The 4th International Workshop on “Higgs as a Probe of New Physics”

Measuring Higgs Property at the LHC and e^+e^- Collider

Qing-Hong Cao

School of Physics, Peking University

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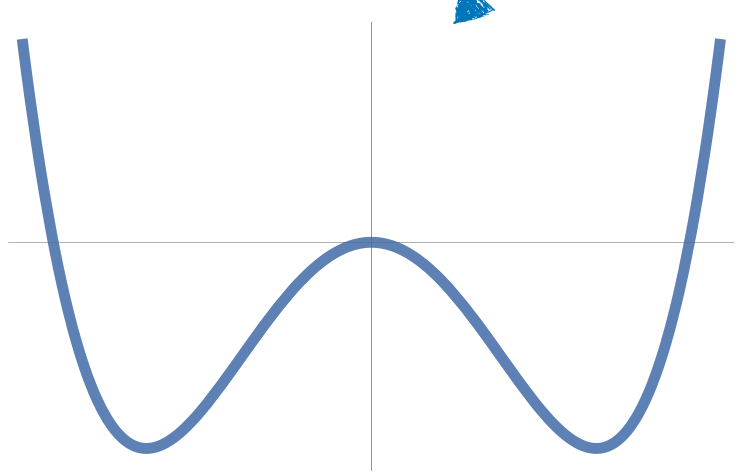
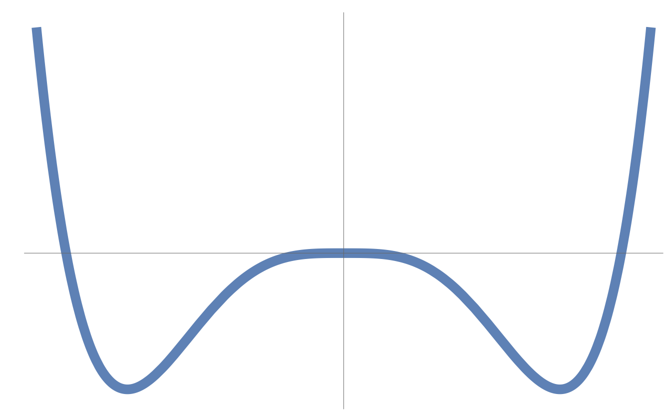
1. Higgs-self Interaction

(probing potential at electroweak scale)

$$V(\phi) = -\mu^2\phi^2 + \lambda(\mu)\phi^4 + \frac{\kappa(\mu)}{\Lambda^2}\phi^6 + \cdots$$

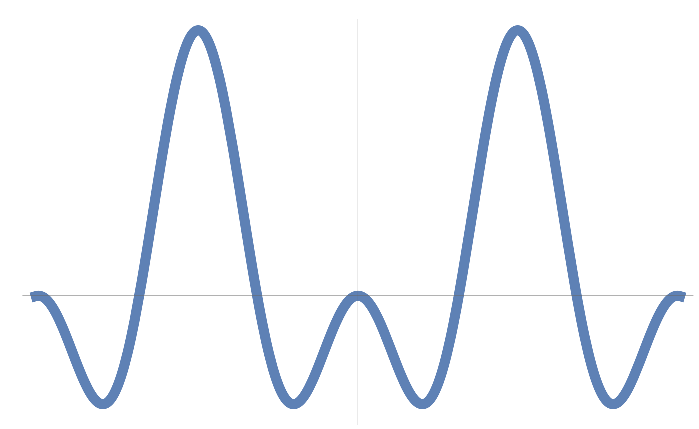


Coleman-Weinberg Higgs



$$V(\phi) = \lambda(\phi^\dagger\phi)^2 + \epsilon(\phi^\dagger\phi)^2 \log\frac{\phi^\dagger\phi}{\mu^2}$$

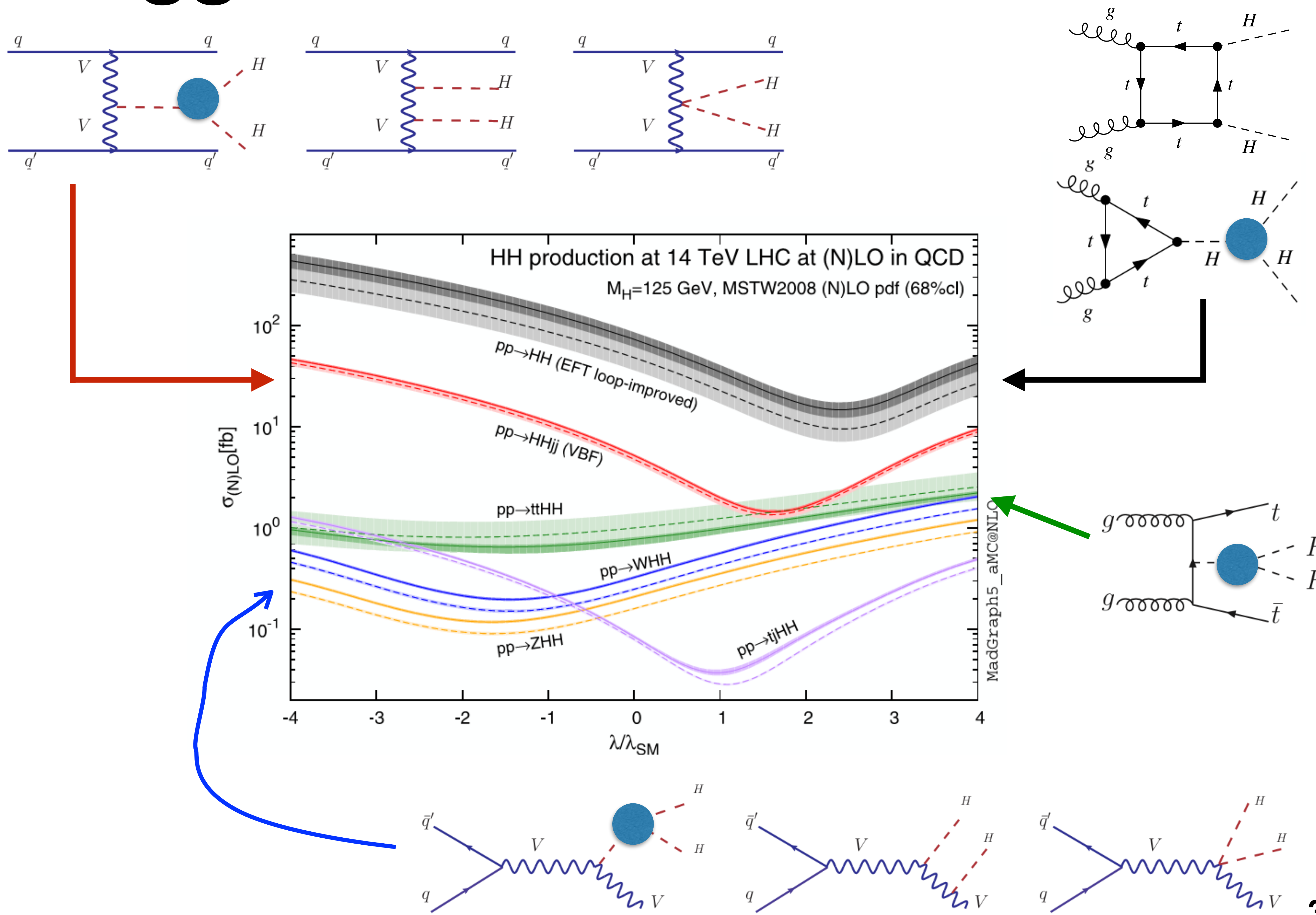
Pseudo-Goldstone Higgs



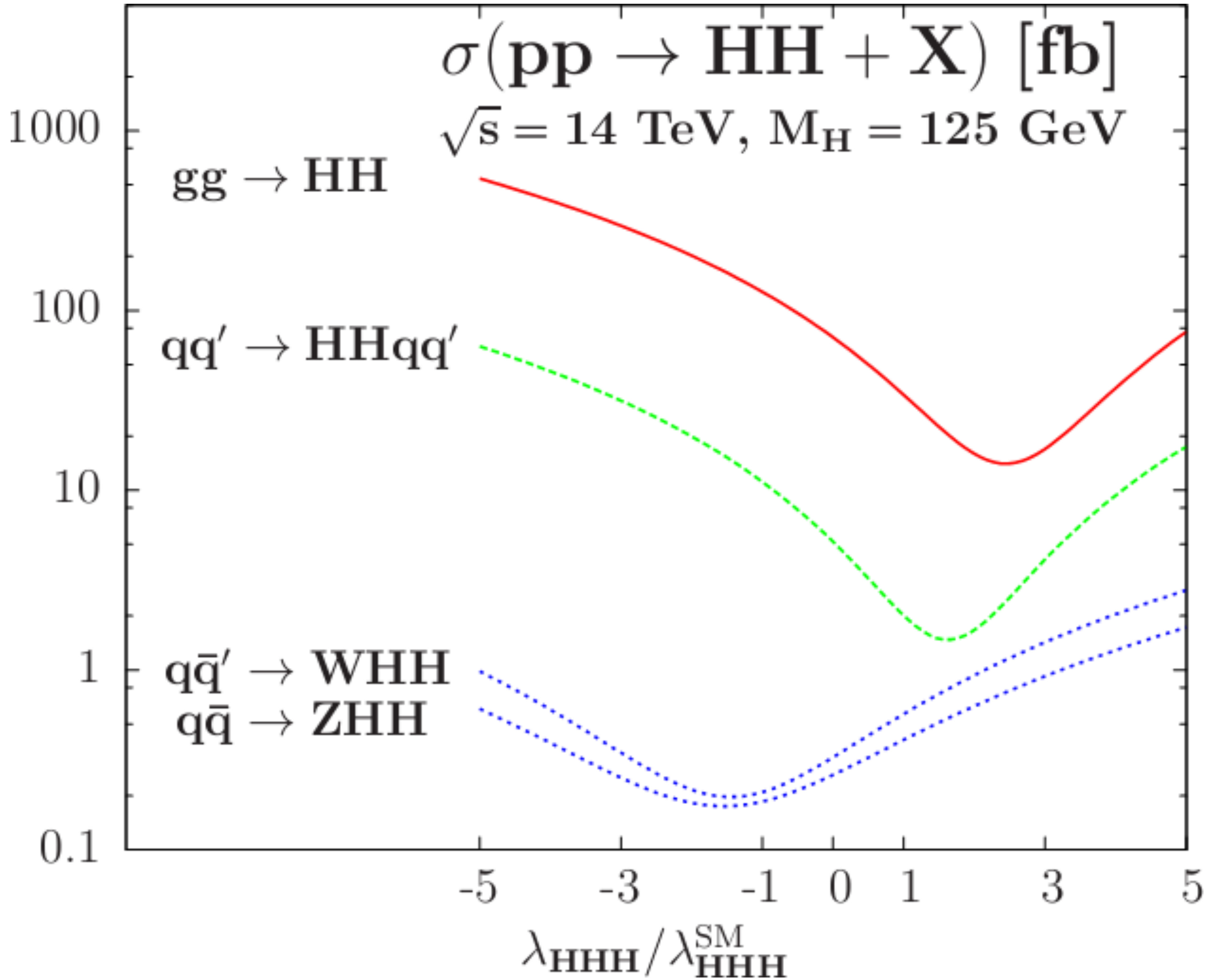
$$V(\phi) = a\sin^2(\phi/f) + b\sin^4(\phi/f)$$

The LHC

Higgs Boson Pair Production



Sensitive to *HHH* coupling very differently



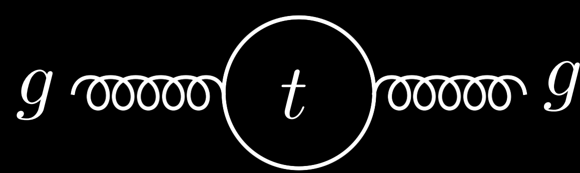
J. Baglio, A. Djouadi et al. JHEP 1304(2013)51

Sensitivity to HHH coupling: 1) gg->HH

Low Energy Theorem

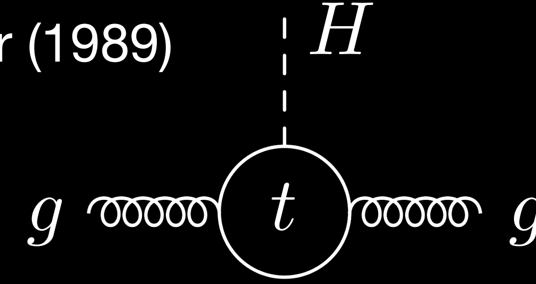
Shiftman, et al (1979)

Dawson and Haber (1989)

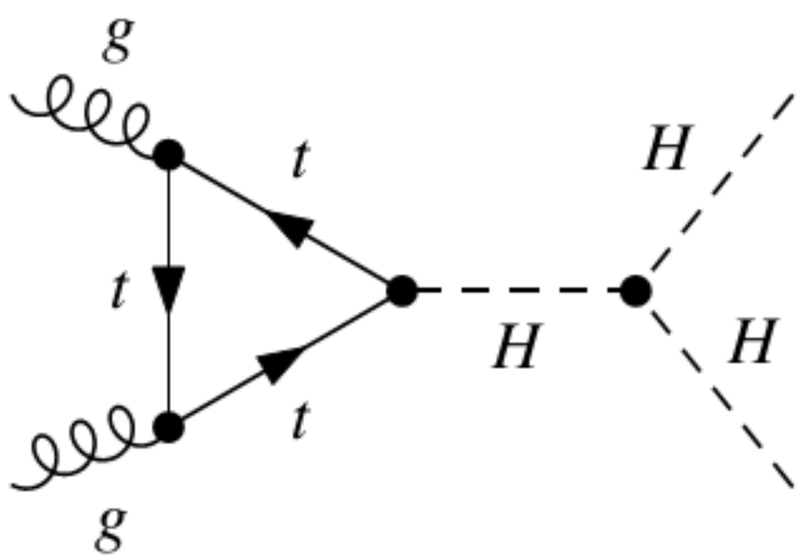


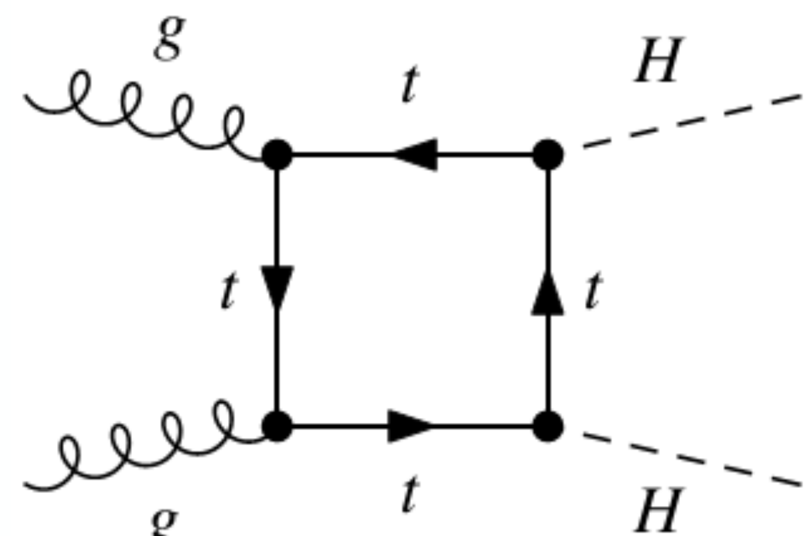
$$\sim -\frac{\alpha_s}{24\pi} G^a_{\mu\nu} G^{\mu\nu}_a \log \frac{\Lambda^2}{m_t^2}$$

$$\xrightarrow{\;y_t \frac{\partial}{\partial m_t}\;}$$



$$\frac{\alpha_s}{12\pi v} G^a_{\mu\nu} G^{\mu\nu}_a H$$





$$-\frac{\alpha_s}{24\pi} G^{a,\mu\nu} G^a_{\mu\nu} \sum_n \frac{y_t^n h^n}{n!} \frac{\partial^n}{\partial m_t^n} \log\left(\frac{\Lambda_{UV}^2}{m_t^2}\right)$$

n=1

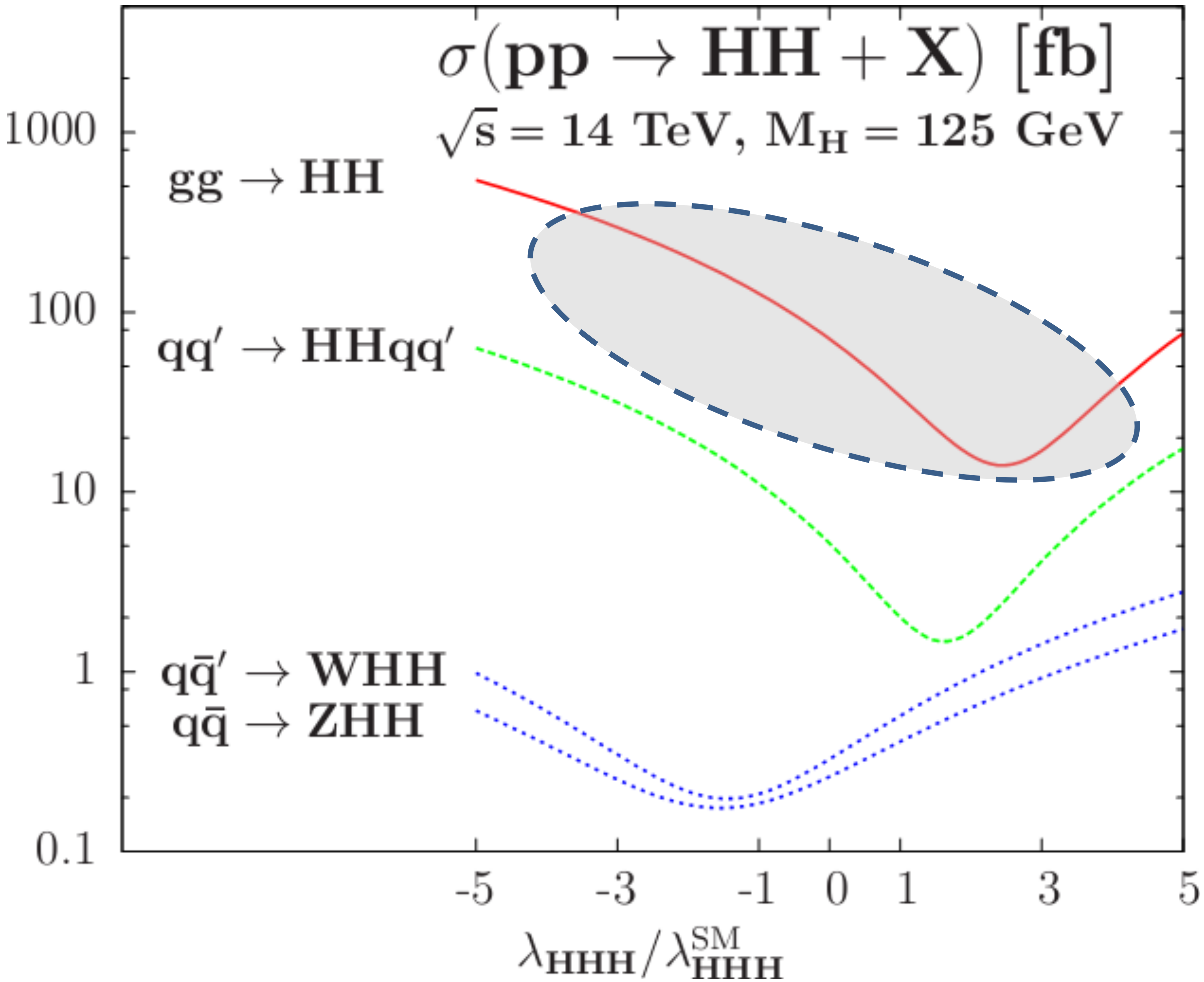
$$\frac{\alpha_s}{12\pi v} G^{a,\mu\nu} G^a_{\mu\nu} h$$

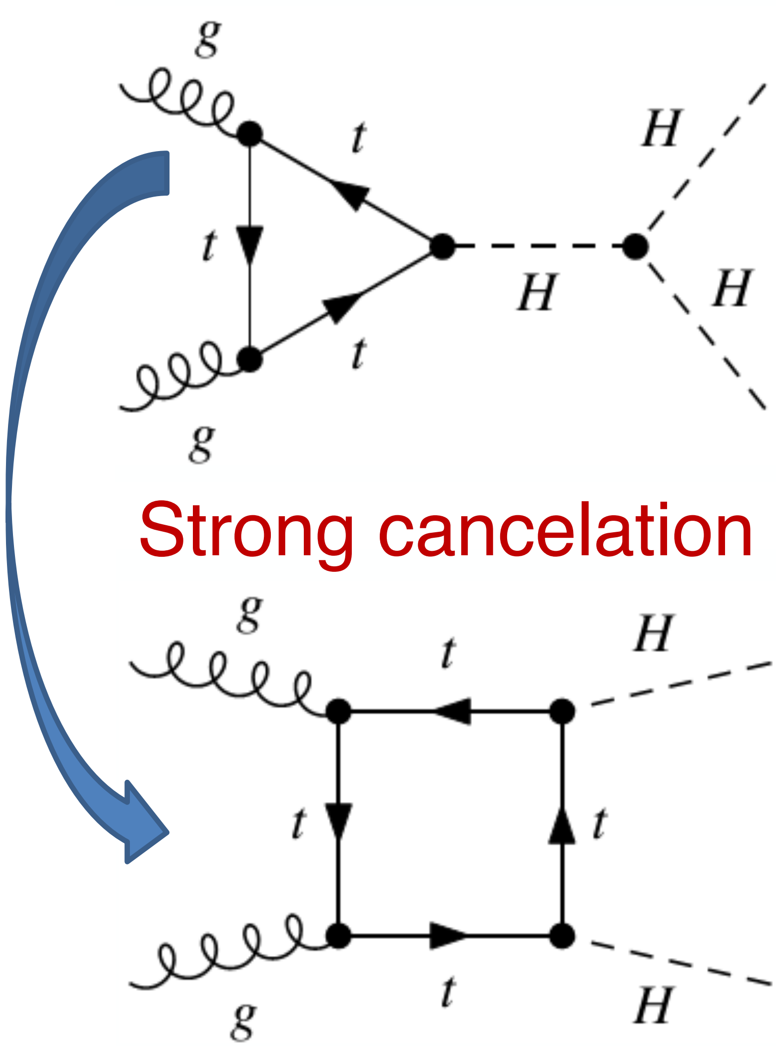
n=2

$$- \frac{\alpha_s}{24\pi v^2} G^{a,\mu\nu} G^a_{\mu\nu} h^2$$

Strong cancelation

Sensitivity to HHH coupling: 1) gg->HH



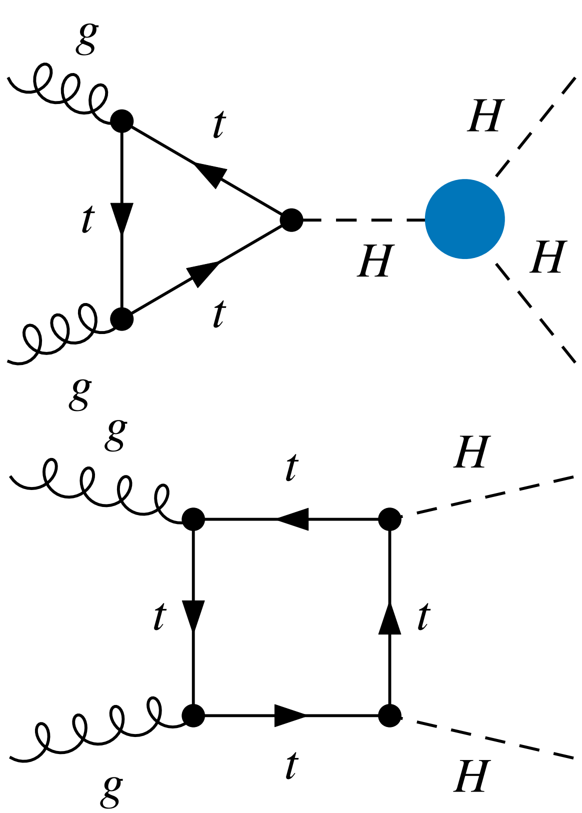


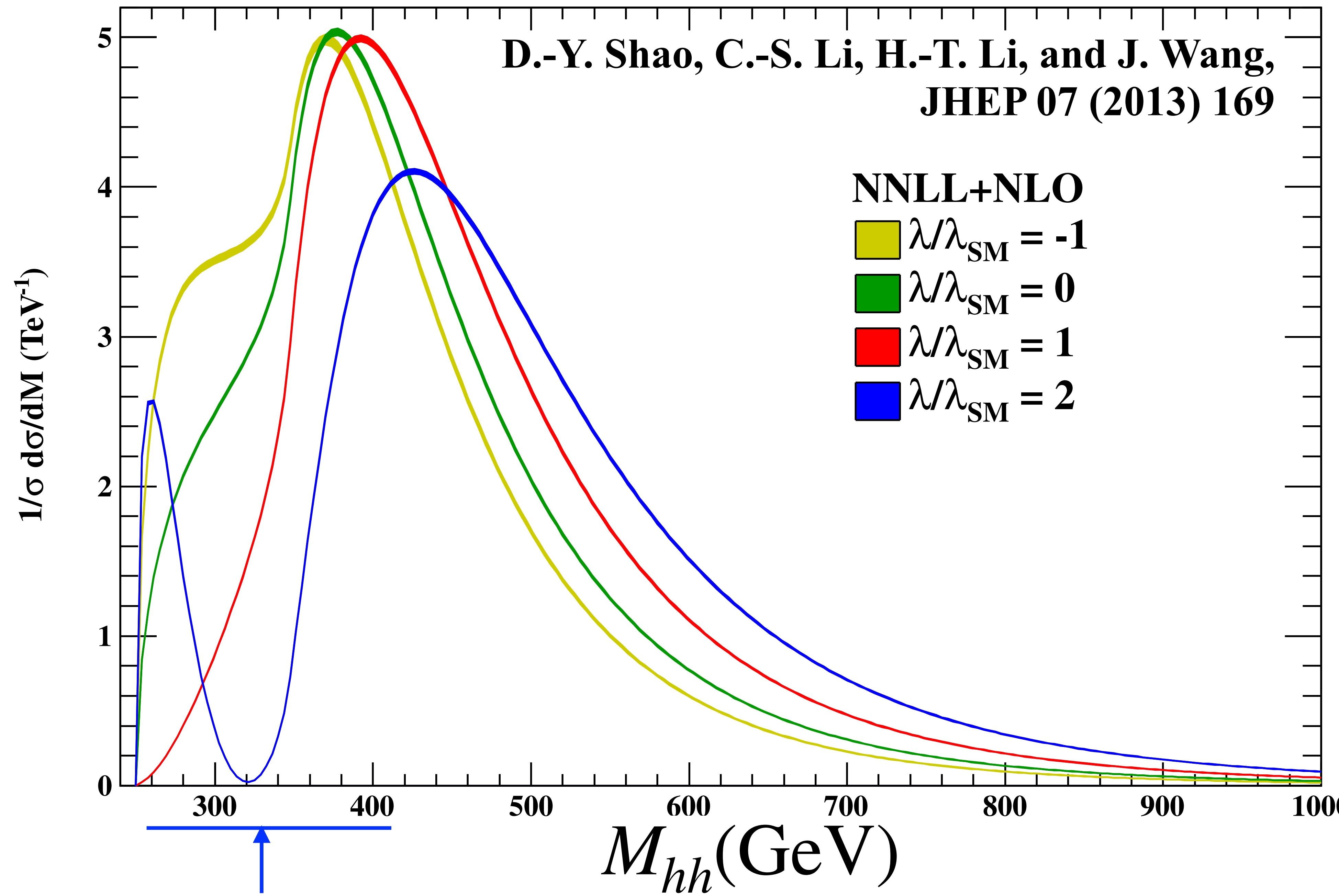
J. Baglio, A. Djouadi et al. JHEP 1304(2013)51

gg->HH: the leading channel

Unfortunately, it is not a easy job at the LHC or even at the SppC.

HH production



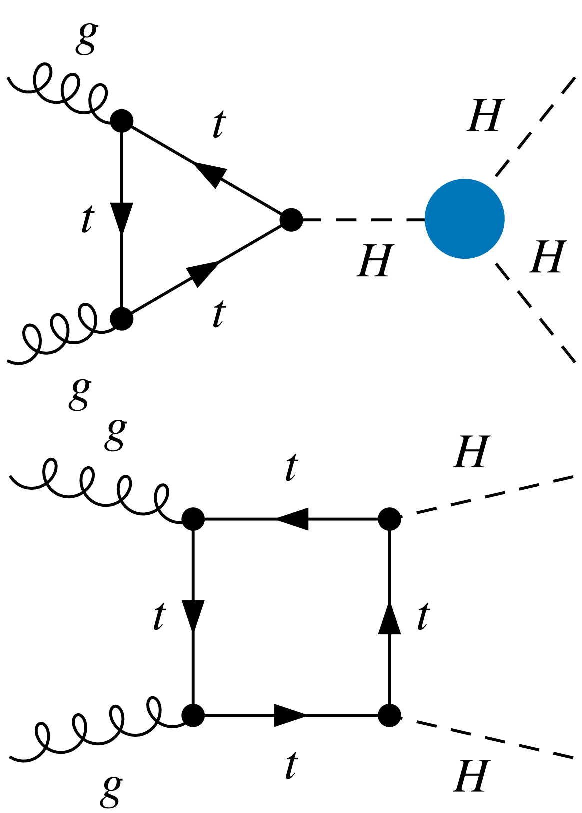


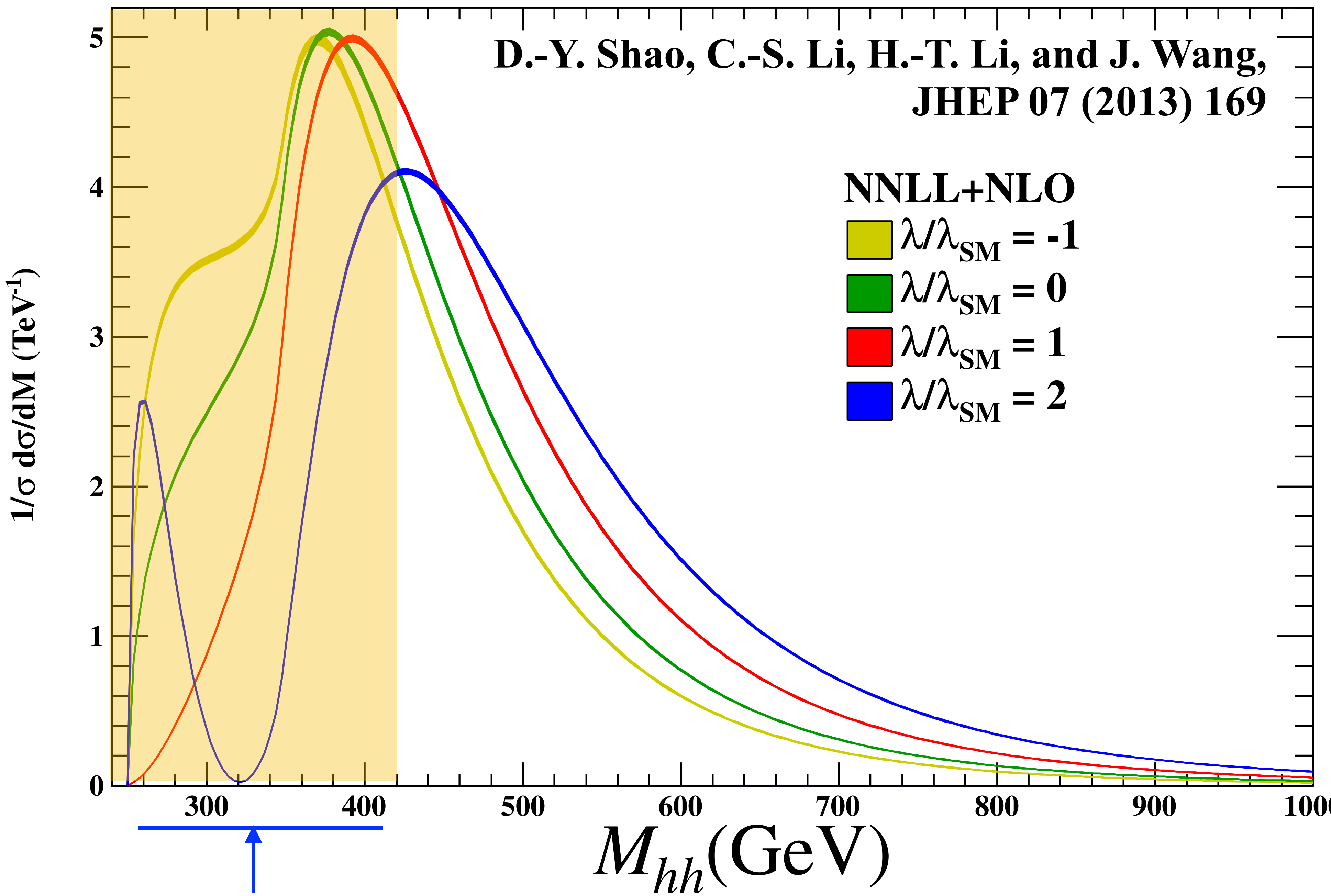
strong interference effects,

gg->HH: the leading channel

Unfortunately, it is not a easy job at the LHC or even at the SppC.

HH production

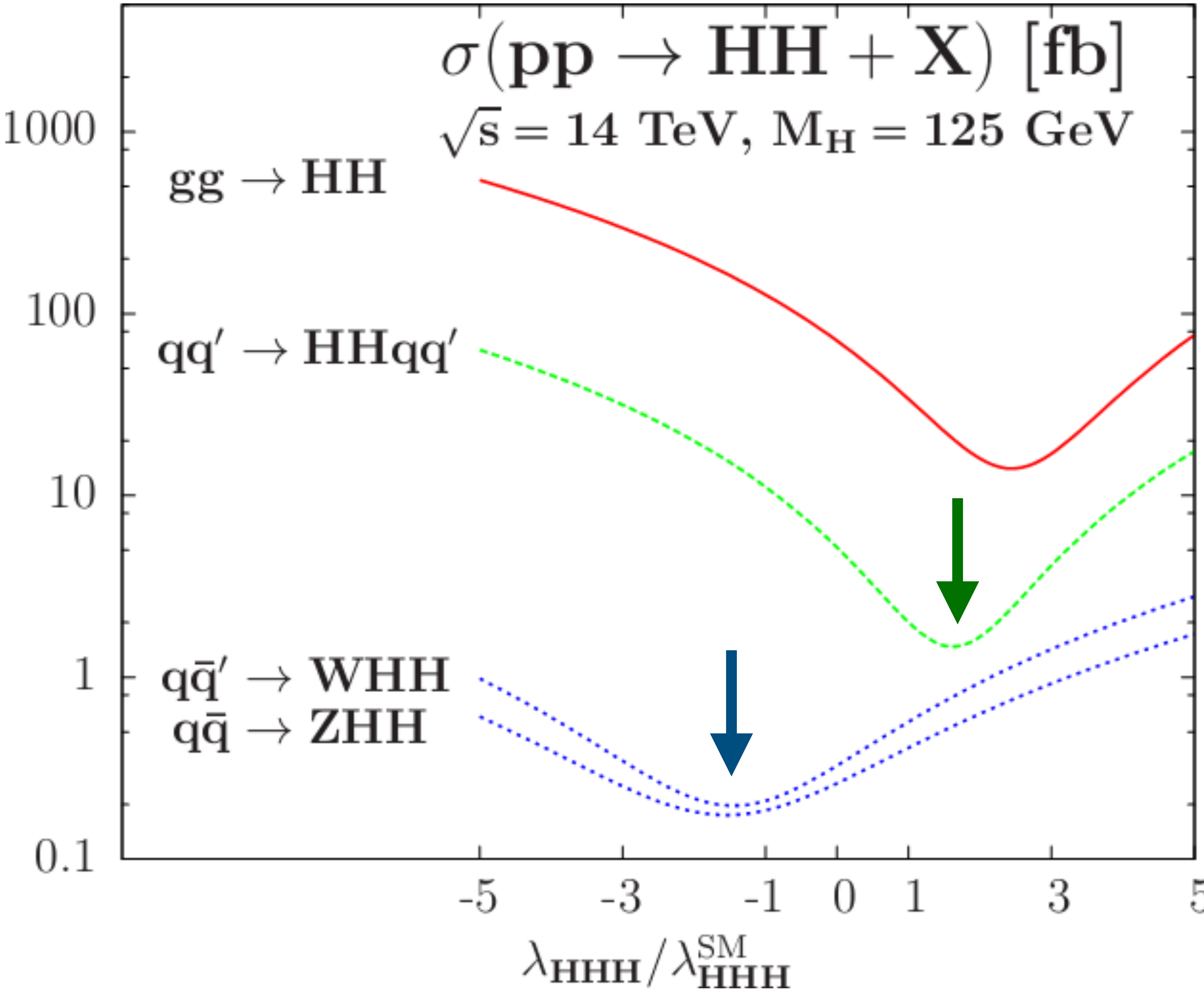


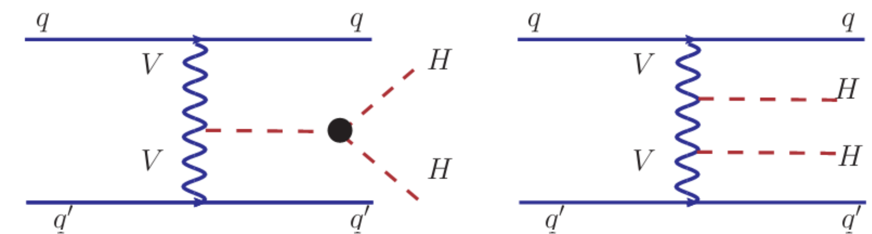


strong interference effects,

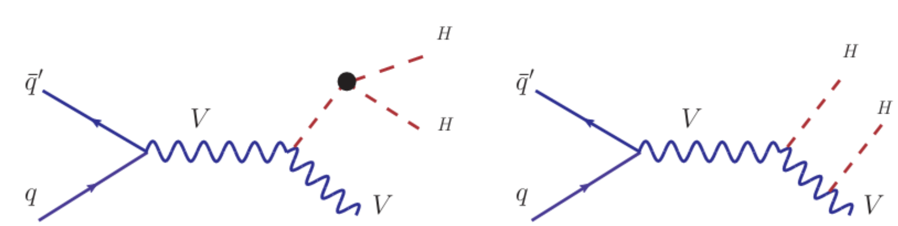
but not accessible at the LHC, due to hard cuts used by our experimental colleagues

Sensitivity to HHH coupling: 2) VBF and VHH



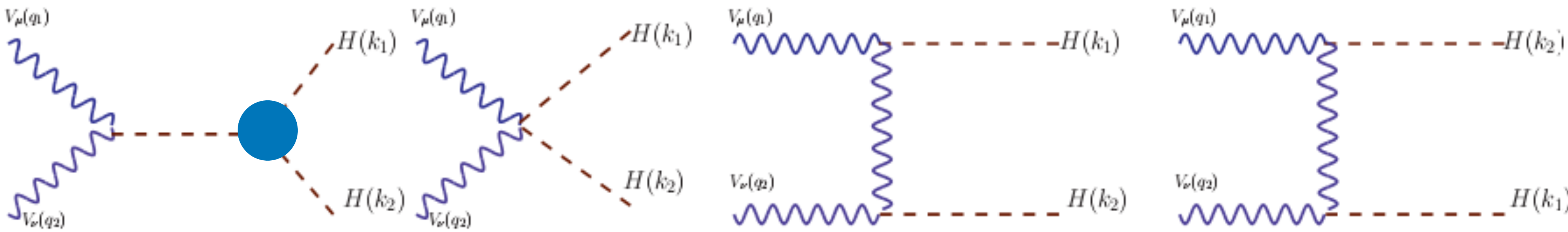


VBF and VHH are sensitive to HHH coupling differently



J. Baglio, A. Djouadi et al. JHEP 1304(2013)51

The VBF and VHH channels share the same subprocess but with different kinematics

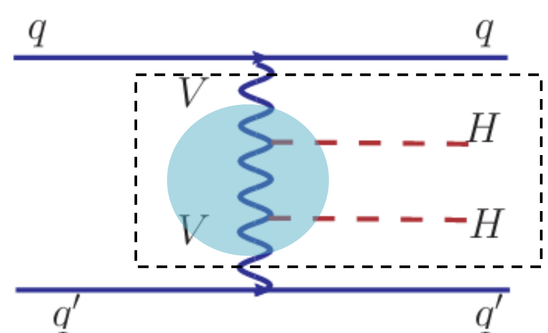


$$M^{\mu\nu} = \left[\frac{m_W^2}{v^2} \frac{6m_H^2}{\hat{s} - m_H^2} \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}} + \frac{2m_W^2}{v^2} + \frac{4m_W^4}{v^2} \left(\frac{1}{\hat{t} - m_W^2} + \frac{1}{\hat{u} - m_W^2} \right) \right] g^{\mu\nu} + \cdots$$

Near the threshold of Higgs-boson pairs

VBF:

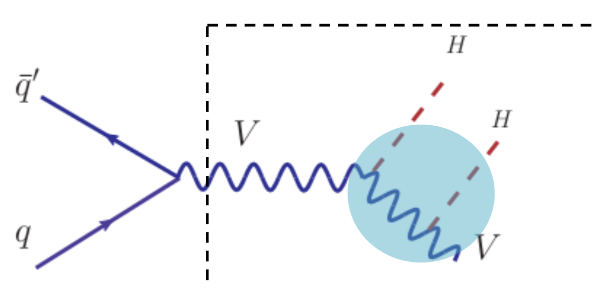
$$\hat{t} = \hat{u} = Q^2 < 0$$



$$M^{\mu\nu} \sim \frac{2m_V^2}{v^2} \left(\frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}} - 3 \right) g^{\mu\nu} + \cdots$$

VHH:

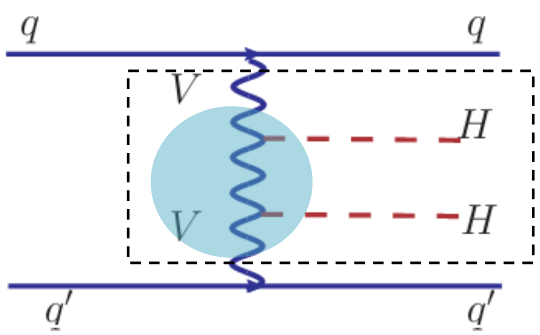
$$\hat{t} = \hat{u} = Q^2 > 0$$



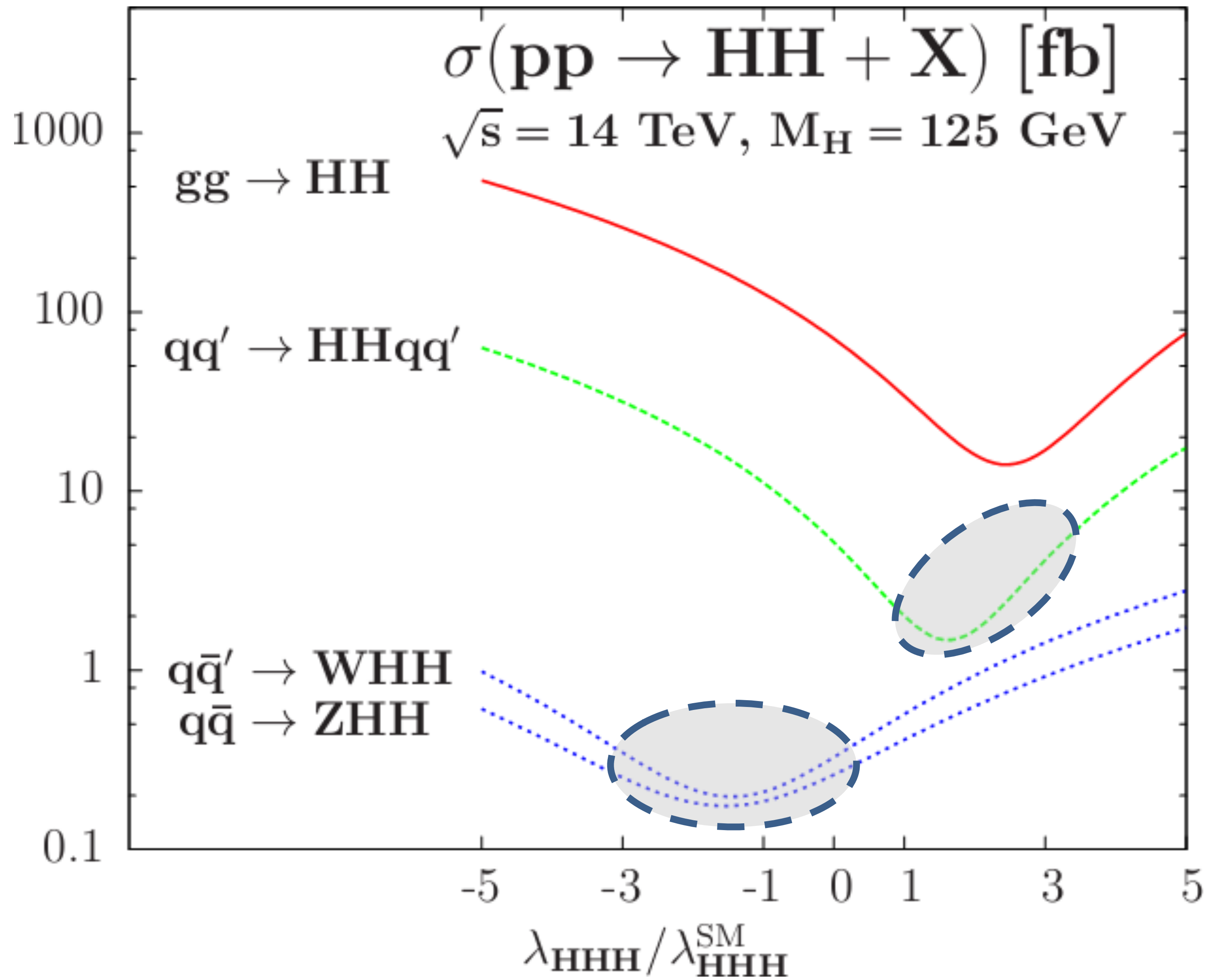
$$M^{\mu\nu} \sim \frac{2m_V^2}{v^2} \left(\frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}} + 1 \right) g^{\mu\nu} + \cdots$$

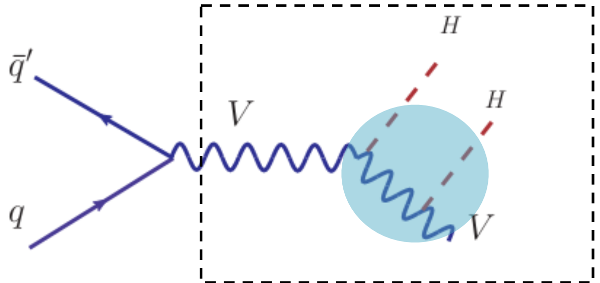
Sensitivity to HHH Coupling

VBF $M^{\mu\nu} \sim \frac{2m_V^2}{v^2}\left(\frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}} - 3\right) g^{\mu\nu} + \cdots$



$Q^2 < 0$

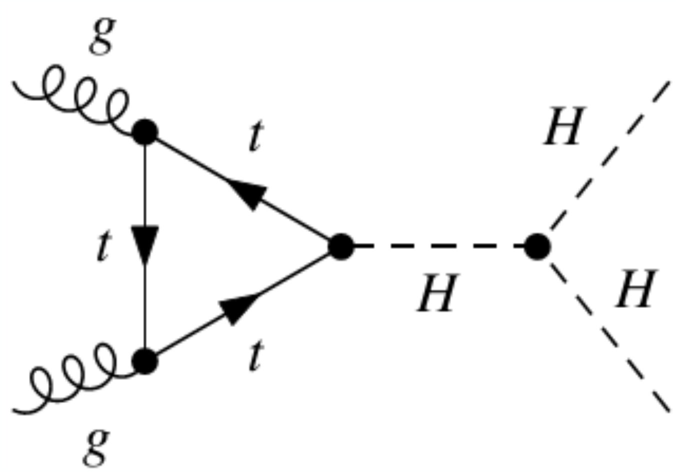




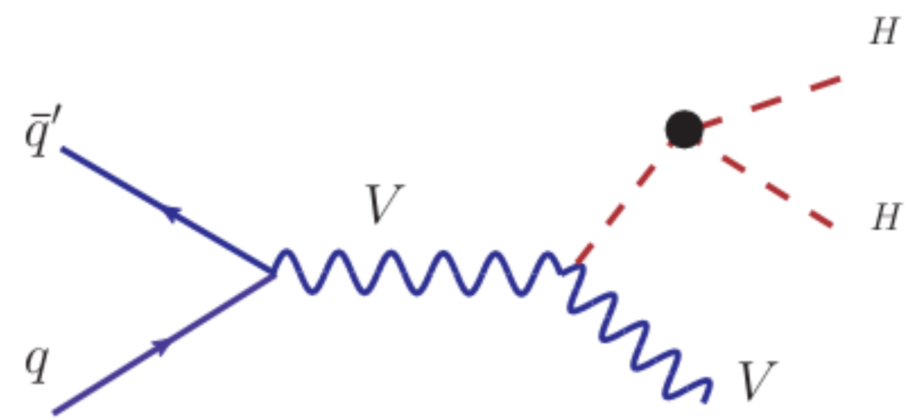
$Q^2 > 0$

VHH $M^{\mu\nu} \sim \frac{2m_V^2}{v^2}\left(\frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}} + 1\right) g^{\mu\nu} + \cdots$

HH and VHH @ HL-LHC



vs



Cross section: 34 fb

>>

Cross section: 0.57 fb

Final states: $bb\gamma\gamma$

$Br(bb\gamma\gamma) = 1.3 \times 10^{-3}$

Final states: $bbbb$

$Br(bbbblv) = 0.073$

$\sigma \times Br(bb\gamma\gamma) = 0.044 \text{ fb}$ $\approx$ $\sigma \times Br(bbbb\ell\nu) = 0.042 \text{ fb}$

Huge backgrounds:

$b\bar{b}\gamma\gamma, c\bar{c}\gamma\gamma, b\bar{b}\gamma j, jj\gamma\gamma,$
$b\bar{b}jj, t\bar{t}, t\bar{t}\gamma, ZH, t\bar{t}H$

Main backgrounds:

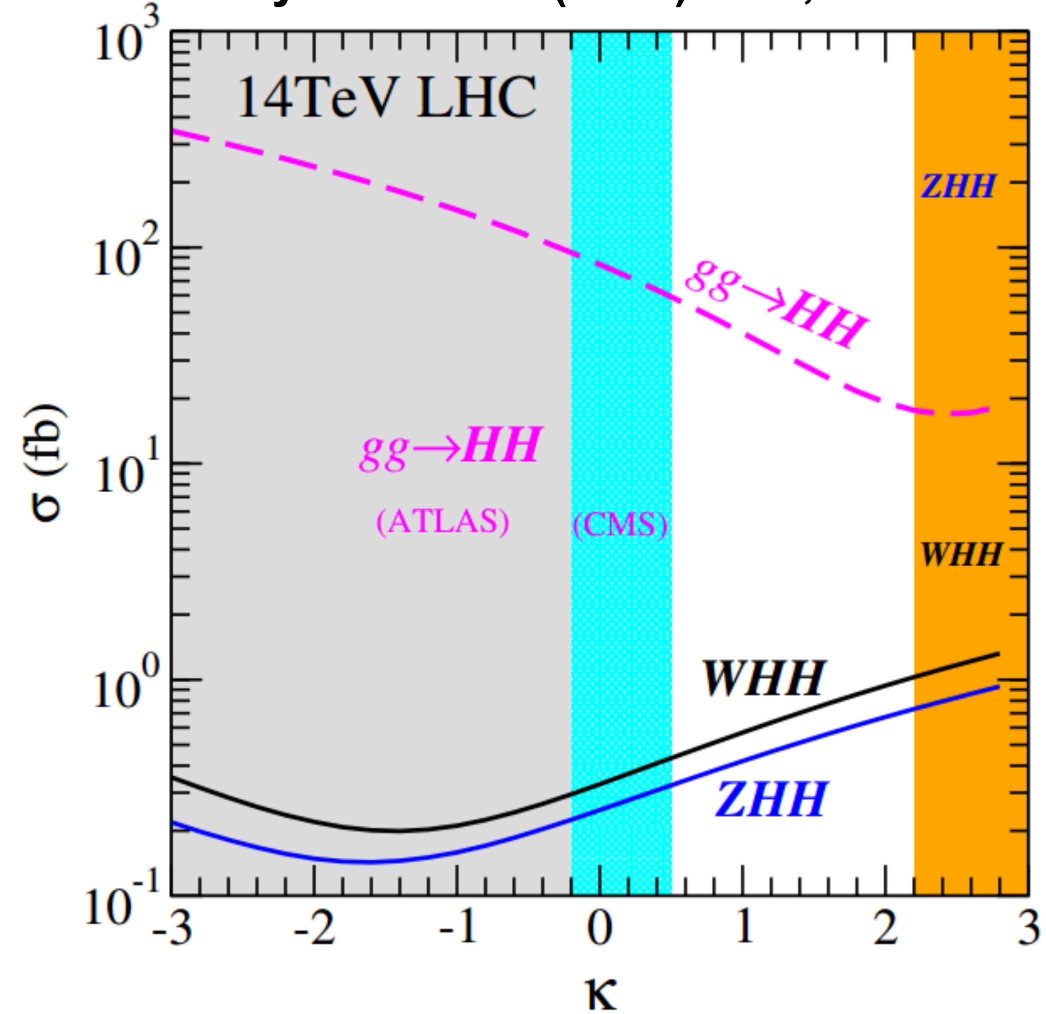
$\text{Zbbbb}, Wbbbb, t\bar{t}, t\bar{t}j,$
$t\bar{t}H, t\bar{t}z, t\bar{t}\text{bb}$

WHH and ZHH Productions

TABLE III: The sensitivity to $\lambda_{HHH} = \kappa\lambda_{HHH}^{SM}$ in several production channels of Higgs boson pairs at the HL-LHC.

	SM ($\kappa = 1$)	5σ discovery potential	2σ exclusion bound
WHH	1.29σ	$\kappa \leq -7.7,\ \kappa \geq 4.8$	$-5.1 \leq \kappa \leq 2.2$
ZHH	1.32σ	$\kappa \leq -8.1,\ \kappa \geq 4.8$	$-5.4 \leq \kappa \leq 2.2$
GF($b\bar{b}\gamma\gamma$) [42]	1.19σ	$\kappa \leq -4.5,\ \kappa \geq 8.1$	$-0.2 \leq \kappa \leq 4.9$
GF($b\bar{b}\gamma\gamma$) [43]	1.65σ	$\kappa \leq -2.6,\ \kappa \geq 6.3$	$0.5 \leq \kappa \leq 4.1$
VBF [20]	0.59σ	$\kappa \leq -1.7,\ \kappa \geq 5.0$	$-0.4 \leq \kappa \leq 3.5$
$t\bar{t}HH$ [21, 22]	1.38σ	$\kappa \leq -11.4, \kappa \geq 6.9$	$-7.2 \leq \kappa \leq 2.5$

QHC, Liu, Yan,
Phys.Rev. D95 (2017) no.7, 073006



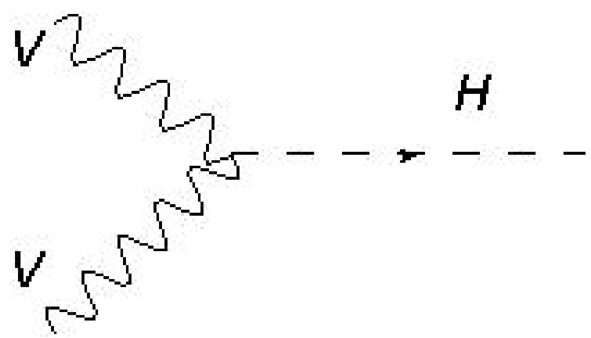
$0.5 \leq \kappa \leq 2.2$

The discovery potential of triple Higgs coupling in VHH production is **comparable** to other channels.

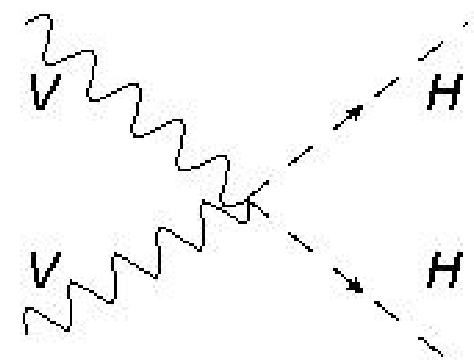
Nordstrom and Papaefstathiou (arXiv:1807.01571) include full detector effects and show that measuring HHH coupling via WHH and VHH channels is still challenging at the HL-LHC

HVV versus HHVV

SM predicts a definite ratio between HVV and HVV couplings



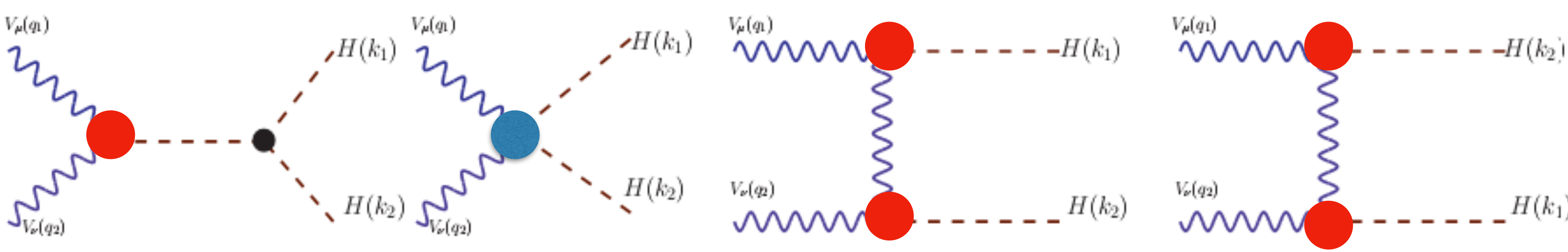
$$2i\frac{M_V^2}{v}g^{\mu\nu}$$



$$2i\frac{M_V^2}{v^2}g^{\mu\nu}$$

$$\frac{g_{hhVV}^{\mathrm{SM}}}{g_{hVV}^{\mathrm{SM}}} = \frac{1}{v} \qquad \frac{g_{hhVV}^{\mathrm{pNGB}}}{g_{hVV}^{\mathrm{pNGB}}} = \frac{1}{v}\frac{1-2\xi}{\sqrt{1-\xi}}$$

If the ratio is modified by NP, the unitarity of $VV \to HH$ is broken



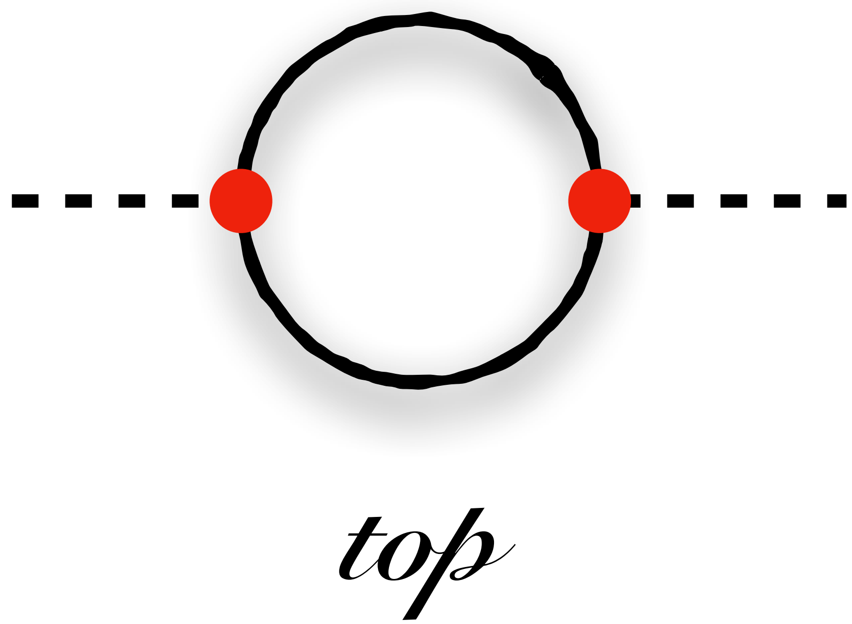
2.
Fundamental (SM-like) or Composite

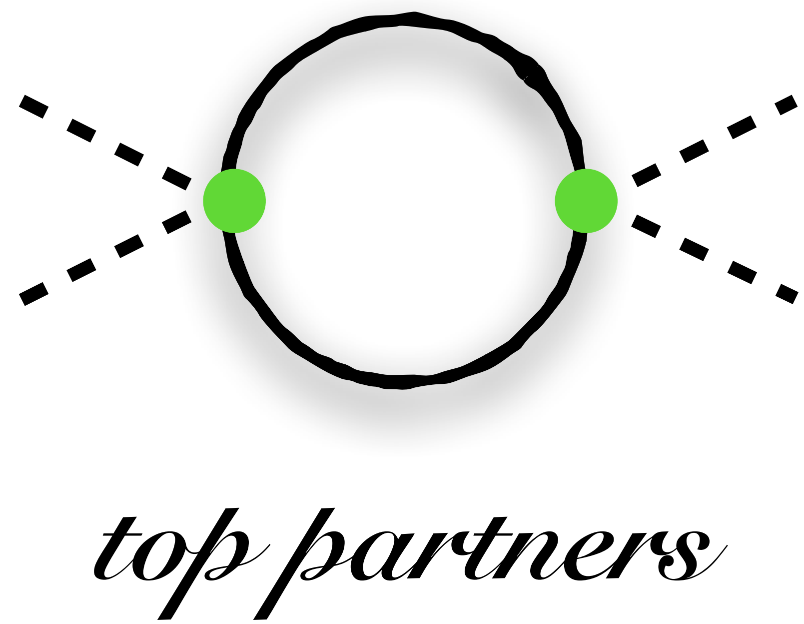
Deciphering Higgs Property through Precision

QHC, Yan, Xu, Zhu, 1810.07661

Higgs Boson as a PNGB

- The PNGB Higgs boson is theoretically motivated to address the little hierarchy problem

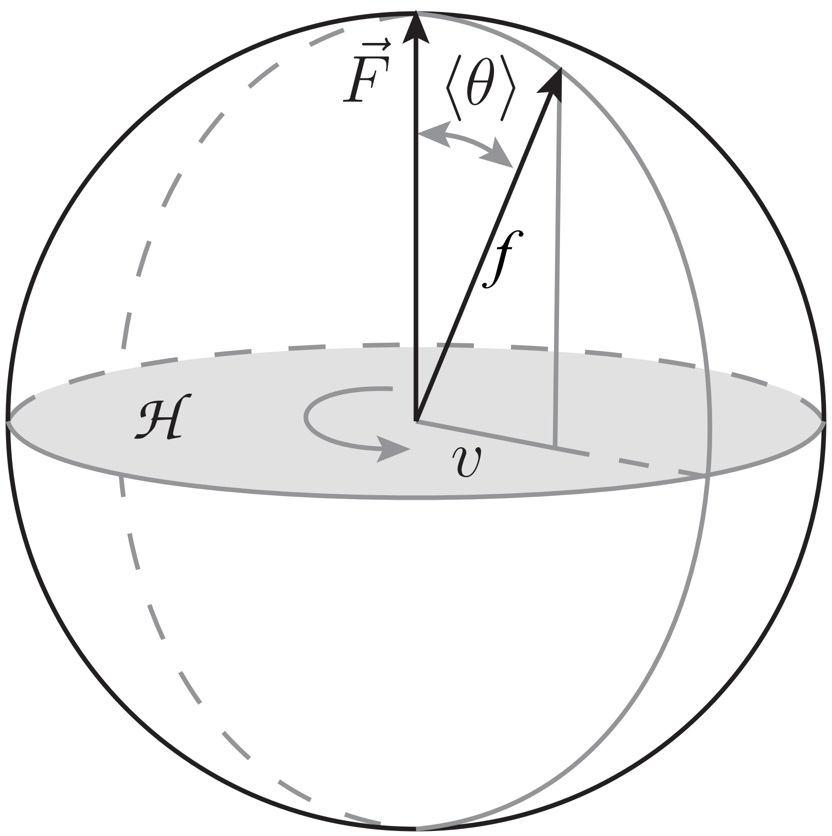


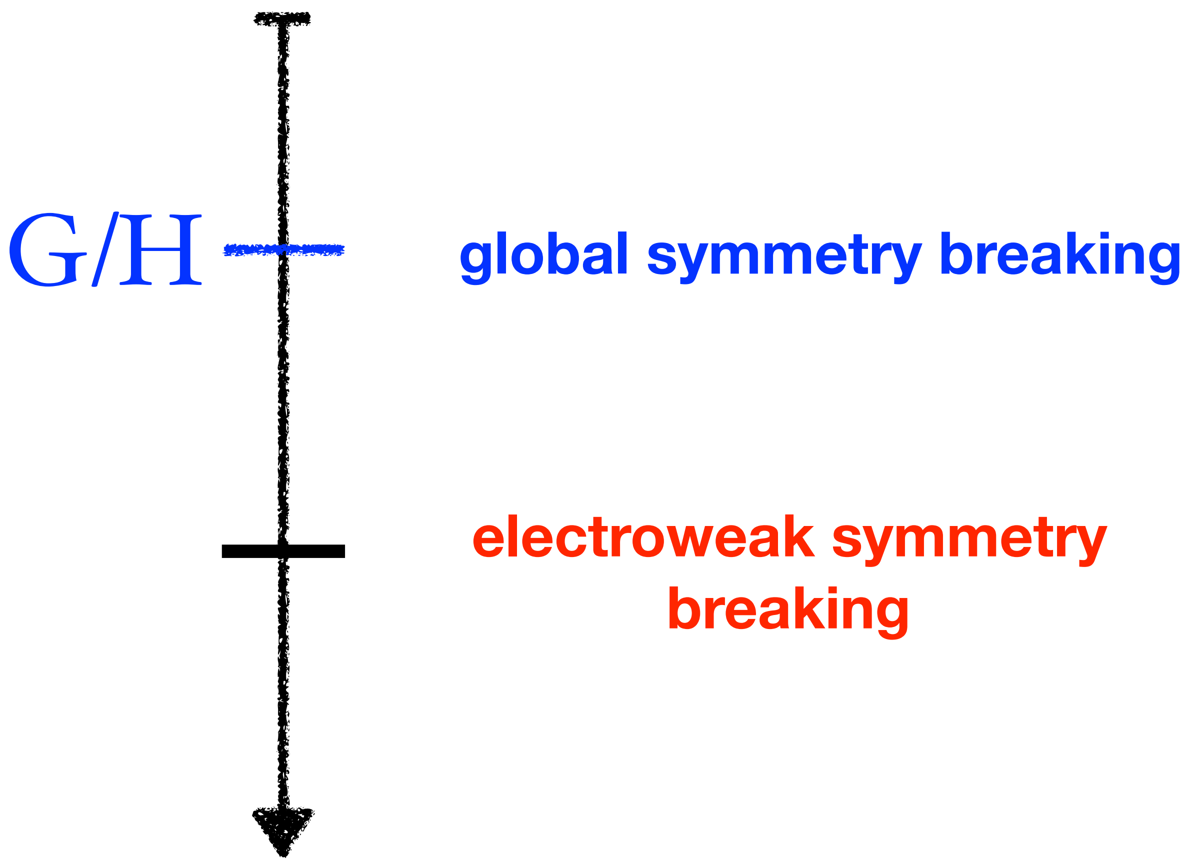


- Many models: little Higgs, holographic/composite Higgs, twin Higgs…

Higgs Nonlinearity

- PNGB Higgs boson can arise from a coset depicted below





Higgs nonlinearity is denoted by the misalignment angle θ .

How to extract the Higgs nonlinearity from Higgs coupling deviations?

General Considerations:

- The Higgs couplings to the top and gluons are more model dependent; depend on fermion embeddings
- Instead we are interested in Higgs couplings only relevant with electroweak symmetry breaking
- Higgs couplings to gauge bosons (W, Z, photon)

PNGB Higgs Couplings

- Top-down approach:

  use CCWZ to describe the PNGB Higgs boson with specific $\mathrm{G/H}$

  SO(5)/SO(4), SU(3)/SU(2)…

  Bellazzini, Csaki, Serra, 1401.2457

- Bottom-up approach:

  use shift symmetry approach with only the group H at infrared;

  Low, 1412.2145, 1412.2146

  Universal up to the normalization of decay constant

  Nonlinear Sigma Model:

$$\mathscr{L}_{\mathrm{NL}\sigma\mathrm{M}} = \mathcal{O}(p^2) + \mathcal{O}(p^4) + \cdots$$

Considering the hVV couplings

- At the order of $\mathcal{O}(p^2)$, custodial symmetry assumed

$$\left(\tilde{D}_\mu H\right)^\dagger \tilde{D}^\mu H$$

$$= \frac{1}{2}\partial_\mu h \partial^\mu h + (2f)^2 \frac{g^2}{4} \sin^2 \frac{\langle h \rangle + h}{\sqrt{2} f} \left(W_\mu^+ W^{-\mu} + \frac{Z^\mu Z_\mu}{2\cos^2\theta_W} \right)$$

$m_{W/Z}$ → $v = \sqrt{2} f \sin \frac{\langle h \rangle}{\sqrt{2} f} = 246$ GeV → $\xi \equiv \frac{v^2}{2f^2} = \sin^2 \frac{\langle h \rangle}{\sqrt{2} f}$

Higgs nonlinearity

$$g_{hVV} = \frac{m_V^2}{v}\sqrt{1-\xi}\, hV_\mu V^\mu$$

$$g_{hhVV} = \frac{m_V^2}{v^2}(1-2\xi)\, hhV_\mu V^\mu$$

Extremely difficult to measure at the LHC

$$\frac{g_{hhVV}}{g_{hVV}} = \begin{cases} \frac{1}{v}\frac{1-2\xi}{\sqrt{1-\xi}} & \text{PNGB} \\ \frac{1}{v} & \text{SM} \end{cases}$$

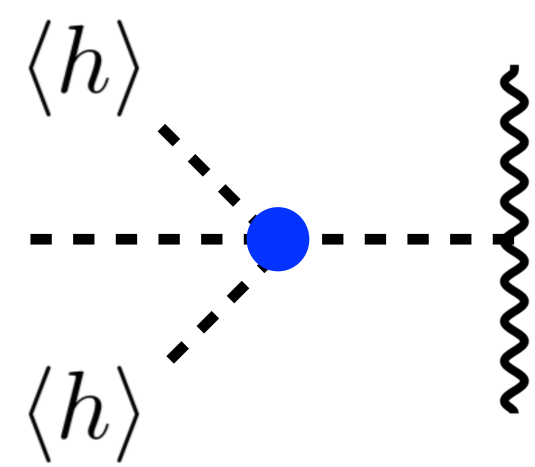
Unfortunately, Higgs nonlinearity is NOT the only source that can modify the hVV couplings!

Heavy Resonance induced operator

$$O_H = \frac{1}{2v^2}\partial_\mu(H^\dagger H)\partial^\mu(H^\dagger H)$$

e.g. a singlet scalar extension model

$$V(H,S) = \lambda m_S H^\dagger H S + m_S^2 S^2$$



- O_H can fake Higgs nonlinearity in hVV deviations, regardless of the Higgs boson nature

$$h \to h/\sqrt{1+c_H}$$

- At dimension-six level, we only consider O_H in hVV deviations

Higgs Nonlinearity & Heavy Particles

- The signal strength of $h \to VV^*$ channels:

$$\mu(h \to V^*V) = \frac{\sigma_h \times \mathrm{BR}(h \to V^*V)}{\sigma_h^{\mathrm{SM}}(h \to V^*V)_{\mathrm{SM}}}$$

$$= \frac{\sigma_h}{\sigma_h^{\mathrm{SM}}} \cdot \frac{\Gamma_{\mathrm{total}}^{\mathrm{SM}}}{\Gamma_{\mathrm{total}}} \cdot F_{\mathrm{PNGB}} \cdot F_{O_H}$$

$$F_{\mathrm{PNGB}} = 1 - \xi$$

$$F_{O_H} = \frac{1}{1 + c_H}$$

- We need to eliminate the faking effects of O_H in hVV couplings

- Since the effect of O_H is universal for all the single Higgs processes, it can be cancelled out in the ratio

$$R \equiv \frac{\mu(h \to Z\gamma)}{\mu(h \to V^*V)}$$

$$\mu(h \to Z^*Z) = \frac{\mathrm{BR(h \to Z^*Z)}}{\mathrm{BR(h \to Z^*Z)_{SM}}}$$

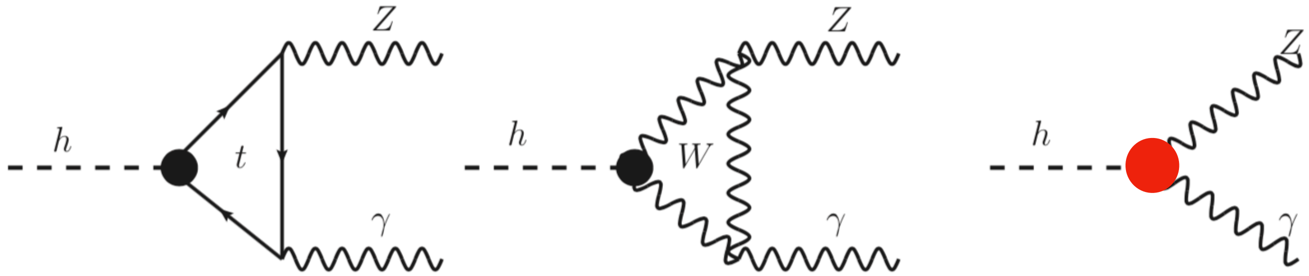
$$\mu(h \to Z\gamma) = \frac{\mathrm{BR}(h \to Z\gamma)}{\mathrm{BR}(h \to Z\gamma)_{\mathrm{SM}}}$$

Considering the $hZ\gamma$ effective coupling

- The following effective coupling at the order of $\mathcal{O}(p^4)$ is insensitive to Higgs nonlinearity (no dependence on ξ).

$$\mathcal{L}_{hZ\gamma} = (\widetilde{c}_{HW}\widetilde{O}_{HW} + \widetilde{c}_{HB}\widetilde{O}_{HB})/M_W^2$$
$$= -\Delta\kappa_{Z\gamma}\tan\theta_W \frac{1}{v}(\partial^\mu h Z^\nu - \partial^\nu h Z^\mu)A_{\mu\nu}$$

$$\tilde{O}_{HB} = (\tilde{D}^\mu H)^\dagger(\tilde{D}^\nu H)B_{\mu\nu}$$
$$\tilde{O}_{HW} = (\tilde{D}^\mu H)^\dagger\sigma^i(\tilde{D}^\nu H)W^i_{\mu\nu}$$



- The signal strength of the $hZ\gamma$ channel:

$$F^W_{Z\gamma} = +0.0087$$
$$F^t_{Z\gamma} = -0.001$$

$$\mu(h\to Z\gamma) = \frac{\sigma_h \times \mathrm{BR}(h\to Z\gamma)}{\sigma_h^{\mathrm{SM}} \times \mathrm{BR}(h\to Z\gamma)_{\mathrm{SM}}}$$
$$= \frac{\sigma_h}{\sigma_h^{\mathrm{SM}}}\cdot\frac{\Gamma^{\mathrm{SM}}_{\mathrm{total}}}{\Gamma_{\mathrm{total}}}\cdot F_{O_H}\cdot\frac{\left|F^t_{Z\gamma} + F^W_{Z\gamma}\sqrt{F_{\mathrm{PNGB}}} + \Delta\kappa_{Z\gamma}\tan\theta_W\right|^2}{|F^t_{Z\gamma}+F^W_{Z\gamma}|^2}$$

The ratio $R \equiv \mu(h \to Z\gamma)/\mu(h \to VV^*)$

$$\mu(h \to VV^*) = \frac{\sigma_h \times \mathrm{BR}(\mathrm{h} \to \mathrm{V^*V})}{\sigma_h^{\mathrm{SM}} \times \mathrm{BR}(\mathrm{h} \to \mathrm{V^*V})_{\mathrm{SM}}} = \frac{\sigma_h}{\sigma_h^{\mathrm{SM}}} \cdot \frac{\Gamma_{\mathrm{total}}^{\mathrm{SM}}}{\Gamma_{\mathrm{total}}} \cdot F_{\mathrm{PNGB}} \cdot F_{O_H}$$

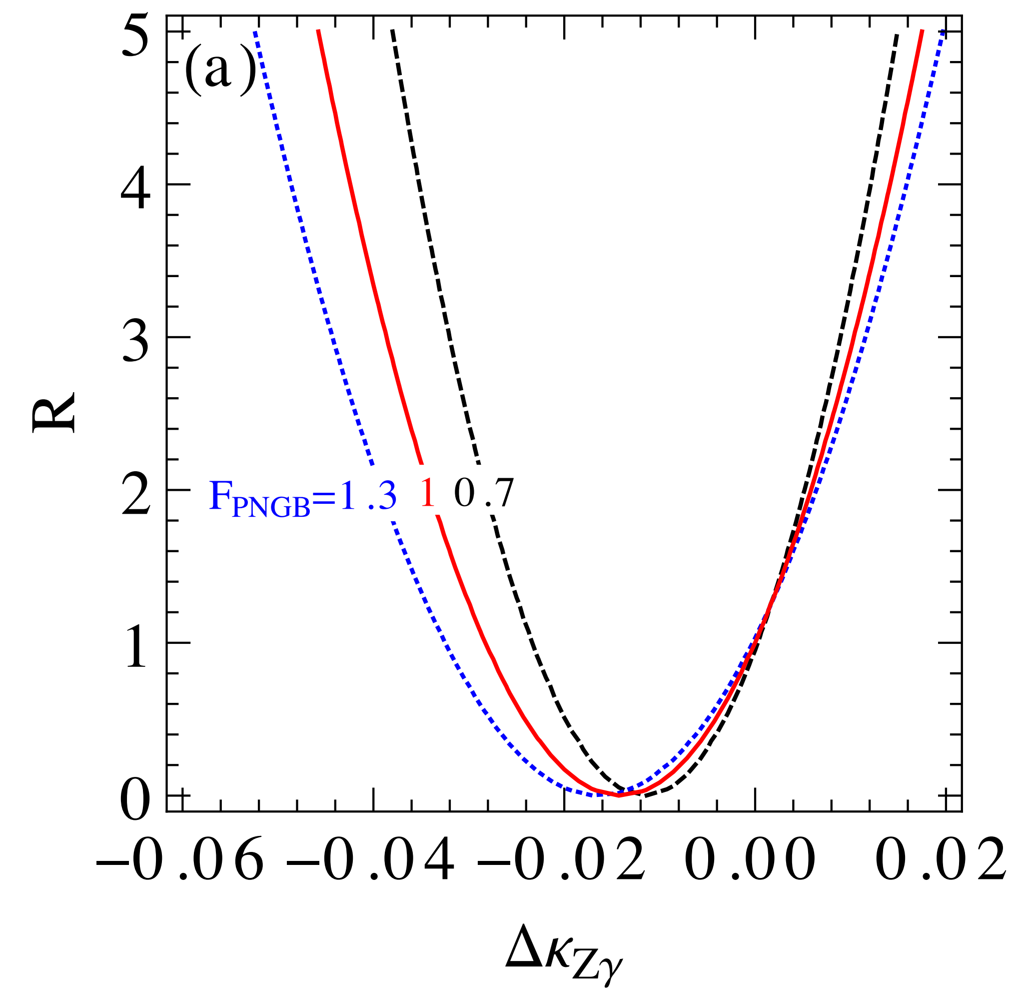
$$F_{\mathrm{PNGB}} = 1 - \xi$$

$$F_{O_H} = \frac{1}{1 + c_H}$$

$$\mu(h \to Z\gamma) = \frac{\sigma_h \times \mathrm{BR}(h \to Z\gamma)}{\sigma_h^{\mathrm{SM}} \times \mathrm{BR}(h \to Z\gamma)_{\mathrm{SM}}}$$

$$= \frac{\sigma_h}{\sigma_h^{\mathrm{SM}}} \cdot \frac{\Gamma_{\mathrm{total}}^{\mathrm{SM}}}{\Gamma_{\mathrm{total}}} \cdot F_{O_H} \cdot \frac{\left| F_{Z\gamma}^t + F_{Z\gamma}^W \sqrt{F_{\mathrm{PNGB}}} + \Delta\kappa_{Z\gamma} \tan\theta_W \right|^2}{|F_{Z\gamma}^t + F_{Z\gamma}^W|^2}$$

$$R \equiv \frac{\mu(h \to Z\gamma)}{\mu(h \to VV^*)} = \frac{\left| F_{Z\gamma}^t + F_{Z\gamma}^W \sqrt{F_{\mathrm{PNGB}}} + \Delta\kappa_{Z\gamma} \tan\theta_W \right|^2}{|F_{Z\gamma}^t + F_{Z\gamma}^W|^2 \; F_{\mathrm{PNGB}}}$$

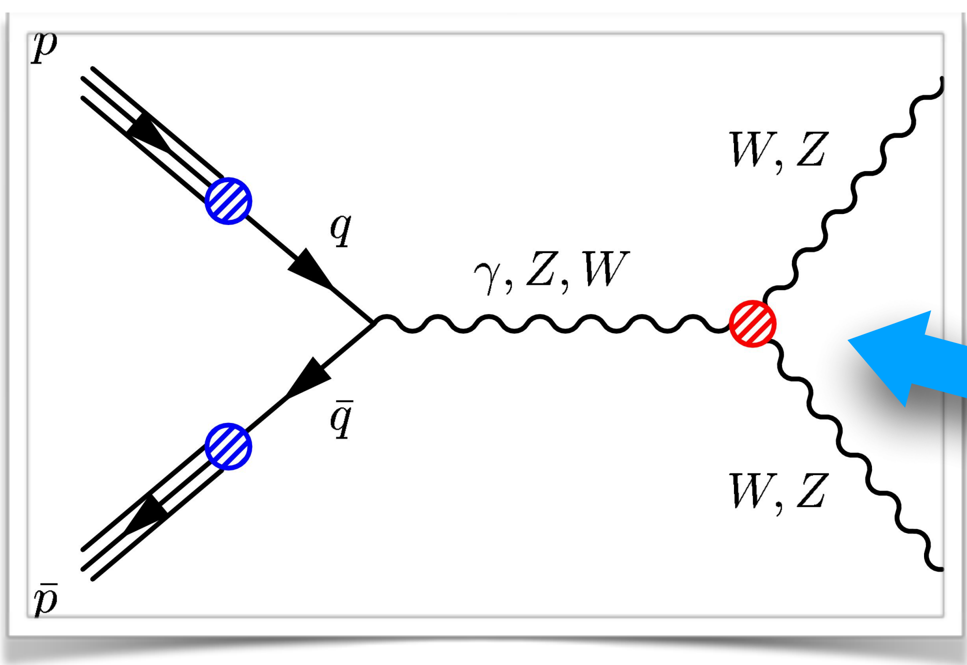


We can determine F_{PNGB} (i.e. ξ) from R and $\Delta\kappa_{Z\gamma}$ measurements.

Triple Gauge Couplings

De Rujula et. al. NPB 1992;
Hagiwara et. al. PRD 1993

$$\mathcal{L}_{\mathrm{TGC}}/g_{WW\bar{V}} = ig_{1,\bar{V}}\left(W^{+}_{\mu\nu}W^{-}_{\mu}\bar{V}_{\nu} - W^{-}_{\mu\nu}W^{+}_{\mu}\bar{V}_{\nu}\right) + i\kappa_{\bar{V}}W^{+}_{\mu}W^{-}_{\nu}\bar{V}_{\mu\nu} + \frac{i\lambda_{\bar{V}}}{M_W^2}W^{+}_{\lambda\mu}W^{-}_{\mu\nu}\bar{V}_{\nu\lambda}$$



$$\Delta g_{1,Z} = \widetilde{c}_{HW}/\cos^2\theta_W$$

$$\Delta\kappa_\gamma = \widetilde{c}_{HW} + \widetilde{c}_{HB}$$

$$\Delta\kappa_{Z\gamma} = \widetilde{c}_{HB} - \widetilde{c}_{HW}$$

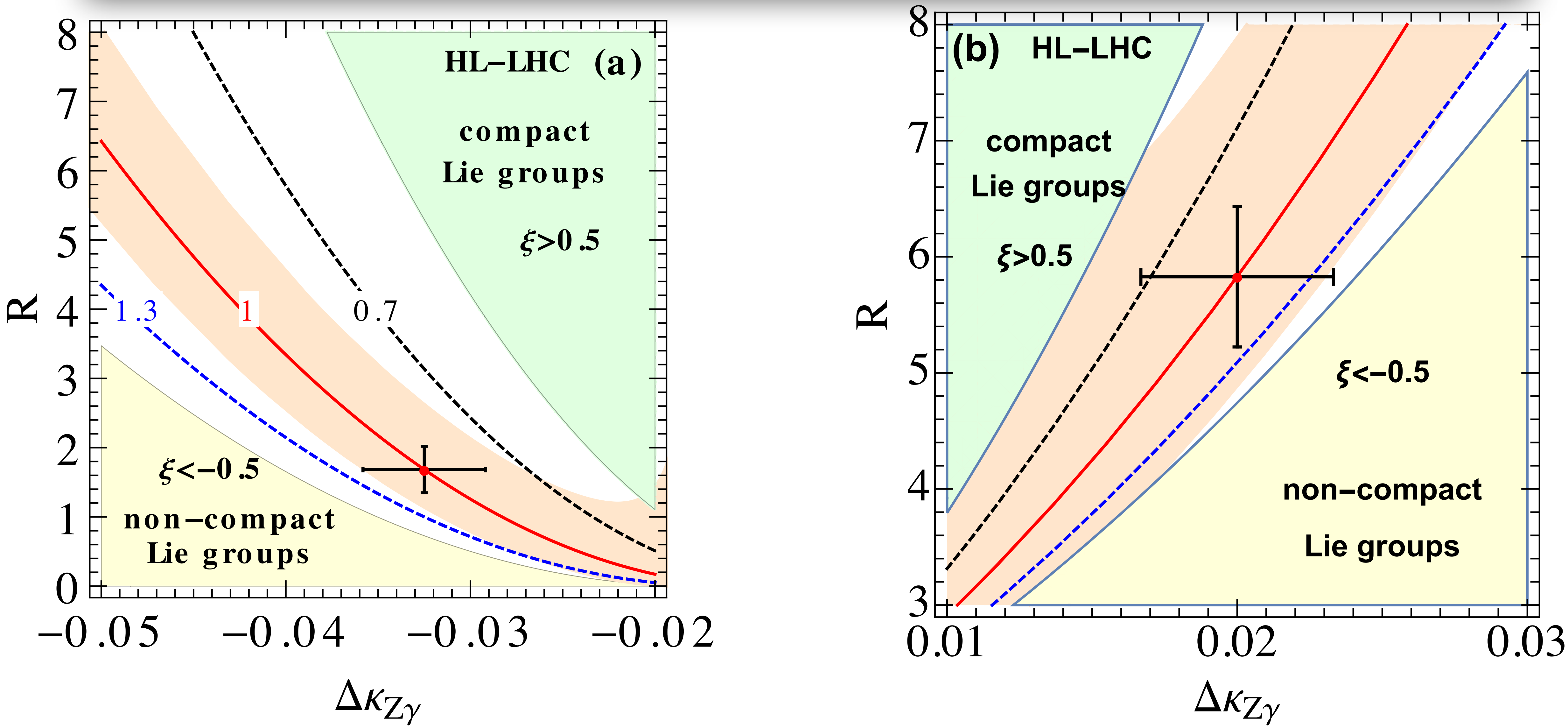
It can be well determined from the TGC measurement.

Determining F_{PNGB} at the HL-LHC

$$F_{\text{PNGB}} = 1 - \xi = 1 - v^2/2f^2$$

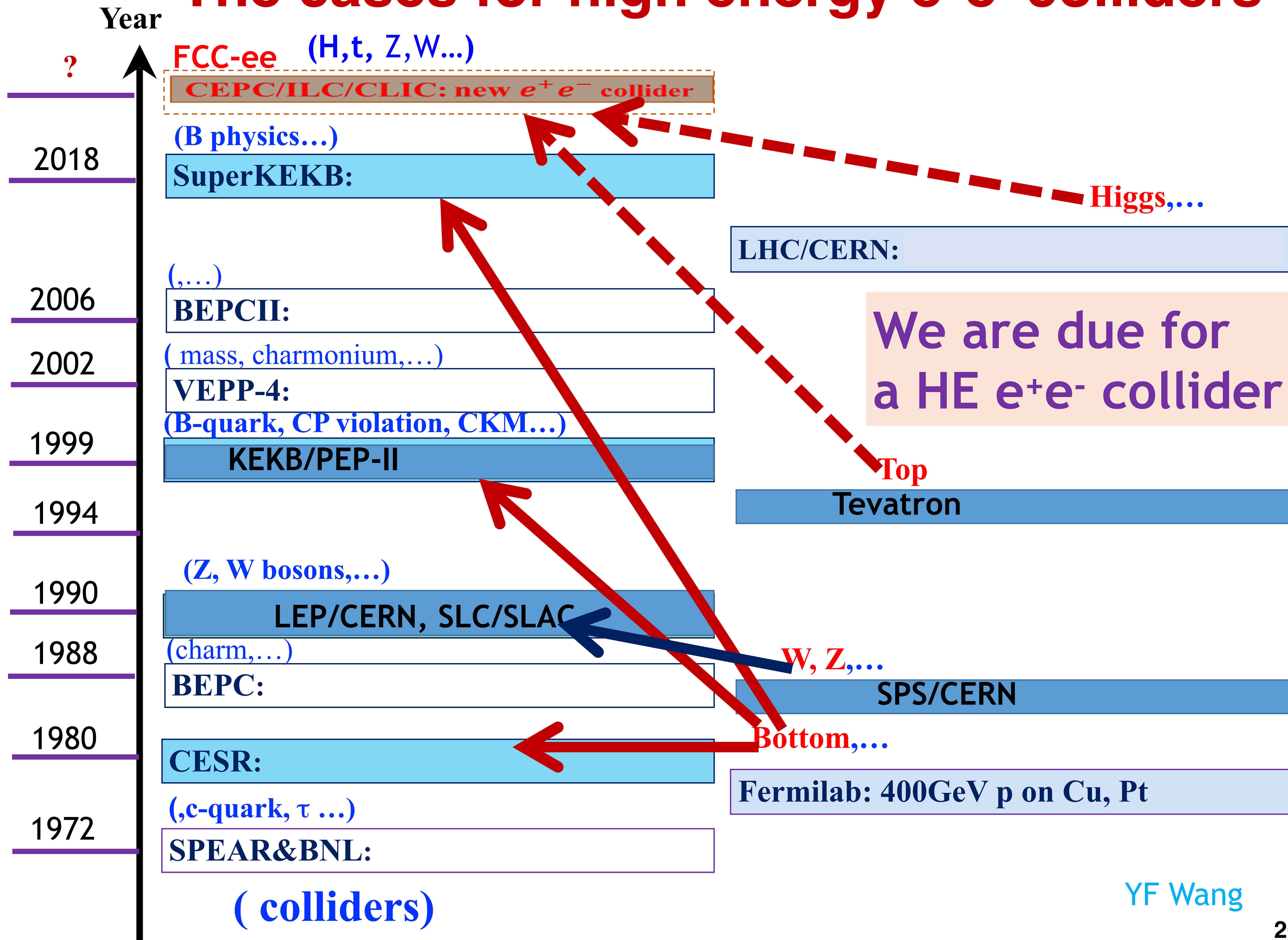
Contour line = 1 ⟶ Higgs is fundamental (or SM-like as $f \gg v$)

Contour line $\neq$ 1 ⟶ Higgs is composite

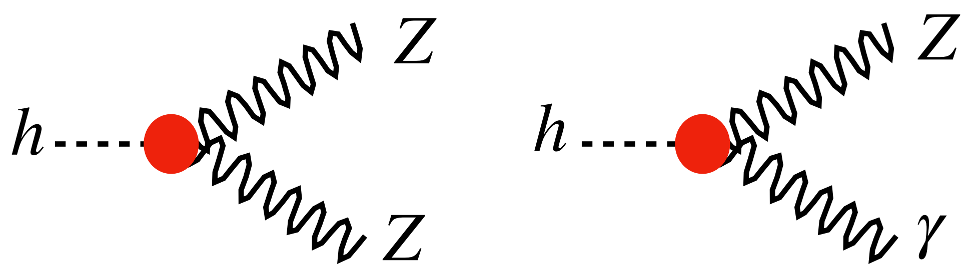


LHC cannot do it ⟶ We need electron-positron colliders (CEPC, FCC-ee, ILC)

The cases for high energy e^+e^- colliders



Determining F_{PNGB} at the CEPC



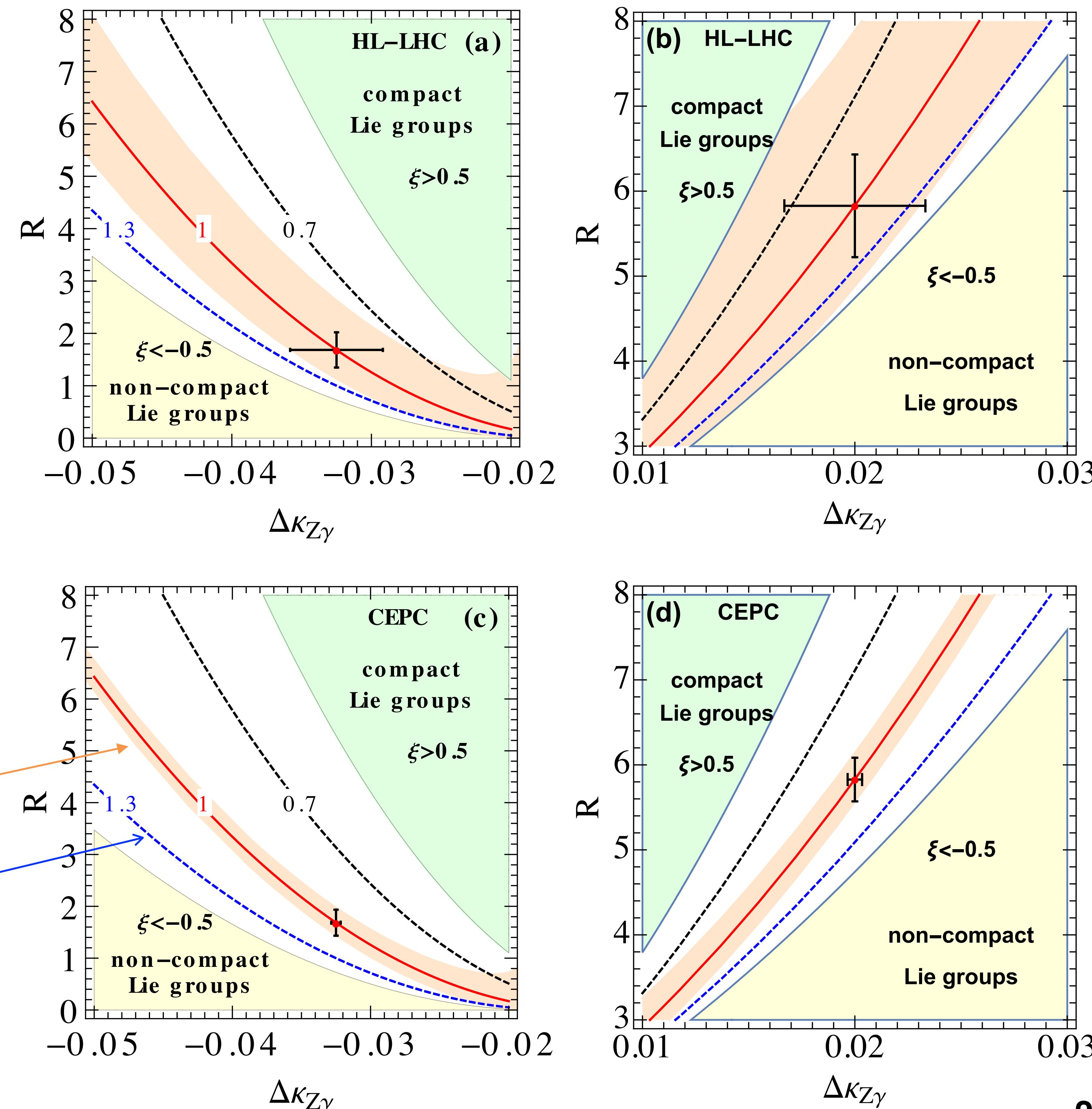
$$F_{\text{PNGB}} = 1 - \xi = 1 - v^2/2f^2$$

QHC, Yan, Xu, Zhu, 1810.07661

$$R \equiv \frac{\mu(h \to Z\gamma)}{\mu(h \to Z^*Z)}$$

$$\mu(h \to Z^*Z) = \frac{\text{BR}(h \to Z^*Z)}{\text{BR}(h \to Z^*Z)_{\text{SM}}}$$

$$\mu(h \to Z\gamma) = \frac{\text{BR}(h \to Z\gamma)}{\text{BR}(h \to Z\gamma)_{\text{SM}}}$$



Fundamental (SM-like)

Composite

Precision = Discovery

Conclusion

It is very challenging but we need measure the HHH coupling from all possible ways to probe the scalar potential.

Precision measurements of Higgs couplings would shed lights on new physics beyond the SM.

- The Higgs nonlinearity $\xi (\equiv v^2/2f^2)$ can be probed in the ratio

$$R \equiv \frac{\mu(h \to Z\gamma)}{\mu(h \to V^*V)}$$

and the faking effects from the O_H operator are cancelled.

- Our result is valid in *any* symmetry breaking patterns, as long as custodial symmetry is assumed.

We are due for a High Energy e^+e^- collider.

Thank You!