希格斯粒子属性的测量

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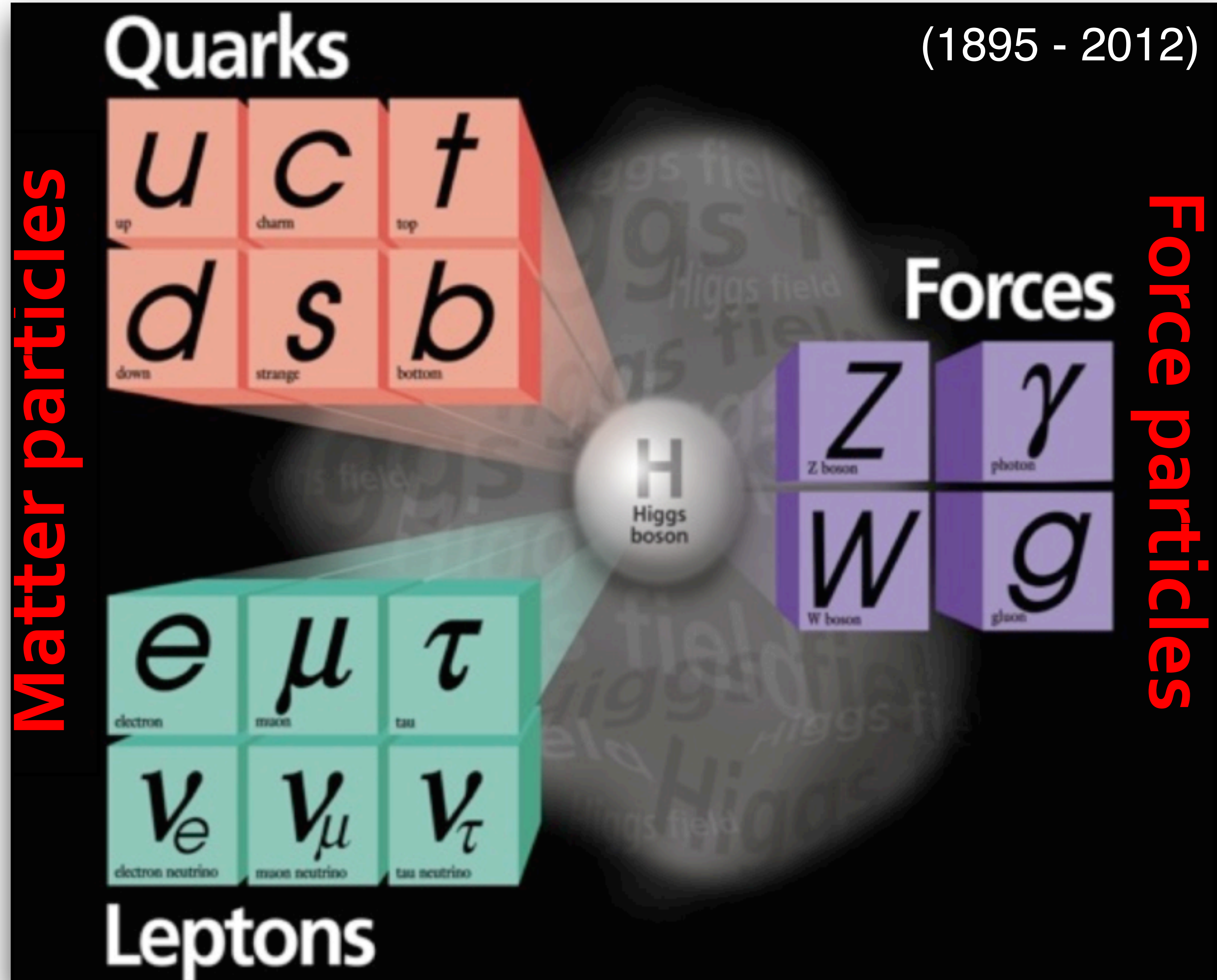
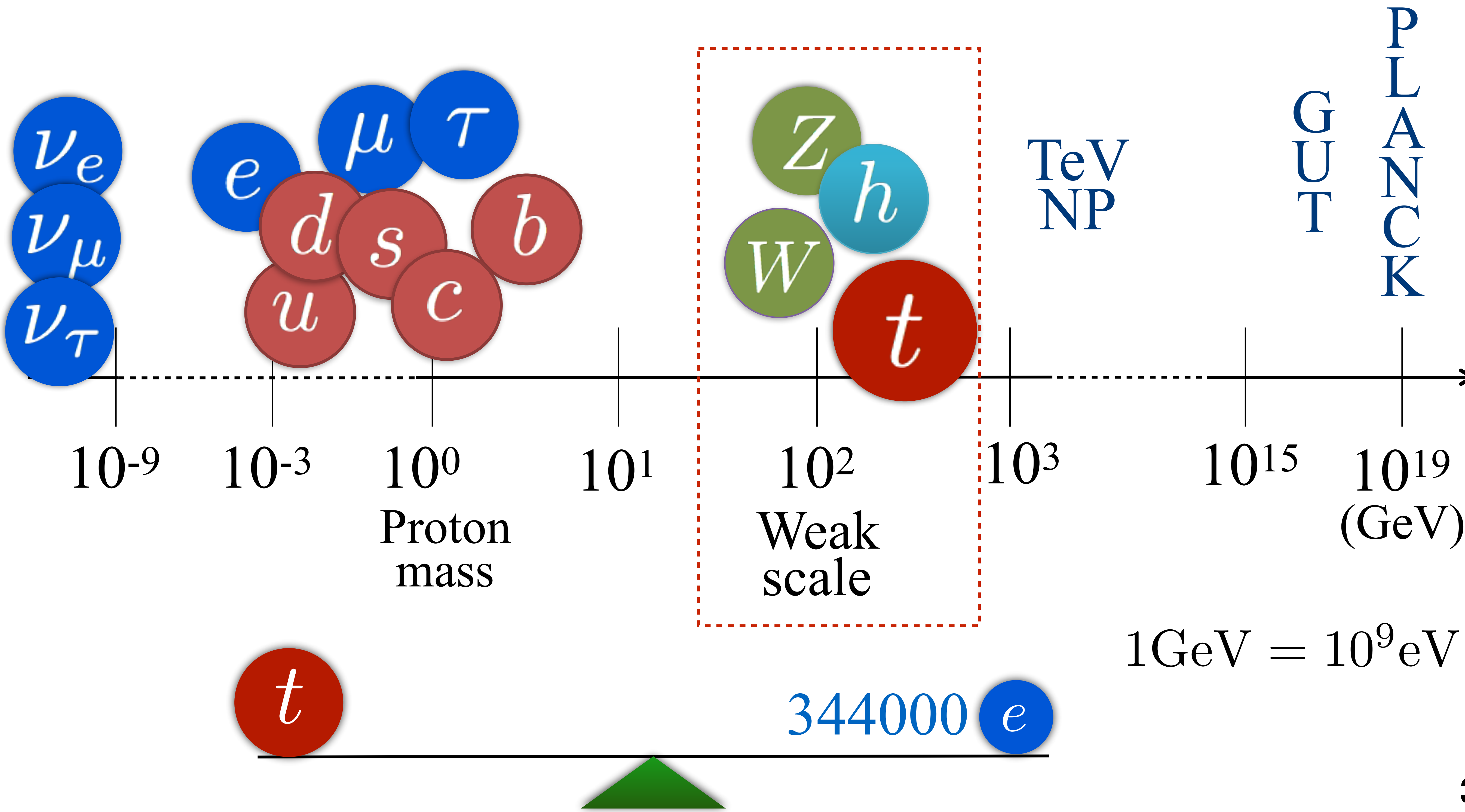
The Great Standard Model



Two outstanding puzzles in SM

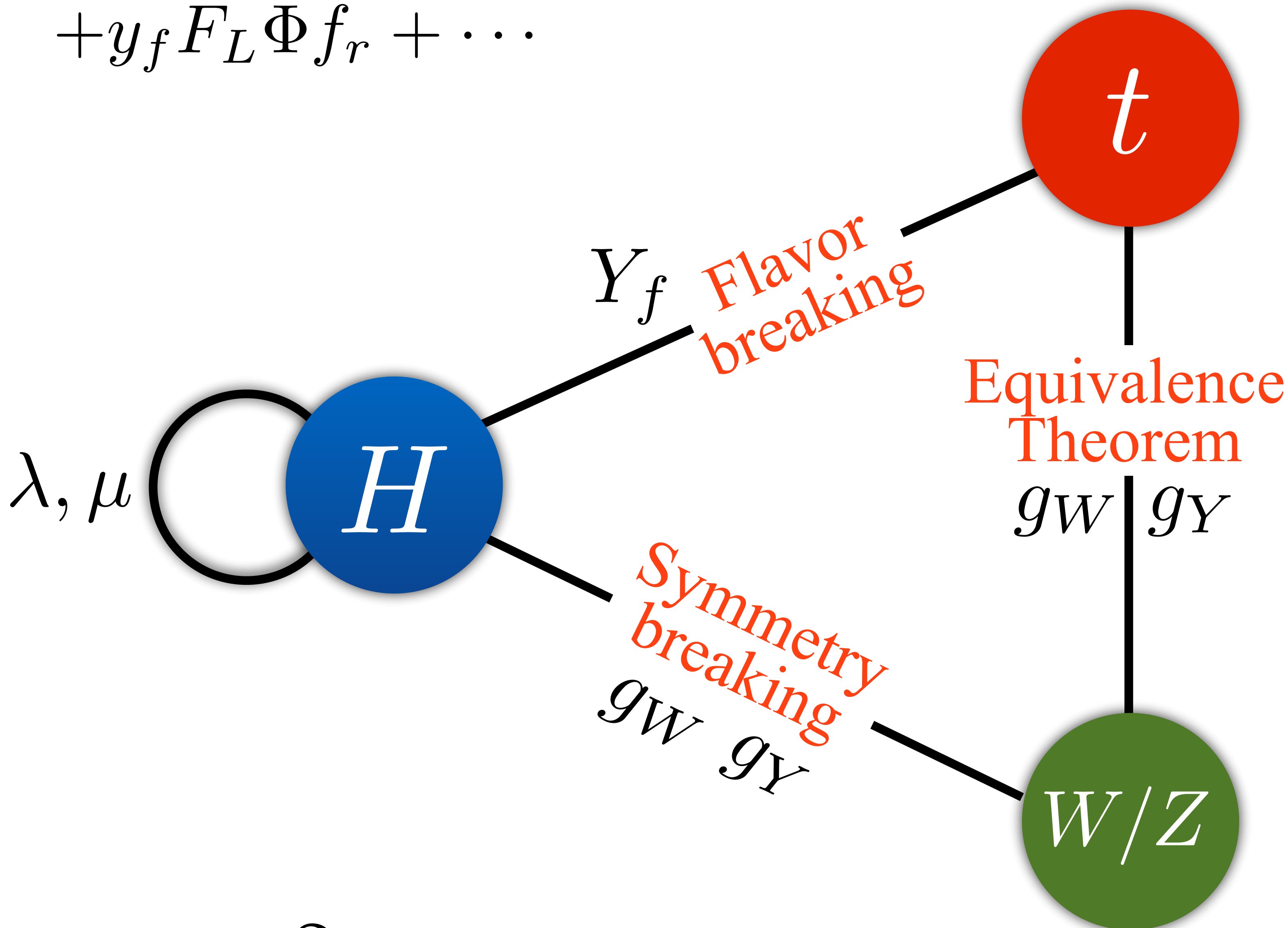
Origins of EWSB and Flavor breaking

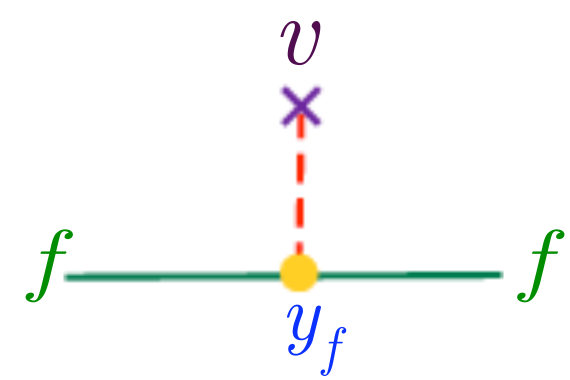
(*W/Z Masses*) (*Fermion Mass*)

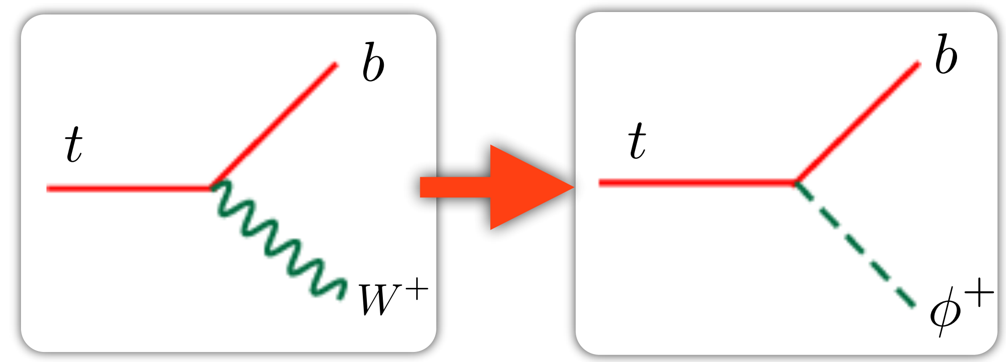


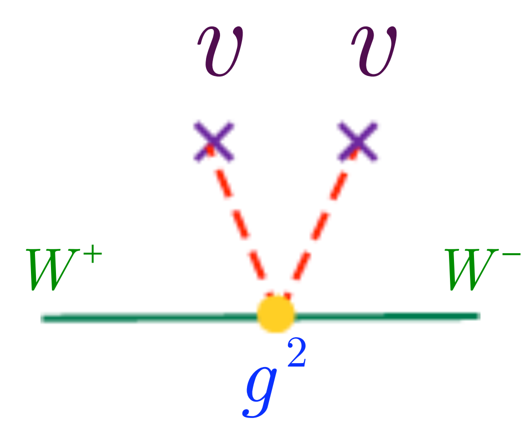
Electroweak Triangle

$$\mathcal{L} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - \mu^2 \Phi^\dagger \Phi + \lambda \left(\Phi^\dagger \Phi\right)^2$$
$$+ y_f \bar{F}_L \Phi f_r + \cdots$$









$$m_h^2 = m_t \times m_Z$$

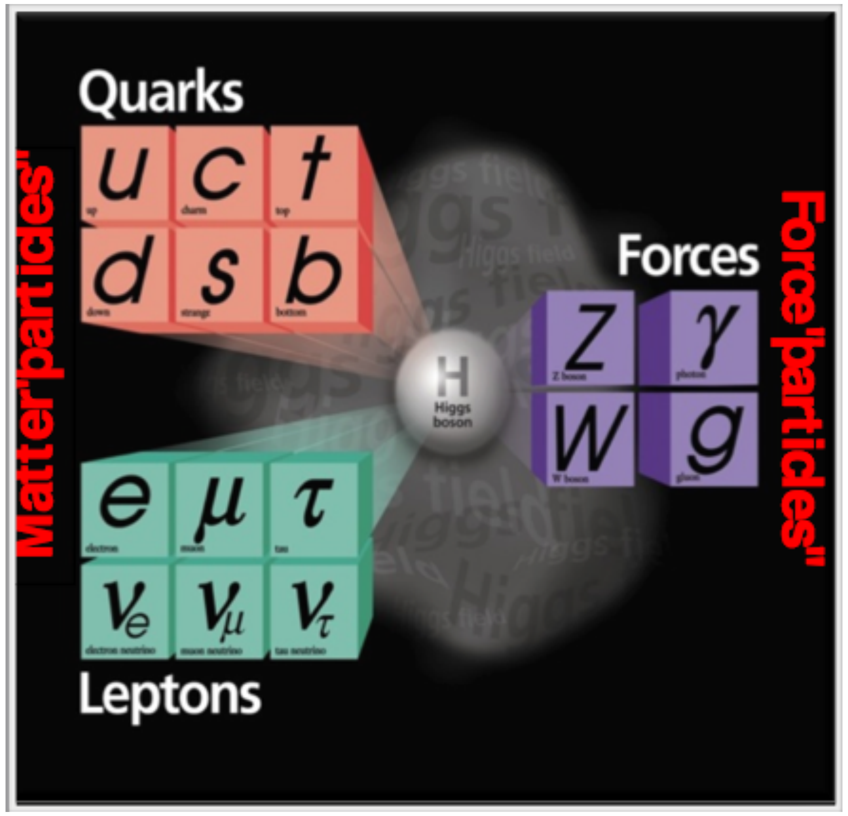
What can Higgs Boson tell us?

HVV coupling

Relation between
M_W and M_Z
(custodial Symmetry)

HFF coupling

Magnitude and CP



Relation between
HVV and *HHVV*
couplings

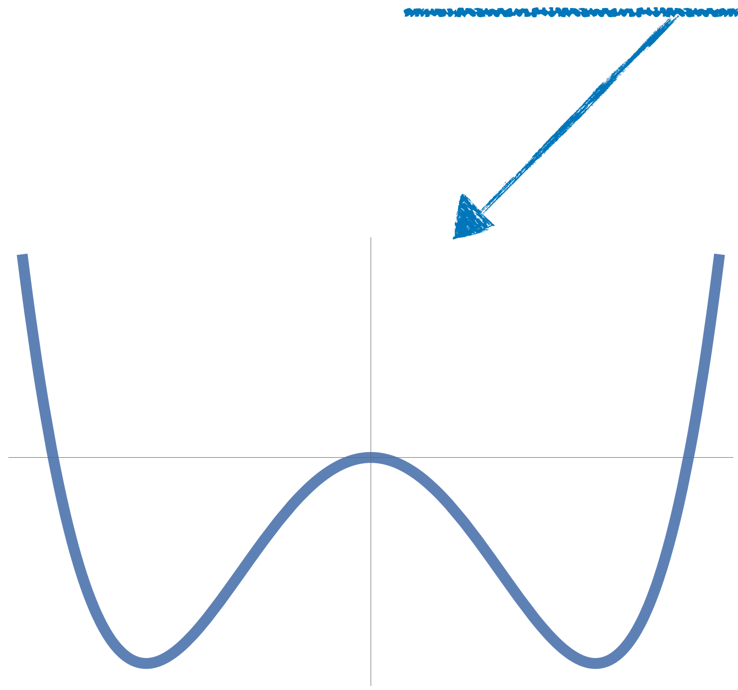
Higgs-self couplings
HHH and *HHHH*

The Higgs boson is important not only for EWSB,
but also as a WINDOW to NP beyond the SM.

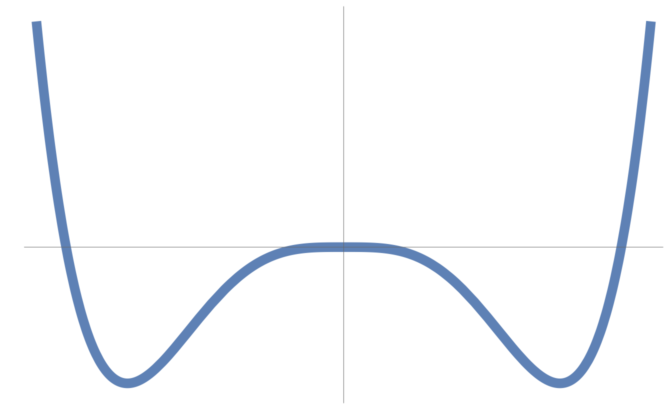
1) Higgs-self Interaction

(probing potential at electroweak scale)

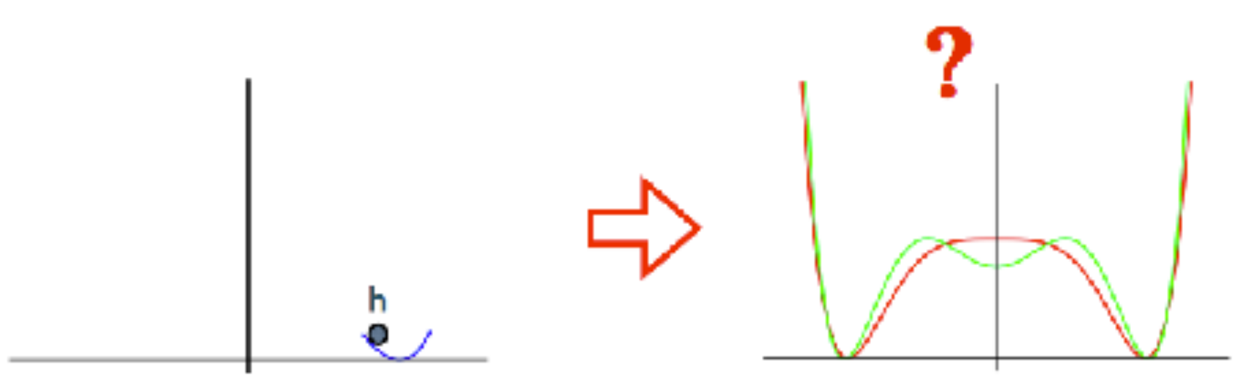
$$V(\phi) = -\mu^2\phi^2 + \lambda(\mu)\phi^4 + \frac{\kappa(\mu)}{\Lambda^2}\phi^6 + \cdots$$



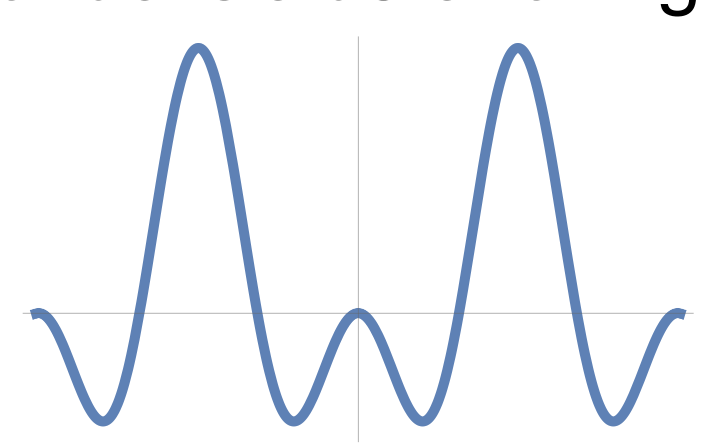
Coleman-Weinberg Higgs



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



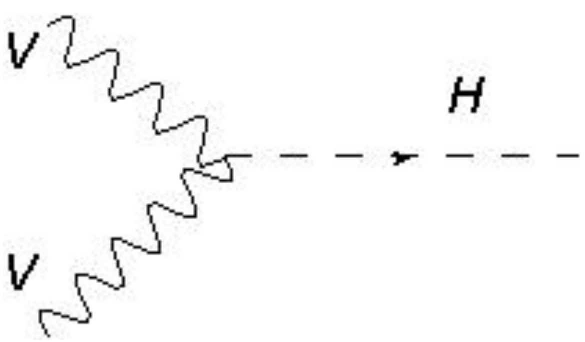
Pseudo-Goldstone Higgs



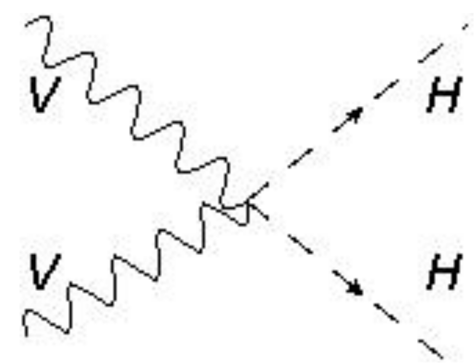
$$V(\phi) = a\sin^2(\phi/f) + b\sin^4(\phi/f)$$

2) HVV versus HHVV

SM predicts a definite ratio between HVV and HVV couplings



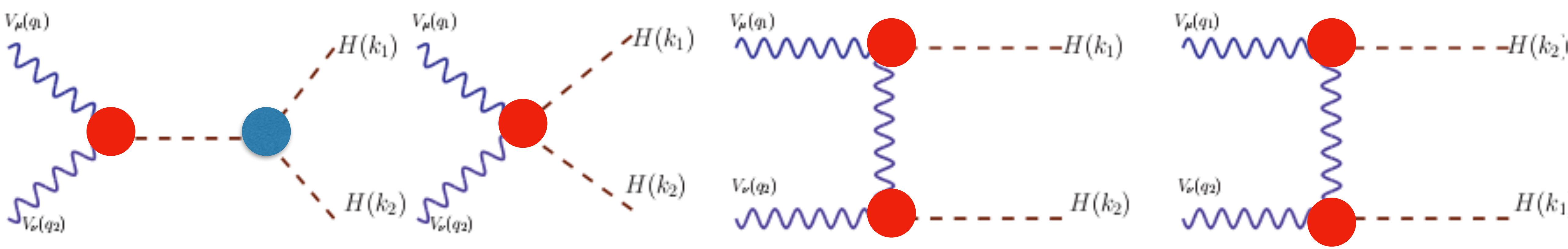
$$2i\frac{M_V^2}{v}g^{\mu\nu}$$



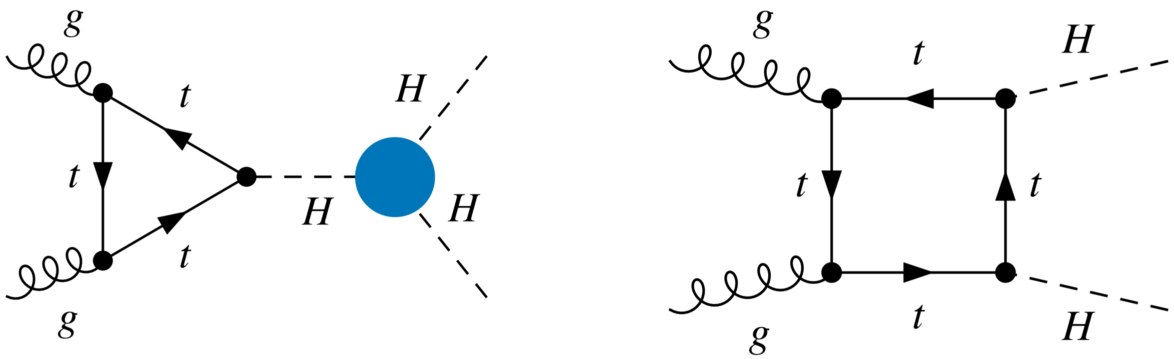
$$2i\frac{M_V^2}{v^2}g^{\mu\nu}$$

tree-level relation

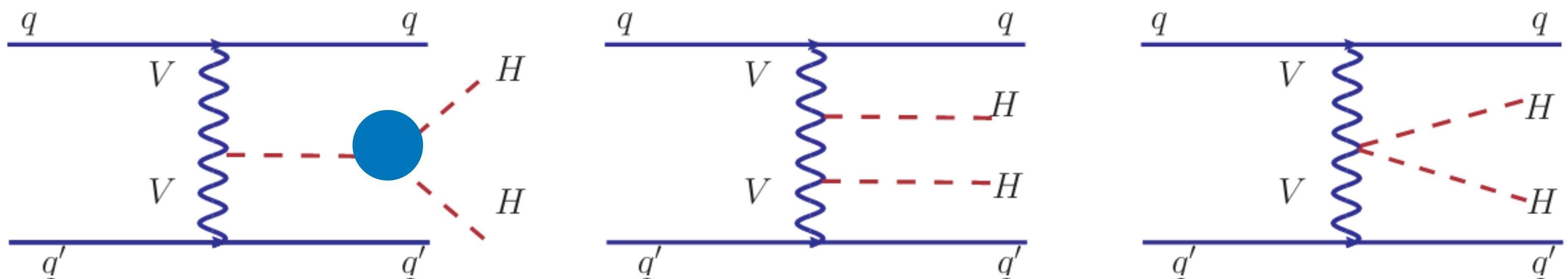
If the ratio is modified by NP, the unitarity of $VV \to HH$ is broken



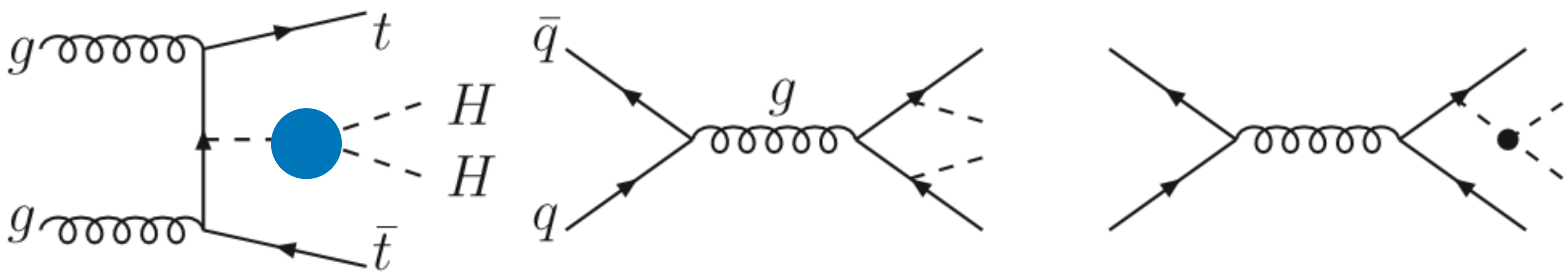
Measuring *HHH* coupling via Higgs Pair Productions



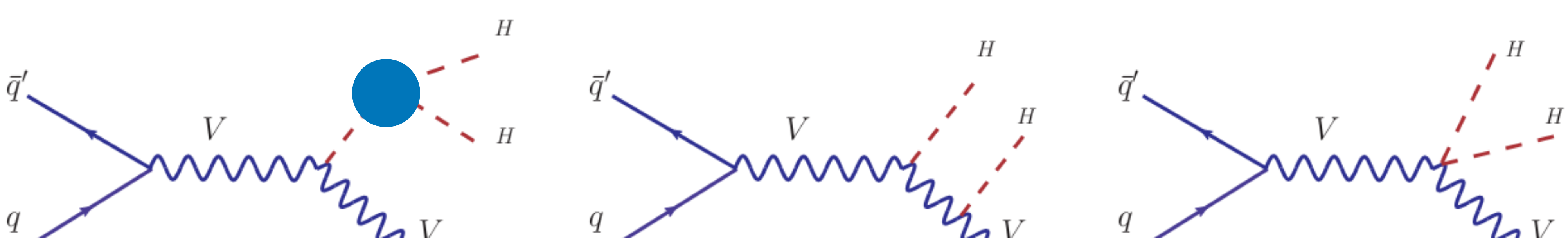
$$gg \to HH$$



$$qq' \to HHqq'$$

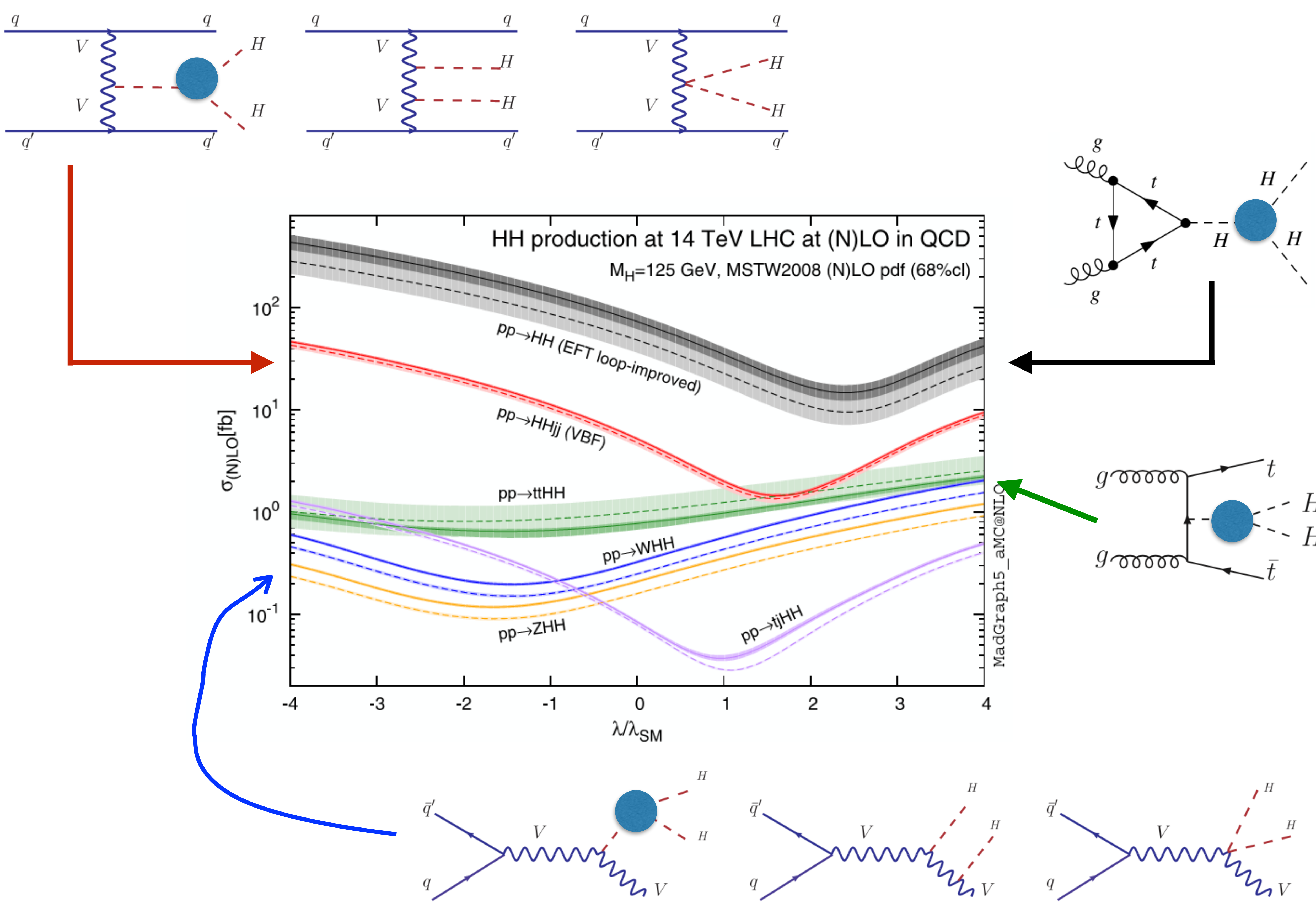


$$gg \to t\bar{t}HH$$

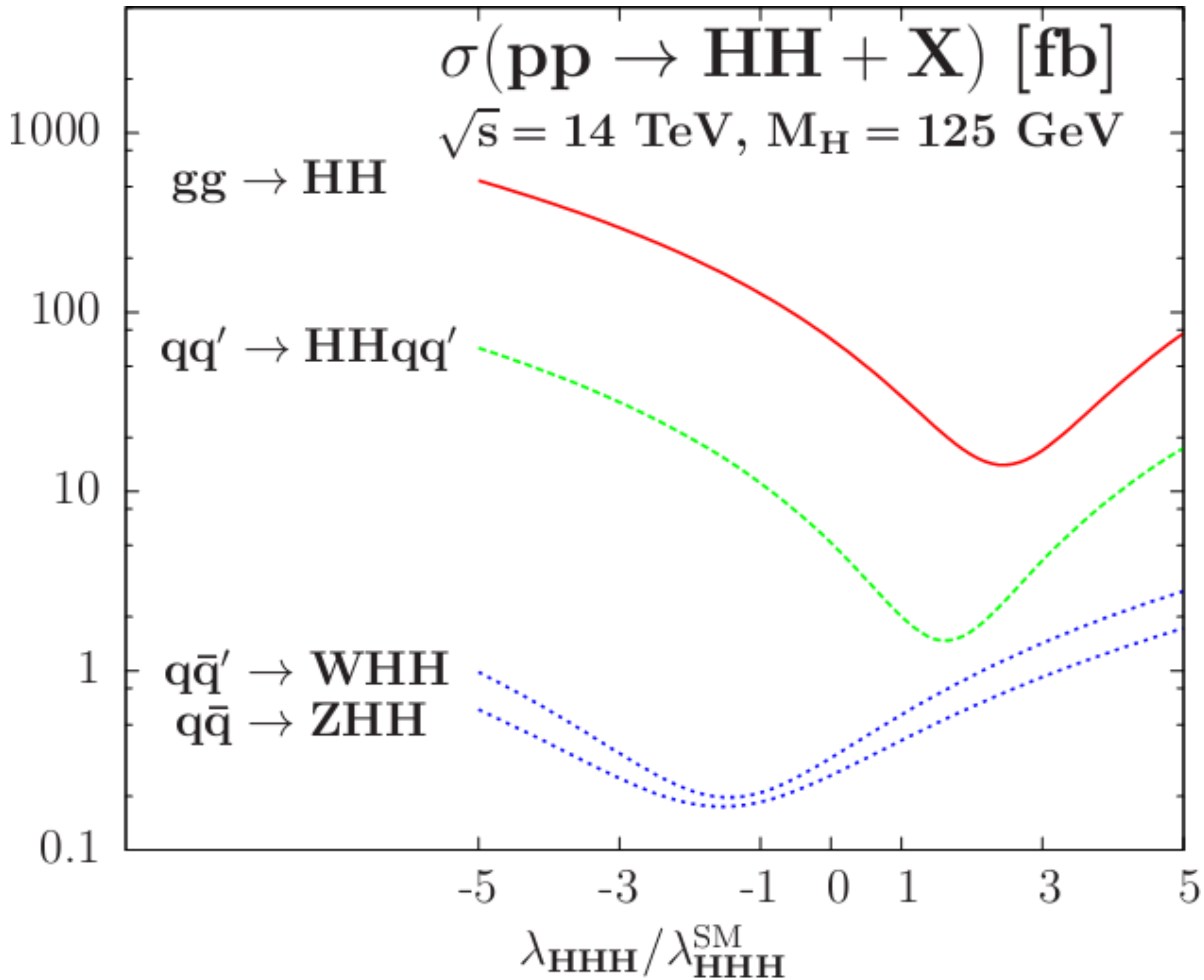


$$q\bar{q}' \to VHH$$

Higgs Boson Pair Production



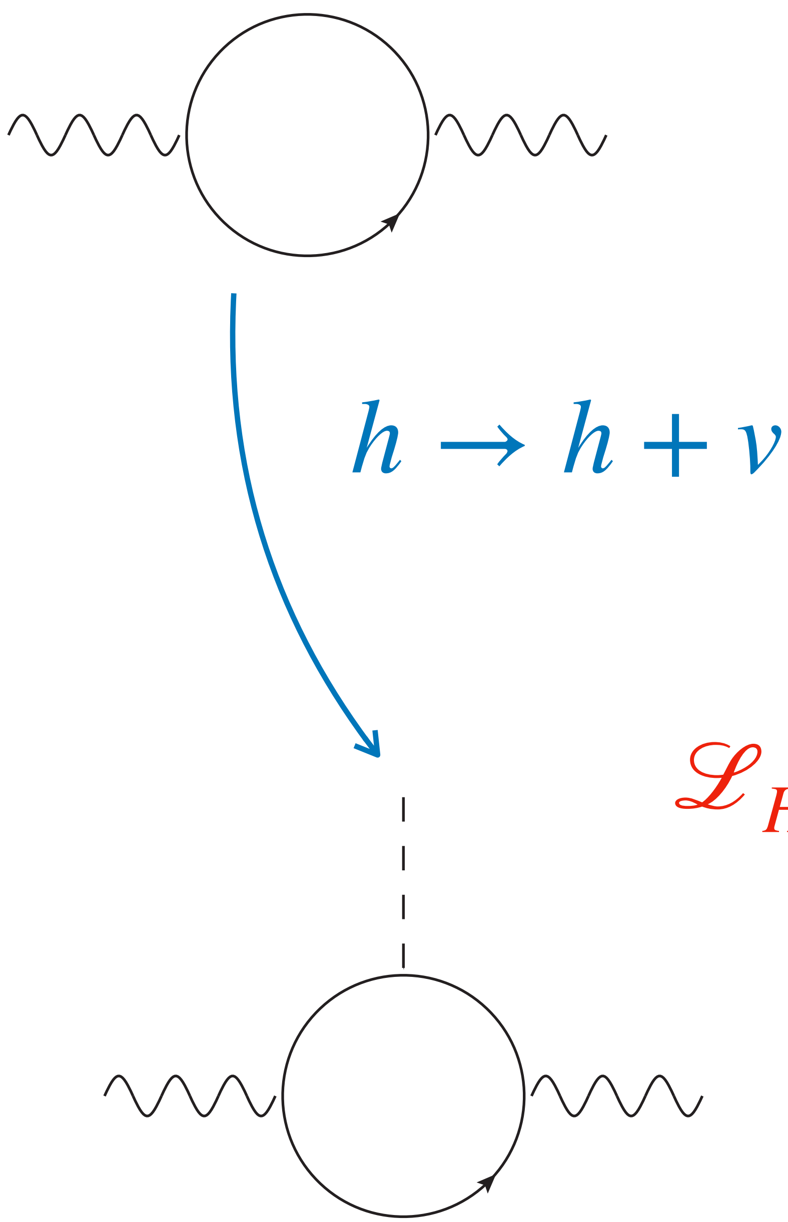
Sensitivity to *HHH* coupling



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

QED effective Lagrangian at one-loop order

$$\mathscr{L} = -\frac{1}{4} A_{\mu\nu} A^{\mu\nu} \sum_i \frac{b_i e^2}{16\pi^2} \log \frac{\Lambda^2}{m_i^2} + \cdots$$



$$b_{1/2} = \frac{4}{3} N_{c,f} Q_f^2$$ Dirac Fermions

$$b_1 = -7$$ W bosons

$$b_0 = \frac{1}{3} N_{c,S} Q_S^2$$ Charged scalars

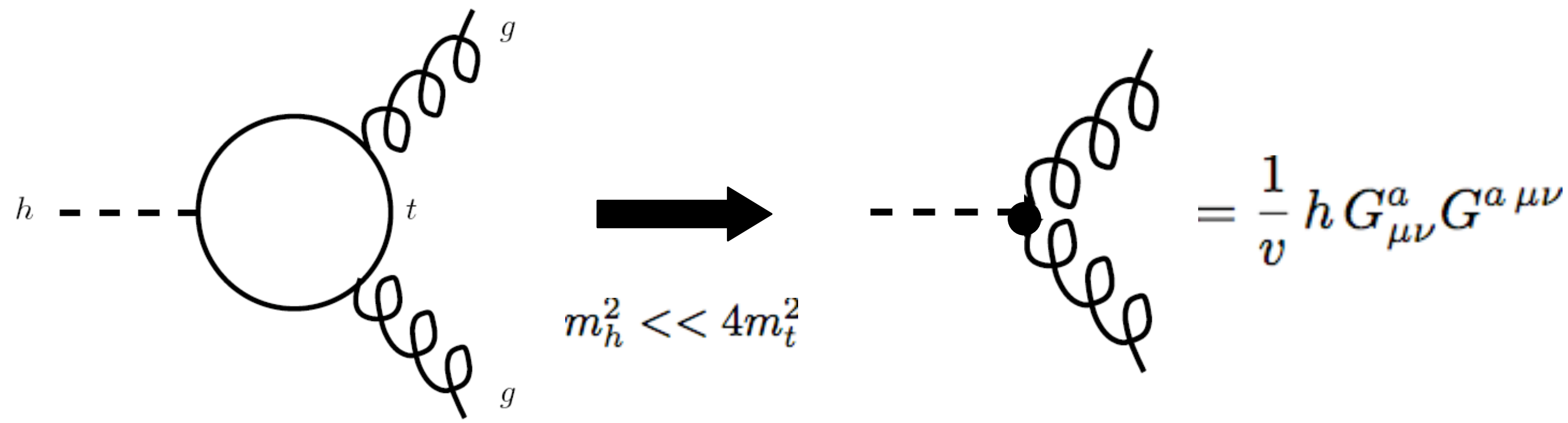
$$\mathscr{L}_{H\gamma\gamma} = \frac{\alpha}{16\pi} \left[\sum_i 2 b_i \frac{\partial}{\partial \log v} \log m_i(v) \right] h A_{\mu\nu} A^{\mu\nu}$$

$$\frac{g_{HVV}}{m_V^2} = \frac{\partial}{\partial v} \log m_V^2(v) \qquad \frac{2 g_{hf\bar{f}}}{m_f} = \frac{\partial}{\partial v} \log m_f^2(v)$$

$$\frac{g_{hSS}}{m_S^2} = \frac{\partial}{\partial v} \log m_S^2(v)$$

Low Energy Theorem

QHC, Jackson, Keung, Low, Shu, 0911.3398



In the SM the dominant contribution comes from the top-quark loop.

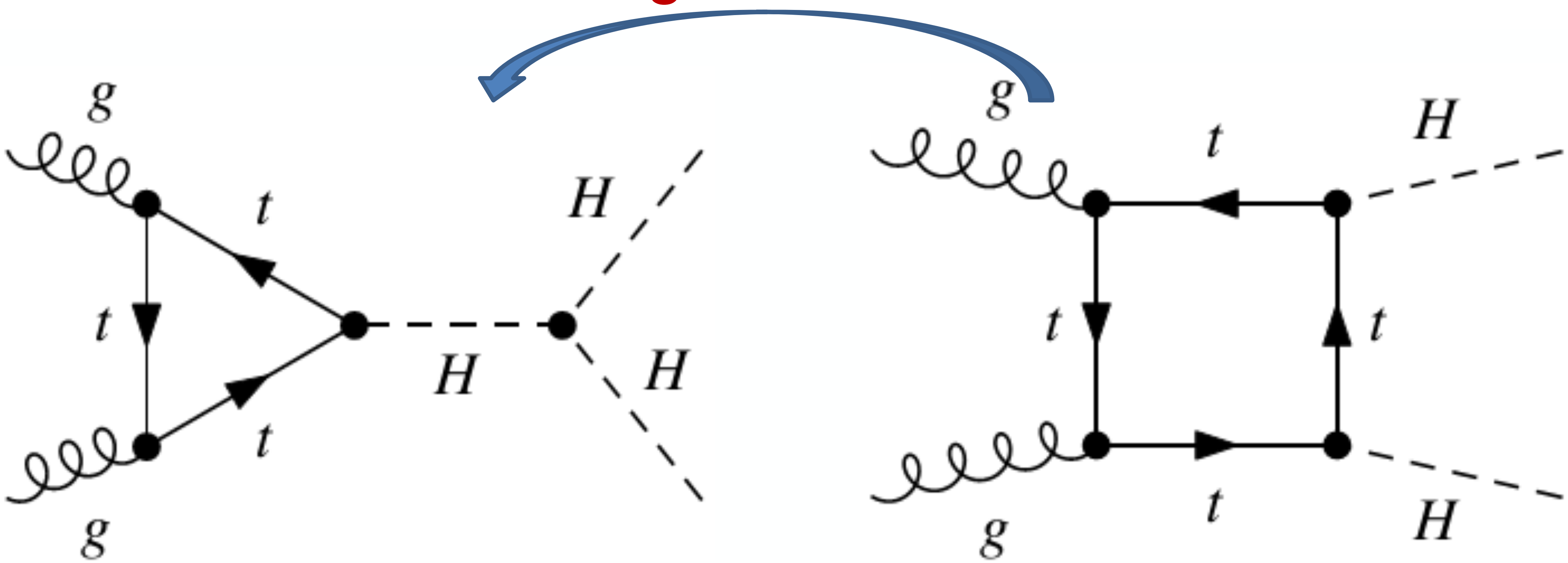
Since the top is “heavy”, the loop can be shrunk to a point and approximated by a dim-5 operator:

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

non-decoupling

Sensitivity to HHH coupling
gg->HH: the leading channel

Strong cancelation



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

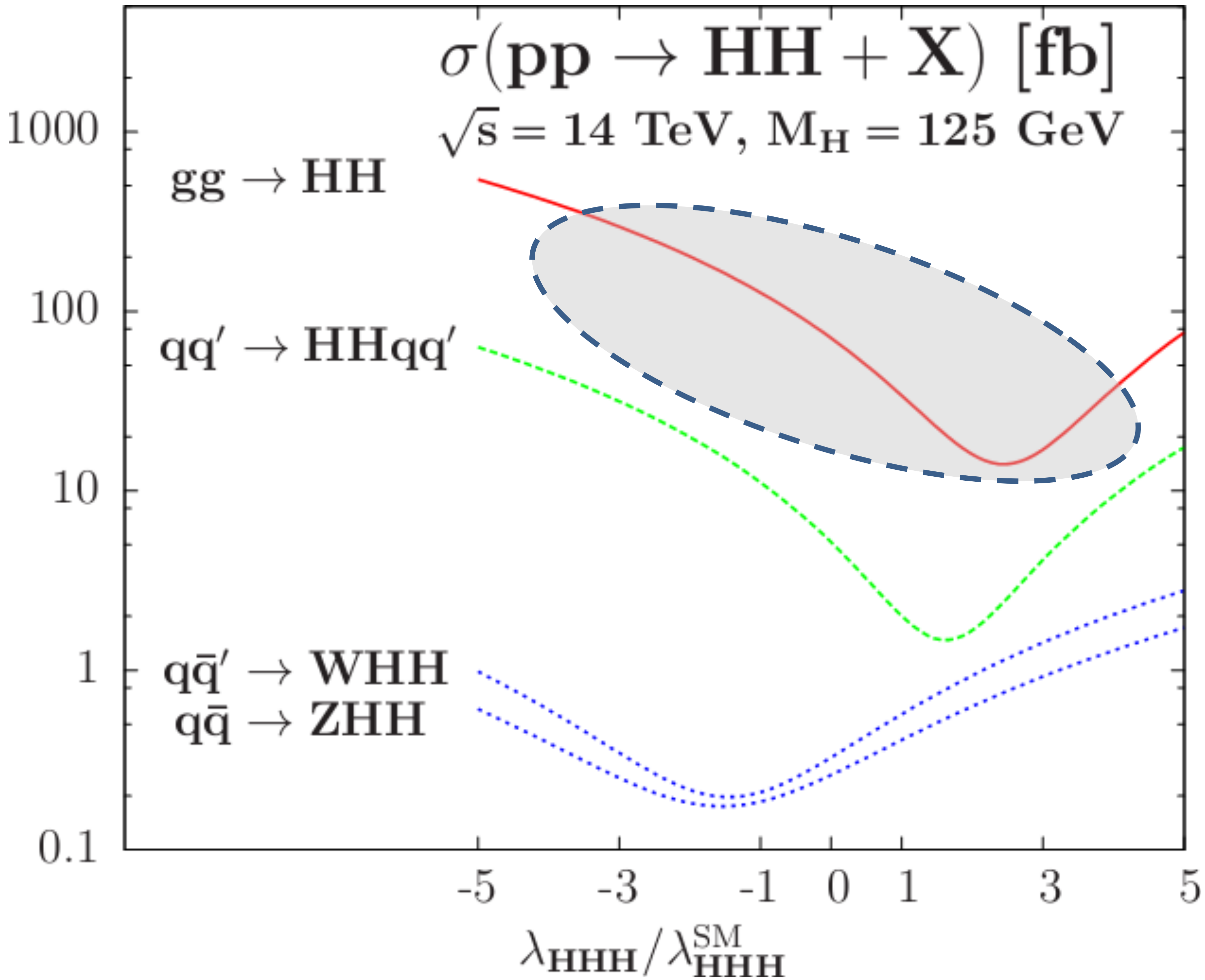
n=1

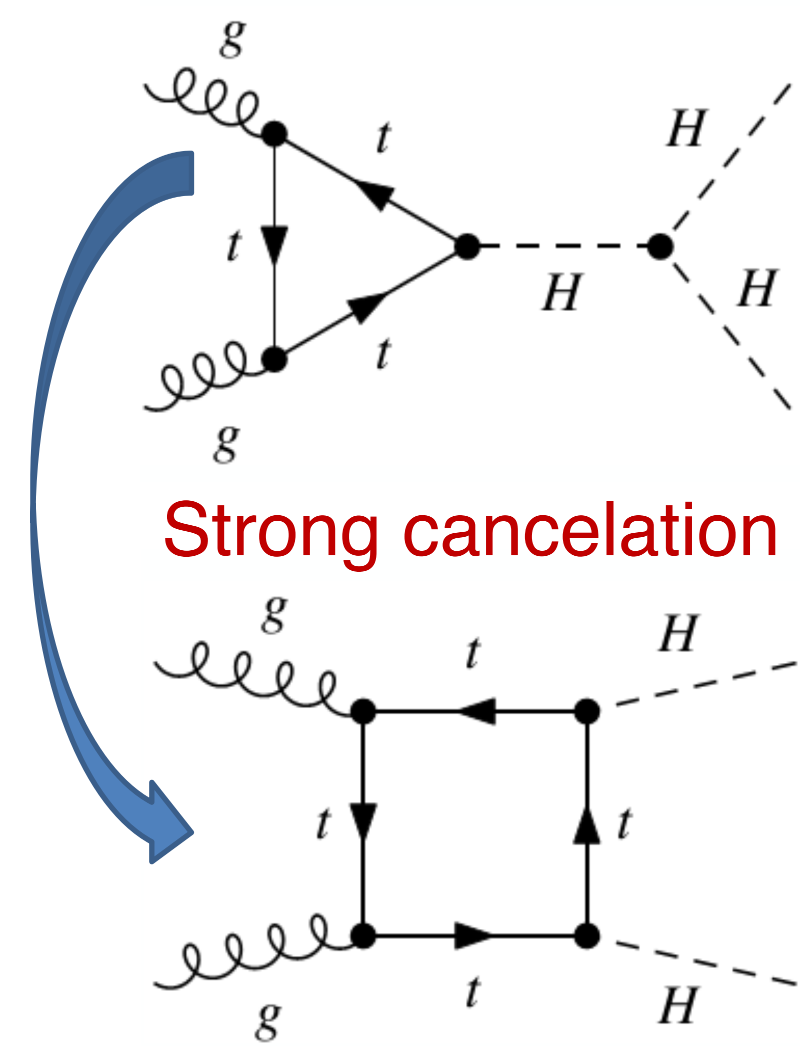
$$\frac{\alpha_s}{12\pi v} G^{a,\mu\nu} G^a_{\mu\nu} h$$

n=2

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

Sensitivity to HHH coupling gg->HH: the leading channel





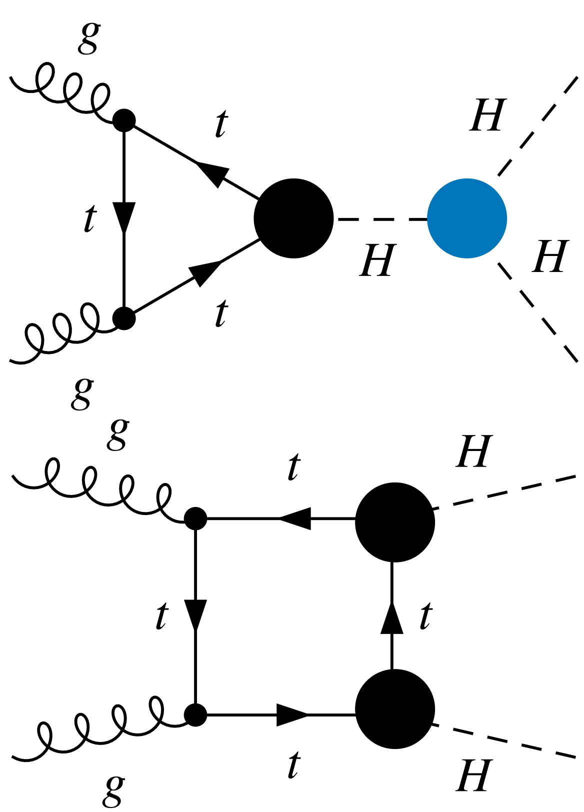
Low Energy Theorem

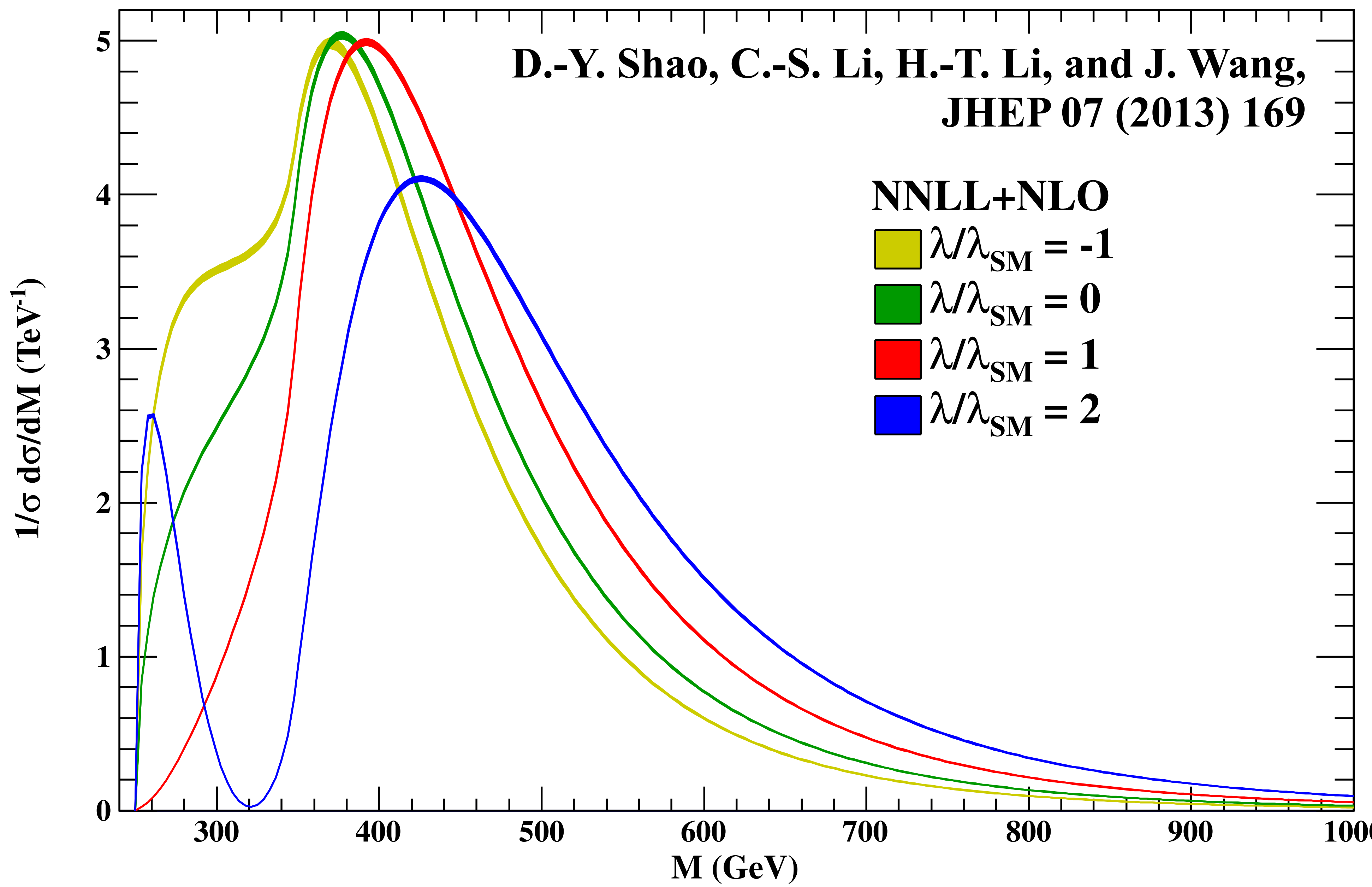
J. Baglio, A. Djouadi et al. JHEP 1304(2013)51

gg->HH: the leading channel

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

HH production

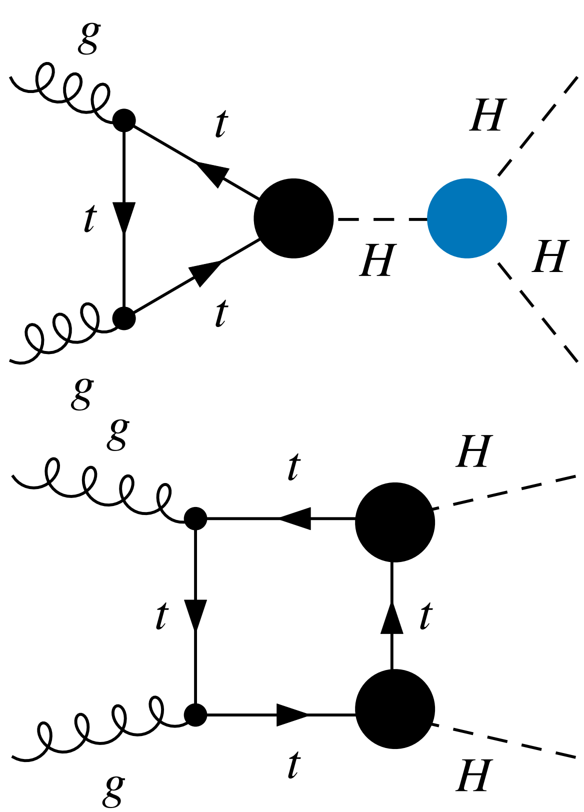


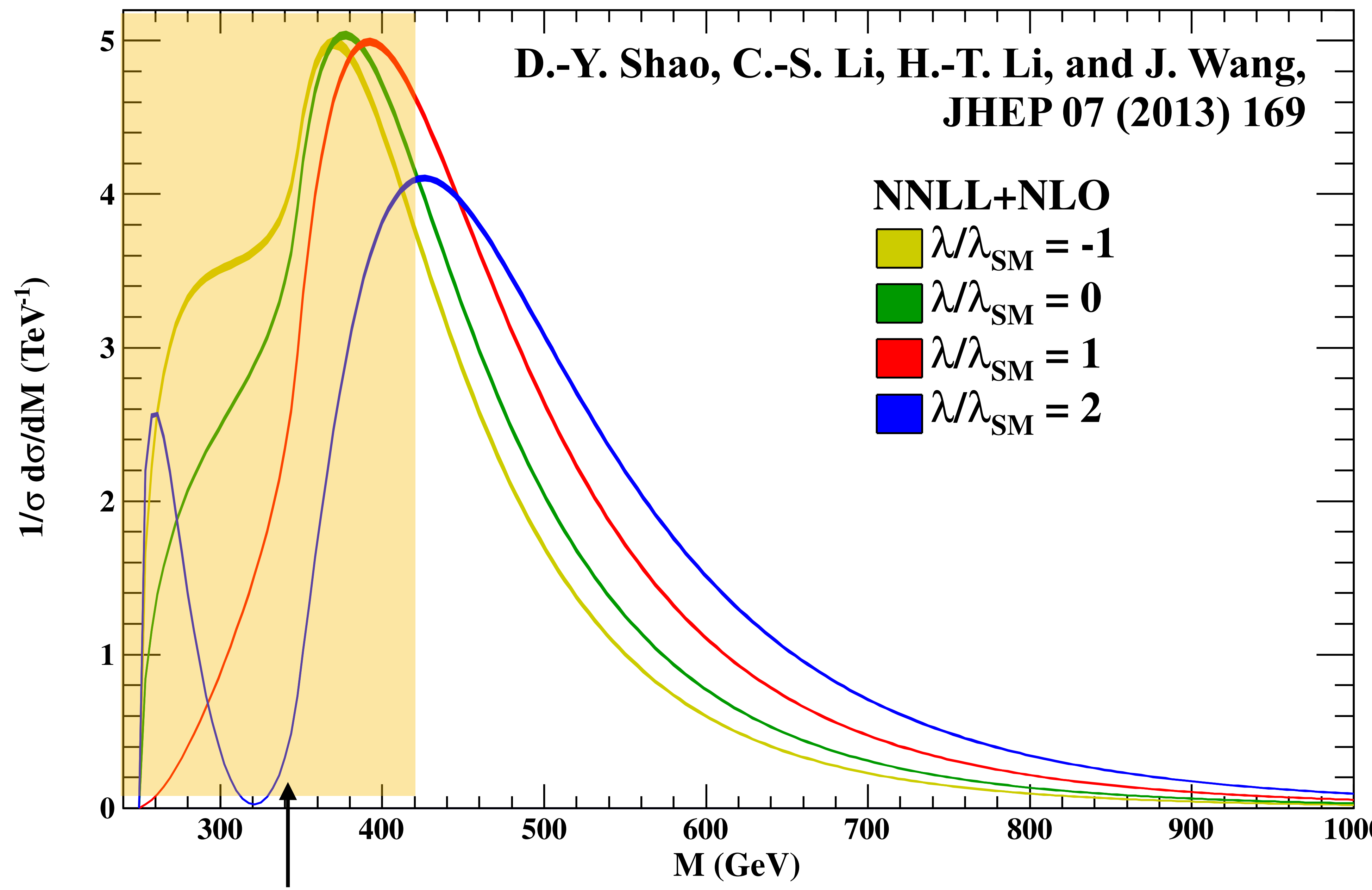


gg->HH: the leading channel

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

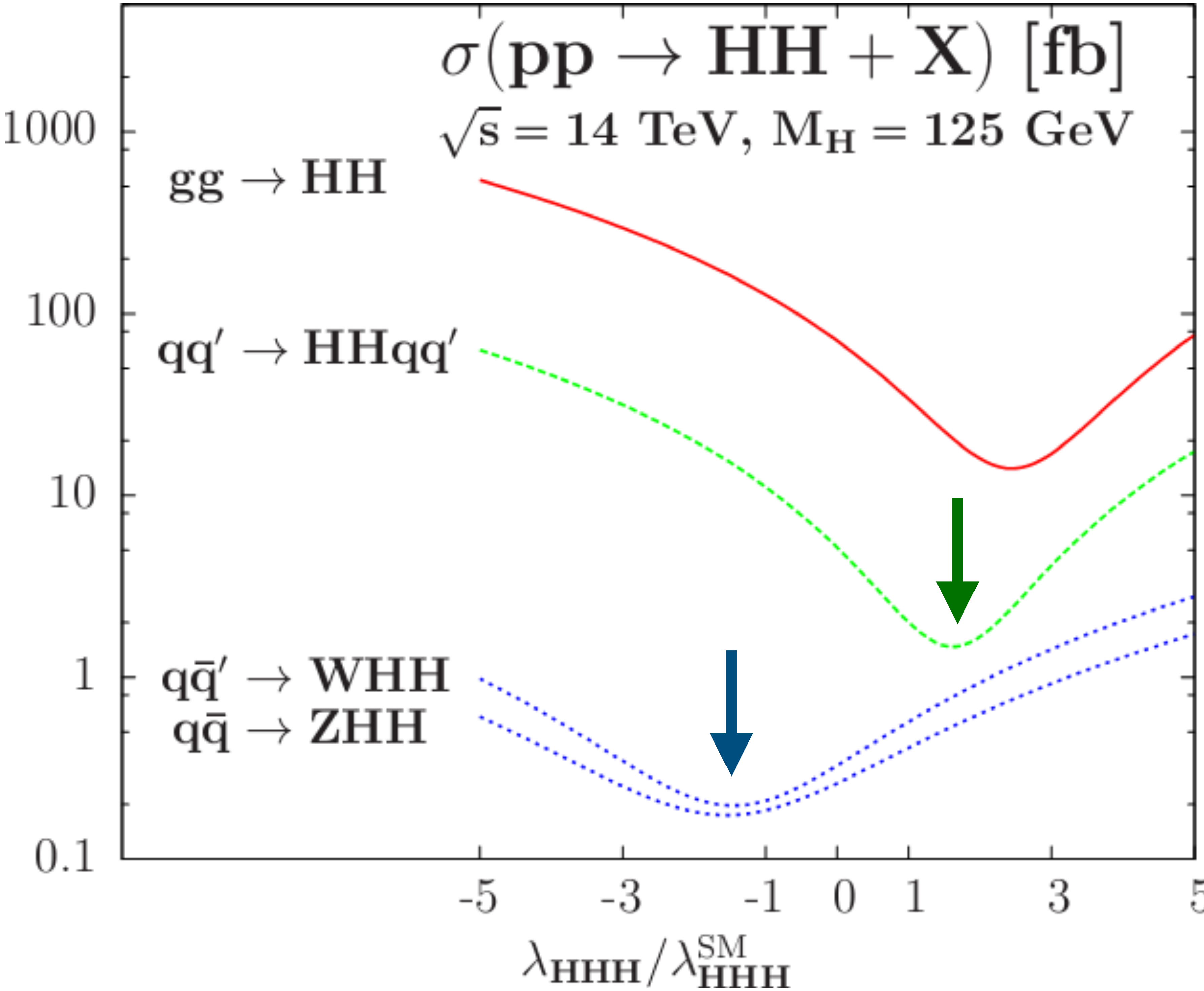
HH production

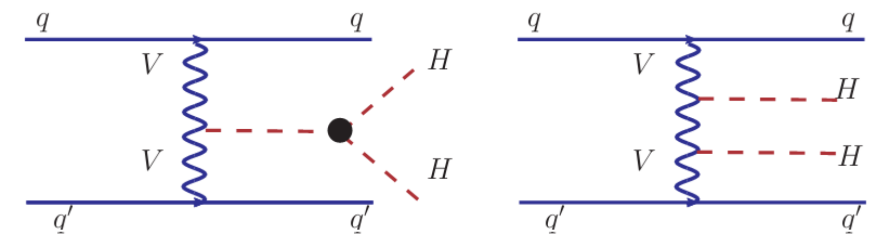




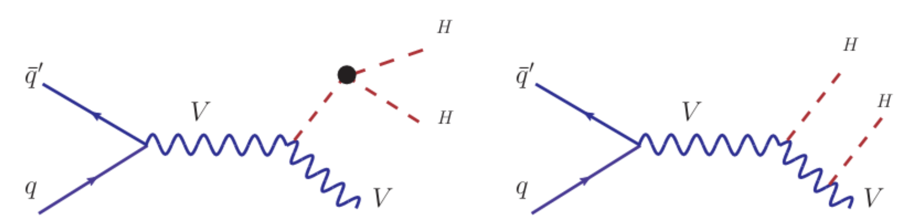
Not accessible at detector!

Sensitivity to HHH coupling: 2) VBF and VHH



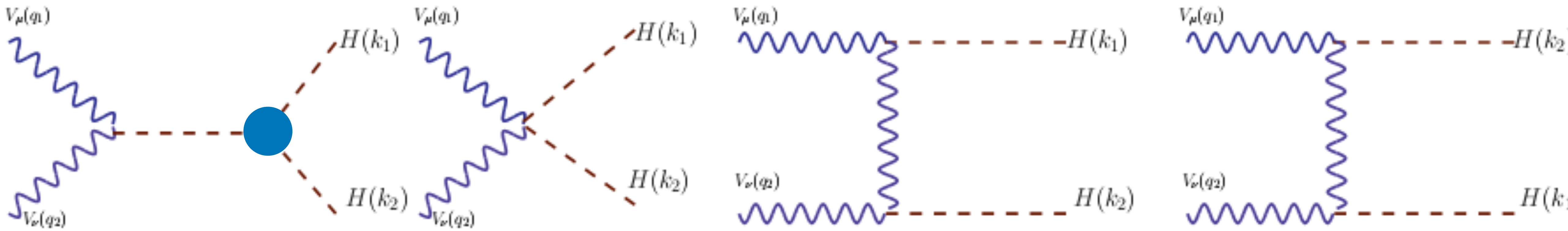


VBF and VHH are sensitive to HHH coupling differently



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

Sensitive to Triple Higgs Coupling Differently

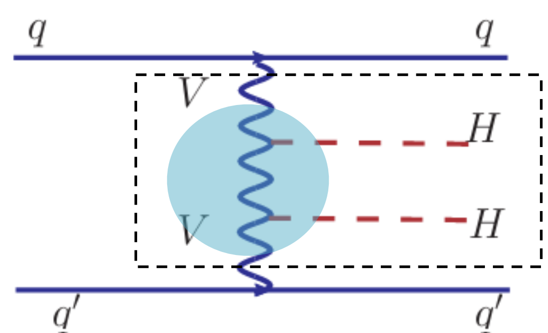


$$M^{\mu\nu} = \left[\frac{m_W^2}{v^2} \frac{6m_H^2}{\hat{s} - m_H^2} \frac{\lambda_{HHH}}{\lambda_{HHH}^{\rm SM}} + \frac{2m_W^2}{v^2} + \frac{4m_W^4}{v^2} \left(\frac{1}{\hat{t} - m_W^2} + \frac{1}{\hat{u} - m_W^2} \right) \right] g^{\mu\nu} + \cdots$$

Near the threshold of Higgs-boson pairs

VBF:

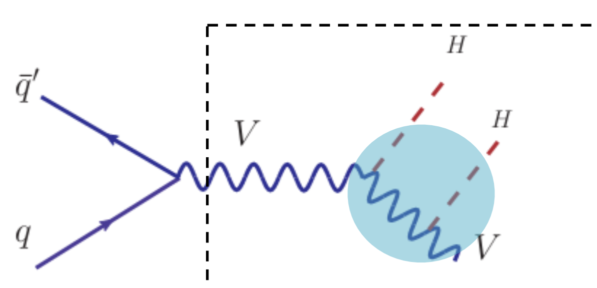
$$\hat{t} = \hat{u} = Q^2 < 0$$



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

VHH:

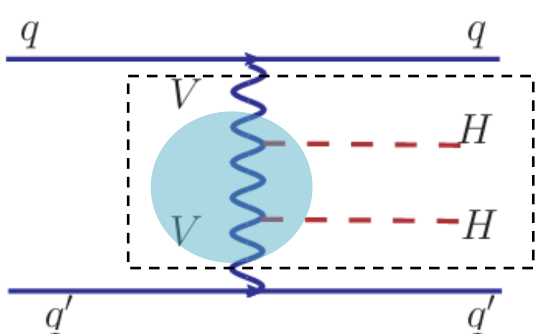
$$\hat{t} = \hat{u} = Q^2 > 0$$



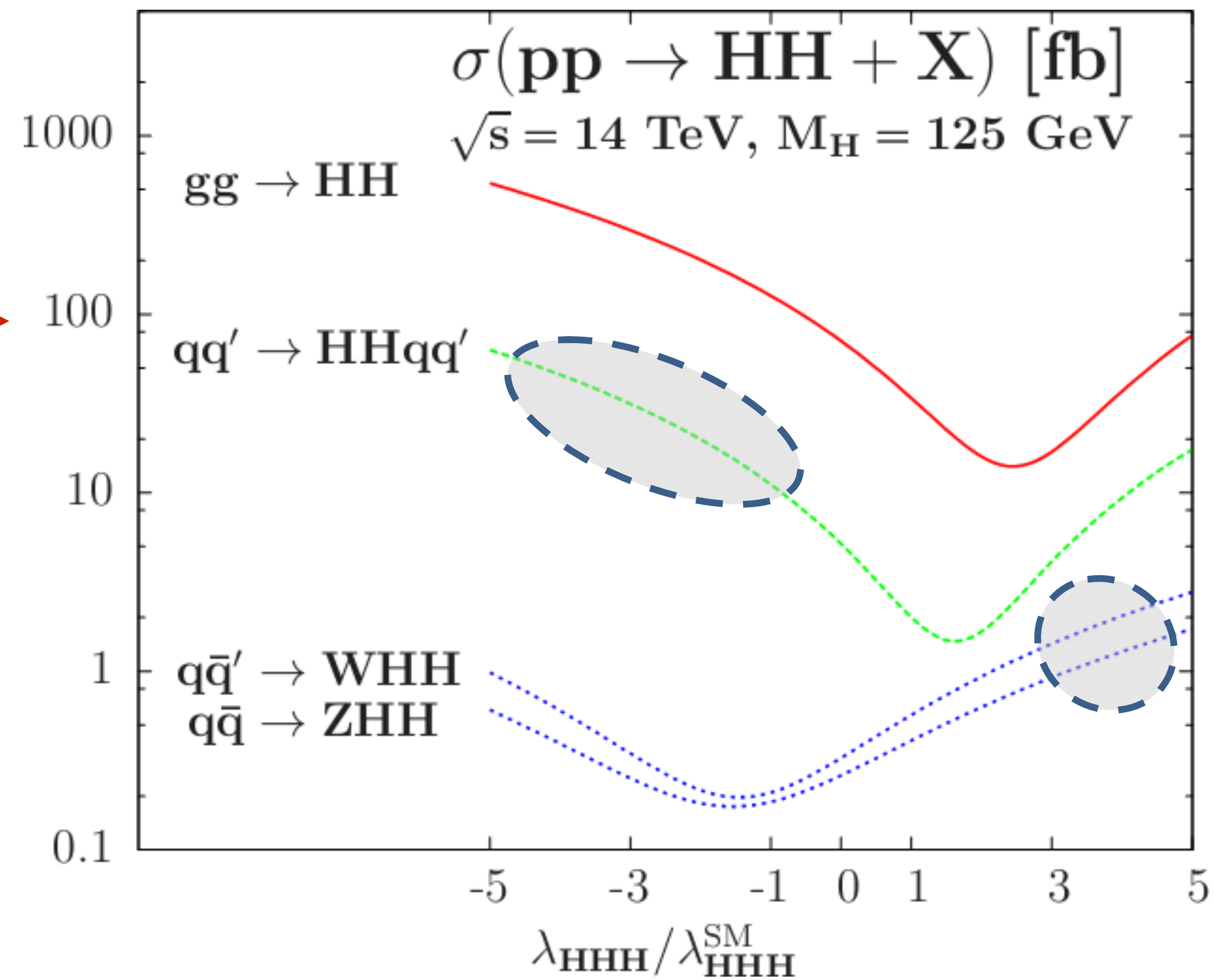
$$M^{\mu\nu} \sim \frac{2m_V^2}{v^2} \left(\frac{\lambda_{HHH}}{\lambda_{HHH}^{\rm SM}} + 1 \right) g^{\mu\nu} + \cdots$$

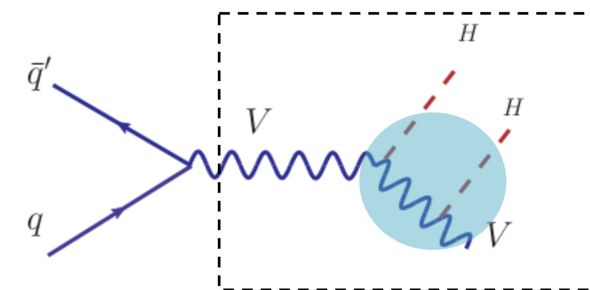
Sensitivity to HHH Coupling

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



$Q^2 < 0$





$Q^2 > 0$

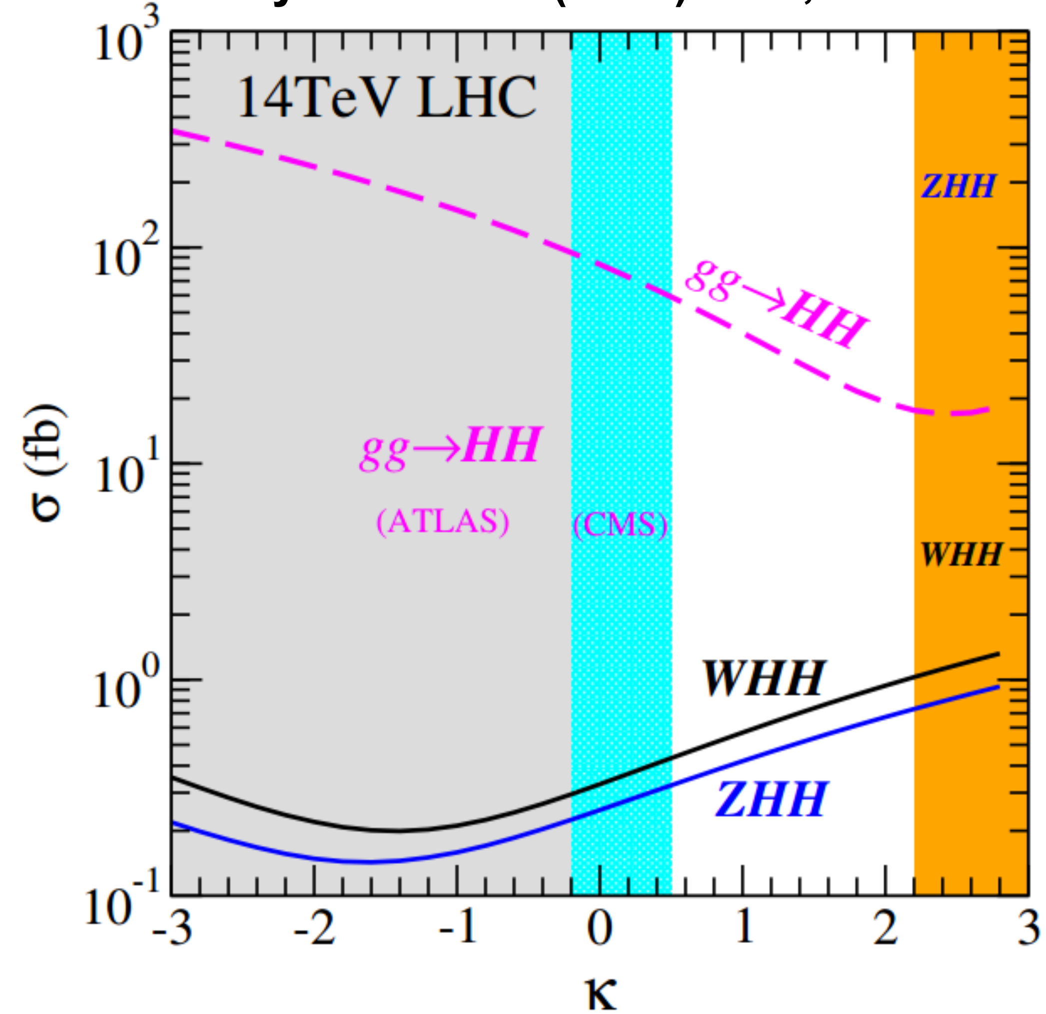
VHH $$M^{\mu\nu} \sim \frac{2m_V^2}{v^2}\left(\frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}} + 1\right) g^{\mu\nu} + \cdots$$

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	$\kappa \le -7.7,\ \kappa \ge 4.8$	$-5.1 \le \kappa \le 2.2$
ZHH	1.32σ	$\kappa \le -8.1,\ \kappa \ge 4.8$	$-5.4 \le \kappa \le 2.2$
GF($b\bar{b}\gamma\gamma$) [42]	1.19σ	$\kappa \le -4.5,\ \kappa \ge 8.1$	$-0.2 \le \kappa \le 4.9$
GF($b\bar{b}\gamma\gamma$) [43]	1.65σ	$\kappa \le -2.6,\ \kappa \ge 6.3$	$0.5 \le \kappa \le 4.1$
VBF [20]	0.59σ	$\kappa \le -1.7,\ \kappa \ge 5.0$	$-0.4 \le \kappa \le 3.5$
$t\bar{t}HH$ [21, 22]	1.38σ	$\kappa \le -11.4, \kappa \ge 6.9$	$-7.2 \le \kappa \le 2.5$

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



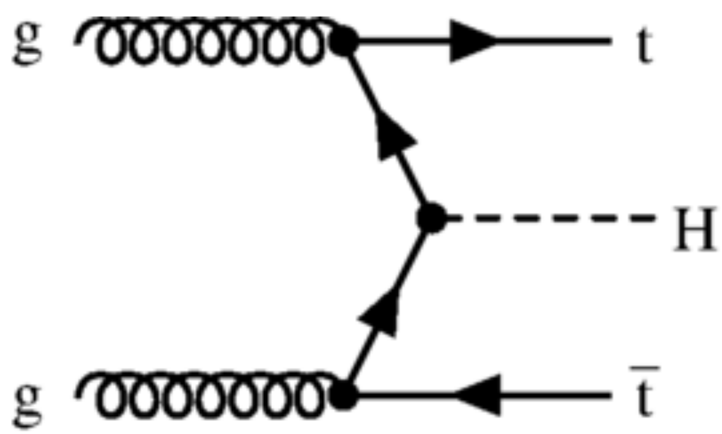
$0.5 \le \kappa \le 2.2$

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 very challenging.

3) Higgs-Fermion Interaction

First observation of Higgs-Top coupling

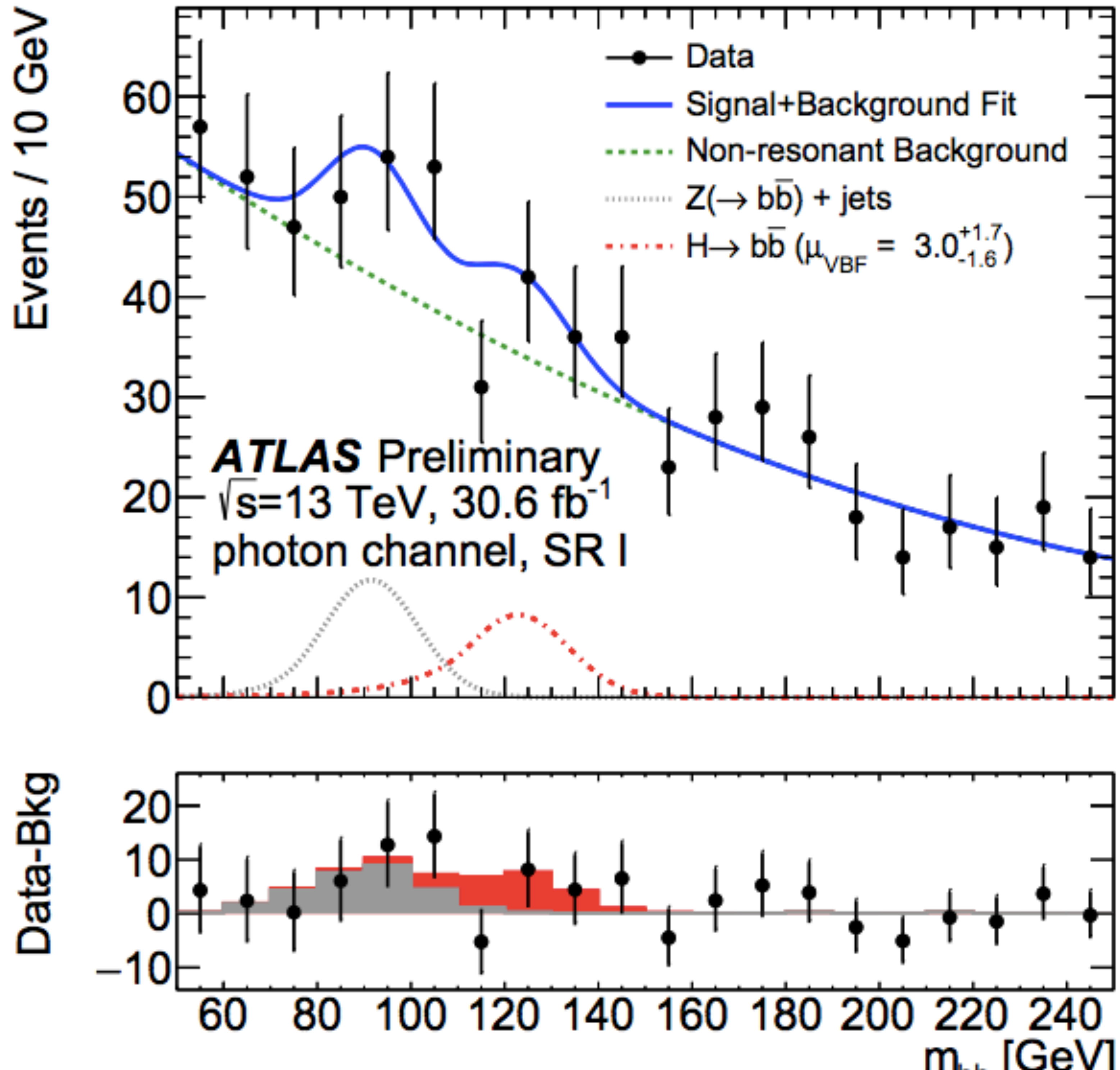


$$\mu_{t\bar{t}H} = 1.26^{+0.31}_{-0.26}$$

CMS: PRL120,231801 (2018)

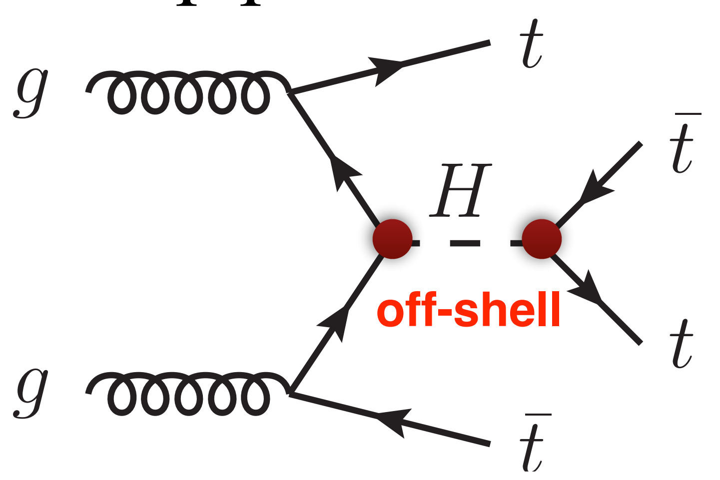
Good News: Higgs-Bottom Coupling

July 9th, ICHEP18, Seoul



Sizing Up Top Quark's Interaction with Higgs

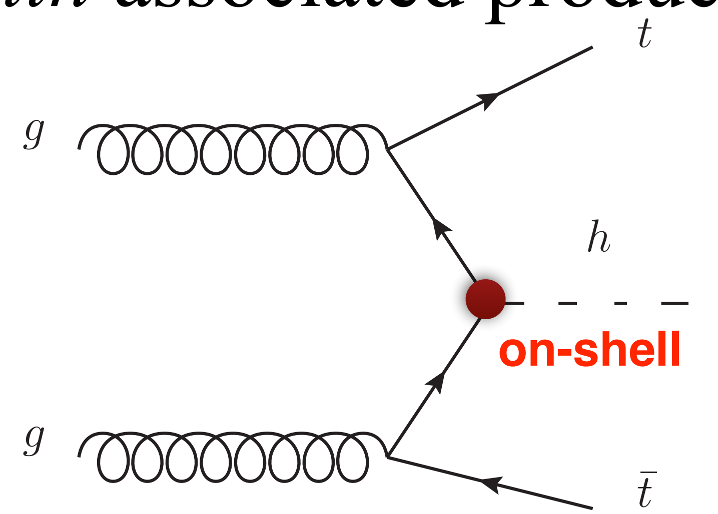
Four-top production



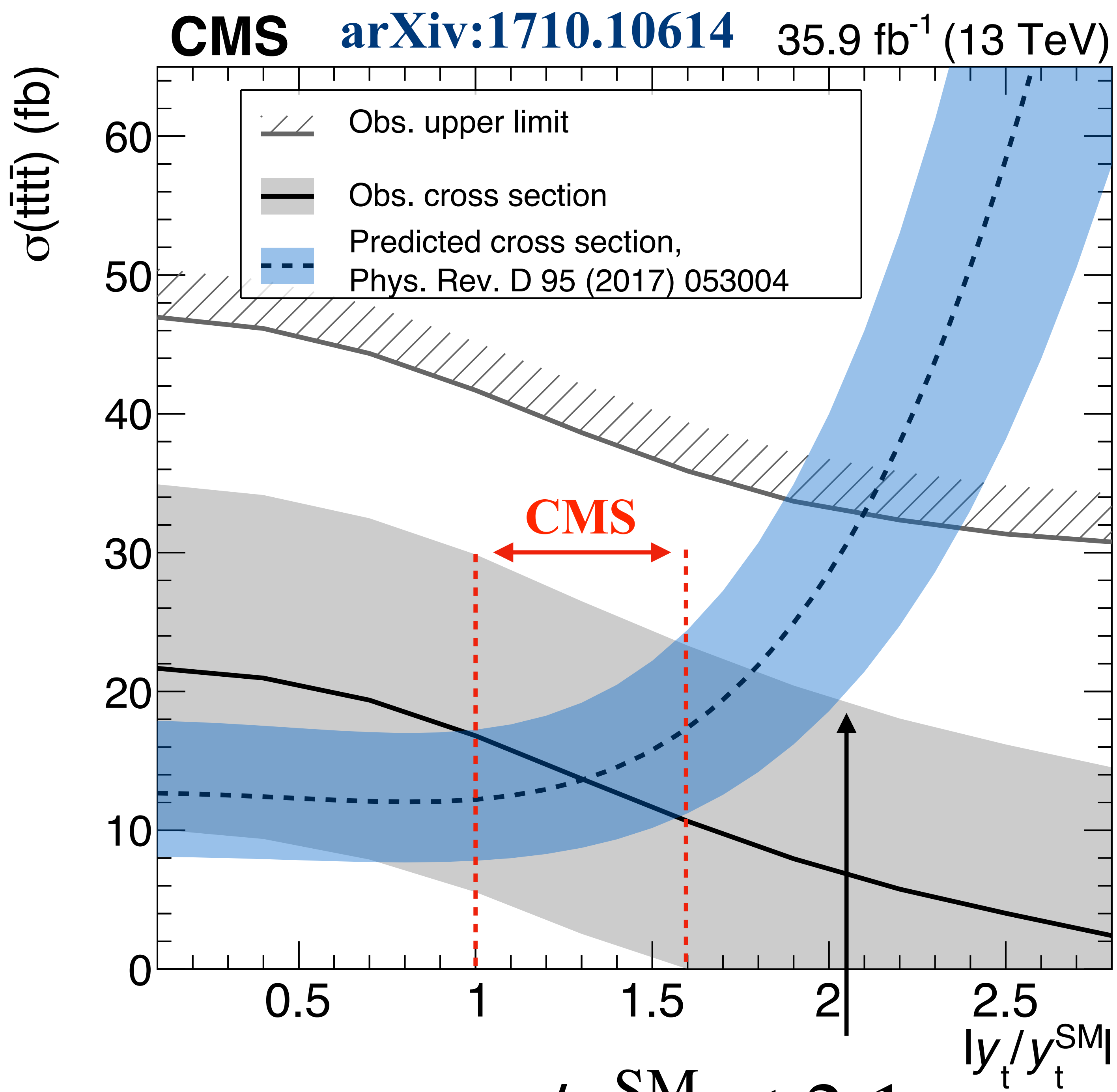
QHC, Chen, Liu
PRD95 (2017) 053004

No assumption made on Higgs decay

tth associated production



Depends on Higgs decay

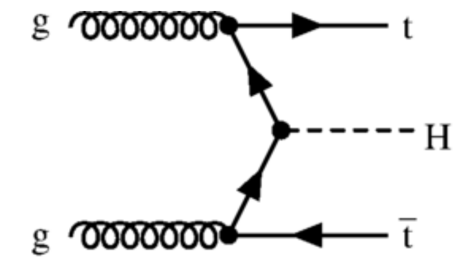


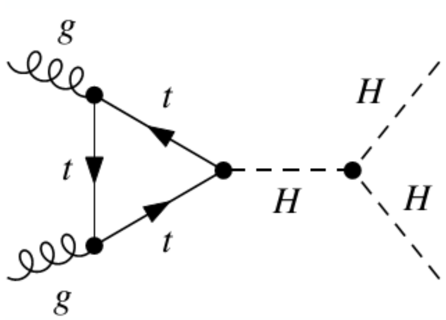
$$y_t/y_t^{SM} \leq 2.1$$

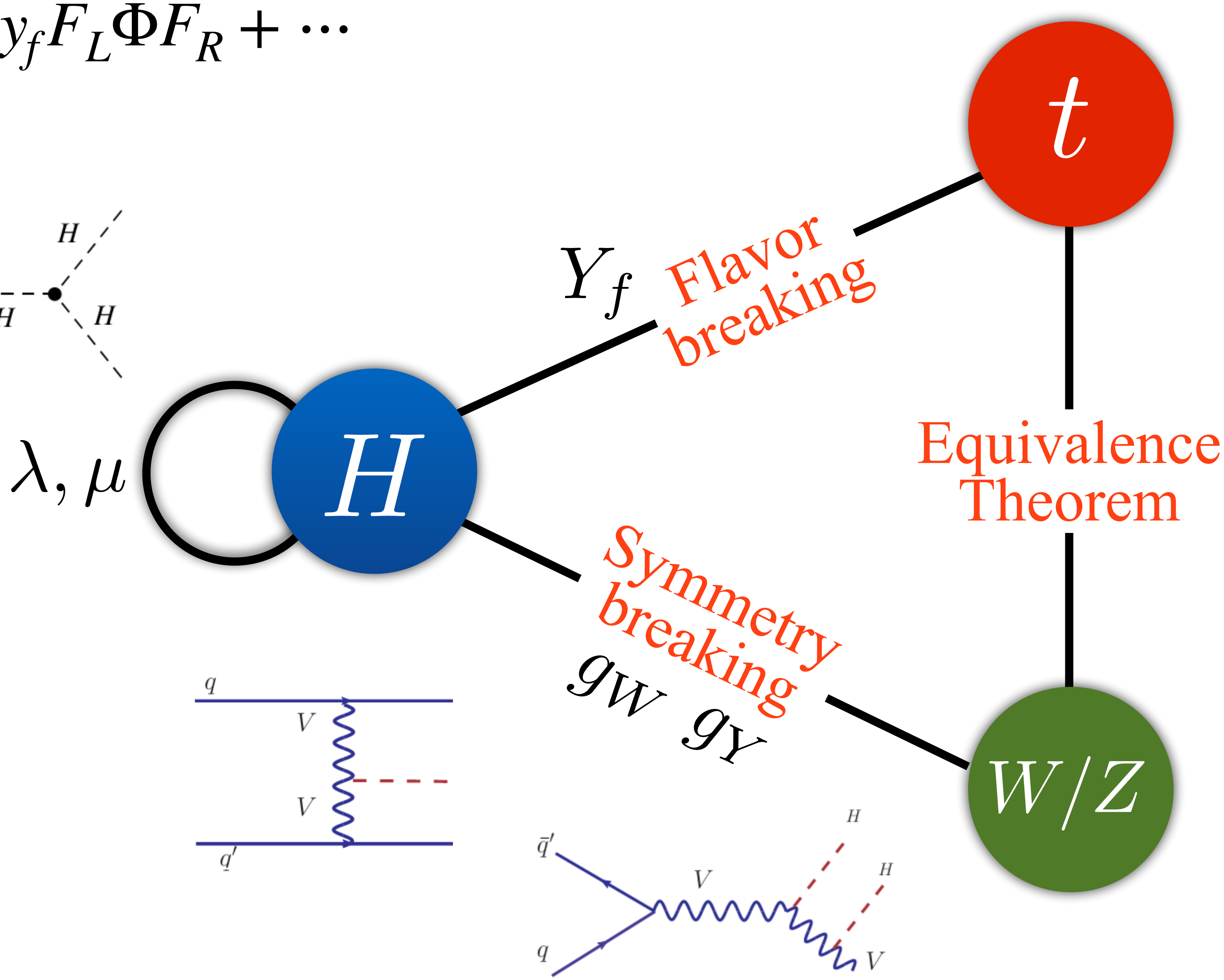
CMS: $\mu_{t\bar{t}H} = 1.26^{+0.31}_{-0.26}$

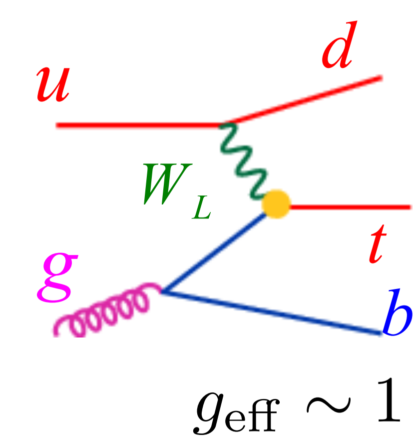
Interim Summary

$$\mathscr{L} = \left(D_\mu \Phi\right)^\dagger (D^\mu \Phi) - \mu^2 \Phi^\dagger \Phi + \lambda \left(\Phi^\dagger \Phi\right)^2$$
$$+ y_f \bar{F}_L \Phi F_R + \cdots$$





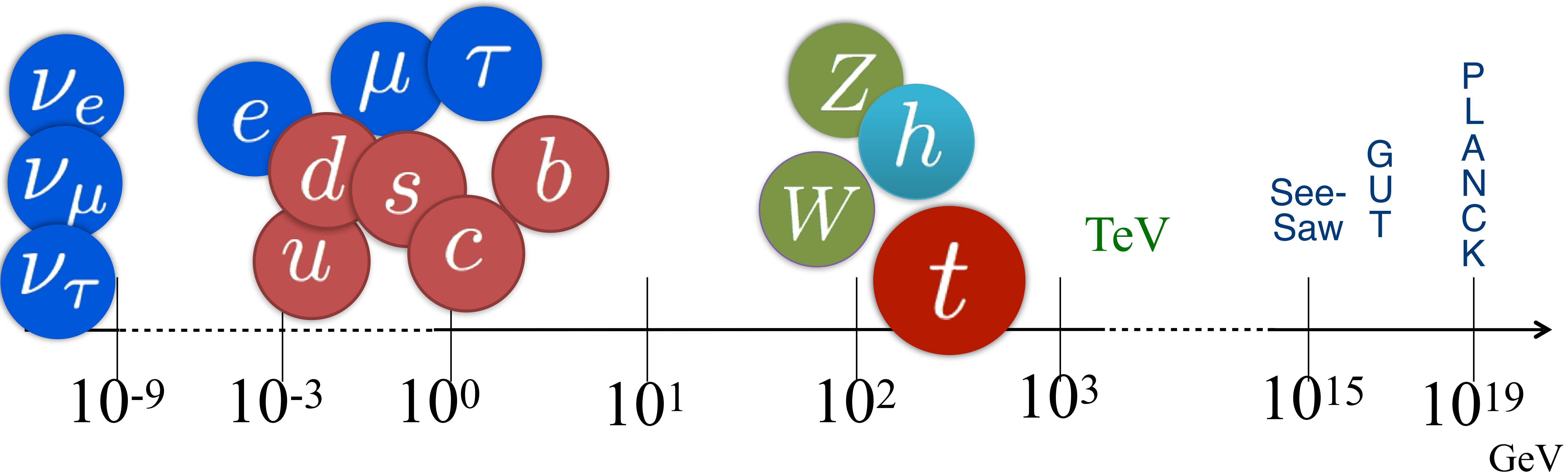




More accurate knowledge of Higgs boson might shed lights on NP.

What if NP knew nothing about Higgs?

Higgs boson discovery —?— the END of the era of SM



Q1. Why are light quarks so light?

Top quark and W/Z bosons are naturally around the weak scale.

Q2. Heavy NP particles cannot achieve mass mainly from Higgs.

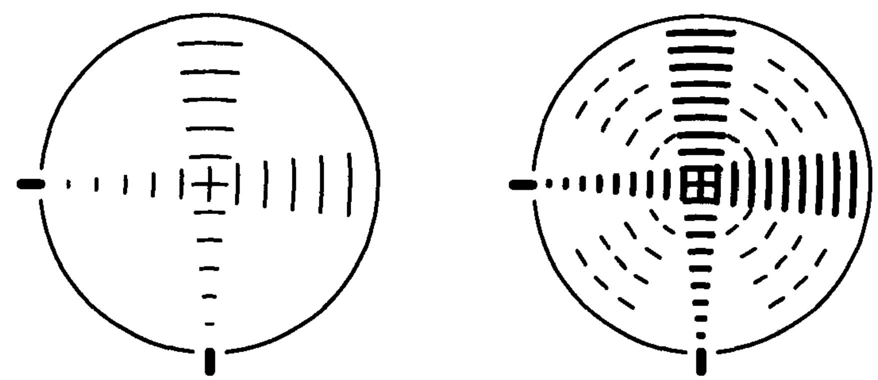
NP scale = New Resonance Mass ~ 2TeV

$$g \times v \sim 8 \times 246\ \text{GeV} = 2\ \text{TeV}$$

The EFT of QED (infinite m_e)

Heisenberg-Euler operator in QED

(Imagine we are living in a world full of photon but not electron)



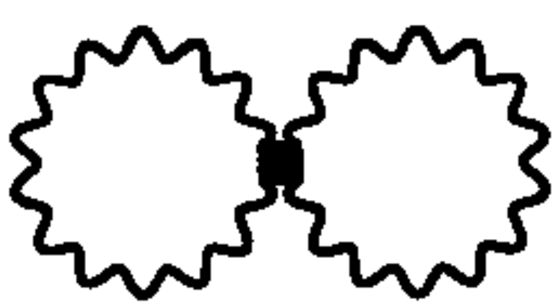
a b

After matching in QED

$$L = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{\alpha^2}{180m^4}\left[-5\left(F_{\mu\nu}F^{\mu\nu}\right)^2 + 14F_{\mu\nu}F^{\nu\alpha}F_{\alpha\beta}F^{\beta\mu}\right]$$

NP scale m_e

Application ($\omega \ll m$)



$$\rho \propto T^4, \;\; \frac{\alpha^2}{m^4}T^8$$

Radiative correction to the Stefan-Boltzmann law

EFT of QED (photon + electron)

$$L = \bar{\psi}(i \not{D} - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{c}{M^2} m\bar{\psi}F_{\mu\nu}\sigma^{\mu\nu}\psi + \cdots$$

NP scale m_μ

Two ways to probe NP:

1. To raise collider energies to produce real new particles (muon);
2. To measure low-energy quantities (e.g. electron magnetic moment) with high precision

We were very lucky 90 years ago when the cosmic rays brought Muon lepton to us.

What about now?

Who ordered that?

PHYSICAL REVIEW D VOLUME 52, NUMBER 11 1 DECEMBER 1995

Spontaneous breaking of vector symmetries and the nondecoupling light Higgs particle

Hanqing Zheng*
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(Received 4 April 1995)

Using a four fermion interaction Lagrangian, we demonstrate that the spontaneous breaking of vector symmetries requires the existence of a light (comparing with the heavy fermion mass) scalar particle, and the low energy effective theory (the σ model) obtained after integrating out heavy fermion degrees of freedom is asymptotically a renormalizable one. When applying the idea to the electroweak symmetry breaking sector of the standard model, the Higgs particle's mass is of the order of the electroweak scale.

PHYSICAL REVIEW D VOLUME 51, NUMBER 1 1 JANUARY 1995

Low energy properties of the heavy vector fermions and electroweak symmetry breaking

Hanqing Zheng*
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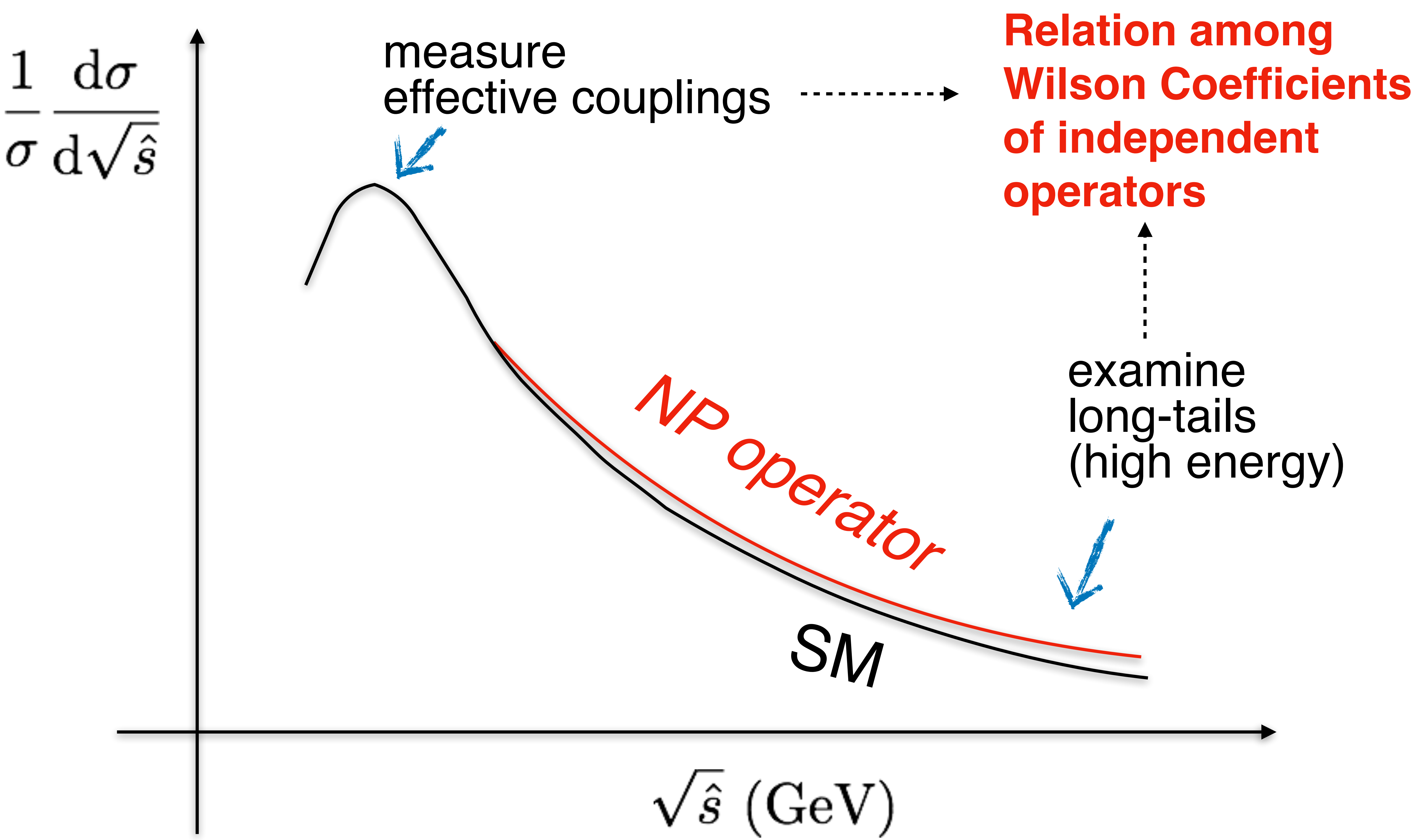
(Received 9 June 1994)

We discuss the properties of the heavy vector fermions with bare Dirac mass terms and an SU(2)×SU(2) global symmetry in the Yukawa interaction Lagrangian. Using the heat kernel expansion method we calculate their contributions to the low energy observables. We argue that these heavy fermions may be responsible for a soft dynamical symmetry breaking through their condensation. We also discuss the possibility of considering ordinary fermions as one part of the vector fermions within our model.

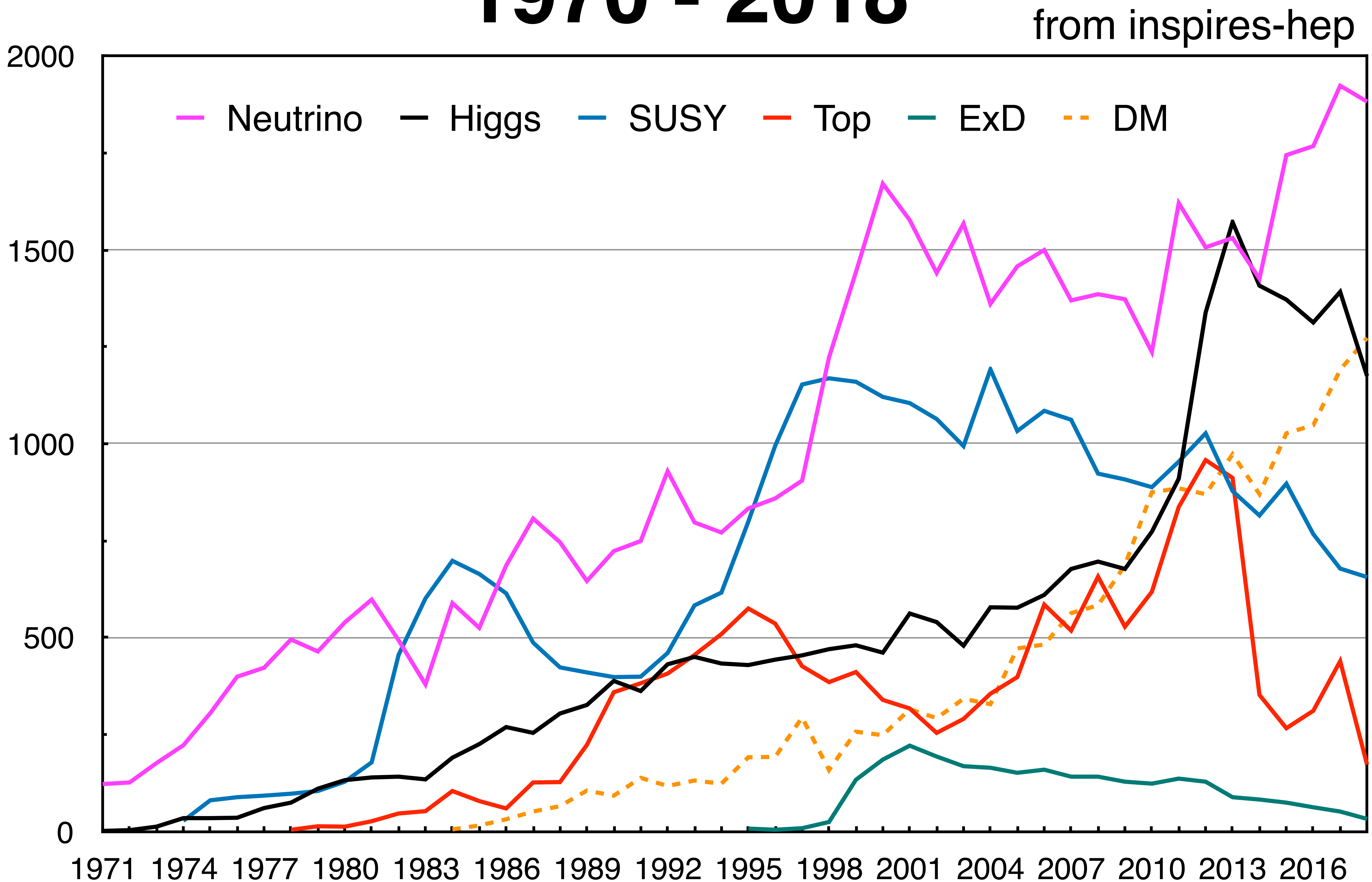
LHC: A Precision Machine

in case of no new resonances found in next 10 years



单个图形在高能区都有坏的行为（散射几率随能量增加而破坏几率守恒），
但自然界巧妙地运用规范对称性将不同图形之间的坏行为相互抵消掉。

1970 - 2018



Thank You!

Dimension five operator and Coefficient

QHC, Jackson, Keung, Low, Shu, 0911.3398

$$\kappa_g \frac{S}{M_S} G^a_{\mu\nu} G^{a\mu\nu} + \kappa_W \frac{S}{M_S} W^i_{\mu\nu} W^{i\mu\nu} + \kappa_B \frac{S}{M_S} B_{\mu\nu} B^{\mu\nu} + \cdots$$

The coefficient of those dimension-5 operators could be related to the one-loop beta function of Strong, Weak and Hypercharge.

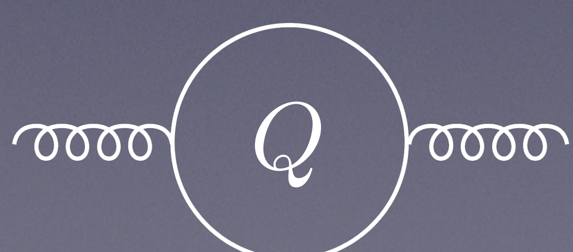
For the electroweak interaction $M_Q Q^c Q + y_Q S Q^c Q$

its contribution to gluon two-point function is

$$-\frac{1}{4}\left[1 - \frac{g_s^2}{16\pi^2} b_F^{(3)} \log \frac{M_Q^2(\mathcal{H})}{\mu^2}\right] G^a_{\mu\nu} G^{a\,\mu\nu}$$

$$b_F^{(3)} = 2/3 \qquad M_Q(\mathcal{H}) = M_Q + y_Q \mathcal{H}$$

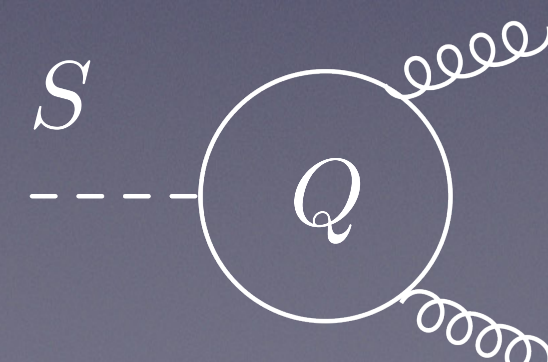
where we turn on the scalar as a background $S \to \mathcal{H}$



Higgs
Low Energy Theorem

→

expand to
the 1st order of $\mathcal{H}$



Physics behind single-top production