# The NMSSM lives -

## with the 750 GeV diphoton excess

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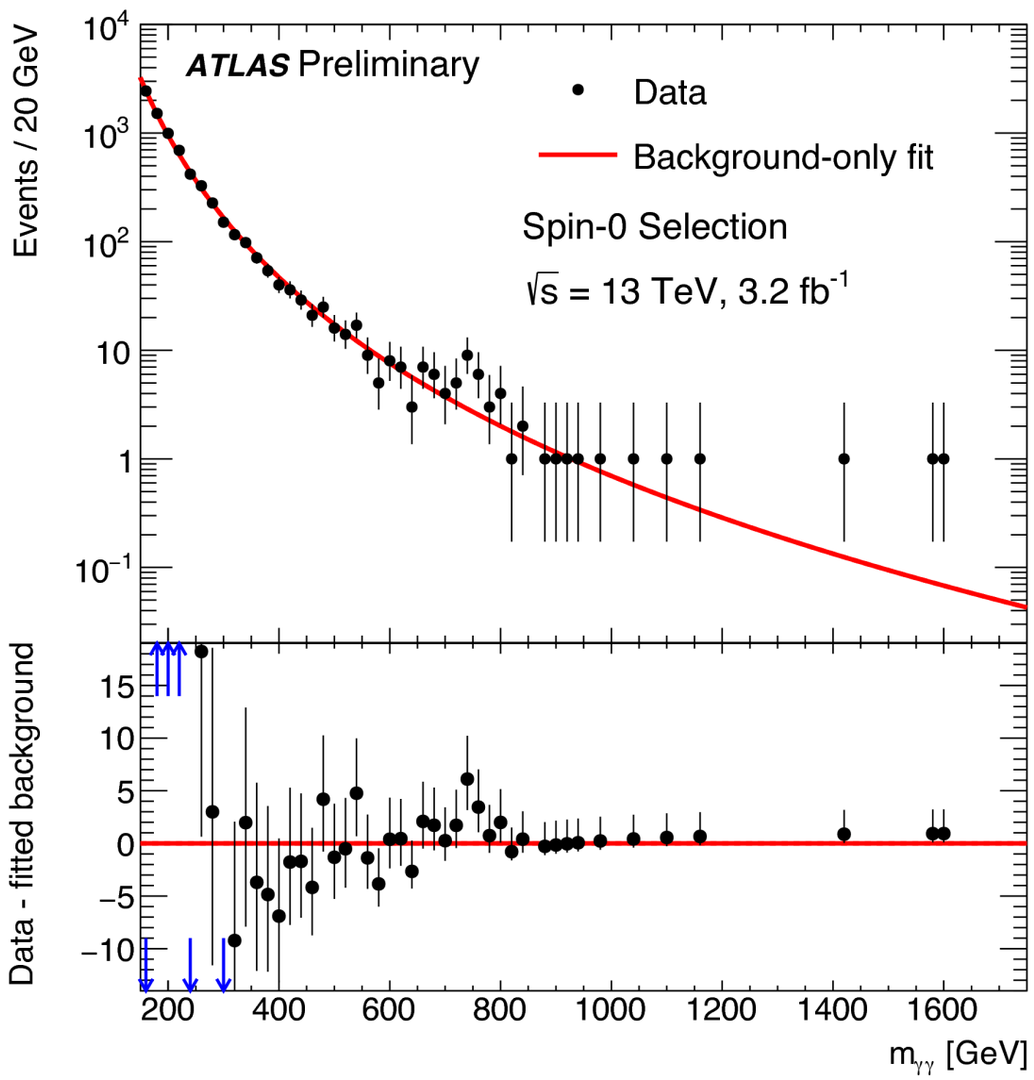
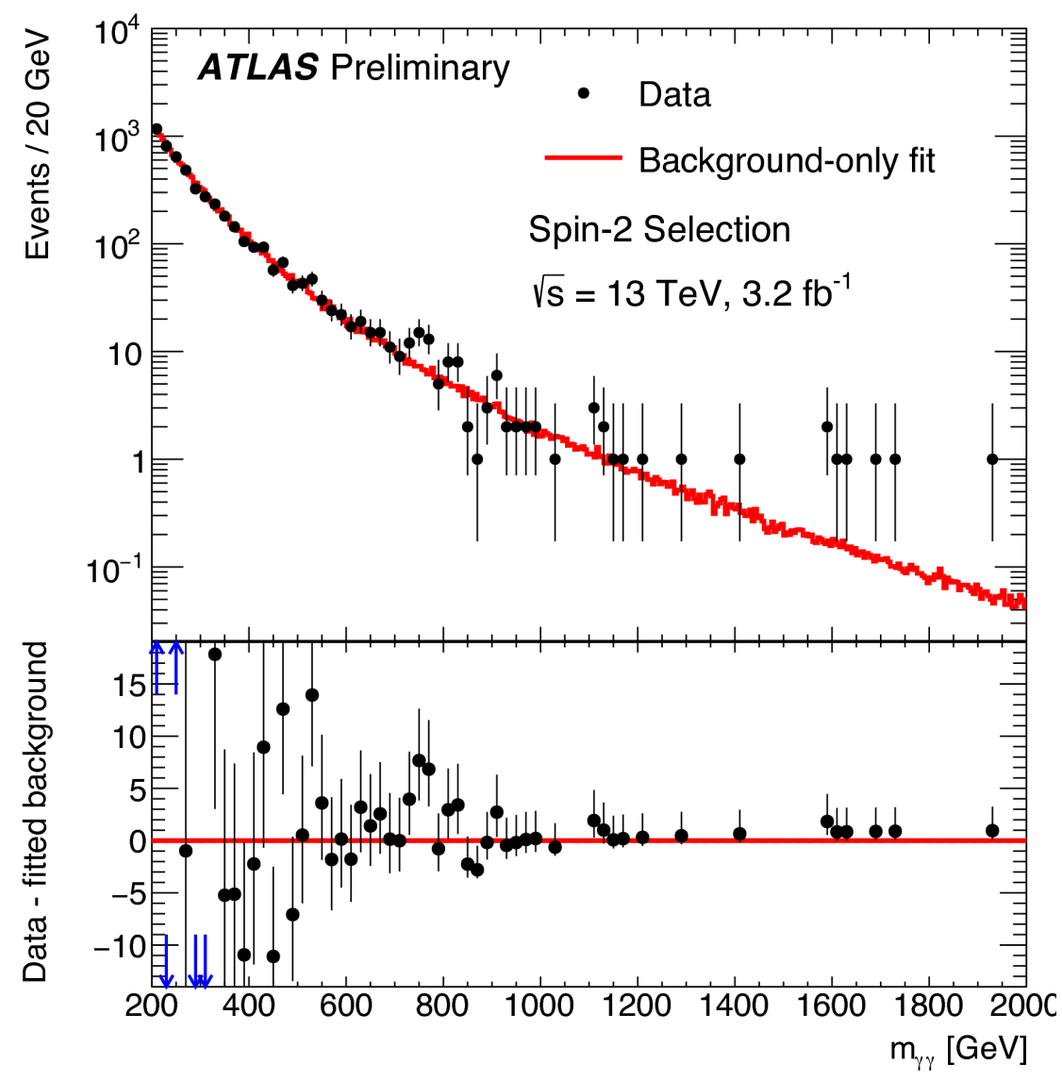
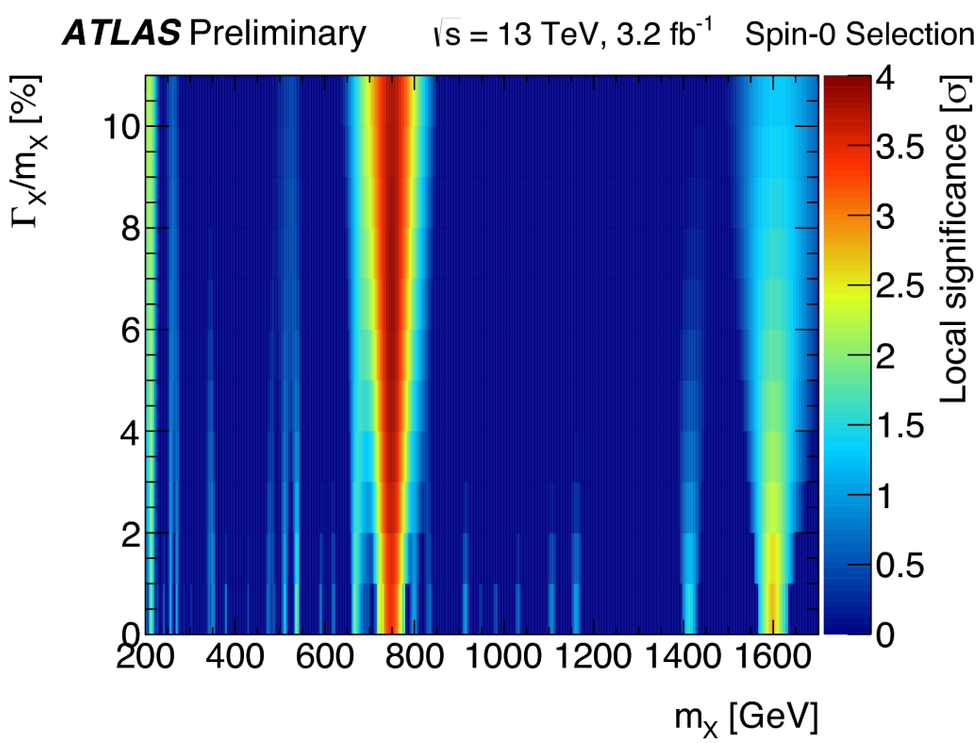
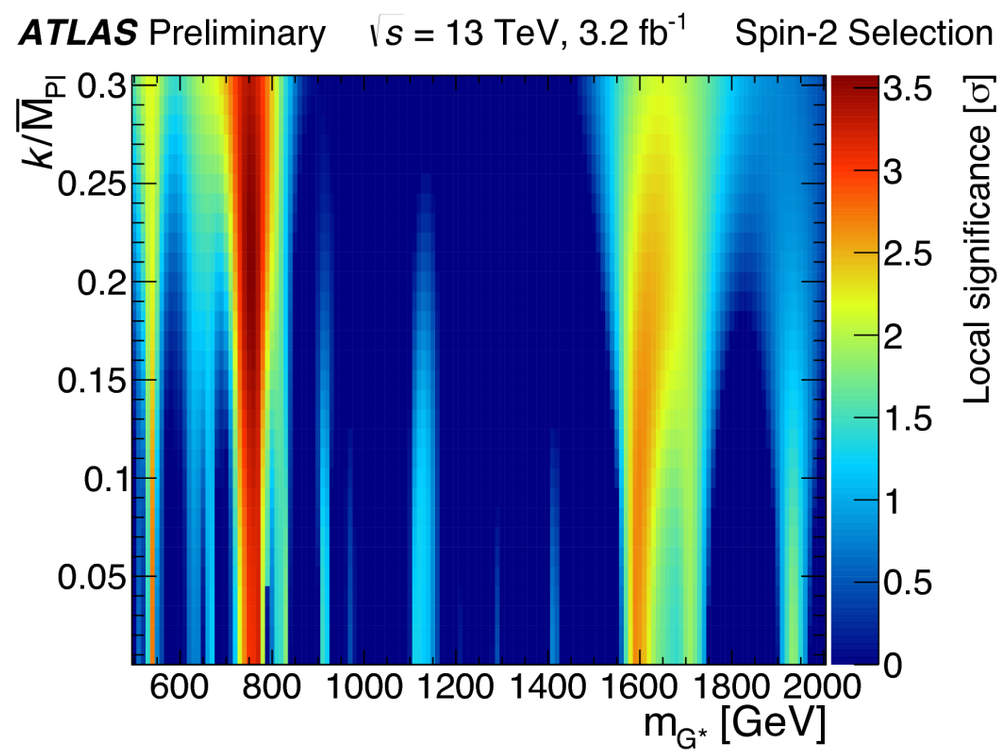
SUSY 2016, Melbourne

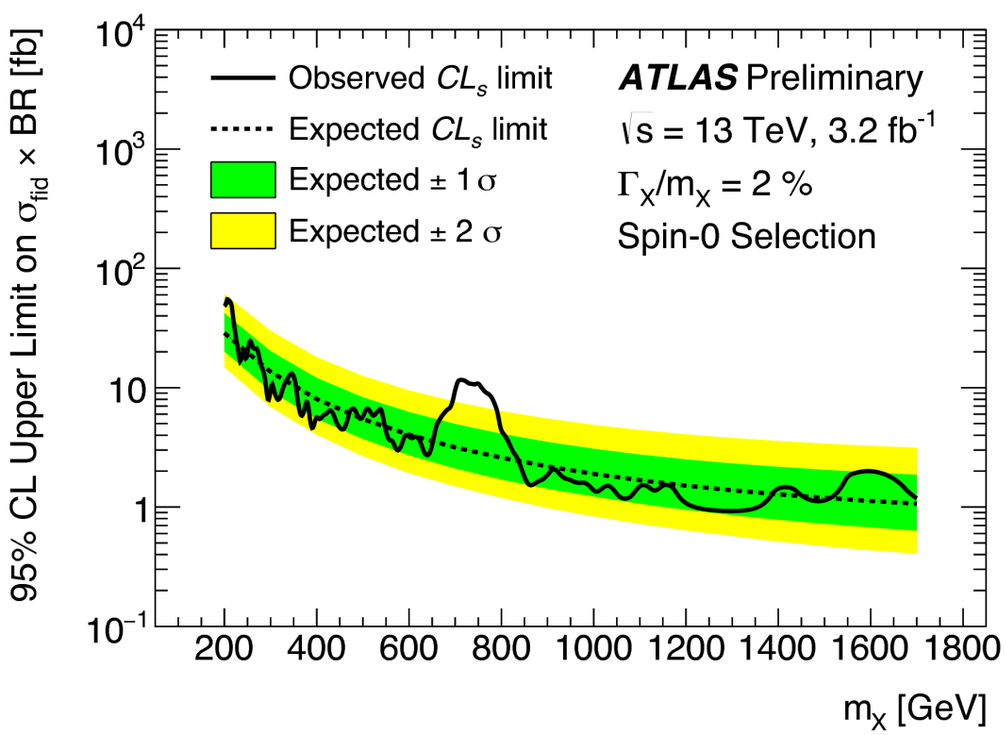
# Diphoton Excess @ 750 GeV

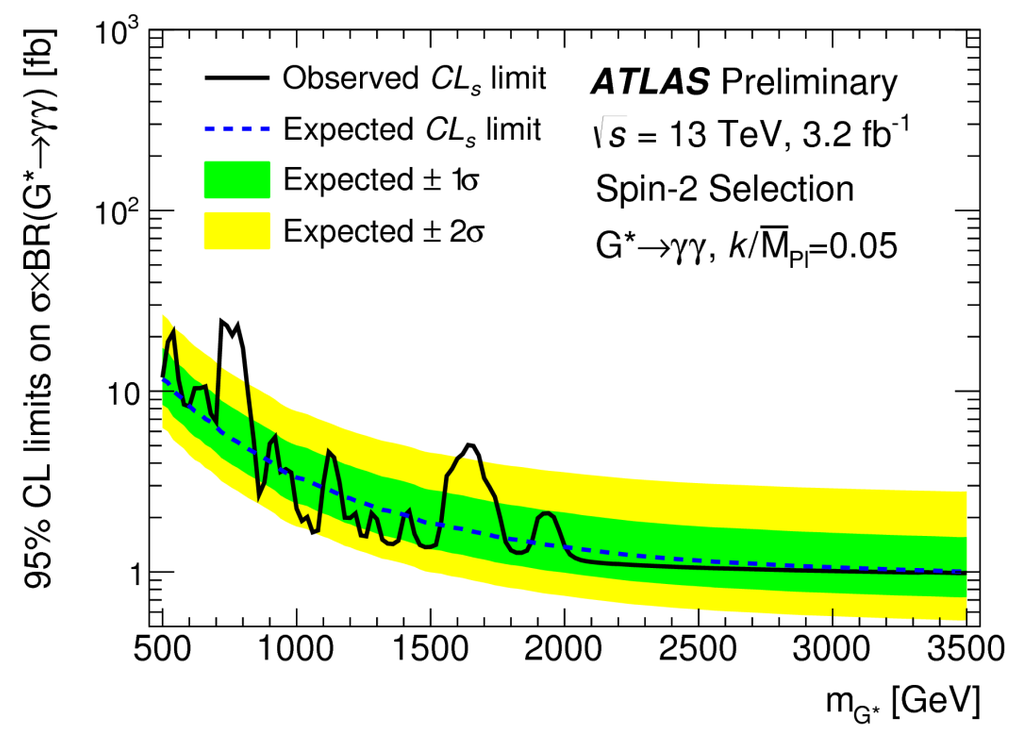



ATLAS Preliminary
√s = 13 TeV, 3.2 fb-1
Spin-0 Selection
ΓX/mX [%]
mX [GeV]
Local significance [σ]


ATLAS Preliminary
√s = 13 TeV, 3.2 fb-1
Spin-2 Selection
k/M̄Pl
mG* [GeV]
Local significance [σ]


Observed CLs limit
Expected CLs limit
Expected ± 1 σ
Expected ± 2 σ
ATLAS Preliminary
√s = 13 TeV, 3.2 fb-1
ΓX/mX = 2 %
Spin-0 Selection
95% CL Upper Limit on σfid × BR [fb]
mX [GeV]


Observed CLs limit
Expected CLs limit
Expected ± 1σ
Expected ± 2σ
ATLAS Preliminary
√s = 13 TeV, 3.2 fb-1
Spin-2 Selection
G*→γγ, k/M̄Pl=0.05
95% CL limits on σ×BR(G*→γγ) [fb]
mG* [GeV]

**ATLAS**

- mγγ=750 GeV
- Γ=45 GeV
- local significance: 3.6-3.9 sigma
- global significance: 1.8-2.0 sigma
- best compatibility with 8 TeV for spin 0 in gluon gluon fusion with 1.2 sigma
- kinematics similar to background

**CMS**

- mγγ=760 GeV
- narrow resonance
- local significance: 2.9 sigma
- global significance:≤1 sigma
- combined 8+13 TeV and NWA: 3.4 sigma

# How to explain the excess… …in SUSY

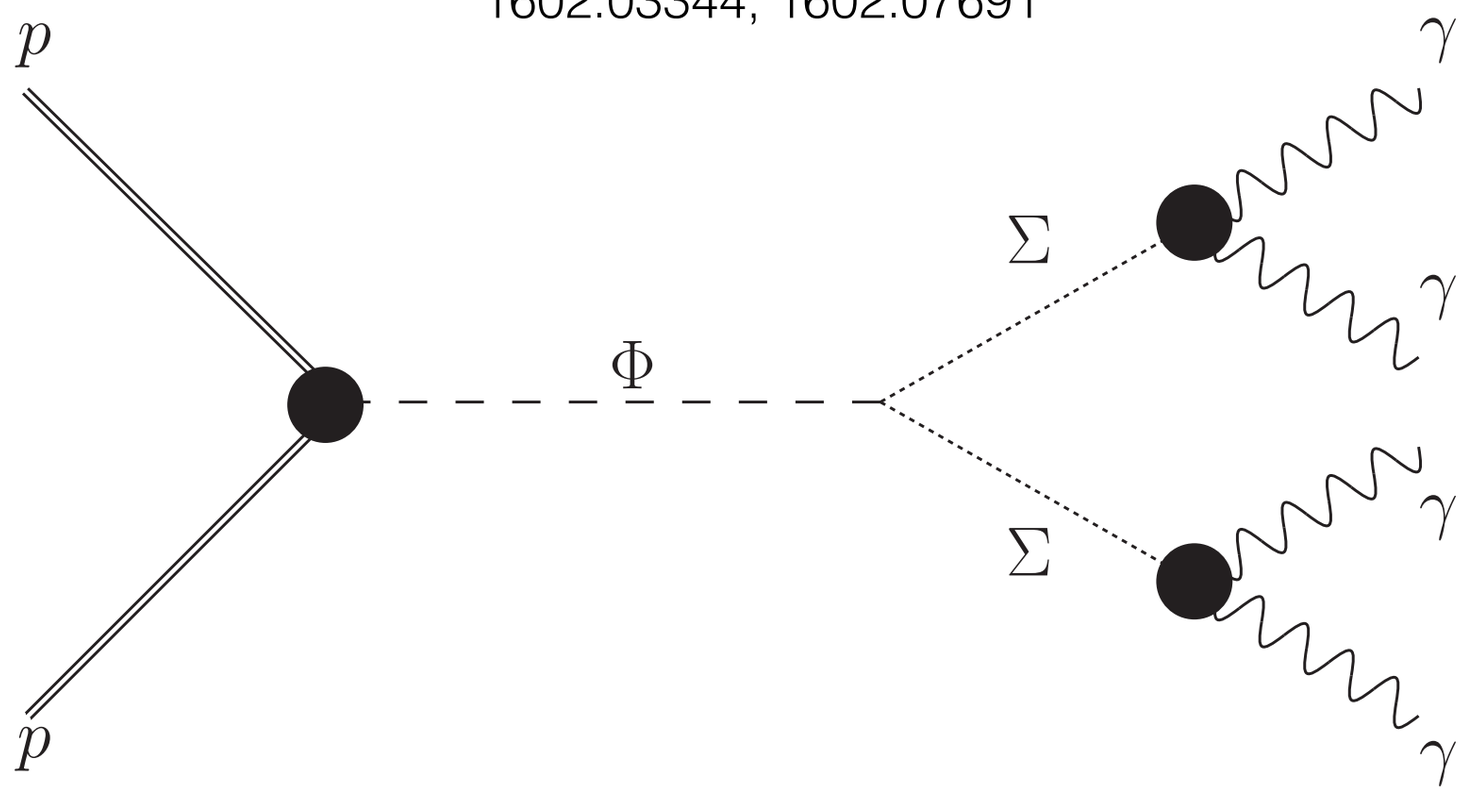
- a heavy SM like Higgs cannot explain the excess, since sigma*BR≈0.0001 fb but O(10) fb is required
- large enhancement is required
- in extended Higgs models such as in the MSSM, H and A are mass degenerate (750 GeV Higgs) and do not decay into gauge bosons but still couples to top (tanβ suppressed) and to bottom (tanβ enhanced)
- the tree level decay into fermions will dominate
- loops of SUSY particles cannot sufficiently enhance the signal rate
- the MSSM (with no new matter) cannot accommodate the excess

# How to explain the excess… …in SUSY

- however, threshold enhancement, i.e. sparticles close to threshold in the loop leads to Coloumb singularity (1603.04464)
- heavy finetuning needed, chargino width≈O(keV)
- stopponium production (1605.00013)
- resonant sneutrino production via LQD operator and decay via LLE operator to diphoton induced by stau loop (1512.07645)
- sgoldstino coupling to gluons and photon in models with very low SUSY breaking scales (1512.07895)

# The Idea

1602.03344, 1602.07691




- each photon corresponds to a light (pseudo)scalar decaying into a pair of photons
- PS must be sufficiently light (≈ π mass), so that the resulting photons are collinear

# NMSSM

- we consider a scale invariant NMSSM

$$W_{\text{Higgs}} = \lambda S H_u H_d + \frac{\kappa}{3} S^3$$

- the corresponding soft breaking terms

$$\mathcal{L}_{\text{soft}} = -\lambda A_\lambda H_u H_d S - \frac{1}{3} A_\kappa S^3 + \ldots$$

- in the NMSSM, the μ parameter is generated via μ=λ<s>

# Is a light pseudoscalar natural?

- a light PS can be identified as a pseudo Goldstone boson of an approximate symmetry of the Higgs sector

- for $\kappa \to 0$: the Higgs potential is invariant under a U(1) Peccei-Quinn symmetry

- for $A_\kappa, A_\lambda \to 0$: Higgs sector is R invariant. It is broken by radiative corrections

# Identifying the light PS state

- tree level squared squared mass matrix for NMSSM CP-odd sector in the doublet singlet basis

$$\mathcal{M}_P^2 = \begin{bmatrix} M_A^2 & -3\kappa\mu v\left(1 - \frac{\lambda}{6\kappa}\frac{M_A^2}{\mu^2}\sin 2\beta\right) \\ -3\kappa\mu v\left(1 - \frac{\lambda}{6\kappa}\frac{M_A^2}{\mu^2}\sin 2\beta\right) & m_{A_S}^2 \end{bmatrix} ,$$

$$m_{A_S}^2 \equiv 3\frac{\kappa}{\lambda}\mu\left[-A_\kappa + \frac{\lambda^2 v^2}{2\mu}\sin 2\beta\left(1 + \frac{\lambda}{6\kappa}\frac{M_A^2}{\mu^2}\sin 2\beta\right)\right]$$

- mass of A_S is determined by Akappa

- a very small value of Akappa provides a candidate!

# A candidate for a light pseudoscalar

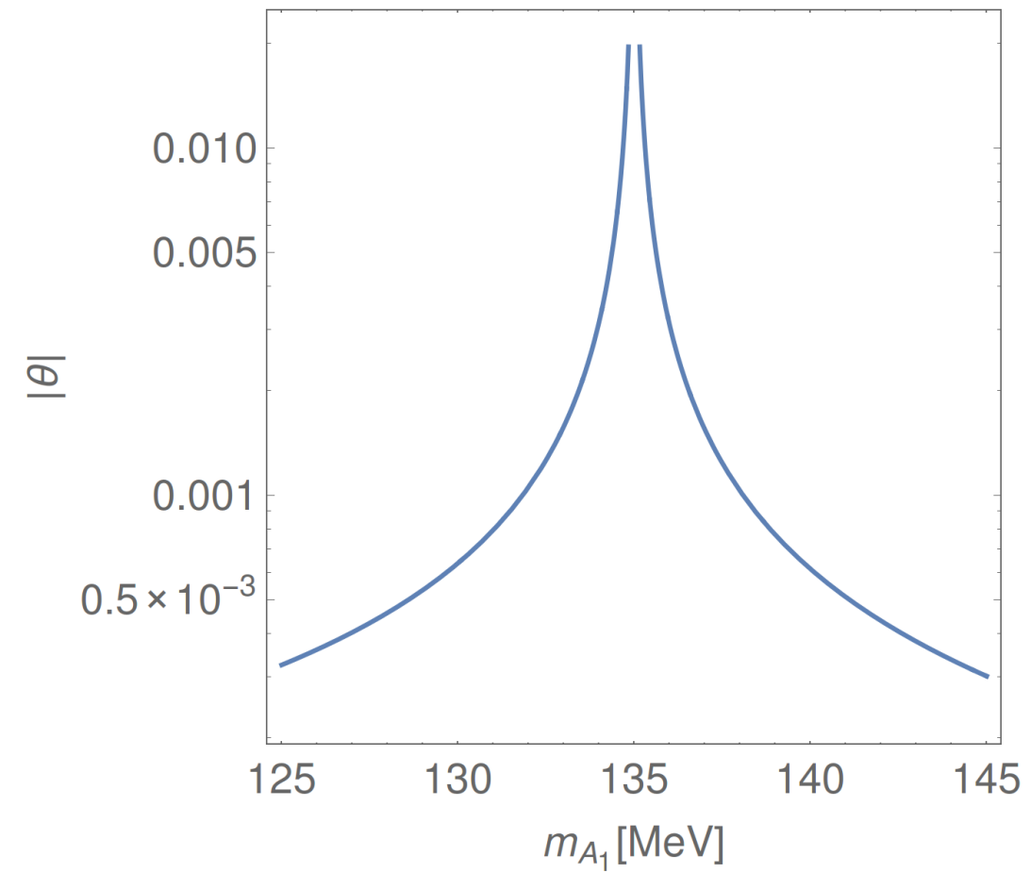
- the singlet PS mass is largely determined by $A_\kappa$
- low values ensures that the singlet PS is light
- the diphoton decay rate is suppressed as long as hadronic and muonic decay modes are kinematically possible
- diphoton BR of 70% below the muon threshold
- however, the decay length is 2cm in rest frame for a singlet with 200 MeV
- including boost factor, decay length is 40m! The singlet becomes invisible at the LHC (decay length)

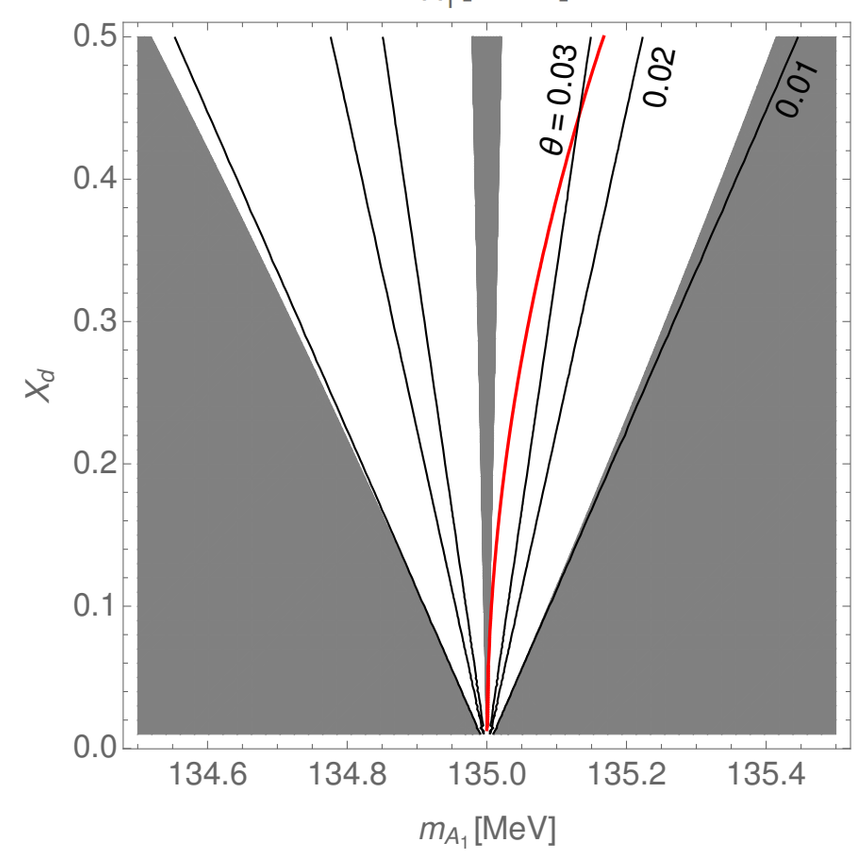
# However,...

- the partonic picture is too simple!
- hadronic effects will affect the light singlet PS decays
- the Higgs PS can mix with PS mesons such as the pion or eta mesons
- the mixing can be estimated with chiral perturbation theory and axial-flavor currents

- mixing is only relevant in the immediate mass vicinity of the mesons
- a mixing of order 0.01 requires a mass splitting of roughly MeV
- the mixing has dramatic consequences on the decay pattern
- the decay width into diphoton of the light PS singlet via its pion component increases by 2 orders of magnitude
- the light singlet PS can now decay before reaching ECAL!

$$X_d = P_d(\tan\beta^{-1} - \tan\beta)$$



# Identifying the 750 GeV state

- tree level squared squared mass matrix for NMSSM CP-even sector the basis,

$$(H_{\rm SM} = \cos\beta\, h_d + \sin\beta\, h_u, H_D = -\sin\beta\, h_d + \cos\beta\, h_u, H_S = h_s)$$

$$\mathcal{M}_S^2 = \begin{bmatrix} M_Z^2\cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta & (\lambda^2 v^2 - M_Z^2)\sin 2\beta\cos 2\beta & 2\lambda\mu v\left[1-\left(\frac{M_A \sin 2\beta}{2\mu}\right)^2\right] \\ (\lambda^2 v^2 - M_Z^2)\sin 2\beta\cos 2\beta & M_A^2 + (M_Z^2 - \lambda^2 v^2)\sin^2 2\beta & -\frac{\lambda v}{2\mu} M_A^2 \sin 2\beta\cos 2\beta \\ 2\lambda\mu v\left[1-\left(\frac{M_A \sin 2\beta}{2\mu}\right)^2\right] & -\frac{\lambda v}{2\mu} M_A^2 \sin 2\beta\cos 2\beta & m_{H_S}^2 \end{bmatrix},$$

$$m_{H_S}^2 \equiv \left(\frac{2\kappa}{\lambda}\mu\right)^2\left[1+\frac{\lambda A_\kappa}{4\kappa\mu}\right] - \frac{\kappa\lambda}{2} v^2 \sin 2\beta\left[1-\frac{\lambda M_A^2}{\kappa\mu^2}\right]$$

- the doublet state would give the correct production cross section

# However,...

- the decay widths of the heavy resonance

$$\Gamma[\Phi \to t\bar{t}] \sim \frac{3G_F m_t^2}{4\sqrt{2}\pi} m_\Phi \left(1 - 4\frac{m_t^2}{m_\Phi^2}\right)^{3/2} \left(\frac{g_{\Phi t\bar{t}}}{g_{\Phi t\bar{t}}^{\rm SM}}\right)^2 \sim (30\ {\rm GeV}) \left(\frac{g_{\Phi t\bar{t}}}{g_{\Phi t\bar{t}}^{\rm SM}}\right)^2$$

$$\Gamma[\Phi \to b\bar{b}] \sim \frac{3G_F m_b^2}{4\sqrt{2}\pi} m_\Phi \left(1 - 4\frac{m_b^2}{m_\Phi^2}\right)^{3/2} \left(\frac{g_{\Phi b\bar{b}}}{g_{\Phi b\bar{b}}^{\rm SM}}\right)^2 \sim (0.03\ {\rm GeV}) \left(\frac{g_{\Phi b\bar{b}}}{g_{\Phi b\bar{b}}^{\rm SM}}\right)^2$$

$$\Gamma[\Phi \to A_1 A_1] = \frac{g_{\Phi A_1 A_1}^2}{32\pi m_\Phi} \sqrt{1 - 4\frac{m_{A_1}^2}{m_\Phi^2}} \simeq (1 \cdot 10^{-5}\ {\rm GeV}^{-1})\, g_{\Phi A_1 A_1}^2$$

- for CP even doublet coupling to CP odd Higgs

$$g_{H_D A_1 A_1} \sim \sqrt{2}\lambda(\lambda + \kappa)\cos 2\beta\, v, \quad \lambda, \kappa = \mathcal{O}(0.1)$$

- fermionic SM decay modes are dominant!

# On the other hand,…

- the decay widths can be estimated as:

$$\Gamma[\Phi \to t\bar{t}] \sim \frac{3G_F m_t^2}{4\sqrt{2}\pi} m_\Phi \left(1 - 4\frac{m_t^2}{m_\Phi^2}\right)^{3/2} \left(\frac{g_{\Phi t\bar{t}}}{g_{\Phi t\bar{t}}^{\rm SM}}\right)^2 \sim (30\ {\rm GeV}) \left(\frac{g_{\Phi t\bar{t}}}{g_{\Phi t\bar{t}}^{\rm SM}}\right)^2$$

$$\Gamma[\Phi \to b\bar{b}] \sim \frac{3G_F m_b^2}{4\sqrt{2}\pi} m_\Phi \left(1 - 4\frac{m_b^2}{m_\Phi^2}\right)^{3/2} \left(\frac{g_{\Phi b\bar{b}}}{g_{\Phi b\bar{b}}^{\rm SM}}\right)^2 \sim (0.03\ {\rm GeV}) \left(\frac{g_{\Phi b\bar{b}}}{g_{\Phi b\bar{b}}^{\rm SM}}\right)^2$$

$$\Gamma[\Phi \to A_1 A_1] = \frac{g_{\Phi A_1 A_1}^2}{32\pi m_\Phi} \sqrt{1 - 4\frac{m_{A_1}^2}{m_\Phi^2}} \simeq (1 \cdot 10^{-5}\ {\rm GeV}^{-1})\, g_{\Phi A_1 A_1}^2$$

- for **CP even singlet** coupling to CP odd Higgs

$$g_{\Phi A_1 A_1} \leftarrow g_{H_S A_1 A_1} \sim \sqrt{2}\kappa \left(2\frac{\kappa}{\lambda}\mu - A_\kappa\right)$$

- we can obtain the correct partial width of O(1) GeV

# The heavy resonance

- we want to identify the heavy resonance with the heavy Higgs states

- we require large production cross sections while having large BR into the light singlet PS

- there are two candidates

  1) “MSSM” like scalar, $M_A \approx 750\,\mathrm{GeV}$
  2) the singlet like scalar, $H_S \approx 2\frac{\kappa}{\lambda}\mu \approx 750\,\mathrm{GeV}$

- the SU(2) doublet Higgs potentially has a large production cross section
- the SU(2) singlet Higgs has a large BR into the light singlet PS
- idea: if both scalars are sufficiently close in mass, they will mix -> large production and large BR into A1A1
- they appear as a single excess for small mass splitting
- the excess would appear as a broad resonance

# Our scenario

- a light singlet PS with mass ≈135 MeV mixing with π resulting in large decay width into diphotons and BR(PS->diphoton)=0.99
- we have a SU(2) doublet scalar and a singlet scalar with mass ≈750 GeV
- both mixes $H_{2,3} \sim \frac{1}{\sqrt{2}}(H_D \pm H_S)$ $\quad m_{H_3} - m_{H_2}|_{\min} \simeq \frac{\kappa v}{2}|\sin 4\beta|$
- both have a large branching ratio into the light PS
- production via *gg*F or associated production via *b* quarks

# Constraints

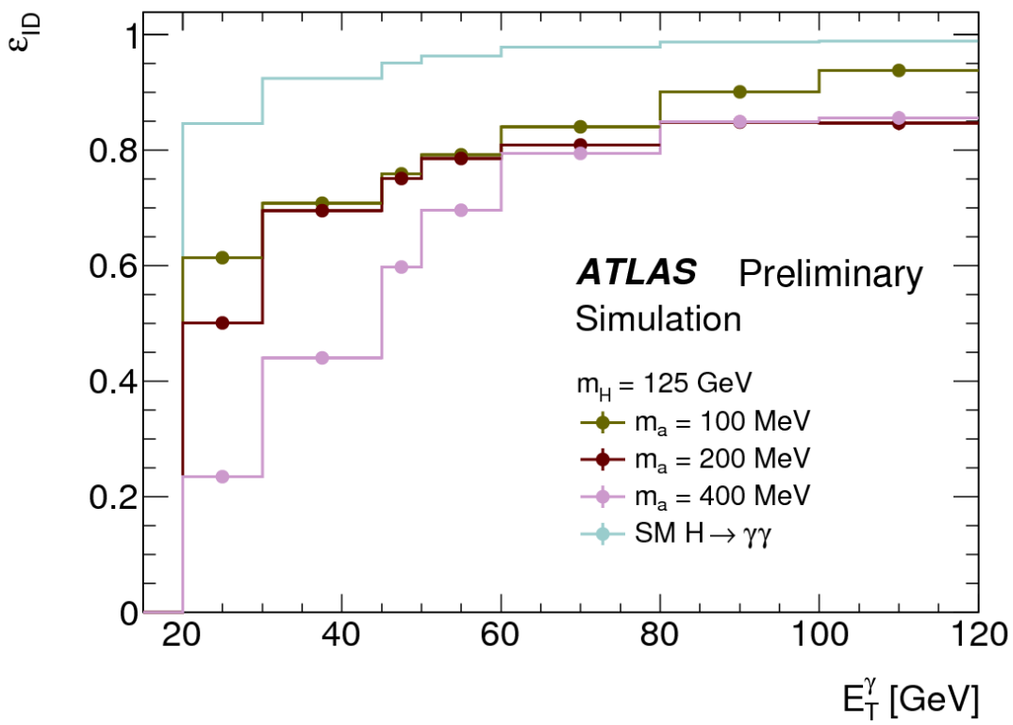
- decay length of the light singlet PS must be less than ≈1m, i.e. it must decay before it reaches the ECAL
- BR[H_SM->A1 A1]≤1%, since otherwise our scenario will be incompatible with the SM Higgs
- however, we need large BR[H2->A1A1], which requires $A_\lambda \approx 0$
- b physics constraints, e.g. B->Ke+e-
- other meson constraints such as K->πe+e- and radiative upsilon decays
- constraints from dump experiments such as the CHARM search for axions

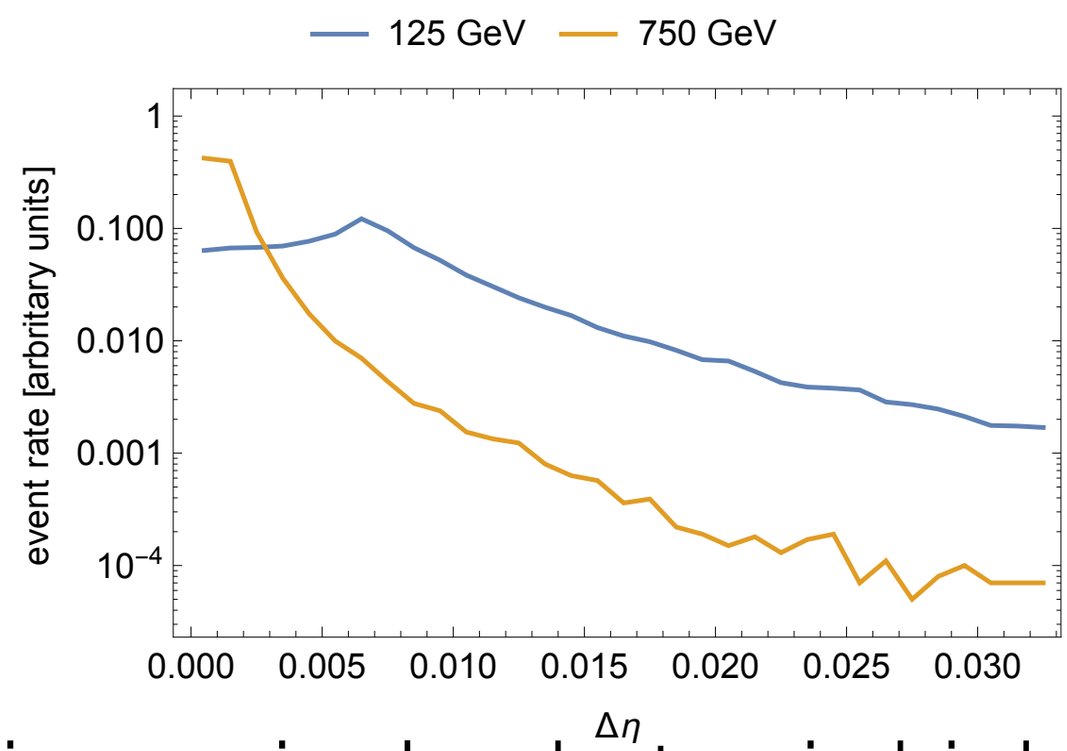
# Collider Analysis

# Benchmark points

| | P2 | P6 |
|---|---|---|
| lambda | 0.08 | 0.21 |
| kappa | 0.2 | 0,3 |
| tanbeta | 10 | 5 |
| mu [GeV] | 150 | 296.5 |
| MA [GeV] | 784 | 785.5 |
| Akappa [GeV] | 0.0057 | 0.15 |
| mH1 [GeV] | 124 | 125 |
| mH2 [GeV] | 741 | 734 |
| mH3 [GeV] | 758 | 759 |
| mA1 [GeV] | 0,135 | 0,135 |
| mA2 [GeV] | 750 | 750 |
| sigma(fb) @8TeV | 1.6 | 2.2 |
| sigma(fb) @13TeV | 8.5 | 10.2 |
| BR[H1->A1A1] | 0,000007 | 0,0000003 |
| BR[H2->A1A1] | 0,306 | 0,373 |
| BR[H3->A1A1] | 0,231 | 0,226 |

# Collider analysis

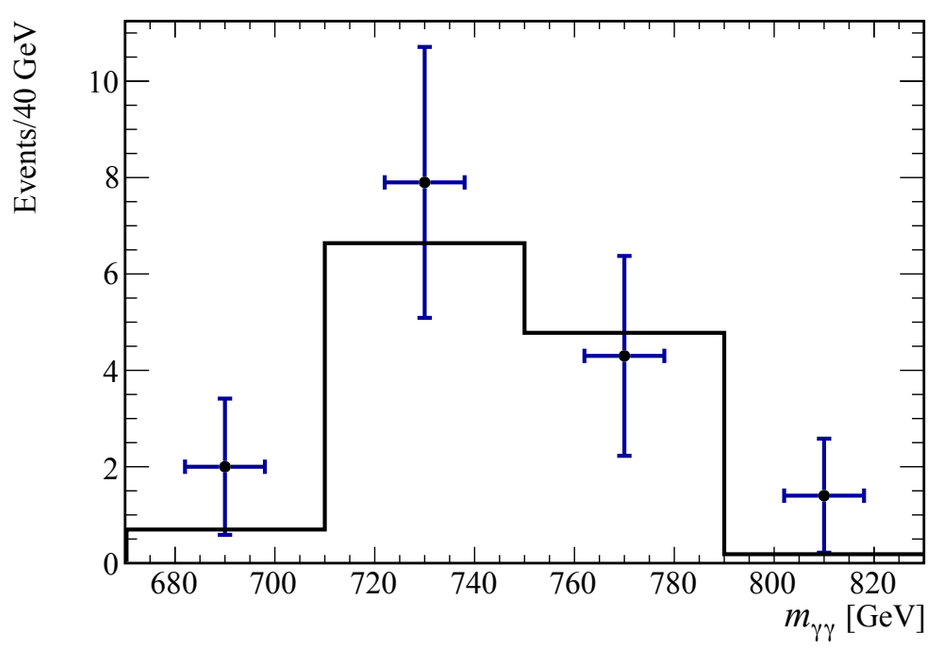


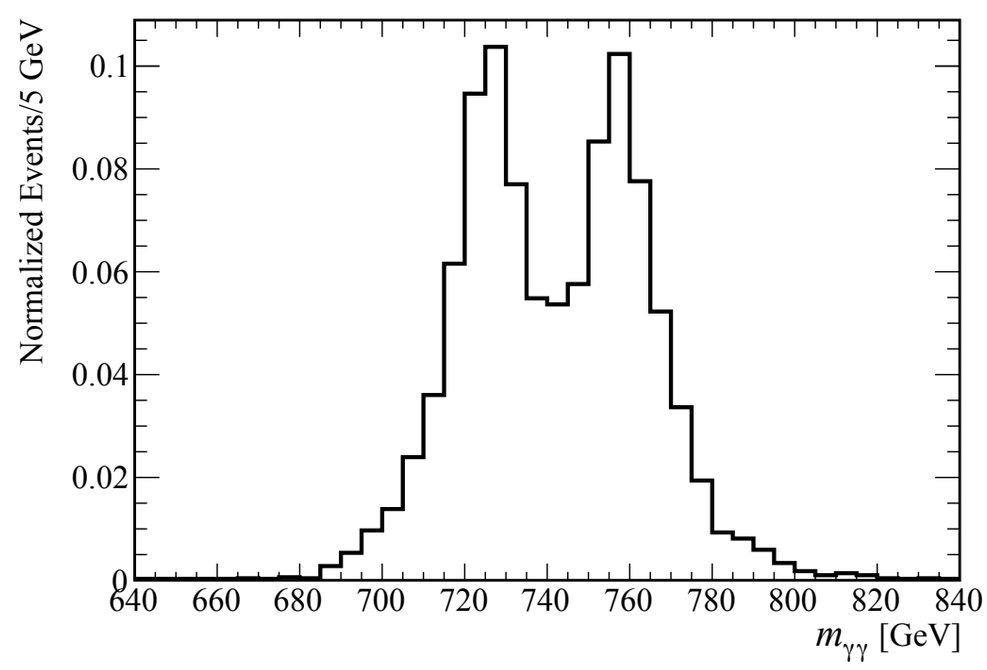

- efficiency of reconstructing a single photon is high ≈ 90%
- collimation is highly sensitive to the resonance mass
- we generated truth level events and passed them to a fast detector simulation and we implemented the ATLAS and CMS searches with <u>CheckMATE</u>

# Collider analysis

| Search | sig. | S95 | P2 | P6 |
|---|---|---|---|---|
| ATLAS13 | 16.6 | 27 | 10.3 | 12.3 |
| CMS13 EBEB | 4.5 | 12.8 | 10.5 | 12.6 |
| CMS13EBEE | 0 | 9.5 | 4 | 4.7 |




P6



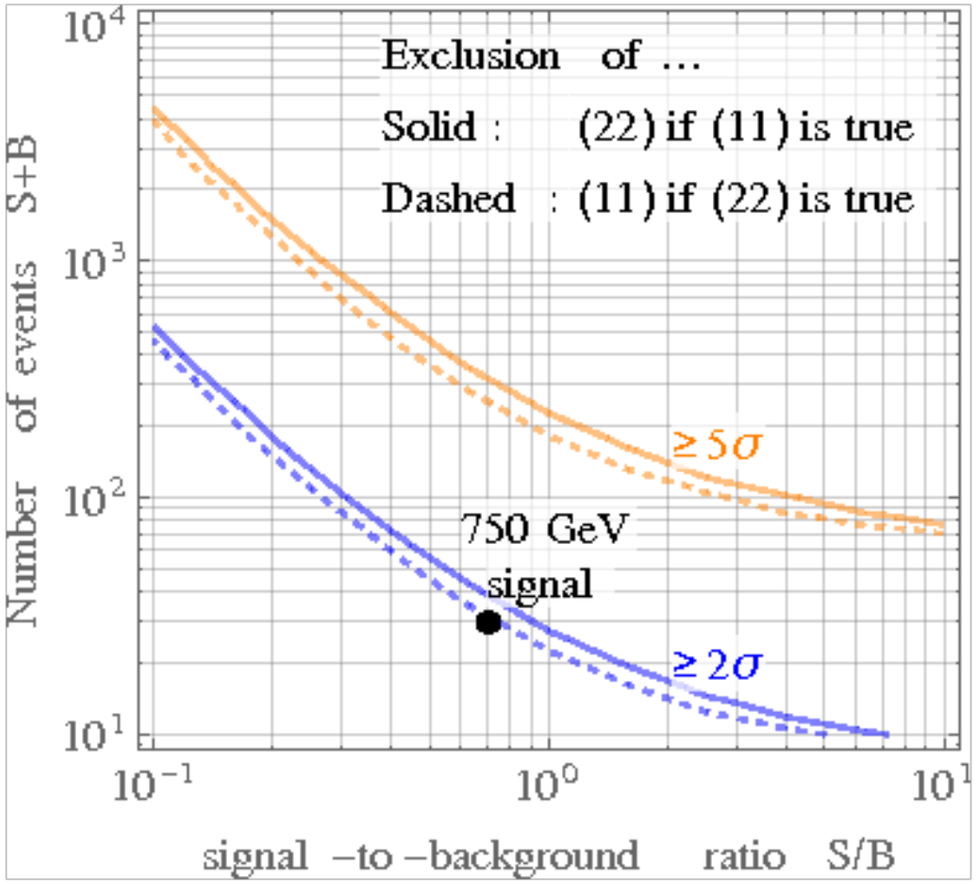

P6

# Future directions

- photon jets can be distinguished from isolated photons since photons convert to e+e- pairs with high probability (40%)

- for photon jets the probability is higher than for isolated photons

- photon conversion might be exploited to determine the decay length of the PS




1602.04692

# Conclusion

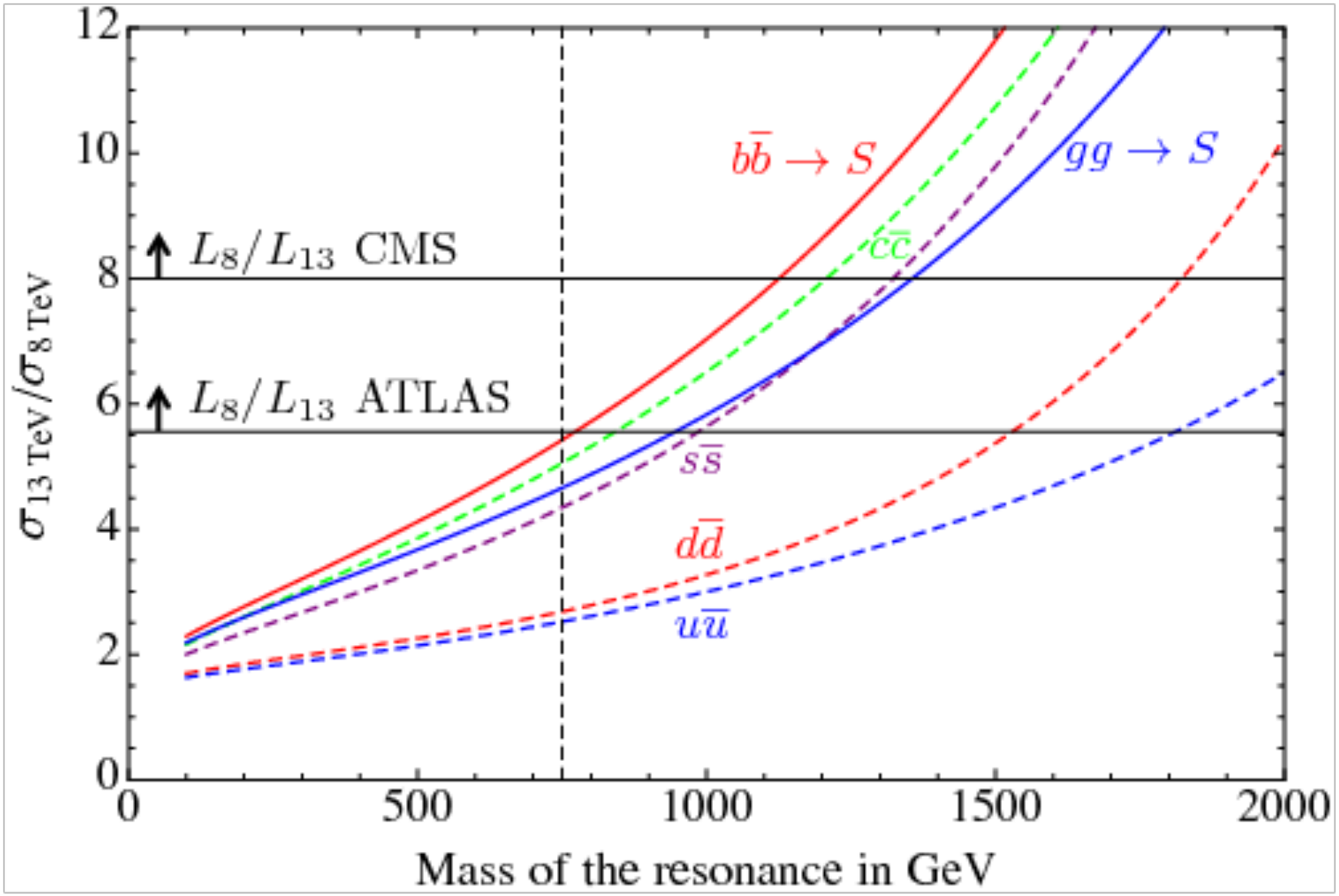
- we explained the diphoton excess within the NMSSM without invoking new exotic particles
- pp -> H2 (H3) -> A1 A1 -> γ γ γ γ
- the photons in A1-> γ γ appear as a single photon for m(A1)≤500 MeV
- the decay width into diphoton has been significantly increased via mixing with pions, i.e. m(A1)≈m(π)
- we satisfy all low energy constraints
- we do not expect ZZ and Zγ final states

# Backup slides

| | P1 | P2 | P3 | P4 | P5 | P6 | P7 | P8 | P9 |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Parameters | | | | | |
| $\lambda$ | 0.1 | 0.08 | 0.08 | 0.06 | 0.15 | 0.21 | 0.2 | 0.13 | 0.05 |
| $\kappa$ | 0.25 | 0.2 | 0.24 | 0.22 | 0.19 | 0.265 | 0.2 | 0.26 | 0.17 |
| $\tan\beta$ | 10 | 10 | 12 | 15 | 5 | 5 | 4 | 8 | 14 |
| $\mu$ (GeV) | 150 | 150 | 127 | 103 | 296 | 296.5 | 375 | 188 | 110 |
| $M_A$ (GeV) | 760 | 784 | 780 | 775 | 785.5 | 785.5 | 810 | 770 | 765 |
| $A_\kappa$ (GeV) | 0.003059 | 0.0573065 | 0.0151443 | 0.0012258 | 0.149903 | 0.303953 | 0.4206824 | 0.025274 | −0.0017404 |
| $m_{\tilde{Q}}$ (TeV) | 1.75 | 10 | 3 | 3 | 10 | 10 | 15 | 3 | 2 |
| $A_t$ (TeV) | −4 | −8.519135 | −5 | −5 | −16 | −14 | −35 | −6 | −4 |
| $m_{\tilde{L}}$ (TeV) | 0.3 | 0.3 | 0.3 | 0.3 | 0.305 | 0.32 | 0.4 | 0.4 | 0.4 |
| $M_2$ (TeV) | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 |
| | | | | Higgs spectrum | | | | | |
| $m_{H_1}$ (GeV) | 124 | 125 | 125 | 125 | 125 | 124 | 125 | 125 | 125 |
| $m_{H_2}$ (GeV) | 741 | 740 | 753 | 748 | 734 | 726 | 733 | 738 | 744 |
| $m_{H_3}$ (GeV) | 758 | 754 | 766 | 758 | 757 | 759 | 763 | 760 | 753 |
| $m_{A_1}$ (GeV) | 0.135 | 0.135 | 0.135 | 0.135 | 0.135 | 0.135 | 0.135 | 0.135 | 0.135 |
| $m_{A_2}$ (GeV) | 750 | 747 | 759 | 752 | 744 | 744 | 750 | 749 | 750 |
| $m_{H^\pm}$ (GeV) | 754 | 751 | 763 | 757 | 747 | 746 | 753 | 753 | 754 |
| | | | | $A_1$ mixing | | | | | |
| $P_d$ | 0.023 | 0.019 | 0.018 | 0.014 | 0.036 | 0.050 | 0.047 | 0.031 | 0.012 |
| | | | | Higgsinos | | | | | |
| $m_{\tilde{\chi}_1^0}$ (GeV) | 147 | 149 | 124 | 100 | 294 | 294 | 370 | 185 | 107 |
| $m_{\tilde{\chi}_2^0}$ (GeV) | 158 | 160 | 135 | 111 | 310 | 311 | 393 | 197 | 117 |
| $m_{\tilde{\chi}_1^\pm}$ (GeV) | 152 | 155 | 130 | 105 | 303 | 303 | 384 | 191 | 112 |

| | P1 | P2 | P3 | P4 | P5 | P6 | P7 | P8 | P9 |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Higgs decays | | | | | |
| $\mathrm{BR}[H_1 \to A_1 A_1]$ | $7 \cdot 10^{-6}$ | $6 \cdot 10^{-5}$ | $1 \cdot 10^{-5}$ | $9 \cdot 10^{-6}$ | $3 \cdot 10^{-6}$ | $3 \cdot 10^{-7}$ | $8 \cdot 10^{-6}$ | $1 \cdot 10^{-6}$ | $5 \cdot 10^{-6}$ |
| $\Gamma_{H_2}$ (GeV) | 1.60 | 1.53 | 2.04 | 2.71 | 1.30 | 1.53 | 1.29 | 1.37 | 1.41 |
| $\mathrm{BR}[H_2 \to A_1 A_1]$ | 0.306 | 0.174 | 0.188 | 0.113 | 0.190 | 0.373 | 0.288 | 0.363 | 0.186 |
| $\mathrm{BR}[H_2 \to b\bar{b}]$ | 0.332 | 0.397 | 0.439 | 0.527 | 0.117 | 0.087 | 0.056 | 0.269 | 0.599 |
| $\mathrm{BR}[H_2 \to t\bar{t}]$ | 0.094 | 0.121 | 0.064 | 0.032 | 0.533 | 0.357 | 0.551 | 0.186 | 0.046 |
| $\mathrm{BR}[H_2 \to \tau\bar{\tau}]$ | 0.048 | 0.058 | 0.064 | 0.077 | 0.017 | 0.013 | 0.008 | 0.039 | 0.087 |
| $\mathrm{BR}[H_2 \to \tilde{h}\tilde{h}]$ | 0.012 | 0.004 | 0.003 | 0.003 | 0.021 | 0.040 | 0 | 0.027 | 0.002 |
| $\Gamma_{H_3}$ (GeV) | 1.92 | 1.55 | 2.00 | 2.28 | 1.52 | 2.09 | 2.27 | 1.71 | 2.05 |
| $\mathrm{BR}[H_3 \to A_1 A_1]$ | 0.231 | 0.213 | 0.247 | 0.185 | 0.191 | 0.226 | 0.099 | 0.301 | 0.082 |
| $\mathrm{BR}[H_3 \to b\bar{b}]$ | 0.279 | 0.292 | 0.327 | 0.427 | 0.073 | 0.062 | 0.043 | 0.182 | 0.608 |
| $\mathrm{BR}[H_3 \to t\bar{t}]$ | 0.096 | 0.104 | 0.055 | 0.029 | 0.452 | 0.395 | 0.655 | 0.162 | 0.052 |
| $\mathrm{BR}[H_3 \to \tau\bar{\tau}]$ | 0.041 | 0.043 | 0.048 | 0.062 | 0.011 | 0.009 | 0.006 | 0.027 | 0.089 |
| $\mathrm{BR}[H_3 \to \tilde{h}\tilde{h}]$ | 0.165 | 0.154 | 0.135 | 0.090 | 0.112 | 0.123 | 0.002 | 0.222 | 0.087 |
| $\Gamma_{A_2}$ (GeV) | 2.40 | 2.37 | 3.02 | 4.19 | 2.18 | 2.30 | 2.83 | 1.80 | 2.99 |
| $\mathrm{BR}[A_2 \to \tau\tau]$ | 0.065 | 0.065 | 0.075 | 0.084 | 0.018 | 0.016 | 0.009 | 0.055 | 0.102 |
| | | | | Higgs production | | | | | |
| $\sigma^{gg!}_{8\mathrm{TeV}}[H_2]$ (fb) | 0.60 | 0.74 | 0.50 | 0.50 | 3.07 | 2.62 | 3.23 | 1.01 | 0.34 |
| $\sigma^{bbh}_{8\mathrm{TeV}}[H_2]$ (fb) | 3.90 | 4.53 | 5.98 | 9.91 | 1.21 | 1.13 | 0.58 | 2.78 | 6.01 |
| $\sigma^{gg!}_{8\mathrm{TeV}}[H_3]$ (fb) | 0.60 | 0.55 | 0.35 | 0.32 | 2.40 | 2.84 | 5.02 | 0.88 | 0.48 |
| $\sigma^{bbh}_{8\mathrm{TeV}}[H_3]$ (fb) | 3.37 | 3.00 | 3.84 | 6.17 | 0.71 | 0.82 | 0.59 | 1.95 | 8.20 |
| $\sigma^{gg!}_{13\mathrm{TeV}}[H_2]$ (fb) | 2.62 | 3.25 | 2.21 | 2.15 | 10.36 | 11.52 | 14.33 | 4.47 | 1.49 |
| $\sigma^{bbh}_{13\mathrm{TeV}}[H_2]$ (fb) | 20.70 | 24.08 | 32.14 | 53.05 | 6.35 | 5.89 | 3.03 | 14.72 | 32.05 |
| $\sigma^{gg!}_{13\mathrm{TeV}}[H_3]$ (fb) | 2.66 | 2.45 | 1.57 | 1.39 | 10.87 | 12.90 | 22.88 | 3.97 | 2.12 |
| $\sigma^{bbh}_{13\mathrm{TeV}}[H_3]$ (fb) | 18.21 | 16.17 | 20.95 | 34.00 | 3.86 | 4.46 | 3.23 | 10.54 | 44.11 |
| $\sigma^{gg!}_{13\mathrm{TeV}}[A_2]$ (fb) | 12.97 | 13.42 | 10.46 | 10.14 | 37.73 | 37.79 | 53.74 | 17.10 | 10.41 |
| $\sigma^{bbh}_{13\mathrm{TeV}}[A_2]$ (fb) | 38.62 | 40.05 | 52.81 | 86.19 | 10.19 | 10.20 | 6.25 | 25.01 | 75.85 |
| | | | | $\gamma\gamma$@750 GeV | | | | | |
| $\sigma^{\mathrm{incl}}_{8\mathrm{TeV}}$ (fb) | 2.2 | 1.6 | 2.5 | 2.32 | 1.37 | 2.18 | 1.61 | 2.23 | 1.85 |
| $\sigma^{\mathrm{incl}}_{13\mathrm{TeV}}$ (fb) | 11.7 | 8.5 | 13.55 | 12.48 | 5.83 | 10.17 | 7.40 | 11.06 | 9.80 |

# *bb* versus *gg*




1512.04933

# SM Higgs Constraints

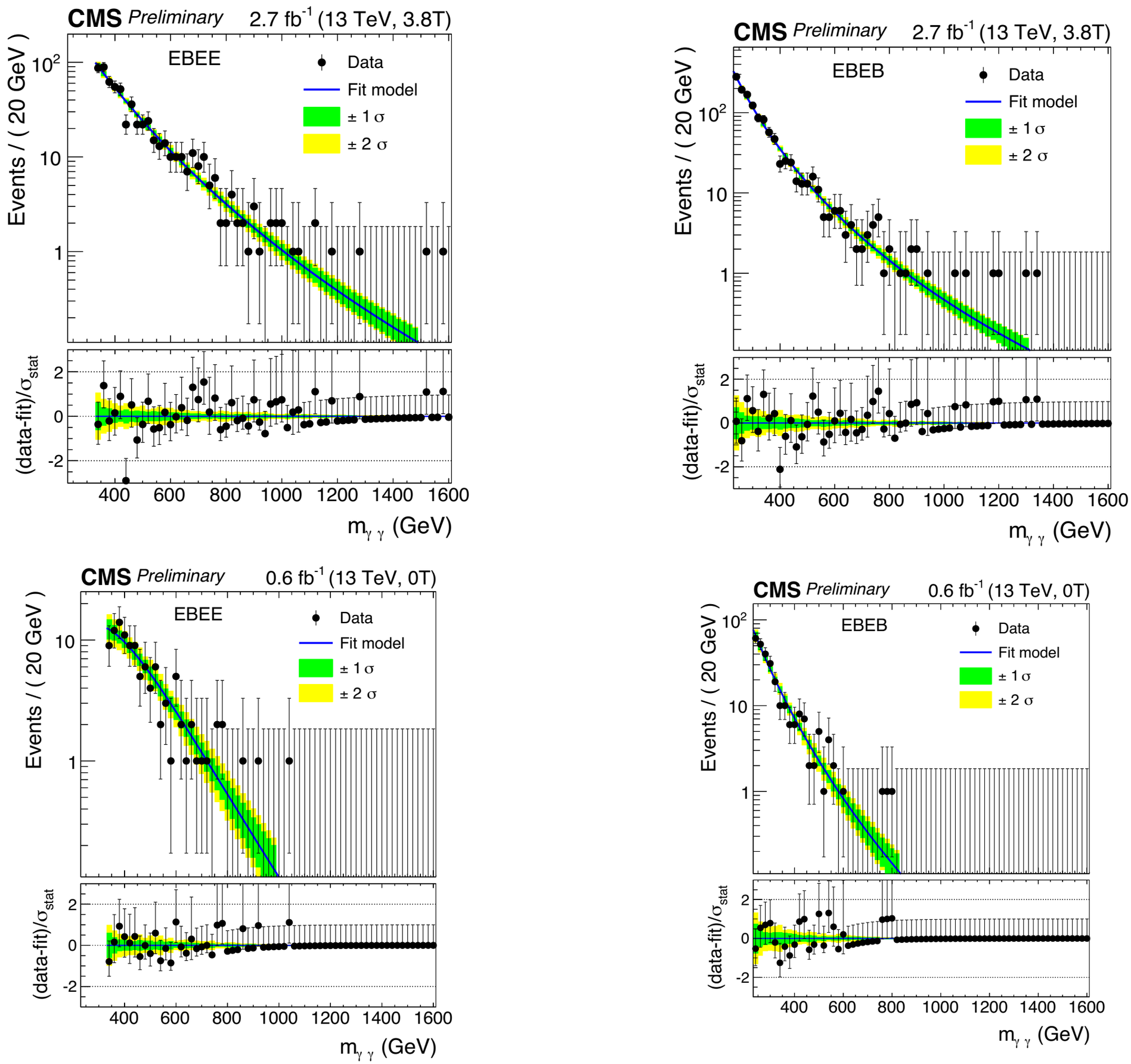
- 125 GeV Higgs scalar has SM like properties
- however, it can also decay into the light PS!

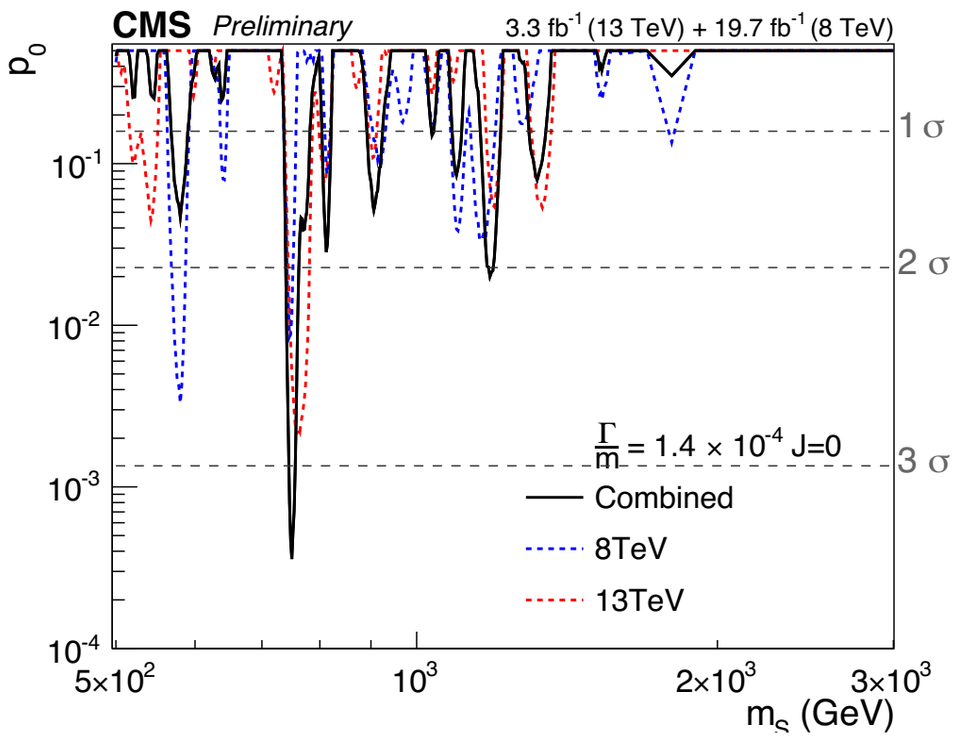
$$\Gamma[H_{\rm SM} \to A_1 A_1] = \frac{g^2_{H_{\rm SM} A_1 A_1}}{32\pi m_{H_{\rm SM}}} \sqrt{1 - 4\frac{m^2_{A_1}}{m^2_{H_{\rm SM}}}} \simeq (8 \cdot 10^{-5}\ {\rm GeV}^{-1})\, g^2_{H_{\rm SM} A_1 A_1}$$

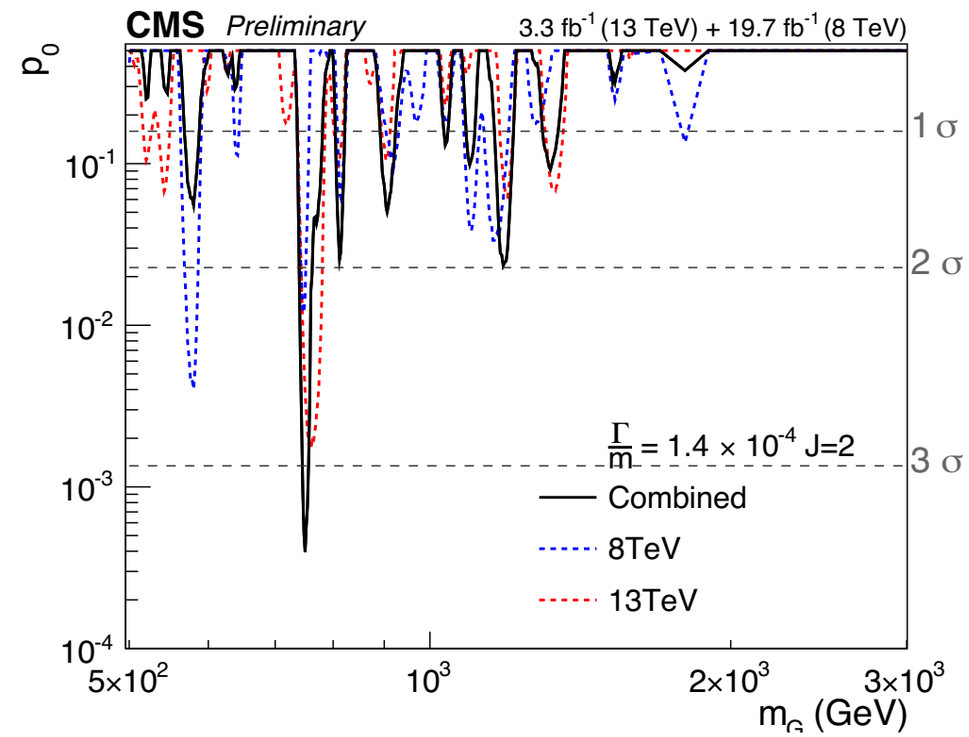
- this decay must be heavily suppressed

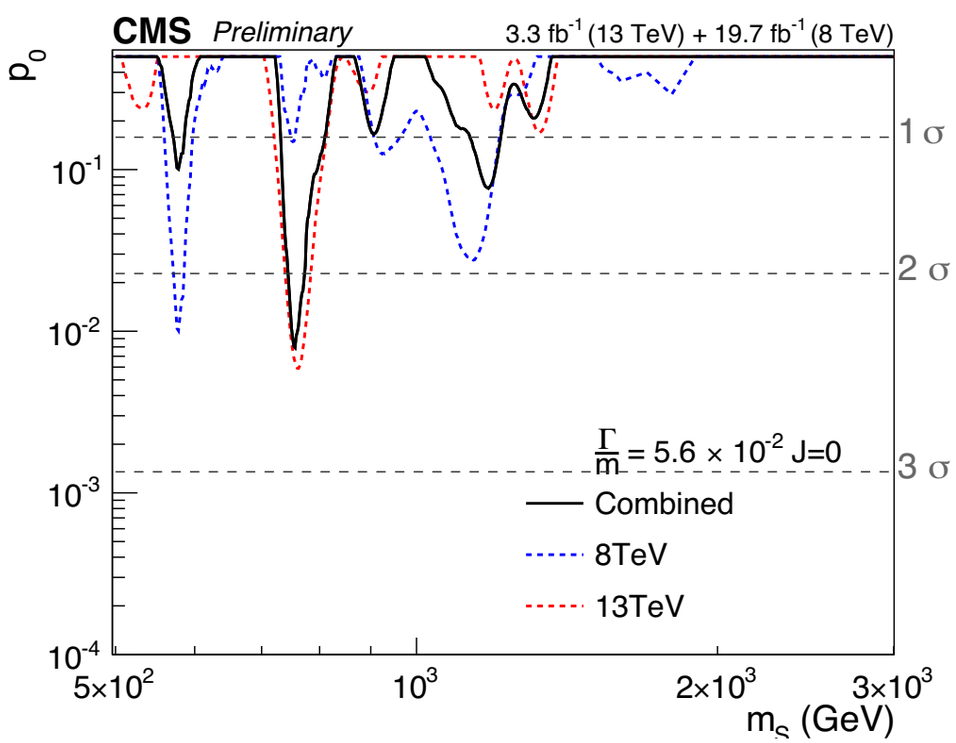
$$\Gamma(H_{\rm SM} \to A_1 A_1) \ll \Gamma_{\rm SM} \cdot {\rm BR}^{\rm SM}({\rm H}_{\rm SM} \to \gamma\gamma) \sim 8 \cdot 10^{-6} {\rm GeV}$$

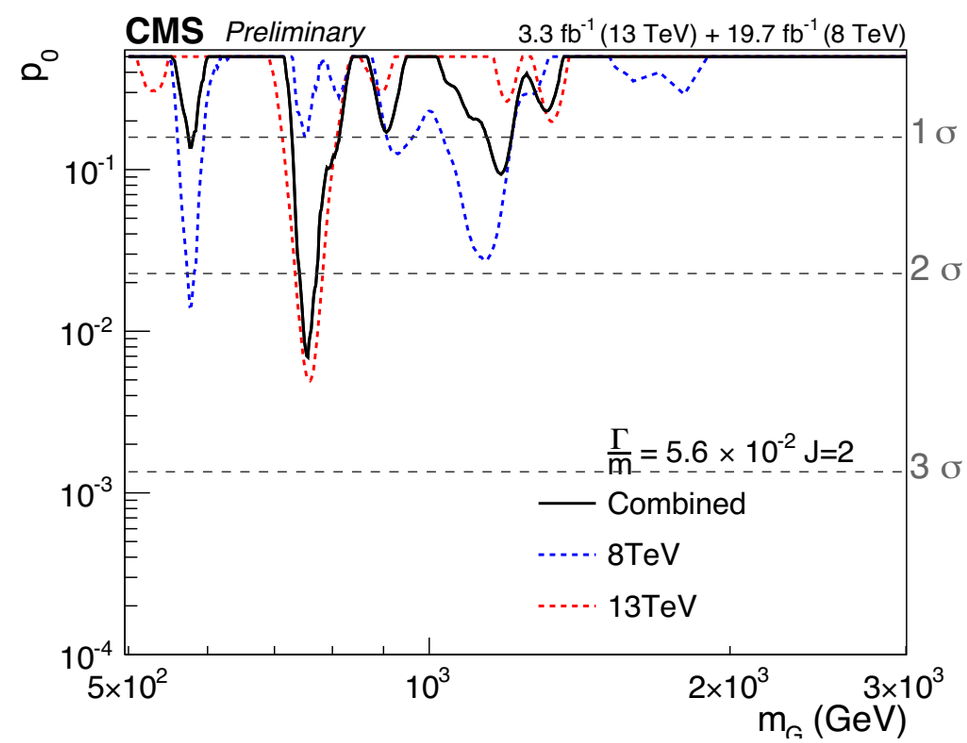
- the following condition arises, $\lambda^2 \left[1 - \frac{2\kappa}{\lambda} \sin 2\beta\right] \leq \cdot 10^{-3}$
- can be motivated from R-symmetry, $A_\lambda \simeq -\frac{M_A}{2}\left[1 - \frac{2\kappa}{\lambda}\sin 2\beta\right]$

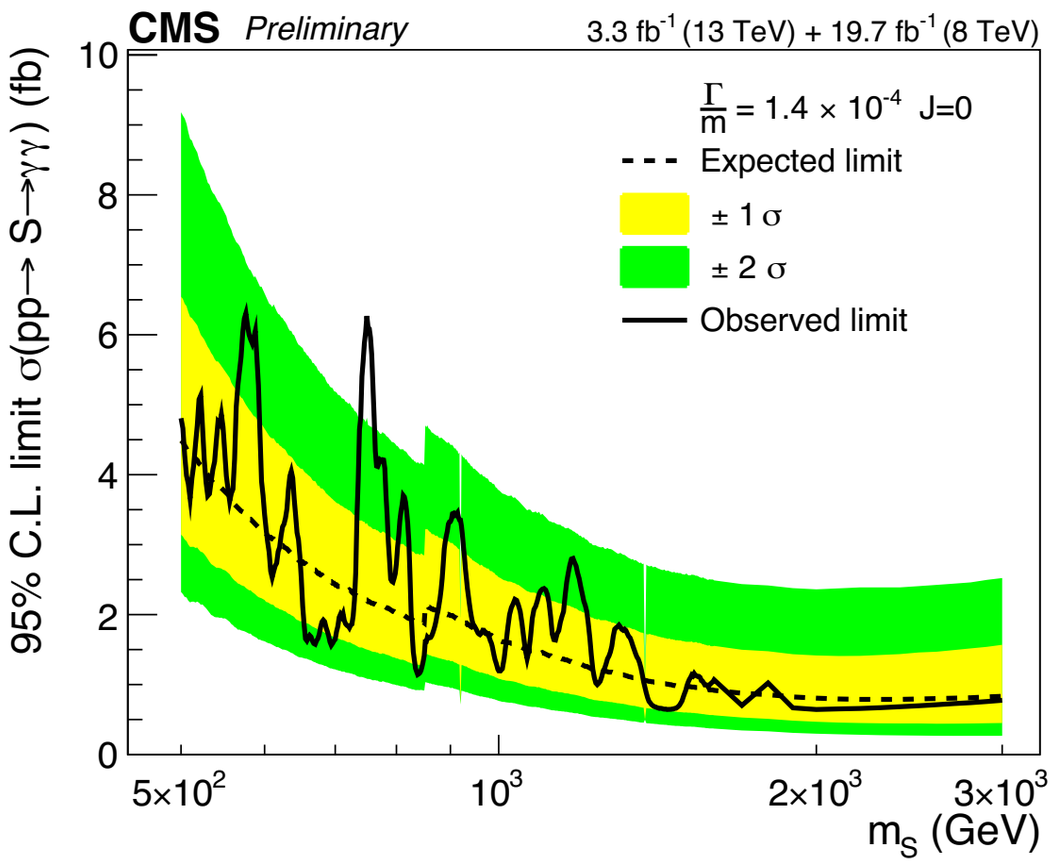

CMS Preliminary 2.7 fb$^{-1}$ (13 TeV, 3.8T)
EBEE
Data
Fit model
± 1 σ
± 2 σ
Events / ( 20 GeV )
(data-fit)/$\sigma_{stat}$
$m_{\gamma\gamma}$ (GeV)
CMS Preliminary 2.7 fb$^{-1}$ (13 TeV, 3.8T)
EBEB
Data
Fit model
± 1 σ
± 2 σ
Events / ( 20 GeV )
(data-fit)/$\sigma_{stat}$
$m_{\gamma\gamma}$ (GeV)
CMS Preliminary 0.6 fb$^{-1}$ (13 TeV, 0T)
EBEE
Data
Fit model
± 1 σ
± 2 σ
Events / ( 20 GeV )
(data-fit)/$\sigma_{stat}$
$m_{\gamma\gamma}$ (GeV)
CMS Preliminary 0.6 fb$^{-1}$ (13 TeV, 0T)
EBEB
Data
Fit model
± 1 σ
± 2 σ
Events / ( 20 GeV )
(data-fit)/$\sigma_{stat}$
$m_{\gamma\gamma}$ (GeV)

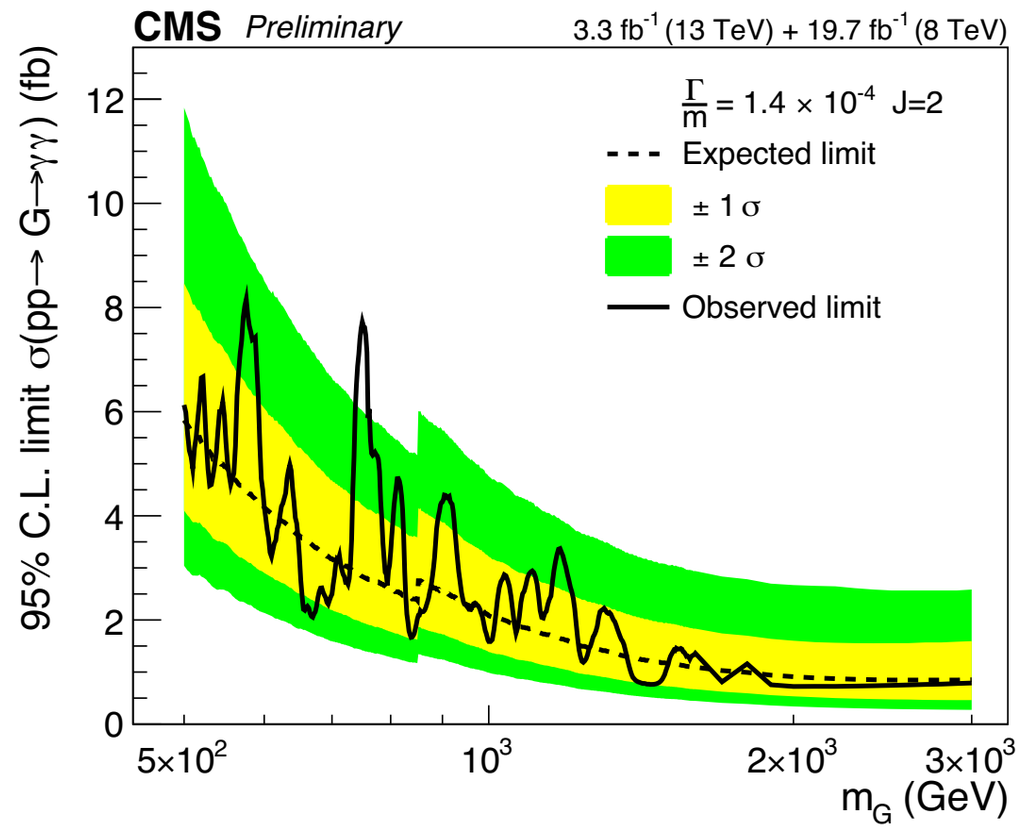

CMS Preliminary
3.3 fb-1 (13 TeV) + 19.7 fb-1 (8 TeV)
p0
1 σ
2 σ
3 σ
Γ/m = 1.4 × 10-4 J=0
Combined
8TeV
13TeV
5×10^2
10^3
2×10^3
3×10^3
mS (GeV)

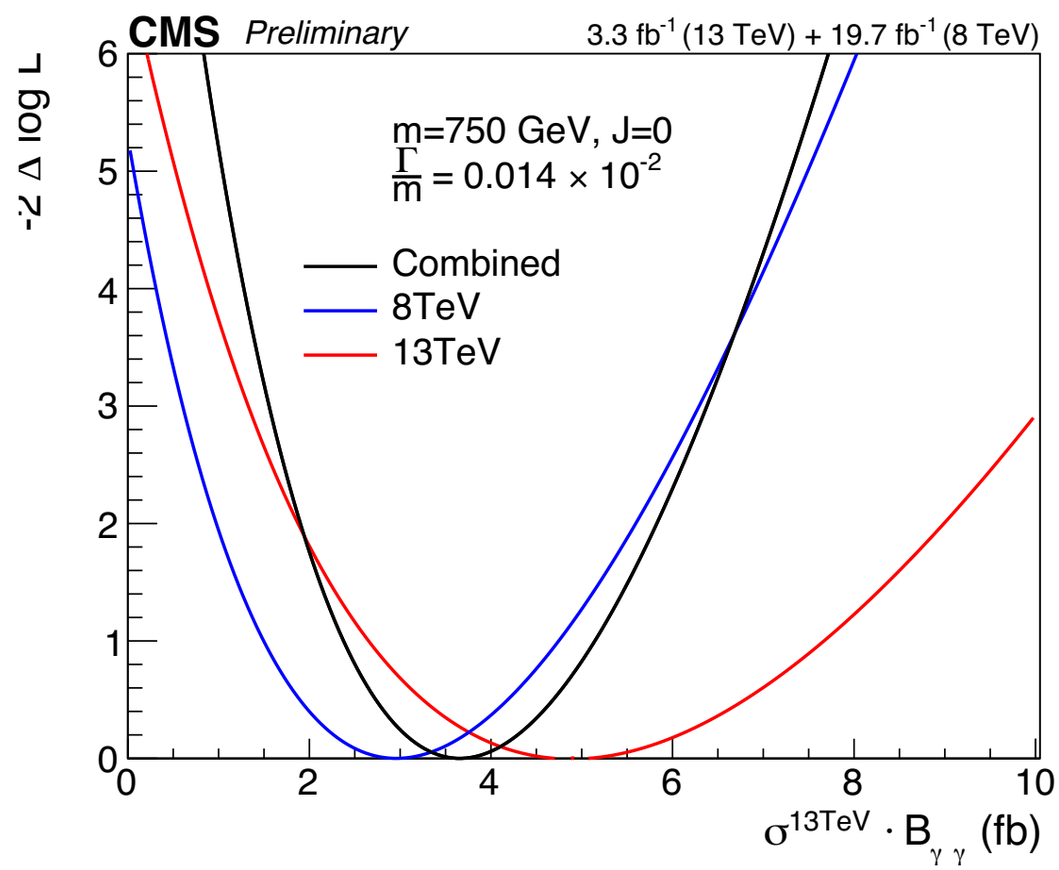

CMS Preliminary
3.3 fb-1 (13 TeV) + 19.7 fb-1 (8 TeV)
p0
1 σ
2 σ
3 σ
Γ/m = 1.4 × 10-4 J=2
Combined
8TeV
13TeV
5×10^2
10^3
2×10^3
3×10^3
mG (GeV)

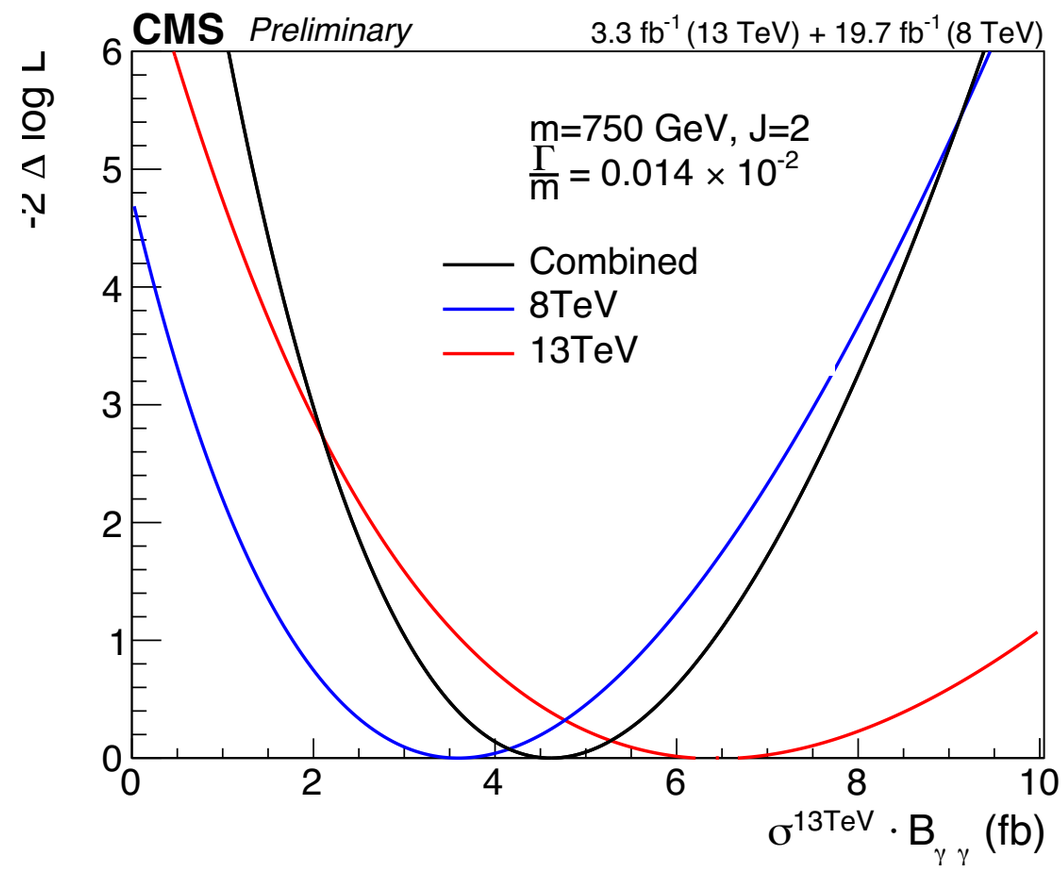

CMS Preliminary
3.3 fb-1 (13 TeV) + 19.7 fb-1 (8 TeV)
p0
1 σ
2 σ
3 σ
Γ/m = 5.6 × 10-2 J=0
Combined
8TeV
13TeV
5×10^2
10^3
2×10^3
3×10^3
mS (GeV)

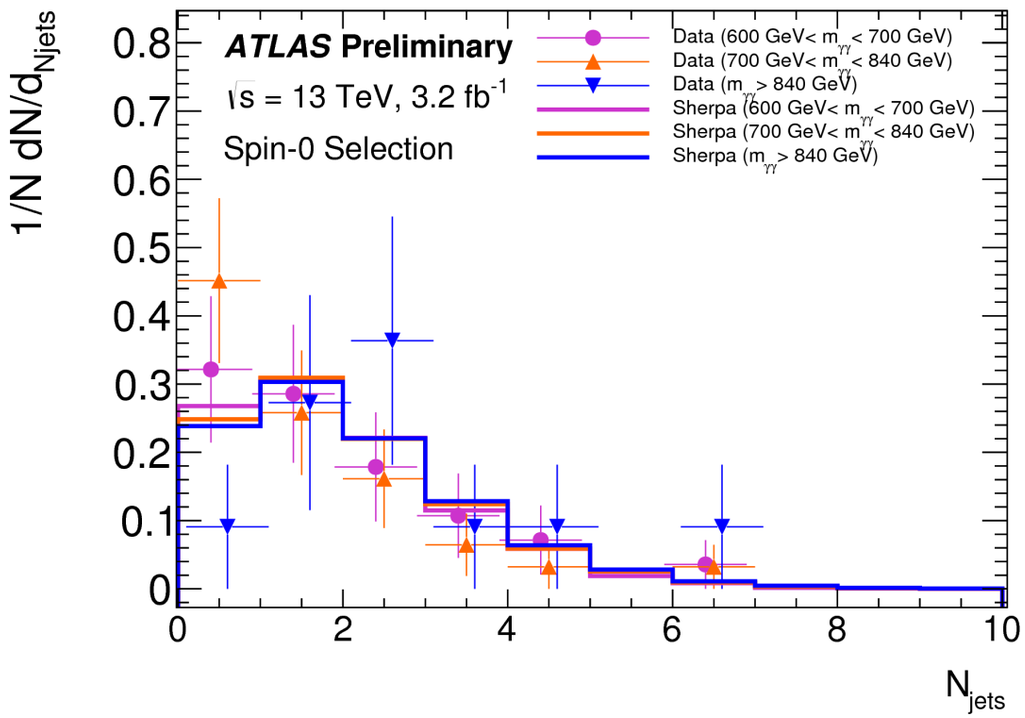

CMS Preliminary
3.3 fb-1 (13 TeV) + 19.7 fb-1 (8 TeV)
p0
1 σ
2 σ
3 σ
Γ/m = 5.6 × 10-2 J=2
Combined
8TeV
13TeV
5×10^2
10^3
2×10^3
3×10^3
mG (GeV)

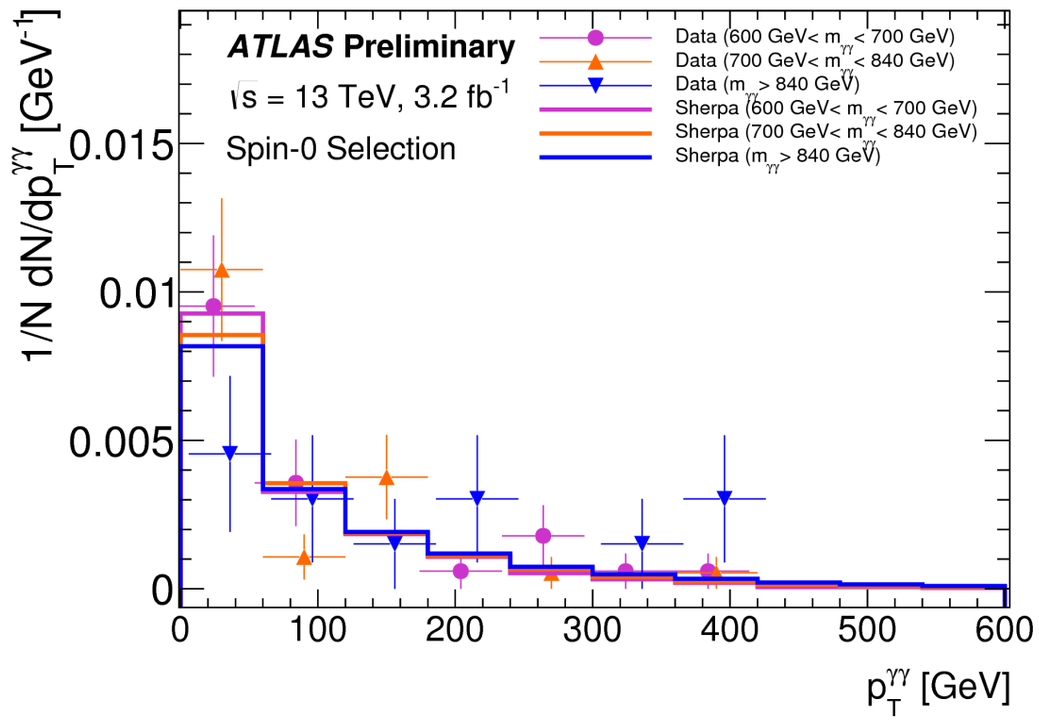

CMS Preliminary
3.3 fb-1 (13 TeV) + 19.7 fb-1 (8 TeV)
Γ/m = 1.4 × 10-4 J=0
Expected limit
± 1 σ
± 2 σ
Observed limit
95% C.L. limit σ(pp→ S→γγ) (fb)
mS (GeV)

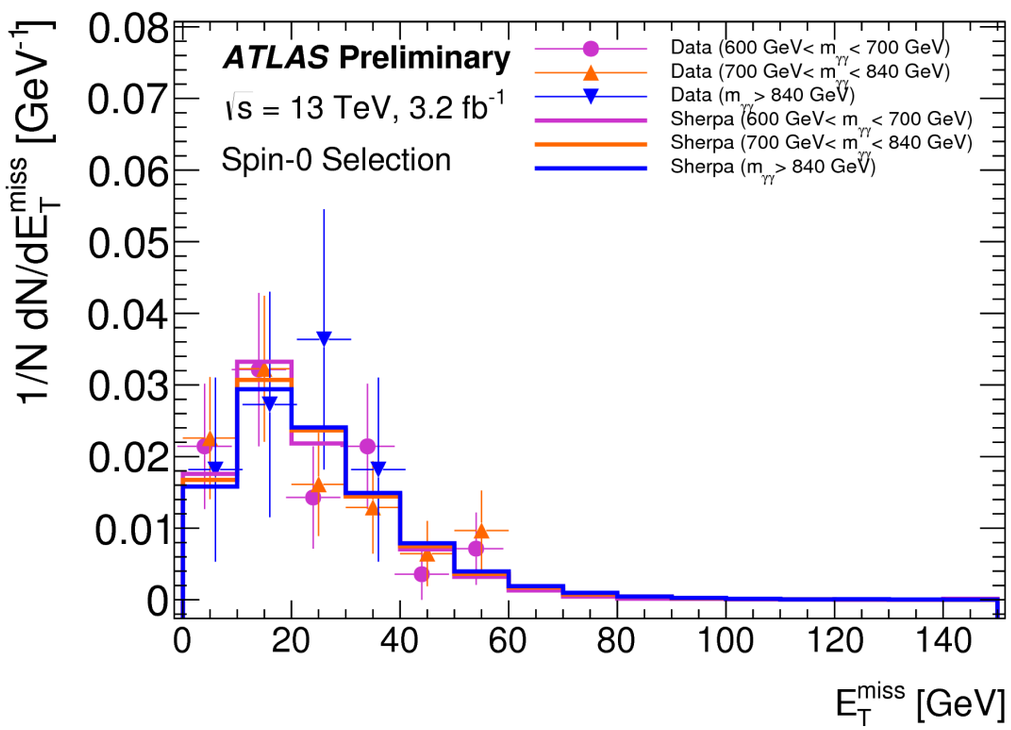

CMS Preliminary
3.3 fb-1 (13 TeV) + 19.7 fb-1 (8 TeV)
Γ/m = 1.4 × 10-4 J=2
Expected limit
± 1 σ
± 2 σ
Observed limit
95% C.L. limit σ(pp→ G→γγ) (fb)
mG (GeV)

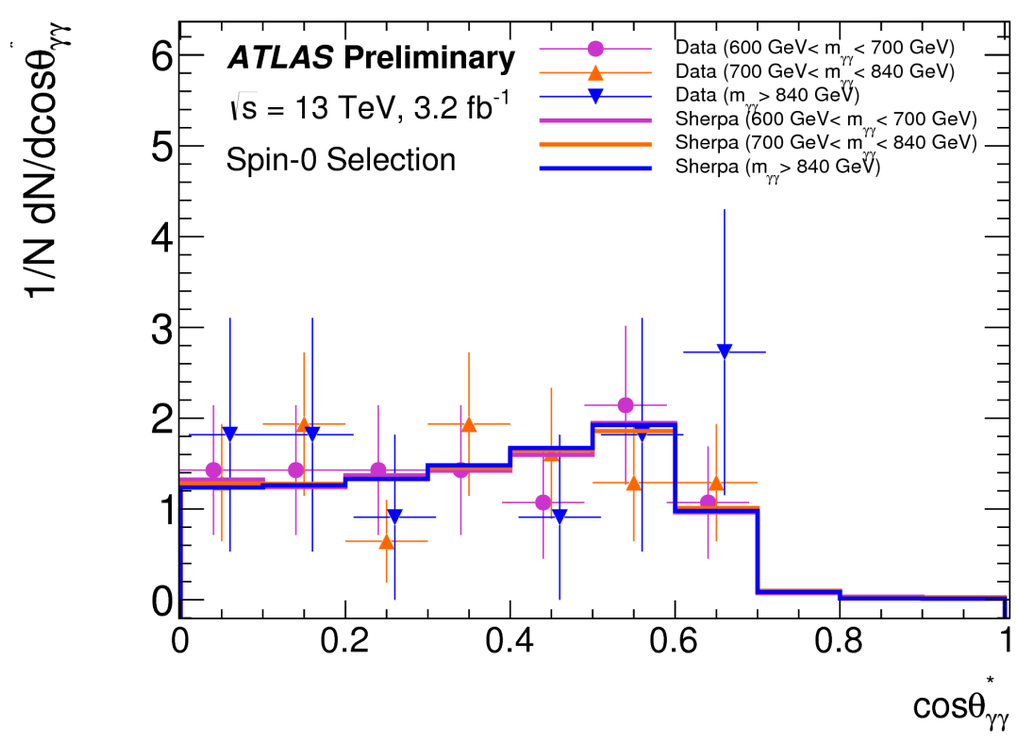

CMS Preliminary
3.3 fb-1 (13 TeV) + 19.7 fb-1 (8 TeV)
m=750 GeV, J=0
Γ/m = 0.014 × 10-2
Combined
8TeV
13TeV
-2 Δ log L
σ13TeV · Bγγ (fb)


CMS Preliminary
3.3 fb-1 (13 TeV) + 19.7 fb-1 (8 TeV)
m=750 GeV, J=2
Γ/m = 0.014 × 10-2
Combined
8TeV
13TeV
-2 Δ log L
σ13TeV · Bγγ (fb)


ATLAS Preliminary
√s = 13 TeV, 3.2 fb-1
Spin-0 Selection
Data (600 GeV< mγγ < 700 GeV)
Data (700 GeV< mγγ < 840 GeV)
Data (mγγ > 840 GeV)
Sherpa (600 GeV< mγγ < 700 GeV)
Sherpa (700 GeV< mγγ < 840 GeV)
Sherpa (mγγ > 840 GeV)
1/N dN/dNjets
Njets


ATLAS Preliminary
√s = 13 TeV, 3.2 fb-1
Spin-0 Selection
Data (600 GeV< mγγ < 700 GeV)
Data (700 GeV< mγγ < 840 GeV)
Data (mγγ > 840 GeV)
Sherpa (600 GeV< mγγ < 700 GeV)
Sherpa (700 GeV< mγγ < 840 GeV)
Sherpa (mγγ > 840 GeV)
1/N dN/dpTγγ [GeV-1]
pTγγ [GeV]


ATLAS Preliminary
√s = 13 TeV, 3.2 fb-1
Spin-0 Selection
Data (600 GeV< mγγ < 700 GeV)
Data (700 GeV< mγγ < 840 GeV)
Data (mγγ > 840 GeV)
Sherpa (600 GeV< mγγ < 700 GeV)
Sherpa (700 GeV< mγγ < 840 GeV)
Sherpa (mγγ > 840 GeV)
1/N dN/dETmiss [GeV-1]
ETmiss [GeV]


ATLAS Preliminary
√s = 13 TeV, 3.2 fb-1
Spin-0 Selection
Data (600 GeV< mγγ < 700 GeV)
Data (700 GeV< mγγ < 840 GeV)
Data (mγγ > 840 GeV)
Sherpa (600 GeV< mγγ < 700 GeV)
Sherpa (700 GeV< mγγ < 840 GeV)
Sherpa (mγγ > 840 GeV)
1/N dN/dcosθγγ
cosθ*γγ

# NMSSM

- the whole Higgs sector can be parametrized with six parameters

$$\lambda, \kappa, A_\lambda, A_\kappa, \mu, \tan\beta$$

We trade $A_\lambda$ with $M_A$

$$\lambda, \kappa, M_A, A_\kappa, \mu, \tan\beta$$

where

$$M_A^2 = \frac{2\lambda s}{\sin 2\beta}(A_\lambda + \kappa s)$$