

Traces of composite light quarks at the LHC

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based on [arxiv:1303.!!!!](#) w/ Grojean-Perez
1306.asap w/ Flacke-Lee-Panico-Perez
1306.asap w/ Blanke-Martin-Perez

Outline

- Naturalness $\rightarrow$ there's a top sector $\sim < \text{TeV}$
but no hint for (a scale for) flavor physics
- Composite PNGB Higgs & partial compositeness
$$\begin{aligned} |SM\rangle &= \cos\theta |elementary\rangle + \sin\theta |composite\rangle \\ |partner\rangle &= -\sin\theta |elementary\rangle + \cos\theta |composite\rangle \end{aligned}$$
- Constraining light quark compositeness w/
 - dijet searches
 - direct searches of partners
 - Higgs couplings to gluons and photons
- Hidding top partners with top/charm mixing

Q: what makes the observed SM-like Higgs light?

$$\delta m^2 = \text{[Feynman diagram: a dashed circle labeled 'H' connected to a solid circle labeled 'top', which is connected to a wavy circle labeled 'W,Z']} \sim \frac{y_t^2 \Lambda^2}{16\pi^2}$$

What's Λ ? natural theory if $\delta m^2 \sim m^2 \rightarrow \Lambda \sim \text{TeV}$

If nothing but gravity $\rightarrow \Lambda = M_{\text{Pl}} \sim 10^{19} \text{ GeV} = \text{hierarchy problem}$

2 new physics paths:

- $\Lambda \sim M_{\text{Pl}}$ but there's a new symmetry above the TeV scale
e.g. supersymmetry
- SM fields couple to a new strong dynamics with $\Lambda \sim \text{TeV}$
e.g. composite Higgs models

be it weakly or strongly coupled,
natural BSM theories have
top partners $< 1 \text{ TeV}$
to soften the UV sensitivity of the Higgs mass

Q: where are they?

SUSY → light stops

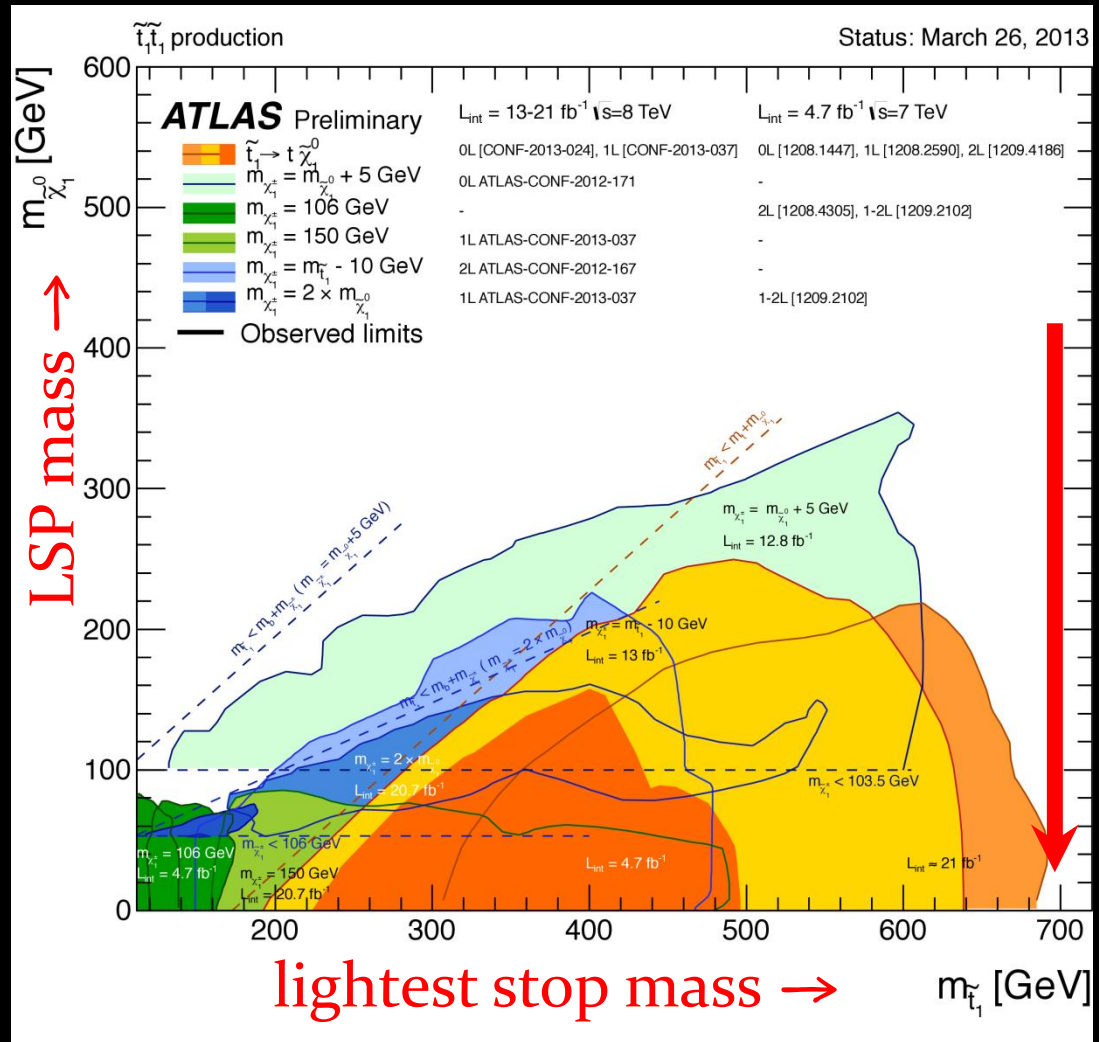
Barbieri-Giudice '88,..., Papucci-Ruderman-Weiler '11

current limits are rather strong:

$$m_{\text{stop}} > \sim 700 \text{ GeV}$$

unless
compressed spectrum?

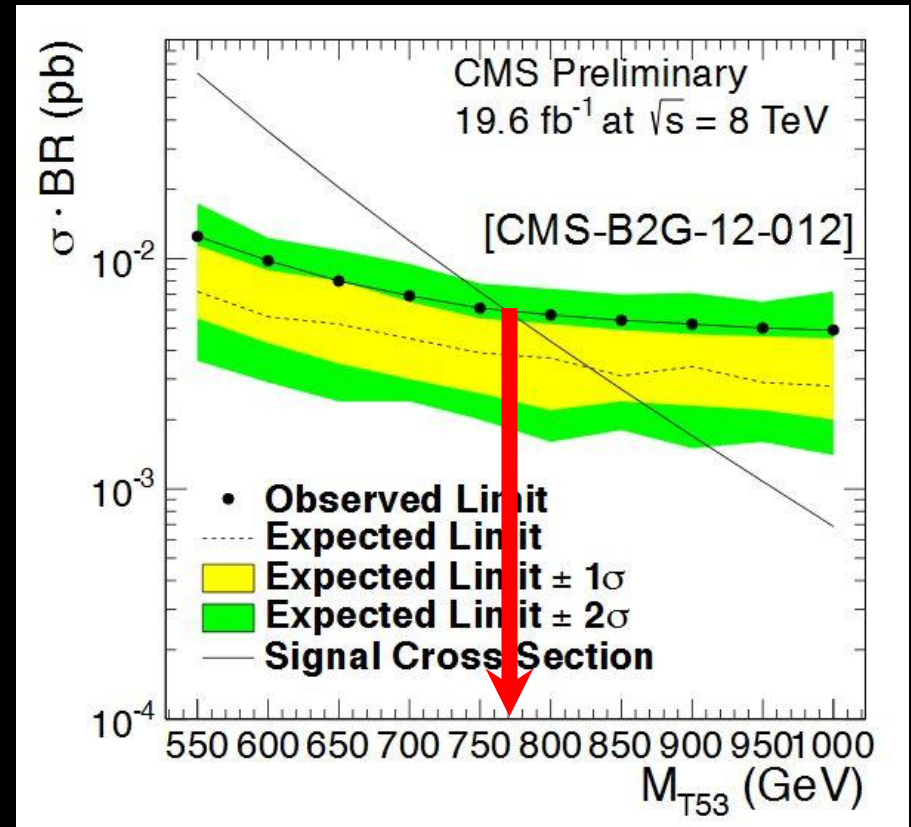
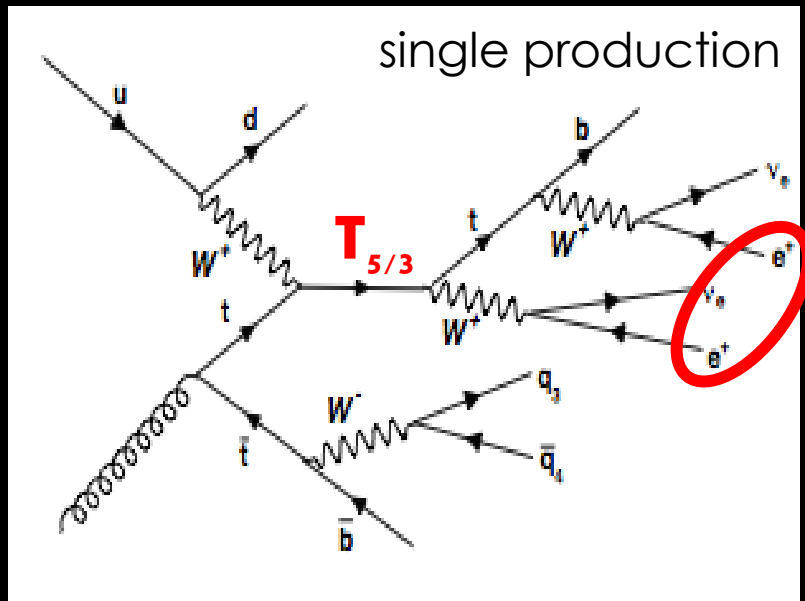
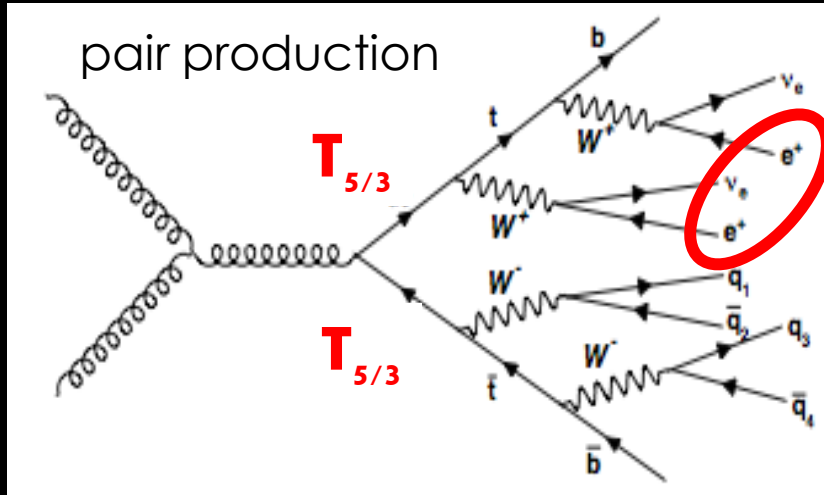
$$m_{stop} \sim m_{top}$$



composite pGB Higgs models → cleanest signal = $T_{5/3}$

Contino-Servant '08, Mrazek-Wulzer '09, Rattazzi et al. '12

vector-like quark ($Q=5/3$)
« custodial » partner of top



$$m_{T_{5/3}} > \sim 770 \text{ GeV}$$

taken from Stelzer @HCP'12

direct searches of top partners at the LHC₇₊₈
have started to pressure naturalness

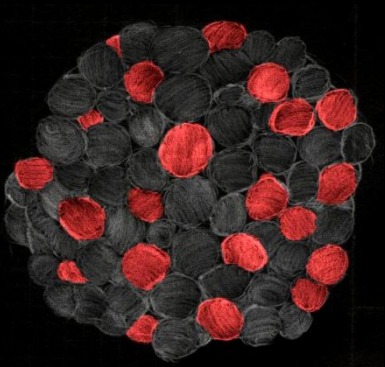
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light quarks are (almost exactly) blind to EWSB,
no hint for flavor physics from naturalness

Q₁: do they have partners too? within LHC reach?

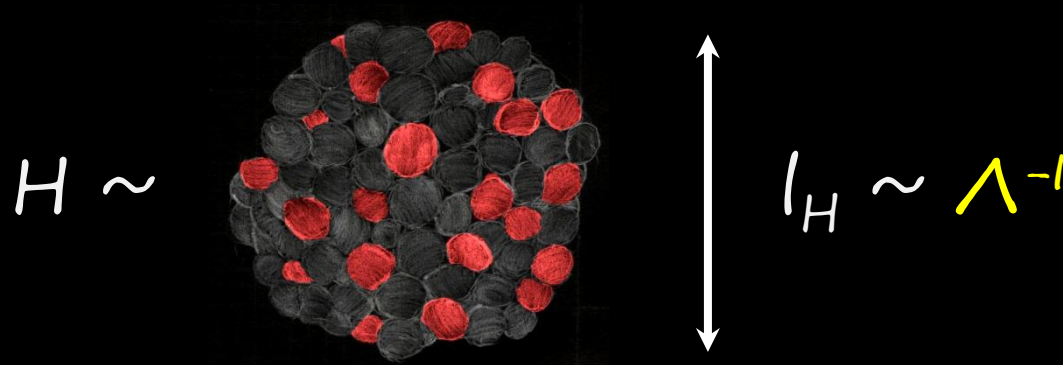
Q₂: are light quark composite objects?

Assume a new QCD-like force confining at $\Lambda \sim \text{few TeV}$

$$H \sim \text{[Composite Higgs Diagram]} \quad \longleftrightarrow \quad l_H \sim \Lambda^{-1}$$
A diagram of a composite Higgs boson, represented as a cluster of red and black spheres. The spheres are arranged in a roughly spherical shape, with red spheres interspersed among black ones. The entire cluster is set against a dark background.

EW symmetry breaking through a **composite Higgs** has
no (big) hierarchy problem! *Georgi-Kaplan '84*

Assume a new QCD-like force confining at $\Lambda \sim \text{few TeV}$



EW symmetry breaking through a **composite Higgs** has
no (big) hierarchy problem! *Georgi-Kaplan '84*

to solve little hierarchy problem *and* naturally get $m_H \ll \text{TeV}$:

make H a “pion” i.e. a PNGB : $H \subset \frac{G}{\mathcal{H}}$

(QCD pions $\subset SU(2)_L \times SU(2)_R / SU(2)_V$)

Contino-Nomura-Pomarol '03
Agashe-Contino-Pomarol '04

CHM 2-site description

Contino-Kramer-Son-Sundrum '06
Redi-Tesi '11

elementary sector

$$\Lambda \sim M_{Pl}$$

$$\begin{matrix} q_L & u_R & d_R \\ & W_\mu & B_\mu & G_\mu \end{matrix}$$

← mass mixing →

$$g_i \psi_i O_i$$

$$\epsilon_i = g_i / g_\rho$$

strong sector $\Lambda = 4\pi f$
 $\sim \text{few TeV}$

$$H \in \mathcal{G}/\mathcal{H}$$

$$+ \text{ resonances } m_\rho = g_\rho f$$

f = Higgs “decay constant”, $g_\rho < 4\pi$

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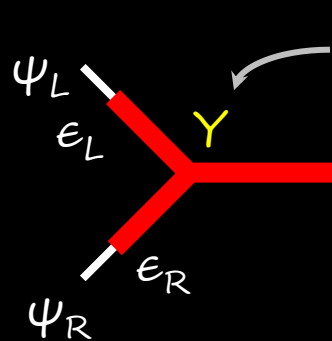
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smallest coset w/ unbroken custodial symmetry: $SO(5)/SO(4)$
fermion masses induced by ϵ_i



$$y_{SM} \approx \epsilon_L Y \epsilon_R$$

partial compositeness:

$$|SM\rangle = \cos |elem\rangle + \sin |comp\rangle \\ \approx |elem\rangle + \epsilon |comp\rangle$$

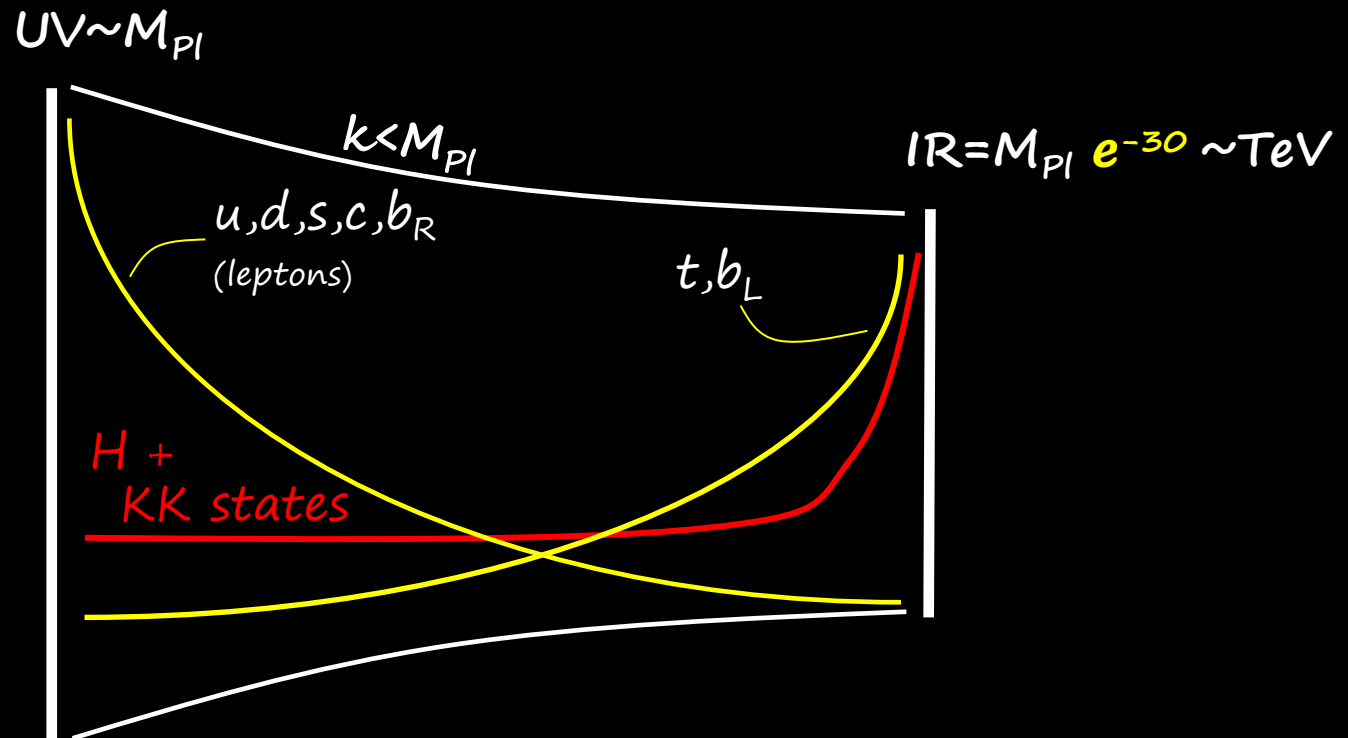
Higgs=NGB → no tree-level potential

EWSB $SO(4) \rightarrow SO(3)$ radiatively induced by top mixings ϵ_{tL} , ϵ_{tR}

CHM 5D warped duals

Maldacena'97: « strong 4D SYM theories are dual to gravity in $AdS_5 \times S^5$ »

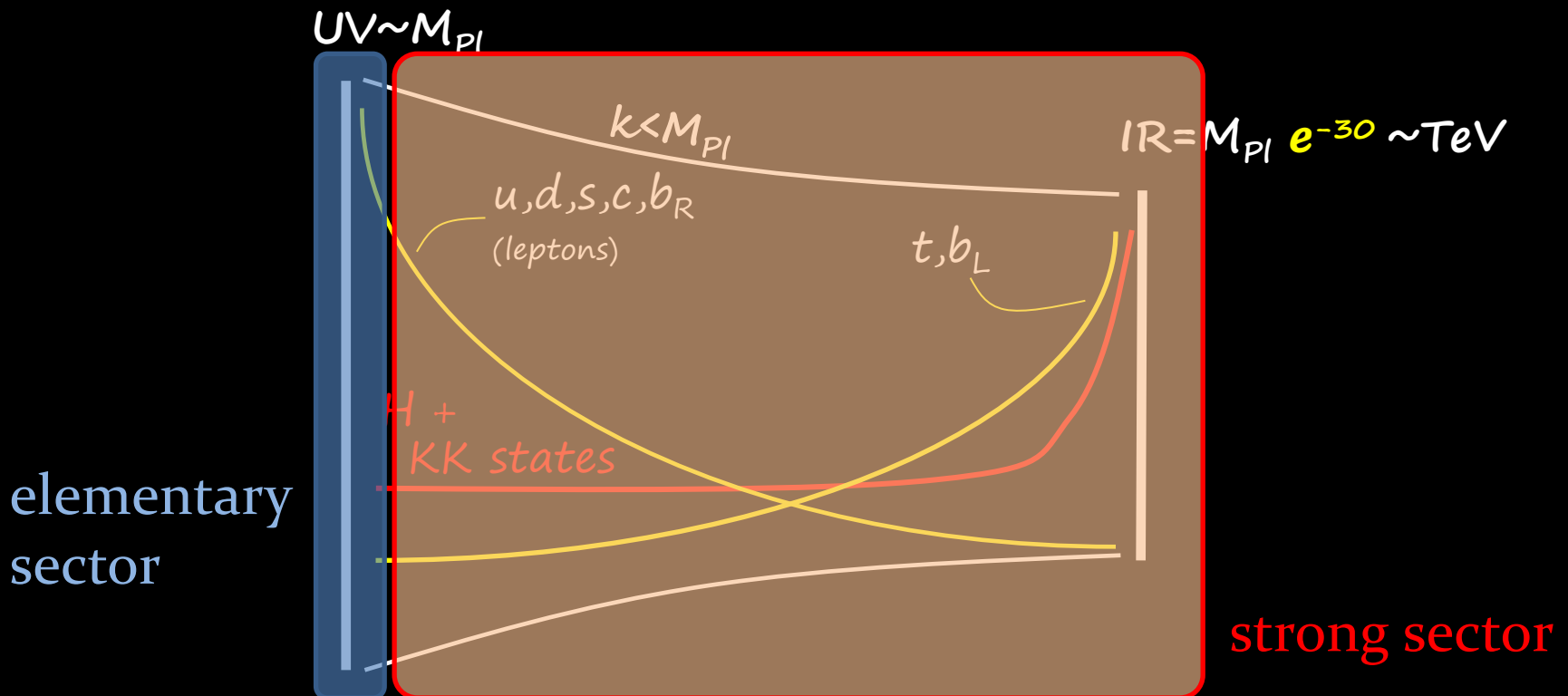
RS'99: « Hierarchy problem is solved in AdS_5 bckg: $ds^2 = e^{-2ky} dx^2 - dy^2$ »



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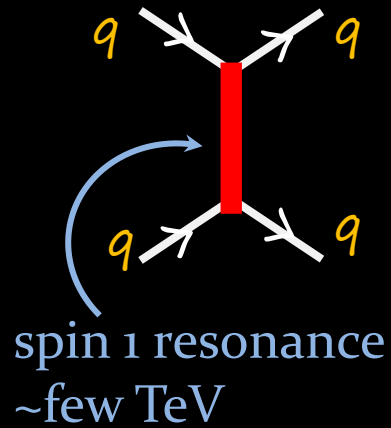
$\epsilon \sim$ IR zero-mode-wavefunction $f(c)$,

$c =$ 5D fermion mass $\sim$ anomalous dim' of chiral operators

Arkani-Hamed-Porrati-Randall '00

Q: are light quarks also composite?

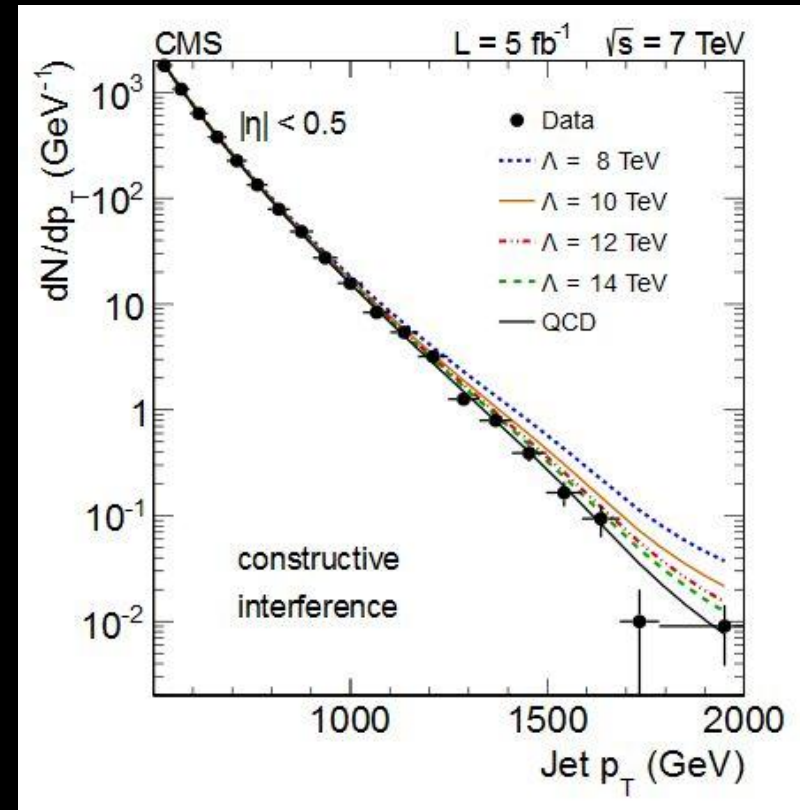
1) dijets searches:



low E $\frac{qqqq}{\Lambda^2}$

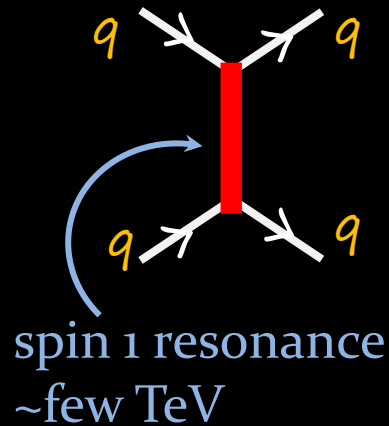
« compositeness scale »

$\Lambda \sim f/\epsilon_q$

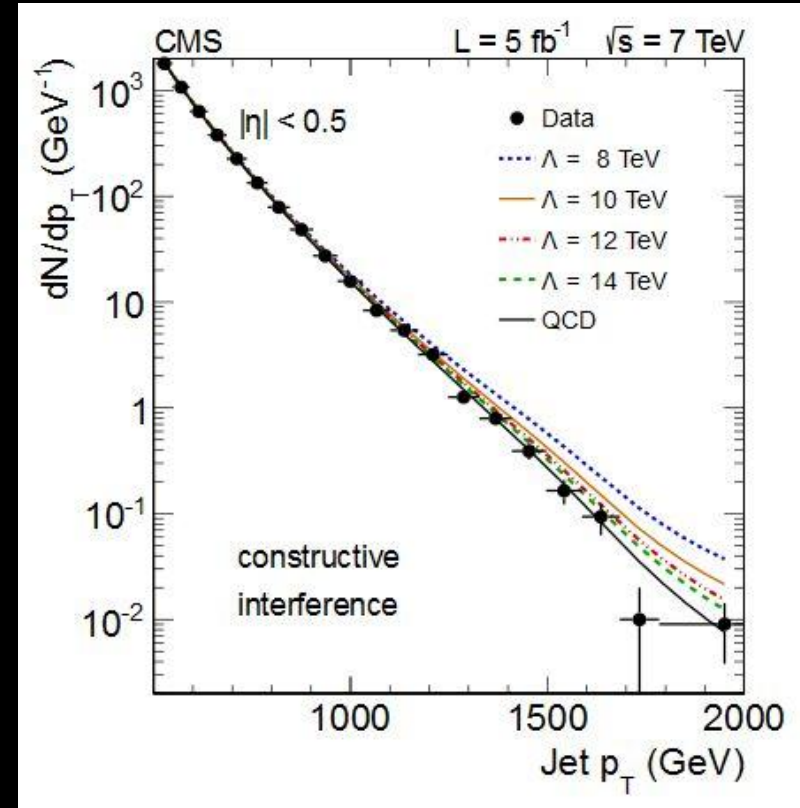


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$q=u,d: \Lambda > 4-6 \text{ TeV}$ e.g. CMS-EXO-11-010 '13

$q=s,c: \Lambda > o(300) \text{ GeV}$ DaRold-CD-Grojean-Perez '12

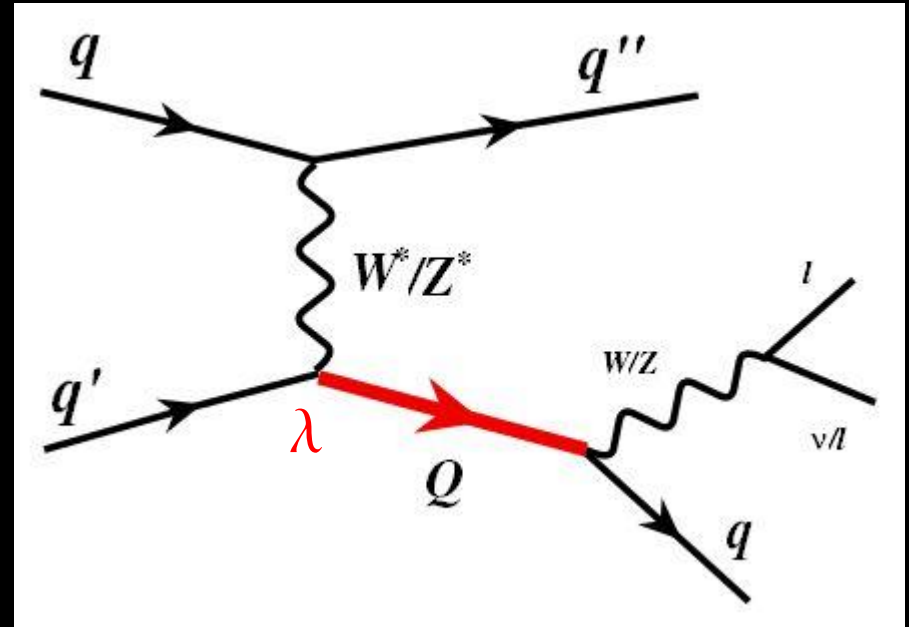
→ 2nd generation's not constrained thanks to small pdf

Q: are light quarks also composite?

2) direct searches of partners = vector-like Q

Carena-Han-Santiago et al. '11

$$\lambda \sim v/f \times \epsilon_q$$

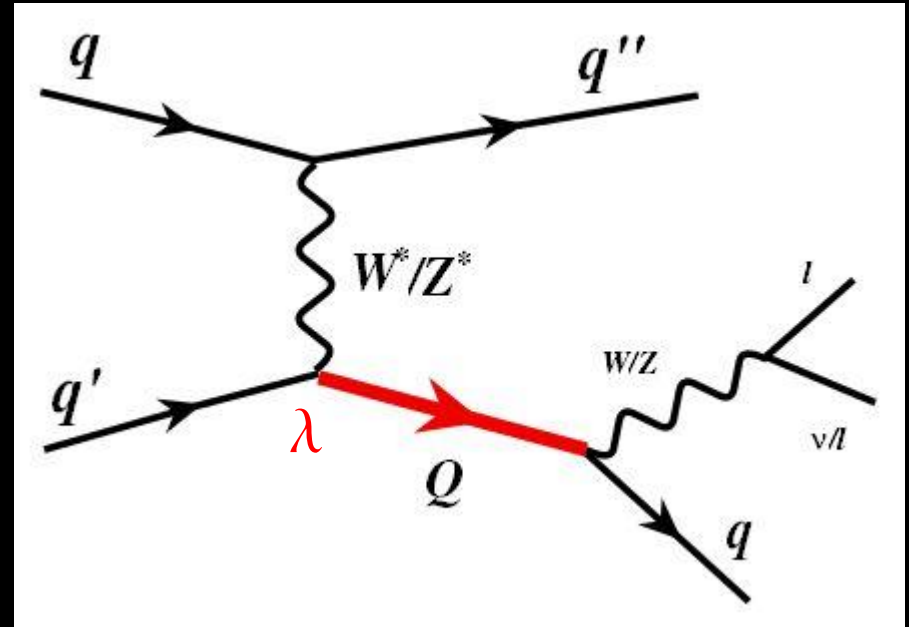


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$$\lambda \sim v/f \times e_q$$



$Q=u,d$ partners: $m_Q > 1.0-1.4 \text{ TeV}$ ATLAS-CONF-2012-137

driven by valence quark PDFs + t -channel (assumed $\lambda \sim v/m_Q$)

$Q=c,s$ partners: $m_Q > \sim \text{few } 100 \text{ GeV}$

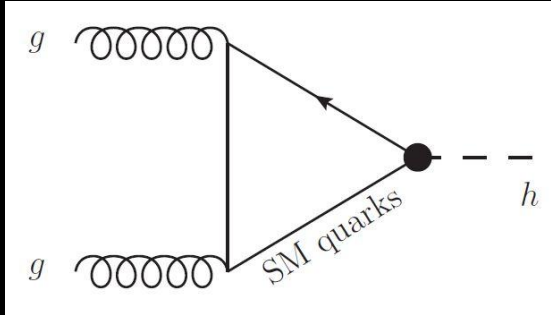
CD-Flacke-Gonzalez-Lee-Panico-Perez,
to appear

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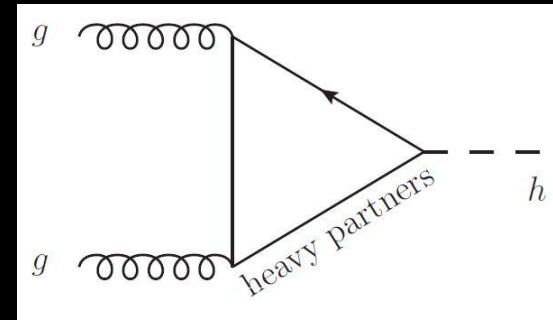
CD-Grojean-Perez '13

3) Higgs (radiative) couplings:

$$M_{gg \rightarrow h} =$$



+

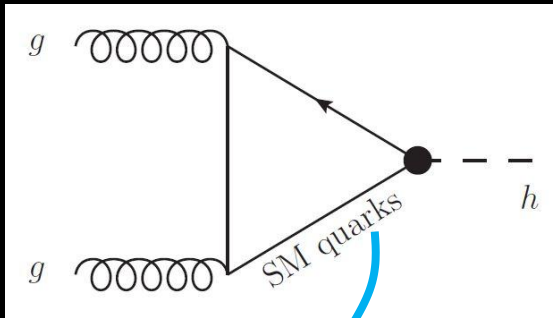


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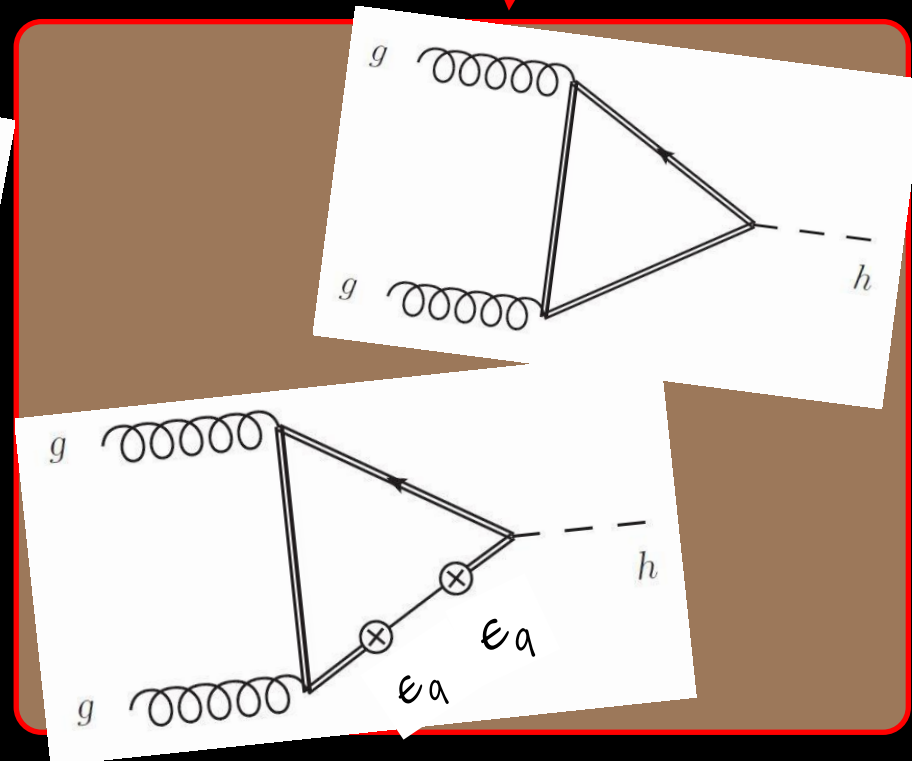
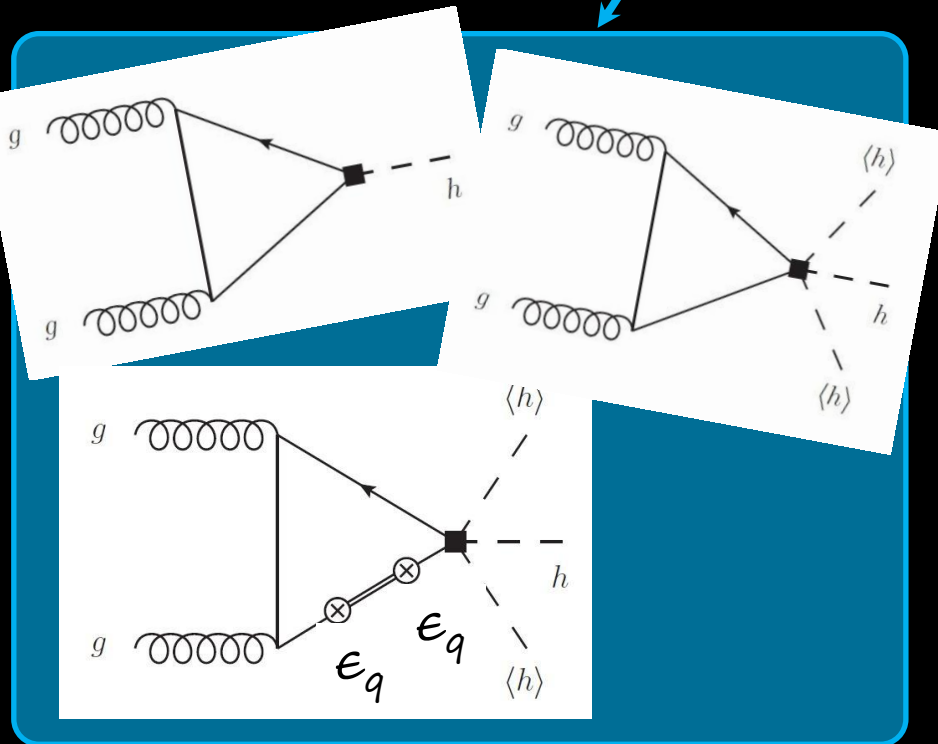
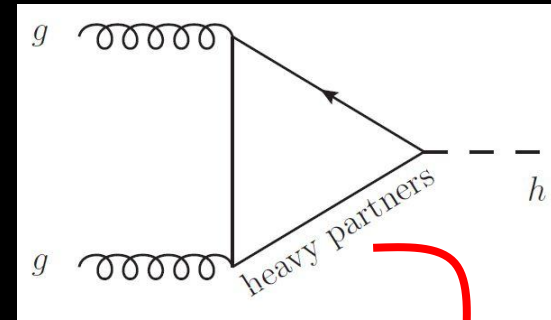
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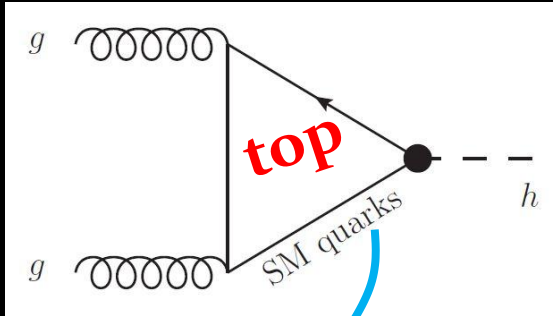


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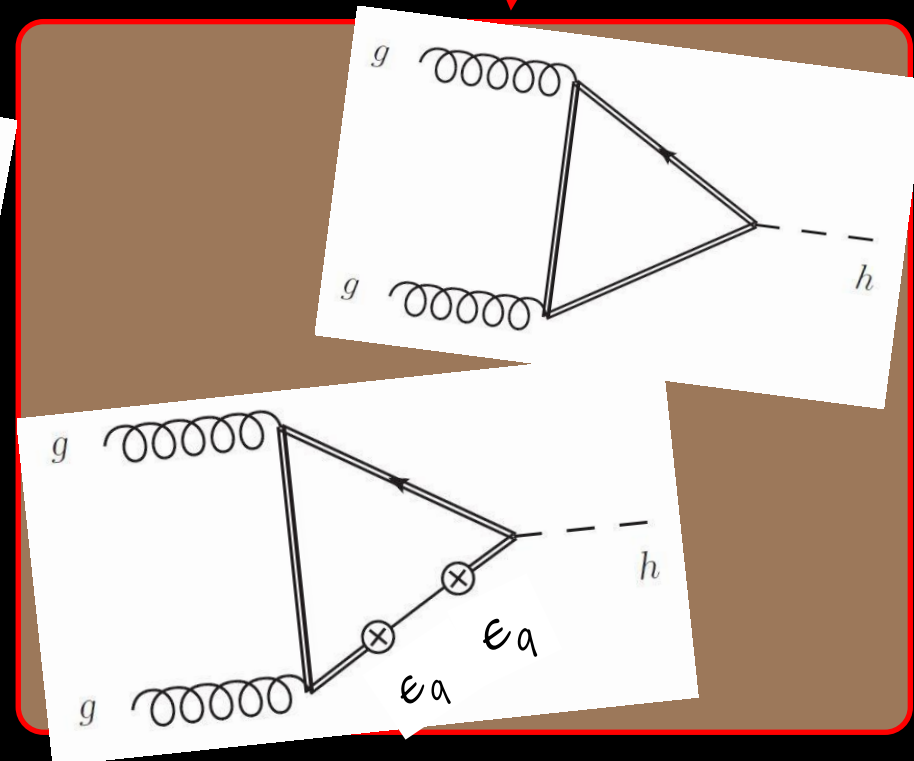
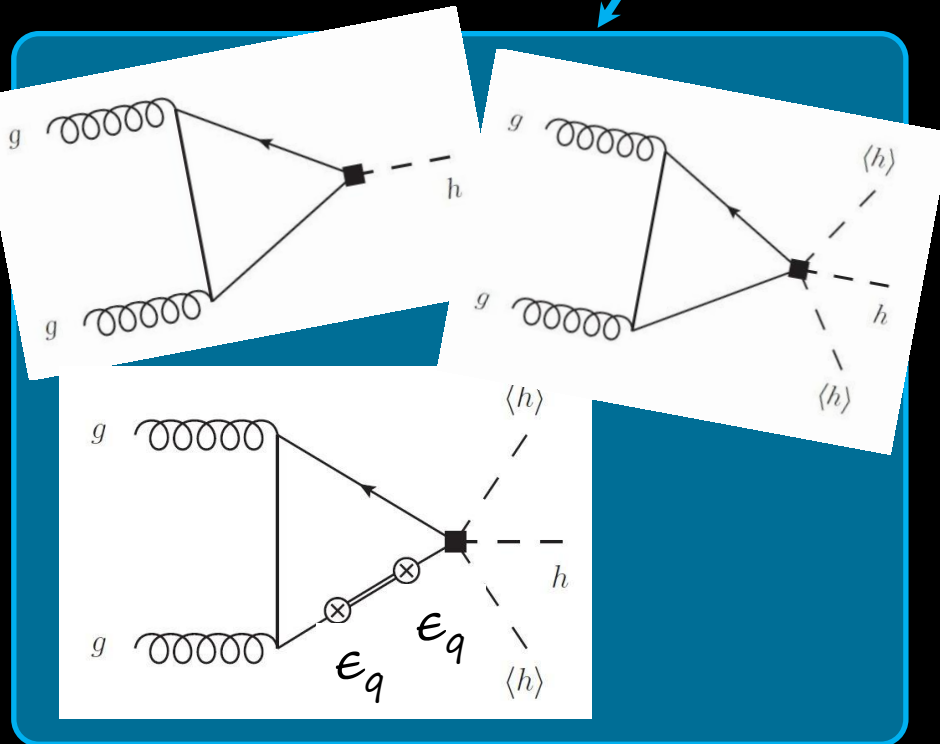
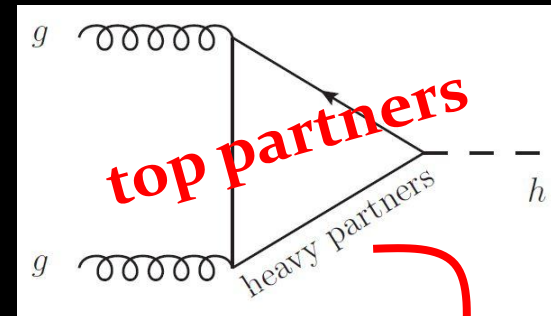
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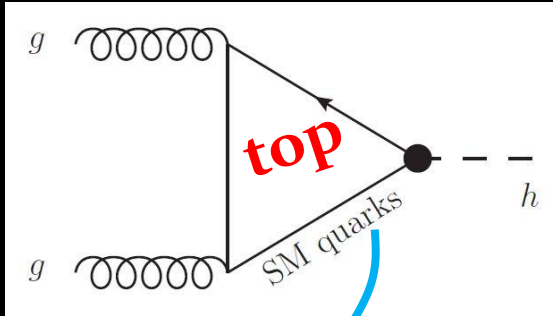


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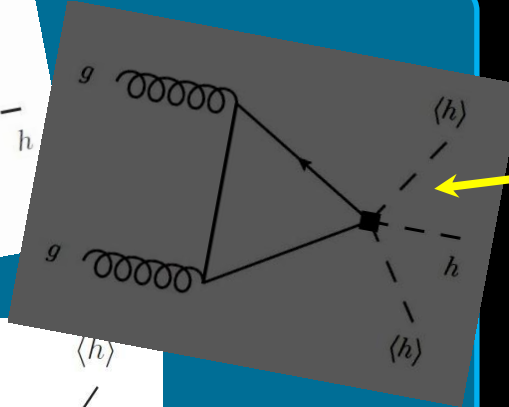
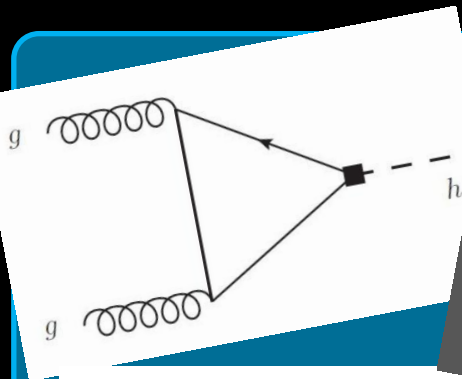
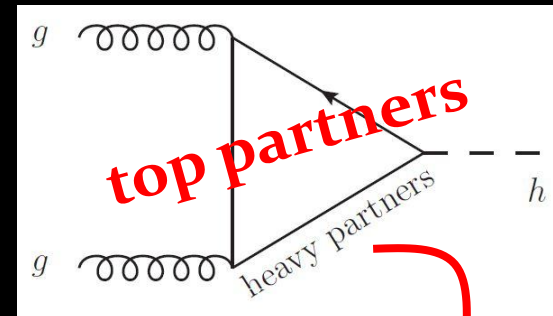
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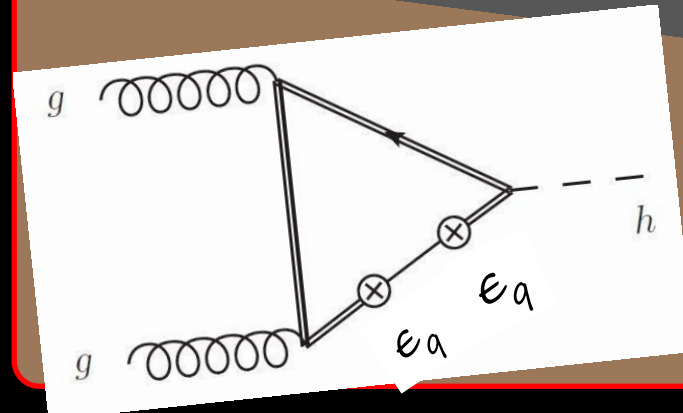
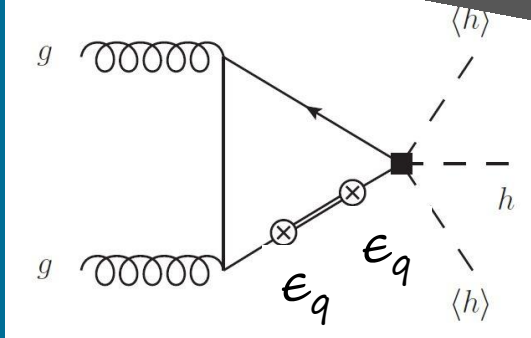
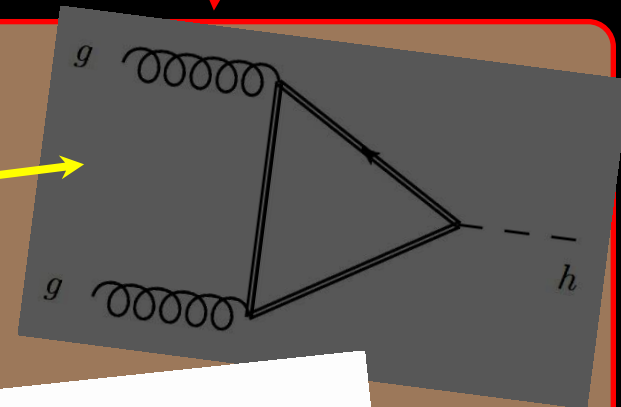
$$M_{gg \rightarrow h} =$$



+



cancel

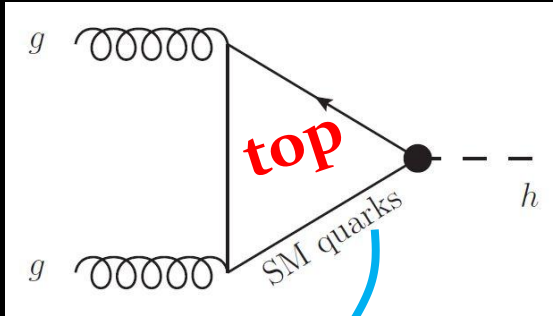


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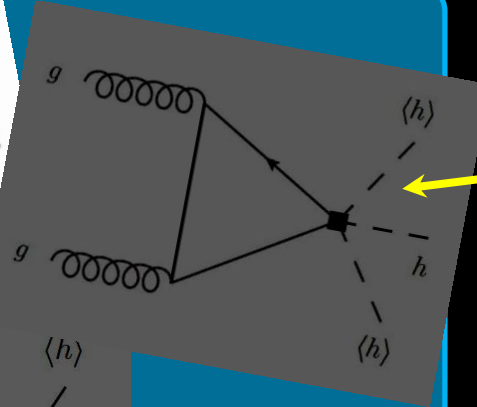
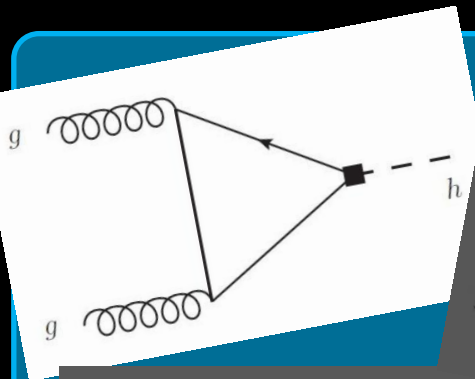
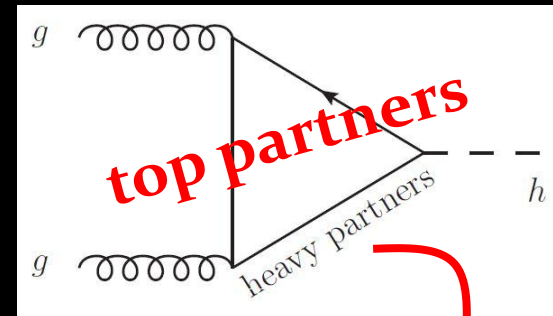
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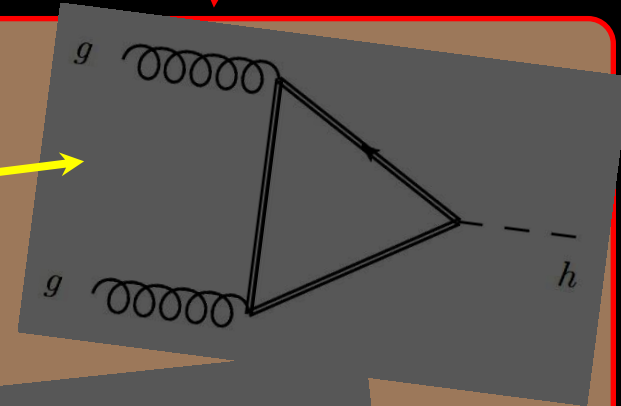
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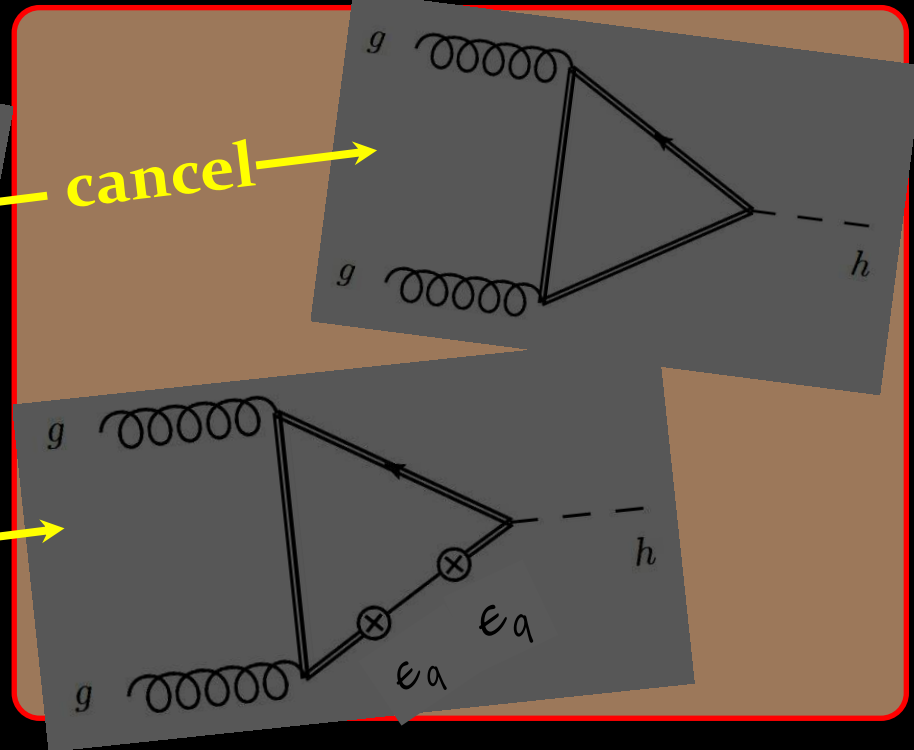
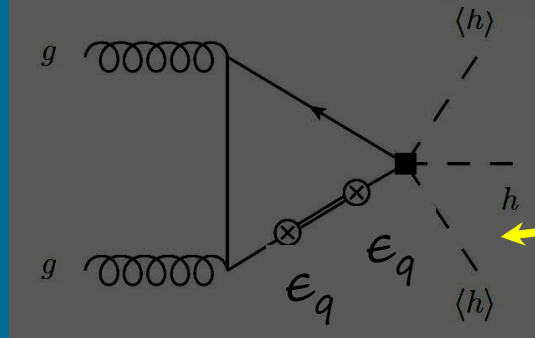
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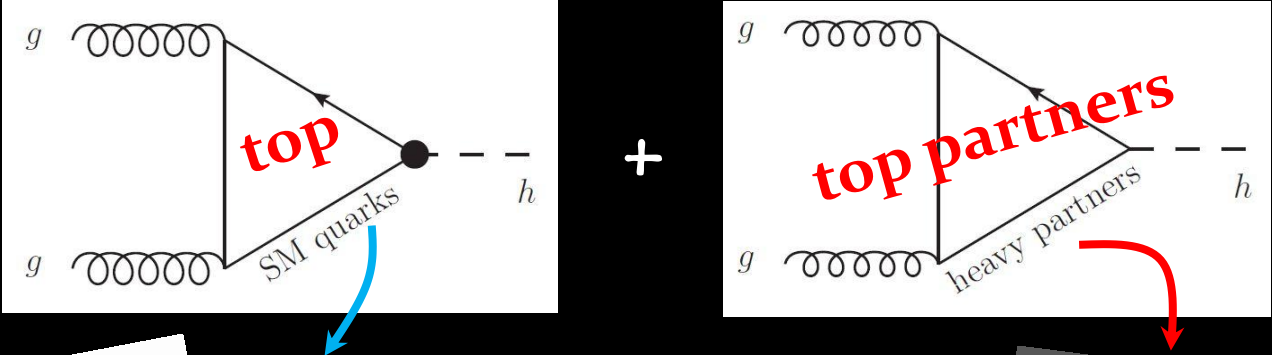
cancel



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CD-Grojean-Perez '13

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Low-energy Higgs theorem:
Vainshtein-Voloshin-Zakharov-Shifman '79

$$M_{gg \rightarrow h} \propto \left(\frac{\partial}{\partial \log H} \log \det \mathcal{M}^2(H) \right)_{H=v}$$

$\propto 1$

→ no sensitivity to top compositeness and top partners spectrum

typical structure in CHM:

$$\mathcal{M} = \begin{pmatrix} 0 & \lambda_q & 0 \\ 0 & M_Q & Y \tilde{H} \\ \lambda_u & \tilde{Y} \tilde{H}^\dagger & M_U \end{pmatrix}$$

$$\det M \propto H$$

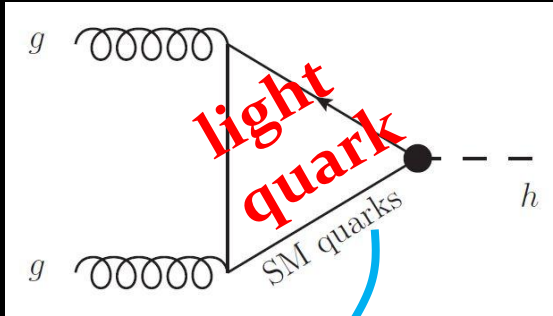
Falkowski '08, Azatov-Galloway '10

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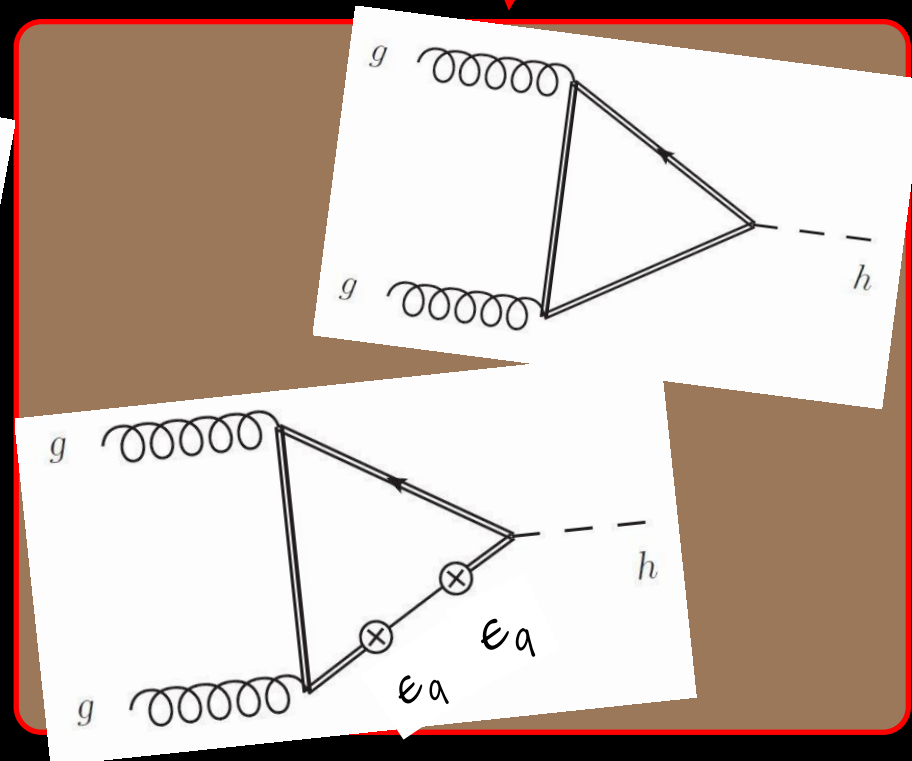
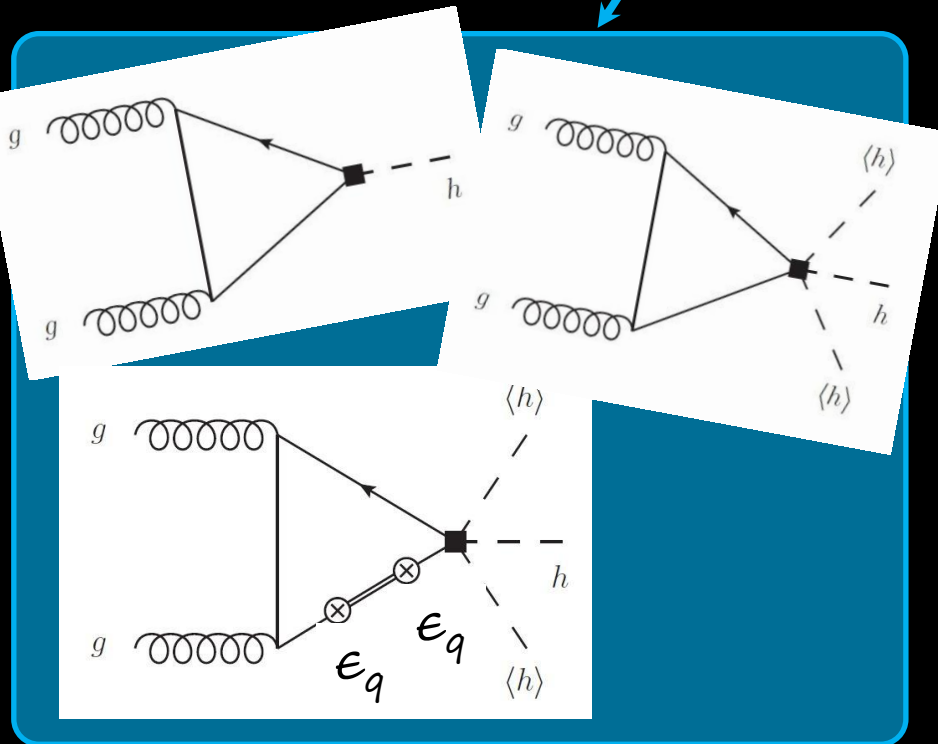
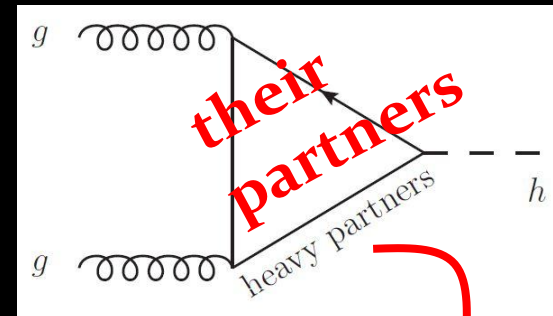
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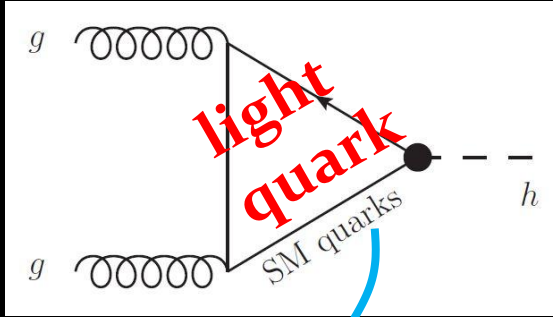


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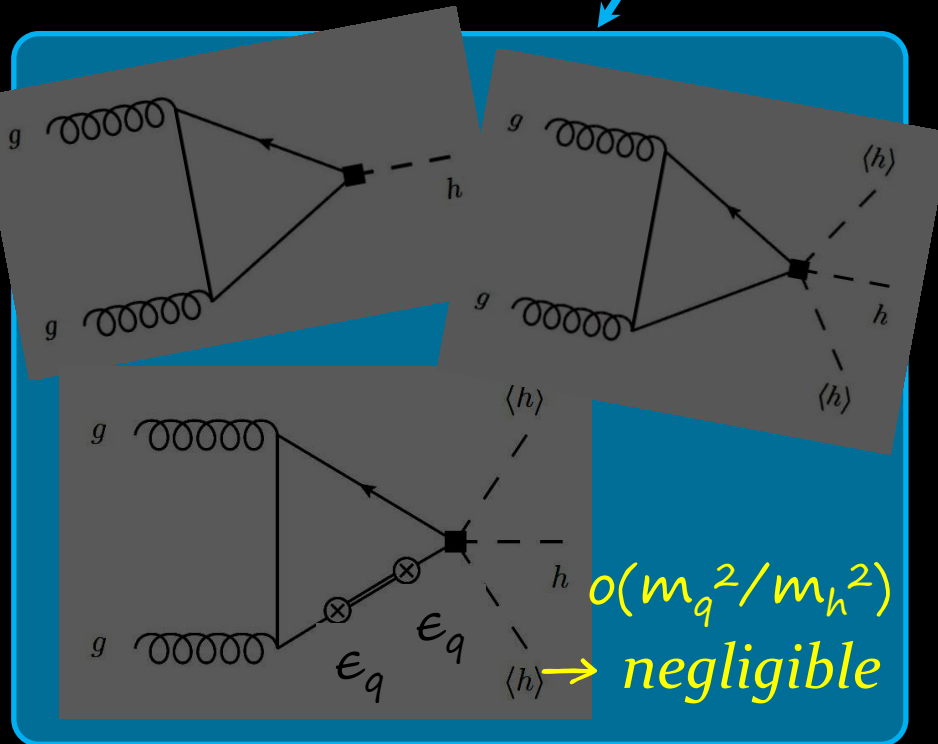
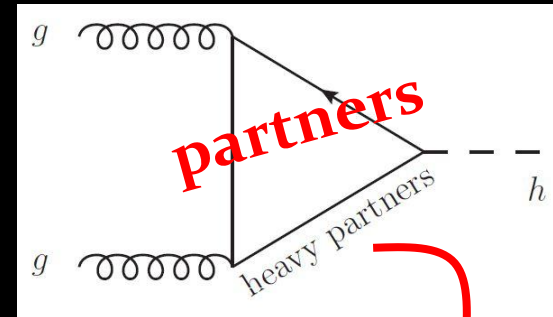
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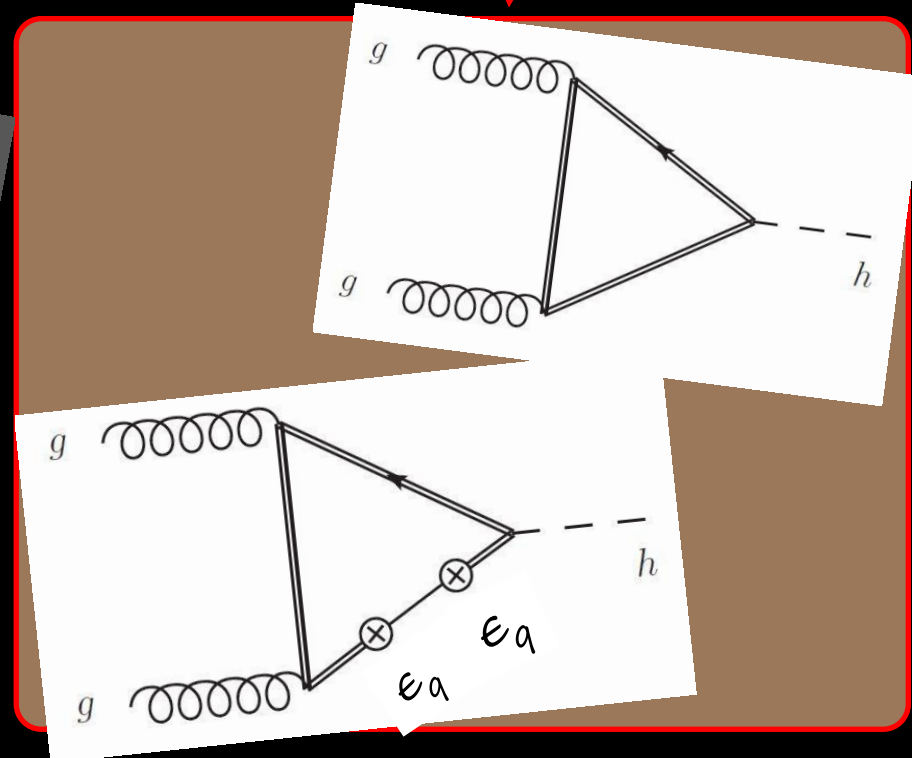
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+



$\propto (m_q^2/m_h^2)$
→ negligible

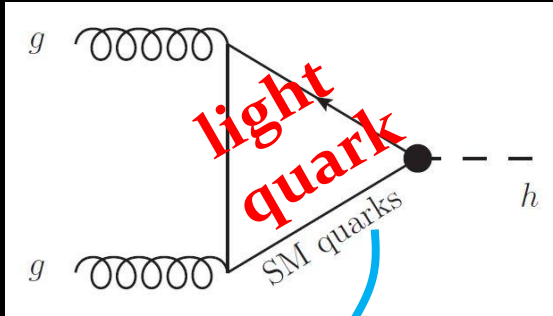


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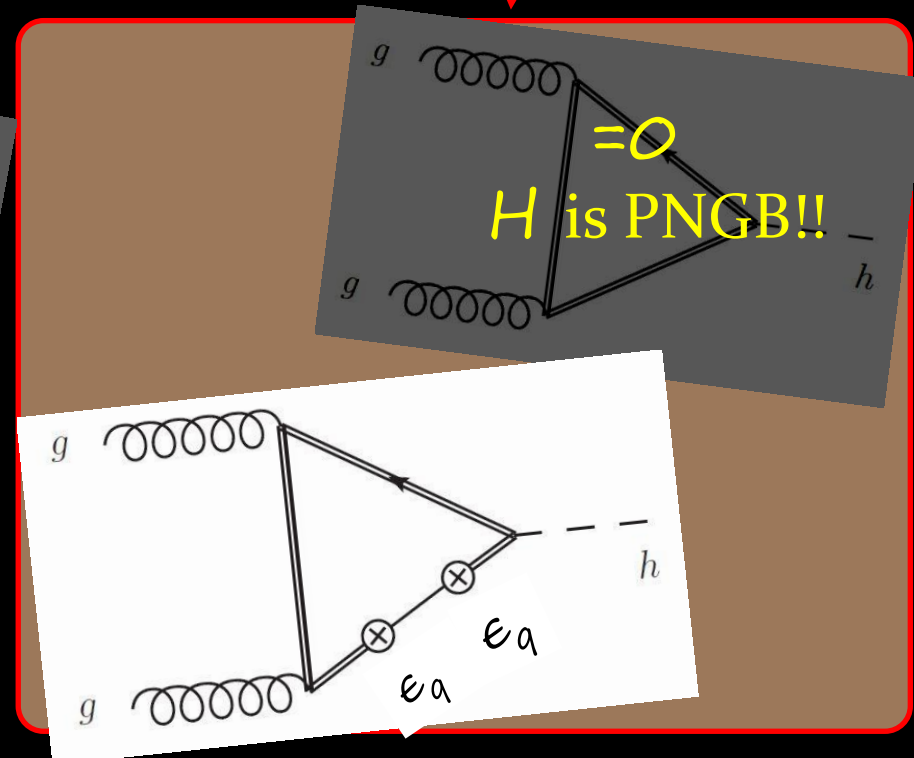
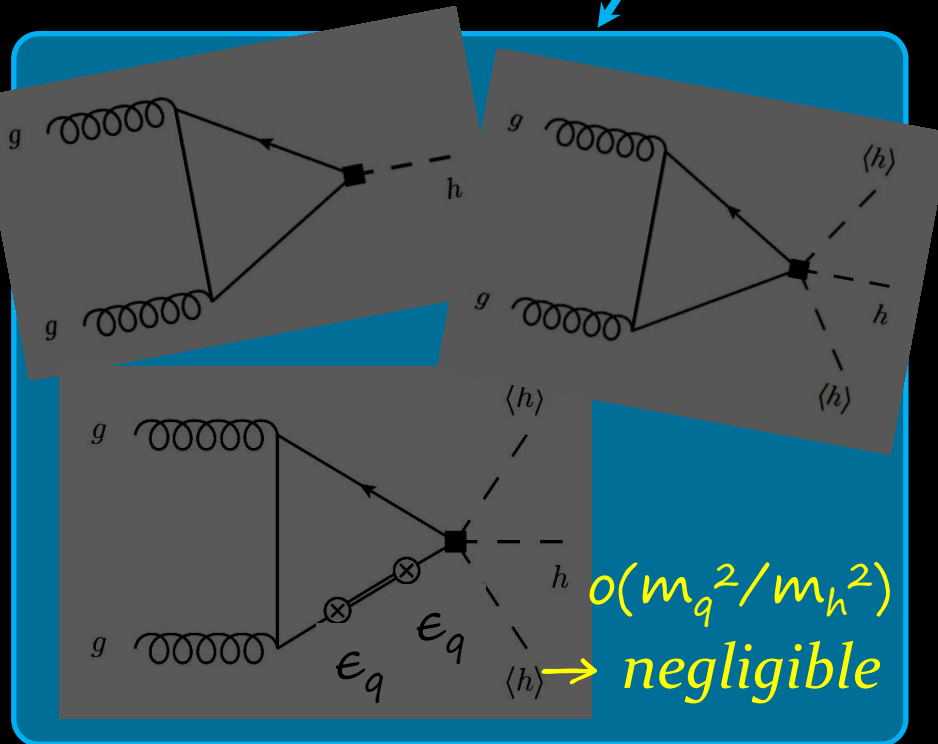
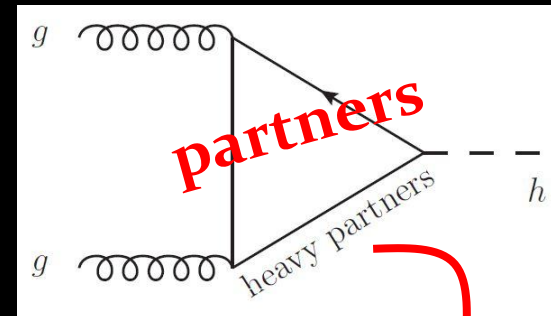
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CD-Grojean-Perez '13

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The image shows two Feynman diagrams for the process $gg \rightarrow h$. The first diagram, labeled 'light quark' in red, shows a loop of Standard Model (SM) quarks. The second diagram, labeled 'partners' in red, shows a loop of heavy partners. Both diagrams have two incoming gluon lines (g) and one outgoing Higgs line (h). A blue arrow points from the 'light quark' diagram to the text below, and a red arrow points from the 'partners' diagram to the text below.

→ composite higgs couplings to gluon and photon probe light quark compositeness !!

net effect scales like e_L^2 or e_R^2 but not $e_L e_R$ (hgg is flavor singlet)

→ one chirality composite is enough, say RH to pass EWPTs

The diagram shows a gluon line (g) entering a loop of quarks, which then splits into a Higgs line (h). The loop is labeled with e_q and e_q . The text $o(m_q/m_h)$ is written above the loop, and $\langle h \rangle \rightarrow$ negligible is written below it.

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$$\frac{\sigma_{gg \rightarrow h}}{\sigma_{gg \rightarrow h|SM}} = X_{gg}^{\text{MCHM}} \simeq 1 - 3\xi + 2 \sum_{i=u,d} N_i x_i \sin^2 \theta_i (1 + 2r_i) + \dots$$

top sector

$\xi = (v/f)^2 \rightarrow$ suppresses ggh
Rattazzi-Low '09

light q_R sector

$N = \#$ composite flavors

$x = (Y v/M)^2$

$\sin \theta_R \approx e_R$

$r = M/Yf \sim o(1)$

$\rightarrow$ enhances ggh

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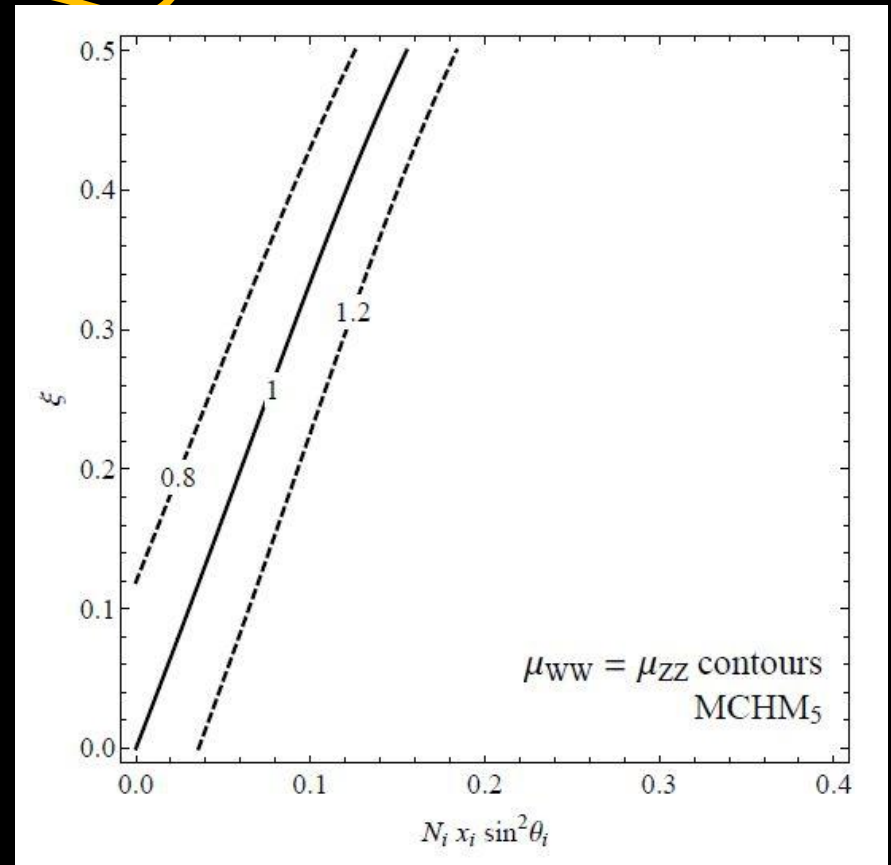
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Higgs compositeness $\rightarrow$



light quark compositeness $\rightarrow$

Q: are light quarks also composite?

CD-Grojean-Perez '13

3) Higgs (radiative) couplings:

$$\frac{\sigma_{gg \rightarrow h}}{\sigma_{gg \rightarrow h}|_{SM}} = X_{gg}^{\text{MCHM}} \simeq 1 - 3\xi + 2 \sum_{i=u,d} N_i x_i \sin^2 \theta_i (1 + 2r_i) + \dots$$

top sector

$\xi = (v/f)^2 \rightarrow$ suppresses ggh
Rattazzi-Low '09

light q_R sector

$N = \#$ composite flavors

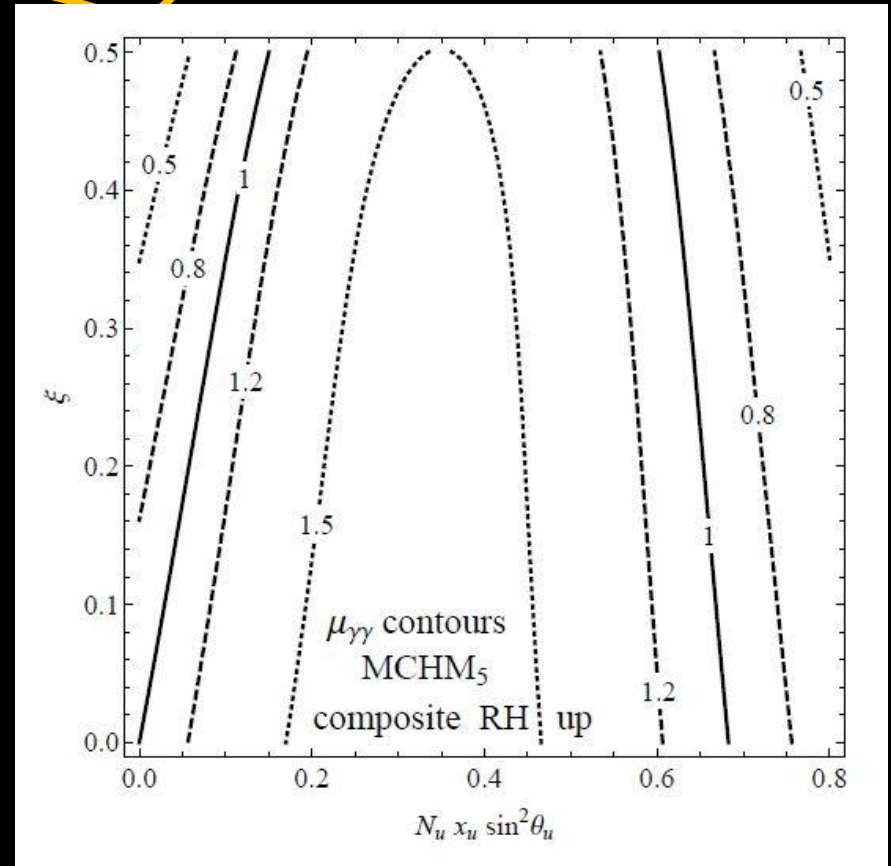
$x = (Y v/M)^2$

$\sin \theta_R \approx \epsilon_R$

$r = M/Yf \sim o(1)$

$\rightarrow$ enhances ggh

Higgs compositeness $\rightarrow$



light quark compositeness $\rightarrow$

Q: can one bury composite top partners @LHC?

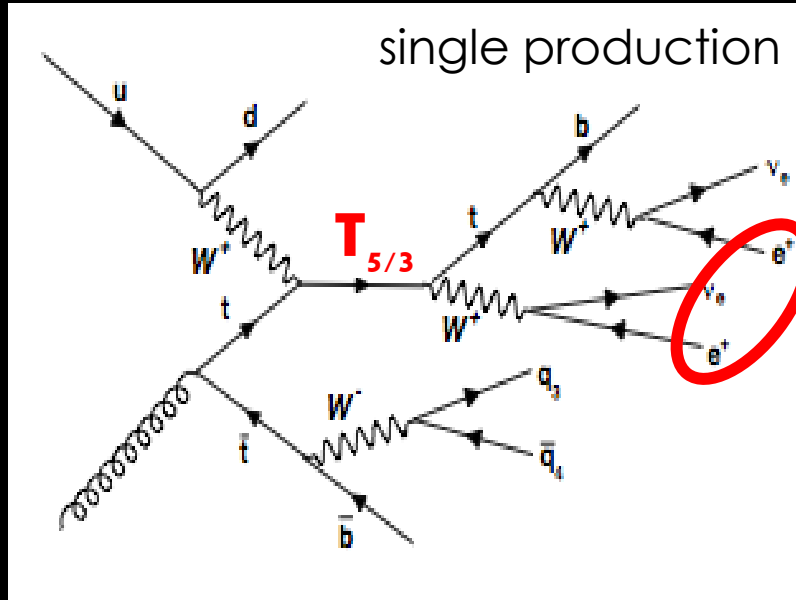
Yes! by mixing (RH) top with composite charm

Blancke-CD-Martin-Perez
to appear

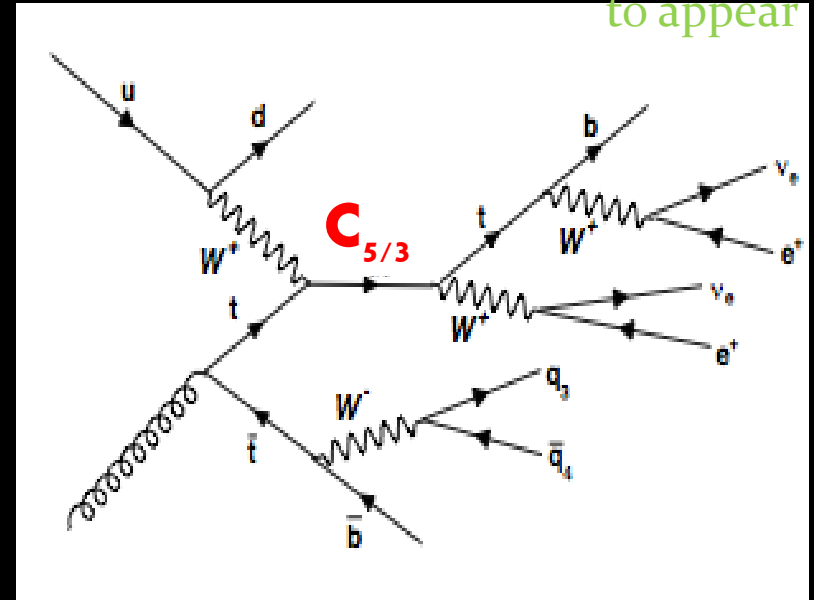
Q: can one bury composite top partners @LHC?

Yes! by mixing (RH) top with composite charm

Blanke-CD-Martin-Perez
to appear



+



$$\sigma = \sigma(m_T) (\cos\theta_{ct})^2$$

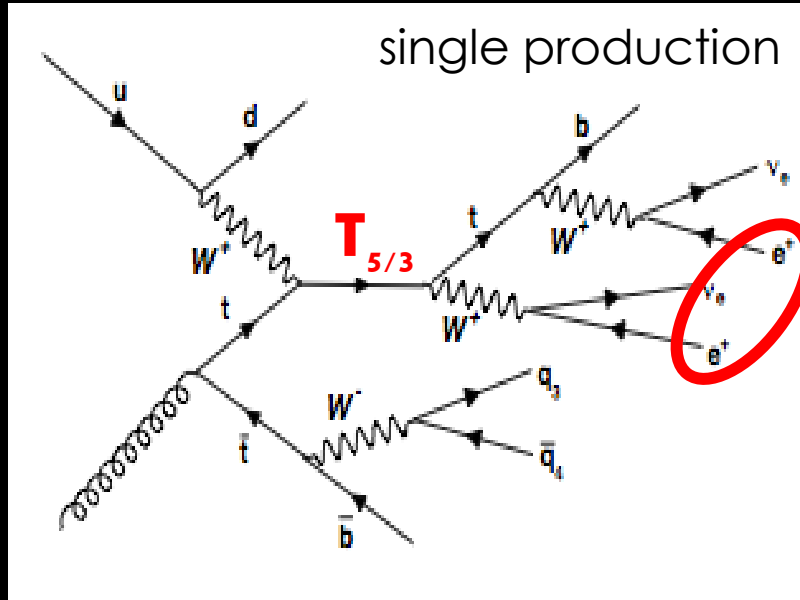
+

$$\sigma(m_C) (\sin\theta_{ct})^2$$

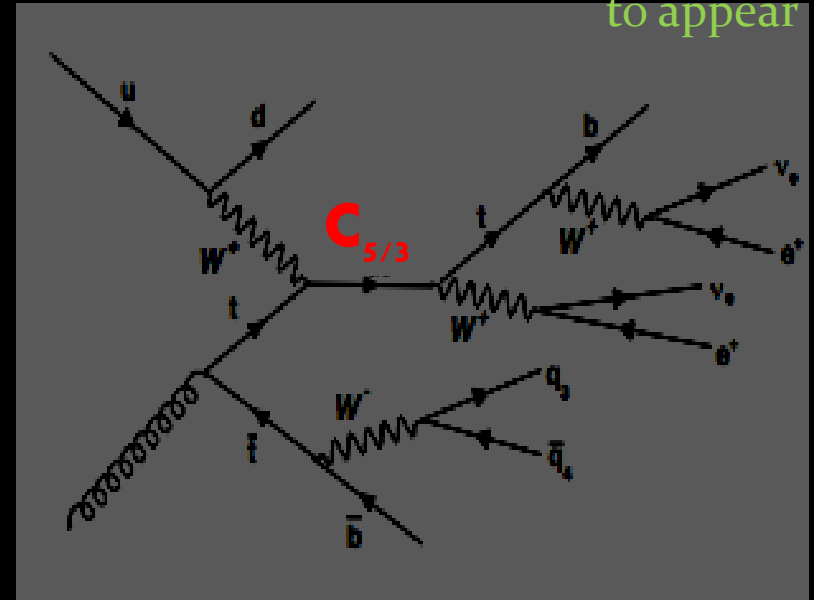
Q: can one bury composite top partners @LHC?

Yes! by mixing (RH) top with composite charm

Blanke-CD-Martin-Perez
to appear



+



$$\sigma = \sigma(m_T) (\cos\theta_{ct})^2 + \sigma(m_C) (\sin\theta_{ct})^2$$

PNGB Higgs potential is controlled by ϵ^2

→ one can slightly decouple $C_{5/3}$ without introducing fine-tuning
since the c/t mixing is in the RH sector!

→ limit on top partners much weaker, $T_{2/3}$ dominated

