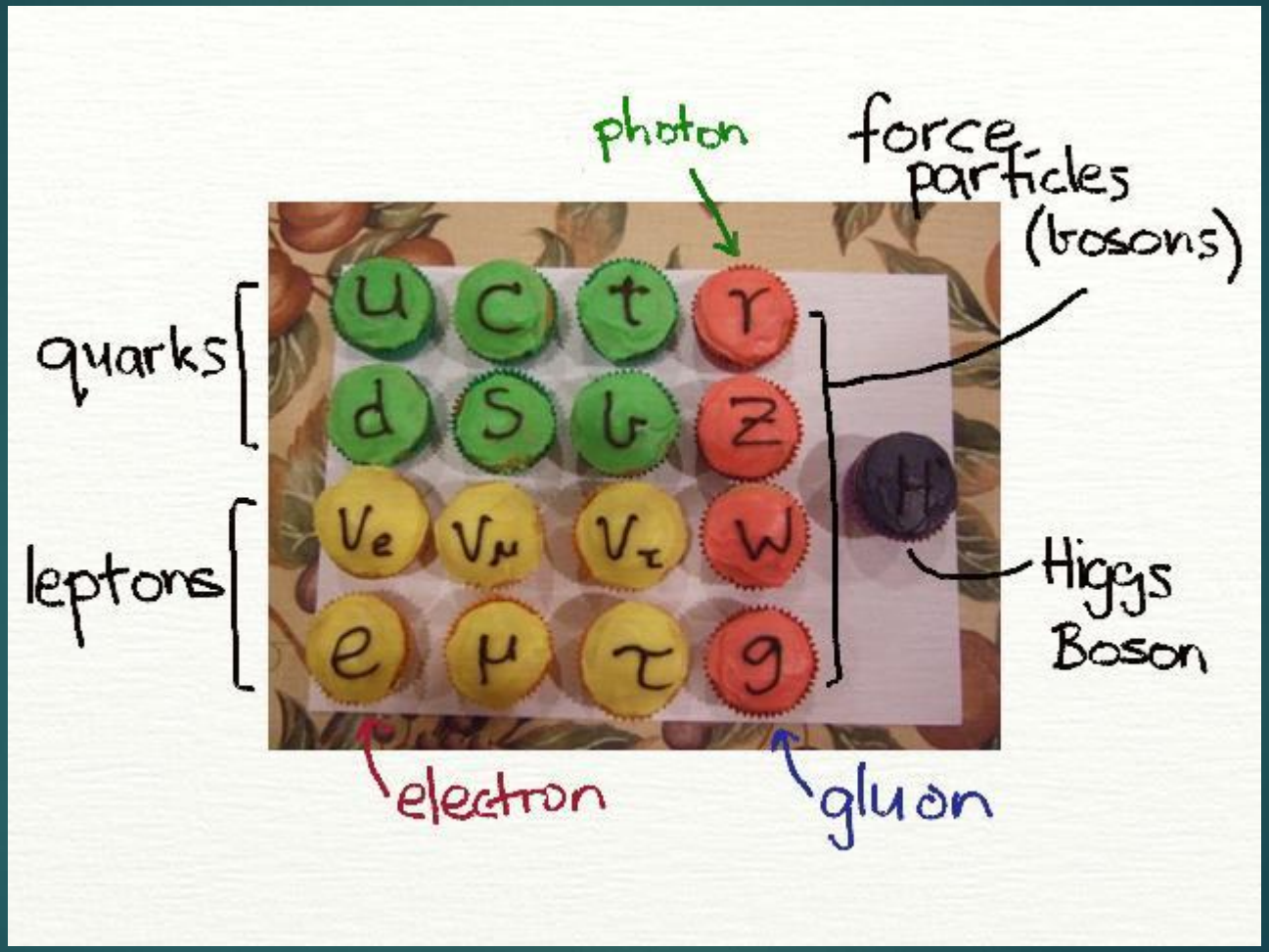
# Radiative decays of a singlet scalar boson in an extended standard model

Yeo Woong Yoon (KU)

In collaboration with
Kingman Cheung, Sin Kyu Kang, Jeonghyeon Song
based on 1705.05486
Seminar at SNU, on 2017. 6. 12

# The SM is TOO good.

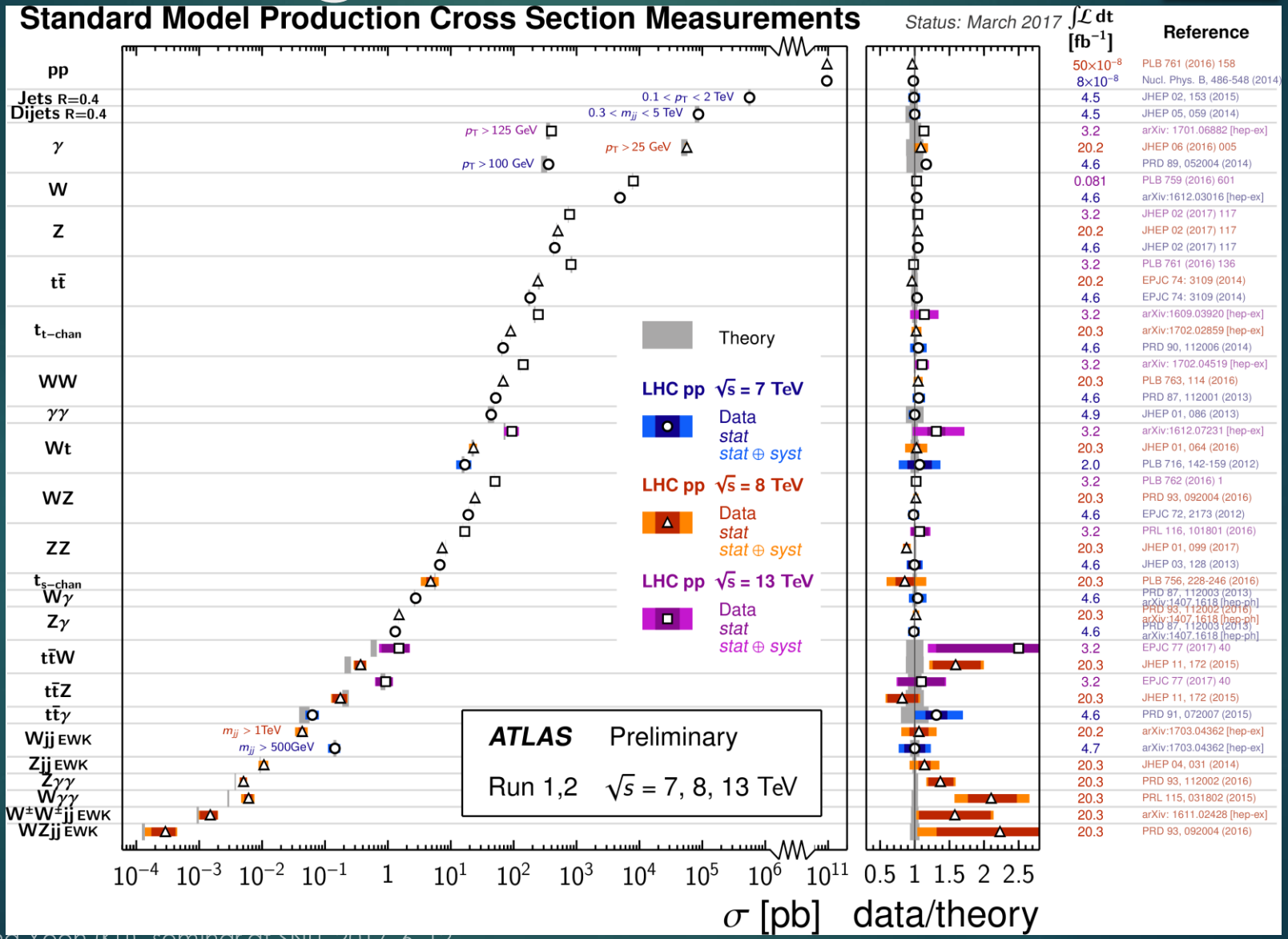





The Standard Model of Particle Physics in the cupcake representation. Credit: E. Bland

# No NP signal at the LHC





# What remains after Digamma(750) has gone

- December 15, 2015, ATLAS and CMS reported digamma excess around 750GeV with significances 3.9σ and 3.4σ
- Collecting the first half of 2016 data,
  those excesses are turned out to be statistical fluctuations.
- But, we could obtain many new ideas on constructing models about new heavy scalar boson with significant signal strength.

| | | |
|---|---|---|
| Singlet + VLQ, | Axion, | Extra Dimension, |
| 2HDM, | Dilaton, | Leptoquark, |
| MSSM, | Techipion, | See-Saw, |
| Georgi-Machacek, | Radion, | GUT, |
| Manohar-Wise, | Gravition | Left-Right …. |

# Extension of the SM

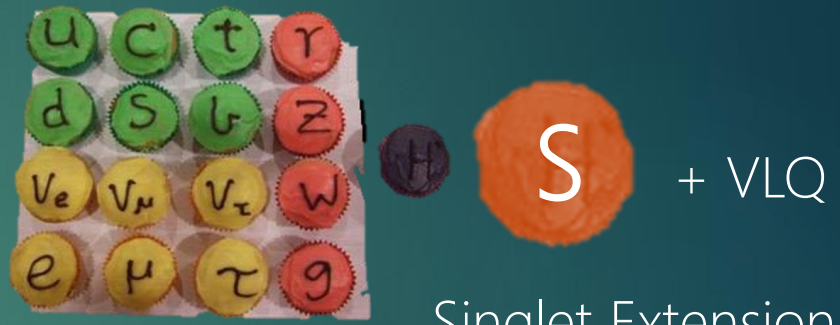




SM



2HDM



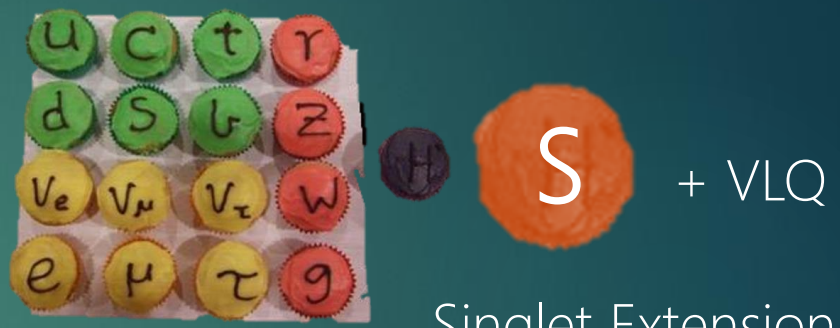
Singlet Extension



MSSM

# Benefits from the singlet extension






## Higgs Portal & Dark Matter

Schabinger, Wells, PRD (2005) ; Patt, Wilczek, 0605188;
Englert et. al., PLB(2011); Batell, Gori, Wang, JHEP(2012);
Robens, Stefaniak, EPJC(2015)

McDonald, PRD(1994); Burgess, Pospelov, Veldhuis, NPB(2001);
Davoudiasl, Kitano, Li, Murayama, PLB(2005); Kusenko, PRL(2006);
Andreas et. al, PRD(2010); ...

## EW Baryogenesis

Profumo, Ramsey-Musolf, Shaughnessy, JHEP(2007);
Espinosa, Konstandin, Riva, NPB(2012); Curtin, Meade, Yu (2014)

## EW Vacuum Stabilization

Batell, Jung, Lee, JHEP(2012); Cao et. al., JHEP(2014); Xiao, Yu, PRD (2014);

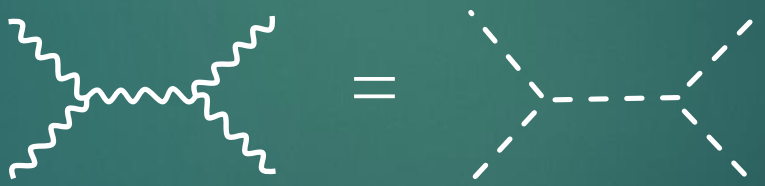
# Equivalence Theorem



Mass Gauge Bosons' Polarization Vectors:

$$\epsilon^{\mu}_{T_1} = (0, 1, 0, 0), \qquad \epsilon^{\mu}_{T_2} = (0, 0, 1, 0)$$

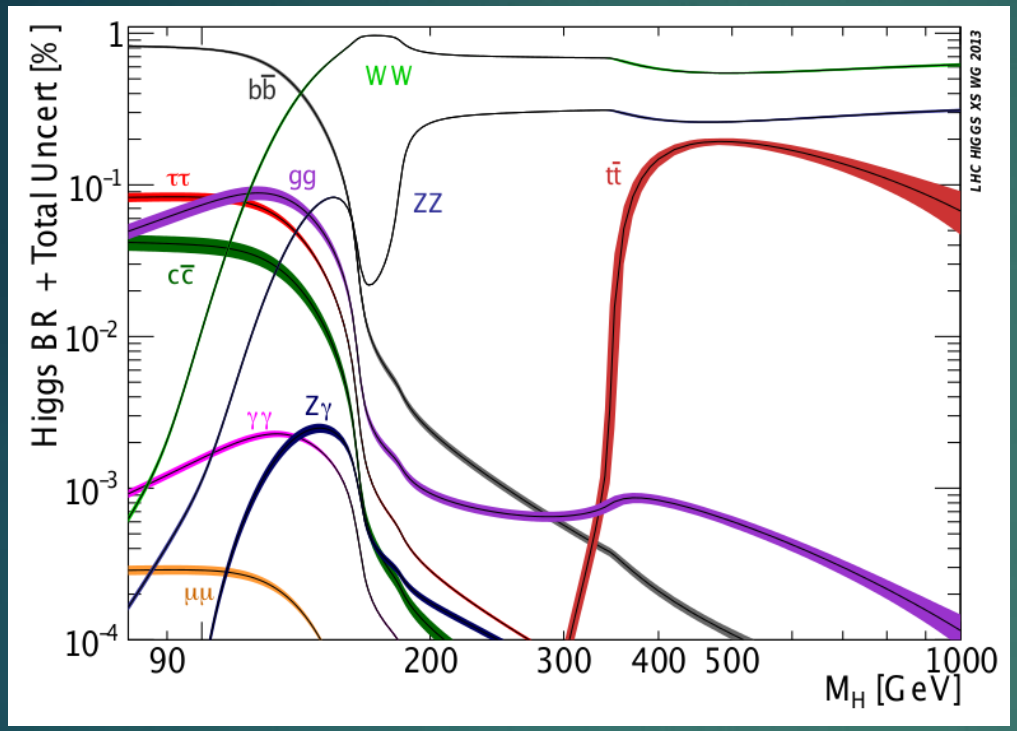
$$\epsilon^{\mu}_{L} = \left( \frac{|\vec{p}|}{M_V}, 0, 0, \frac{E}{M_V} \right)$$ ← Dominant at high Energy

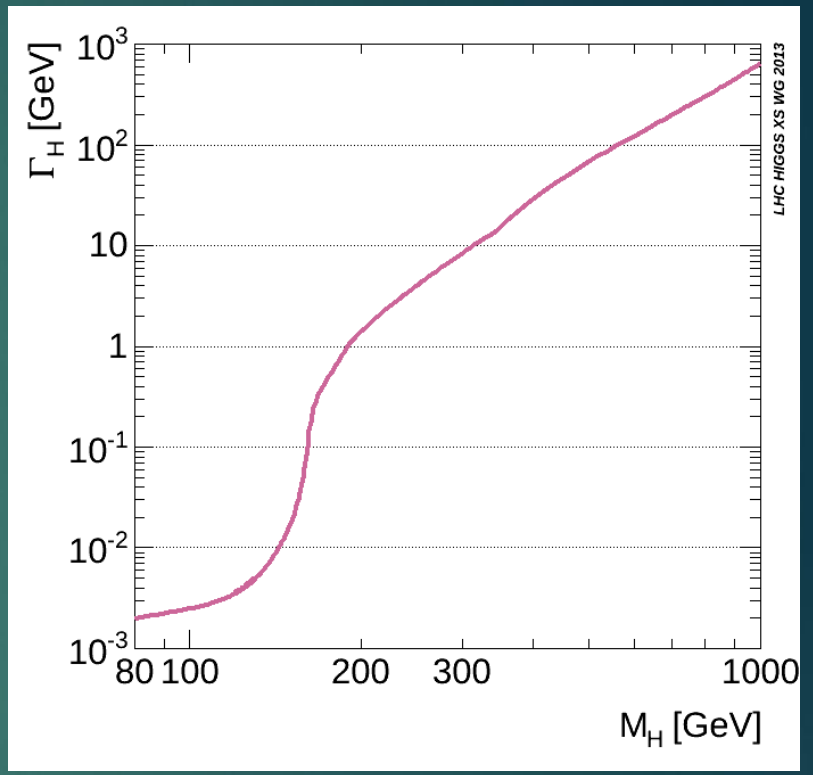


ElectroWeak Equivalence Theorm:
At very high energies, the longitudinal massive vector bosons can be replaced by the Goldstone bosons.

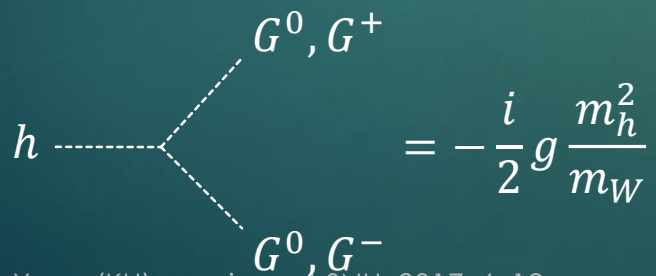
# Longitudinal Enhancement






Due to Goldstone Equivalence Theorem




$$= -\frac{i}{2} g \frac{m_h^2}{m_W}$$

Djouadi, '*Tome I*', PR(2008)

$$\frac{\Gamma_L}{\Gamma_L + \Gamma_T} = \frac{1 - 4x + 4x^2}{1 - 4x + 12x^2} \xrightarrow{M_H \gg M_V} 1$$

# Longitudinal Enhancement



- ✓ Is the Longitudinal Enhancement also applied to the singlet scalar decay?

→ Yes it is, under some condition.

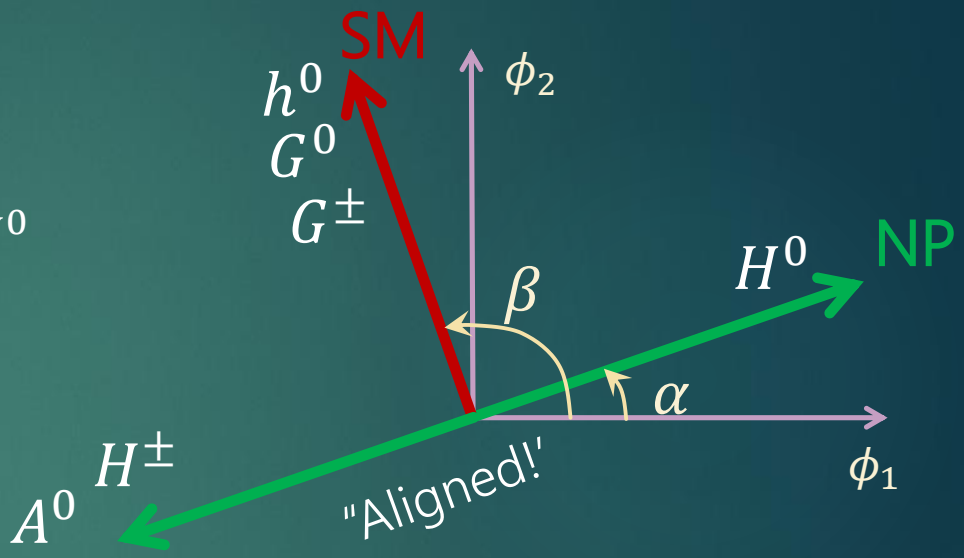
→ However, equivalence theorem may not work for singlet scalar.

# Decoupling limit



$h^0_{SM} = \sin(\beta-\alpha)h^0 + \cos(\beta-\alpha)H^0$

"Alignment Limit" $\sin(\beta-\alpha) = 1$




- Light neutral Higgs h exactly corresponds to the SM Higgs.
- Heavy neutral Higgs H becomes gauge-phobic.

$$ZZH: \quad \frac{igm_Z}{\cos\theta_W}\cos(\beta-\alpha)g^{\mu\nu} \qquad WWH: \quad igm_W\cos(\beta-\alpha)g^{\mu\nu}$$

- The "Feed-down" processes are turned off

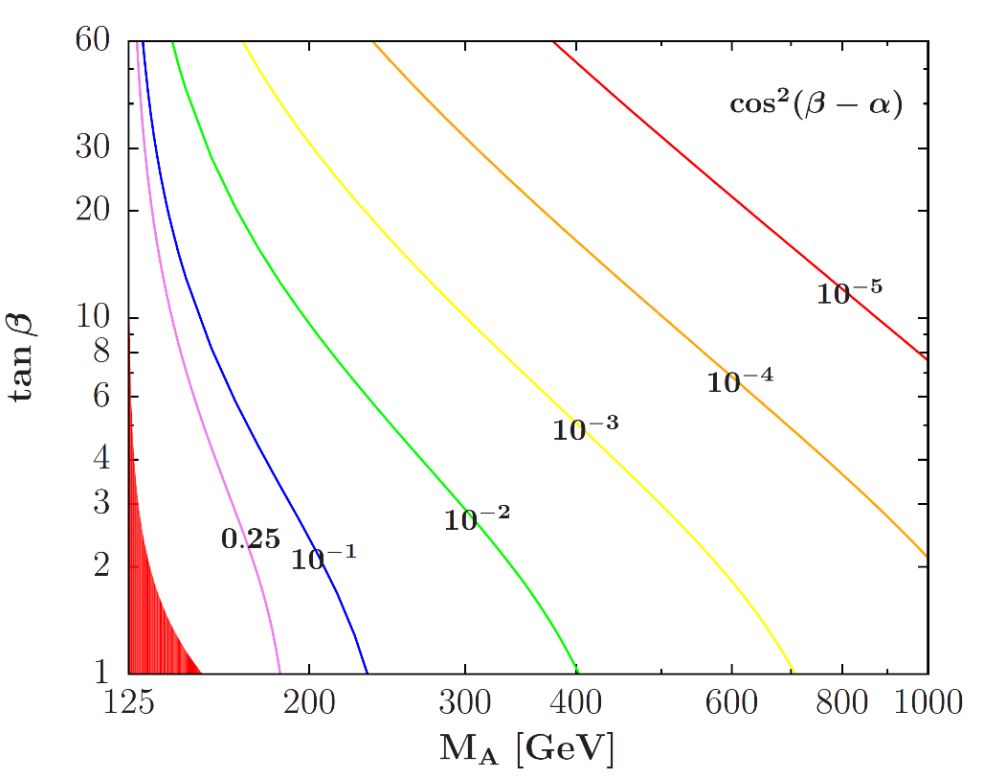
$A \to Zh, \quad H^+ \to W^+h, \quad H \to hh$ → vanish at tree level

# Decoupling limit



hMSSM get close to alignment limit for large MA and large tanbeta.

$$\frac{\tan 2\alpha}{\tan 2\beta} = \left(\frac{m_{A^0}^2 + m_Z^2}{m_{A^0}^2 - m_Z^2}\right)$$




Djouadi et. al., 1502.05653

# Non-Decoupling effect at One-Loop Level

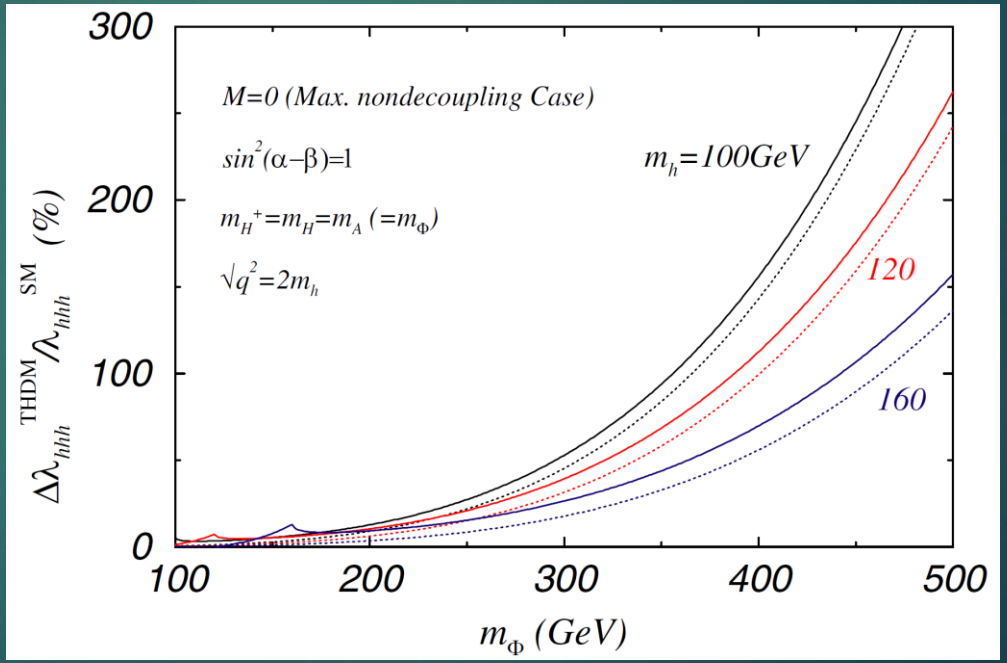
In the alignment limit, $\sin(\beta-\alpha)=1$

$$\Gamma^{(\text{tree})}_{hhh} = -\frac{3m_h^2}{v}$$

Under the following condition

$$(0 < M^2 < m_\Phi^2)$$

Triple Higgs coupling can be changed by more than 100%



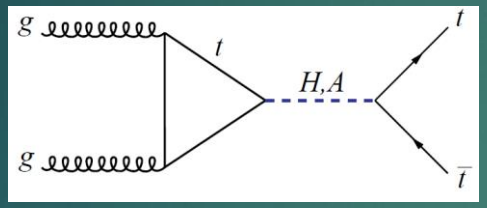

Kanemura, Okada, Senaha, Yuan, PRD (2004)

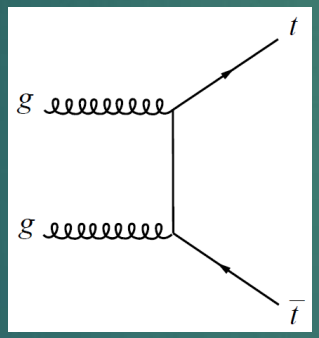
# Non-Decoupling effect at One-Loop Level

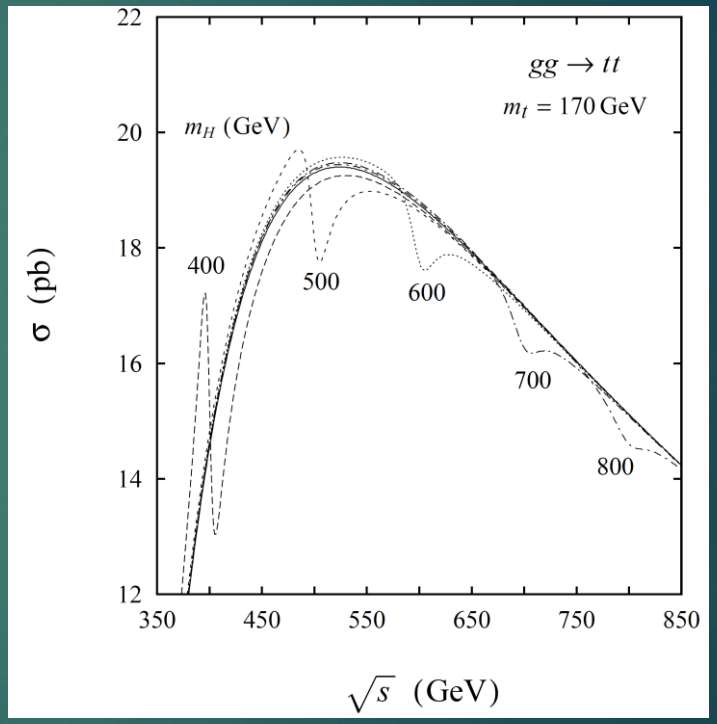


→ We find the Non-decoupling effect also arises at one-loop level in the singlet extended SM under some condition.

# continuum severely distorts signal events




Dicus, Stange, Willenbrock, (1994) PLB

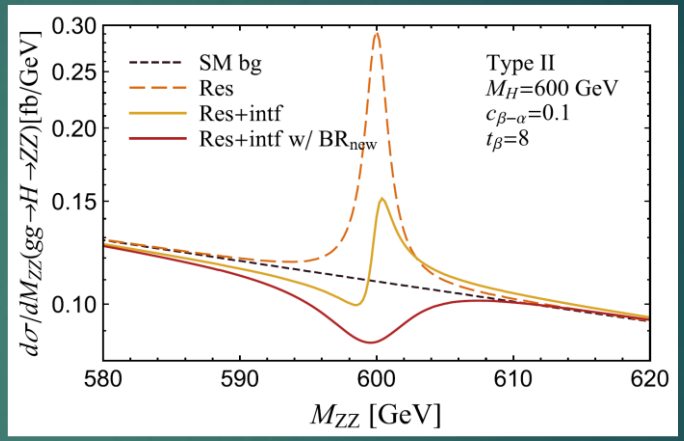
The interference effect changes the line shape and/or signal strength.

Jung, Song, YWY,, PRD (2015); JHEP (2016)

# continuum severely distorts signal events

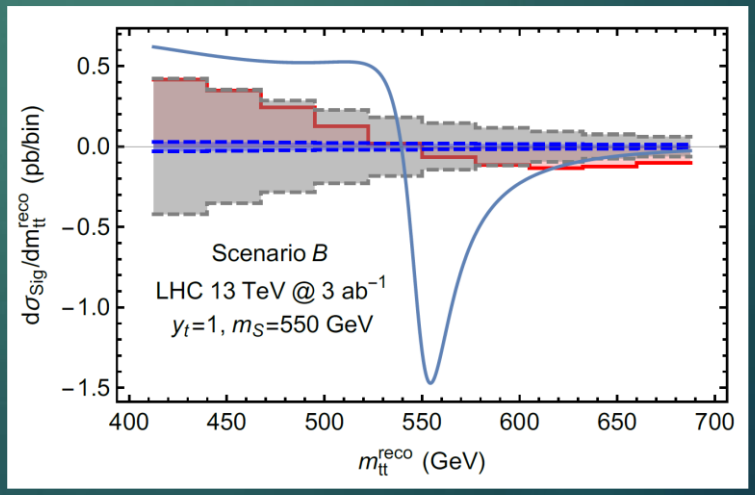
The Interference effects for $S \to \gamma\gamma, ZZ$ processes

Song, YWY, Jung, PRD (2016)

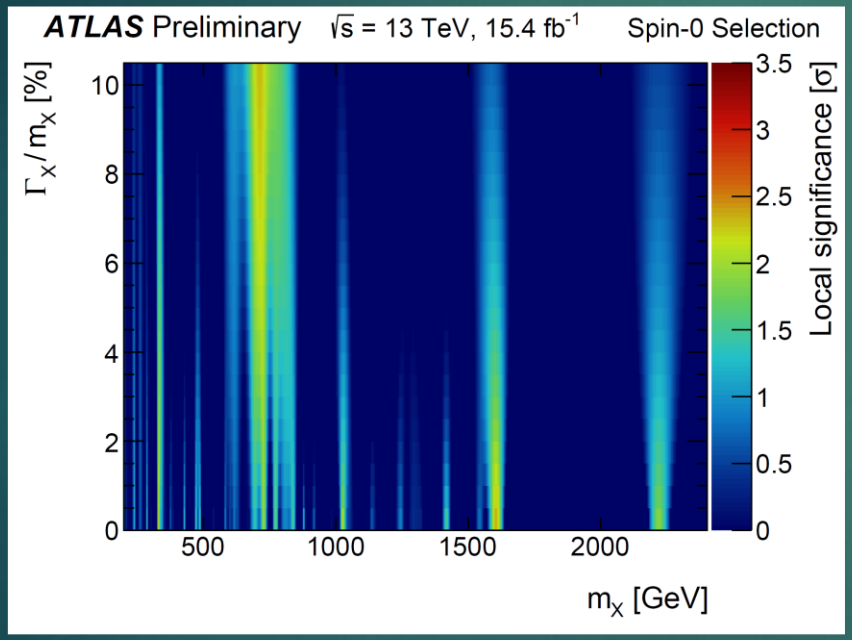


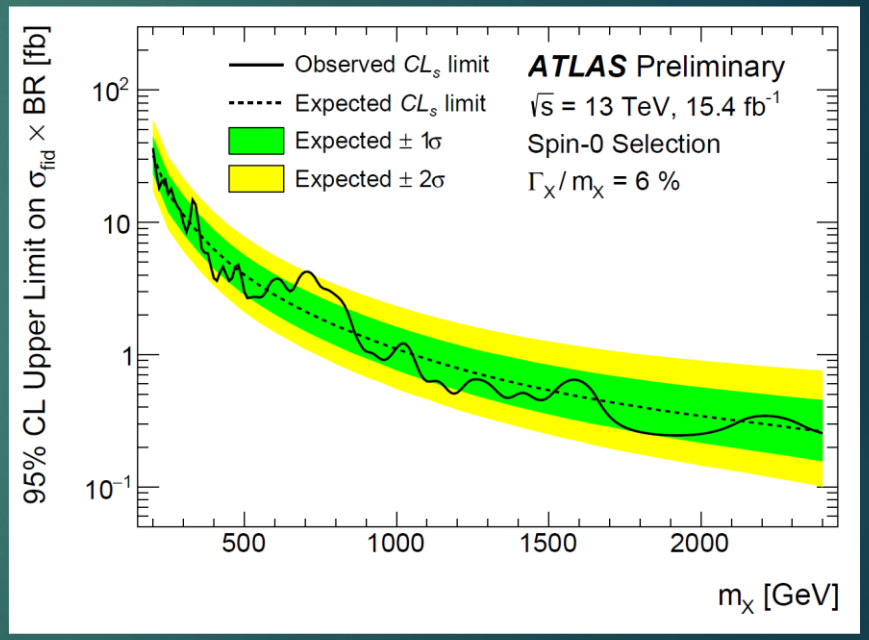

The Interference effects in association with smearing effect for $S \to \bar{t}t$ processes

Carena, Liu, JHEP (2016)



# Experimental status of searching for the scalar particle

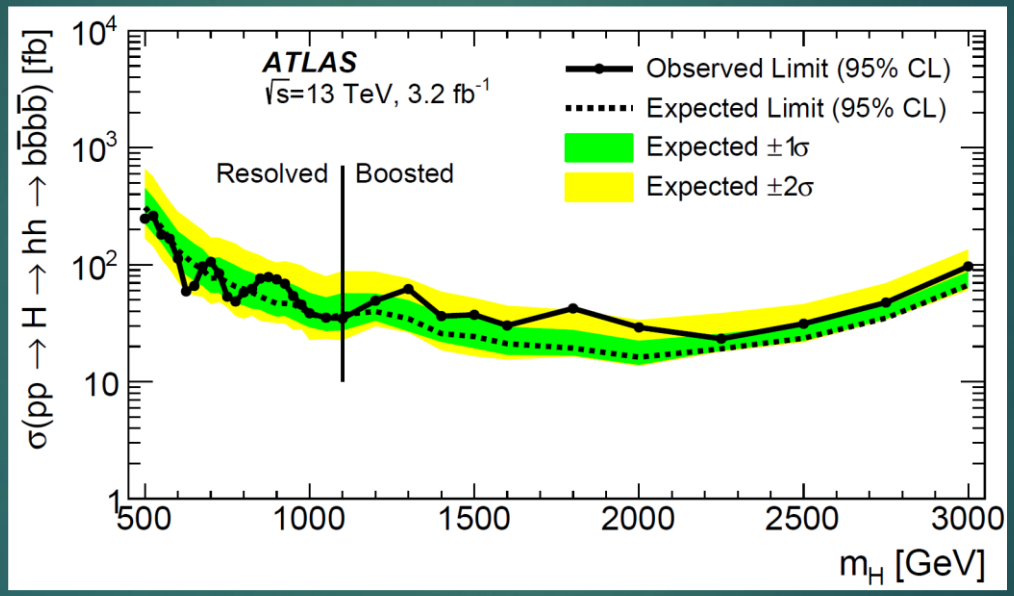



ATLAS-CONF-2016-059

$S \to \gamma\gamma$ searches: No significant excess

# Experimental status of searching for the scalar particle

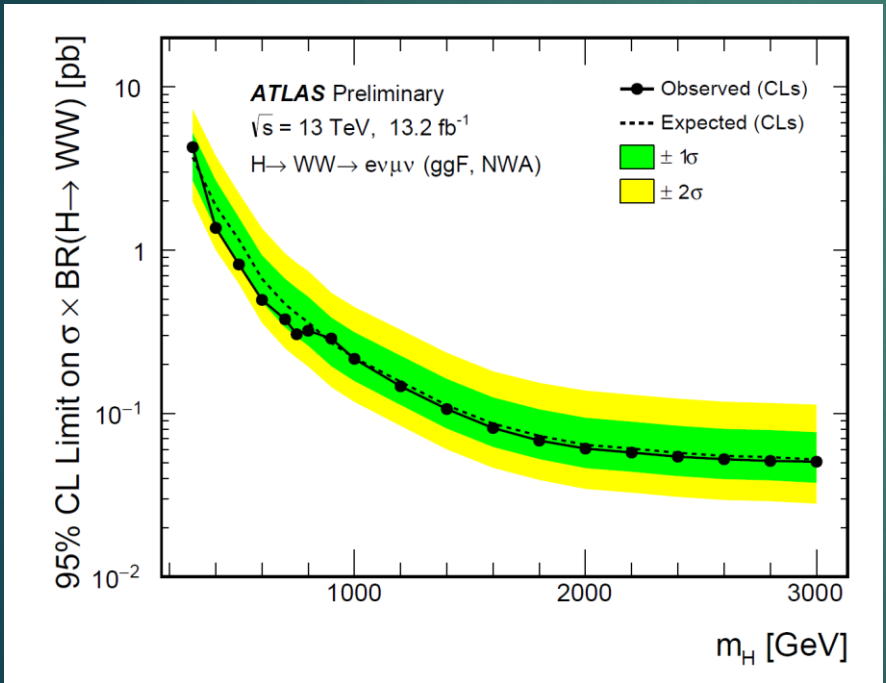



ATLAS 1606.04782

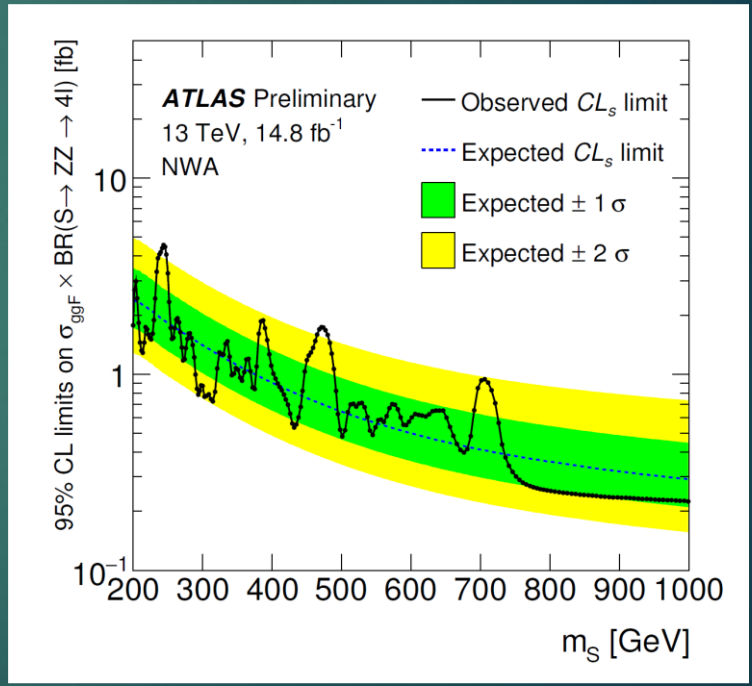
$S \to hh$ searches: No significant excess

# Experimental status of searching for the scalar particle

$S \to WW, ZZ$ searches: No significant excess




ATLAS-CONF-2016-074




ATLAS-CONF-2016-079

# EFT approach



**Transverse polarization part of S→ WW, ZZ**

$$g_3^2 S\left(\frac{G_{\mu\nu}^2}{2\Lambda_g}+\frac{G_{\mu\nu}\tilde{G}^{\mu\nu}}{2\tilde{\Lambda}_g}\right)+g_2^2 S\left(\frac{W_{\mu\nu}^2}{2\Lambda_W}+\frac{W_{\mu\nu}\tilde{W}^{\mu\nu}}{2\tilde{\Lambda}_W}\right)+g_1^2 S\left(\frac{B_{\mu\nu}^2}{2\Lambda_B}+\frac{B_{\mu\nu}\tilde{B}^{\mu\nu}}{2\tilde{\Lambda}_B}\right)+$$
$$+S\left(\frac{H\bar{\psi}_L\psi_R}{\Lambda_\psi}+\text{h.c.}\right)+S\frac{|D_\mu H|^2}{\Lambda_H}+S\frac{H^\dagger D^2 H+\text{h.c.}}{\Lambda_S},$$

Franceschini et.al.
JHEP03(2016)144

**Longitudinal polarization part of S→ WW, ZZ**

| operator | $\frac{\Gamma(S\to Z\gamma)}{\Gamma(S\to\gamma\gamma)}$ | $\frac{\Gamma(S\to ZZ)}{\Gamma(S\to\gamma\gamma)}$ | $\frac{\Gamma(S\to WW)}{\Gamma(S\to\gamma\gamma)}$ |
|---|---|---|---|
| $WW$ only | $2/\tan^2\theta_W\approx 7$ | $1/\tan^4\theta_W\approx 12$ | $2/\sin^4\theta_W\approx 40$ |
| $BB$ only | $2\tan^2\theta_W\approx 0.6$ | $\tan^4\theta_W\approx 0.08$ | 0 |

Note that these estimation DO NOT include longitudinal polarization terms.

# Model



We introduce one SU(2) doublet VLQ and two SU(2) singlet VLQs.

$$\mathcal{Q}_{L/R} = \begin{pmatrix} \mathcal{U}' \\ \mathcal{D}' \end{pmatrix}_{L/R}, \quad \mathcal{U}_{L/R}, \quad \mathcal{D}_{L,R}.$$

Yukawa couplings are as follows

$$\begin{aligned} -\mathscr{L}_Y &= S_0 \left[ y_{\mathcal{Q}} \bar{\mathcal{Q}}\mathcal{Q} + y_{\mathcal{U}} \bar{\mathcal{U}}\mathcal{U} + y_{\mathcal{D}} \bar{\mathcal{D}}\mathcal{D} \right] + M_{\mathcal{Q}} \bar{\mathcal{Q}}\mathcal{Q} + M_{\mathcal{U}} \bar{\mathcal{U}}\mathcal{U} + M_{\mathcal{D}} \bar{\mathcal{D}}\mathcal{D} \\ &\quad + \left[ Y_{\mathcal{D}} \bar{\mathcal{Q}}_L H \mathcal{D}_R + Y'_{\mathcal{D}} \bar{\mathcal{Q}}_R H \mathcal{D}_L + Y_{\mathcal{U}} \bar{\mathcal{Q}}_L \widetilde{H} \mathcal{U}_R + Y'_{\mathcal{U}} \bar{\mathcal{Q}}_R \widetilde{H} \mathcal{U}_L + H.c. \right], \end{aligned}$$

Mixing among VLQs:

$$\mathbb{M}_F = \begin{pmatrix} M_{\mathcal{Q}} & \frac{Y_F v}{\sqrt{2}} \\ \frac{Y_F v}{\sqrt{2}} & M_F \end{pmatrix}$$

$$M_{F_1,F_2} = \frac{1}{2} \left[ M_{\mathcal{Q}} + M_F \mp \sqrt{(M_F - M_{\mathcal{Q}})^2 + 2Y_F^2 v^2} \right]$$

$$s_{2\theta_F} = \frac{\sqrt{2} Y_F v}{M_{F_2} - M_{F_1}},$$

U2, D2 → doublet-like, U1, D1 → singlet-like

# Model



Extension of the Scalar Potential:

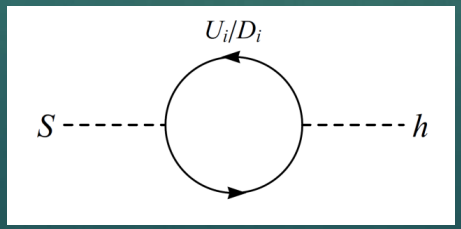
$$V(H,S_0) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2 + \frac{a_1}{2} S_0 H^\dagger H + \frac{a_2}{2} S_0^2 H^\dagger H + b_1 S_0 + \frac{b_2}{2} S_0^2 + \frac{b_3}{3} S_0^3 + \frac{b_4}{4} S_0^4.$$

We assume the decoupling limit:

$$a_1^{\text{tree}} = 0 = a_2^{\text{tree}}$$

$\langle H \rangle = v, \langle S \rangle = 0,$ ← by redefining $a_i, b_i$

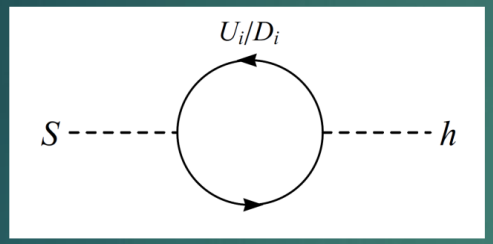
S-h mixing occurs only through loop correction



# Model



## S-h mixing:



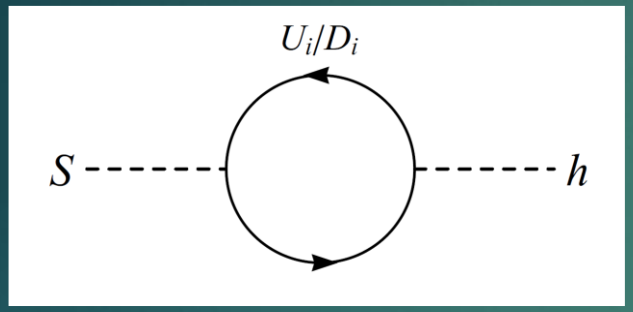

$$\delta M_{Sh}^2 = -\frac{y_S N_c}{4\pi^2} \sum_F \sum_i y_{h F_i F_i} M_{F_i}^2 \left[ 4(\tau_{F_i}^S - 1) g(\tau_{F_i}^S) - 4\tau_{F_i}^S + 5 \right]$$

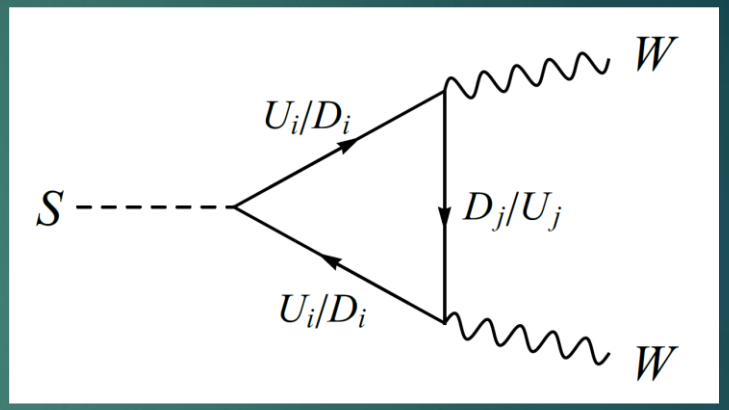
$$s_{2\eta} = -\frac{2\,\delta M_{Sh}^2}{m_S^2 - m_h^2}$$

$$h_0 = c_\eta h + s_\eta S$$

# Decay processes






$S \to WW, ZZ, hh$

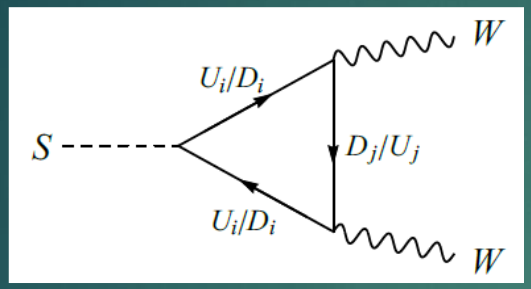
$S \to \bar{t}t$

$S \to WW, ZZ, hh$

$S \to \gamma\gamma, Z\gamma$

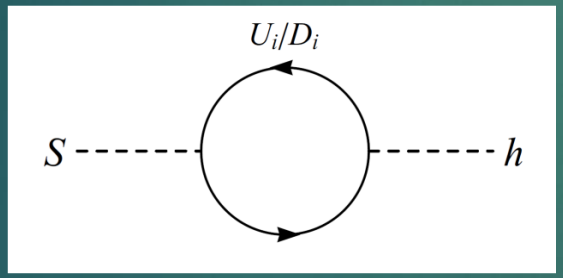
# Renormalization



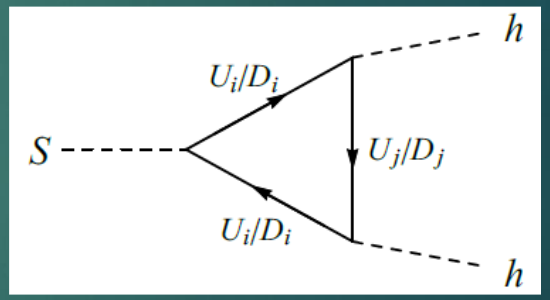



UV finite

$$S \to WW, ZZ, \gamma\gamma, Z\gamma$$




UV div.




UV div.

These divergences are canceled by a single renormalization counter term $\delta a_1$.

# Longitudinal Enhancement



$$S(p)V_\mu(p_1)V'_\nu(p_2) : m_S \left[\mathcal{A}\, g_{\mu\nu} + \mathcal{B}\, \frac{p_{2\mu}p_{1\nu}}{m_S^2}\right]$$
$$Shh : m_S\, \mathcal{C},$$

→ Effective couplings of S

$$\langle V_\mu(p_1,\lambda_1)V'_\nu(p_2,\lambda_2)|S(P)\rangle \equiv m_S \mathcal{T}_{\lambda_1\lambda_2}$$

$$\mathcal{T}_{++} = \mathcal{T}_{--} = -\mathcal{A},$$
$$\mathcal{T}_{00} = \begin{cases} \dfrac{m_S^2}{4m_V^2}(2\mathcal{A}+\mathcal{B}) - (\mathcal{A}+\mathcal{B}), & \text{if } m_V \equiv m_{V_1} = m_{V_2} \neq 0; \\ 0, & \text{if } m_{V_1} = 0 \text{ or } m_{V_2} = 0, \end{cases}$$

→ Non-zero (2A+B) implies Longitudinal Enhancement.

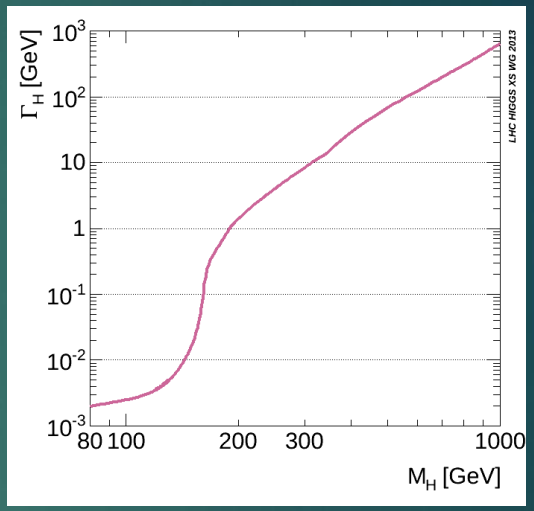
# Longitudinal Enhancement



## SM:

$$\mathcal{A}^{h_{\rm SM}} = \frac{2m_V^2}{vm_h}, \quad \mathcal{B}^{h_{\rm SM}} = 0.$$

(2A+B) ≠ 0 → Longitudinal Enhancement




## Effective Operator

$$\frac{g_2^2}{2\Lambda_W} S W_{\mu\nu} W^{\mu\nu}$$

$\mathcal{A} = g_2^2 \frac{M_S}{\Lambda_W}$, $\mathcal{B} = -2g_2^2 \frac{M_S}{\Lambda_W}$ → $2\mathcal{A} + \mathcal{B} = 0$ → No Longitudinal Enhancement

# Longitudinal Enhancement



In our model:

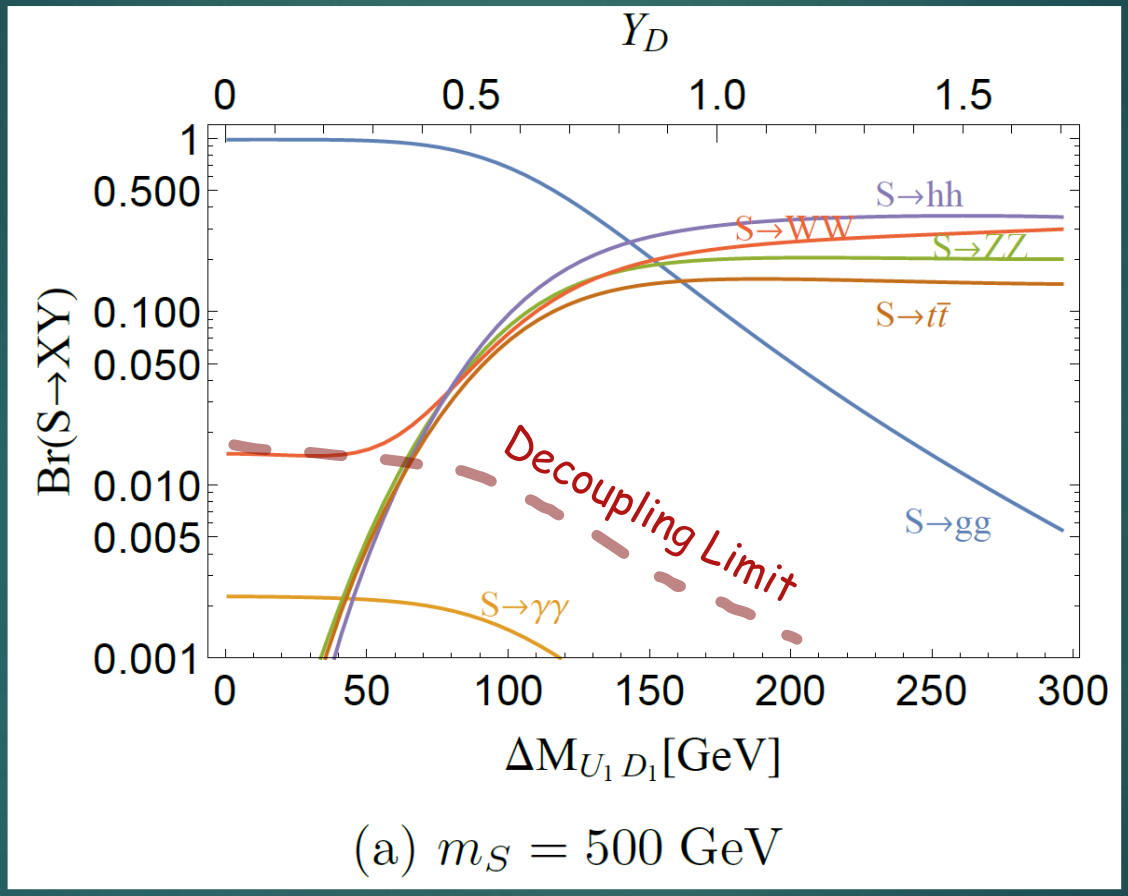
$$
\begin{aligned}
\sqrt{\tau}\,\mathcal{A}_T &= 1 + (1-\tau^{-1})f(\tau) \\
&\quad + \left(\frac{\Delta_F^2}{M^2}\right)\left[-\frac{1}{4} + \frac{(3\tau-4)f(\tau)}{4\tau^2} + \frac{(\tau^2+4\tau-8)g(\tau)}{4\tau(\tau-1)}\right] \\
&\quad + 2\left(\frac{m_V^2}{m_S^2}\right)\left[3-\tau-\tau^{-1}f(\tau)-2g(\tau)\right] + \mathcal{O}\left(\frac{\Delta_F^4}{M^4}\right) + \mathcal{O}\left(\frac{m_V^4}{m_S^4}\right), \\
\sqrt{\tau}\,\mathcal{B}_T &= -2 - 2(1-\tau^{-1})f(\tau) \\
&\quad + \left(\frac{\Delta_F^2}{M^2}\right)\left[\frac{5}{2} + \frac{(8-5\tau)f(\tau)}{2\tau^2} - \frac{(\tau^2+12\tau-16)g(\tau)}{2\tau(\tau-1)}\right] \\
&\quad + 4\left(\frac{m_V^2}{m_S^2}\right)\left[\tau-4+(2-\tau)\tau^{-1}f(\tau)+2g(\tau)\right] + \mathcal{O}\left(\frac{\Delta_F^4}{M^4}\right) + \mathcal{O}\left(\frac{m_V^4}{m_S^4}\right)
\end{aligned}
$$

$$2\mathcal{A} + \mathcal{B} \propto \frac{\Delta_F^2}{M^2} \qquad (\Delta_F = M_{F_1} - M_{F_2})$$

→ Longitudinal Enhancement occurs for large mass difference in the loop

# Branching Ratios



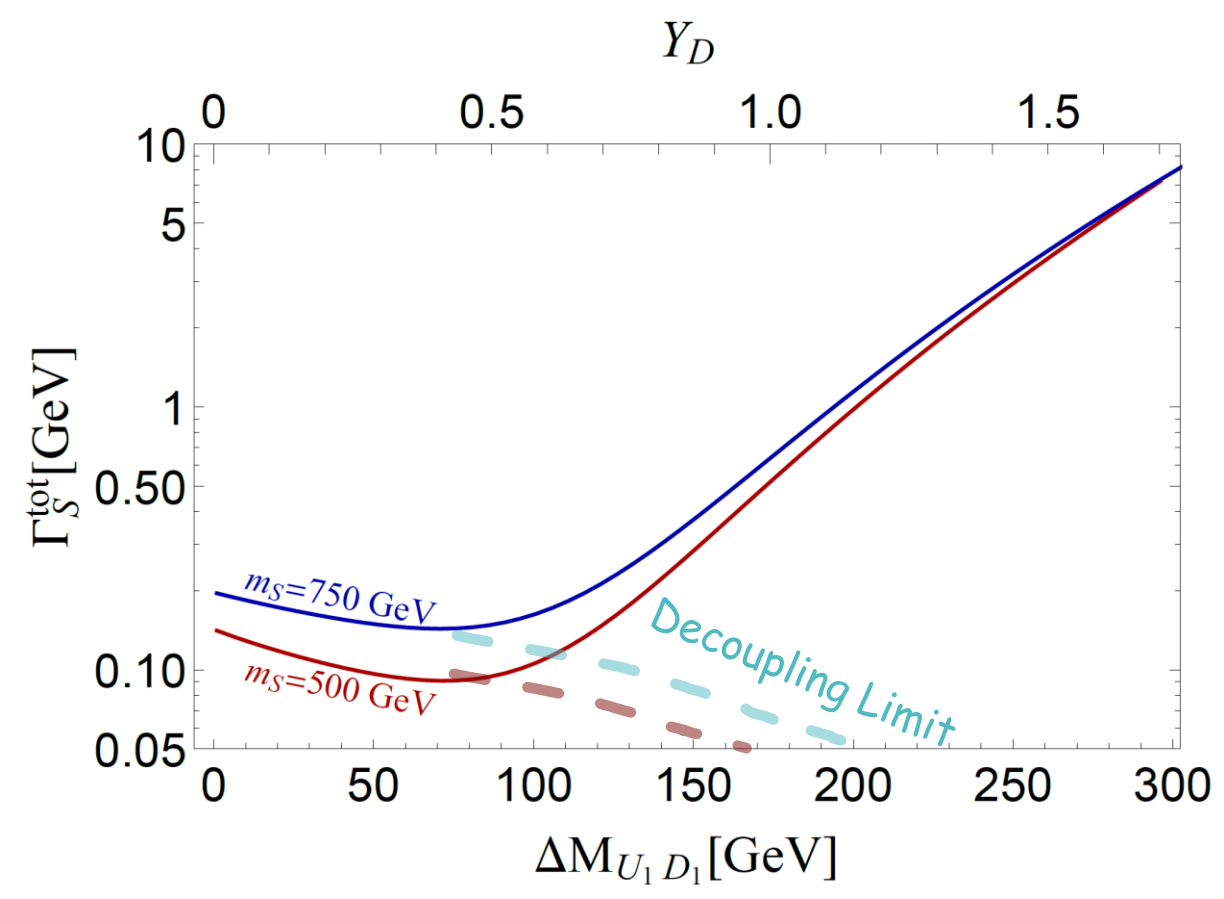



(a) $m_S = 500$ GeV

Longitudinal Enhancement for large mass difference in the loop

# Total Decay rates






Longitudinal Enhancement for large mass difference in the loop

# On the Equivalence Theorem



Consider following term in the scalar potential

$$\frac{a_1}{2} S_0 H^\dagger H$$

$$\Gamma(S \to G^+ G^-) = 2 \times \Gamma(S \to G^0 G^0) = 2 \times \Gamma(S \to hh)$$

However,

$$\Gamma(S \to W^+ W^-) \neq 2 \times \Gamma(S \to ZZ) \neq 2 \times \Gamma(S \to hh)$$

- Equivalence Theorem is not applicable to S decays in this model.
- The loop correction does not obey the equivalence theorem.

# Higgs Precision



$$h_0 = c_\eta h + s_\eta S$$

VLQ loop contributes to the effective $hgg, h\gamma\gamma$ vertices.

$$\kappa_{g,\gamma} = \frac{c_\eta A^{\rm SM}_{hgg,h\gamma\gamma} + \mathcal{A}^{\rm VLQ}_{hgg,h\gamma\gamma}}{A^{\rm SM}_{hgg,h\gamma\gamma}}$$

Since the W loop contribution dominates $h\gamma\gamma$ vertex. It acts as a buffer against the NP contribution.

Constraints from $hgg$ is stronger.

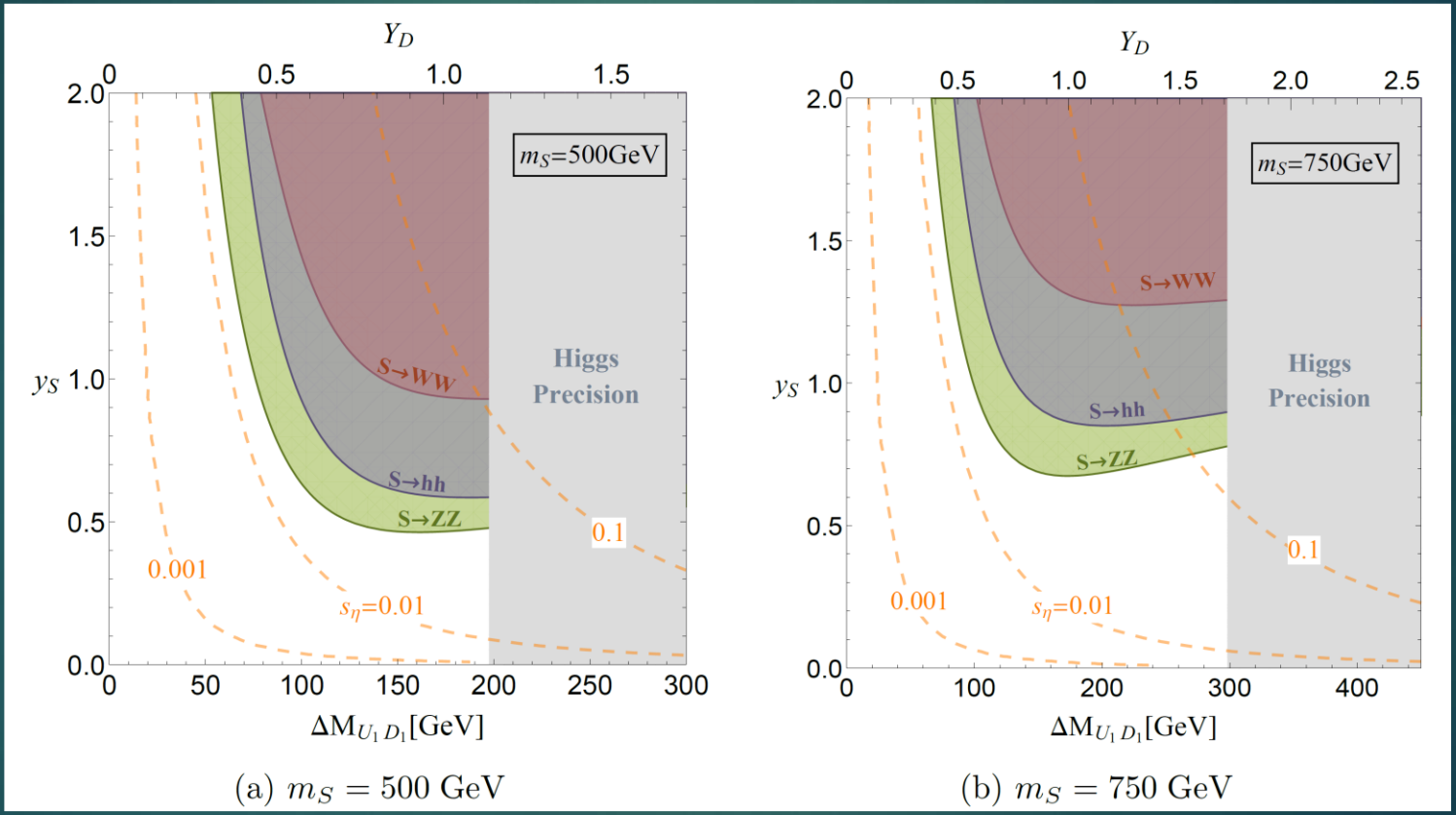
Experimental bounds are

$$\kappa_V = 0.97 \pm 0.060,\ \kappa_g = 0.81^{+0.13}_{-0.10},\ \text{and}\ \kappa_\gamma = 0.90^{+0.10}_{-0.09}$$

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# Excluded region from the current Exp.






(a) $m_S = 500$ GeV (b) $m_S = 750$ GeV

# Summary



- Even in the parameter set of complete decoupling limit the real phenomena do not necessarily follow the decoupling limit at one-loop level
- The Longitudinal Enhancement and the Non-decoupling effect arise in S decays when the mass difference between VLQs inside the loop is large.
- The ZZ, hh, WW channels are still promising to probe Singlet scalar at the LHC even we set the tree level parameters of complete decoupling limit.