Q-onium
(and the 750GeV diGamma)

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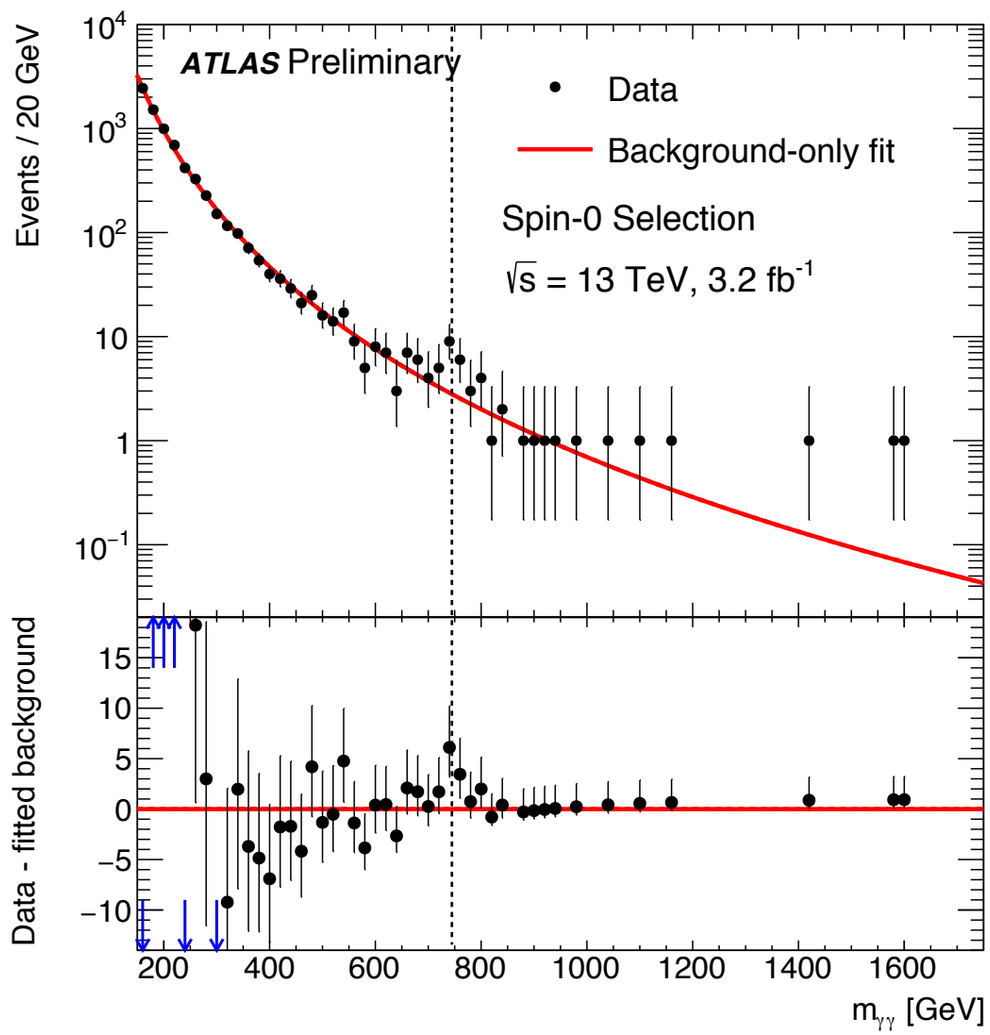
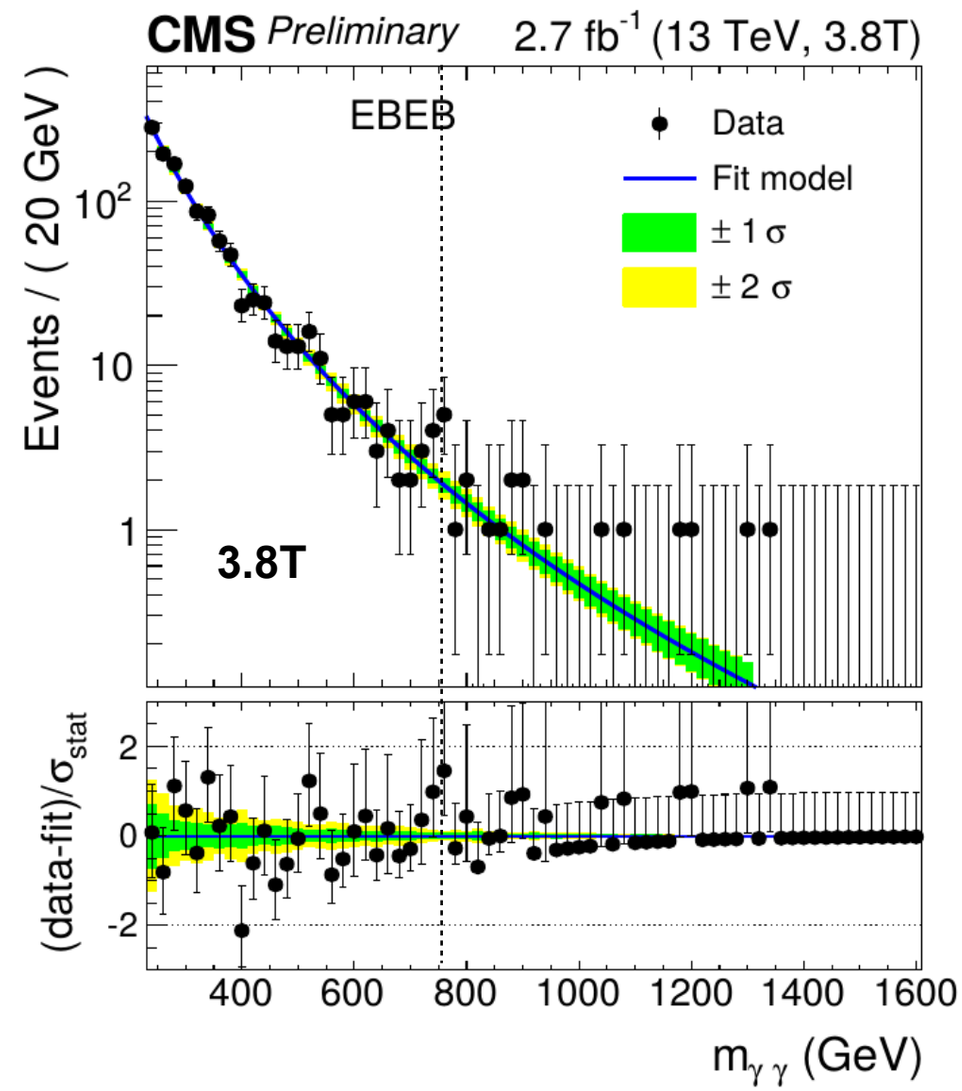
First LHC 13TeV data exhibits an excess in the di-photon spectrum





Most likely just a statistical fluctuation...

What if?

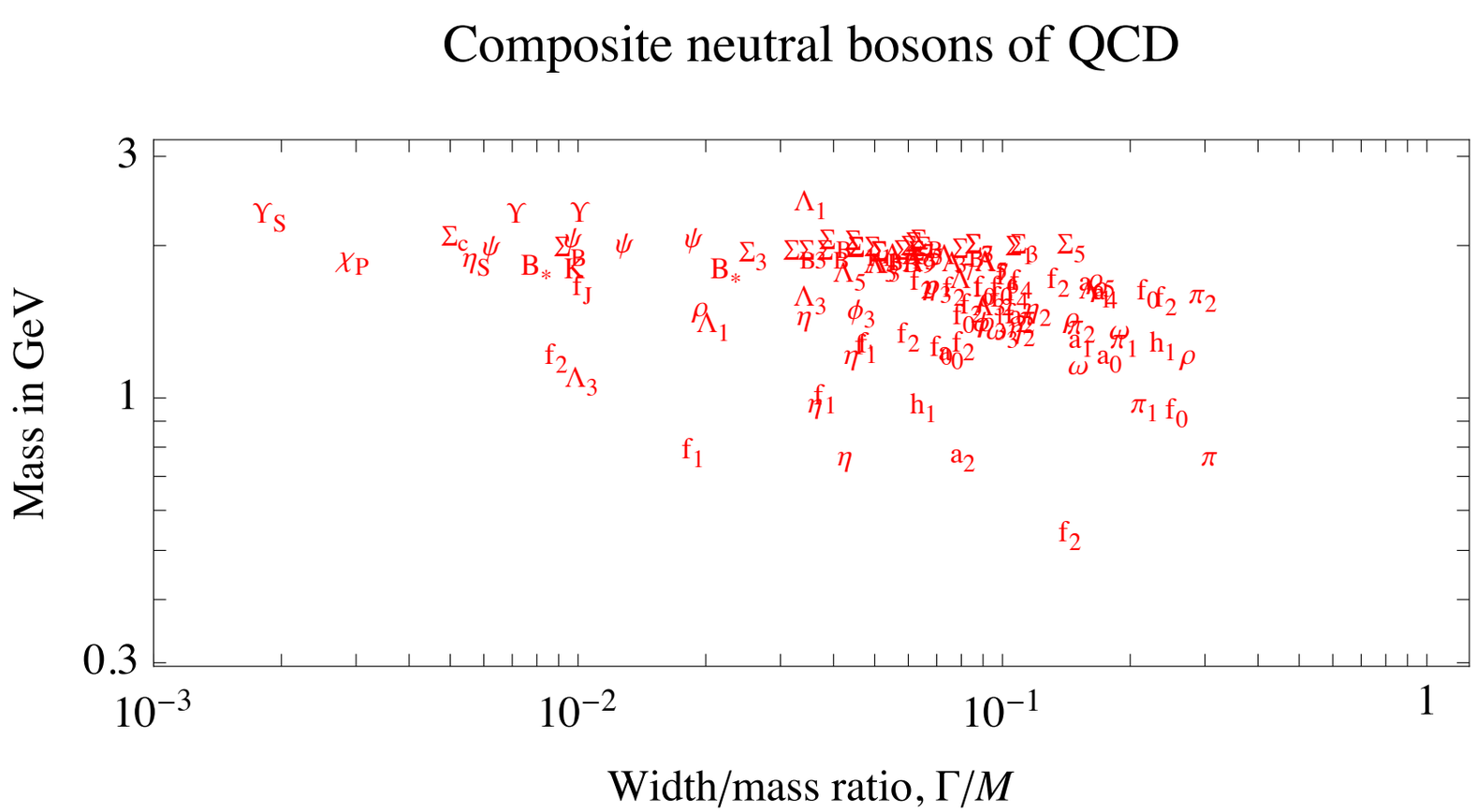
Data compatible with spin = 0,2,.. resonance

Promptly produced through gluon fusion or heavy flavor annihilation

1603.06566

Sizable rate into di-photons $\sigma_{\gamma\gamma} \sim 5$ fb suggests composite nature

1512.04933
see also
1512.04850
1512.05330
1512.07733
1512.06106
...



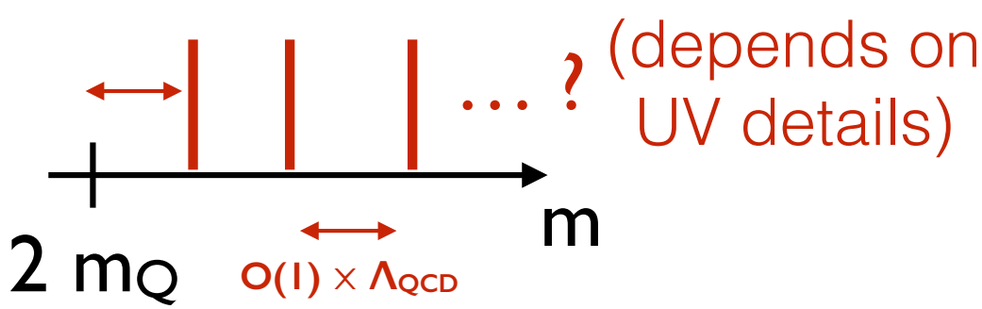
Q-onia

- ‘Molecular’ bound states of massive particles (Q) charged under confining dynamics - TC (can be QCD?) below Λ_{TC} with $M > \Lambda_{TC}$
- (Some) characteristics similar to QCD quarkonia or even positronium?
- Naturally sizable couplings to pairs of SM gauge bosons
- Multiple low lying states can fake wide resonance?

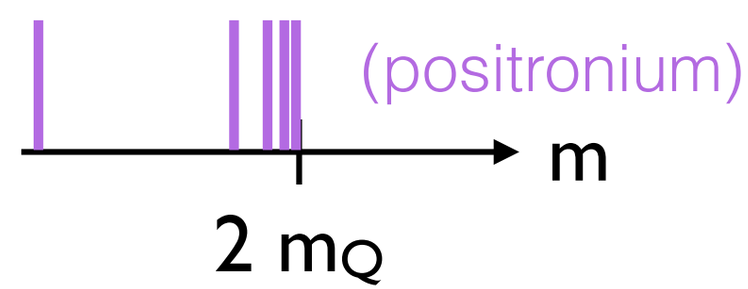
Binding

Confining regime ⟷ Coulomb regime

$\alpha_{\rm TC} M \ll \Lambda_{\rm TC}$



$\alpha_{\rm TC} M \gg \Lambda_{\rm TC}$



case for QCD quarkonia

$$\Delta E^{(n,l)}_{\rm Coul.} = -\frac{C_N^2 \alpha_{\rm TC}^2}{8n^2} M$$

(topomonium in the middle)

Hagiwara et al. Nucl.Phys. B344 (1990)

Production & Decays

- Close to threshold, QQ production dominated by prompt single Q-onium production

$$\sigma(pp \to X) = \frac{(2J_X+1)D_X}{Ms} \sum_{\mathcal{P}} C_{\mathcal{P}\mathcal{P}} K^X_{\mathcal{P}\mathcal{P}} \Gamma(X \to \mathcal{P}\mathcal{P}) \,,$$

- spin-0,2… Q-onia produced through gluon fusion

$$\frac{\Gamma(\eta^1_{\mathcal{Q}} \to gg)}{M} = 32 N_{\rm TC} d_2 \frac{I_3^2}{d_3} \alpha_s^2 \frac{|R_1(0)|^2}{M^3}$$

Relative rates to VV completely fixed by gauge numbers

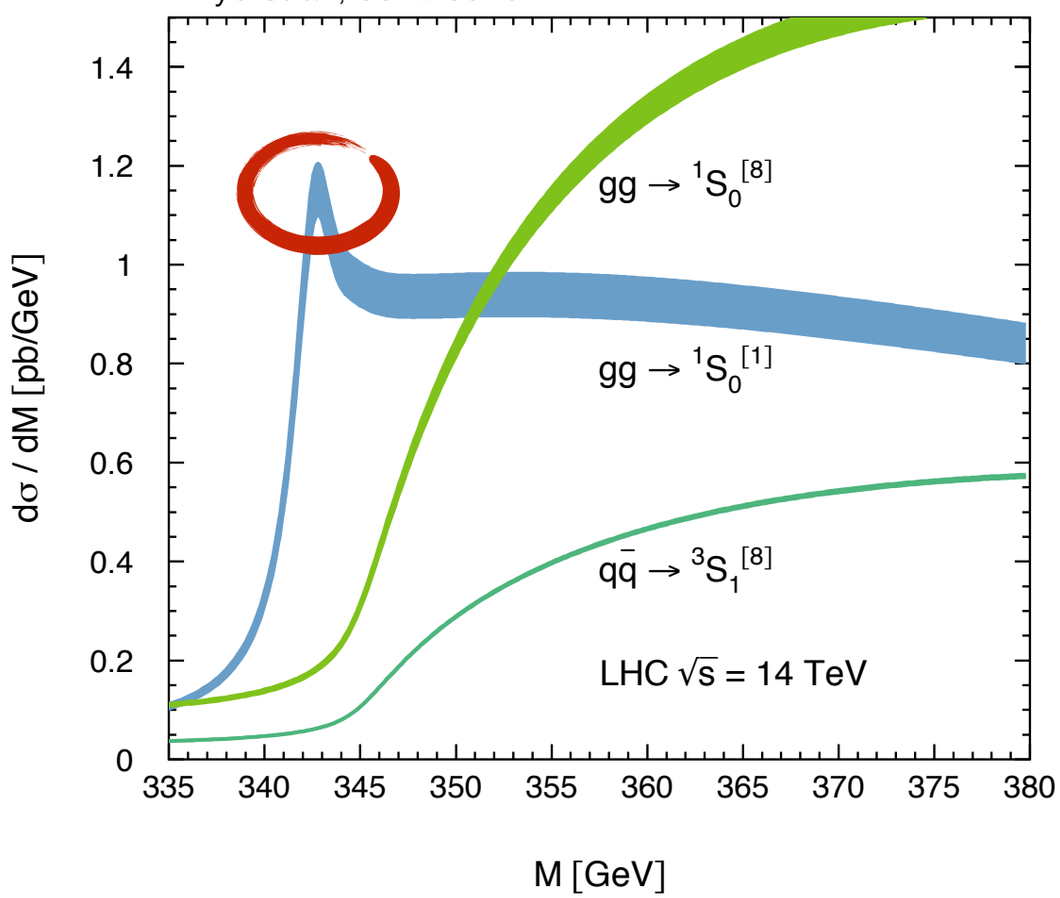
- spin-1 states mix with SM gauge bosons - quark annihilation

$$\frac{\Gamma(\psi^1_{\mathcal{Q}} \to f\bar{f})}{\Gamma(\eta^1_{\mathcal{Q}} \to gg)} = \frac{d_3^2}{48\, s_W^4\, c_W^4} \left(\frac{c_W^2\, T^3_{\mathcal{Q}} T^3_f + s_W^2\, Y_{\mathcal{Q}} Y_f}{I_3} \right)^2 \frac{\alpha^2}{\alpha_s^2}$$

Prelude: QCD bound states of new heavy Q

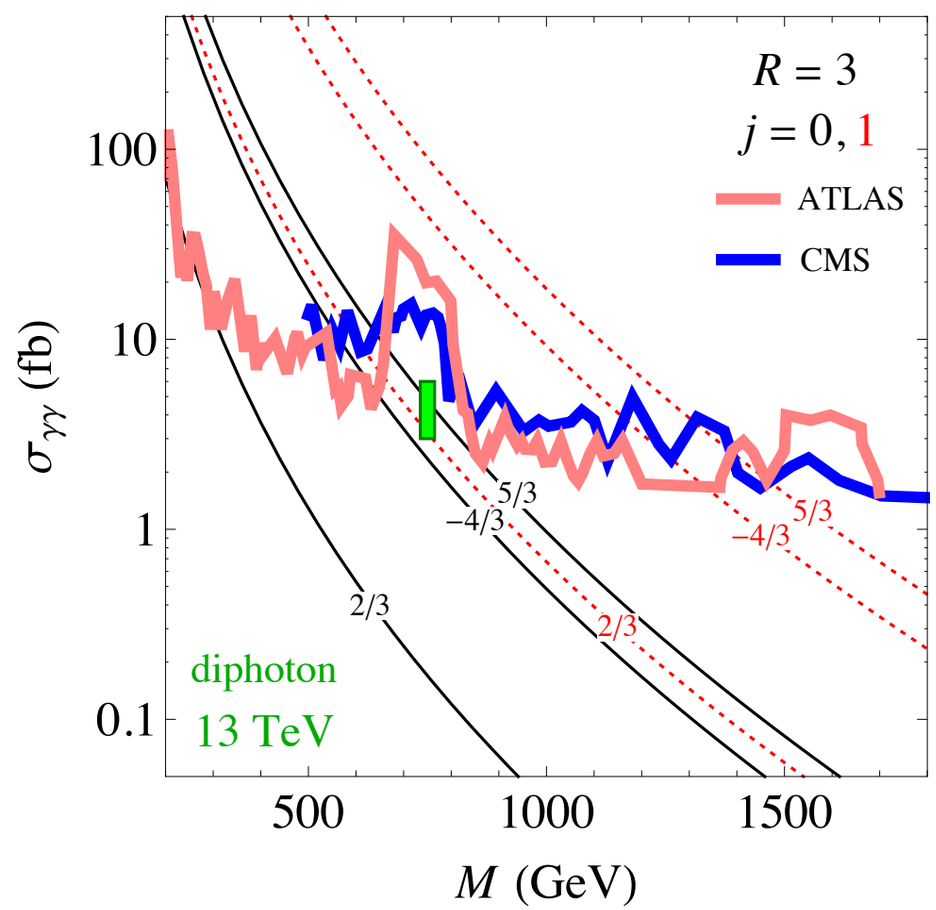
Long-lived colored particles will form QCD bound states close to threshold of pair production

Kiyo et al., 0812.0919



(toponium example)

Kats & Strassler, 1602.08819



Prelude: QCD bound states of new heavy Q

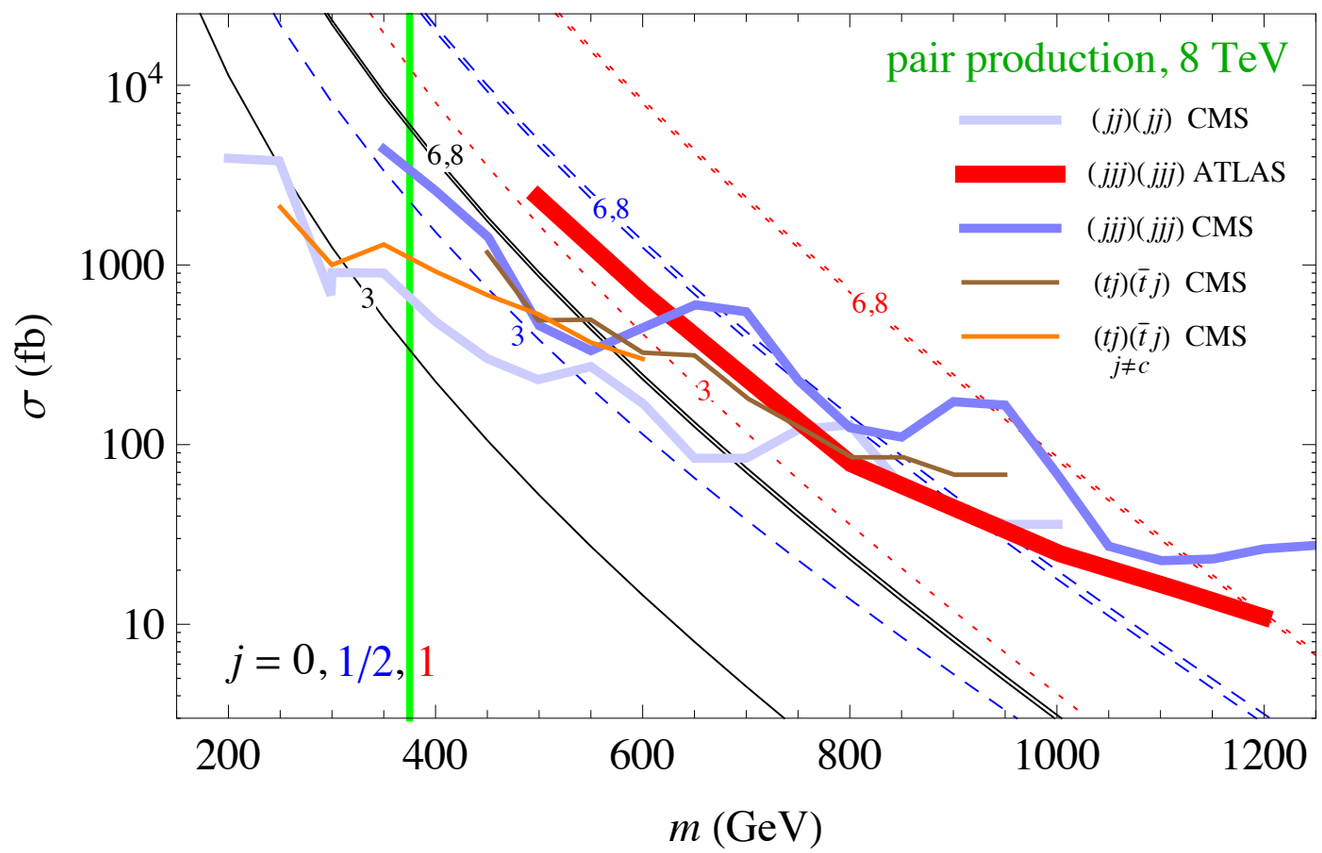
Main issues:

Need to assume large QCD bound wavefunction at origin
1508.07080
(or exotic charges)

di-jet, jet+photon, di-lepton bounds for large QCD reps.

Need Q-mass of ~375GeV
→direct search constraints

If short-lived enough, decays to (displaced?) di-jets, can be ok



Q-onium

J.F.K. & Redi, 1603.07719

In models of vector-like (TC) confinement with VL masses M_Q comparable to confinement scale Λ_{TC}

Lightest scalars can be bound QQ states (& TC glueballs)

For Q in SM rep. $R = (r_3, r_2)_Y$

expect resonances in

$$R \times \bar{R} = (1,1)_0 + (8,1)_0 + \ldots$$

⇒ colored spin=0,1,… states

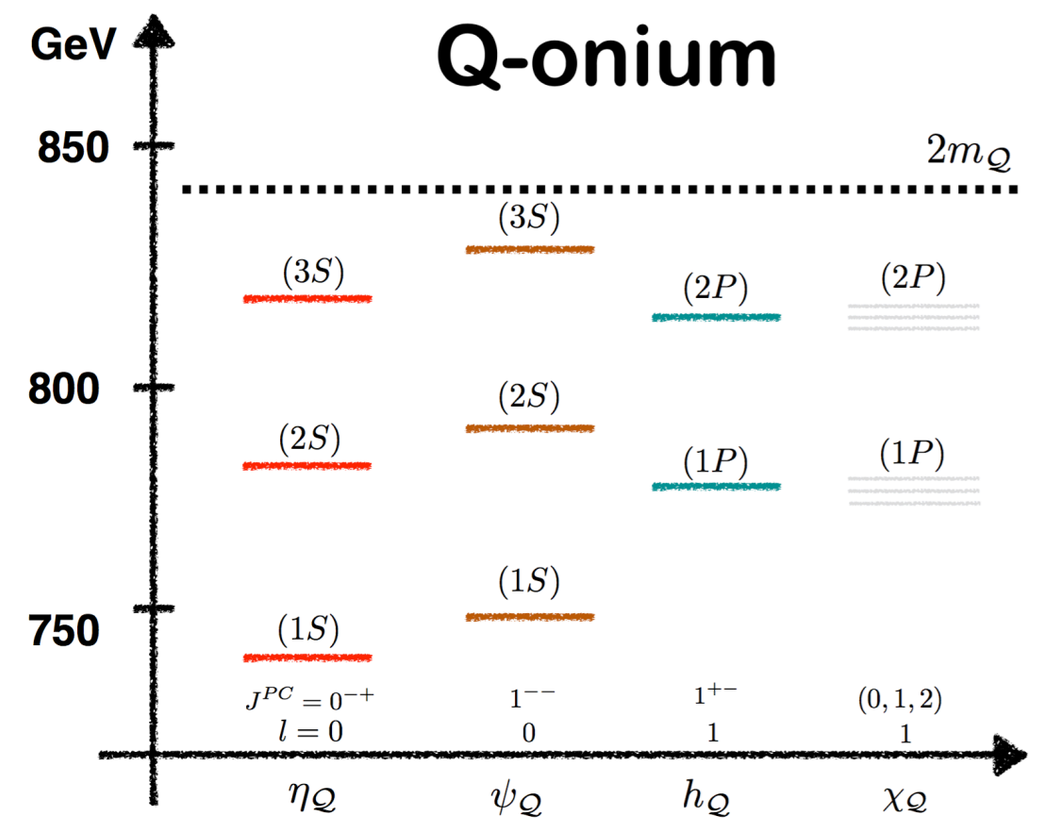
almost degenerate with S

⇒ absent in models with uncolored Q

1604.07776, 1604.02803

(disfavored by 8TeV/13TeV compatibility)

1603.06566



Main constraints

Depend on spin & color:

⇒ spin-0 color-1

decays to EW gauge bosons

$$-3.5 < \frac{d_2^2 - 1}{Y^2} < 30$$

	σ_U[fb]	σ_X[fb]	σ_Q[fb]	σ_Y[fb]	σ[fb]
$pp \to \eta^1 \to gg$	200	12	500	25	<2500
$pp \to \eta^1 \to \gamma Z$	0.6	0.6	5	0.4	< 11
$pp \to \eta^1 \to ZZ$	0.1	0.1	9	1.2	< 12
$pp \to \psi^1 \to e\bar{e}$	0.3	0.07	0.05	0.1	<1.2
$pp \to \eta^8 \to gg$	500	30	1250	60	<2500
$pp \to \eta^8 \to g\gamma$	80	20	13	20	< 30
$pp \to \psi^8 \to jj$	600	35	1450	70	<2500
$pp \to \psi^8 \to t\bar{t}$	110	7	290	15	<600

⇒ spin-0 color-8: γ-j resonances

⇒ spin-1 color-1: di-leptons

⇒ spin-1 color-8: di-jets

QCD contributions suppress $R_8(0)$

$C_N \alpha_{\rm TC} \to C_N \alpha_{\rm TC} + (C_3 - 3/2)\alpha_s$

suppressed for spin-0 Q (p-wave)

⇒ Benchmarks: $U = (3,1)_{2/3}$ $Q = (3,2)_{1/6}$ $X = (3,1)_{4/3}$ $Y = (3,2)_{-5/6}$

Benchmarks

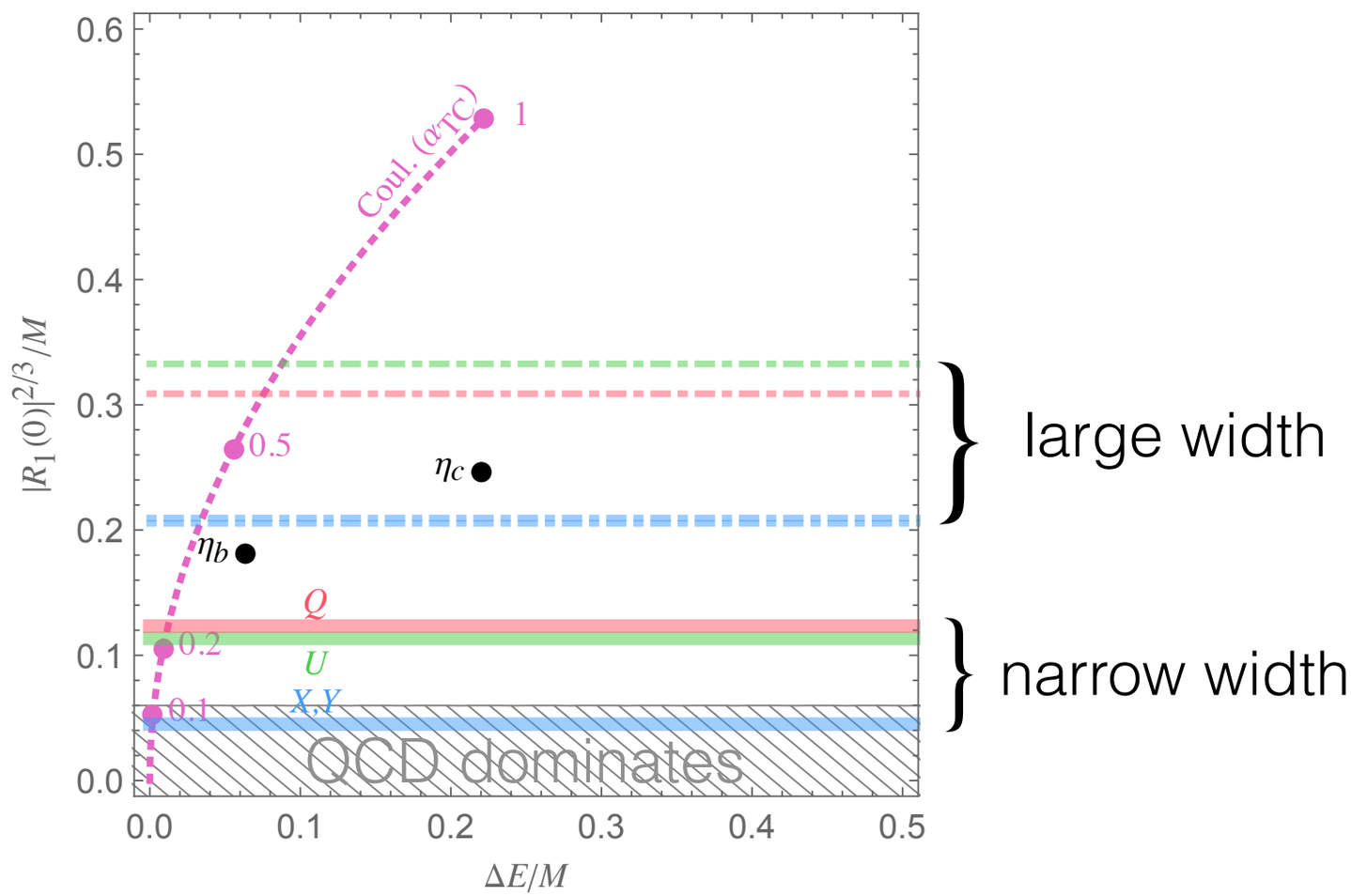
Basic parameters:

⇒ binding energy (ΔE)

⇒ size of bound state ($\sim R(0)$)

⇒ Good fit to data possible even close to Coulomb limit.

⇒ Room for additional decays (to TC glueballs, TC pions).



Mass spectra

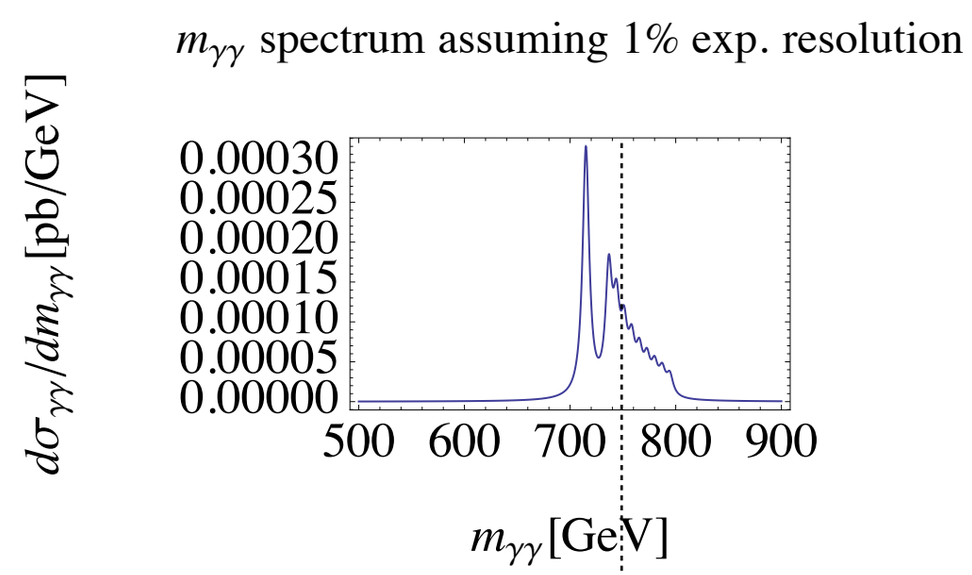
Higher n-states split by few %

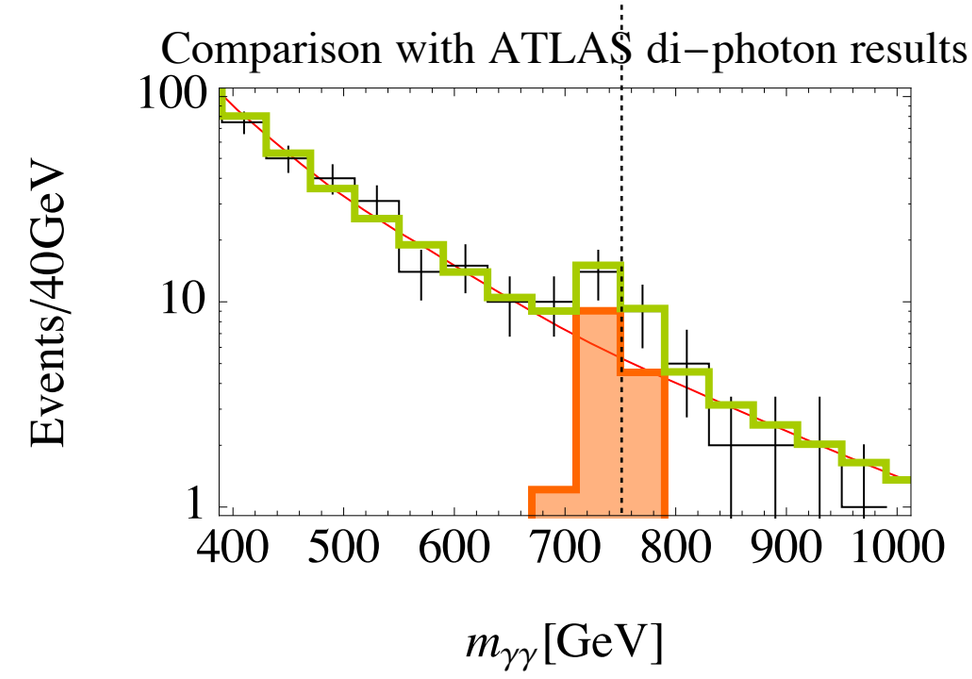
$$\Delta E^{(n,l)}_{\text{Coul.}} = -\frac{C_N^2 \alpha_{\text{TC}}^2}{8n^2} M$$

⇒ can fake a broad S peak

(requires departures from Coulomb limit)

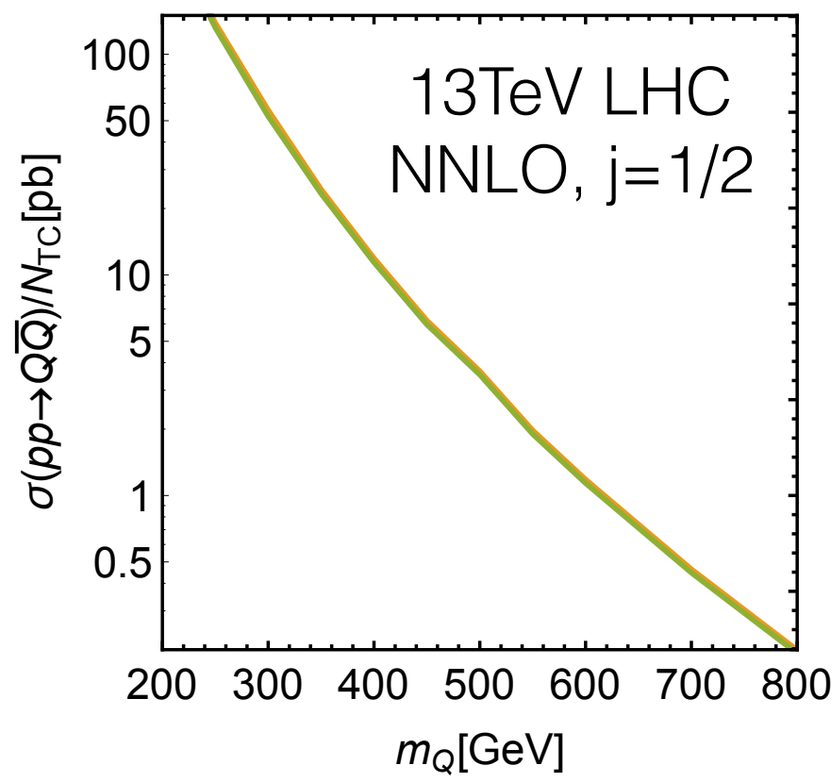
⇒ should be discernible with more data in di-photon mass





Continuum QQ production

Czakon, Fiedler & Mitov, 1303.6254



Well described by perturbative QCD dynamics

Suppressed (delayed) in deeply bound regime

Signatures very model dependent

depends on the complete TC spectrum and dynamics

Q confinement (quirky) regime

Curtin & Verhaaren, 1512.05753

production of highly excited QQ states

de-excitation via (TC) radiation

problematic if significant fraction into spin-1

⇒ di-lepton resonances

open Q regime

pair production of Q-hadrons

⇒ diverse signatures

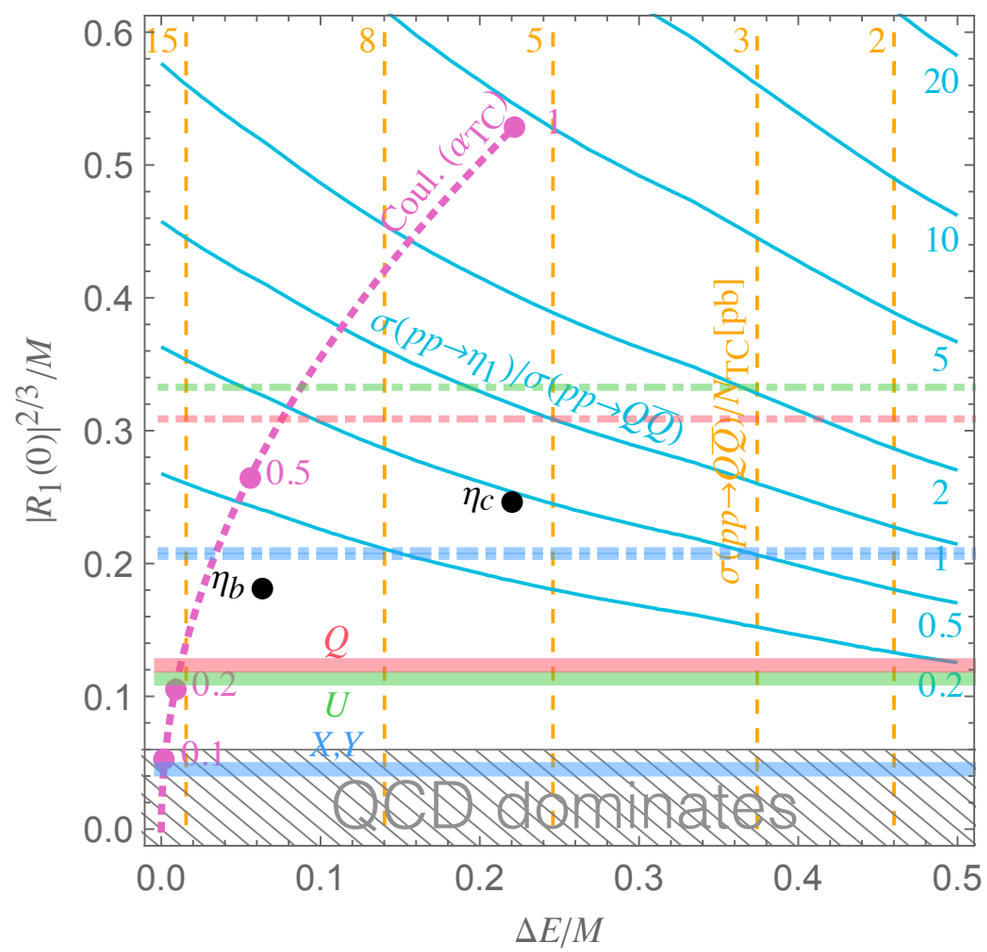
(multi-jet, leptons,…)

Continuum vs prompt production

Prompt production can dominate in deeply bound regime

⇒ Requires additional Q-onium decay modes (to TC glueballs, TC pions)

$$\frac{\Gamma(\eta_{\mathcal{Q}}^1 \to GG)}{\Gamma(\eta_{\mathcal{Q}}^1 \to gg)} \approx \frac{9}{32 I_3^2} \frac{N_{\rm TC}^2 - 1}{N_{\rm TC}^2} \frac{\alpha_{\rm TC}^2}{\alpha_s^2}$$



Conclusions

- BSM Q-onium like states could explain 750GeV diGamma
- Pure QCD bound states marginally viable for large Q-charges
- Extra TC dynamics has richer phenomenology
  - (degenerate) colored resonances,
  - possibly suppressed continuum production,
  - decays to (hidden) lighter TC hadrons,
  - apparent large width to be resolved into several peaks
- Most severe constraints from presence of spin-1 partners
  $\Rightarrow$ suppressed in case of scalar Q; in deeply bound regime
- More quantitative predictions with (BSM) Lattice inputs?

Backup

What if?

Di-photon peak over monotonously varying (falling) background - *theoretically clean, experimentally simple*

The background composition of $\gamma\gamma$ and γj events

high (mostly >90%) $\gamma\gamma$ purity ATLAS-CONF-2015-081

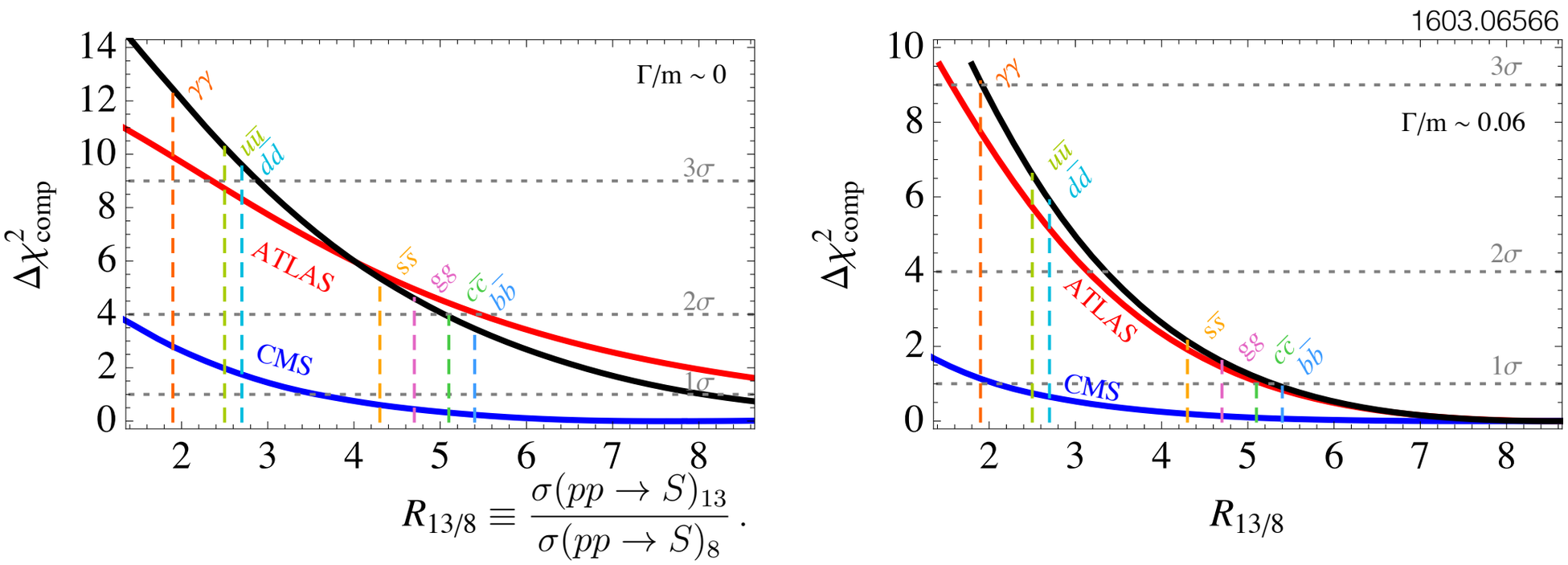
good agreement with NNLO QCD predictions Campbell et al., 1603.02663

Events in excess region do not exhibit unusual characteristics (MET, hadronic activity, angular distributions)

In the following consider 750GeV di-photon excess assuming real NP (new particle ‘S’) effect

Diagnosing a di-photon resonance at LHC

Main production issue: compatibility with 8TeV data



singles out preferred production modes

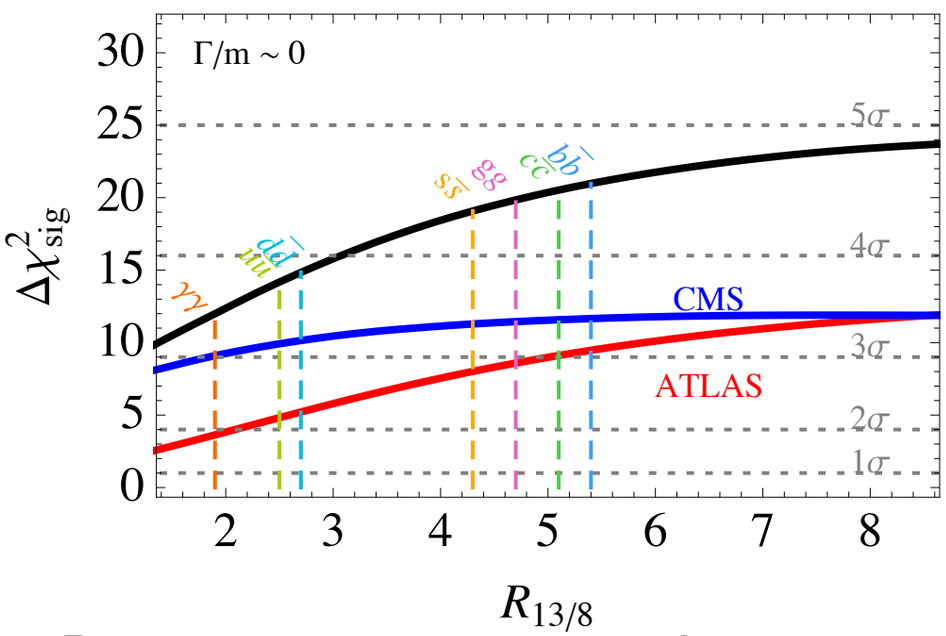
- heavy flavor annihilation / gluon fusion with $\sigma_{\gamma\gamma} = (3 - 10)\text{fb}$ @13TeV (depending on width/spin

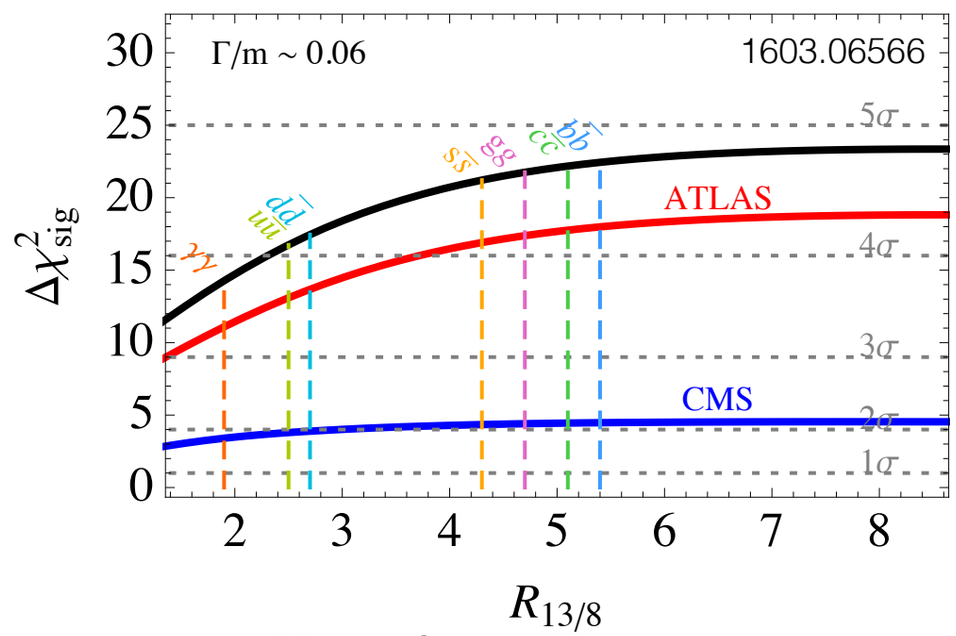
see also
1512.05751
1601.00638
1601.01712
1601.03772
1603.04874
1601.07187
...

Diagnosing a di-photon resonance at LHC

ATLAS data prefers sizable width: $\Gamma/M \simeq 0.06$

CMS excesses in both 8TeV and 13TeV data more significant if narrow - currently no preference for S width



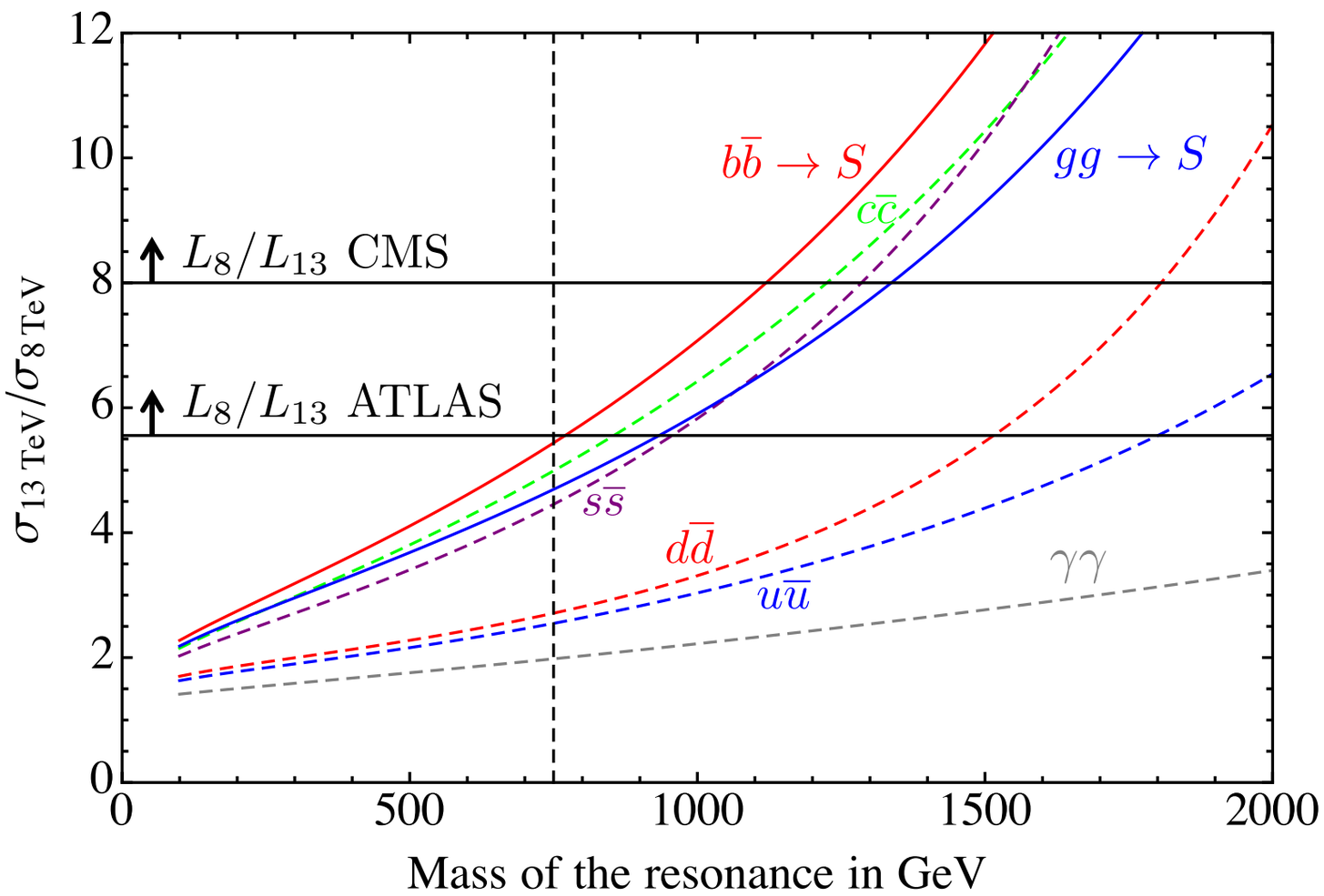


CMS cuts more inclusive ($p_{T\gamma}$>75GeV)

ATLAS excess slightly more significant for harder ($p_{T\gamma 1(2)}$>$0.4(0.3)m_{\gamma\gamma}$) cuts - currently no preference of spin 0,2

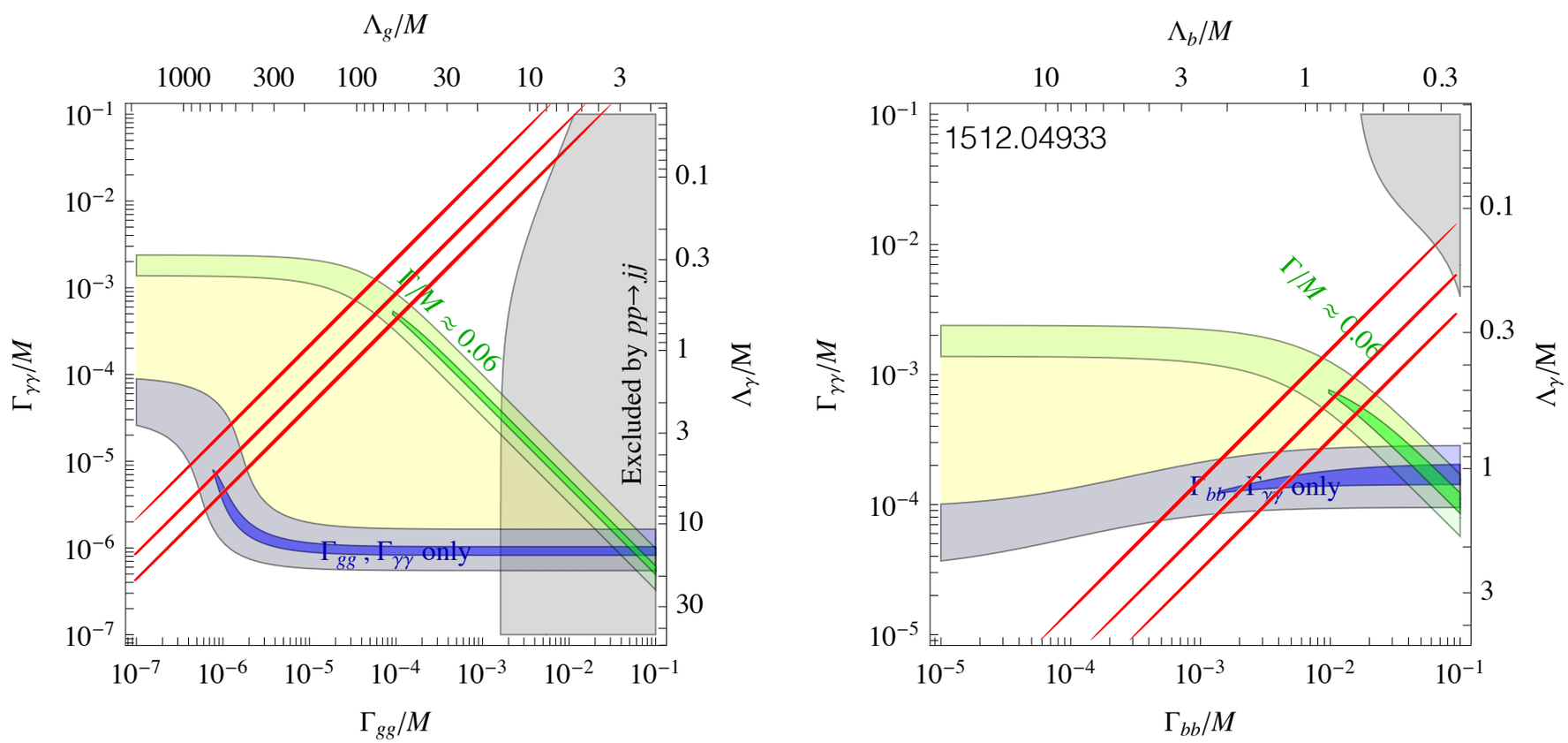
Improving 8TeV vs. 13TeV compatibility

Ratio of production cross sections increases with inv. mass



Possible decay channels of S

If S only couples to production channel & photons, the system completely constrained



$$\frac{\sigma_{\gamma\gamma}}{\sigma_{gg,bb}} = \{1/2, 1/5, 1/10\}$$

⇒ Room for additional decay modes

Possible decay channels of S

Many existing 8TeV (and some 13TeV) searches for (spin 0/2 narrow/wide) 750GeV resonances in SM final states

1512.04933

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

Implications of weak isospin invariance

SU(2)$_L$ invariance correlates different EW final states

operator	$\frac{\Gamma(S \to Z\gamma)}{\Gamma(S \to \gamma\gamma)}$	$\frac{\Gamma(S \to ZZ)}{\Gamma(S \to \gamma\gamma)}$	$\frac{\Gamma(S \to WW)}{\Gamma(S \to \gamma\gamma)}$
WW only	$2/\tan^2\theta_{\rm W} \approx 7$	$1/\tan^4\theta_{\rm W} \approx 12$	$2/\sin^4\theta_{\rm W} \approx 40$
BB only	$2\tan^2\theta_{\rm W} \approx 0.6$	$\tan^4\theta_{\rm W} \approx 0.08$	0

More generally can write decay amplitude sum rules

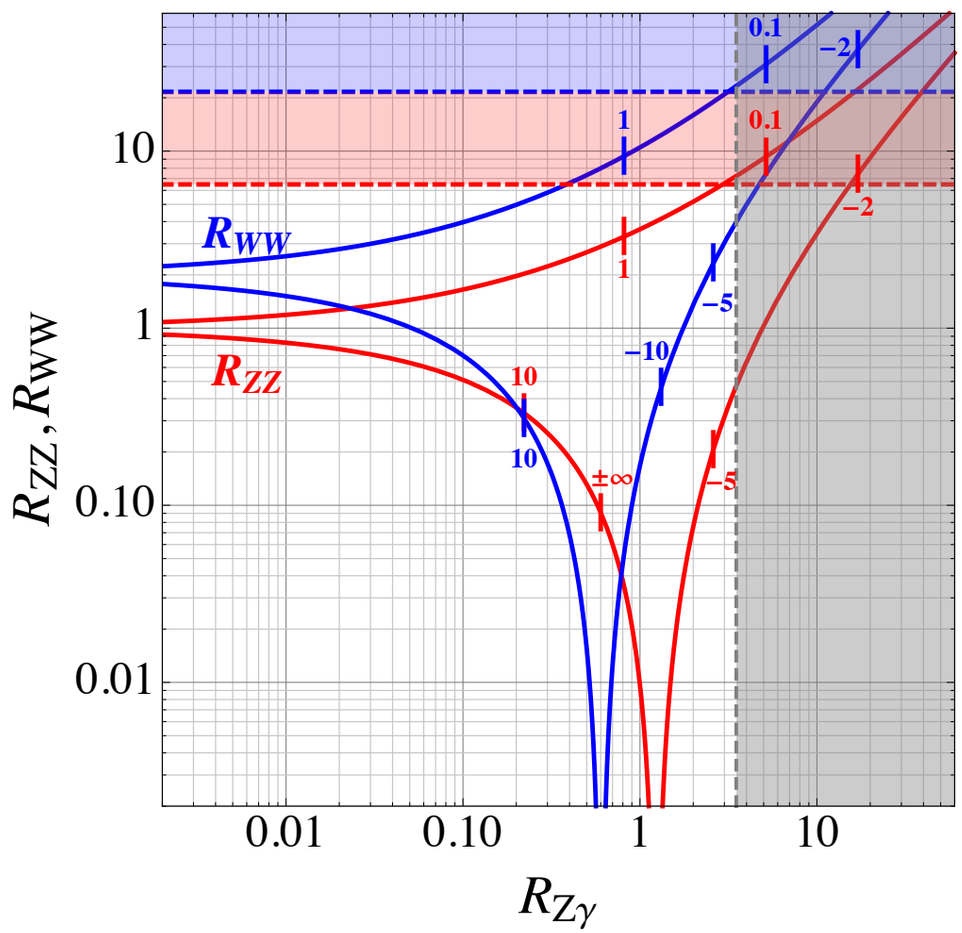
see also
1512.04929
1512.05327
1512.05328
1512.05332
1512.05775
1512.06799
1512.07616
1512.07733
1512.09089
...

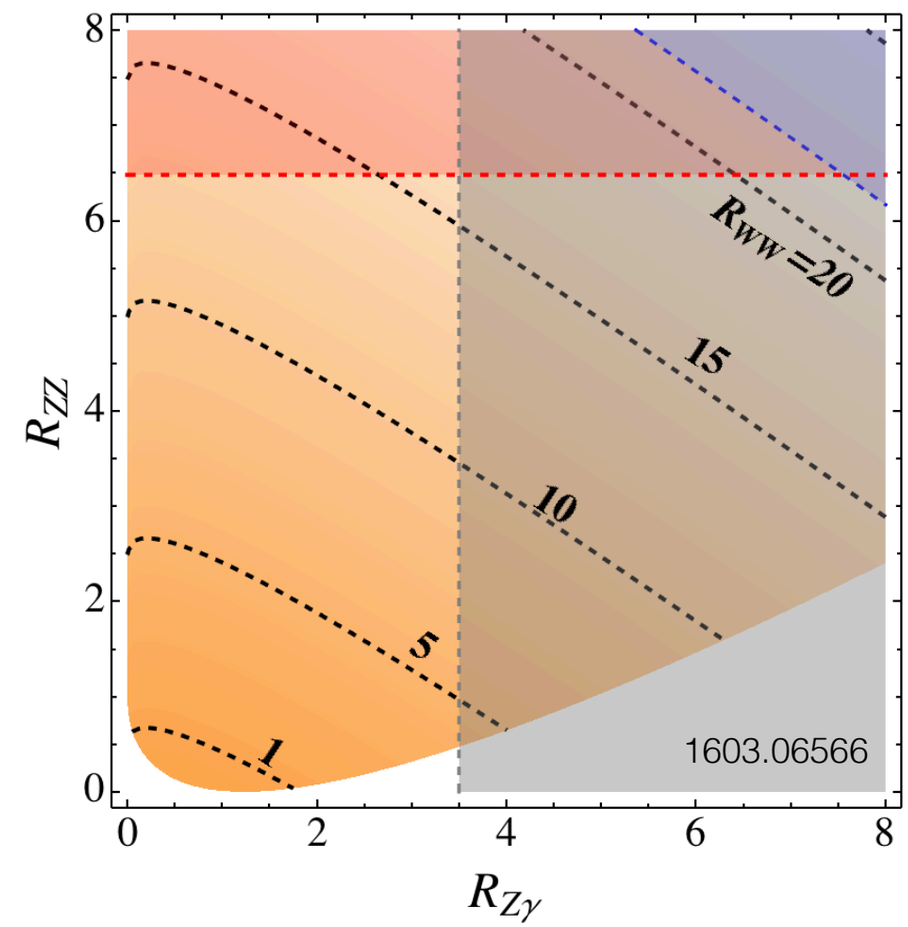
$$\mathcal{A}_{ZZ}c_W^2 + \mathcal{A}_{\gamma\gamma}s_W^2 = \frac{c_W^2 - s_W^2}{\sqrt{2}}\mathcal{A}_{WW}\,, \qquad \mathcal{A}_{ZZ} + \mathcal{A}_{\gamma\gamma} = \frac{c_W^2 - s_W^2}{\sqrt{2}s_W c_W}\mathcal{A}_{\gamma Z}\,,$$

$$\mathcal{A}_{WW} + \sqrt{2}\mathcal{A}_{\gamma\gamma} = \frac{c_W}{s_W}\mathcal{A}_{\gamma Z}\,, \qquad \mathcal{A}_{WW} - \frac{1}{\sqrt{2}}\mathcal{A}_{ZZ} = \frac{s_W}{c_W}\mathcal{A}_{\gamma Z}\,.$$

Implications of weak isospin invariance

SU(2)$_L$ invariance correlates different EW final states





⇒ At least two additional EW modes non-vanishing

see also
1512.04850
1512.05330
1512.07733
1512.06106
...

Candidates in strongly coupled models

Scalar resonances

pseudo-Goldstones

Dilaton

} Composite Higgs models (addressing EW hierarchy)

Techni-eta's

Q-onium

} Vector-like Confinement (not directly related to EW scale)

Can also be (re)interpreted in models with extra dimensions:
e.g. Dilaton = radion; special role: spin-2 (KK graviton)

c.f. 1512.05771, 1602.02393, 1603.05978, 1603.06980, 1603.07303, 1603.08250, 1603.08913.