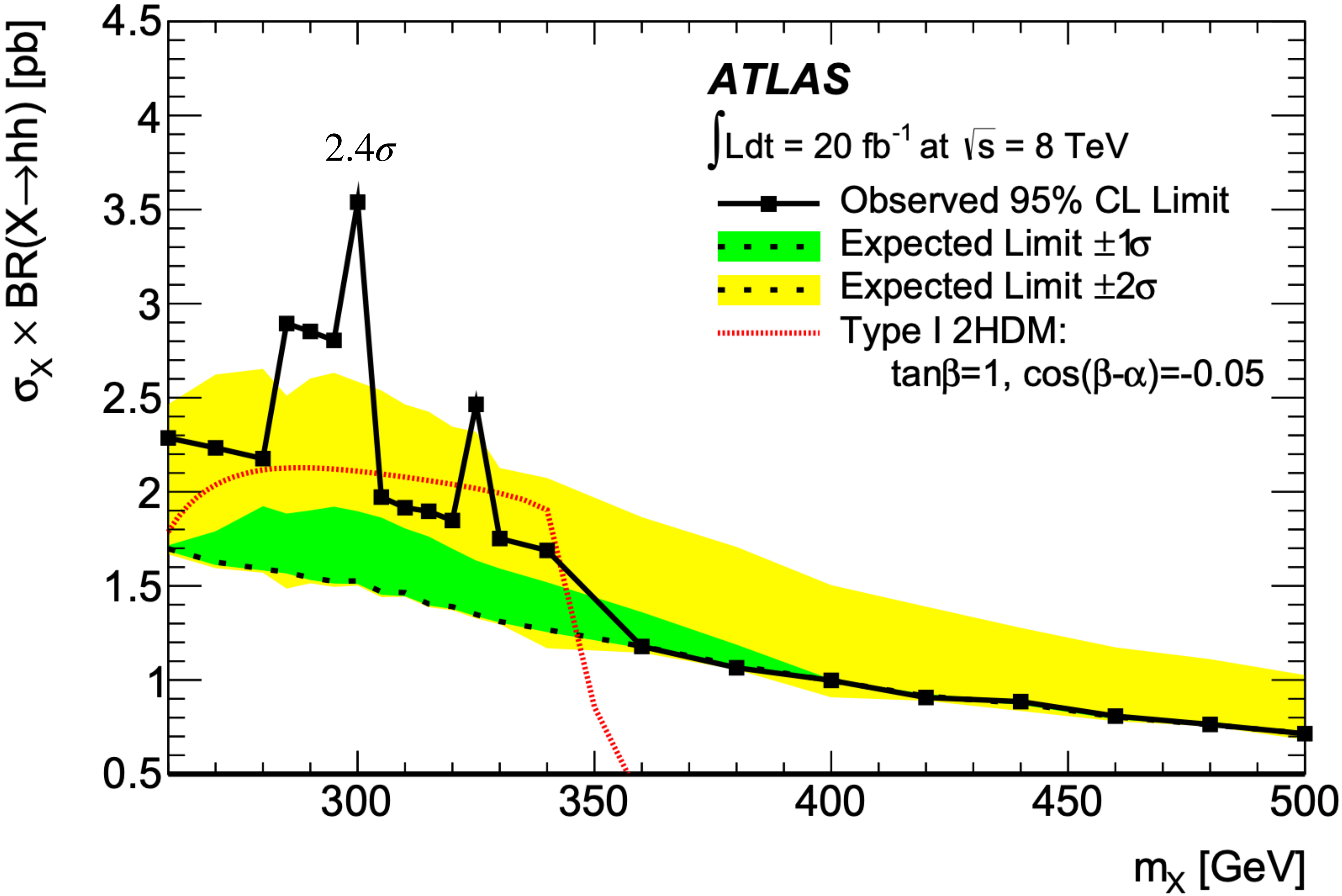
Enhancing Di-Higgs signal by new resonance

SEONG CHAN PARK (YONSEI)

Di-Higgs day

Konkuk University, June 27, 2019

ATLAS, Phys. Rev. Lett. 114, 081802 (2015), $bb\gamma\gamma$



- Koji Nakamura (KEK, ATLAS), Kenji Nishiwaki, Kin-ya Oda, SCP, Yasuhiro Yamamoto, 1701.06137 (EPJC 2017).

- Kayoung Ban, Won-Sang Cho, SCP in $bb\tau\tau$ (to appear soon)

Di-Higgs as a Motif

THE ‘SM’ Higgs:

$$H(1,2)_{Y=1/2}$$

$$H = \begin{pmatrix} \phi^+ \\ (h + v + i\phi^0)/\sqrt{2} \end{pmatrix}$$

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$$\phi^+ \sim W_L^+, \phi^0 \sim Z_L^0$$

Goldstone equivalence

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$$H(1,2)_{Y=1/2}$$

$$v = \frac{1}{\sqrt{\sqrt{2}G_F}} = \frac{2m_W}{g} = 246.22\ \mathrm{GeV}$$

Known since 1970s

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Goldstone equivalence

$h:$ **Physical 'Higgs' boson**

Di-Higgs as a Motif

$$V(H) = \lambda \left(H^\dagger H - \frac{v^2}{2} \right)^2$$

V.E.V.

$$\langle H \rangle = \frac{v}{\sqrt{2}}$$

$$= \lambda (H^\dagger H)^2 - \lambda v^2 H^\dagger H + \lambda v^4/4$$

quartic

quadratic
:tachyonic
==> unstable

c.c.?

Di-Higgs as a Motif

$$V(H) = \lambda \left(H^\dagger H - \frac{v^2}{2} \right)^2$$

Unitary gauge

$$H = \begin{pmatrix} 0 \\ (h+v)/\sqrt{2} \end{pmatrix}$$

$$= \frac{\lambda}{4} h^4 + \lambda v h^3 + \lambda h^2 v^2$$ **+no c.c.**

$$= \frac{1}{2} m_h^2 \longrightarrow \lambda = \frac{m_h^2}{2v^2} \approx \frac{1}{8}$$

LHC 2012

$$\equiv \frac{\lambda_4}{4!} h^4 + \frac{\lambda_3}{3!} h^3 + \cdots$$

quartic **cubic**

$$\lambda_3 \equiv 3!\lambda v = 3m_h^2/v$$

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Di-Higgs as a Motif

$$\lambda_{hhhh}^{\rm SM} \equiv \lambda_4 = 6\lambda = 3m_h^2/v^2$$

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==> These 'self interactions' are PREDICTIONS of the SM

==> ,which never have got tested so far

Di-Higgs as a Motif

$\lambda_{hhhh}^{\text{SM}} \equiv \lambda_4 = 6\lambda = 3m_h^2/v^2$

m_h^2

c.c.

“Higgs potential”

$$V(h) = V(0) + V'(0)h + \frac{V''(0)}{2}h^2 + \frac{V'''(0)}{3!}h^3 + \frac{V''''(0)}{4!}h^4 + \cdots$$

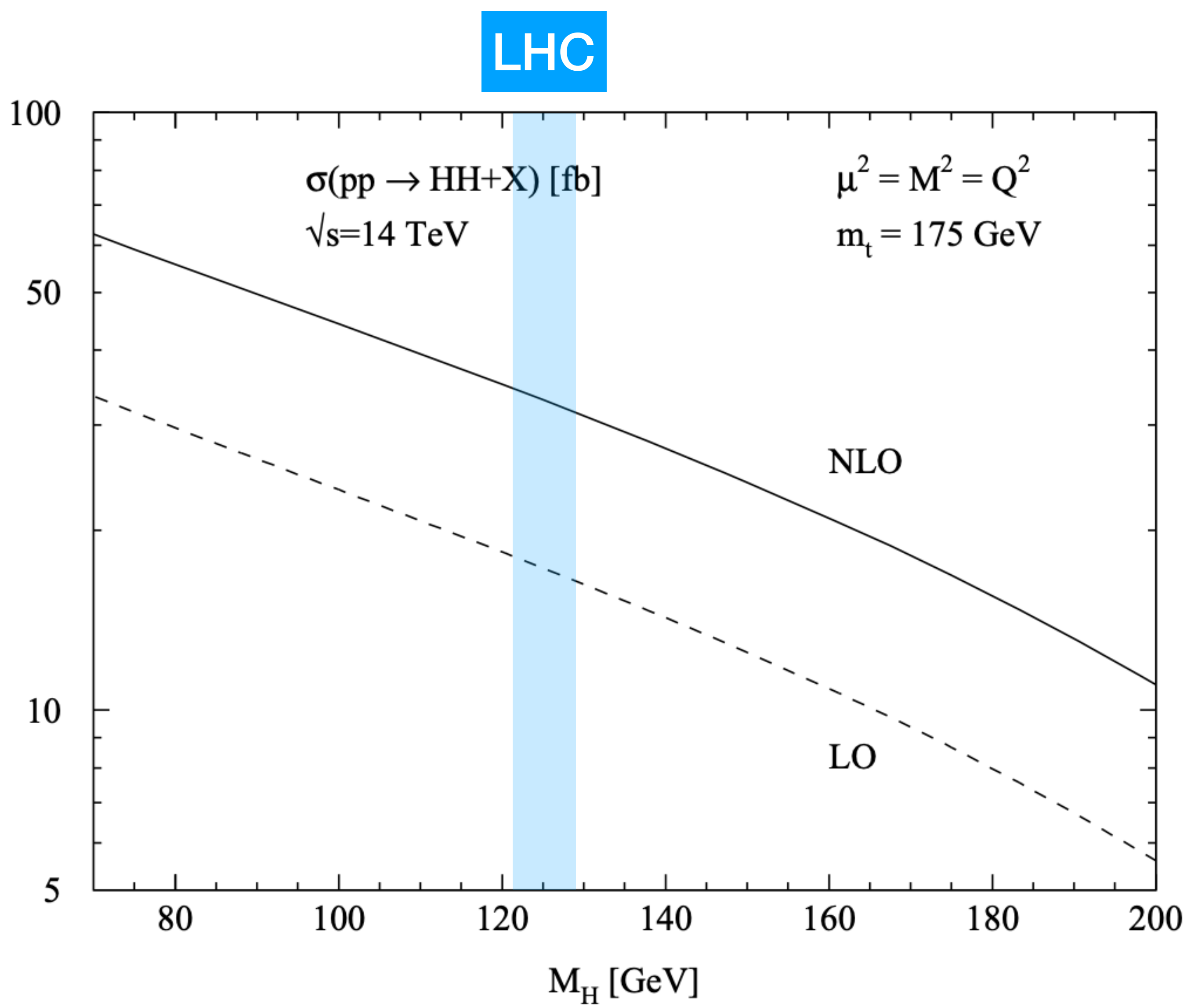
=0

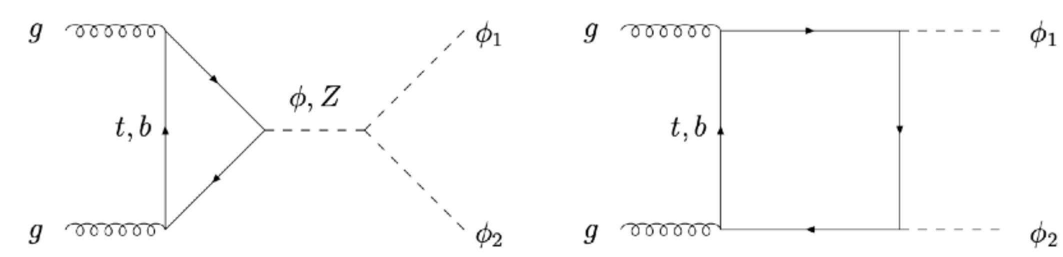
$\lambda_{hhh}^{\text{SM}} \equiv \lambda_3 = 6\lambda v = 3m_h^2/v$

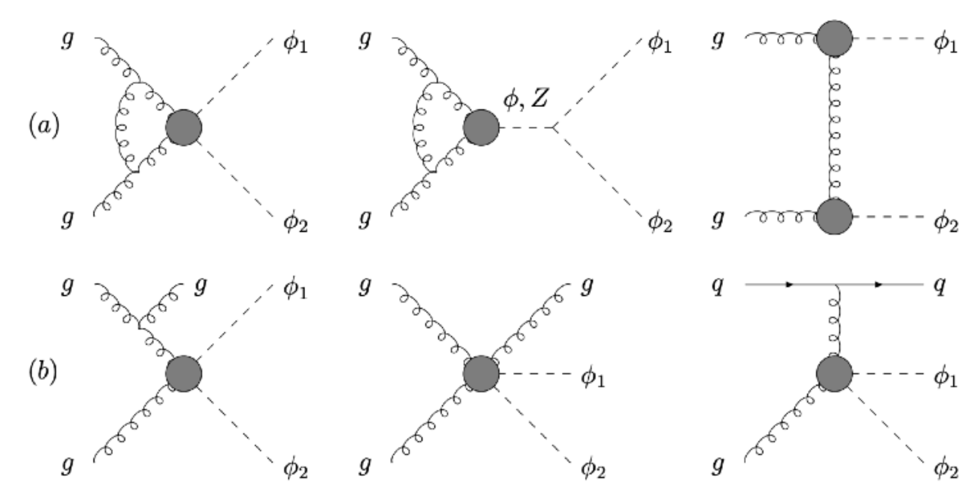
These are our next goal!
(the only problem remaining within the SM)

Dawson, Dittmaier, Spira

hep-ph/9805244

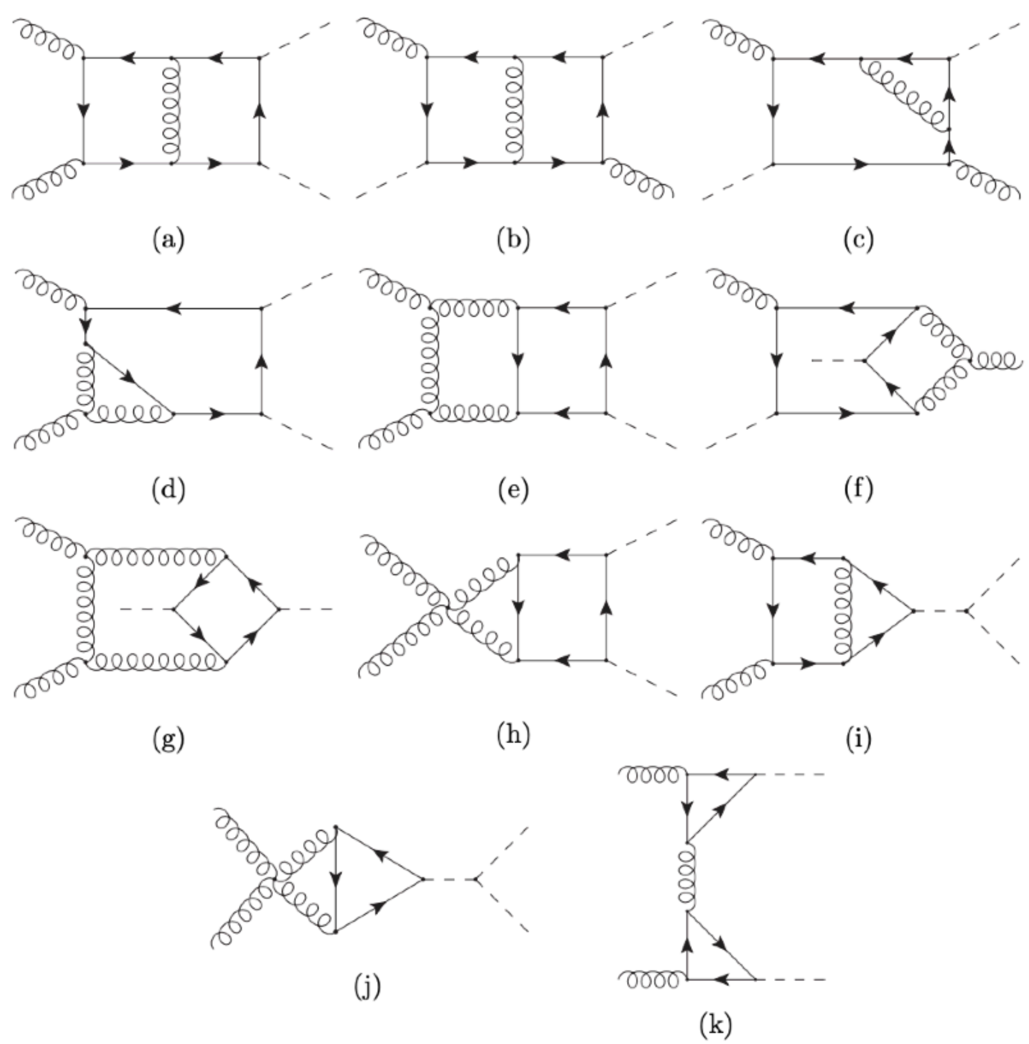




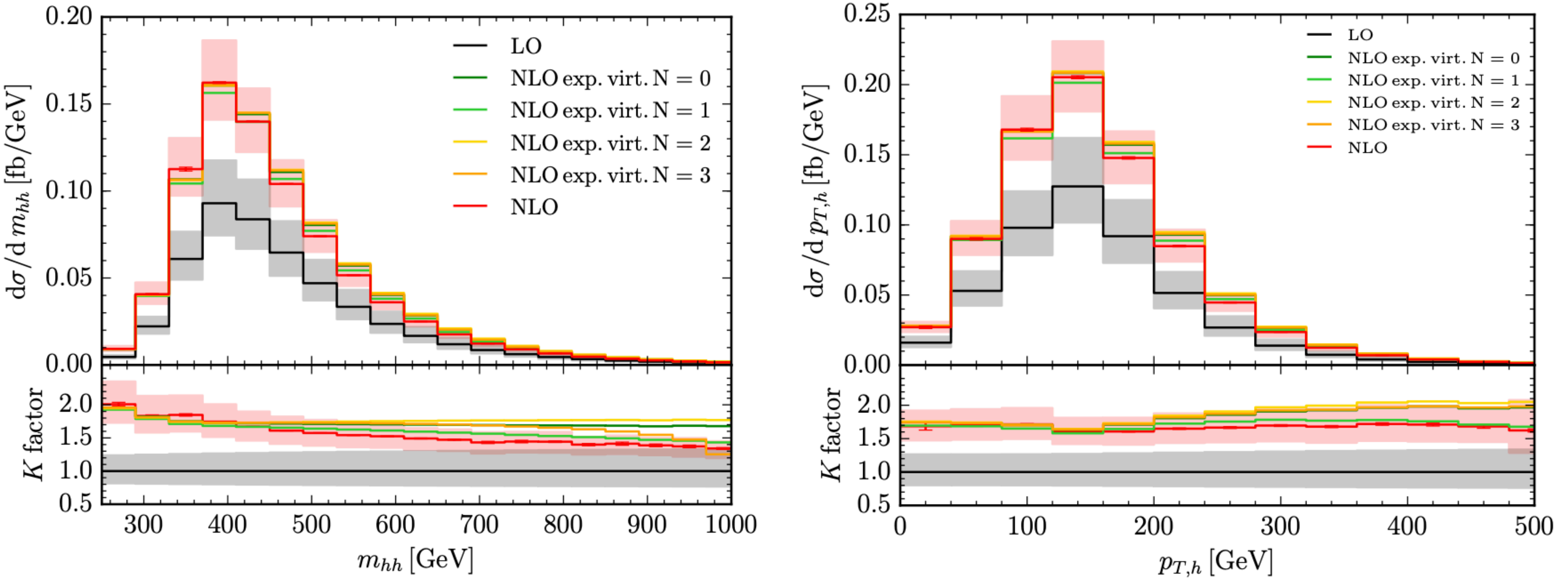


Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Zirke [1608.04798]

Full top quark mass dependence in Higgs boson pair production at NLO



NLO $\quad O\left(\frac{1}{m_t^2}\right)^N$



(a) 14 TeV, m_{hh} (b) 14 TeV, $p_{T,h}$

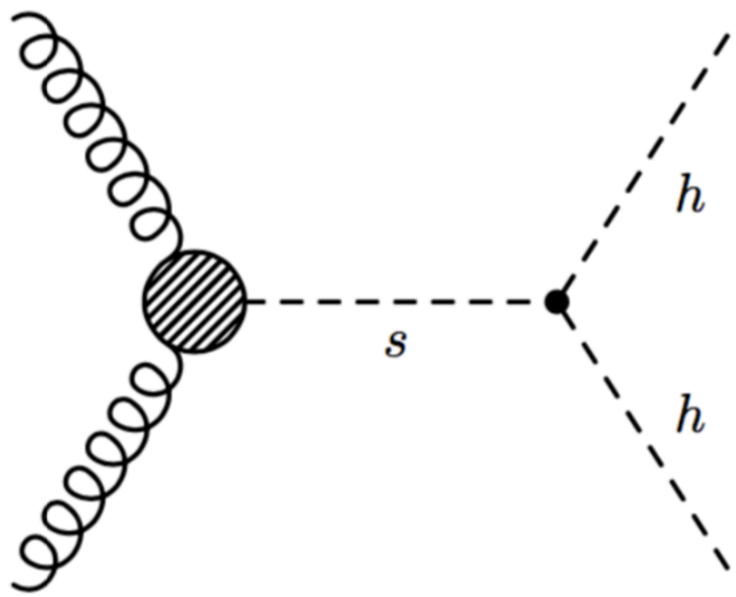
Pheno studies

Process	S(600/fb)	B(600/fb)	Reference
$b\bar{b}\tau^+\tau^-$	50	104	Dolan, Englert, Spannowsky [6] Ban, Cho, SCP
$b\bar{b}W^+W^-$	12	8	Papaefstathiou, L.L. Yang, Zurita [7]
$b\bar{b}\gamma\gamma$	9	11	Baglio, Djouadi, Gröber, Mühlleitner, Quevillon, Spira [8]
	6	12.5	Baur, Plehn, Rainwater [9]
$b\bar{b}b\bar{b}$	48	2000	Behr, Bortoletto, Frost, Hartland, Issever, Rojo [10]
	50	2500	Ferreira da Lima, Papaefstathiou, Spannowsky [11]

Table 1: Pheno studies of the di-Higgs process in several final states. We normalized all the studies to the cross section of Ref. [2] and assumed a b-tagging efficiency of 70 % with a 1% light jet rejection.

Nakamura-Nishiwaki-Oda-Park-Yasuhiro 17'

H (**doublet**), S (**signlet**)



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

$$\Delta\mathcal{L} = -\frac{\mu_{\rm eff}\sin\theta}{2} s h^2$$

fixed by model

detail

H (**doublet**), S (**signlet**)

Scalar Potential

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

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

$$V_H = m_H^2 |H|^2 + \frac{\lambda_H}{2} |H|^4,$$

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

Vacuum Condition

$$\lambda_H |H|^2 + \mu S + \frac{\kappa}{2} S^2 = -m_H^2,$$

$$|H|^2 (\mu + \kappa S) + \frac{\mu_S}{2} S^2 + \frac{\lambda_S}{3!} S^3 = -m_S^2 S.$$

Mixing Angle

$$\tan 2\theta = \frac{v\,(f\kappa + \mu)}{\frac{\lambda_S}{3!} f^2 - \frac{\lambda_H}{2} v^2 + \frac{\mu_S}{4} f - \frac{\mu}{4}\frac{v^2}{f}}.$$

$$\mu_{\rm eff} = (\kappa f + \mu)\frac{\cos^3\theta}{\sin\theta} + v\,(3\lambda_H - 2\kappa)\cos^2\theta + [f\,(\lambda_S - 2\kappa) - 2\mu + \mu_S]\cos\theta\sin\theta + \kappa v \sin^2\theta.$$

Z2 symmetric

(theoretically better motivated?)

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

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

$$V_H = m_H^2 |H|^2 + \frac{\lambda_H}{2} |H|^4,$$

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

$$\mu = 0 = \mu_S$$

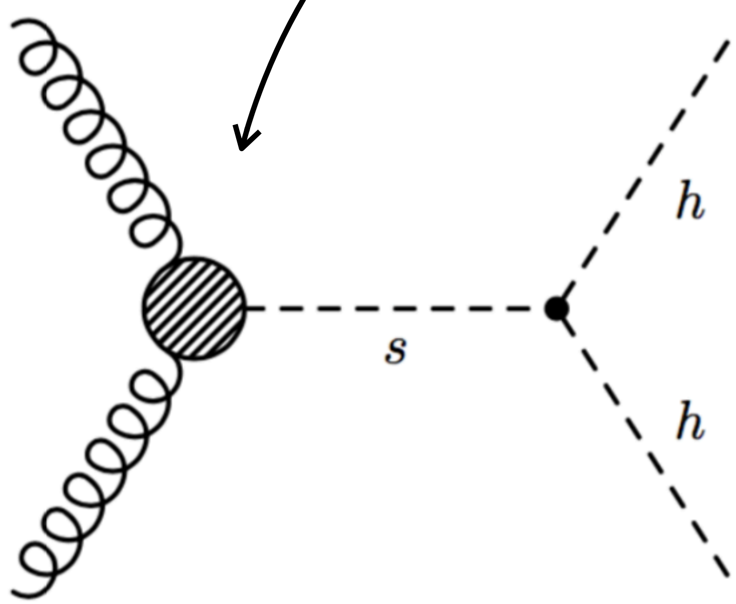
$$\tan 2\theta = \frac{v\,(f\kappa + \mu)}{\frac{\lambda_S}{3!} f^2 - \frac{\lambda_H}{2} v^2 + \frac{\mu_S}{4} f - \frac{\mu}{4} \frac{v^2}{f}}.$$

$\longrightarrow$

$$\tan 2\theta = \frac{\kappa v}{\frac{\lambda_S}{3!} f - \frac{\lambda_H}{2} \frac{v^2}{f}}.$$

$$\mu_{\rm eff} \to v \left(\lambda_H + \frac{m_s^2 + m_h^2}{v^2} \right) = \frac{m_s^2 + 2m_h^2}{v}.$$

New colored particles in 'Blob'



	Dirac spinor			complex scalar			
field	T	B	$\dots$	$\phi_{\mathbf{3}}$	$\phi_{\mathbf{6}}$	$\phi_{\mathbf{8}}$	$\dots$
$SU(3)_C$	$\mathbf{3}$	$\mathbf{3}$	$\dots$	$\mathbf{3}$	$\mathbf{6}$	$\mathbf{8}$	$\dots$
Q	$\frac{2}{3}$	$-\frac{1}{3}$	$\dots$	$-\frac{1}{3},\ -\frac{4}{3}$	$\frac{1}{3},\ -\frac{2}{3},\ \frac{4}{3}$	$0,\ -1$	$\dots$

effective coupling

$$\mathscr{L}_{eff} = -\frac{1}{4g_s^2} G^a_{\mu\nu} G^{a\mu\nu}$$

$$\frac{1}{g_s^2} \longrightarrow \frac{1}{g_s^2} - \frac{2}{(4\pi)^2} \left(b_g^{\rm top} \frac{h\cos\theta + s\sin\theta}{v} + \Delta b_g \, y_T \frac{-h\sin\theta + s\cos\theta}{M_T} \right)$$

t-loop **T-loop**

Vectorlike, fundamental 3-rep. => $b_g^t = \Delta b_g = \frac{1}{2} \times \frac{4}{3} = \frac{2}{3}$

Loop level interactions

$$\mathcal{L}_{\rm eff}^{hgg} = \frac{\alpha_s}{8\pi v}\left(b_g^{\rm top}\cos\theta - \Delta b_g \eta \sin\theta\right) h\, G^a_{\mu\nu}G^{a\mu\nu},$$
$$\mathcal{L}_{\rm eff}^{sgg} = \frac{\alpha_s}{8\pi v}\left(\Delta b_g \eta \cos\theta + b_g^{\rm top}\sin\theta\right) s\, G^a_{\mu\nu}G^{a\mu\nu},$$
$$\mathcal{L}_{\rm eff}^{h\gamma\gamma} = \frac{\alpha}{8\pi v}\left(b_\gamma^{\rm SM}\cos\theta - \Delta b_\gamma\, \eta \sin\theta\right) hF_{\mu\nu}F^{\mu\nu},$$
$$\mathcal{L}_{\rm eff}^{s\gamma\gamma} = \frac{\alpha}{8\pi v}\left(\Delta b_\gamma\, \eta \cos\theta + b_\gamma^{\rm SM}\sin\theta\right) sF_{\mu\nu}F^{\mu\nu},$$

$$M_T = m_T + y_T f \qquad M_\phi^2 = m_\phi^2 + \frac{\kappa_\phi}{2}\langle S\rangle^2$$

$$\eta = y_T N_T \frac{v}{M_T}$$

$$b_\gamma^{\rm SM} \simeq -6.5$$

$$b_g = -\frac{1}{2}\left(\Delta b_g\, \eta\cos\theta + b_g^{\rm top}\sin\theta\right),$$
$$b_\gamma = -\frac{1}{2}\left(\Delta b_\gamma\, \eta\cos\theta + b_\gamma^{\rm SM}\sin\theta\right).$$

Decay widths

$$\Gamma(s \to hh) = \frac{\mu_{\rm eff}^2}{32\pi m_s}\sqrt{1-4x_h}\,\sin^2\theta$$

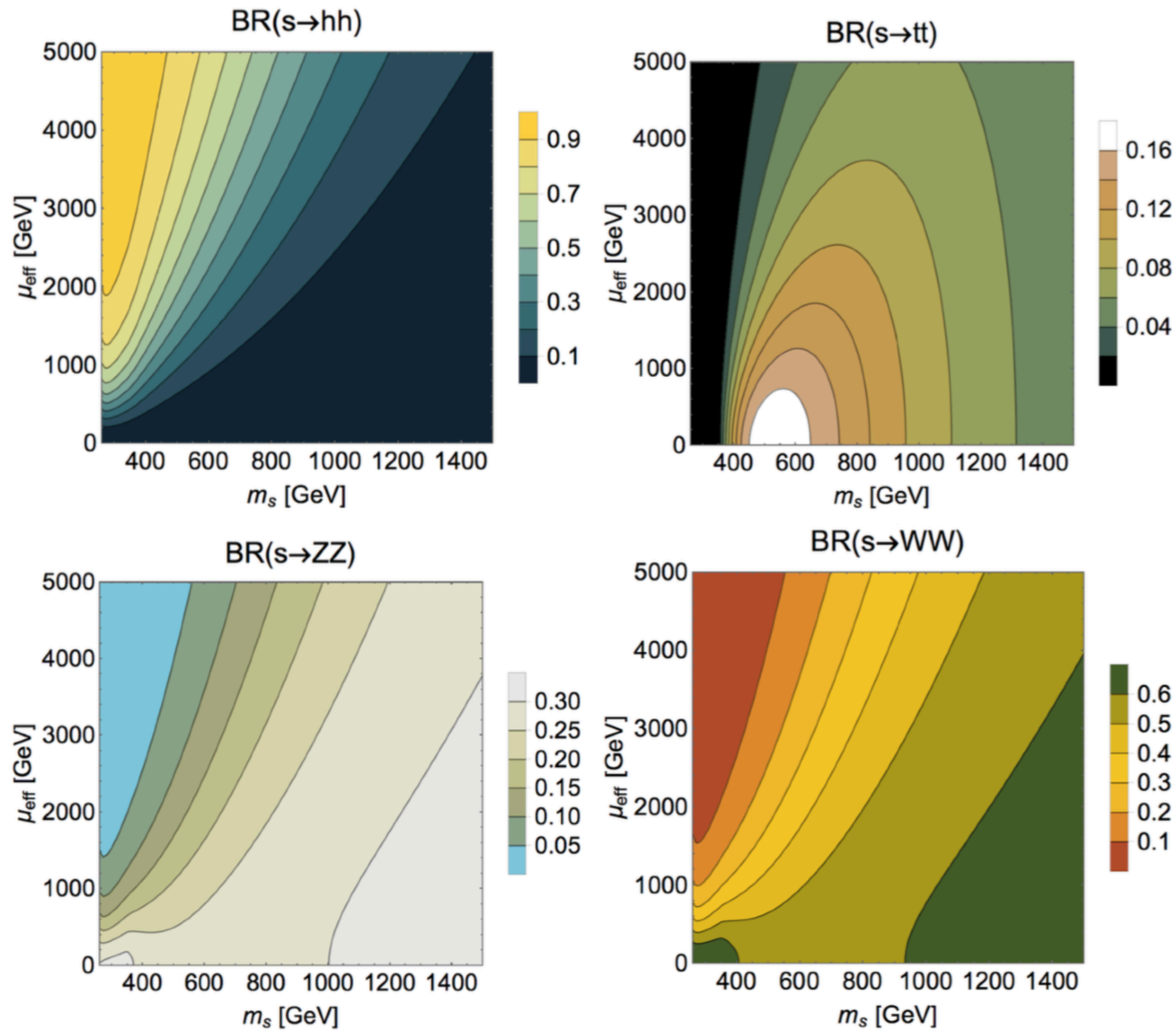
$$\Gamma(s \to VV) = \frac{m_s^3}{32\pi v^2}\delta_V\sqrt{1-4x_V}(1-4x_V+12x_V^2)\sin^2\theta$$

$$\Gamma(s \to t\bar{t}) = \frac{N_C m_s m_t^2}{8\pi v^2}(1-4x_t)^{3/2}\sin^2\theta$$

$$x_i = \frac{m_i^2}{m_s^2}, \delta_Z = 1, \delta_W = 2$$

$$\Gamma(s \to gg) = \left(\frac{\alpha_s b_g}{4\pi v}\right)^2 \frac{2m_s^3}{\pi}$$

$$\Gamma(s \to \gamma\gamma) = \left(\frac{\alpha b_\gamma}{4\pi v}\right)^2 \frac{m_s^3}{\pi}$$



overall

	Dirac spinor			complex scalar			
field	T	B	$\dots$	$\phi_{\mathbf{3}}$	$\phi_{\mathbf{6}}$	$\phi_{\mathbf{8}}$	$\dots$
$SU(3)_C$	$\mathbf{3}$	$\mathbf{3}$	$\dots$	$\mathbf{3}$	$\mathbf{6}$	$\mathbf{8}$	$\dots$
Q	$\frac{2}{3}$	$-\frac{1}{3}$	$\dots$	$-\frac{1}{3},\ -\frac{4}{3}$	$\frac{1}{3},\ -\frac{2}{3},\ \frac{4}{3}$	$0,\ -1$	$\dots$
Δb_g	$\frac{2}{3}$	$\frac{2}{3}$	$\dots$	$\frac{1}{6}$	$\frac{5}{6}$	1	$\dots$
Δb_γ	$\frac{16}{9}$	$\frac{4}{9}$	$\dots$	$\frac{1}{9},\ \frac{16}{9}$	$\frac{2}{9},\ \frac{8}{9},\ \frac{32}{9}$	$0,\ \frac{8}{3}$	$\dots$
η	$y_F N_F \frac{v}{M_F}$			$\kappa_\phi N_\phi \frac{fv}{M_\phi^2}$			

$$\eta = y_T N_T \frac{v}{M_T}$$

LHC is already good

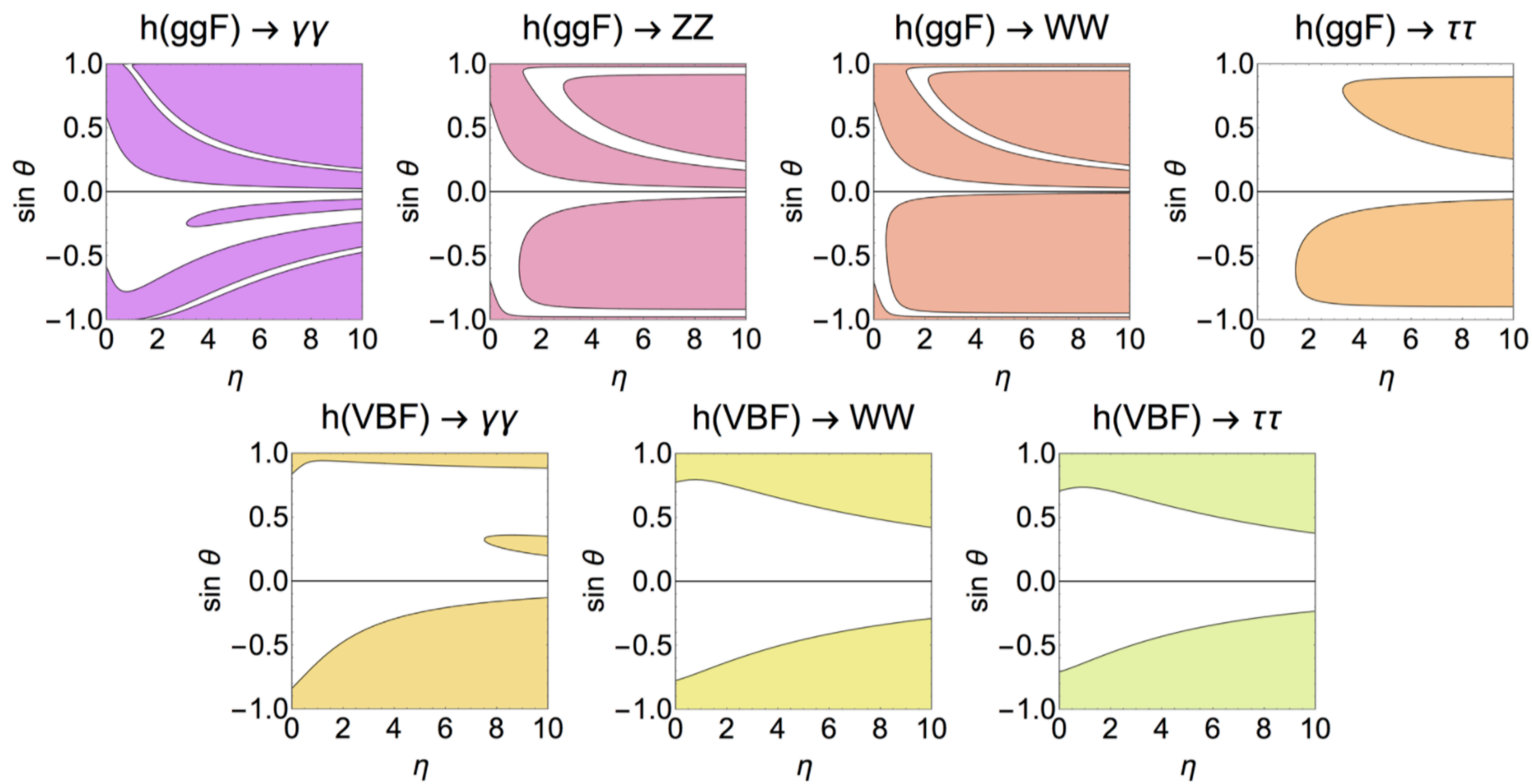


Figure 5: The 2σ-excluded regions from the signal strength of 125 GeV Higgs. The top-partner parameters are chosen as an illustration to present the contribution from each channel.

LHC is already good

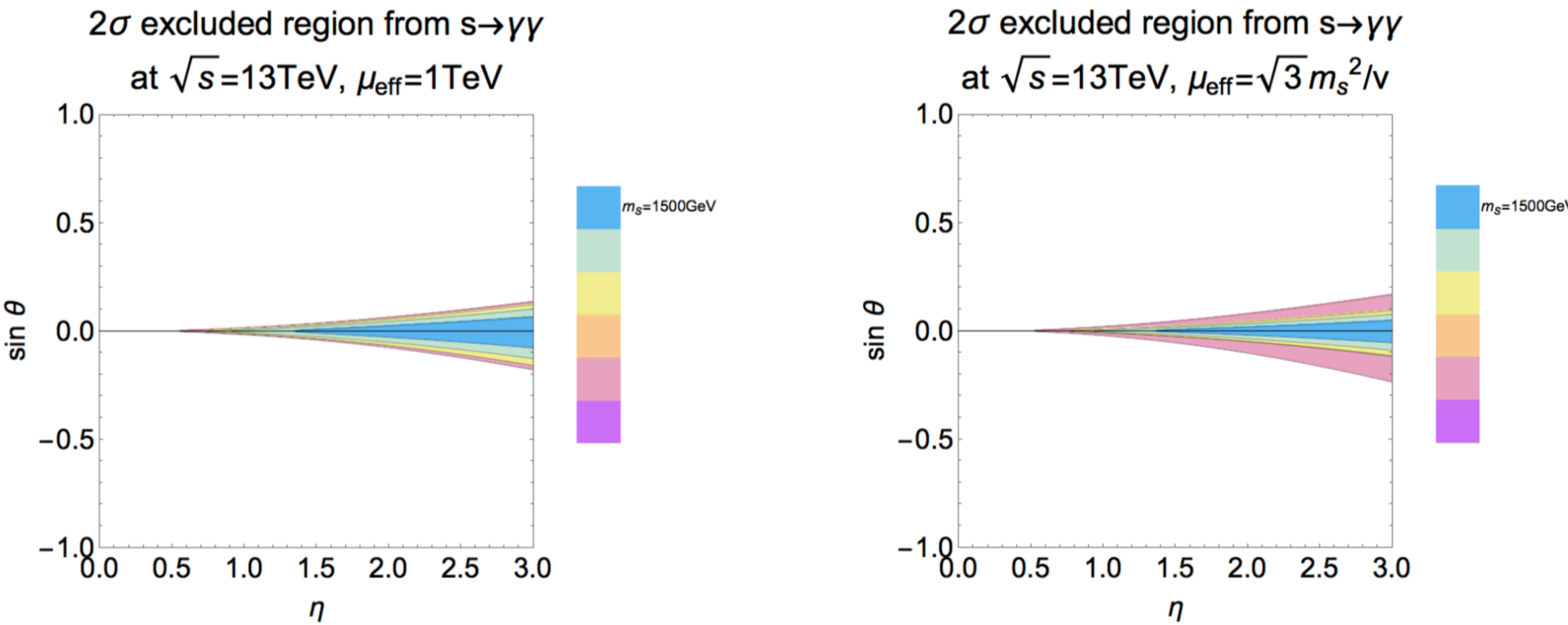
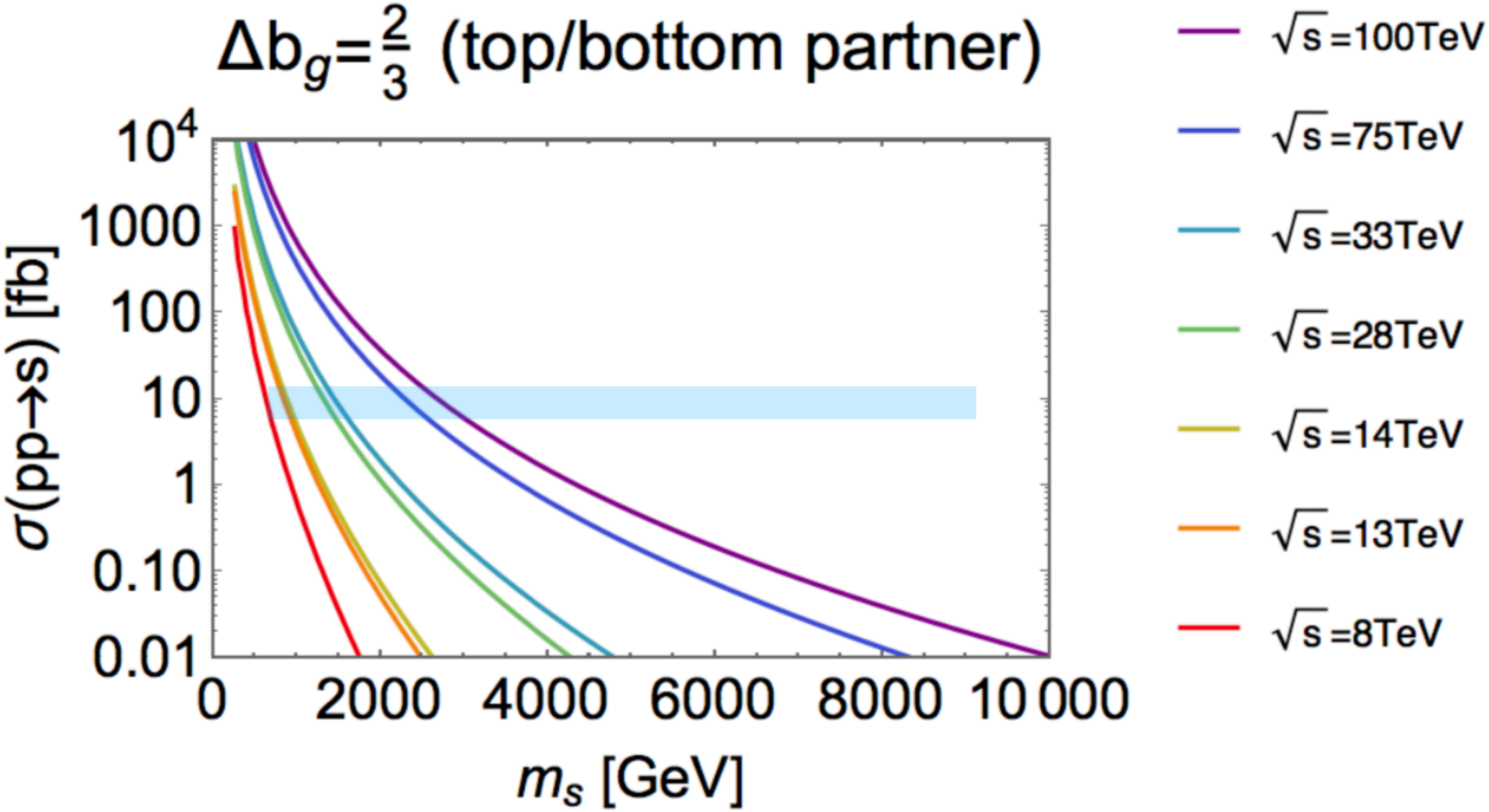


Figure 8: The 2σ-excluded regions from $s \to \gamma\gamma$ bound in the $\sin\theta$ vs η plane for various m_s with $\mu_{\rm eff} = 1$ TeV and $\sqrt{3}m_s^2/v$. The color is changed in increments of 300 GeV. K-factor is set to be $K = 1.6$.

For future

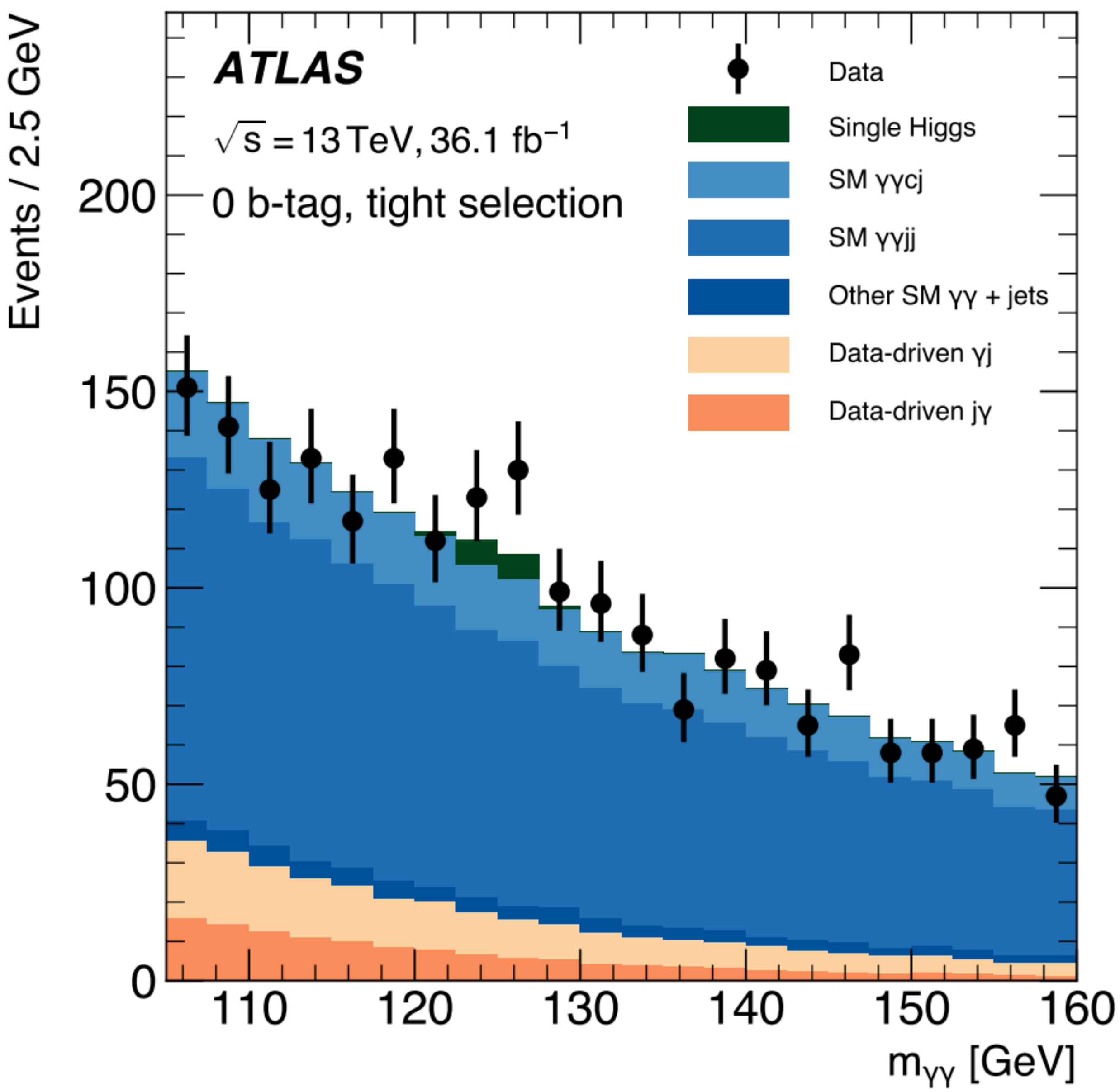
$$|b_g| = \frac{\Delta b_g}{2} \frac{v}{m_s},$$



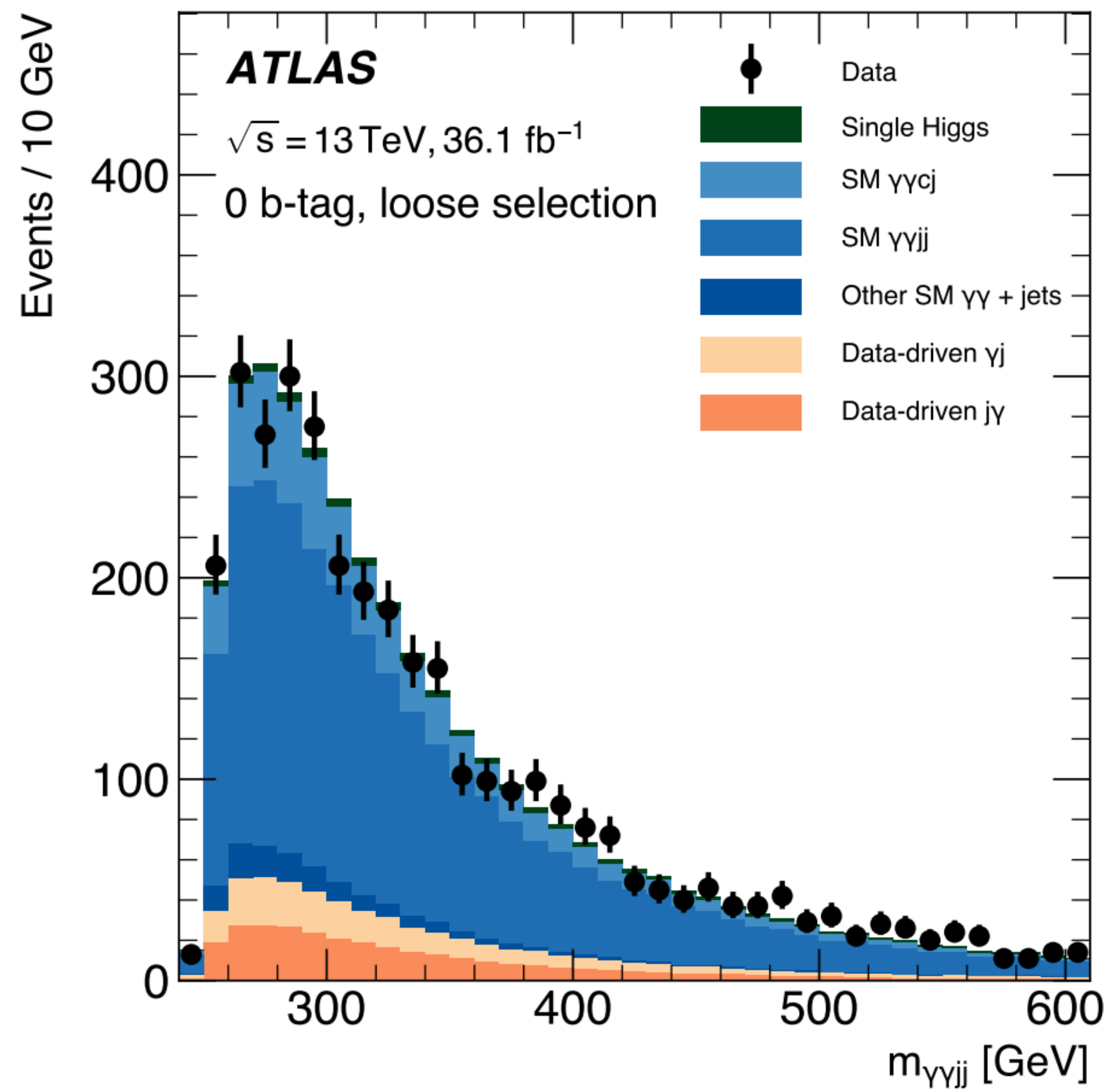
Summary

- Di-Higgs is enhanced e.g. by a new resonance
- but needs colored particles in the 'blob' so that "gg-s" is allowed
- depending on their properties, of course, the corresponding phenomenology can be modified
- We have considered colored Dirac fermions (T, B) and Scalars (3,6,8)-representations
- (sometimes, even '**anomaly**' can show up e.g. 2.4σ excess in $bb\gamma\gamma$ with $m_s = 300\ \mathrm{GeV}\ldots$) I do not want to mention this.

ATLAS 1807.04873, $bb\gamma\gamma$



(a)



(b)