New LHC bound on low-mass diphoton resonances

Workshop on the physics of HL-LHC & perspectives @ HE-LHC

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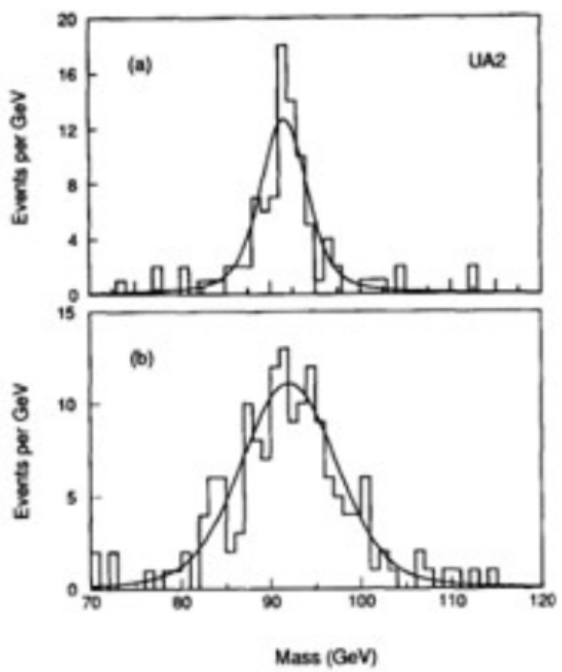
INTRODUCTION

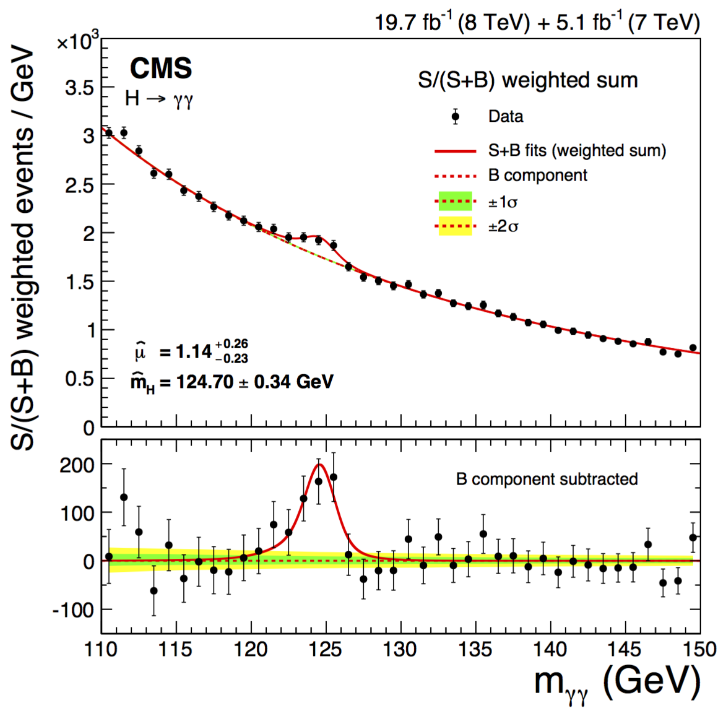
experimental & theoretical motivation

Searches for (neutral) resonances decaying 2-body are strong discovery method at colliders

famous discoveries:

$$J/\psi \,, \Upsilon \,, Z \,, h \ldots$$





extensive coverage at the LHC:

diphotons   *dileptons* $(e \,, \mu)$ *dibosons (Z, W)*

dijets   *dittaus*   *dihiggses*

Coverage good for masses *above* 100 GeV

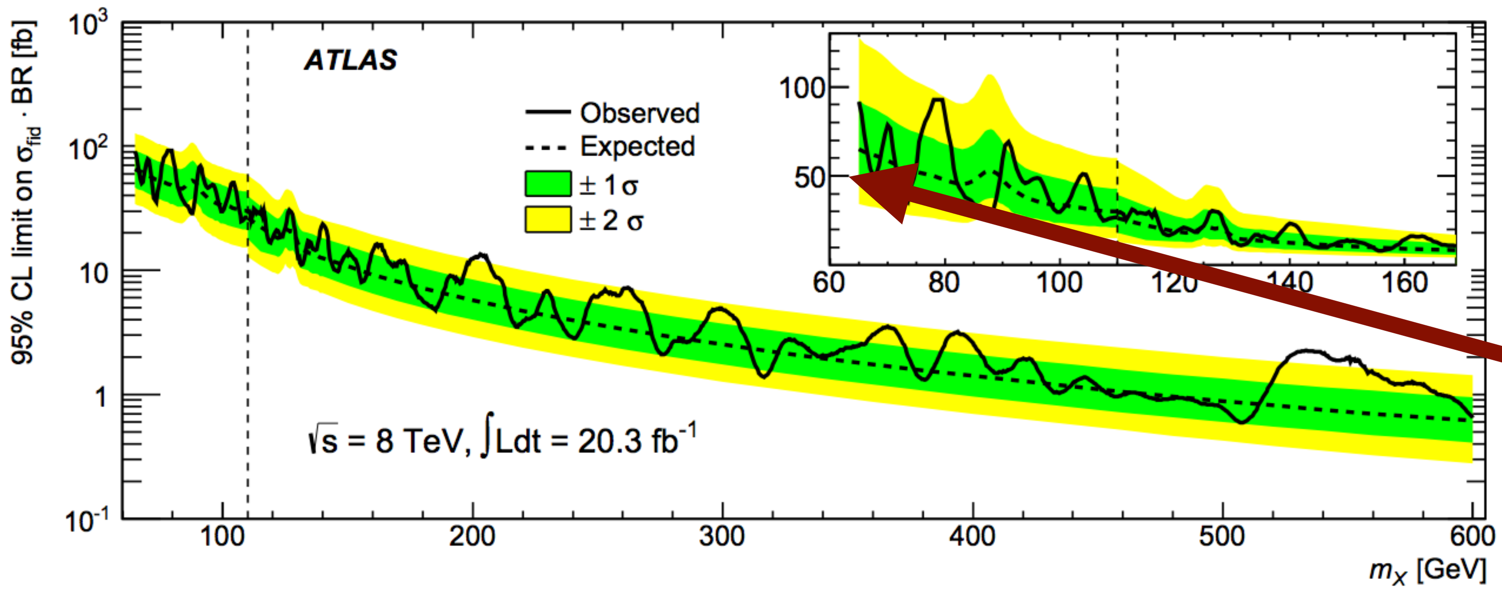
Why not *below* ?

1) Theoretical bias/motivation towards high mass (extra Higgses, Z'…)

2) Low mass range already constrained by previous machines/prec. measurements

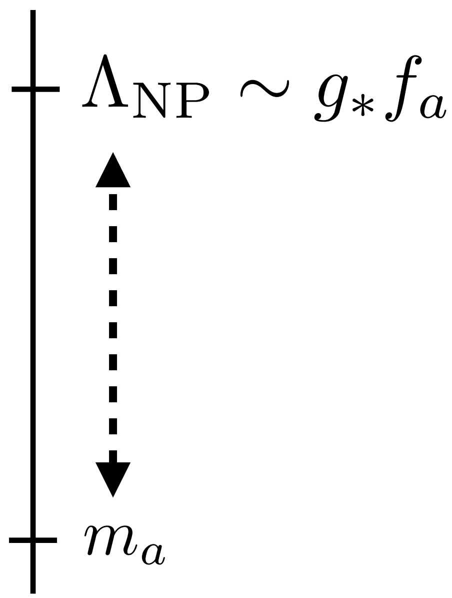
3) Low mass is challenging due to the minimal triggers pT cuts

diphoton :



Can we go *below* that?

A PHYSICS CASE: *Axion-like particles*



Pseudo Nambu Golstone Bosons (pNGBs) $a \to a + c$

1) The mass m_a can be *arbitrarily below* the new physics scale Λ_{NP}

2) The couplings with the SM are controlled by *decay constant* f_a

$f_a \sim 0.1 - 10\ \mathrm{TeV}$ relevant range @ present colliders

UV MOTIVATIONS

1) The usual suspects addressing Naturalness of EW scale — "SUSY R-axion" **Bellazzini, Mariotti, D.R., Sala, Serra ('17)**; "Ferretti's cosets" **Barnard, Gherghetta, Ray ('13), Ferretti ('16)...**

2) Cool axion models addressing strong CP — "Heavy QCD-axion" **Dimopoulos, Hook, Huang, Marques-Tavares ('16)**; **Gherghetta, Nagata, Shifman ('16)**; **Agrawal, Howe ('17)**

3) New pions from hidden QCD — "Vector-like confinement" **Kilic, Okui, Sundrum ('09) ...**

4) Light Dark Matter mediators — "top-philic dark matter" **Banerjee, Barducci, Blanger, Fuks, Goudelis, Zaldivar ('09) ...**

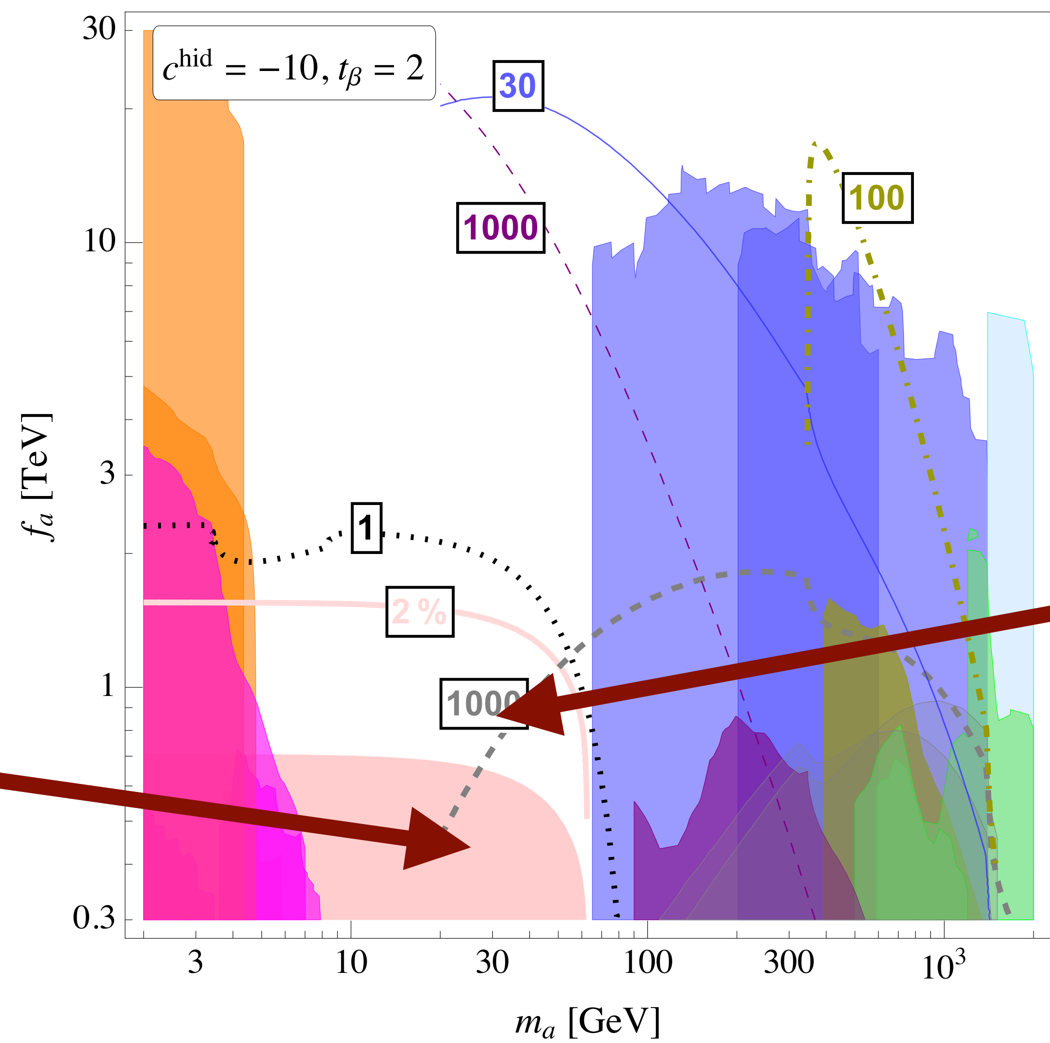
FOCUS HERE: dominant WZW couplings with gauge bosons (KSVZ ALPs)

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

$$\alpha_1 = 5/3\alpha'$$

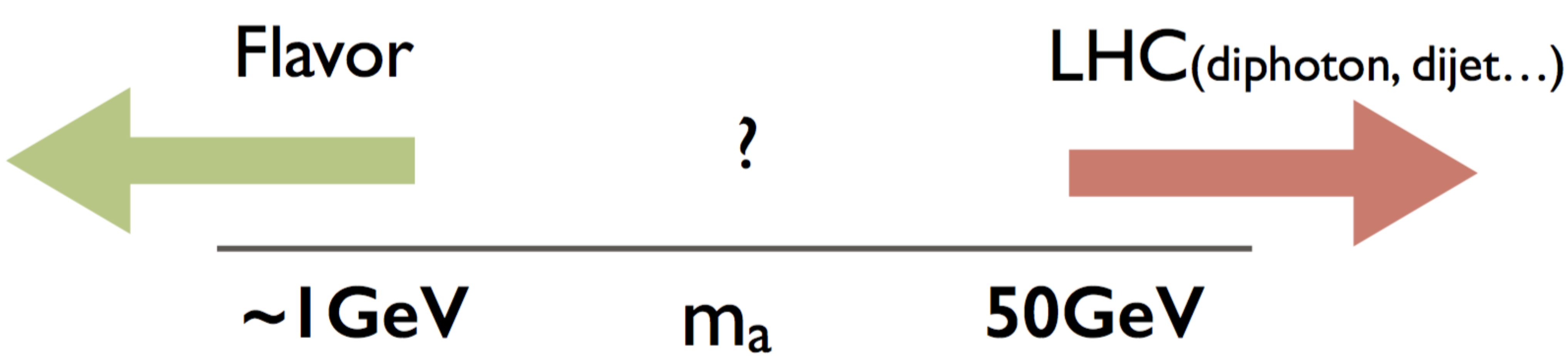
I suspect there could be a similar story for fermion couplings…

Specifically for Axion-like particles of the KSVZ-type



Huge hole between 10-50 GeV

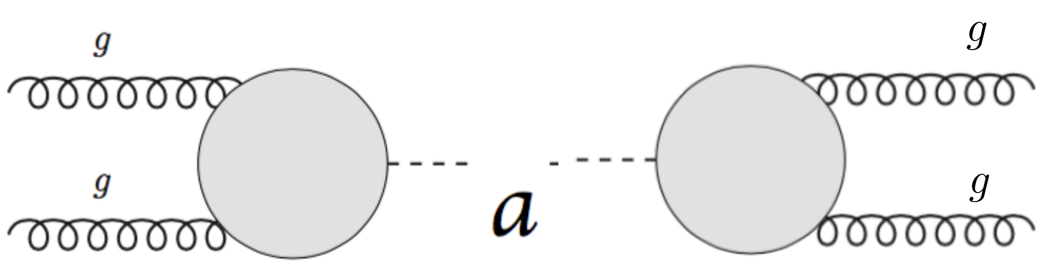
bounds from $h \to aa$



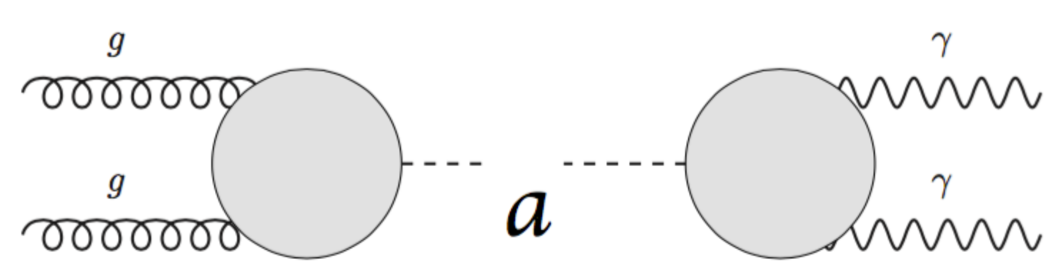
NEW BOUND(s)

from xsec diphoton measurements Mariotti, D.R., Sala, Tobioka ('17)

from boosted dijets searches CMS ('17)



dijets



diphotons

Lower bound on the invariant mass

$$m_{\gamma\gamma} > \Delta R \sqrt{p_{T_1}^{\min} p_{T_2}^{\min}}$$

Photon/jet Isolation

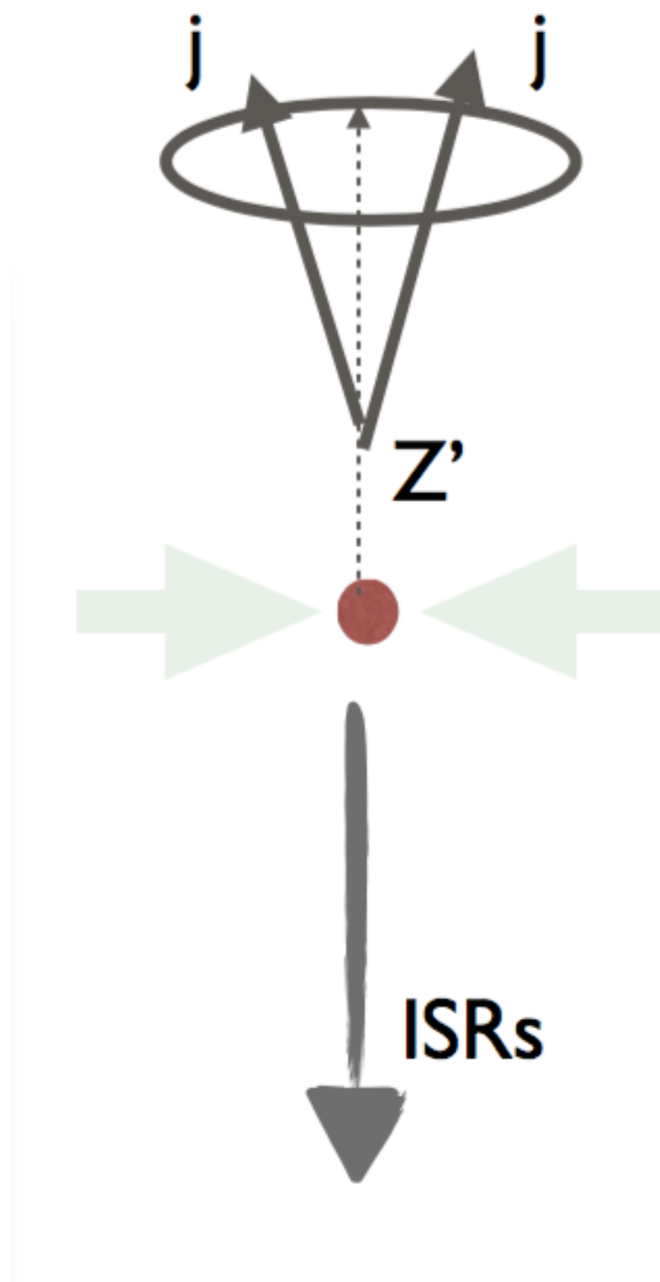
$$\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

Minimal pT cuts

Two ways to lower $m_{\gamma\gamma}$

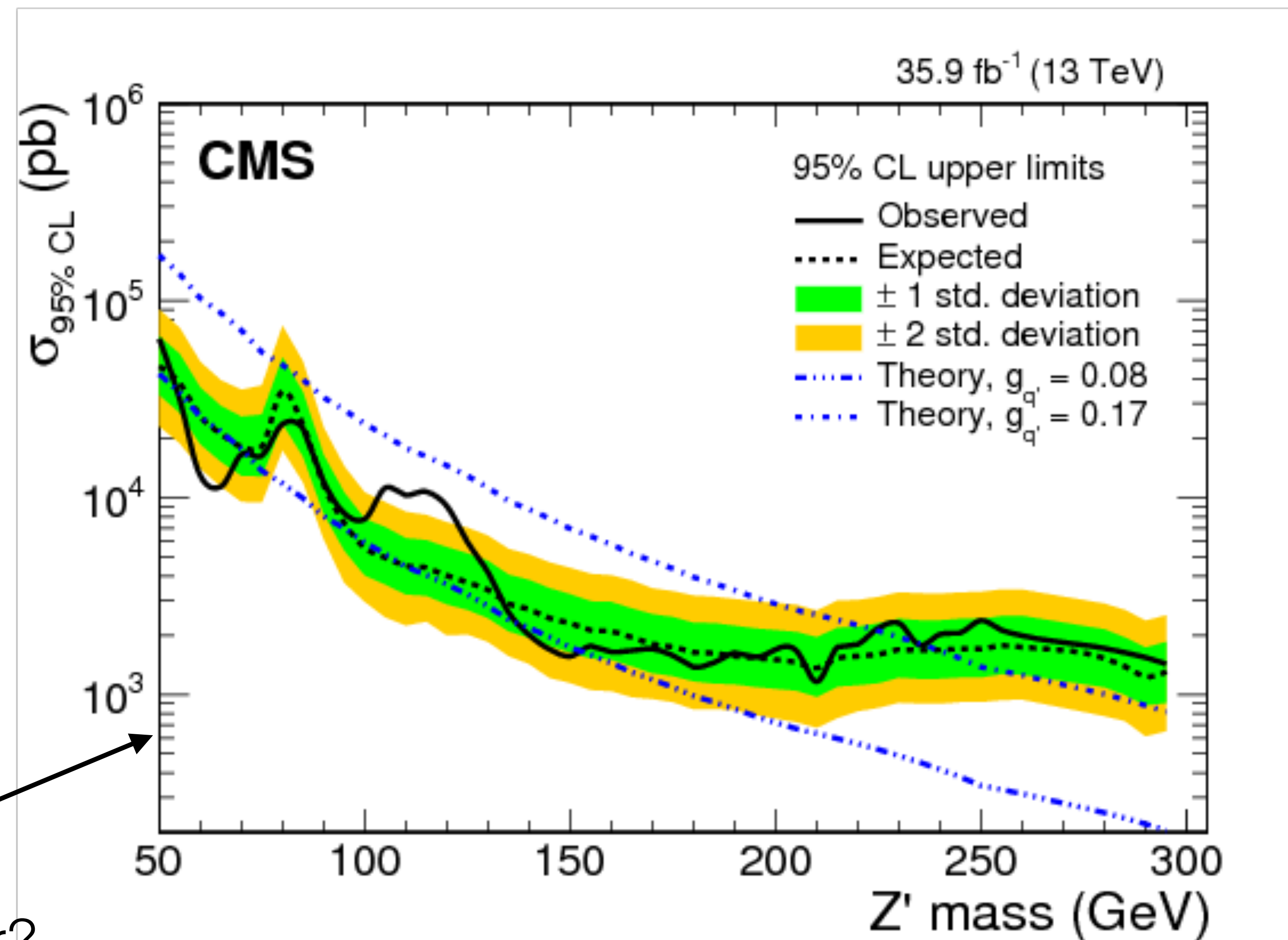
- Lower ΔR
- Lower $p_T^{\min}$

- Lower ΔR → extra hard object to pass to trigger



Boosted dijets (highly collimated)

Resonance can be seen in the substructure

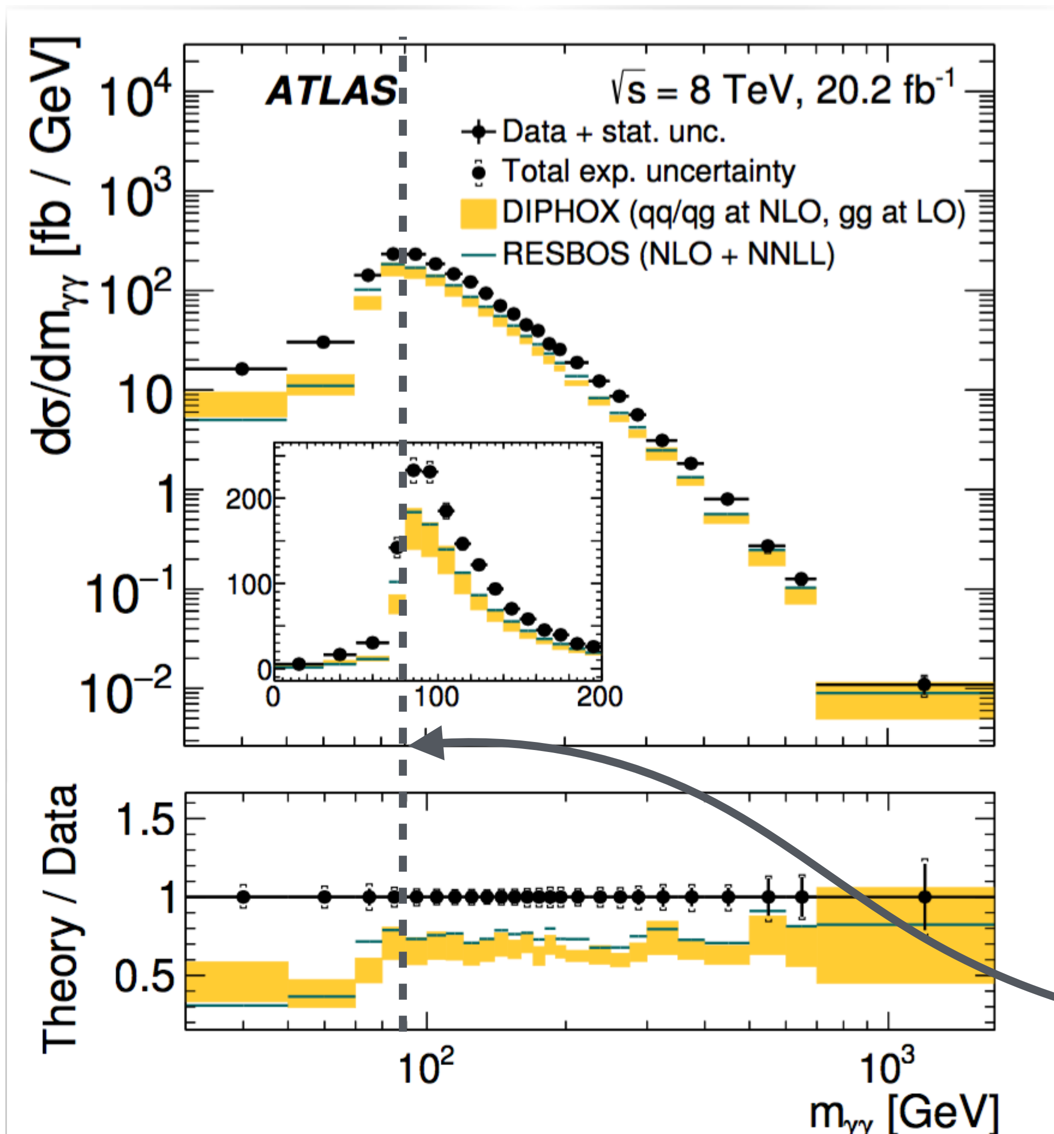


can it
go lower?

What is the lowest $p_T^{\min}$ in current diphotons x-sec measurements?

ATLAS	$pp \to a \to \gamma\gamma$	4.9 fb^{-1}	7 TeV	$p_{T_1,T_2} > 25\,,22$ GeV
ATLAS	$pp \to a \to \gamma\gamma$	20.2 fb^{-1}	8 TeV	$p_{T_1,T_2} > 40\,,30$ GeV
CMS	$pp \to a \to \gamma\gamma$	5.0 fb^{-1}	7 TeV	$p_{T_1,T_2} > 40\,,25$ GeV

background shape



standard
ISOLATION requirement

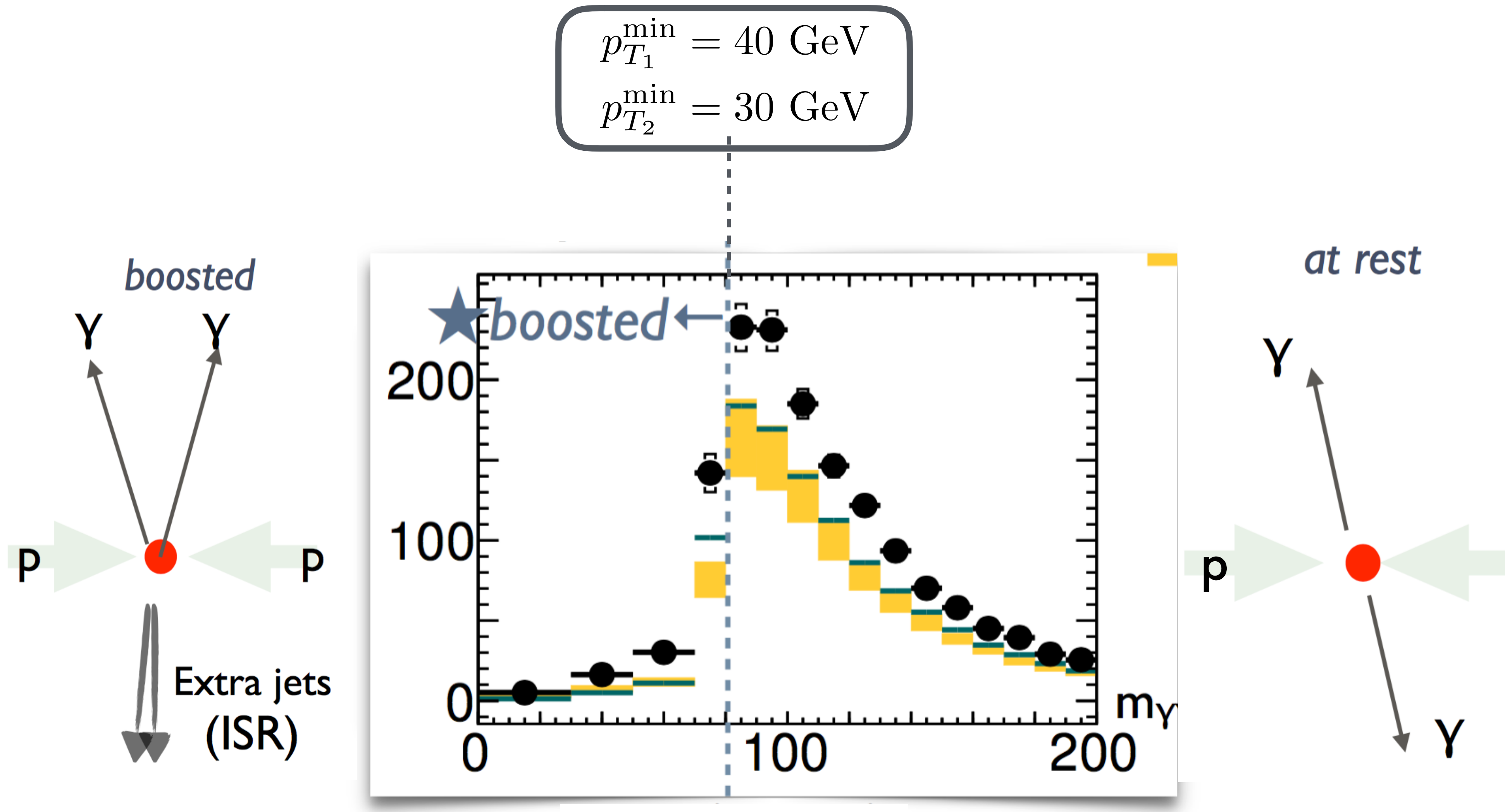
$\Delta R > 0.4$

low mass reach
9.4 GeV
13.9 GeV
14.2 GeV

effect of pT cuts

$p_{T_1}^{\min} = 40$ GeV

$p_{T_2}^{\min} = 30$ GeV



below pT cuts

the background has a structure so data-driven bkd. estimate are difficult

BUT

the signal efficiency does not drop to zero below the pT cuts!

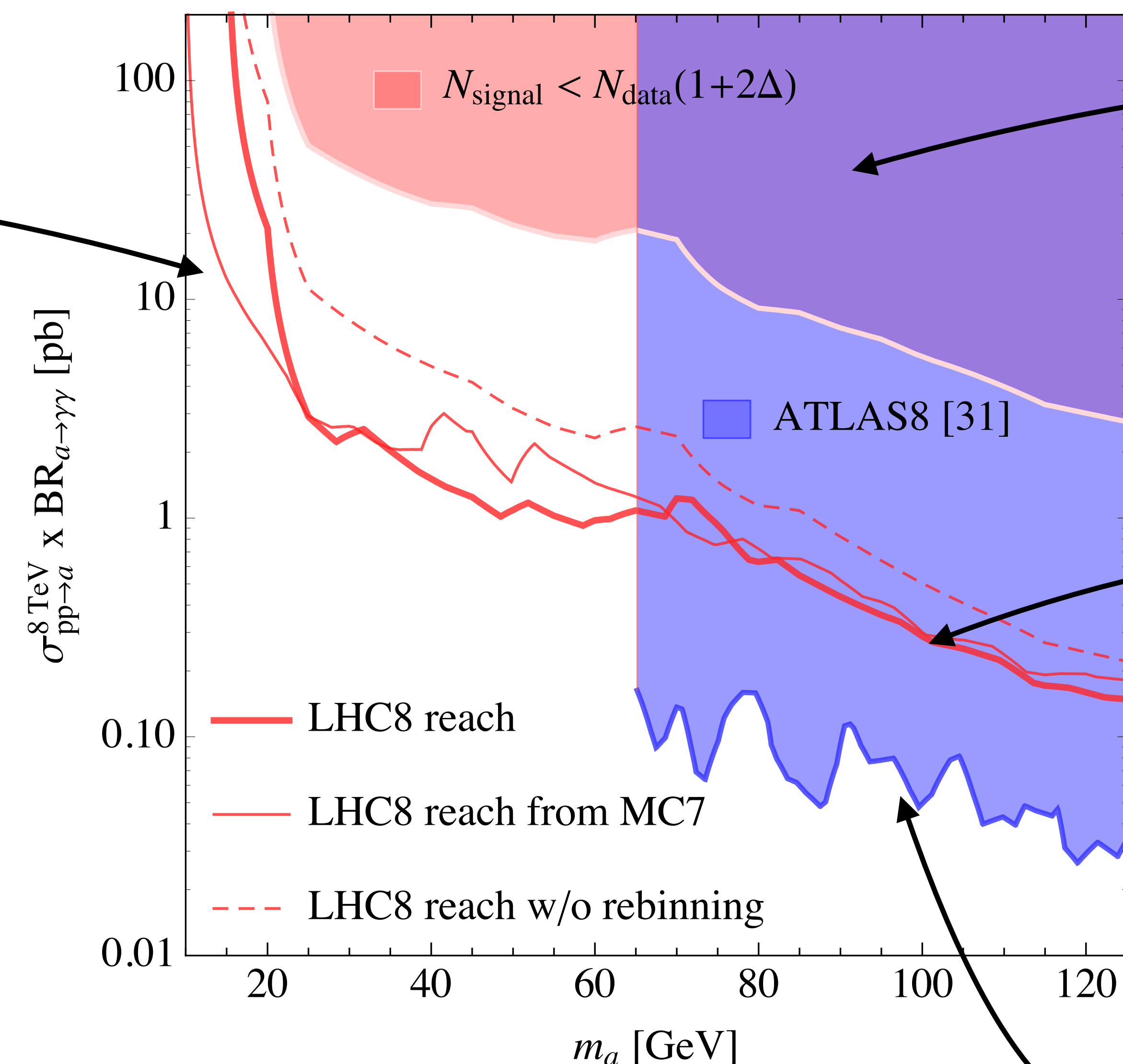
m_a in GeV	10	20	30	40	50	60	70	80	90	100	110	120
ϵ_S for $\sigma_{8\text{TeV}}$ ATLAS [9]	0	0.0007	0.008	0.014	0.024	0.037	0.071	0.233	0.347	0.419	0.452	0.484

projection $(\sqrt{s}_{\rm low}, L_{\rm low}) \to (\sqrt{s}_{\rm high}, L_{\rm high})$

$$\frac{\sigma_{\rm high}}{\sigma_{\rm high}} = \sqrt{\frac{L_{\rm low}}{L_{\rm high}} \cdot \frac{\sigma_{\rm high}}{\sigma_{\rm low}} \cdot \frac{\epsilon^{\rm low}}{\epsilon^{\rm high}}}$$

7 TeV reach
projected at 8 TeV

low mass reach
9.4 GeV
13.9 GeV
14.2 GeV



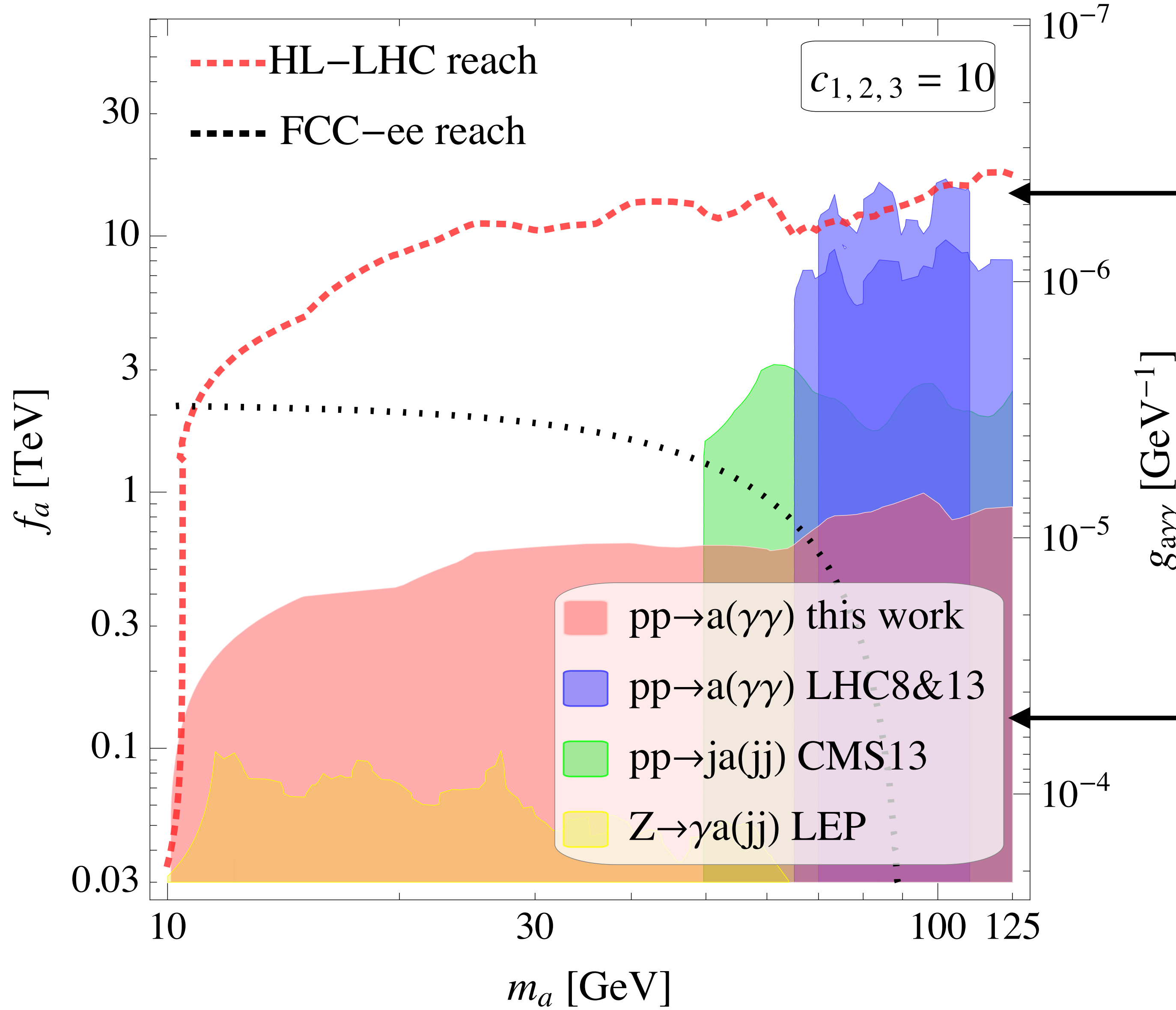
conservative bound
from 8 TeV data

rebinning
with ECAL resolution

$$\frac{\delta E_\gamma}{E_\gamma} = 10\% \cdot \left(\frac{\rm GeV}{E_\gamma}\right)^{1/2}$$

N.B. An unbinned shape analysis still does ~5 better!

ALP mass plane



HL-LHC beats FCC-ee!

LHC beats LEP!

FCC-ee: $\mathrm{BR}(Z \to \gamma + jj) < 10^{-4} \cdot \sqrt{\frac{Z\text{'s LEP}}{Z\text{'s FCC-ee}}} \sim 10^{-7}$

ALPs LANDSCAPE

ATLAS & CMS can do ~ 10 better than our bound!

Many more things to try for light stuff with more Lumi...

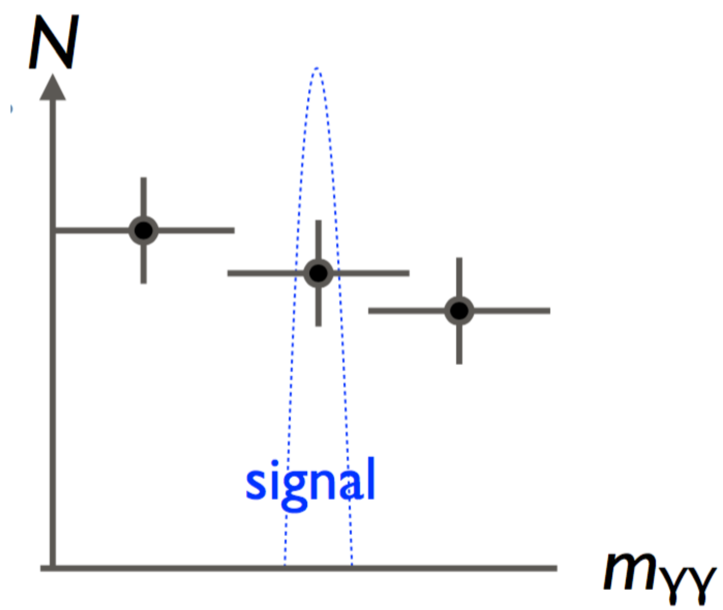
Data parking, Data scouting, pre-scaled triggers to lower photon pT's?

Extend substructure techniques to other calorimeter objets: Boosted diphotons+ jet?

BACKUP

more details

Extend the bump searches using xsec. measurements



1) **conservative bound** (no *bkd* knowledge)

$$\sigma^{\rm S}(m_a)\cdot\epsilon_S(m_a) < m_{\gamma\gamma}^{\rm Bin}\cdot\frac{{\rm d}\sigma}{{\rm d}m_{\gamma\gamma}}\cdot(1+2\Delta)$$

2) **sensitivity** (*bkd* dominated by SM diphotons)

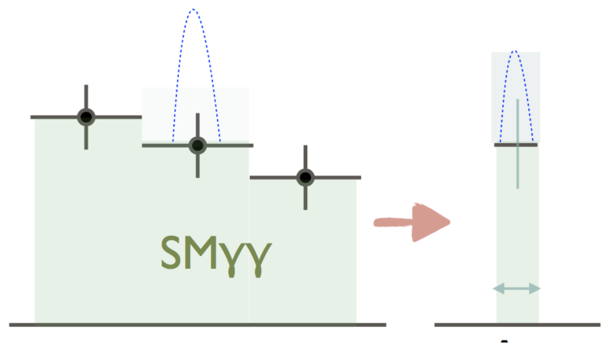
$$\sigma^{\rm S}(m_a)\cdot\epsilon_S(m_a) < m_{\gamma\gamma}^{\rm Bin}\cdot\frac{{\rm d}\sigma}{{\rm d}m_{\gamma\gamma}}\cdot 2\Delta$$

Δ = error on measure

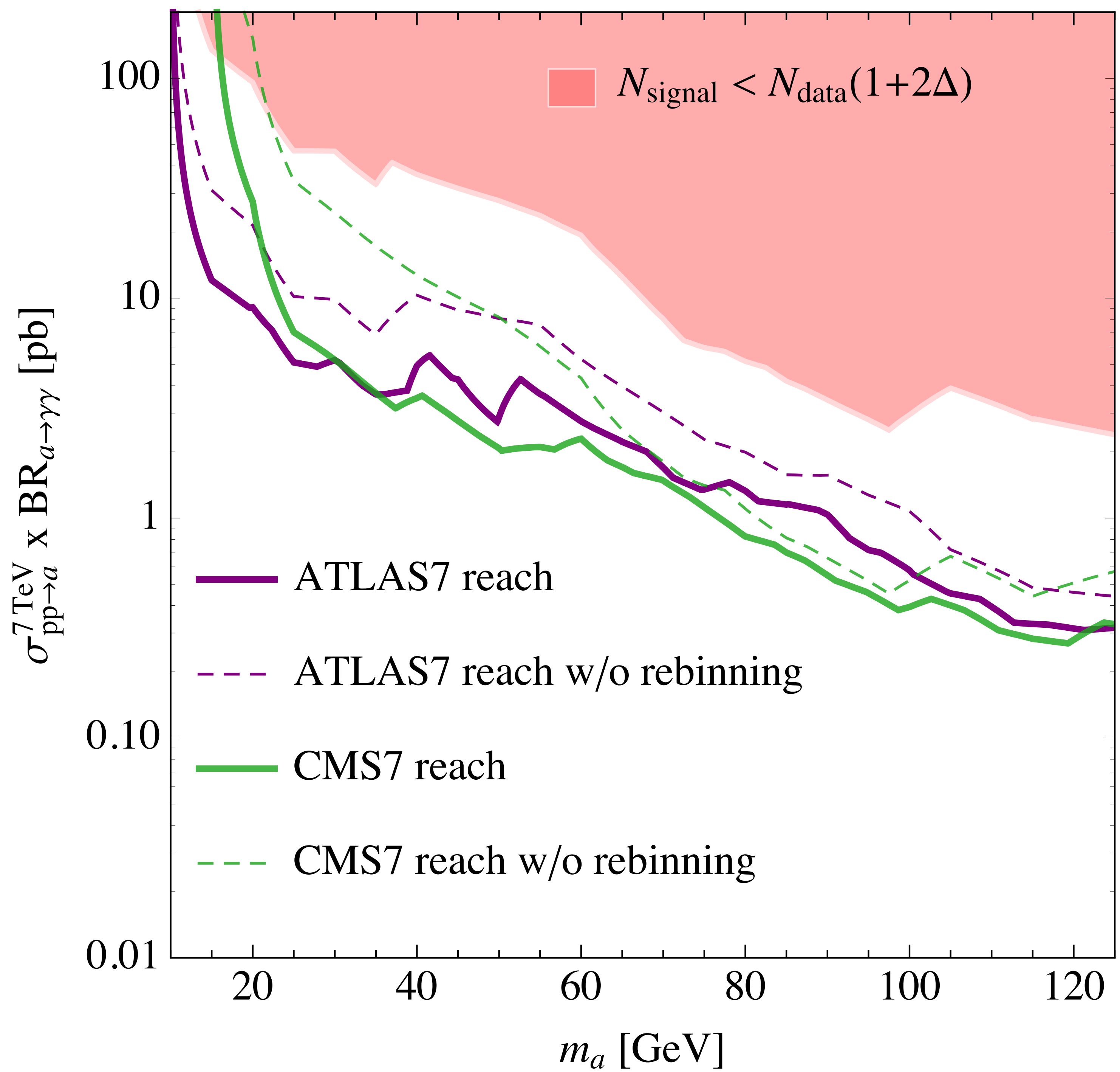
$m_{\gamma\gamma}^{\rm Bin}\cdot\frac{{\rm d}\sigma}{{\rm d}m_{\gamma\gamma}}$ = bin size • measure

ϵ_S = signal efficiency

3) **rebinning** (shrinking the bin S/B increases)

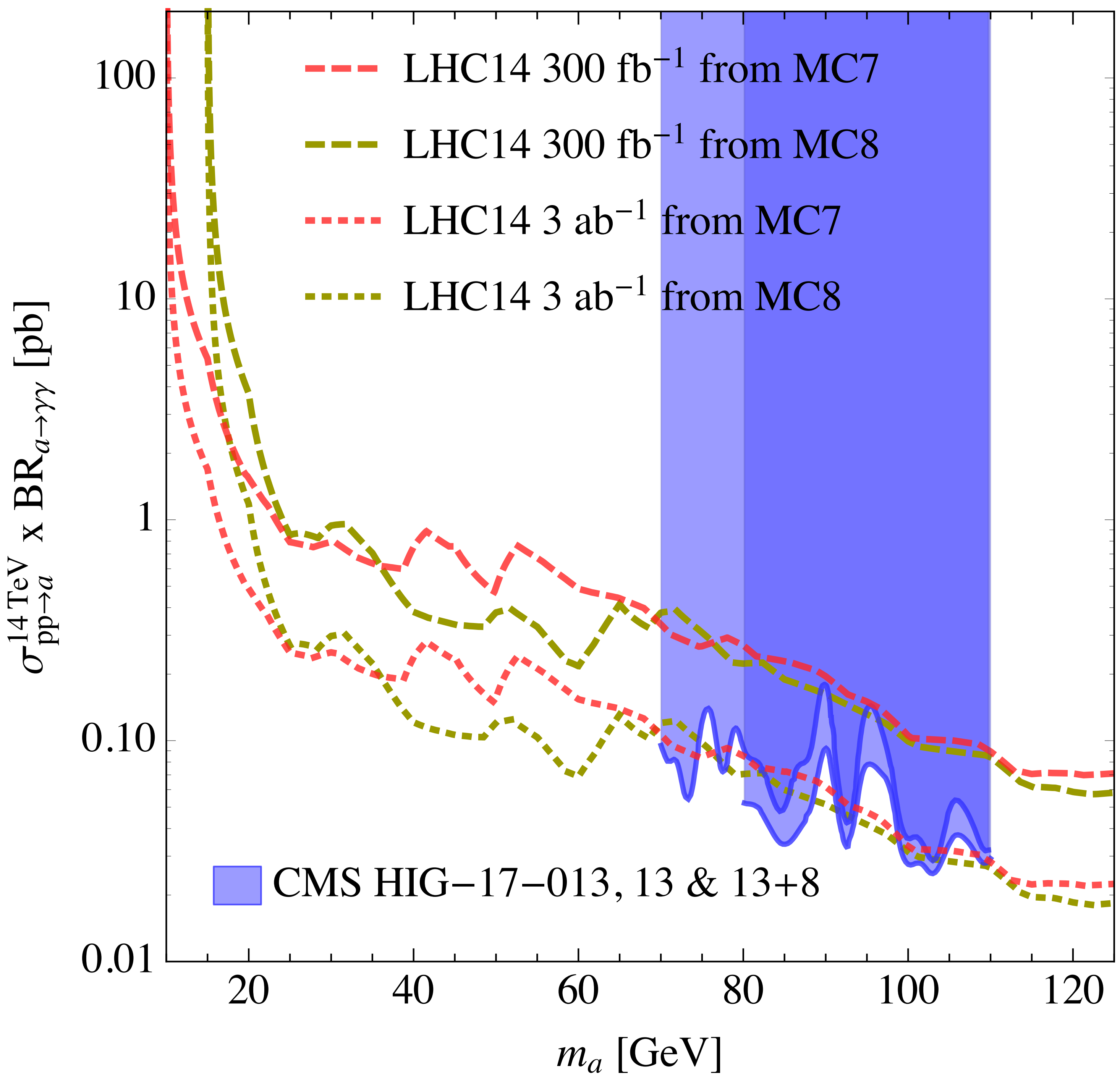


7 TeV data



$N_{\rm signal} < N_{\rm data}(1+2\Delta)$
ATLAS7 reach
ATLAS7 reach w/o rebinning
CMS7 reach
CMS7 reach w/o rebinning
$\sigma^{7\,\rm TeV}_{pp\to a}$ x $\mathrm{BR}_{a\to\gamma\gamma}$ [pb]
100
10
1
0.10
0.01
20
40
60
80
100
120
m_a [GeV]

14 TeV projections

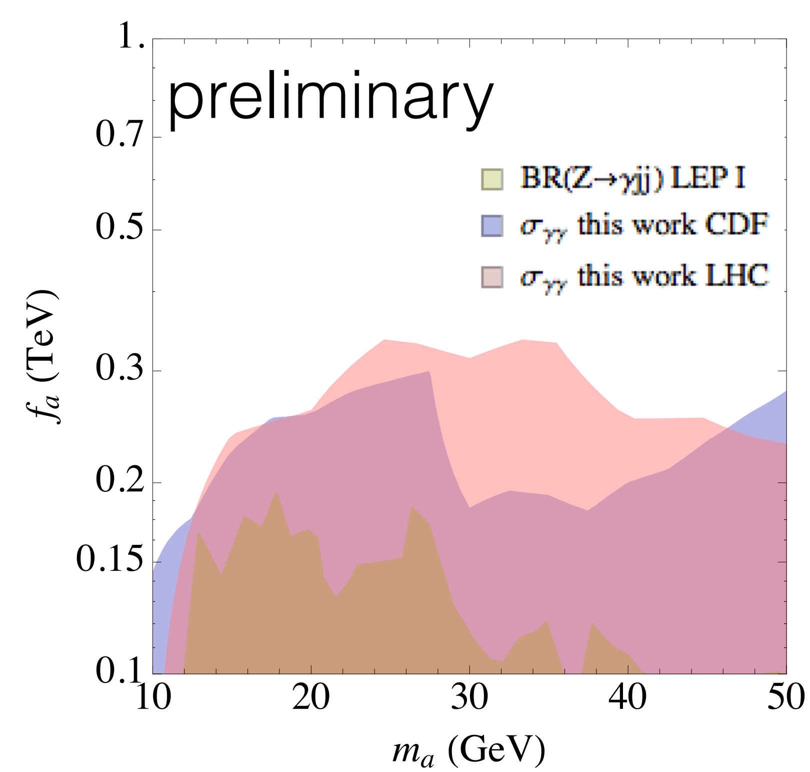


Did we dig carefully enough?

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	[25]
LEPI	$e^+e^- \to Z \to \gamma a \to \gamma\gamma\gamma$	78 pb^{-1}	Z-pole	3 GeV	[26]
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	[27]
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	[27, 28]
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	[27]
D0/CDF	$p\bar{p} \to a \to \gamma\gamma$	7/8.2 fb^{-1}	1.96 TeV	100 GeV	[29]
ATLAS	$pp \to a \to \gamma\gamma$	20.3 fb^{-1}	8 TeV	65 GeV	[30]
CMS	$pp \to a \to \gamma\gamma$	19.7 fb^{-1}	8 TeV	80 GeV	[31]
CMS	$pp \to a \to \gamma\gamma$	19.7 fb^{-1}	8 TeV	150 GeV	[32]
CMS	$pp \to a \to \gamma\gamma$	35.9 fb^{-1}	13 TeV	70 GeV	[33]
UA2	$p\bar{p} \to a \to \gamma\gamma$	13.2 pb^{-1}	0.63 TeV	17.9 GeV	[34]
D0	$p\bar{p} \to a \to \gamma\gamma$	4.2 fb^{-1}	1.96 TeV	8.2 GeV	[35]
CDF	$p\bar{p} \to a \to \gamma\gamma$	5.36 fb^{-1}	1.96 TeV	6.4 GeV	[36]
ATLAS	$pp \to a \to \gamma\gamma$	4.9 fb^{-1}	7 TeV	9.4 GeV	[8]
ATLAS	$pp \to a \to \gamma\gamma$	20.2 fb^{-1}	8 TeV	13.9 GeV	[9]
CMS	$pp \to a \to \gamma\gamma$	5.0 fb^{-1}	7 TeV	14.2 GeV	[10]

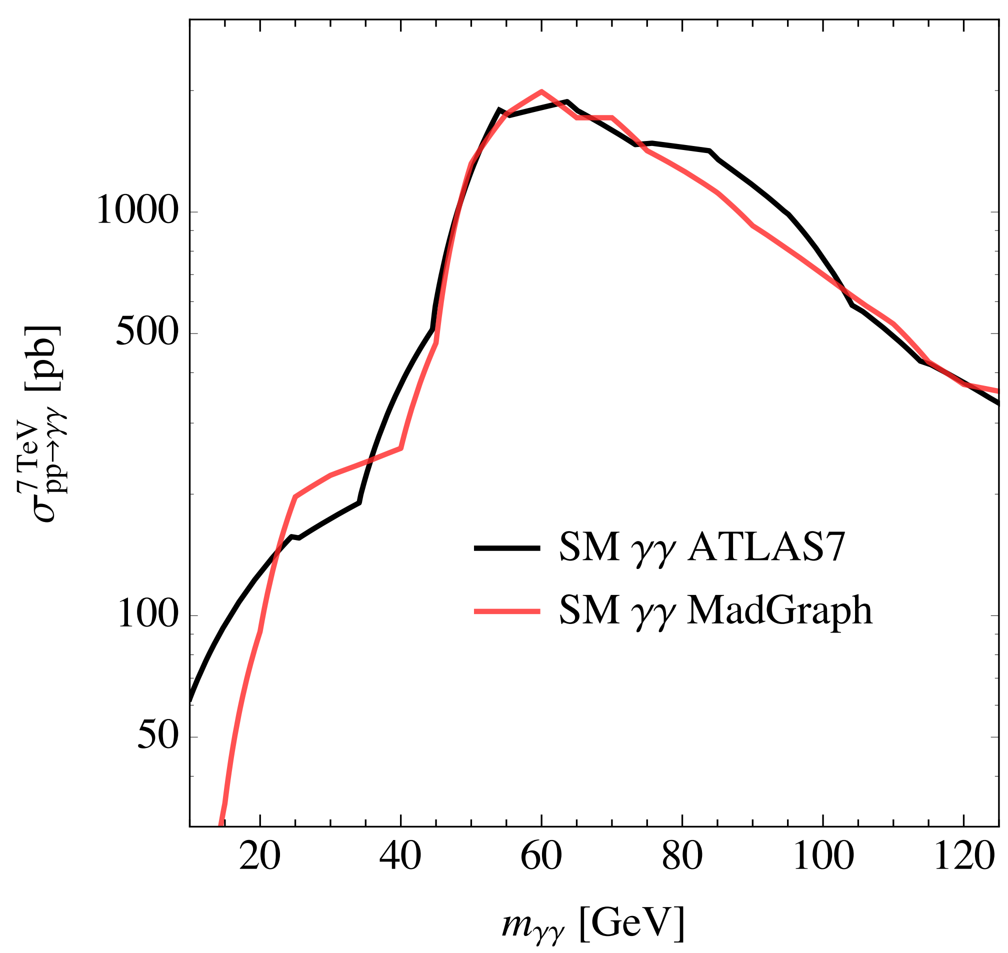
UA2? looked only at almost back to back photons

Tevatron? It is comparable with LHC at low mass!



diphoton backgrounds

we validated only the one from real photons



photon+jet is ~ 30% of the background but it does not modify the shape significantly

jet+jet is irrelevant