750 GeV Diphoton Excess as a Composite (Pseudo)scalar Boson from New Strong Interaction

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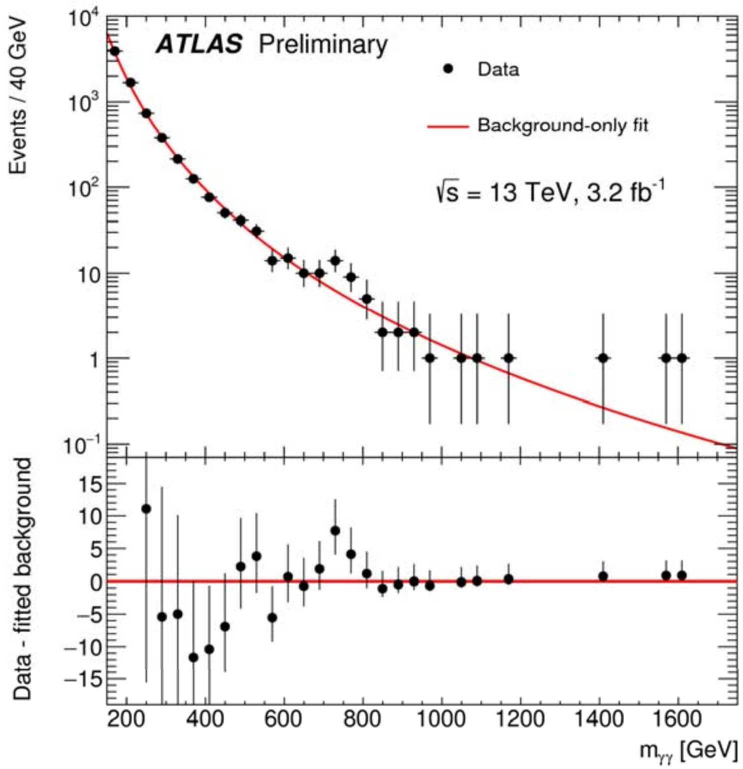
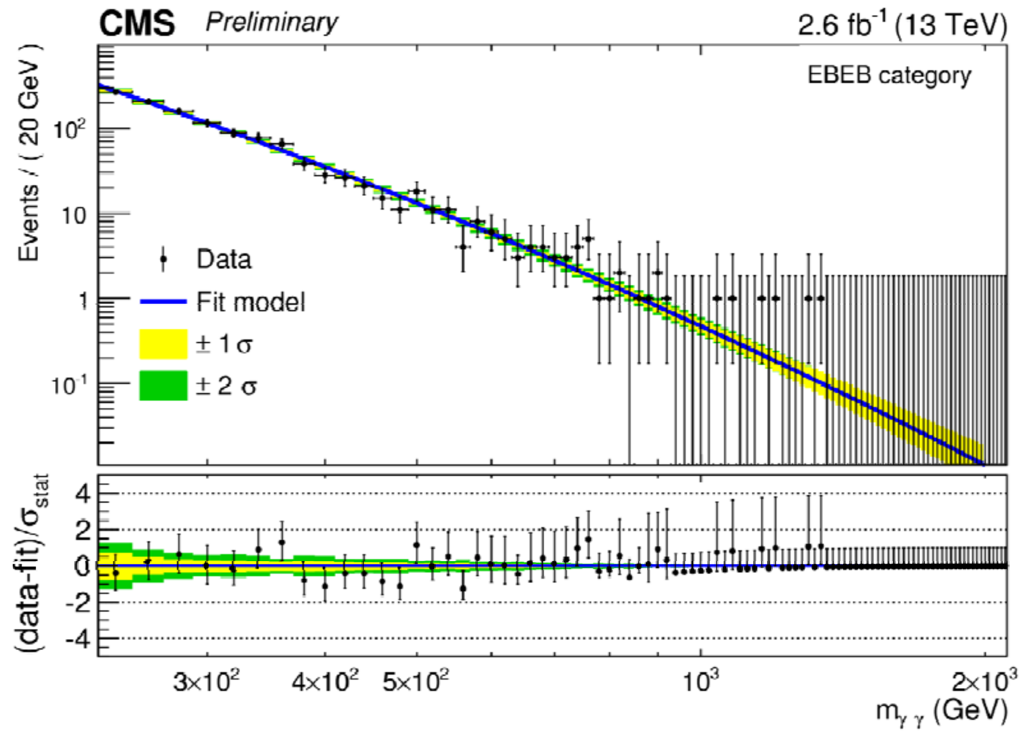
Collaboration with P. Ko (KIAS) , T.C. Yuan (AS)

Based on arXiv:1603.08802; work in progress

CYCU seminar, Apr 26, 2016

Diphoton excess Run-II





ATLAS: local 3.6σ (global 2.0σ)

$\sigma(pp\to\gamma\gamma)$ ~ 10 fb with Γ~45 GeV

CMS: local 2.6σ for narrow width
<2σ for wide width
(global <1.2σ)

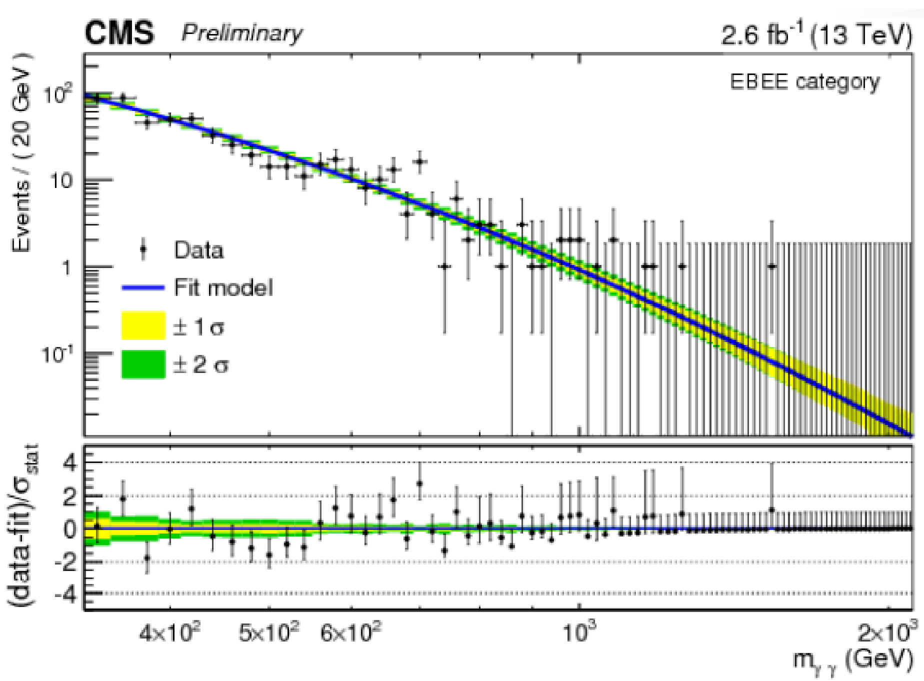
ATLAS data prefer large width Γ/M~0.06 while CMS data prefer narrow width

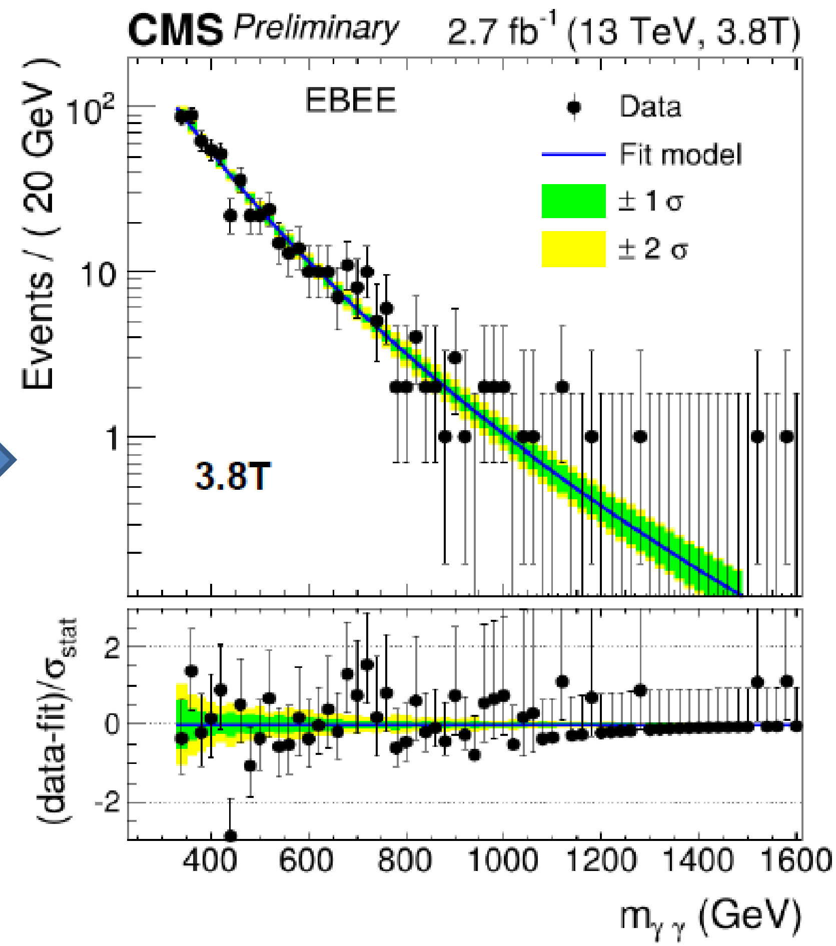
What's new in CMS data

Small enhancement in data : 2.6 fb^{-1} → 2.7 fb^{-1}

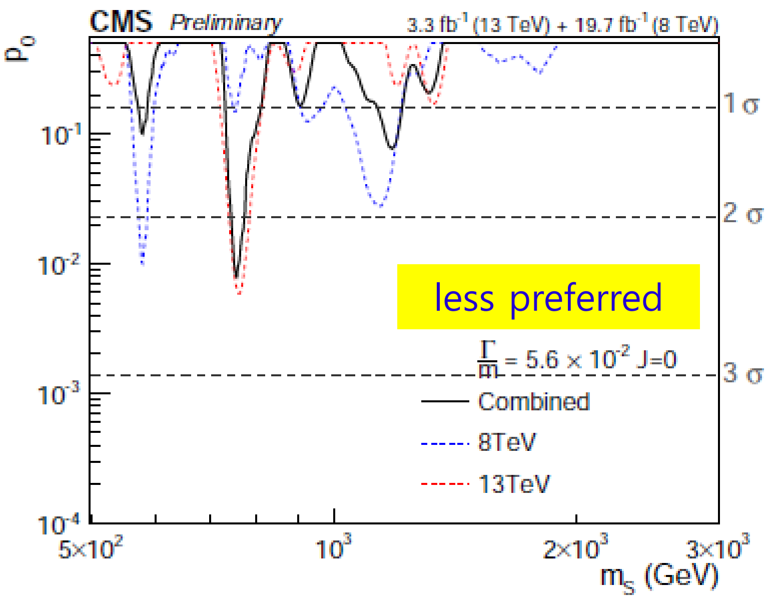
Data re-reconstruction, using updated channel-to-channel calibration

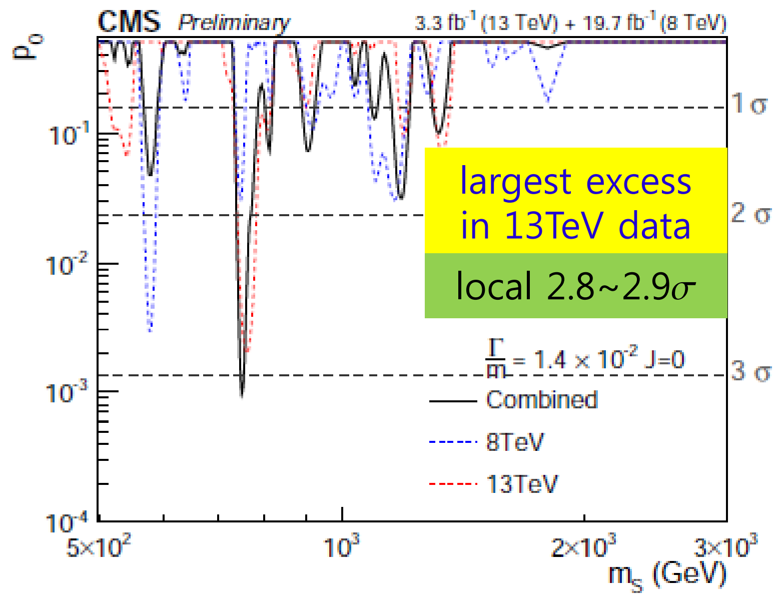
~30% improvement of resolution in high mass region

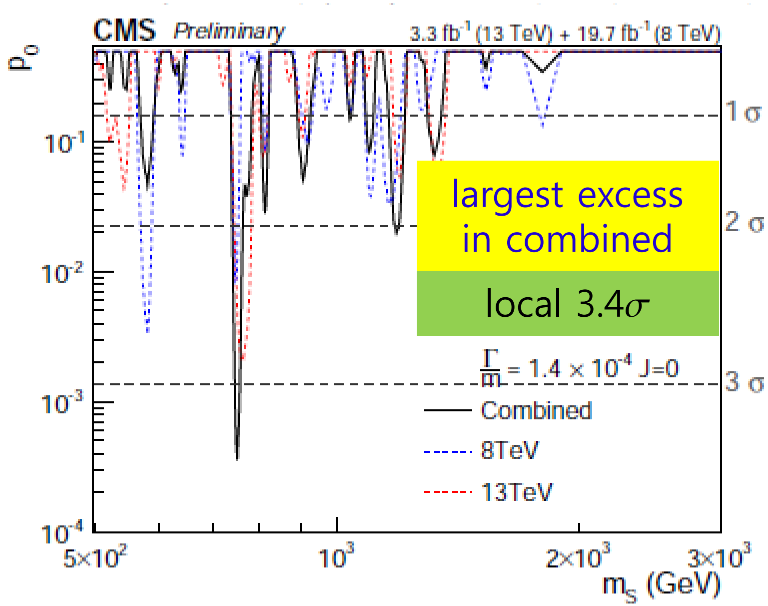


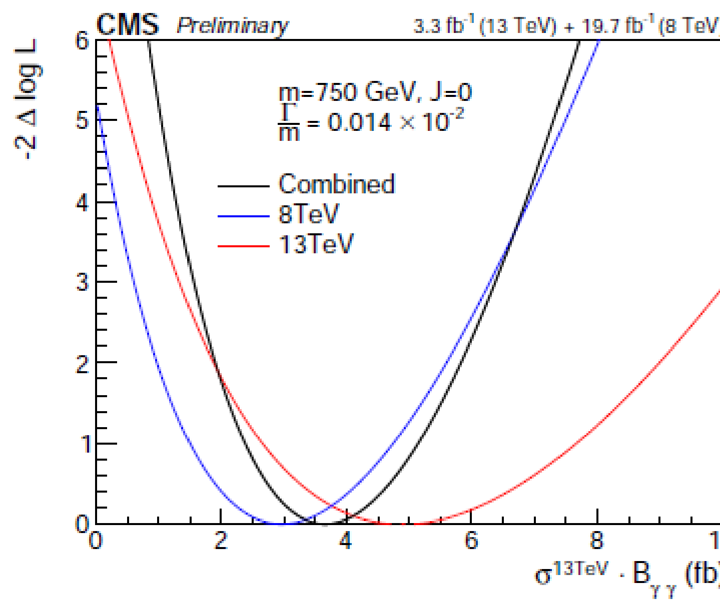


CMS RunI + RunII

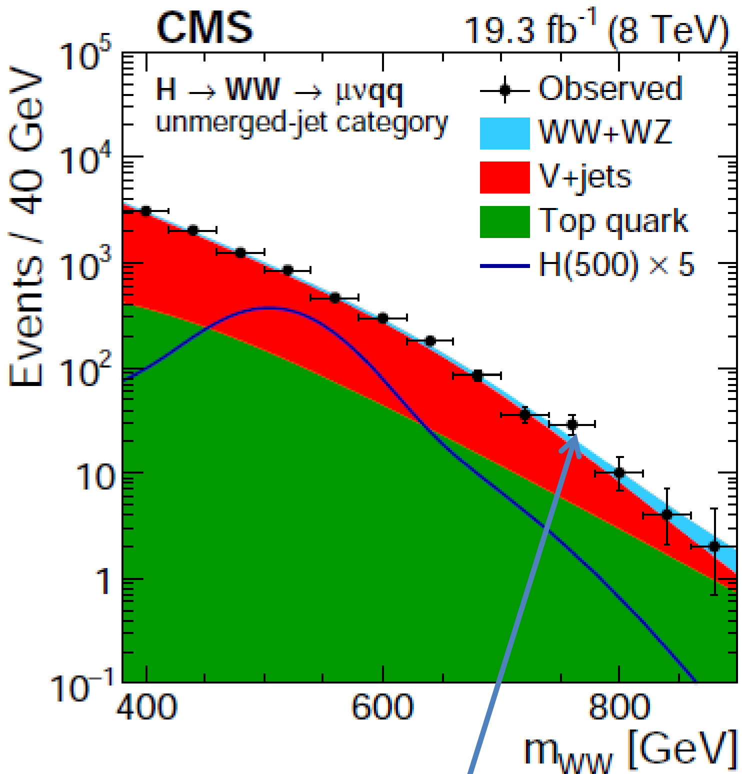


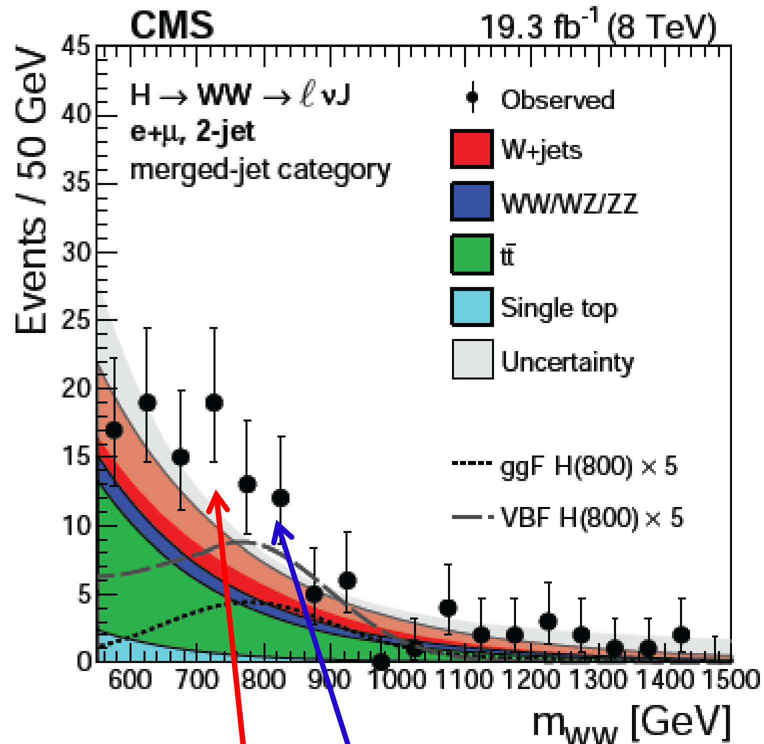






Some hints in CMS Run-I ?





local excess of 2.1σ

small excess at 750 GeV

local excess of 2.6σ

But, there is no excess
in the 0+1 jet category

New Physics or not

Statistical fluctuation

The excess is near to the event tail.

No excess in other channels so far – constrain new physics models.

There have been many other 2~4σ signals at LHC, but many of them were already washed out.

New physics

Both ATLAS and CMS see the excess – similar to Higgs boson discovery

About 300 papers have tried to interpret the diphoton excess as NP

The diphoton excess deserves investigation of all possible BSMs

Run-I constraints

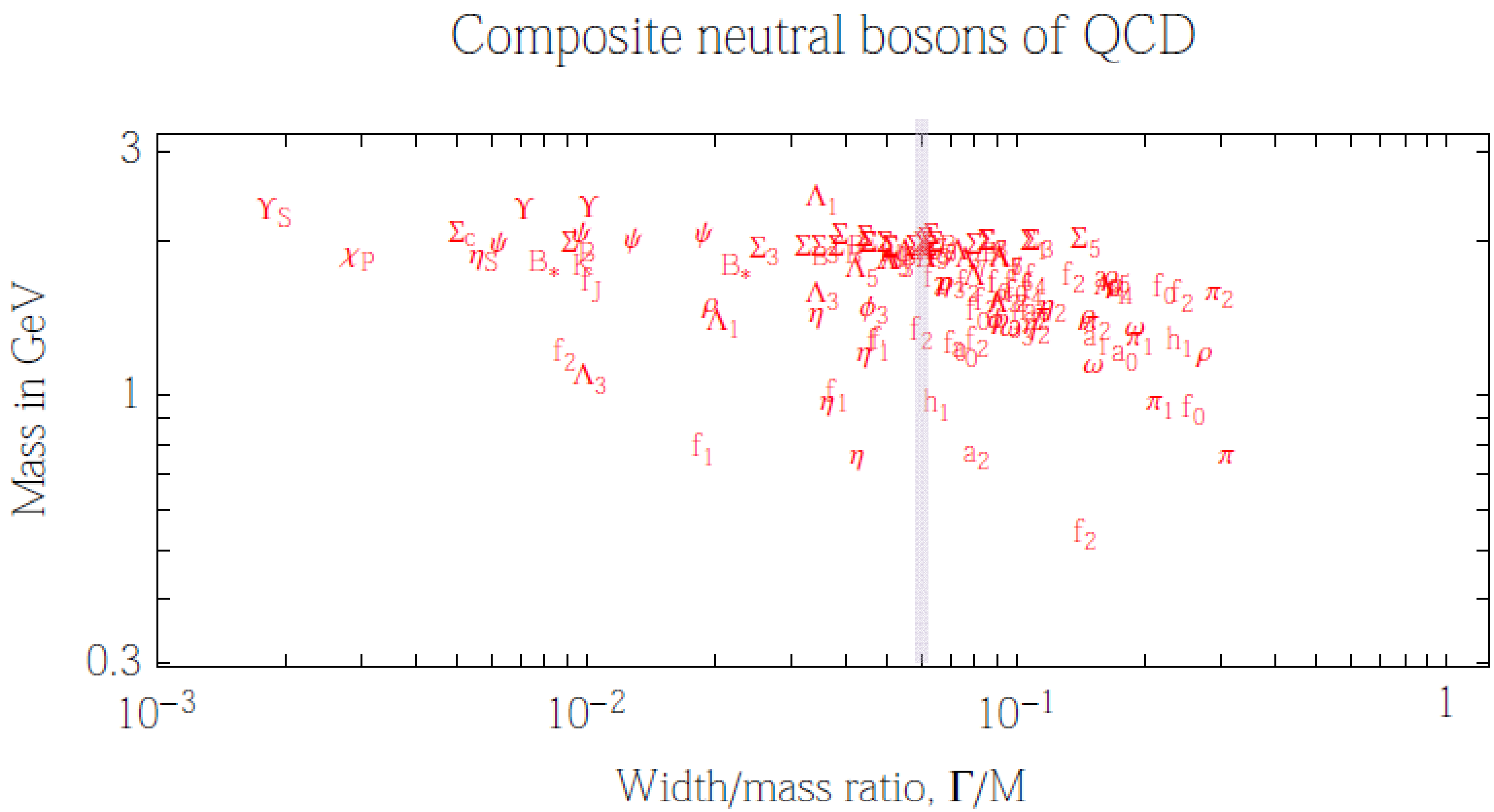
Diphoton resonance could decay into other SM particles, in particular Zγ and ZZ due to gauge invariance.

Monojet search also constrain new physics models for the diphoton excess – implication on dark matter

final state f	σ at $\sqrt{s} = 8\,\text{TeV}$ observed	expected	ref.	implied bound on $\Gamma(S \to f)/\Gamma(S \to \gamma\gamma)_{\text{obs}}$
$\gamma\gamma$	< 1.5 fb	< 1.1 fb	[6, 7]	$< 0.8\ (r/5)$
$e^+e^- + \mu^+\mu^-$	< 1.2 fb	< 1.2 fb	[8]	$< 0.6\ (r/5)$
$\tau^+\tau^-$	< 12 fb	< 15 fb	[9]	$< 6\ (r/5)$
$Z\gamma$	< 4.0 fb	< 3.4 fb	[10]	$< 2\ (r/5)$
ZZ	< 12 fb	< 20 fb	[11]	$< 6\ (r/5)$
Zh	< 19 fb	< 28 fb	[12]	$< 10\ (r/5)$
hh	< 39 fb	< 42 fb	[13]	$< 20\ (r/5)$
W^+W^-	< 40 fb	< 70 fb	[14, 15]	$< 20\ (r/5)$
$t\bar{t}$	< 550 fb	-	[16]	$< 300\ (r/5)$
invisible	< 0.8 pb	-	[17]	$< 400\ (r/5)$
$b\bar{b}$	$\lesssim 1$ pb	$\lesssim 1$ pb	[18]	$< 500\ (r/5)$
jj	$\lesssim 2.5$ pb	-	[5]	$< 1300\ (r/5)$

Franceschini et al., arXiv:1512.04933

Typical Γ/M in QCD



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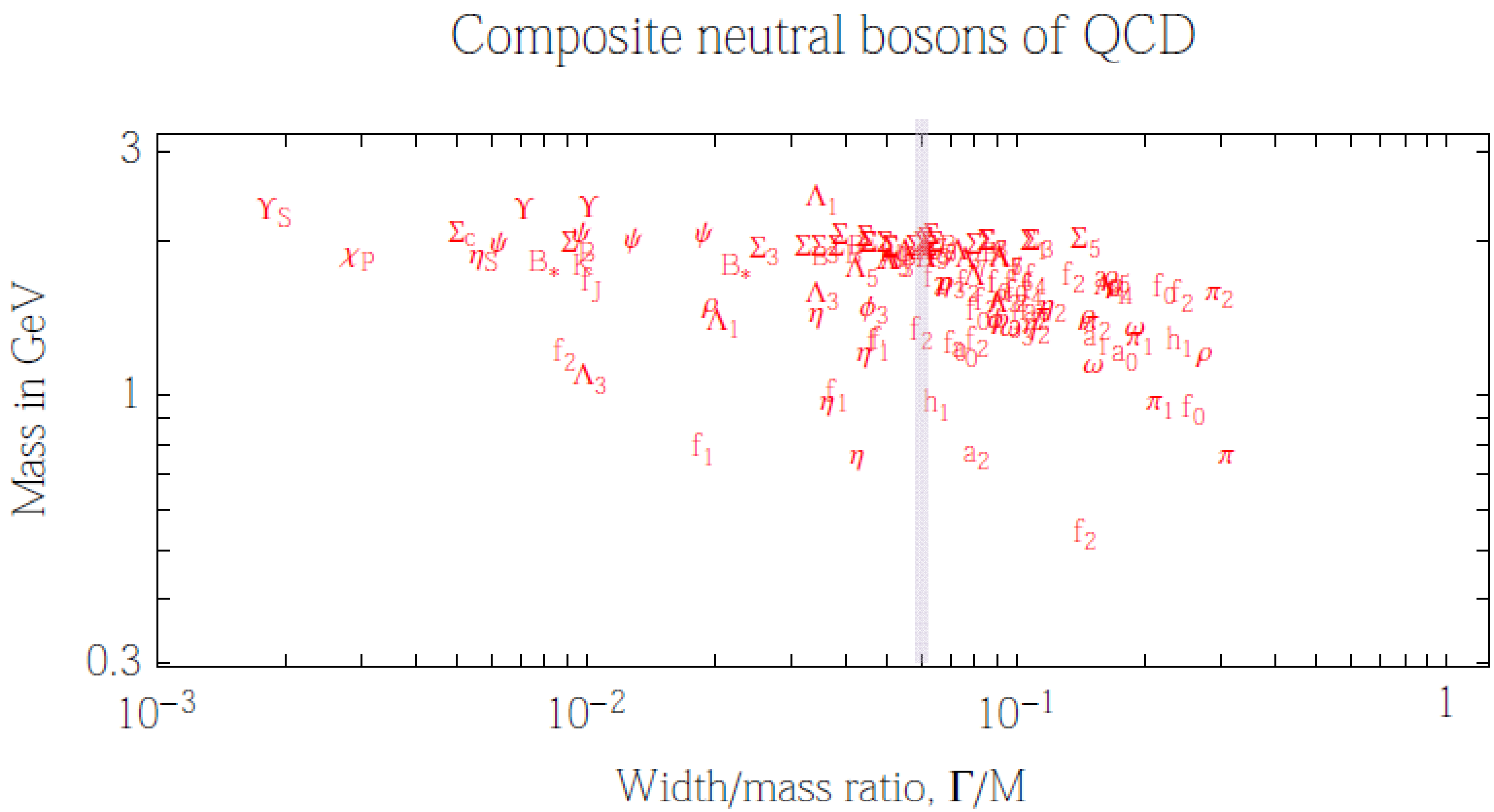
Typical Γ/M in QCD



Franceschini et al., arXiv:1512.04933

Large Γ/M may easily be achieved in the composite model with QCD or QCD-like interactions, but model-dependent.

Composite model (SU(2) singlet)

- a new confining gauge group SU(N_h) with the confinement scale Λ_h.

$$\Lambda_h \simeq M \exp\left[-\frac{6\pi}{(11N_h - 2n_f)\alpha_h(M)}\right]$$

- a new vector-like h-quark (hyper quark) Q and its partner $\bar{Q}$ (or scalar h-quark $\tilde{Q}$ and its antiparticle $\tilde{Q}^\dagger$).

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times SU(N_h) : (3,1,Y;N_h)$$

- both Q and $\tilde{Q}$ are heavier than the confinement scale Λ_h.

  - $Q\bar{Q}(\tilde{Q}\tilde{Q}^\dagger)$ bound states can be treated as heavy quarkonia, in analogous to $J/\psi, \eta_c$, etc. in QCD.

- assume that Q is the only hyper-quark or the lightest one.

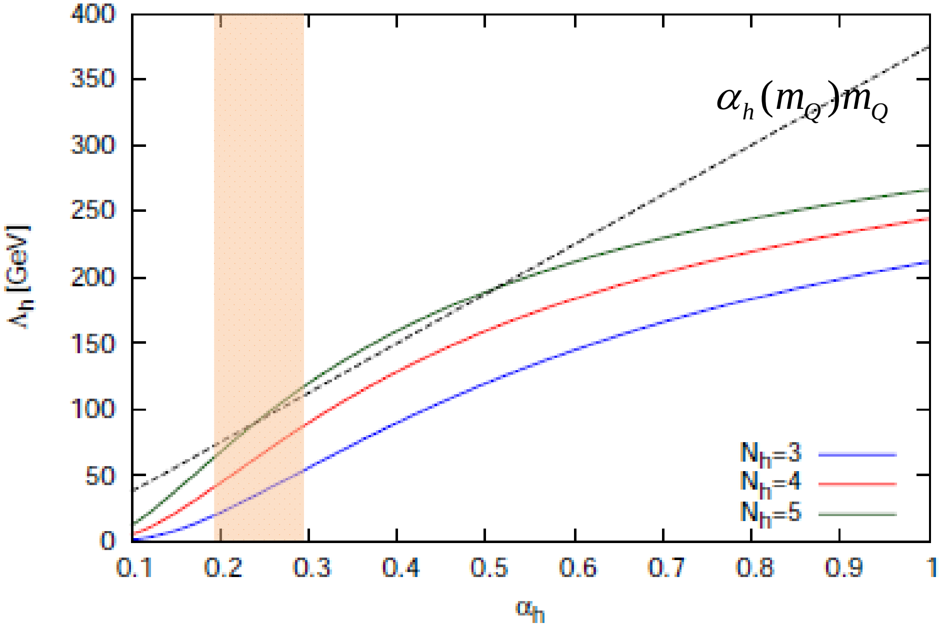
Composite model (SU(2) singlet)

• vector-like mass $\Longrightarrow$ weak constraint from EWPO

• SU(2) doublet model: constrained by EWPOs and Higgs signal strength at the LHC

• constraint from cosmology, for example, BBN

Potential of bound state



$$\alpha_h(m_Q v_Q)m_Q > \alpha_h(m_Q)m_Q > \Lambda_h$$

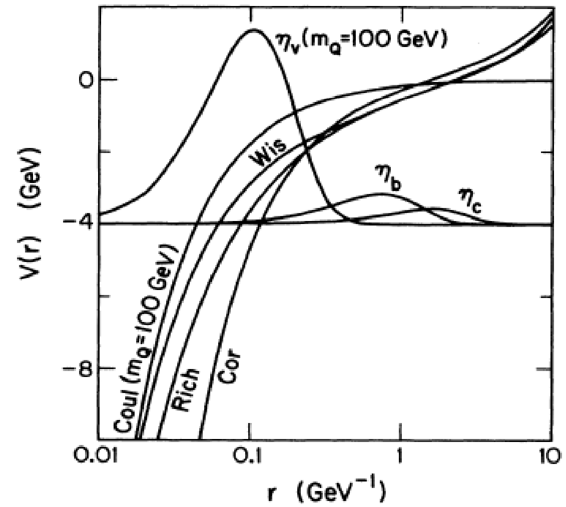
The bound state would be more like a Coulombic bound state since the nonperturbative confinement effect would be smaller than the Coulomb interaction.

- Coulomb dominance might be a reasonable good approximation for the entire range of α_h.

- Assume the binding potential is Coulombic $V = -\frac{C_h \alpha_h}{r}$

- In order to get more reliable results, more precise calculations such as lattice h-QCD simulations would be required.

Wavefunction at the origin



Coulomb $V(r) = -\frac{4}{3}\frac{\alpha_s(m_Q{}^2)}{r}$

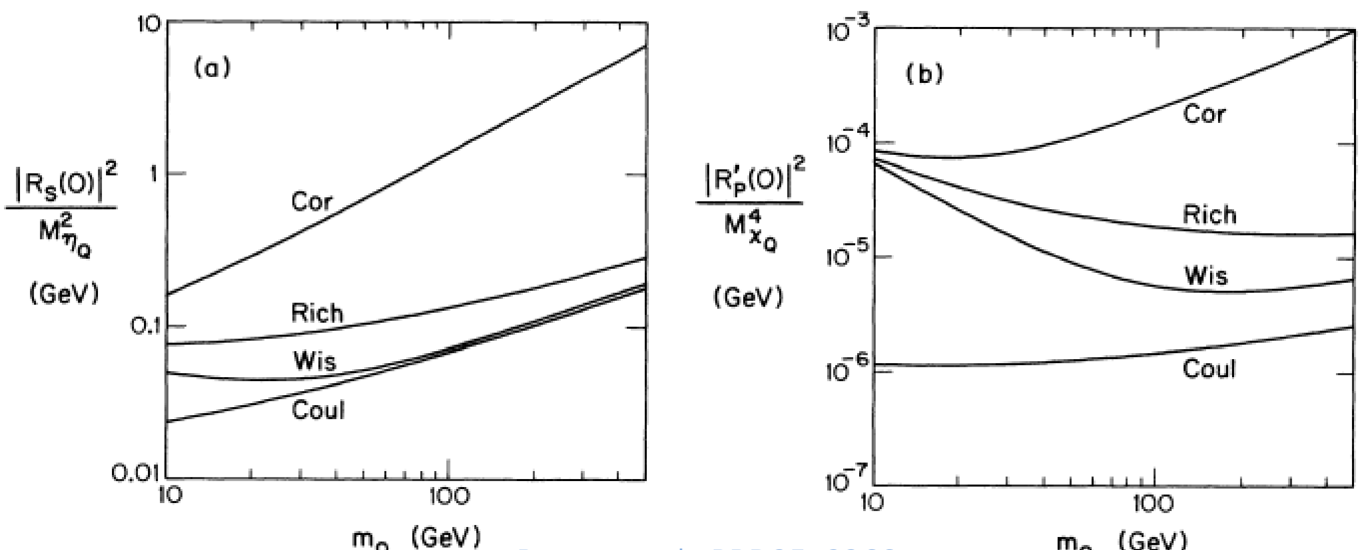
Cornell $V(r) = -k/r + ar$

Richardson $V(Q) = -\frac{4}{3}\frac{12\pi}{33-2N_f}\frac{1}{Q^2}\frac{1}{\ln(1+Q^2/\Lambda^2)}$

Wisconsin $V(r) = V_S(r) + V_I(r) + ar$

$V_S(r) = -4\alpha_s(r)/3r$

$V_I(r) = r(c_1 + c_2 r)e^{-r/r_0}$



Barger et al., PRD35, 3366

SU(2) singlet fermion model

- fix m_Q=375 GeV for interpreting the diphoton excess as a bound state of $Q\bar{Q}$ in the spin-singlet S-wave state, η_Q .

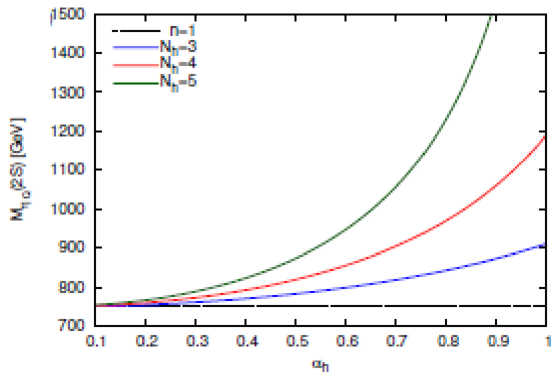
- the binding energy is

$$M(n^{2S+1}L_J) \simeq 2m_Q\left[1-\frac{C_h^2\alpha_h^2}{8n^2}\right]$$

Degeneracy in the orbital quantum number l for Coulomb potential

- the mass of the excited state is

$$M(\eta_Q') = 750\text{GeV}\left(\frac{1-C_h^2\alpha_h^2/32}{1-C_h^2\alpha_h^2/8}\right)$$



- exists the spin-triplet partner, ψ_Q .

$$\Delta M \equiv M_{\psi_Q} - M_{\eta_Q} = M_{\eta_Q}\frac{16\pi}{3}\alpha_h\frac{|R_S(0)|^2}{M^3} \approx M_{\eta_Q}\frac{\pi}{3n^2}(C_h\alpha_h)^4$$

Mass splitting by hyperfine interaction

$$\Delta M \lesssim (4, 13, 35)\ \text{GeV for}\ N_h = (3,4,5)$$

η_Q decay

$$\Gamma(\eta_Q \to \gamma\gamma) = \frac{N_c N_h \alpha^2 e_Q^4}{m_Q^2} |R_{1S}(0)|^2 \propto e_Q^4$$

$$\Gamma(\eta_Q \to \gamma Z) = \frac{N_c N_h \alpha^2 e_Q^4 x_w (4 - r_Z)}{2 m_Q^2 (1 - x_w)} |R_{1S}(0)|^2$$

$$\Gamma(\eta_Q \to ZZ) = \frac{4 N_c N_h \alpha^2 e_Q^4 x_w^2 (1 - r_Z)^{3/2}}{m_Q^2 (2 - r_Z)^2 (1 - x_w)^2} |R_{1S}(0)|^2$$

Decays into WW or ff are forbidden due to SU(2) singlet nature or charge conjugation symmetry

$$\Gamma(\eta_Q \to gg) = \frac{C_F N_h \alpha_s^2}{2 m_Q^2} |R_{1S}(0)|^2$$

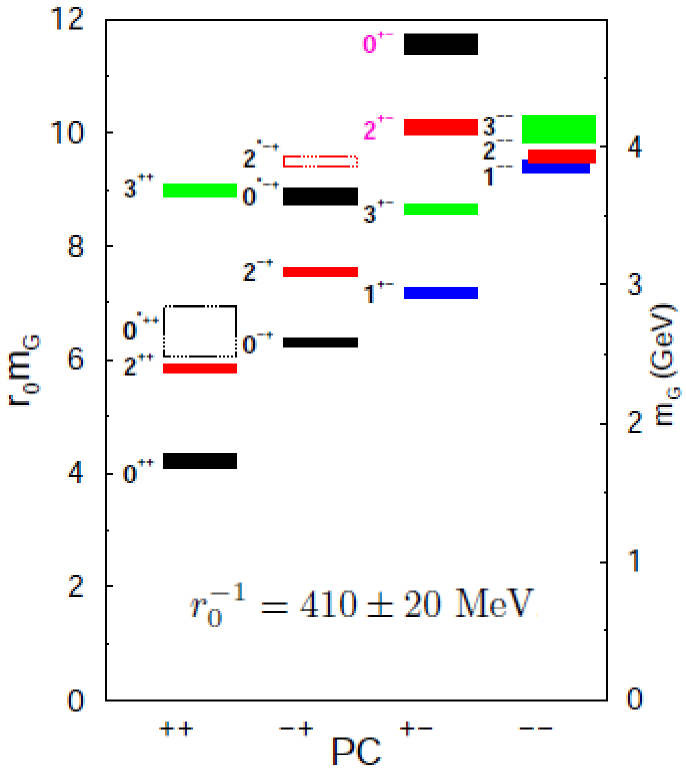
$$\Gamma(\eta_Q \to g_h g_h) = \frac{C_h N_c \alpha_h^2}{2 m_Q^2} |R_{1S}(0)|^2$$

Eventually h-gluons would evolve into h-glueballs if kinematically allowed

If there exist lighter h-quarks, η_Q can decay into the bound states made of the light h-quarks.

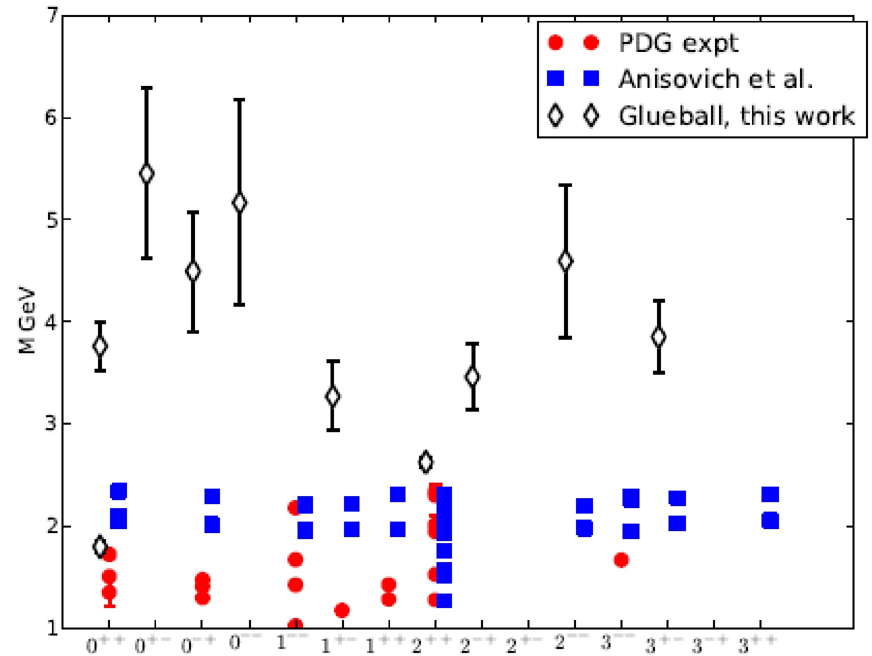
Glueball mass in pure SU(3)

quenched lattice calculation



Chen et al., PRD73, 014516

unquenched lattice calculation

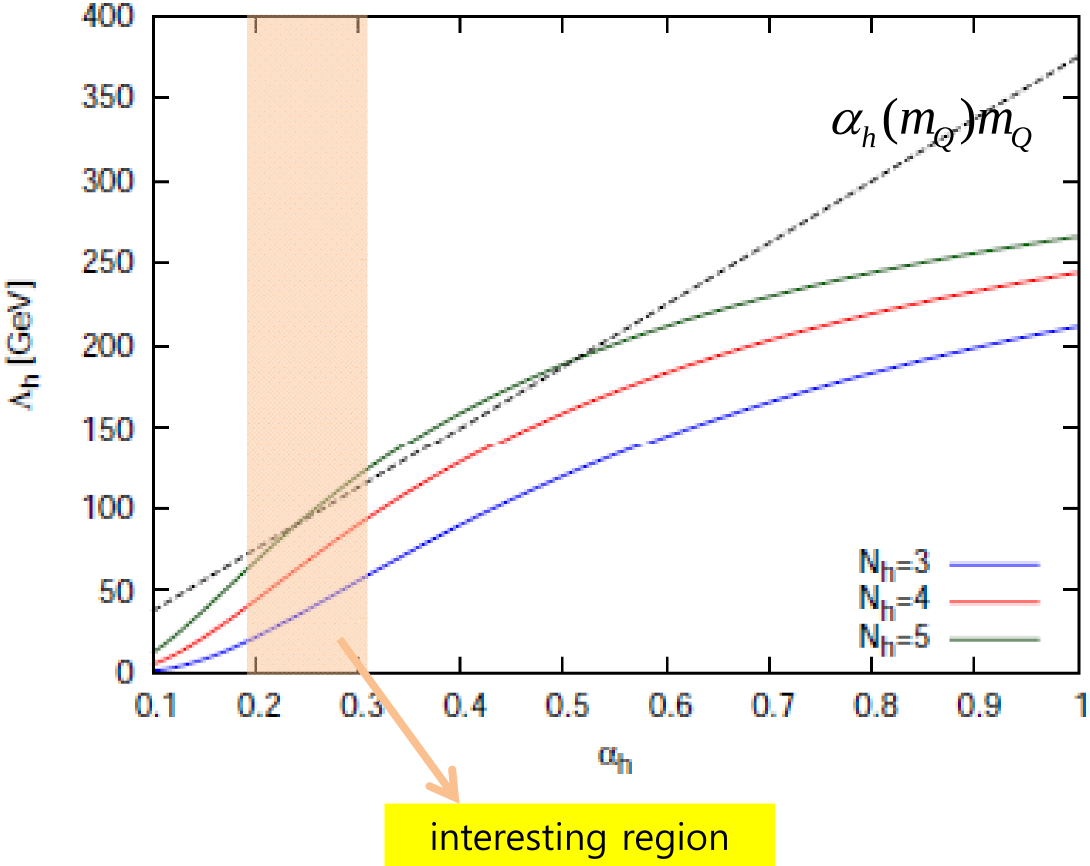


Gregory et al., 1208.1858

Glueball has not been detected and the mass prediction might have uncertainties

$$M_G \simeq (4 \sim 7) \times \Lambda$$

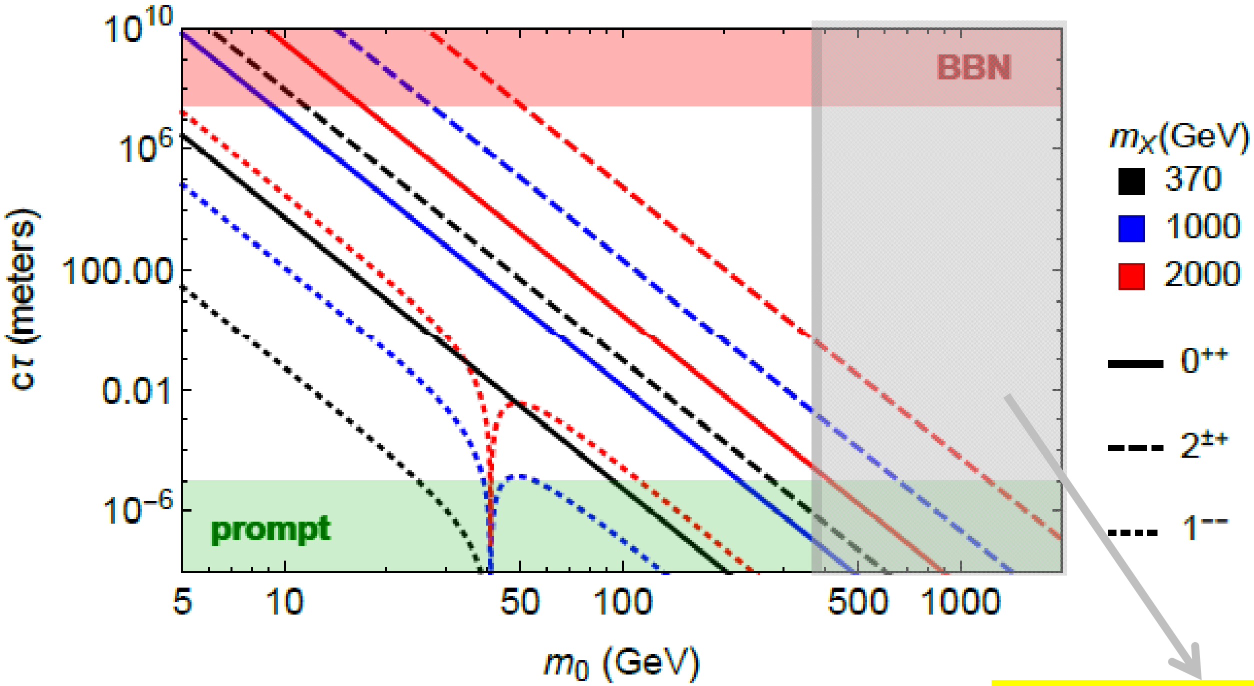
Glueball mass in pure SU(3)



$$M_G = 80 \sim 500 \text{ GeV}$$

Glueball decay length

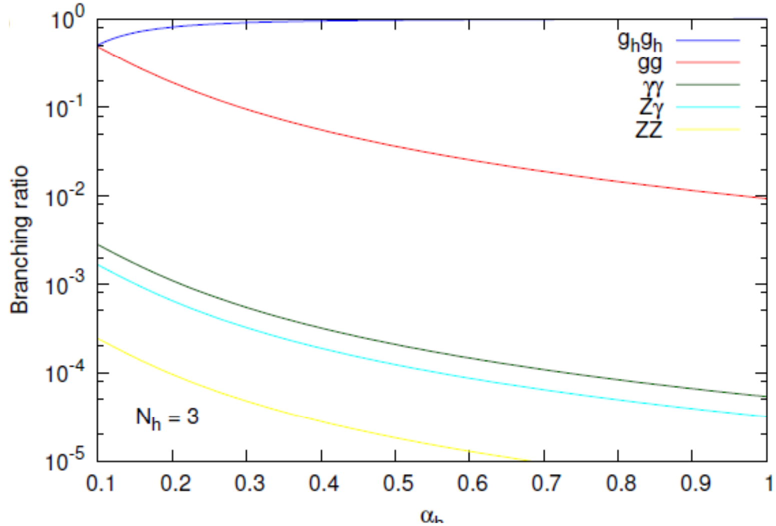
Curtin, Verhaaren, 1512.05753

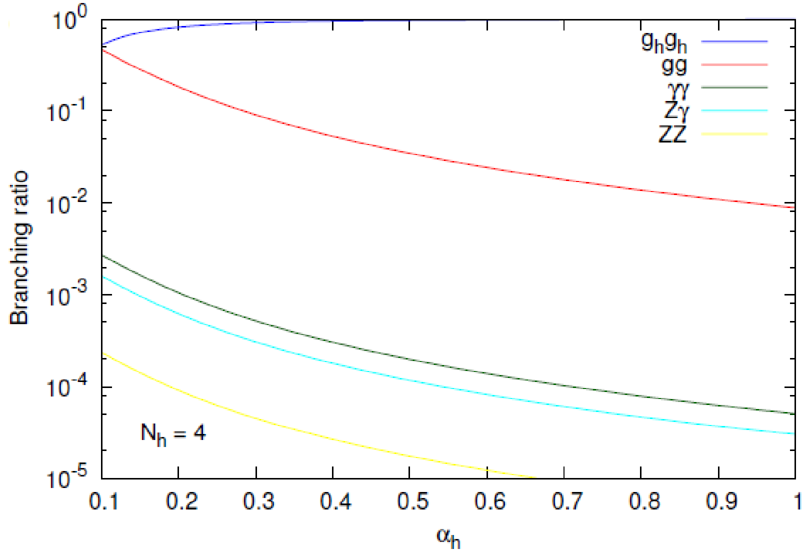


A 750 GeV resonance cannot decay into glueballs

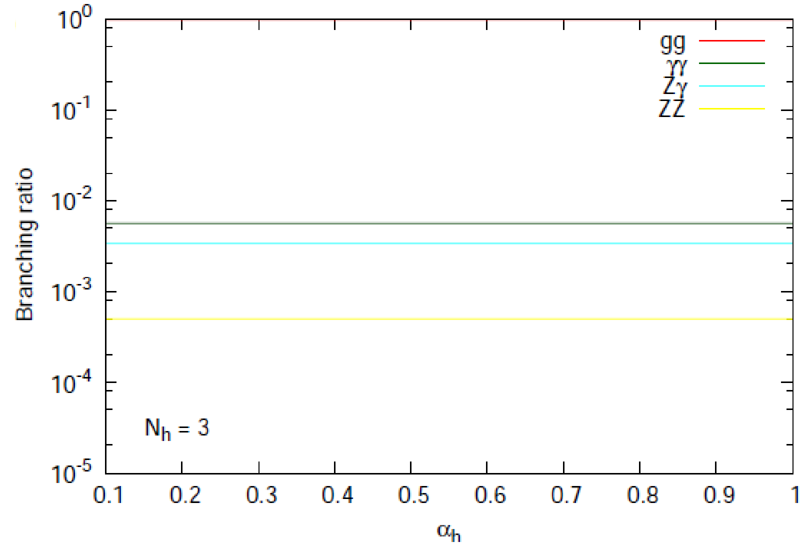
Branching ratios

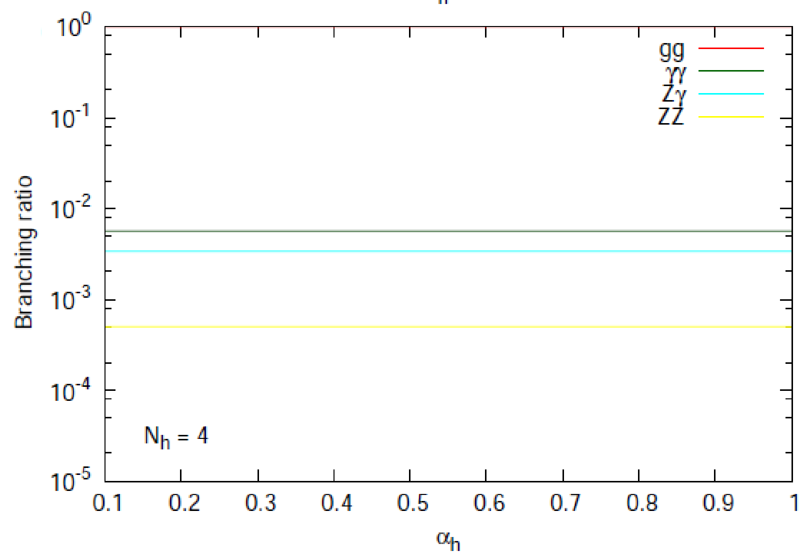
$\eta_Q \to g_h g_h$



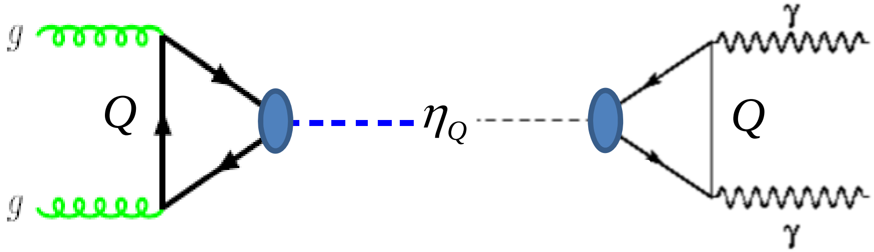


$\eta_Q \not\to g_h g_h$





Production cross section



$$\sigma(gg \to \eta_Q \to \gamma\gamma) = \frac{C_{gg}}{s m_{\eta_Q} \Gamma_{\rm tot}} \Gamma[\eta_Q \to gg]\Gamma[\eta_Q \to \gamma\gamma] \quad \propto e_Q^4$$

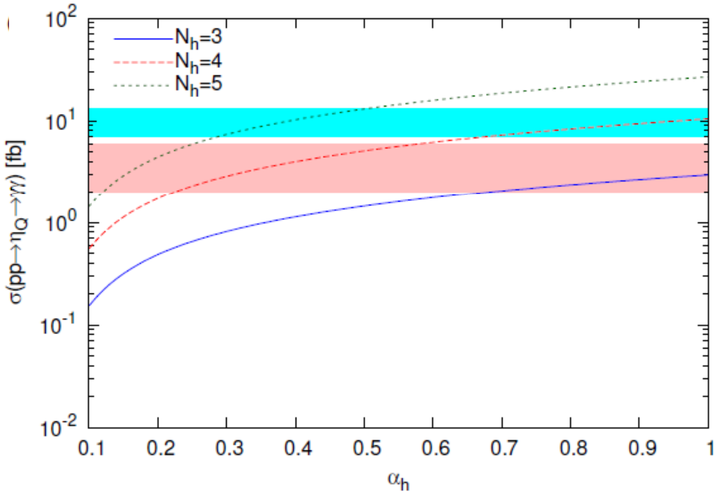
$$C_{gg} \;=\; \frac{\pi^2}{8}\int_{M^2/s}^{1} \frac{dx}{x} g(x) g(\frac{M^2}{sx})$$

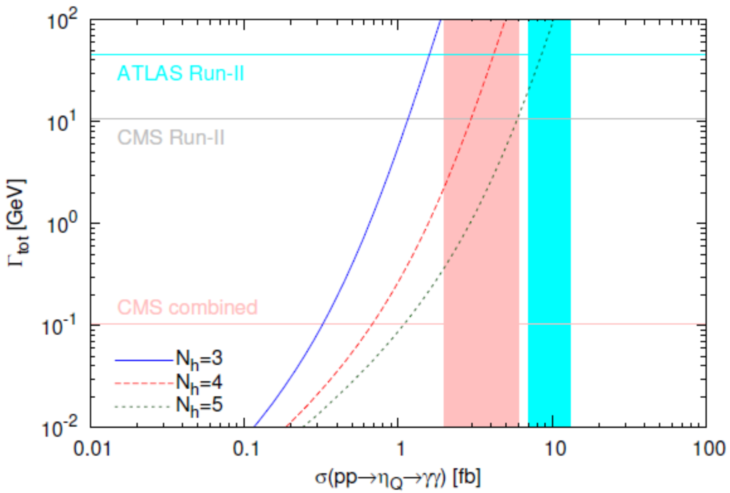
$\sqrt{s}$	$C_{b\bar{b}}$	$C_{c\bar{c}}$	$C_{s\bar{s}}$	$C_{d\bar{d}}$	$C_{u\bar{u}}$	C_{gg}
8 TeV	1.07	2.7	7.2	89	158	174
13 TeV	15.3	36	83	627	1054	2137

The production cross section $\propto$ the wavefunction at the origin

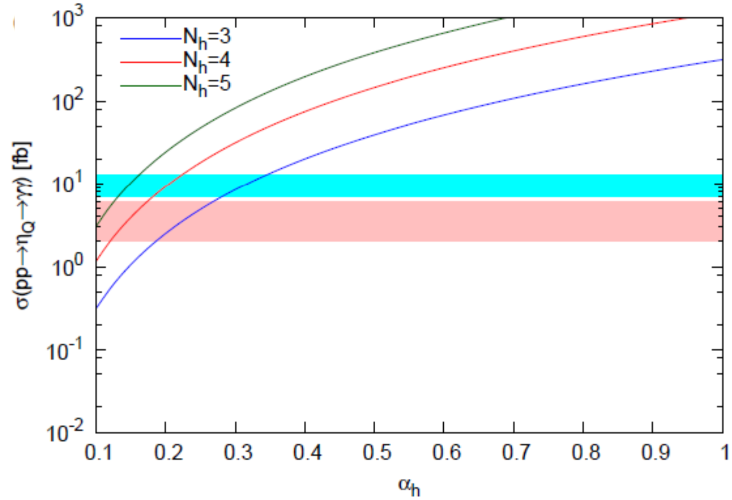
Diphoton cross section

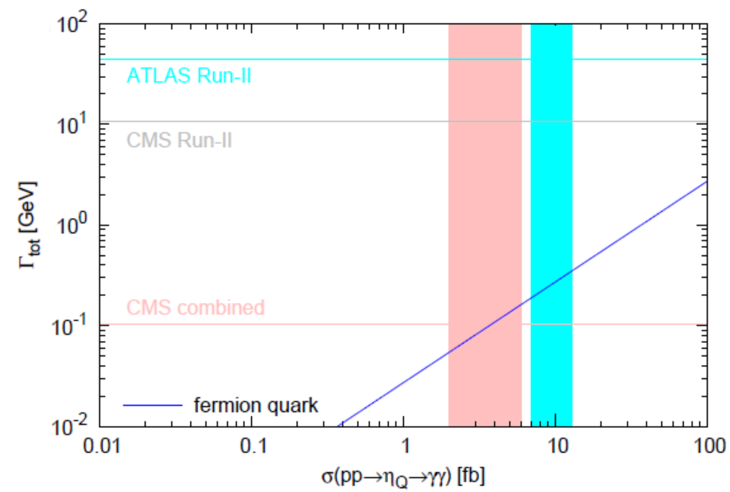
$\eta_Q \to g_h g_h$





$\eta_Q \not\to g_h g_h$





Spin-triplet partner ψ_Q

$$\Gamma(\psi_Q \to g_h g_h g_h) = \frac{(\pi^2-9)\alpha_h^3}{36\pi m_Q^2}\frac{N_c(N_h^2-1)(N_h^2-4)}{N_h^2}|R_{1S}(0)|^2$$

➡ may be forbidden kinematically

$$\Gamma(\psi_Q \to ggg) = \frac{(\pi^2-9)\alpha_s^3}{36\pi m_Q^2}\frac{N_h(N_c^2-1)(N_c^2-4)}{N_c^2}|R_{1S}(0)|^2$$

ψ_Q can decay into a pair of fermions via γ or Z exchanges

$$\Gamma(\psi_Q \to l^+l^-) = \frac{N_c N_h \alpha^2 e_Q^2}{3m_Q^2}\left[1 - \frac{2(1-4x_w)}{(4-r_Z)(1-x_w)} + \frac{2(1-4x_w+8x_w^2)}{(4-r_Z)^2(1-x_w)^2}\right]|R_{1S}(0)|^2$$

ψ_Q does not decay into $\gamma\gamma$, γZ, ZZ due to SU(2) singlet nature, but it can decay into WW through small SU(2) breaking terms

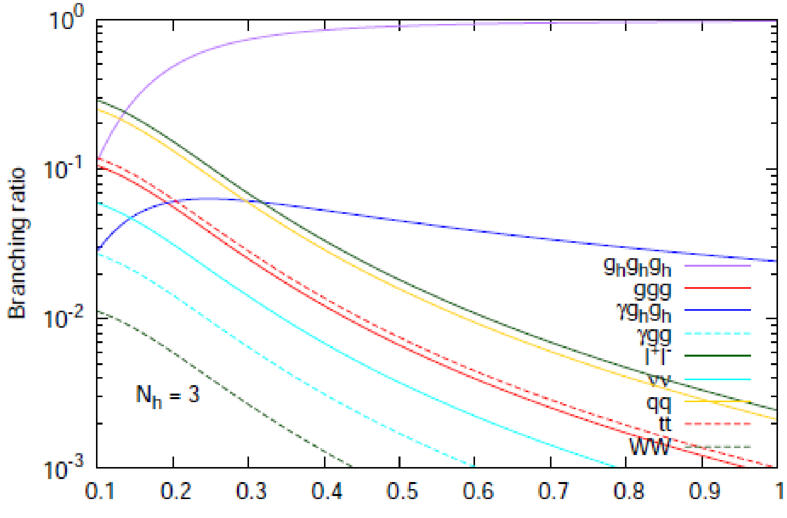
$$\Gamma(\psi_Q \to \gamma g g) = \frac{(\pi^2-9)\alpha_s^2\alpha e_Q^2}{3\pi m_Q^2}\frac{N_h(N_c^2-1)}{N_c}|R_{1S}(0)|^2$$

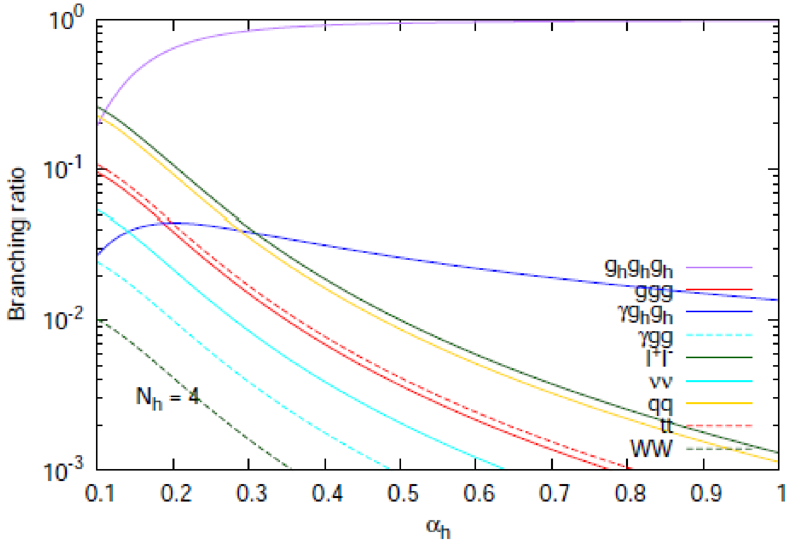
$$\Gamma(\psi_Q \to \gamma g_h g_h) = \frac{(\pi^2-9)\alpha_h^2\alpha e_Q^2}{3\pi m_Q^2}\frac{N_c(N_h^2-1)}{N_h}|R_{1S}(0)|^2$$

➡ $g_h g_h$ evolves into a h-glueball if kinematically allowed

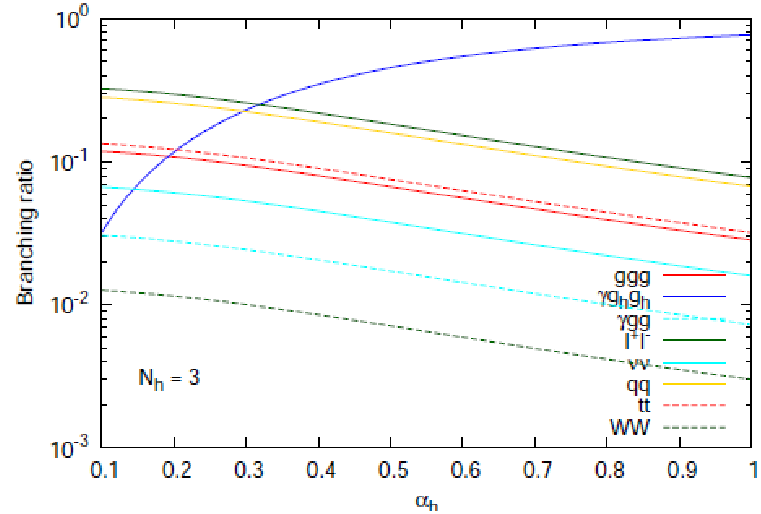
Spin-triplet partner ψ_Q

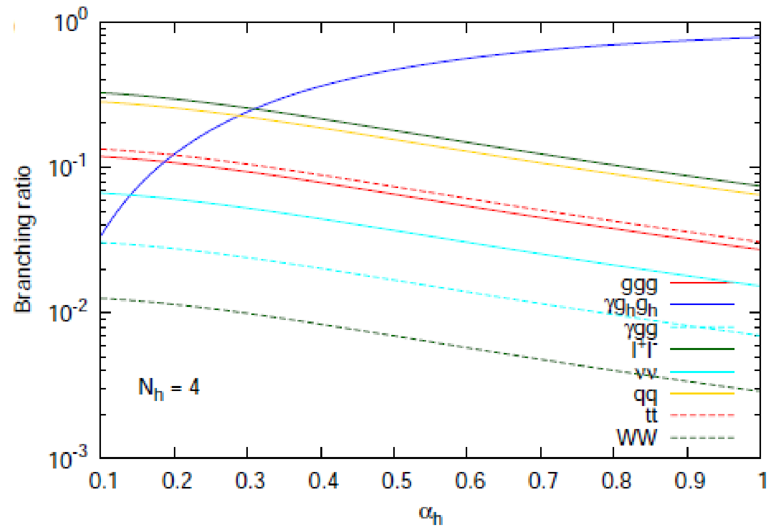
$\psi_Q \rightarrow g_h g_h g_h$





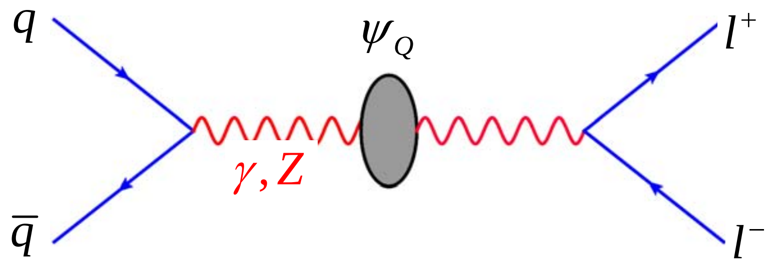
$\psi_Q \not\rightarrow g_h g_h g_h$





Production cross section of ψ_Q

Drell-Yan

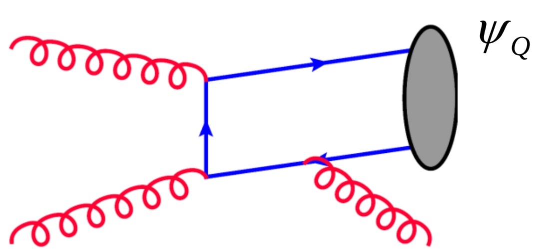


$$\sigma_{\rm DY}(q\bar{q} \to \psi_Q \to l^+l^-) = \frac{(2J_{\psi_Q}+1)\Gamma(\psi_Q \to l^+l^-)}{s m_{\psi_Q}\Gamma_{\psi_Q}} \sum_{q\bar{q}} C_{q\bar{q}}\Gamma(\psi_Q \to q\bar{q})$$

$$C_{q\bar{q}} = \frac{4\pi^2}{9}\int_{M^2/s}^{1}\frac{dx}{x}\left[q(x)\bar{q}(\frac{M^2}{sx}) + \bar{q}(x)q(\frac{M^2}{sx})\right]$$

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

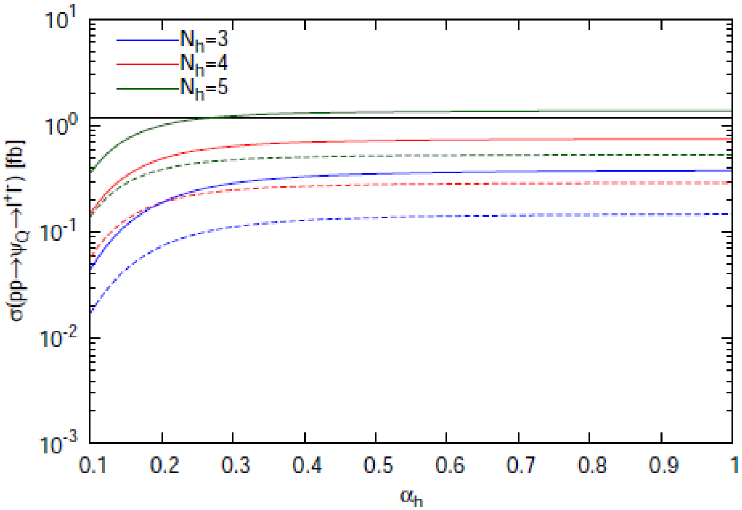
hadro-production

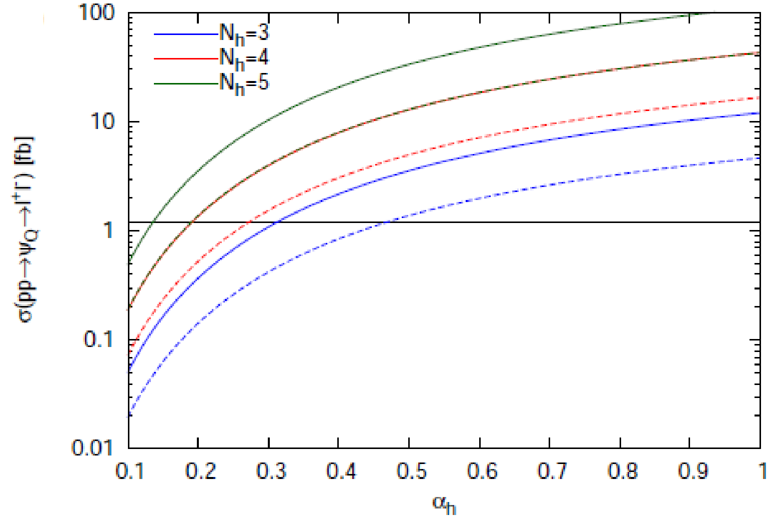


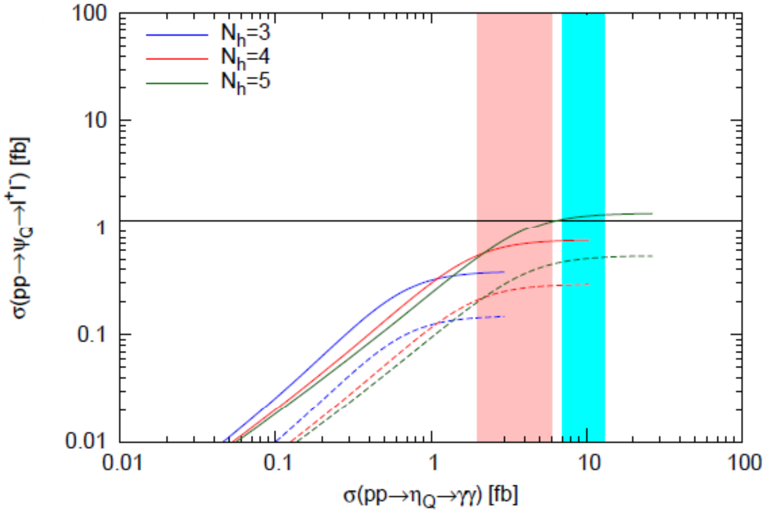
Drell-Yan production

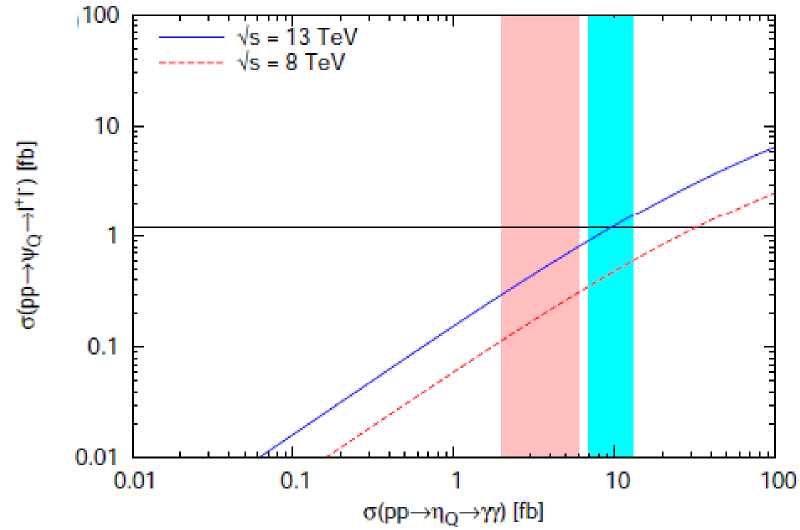
$\psi_Q \to g_h g_h g_h$

$\psi_Q \not\to g_h g_h g_h$



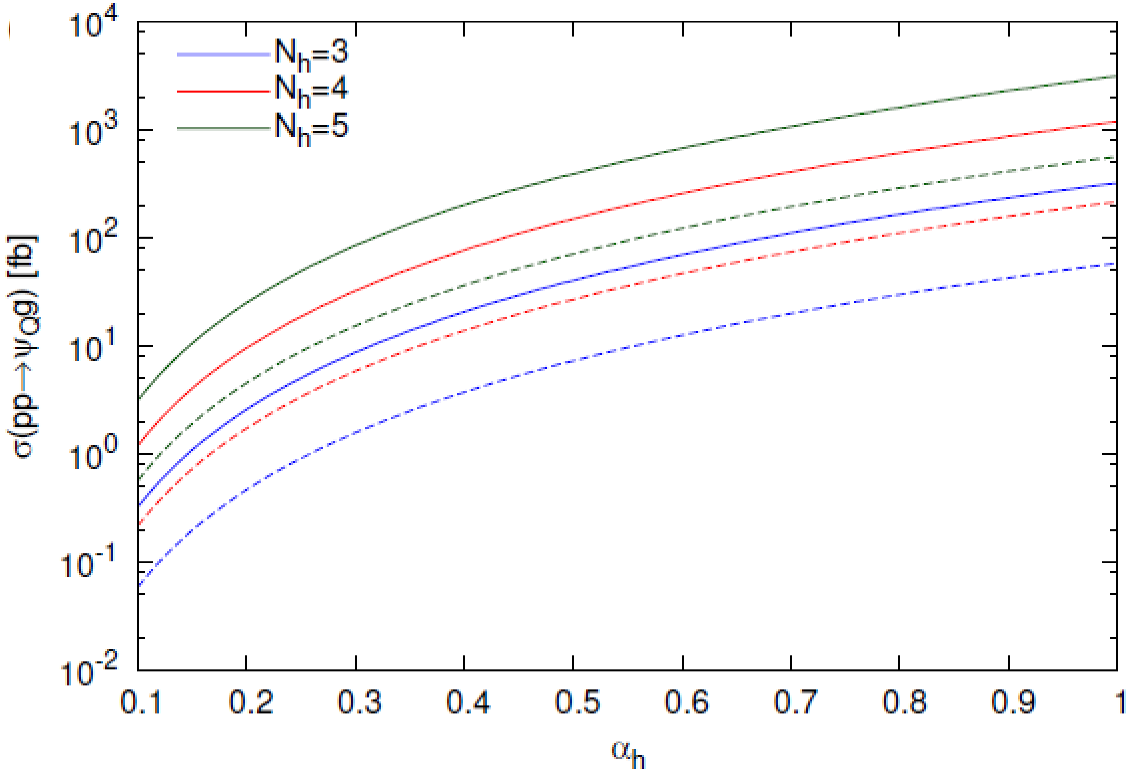






hadro-production

$\psi_Q \to g_h g_h g_h$



SU(2) singlet scalar model

- fix m_Q=375 GeV for interpreting the diphoton excess as a bound state of $\tilde{Q}\tilde{Q}^\dagger$ in the hypercolor-singlet S-wave state, $\eta_{\tilde{Q}}$.

- no spin-triplet partner since the constituent particles are scalar quarks

- $J^{PC}=1^{--}$ state comes from radial excitation with nonzero orbital angular momentum, J=L=1.

$$\Gamma(\eta_{\widetilde{Q}} \to \gamma\gamma) = \frac{N_c N_h \alpha^2 e_Q^4}{2m_Q^2}\left|\widetilde{R}_{1S}(0)\right|^2$$

$$\Gamma(\eta_{\widetilde{Q}} \to \gamma Z) = \frac{N_c N_h \alpha^2 e_Q^4 x_w (4-r_Z)}{4m_Q^2(1-x_w)}\left|\widetilde{R}_{1S}(0)\right|^2$$

$$\Gamma(\eta_{\widetilde{Q}} \to gg) = \frac{N_h(N_c^2-1)\alpha_s^2}{8N_c m_Q^2}\left|\widetilde{R}_{1S}(0)\right|^2$$

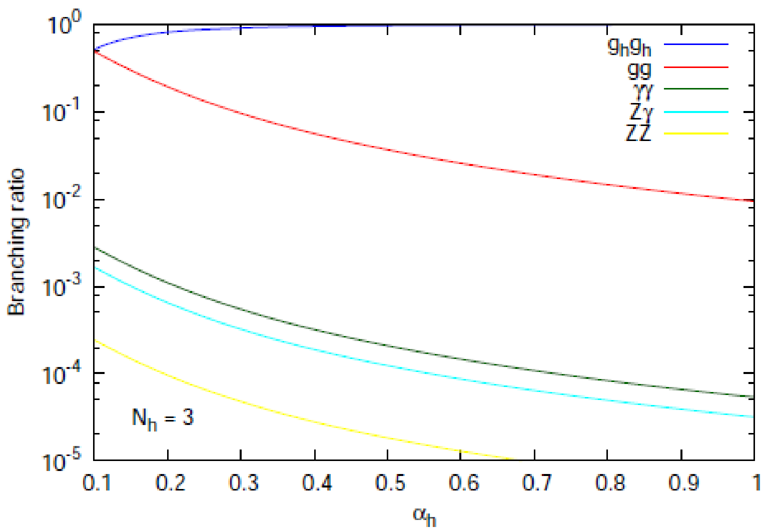
$$\Gamma(\eta_{\widetilde{Q}} \to ZZ) = \frac{N_c N_h \alpha^2 e_Q^4 x_w^2 (8-8r_Z+3r_Z^2)\sqrt{1-r_Z}}{4m_Q^2(2-r_Z)^2(1-x_w)^2}\left|\widetilde{R}_{1S}(0)\right|^2$$

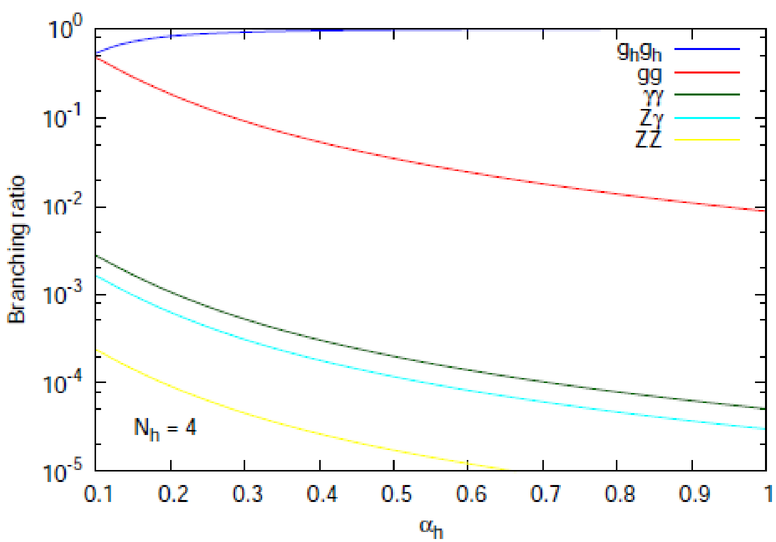
$$\Gamma(\eta_{\widetilde{Q}} \to g_h g_h) = \frac{N_c(N_h^2-1)\alpha_h^2}{8N_h m_Q^2}\left|\widetilde{R}_{1S}(0)\right|^2$$

⇒ Eventually h-gluons would evolve into h-glueballs

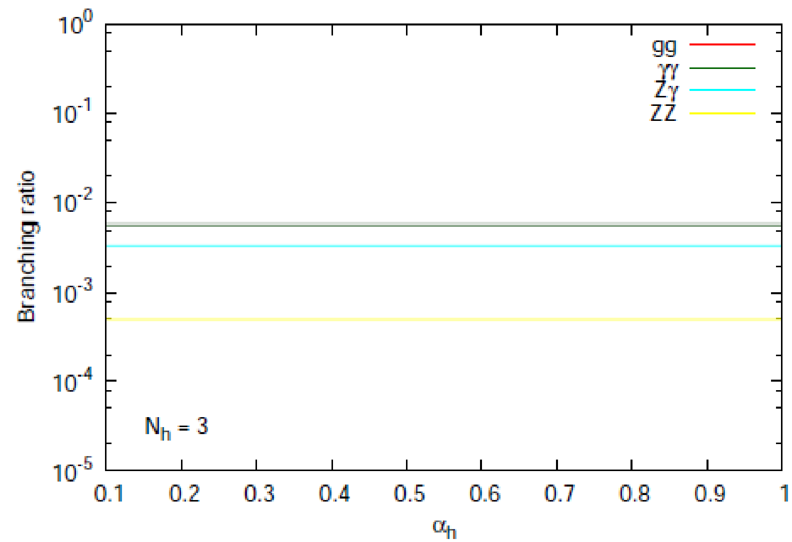
SU(2) singlet scalar model

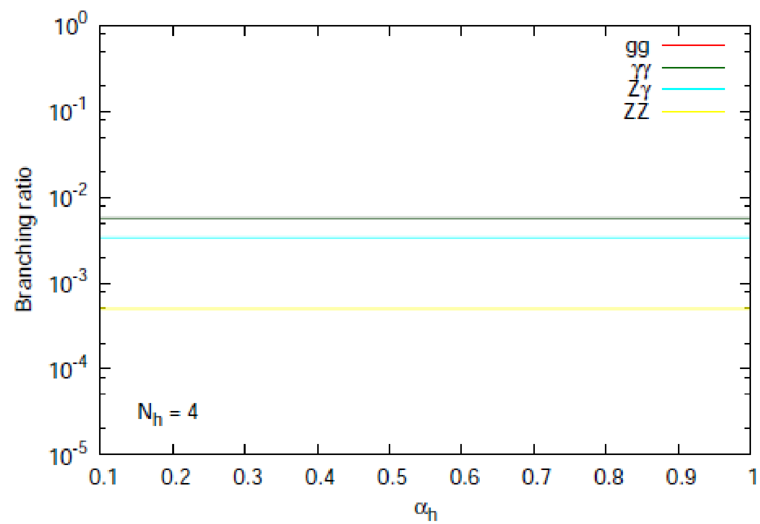
$\eta_{\tilde{Q}} \to g_h g_h$





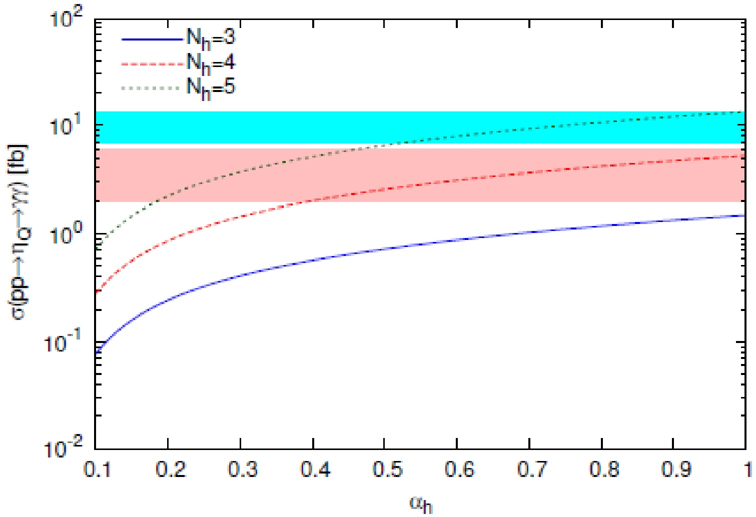
$\eta_{\tilde{Q}} \not\to g_h g_h$

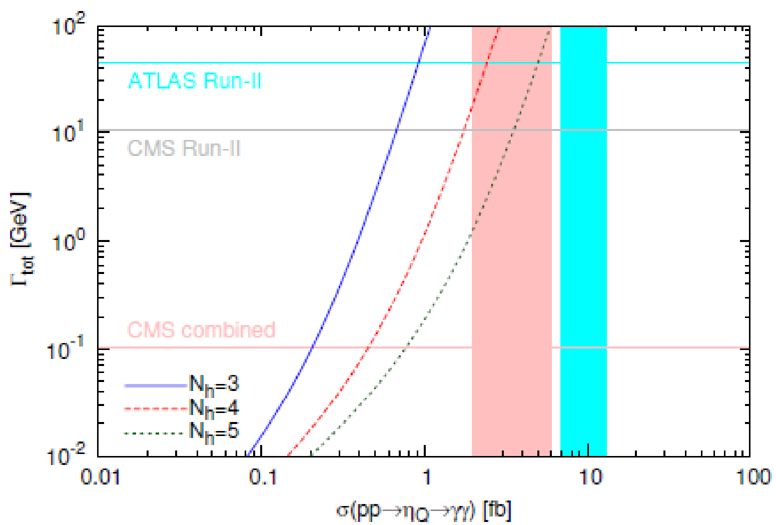




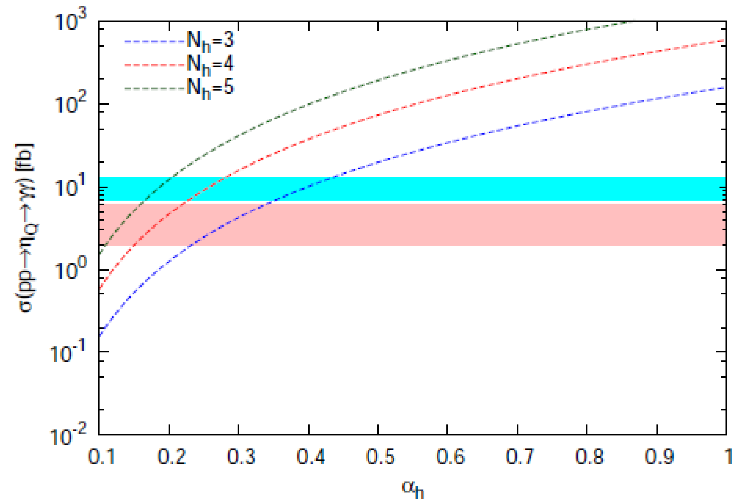
SU(2) singlet scalar model

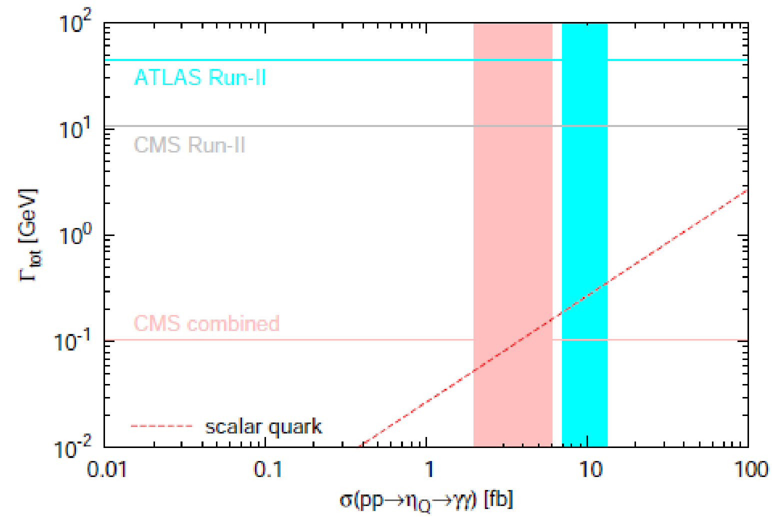
$\eta_{\tilde{Q}} \to g_h g_h$





$\eta_{\tilde{Q}} \not\to g_h g_h$





P-wave state $\chi_{\tilde{Q}}$

Prelimenary

$$\Gamma(\chi_{\tilde{Q}} \to u\bar{u}) = \frac{N_c^2 N_h \alpha^2 e_Q^2}{9 m_Q^4}\left[2 - \frac{2(3-8x_w)}{(4-r_Z)(1-x_w)} + \frac{9-24x_w+32x_w^2}{(4-r_Z)^2(1-x_w)^2}\right]|R'_{2P}(0)|^2$$

$$\Gamma(\chi_{\tilde{Q}} \to d\bar{d}) = \frac{N_c^2 N_h \alpha^2 e_Q^2}{18 m_Q^4}\left[1 - \frac{2(3-4x_w)}{(4-r_Z)(1-x_w)} + \frac{2(9-12x_w+8x_w^2)}{(4-r_Z)^2(1-x_w)^2}\right]|R'_{2P}(0)|^2$$

$$\Gamma(\chi_{\tilde{Q}} \to l^+ l^-) = \frac{N_c^2 N_h \alpha^2 e_Q^2}{2 m_Q^4}\left[1 - \frac{2(1-4x_w)}{(4-r_Z)(1-x_w)} + \frac{2(1-4x_w+8x_w^2)}{(4-r_Z)^2(1-x_w)^2}\right]|R'_{2P}(0)|^2$$

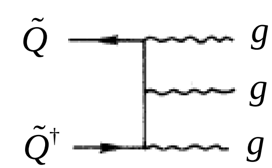
$$\Gamma(\chi_{\tilde{Q}} \to \nu\bar{\nu}) = \frac{N_c^2 N_h \alpha^2 e_Q^2}{m_Q^4(4-r_Z)^2(1-x_w)^2}|R'_{2P}(0)|^2$$

$$\Gamma(\tilde{\chi}_Q \to ggg) = \frac{(N_c^2-1)(N_c^2-4)N_h}{N_c^2}\frac{\alpha_s^3}{4m_Q^4}\log\frac{m_Q}{\Delta}|R'_{2P}(0)|^2$$

$$\Gamma(\tilde{\chi}_Q \to g_h g_h g_h) = \frac{(N_h^2-1)(N_h^2-4)N_c}{N_h^2}\frac{\alpha_s^3}{4m_Q^4}\log\frac{m_Q}{\Delta}|R'_{2P}(0)|^2$$

$$\Gamma(\tilde{\chi}_Q \to \gamma gg) = \frac{(N_c^2-1)N_h}{N_c}\frac{\alpha_s^2\alpha e_Q^2}{48m_Q^4}\log\frac{m_Q}{\Delta}|R'_{2P}(0)|^2$$

$$\Gamma(\tilde{\chi}_Q \to \gamma g_h g_h) = \frac{(N_h^2-1)N_c}{N_h}\frac{\alpha_s^2\alpha e_Q^2}{48m_Q^4}\log\frac{m_Q}{\Delta}|R'_{2P}(0)|^2$$



IR divergent

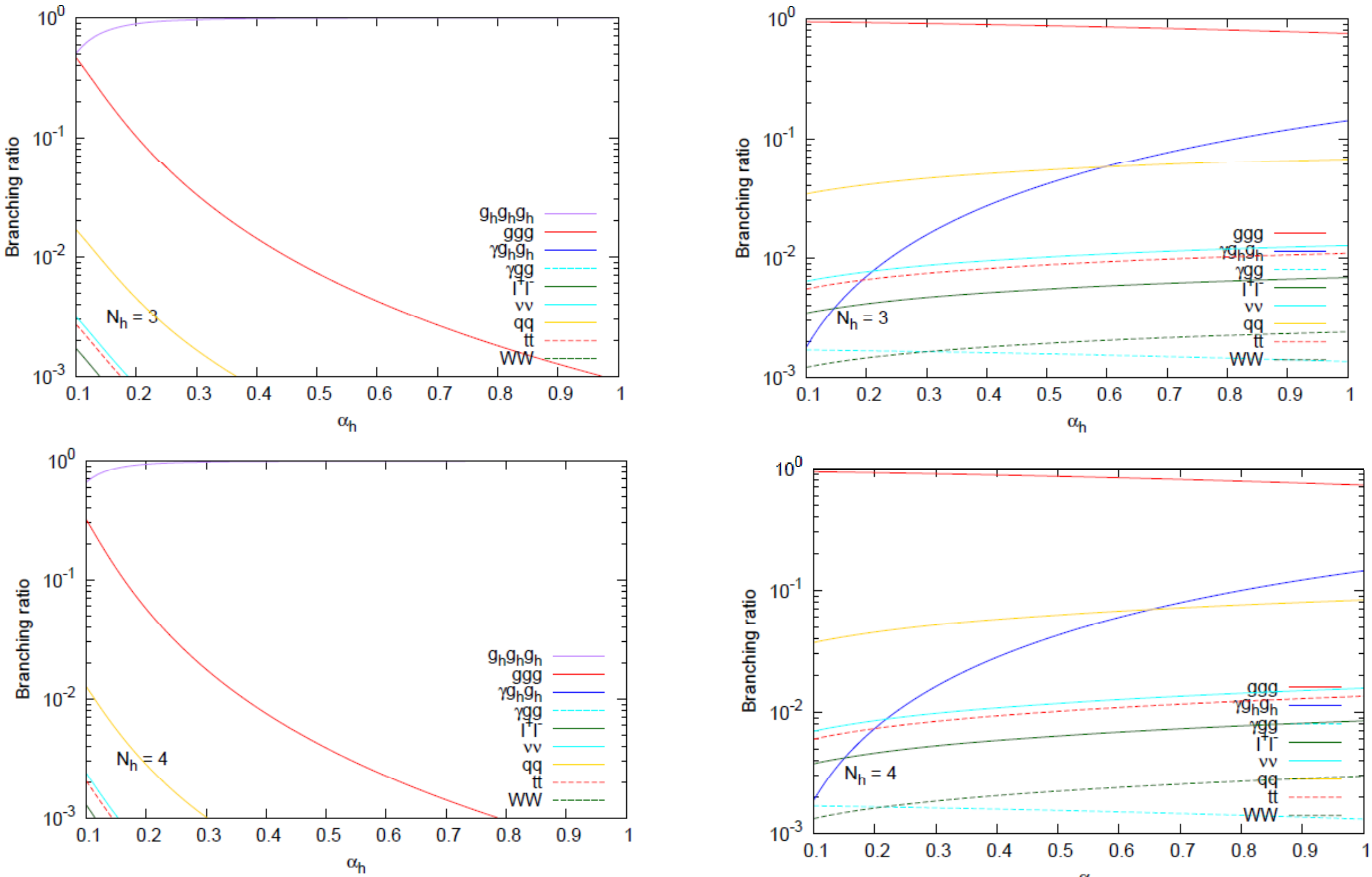
Δ=IR regulator

P-wave state $\chi_{\tilde{Q}}$

Prelimenary

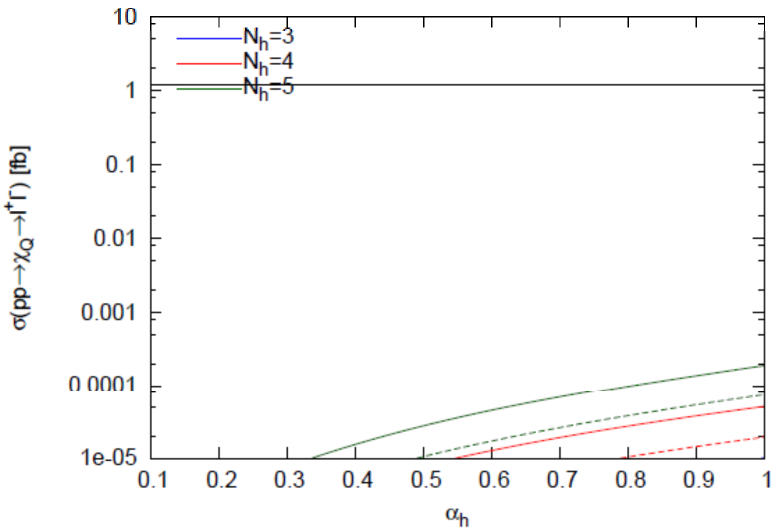
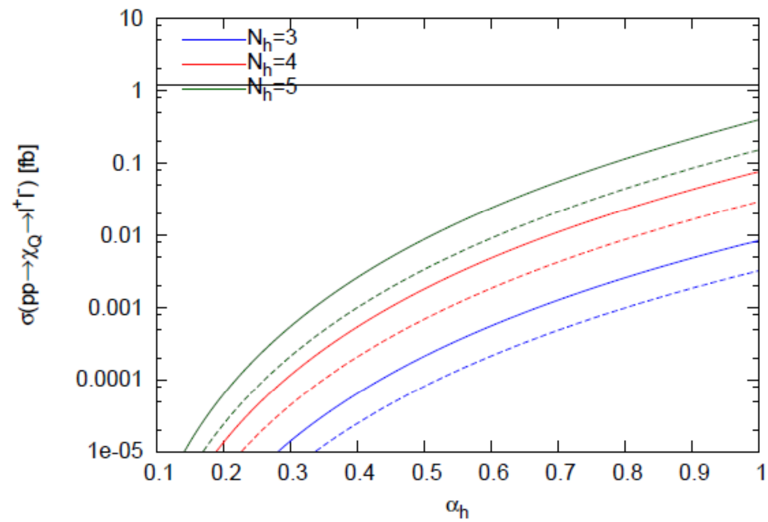
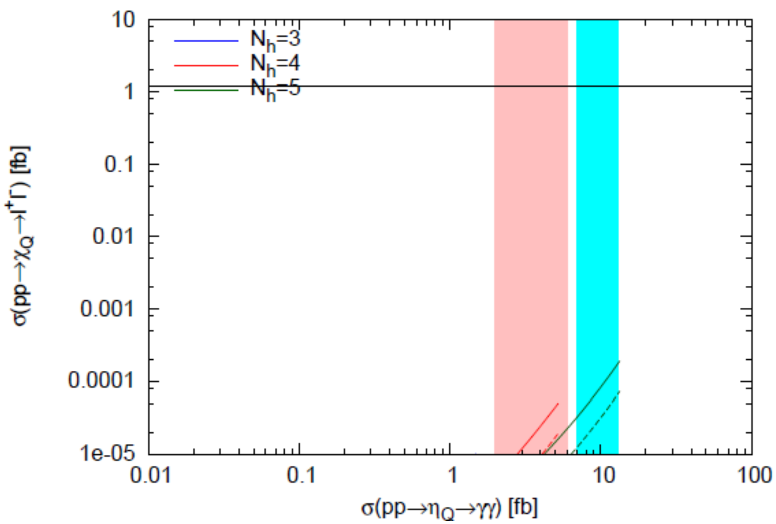
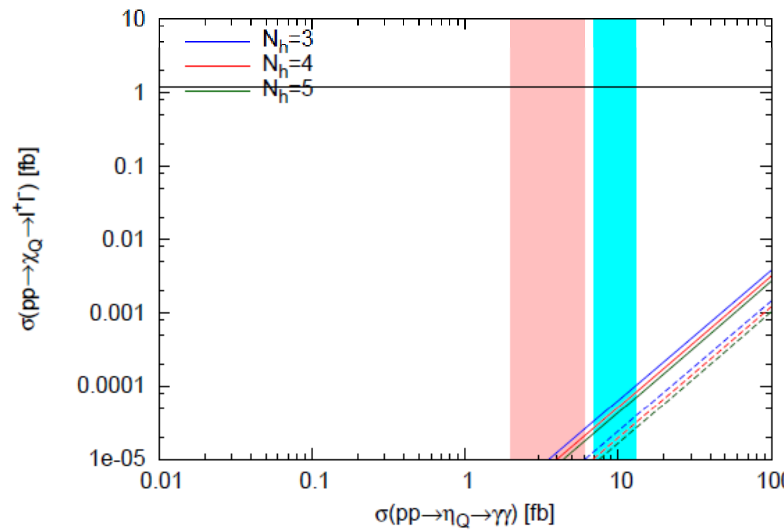
$\chi_{\tilde{Q}} \to g_h g_h g_h$

$\chi_{\tilde{Q}} \not\to g_h g_h g_h$



Drell-Yan production

Prelimenary

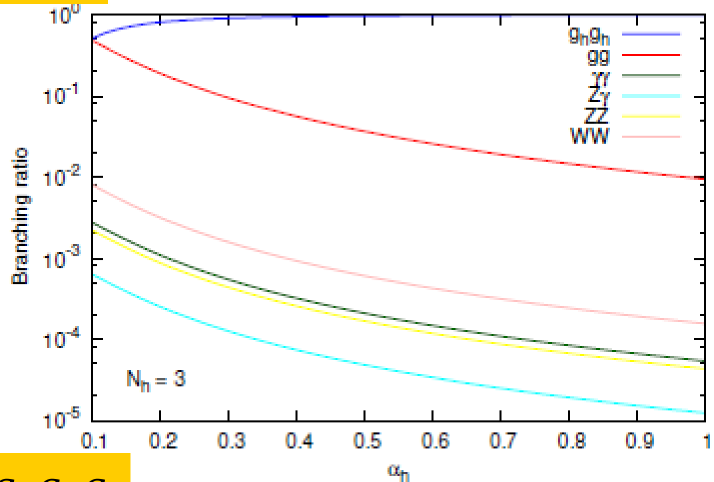
$\chi_{\tilde{Q}} \to g_h g_h g_h$	$\chi_{\tilde{Q}} \not\to g_h g_h g_h$
	
	

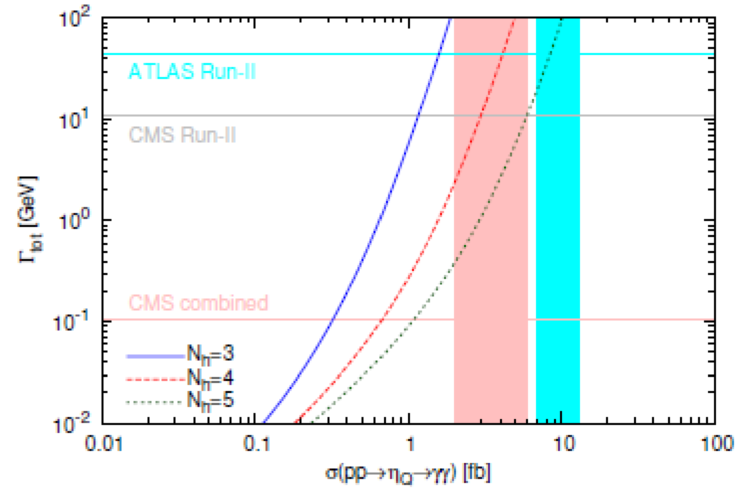
SU(2) doublet fermionic model

Prelimenary

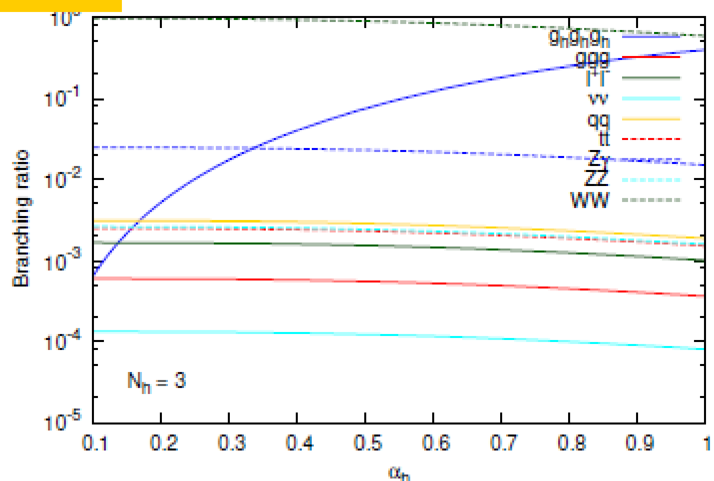
Q_L^i	U_R^i	D_R^i	L_L^i	E_R^i	N_R^i
$(3,2,1/6;N_h)$	$(3,1,2/3;N_h)$	$(3,1,-1/3;N_h)$	$(1,2,-1/2;N_h)$	$(1,1,-1;N_h)$	$(1,1,0;N_h)$

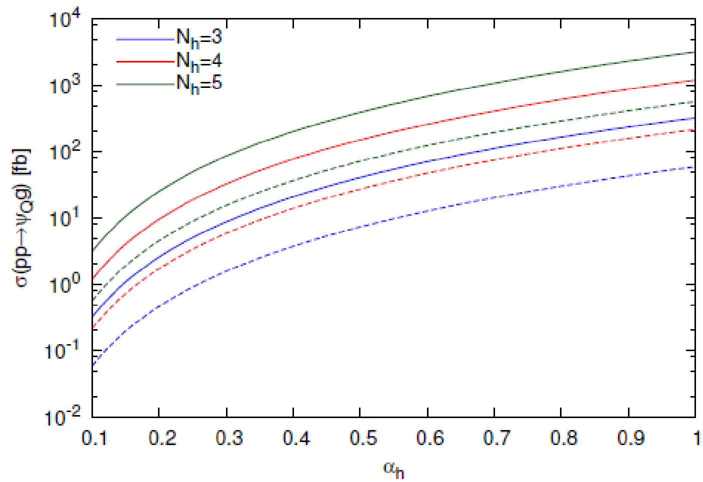
$\eta_Q \to g_h g_h$





$\psi_Q \to g_h g_h g_h$





How to distinguish models?

	η_Q	$\eta_{\tilde{Q}}$
J^{PC}	0^{-+}	0^{++}

- The polarization of two photons in the final state should be

  orthogonal vs. parallel

- the azimuthal angle distribution of the forward dijet in

$$gg \to \eta_Q (\text{or } \eta_{\tilde{Q}}) \to \gamma\gamma$$

- the angular distribution of decay products of Z bosons in

$$gg \to \eta_Q (\text{or } \eta_{\tilde{Q}}) \to ZZ$$

- the Drell-Yan production of the spin-triplet partners, etc.

Conclusions

• It is too early to conclude that the 750 GeV diphoton excess is a new resonance, but it deserves investigation of all possible BSMs.

• We consider a possibility that the diphoton excess is a composite (pseudo)scalar boson made of $Q\overline{Q}$ or $\widetilde{Q}\widetilde{Q}^\dagger$.

• The composite models predict the spin-triplet partner and higher-resonant states, which will also be observed soon at the LHC.

• The models can be distinguished by using the J^{PC} determination of the diphoton resonance and the DY production via the spin-triplet partners.