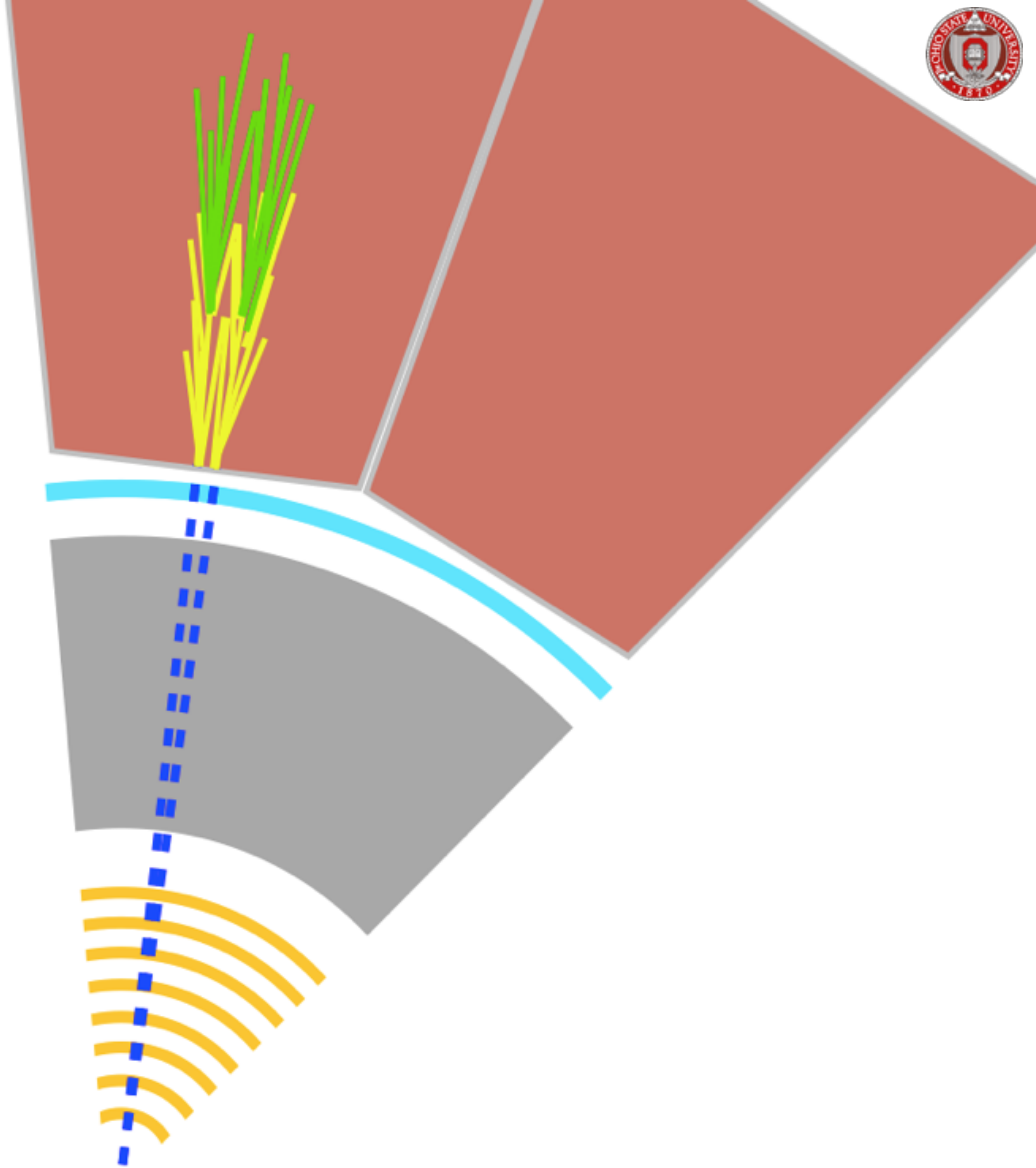
Multi-photon decays of the SM Higgs with ATLAS



Results at 7/8 TeV; current work and prospects at 13 TeV

Outline

How standard is h125?

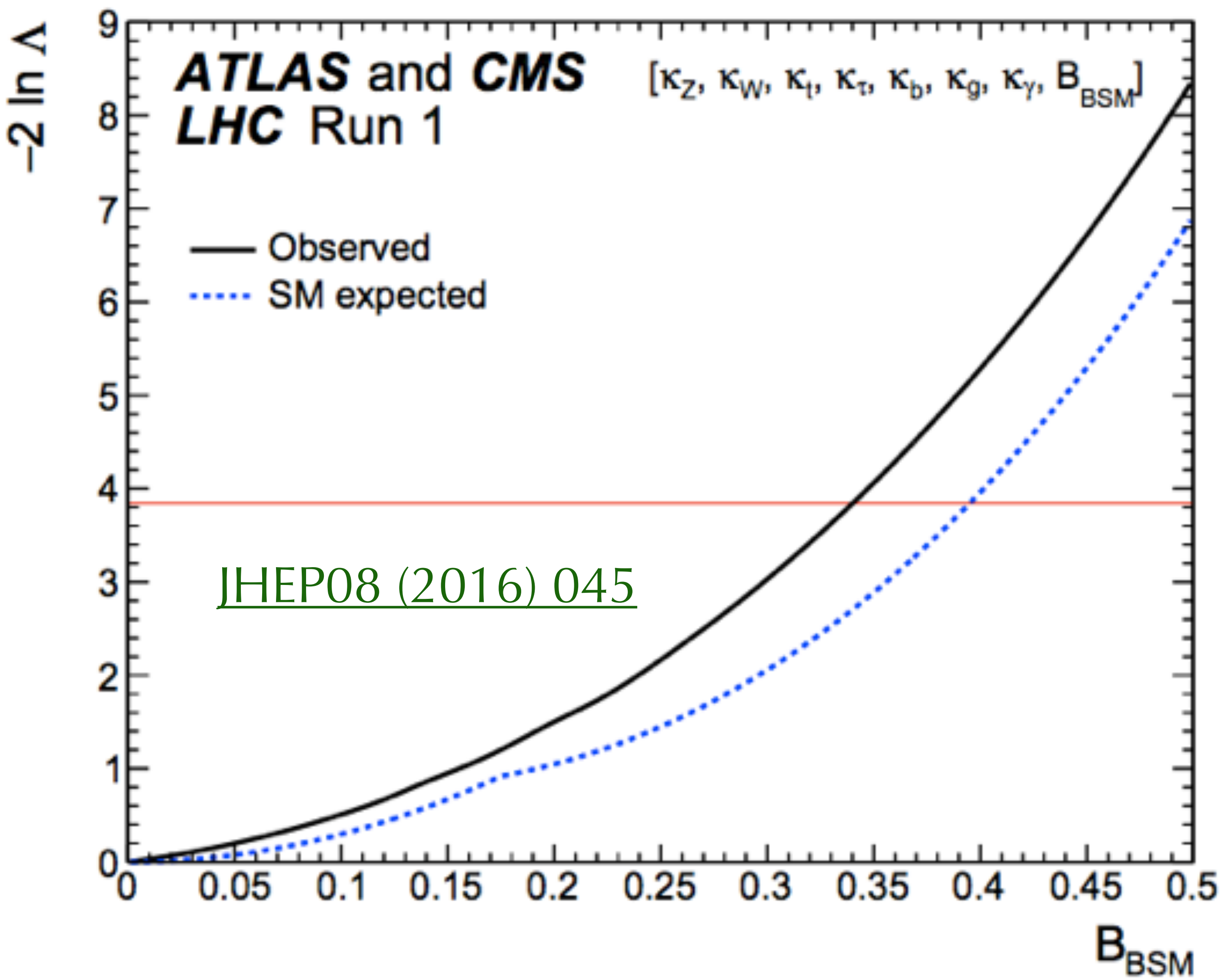
Photons as a discovery tool

Multi-photon decays of h125

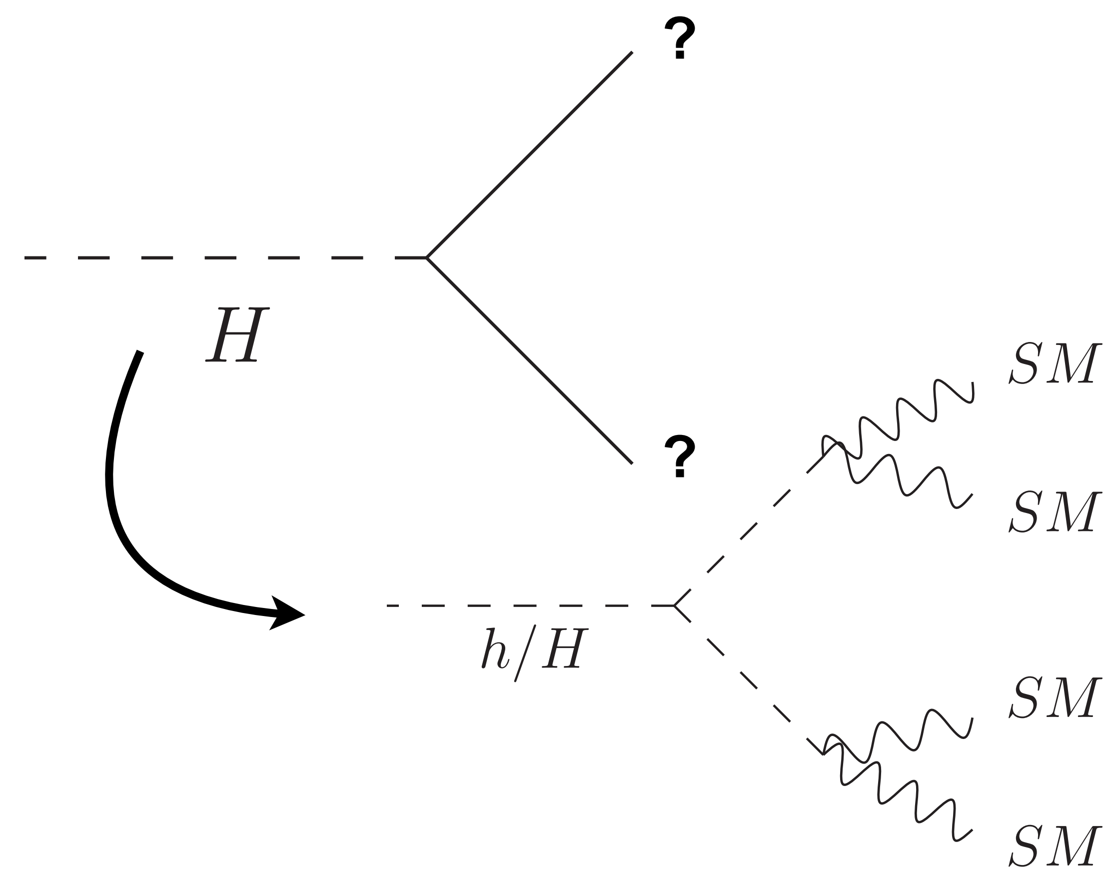
ATLAS results at 7 and 8 TeV

Current work at 13 TeV

Current (and future) LHC precision of measurements of couplings to SM particles leaves ample room for BSM physics

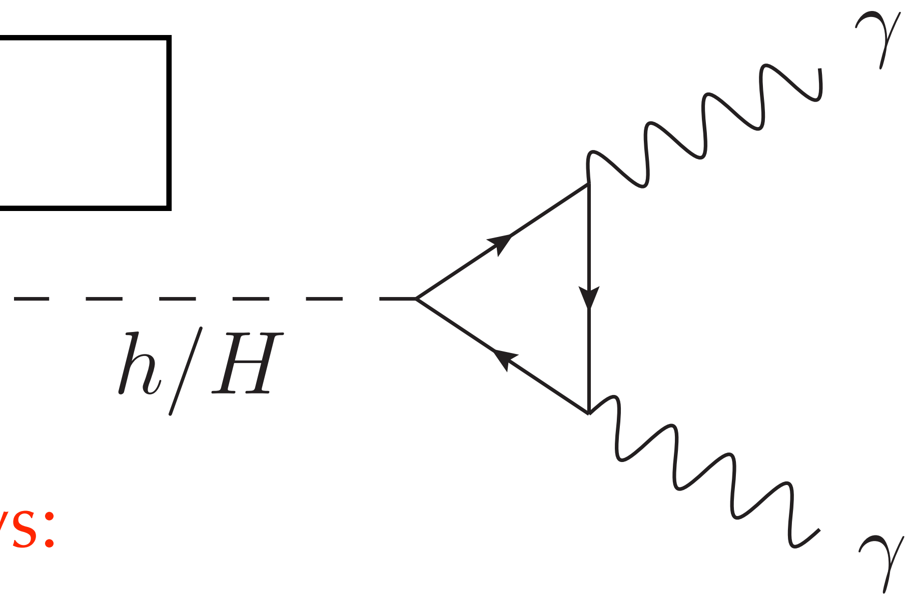


Some fits predict branching ratio of Higgs to invisible could be as large as 20 to 30%



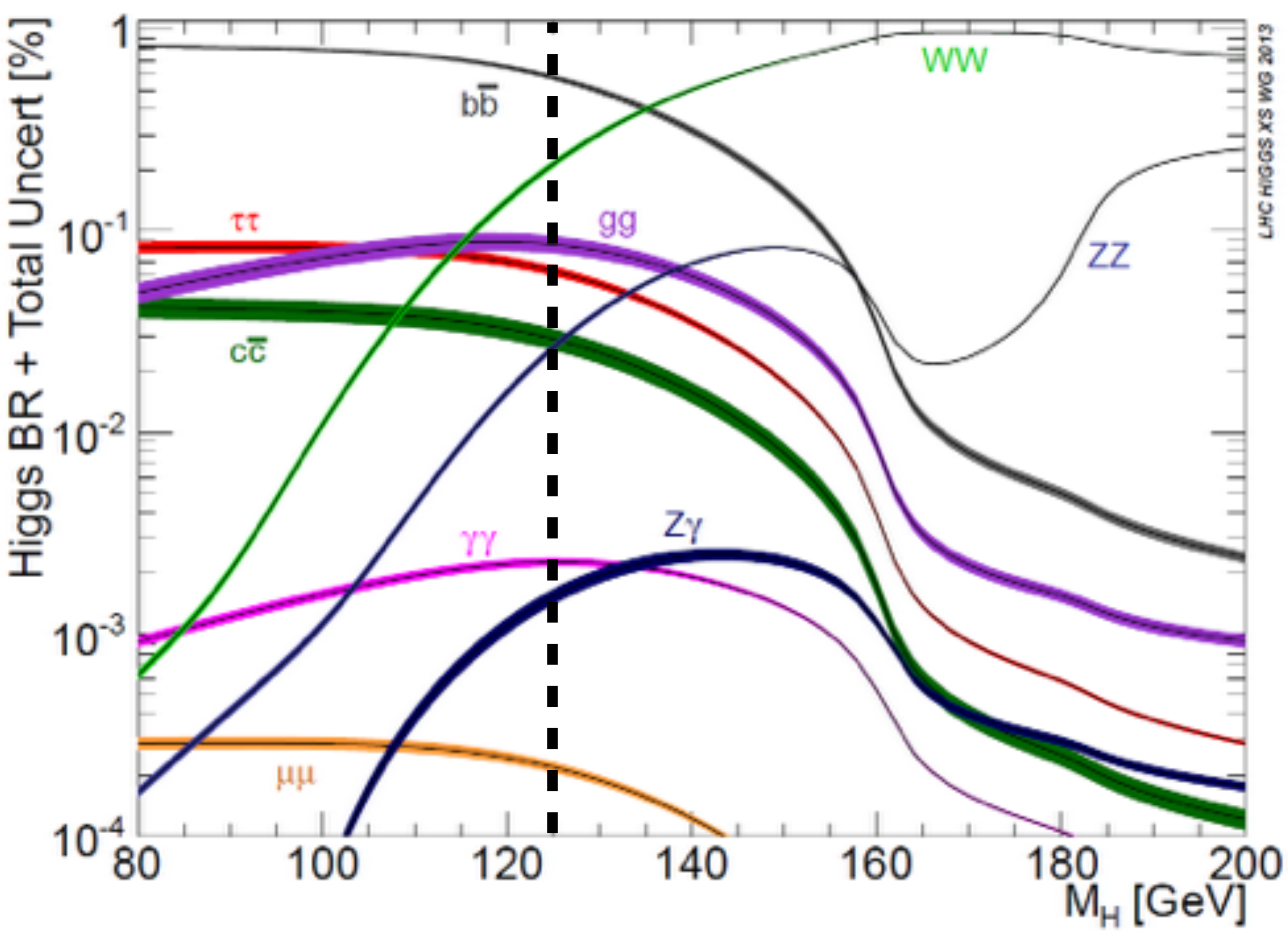
- Robust tradition in ATLAS of searching for exotic decays of h125 and beyond:
  Run 1: 2μ2tau, $Z_{(d)}Z_d$ —> 4L, 4γ, lepton-jets
  Run 2: 4b + many in the pipeline right now
- For many final states, difficult to access region with small m_a/m_H
  ==> fantastic places for new-signature R&D
- Here discussing multi-photon final states

SM



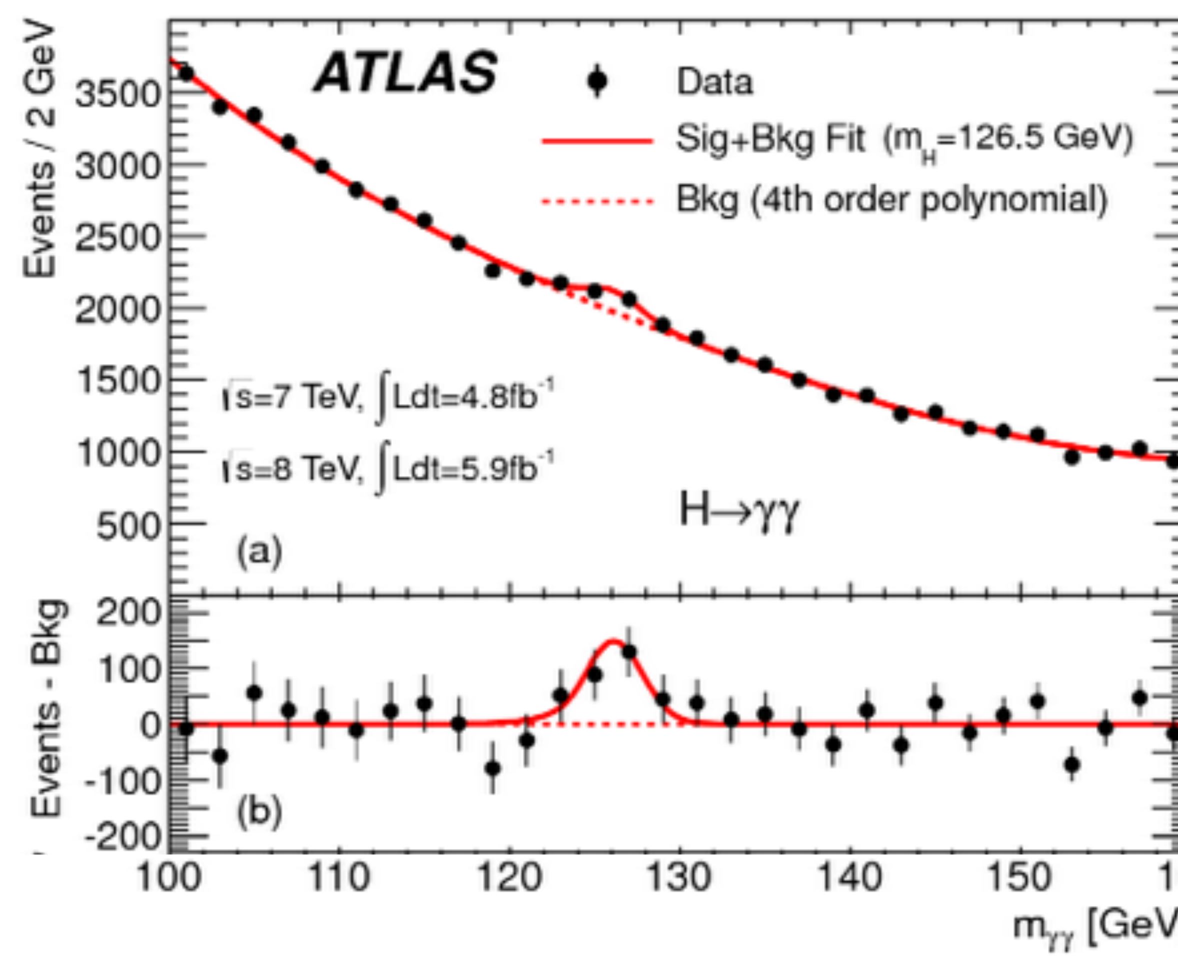
The bad news:

Small branching ratios

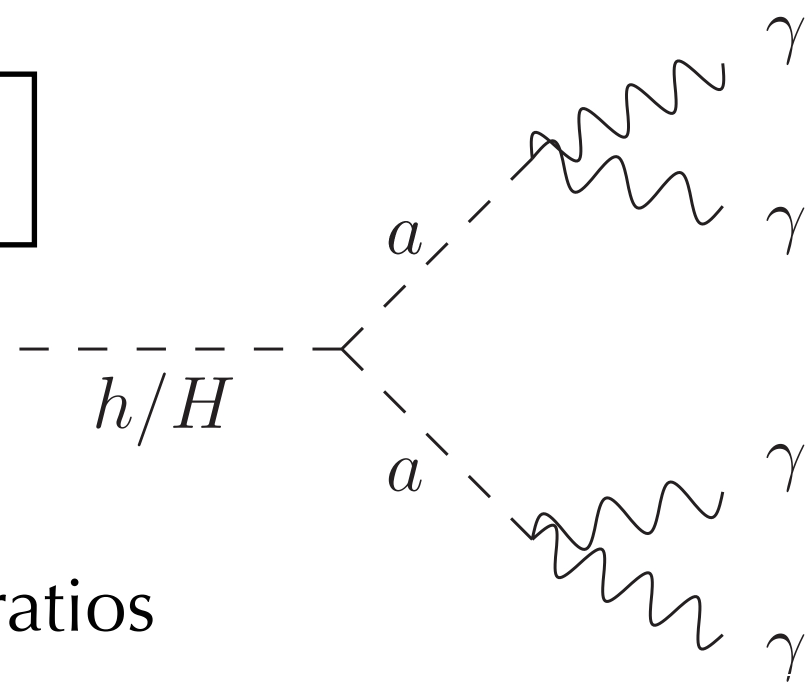


The good news:

Excellent isolated photon ID



BSM



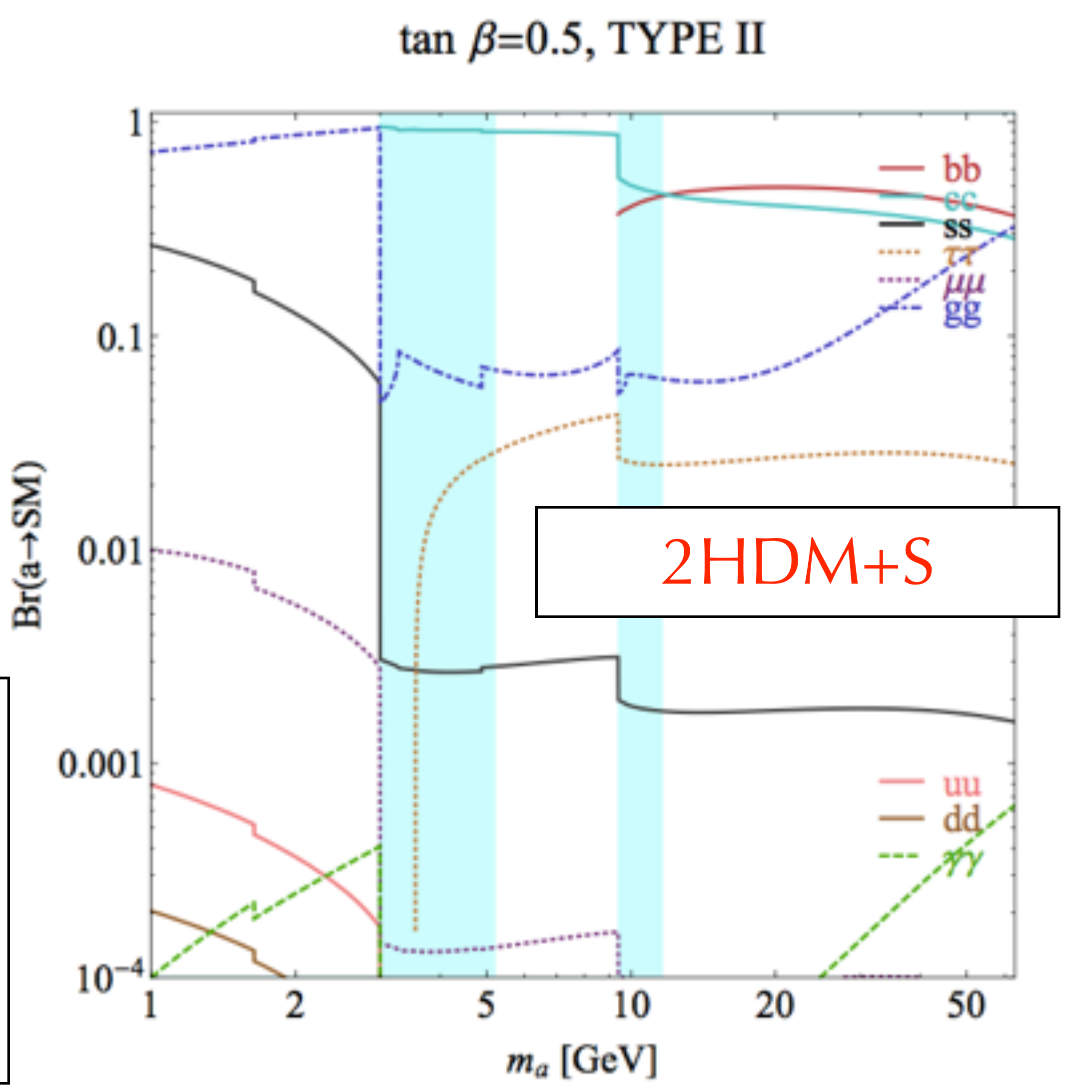
The bad news:

Small branching ratios

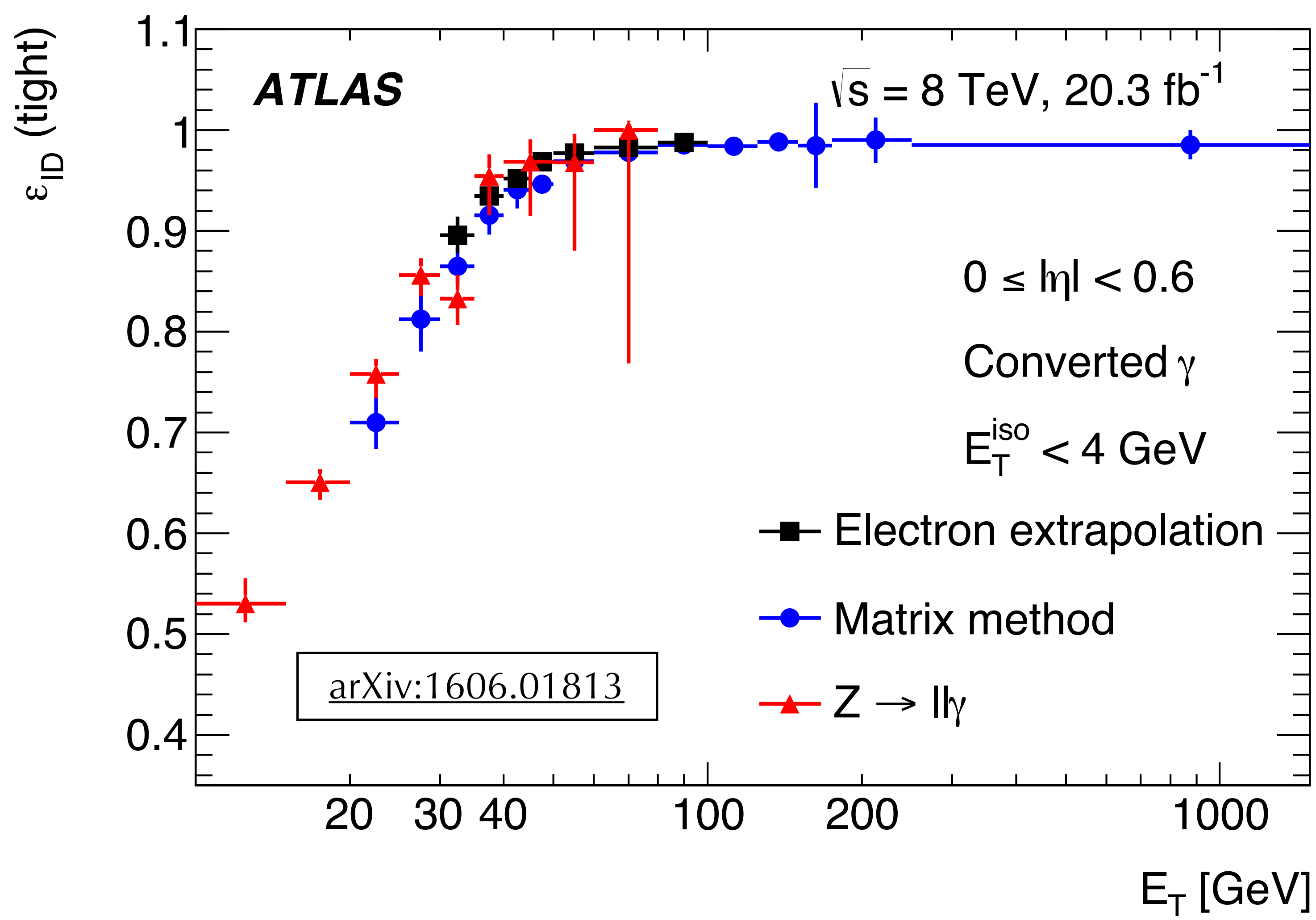
The good news:

Excellent isolated photon ID…

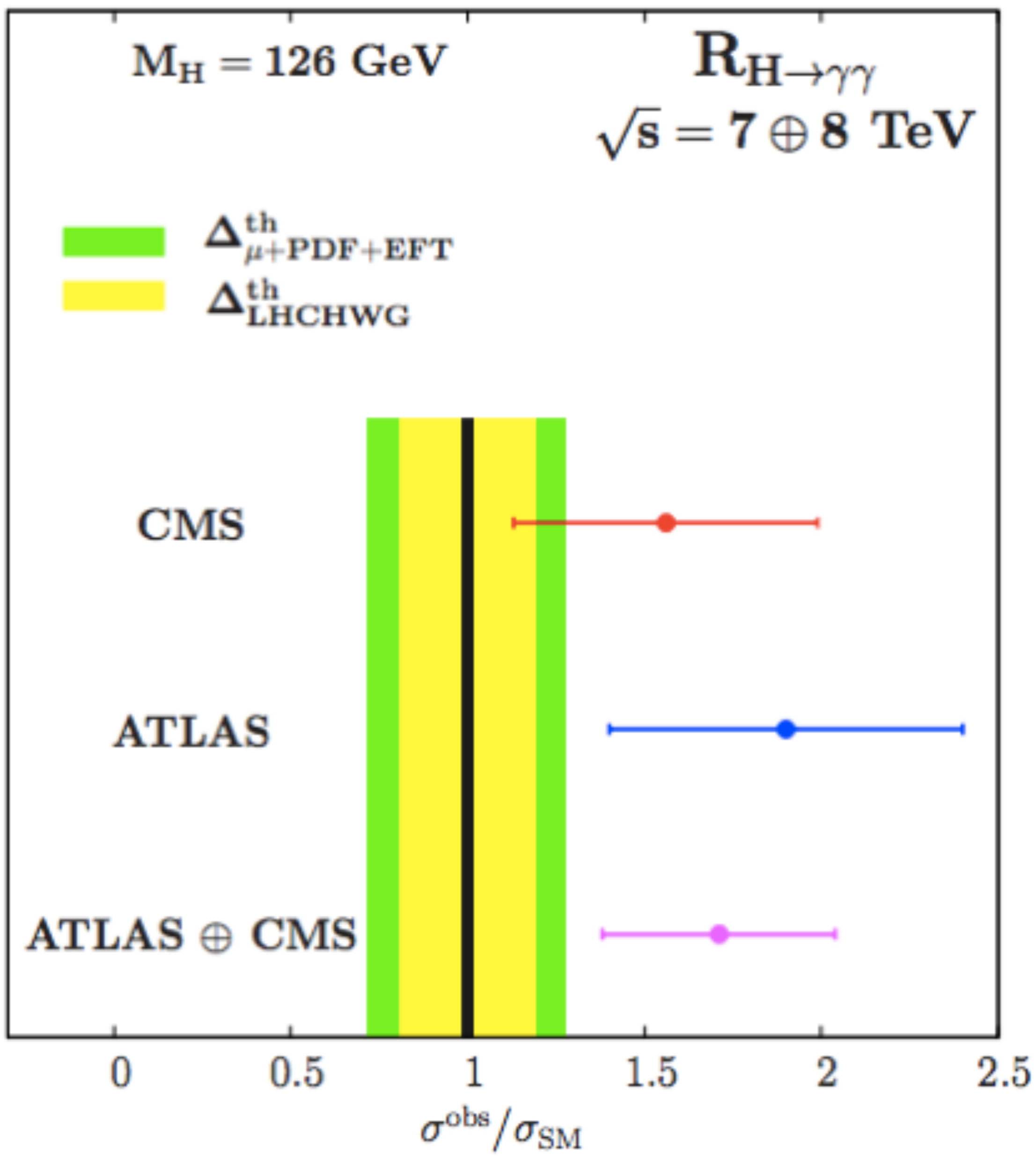
…plus extremely good calorimeters



arXiv:1312.4992

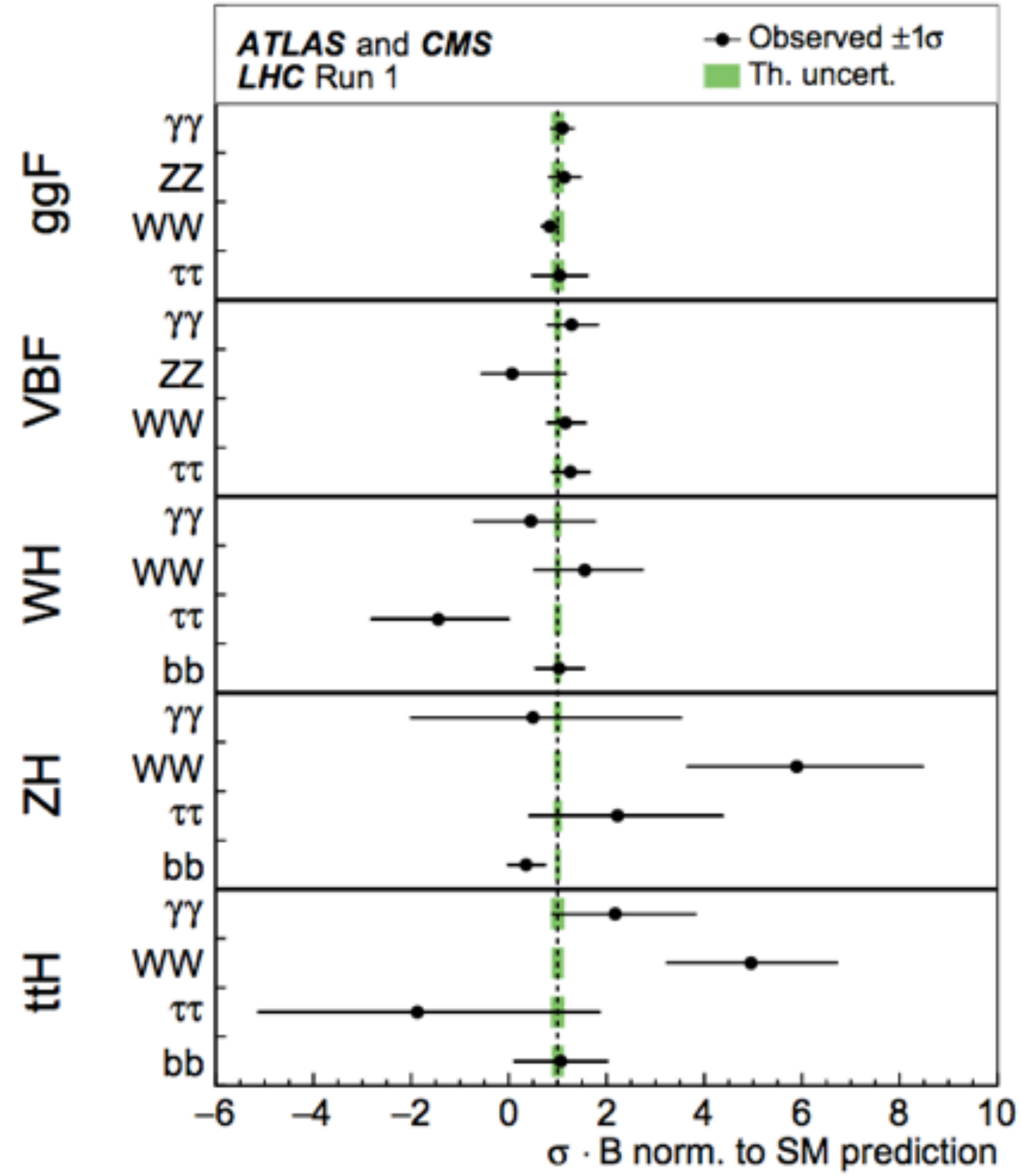


h125 —> 2γ in July of 2012



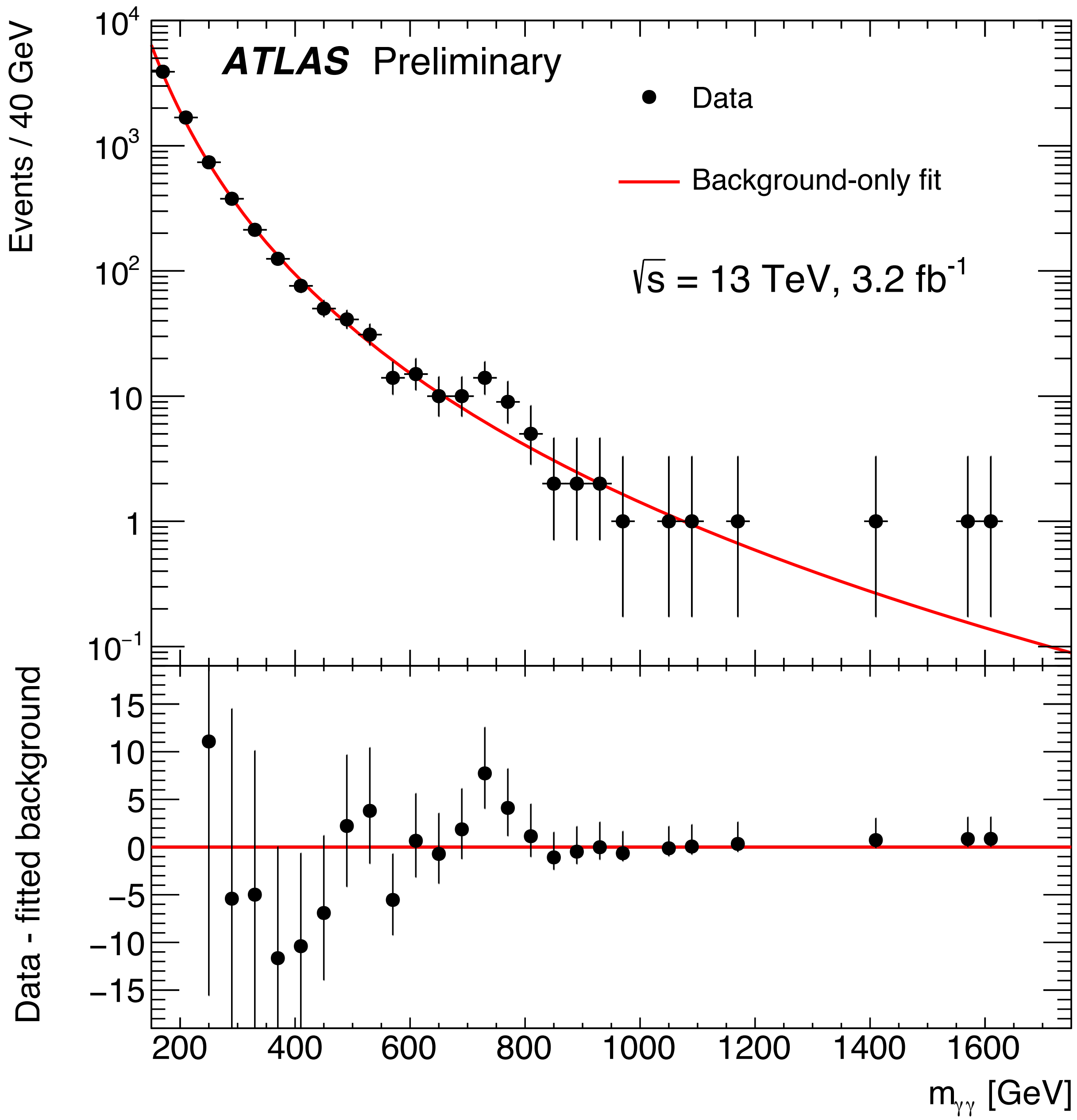
PLB 716:203-207,2012

h125 —> 2γ after Run 1

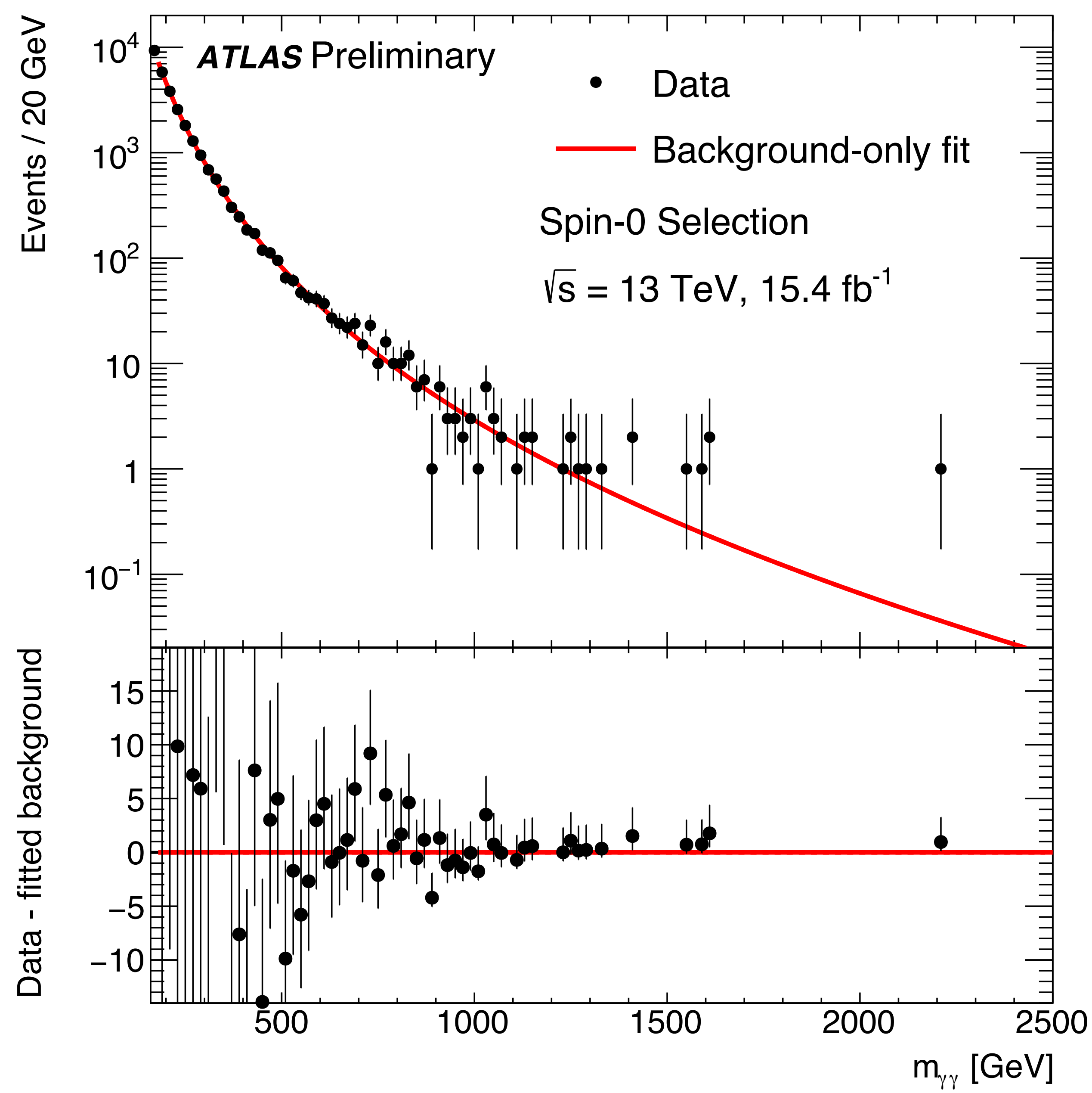


JHEP 08 (2016) 045

X750 in December of 2015



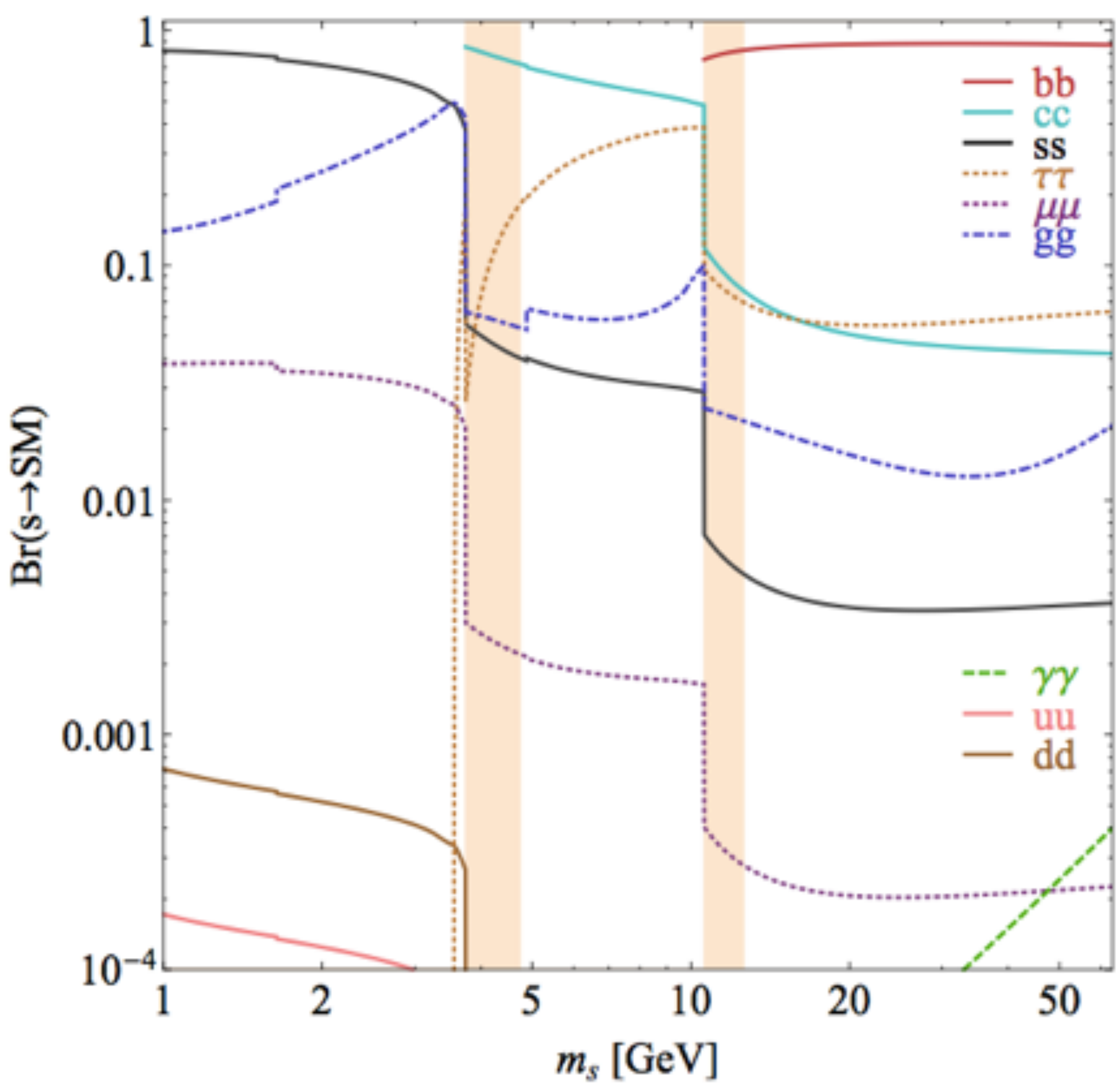
No750 in August of 2016



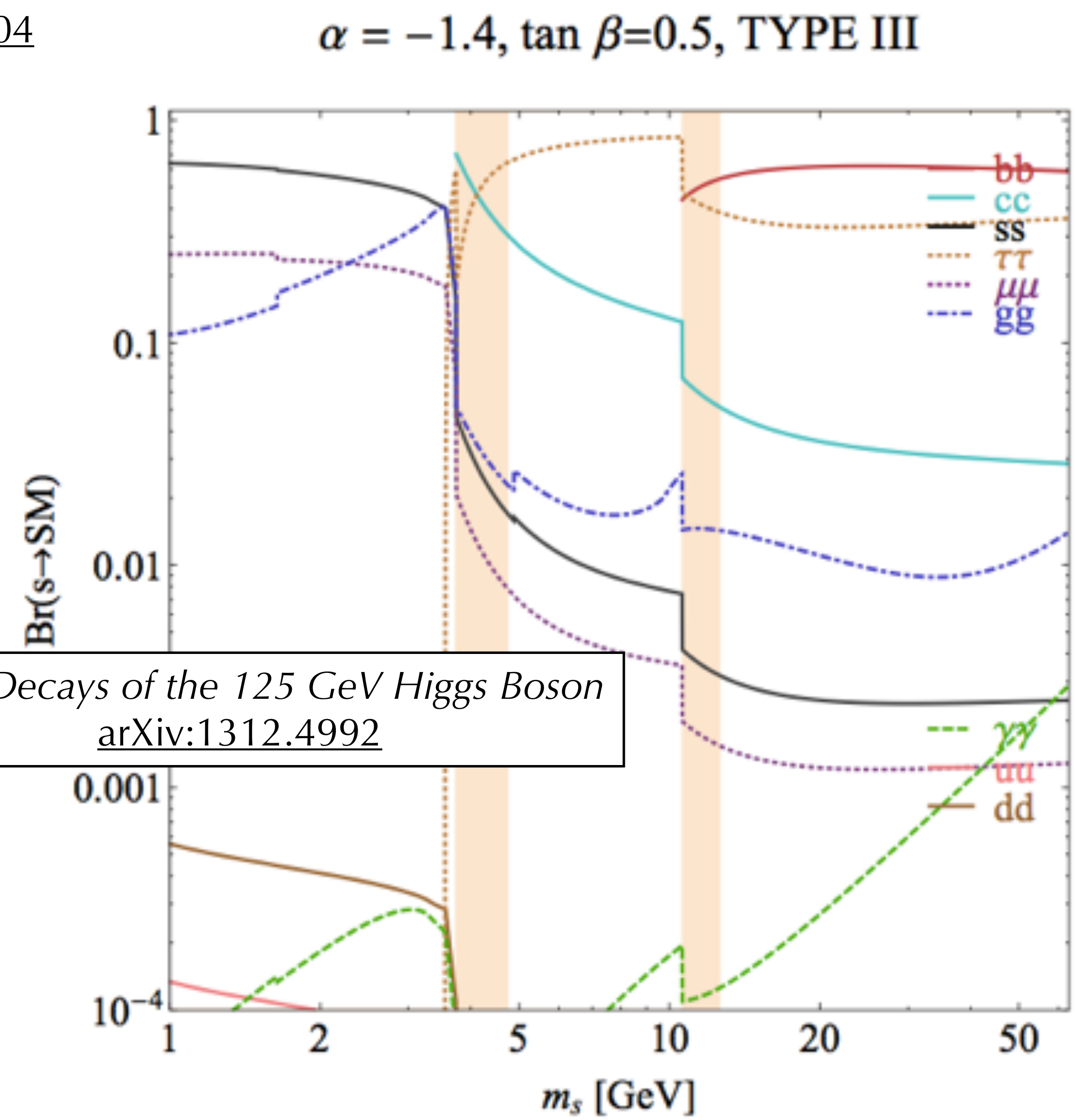
Multi-photon decays of h125

Many extensions of the SM Higgs sector include CP-odd particles (a) with couplings to the Higgs and branching ratios into photons visible at the LHC

- Pre-h125, pre-X750 examples:
  - Chang, Fox, Weiner, http://arxiv.org/abs/hep-ph/0608310
  - Dobrescu, Landsberg, Matchev, http://arxiv.org/abs/hep-ph/0005308v1
  - Larios, Tavares-Velasco, Yuan, http://arxiv.org/abs/hep-ph/0205204



SM+S



Exotic Decays of the 125 GeV Higgs Boson
arXiv:1312.4992

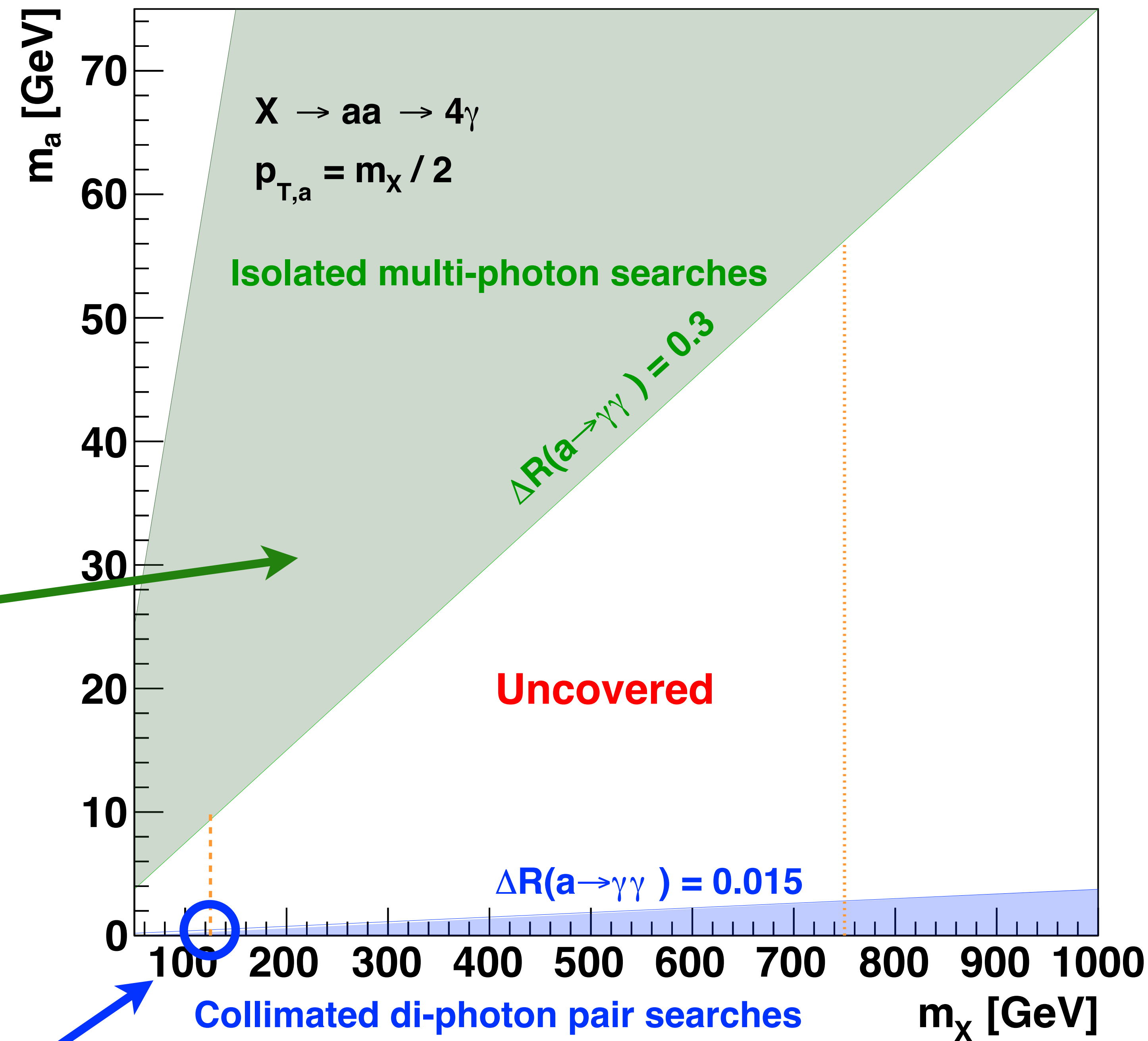
2HDM+S

But from a detector-signature standpoint, this is moot:

We look because we can and we haven't

8 TeV: EPJC 76 (2016) 4, 210

7 TeV: ATLAS-CONF-2012-079



Rule-of-thumb:
Opening angle of decay products of X particle:
$\Delta R \sim 2 * m_X / p_{T,X}$

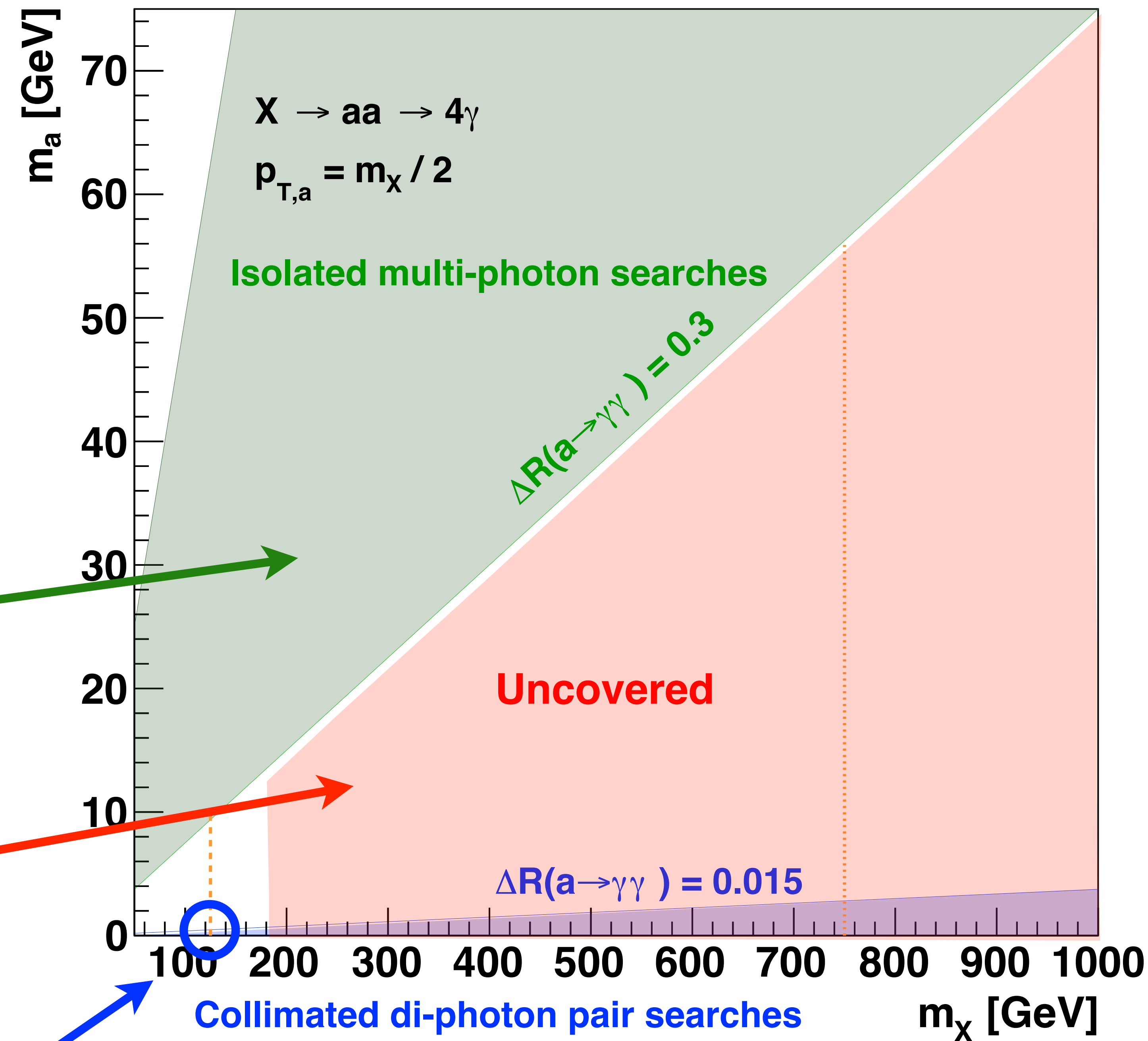
But from a detector-signature standpoint, this is moot:

We look because we can and we haven't

8 TeV: EPJC 76 (2016) 4, 210

13 TeV: Current work

7 TeV: ATLAS-CONF-2012-079



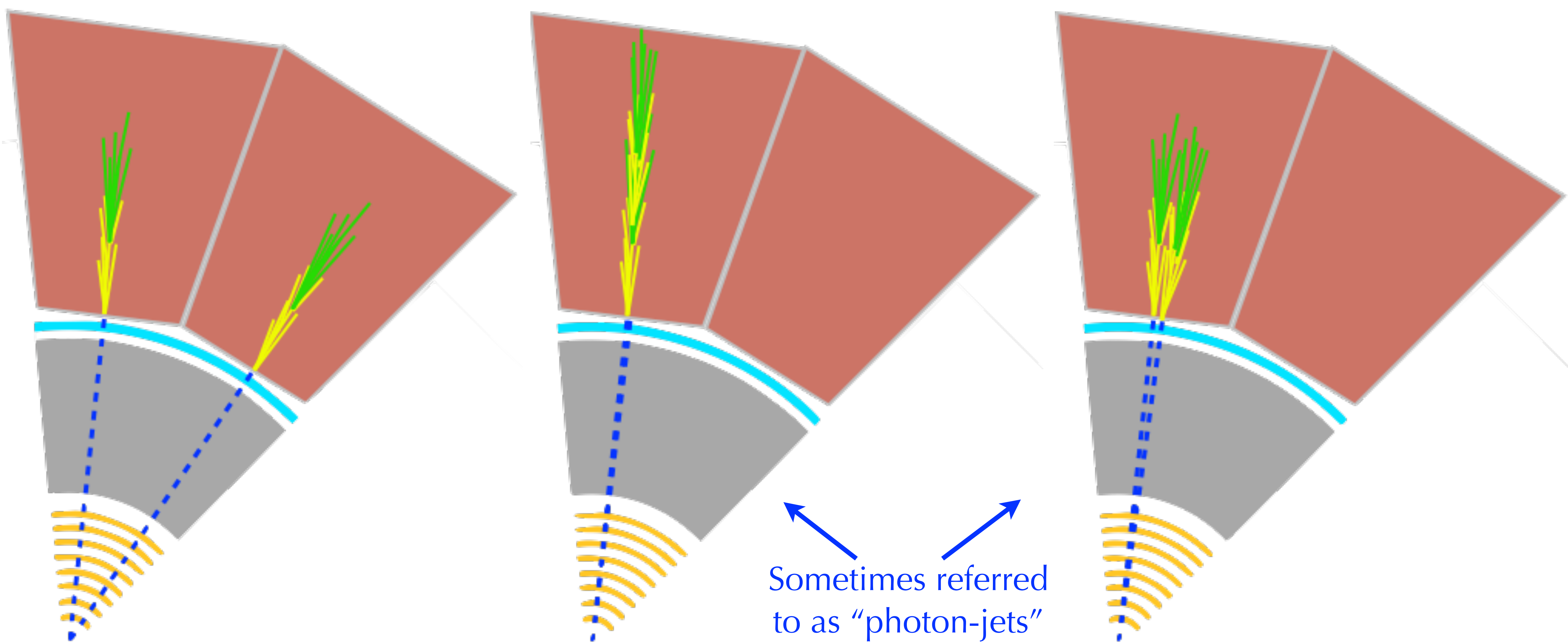
Rule-of-thumb:
Opening angle of decay products of X particle:
$\Delta R \sim 2 * m_X / p_{T,X}$

Multi-photon signatures

- Standard isolation calculated based on some fixed ΔR cone size (e.g., 0.4)
- Real photons have narrower shower shapes than jets
- Lots of extra energy in the cone ==> jet faking a photon
- Distinguish photons from jets-faking-photons by requiring stringent isolation
- —> Straightforward for high mass diphoton resonance searches
- —> Challenge arises for low-mass resonances with low-p_T photons or highly boosted states

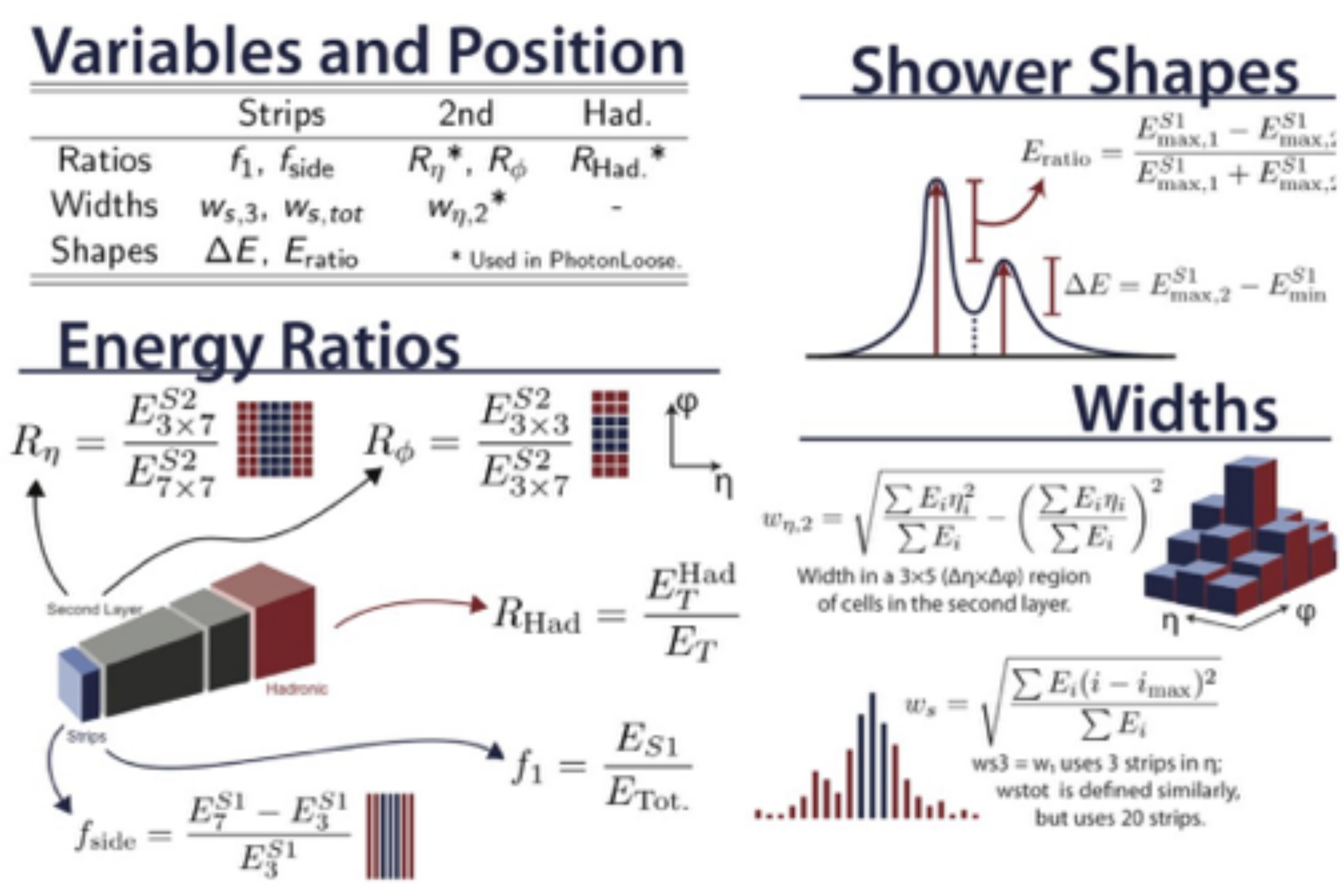
$$\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

Two well-separated photons (!) | **Two completely overlapping photons (!)** | **Two (or more) nearly-merged photons (?)**



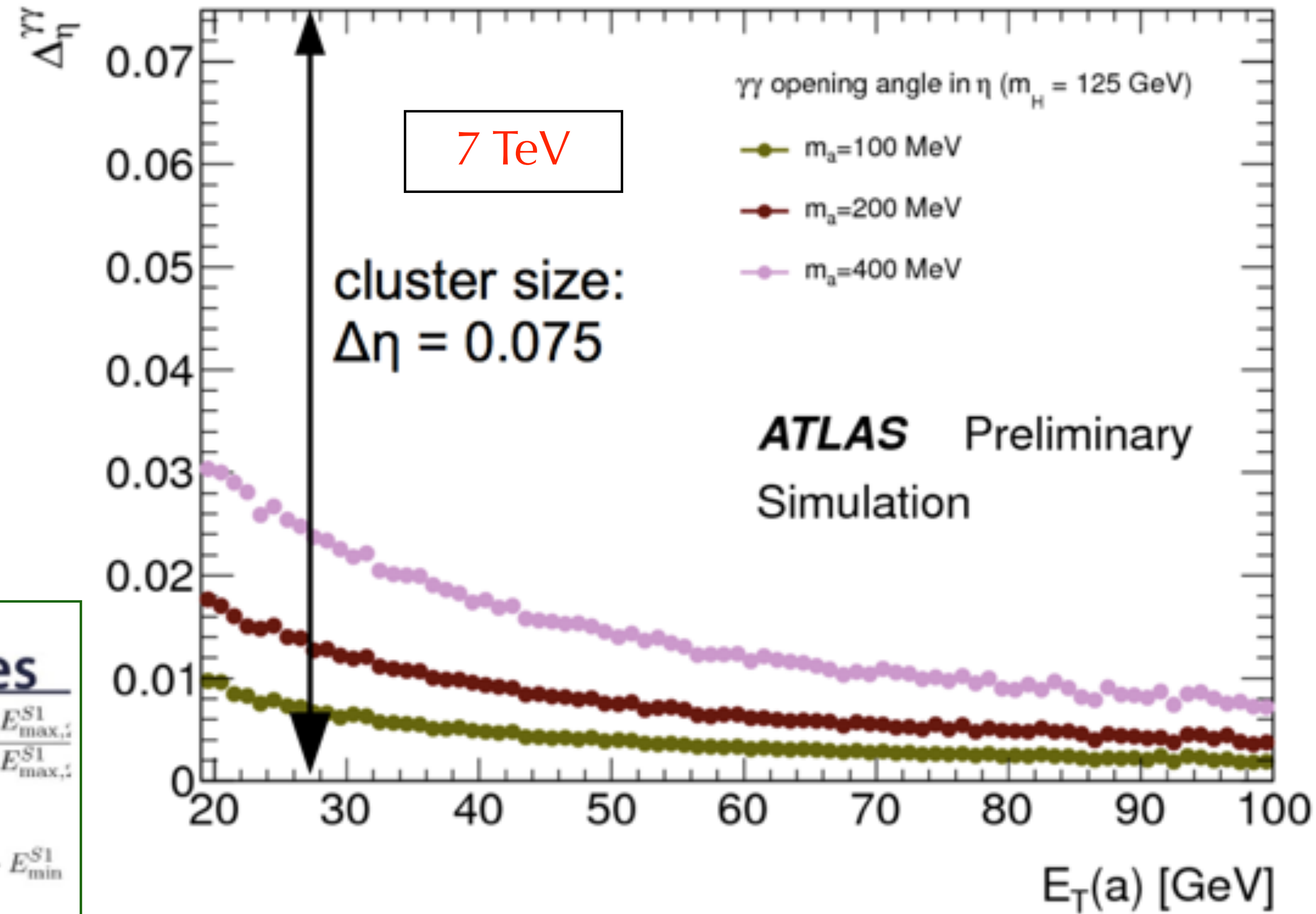
ATLAS search for h125 —> aa —> 4γ

- Motivated by the slight excess seen in the h125 diphoton channel at the time
  - Looked at 100 MeV < m_a < 400 MeV
- Separated single photons from two collimated photons with a custom photon ID



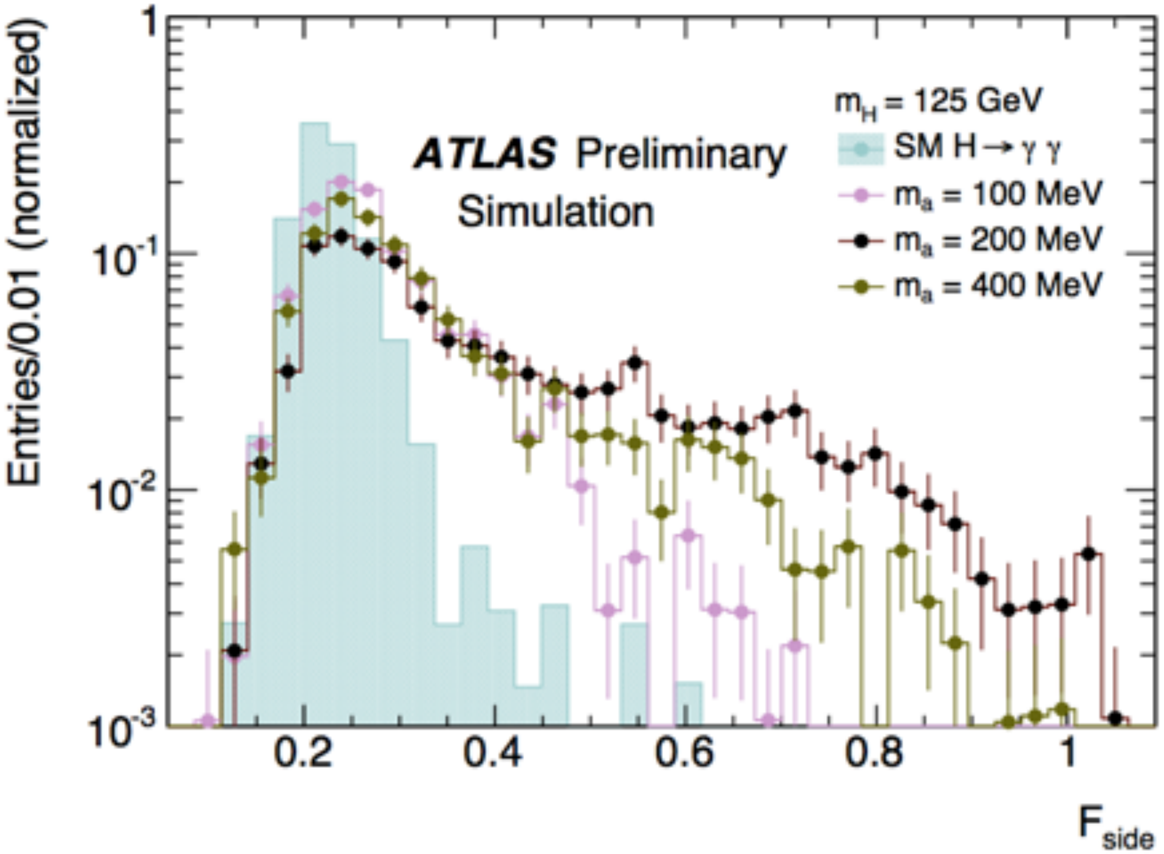
Cut-based tight is a combination of nine discriminants based on energy in ECal cells in layers 1 and 2 and leakage in the HCal

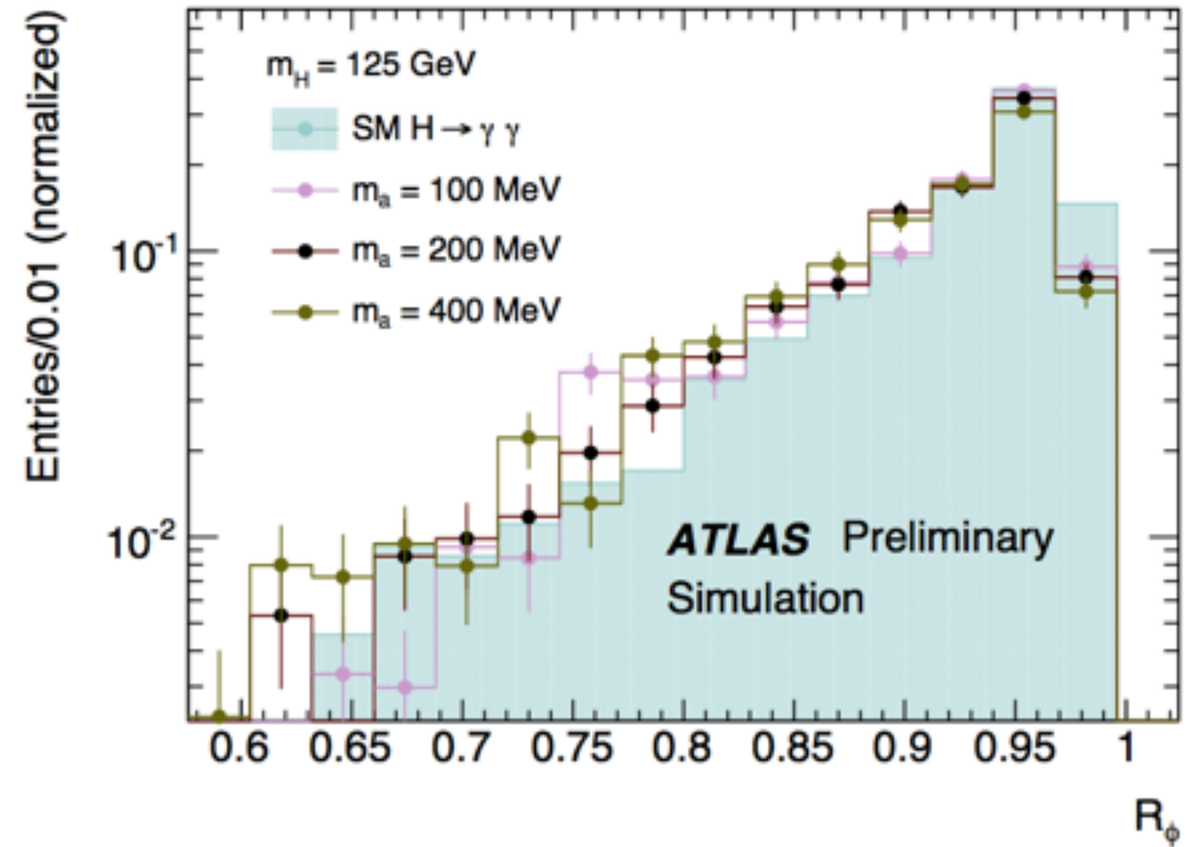
R_{had}, R_η, R_ϕ, $w_{\eta,2}$, ΔE, $w_{s,tot}$, f_{side}, $w_{\eta,1}$, E_{ratio}



- Separated single photons from two collimated photons with a custom photon ID
- Standard “tight” ID, two kinds of variables: Width and shower structure
- For custom ID, keep only those variables least sensitive to inner structure of the showers

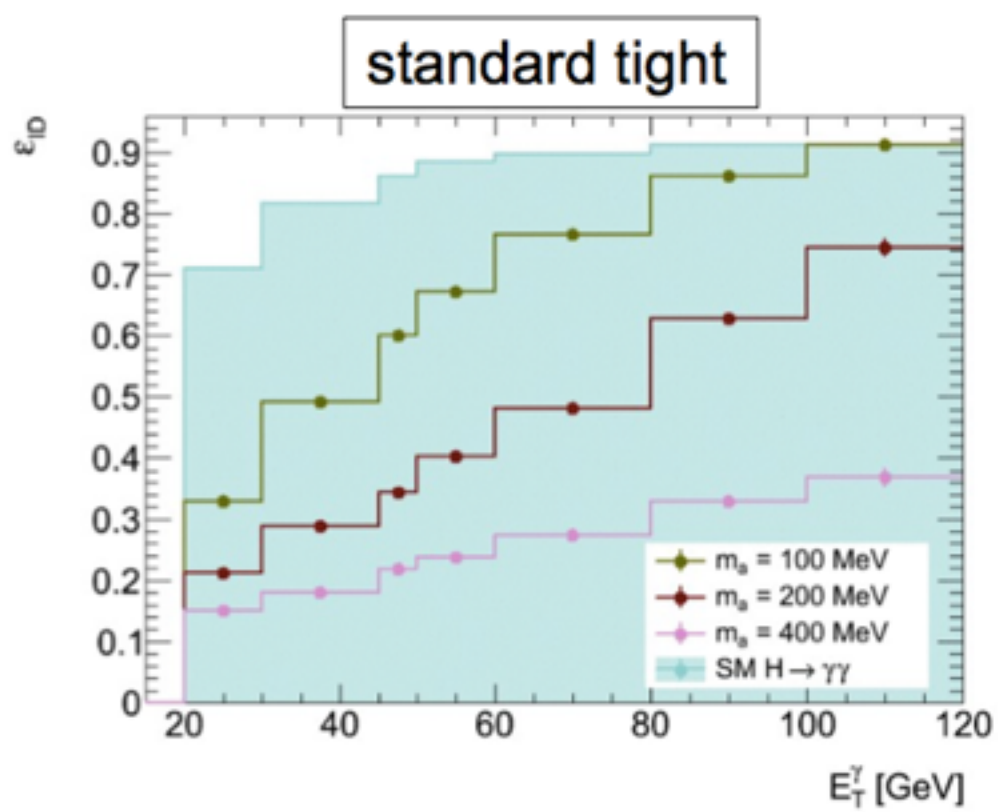
Choosing shower shape variables

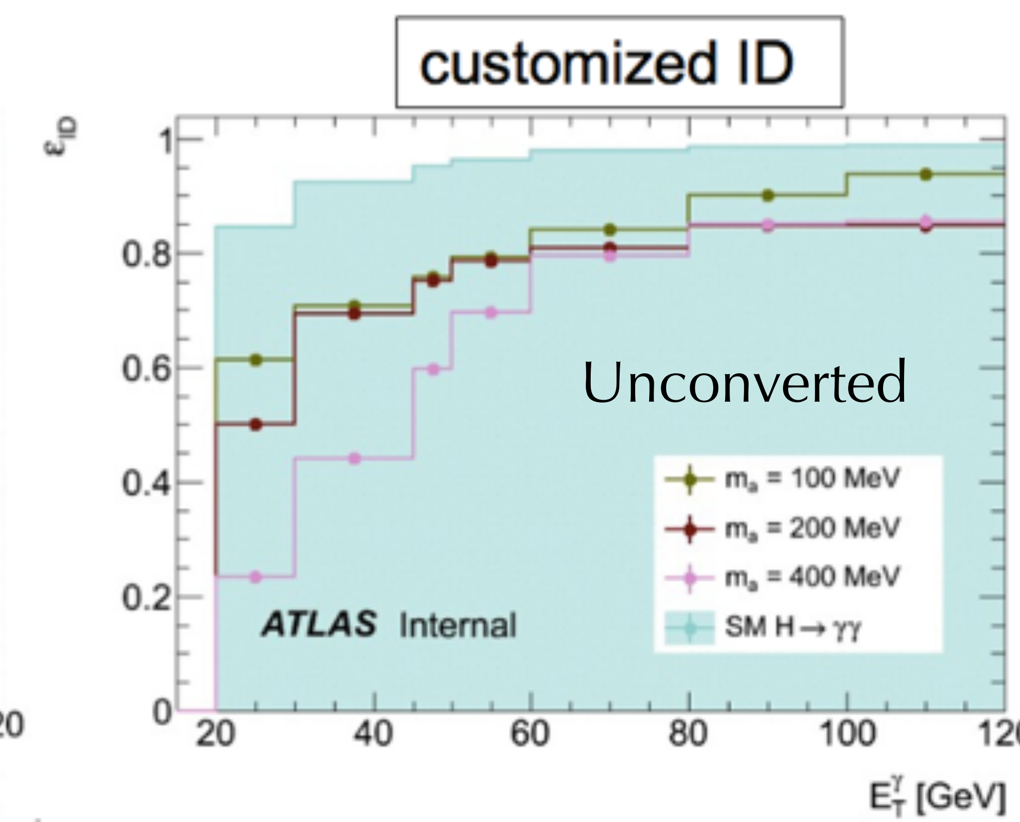




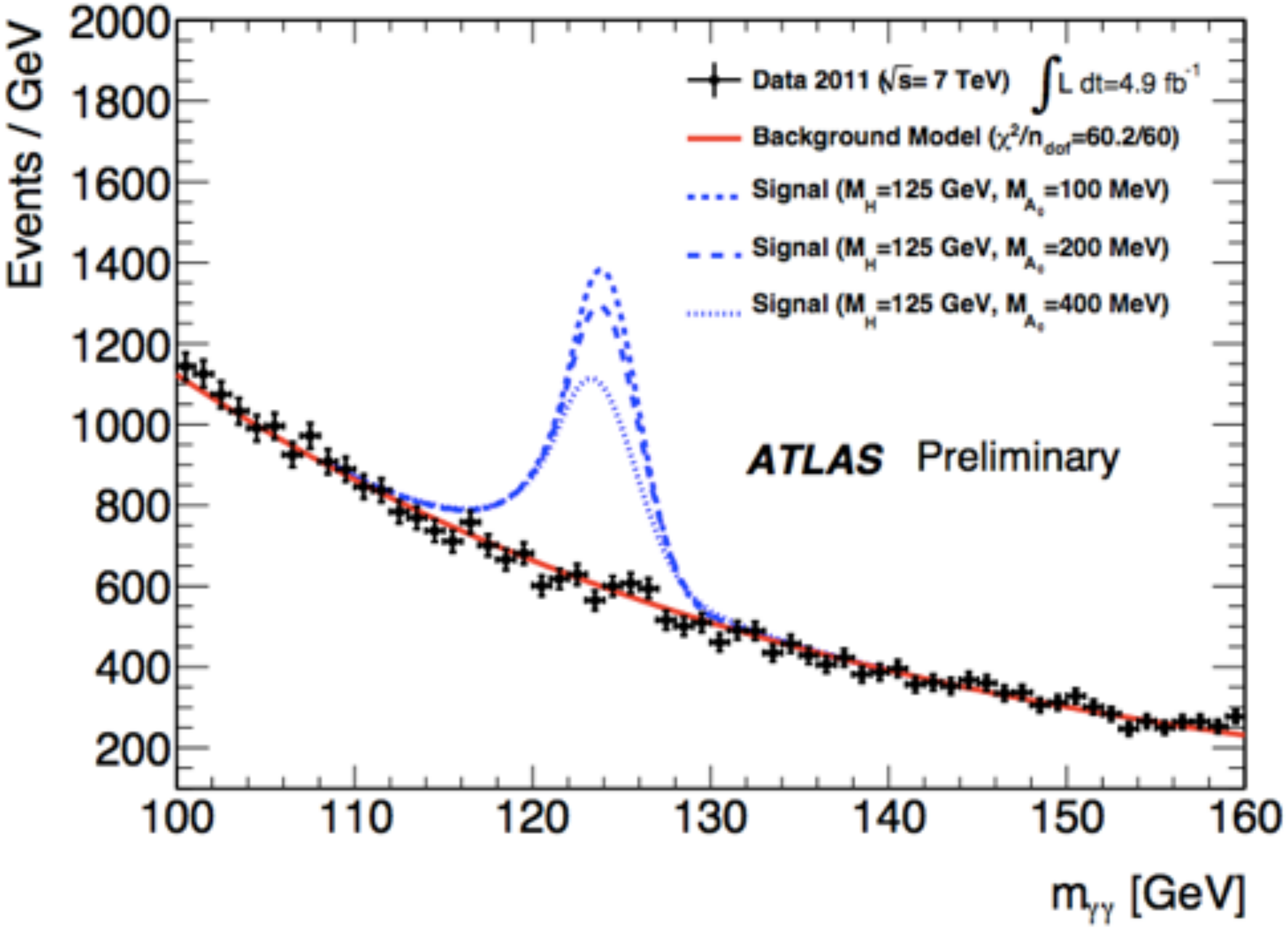
F_{side}: fraction of energy leaked outside the central core of three cells centered around the cell with most energy in the cluster, but still within seven cells

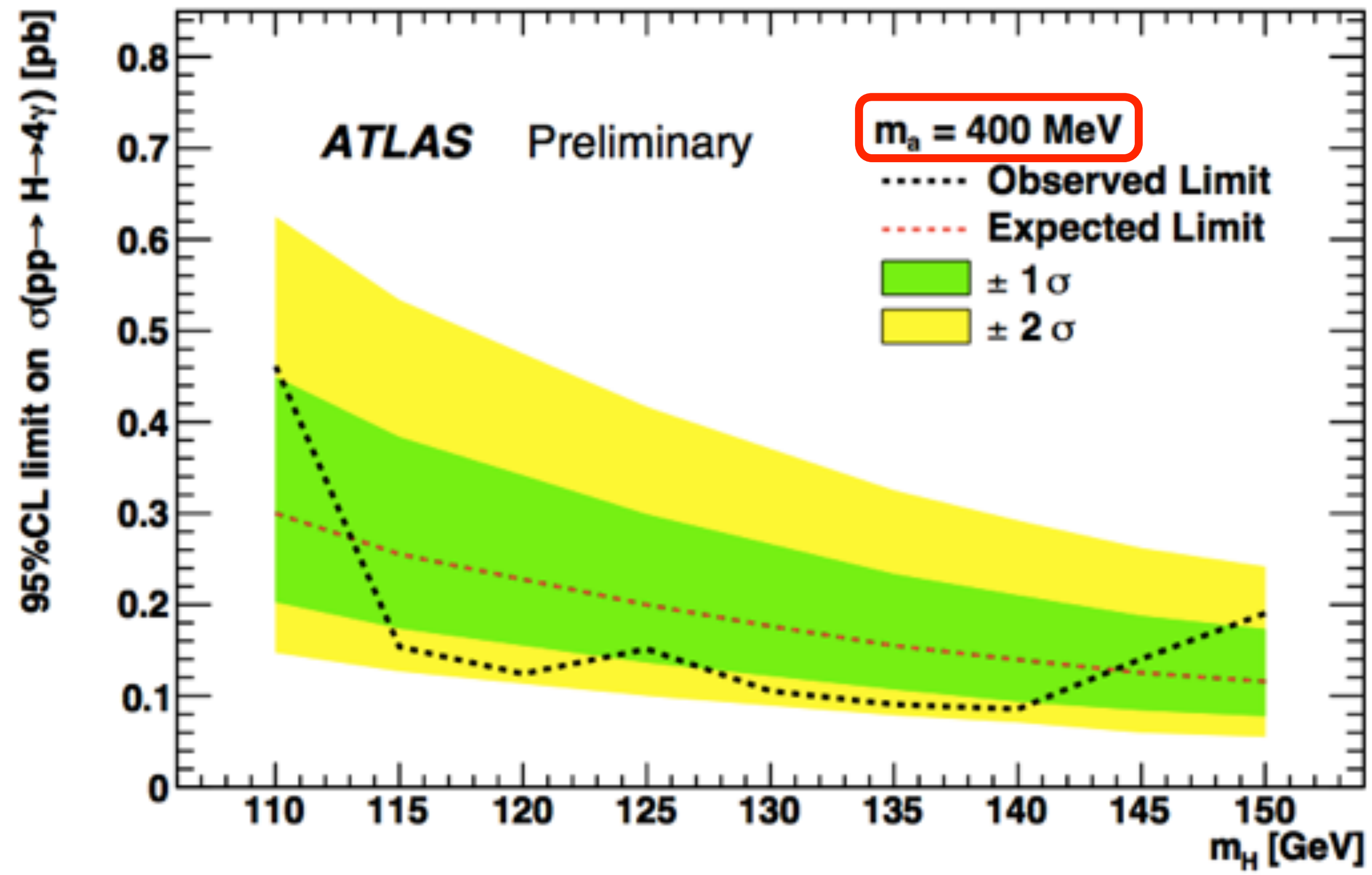
Clearly this will be different for photon-jets and photons





Results and limits



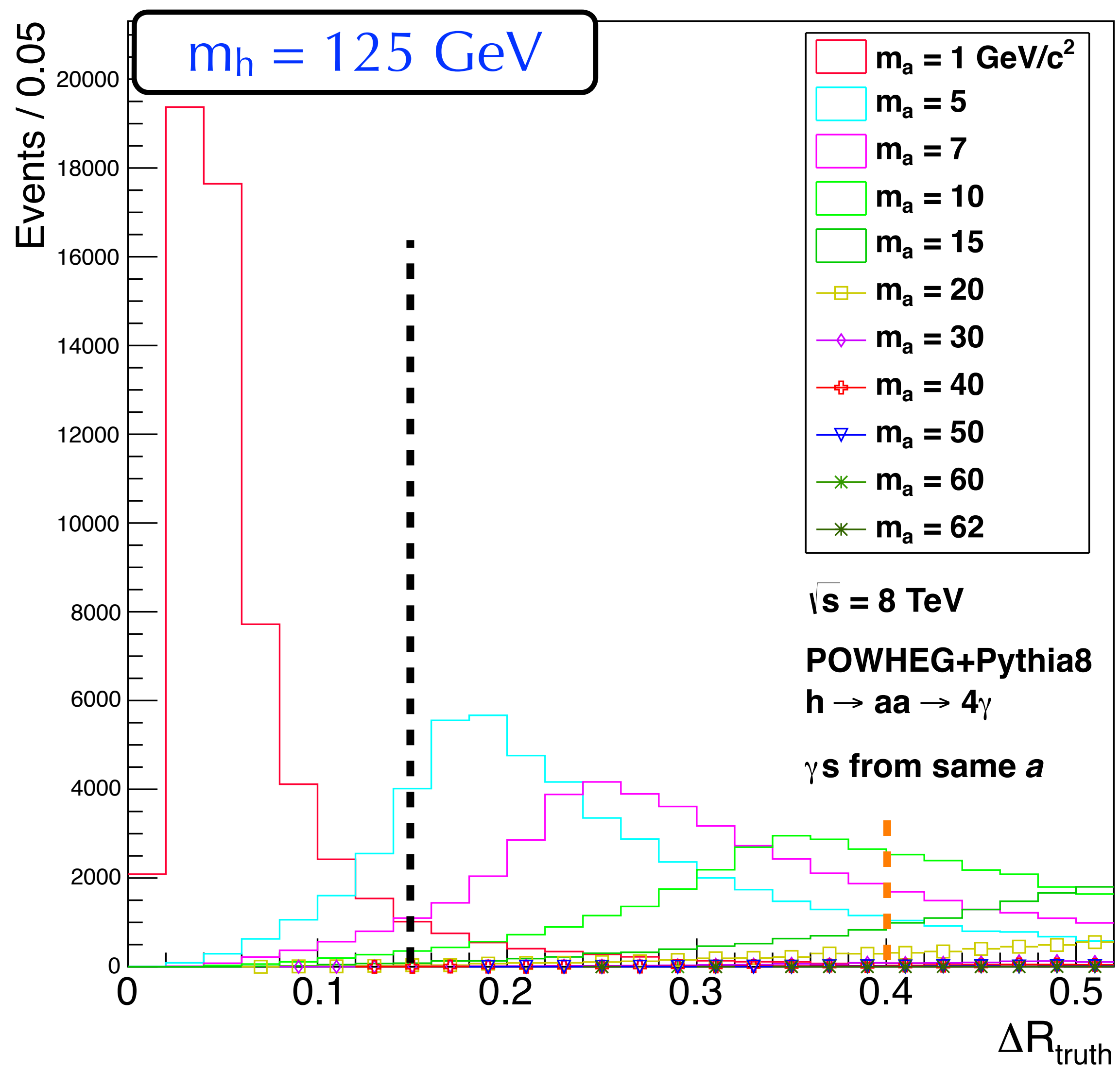


Background model is a fit to the diphoton mass spectrum with the custom ID

- Signal model: Crystal Ball + Gaussian from fits to Powheg+Pythia signal
- No excess seen and good exclusions made for 100 MeV < m_a < 400 MeV
- Limit can be improved, though, either with the full 20.3/fb at 8 TeV or 13 TeV

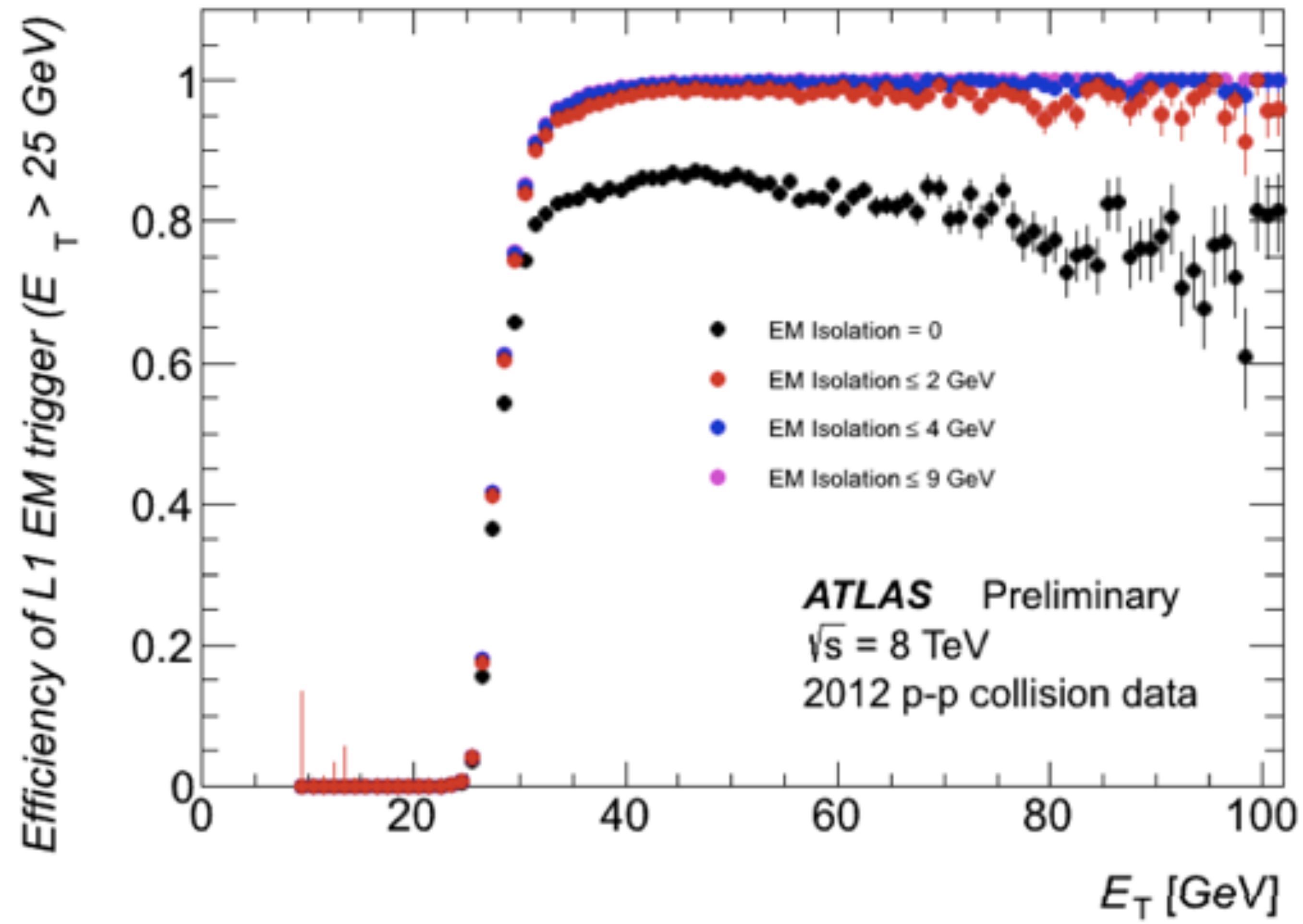
Level 1 EM triggers use "EM ring" and "hadronic core" isolation

- Immediately limits sensitivity to photon-jets scenarios like h125 —> aa —> 4γ



5x7 cluster ==>

<ΔR> = 0.15



Efficiencies of L1 triggers with E_T > 25 GeV with optimisation of threshold depending on η

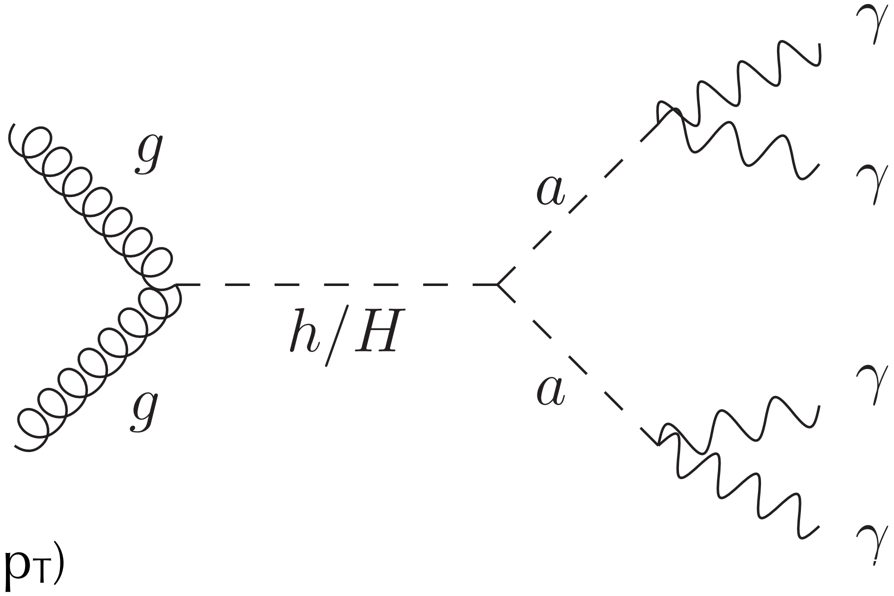
Hadronic leakage and electromagnetic ring isolation requirements as a function of offline electron E_T

Inclusive three photon search at 8 TeV

Started as a dedicated search for

h125 —> aa —> 4γ for higher m_a

- Event selection straightforward, low background



Challenges

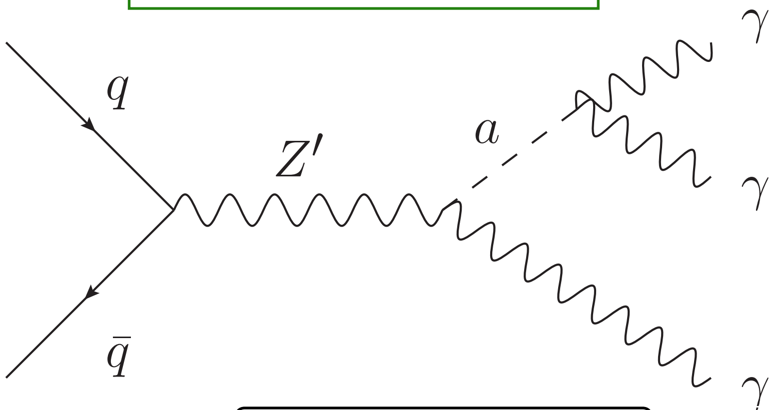
- Signal efficiency for 4γ low (h125 ==> relatively low photon p_T)
- Background estimate difficult (sub-optimal jet MC statistics)
- Needed data-driven jet background estimate;
  was unclear if existing methods would work for higher photon candidate multiplicity

Removed requirement on 4th γ

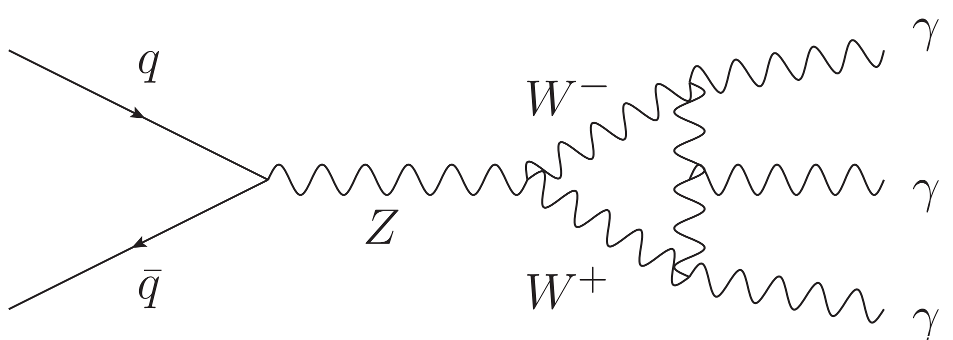
- Signal efficiency much higher for 3γ
- Still sensitive to resonances in 2γ spectrum
- Found we were sensitive to
  many other signal scenarios

Became a general search for new phenomena in events with at least three photons

Other scenarios



Z′ to photons



Rare Z decays

Inclusive three photon search at 8 TeV

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h125 —> aa —> 4γ for higher m_a

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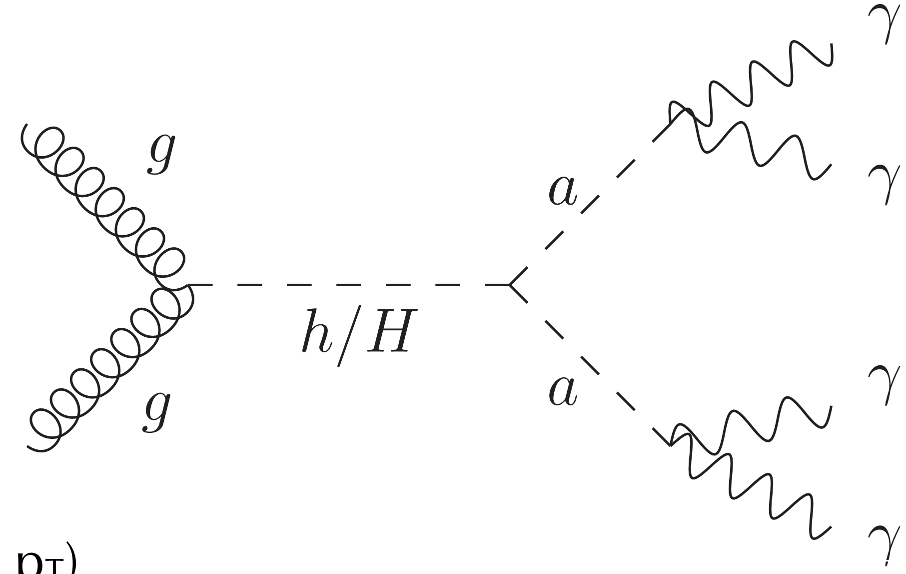

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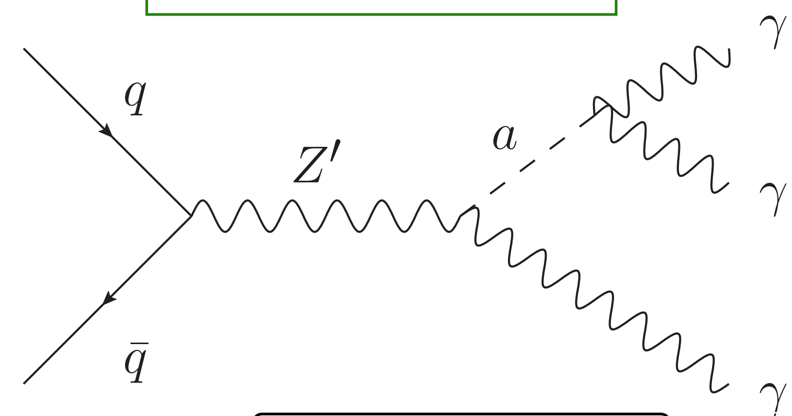

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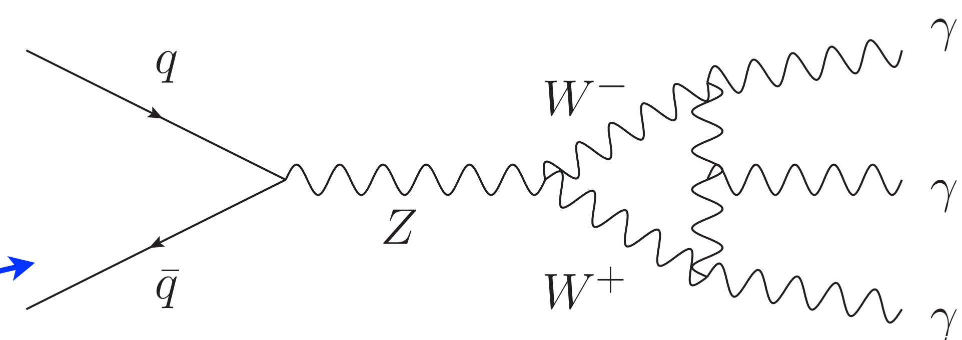


Rare Z decays

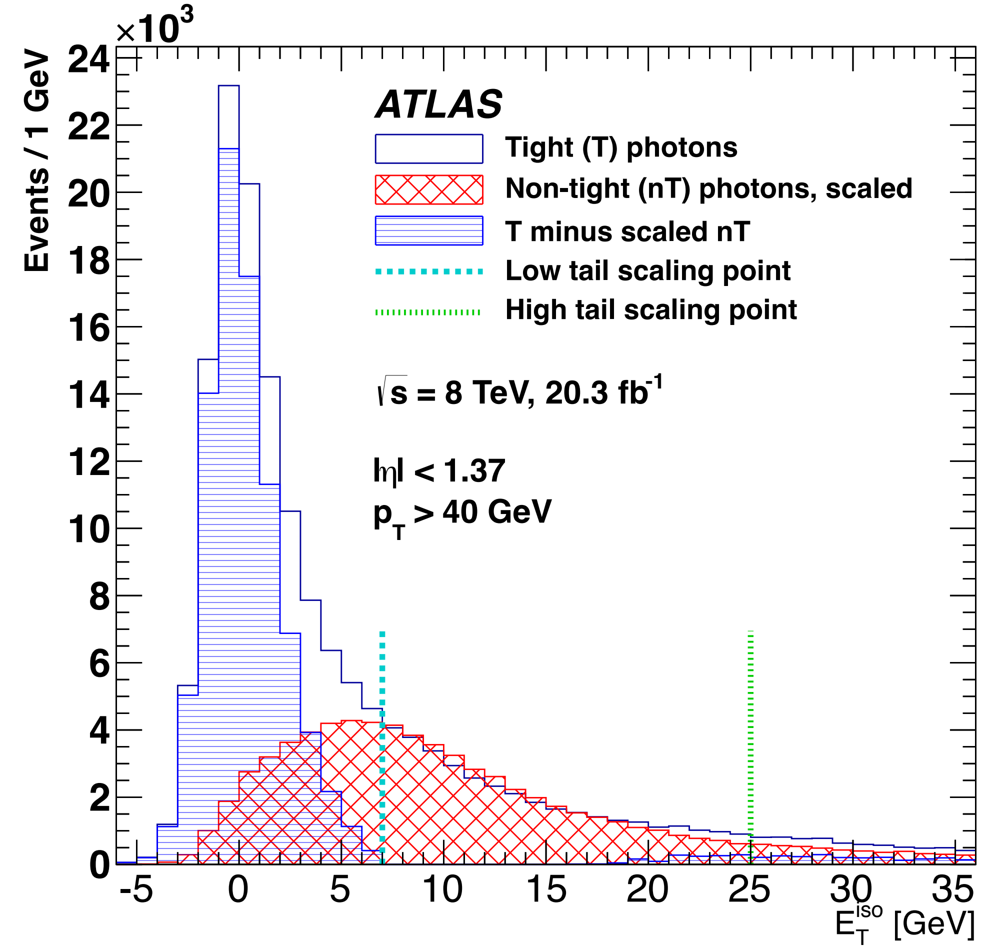
Became a general search for new phenomena in events with at least three photons

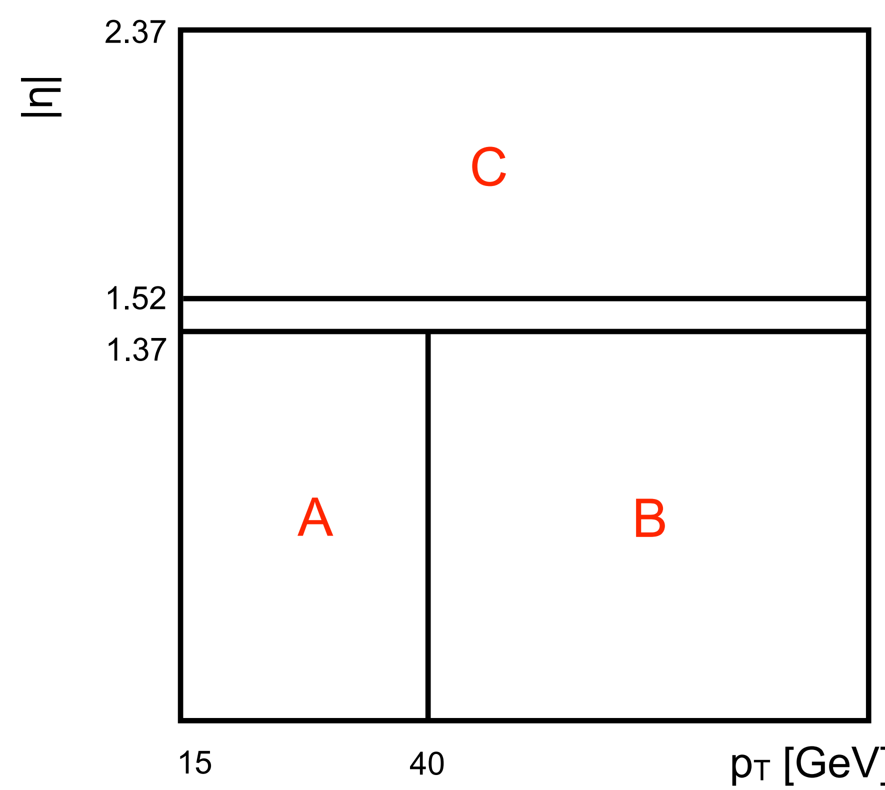
Shameless plug

World's best limit on BR(Z—>3γ)
- 2.2(2.0)e-6 obs(exp) (almost 5 times better than LEP)
- SM prediction: 5e-10

Search and presentation of results

- Event-counting in inclusive signal region, Z —> 3γ signal region, and fiducial kinematic region
  - Most general results on fiducial cross section for new phenomena
  - Backgrounds: Combination of data-driven (for jets) and MC (all other)
  - Jet background estimate using likelihood matrix method, exploiting photon-candidate isolation profiles/efficiencies for "tight" vs. "non-tight" that are enriched in true photons vs. true jets





- Resonance searches in 2/3γ mass spectra
  - Search for local excesses corresponding to detector mass resolution
  - Background entirely from data, via sideband fit

Each is relevant for h125 —> aa —> 4γ

Object and event selection

Three-photon trigger; all photon candidates with $p_T > 15$ GeV

Object pre-selection

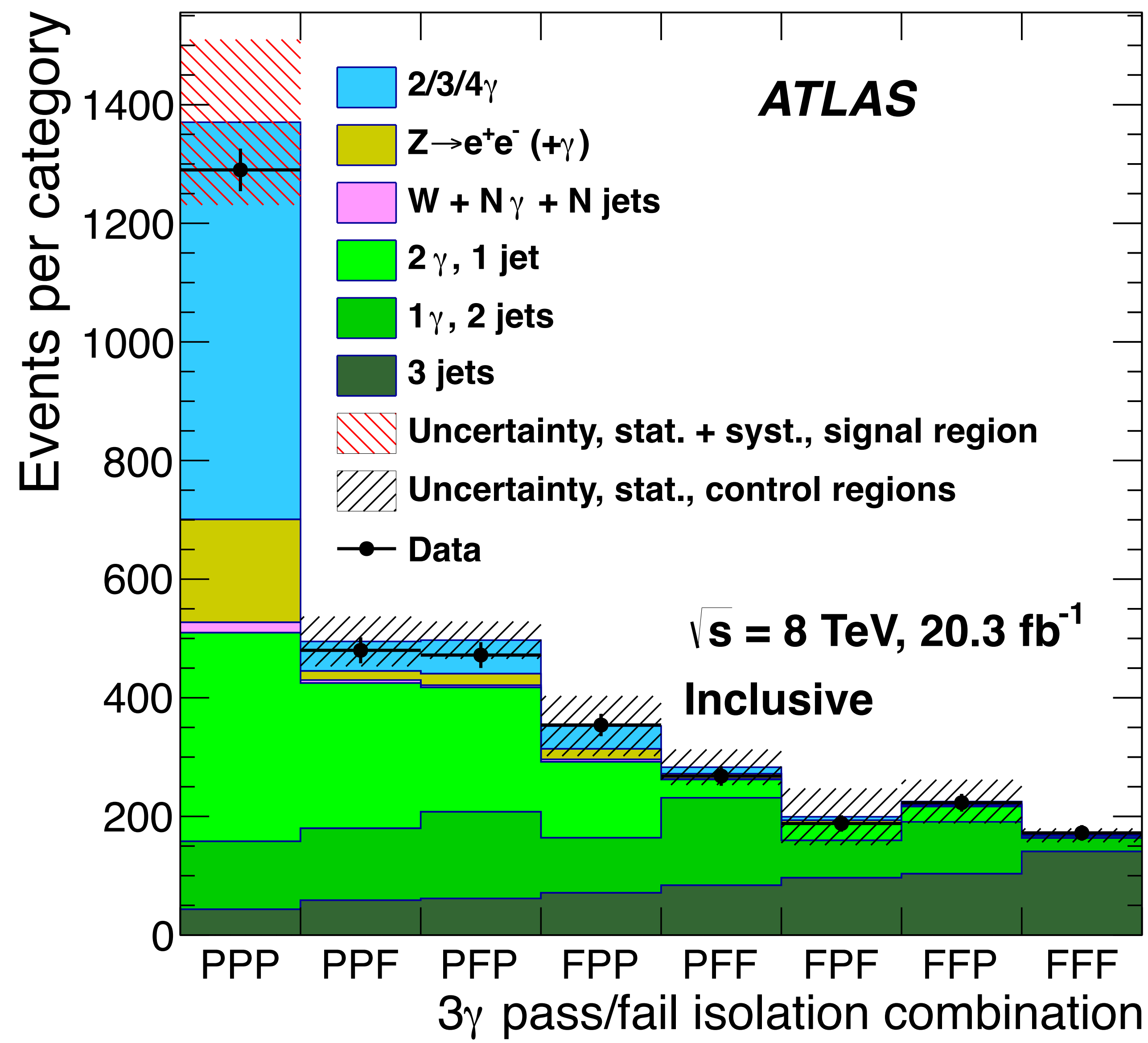
- Pseudorapidity:
  Good photon candidates satisfy
  $|\eta| < 1.37$ or > 1.52, $|\eta| < 2.37$
- Photon ID: Loose
- $\Delta R > 0.15$ for all pairings of pre-selected photons

Final event selection (signal region)

- $N_{ph} \geq 3$ photon candidates
- p_T : γ_1 and γ_2 both with $p_T > 22$ GeV,
  γ_3 with $p_T > 17$ GeV
- Photon ID: Tight
- Isolation: Cone: $\Delta R = 0.4$; $E_T^{iso} < 4$ GeV
  - Correction applied to isolation for photons with another high-pT photon within isolation cone; improves low-$m_{2\gamma}$ signal efficiency significantly

Results and general results

Process	Inclusive signal region
2γ (sim.)	330 ± 50
3γ (sim.)	340 ± 110
4γ (sim.)	1.3 ± 0.4
2γ,1j (D-D)	350 ± 60
1γ,2j (D-D)	110 ± 40
3j (D-D)	43 ± 11
Zee (sim.)	85 ± 22
Z+γ (sim.)	89 ± 11
W+γ+(0,1,2)j (sim.)	11.4 ± 1.5
W+2γ+(0,1,2)j (sim.)	6.1 ± 0.5
Total SM exp.	1370 ± 140
Observed	1290



Number-counting limits

Expected background	Observed	Obs. (exp.) 95% C.L. upper limit on N_{sig}
1370 ± 140	1290	240 (273^{+83}_{-66})

Fiducial cross section

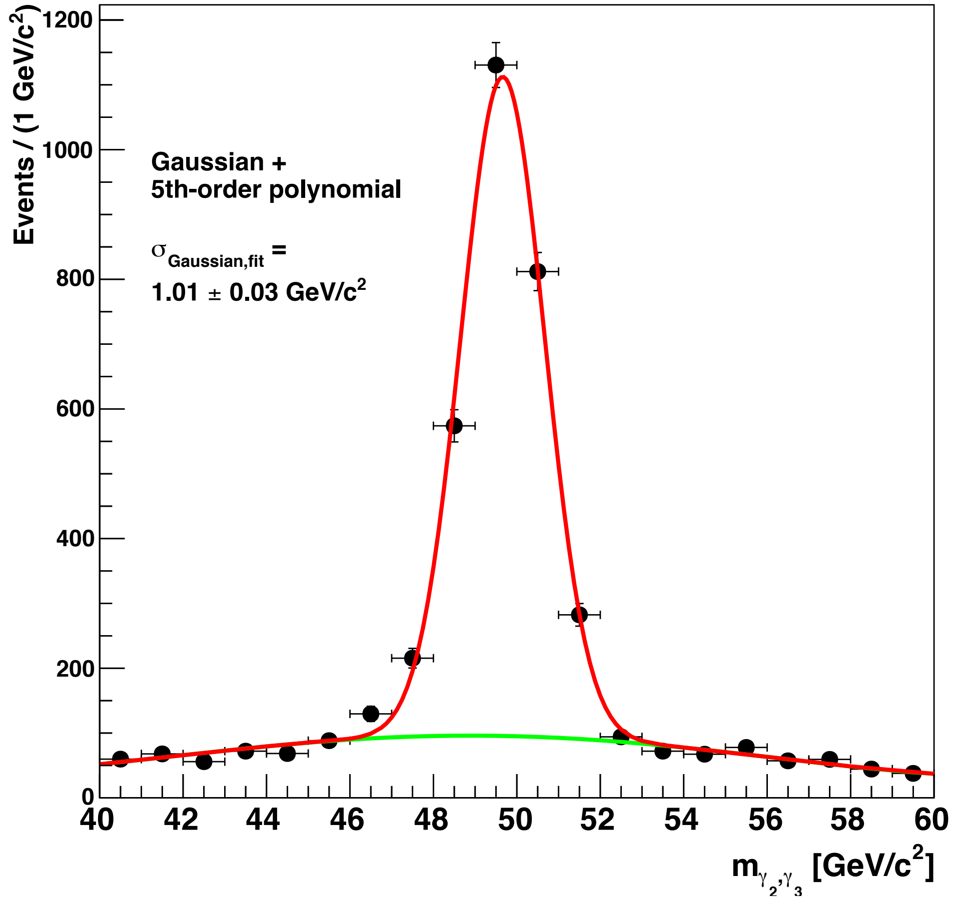
Signal process [GeV]		Fiducial efficiency	Obs. (exp.) upper limit, $\sigma_{fid} \times \mathcal{A}$ [fb]
$h \to aa \to 4\gamma$			
m_h	m_a		
125	10	0.374 ± 0.005	32 (36^{+11}_{-9})
125	62	0.490 ± 0.004	24 (27^{+8}_{-7})
300	100	0.643 ± 0.003	18 (21^{+6}_{-5})
600	100	0.688 ± 0.003	17 (20^{+6}_{-5})
900	100	0.680 ± 0.003	17 (20^{+6}_{-5})

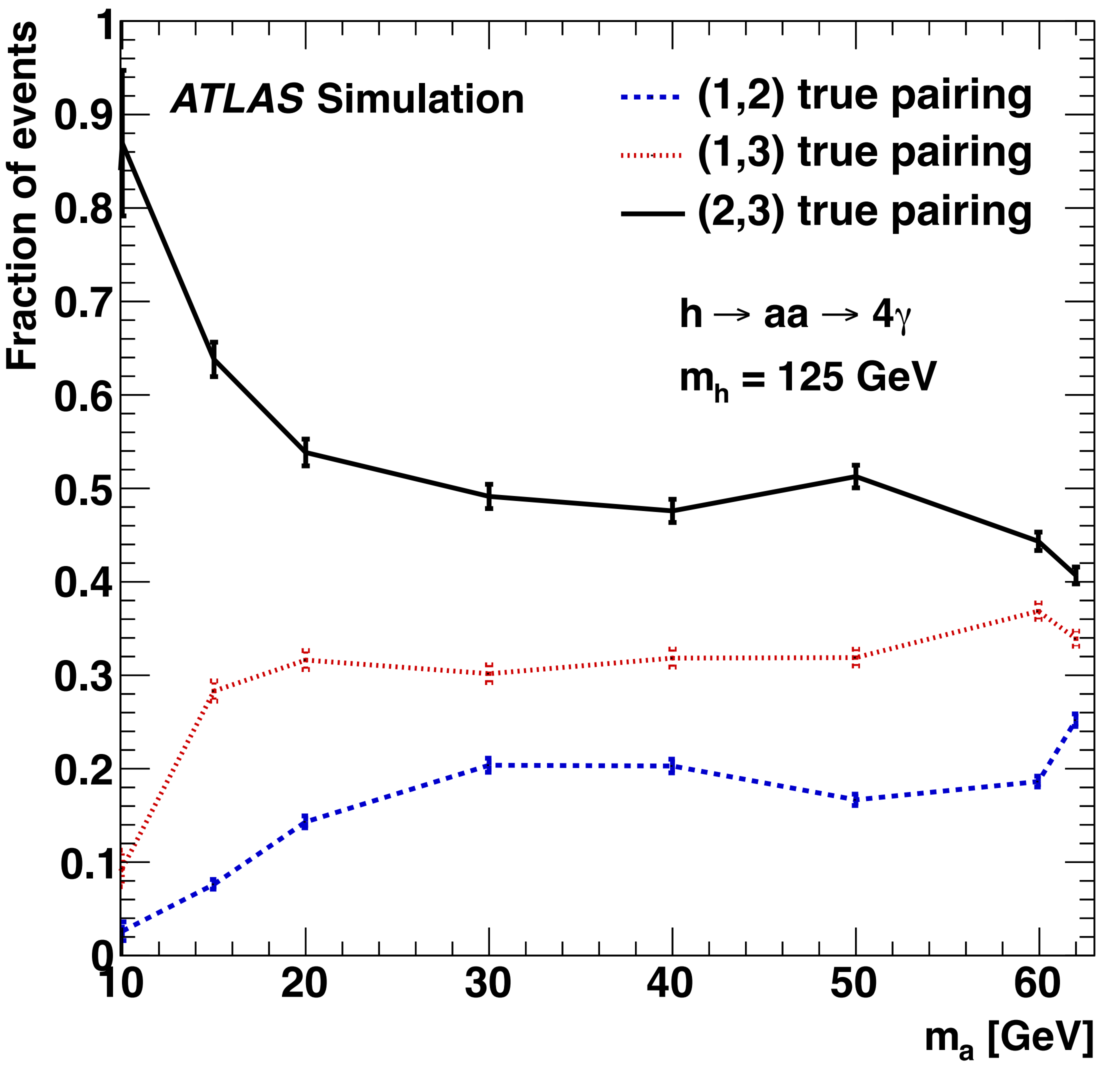
General results for h125 —> aa —> 4γ…

…but we can do better than this

Searches are performed for resonances with widths corresponding to mass resolution for 2γ cases

- Resonance widths are determined via fits to signal MC
- Since pseudoscalar *a* (for $m_{2\gamma}$) is generated with a narrow-width approximation, mass resolution corresponds to the general detector resolution



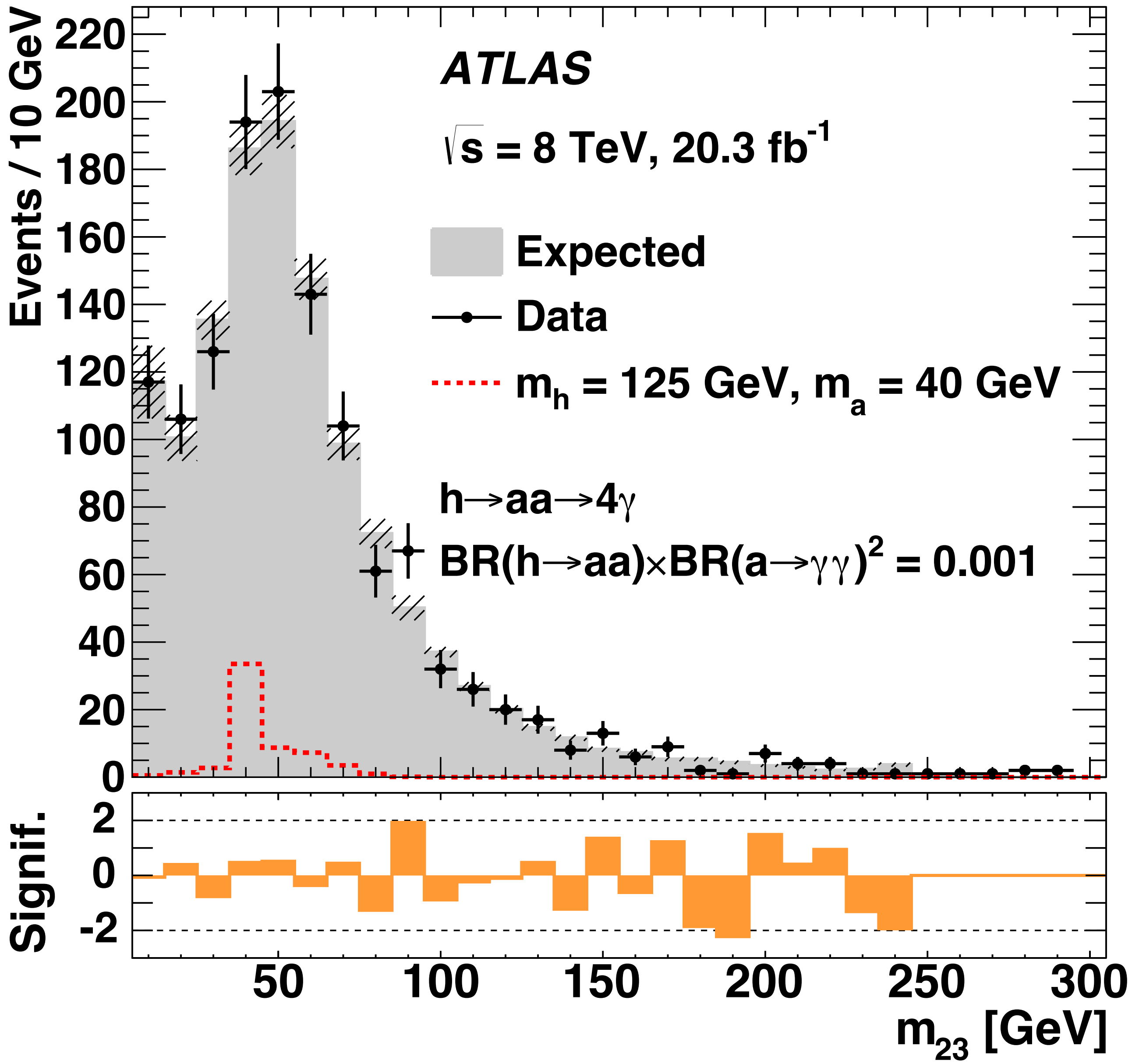


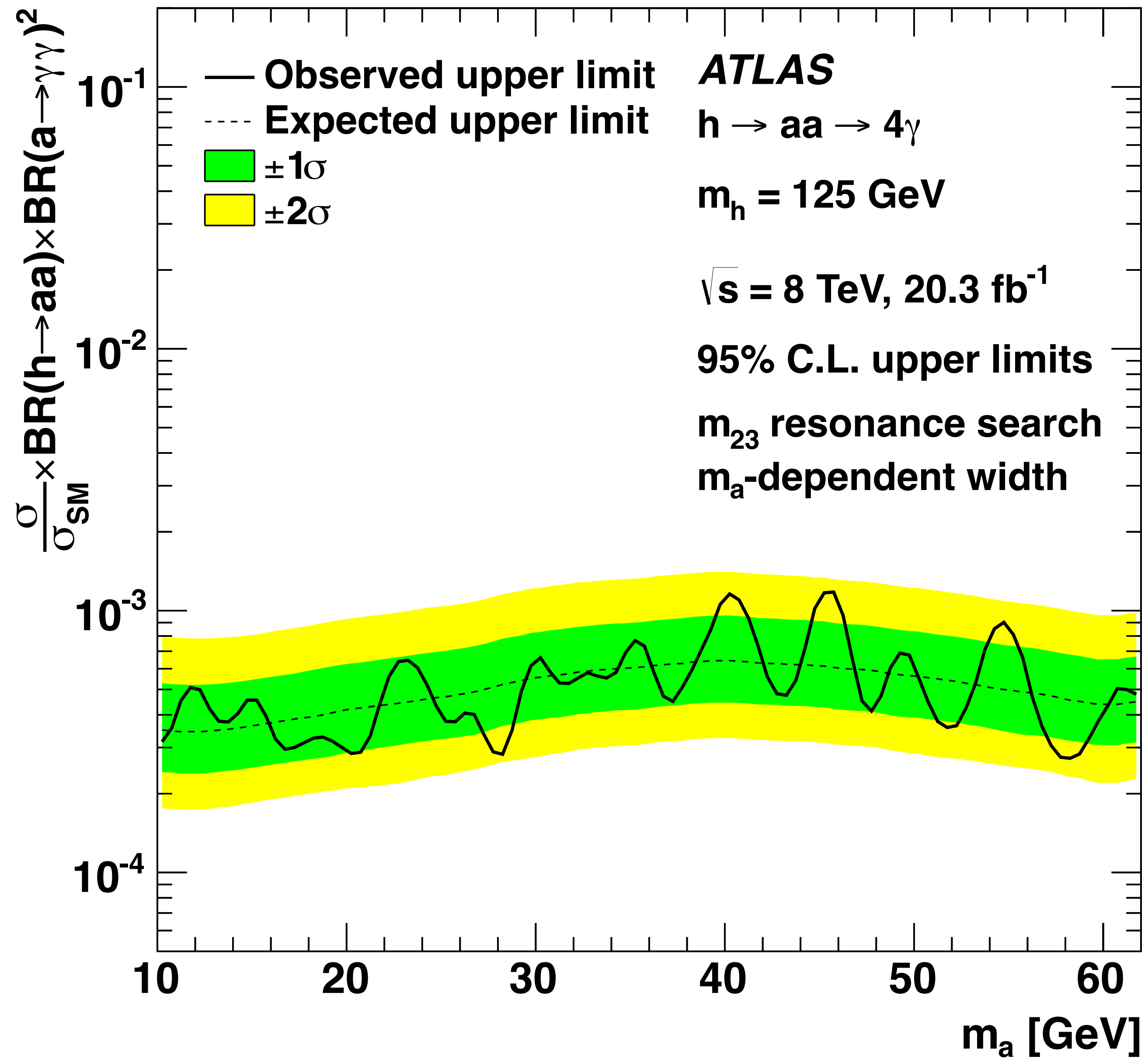
The resonance searches are translated into limits on cross sections for BSM processes; h —> aa —> 4γ for $m_{2\gamma}$

Three possible choices for 2γ pairings in 3γ signal region events

- p_T-ordered photons
  - Calculate widths separately for each pairing: $\{\gamma_1,\gamma_2\},\{\gamma_1,\gamma_3\},\{\gamma_2,\gamma_3\}$
  - Perform three separate resonance searches in three $m_{2\gamma}$ spectra
  - Factor in "m_{ij} efficiency" when determining limit

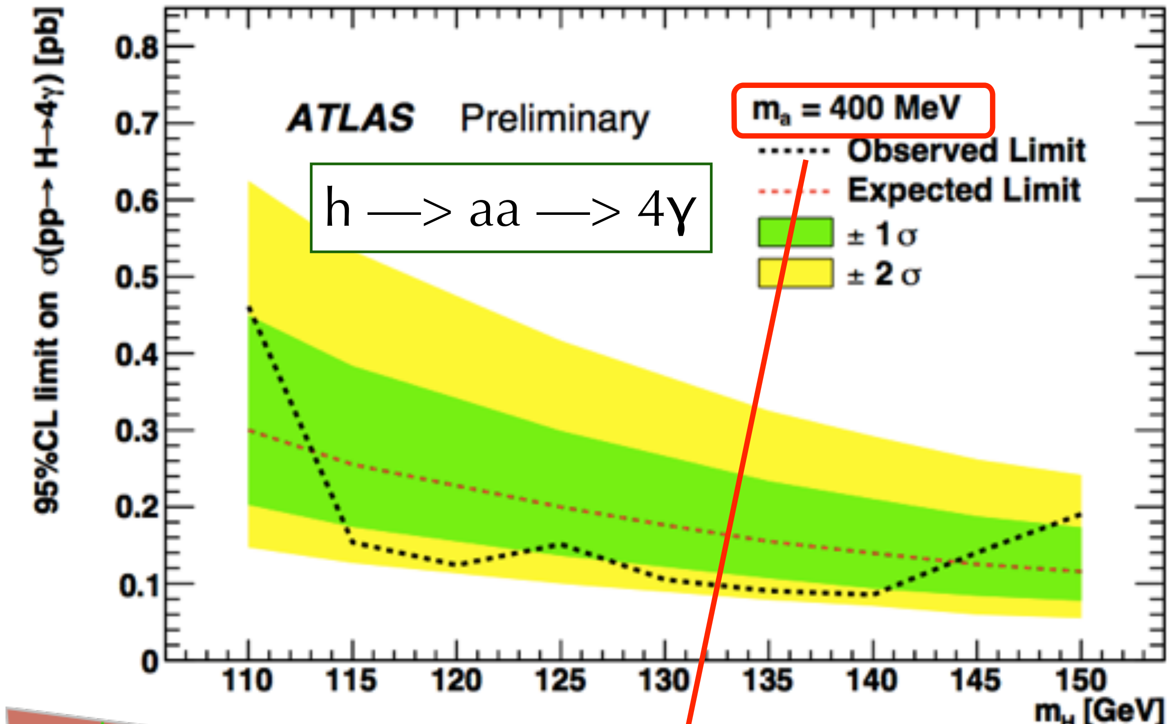
Resonance search results for h125 —> aa —> 4γ

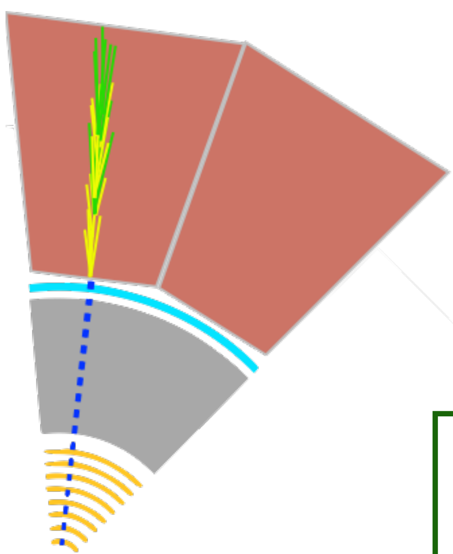


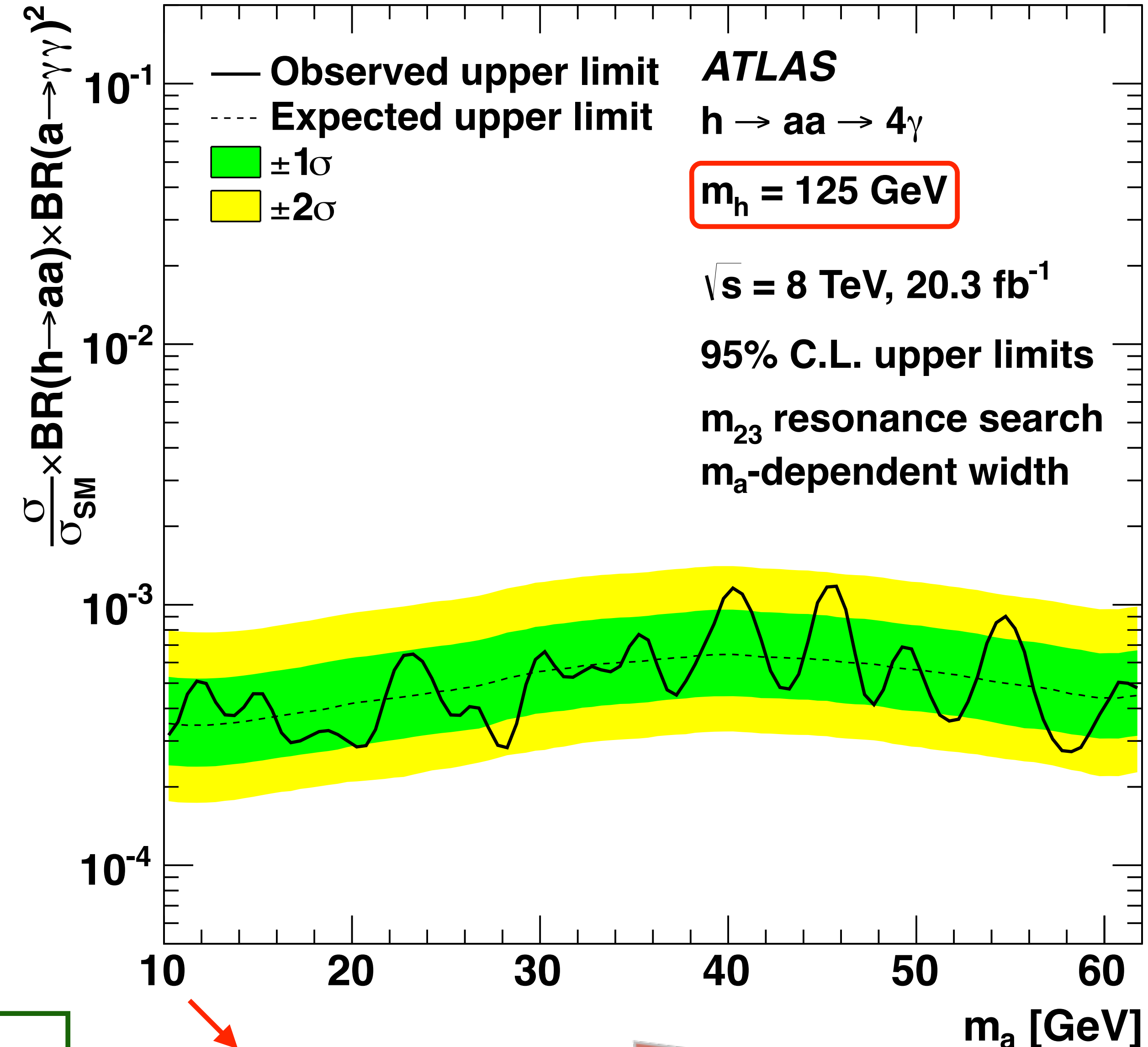


Multi-photon signatures

Limited sensitivity at medium-low-mass two-photon resonances

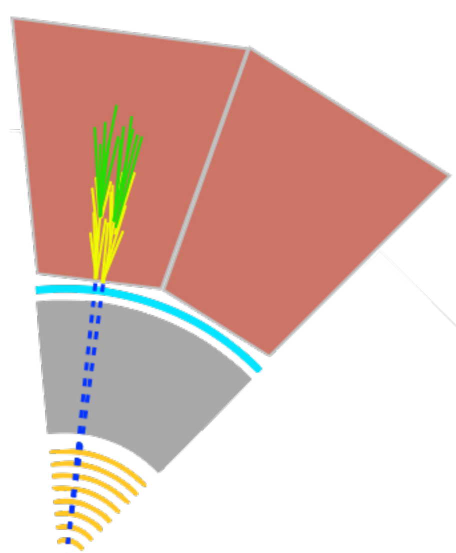




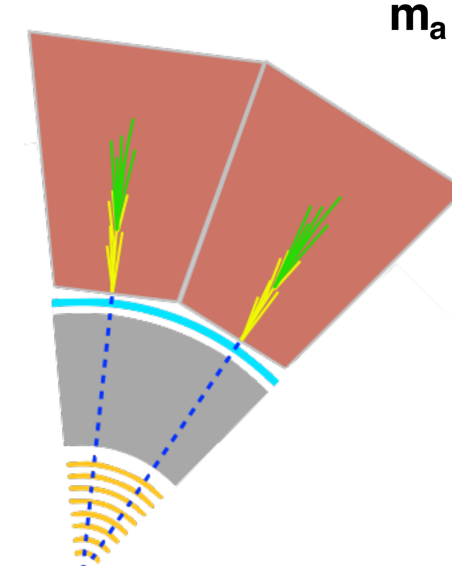


Highest limit for m_a ~ 400 MeV

Lowest limit for m_a = 10 GeV



Gap in the search for this BSM Higgs decay, where the two photons are nearly-merged

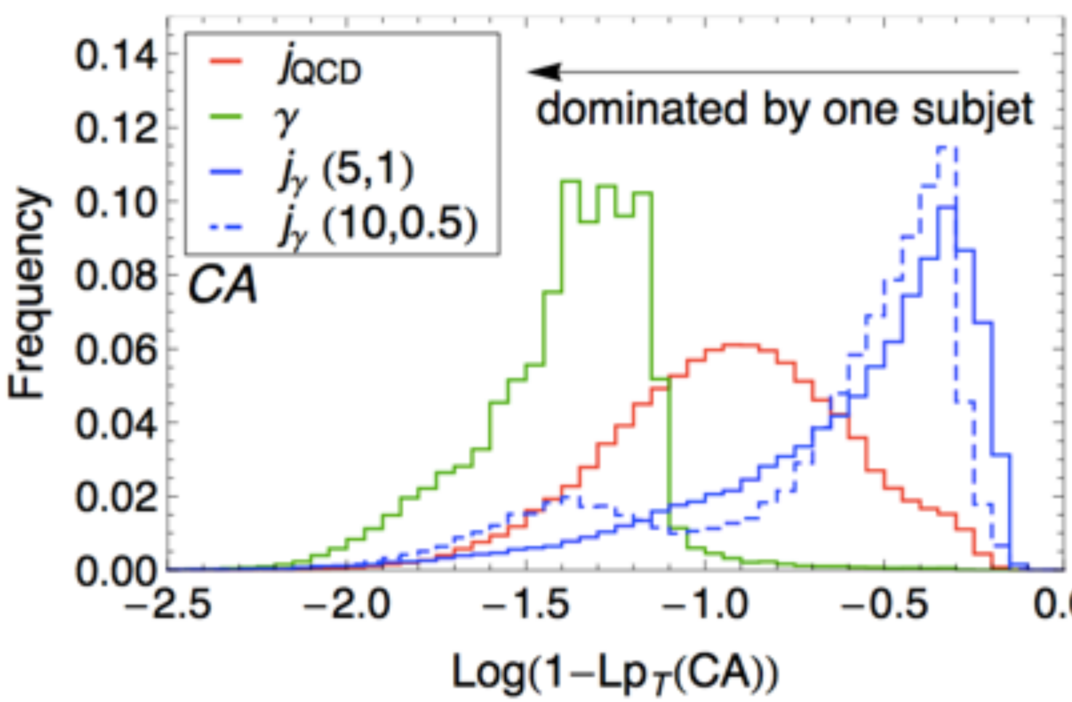


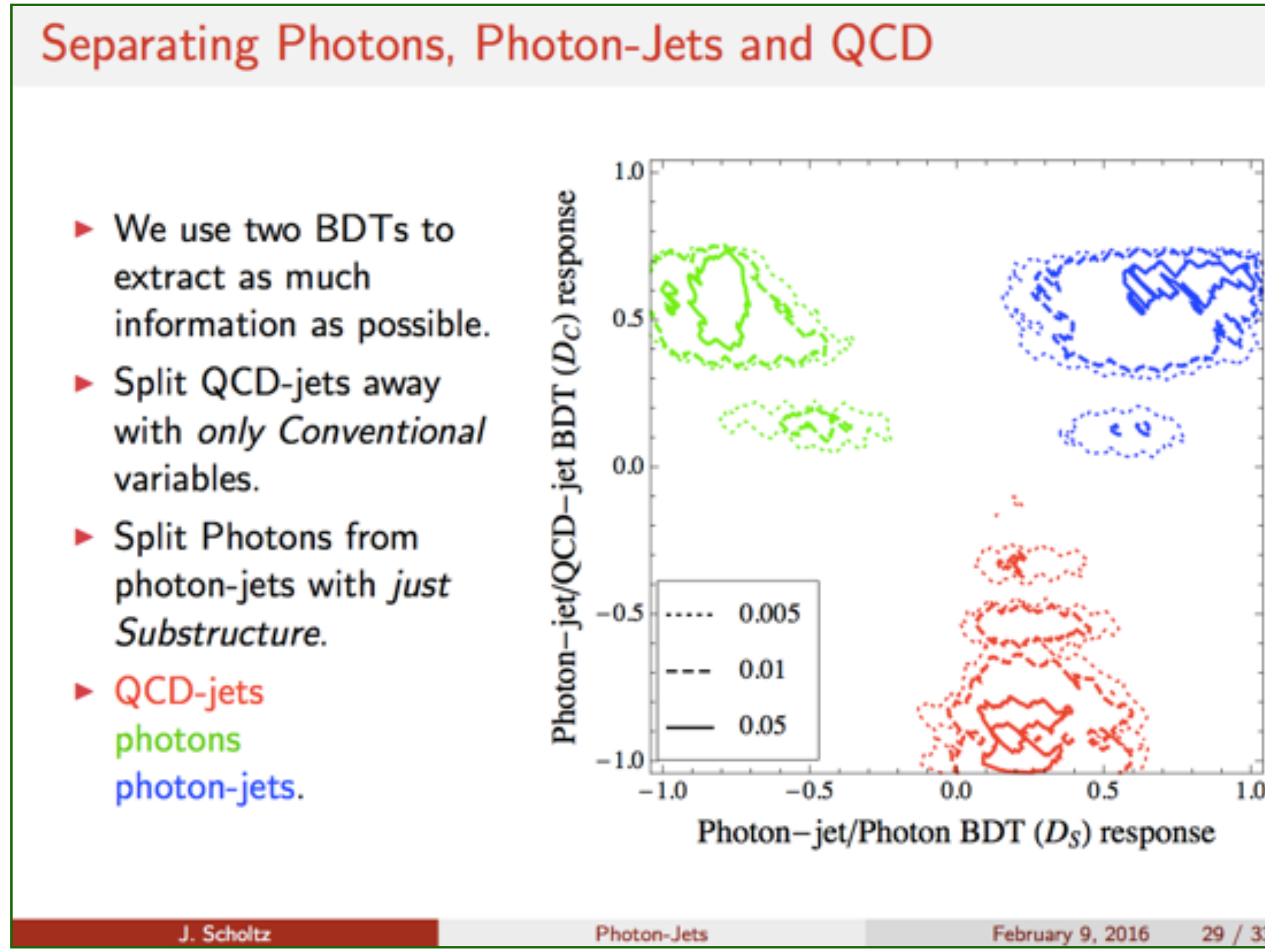
Photon-jets

- J. Scholtz and his collaborators S. Ellis and T. Roy developed multiple methods involving conventional and jet-substructure-inspired ways to ID these objects and separate them from background

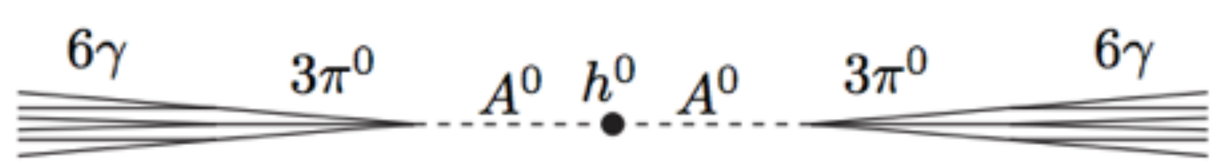
PRD 87, 014015
PRL 110, 122003

$$Lp_T = \frac{p_T \text{ of the hardest subjet}}{p_T \text{ of the entire jet}}$$



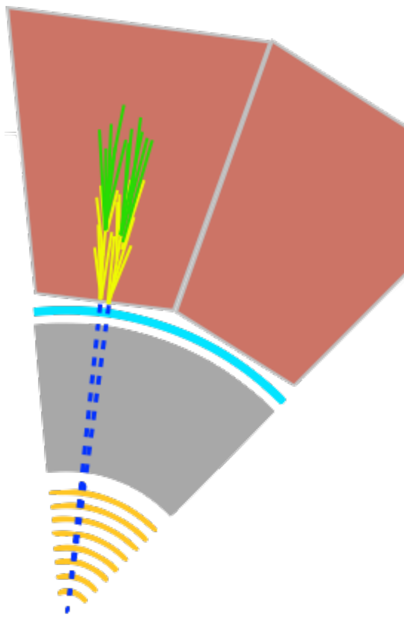


- Investigation of these and other methods is ongoing at 13 TeV, involving new triggers, photon-jet ID, etc.
- Higher multiplicity photon-jet possibilities, too

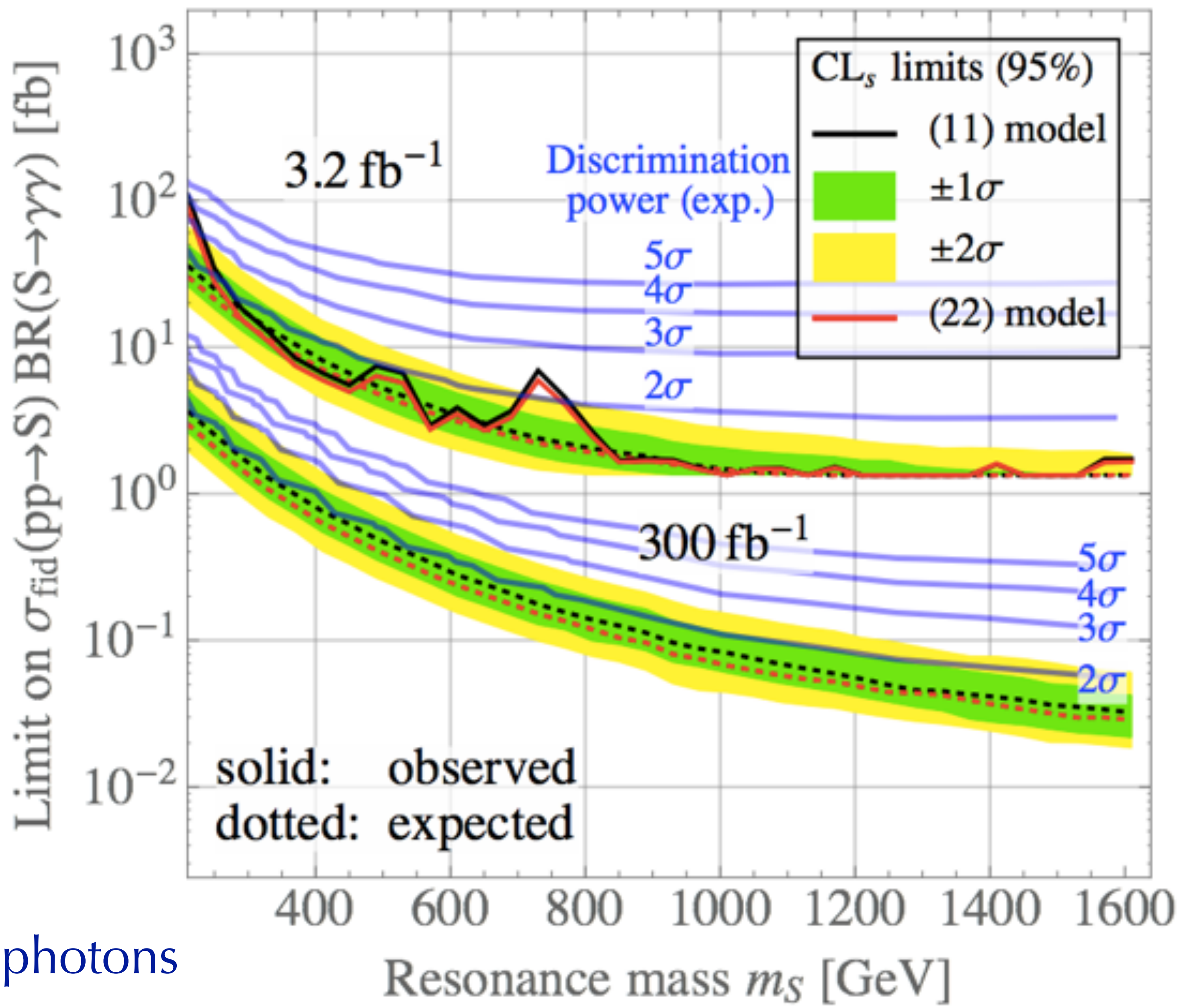


Side benefits of X750 fire drill

- A few more people thought a little more carefully about big-H, boosted-a scenarios



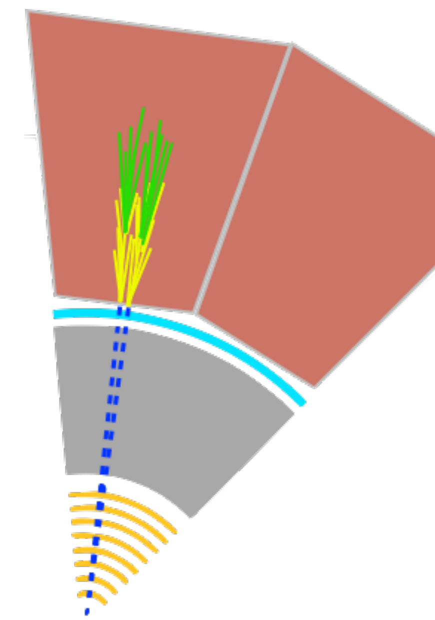
Example:
arXiv:1602.04692



- (11) = two real photons
- (22) = two photon-jets
- Discrimination here to use photon conversion rate to distinguish between scenarios with the December 2015 diphoton mass spectrum

Conclusions

Photons are an excellent handle to search for exotic decays of h125

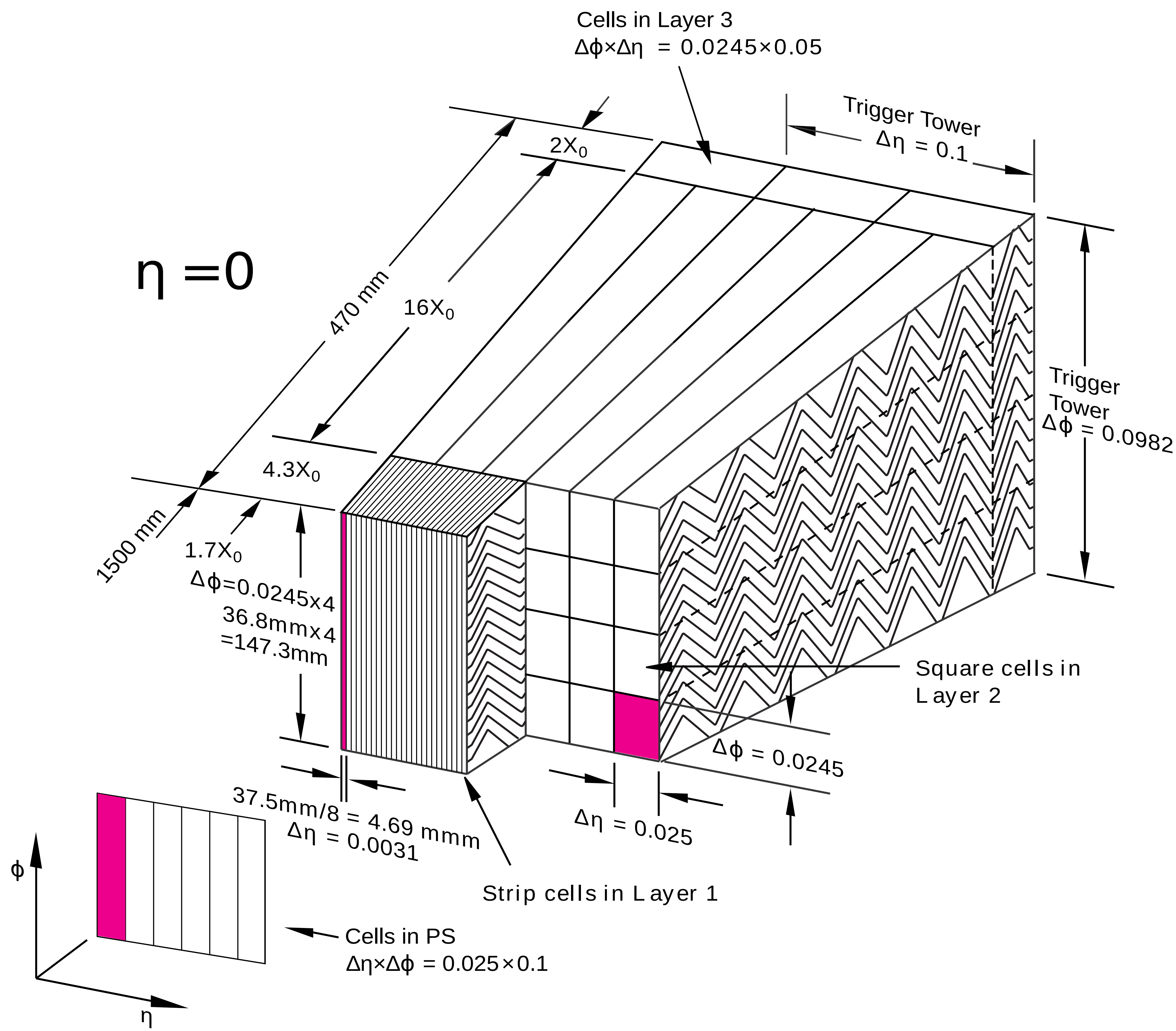


- For h125 —> aa —> 4γ ATLAS has results at 7 TeV for the completely collimated photon-jets case (100 MeV < m_a < 400 MeV) and at 8 TeV for the at-least-three isolated photons case (10 GeV < m_a < 62 GeV)
- Gap between these being filled now with new work involving triggers, new photon-jets ID with substructure, etc.
- Can improve reach for the isolated regime with a dedicated four-photon search with a large Run 2 dataset
- New methods will additionally help cover a wider range of m_h and m_a for more generic extended Higgs sectors (and otherwise)
- Also investigating other explicitly distinct highly-collimated photon-jet scenarios such as a —> $3\pi^0$

Future future work

- Di-Higgs production and decays to 4γ (10s of ab^{-1} at FCC?)

Reserve slides


Cells in Layer 3
Δϕ×Δη = 0.0245×0.05
Trigger Tower
Δη = 0.1
2X0
η =0
470 mm
16X0
Trigger
Tower
Δϕ = 0.0982
4.3X0
1500 mm
1.7X0
Δϕ=0.0245x4
36.8mmx4
=147.3mm
Square cells in
Layer 2
Δϕ = 0.0245
37.5mm/8 = 4.69 mmm
Δη = 0.0031
Δη = 0.025
Strip cells in Layer 1
ϕ
Cells in PS
Δη×Δϕ = 0.025×0.1
η

Resonance search results

m23 | m13 | m3γ