The Di-Photon-Excess at 750 GeV

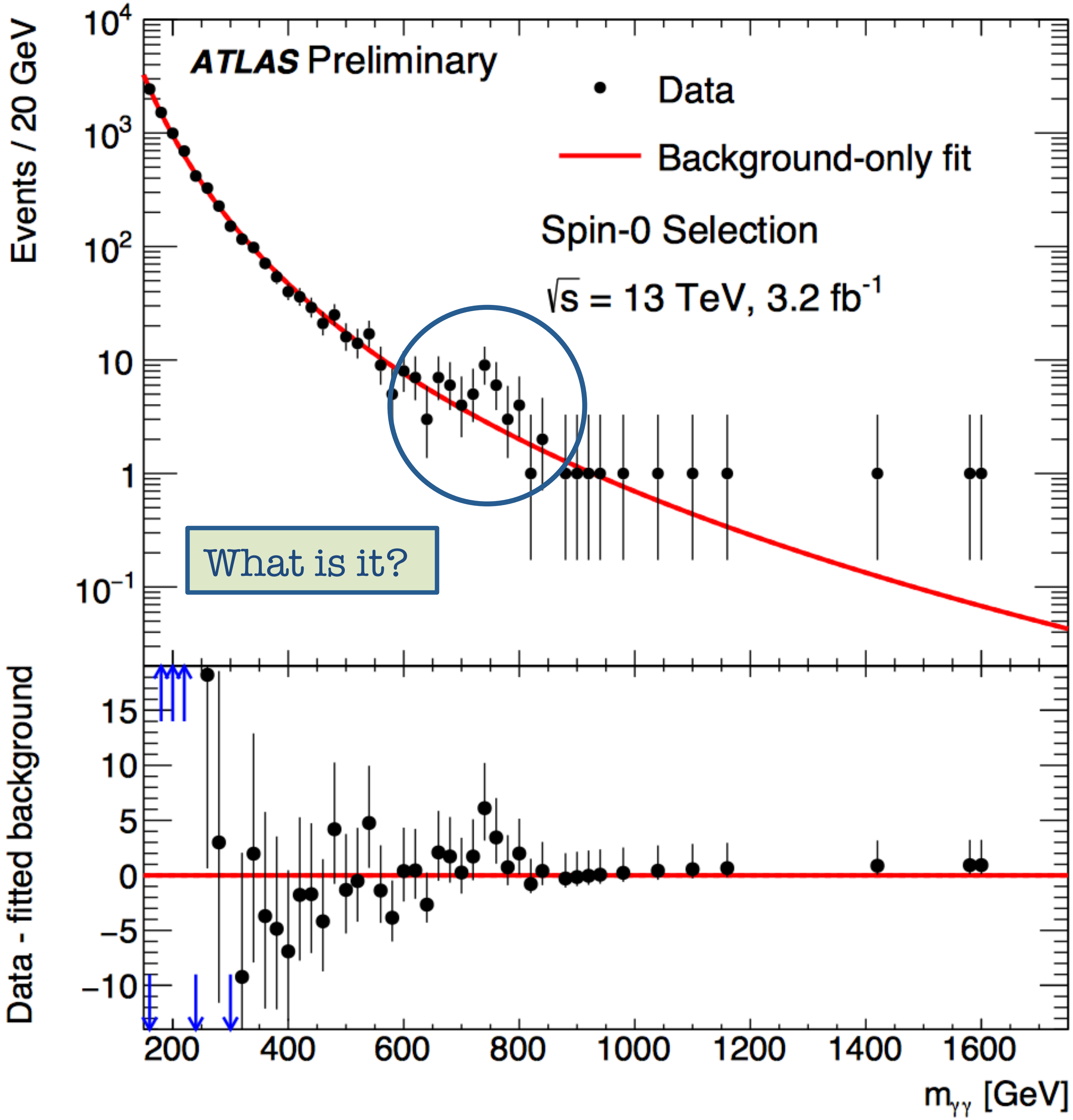
An Overview of Possible Explanations

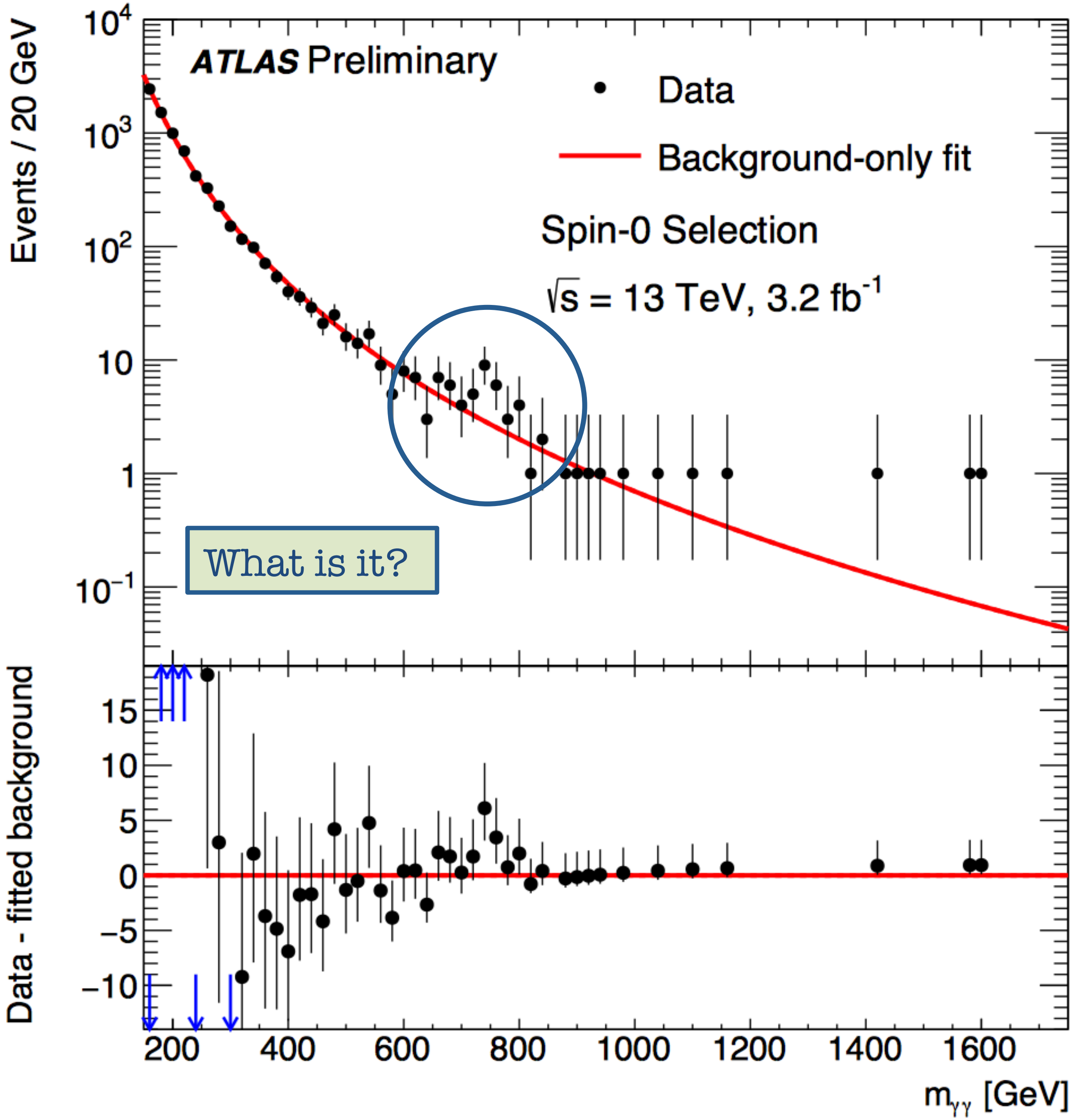
Universität Freiburg
May 4th 2016

Based on work with Franceschini, Giudice, Kamenik, Pomarol, Rattazzi, Redi, Riva, Strumia, & Torre.

What is the $\gamma\gamma$ resonance at 750 GeV? 1512.04933
Digamma, what next? 1604.06446

Matthew McCullough


ATLAS Preliminary
Data
Background-only fit
Spin-0 Selection
$\sqrt{s}$ = 13 TeV, 3.2 fb^{-1}
What is it?
Events / 20 GeV
Data - fitted background
$m_{\gamma\gamma}$ [GeV]



This is what I was asked to talk about:

An excess in one or two bins in the diphoton searches by ATLAS and CMS.

Question
How much could there be to say about such a small amount of information?

Answer
I am a theorist… my job is to speculate!

A Minimal Explanation

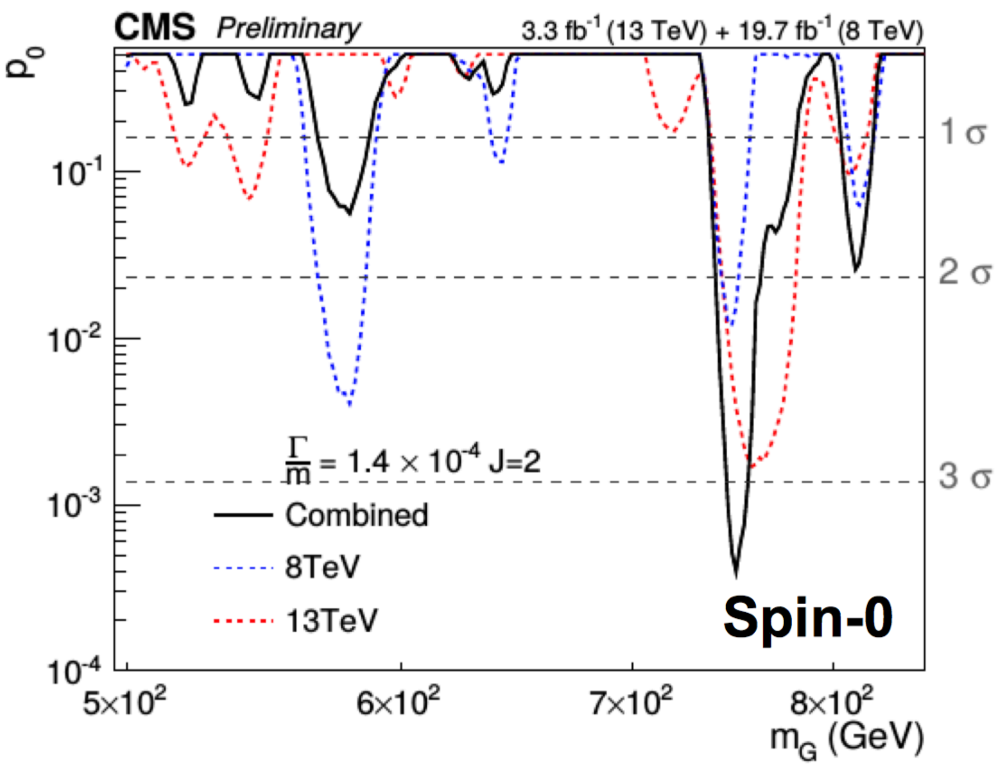
Statistical Fluctuation

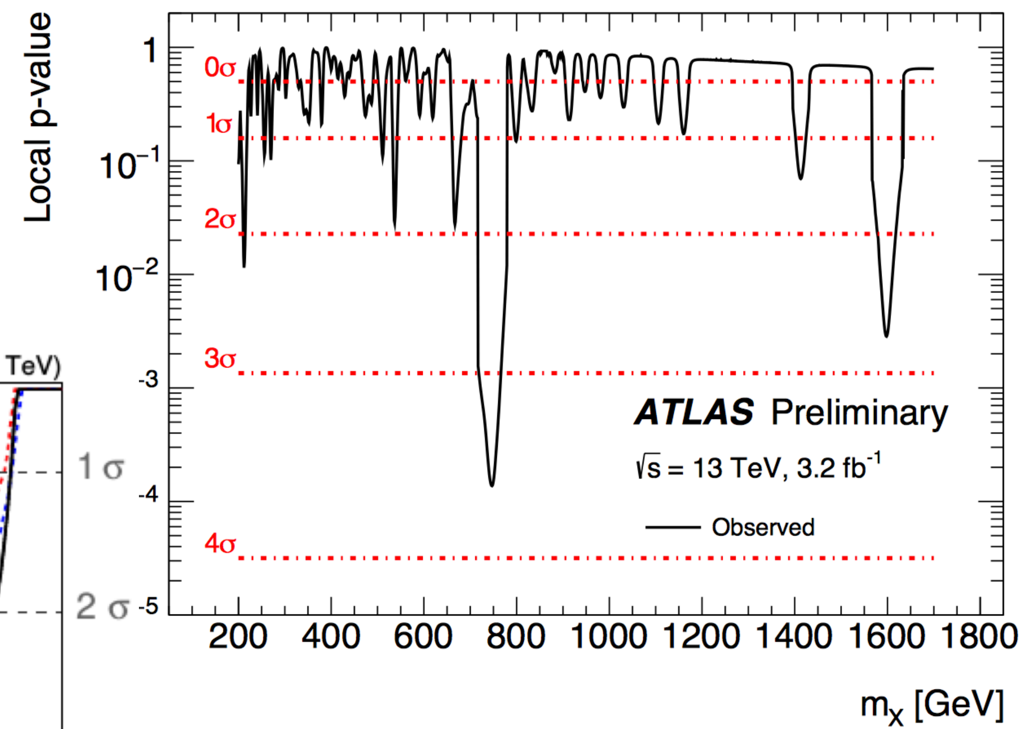
A Minimal Explanation

Statistical Fluctuation

For the rest of this talk I will try not to repeat “if it is real” etc.

What is it?





Would be crazy to ignore this one.

What is it?

<u>Only data will tell.</u>

Know only one thing for certain...

What is it?

It is called:

$$F$$

\digamma

Plan for this talk

- First focus on upcoming experimental observables, guided by the simplest class of models: Singlet Scalar coupled to SM fields.

- Along the way, can we answer some big picture questions using these observables?
  - Invisible decays: Something to do with DM?
  - CP: A Higgs? A Goldstone boson?
  - Width: Weakly or Strongly interacting?
  - Pair production: Other resonances?

- Finish with a sampling menu of other interesting models.

What is it?

- I am a theorist.

$$N \cdot \begin{cases} e^{-t^2/2} & \text{if } -\alpha_{\text{low}} \geq t \geq \alpha_{\text{high}} \\ \dfrac{e^{-0.5\alpha_{\text{low}}^2}}{\left[\frac{\alpha_{\text{low}}}{n_{\text{low}}}\left(\frac{n_{\text{low}}}{\alpha_{\text{low}}} - \alpha_{\text{low}} - t\right)\right]^{n_{\text{low}}}} & \text{if } t < -\alpha_{\text{low}} \\ \dfrac{e^{-0.5\alpha_{\text{high}}^2}}{\left[\frac{\alpha_{\text{high}}}{n_{\text{high}}}\left(\frac{n_{\text{high}}}{\alpha_{\text{high}}} - \alpha_{\text{high}} + t\right)\right]^{n_{\text{high}}}} & \text{if } t > \alpha_{\text{high}}, \end{cases}$$

- My crystal ball does not look like this.

What is it?

- I am a theorist.

$$\mathcal{L}_5^{CP-even} = \frac{F}{\Lambda}\Big[c_{gg}\frac{g_3^2}{2}G^a_{\mu\nu}G^{a\,\mu\nu} + c_{WW}\frac{g_2^2}{2}W^a_{\mu\nu}W^{a\,\mu\nu} + c_{BB}\frac{g_1^2}{2}B_{\mu\nu}B^{\mu\nu}$$

$$+ c_\psi\left(H\bar{\psi}_L\psi_R + h.c.\right) + c_H|D_\mu H|^2 - c'_H(|H|^4 - v^4)\Big]$$

- My crystal ball looks like this.

What is it?

- Effective field theory is the appropriate tool when you do not know the full theory.
- For first part of talk, assume singlet scalar.

$$\mathcal{L}_5^{CP-even} = \frac{F}{\Lambda}\Big[c_{gg}\frac{g_3^2}{2}G^a_{\mu\nu}G^{a\,\mu\nu} + c_{WW}\frac{g_2^2}{2}W^a_{\mu\nu}W^{a\,\mu\nu} + c_{BB}\frac{g_1^2}{2}B_{\mu\nu}B^{\mu\nu}$$
$$+ c_\psi\left(H\bar{\psi}_L\psi_R + h.c.\right) + c_H|D_\mu H|^2 - c'_H(|H|^4 - v^4)\Big]$$

- Write down all operators (couplings) consistent with symmetries.
- If a scale separation present ($M_F \ll \Lambda$) this EFT should accurately capture all pheno.

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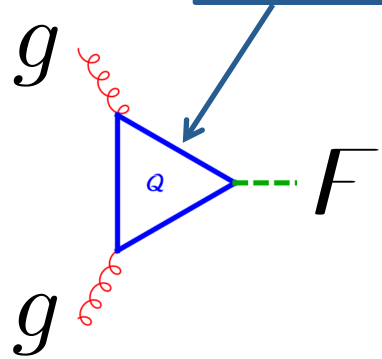
$$\left. + c_\psi\left(H\bar{\psi}_L\psi_R + h.c.\right) + c_H|D_\mu H|^2 - c'_H(|H|^4 - v^4)\right]$$

- Coupling to gluons…

New coloured fields!



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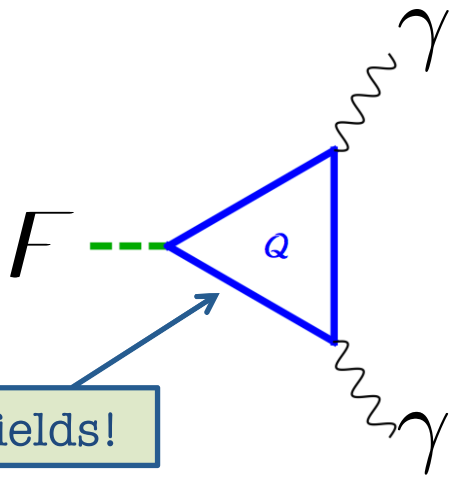
- Coupling to photons, W, Z, h…



New $U(1)_Y$, $SU(2)_W$ charged fields!

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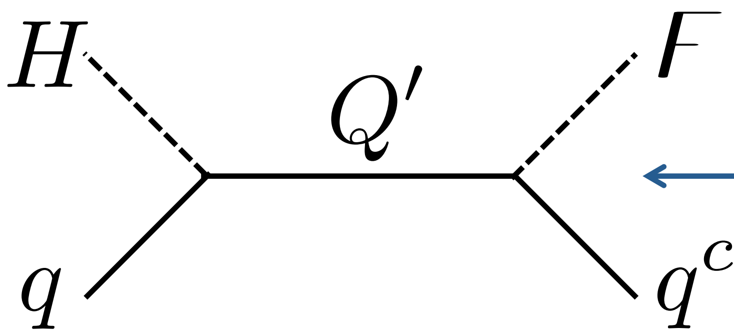
$$\left. + c_\psi\left(H\bar{\psi}_L\psi_R + h.c.\right) + c_H|D_\mu H|^2 - c'_H(|H|^4 - v^4)\right]$$

- Comes from…



Can arise at tree-level. Need new heavy quarks, or extended scalar sector (2HDM).

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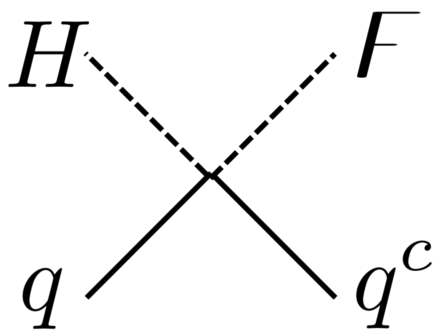
$$+ c_\psi\left(H\bar{\psi}_L\psi_R + h.c.\right) + c_H|D_\mu H|^2 - c'_H(|H|^4 - v^4)\Big]$$

- ...after integrating out heavy fields...



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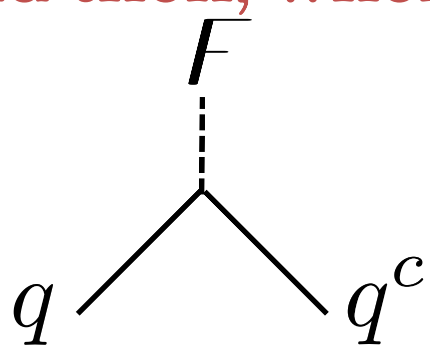
$$\left. + c_\psi\left(H\bar{\psi}_L\psi_R + h.c.\right) + c_H|D_\mu H|^2 - c'_H(|H|^4 - v^4)\right]$$

- ... and then, whenever $H \to \frac{v+h}{\sqrt{2}}$



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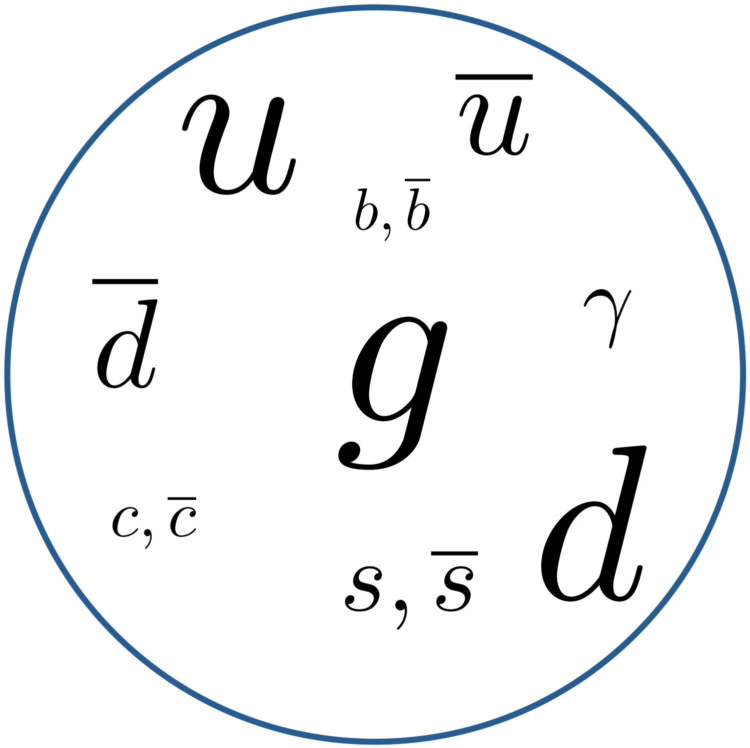
$$+ c_\psi\left(H\bar{\psi}_L\psi_R + h.c.\right) + c_H|D_\mu H|^2 - c'_H(|H|^4 - v^4)\Big]$$

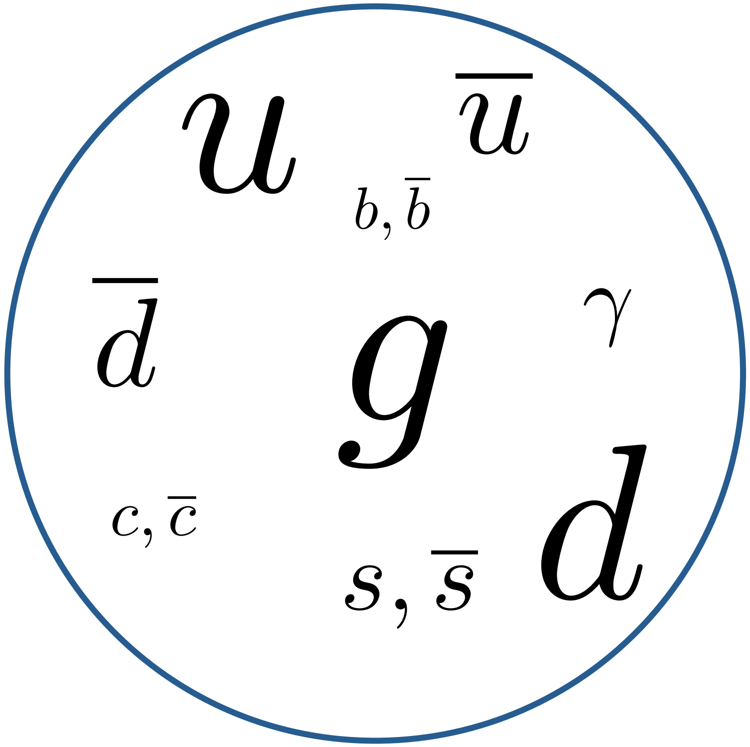
- This is everything you need for a low energy description!

What makes it?

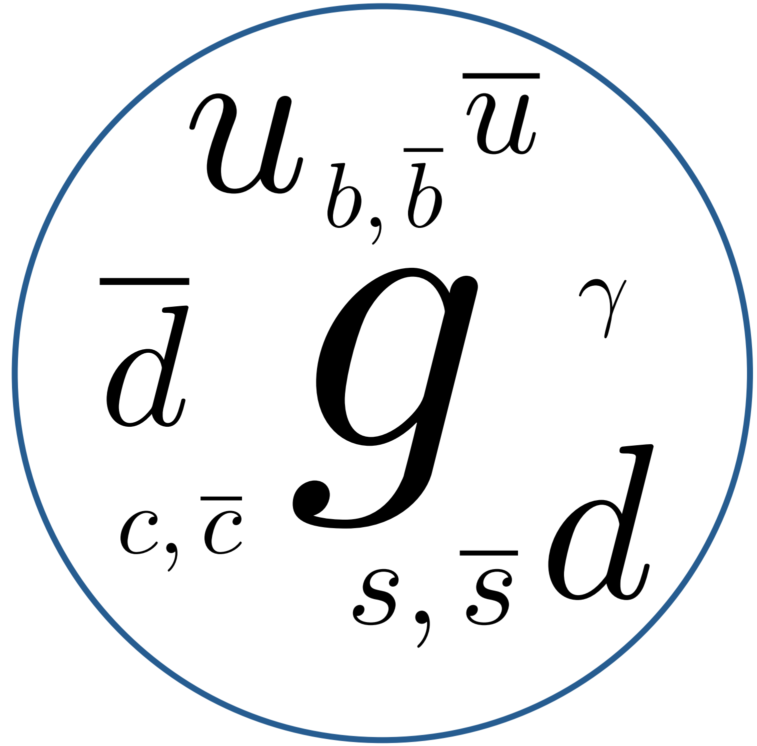


A proton at 8 TeV,
probed at 750 GeV.

What makes it?

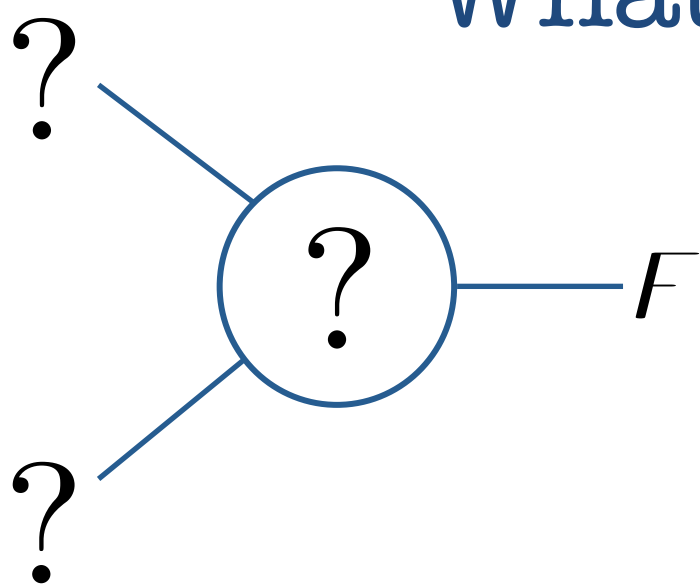


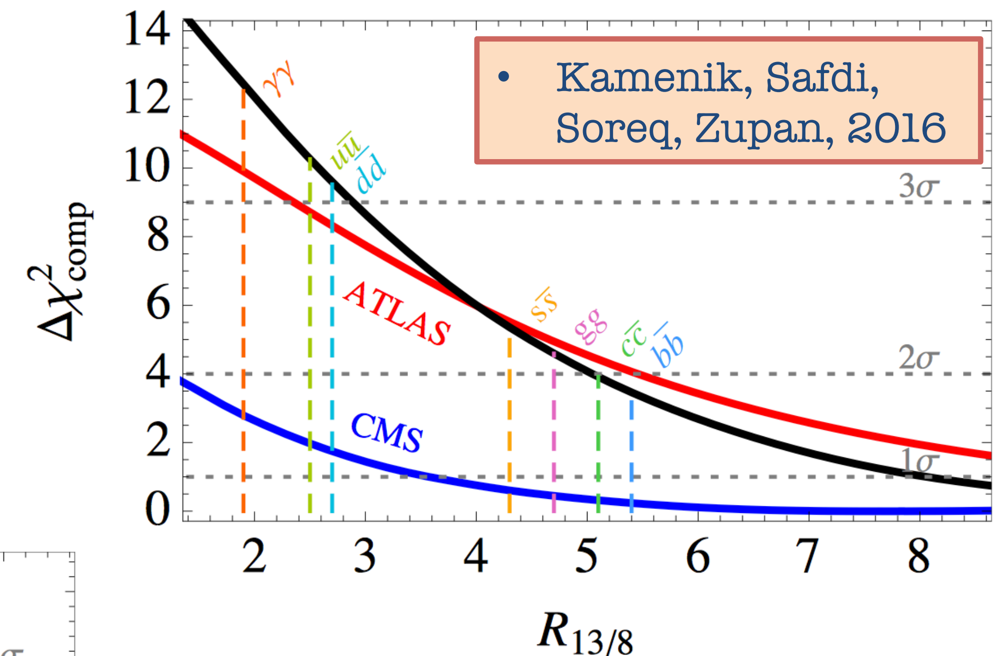
A proton at 8 TeV, probed at 750 GeV.

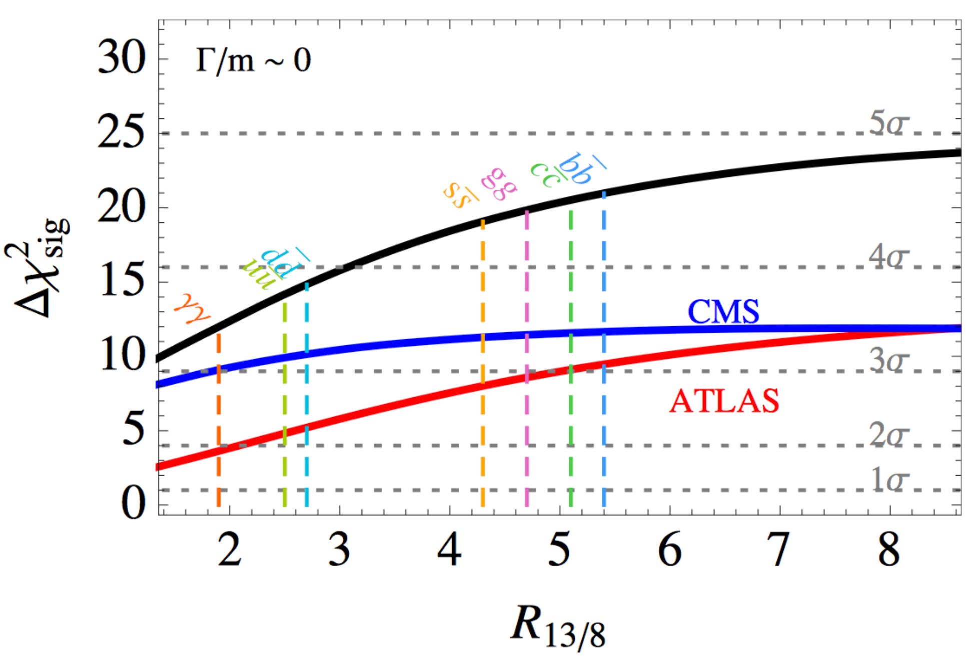


A proton at 13 TeV, probed at 750 GeV.

What makes it?



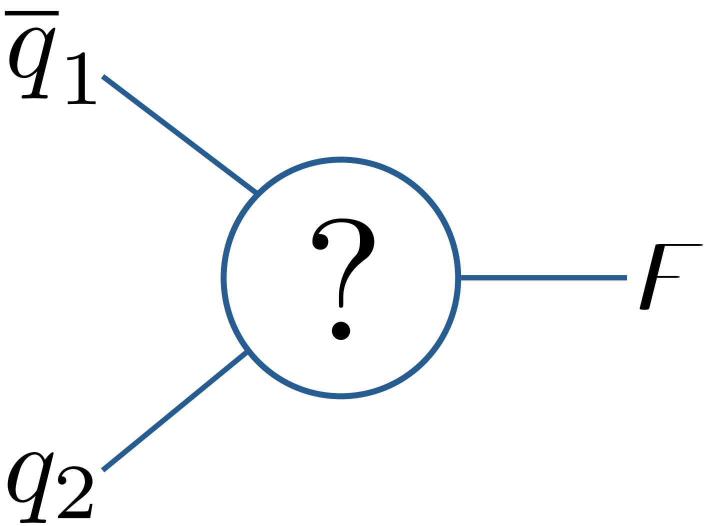




Surprisingly, we already have some pretty good guidance on production modes simply by comparing Run I and Run II.

Valence quarks, photons, disfavoured.

What makes it?



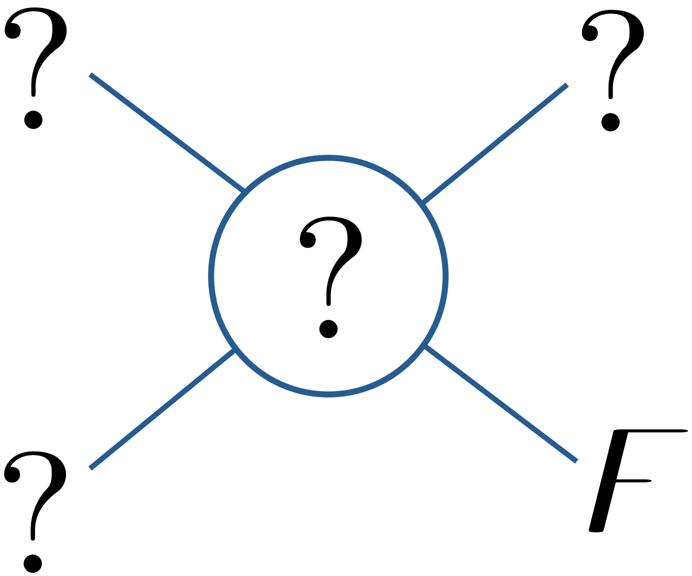
Flavour constraints already very tough, so off-diagonal couplings to quarks must be extremely small.

Flavour-diagonal production implied.

Observable	Bound
Δm_K	$\sqrt{\mathrm{Re}\, c_{sd} c^*_{ds}} < 2 \times 10^{-4}\, (\Lambda/\mathrm{TeV})$
ϵ_K	$\sqrt{\mathrm{Im}\, c_{sd} c^*_{ds}} < 1 \times 10^{-5}\, (\Lambda/\mathrm{TeV})$
Δm_D	$\sqrt{\mathrm{Re}\, c_{cu} c^*_{uc}} < 7 \times 10^{-4}\, (\Lambda/\mathrm{TeV})$
$\lvert q/p \rvert, \phi_D$	$\sqrt{\mathrm{Im}\, c_{cu} c^*_{uc}} < 3 \times 10^{-4}\, (\Lambda/\mathrm{TeV})$
Δm_{B_d}	$\sqrt{\mathrm{Re}\, c_{bd} c^*_{db}} < 2 \times 10^{-3}\, (\Lambda/\mathrm{TeV})$
$S_{\psi K_s}$	$\sqrt{\mathrm{Im}\, c_{bd} c^*_{db}} < 1 \times 10^{-3}\, (\Lambda/\mathrm{TeV})$
Δm_{B_s}	$\sqrt{\mathrm{Re}\, c_{bs} c^*_{sb}} < 1 \times 10^{-2}\, (\Lambda/\mathrm{TeV})$

Table from: "What next?" Franceschini, Giudice, Kamenik, MM, Riva, Strumia, Torre. 2016

What makes it?



In the longer term we will be able to use associated production to determine production modes.

		F couples to					
$\sqrt{s} = 13\,\text{TeV}$	eq.	$b\bar{b}$	$c\bar{c}$	$s\bar{s}$	$u\bar{u}$	$d\bar{d}$	GG
σ_{Fj}/σ_F	(20a)	9.2%	7.6%	6.8%	6.7%	6.2%	27.%
σ_{Fb}/σ_F	(20b)	6.2%	0	0	0	0	0.32%
σ_{Fjj}/σ_F	(20c)	1.4%	1.0%	0.95%	1.2%	1.0%	4.7%
σ_{Fjb}/σ_F	(20d)	1.2%	0.18%	0.19%	0.34%	0.31%	0.096%
σ_{Fbb}/σ_F	(20e)	0.31%	0.17%	0.18%	0.34%	0.31%	0.024%
$\sigma_{F\gamma}/\sigma_F$	(28b)	0.37%	1.5%	0.38%	1.6%	0.41%	$\ll 10^{-6}$
σ_{FZ}/σ_F	(28b)	1.1%	1.1%	1.3%	2.0%	1.9%	$3\ 10^{-6}$
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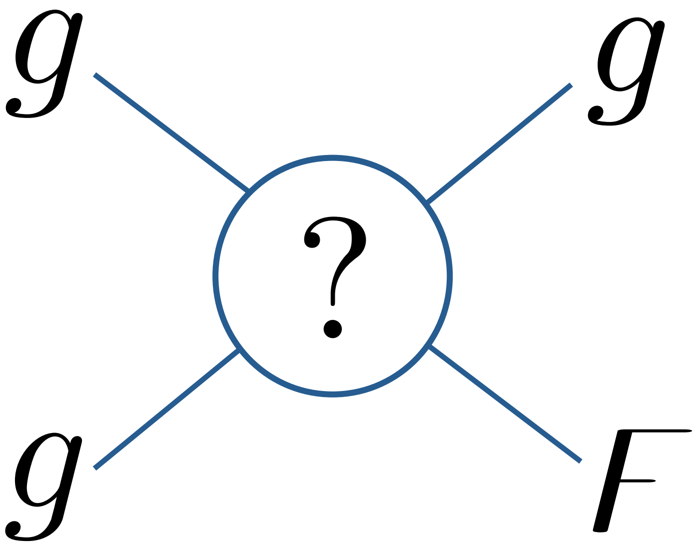

If it is produced by gluon fusion, this can be distinguished from quark production due to large fraction of additional jets.

$\sqrt{s} = 13\,\text{TeV}$	eq.	F couples to $b\bar{b}$	$c\bar{c}$	$s\bar{s}$	$u\bar{u}$	$d\bar{d}$	GG
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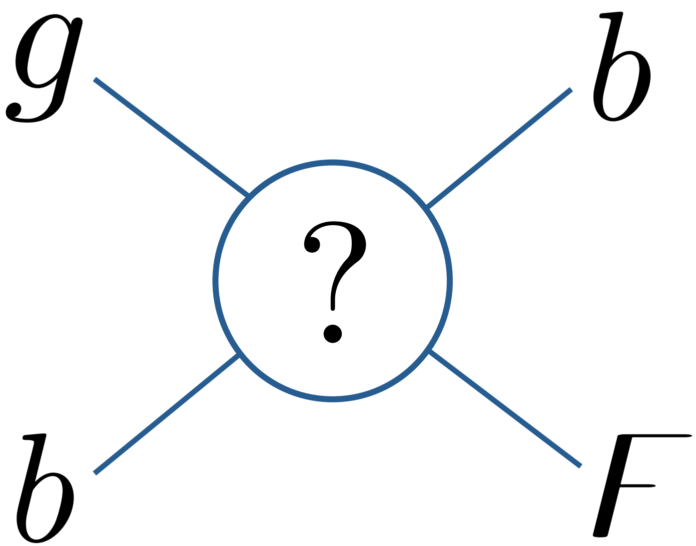

If it is produced from bottom quarks, this can be distinguished from other channels by large associated bottom-quark production.

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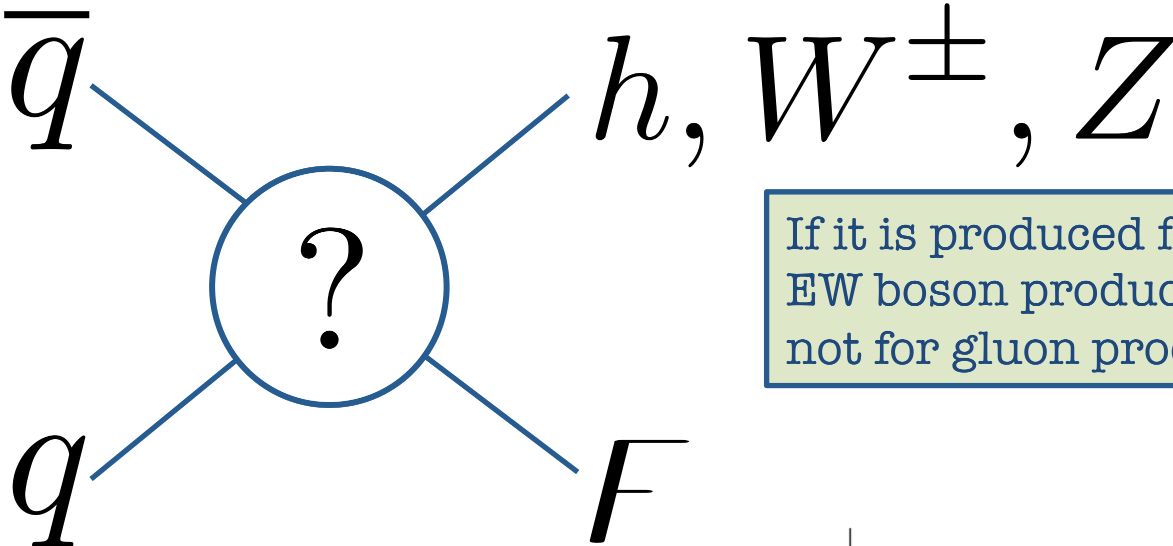

If it is produced from quarks, associated EW boson production is expected, but not for gluon production.

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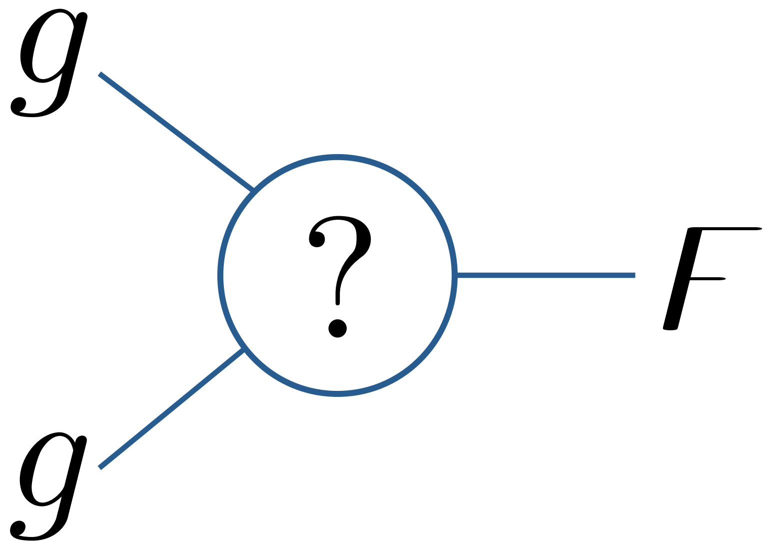
Table from:
"What next?"
Franceschini, Giudice, Kamenik, MM, Riva, Strumia, Torre. 2016

What do we learn?

- Produced from



- Means new coloured states just around the corner.

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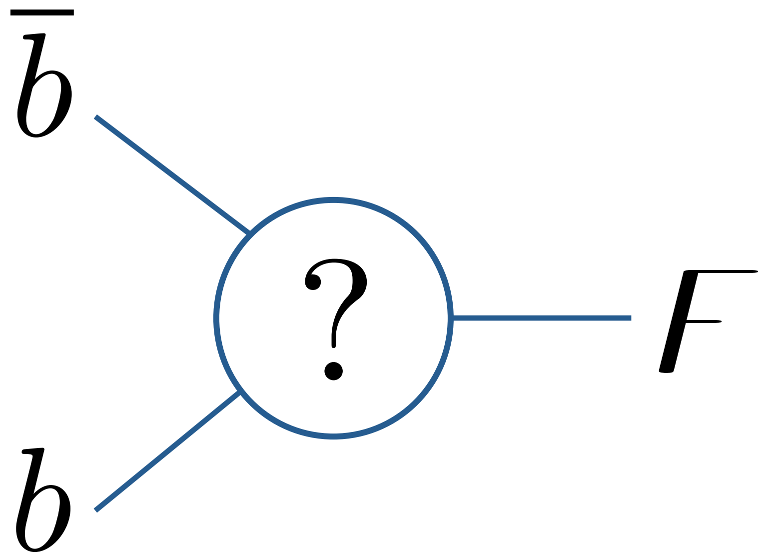

- Means it might be related to the Higgs sector. Maybe 2HDM? Maybe new third-generation related heavy quarks?

What do we learn?

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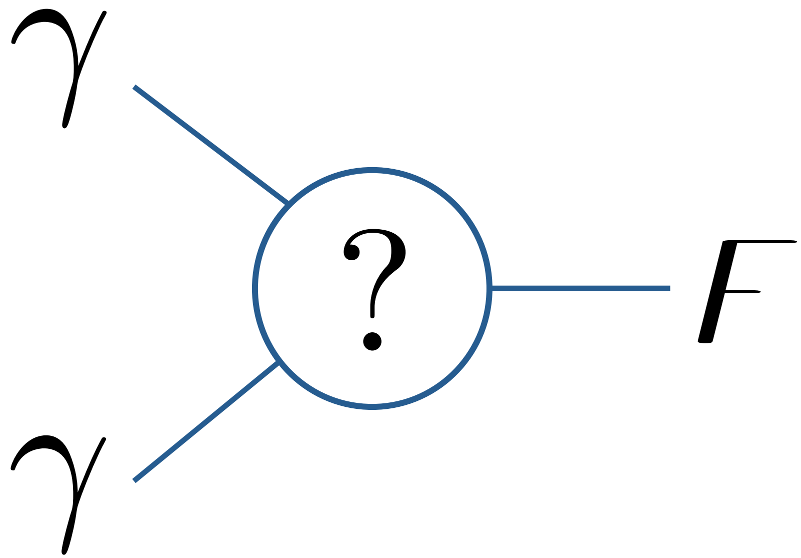
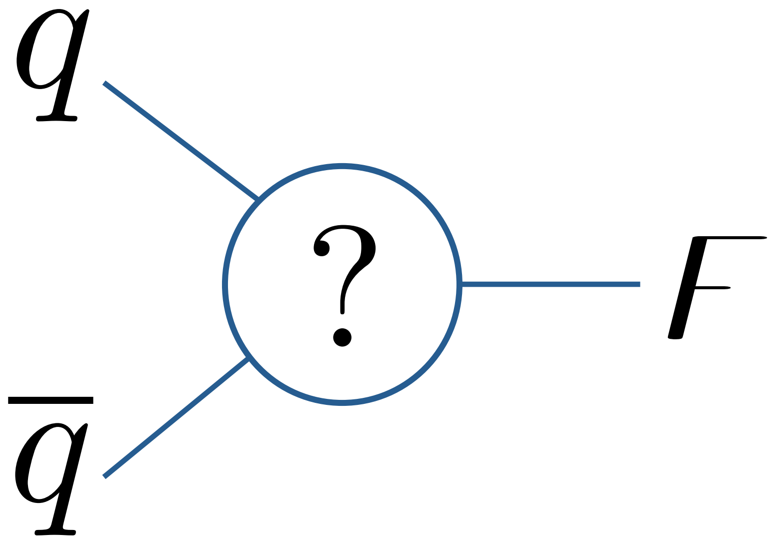


- Means large couplings/multiplicities of new electrically charged states. New physics weak-sector only?

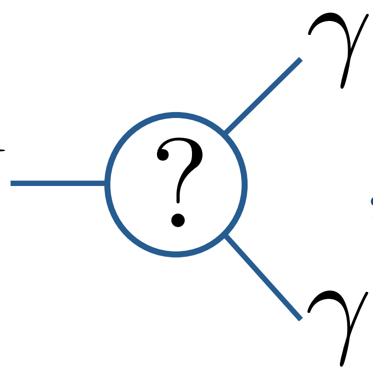
What do we learn?

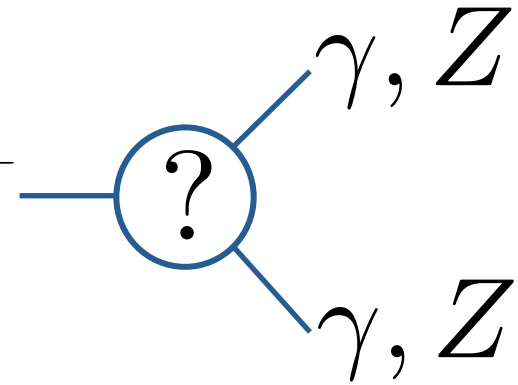
- Produced from



- I have no idea what is going on if this is the case...

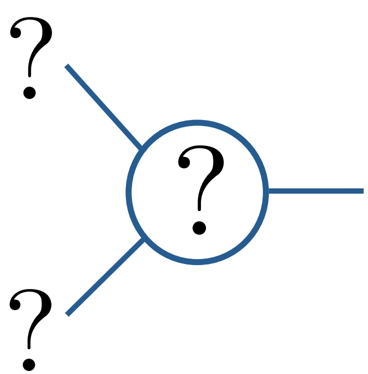
What does it decay to?

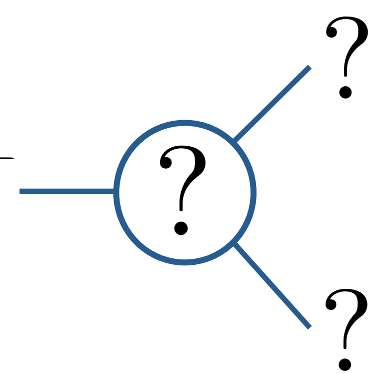
- Photons F 

, bosons F 

,

and whatever makes it...



F implies F 

,

and probably other things as well...

What does it decay to?

- Excess already points towards 3 fb in digamma.

$\sigma(pp \to \gamma\gamma)$	$\sqrt{s} = 8\,\text{TeV}$ narrow	broad	$\sqrt{s} = 13\,\text{TeV}$ narrow	broad
CMS	$0.63 \pm 0.31\,\text{fb}$	$0.99 \pm 1.05\,\text{fb}$	$4.8 \pm 2.1\,\text{fb}$	$7.7 \pm 4.8\,\text{fb}$
ATLAS	$0.21 \pm 0.22\,\text{fb}$	$0.88 \pm 0.46\,\text{fb}$	$5.5 \pm 1.5\,\text{fb}$	$7.6 \pm 1.9\,\text{fb}$

Other channels already place interesting constraints, and set the scene for the cross section required for discovery in other other decay modes.

final state f	σ at $\sqrt{s} = 8\,\text{TeV}$ observed	expected	ref.	σ at $\sqrt{s} = 13\,\text{TeV}$ observed	expected	ref.
$e^+e^-, \mu^+\mu^-$	< 1.2 fb	< 1.2 fb	[3]	< 5 fb	< 5 fb	[259]
$\tau^+\tau^-$	< 12 fb	< 15 fb	[3]	< 60 fb	< 67 fb	[260]
$Z\gamma$	< 11 fb	< 11 fb	[3]	< 28 fb	< 40 fb	[261]
ZZ	< 12 fb	< 20 fb	[3]	< 200 fb	< 220 fb	[262]
Zh	< 19 fb	< 28 fb	[3]	< 116 fb	< 116 fb	[263]
hh	< 39 fb	< 42 fb	[3]	< 120 fb	< 110 fb	[264]
W^+W^-	< 40 fb	< 70 fb	[3]	< 300 fb	< 300 fb	[265]
$t\bar{t}$	< 450 fb	< 600 fb	[3]			
invisible	< 0.8 pb	-	[3]			
$b\bar{b}$	$\lesssim 1$ pb	$\lesssim 1$ pb	[3]			
jj	$\lesssim 2.5$ pb	-	[3]			

What does it decay to?

- Excess already points towards 3 fb in digamma.

$\sigma(pp \to \gamma\gamma)$	$\sqrt{s} = 8\,\mathrm{TeV}$ narrow	$\sqrt{s} = 8\,\mathrm{TeV}$ broad	$\sqrt{s} = 13\,\mathrm{TeV}$ narrow	$\sqrt{s} = 13\,\mathrm{TeV}$ broad
CMS	$0.63 \pm 0.31\,\mathrm{fb}$	$0.99 \pm 1.05\,\mathrm{fb}$	$4.8 \pm 2.1\,\mathrm{fb}$	$7.7 \pm 4.8\,\mathrm{fb}$
ATLAS	$0.21 \pm 0.22\,\mathrm{fb}$	$0.88 \pm 0.46\,\mathrm{fb}$	$5.5 \pm 1.5\,\mathrm{fb}$	$7.6 \pm 1.9\,\mathrm{fb}$

Lepton decays strongly constrained. Already puts universal graviton in tension.

final state f	σ at $\sqrt{s} = 8\,\mathrm{TeV}$ observed	expected	ref.	σ at $\sqrt{s} = 13\,\mathrm{TeV}$ observed	expected	ref.
$e^+e^-, \mu^+\mu^-$	< 1.2 fb	< 1.2 fb	[3]	< 5 fb	< 5 fb	[259]
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$b\bar{b}$	$\lesssim 1$ pb	$\lesssim 1$ pb	[3]			
jj	$\lesssim 2.5$ pb	-	[3]			

What does it decay to?

- Excess already points towards 3 fb in digamma.

$\sigma(pp \to \gamma\gamma)$	$\sqrt{s} = 8\,\text{TeV}$		$\sqrt{s} = 13\,\text{TeV}$	
	narrow	broad	narrow	broad
CMS	$0.63 \pm 0.31\,\text{fb}$	$0.99 \pm 1.05\,\text{fb}$	$4.8 \pm 2.1\,\text{fb}$	$7.7 \pm 4.8\,\text{fb}$
ATLAS	$0.21 \pm 0.22\,\text{fb}$	$0.88 \pm 0.46\,\text{fb}$	$5.5 \pm 1.5\,\text{fb}$	$7.6 \pm 1.9\,\text{fb}$

Weak decays very interesting. Already rules out significant mixing with the Higgs.

final state f	σ at $\sqrt{s} = 8\,\text{TeV}$ observed	expected	ref.	σ at $\sqrt{s} = 13\,\text{TeV}$ observed	expected	ref.
$e^+e^-, \mu^+\mu^-$	< 1.2 fb	< 1.2 fb	[3]	< 5 fb	< 5 fb	[259]
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jj	$\lesssim 2.5$ pb	-	[3]			

What does it decay to?

- Excess already points towards 3 fb in digamma.

$\sigma(pp \to \gamma\gamma)$	$\sqrt{s} = 8$ TeV narrow	$\sqrt{s} = 8$ TeV broad	$\sqrt{s} = 13$ TeV narrow	$\sqrt{s} = 13$ TeV broad
CMS	0.63 ± 0.31 fb	0.99 ± 1.05 fb	4.8 ± 2.1 fb	7.7 ± 4.8 fb
ATLAS	0.21 ± 0.22 fb	0.88 ± 0.46 fb	5.5 ± 1.5 fb	7.6 ± 1.9 fb

final state f	σ at $\sqrt{s} = 8$ TeV observed	expected	ref.	σ at $\sqrt{s} = 13$ TeV observed	expected	ref.
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$b\bar{b}$	$\lesssim 1$ pb	$\lesssim 1$ pb	[3]			
jj	$\lesssim 2.5$ pb	-	[3]			

Top decays already so constraining that they cannot be “coloured guys in loop”.

What does it decay to?

- Excess already points towards 3 fb in digamma.

$\sigma(pp \to \gamma\gamma)$	$\sqrt{s} = 8\,\mathrm{TeV}$		$\sqrt{s} = 13\,\mathrm{TeV}$	
	narrow	broad	narrow	broad
CMS	0.63 ± 0.31 fb	0.99 ± 1.05 fb	4.8 ± 2.1 fb	7.7 ± 4.8 fb
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final state f	σ at $\sqrt{s} = 8\,\mathrm{TeV}$ observed	expected	ref.	σ at $\sqrt{s} = 13\,\mathrm{TeV}$ observed	expected	ref.
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$t\bar{t}$	< 450 fb	< 600 fb	[3]			
invisible	< 0.8 pb	-	[3]			
$b\bar{b}$	$\lesssim 1$ pb	$\lesssim 1$ pb	[3]			
jj	$\lesssim 2.5$ pb	-	[3]			

B-quark decays not too important yet.

What does it decay to?

- Excess already points towards 3 fb in digamma.

$\sigma(pp \to \gamma\gamma)$	$\sqrt{s} = 8\,\text{TeV}$ narrow	$\sqrt{s} = 8\,\text{TeV}$ broad	$\sqrt{s} = 13\,\text{TeV}$ narrow	$\sqrt{s} = 13\,\text{TeV}$ broad
CMS	0.63 ± 0.31 fb	0.99 ± 1.05 fb	4.8 ± 2.1 fb	7.7 ± 4.8 fb
ATLAS	0.21 ± 0.22 fb	0.88 ± 0.46 fb	5.5 ± 1.5 fb	7.6 ± 1.9 fb

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invisible	< 0.8 pb	-	[3]			
$b\bar{b}$	$\lesssim 1$ pb	$\lesssim 1$ pb	[3]			
jj	$\lesssim 2.5$ pb	-	[3]			

Dijet constraints actually weakest!

What does it decay to?

- Excess already points towards 3 fb in digamma.

$\sigma(pp \to \gamma\gamma)$	$\sqrt{s} = 8\,\text{TeV}$ narrow	broad	$\sqrt{s} = 13\,\text{TeV}$ narrow	broad
CMS	0.63 ± 0.31 fb	0.99 ± 1.05 fb	4.8 ± 2.1 fb	7.7 ± 4.8 fb
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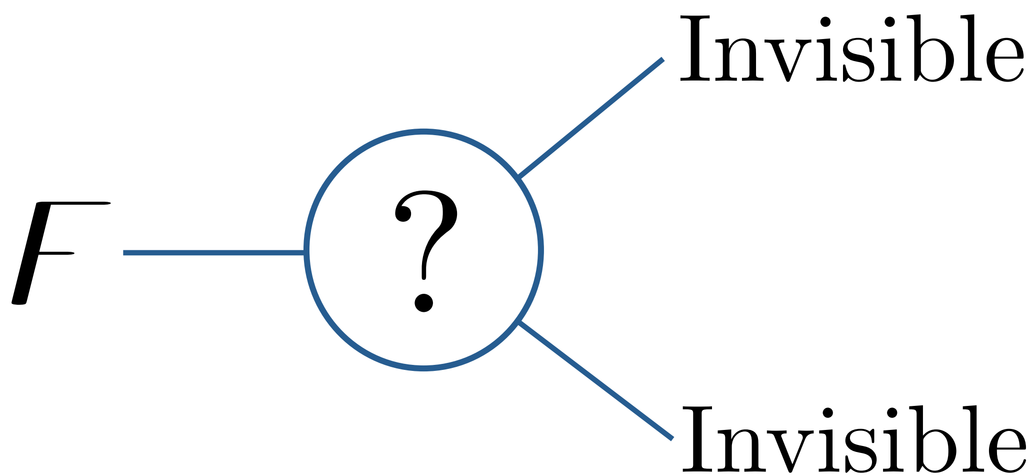
$b\bar{b}$	$\lesssim 1$ pb	$\lesssim 1$ pb	[3]			
jj	$\lesssim 2.5$ pb	-	[3]			

Invisible decays...

What do we learn?

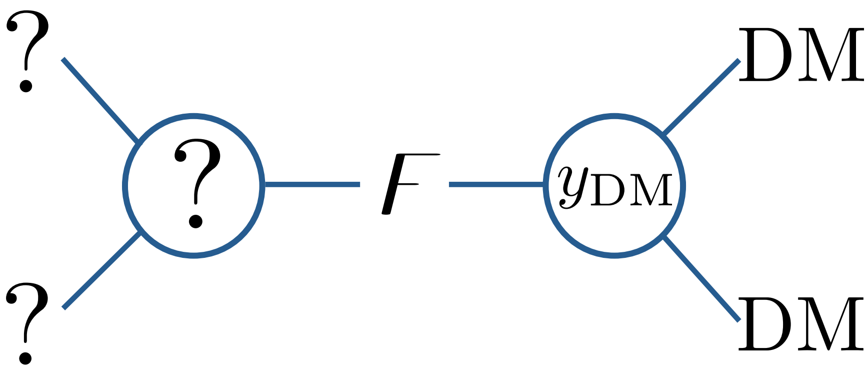
- Decays to



- Would tell us of a connection to the dark sector, giving us our first handle on one of the biggest questions in fundamental physics.

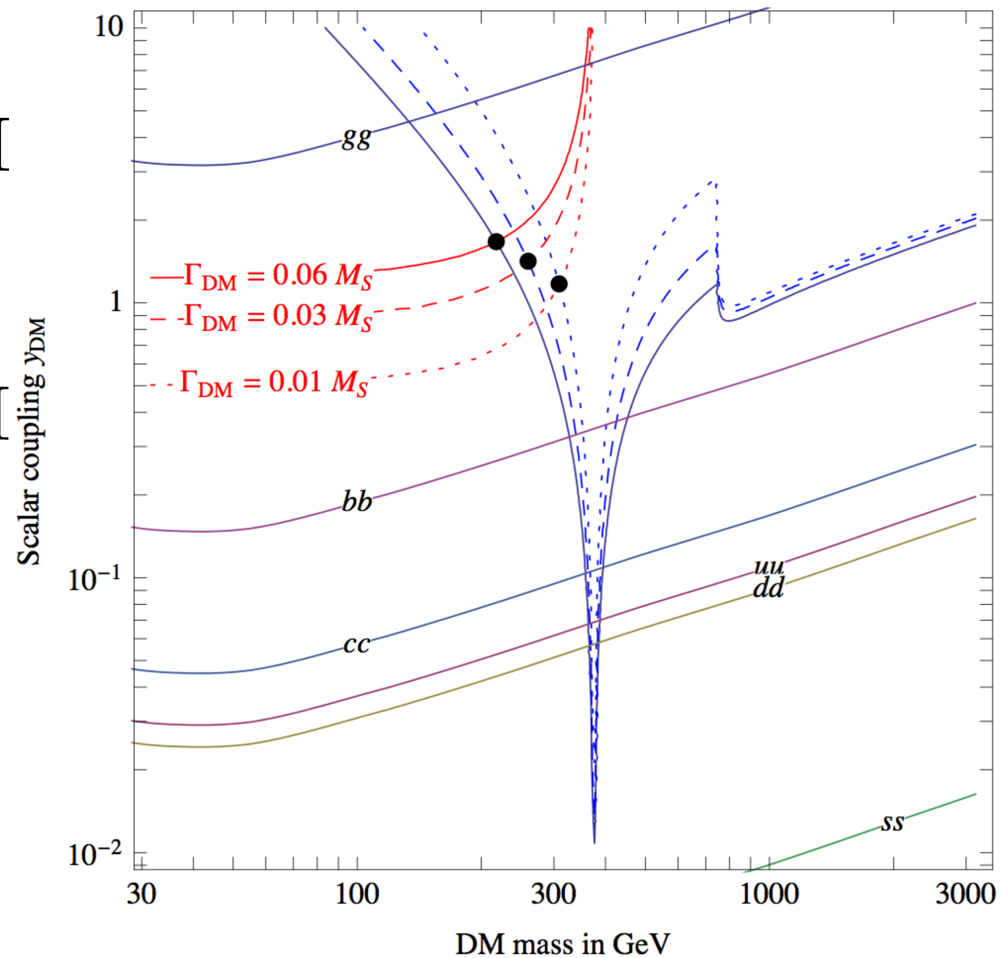
What do we learn?

- In fact, reasonable dark matter connections are possible.



Once the F couplings are chosen, can calculate relic density, direct detection signatures.

Story can be consistent with a dark matter story.



Width 6% everywhere in this plot.

What does it decay to?

- From the effective theory we see that only three parameters

$$c_H, c_{BB}, c_{WW}$$

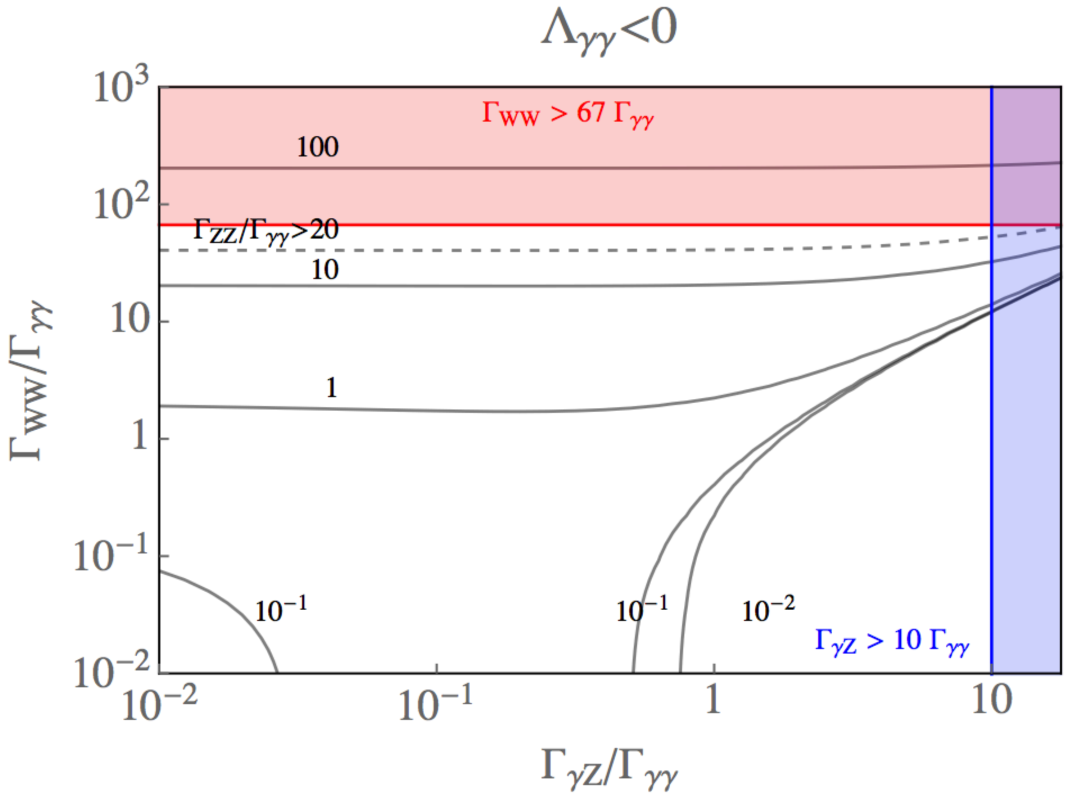
determine the four decays:

$$F \to \gamma\gamma, \gamma Z, ZZ, W^+W^-$$

- Thus, if all were observed, system is over-constrained. Before they are all observed can make predictions!

What does it decay to?

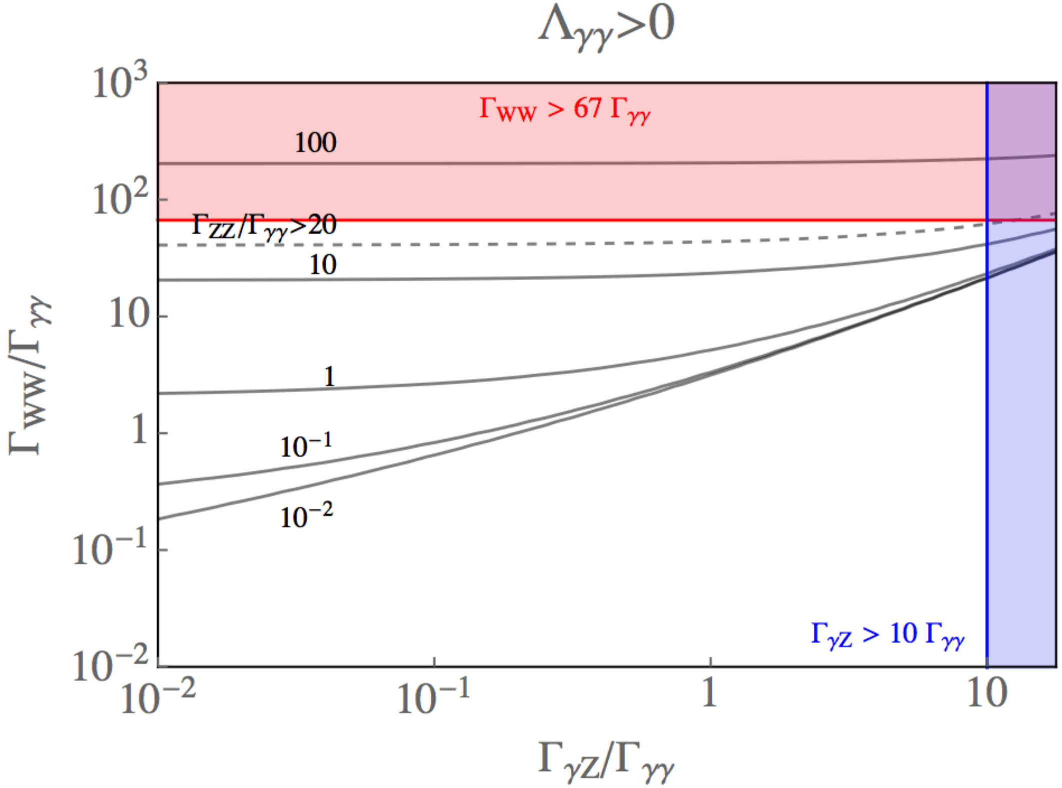
- For CP-even, use ratios to remove one parameter:



- Note cannot have all decays vanishing. One more <u>must</u> exist with measurable branching ratio.
- Constraints already relevant!

What does it decay to?

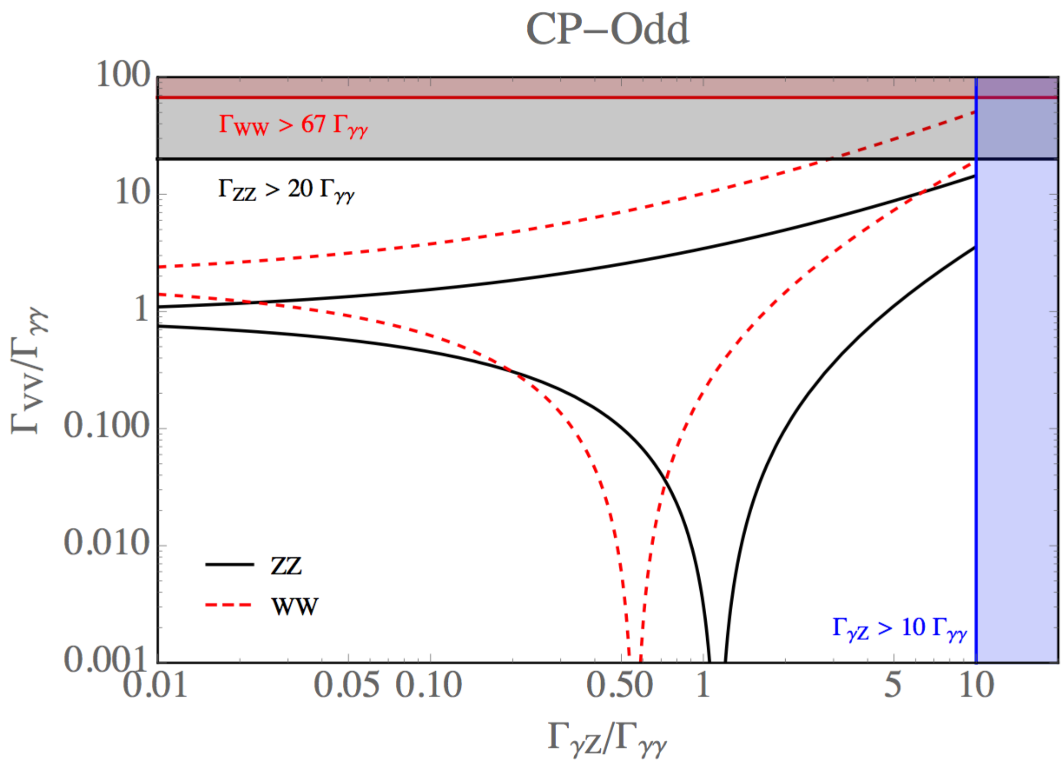
- For CP-even, use ratios to remove one parameter:



- Sign ambiguity for CP-even operator means two plots, similar in asymptotic corners.

What does it decay to?

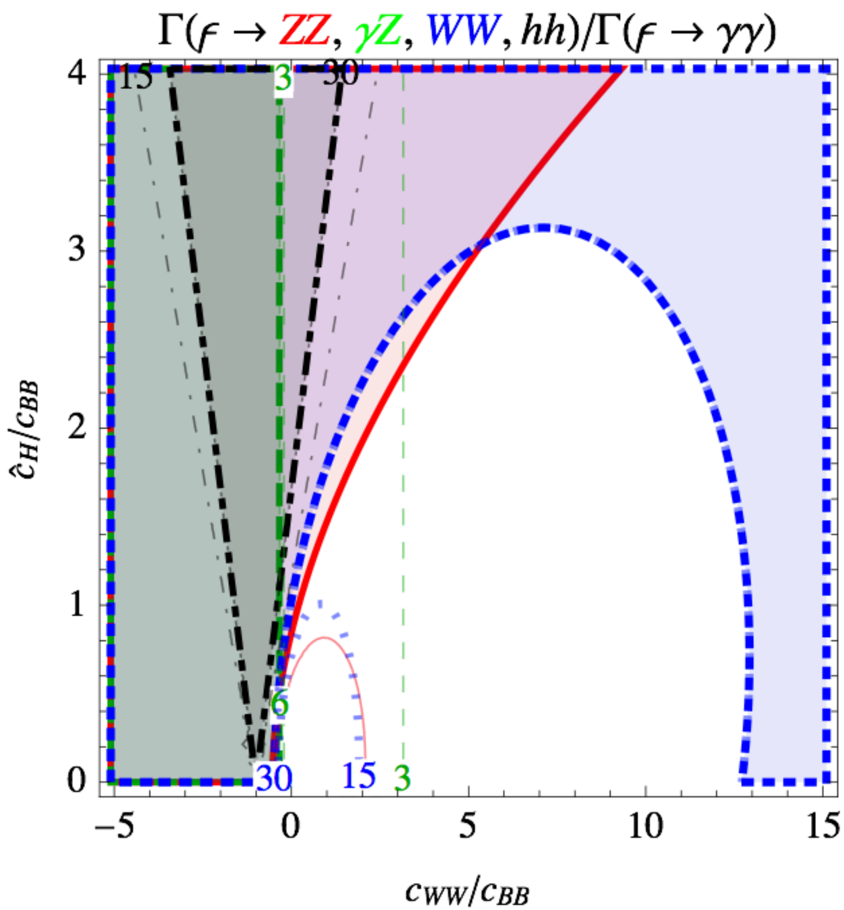
- For CP-odd, even fewer parameters:



- See even more clearly that it is impossible to avoid a signature in another channel!

What we know?

- We already have pretty strong constraints…



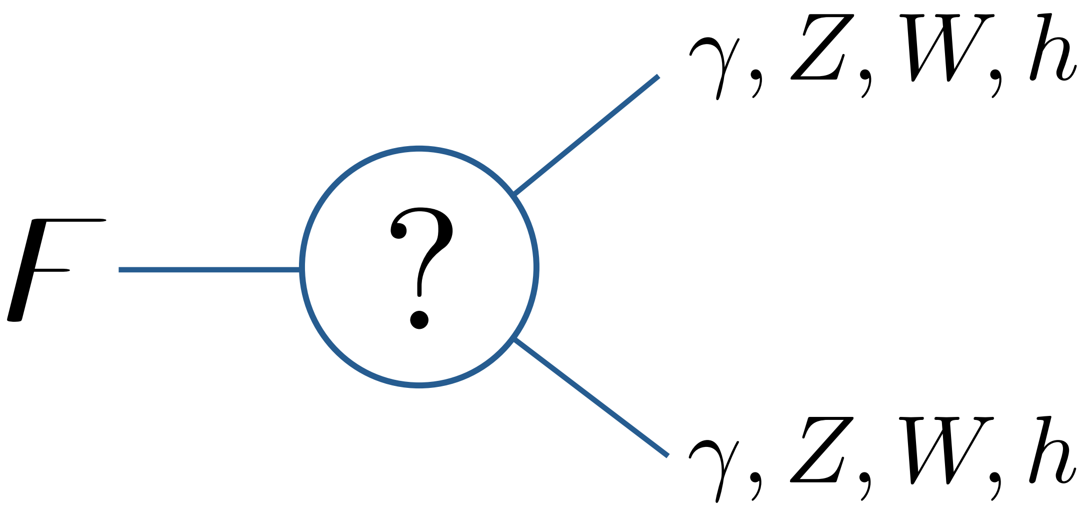
Clearly additional constraints are important. For example, digamma decays coming only from the coupling:

$$c_{WW}\,\frac{g_2^2}{2}\,W^a_{\mu\nu}W^{a\,\mu\nu}$$

are ruled out already! This is important as it means new charged matter in loops must carry hypercharge!

What do we learn?

- Decays to



- Would give
  - Hints on the quantum numbers of new EW states.
  - On mixing with the Higgs.
  - On validity of EFT description.

Pair Production?

- In the longer term, if you can produce it singly, you can produce it doubly.

- Can parameterise in terms of dimension-6 operators

$$\mathscr{L}_6 = \frac{F^2}{\Lambda^2}\Big[c_{gg}^{(6)}\frac{g_3^2}{2}G^a_{\mu\nu}G^{a\,\mu\nu} + c_{WW}^{(6)}\frac{g_2^2}{2}W^a_{\mu\nu}W^{a\,\mu\nu} + c_{BB}^{(6)}\frac{g_1^2}{2}B_{\mu\nu}B^{\mu\nu} + c_\psi^{(6)}\left(H\bar{\psi}_L\psi_R + \text{h.c.}\right)$$
$$+c_H^{(6)}|D_\mu H|^2 - c_H^{(6)\prime}(|H|^4 - v^4)\Big] + \frac{c_{H2}^{(6)}}{\Lambda^2}\frac{(\partial_\mu F)^2}{2}\left(|H|^2 - v^2\right) + \mathcal{O}(F^4)\,,$$

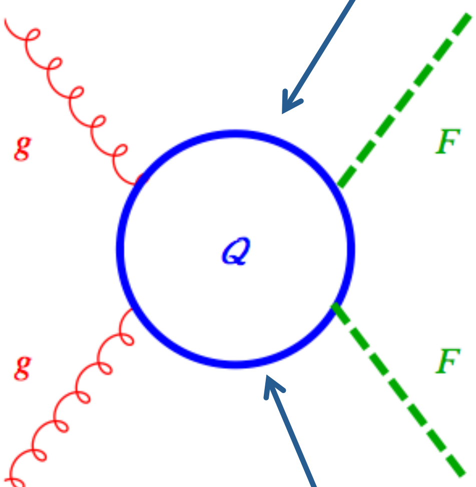
- In fact, this is the most general set of operators.

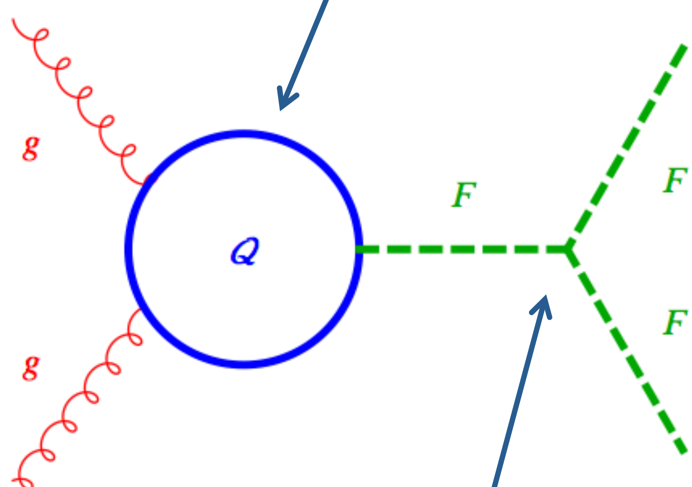
- However, single production gives no guidance on double...

Pair Production?

- If we have a model, we can make predictions based on chosen parameters.

New coloured fields will in general contribute from coupling: $\mathcal{L} \supset y_Q F Q^c Q$



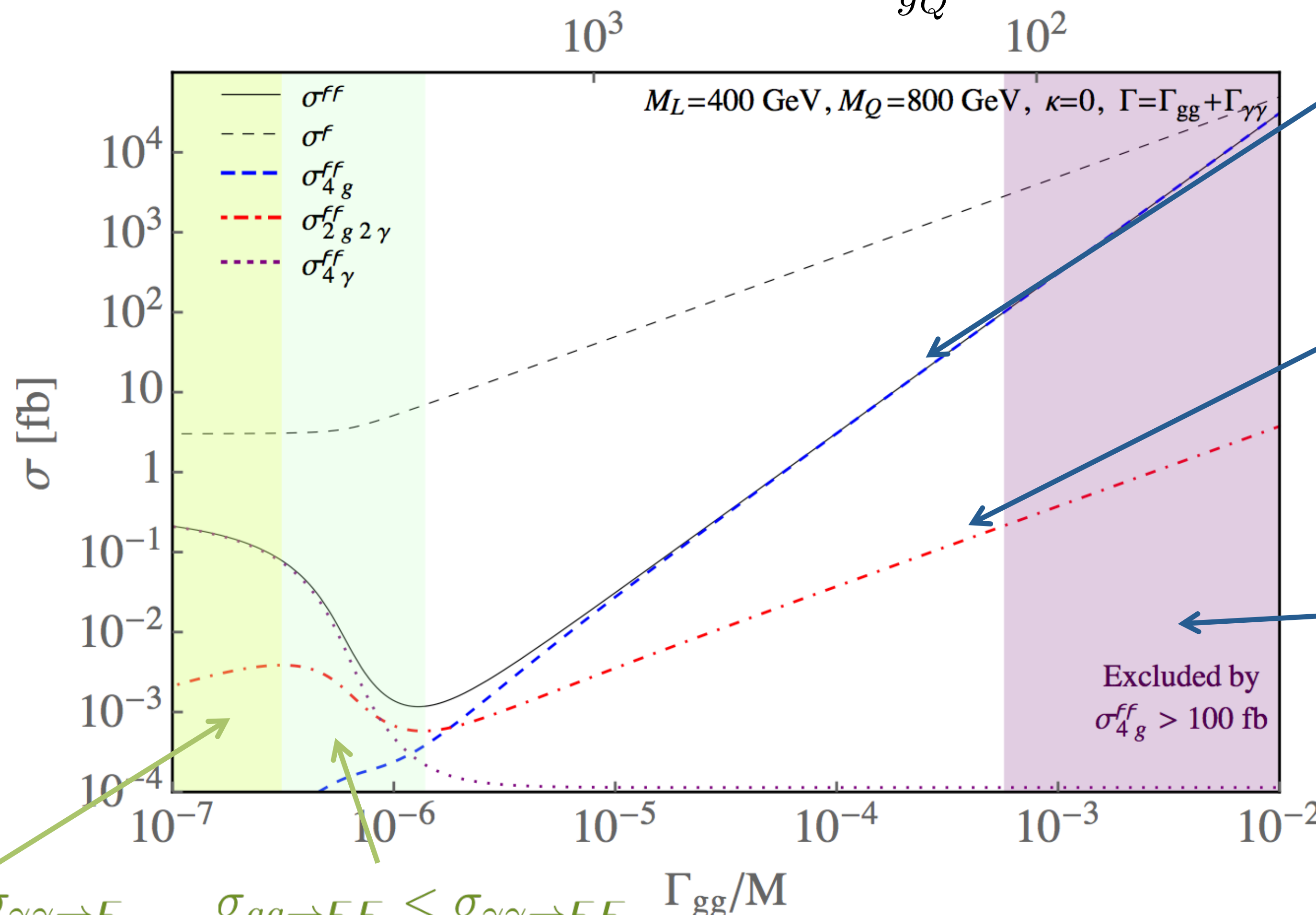


In limit of heavy new fields, results captured by one parameter: $$v_Q = \frac{M_Q}{y_Q}$$

Self-coupling also plays a role!

Pair Production?

- If we have a model, we can make predictions based on chosen parameters. $v_Q\,[\mathrm{GeV}] = \dfrac{M_Q}{y_Q}$



$4g$
final state may show up soon enough.

$2\gamma 2g$
final state may take longer.

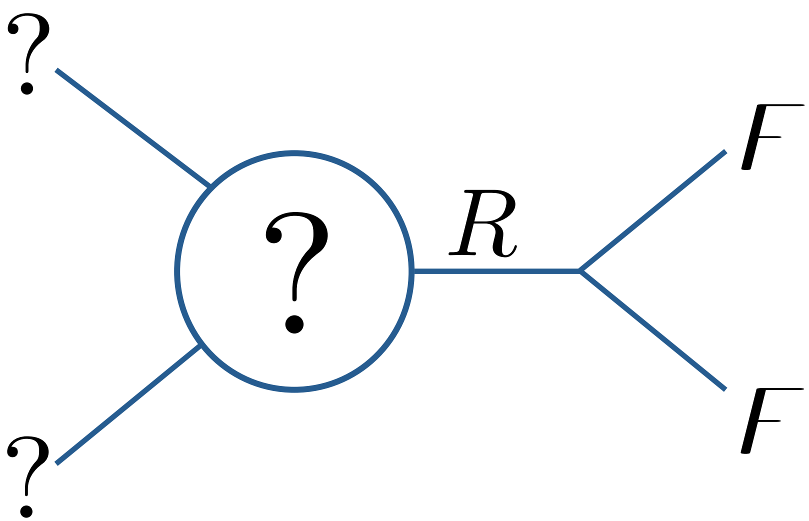
Pair production is already a constraint on this model!

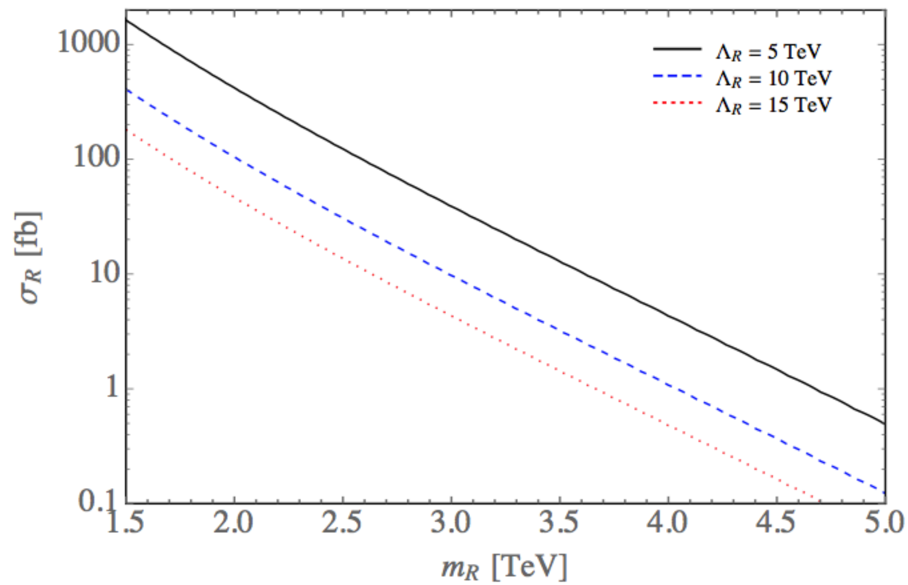
$\sigma_{gg\to F} < \sigma_{\gamma\gamma\to F}$

$\sigma_{gg\to FF} < \sigma_{\gamma\gamma\to FF}$

Pair Production?

- If there are other scalar resonances, pair production could be resonantly enhanced..

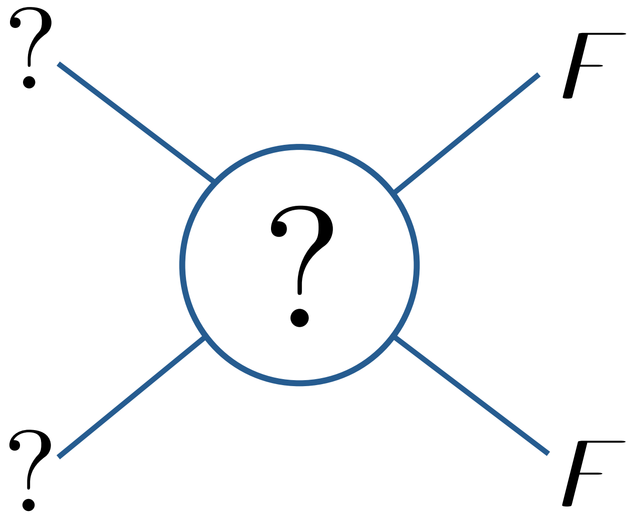




For reasonable parameters "R" production cross section can be large, thus pair production is enhanced.

What do we learn?

- Pair production of the resonance is possible

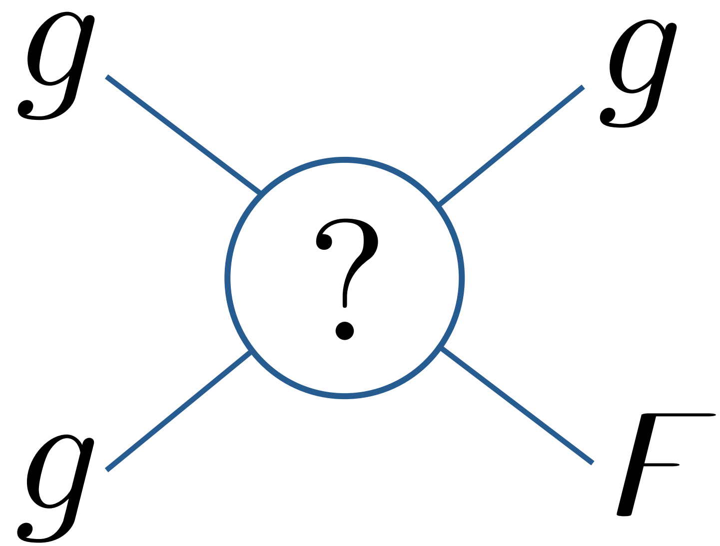


and, if we are lucky, could be observed at the LHC.

- This would give us guidance on the underlying theory and maybe even the self-coupling.
- It could also be the discovery channel for other new scalars!

Is $\mathrm{CP}(F) = F$?

- How might we tell the CP of this state?



Associated production with a single jet cannot discriminate CP. Rates equal for odd and even!

$$
\begin{aligned}
\frac{d\sigma}{dt}(gg \to F g) &= \frac{3 g_3^6}{128 \pi s^2 \Lambda^2}(c_{gg}^2 + \tilde{c}_{gg}^2)\frac{M_F^8 + s^4 + t^4 + u^4}{stu} \\
\frac{d\sigma}{dt}(q\bar{q} \to F g) &= \frac{g_3^2}{36 \pi s^2 \Lambda^2}\left[(c_{gg}^2 + \tilde{c}_{gg}^2)\frac{g_3^4(t^2+u^2)}{s} + \frac{v^2}{2}(c_q^2 + \tilde{c}_q^2)\frac{M_F^4 + s^2}{tu}\right] \\
\frac{d\sigma}{dt}(gq \to F q) &= \frac{-g_3^2}{96 \pi s^2 \Lambda^2}\left[(c_{gg}^2 + \tilde{c}_{gg}^2)\frac{g_3^4(s^2+u^2)}{t} + \frac{v^2}{2}(c_q^2 + \tilde{c}_q^2)\frac{M_F^4 + t^2}{su}\right]
\end{aligned}
$$

Aside, for scalars much machinery can be migrated from work on Higgs. For example, these formulae from classic Higgs+jet text, Ellis, Hinchliffe, Soldate, Van Der Bij, 1988.

Is $\mathrm{CP}(F) = F$?

- How might we tell the CP of this state?

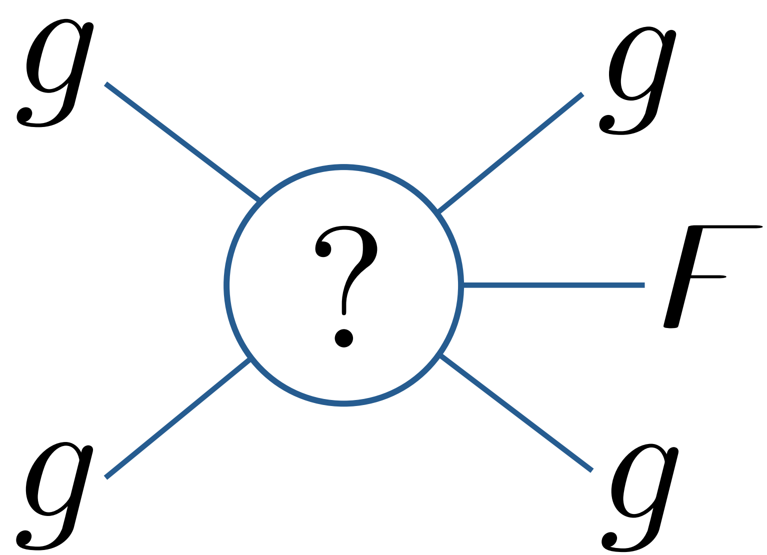
In the associated production process:

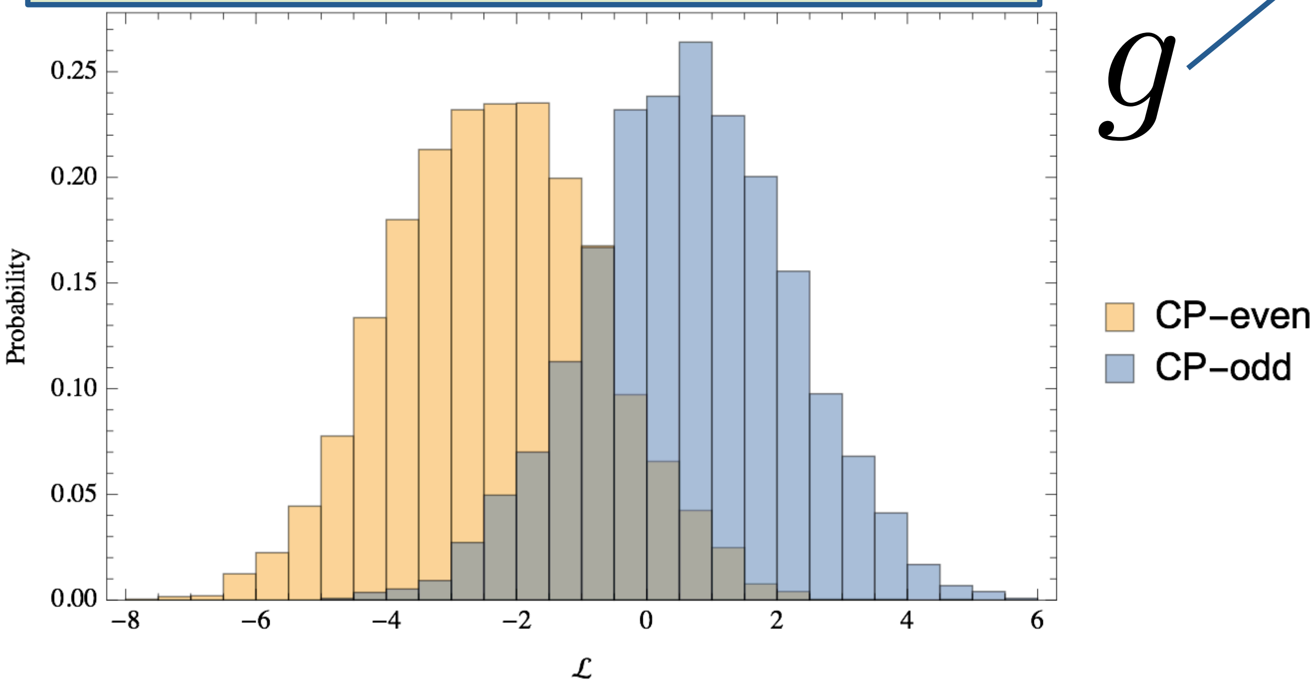
$$pp \to F jj$$

A test statistic constructed from the angle

$$\Delta\phi_{jj}$$

Can distinguish CP-even and CP-odd





This distribution looks promising. However, cross section is about 1% of total production rate, so might have to wait a while!

Is $\mathrm{CP}(F) = F$?

The decay

$$F \to \gamma\gamma$$

Predicts the four-body decay

$$F \to \gamma^*\gamma^*$$

$$\to l^+ l^- l'^+ l^- l'^-$$

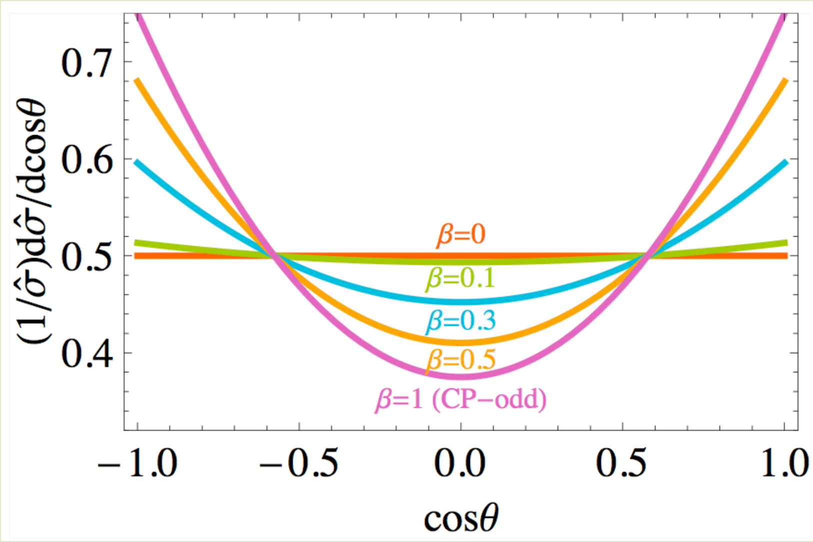
If observed with high enough statistics, angular variables could discriminate CP.

However, the decay rate is about 0.1% of the total photon rate, so would have to wait a long time...

Depending on the couplings, angular distribution in associated production

$$pp \to ZF$$

Could be used



Finally, if observed, the decay $F \to hh$ would unambiguously single out CP-even.

What do we learn?

- Learning the CP would be a huge boon with regards to the full theory.

CP-Even

Perhaps it is some sort of Higgs boson of a new sector of particles? Or even a second Higgs boson of a 2HDM?

Typically difficult to have CP-even scalars significantly lighter than other states, so should be other states nearby.

CP-Odd

Perhaps it is a pion of some hidden sector strong dynamics?

Due to Goldstone's theorem, a pseudo-Goldstone boson can be naturally light, thus no theoretical motivation for additional states nearby (although couplings may point towards that situation anyway)

Health warning, speculation…

What do we learn?

- Learning the CP would be a huge boon with regards to the full theory.

CP-Even

Perhaps it is some sort of Higgs boson of a new sector of particles? Or even a second Higgs boson of a 2HDM?

Typically difficult to have CP-even scalars significantly lighter than other states, so should be other states nearby.

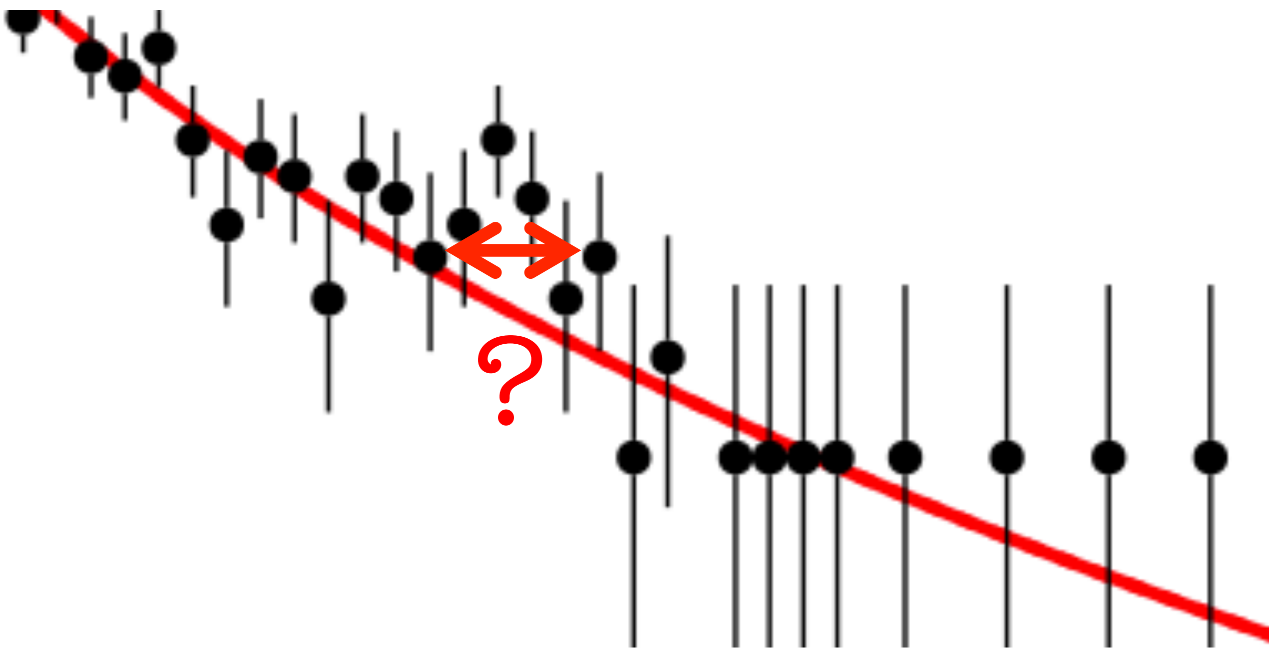
CP-Odd

Perhaps it is a pion of some hidden sector strong dynamics?

Due to Goldstone's theorem, a pseudo-Goldstone boson can be naturally light, thus no theoretical motivation for additional states nearby (although couplings may point towards that situation anyway)

What is the width?

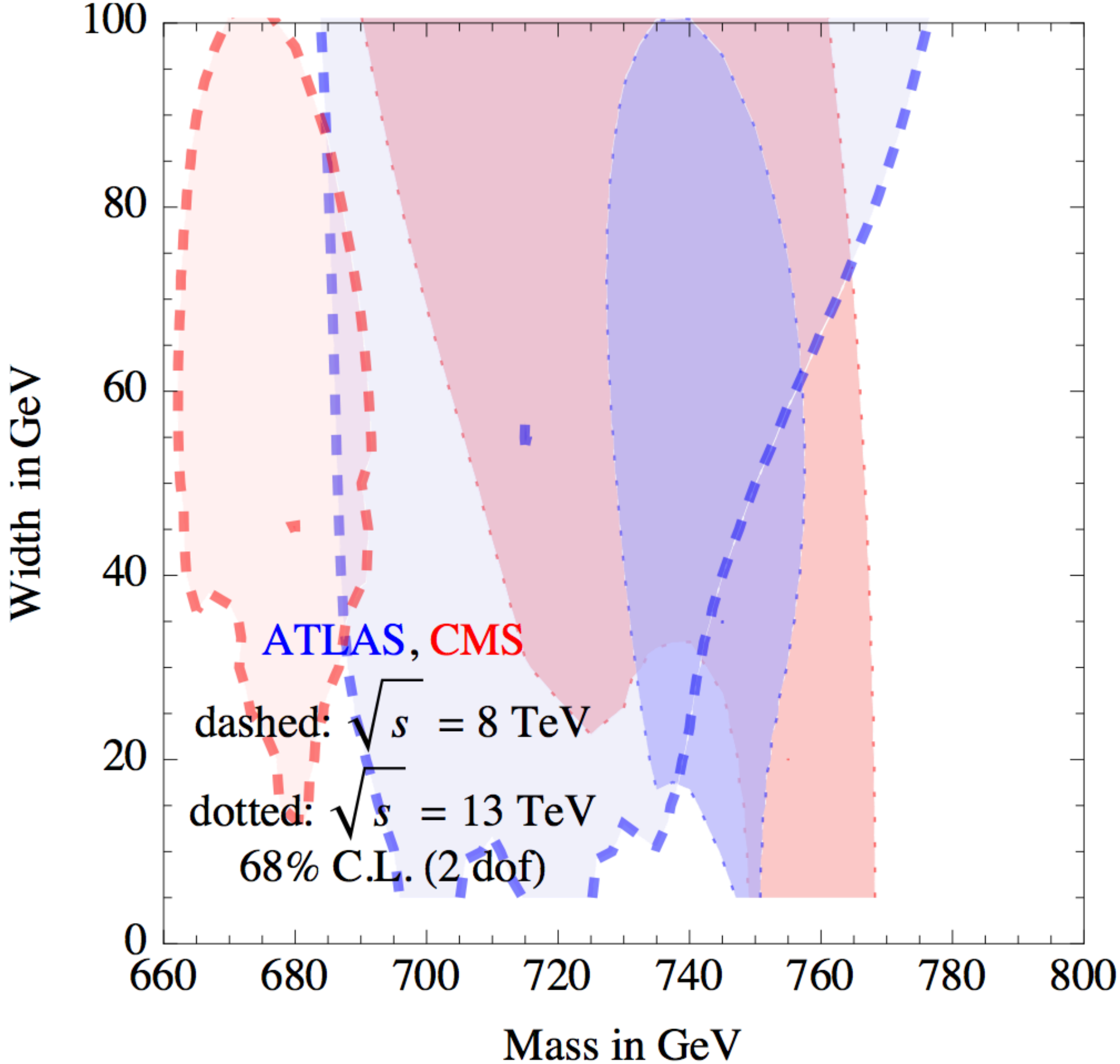
- Realistically, best chance to measure it is:



- There were indications in December that maybe the width was large, about 6%...

What is the width?

- Now the situation is somewhat clearer:



Width is something between very narrow, and about 13%!

What do we learn?

- The width is a crucial indicator of the big picture. Would give clues as to the overarching structure.
  - Difficult to get large width in perturbative models, especially with loops.
  - If couplings are large (non-perturbative) then it is much easier to generate a large width.

- Also, with width can convert rates to absolute couplings!

$$\sigma(XX \to F \to YY) \propto \frac{c_{XX}^2 c_{YY}^2}{\Gamma}$$

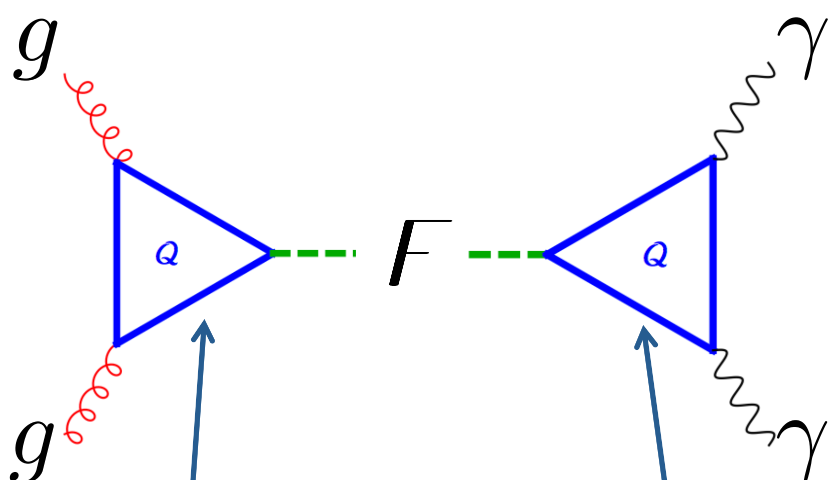
Comment on Future…

- The diphoton channel is very clean and, much like the Higgs discovery, not much machinery is needed to extract the overall signal.

- For most of what I have said:
  - Other decay channels
  - Associated production
  - Distributions
  - ….
- This will not be the case. To understand new particle and tease out properties, precision SM will play a central role, just as it is with Higgs.

Weakly Coupled Models

- For a weakly coupled model there are not so many options. Most popular is



New coloured fields! Not too heavy. Should be discovered very soon…

New $U(1)_Y$, $SU(2)_W$ charged fields! Also not too heavy. Maybe discovered soon…

Weakly Coupled Models

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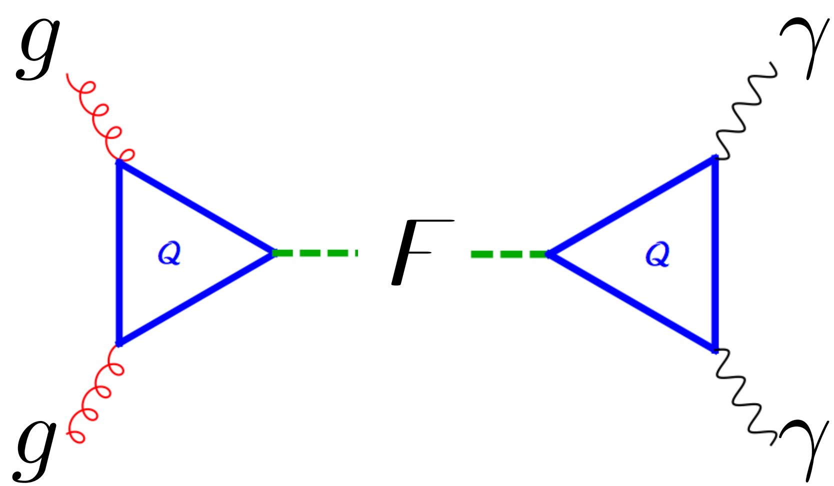

Of course, this structure may be embedded in any number of other models…

Weakly Coupled Models

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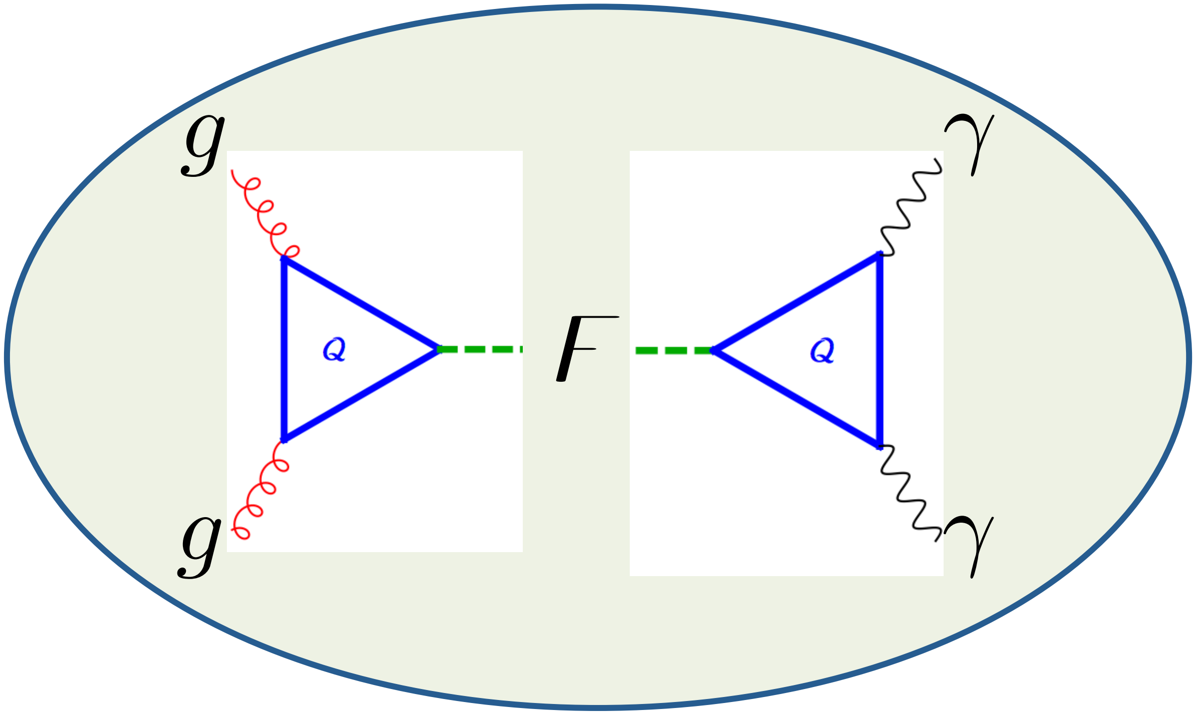

"This is the MSSM!

If I add some vector-like quarks..."

Weakly Coupled Models

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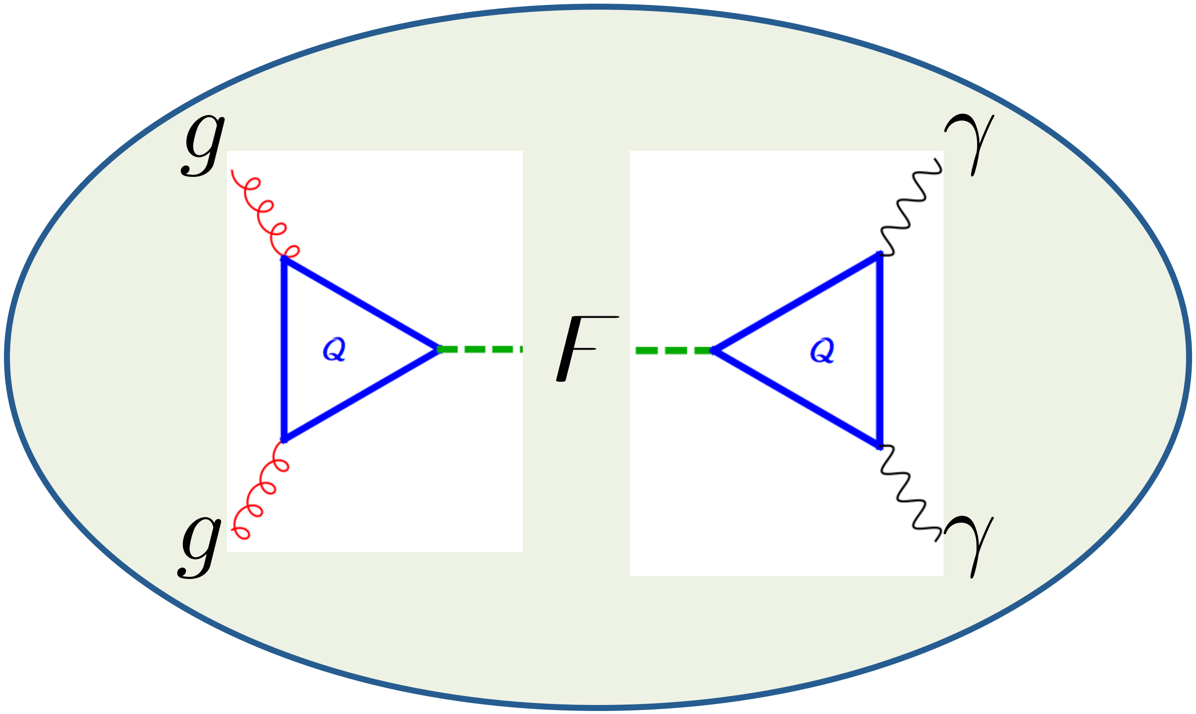

"This is the NMSSM!

If I add some vector-like quarks..."

Weakly Coupled Models

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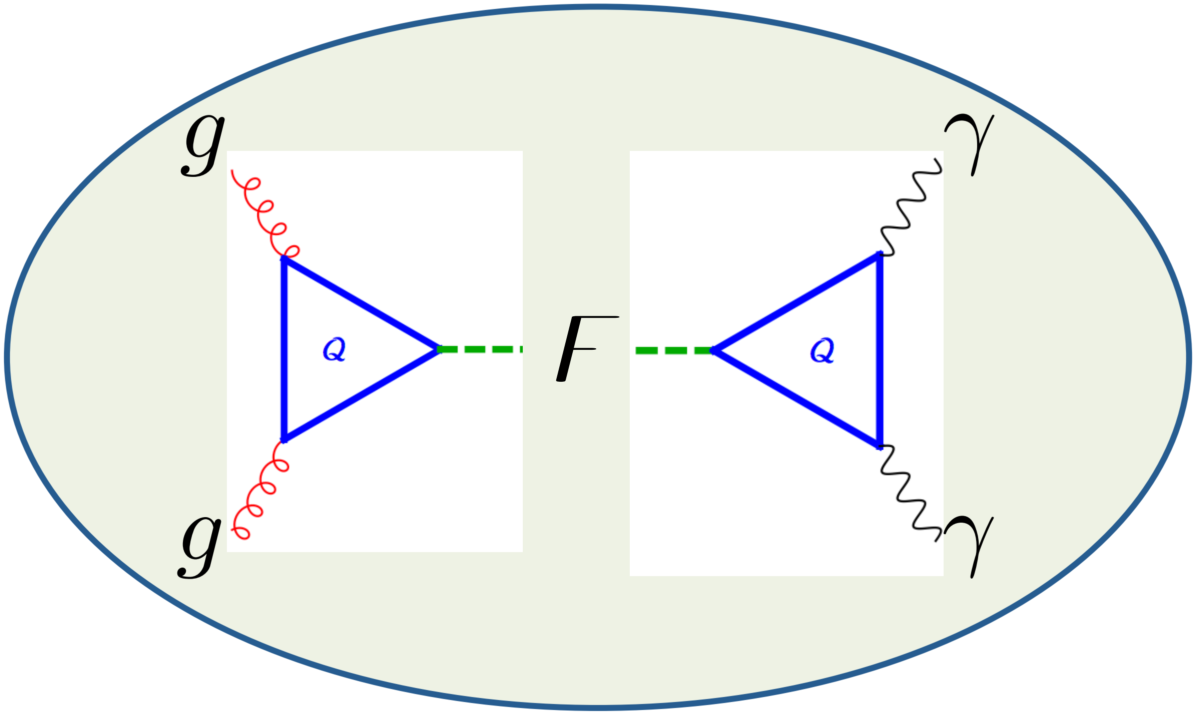

"This is the MRSSM!

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Weakly Coupled Models

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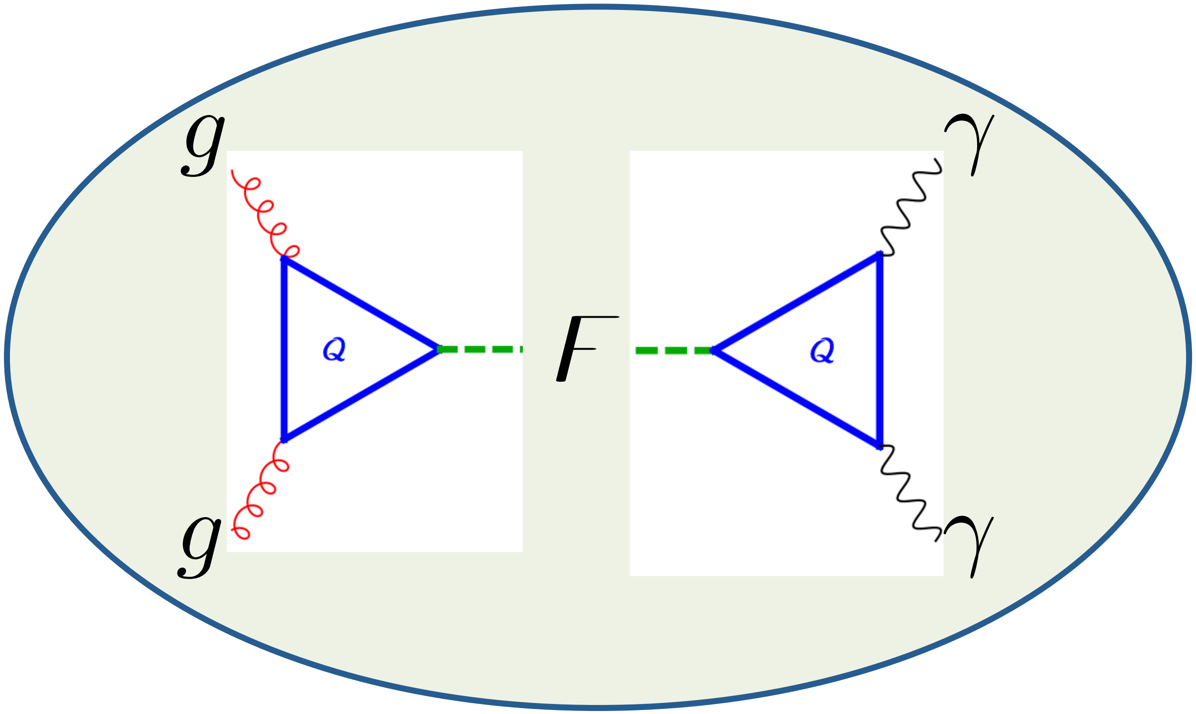

"This is a GUT!

If I add some vector-like quarks..."

Weakly Coupled Models

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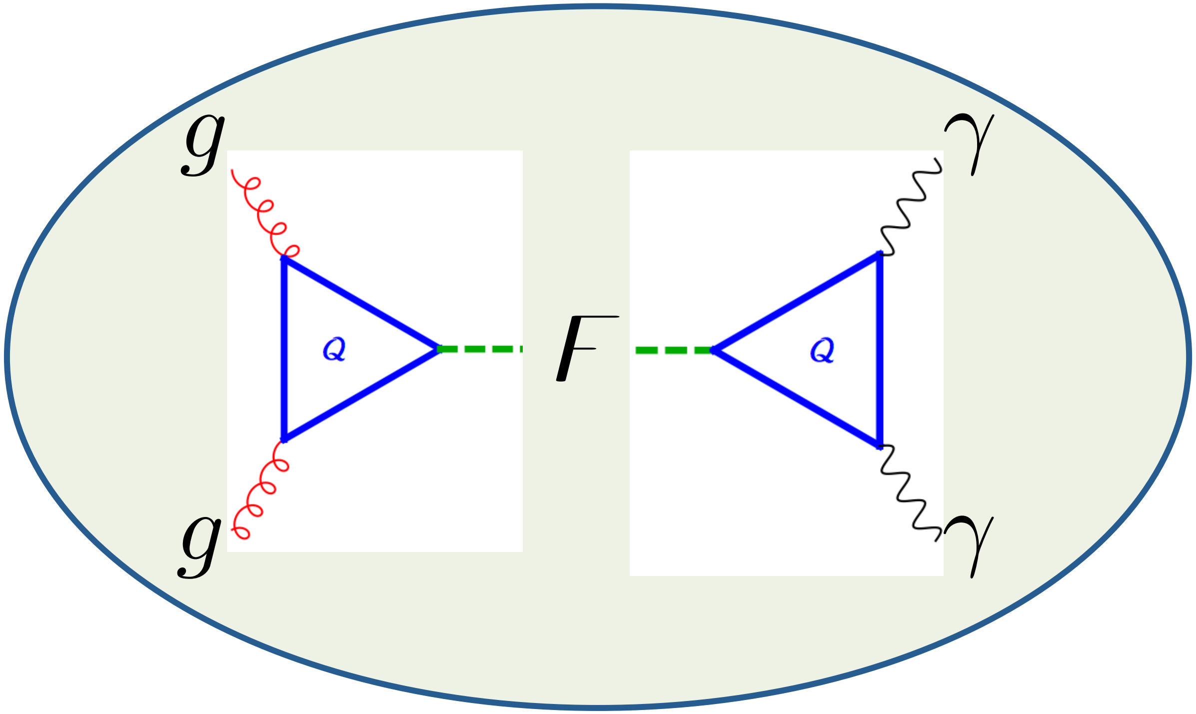
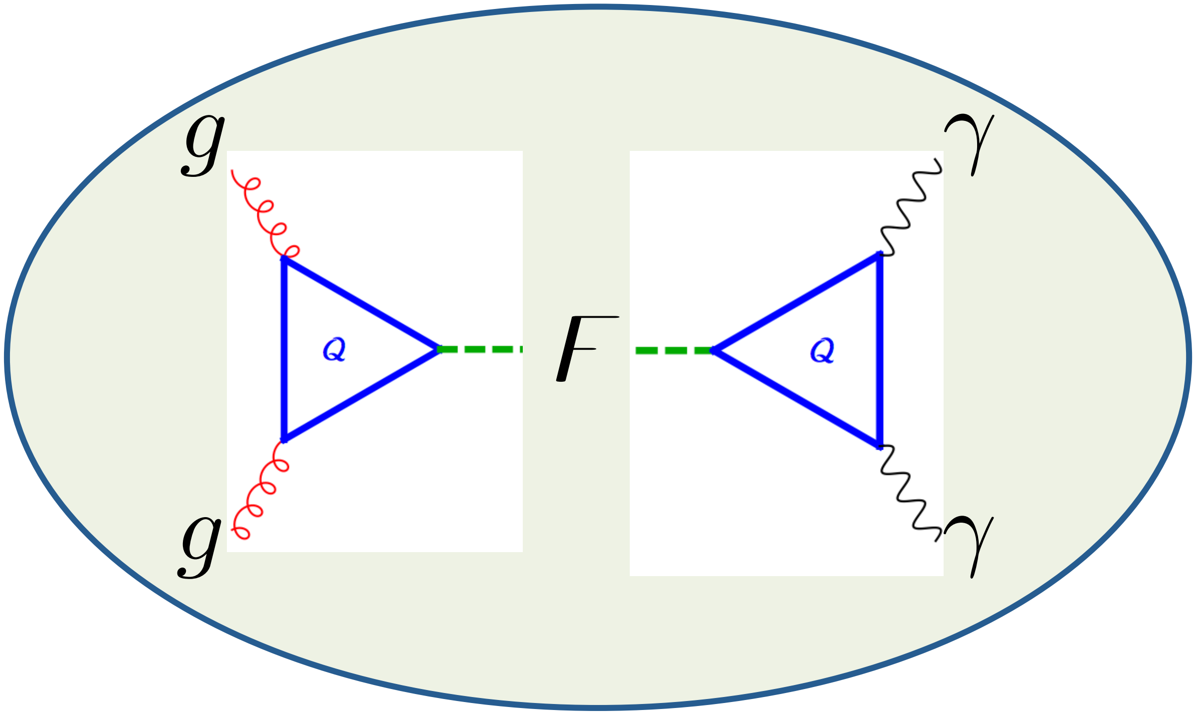


"This is a Left-Right Model!

If I add some vector-like quarks..."

Weakly Coupled Models

- For a weakly coupled model there are not so many options. Most popular is

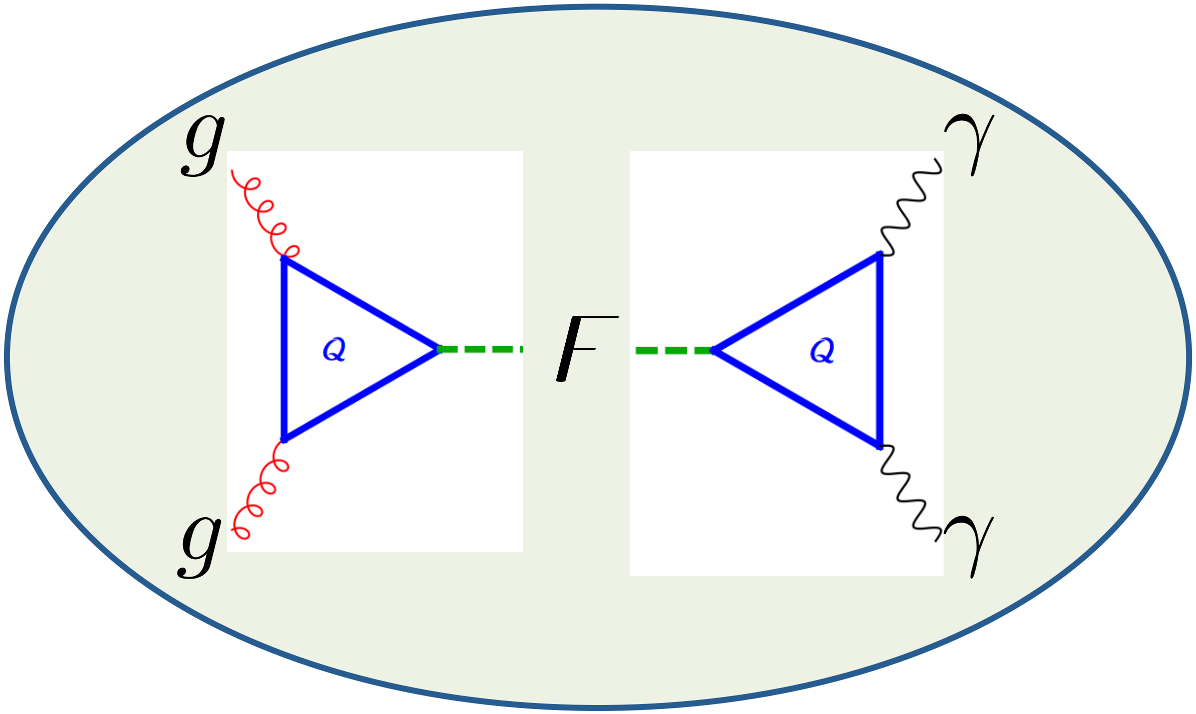


"This is my neutrino mass model!

If I add some vector-like quarks…"

Weakly Coupled Models

- For a weakly coupled model there are not so many options. Most popular is



"This is my dark matter model!

If I add some vector-like quarks…"

Weakly Coupled Models

- For a weakly coupled model there are not so many options.

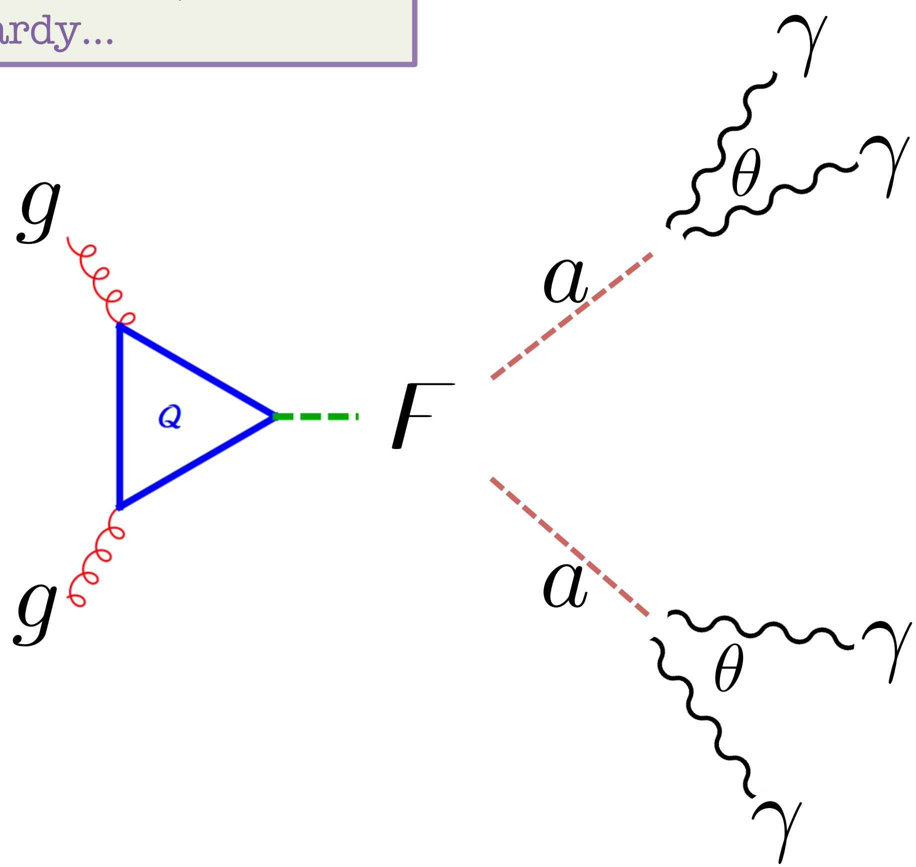
Always read the fine print.

In my opinion, this is not (yet) pointing clearly towards any particular perturbative UV framework.

Weakly Coupled Models

- These are a few of my favourite things….

See Papucci…
Kahlhoefer,…
Hardy…



Since we have:

$$\theta \propto \frac{m_a}{m_F}$$

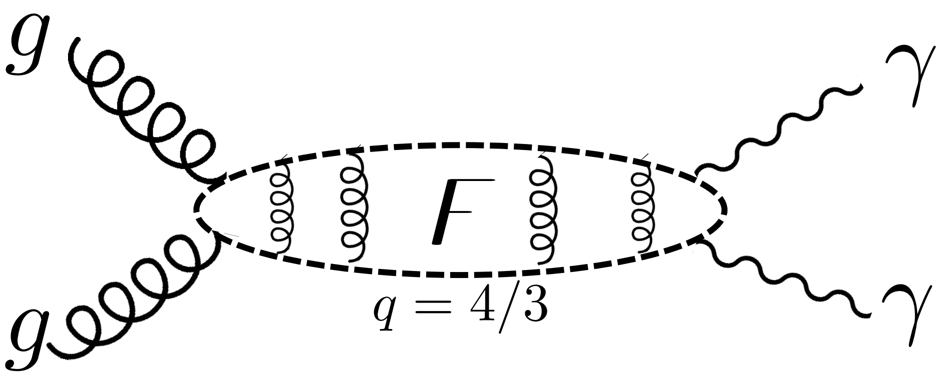
If the mass of the new pseudoscalar is small enough, something like 100's MeV, then photons appear as one!

Should be testable if they can be resolved.

Weakly Coupled Models

- These are a few of my favourite things....

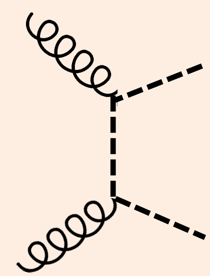
See Kats & Strassler.



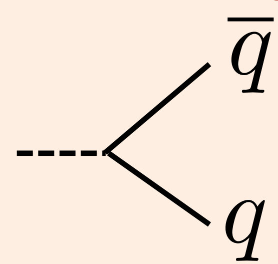
Quite surprisingly, the resonance could be a pair of charged and coloured scalars in a very weakly bound state due to QCD.

Same works for fermions!

Of course, there is still continuum production of the scalars...

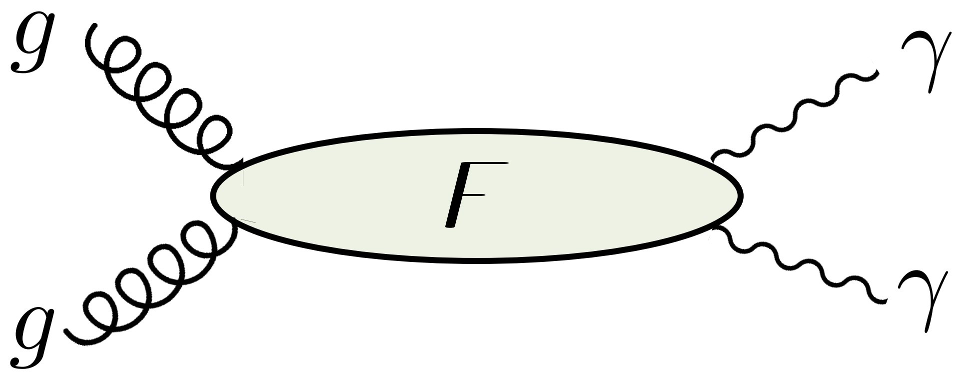


But this can be (just!) hidden from decays to dijets:



Strongly Coupled Models

- Somehow, an explanation based on a new strongly coupled sector seems appealing.

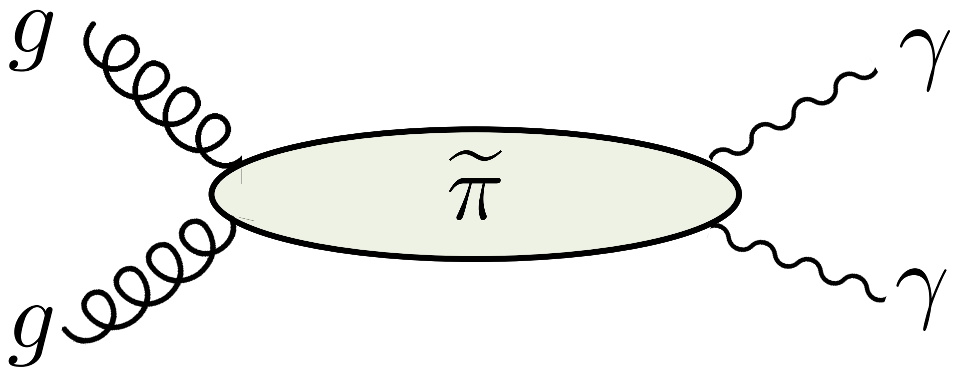


- If a large width persists this will be very suggestive of strongly coupled, although could also be narrow in strongly coupled scenarios.

- May fit nicely within composite Higgs models, although the following may arise with connection to EW sector too.

Strongly Coupled Models

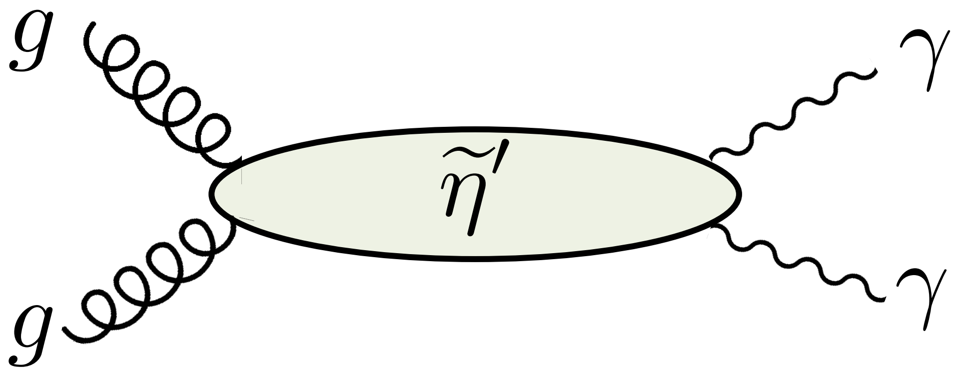
- Somehow, an explanation based on a new strongly coupled sector seems appealing.



The new state could plausibly be the pion of a new strong sector, analogous to the pions we observe in the SM. May be difficult to get large enough couplings to gauge field though if spontaneously broken global symmetry commutes with SM gauge symmetries.

Strongly Coupled Models

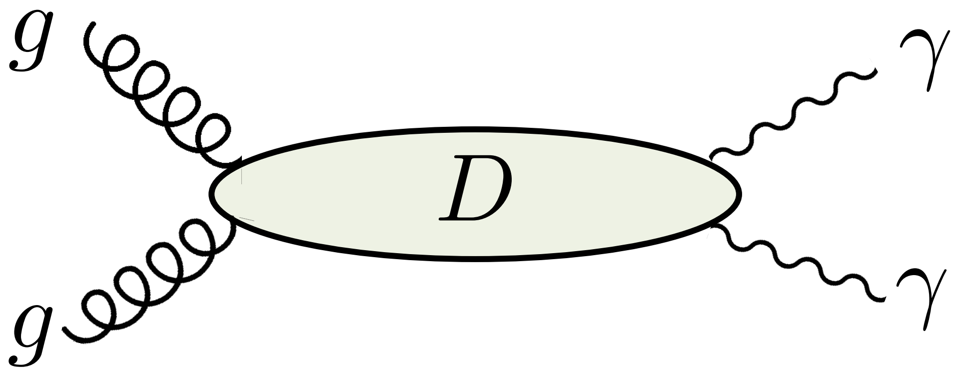
- Somehow, an explanation based on a new strongly coupled sector seems appealing.



Perhaps it could be more like the eta' of SM QCD. In this case, for example, the global symmetry is anomalous under the SM gauge symmetries, thus larger couplings to gauge fields can arise.

Strongly Coupled Models

- Somehow, an explanation based on a new strongly coupled sector seems appealing.

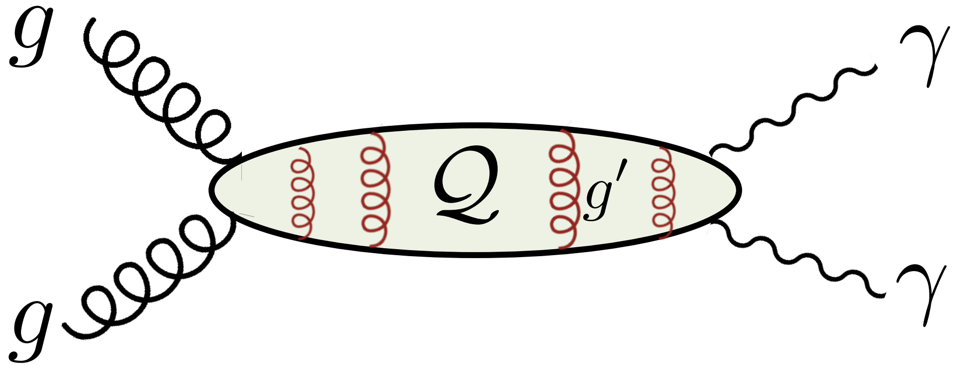


Similarly, it could be the dilaton, which is the pseudo-Goldstone-boson of spontaneously broken conformal (i.e. energy-scale) invariance.

In this case the couplings can also be large enough.

Strongly Coupled Models

- Somehow, an explanation based on a new strongly coupled sector seems appealing.



If there are new heavy quarks charged under a new strongly coupled gauge group, but with mass near the strong coupling scale:

$$M_q \gtrsim \Lambda'$$

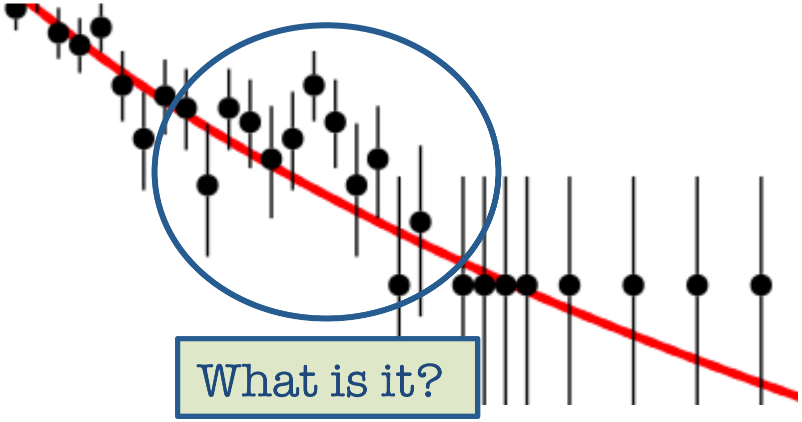
Then the state could be like quarkonium (think of it as J/ψ or Υ). Maybe we could see the excited states?

Summary

A Minimal Explanation

Statistical Fluctuation

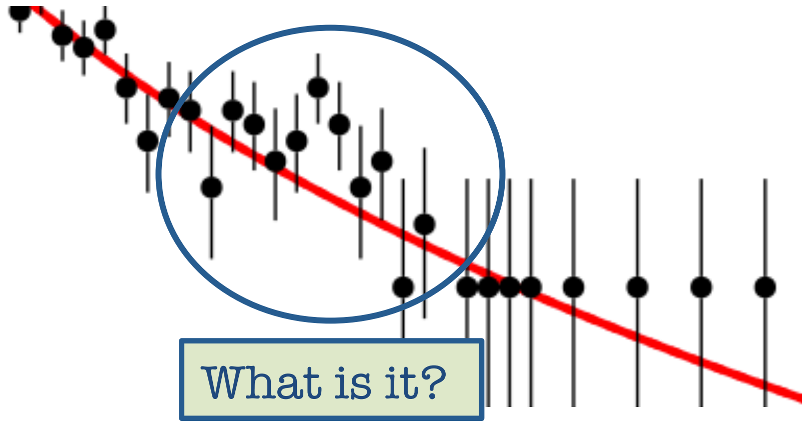
Summary



- This could be the first evidence of particles beyond the Standard Model (don't say neutrino masses.)

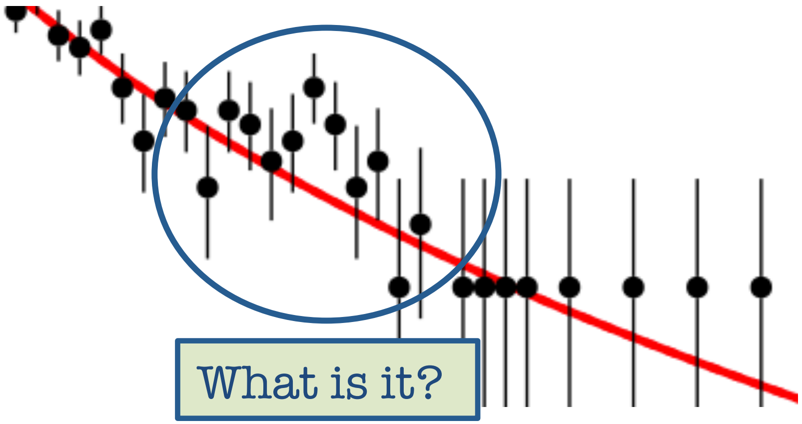
- Theory community reacting accordingly:
  - Many ideas for models
  - Emerging ideas for phenomenological tests

Summary



- In this talk we have seen:
  - We already have quite a lot of info from other null searches.
  - There are many ways to determine the properties of this particle.
    - Other decays should be there soon.
    - Associated production will clarify many properties.

Summary

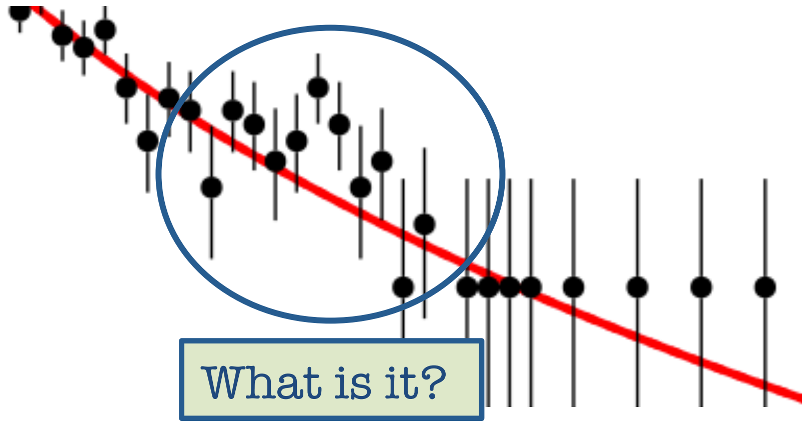


- In this talk we have seen:

- In almost every model this must be the tip of the iceberg…

  – Weakly coupled: New coloured states soon.
  – Strongly coupled: An arsenal of resonances should be waiting in the wings.

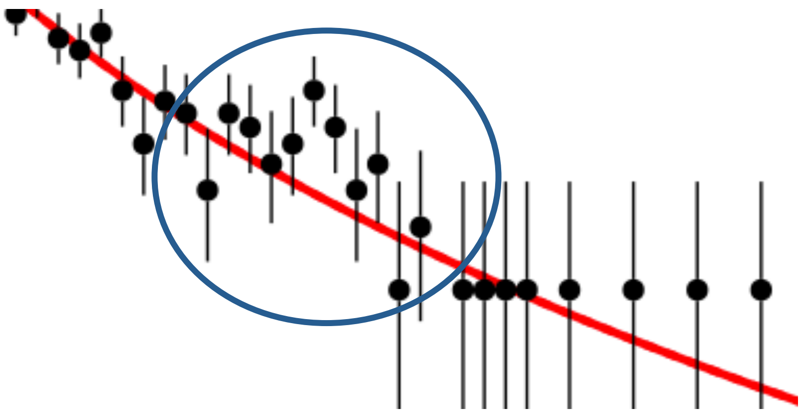
Summary



- In this talk we have seen:

- If it is real, this particle is in itself thrilling. However, it may also hold the key to some of natures greatest mysteries!
  - Is there a connection with dark matter?
  - Is there a connection with the hierarchy problem?

Summary



Who ordered that?