Enhanced di-Higgs signals at hadron colliders probe singlet scalar, coupled to colored sector

Kenji Nishiwaki (KIAS)

KOREA INSTITUTE FOR ADVANCED STUDY

based on collaboration with

Koji Nakamura(KEK & CERN), Kin-ya Oda(Osaka Univ.), Seong Chan Park(Yonsei Univ.), Yasuhiro Yamamoto(Yonsei Univ.)

arXiv:1701.06137 [hep-ph]

HPNP2017

1.–5. March 2017

UNIVERSITY OF TOYAMA

Short Talk @ Higgs as a Probe of New Physics,
University of Toyama, Toyama, 2nd Mar. 2017 (Thur.)

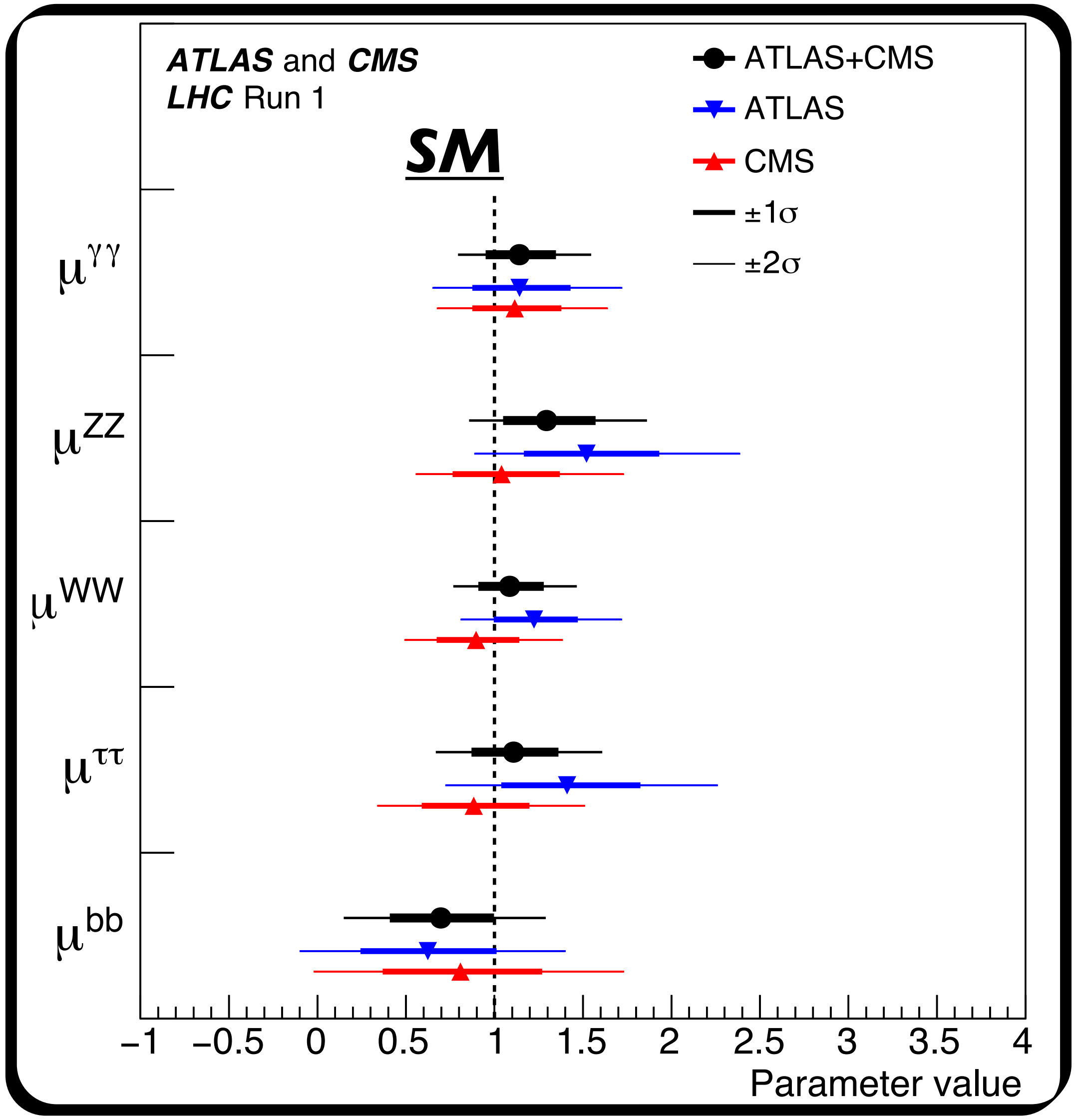
the SM was "confirmed!", BUT...

- **discovery of the SM-like Higgs**

[“5σ confirmation” on 4 July 2012, CERN]

A 125GeV scalar was discovered, which looks SM-like.

[ATLAS+CMS, arXiv:1606.02266]



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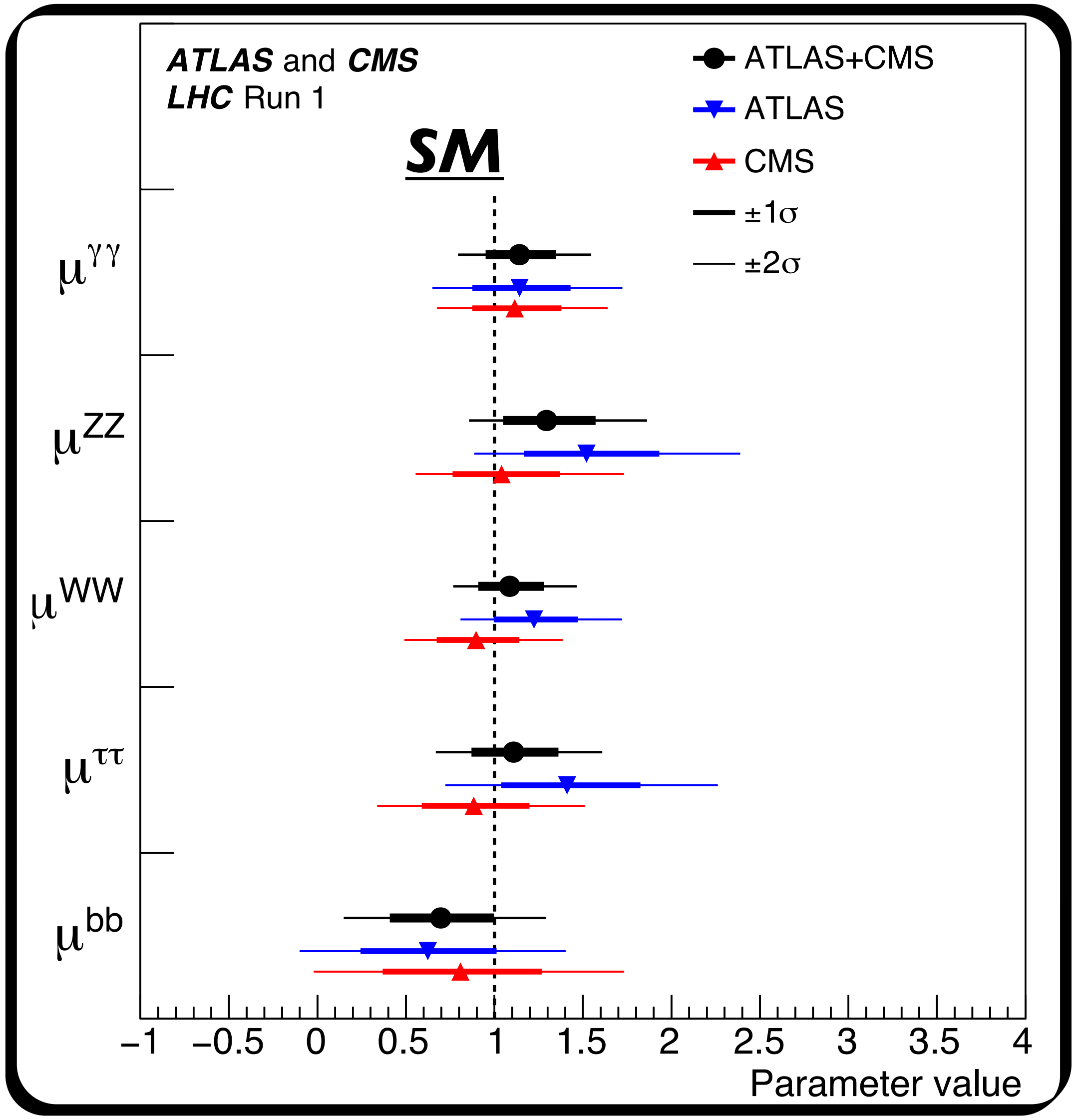

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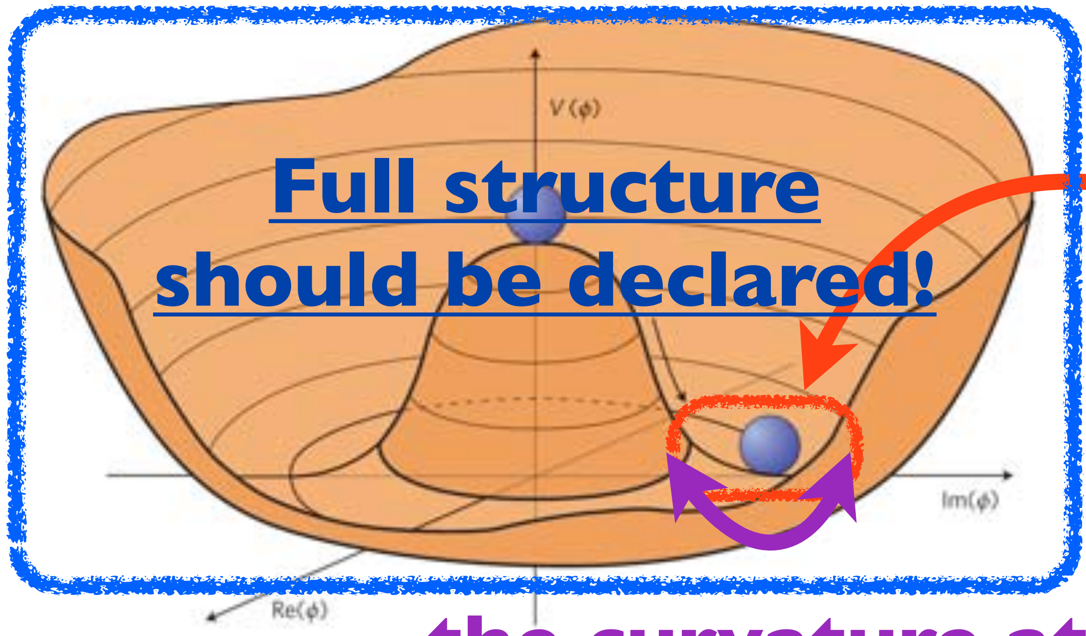
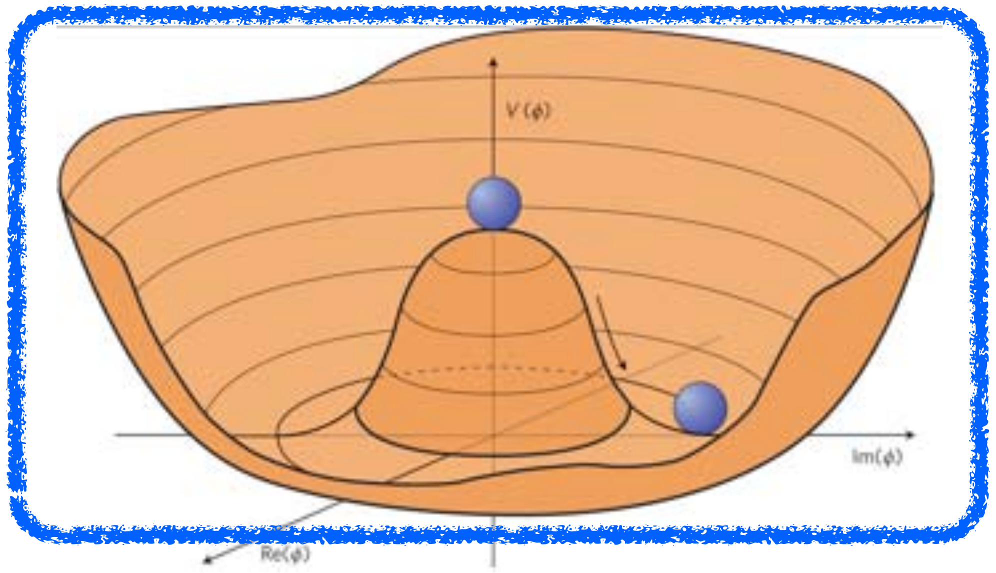


Full structure should be declared!

But, we know only few on Higgs potential yet!

the curvature at the bottom = Higgs mass

di-Higgs production @ LHC



effective couplings **the Higgs**

$$V = c_4 (H^0)^4 + c_3 (H^0)^3 + c_2 (H^0)^2 + \cdots$$

next target **measured**

$$\left(c_3^{\rm SM} = \lambda^{\rm SM} v,\ c_2^{\rm SM} = 2\lambda^{\rm SM} v^2\right) \qquad v = 246\,{\rm GeV} \quad \lambda^{\rm SM} \sim 0.1$$

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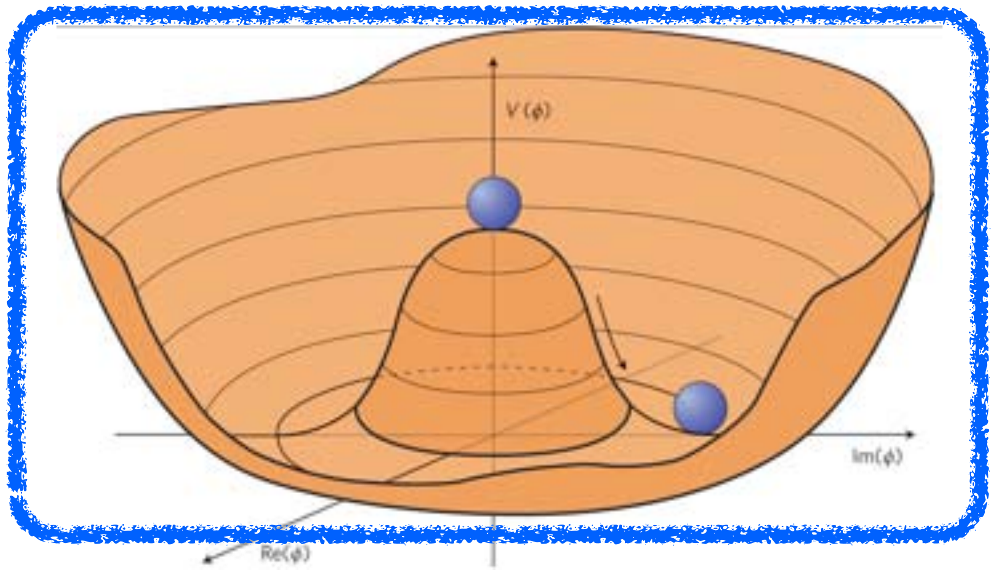

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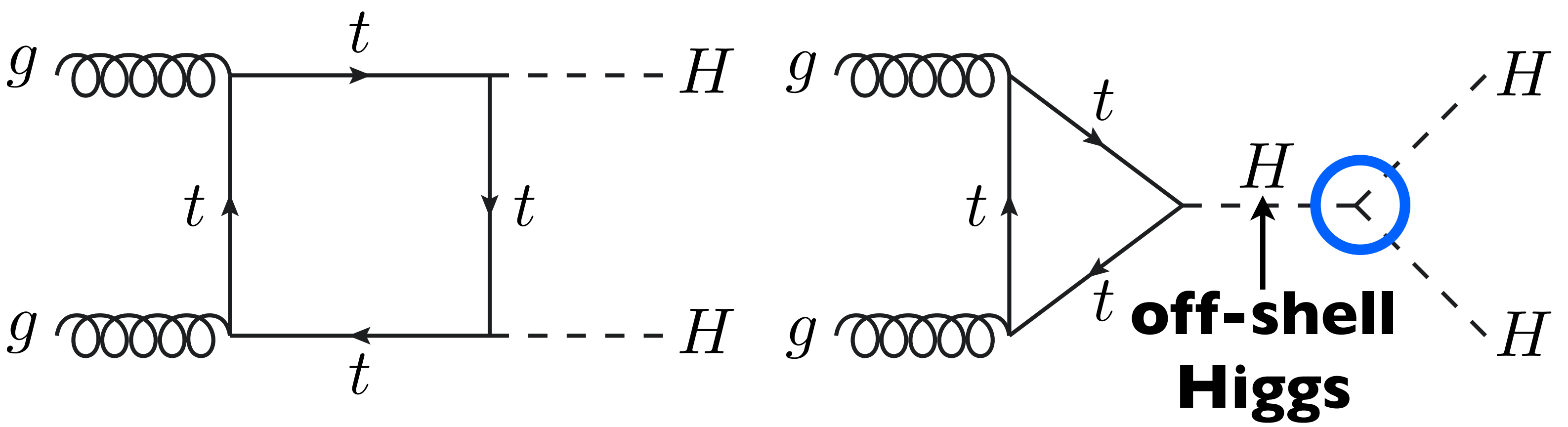
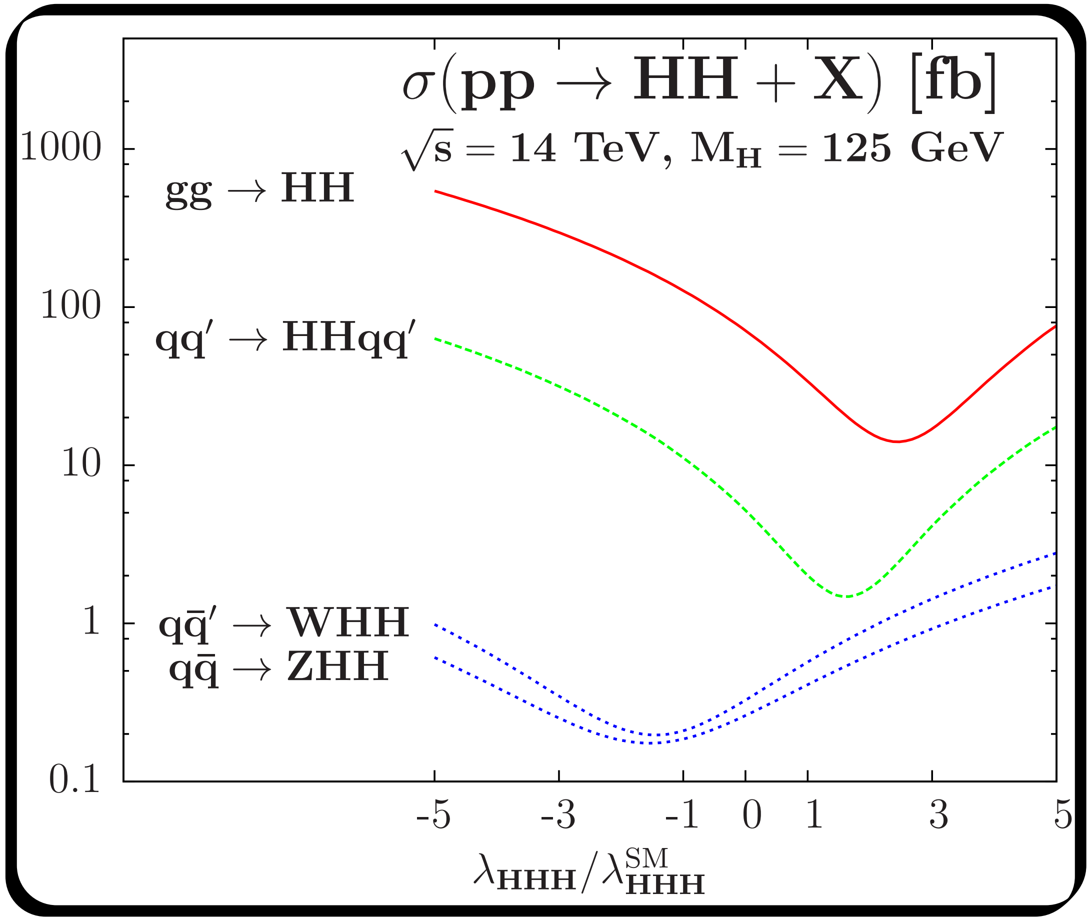
How to address c_3 (in the SM) → di-Higgs production



[Baglio et al., arXiv:1212.5581]

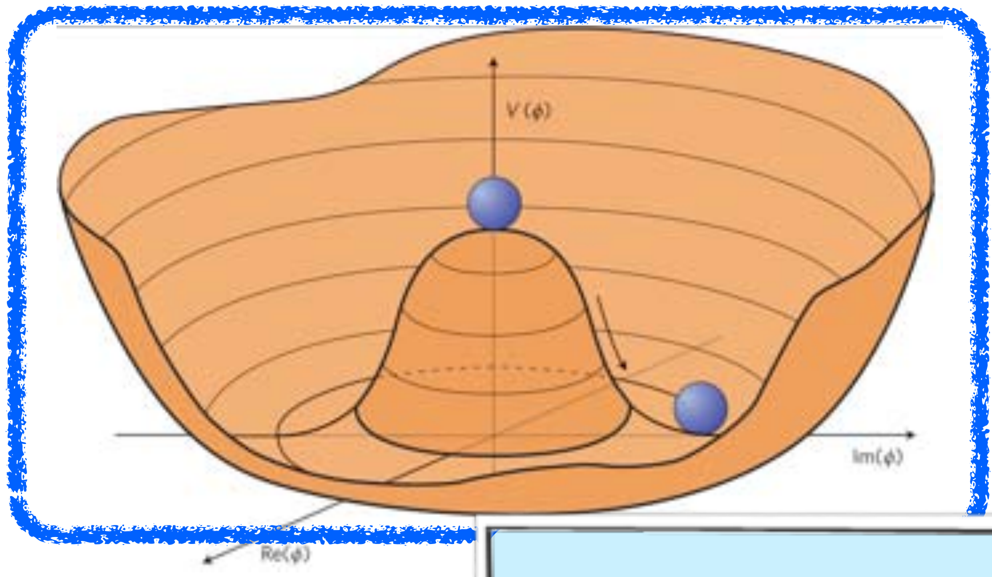


☑ **Cross section is not so large.**

☑ **A featured decay branch is HH→bbγγ**
(Br[HH→bbγγ] ~ 3 * 10^{-3})
← suppressed

Lots of data would be required...

di-Higgs production @ LHC



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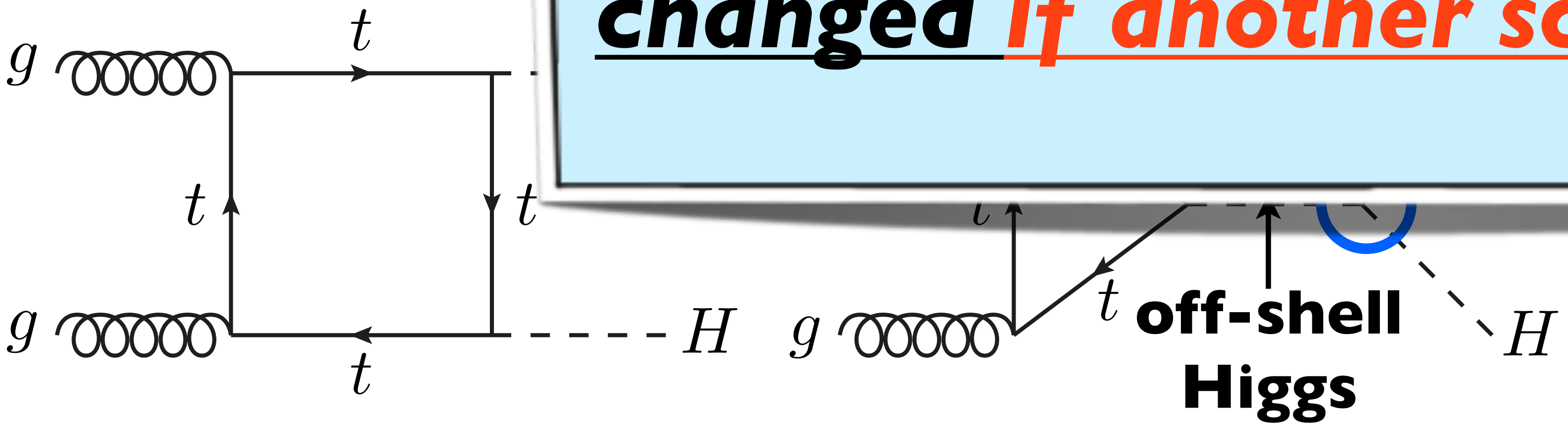
next target **measured**

$v = 246$ G

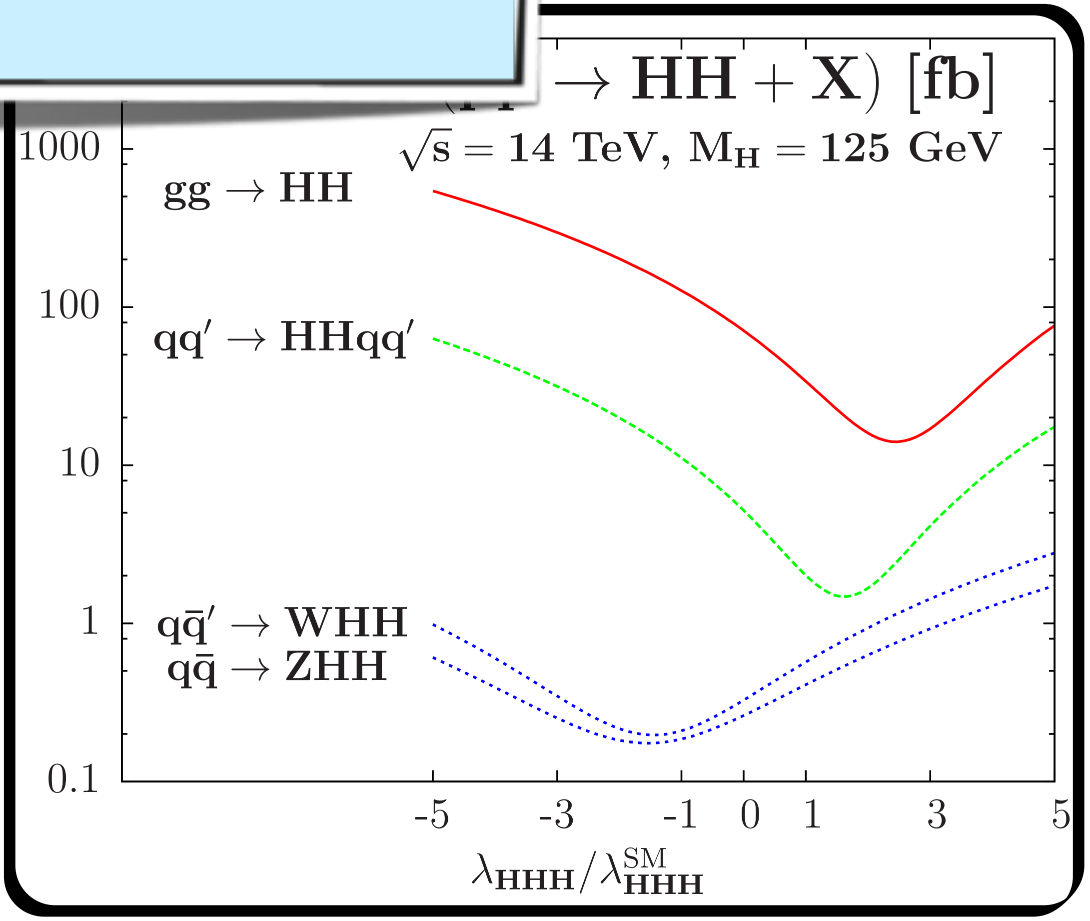
$\lambda^{\rm SM} \sim 0.1$

Situation can be drastically changed if another scalar exists!

How to add



rXiv:1212.5581]



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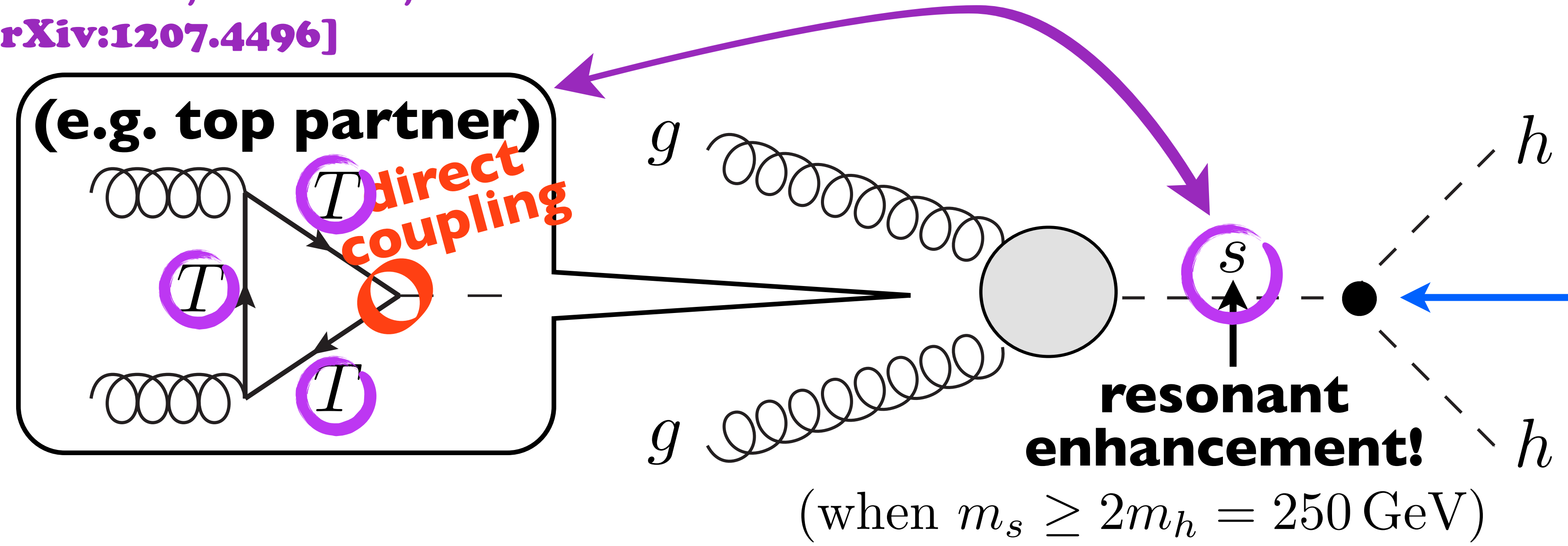
di-Higgs production @ LHC

- **Significant enhancement happens: $SU(2)_L$ singlet s coupling to (new) colored sector**

We consider both of them.

e.g. [G.D.Kribs, A.Martin, arXiv:1207.4496]

e.g. [I.M.Lewis, M Sullivan, arXiv:1701.08774]



information on scalar potential!

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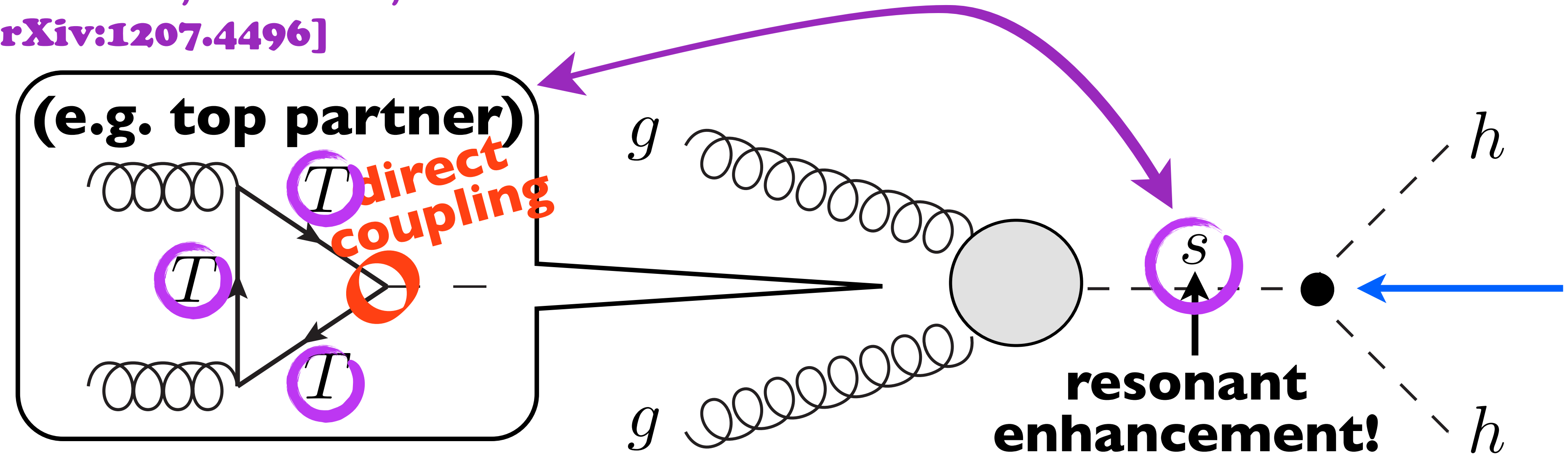


resonant enhancement!

(when $m_s \geq 2m_h = 250\,\text{GeV}$)

information on scalar potential!

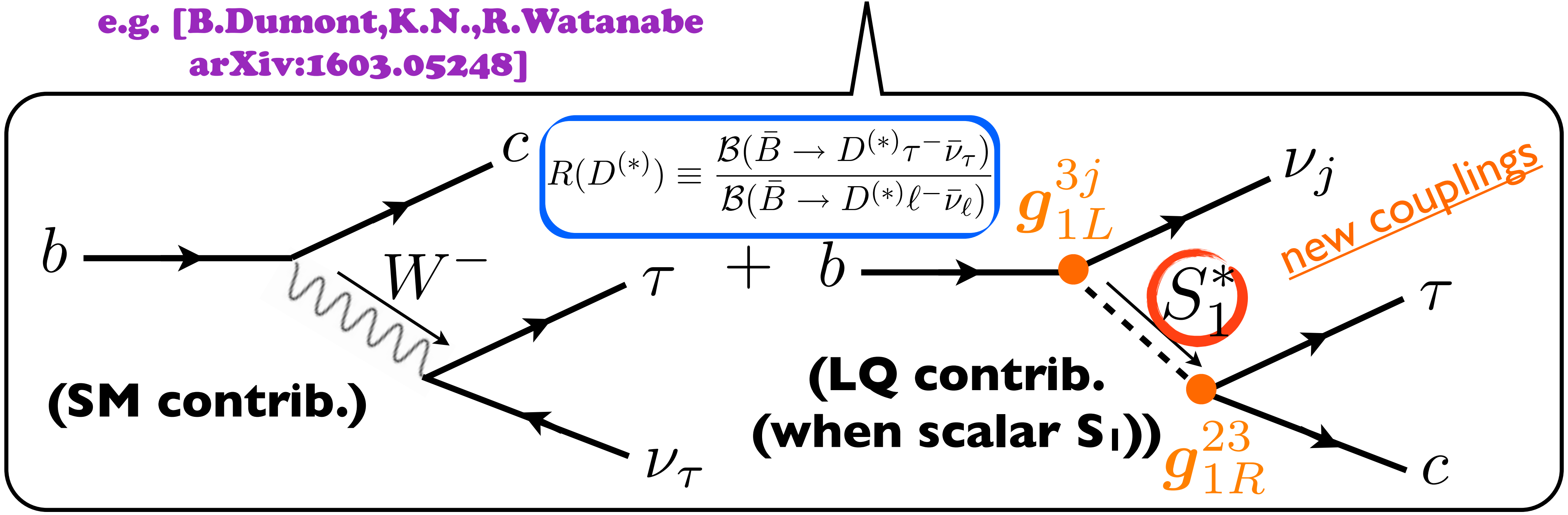
[motivation for new colored particle]

e.g. ☑ **Addressing flavor anomaly (leptoquark)**

e.g. [B.Dumont,K.N.,R.Watanabe arXiv:1603.05248]

[motivation for singlet scalar]

e.g. ☑ **1st order electroweak transition**

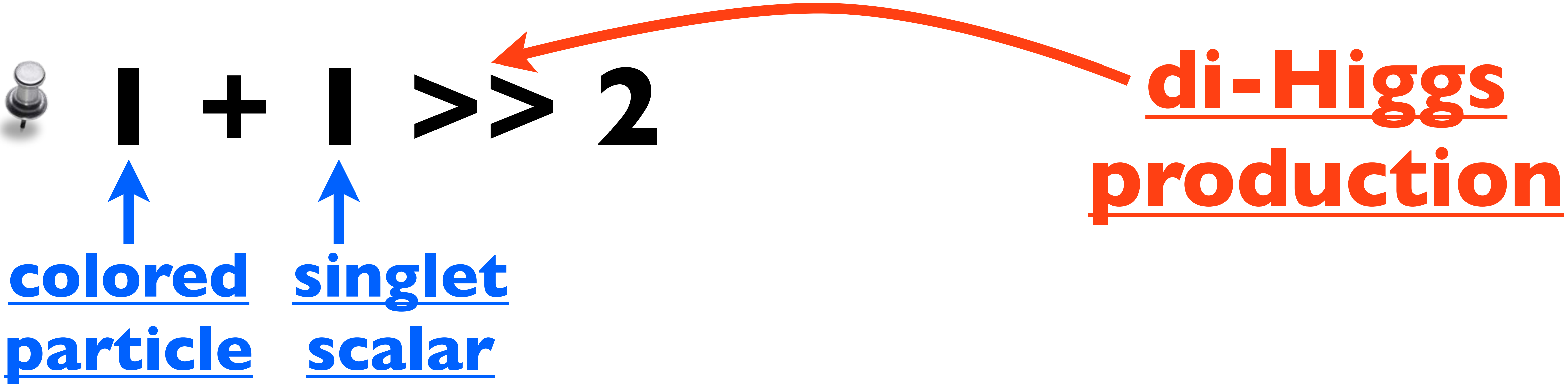


$$R(D^{(*)}) \equiv \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}$$

(SM contrib.)

(LQ contrib. (when scalar S$_1$))

SHORT SUMMARY



- 1 + 1 >> 2

SHORT SUMMARY

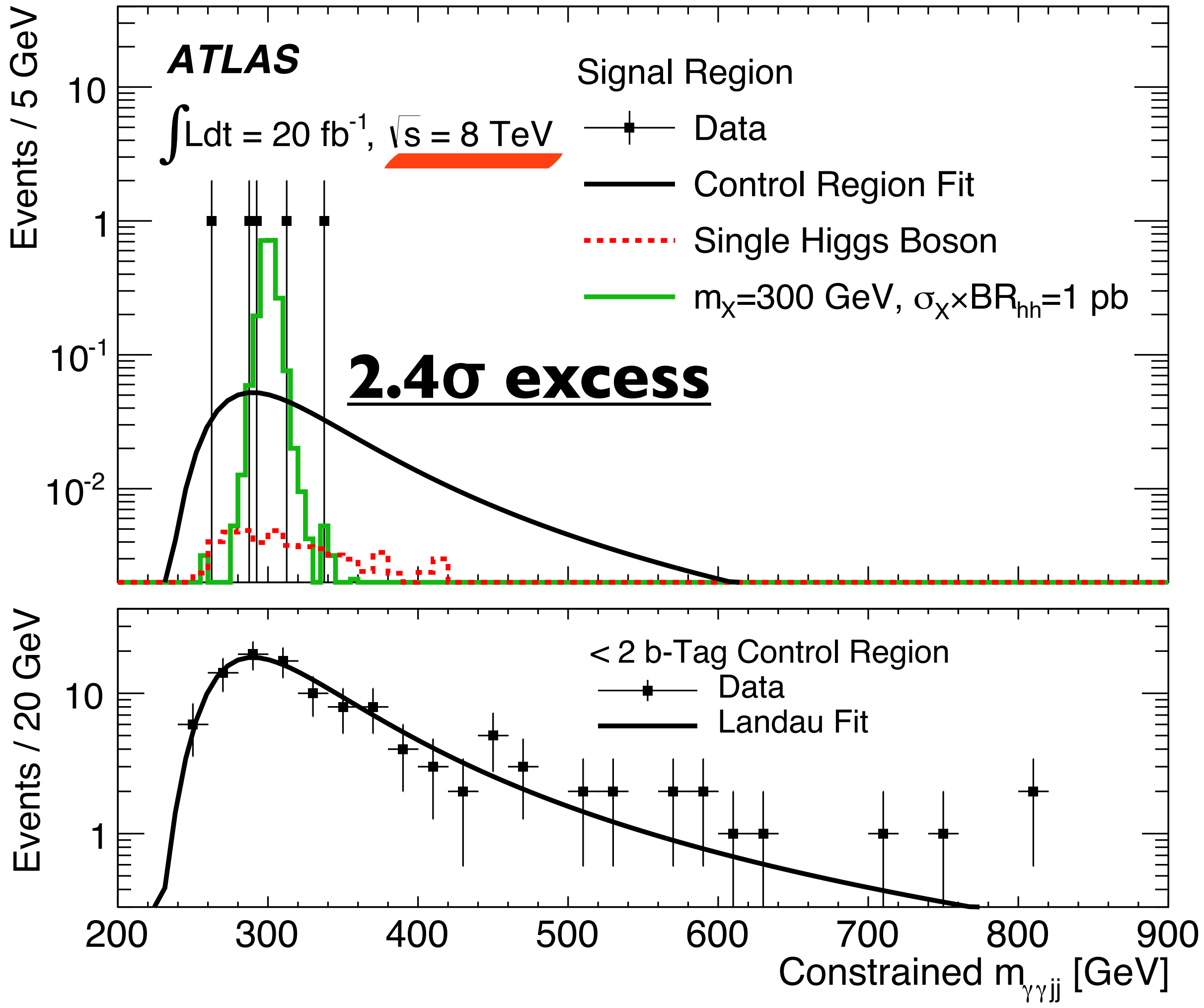
- **1 + 1 >> 2**

colored particle **singlet scalar**

di-Higgs production

A resonant bump was reported in HH→bbγγ (5 events) around 300GeV.

- **A nice benchmark is:** [ATLAS, arXiv:1406.5053]



2.4σ excess

☑ $\sigma_{SM}(pp \to HH)|_{8TeV} = 9.2$fb,

☑ **expected events:**
- non-H BG: 1.3±0.5,
- single-H: 0.17±0.04,
- SM HH: 0.04,

→ 3.5 events would be from NP.

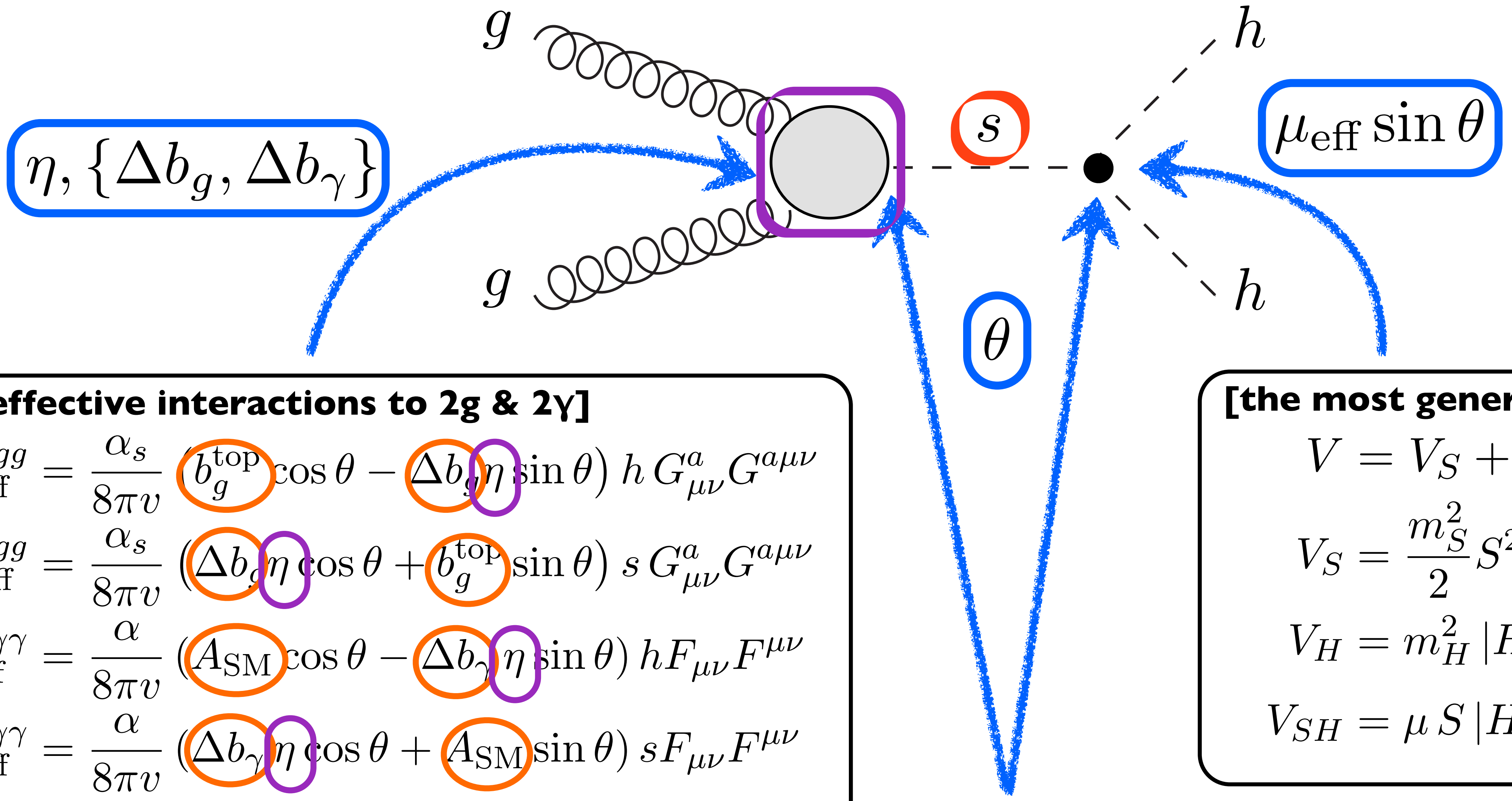
☑ **3.5/0.04 → 87.5-time larger, $\sigma(pp \to HH) = 800$fb.**

☑ **still consistent with other branches**

$$\sigma(pp \to s \to hh)_{8\,\mathrm{TeV}} < \begin{cases} 1.1\,\mathrm{pb} & (b\bar{b}\gamma\gamma \text{ at CMS}), \\ 1.7\,\mathrm{pb} & (b\bar{b}\tau\tau \text{ at ATLAS}), \end{cases}$$

Setup

Setup: SM + real singlet scalar + colored particle(s)



[effective interactions to 2g & 2γ]

$$\mathcal{L}_{\rm eff}^{hgg} = \frac{\alpha_s}{8\pi v}\left(b_g^{\rm top}\cos\theta - \Delta b_g \eta \sin\theta\right) h\, G^a_{\mu\nu} G^{a\mu\nu}$$

$$\mathcal{L}_{\rm eff}^{sgg} = \frac{\alpha_s}{8\pi v}\left(\Delta b_g \eta \cos\theta + b_g^{\rm top}\sin\theta\right) s\, G^a_{\mu\nu} G^{a\mu\nu}$$

$$\mathcal{L}_{\rm eff}^{h\gamma\gamma} = \frac{\alpha}{8\pi v}\left(A_{\rm SM}\cos\theta - \Delta b_\gamma \eta \sin\theta\right) h F_{\mu\nu} F^{\mu\nu}$$

$$\mathcal{L}_{\rm eff}^{s\gamma\gamma} = \frac{\alpha}{8\pi v}\left(\Delta b_\gamma \eta \cos\theta + A_{\rm SM}\sin\theta\right) s F_{\mu\nu} F^{\mu\nu}$$

beta functions (showing loop effects) **factorized coupling to S**

[the most generic potential]

$$V = V_S + V_H + V_{SH}$$

$$V_S = \frac{m_S^2}{2} S^2 + \frac{\mu_S}{3!} S^3 + \frac{\lambda_S}{4!} S^4$$

$$V_H = m_H^2 |H|^2 + \lambda_H |H|^4$$

$$V_{SH} = \mu\, S\, |H|^2 + \frac{\kappa}{2} S^2 |H|^2$$

[Carena et al., arXiv:1206.1082]
[Abe et al., arXiv:1209.4544]

[mixing angle]

246GeV

$$H^0 = \frac{v + h\cos\theta + s\sin\theta}{\sqrt{2}}$$

[SU(2)$_L$ doublet]

$$S = f - h\sin\theta + s\cos\theta$$

[SU(2)$_L$ singlet]

125GeV **≥250GeV**

$$\eta_{\rm LQ} = \kappa_{\rm LQ} N_{\rm LQ} \frac{f v}{M_{\rm LQ}^2} \qquad M_{\rm LQ}^2 = m_{\rm LQ}^2 + \frac{\kappa_{\rm LQ}}{2} f^2$$

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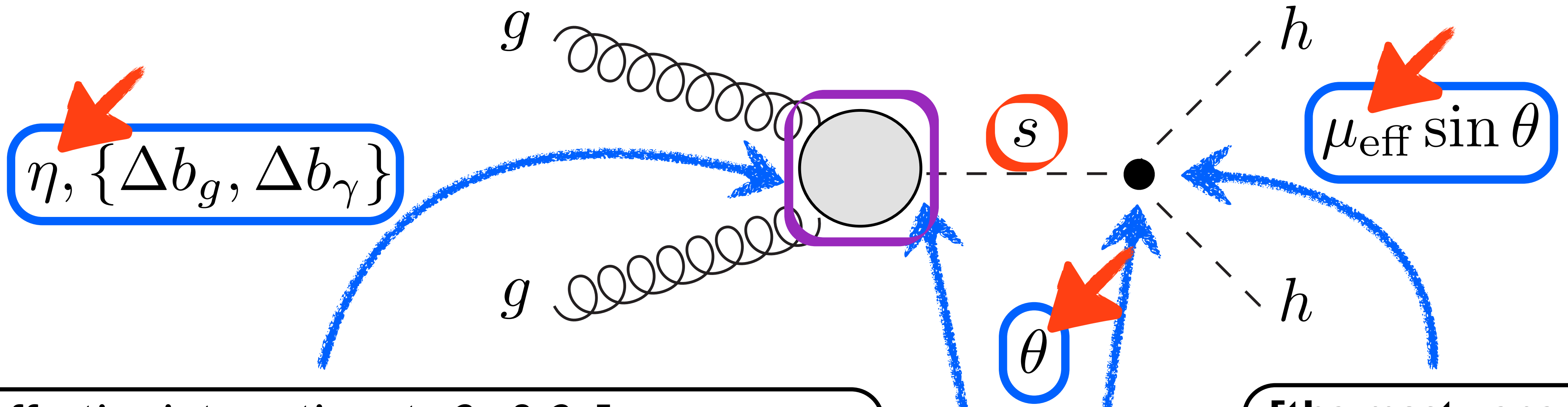

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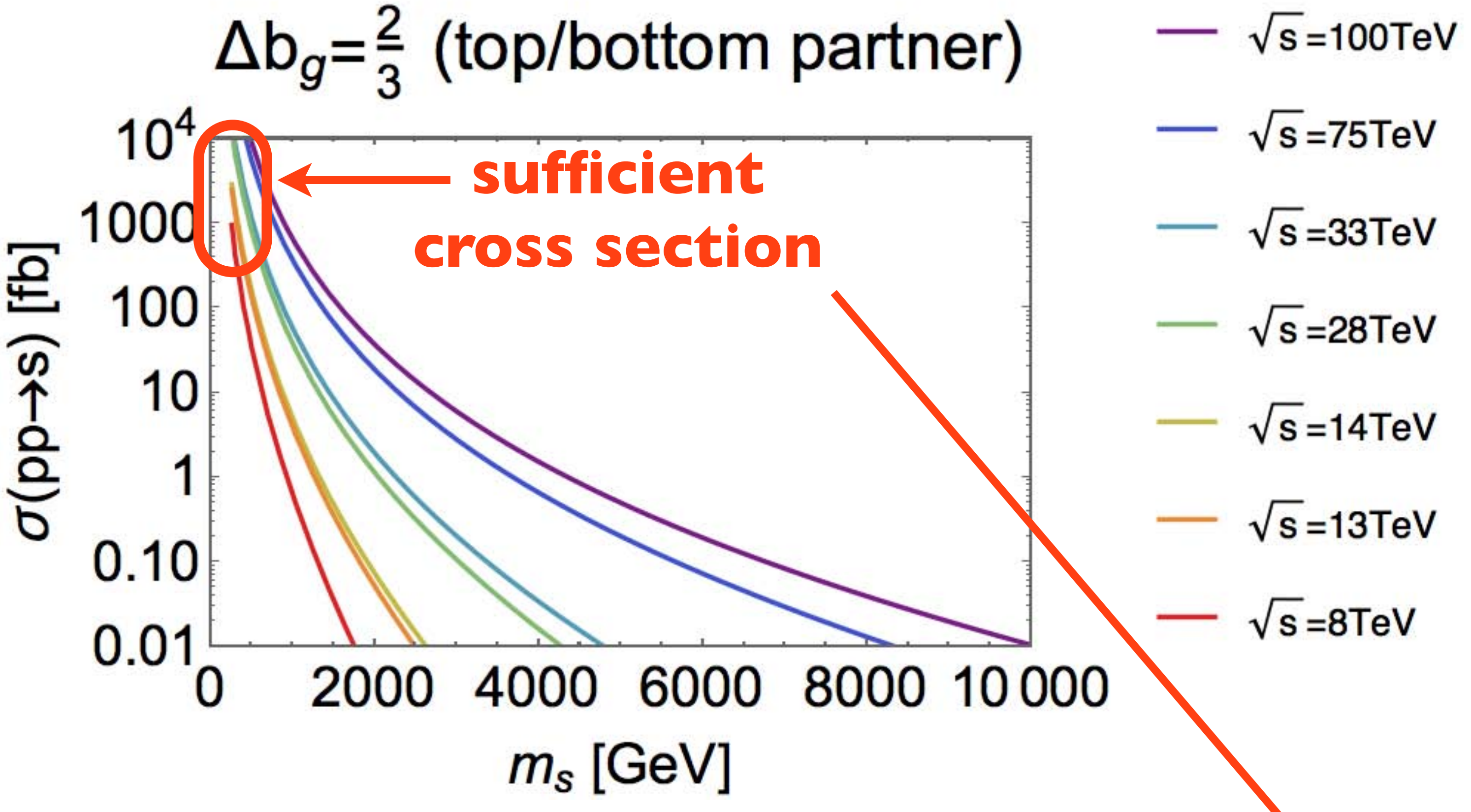
Results

- **huge enhancement:** $|b_g| = \frac{\Delta b_g}{2}\frac{v}{m_s}$,



$$\sigma(pp \to s)_{m_s = 300\,\mathrm{GeV}} \simeq \left[\frac{b_g}{-1/3}\right]^2 \left[\frac{\alpha_s}{0.1}\right]^2 \left[\frac{K}{1.6}\right] \times \begin{cases} \boxed{1.0\,\mathrm{pb}} & (\sqrt{s} = 8\,\mathrm{TeV}), \\ 3.2\ (3.8)\,\mathrm{pb} & (\sqrt{s} = 13\ (14)\,\mathrm{TeV}), \\ 15\ (18)\,\mathrm{pb} & (\sqrt{s} = 28\ (33)\,\mathrm{TeV}), \\ 130\ (83)\,\mathrm{pb} & (\sqrt{s} = 100\ (75)\,\mathrm{TeV}). \end{cases}$$

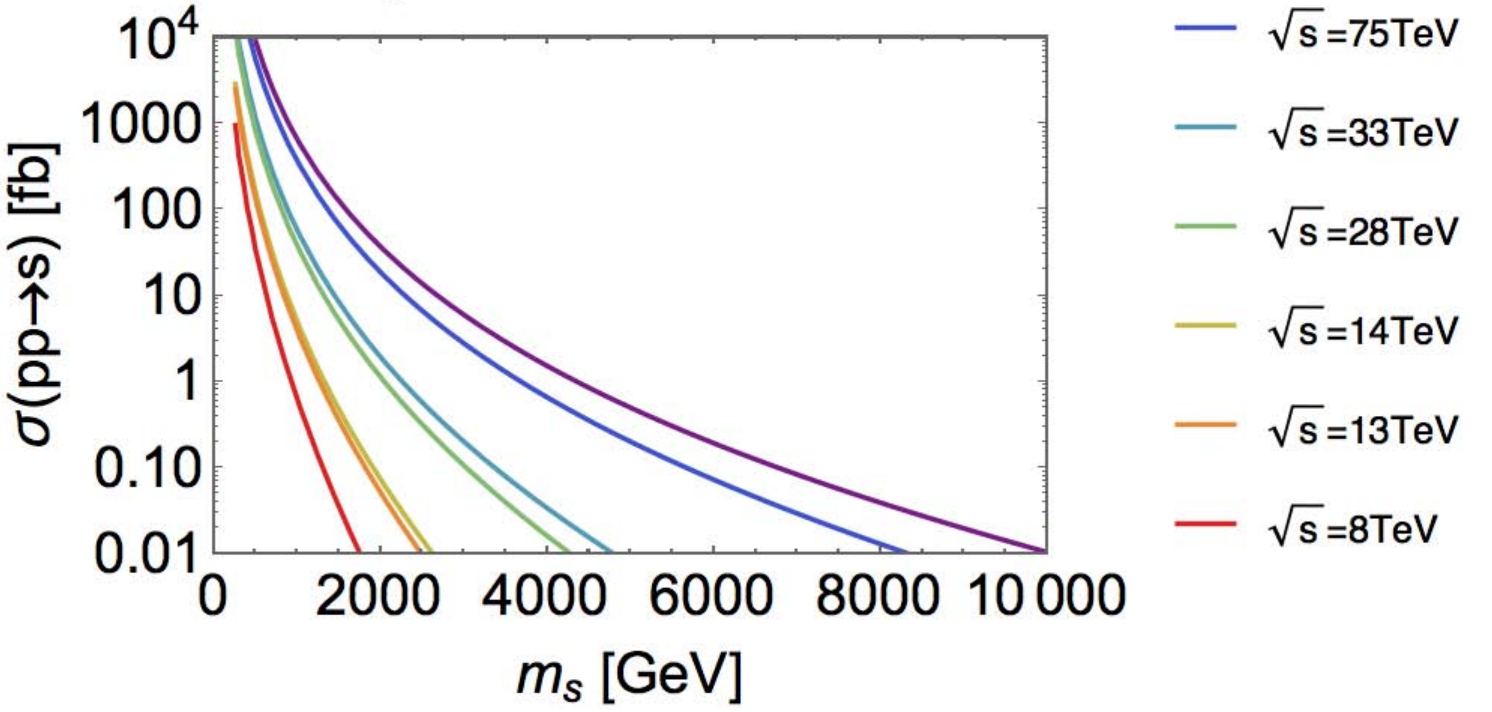
☑ **coupling to gluons scaled as like in vector-like quark for illustration**

$$b_g = -\frac{1}{2}\left(\Delta b_g\,\eta\cos\theta + b_g^{\mathrm{top}}\sin\theta\right) \qquad \eta = y_T N_T \frac{v}{M_T}$$

Results

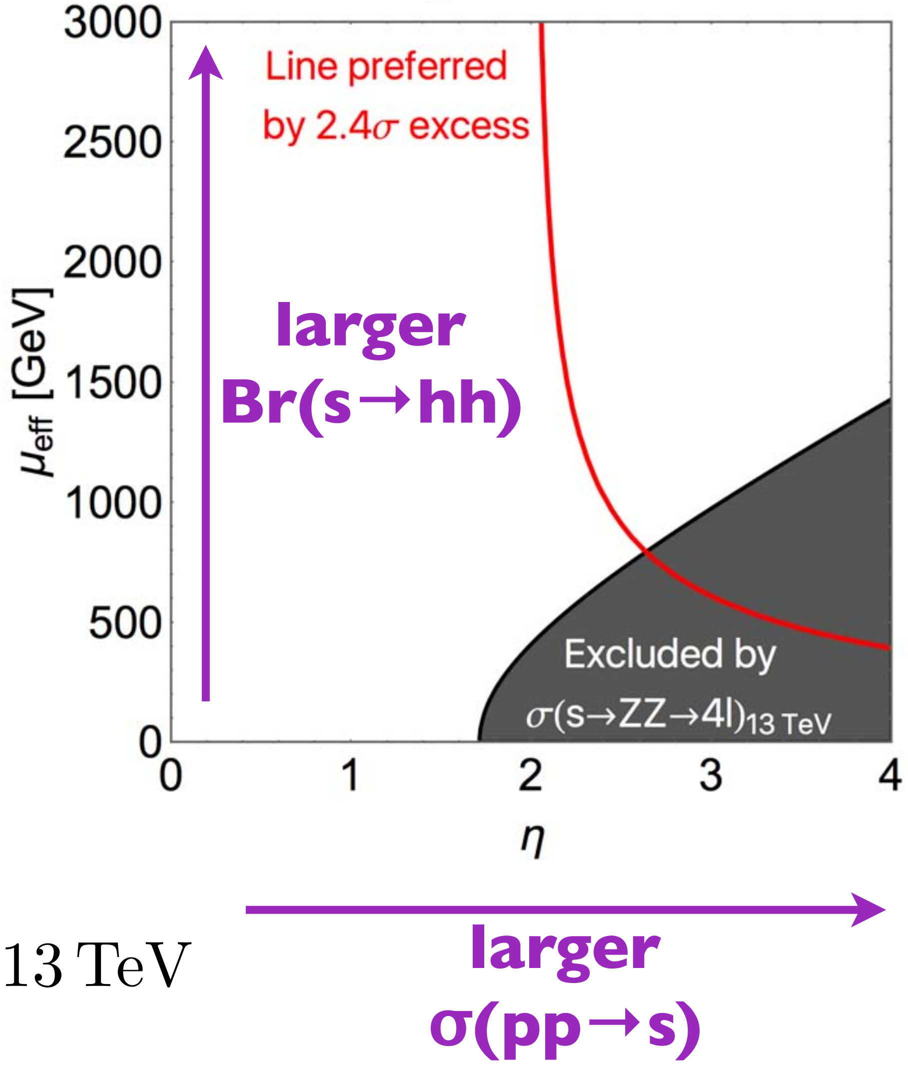
- **huge enhancement:** $|b_g| = \frac{\Delta b_g}{2}\frac{v}{m_s}$,

$\Delta b_g = \frac{2}{3}$ (top/bottom partner)



- **favored μ_{eff} & η**

Leptoquark
m_s=300GeV



☑ $$\eta_{\rm LQ} = \kappa_{\rm LQ} N_{\rm LQ}\frac{fv}{M_{\rm LQ}^2} \xrightarrow[\text{(13TeV LHC bound)}]{} \kappa_{\rm LQ} f N_{\rm LQ} \gtrsim 5 \sim 13\,\mathrm{TeV}$$

$m_{LQ} \leq$ 0.7~1.1TeV
(13TeV LHC bound)

[ATLAS, arXiv:1605.06035]

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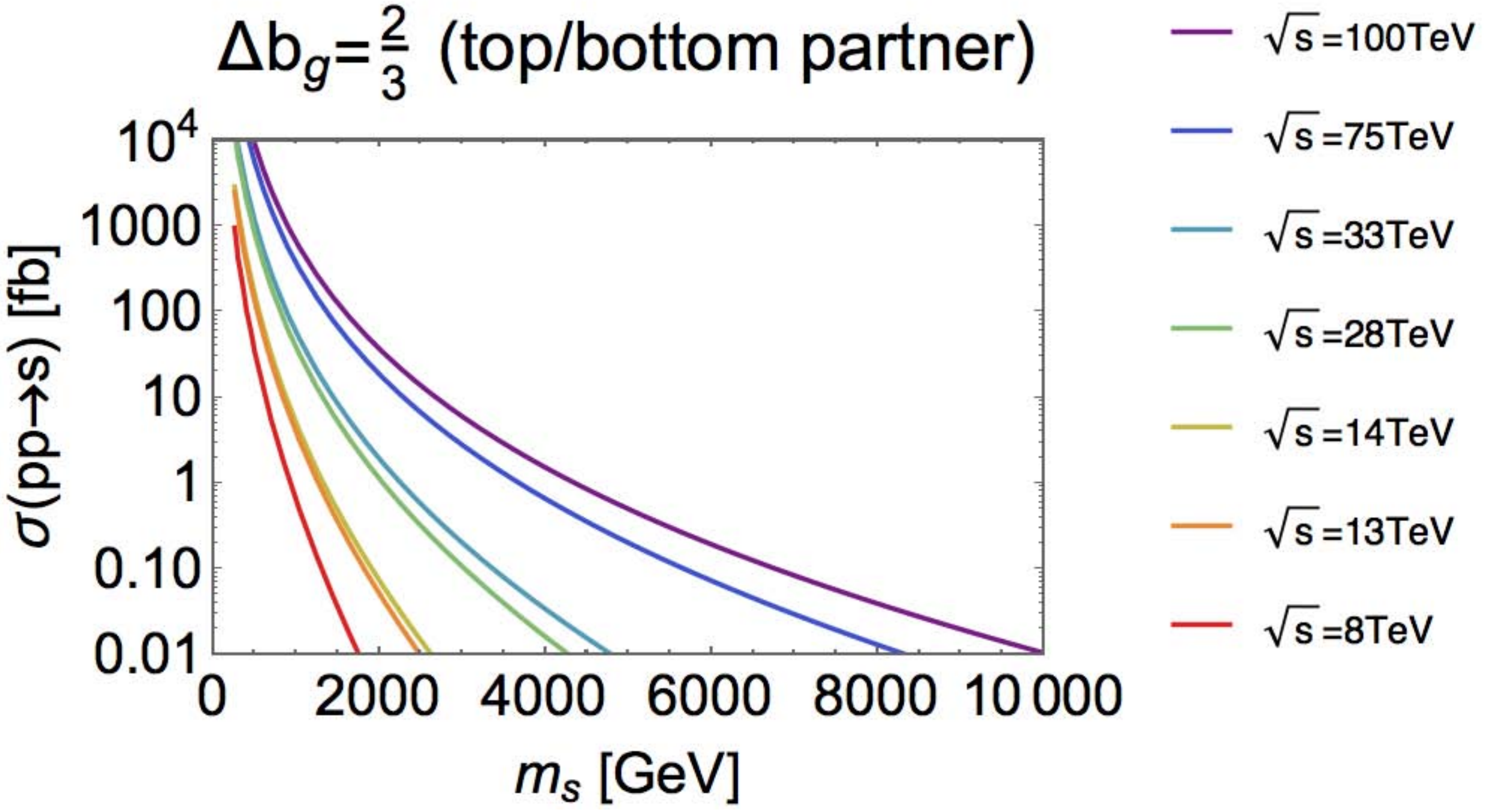

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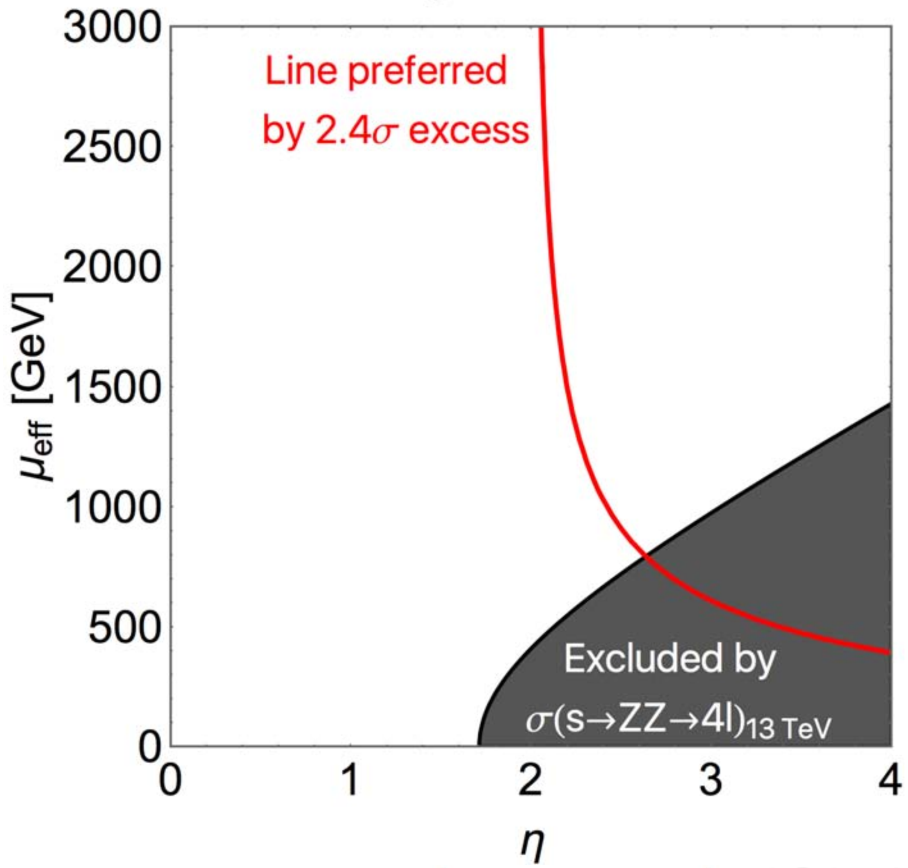


- **consistent with current data**

$$\sigma(pp\to s\to\gamma\gamma)_{13\,\mathrm{TeV}} \sim 7.4\,\mathrm{fb}\left[\frac{b_g}{-1/3}\right]^2\left[\frac{b_\gamma}{-8/9}\right]^2\left[\frac{\alpha_s}{0.1}\right]^2\left[\frac{\alpha}{1/129}\right]^2\left[\frac{\mu_{\rm eff}}{800\,\mathrm{GeV}}\right]^{-2}\left[\frac{\sin\theta}{0.01}\right]^{-2}$$

|sinθ| ≧ 0.01

☑ **pp→s→γγ @ 13TeV LHC**

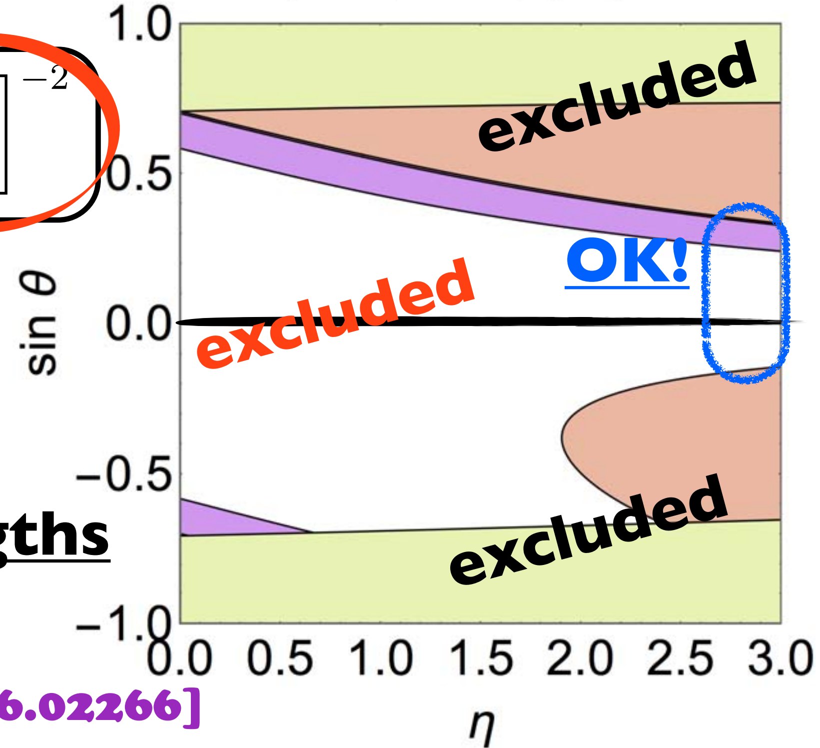
(σ(pp→s→γγ)$_{13\mathrm{TeV}}$ ≲ 10fb)

[ATLAS,ATLAS-CONF-2016-059]

☑ **125GeV Higgs signal strengths**

[ATLAS+CMS, arXiv:1606.02266]

Leptoquark, |Q|=1/3



SUMMARY

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  colored particle ↑ singlet scalar ↑

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  A resonant bump was reported in HH→bbγγ (5 events) around 300GeV.

- A nice benchmark is: [ATLAS, arXiv:1406.5053]

  ☑ 3.5/0.04 → 87.5-time larger, σ(pp→HH) = 800fb.

- Color-boosted resonant one will be seen as a nice probe of the nature of Higgs potential.

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thank you:-)

BACKUP

Setup (Con’d)

- **Possible choices of the colored particle(s) [SU(2)$_L$ singlets, assumed]:**

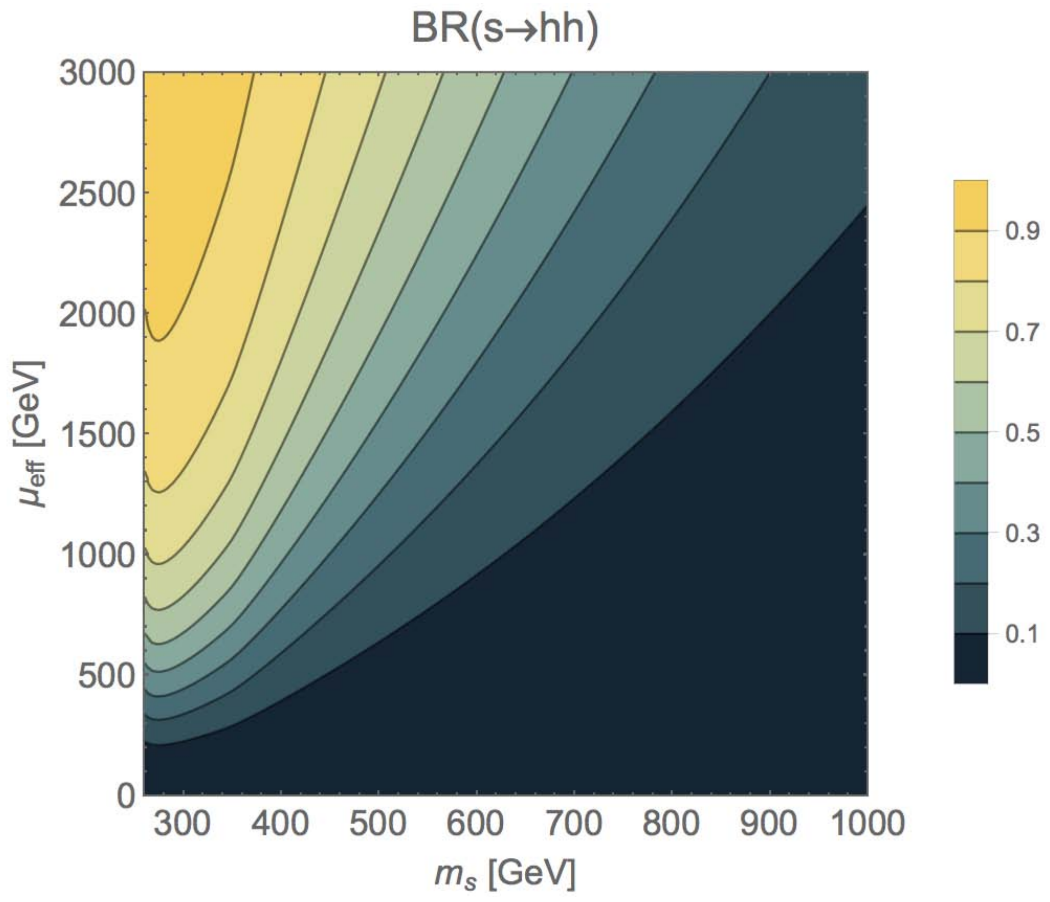
	Dirac spinor		complex scalar			
field	**top partner** T	**bottom partner** B	**leptoquark** $\phi_{\mathbf{3}}$	**diquark** $\phi_{\mathbf{6}}$	**coloron** $\phi_{\mathbf{8}}$	$\ldots$
$SU(3)_C$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{6}$	$\mathbf{8}$	$\ldots$
Y	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{3},\ -\frac{4}{3}$	$\frac{1}{3},\ -\frac{2}{3},\ \frac{4}{3}$	$0,\ -1$	$\ldots$
Δb_g	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{1}{6}$	$\frac{5}{6}$	1	$\ldots$
Δb_γ	$\frac{16}{9}$	$\frac{4}{9}$	$\frac{1}{9},\ \frac{16}{9}$	$\frac{2}{9},\ \frac{8}{9},\ \frac{32}{9}$	$0,\ \frac{8}{3}$	$\ldots$
η	$y_T N_T \frac{v}{M_T}$	$y_B N_B \frac{v}{M_B}$	$\kappa_\phi N_\phi \frac{fv}{M_\phi^2}$			
latest bound	≥ 800 GeV		≥ 0.7-1.1 TeV	≥ 7 TeV	≥ 5.5 TeV	

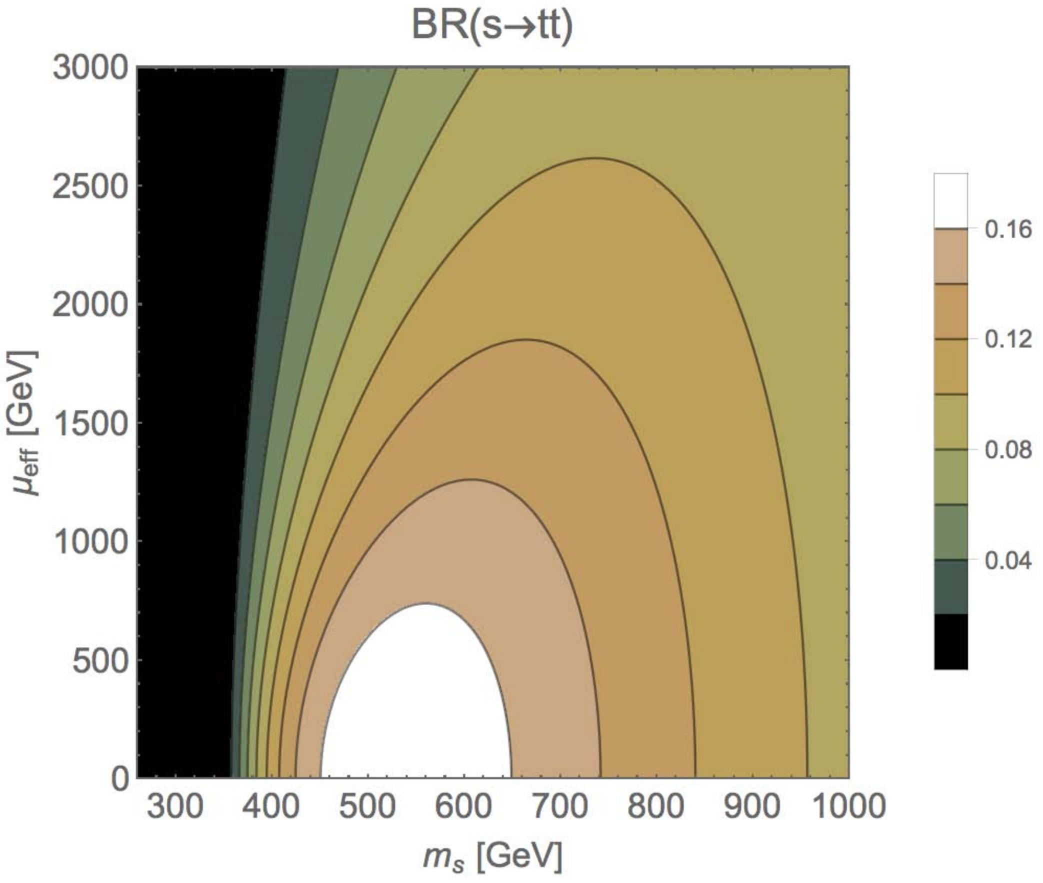
[ATLAS, arXiv:1505.04306]
[ATLAS,ATLAS-CONF-2016-101]

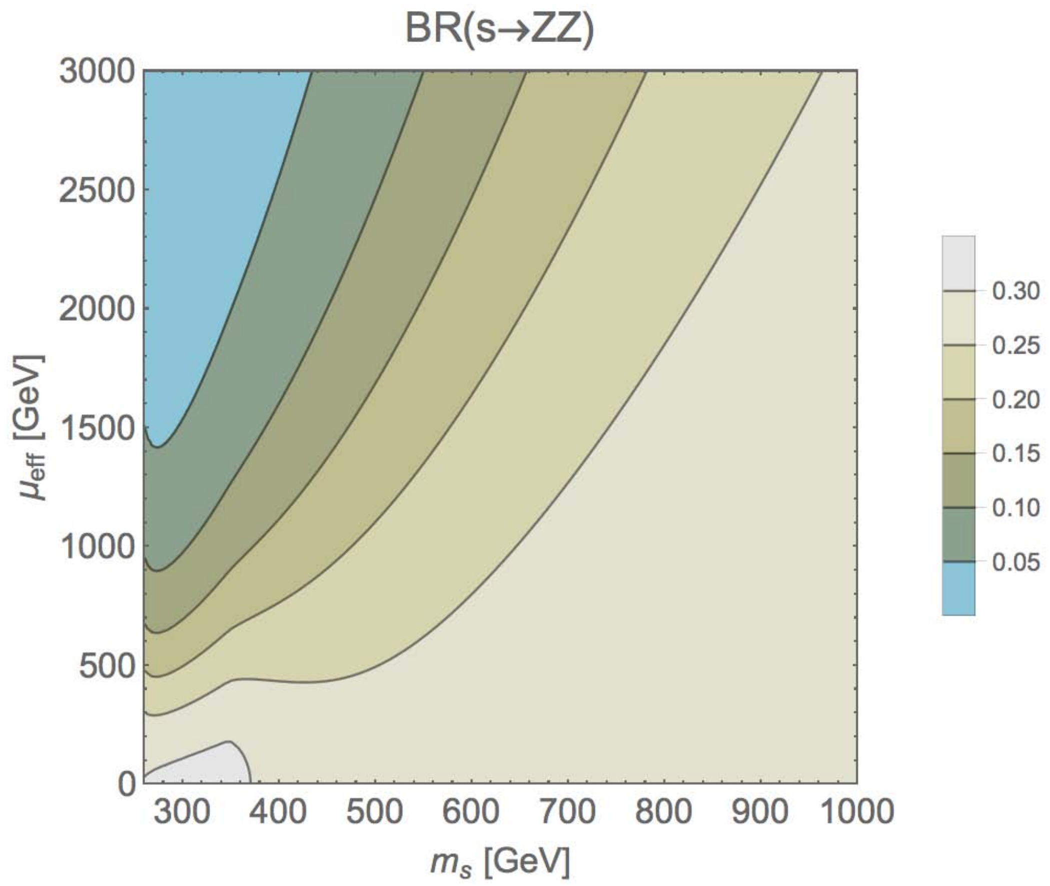
[ATLAS, arXiv:1605.06035]
[CMS, arXiv:1612.01190]
[CMS, arXiv:1611.03568]

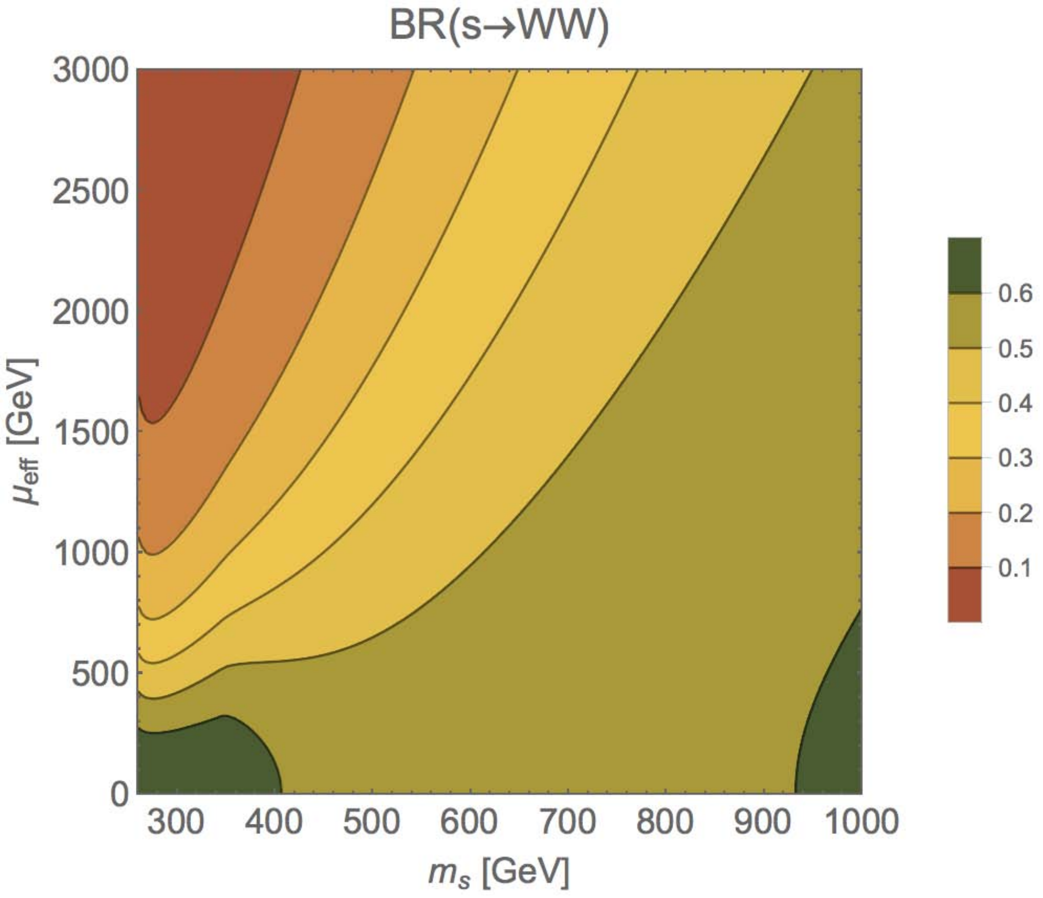
(note: they can decay into a pair of SM particles through mixings or Yukawa-type interactions.)

Branching ratios of s

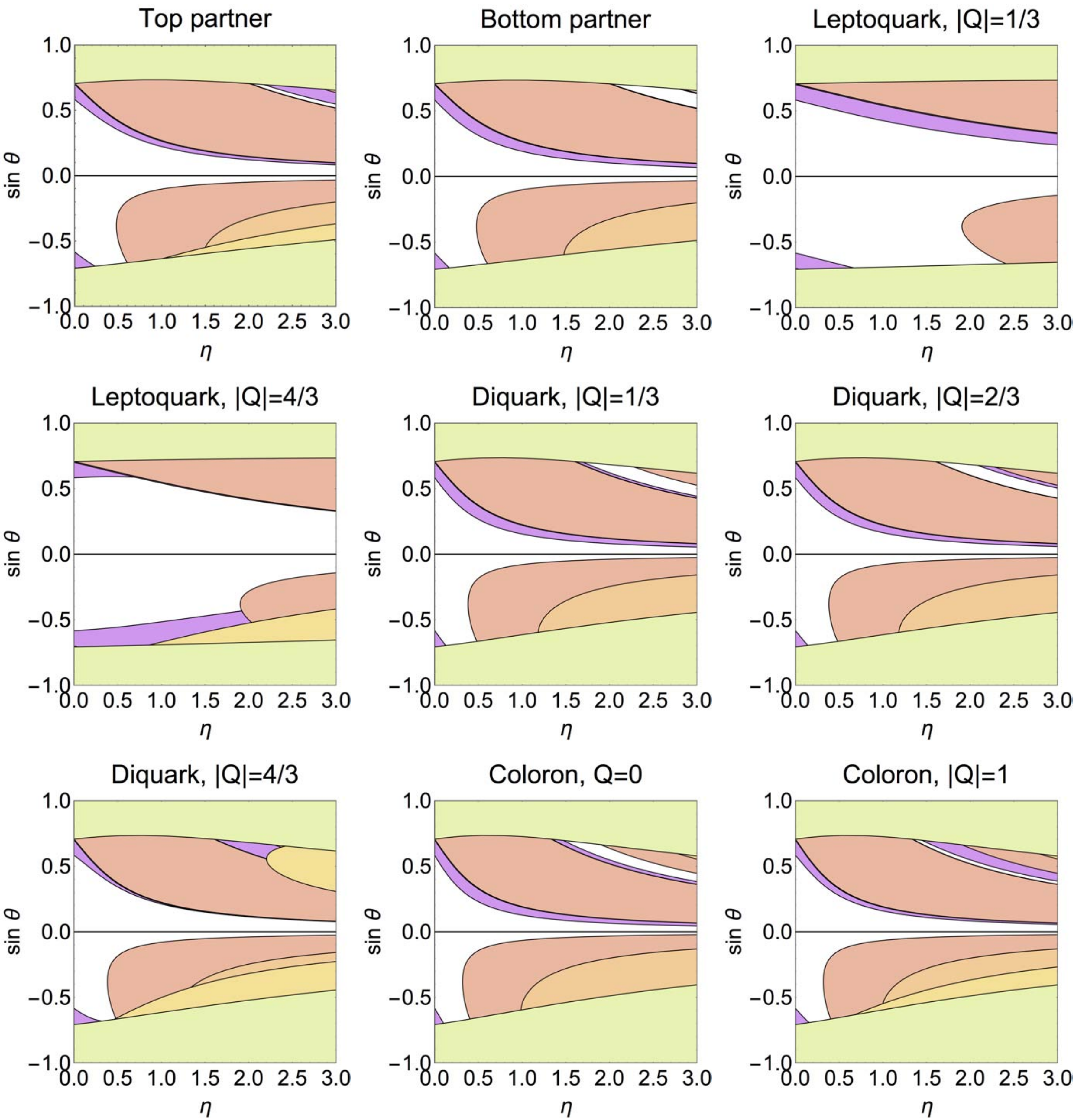

BR(s→hh)

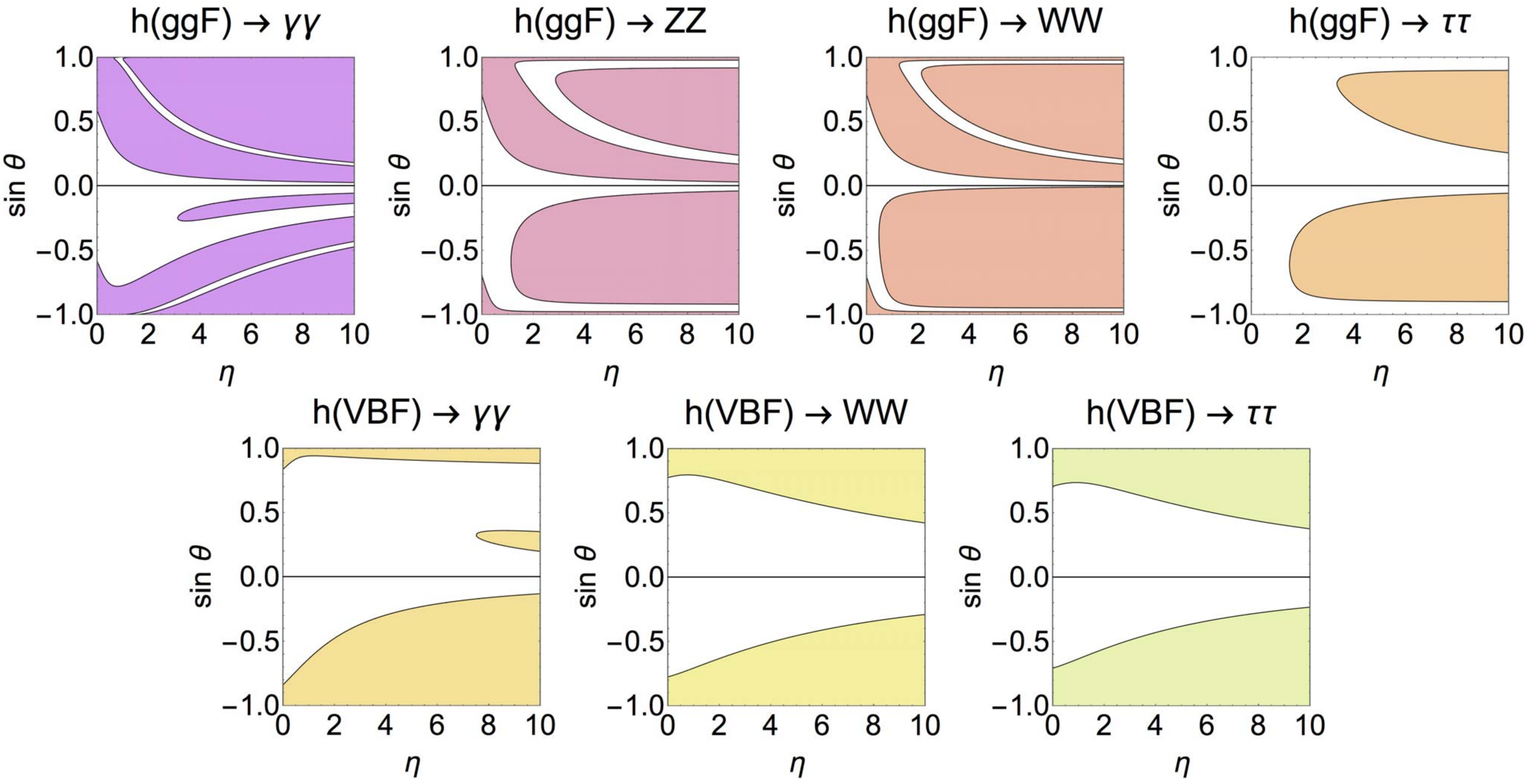

BR(s→tt)


BR(s→ZZ)


BR(s→WW)

Constraints via 125GeV Higgs signal strengths




h(ggF) → γγ
h(ggF) → ZZ
h(ggF) → WW
h(ggF) → ττ
h(VBF) → γγ
h(VBF) → WW
h(VBF) → ττ
sin θ
η
1.0
0.5
0.0
−0.5
−1.0
0
2
4
6
8
10

Yukawa interactions for decay

Φ_3 (leptoquark):

$(\phi_{\mathbf{3}})^* \, \overline{(q_{\rm L})^c} \cdot \ell_{\rm L}$, $(Q_\Phi = -1/3)$

$(\phi_{\mathbf{3}})^* \, \overline{(u_{\rm R})^c} e_{\rm R}$, $(Q_\Phi = -1/3)$

$(\phi_{\mathbf{3}})^* \, \overline{(d_{\rm R})^c} e_{\rm R}$, $(Q_\Phi = -4/3)$

$\epsilon^{abc}\epsilon^{ij} \, (\phi_{\mathbf{3}})_a \, \overline{(q_{\rm L})^c}_{bi} \, (q_{\rm L})_{cj}$, $(Q_\Phi = -1/3)$

$\epsilon^{abc} \, (\phi_{\mathbf{3}})_a \, \overline{(u_{\rm R})^c}_b \, (u_{\rm R})_c$, $(Q_\Phi = -4/3)$

$\epsilon^{abc} \, (\phi_{\mathbf{3}})_a \, \overline{(d_{\rm R})^c}_b \, (d_{\rm R})_c$, $(Q_\Phi = 2/3)$

$\epsilon^{abc} \, (\phi_{\mathbf{3}})_a \, \overline{(u_{\rm R})^c}_b \, (d_{\rm R})_c$, $(Q_\Phi = -1/3)$

Φ_6 (di-quark):

$\overline{(u_{\rm R})^c_a} \, (\phi_{\mathbf{6}})^{*ab} \, (u_{\rm R})_b$, $(Q_\Phi = 4/3)$

$\overline{(d_{\rm R})^c_a} \, (\phi_{\mathbf{6}})^{*ab} \, (u_{\rm R})_b$, $(Q_\Phi = 1/3)$

$\overline{(d_{\rm R})^c_a} \, (\phi_{\mathbf{6}})^{*ab} \, (d_{\rm R})_b$, $(Q_\Phi = -2/3)$

$\epsilon^{ij} \overline{(q_{\rm L})^c_{ai}} \, (\phi_{\mathbf{6}})^{*ab} \, (q_{\rm L})_{bj}$, $(Q_\Phi = 1/3)$

Φ_8 (coloron):

$\frac{1}{\Lambda} \overline{u_{\rm R}}^a \, (\phi_{\mathbf{8}})_a{}^b \, (q_{\rm L})_{bi} \, \epsilon^{ij} H_j$, $(Q_\Phi = 0)$

$\frac{1}{\Lambda} \overline{u_{\rm R}}^a \, (\phi_{\mathbf{8}})_a{}^b \, (q_{\rm L})_{bi} \, (H^*)^i$, $(Q_\Phi = -1)$

$\frac{1}{\Lambda} \overline{d_{\rm R}}^a \, (\phi_{\mathbf{8}})_a{}^b \, (q_{\rm L})_{bi} \, \epsilon^{ij} H_j$, $(Q_\Phi = -1)$

$\frac{1}{\Lambda} \overline{d_{\rm R}}^a \, (\phi_{\mathbf{8}})_a{}^b \, (q_{\rm L})_{bi} \, (H^*)^i$, $(Q_\Phi = 0)$