Signature of Pseudo Nambu-Goldstone Higgs Boson in its Decay

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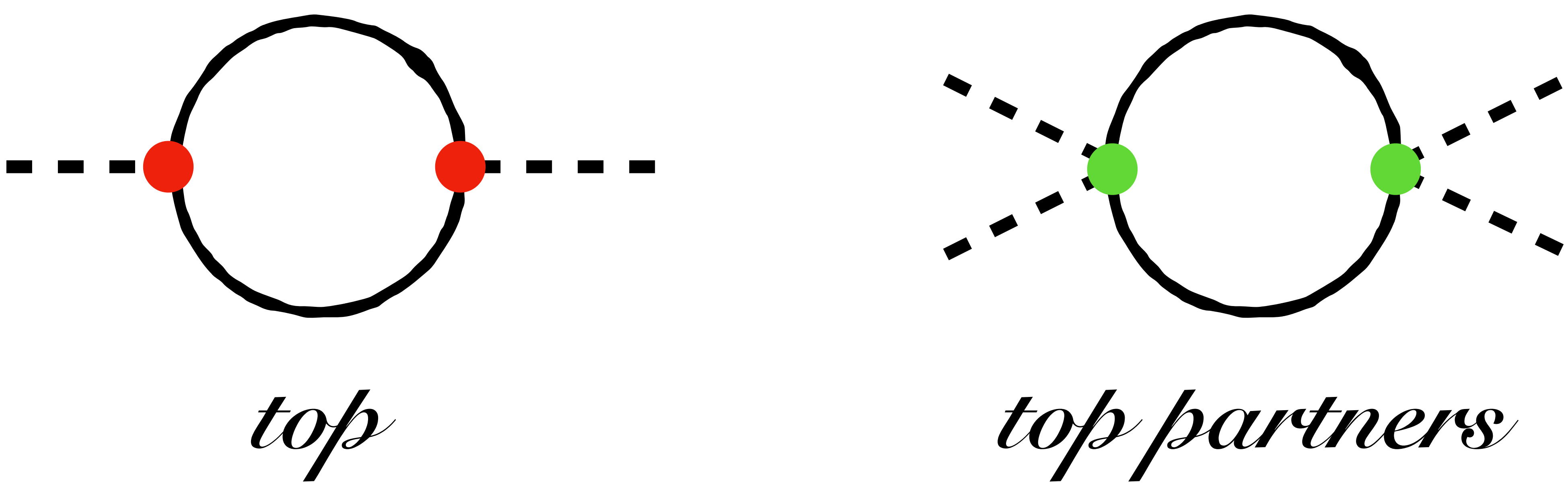
Higgs Boson as a PNGB

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

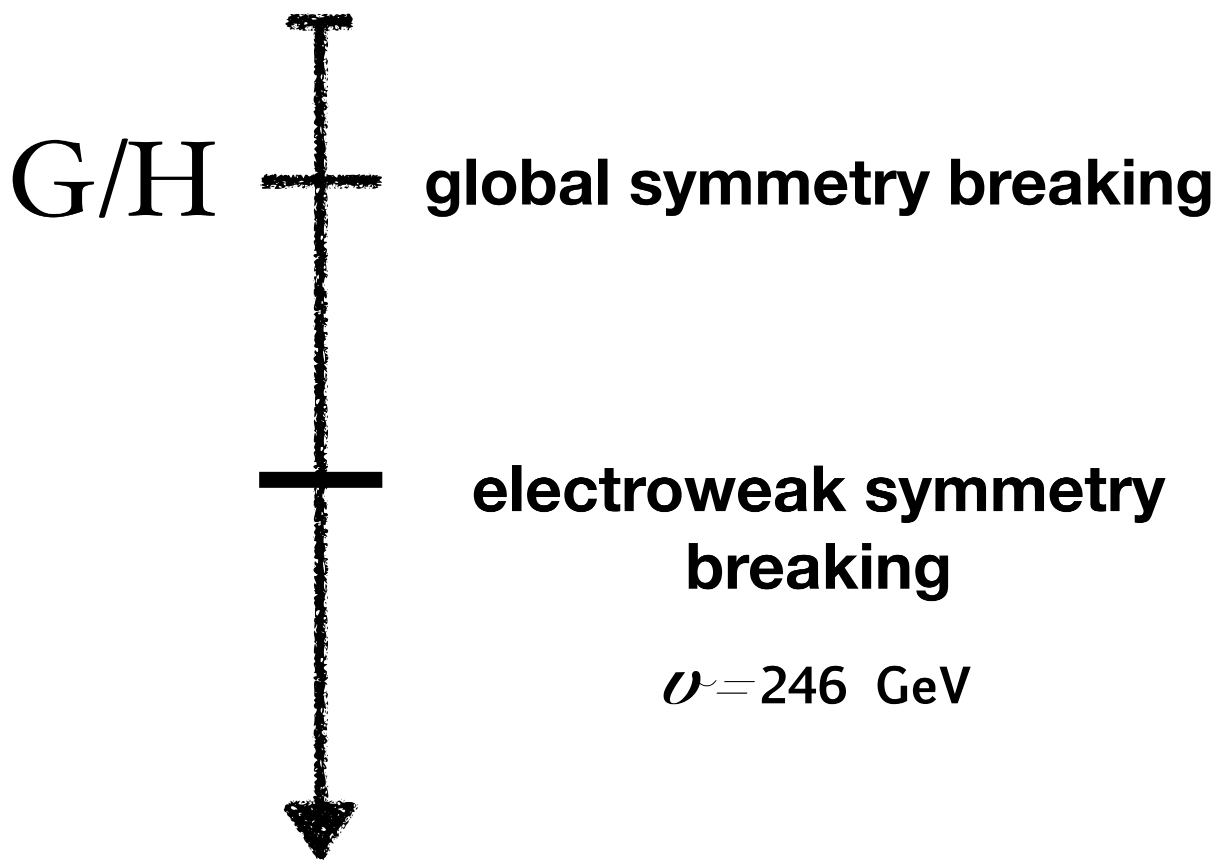


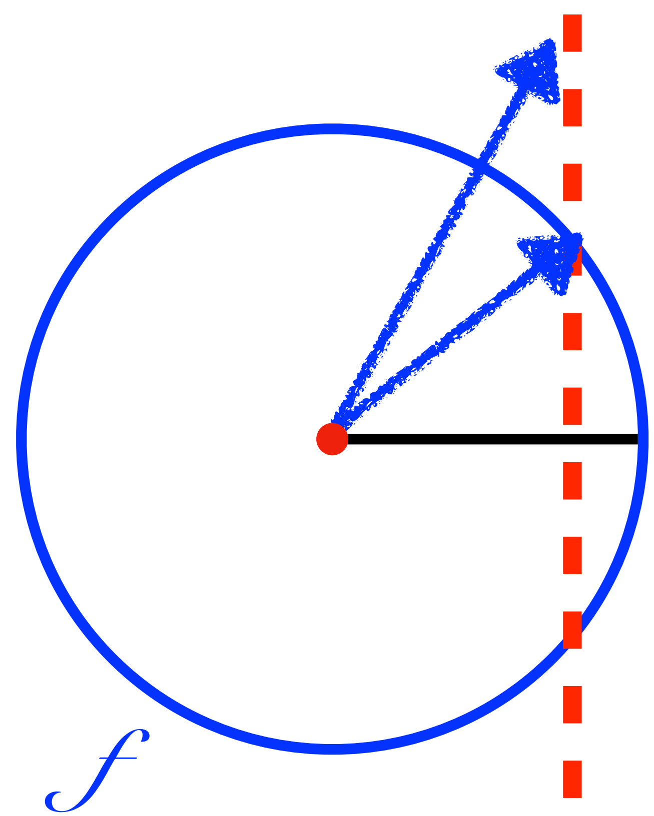
$$V(h) \sim \Lambda^2 \cdot (s_h^2 + c_h^2)$$

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

Higgs Nonlinearity

- PNGB Higgs boson can arise from a coset depicted below





also see Jiang-Hao Yu's talk

- Higgs nonlinearity is denoted by the misalignment angle

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: use CCWZ with specific $\mathrm{G/H}$
- SO(5)/SO(4), SU(3)/SU(2)…

Bellazzini, Csaki, Serra, 1401.2457

- Bottom-up: 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:

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

Considering the hVV couplings

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

$$
\begin{aligned}
&(\widetilde{D}_\mu H)^\dagger \widetilde{D}^\mu H \\
&= \frac{1}{2}\partial_\mu h \partial^\mu h \\
&\quad + (2f^2)\frac{g^2}{4}\sin^2\frac{\langle h\rangle + h}{\sqrt{2}f}\left(W_\mu^+ W^{-\mu} + \frac{Z^\mu Z_\mu}{2\cos^2\theta_W}\right)
\end{aligned}
$$

Higgs nonlinearity:

$$\xi \equiv \frac{v^2}{2f^2} = \sin^2\frac{\langle h\rangle}{\sqrt{2}f}$$

$$\mathcal{L}_{hVV} = \frac{M_V^2}{v}\sqrt{1-\xi}\; hV_\mu V^\mu$$

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

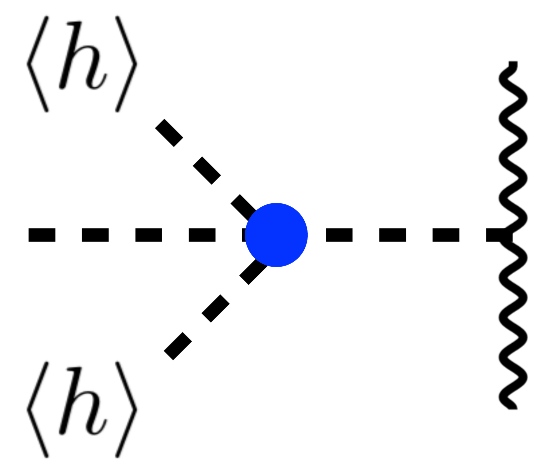
Heavy Particles

- e.g. considering a scalar singlet

also see Jing Shu's talk

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

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



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

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

Higgs Nonlinearity & Heavy Particles

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

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

- One cannot distinguish the Higgs nonlinearity from O_H with only the information of hVV couplings

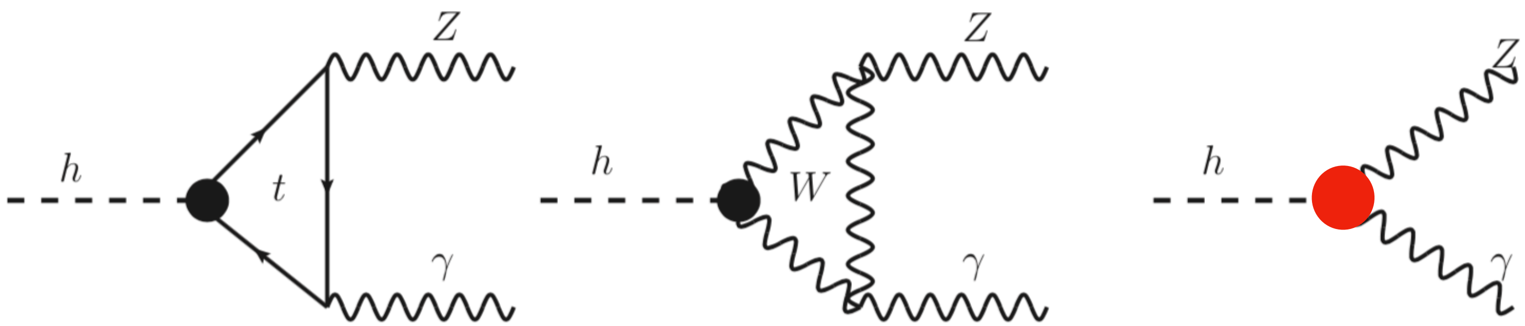
$$F_{\mathrm{PNGB}} = 1 - \xi \qquad\qquad F_{O_H} = \frac{1}{1+c_H}$$

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

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

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

Considering the $hZ\gamma$ effective coupling



- The following effective coupling at the order of $\mathcal{O}(p^4)$ is insensitive to Higgs nonlinearity

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

- Identical to dimension-six operators ($\xi \to 0$)

CCWZ for SO(5)/SO(4) at $\mathcal{O}$(p^4)

Azatov, Contino, Di Iura, Galloway, 1308.2676

$$\mathcal{L} = \frac{f^2}{4}\mathrm{Tr}[d_\mu d^\mu] + \sum_i c_i O_i$$

$$O_1 = \mathrm{Tr}[d_\mu d^\mu]^2$$

$$O_2 = \mathrm{Tr}[d_\mu d_\nu]\,\mathrm{Tr}\,[d^\mu d^\nu]$$

$$O_3^\pm = \mathrm{Tr}\big[(E^L_{\mu\nu})^2 \pm (E^R_{\mu\nu})^2\big]$$

$$O_4^\pm = \mathrm{Tr}\big[\big(E^L_{\mu\nu} \pm E^R_{\mu\nu}\big)\, i[d^\mu, d^\nu]\big]$$

$$O_5 = \sum_{a_L=1}^{3} \mathrm{Tr}(T^{a_L}[d_\mu, d_\nu])^2 - \sum_{a_R=1}^{3} \mathrm{Tr}\,(T^{a_R}[d_\mu, d_\nu])^2$$

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

- Consistent with out results on the $hZ\gamma$ effective coupling

- The signal strength of the $h \to Z\gamma$ channel:

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

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

$$F_{Z\gamma}^W = 0.0087$$

$$F_{Z\gamma}^t = -0.00097$$

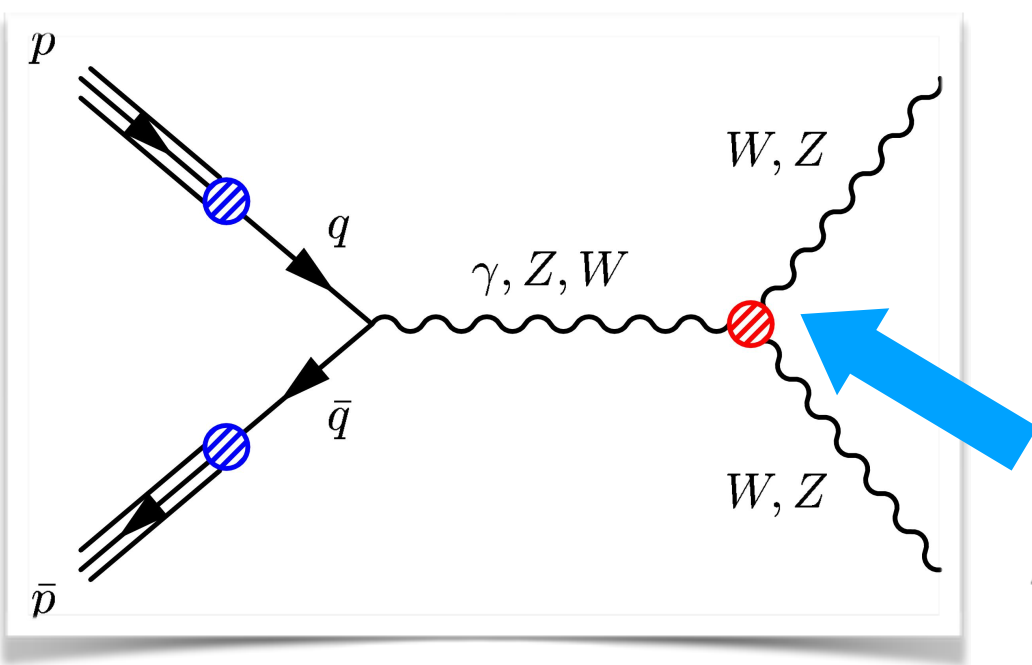
- <u>The Ratio:</u>

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

Triple Gauge Couplings

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

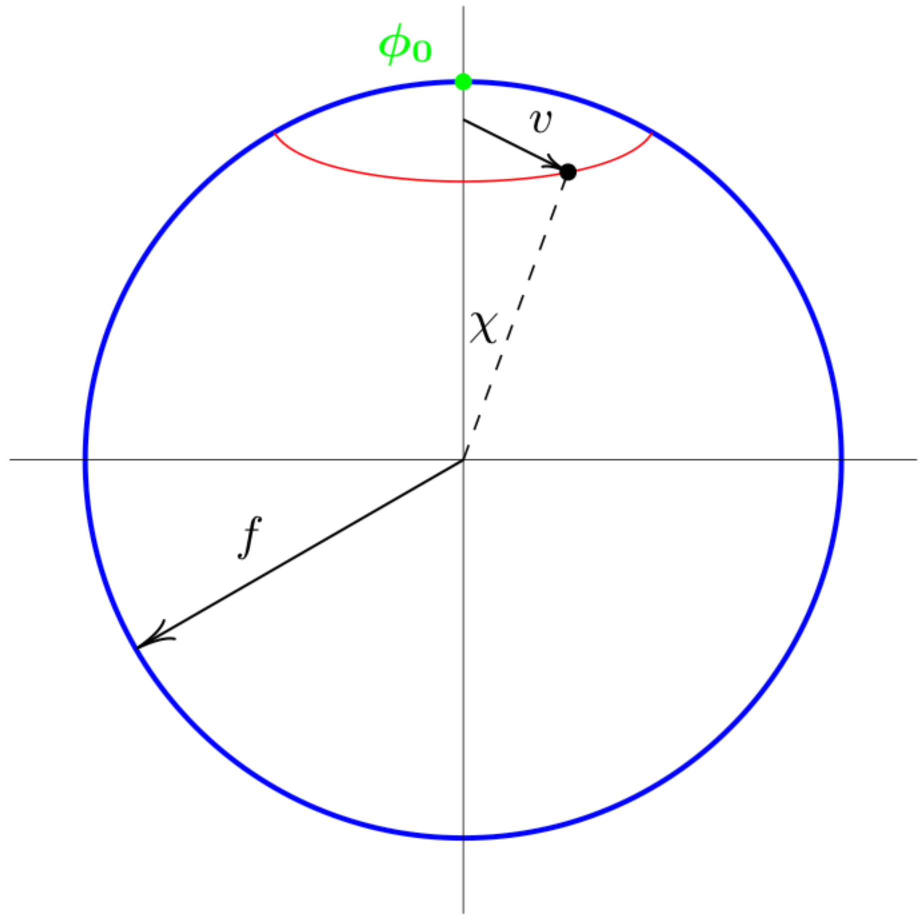
$$\mathcal{L}_{\rm TGC}/g_{WW\mathbb{V}} = ig_{1,\mathbb{V}}\Big(W^+_{\mu\nu}W^-_\mu\mathbb{V}_\nu - W^-_{\mu\nu}W^+_\mu\mathbb{V}_\nu\Big) + i\kappa_\mathbb{V}W^+_\mu W^-_\nu\mathbb{V}_{\mu\nu} + \frac{i\lambda_\mathbb{V}}{M_W^2}W^+_{\lambda\mu}W^-_{\mu\nu}\mathbb{V}_\nu$$



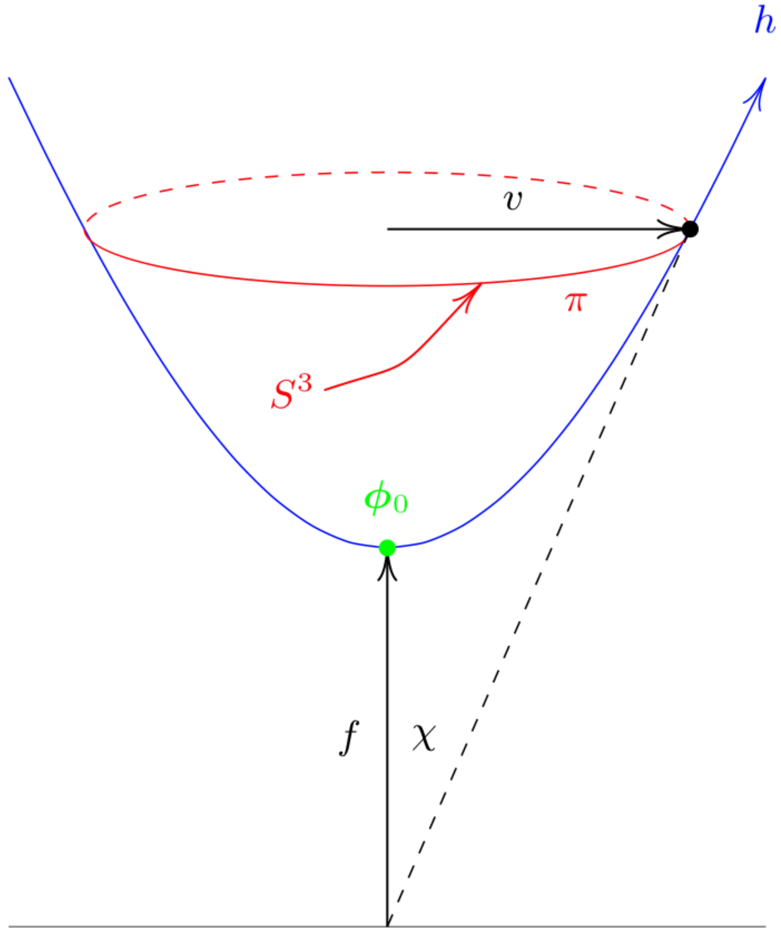
$$\Delta\kappa_{Z\gamma} = \Delta\kappa_\gamma - 2\Delta g_{1,Z}\cos\theta_W^2$$

Non-Compact Cosets

Alonso, Jenkins, Manohar, 1602.00706



$O(5) \to O(4)$



$O(4,1) \to O(4)$

- Only the substitution $\xi \to -\xi$ is needed

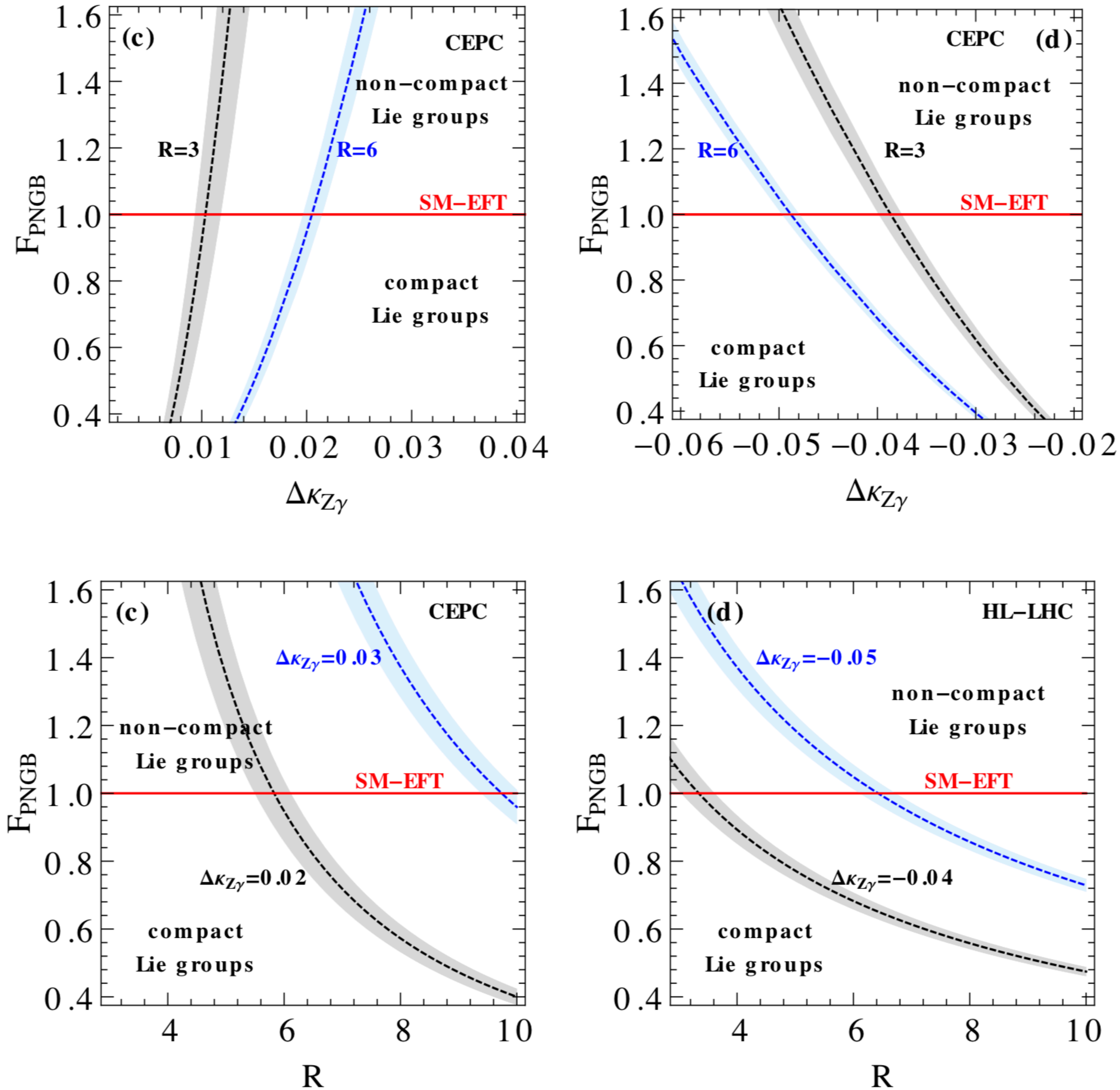
Uncertainties

- HL-LHC: 14 TeV with integrated luminosity of 3 ab^{-1}
- CEPC: 240 GeV with integrated luminosity of 5 ab^{-1}

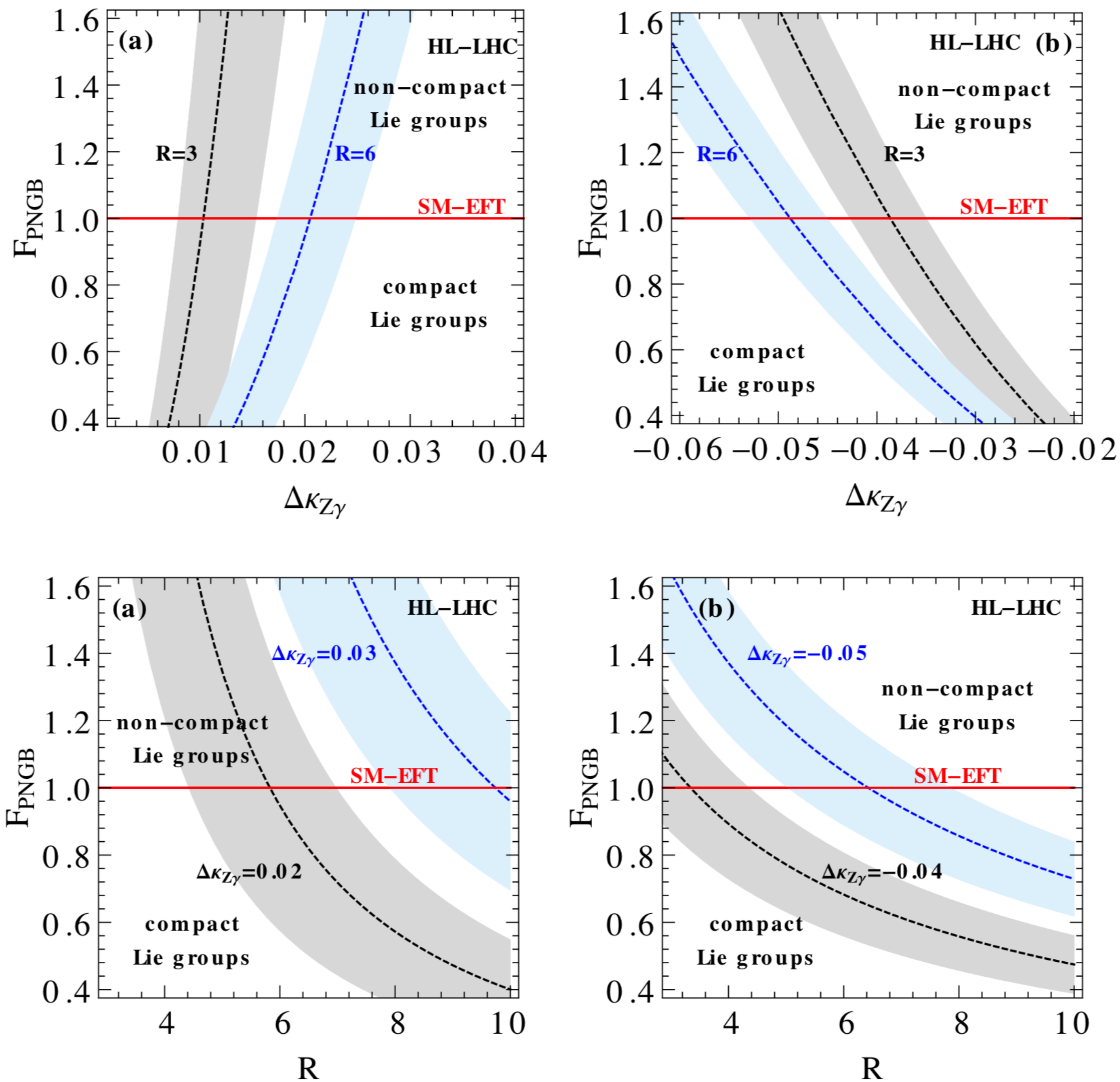
	$\delta\mu_{h\to Z\gamma}$	$\delta\mu_{h\to VV^*}$	$\delta\kappa_\gamma$	$\delta g_{1,Z}$	$\delta\kappa_{Z\gamma}$
HL-LHC	0.3	0.1	0.0029	0.0011	0.0033
CEPC	0.25	0.01	0.00022	0.00016	0.00034

ATL-PHYS-PUB-2014-006, 1307.7135, 1704.02333, 1507.02238…

- Higgs nonlinearity at CEPC:



- Higgs nonlinearity at high luminosity LHC:



Conclusions

- The Higgs nonlinearity can be probed in the ratio

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

- The faking effects from the O_H operator is cancelled

- Our result is valid in *<u>any</u>* symmetry breaking patterns, as long as custodial symmetry is assumed

- Our result does not depend on the Higgs boson production and the Higgs boson total width

Thank you!

Backup Slides

Goldstone Covariants

$$\mathcal{D}_\mu \vec{h} = \frac{1}{f}\partial_\mu \vec{h} + \frac{1}{f\vec{h}\cdot\vec{h}}\left(1 - \frac{f\sqrt{2}}{\sqrt{\vec{h}\cdot\vec{h}}}\sin\frac{\sqrt{\vec{h}\cdot\vec{h}}}{f}\right)(\vec{h}\cdot\partial_\mu\vec{h}\ \vec{h} - \vec{h}\cdot\vec{h}\ \partial_\mu\vec{h})\ ,$$

$$\mathcal{E}_\mu^A = \frac{2i}{\vec{h}\cdot\vec{h}}\left(-1 + \cos\frac{\sqrt{\vec{h}\cdot\vec{h}}}{\sqrt{2}f}\right)\partial_\mu\vec{h}^T T^A \vec{h}\ ,$$

Low, 1412.2146

Higgs Nonlinearity Factor

- when $F^t_{Z\gamma} + F^W_{Z\gamma}\sqrt{F_{\rm PNGB}} + \Delta\kappa_{Z\gamma}\tan\theta_W > 0$:

$$F_{\rm PNGB} = \left(\frac{F^t_{Z\gamma} + \Delta\kappa_{Z\gamma}\tan\theta_W}{\sqrt{R}|F^t_{Z\gamma} + F^W_{Z\gamma}| - F^W_{Z\gamma}}\right)^2 \simeq \left(\frac{\Delta\kappa_{Z\gamma}\tan\theta_W}{(\sqrt{R}-1)F^W_{Z\gamma}}\right)^2$$

- otherwise,

$$F_{\rm PNGB} = \left(\frac{F^t_{Z\gamma} + \Delta\kappa_{Z\gamma}\tan\theta_W}{\sqrt{R}|F^t_{Z\gamma} + F^W_{Z\gamma}| + F^W_{Z\gamma}}\right)^2 \simeq \left(\frac{\Delta\kappa_{Z\gamma}\tan\theta_W}{(\sqrt{R}+1)F^W_{Z\gamma}}\right)^2$$

Error Propagation

- when $F^t_{Z\gamma} + F^W_{Z\gamma}\sqrt{F_{\rm PNGB}} + \Delta\kappa_{Z\gamma}\tan\theta_W > 0$:

$$\frac{\delta\sqrt{F_{\rm PNGB}}}{\sqrt{F^0_{\rm PNGB}}} = \sqrt{\left(\frac{\delta\kappa_{Z\gamma}}{\Delta\kappa^0_{Z\gamma}}\right)^2 + \left(\frac{\delta\sqrt{R}}{\sqrt{R_0}-1}\right)^2}$$

- otherwise,

$$\frac{\delta\sqrt{F_{\rm PNGB}}}{\sqrt{F^0_{\rm PNGB}}} = \sqrt{\left(\frac{\delta\kappa_{Z\gamma}}{\Delta\kappa^0_{Z\gamma}}\right)^2 + \left(\frac{\delta\sqrt{R}}{\sqrt{R_0}+1}\right)^2}$$

$$\delta\kappa_{Z\gamma} = \sqrt{\delta\kappa^2_\gamma + 4\cos\theta^4_W\,\delta g^2_{1,Z}}$$

$$\delta R = \sqrt{\left(\delta\mu_{h\to Z\gamma}\right)^2 + R^2_0\left(\delta\mu_{h\to VV^*}\right)^2}$$

Other Materials

hVV	PNGB	SM-like	$hZ\gamma$	PNGB	SM-like
ξ-effect	$\surd$	$\times$	ξ-effect	$\times$	$\times$
O_H	$\surd$	$\surd$	O_H	$\surd$	$\surd$