A $\gamma \gamma$ resonance at 750 GeV?

1) Widths
2) Models
3) Theories
4) What next?

Alessandro Strumia, talk at SUSY 2016, July 8, 2016
News from the outback of physics

Explores went to Australian inland carrying boats because naturalness predicted great lakes and mountains. They found a lot of nothing. Wandering through the flatland, a peak or maybe a mirage appeared on the horizon...
First LHC data at 13 TeV

Depressing flatland plus maybe a peak at $m_{\gamma\gamma} \approx 750$ GeV

Theoretically clean. Experimentally simple.

Significance | ATLAS $\sigma$ | CMS $\sigma$ | naive combination $\sigma$
--- | --- | --- | ---
Local | 3.9 | 3.4 | $\approx 4.5$
Global | $\approx 2.1$ | $\approx 1.6$ | $\sim 3$}

Denote as $\digamma$, ‘digamma’ in archaic greek. Later $\digamma = 6 = 750/125$. 
Needless to say

Either the main discovery in 30 years
or the main statistical fluctuation.

God plays loaded dices?
Physics = experiment + i theory

The Gold Rush: [INSPIRES][list]

<table>
<thead>
<tr>
<th>Date</th>
<th>papers</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 Dec</td>
<td>10</td>
</tr>
<tr>
<td>25 Dec</td>
<td>101</td>
</tr>
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<td>1 Jan</td>
<td>137</td>
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<tr>
<td>1 Feb</td>
<td>212</td>
</tr>
<tr>
<td>1 Jun</td>
<td>411</td>
</tr>
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<td>1 Aug</td>
<td>?</td>
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</table>
Rates

**Width: narrow or large, \( \Gamma/M \sim 0.06? \)**

<table>
<thead>
<tr>
<th></th>
<th>( \sigma(pp \rightarrow F \rightarrow \gamma\gamma) )</th>
<th>( \sqrt{s} = 8 \text{ TeV} )</th>
<th>( \sqrt{s} = 13 \text{ TeV} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>narrow</td>
<td>broad</td>
<td>narrow</td>
</tr>
<tr>
<td>CMS</td>
<td>0.63 ± 0.31 fb</td>
<td>0.99 ± 1.05 fb</td>
<td>4.8 ± 2.1 fb</td>
</tr>
<tr>
<td>ATLAS</td>
<td>0.21 ± 0.22 fb</td>
<td>0.88 ± 0.46 fb</td>
<td>5.5 ± 1.5 fb</td>
</tr>
</tbody>
</table>
The background $q\bar{q} \rightarrow \gamma\gamma$ at 750 GeV grows by 2.3.
The signal grows by $\approx 5$ if produced from $gg, b\bar{b}, c\bar{c}, s\bar{s}$: ok.
The signal grows by $\approx 2.5$ if produced from $\gamma\gamma, u\bar{u}, d\bar{d}$: disfavored.

Compatibility between 8/13 TeV improved if $\mathcal{F}$ decays from a heavier particle.
A more complicated kinematics?

Tuning \( M_P \approx M_F + M_R \) needed to avoid \( \phi_T \). \( F \) virtuality can fake \( F \) width.

Or large \( F \to \Pi \Pi \) with \( \Pi \to \gamma \gamma \), collimated and seen as a single \( \gamma \) if \( M_\Pi \ll M_F \). Traveling in the detector material, ‘photon jets’ give more \( \gamma \to e^+e^- \).

Or two nearby narrow resonances.

Or a QCD bound state of a new quark with \( M \sim 380 \text{ GeV} \) and obscure decays.
Widths
## Cross section

Can be computed in terms of (narrow) widths:

\[
\sigma(pp \to F \to \gamma\gamma) = \frac{2J + 1}{s} \left[ \sum_\varphi C_{\varphi\bar{\varphi}} \frac{\Gamma(F \to \varphi\bar{\varphi})}{M} \right] \frac{\Gamma(F \to \gamma\gamma)}{\Gamma} 
\]

The parton $\varphi$ luminosities are:

<table>
<thead>
<tr>
<th>$\sqrt{s}$</th>
<th>$C_{b\bar{b}}$</th>
<th>$C_{c\bar{c}}$</th>
<th>$C_{s\bar{s}}$</th>
<th>$C_{d\bar{d}}$</th>
<th>$C_{u\bar{u}}$</th>
<th>$C_{gg}$</th>
<th>$C_{\gamma\gamma}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 TeV</td>
<td>1.07</td>
<td>2.7</td>
<td>7.2</td>
<td>89</td>
<td>158</td>
<td>174</td>
<td>54</td>
</tr>
<tr>
<td>13 TeV</td>
<td>15.3</td>
<td>36</td>
<td>83</td>
<td>627</td>
<td>1054</td>
<td>2137</td>
<td>11</td>
</tr>
</tbody>
</table>
Extreme cases: \( gg \) and \( b\bar{b} \)

\[
F \leftrightarrow \gamma\gamma + gg + ?
\]

\[
F \leftrightarrow \gamma\gamma + b\bar{b} + ?
\]
## Bounds on other decay modes

<table>
<thead>
<tr>
<th>final state $f$</th>
<th>$\sigma$ at $\sqrt{s} = 8,\text{TeV}$ observed</th>
<th>expected</th>
<th>implied bound on $\Gamma(F \to f)/\Gamma(F \to \gamma\gamma)_{\text{obs}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma\gamma$</td>
<td>$&lt; 1.5,\text{fb}$</td>
<td>$&lt; 1.1,\text{fb}$</td>
<td>$&lt; 0.8\ (r/5)$</td>
</tr>
<tr>
<td>$e^+e^-, \mu^+\mu^-$</td>
<td>$&lt; 1.2,\text{fb}$</td>
<td>$&lt; 1.2,\text{fb}$</td>
<td>$&lt; 0.6\ (r/5)$</td>
</tr>
<tr>
<td>$\tau^+\tau^-$</td>
<td>$&lt; 12,\text{fb}$</td>
<td>$&lt; 15,\text{fb}$</td>
<td>$&lt; 6\ (r/5)$</td>
</tr>
<tr>
<td>$Z\gamma$</td>
<td>$&lt; 11,\text{fb}$</td>
<td>$&lt; 12,\text{fb}$</td>
<td>$&lt; 6\ (r/5)$</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>$&lt; 12,\text{fb}$</td>
<td>$&lt; 20,\text{fb}$</td>
<td>$&lt; 6\ (r/5)$</td>
</tr>
<tr>
<td>$Zh$</td>
<td>$&lt; 19,\text{fb}$</td>
<td>$&lt; 28,\text{fb}$</td>
<td>$&lt; 10\ (r/5)$</td>
</tr>
<tr>
<td>$hh$</td>
<td>$&lt; 39,\text{fb}$</td>
<td>$&lt; 42,\text{fb}$</td>
<td>$&lt; 20\ (r/5)$</td>
</tr>
<tr>
<td>$W^+W^-$</td>
<td>$&lt; 40,\text{fb}$</td>
<td>$&lt; 70,\text{fb}$</td>
<td>$&lt; 20\ (r/5)$</td>
</tr>
<tr>
<td>$tt$</td>
<td>$&lt; 450,\text{fb}$</td>
<td>$&lt; 600,\text{fb}$</td>
<td>$&lt; 300\ (r/5)$</td>
</tr>
<tr>
<td>invisible</td>
<td>$&lt; 0.8,\text{pb}$</td>
<td>-</td>
<td>$&lt; 400\ (r/5)$</td>
</tr>
<tr>
<td>$b\bar{b}$</td>
<td>$\lesssim 1,\text{pb}$</td>
<td>$\lesssim 1,\text{pb}$</td>
<td>$&lt; 500\ (r/5)$</td>
</tr>
<tr>
<td>$jj$</td>
<td>$\lesssim 2.5,\text{pb}$</td>
<td>-</td>
<td>$&lt; 1300\ (r/5)$</td>
</tr>
</tbody>
</table>

Here $r = \sigma_{13\,\text{TeV}}/\sigma_{8\,\text{TeV}}$. Using run 2 data only would be safer.

Even invisible modes are constrained.
**Global fits,** $F \leftrightarrow gg, \gamma\gamma, X$

Regions that fit $\sigma(pp \to \gamma\gamma)_{8,13}$, the width $\Gamma$ and that satisfy all bounds:

---

*Broad, $\Gamma/M = 0.06$*

*Narrow*

---

Large width needs $\Gamma(F \rightarrow \gamma\gamma)/M \gtrsim 10^{-5}$: it’s big!
Effective theory

Valid if extra particles that mediate operators are much heavier than $\frac{1}{2}750$ GeV.

If $F$ is a CP-even scalar singlet:

$$
\mathcal{L}^{\text{dim} \leq 5}_{\text{eff}} = F \left[ g_3^2 \frac{G_{\mu\nu}^2}{2\Lambda_{gg}} + g_2^2 \frac{W_{\mu\nu}^2}{2\Lambda_{WW}} + g_1^2 \frac{B_{\mu\nu}^2}{2\Lambda_{BB}} + \left( \frac{H \bar{\psi}_L \psi_R}{\Lambda_{\psi}} + \text{h.c.} \right) + \right.
\left. - \kappa_{FH} M_F (|H|^2 - v^2) + \frac{|D_\mu H|^2}{\Lambda_H} - \kappa_{F} M_F F^2 + \frac{(\partial_\mu F)^2}{2\Lambda_F} \right]
$$

If $F$ is a CP-odd scalar singlet:

$$
\mathcal{L}^{\text{dim} \leq 5}_{\text{eff}} = F \left[ g_3^2 \frac{\tilde{G}_{\mu\nu}}{2\tilde{\Lambda}_{gg}} + g_2^2 \frac{\tilde{W}_{\mu\nu}}{2\tilde{\Lambda}_{WW}} + g_1^2 \frac{\tilde{B}_{\mu\nu}}{2\tilde{\Lambda}_{BB}} + \left( \frac{H \bar{\psi}_L i\gamma_5 \psi_R}{\tilde{\Lambda}_\psi} + \text{h.c.} \right) \right]
$$
SU(2)\textsubscript{L} invariance implies $\Gamma_{\text{extra}} > 0.3\Gamma_{\gamma\gamma}$

<table>
<thead>
<tr>
<th>operator</th>
<th>$\Gamma(F \to Z\gamma)/\Gamma(F \to \gamma\gamma)$</th>
<th>$\Gamma(F \to ZZ)/\Gamma(F \to \gamma\gamma)$</th>
<th>$\Gamma(F \to WW)/\Gamma(F \to \gamma\gamma)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>WW only</td>
<td>$2/\tan^2 \theta_W \approx 7$</td>
<td>$1/\tan^4 \theta_W \approx 12$</td>
<td>$2/\sin^4 \theta_W \approx 40$</td>
</tr>
<tr>
<td>BB only</td>
<td>$2 \tan^2 \theta_W \approx 0.6$</td>
<td>$\tan^4 \theta_W \approx 0.08$</td>
<td>$0$</td>
</tr>
</tbody>
</table>

Isocurves of $\Gamma(f \to ZZ, \gamma Z, WW, hh)/\Gamma(f \to \gamma\gamma)$
Models
VolksModell (the everybody’s model)

The $Fgg$ and $F\gamma\gamma$ operators can be generated if $F$ couples to charged particles

$$F \bar{Q}_f(y_f + i y_5 f \gamma_5) Q_f + FA_s \bar{Q}_s \bar{Q}_s$$

Extra fermions $Q$ or scalars $\bar{Q}$ needed

SM loop excluded: the tree level decay would be too large e.g. $\frac{\Gamma_{\bar{t}t}}{\Gamma_{\gamma\gamma}} \approx 10^5$. 
Can loops give the needed widths?

At one loop

\[
\frac{\Gamma(F \to gg)}{M} \approx 7.2 \times 10^{-5} \left| \sum_f I_{rf}y_f \frac{M}{2M_f} + \sum_s I_{rs} \frac{A_s M}{16 M_s^2} \right|^2
\]

\[
\frac{\Gamma(F \to \gamma\gamma)}{M} \approx 5.4 \times 10^{-8} \left| \sum_f d_{rf} Q_f^2 y_f \frac{M}{2M_f} + \sum_s d_{rs} Q_s^2 \frac{A_s M}{16 M_s^2} \right|^2
\]

- Loop decays cannot make a large total width \( \Gamma/M \sim 0.06 \) which is typical of a 1 \( \to \) 2 tree level decay with coupling \( y \sim 1 \).

- If \( \Gamma \) is large, data want \( \Gamma(F \to \gamma\gamma) \gtrsim 10^{-4} M \), which again seems too large?

- If \( \Gamma \) is small, data want \( \Gamma(F \to \gamma\gamma) \gtrsim 10^{-6} M \), which can be done. E.g. a \( H' \), with \( S \) and \( P \) splitted by \( \Delta M = \lambda v^2/M = \lambda \times 40 \text{ GeV} \) (< 6 GeV in MSSM).
Good particles in the loop: $L$, $E$, $U$
Large width $\Rightarrow$ non-perturbativity

Enhance $\Gamma(F \rightarrow \gamma\gamma)$ with: a) many fermions; b) big Yukawa $y$; c) big charge.

In any case: nearby Landau poles for $g_3$ or $e$ or $y$:

$\Gamma(S \rightarrow \gamma\gamma)$ from a fermion loop, $M_\psi = 375$ GeV

$\Gamma(S \rightarrow \gamma\gamma)$ from a fermion loop, $M_\psi = 1$ TeV

Much larger $y$ and $\Gamma_{\gamma\gamma}$ if gauged SU($N$) with IR fixed point. Then $pp \rightarrow FF$. 


Similar results with extra scalars

A large cubic does not give Landau poles, but it is limited by vacuum decay.

\[ \Gamma(S \rightarrow \gamma\gamma) \text{ from a scalar loop, } M_X = 375 \text{ GeV} \]

\[ \Gamma(S \rightarrow \gamma\gamma) \text{ from a scalar loop, } M_X = 1 \text{ TeV} \]

\[ \Gamma_{\gamma\gamma} \text{ can be much larger if gauged } SU(N) \text{ with IR fixed point} \]
Extra $Q = \text{Dark Matter}$?

1) The connection with $\Omega_{\text{DM}}$ is interesting on its own;
2) if $\Gamma/M \sim 0.06$ allows to hide many particles that enhance $F \rightarrow \gamma\gamma$;
3) if $\Gamma/M \sim 0.06$ allows to get tree level $F \rightarrow \text{DM DM}$ decays.

Direct detection bounds are (weak) irrelevant if $F$ is a scalar (pseudo-scalar).
A resonance?

A heavy quark or squark with mass $M_Q \approx \frac{1}{2}750$ GeV?

$\Lambda_{QCD} \ll M_Q$: only a small fraction of $pp \rightarrow Q\bar{Q}$ manifests as a peak, extra distortions, need poorly detectable $\Gamma_Q \ll \Gamma_{Q\bar{Q}}$ and favourable QCD factors.

Add extra strong force with $\Lambda_{TC} \ll M_Q$ to get TC-charmonium resonances:

$$M_n = 2M_Q(1 - \frac{\alpha^2_{\text{eff}}}{8n^2}), \quad \frac{\Gamma(F_1 \rightarrow \gamma\gamma)}{M_F} = \frac{q^4N}{4}\alpha_{\text{em}}^2\alpha_{\text{eff}}^3 = 10^{-6}Nq^4(\frac{\alpha_{\text{eff}}}{0.4})^3$$

But $3 \otimes \bar{3} = 1 \oplus 8$: predicts coloured octets close to 750 GeV.

Focus on models where the $F$ singlet is lighter than the other unseen states:

1) pseudo-Goldstone of a chiral symmetry: pseudo-scalar TC$\eta$;
2) rough pseudo-Goldstone of scale invariance: scalar dilaton.
Strongly coupled models

3 main options:

**Technicolor: SU(2)$_L$ broken by strong dynamics.** Bonus/malus:
+ Simple UV-complete fundamental theories. E.g. extra fermions $Q$ *chiral* under SU(2)$_L$ and charged under extra SU($N_{TC}$) strong at $\Lambda_{TC} \sim M_h$.
+ TC$\eta'$ is a perfect 750 GeV candidate.
  – All the rest is a problem: flavor, precision data, $h$: dead?

**Technidreams, composite $H$ and $F$.** Bonus/malus:
– Postulates $\mathcal{L}_{eff}$ that avoid problems, fundamental theory with TC scalars.
+ Allows large width trough $F \rightarrow t\bar{t}$.
+ 750 GeV compatible with usual (fine-tuned) naturalness.

**Composite $F$, elementary $H$ and SM.** Bonus/malus:
+ No problems, simple UV-complete fundamental theories. E.g. extra particles $Q$ *non-chiral* under SM and extra strong SU($N_{TC}$).
+ Dark Matter could be a stable TC$\pi$, and $F$ could decay into it.
+ 750 GeV could source $M_h \sim$ loop $\times \Lambda_{TC}$ in modified naturalness?
$F$ as $\mathbf{TC\eta}$

$$\frac{\Gamma(F \to \gamma\gamma)}{M_F} = \frac{\alpha_{em}^2 \kappa_{\gamma\gamma}^2 M_F^2}{64\pi^3 f_{\mathbf{TC}}^2} = 10^{-6} \left( \frac{\kappa_{\gamma\gamma} 120 \text{ GeV}}{f_{\mathbf{TC}}} \right)^2.$$ 

$$\frac{1}{\Lambda_{VV'}} = \frac{\kappa_{VV'}}{8\pi^2 f_{\mathbf{TC}}}, \quad \kappa_{VV'} = N \text{ Tr} (T_F T^V T^{V'})$$

Sample model: extra $\text{SU}(N_{\mathbf{TC}})$ with $Q = N_1 \oplus N_2 \oplus U$.

$$\mathbf{TC\pi} = (8,1)_0 \oplus 2 \times [(\bar{3},1)_{-2/3} + (3,1)_{2/3}] \oplus 4 \times (1,1)_0 \quad \begin{array}{l}
\chi \sim U \bar{U} \\
\phi_i \sim U \bar{N}_i, \phi_i^* \\
\Pi \sim N_1 \bar{N}_2, \Pi^*, \eta_{1,2}
\end{array}$$

$$\eta_2 \sim N_1 \bar{N}_1 - N_2 \bar{N}_2, \eta_1 \sim N_i \bar{N}_i - \frac{3}{2} U \bar{U}, \eta' \sim Q \bar{Q} \text{ up to mixings } \propto m_{N_1} - m_{N_2}.$$ 

$\mathbf{TC\pi}$ masses in terms of $B_0 \sim \Lambda_{\mathbf{TC}}$ for $\mathbf{TCQ}$ masses $\Lambda_{\mathbf{TC}} \sim m_U > \frac{7}{2} m_{N_{1,2}}$

**DM:** $m_\Pi^2 = B_0(m_{N_1} + m_{N_2})$

**$750$ GeV $F$:** $m_{\eta_1}^2 \approx \frac{4}{5} B_0 m_U$  \hspace{1cm} $m_{\eta'} \sim \Lambda_{\mathbf{TC}}$  \hspace{1cm} $m_{\eta_2} \lesssim m_\Pi$

Extra colored: $m_\chi^2 = 2B_0 m_U + \Delta_\chi$  \hspace{1cm} $m_{\phi_i} = B_0(m_U + m_{N_i}) + \Delta_\phi$

$$\Gamma(\eta_1 \to \Pi \Pi^*) \sim \text{GeV} \times \theta_{\mathbf{TC}}^2.$$

Predictive! Look for extra resonances.
\( F \) as dilaton

aka “the Higgs of the Higgs”: all masses \( M \) arise from \( \langle F \rangle \).

**Signature:** \( F \) couples to everybody as \( M/\langle F \rangle \).

\( F \to \gamma\gamma \) if extra heavy charged particles get mass as \( M = y\langle F \rangle \), \( y \) cancels out

\[
\mathcal{L}_{\text{eff}} = \sum_{i,Q} \Delta b_i (\frac{\alpha_i}{8\pi}) (F_{\mu\nu})^2 \ln \left( \frac{M_Q(F)}{M_Q} \right) \frac{\Gamma(F \to \gamma\gamma)}{M_F} = 10^{-6} (\Delta b_{\text{em}} \frac{120 \text{ GeV}}{\langle F \rangle})^2
\]

**Strongly coupled** models where \( g_{TC} \) ‘walks’ non-perturbative around 750 GeV, \( F \) can be the composite TC\( \sigma \). RS radion in models with AdS dual.

**Weakly coupled** models where \( F \) is a fundamental scalar and its quartic runs negative around 750 GeV generating \( M_F, M_h, M_W, \ldots \) a la Coleman-Weinberg.
Theories
The Big Picture

‘Who ordered that?’ Naturalness?

$F \to \gamma\gamma$ needs extra charged states, why are they light?

**SUSY:** $F$ could be $H$, $A$, $\tilde{\nu}$, NMSSM, sgoldstinos + sparticles in the loop...

**Unification** could give extra light multiplets, **extra dimensions**, **strings**...

**Scale invariance** would keep extra states light.

**Extended gauge group** can imply extra chiral fermions, need extra scalars:

<table>
<thead>
<tr>
<th>$G$</th>
<th>extra $\psi$</th>
<th>diphoton</th>
<th>diboson</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{SU}(3)_L \otimes \text{U}(1) \otimes \text{SU}(3)_c$</td>
<td>$L, D$</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>$\text{SU}(3)_L \otimes \text{SU}(3)_R \otimes \text{SU}(3)_c$</td>
<td>$L, D$</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>$\text{SU}(2)_L \otimes \text{SU}(2)_R \otimes \text{U}(1) \otimes \text{SU}(3)_c$</td>
<td>–</td>
<td>ad hoc</td>
<td>yes</td>
</tr>
</tbody>
</table>
What next?
A 750 GeV $\gamma\gamma$ peak reminds the 125 GeV $\gamma\gamma$ peak. But $H \neq F$: (circumnavigating Elba island) $\neq$ (going beyond Hercules pillars).

$H$: SM NNNLO predictions $\Rightarrow$ neural network analyses of issues ‘with the same potential for surprises as Brasil-Tonga’.

$F$: deep sea, all issues open $\Rightarrow$ I will focus on VolksModel@LHC just not to get lost in a plethora of possibilities. But

$\text{VM} \neq \text{SM}$. 
More decay channels

1. \( F \rightarrow ZZ, \gamma Z \): a must implied by \( F \rightarrow \gamma \gamma \).
2. \( F \rightarrow W^+W^- \) (or correlations of 1) would tell that SU(2)_L is involved.
3. \( F \rightarrow hh \) (or correlations of 1,2) would tell that \( H \) is involved.
4. \( F \rightarrow t\bar{t}, b\bar{b}, \ldots \) DM, ? would point to different directions.
Confirm spin 0 or exclude spin 2,3... 

(The speaker is biased, and data too...)

Randall-Sundrum graviton could fit with $\Lambda \sim 60$ TeV predicting $\Gamma/M \sim 10^{-5}$.

But the graviton is already disfavoured because it predicts
\[
\sigma(pp \to e^+e^- + \mu^+\mu^-) = \sigma(pp \to \gamma\gamma)
\]
and no peaks seen in leptons, $\sigma(pp \to \ell^+\ell^-) < 5$ fb (ATLAS) and $\lesssim 3$ fb (CMS).

Spin 2 can be resurrected by assuming that it couples more to $\gamma$ than to $\ell$. But this would give bad $1/M_f^4$ terms: only the universal $T_{\mu\nu}$ is conserved. The zombie could even be CP-odd: discriminate with $\Delta\eta_{\gamma}$ and 50 fb$^{-1}$. Or look at extra resonances.
Which initial state?

1) $F\gamma\gamma$ and $Fq\bar{q}$ already disfavoured by $\sigma_{13}/\sigma_{8}$.
2) $\varphi \rightarrow F$ implies $F \rightarrow \varphi$.
3) $Fq\bar{q}H$ implies a large $\Gamma(F \rightarrow q\bar{q}H) \sim 1\% \times \Gamma(F \rightarrow q\bar{q})$ where $H = \{h, Z, W^\pm\}$.
4) Distributions of $p_{TF}$ and $\eta_F$
5) $Fj, Fb, FV$

<table>
<thead>
<tr>
<th>$\sqrt{s} = 13$ TeV</th>
<th>$b\bar{b}$</th>
<th>$c\bar{c}$</th>
<th>$s\bar{s}$</th>
<th>$u\bar{u}$</th>
<th>$d\bar{d}$</th>
<th>GG</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{Fj}/\sigma_F$</td>
<td>9.2%</td>
<td>7.6%</td>
<td>6.8%</td>
<td>6.7%</td>
<td>6.2%</td>
<td>27.9%</td>
</tr>
<tr>
<td>$\sigma_{Fb}/\sigma_F$</td>
<td>6.2%</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.32%</td>
</tr>
<tr>
<td>$\sigma_{Fjj}/\sigma_F$</td>
<td>1.4%</td>
<td>1.0%</td>
<td>0.95%</td>
<td>1.2%</td>
<td>1.0%</td>
<td>4.7%</td>
</tr>
<tr>
<td>$\sigma_{Fjb}/\sigma_F$</td>
<td>1.2%</td>
<td>0.18%</td>
<td>0.19%</td>
<td>0.34%</td>
<td>0.31%</td>
<td>0.096%</td>
</tr>
<tr>
<td>$\sigma_{Fbb}/\sigma_F$</td>
<td>0.31%</td>
<td>0.17%</td>
<td>0.18%</td>
<td>0.34%</td>
<td>0.31%</td>
<td>0.024%</td>
</tr>
<tr>
<td>$\sigma_{F\gamma}/\sigma_F$</td>
<td>0.37%</td>
<td>1.5%</td>
<td>0.38%</td>
<td>1.6%</td>
<td>0.41%</td>
<td>$\ll 10^{-6}$</td>
</tr>
<tr>
<td>$\sigma_{FZ}/\sigma_F$</td>
<td>1.1%</td>
<td>1.1%</td>
<td>1.3%</td>
<td>2.0%</td>
<td>1.9%</td>
<td>3 $10^{-6}$</td>
</tr>
<tr>
<td>$\sigma_{FW^+}/\sigma_F$</td>
<td>$5 \times 10^{-5}$</td>
<td>1.7%</td>
<td>2.4%</td>
<td>2.6%</td>
<td>4.1%</td>
<td>$\ll 10^{-6}$</td>
</tr>
<tr>
<td>$\sigma_{FW^-}/\sigma_F$</td>
<td>$3 \times 10^{-5}$</td>
<td>2.3%</td>
<td>1.2%</td>
<td>1.0%</td>
<td>1.7%</td>
<td>$\ll 10^{-6}$</td>
</tr>
<tr>
<td>$\sigma_{Fh}/\sigma_F$</td>
<td>1.0%</td>
<td>1.1%</td>
<td>1.2%</td>
<td>1.9%</td>
<td>1.8%</td>
<td>1 $10^{-6}$</td>
</tr>
</tbody>
</table>
Singlet or doublet or...?

1) Extra component of multiplets must be around 750 GeV.

2) From the production mode: normally
   - if dominantly coupled to $gg$ it’s a singlet;
   - if dominantly coupled to $q\bar{q}$ it’s a doublet.

3) $p_T$ in associated production tells the dimension of the operator, testing abnormalities:
   - singlet coupled to $q\bar{q}$ gives hard $q\bar{q} \rightarrow FV_L$
   - doublet coupled to $gg$ gives hard $gg \rightarrow FV_LV_L$
# Scalar or pseudo-scalar?

How to measure the CP-parity of \( F \) (or discover that CP is violated):

<table>
<thead>
<tr>
<th>Technique</th>
<th>Problems</th>
</tr>
</thead>
<tbody>
<tr>
<td>measure ( F \to \gamma^<em>\gamma^</em> \to 4\ell )</td>
<td>( \Gamma_{4\ell}/\Gamma_{\gamma\gamma} \approx 10^{-3} )</td>
</tr>
<tr>
<td>measure ( F \to \gamma\gamma \to 4\ell ) in matter</td>
<td>Small ( e^+e^- ) angle</td>
</tr>
<tr>
<td>measure ( pp \to Fjj )</td>
<td>( \sigma_{Fjj}/\sigma_F = 0.04 )</td>
</tr>
<tr>
<td>Even if ( F \to hh )</td>
<td>( Fhh ) exists?</td>
</tr>
<tr>
<td>Odd if ( F \to hZ )</td>
<td>( FhZ ) exists??</td>
</tr>
<tr>
<td>measure ( F \to ZZ \to 4\ell )</td>
<td>( FZZ ) exists*?</td>
</tr>
<tr>
<td>measure ( pp \to Z \to FZ )</td>
<td>( FZZ ) exists*?</td>
</tr>
<tr>
<td>measure ( F \to Z\gamma(\ast) \to 4\ell )</td>
<td>( FZ\gamma ) exists?</td>
</tr>
</tbody>
</table>

\[
\ast \quad \sigma(pp \to FZ) = 1.7 \text{ pb} \frac{\Gamma_{ZZ}}{M} \pm 0.66 \text{ pb} \frac{\sqrt{\Gamma_{ZZ}\Gamma_{\gamma Z}}}{M} + 0.53 \text{ pb} \frac{\Gamma_{\gamma Z}}{M}
\]
$F$ couplings?

1) From $\Gamma$ if large enough,
2) one could even see interference with SM background.
3) $SU(2)_L$ relates different widths allowing to identify operators.
4) $F \rightarrow DM \ DM$ from $E_T$ as usual.
5) $pp \rightarrow Fj, FV \ldots$ probe the energy dependence of the couplings.
6) $pp \rightarrow FF$ would imply large $F^3$ or $FQQ$. 
Double $F$ production

Can be sizeable, especially if strong interactions $y \sim 4\pi$. The VM predicts

$$\sigma(pp \to FF) \sim \left( \frac{y M_F}{4\pi M_Q} + \frac{\kappa}{4\pi M_F} \right)^2 \sigma(pp \to F)$$

In the limit $M_Q \gg M_F$ the ‘low energy theorem’ provides an exact generic result for the Yukawa effect:

$$\mathcal{L}_{\text{eff}} = \frac{\alpha_3 I N}{6\pi} G_{\mu\nu}^2 \ln(1 + \frac{F}{v_Q}) \frac{1}{v_Q} \equiv \frac{y}{M_Q}$$

Signals: $pp \to FF \to jjjj, jj\gamma\gamma, \gamma\gamma\gamma$
Extra fermions or scalars

A) Discover $Q$ at LHC (some anomalies...).

LHC can miss DM multiplets, especially if quasi degenerate (soft tag). Then:

B) High-energy tails of

$$\sigma(pp \rightarrow \ell^+\ell^-) \propto g^4(\bar{\mu} \sim m_{\ell\ell})$$

sensitive to $\Delta b$ (BSM running of $g_Y, g_2$). 8 TeV:

C) $e^+e^-$ collider: even if $Q$ is too heavy, it could be probed indirectly as $W, Y$...

![Figure 2](image-url)

**Figure 2**: Left panel. Correlation matrix in Eq. (4.2) derived from the experimental covariance error matrix $\Sigma_{exp}$. Right panel. Comparison between data and theoretical cross-section at large dilepton invariant mass. We show the impact of running couplings for $M_X = 400$ GeV and different values of the combination $d_{XNQ^2}$.

Let us now discuss the impact of the new vector-like fermions. For illustrative purposes we fix $M_X = 400$ GeV, and, to better visualize the impact of running couplings, we show two specific cases with $d_{XNQ^2} = 150$ (lighter blue) and $d_{XNQ^2} = 200$ (darker blue). In the dilepton invariant mass range $500 \leq M_{\ell\ell} \leq 1000$ GeV the differential cross-section is measured with a 10% accuracy. For $M_{\ell\ell} \approx M_X$ the vector-like fermions actively participate to the hypercharge running, and their impact on the differential cross-section may easily overshoot the data points, as qualitatively shown in Fig. 2, for sufficiently large $d_{XNQ^2}$. In the right panel of Fig. 2 we show the correlation matrix derived in Eq. (4.2). As expected, the plot highlights the presence of strong correlations between adjacent bins. The inclusion of the correlation matrix in the fit plays an important role since it allows to constrain—in addition to the absolute deviation from the observed values in each individual bin—also the slope of theoretical cross-section.

Let us now discuss the size of PDF uncertainties. The differential cross-section in Eq. (3.11) was obtained considering the central PDF set (corresponding to the PDF best-fit). In order to assess the impact of PDF uncertainties we need to statistically quantify—using all the remaining eigenvector PDF sets—the relative change in the cross-section. Let us discuss this point in more detail. In order to construct the covariance error matrix $\Sigma_{PDF}$ we need two ingredients

- PDF uncertainties in individual bins;
- Correlation matrix among different bins.
Conclusions

- $\gamma\gamma@750$ should be accompanied by $\gamma Z, ZZ@750$ and by new particles.
- $\Gamma/M \sim 0.06$ difficult to reproduce even with new strong interactions.
- A jungle of reasonable models can reproduce a small width

Narrow or broad? Spin 0 or 2 or...? Singlet or doublet or...? Scalar or pseudo or CP? Elementary or composite? A cousin of $H$ or not? [...] **Real or not?**

Expect $\sigma_{13}(pp \to F \to \gamma\gamma) \approx 3\text{ fb}$, not more. New data to be shown at ICHEP.
No rumors, a moment of silence

“Any significant (i.e. discovery-like) result has first to be announced in a seminar at CERN”.

† DG

no diphoton ⇔ no party

“4 fb$^{-1}$ seen now”.

†† CMS@SUSY

“Where the wild roses grow, since, all beauty must die”.

† † † ATLAS@SUSY