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How to unscramble the NP effects on the nonresonant diHiggs process at the LHC

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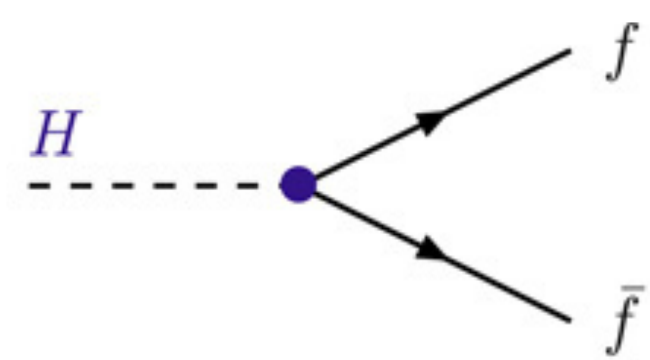
w/ K.Cheung, A.Jueid, C.Lu, Y.W. Yoon, PRD 103 (2021)

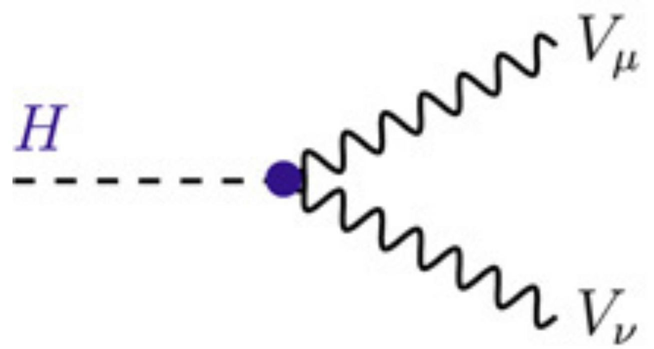
1. Motivation
2. Driving question
3. 2HDM with VLQs
4. Results
5. Conclusions

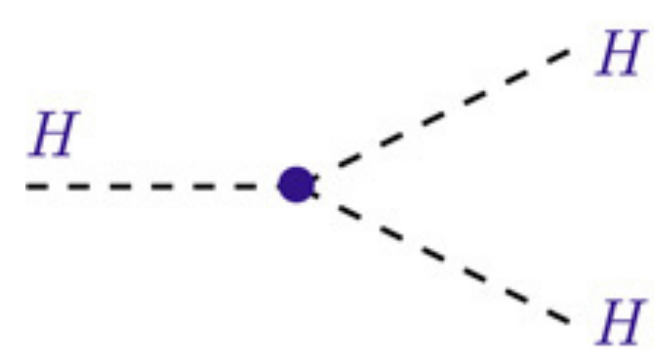
1. Motivation

Higgs couplings in the SM are well defined, associated with the masses.

$$\Phi(x) \to e^{-i\theta_a(x)\tau^a(x)}\,\Phi(x) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$







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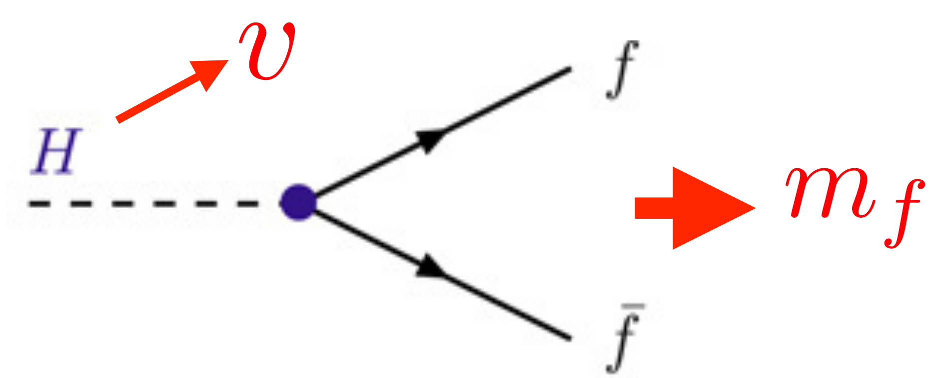
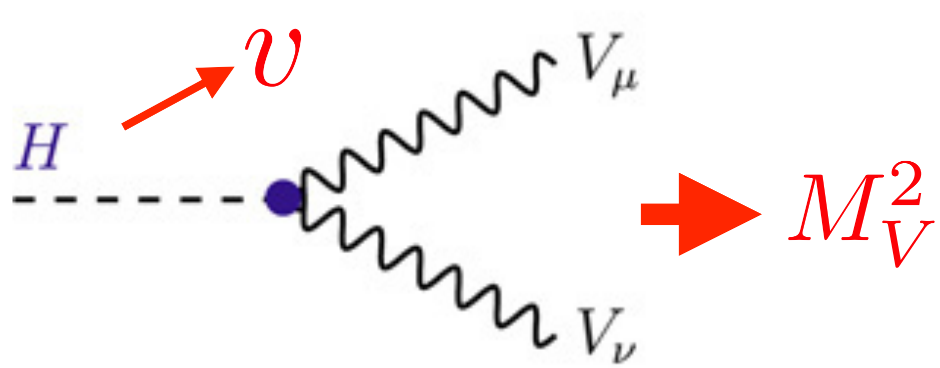
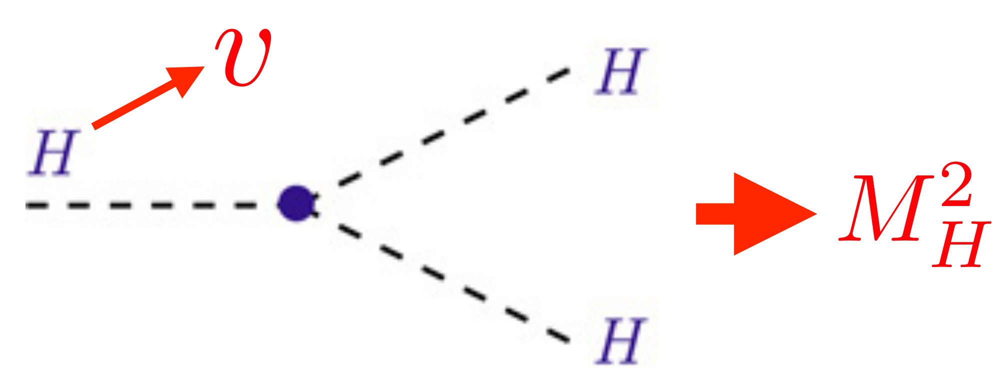
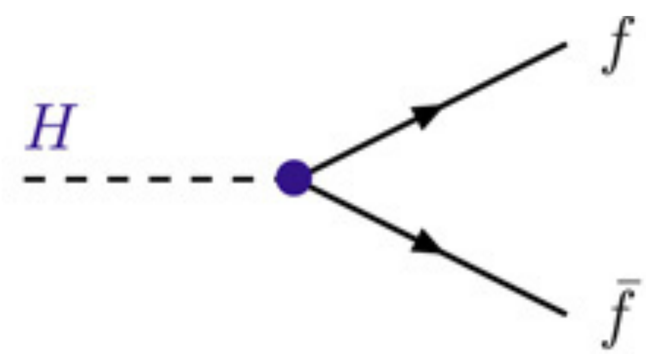
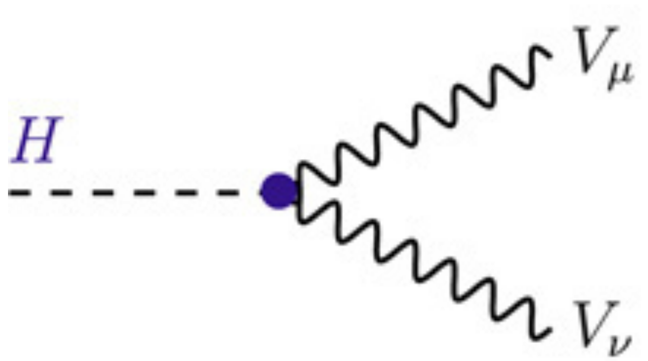


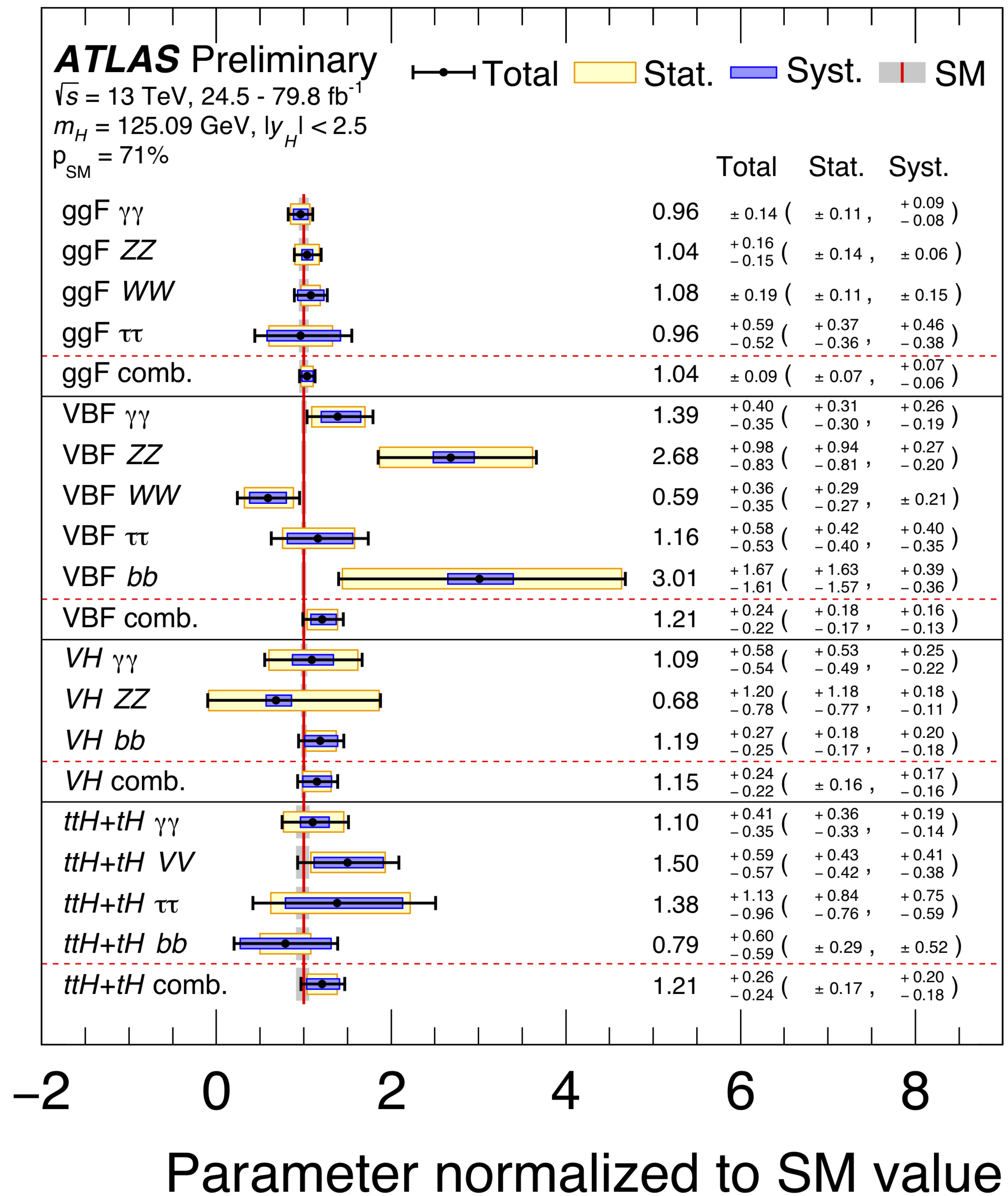




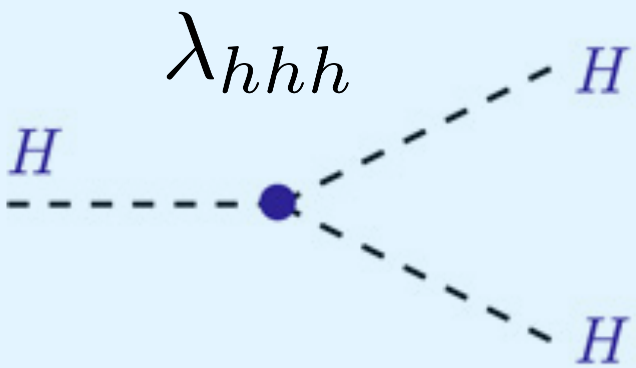
The couplings involving a single Higgs boson are measured to be SM-like.





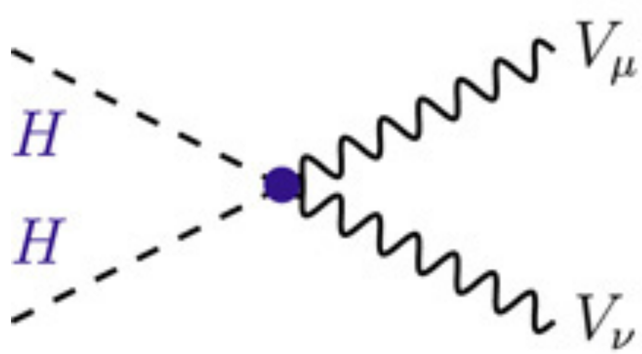


Trilinear Higgs coupling is the first target among unmeasured couplings.

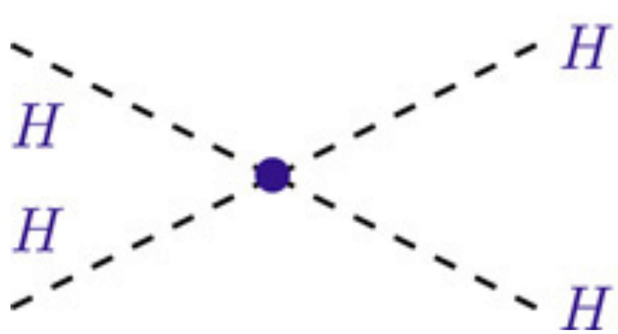


Challenging at the LHC

$$\kappa_\lambda \equiv \frac{\lambda_{hhh}}{\lambda_{hhh}^{\mathrm{SM}}}$$

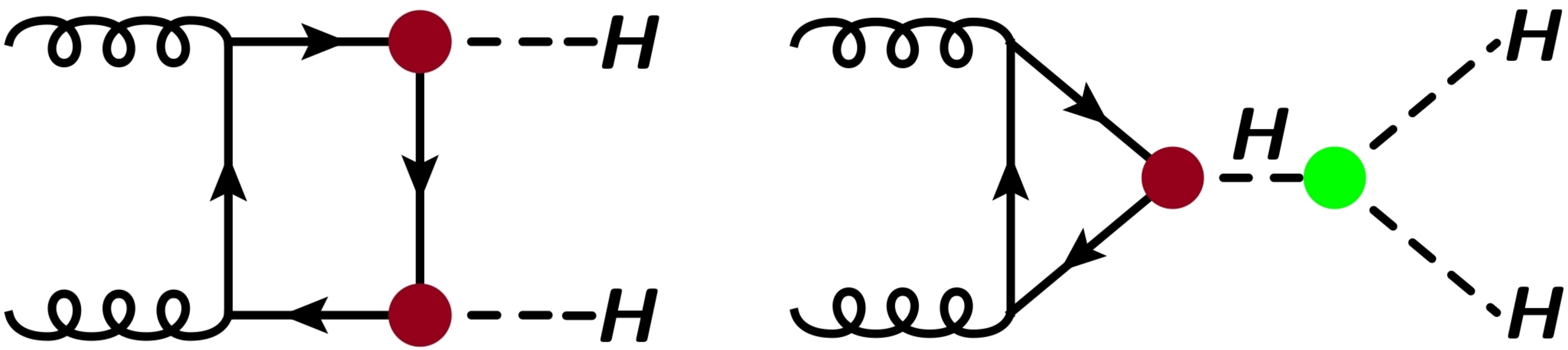


Very challenging at the LHC



Almost impossible at the LHC

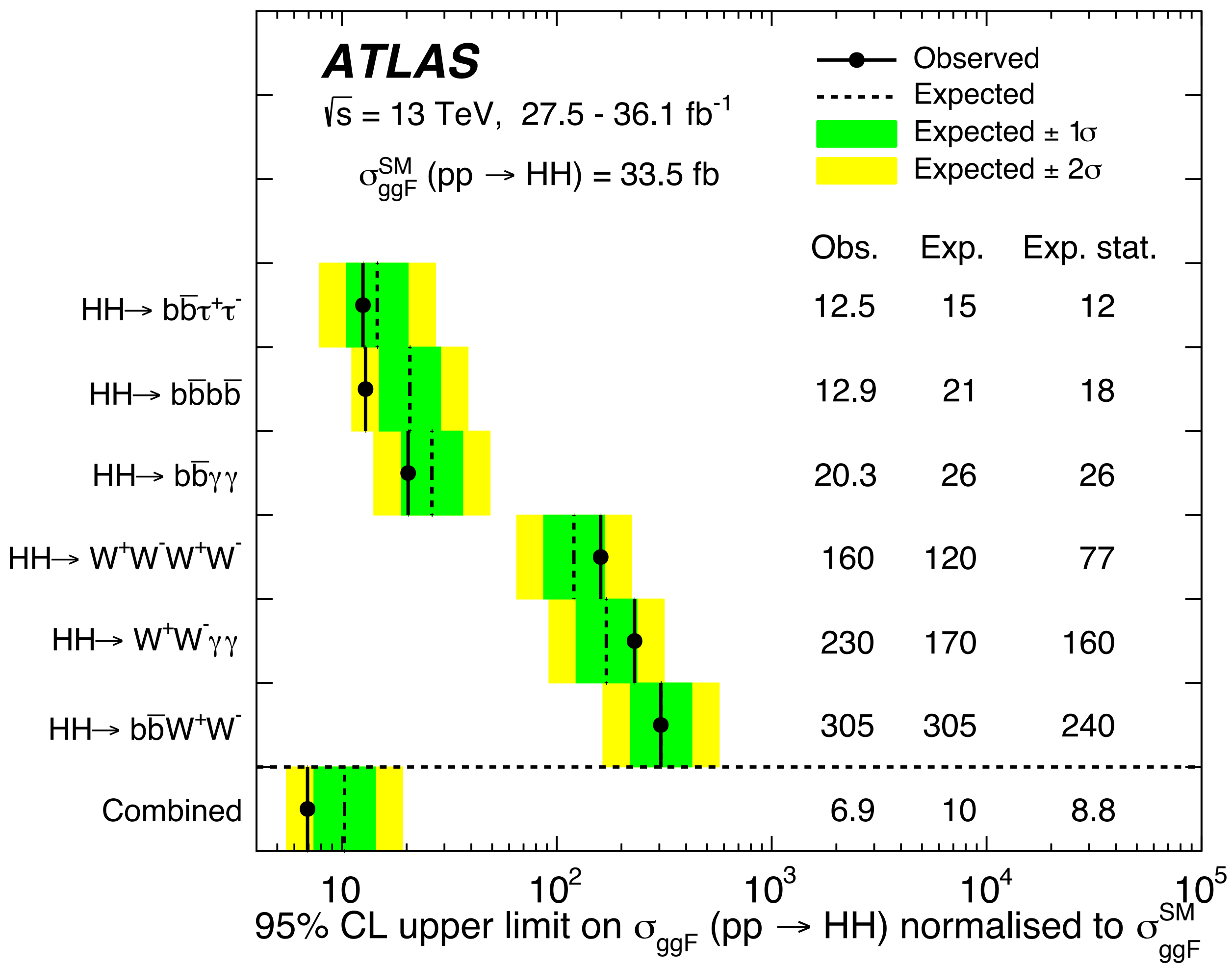
DiHiggs process via gluon fusion at the LHC has the best chance to probe κ_λ.

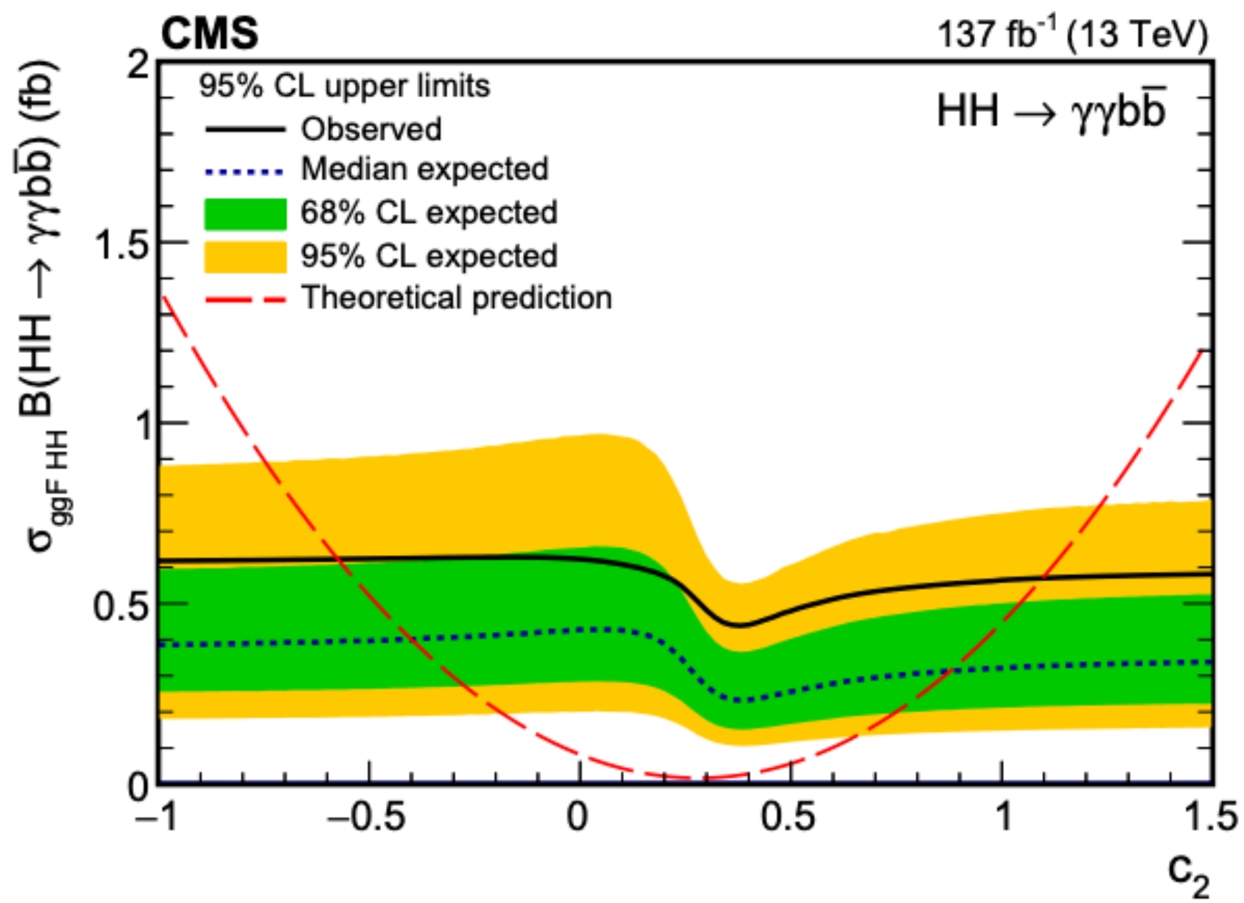


Higgs-fermion Yukawa coupling

Higgs boson self-coupling

Dedicated searches for the diHiggs process have been performed by ATLAS and CMS.





ATLAS,1906.02025

CMS, 2011.12373

Destructive interference suppresses the diHiggs signal rate in the SM.

$$\frac{d\hat{\sigma}(gg \to HH)}{dt} = \frac{\alpha_s^2}{2^{15}\pi^3 v^4} \frac{|F_1(s,t,u,m_t^2)|^2 + |F_2(s,t,u,m_t^2)|^2}{s^2},$$

LET (Low Energy Theorem):

λ_{hhh}

Box **Triangle**

$$F_1(s,t,u,m_t^2)|_{\mathrm{LET}} \to \left(-\frac{4}{3} + \frac{4m_H^2}{s - m_H^2}\right)s,$$

$$F_2(s,t,u,m_t^2)|_{\mathrm{LET}} \to 0.$$ **Box**

$\sqrt{s}$	13 TeV	14 TeV
$\mathrm{NNLO_{FTapprox}}$ [fb]	$31.05^{+2.2\%}_{-5.0\%}$	$36.69^{+2.1\%}_{-4.9\%}$

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGHH

2. Driving question

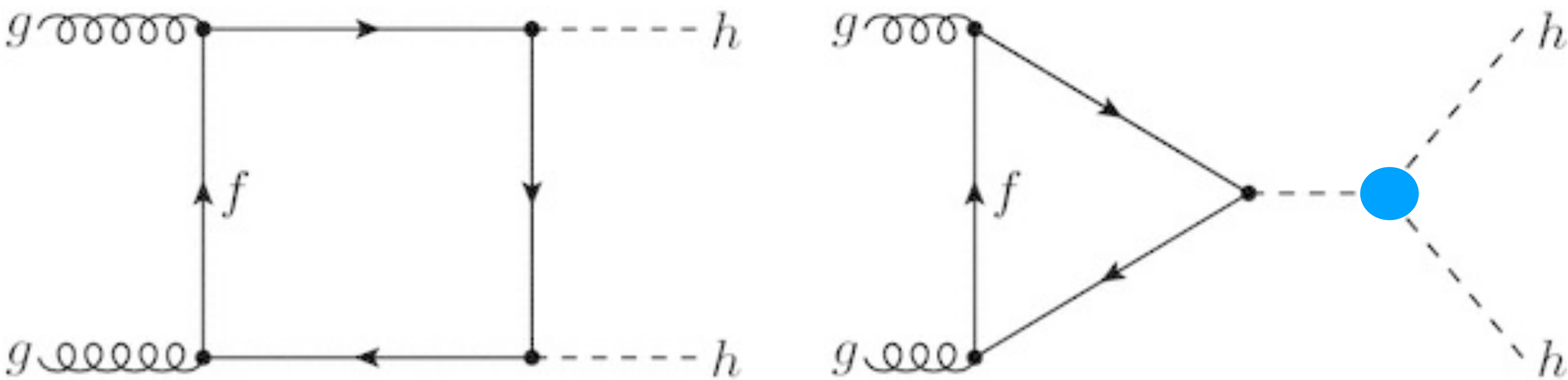

Don't
BE
HAPPY
worry

If the diHiggs rate is larger than the SM prediction, can we tell the NP origin?

For illustrative purpose, we make 2 assumptions.

1. $\kappa_{Hij} = 1$ for all SM particles.
2. $\dfrac{\sigma}{\sigma_{\text{SM}}}(gg \to HH) = 3.$

There are 3 kinds of NP effects on the diHiggs process via gluon fusion.



$$\kappa_\lambda = -0.5, 5.5$$

$$\text{for } \frac{\sigma}{\sigma_{\text{SM}}}(gg \to HH) = 3$$

1. New κ_λ
2. New spin-0 or spin-2 particle
3. New colored fermions

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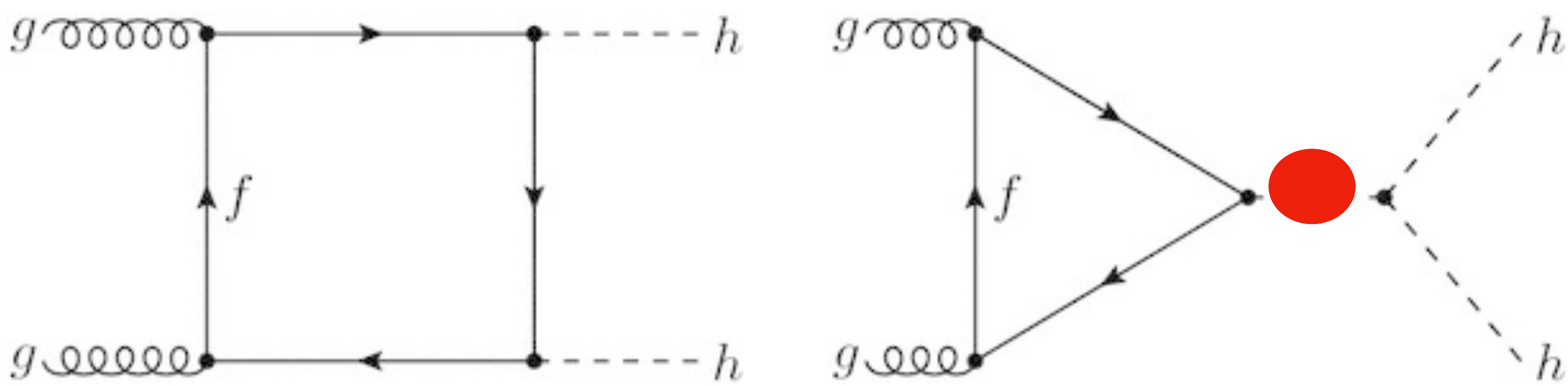

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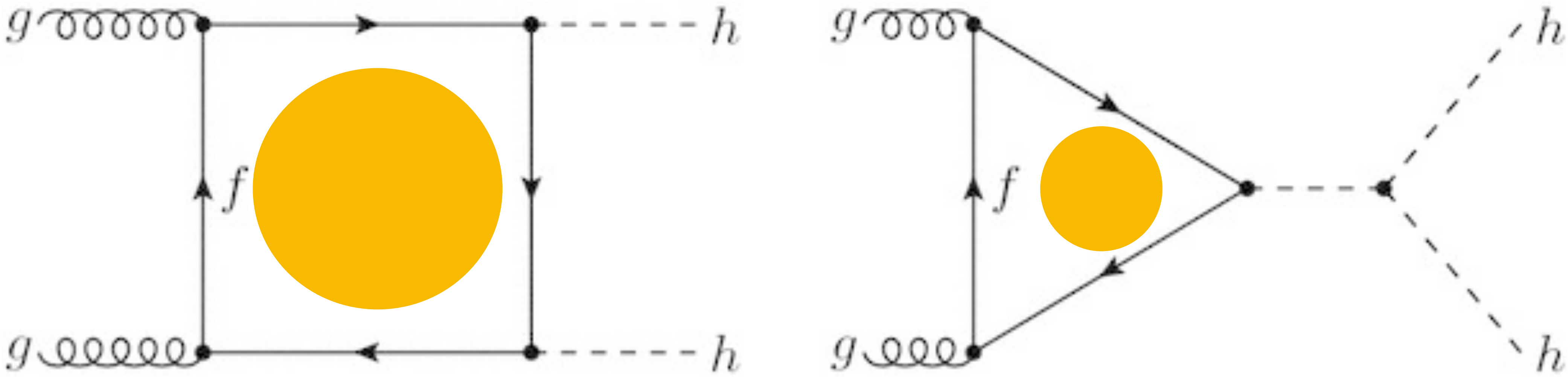

1. New κ_λ
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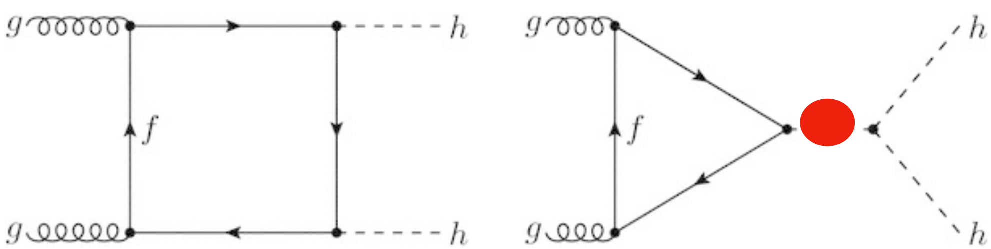
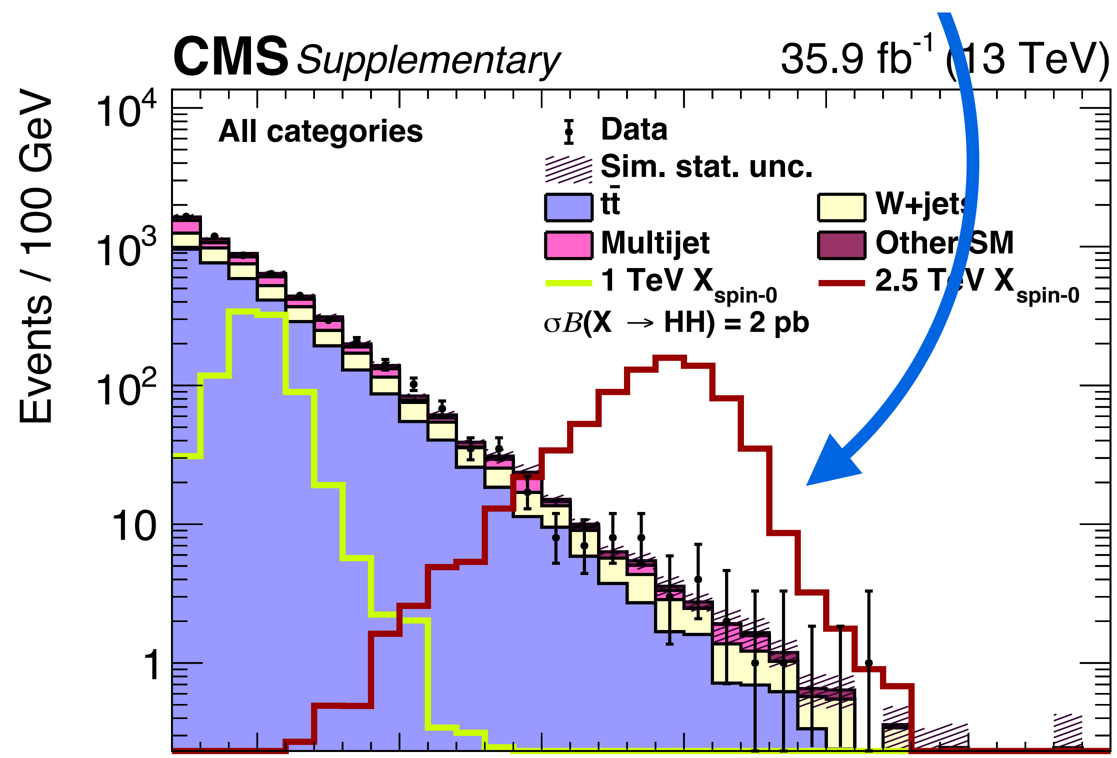
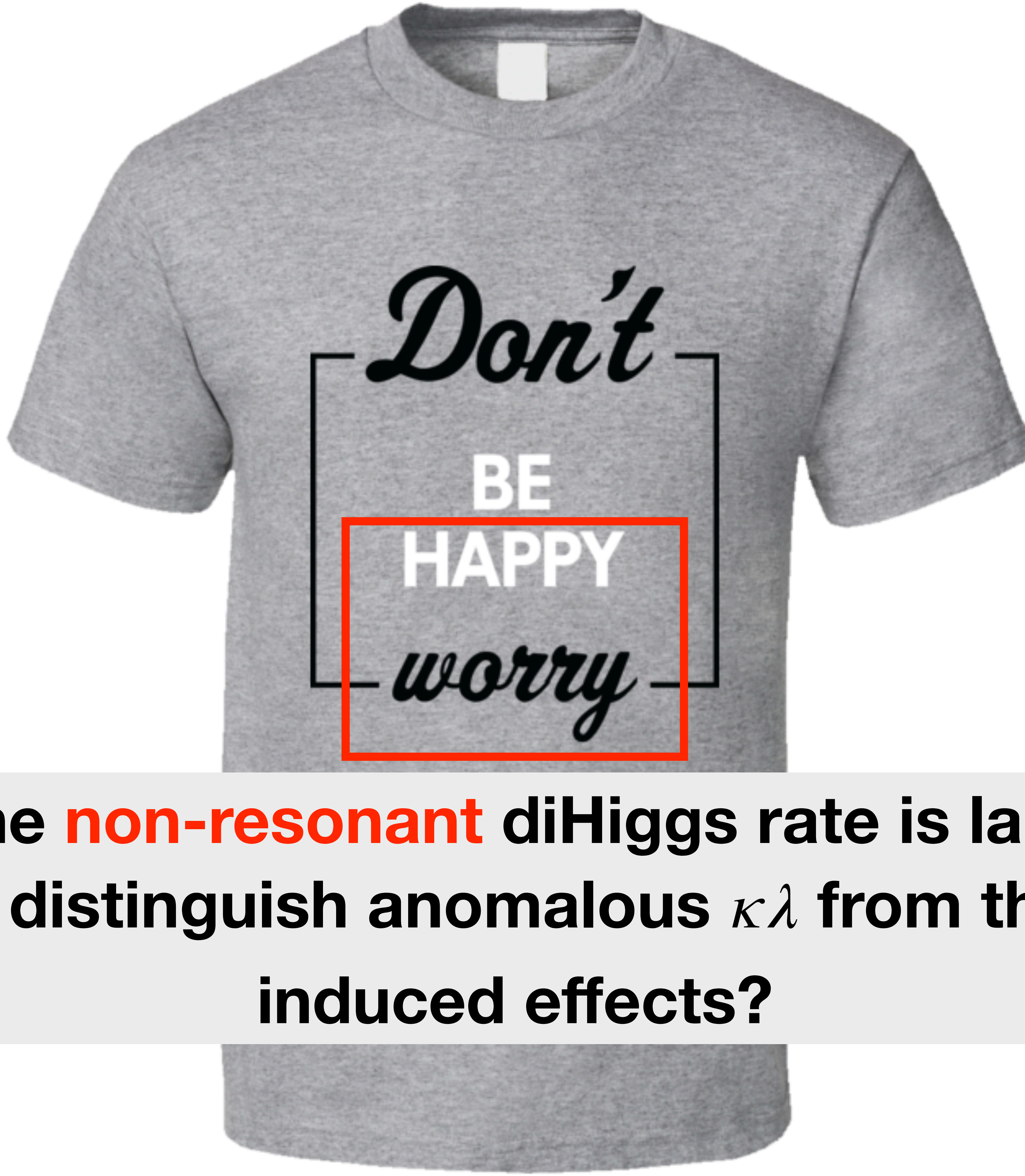
(Narrow) resonances can be identified through 2D bump hunt.



1. New κ_λ
2. New spin-0 or spin-2 particle
3. New colored fermions

	H→b$\bar{b}$ mass	Resonance mass
Signal	Peak at m_H	Peak at m_X
Bkg.	Smooth at m_H	Smoothly falling





If the non-resonant diHiggs rate is large, can we distinguish anomalous $\kappa\lambda$ from the loop-induced effects?

Such a large loop effect?

2. 2HDM with VLQs for $\sigma/\sigma_{SM}=3$

We consider the type-II 2HDM with softly broken Z2 symmetry and CP invariance.

$$\Phi_a = \begin{pmatrix} \phi_a^+ \\ \dfrac{v_a + \rho_a + i\eta_a}{\sqrt{2}} \end{pmatrix}, \quad a = 1, 2.$$

$$\Phi_1 \to \Phi_1 \text{ and } \Phi_2 \to -\Phi_2$$

$$h_{\rm SM} = s_{\beta-\alpha} h + c_{\beta-\alpha} H.$$

We also introduce both doublets and singlets of VLQs.

$$\text{VLF doublet}: \quad \mathcal{Q}_L = \begin{pmatrix} \mathcal{U}'_L \\ \mathcal{D}'_L \end{pmatrix}, \;\; \mathcal{Q}_R = \begin{pmatrix} \mathcal{U}'_R \\ \mathcal{D}'_R \end{pmatrix},$$

$$\text{VLF singlets}: \quad \mathcal{U}_L, \quad \mathcal{U}_R, \quad \mathcal{D}_L, \quad \mathcal{D}_R\,.$$

Crucial to allow the Higgs Yukawa couplings

Yukawa interactions yield two VLQ mixing angles, and 4 VLQ mass eigenstates.

$$
\begin{aligned}
-\mathcal{L}_{\rm Yuk} &= M_{\mathcal{F}}\overline{\mathcal{Q}}\mathcal{Q} + M_{\mathcal{U}}\overline{\mathcal{U}}\mathcal{U} + M_{\mathcal{D}}\overline{\mathcal{D}}\mathcal{D} \\
&\quad + \left[Y_{\mathcal{D}}\overline{\mathcal{Q}}\Phi_1\mathcal{D} + Y_{\mathcal{U}}\overline{\mathcal{Q}}\,\widetilde{\Phi}_2\mathcal{U} + \text{h.c.}\right]
\end{aligned}
$$

$$
\mathbb{M}_{\mathcal{D}} = \begin{pmatrix} M_{\mathcal{Q}} & \frac{1}{\sqrt{2}}Y_{\mathcal{D}}vc_\beta \\ \frac{1}{\sqrt{2}}Y_{\mathcal{D}}vc_\beta & M_{\mathcal{D}} \end{pmatrix}, \quad \mathbb{M}_{\mathcal{U}} = \begin{pmatrix} M_{\mathcal{Q}} & \frac{1}{\sqrt{2}}Y_{\mathcal{U}}vs_\beta \\ \frac{1}{\sqrt{2}}Y_{\mathcal{U}}vs_\beta & M_{\mathcal{U}} \end{pmatrix}.
$$

$$
\mathcal{F}_i = \mathcal{U}_1, \mathcal{U}_2, \mathcal{D}_1, \mathcal{D}_2
$$

Constraint 1: Single Higgs data

1. Alignment limit: SM-like Higgs sector

$$\alpha = \beta - \frac{\pi}{2} \quad \text{(alignment limit)}$$

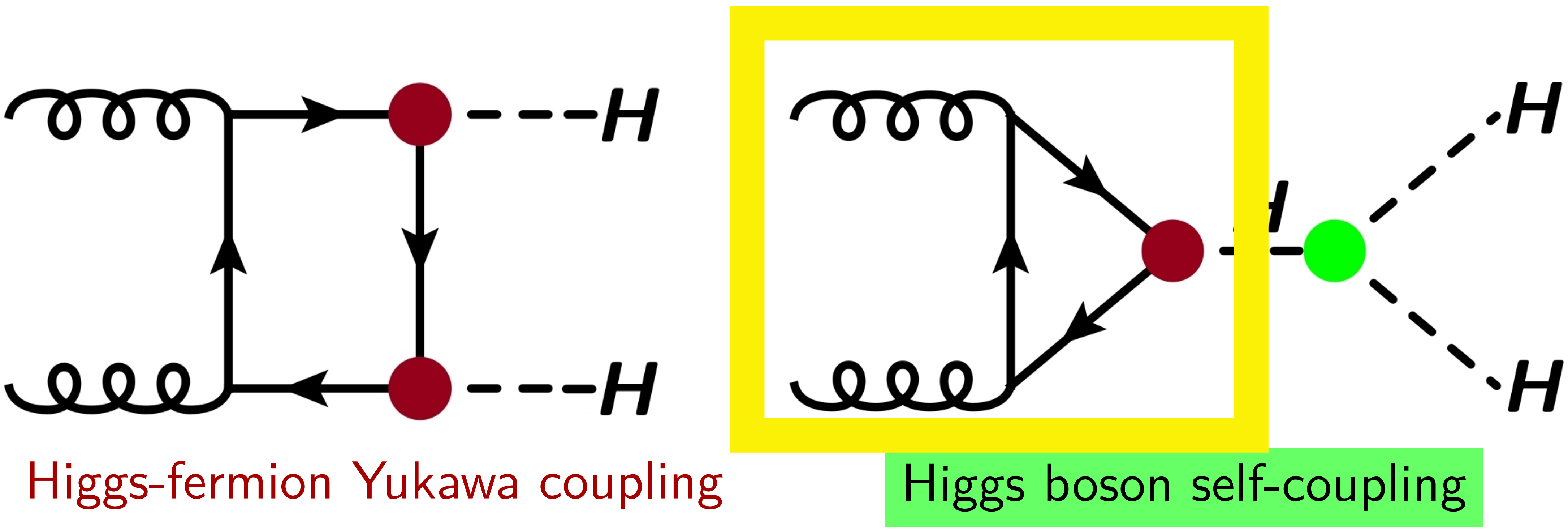
$$\longrightarrow \quad \kappa_u = \kappa_d = 1,$$

2. Wrong-sign limit: extended Higgs sector

$$\alpha = \frac{\pi}{2} - \beta \quad \text{(exact wrong-sign limit)}$$

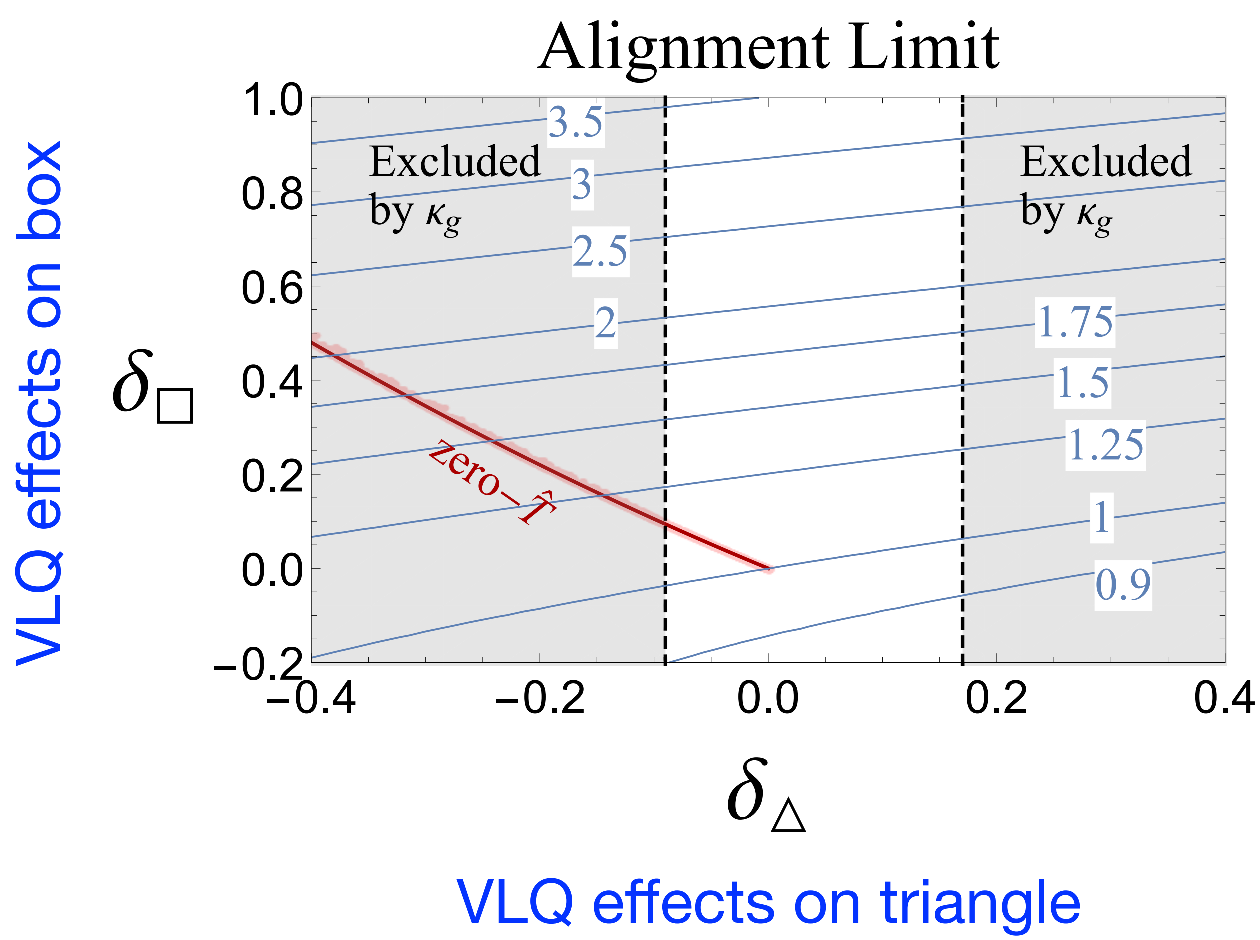
$$\longrightarrow \quad \kappa_u = 1, \quad \kappa_d = -1$$

Correlation with the single Higgs rate is crucial in allowing $\sigma/\sigma_{SM}=3$.



To avoid strong correlation with the single Higgs rate, we take the wrong-sign limit.

Scatter plot study $M_{\mathcal{U}_{1,2}}, M_{\mathcal{D}_{1,2}} > 600\ \text{GeV}, \quad \bar{Y}_{\mathcal{U}}(\equiv Y_{\mathcal{U}} s_\beta),\ \bar{Y}_{\mathcal{D}}(\equiv Y_{\mathcal{D}} c_\beta) < 4\pi\,.$



Red dots: EWPD

Grey regions: NO

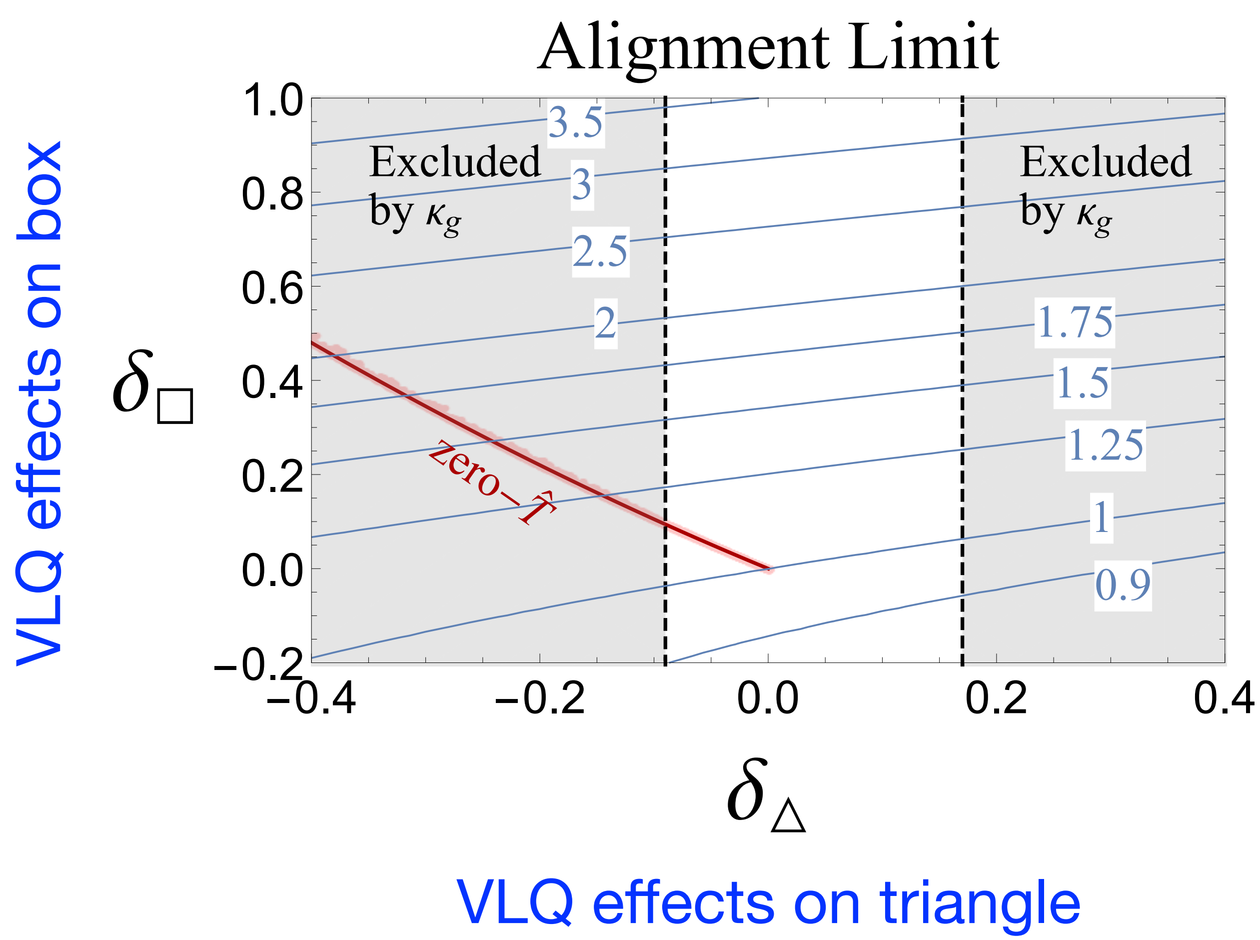
Blue values: $\sigma/\sigma_{SM}=3$

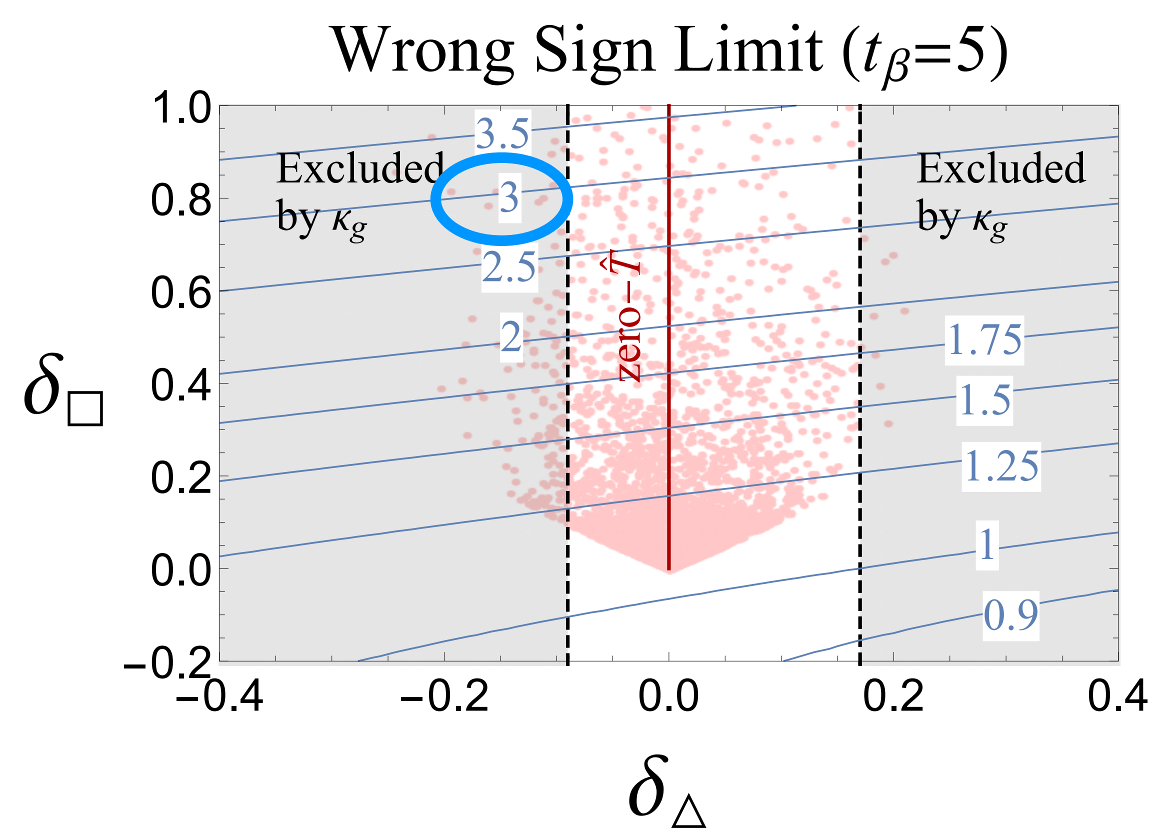
Strong correlation

To avoid strong correlation with the single Higgs rate, we take the wrong-sign limit.

Scatter plot study

$$M_{\mathcal{U}_{1,2}}, M_{\mathcal{D}_{1,2}} > 600 \ \text{GeV}, \quad \bar{Y}_{\mathcal{U}}(\equiv Y_{\mathcal{U}} s_\beta),\ \bar{Y}_{\mathcal{D}}(\equiv Y_{\mathcal{D}} c_\beta) < 4\pi \,.$$

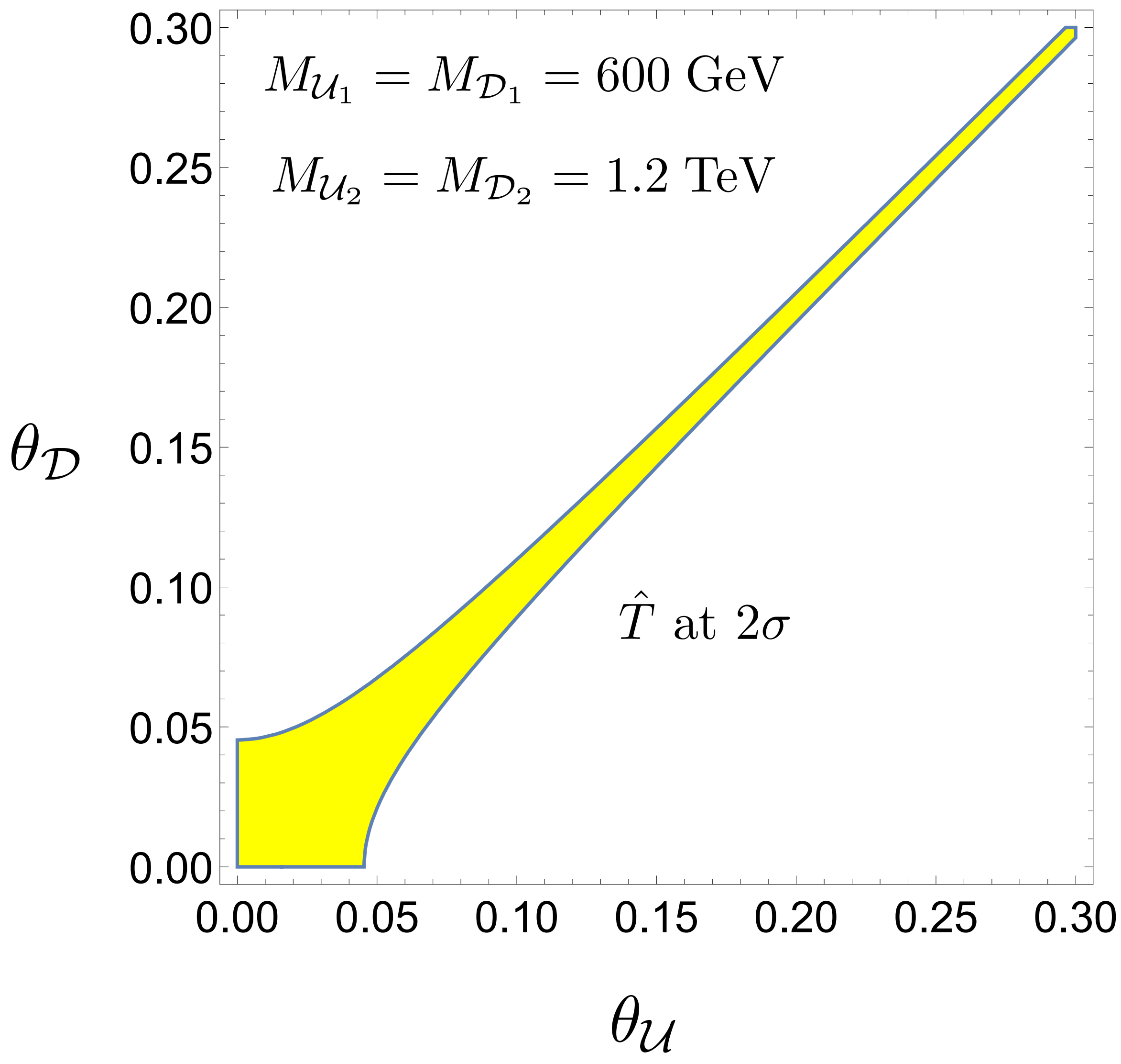




Almost independent

Constraint 2: Peskin-Takeuchi oblique parameters

Ansatz $$M_{\mathcal{U}_1} = M_{\mathcal{D}_1}, \quad M_{\mathcal{U}_2} = M_{\mathcal{D}_2}, \quad \theta_{\mathcal{U}} = \theta_{\mathcal{D}}.$$

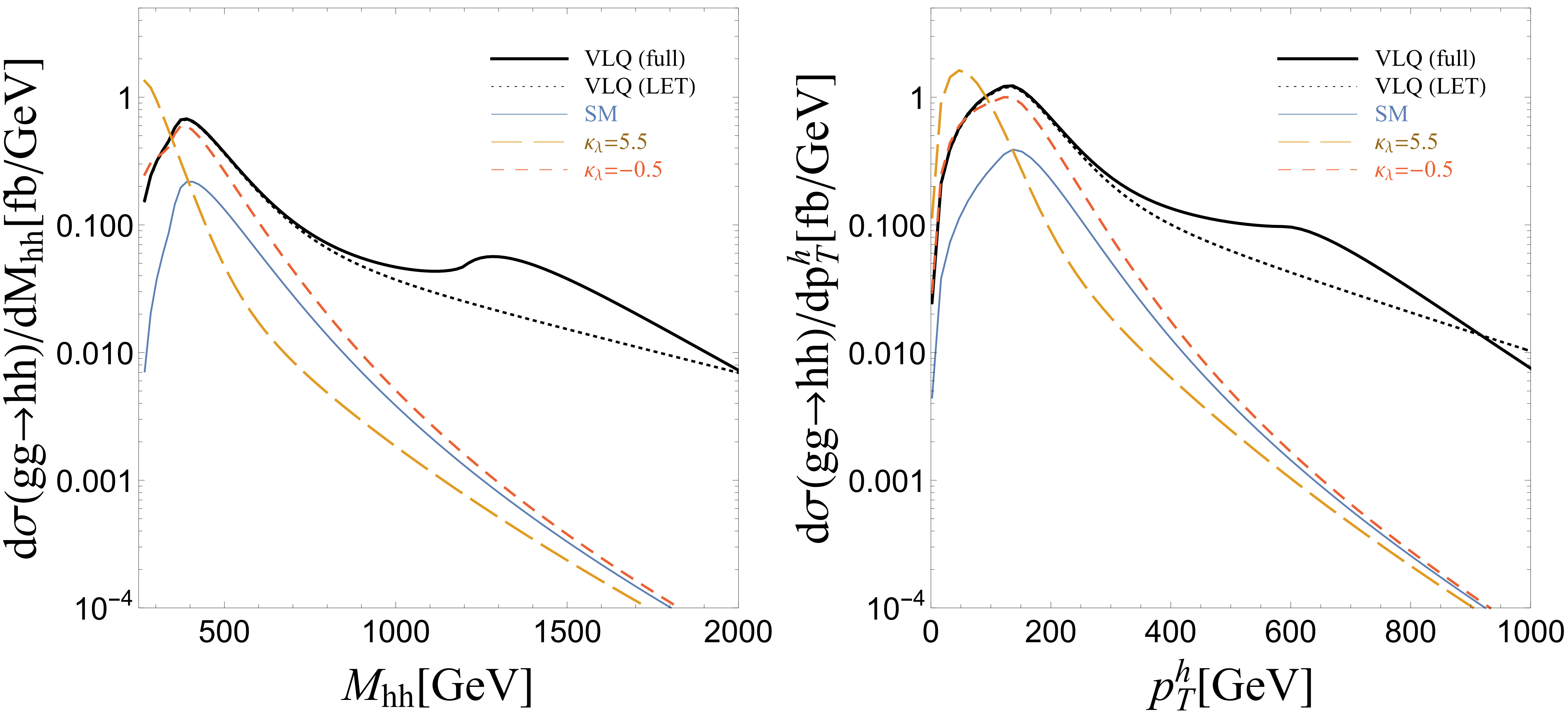


Our benchmark

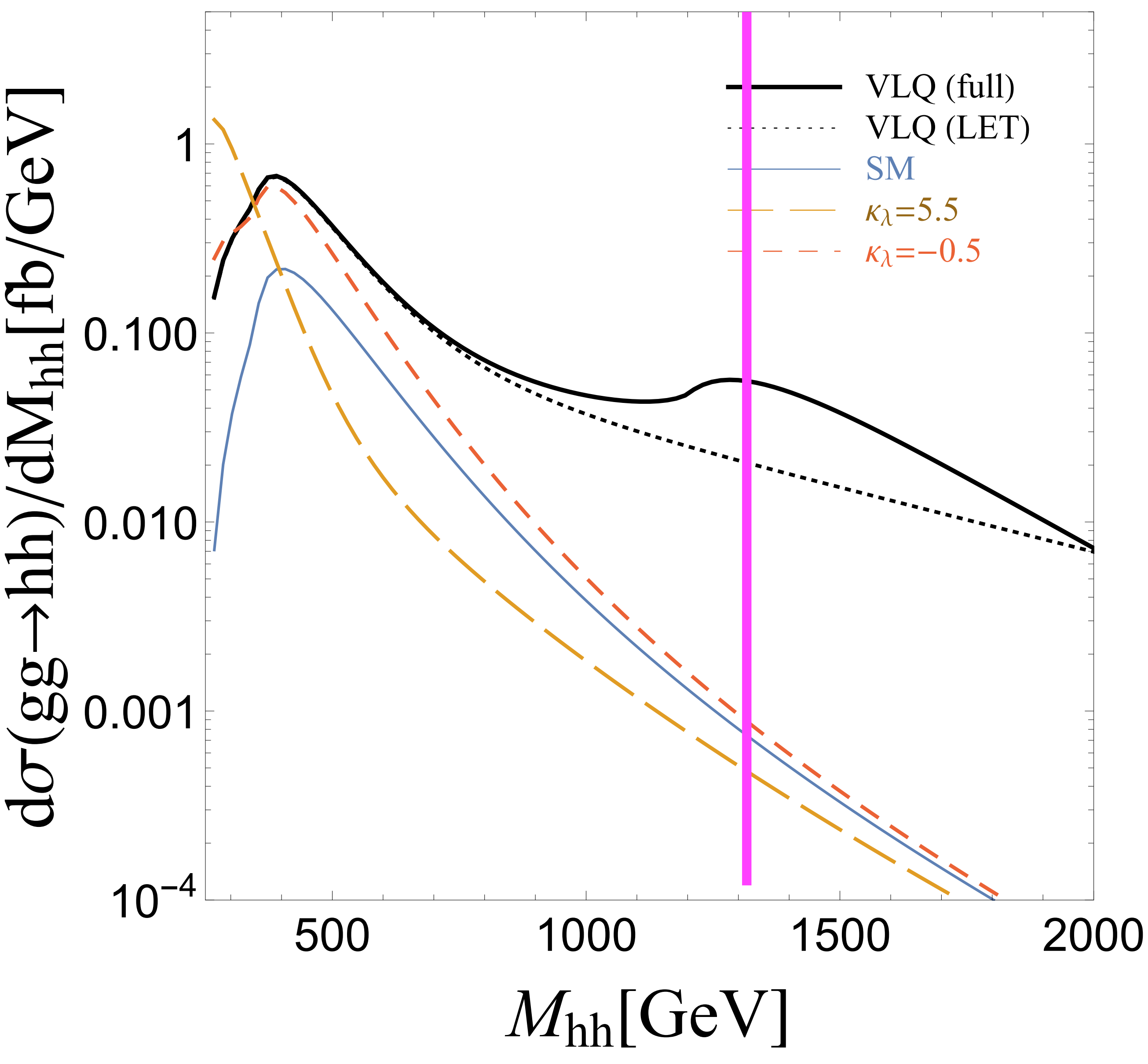
$$\text{benchmark:}\ \ \beta+\alpha=\frac{\pi}{2},\quad t_\beta=5,$$
$$M_1=600\ \text{GeV},\quad \Delta M=900\ \text{GeV},\quad \theta=0.6.$$

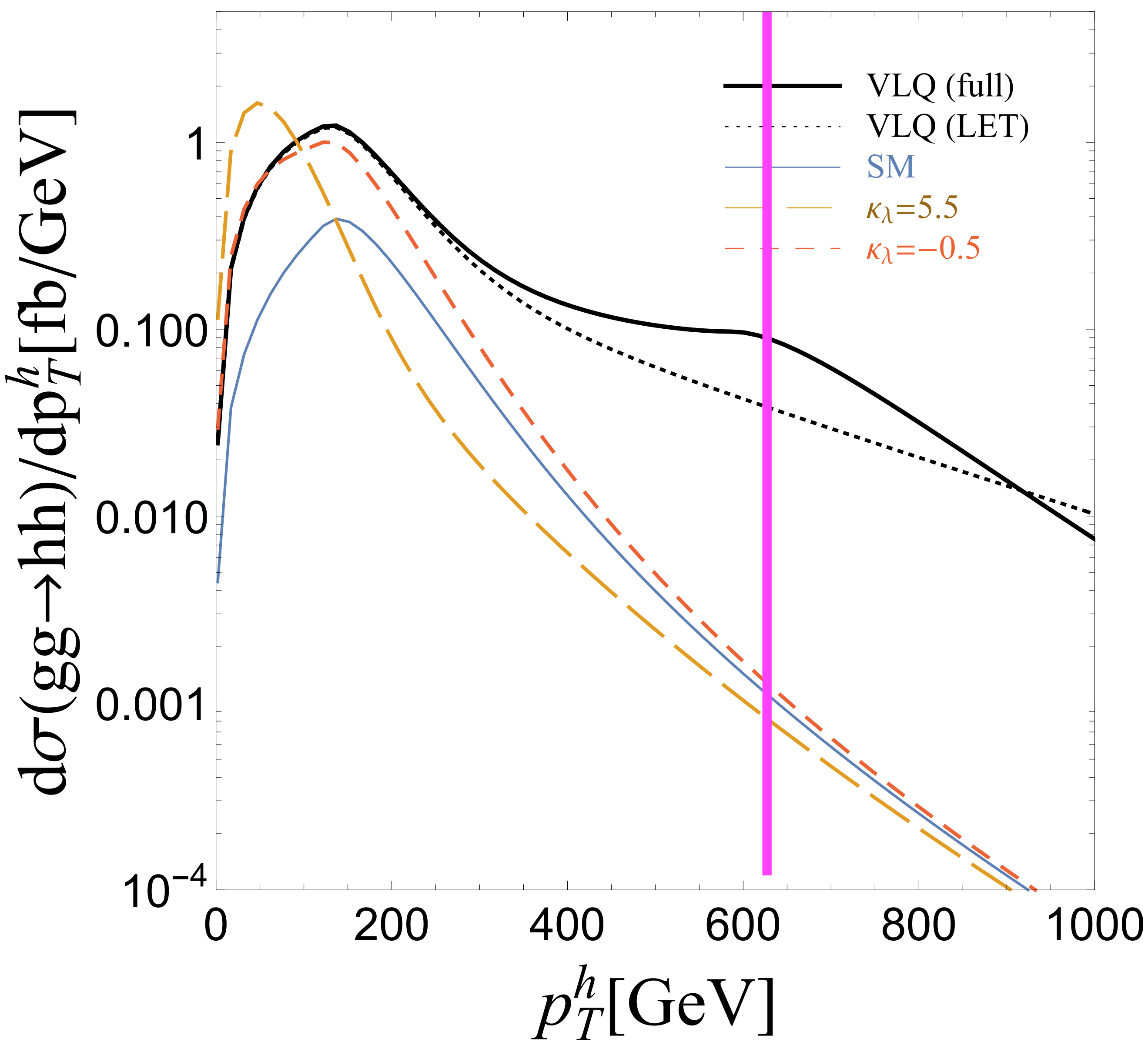
4. Results

Distinction is possible through kinematic distributions.



(1) Bump structures: The positions of two bumps are related.

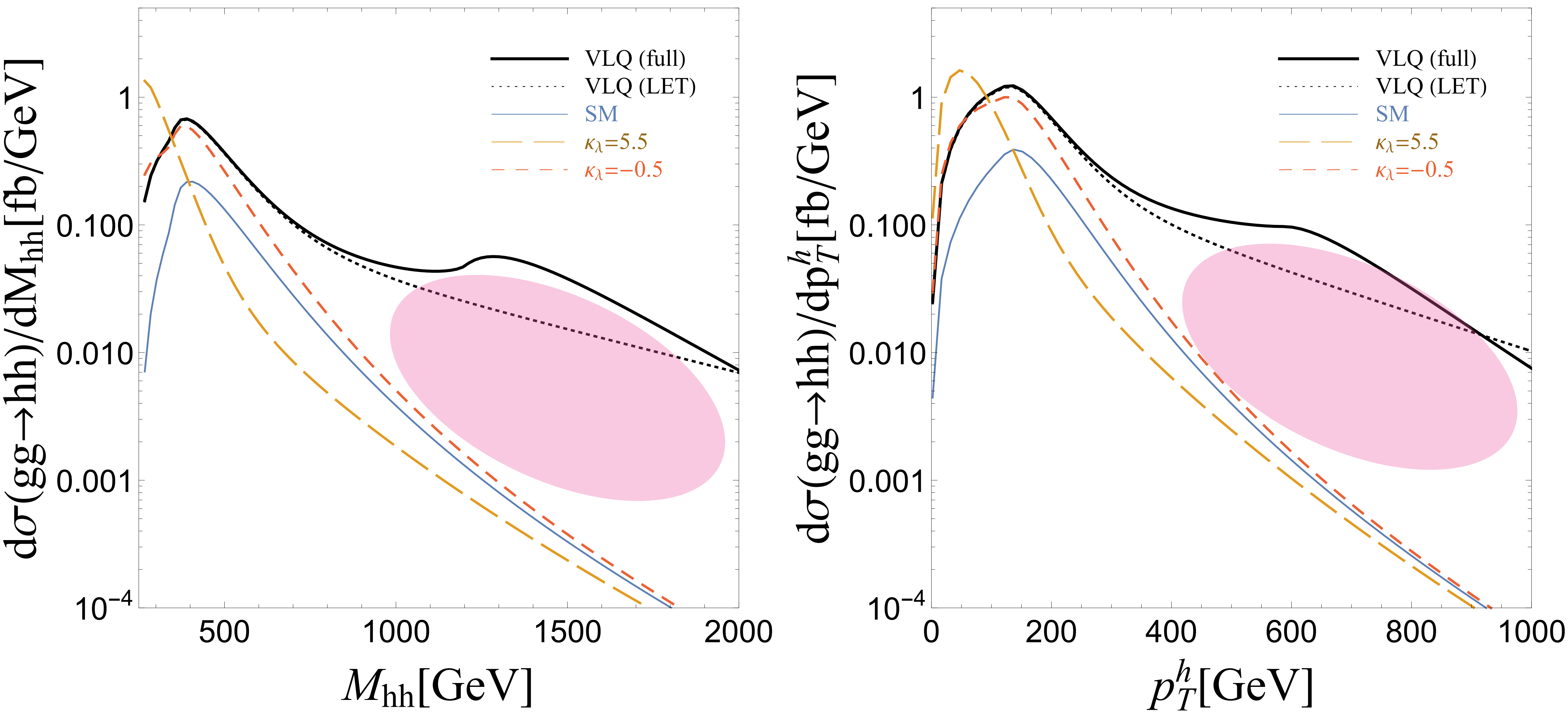




$2M_{\mathrm{VLQ}}$

M_{VLQ}

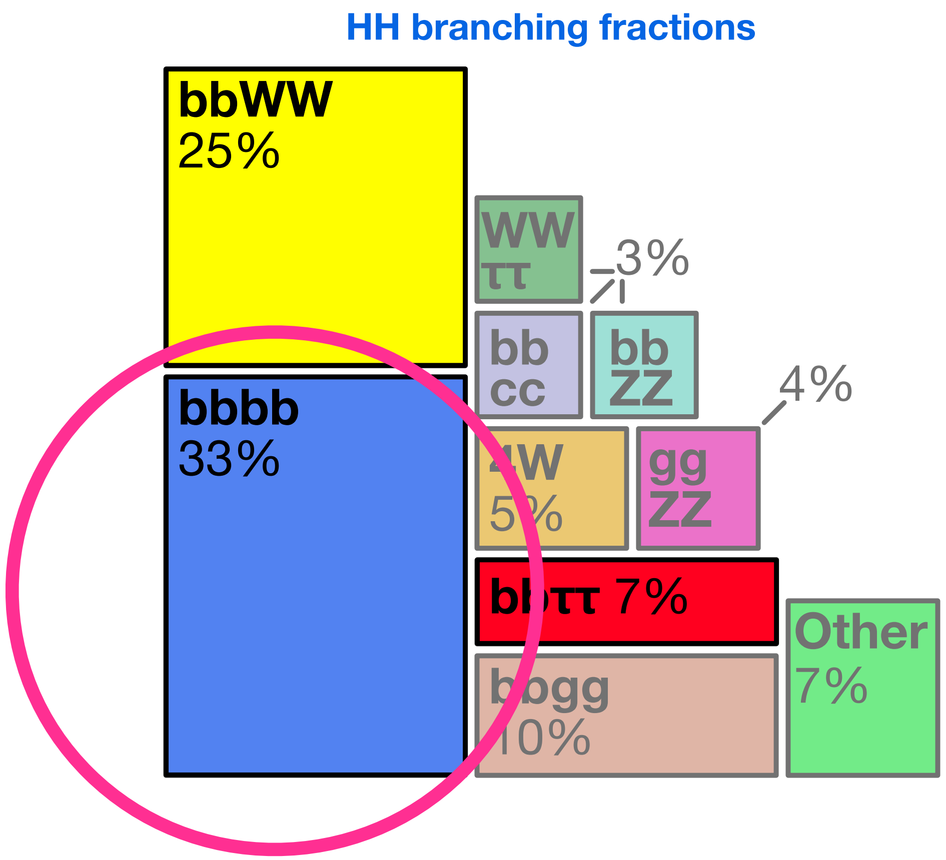
(2) Slow fall in high M_{HH} and p_T regions.



Loop-induced signal have more data in high pT region.

$$\frac{\sigma(gg \to hh; p_T^h > 300\ \text{GeV})}{\sigma_{\text{tot}}(gg \to hh)} = \begin{cases} 6.1\%, & (\text{SM}) \\ 14.5\%, & (\text{VLQ-2HDM}) \\ 3.2\%, & (\kappa_\lambda = -0.5) \\ 1.2\%. & (\kappa_\lambda = 5.5) \end{cases}$$

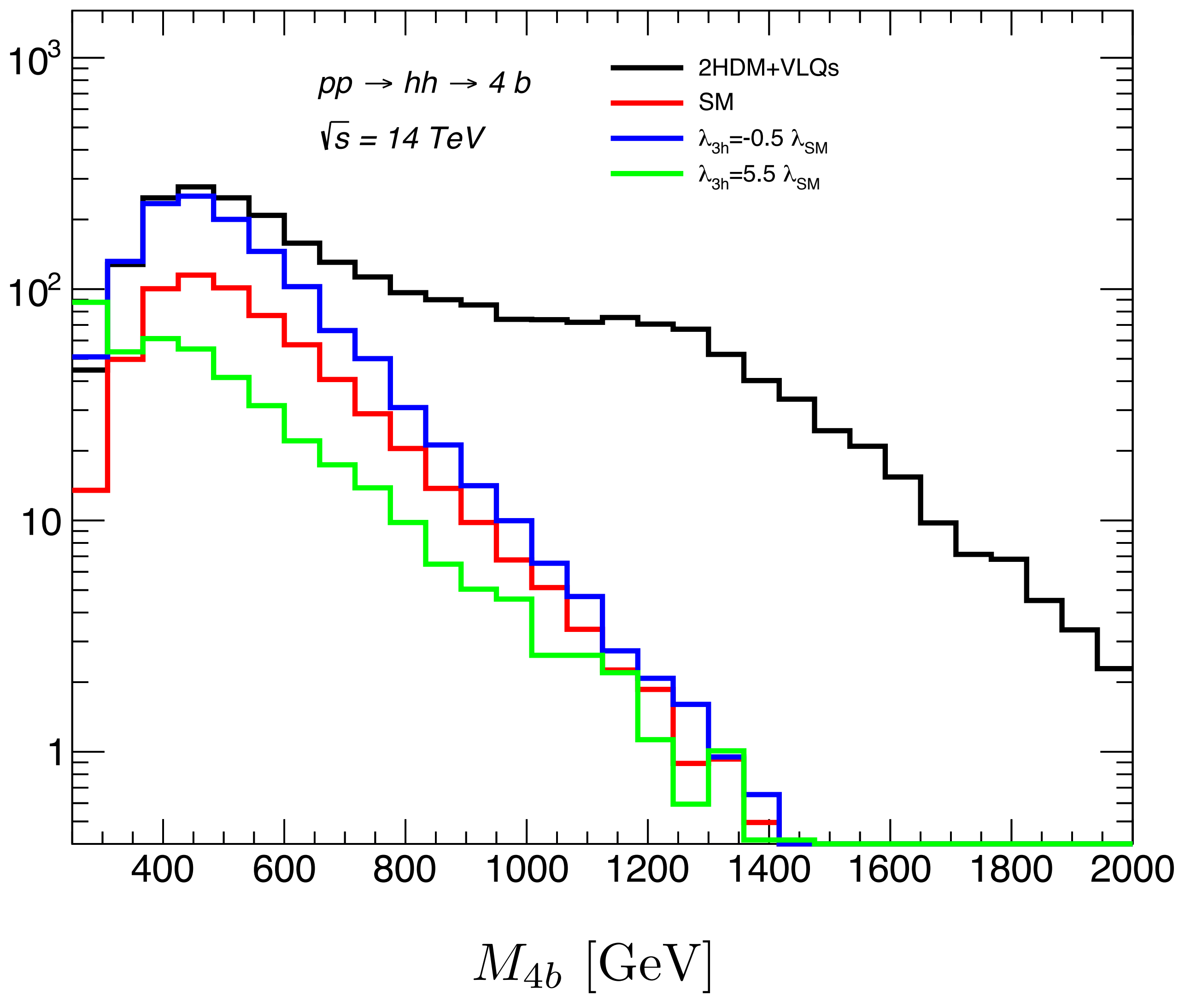
Shall the characteristic features remain after the full simulation?

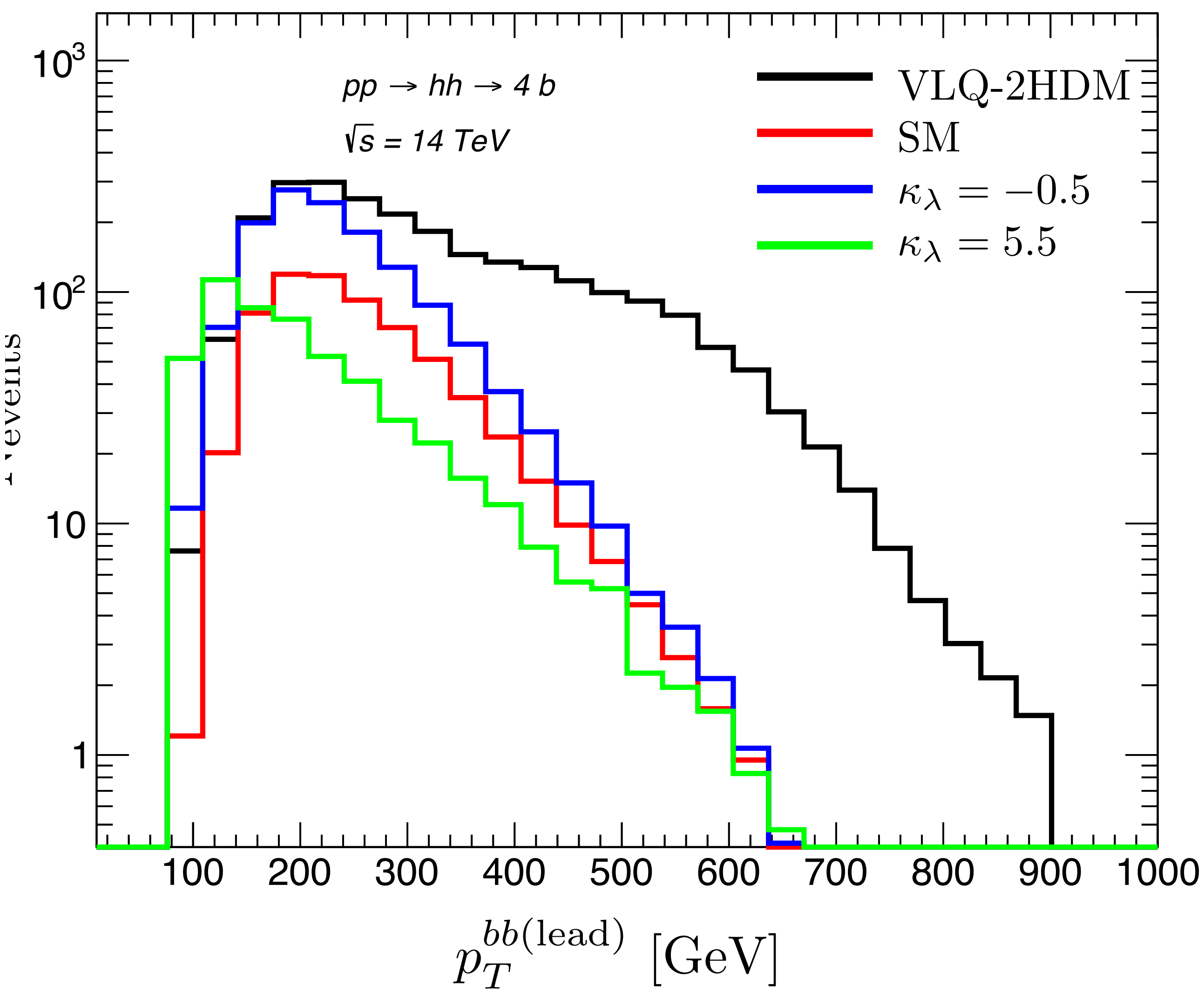


4b mode

- at least 4 b jets with $p_T > 40$ GeV and $|\eta^b| < 2.5$
- Two di-b-jet systems with $\Delta R < 1.5$.

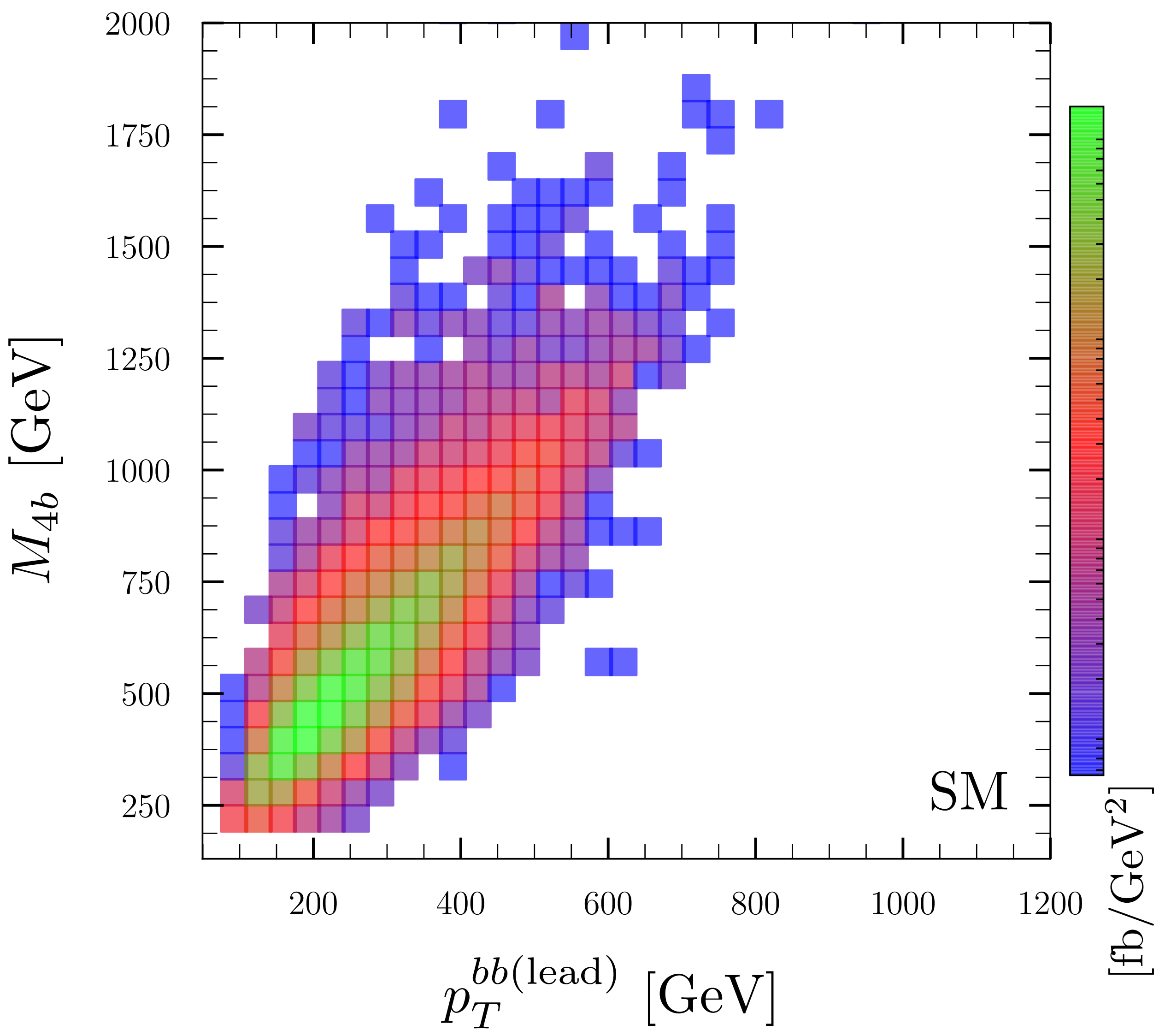
The answer is yes!



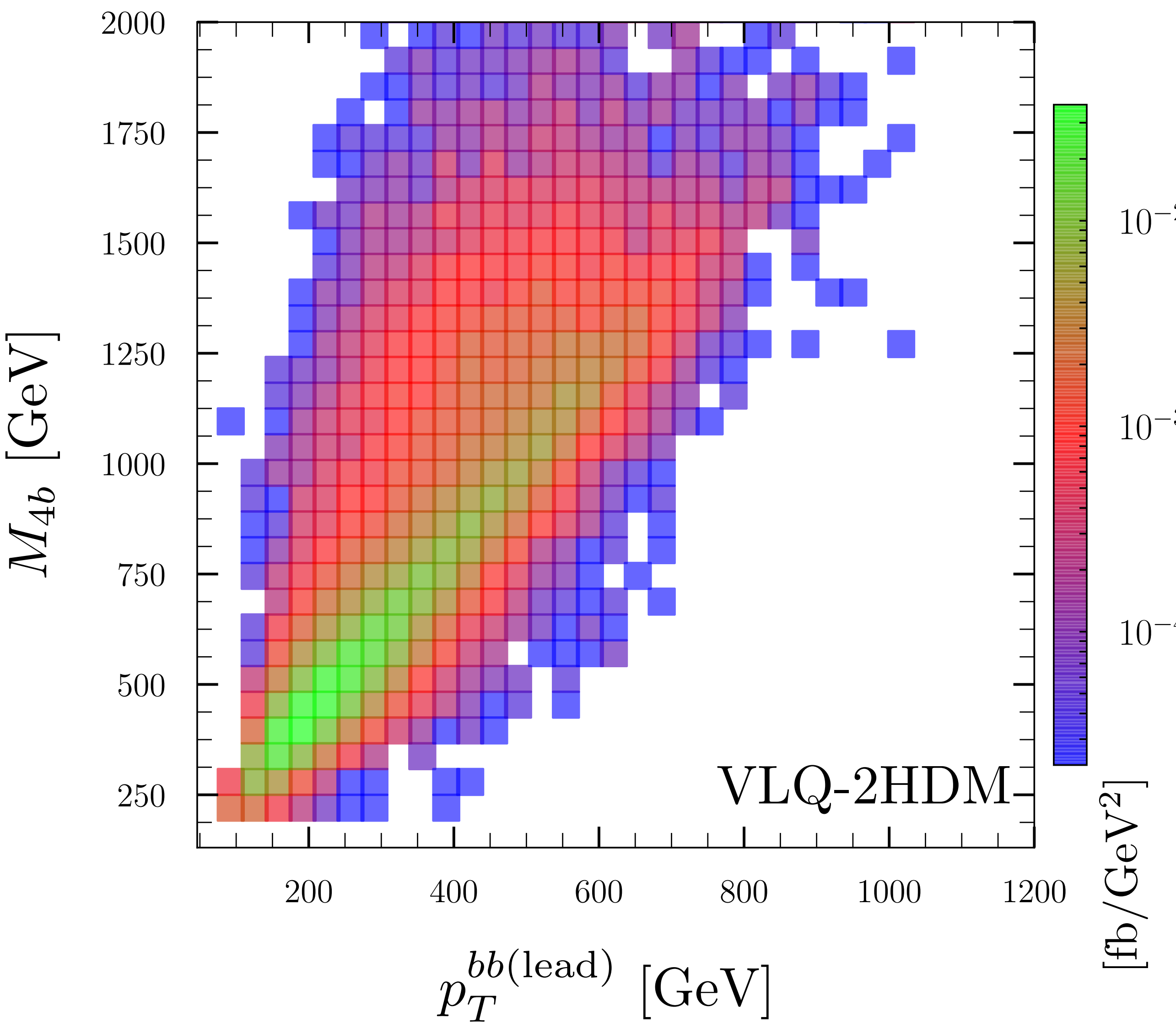


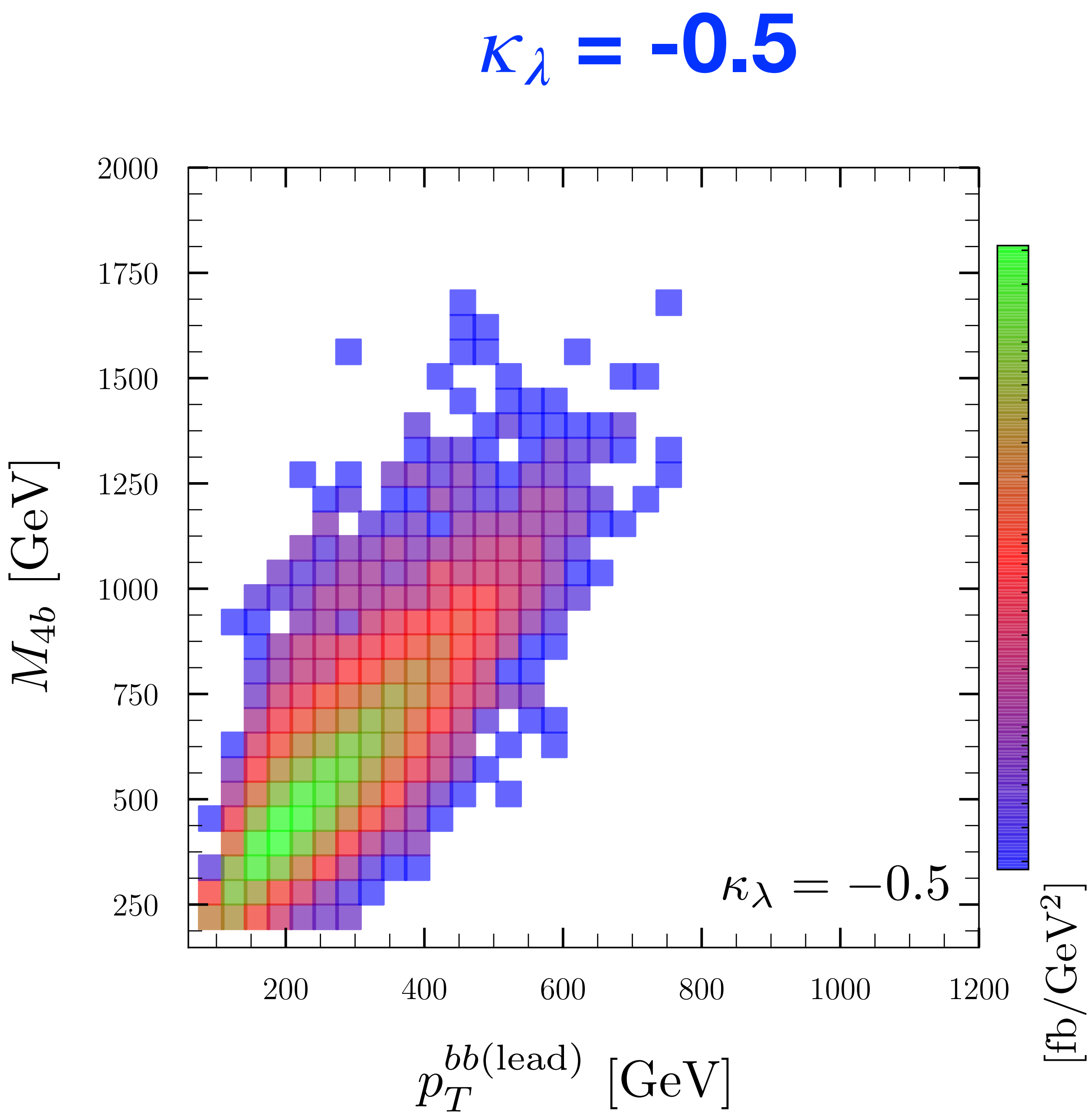
Double differential cross sections show the difference more clearly.

SM

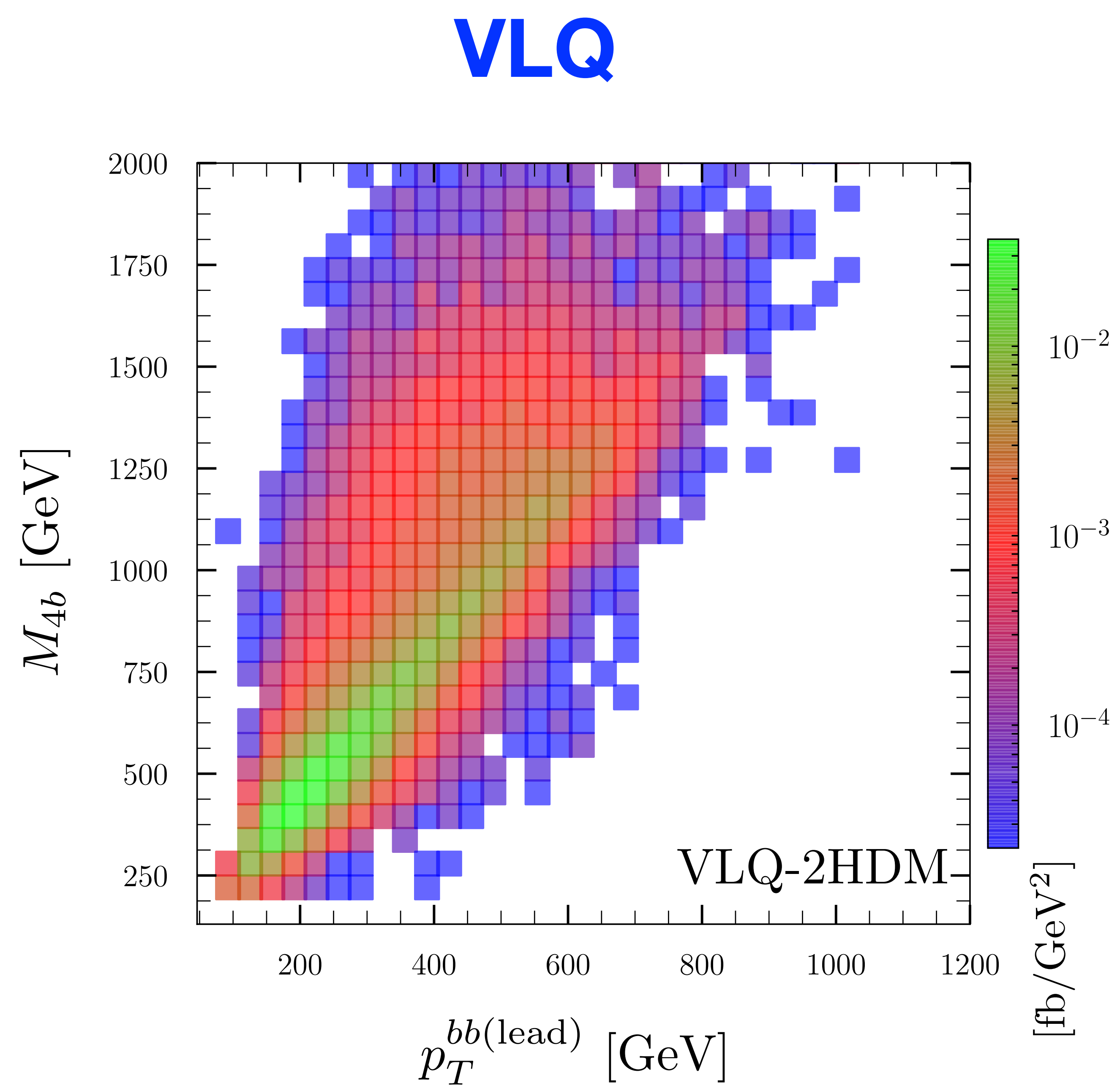


VLQ



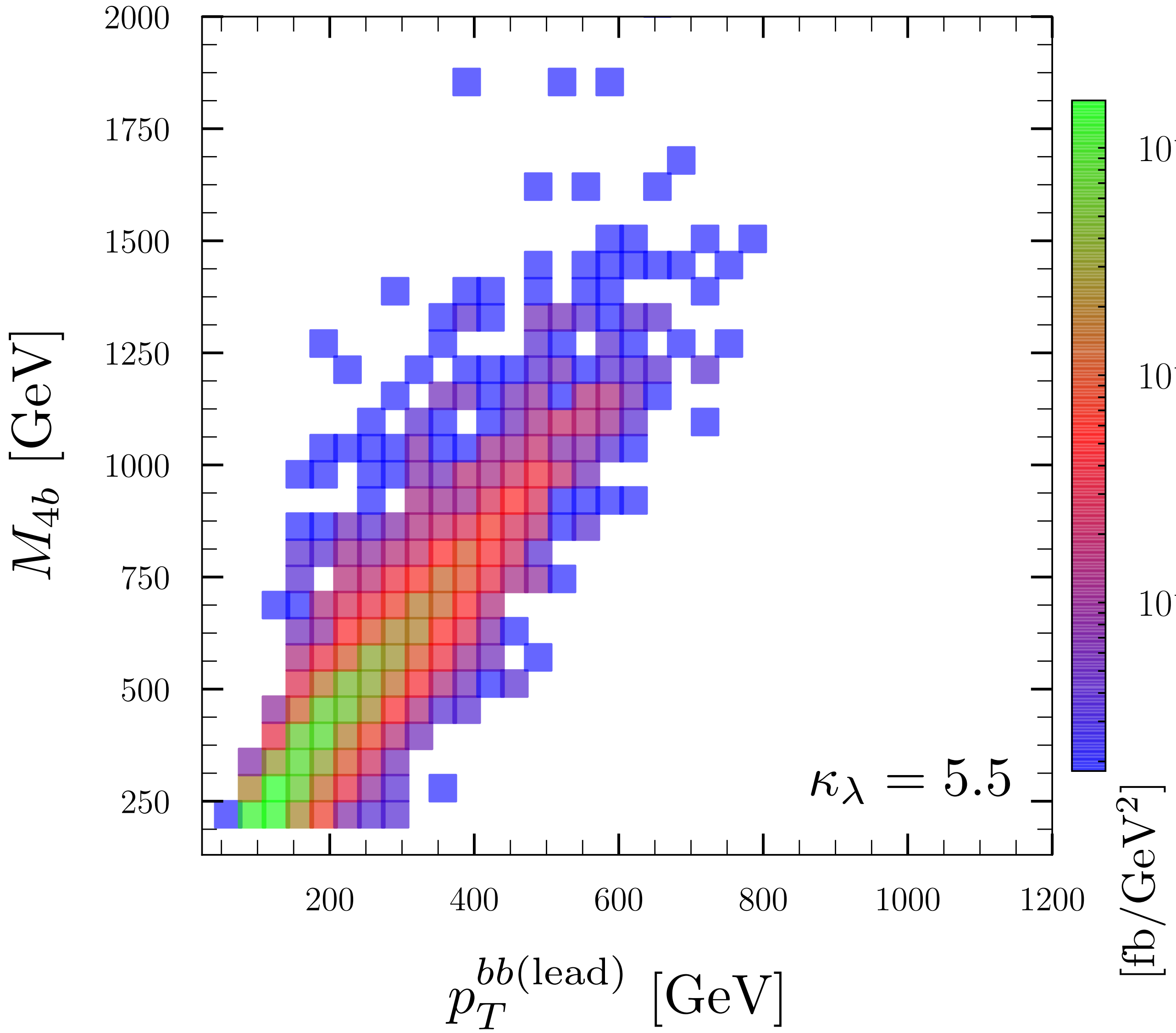


κ_λ = -0.5
2000
1750
1500
1250
1000
750
500
250
200
400
600
800
1000
1200
M_4b [GeV]
p_T^bb(lead) [GeV]
κ_λ = −0.5
[fb/GeV^2]

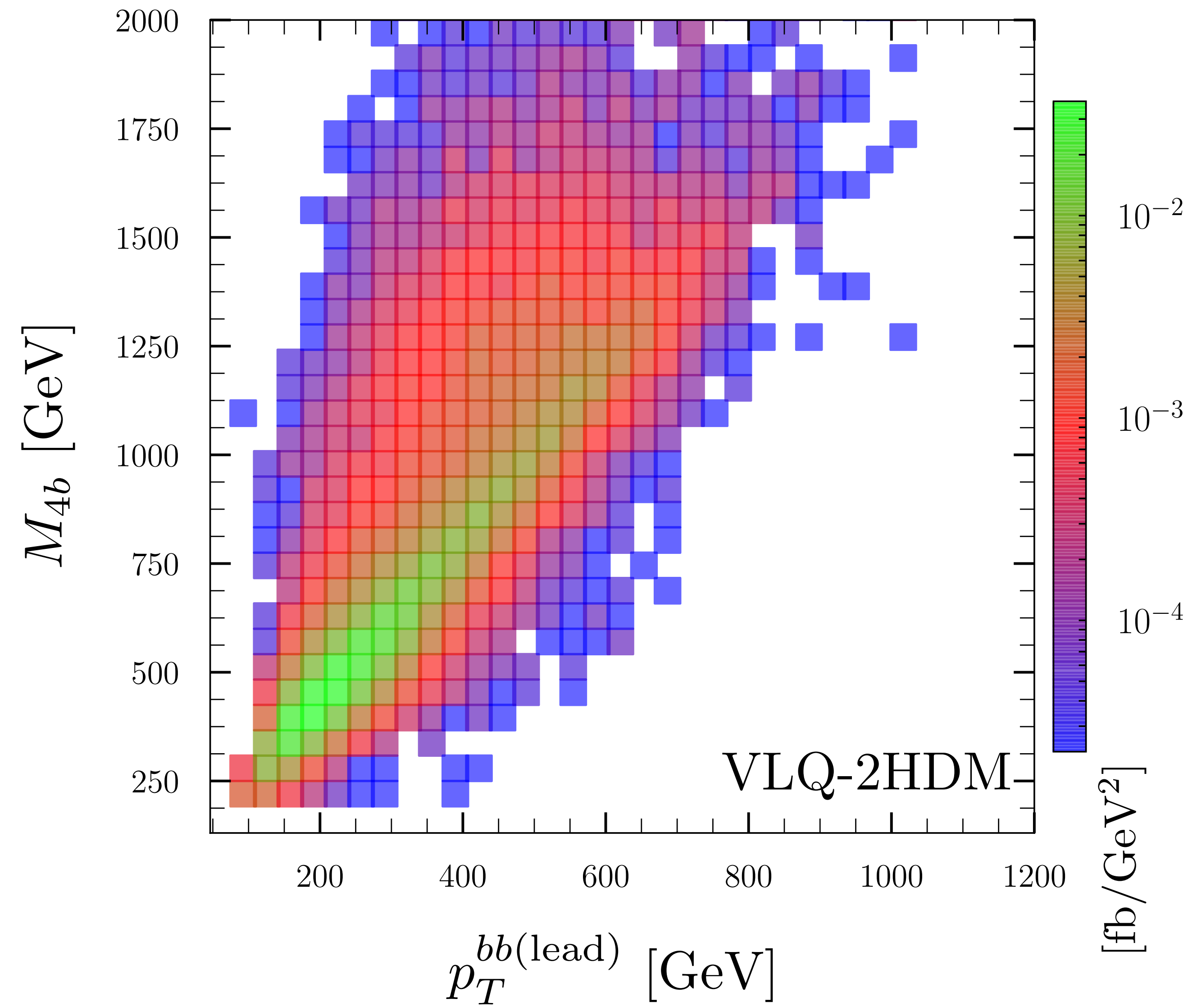


VLQ
2000
1750
1500
1250
1000
750
500
250
200
400
600
800
1000
1200
M_4b [GeV]
p_T^bb(lead) [GeV]
VLQ-2HDM
10^-2
10^-3
10^-4
[fb/GeV^2]

κ_λ = 5.5



VLQ



Clear difference: loop effects around high M(4b) and pT(b)

5. Conclusions

- Unique features of the loop-induced effects on the non-resonant diHiggs process
  - Correlated bumps in M(hh) and pT(h)
  - mostly in high M(HH) and p_T(H)