Probing Non-Universal Theories Through Higgs Processes at Hadron Colliders

Zhen Liu
University of Maryland

3rd FCC week @ CERN
Jan 15th , 2020

Base on W. H. Chiu, ZL, L.-T. Wang, 1909.04549

Motivation

Generic BSM models often induce flavor dependent structures:
SUSY, Composite fermions, etc.

One generically expect flavor non-universality from

- Direct flavor violation of the underlying theory
- Renormalization group (& threshold corrections)

Many are constrained by low-energy precision measurements, such as D-Dbar mixing, Electron/Neutron dipole moments, etc.

e.g., in recent studies, Altmannshofer, Gori et al, 1210.2465, 1507.07927, 1610.02398, 1703.05873, 1712.01847; Bauer, Carena, et al, 1506.01719, 1512.03458, 1801.00363; Low, Tesi, L.T. Wang, 1507.07557; Evans, Shih, Thalapillil, 1504.00930 and many motivated by current/recent flavor anomalies

Motivation

Generic BSM models often induce flavor dependent structures:
SUSY, Composite fermions, etc.

One generically expect flavor non-universality from

- Direct flavor violation of the underlying theory
- Renormalization group (& threshold corrections)

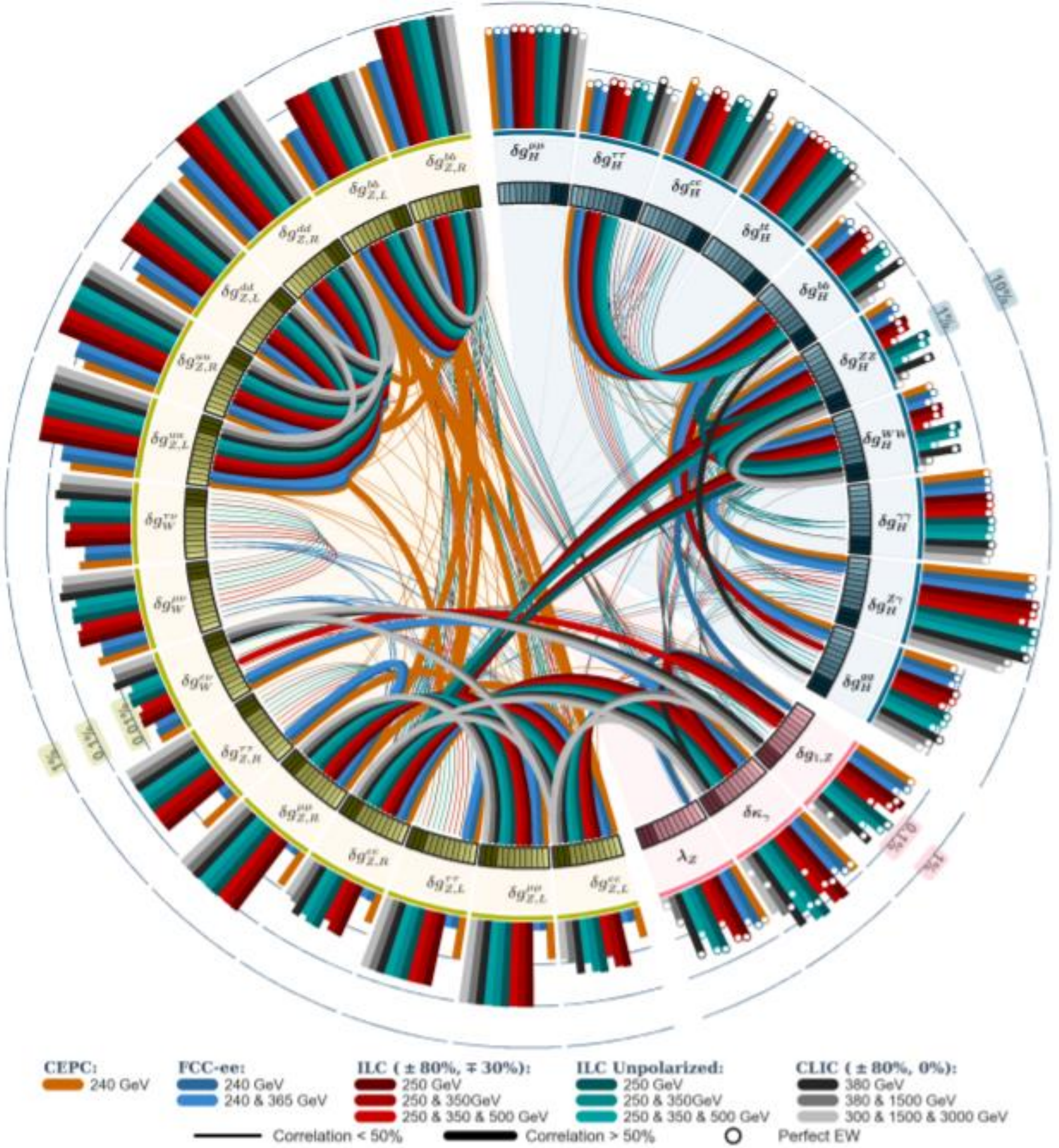
Many are constrained by low-energy precision measurements, such as D-Dbar mixing, Electron/Neutron dipole moments, etc.

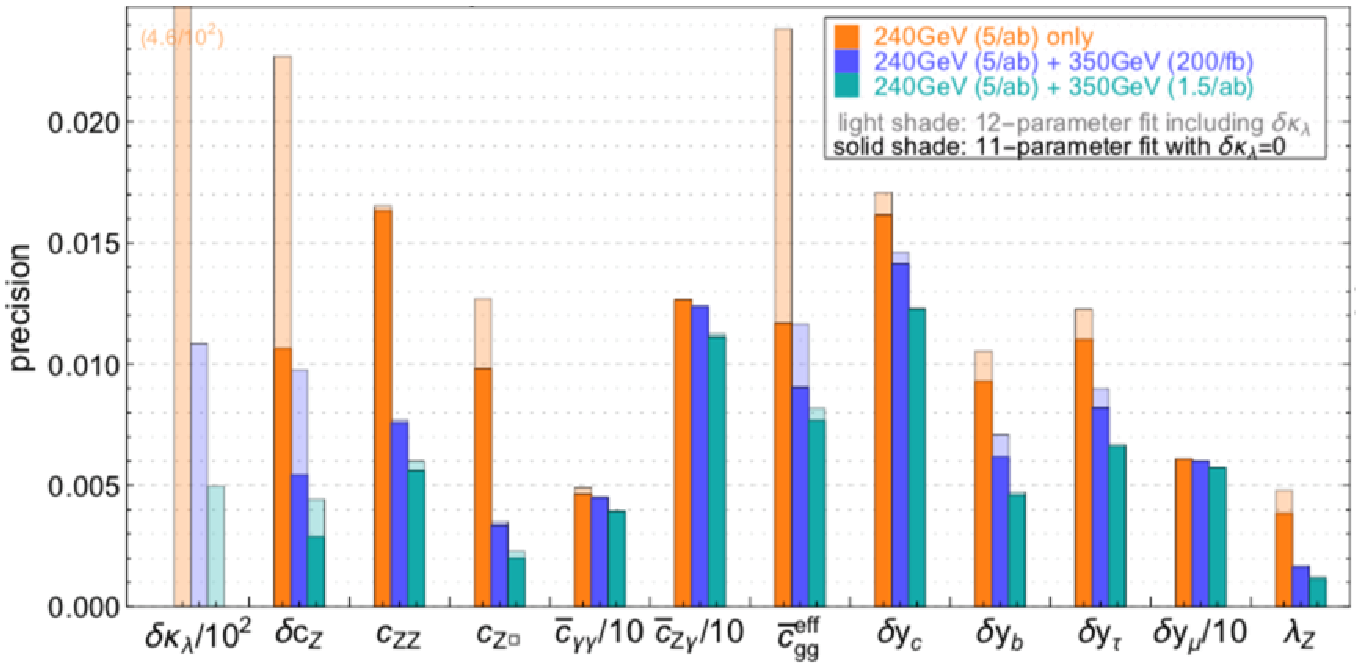
Question: Will high energy pp colliders have any new (& meaningful) information to add?

e.g., in recent studies, Altmannshofer, Gori et al, 1210.2465, 1507.07927, 1610.02398, 1703.05873, 1712.01847; Bauer, Carena, et al, 1506.01719, 1512.03458, 1801.00363; Low, Tesi, L.T. Wang, 1507.07557; Evans, Shih, Thalapillil, 1504.00930 and many motivated by current/recent flavor anomalies

Global fits of assumes Universal Theories

See talk from De Blas yesterday.





Higgs fit *without* trilinear, see Durieux, Grojean, Gu, Wang, 1704.02333, Jiayin Gu's talk next , and with trilinear + more observables, +ZL , S. Di Vita, G. Panico, M. Riembau, T. Vantalon, 1711.03978, De Blas, Durieux, Grojean, Gu, 1907.04311

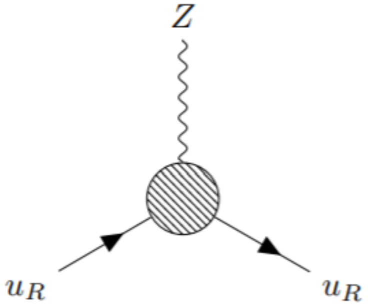
Parametrized by EFT

1

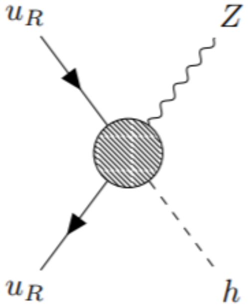
Parametrized by EFT

Operators		
$\mathcal{O}_{Hu}$	$\left(iH^\dagger \overleftrightarrow{D}_\mu H\right)(\bar{u}_R\gamma^\mu u_R)$	1
$\mathcal{O}_{Hd}$	$\left(iH^\dagger \overleftrightarrow{D}_\mu H\right)(\bar{d}_R\gamma^\mu d_R)$	
$\mathcal{O}_{HQ}$	$\left(iH^\dagger \overleftrightarrow{D}_\mu H\right)(\bar{Q}_L\gamma^\mu Q_L)$	
$\mathcal{O}_{HQ}^{(3)}$	$\left(iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H\right)(\bar{Q}_L\gamma^\mu \sigma^a Q_L)$	

Parametrized by EFT



$$= -i\frac{gv^2}{2c_w}\frac{c_{Hu}}{\Lambda^2}$$

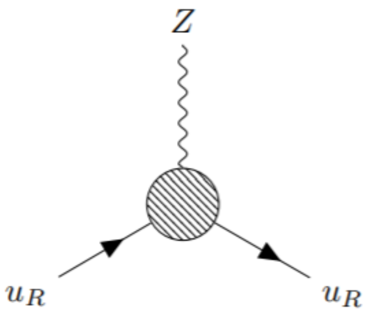


$$= -i\frac{gv}{c_w}\frac{c_{Hu}}{\Lambda^2}$$

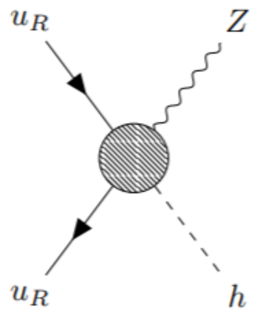
1

Operators	
$\mathcal{O}_{Hu}$	$\left(iH^\dagger \overleftrightarrow{D}_\mu H\right)(\bar{u}_R\gamma^\mu u_R)$
$\mathcal{O}_{Hd}$	$\left(iH^\dagger \overleftrightarrow{D}_\mu H\right)(\bar{d}_R\gamma^\mu d_R)$
$\mathcal{O}_{HQ}$	$\left(iH^\dagger \overleftrightarrow{D}_\mu H\right)(\bar{Q}_L\gamma^\mu Q_L)$
$\mathcal{O}_{HQ}^{(3)}$	$\left(iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H\right)(\bar{Q}_L\gamma^\mu \sigma^a Q_L)$

Parametrized by EFT



$$= -i\frac{gv^2}{2c_w}\frac{c_{Hu}}{\Lambda^2}$$



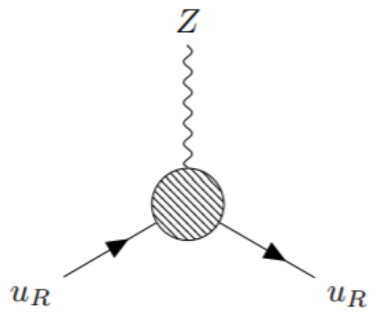
$$= -i\frac{gv}{c_w}\frac{c_{Hu}}{\Lambda^2}$$

Operators	
$\mathcal{O}_{Hu}$	$\left(iH^\dagger \overleftrightarrow{D}_\mu H\right)(\bar{u}_R\gamma^\mu u_R)$
$\mathcal{O}_{Hd}$	$\left(iH^\dagger \overleftrightarrow{D}_\mu H\right)(\bar{d}_R\gamma^\mu d_R)$
$\mathcal{O}_{HQ}$	$\left(iH^\dagger \overleftrightarrow{D}_\mu H\right)(\bar{Q}_L\gamma^\mu Q_L)$
$\mathcal{O}_{HQ}^{(3)}$	$\left(iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H\right)(\bar{Q}_L\gamma^\mu \sigma^a Q_L)$

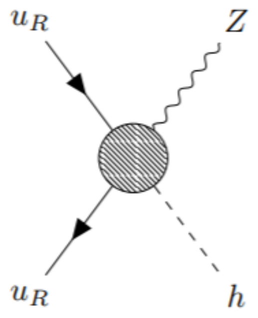
Process	High – energy primaries [1]
$\bar{u}_L d_L \to W_L Z_L, W_L h$	$\sqrt{2}c_L^{(3)}/\Lambda^2$
$\bar{u}_L u_L \to W_L W_L$ $\bar{d}_L d_L \to Z_L h$	$\left(c_L + c_L^{(3)}\right)/\Lambda^2$
$\bar{d}_L d_L \to W_L W_L$ $\bar{u}_L u_L \to Z_L h$	$\left(c_L - c_L^{(3)}\right)/\Lambda^2$
$\bar{f}_R f_R \to W_L W_L, Z_L h$	c_{Hf}/Λ^2

[1]R. Franceschini et at, 1712.01310. See also: C. Grojean et al, 1810.05149 & S. Banerjee et al, 1807.01796, Ruderman et al 1609.08157, 1706.03068, 1712.02347, also talk earlier from M. Riembau

Parametrized by EFT



$$= -i\frac{gv^2}{2c_w}\frac{c_{Hu}}{\Lambda^2}$$



$$= -i\frac{gv}{c_w}\frac{c_{Hu}}{\Lambda^2}$$

Flavor dependence possible

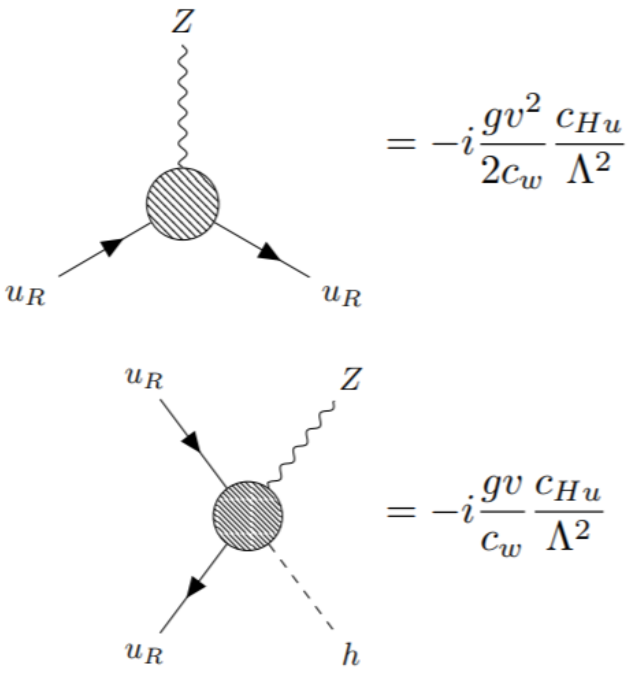
Operators	
$\mathcal{O}_{Hu}$	$\left(iH^\dagger \overleftrightarrow{D}_\mu H\right)(\bar{u}_R\gamma^\mu u_R)$
$\mathcal{O}_{Hd}$	$\left(iH^\dagger \overleftrightarrow{D}_\mu H\right)(\bar{d}_R\gamma^\mu d_R)$
$\mathcal{O}_{HQ}$	$\left(iH^\dagger \overleftrightarrow{D}_\mu H\right)(\bar{Q}_L\gamma^\mu Q_L)$
$\mathcal{O}_{HQ}^{(3)}$	$\left(iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H\right)(\bar{Q}_L\gamma^\mu \sigma^a Q_L)$

Process	High – energy primaries [1]
$\bar{u}_L d_L \to W_L Z_L, W_L h$	$\sqrt{2}c_L^{(3)}/\Lambda^2$
$\bar{u}_L u_L \to W_L W_L$ $\bar{d}_L d_L \to Z_L h$	$\left(c_L + c_L^{(3)}\right)/\Lambda^2$
$\bar{d}_L d_L \to W_L W_L$ $\bar{u}_L u_L \to Z_L h$	$\left(c_L - c_L^{(3)}\right)/\Lambda^2$
$\bar{f}_R f_R \to W_L W_L, Z_L h$	c_{Hf}/Λ^2

[1]R. Franceschini et at, 1712.01310. See also: C. Grojean et al, 1810.05149 & S. Banerjee et al, 1807.01796, Ruderman et al 1609.08157, 1706.03068, 1712.02347, also talk earlier from M. Riembau

Parametrized by EFT

What dominates all the pheno discussions of the diboson processes are the first generation couplings.



Flavor dependence possible

Operators	
$\mathcal{O}_{Hu}$	$\left(iH^\dagger \overleftrightarrow{D_\mu} H\right)(\bar{u}_R\gamma^\mu u_R)$
$\mathcal{O}_{Hd}$	$\left(iH^\dagger \overleftrightarrow{D_\mu} H\right)(\bar{d}_R\gamma^\mu d_R)$
$\mathcal{O}_{HQ}$	$\left(iH^\dagger \overleftrightarrow{D_\mu} H\right)(\bar{Q}_L\gamma^\mu Q_L)$
$\mathcal{O}_{HQ}^{(3)}$	$\left(iH^\dagger\sigma^a \overleftrightarrow{D_\mu} H\right)(\bar{Q}_L\gamma^\mu\sigma^a Q_L)$

Process	High – energy primaries [1]
$\bar{u}_L d_L \to W_L Z_L, W_L h$	$\sqrt{2}c_L^{(3)}/\Lambda^2$
$\bar{u}_L u_L \to W_L W_L$ $\bar{d}_L d_L \to Z_L h$	$\left(c_L + c_L^{(3)}\right)/\Lambda^2$
$\bar{d}_L d_L \to W_L W_L$ $\bar{u}_L u_L \to Z_L h$	$\left(c_L - c_L^{(3)}\right)/\Lambda^2$
$\bar{f}_R f_R \to W_L W_L, Z_L h$	c_{Hf}/Λ^2

[1] R. Franceschini et at, 1712.01310. See also: C. Grojean et al, 1810.05149 & S. Banerjee et al, 1807.01796, Ruderman et al 1609.08157, 1706.03068, 1712.02347, also talk earlier from M. Riembau

Probing EFT parameter space

Probing EFT parameter space

- High Λ suppression $\Rightarrow$ Needs precision measurements

Probing EFT parameter space

- High Λ suppression $\Rightarrow$ Needs precision measurements
- Typically associated with precision observables

$$\delta \lesssim \mathcal{O}(1\%)$$

Probing EFT parameter space

- High Λ suppression $\Rightarrow$ Needs precision measurements
- Typically associated with precision observables
$$\delta \lesssim \mathcal{O}(1\%)$$
- Does hadron collider play any rule?

Probing EFTs with hadron colliders

- Doable if

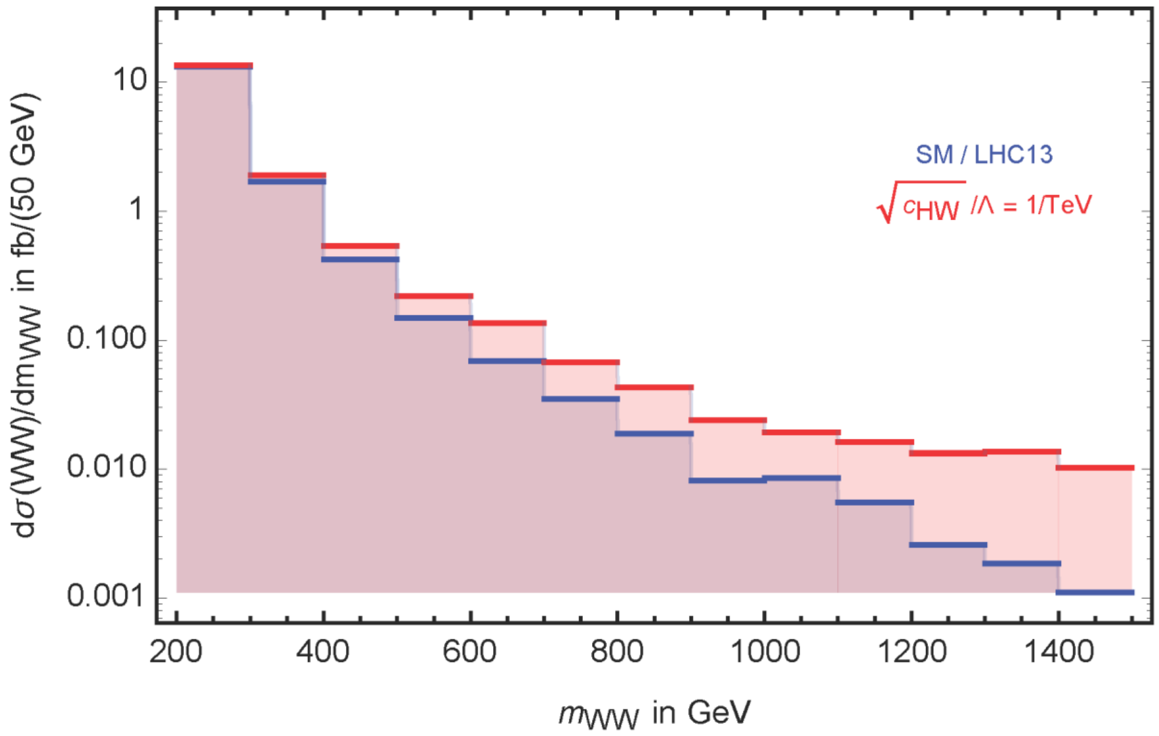
$$\frac{S}{B} \propto E^n, \qquad n > 0$$

Probing EFTs with hadron colliders

- Doable if

$$\frac{S}{B} \propto E^n, \qquad n > 0$$

- Example: Diboson processes

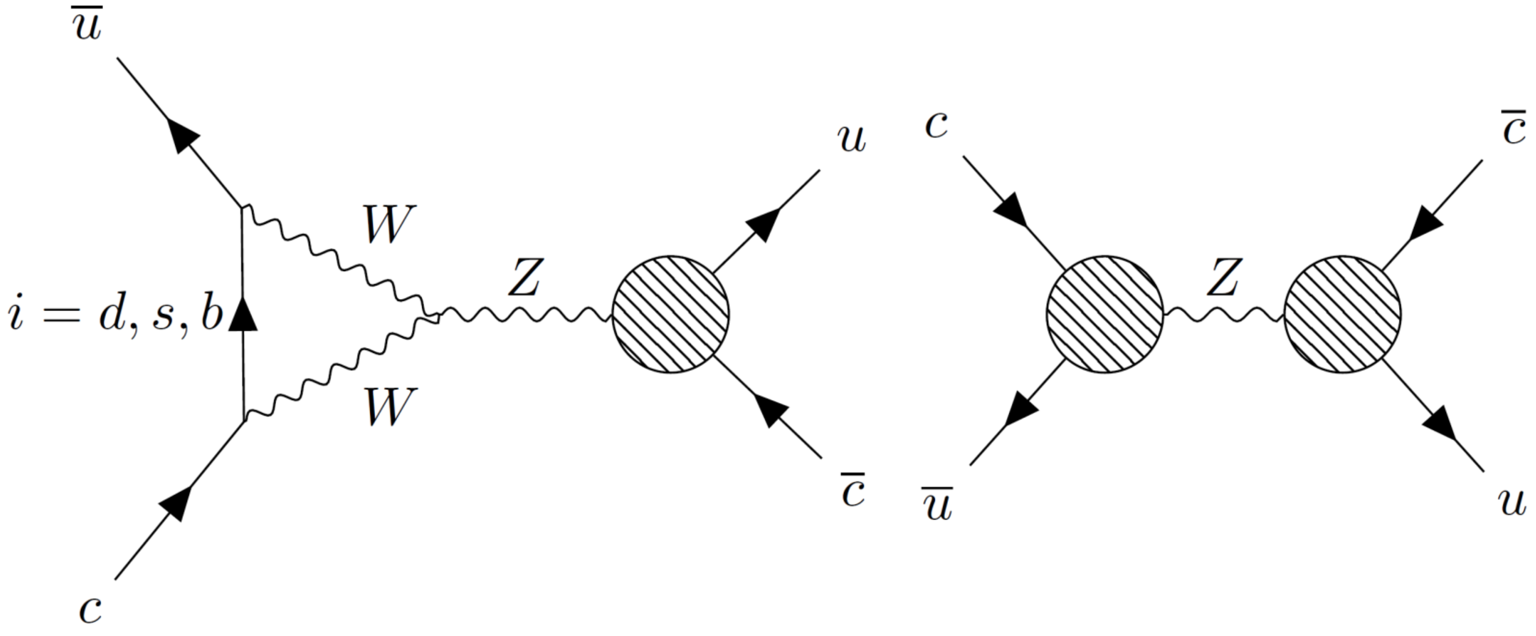


Constraints from flavor

- This type of model contributes to FCNCs, strongest constraint form D-Dbar mixing

Constraints from flavor

- This type of model contributes to FCNCs, strongest constraint form D-Dbar mixing
- For $\Delta C = 2$, 2 classes of processes:



Constraints from flavor (cont.)

- Contributes to 2 different $\Delta C = 2, d = 6$ operators:

  $\bar{c}_L u_R \bar{c}_R u_L$ and $\bar{c}_R \gamma_\mu u_R \; \bar{c}_R \gamma^\mu u_R$

[1] O. Gedalia, Y. Grossman, Y. Nir, G. Perez, [0906.1879]

Constraints from flavor (cont.)

- Contributes to 2 different $\Delta C = 2$, $d = 6$ operators:

$$\bar{c}_L u_R \bar{c}_R u_L \text{ and } \bar{c}_R \gamma_\mu u_R\ \bar{c}_R \gamma^\mu u_R$$

- Parametrically, the corresponding Wilson coefficients are given by

$$\frac{1}{16\pi^2} \frac{v^2}{M_Z^2} \frac{M_b^2}{M_W^2} \frac{c_{Hu}}{\Lambda^2} |V_{ub}||V_{cb}| \left(U_{R,uu}^\dagger U_{R,uc} \right) \lesssim 1.6 \times 10^{-7} \left(\frac{1}{1\text{ TeV}} \right)^2$$

$$3 \left| \frac{c_{Hu}}{\Lambda^2} v \left(U_{R,uu}^\dagger U_{R,uc} \right) \right|^2 \lesssim 5.7 \times 10^{-7} \left(\frac{1}{1\text{ TeV}} \right)^2$$

[1] O. Gedalia, Y. Grossman, Y. Nir, G. Perez, [0906.1879]

Constraints from flavor (cont.)

- Consider 1st and 2nd generation partially universal theories

$$U_{R,uu}^{\dagger} U_{R,uc} \to U_{R,uu}^{\dagger} U_{R,uc} + U_{R,uc}^{\dagger} U_{R,cc} = -U_{R,ut}^{\dagger} U_{R,tc}$$

[1]

[1] PDG, Phys.Rev.D**98**, 030001

Constraints from flavor (cont.)

- Consider 1st and 2nd generation partially universal theories

$$U^\dagger_{R,uu} U_{R,uc} \to U^\dagger_{R,uu} U_{R,uc} + U^\dagger_{R,uc} U_{R,cc} = -U^\dagger_{R,ut} U_{R,tc}$$

- Dominated by

$$\frac{\Delta\Gamma(Z \to c\bar{c})}{\Gamma(Z \to c\bar{c})} \approx 1.6\%\ [1]$$

$$\to \frac{c_{Hu}}{\Lambda^2_{\mathrm{TeV}}} \lesssim 0.163$$

[1] PDG, Phys.Rev.D**98**, 030001

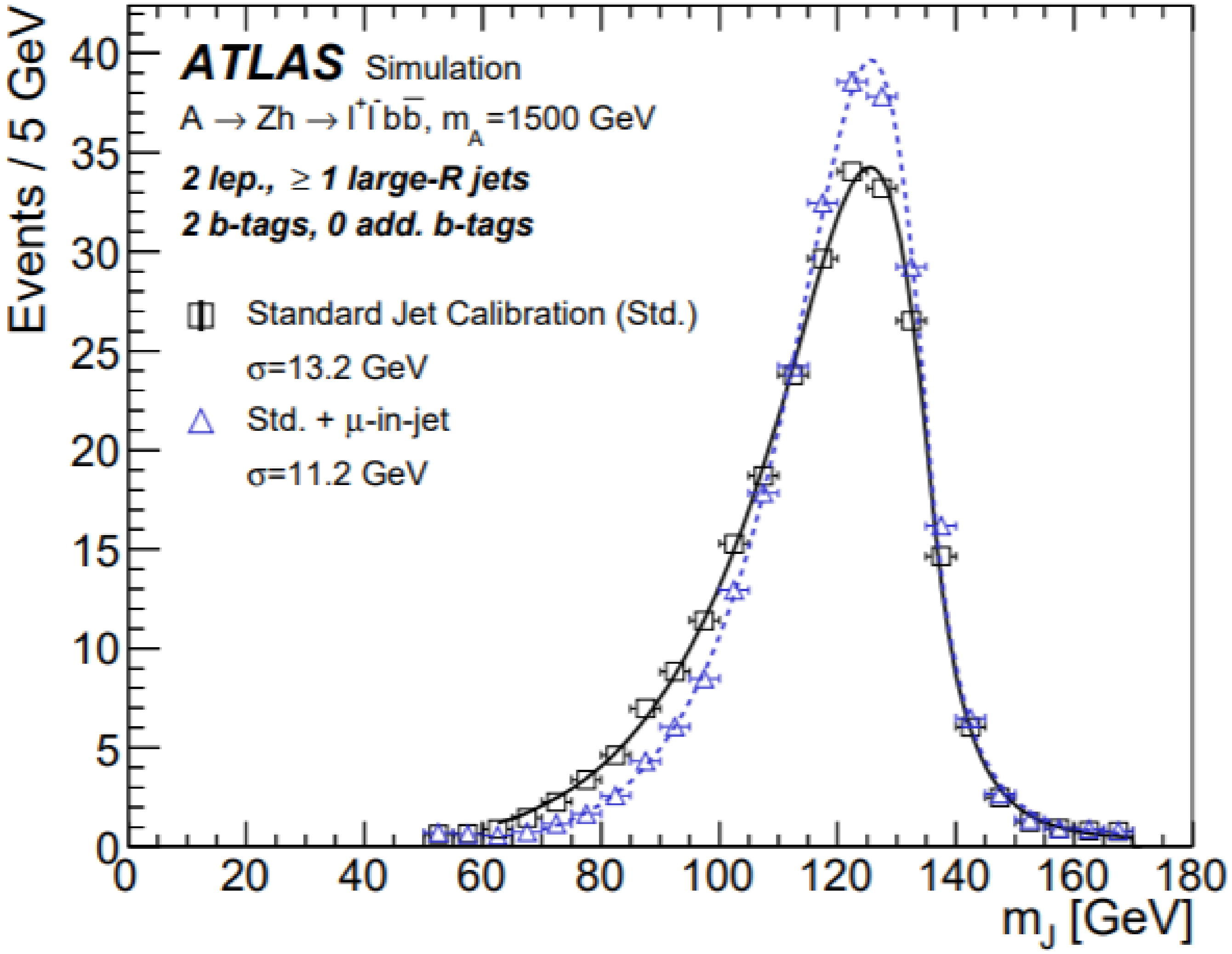
Analysis

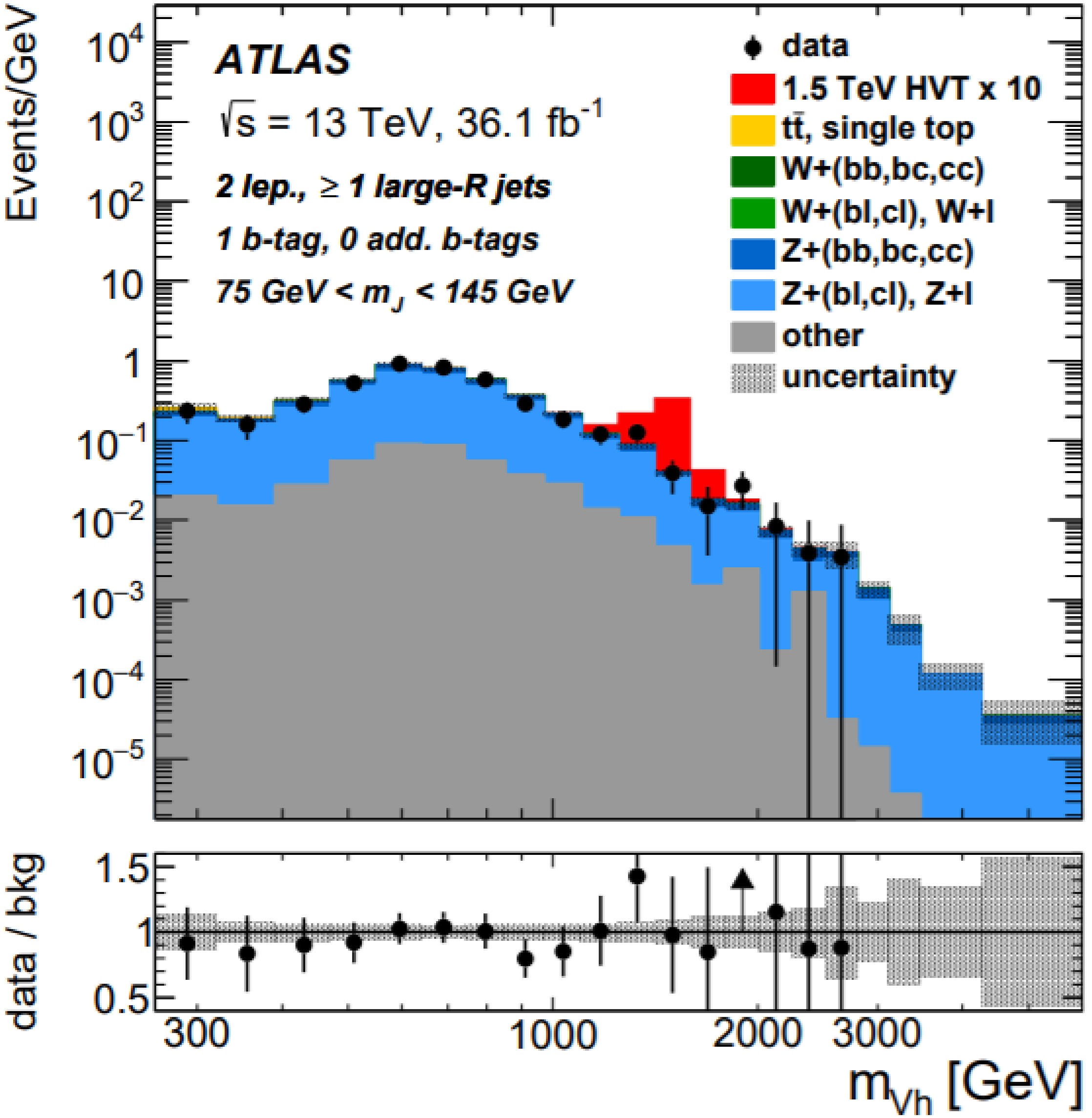
- Implemented operator in MadGraph5 using a UFO file from FeynRules
- Generated Zh events while scanning values of c_{Hu}/Λ^2
- Background estimated from 2017 ATLAS heavy resonance search[1]
    - Extended range by fixed background selection efficiency
- Cuts imposed to mimic the ATLAS study and scaled to match SM Zh

[1] The ATLAS Collaboration, [1712.06518]

Analysis Zh->(ll)(bb)

This is a competitive and clean channel compared to the WW process. Wh process not sensitive to this operator.





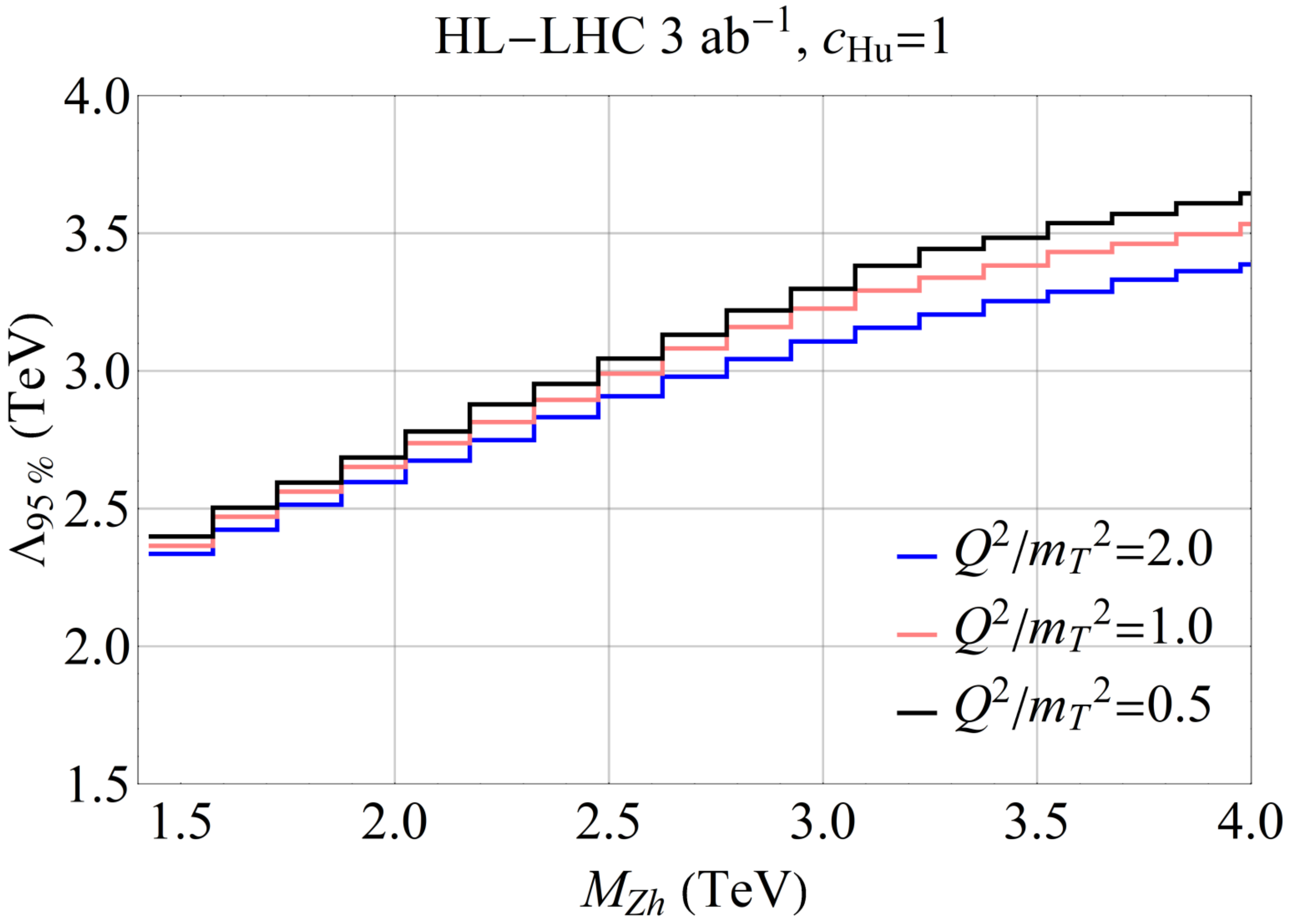
[1] The ATLAS Collaboration, [1712.06518](1712.06518)

Analysis

- Data binned by M_{Zh} with bin sizes of 150 GeV
- Estimated sensitivity regions with total significance of bins with $M_{Zh} < \Lambda$ greater than 2 (for 95% exclusion)

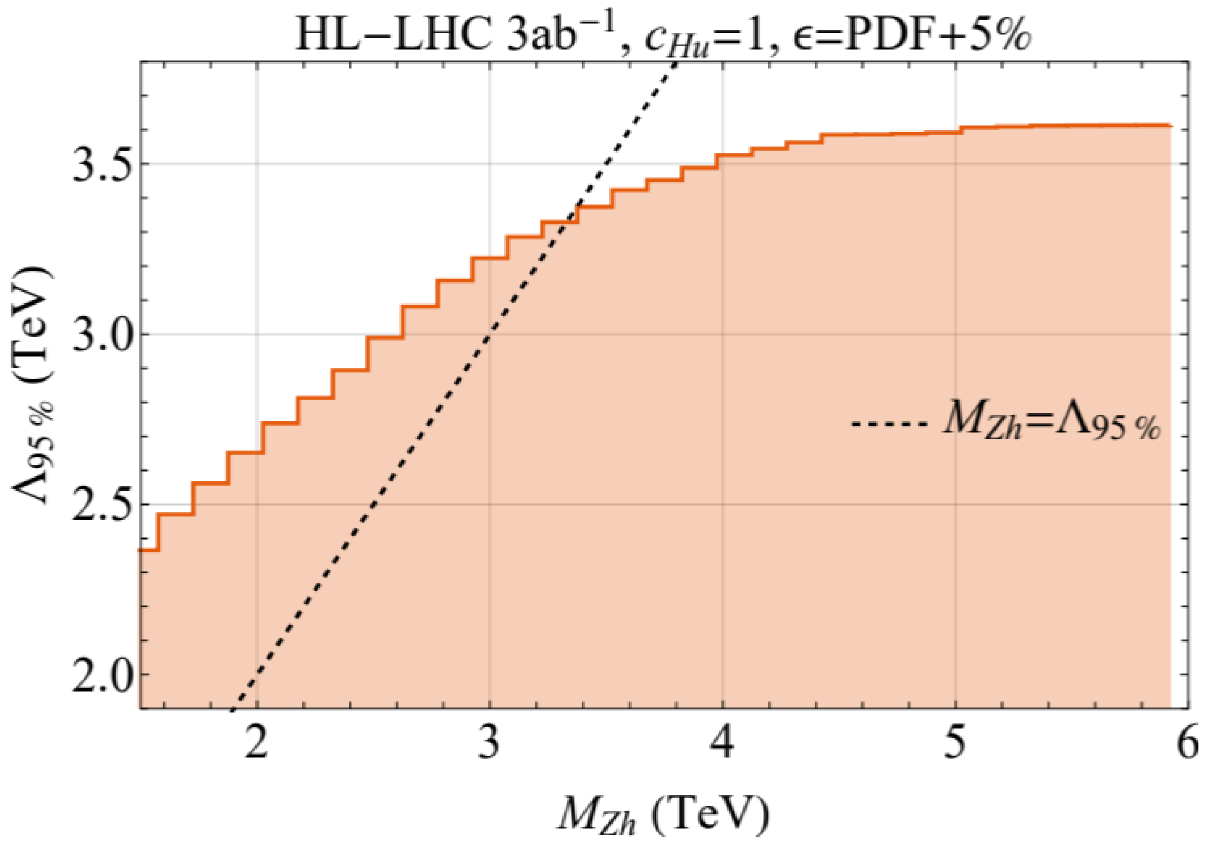
Uncertainty estimates

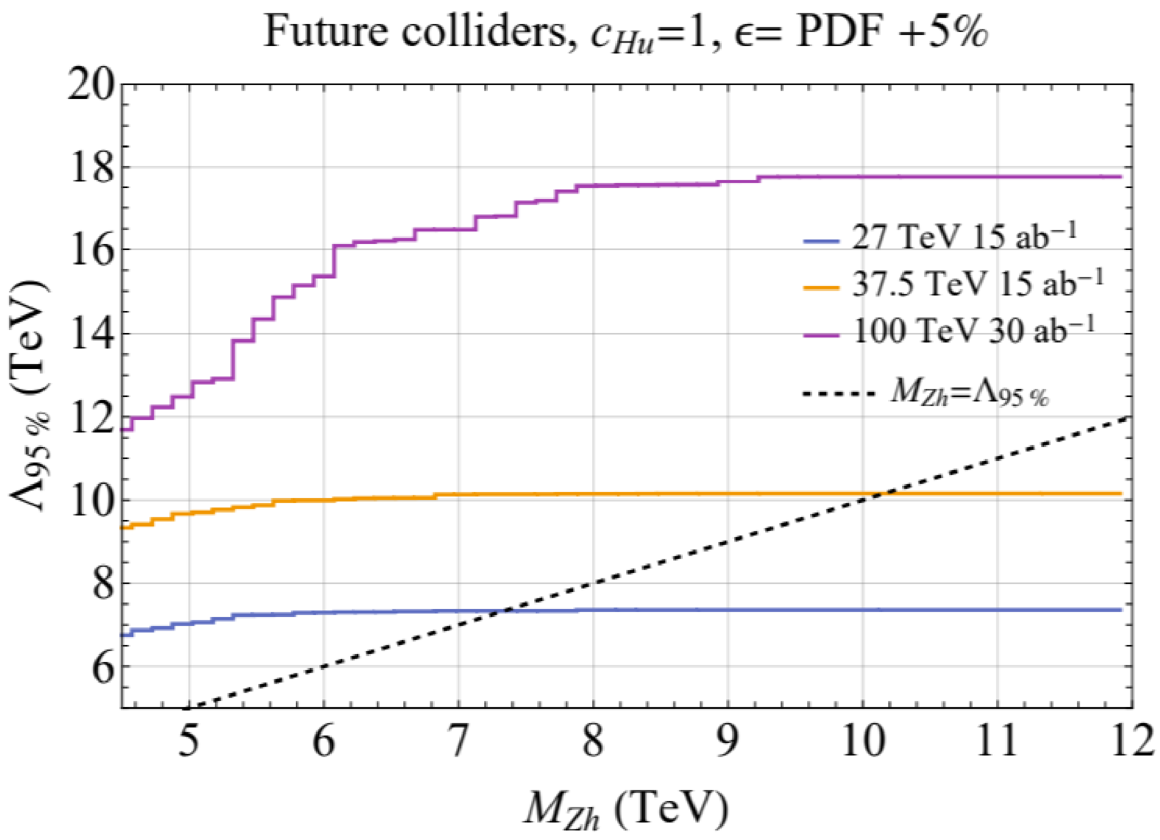
- Assume a universal 5% systematic uncertainty
- Included scale uncertainty



Sensitivities and upper cut on c.o.m. energy

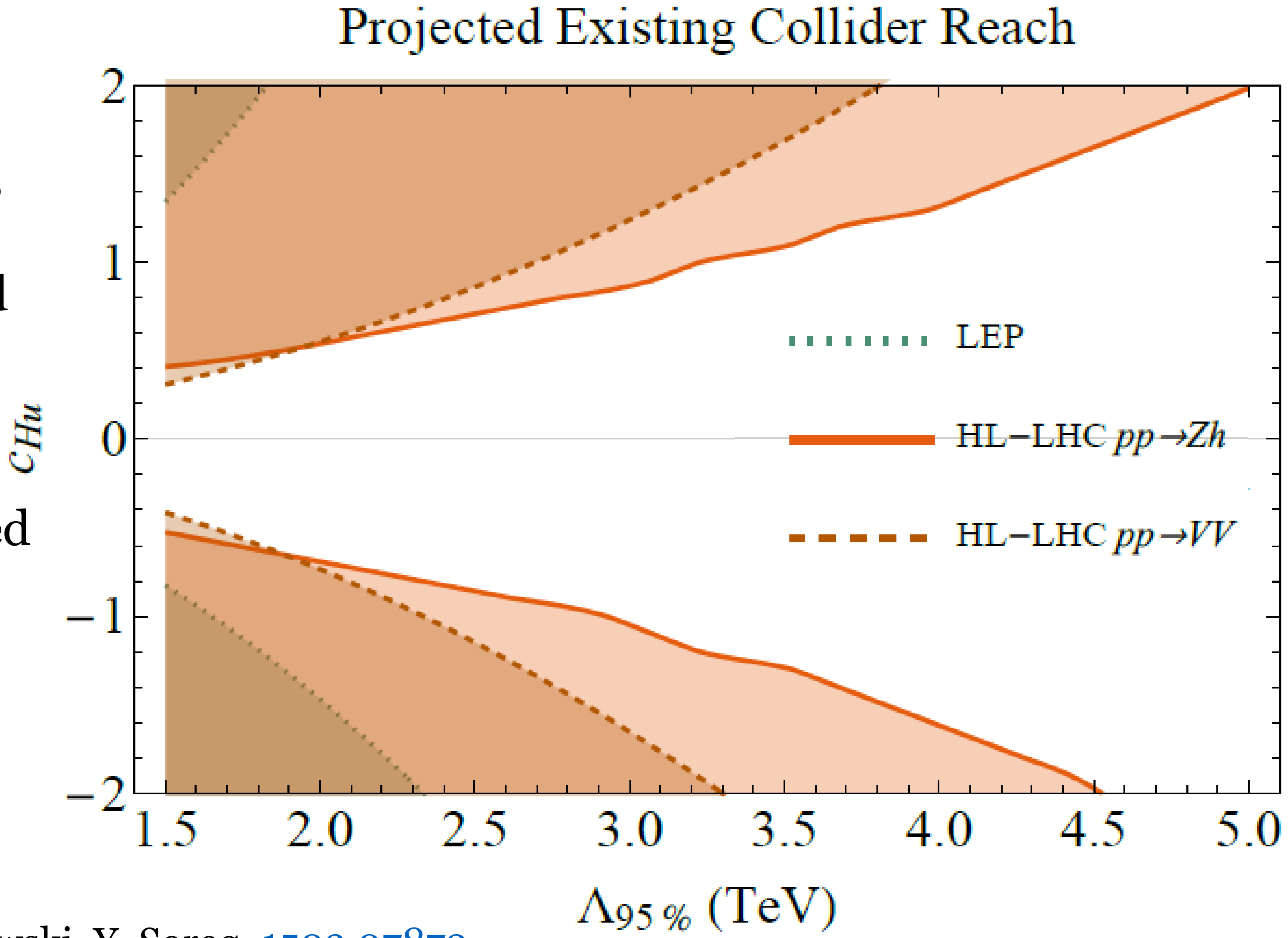
High invariant mass bins are cut-off by the break down of EFTs (depending on the Wilson-coefficients)





Results (HL-LHC)

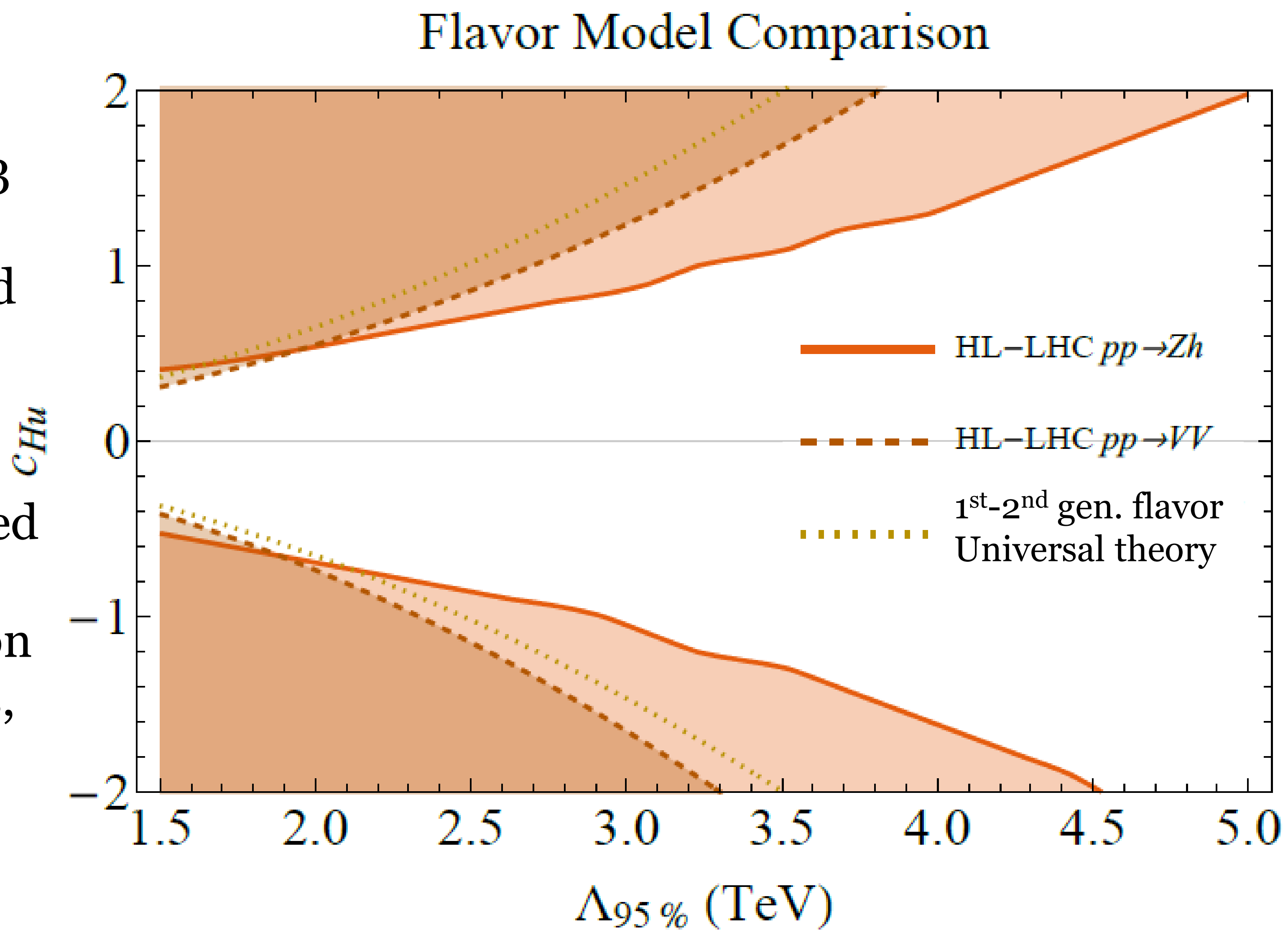
- For Unity Wilson Coefficient, HL-LHC ZH process can probe up to 3 TeV
- Sensitivity extend beyond 4.5 TeV for stronger interactions
- One does obtain more sensitivity when compared to LEP



LEP constraints A. Efrati, A. Falkowski, Y. Soreq, [1503.07872](1503.07872)

Results (HL-LHC)

- For Unity Wilson Coefficient, HL-LHC ZH process can probe up to 3 TeV
- Sensitivity extend beyond 4.5 TeV for stronger interactions
- One does obtain more sensitivity when compared to LEP
- In the first two-generation partial universal theories, covers more than FCNC



Analysis (future pp colliders)

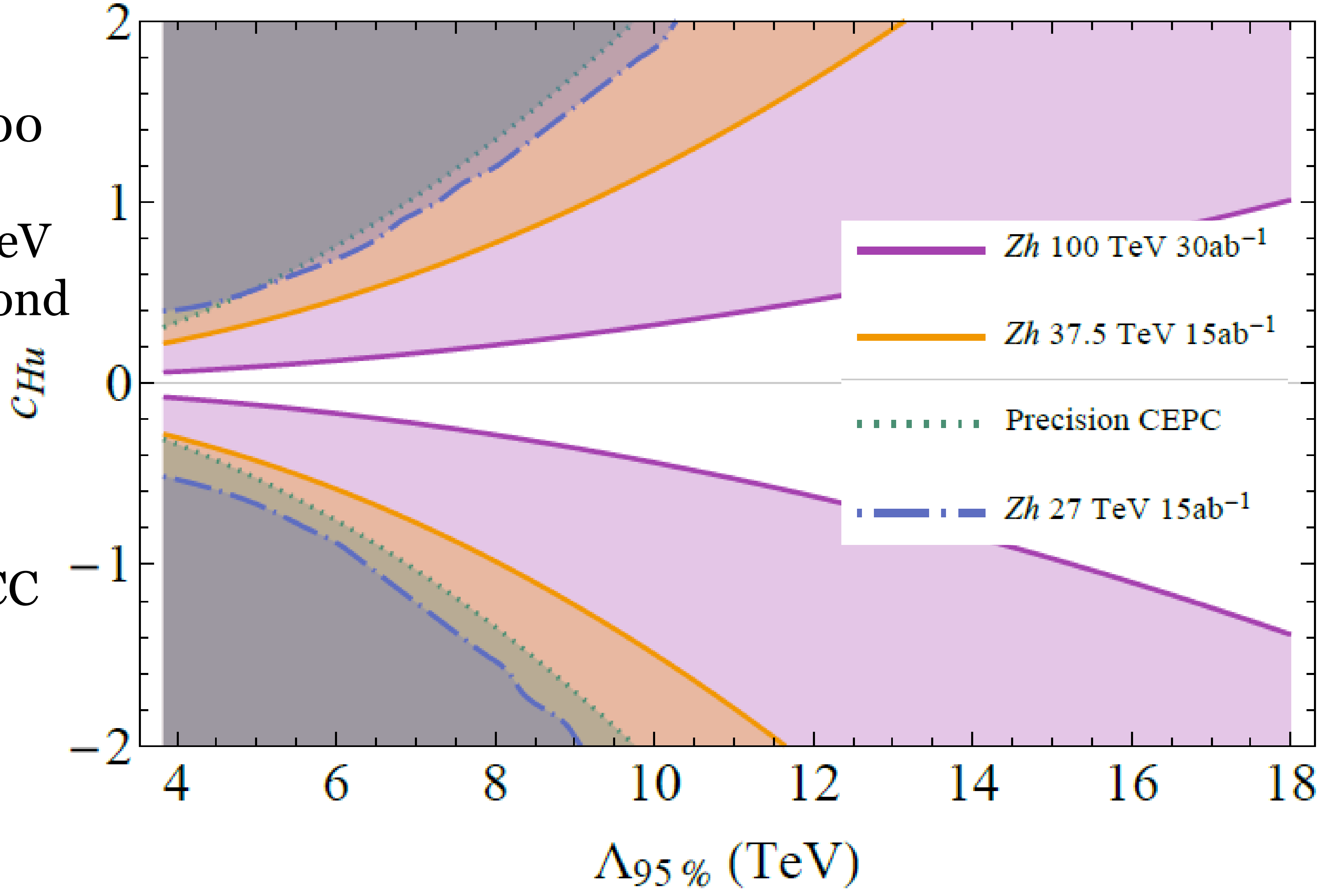
- Repeated analysis for several potential future colliders:

Collider	$\sqrt{s}$	$\int \mathcal{L} dt$
HE-LHC	27 TeV	15 ab^{-1}
FCC-hh	37.5 TeV	30 ab^{-1}
FCC-hh	100 TeV	30 ab^{-1}

- Estimated background via differential rescaling from parton luminosity ratios

Future pp Colliders

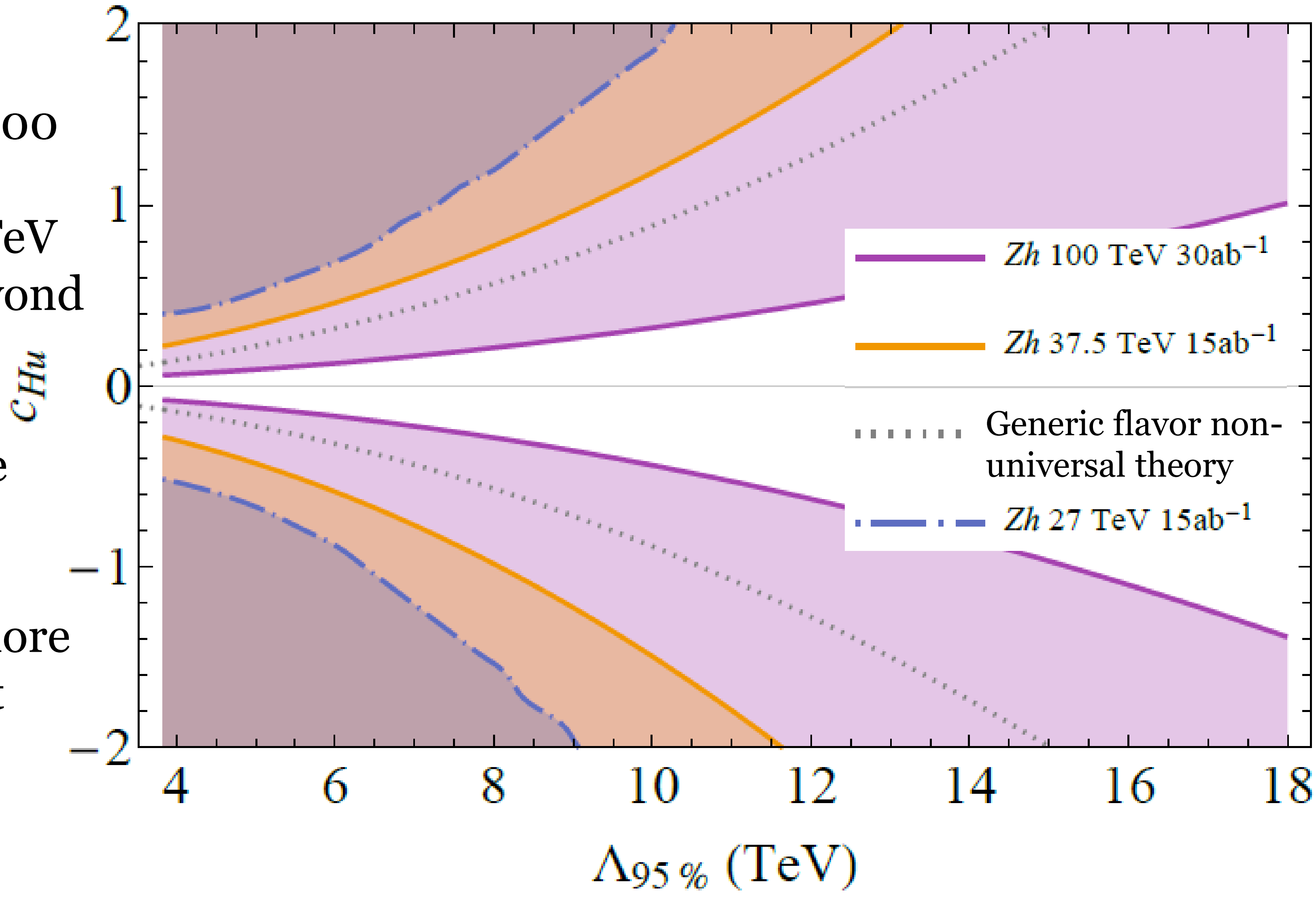
- For Unity Wilson Coefficient, 27/37.5/100 TeV ZH process can probe up to 8/10/18 TeV
- Sensitivity extend beyond 10/13/20 TeV for stronger interactions
- One does obtain more sensitivity when compared to CEPC/FCC



[1] Numbers from S. Di Vita, G. Durieux, Grojean, Gu, ZL , G. Panico, M. Riembau, T. Vantalon, [1711.03978](1711.03978)

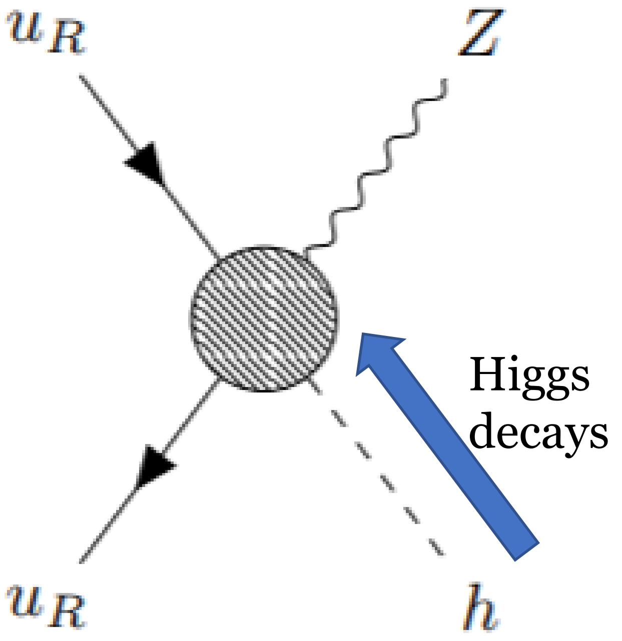
Future pp Colliders

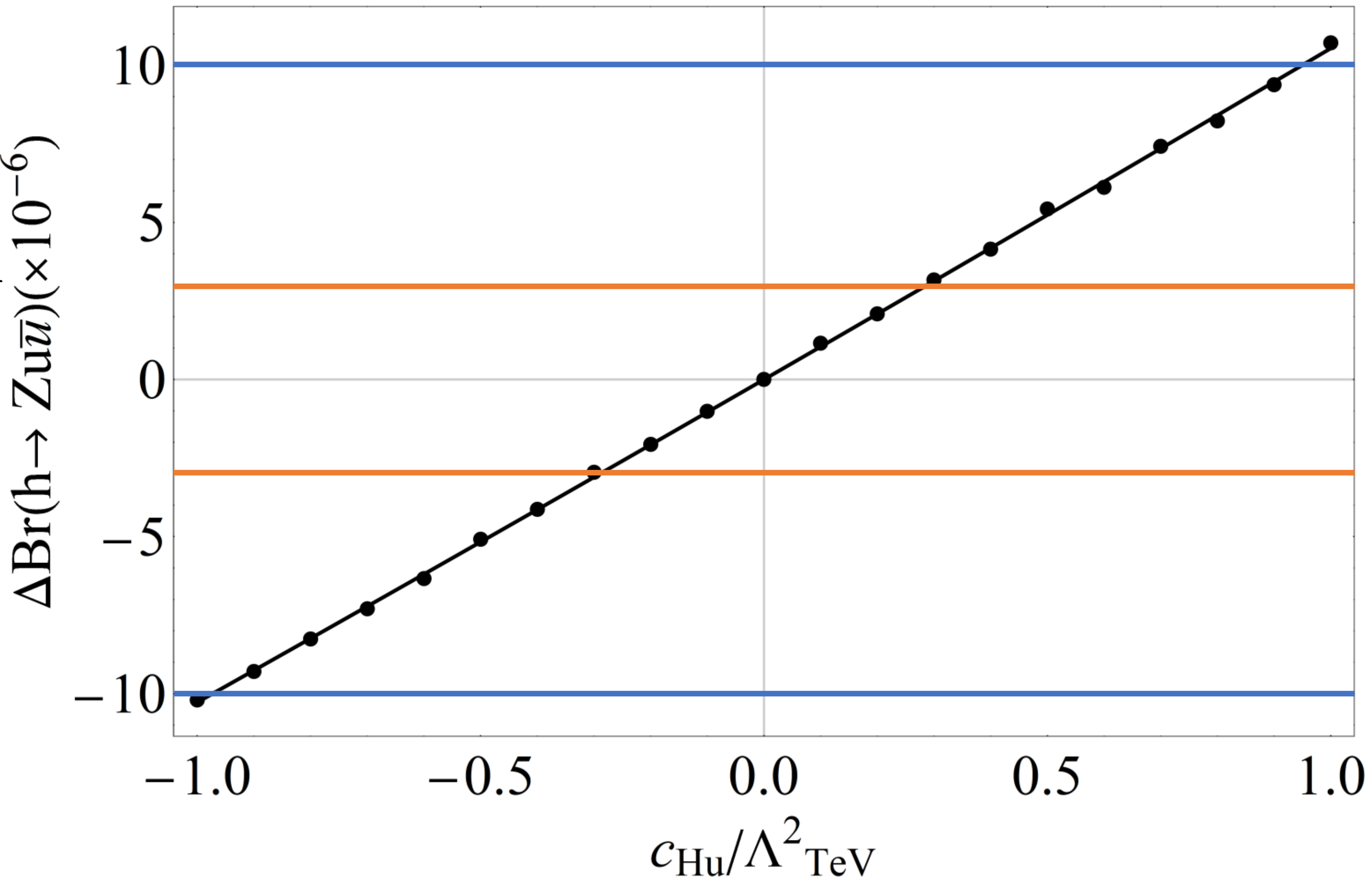
- For Unity Wilson Coefficient, 27/37.5/100 TeV ZH process can probe up to 8/11/18 TeV
- Sensitivity extend beyond 10/14/20 TeV for stronger interactions
- One does obtain more sensitivity when compared to CEPC
- At 100 TeV collider more coverage than current FCNC in flavor non-protected theory



Complementarity with Higgs exotic decays

- Operator also modifies Higgs decays.
- Future collider Higgs factories can provide complimentary information through the exotic Higgs decay precision program





Future lepton collider projections: ZL, H. Zhang, L.-T. Wang, [1612.09284](https://arxiv.org/abs/1612.09284)

Summary

- Probing Non-Universal Theories Through Higgs Processes at Hadron Colliders
- Zh shows competitive reach for contact operators;
- The energy growth can be utilized and should be interpreted in a flavor dependent way;
- pp->ZH->(ll)(bb) in the boosted regime a competitive channel for the diboson process
- Can be a useful input for future Global fit;

Summary

- Probing Non-Universal Theories Through Higgs Processes at Hadron Colliders
- Zh shows competitive reach for contact operators;
- The energy growth can be utilized and should be interpreted in a flavor dependent way;
- pp->ZH->(ll)(bb) in the boosted regime a competitive channel for the diboson process
- Can be a useful input for future Global fit;

Thank you!

Back up

$$[c_{\ell\ell}]_{1221} = (4.8 \pm 1.6) \times 10^{-2},$$

$$[\hat{c}'_{H\ell}]_{ii} = \begin{pmatrix} -1.09 \pm 0.64 \\ -1.45 \pm 0.59 \\ 1.86 \pm 0.79 \end{pmatrix} \times 10^{-2}, \quad [\hat{c}_{H\ell}]_{ii} = \begin{pmatrix} 1.03 \pm 0.63 \\ 1.31 \pm 0.62 \\ -2.01 \pm 0.80 \end{pmatrix} \times 10^{-2},$$

$$[\hat{c}_{He}]_{ii} = \begin{pmatrix} 0.22 \pm 0.66 \\ -0.6 \pm 2.6 \\ -1.3 \pm 1.3 \end{pmatrix} \times 10^{-3},$$

$$\left[\hat{c}'_{Hq}\right]_{ii} = \begin{pmatrix} 0.1 \pm 2.7 \\ -1.2 \pm 2.8 \\ -0.7 \pm 3.8 \end{pmatrix} \times 10^{-2}, \quad [\hat{c}_{Hq}]_{ii} = \begin{pmatrix} 1.8 \pm 7.1 \\ -0.8 \pm 2.9 \\ 0.0 \pm 3.8 \end{pmatrix} \times 10^{-2},$$

$$[\hat{c}_{Hu}]_{ii} = \begin{pmatrix} -3 \pm 10 \\ 0.8 \pm 1.0 \\ \times \end{pmatrix} \times 10^{-2}, \quad [\hat{c}_{Hd}]_{ii} = \begin{pmatrix} -6 \pm 32 \\ -7 \pm 10 \\ -4.6 \pm 1.6 \end{pmatrix} \times 10^{-2},$$

Anomalous Quark-Gauge Boson Couplings

- Anomalous quark-gauge boson couplings occur from the operators

$$
\begin{aligned}
O^{(3)}_{HF,ij} &= i\left(\Phi^\dagger\sigma^a D_\mu\Phi - (D_\mu\Phi)^\dagger\sigma^a\Phi\right)\bar{Q}_{Li}\gamma^\mu\sigma^a Q_{Lj} \\
O^{(1)}_{HF,ij} &= i\left(\Phi^\dagger D_\mu\Phi - (D_\mu\Phi)^\dagger\Phi\right)\bar{Q}_{Li}\gamma^\mu Q_{Lj} \\
O_{Hf,ij} &= i\left(\Phi^\dagger D_\mu\Phi - (D_\mu\Phi)^\dagger\Phi\right)\bar{q}_{Ri}\gamma^\mu q_{Rj}
\end{aligned}
$$

- Assuming flavor diagonal ($i = j$) and universal,

$$\delta g_L^{Zu} = -\frac{v^2}{2\Lambda^2}(C^{(1)}_{HF} - C^{(3)}_{HF}) \qquad \delta g_L^{Zd} = -\frac{v^2}{2\Lambda^2}(C^{(1)}_{HF} + C^{(3)}_{HF})$$

$$\delta g_R^{Zu} = -\frac{v^2}{2\Lambda^2}C_{Hu} \qquad \delta g_R^{Zd} = -\frac{v^2}{2\Lambda^2}C_{Hd}$$

$$\delta g_W = \delta g_L^{Zu} - \delta g_L^{Zd}$$

Aside: Comment on Calculating Cross Sections

- Amplitude has terms up to Λ^{-2}.
- Amplitude squared includes terms that go as Λ^{-4}.:

$$|\mathcal{A}|^2 \sim |g_{SM} + \frac{c_{dim-6}}{\Lambda^2}|^2 \sim g_{SM}^2 + g_{SM} \times \frac{c_{dim-6}}{\Lambda^2} + \frac{c_{dim-6}^2}{\Lambda^4}$$

  - g_{SM} is a generic Standard Model coupling.
- Same order as dimension-8 contributions:

$$\begin{aligned} |\mathcal{A}|^2 &\sim |g_{SM} + \frac{c_{dim-6}}{\Lambda^2} + \frac{c_{dim-8}}{\Lambda^4}|^2 \\ &\sim g_{SM}^2 + g_{SM} \times \frac{c_{dim-6}}{\Lambda^2} + \frac{c_{dim-6}^2}{\Lambda^4} + g_{SM} \times \frac{c_{dim-8}}{\Lambda^4} + O(\Lambda^{-6}) \end{aligned}$$

- Validity of keeping dimension-6 squared without dimension-8:
  - Strongly interacting theory: $c \gg g_{SM}$ so that $c_{dim-6}^2 \gg c_{dim-8} \times g_{SM}$ *(basis dependent statement)
  - Or the UV completion suppresses the dimension-8 terms.
  - Sometimes there are good reasons that $g_{SM} \times c_{dim-6}$ are suppressed and $1/\Lambda^4$ is dominant.