Hunt for low mass diphoton resonance at LHC and Kaon factory

Kavli IPMU, July 11, 2018

Kohsaku Tobioka
YITP, Stony Brook University

based on
1710.01743 and preliminary works
with Alberto Mariotti, Diego Redigolo, Filippo Sala, Matt Low
Stefania Gori, Gilad Perez

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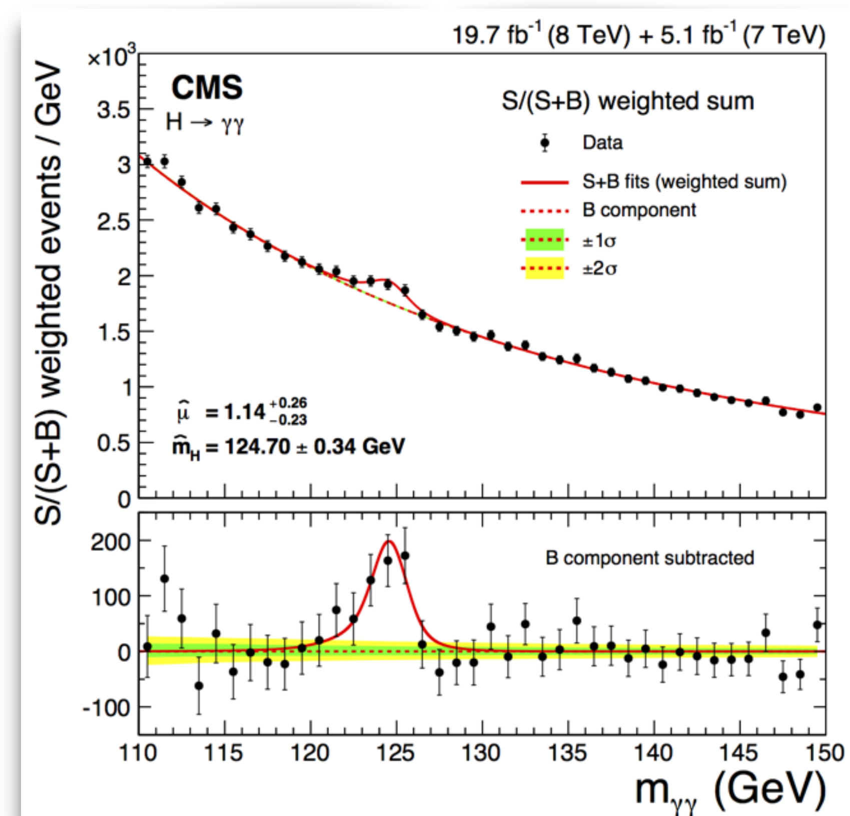
Resonance Searches

Resonance search: strong discovery method at collider

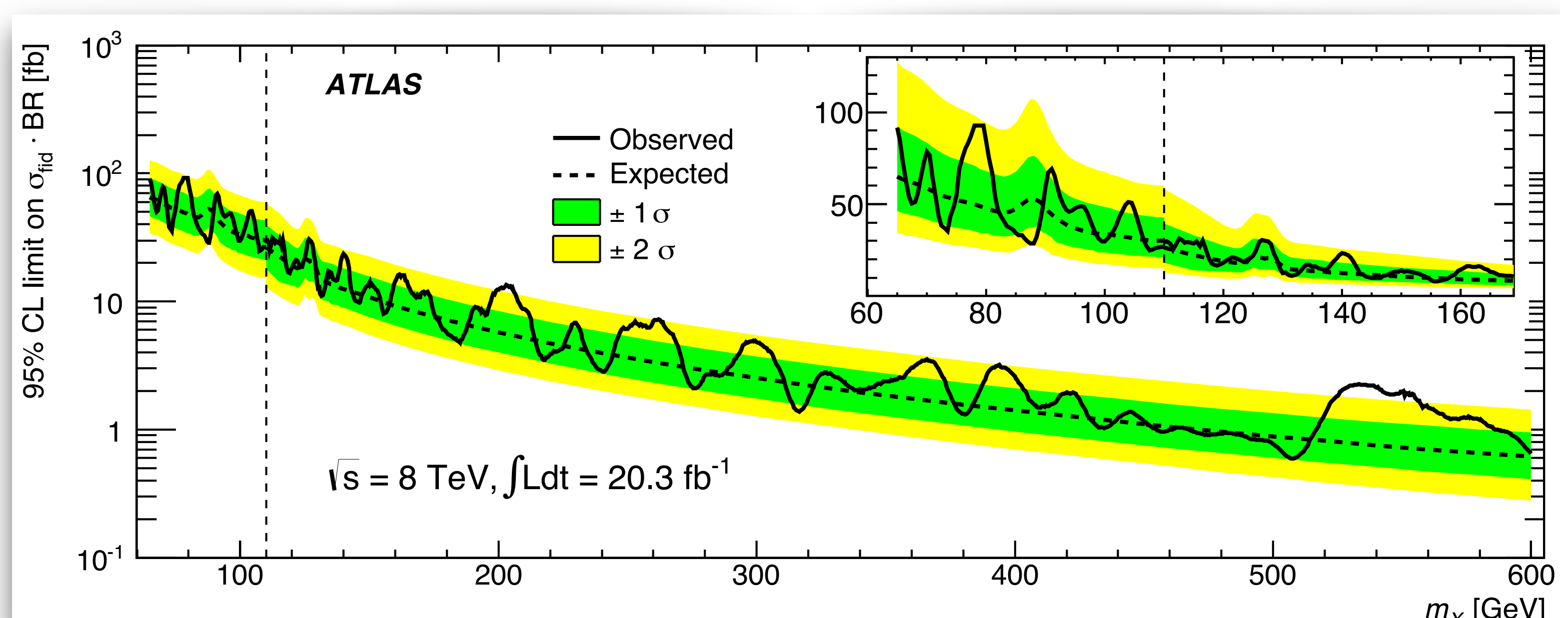
Dilepton Diphoton Dijet

4lepton Diboson(Z/W) etc.

Success: $J/\psi, Y, Z, h..,$ and toward BSM



Typically prove beyond 100GeV



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Dilepton | Diphoton | Dijet

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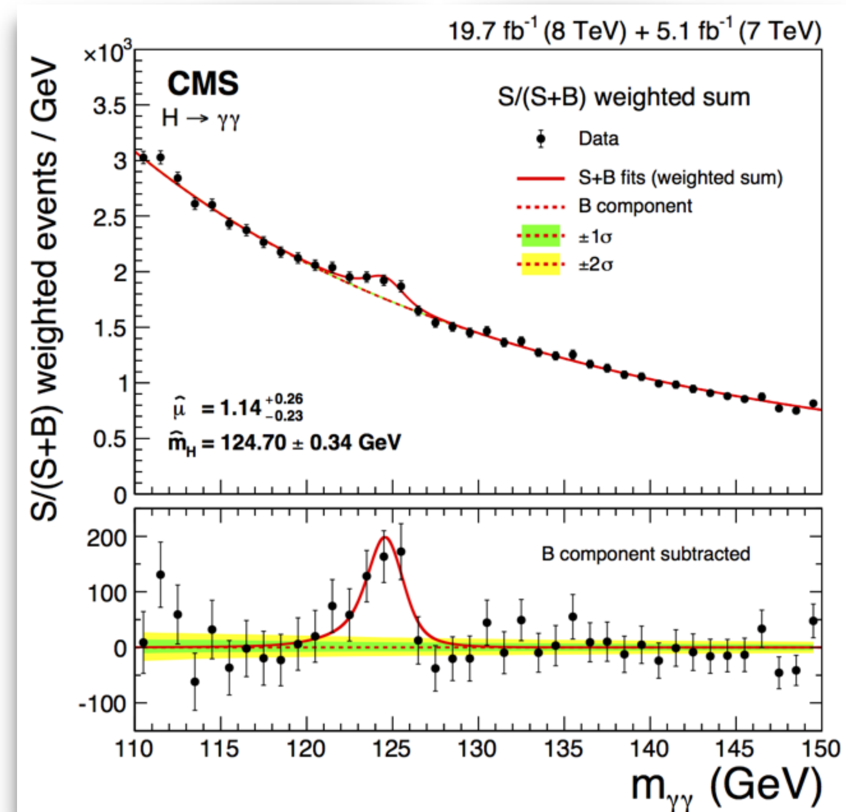

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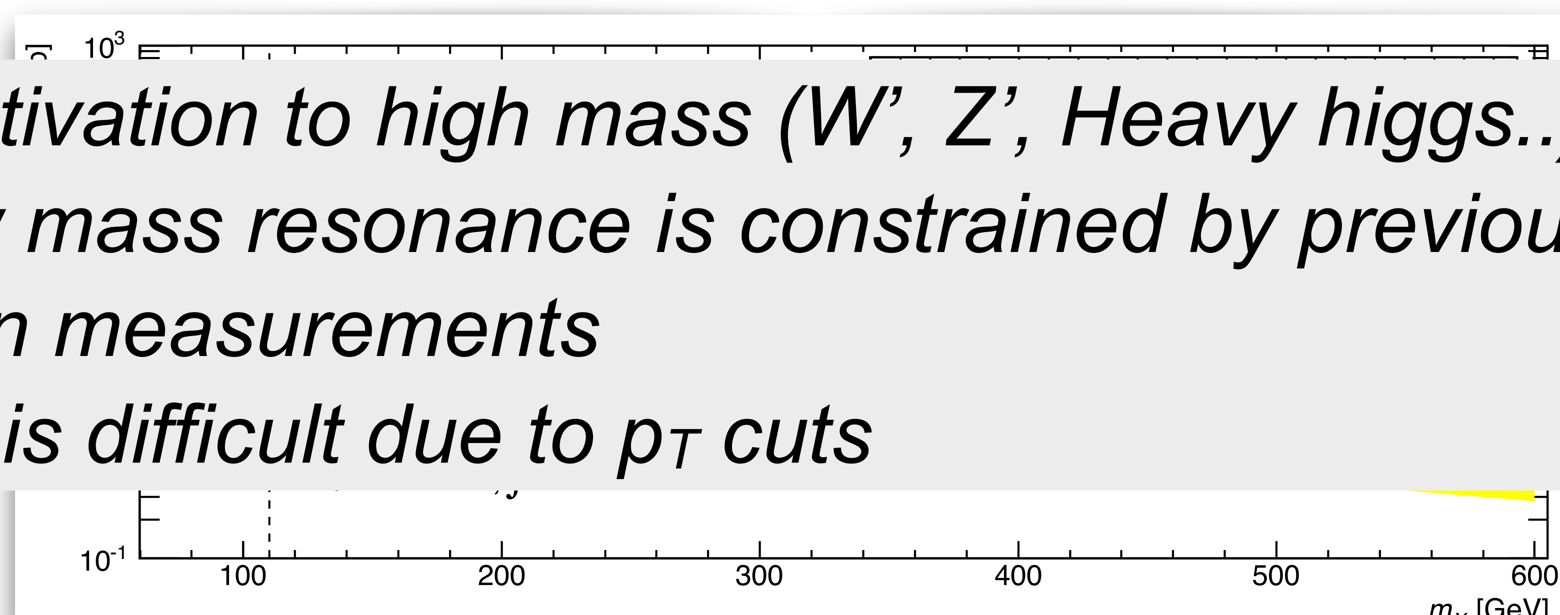
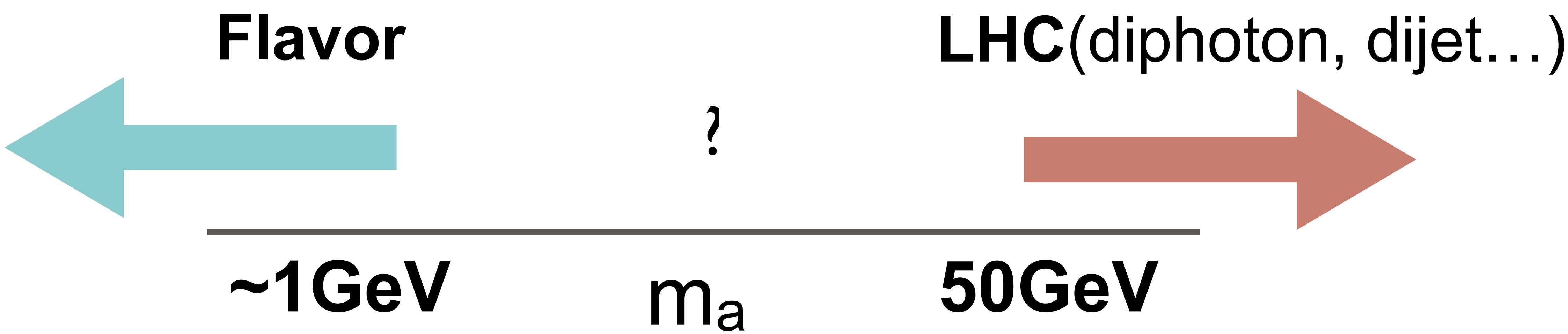


1. *Theoretical bias/motivation to high mass (W', Z', Heavy higgs..)*
2. *Common belief, low mass resonance is constrained by previous colliders or precision measurements*
3. *For LHC, low mass is difficult due to p_T cuts*

Resonance Searches

However, poorly constrained mass range exists



This talk

1. LHC
Constraint mass range 10-100GeV using
x-section measurements, boosted object

2. Kaon Factories **[KOTO]**
Diphoton resonance at 10-100MeV

Theory perspectives
&
Search Framework

Theory perspective

pNGB: pseudo Nambu Goldstone bosons

common among BSM models, mass can be arbitrary light,

e.g. π

Focus: **Axion-like-particles**(ALPs) e.g.

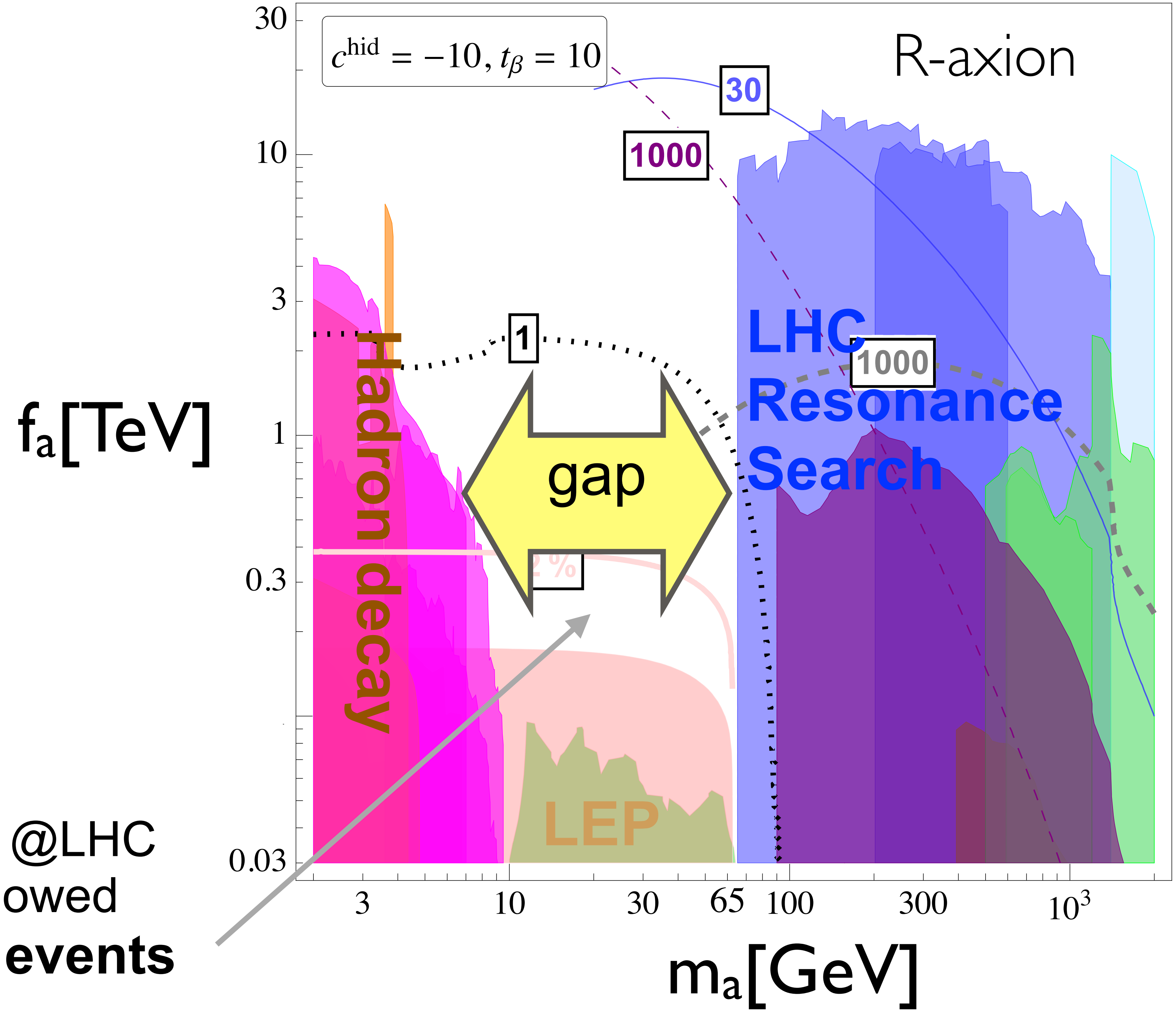
- R-axion from low-scale SUSY $m_{a_R}{}^2 \sim \varepsilon_{\not R} F / f_a$
  Bellazzini, Mariotti, Redigolo, Sala, Serra(1702.02152)…
  $$\sim (1\mathrm{MeV})^2 \cdot \frac{M_*}{\mathrm{TeV}} \cdot \frac{M_{3/2}}{0.01\mathrm{eV}}$$
- pNGB from composite Higgs
  Barnard, Gherghetta, Ray('13), Ferretti('16)…
- New pion from TeV QCD' $m_{\pi'}{}^2 = m_{q'} \times f_a$
  Kilic, Okui, Sundrum('09), Nakai, Sato, KT ('16) …
- Heavy Axion/Visible Axion $m_{a_{Vis}} = m_{\pi'} f_{\pi'} / f_a$
  Rubakov{'97}, Fukuda, Harigaya, Ibe, Yanagida ('15)

Unlike QCD axion case, $m_a \sim m_\pi f_\pi / f_a$
mass and coupling ($1/f_a$) are separated

such ALP/pNGB can be the first signal of BSM

Theory perspective

Bellazzini, Mariotti, Redigolo, Sala, Serra('17)



10^5pb @LHC
still allowed
⇒**10^9 events**

ALP Effective Lagrangian

Consider only anomaly (WZW) terms

$$\mathcal{L}_{\rm int} = \frac{a}{4\pi f_a}\left[\alpha_s c_3 G\tilde{G} + \alpha_2 c_2 W\tilde{W} + \alpha_1 c_1 B\tilde{B}\right]$$

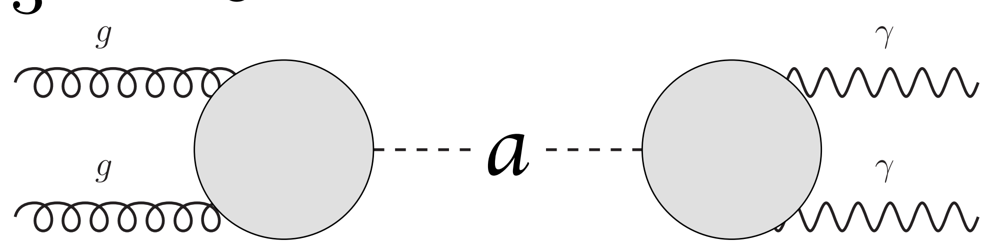
$\alpha_1 = 5/3\alpha'$

Broad class of models

$$f_a \sim 0.1 - 10 \text{ TeV and } \underline{c_3 \neq 0}$$

irreducible contributions from loops of gluinos, tops

Take $c_1 = c_2 = c_3 = 10$ for benchmark



$$\sigma_{\rm ggF} \propto \left(\frac{c_3}{f_a}\right)^2$$

$$\text{Br}(a \to \gamma\gamma) \propto \frac{(c_\gamma/f_a)^2}{(c_3/f_a)^2}$$

- production@LHC is gluon fusion,
- prompt decay to dijet or diphoton due to (m_a<m_Z)

ALP Effective Lagrangian

Consider only anomaly (WZW) terms

$$\mathcal{L}_{\rm int} = \frac{a}{4\pi f_a}\left[\alpha_s c_3 G\tilde{G} + \alpha_2 c_2 W\tilde{W} + \alpha_1 c_1 B\tilde{B}\right]$$

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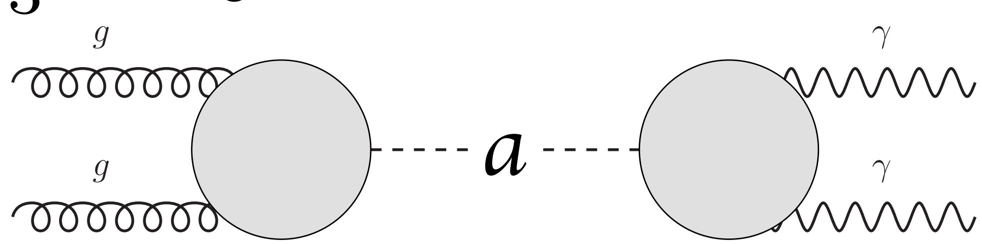

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many previous studies for ALPs:

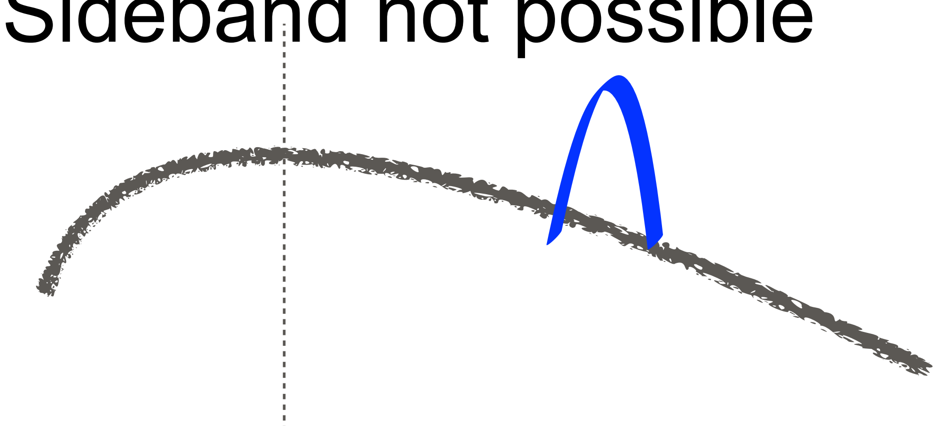
Photonphilic ALP: LEP[Jaeckel, Spannowsky('15)] Heavy-ion[Knapen et al('16)]
Sub 10GeV, ALP-W int. induces FCNC(B->Ka) [Izaguirre, Lin, Shuve('16)],
Higgs decay [Bauer, Tamm, Neubert ('17)] etc.

Existing constraints &New LHC bound

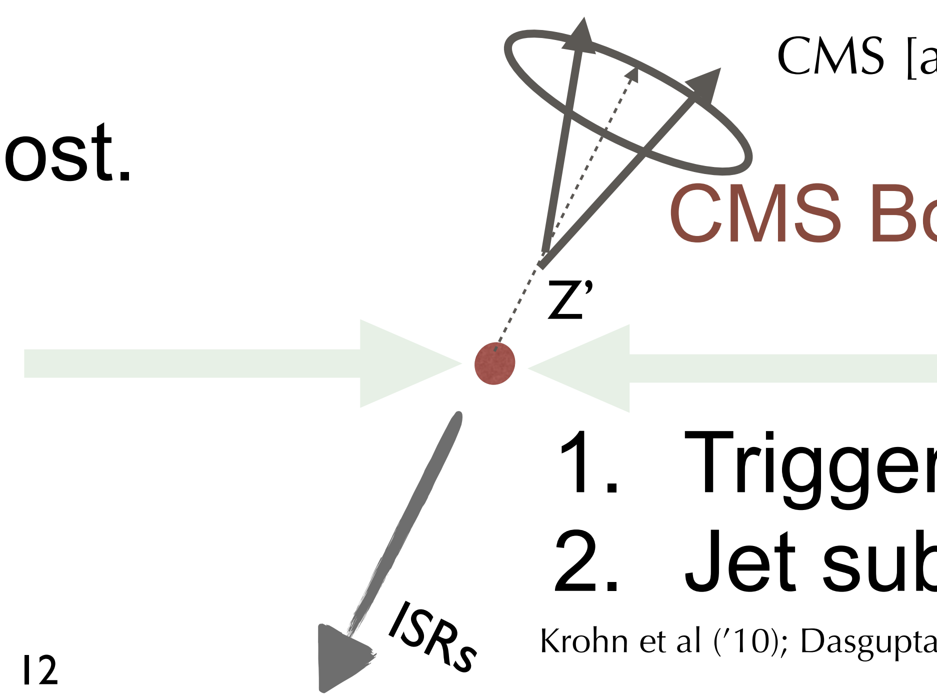
Existing constraints for diphoton/dijet

Experiment	Process	Lumi	$\sqrt{s}$	low mass reach	ref.
LEPI	$e^+e^- \to Z \to \gamma a \to \gamma jj$	12 pb^{-1}	Z-pole	10 GeV	[29]
LEPI	$e^+e^- \to Z \to \gamma a \to \gamma\gamma\gamma$	78 pb^{-1}	Z-pole	3 GeV	[30]
LEPII	$e^+e^- \to Z^*, \gamma^* \to \gamma a \to \gamma jj$	9.7,10.1,47.7 pb^{-1}	161,172,183 GeV	60 GeV	[31]
LEPII	$e^+e^- \to Z^*, \gamma^* \to \gamma a \to \gamma\gamma\gamma$	9.7,10.1,47.7 pb^{-1}	161,172,183 GeV	60 GeV	[31, 32]
LEPII	$e^+e^- \to Z^*, \gamma^* \to Za \to jj\gamma\gamma$	9.7,10.1,47.7 pb^{-1}	161,172,183 GeV	60 GeV	[31]
D0/CDF	$p\bar{p} \to a \to \gamma\gamma$	7/8.2 fb^{-1}	1.96 TeV	100 GeV	[33]
ATLAS	$pp \to a \to \gamma\gamma$	20.3 fb^{-1}	8 TeV	65 GeV	[34]
CMS	$pp \to a \to \gamma\gamma$	19.7 fb^{-1}	8 TeV	80 GeV	[35]
CMS	$pp \to a \to \gamma\gamma$	19.7 fb^{-1}	8 TeV	150 GeV	[36]
CMS	$pp \to a \to \gamma\gamma$	35.9 fb^{-1}	13 TeV	70 GeV	[37]
CMS	$pp \to a \to jj$	18.8 fb^{-1}	8 TeV	500 GeV	[38]
ATLAS	$pp \to a \to jj$	20.3 fb^{-1}	8 TeV	350 GeV	[39]
CMS	$pp \to a \to jj$	12.9 fb^{-1}	13 TeV	600 GeV	[40]
ATLAS	$pp \to a \to jj$	3.4 fb^{-1}	13 TeV	450 GeV	[41]
CMS	$pp \to ja \to jjj$	35.9 fb^{-1}	13 TeV	50 GeV	[42]

Below lowest mass,
smooth background structure is lost.
Sideband not possible



CMS [arXiv:1710.00159]

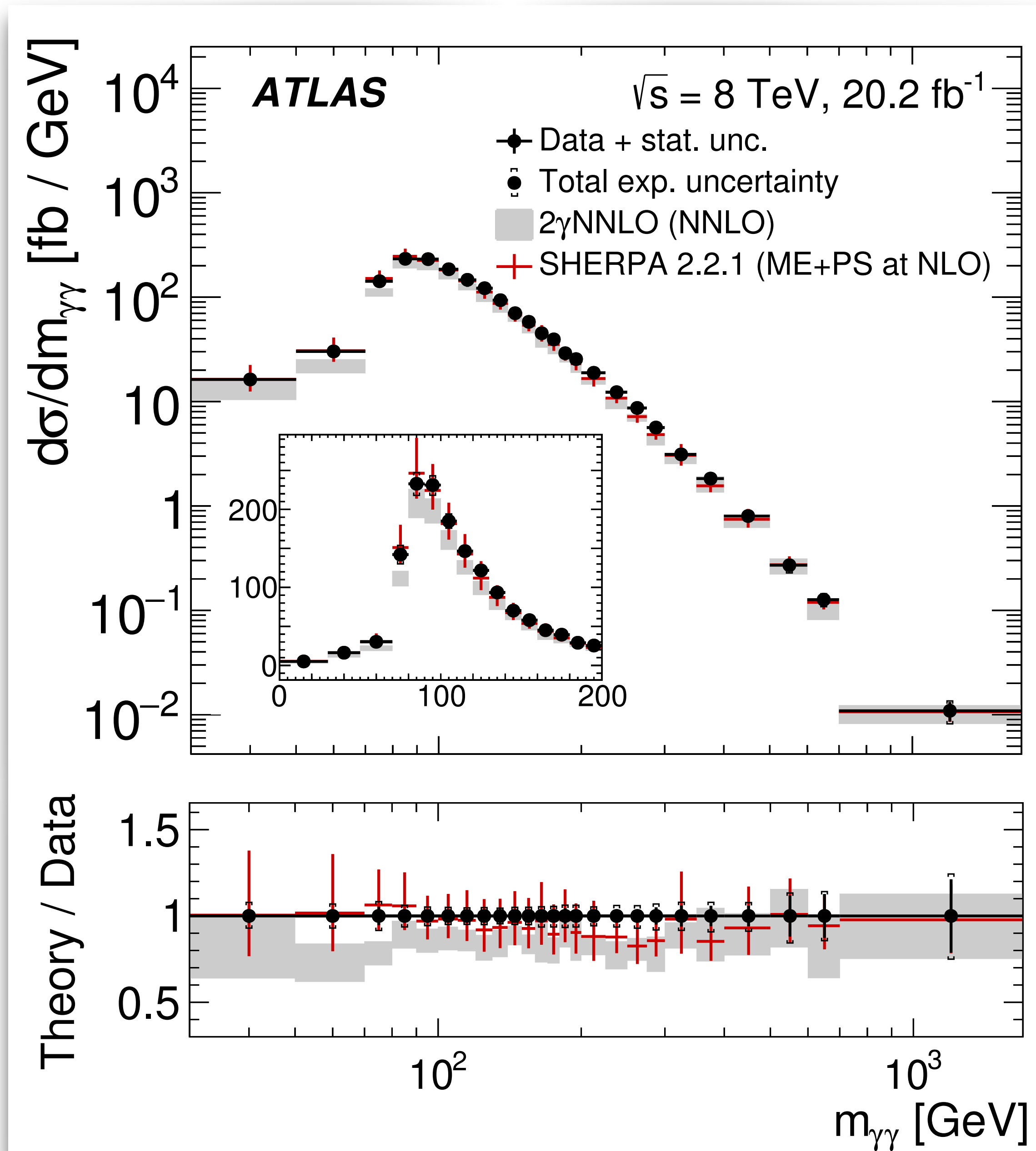


1. Trigger ISR
2. Jet substructure

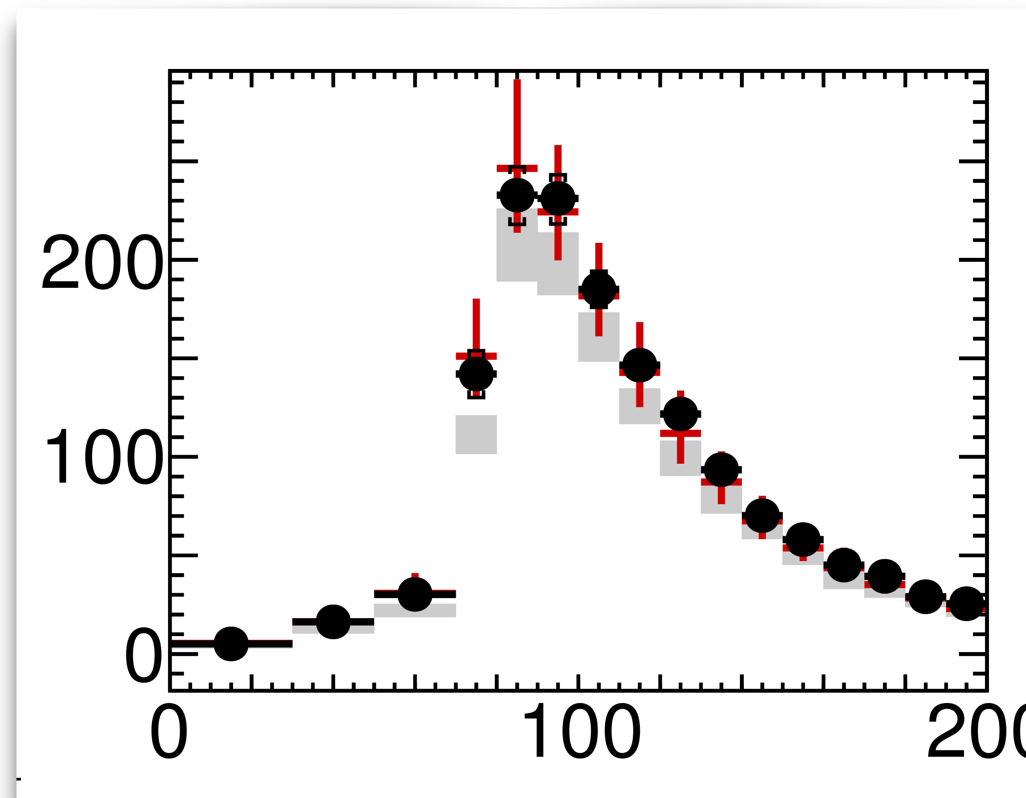
Krohn et al ('10); Dasgupta et al ('13); Larkoski et al ('14)

Diphoton x-section measurements

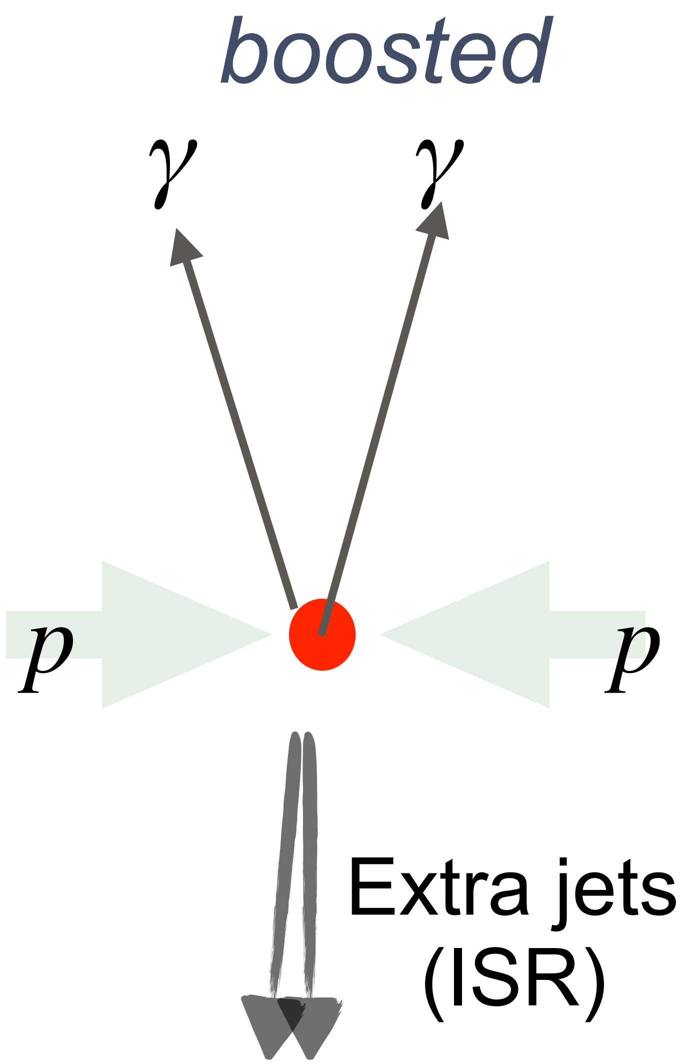
D0 ($\sigma_{\gamma\gamma}$)	$p\bar{p} \to a \to \gamma\gamma$	4.2 fb^{-1}	1.96 TeV	$p_{T_1,T_2} > 21\,,20$ GeV	m_a> 8.2GeV
CDF ($\sigma_{\gamma\gamma}$)	$p\bar{p} \to a \to \gamma\gamma$	5.36 fb^{-1}	1.96 TeV	$p_{T_1,T_2} > 17\,,15$ GeV	(m_a> 6.4 GeV)
ATLAS	$pp \to a \to \gamma\gamma$	4.9 fb^{-1}	7 TeV	$p_{T_1,T_2} > 25\,,22$ GeV	m_a> 9.4 GeV
ATLAS	$pp \to a \to \gamma\gamma$	20.2 fb^{-1}	8 TeV	$p_{T_1,T_2} > 40\,,30$ GeV	m_a>13.9 GeV
CMS	$pp \to a \to \gamma\gamma$	5.0 fb^{-1}	7 TeV	$p_{T_1,T_2} > 40\,,25$ GeV	m_a>14.2 GeV

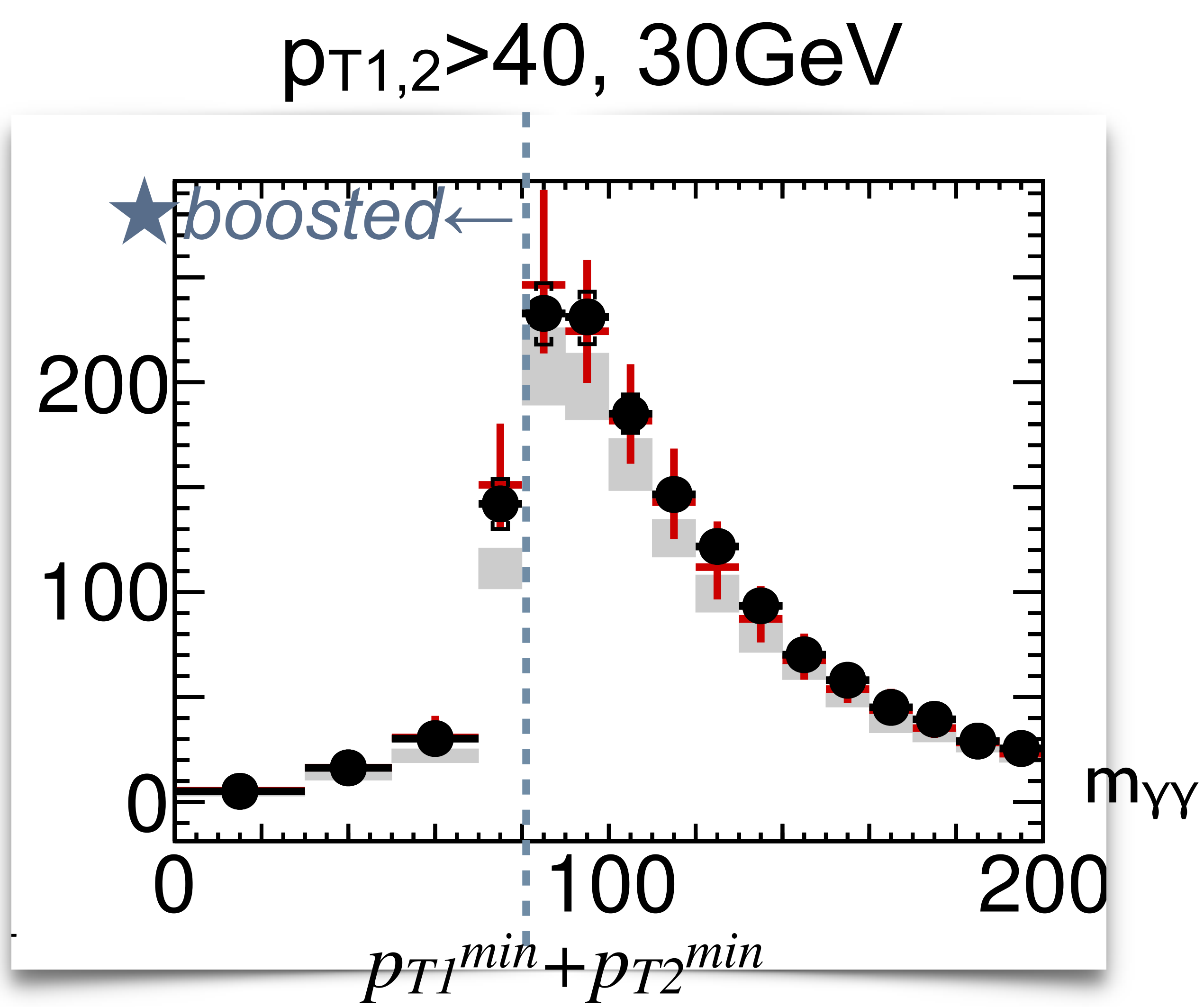


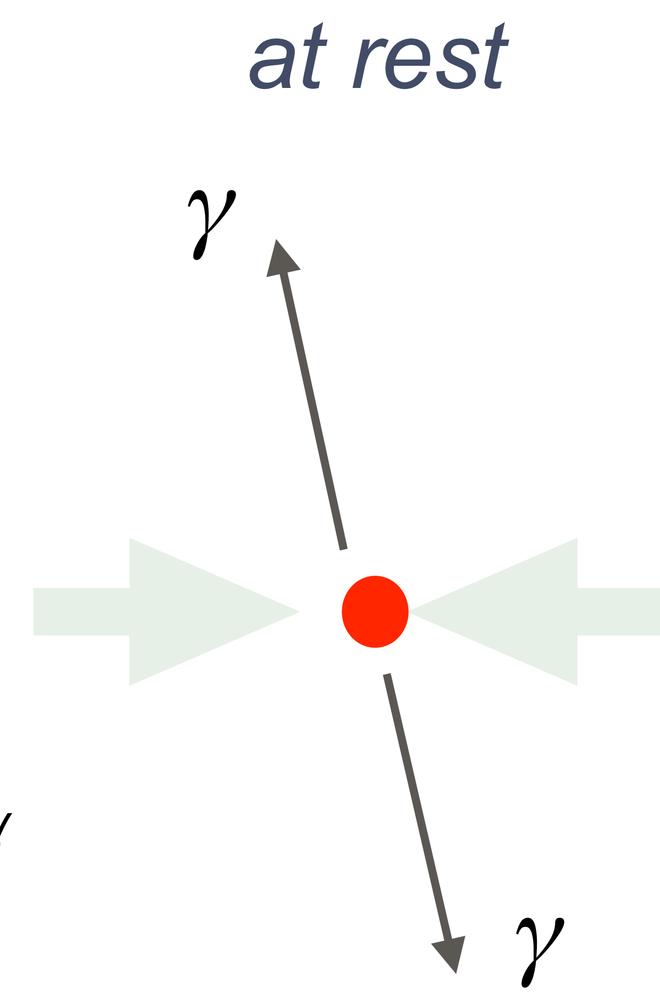
They report lower mass!



Diphoton x-section measurements







★strict lower bound of $m_{\gamma\gamma}$ from $\Delta R>0.4$

diphoton angular separation

$$m_{\gamma\gamma} > \Delta R \cdot \sqrt{p_{T1}^{\min} p_{T2}^{\min}}$$ ~13.8GeV

m_a in GeV	10	20	30	40	50	60	70	80	90	100	110	120
ϵ_S for $\sigma_{8\mathrm{TeV}}$ ATLAS [9]	0	0.0007	0.008	0.014	0.024	0.037	0.071	0.233	0.347	0.419	0.452	0.484

Signal Efficiency

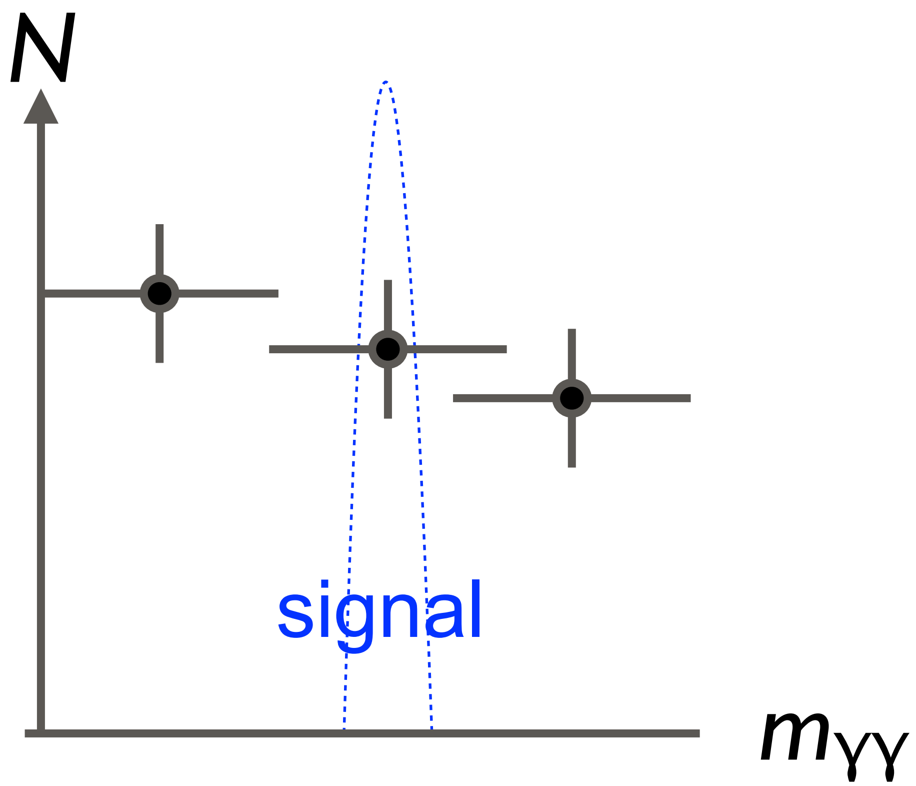
Bound from Diphoton x-section measurement

For this measurement, signal is SM$\gamma\gamma$...

1. Conservative **bound**

   data=signal

   $S_a < N_{bin} + 2\Delta N_{bin}$



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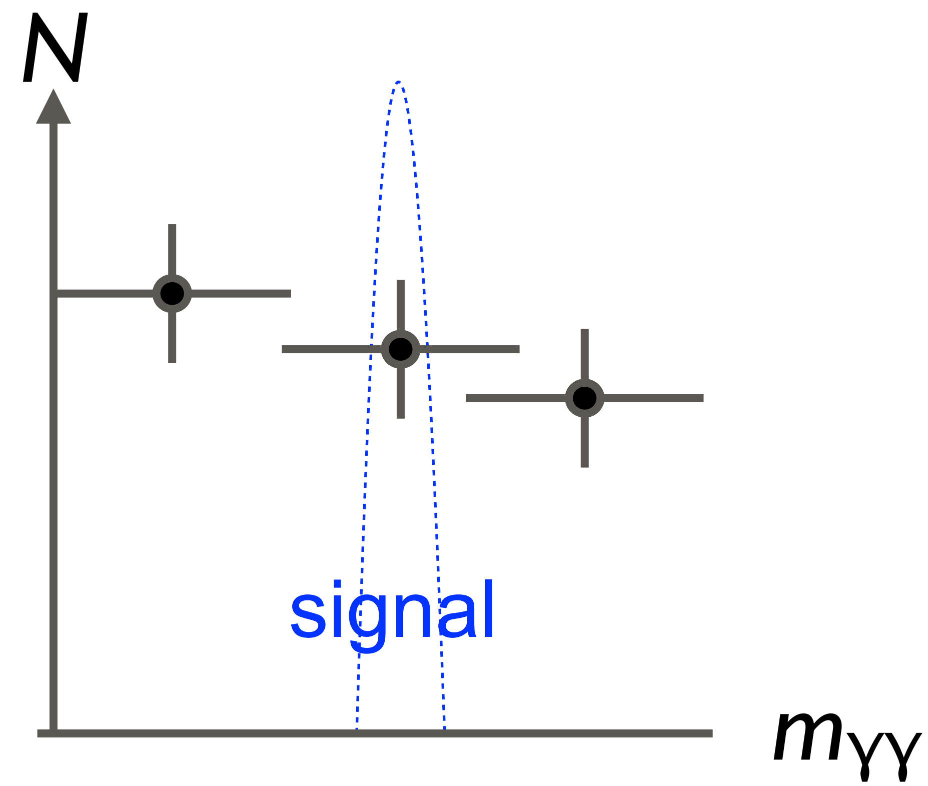
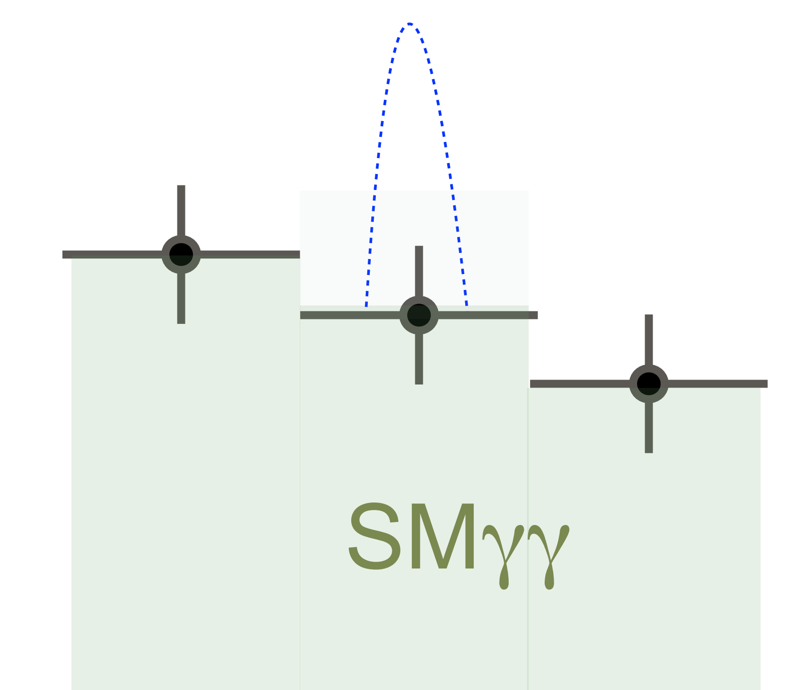
2. Sensitivity(**current reach**)

   assume data=SM$\gamma\gamma$

   $S_a < 2\Delta N_{bin}$





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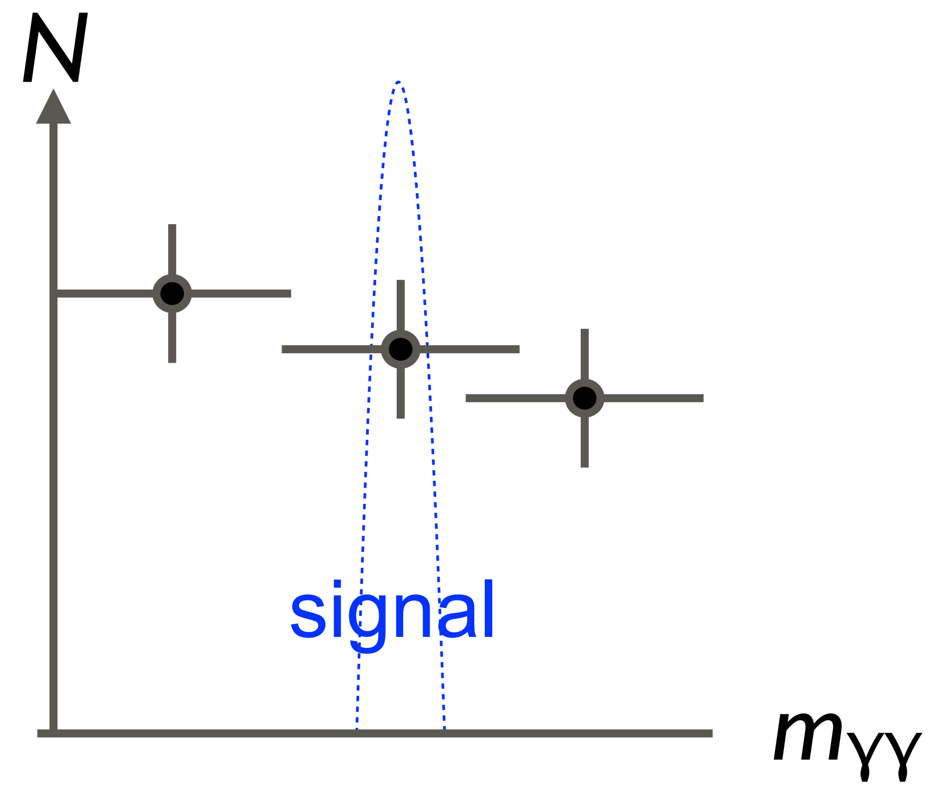

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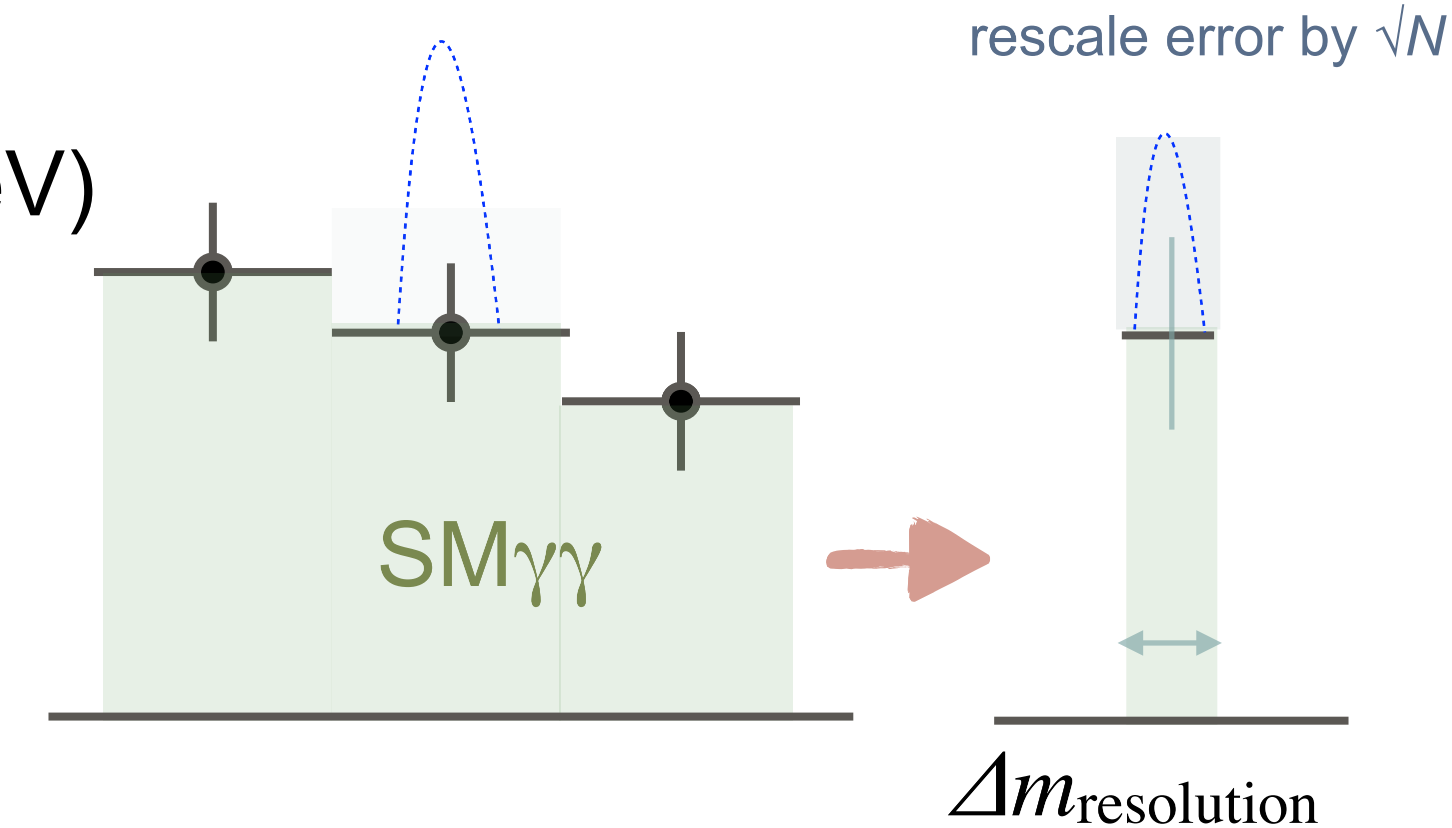
3. Narrow given bin(~10GeV) to mass resolution(~3GeV)

   $S_a < 2\Delta N_{resolution}$



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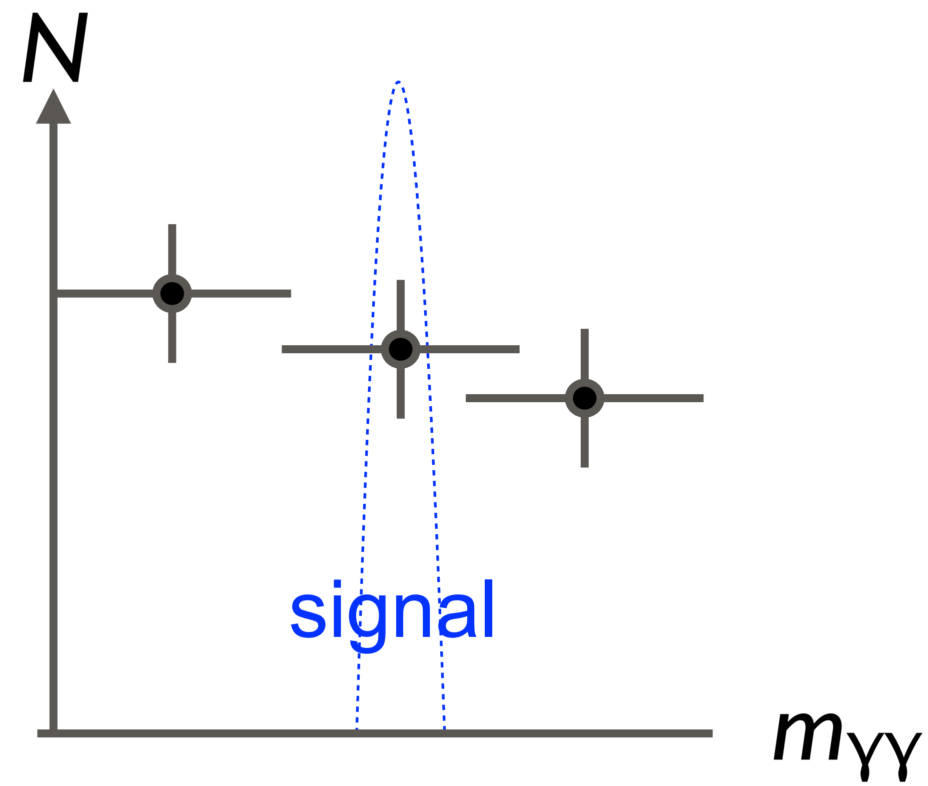

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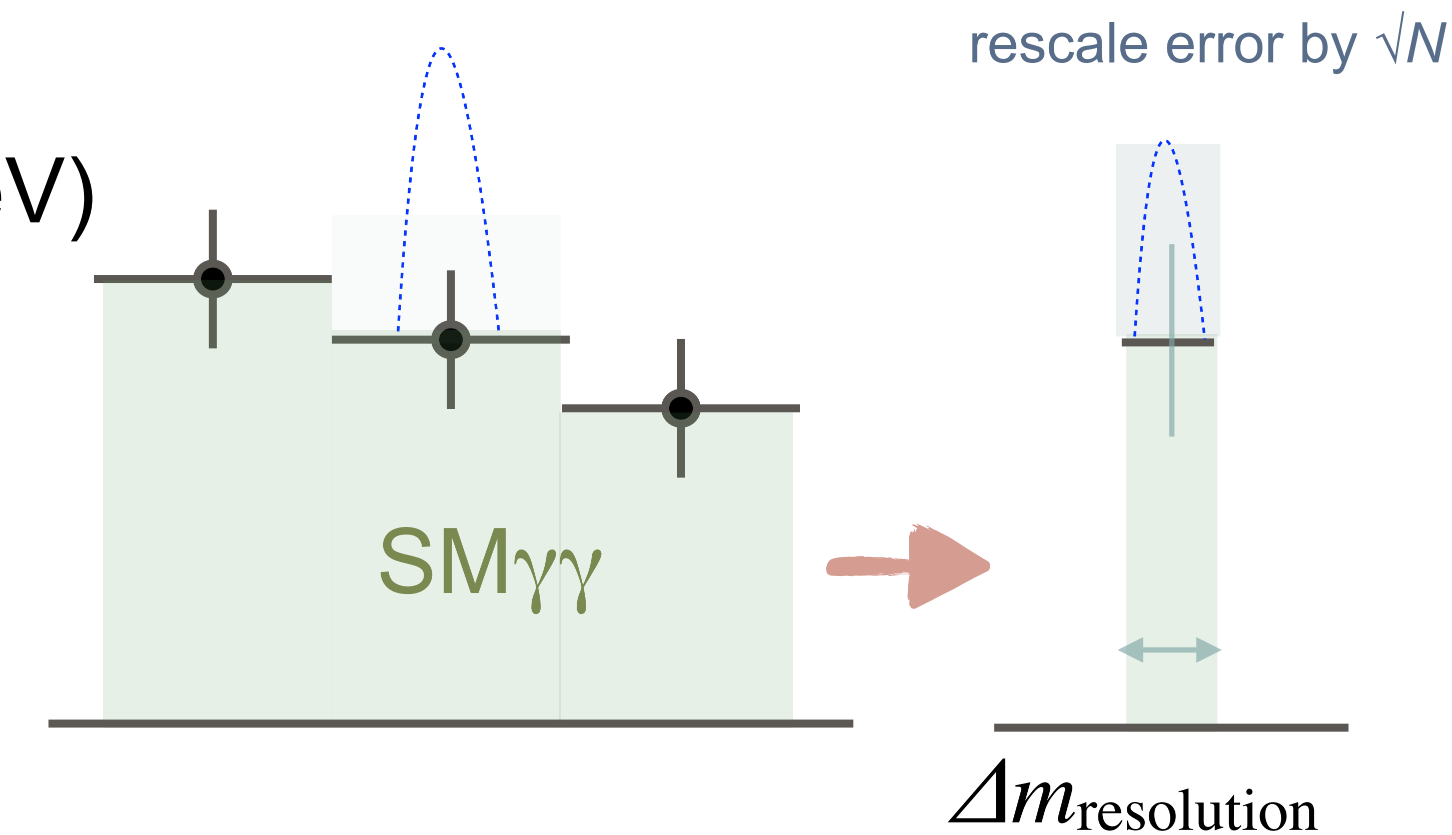
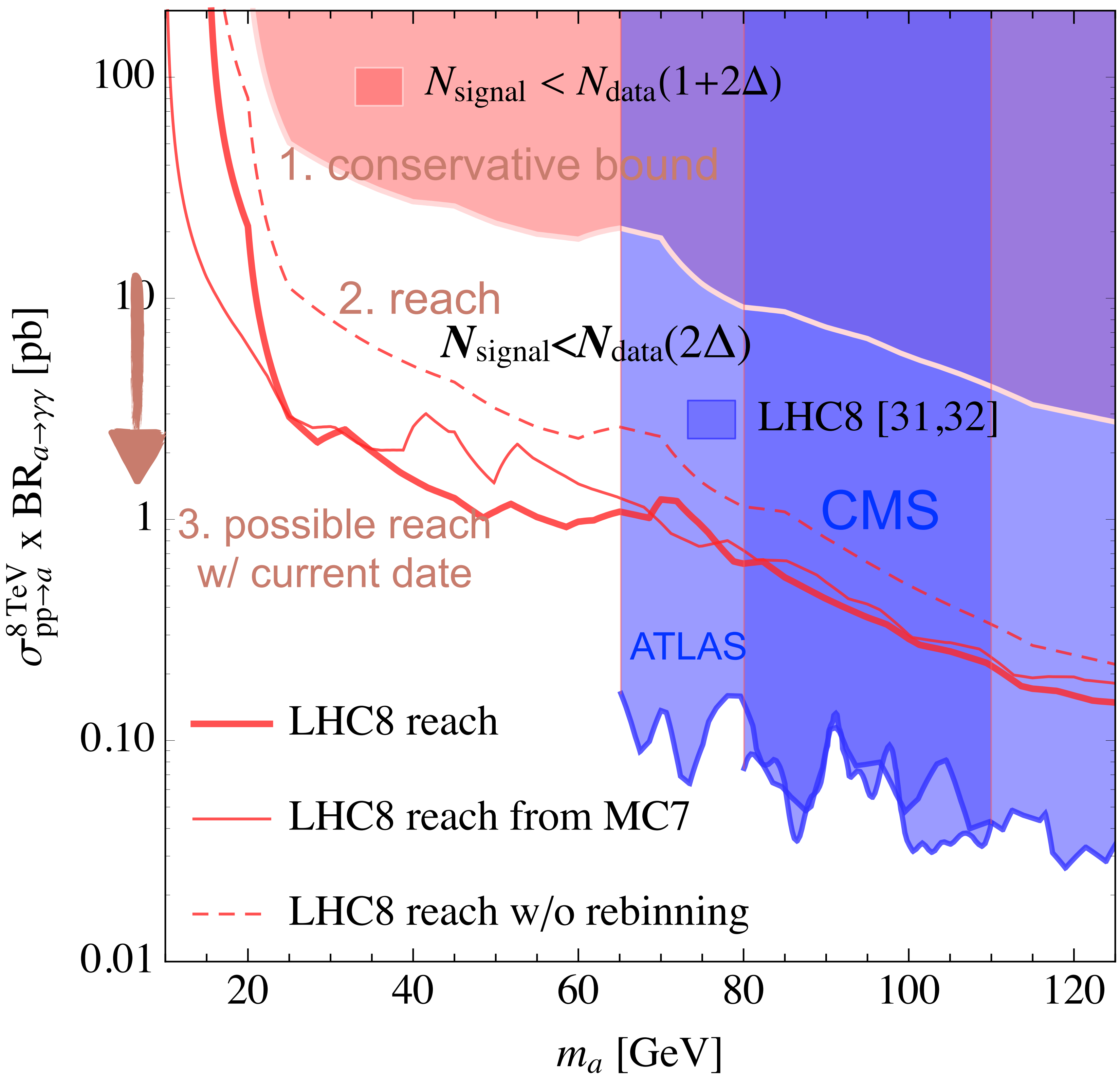


4. Future reach estimated by statistical scaling

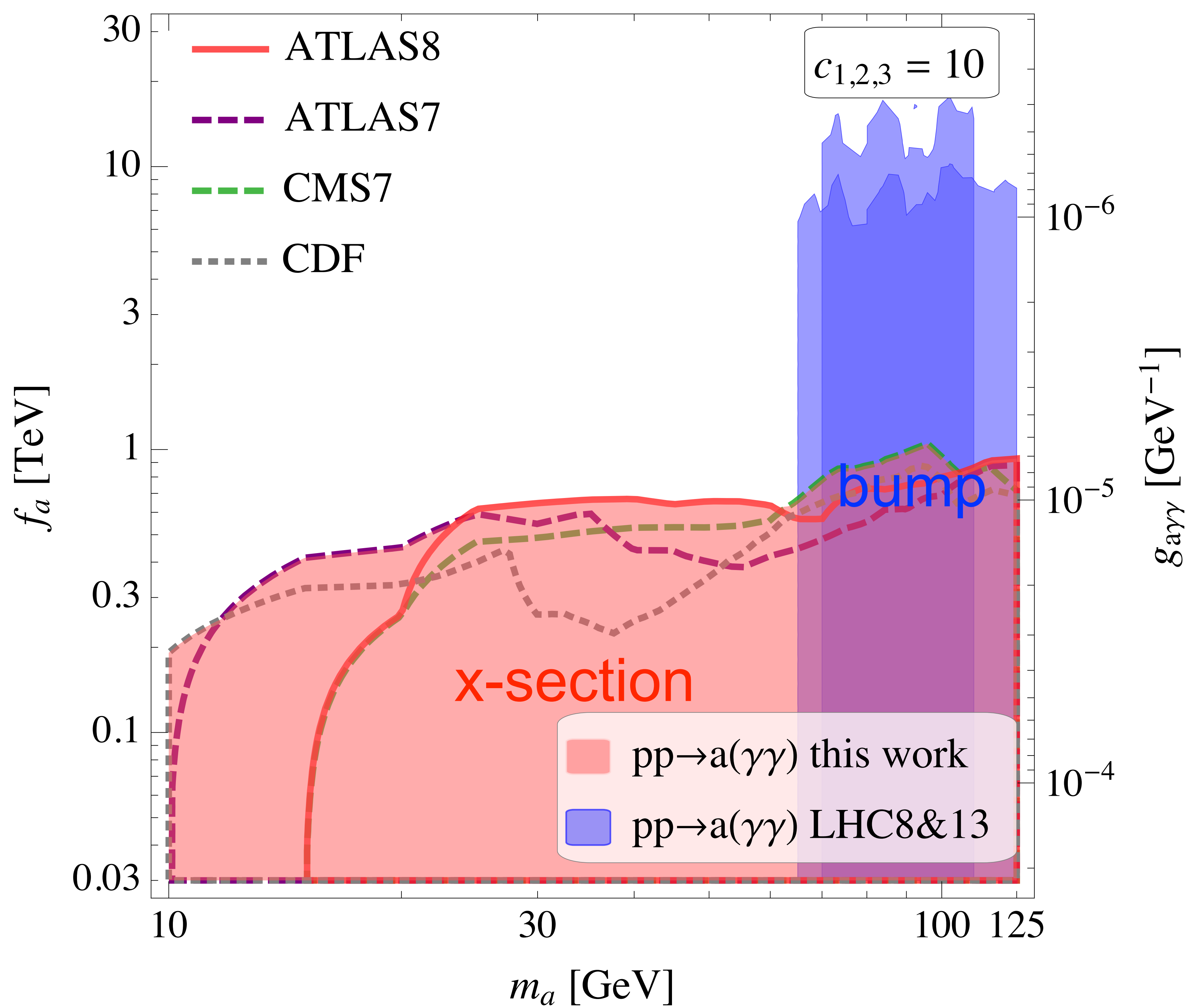
$$\Delta_{\rm high} = \sqrt{L_{\rm low}/L_{\rm high}}\sqrt{\sigma^{\rm MC}_{\rm low}/\sigma^{\rm MC}_{\rm high}}\,\Delta_{\rm low}.$$

Bound/sensitivity on cross section

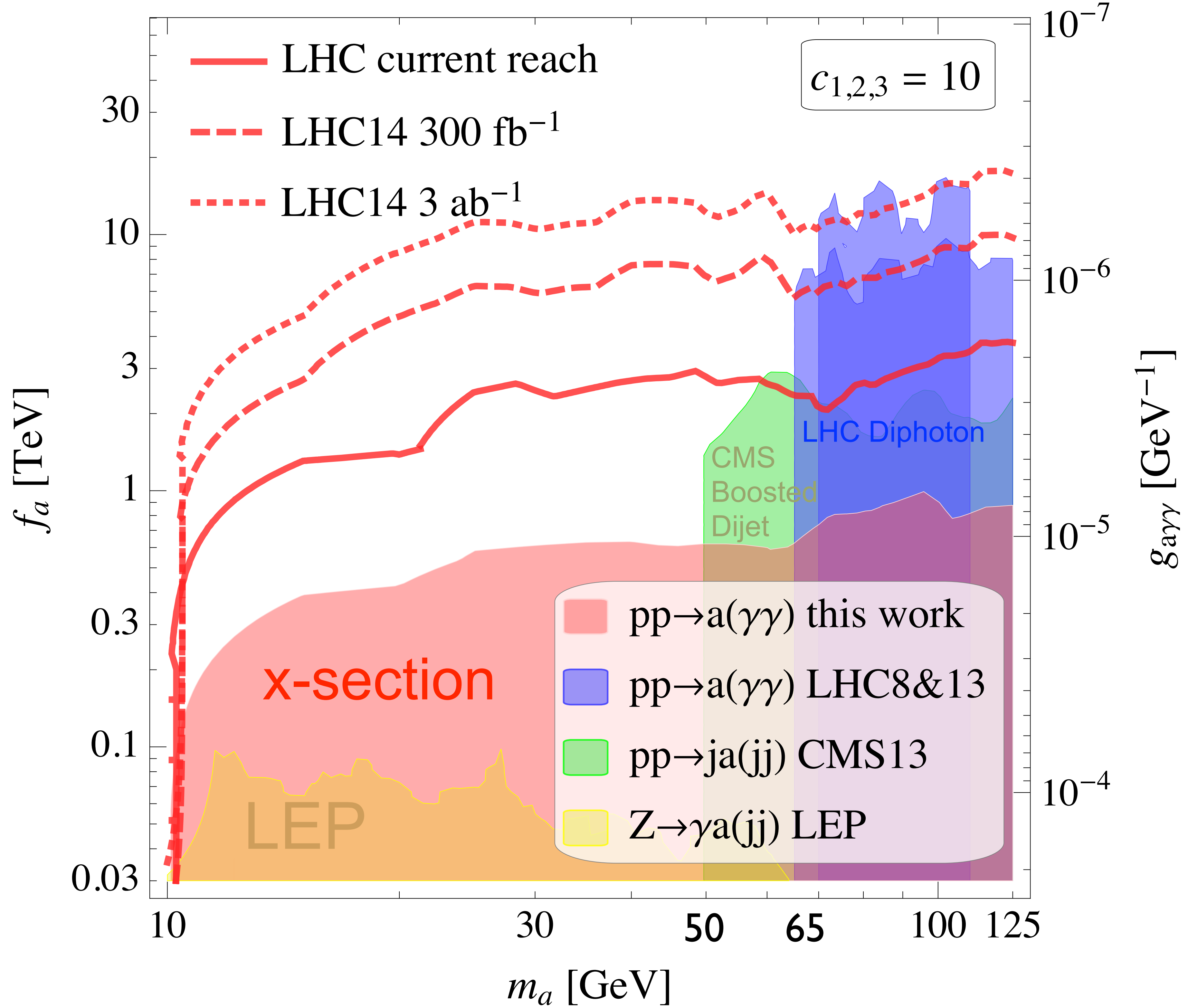
8TeV



Diphoton bounds in ALP parameter space



ALP parameter space

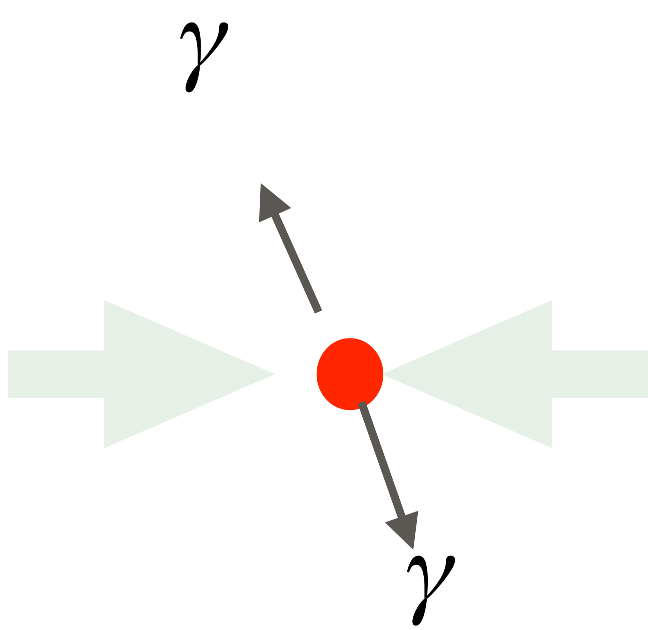


LHC>>LEP!

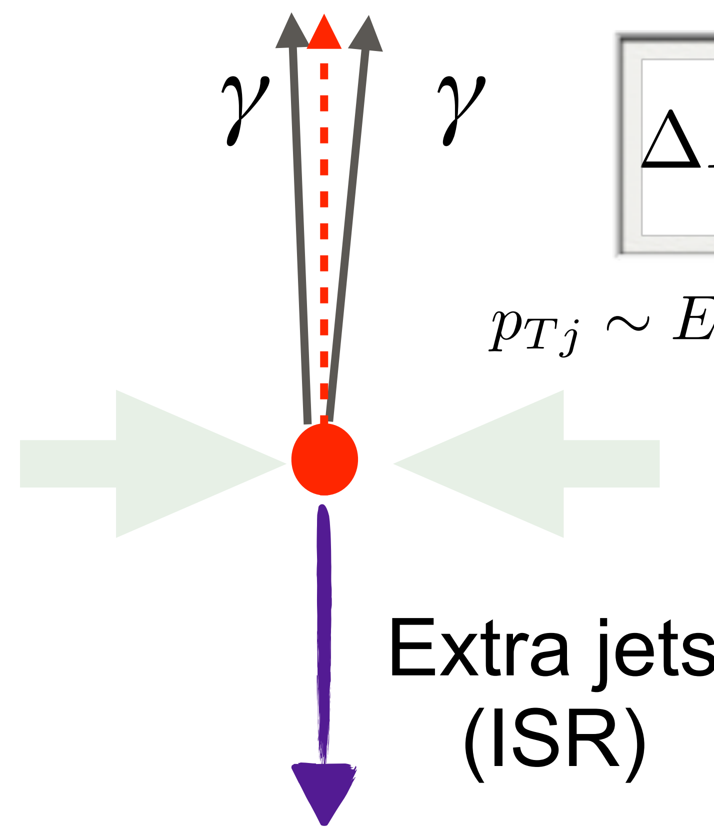
Possible Improvement

Challenge for low mass: trigger & isolation

Production at rest
$p_{T\gamma}$ too weak to be triggered



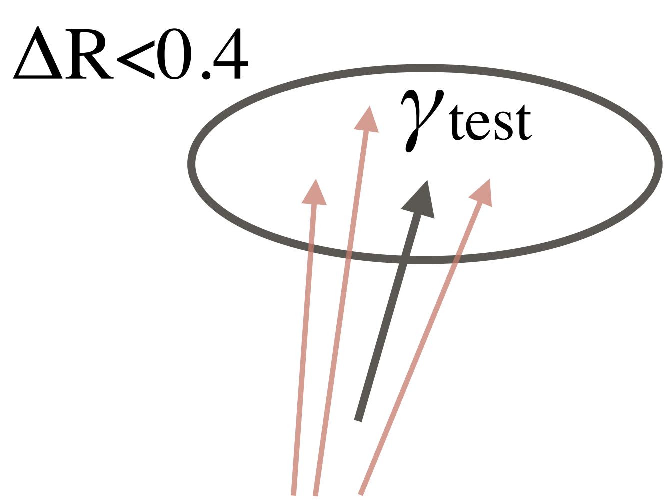
Production with boost
Isolation discards photons



$$\Delta R_{\gamma\gamma} \simeq \frac{2m_a}{E_{Ta}}$$

$$p_{Tj} \sim E_{Ta}, \; p_{T\gamma} \sim E_{Ta}/2$$

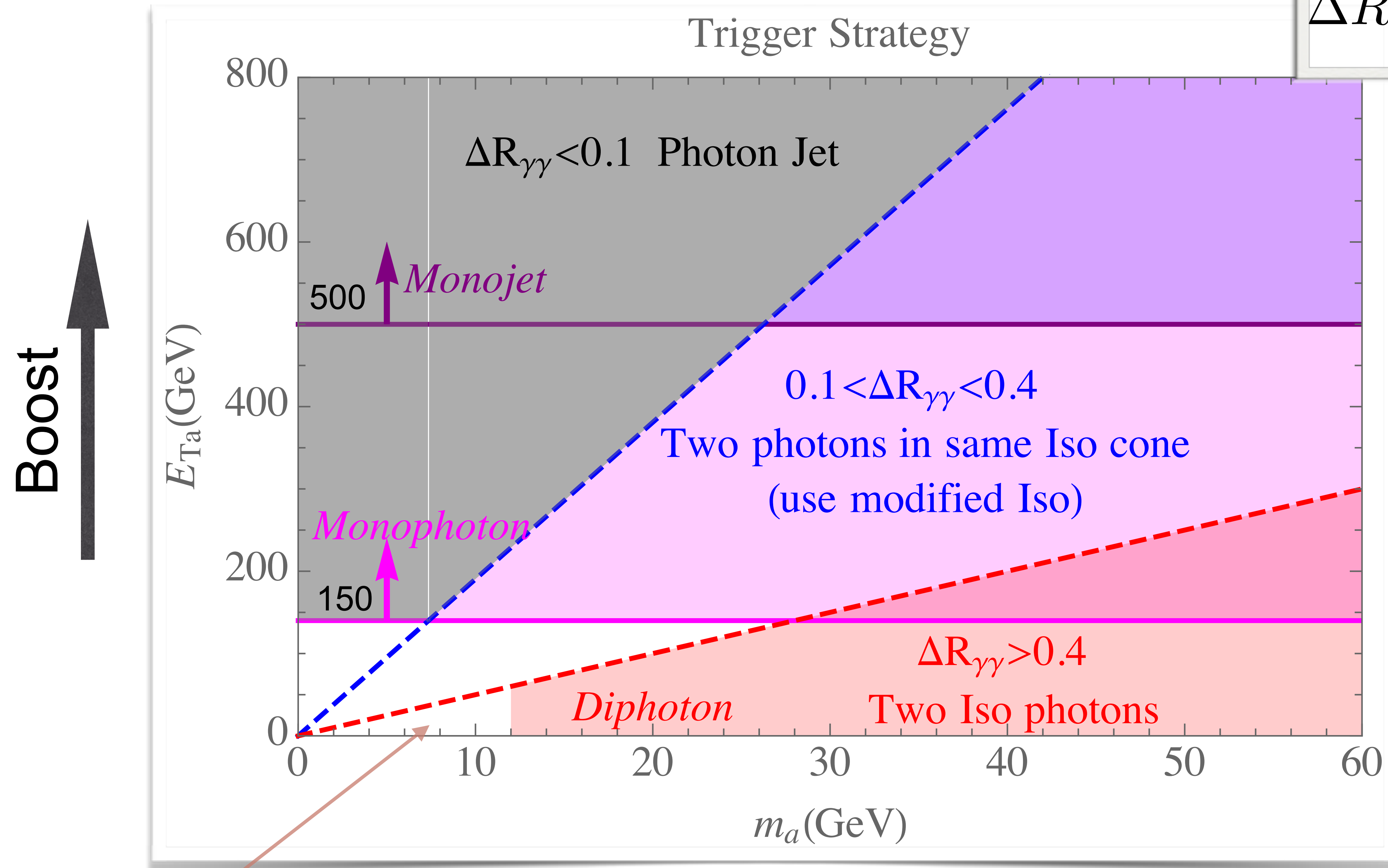
Isolation to suppress fake photon from jet



$$E_T^{\text{iso}} \equiv \sum_{i \neq \gamma_{\text{test}}}^{\Delta R_{i,\gamma_{\text{test}}} < 0.4} E_{T_i} \quad < 10\text{GeV}$$

Strategy with Other Triggers

$$\Delta R_{\gamma\gamma} \simeq \frac{2m_a}{E_{Ta}}$$



Diphoton at LHCb?

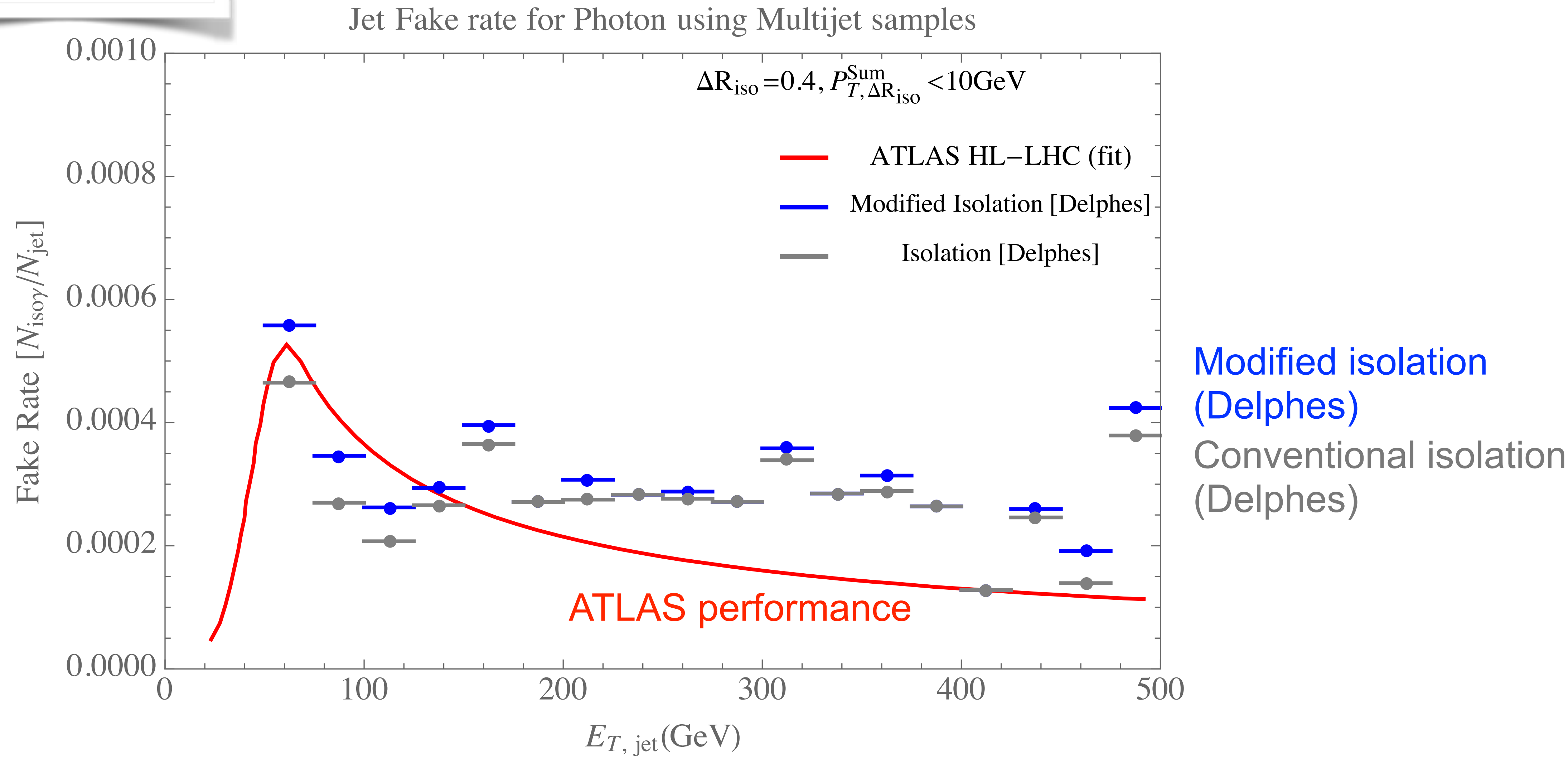
Modified Isolation: $E_T^{\mathrm{iso}} - E_{T_{\gamma_1}}$

→*ALP with Monojet or Monophoton triggers*

Validation of modified Isolation

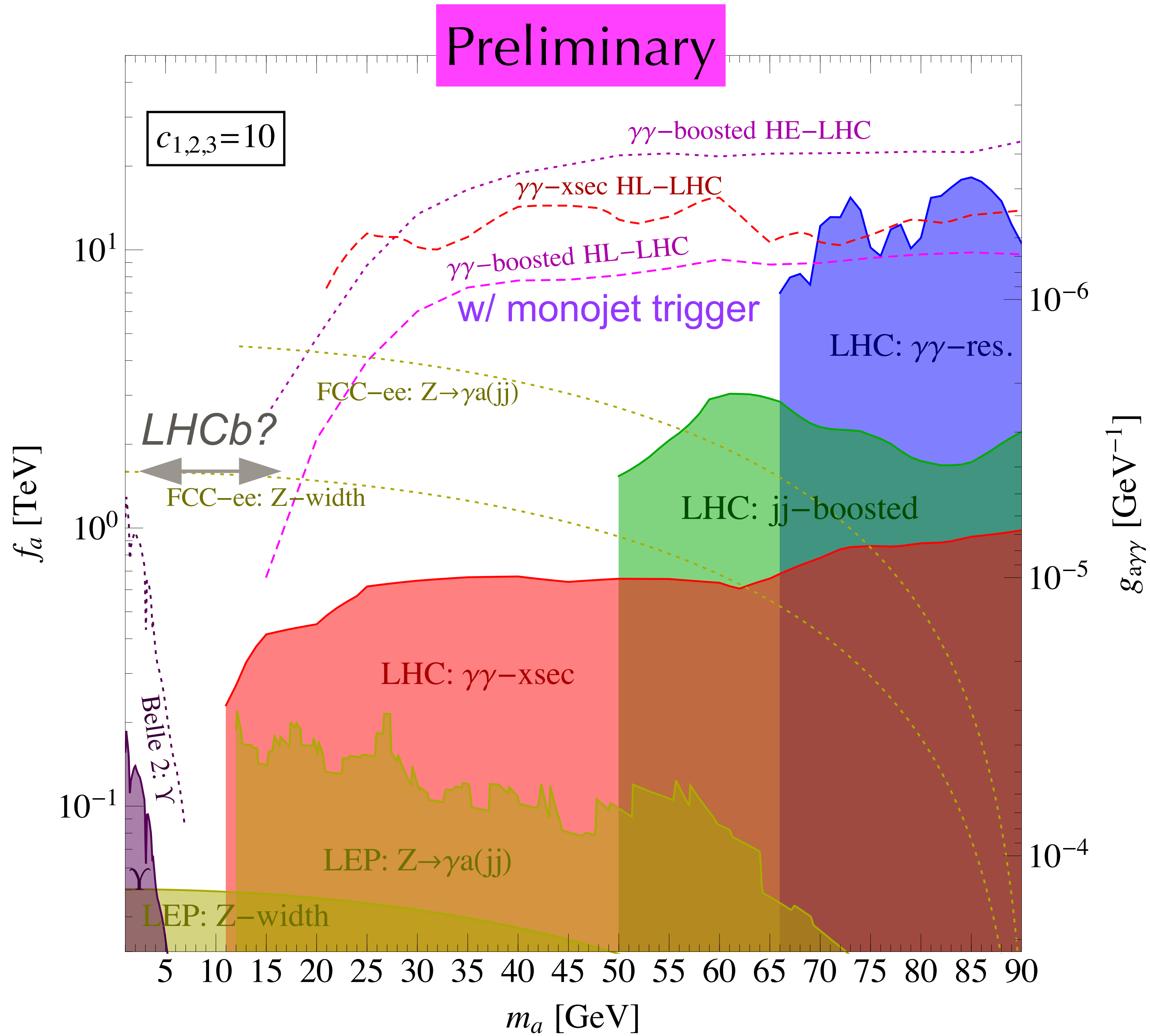
Modified Isolation works equally good to reject BG

Fake rate



Study monojet(>500GeV)+Boosted Diphoton w/ mod Iso

LHC bound +Projections



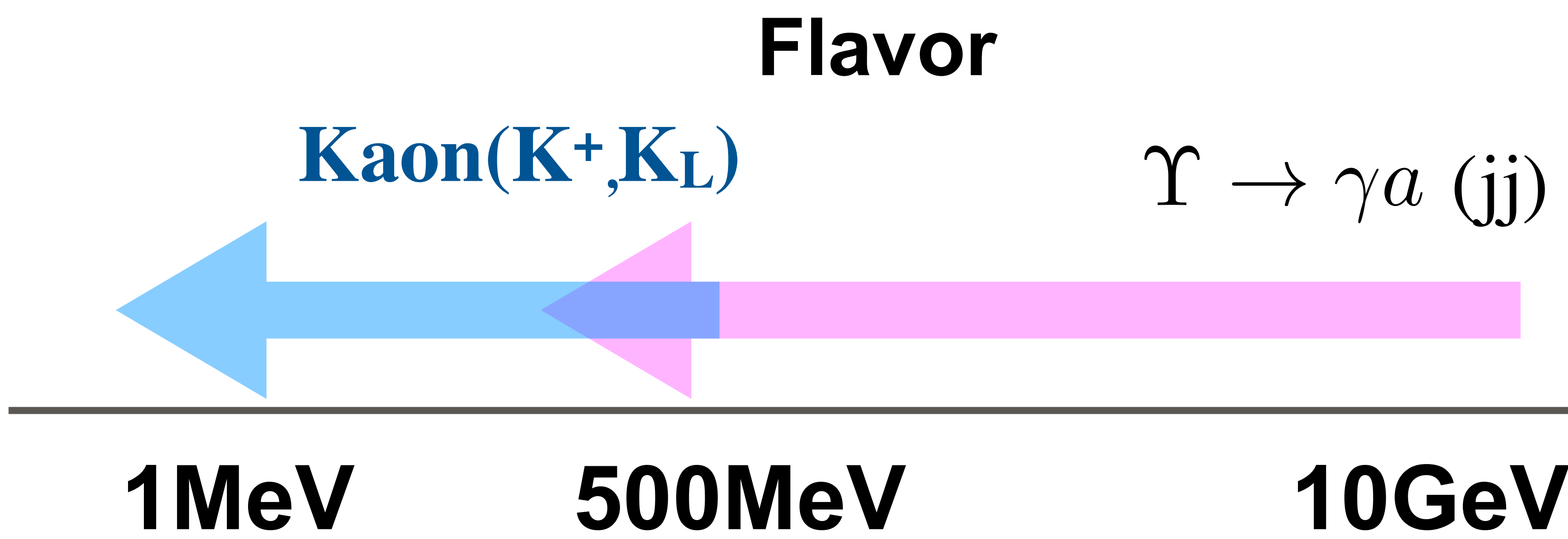
Study monojet(>500GeV)+Boosted Diphoton w/ mod Iso

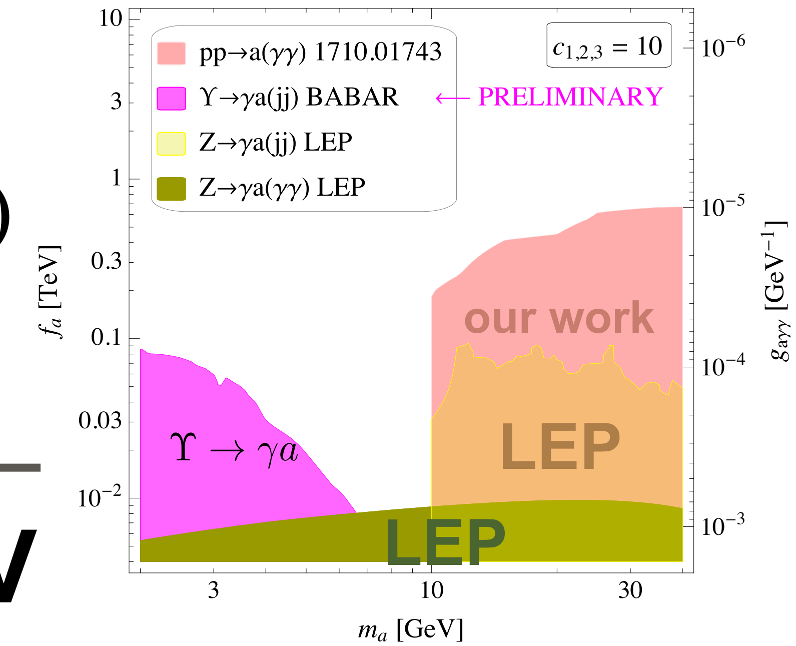
one w/ mono photon trigger goes below 10GeV (in progress)

ALP
at Kaon Factory

Preliminary work with Gilad Perez, Stefania Gori

Resonance Searches

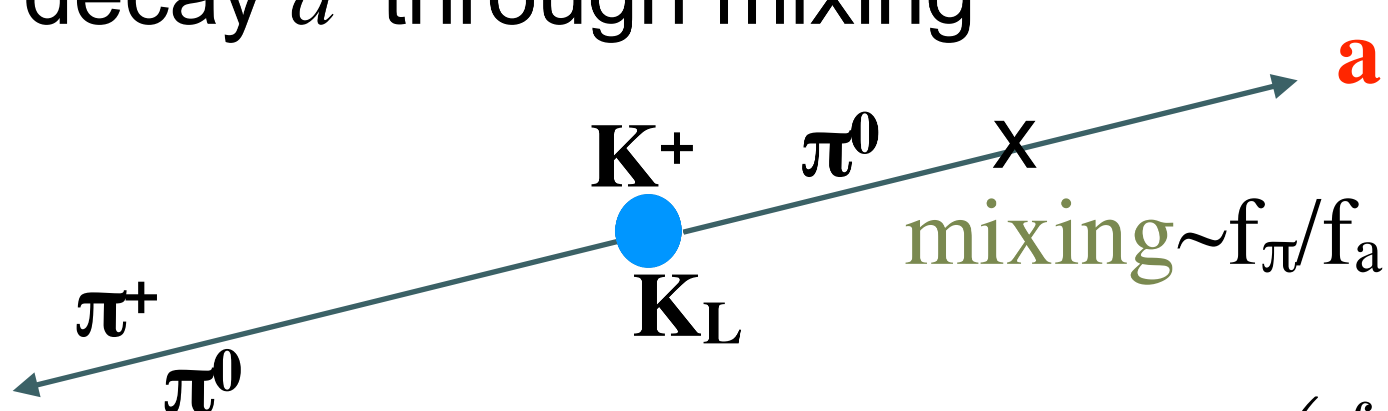




m_a

$aG\tilde{G}/f_a$ coupling generates a-π^0 mixing

Kaon decay a through mixing



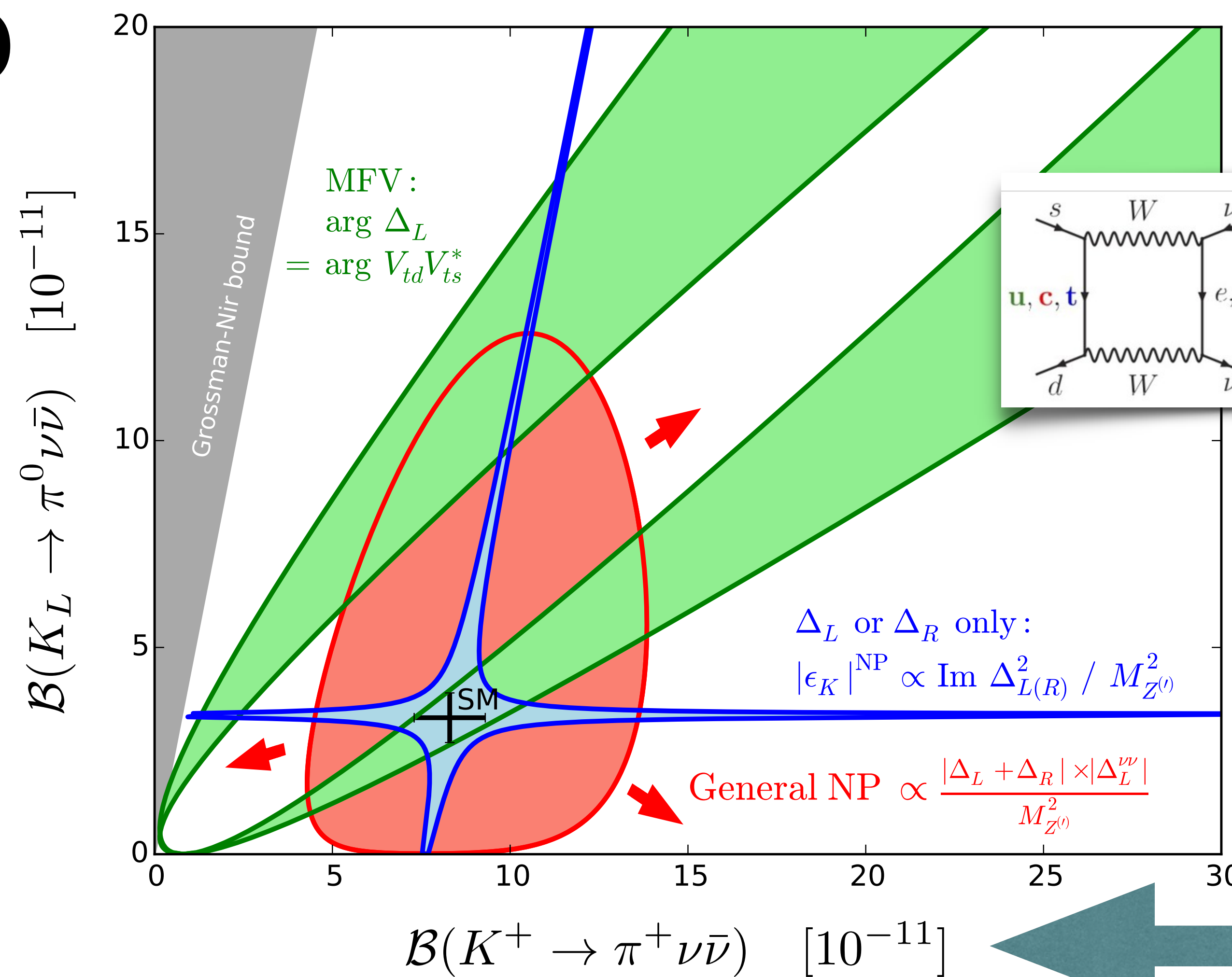
$$\mathrm{Br}(K \to \pi a) \simeq \left(\frac{f_\pi}{f_a}\right)^2 \mathrm{Br}(K \to \pi\pi)$$

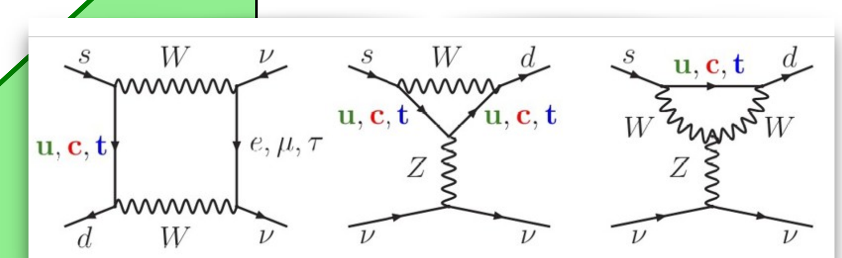
Two Active Kaon factories

High intensity Kaon factories look for rare decay

$$\mathrm{Br}(K^+ \to \pi^+ \nu\bar{\nu}) = (8.22^{+0.74}_{-0.65} \pm 0.29) \times 10^{-11}$$
$$\mathrm{Br}(K_L \to \pi^0 \nu\bar{\nu}) = (2.57^{+0.38}_{-0.36} \pm 0.04) \times 10^{-11}$$

KOTO





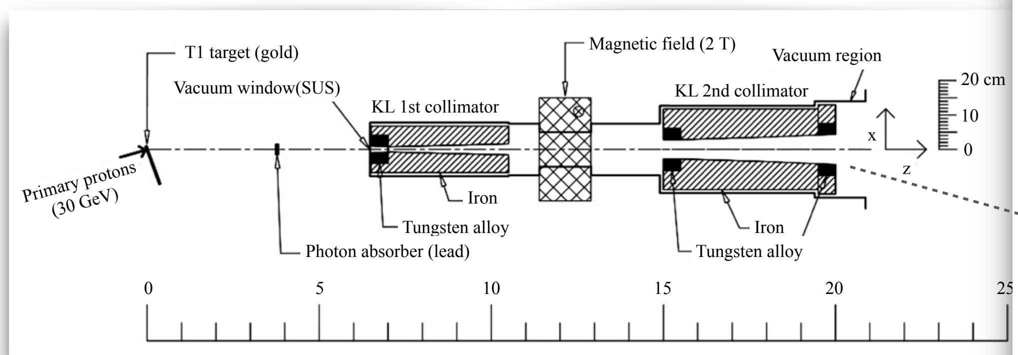
Buras et al('15)

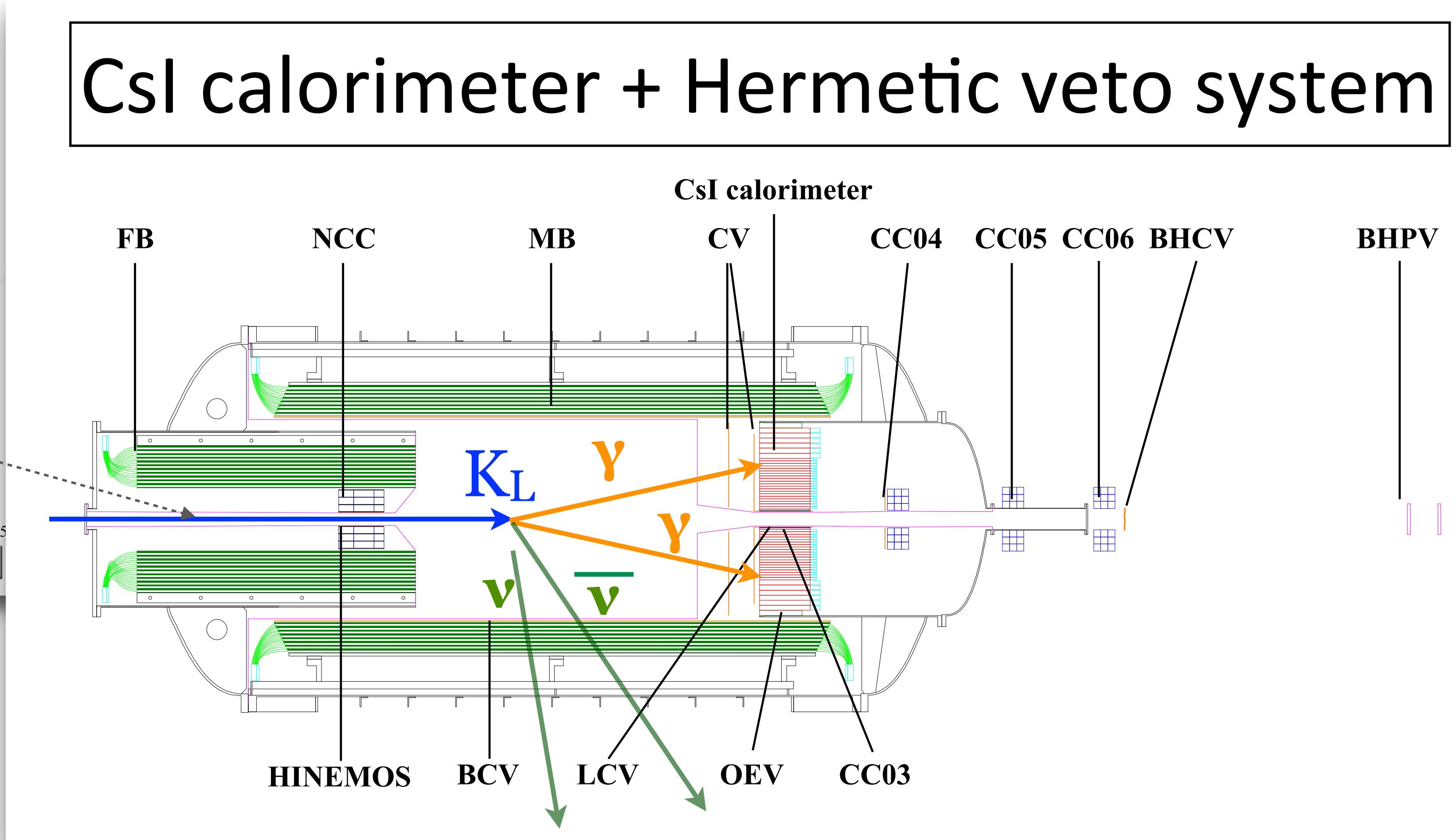
NA62

1. # of Kaon will be ~10^{14} to reach SM prediction!
2. can be used for new particle hunt (peak)

30GeV Main Ring
started at 2013

@J-PARC, Tokai, Japan





1. Pure K_L flux in decay region
2. CsI ECAL for photon in forward, No charged tracker
3. K_L decay point is unknown

Comparison

	J-PARC **KOTO**	CERN **NA62**
Main Target	$K_L \to \pi^0(\gamma\gamma)\nu\nu$	$K^+ \to \pi^+\nu\nu$
Signal	**Photon, invisible**	**Charged particle, invisible**
BG	$K_L \to 3\pi,\ 2\pi$	$K^+ \to \pi^+\pi^0\ ,\ \mu^+\nu$
VETO	Charged particle	Photon
# of K, now	~10^13	~10^12
Size& pBeam	30GeV,~30m	400GeV, 250m
BSM opportunity	ALP, Vector Portal	ALP, Vector Portal, $Z'_{\mu\text{-}\tau}$ Neutrino Portal

Bump hunt at KOTO

Physics target: $\mathbf{K_L \to \pi^0 a \to 4\gamma}$ and $\mathbf{m_a < m_\pi}$

*assume prompt decay

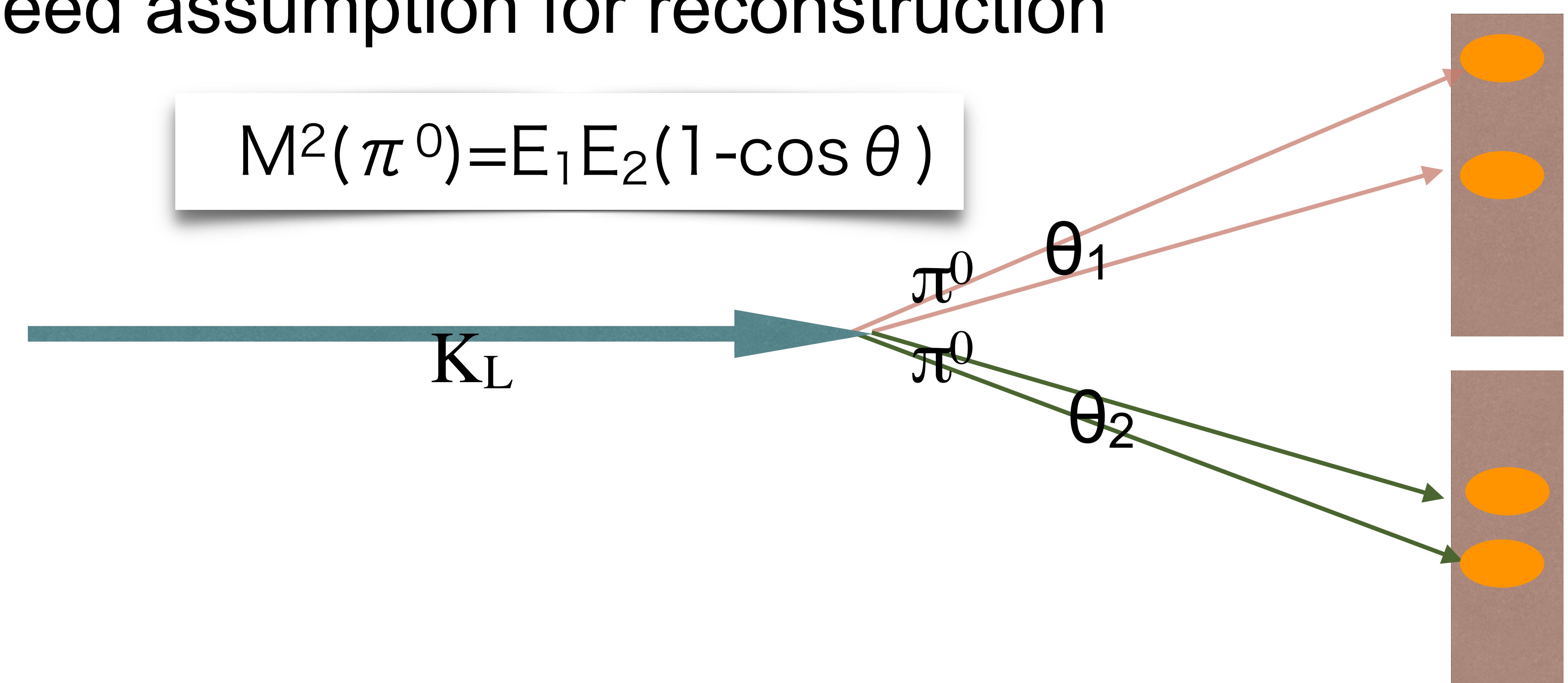
Rate: $$\mathrm{Br}(K \to \pi^0 a) \simeq \left(\frac{f_\pi}{f_a}\right)^2 \mathrm{Br}(K \to \pi^0 \pi^0)$$

CPV ~10^{-3}

Background: $K_L \to \pi^0\pi^0 \to 4\gamma$

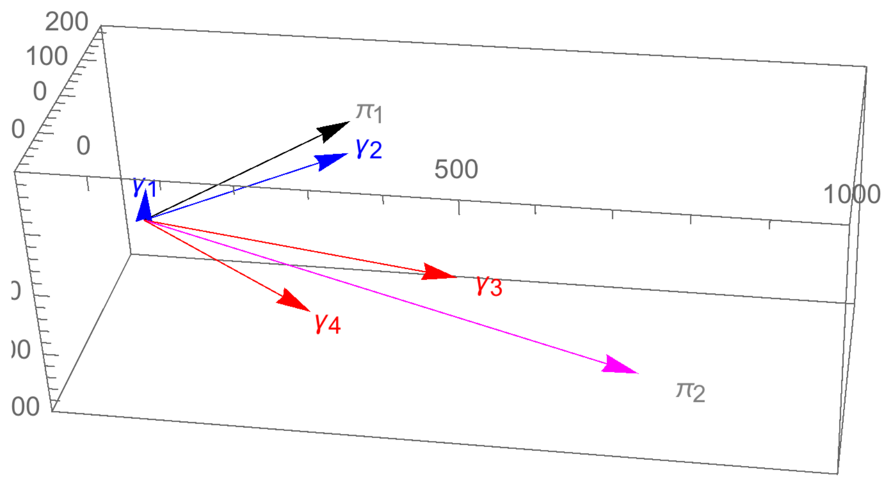
Need assumption for reconstruction

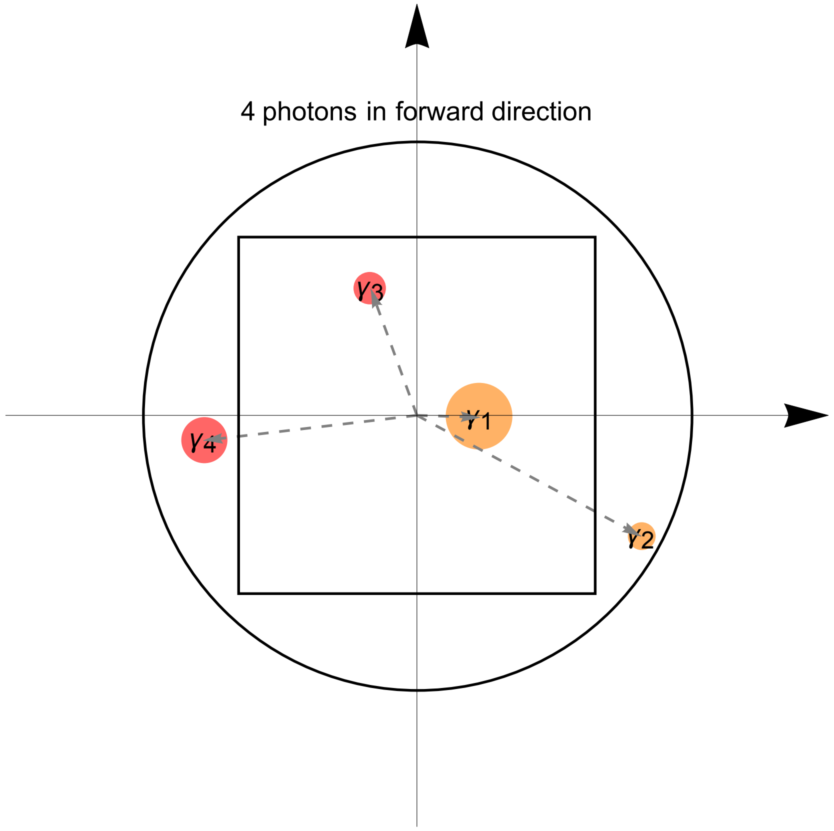
$M^2(\pi^0) = E_1 E_2 (1 - \cos\theta)$



Bump hunt at KOTO

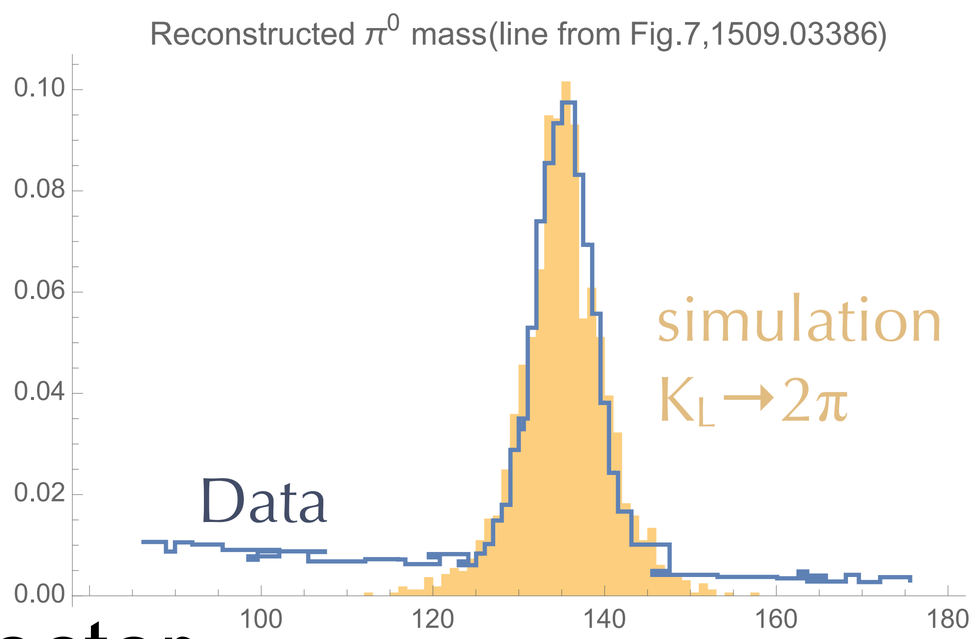
Setup MC simulation (Evt generation+Detector+Recon.)

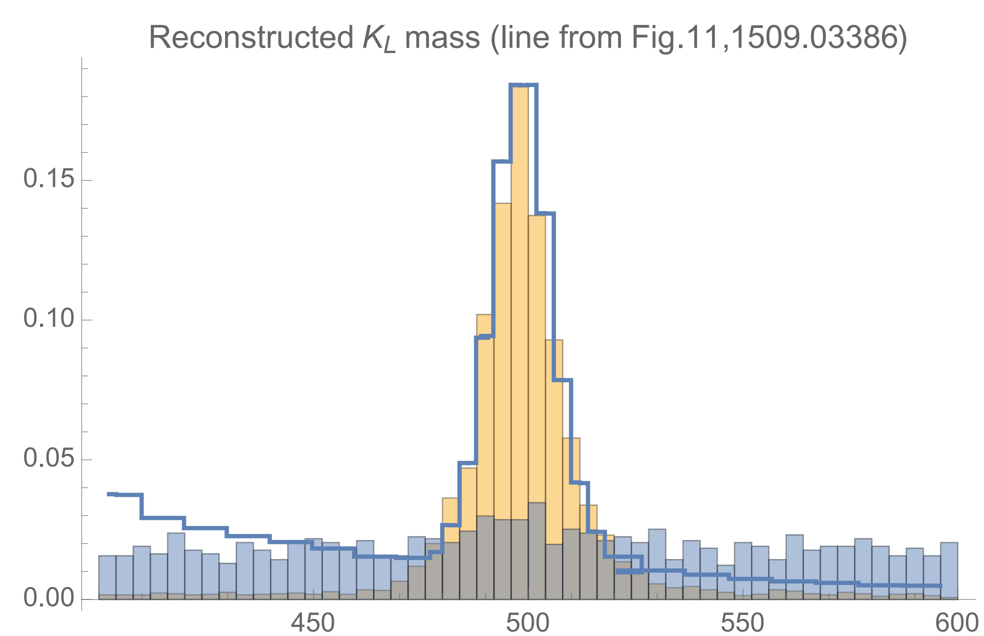




Validation

arbitrary normalization





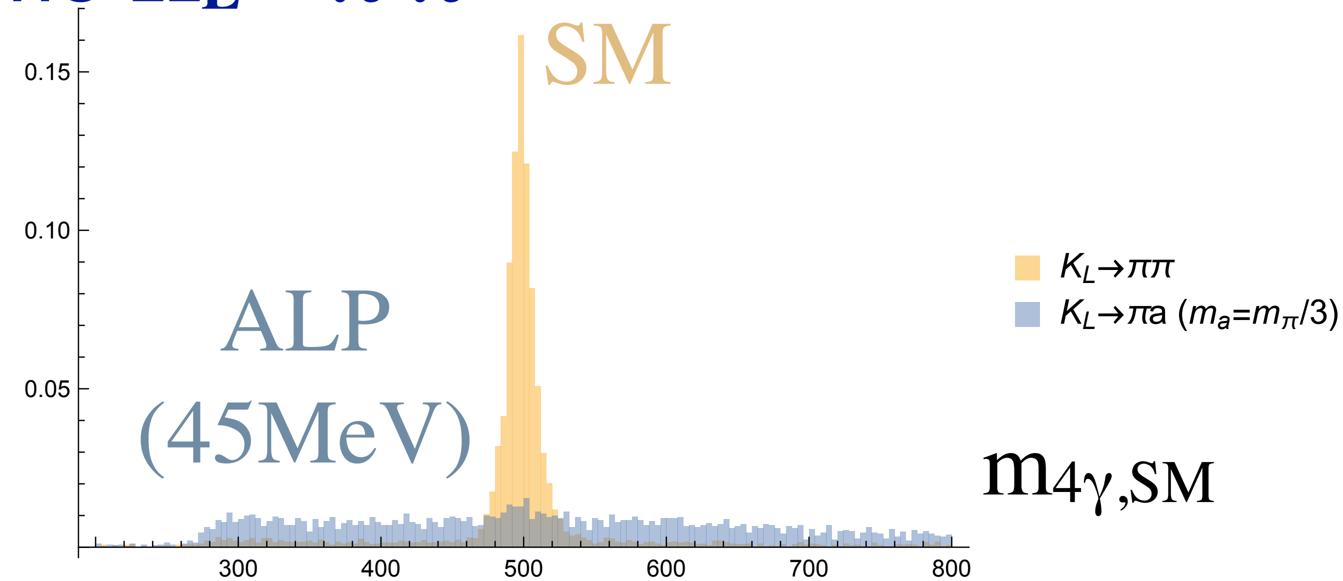
detector

reconstruction

Bump hunt at KOTO

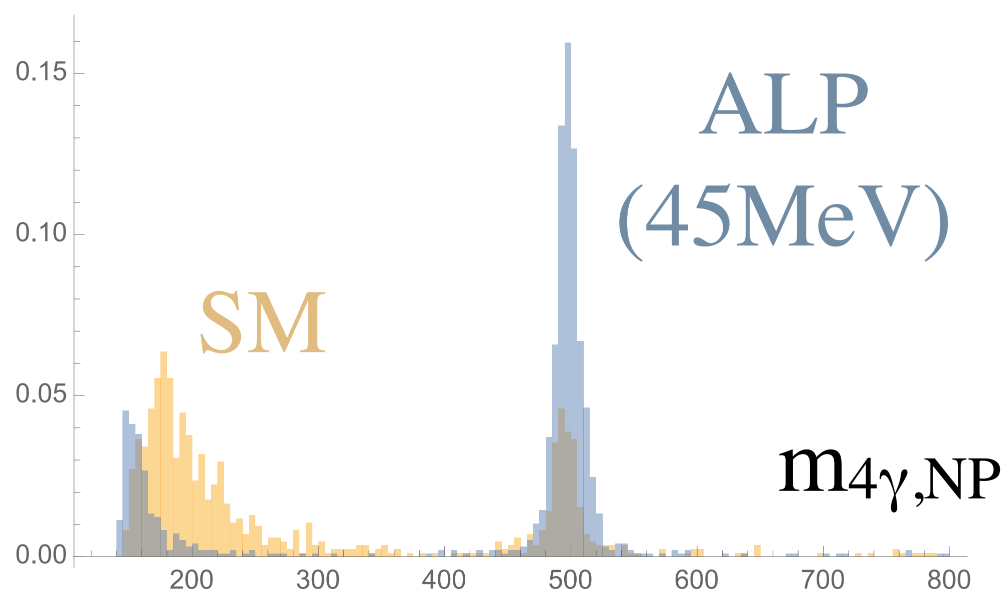
Reconstruction for SM: assume $K_L \to \pi^0\pi^0$

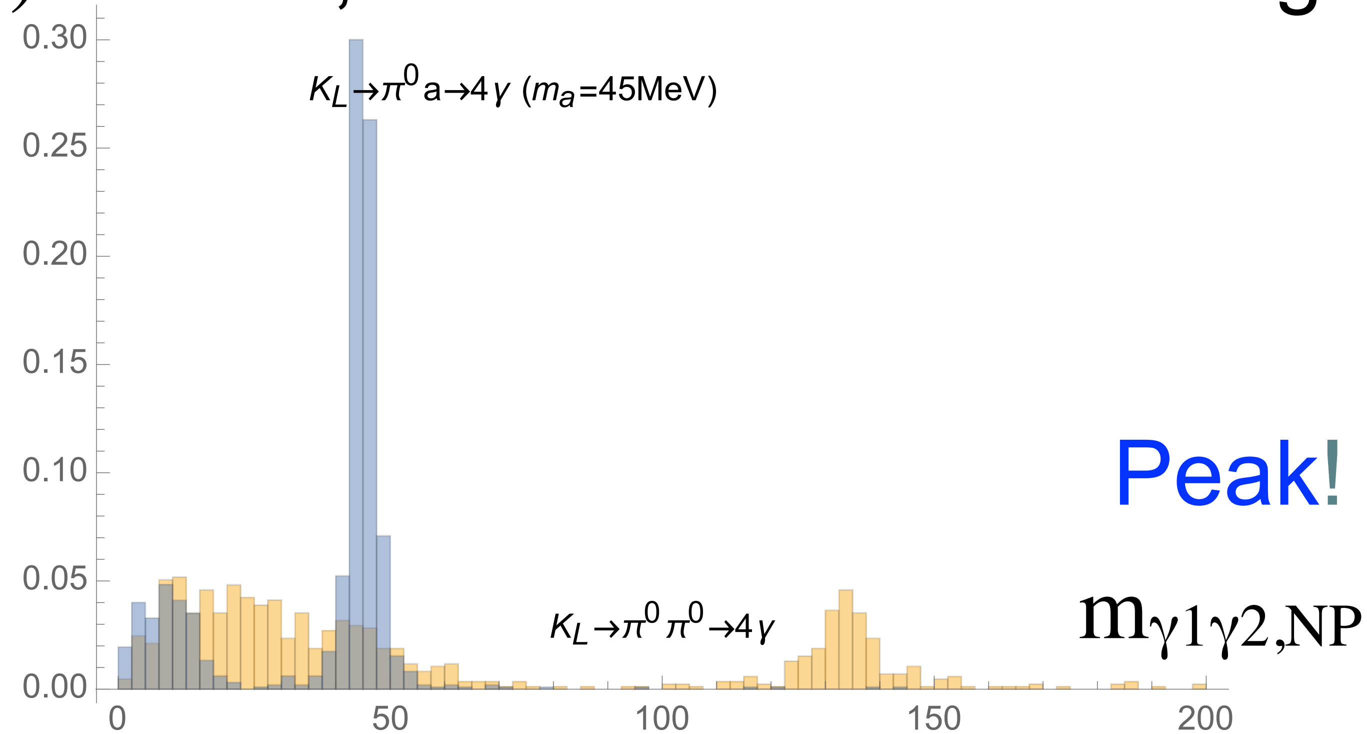
arbitrary normalization



Reconstruction for NP: assume $K_L \to \pi^0 a$

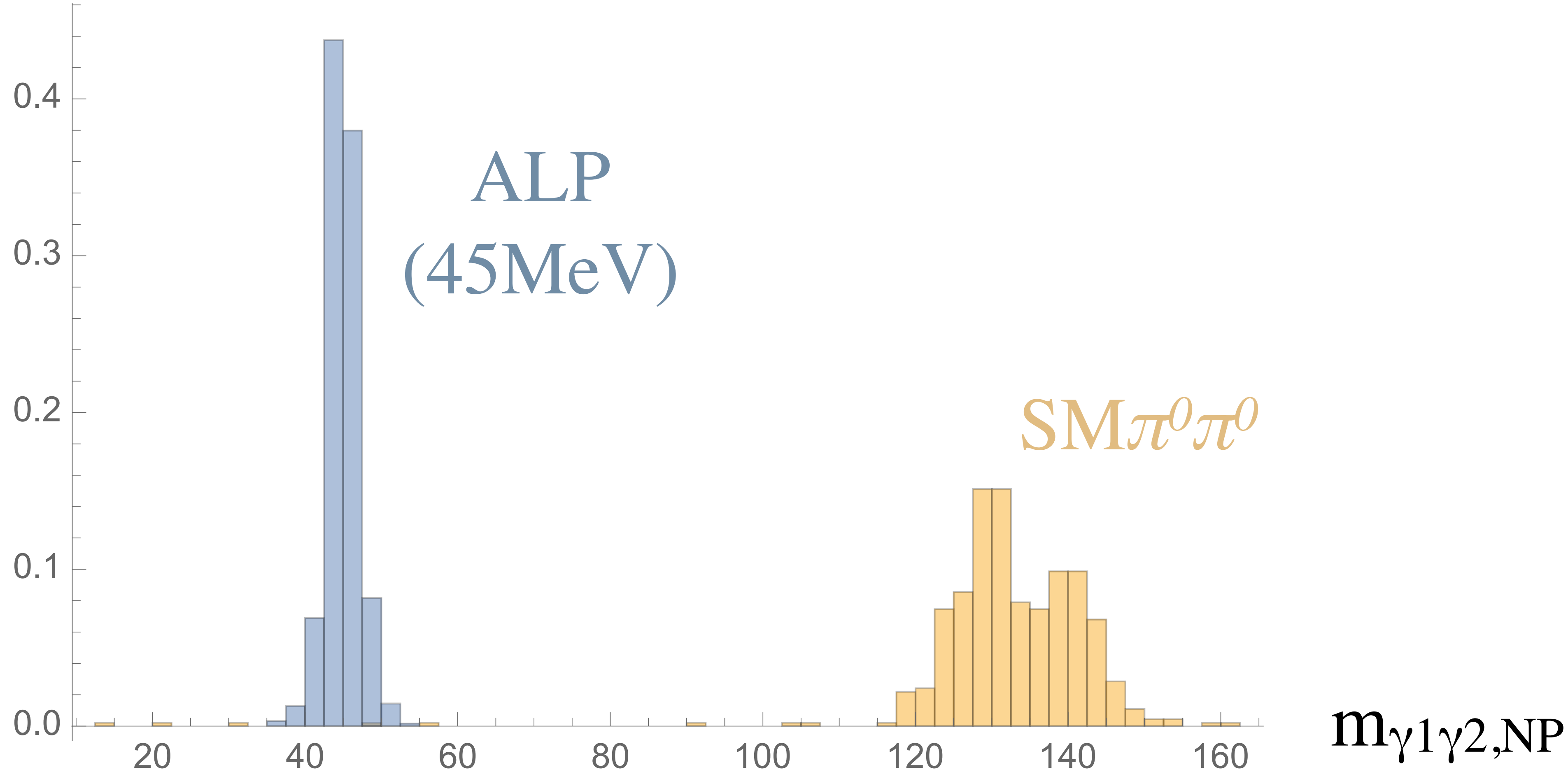
- jet distance: $E_i E_j \Delta r_{ij}^2$ ~mass^2, a→closest 2photons (1,2)
- the other two photons (3,4) from π^0, reconstruct vtx assuming m_π





Bump hunt at KOTO

Require 4γ on target, Remove K_L in $m_{4\gamma,SM}$, Keep K_L in $m_{4\gamma,NP}$



Efficiencies Sig(45MeV) 6% With $N_K=10^{13}$

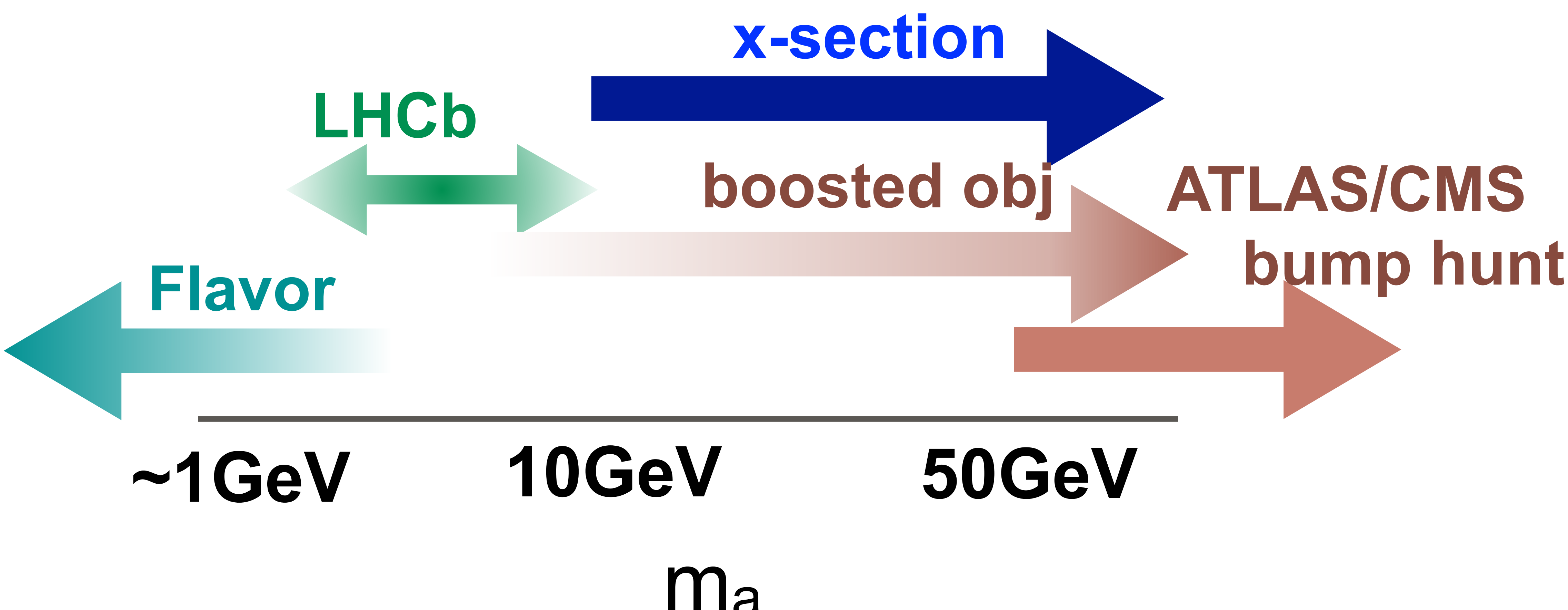
BG($\pi^0\pi^0$) 10^{-5} Preliminary **Br($K_L \rightarrow \pi^0 a$)>10^{-9}**

f_a>500GeV with c_3=10

Need to consider: 3πBG, study $m_a>m_\pi$, 6γ, inv decay, Beam dump

Summary

- ALP(f_a~TeV) predicted by BSM models, can be first signal as a resonance
- Gap: 10-100GeV can be covered by x-sec measurement
- Boosted diphoton w/ mod. iso. also probes low mass ALP
- **KOTO** is sensitive to ALP diphoton! Need to explore more.



pic from http://us.france.fr/en/discover/alps-0

Thank you!

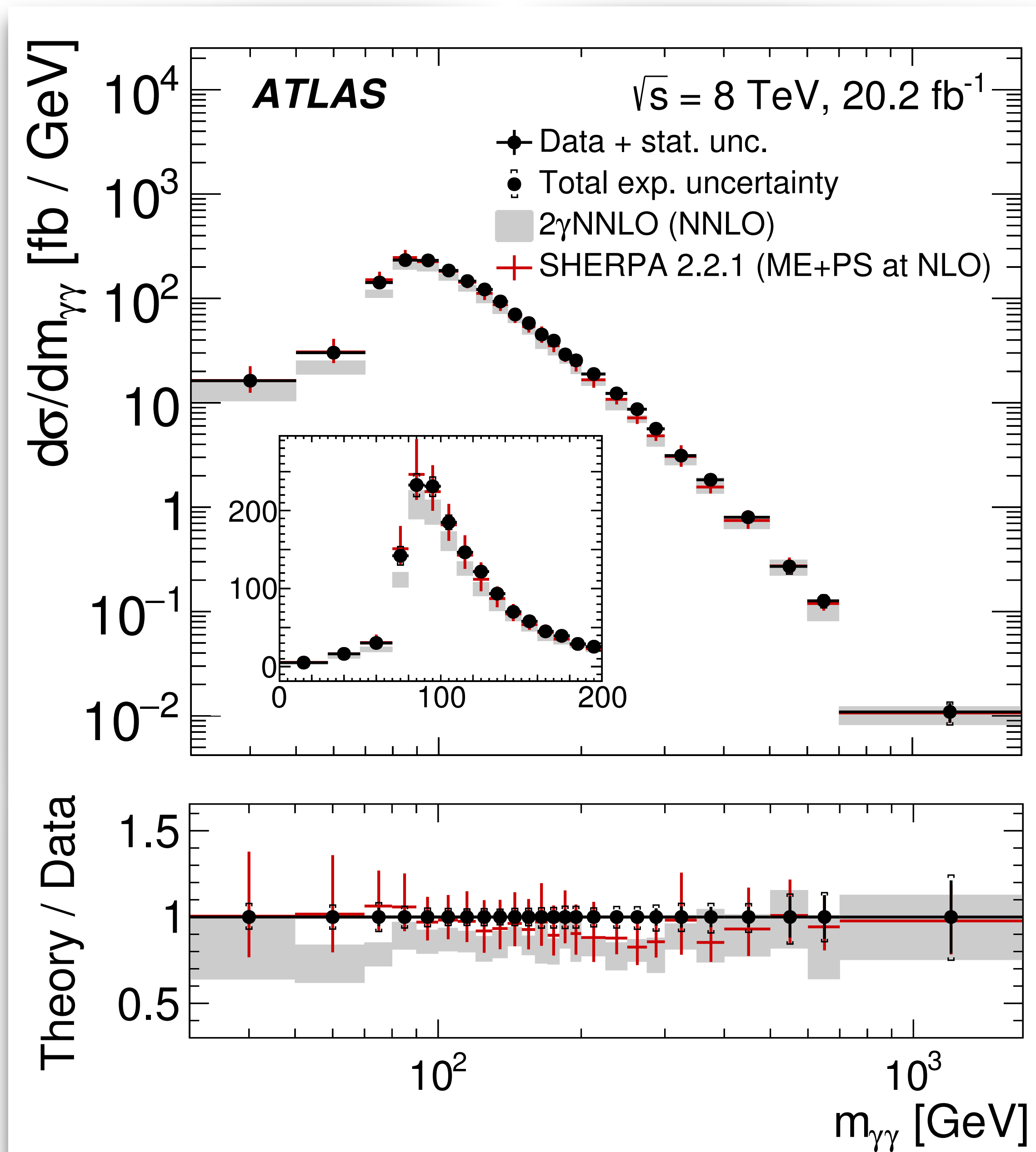
Backup I

Experiment	Process	Lumi	$\sqrt{s}$	low mass reach	ref.
LEPI	$e^+e^- \to Z \to \gamma a \to \gamma jj$	12 pb^{-1}	Z-pole	10 GeV	[29]
LEPI	$e^+e^- \to Z \to \gamma a \to \gamma\gamma\gamma$	78 pb^{-1}	Z-pole	3 GeV	[30]
LEPII	$e^+e^- \to Z^*, \gamma^* \to \gamma a \to \gamma jj$	9.7,10.1,47.7 pb^{-1}	161,172,183 GeV	60 GeV	[31]
LEPII	$e^+e^- \to Z^*, \gamma^* \to \gamma a \to \gamma\gamma\gamma$	9.7,10.1,47.7 pb^{-1}	161,172,183 GeV	60 GeV	[31, 32]
LEPII	$e^+e^- \to Z^*, \gamma^* \to Z a \to jj\gamma\gamma$	9.7,10.1,47.7 pb^{-1}	161,172,183 GeV	60 GeV	[31]
D0/CDF	$p\bar{p} \to a \to \gamma\gamma$	7/8.2 fb^{-1}	1.96 TeV	100 GeV	[33]
ATLAS	$pp \to a \to \gamma\gamma$	20.3 fb^{-1}	8 TeV	65 GeV	[34]
CMS	$pp \to a \to \gamma\gamma$	19.7 fb^{-1}	8 TeV	80 GeV	[35]
CMS	$pp \to a \to \gamma\gamma$	19.7 fb^{-1}	8 TeV	150 GeV	[36]
CMS	$pp \to a \to \gamma\gamma$	35.9 fb^{-1}	13 TeV	70 GeV	[37]
CMS	$pp \to a \to jj$	18.8 fb^{-1}	8 TeV	500 GeV	[38]
ATLAS	$pp \to a \to jj$	20.3 fb^{-1}	8 TeV	350 GeV	[39]
CMS	$pp \to a \to jj$	12.9 fb^{-1}	13 TeV	600 GeV	[40]
ATLAS	$pp \to a \to jj$	3.4 fb^{-1}	13 TeV	450 GeV	[41]
CMS	$pp \to ja \to jjj$	35.9 fb^{-1}	13 TeV	50 GeV	[42]
UA2	$p\bar{p} \to a \to \gamma\gamma$	13.2 pb^{-1}	0.63 TeV	17.9 GeV	[43]
D0	$p\bar{p} \to a \to \gamma\gamma$	4.2 fb^{-1}	1.96 TeV	8.2 GeV	[44]
CDF	$p\bar{p} \to a \to \gamma\gamma$	5.36 fb^{-1}	1.96 TeV	6.4 GeV	[45, 46]
ATLAS	$pp \to a \to \gamma\gamma$	4.9 fb^{-1}	7 TeV	9.4 GeV	[8]
CMS	$pp \to a \to \gamma\gamma$	5.0 fb^{-1}	7 TeV	14.2 GeV	[10]
ATLAS	$pp \to a \to \gamma\gamma$	20.2 fb^{-1}	8 TeV	13.9 GeV	[9]

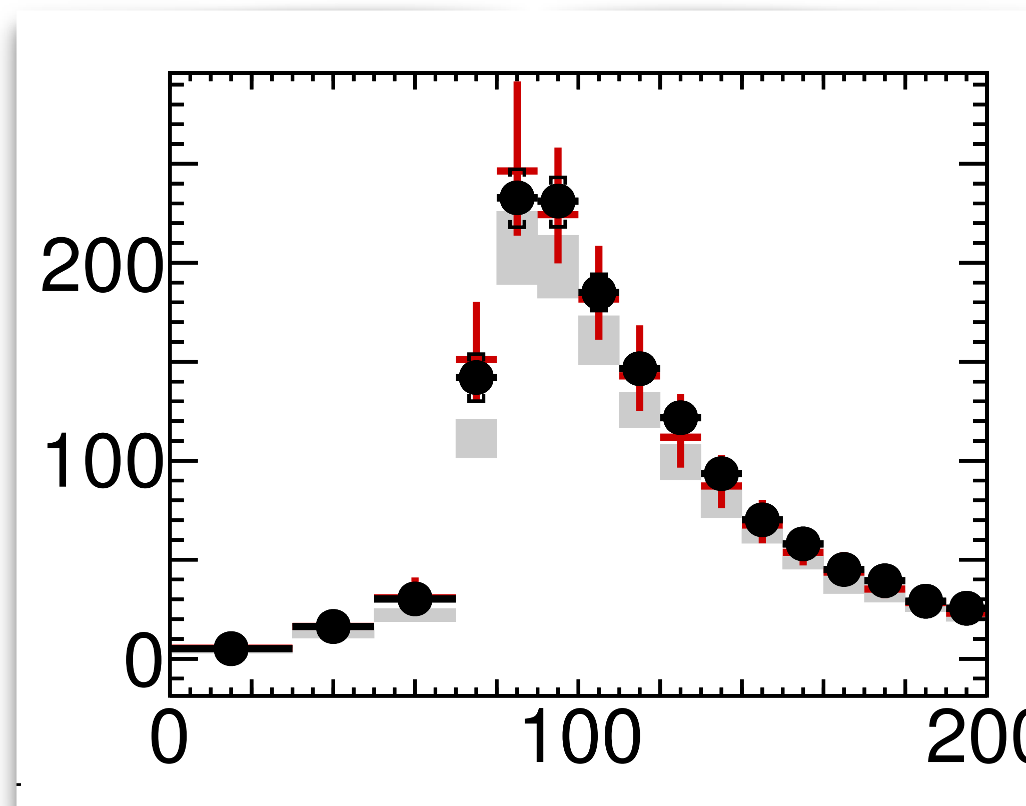
TABLE I: In the top of the Table we list the relevant searches involving at least a photon in the final state at different colliders, and lowest value of invariant mass that they reach. In the middle we also include the most recent LHC dijet searches (see Ref. [28] for a list of older searches). On the lower part of the Table we summarize the available diphoton cross section measurements with their minimal invariant mass reach, which we estimate via Eq. (8) from the minimal p_T cuts on the leading and subleading photon and the isolation cuts of the diphoton pair (see Appendix C for more details on the cross section measurements at UA2, at the Tevatron and at the LHC).

Diphoton x-section measurements

D0 ($\sigma_{\gamma\gamma}$)	$p\bar{p} \to a \to \gamma\gamma$	4.2 fb^{-1}	1.96 TeV	$p_{T_1,T_2} > 21, 20$ GeV	m_a> 8.2GeV
CDF ($\sigma_{\gamma\gamma}$)	$p\bar{p} \to a \to \gamma\gamma$	5.36 fb^{-1}	1.96 TeV	$p_{T_1,T_2} > 17, 15$ GeV	(m_a> 6.4 GeV)
ATLAS	$pp \to a \to \gamma\gamma$	4.9 fb^{-1}	7 TeV	$p_{T_1,T_2} > 25, 22$ GeV	m_a> 9.4 GeV
ATLAS	$pp \to a \to \gamma\gamma$	20.2 fb^{-1}	8 TeV	$p_{T_1,T_2} > 40, 30$ GeV	m_a>13.9 GeV
CMS	$pp \to a \to \gamma\gamma$	5.0 fb^{-1}	7 TeV	$p_{T_1,T_2} > 40, 25$ GeV	m_a>14.2 GeV



report lower mass

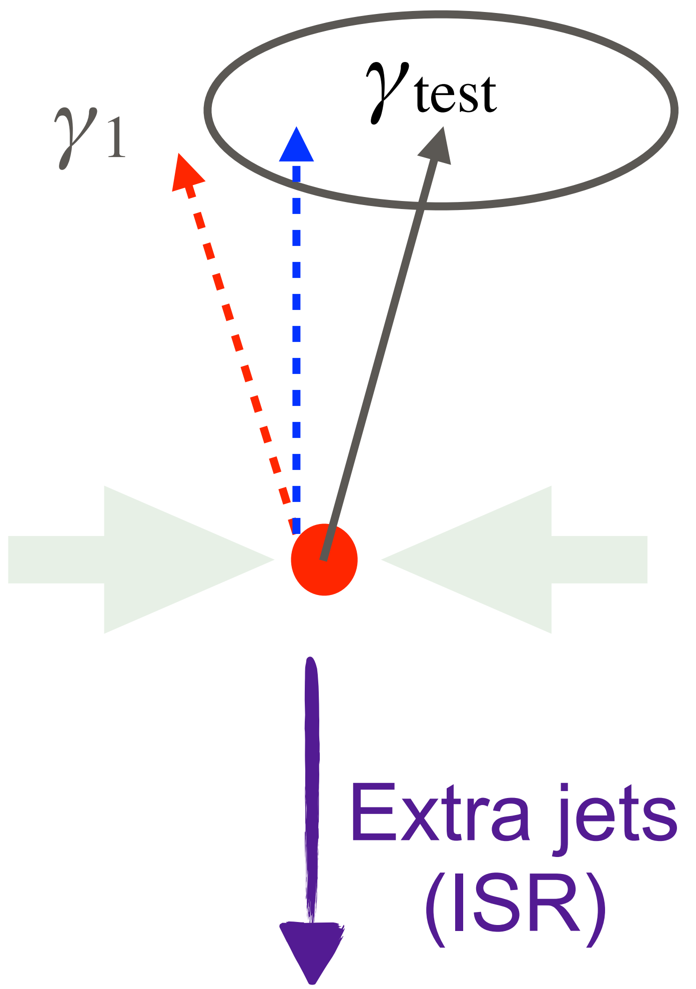


Strategy with Other Triggers

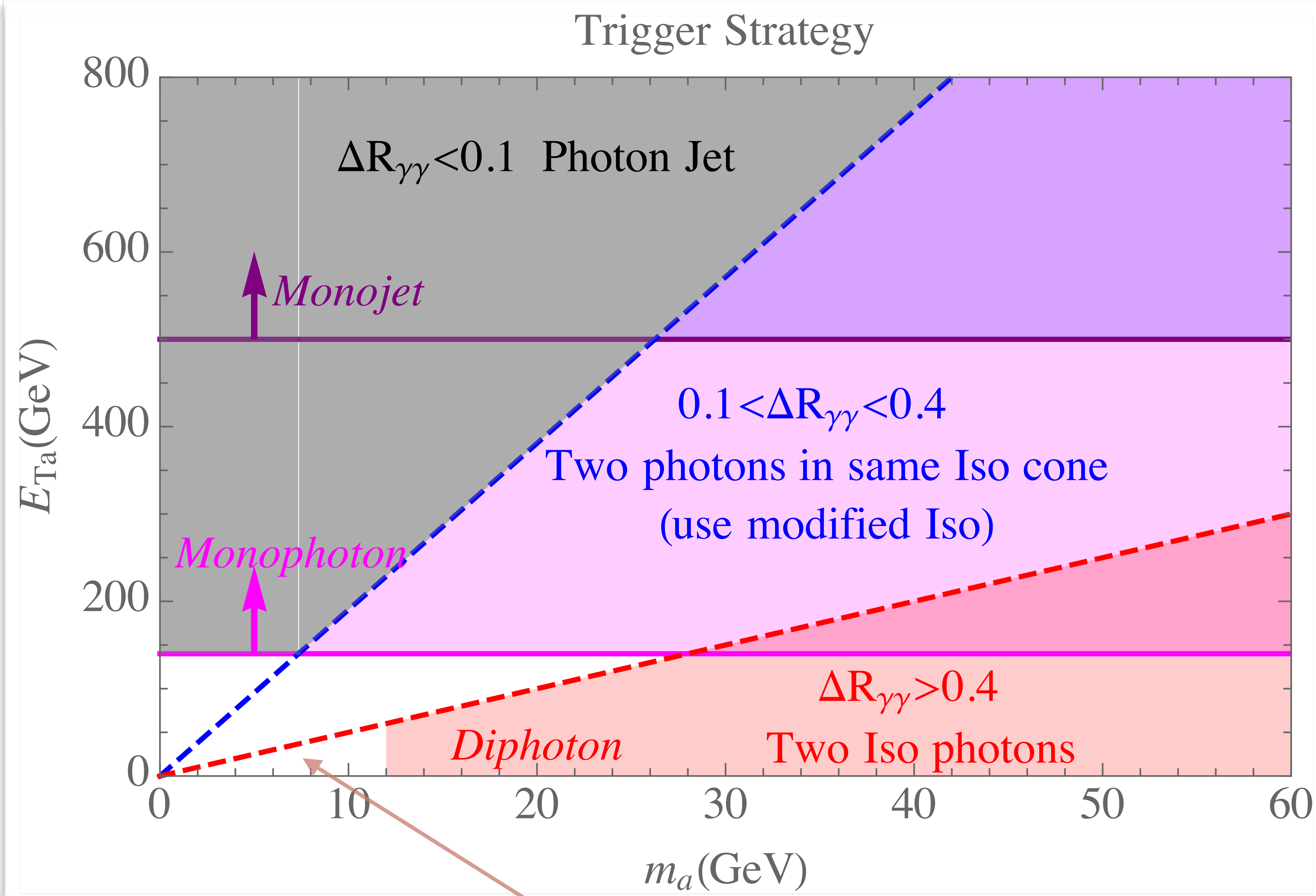
Isolation to suppress fake BG

$$\Delta R_{\gamma\gamma} \simeq \frac{2m_a}{E_{Ta}}$$

$$E_T^{\rm iso} \equiv \sum_{i \neq \gamma_{\rm test}}^{\Delta R_{i,\gamma_{\rm test}}<0.4} E_{T_i}$$



$p_{Tj} \sim E_{Ta},\ p_{T\gamma} \sim E_{Ta}/2$

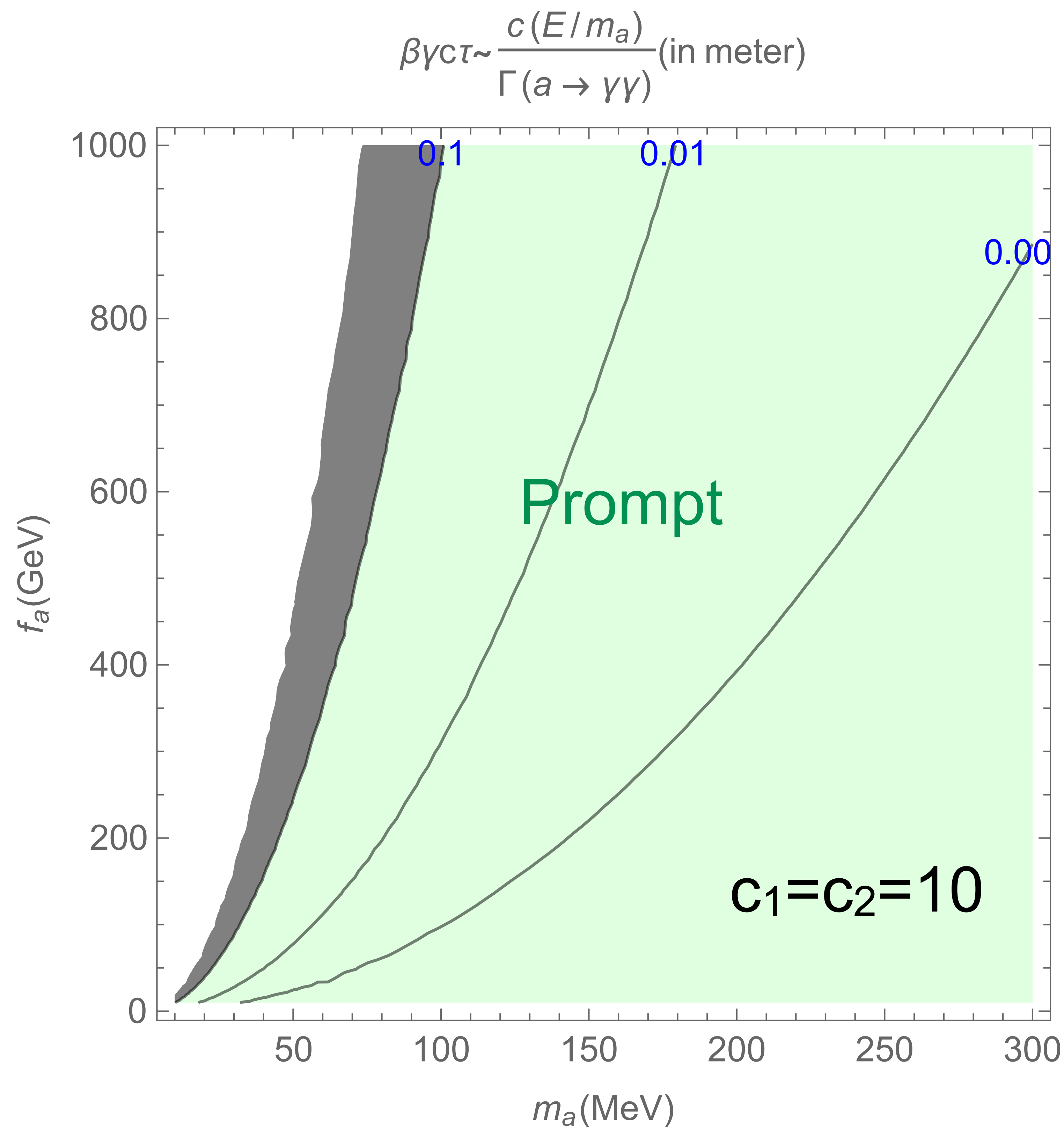


Diphoton at LHCb?

Modified Isolation: $E_T^{\rm iso} - E_{T_{\gamma_1}}$

→*ALP with Monojet, Monophoton triggers*

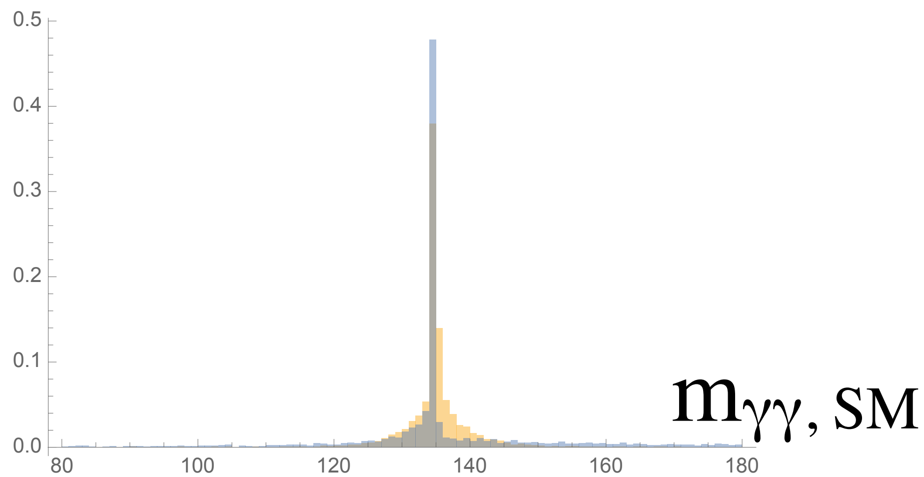
Lifetime and Decay Length

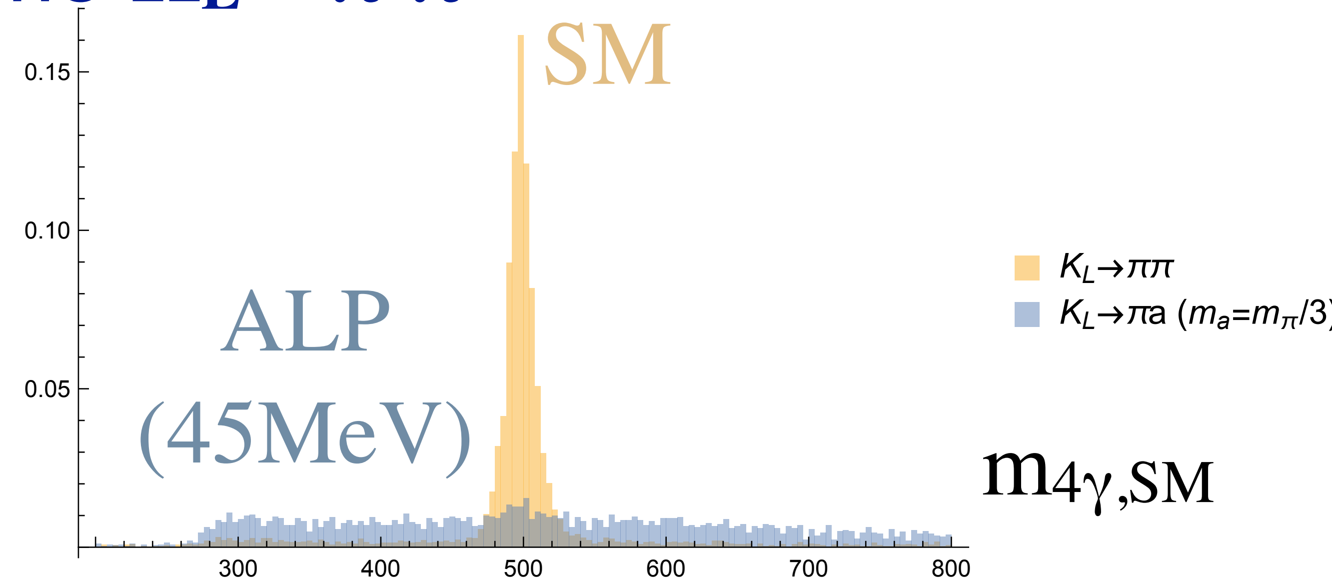


Bump hunt at KOTO

Reconstruction for SM: assume $K_L \to \pi^0 \pi^0$

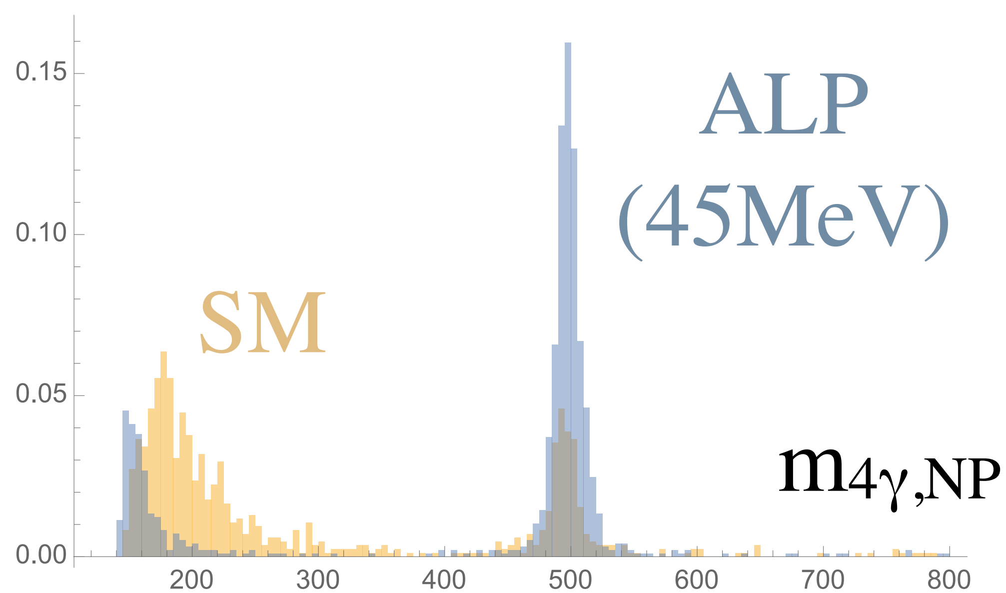
arbitrary normalization

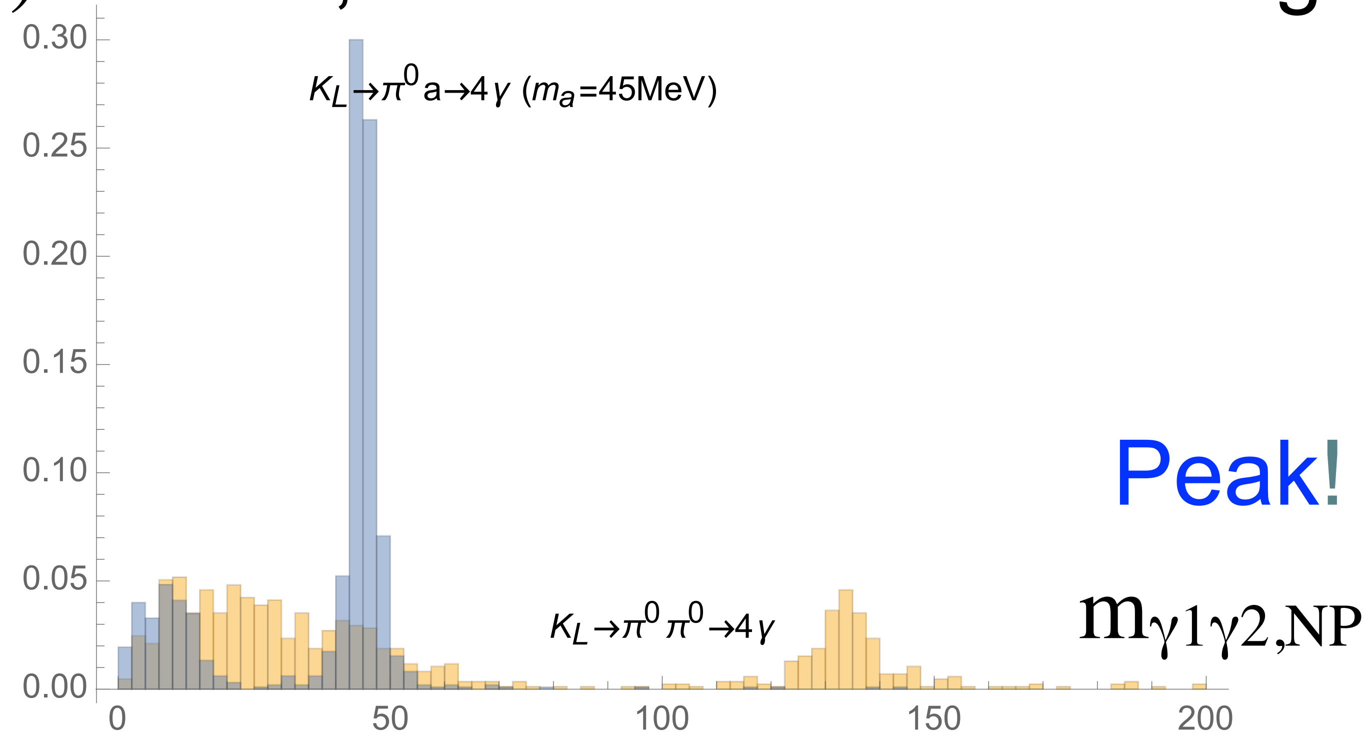




Reconstruction for NP: assume $K_L \to \pi^0 a$

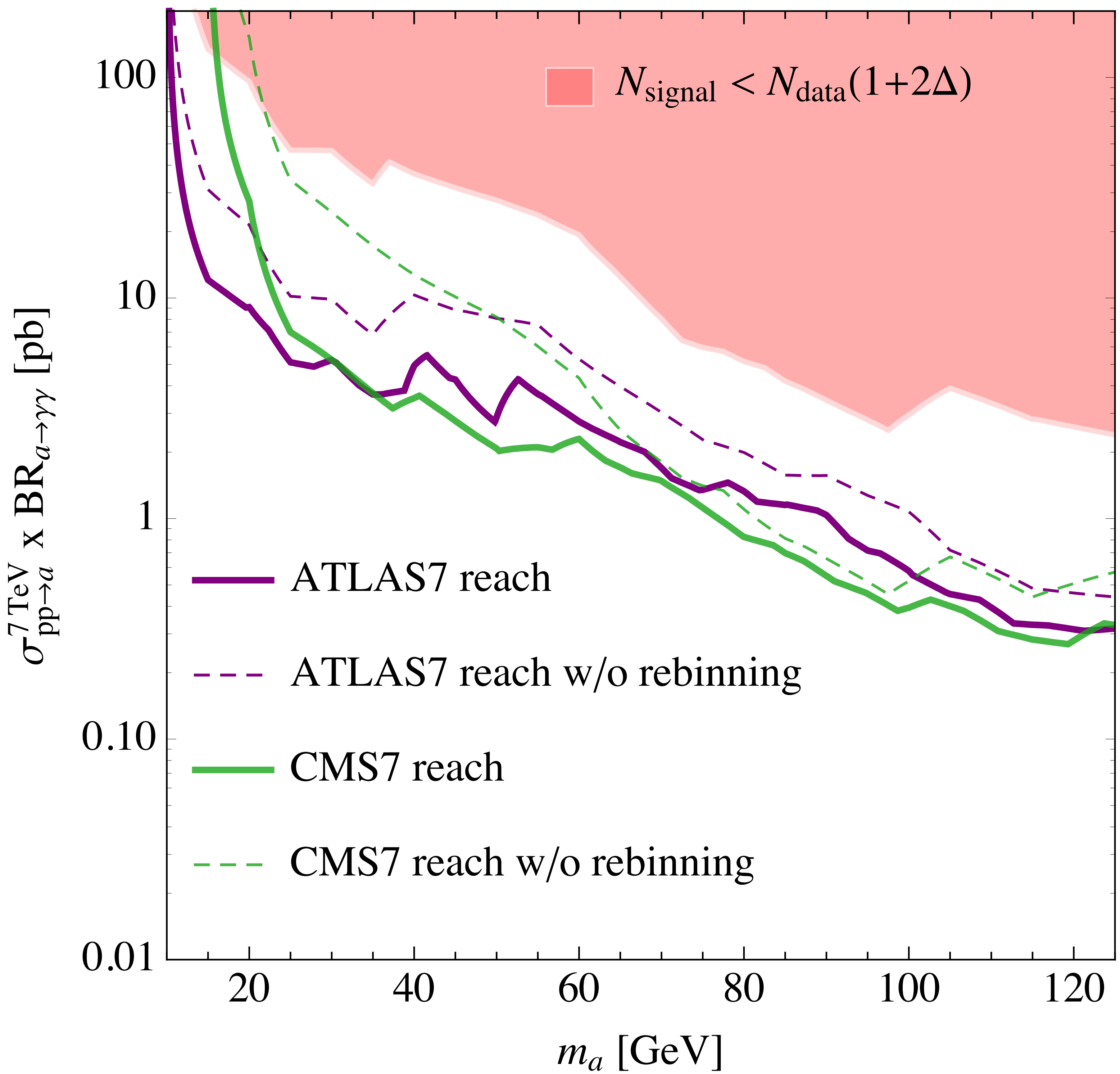
- jet distance: $E_i E_j \Delta r_{ij}^2$ ~mass^2, a→closest 2photons (1,2)
- the other two photons (3,4) from π^0, reconstruct vtx assuming m_π





Bound/sensitivity on cross section

7TeV



ATLAS7 down to 10GeV