Composite models for 750 GeV diphoton excess at the LHC

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

Based on arXiv:1603.08802; work in progress

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Diphoton excess

- Resonance in the $\gamma\gamma$ mode at 750 GeV

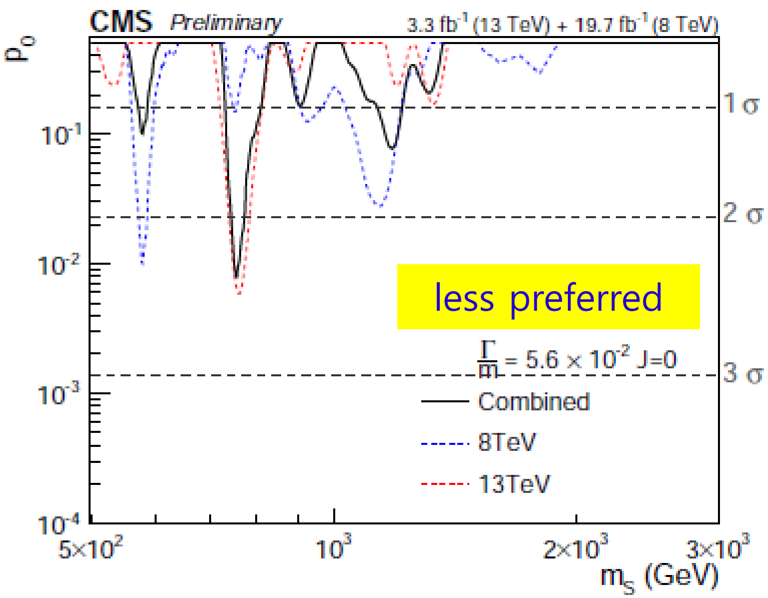
- Local significance = 3.9σ (ATLAS), 3.4σ (CMS) , but LEE significantly reduce the significance ~ 2σ

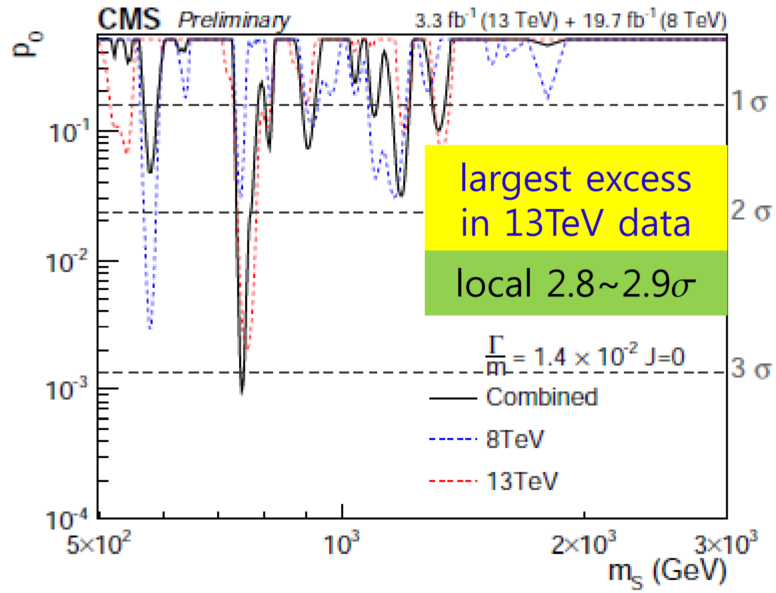
- spin=0 or spin=2,
  spin=1 may be OK (with cascade decays, ex. photon jets)

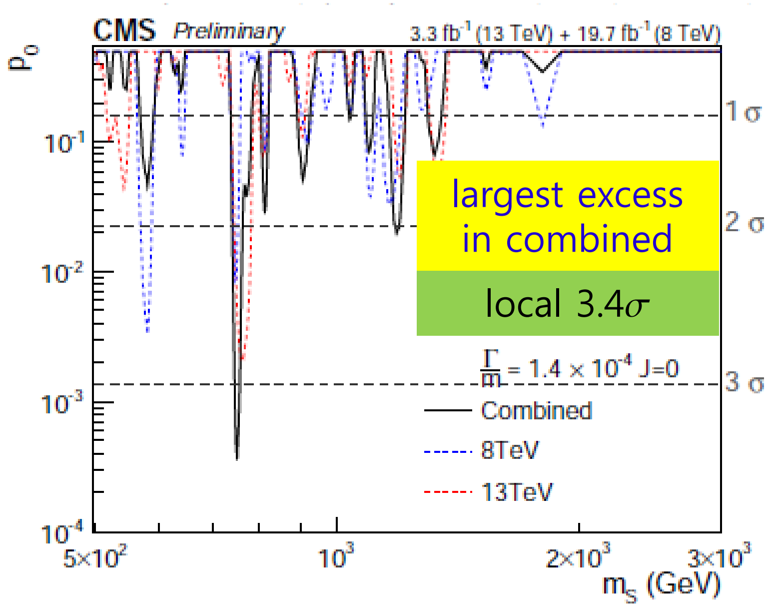
- Γ/M ~ 0.06 (ATLAS), 10^{-2}~10^{-4} (CMS) preferred

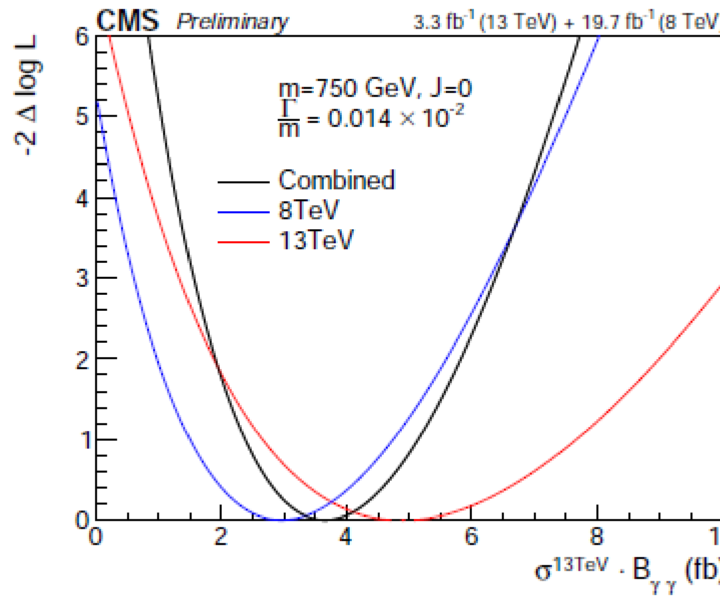
- Cross section = 10±3 fb (ATLAS), 2~6 fb (CMS)

CMS RunI + RunII









Composite models

- a new confining gauge force described by gauge group SU(N_h)

- a new vector-like h-quark (hyper quark) Q or scalar quark $\tilde{Q}$

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

free parameter, set Y to be +2/3

- the confinement scale Λ_h

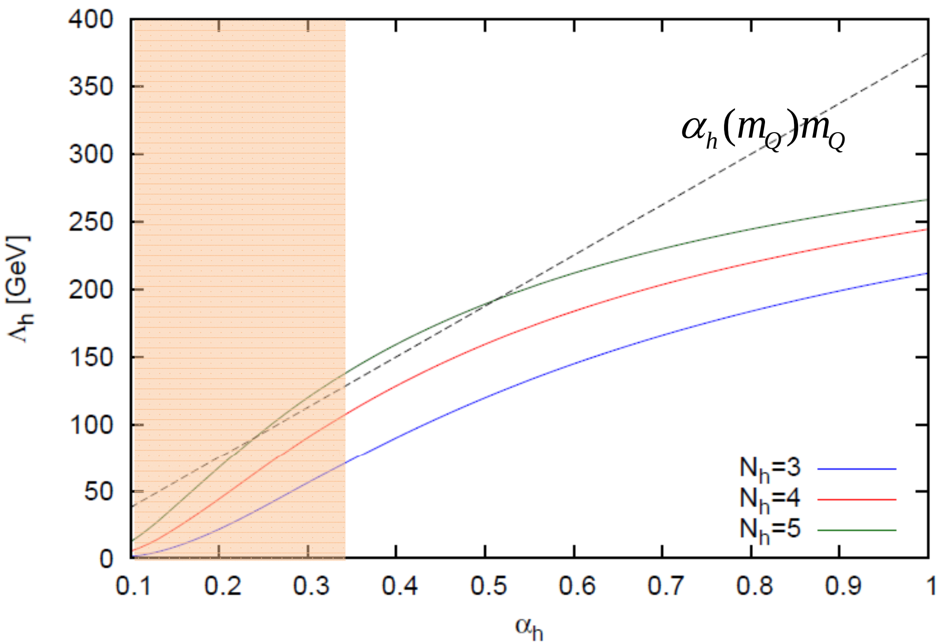
$$\Lambda_h \simeq M \exp\left[-\frac{6\pi}{(11N_h - 2n_f)\alpha_h(M)}\right]$$

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

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

- h-gluons evolve into h-glueballs which eventually decay into SM particles through Q loop

Potential of bound state

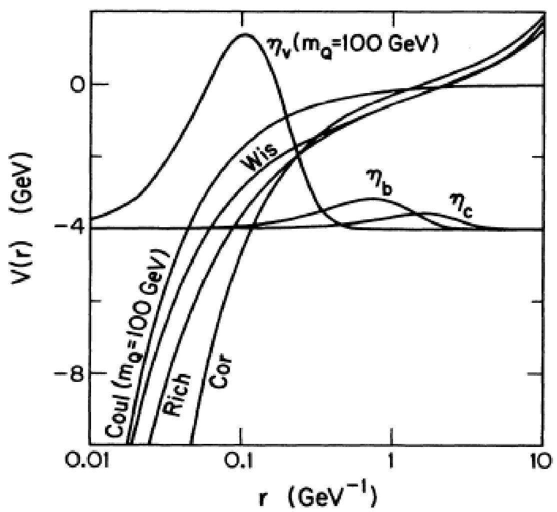


$$\alpha_h(m_Q v_Q)m_Q > \alpha_h(m_Q)m_Q > \Lambda_h$$

- Coulomb dominance may be a reasonably good approximation for the entire range of α_h.

- Assume the Coulomb potential $V = -\frac{C_h \alpha_h}{r} - \frac{C_F \alpha_s}{r}$

Wavefunction at the origin



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

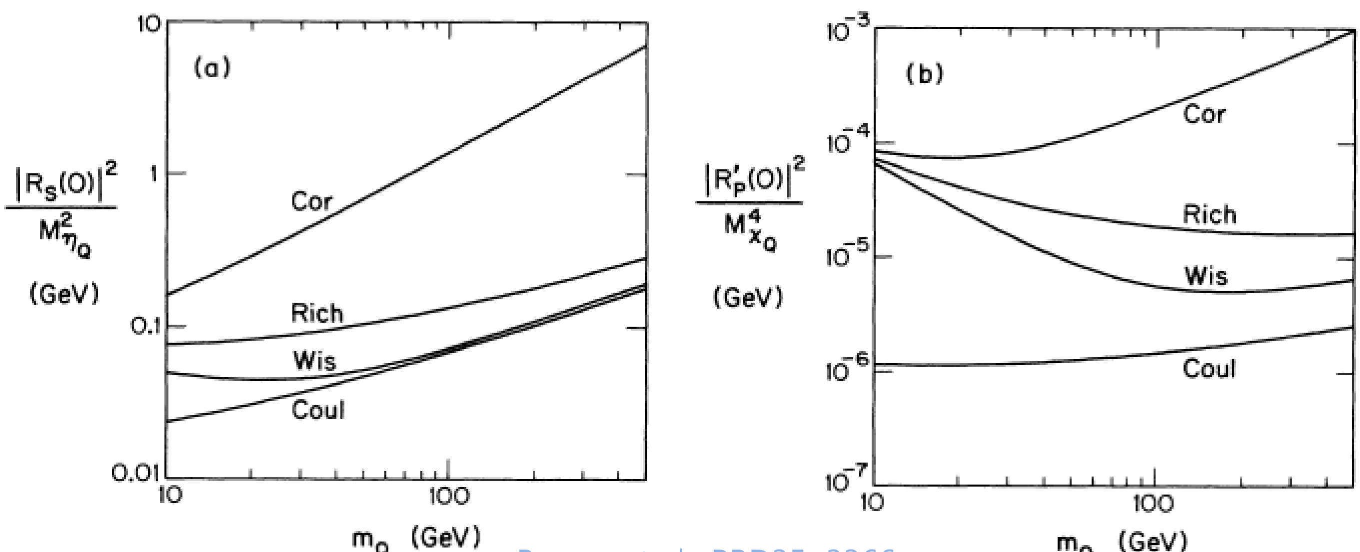
Cornell $V(r) = -k/r + ar$

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

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

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

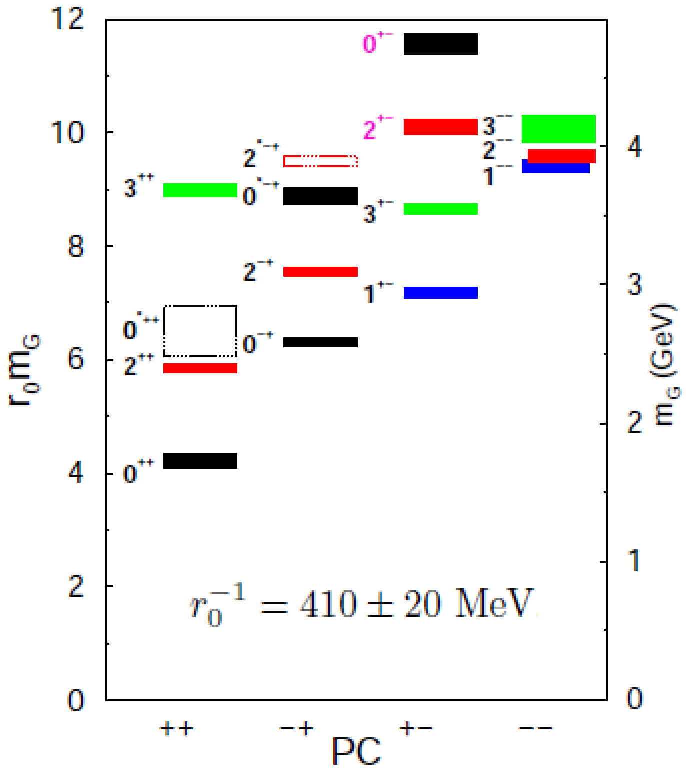


Barger et al., PRD35, 3366

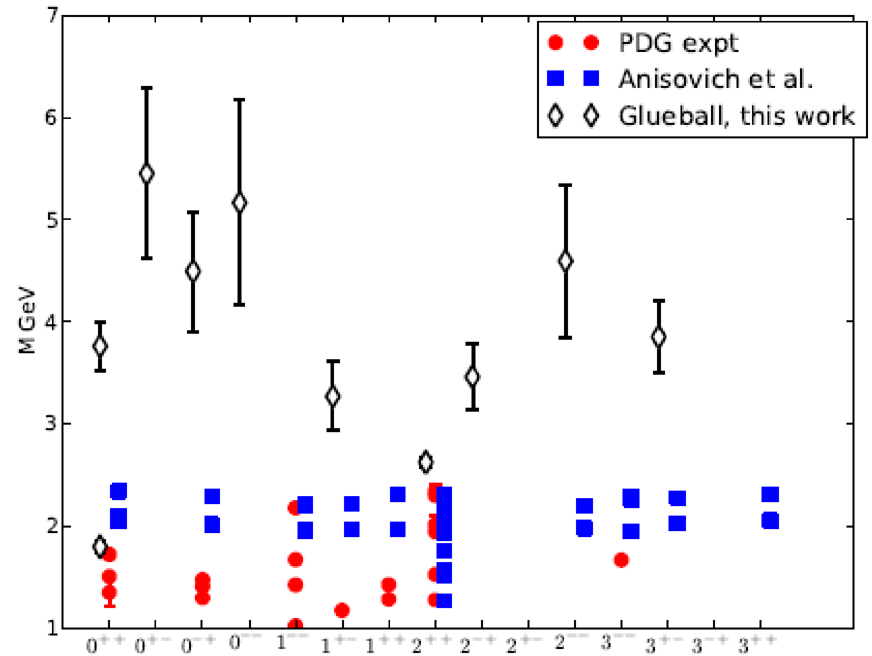
Glueball mass in pure SU(3)

quenched lattice calculation

unquenched lattice calculation



Chen et al., PRD73, 014516

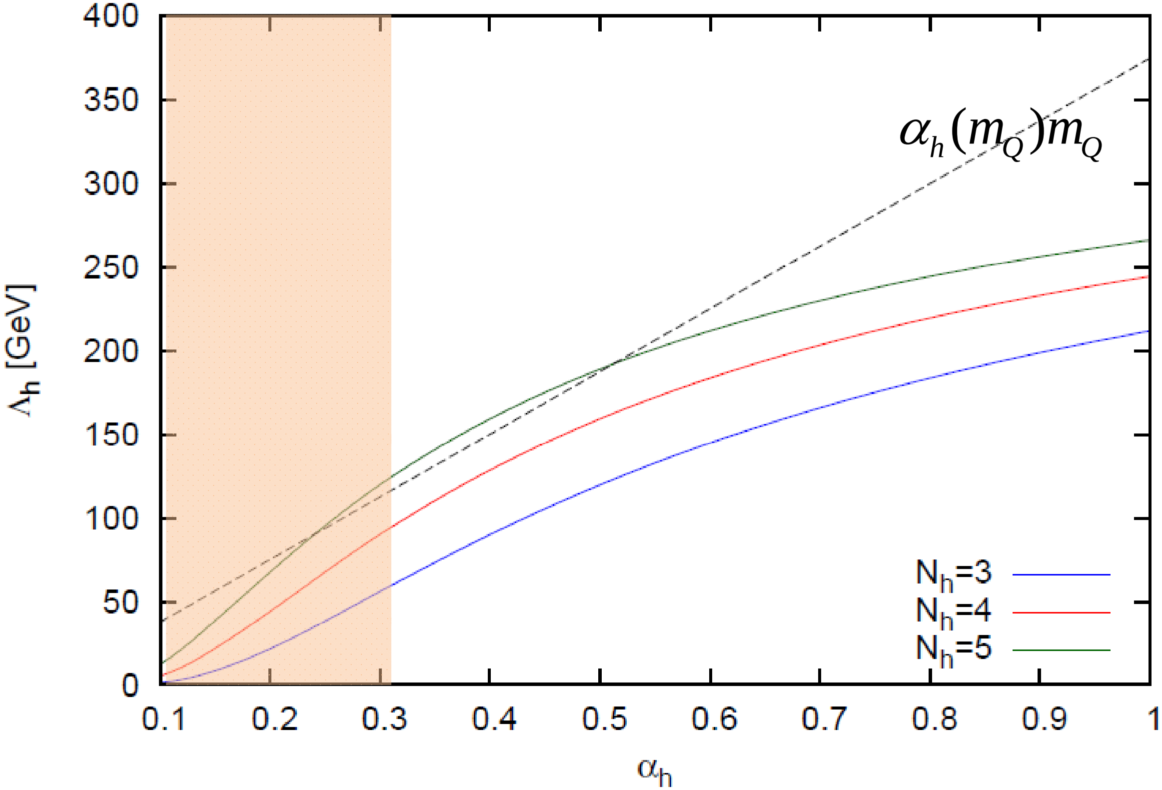


Gregory et al., 1208.1858

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)



$$M_G = 5 \sim 500 \text{ GeV}$$

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 .

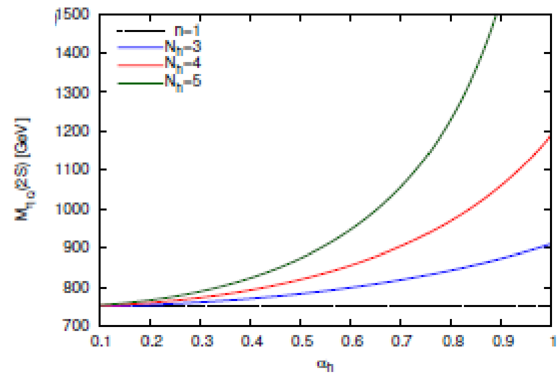
- the binding energy is

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

Degeneracy in the orbital quantum number l for Coulomb potential

- the mass of the excited state is

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



- 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

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

η_Q decay

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

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

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

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

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

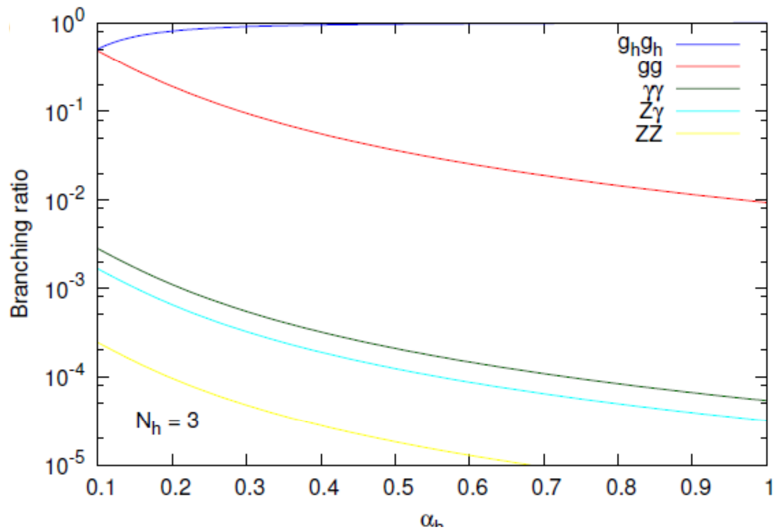
$$\Gamma(\eta_Q \to g_h g_h) = \frac{C_h N_c \alpha_h^2}{2m_Q^2} |R_{1S}(0)|^2$$

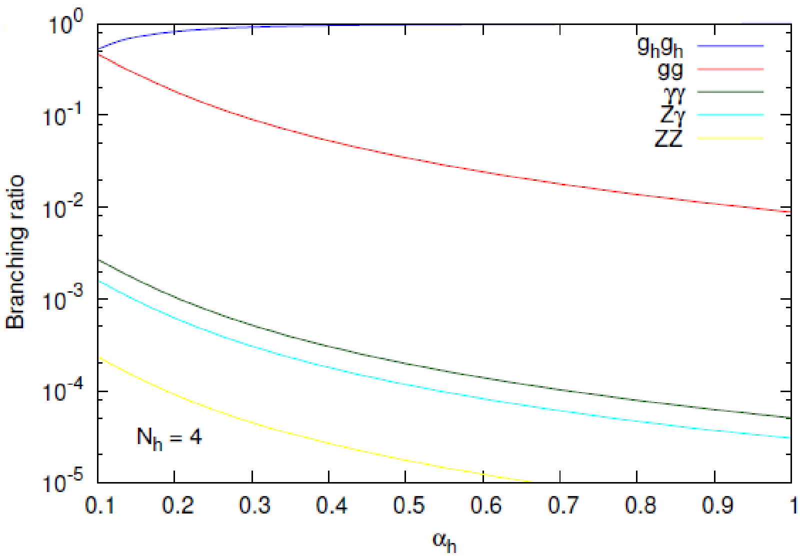
Eventually h-gluons would evolve into h-glueballs if kinematically allowed

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

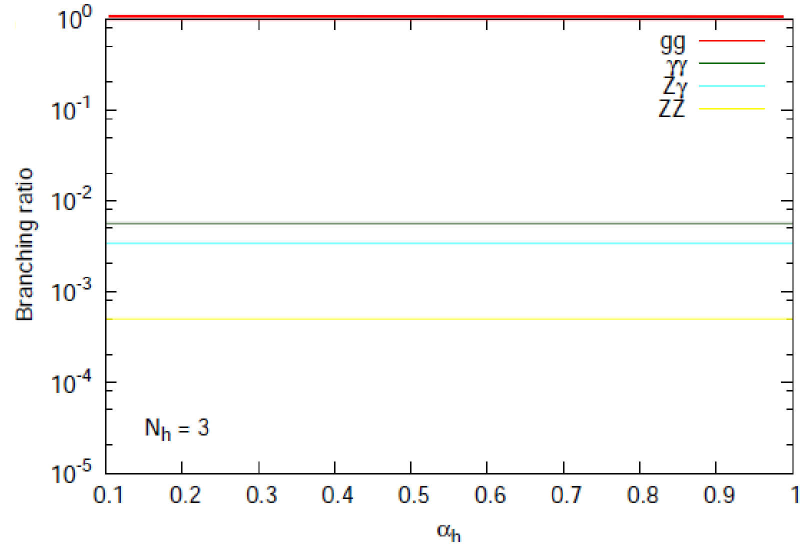
Branching ratios

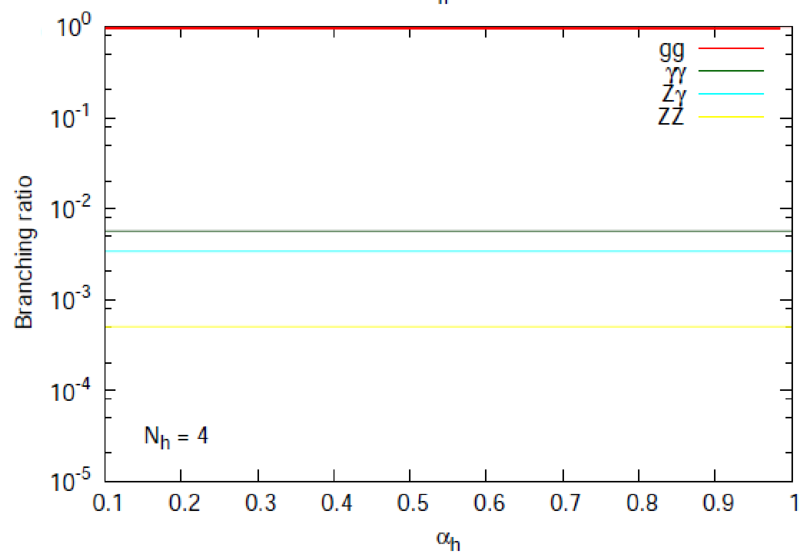
$\eta_Q \to g_h g_h$



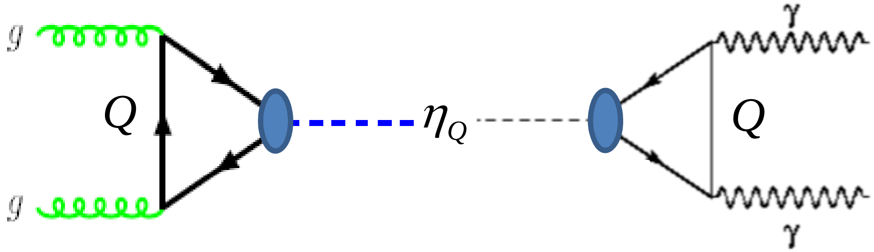


$\eta_Q \not\to g_h g_h$





Production cross section



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

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

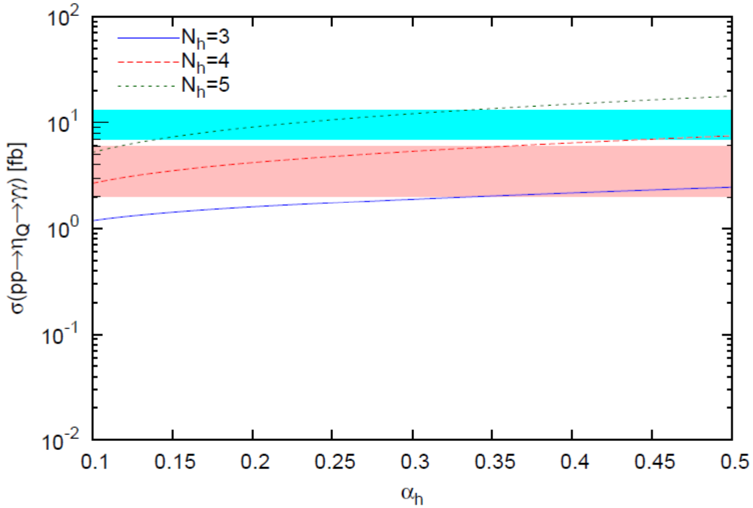
$\sqrt{s}$	$C_{b\bar{b}}$	$C_{c\bar{c}}$	$C_{s\bar{s}}$	$C_{d\bar{d}}$	$C_{u\bar{u}}$	C_{gg}
8 TeV	1.07	2.7	7.2	89	158	174
13 TeV	15.3	36	83	627	1054	2137

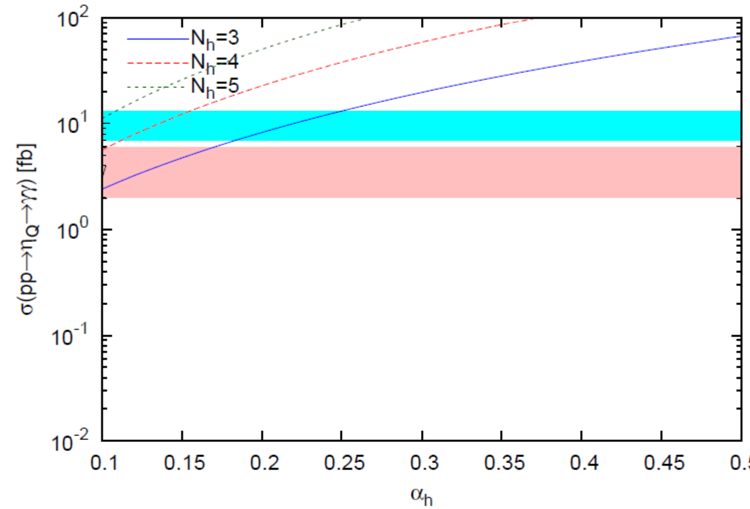
The production cross section $\propto$ the wavefunction at the origin

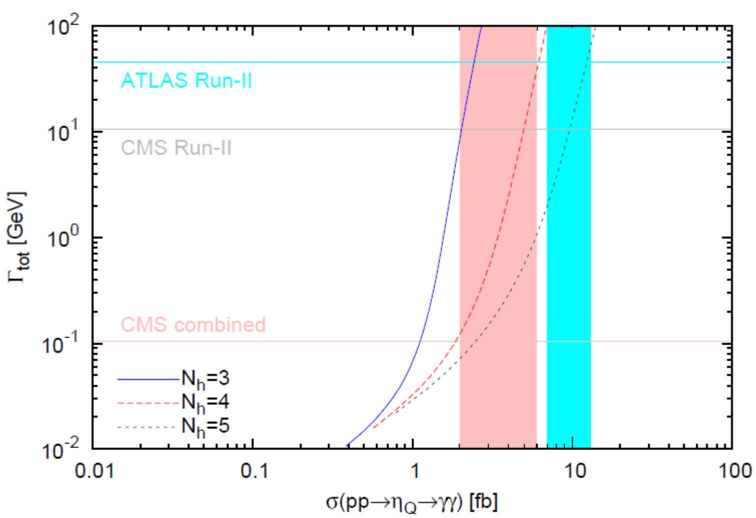
Diphoton cross section

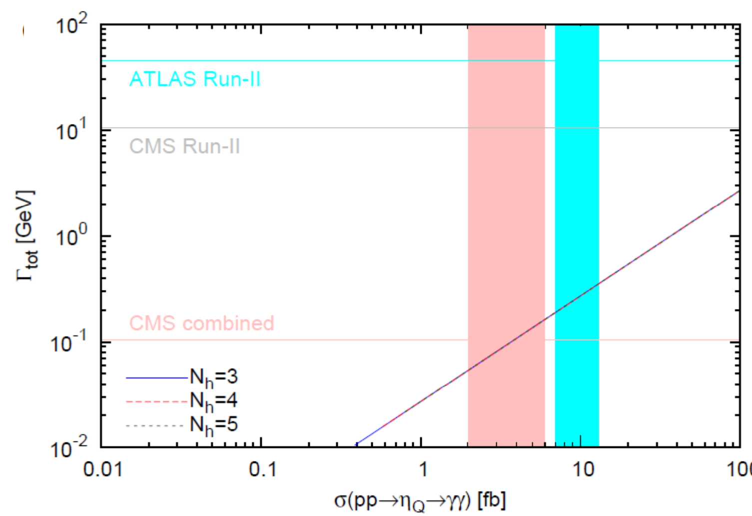
$\eta_Q \to g_h g_h$

$\eta_Q \not\to g_h g_h$









Spin-triplet partner ψ_Q

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

might 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

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

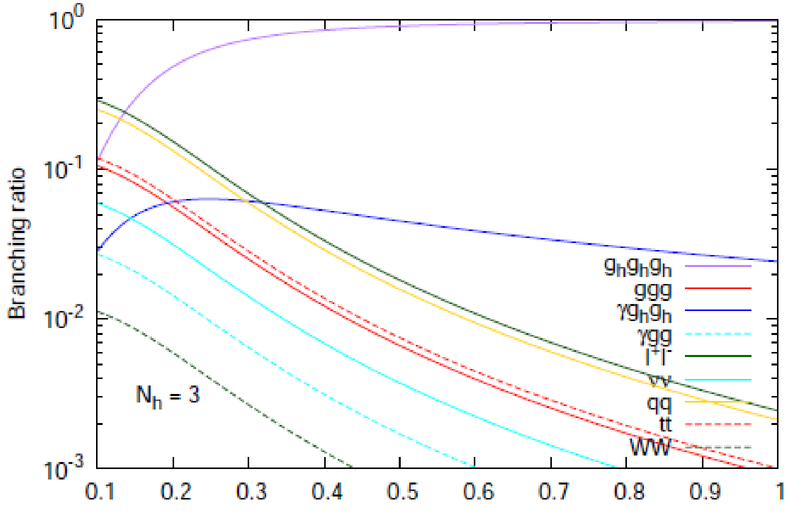
$$\Gamma(\psi_Q \to \gamma g_h g_h) = \frac{(\pi^2-9)\alpha_h^2\alpha e_Q^2}{3\pi m_Q^2}\frac{N_c(N_h^2-1)}{N_h}|R_{1S}(0)|^2$$

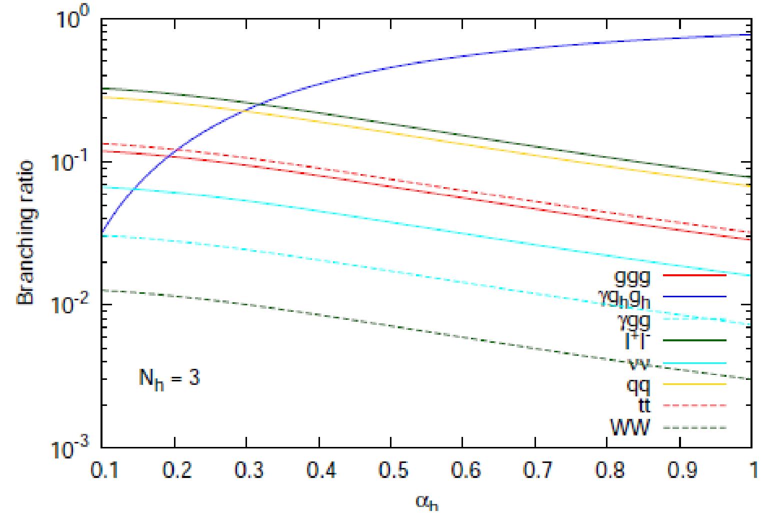
$g_h g_h$ evolves into a h-glueball if kinematically allowed

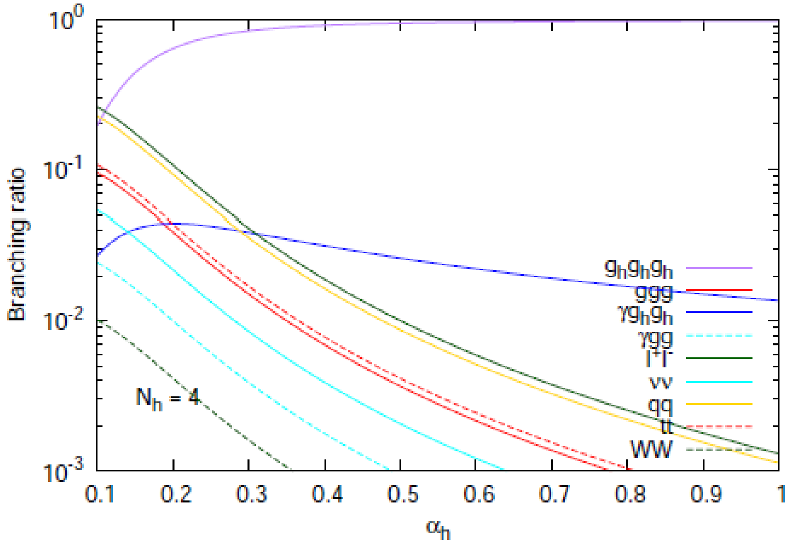
Spin-triplet partner ψ_Q

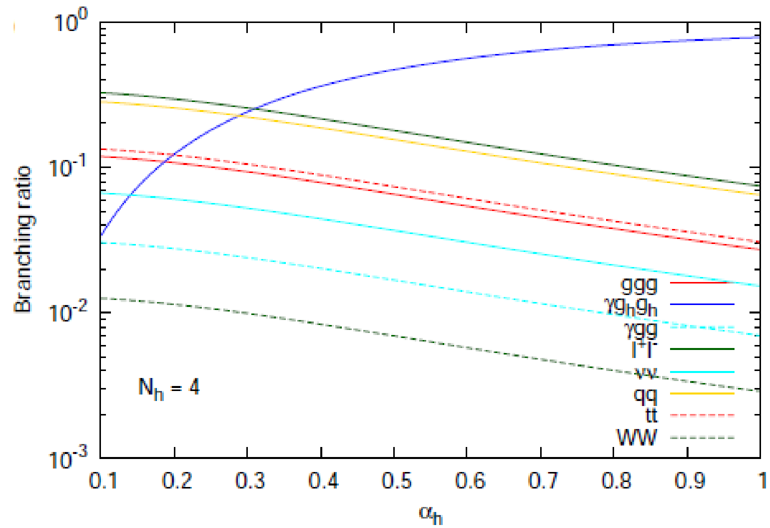
$\psi_Q \to g_h g_h g_h$

$\psi_Q \not\to g_h g_h g_h$



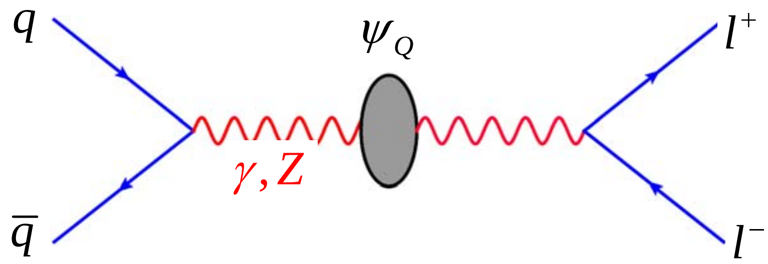






Production cross section of ψ_Q

Drell-Yan

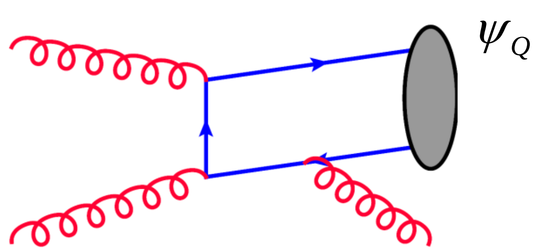


$$\sigma_{\mathrm{DY}}(q\bar{q} \to \psi_Q \to l^+l^-) = \frac{(2J_{\psi_Q}+1)\Gamma(\psi_Q \to l^+l^-)}{s m_{\psi_Q}\Gamma_{\psi_Q}} \sum_{q\bar{q}} C_{q\bar{q}}\Gamma(\psi_Q \to q\bar{q})$$

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

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

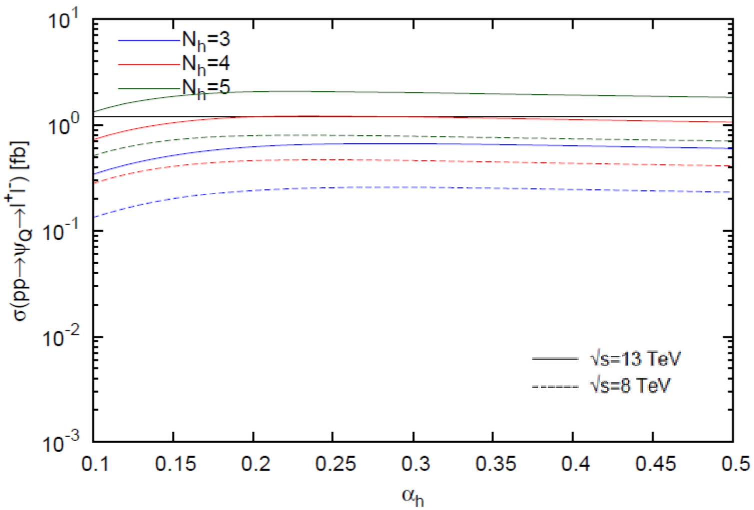
hadro-production

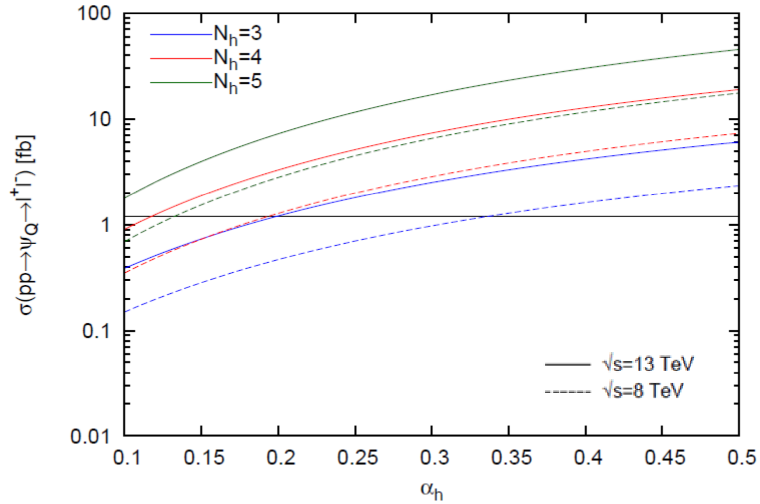


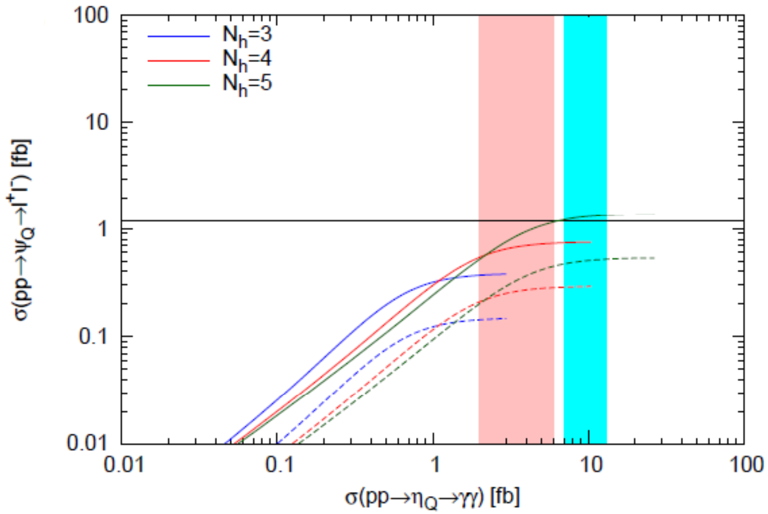
Drell-Yan production

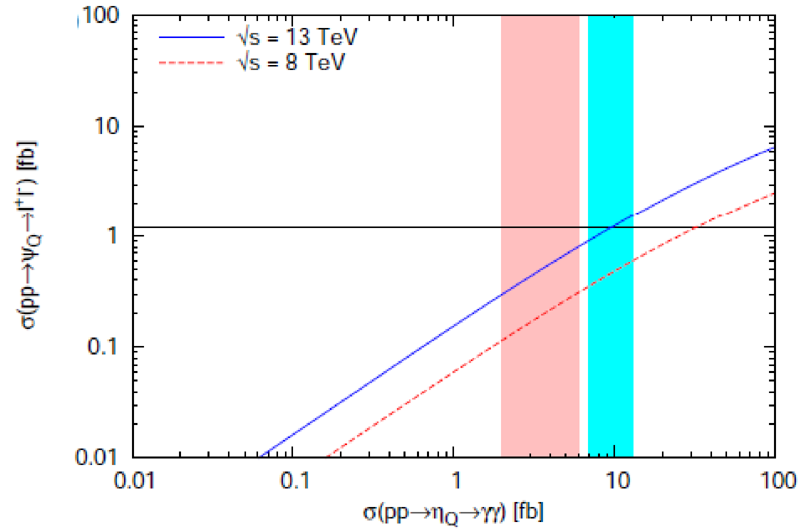
$\psi_Q \to g_h g_h g_h$

$\psi_Q \not\to g_h g_h g_h$









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.

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

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

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

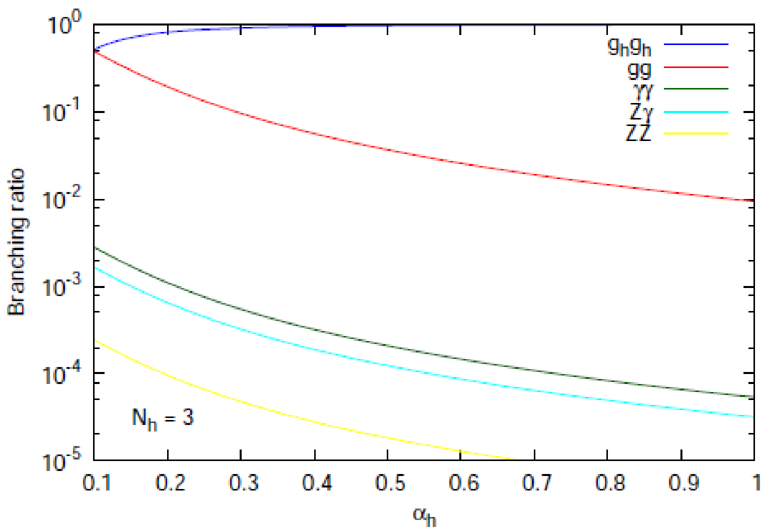
$$\Gamma(\eta_{\tilde{Q}} \to ZZ) = \frac{N_c N_h \alpha^2 e_Q^4 x_w^2 (8 - 8r_Z + 3r_Z^2)\sqrt{1 - r_Z}}{4m_Q^2 (2 - r_Z)^2 (1 - x_w)^2} \left|\widetilde{R}_{1S}(0)\right|^2$$

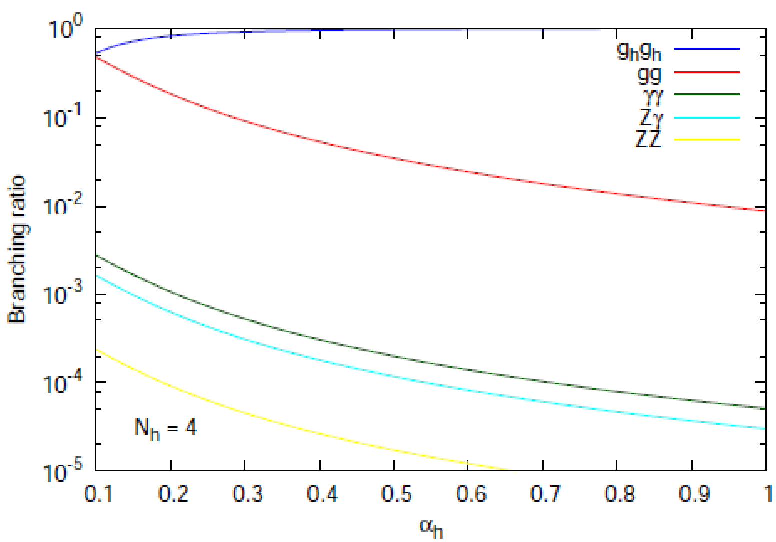
$$\Gamma(\eta_{\tilde{Q}} \to g_h g_h) = \frac{N_c (N_h^2 - 1)\alpha_h^2}{8N_h m_Q^2} \left|\widetilde{R}_{1S}(0)\right|^2$$

Eventually h-gluons would evolve into h-glueballs

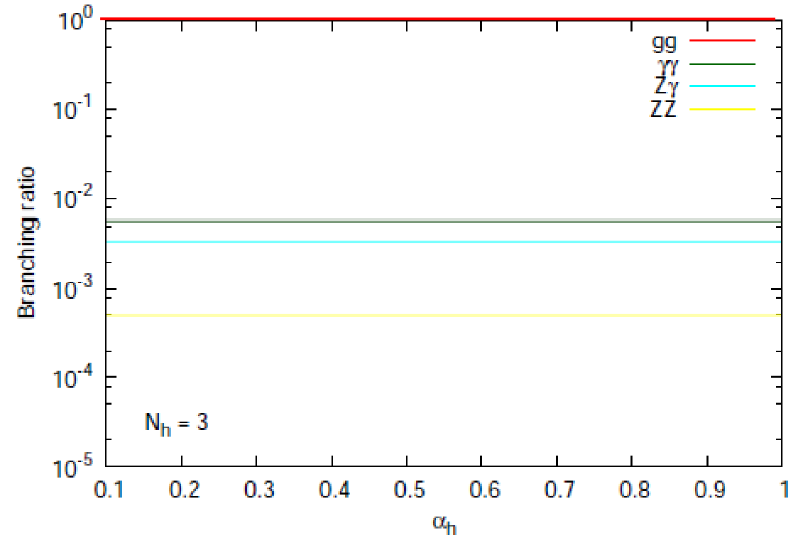
SU(2) singlet scalar model

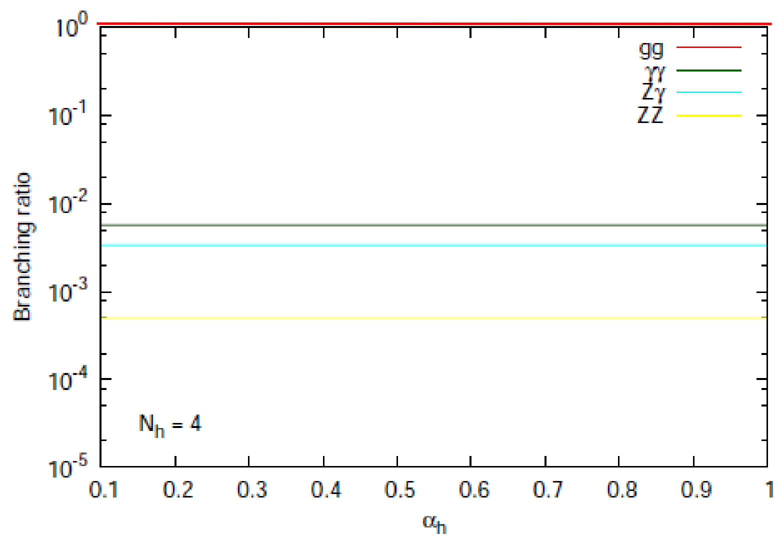
$\eta_{\tilde{Q}} \to g_h g_h$





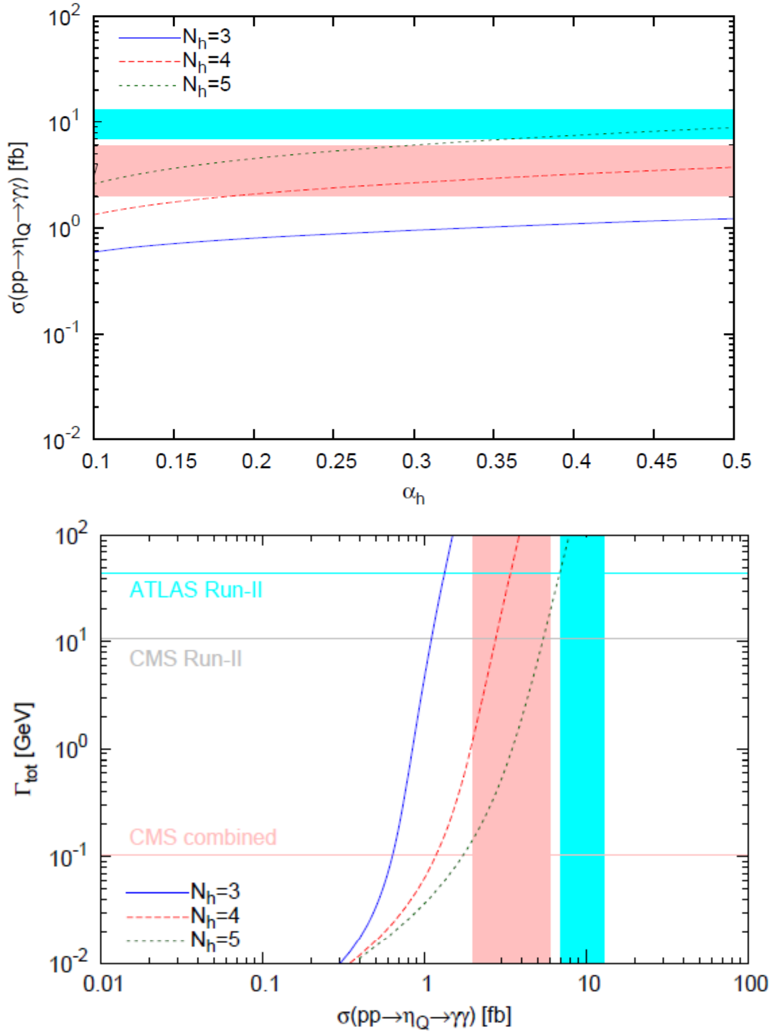
$\eta_{\tilde{Q}} \not\to g_h g_h$



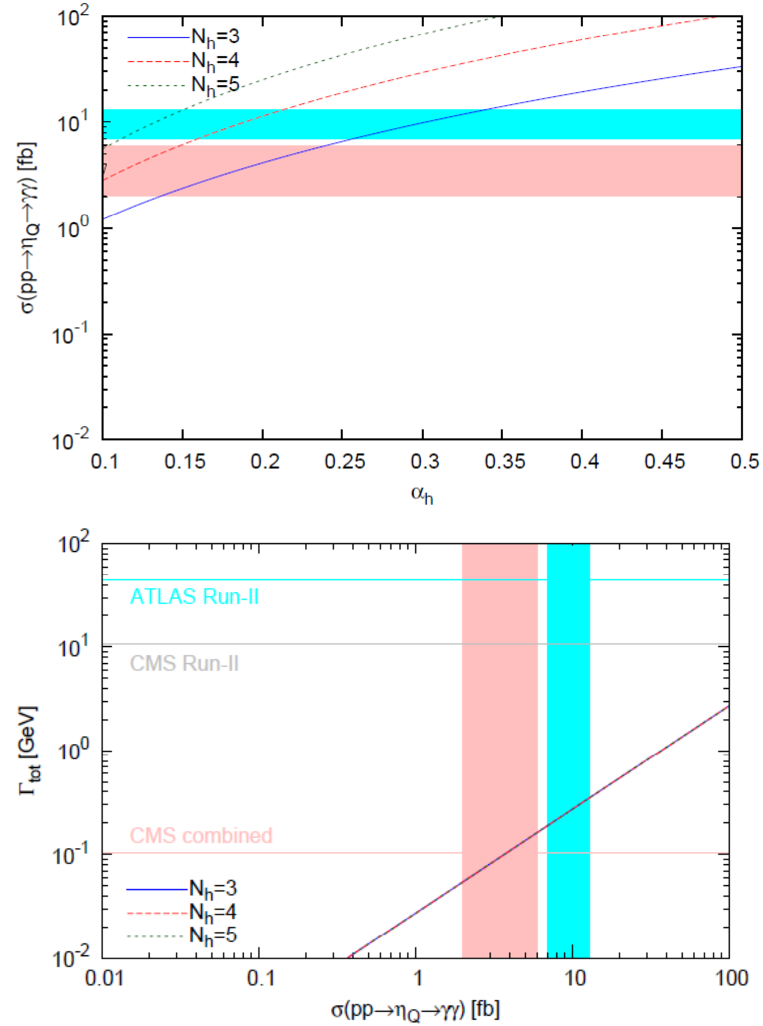


SU(2) singlet scalar model

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



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



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

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

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

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

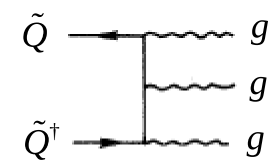
$$\Gamma(\chi_{\tilde{Q}} \to \nu\bar{\nu}) = \frac{N_c^2 N_h \alpha^2 e_Q^2}{m_Q^4(4-r_Z)^2(1-x_w)^2}|R'_{2P}(0)|^2$$

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

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

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

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

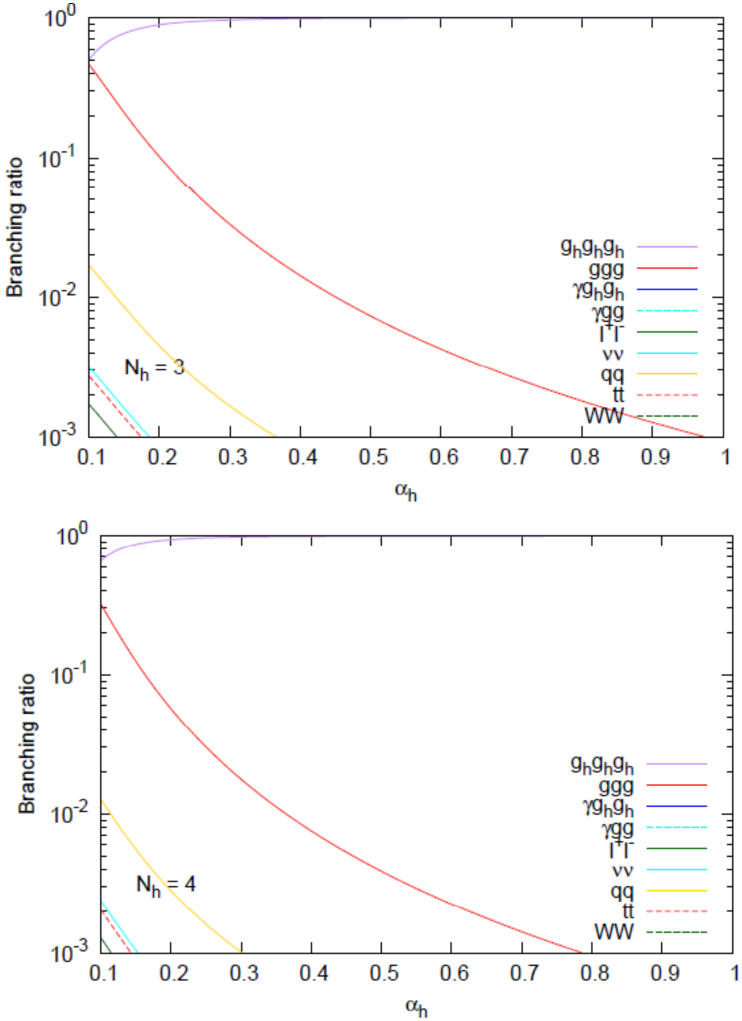


IR divergent

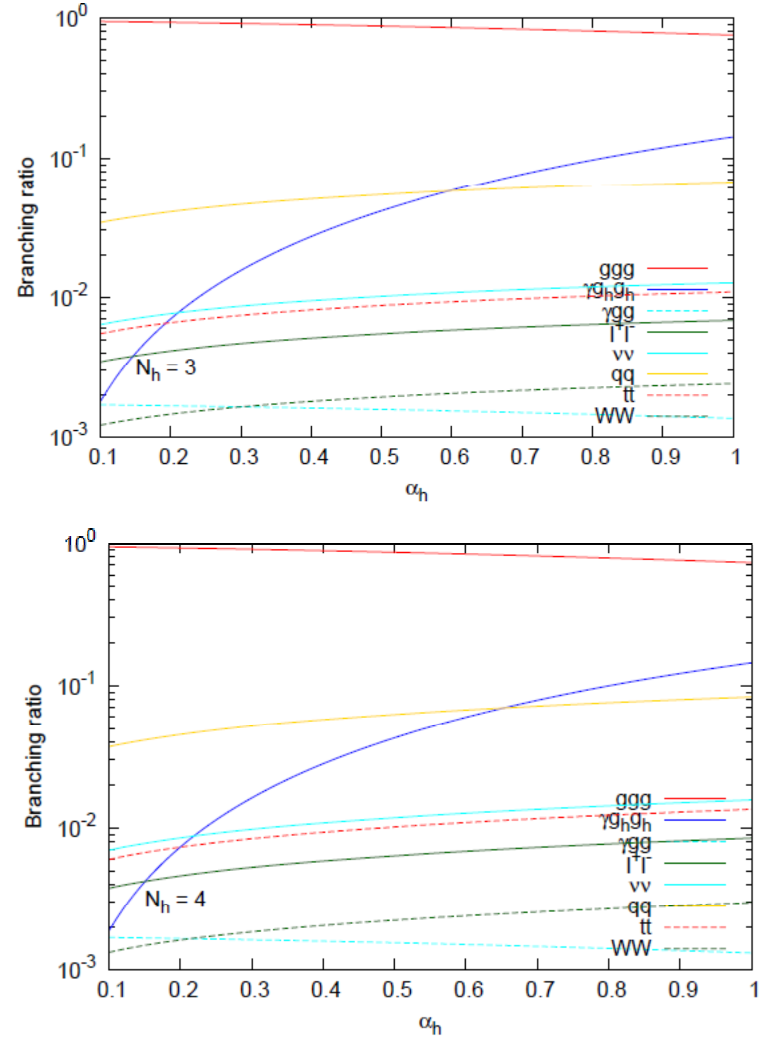
Δ=IR regulator

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

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



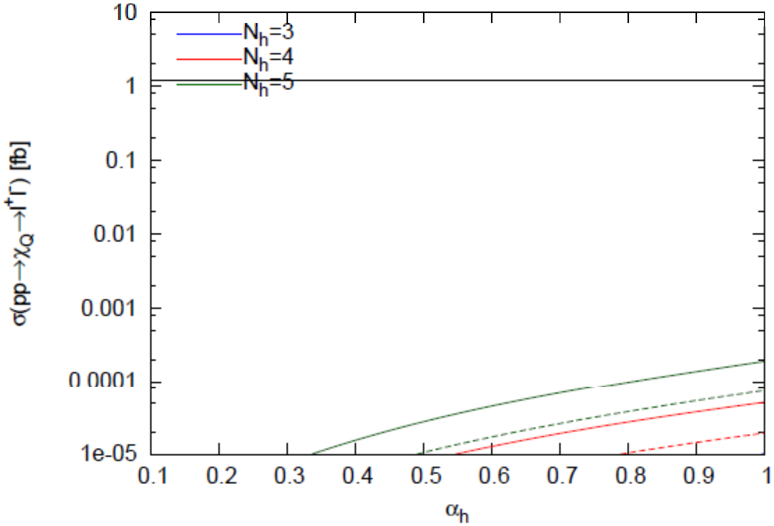
$\chi_{\tilde{Q}} \not\to g_h g_h g_h$

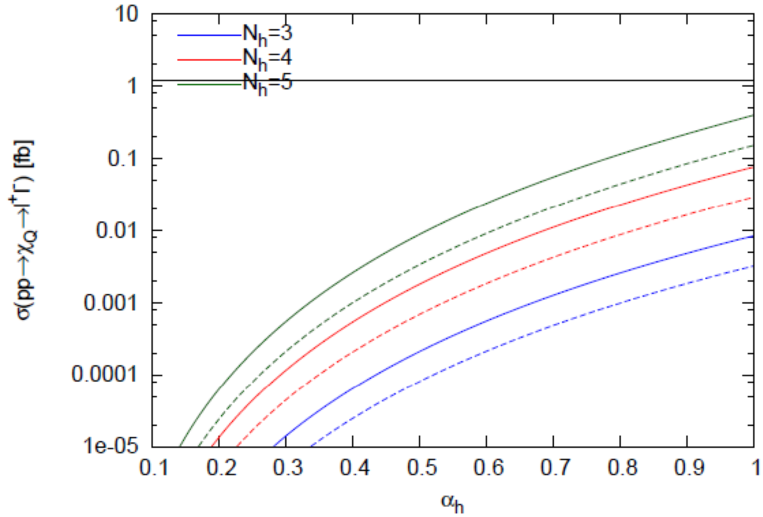


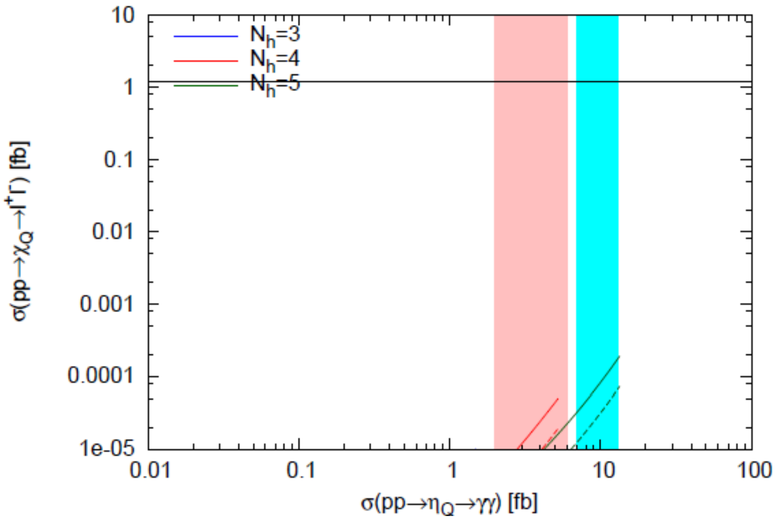
Drell-Yan production

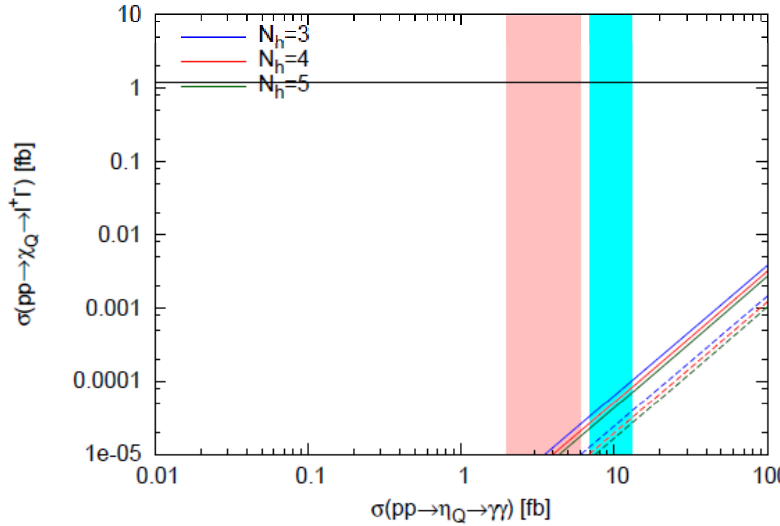
$\chi_{\tilde{Q}} \to g_h g_h g_h$

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









Color-octet bound state

- h-color-singlet but QCD-color-octet bound state

$$V = -\frac{C_h \alpha_h}{r} + \frac{C_8 \alpha_s}{r}$$

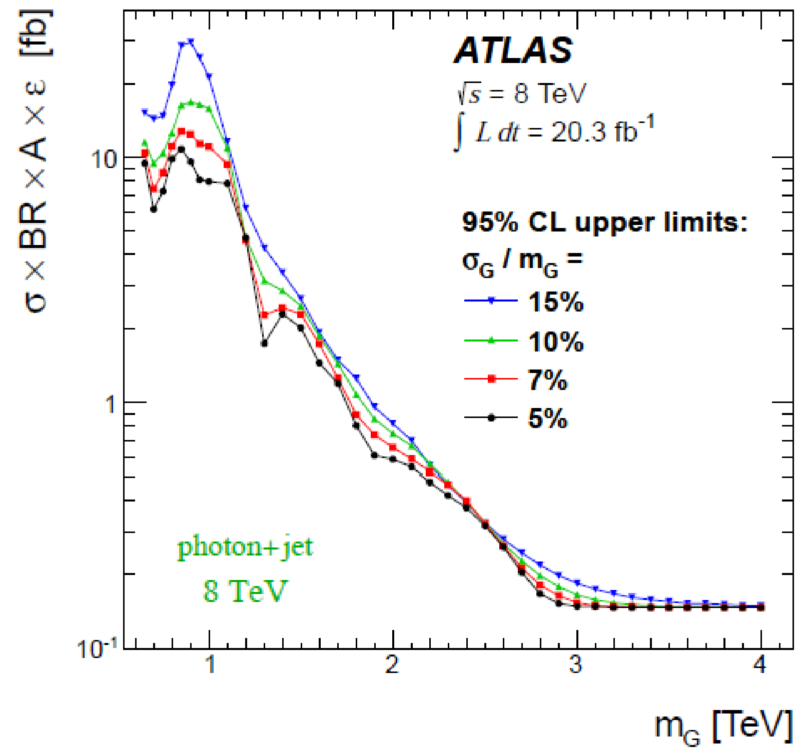
$$C_8 = \frac{C_A}{2} - C_F$$

- η_Q^8 can decay into gg, gγ, gZ

$$\Gamma[\eta_Q^8 \to gg] = \frac{(N_c^2-1)(N_c^2-4)N_h \alpha_s^2}{8N_c m_Q^2} \left| R_{\eta_Q}^8(0) \right|^2$$

$$\Gamma[\eta_Q^8 \to g\gamma] = \frac{(N_c^2-1)N_h \alpha_s \alpha e_Q^2}{m_Q^2} \left| R_{\eta_Q}^8(0) \right|^2$$

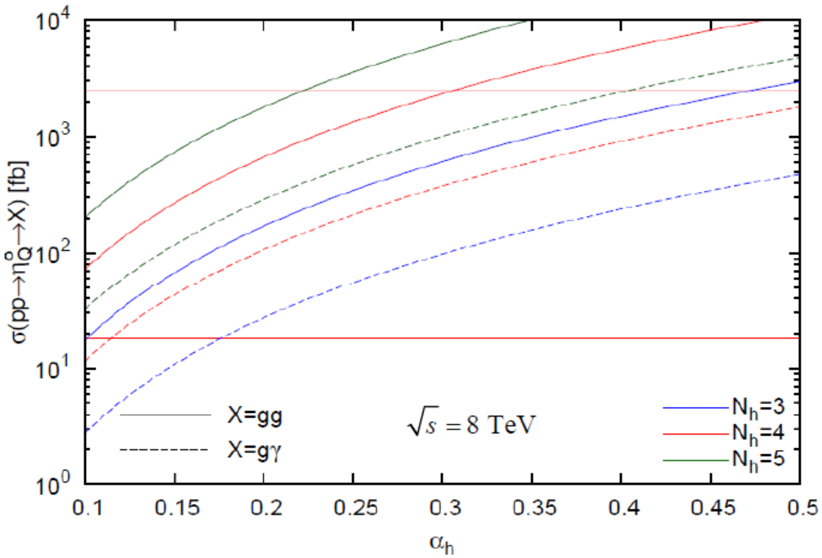
- constrained by dijet search and photon+jet search

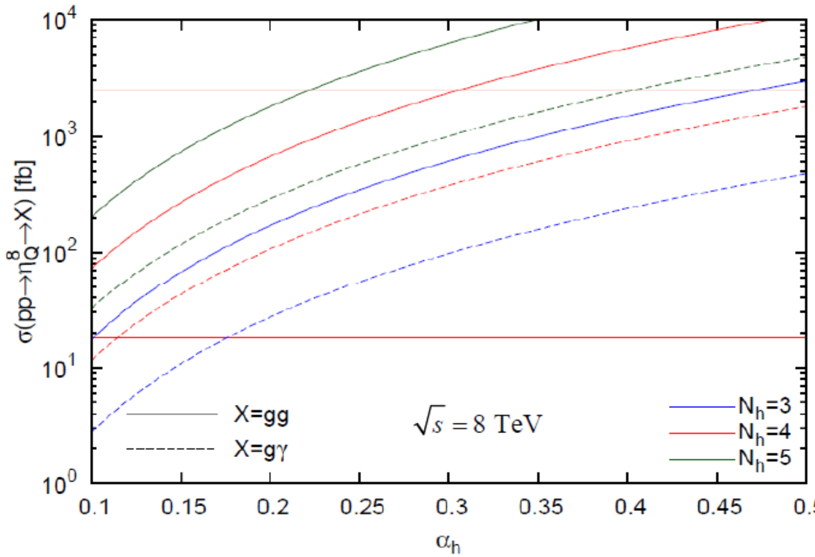


Color-octet bound state

$\eta_Q \not\to g_h g_h$

$\eta_Q \to g_h g_h$

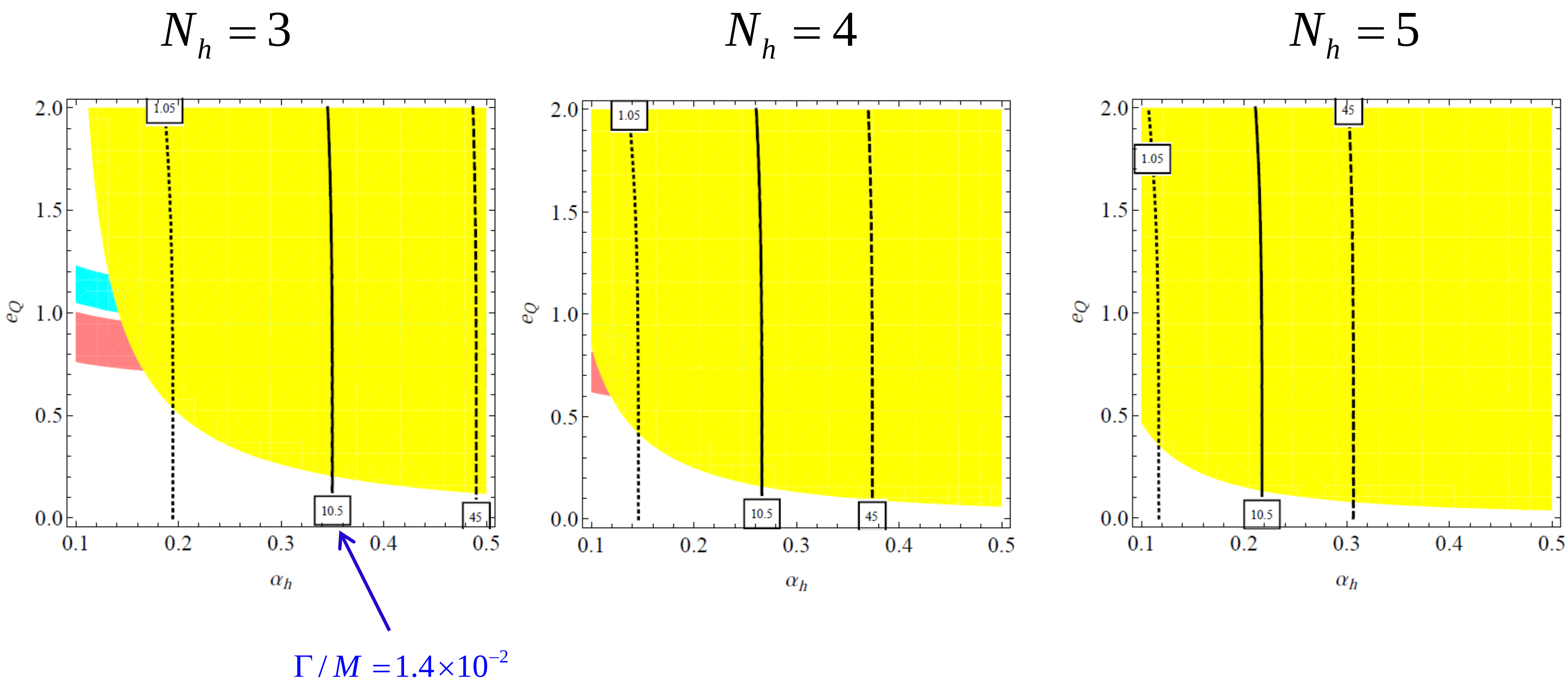




- Assuming (acceptance×efficiency) ~ 0.33 for the photon+jet search

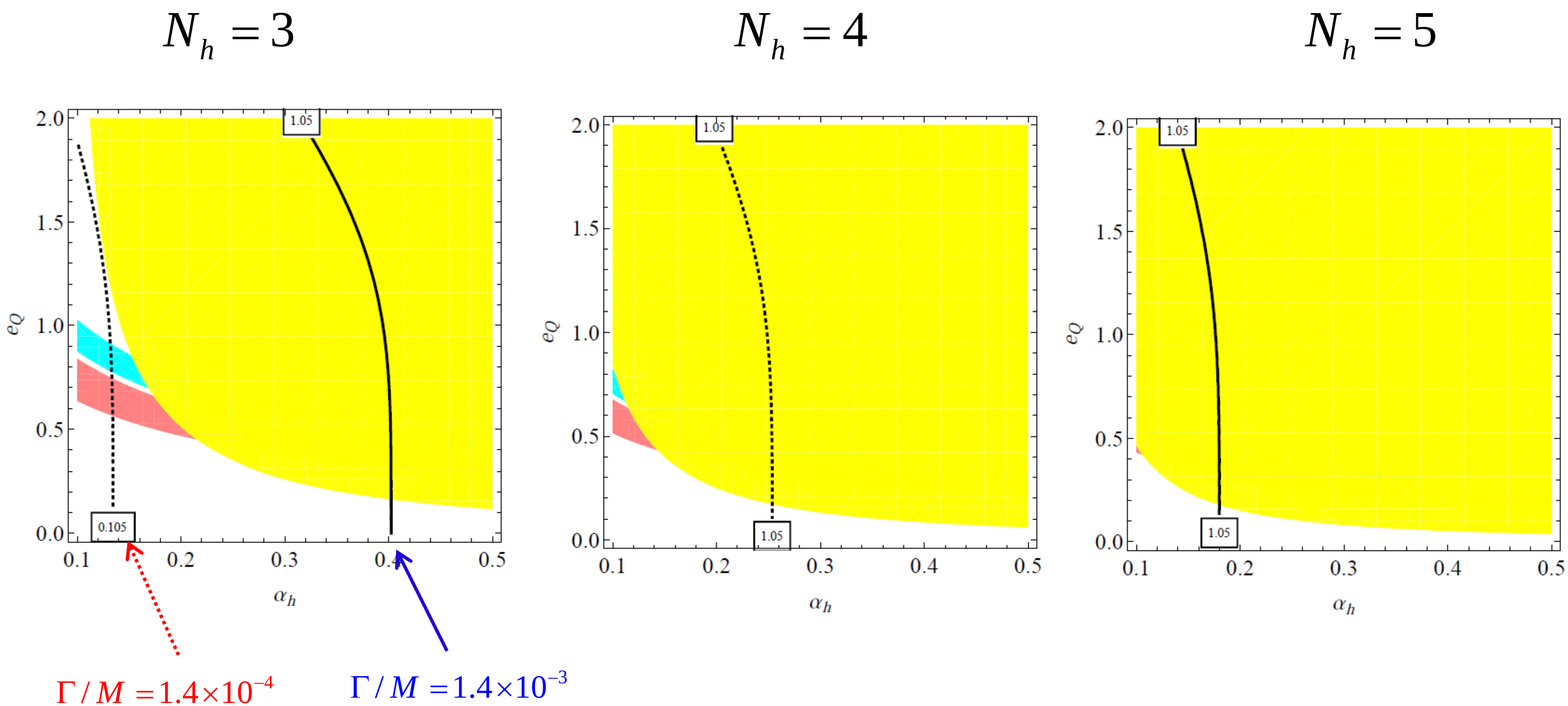
Fermionic quark

$\eta_Q \to g_h g_h$



Fermionic quark

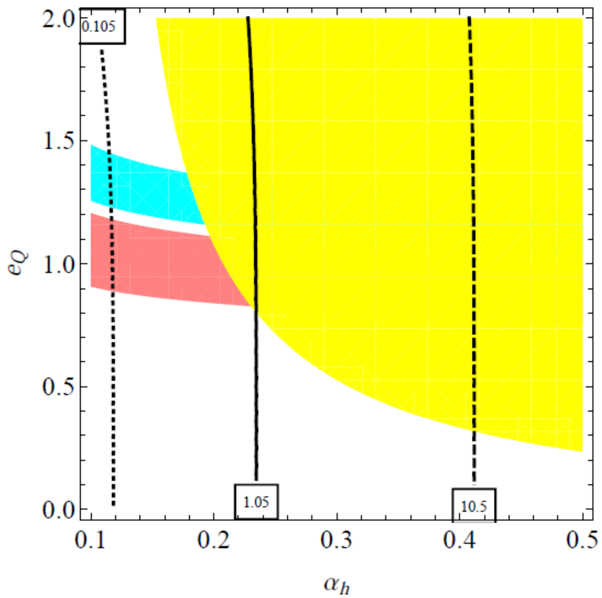
$\eta_Q \not\to g_h g_h$



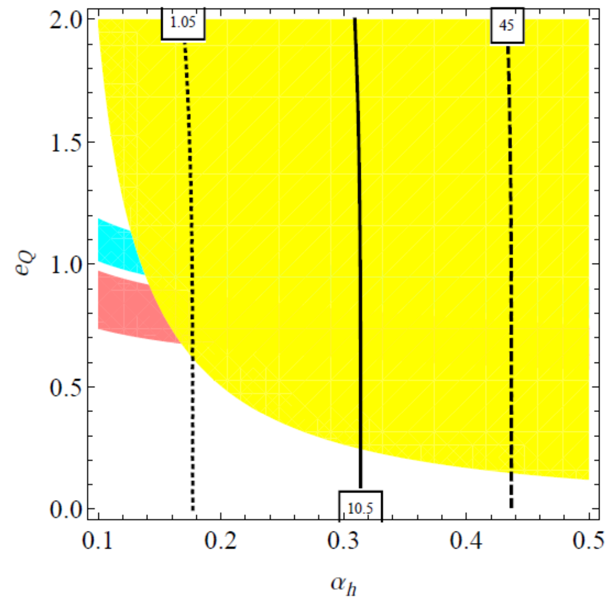
Scalar quark

$\eta_Q \to g_h g_h$

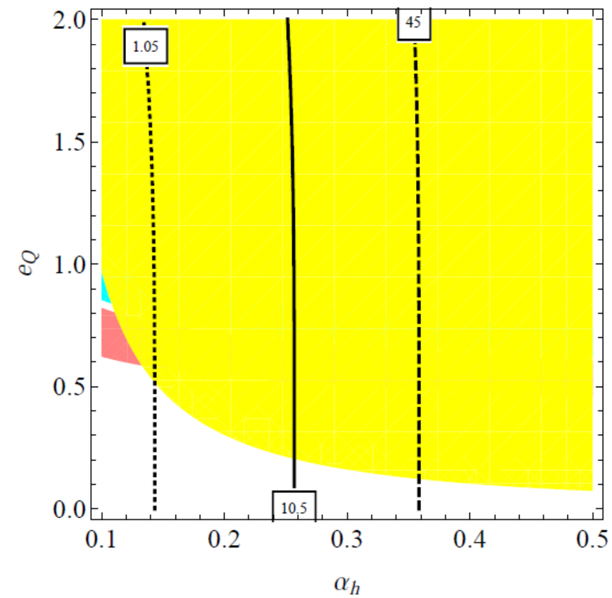
$N_h = 3$



$N_h = 4$



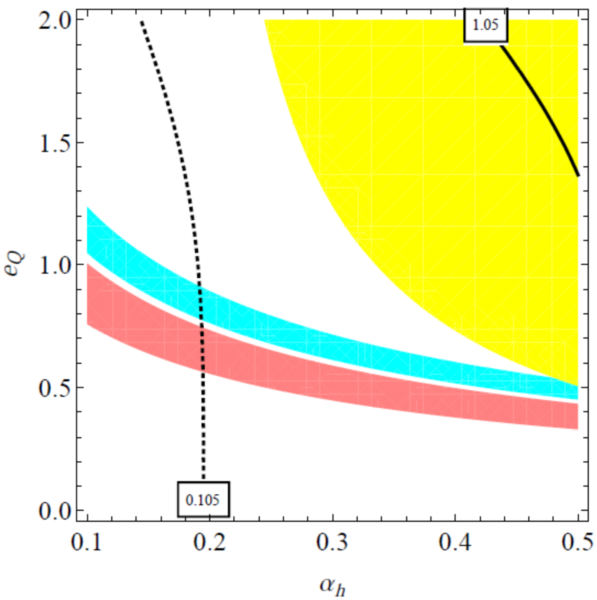
$N_h = 5$



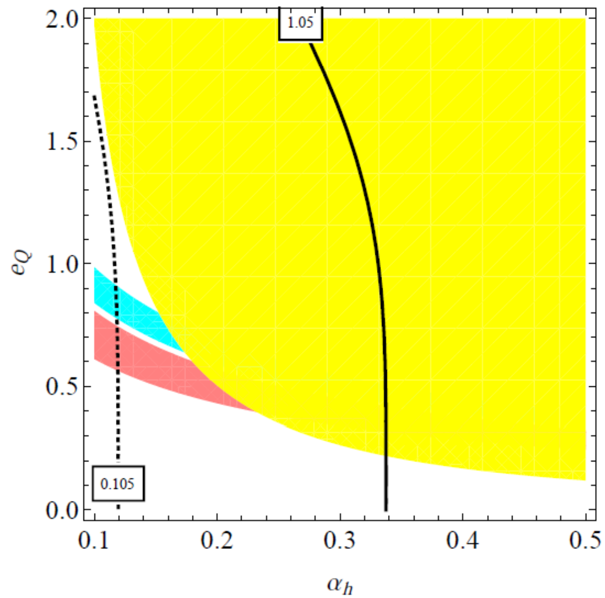
Scalar quark

$\eta_Q \not\to g_h g_h$

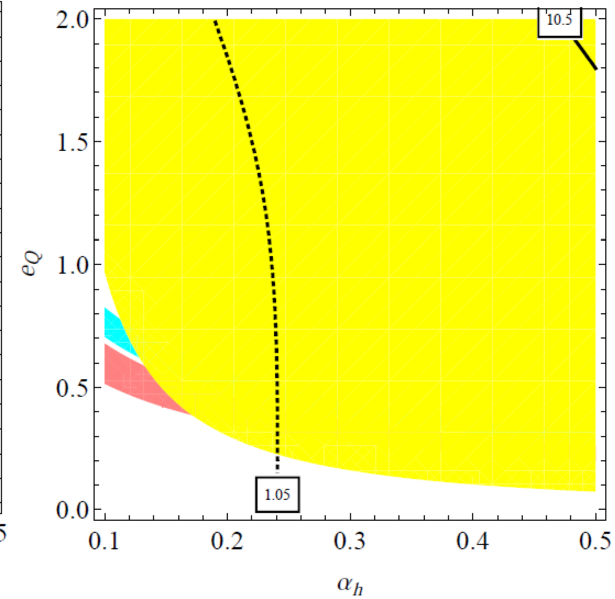
$N_h = 3$



$N_h = 4$



$N_h = 5$



Conclusions

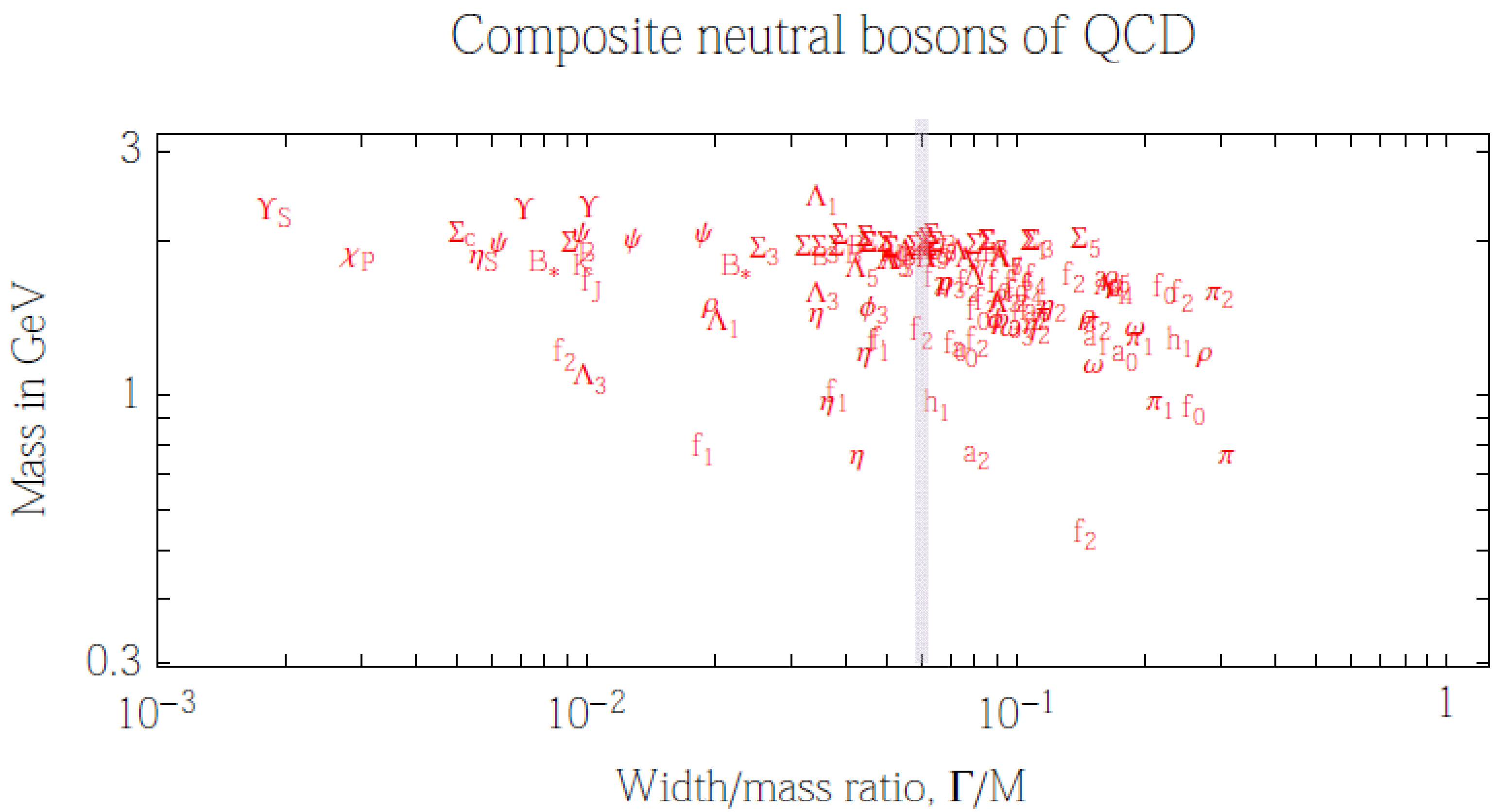
- We consider a possibility that the diphoton excess is a composite (pseudo)scalar boson made of $Q\overline{Q}$ or $\widetilde{Q}\widetilde{Q}^\dagger$.

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

- The photon+jet search gives the most stringent bound to the composite models with new strong interactions.

- need more data to conclude….

Typical Γ/M in QCD

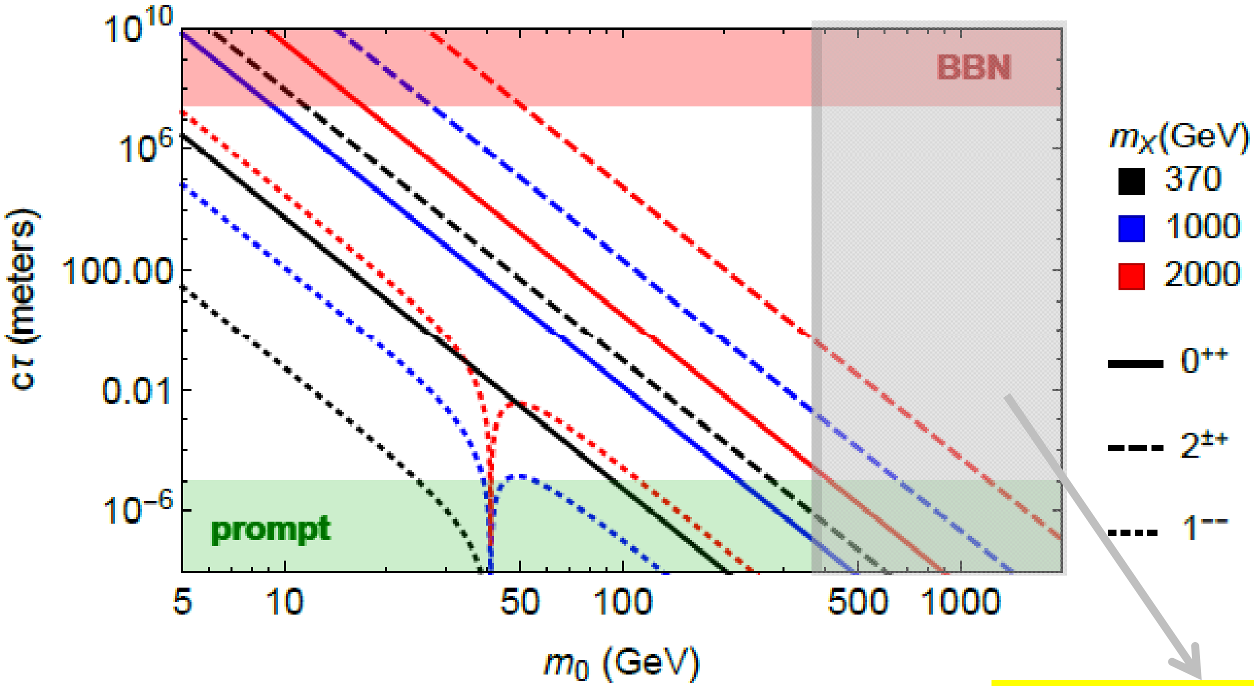


Franceschini et al., arXiv:1512.04933

Large Γ/M might be achieved in the composite model with QCD-like interactions, but requires a large coupling

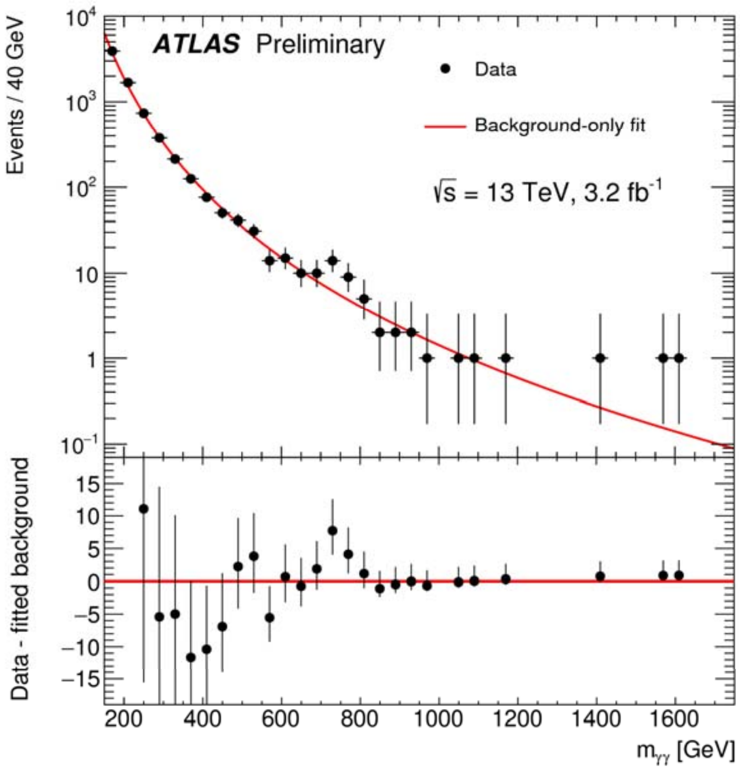
Glueball decay length

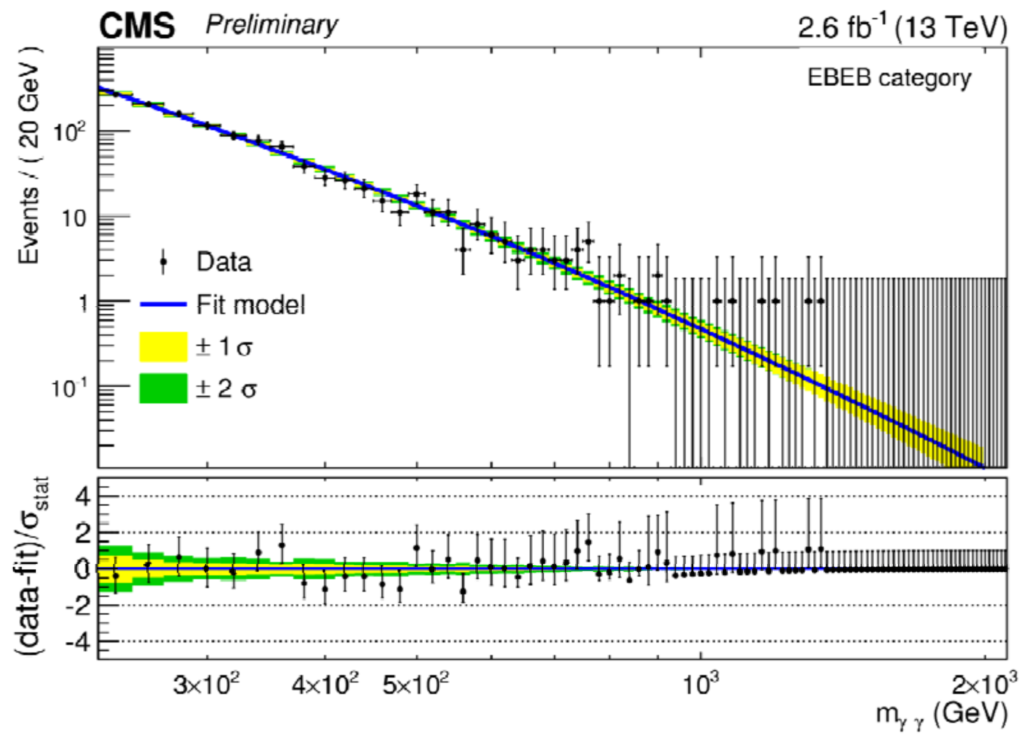
Curtin, Verhaaren, 1512.05753



The 750 GeV resonance
cannot decay into glueballs

Diphoton excess Run-II





ATLAS: local 3.6σ (global 2.0σ)

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

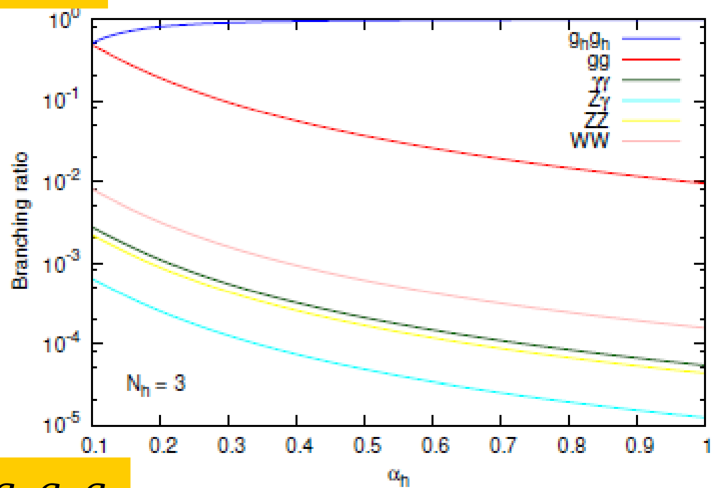
CMS: local 2.6σ for narrow width
<2σ for wide width
(global <1.2σ)

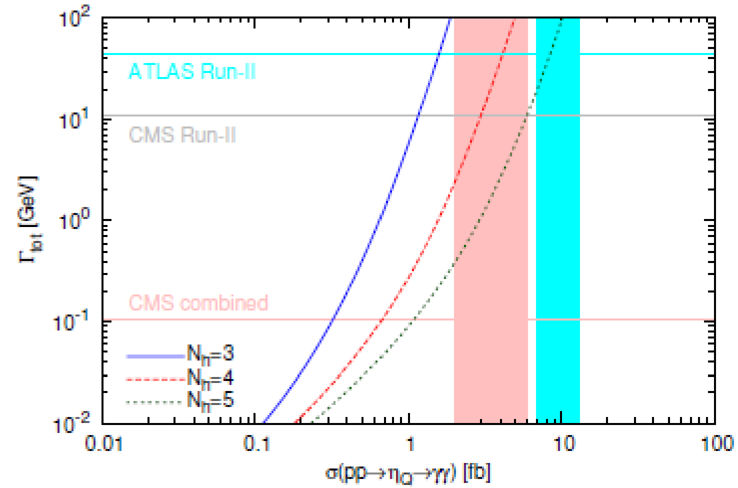
ATLAS data prefer large width Γ/M~0.06 while CMS data prefer narrow width

SU(2) doublet fermionic model

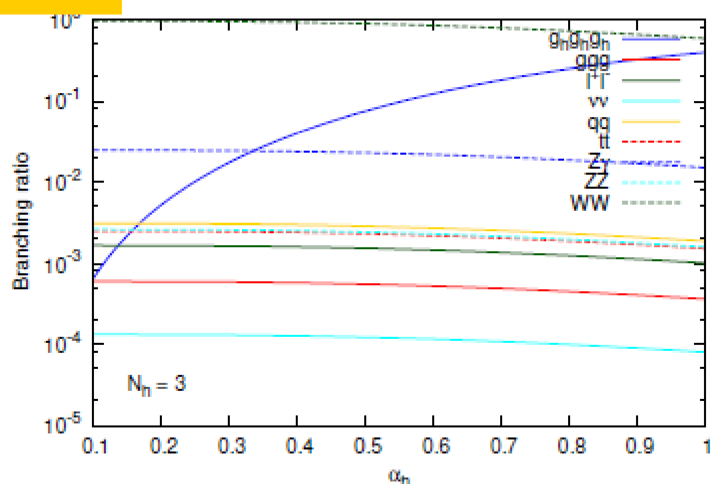
Q_L^i	U_R^i	D_R^i	L_L^i	E_R^i	N_R^i
$(3,2,1/6;N_h)$	$(3,1,2/3;N_h)$	$(3,1,-1/3;N_h)$	$(1,2,-1/2;N_h)$	$(1,1,-1;N_h)$	$(1,1,0;N_h)$

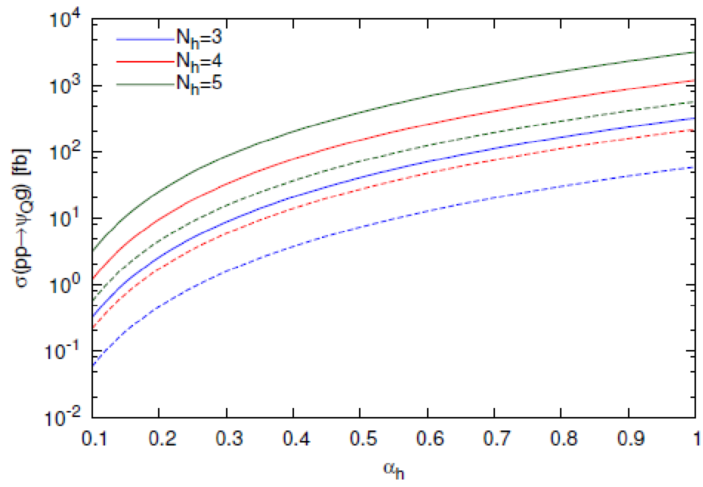
$\eta_Q \to g_h g_h$





$\psi_Q \to g_h g_h g_h$





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.