Low mass resonance search in bb final state at the LHC

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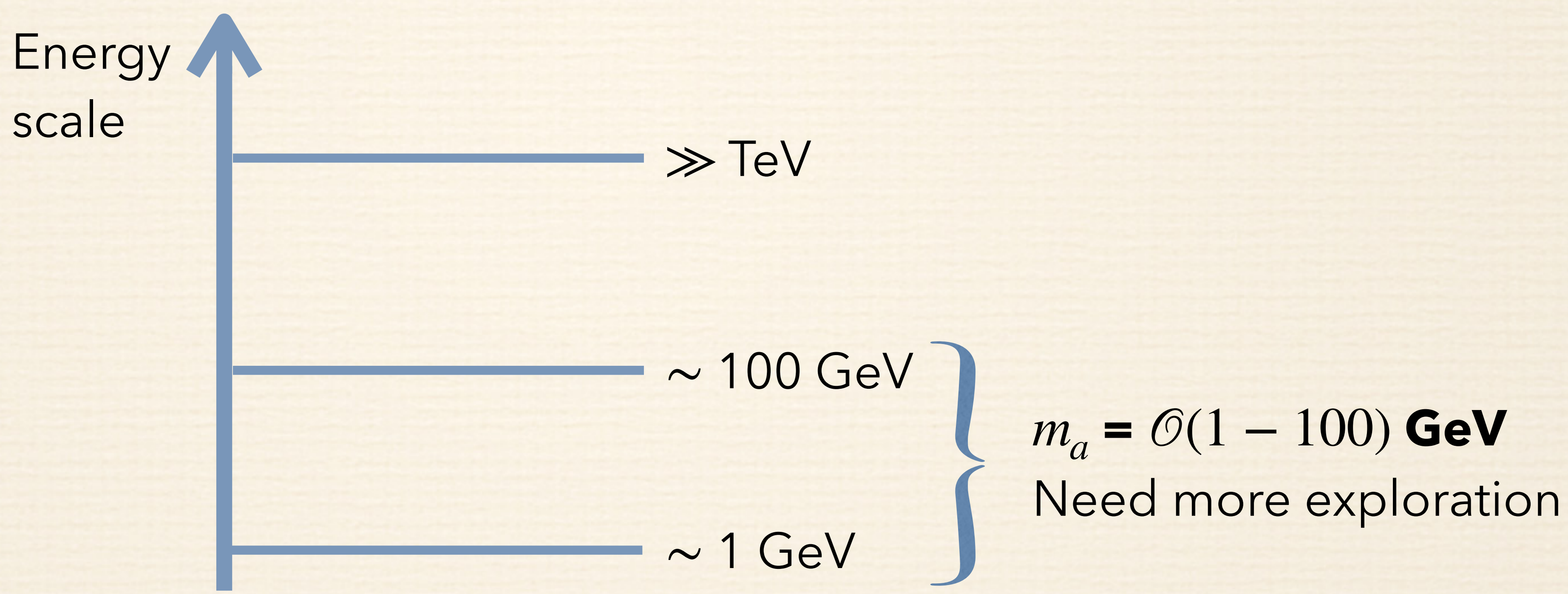
Based on

2410.09033, with Aoife Bharucha, Lorenzo Feligioni and Michele Frigerio

Extended Scalar Sectors From All Angles, CERN, 21-25 October

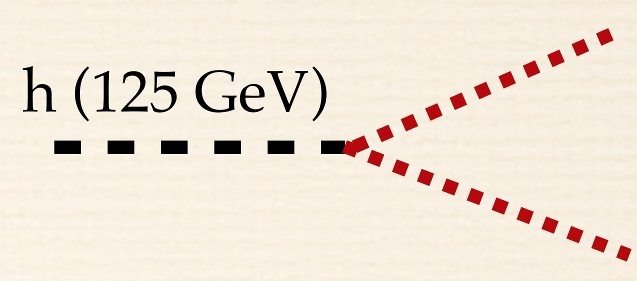
Why to look for light resonances?

Well-motivated beyond the SM (BSM) models : LHC is searching for new states and pushing the scale to $\gg$ TeV. But new light states could be present.



How to look for them at LHC?

1. From exotically decaying SM Higgs boson :



$m_a \lesssim 62.5$ GeV

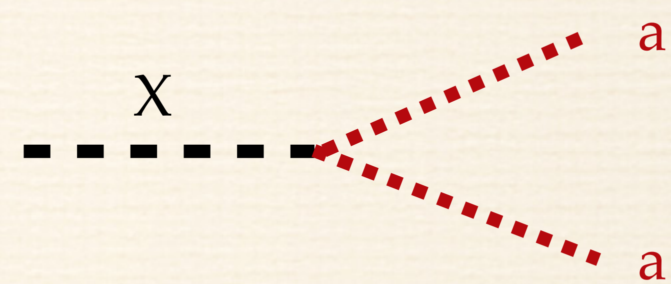
Curtin et. al. 1312.4992

Cepeda et.al. 2111.12751

ATL-PHYS-PROC-2024-018

Adhikary et.al. 2211.07674

2. From heavier states :

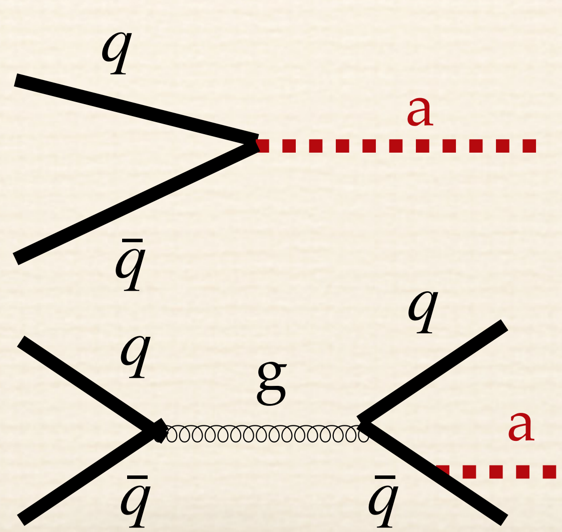


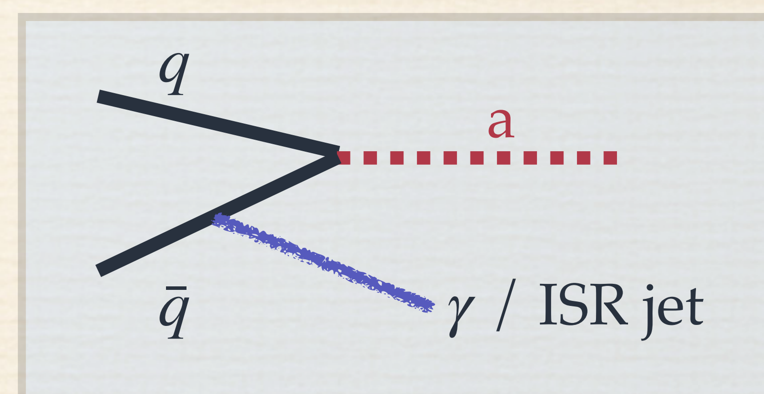
$m_a < \frac{m_X}{2}$

ATLAS: 1703.09127

CMS-EXO-17-001

3. Direct or **associated** production :





…

ATLAS: 1801.08769

CMS : 1905.10331

Difficulties and possible solutions

Object reconstruction : decay products are collimated if produced with large p_T.

Backgrounds : large QCD background can obscure the search at low mass

Trigger : trigger p_T threshold might not be optimal in probing low mass region.

Jet substructure techniques : can improve the search for boosted resonances.

Prong discriminant : useful to substantially reduce QCD backgrounds with some limitations (later).

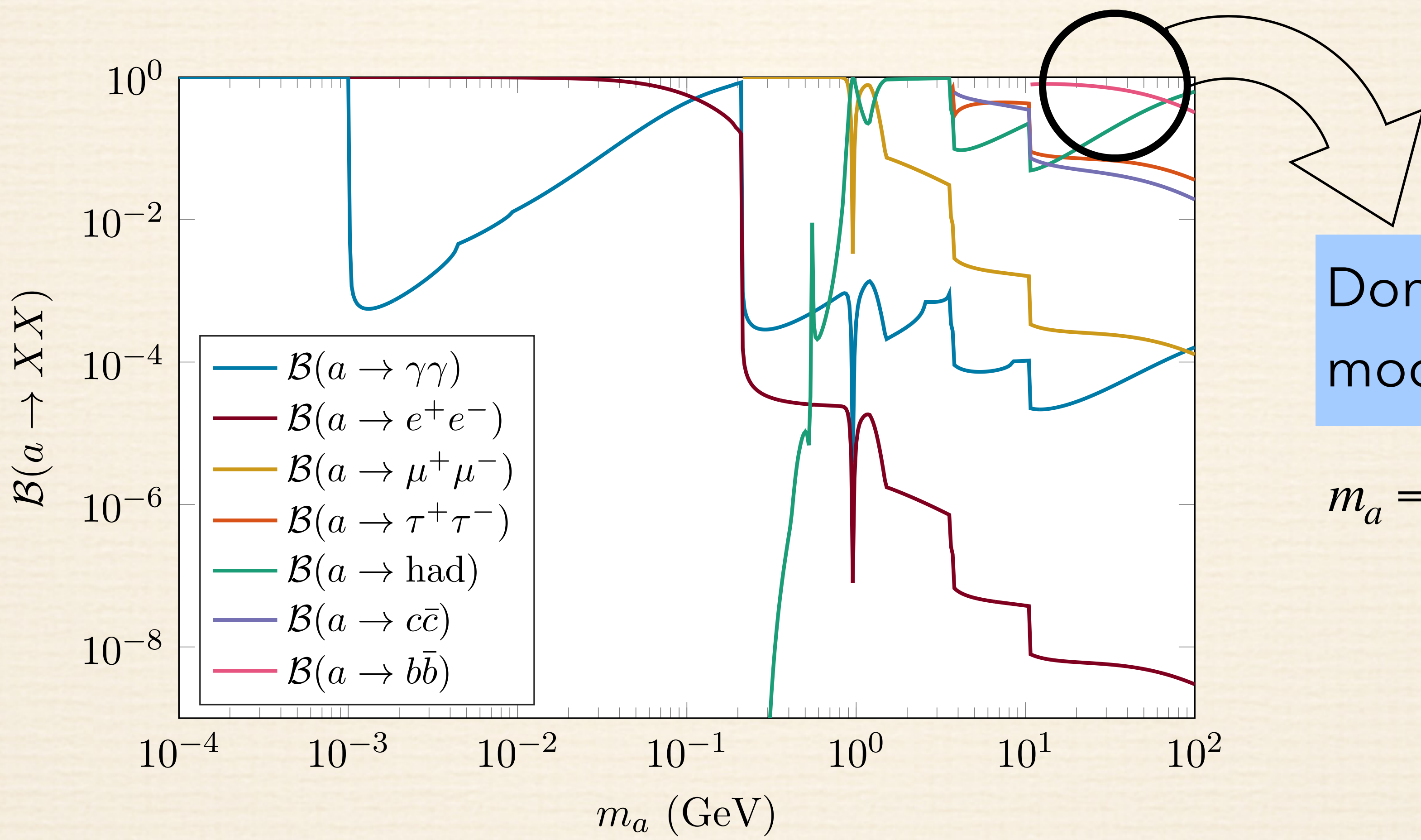
Lowering trigger p_T threshold : improving the reach in probing low mass region.

Pseudoscalar (ALP) Model

$$\mathscr{L}_{\rm ALP} \supset \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2 + i \sum_f g_{aff} m_f a \bar{f} \gamma_5 f\,, \quad (m_a,\ g_{aff})$$

ALP-fermion coupling : $g_{aff} = \dfrac{C_f}{f_a}$, C_f is dimensionless and f_a is an energy scale. We assume C_f to be universal for all SM fermions.

2209.03932, A. Bharucha, F. Brümmer, N. Desai, S. Mutzel



Dominant decay mode is $a \to b\bar{b}$

$m_a = \mathcal{O}(10 - 100)$ GeV

Branching ratio, $B(a \to b\bar{b}) = \dfrac{\Gamma(a \to b\bar{b})}{\Gamma_{\rm total}}$

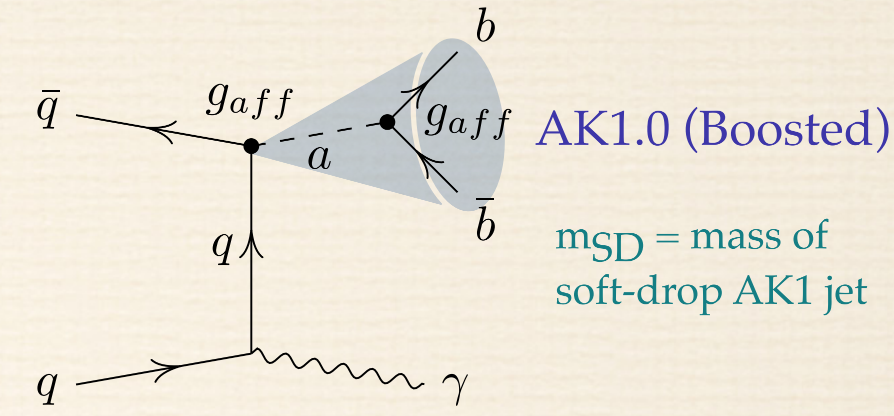
Signature we are looking for...(Signal and Backgrounds)

Signal :

$pp \rightarrow a\gamma \rightarrow b\bar{b}\gamma$ (a ≡ ALP)

ALP Mass Range : m_a = [12 , 100] GeV

Madgraph, Pythia8, Delphes

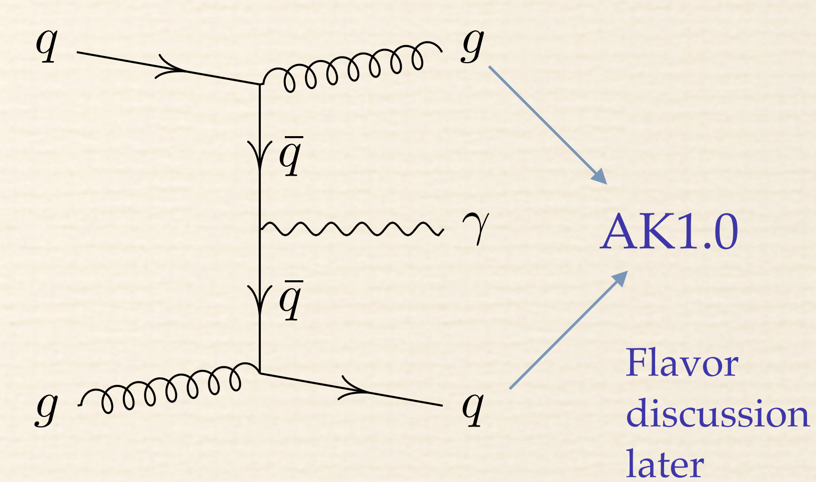


high $p_{T,\gamma}$

Backgrounds :

Multijet ∈ Multijet+γ, $W+\gamma$, $Z+\gamma$

Pythia8, Pythia8, Delphes



Grooming AK1.0 jet : Soft-drop ($z_{cut} = 0.1,\ \beta = 1$)

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2-prong discriminant observable

$$N_2^{DDT}(\rho, p_T) \equiv N_2 - N_2^{10\%}(\rho, p_T)$$

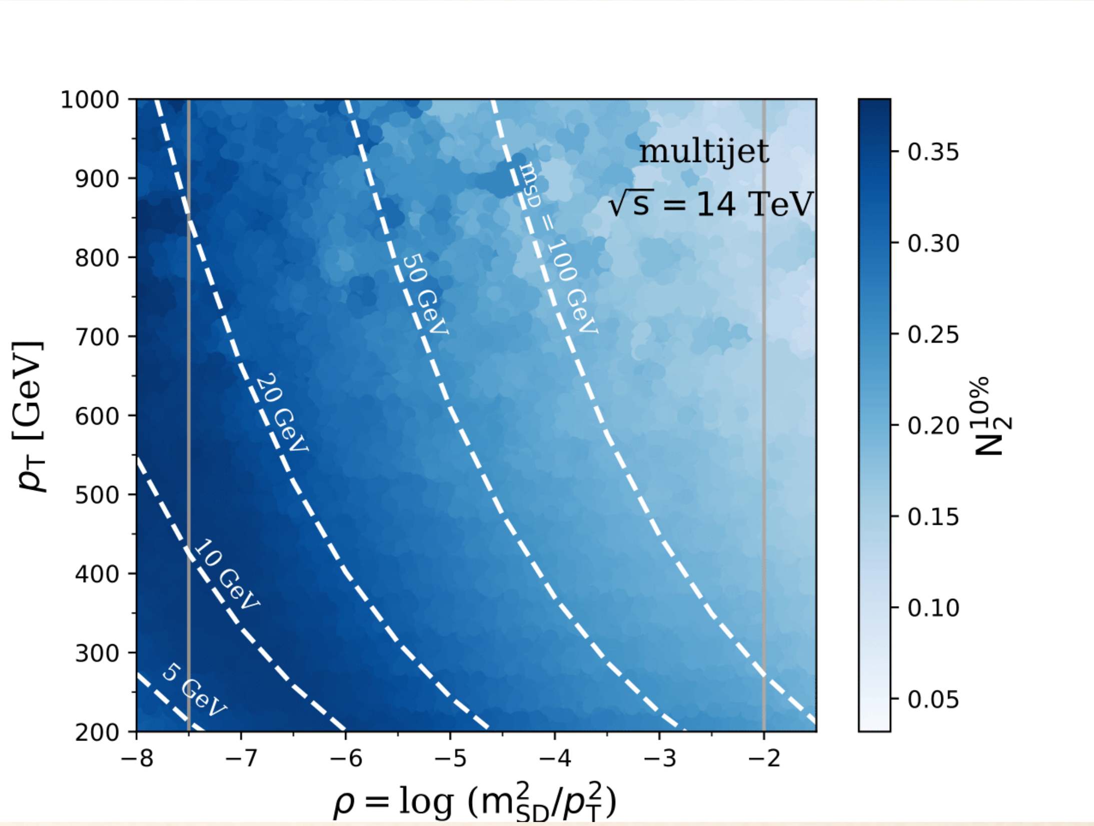
1603.00027, James Dolen, Philip Harris, Simone Marzani, Salvatore Rappoccio, Nhan Tran

N_2 **= 2-prong discriminating observable**

$$= \frac{{}_2e_3}{({}_1e_2)^2}$$

$N_2^{10\%}$ **= cut on N_2 to reject $90\,\%$ of multijet background events**

$\rho = \log(m_{SD}^2/p_T^2)$, a dimensionless scaling variable



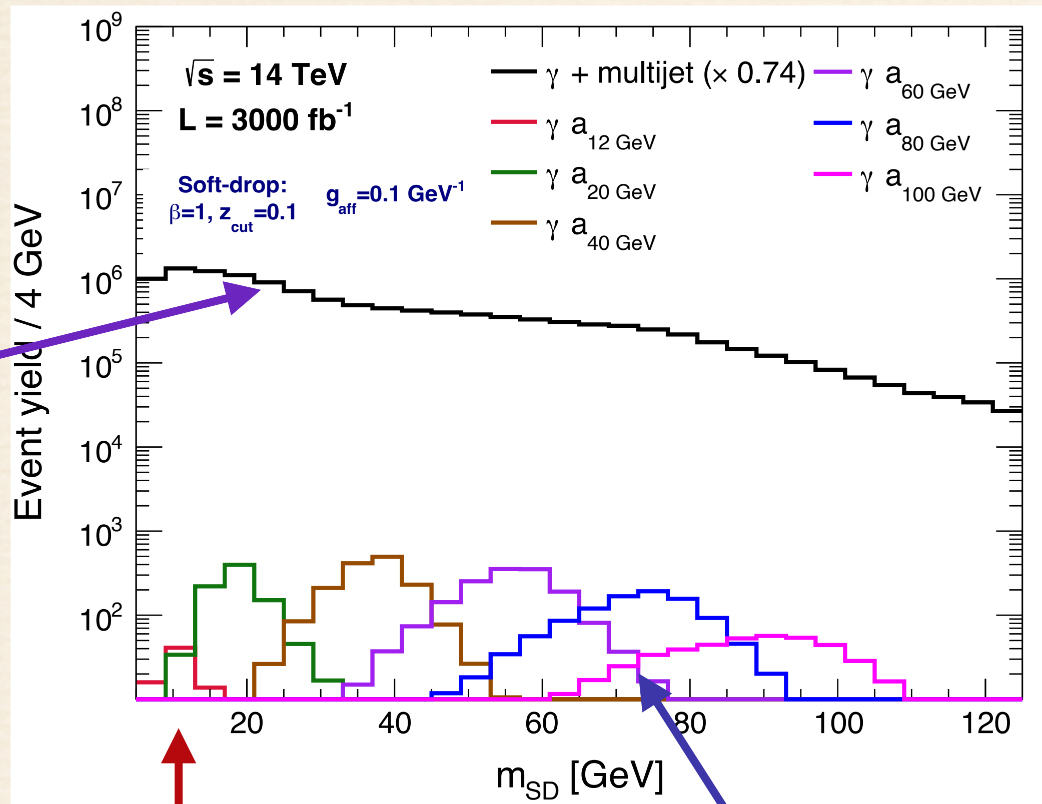
$N_2 = \frac{{}_2e_3}{({}_1e_2)^2}$ **= Ratio of energy correlation functions (ECF)**

1609.07483, Ian Moult, Lina Necib, Jesse Thaler

$${}_1e_2 = \sum_{1\le i<j\le N} z_i z_j \Delta R_{ij}\,, \quad {}_2e_3 = \sum_{1\le i<j<k\le N} z_i z_j z_k \min\left\{\Delta R_{ij}\Delta R_{ik}\,, \Delta R_{ij}\Delta R_{jk}\,, \Delta R_{ik}\Delta R_{jk}\right\}, \qquad z_i \equiv \frac{p_{T,i}}{p_{T,jet}}$$

m_{SD} variable and selection requirements

The shape of the QCD background distribution is matched to data samples.



Selection requirements	
$p_{\mathrm{T},\gamma}$	> 160 GeV
$\lvert\eta_\gamma\rvert$	< 2.1
$p_{\mathrm{T,AK1.0}}$	> 200 GeV
$\Delta R(\gamma,\ \mathrm{AK1.0})$	> 2.2
ρ	$[-7.5, -2.0]$
$\mathrm{N}_2^{\mathrm{DDT}}$	< 0

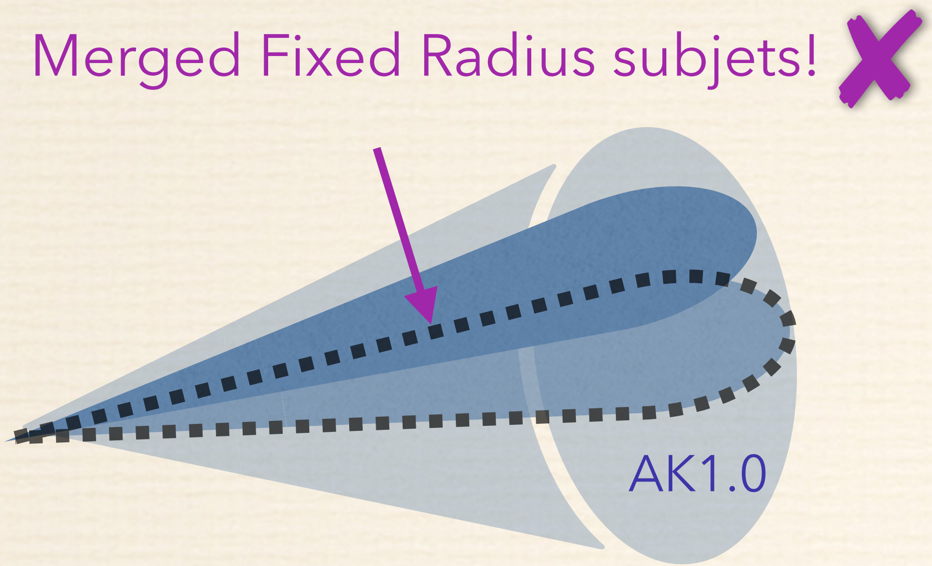
N_2 is inefficient for low mass resonances :

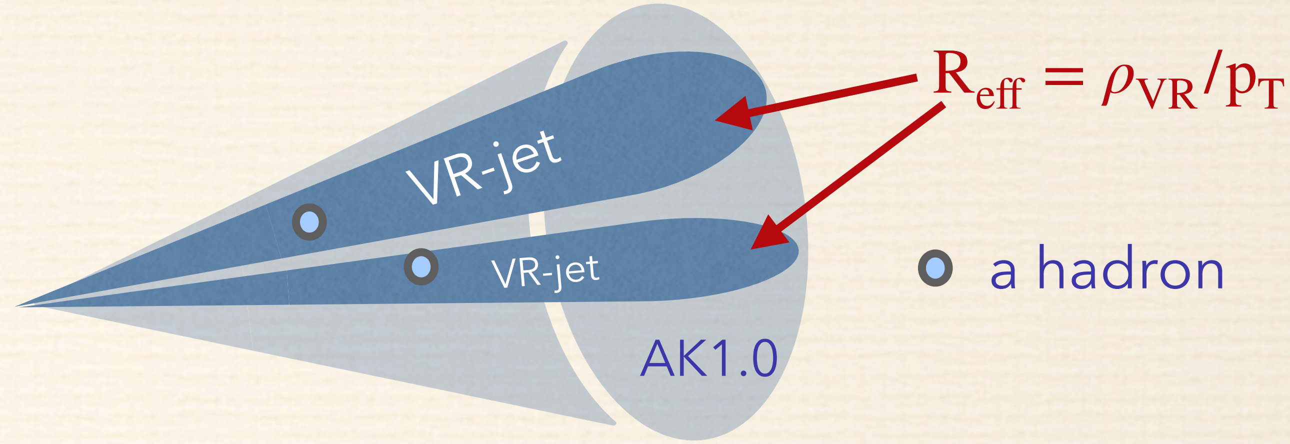
In the limit of mass << p_T , jet loses 2-prong feature.

AK1.0 jet radius is insufficient to contain all hadronisation objects

b-tagging of AK1.0 jet

Find two small radius subjets, variable radius (VR), inside AK1.0 jet and **match each of them to a hadron** in event.





Categories in multijet background : **bb, bc, bl, ll,cl,cc**

b : b-jet **c** : c-jet **l** : light-jet

Multijet background						
Category	*bb*	*bc*	*bl*	*ll*	*cl*	*cc*
Fractional composition (%)	0.6	0.5	1.2	84.4	10.5	2.8
GN2X efficiency [50]	0.59	0.21	0.07	0.21×10^{-3}	0.41×10^{-2}	0.02

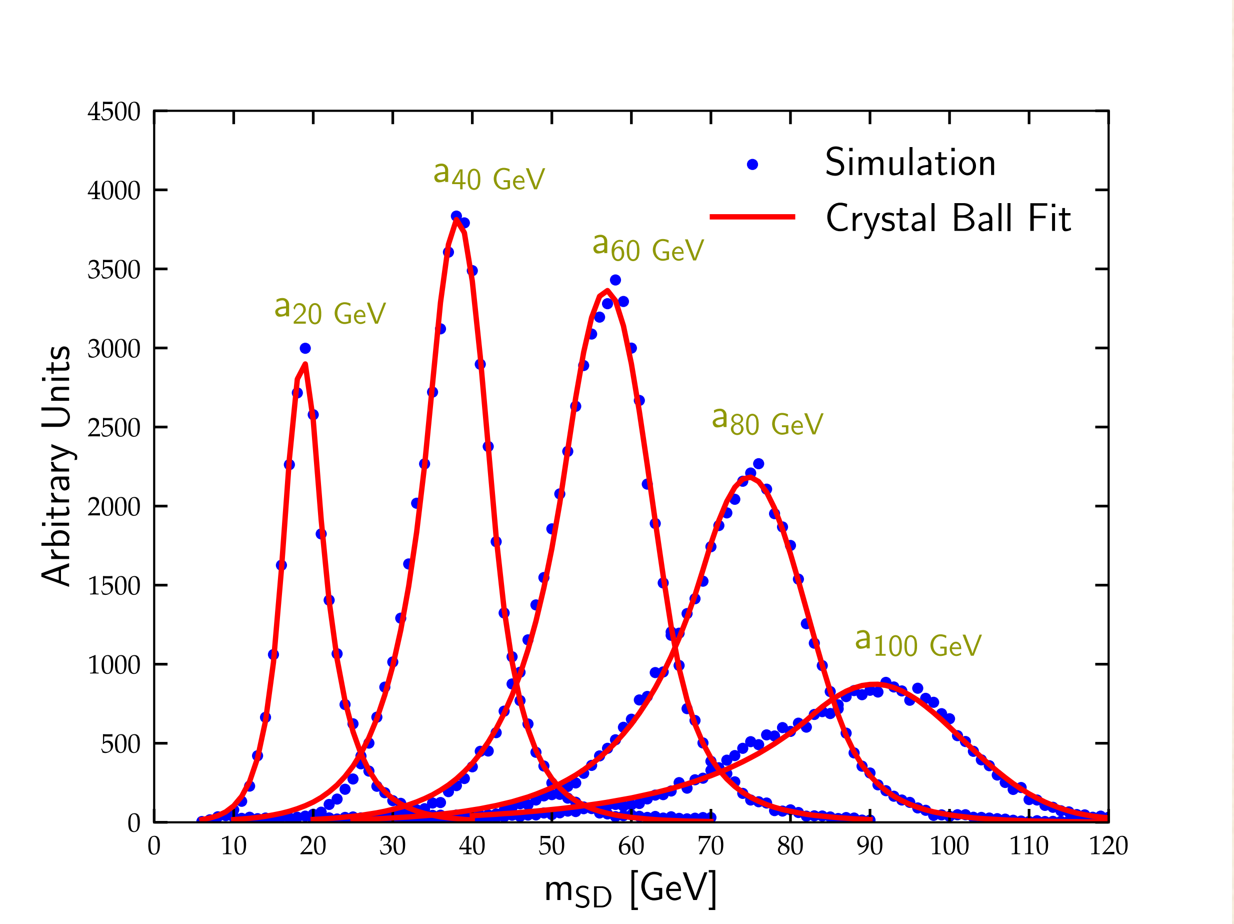
corresponding to **80% bb-tag**ging efficiency

ATL-PHYS-PUB-2023-021

VR parameters	
$p_{T,subjet}$	> 7 GeV
R_{min}	0.02
R_{max}	0.4
m_a [GeV]	ρ_{VR} [GeV]
12, 20, 30	5
40, 50	10
60, 70	20
80, 90, 100	30
Matching parameters	
$p_{T,hadron}$	> 5 GeV
ΔR(hadron, VR)	< 0.3
ΔR(hadron/VR, AK1.0)	< 1.0

Signal and background estimation

Crystal ball fits to the m_{SD} variable :



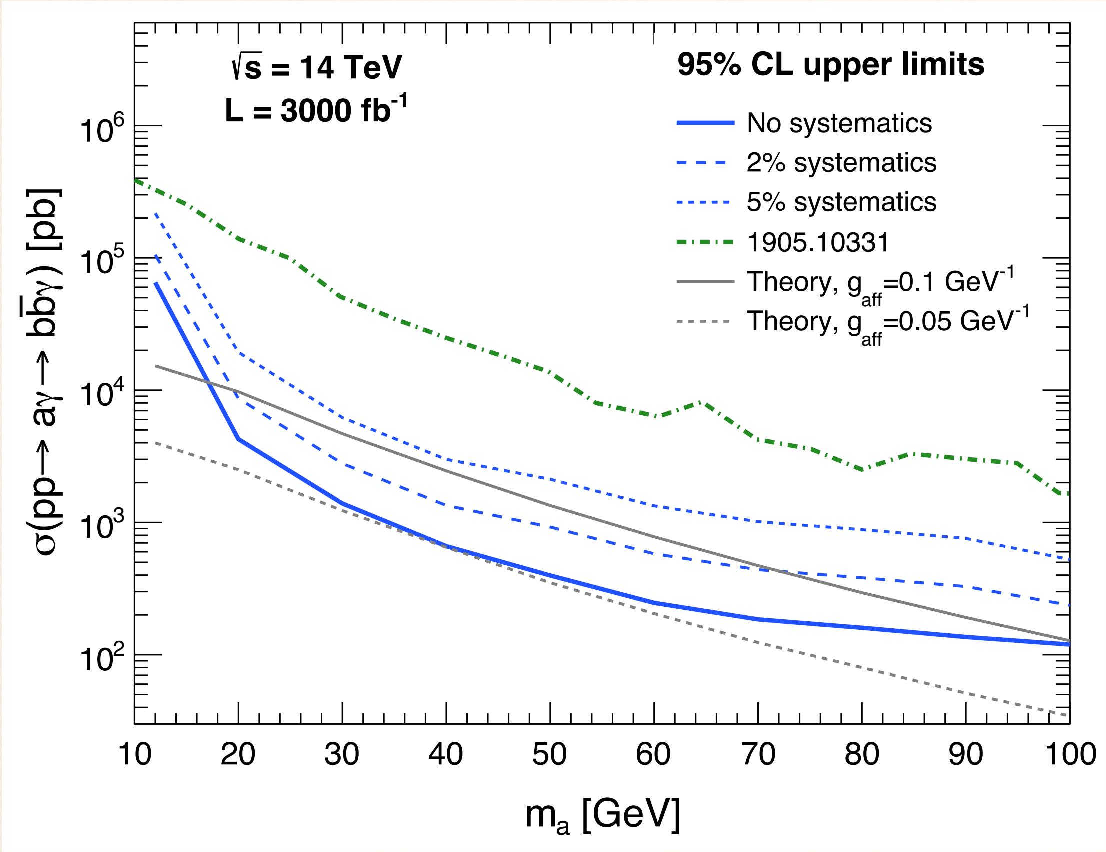
Chosen mass range = $[\mu + \sigma, \mu - \sigma]$.

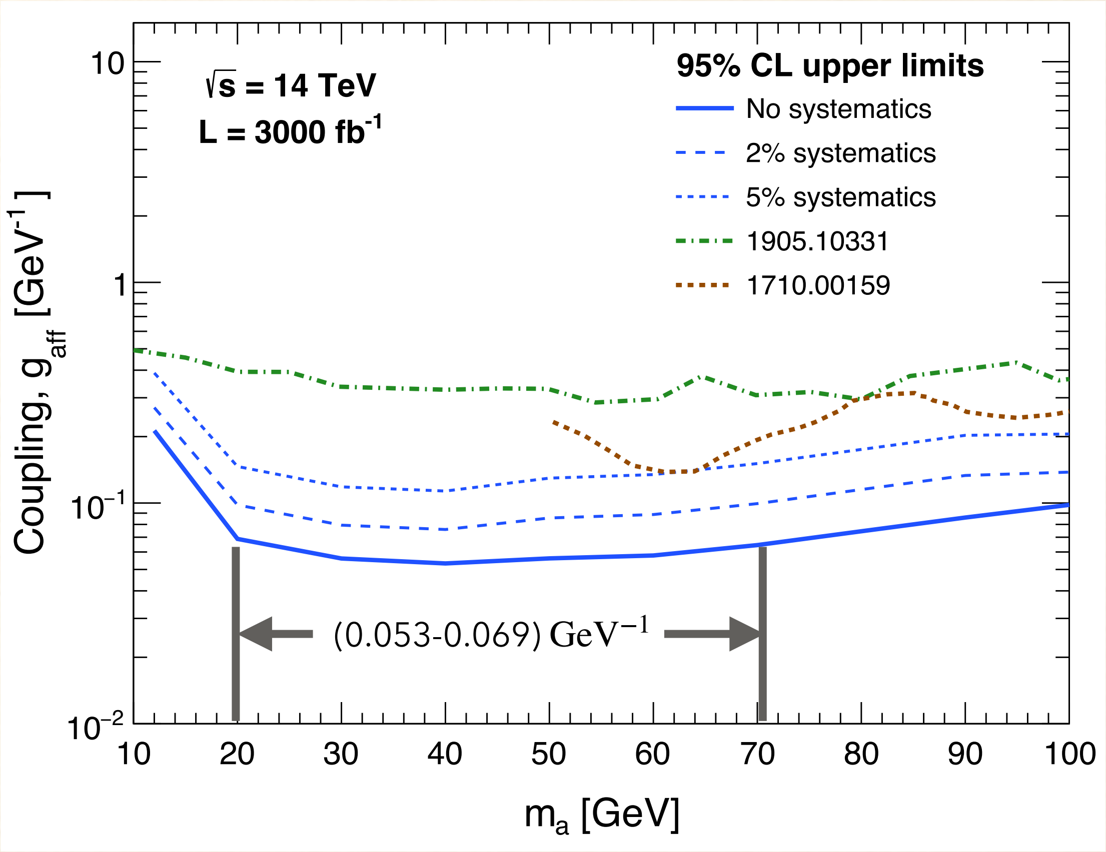
Projected sensitivities

95 % **CL exclusions on :**

$\sigma(pp \to a\gamma \to b\bar{b}\gamma)$

g_{aff}



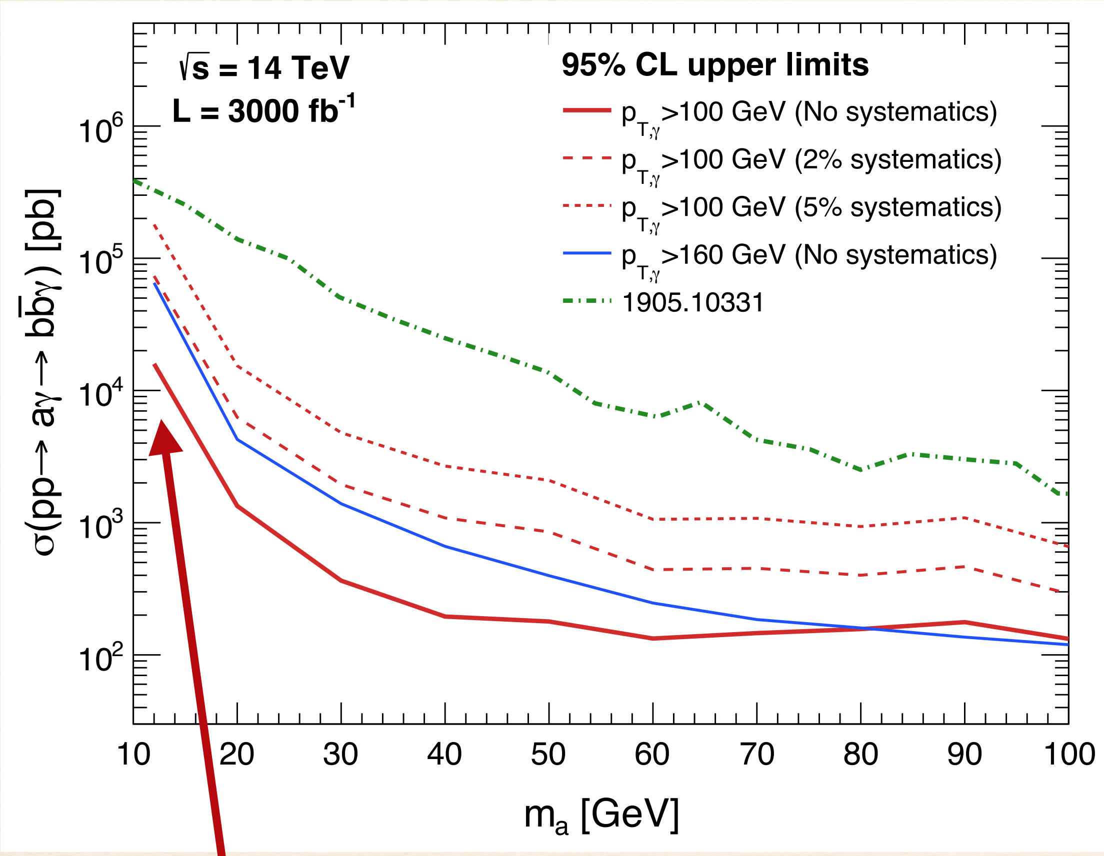


Lowering p_T threshold

$p_{T,\gamma} >$ **100 GeV** , $p_{T,AK1.0}$ **= 100 GeV**

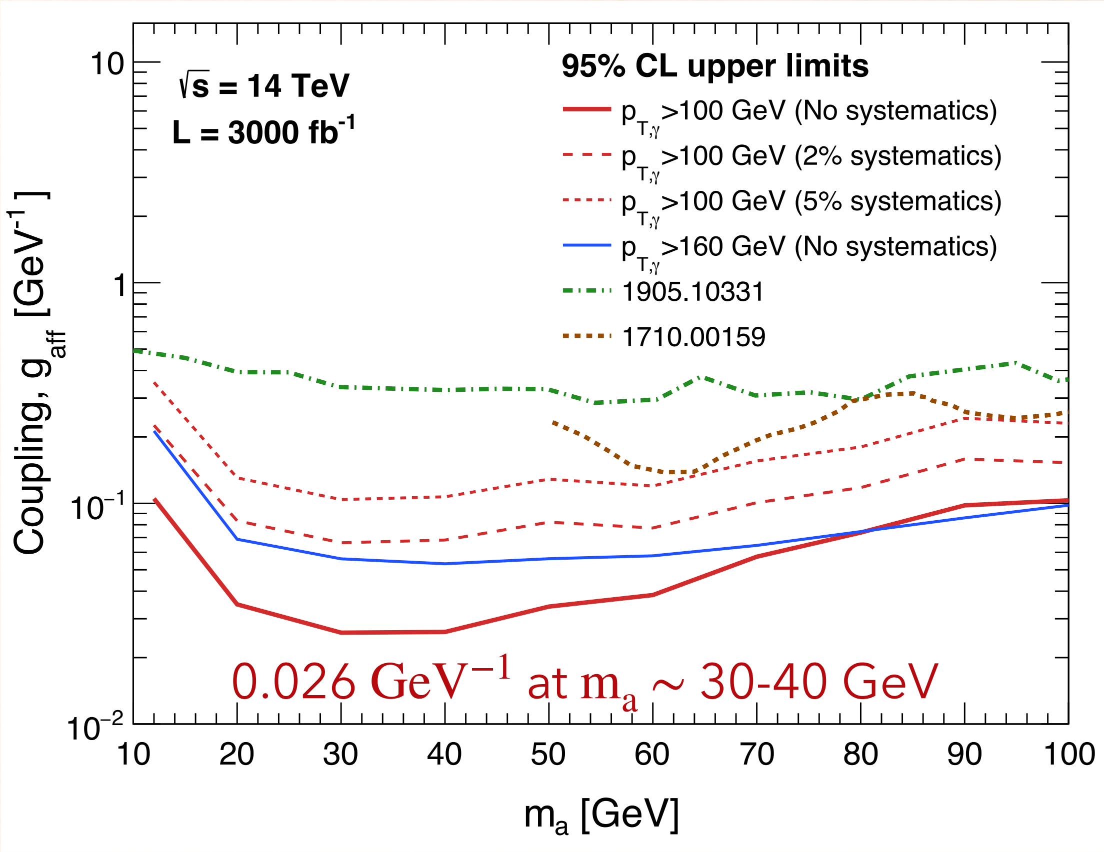
95 % **CL exclusions on :**

$\sigma(pp \to a\gamma \to b\bar{b}\gamma)$



4x improvement at m_a = 12 GeV

g_{aff}



Summary and outlook

- Light resonance searches are important along with TeV scale physics as a solution to many BSM physics.
- ALPs are an interesting avenue to look for light scalars.
- They can be looked for in different kind of final states at LHC. We explored associated production here.
- Jet substructure techniques can improve analysis in most of the low mass regions.
- b-tagging is important to reject backgrounds in these kinds of signature.
- Possibly new trigger requirements may improve these searchers further.
- The techniques used can be applied to any low mass resonance decaying to $b\bar{b}$.
- Machine learning can be used over jet substructure observables.

Thank you

Changing the β parameter

Soft-drop condition : $\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$