon >45 MeV @ trigger level



back to back topology @ trigger level



Taken from *MEG-RMD measurement 1312.3217*

In numbers…

Besides $R_{\mu^+}^{\mathrm{MEG}} = 3 \times 10^7 \mu^+/\mathrm{sec}$ intensity

Very little data can be saved on disk or analysed offline at MEG II

The maximal allowed stream is around 10 Hz

Online the trigger should select 1 “interesting” muon event out of 10^7

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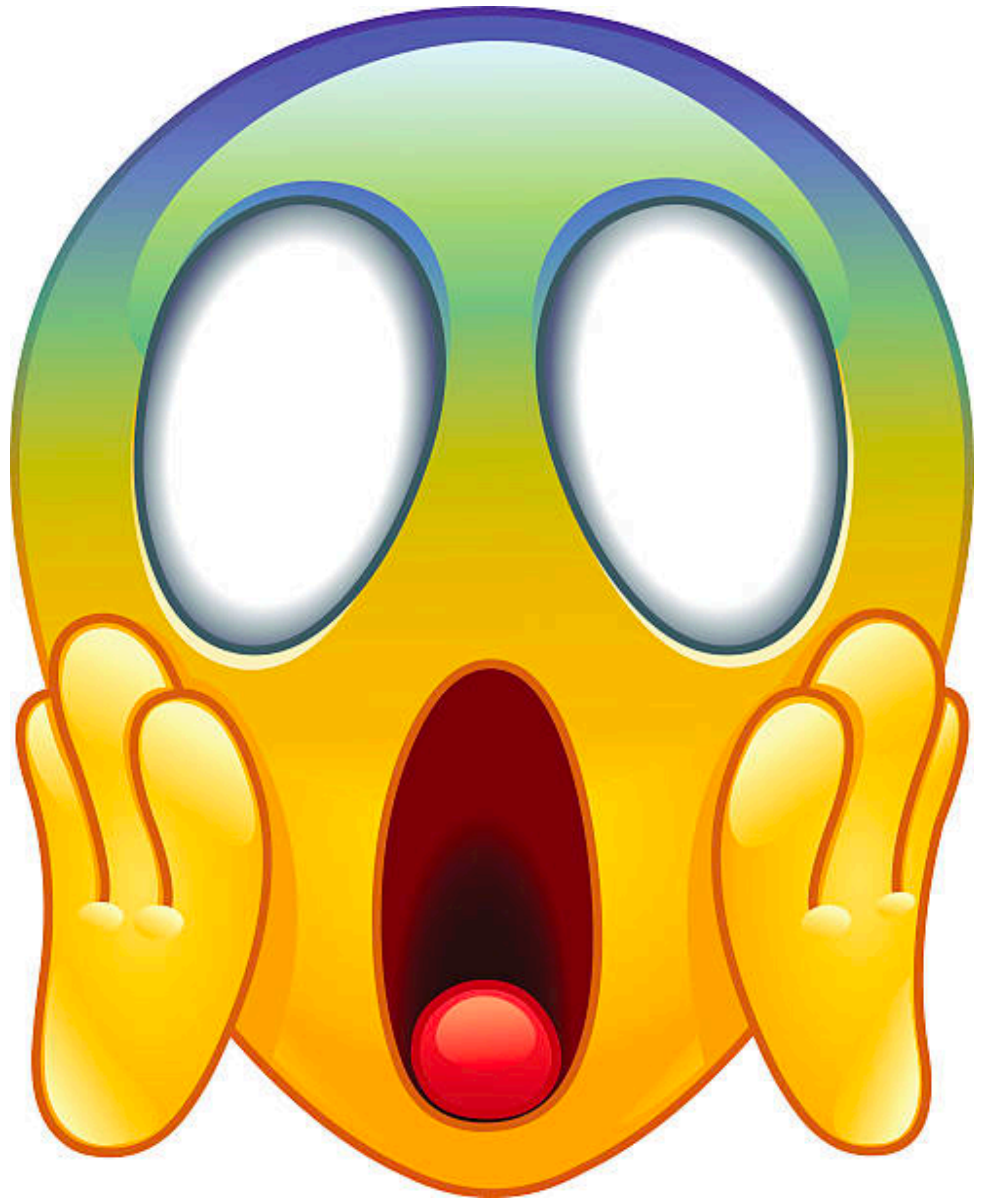
All the rest of the data is lost!



Light new physics vs Lepton Flavor

Accidental symmetries of the Standard Model might be broken by light new particles feebly coupled to the SM

These light particles naturally emerges in models where Lepton Flavor is broken spontaneously at high scale (familon, axion, axion-like particles, majorons)

See. *L. Calibbi, D.R., R. Ziegler, J. Zupan 2006.04795*

Light pseudo-Goldstone bosons (or ALP) $m_a \ll m_\mu$

LFV @ dimension 5

$$\mathcal{L}_{\rm eff}^{\rm LFV} \supset \frac{\partial_\mu a}{2 f_a}\, \bar{\mu}\gamma^\mu (C^V_{\mu e} + C^A_{\mu e}\gamma_5) e + \frac{\partial_\mu a}{f_a} \bar{e}\gamma^\mu\gamma_5 e + \frac{m_a^2}{2} a^2 + \frac{1}{f_a^2} \dots$$

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Heavy scale not accessible with dipoles

$$c\tau \sim \frac{8\pi f_a^2}{m_a^3} \gg L_{\rm detector}$$

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Interplay between flavor experiments and astrophysics

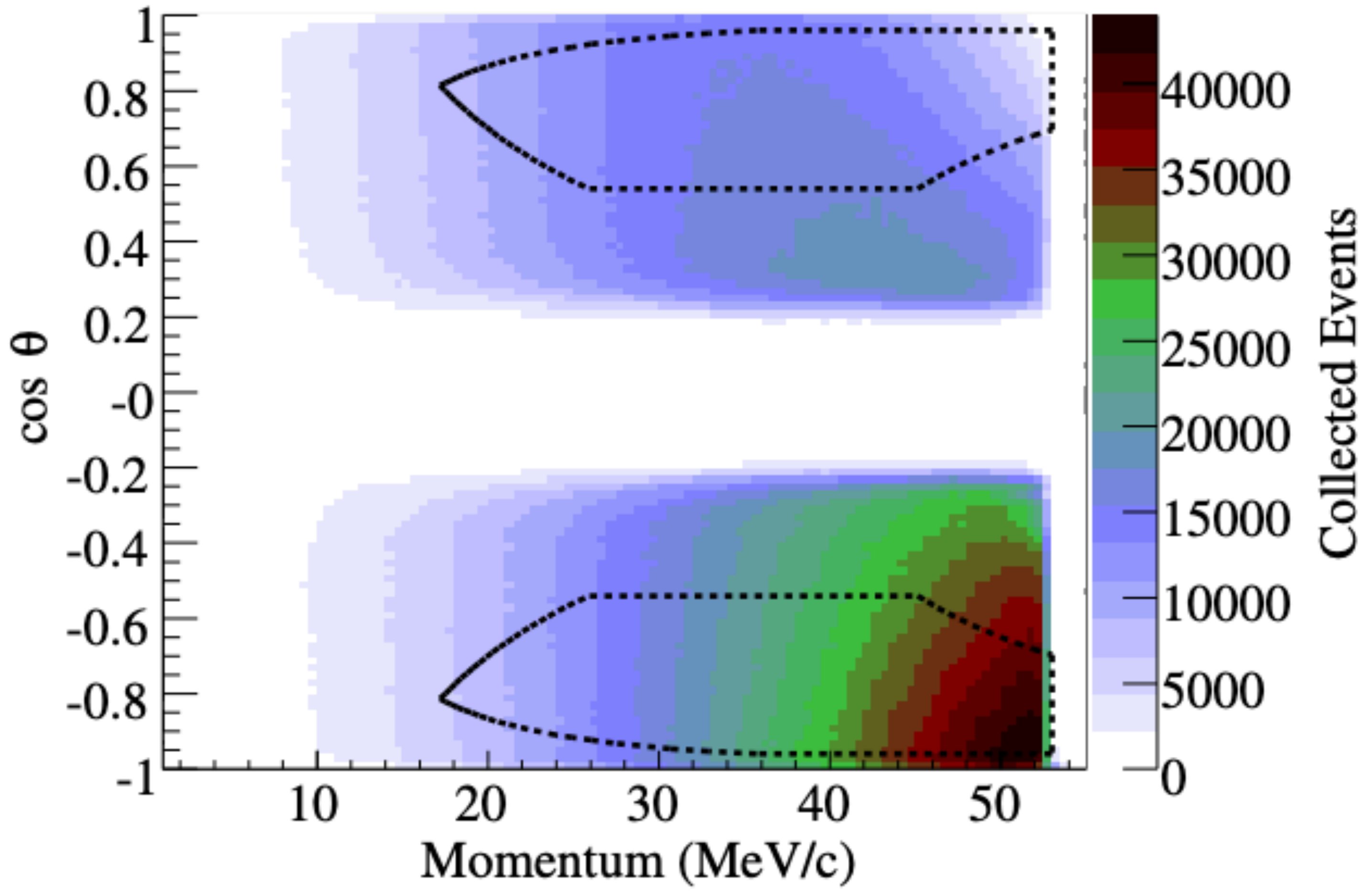
Light new physics experimental paradigm

Hunt for rare muon decays with missing energy

$\mu \to ea$

Huge irreducible background from Michel $\mu \to e\nu\bar{\nu}$

See. *TWIST 1409.0638*



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bkd suppressed in the fwd region

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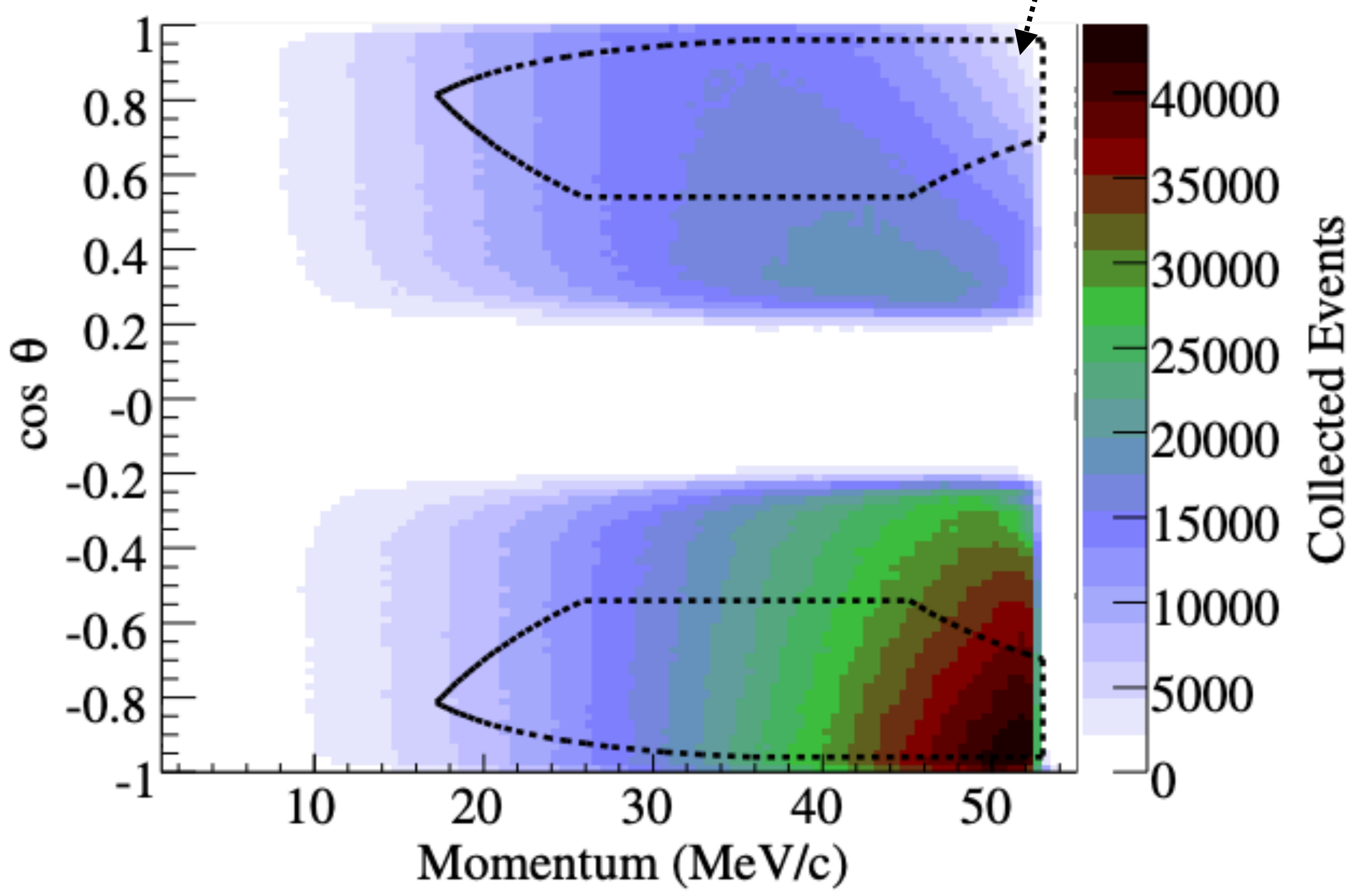

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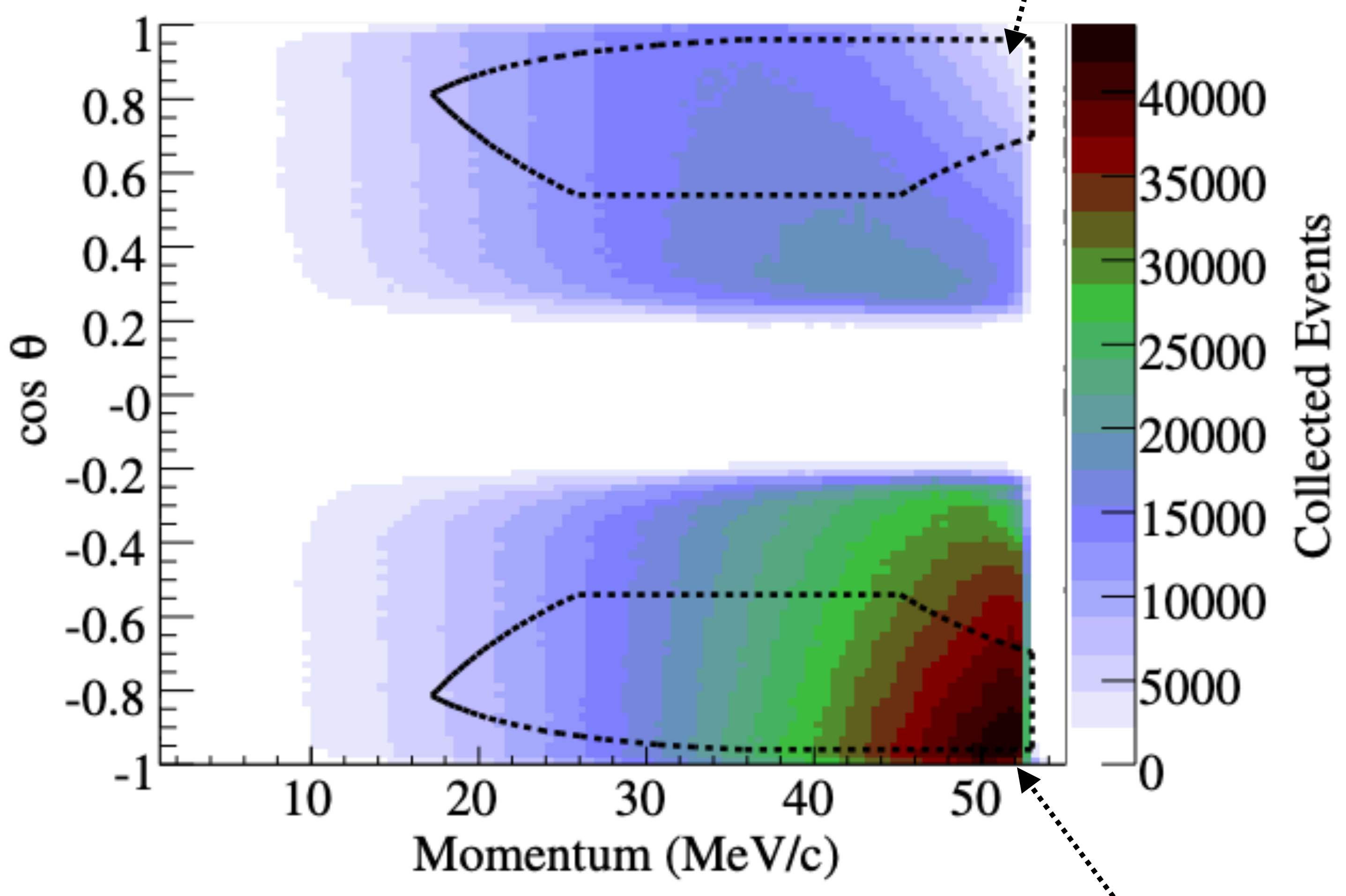

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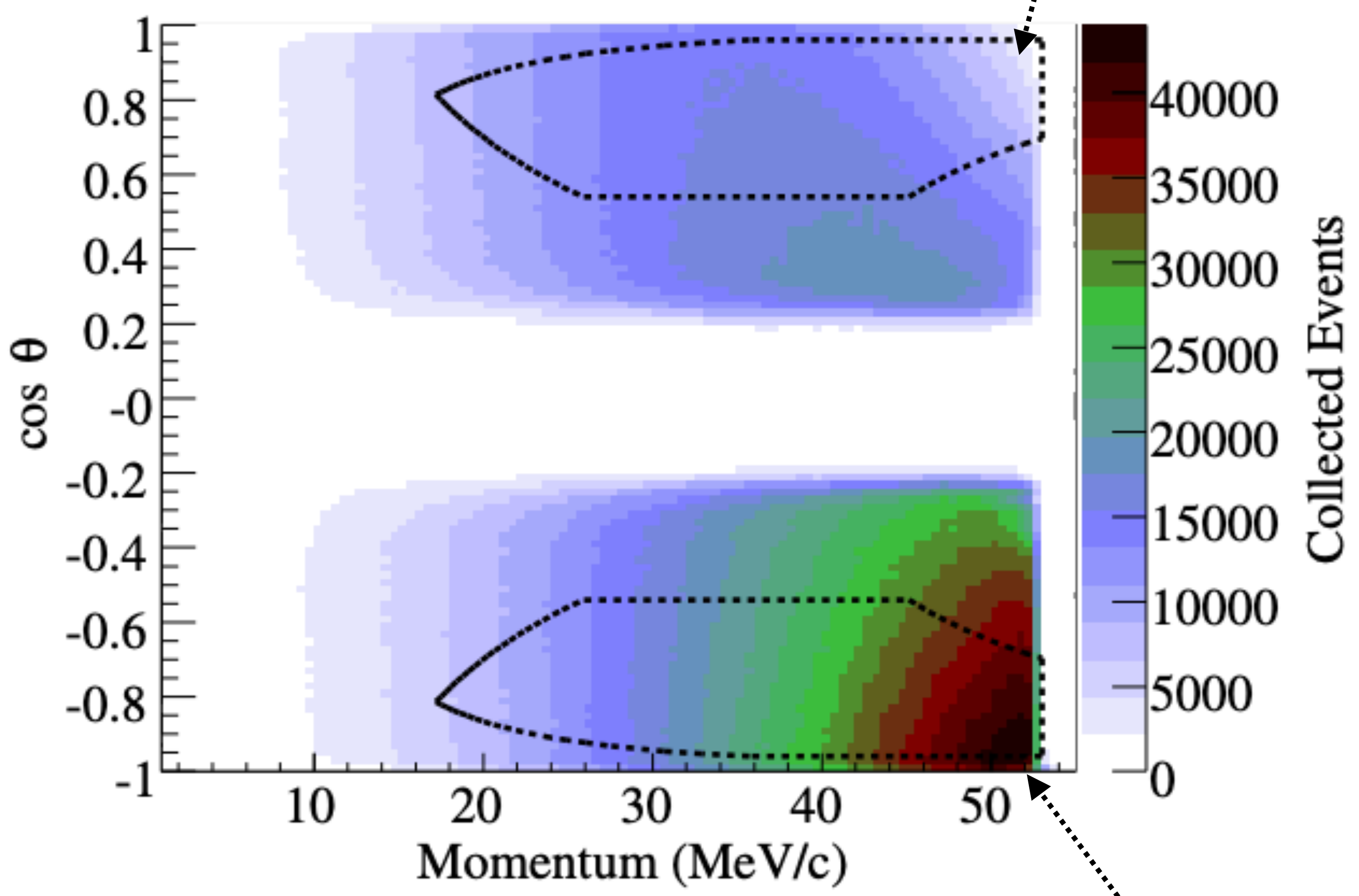


bkd enhanced in the bkwd region

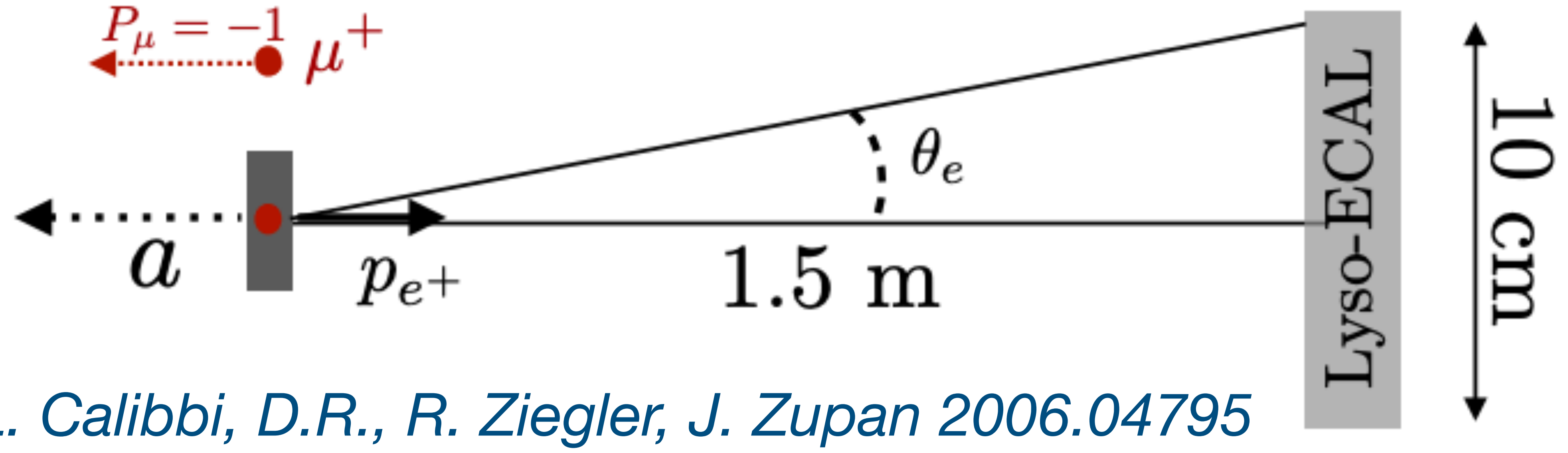
$\mu \to ea\gamma$

The extra photon helps constructing a missing mass distribution which is not used for calibration

The price to pay is a reduced signal by $\sim \frac{\alpha}{2\pi} \log \frac{2E_\gamma}{m_\mu}$

See *Jho, Knapen, D.R. 2112.07720*

Looking forward for right-handed ALPs



L. Calibbi, D.R., R. Ziegler, J. Zupan 2006.04795

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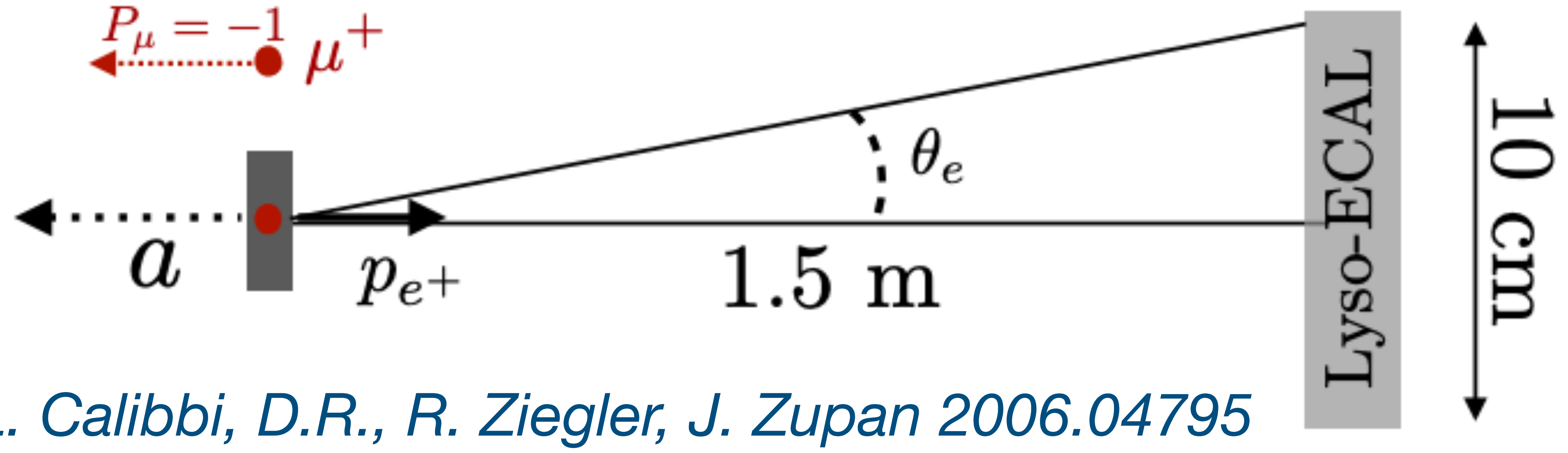

L. Calibbi, D.R., R. Ziegler, J. Zupan 2006.04795

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1) good momentum resolution $\delta x_e \sim \%$
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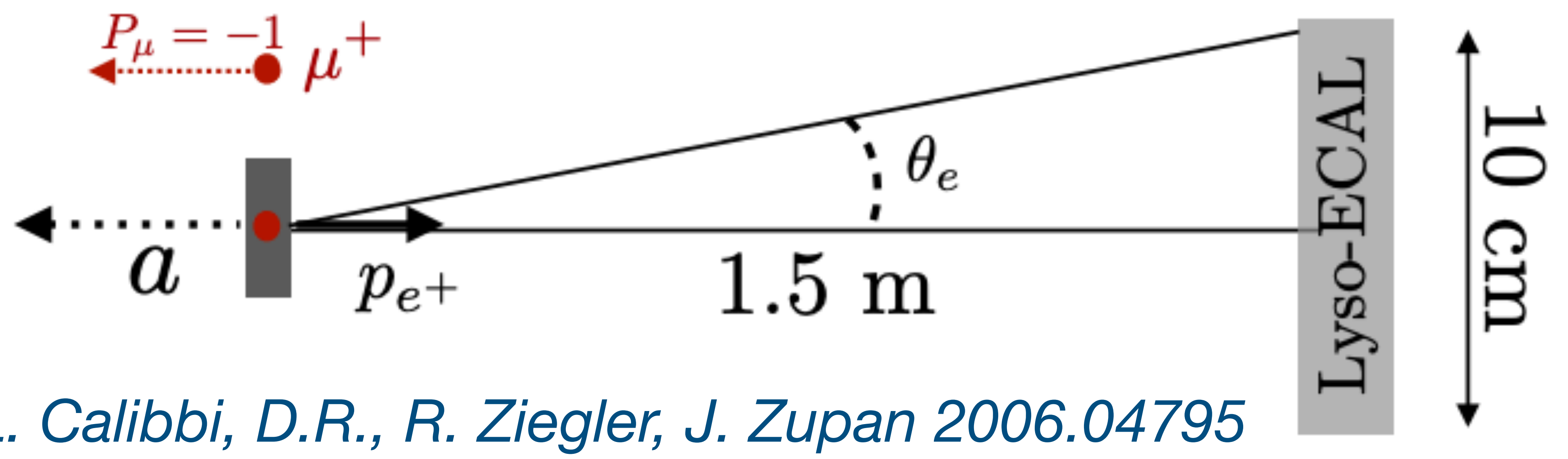

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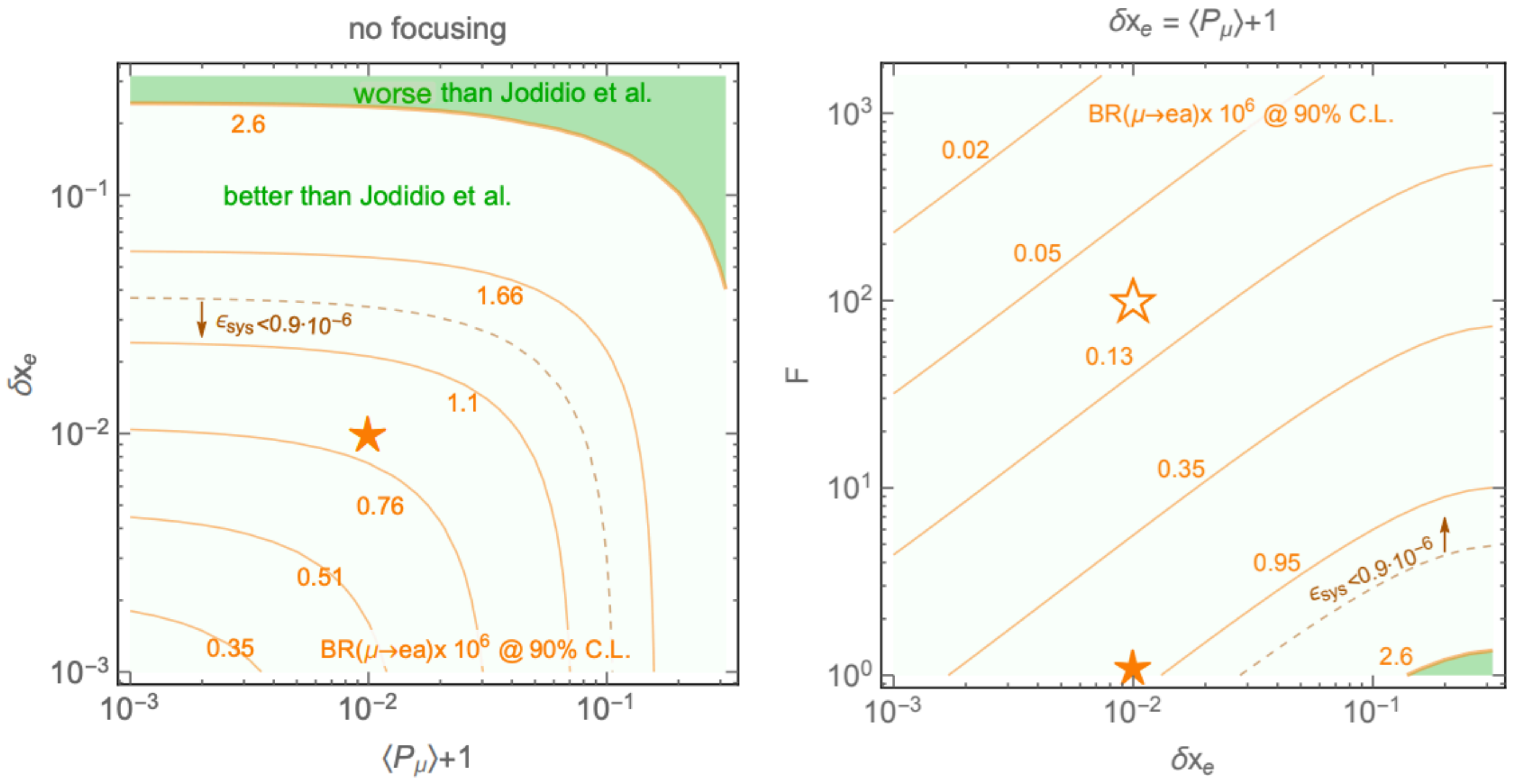

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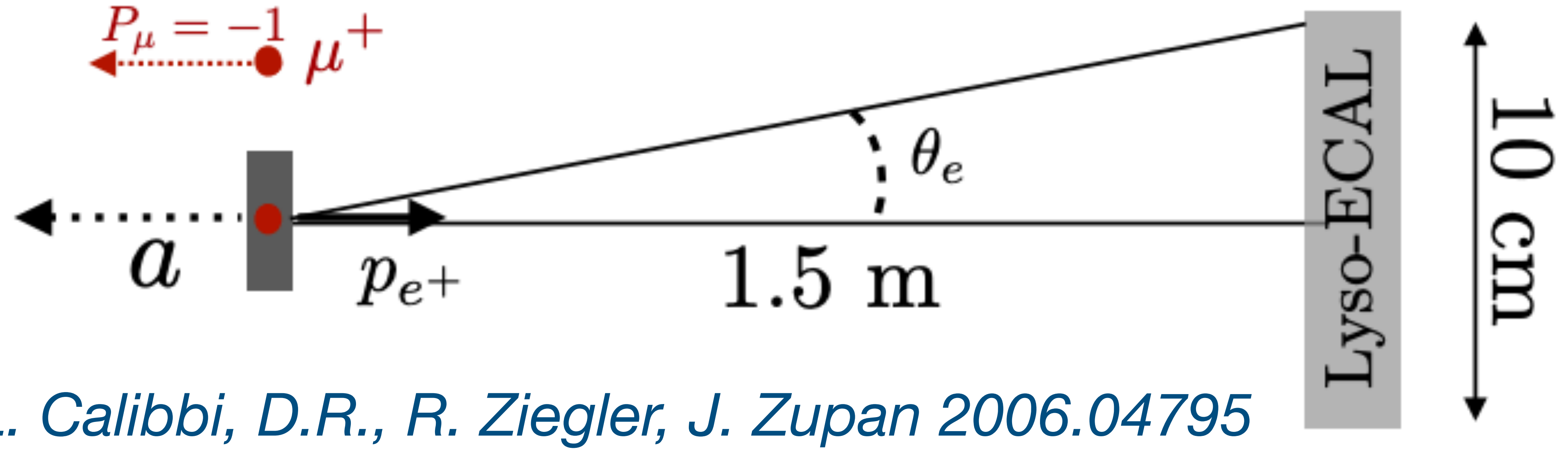

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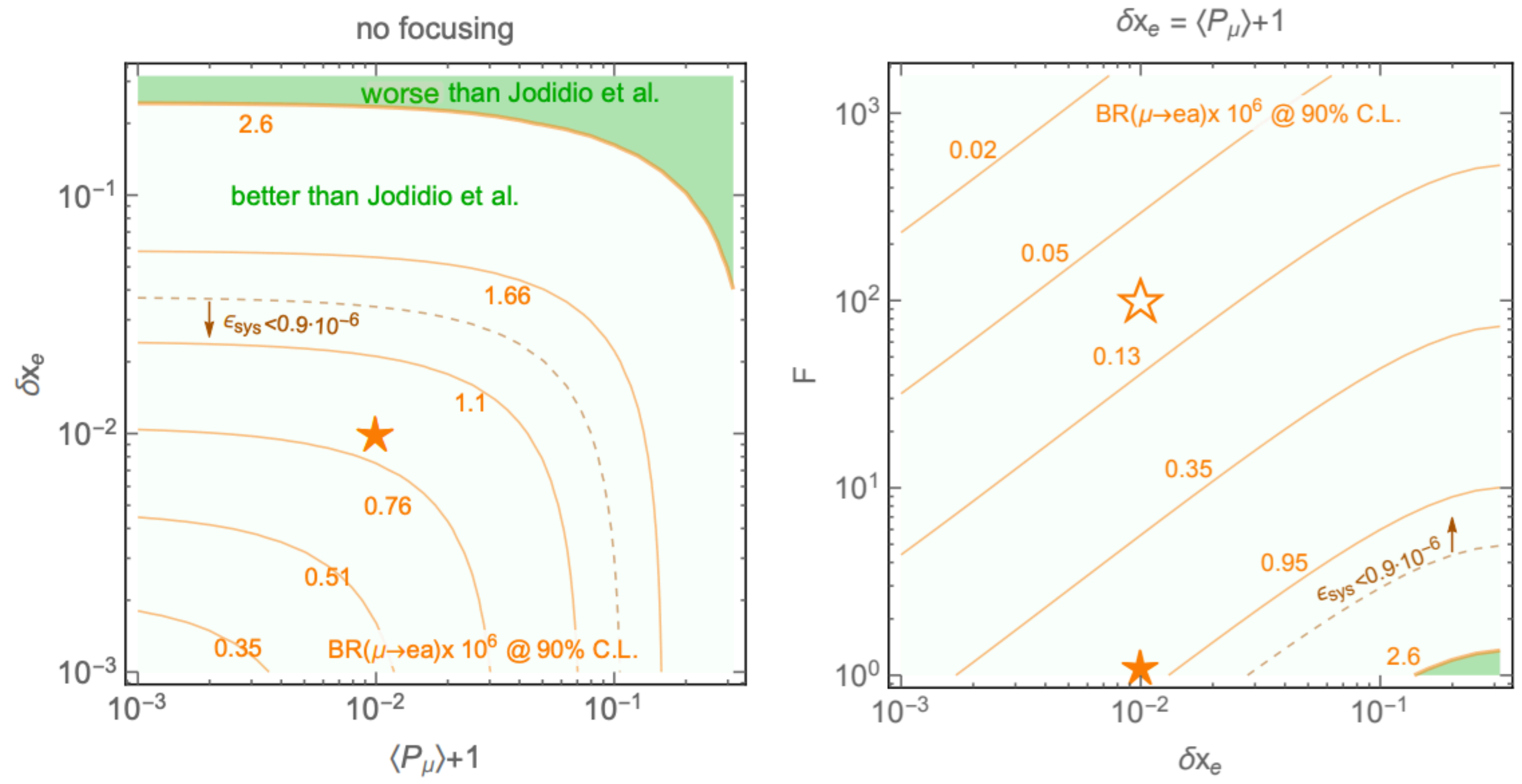

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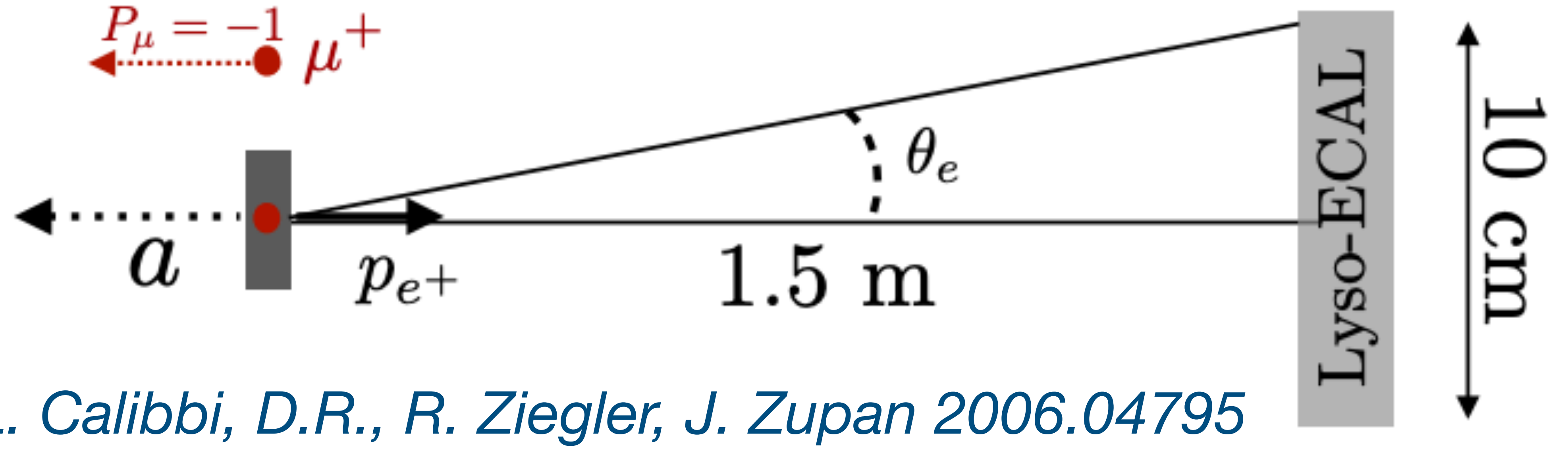
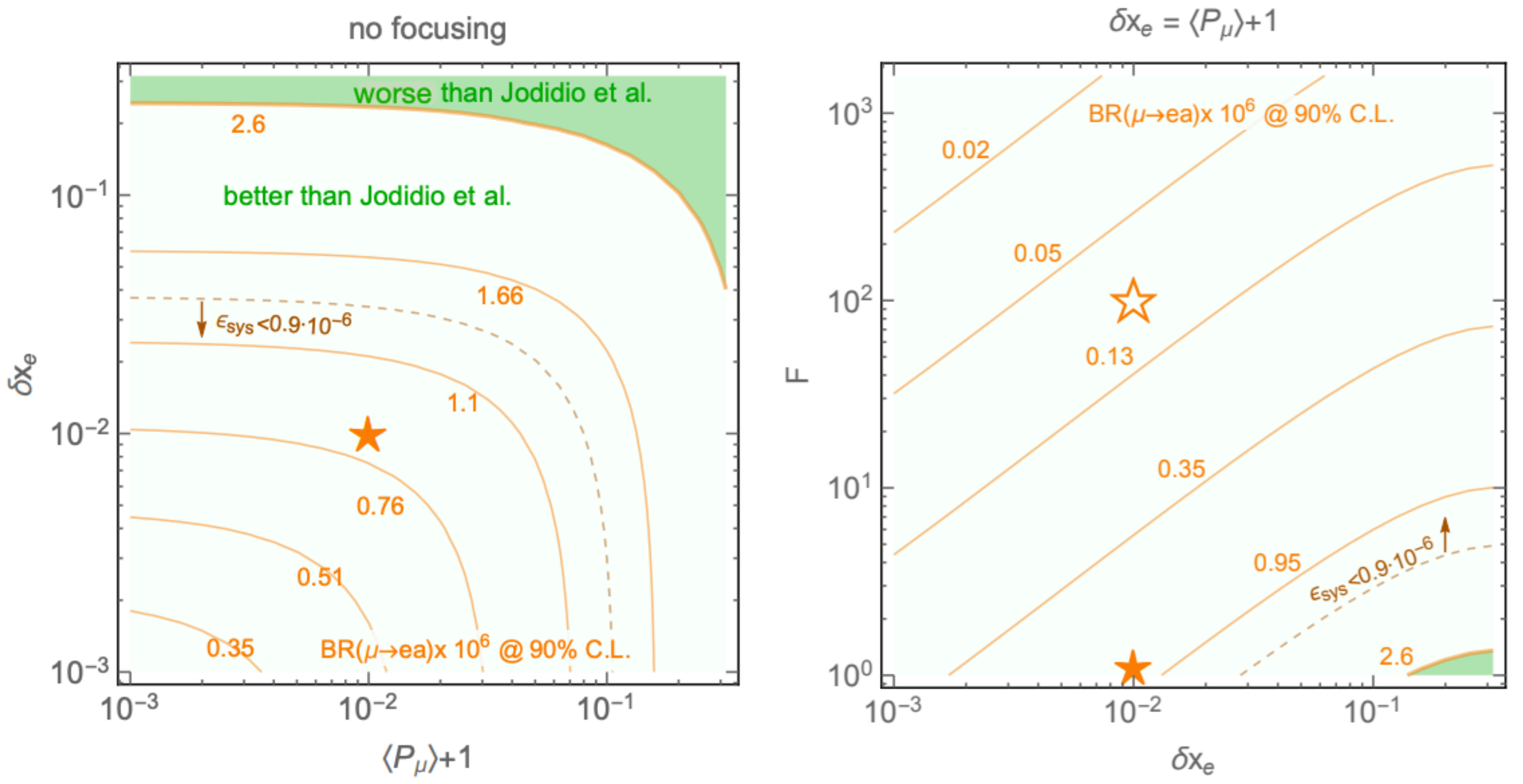
2) purely polarized muon beam $\delta P_\mu \sim 10^{-2}$

A good signal reach requires further:
3) magnetic field focusing F $F \sim 10^2$
4) large luminosity $N_\mu \sim 10^{14} \mu^+$
5) very low systematics

Looking forward for right-handed ALPs



L. Calibbi, D.R., R. Ziegler, J. Zupan 2006.04795



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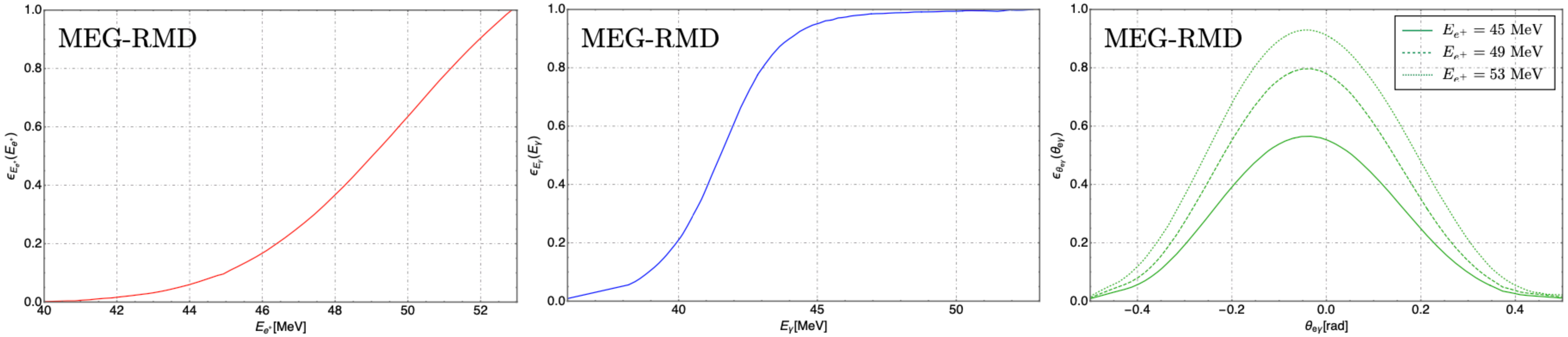
These conditions have been realized before in the Iodidio's exp.

Iodidio et al. (1986)

Can it be done again?

Towards a new data taking strategy

Logic: the trigger requirements are killing the ALP signal



*

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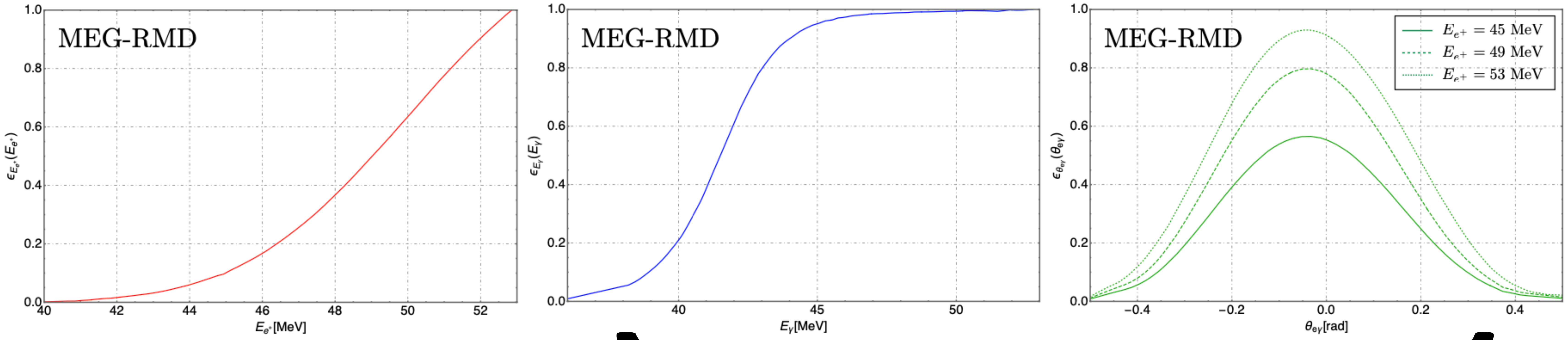

1) Eliminating the matching of the TC hit which assumes back to back topology

2) Lowering the photon trigger threshold reducing the beam intensity

*

Towards a new data taking strategy

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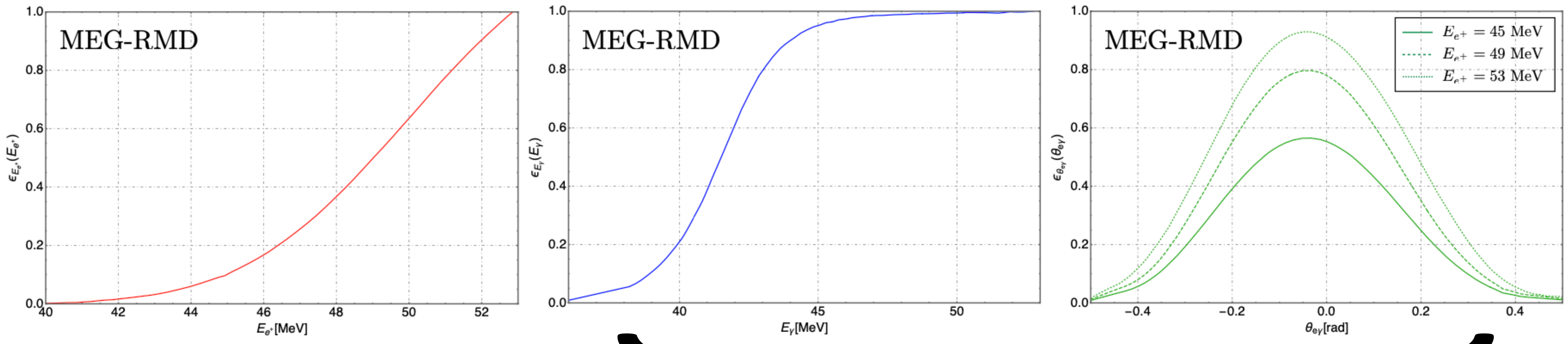


1) Eliminating the matching of the TC hit which assumes back to back topology

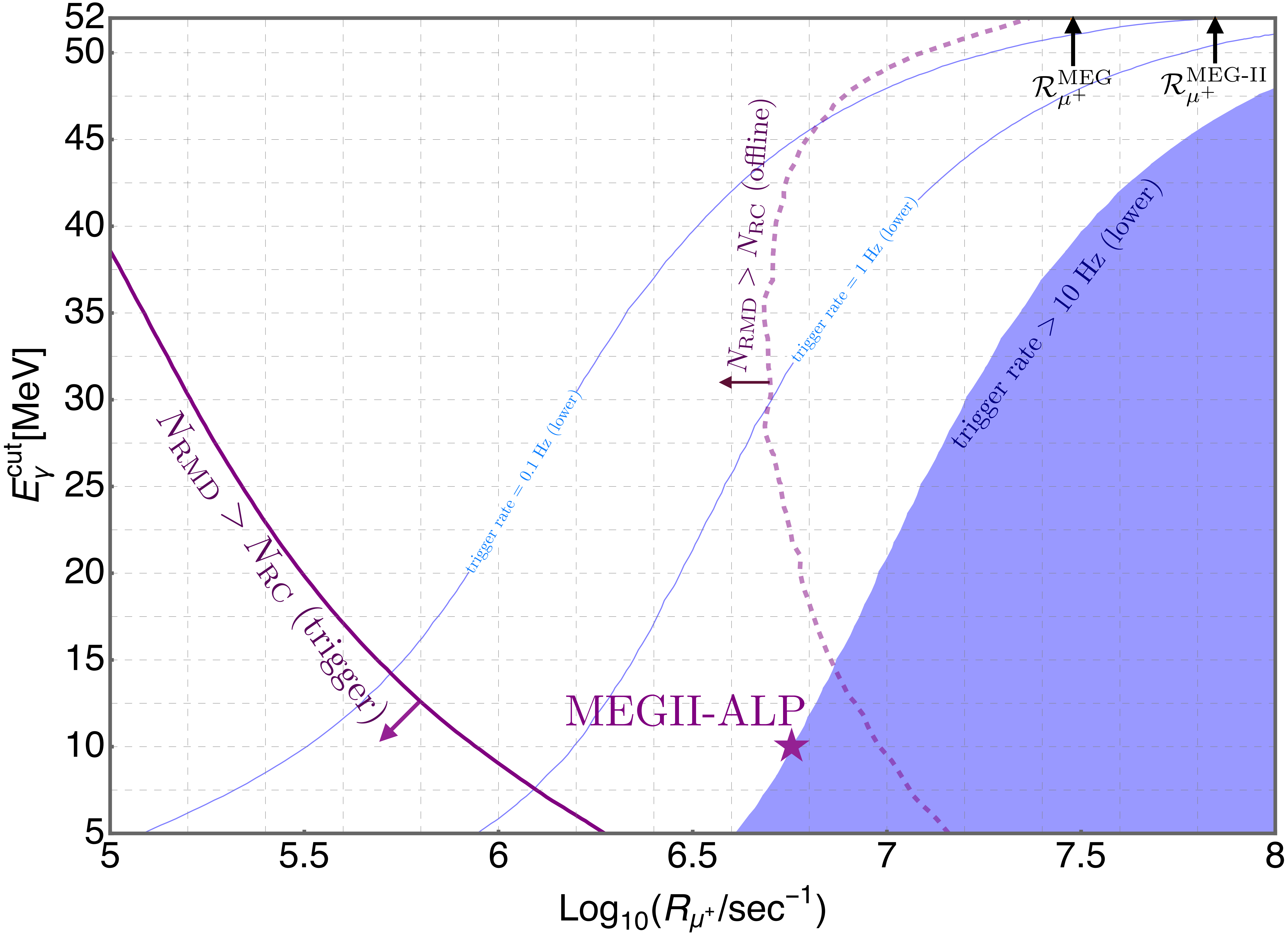
2) Lowering the photon trigger threshold reducing the beam intensity

The RC dominates the trigger rate but it can be suppressed by reducing* the intensity

$$\mathrm{RC} \sim R_\mu^2 \quad \mathrm{RMD} \sim R_\mu$$

**many thanks to Luca Galli for teaching us all this!*

Towards a new data taking strategy



Max trigger rate 10 Hz

fixes the intensity vs photon cut

RMD becomes the dominant bed

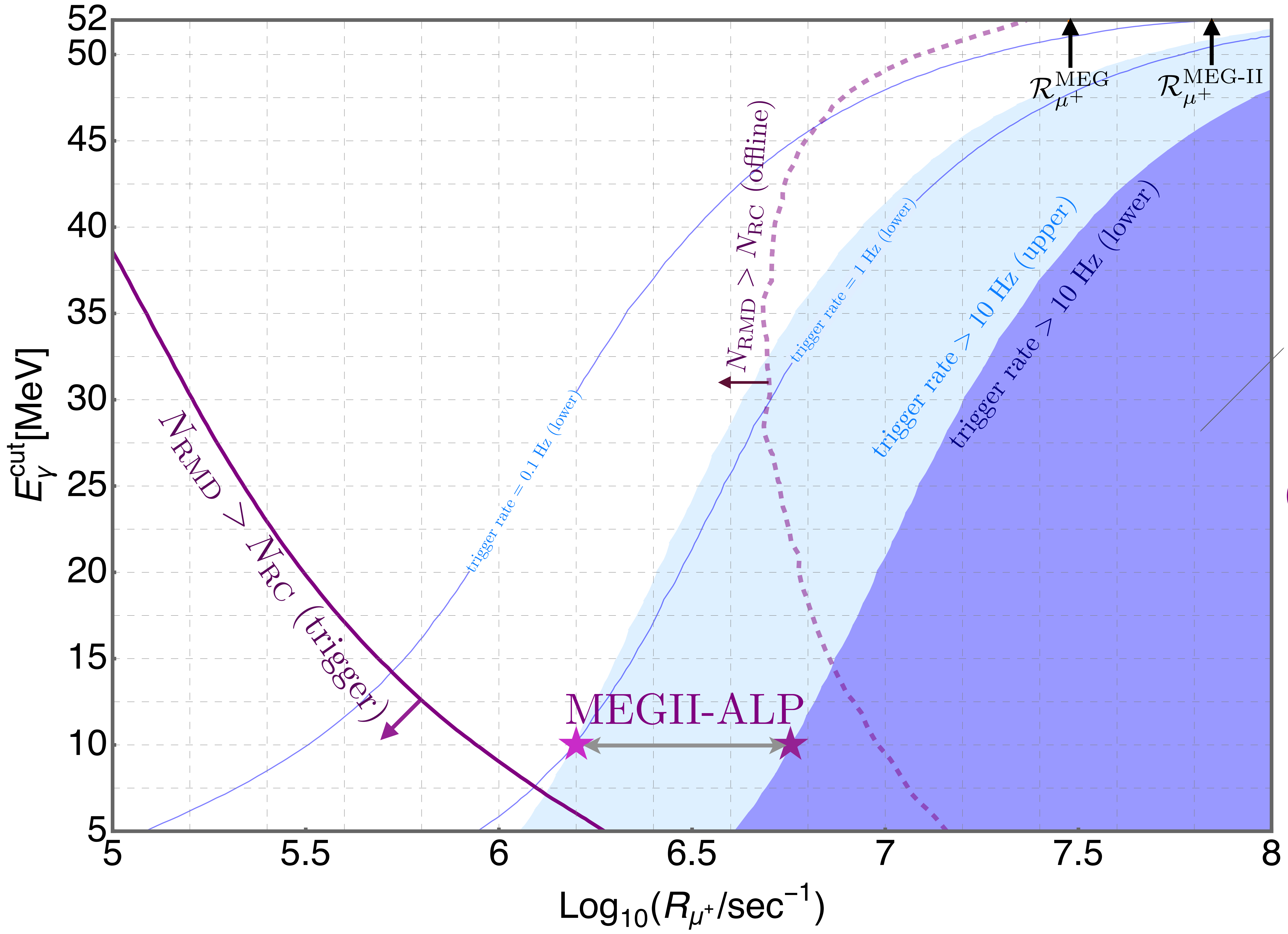
below a certain intensity

(harder to suppress RMD online)

★

Benchmark fixed to the highest intensity for photon energy of 10 MeV given our estimate of the trigger rate

Towards a new data taking strategy



Max trigger rate 10 Hz

fixes the intensity vs photon cut

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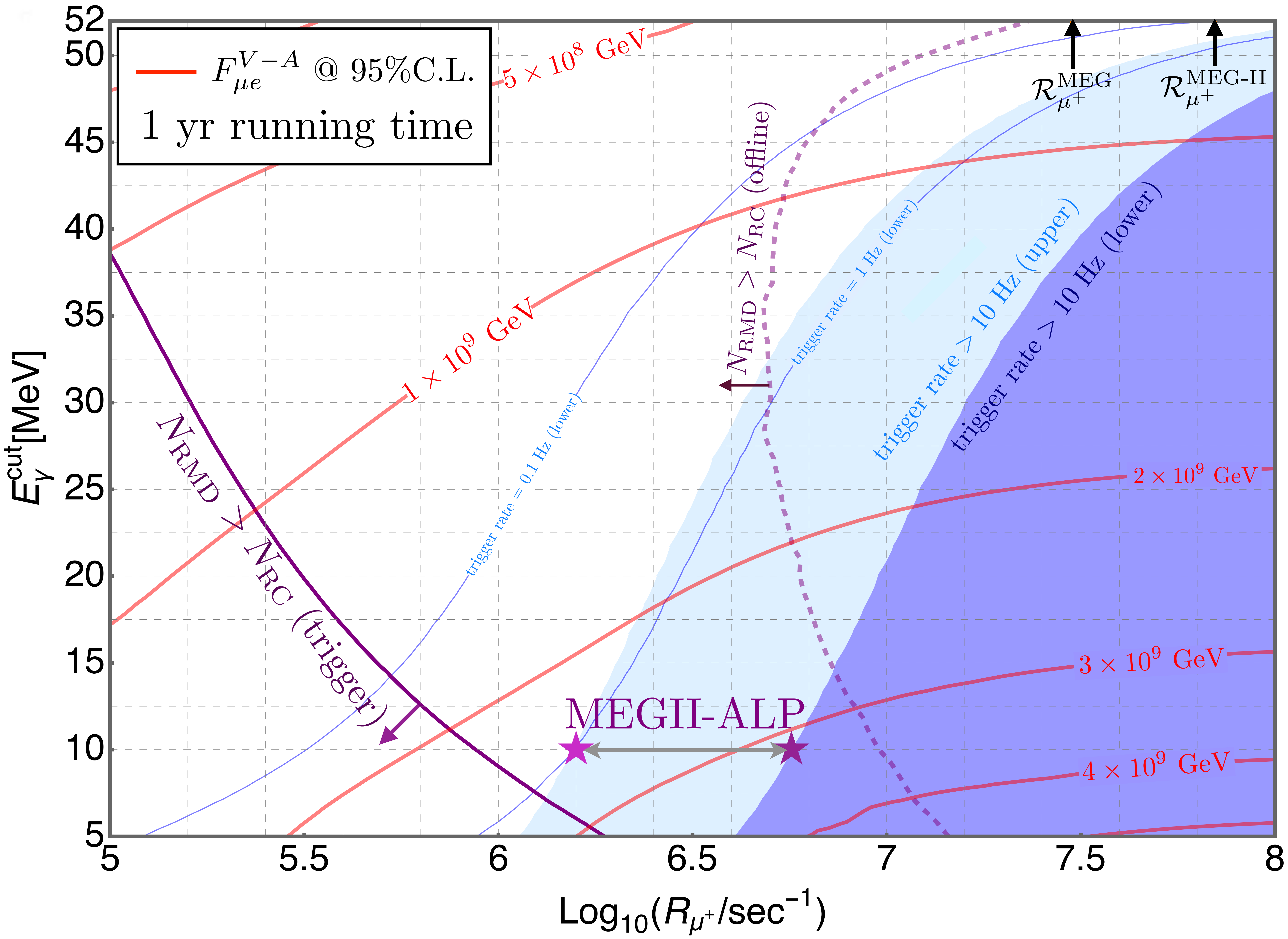
(harder to suppress RMD online)

Uncertainty in trigger rate results in two different benchmark for the same photon energy

Towards a new data taking strategy



Max trigger rate 10 Hz

fixes the intensity vs photon cut

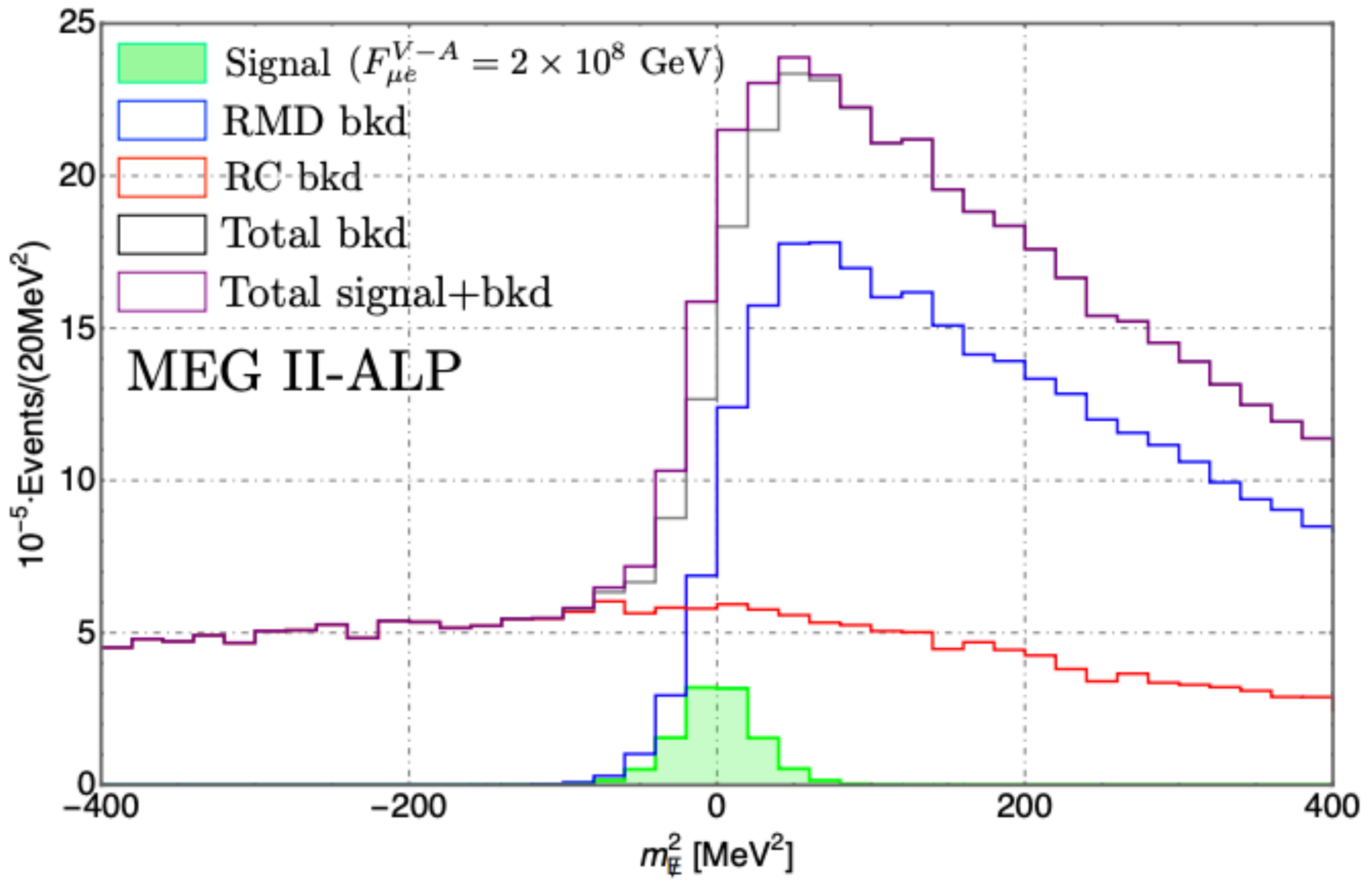
RMD becomes the dominant bkd

below a certain intensity

(harder to suppress RMD online)

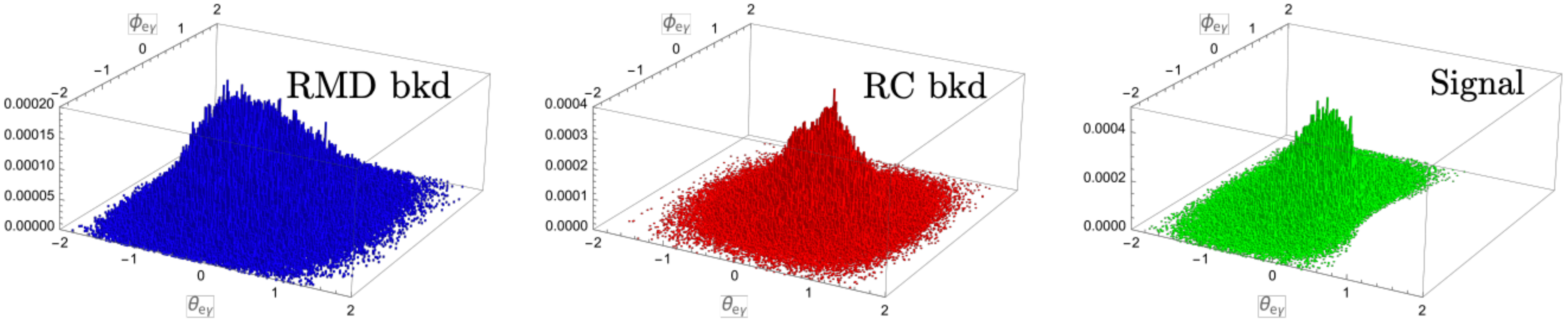
Reach extracted at each point!

Final reach



Bump hunt in missing mass*

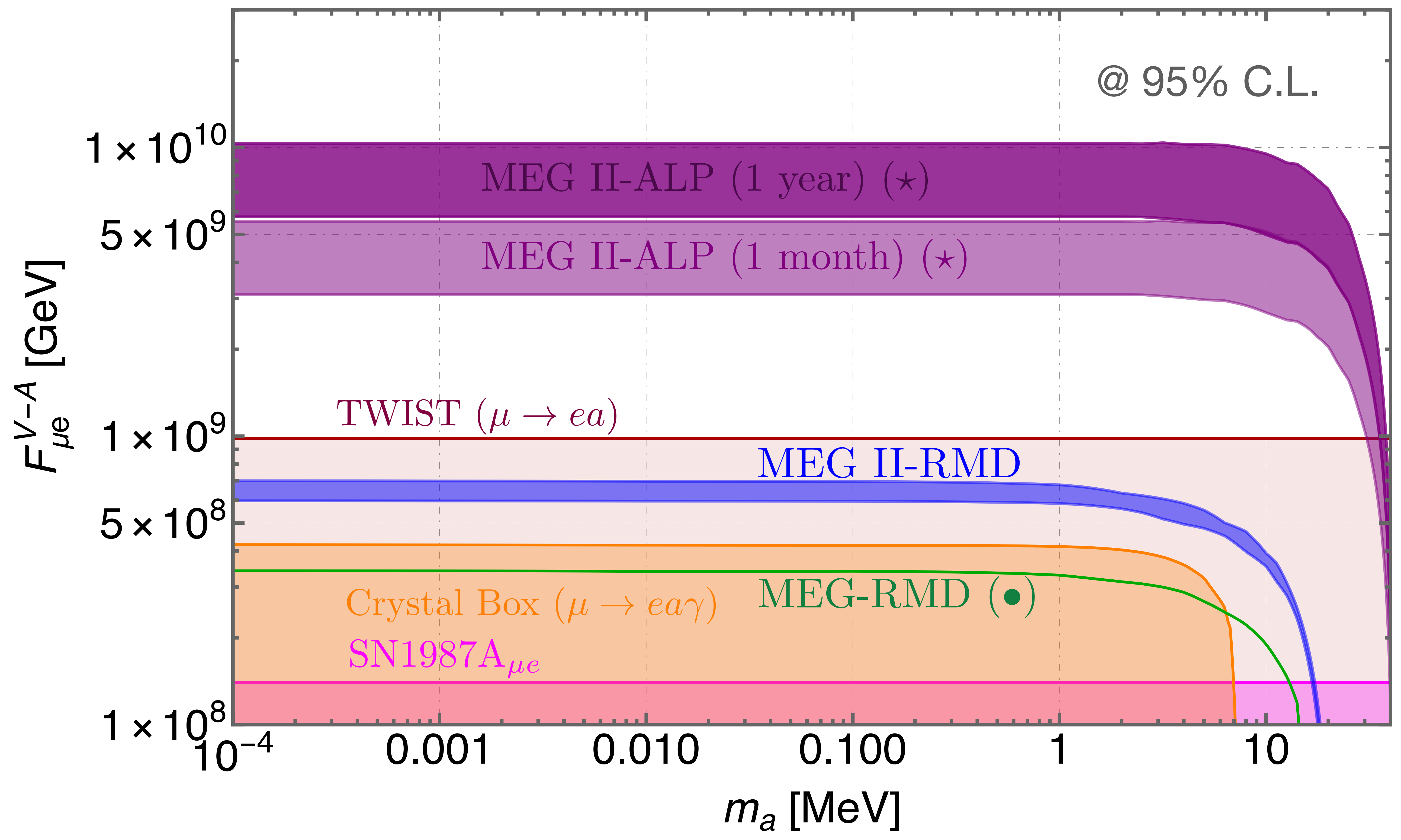
*for a massless object we are close to a cliff of the bkd (systematics has to be taken into account)



Log-likelihood on angular variables

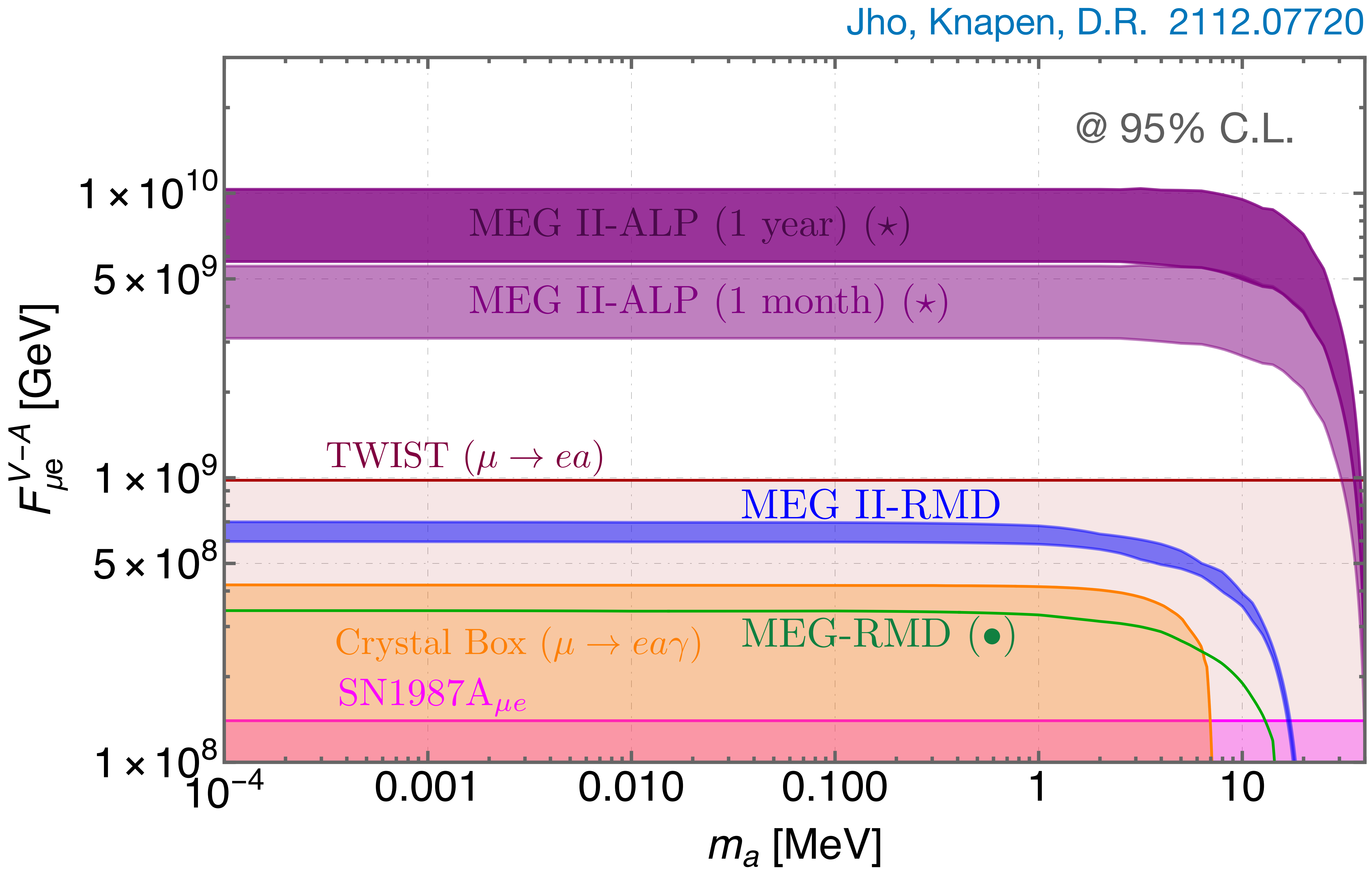
What can we test?

Jho, Knapen, D.R. 2112.07720



MEG-II ALP is the best way to explore ~ a decade of unconstrained parameter space ~ NOW

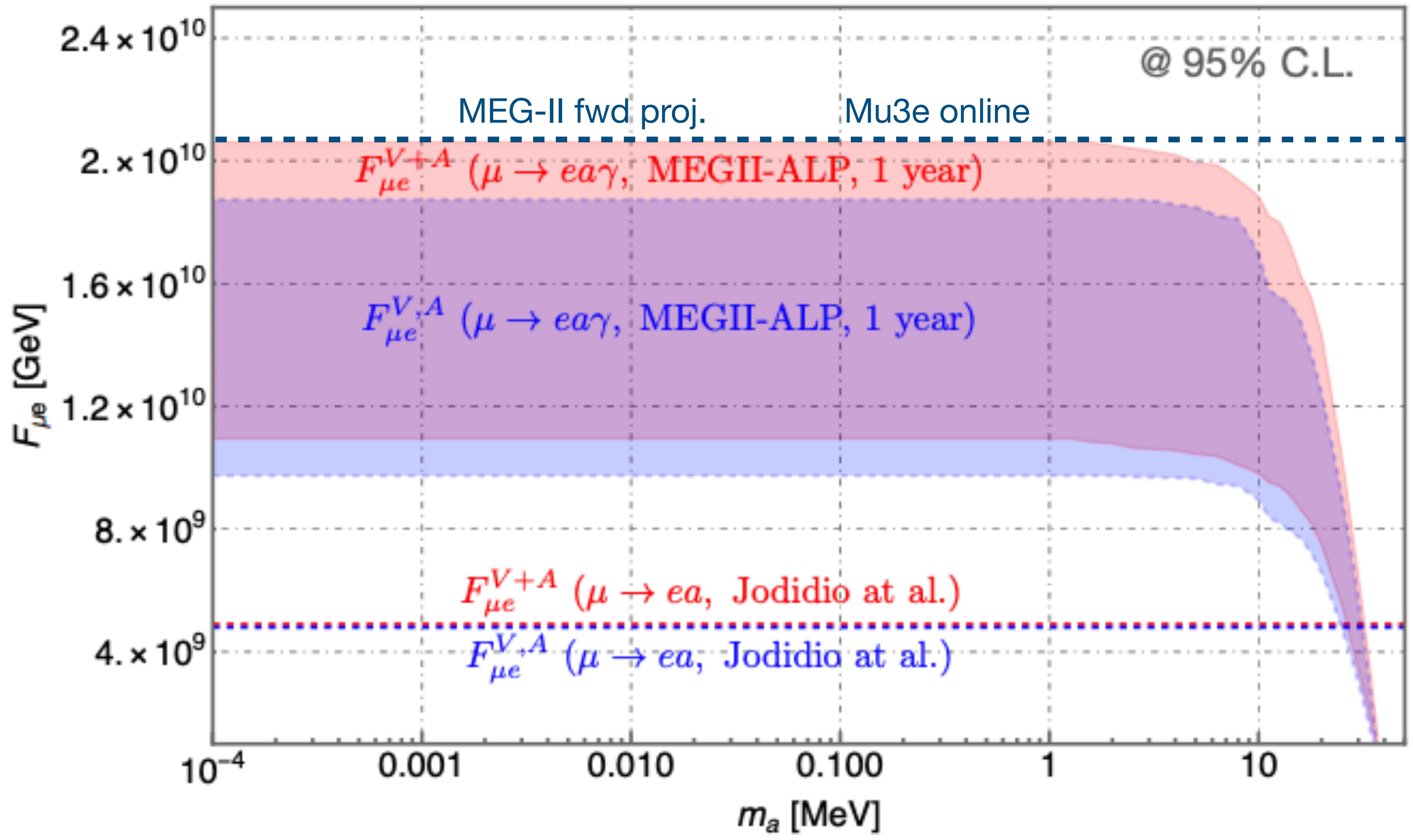
What can we test?



MEG II-ALP can improve on TWIST with only 1 month of data taking*

MEG-II ALP is the best way to explore ~ a decade of unconstrained parameter space ~ NOW

Different chiral structures



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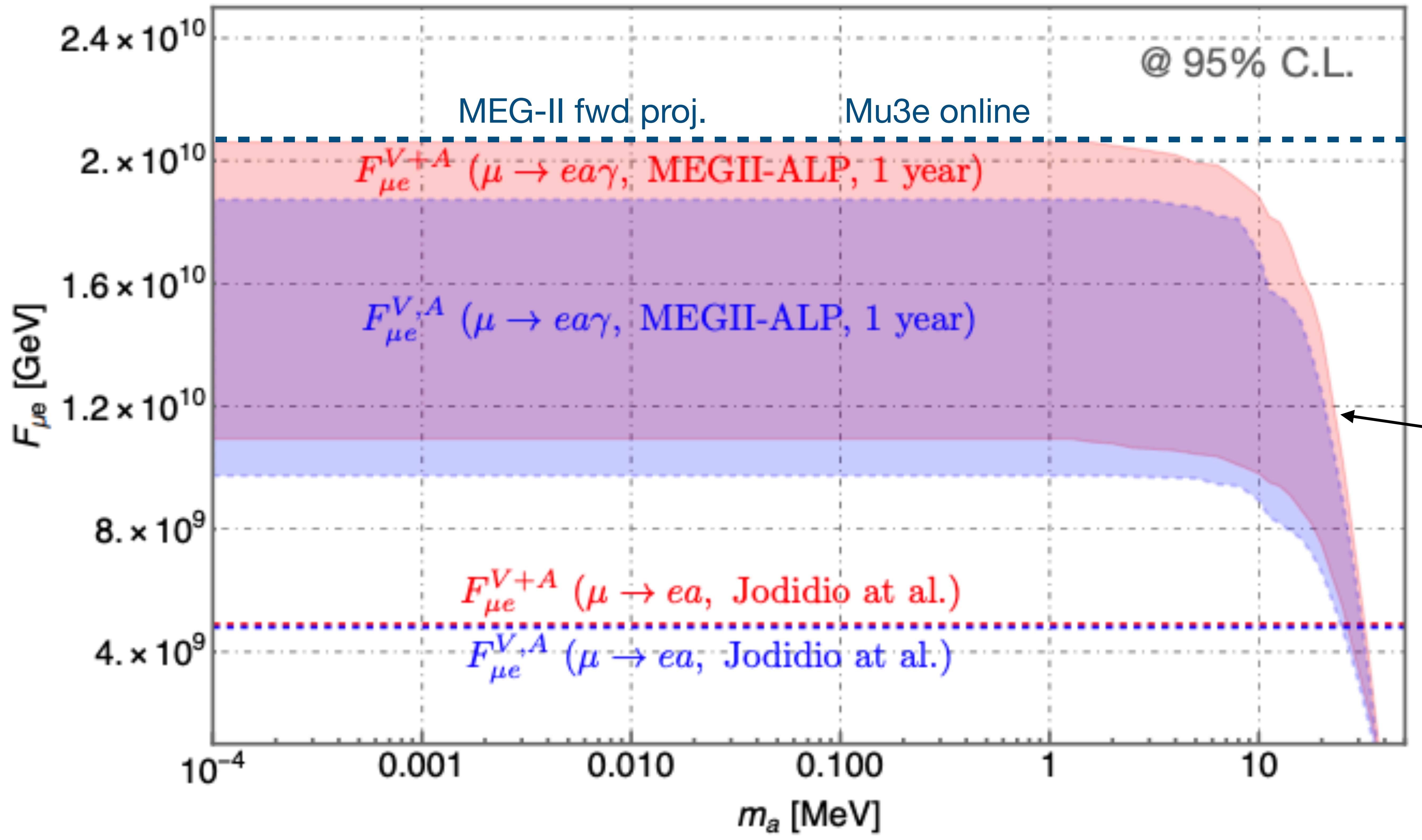

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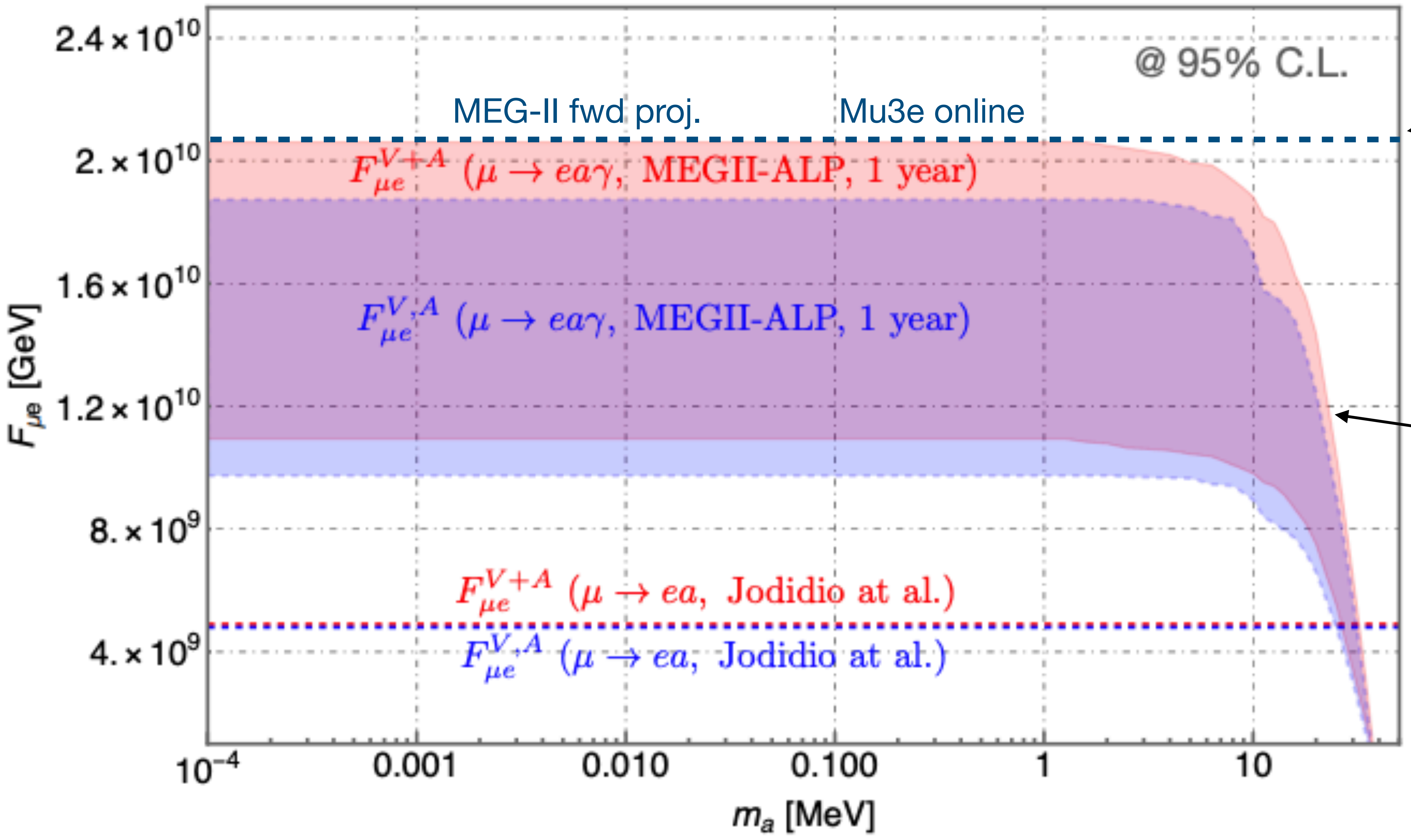


Mu3e online. *Perrevoort 2018*

A dedicated fwd experiment
under optimal experimental conditions
F=100, % level precision, 10^14 muons

MEG II-ALP can improve
on TWIST with only
1 month of data taking*

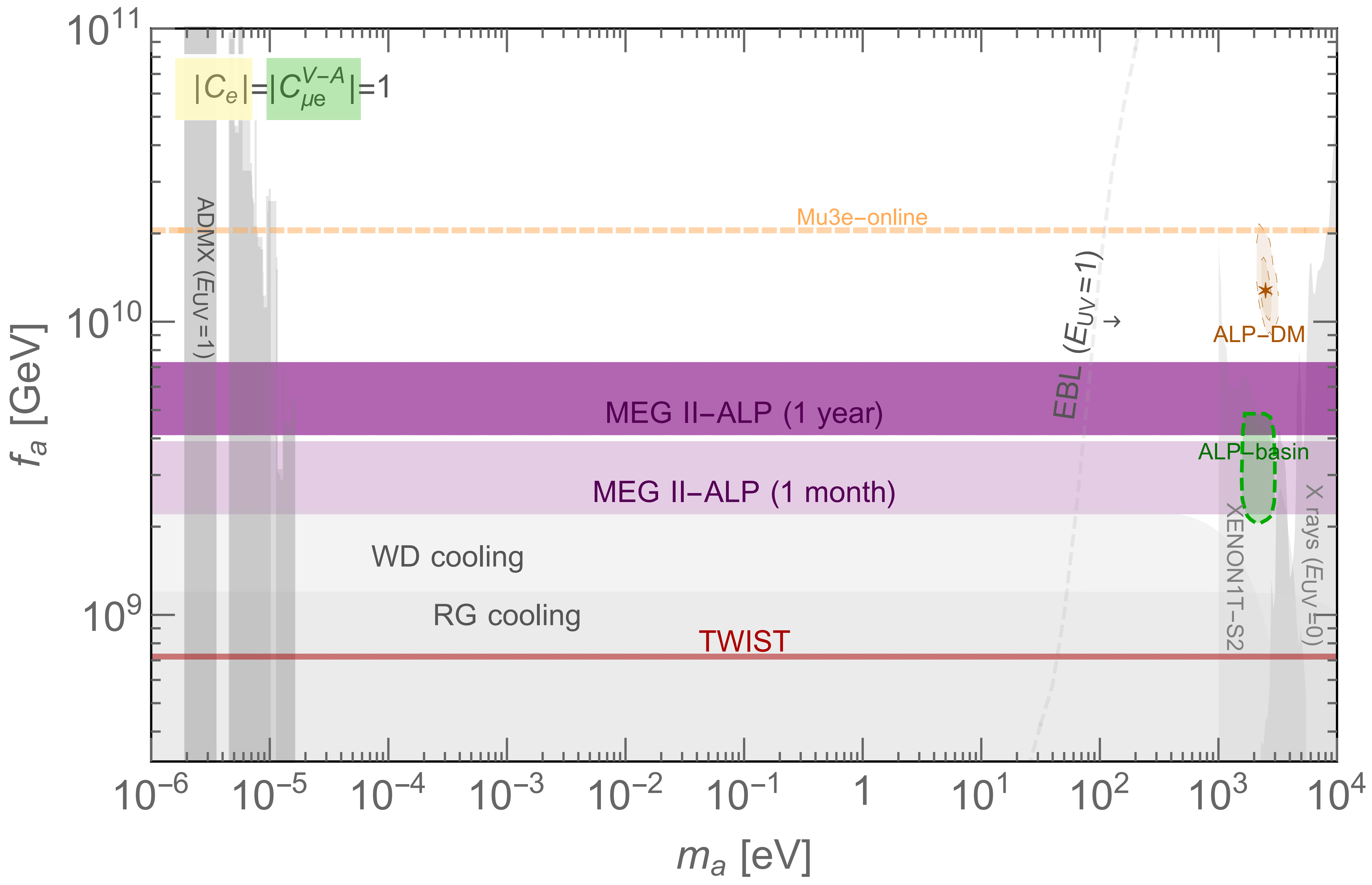
MEG-II ALP is the best way to explore ~ a decade of unconstrained parameter space ~ NOW

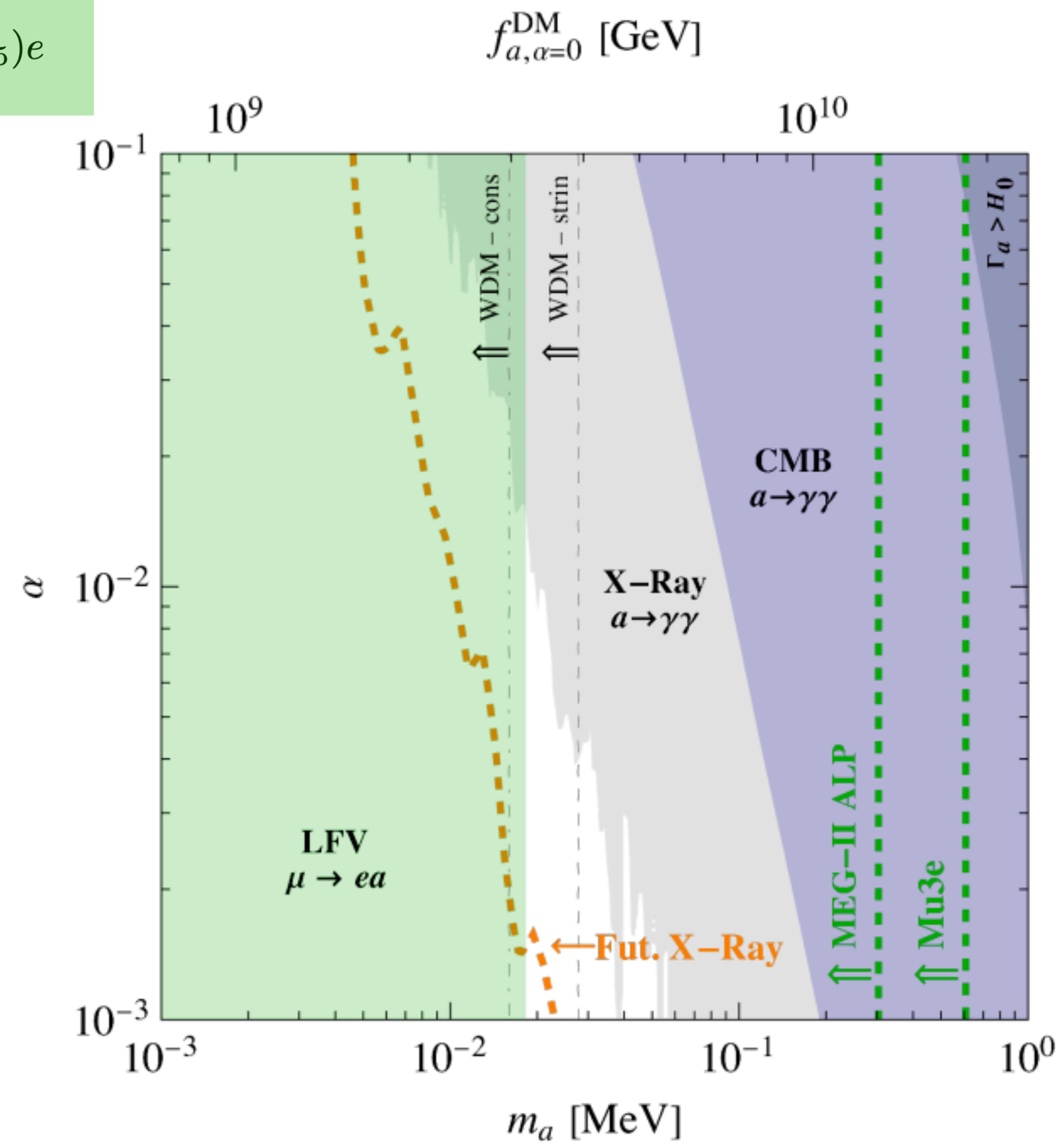
Back to theory

axions coupled to leptons anarchically: *flavor diagonal* = *flavor off-diagonal*

$$\frac{\partial_\mu a}{f_a}\bar{e}\gamma^\mu\gamma_5 e \qquad \frac{\partial_\mu a}{2f_a}\bar{\mu}\gamma^\mu(C^V_{\mu e}+C^A_{\mu e}\gamma_5)e$$

Panci, Redigolo, Schwetz Ziegler 2209.03371





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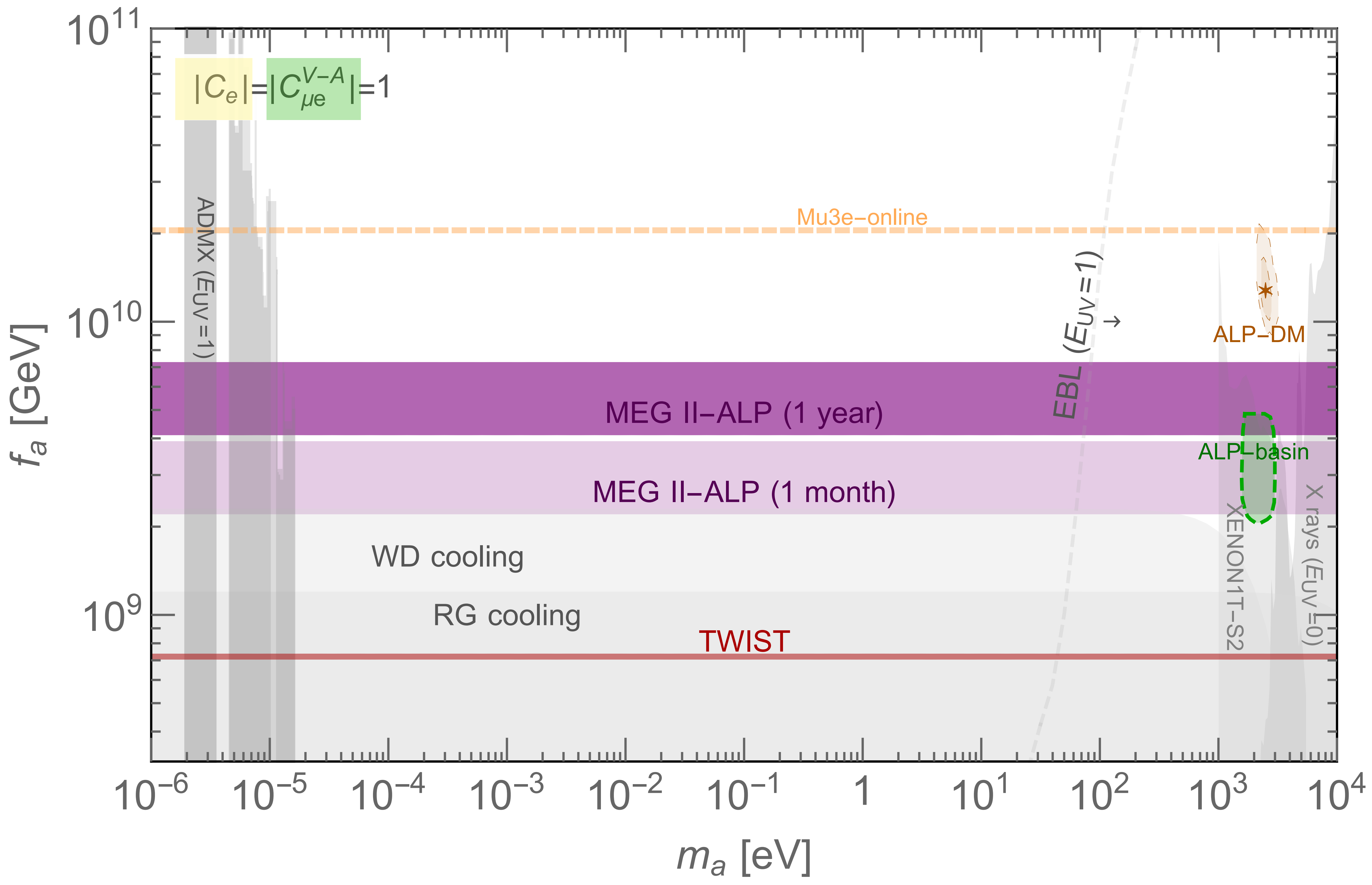

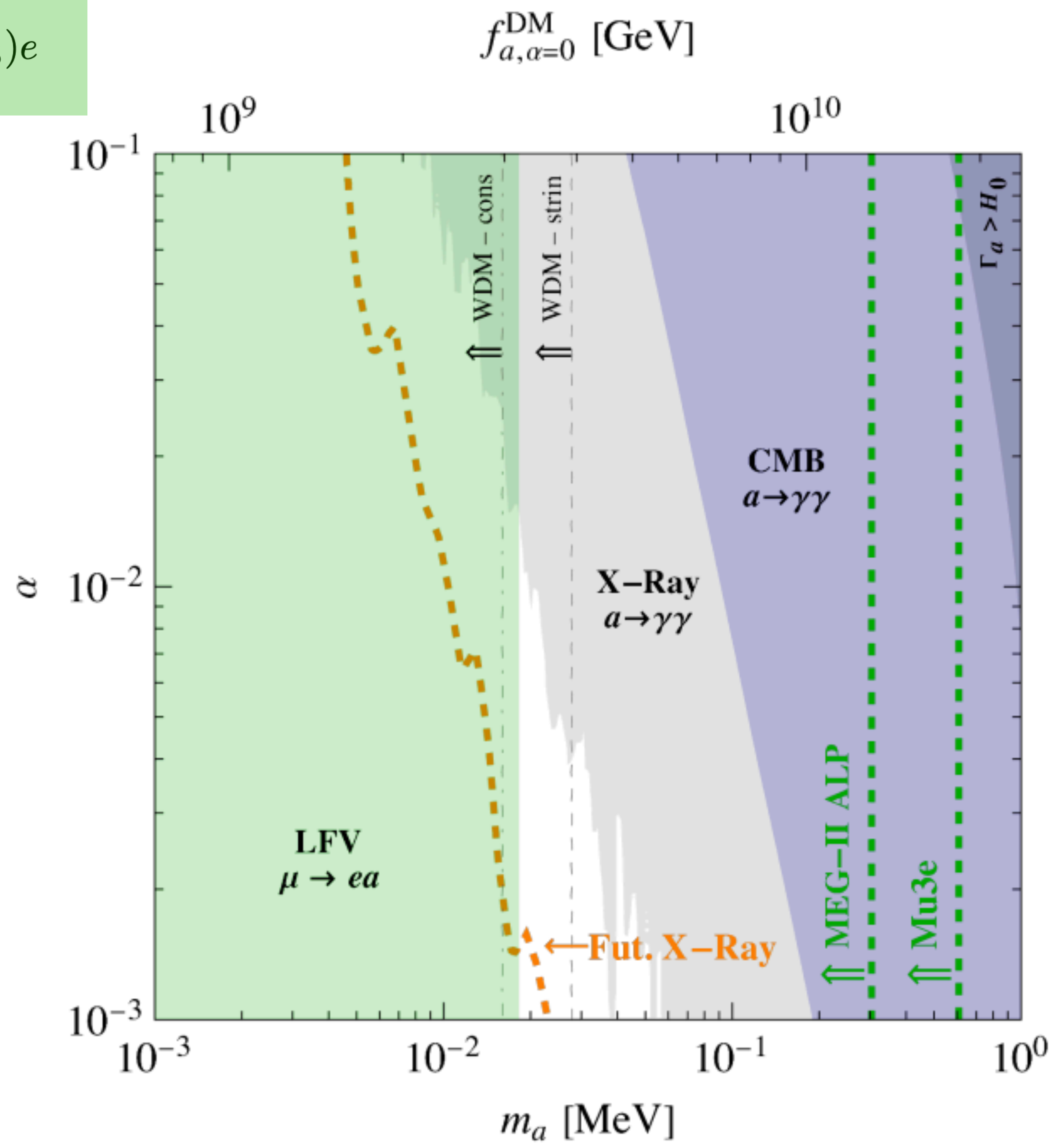

MEG-II can surpass bounds from star cooling!

Back to theory

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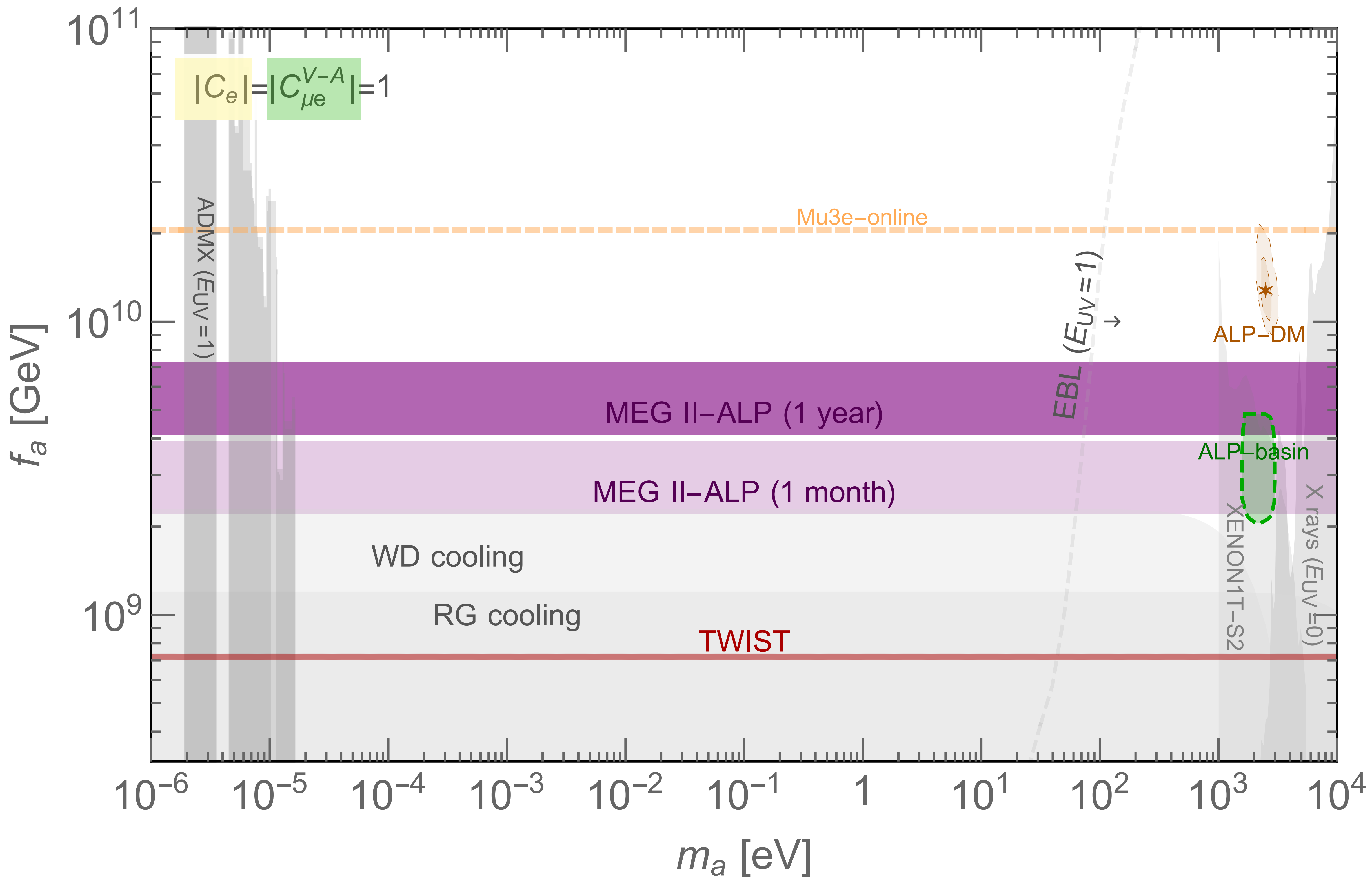

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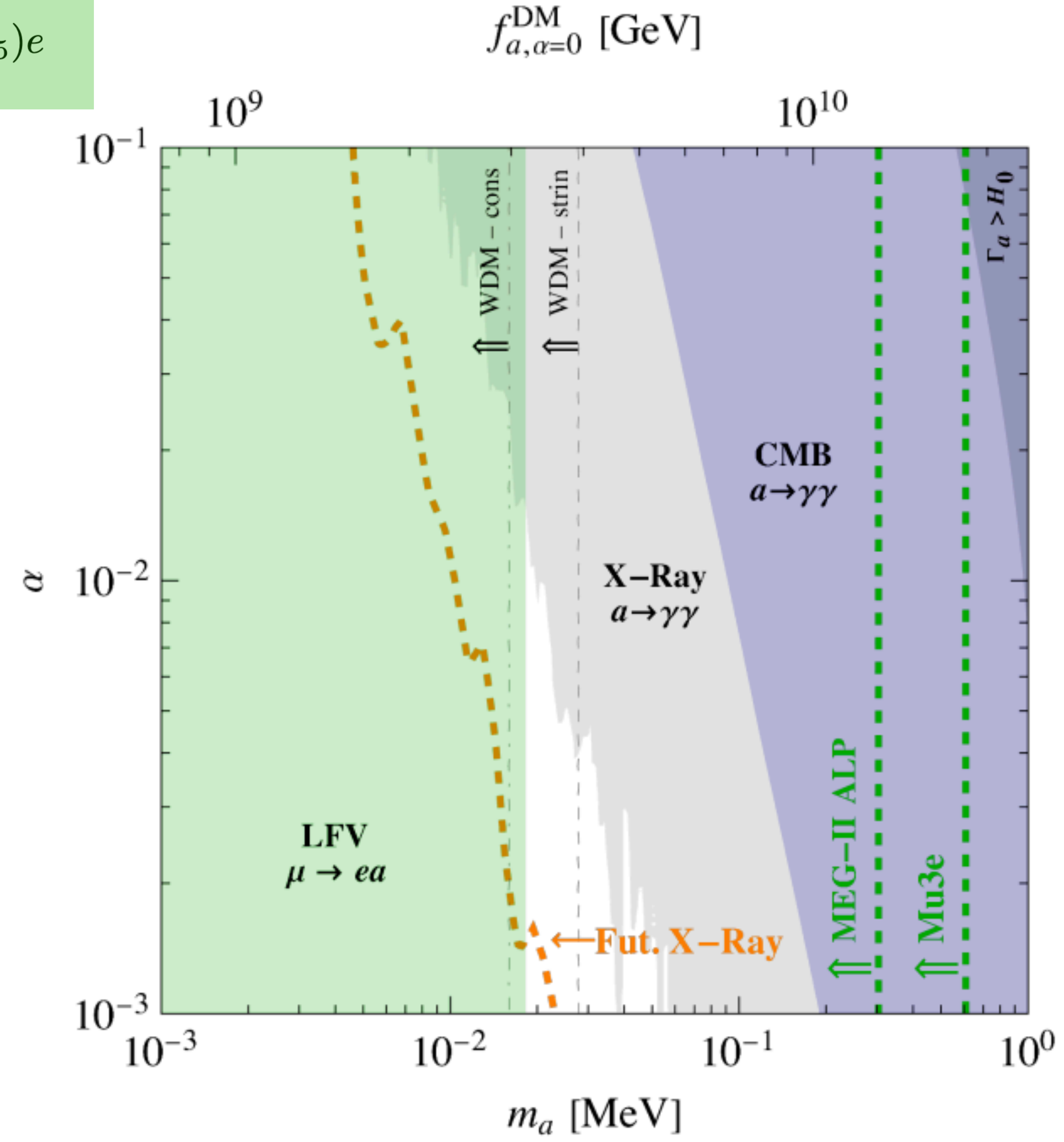


MEG-II can completely test Freeze-in model based on LFV decays

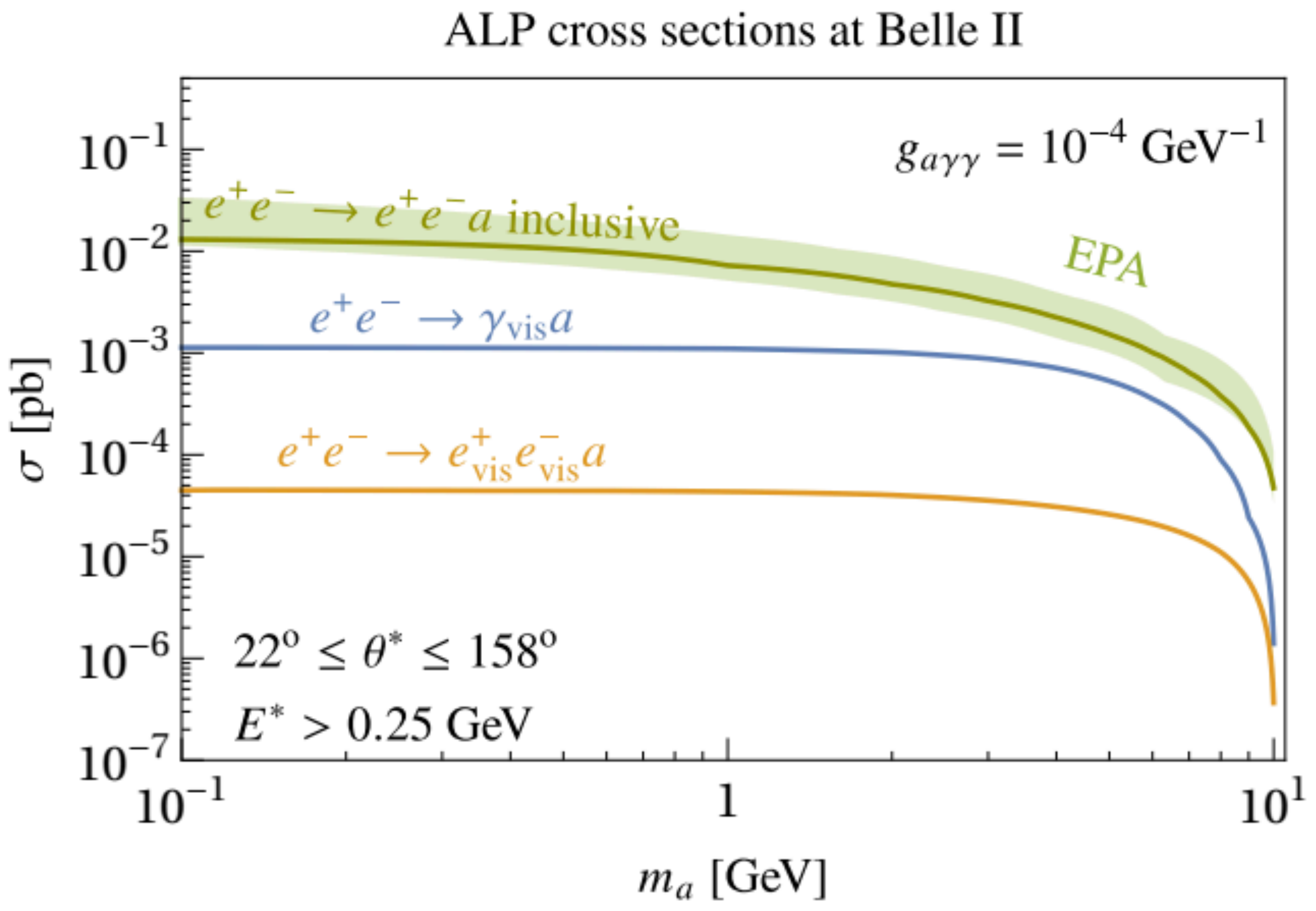
New searches

Maximising the experimental reach…

Looking at final states where the separation between signal and bkd is sharper

Belle II as an example

ALPs production @ Belle II



Dolan, Ferber, Heary, Kahlhofer, Schmidt-Hoberg 1709.00009

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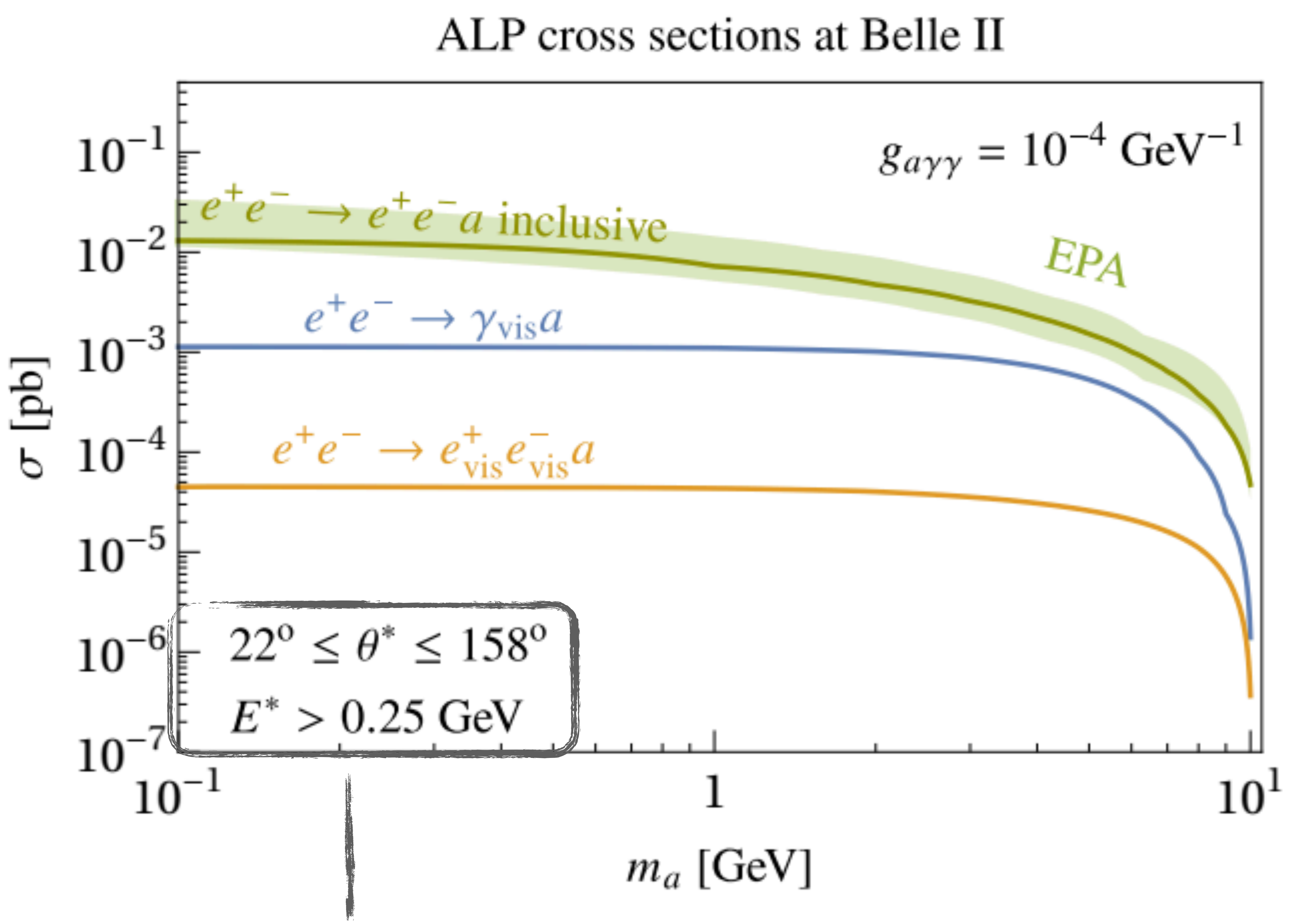

Belle II ECAL acceptance

Dolan, Ferber, Heary, Kahlhofer, Schmidt-Hoberg 1709.00009

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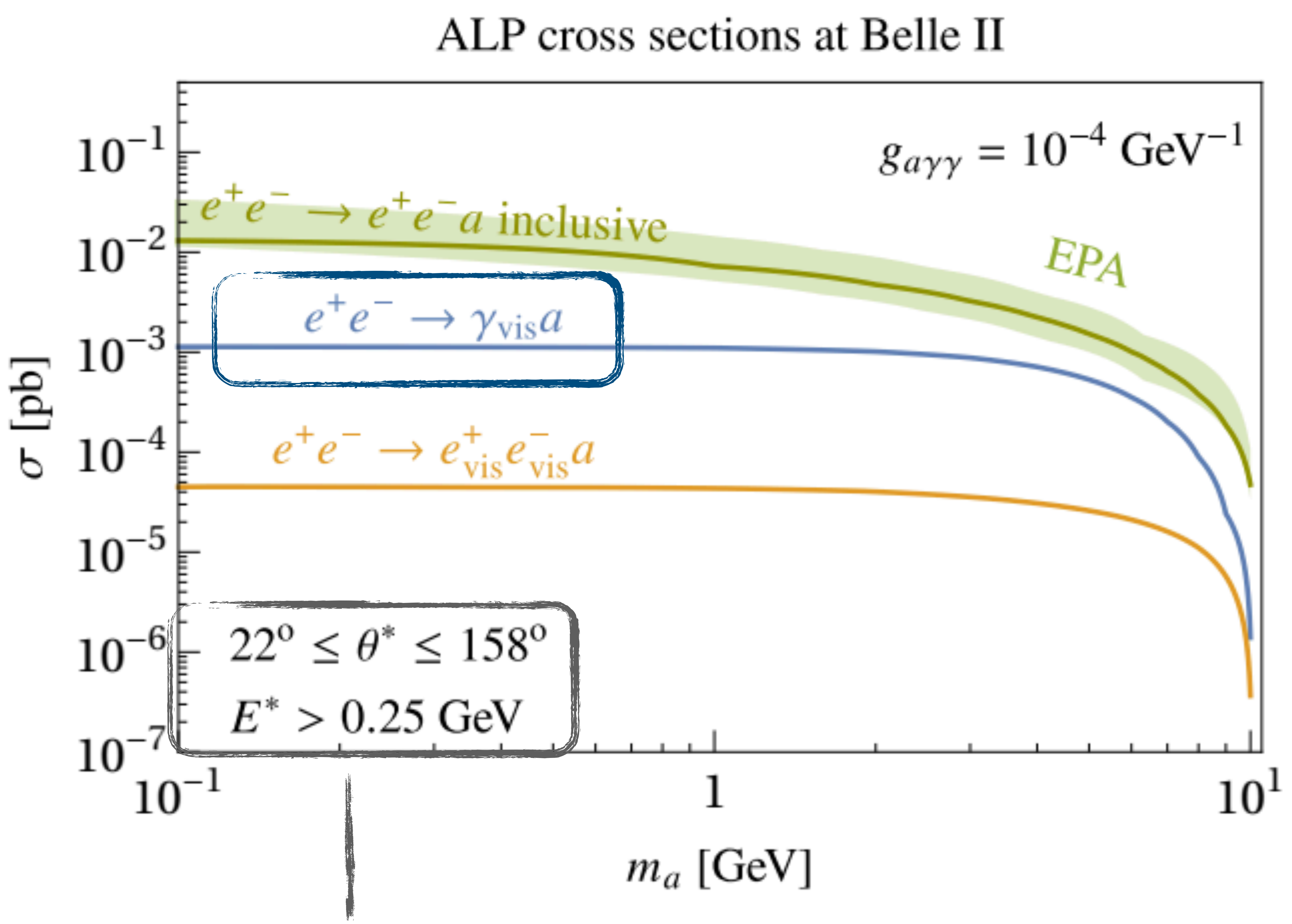

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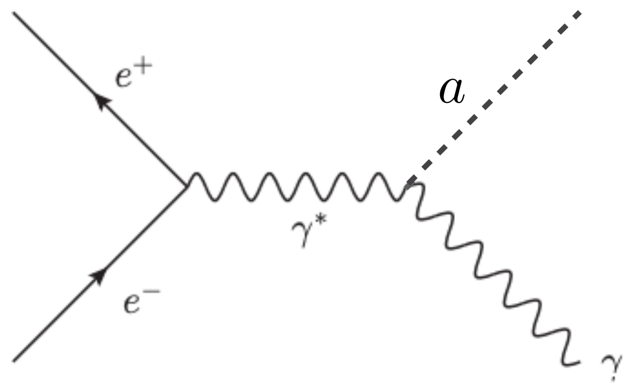

ALP-strahlung

$\gamma + a$

Dolan, Ferber, Heary, Kahlhofer, Schmidt-Hoberg 1709.00009

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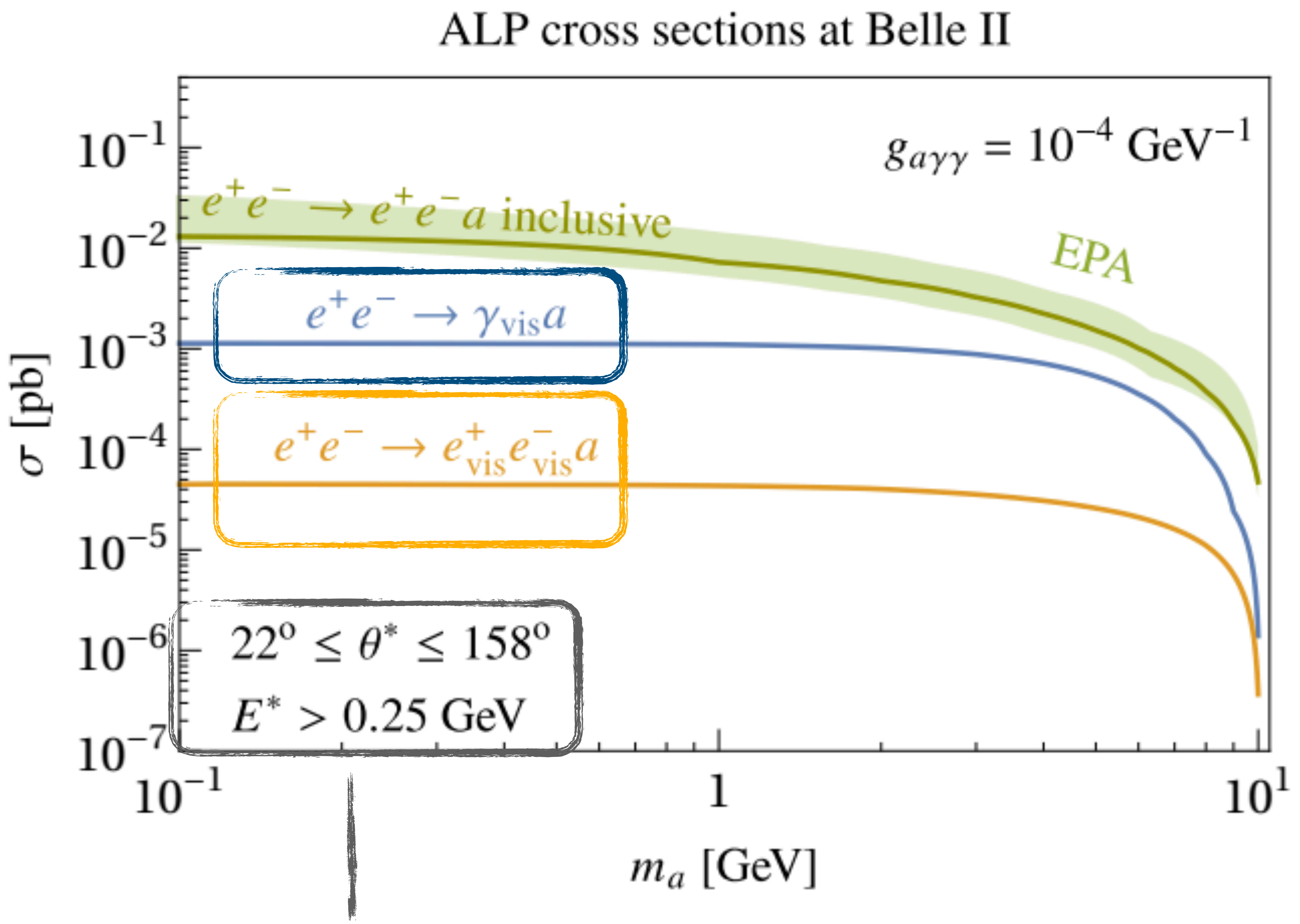

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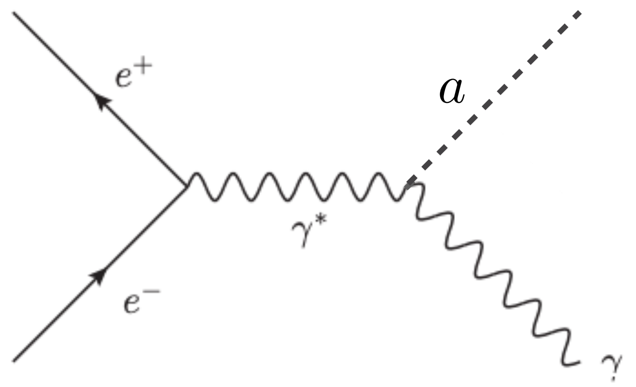

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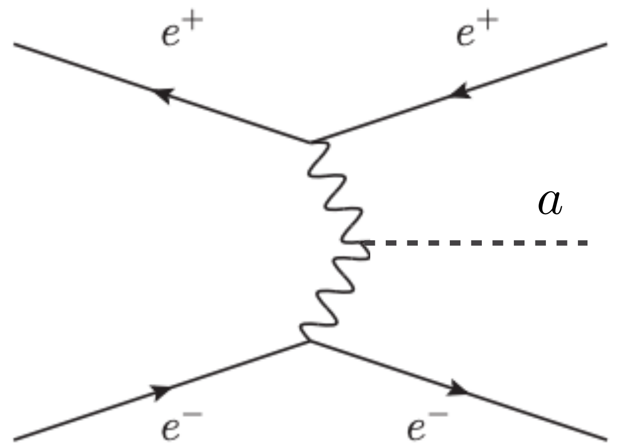

Photon-fusion

$e^+ + e^- + a$ $\ll$ EPA

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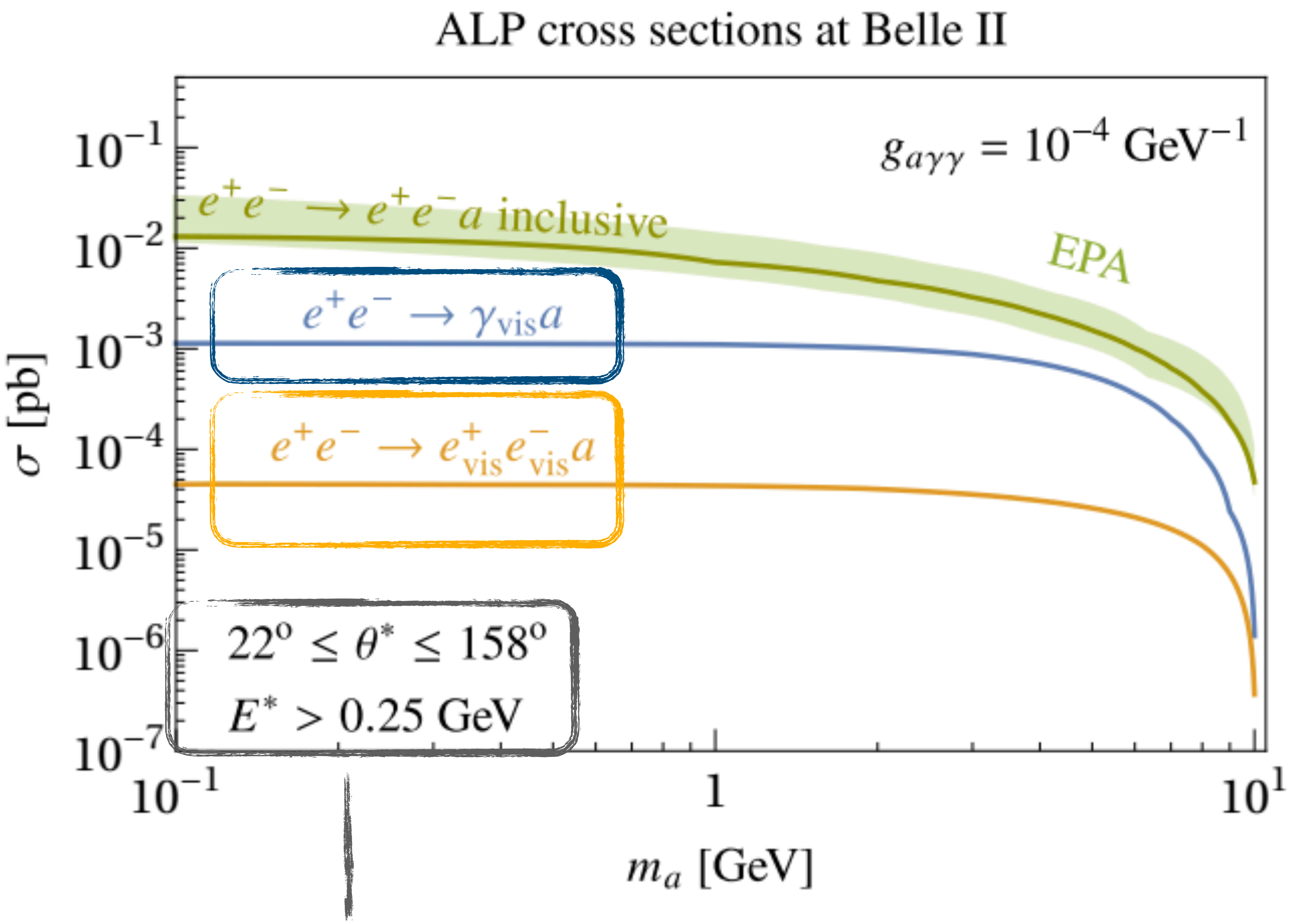

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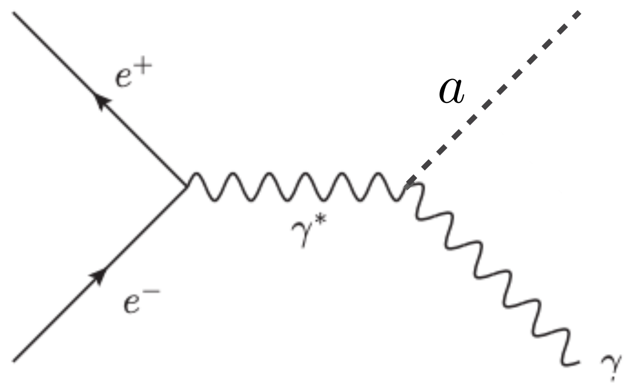

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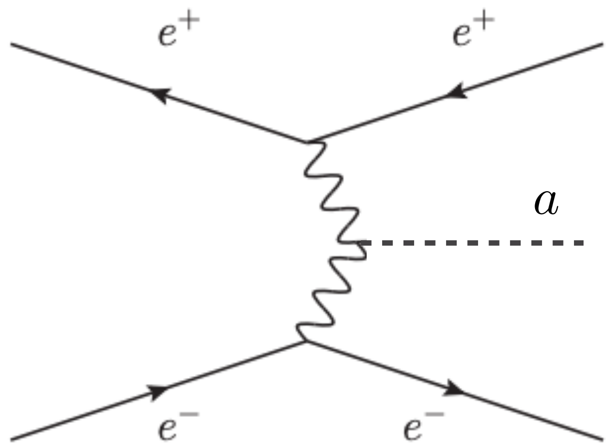
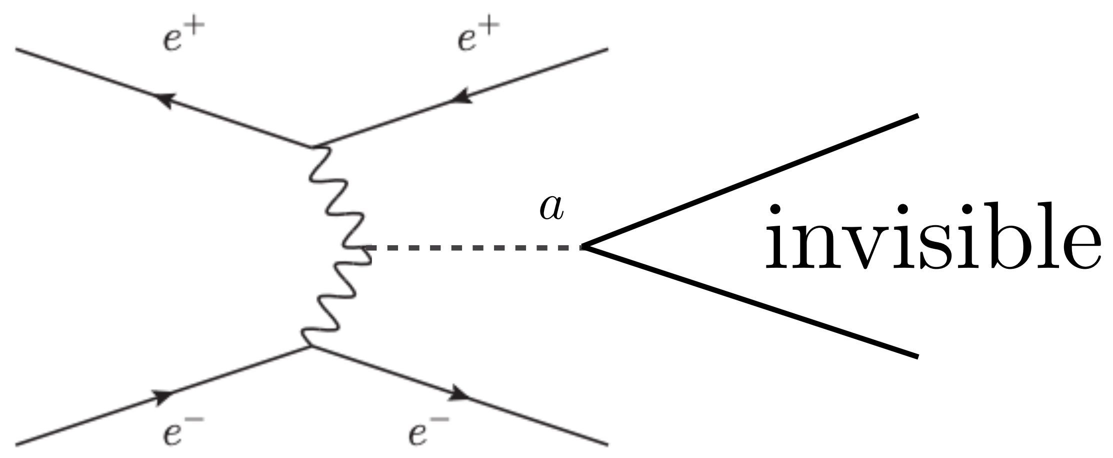


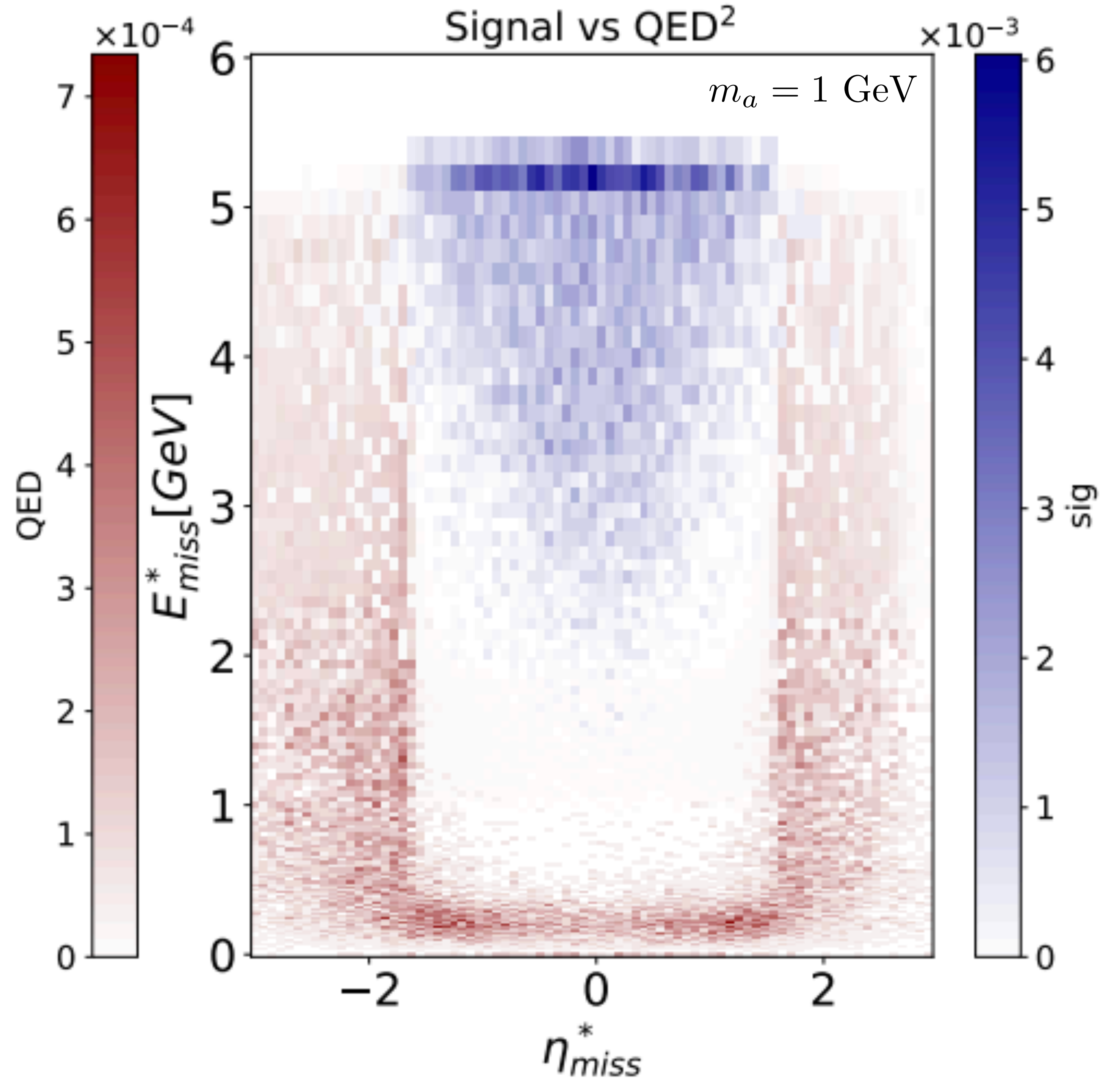
Photon-fusion
$e^+ + e^- + a$ $\ll$ EPA

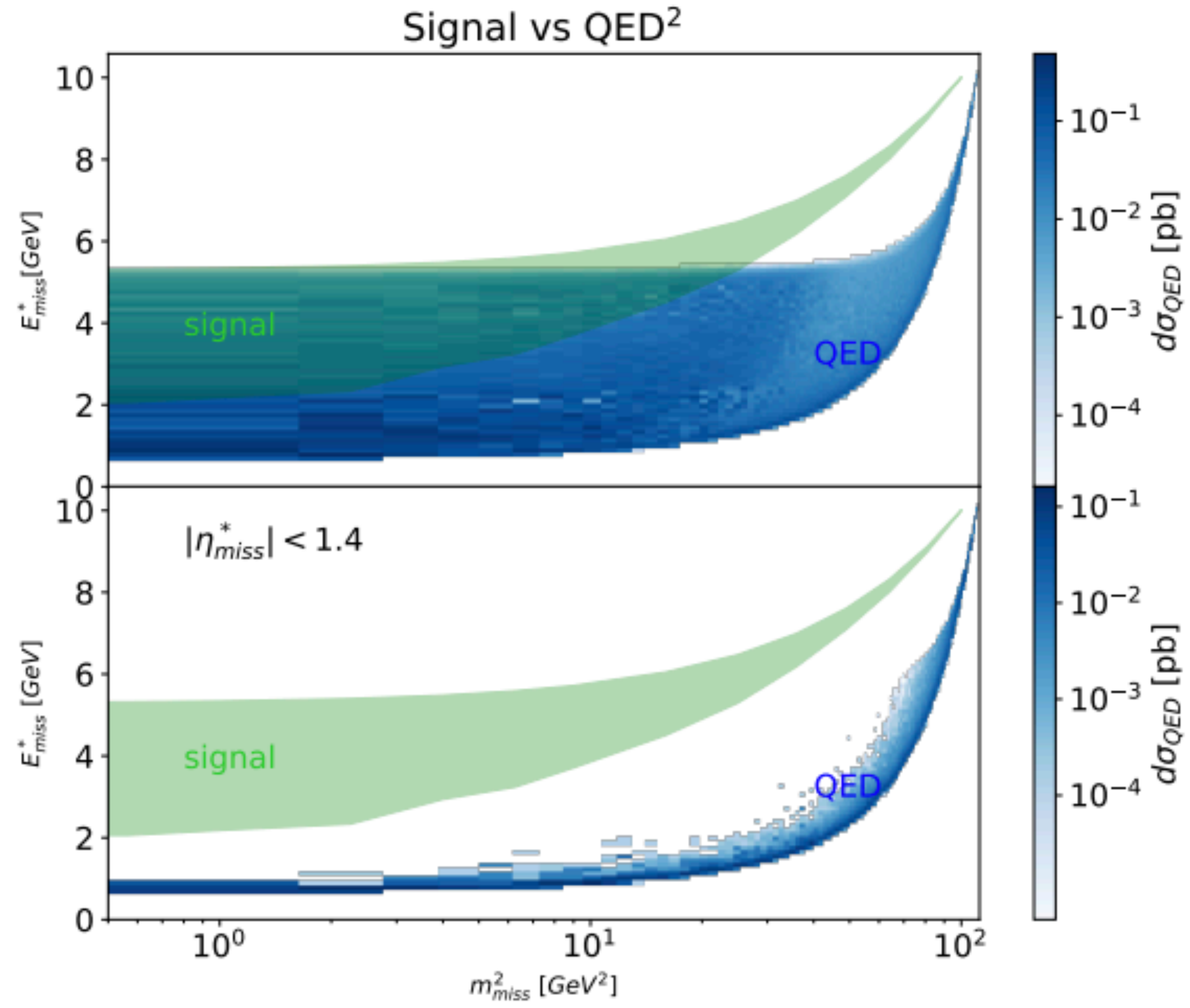
If the ALP mediates the DM freeze-out and the DM is lighter → The ALP decays purely invisibly

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

Fusing photons into nothing







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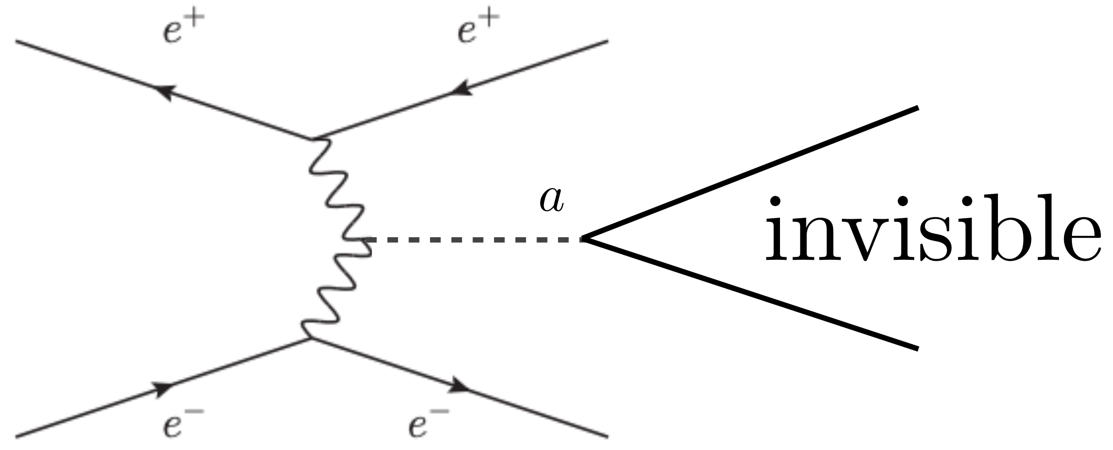
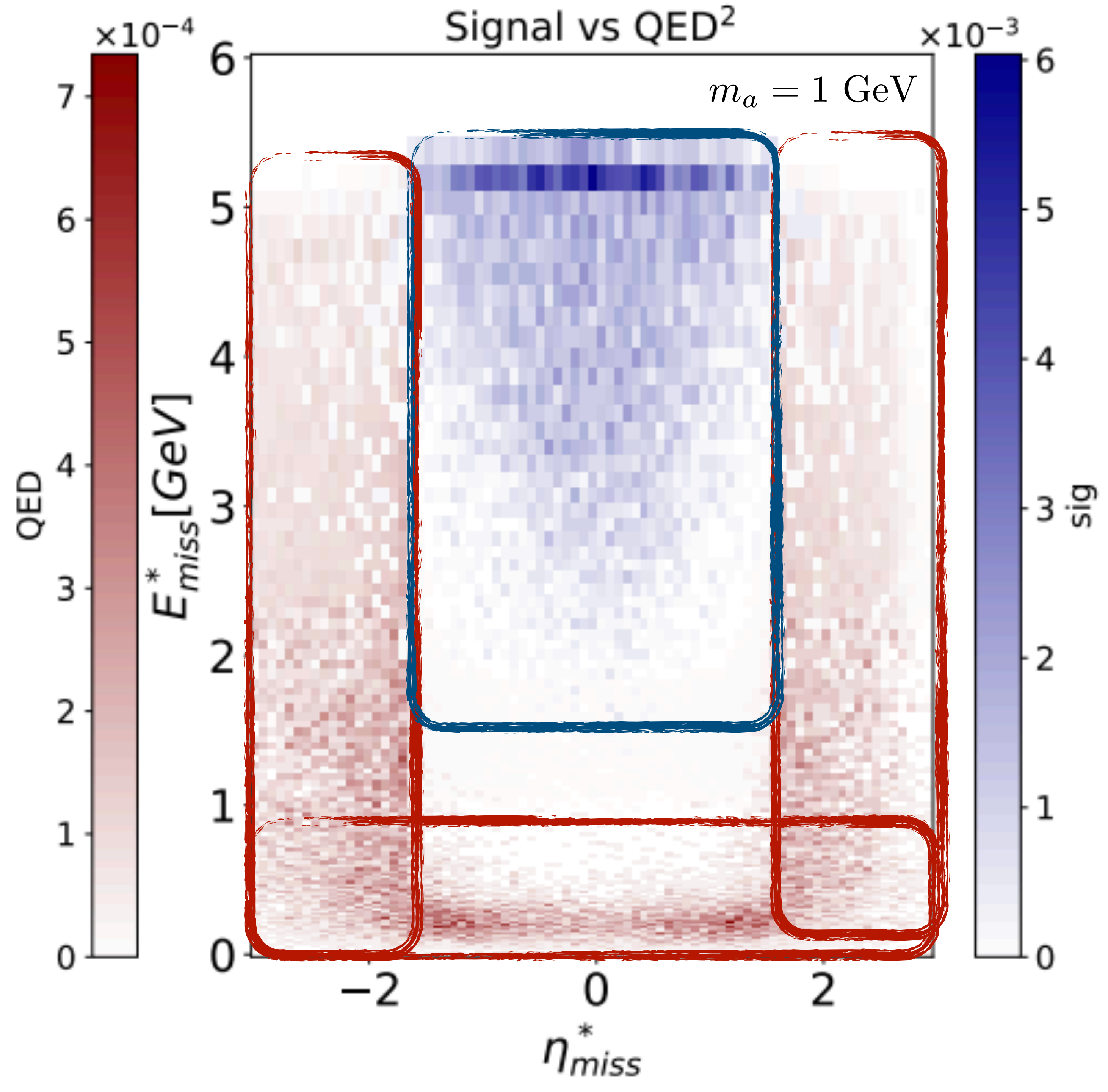
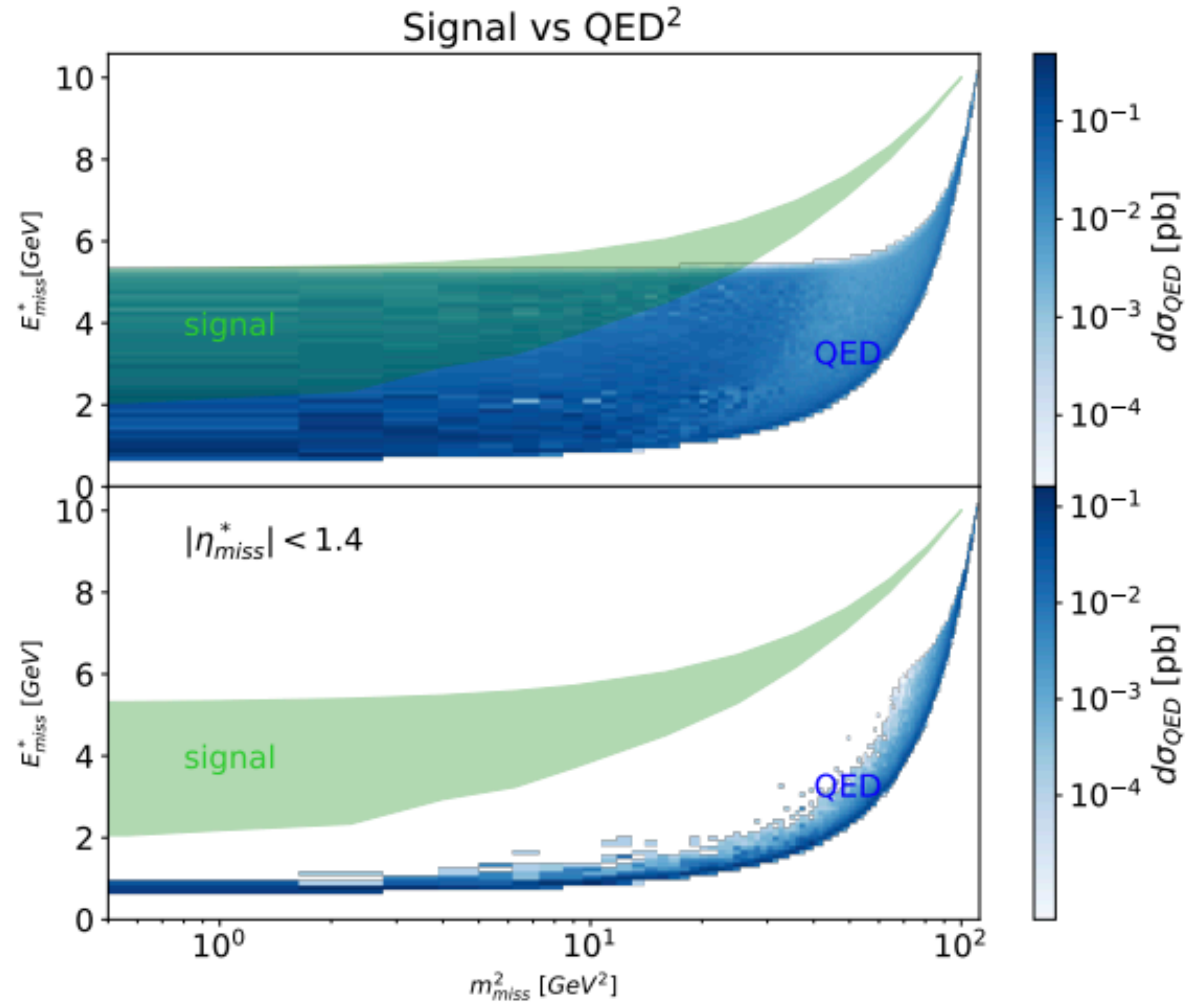
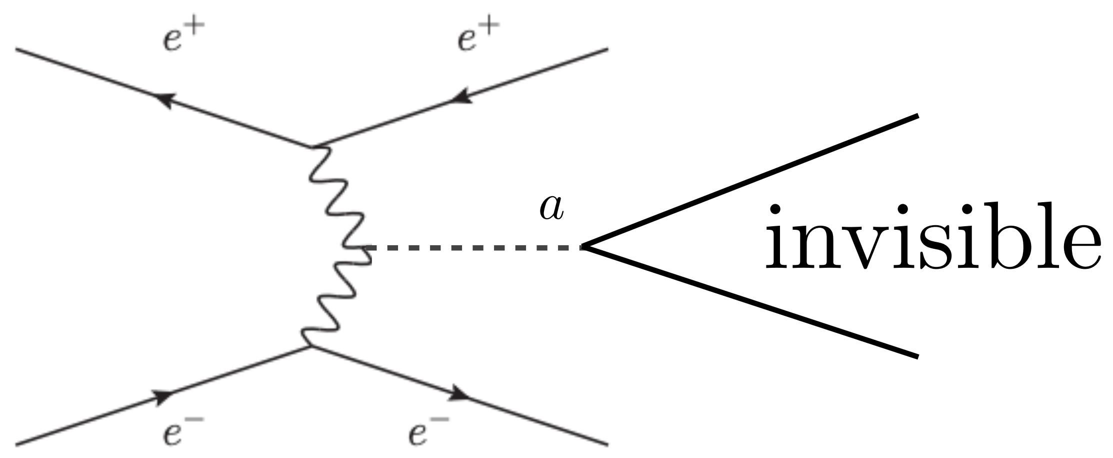


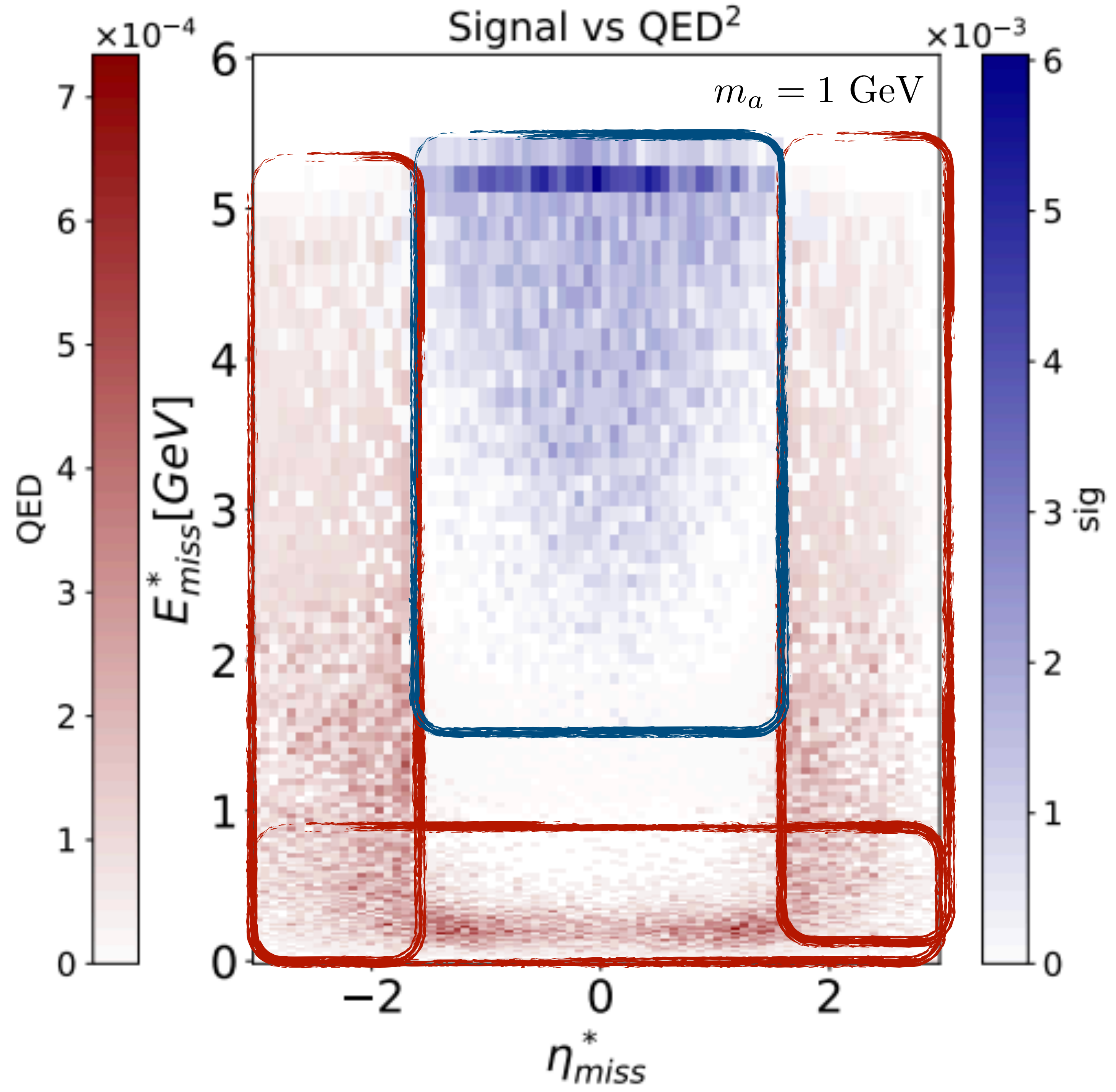


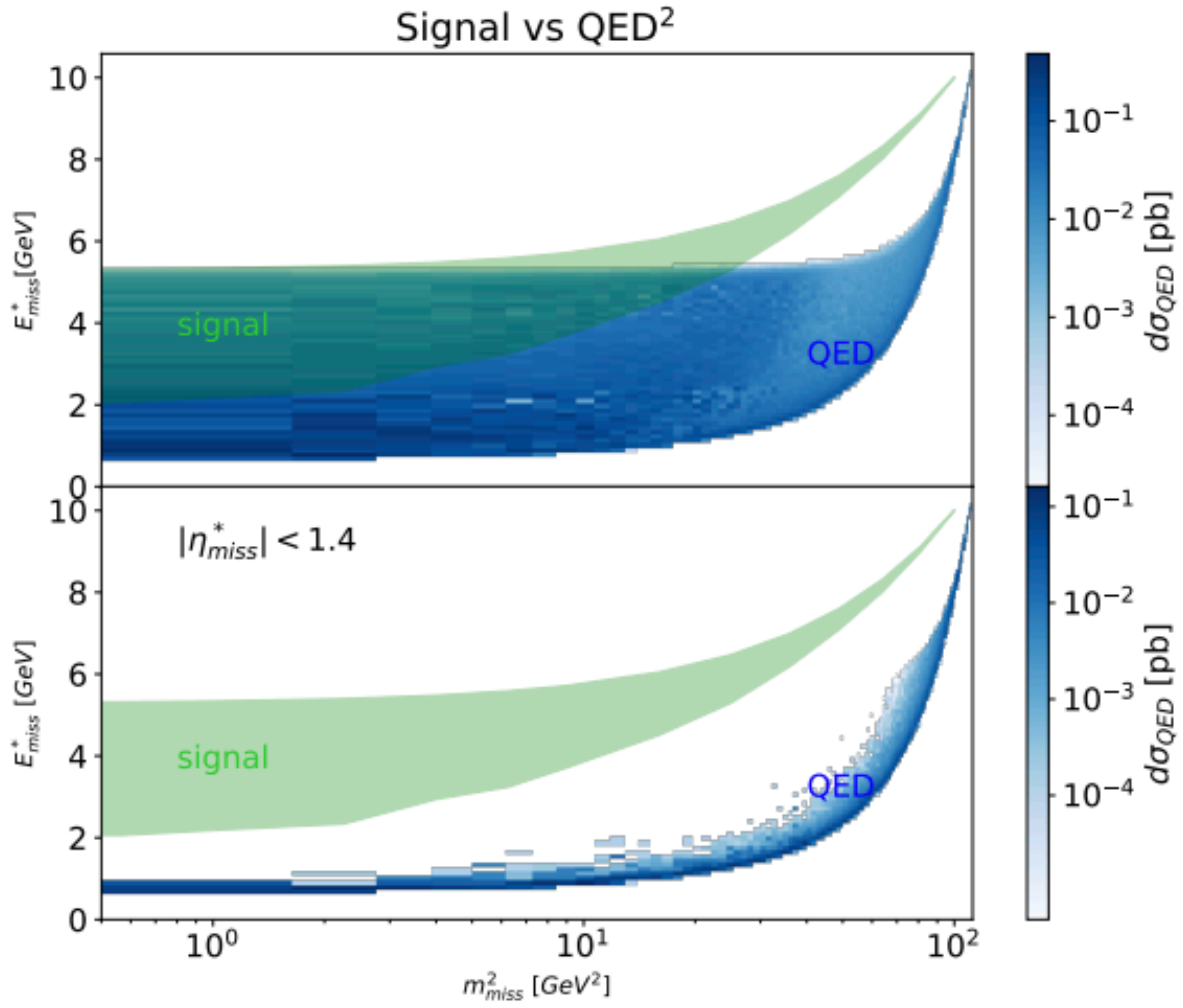


A large separation from QED background
can be obtained @ small masses

Fusing photons into nothing







A large separation from QED background
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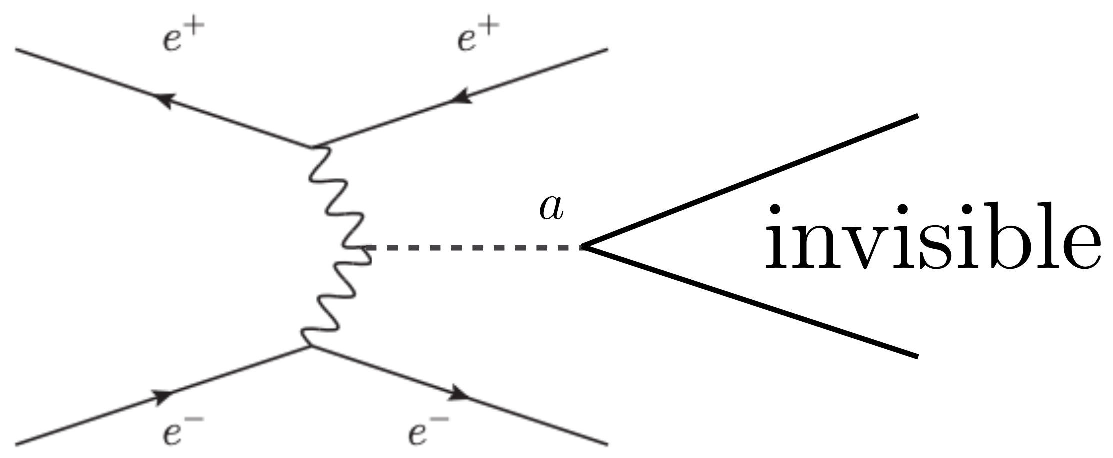
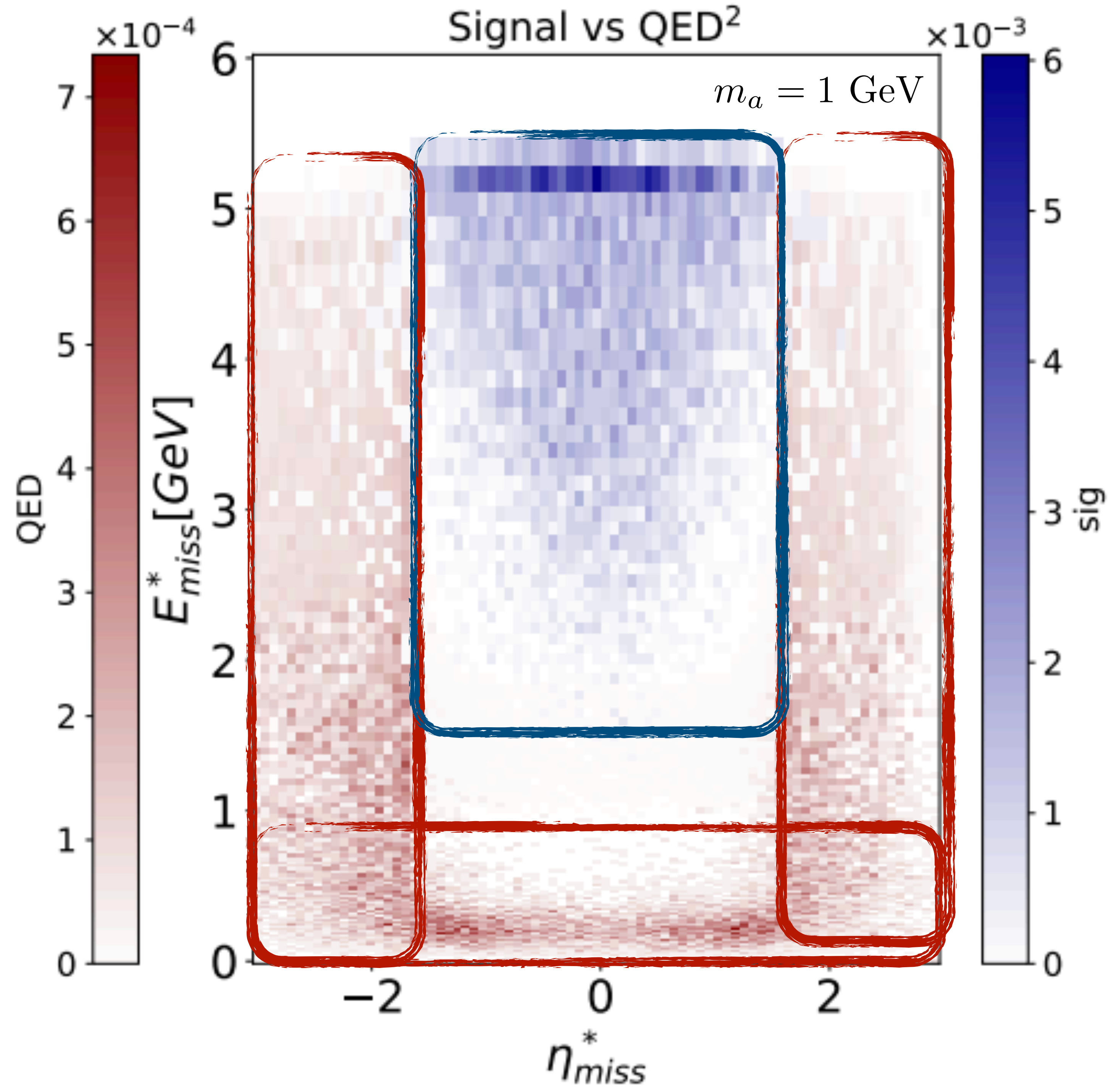
The signal has LARGE missing energy + it is CENTRAL
+ SMALL missing mass

Fusing photons into nothing





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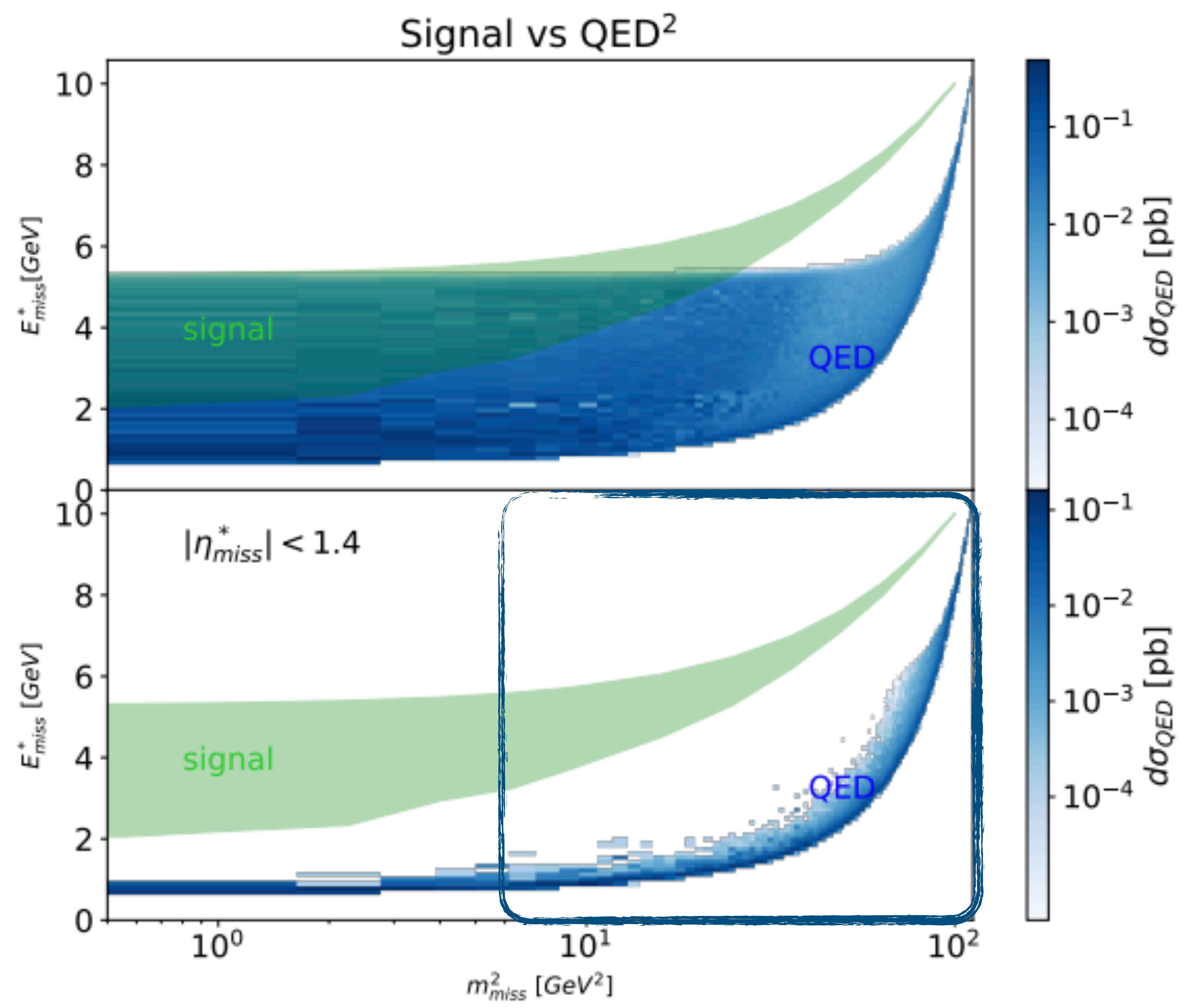
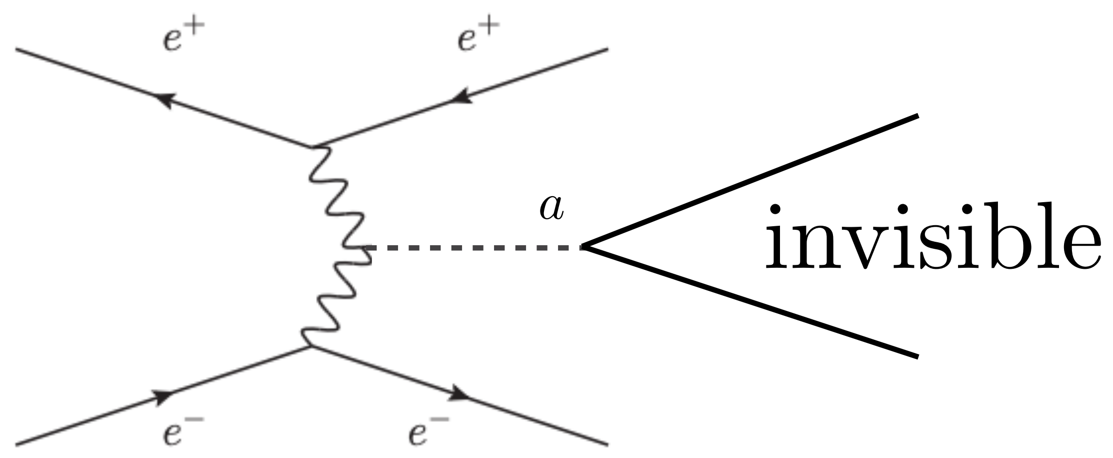
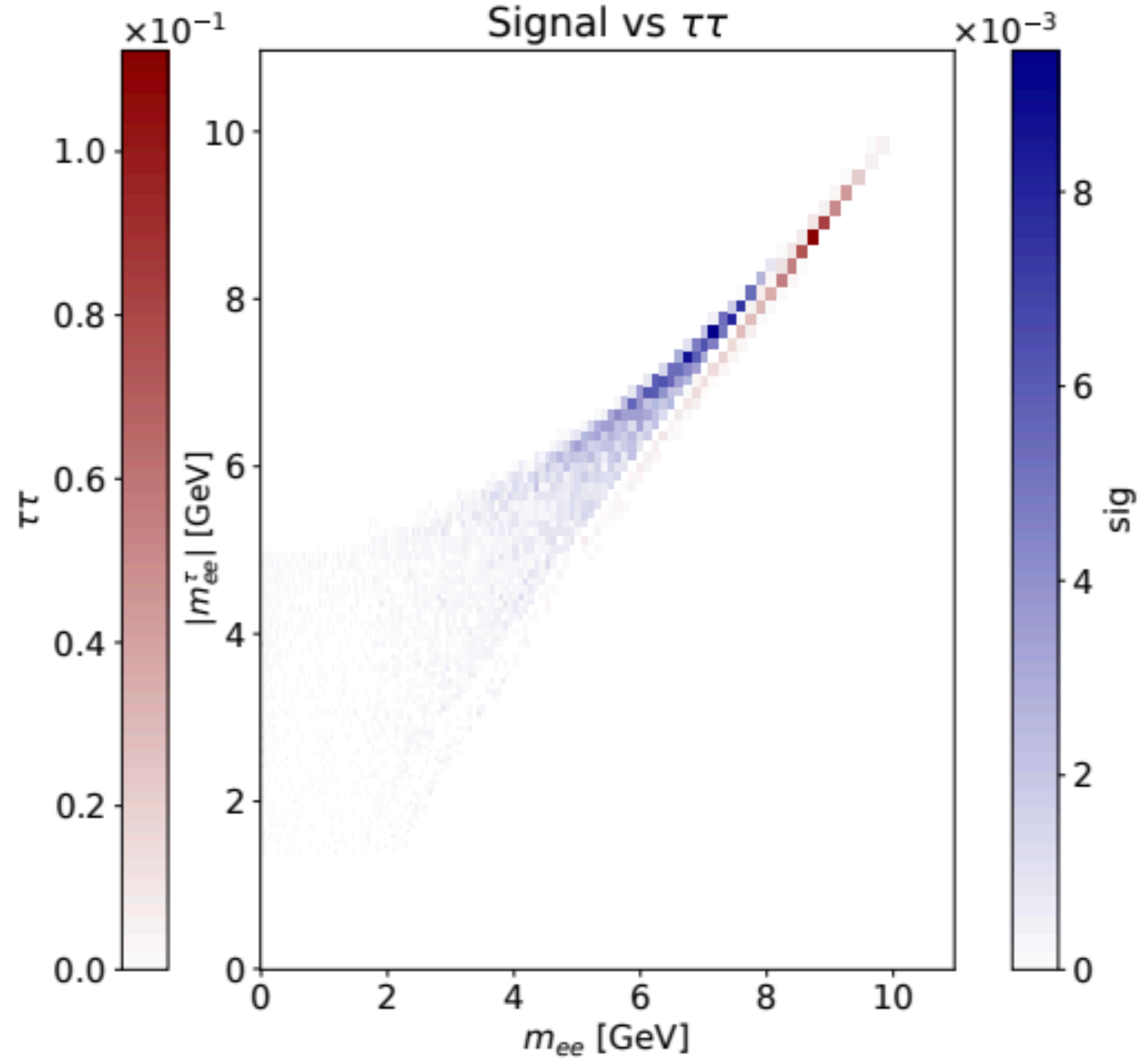
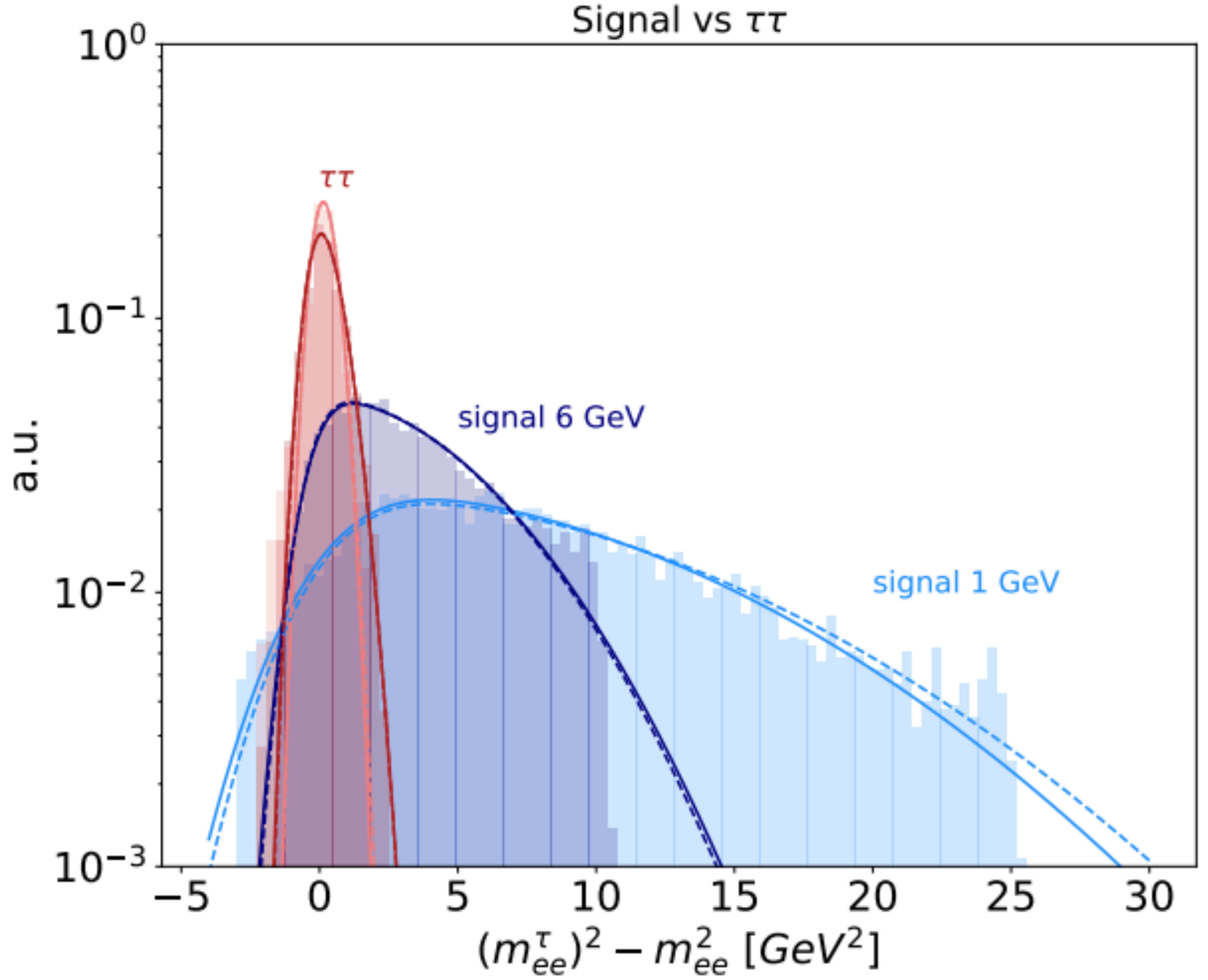


The separation holds at higher masses because the MET in the signal event grows

Fusing photons into nothing



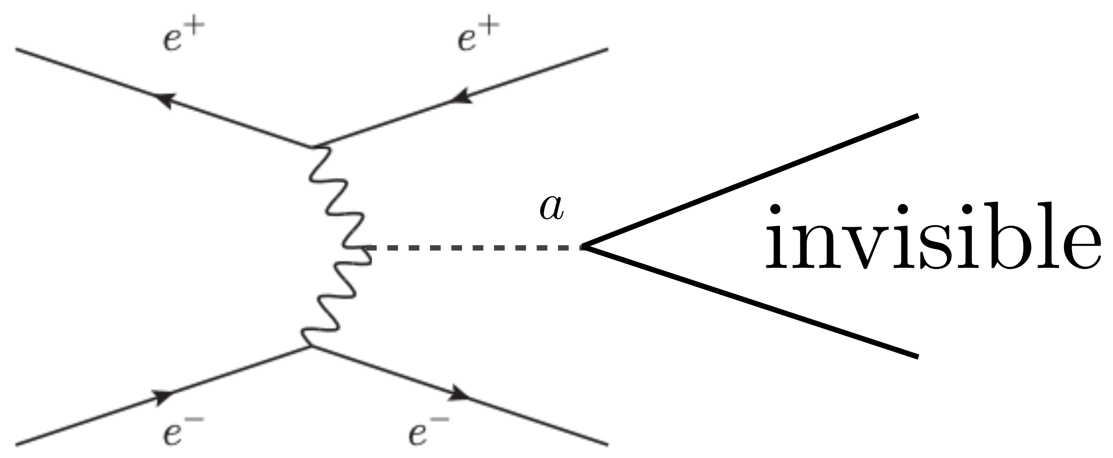


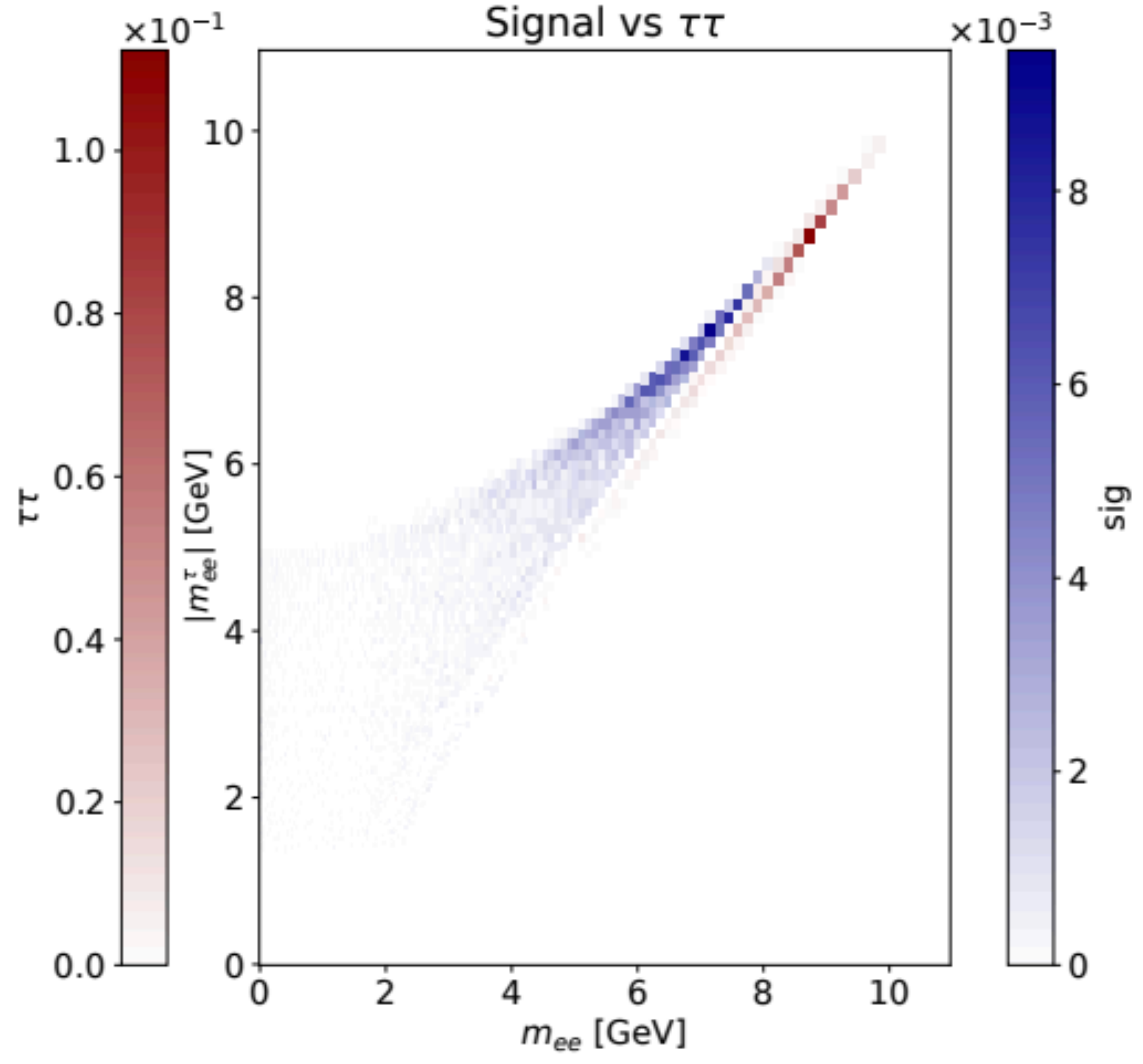


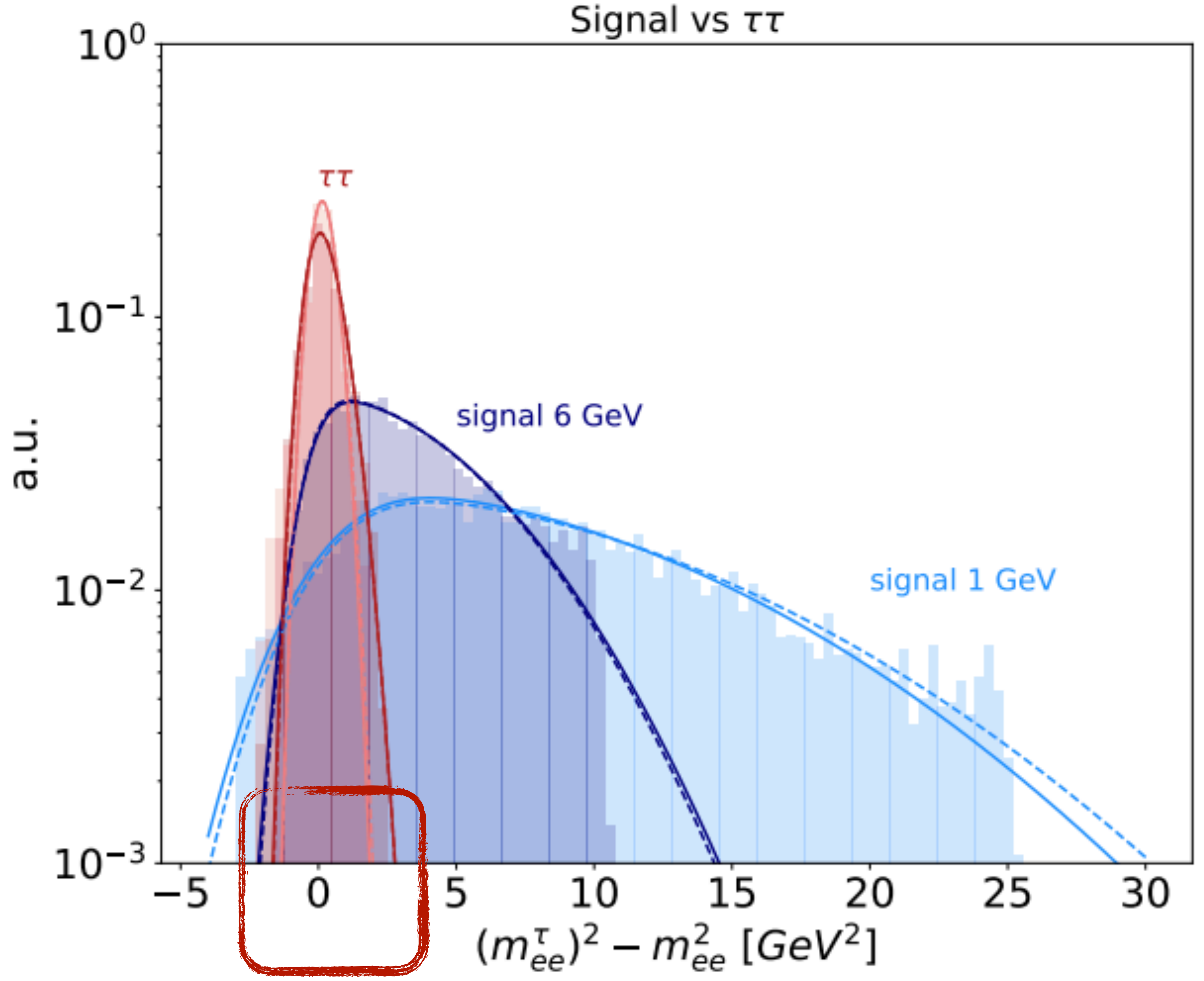
The separation from the tau-tau background is achieved using the antler topology of tau-tau

Han, Kim, Song 0906.5009, Franceshini et al. 2206.13431

Fusing photons into nothing







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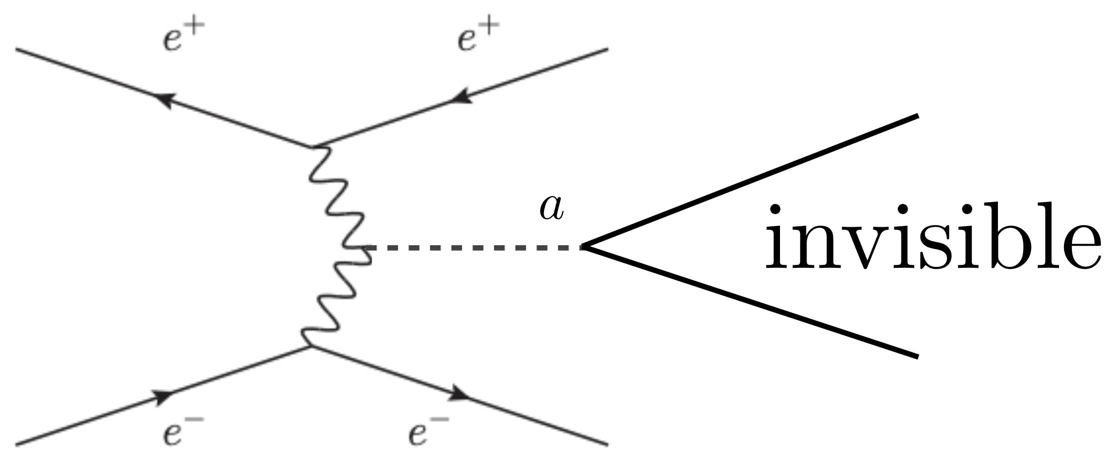
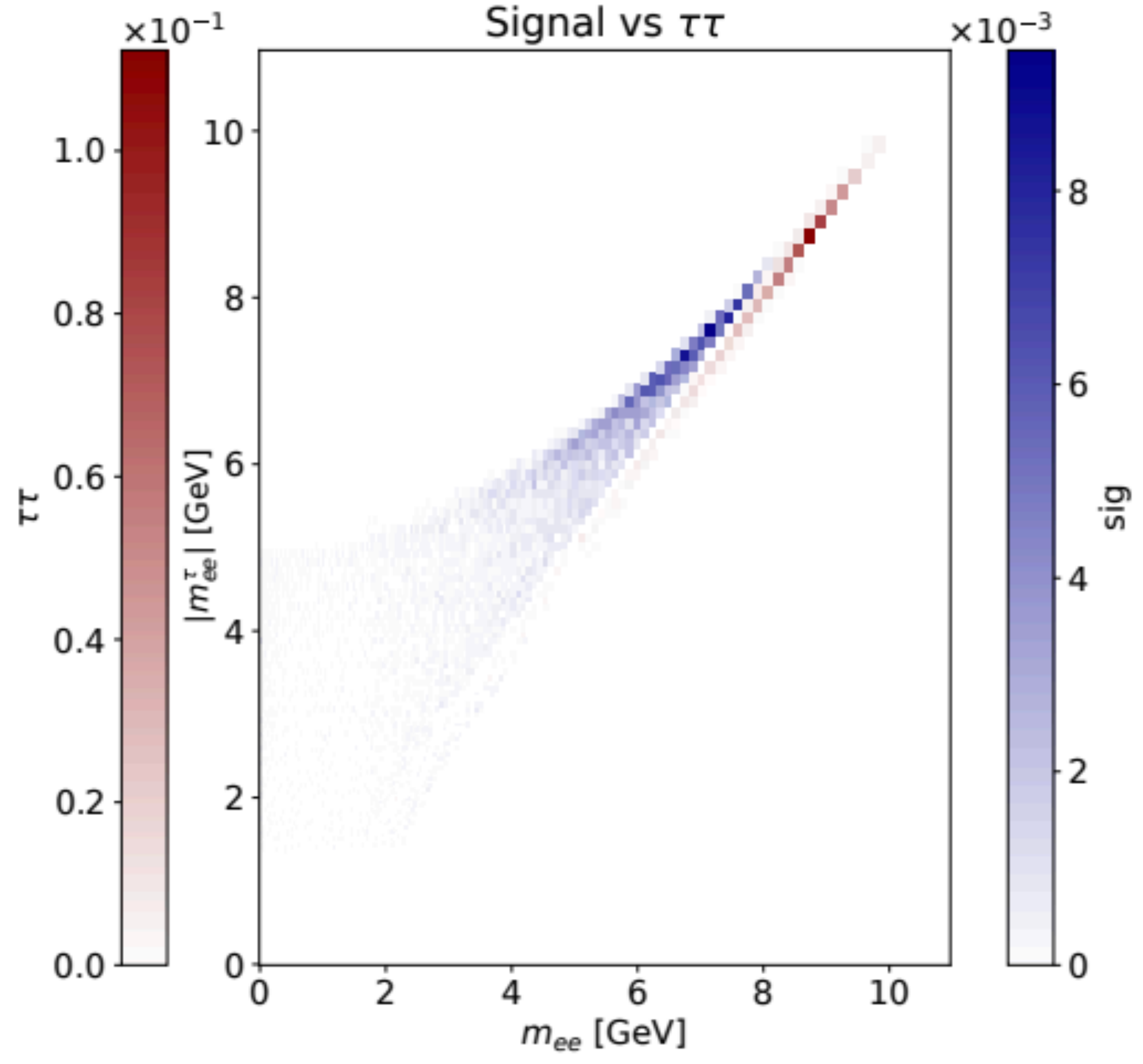
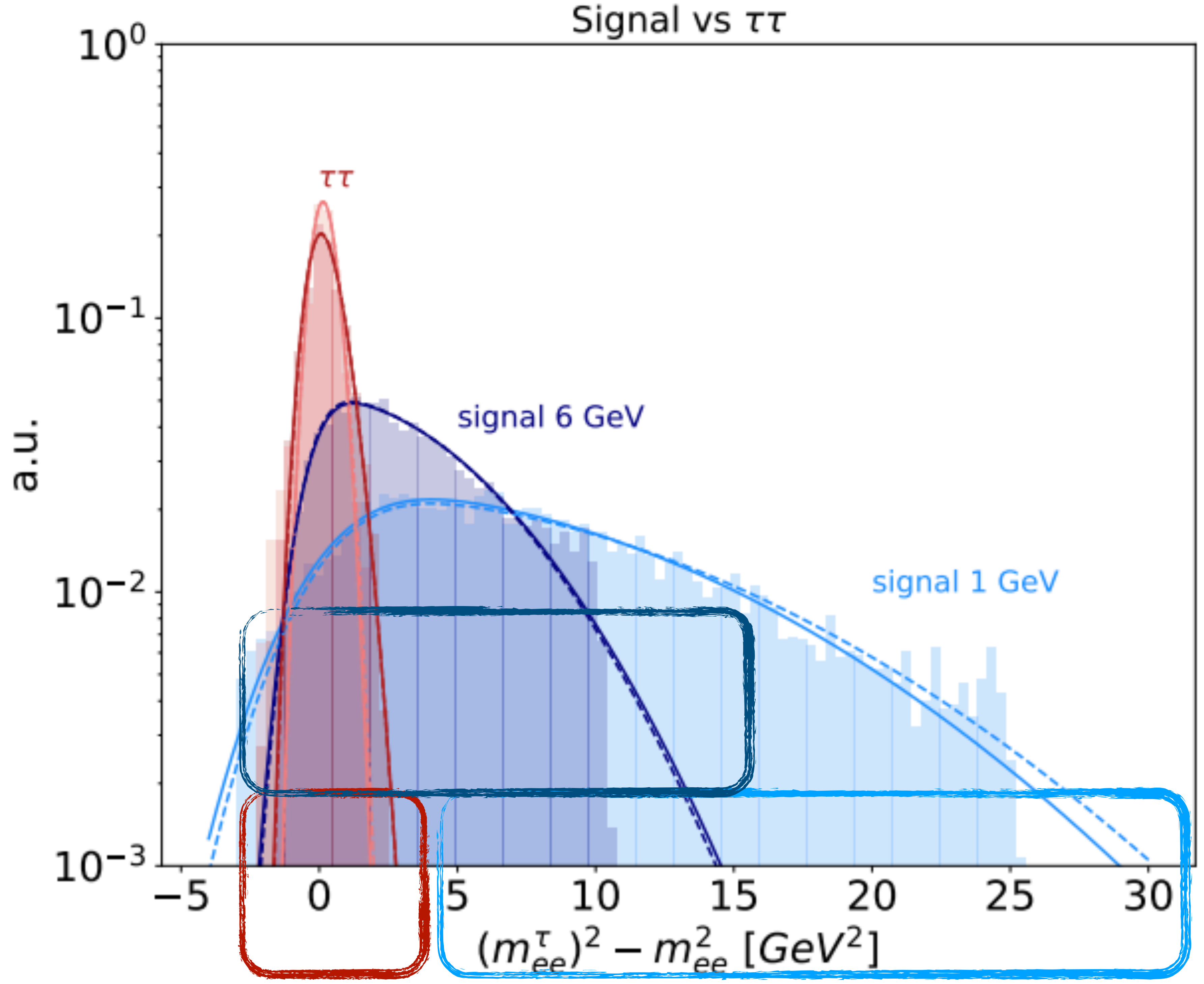
The tau-tau background is peaked

Fusing photons into nothing







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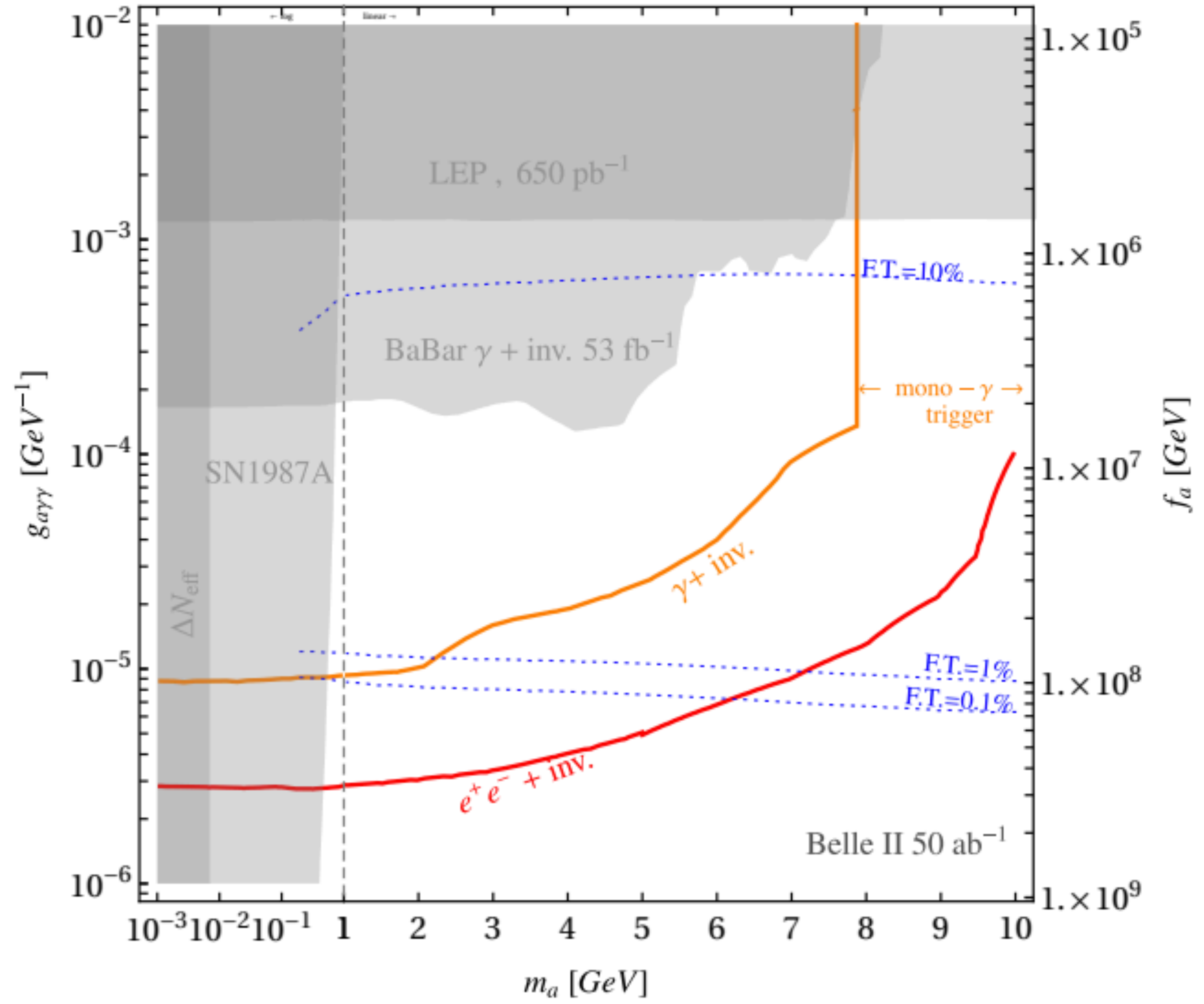
The tau-tau background is peaked

The signal is spread for small masses but less for high masses

What more can be squeezed?

Acanfora, Franceschini, Mastroddi, D.R. 2307.06369



$\gamma + \text{inv}$

Photon-fusion is a complementary probe of the invisible ALP!

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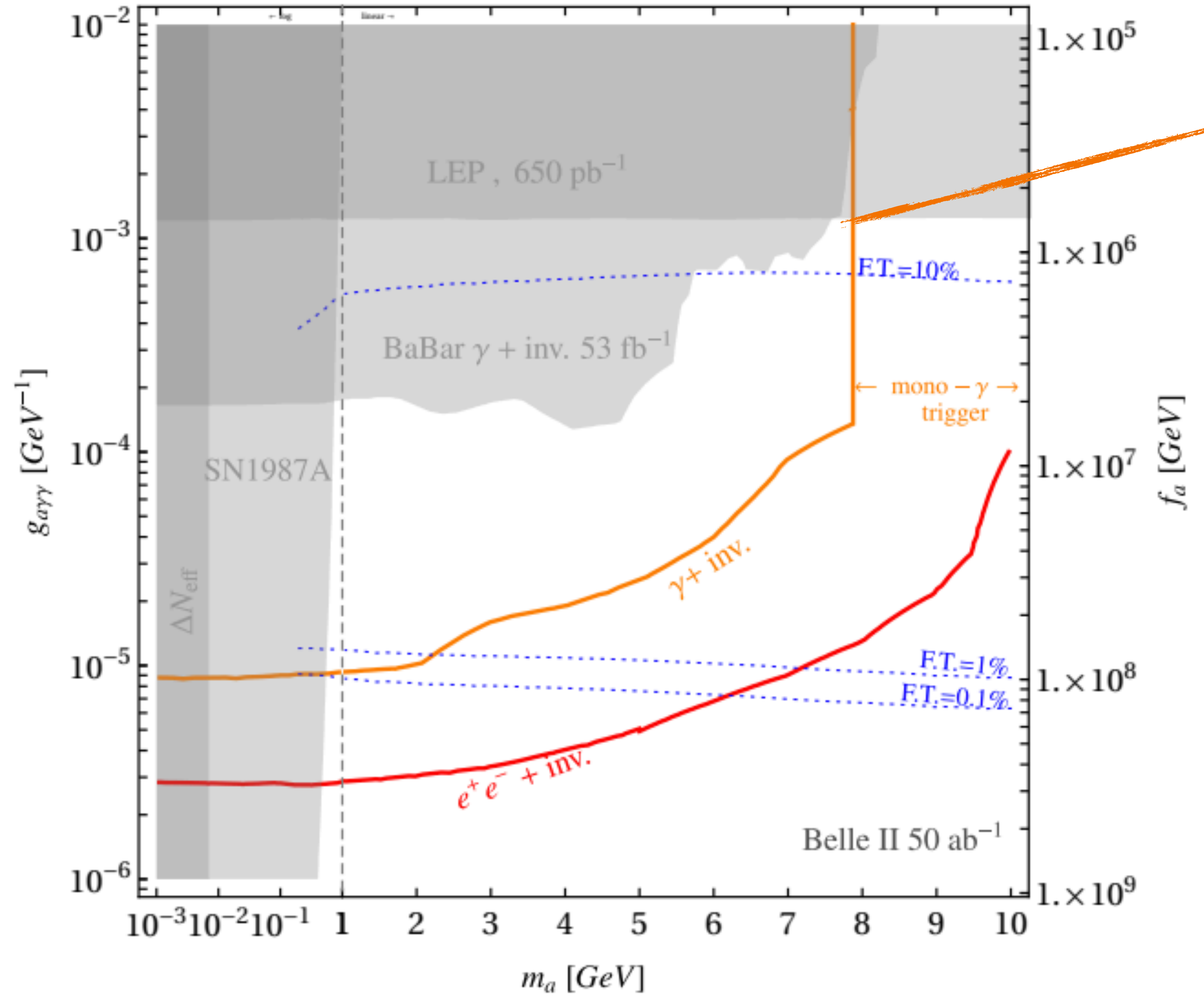
Acanfora, Franceschini, Mastroddi, D.R. 2307.06369



Reach of $\gamma + \text{inv}$

Dolan, Ferber, Heary, Kahlhofer, Schmidt-Hoberg 1709.00009

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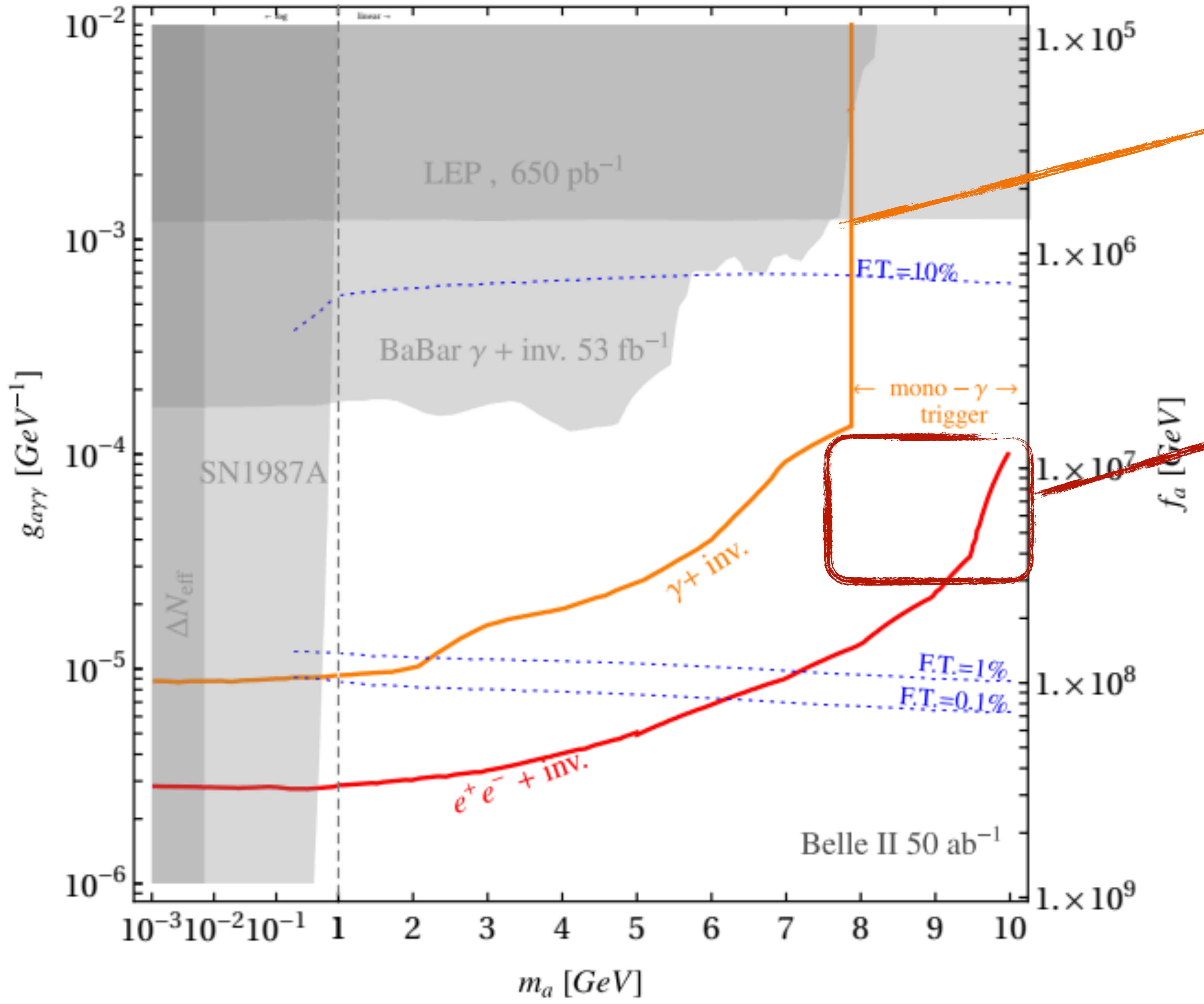


Reach of $\gamma + \text{inv}$

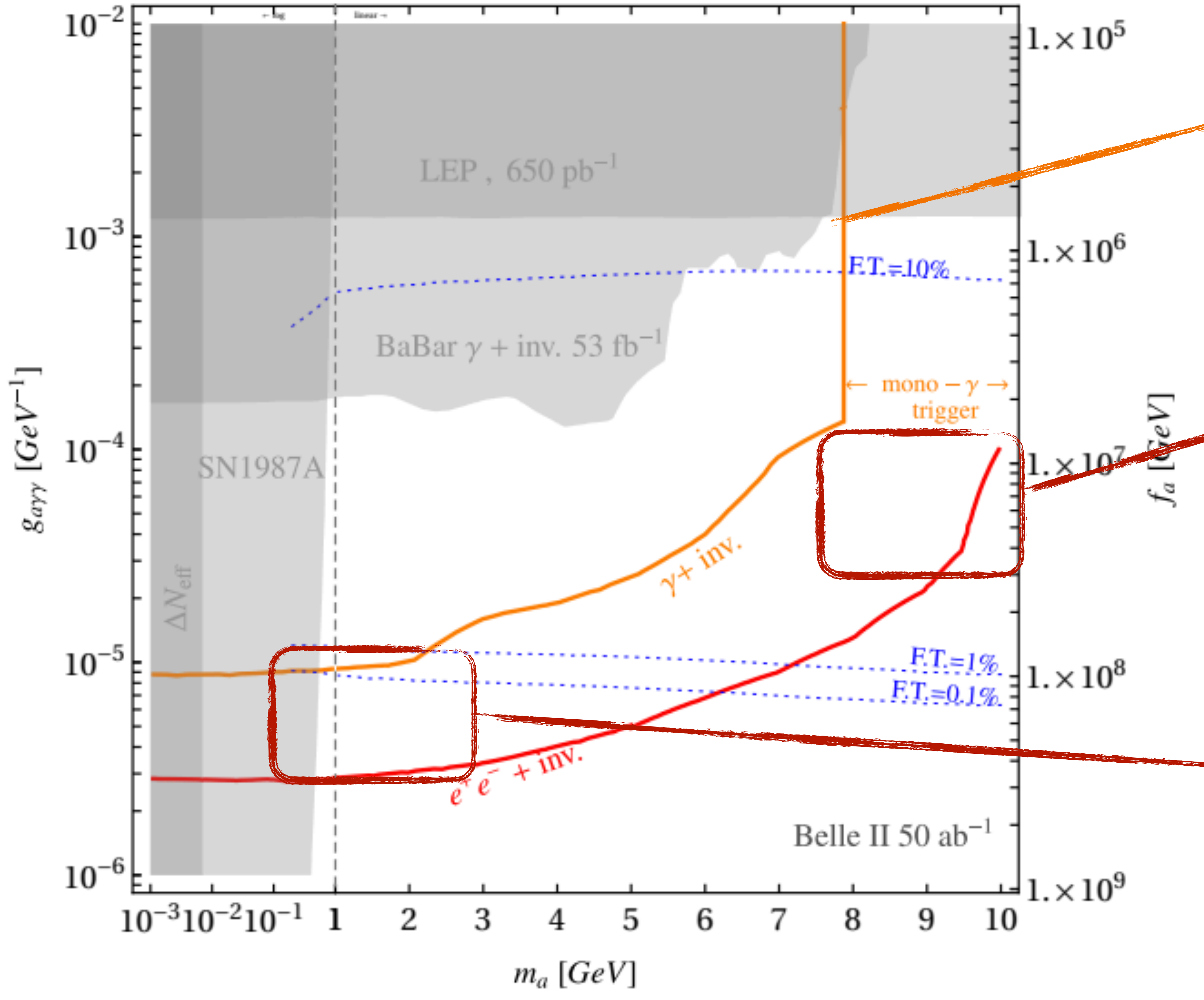
Dolan, Ferber, Heary, Kahlhofer, Schmidt-Hoberg 1709.00009

The new search does not deteriorate at high masses for trigger requirements

Photon-fusion is a complementary probe of the invisible ALP!

What more can be squeezed?

Acanfora, Franceschini, Mastroddi, D.R. 2307.06369



Reach of $\gamma + \text{inv}$

Dolan, Ferber, Heary, Kahlhofer, Schmidt-Hoberg 1709.00009

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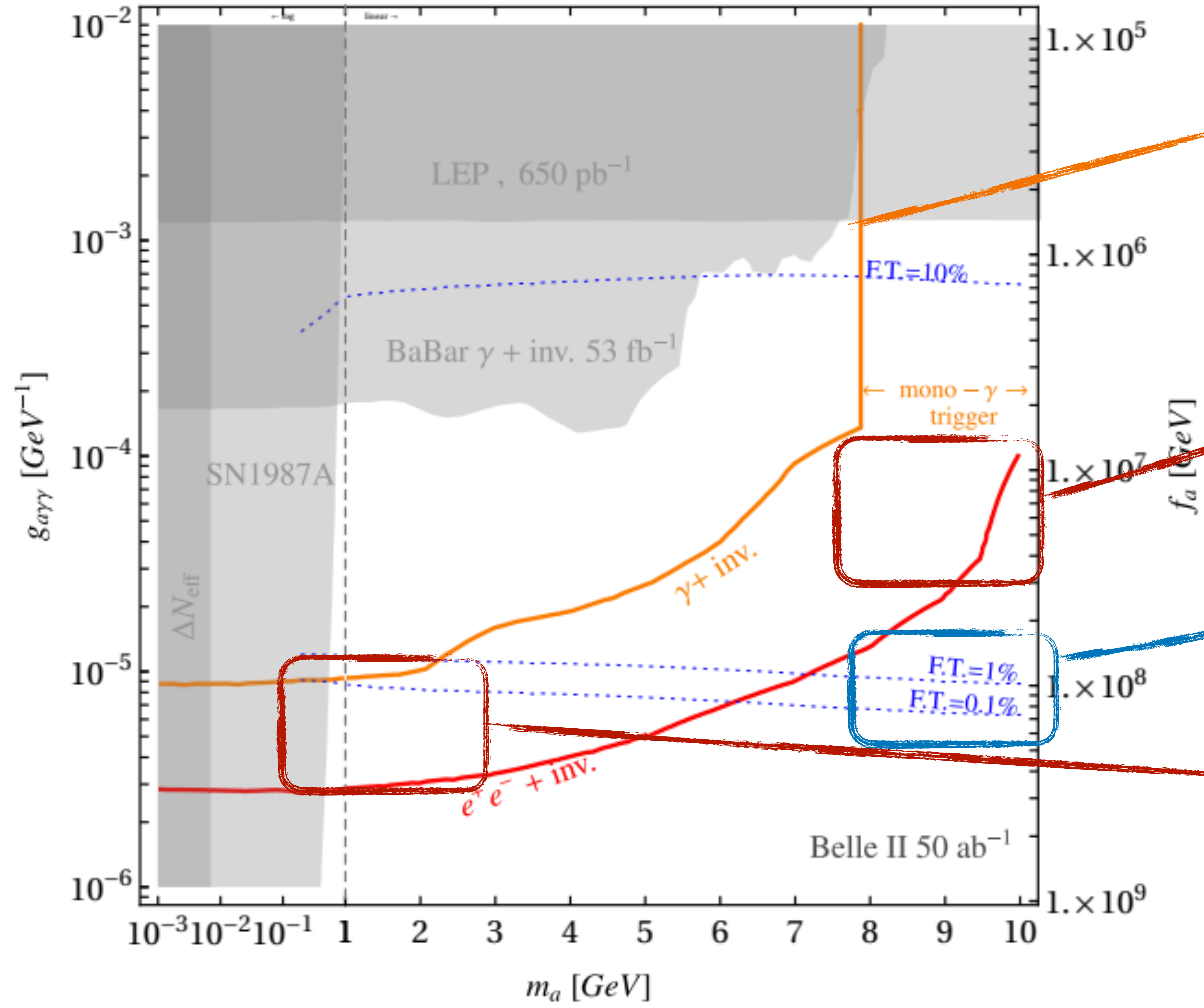

Reach of $\gamma + \mathrm{inv}$

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The new search does not deteriorate at high masses for trigger requirements

It can probe DM resonant freeze-out completely!

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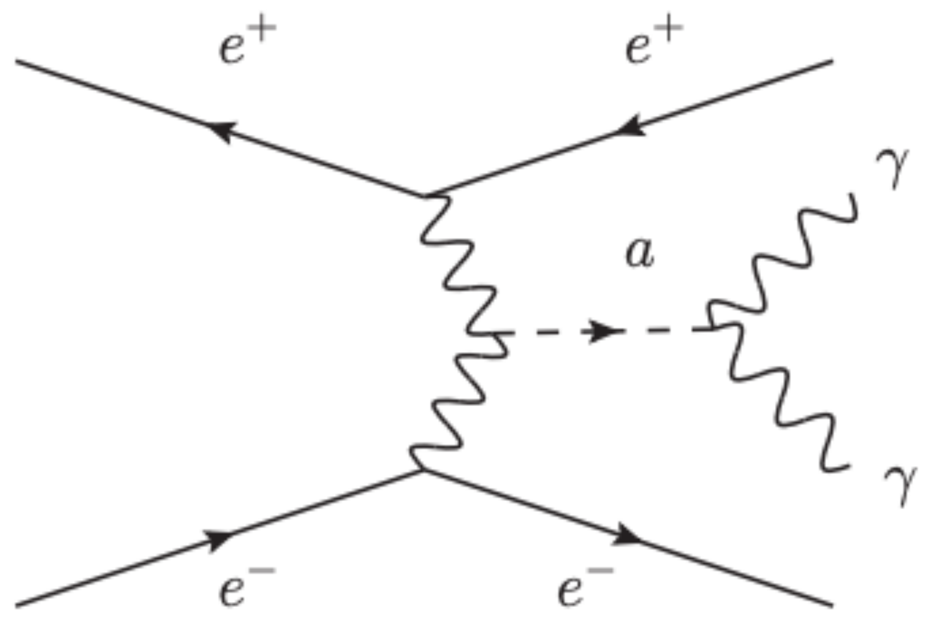
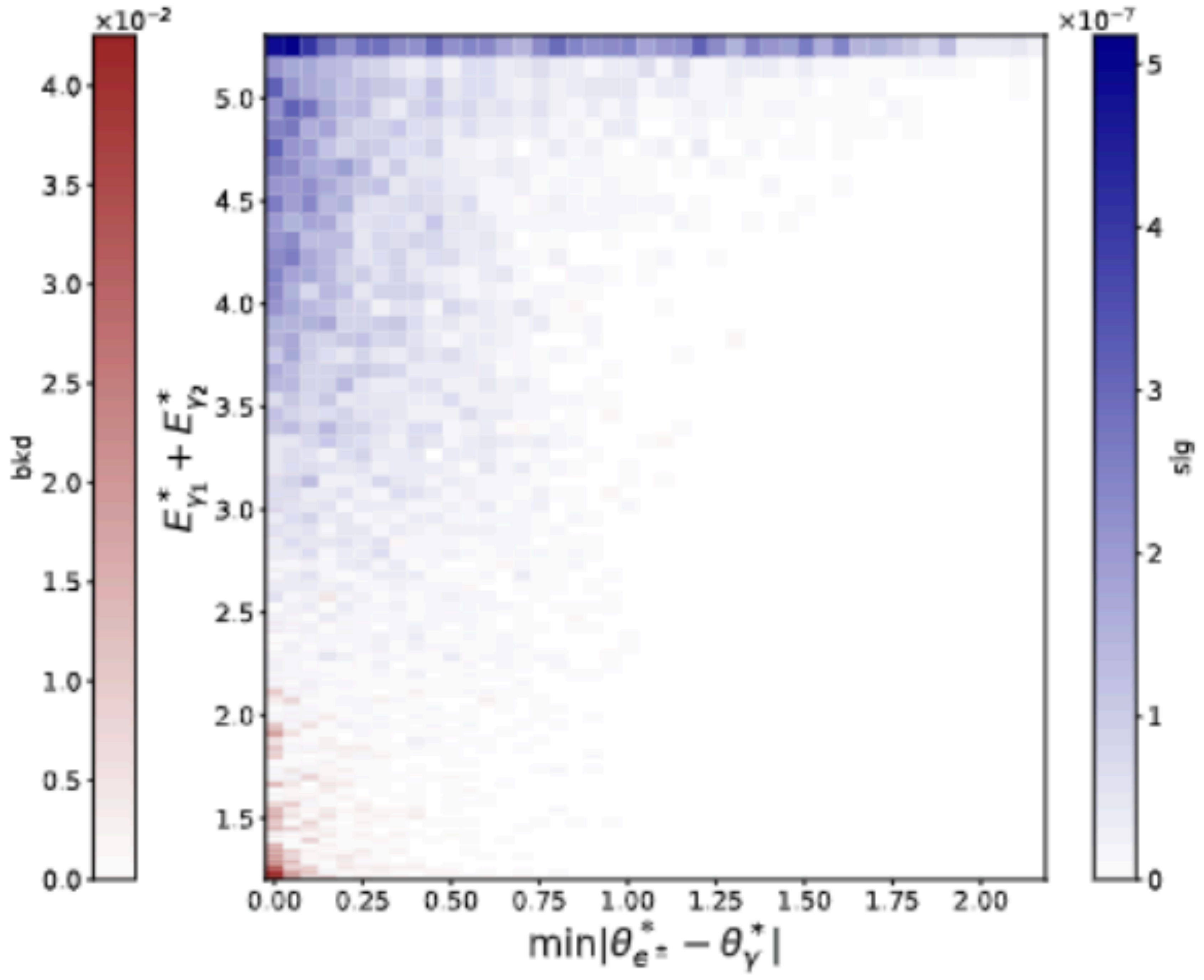
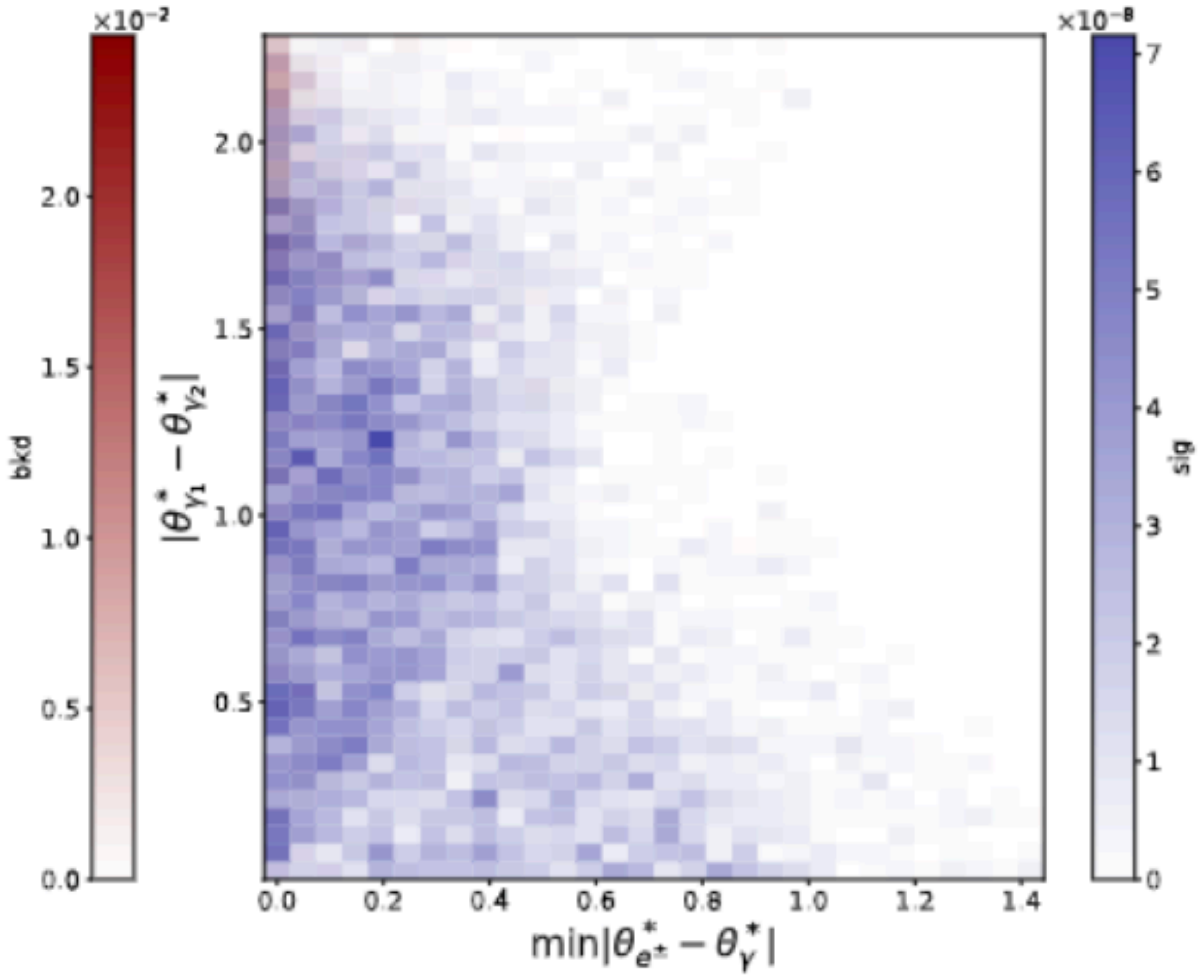
Fusing photons into diphoton resonance

Diphoton resonances produced in photon fusions

$$e^+ + e^- + a\ (\gamma\gamma)_{\rm res}$$







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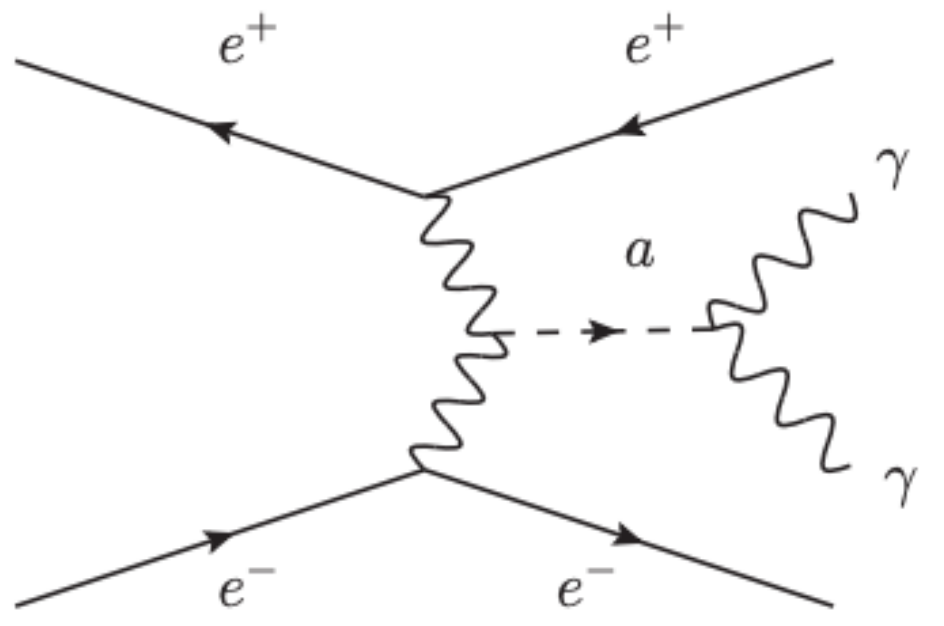

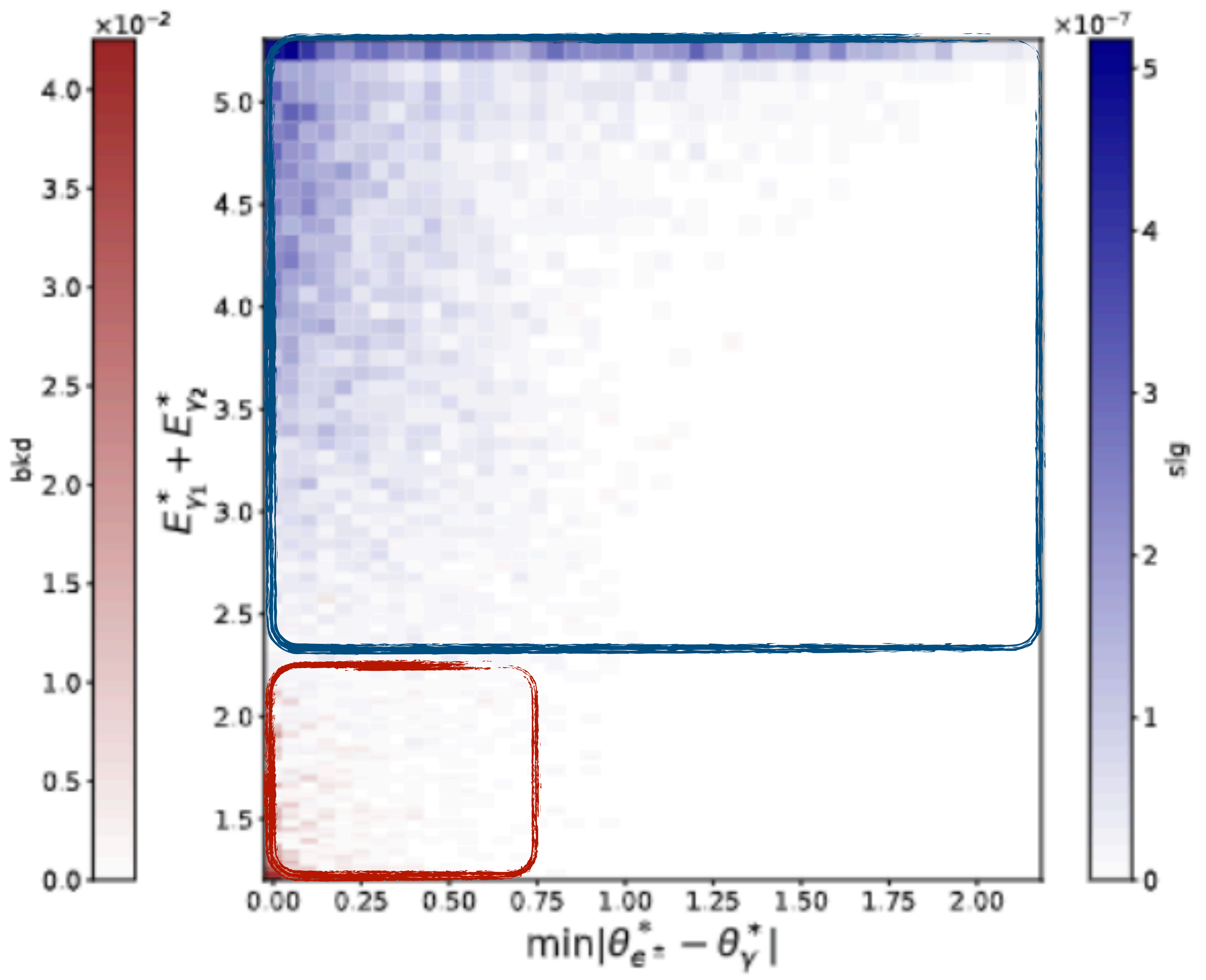

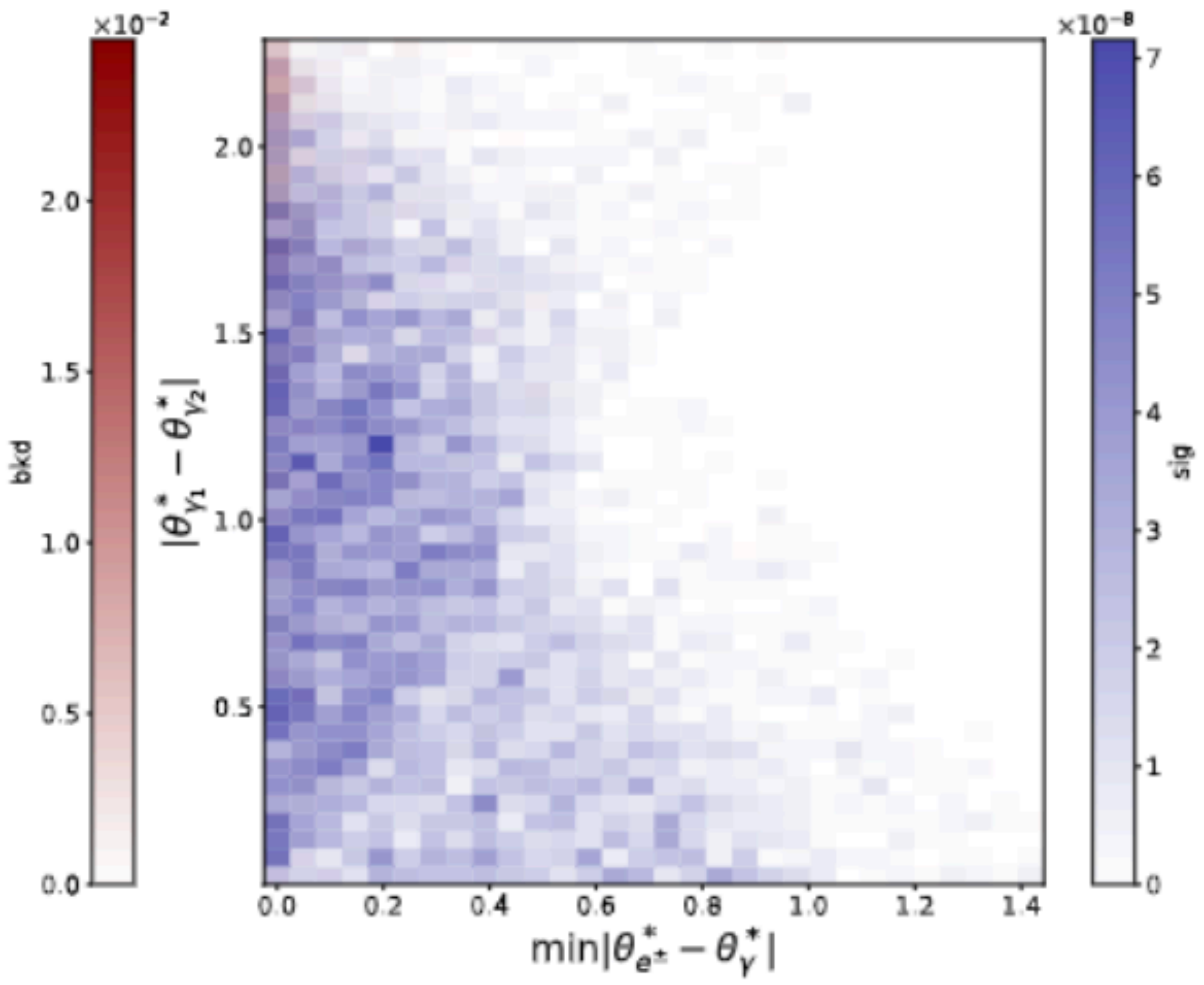

@ *small diphoton mass* the background photons tend to be soft and collinear with the electron/positron

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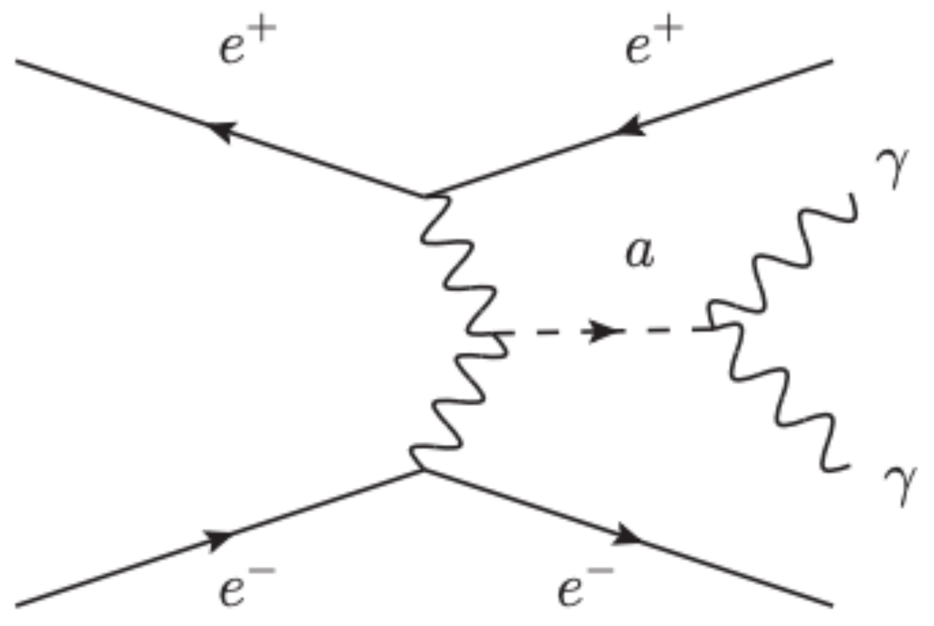
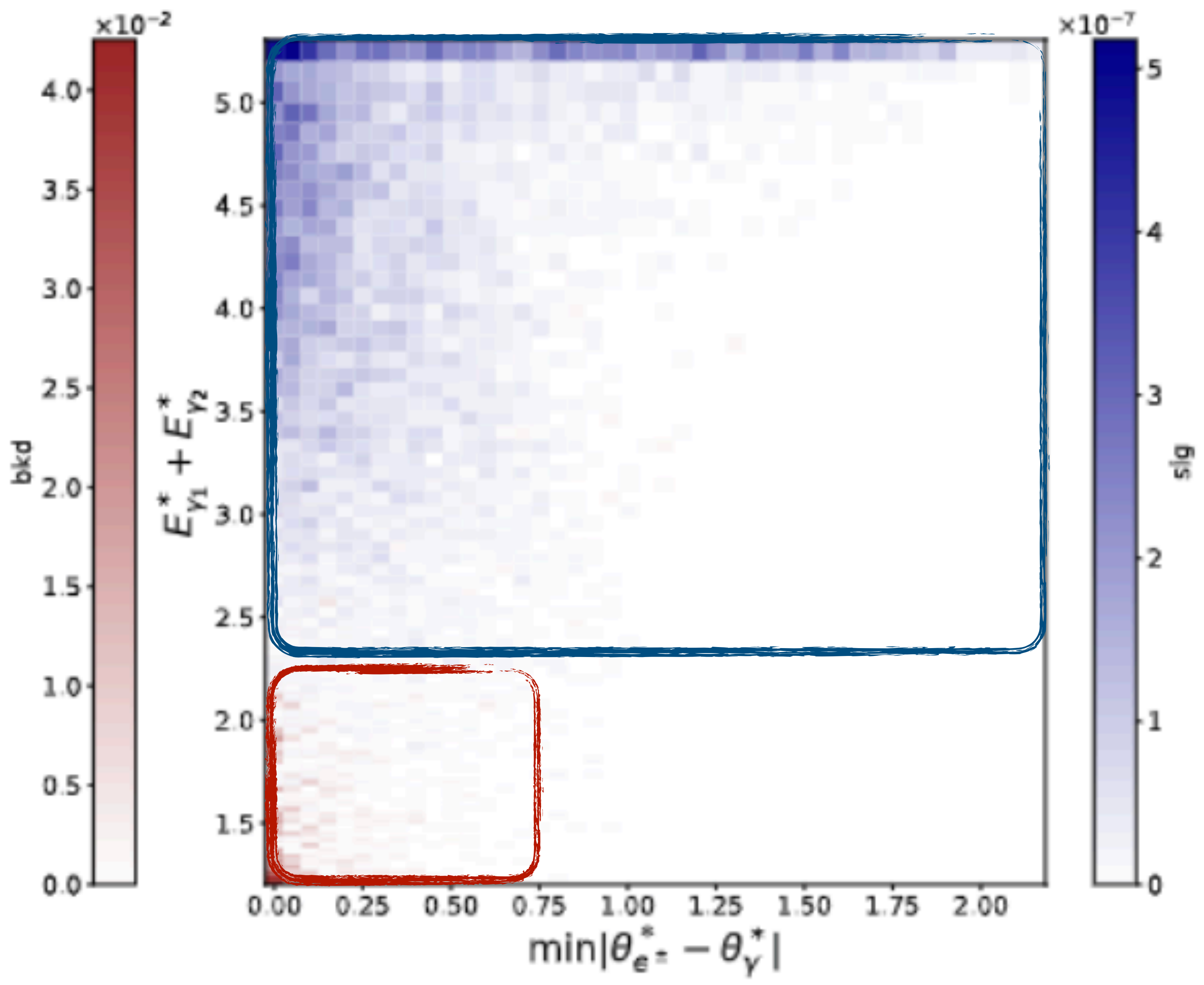
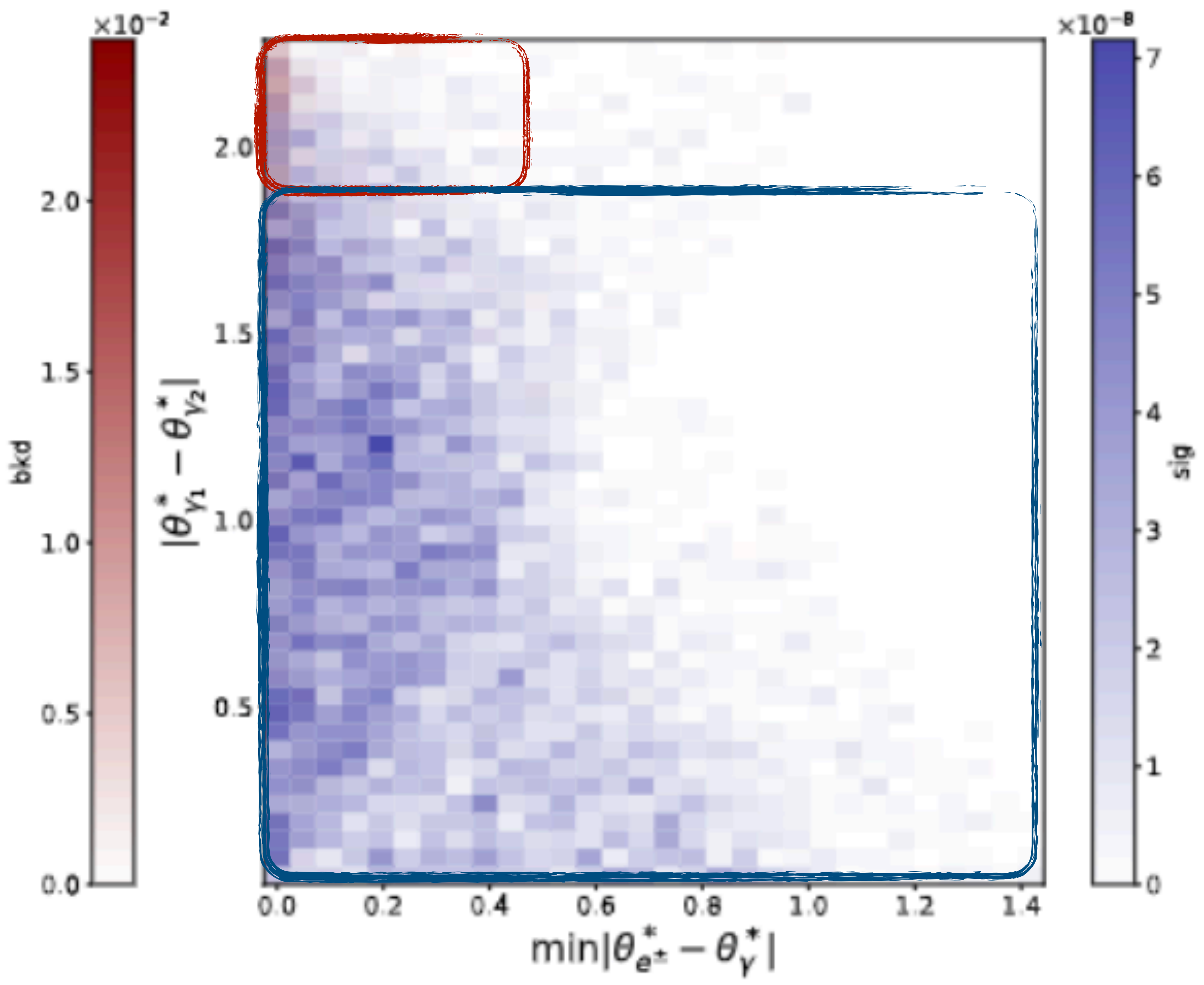




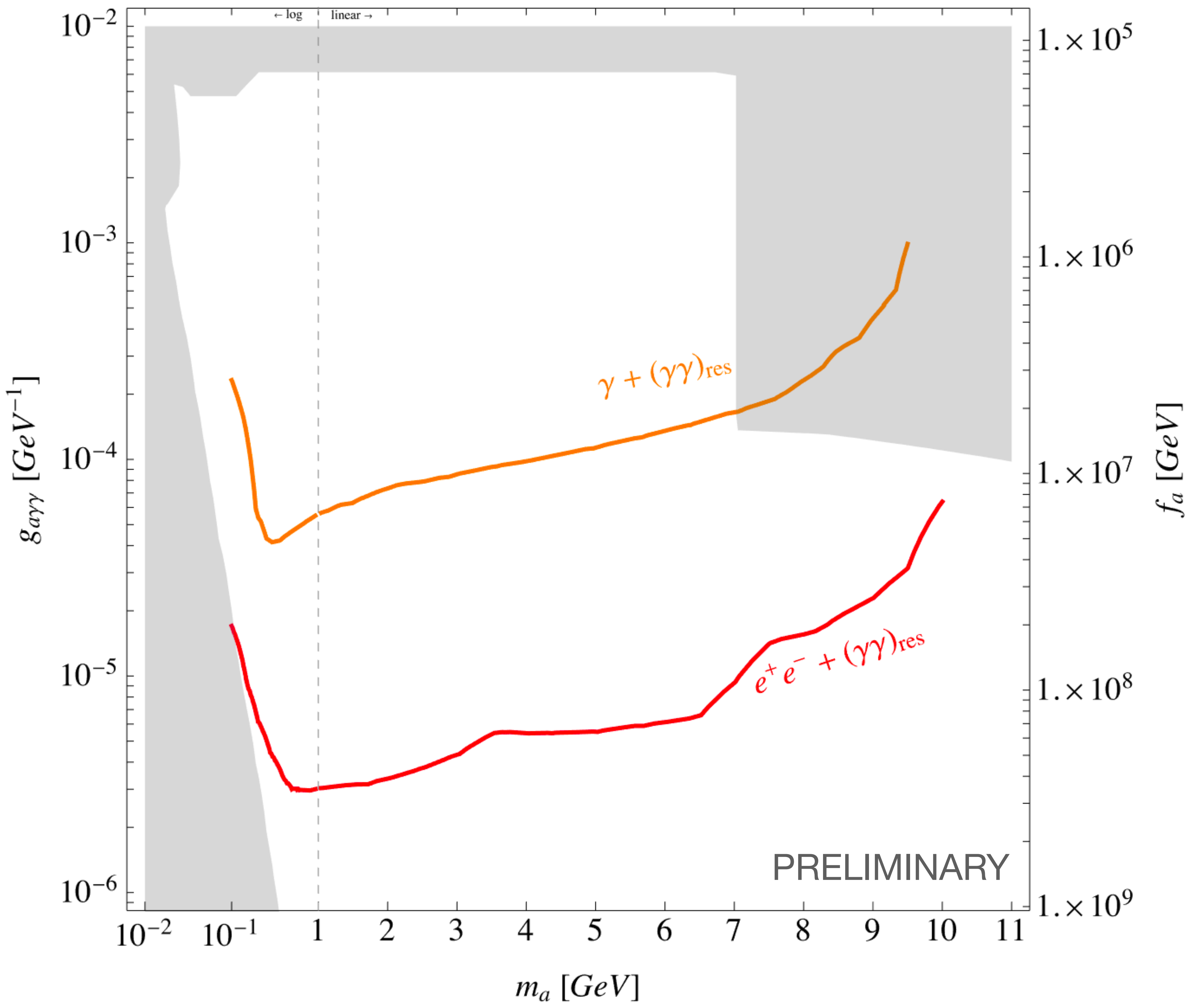


@ *small diphoton mass* the background photons tend to be soft and collinear with the electron/positron

@ *high diphoton mass* the background photons tend to be widely separated and still collinear with the electron/positron

What more can be squeezed?

Acanfora, Franceschini, Mastroddi, D.R. to appear



Photon-fusion is a unique probe of the visible ALP!

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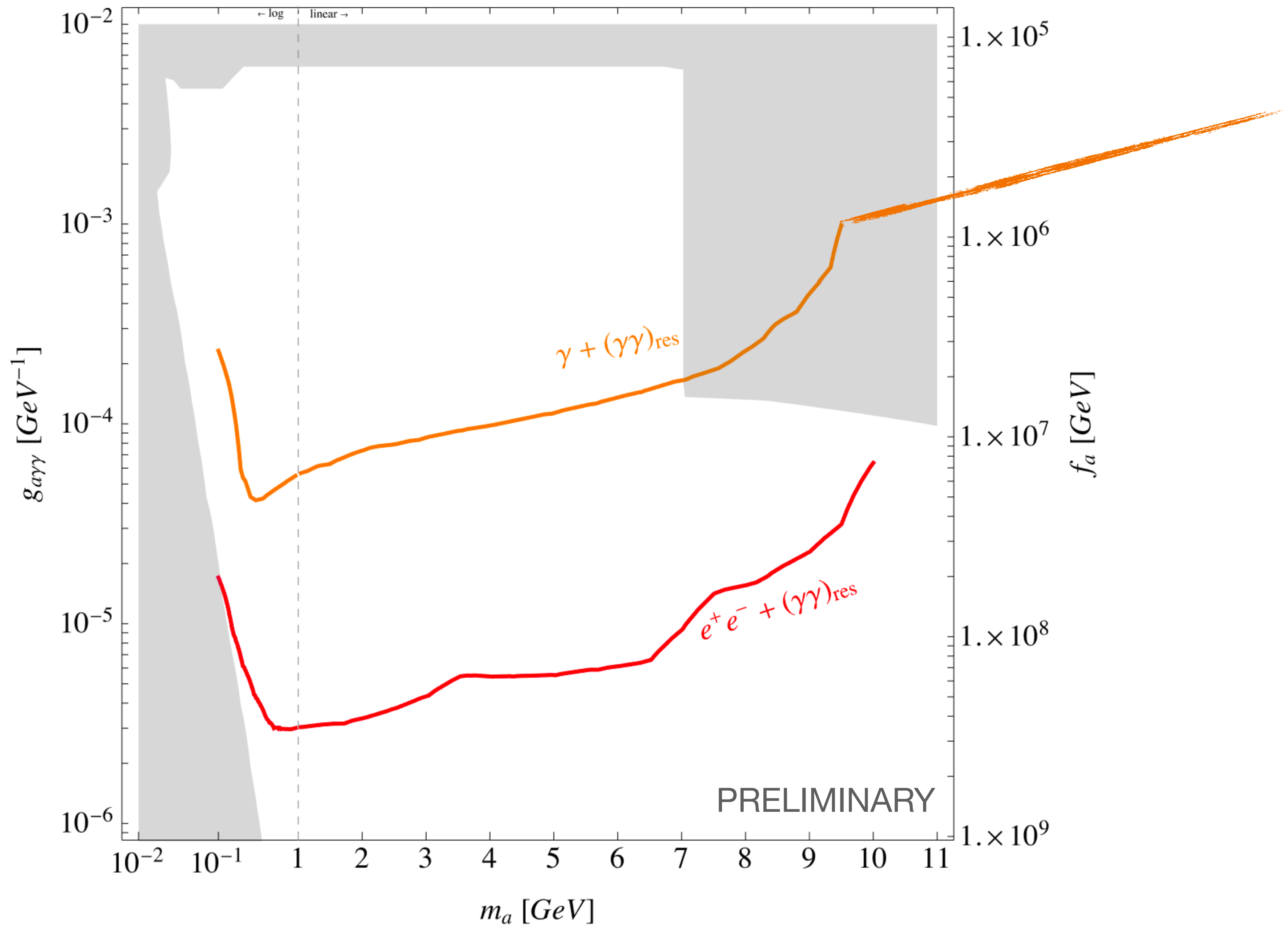

Reach of $\gamma + (\gamma\gamma)_{\rm res}$

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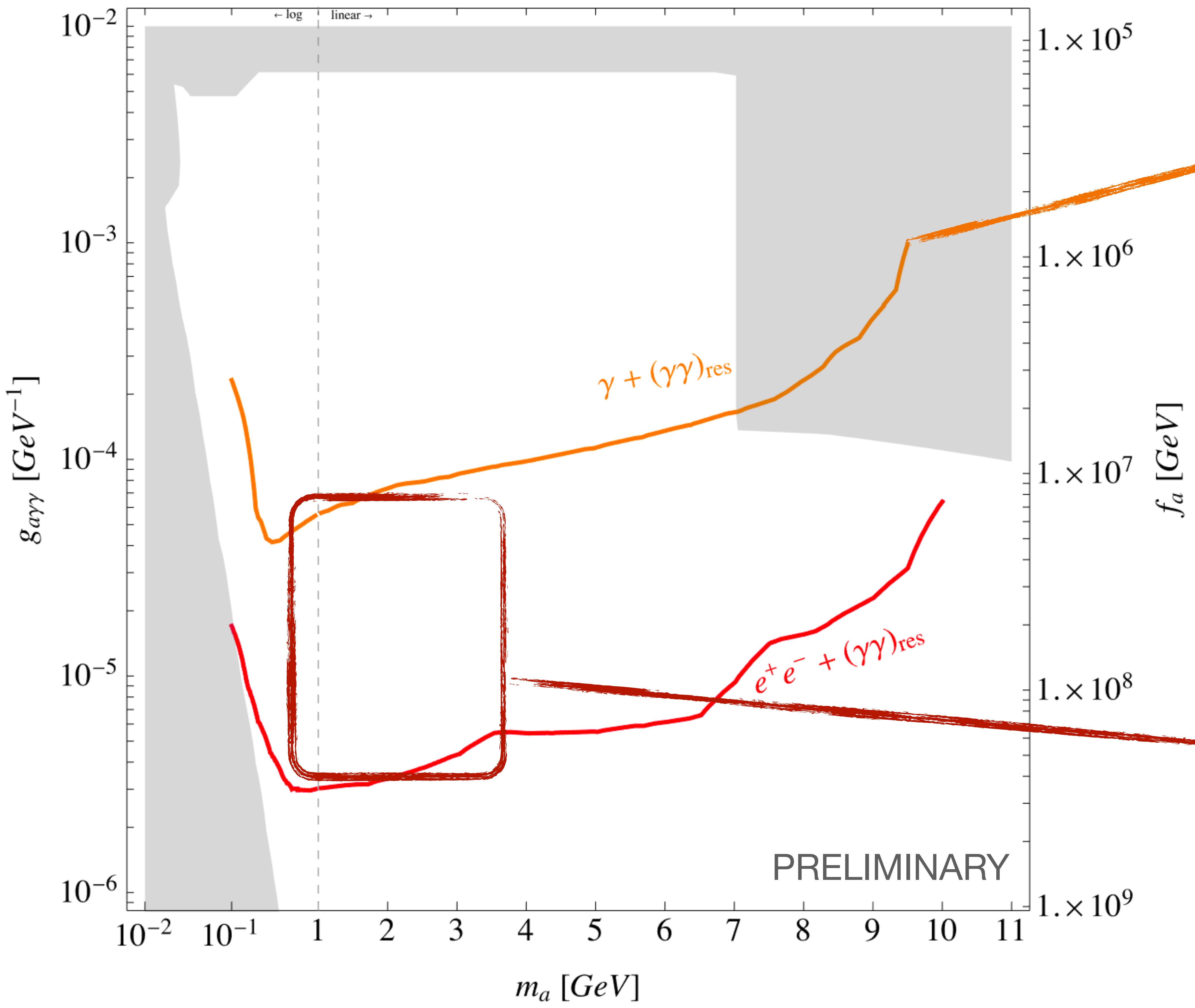

Reach of $\gamma + (\gamma\gamma)_{\rm res}$

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The search is essentially background-free @ small masses

$\mathcal{O}(10)$ Improvement in the reach compared to previous studies

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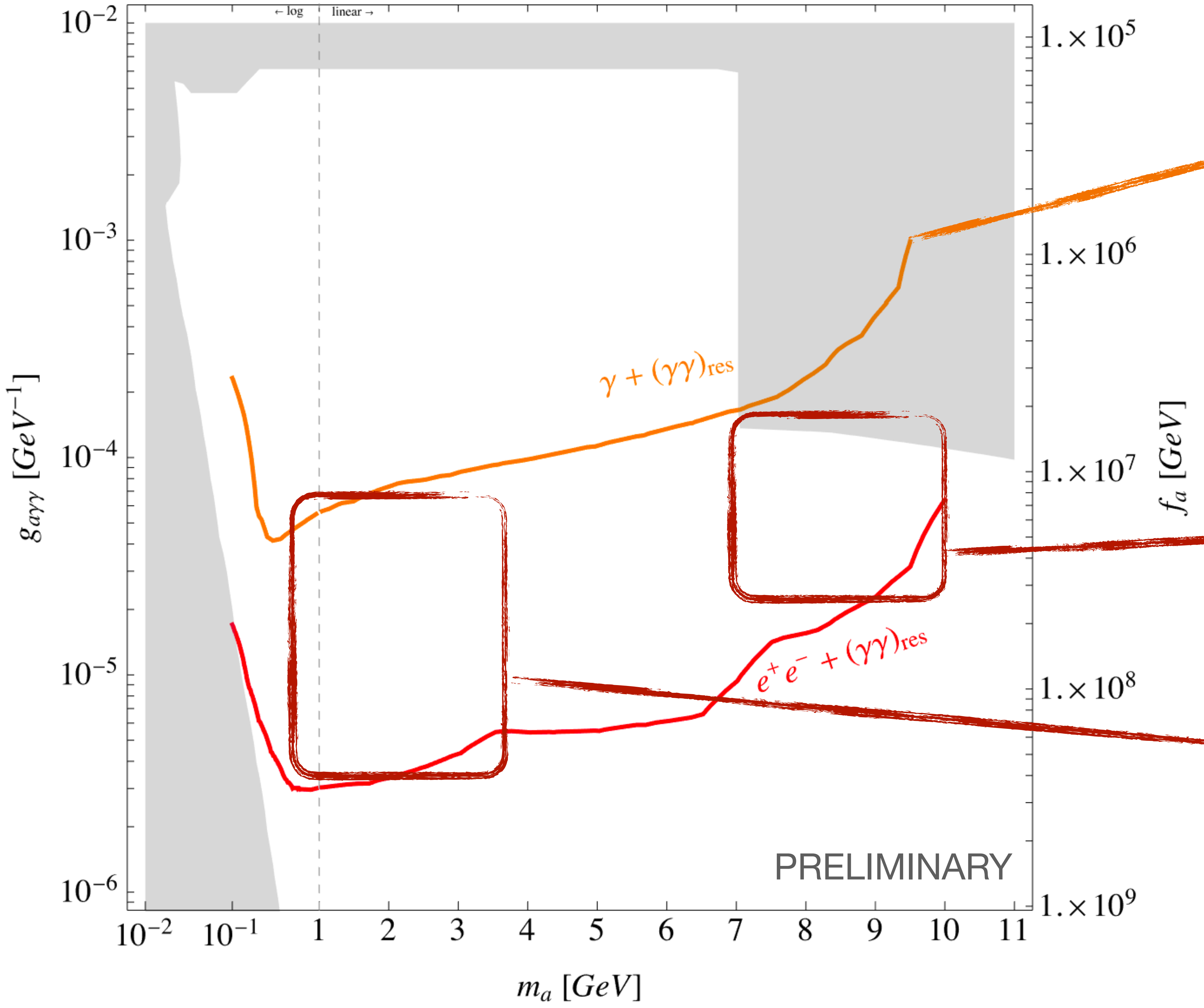

Reach of $\gamma + (\gamma\gamma)_{\rm res}$

Dolan, Ferber, Heary, Kahlhofer, Schmidt-Hoberg 1709.00009

The gain is still sizeable at high masses

The search is essentially background-free @ small masses

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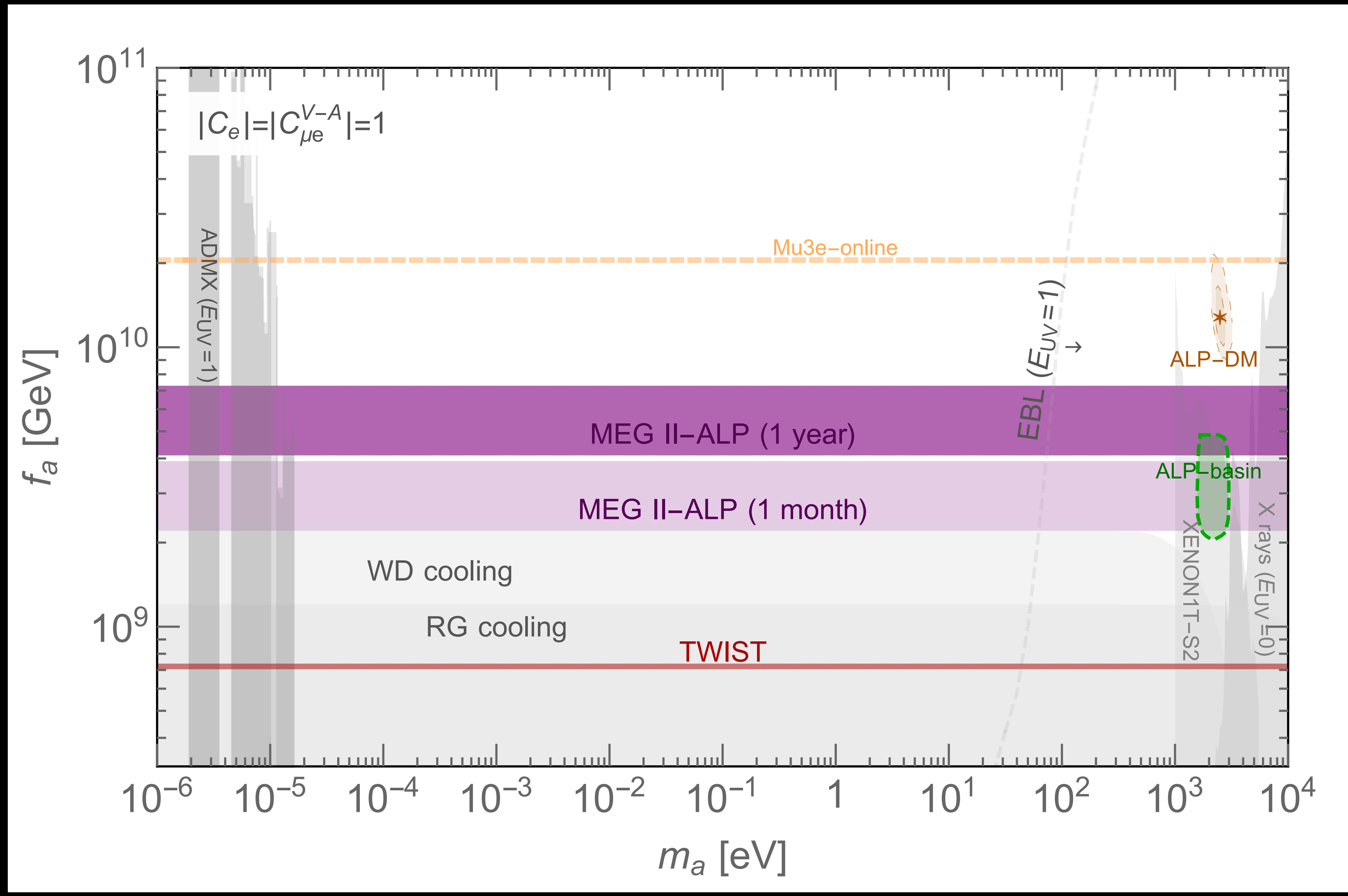
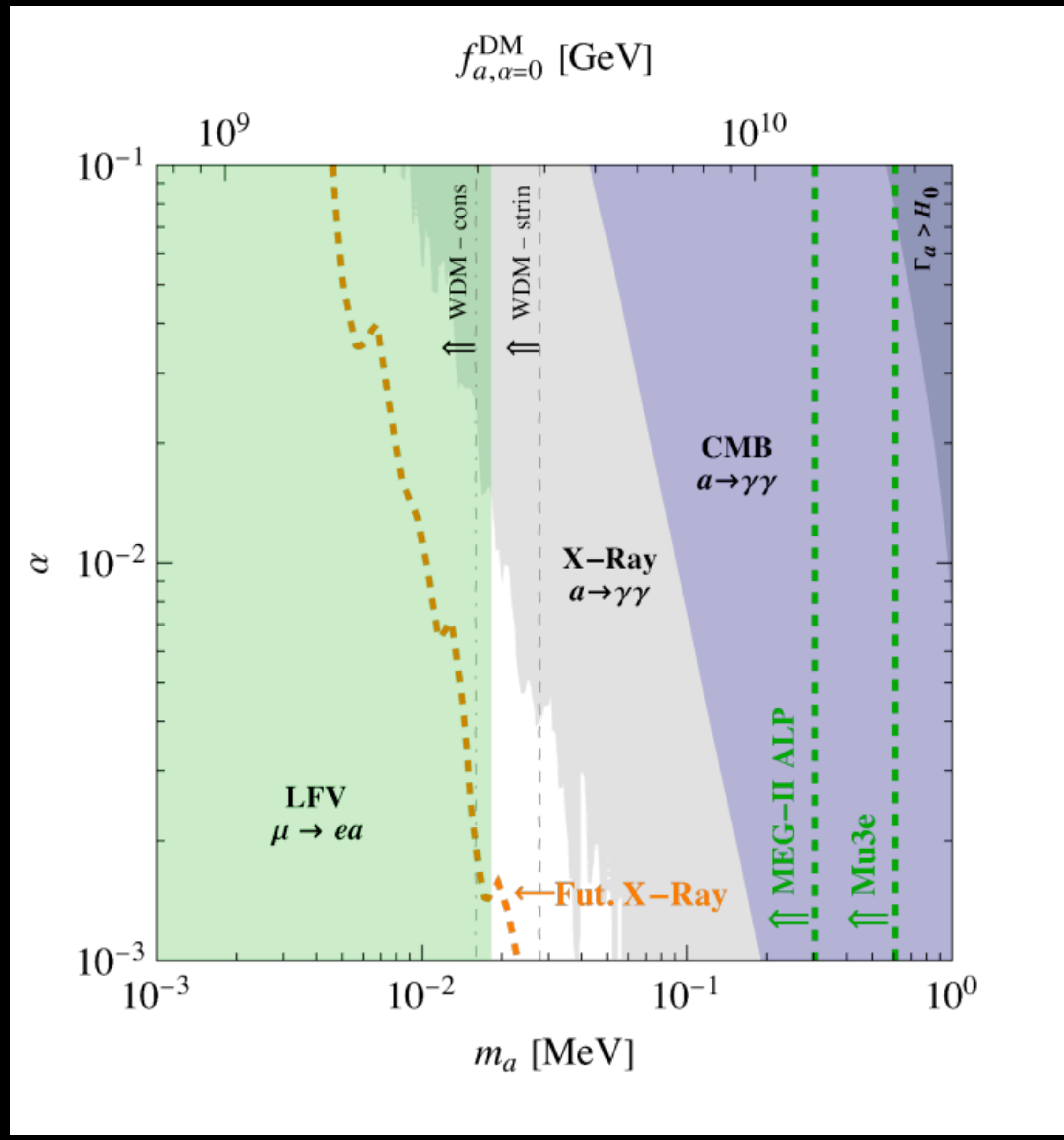
Photon-fusion is a unique probe of the visible ALP!

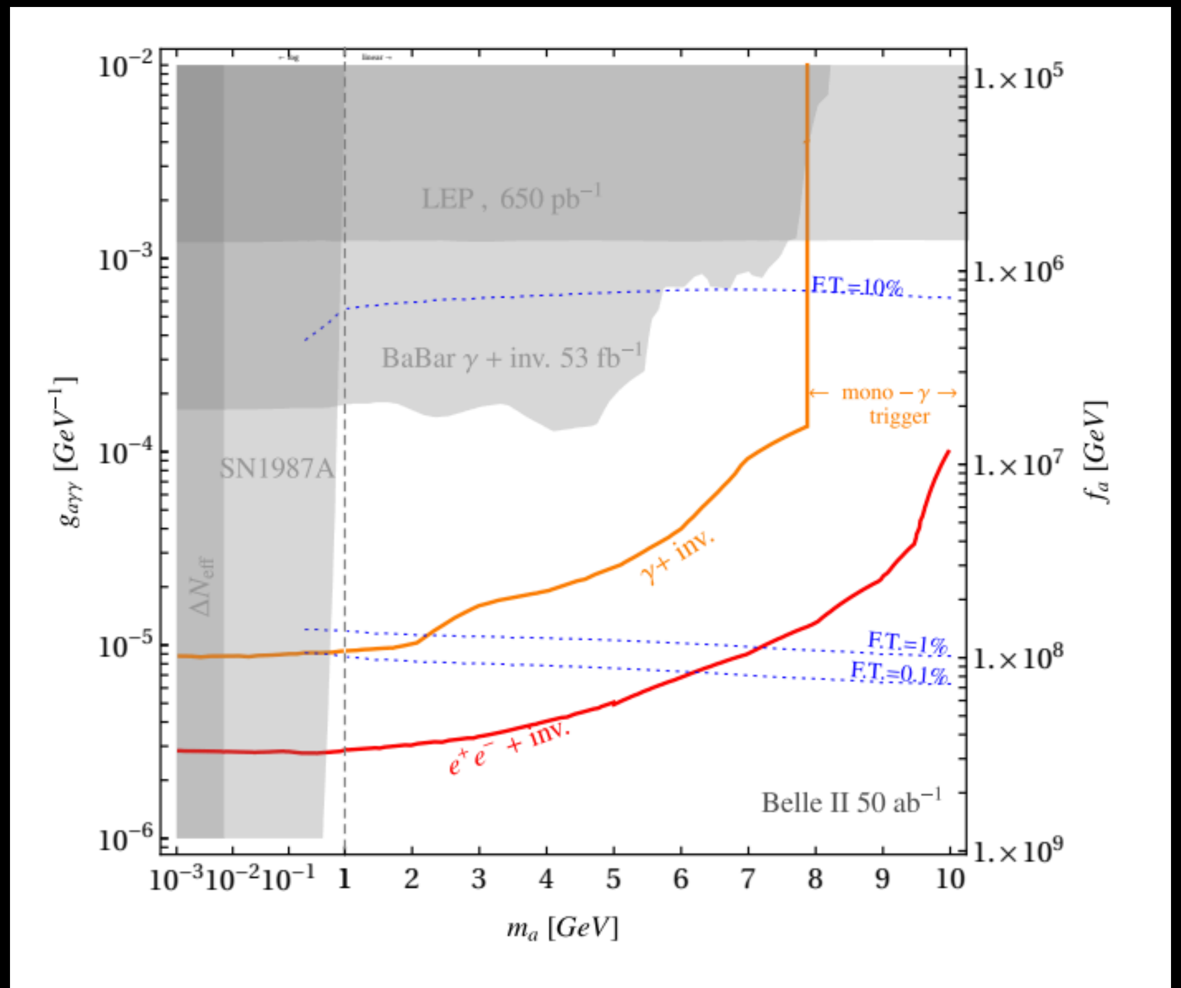
Dark Matter & Flavor Factories

LFV ALP @ MEG II





PHOTON FUSION @ Belle II



Thanks…