Higgs Boson:
the Unique Window to New Physics

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《 The Higgs Era 》

$$
\begin{aligned}
\mathcal{L} = \\
& -\frac{1}{4g'^4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4g^2} W^a_{\mu\nu} W^{\mu\nu a} - \frac{1}{4g_s^2} G^a_{\mu\nu} G^{\mu\nu a} \\
& + \bar{Q}_i i \not{D} Q_i + \bar{u}_i i \not{D} u_i + \bar{d}_i i \not{D} d_i + \bar{L}_i i \not{D} L_i + \bar{\ell}_i i \not{D} \ell_i \\
& + \left(Y_u^{ij} \bar{Q}_i u_j \tilde{H} + Y_d^{ij} \bar{Q}_i d_j H + Y_l^{ij} \bar{L}_i \ell_j H + c.c. \right) \\
& - \lambda (H^\dagger H)^2 + \lambda v^2 H^\dagger H - (D^\mu H)^\dagger D_\mu H
\end{aligned}
$$

Higgs Boson h(125GeV) opens a Key Window for New Physics!

⟶ New Clues & New Opportunities!

- ★ **h is the Unique Spin-0 Fundamental Scalar Particle in SM.**
- ★ **h joins 2 New Forces: Self-Interaction & Yukawa Forces.**
- ★ **h determines Vacuum SSB & Stability, generates All Masses.**
- ★ **Unique Higgs Portal: $\mu^2 H^+H$ ⟶ (??) H^+H .**

Particle Physics in the《Higgs Era》

Higgs Boson h(125GeV) opens a Key Window to New Physics!

⟶ **New Clues + New Opportunities !**

★ **h is the Unique Spin-0 Fundamental Scalar in the SM.**

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★ **h determines Vacuum SSB & Stability, and generates All Masses.**

SM cannot ensure at Loop

LHC gives partial probe

Representation of Lorentz Group

- **Isomorphic Lorentz Group: SO(3,1) ≈ SU(2) x SU(2)**

- **Irreducible Representation (j) of SU(2): j=0, ½, 1, 3/2, 2…**

  → **Representations of Lorentz Group: (j , j′) .**
  (½ , 0), (0, ½) → Quarks/Leptons; (½ , ½) → Gauge Bosons.

- **But, the Simplest Lorentz Group Representation is Scalar Representation:**

$$(0, 0)$$

★ **Special Relativity predicted Scalar Particle (Higgs Boson) more than 100 years ago !!**

Representation of Lorentz Group

- The Simplest Lorentz Group Representation is Scalar Representation: (0, 0) → Scalar (Higgs Boson!)
- Graviton of GR fits in Spin-2 Representation (1, 1).
- Up to Spin-2, j = 0, ½, 1, 3/2, 2, we expect a possible new state with Spin-3/2 to fit in Repressentation (1, ½). → a natural indication of Gravitino of Spin-3/2 from Supergravity ! BUT, no prediction for *Gravitino Mass*! (<<1GeV or > 100TeV.)

★ 2 Strong Hints:

— Higgs Boson should be as *fundamental* as W, Z and Photon!
→ Higgs boson is very unlikely Composite at this level…

— Spin-3/2 Entry has a natural candidate Gravitino!
→ This is the strongest model-independent support of SUSY ,
but, Gravitino mass (S~~U~~SY Scale) can be very high.
This does not ensure Weak Scale SUSY unfortunately……

- **Spin-0 Particle is truly Special !**
- **A Unique Window to *New Physics* ?**

Spin-0 Higgs Boson Itself
is
New Physics !!!

Spin-0 Higgs Boson Itself is New Physics:

- EWSB – W,Z Masses
- and Fermion Masses – Quarks/Leptons/Neutrinos(?)

- Higgs Boson Mass: Naturalness
- Higgs Self-interactions

- Vacuum Structure (Stability…)
- Vacuum Energy (Dark Energy…)

- Higgs boson as Inflaton (H^+HR, …)
- Higgs Portal to Dark Matter, Gravity…

- CP Violation: Baryogenesis, Leptogenesis…

Higgs Boson (125GeV)

➢ **Higgs is not only a New Particle, but also New Forces !!!**

1. Higgs Gauge ineractions,
2. Higgs Yukawa interactions,
3. Higgs Self-interactions.

Even *within SM Forces*, strongly motivated to quantitatively probe Type-2 + Type-3 New Forces: ★ **Higgs Yukawa Forces**
★ **Higgs Self Interaction Forces**

★ **Note: Due to EW Gauge Invariance, it can also induce modified Pure Gauge Couplings via higher-dim Effective Operators. E.g., nTGC cannot arise from pure gauge operator alone!**

⇨ **Most likely Places for New Physics !**

Higgs Potal: — Window to New Physics

⇨ **SM has a Unique Higgs Potal:**

$(H^{+}H)(XX)$, $(H^{+}H)X$, $(H^{+}H)R$, ……

➢ **Here, X = Φ (new doublet), S (new singlet), which can give DM candidate as well.**

⇨ **More Higgs Bosons? → Yes .**

PHYSICAL REVIEW D 88, 096013 (2013)

Gravitational interaction of Higgs boson and weak boson scattering

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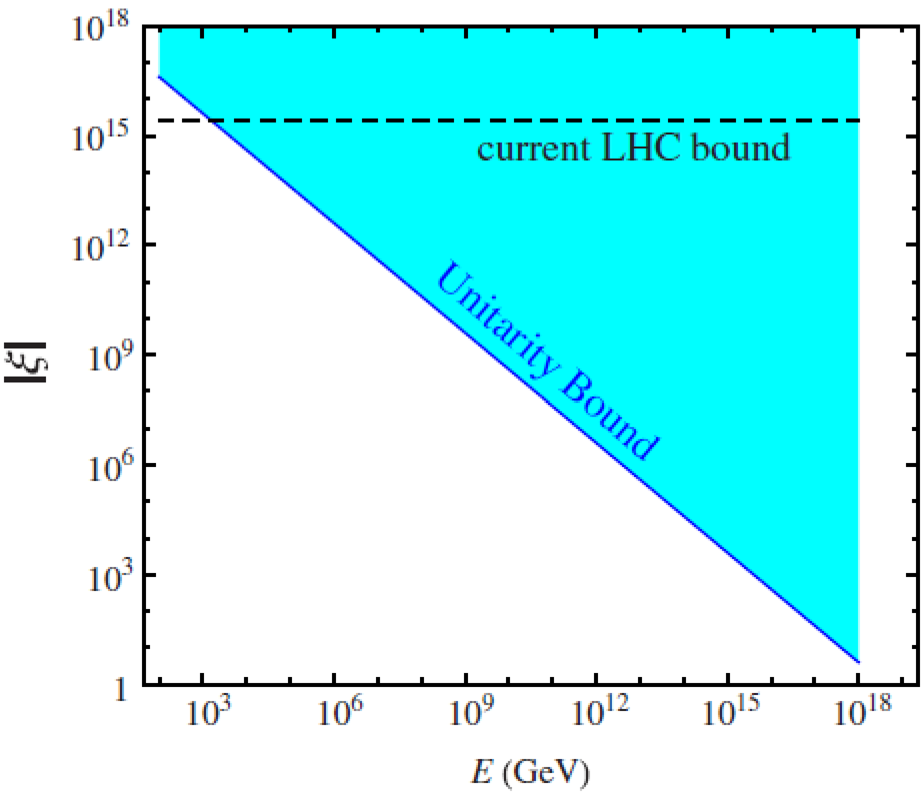
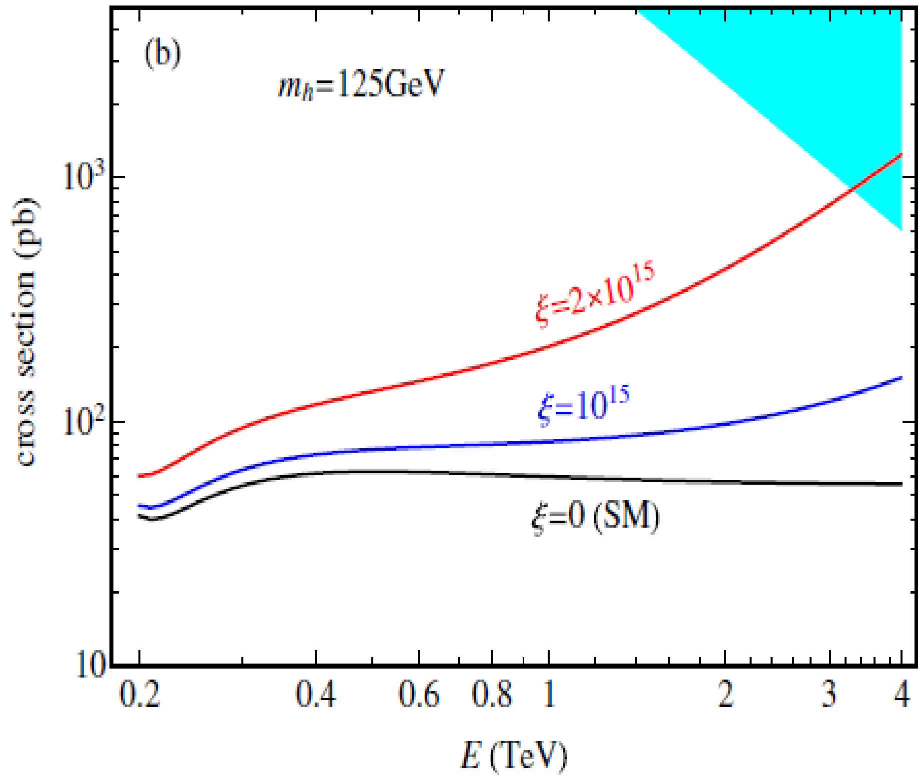
★ Higgs-Gravity Coupling: ξ RHH

General Unitarity Bound



$W^+W^+ \to W^+W^+$ for LHC

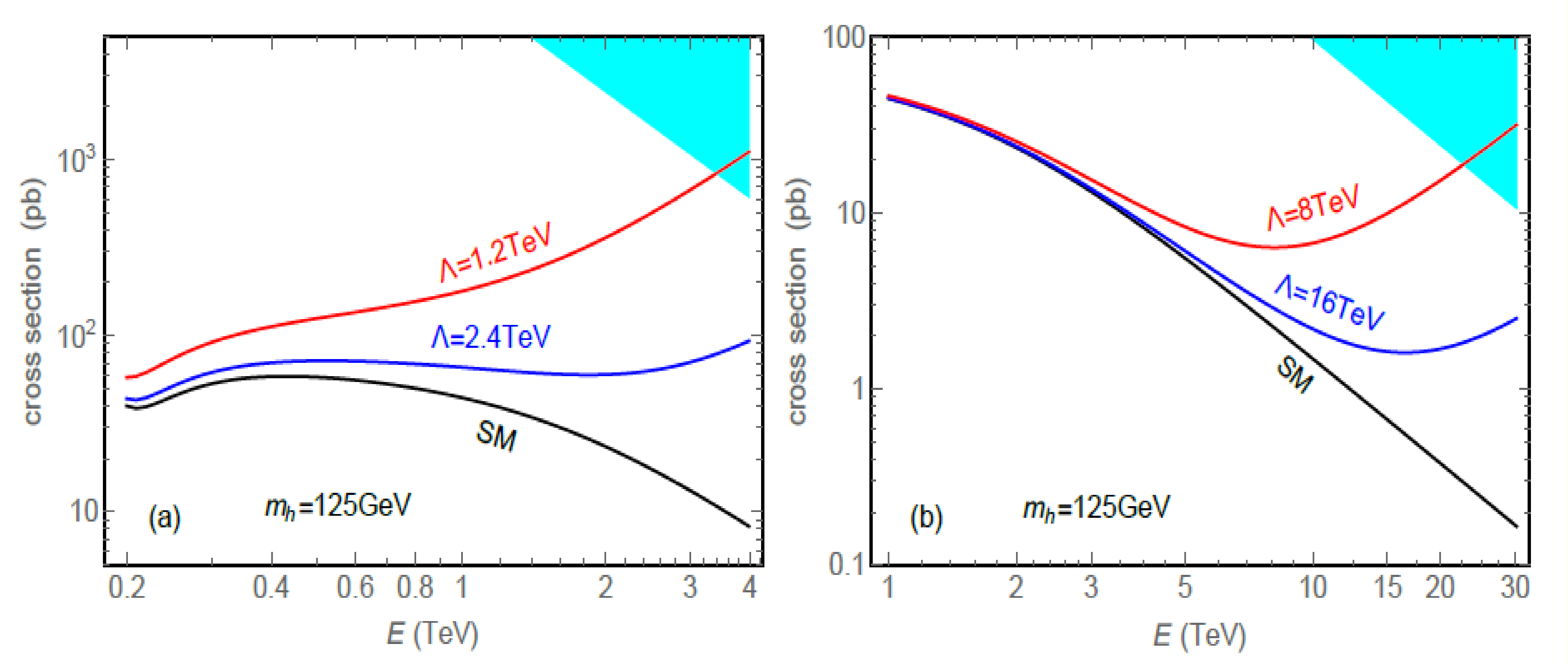


Collider Probe of Higgs-Gravity Coupling

$W^+W^+ \Longrightarrow W^+W^+$

★ **Actual Cutoff:** $\Lambda = M_P/\xi$

at LHC (14TeV): **at pp(100TeV):**

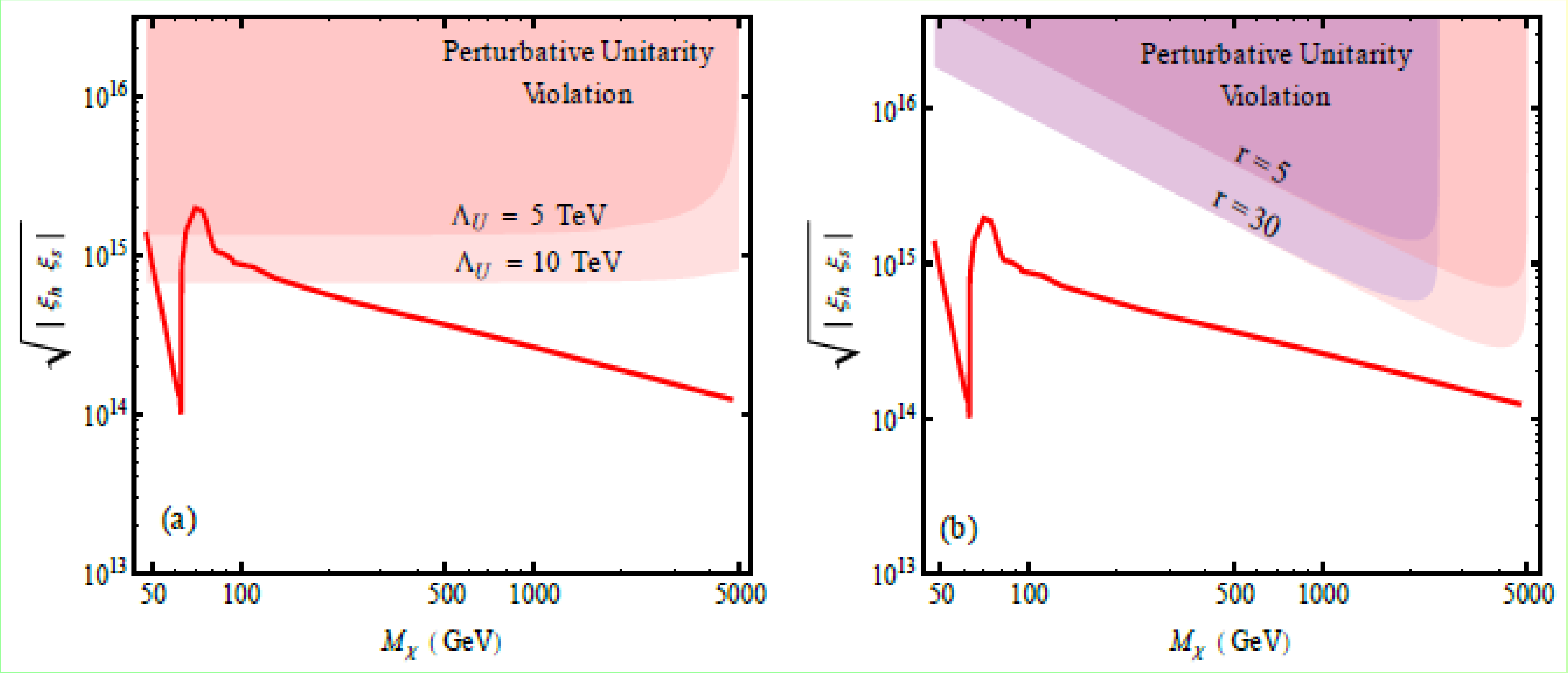


Ren, Xianyu, HJH, JCAP 06 (2014) 032

Gravitational Dark Matter (GDM) — Higgs Portal and DM Portal to Gravity

Ren & HJH, JCAP 03 (2016) 052

- **Higgs and DM Potals:** $\xi_h (H^{+}H) R + \xi_s (XX) R$



Gravitational Dark Matter (GDM) — Higgs Portal and DM Portal to Gravity

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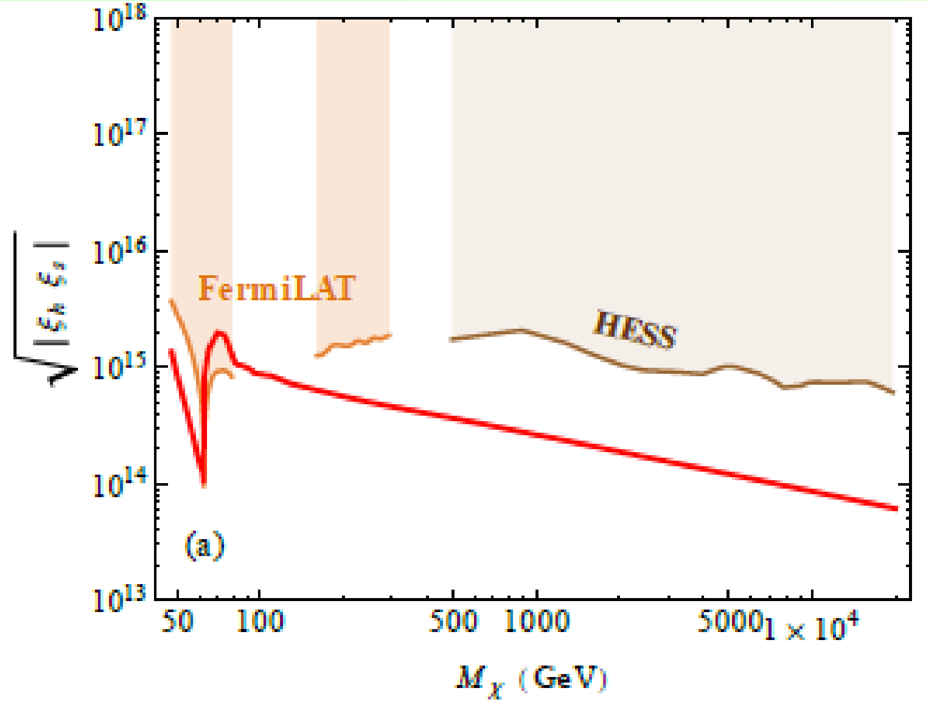
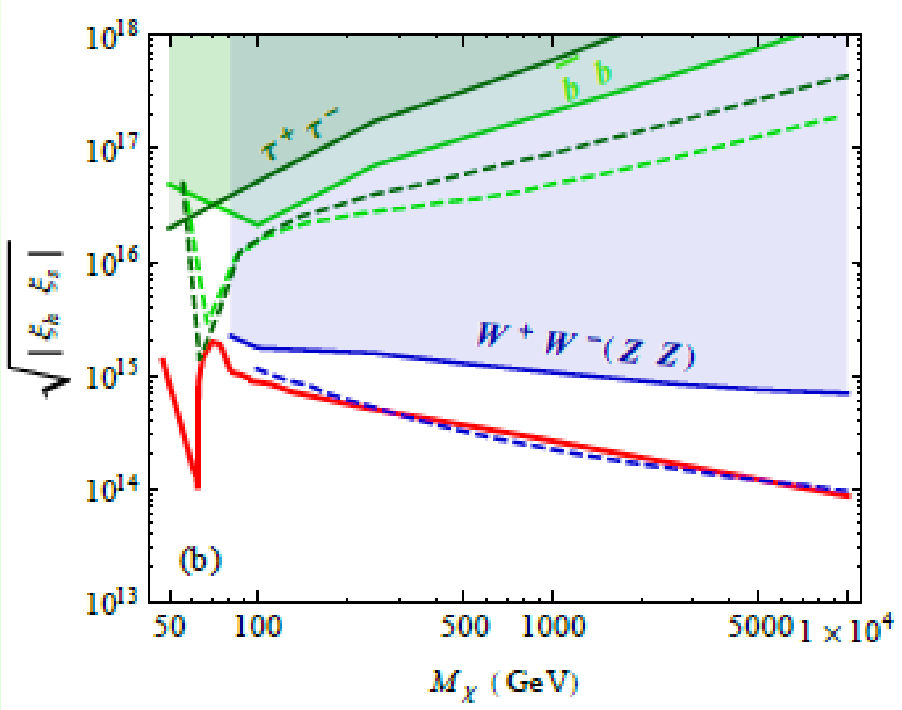
- **Higgs and DM Potals:** $\xi_h (H^+H) R + \xi_s (XX) R$

Gamma ray line search limits:

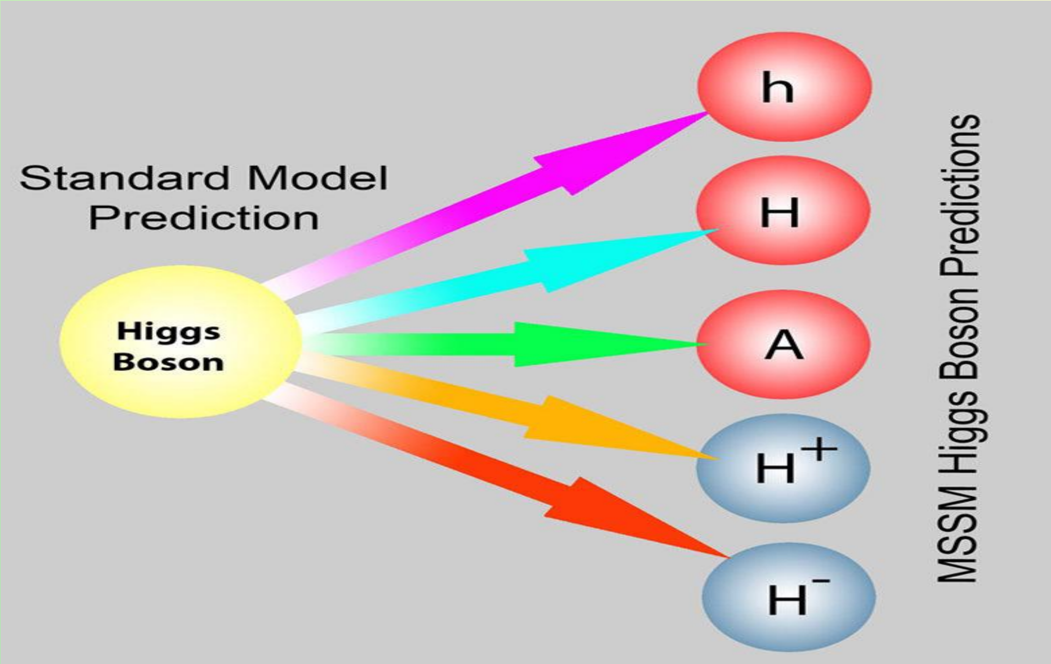


Gamma ray spectrum
FermiLAT & CAT



New Higgs Bosons *at Colliders*

★ **Higgs Boson h(125) is the Unique Spin-0 Scalar in SM.**
It opens a New Window for probing all New Higgs Bosons !



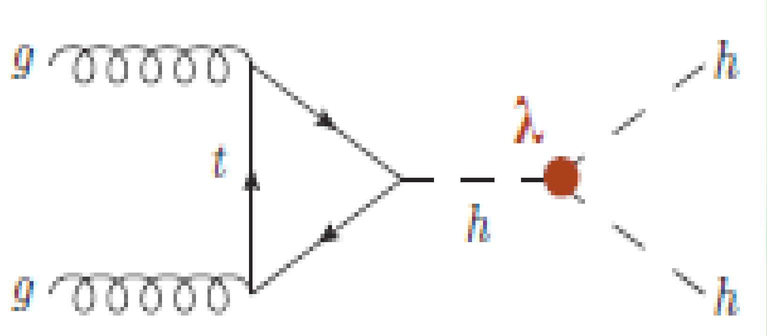
★ **Most SM extensions require More Higgs Bosons. 2HDM is a Minimal Extension & predicts New Higgs (H^0, A^0, $H^{+/-}$) for LHC.**

E.g., Ren, Xiao, Zhou, Fang, HJH, Yao, JHEP 06 (2018) 090.
Lu, Du, Fang, HJH, Zhang, Phys. Lett. B 755 (2016) 509.
Wang, Du, HJH, Phys. Lett. B723 (2013) 314.

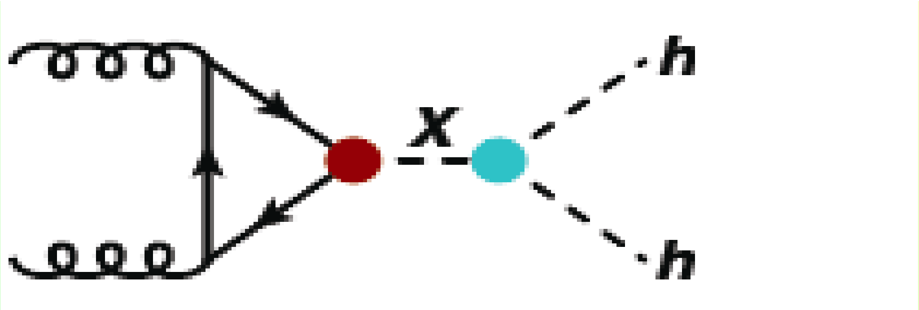
Probing New Physics in diHiggs Channel

★ **Study LHC Higgs Pair Production, probe new physics in Higgs self-interaction and discover New Higgs Boson H via resonant diHiggs Production *at the same time* !**

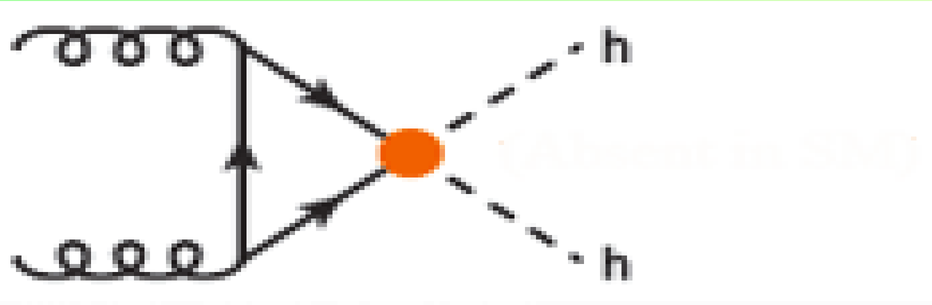
Standard Model



New Resonance

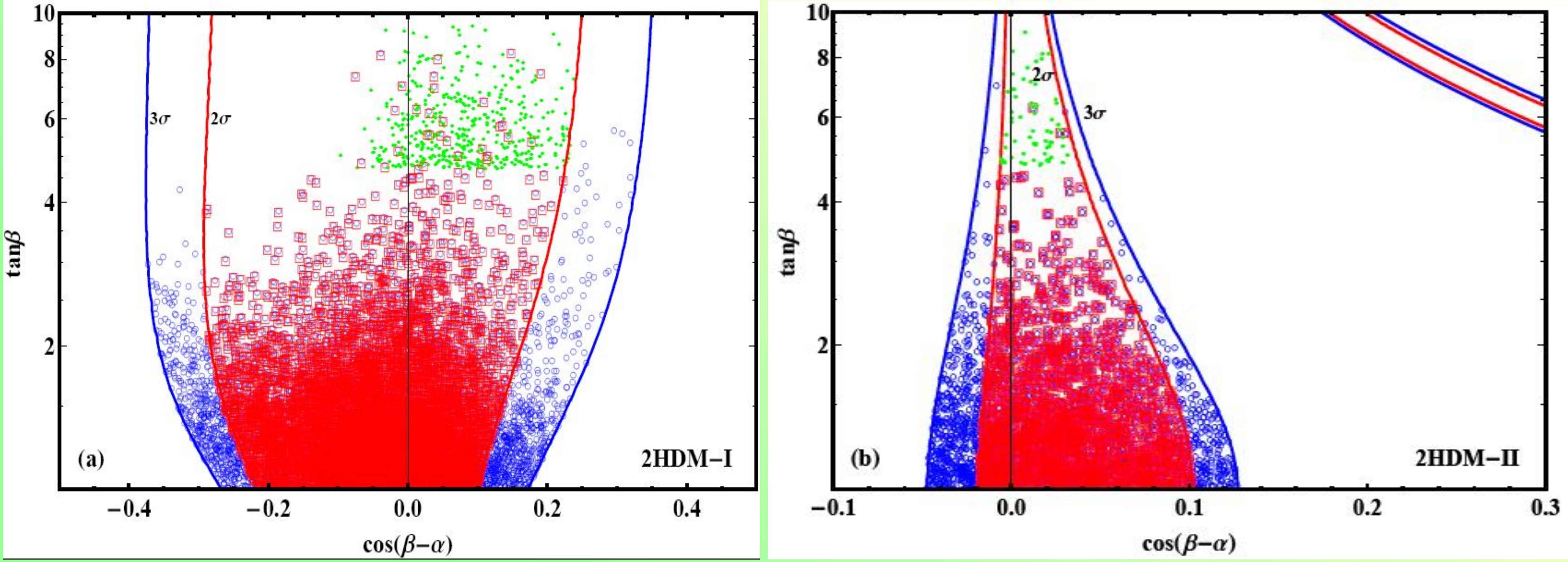


New Interaction



Higgs Physics at LHC

★ Higgs Global Fit of LHC Run-1+2 Data on 2HDM:



Ren, Xiao, Zhou, Fang, HJH, Yao, JHEP 06 (2018) 090

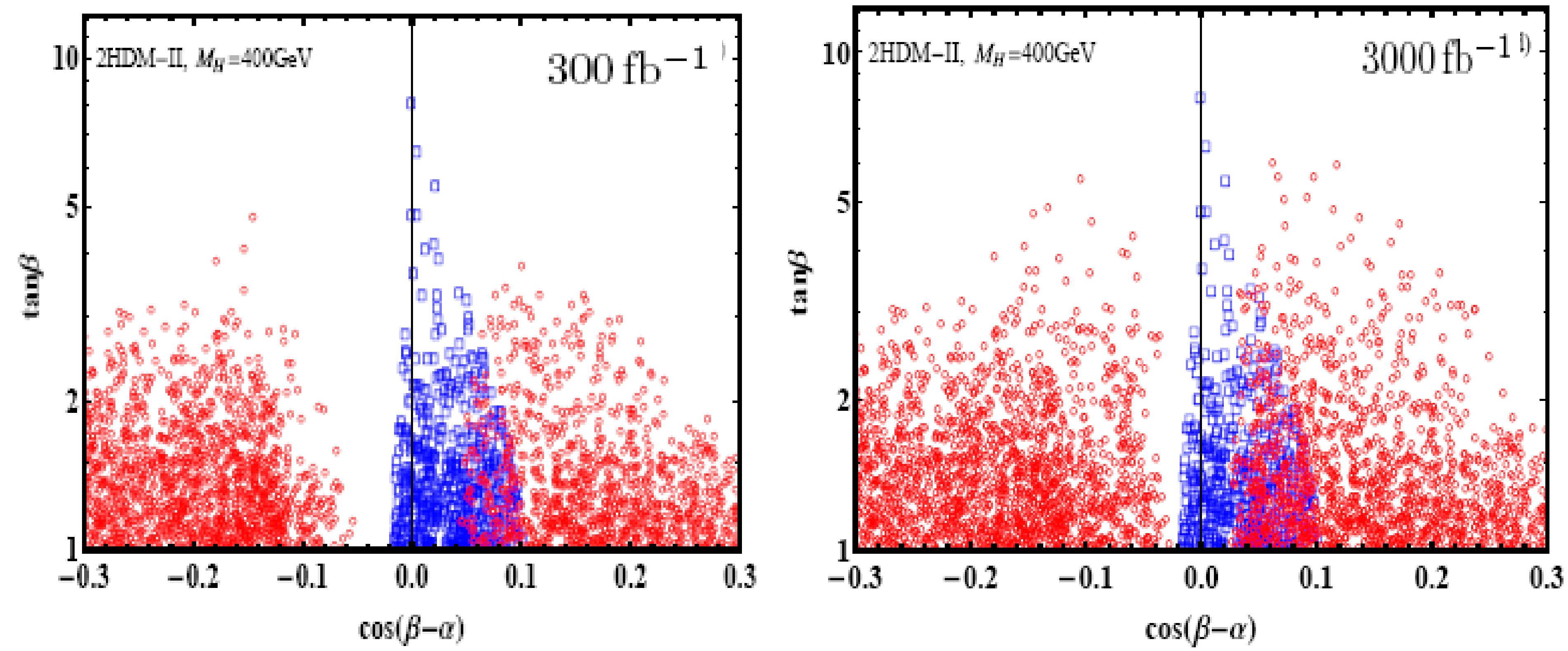
★ 2HDM is a Minimal Extension of the SM.

★ Conclusions: Current LHC Data favor small $\tan\beta < 9$ for 2HDM-I, and $\tan\beta < 6$ for 2HDM-II. The bound is tighter for 2HDM-II: $-0.05 < \cos(\beta - \alpha) < 0.13$. -- Still rooms for New Physics!

LHC: Higgs Self-Interaction & New Higgs Boson

★ **Study LHC Resonant Higgs Pair production, Probe Hhh self-interaction, and Discover New Higgs Boson H .**

$$gg \to H^0 \to h^0 h^0 \to WW^* WW^*$$



Ren, Xiao, Zhou, Fang, HJH, Yao,
JHEP 06 (2018) 090 [arXiv:1706.05980]

Effective Higgs Couplings: Gauge & Yukawa

$$\mathcal{L} = \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H$$
$$+ \kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H$$
$$- \left(\kappa_t \sum_{f=u,c,t} \frac{m_f}{v} f\bar{f} + \kappa_b \sum_{f=d,s,b} \frac{m_f}{v} f\bar{f} + \kappa_\tau \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\bar{f} \right) H$$

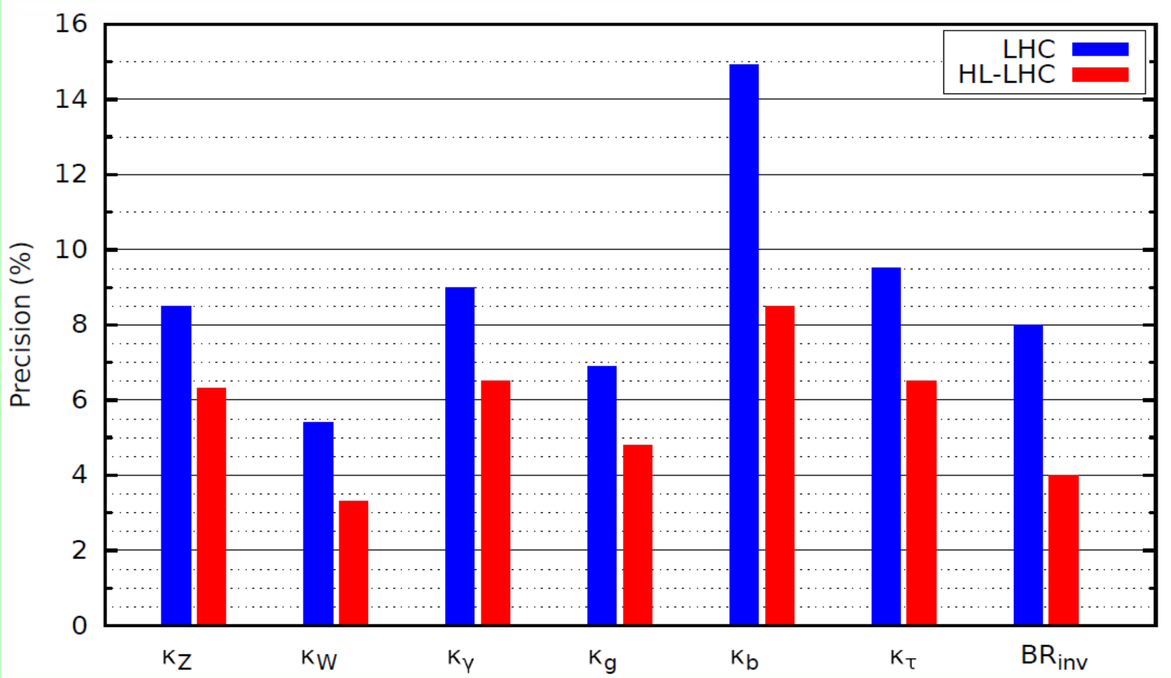
Note:

Effective Higgs-Gauge Couplings & Pure Gauge Couplings may be *connected* due to EW Gauge-Invariance.

→ Especially, neutral Triple Gauge Couplings (nTGC), such as ZZγ, Zγγ arise from Dim-8 Higgs-related Operators Only !

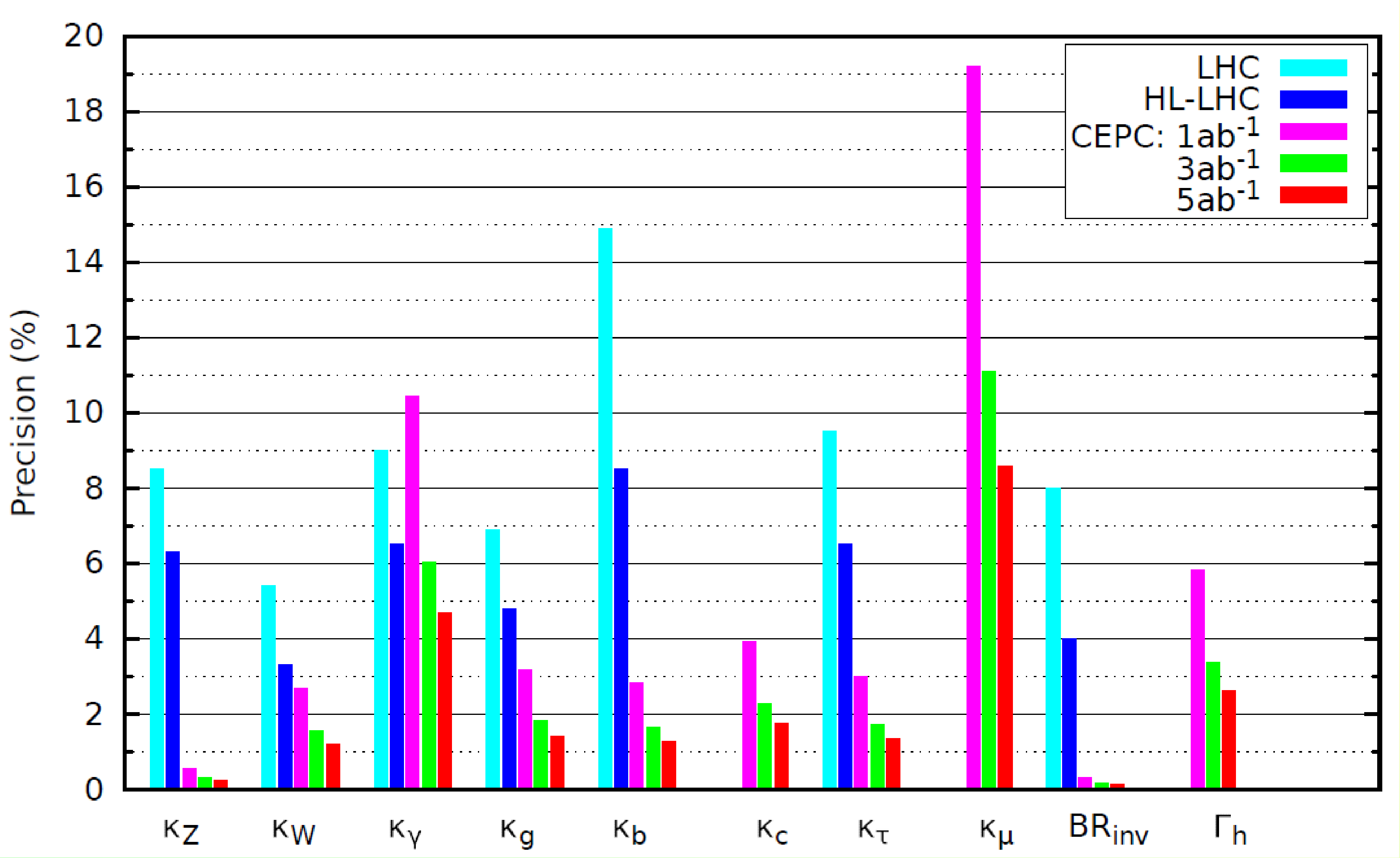
What beyond the LHC ?

- **HL-LHC (up to 3/ab): more precise measurements, but not enough!**
- **HE-LHC (28TeV)? bigger discovery potential, but technology+cost challenges**
- **Circular Higgs Factory CEPC (up to 250GeV):**
  - **→ Will surpass the precision of HL-LHC**
  - **→ Will be complementary to HE-LHC-28TeV (if built at all)…**
  - **→ 2nd-Phase SPPC will surpass LHC+ and fully explore TeV Scales**



LHC(300/fb) + HL-LHC(3/ab)
M. E. Peskin, Snowmass Study, arxiv:1312.4974

Testing Higgs Coupling: CEPC vs LHC



Ge, HJH, Xiao, JHEP 10(2016)007 [arXiv:1603.03385]

Indirect Probe of Higgs related New Physics by Model-Independent Effective Operators @ Dimension-6

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{M^2}\mathcal{O}_{6,i}$$

Higgs	EW Gauge Bosons	Fermions
$\mathcal{O}_H = \frac{1}{2}(\partial_\mu \lvert H\rvert^2)^2$	$\mathcal{O}_{WW} = g^2 \lvert H\rvert^2 W^a_{\mu\nu} W^{a\mu\nu}$	$\mathcal{O}_L^{(3)} = (iH^\dagger \sigma^a \overset{\leftrightarrow}{D}_\mu H)(\overline{\Psi}_L \gamma^\mu \sigma^a \Psi_L)$
$\mathcal{O}_T = \frac{1}{2}(H^\dagger \overset{\leftrightarrow}{D}_\mu H)^2$	$\mathcal{O}_{BB} = g^2 \lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{LL}^{(3)} = (\overline{\Psi}_L \gamma_\mu \sigma^a \Psi_L)(\overline{\Psi}_L \gamma^\mu \sigma^a \Psi_L)$
	$\mathcal{O}_{WB} = gg' H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_L = (iH^\dagger \overset{\leftrightarrow}{D}_\mu H)(\overline{\Psi}_L \gamma^\mu \Psi_L)$
Gluon	$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	$\mathcal{O}_R = (iH^\dagger \overset{\leftrightarrow}{D}_\mu H)(\overline{\psi}_R \gamma^\mu \psi_R)$
$\mathcal{O}_g = g_s^2 \lvert H\rvert^2 G^a_{\mu\nu} G^{a\mu\nu}$	$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$	$\mathcal{O}_y^u = \lvert H\rvert^2 \overline{\Psi}_L^q \tilde{H} u_R$
	$\mathcal{O}_W = \frac{ig}{2}(H^\dagger \sigma^a \overset{\leftrightarrow}{D}_\mu H) D_\nu W^{a\mu\nu}$	$\mathcal{O}_y^d = \lvert H\rvert^2 \overline{\Psi}_L^q H d_R$
	$\mathcal{O}_B = \frac{ig'}{2}(H^\dagger \overset{\leftrightarrow}{D}_\mu H) D_\nu B^{\mu\nu}$	$\mathcal{O}_y^\ell = \lvert H\rvert^2 \overline{\Psi}_L^\ell H \ell_R$

What happens to Pure Gauge Couplings?

- At dim-6, the unique Pure Gauge operator:

$$\mathcal{O}_{3W} = g\frac{\epsilon_{abc}}{3!} W^{a\,\nu}_{\mu} W^{b}_{\nu\rho} W^{c\,\rho\mu}$$

but only gives charged TGCs of WWZ, WWA.

- Neutral Triple Gauge Couplings (nTGC)?
How to generate ZZA, ZAA couplings?

→ They do not exist in SM and at dim-6 !

⇒ They could only arise from dim-8 operators!

Higgs related New Physics: ZZγ Coupling from Effective Operators @ Dim-8 !

$$\Delta\mathcal{L}(\text{dim-8}) = \sum_{j=1}^{4} \frac{c_j}{\tilde{\Lambda}^4}\mathcal{O}_j = \sum_{j=1}^{4} \frac{\text{sign}(c_j)}{\Lambda_j^4}\mathcal{O}_j$$

$$\begin{aligned}
\mathcal{O}_{\widetilde{B}W} &= \mathrm{i}\, H^\dagger \widetilde{B}_{\mu\nu} W^{\mu\rho}\{D_\rho, D^\nu\}H + \text{h.c.},\\
\mathcal{O}_{B\widetilde{W}} &= \mathrm{i}\, H^\dagger B_{\mu\nu} \widetilde{W}^{\mu\rho}\{D_\rho, D^\nu\}H + \text{h.c.},\\
\mathcal{O}_{\widetilde{W}W} &= \mathrm{i}\, H^\dagger \widetilde{W}_{\mu\nu} W^{\mu\rho}\{D_\rho, D^\nu\}H + \text{h.c.},\\
\mathcal{O}_{\widetilde{B}B} &= \mathrm{i}\, H^\dagger \widetilde{B}_{\mu\nu} B^{\mu\rho}\{D_\rho, D^\nu\}H + \text{h.c.},
\end{aligned}$$

← **must invoke Higgs!**

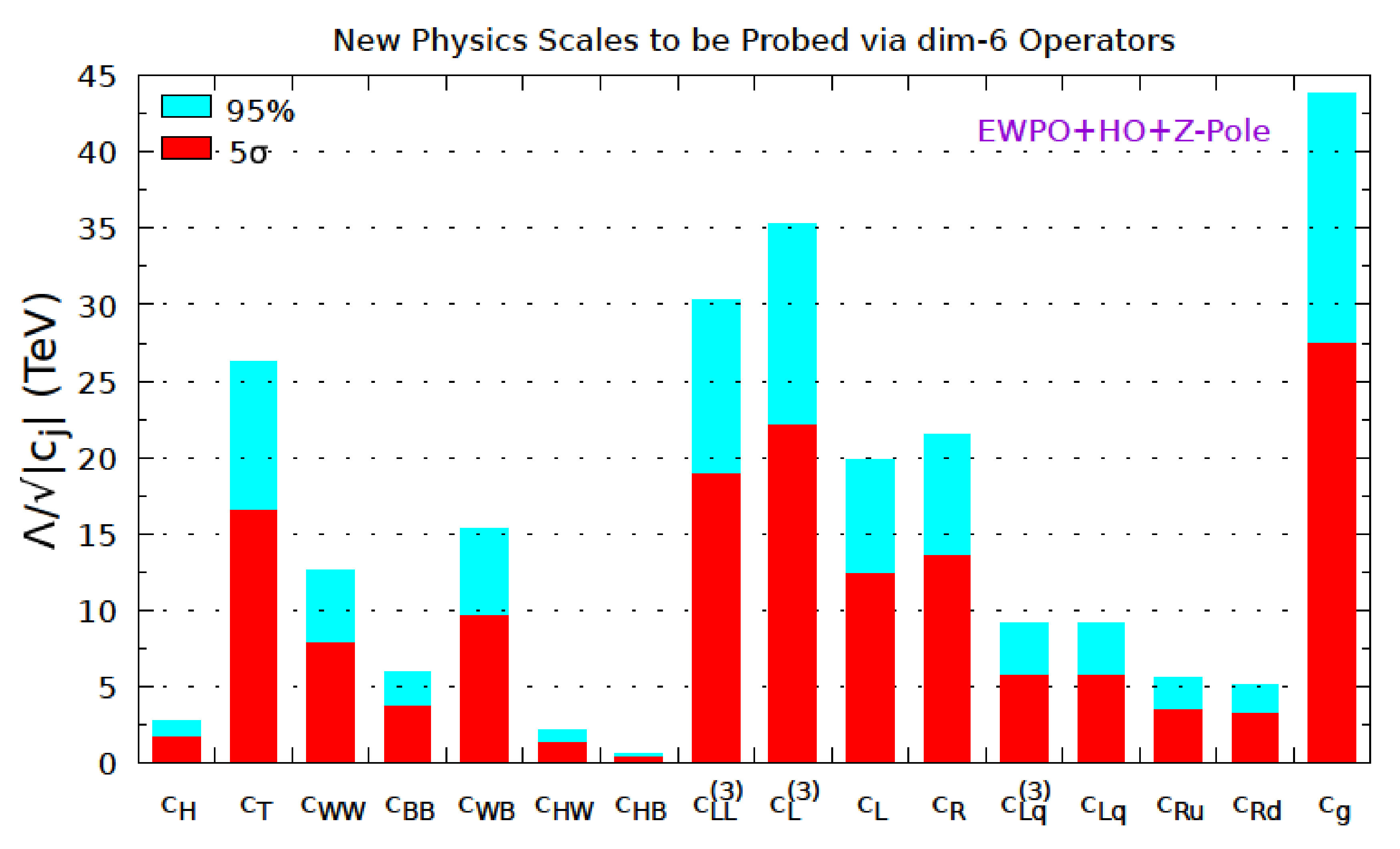
$\mathcal{O}_{B\widetilde{W}}$ is equivalent to $\mathcal{O}_{\widetilde{B}W}$

$\mathcal{O}_{\widetilde{W}W}$ and $\mathcal{O}_{\widetilde{B}B}$ do not contribute to $ZV\gamma$ coupling for on-shell Z and γ.

$$\mathrm{i}\,\Gamma^{\mu\nu\alpha}_{Z\gamma Z^*}(q_1, q_2, q_3) = \text{sign}(c_j)\frac{vM_Z(q_3^2 - M_Z^2)}{\Lambda^4}\epsilon^{\mu\nu\alpha\beta}q_{2\beta}$$

CEPC Sensitivity from EWPO+HO+Z-Pole

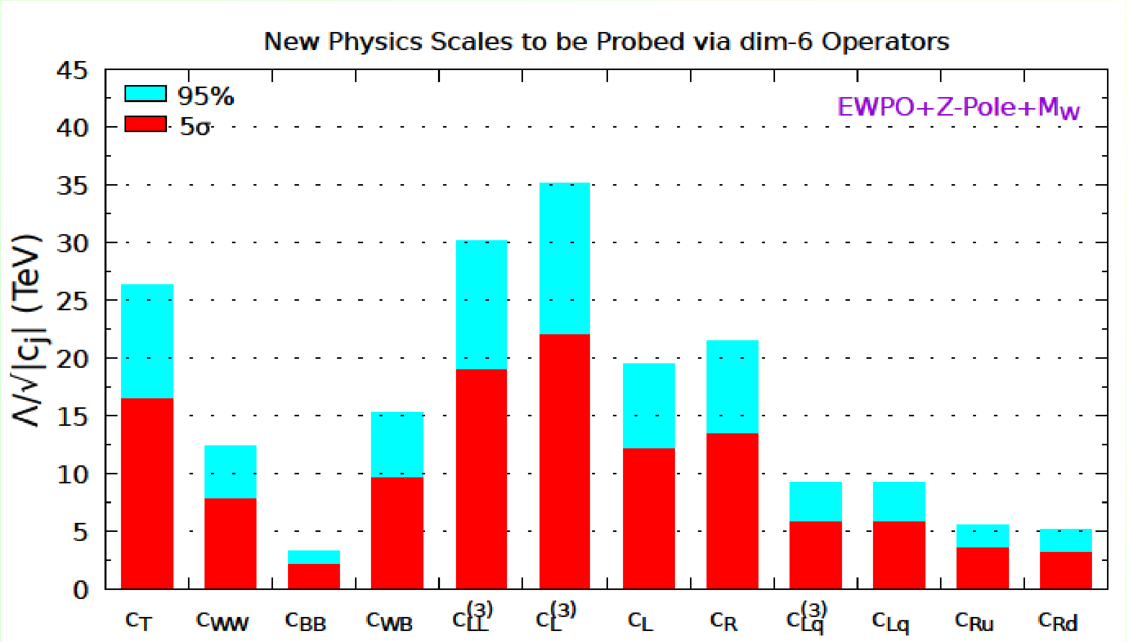
(Operators of dim-6)



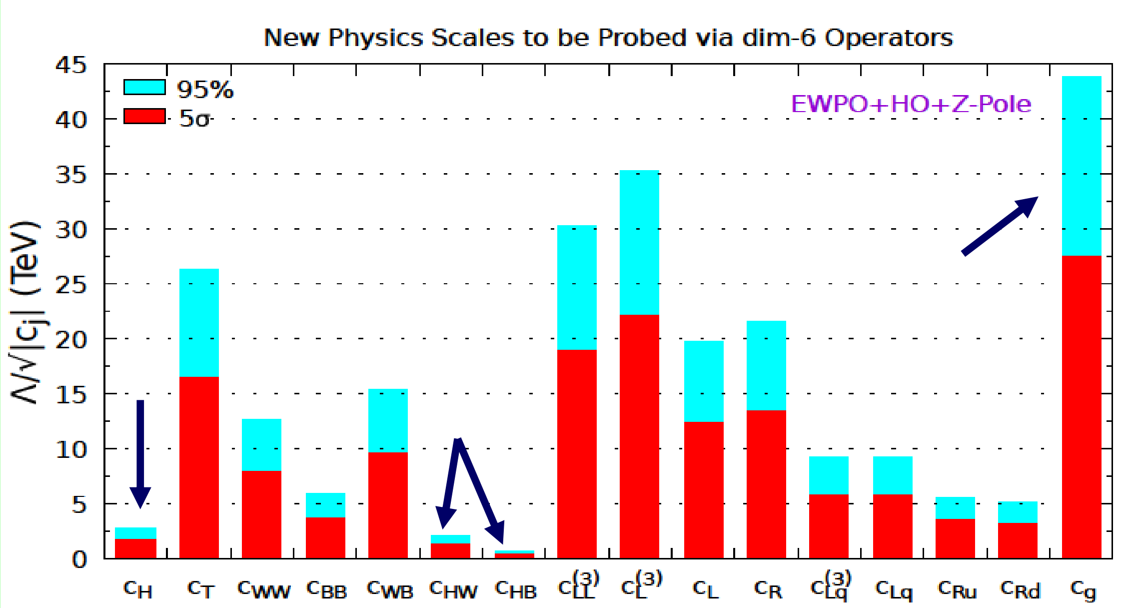
Ge, HJH, Xiao, JHEP 10(2016)007 [arXiv:1603.03385]

Probing New Physics Scales: EWPO+Z-pole+M_W vs Higgs Observables(HO)

(Operators of dim-6)



EWPO+Z-pole+M_W



EWPO +Z-pole+M_W+HO

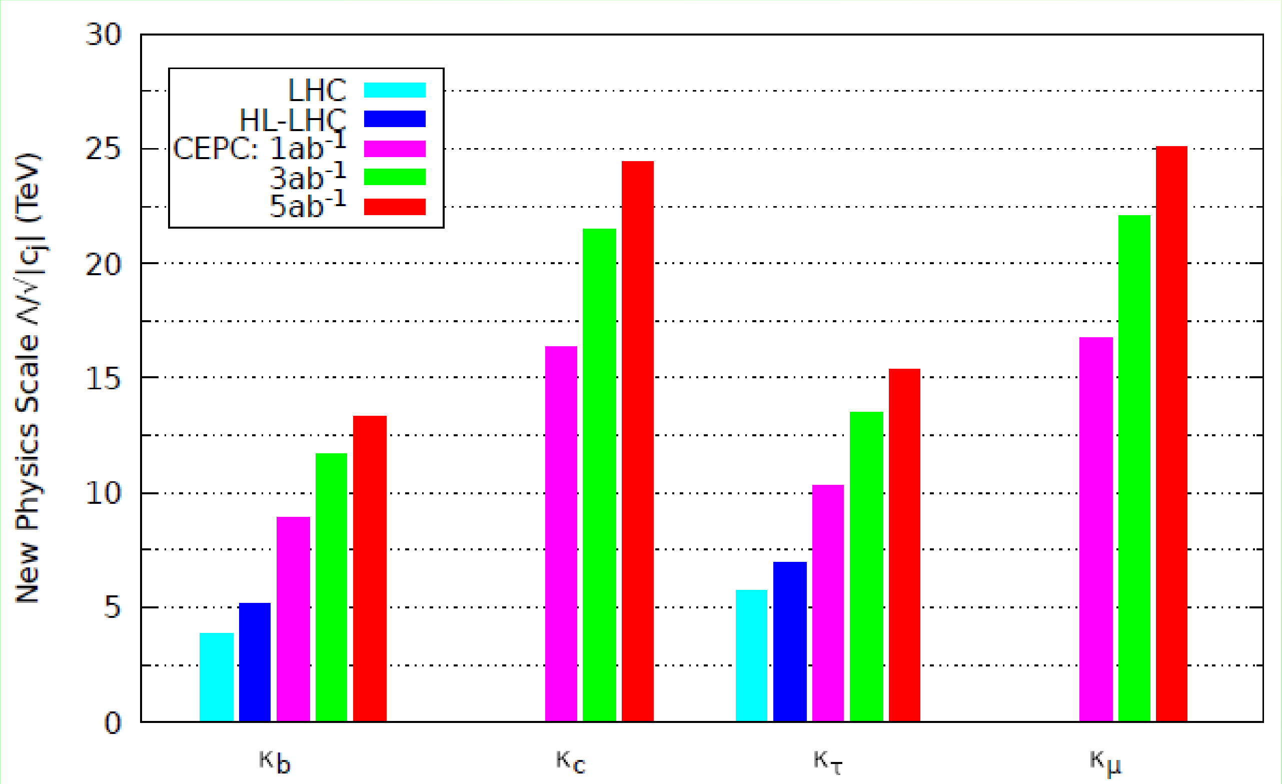
Ge, HJH, Xiao, JHEP 10(2016)007

Probing New Physics Scales: Higgs Observables Alone

- ➢ **Yukawa-type Dim-6 Operators cannot be probed by (EWPO, Z-pole, M_W).**
- ➢ **Yukawa-type Dim-6 Operators can only be probed at Higgs Factory!!**

$$\mathcal{O}_y^u = |H|^2\, \overline{\Psi}_L^q \tilde{H} u_R$$
$$\mathcal{O}_y^d = |H|^2\, \overline{\Psi}_L^q H d_R$$
$$\mathcal{O}_y^\ell = |H|^2\, \overline{\Psi}_L^\ell H \ell_R$$

← **~ Fermion Mass Generation!!**

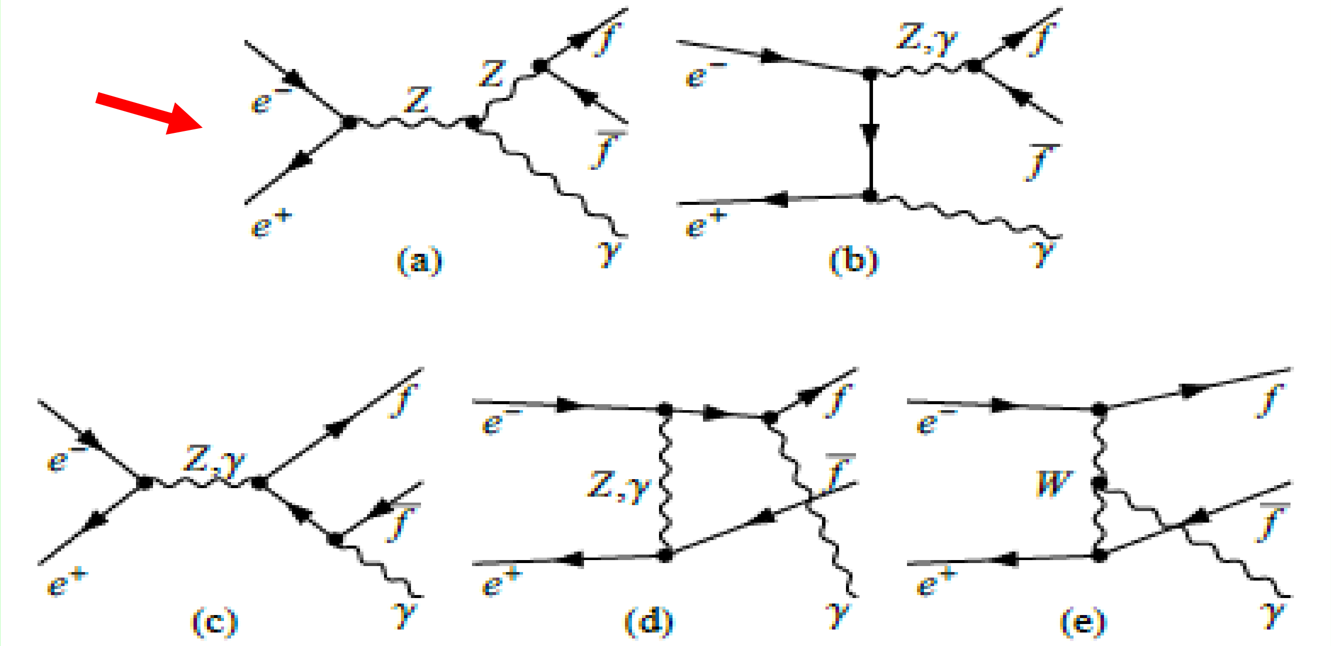


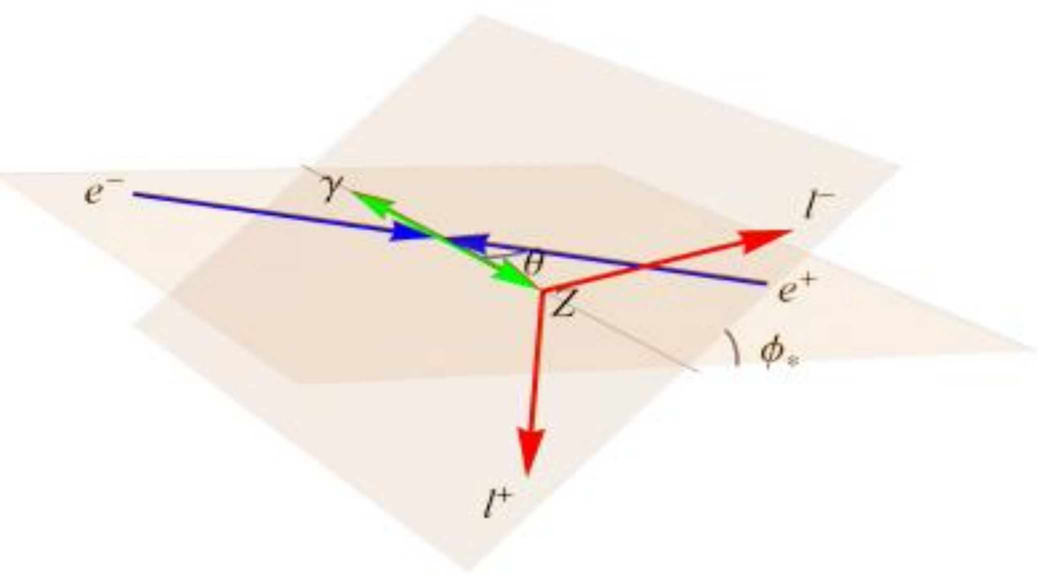
$$\frac{\Lambda}{\sqrt{|c_f|}} \geqslant \sqrt{\frac{v^3}{\sqrt{2}\, m_f \Delta\tilde{\kappa}_f}}$$

Probe New Physics Scales of Fermion Mass Generation!!

Ge, HJH, Xiao, JHEP 10(2016)007

ZZγ from dim-8: $e^+e^- \to Z\gamma \to \ell\ell\gamma,\ \nu\nu\gamma$

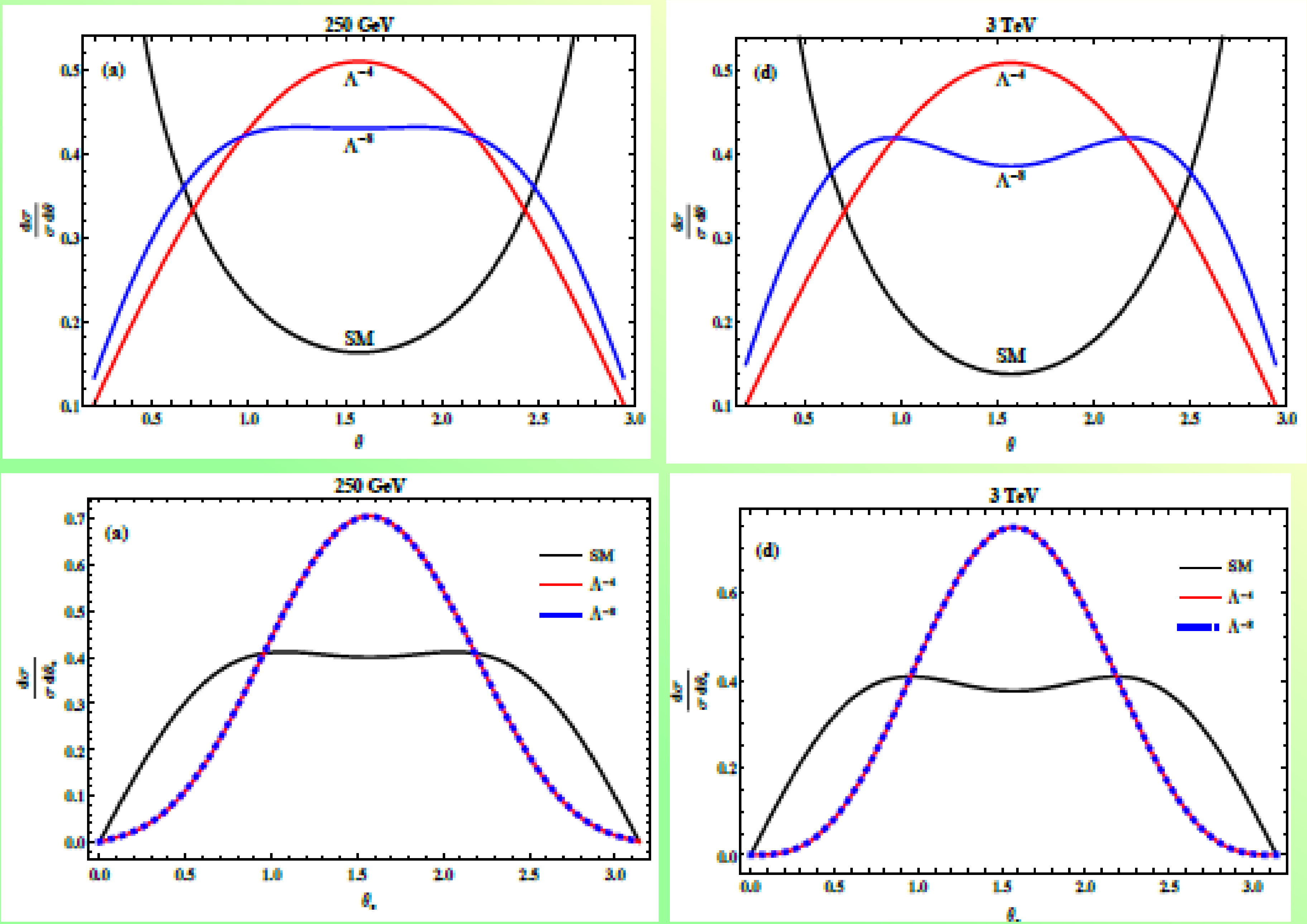




Ellis, Ge, HJH, Xiao
arXiv:1902.06631.v2

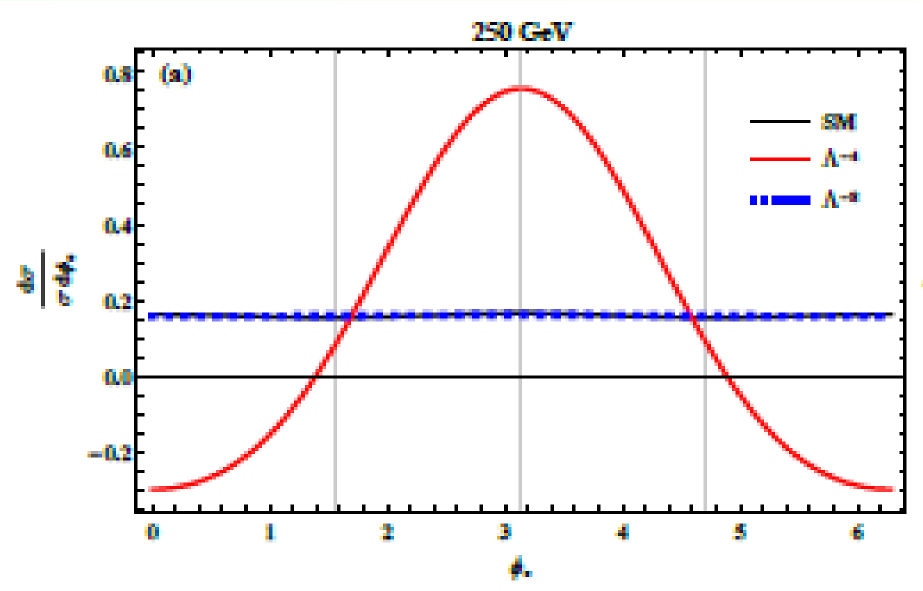
$e^+e^-\to Z\gamma\to\ell\ell\gamma$ channel

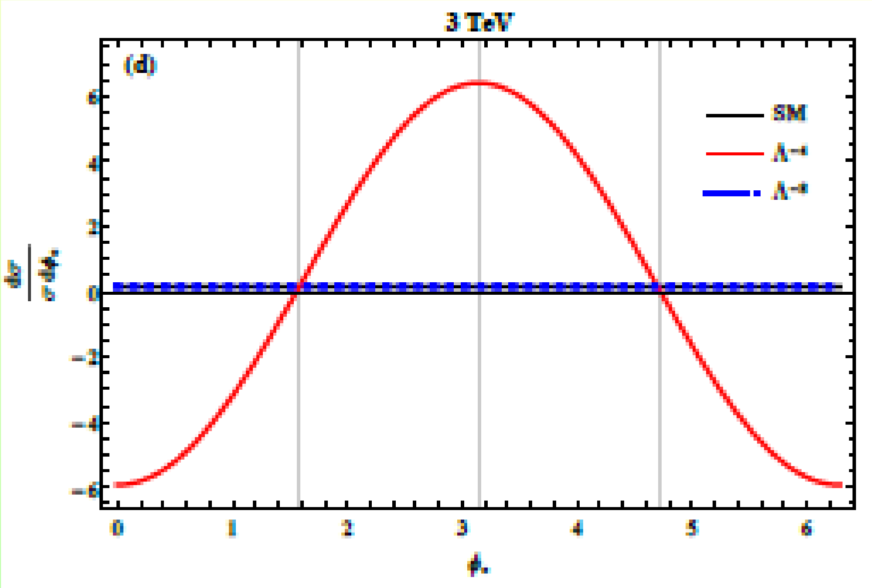
arXiv:1902.06631



$e^+e^- \to Z\gamma \to \ell\,\ell\,\gamma$ channel

arXiv:1902.06631





$$f^0_{\phi_*} = \frac{1}{2\pi} + \frac{3\pi^2(c_L^2-c_R^2)^2 M_Z\sqrt{s}\,(s+M_Z^2)\cos\phi_* - 8(c_L^2+c_R^2)^2 M_Z^2\, s\cos 2\phi_*}{16\pi(c_L^2+c_R^2)^2\left[(s-M_Z^2)^2+2(s^2+M_Z^4)\ln\left(\sin\frac{\delta}{2}\right)\right]} + O(\delta),$$

$$f^1_{\phi_*} = \frac{1}{2\pi} - \frac{9\pi^2\sqrt{s}\,(s+M_Z^2)\cos\phi_* - 32 M_Z\, s\cos 2\phi_*}{128\pi M_Z(s+M_Z^2)} + O(\delta),$$

$$f^2_{\phi_*} = \frac{1}{2\pi} - \frac{9\pi(c_L^2-c_R^2)^2 M_Z\sqrt{s}\cos\phi_*}{128(c_L^2+c_R^2)^2(s+M_Z^2)} + O(\delta)\,,$$

$e^+e^- \to Z\gamma$ production

Ellis, Ge, HJH, Xiao, arXiv:1902.06631

$$\sigma(Z\gamma) = \frac{e^4(1-4s_W^2+8s_W^4)\left[-(s-M_Z^2)^2-2(s^2+M_Z^4)\ln\left(\sin\frac{\delta}{2}\right)\right]}{32\pi s_W^2 c_W^2 (s-M_Z^2)s^2}$$
$$\pm\frac{e^2(1-4s_W^2)M_Z^2(s-M_Z^2)(s+M_Z^2)}{32\pi s_W c_W \Lambda^4 s^2}$$
$$+\frac{(1-4s_W^2+8s_W^4)M_Z^2(s+M_Z^2)(s-M_Z^2)^3}{192\pi\Lambda^8 s^2}+O(\delta)\,,$$

$$Z_4 \propto \frac{M_Z\, s}{\Lambda^4}\sqrt{\mathcal{L}\times\epsilon}\,.$$

$$\Lambda \propto \left(\frac{M_Z\sqrt{\mathcal{L}\times\epsilon}}{Z_4}\right)^{\frac{1}{4}} \times \left(\sqrt{s}\right)^{\frac{1}{2}}\,.$$

$$Z_8 \propto \frac{M_Z^2\left(\sqrt{s}\right)^5}{\Lambda^8}\sqrt{\mathcal{L}\times\epsilon}\,,$$

$$\Lambda \propto \left(\frac{M_Z^2\sqrt{\mathcal{L}\,\epsilon}}{Z_8}\right)^{\frac{1}{8}} \left(\sqrt{s}\right)^{\frac{5}{8}}\,.$$

$e^+e^- \to Z\gamma$ production

- With basic angular cut $\theta > 0.2$,

$$\sqrt{s} = 250\text{GeV}, \quad \sigma(Z\gamma) = \left[7749 \pm 8.90\left(\frac{0.5\text{TeV}}{\Lambda}\right)^4 + 1.98\left(\frac{0.5\text{TeV}}{\Lambda}\right)^8\right]\text{fb},$$

$$\sqrt{s} = 3\text{TeV}, \quad \sigma(Z\gamma) = \left[42.9 \pm 0.0354\left(\frac{2\text{TeV}}{\Lambda}\right)^4 + 0.843\left(\frac{2\text{TeV}}{\Lambda}\right)^8\right]\text{fb},$$

- With optimal angular cuts on θ, θ_* ,

$$\sqrt{s} = 250\ \text{GeV}, \quad \sigma(Z\gamma) = \left[2427 \pm 6.62\left(\frac{0.5\text{TeV}}{\Lambda}\right)^4 + 1.39\left(\frac{0.5\text{TeV}}{\Lambda}\right)^8\right]\text{fb},$$

$$\sqrt{s} = 3\ \text{TeV}, \quad \sigma(Z\gamma) = \left[10.1 \pm 0.0252\left(\frac{2\text{TeV}}{\Lambda}\right)^4 + 0.554\left(\frac{2\text{TeV}}{\Lambda}\right)^8\right]\text{fb},$$

Ellis, Ge, HJH, Xiao, arXiv:1902.06631

$e^+e^-\to Z\gamma\to \ell\ell\gamma$: New Physics Reach

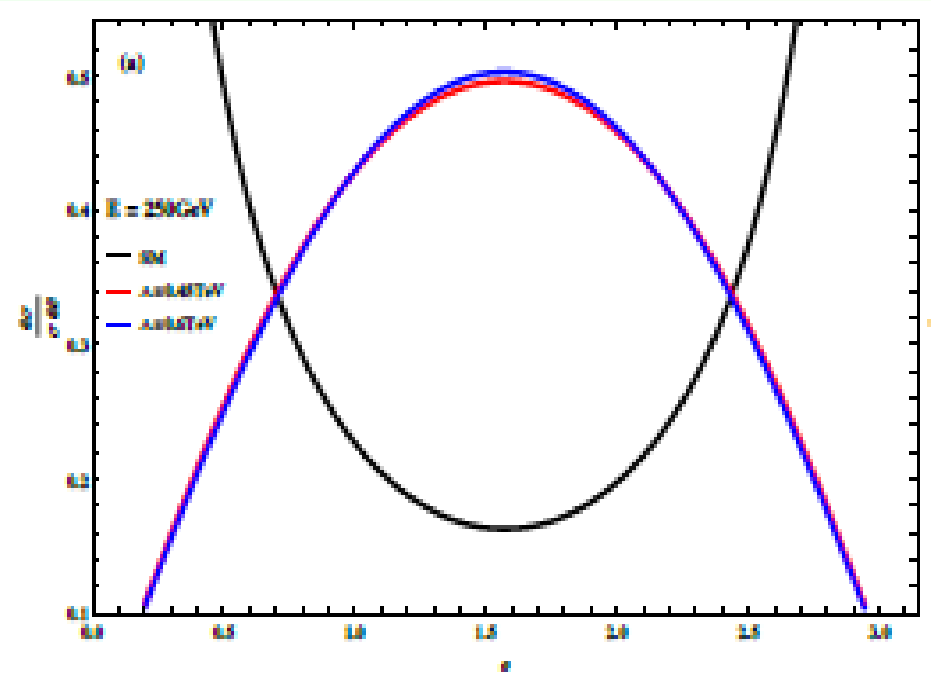
- **With Luminosity = 2 /ab .**
- **Note: Numbers inside (…) denote the case where dim-8 Operator has negative coefficients.**

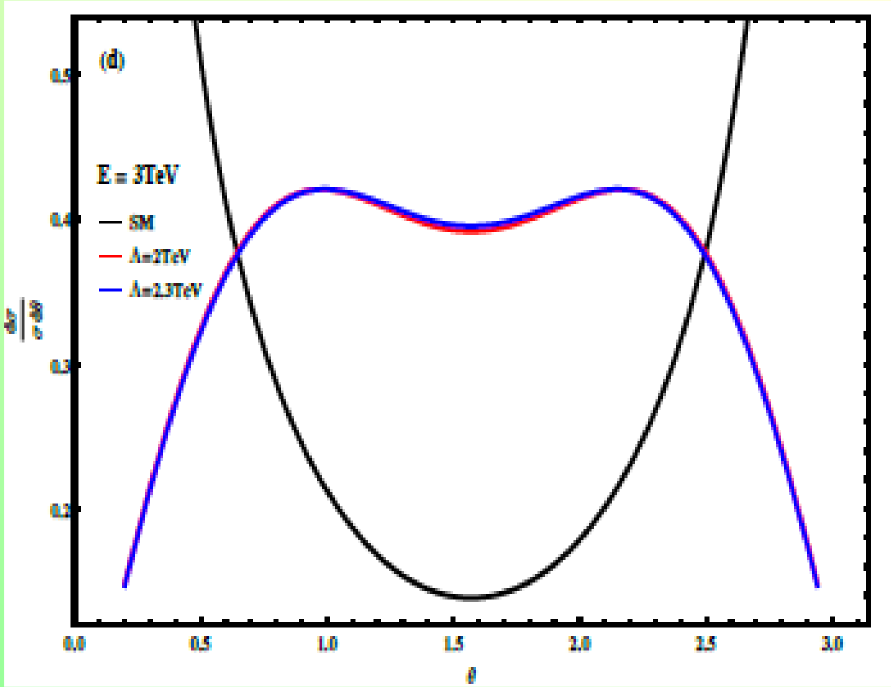
$\sqrt{s}$ (GeV)	250	500	1000	3000	5000
$\Lambda_{\ell\ell}^{2\sigma}$ (TeV)	0.57(0.56)	0.82(0.80)	1.2	2.1	2.9
$\Lambda_{\ell\ell}^{5\sigma}$ (TeV)	0.46(0.44)	0.67(0.64)	0.98(0.95)	1.9	2.5

Ellis, Ge, HJH, Xiao, arXiv:1902.06631

Invisible Channel: $e^+e^- \to Z\gamma \to \nu\nu\gamma$

- For invisible channel, we could only impose cuts on the scattering angle θ of the final state mono-photon.





Ellis, Ge, HJH, Xiao, arXiv:1902.06631.v2

Invisible Channel: $e^+e^- \to Z\gamma \to \nu\nu\gamma$

arXiv:1902.06631.v2

- **$Z\gamma$ cross section under optimal cut $\theta > \delta_m$,**

$$\sqrt{s} = 250 \text{ GeV}, \qquad \sigma(Z\gamma) = \left[3236 \pm 7.25\left(\frac{0.5\text{TeV}}{\Lambda}\right)^4 + 1.53\left(\frac{0.5\text{TeV}}{\Lambda}\right)^8\right]\text{fb},$$

$$\sqrt{s} = 3 \text{ TeV}, \qquad \sigma(Z\gamma) = \left[17.1 \pm 0.0291\left(\frac{2\text{TeV}}{\Lambda}\right)^4 + 0.640\left(\frac{2\text{TeV}}{\Lambda}\right)^8\right]\text{fb}$$

- **Signal Significance of invisible channel:**

$$\sqrt{s} = 250\,\text{GeV}, \qquad \mathcal{Z}_8 = \left|\pm 2.55\left(\frac{0.5\text{TeV}}{\Lambda}\right)^4 + 0.538\left(\frac{0.5\text{TeV}}{\Lambda}\right)^8\right| \times \sqrt{\epsilon}\,,$$

$$\sqrt{s} = 3\,\text{TeV}, \qquad \mathcal{Z}_8 = \left|\pm 0.141\left(\frac{2\,\text{TeV}}{\Lambda}\right)^4 + 3.10\left(\frac{2\,\text{TeV}}{\Lambda}\right)^8\right| \times \sqrt{\epsilon}\,,$$

New Physics Reach: $\ell\ell\gamma$ + $\nu\nu\gamma$ channels

- Lepton channel is more sensitive for E < 2TeV .
- Invisible channel becomes more sensitive for E > 2TeV .
- We see: combination helps to raise significance !

$\sqrt{s}$ (GeV)	250	500	1000	3000	5000
Λ (TeV)	0.5	0.7	1.0	1.9	2.7
$\mathcal{Z}_{\ell\bar{\ell}}$	3.6(3.2)	4.1(3.4)	4.5(3.9)	4.4(4.2)	3.2(3.1)
$\mathcal{Z}_{8,\nu\bar{\nu}}$	3.1(2.0)	3.1(0.10)	3.9(2.5)	4.8(4.5)	3.7(3.5)
$\mathcal{Z}$(combined)	4.7(3.8)	5.2(3.4)	6.0(4.6)	6.5(6.1)	4.9(4.7)

Ellis, Ge, HJH, Xiao, arXiv:1902.06631.v2

- With Luminosity = 2 /ab .
- Note: Numbers inside (…) denote the case where dim-8 Operator has negative coefficients.

New Physics Reach: $\ell\ell\gamma$ + $\nu\nu\gamma$ channels

$\sqrt{s}$ (GeV)	250	500	1000	3000	5000
$\Lambda^{2\sigma}_{\ell\bar{\ell}}$ (TeV)	0.57(0.56)	0.82(0.80)	1.2	2.1	2.9
$\Lambda^{5\sigma}_{\ell\bar{\ell}}$ (TeV)	0.46(0.44)	0.67(0.64)	0.98(0.95)	1.9	2.5
$\Lambda^{2\sigma}_{\nu\bar{\nu}}$ (TeV)	0.55(0.32)	0.75(0.62)	1.1	2.1	2.9
$\Lambda^{5\sigma}_{\nu\bar{\nu}}$ (TeV)	0.45(0.32)	0.65(0.57)	0.97(0.93)	1.9	2.6
$\Lambda^{2\sigma}_{\ell\nu,\mathrm{comb}}$ (TeV)	0.61(0.59)	0.85(0.80)	1.2	2.3	3.0
$\Lambda^{5\sigma}_{\ell\nu,\mathrm{comb}}$ (TeV)	0.49(0.46)	0.70(0.64)	1.0	2.0	2.7

arXiv:1902.06631.v2

Recall:

$$\mathcal{Z}_4 \propto \frac{M_Z\, s}{\Lambda^4}\sqrt{\mathcal{L}\times\epsilon}\,.$$

$$\Lambda \propto \left(\frac{M_Z\sqrt{\mathcal{L}\times\epsilon}}{\mathcal{Z}_4}\right)^{\frac{1}{4}} \times (\sqrt{s})^{\frac{1}{2}}\,.$$

$$\mathcal{Z}_8 \propto \frac{M_Z^2(\sqrt{s})^5}{\Lambda^8}\sqrt{\mathcal{L}\times\epsilon}\,,$$

$$\Lambda \propto \left(\frac{M_Z^2\sqrt{\mathcal{L}\,\epsilon}}{\mathcal{Z}_8}\right)^{\frac{1}{8}} (\sqrt{s})^{\frac{5}{8}}\,.$$

(e^-, e^+) Polarization: $\ell\ell\gamma$, $\nu\nu\gamma$ channels

- Taking **beam polarizations** $(P_L^e, P_R^{\bar{e}}) = (90\%, 65\%)$, we derived improved reaches on Λ :

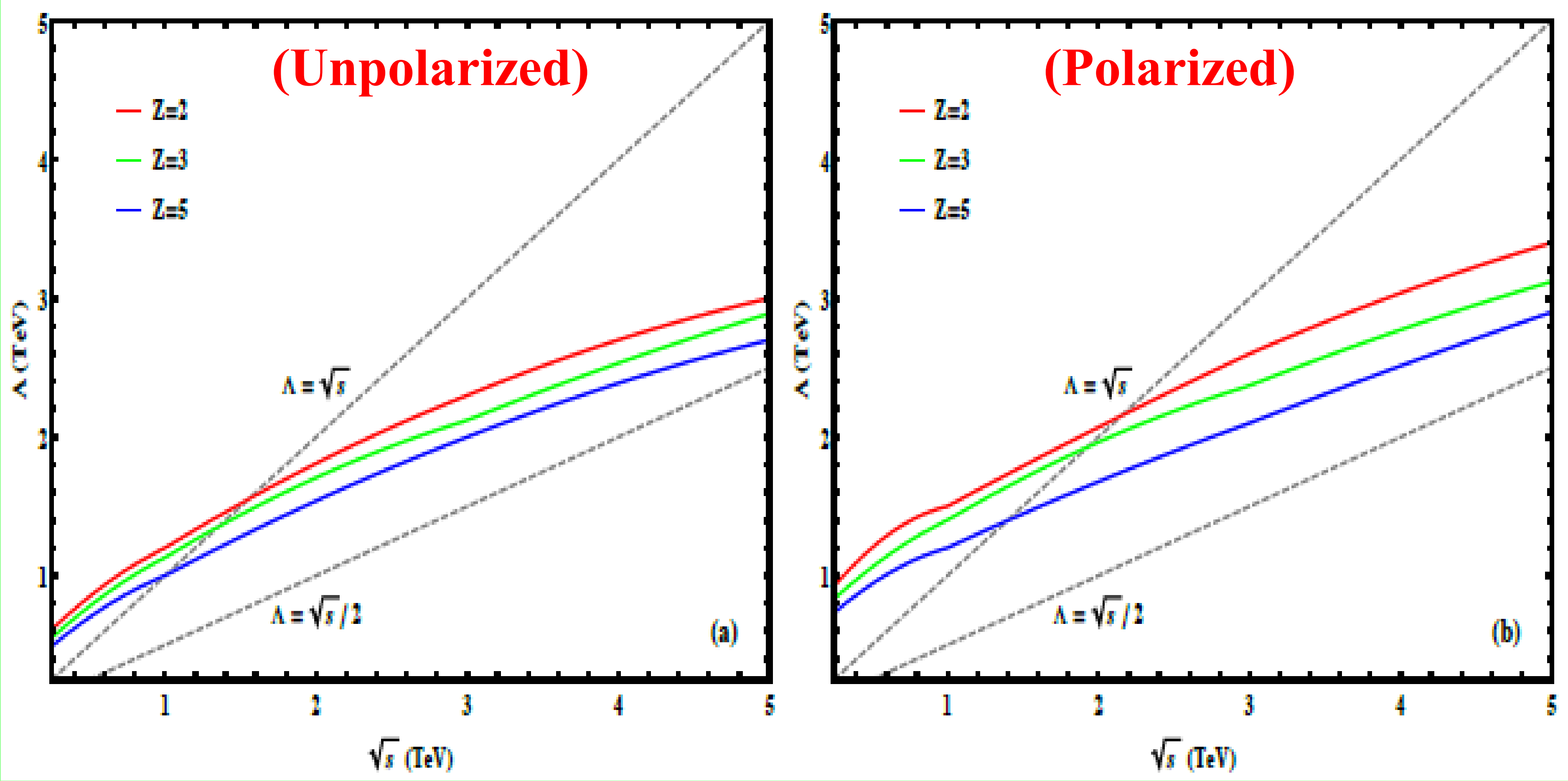
$\sqrt{s}$ (GeV)	250	500	1000	3000	5000
$\Lambda_{\ell\bar{\ell}}^{2\sigma}$ (TeV)	0.81	1.1	1.5(1.4)	2.5	3.2
$\Lambda_{\ell\bar{\ell}}^{5\sigma}$ (TeV)	0.64	0.87(0.85)	1.2(1.1)	2.1(2.0)	2.7
$\Lambda_{\nu\bar{\nu}}^{2\sigma}$ (TeV)	0.87	1.1	1.3(0.87)	2.3(2.1)	3.0(2.9)
$\Lambda_{\nu\bar{\nu}}^{5\sigma}$ (TeV)	0.69	0.86(0.83)	1.1(0.84)	2.0(1.9)	2.7(2.6)
$\Lambda_{\ell\nu}^{2\sigma}$ (TeV)	0.92	1.2	1.5	2.6(2.5)	3.4(3.3)
$\Lambda_{\ell\nu}^{5\sigma}$ (TeV)	0.73	0.94(0.92)	1.2	2.1	2.9(2.8)

arXiv:1902.06631.v2

(e^-, e^+) Polarizations: $\ell\ell\gamma$, $\nu\nu\gamma$ channels

- **Taking beam polarizations** $(P_L^e, P_R^{\bar{e}}) = (90\%, 65\%)$, **we derived improved reaches on Λ :**

arXiv:1902.06631.v2



Summary

- **Key Window to New Physics:**
  → Discover New Higgs Boson via Higgs Self-Interactions (Hhh) !
  → Higgs Portal & DM Portal: Gravity Interactions of Higgs and DM !
  → Probe Higgs Interactions & Higgs-Induced Corrections to Gauge Force (Couplings).

- **SMEFT: — New Physics Beyond SM can ALL be described by a set of Gauge-Invariant dim-6 & dim-8 Effective Operators (including Higgs) with generic Cutoff Λ characterizing New Physics Scale.**

- **Higgs Operators can modify both Higgs Couplings & Gauge Couplings !!**
- **It is important to probe New Physics Scale Λ from *both* Higgs Processes and Gauge Boson Processes (with no Higgs invoked).**

- **CEPC(90-250GeV) can indirectly probe New Physics up to 20-35TeV range, which complementarily cover the discovery reach of SPPC(100TeV).**

- **Pure Gauge Coupling, nTGC, can only arise from Higgs-related operators of dimension-8 ! → Channels $e^+e^- \to Z\gamma \to \ell\ell\gamma,\ \nu\nu\gamma$ at CEPC, FCC, ILC, CLIC can probe nTGC via dim-8 Operators and probe associated New Physics Scale into multi-TeV region !**


Thank You !