Low-mass resonances at the LHC

Diego Redigolo

based on 1710.01743, 1810.09452 and to appear

with X. Cid Vidal, M. Low, A. Mariotti, F. Sala, K. Tobioka

+ preliminary work with ATLAS

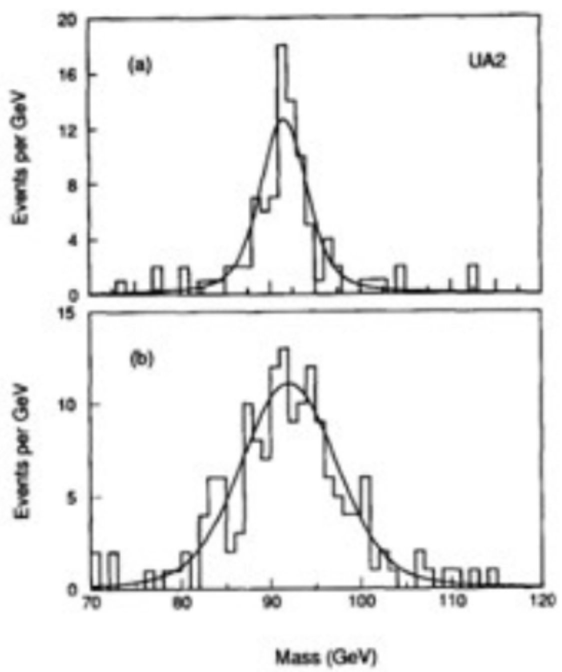
INTRODUCTION

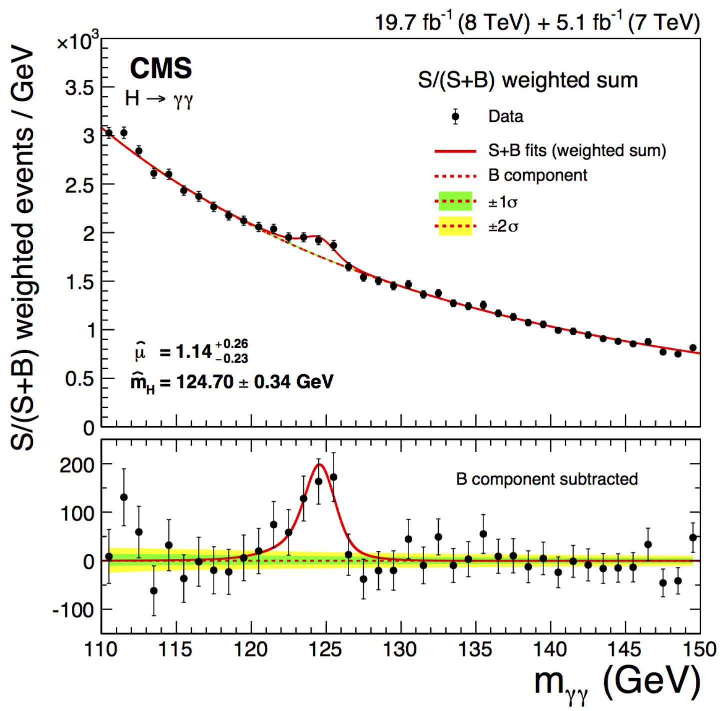
experimental & theoretical motivation

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

famous discoveries:

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





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 …

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How to go further?

I will show that 1) and 2) are not justified assumptions
in the specific example of diphoton resonances and comment in the end on other cases

I would like to make some general comments about 3)

How to go further?

1) The current status highly depends on the nature of the final state

2) A systematic study of light resonances
decaying into two objects with different production mechanisms is needed!

FINAL STATES

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

dijets *dittaus* *dihiggses*

PROD.

single *associated* *VBF*

gluon-fusion

+jet

…

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PROD.

single — gluon-fusion | *associated* — +jet | *VBF*

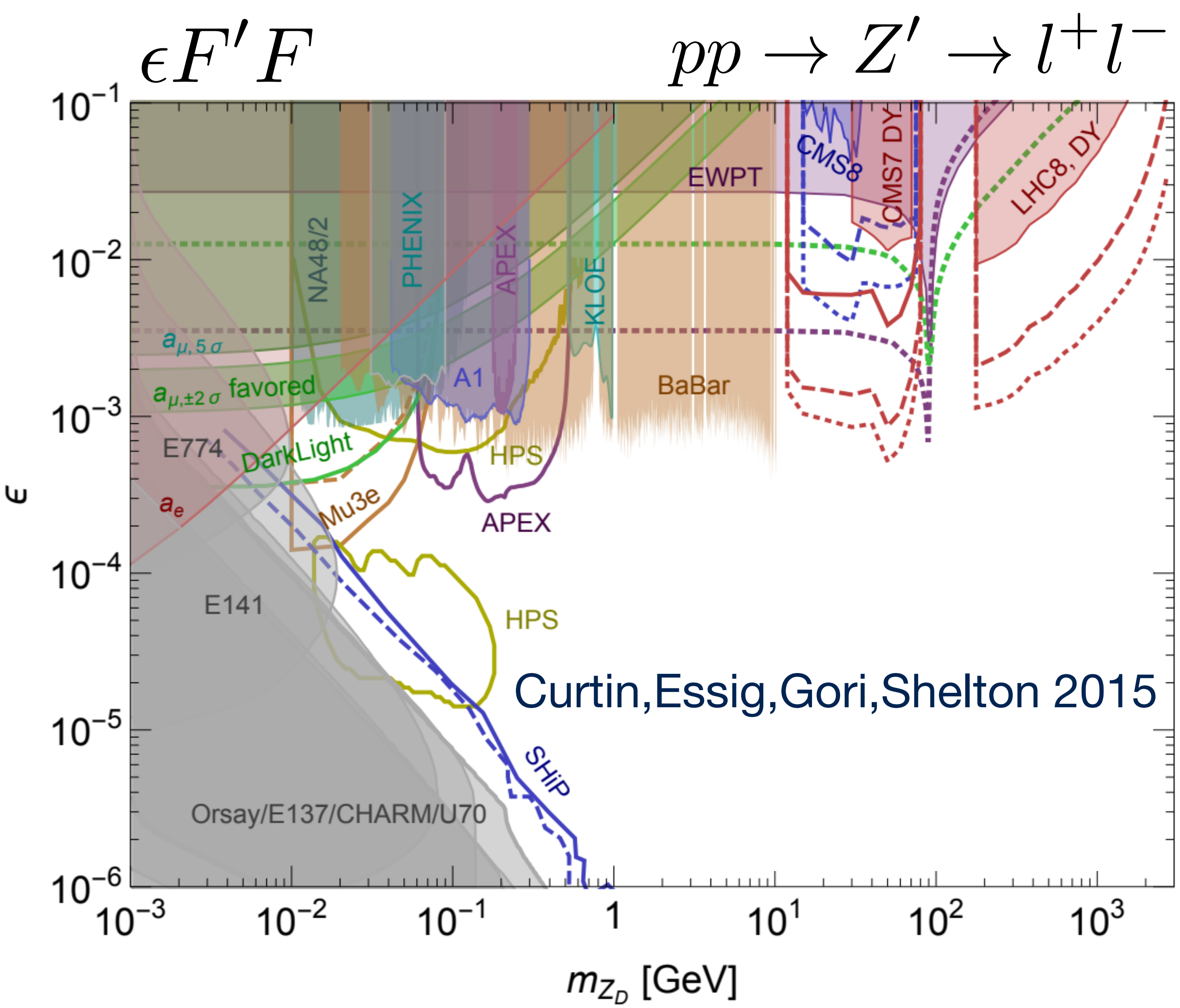
. . .

FOCUS OF THIS TALK

The "easy" case

of di-lepton resonances

dileptons $(e\,,\mu)$



- as low as 10 GeV with standard triggers
- LHCb promises to improve @ low masses

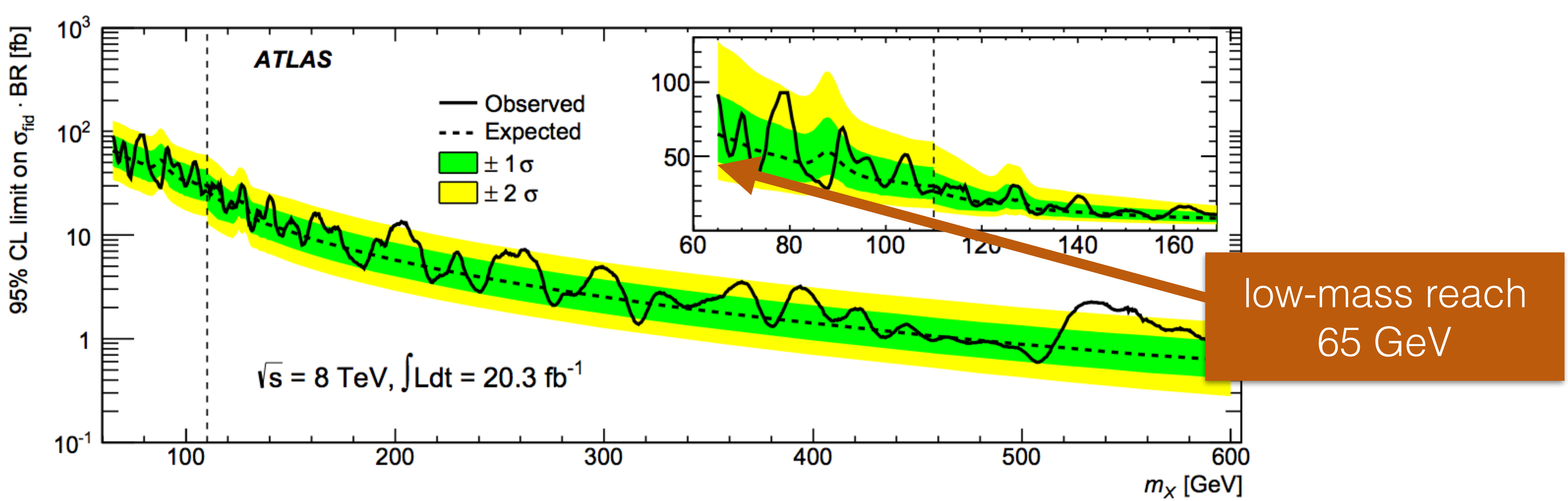
  Ilten, Soreq, Thaler, Williams, Xue 2016

- Below 10 GeV B factories take over

The harder case

of di-photon resonances

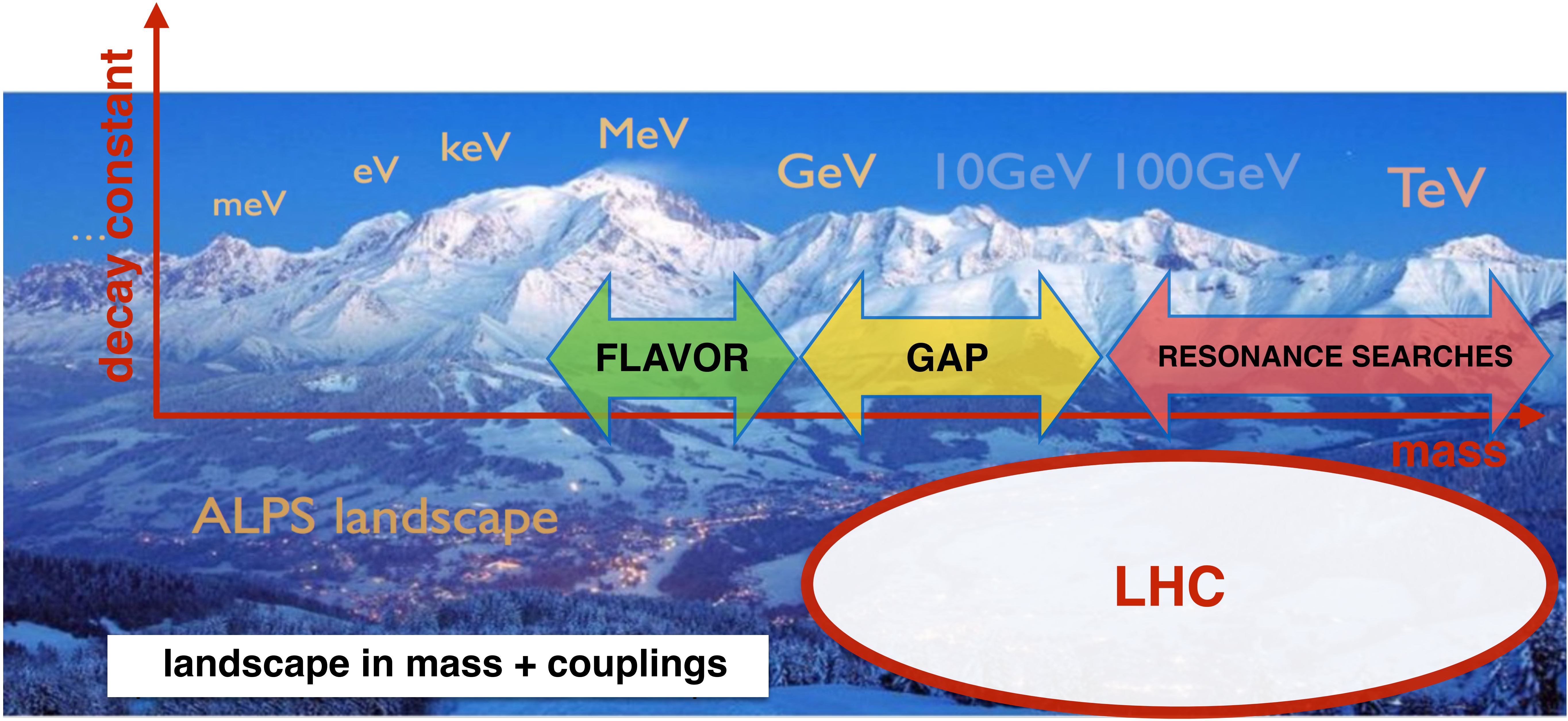
diphoton :



Can we go *below* that?

Is there a motivation?

ALPs at colliders



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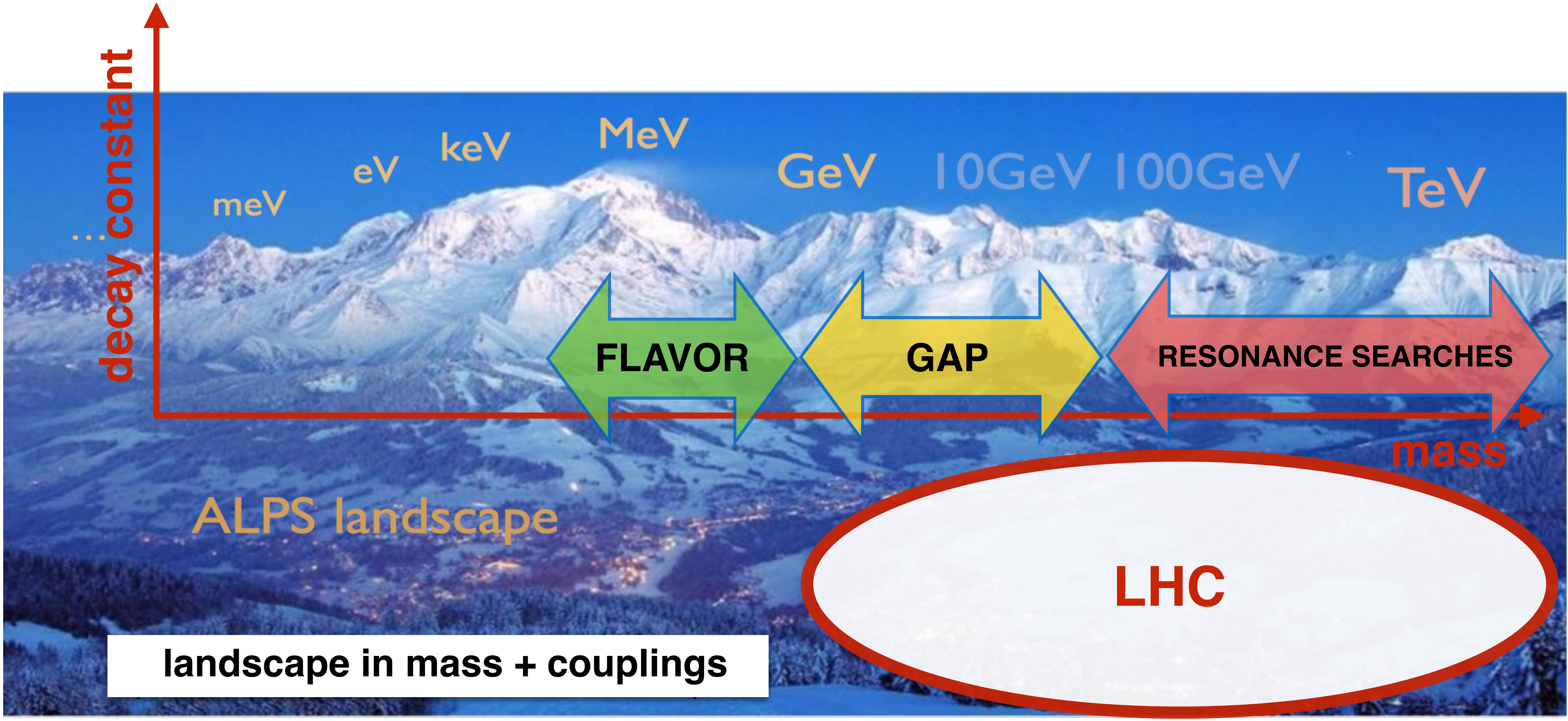
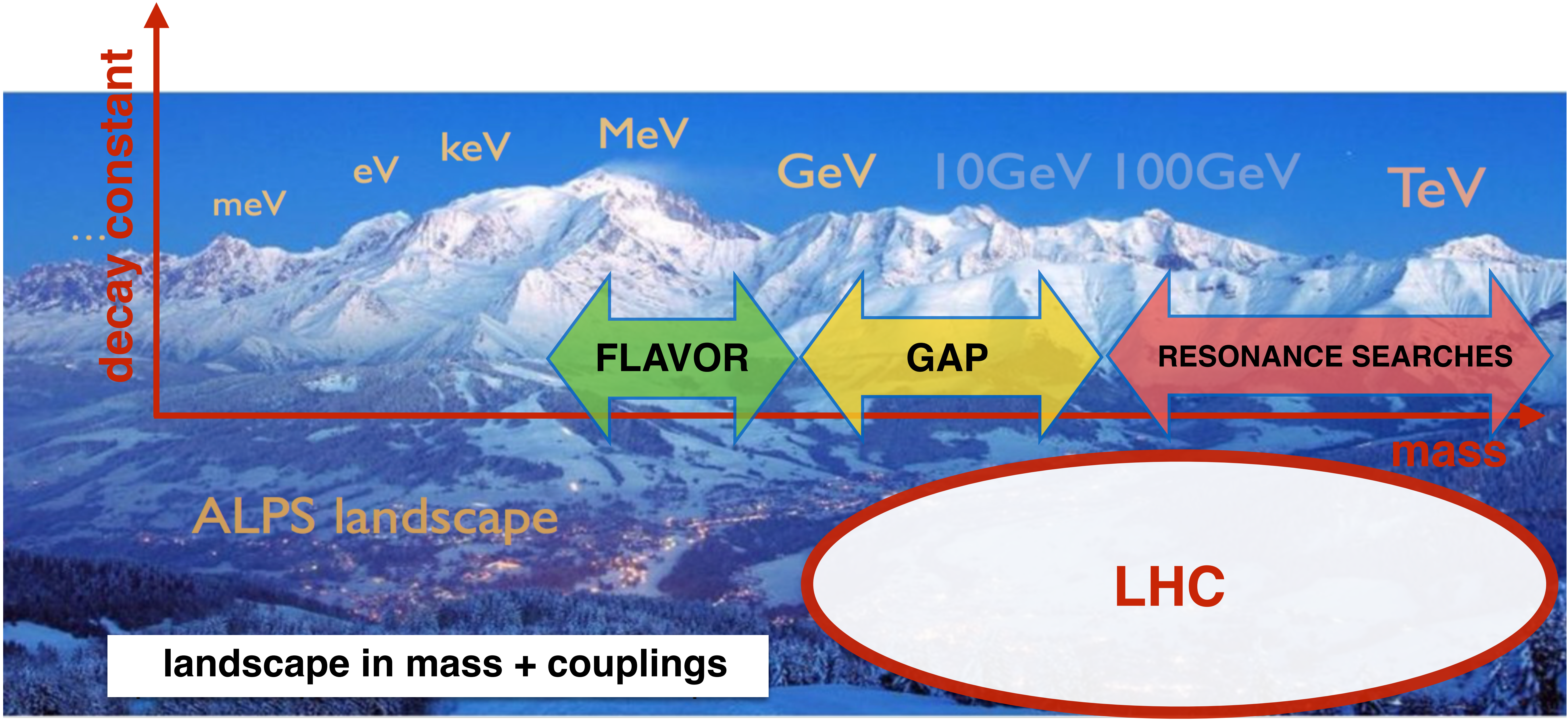


GAP in the reach between 65 and 1 GeV not covered by flavor searches!

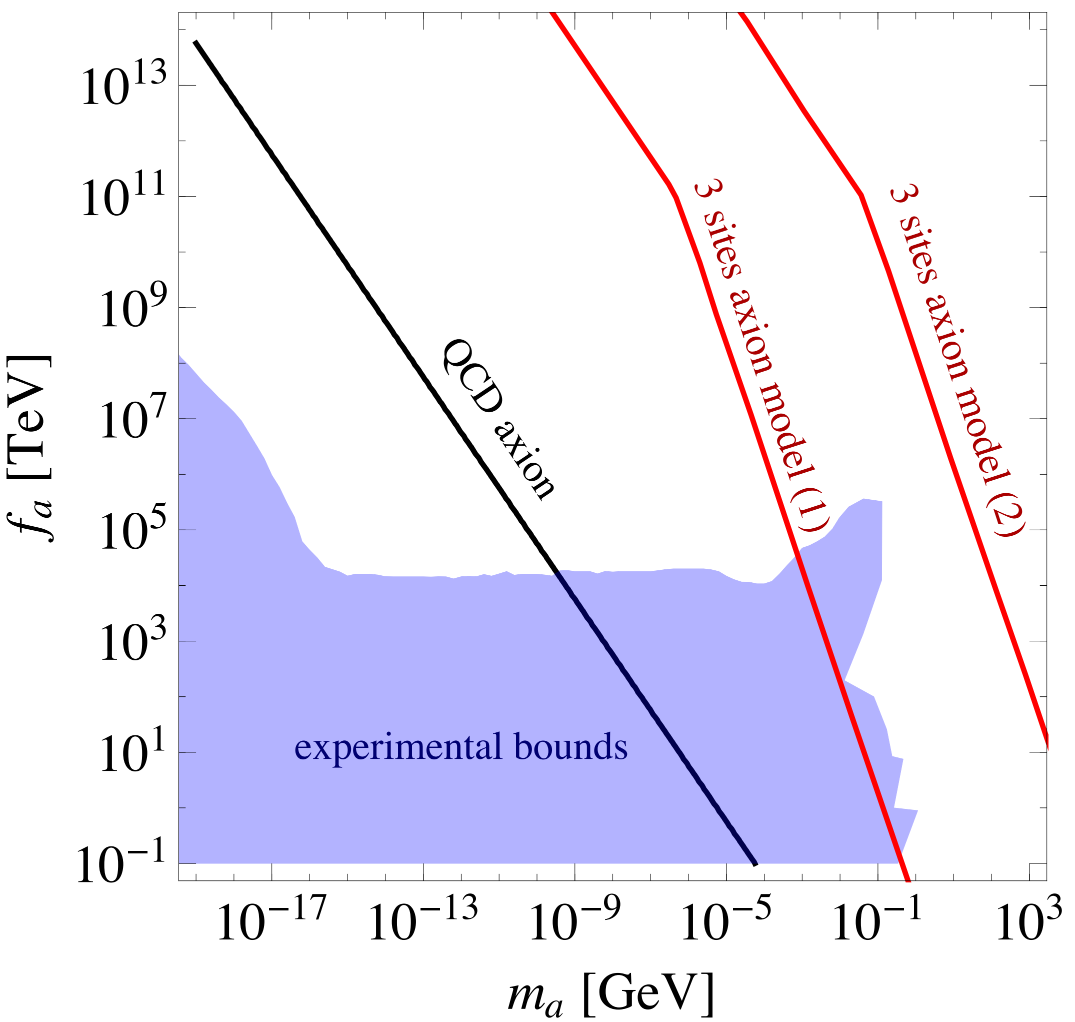
ALPs at colliders



GAP in the reach between 65 and 1 GeV not covered by flavor searches!

How we fill this GAP?

MOTIVATION I: *LHC can test solutions of the strong CP problem*



- "UV Axion models" predict "heavy axion"

  Berezhiani et al.'00, Hook '14 -'16, Yanagida et al '15,
  Dine-Seiberg '86, Agrawal Howe '17…

- Coupling to gluons to address strong CP

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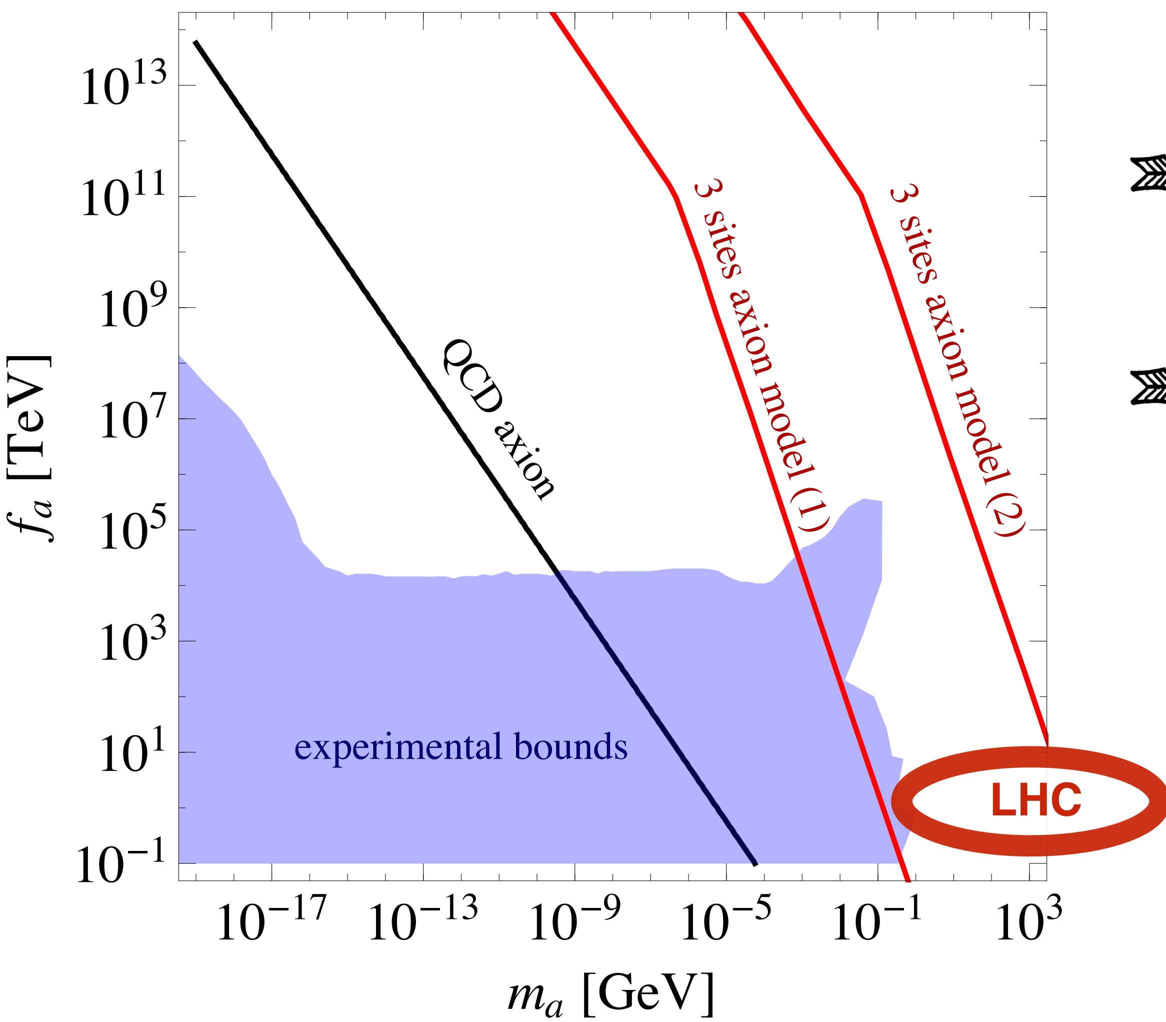

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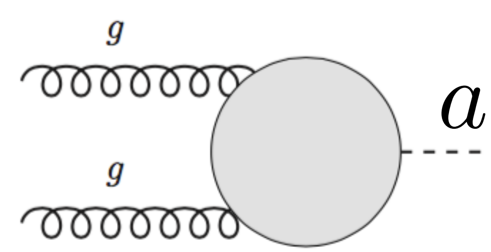
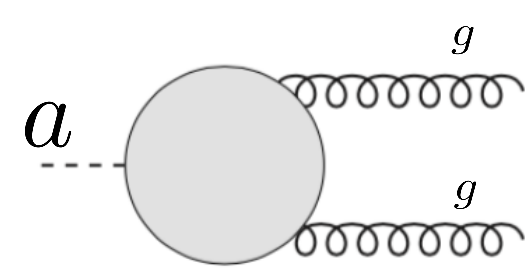


gluon fusion



promptly decay

$m_a \gtrsim 3 m_\pi$

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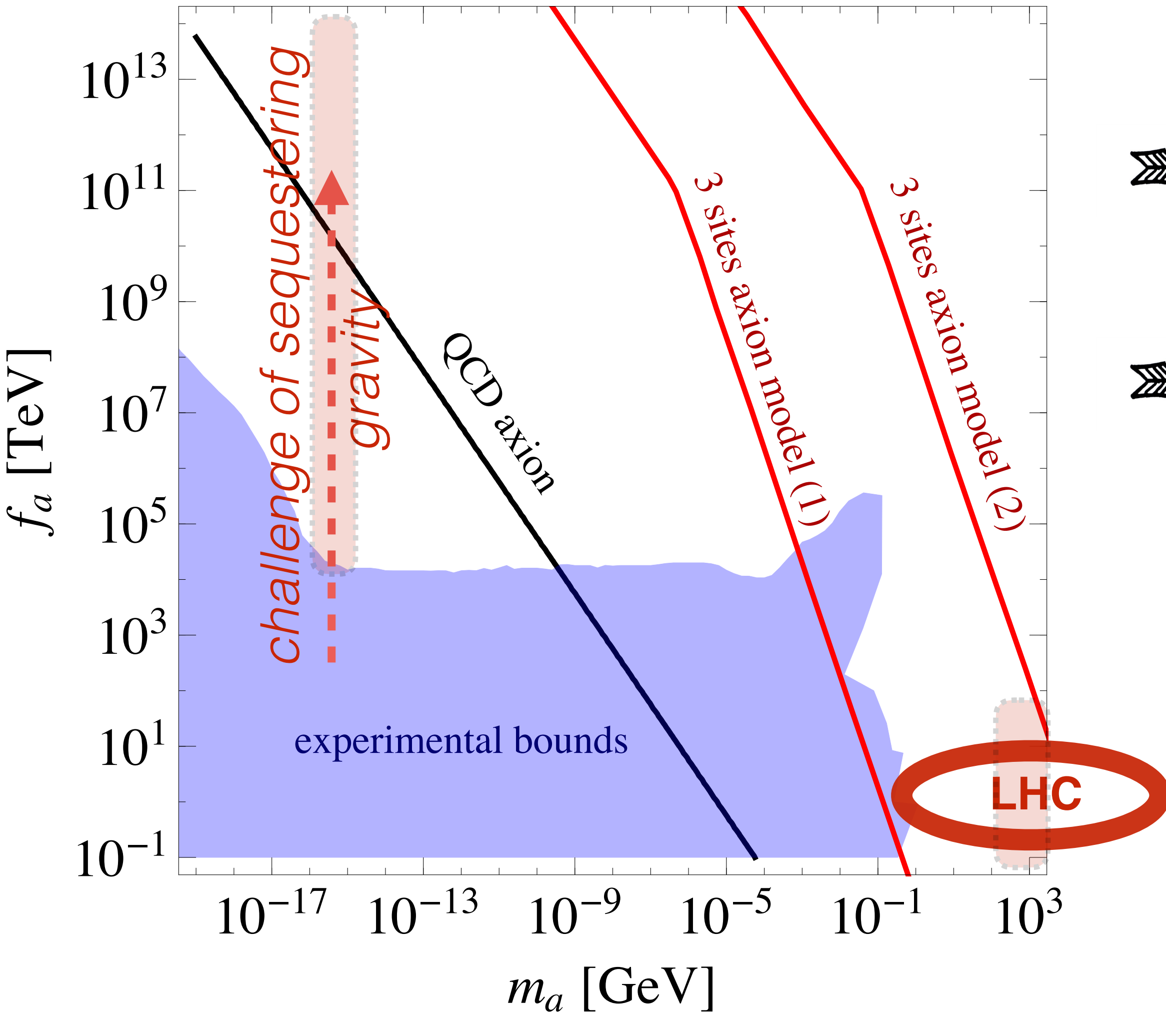

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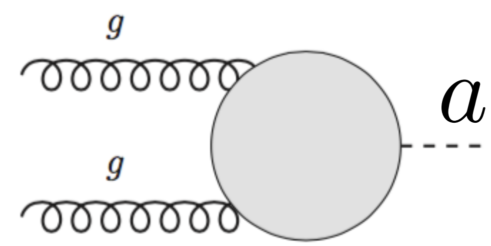

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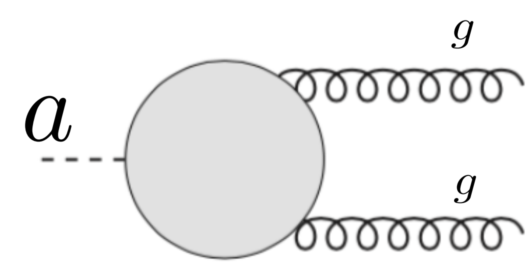
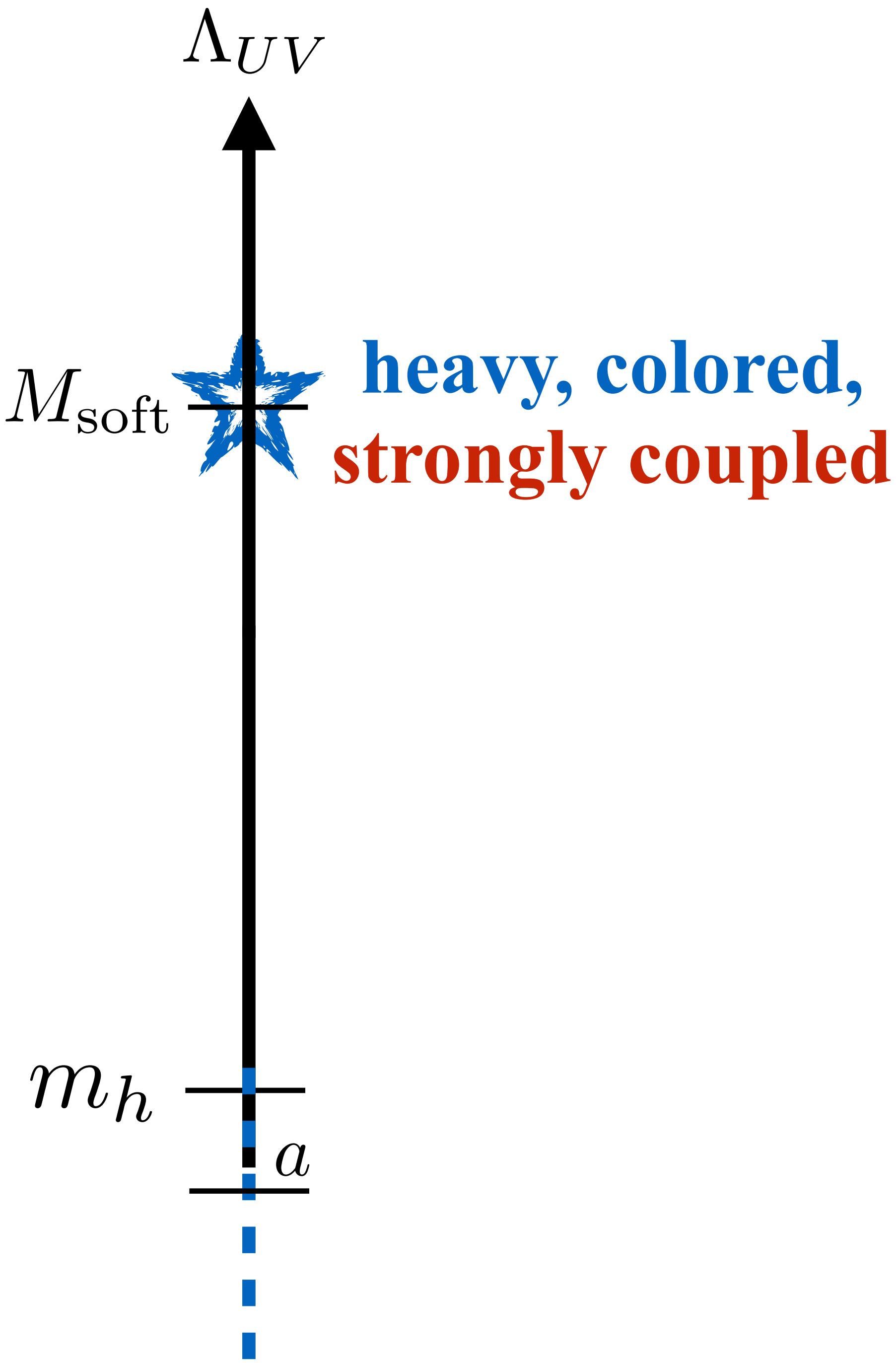


promptly decay

$m_a \gtrsim 3 m_\pi$

LHC can probe the region where the "axion quality" is solved

MOTIVATION II: *schemes of Naturalness*



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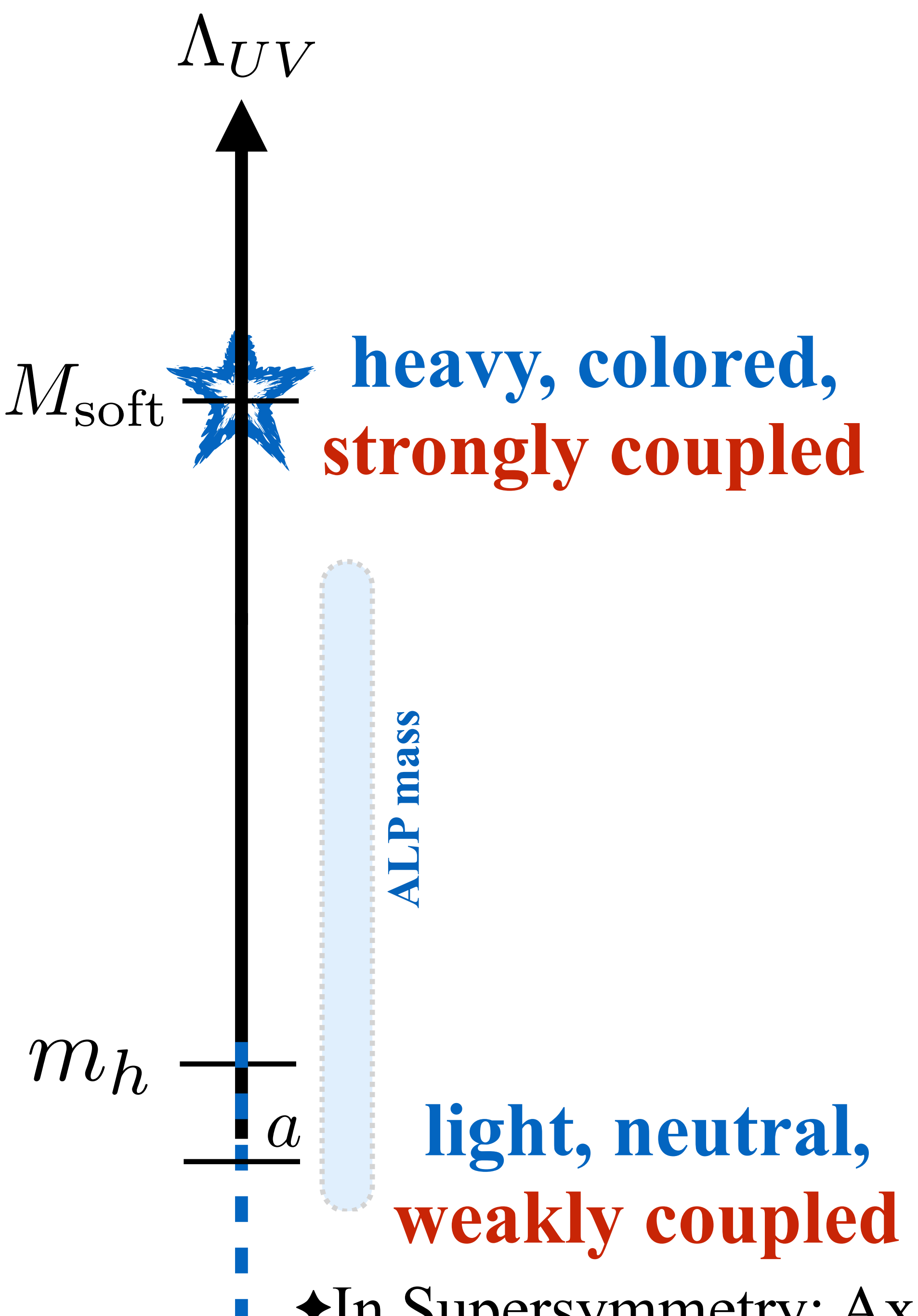

✦In Supersymmetry: Axion from R-symmetry

(Bellazzini Mariotti, D.R , Sala, Serra,'17)

✦In Composite Higgs: Extra PGB from Ferretti's cosets

(Ferretti et al. '17)

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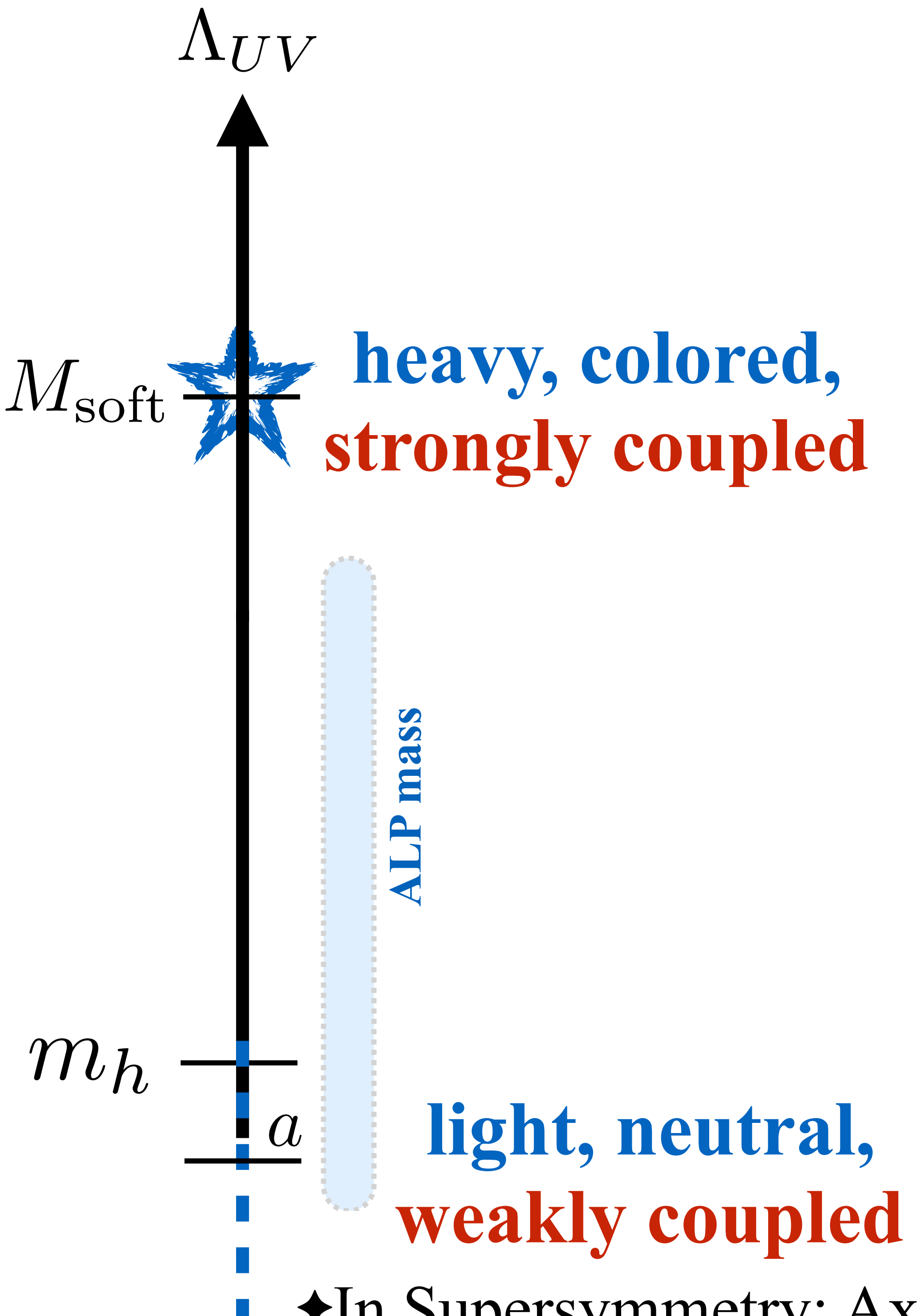

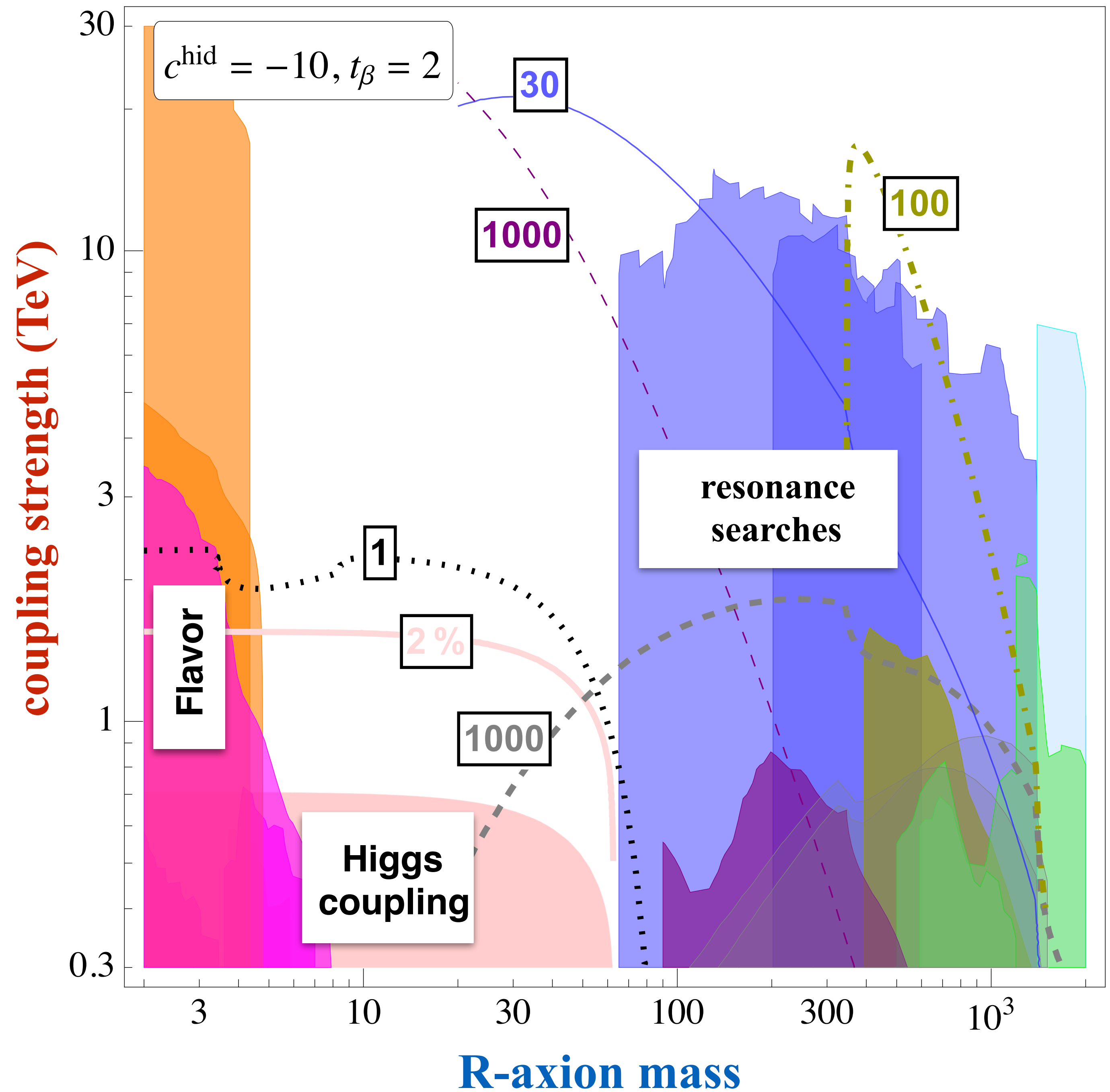

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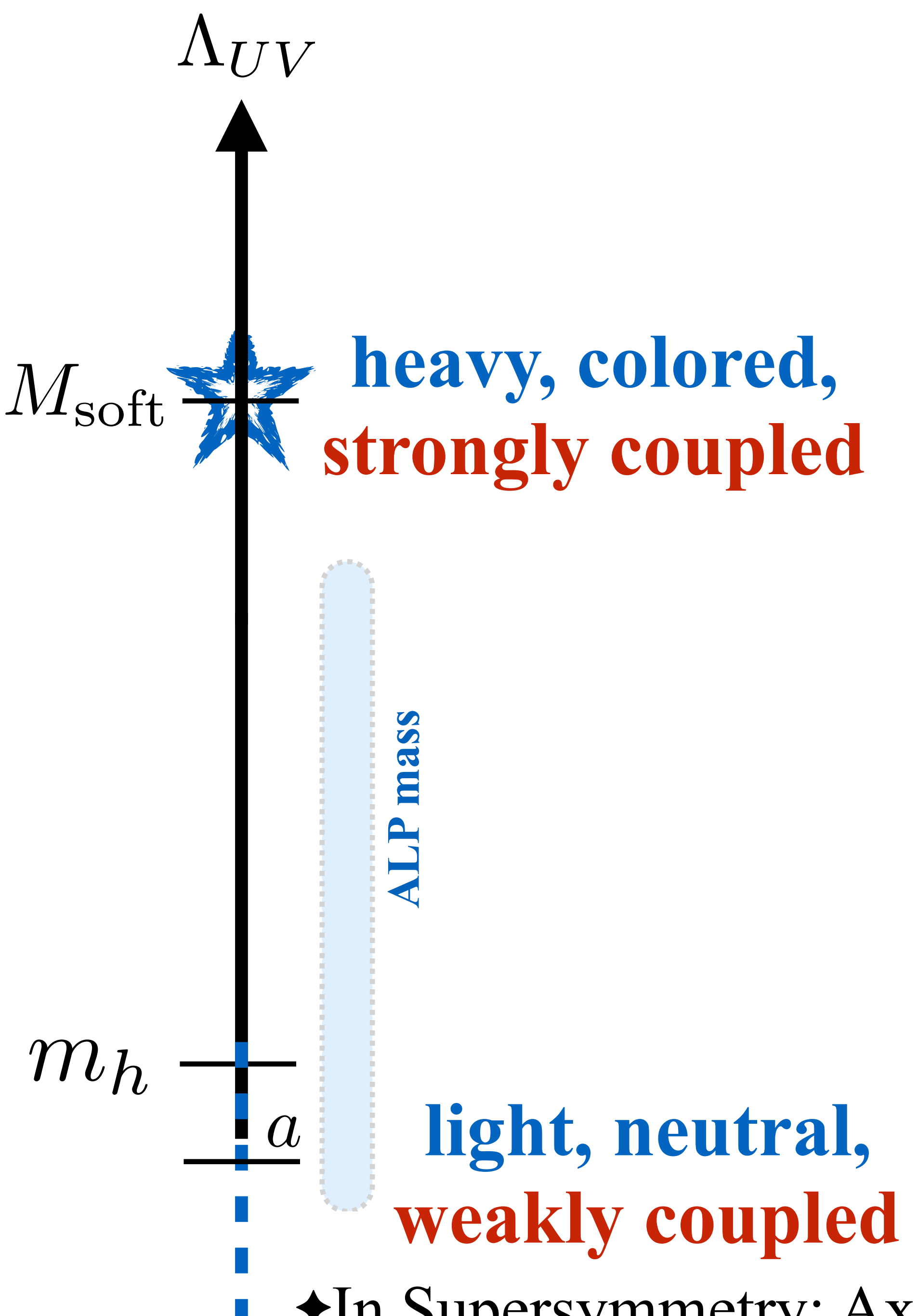

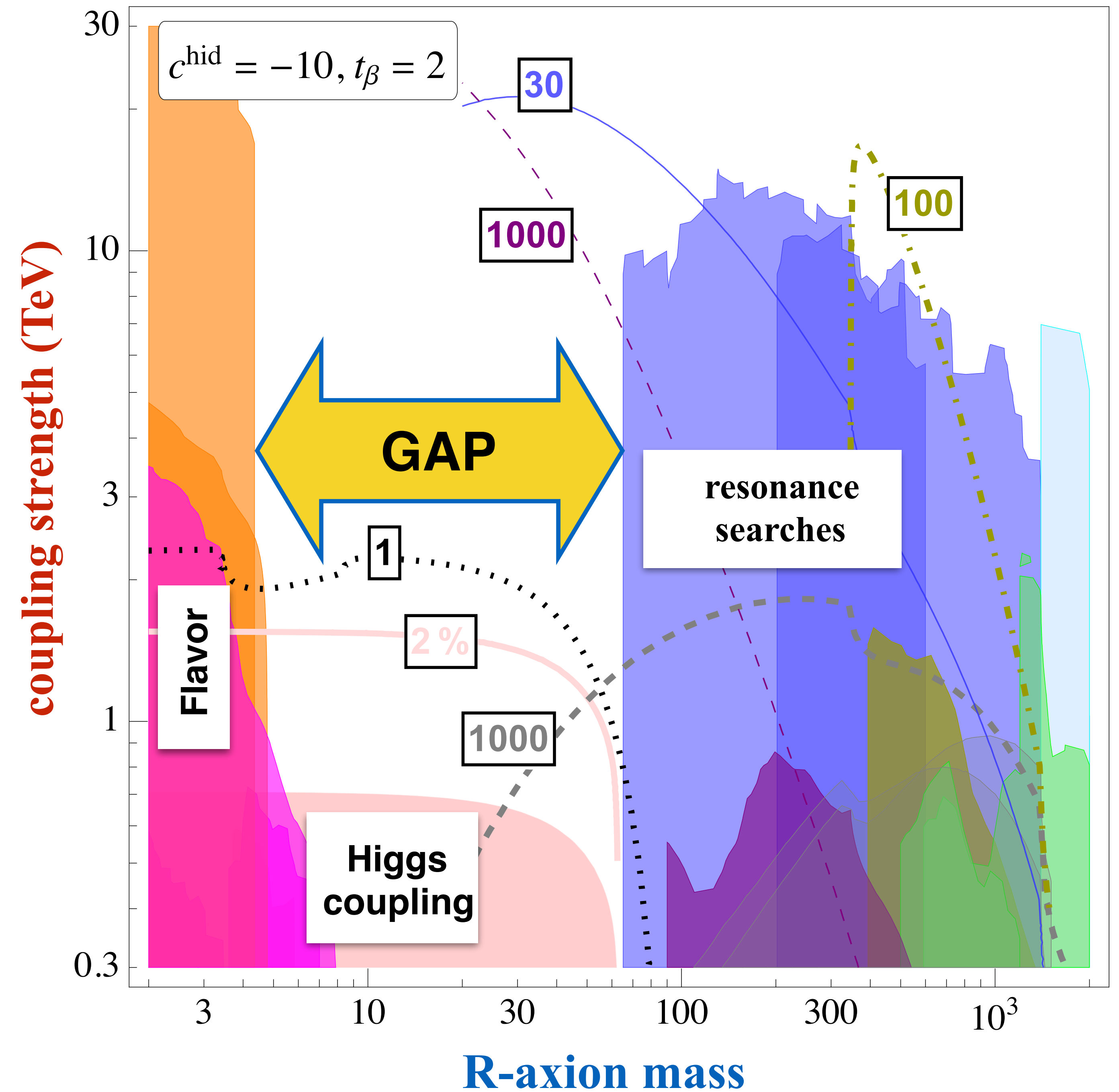

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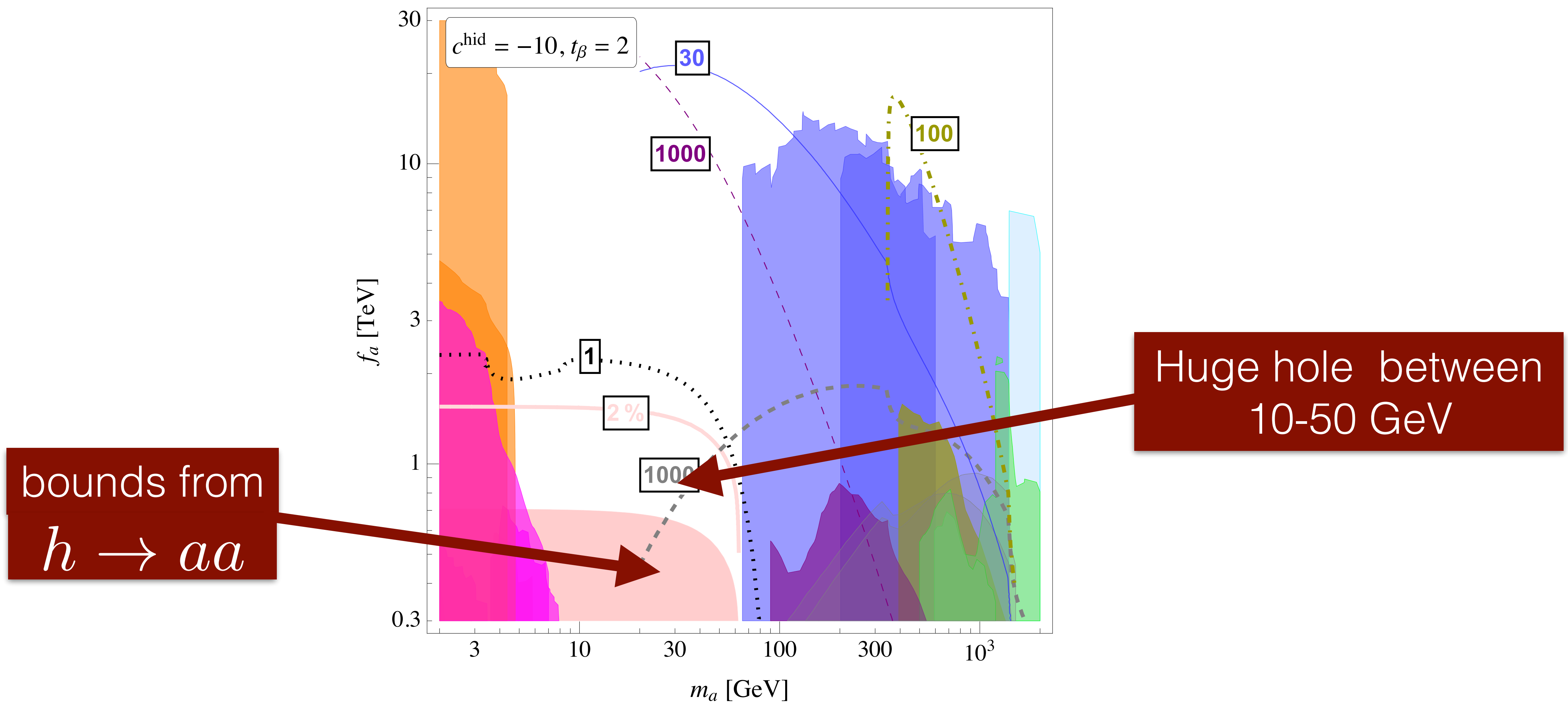
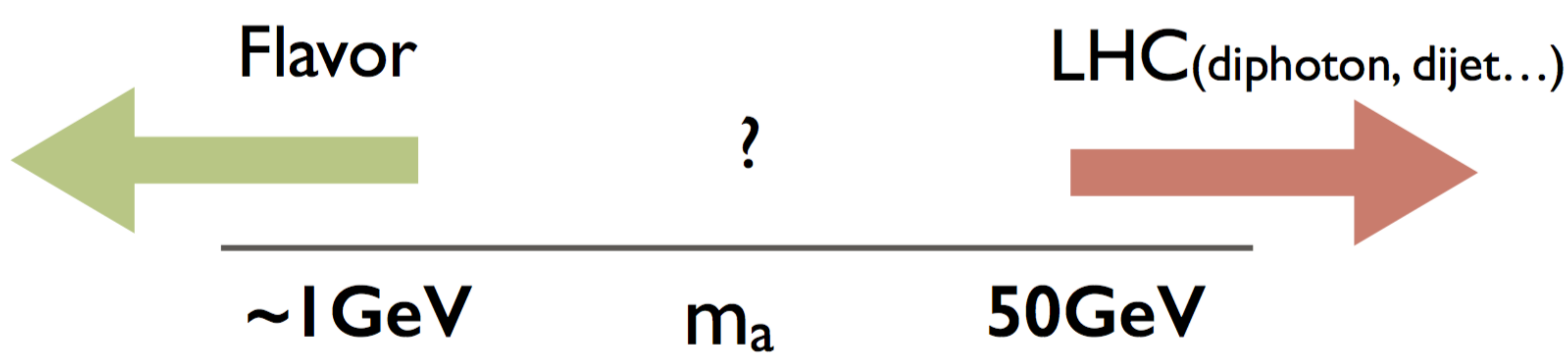
Specifically for Axion-like particles of the KSVZ-type

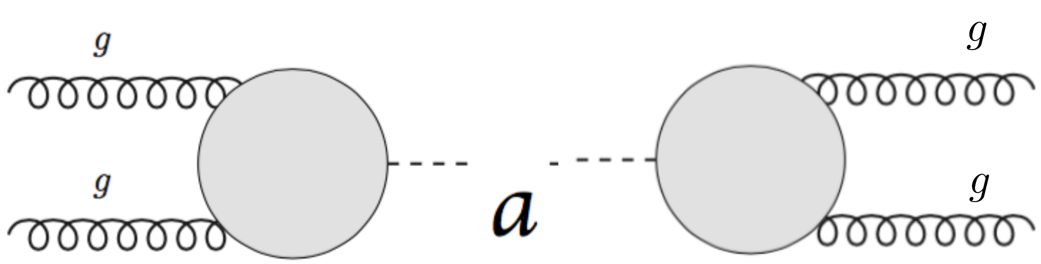




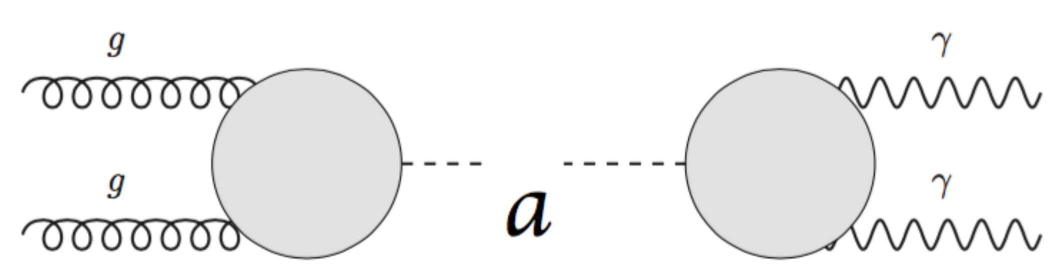
NEW BOUND(s)

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

from boosted dijets searches CMS ('17)



dijets



diphotons

Lower bound on the invariant mass

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

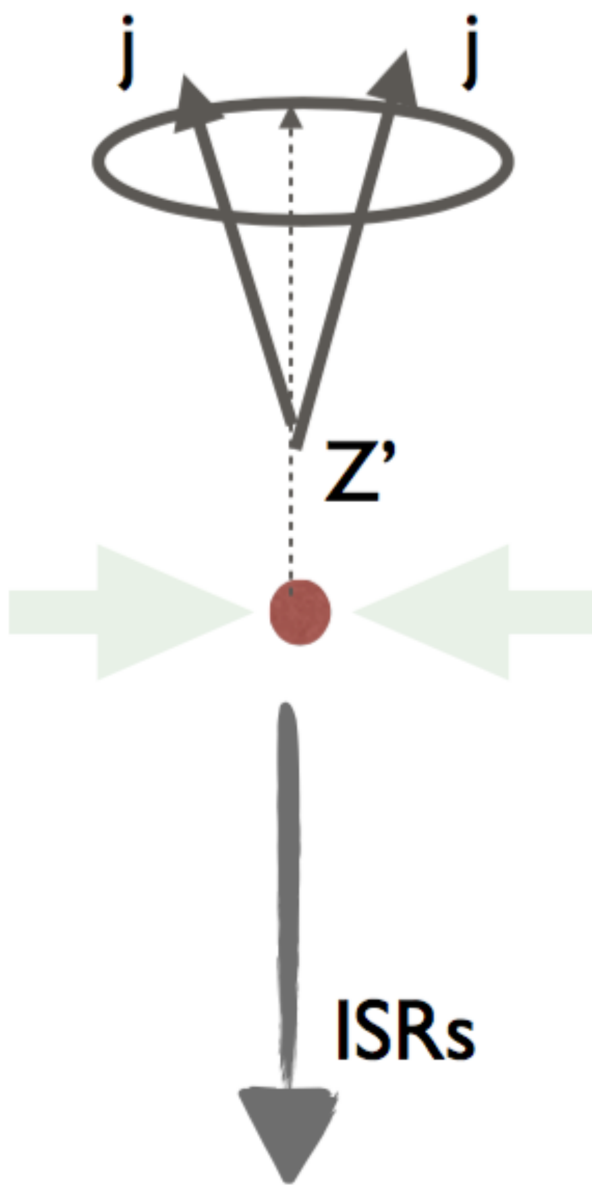
Photon/jet Isolation

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

Minimal pT cuts

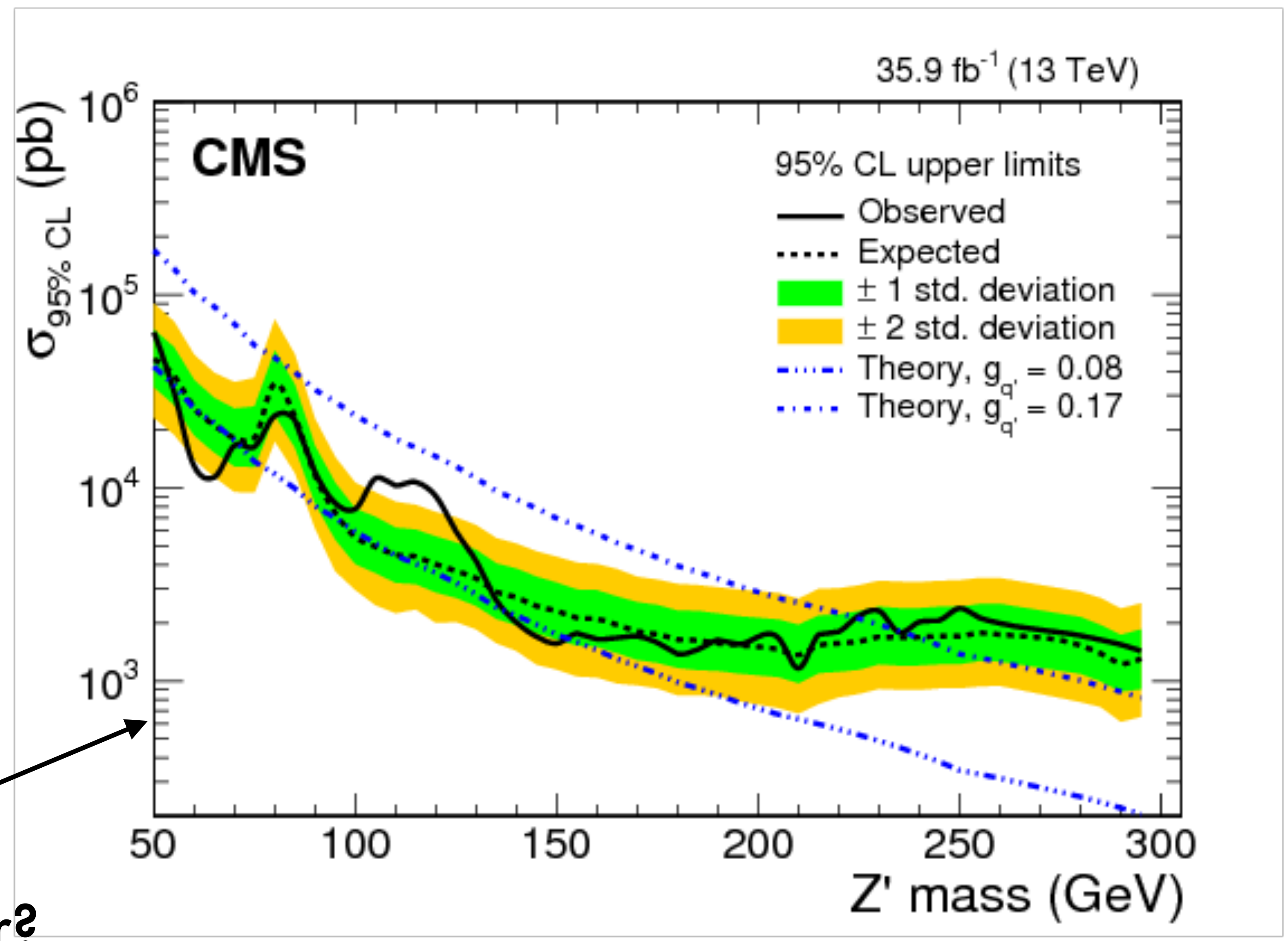
- Lower ΔR
- Lower $p_T^{\min}$

- Lower ΔR → extra hard object to pass to trigger



Boosted dijets (highly collimated)

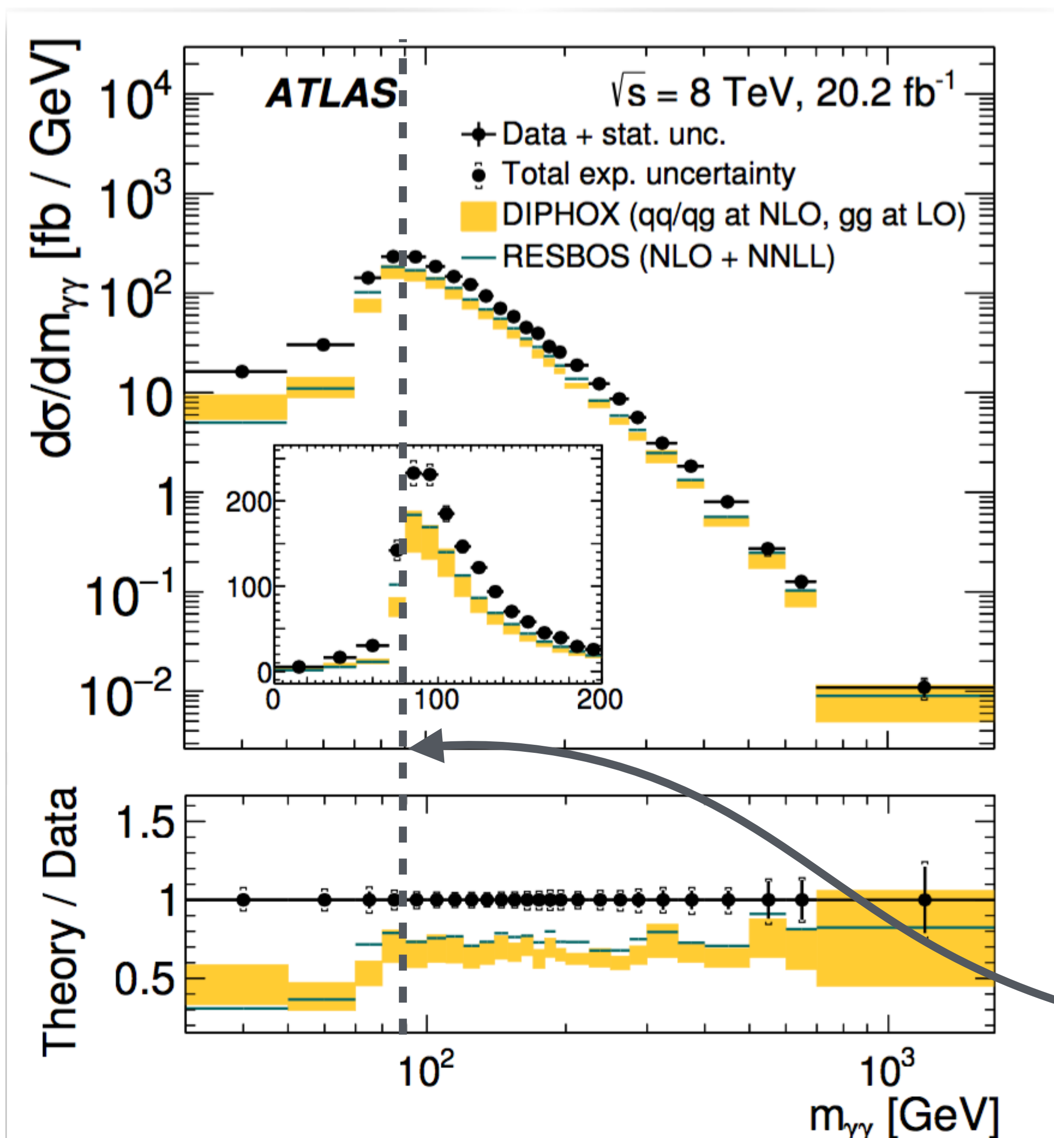
Resonance can be seen in the substructure



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

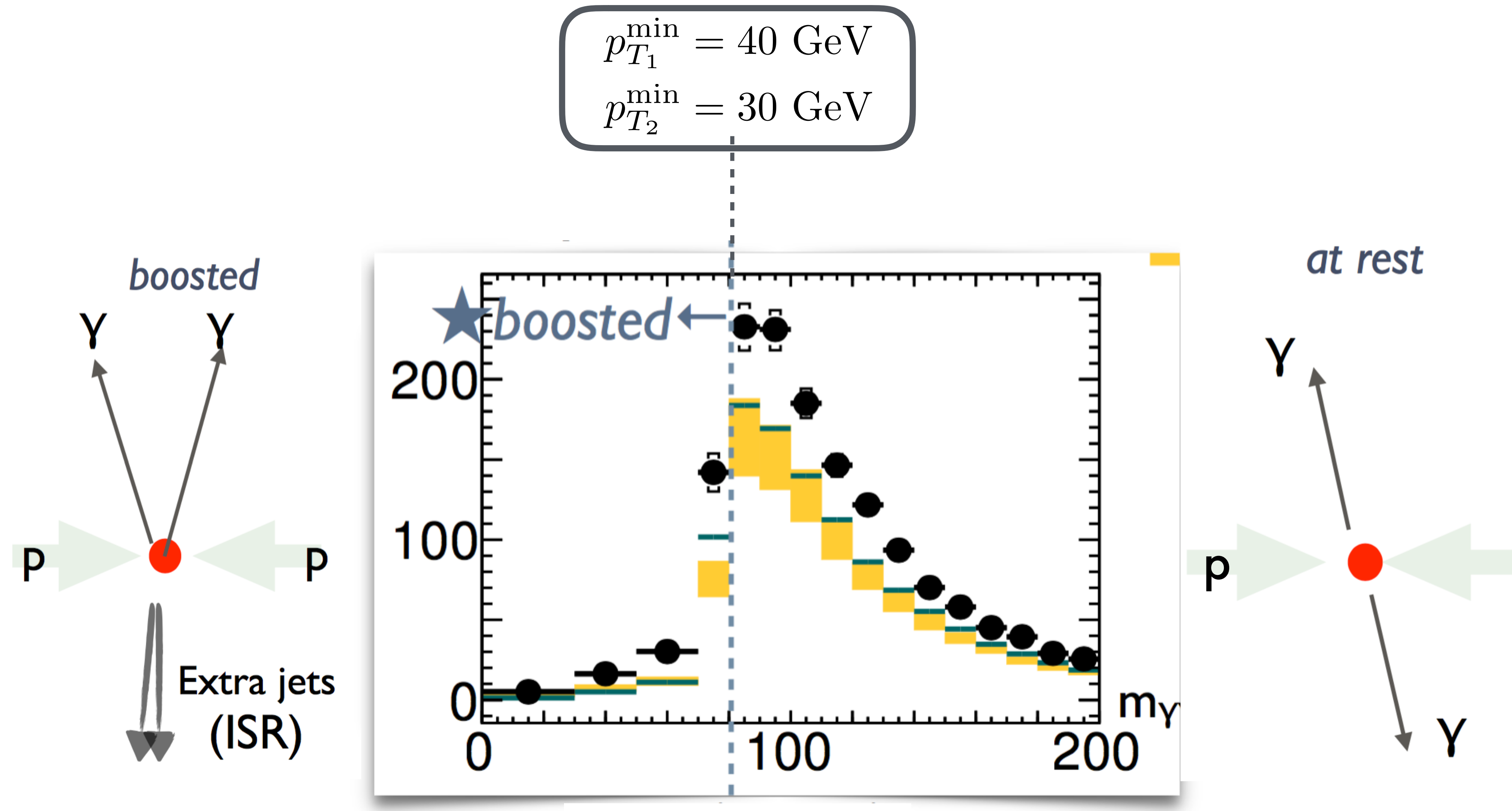
$$\Delta R > 0.4$$

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

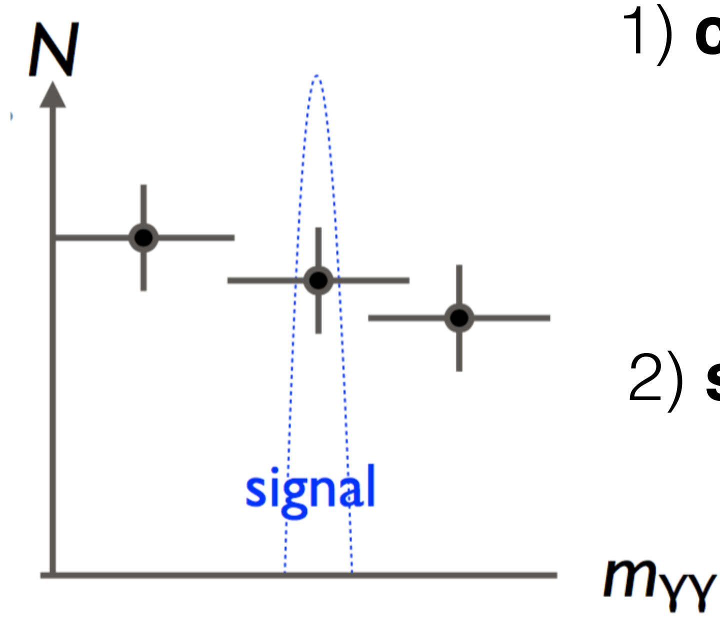
the background has a structure so data-driven bkd. estimate are difficult

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

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** (*uncertainty dominated by MC modelling)*

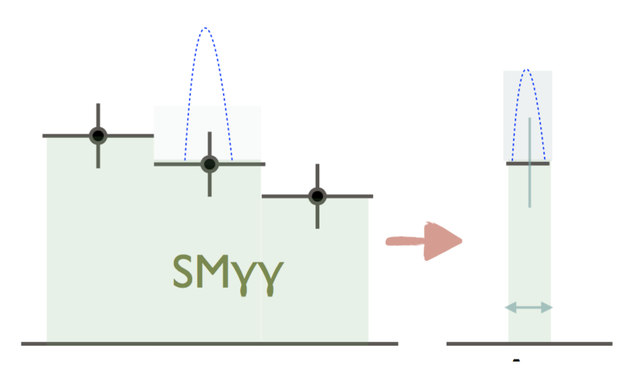
$$\sigma^{\rm S}(m_a)\cdot\epsilon_S(m_a) < m_{\gamma\gamma}^{\rm Bin}\cdot\frac{{\rm d}\sigma}{{\rm d}m_{\gamma\gamma}}\cdot 2\Delta$$

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)

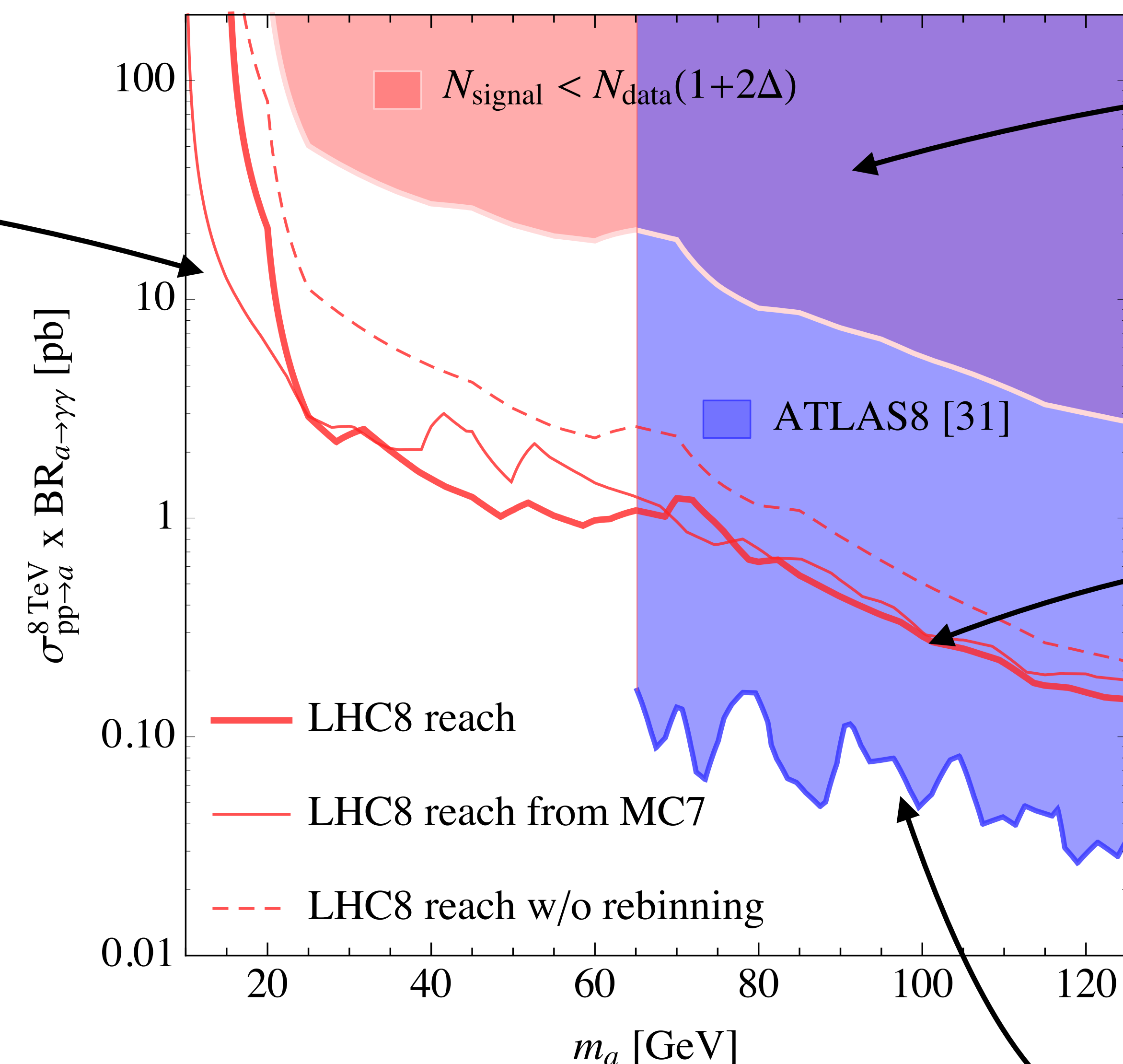


projection $(\sqrt{s}_{\text{low}}, L_{\text{low}}) \rightarrow (\sqrt{s}_{\text{high}}, L_{\text{high}})$

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

7 TeV reach
projected at 8 TeV

low mass reach
9.4 GeV
13.9 GeV
14.2 GeV



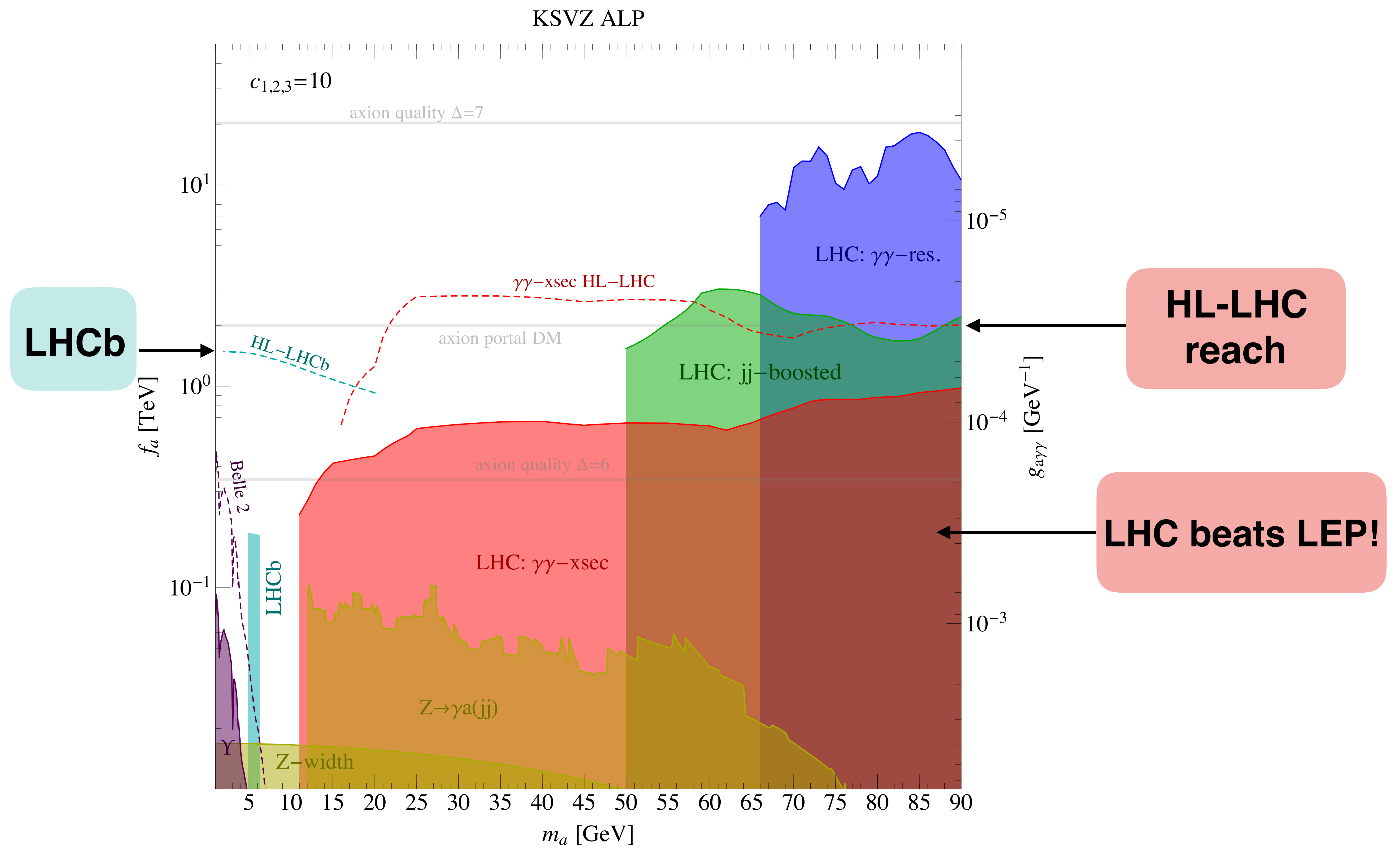
conservative bound
from 8 TeV data

rebinning
with ECAL resolution

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

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

THE ALP PARAMETER SPACE



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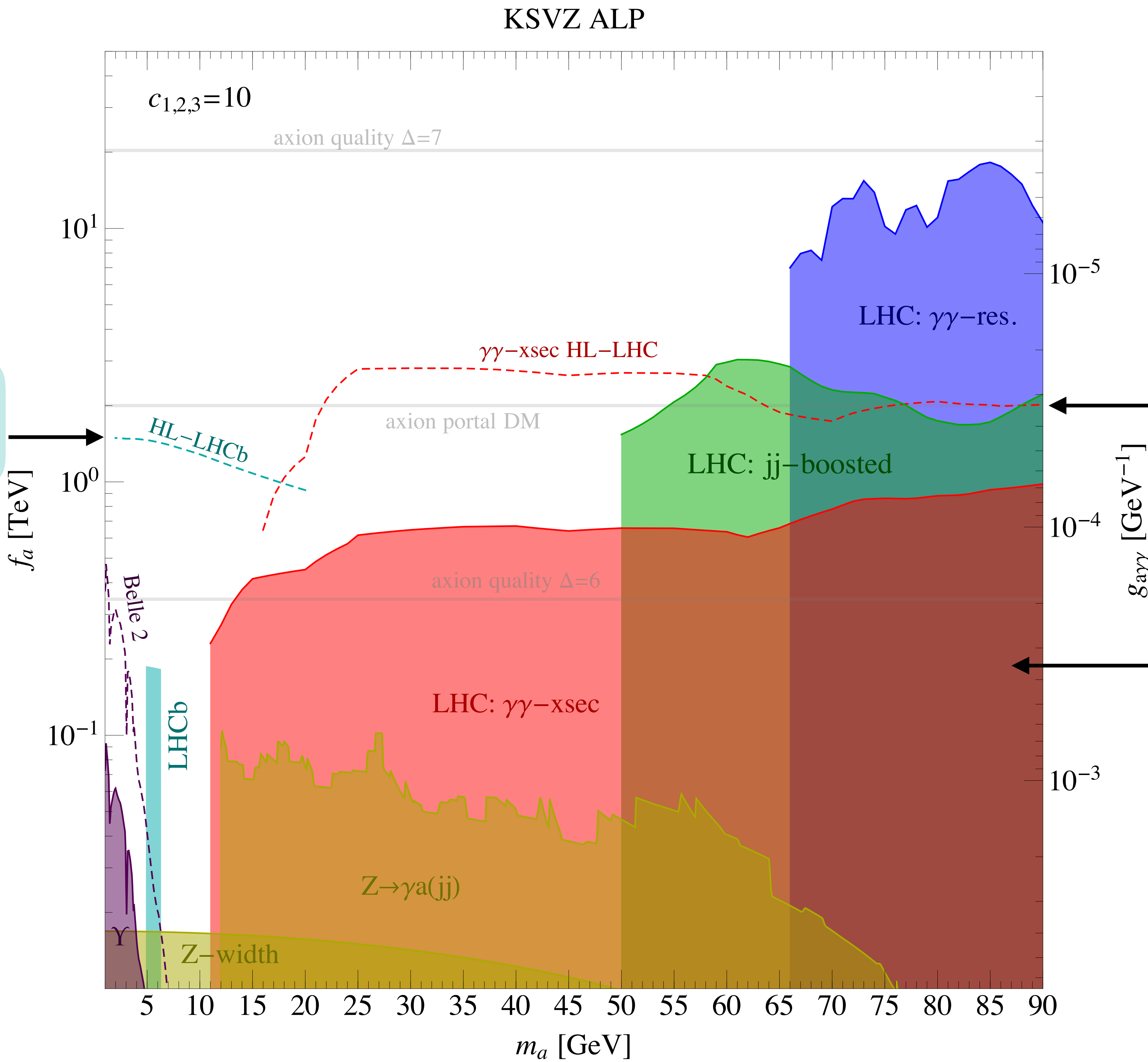


LHCb

HL-LHC reach

LHC beats LEP!

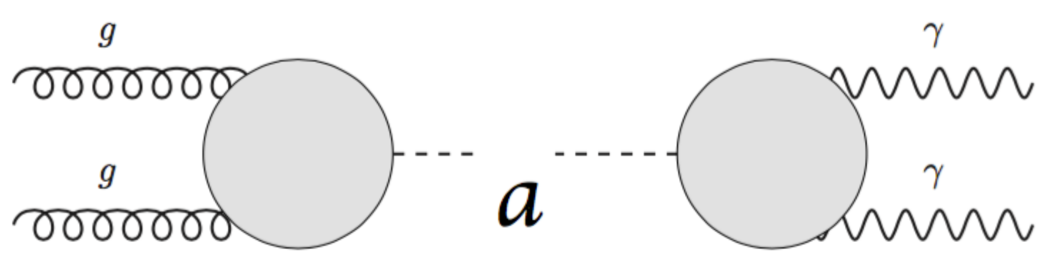
sensitivity limited by the systematic *uncertainty on the MC modelling!* → **limited improvement with LUMI!**

NEW SEARCH

boosted diphotons

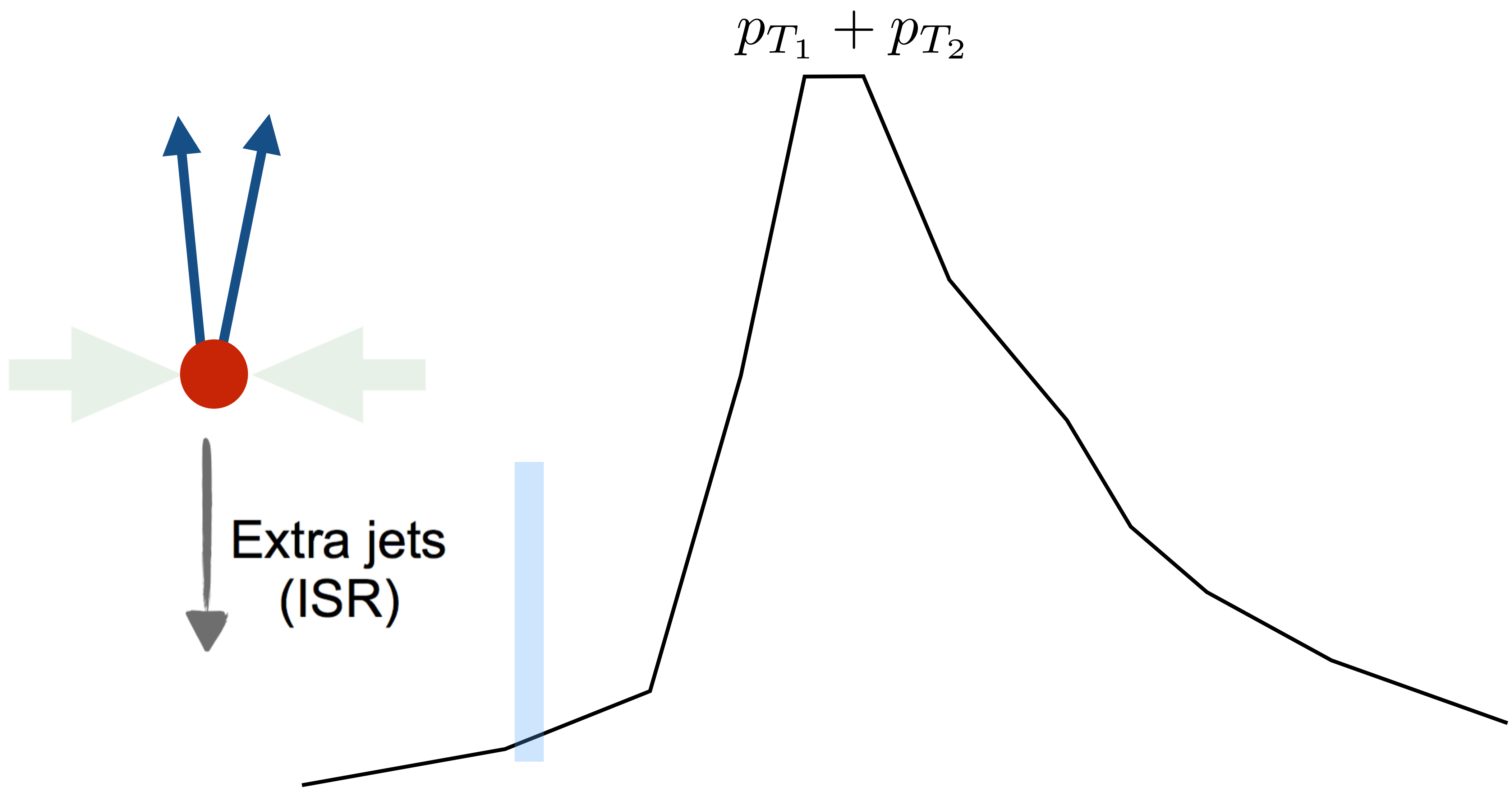
to appear with M. Low, A. Mariotti, F. Sala, K. Tobioka

+ preliminary discussions with ATLAS



diphotons

A bump-hunt on the l.h.s of the structure?



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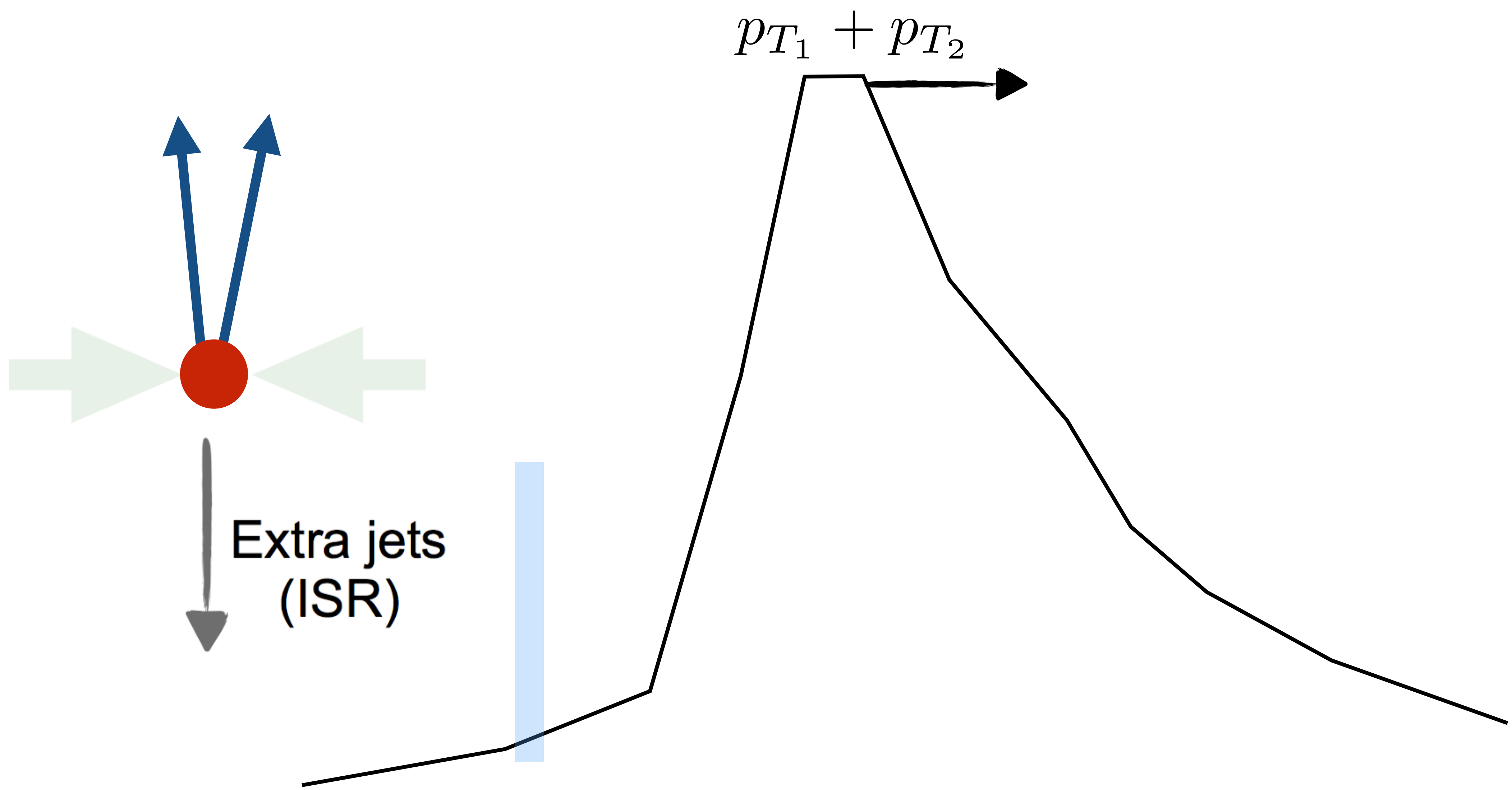
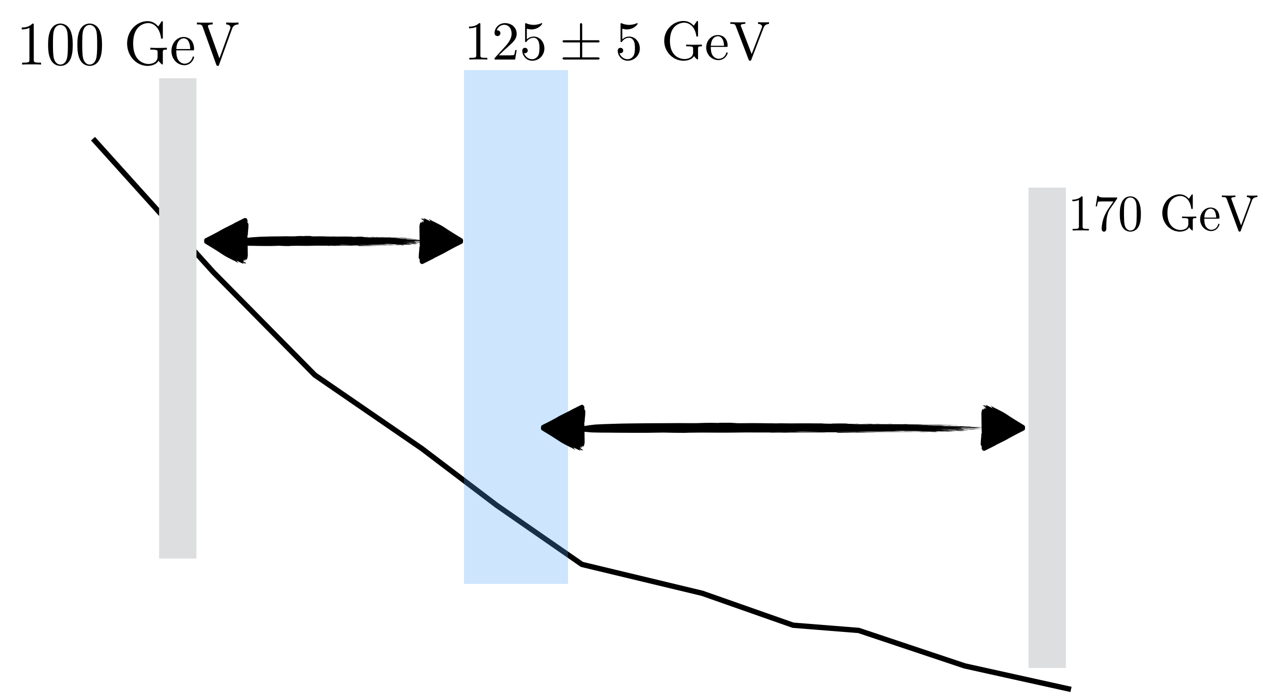


Boosting the system we can move the structure to the left!

Optimal diphoton cuts to do a bump hunt?

From the Higgs we know
we need a certain “window” around the resonance



to get a good fit from side-band

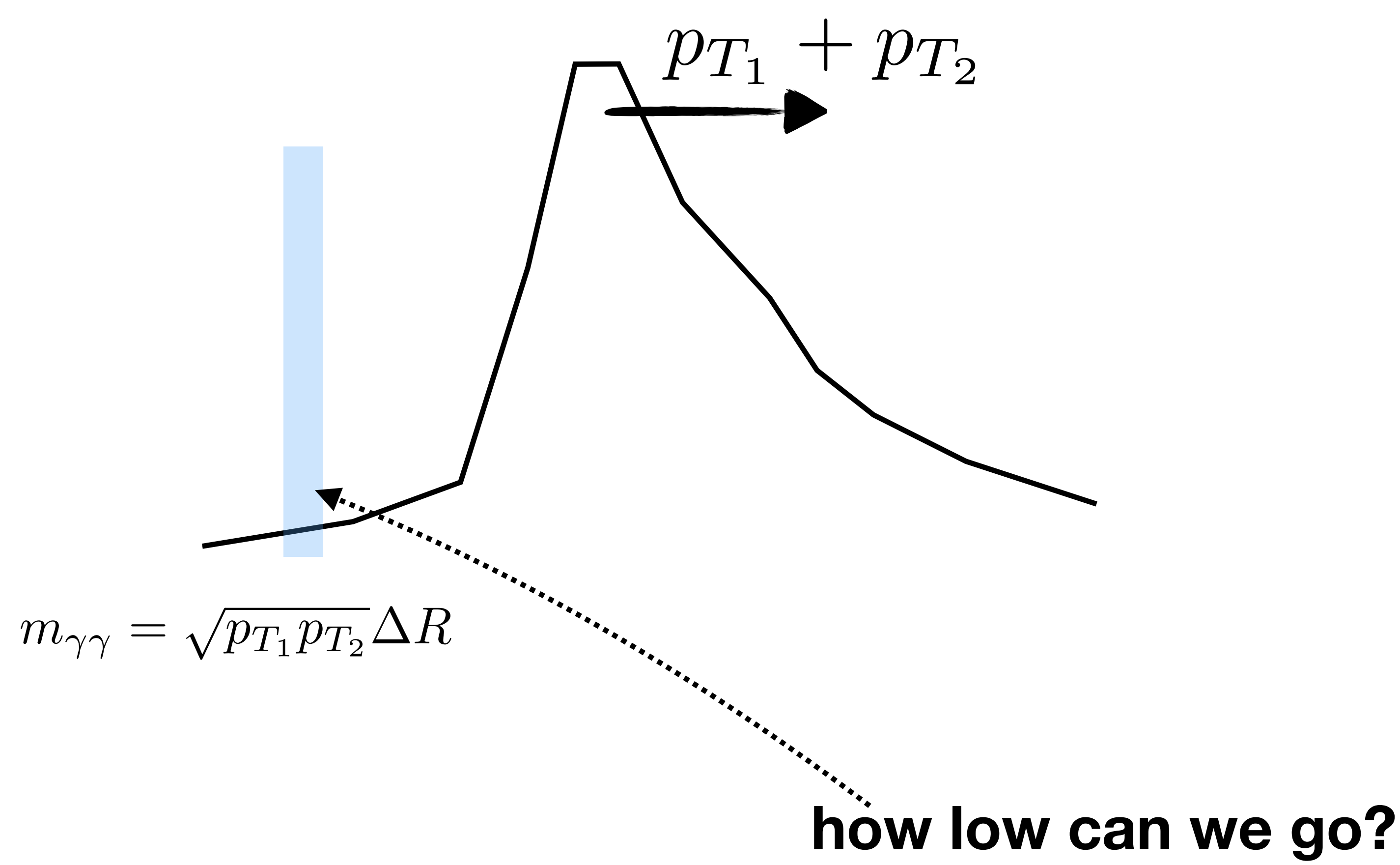
Optimal diphoton cuts to do a bump hunt?

we need 50 GeV on r.h.s of the signal

$$50 + 65 = 115\ \mathrm{GeV}$$

the highest invariant mass we are interested in

sets the sum of the photon cuts



$$\Delta R = 0.4$$

saturating Pitagora's

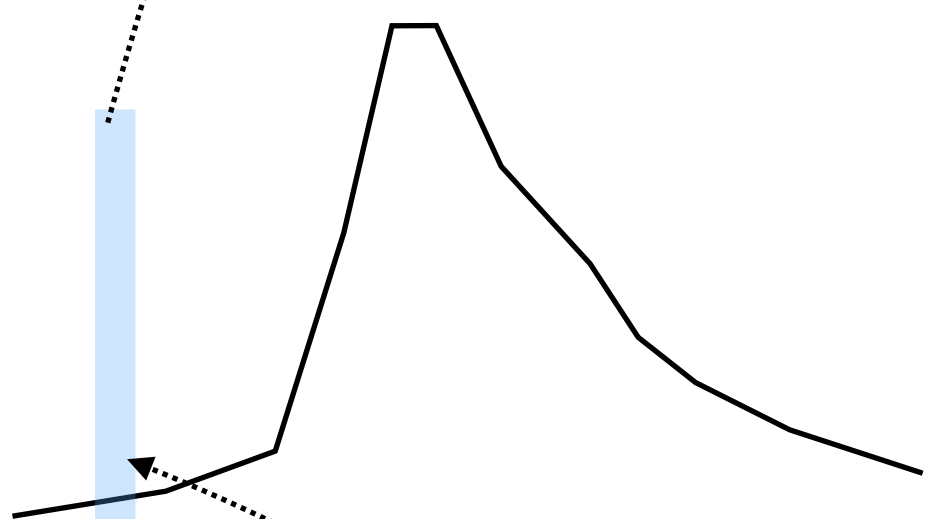
$$m_{\gamma\gamma} \gtrsim \sqrt{(115 - p_{T_2})p_{T_2}}\,\Delta R$$

What is the minimal pT of the second photon?

$p_{T_2} = 20$ GeV $m_{\gamma\gamma} \gtrsim 17$ GeV

$p_{T_2} = 10$ GeV $m_{\gamma\gamma} \gtrsim 13$ GeV

$\ldots$



$m_{\gamma\gamma} = \sqrt{p_{T_1} p_{T_2}}\,\Delta R$

how low can we go?

No lower than ~10 GeV by keeping standard ISO

$$\Delta R = 0.4$$

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

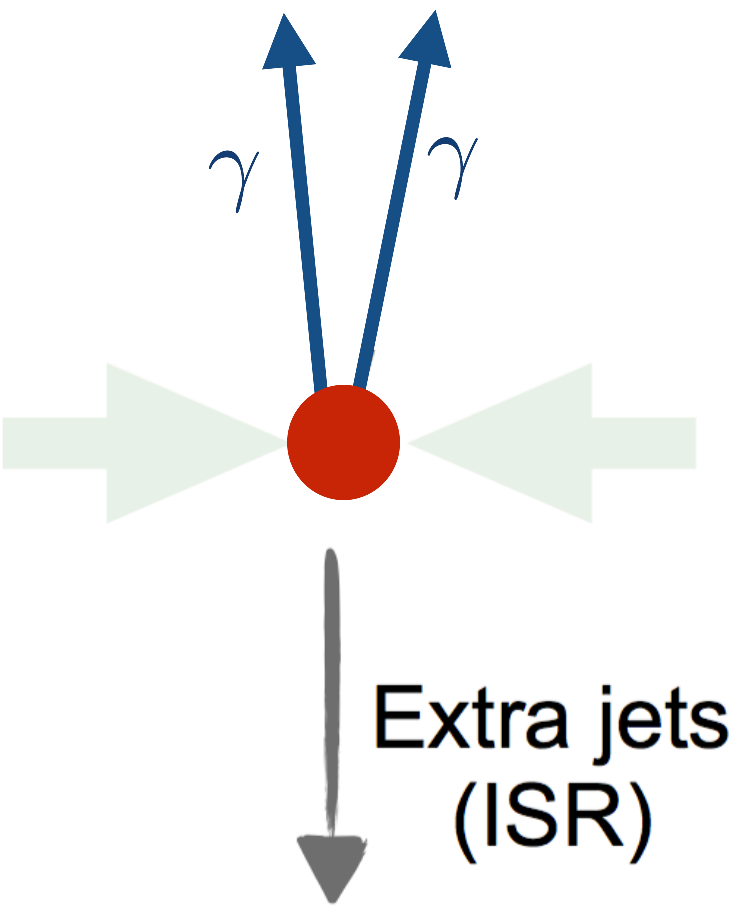
CAN WE LOWER THE ISOLATION?

A concrete case of study: **the mono-jet trigger**

to appear with M. Low, A. Mariotti, F. Sala, K. Tobioka

➳ triggering a 500 GeV jet

$$m_{\gamma\gamma} \gtrsim \sqrt{(500 - p_{T_2})p_{T_2}}\Delta R$$



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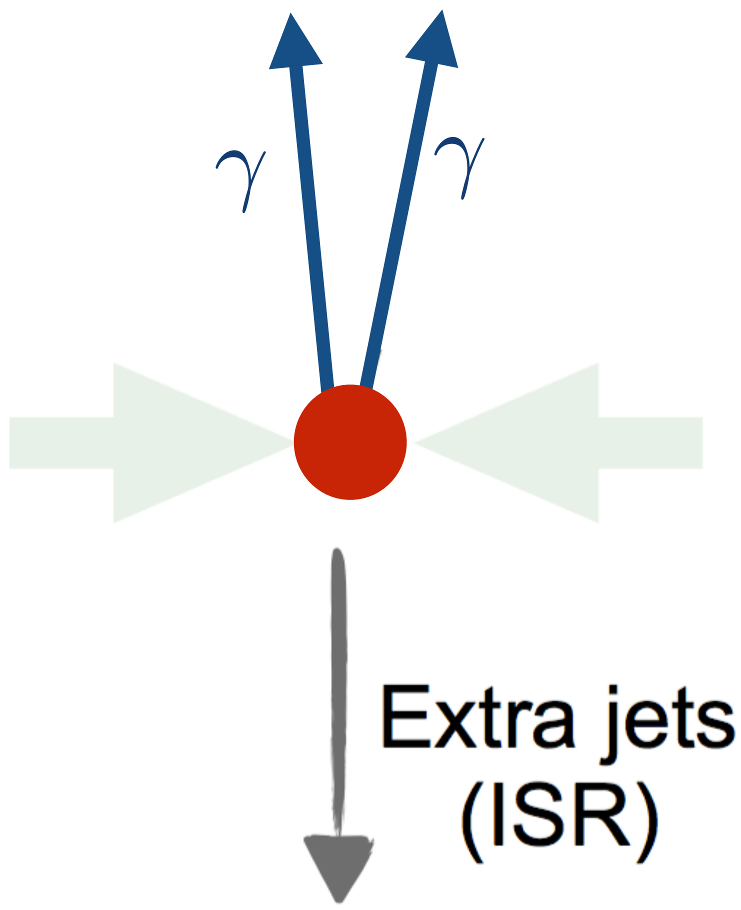
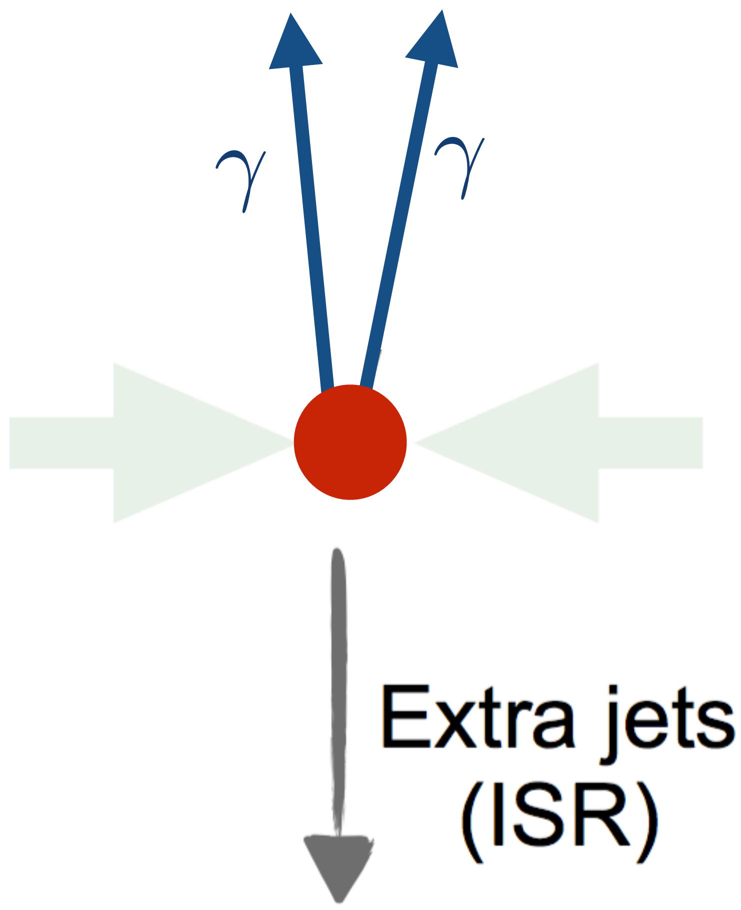


➳ the two photons get collimated

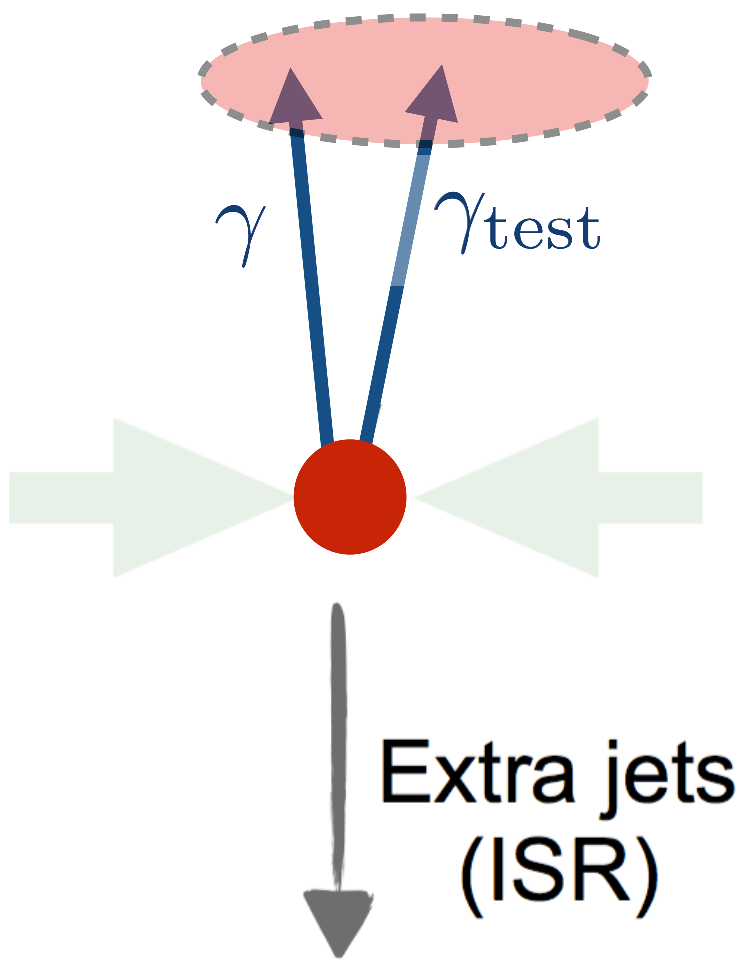


- triggering a 500 GeV jet

$$m_{\gamma\gamma} \gtrsim \sqrt{(500 - p_{T_2})p_{T_2}}\Delta R$$

- the two photons get collimated

- standard isolation would reject the signal



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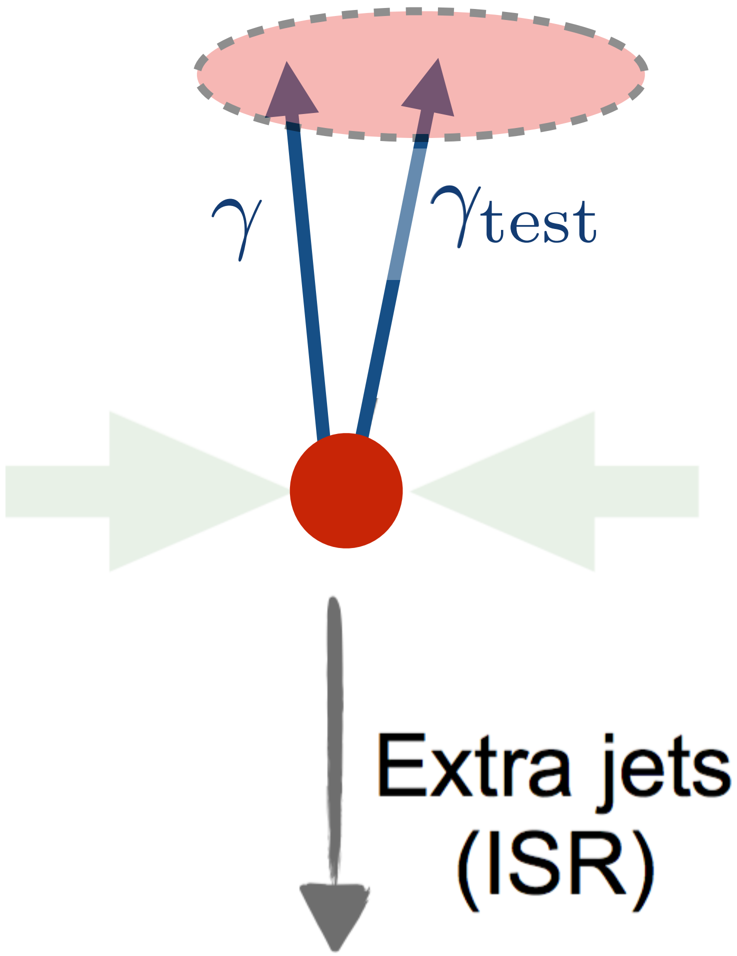
$$\sum_{i \neq \gamma_{\text{test}}}^{\Delta R < R_{\text{iso}}} p_{T,i} < \# \qquad \sum_{i \neq \gamma_{\text{test}}}^{\Delta R < R_{\text{iso}}} p_{T,i} \Big/ E_{T,\gamma_{\text{test}}} < \#$$



- triggering a 500 GeV jet

$$m_{\gamma\gamma} \gtrsim \sqrt{(500 - p_{T_2})p_{T_2}}\Delta R$$

- the two photons get collimated

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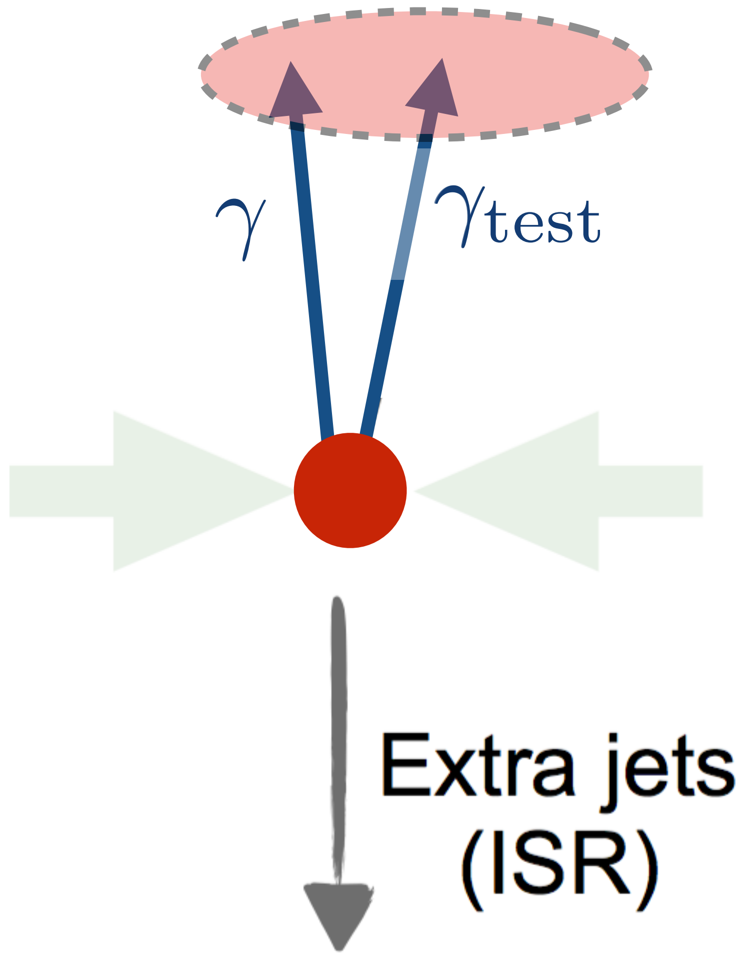
$$\sum_{i\neq\gamma_{\rm test}}^{\Delta R<R_{\rm iso}} p_{T,i} < \# \qquad \sum_{i\neq\gamma_{\rm test}}^{\Delta R<R_{\rm iso}} p_{T,i} \Big/ E_{T,\gamma_{\rm test}} < \#$$

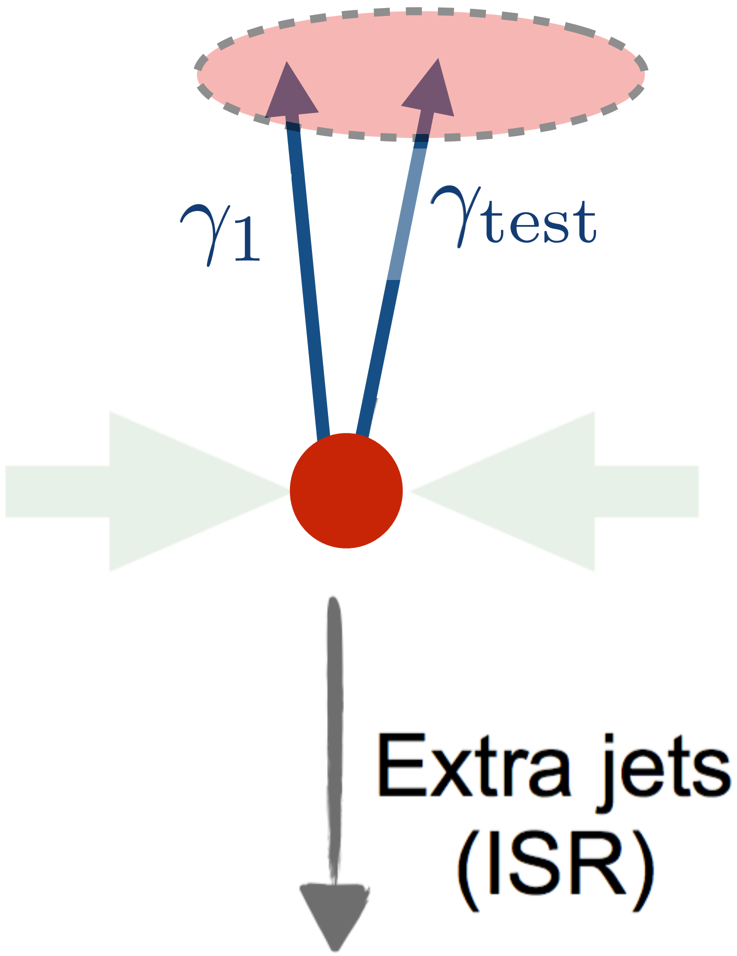
CAN WE MODIFY THIS KEEPING JET-FAKES UNDER CONTROL?

Modifying standard photon isolation



→ **NEW ISOLATION**

Modifying standard photon isolation



NEW ISOLATION

$$\sum_{i \neq \gamma_{\rm test}, \gamma_1}^{\Delta R < R_{\rm iso}} p_{T,i} \qquad \sum_{i \neq \gamma_{\rm test}, \gamma_1}^{\Delta R < R_{\rm iso}} p_{T,i} \Big/ E_{T,\gamma_{\rm test}}$$

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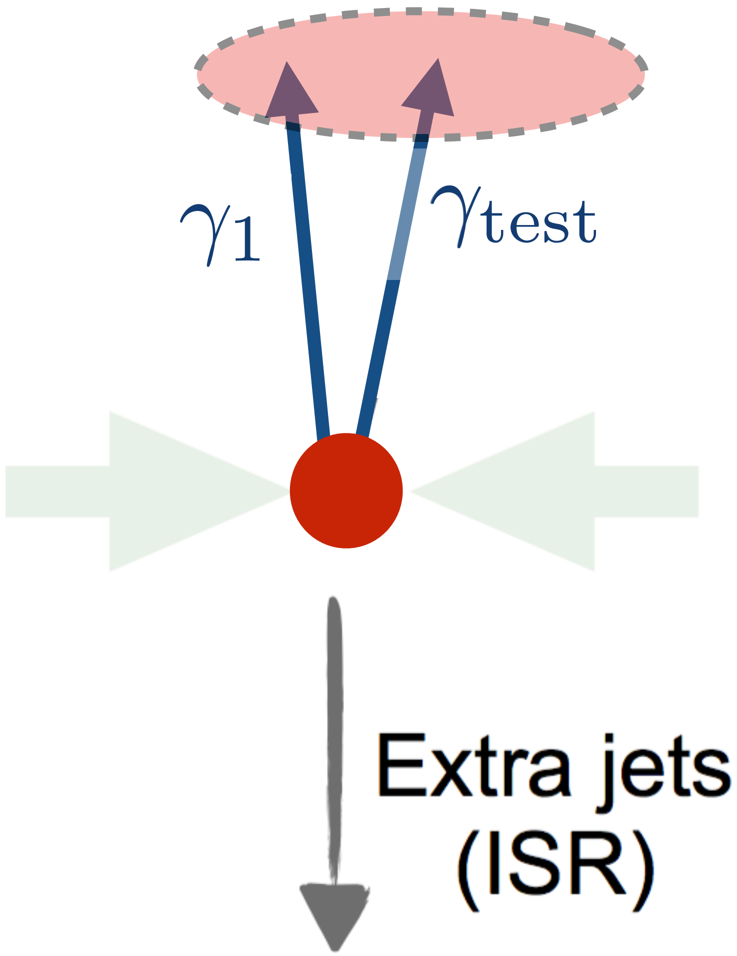

NEW ISOLATION

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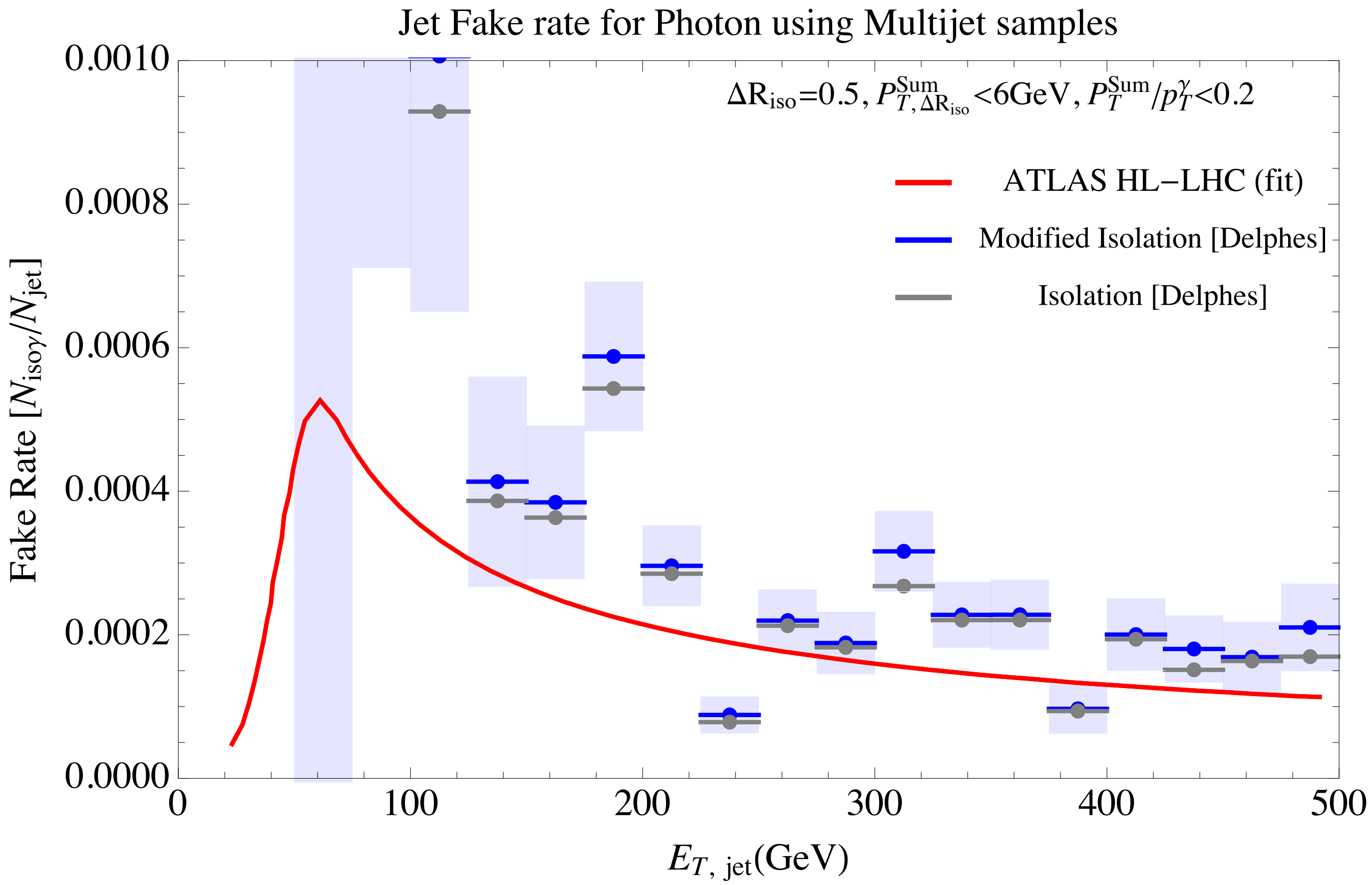
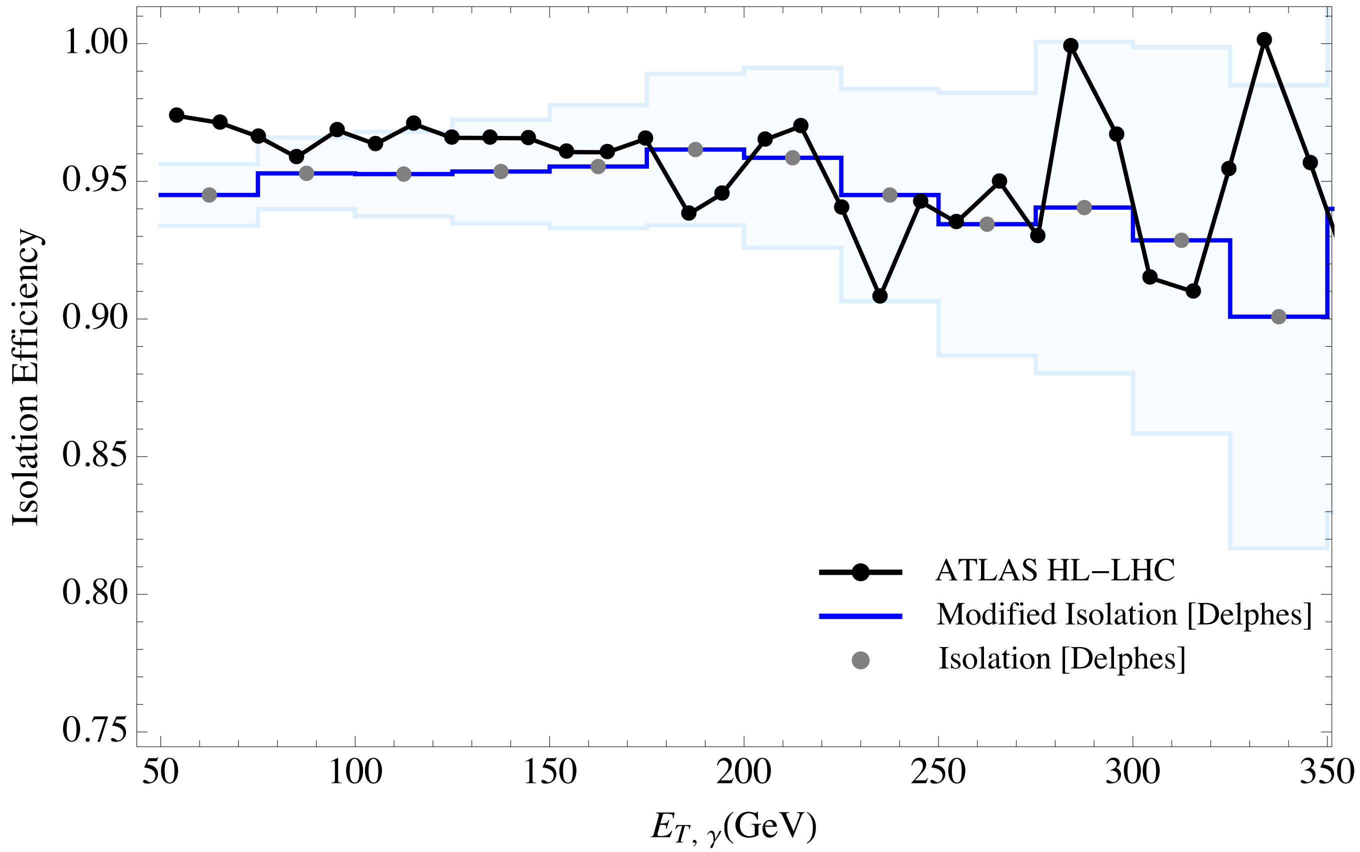
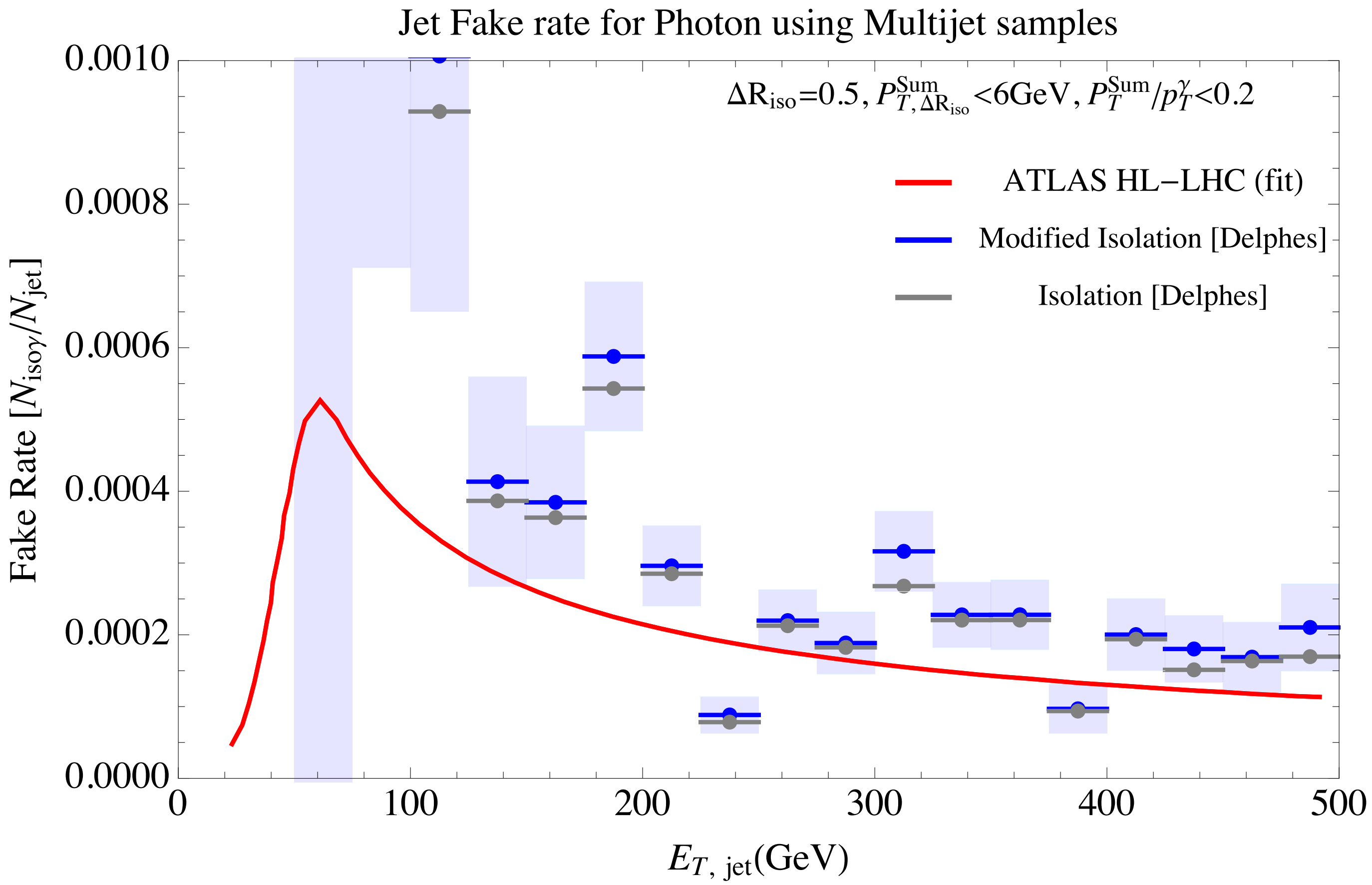
Rejecting the pions (jet activity) keeping the hard photon γ_1

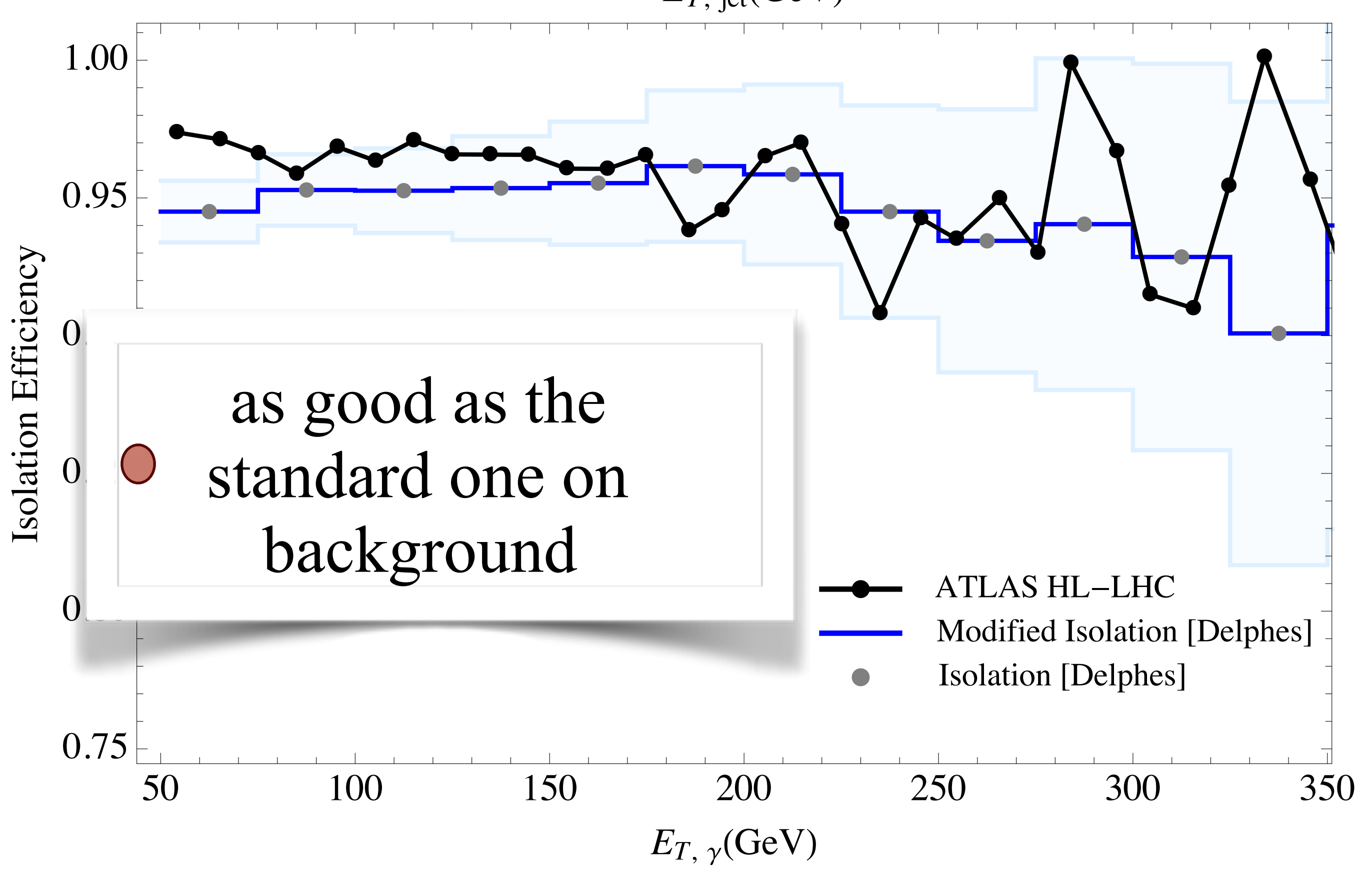
Testing the new iso...





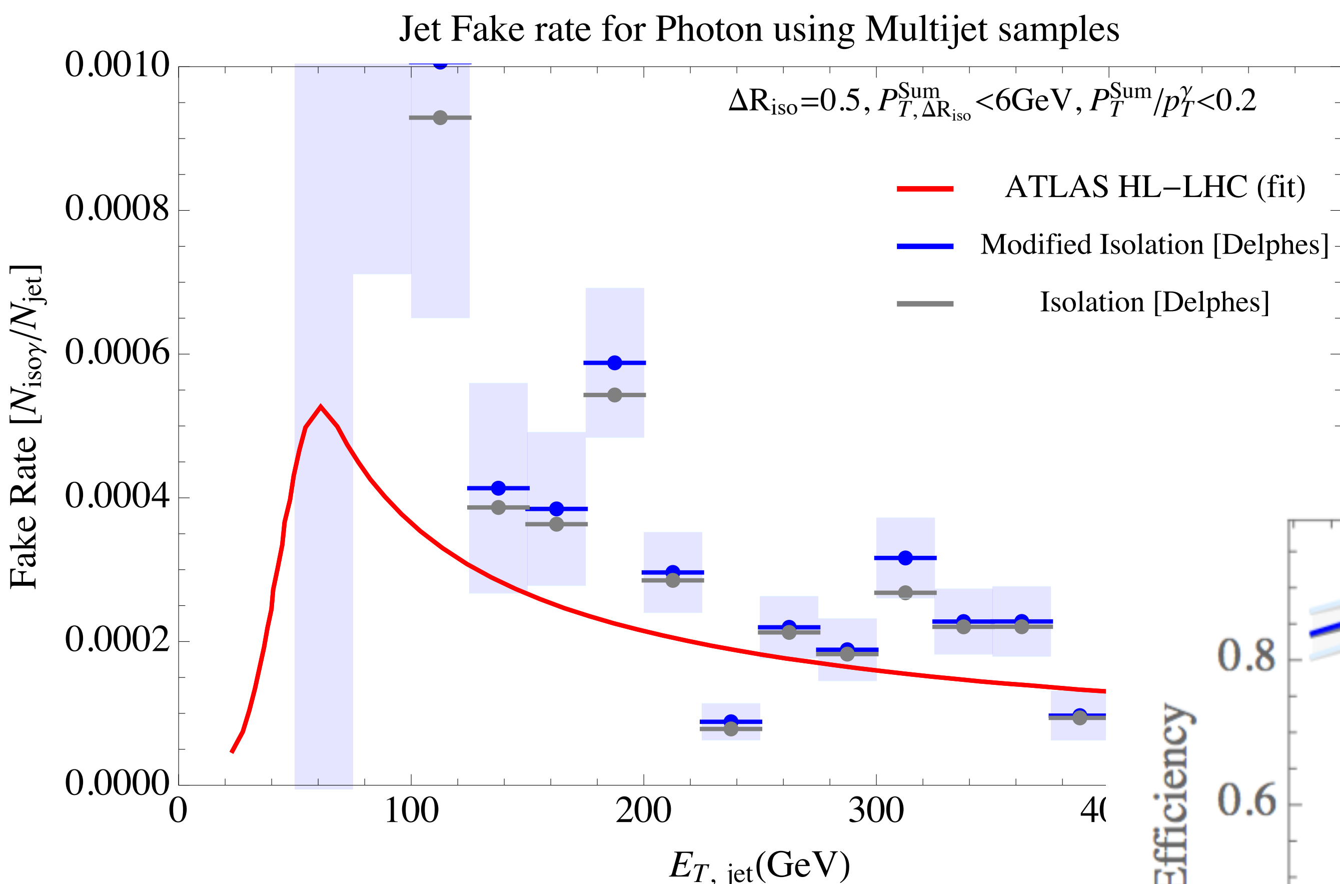
Testing the new iso...

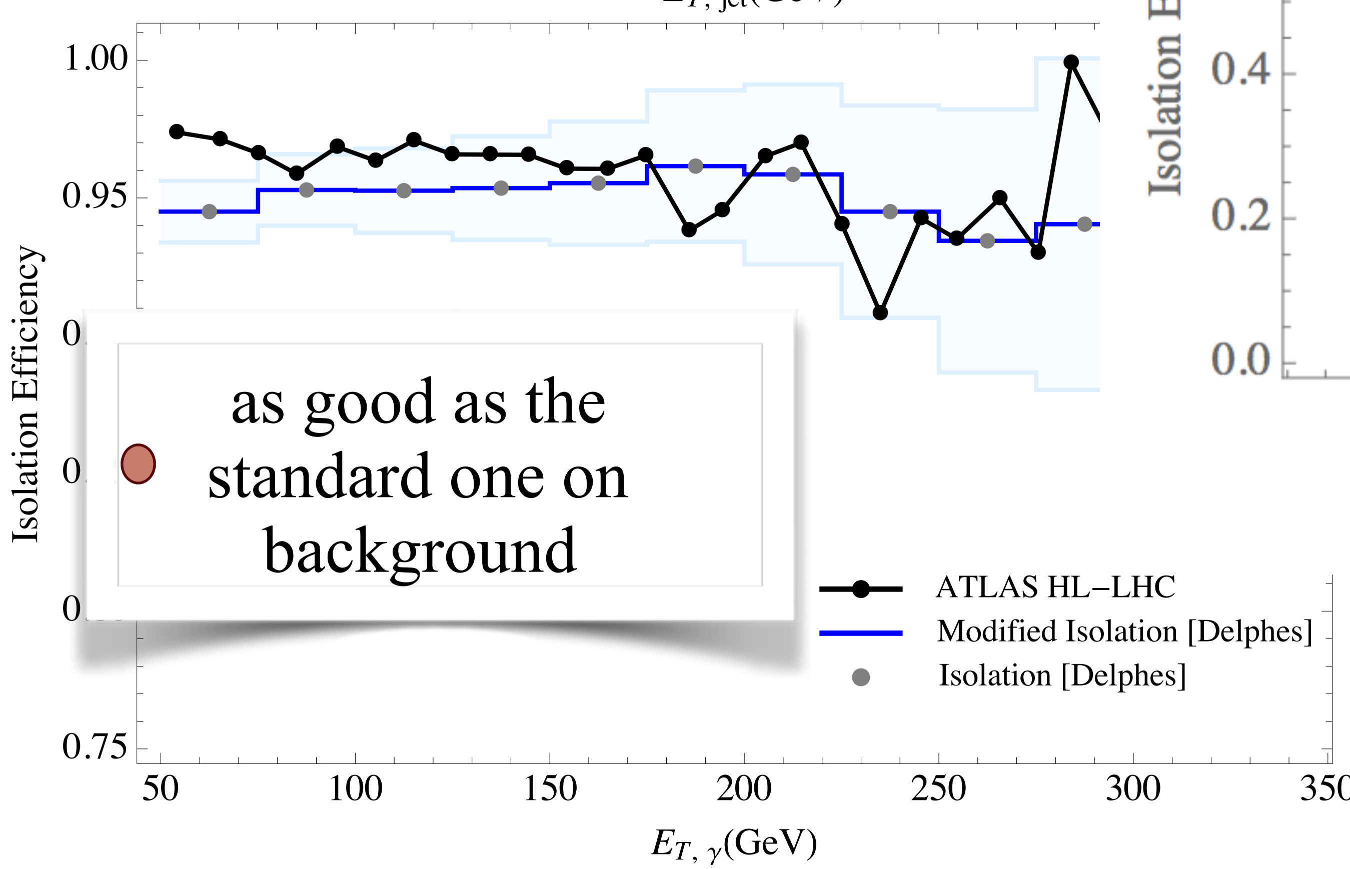




- as good as the standard one on background

Testing the new iso...





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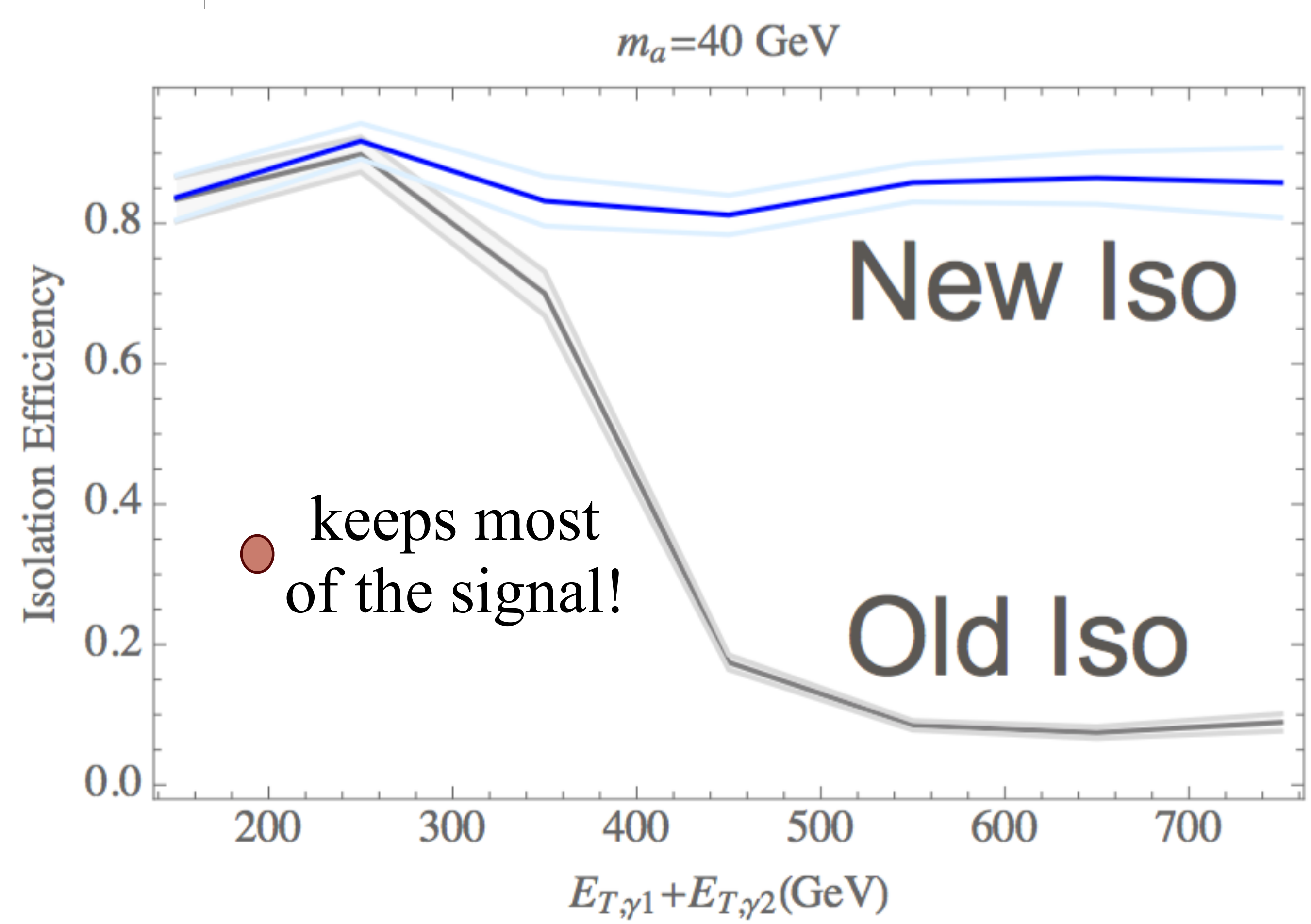
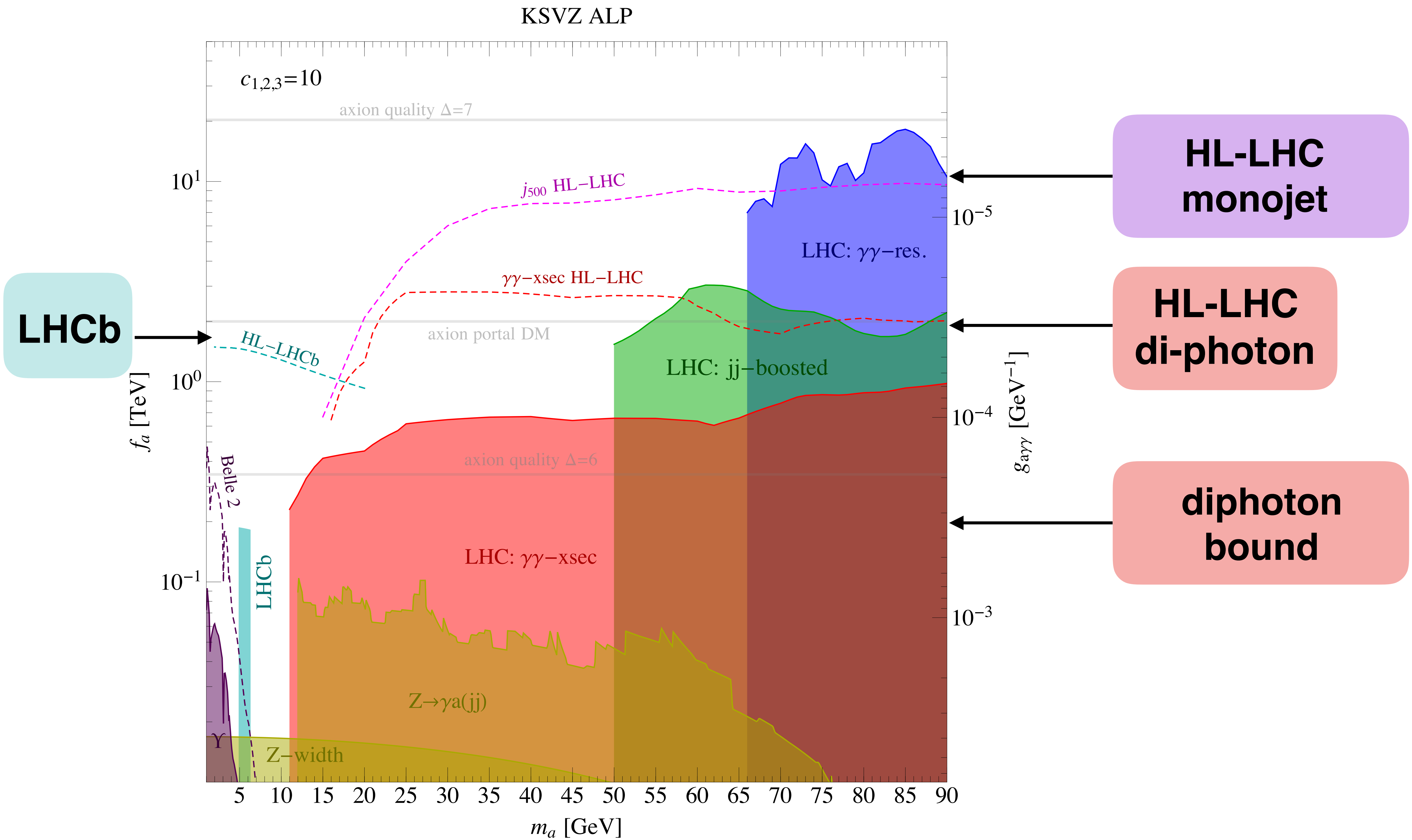


keeps most of the signal!

THE ALP PARAMETER SPACE



THE REACH can be improved in the boosted regime!

Given an invariant mass an optimal cut on the hard object can MAX the sensitivity

How to go further?

1) The current status highly depend on the nature of the final state

2) A systematic study of light resonances
decaying into two objects with different production mechanisms is needed!

FINAL STATES

diphotons

dileptons $(e\,,\mu)$

dibosons (Z, W)

dijets

dittaus

dihiggses

PROD.

single

gluon-fusion

associated

+jet

…

VBF

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FOCUS OF THIS TALK

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What about di-taus?

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FINAL STATES

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

dijets *dittaus* *dihiggses*

What about b-jets?

PROD.

single *associated* *VBF*

gluon-fusion

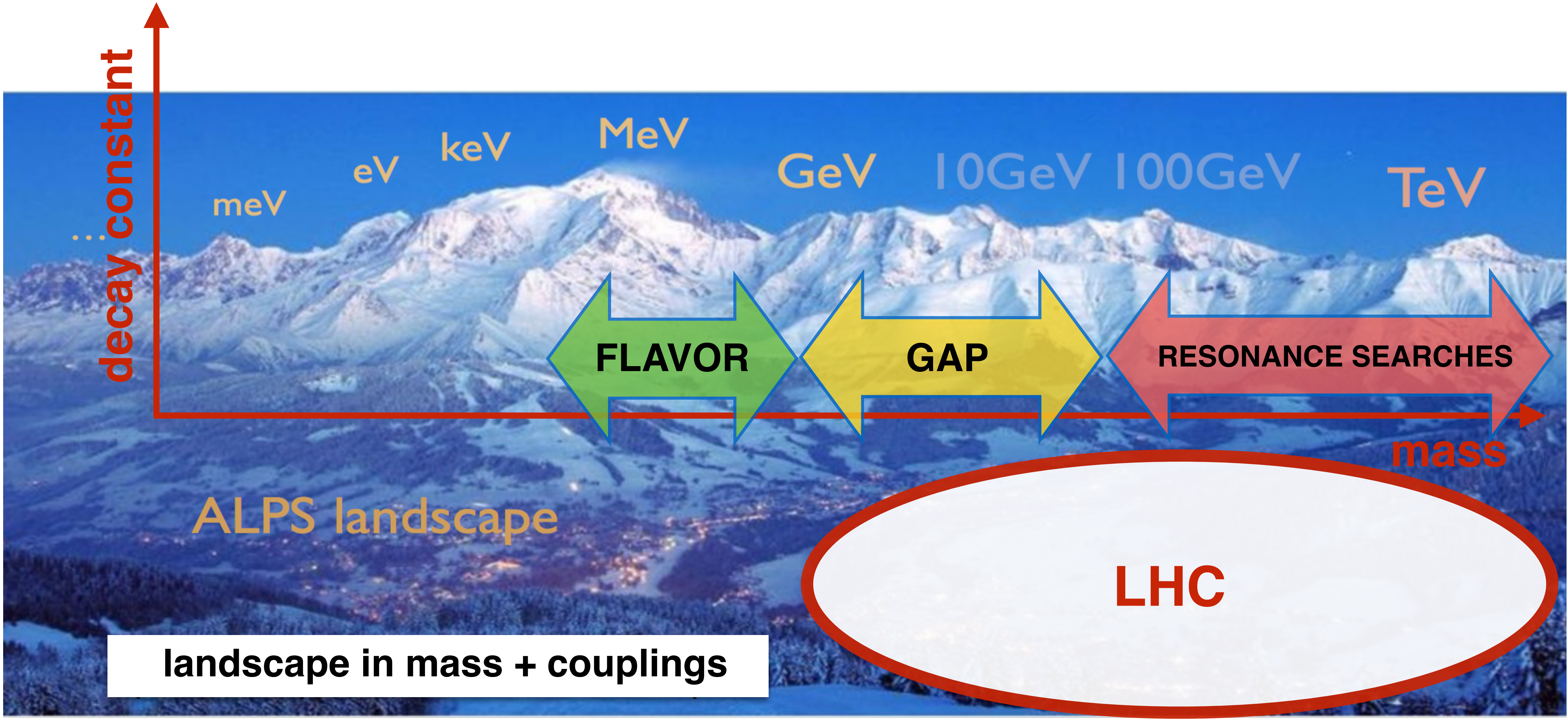
+jet

. . .

What about di-taus?

Is there a motivation?

ALPs at colliders



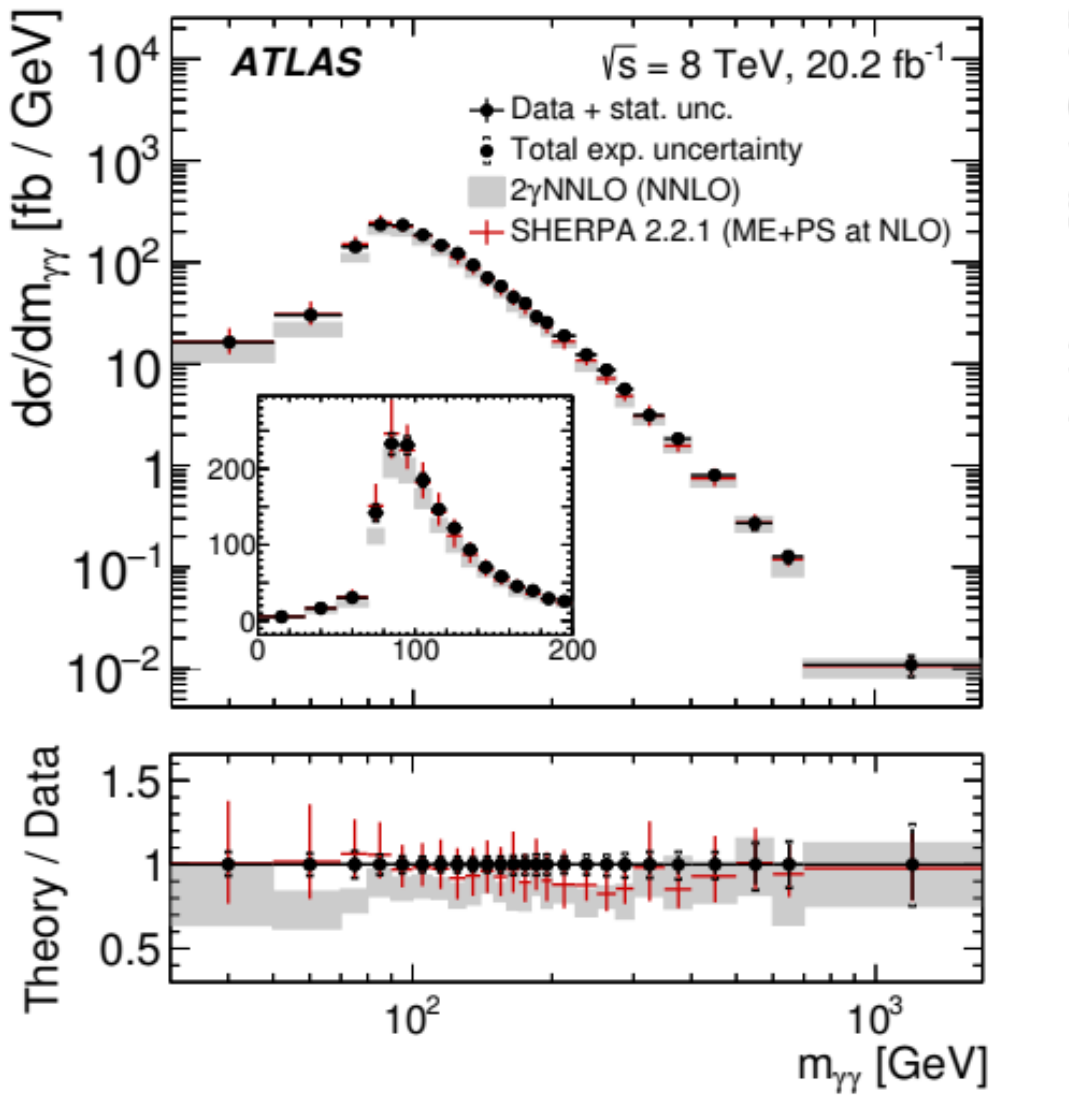
$$\frac{\Gamma_{\tau\tau}}{\Gamma_{\mu\mu}} \sim \left(\frac{m_\tau}{m_\mu}\right)^2 \sim 300 \qquad \frac{\Gamma_{bb}}{\Gamma_{cc}} \sim \left(\frac{m_b}{m_c}\right)^2 \sim 25$$

A HUNT

TO BE CONTINUED…

BACKUP SLIDES

the challenge of background modelling



modeling of the calorimeter isolation variable in simulated samples. Predicted cross sections from fixed-order QCD calculations implemented in DIPHOX and RESBOS at next-to-leading order, and in 2γNNLO at next-to-next-to-leading order, are about 36%, 28% and 16% lower than the data, respectively. The relative errors associated to the predictions from DIPHOX (2γNNLO) are 10–15% (5–10%).