THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

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Photon-jet Events as a Probe of Axion-like Particles at the LHC

IAS Program High Energy Physics (2023)

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Based on: *Phys.Rev.D 104 (2021) 9, 095016* Daohan Wang, Lei Wu, Jin Min Yang, MZ
JHEP 11 (2021) 138 Jie Ren, Daohan Wang, Lei Wu, Jin Min Yang, MZ

Outline

1.Model introduction and its collider search problem

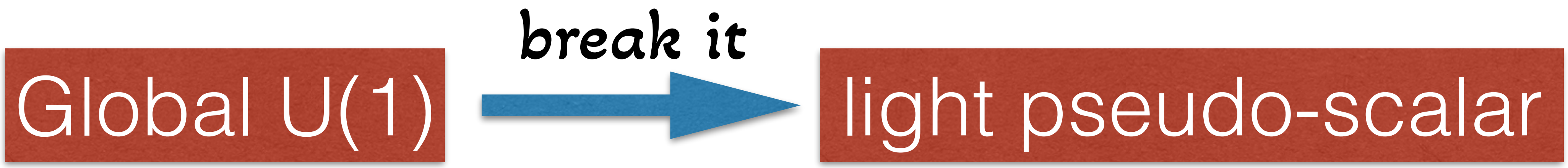
2.Photon-jet tagging via jet sub-structure method

3.Real study on the LHC

4.Discussion and Conclusion

Model Introduction

Consider a New Physics model if there is a Global U(1) symmetry:



(called Axion-like particle, ALP)

ALP also arise in String theory when you do “compactification” of extra dimensions.

In a word, ALP is a very common prediction in BSM building.

Model Introduction

To be more specific, the effective Lagrangian is like:

$$\mathscr{L}_{eff} \supset \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2}m_a^2 - \frac{C_{BB}}{f_a} a B_{\mu\nu}\tilde{B}^{\mu\nu} - \frac{C_{WW}}{f_a} a W^i_{\mu\nu}\tilde{W}^{\mu\nu,i}$$

(In this work we focus on the Electroweak sector, so we ignore coupling with gluons)

The above is the effective Lagrangian before EW breaking. After EW breaking we will obtain 4 couplings:

$$g_{a\gamma\gamma} = \frac{4}{f_a}(C_{BB}\cos\theta_W^2 + C_{WW}\sin\theta_W^2)$$

$$g_{aWW} = \frac{4}{f_a}C_{WW}$$

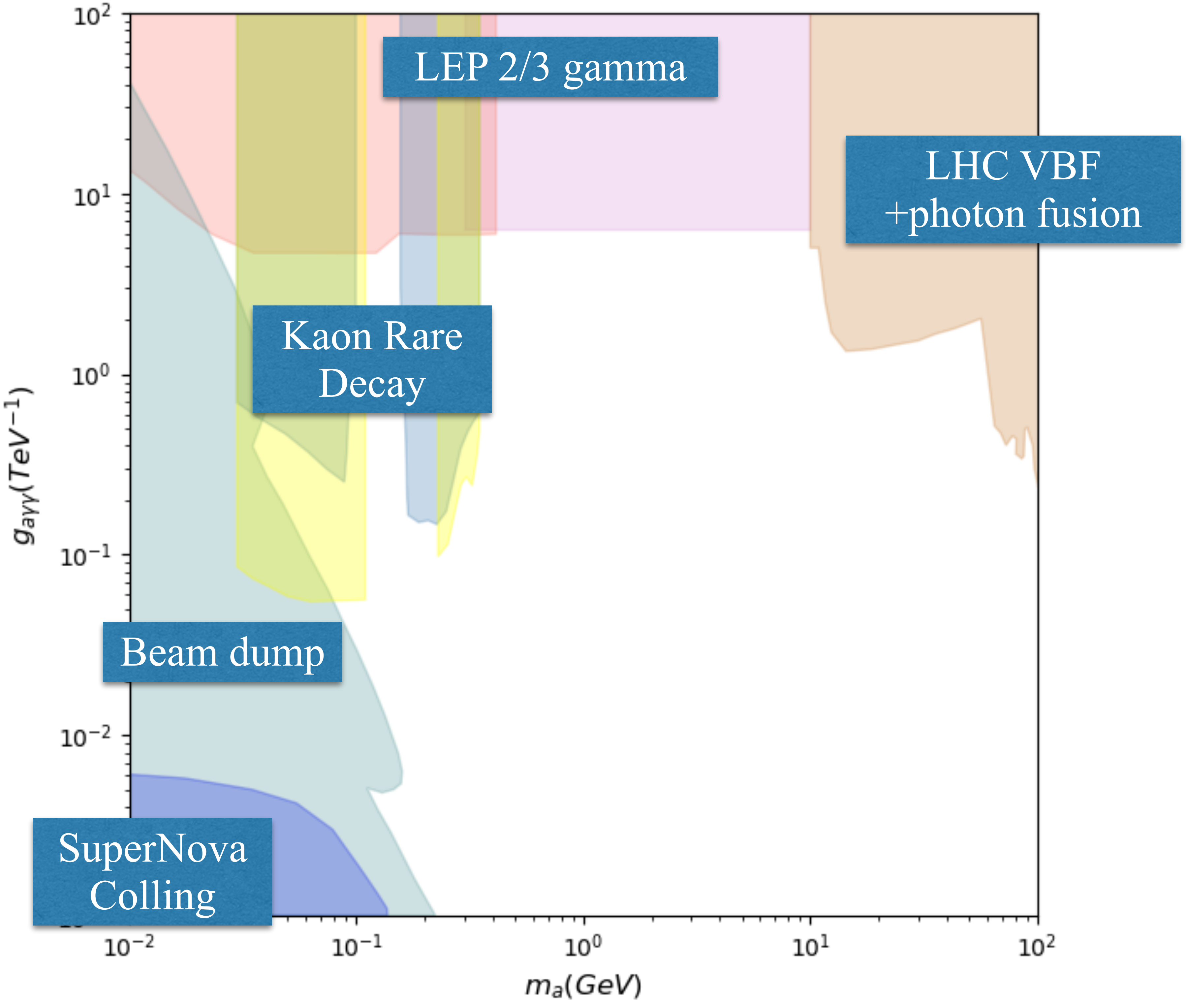
$$g_{aZZ} = \frac{4}{f_a}(C_{BB}\sin\theta_W^2 + C_{WW}\cos\theta_W^2)$$

$$g_{a\gamma Z} = \frac{8}{f_a}\cos\theta_W \sin\theta_W (C_{WW} - C_{BB})$$

For simplicity, we choose $C_{WW} = C_{BB}$. So, there are 2 free parameters in this model: m_a and $g_{a\gamma\gamma}$.

Current search status

We haven't seen ALP, so we have lots of exclusion limits:



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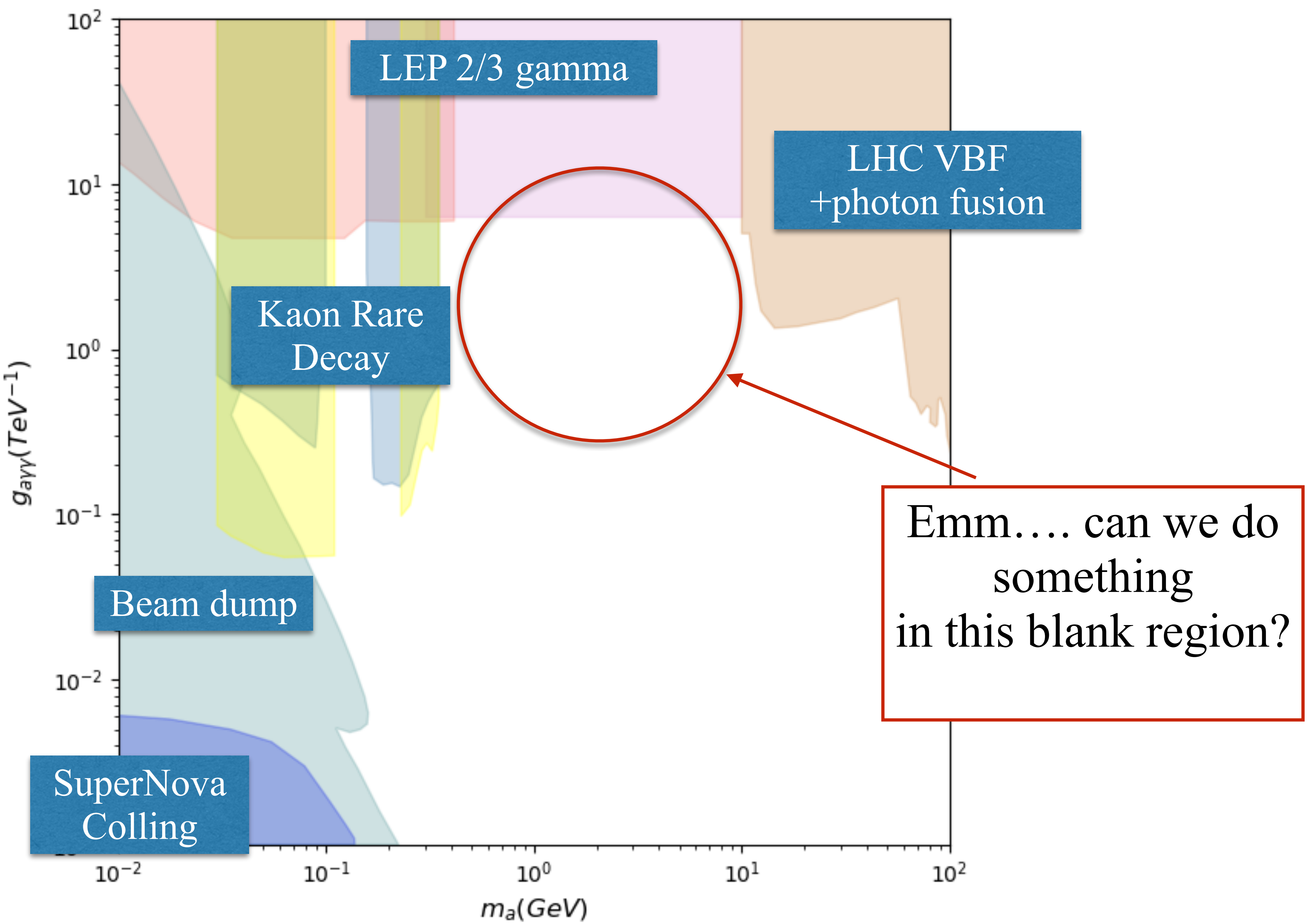
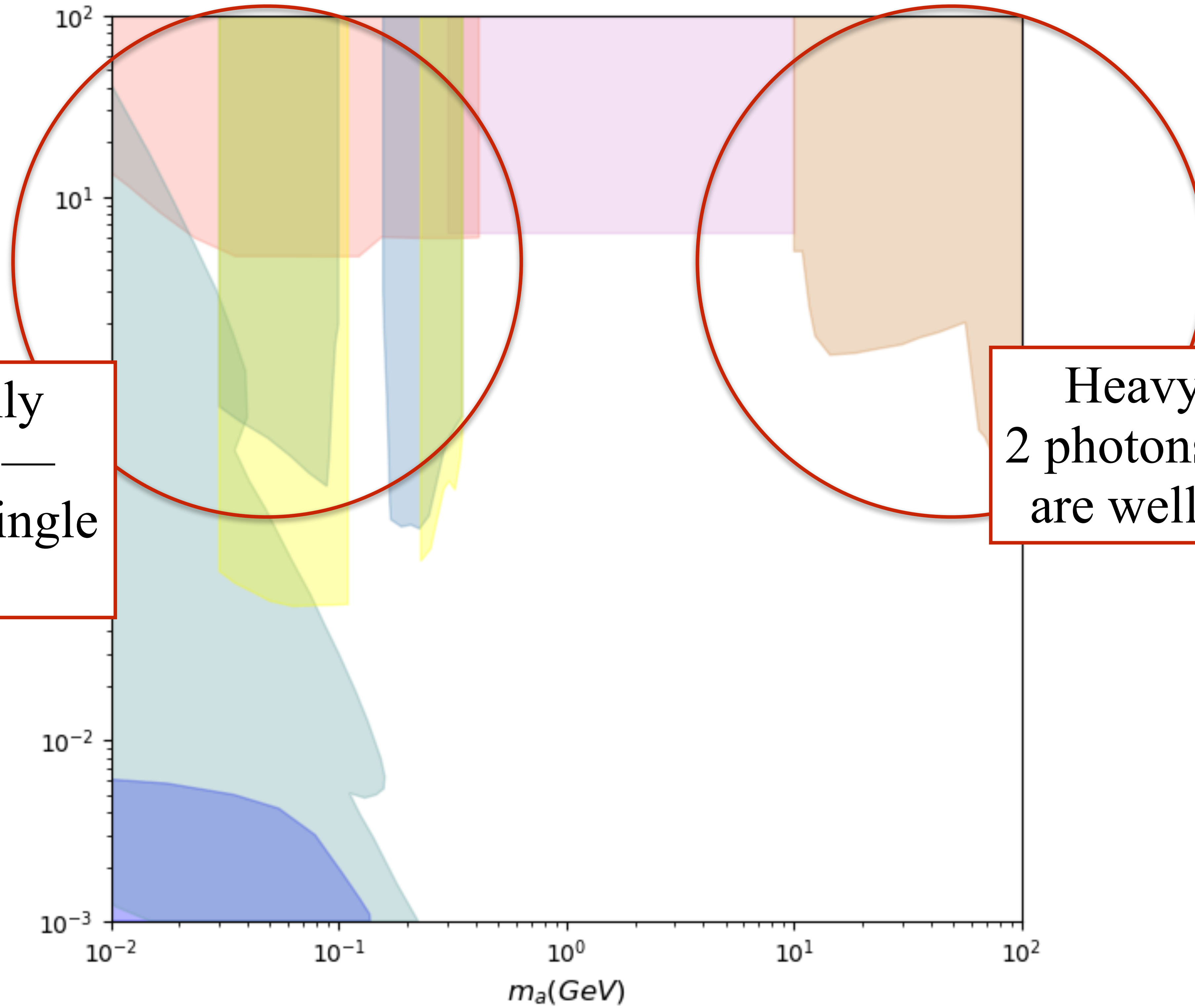


What difficulty we need to overcome at collider search?



Light & highly boosted ALP — it looks like a single photon!

Heavy ALP — 2 photons from ALP are well separated

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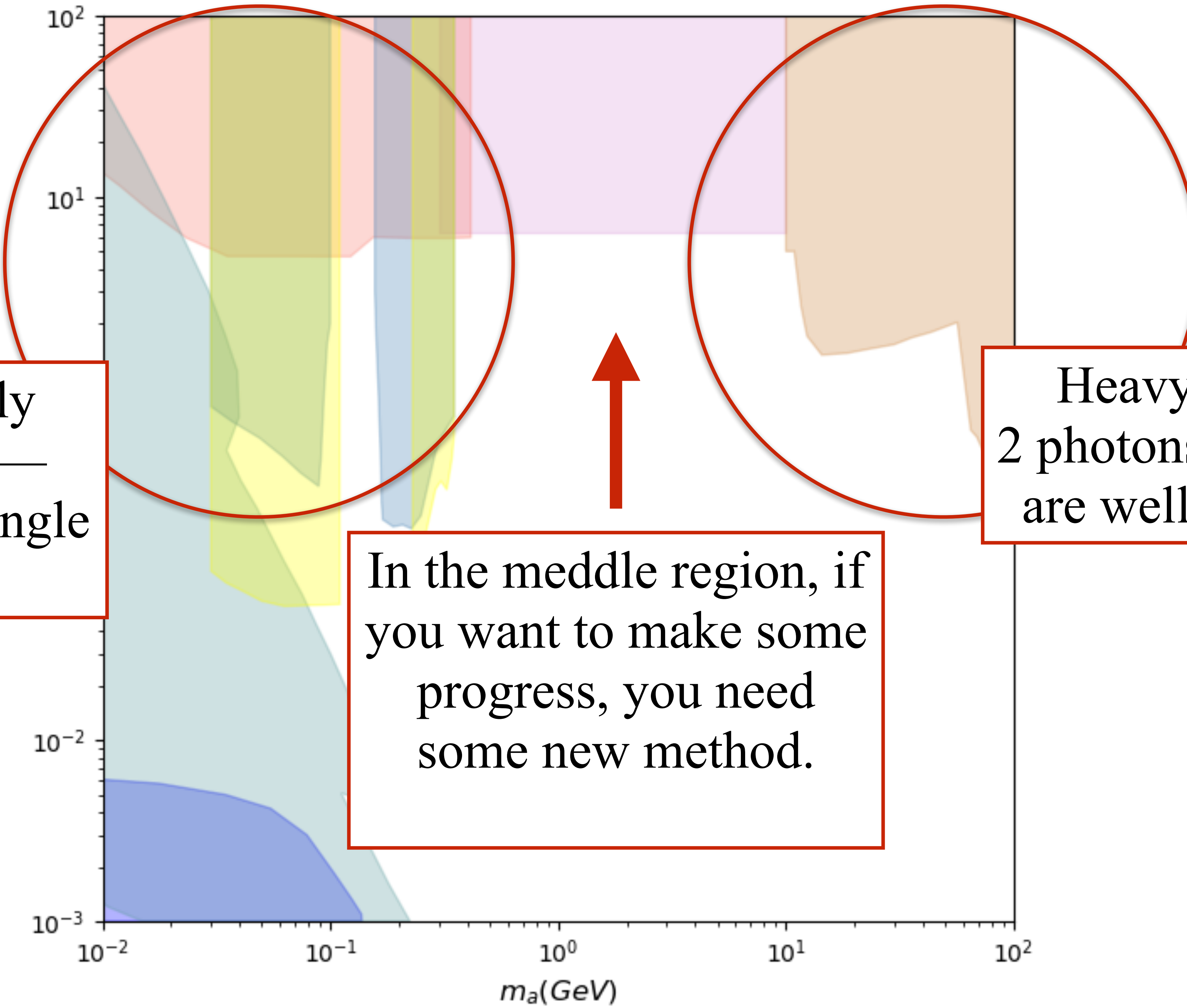


Light & highly boosted ALP — it looks like a single photon!

In the meddle region, if you want to make some progress, you need some new method.

Heavy ALP — 2 photons from ALP are well separated

Photon jet & its tagging

In the meddle region (0.1 GeV $\lesssim m_a \lesssim$ 10 GeV). 2 photons from ALP decay are not so collimated. We can call it "photon jet", a jet composed by photons.

(pioneer work see "*S. D. Ellis, T. S. Roy, and J. Scholtz, Phys. Rev. D 87, 014015 (2013)* ")

Now the problem become: how to tag the "photon jet" at collider?

One question: How to describe a jet ?

Emm…. p_T , ϕ , η . Right ?

Describing a jet by these 3 variables, you lose lots information of a jet. There is a rich "sub-structure" of a jet.

Photon jet & its tagging

Jet sub-structure has been largely used in collider study.

Most popular examples:

1) Boosted H/W/Z/Top tagging (mass drop algorithm)

2) quark jet & gluon jet discrimination

Photon jet tagging is more like example 2), because ALP is too light to use mass drop algorithm.

Just like quark jet & gluon jet discrimination, we need to design some variables to “describe” a jet in more detail.

Photon jet & its tagging

Jet sub-structure variable example: $\log \theta_J$

θ_J is called "hadronic energy fraction", and defined by:

$$\theta_J = \frac{\text{(Energy measured by hadron Cal)}}{\text{(Total energy of a jet)}}$$

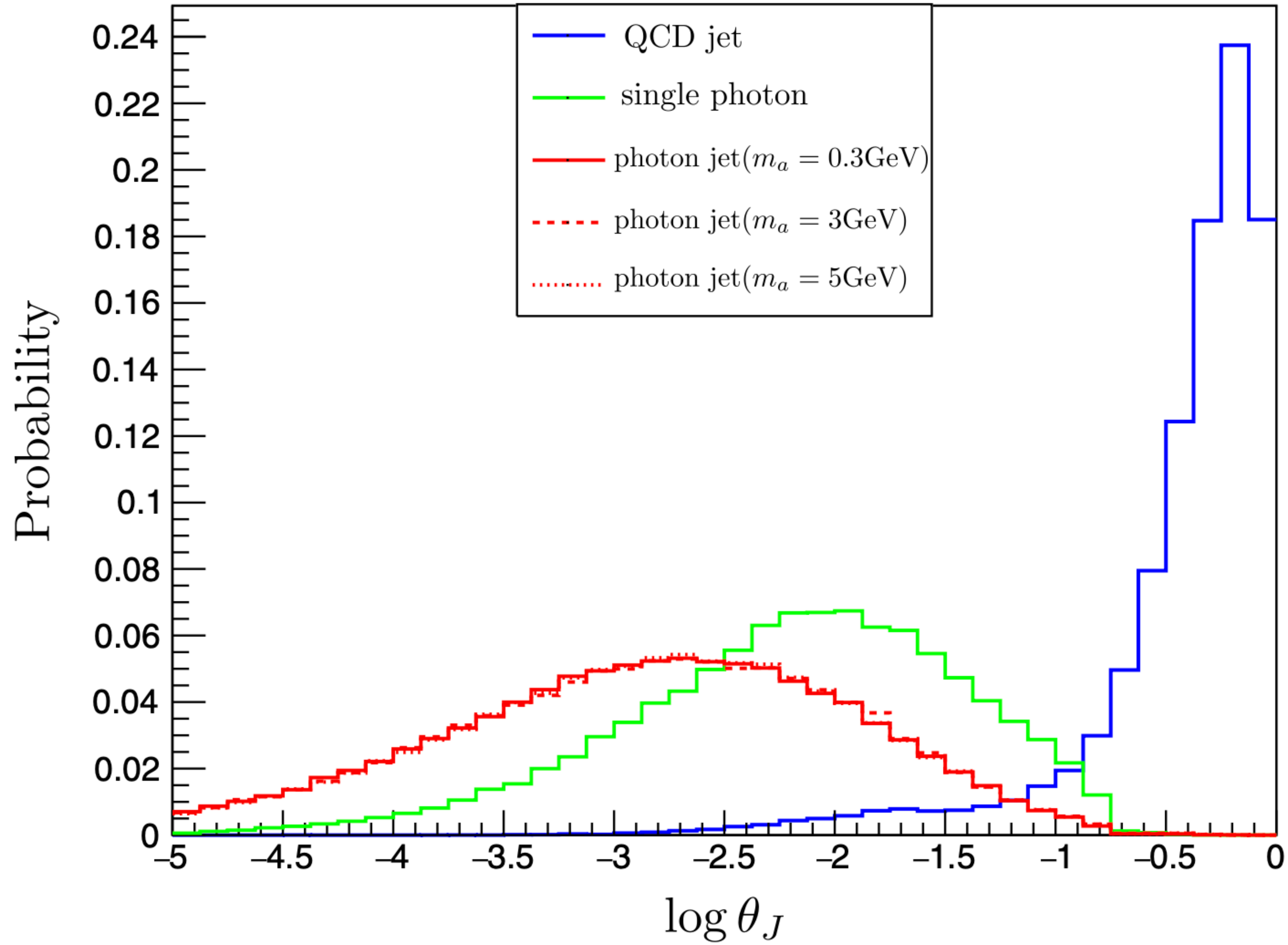
For QCD jet, $\theta_J \approx 2/3$. Because only $\pi^{\pm}$ can reach hadron Cal.

But for photon or photon jet, generally speaking $\theta_J \ll 1$.

So the log value of θ_J, $\log \theta_J$, is a good variable to distinguish photon/photon jet from QCD jet.

Photon jet & its tagging

The performance of $\log \theta_J$:

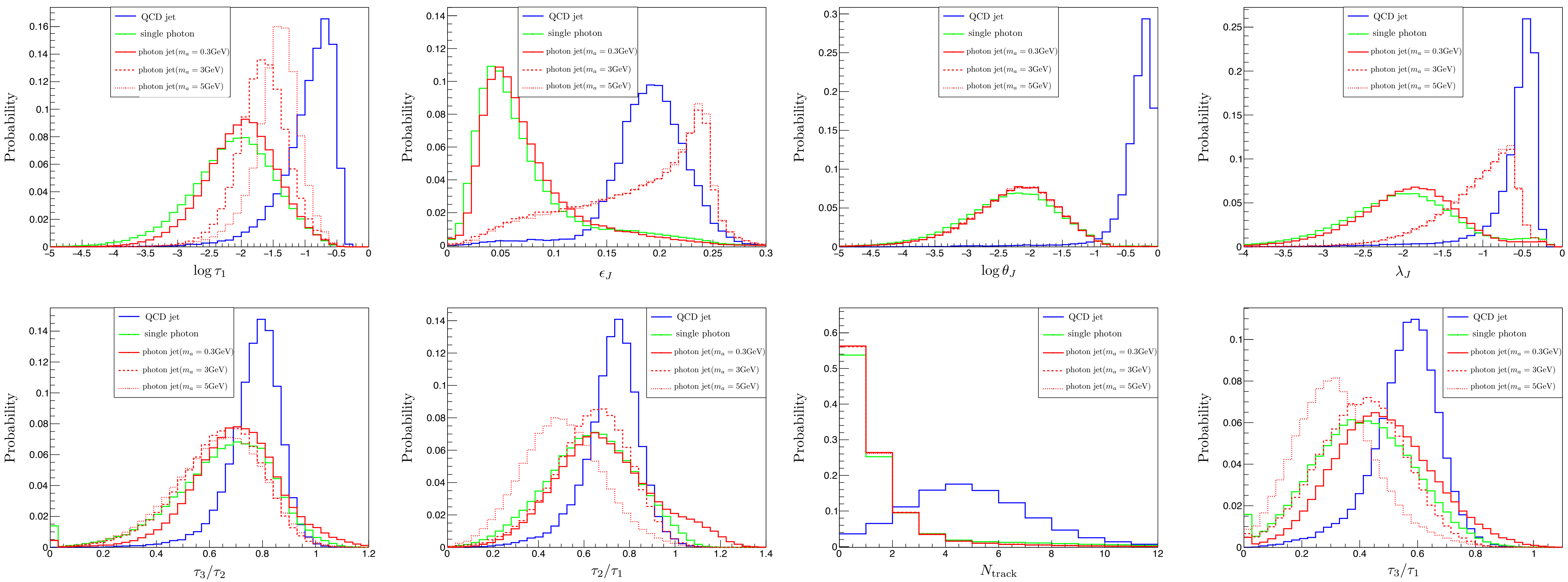


(To understand the result, don't forget the contamination at LHC.)

Photon jet & its tagging

We use 8 variables in total:

$$\{\log\theta_J,\ N_T,\ \log\tau_1,\ \tau_2/\tau_1,\ \tau_3/\tau_1,\ \tau_3/\tau_2,\ \lambda_j,\ \epsilon_J\}$$



Now, you need to do cut on a "dimension-8" parameter space.
For such a "multi-variable analysis" problem, we can use boosted decision tree (BDT) to help us.

Photon jet & its tagging

Operational process of BDT.

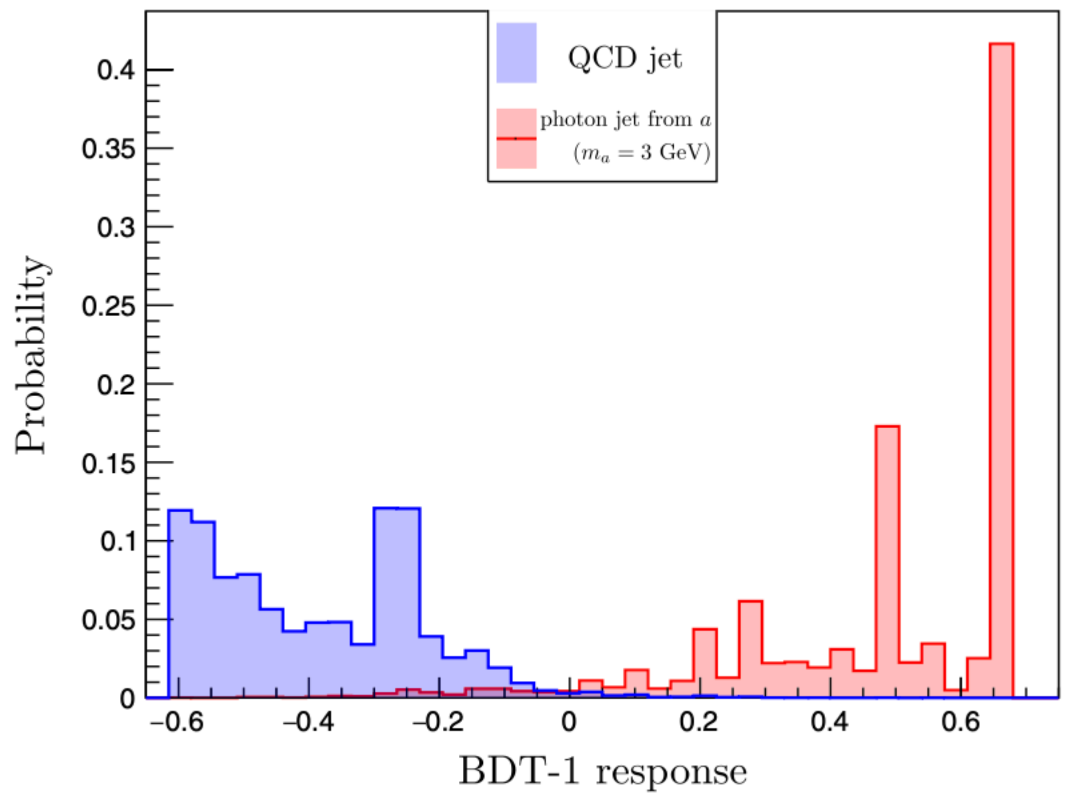
Firstly you need lots of sample to train the BDT:

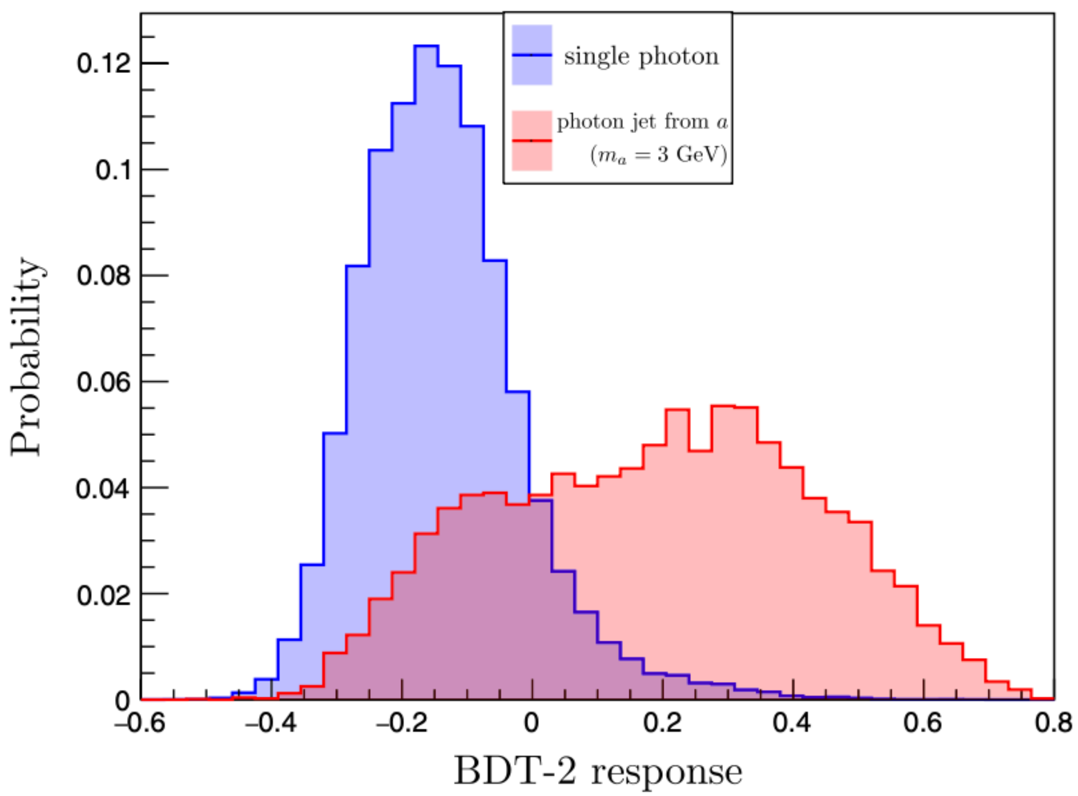
Then you can use the well trained BDT to do discrimination:

$\{\log\theta_J,\ N_T,\ \log\tau_1,\ \tau_2/\tau_1,\ \tau_3/\tau_1,\ \tau_3/\tau_2,\ \lambda_j,\ \epsilon_J\}$ of a jet

Photon jet & its tagging

Actually we have 2 BDTs. BDT-1 is used to distinguish QCD jet for photon/photon jet. BDT-2 is used to distinguish photon from photon jet.



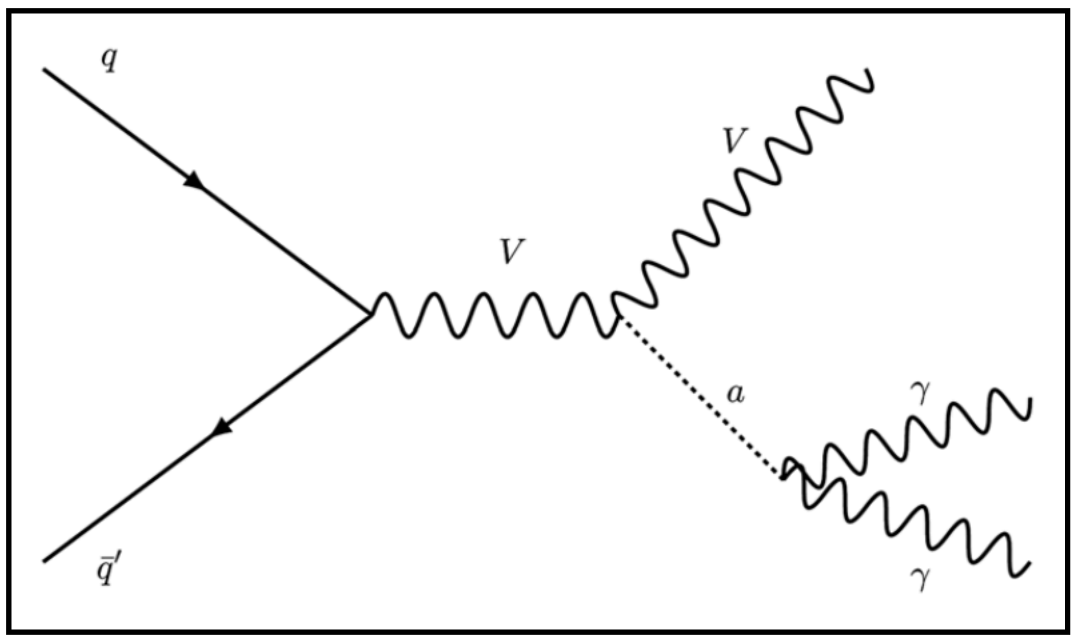


Cut on BDT-1 score and BDT-2 score. We can do a quite good photon jet tagging.

Study on the LHC

Now we can use the powerful photon-jet tagging method to do some real collider search job.
We consider high-luminosity LHC (14 TeV , 3000 fb-1).
Signal process is ALP-strahlung process:

$$pp \to W^{\pm}a, \text{ or } pp \to Za$$



Main background:

$pp \to W^{\pm}a$: QCD di-jet, $W^{\pm}j$, $W^{\pm}\gamma$, $t\bar{t}$, tj

$pp \to Za$: $Z\gamma$, Zj

Study on the LHC

Cut flow table:

$pp \to W^{\pm}a$

Cut flow	Signal	jj	$W^{\pm}\gamma$	$W^{\pm}j$	$t\bar{t}$	tj
1 lepton with $p_T > 20$ GeV and $\lvert\eta\rvert < 2.5$	36.24	19357.15	12.31	4448.53	151.86	29.39
The hardest jet with $p_T > 50$ GeV and $\lvert\eta\rvert < 2.5$	23.31	12893	2.54	1605.92	136.41	18.90
The hardest jet's BDT-1 > 0 and BDT-2 > 0.4	4.14	3.30	0.001	0.77	0.094	0.012

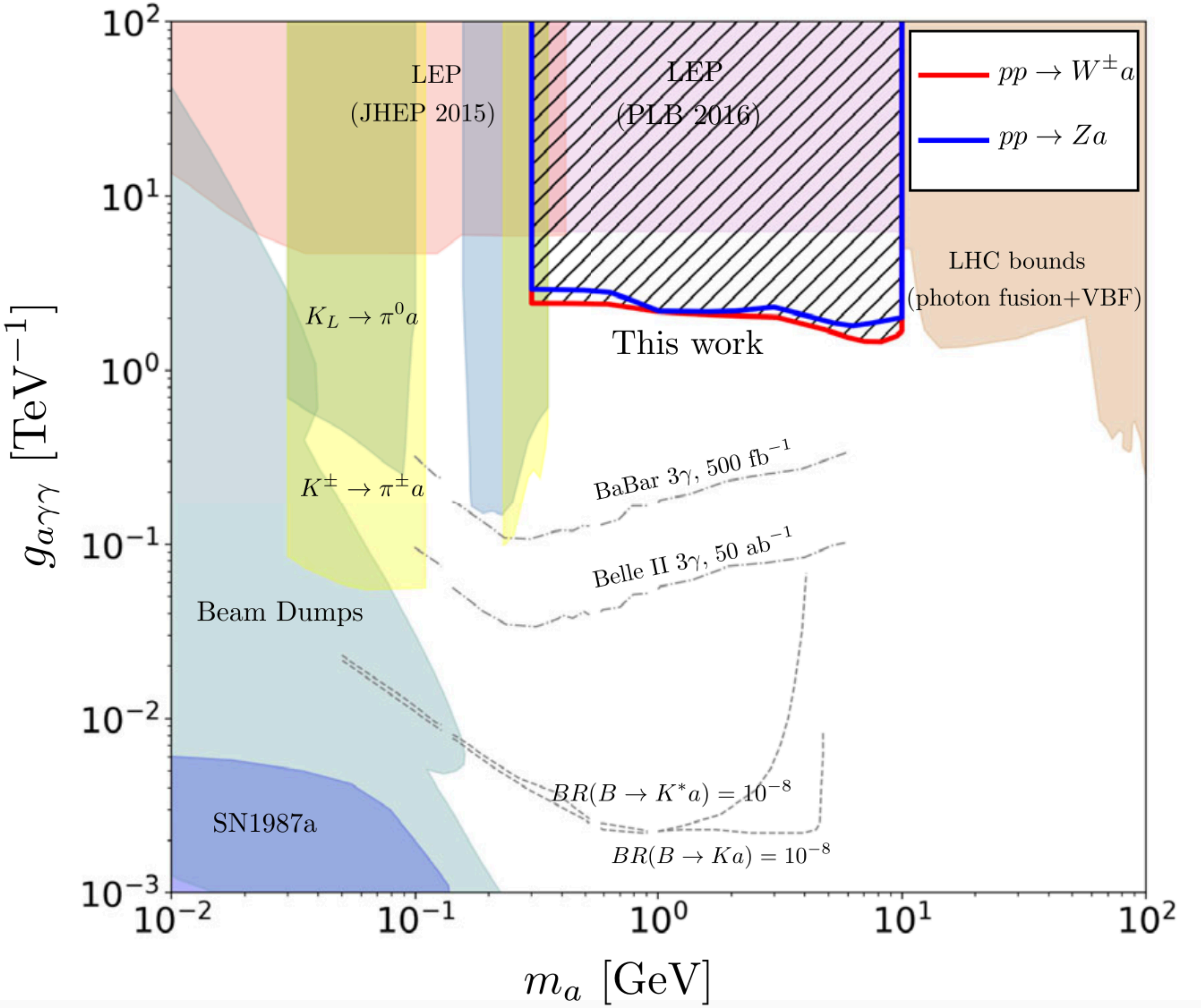
$pp \to Za$

Cut flow	Signal	$Z\gamma$	Zj
2 leptons with $p_T > 20$ GeV and $\lvert\eta\rvert < 2.5$	2.65	1.93	279.90
Oppositely charged lepton pair with same flavorand $\lvert m_{ll} - m_Z\rvert < 20$ GeV	2.55	1.85	275.08
The hardest jet with $p_T > 50$ GeV and $\lvert\eta\rvert < 2.5$	1.79	0.44	104.476
The hardest jet's BDT-1 > 0 and BDT-2 > 0.4	0.29	0.0003	0.027

Photon jet tagging is important!
Without this you can see nothing!

Study on the LHC

Here is the final exclusion limits we obtained:



Improve our work by Neural Network

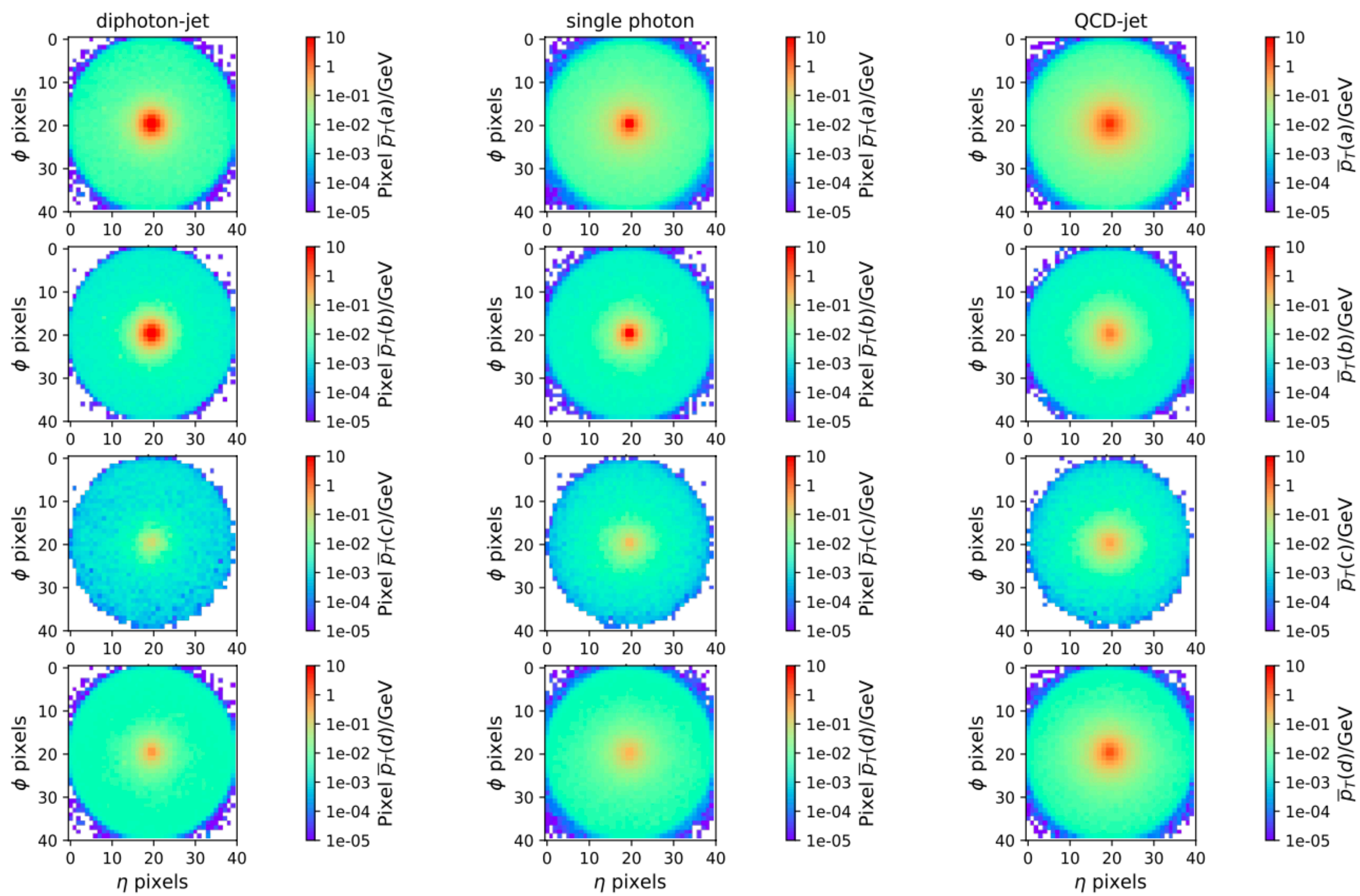
Alright, let's try to use all the information we can get.
"Jet image"

summation of all energy

energy on E-Cal

energy of charged hadron

energy of neutral hadron

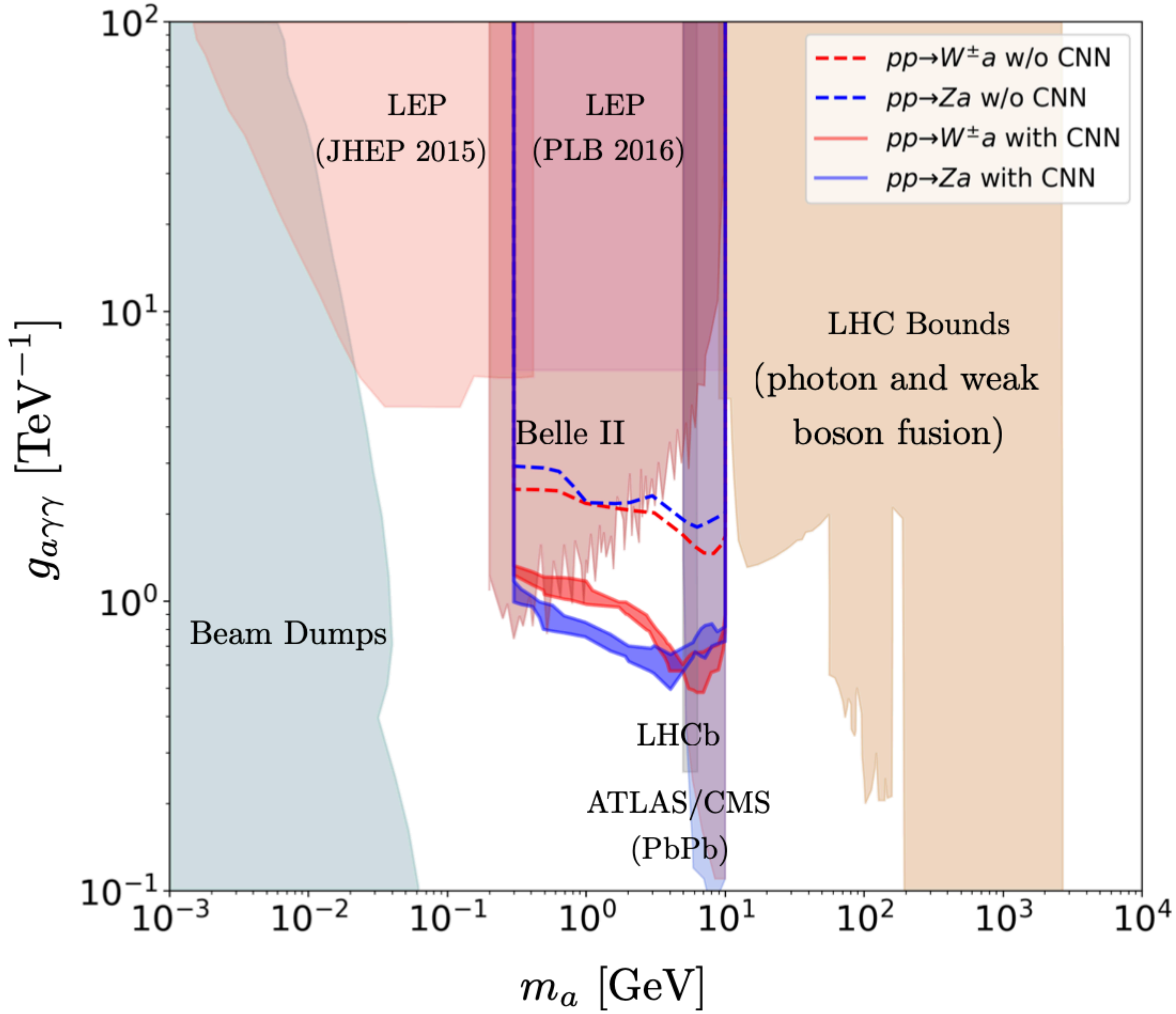


(a) diphoton-jet (b) single photon (c) QCD-jet

(Almost) all the information of a jet has been included ~

Improve our work by Neural Network

The result is certainly better.



I think we already reach the limit of LHC.

Conclusion

For the ALP within mass range 0.1 GeV $\lesssim m_a \lesssim$ 10 GeV, its collider detection is quite difficult.

By using "photon jet" tagging method, we can reach a parameter region which is unreachable by previous studies.