# Axion-like-particle at LHC and Kaon factories

*FP Capri 2018, June 9*

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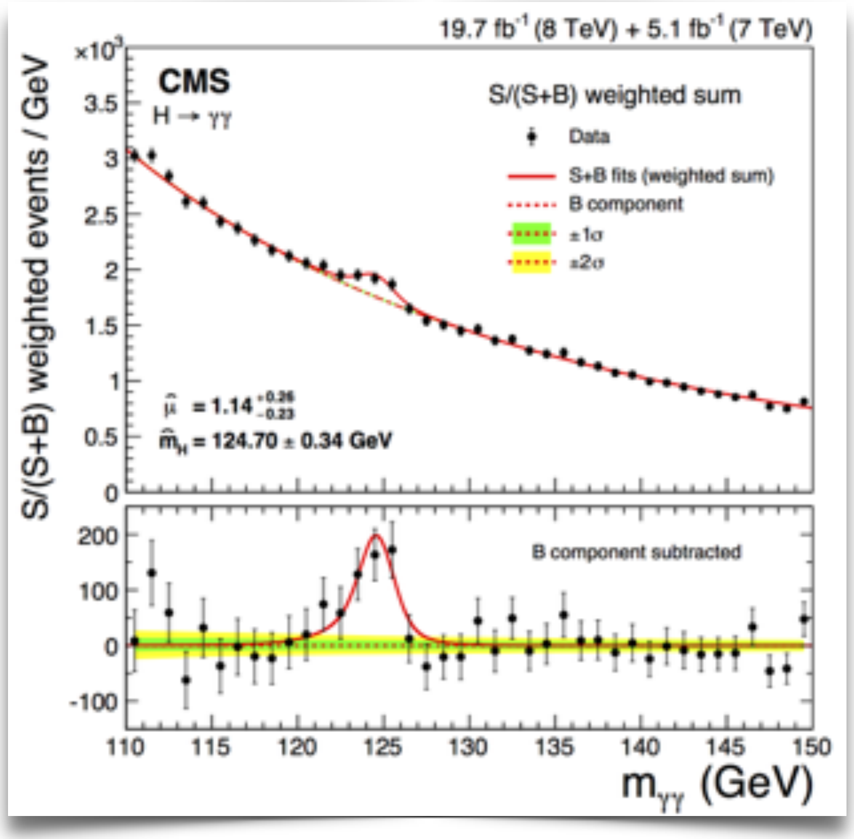
based on
1710.01743 and preliminary works
with Alberto Mariotti, Diego Redigolo, Filippo Sala +Matt Low
Stefania Gori, Gilad Perez

# Resonance Searches

Resonance search: strong discovery method at collider

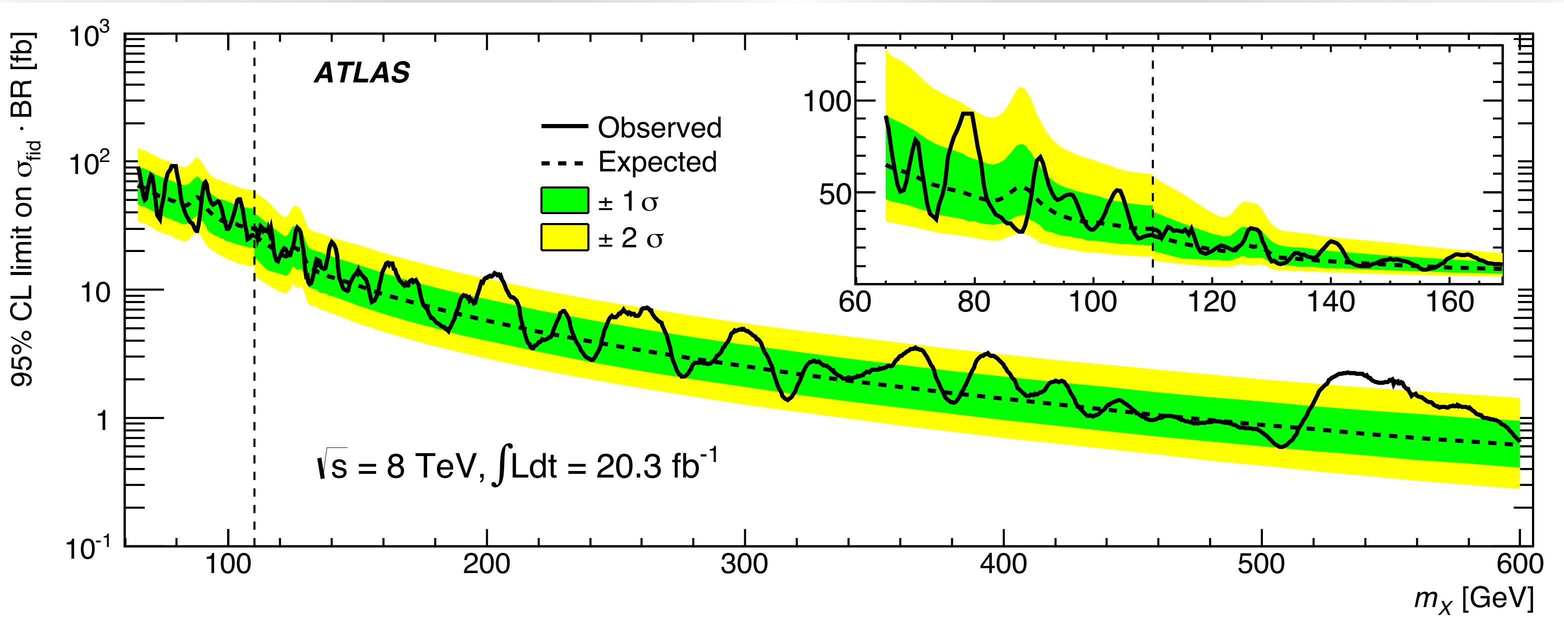
Dilepton　Diphoton　Dijet

4lepton　Diboson(Z/W) etc.




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

Typically prove beyond 100GeV



# Resonance Searches

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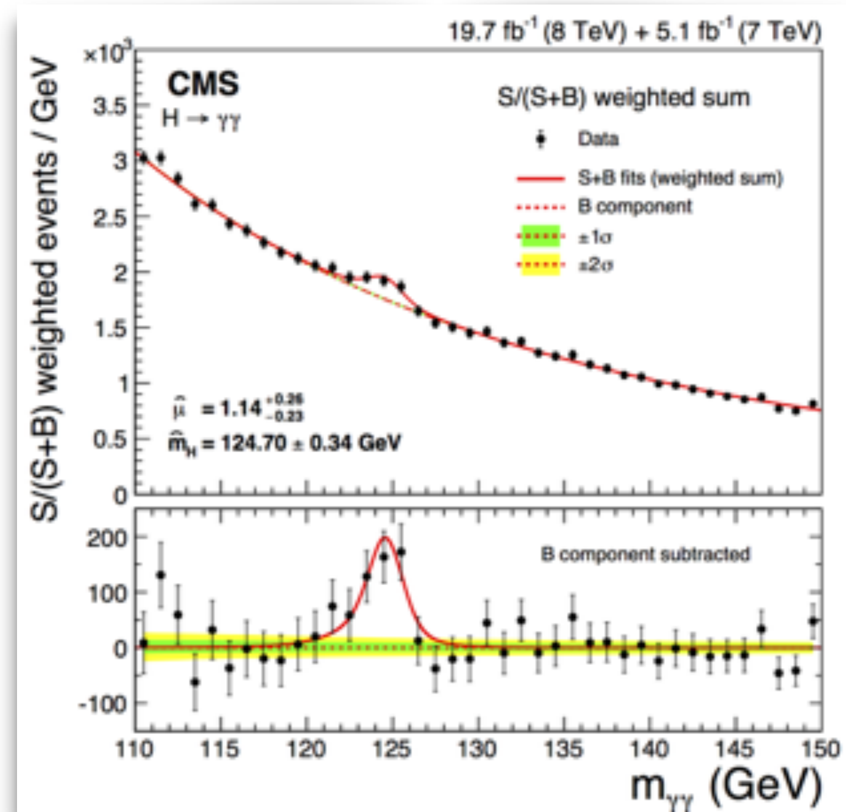


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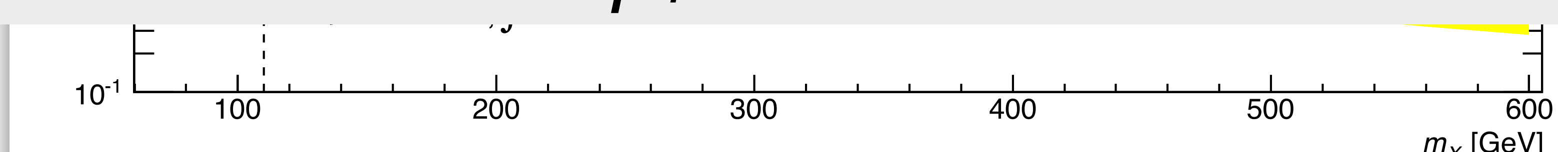
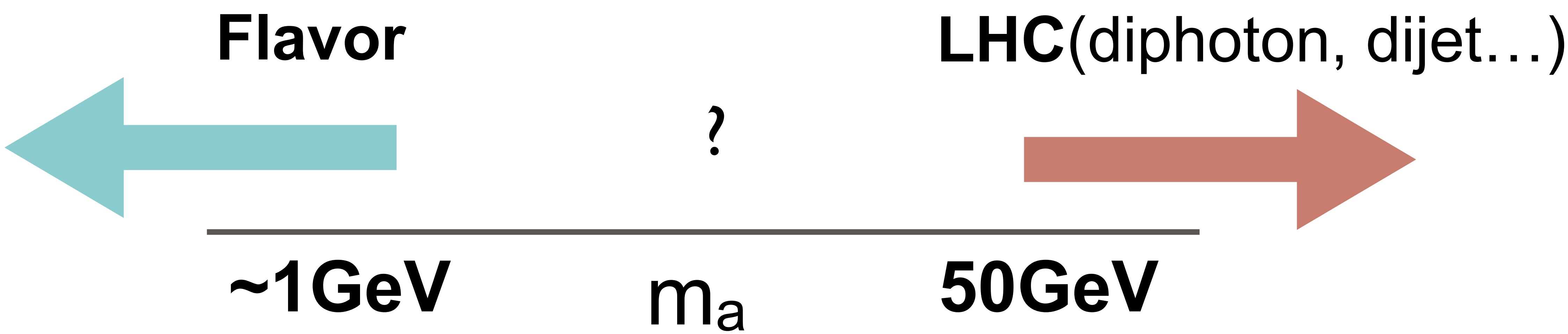



1. *Theoretical bias/motivation to high mass (W', Z', Heavy higgs..)*
2. *Common belief, low mass resonance is constrained by previous colliders or precision measurements*
3. *For LHC, low mass is difficult due to $p_T$ cuts*

# Resonance Searches

However, poorly constrained mass range exists




*This talk*

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

[talk by F.Sala in MITP program]

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. $\pi$

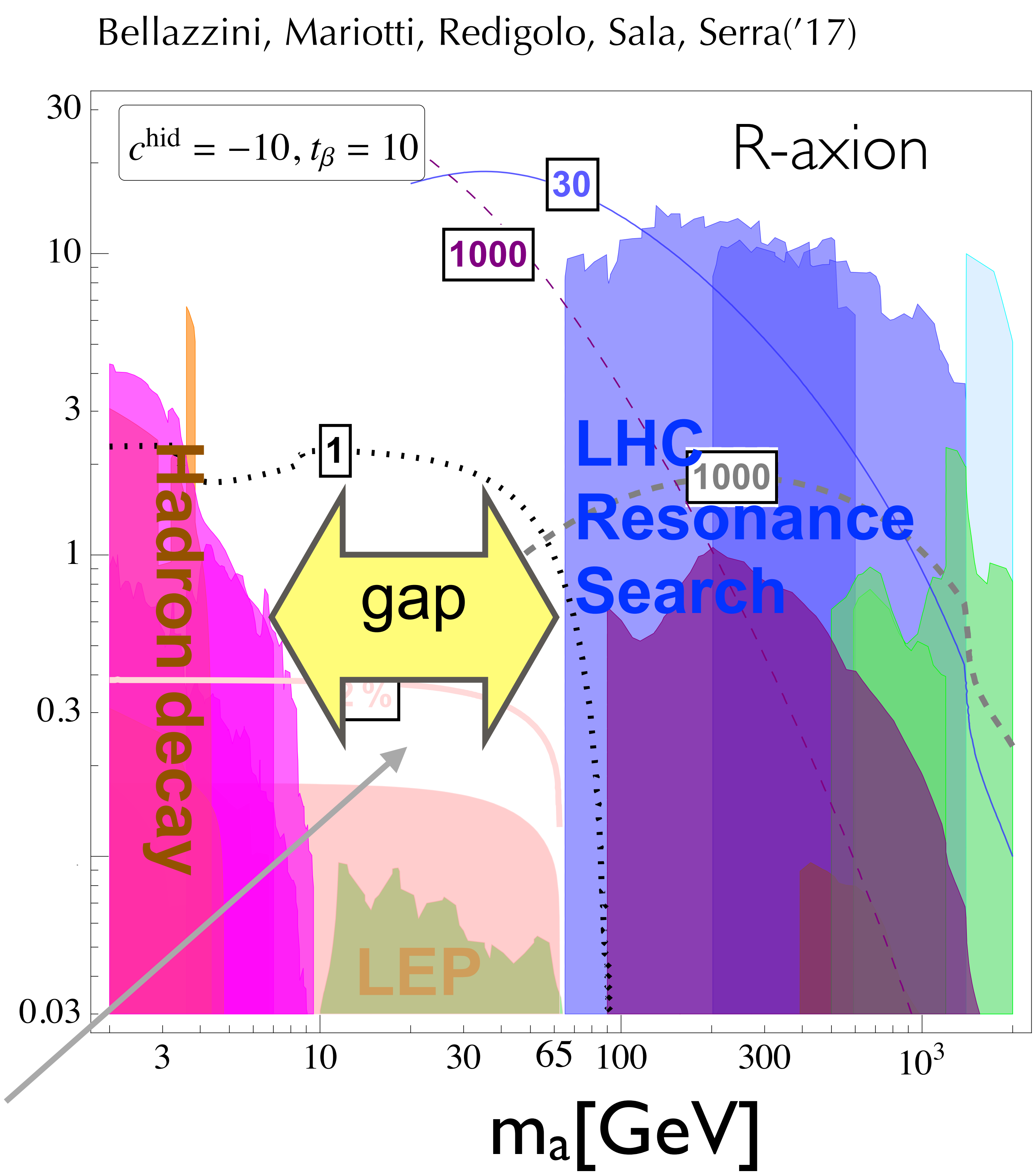
Focus: **Axion-like-particles**(ALPs) e.g.

- 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




$10^5$pb @LHC
still allowed
$\Rightarrow$**$10^9$ events**

# ALP Effective Lagrangian

Consider only anomaly (WZW) terms

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

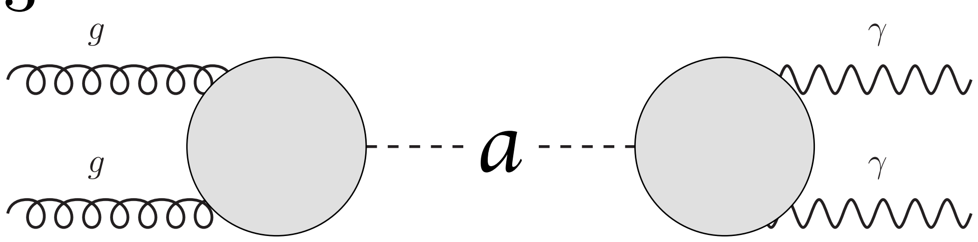
$\alpha_1 = 5/3\alpha'$

Broad class of models

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

irreducible contributions from loops of gluinos, tops

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




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

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

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

# ALP Effective Lagrangian

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## Broad class of models

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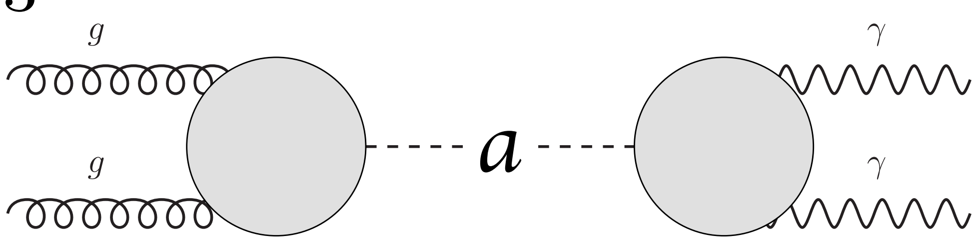


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many previous studies for ALPs:

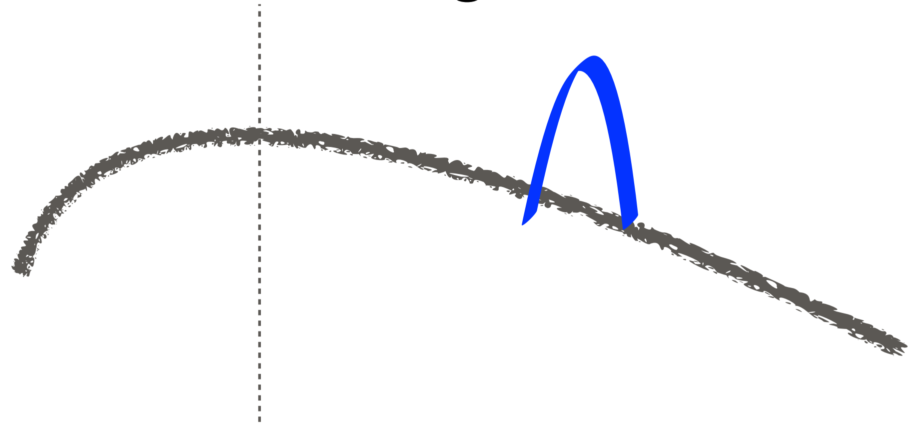
Photonphilic ALP: LEP[Jaeckel, Spannowsky('15)] Heavy-ion[Knapen et al('16)]
Sub 10GeV, ALP-W int. induces FCNC(B->Ka) [Izaguirre, Lin, Shuve('16)],
Higgs decay [Bauer, Tamm, Neubert ('17)] etc.

# Existing constraints &New LHC bound

# Existing constraints for diphoton/dijet

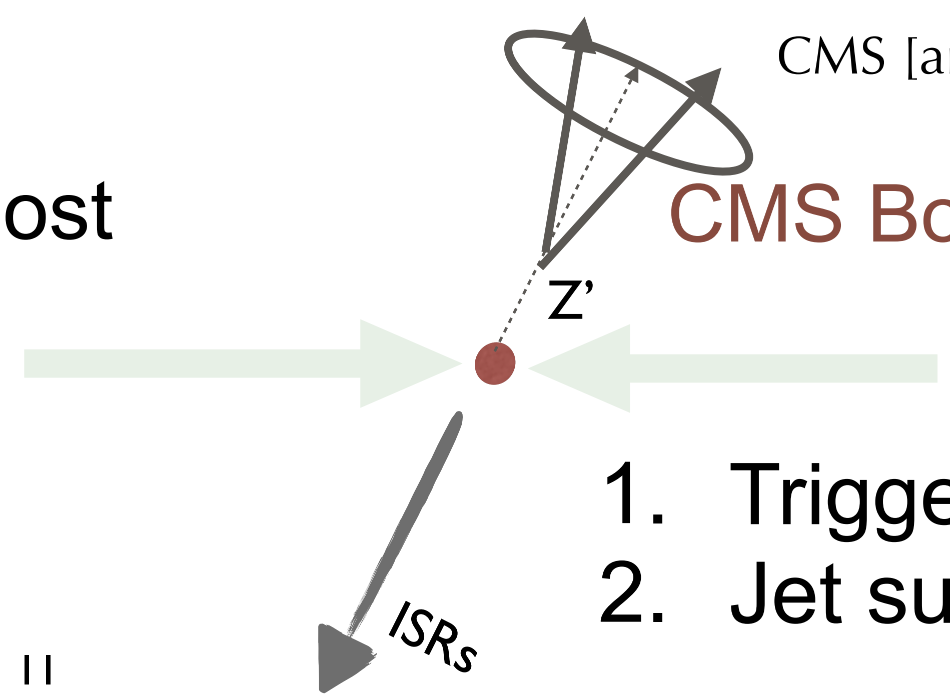
| Experiment | Process | Lumi | $\sqrt{s}$ | low mass reach | ref. |
|---|---|---|---|---|---|
| LEPI | $e^+e^- \to Z \to \gamma a \to \gamma jj$ | 12 $\mathrm{pb}^{-1}$ | Z-pole | 10 GeV | [29] |
| LEPI | $e^+e^- \to Z \to \gamma a \to \gamma\gamma\gamma$ | 78 $\mathrm{pb}^{-1}$ | Z-pole | 3 GeV | [30]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

Below lowest mass,
smooth background structure is lost



CMS [arXiv:1710.00159]

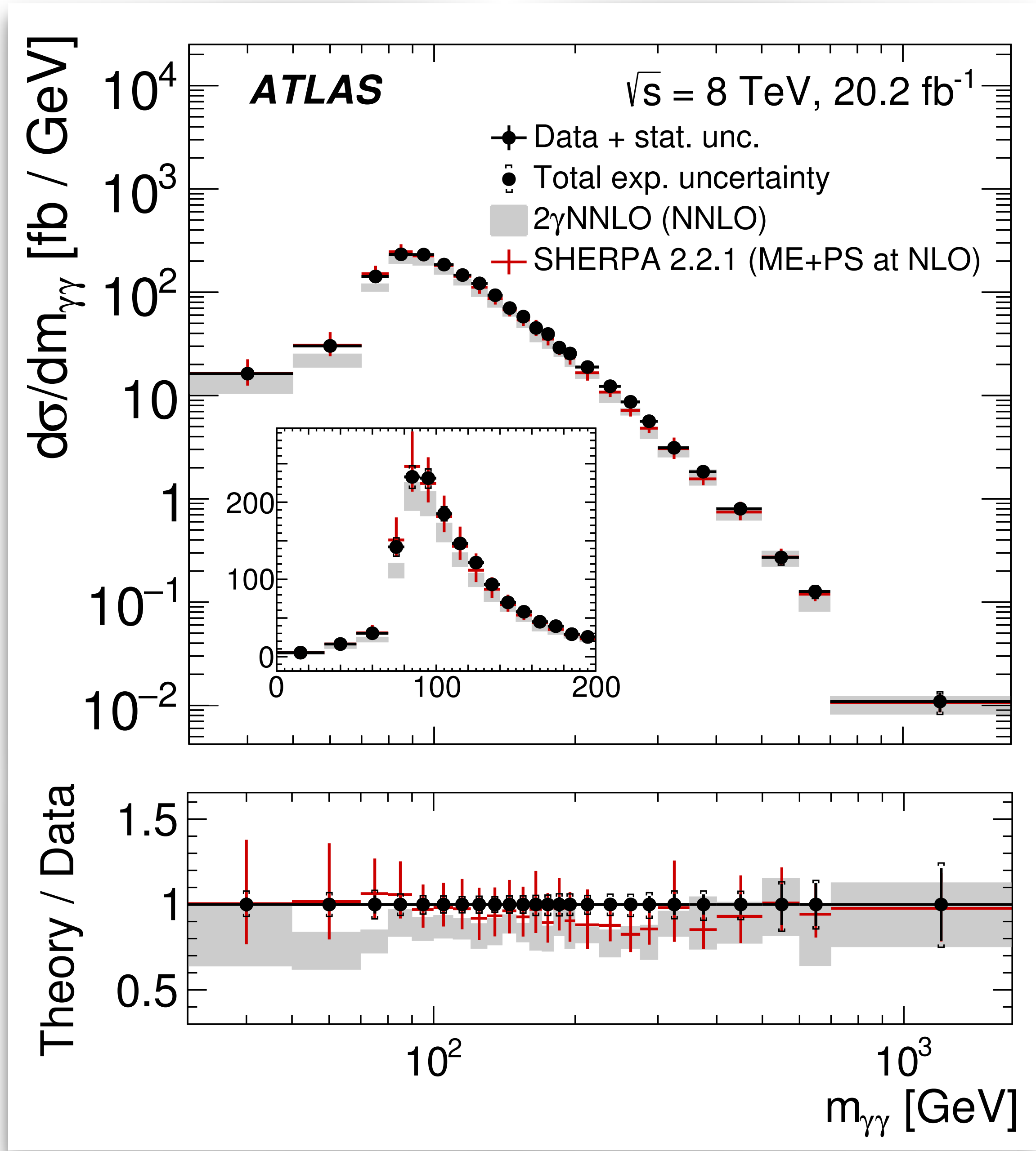
CMS Boosted dijet



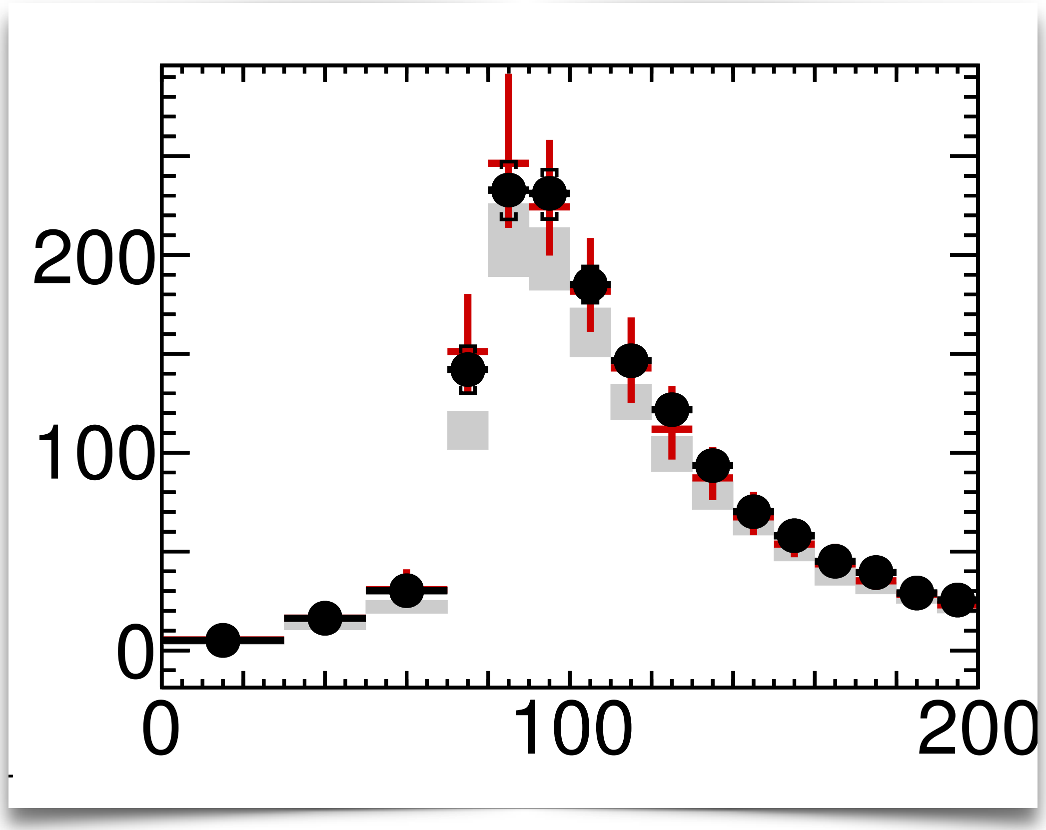

1. Trigger ISR
2. Jet substructure

# Diphoton x-section measurements

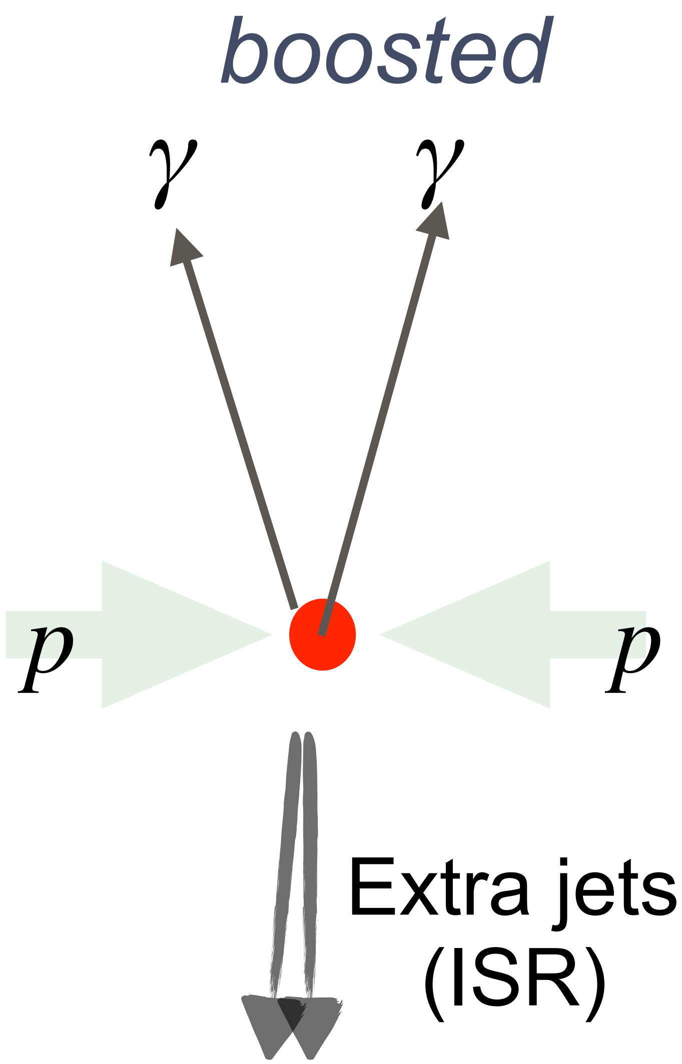
| | | | | | |
|---|---|---|---|---|---|
| D0 ($\sigma_{\gamma\gamma}$) | $p\bar{p} \to a \to \gamma\gamma$ | 4.2 $\mathrm{fb}^{-1}$ | 1.96 TeV | $p_{T_1,T_2} > 21, 20$ GeV | $m_a$> 8.2GeV |
| CDF ($\sigma_{\gamma\gamma}$) | $p\bar{p} \to a \to \gamma\gamma$ | 5.36 $\mathrm{fb}^{-1}$ | 1.96 TeV | $p_{T_1,T_2}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



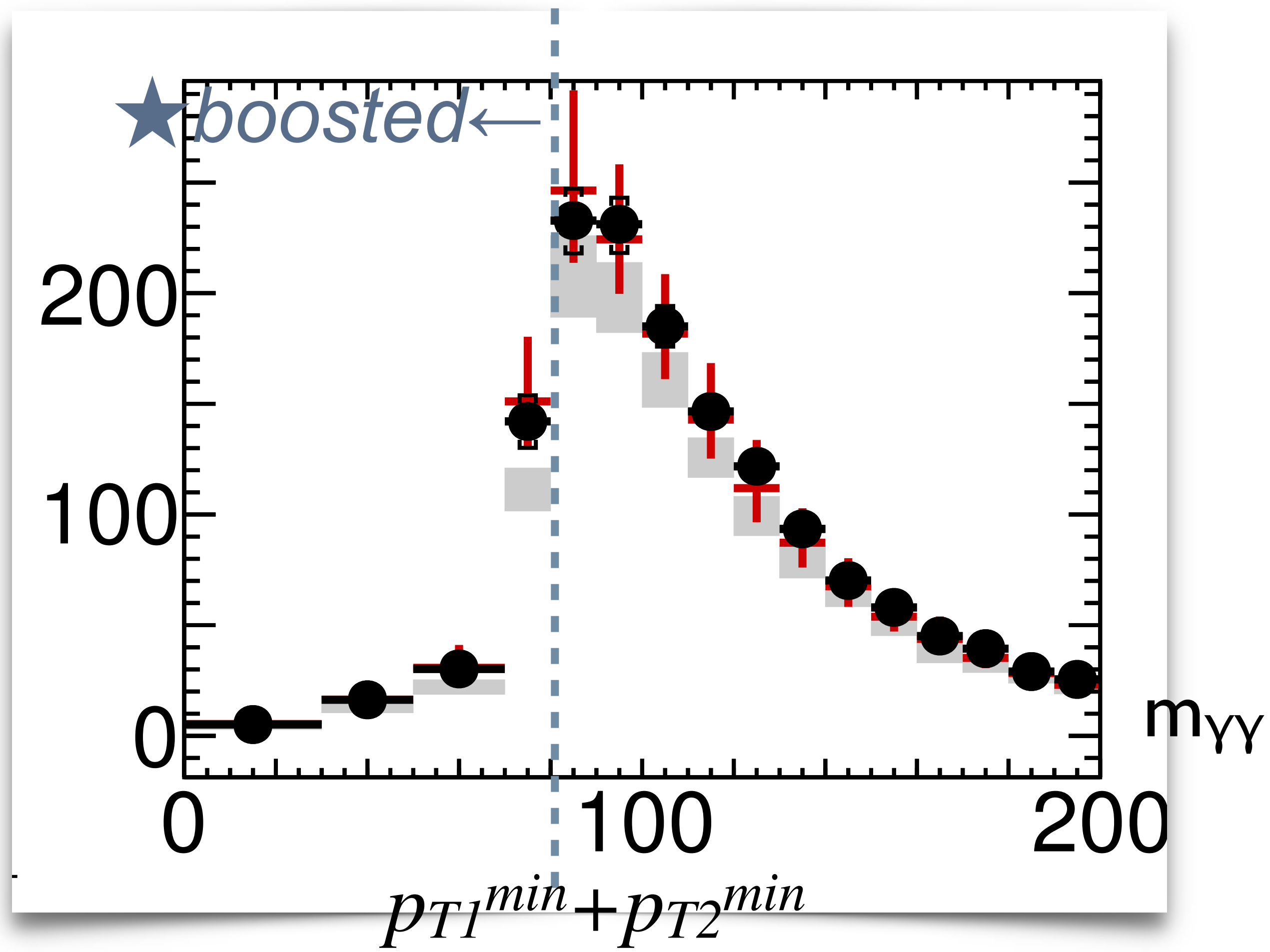

report lower mass

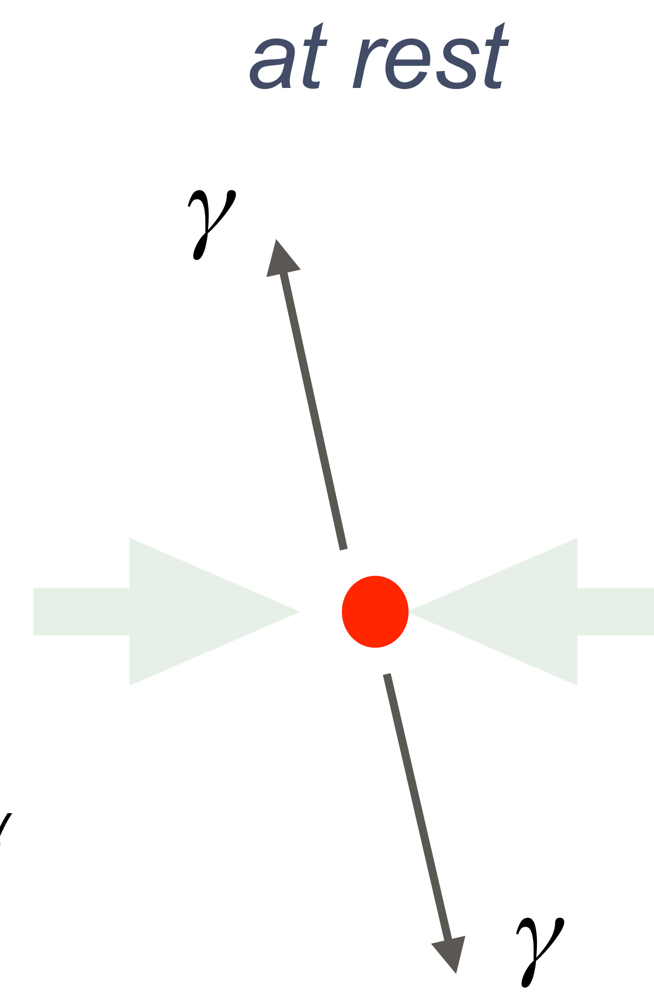


# Diphoton x-section measurements




$p_{T1,2}$>40, 30GeV




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

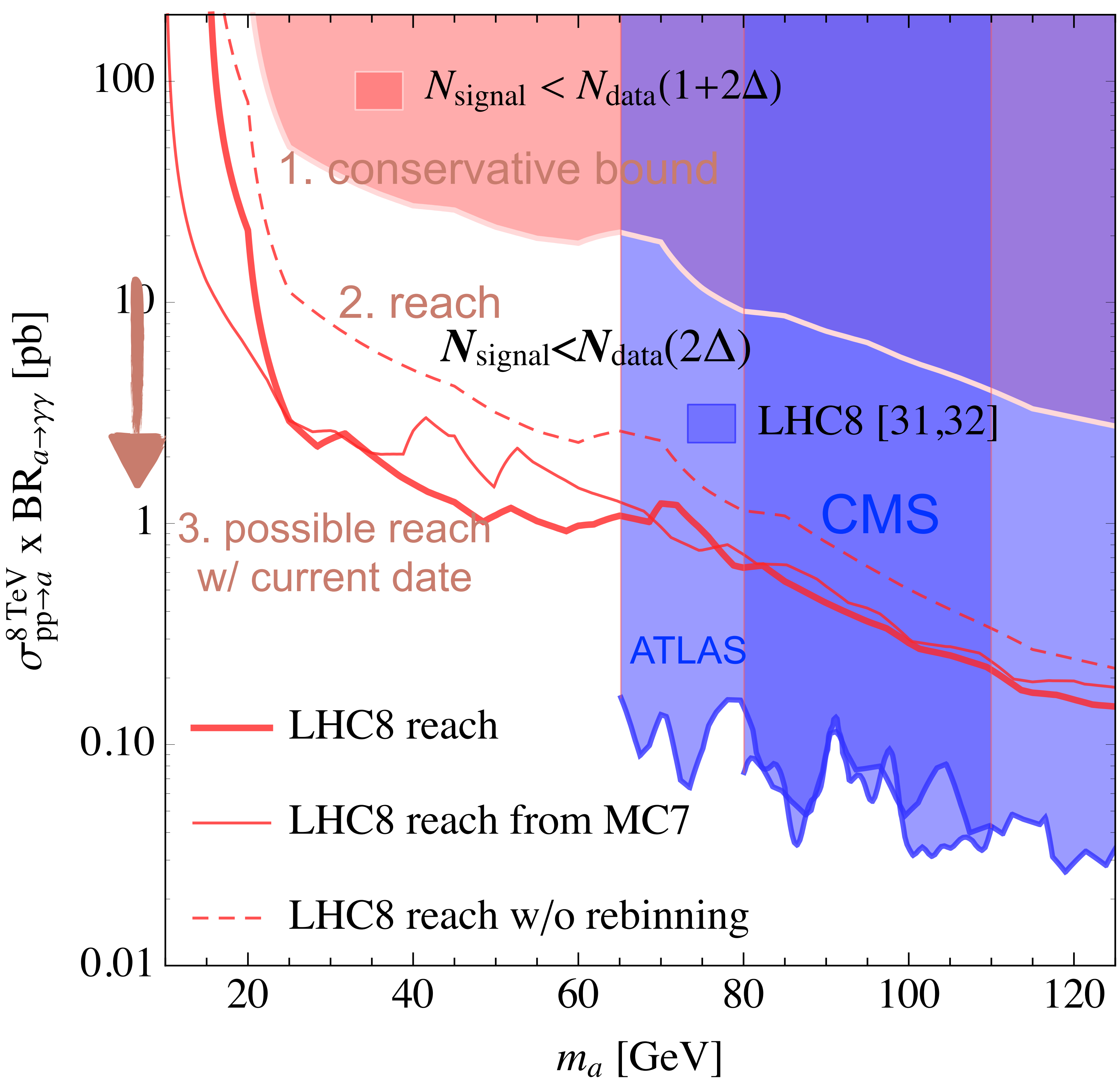
diphoton angular separation

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

| $m_a$ in GeV | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 | 110 | 120 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\epsilon_S$ 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 |

# Bound/sensitivity on cross section

8TeV



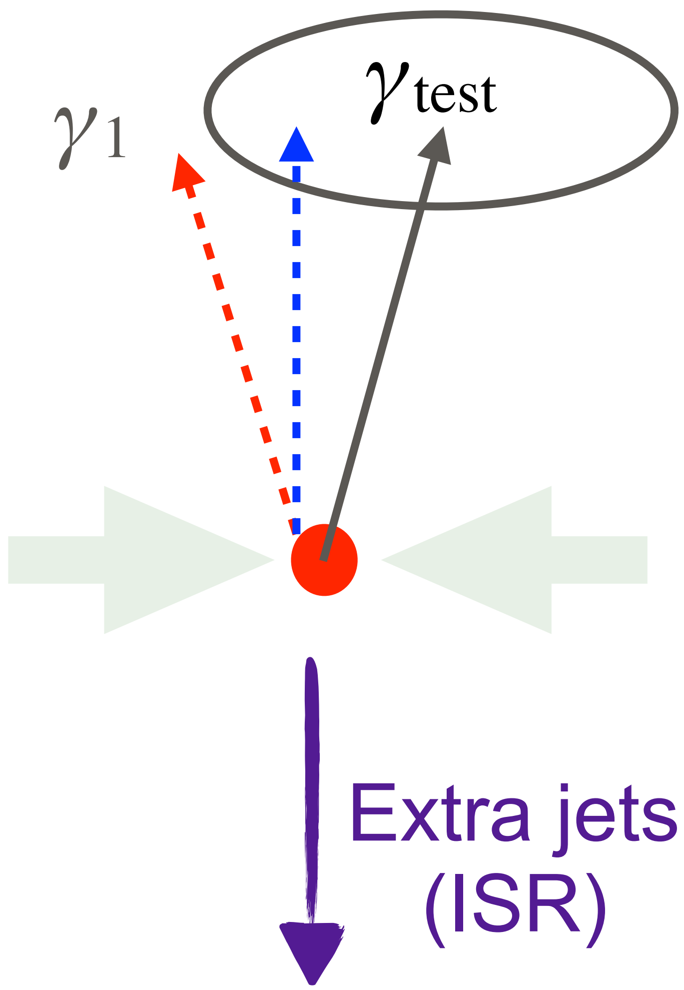
# Possible Improvement

# Strategy with Other Triggers

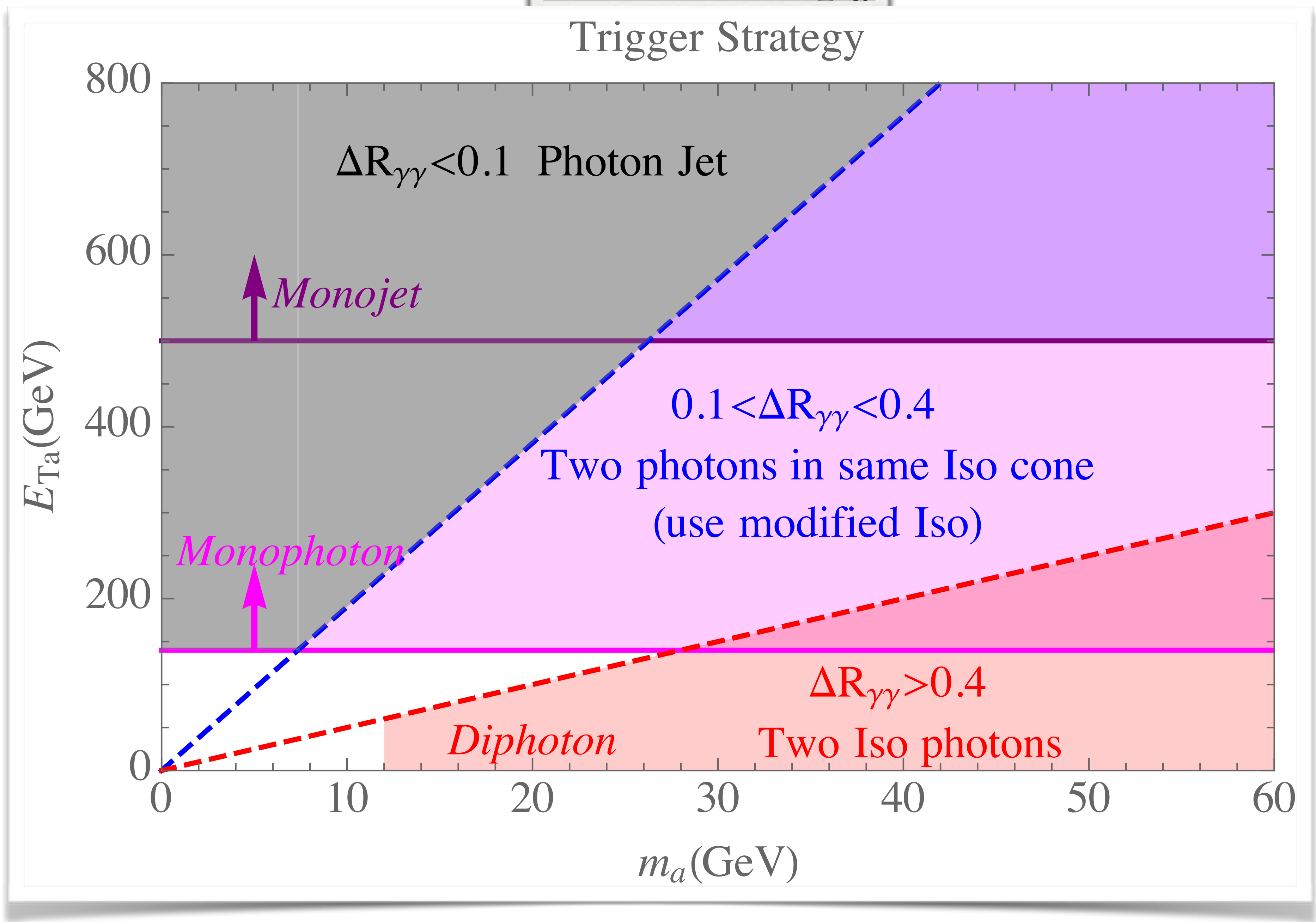
## Isolation to suppress fake BG

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

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




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



# Strategy with Other Triggers

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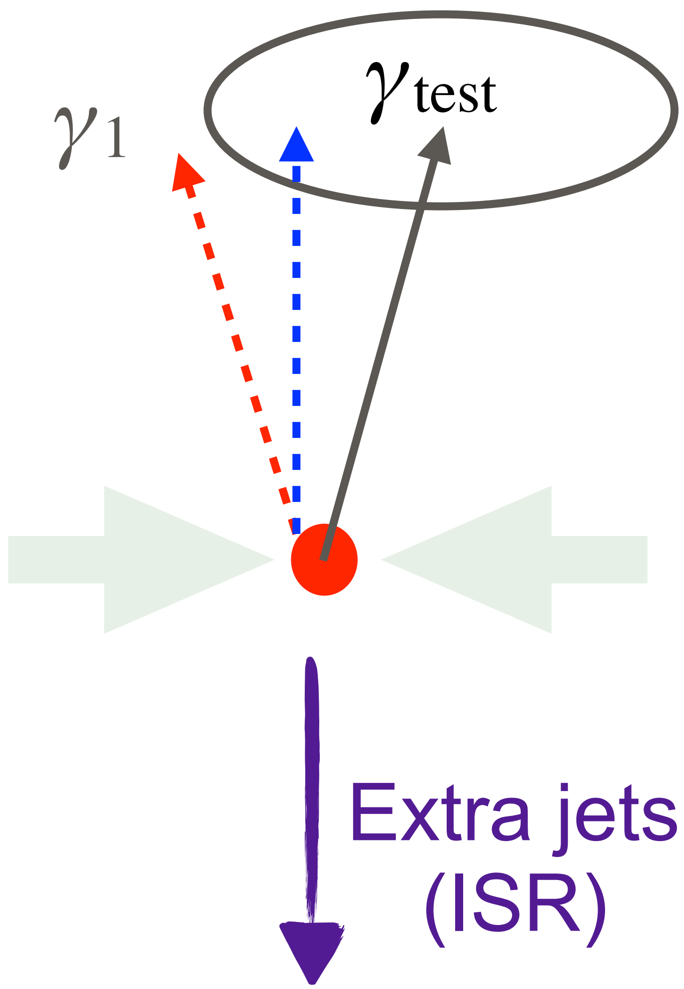
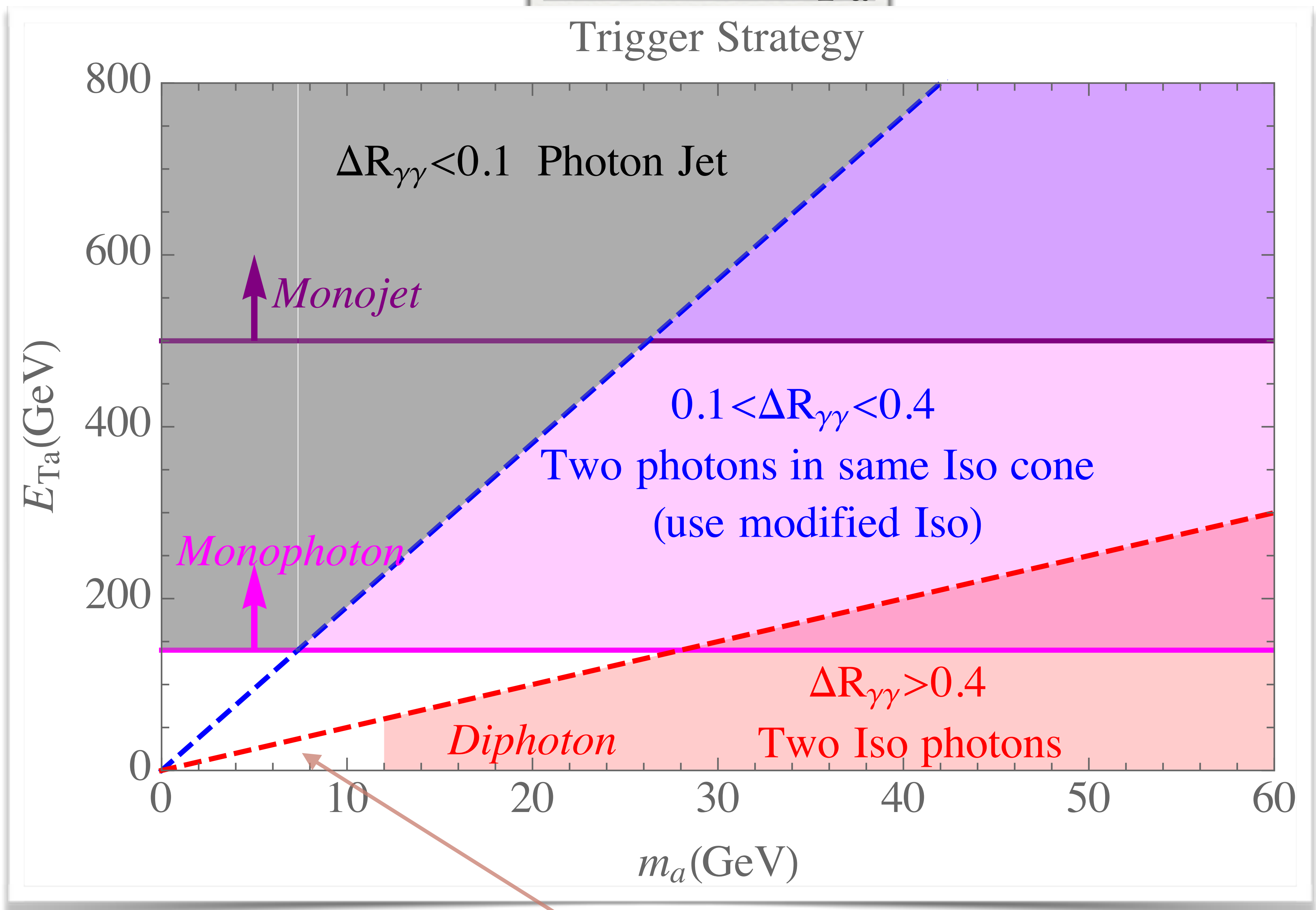



$p_{Tj} \sim E_{Ta},\ p_{T\gamma} \sim E_{Ta}/2$




*Diphoton at LHCb?*

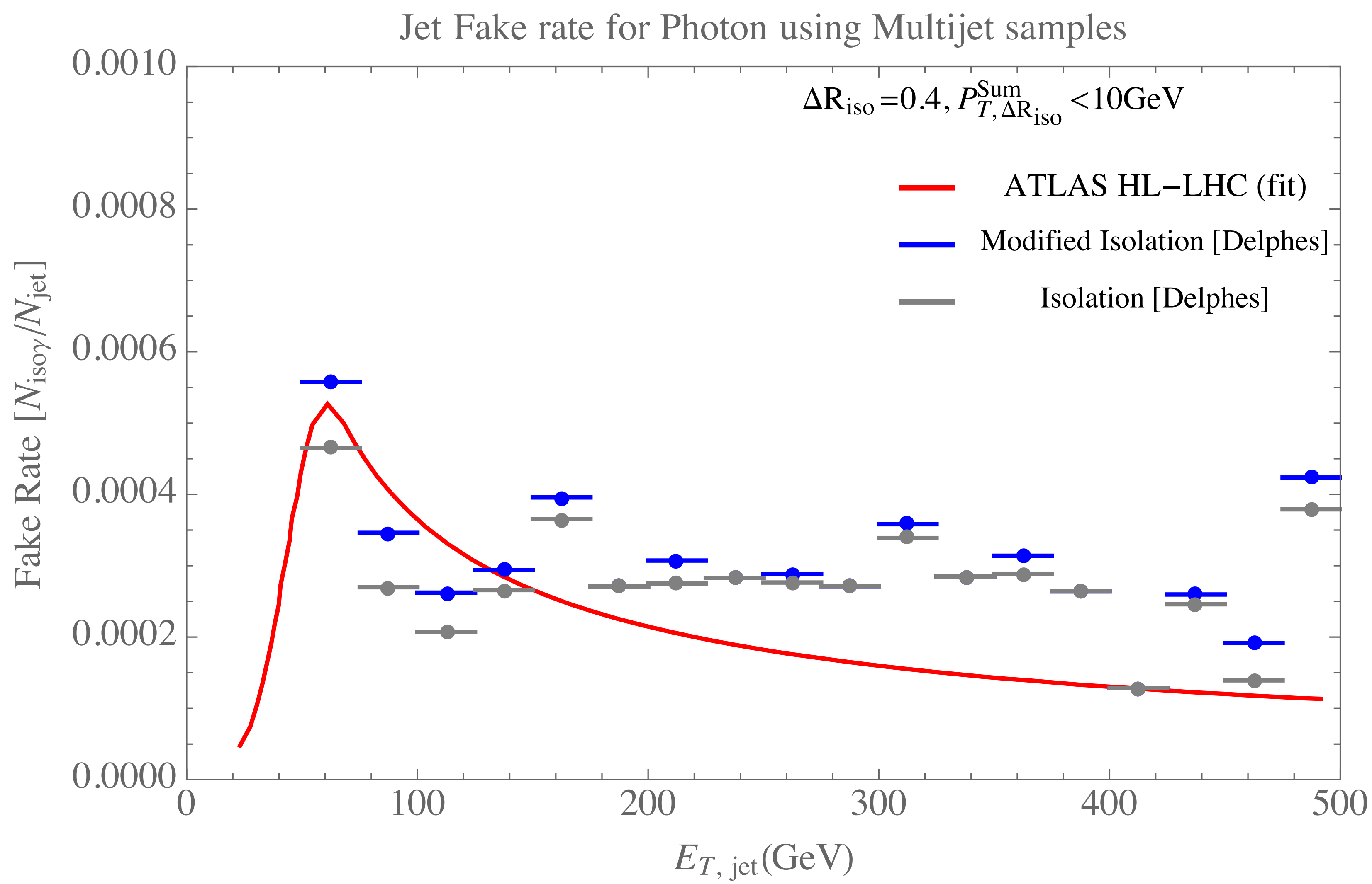
**Modified Isolation:** $E_T^{\rm iso} - E_{T_{\gamma_1}}$

→*ALP with Monojet, Monophoton triggers*

# Strategy with Other Triggers

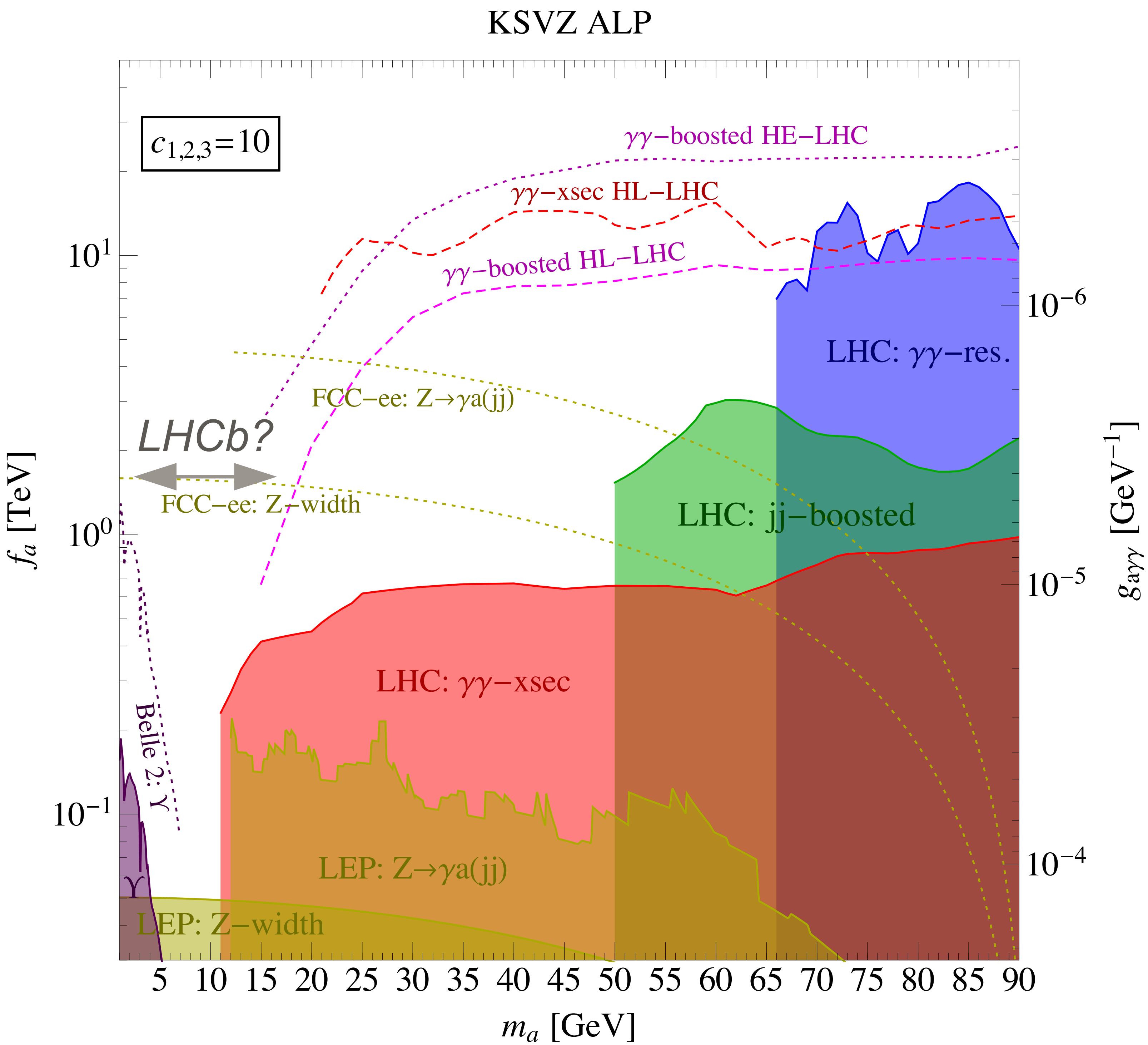
***Modified Isolation*** works equally good to reject BG

Fake rate




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

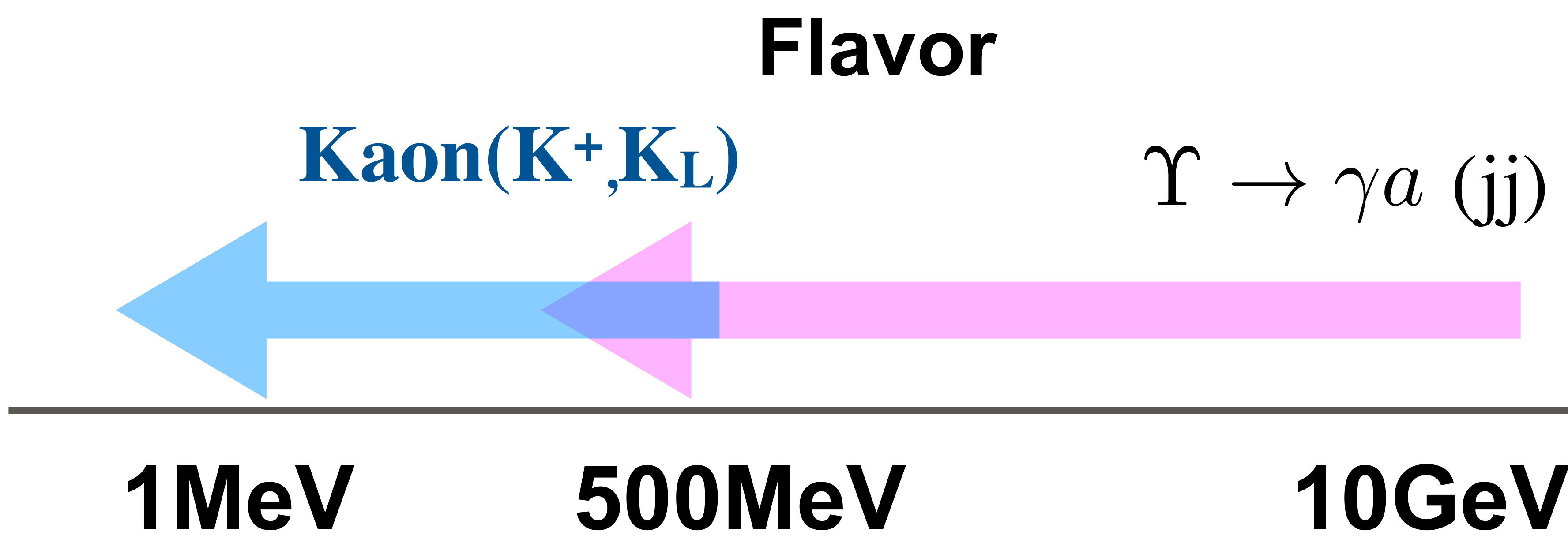
# LHC bound +Projections

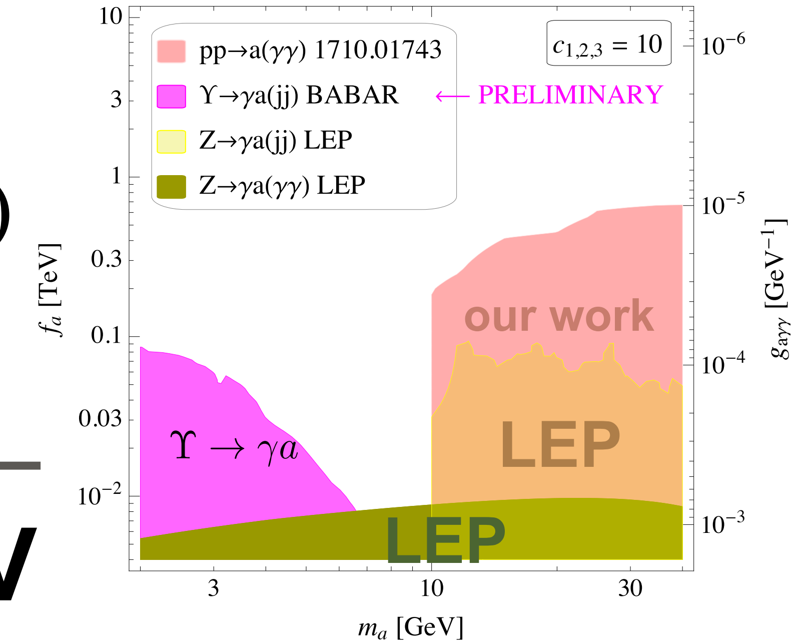


# ALP
# at Kaon Factory

Preliminary work with Gilad Perez, Stefania Gori

# Resonance Searches

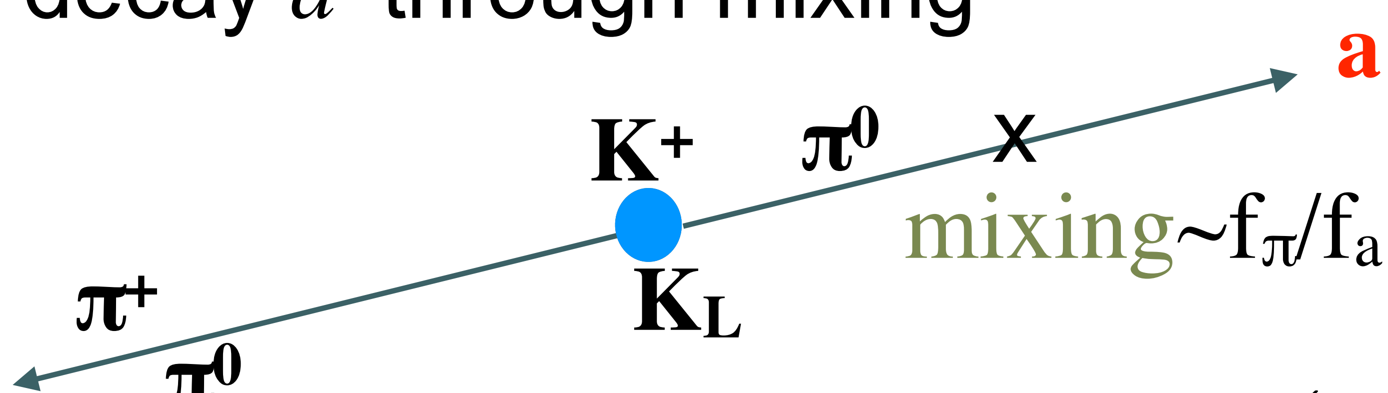



$m_a$

$(a/f_a)G\tilde{G}$ coupling generates $a$-π mixing

Kaon decay $a$ through mixing



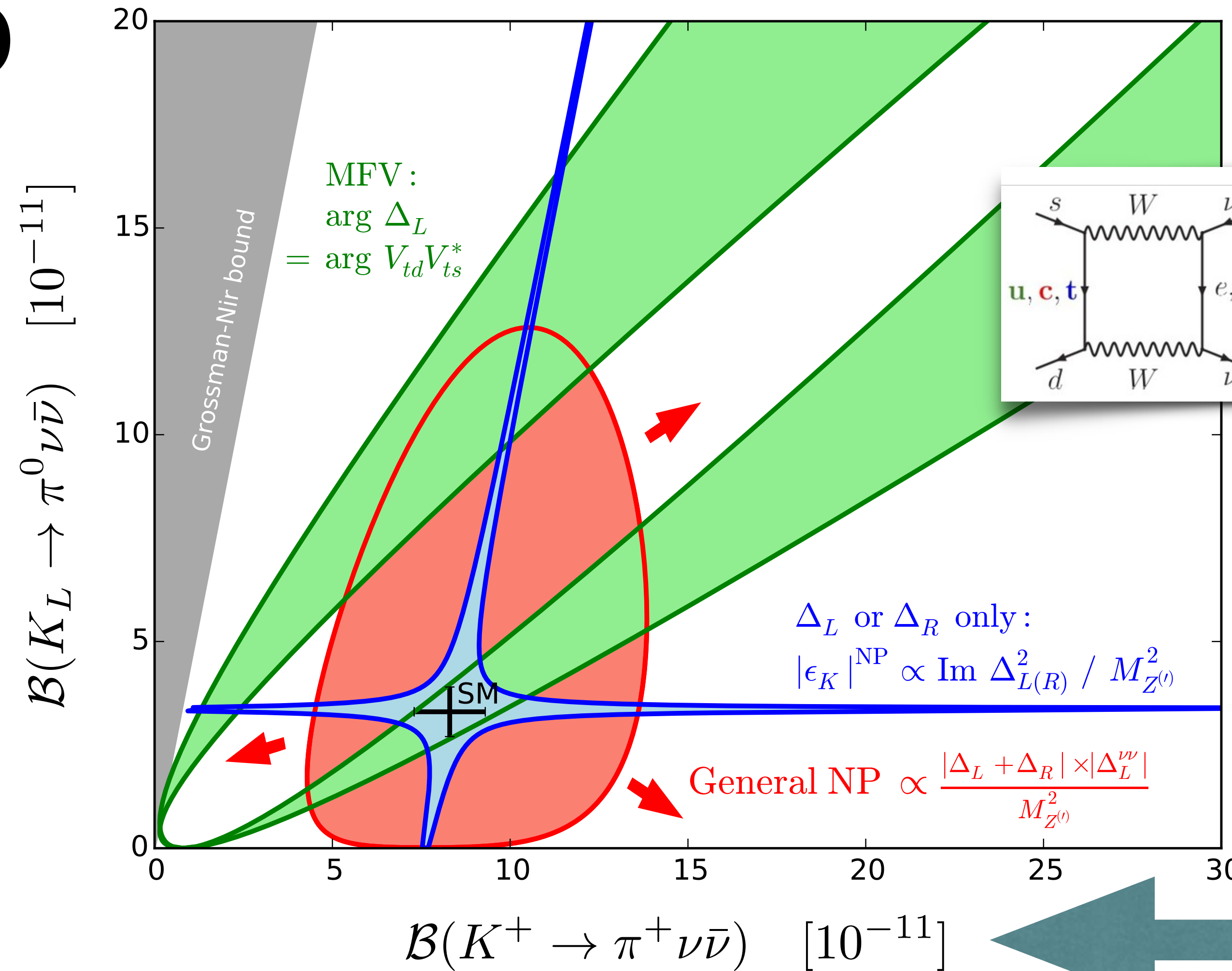

$$\mathrm{Br}(K \to \pi a) \simeq \left(\frac{f_\pi}{f_a}\right)^2 \mathrm{Br}(K \to \pi\pi)$$

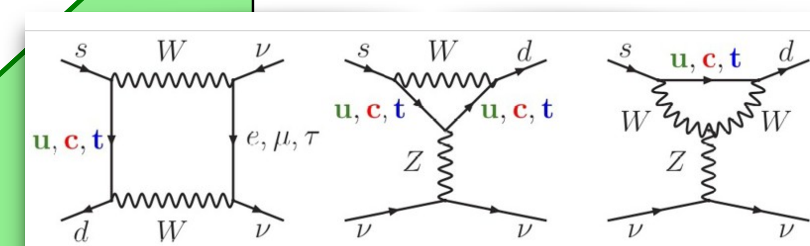
# Two Active Kaon factories

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**



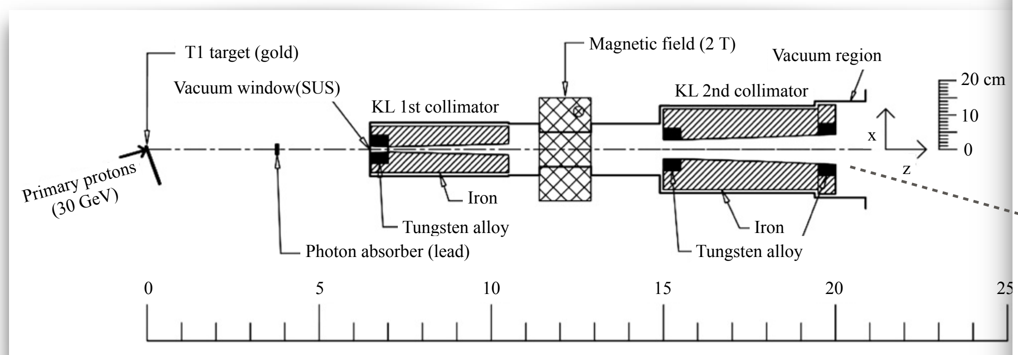

Buras et al(‘15)

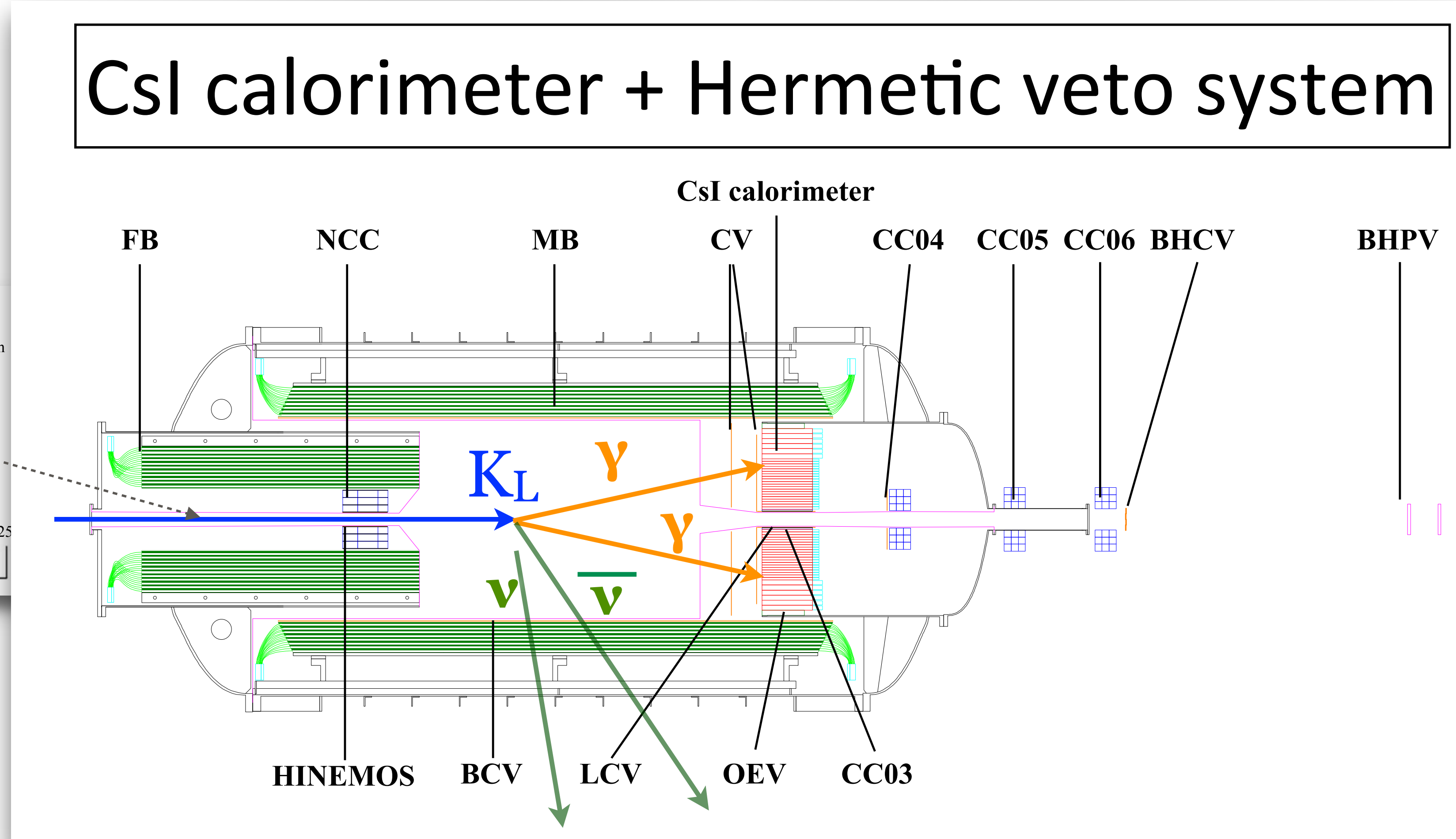
**NA62**

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

| | KOTO | NA62 |
|---|---|---|
| Main Target | $K_L \rightarrow \pi^0(\gamma\gamma)\nu\nu$ | $K^+ \rightarrow \pi^+\nu\nu$ |
| BG | $K_L \rightarrow 3\pi, 2\pi$ | $K^+ \rightarrow \pi^+\pi^0$ , $\mu^+\nu$ |
| Signal | **Photon, invisible** | **Charged particle, invisible** |
| 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, $Z'_{\mu\text{-}\tau}$<br>Neutrino Portal |

# Bump hunt at KOTO

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

*assume prompt decay

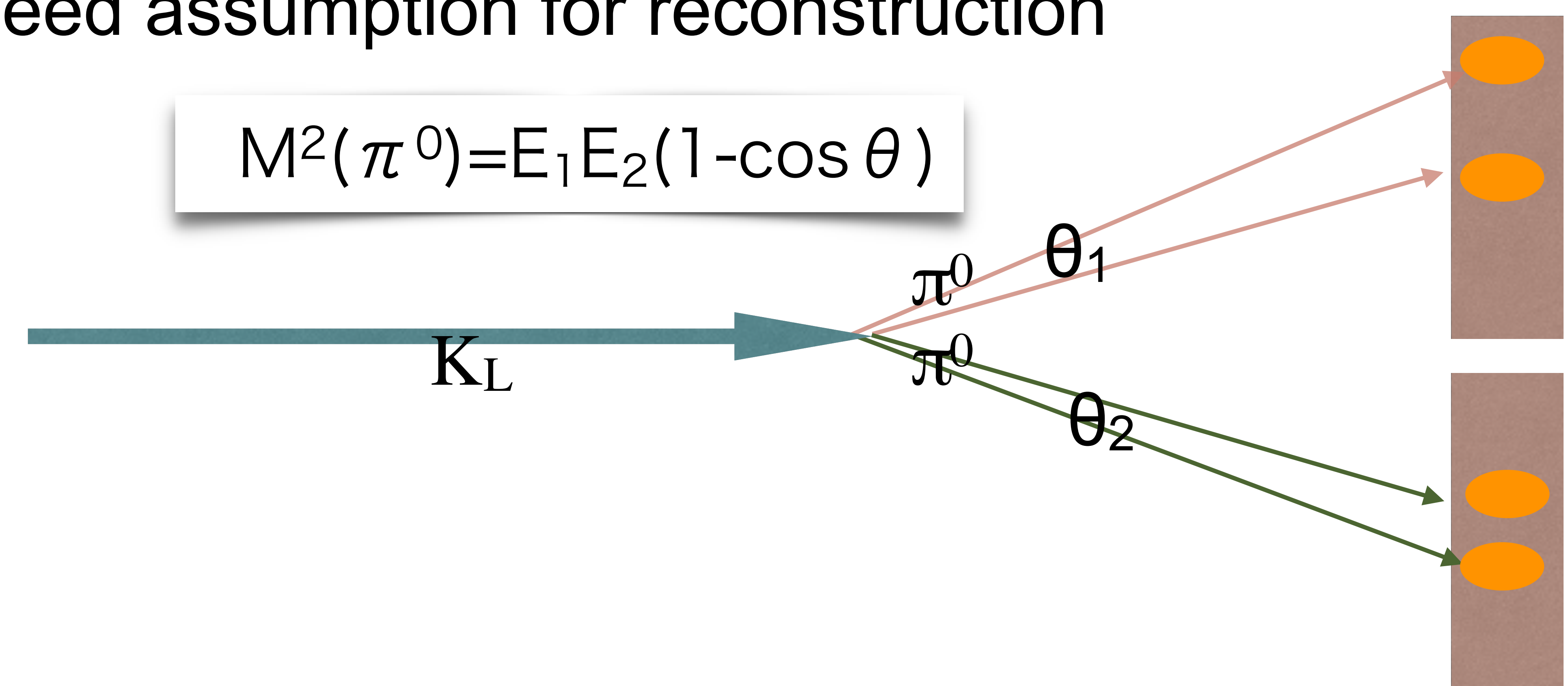
Rate: $$\mathrm{Br}(K \to \pi^0 a) \simeq \left(\frac{f_\pi}{f_a}\right)^2 \mathrm{Br}(K \to \pi^0\pi^0)$$

CPV ~$10^{-3}$

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

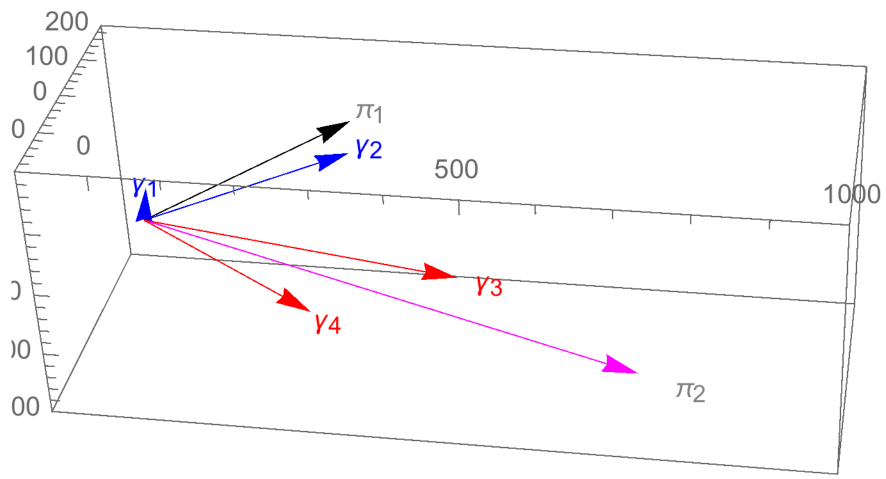
Need assumption for reconstruction

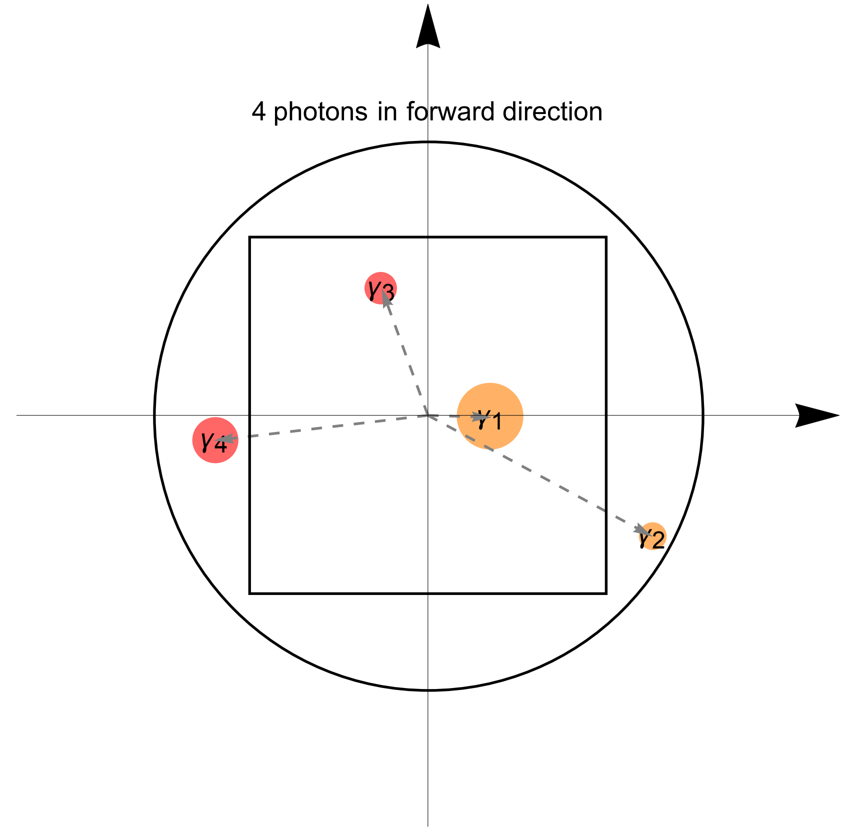
$$M^2(\pi^0) = E_1 E_2 (1 - \cos\theta)$$



# Bump hunt at KOTO

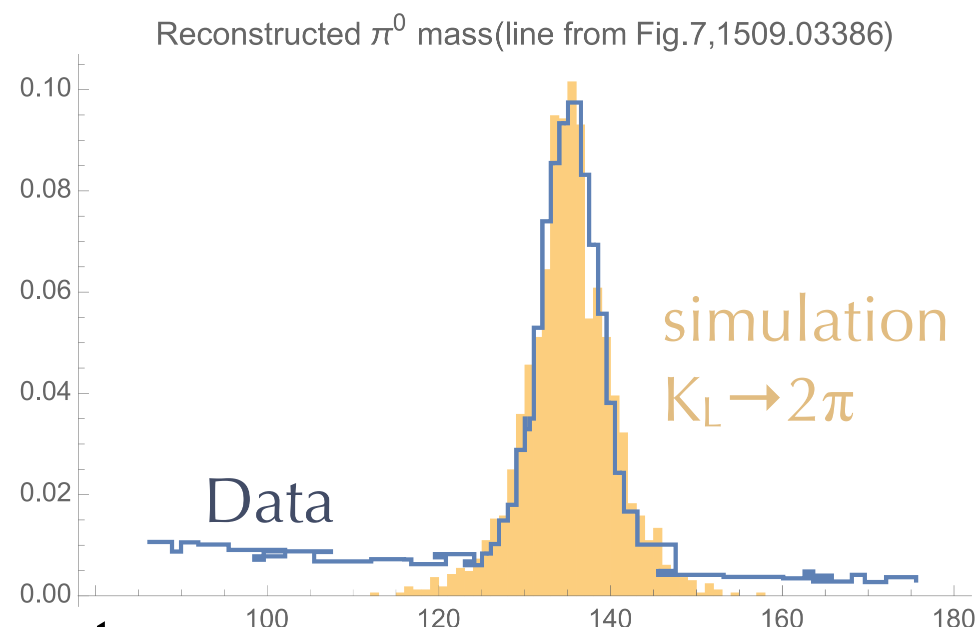
## Setup MC simulation (Evt generation+Detector+Recon.)

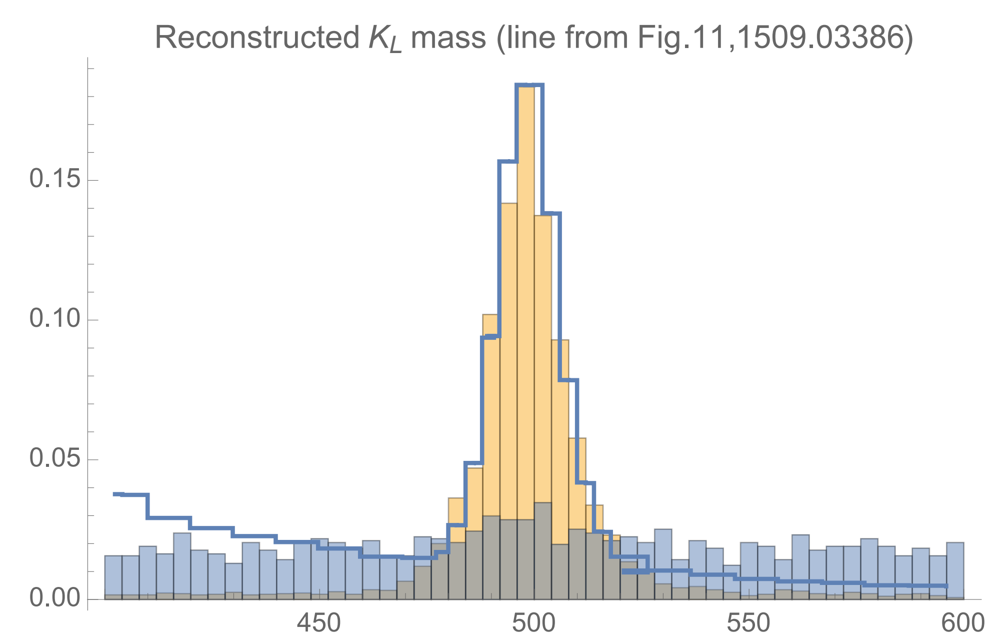



## Validation

arbitrary
normalization



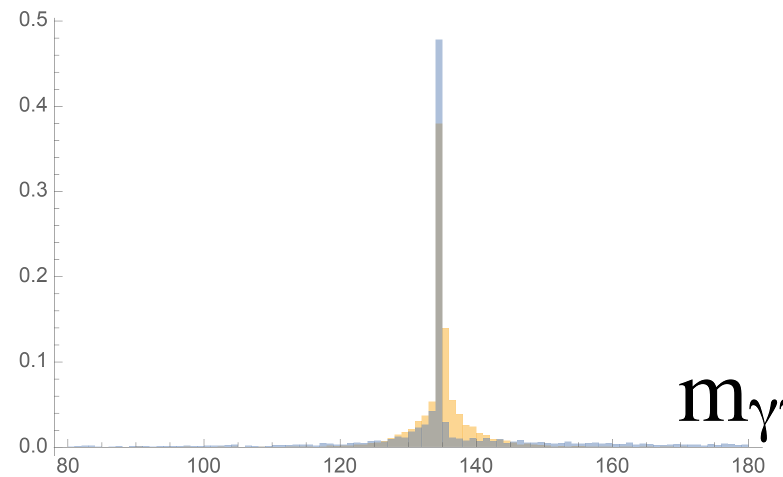

detector

reconstruction

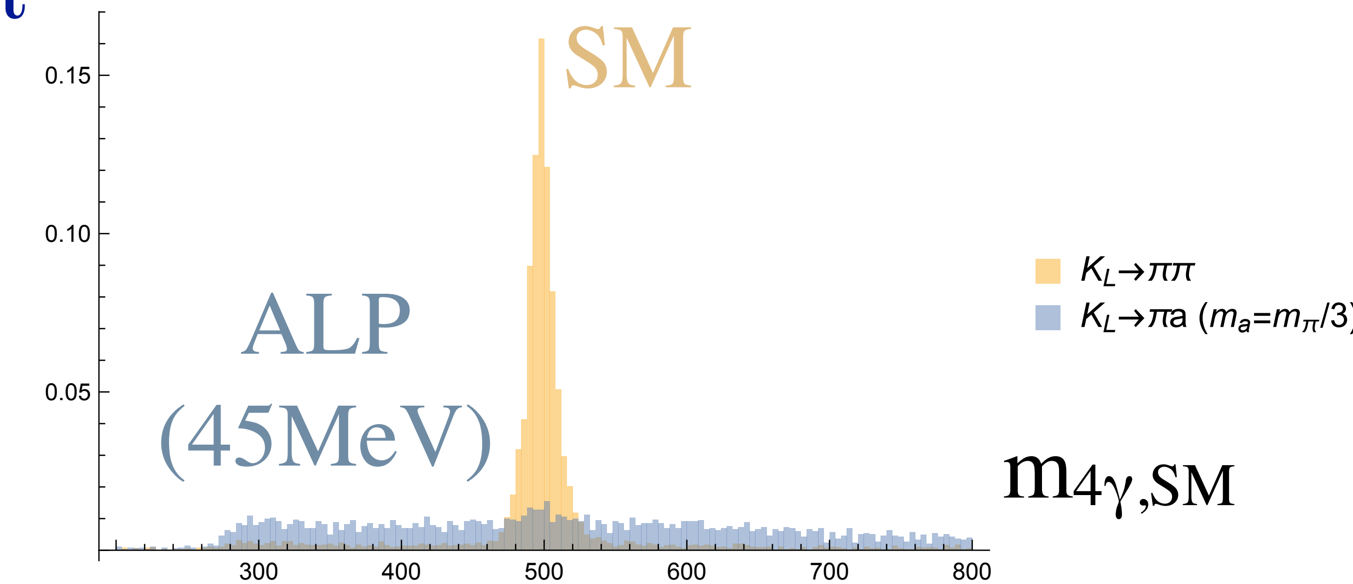
# Bump hunt at KOTO

## Recon SM: assume $K_L \to \pi^0 \pi^0$

arbitrary normalization



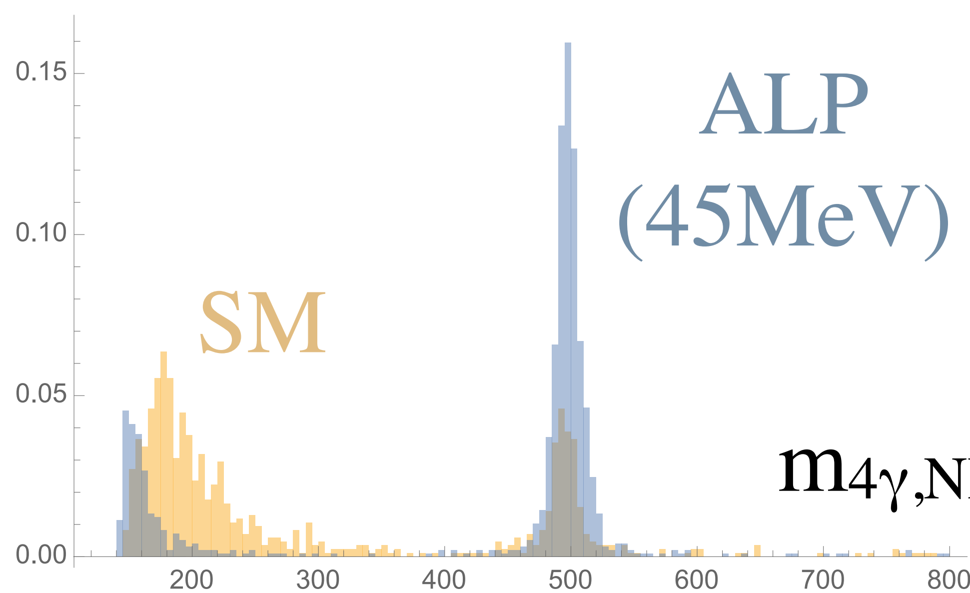

$m_{\gamma\gamma, \mathrm{SM}}$




$m_{4\gamma, \mathrm{SM}}$

## Recon 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 $\pi^0$, reconstruct vtx assuming $m_\pi$



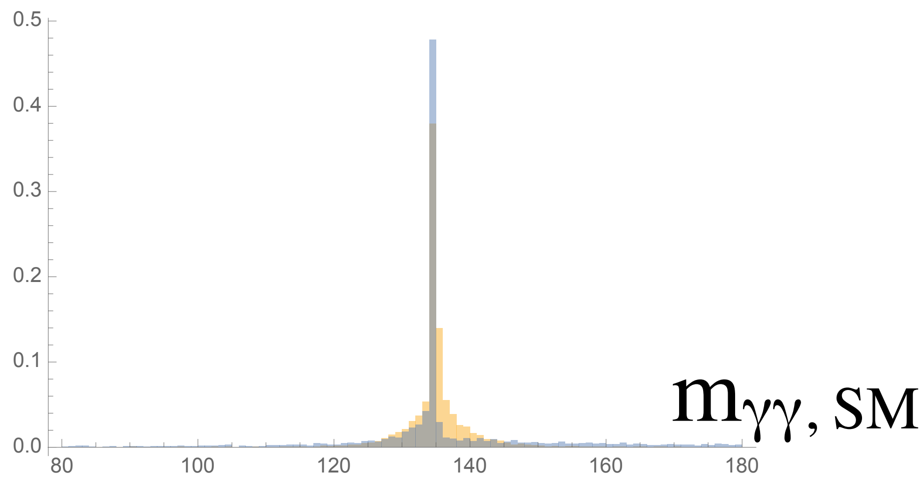

$m_{4\gamma, \mathrm{NP}}$

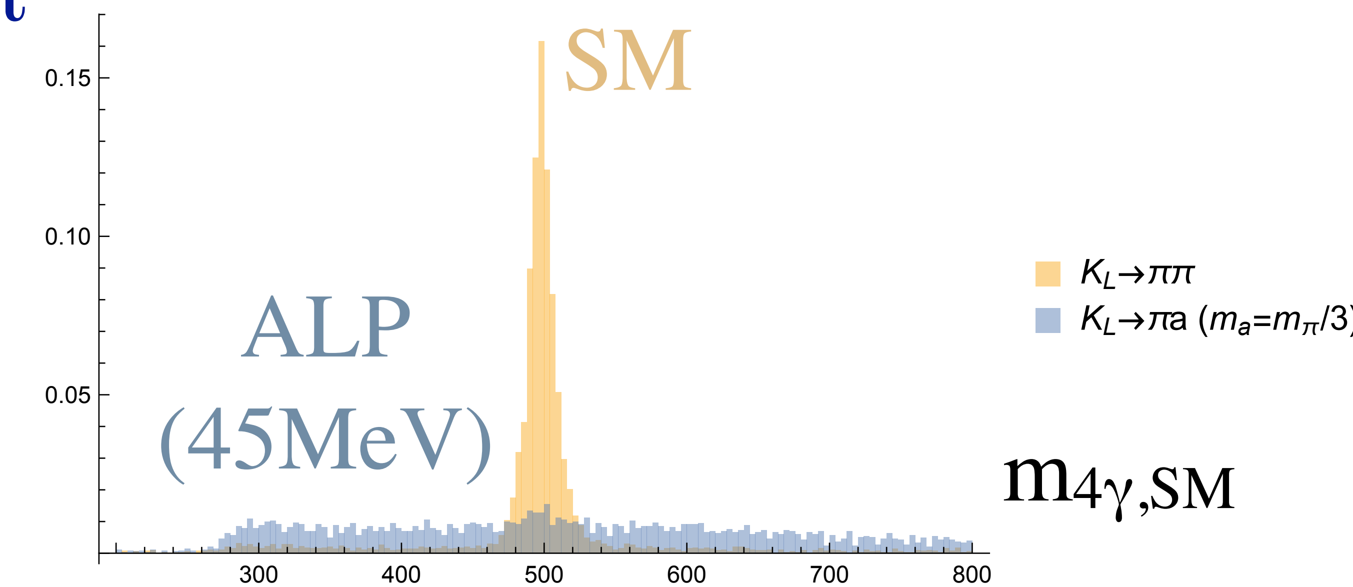
$m_{\gamma 1 \gamma 2, \mathrm{NP}}$

# Bump hunt at KOTO

## Recon SM: assume $K_L \to \pi^0\pi^0$

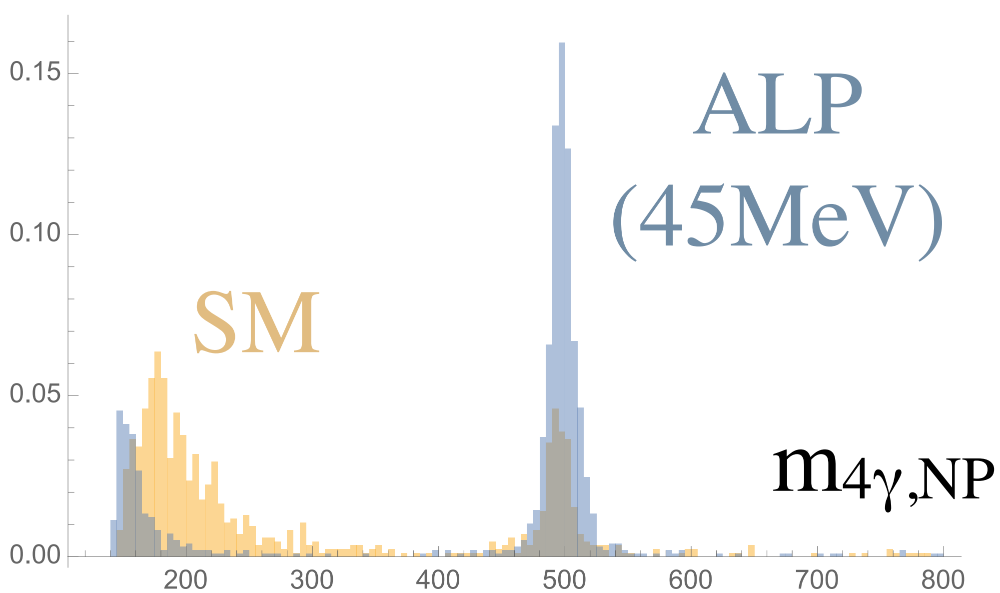
arbitrary normalization

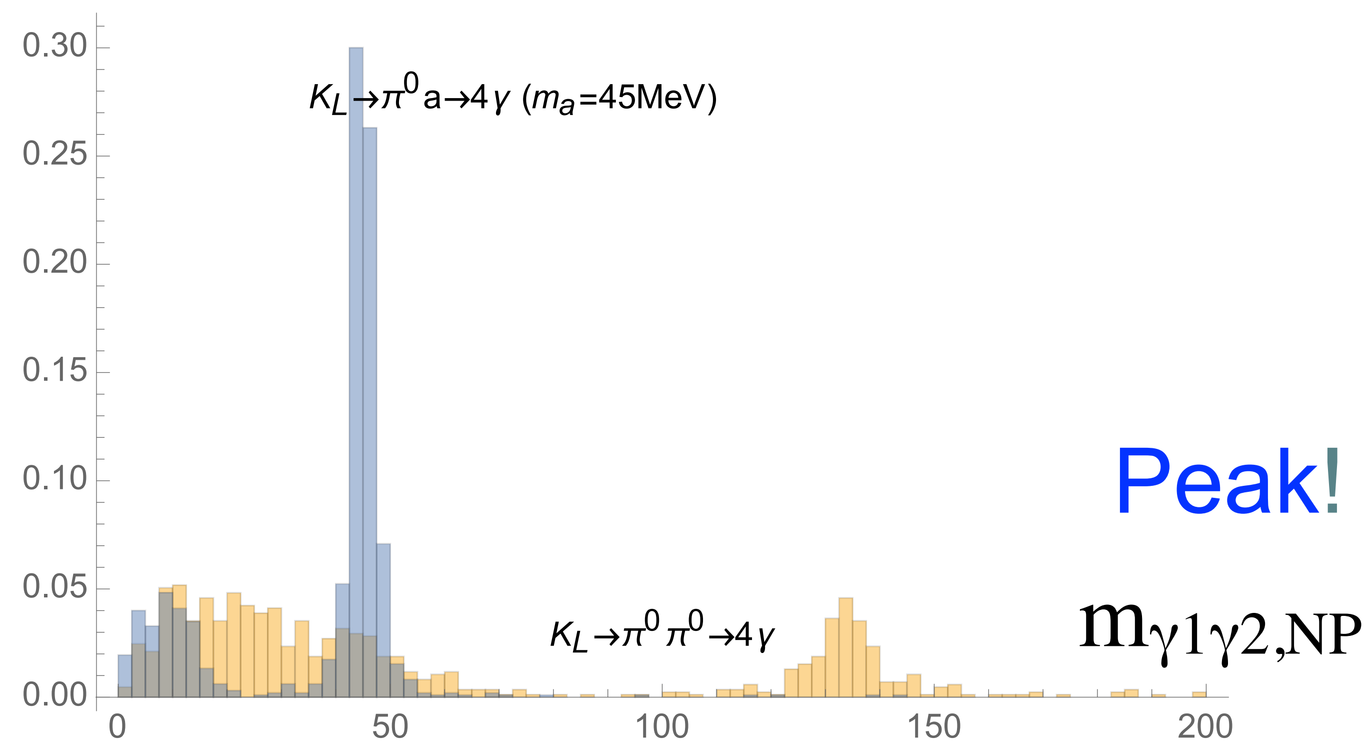



## Recon NP: assume $K_L \to \pi^0 a$

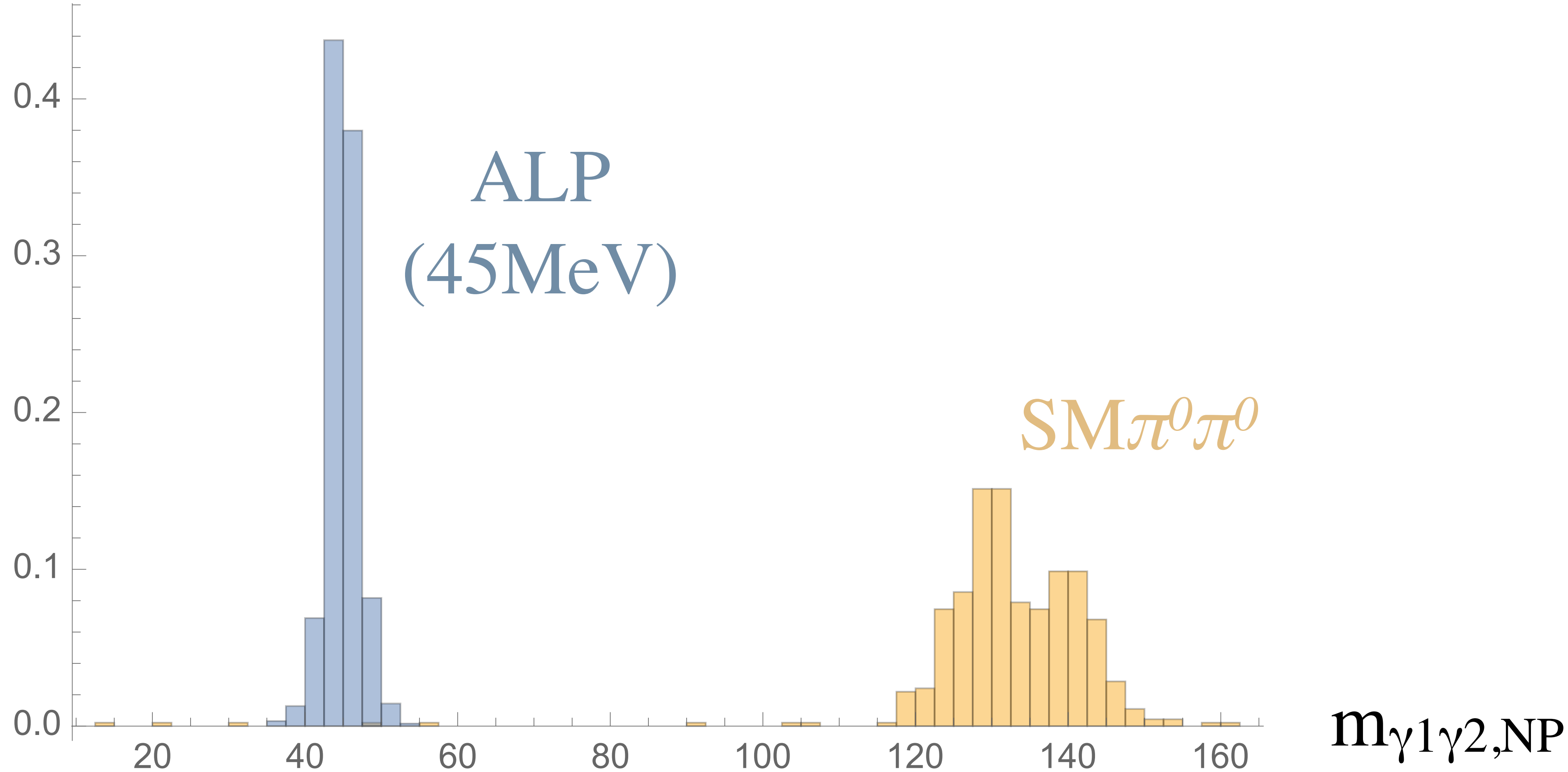
- jet distance: $E_i E_j \Delta r_{ij}^2$ ~mass$^2$, a→closest 2photons(1,2)
- the other two photons(3,4) from $\pi^0$, reconstruct vtx assuming $m_\pi$



# Bump hunt at KOTO

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




Efficiencies Sig(45MeV) 6%

BG($\pi^0\pi^0$) $10^{-5}$

With $N_K=10^{13}$

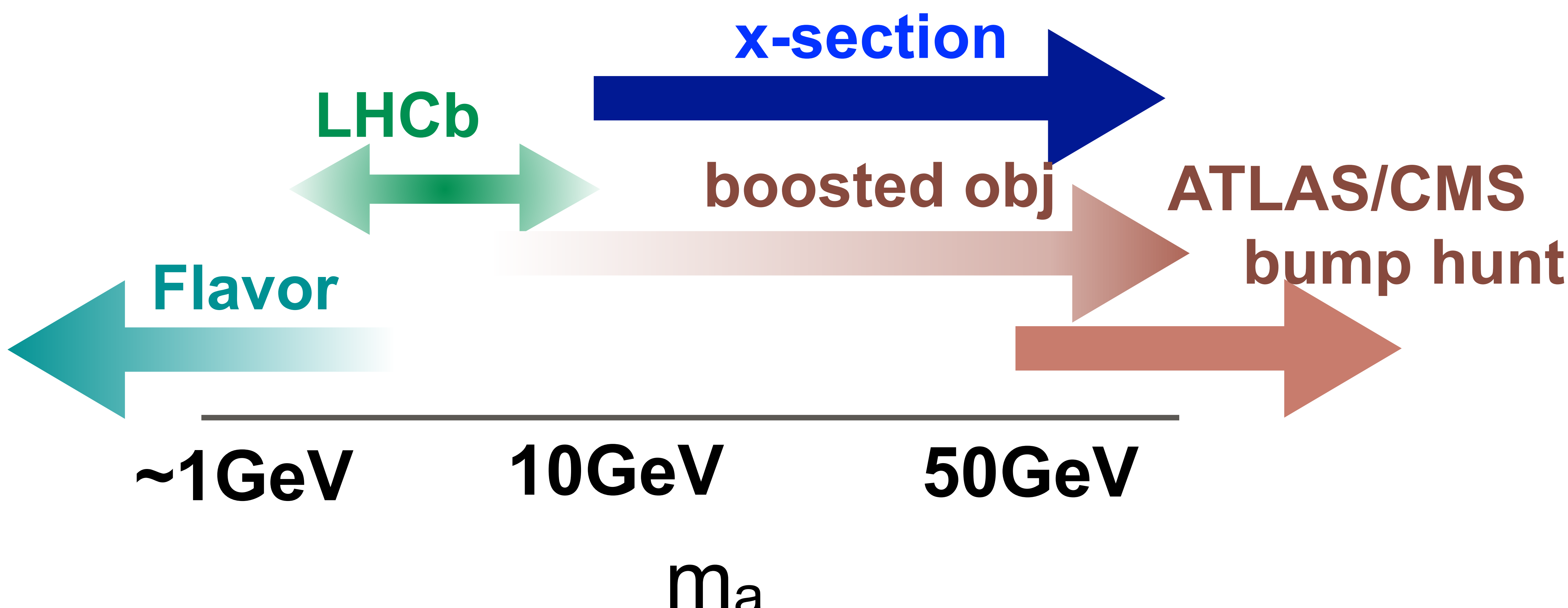
Preliminary $\mathbf{Br(K_L \to \pi^0 \mathit{a}) > 10^{-9}}$

$f_a > 500$GeV with $c_3=10$

Need to consider $3\pi$BG, study $m_a > m_\pi$ , $6\gamma$, 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
- Mono triggers [boosted obj] will improve 10-50GeV
- **KOTO** is sensitive to ALP diphoton! Need to explore more.




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

*Thank you!*

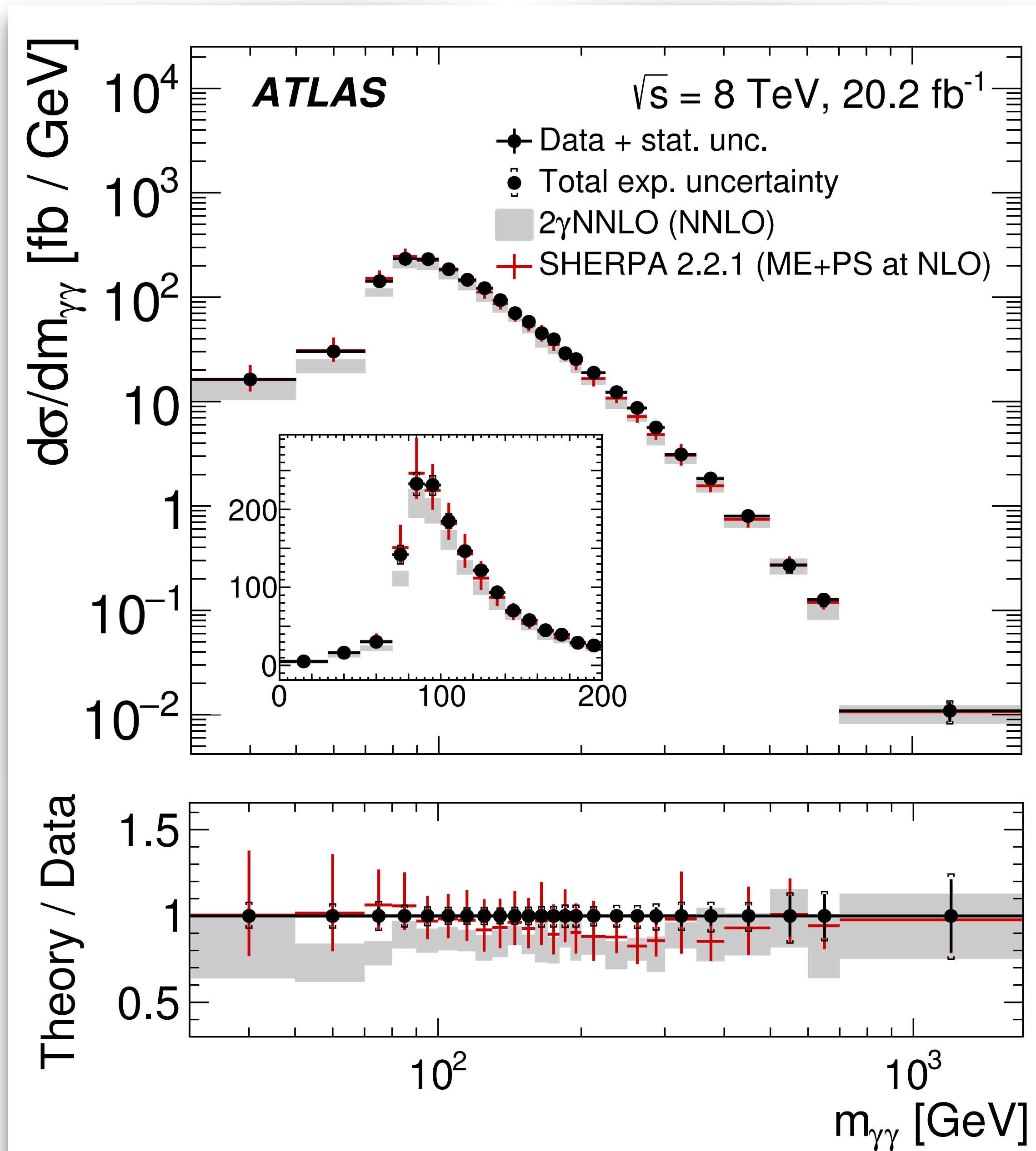
# Backup I

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

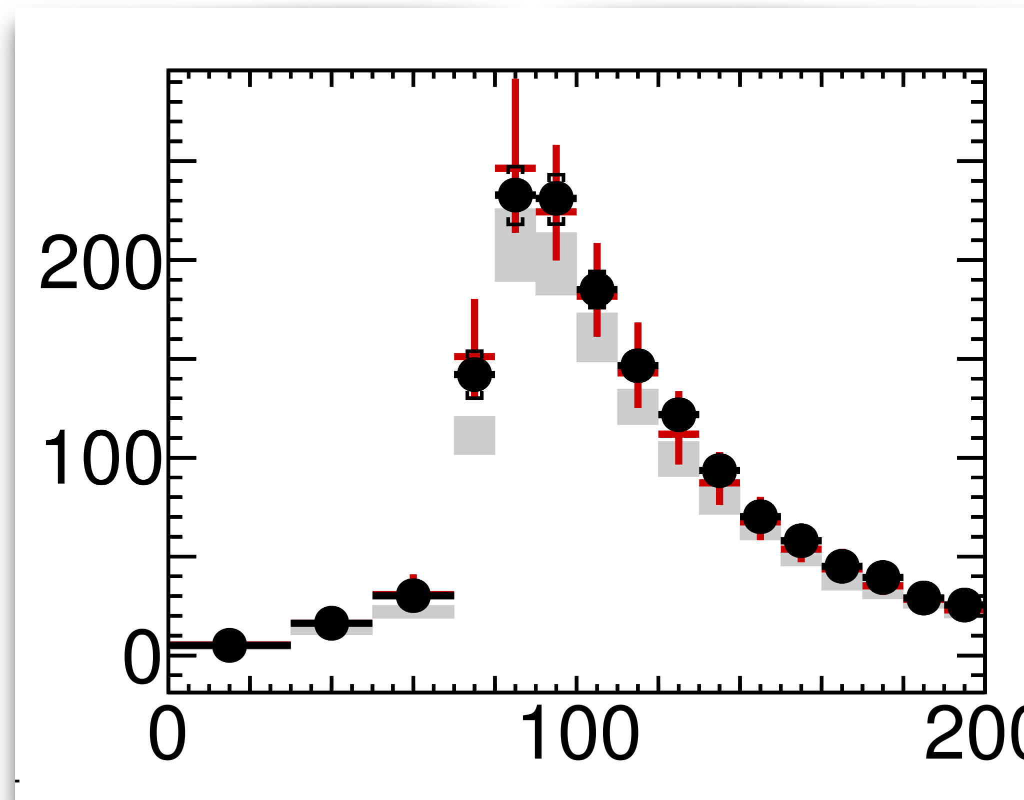
TABLE I: In the top of the Table we list the relevant searches involving at least a photon in the final state at different colliders, and lowest value of invariant mass that they reach. In the middle we also include the most recent LHC dijet searches (see Ref. [28] for a list of older searches). On the 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

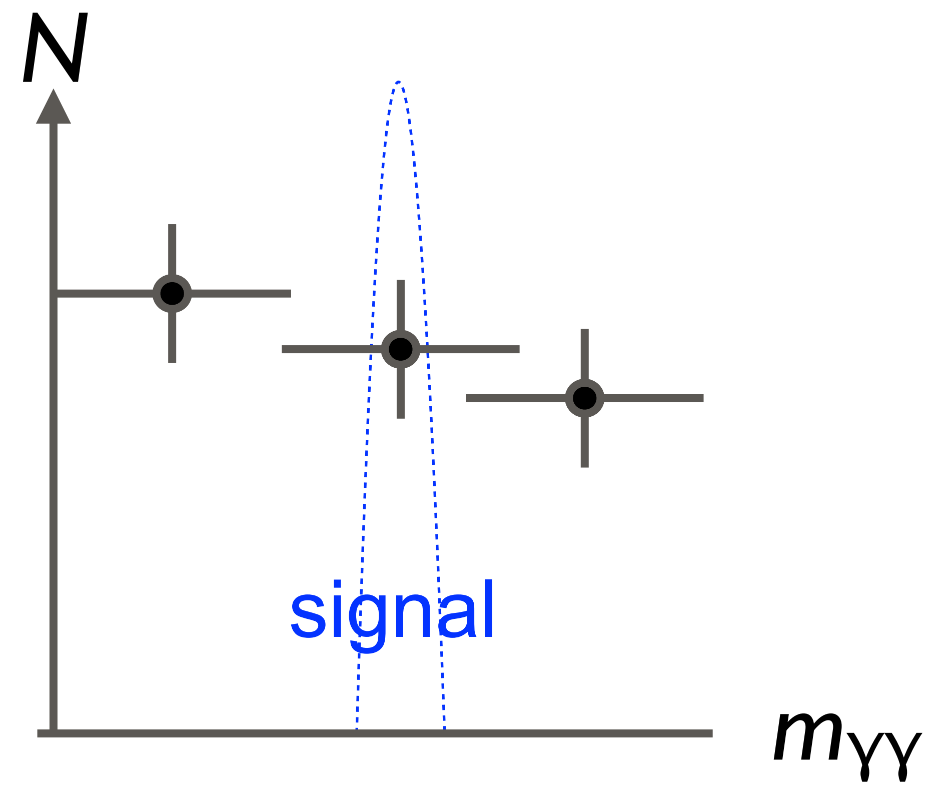


# Bound from Diphoton x-section measurement

*For this measurement, signal is SM$\gamma\gamma$…*

1. Conservative **bound**
   data=signal

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




2. Sensitivity(**current reach**)
   assume data=SM$\gamma\gamma$

   $S_a < 2\Delta N_{bin}$

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

   $S_a < 2\Delta N_{resolution}$

4. Future reach estimated by statistical scaling

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