The LHC challenge

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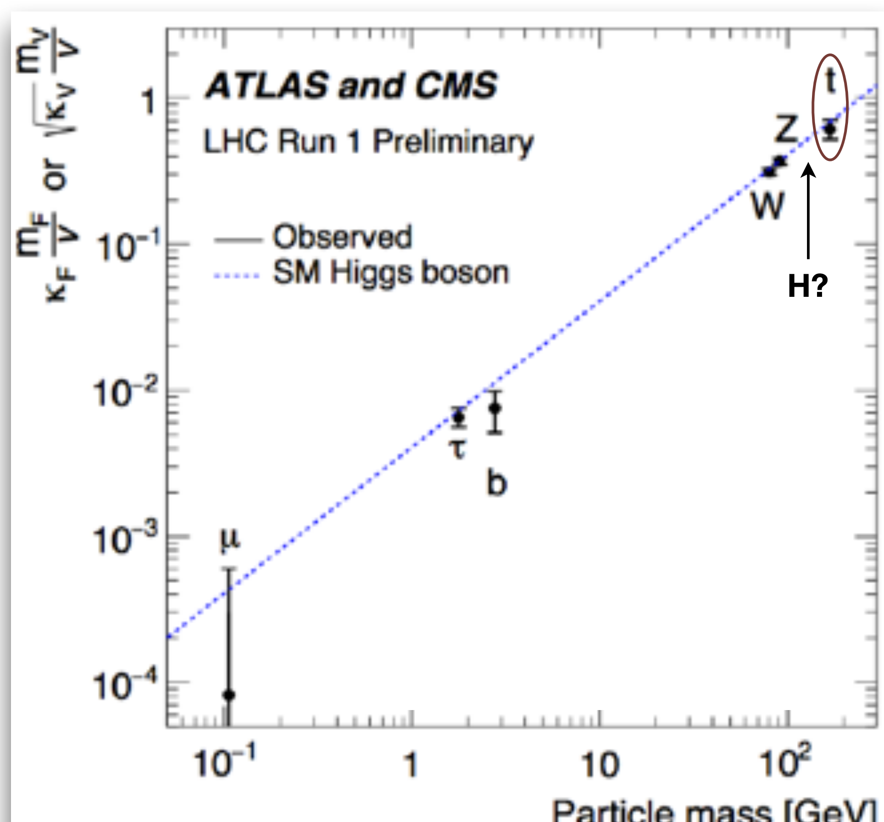
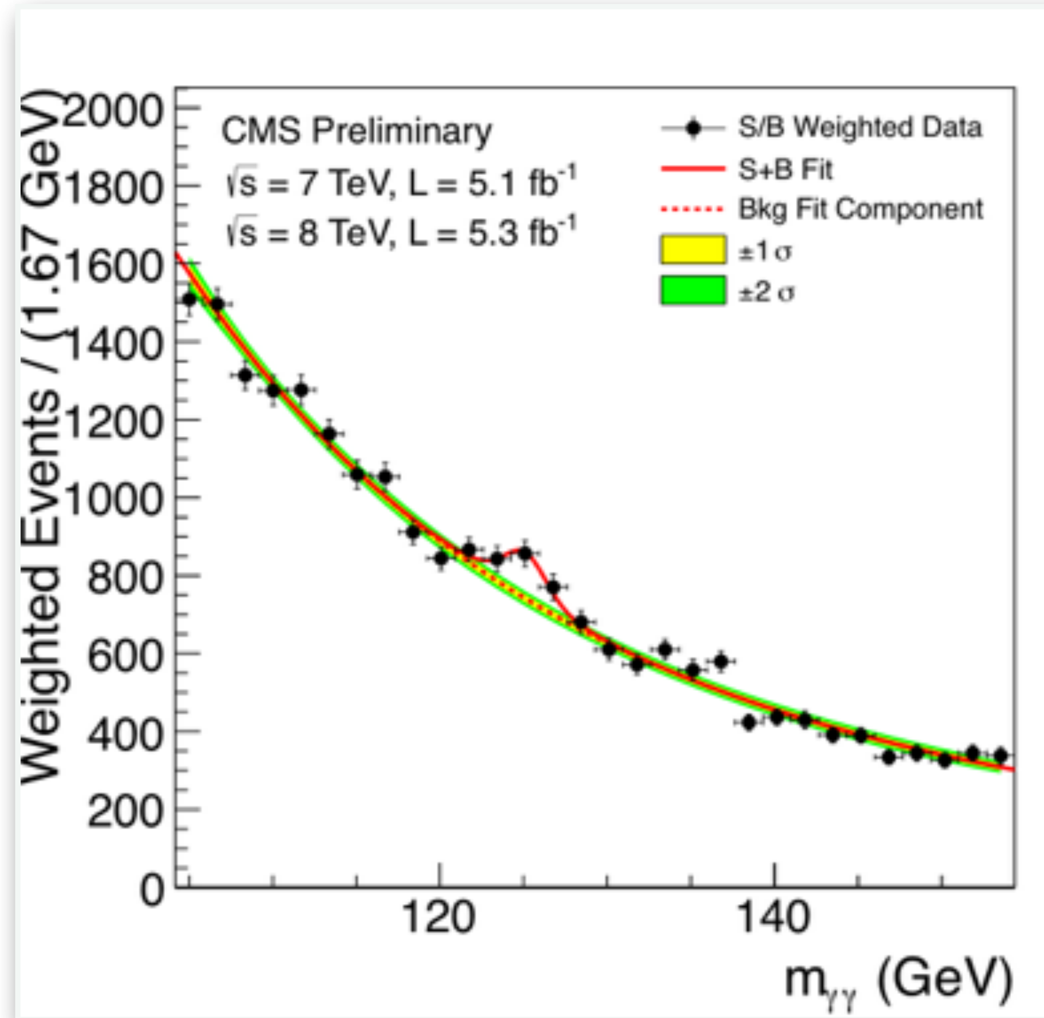
The LHC triumph

- h has S = 0 and P = 1
- h is $SU(3)_c \times U(1)_{em}$ neutral
- h belongs to $SU(2)_L$ doublet
- h couplings prop. to masses





Understanding the EW scale

- $V = \mu^2|H|^2 + \lambda|H|^4$

- **μ^2** Higgs potential parameter (tree level)

- **M^2** scale of superheavy dofs with coupling g to H, e.g. $O(10^{16}\text{GeV})^2$

$$m_H^2 \sim -2\mu^2 + \frac{g^2}{(4\pi)^2} M^2$$

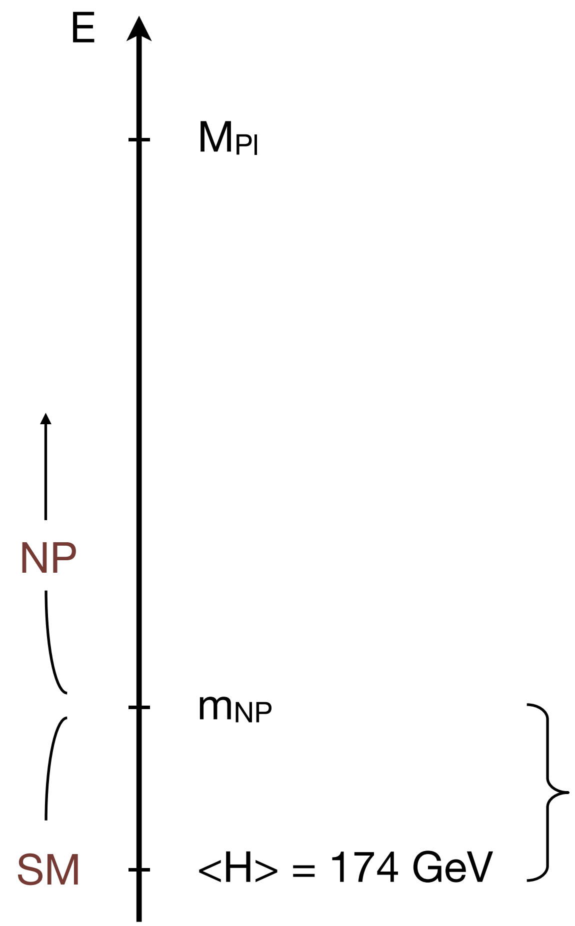
The LHC challenge (I)

- No superheavy (coupled) degrees of freedom
  (finite naturalness?)

- Large sensitivity to superheavy scales, but cancellation not accidental
  (environmental selection? unknown dynamics?)

- New TeV physics taming sensitivity to high scales
  (supersymmetry? composite Higgs?)

The scale of “natural” new physics



$$\delta m_h^2 \sim \frac{g^2}{(4\pi)^2} m_{\rm NP}^2 \approx (125\,{\rm GeV})^2 \left(\frac{m_{\rm NP}}{0.5\,{\rm TeV}}\right)^2$$

top contribution

$$\Delta \sim \left(\frac{m_{\rm NP}}{0.5\,{\rm TeV}}\right)^2$$

Example: supersymmetry

$$\Delta \sim \left(\frac{m_{\rm NP}}{0.5\,{\rm TeV}/\sqrt{\log}}\right)^2 \qquad \log = \log\frac{M^2}{m_{\rm NP}^2}$$

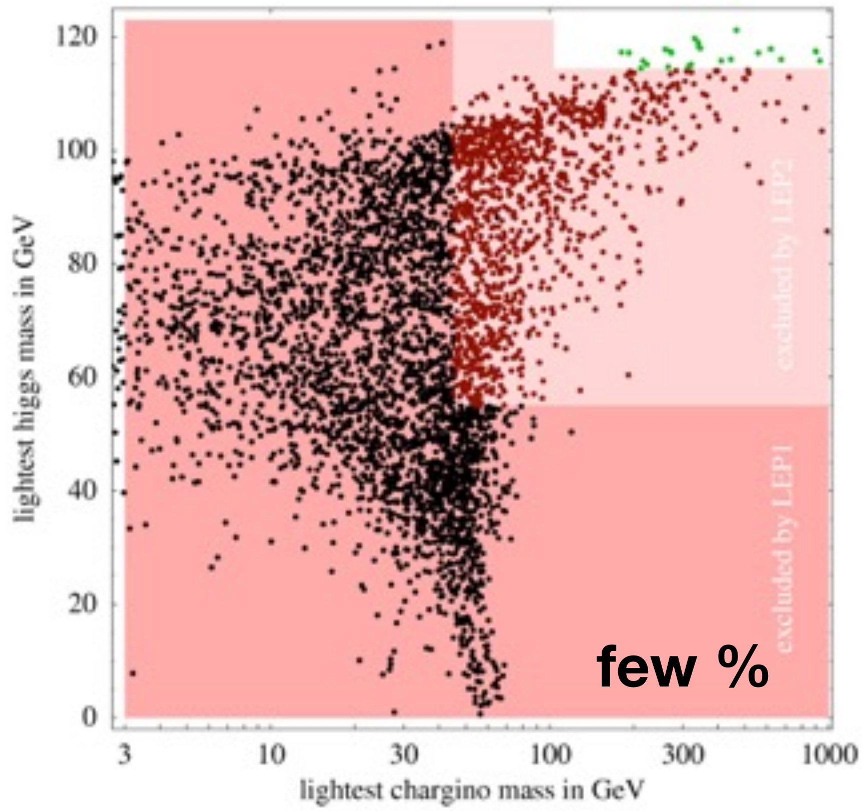
M = mediation scale

Example: supergravity

$M = M_{Planck}$

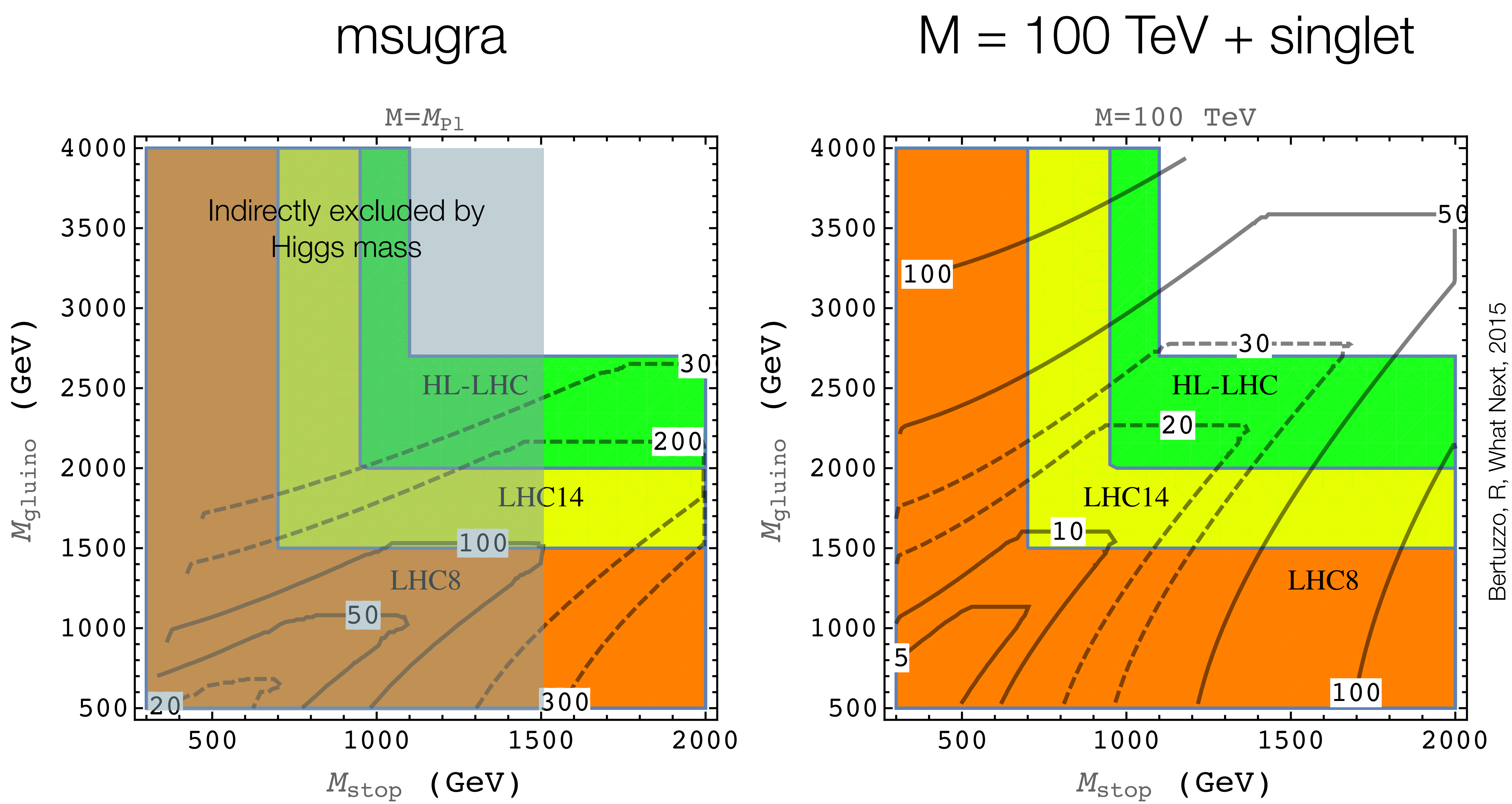
log ~ 70

$\Delta \sim 1$ for $m_{NP} \sim M_Z$



[Giusti R Strumia, 1998]

Message: low M?



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"Hints" of physics MUCH above the EW scale

- $M_{Pl} \approx 1.2 \times 10^{19}$ GeV — who knows

- Quantum number unification
- Neutrino masses

} give up

The LHC challenge (I)

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Environmental selection

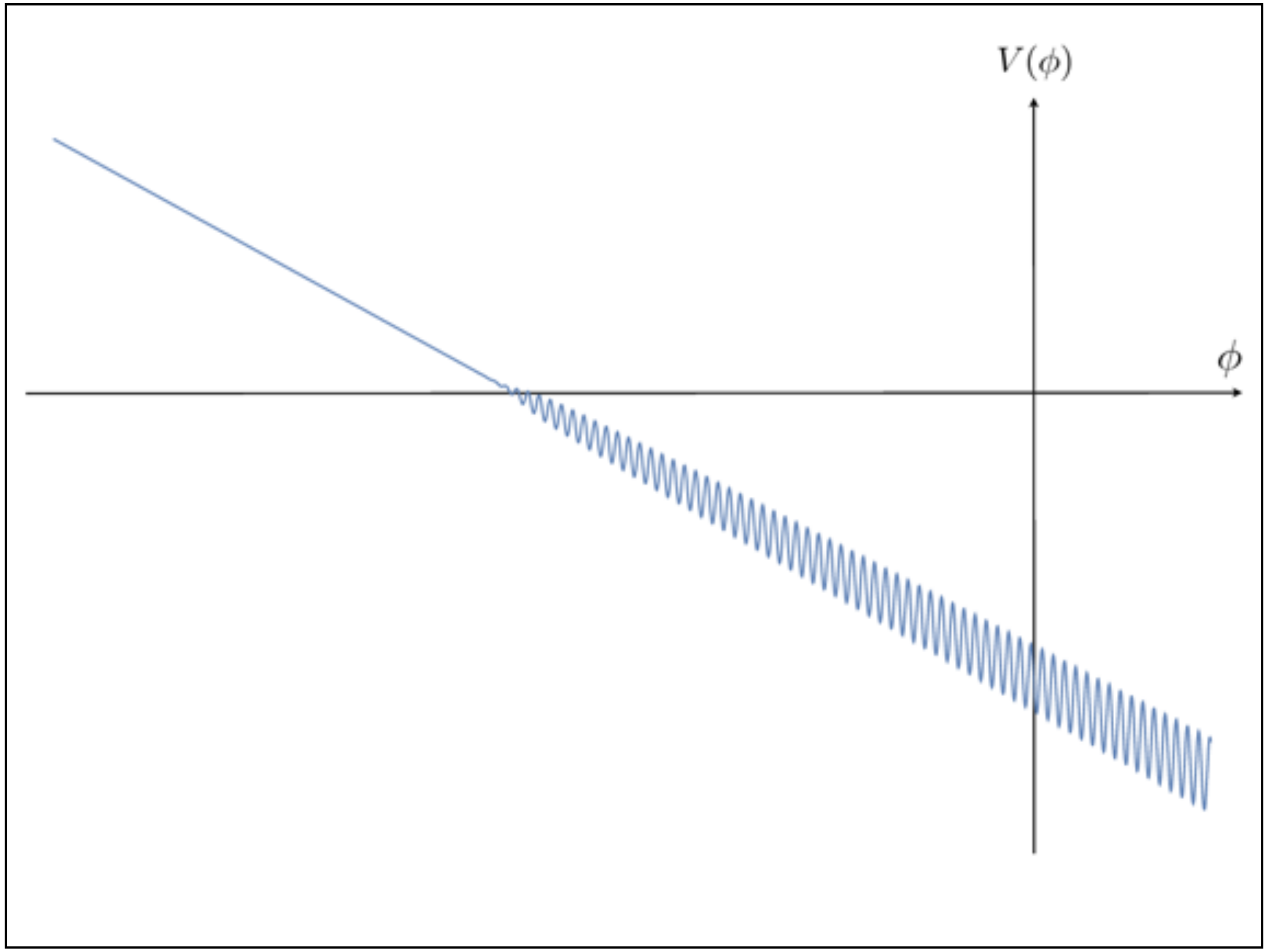
- Give up reductionist understanding of EW scale
- Assume cosmology populates a landscape of vacua
- Retain the understanding of SM gauge quantum numbers, neutrino masses, success of gauge coupling unification, WIMP miracle

Cosmological relaxation

- Original proposal:
    - Accept field excursion up to 10^{30} GeV $(M/10\text{TeV})^2$
    - Invoke inflation model with $N \sim 10^{30}$ e-foldings
    - Non trivial low-E inflation dynamics to avoid $\theta_{QCD} \sim 1$
    - Low cutoff anyway $M \lesssim 30$TeV
- (a starting point…)

Relaxion

$$\mathcal{L} = \mathcal{L}_{\rm SM} + (M^2 - \epsilon M \phi)|H|^2 + V(\epsilon\phi) + \Lambda^3 \lambda_q |H| \cos(\phi/f)$$

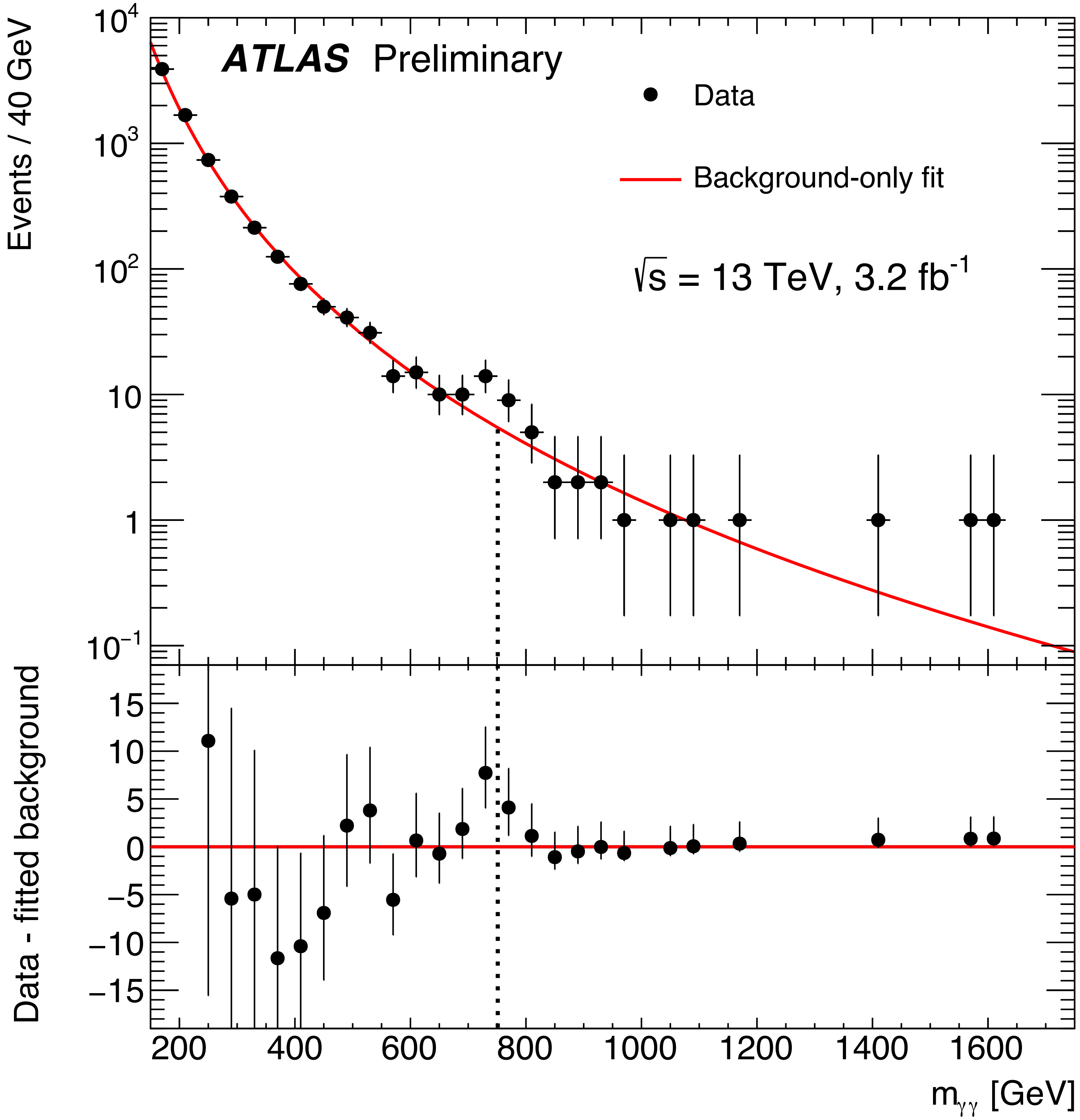


$$|H| \sim \frac{\epsilon}{\lambda_q}\left(\frac{M}{\Lambda}\right)^3 f \Rightarrow \epsilon \lesssim 10^{-27}$$

$$\Delta\phi \sim \frac{M}{\epsilon} \Rightarrow N_e \gtrsim 10^{30}$$

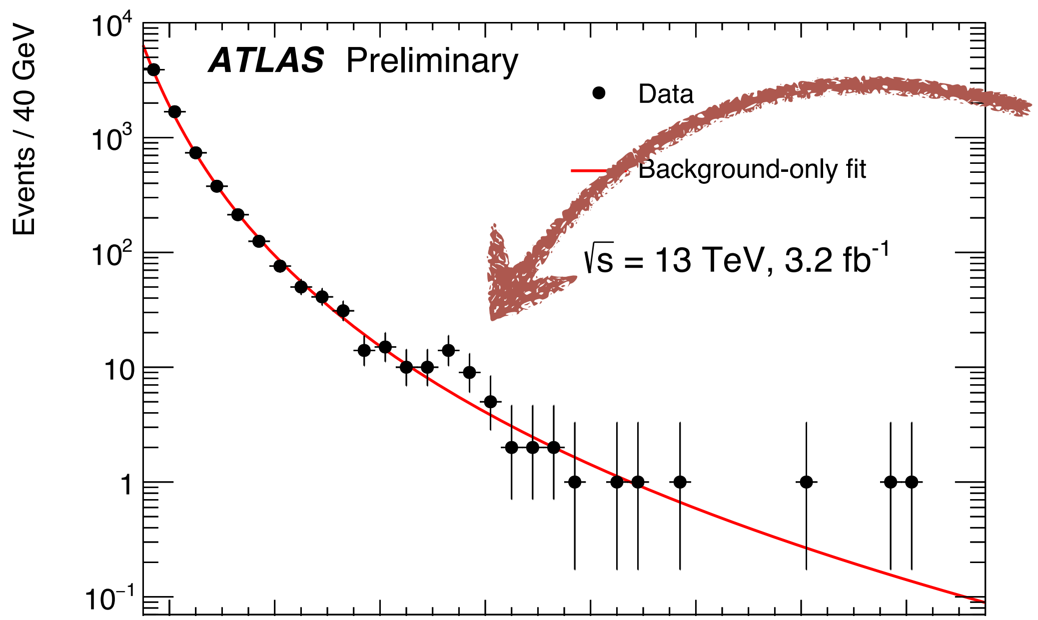
$$\theta_{\rm QCD} \sim 1$$

A new resonance in pp → γγ?

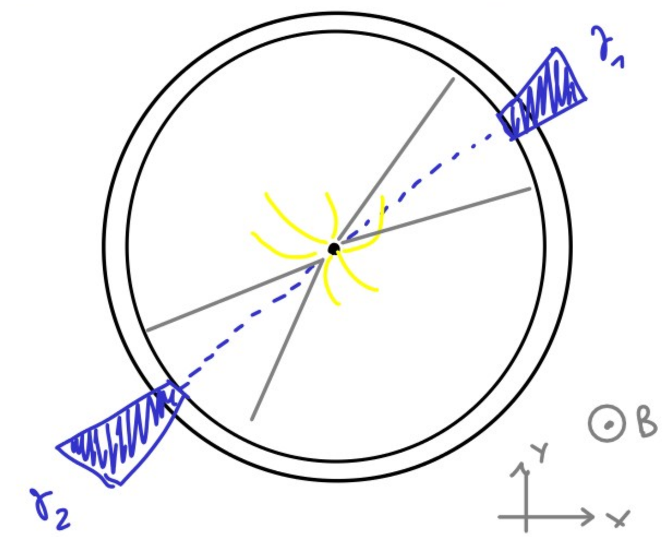


"Who ordered the rabbit?"

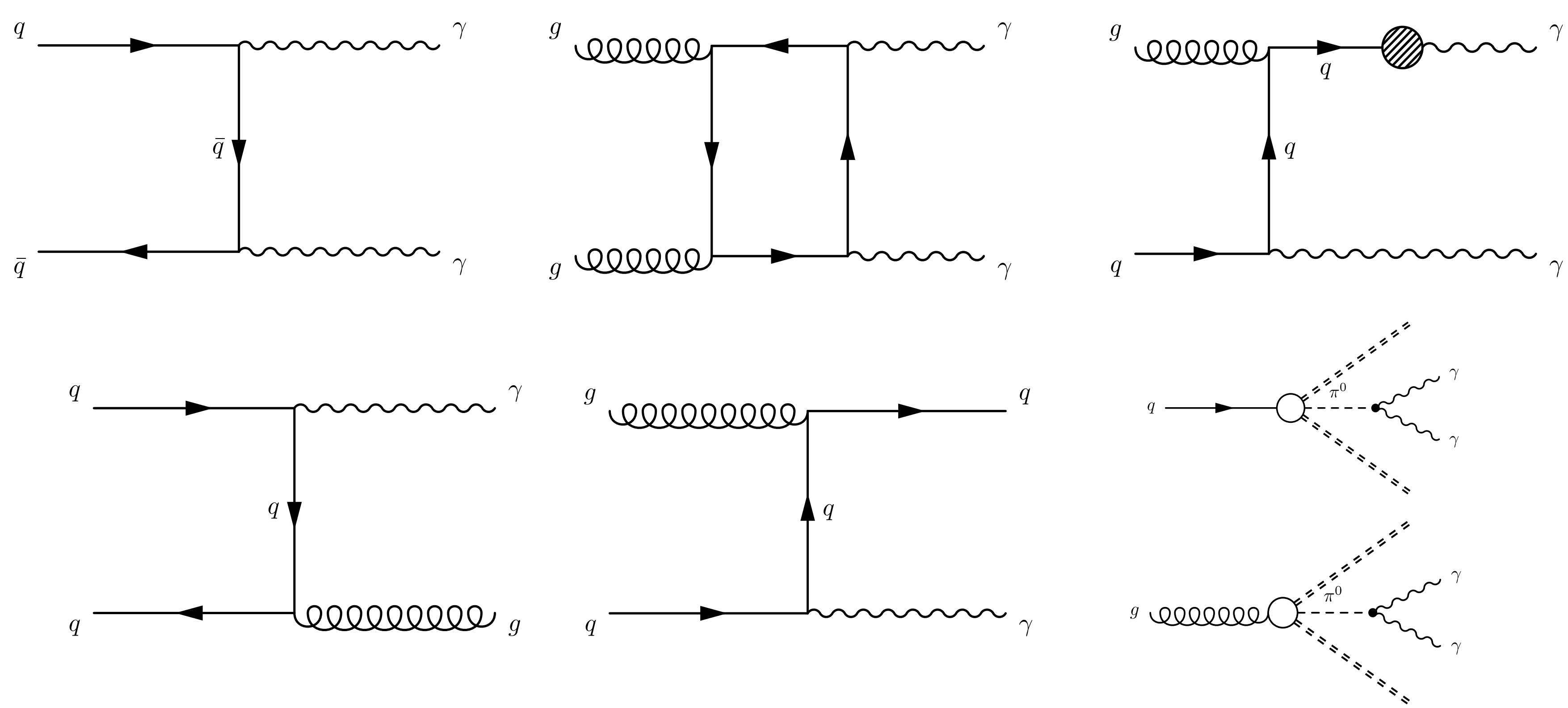
Basics



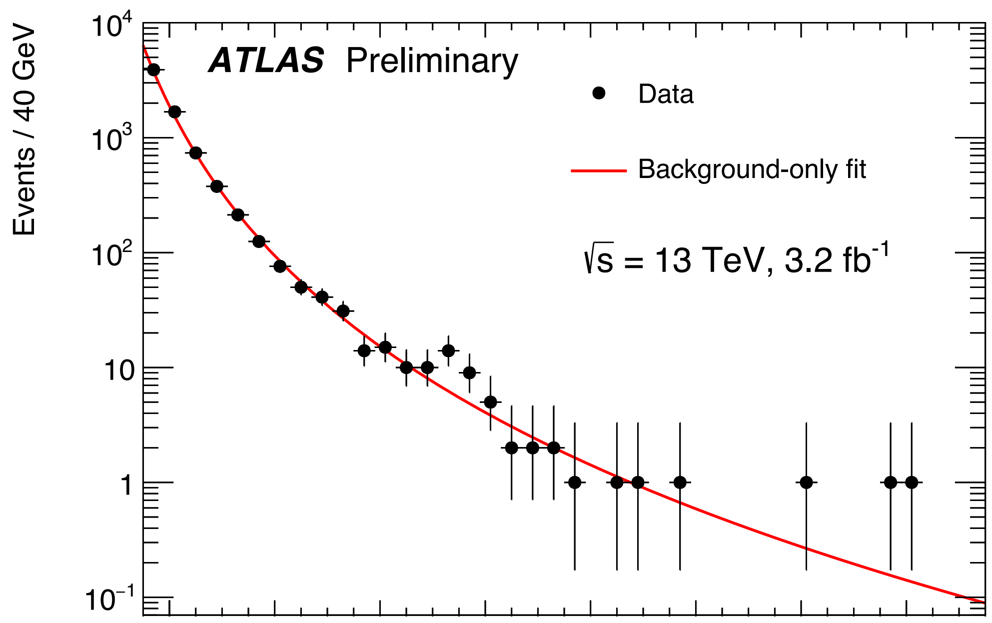
$pp \to X \to \gamma\gamma$

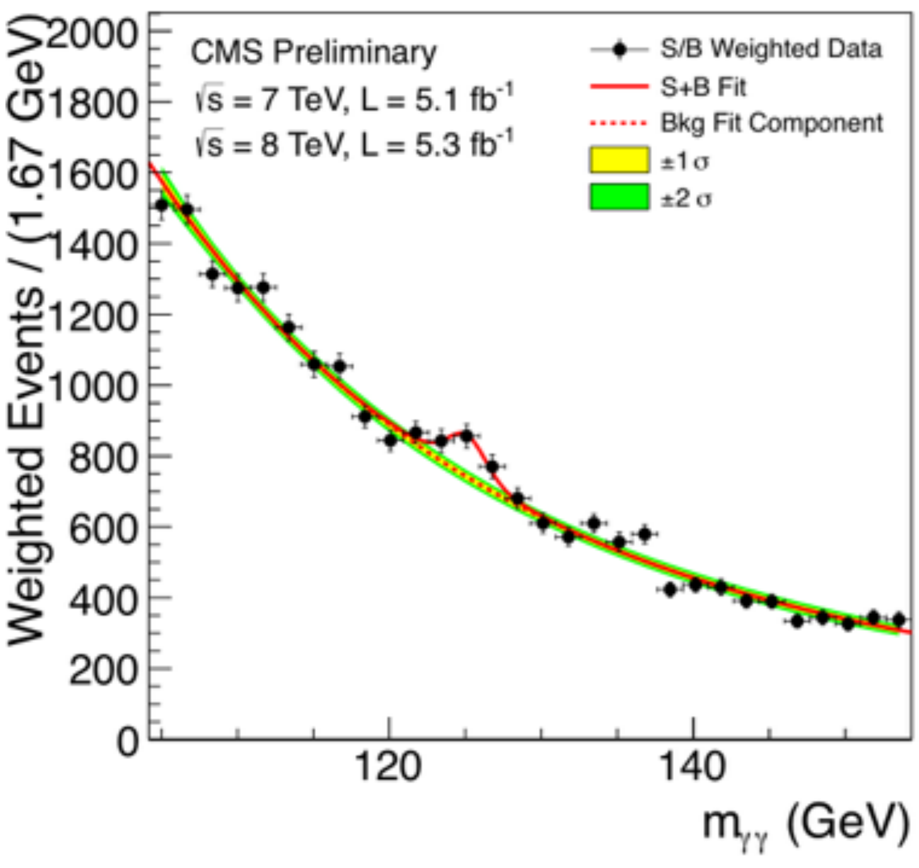


→ talk by Leandro Cieri

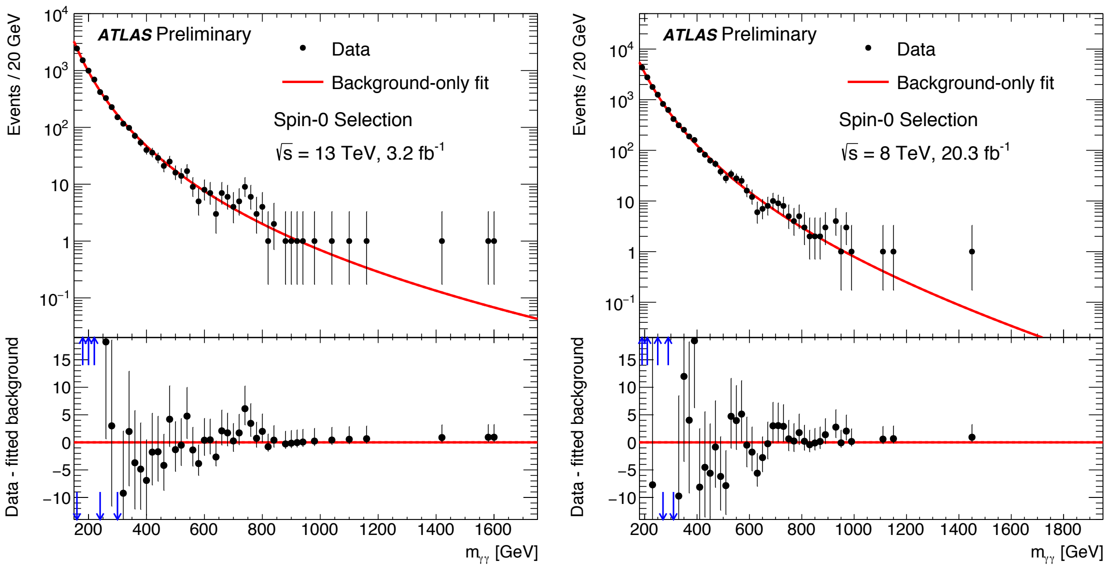


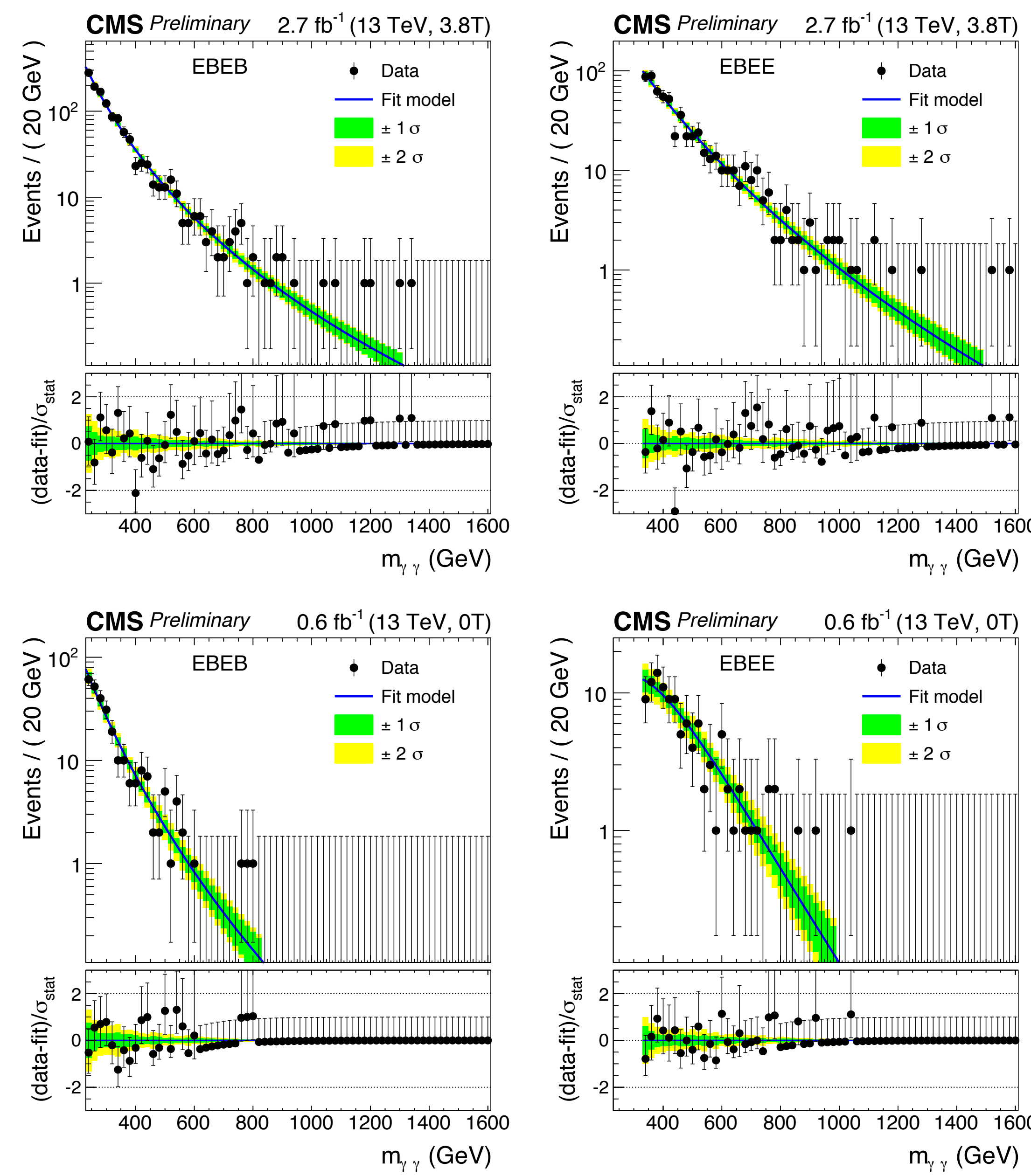
Basics


ATLAS Preliminary
Data
Background-only fit
√s = 13 TeV, 3.2 fb⁻¹
Events / 40 GeV
10⁴
10³
10²
10
1
10⁻¹


CMS Preliminary
√s = 7 TeV, L = 5.1 fb⁻¹
√s = 8 TeV, L = 5.3 fb⁻¹
S/B Weighted Data
S+B Fit
Bkg Fit Component
±1 σ
±2 σ
Weighted Events / (1.67 GeV)
m_γγ (GeV)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
120
140

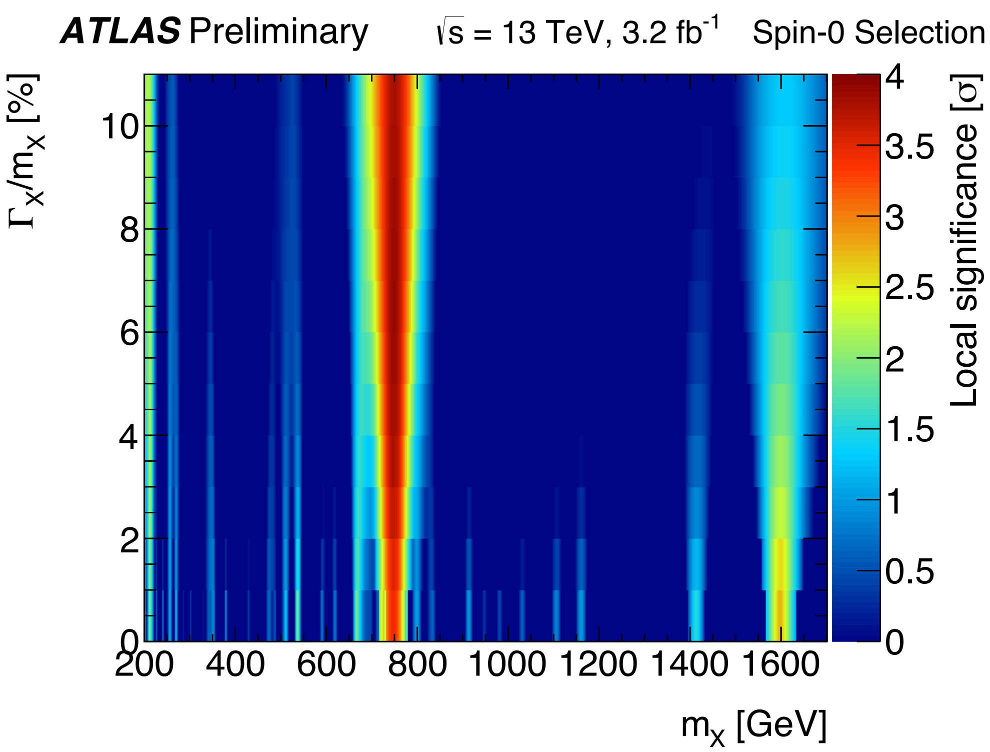
Significant?

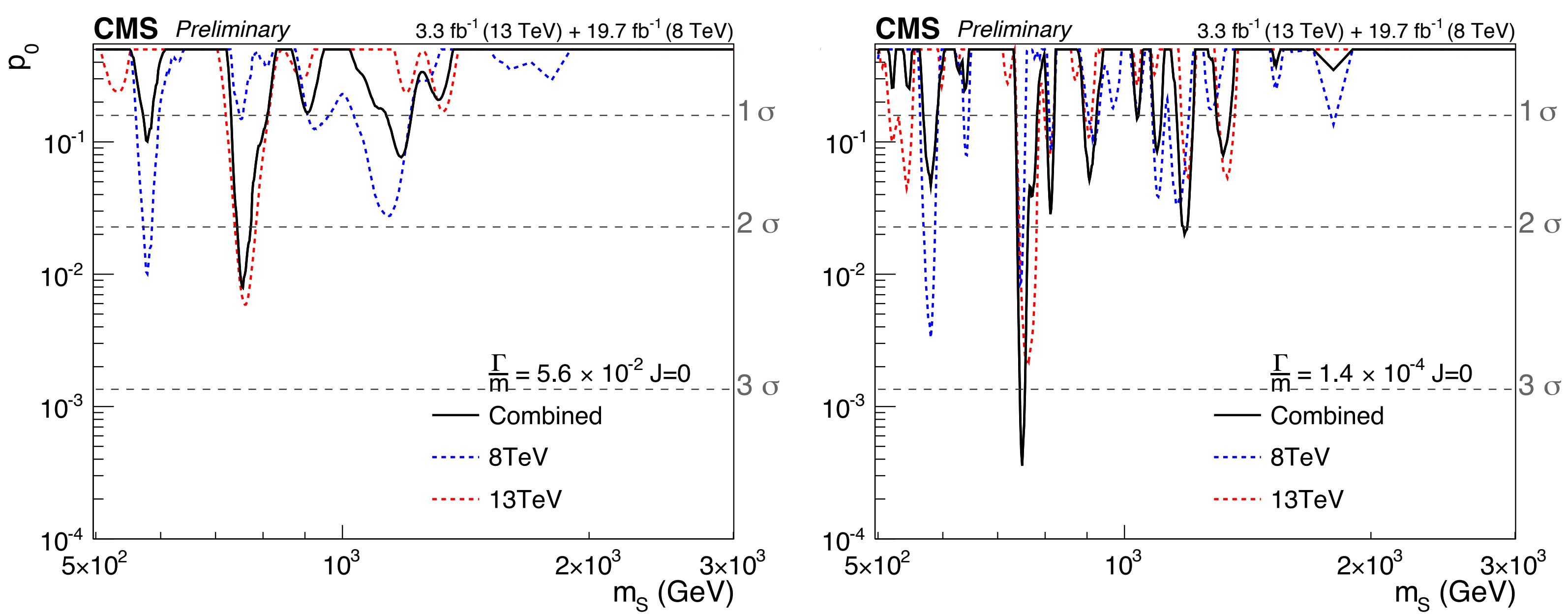




ATLAS	13 TeV 3.2 fb^{-1}	3.9 σ
ATLAS	8 TeV 20.3 fb^{-1}	1.9 σ
CMS	13 TeV + 8 TeV	3.4 σ

Significant?





ATLAS 13 TeV only

best fit m ≈ 750 GeV, Γ ≈ 45 GeV

3.9 σ local

Slight preference for large Γ

CMS 13 TeV + 8 TeV

best fit m ≈ 750 GeV, Γ ≈ narrow

3.4 σ local

Slightly preference for narrow Γ

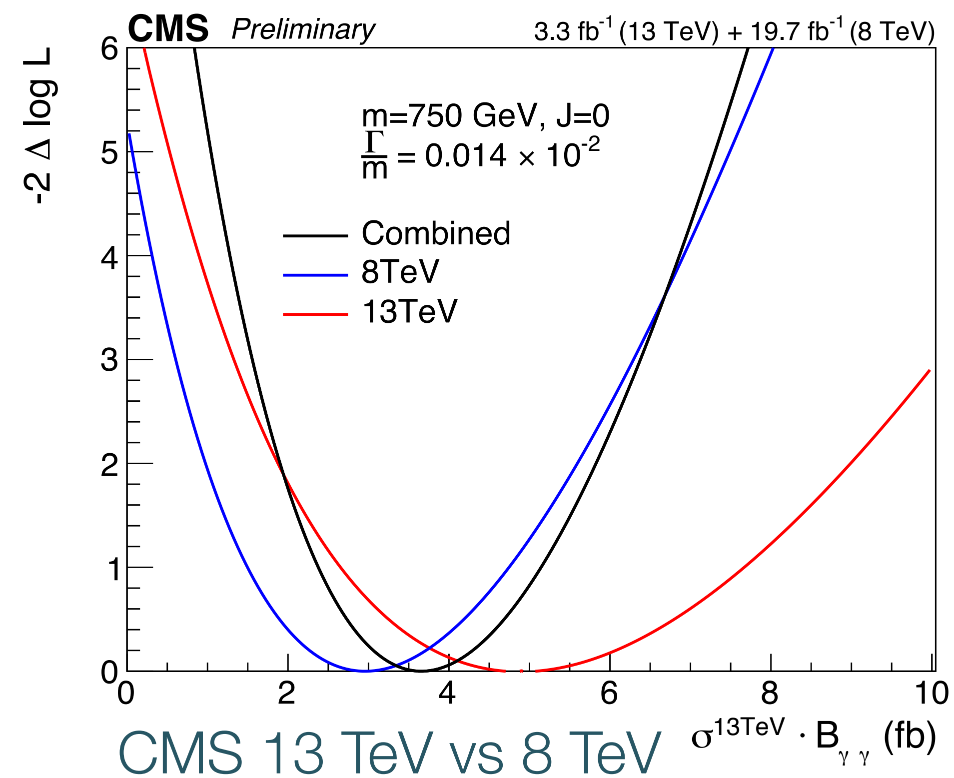
Compatible (S = 0)?

ATLAS 13 TeV vs 8 TeV

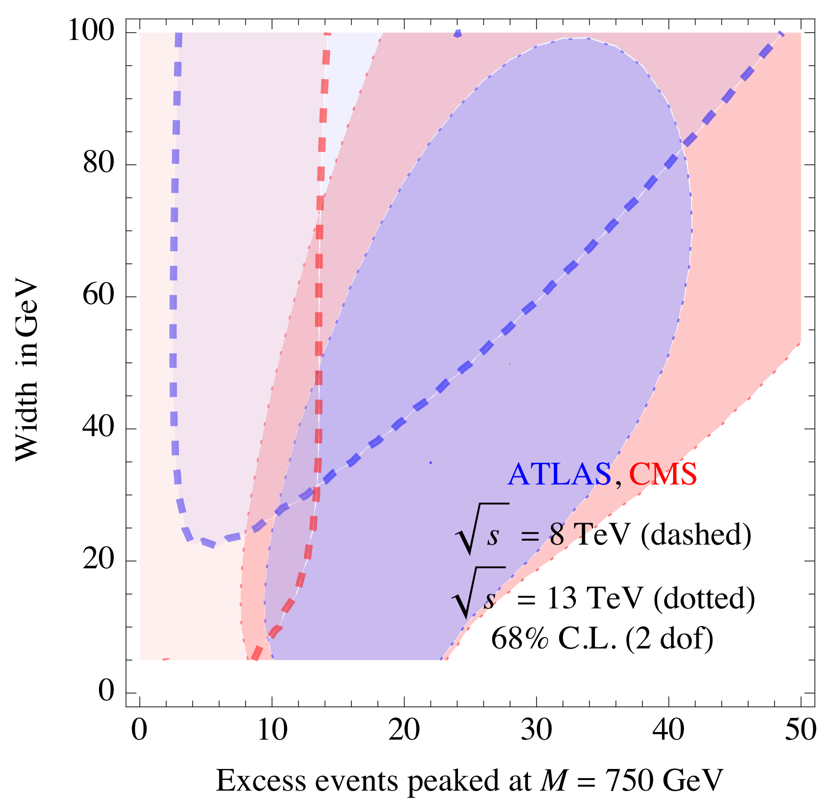
8 TeV has smaller strength

compatible at 1.2 σ with 13 TeV best fit

for S = 0 and gg production



CMS 13 TeV vs 8 TeV



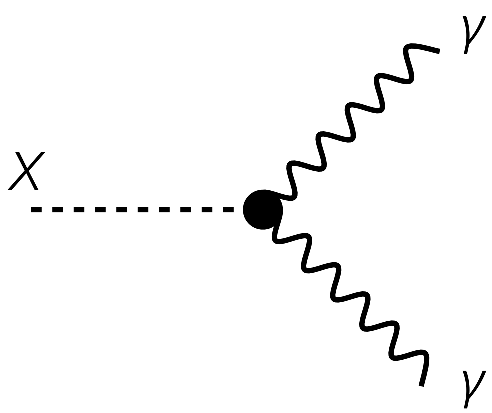
arXiv:1604.06446 (cern-th bis)

ATLAS vs CMS

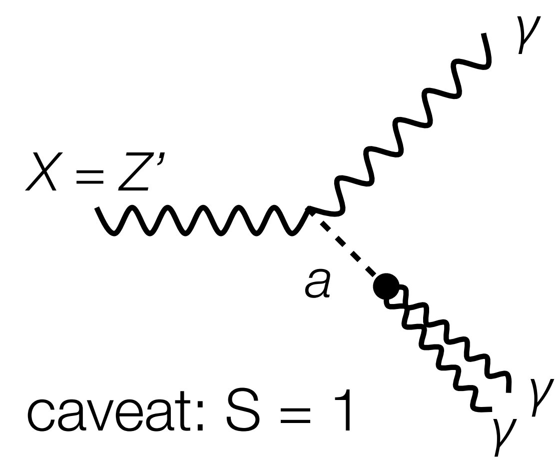
What if pp → X → γγ

- Celebrate
- $\mathcal{L}_{SM}$ + ?
  - which field? (spin? SM quantum numbers?)
  - which interaction? (parity? width? production and decay?)
- Who ordered that?

Spin



⇒ S = 0, 2…

(


caveat: S = 1)

ATLAS	S = 0	1.2 σ (gg)	2.1 σ (qq)
	S = 2	2.7 σ (gg)	3.3 σ (qq)

8 TeV → 13 TeV
scaling: 4.7

8 TeV → 13 TeV
scaling: 2.7

Production

$\sqrt{s}$	C_{gg}	$C_{u\bar{u}}$	$C_{d\bar{d}}$	$C_{s\bar{s}}$	$C_{c\bar{c}}$	$C_{b\bar{b}}$	$C_{\gamma\gamma}$
13 TeV	2137	1054	627	83	36	15.3	54
8 TeV	174	158	89	7.2	2.7	1.07	11
σ_{13}/σ_8	4.7	2.5	2.7	4.4	5.0	5.4	1.9

- Large C allows smaller $\Gamma(X\to\gamma\gamma) \equiv \Gamma_{\gamma\gamma}$ (more plausible?)

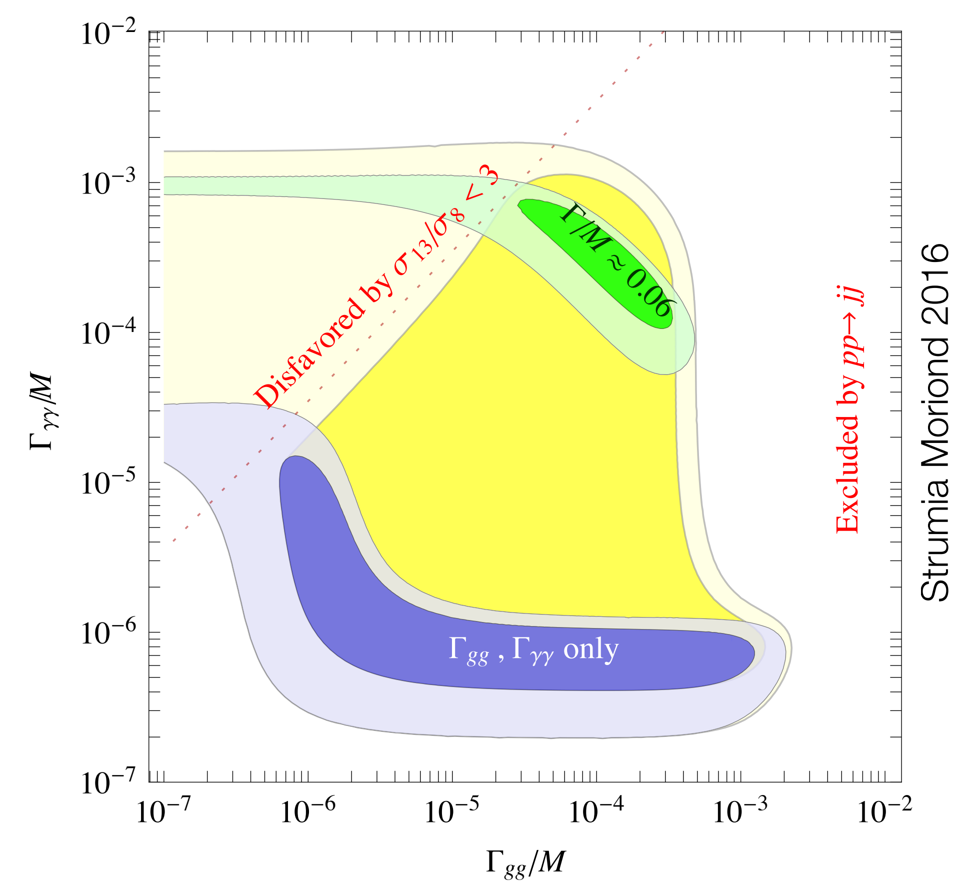
$$\sigma_{\gamma\gamma} \equiv \sigma(pp \to X \to \gamma\gamma) \quad \text{determines} \quad C_{\mathcal{PP}} \frac{\Gamma_{\mathcal{PP}}}{M_X} \frac{\Gamma_{\gamma\gamma}}{\Gamma} \quad \text{(if parton } \mathcal{P} \text{ dominates)}$$

$$\frac{\Gamma_{\gamma\gamma}}{M} \approx \frac{10^{-3}}{C_{\mathcal{PP}}} \left(\frac{\Gamma}{\Gamma_{\mathcal{PP}}}\right) \left(\frac{\sigma_{\gamma\gamma}}{6\,\mathrm{fb}}\right) \overset{gg}{\approx} 0.5 \cdot 10^{-6} \left(\frac{\Gamma}{\Gamma_{gg}}\right) \left(\frac{\sigma_{\gamma\gamma}}{6\,\mathrm{fb}}\right)$$

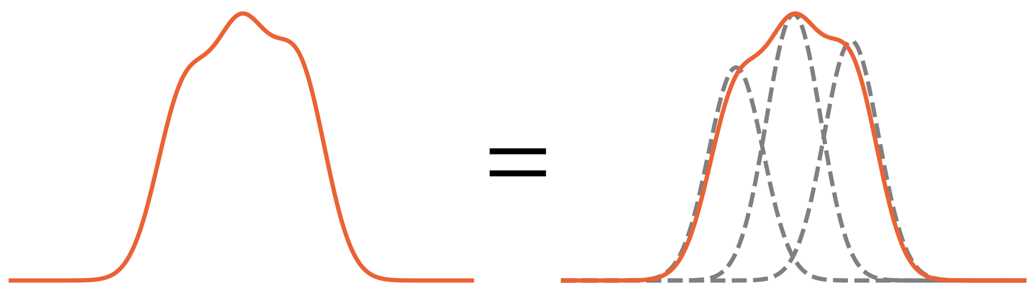
- Large σ_{13}/σ_8 ratio improves compatibility 13 TeV vs 8 TeV
- Will assume gg production when relevant

Decay and width

- $\Gamma = \Gamma_{\gamma\gamma} + \Gamma_{gg} + \Gamma_{extra}$
- large ($\Gamma/M \sim 0.06$) or narrow ($\Gamma/M \sim$ few 10^{-6})?
- $\Gamma/M \sim 0.06$
    - $\Gamma/M \sim g^2/(8\pi) \rightarrow g \sim 1$
    - accounted for by Γ_{extra} (tree level?)
    - experimental bounds $\Gamma_{extra} / \Gamma_{\gamma\gamma}$ drag $\Gamma_{\gamma\gamma}/M \gtrsim 10^{-4}$
    - strongly coupled models? → talk by Elena Vigiani

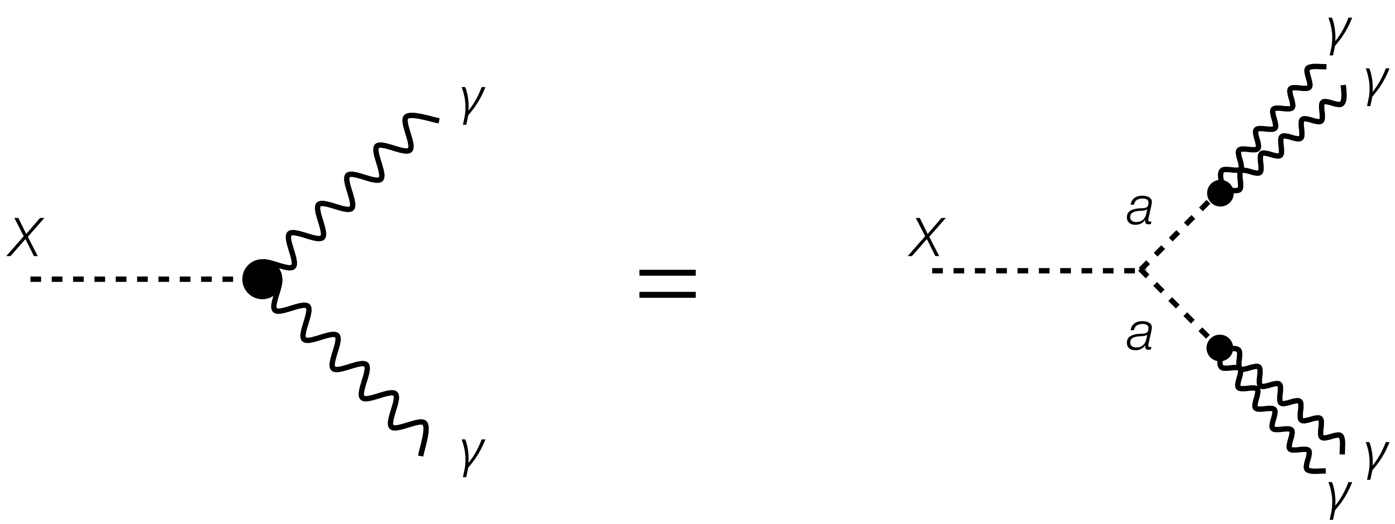


OR

- 

  exp resolution ~ 10 GeV
  $\Gamma = 0.06\ M \approx 45$ GeV

  $M_i^2 = M^2 + O(v^2)$
  $\Delta M_i \sim v^2/2M \approx$ 20 GeV

- 

  $m_a \ll M \rightarrow \gamma\gamma \sim \gamma$

  - width large because of tree level $X \rightarrow aa$
  - signal large because of tree level $X \rightarrow aa$
  - $\Gamma(a \rightarrow \gamma\gamma)$ “only” affects lifetime of a

Knapen Melia Papucci Zurek 1512.04928
Agrawal Fan Heidenreich Reece Strassler 1512.05775
Chang Cheung Lu 1512.06671
Bi et al.1512.08497

X → aa → 4γ

- Why $m_a \ll M$? ➔ a = pNGB of anomalous global U(1)

Aparicio Azatov Hardy R 1602.00949

$$\phi = \frac{f + s}{\sqrt{2}}\, e^{ia/f} \qquad \Gamma(s \to aa) = \frac{M^3}{32\pi f^2}$$

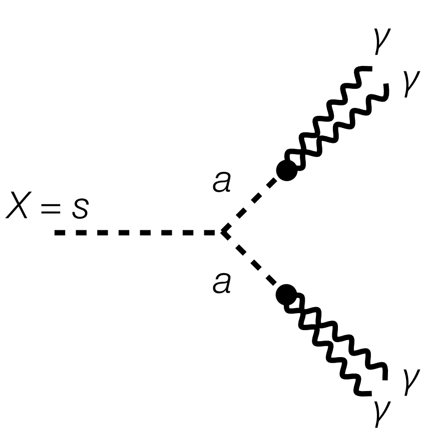
$$|D_\mu \phi|^2 \to \frac{s}{f}(\partial_\mu a)^2 \qquad \Gamma(a \to \gamma\gamma) = \left(\frac{\alpha}{8\pi f}\right)^2 \frac{m_a^3}{\pi}(Q^2 N)^2$$

f ⬌ U(1) breaking

Γ = 45 GeV ⬌ f ≈ 300 GeV

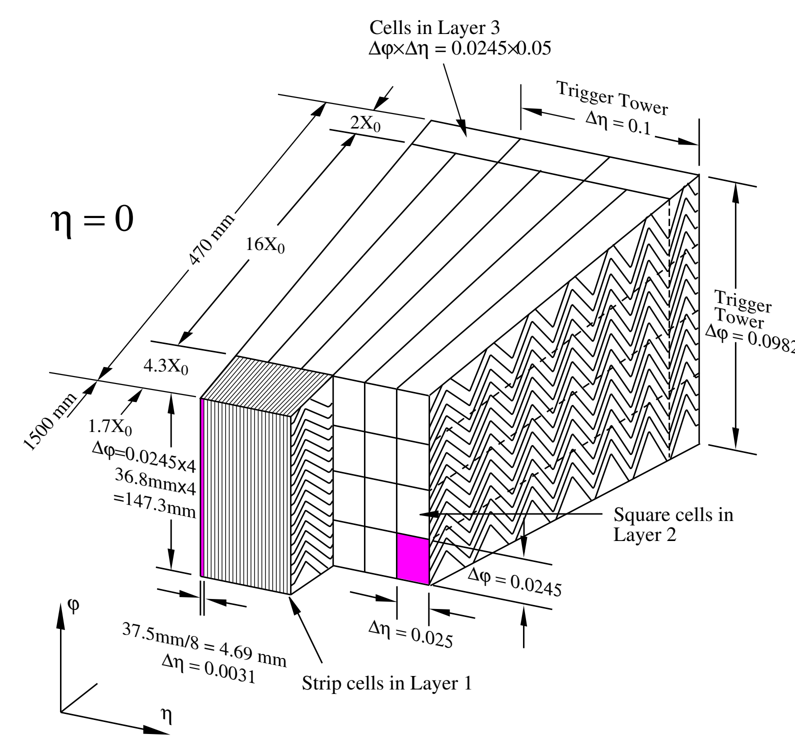
- $m_a \lesssim 0.2$ GeV + $L_{lab} \lesssim 0.6$ ➔ need $\sqrt{N}Q \gtrsim 4\left(\frac{0.2\,\text{GeV}}{m_a}\right)$

Caveat:
mixing with π
$m_a \approx m_\pi$



Δη = 0.0031

d ≈ 1.3 m



Prediction:
NO jj, γZ, ZZ, WW

Discrimination:
photon conversion
(depends on lifetime)
1602.04692

Narrow width

- Smallest $\Gamma_{\gamma\gamma}$ for i) gg production ii) dominant Γ_{gg}
  $\Gamma_{\gamma\gamma}/M \approx 0.5\ 10^{-6}$ ➔ $\Gamma/M \lesssim 10^{-3}$
- Then 

($\phi \neq$ SM fields)
- Extra charged, colored degrees of freedom! → talk by Dario Buttazzo
  - Who ordered those as well?

Who ordered X? And ϕ?

- Supersymmetry: SM ↔ $\widetilde{\text{SM}}$ $\tilde{m} > m$

- Spontaneously broken through $X = M + \frac{s + ia}{\sqrt{2}} + \theta\psi + F\theta^2$

breaks supersymmetry

sgoldstino $m = \tilde{m}$

goldstino $m = 0$ eaten by gravitino

- Gauginos (and sfermions) get mass by coupling to X

$$\frac{M_a}{2F}\int d^2\theta\, X W_a^{\alpha} W_{\alpha}^{a} = \frac{M_a}{2}\lambda_a\lambda_a + \frac{M_a}{2\sqrt{2}F}\left(s\, v_a^{\mu\nu} v_{\mu\nu}^{a} - a\, v_a^{\mu\nu}\tilde{v}_{\mu\nu}^{a}\right) + \dots$$

Bellazzini Franceschini Sala Serra 1512.05330
Petersson Torre 1512.05333
Demidov Gorbunov 1512.05723
Casas Espinosa Moreno 1512.07895

UV completion?

- W = λ X $\phi\,\bar{\phi}$ (minimal gauge mediation)

  Baratella Elias-Miro Penedo R 1603.05682
  Bardhan Byakti Ghosh Sharma 1603.05251

  - couple F to gluino and photino
  - couple s to gluon and photon

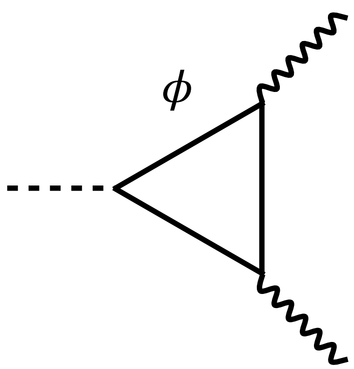
- Numbers: $$\Gamma(s \to \gamma\gamma) = \frac{M_s^3 M_\gamma^2}{32\pi F^2} \qquad M_\gamma = c_W^2 M_1 + s_W^2 M_2$$

$$\sqrt{F} \lesssim 5\,\mathrm{TeV}\left(\frac{M_\gamma}{200\,\mathrm{GeV}}\right)^{1/2}\left(\frac{4\,\mathrm{fb}}{\sigma_{\gamma\gamma}}\right)^{1/4}$$

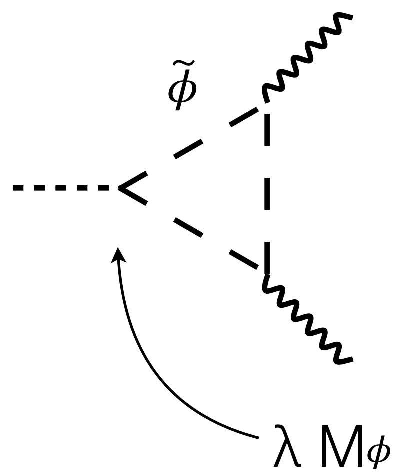
- On the other hand: $$M_3 = \frac{\alpha_3}{4\pi} N_3 \frac{F}{M} \quad \to \quad \lambda N_\gamma N_3 \gtrsim 1500 \frac{M_3}{\mathrm{TeV}}\left(\frac{\sigma_{\gamma\gamma}}{4\,\mathrm{fb}}\right)^{1/2}$$

However

- $M_\phi = \lambda M$



$m_\pm^2 = M_\phi^2 \pm \lambda F$ $\quad M_\phi > \sqrt{\lambda F}$



$$g_{\rm eff} = \frac{\lambda M_\phi}{m_-}$$

non-perturbative
near the critical point

Veneziano NPB44 (1972)

$M_\phi \approx \sqrt{\lambda F}$

(10-100) TeV —— $\phi, \ \tilde{\phi}_+$

2 gains
- loop suppressed by O(TeV)
- coupling enhanced by $g_{\rm eff}$

O(TeV) —— $s, \ \tilde{\phi}_-, \ \tilde{g}$

Baratella Elias-Miro Penedo R 1603.05682

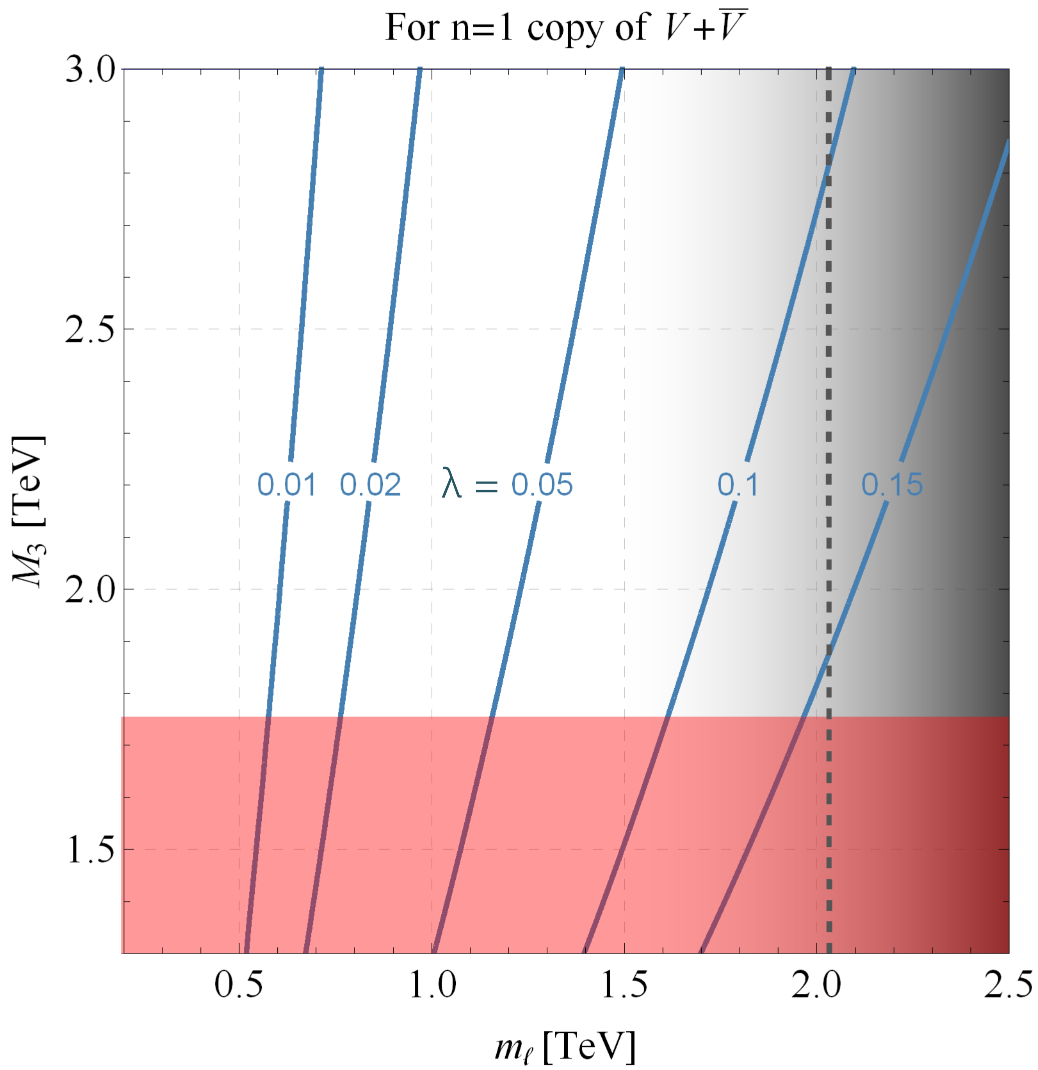
- Supersymmetric effective description fails: $\lambda M \approx F$
- Fine-tuning ~ $(g_{eff}/\lambda)^2$
- For $g_{eff} \sim 4\pi$, ϕ_- bound states can form (and mix with s)
- IR non-perturbativity - does not spoil nice UV properties of supersymmetry
- M ~ 100 TeV, as previously argued
- Sfermions heavier than O(TeV) (tree-level) if X has $U(1)_X$ charge

Example

- $\phi + \overline{\phi}$ ~ (3, 2, -5/6) + ($\overline{3}$, 2, -5/6)   from Σ SU(5) adjoint

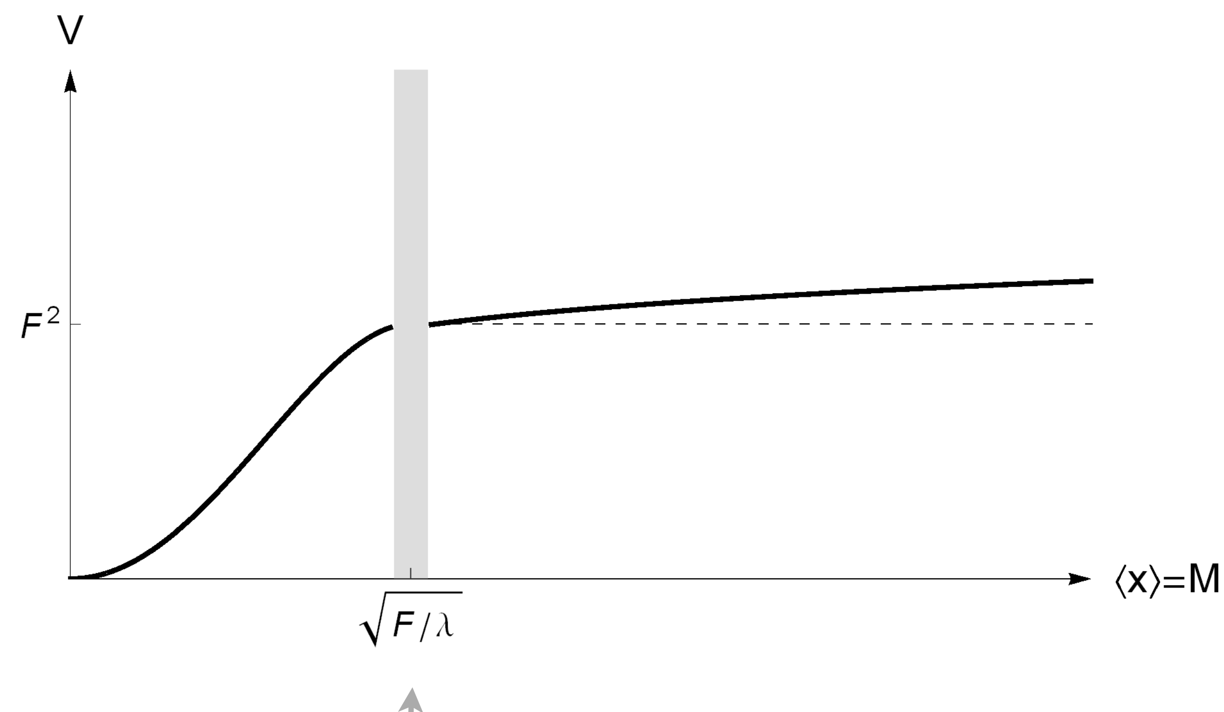
- N = 5 (barely UV perturbative)

$$\frac{\Gamma_{ZZ}}{\Gamma_{\gamma\gamma}} \approx 1.3 \qquad \frac{\Gamma_{Z\gamma}}{\Gamma_{\gamma\gamma}} \approx 0 \qquad \frac{\Gamma_{WW}}{\Gamma_{\gamma\gamma}} \approx 2.8$$



Wild speculations

$$W = W_{\rm MSSM} + \lambda X \phi \bar{\phi} + F X$$



$$\frac{|\lambda M^2 - F|}{F} \lesssim \frac{1}{(4\pi)^2}$$

(and an R-axion with m_a = O(0.1 GeV)…)

Conclusions

- The LHC has confirmed what we thought about the Higgs
- Has provided a puzzle to solve: where is everybody else
- And, IF the diphoton excess turns into a new resonance, an unexpected twist
    - whose interpretation would be tremendously exciting
    - which could be the first of a series of new discoveries