NEW PHYSICS @ the LHC: SMEFT and BEYOND

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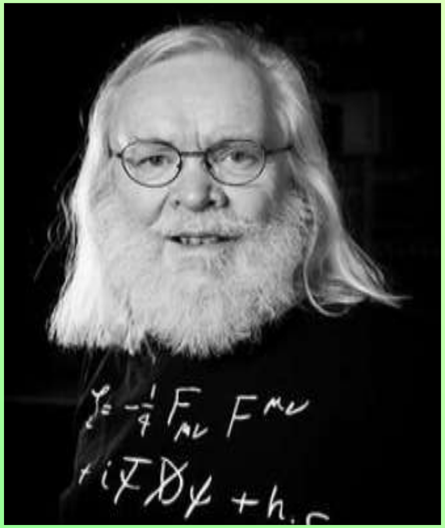
Collaborators:



John Ellis

Rui-Qing Xiao

Based on:

PRD Letter (2023), in press, arXiv:2308.16887

PRD (Editors' Suggestion, 2022) arXiv:2206.11676.

Science China (2021), Cover Article, arXiv:2008.04298

New Physics $\stackrel{?}{=}$ New Particles

New Physics = New Phenomena !

New Physics = New Principles !!

**E.g., Special Relativity, Photo-electronic Effect, GR,
P and CP Violations, ……**

Implications of Non-Discovery

- Michelson-Morley Exp → No Aether!
  But, it leads to New Revolation: → Special Relativity!

- Discrepancy in Procession of Mercury's Perihelion
  Using known Newton gravity Le Verrier postulated:
  → New Planet "Vulcan" (祝融星), but No Discovery of it !
  → Real Solution: General Relativity !

- Question and Challenge today:
  After h(125), what does the Non-discovery of LHC imply ???

- I am moderately (non) optimistic……

Particle Physics in the Post-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.**

SM spoils it at Loop

LHC gives partial probe

Making of the Standard Model (123)

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

No DM !

No Dark Energy !

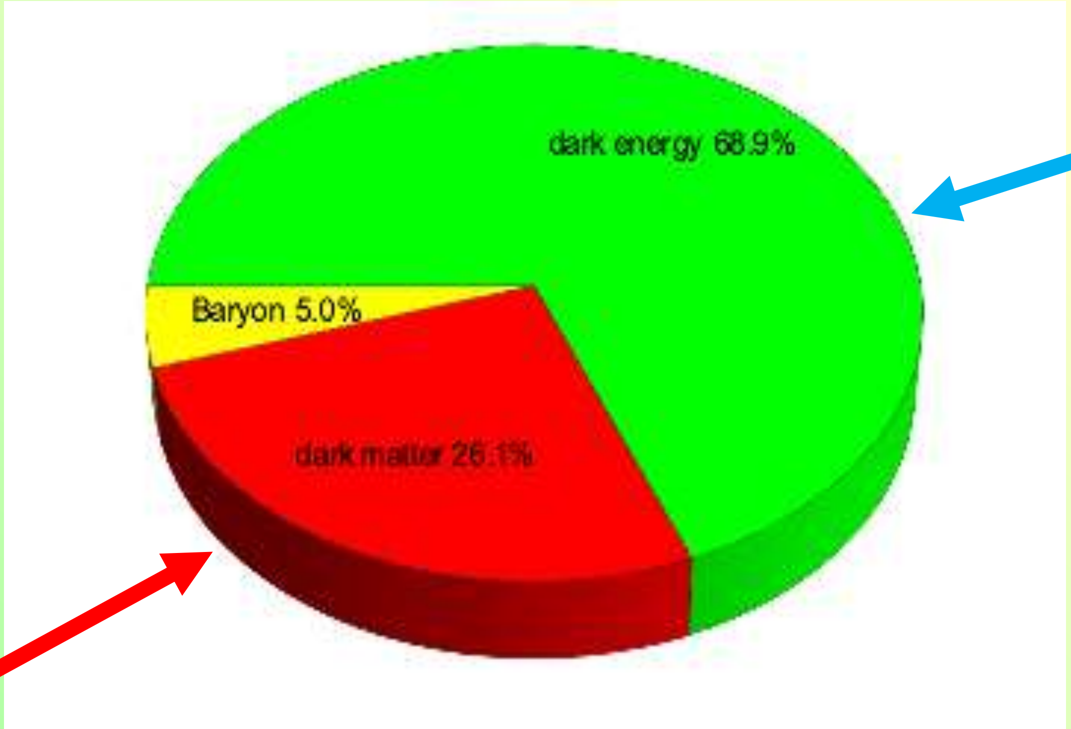
SM Structure seems complete, but ....

Recall: situation around 1900 –

→ **What is *Missing* in the SM ???**

Composition of the Universe

— Visible vs Dark Universe —



Making of the Standard Model (123)

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\begin{aligned}
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& + \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}
$$

No DM !

No Dark Energy !

No Gravity!

SM Structure seems complete, but ....

Recall: situation around 1900 –

→ **What is *Missing* in the SM ??**

→→ **No full understanding on Quantum Gravity !!!**

Particle Physics in the Post-Higgs Era !

Higgs Boson h(125GeV) opens a Key Window for New Physics!
→ New Clues + New Opportunities !

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

★ h joins 2 New Forces: Self-Interaction Force & Yukawa Force.

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

SM cannot ensure at Loop

LHC gives partial probe

★ New Physics in Higgs-Gauge Boson Couplings ?

★ New Physics in Gauge Boson Self-Couplings ?

← Higher Sensitivity !

★ Pure Gauge Couplings are connected to Higgs-Gauge Couplings, and to some Higgs-self-couplings as well.

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

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_j \frac{c_j}{\tilde{\Lambda}^2}\mathcal{O}_j = \mathcal{L}_{\text{SM}} + \sum_j \frac{\pm 1}{\Lambda_j^2}\mathcal{O}_j$$

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

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:**

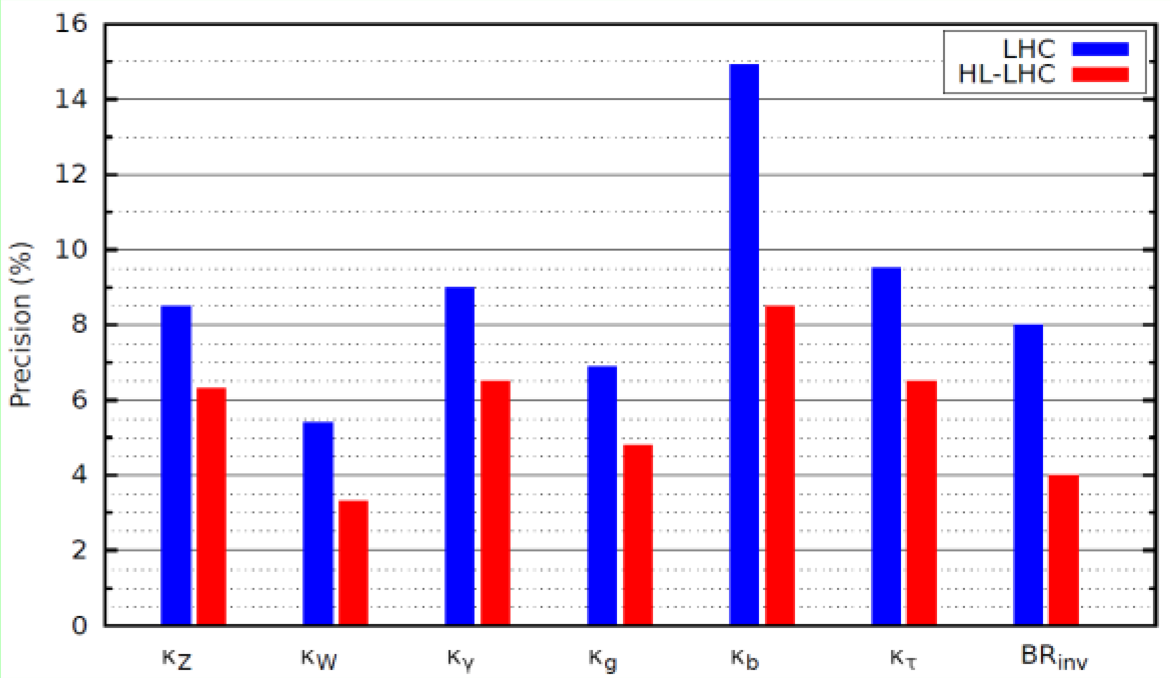
Effective Higgs-Gauge Couplings & Pure Gauge Couplings are *connected*
At dim-6 and beyond due to EW gauge-invariance.

→ Example: neutral Triple Gauge Couplings (nTGC), such as
ZZZ, ZZγ, Zγγ may arise from dim-8 Higgs-related operators !

What beyond the LHC ?

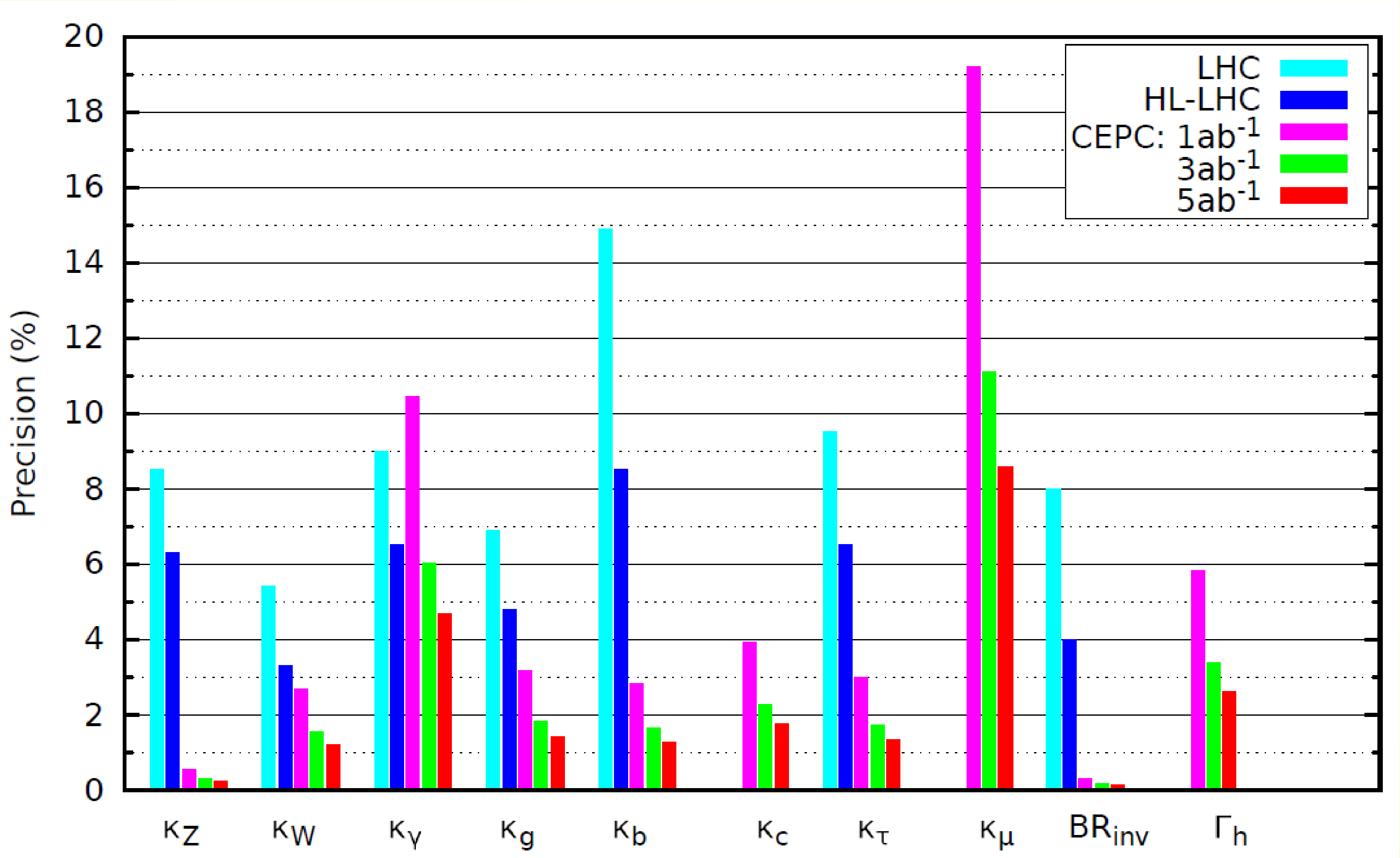
- **HL-LHC (up to 3/ab): more precise measurements, but not enough!**

- **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

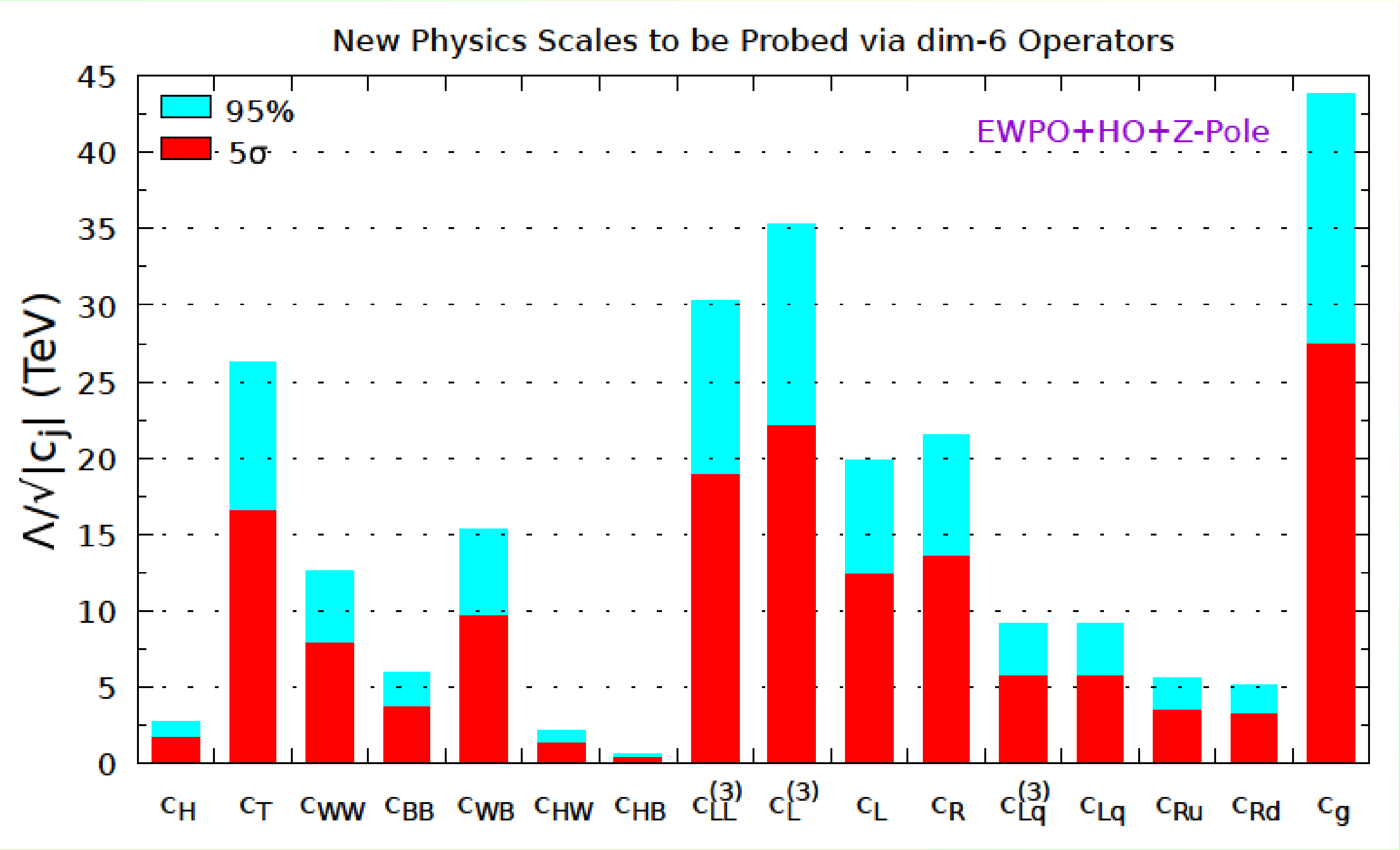
Testing Higgs Coupling: CEPC vs LHC



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

CEPC Sensitivity from EWPO+HO+Z-Pole

(Operators of dim-6)



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

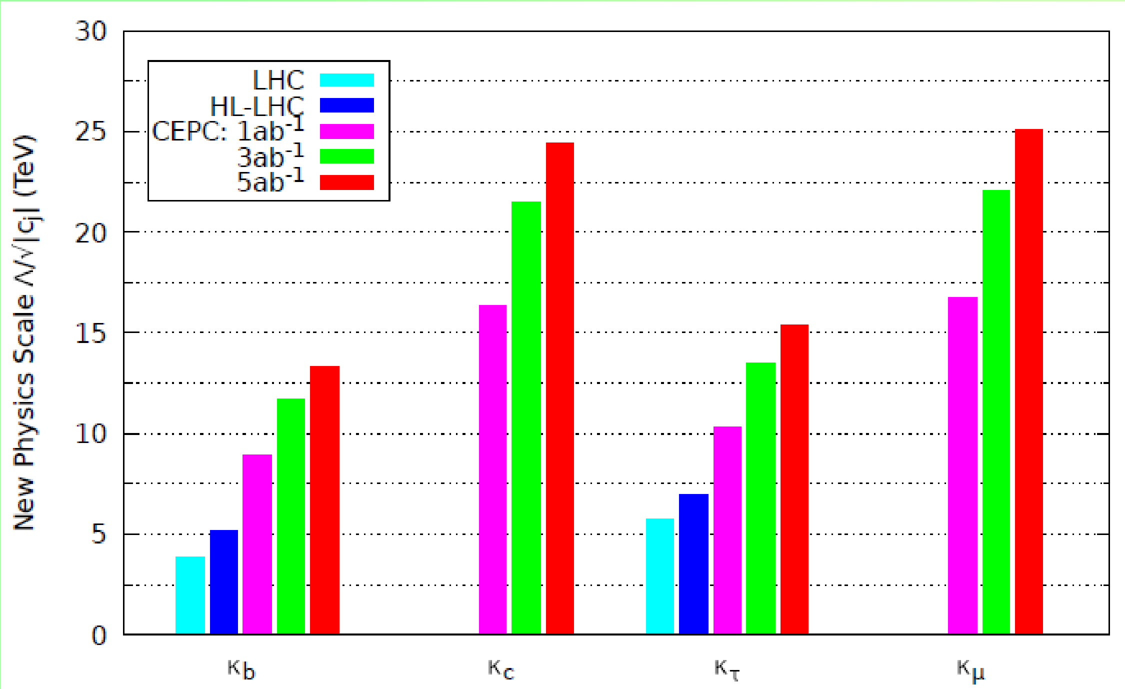
Probing New Physics Scales: Higgs Observables Alone

- 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!!

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

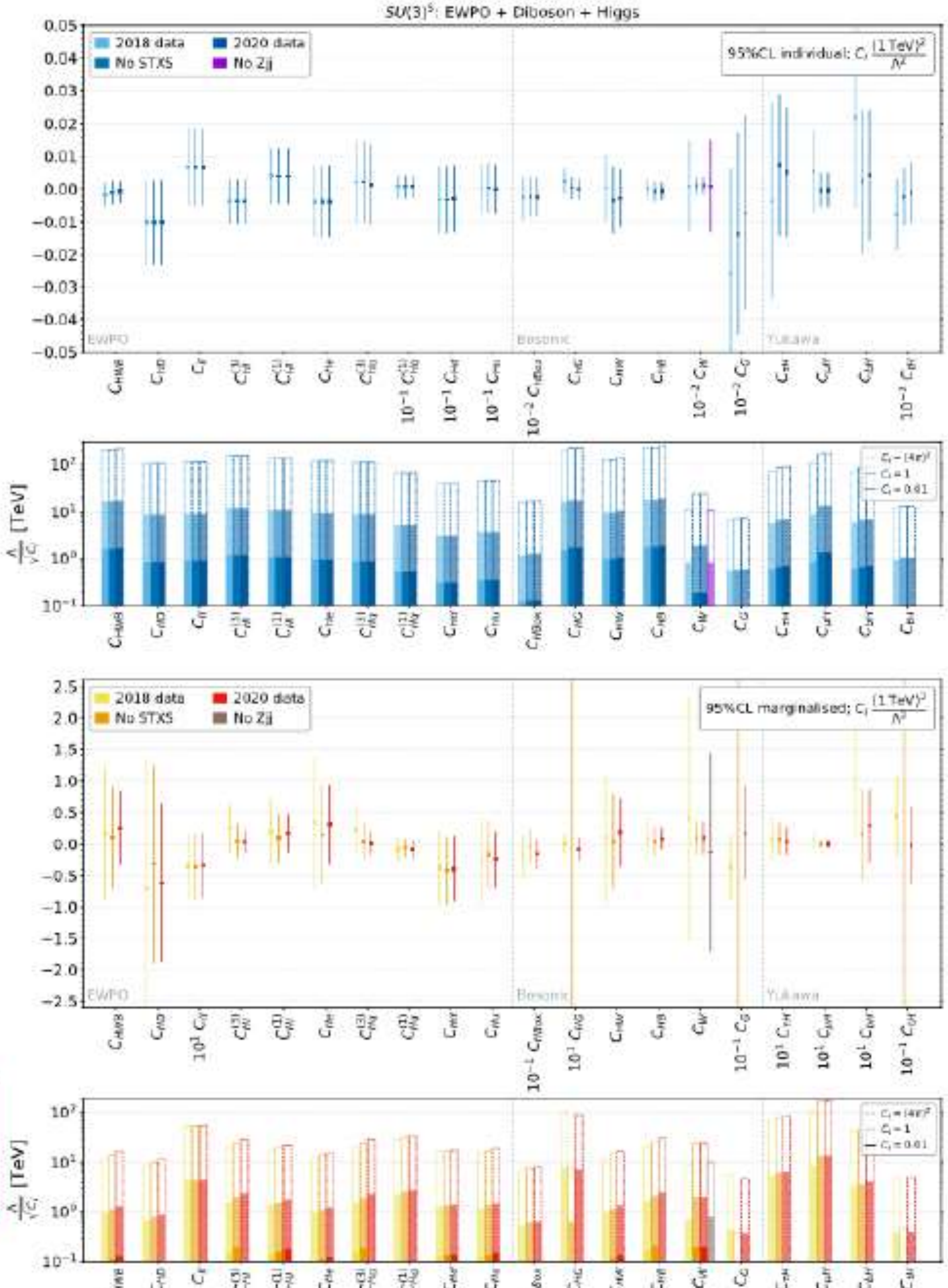


← Probe New Physics Scales of Fermion Mass Generation!!

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

Dimension-6 Constraints with Flavour-Universal SU(3)^5 Symmetry

- Individual operator coefficients
- Marginalised over all other operator coefficients



No significant deviations from SM

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

New Physics from Effective Operators @ Dim-8

Why & When will this be Unique ?

$$\Delta\mathcal{L}(\text{dim-8}) = \sum_j \frac{\tilde{c}_j}{\tilde{\Lambda}^4}\mathcal{O}_j = \sum_j \frac{\text{sign}(\tilde{c}_j)}{\Lambda_j^4}\mathcal{O}_j$$

Neutral Triple Gauge Couplings (nTGC):

- **Absent in the SM of dimension-4.**
- **Absent at dimension-6 Level.**
- **First appear at Dimension-8 Level.** ←

- **nTGCs provide a clean Window to New Physics at Dimension-8**

nTGC Operators at Dimension-8

- **Contains CP Conserving (CPC) & CP Violating (CPV) Operators:**

Higgs related operators:

$$\text{CPC:} \quad \mathcal{O}_{\widetilde{B}W} = \mathrm{i}H^\dagger \widetilde{B}_{\mu\nu} W^{\mu\rho} \{D_\rho, D^\nu\} H + \text{h.c.},$$

$$\text{CPC:} \quad \mathcal{O}_{\widetilde{BW}} = \mathrm{i}H^\dagger (D_\sigma \widetilde{W}^a_{\mu\nu} W^{a\mu\sigma} + D_\sigma \widetilde{B}_{\mu\nu} B^{\mu\sigma}) D^\nu H + \text{h.c.},$$

$$\text{CPV:} \quad \widetilde{\mathcal{O}}_{BW} = \mathrm{i}H^\dagger B_{\mu\nu} W^{\mu\rho} \{D_\rho, D^\nu\} H + \text{h.c.},$$

$$\text{CPV:} \quad \widetilde{\mathcal{O}}_{WW} = \mathrm{i}H^\dagger W_{\mu\nu} W^{\mu\rho} \{D_\rho, D^\nu\} H + \text{h.c.},$$

$$\text{CPV:} \quad \widetilde{\mathcal{O}}_{BB} = \mathrm{i}H^\dagger B_{\mu\nu} B^{\mu\rho} \{D_\rho, D^\nu\} H + \text{h.c.},$$

Pure Gauge operators:

$$\text{CPC:} \quad g\mathcal{O}_{G+} = \widetilde{B}_{\mu\nu} W^{a\mu\rho} (D_\rho D_\lambda W^{a\nu\lambda} + D^\nu D^\lambda W^a_{\lambda\rho}),$$

$$\text{CPC:} \quad g\mathcal{O}_{G-} = \widetilde{B}_{\mu\nu} W^{a\mu\rho} (D_\rho D_\lambda W^{a\nu\lambda} - D^\nu D^\lambda W^a_{\lambda\rho}),$$

$$\text{CPV:} \quad g\widetilde{\mathcal{O}}_{G+} = B_{\mu\nu} W^{a\mu\rho} (D_\rho D_\lambda W^{a\nu\lambda} + D^\nu D^\lambda W^a_{\lambda\rho}),$$

$$\text{CPV:} \quad g\widetilde{\mathcal{O}}_{G-} = B_{\mu\nu} W^{a\mu\rho} (D_\rho D_\lambda W^{a\nu\lambda} - D^\nu D^\lambda W^a_{\lambda\rho}),$$

Conventional nTGC Form Factors: Inconsistent!

- Conventional CPC Form Factors of V*Zγ respect only Lorentz invariance and Residual QED U(1) :

$$\widetilde{\Gamma}^{\alpha\beta\mu(\mathrm{CPC})}_{Z\gamma V^*} = \frac{e\,(q_3^2 - M_V^2)}{M_Z^2}\left[h_3^V\, q_{2\nu}\epsilon^{\alpha\beta\mu\nu} + \frac{h_4^V}{M_Z^2}\, q_2^\alpha\, q_{3\nu}\, q_{2\sigma}\,\epsilon^{\beta\mu\nu\sigma}\right],$$

$$\widetilde{\Gamma}^{\alpha\beta\mu(\mathrm{CPV})}_{Z\gamma V^*} = \frac{e\,(q_3^2 - M_V^2)}{M_Z^2}\left[h_1^V\,(q_2^\alpha g^{\mu\beta} - q_2^\mu g^{\alpha\beta}) + \frac{h_2^V}{2M_Z^2}\, q_2^\alpha g^{\mu\beta}(M_Z^2 - q_3^2)\right].$$

- But it could be inconsistent for the EW Sector !
- Because the Fully EW Gauge Symmetry is not just QED U(1), but the

SU(2) x U(1) with Spontaneous Breaking

Matching: nTGC Form Factors *from* dim-8 Operators

- **From Complete Set of dim-8 Operators, we deduce a Complete Set of nTGC Vertices in the electroweak broken phase, with which we construct the first consistent formulation of nTGC Form Factors.**

- **Important Point:**
  The Spontaneous Breaking EW Gauge Symmetry SU(2) x U(1) plays a Key Role to determine the correct structure of nTGC Form Factors.

Matching: nTGC Form Factors *from* dim-8 Operators

- **From a Complete Set of CPC dim-8 Operators, we deduce a Complete Set of CPC nTGC Vertices in the electroweak broken phase, with which we construct the consistent formulation of nTGC Form Factors:**

$$
\begin{aligned}
\mathcal{L}_{\rm nTGC}^{\rm CPC} = \; & \frac{e\hat{h}_3^Z}{2M_Z^2}\left(c_W^2\widetilde{A}_{\mu\nu}Z^{\mu\rho} - s_W^2\widetilde{Z}_{\mu\nu}A^{\mu\rho} + c_W s_W\widetilde{A}_{\mu\nu}A^{\mu\rho} - c_W s_W\widetilde{Z}_{\mu\nu}Z^{\mu\rho}\right)\left(\partial^\nu Z_\rho + \partial_\rho Z^\nu\right) \\
& - \frac{e\hat{h}_4}{2M_Z^4}\left(c_W^2\widetilde{A}_{\mu\nu}Z^{\mu\rho} - s_W^2\widetilde{Z}_{\mu\nu}A^{\mu\rho} + c_W s_W\widetilde{A}_{\mu\nu}A^{\mu\rho} - c_W s_W\widetilde{Z}_{\mu\nu}Z^{\mu\rho}\right)\partial^2\left(Z^\nu{}_\rho + \frac{s_W}{c_W}A^\nu{}_\rho\right) \\
& + \frac{e c_W\hat{h}_3^\gamma}{2s_W M_Z^4}\left(c_W^2\widetilde{A}_{\mu\nu}Z^{\mu\rho} - s_W^2\widetilde{Z}_{\mu\nu}A^{\mu\rho} + c_W s_W\widetilde{A}_{\mu\nu}A^{\mu\rho} - c_W s_W\widetilde{Z}_{\mu\nu}Z^{\mu\rho}\right)\times \\
& \quad \left[\partial^2\left(\partial^\nu Z_\rho + \partial_\rho Z^\nu + \frac{s_W}{c_W}\partial^\nu A_\rho + \frac{s_W}{c_W}\partial_\rho A^\nu\right) - 2\partial^\nu\partial_\rho\left(\partial\cdot Z + \frac{s_W}{c_W}\partial\cdot A\right)\right] \\
& + \frac{e h_{31}^\gamma}{2M_Z^2}\left(\partial_\rho\widetilde{Z}_{\mu\nu}Z^{\mu\rho} + \partial_\rho\widetilde{A}_{\mu\nu}A^{\mu\rho}\right)Z^\nu\,,
\end{aligned}
$$

- **We stress: the above CPC nTGC Form Factors are Fully Off-Shell !**
  →→ they are the most general formulation (including all special cases)!

Matching: nTGC Form Factors *from* dim-8 Operators

- **Fully Off-Shell CPC nTGC Form Factors at Lagrangian Level:**

$$\mathcal{L}_{\rm nTGC}^{\rm CPC} = \frac{e\hat{h}_3^Z}{2M_Z^2}\left(c_W^2 \widetilde{A}_{\mu\nu}Z^{\mu\rho} - s_W^2 \widetilde{Z}_{\mu\nu}A^{\mu\rho} + c_W s_W \widetilde{A}_{\mu\nu}A^{\mu\rho} - c_W s_W \widetilde{Z}_{\mu\nu}Z^{\mu\rho}\right)\left(\partial^\nu Z_\rho + \partial_\rho Z^\nu\right)$$
$$-\frac{e\hat{h}_4}{2M_Z^4}\left(c_W^2 \widetilde{A}_{\mu\nu}Z^{\mu\rho} - s_W^2 \widetilde{Z}_{\mu\nu}A^{\mu\rho} + c_W s_W \widetilde{A}_{\mu\nu}A^{\mu\rho} - c_W s_W \widetilde{Z}_{\mu\nu}Z^{\mu\rho}\right)\partial^2\left(Z^\nu{}_\rho + \frac{s_W}{c_W}A^\nu{}_\rho\right)$$
$$+\frac{e c_W \hat{h}_3^\gamma}{2s_W M_Z^4}\left(c_W^2 \widetilde{A}_{\mu\nu}Z^{\mu\rho} - s_W^2 \widetilde{Z}_{\mu\nu}A^{\mu\rho} + c_W s_W \widetilde{A}_{\mu\nu}A^{\mu\rho} - c_W s_W \widetilde{Z}_{\mu\nu}Z^{\mu\rho}\right)\times$$
$$\left[\partial^2\left(\partial^\nu Z_\rho + \partial_\rho Z^\nu + \frac{s_W}{c_W}\partial^\nu A_\rho + \frac{s_W}{c_W}\partial_\rho A^\nu\right) - 2\partial^\nu\partial_\rho\left(\partial\cdot Z + \frac{s_W}{c_W}\partial\cdot A\right)\right]$$
$$+\frac{e h_{31}^\gamma}{2M_Z^2}\left(\partial_\rho \widetilde{Z}_{\mu\nu}Z^{\mu\rho} + \partial_\rho \widetilde{A}_{\mu\nu}A^{\mu\rho}\right)Z^\nu ,$$

- **Matching Form Factors with CPC Dim-8 Operators:**

$$\hat{h}_4 = \frac{\hat{r}_4}{[\Lambda_{G+}^4]}, \quad \hat{h}_3^Z = \frac{\hat{r}_3^Z}{[\Lambda_{\widetilde{B}W}^4]}, \quad \hat{h}_3^\gamma = \frac{\hat{r}_3^\gamma}{[\Lambda_{G-}^4]}, \quad h_{31}^\gamma = \frac{r_{31}^\gamma}{[\Lambda_{\widetilde{BW}}^4]},$$
$$\hat{r}_4 = -\frac{v^2 M_Z^2}{s_W c_W}, \quad \hat{r}_3^Z = \frac{v^2 M_Z^2}{2 s_W c_W}, \quad \hat{r}_3^\gamma = -\frac{v^2 M_Z^2}{2 c_W^2}, \quad r_{31}^\gamma = -\frac{v^2 M_Z^2}{s_W c_W},$$

Matching: nTGC Form Factors *from* dim-8 Operators

- **From a Complete Set of CPV dim-8 Operators, we deduce a Complete Set of CPV nTGC Vertices in the electroweak broken phase, with which we construct the consistent formulation of nTGC Form Factors:**

$$\mathcal{L}_{\mathrm{nTGC}}^{\mathrm{CPV}} = \frac{e\hat{h}_1^Z}{M_Z^2}\left(A_{\mu\nu}Z^{\mu\rho}+Z_{\mu\nu}A^{\mu\rho}\right)\partial^\nu Z_\rho + \frac{e\hat{h}_{11}^\gamma}{M_Z^2}A_{\mu\nu}A^{\mu\rho}\partial^\nu Z_\rho - \frac{e\hat{h}_2}{2M_Z^4}A_{\mu\nu}Z^{\mu\rho}\partial^2\left(Z^\nu{}_\rho + \frac{s_W}{c_W}A^\nu{}_\rho\right)$$
$$- \frac{e\hat{h}_1^\gamma}{M_Z^4}\left[c_{2W}\left(A_{\mu\nu}Z^{\mu\rho}+Z_{\mu\nu}A^{\mu\rho}\right)+s_{2W}\left(A_{\mu\nu}A^{\mu\rho}-Z_{\mu\nu}Z^{\mu\rho}\right)\right]$$
$$\times\left[\partial^2\partial^\nu\left(\frac{c_W}{s_W}Z_\rho + A_\rho\right) - \partial^\nu\partial_\rho\partial\cdot\left(\frac{c_W}{s_W}Z + A\right)\right].$$

- **We stress: the above CPV nTGC Form Factors are Fully Off-Shell !**

Matching: nTGC Form Factors *from* dim-8 Operators

- **Fully Off-Shell CPV nTGC Form Factors at Lagrangian Level:**

$$\mathcal{L}_{\rm nTGC}^{\rm CPV} = \frac{e\hat{h}_1^Z}{M_Z^2}\left(A_{\mu\nu}Z^{\mu\rho}+Z_{\mu\nu}A^{\mu\rho}\right)\partial^\nu Z_\rho + \frac{e h_{11}^\gamma}{M_Z^2}A_{\mu\nu}A^{\mu\rho}\partial^\nu Z_\rho - \frac{e\hat{h}_2}{2M_Z^4}A_{\mu\nu}Z^{\mu\rho}\partial^2\left(Z^\nu{}_\rho + \frac{s_W}{c_W}A^\nu{}_\rho\right)$$
$$-\frac{e\hat{h}_1^\gamma}{M_Z^4}\left[c_{2W}\left(A_{\mu\nu}Z^{\mu\rho}+Z_{\mu\nu}A^{\mu\rho}\right)+s_{2W}\left(A_{\mu\nu}A^{\mu\rho}-Z_{\mu\nu}Z^{\mu\rho}\right)\right]$$
$$\times\left[\partial^2\partial^\nu\left(\frac{c_W}{s_W}Z_\rho+A_\rho\right)-\partial^\nu\partial_\rho\partial\cdot\left(\frac{c_W}{s_W}Z+A\right)\right].$$

- **Matching Form Factors with CPV Dim-8 Operators:**

$$\hat{h}_1^Z = v^2M_Z^2\left(-\frac{1}{4[\Lambda_{WW}^4]}+\frac{c_W^2-s_W^2}{4c_Ws_W[\Lambda_{WB}^4]}+\frac{1}{[\Lambda_{BB}^4]}\right)$$

$$h_{11}^\gamma = v^2M_Z^2\left(-\frac{s_W}{4c_W[\Lambda_{WW}^4]}+\frac{1}{2[\Lambda_{WB}^4]}-\frac{c_W}{s_W[\Lambda_{BB}^4]}\right)$$

$$\hat{h}_1^\gamma = \frac{v^2M_Z^2}{4c_W^2[\Lambda_{\tilde{G}-}^4]},$$

$$\hat{h}_2 = -\frac{v^2M_Z^2}{2s_Wc_W[\Lambda_{\tilde{G}+}^4]}$$

Form Factors for Singly Off-Shell nTGV V*Zγ

- **Conventional CPC Form Factors for Singly Off-Shell nTGVs:**

$$\widetilde{\Gamma}^{\alpha\beta\mu(\mathrm{CPC})}_{Z\gamma V^*} = \frac{e\,(q_3^2 - M_V^2)}{M_Z^2}\left[h_3^V\, q_{2\nu}\,\epsilon^{\alpha\beta\mu\nu} + \frac{h_4^V}{M_Z^2}\, q_2^\alpha\, q_{3\nu}\, q_{2\sigma}\,\epsilon^{\beta\mu\nu\sigma}\right],$$

$$\widetilde{\Gamma}^{\alpha\beta\mu(\mathrm{CPV})}_{Z\gamma V^*} = \frac{e\,(q_3^2 - M_V^2)}{M_Z^2}\left[h_1^V\,(q_2^\alpha g^{\mu\beta} - q_2^\mu g^{\alpha\beta}) + \frac{h_2^V}{2M_Z^2}\, q_2^\alpha g^{\mu\beta}(M_Z^2 - q_3^2)\right].$$

- **Our New CPC Form Factors for Singly Off-Shell nTGVs:**

$$\Gamma^{\alpha\beta\mu(\mathrm{CPC})}_{Z\gamma V^*} = \frac{e\,(q_3^2 - M_V^2)}{M_Z^2}\left[\left(h_3^V + h_5^V\frac{q_3^2}{M_Z^2}\right) q_{2\nu}\,\epsilon^{\alpha\beta\mu\nu} + \frac{h_4^V}{M_Z^2}\, q_2^\alpha\, q_{3\nu}\, q_{2\sigma}\,\epsilon^{\beta\mu\nu\sigma}\right],$$

$$\Gamma^{\alpha\beta\mu(\mathrm{CPV})}_{Z\gamma V^*} = \frac{e\,(q_3^2 - M_V^2)}{M_Z^2}\left[\left(h_1^V + h_6^V\frac{q_3^2}{M_Z^2}\right)(q_2^\alpha g^{\mu\beta} - q_2^\mu g^{\alpha\beta}) + \frac{h_2^V}{2M_Z^2}\, q_2^\alpha g^{\mu\beta}(M_Z^2 - q_3^2)\right]$$

- **Our New Relations:**

$$h_4^V = 2h_5^V\,, \qquad h_2^V = 2h_6^V\,,$$

$$h_4^Z = \frac{c_W}{s_W}h_4^\gamma\,, \qquad h_2^Z = \frac{c_W}{s_W}h_2^\gamma$$

Form Factors for Singly Off-Shell nTGV V*Zγ

- **Conventional CPC Form Factors for Singly Off-Shell nTGVs:**

$$\widetilde{\Gamma}^{\alpha\beta\mu(\mathrm{CPC})}_{Z\gamma V^*} = \frac{e\,(q_3^2 - M_V^2)}{M_Z^2}\left[h_3^V\, q_{2\nu}\epsilon^{\alpha\beta\mu\nu} + \frac{h_4^V}{M_Z^2}\, q_2^\alpha\, q_{3\nu}\, q_{2\sigma}\,\epsilon^{\beta\mu\nu\sigma}\right],$$

$$\widetilde{\Gamma}^{\alpha\beta\mu(\mathrm{CPV})}_{Z\gamma V^*} = \frac{e\,(q_3^2 - M_V^2)}{M_Z^2}\left[h_1^V\,(q_2^\alpha g^{\mu\beta} - q_2^\mu g^{\alpha\beta}) + \frac{h_2^V}{2M_Z^2}\, q_2^\alpha g^{\mu\beta}(M_Z^2 - q_3^2)\right].$$

- **Our New CPC Form Factors for Singly Off-Shell nTGVs:**

$$\Gamma^{\alpha\beta\mu(\mathrm{CPC})}_{Z\gamma V^*} = \frac{e\,(q_3^2 - M_V^2)}{M_Z^2}\left[\left(h_3^V + h_4^V\frac{q_3^2}{2M_Z^2}\right) q_{2\nu}\epsilon^{\alpha\beta\mu\nu} + \frac{h_4^V}{M_Z^2}\, q_2^\alpha\, q_{3\nu}\, q_{2\sigma}\,\epsilon^{\beta\mu\nu\sigma}\right],$$

$$\Gamma^{\alpha\beta\mu(\mathrm{CPV})}_{Z\gamma V^*} = \frac{e\,(q_3^2 - M_V^2)}{M_Z^2}\left[h_1^V(q_2^\alpha g^{\mu\beta} - q_2^\mu g^{\alpha\beta}) + h_2^V\frac{M_Z^2\, q_2^\alpha\, g^{\mu\beta} - q_3^2 q_2^\mu\, g^{\alpha\beta}}{2M_Z^2}\right].$$

Form Factors for Singly Off-Shell nTGV V*Zγ

Leading Contribution

- **Nontrivial Energy Cancellations:**

$$\mathcal{T}[Z_T\gamma_T](\mathrm{CPC}) = h_3^V O(E^2) + h_5^V O(E^4),$$
$$\mathcal{T}[Z_L\gamma_T](\mathrm{CPC}) = h_3^V O(E^3) + \underline{h_4^V O(E^5) + h_5^V O(E^5)},$$
$$\mathcal{T}[Z_T\gamma_T](\mathrm{CPV}) = h_1^V O(E^2) + h_6^V O(E^4),$$
$$\mathcal{T}[Z_L\gamma_T](\mathrm{CPV}) = h_1^V O(E^3) + \underline{h_2^V O(E^5) + h_6^V O(E^5)}.$$

$E^5 \rightarrow E^3$

- **According to EW Equivalence Theorem:**

$$\mathcal{T}[Z_L, \gamma_T] = \mathcal{T}[-\mathrm{i}\pi^0, \gamma_T] + B,$$

$$B = \mathcal{T}[v^\mu Z_\mu, \gamma_T]$$
$$v^\mu \equiv \epsilon_L^\mu - q_Z^\mu / M_Z = O(M_Z/E_Z)$$

→→ **It proves Energy Cancellations and impose Constraints:**

$$h_4^V / h_5^V = 2, \qquad h_2^V / h_6^V = 2,$$

Form Factors *for* Doubly Off-Shell nTGV V*Z*γ

- **CPC Form Factors for Doubly Off-Shell nTGVs:**

$$\Gamma^{\alpha\beta\mu}_{Z^*\gamma\gamma^*}(q_1,q_2,q_3) = \frac{e}{M_Z^2}\left(h_{31}^{\gamma} + \frac{\hat{h}_3^{\gamma} q_1^2}{M_Z^2}\right) q_3^2 q_{2\nu}\epsilon^{\alpha\beta\mu\nu} + \frac{e s_W \hat{h}_4 q_3^2}{2 c_W M_Z^4}\left(2q_2^{\alpha} q_{3\nu} q_{2\sigma}\epsilon^{\beta\mu\nu\sigma} + q_3^2 q_{2\nu}\epsilon^{\alpha\beta\mu\nu}\right),$$

$$\Gamma^{\alpha\beta\mu}_{Z^*\gamma Z^*}(q_1,q_2,q_3) = \frac{e(q_3^2 - q_1^2)}{M_Z^2}\left[\hat{h}_3^{Z} q_{2\nu}\epsilon^{\alpha\beta\mu\nu} + \frac{\hat{h}_4}{2M_Z^2}\left(2q_2^{\alpha} q_{3\nu} q_{2\sigma}\epsilon^{\beta\mu\nu\sigma} + q_3^2 q_{2\nu}\epsilon^{\alpha\beta\mu\nu}\right)\right].$$

- **Matching Form Factors with CPC Dim-8 Operators:**

$$\hat{h}_4 = \frac{\hat{r}_4}{[\Lambda^4_{G+}]}, \quad \hat{h}_3^Z = \frac{\hat{r}_3^Z}{[\Lambda^4_{\widetilde{B}W}]}, \quad \hat{h}_3^{\gamma} = \frac{\hat{r}_3^{\gamma}}{[\Lambda^4_{G-}]}, \quad h_{31}^{\gamma} = \frac{r_{31}^{\gamma}}{[\Lambda^4_{\widetilde{BW}}]},$$

$$\hat{r}_4 = -\frac{v^2 M_Z^2}{s_W c_W}, \quad \hat{r}_3^Z = \frac{v^2 M_Z^2}{2 s_W c_W}, \quad \hat{r}_3^{\gamma} = -\frac{v^2 M_Z^2}{2 c_W^2}, \quad r_{31}^{\gamma} = -\frac{v^2 M_Z^2}{s_W c_W},$$

→→ **Important for Invisible Channel:** $pp(q\bar{q}) \to Z^*\gamma \to \nu\bar{\nu}\gamma$

Form Factors for Doubly Off-Shell nTGV V*Z*γ

- **CPV Form Factors for Doubly Off-Shell nTGVs:**

$$\Gamma^{\alpha\beta\mu}_{Z^*\gamma\gamma^*}(q_1,q_2,q_3) = \frac{e}{M_Z^2}\left(h_{11}^{\gamma} + \frac{\hat{h}_1^{\gamma} q_1^2}{M_Z^2}\right) q_3^2 \left(q_2^{\alpha} g^{\mu\beta} - q_2^{\mu} g^{\alpha\beta}\right) + \frac{e\, s_W \hat{h}_2 q_3^2}{2 c_W M_Z^4}\left(q_1^2 q_2^{\alpha} g^{\mu\beta} - q_3^2 q_2^{\mu} g^{\alpha\beta}\right),$$

$$\Gamma^{\alpha\beta\mu}_{Z^*\gamma Z^*}(q_1,q_2,q_3) = \frac{e\,(q_3^2 - q_1^2)}{M_Z^2}\left[\hat{h}_1^{Z}\left(q_2^{\alpha} g^{\mu\beta} - q_2^{\mu} g^{\alpha\beta}\right) + \frac{\hat{h}_2}{2M_Z^2}\left(q_1^2 q_2^{\alpha} g^{\mu\beta} - q_3^2 q_2^{\mu} g^{\alpha\beta}\right)\right],$$

- **Matching Form Factors with Dim-8 CPV Operators:**

$$\hat{h}_1^{Z} = v^2 M_Z^2\left(-\frac{1}{4[\Lambda_{WW}^4]} + \frac{c_W^2 - s_W^2}{4 c_W s_W [\Lambda_{WB}^4]} + \frac{1}{[\Lambda_{BB}^4]}\right),$$

$$h_{11}^{\gamma} = v^2 M_Z^2\left(-\frac{s_W}{4 c_W [\Lambda_{WW}^4]} + \frac{1}{2[\Lambda_{WB}^4]} - \frac{c_W}{s_W [\Lambda_{BB}^4]}\right),$$

$$\hat{h}_1^{\gamma} = \frac{v^2 M_Z^2}{4 c_W^2 [\Lambda_{\tilde{G}-}^4]},$$

$$\hat{h}_2 = -\frac{v^2 M_Z^2}{2 s_W c_W [\Lambda_{\tilde{G}+}^4]}.$$

$V^*Z^*\gamma$: Comparison with LHC Exp Analysis

- **For $pp(q\bar{q}) \to Z^*\gamma \to \nu\bar{\nu}\gamma$, ATLAS Exp Limits with 36.1/fb at LHC(13TeV):**

$$h_3^\gamma \in (-3.7,\, 3.7)\times 10^{-4}, \qquad h_3^Z \in (-3.2,\, 3.3)\times 10^{-4},$$
$$h_4^\gamma \in (-4.4,\, 4.3)\times 10^{-7}, \qquad h_4^Z \in (-4.5,\, 4.4)\times 10^{-7}.$$

- **Our New Predictions with the same inputs and kinetic cuts:**

$$|h_{31}^\gamma| < 3.5\times 10^{-4}, \quad |\hat{h}_3^\gamma| < 2.3\times 10^{-4}, \quad |\hat{h}_3^Z| < 3.1\times 10^{-4}, \quad |\hat{h}_4| < 1.4\times 10^{-5}.$$

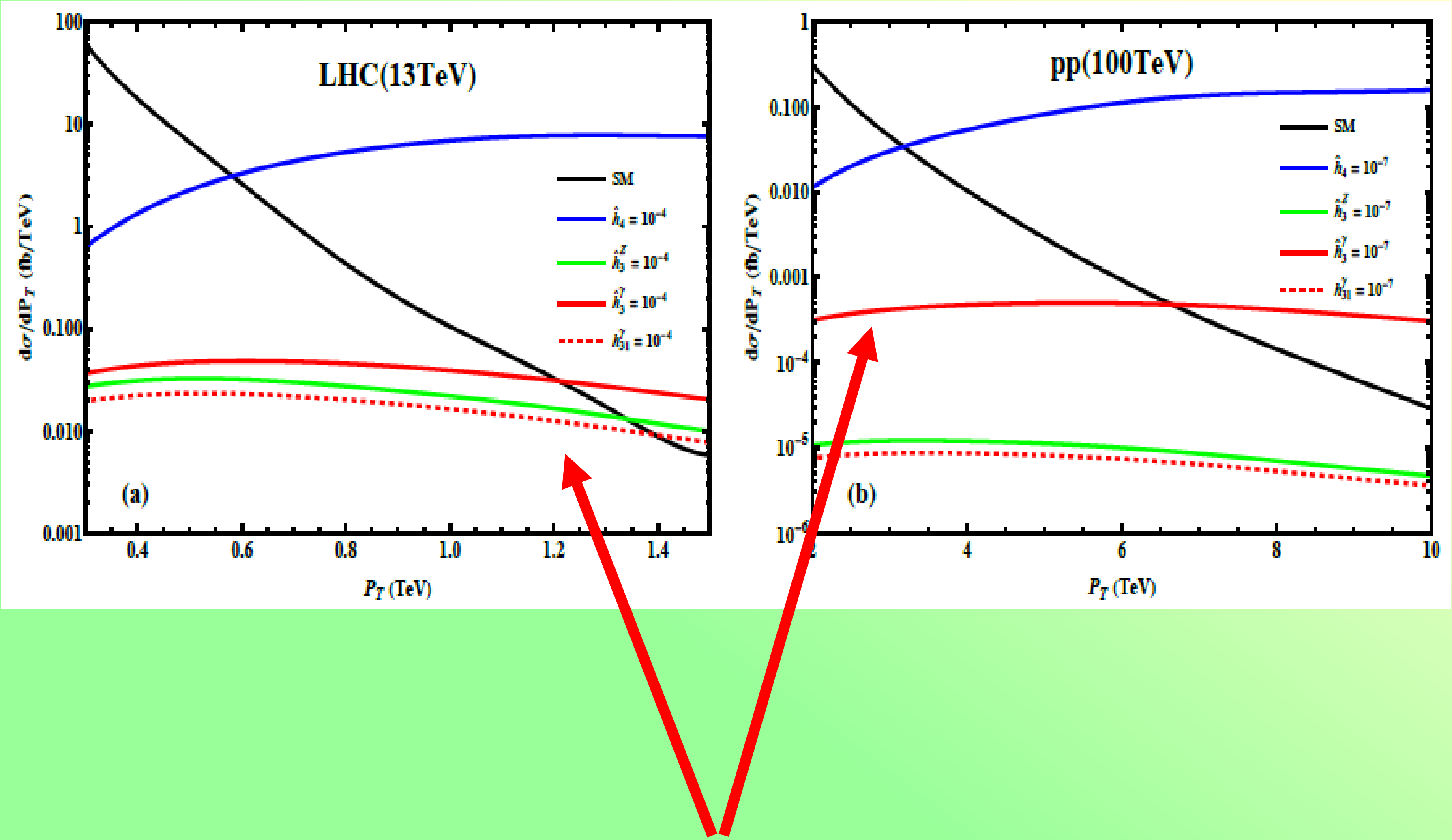
- **Differences:**

  →→ Our h_3^γ sensitivity is enhanced by (50-60)% by Off-Shell Z* Effects.

  →→ Atlas Exp Bounds on (h_4^γ, h_4^Z) are too large by a factor of 32 .

LHC Sensitivity to nTGCs

- **For** $pp(q\bar{q}) \to Z^*\gamma \to \nu\bar{\nu}\gamma$ **at LHC(13TeV):** **$P_T(\gamma)$ Distributions**



Probing nTGCs at LHC + pp(100TeV)

- For $pp(q\bar{q}) \to Z^*\gamma \to \nu\bar{\nu}\gamma$ at LHC and pp(100TeV) Collider:

→→ Our h_3^γ sensitivity is enhanced by (50-60)% at LHC and by factor ~10 at pp(100TeV) Collider due to Off-Shell Z* Effects !

→→ Sensitivities on $\hat{h}_2$ and $\hat{h}_4$ are much higher than $\hat{h}_{3,1}^\gamma$.

→→ Conventional Formula Bounds on (h_4^γ, h_4^Z) are too large by a factor of O(30) at LHC and O(100) at pp(100TeV).

$\sqrt{s}$	13 TeV				100 TeV		
$\mathcal{L}(\text{ab}^{-1})$	0.14	0.3	3		3	10	30
$\lvert\hat{h}_{4,2}\rvert\times 10^6$	11	8.5	4.2	$\lvert\hat{h}_{4,2}\rvert\times 10^9$	4.5	2.9	2.0
$\lvert\hat{h}_{3,1}^Z\rvert\times 10^4$	2.2	1.7	0.90	$\lvert\hat{h}_{3,1}^Z\rvert\times 10^7$	7.0	4.8	3.4
$\lvert\hat{h}_{3,1}^\gamma\rvert\times 10^4$	1.6	1.3	0.67	$\lvert\hat{h}_{3,1}^\gamma\rvert\times 10^7$	0.94	0.62	0.44
$\lvert h_{31,11}^\gamma\rvert\times 10^4$	2.5	2.0	1.0	$\lvert h_{31,11}^\gamma\rvert\times 10^7$	8.3	5.7	4.0

Probing nTGCs at LHC + pp(100TeV)

- **For** $pp(q\bar{q}) \to Z^*\gamma \to \nu\bar{\nu}\gamma$ **at LHC and pp(100TeV) Collider:**

→→ **Sensitivities to nTGC New Physics Scales reach (1-4)TeV at LHC and (4-28)TeV at pp(100TeV) Collider.**

$\sqrt{s}$	13 TeV			100 TeV		
$\mathcal{L}\,(\text{ab}^{-1})$	0.14	0.3	3	3	10	30
Λ_{G+}(CPC)	3.2	3.5	4.1	23	25	28
Λ_{G-}(CPC)	1.2	1.3	1.5	7.7	8.5	9.3
$\Lambda_{\widetilde{B}W}$(CPC)	1.3	1.4	1.6	5.4	5.9	6.4
$\Lambda_{\widetilde{BW}}$(CPC)	1.5	1.6	1.8	6.2	6.8	7.4
$\Lambda_{\widetilde{G}+}$(CPV)	2.7	2.9	3.5	19	21	23
$\Lambda_{\widetilde{G}-}$(CPV)	1.0	1.1	1.3	6.5	7.2	7.8
Λ_{WW}(CPV)	0.93	0.98	1.2	3.9	4.3	4.6
Λ_{WB}(CPV)	1.1	1.2	1.4	4.6	5.1	5.5
Λ_{BB}(CPV)	1.3	1.4	1.7	5.6	6.2	6.8

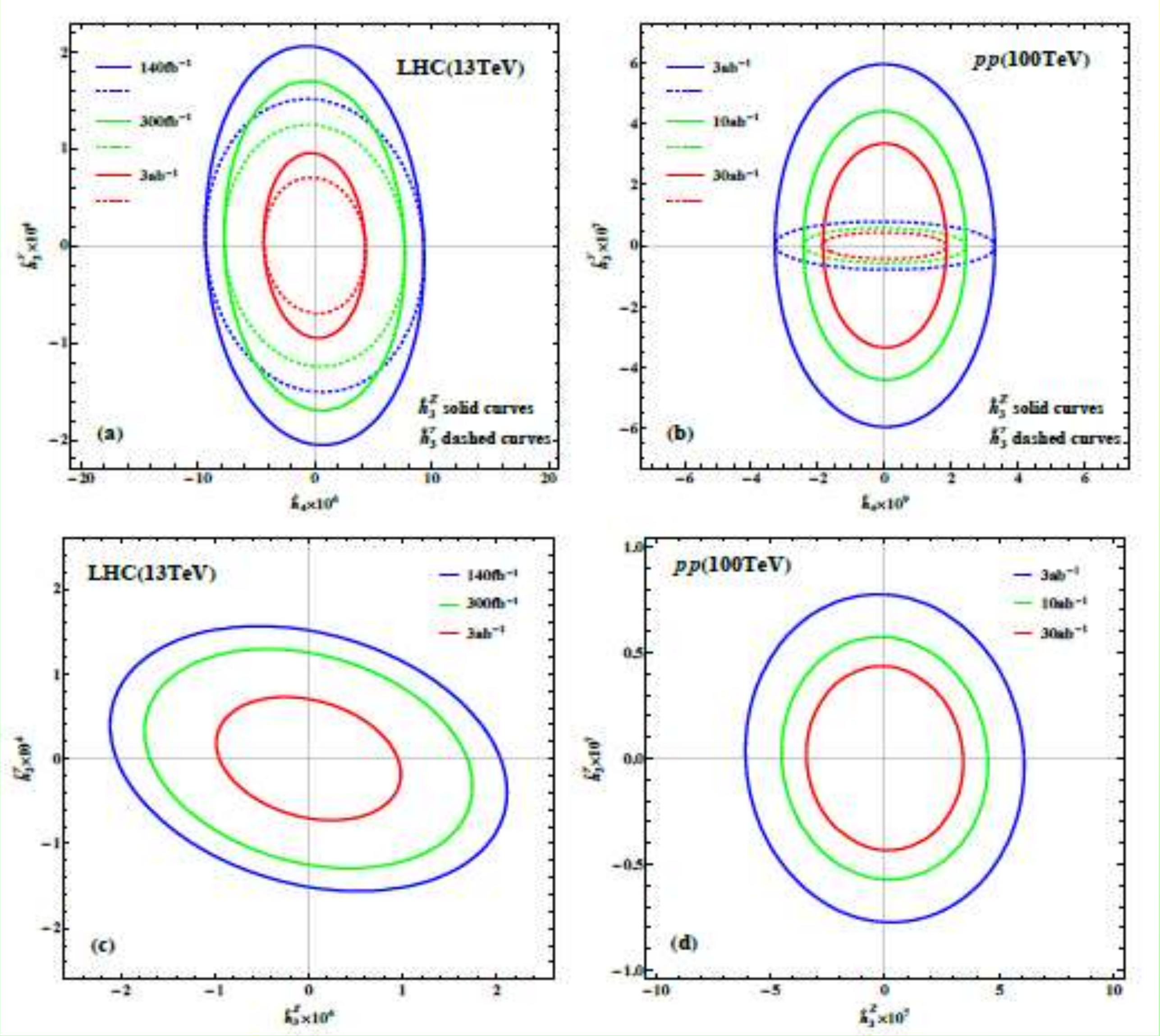
nTGCs: Combined via Lepton + Invisible Channels

- **For** $pp(q\bar{q}) \to Z^{*}\gamma \to \nu\bar{\nu}\gamma$ **at LHC and pp(100TeV) Collider:**
  $pp(q\bar{q}) \to Z\gamma \to \ell^{+}\ell^{-}\gamma$

$\sqrt{s}$	13 TeV				100 TeV		
$\mathcal{L}(\text{ab}^{-1})$	0.14	0.3	3		3	10	30
$\lvert\hat{h}_{4,2}\rvert \times 10^{6}$	9.6	7.5	3.8	$\lvert\hat{h}_{4,2}\rvert \times 10^{9}$	3.9	2.6	1.8
$\lvert\hat{h}^{Z}_{3,1}\rvert \times 10^{4}$	1.9	1.5	0.80	$\lvert\hat{h}^{Z}_{3,1}\rvert \times 10^{7}$	6.1	4.2	3.0
$\lvert\hat{h}^{\gamma}_{3,1}\rvert \times 10^{4}$	1.6	1.2	0.65	$\lvert\hat{h}^{\gamma}_{3,1}\rvert \times 10^{7}$	0.94	0.62	0.44
$\lvert h^{\gamma}_{31,11}\rvert \times 10^{4}$	2.2	1.8	0.94	$\lvert h^{\gamma}_{31,11}\rvert \times 10^{7}$	7.1	4.9	3.5

nTGCs at LHC + pp(100TeV): Correlations

➢ **For** $pp(q\bar{q}) \to Z^*\gamma \to \nu\bar{\nu}\gamma$ **at LHC and pp(100TeV) Collider:**



Unitarity Bounds on nTGCs: Safe

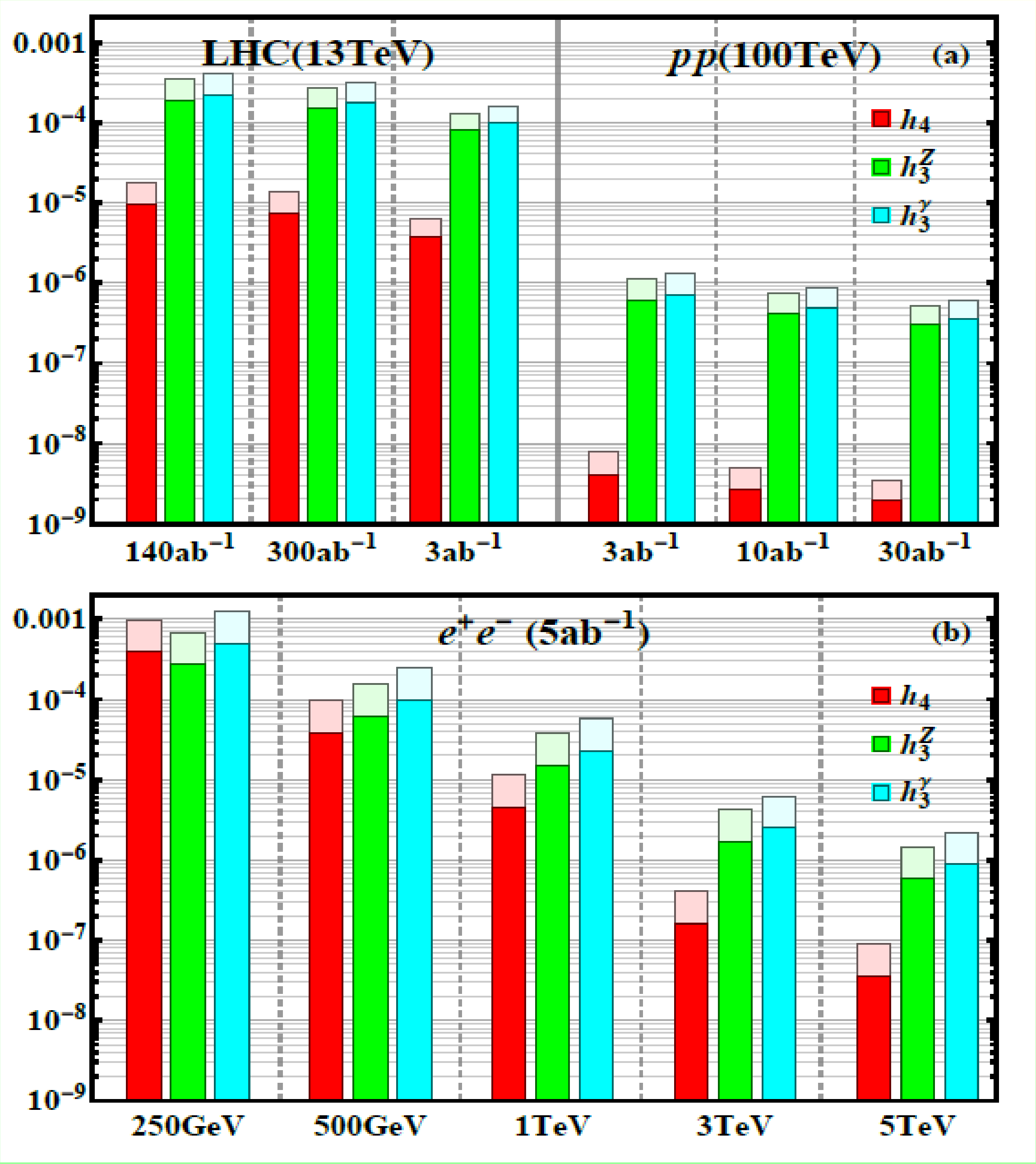
- **For** $pp(q\bar{q}) \to Z^*\gamma \to \nu\bar{\nu}\gamma$ **at LHC and pp(100TeV) Collider:**

→→ Unitarity Bounds are much weaker than our Collider Bounds.

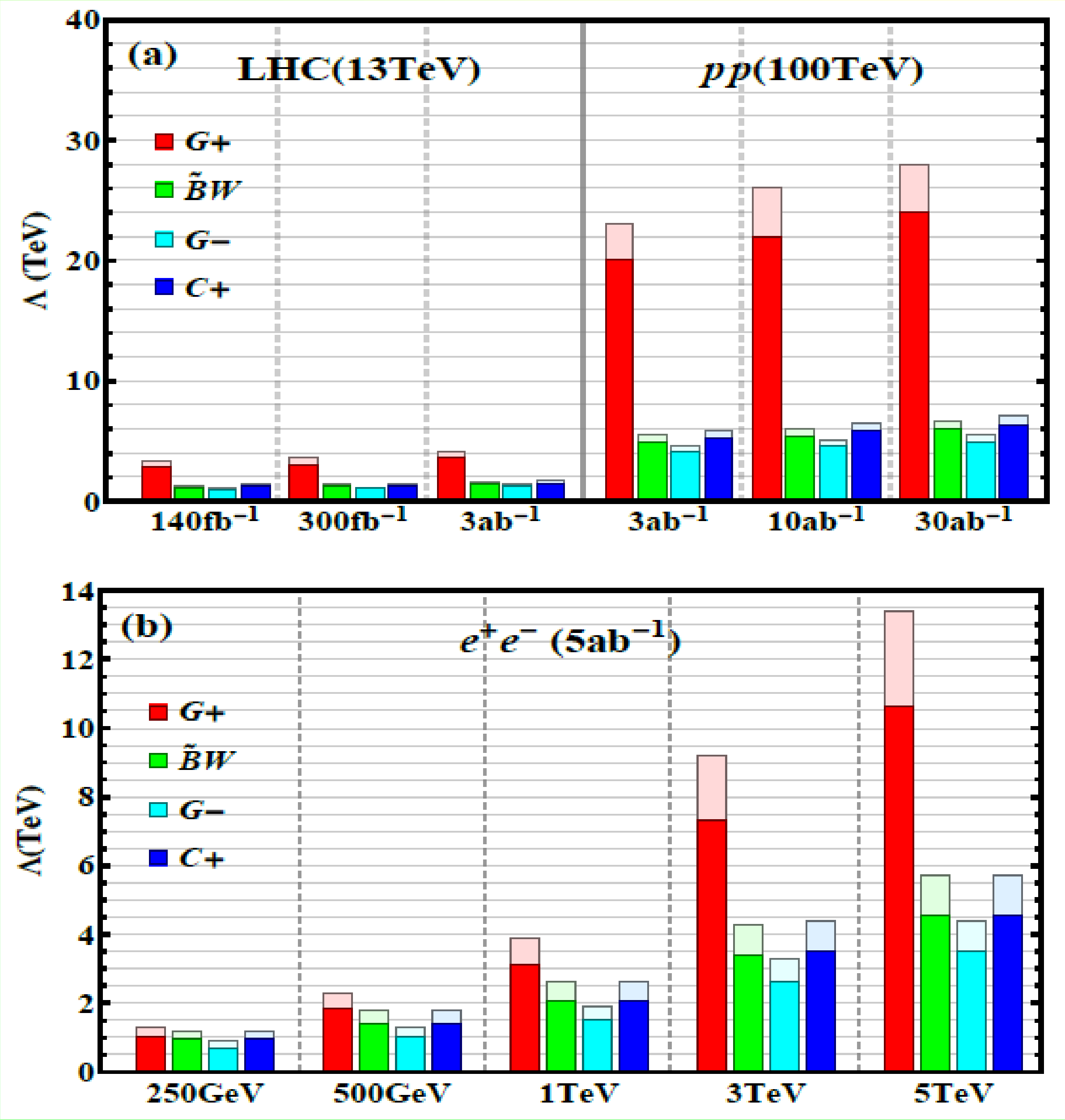
$E_{\rm CM}$ (TeV)	0.25	0.5	1	3	5	25	40
Λ_{G+}	0.078	0.16	0.31	0.93	1.6	7.8	12
Λ_{G-}	0.050	0.084	0.14	0.32	0.47	1.6	2.2
$\Lambda_{\widetilde{B}W}$	0.058	0.098	0.16	0.37	0.55	1.8	2.6
$\Lambda_{\widetilde{BW}}$	0.069	0.12	0.20	0.44	0.65	2.2	3.1
$\Lambda_{\widetilde{G}+}$	0.065	0.13	0.26	0.79	1.3	6.5	10
$\Lambda_{\widetilde{G}-}$	0.042	0.071	0.12	0.27	0.40	1.3	1.9
Λ_{WW}	0.041	0.069	0.12	0.26	0.39	1.3	1.8
Λ_{WB}	0.051	0.086	0.14	0.33	0.48	1.6	2.3
Λ_{BB}	0.069	0.12	0.20	0.44	0.65	2.2	3.1
$\lvert h_{4,2}\rvert$	33	2.0	0.13	1.6×10^{-3}	2.0×10^{-4}	3.3×10^{-7}	5.0×10^{-8}
$\lvert h_{3,1}^{Z}\rvert$	53	6.6	0.83	0.031	6.6×10^{-3}	5.3×10^{-5}	1.3×10^{-5}
$\lvert h_{3,1}^{\gamma}\rvert$	53	6.6	0.83	0.031	6.6×10^{-3}	5.3×10^{-5}	1.3×10^{-5}

Ellis, HJH, Xiao, arXiv:2308.16887

nTGCs: pp Colliders vs e+e- Colliders



nTGCs: pp Colliders vs e+e- Colliders



Summary

- nTGCs provide unique probe of dimension-8 SMEFT operators
- Opportunity to look for new physics without contributions from SM or dimension-6 SMEFT operators
- Preferred form factor formalism: SM SU(2)⊗U(1) invariance

JE, He & Xiao, arXiv:2206.11676

- Extension of previous analysis to include operators contributing to off-shell $Z^* \to \bar{\nu}\nu$: needed for pp colliders
- Comparisons to ATLAS analysis, combination with $Z \to \ell^+\ell^-$
- Also extension to CP-violating operators

JE, He & Xiao, arXiv:2308.16887

Summary

- **Testing Higgs Interaction Forces and Higgs-Induced Corrections to Gauge Force (Couplings) is the KEY Window to New Physics.**

- **New Physics in Higgs-Gauge Couplings, Pure Gauge Couplings, Higgs Self-Couplings may be connected.**

- **Important: Make Use of Full SU2) x U(1) EW Gauge Symmetry !**

- **Important to probe New Physics Scale Λ from *both* Higgs Processes and Gauge Boson Processes.**

→ **SMEFT is a Powerful Tool for Probing New Physics !**


Thank You !

nTGC related Fermionic Contact Operators

Ellis, HJH, Xiao, arXiv:2008.04298

2 Pure Gauge operators:

$$g\mathcal{O}_{G+} = \widetilde{B}_{\mu\nu} W^{a\mu\rho}(D_\rho D_\lambda W^{a\nu\lambda} + D^\nu D^\lambda W^a_{\lambda\rho}),$$
$$g\mathcal{O}_{G-} = \widetilde{B}_{\mu\nu} W^{a\mu\rho}(D_\rho D_\lambda W^{a\nu\lambda} - D^\nu D^\lambda W^a_{\lambda\rho}).$$

Eq of Motion:

$$\mathcal{O}_{G+} = \{\mathrm{i}H^\dagger \widetilde{B}_{\mu\nu} W^{\mu\rho}[D_\rho, D^\nu]H + \mathrm{i}\,2(D_\rho H)^\dagger \widetilde{B}_{\mu\nu} W^{\mu\rho} D^\nu H + \mathrm{h.c.}\} + \mathcal{O}_{C-},$$
$$\mathcal{O}_{G-} = \mathcal{O}_{\widetilde{B}W} + \mathcal{O}_{C+},$$

Fermionic Contact Operators: (contributing to ee → Zγ, ZZ)

$$\mathcal{O}_{C+} = \widetilde{B}_{\mu\nu} W^{a\mu\rho}[D_\rho(\overline{\psi_L} T^a \gamma^\nu \psi_L) + D^\nu(\overline{\psi_L} T^a \gamma_\rho \psi_L)],$$
$$\mathcal{O}_{C-} = \widetilde{B}_{\mu\nu} W^{a\mu\rho}[D_\rho(\overline{\psi_L} T^a \gamma^\nu \psi_L) - D^\nu(\overline{\psi_L} T^a \gamma_\rho \psi_L)].$$

→ O_{G+}, O_{C-} give identical contributions to f f → Zγ, ZZ