BSM round-up

Riccardo Rattazzi, EPFL

Annual Theory Christmas Meeting, 2015, IPPP Durham

Weak Scale Naturalness:

Ideology, Ingenuity & Reality

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In QM whatever is *possible* is also *compulsory*

selection rules

$$\mathcal{O} = \sum_i \mathcal{O}_i \qquad \underbrace{\mathcal{O}_i}_{\dim\,=\,\Delta} = c_i \underbrace{\lambda_1^{n_{1i}} \ldots \lambda_k^{n_{ki}}}_{\dim\,=\,\Delta}$$

If $\mathcal{O}|_{\mathrm{exp}} \ll \max|\mathcal{O}_i|$ it seems we are missing something

Un-Naturalness = failure of dimensional analysis and selection rules

Mass Hierarchies

Λ_{UV}

$\sim$ scale invariant dynamics

$\mathcal{L} \sim$ fixed point of RG

Λ_{IR}

Naturalness of $\Lambda_{IR} \ll \Lambda_{UV}$ $\Leftrightarrow$ stability of fixed point

3 options

1. Marginality

Λ_{UV}

the fixed point theory does not possess scalar operators with dimension strictly less than 4

Λ_{IR}

$$\mathcal{L}_{\rm mass} = c\,\Lambda_{UV}^{\epsilon}\,\mathcal{O}_{4-\epsilon}$$

$$\Lambda_{IR}^{\epsilon} = c\,\Lambda_{UV}^{\epsilon} \qquad\qquad \Lambda_{IR} = c^{1/\epsilon}\,\Lambda_{UV}$$

algebraically small c and ϵ is enough to produce hierarchy

Ex: Yang-Mills, TechniColor, Randall-Sundrum model

Rattazzi, Zaffaroni 01
Strassler 03

2. Symmetry

Λ_{UV}

$$\mathcal{L}_{\rm mass} = \underbrace{\epsilon}_{\text{small parameter protected by symmetry}} \Lambda_{UV}^2 \, \mathcal{O}_2$$

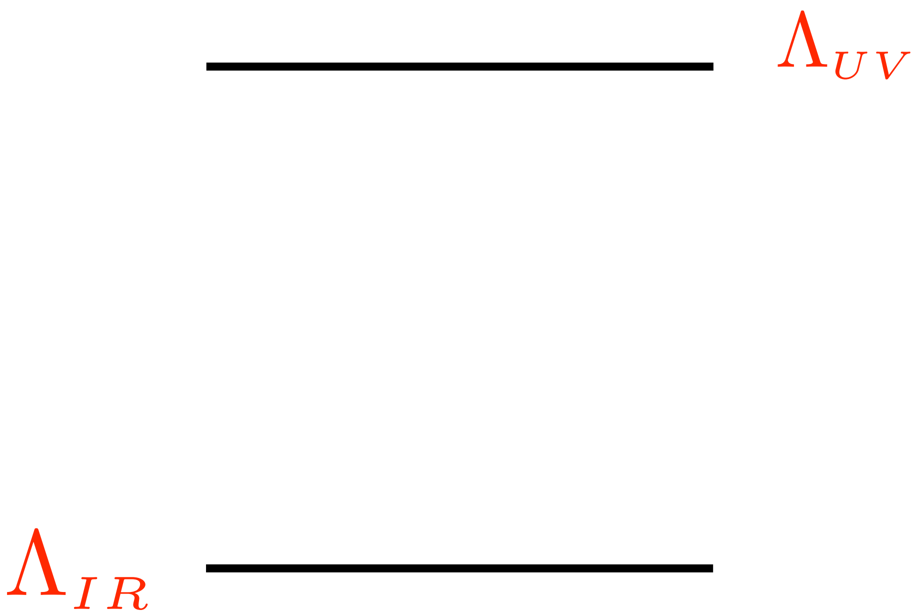
Λ_{IR}

$$\Lambda_{IR} = \sqrt{\epsilon}\,\Lambda_{UV}$$

- ϵ must be *hierarchically* small
- how does this smallness originate?

Ex: QCD, Supersymmetry

3. Sequestering



3. Sequestering

Λ_{UV}

Λ_{IR}

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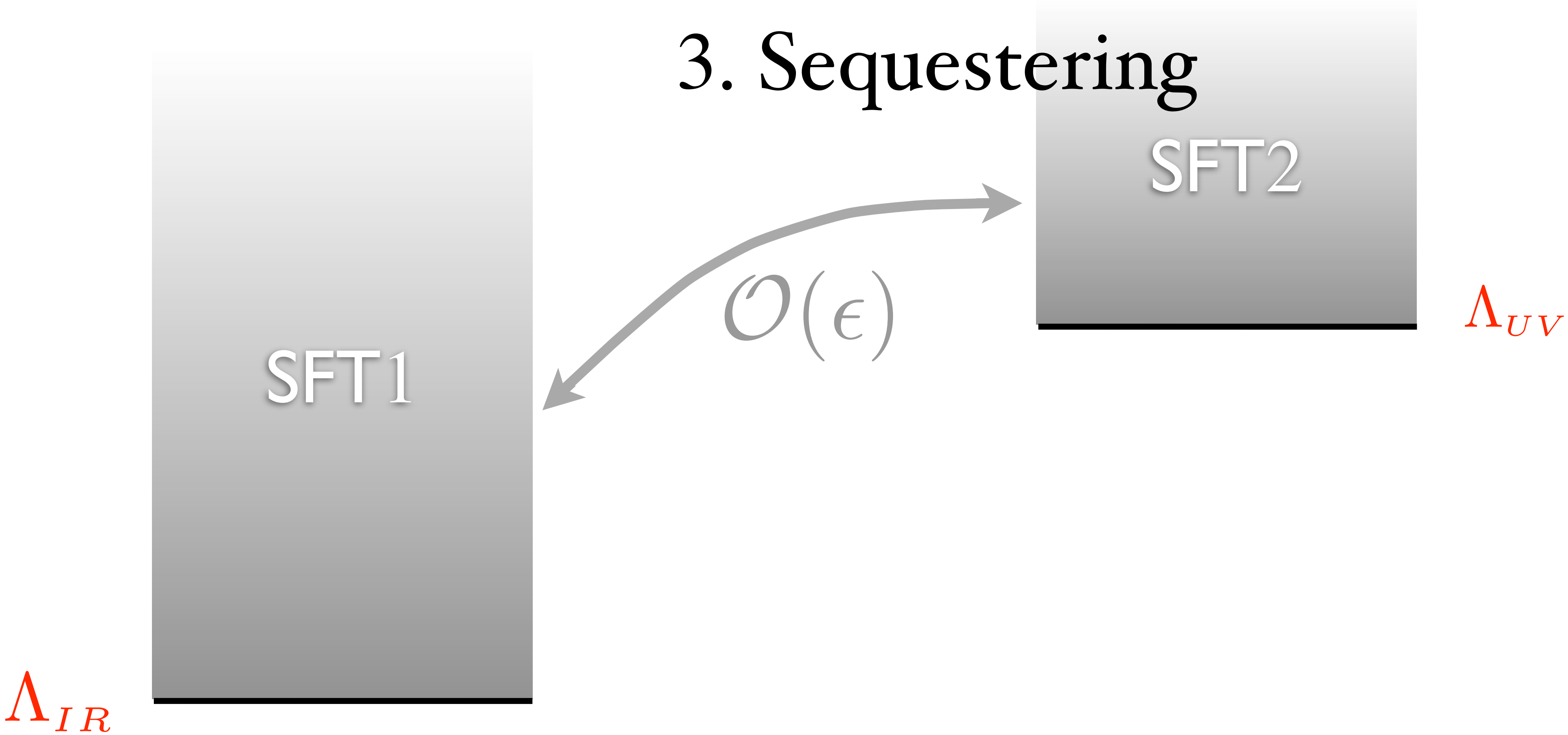

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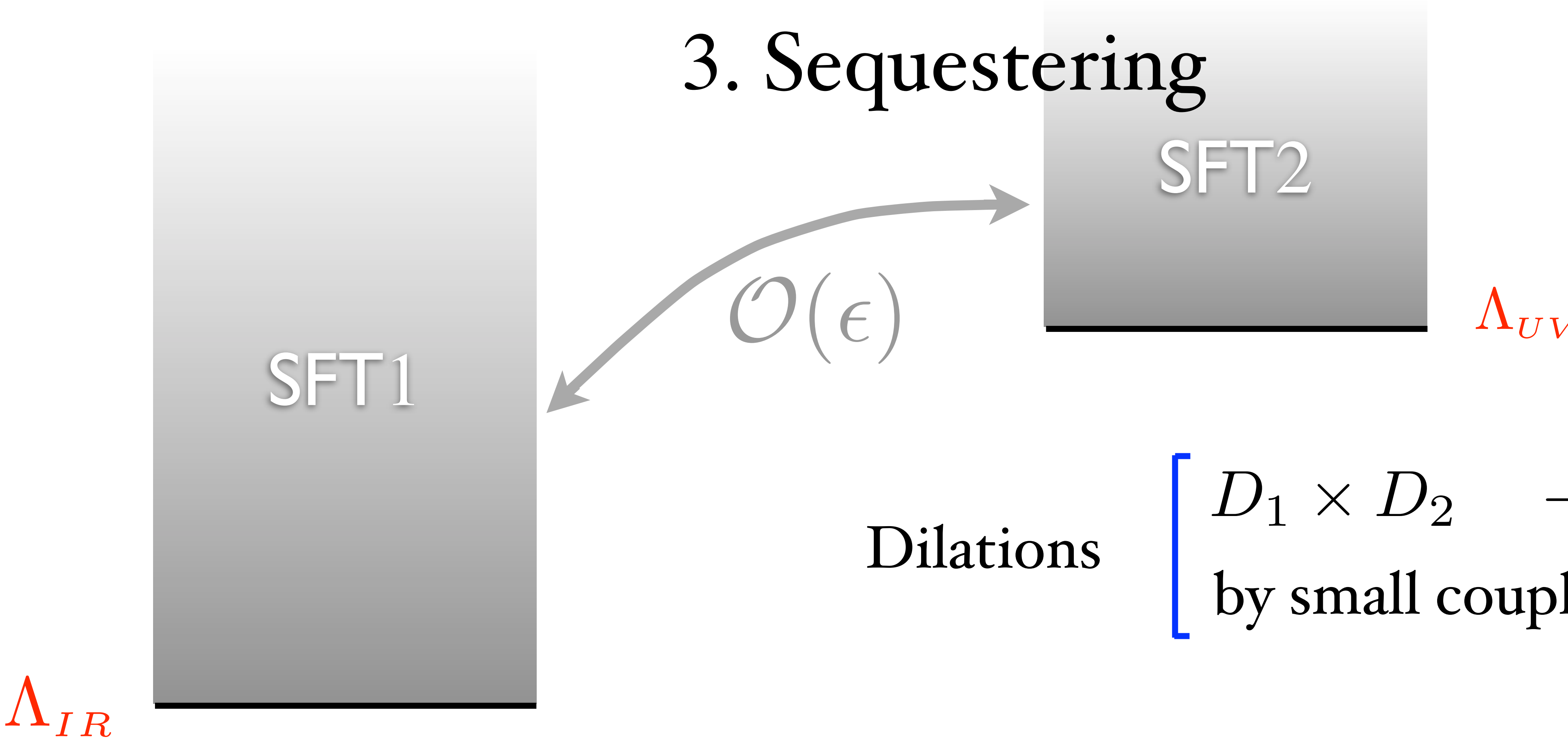
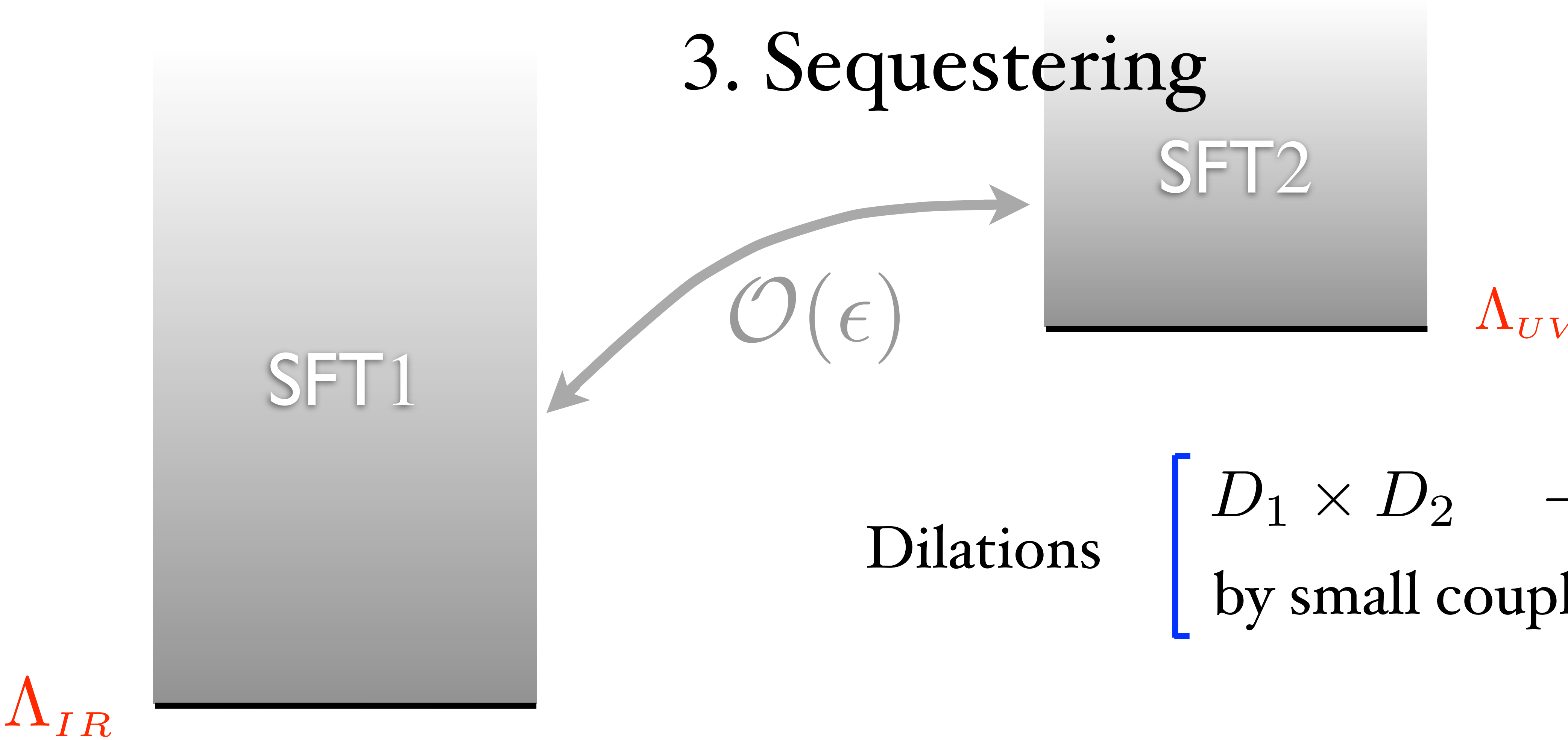


Dilations $\left[\begin{array}{l} D_1 \times D_2 \quad \rightarrow \quad D_{1+2} \\ \text{by small coupling} \quad \epsilon \end{array}\right.$

$\Lambda_{IR} \sim \epsilon\, \Lambda_{UV}$ technically natural

3. Sequestering



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$\Lambda_{IR} \sim \epsilon\, \Lambda_{UV}$ technically natural

- SFT2 = ‘UV completion of gravity’ $\epsilon = \Lambda_{UV}/M_P$

Ex. a-gravity

Salvio, Strumia 2012

- not clearly compatible with basic principles
- but imagine there was a gorgeous candidate for SFT1?

....well there isn’t: Giudice, Isidori, Salvio, Strumia 2014

The Standard Model

Λ_{UV}

$\Lambda_{IR} \sim m_W$

$\mathcal{L}_{SM} \sim \mathcal{L}_{free} \equiv$ fixed point

$H^\dagger H \equiv$ relevant and unprotected

Naturalness demands not too large Λ_{UV}

How large Λ_{UV} can we tolerate compatibly with Naturalness?

What can we broadly say about the physics at Λ_{UV} ?

But notice:

a seemingly un-natural hierarchy $\Lambda_{UV} \gg m_W$ offers a remarkable bonus

$$\mathcal{L}_{SM} = \boxed{\mathcal{L}^{(d\leq 4)}} + \frac{1}{\Lambda_{UV}}\mathcal{L}^{(5)} + \frac{1}{\Lambda_{UV}^2}\mathcal{L}^{(6)} + \ldots$$

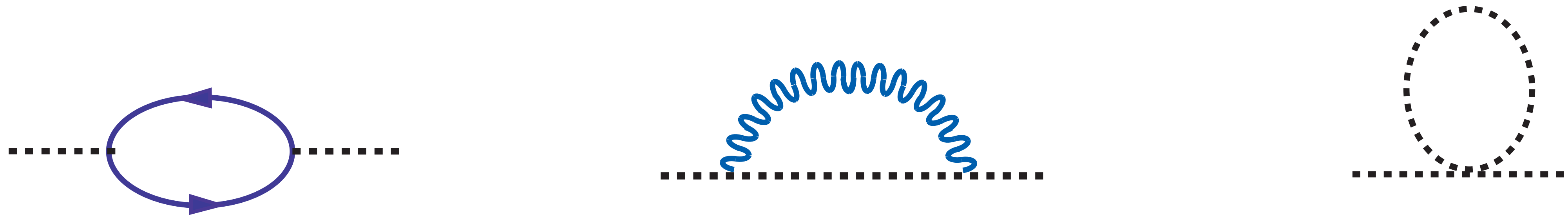
- *Accidentally* possesses all the symmetries we observe in Nature: B, L, Flavor,...
- Not the case in any natural completion of the SM, where we have to resort to extra *ad hoc* assumptions

Λ_{UV}

$\Lambda_{IR} \sim m_W$

How large Λ_{UV} can we tolerate compatibly with Naturalness?

What can we broadly say about the physics at Λ_{UV} ?



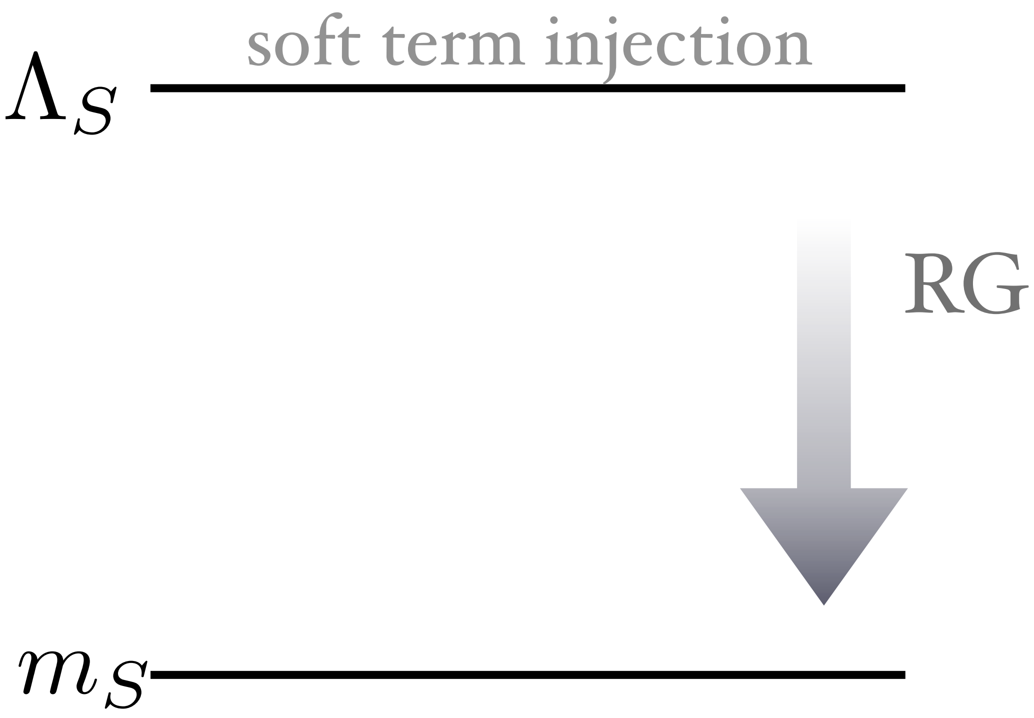
$$\delta m_h^2 \;=\; \frac{3y_t^2}{4\pi^2}\,\Lambda_t^2 - \frac{9g^2}{32\pi^2}\,\Lambda_g^2 - \frac{3g'^2}{32\pi^2}\,\Lambda_{g'}^2 + \ldots$$

$$\Lambda_t \,<\, 0.45\sqrt{\frac{1}{\epsilon}}\ \mathrm{TeV} \qquad \Lambda_g \,<\, 1.1\sqrt{\frac{1}{\epsilon}}\ \mathrm{TeV} \qquad \Lambda_{g'} \,<\, 3.7\sqrt{\frac{1}{\epsilon}}\ \mathrm{TeV}$$

Ingenuity

- ***soft models***
  high scale susy breaking, eg. SUGRA
- ***supersoft models***
  composite Higgs, low scale susy breaking,...
- ***hypersoft models***
  neutral naturalness: twin Higgs, ...

Soft Models: MSSM (and variants) with high scale mediation

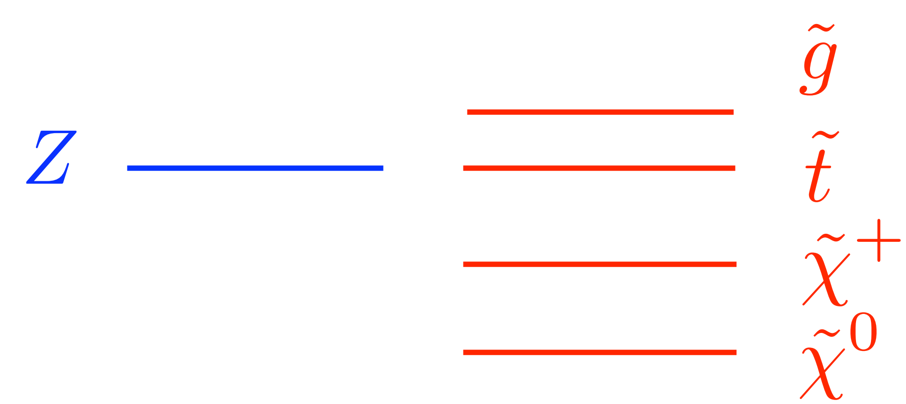


$$m_{\tilde g} \longrightarrow m_{\tilde t} \longleftrightarrow m_H$$

$$m_{\tilde g} \sim m_{\tilde t}$$

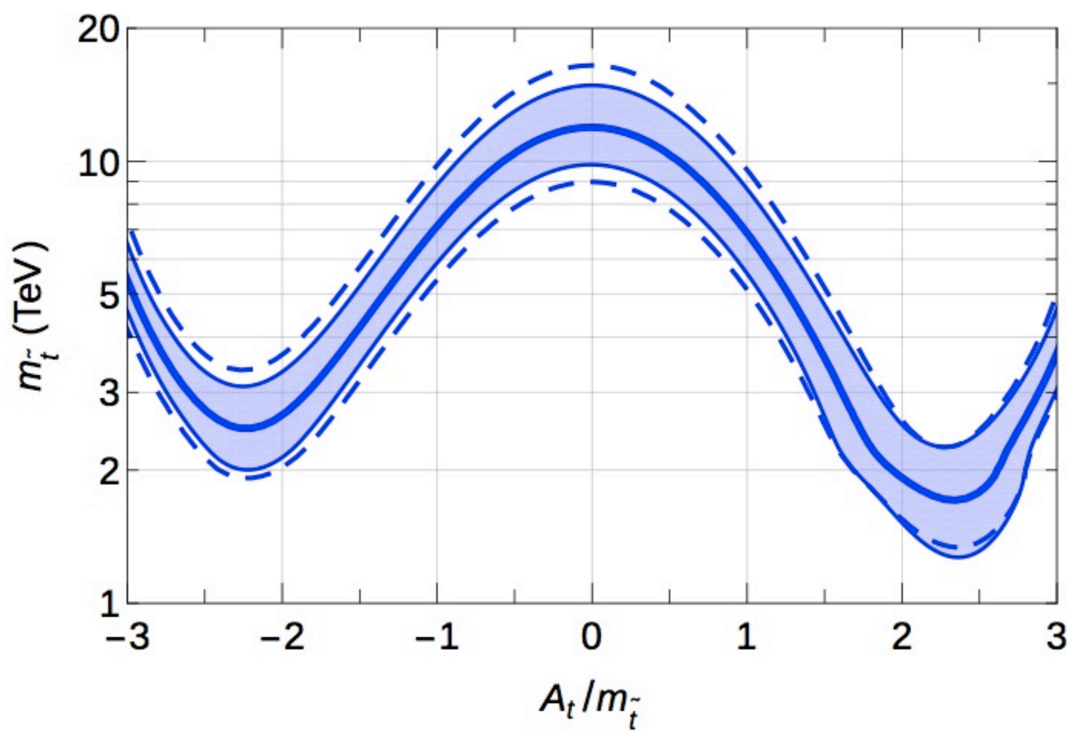
$$\delta m_h^2 \sim \frac{3y_t^2}{4\pi^2} \times \ln \frac{\Lambda_S}{m_S} \times m_{\tilde t}^2 \sim m_{\tilde t}^2$$

LEP scale SUSY expected

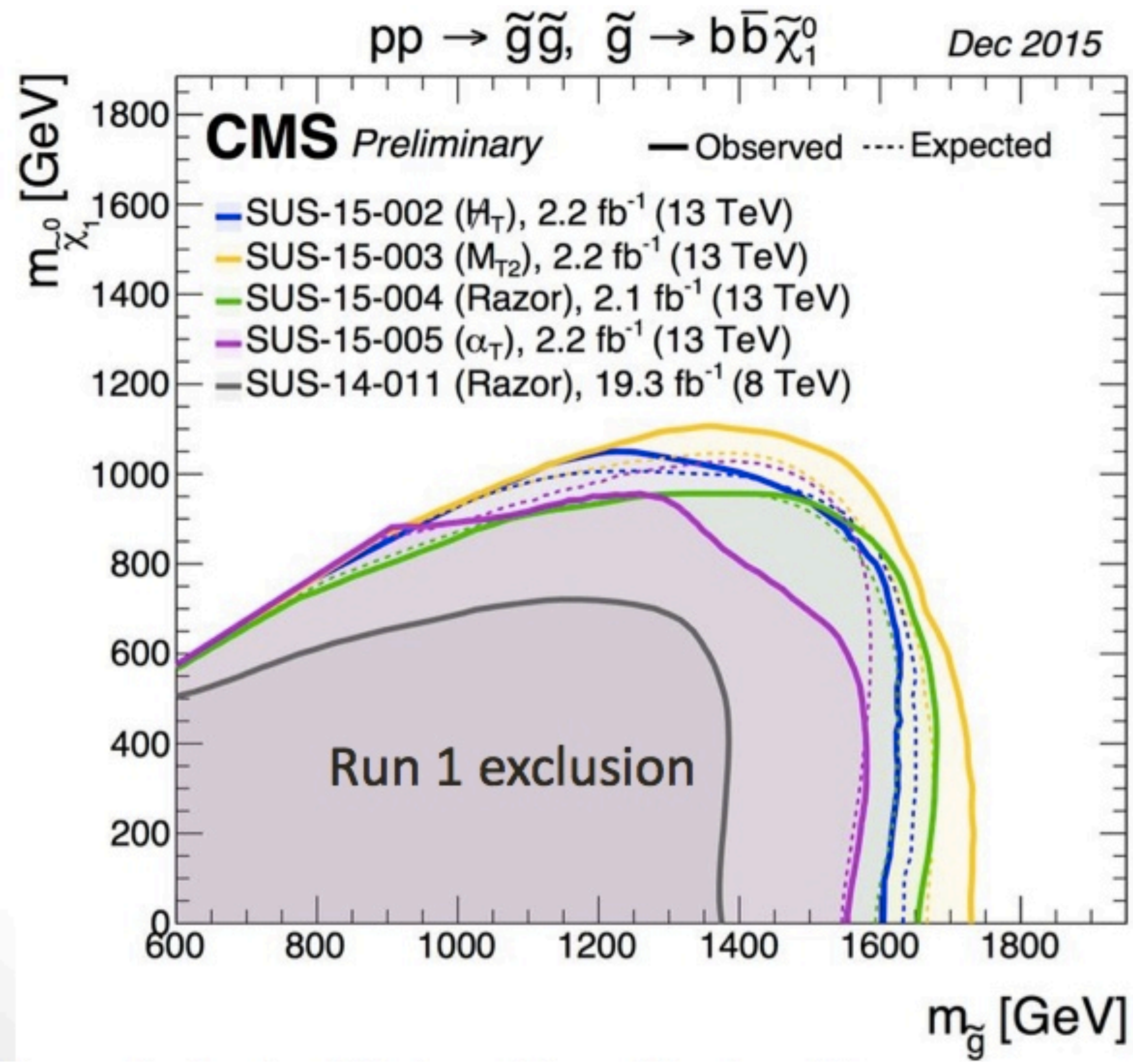


with O(ϵ) tuning

$$\boxed{m_{\tilde t}^2 \sim \frac{m_h^2}{\epsilon}}$$



125 GeV Higgs, within MSSM
pushes stops above TeV



direct bounds similarly imply
tuning to better than 1%

SuperSoft Models

low scale mediation

Λ_S

m_S

$$\delta m_h^2 \sim \frac{3y_t^2}{4\pi^2}\, m_{\tilde t}^2$$

roughly LHC scale SUSY expected

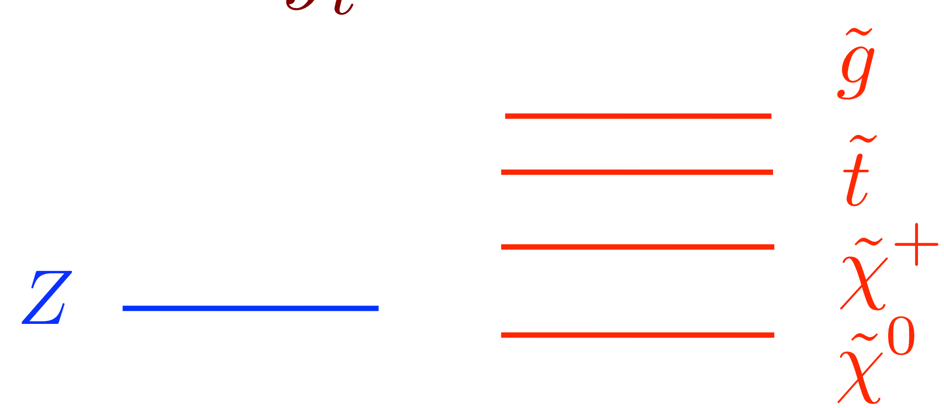
Dirac gauginos

Λ_S

$$\cancel{m_{\tilde g} \longleftrightarrow m_{\tilde t}} \longleftrightarrow m_H$$

m_S

$$m_{\tilde t}^2 \sim \frac{4\pi^2}{3y_t^2}\frac{m_h^2}{\epsilon}$$



SuperSoft Models

low scale mediation

Dirac gauginos

Λ_S

$\cancel{m_{\tilde g} \longleftrightarrow m_{\tilde t}} \longleftrightarrow m_H$

Λ_S m_S

m_S

$$\delta m_h^2 \sim \frac{3y_t^2}{4\pi^2}\, m_{\tilde t}^2$$

$$m_{\tilde t}^2 \sim \frac{4\pi^2}{3y_t^2}\frac{m_h^2}{\epsilon}$$

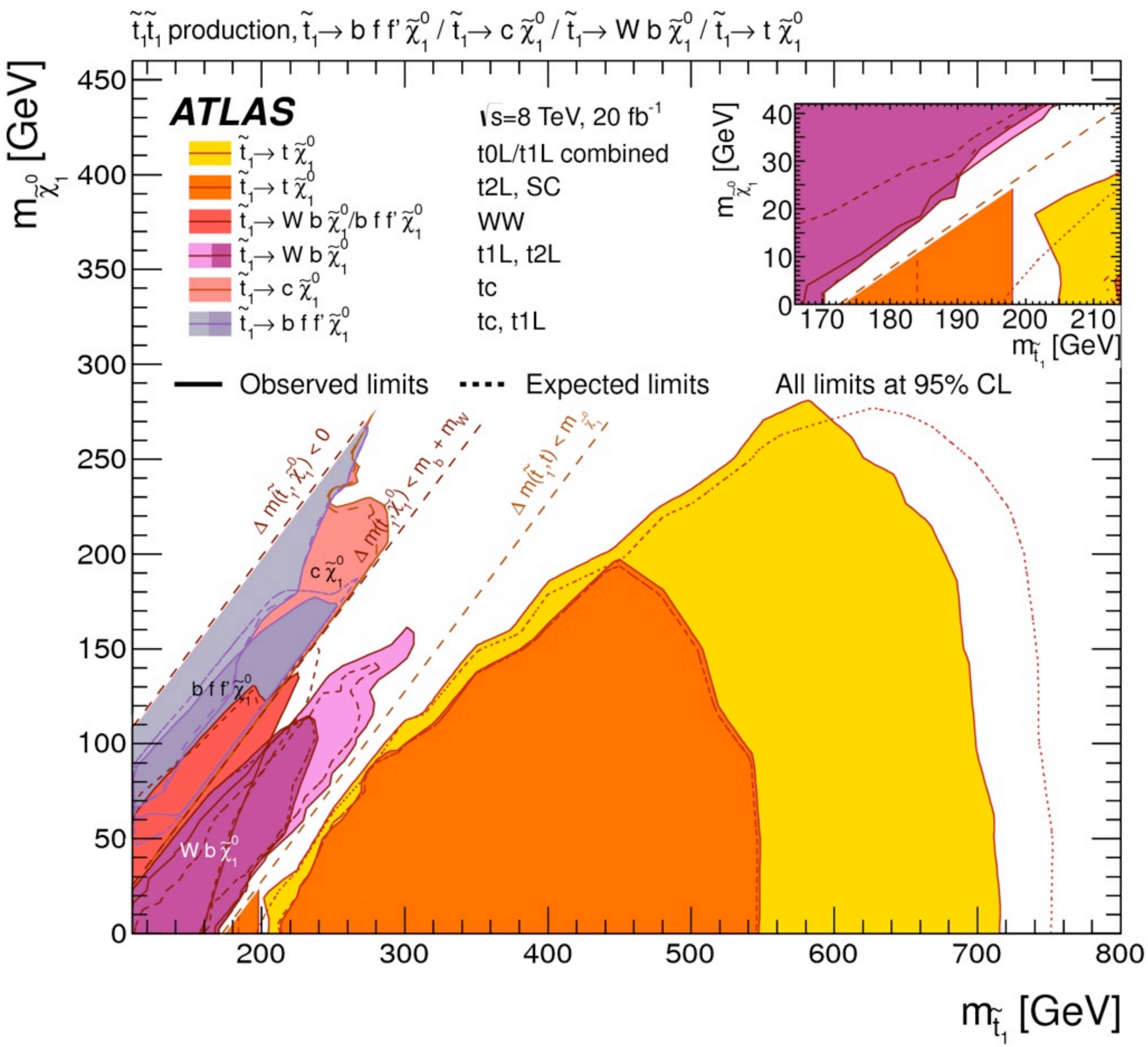
$\tilde g$

$\tilde t$

Z $\tilde\chi^+$

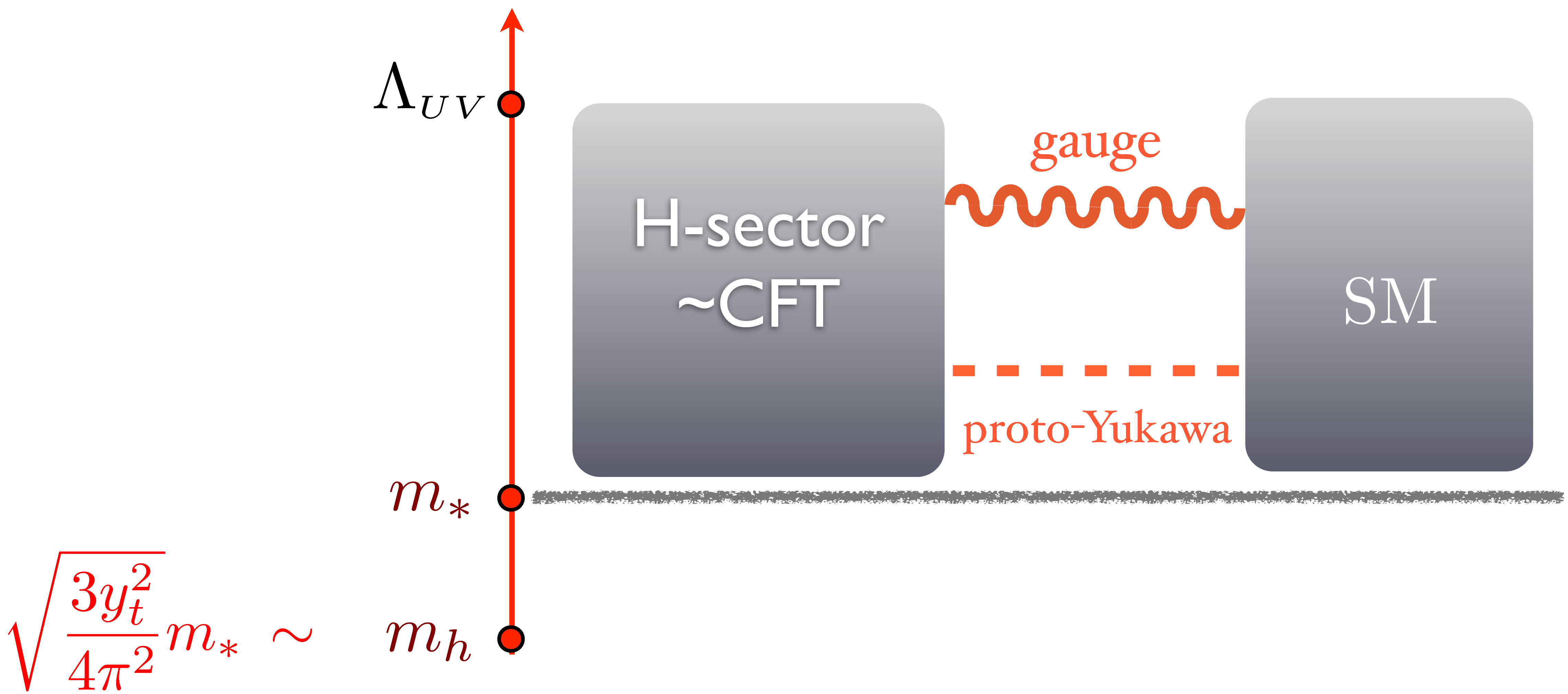
$\tilde\chi^0$

roughly LHC scale SUSY expected



already pressed by data, requiring tuning of order 10%

Modern Composite Higgs



H = composite pseudo-NGB from CFT symmetry broken by SM couplings

Simplest option $\quad H \in SO(5)/SO(4)$

Georgi, Kaplan '84
Arkani-Hamed, Cohen, Katz, Nelson '02
Agashe, Contino, Pomarol '04

- give up search for explicit gauge theory incarnations of CFT
- just characterize CFT in terms of the needed operator spectrum
- holographic realizations via warped compactifications do exist
- simplest option: low energy theory broadly described by 2 parameters

Giudice, Grojean, Pomarol, RR, 2007

$$\left[\begin{array}{ll} m_* & \text{resonance mass scale} \\ g_* & \text{overall coupling} \end{array}\right.$$

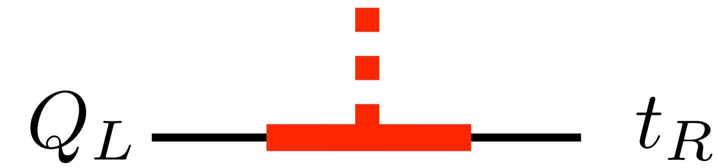
large N
$$\left[\begin{array}{l} g_* \sim \dfrac{4\pi}{\sqrt{N}} \\ f \sim \dfrac{m_*}{g_*} \sim \sqrt{N}\,\dfrac{m_*}{4\pi} \end{array}\right.$$
pseudo-NGB decay const

Measures of tuning

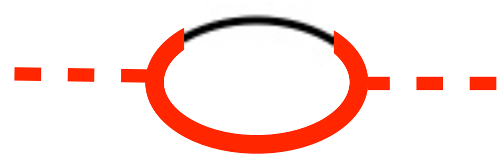
$$\boxed{\epsilon \sim \frac{v_F^2}{f^2} \sim \frac{4\pi^2}{3y_t^2}\,\frac{m_h^2}{m_*^2}}$$

Top mass and Higgs potential

$$\mathcal{L}_{mix} = y_L \bar{Q}_L \mathcal{O}_R + y_R \bar{t}_R \mathcal{O}_L$$



$$y_t \sim \frac{y_L y_R}{g_*}$$

$V(H) =$  $+ \dots$

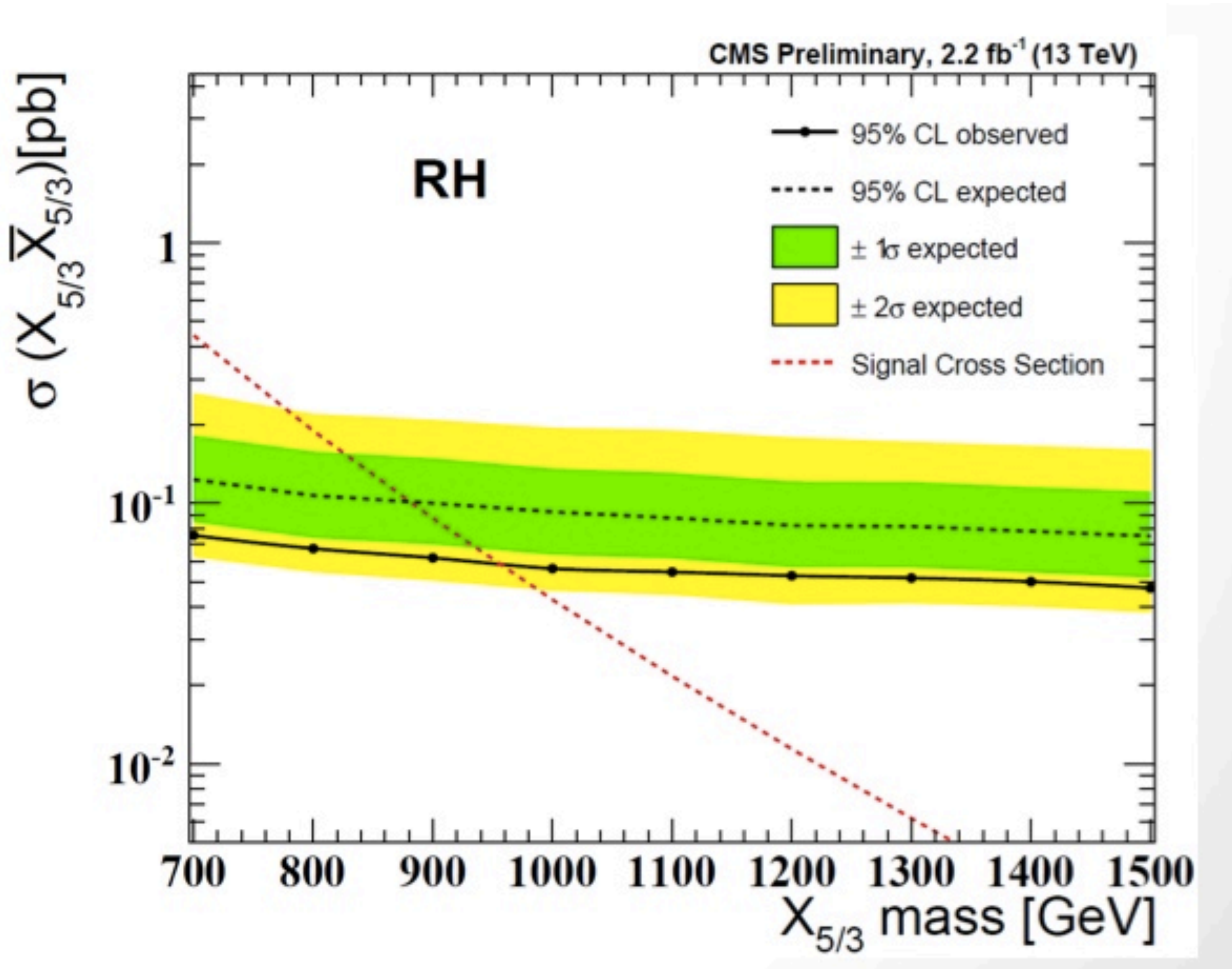
$$m_h^2 \sim \frac{3 y_t^2}{4\pi^2} m_*^2$$

$$|T\rangle \equiv \mathcal{O}_{L,R}|0\rangle$$

fermionic resonances with given q-numbers:
the Top Partners

$$\begin{pmatrix} T \\ B \end{pmatrix} \oplus \begin{pmatrix} X_{5/3} \\ T' \end{pmatrix}$$

Expected in the most plausible cases



$$m_X \gtrsim 950\,\mathrm{GeV}$$

but notice indirect bounds

EWPT	$m_* \gtrsim 2\,\mathrm{TeV}$
Flavor	$m_* \times g_* \gtrsim 5\,\mathrm{TeV}$

Hypersoft Models: Twin Higgs

Chacko, Goh, Harnik 2005

$$\mathrm{SM} \xleftrightarrow{\mathbb{Z}_2} \widetilde{\mathrm{SM}}$$

states with SM color and charge

$m_* \sim g_* f$

$\tilde{t}$ $\quad m_{\tilde{t}} \sim y_t f$

t

h

Λ_{QCD} $\quad \widetilde{\Lambda}_{QCD}$

if $\quad g_* \gg y_t$

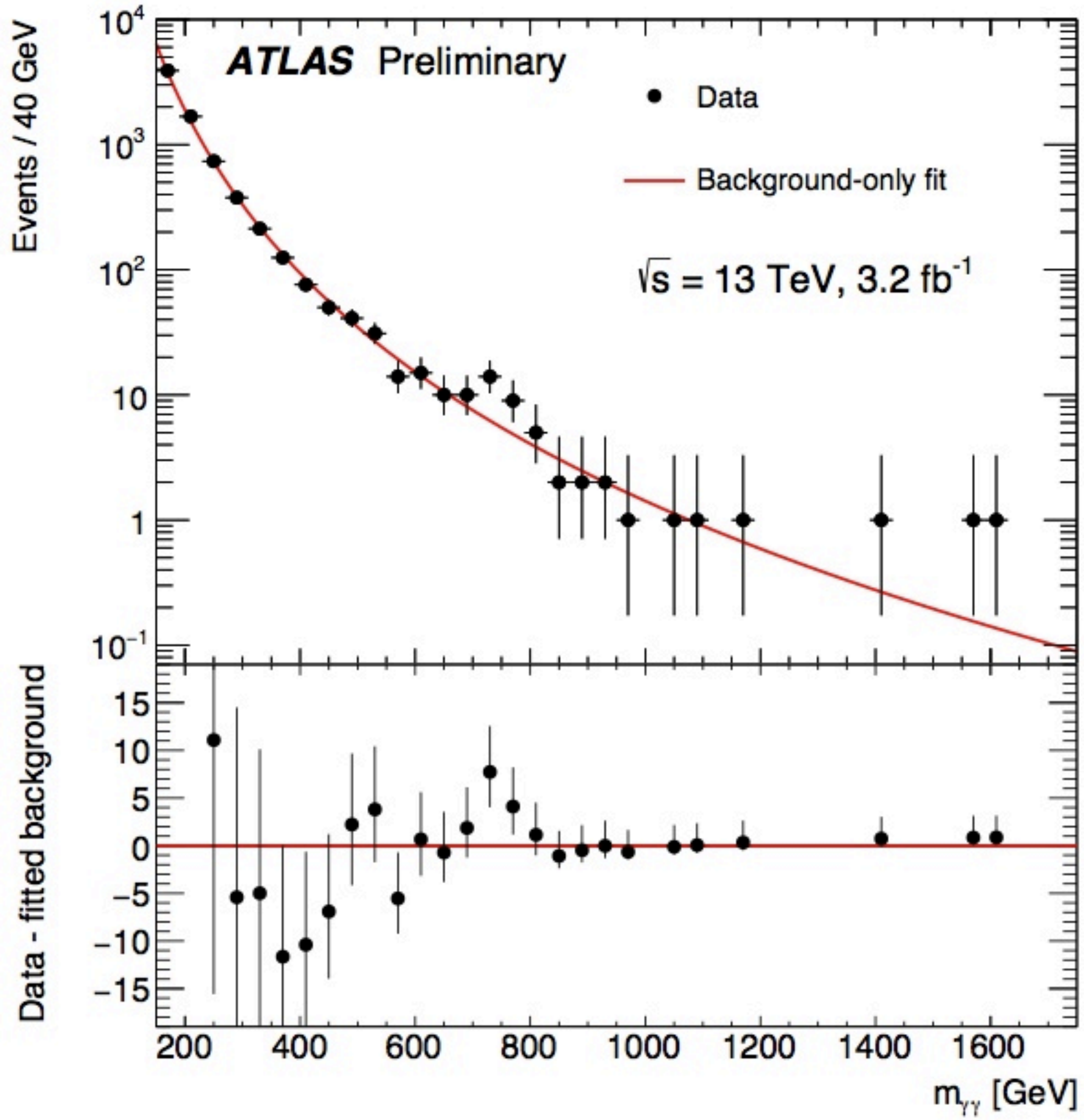
colored resonances outside LHC reach !!

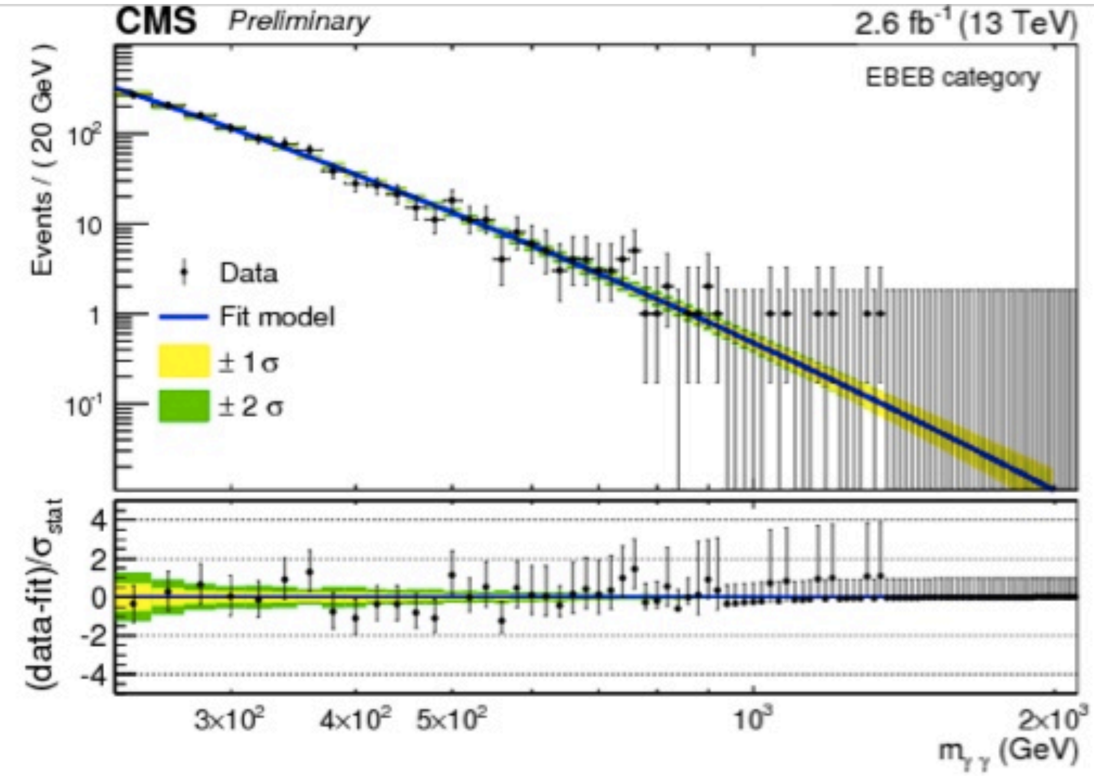
Contino, Greco, Mahbubani, RR to appear

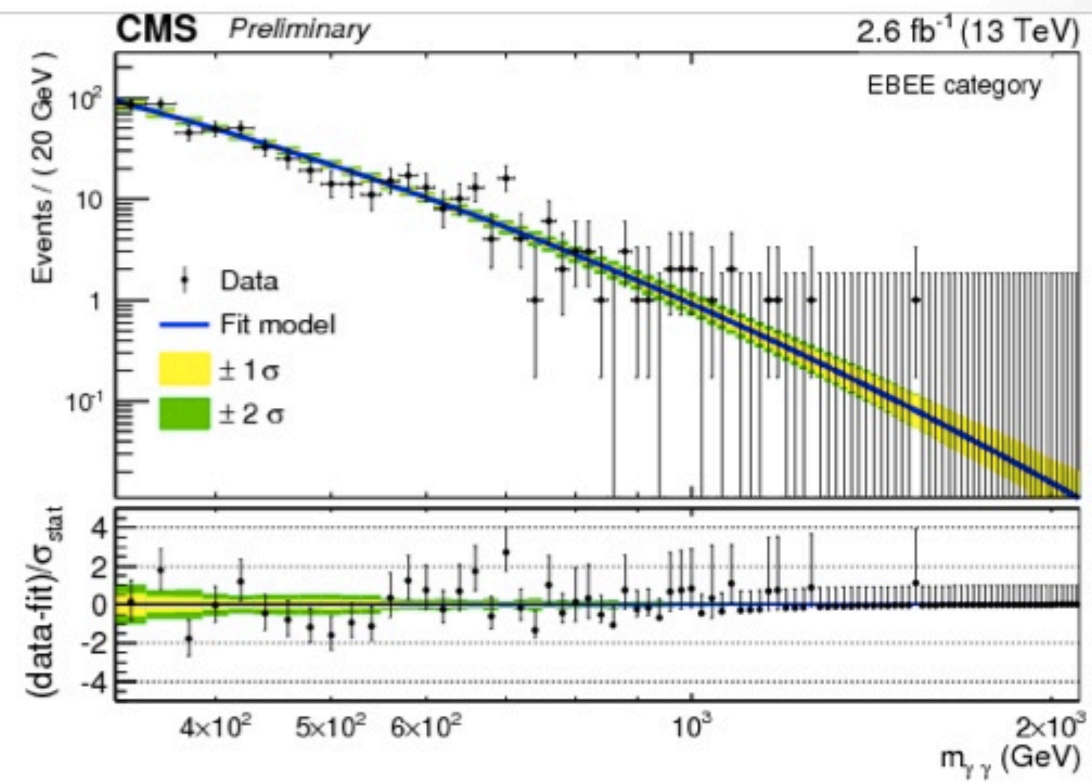
$\gamma\ \gamma$ at 750

arXiv:1512.04933

Roberto Franceschini, Gian F. Giudice, Jernej F. Kamenik, Matthew McCullough, Alex Pomarol, Riccardo Rattazzi, Michele Redi, Francesco Riva, Alessandro Strumia, Riccardo Torre


ATLAS Preliminary
Data
Background-only fit
√s = 13 TeV, 3.2 fb⁻¹
Events / 40 GeV
Data - fitted background
m_γγ [GeV]


CMS Preliminary
2.6 fb⁻¹ (13 TeV)
EBEB category
Data
Fit model
± 1σ
± 2 σ
Events / (20 GeV)
(data-fit)/σ_stat
m_γγ (GeV)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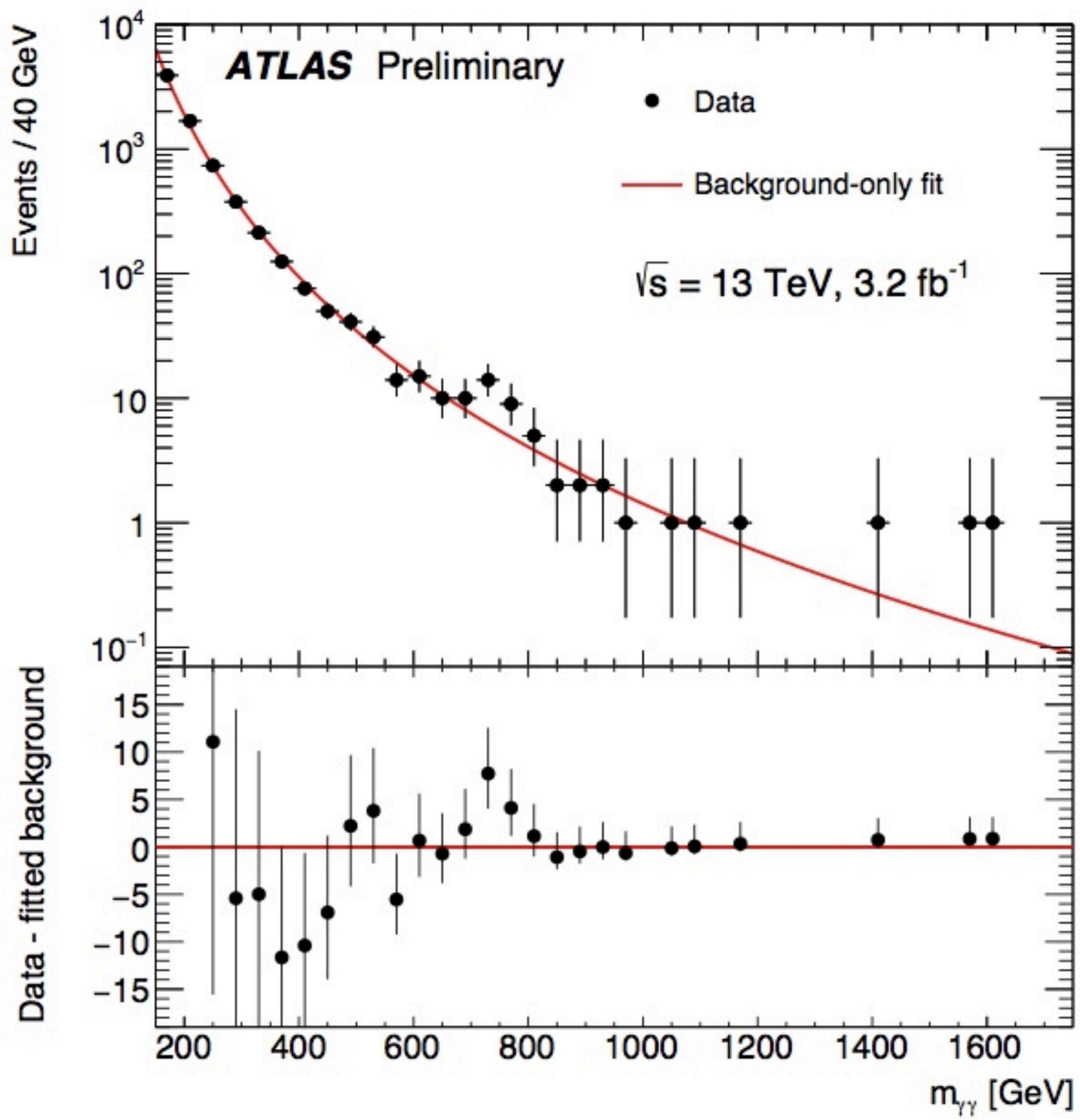
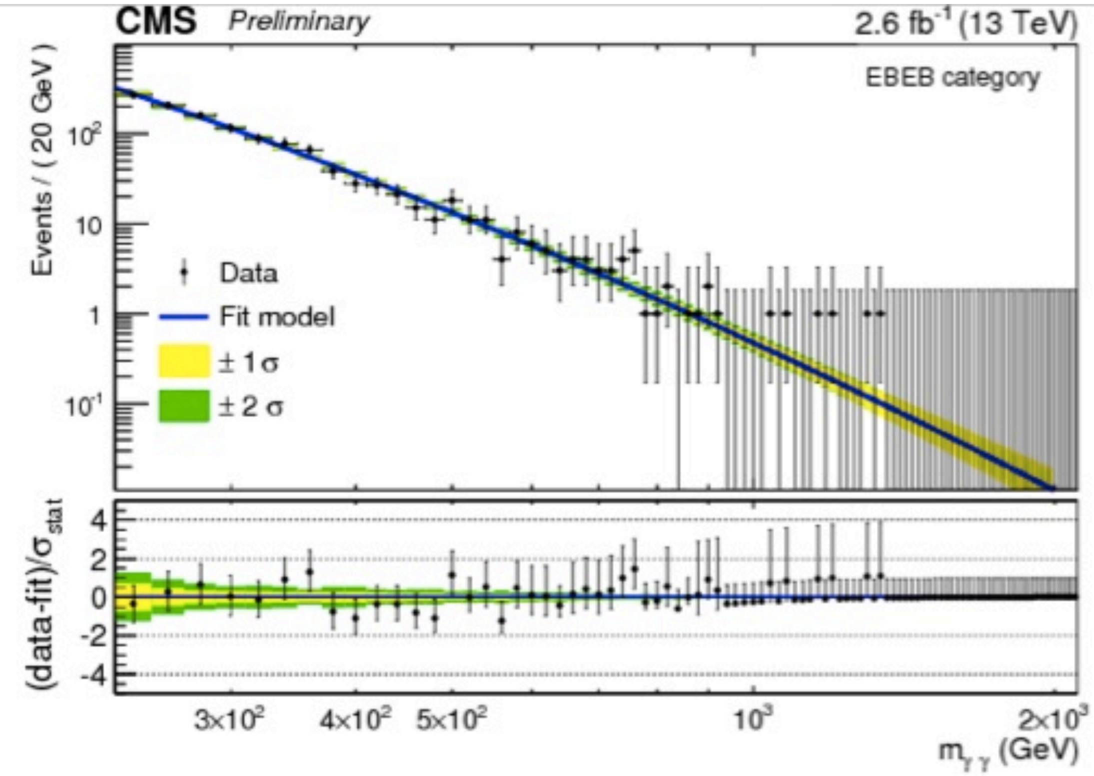
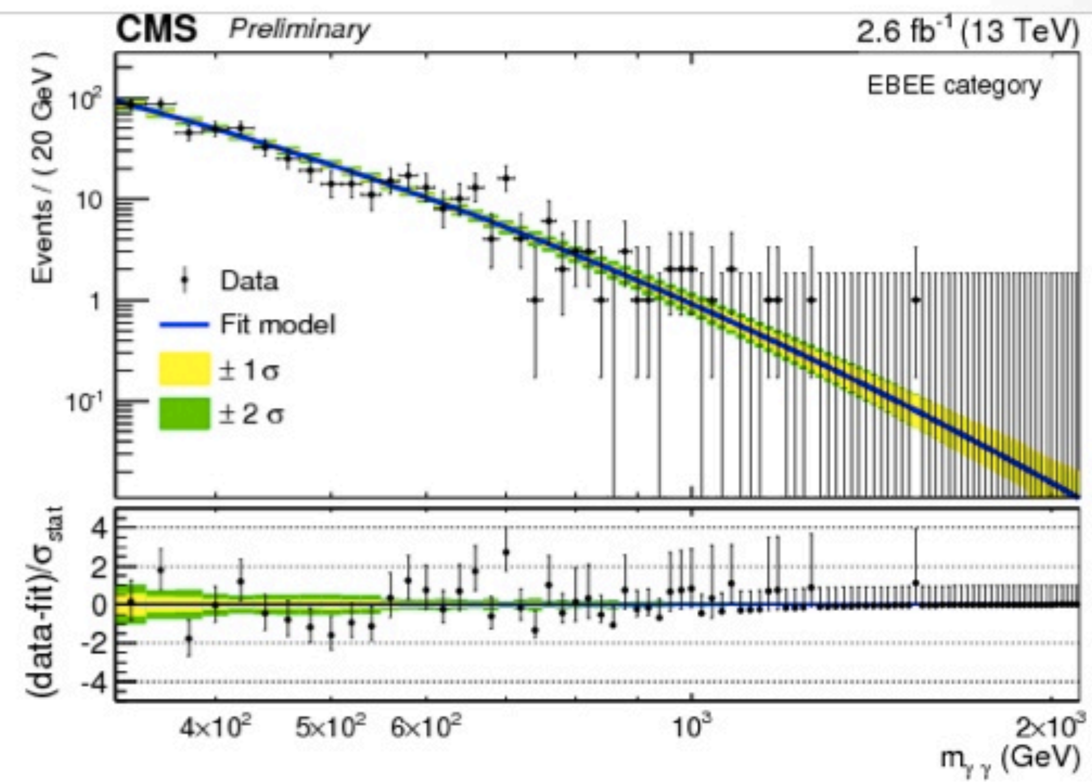
Subtle is the Lord?







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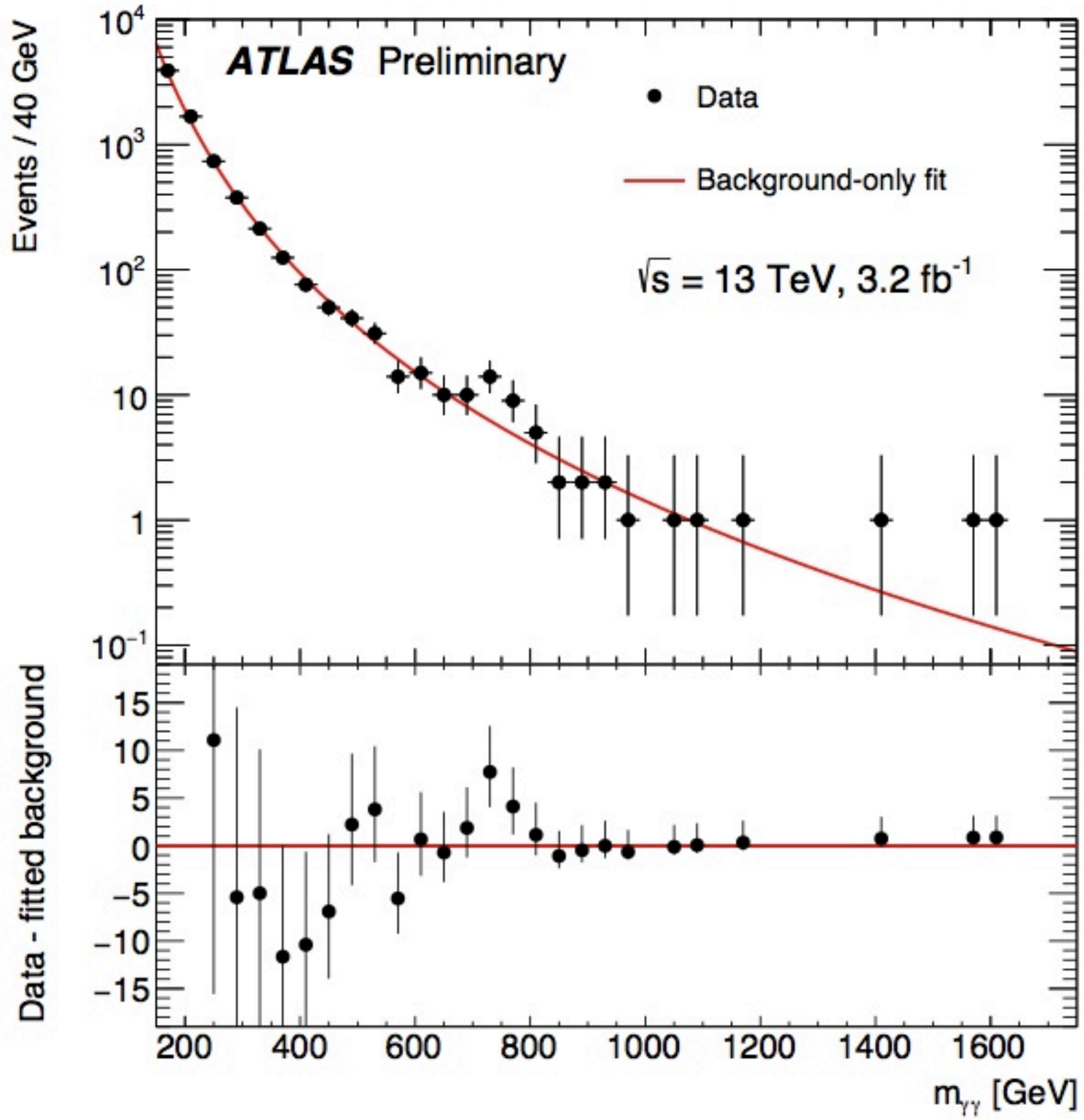
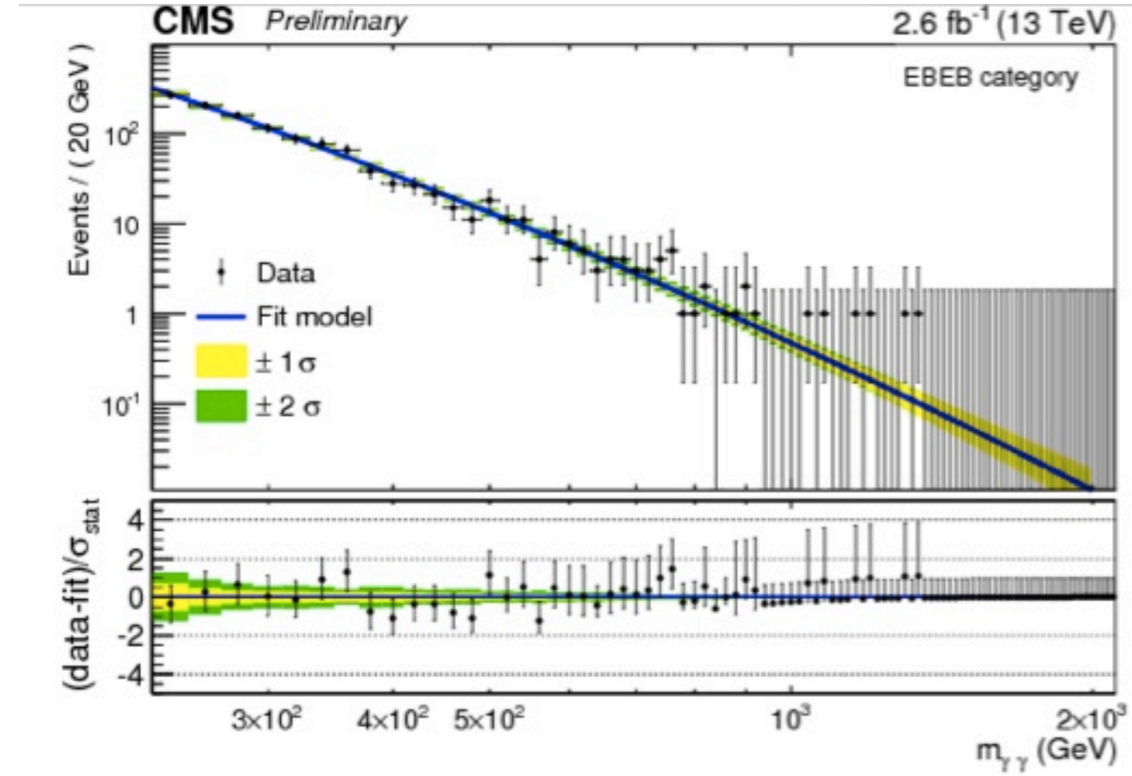
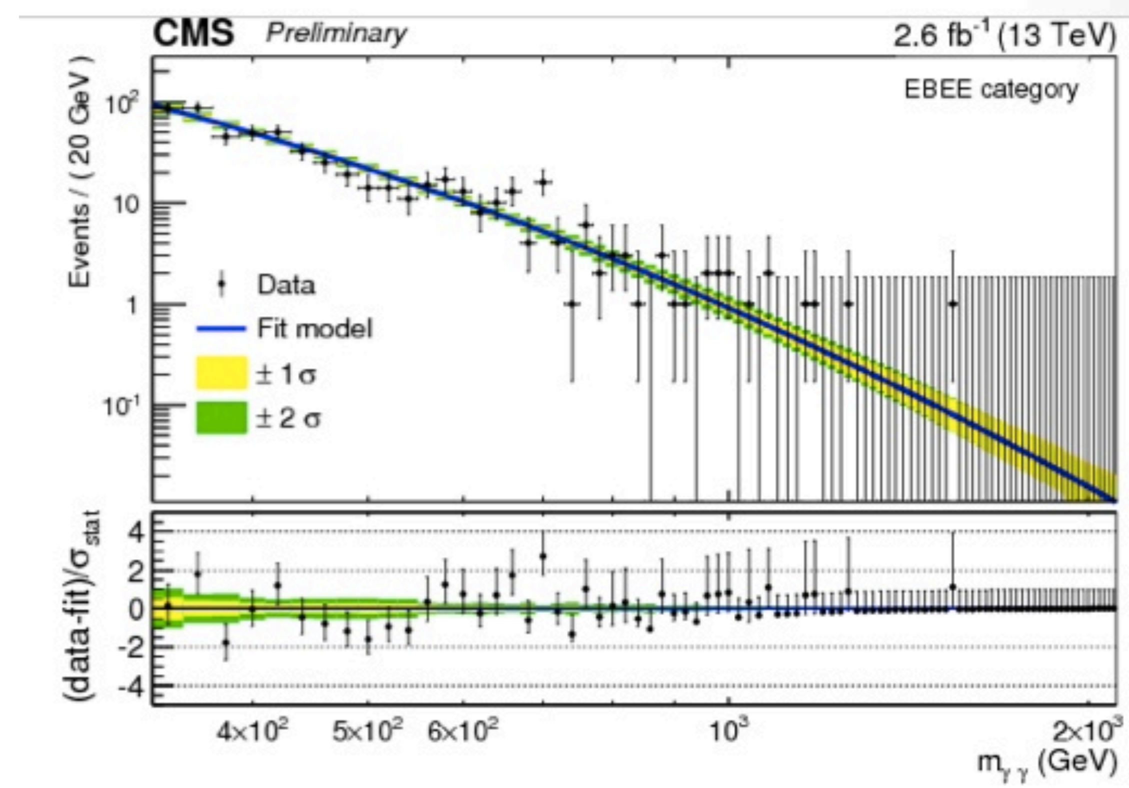


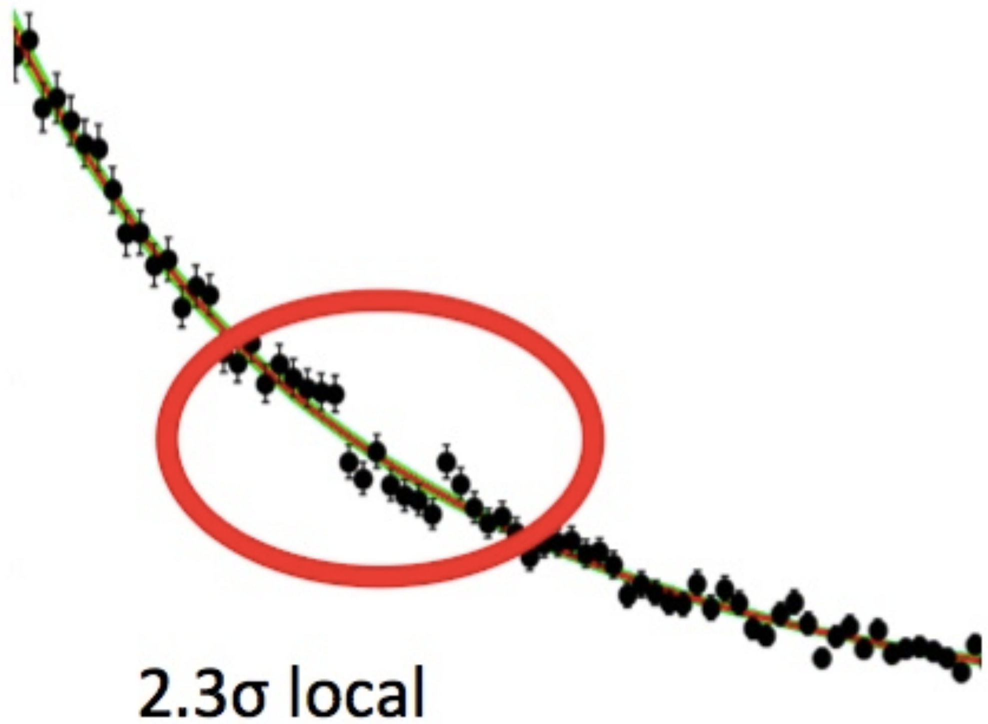


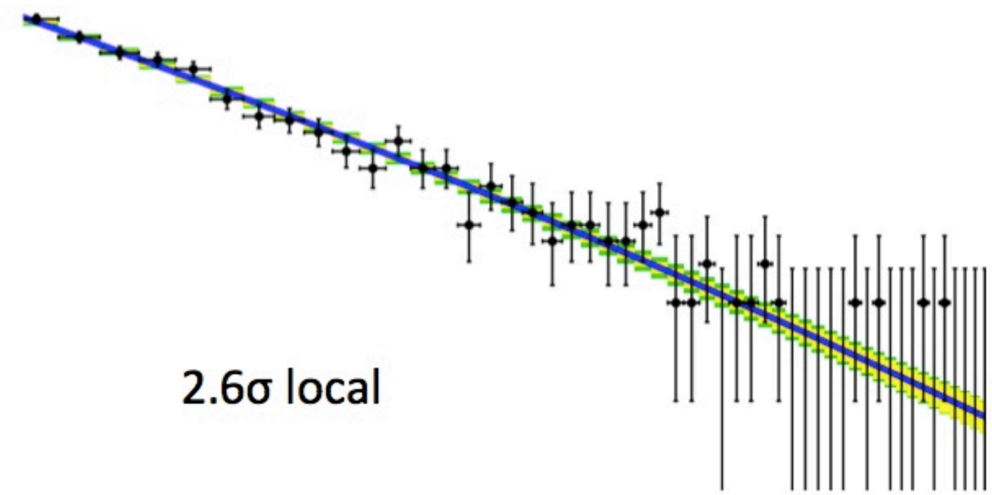


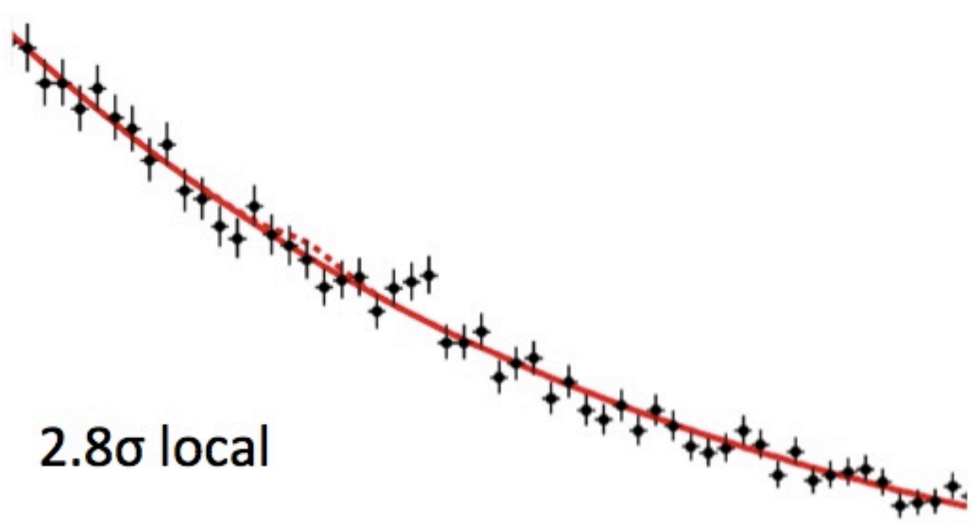
or Malicious is He?

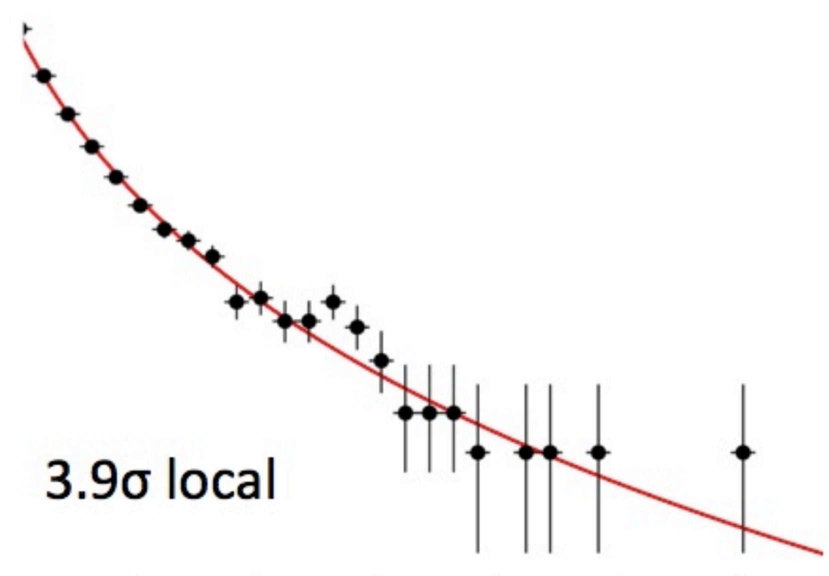
Christmas 2011: the Higgs

Christmas 2015: …









ATLAS

$$M \simeq 750\,\mathrm{GeV} \qquad \Gamma \sim 45\,\mathrm{GeV}$$ favored

$\sim$ 14 events $\quad 3.9\,\sigma$ local $\quad 2.3\,\sigma$ including LEE

CMS

$$M \simeq 760\,\mathrm{GeV}$$ narrow width favored

$\sim$ 10 events $\quad 2.6\,\sigma$ local $\quad 1.2\,\sigma$ including LEE

- No significant $E_{T miss}$, leptons or jets in the events
- No $\gamma\,\gamma$ resonance at 8 TeV but small upward fluctuation

$$\sigma(pp \to \gamma\gamma) \approx \begin{cases} (0.5 \pm 0.6)\,\mathrm{fb} & \text{CMS [2]} & \sqrt{s} = 8\,\mathrm{TeV}, \\ (0.4 \pm 0.8)\,\mathrm{fb} & \text{ATLAS [3]} & \sqrt{s} = 8\,\mathrm{TeV}, \\ (6 \pm 3)\,\mathrm{fb} & \text{CMS [1]} & \sqrt{s} = 13\,\mathrm{TeV} \\ (10 \pm 3)\,\mathrm{fb} & \text{ATLAS [1]} & \sqrt{s} = 13\,\mathrm{TeV} \end{cases}$$

$$\sigma(pp \to S \to \gamma\gamma) = \frac{2J+1}{M\Gamma s}\left[C_{gg}\Gamma(S \to gg) + \sum_q C_{q\bar{q}}\Gamma(S \to q\bar{q})\right]\Gamma(S \to \gamma\gamma)$$

partonic distribution coeffs

$\sqrt{s}$	$C_{b\bar{b}}$	$C_{c\bar{c}}$	$C_{s\bar{s}}$	$C_{d\bar{d}}$	$C_{u\bar{u}}$	C_{gg}
8 TeV	1.07	2.7	7.2	89	158	174
13 TeV	15.3	36	83	627	1054	2137

$$r = \frac{\sigma_{13\,\mathrm{TeV}}}{\sigma_{8\,\mathrm{TeV}}} = \frac{[C_{gg}/s]_{13\,\mathrm{TeV}}}{[C_{gg}/s]_{8\,\mathrm{TeV}}}$$

$r_{b\bar{b}}$	$r_{c\bar{c}}$	$r_{s\bar{s}}$	$r_{d\bar{d}}$	$r_{u\bar{u}}$	r_{gg}
5.4	5.1	4.3	2.7	2.5	4.7

$$\sigma(pp \to \gamma\gamma) \approx \begin{cases} (0.5 \pm 0.6)\,\mathrm{fb} & \mathrm{CMS}\ [2] & \sqrt{s} = 8\,\mathrm{TeV}, \\ (0.4 \pm 0.8)\,\mathrm{fb} & \mathrm{ATLAS}\ [3] & \sqrt{s} = 8\,\mathrm{TeV}, \\ (6 \pm 3)\,\mathrm{fb} & \mathrm{CMS}\ [1] & \sqrt{s} = 13\,\mathrm{TeV}, \\ (10 \pm 3)\,\mathrm{fb} & \mathrm{ATLAS}\ [1] & \sqrt{s} = 13\,\mathrm{TeV}. \end{cases}$$

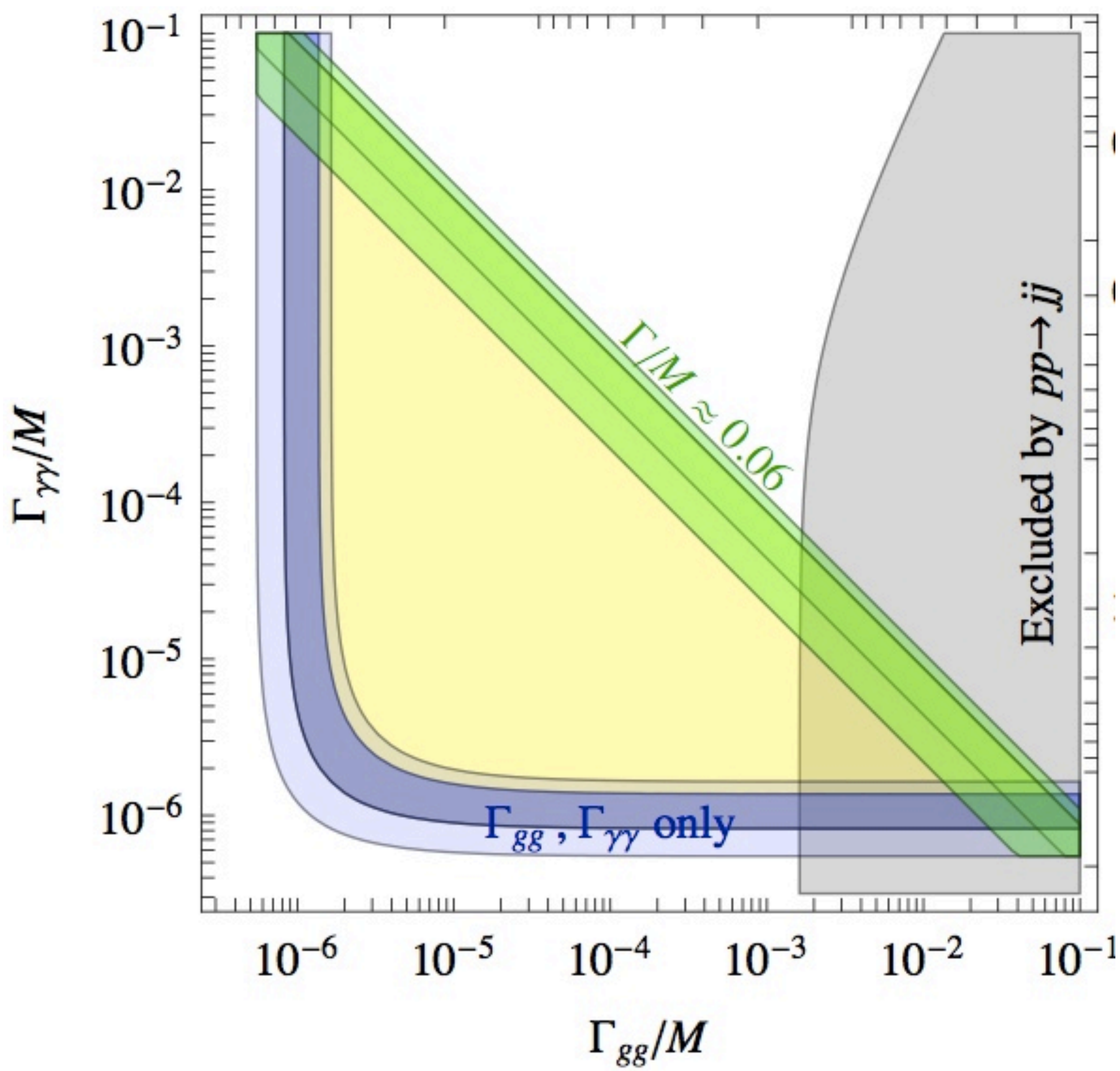
$$r \simeq 5$$

makes 8 TeV and 13 TeV mutually compatible

Spin 0 resonance in gg-fusion

$$\frac{\Gamma}{M} = 0.06$$

$$\frac{\Gamma_{\gamma\gamma}}{M}\frac{\Gamma_{gg}}{M} \approx 1.1 \times 10^{-6} \quad \frac{\Gamma}{M} \approx 6 \times 10^{-8}$$



If large width true need extra decay channel $S \to f$ dominate if $S \to f$ dominates

$$\sigma(pp \to S \to f) \propto \frac{\Gamma_{gg}}{M}\frac{\Gamma_f}{\Gamma} \sim \frac{\Gamma_{gg}}{M} \qquad \frac{\Gamma_{\gamma\gamma}}{M}\frac{\Gamma_{gg}}{M} \approx 6 \times 10^{-8} = \text{fixed}$$

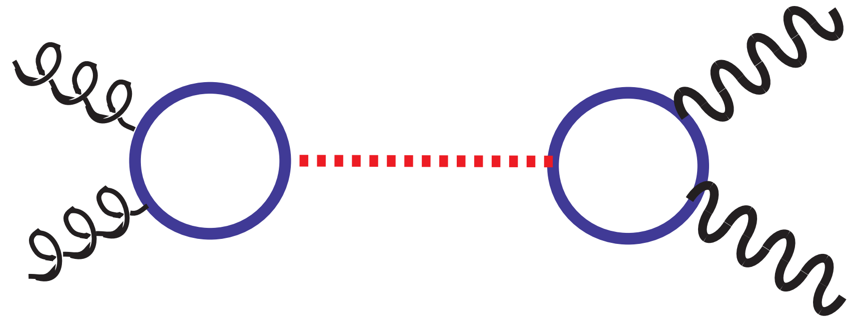
$$\boxed{\frac{\Gamma_{\gamma\gamma}}{M} \propto \frac{1}{\sigma(pp \to S \to f)}}$$

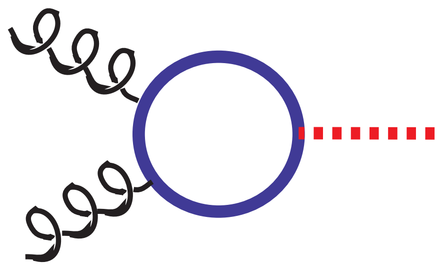
final state f	σ at $\sqrt{s} = 8\,\text{TeV}$ observed	expected	ref.
$\gamma\gamma$	< 1.5 fb	< 1.1 fb	[6,7]
$e^+e^- + \mu^+\mu^-$	< 1.2 fb	< 1.2 fb	[8]
$\tau^+\tau^-$	< 12 fb	< 15 fb	[9]
$Z\gamma$	< 4.0 fb	< 3.4 fb	[10]
ZZ	< 12 fb	< 20 fb	[11]
Zh	< 19 fb	< 28 fb	[12]
hh	< 39 fb	< 42 fb	[13]
W^+W^-	< 40 fb	< 70 fb	[14, 15]
$t\bar{t}$	< 550 fb	-	[16]
invisible	< 0.8 pb	-	[17]
$b\bar{b}$	$\lesssim 1$ pb	$\lesssim 1$ pb	[18]
jj	$\lesssim 2.5$ pb	-	[5]

$$\frac{\Gamma_{\gamma\gamma}}{M} \gtrsim 2 \times 10^{-3}$$

$$\frac{\Gamma_{\gamma\gamma}}{M} \gtrsim 2 \times 10^{-4}$$

A taste of the necessary parameters



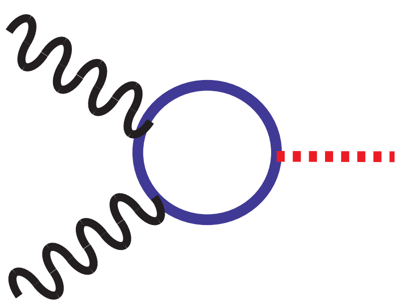


$$\sim \; b_3 \, \frac{\alpha_s}{8\pi} \, \frac{\lambda}{M_\Psi} \, G_{\mu\nu} G^{\mu\nu} \quad \text{or} \quad G_{\mu\nu} \widetilde{G}^{\mu\nu}$$

$\downarrow$

Dynkin index

$\uparrow$



$$\sim \; b_Q \, \frac{\alpha}{8\pi} \, \frac{\lambda}{M_\Psi} \, F_{\mu\nu} F^{\mu\nu} \quad \text{or} \quad F_{\mu\nu} \widetilde{F}^{\mu\nu}$$

Ex:
N color fundamentals
with charge Q

$$b_3 = N$$

$$b_Q = 2NQ^2$$

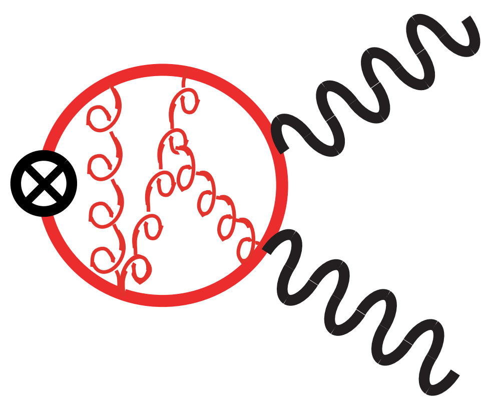
as a rule of thumb estimate
correct also in composite models

$$\frac{\lambda}{M_\Psi} \to \frac{g_*}{m_*} \equiv \frac{1}{f}$$

$$b_{3,Q} \sim N$$

Ex: η' in large N_c QCD

$$m_{\eta'} \sim \frac{1}{\sqrt{N}} m_* = \frac{g_*}{4\pi} m_* \ll m_*$$



$$\sim \; N_c \frac{\alpha}{8\pi} \frac{1}{f_{\eta'}}$$

$$f_{\eta'} \propto \sqrt{N}_c$$

$$\frac{\Gamma_{gg}}{M} = 10^{-5} \times b_3^2 \left(\frac{M}{f}\right)^2 \qquad \frac{\Gamma_{\gamma\gamma}}{M} = 0.75 \times 10^{-8} \times b_Q^2 \left(\frac{M}{f}\right)^2$$

- Assuming narrow width (dominated by gg): **easy to explain**

Ex: one vectorlike quark Q=5/3
$\Psi = (\mathbf{3}, \mathbf{0}, 5/3)$

$$\left.\begin{aligned} b_3 &= 1 \\ b_Q &= 15 \end{aligned}\right. \Rightarrow \frac{M}{f} \sim 1$$

- Assuming $\Gamma = 45\,\mathrm{GeV} \times \eta$

Γ from $t\bar{t}$ or invisible $\Rightarrow$

$$\left[\begin{aligned} b_3 \frac{M}{f} &< 5 \\ b_Q \frac{M}{f} &> 150\sqrt{\eta} \end{aligned}\right.$$

stretchedly compatible with composite model with $N \sim 10 \quad (g_* \sim 3)$

$\eta < 0.1$ would give much more realistic numbers

Final Comments

- Naturalness: Symmetries & Selection Rules

- Natural Hierarchy (business as usual): new states *around* the weak scale

- Unnatural Hierarchy: history and a landscape enter particle physics
  - cosmological constant: first blatant case of fine tuning
  - global symmetries : tuned SM structurally superior to its natural extensions
  - the neatest incarnations of naturalness have since long missed their appointment

- Well motivated model building remains our only way to give shape to the unknown and guide experimental searches

- But we just had a taste of how exciting is to be guided by experiments...