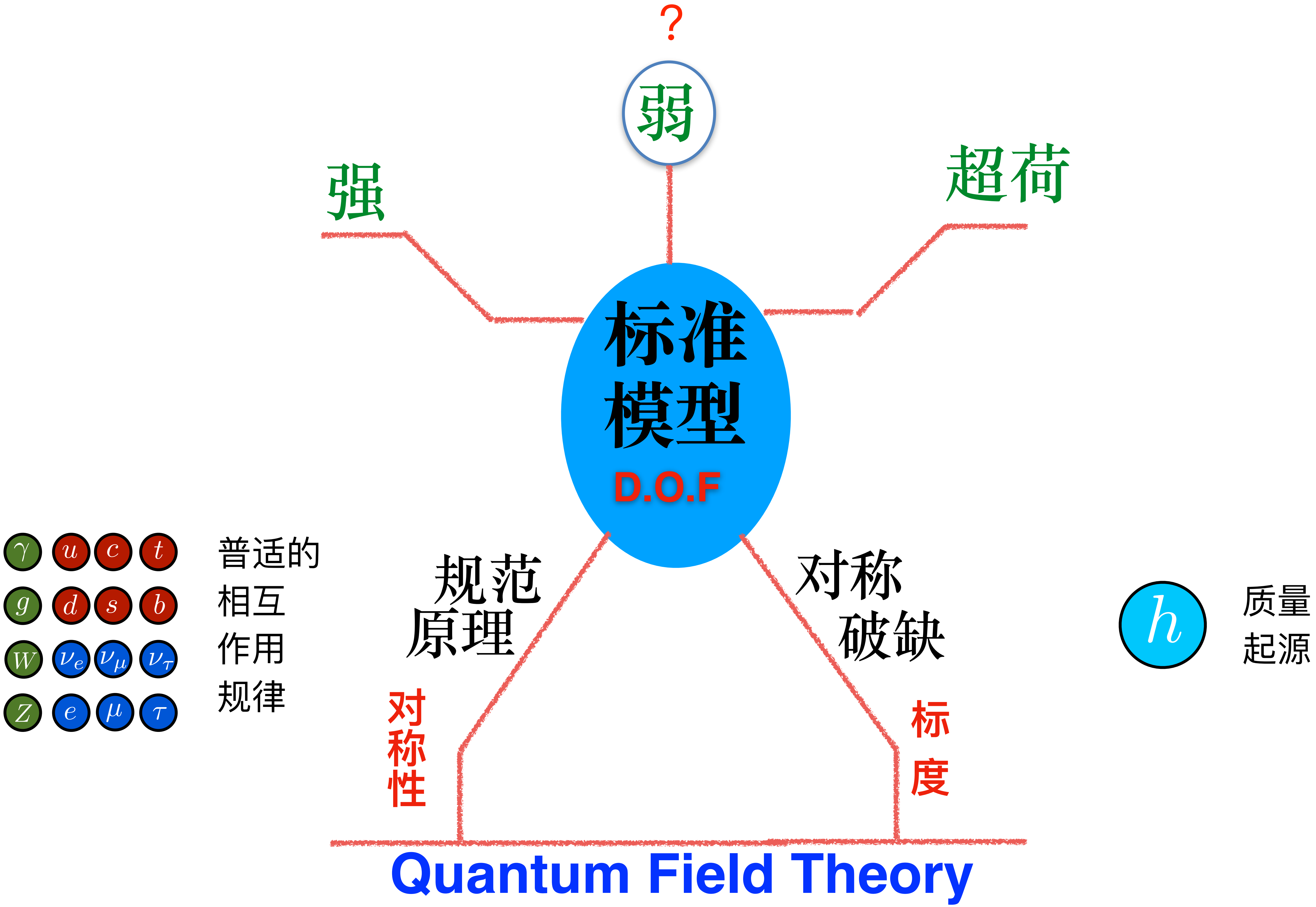
Measuring Higgs Property at the LHC and e^+e^- Collider

Qing-Hong Cao

School of Physics, Peking University

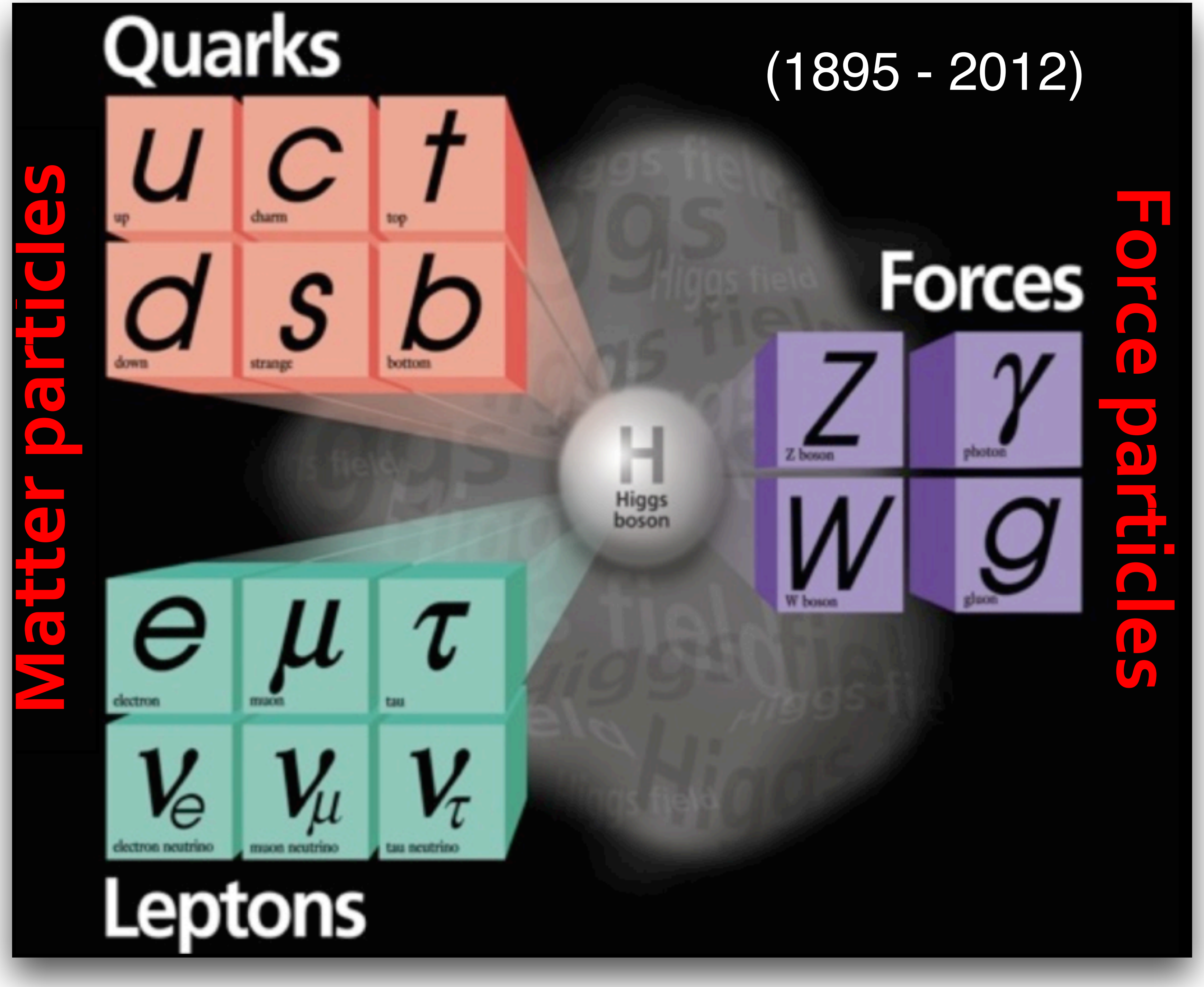
20世纪基础物理学

源于1895年伦琴射线，止于2012年希格斯粒子



Higgs discovery tells us that

Parity Violation ⟷ **Mass Origin** ⟷ **Vacuum Structure**



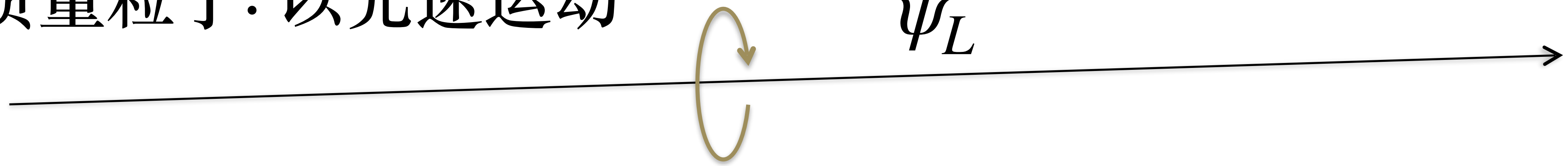
Matter particles

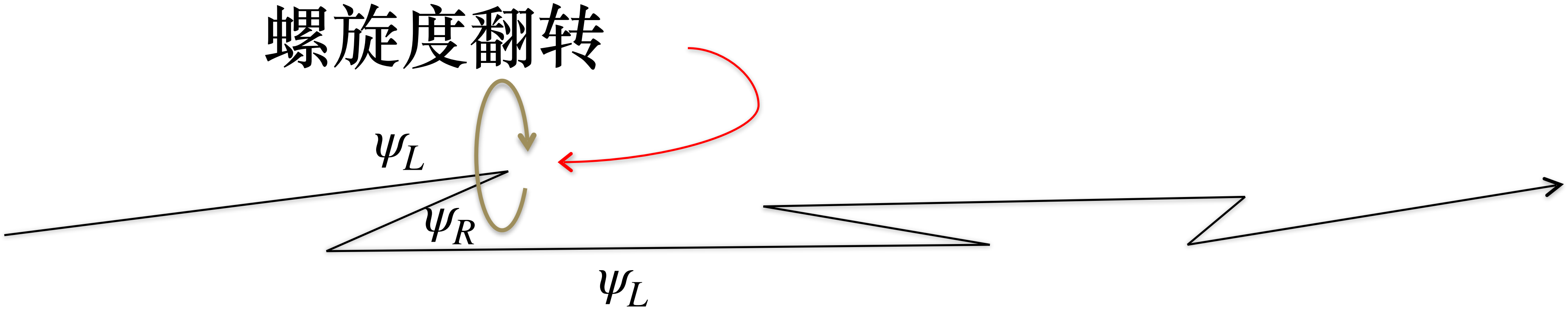
Force particles

有质量粒子的速度要小于光速

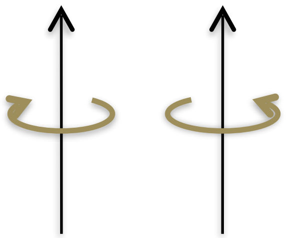
洛伦兹对称性
$SO(4) \simeq SU(2) \otimes SU(2)$ → 费米子质量 $m\bar{\psi}_L\psi_R$
手征对称性破缺

无质量粒子: 以光速运动





有质量粒子：速度小于光速



螺旋度 = 自旋沿着运动方向的投影

有质量粒子的速度要小于光速

洛伦兹对称性

宇称破坏

$m \; \bar{\psi}_L \; \psi_R$

$\bar{\psi}_L$：弱荷、超荷；ψ_R：超荷

$$\xrightarrow[\text{H具有弱荷}]{m \to H}$$

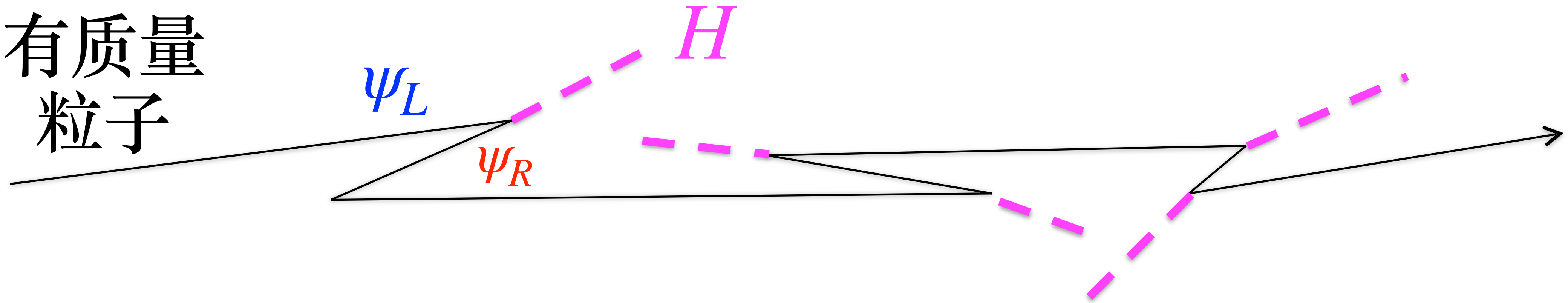
$H\bar{\psi}_L\psi_R$

H：弱荷

弱荷不守恒

弱荷守恒

有质量粒子



密布全空间的
希格斯粒子

真空不空
(弱荷)

$$|0\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

如何实现
$H \to m$?

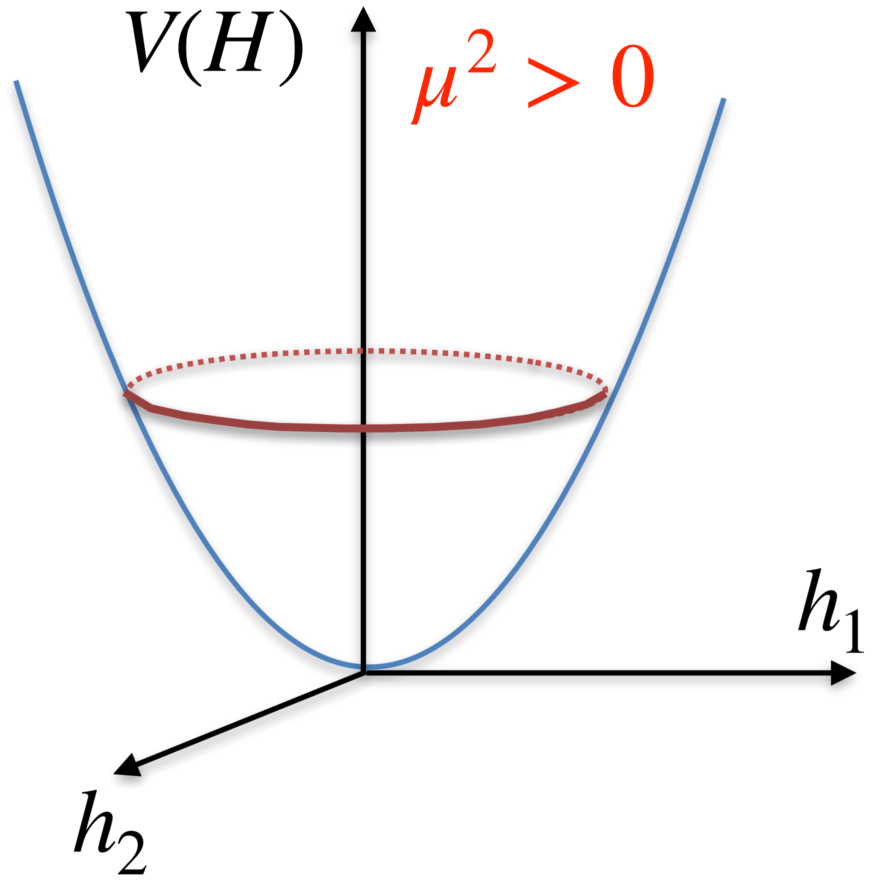
希格斯势函数 和 对称性自发破缺

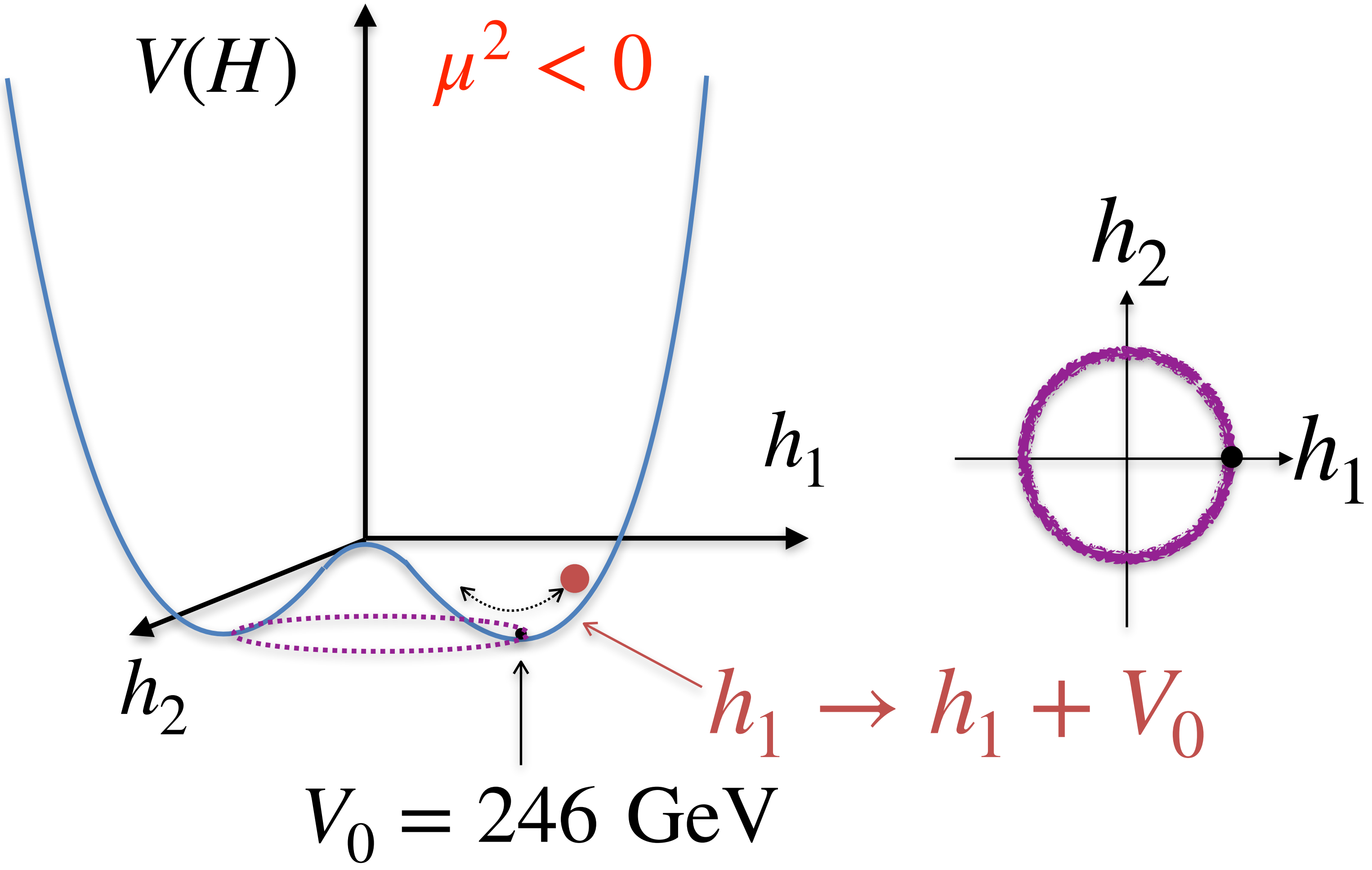
$$V(H) = \mu^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2$$

$$H = \begin{pmatrix} h_3 + i h_4 \\ h_1 + i h_2 \end{pmatrix}$$

$$H^\dagger H = h_1^2 + h_2^2 + h_3^2 + h_4^2$$

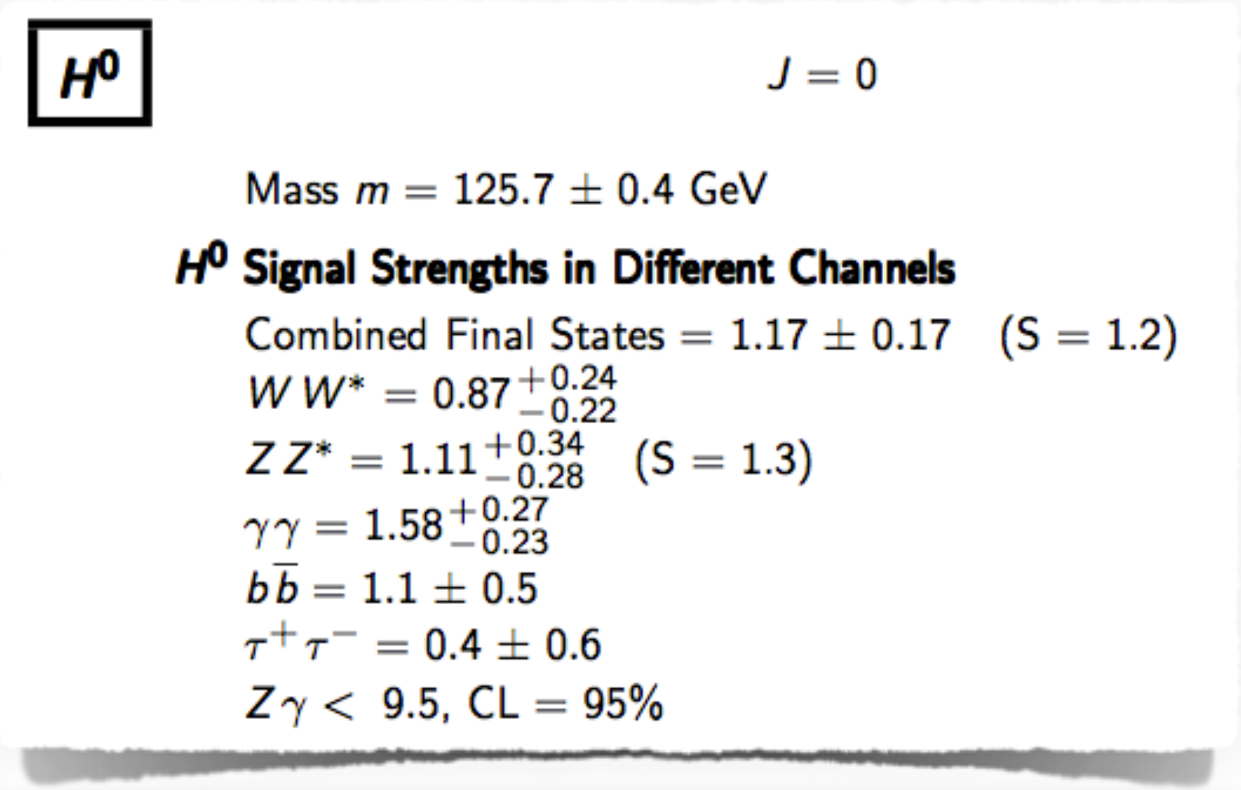
偶然
$SO(4)$
对称性





真空态 —— 能量（势能）最低态

The Particle Data Group has an entry for the Higgs boson after 2012



H^0 $J = 0$

Mass $m = 125.7 \pm 0.4$ GeV

H^0 Signal Strengths in Different Channels

Combined Final States $= 1.17 \pm 0.17$ (S = 1.2)
$W W^* = 0.87^{+0.24}_{-0.22}$
$Z Z^* = 1.11^{+0.34}_{-0.28}$ (S = 1.3)
$\gamma\gamma = 1.58^{+0.27}_{-0.23}$
$b\bar{b} = 1.1 \pm 0.5$
$\tau^+\tau^- = 0.4 \pm 0.6$
$Z\gamma <$ 9.5, CL = 95%

$$\Gamma_H^{\rm SM} = 4 \text{ MeV}$$

$$\frac{\Gamma_H^{\rm SM}}{m_H} = 0.000032$$

A common question:

You guys have discovered the Higgs boson, now what?

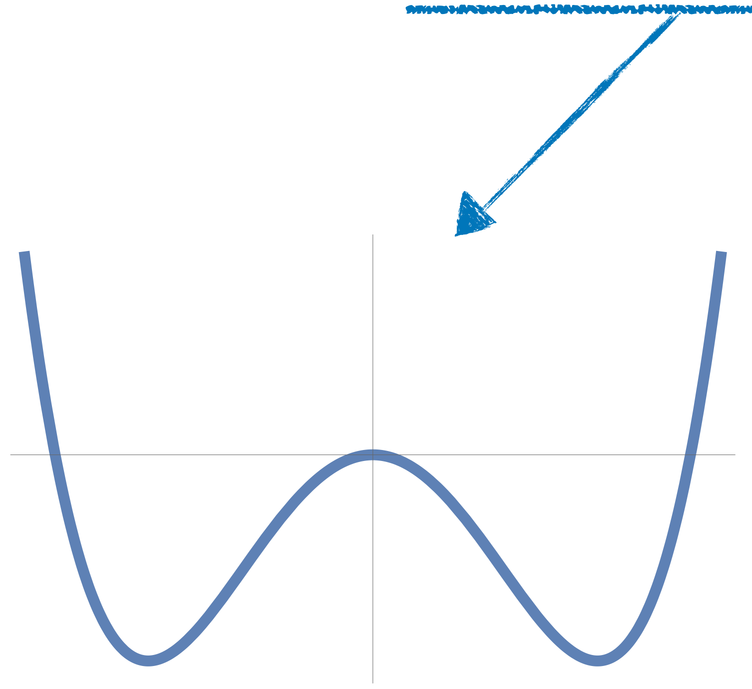
The game just starts.

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

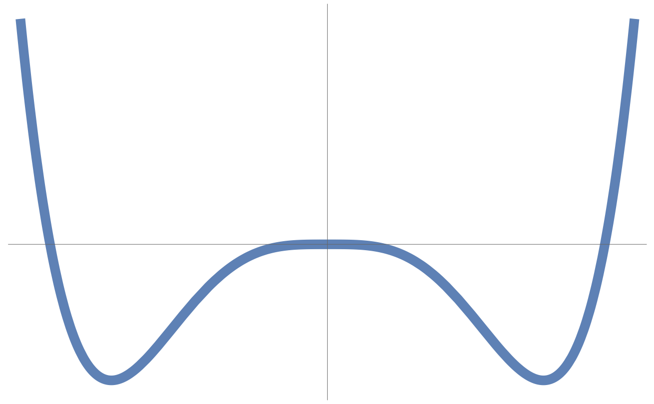
1. Higgs-self Interaction

(probing potential at electroweak scale)

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

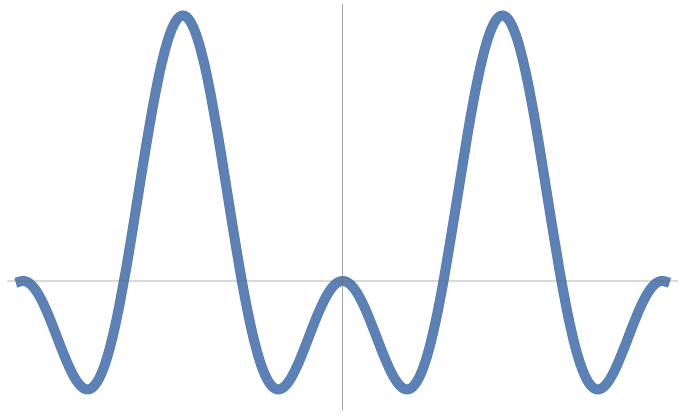


Coleman-Weinberg Higgs

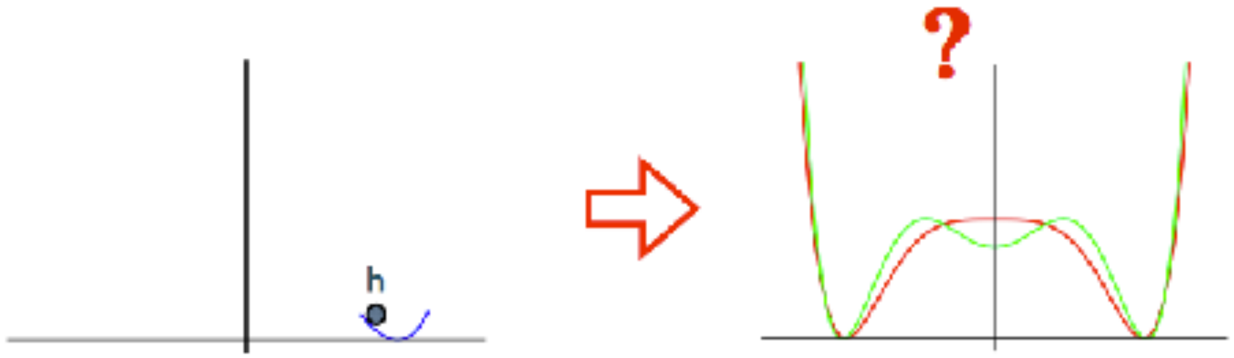


$$V(\phi) = \lambda(\phi^\dagger\phi)^2 + \epsilon(\phi^\dagger\phi)^2 \log\frac{\phi^\dagger\phi}{\mu^2}$$

Pseudo-Goldstone Higgs

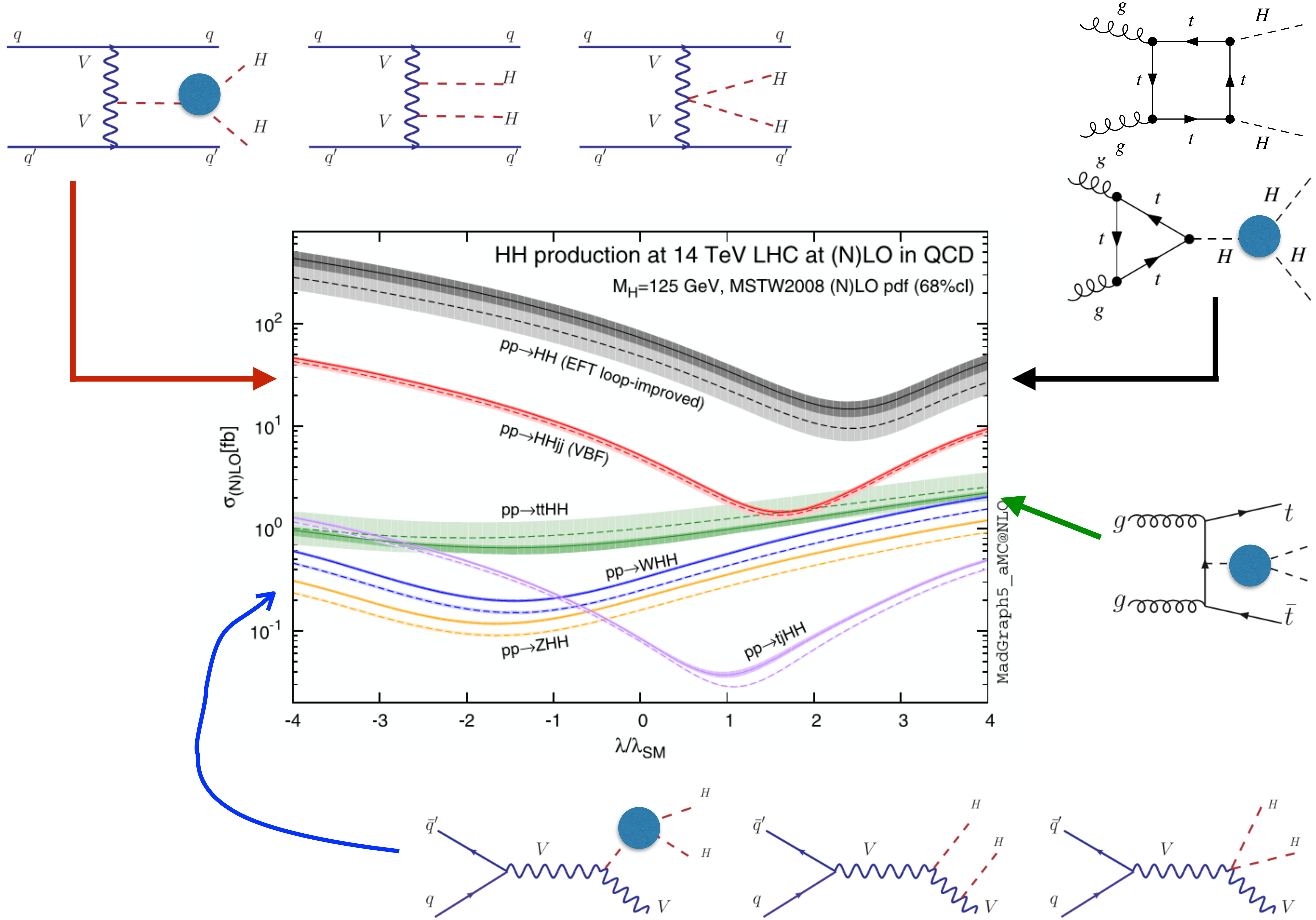


$$V(\phi) = a\sin^2(\phi/f) + b\sin^4(\phi/f)$$

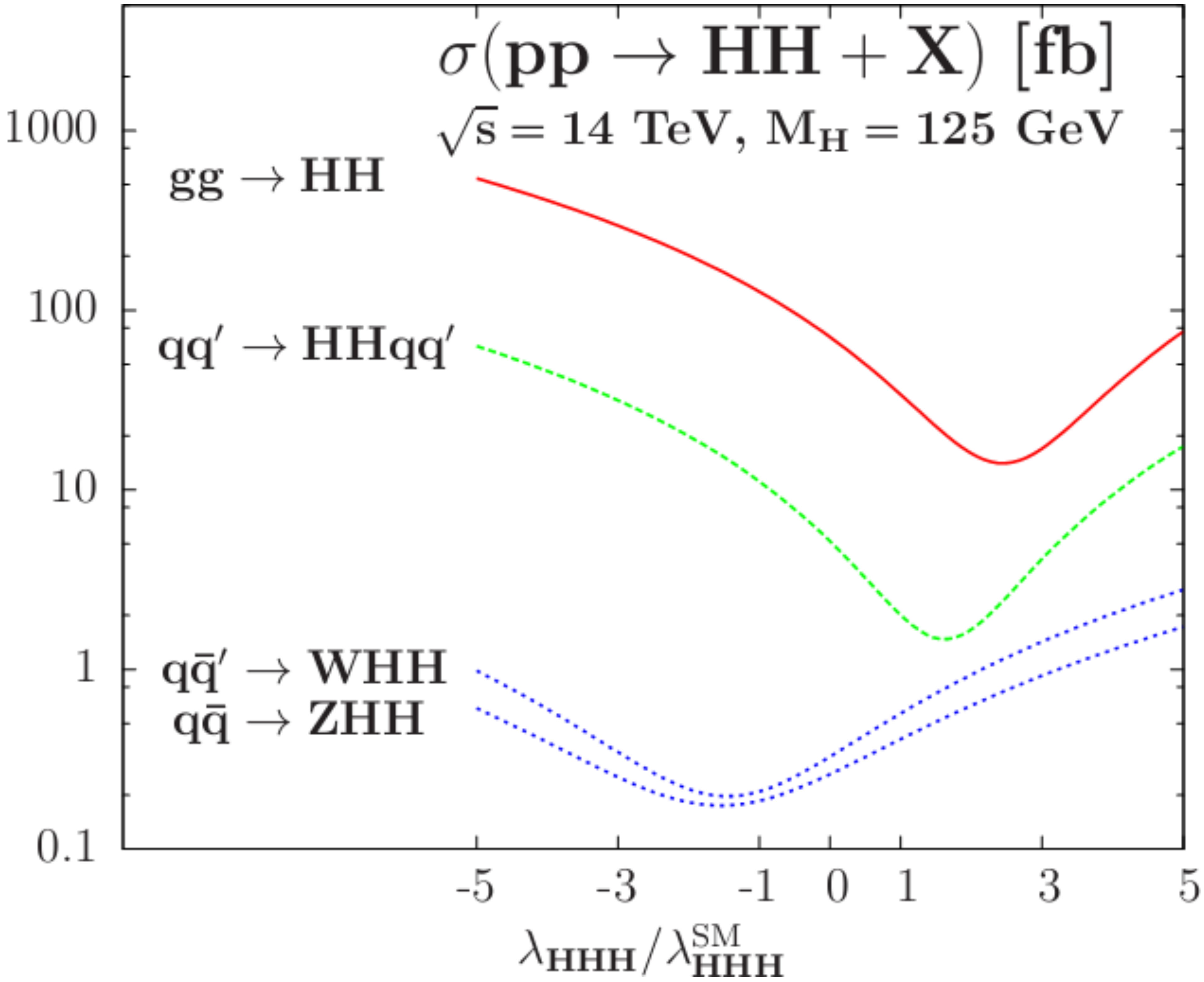


The LHC

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, the leading channel

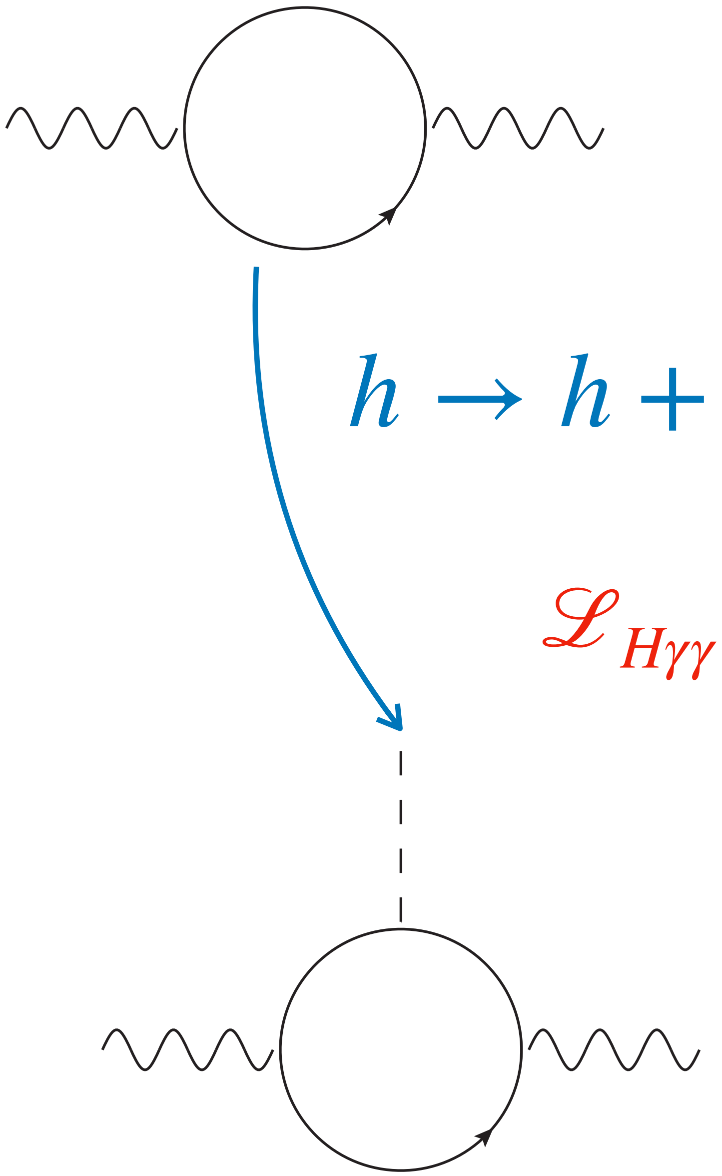
QED effective Lagrangian at one-loop order

Shiftman, Vainshtein,
Voloshin, Zakharov
Sov.J.Null.Phys. 30 (1979) 711

Low Energy Theorem

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

$b_{1/2} = \frac{4}{3}N_{c,f}Q_f^2$	Dirac Fermions
$b_1 = -7$	W bosons
$b_0 = \frac{1}{3}N_{c,S}Q_S^2$	Charged scalars



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

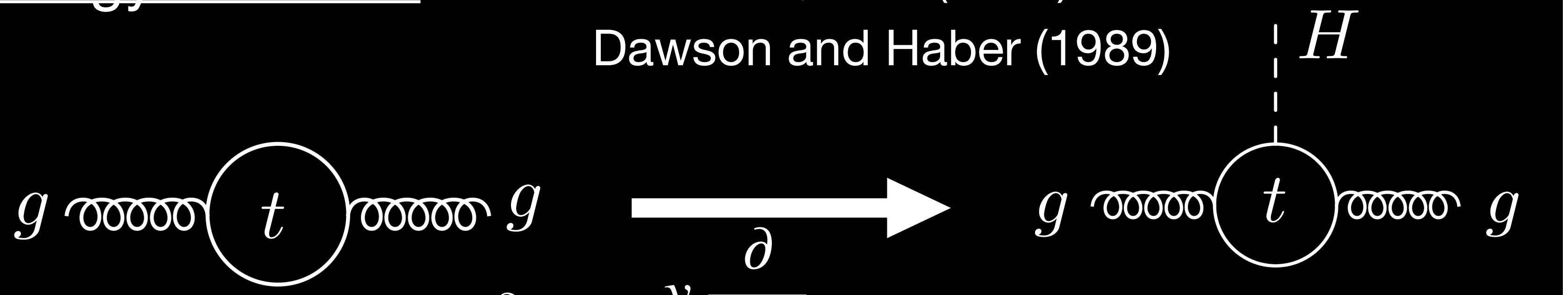
$$\frac{g_{HVV}}{m_V^2} = \frac{\partial}{\partial v}\log m_V^2(v) \quad \frac{2g_{hf\bar{f}}}{m_f} = \frac{\partial}{\partial v}\log m_f^2(v)$$

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

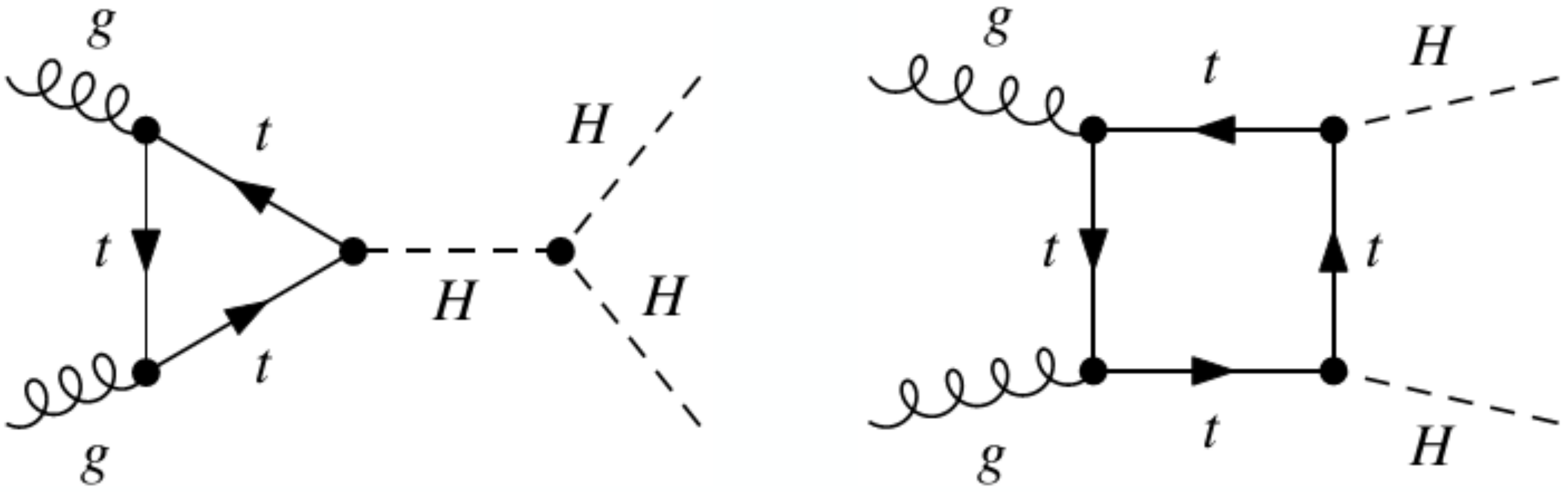
Sensitivity to HHH coupling: 1) gg->HH

Low Energy Theorem

Shiftman, et al (1979)
Dawson and Haber (1989)



$$\sim -\frac{\alpha_s}{24\pi} G^a_{\mu\nu} G^{\mu\nu}_a \log\frac{\Lambda^2}{m_t^2} \xrightarrow{y_t \frac{\partial}{\partial m_t}} \frac{\alpha_s}{12\pi v} G^a_{\mu\nu} G^{\mu\nu}_a H$$



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

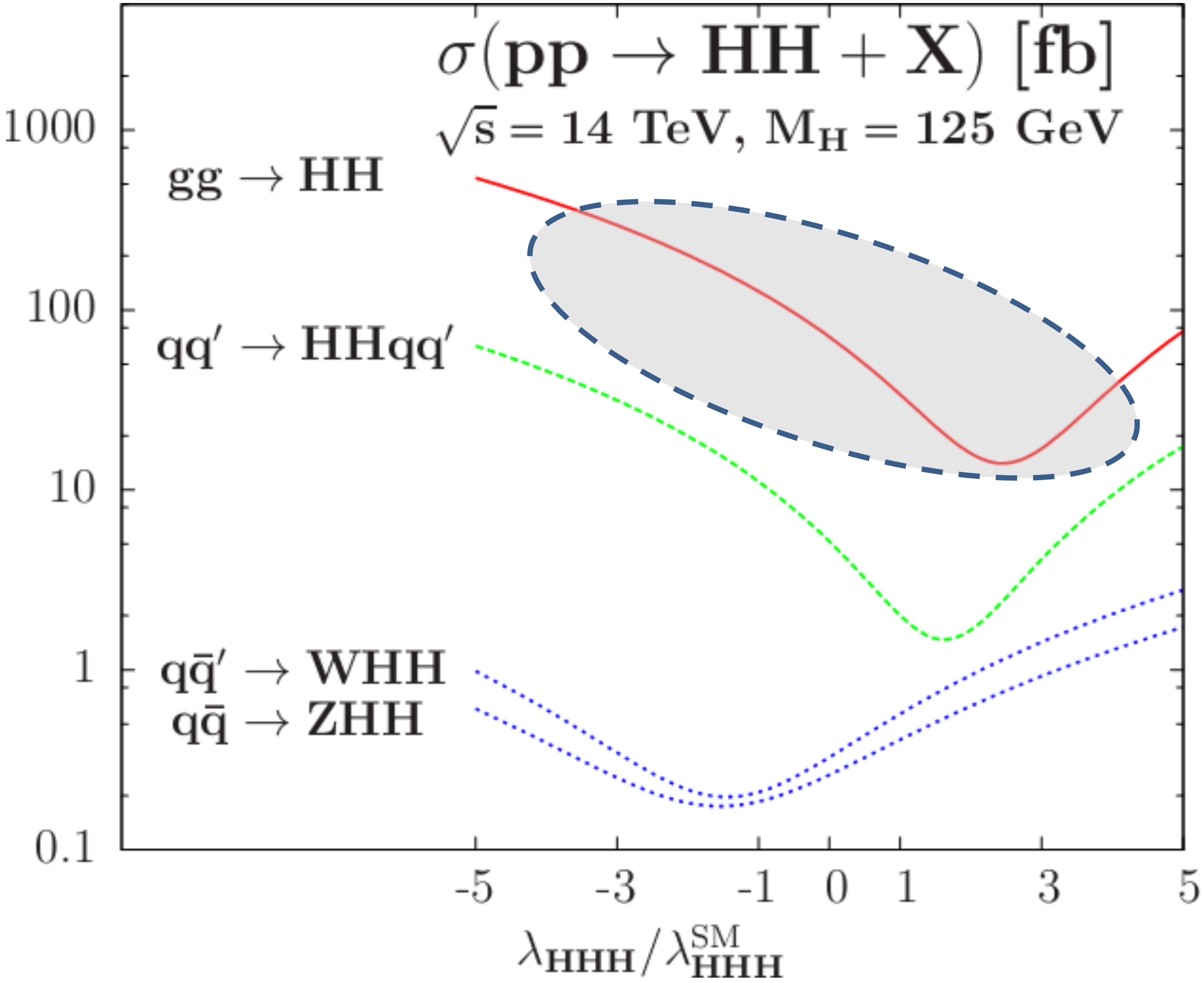
n=1

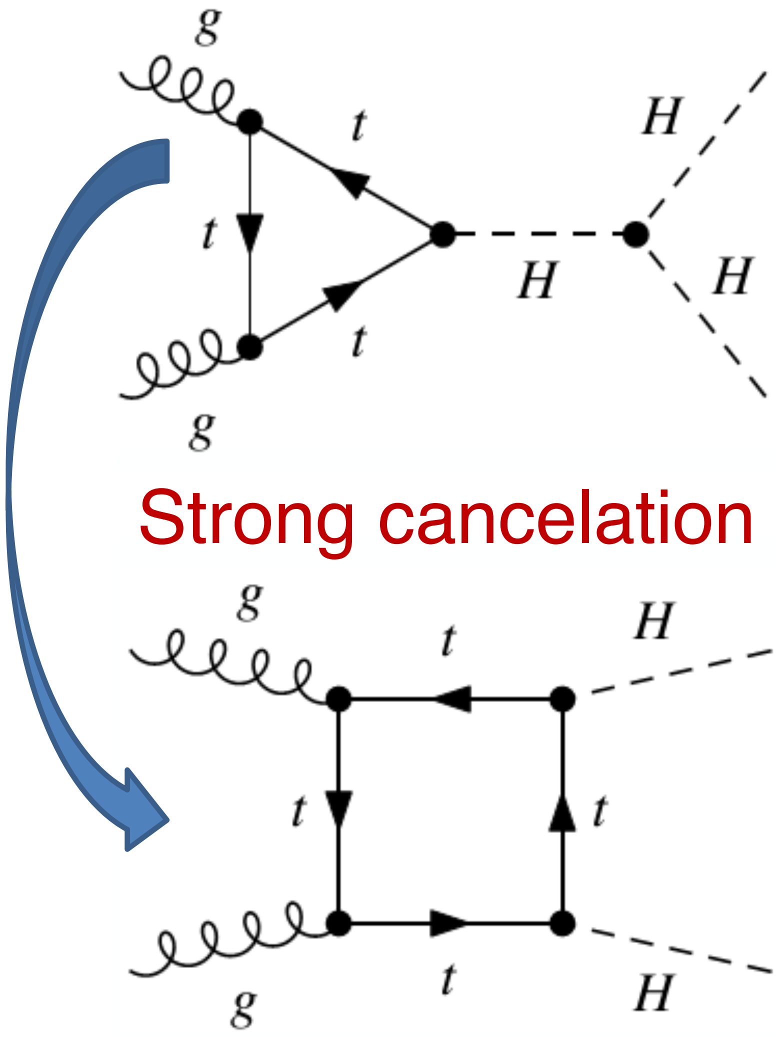
n=2

$$\frac{\alpha_s}{12\pi v} G^{a,\mu\nu} G^a_{\mu\nu} h \qquad - \qquad \frac{\alpha_s}{24\pi v^2} G^{a,\mu\nu} G^a_{\mu\nu} h^2$$

Strong cancelation

Sensitivity to HHH coupling: 1) gg->HH





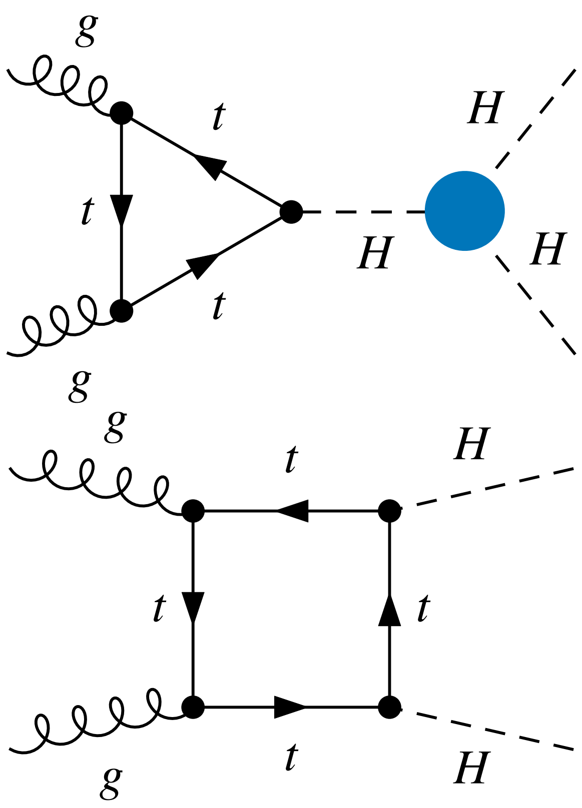
Strong cancelation

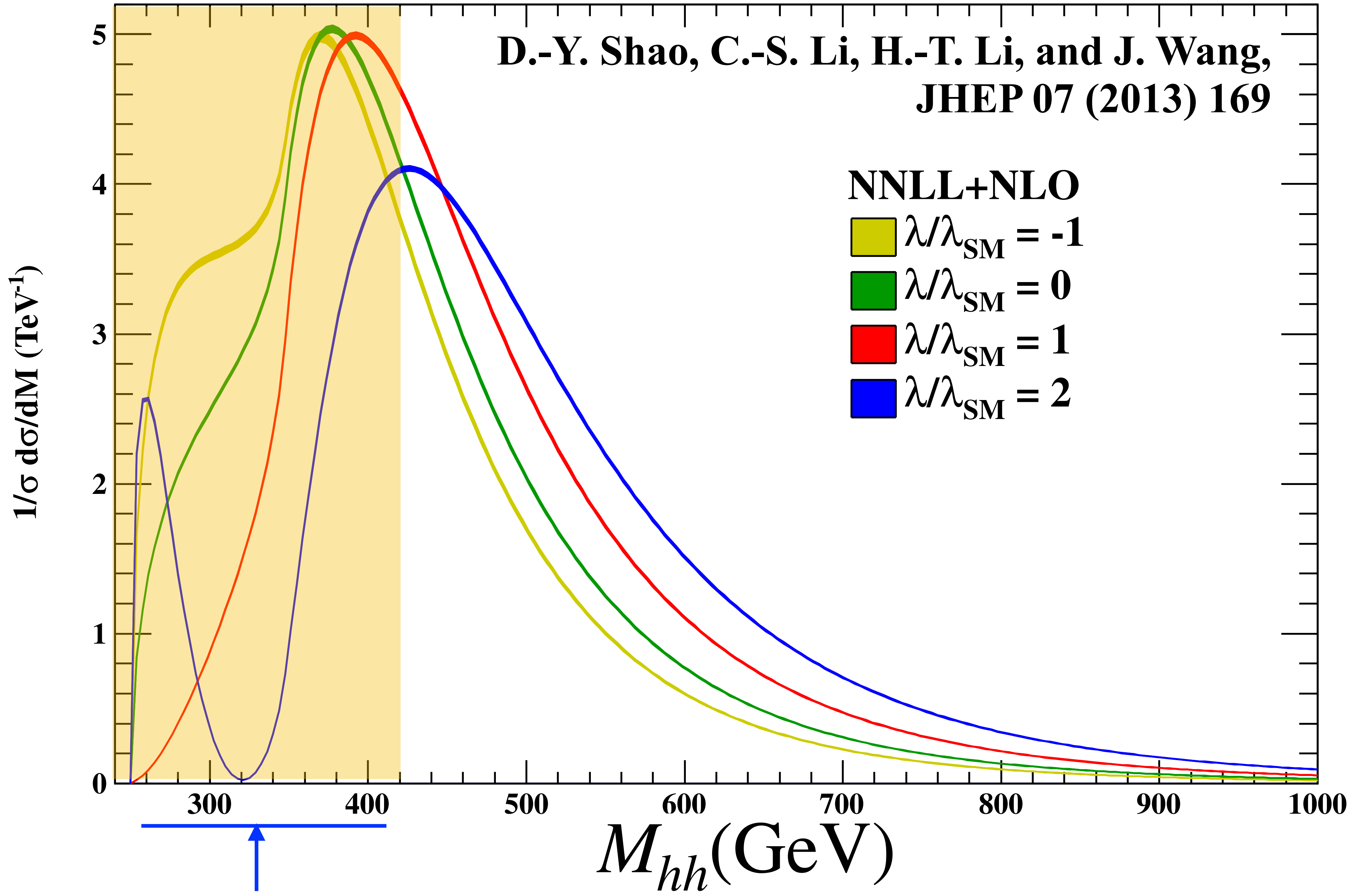
J. Baglio, A. Djouadi et al. JHEP 1304(2013)51

gg->HH: the leading channel

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

HH production

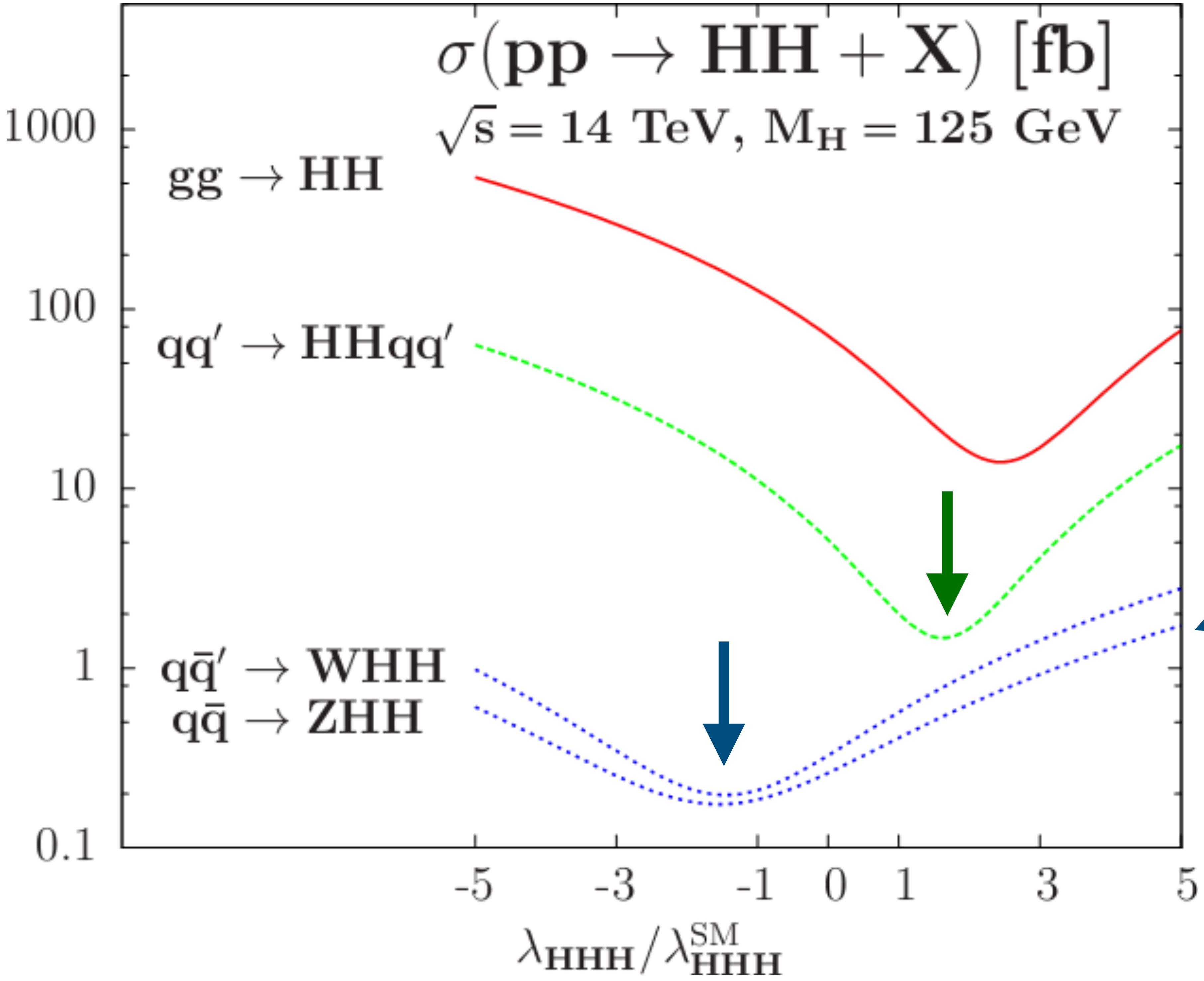


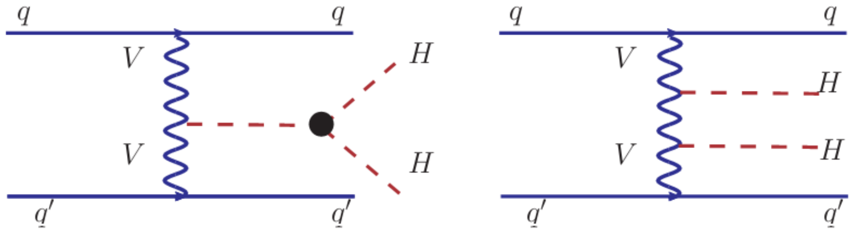

D.-Y. Shao, C.-S. Li, H.-T. Li, and J. Wang, JHEP 07 (2013) 169

strong interference effects,

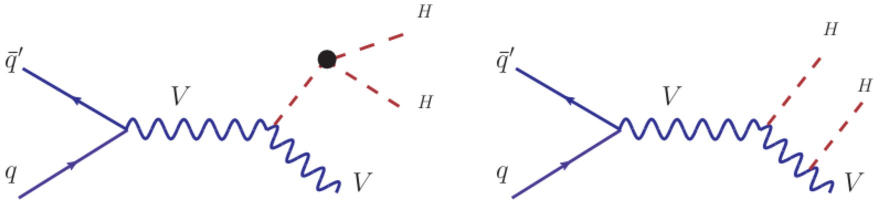
but not accessible at the LHC, due to hard cuts used by our experimental colleagues

Sensitivity to HHH coupling: 2) VBF and VHH



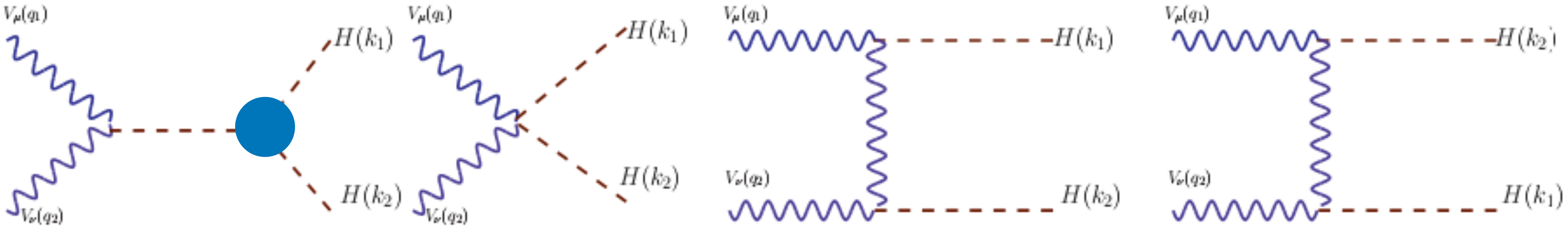


VBF and VHH are sensitive to HHH coupling differently



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

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

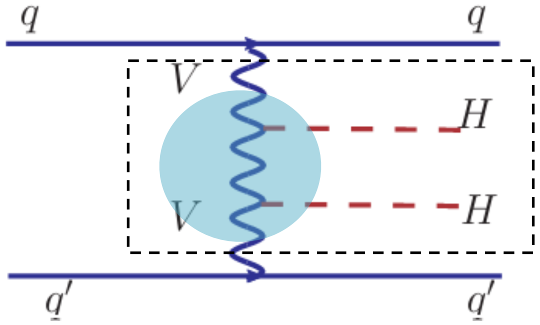


$$M^{\mu\nu} = \left[\frac{m_W^2}{v^2} \frac{6m_H^2}{\hat{s} - m_H^2} \frac{\lambda_{HHH}}{\lambda_{HHH}^{\rm SM}} + \frac{2m_W^2}{v^2} + \frac{4m_W^4}{v^2} \left(\frac{1}{\hat{t} - m_W^2} + \frac{1}{\hat{u} - m_W^2} \right) \right] g^{\mu\nu} + \cdots$$

Near the threshold of Higgs-boson pairs

VBF:

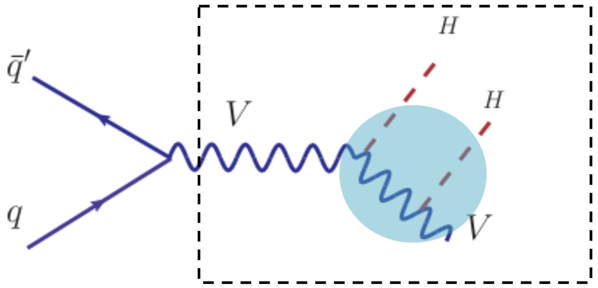
$$\hat{t} = \hat{u} = Q^2 < 0$$



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

VHH:

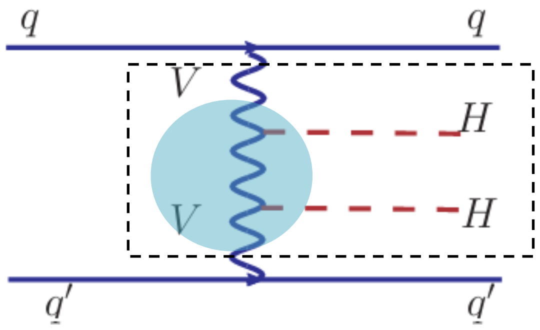
$$\hat{t} = \hat{u} = Q^2 > 0$$



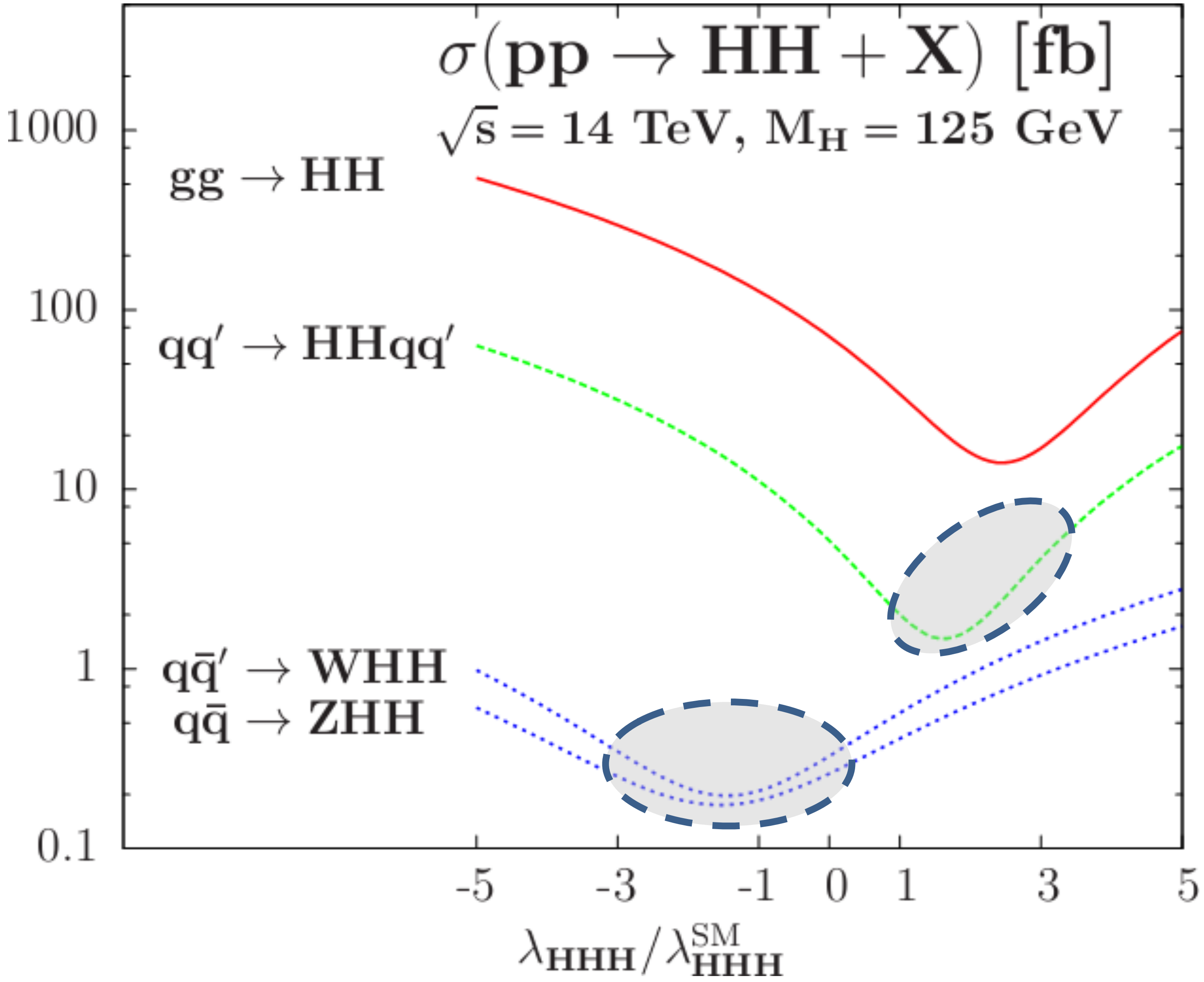
$$M^{\mu\nu} \sim \frac{2m_V^2}{v^2} \left(\frac{\lambda_{HHH}}{\lambda_{HHH}^{\rm SM}} + 1 \right) g^{\mu\nu} + \cdots$$

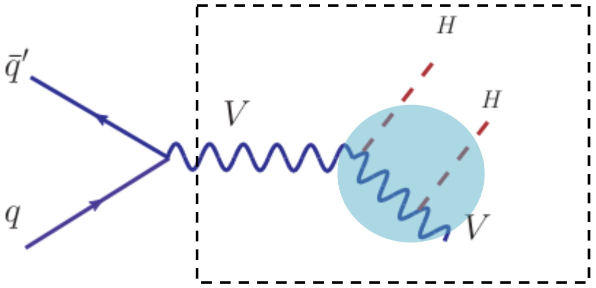
Sensitivity to HHH Coupling

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



$Q^2 < 0$

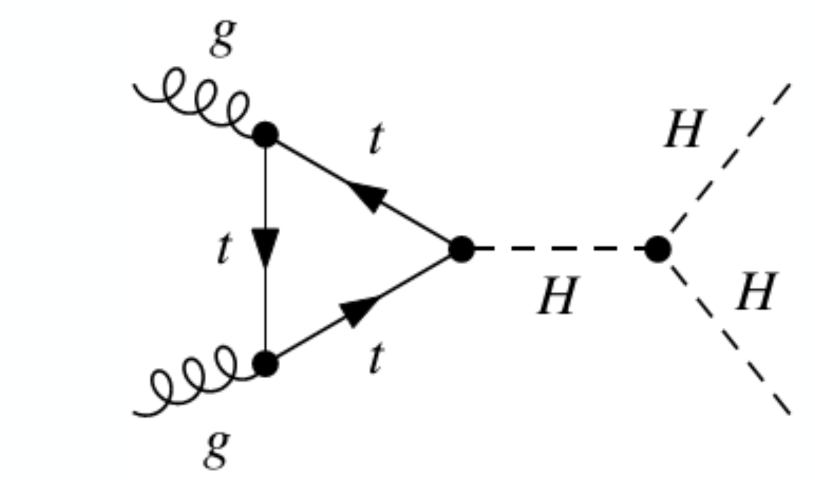




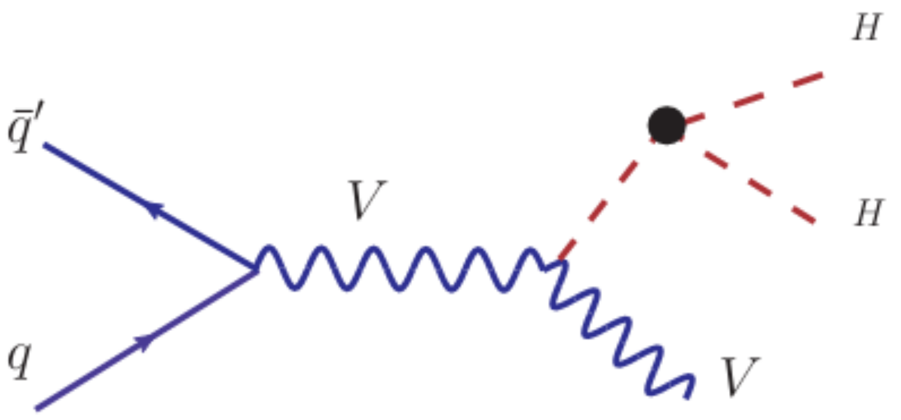
$Q^2 > 0$

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

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: $bbbb$

$Br(bbbblv) = 0.073$

$\sigma \times Br(bb\gamma\gamma) = 0.044\ \mathrm{fb}$

$\approx$

$\sigma \times Br(bbbb\ell\nu) = 0.042\ \mathrm{fb}$

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:

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

WHH and ZHH Productions

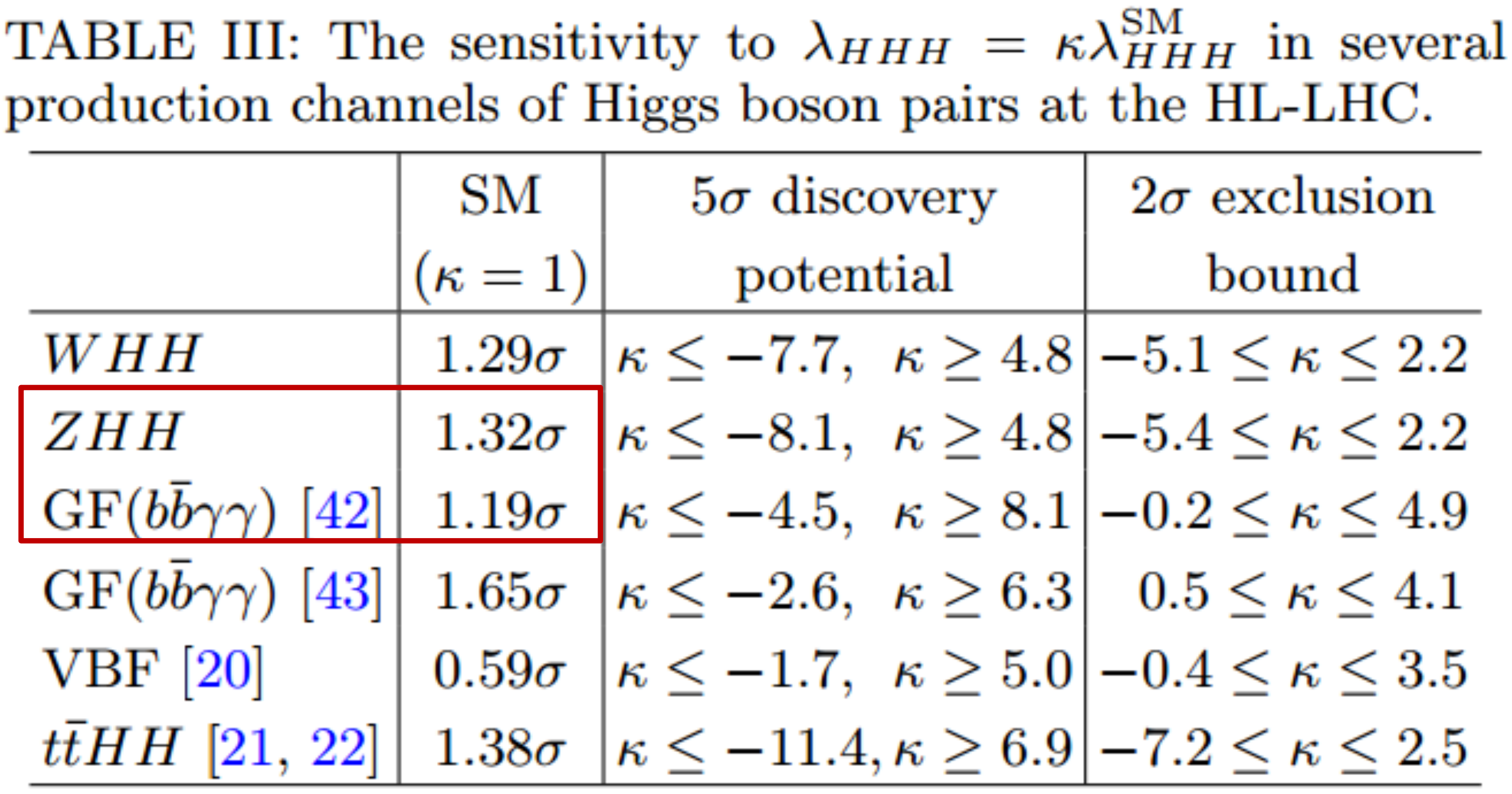
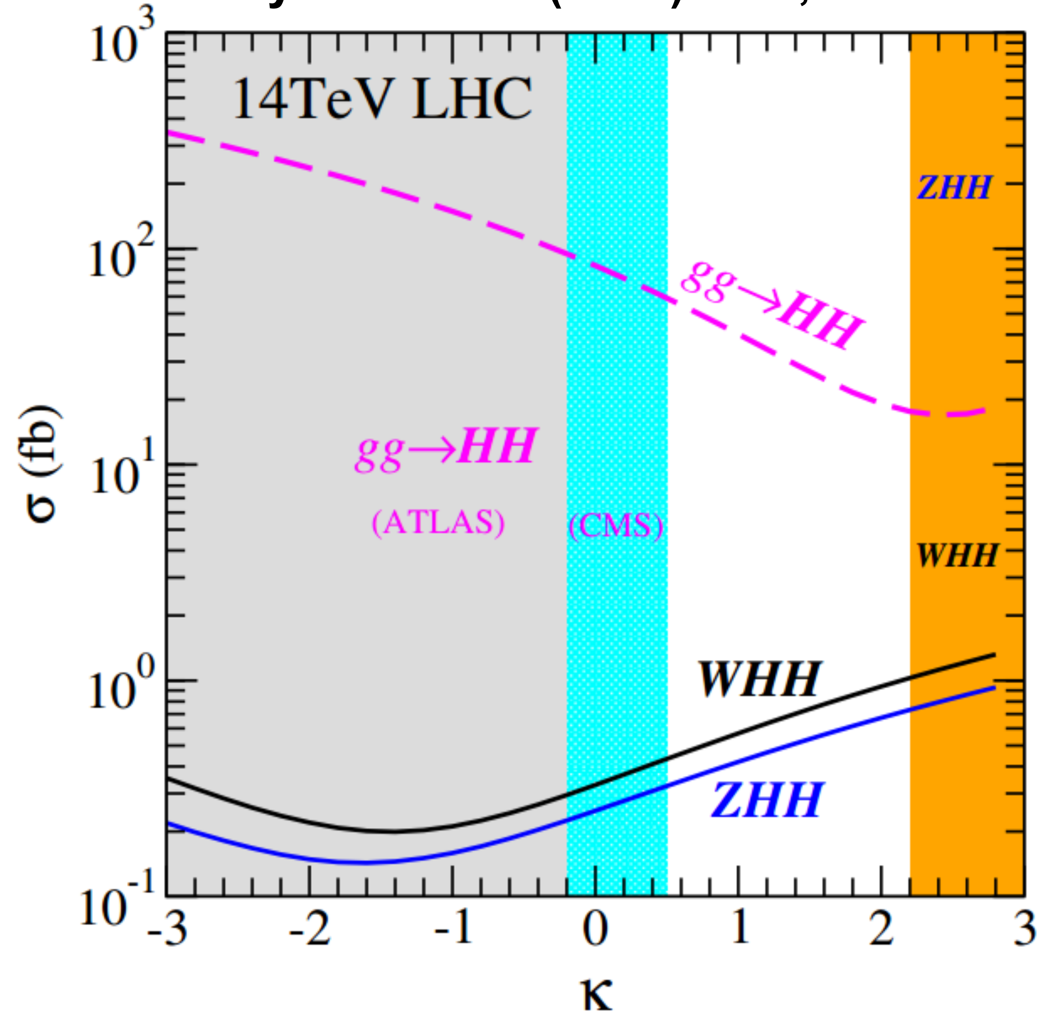


TABLE III: The sensitivity to $\lambda_{HHH} = \kappa\lambda_{HHH}^{\rm SM}$ in several production channels of Higgs boson pairs at the HL-LHC.

	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



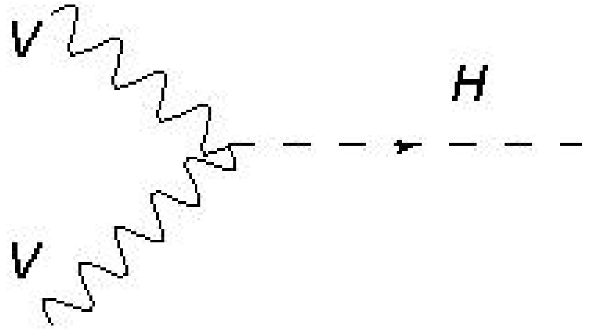
$0.5 \leq \kappa \leq 2.2$

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

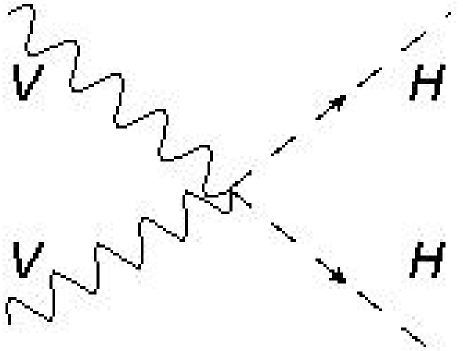
Nordstrom and Papaefstathiou (arXiv:1807.01571) include full detector effects and show that measuring HHH coupling via WHH and VHH channels is still challenging at the HL-LHC

HVV versus HHVV

SM predicts a definite ratio between HVV and HVV couplings



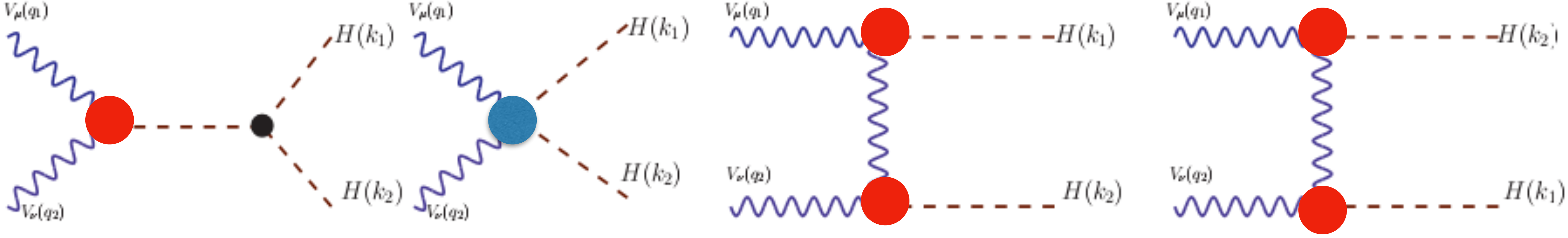
$$\boxed{2i\frac{M_V^2}{v}g^{\mu\nu}}$$



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

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

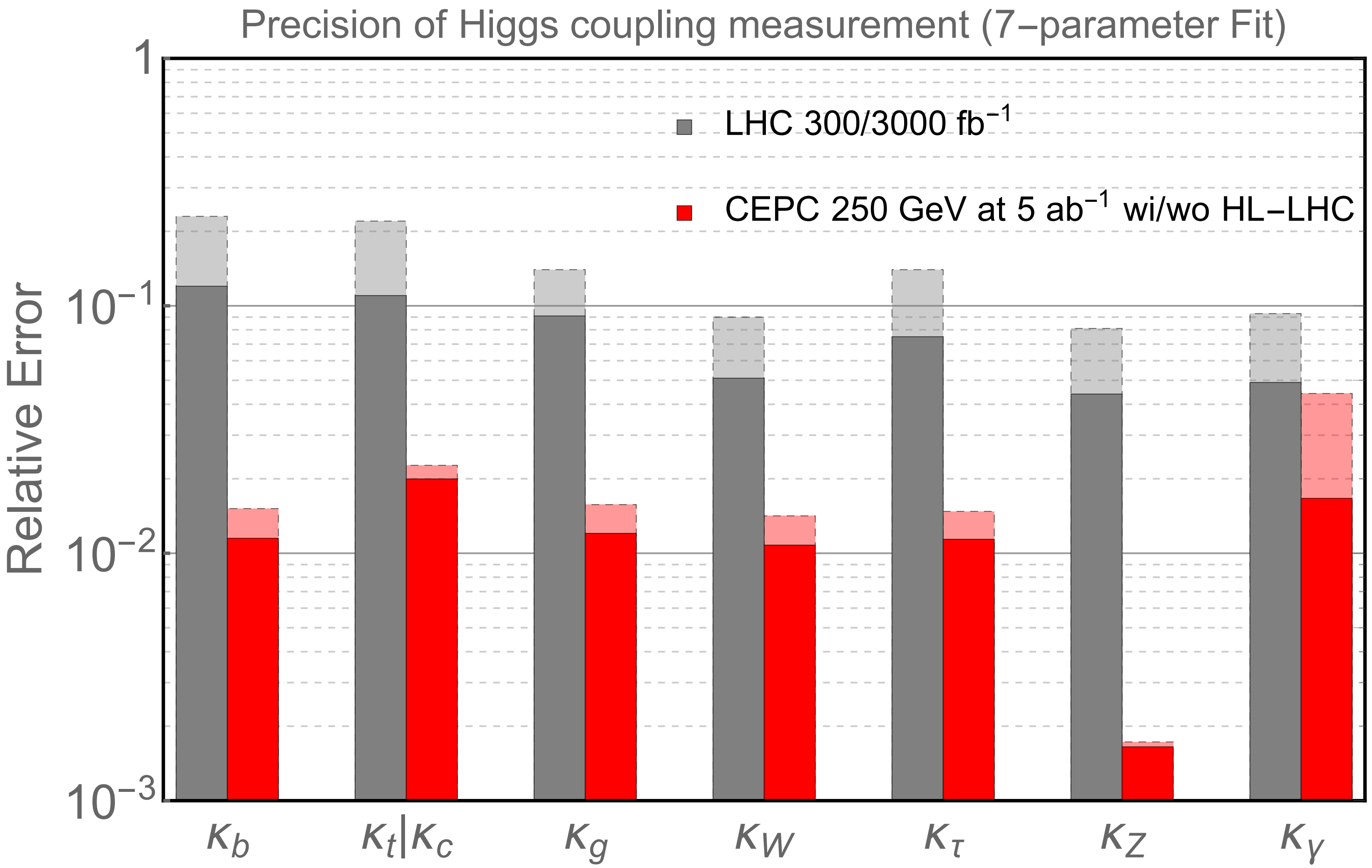
If the ratio is modified by NP, the unitarity of $VV \to HH$ is broken



2.
Fundamental (SM-like) or Composite

Deciphering Higgs Property through Precision at the CEPC

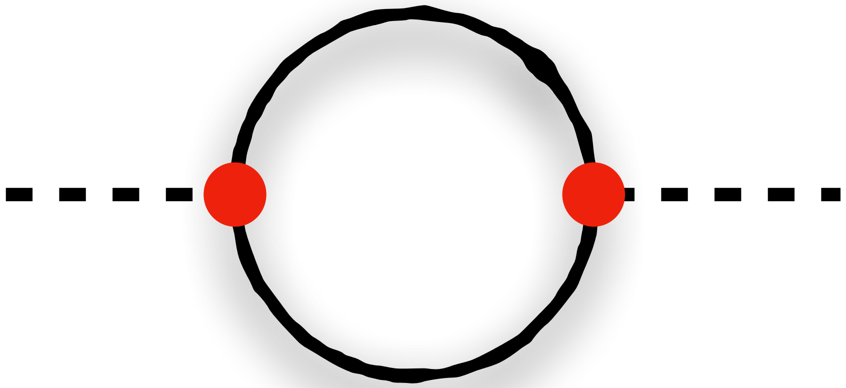
Precision = Discovery !!!



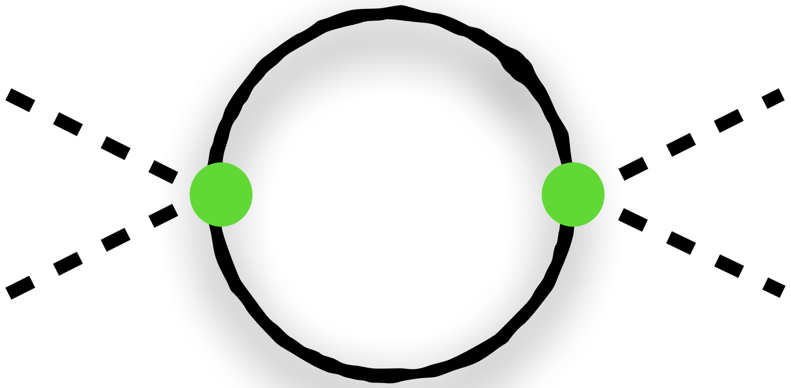
QHC, Yan, Xu, Zhu,
1810.07661,
PLB789 (2019) 233

Higgs Boson as a PNGB

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



top

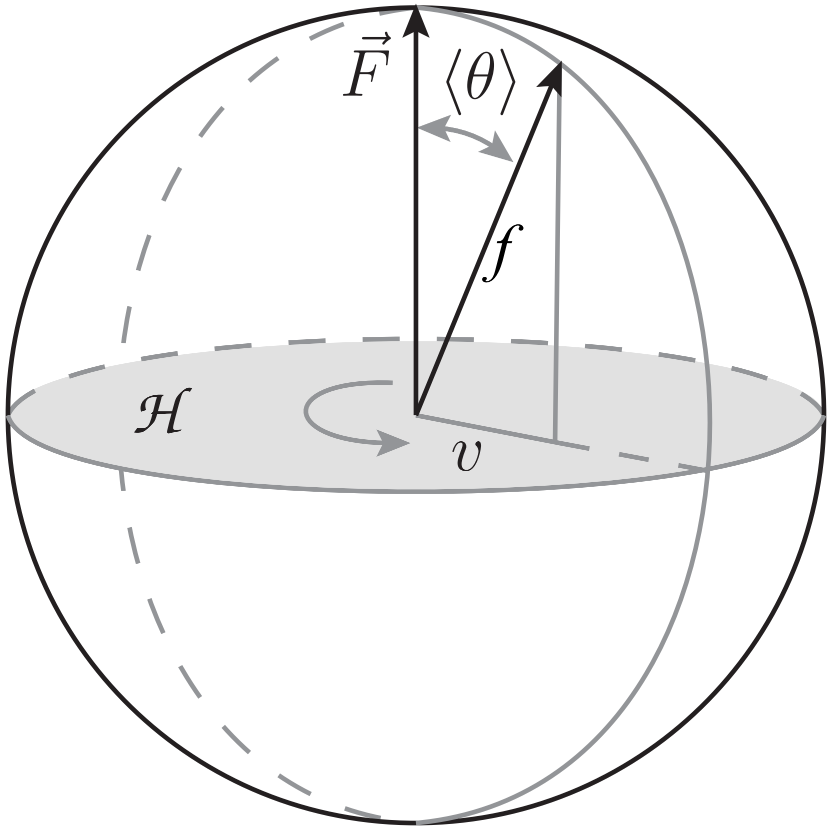


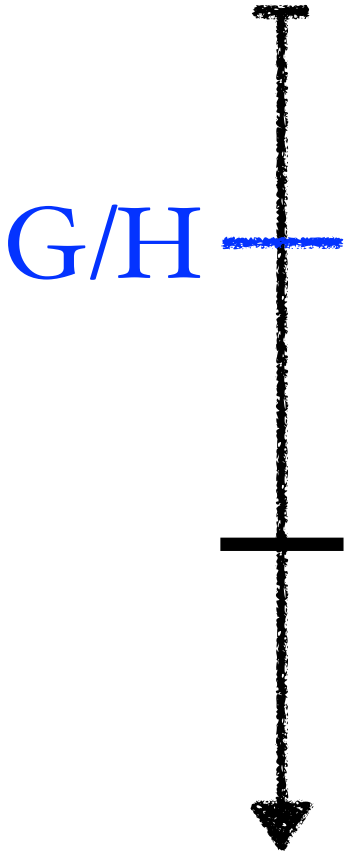
top partners

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

Higgs Nonlinearity

- PNGB Higgs boson can arise from a coset depicted below





global symmetry breaking

electroweak symmetry breaking

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

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

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

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

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

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

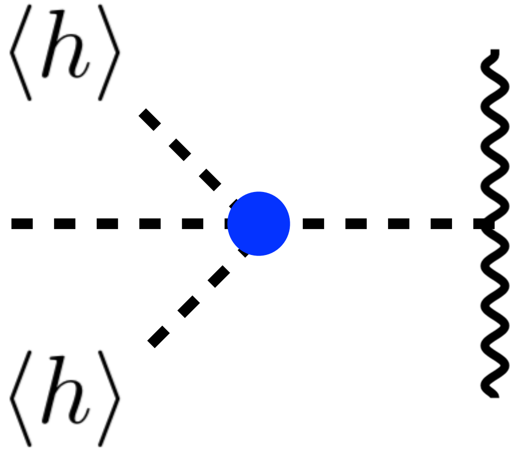
Unfortunately, Higgs nonlinearity is NOT the only source that can modify the hVV couplings!

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

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

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

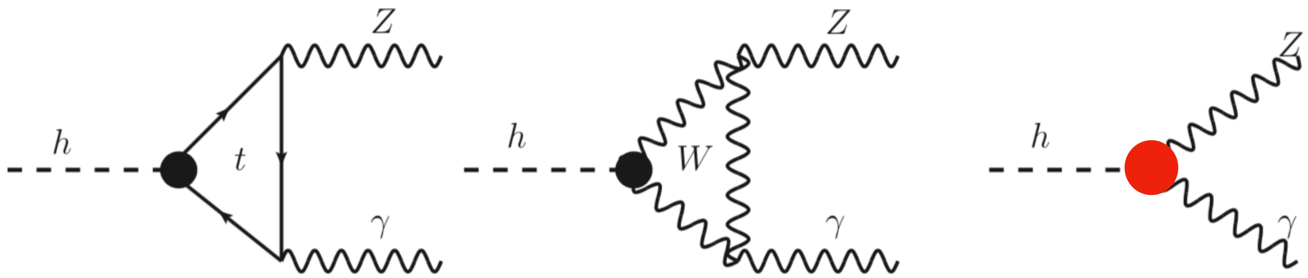
$$\mu(h \to Z\gamma) = \frac{\mathrm{BR}(h \to Z\gamma)}{\mathrm{BR}(h \to Z\gamma)_{\mathrm{SM}}}$$

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

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

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

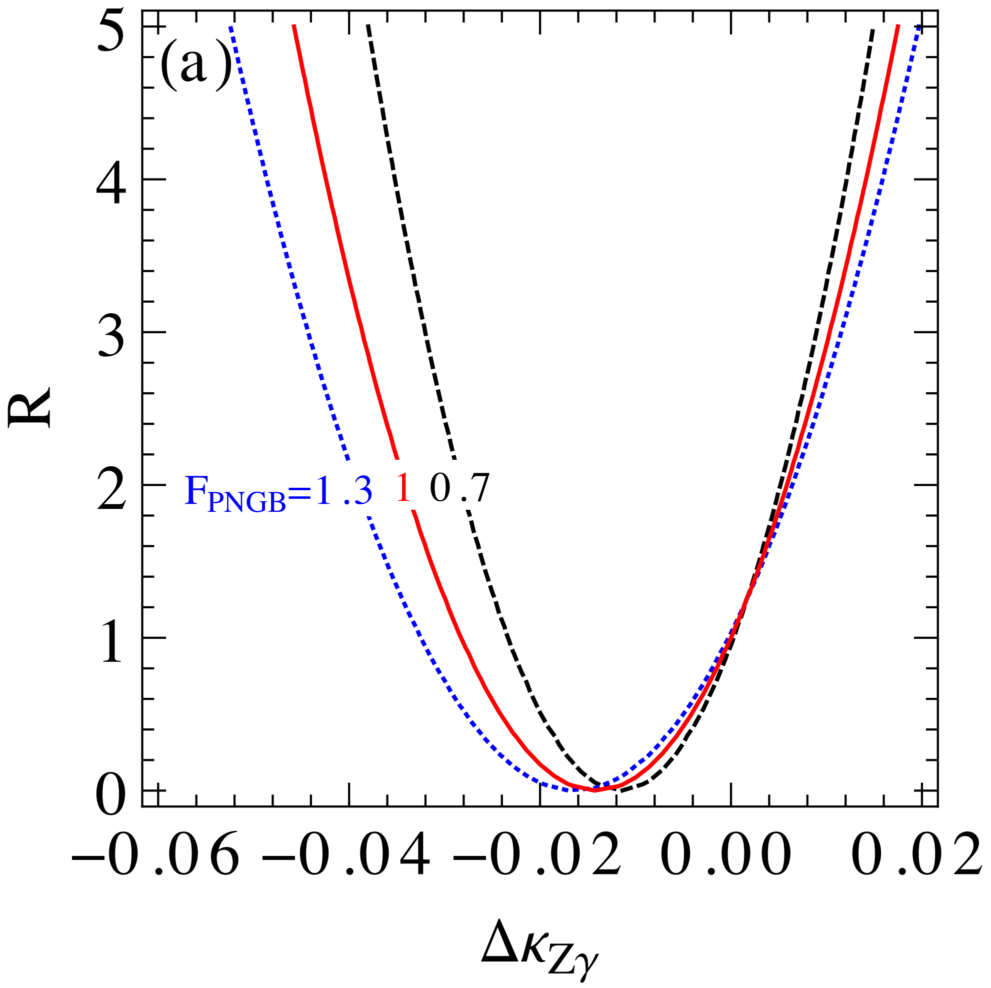
$$F_{O_H} = \frac{1}{1 + c_H}$$

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

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

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

$$= \frac{\left| F_{Z\gamma}^t + F_{Z\gamma}^W \sqrt{F_{\mathrm{PNGB}}} + \Delta\kappa_{Z\gamma} \tan\theta_W \right|^2}{|F_{Z\gamma}^t + F_{Z\gamma}^W|^2 \; F_{\mathrm{PNGB}}}$$

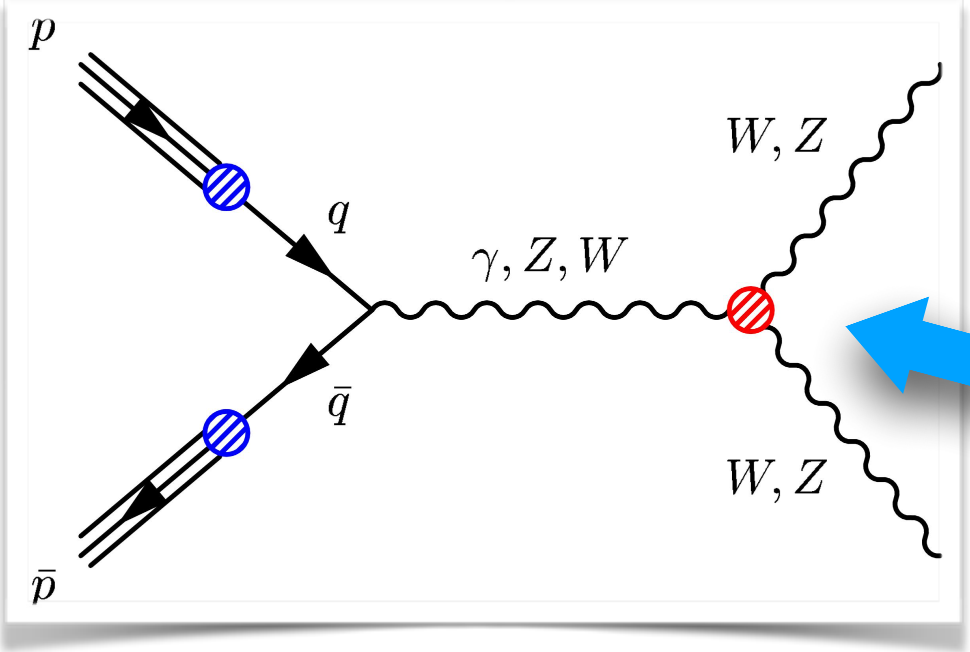


We can determine F_{PNGB} (i.e. ξ) from R and $\Delta\kappa_{Z\gamma}$ measurements.

Triple Gauge Couplings

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

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



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

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

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

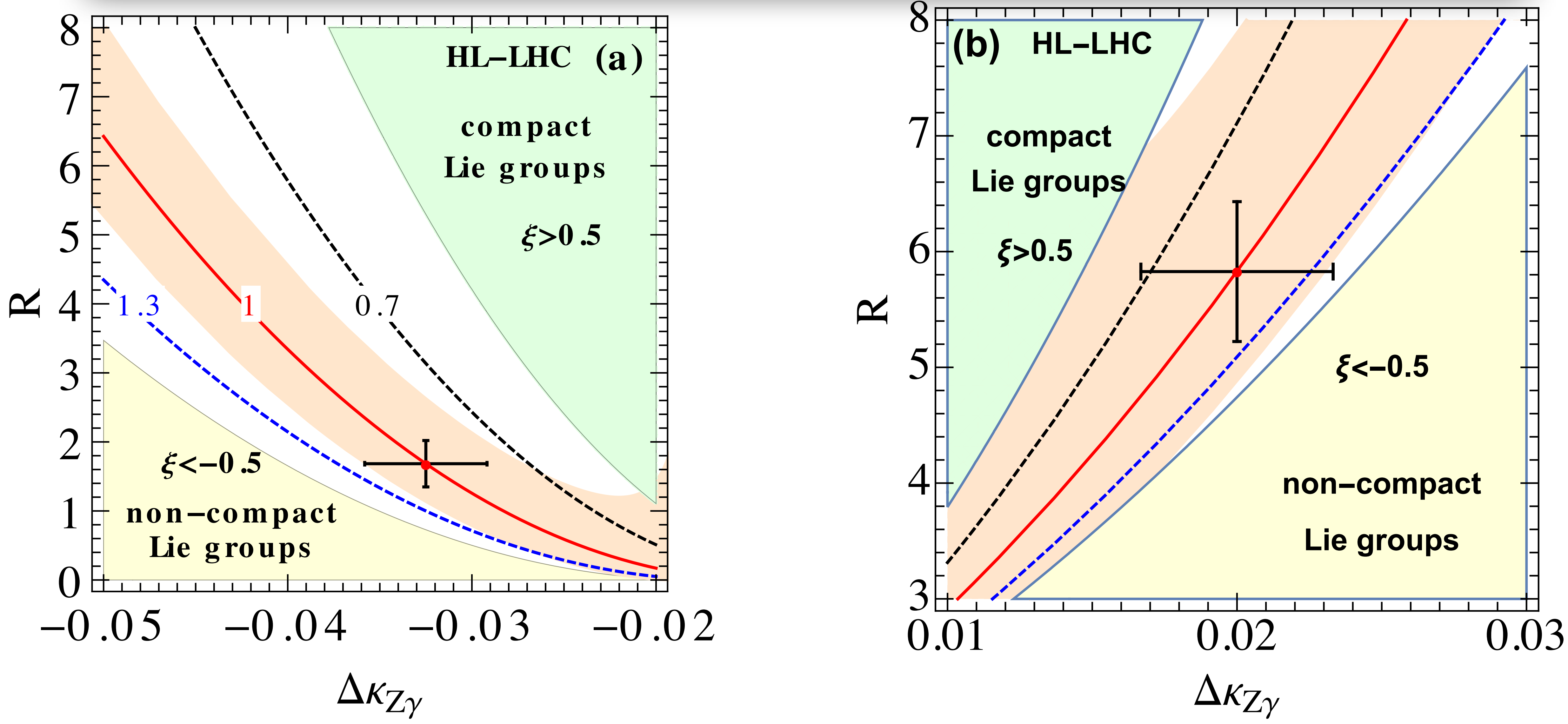
It can be well determined from the TGC measurement.

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 $f \gg v$)

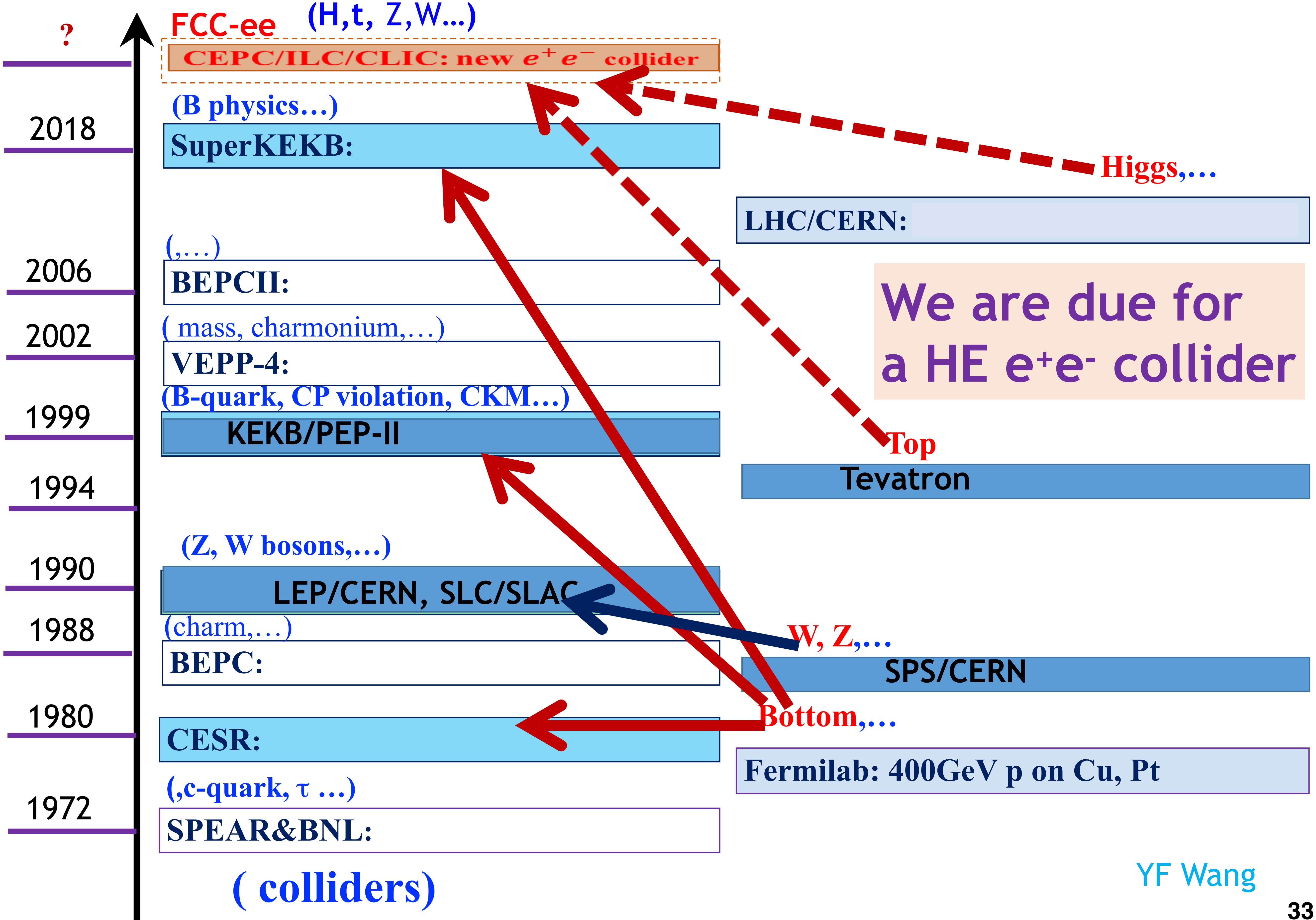
Contour line $\neq$ 1 → Higgs is composite



LHC cannot do it → We need electron-positron colliders

(CEPC, FCC-ee, ILC)

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



Year

?

FCC-ee (H,t, Z,W...)

CEPC/ILC/CLIC: new e^+e^- collider

2018

(B physics…)

SuperKEKB:

Higgs,…

LHC/CERN:

2006

(,…)

BEPCII:

We are due for a HE e^+e^- collider

2002

(mass, charmonium,…)

VEPP-4:

1999

(B-quark, CP violation, CKM…)

KEKB/PEP-II

Top

1994

Tevatron

1990

(Z, W bosons,…)

LEP/CERN, SLC/SLAC

1988

(charm,…)

BEPC:

W, Z,…

SPS/CERN

1980

Bottom,…

CESR:

Fermilab: 400GeV p on Cu, Pt

1972

(,c-quark, τ …)

SPEAR&BNL:

(colliders)

YF Wang

Reminder about the CEPC-SppC

e^+e^- Higgs (Z) factory

$E_{cm} \approx 240$GeV, luminosity ~2×10^{34} $cm^{-2}s^{-1}$, 2IP, 1M H in 10 years

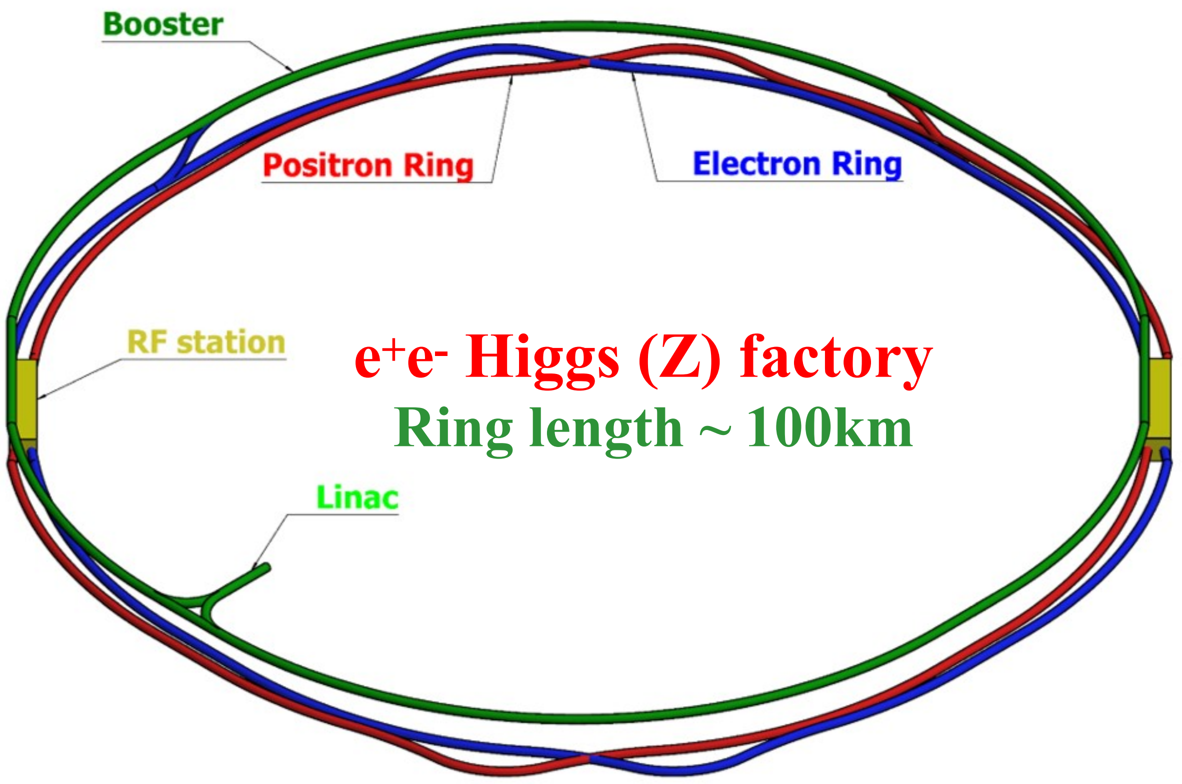
at the Z-pole 10^{10}Z bosons/yr

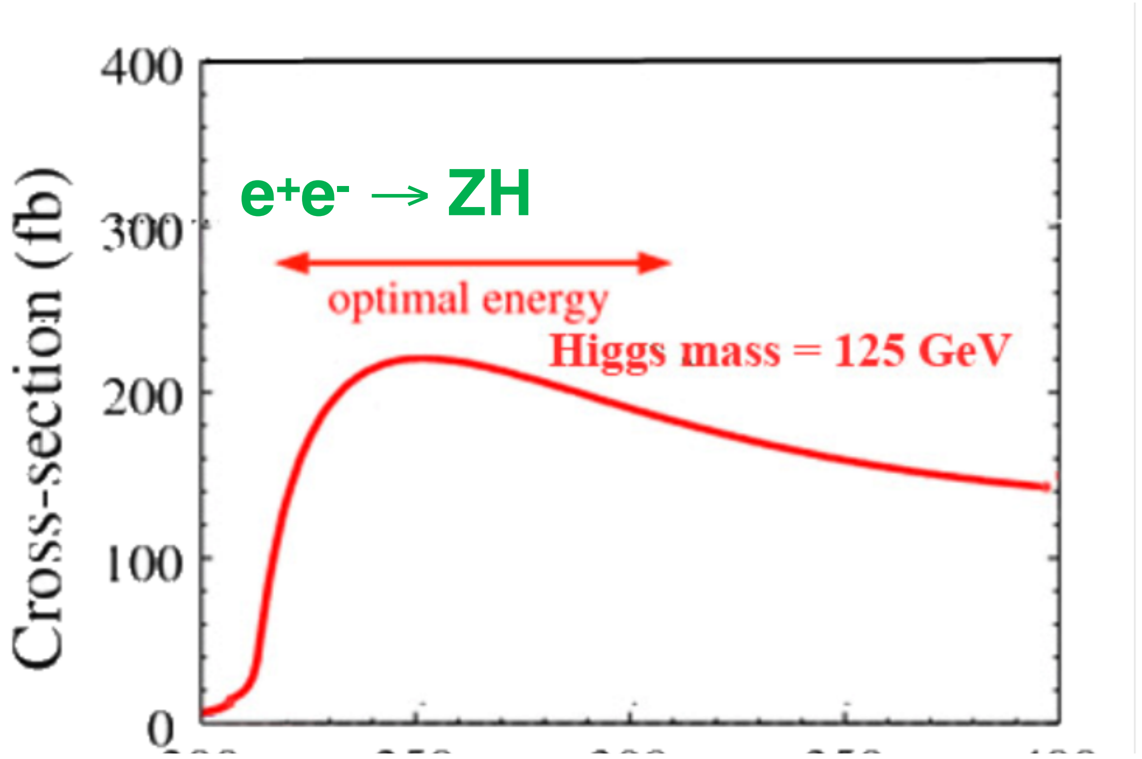
Precision measurement of the Higgs boson (and the Z boson)

Upgradable to pp collision with $E_{cm} \approx$ 50-100 TeV (with ep, HI options)

A discovery machine for BSM new physics

Higgs precision 1% or better



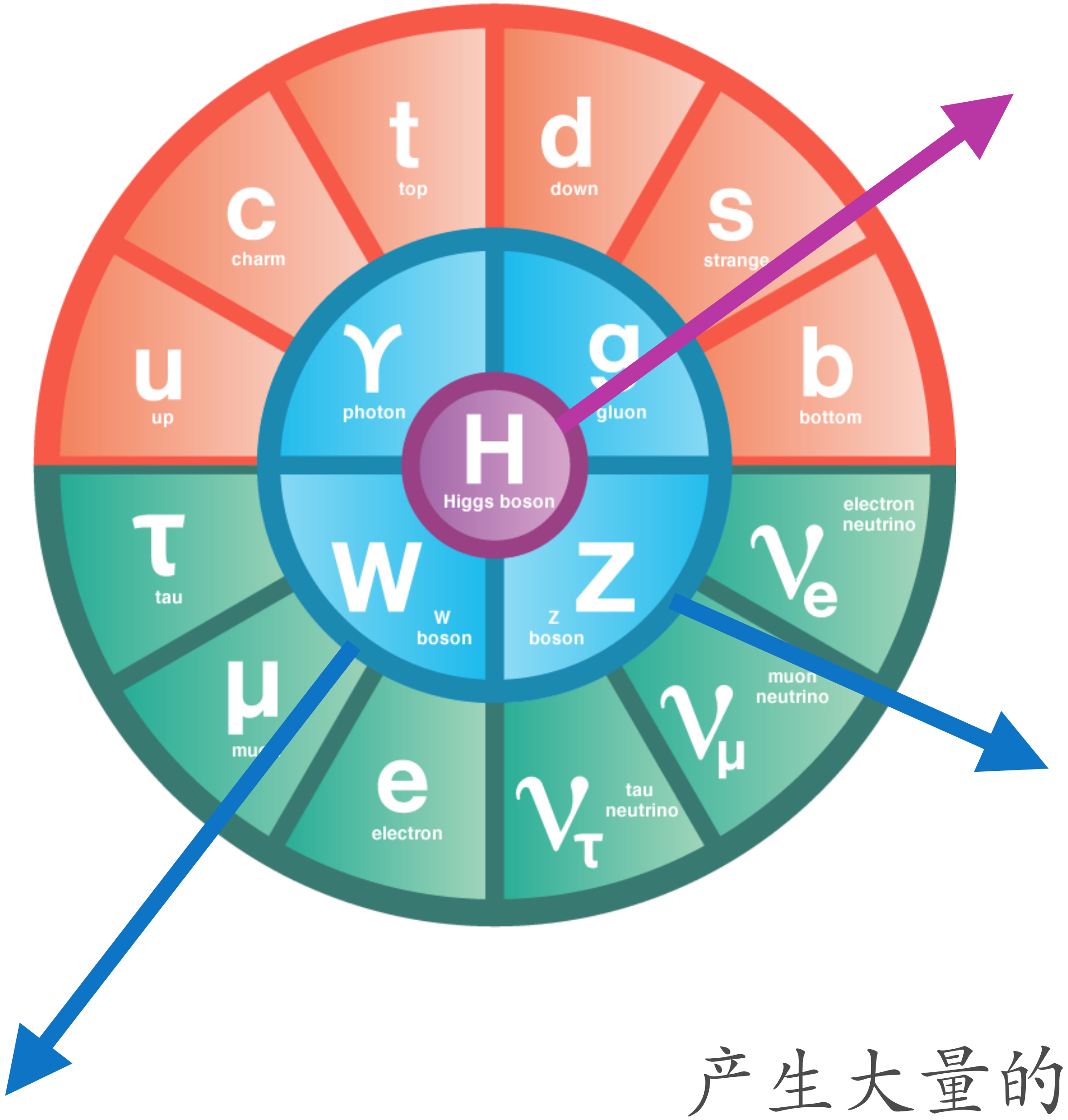


BEPCII will likely complete its mission ~2020s;

CEPC – **possible** accelerator based particle physics program in China after BII

CEPC运行的计划

L.-T. Wang’s talk



10^6 希格斯粒子

10^{12} Z 玻色子

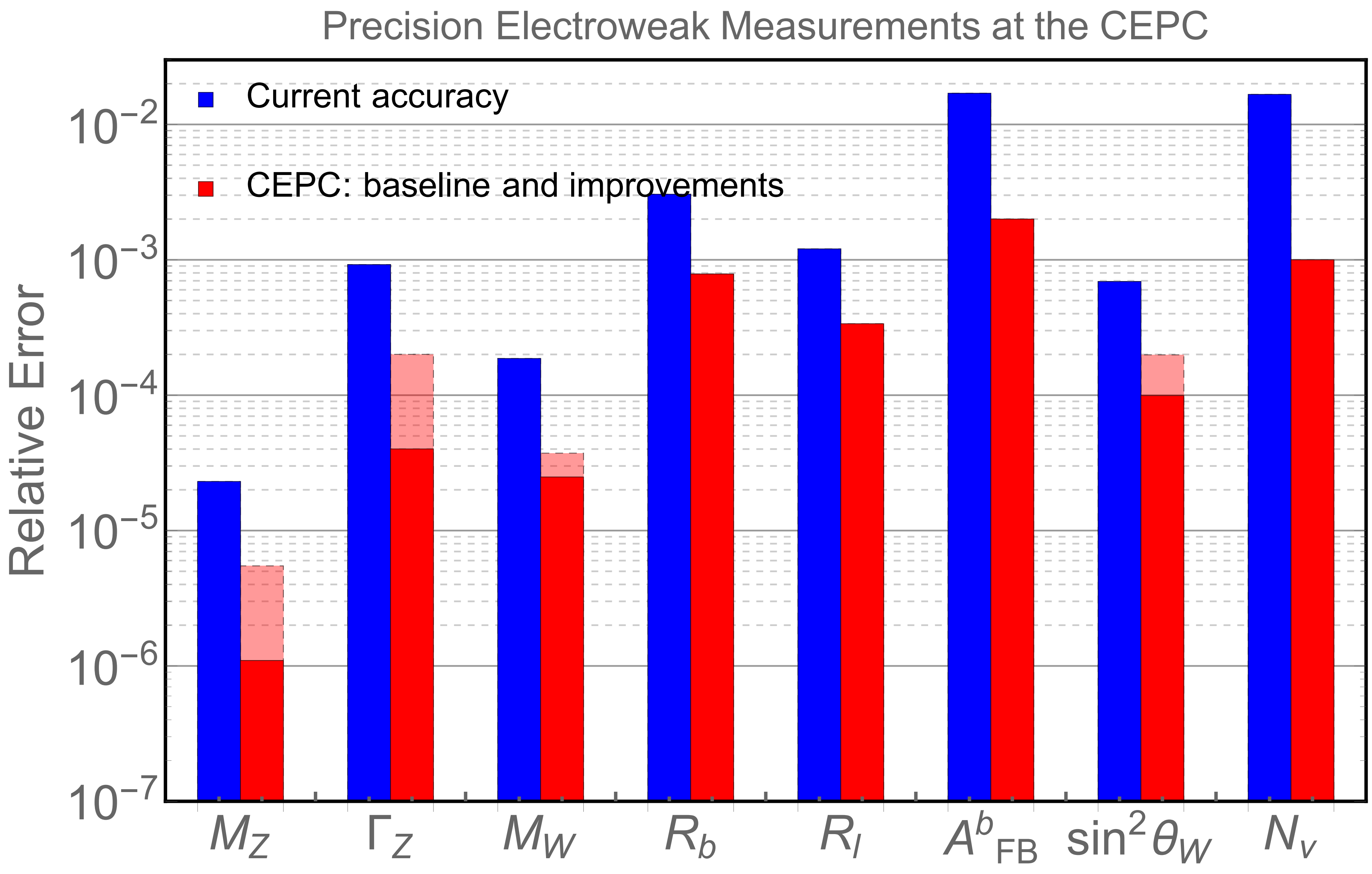
10^7 W玻色子

产生大量的粒子是为了更仔细地研究它们的性质

数量越多，精度越高

L.-T. Wang's talk

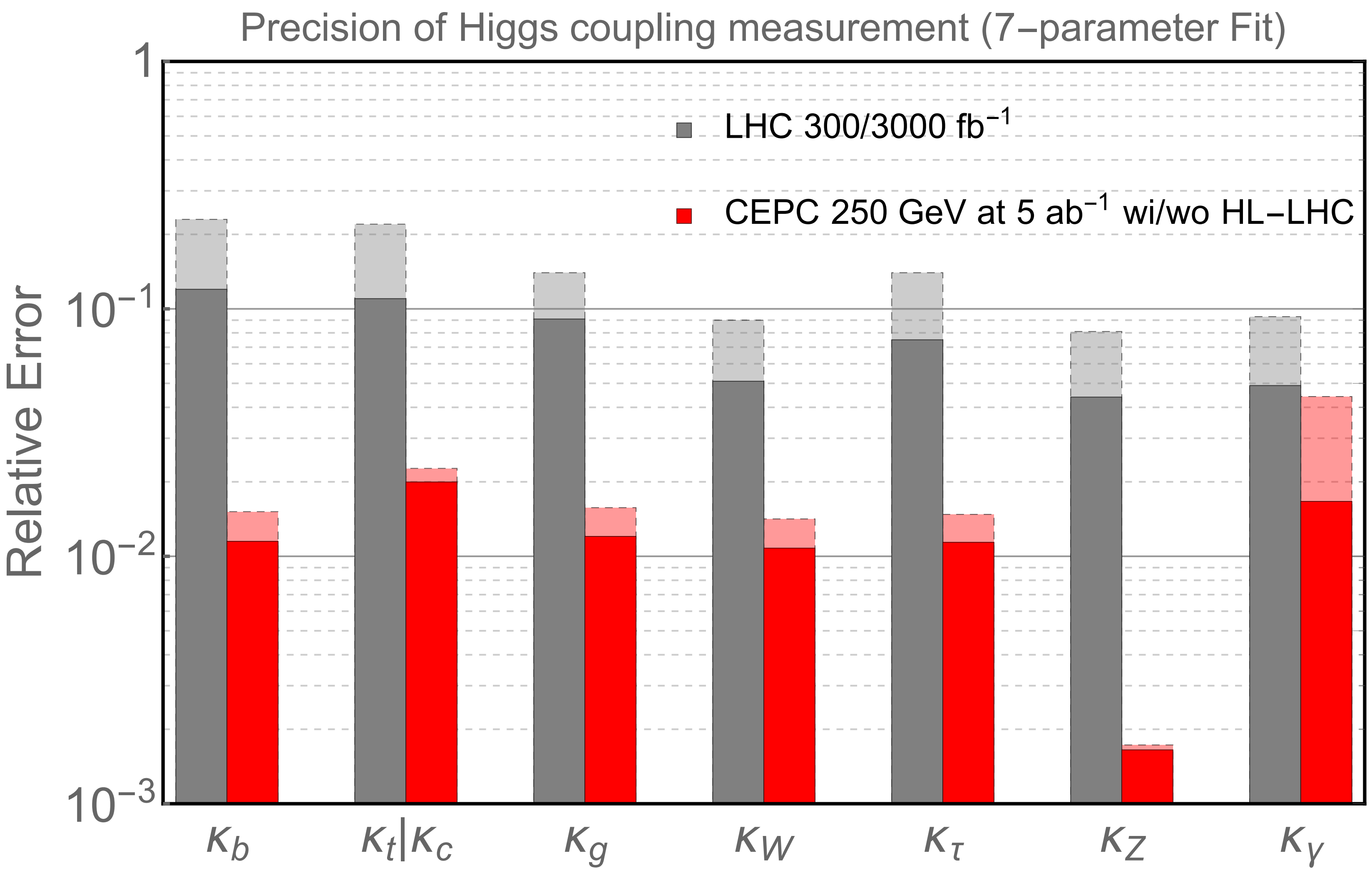
CEPC 的主要物理目标: 精确的测量W和Z玻色子的性质



精度提高10倍以上

CEPC 的主要物理目标: 精确测量希格斯粒子的性质

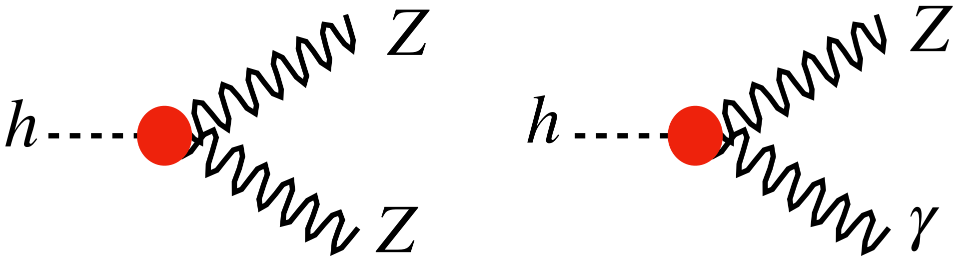
L.-T. Wang’s talk



这也是欧洲核子中心(CERN)大型强子对撞机(LHC)
今后15-20年首要物理目标之一

CEPC 精度超过大型强子对撞机10到几十倍

Determining $F_{\rm PNGB}$ at the CEPC



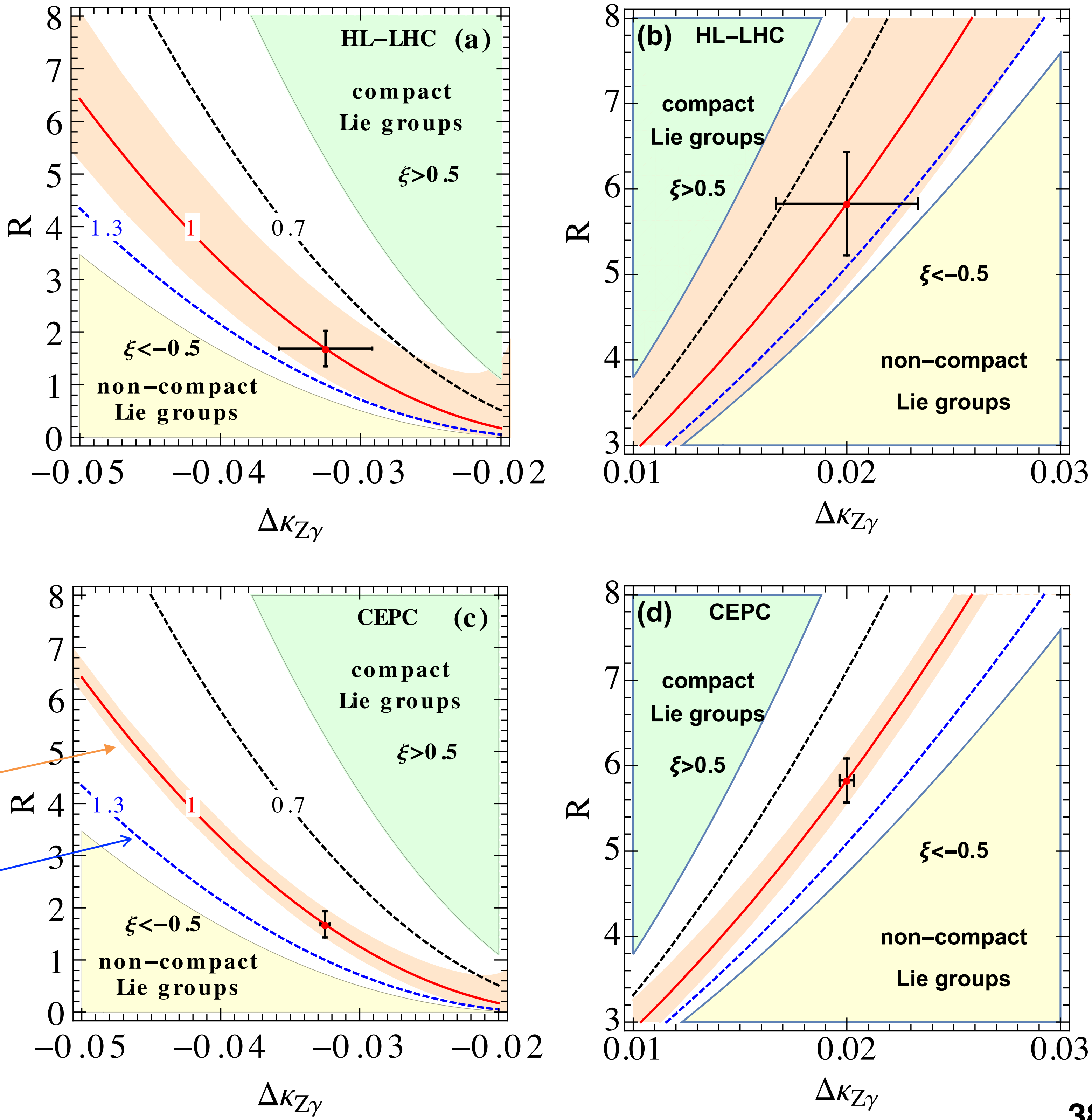
$$F_{\rm PNGB} = 1 - \xi = 1 - v^2/2f^2$$

QHC, Yan, Xu, Zhu, 1810.07661

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

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

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



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.

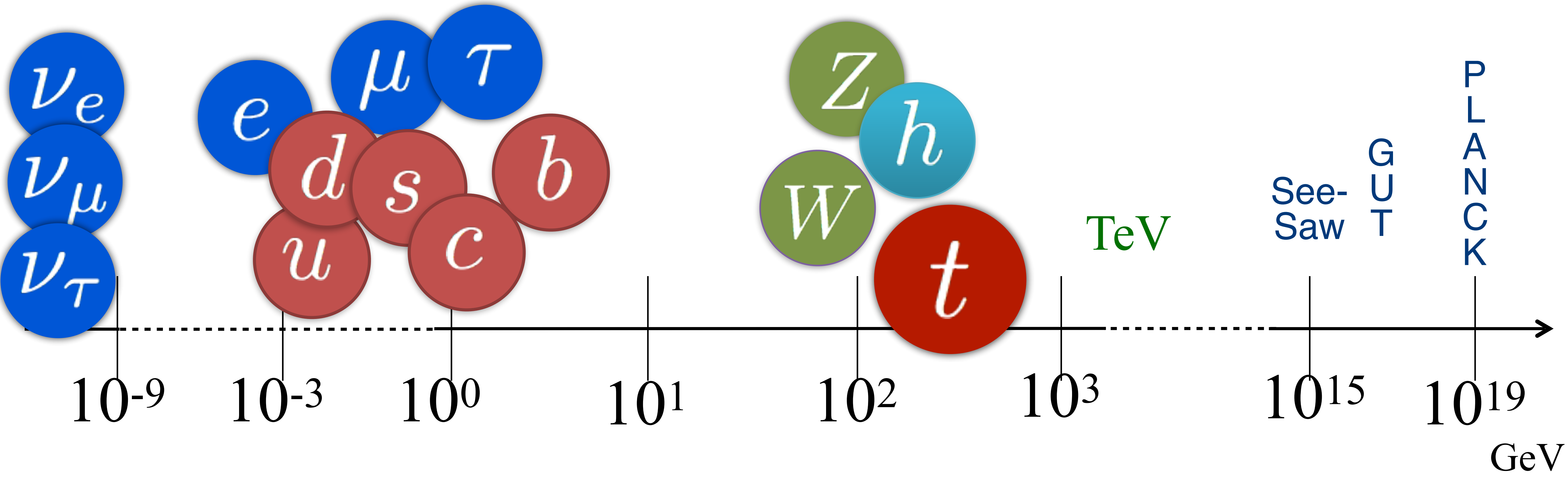
- Our result is valid in *any* symmetry breaking patterns, as long as custodial symmetry is assumed.

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

Thank You!

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.

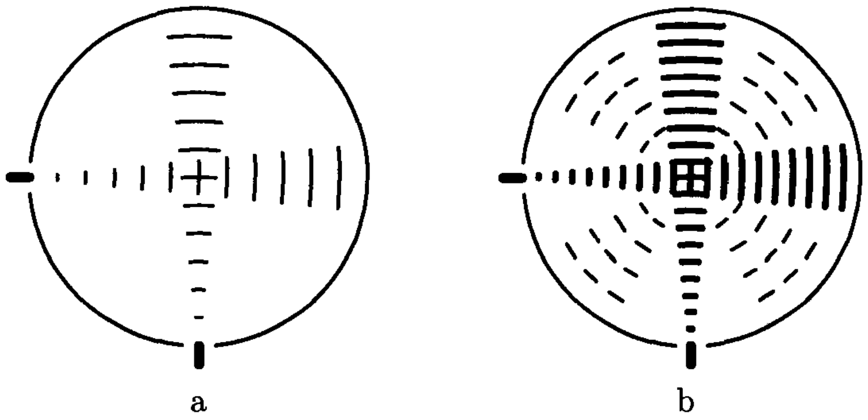
NP scale = New Resonance Mass ~ 2TeV

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

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)

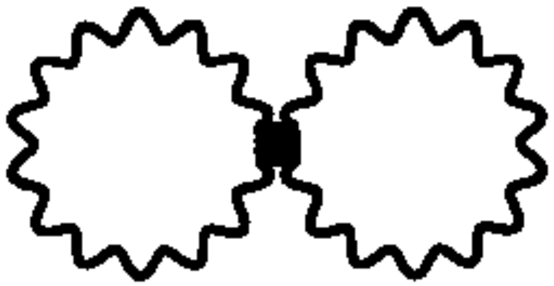


After matching in QED

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

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

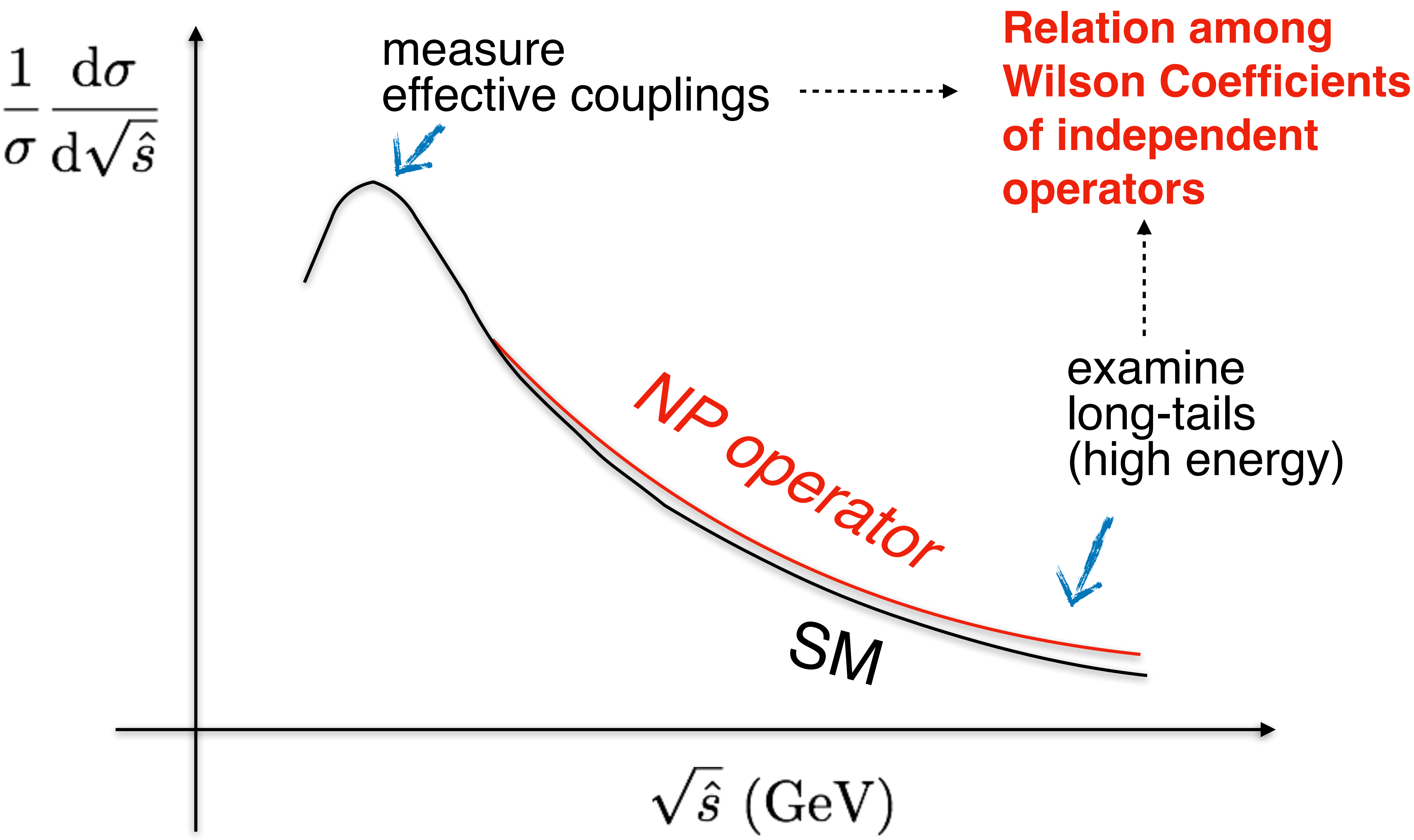
We were very lucky 90 years ago when the cosmic rays brought Muon lepton to us.

What about now?

Who ordered that?

LHC: A Precision Machine

in case of no new resonances found in next 10 years



measure
effective couplings

Relation among Wilson Coefficients of independent operators

examine
long-tails
(high energy)

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。