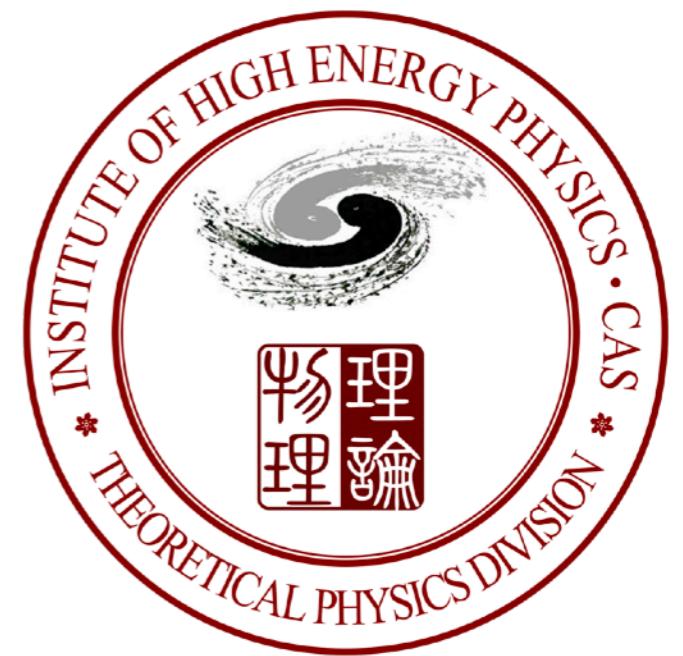


Electroweak fits and H properties and EFT

Cen Zhang

Institute of High Energy Physics
Chinese Academy of Sciences

Higgs Hunting 2019
July 29 Orsay

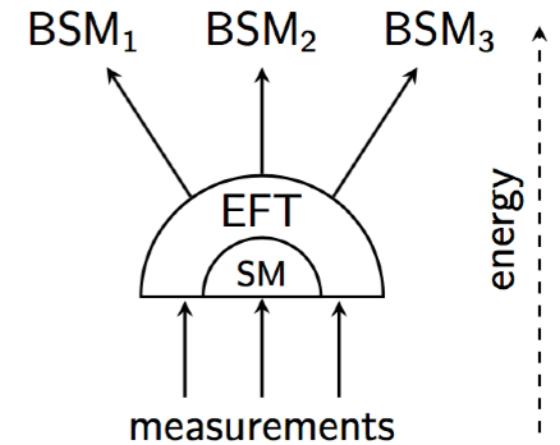


- EW and Higgs sectors in the SM effective field theory (SMEFT)
- Selection of topics focusing on the connection between the Higgs and other parts of the SM, and guided by the following questions (and personal taste...)
 - What can be learnt on the Higgs from measurements in other sectors?
 - What can be learnt on the other sectors from Higgs measurements?
 - Current (and future?) topics of interest in EFT?
- Apologies in advance for not being able to include all relevant works.

Global SMEFT fit

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{f_i^{(6)} O_i^{(6)}}{\Lambda^2} + \sum_i \frac{f_i^{(8)} O_i^{(8)}}{\Lambda^4} + \dots$$

Operators conveniently organized into different sectors:
Higgs, Top, Electroweak, Flavor...



Global SMEFT fit is useful in several ways

- **Testing the SM** → need a framework for deviations from the SM.
- **Quantify the constraining power** of different future colliders and scenarios, HL/HE-LHC, ILC, FCC, CEPC/SppC...
- **Investigate the interplay between different measurements.**

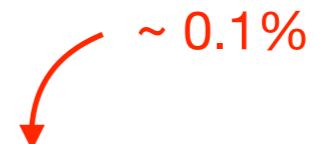
EW Precision Observables

- Z pole: partial widths (ratios), FB/LR asymmetries
- W pole: width/BR
- Masses: top, W/Z, H
- Low energy: APV, Qweak, eDIS,...
- Off-pole: ee>ff, WW

Quantity	Value	Standard Model	Pull
m_t [GeV]	172.74 ± 0.46	172.96 ± 0.45	-0.5
M_W [GeV]	80.387 ± 0.016	80.358 ± 0.004	1.8
	80.376 ± 0.033		0.6
	80.370 ± 0.019		0.6
Γ_W [GeV]	2.046 ± 0.049	2.089 ± 0.001	-0.9
	2.195 ± 0.083		1.3
M_H [GeV]	125.14 ± 0.15	125.14 ± 0.15	0.0
$g_V^{\nu e}$	-0.040 ± 0.015	-0.0398 ± 0.0001	0.0
$g_A^{\nu e}$	-0.507 ± 0.014	-0.5063	0.0
$Q_W(e)$	-0.0403 ± 0.0053	-0.0476 ± 0.0002	1.4
$Q_W(p)$	0.0719 ± 0.0045	0.0711 ± 0.0002	0.2
$Q_W(\text{Cs})$	-72.62 ± 0.43	-73.23 ± 0.01	1.4
$Q_W(\text{Tl})$	-116.4 ± 3.6	-116.87 ± 0.02	0.1
$s_Z^2(\text{eDIS})$	0.2299 ± 0.0043	0.23122 ± 0.00003	-0.3
τ_τ [fs]	290.75 ± 0.36	290.39 ± 2.17	0.1
$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi})$	$(4511.18 \pm 0.77) \times 10^{-9}$	$(4508.63 \pm 0.03) \times 10^{-9}$	3.3

Quantity	Value	Standard Model	Pull
M_Z [GeV]	91.1876 ± 0.0021	91.1884 ± 0.0020	-0.4
Γ_Z [GeV]	2.4952 ± 0.0023	2.4942 ± 0.0008	0.4
$\Gamma(\text{had})$ [GeV]	1.7444 ± 0.0020	1.7411 ± 0.0008	—
$\Gamma(\text{inv})$ [MeV]	499.0 ± 1.5	501.44 ± 0.04	—
$\Gamma(\ell^+\ell^-)$ [MeV]	83.984 ± 0.086	83.959 ± 0.008	—
$\sigma_{\text{had}}[\text{nb}]$	41.541 ± 0.037	41.481 ± 0.008	1.6
R_e	20.804 ± 0.050	20.737 ± 0.010	1.3
R_μ	20.785 ± 0.033	20.737 ± 0.010	1.4
R_τ	20.764 ± 0.045	20.782 ± 0.010	-0.4
R_b	0.21629 ± 0.00066	0.21582 ± 0.00002	0.7
R_c	0.1721 ± 0.0030	0.17221 ± 0.00003	0.0
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01618 ± 0.00006	-0.7
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.6
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017		1.5
$A_{FB}^{(0,b)}$	0.0992 ± 0.0016	0.1030 ± 0.0002	-2.3
$A_{FB}^{(0,c)}$	0.0707 ± 0.0035	0.0735 ± 0.0001	-0.8
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	0.1031 ± 0.0002	-0.5
\bar{s}_ℓ^2	0.2324 ± 0.0012	0.23154 ± 0.00003	0.7
	0.23148 ± 0.00033		-0.2
	0.23104 ± 0.00049		-1.0
A_e	0.15138 ± 0.00216	0.1469 ± 0.0003	2.1
	0.1544 ± 0.0060		1.3
	0.1498 ± 0.0049		0.6
A_μ	0.142 ± 0.015		-0.3
A_τ	0.136 ± 0.015		-0.7
	0.1439 ± 0.0043		-0.7
A_b	0.923 ± 0.020	0.9347	-0.6
A_c	0.670 ± 0.027	0.6677 ± 0.0001	0.1
A_s	0.895 ± 0.091	0.9356	-0.4

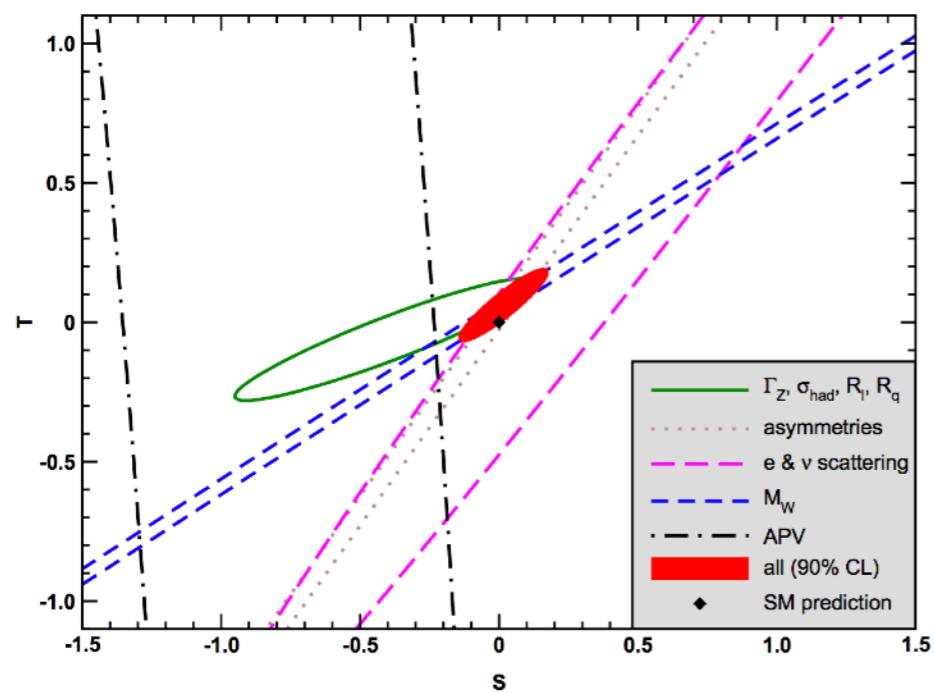
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EWPO constraining new physics

Oblique assumption

BSM only modifies EW
boson self-energies

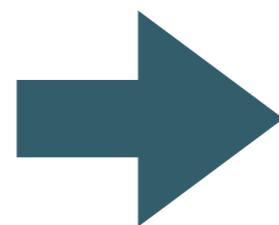


PDG '18

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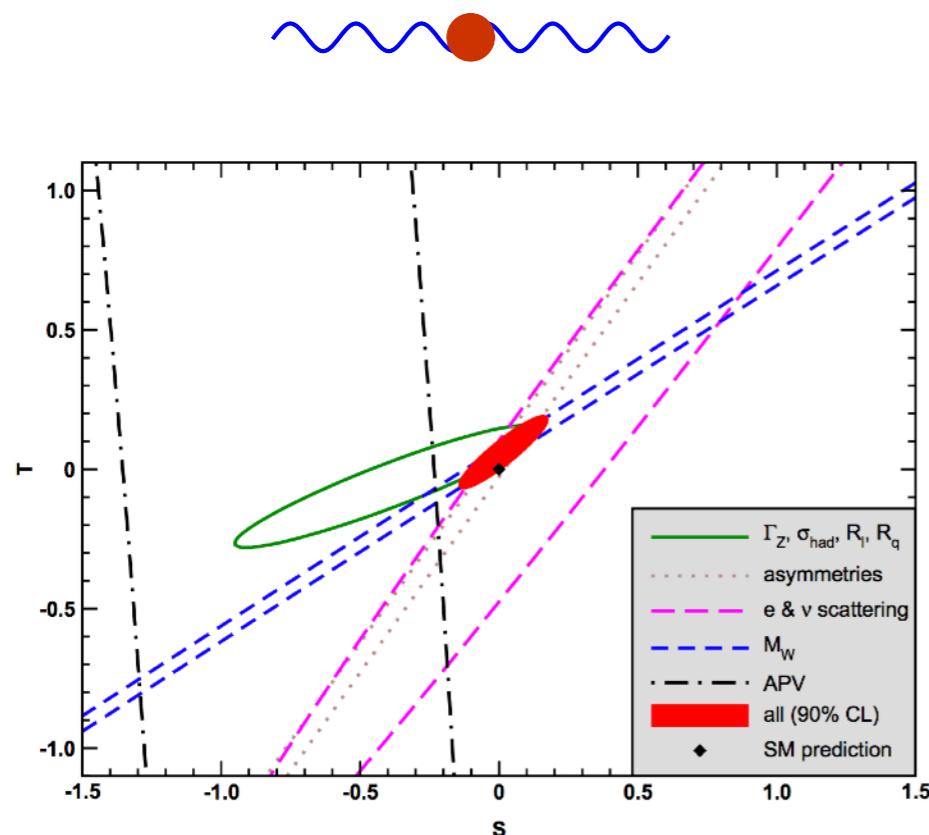
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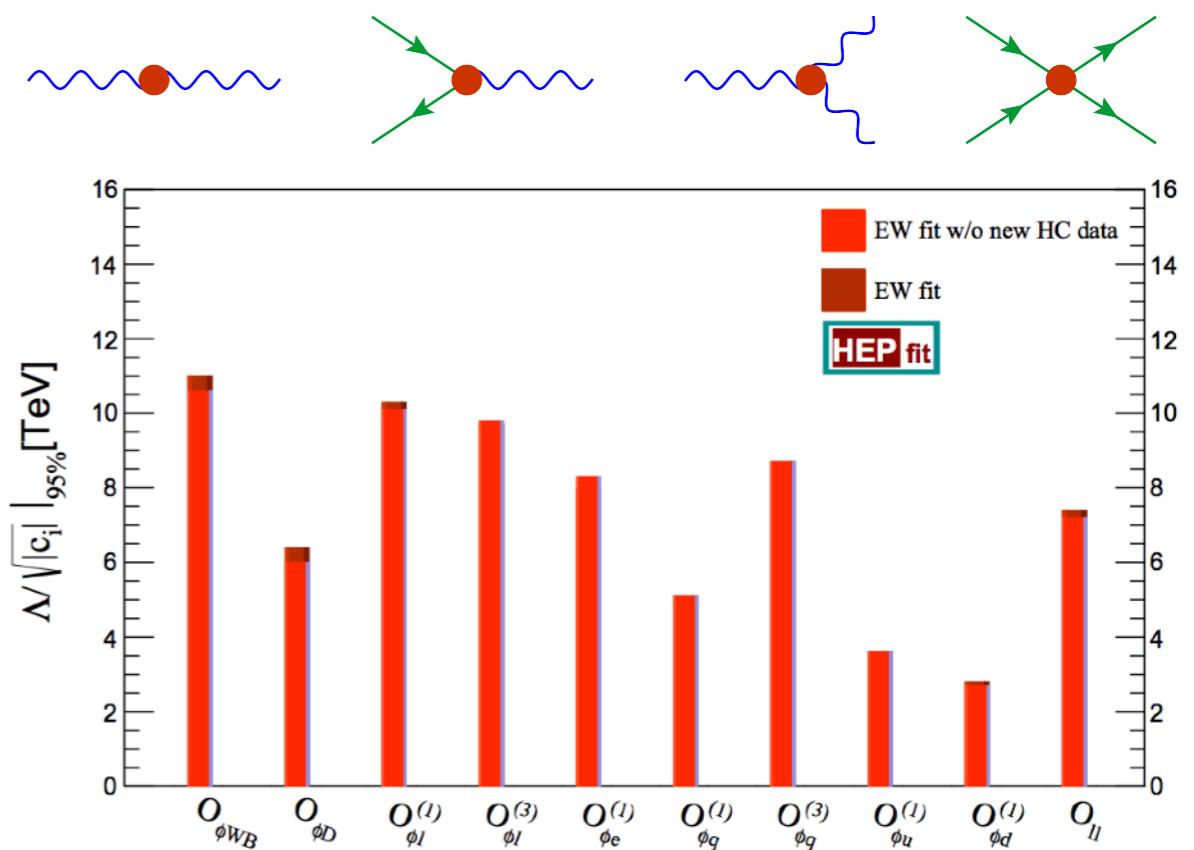


SMEFT

Including all relevant
dim-6 effective operators



PDG '18



[J. de Blas et al. 1710.05402]

See also

[Han and Skiba, hep-ph/0412166]

[Efrati, Falkowski, Soreq, 1503.07872]

[Brivio and Trott 1701.06424]

[Falkowski, Gonzalez-Alonso, Mimouni, 1706.03783]

Adding the Higgs

Assuming U(3)⁵ symmetry, a simplified picture for classifying Higgs/EW operators:

1. EW

8 ops are tightly constrained
by Z-pole data

$\mathcal{O}_W = \frac{ig}{2} \left(H^\dagger \sigma^a \overset{\leftrightarrow}{D}{}^\mu H \right) D^\nu W_{\mu\nu}^a$
(+) $\mathcal{O}_B = \frac{ig'}{2} \left(H^\dagger \overset{\leftrightarrow}{D}{}^\mu H \right) \partial^\nu B_{\mu\nu}$
$\mathcal{O}_T = \frac{1}{2} \left(H^\dagger \overset{\leftrightarrow}{D}_\mu H \right)^2$
$\mathcal{O}_{LL}^{(3)l} = (\bar{L}_L \sigma^a \gamma^\mu L_L) (\bar{L}_L \sigma^a \gamma_\mu L_L)$
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2. TGC

have to access by WW
production

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$\mathcal{O}_{HB} = ig' (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$
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3. Higgs

accessed only by
producing the H

$\mathcal{O}_H = [\partial_\mu (H^\dagger H)]^2$
$\mathcal{O}_{BB} = \frac{g'^2}{4} H ^2 B_{\mu\nu} B^{\mu\nu}$
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$\mathcal{O}_{GG} = \frac{g_s^2}{4} H ^2 G_{\mu\nu}^A G^{A\mu\nu}$
$\mathcal{O}_{y_u} = y_u H ^2 \bar{Q}_L \tilde{H} u_R$
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$\mathcal{O}_{y_e} = y_e H ^2 \bar{L}_L H e_R$
$\mathcal{O}_6 = \lambda H ^6$

Adding the Higgs

Assuming $U(3)^5$ symmetry, a simplified picture for classifying Higgs/EW operators:

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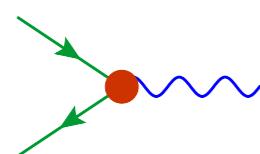
$$\mathcal{O}_{GG} = \frac{g_s^2}{4} |H|^2 G_{\mu\nu}^A G^{A\mu\nu}$$

$$\mathcal{O}_{y_u} = y_u |H|^2 \bar{Q}_L \tilde{H} u_R$$

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Assuming $U(3)^5$ symmetry, a simplified picture for classifying Higgs/EW operators:

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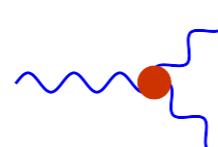
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$(+)$	$(-)$
$\mathcal{O}_T = \frac{1}{2} \left(H^\dagger \overset{\leftrightarrow}{D}_\mu H \right)^2$	
$\mathcal{O}_{LL}^{(3)l} = (\bar{L}_L \sigma^a \gamma^\mu L_L) (\bar{L}_L \sigma^a \gamma_\mu L_L)$	$\mathcal{O}_{HB} = ig' (D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$
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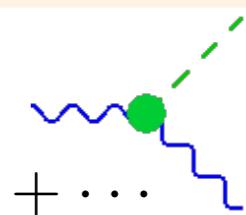
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$$|H|^2 = v^2/2 + \textcolor{red}{vh} + \dots$$

New directions with H!

Adding the Higgs

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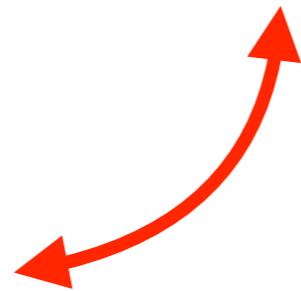
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- The precision of **class 1** OPs was such that they can be ignored when determining Ops of the other classes -> no longer holds for WW at LHC! neither for future colliders

Adding the Higgs

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$\mathcal{O}_6 = \lambda H ^6$



- The precision of **class 1** OPs was such that they can be ignored when determining Ops of the other classes -> **no longer holds for WW at LHC!** neither for future colliders
- Almost all operators involve some H field: nontrivial interplay between EW/H.
e.g. WW and H processes share **two common operators**.

Joint Higgs and EW fit

[J. Ellis et al. 1803.03252]

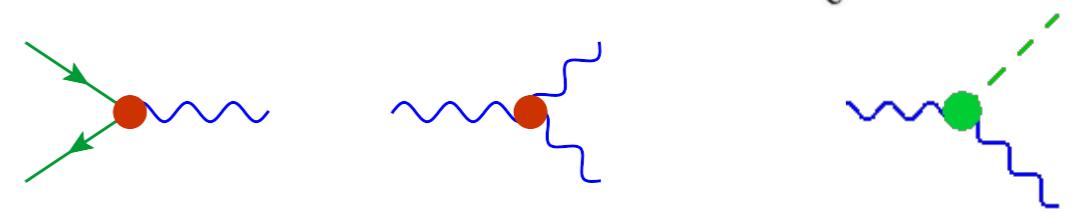
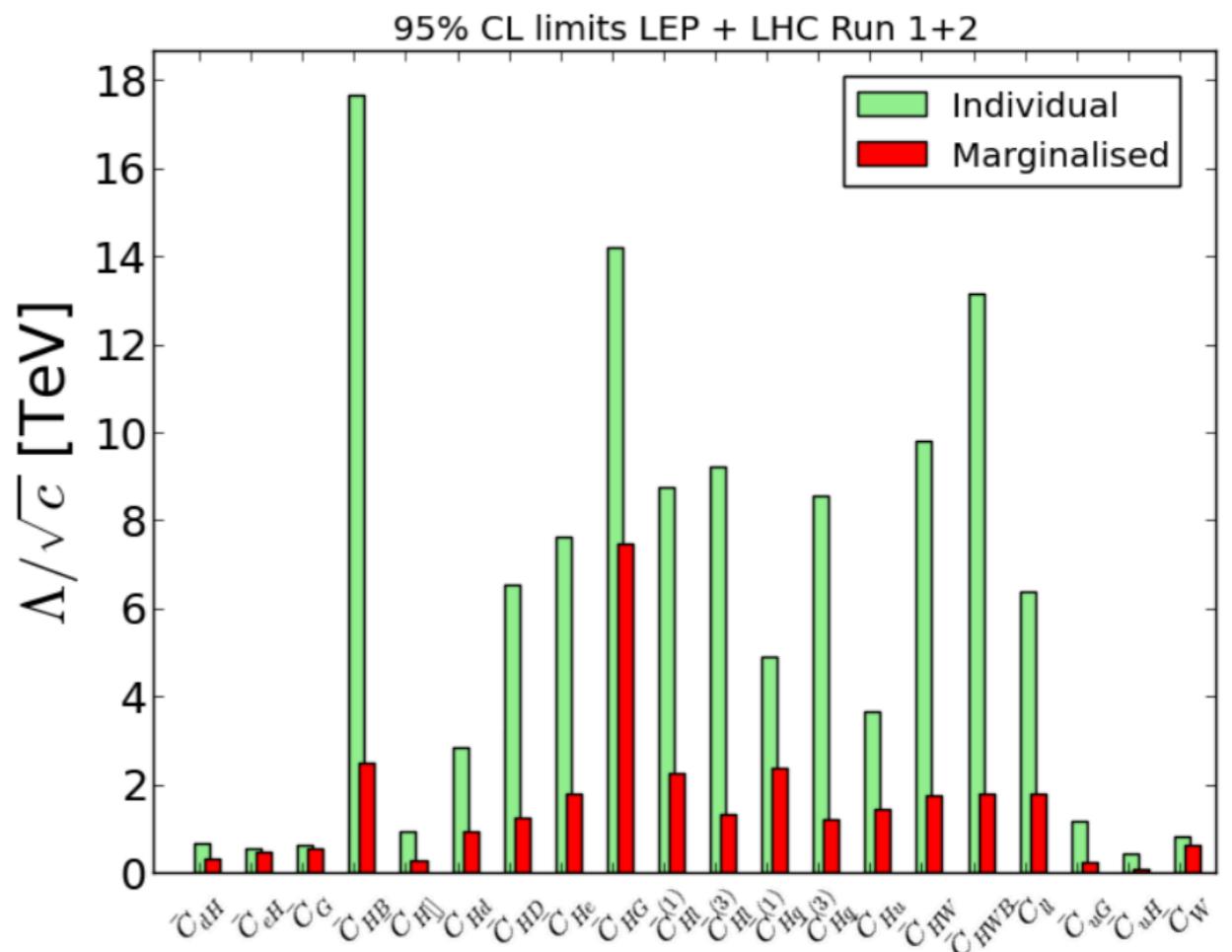
In the past, the precision of the electroweak Z-pole data has been such that the coefficients of the operators affecting them could initially be considered independently of those entering into other observables. However, such a segregated approach is theoretically unsatisfactory, with some bases being more correlated across measurements than others, and is becoming obsolescent with the advent of more precise LHC data on Higgs production and diboson production where the latter, in particular, can no longer be interpreted solely as a measurement of anomalous triple-gauge couplings [50, 51].

50 [Z. Zhang 1610.01618]

51 [Baglio, Dawson, Lewis 1708.03332]

See also Biekotter, Corbett, Plehn '18, J. de Blas et al. '16, and many other Higgs fitters.

LHC run-1: H signal strength
LHC run-2: H STXS and WW
+LEP: Z pole, WW



Top & Higgs sectors

There are also important interplays between H and top

chromo-dipole: ***g*t_t**

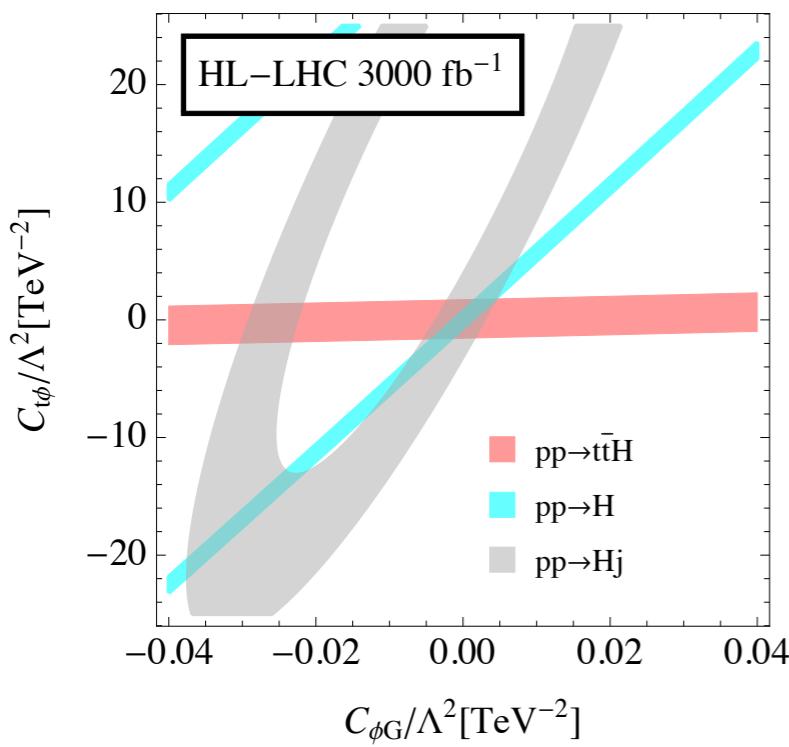
Yukawa: ***t*H**

gluon-Higgs: ***gg*H**

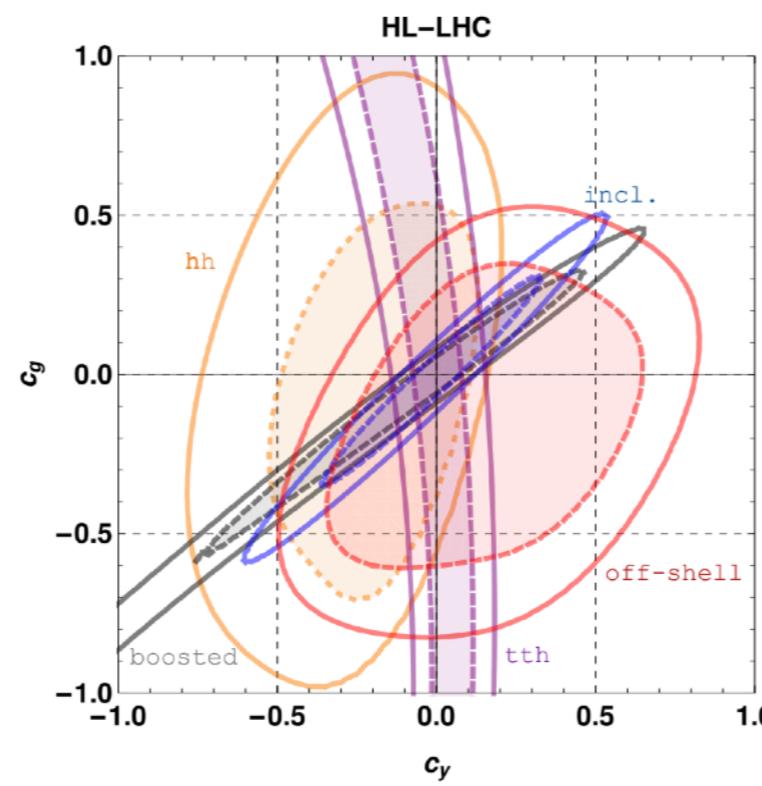
$$O_{tG} = y_t g_s (\bar{Q} \sigma^{\mu\nu} T^A t) \tilde{\phi} G_{\mu\nu}$$

$$O_{t\phi} = y_t^3 (\phi^\dagger \phi) \bar{Q} t \tilde{\phi}$$

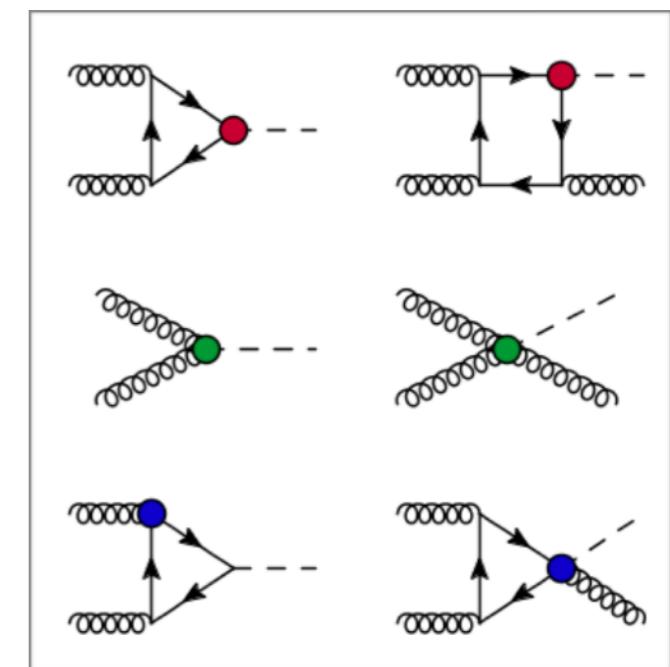
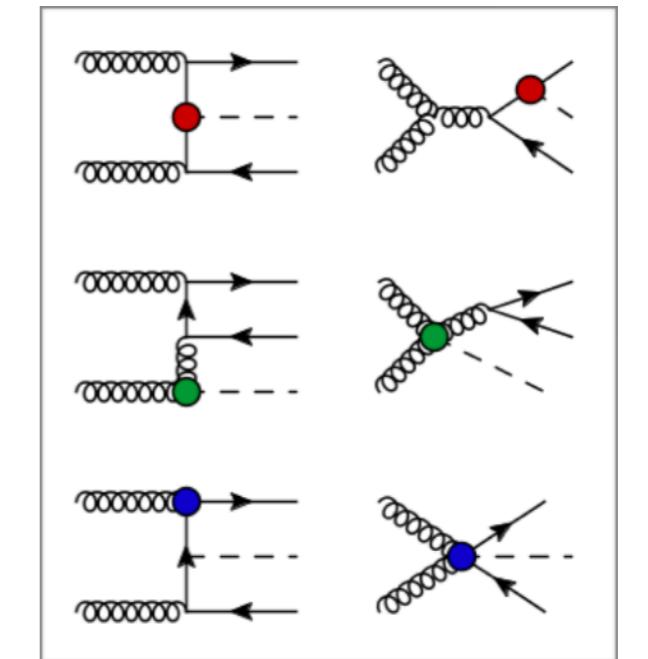
$$O_{\phi G} = y_t^2 (\phi^\dagger \phi) G_{\mu\nu}^A G^{A\mu\nu}$$



[Maltoni, Vryonidou, CZ '16]



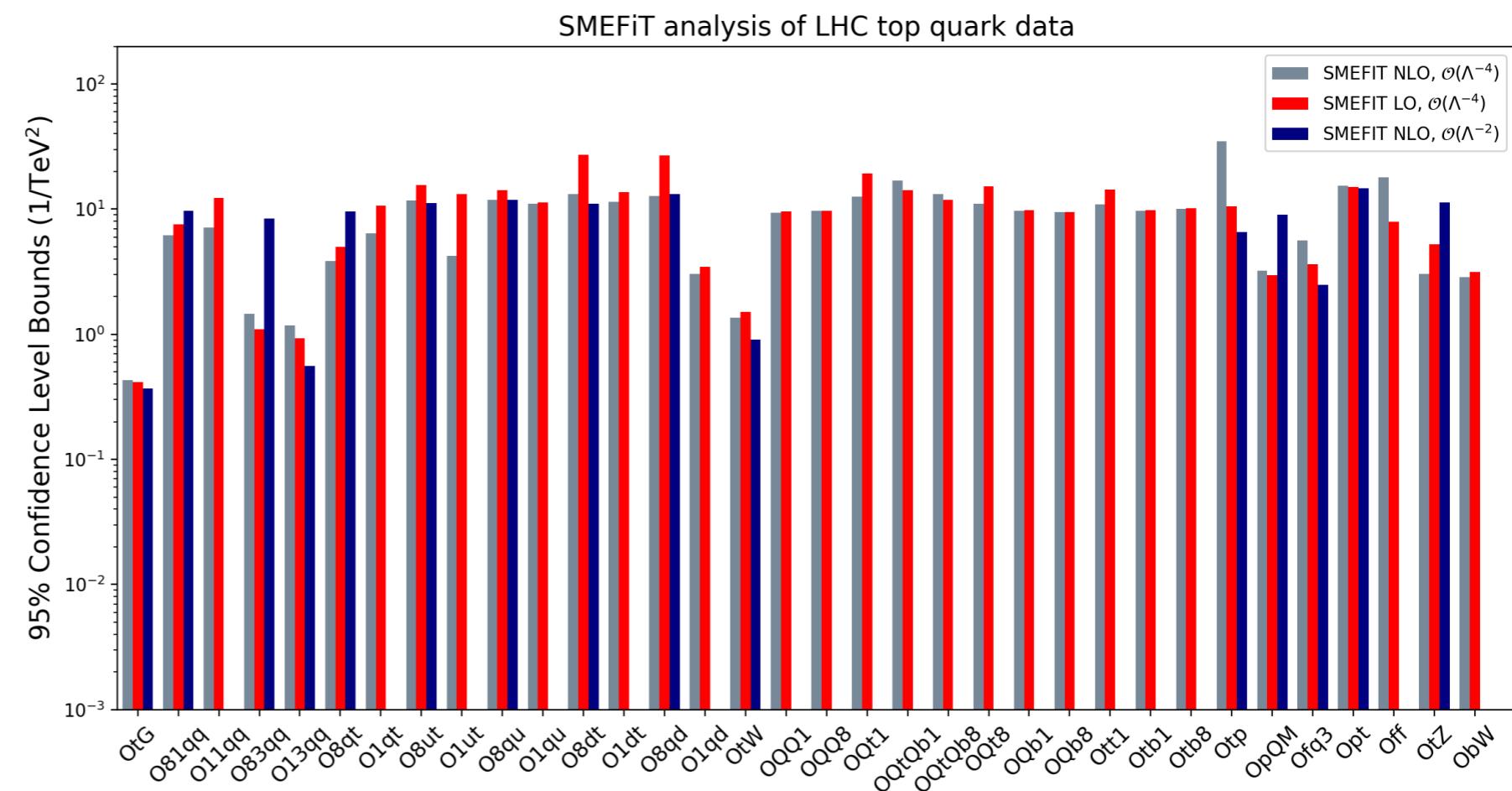
[A. Azatov et al., 1608.00977]



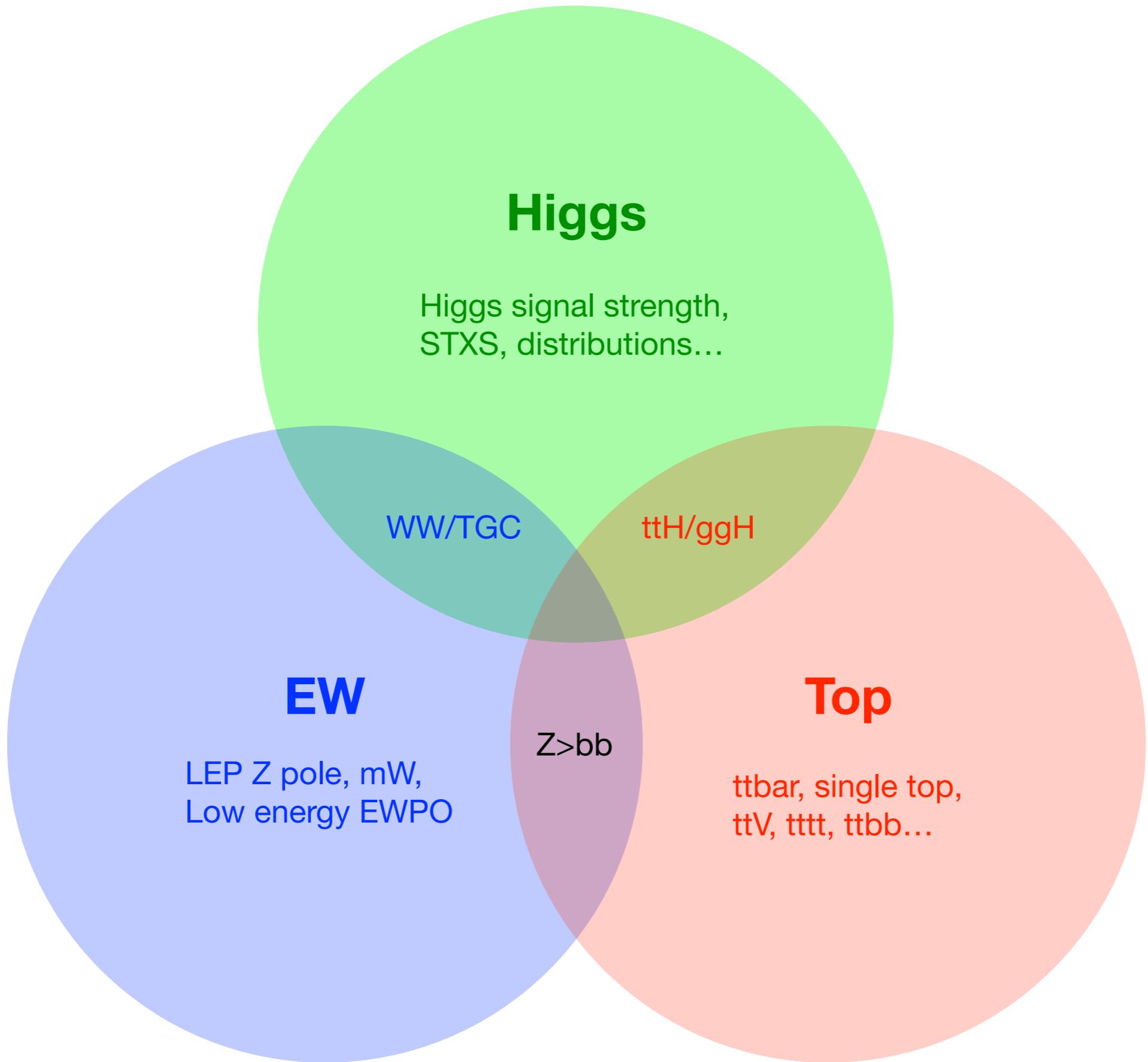
Top fit: decoupled from EW/H, to the leading order...

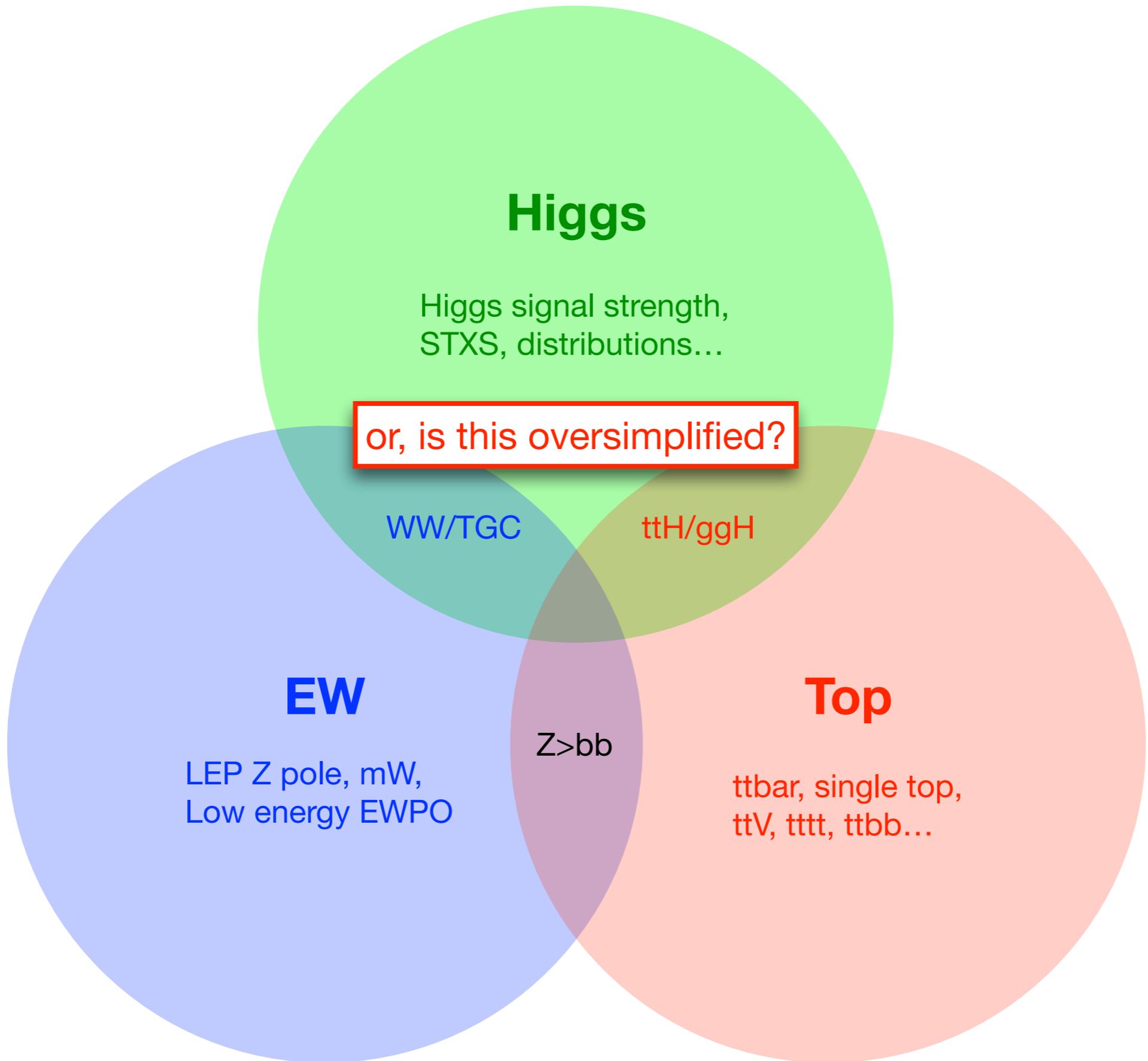
- Fitting approach based on [NNPDF](#): MC replicas + cross validation and closure test
- Theory predictions from [MG5_aMC@NLO](#), i.e. operator contributions are at NLO in QCD
- Parametrization & operator basis etc. are consistent with TOP working group EFT recommendation

[Hartland, Maltoni, Nocera, Rojo, Slade, Vryonidou, **CZ 19**]



See also TopFitter, A. Buckley et al. '15





SM Lagrangian is the most general renormalizable one given the SM fields and symmetries. The couplings are completely fixed by a few input parameters (G_F , m_W , m_Z , a_S ...)

- **To deviate from SM (on the existing Lorentz structure), we need the Higgs vev to reduce dim-6 terms down to dim-4 SM-like couplings.**
- So, by precisely measuring the SM, we have been already learning about the H, without producing it. E.g. from EWPO. There are more ways to do it...
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Constrained in EWPO, by $H \rightarrow v/\sqrt{2}$

What if H is active, by $H \rightarrow h/\sqrt{2}$?

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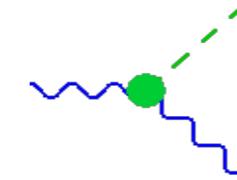


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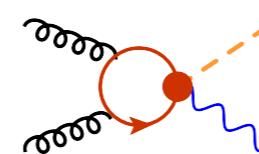


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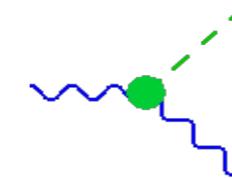
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In addition, loops will mix different kinds of OPs



Constrained in H couplings, by $|H|^2 \rightarrow vh$

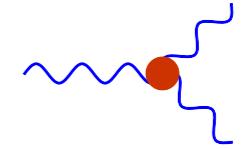
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Example: TGC & H

$$\mathcal{L} = ig_{WWV} \left(g_1^V (W_{\mu\nu}^+ W^{-\mu} - W^{+\mu} W_{\mu\nu}^-) V^\nu + \kappa_V W_\mu^+ W_\nu^- V^{\mu\nu} + \frac{\lambda_V}{M_W^2} W_\mu^+ W_\nu^- V^\mu V^\rho \right)$$

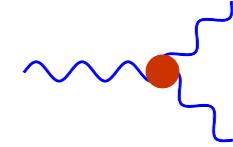
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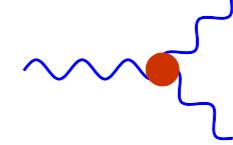
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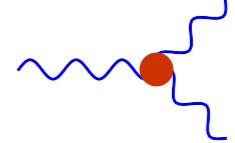
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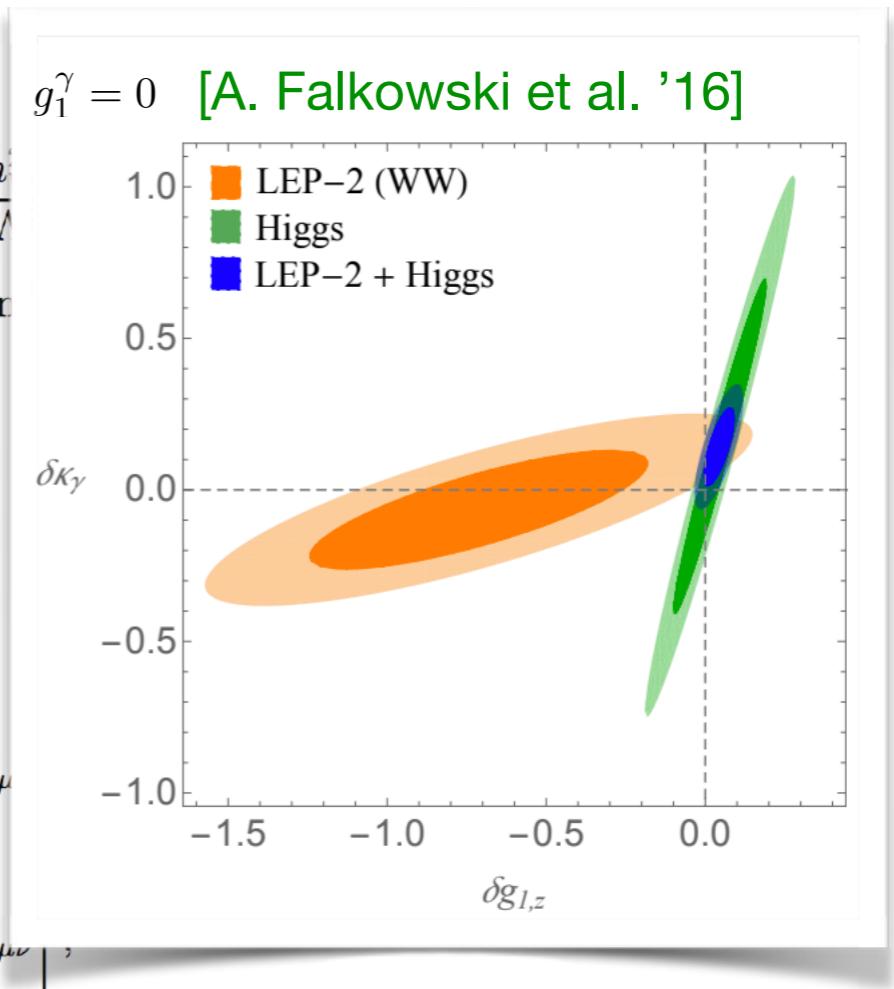
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Significant improvements
by combining Higgs and EW

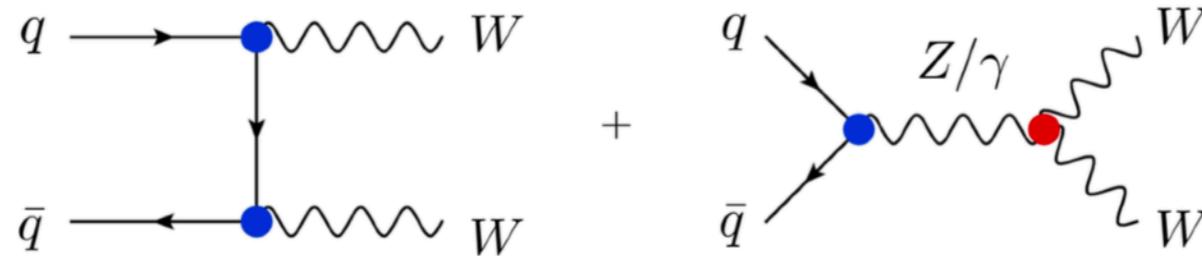
With more and more precise LHC measurements and future collider programs, start to see clearly the connections between different sectors. It is then useful to think what we can learn from them.

Outline:

- Will discuss two kinds of ideas seem to be interesting and promising
 - A. When large energy is accessible, we identify the specific channels in which **the amplitude grows with energy**. i.e. trading high energy for precision.
 - Validity and dim-8 uncertainties.
 - B. When high precision can be reached, we use **loop effects** to open up more opportunities in our measurements.
 - Recent NLO developments, for the investigation of loops.
- Will also emphasize global fits, which are become more important due to the connection between H/EW/top sectors.

Energy for precision

Diboson at the LHC



$$\begin{aligned} \mathcal{L}_{V\bar{q}q} &= \sqrt{g^2 + g'^2} Z_\mu \left[\sum_{f \in u,d} \bar{f}_L \gamma_\mu \left(T_f^3 - s_W^2 Q_f + \delta g_L^{Zf} \right) f_L + \sum_{f \in u,d} \bar{f}_R \gamma_\mu \left(-s_W^2 Q_f + \delta g_R^{Zf} \right) f_R \right] \\ &+ \frac{g}{\sqrt{2}} \left(W_\mu^+ \bar{u}_L \gamma_\mu \left(I_3 + \delta g_L^{Wq} \right) d_L + \text{h.c.} \right). \end{aligned} \quad (3)$$

$$\begin{aligned} \mathcal{L}_{\text{TGC}} &= ie (W_{\mu\nu}^+ W_\mu^- - W_{\mu\nu}^- W_\mu^+) A_\nu + ie [(1 + \delta \kappa_\gamma) A_{\mu\nu} W_\mu^+ W_\nu^-] \\ &+ ig c_W [(1 + \delta g_{1,z}) (W_{\mu\nu}^+ W_\mu^- - W_{\mu\nu}^- W_\mu^+) Z_\nu + (1 + \delta \kappa_z) Z_{\mu\nu} W_\mu^+ W_\nu^-] \\ &+ i \frac{e}{m_W^2} \lambda_\gamma W_{\mu\nu}^+ W_{\nu\rho}^- A_{\rho\mu} + i \frac{g c_W}{m_W^2} \lambda_z W_{\mu\nu}^+ W_{\nu\rho}^- Z_{\rho\mu}. \end{aligned}$$

$\delta g_L^{Zu}, \delta g_R^{Zu}, \delta g_L^{Zd}, \delta g_R^{Zd}$

$\delta \kappa_\gamma, \delta g_{1z}, \lambda_\gamma$

- TGC dominant assumption: the quark couplings are well constrained. Lets focus on TGC...
- But the LEP constraints on δg_L^Z are not strong enough to make them negligible...
- In fact, in the future, WW/WZ/WH/ZH will give the best bounds on $\delta g_L^{Zu}, \delta g_R^{Zu}, \delta g_L^{Zd}, \delta g_R^{Zd}$.

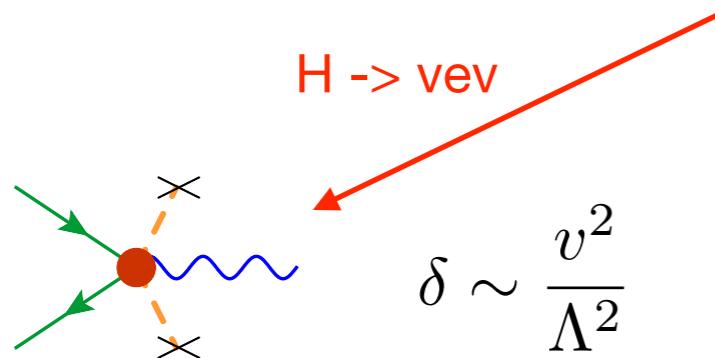
[Z. Zhang 1610.01618]

Diboson at the LHC

- qqZ / $qq'W$ couplings in SM are simply gauge couplings
- To deviate from SM, we need: $\bar{f}\gamma_\mu f H^\dagger \overleftrightarrow{D}_\mu H$

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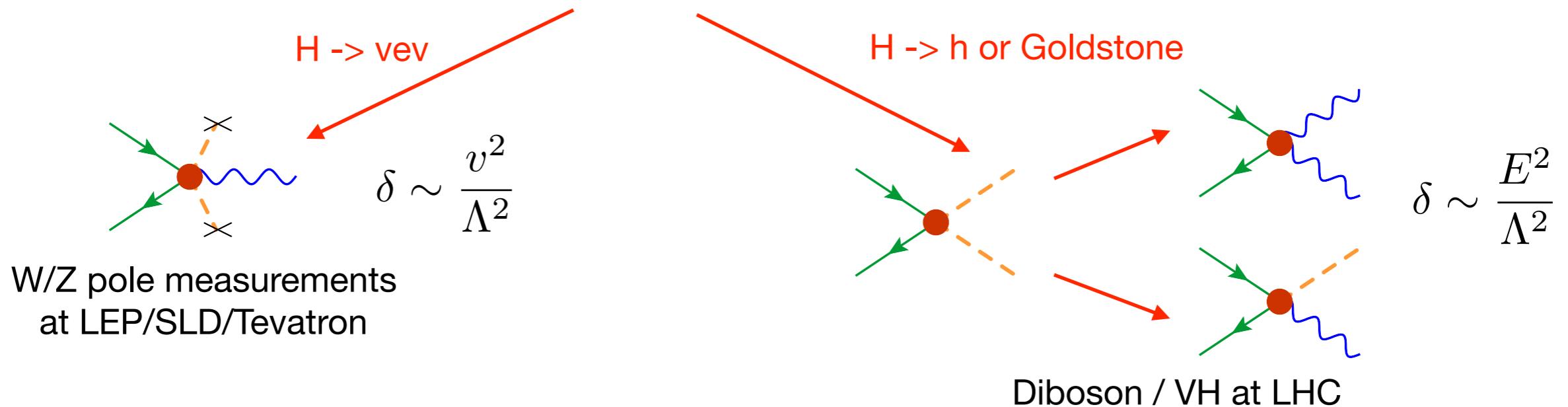


$$\delta \sim \frac{v^2}{\Lambda^2}$$

W/Z pole measurements
at LEP/SLD/Tevatron

Diboson at the LHC

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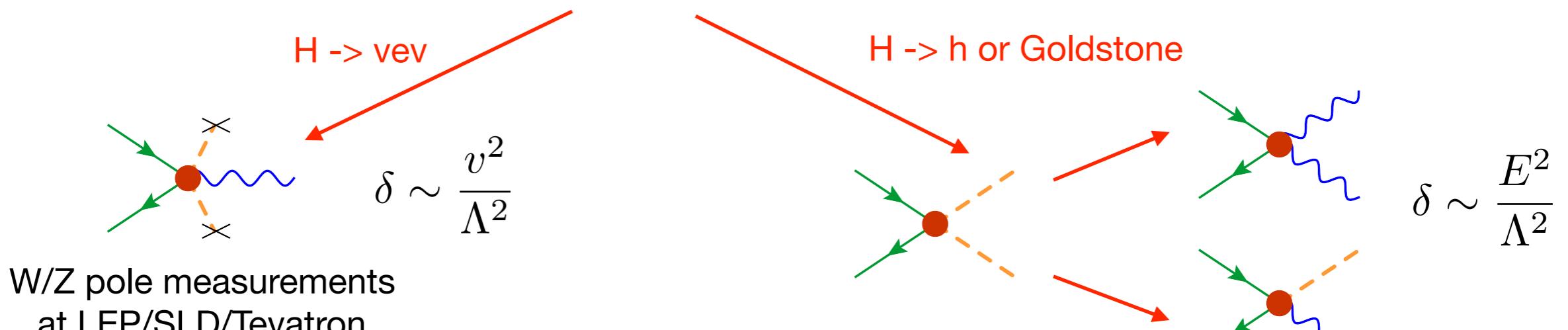


$$\frac{\delta\sigma(\hat{s})}{\sigma_{SM}(\hat{s})} \sim \delta g_i \frac{\hat{s}}{m_Z^2} .$$

30% in $\delta\sigma \Rightarrow 0.3\%$ in couplings

Diboson at the LHC

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W/Z pole measurements
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Diboson / VH at LHC

	SM	BSM
$q_{L,R}\bar{q}_{L,R} \rightarrow V_L V_L(h)$	~ 1	$\sim E^2/M^2$
$q_{L,R}\bar{q}_{L,R} \rightarrow V_\pm V_L(h)$	$\sim m_W/E$	$\sim m_W E/M^2$
$q_{L,R}\bar{q}_{L,R} \rightarrow V_\pm V_\pm$	$\sim m_W^2/E^2$	$\sim E^2/M^2$
$q_{L,R}\bar{q}_{L,R} \rightarrow V_\pm V_\mp$	~ 1	~ 1

[R. Franceschini et al. 1712.01310]

Warsaw Basis

$$\mathcal{O}_L^{(3)} = (\bar{Q}_L \sigma^a \gamma^\mu Q_L)(iH^\dagger \sigma^a \overset{\leftrightarrow}{D}_\mu H)$$

$$\mathcal{O}_L = (\bar{Q}_L \gamma^\mu Q_L)(iH^\dagger \overset{\leftrightarrow}{D}_\mu H)$$

$$\mathcal{O}_R^u = (\bar{u}_R \gamma^\mu u_R)(iH^\dagger \overset{\leftrightarrow}{D}_\mu H)$$

$$\mathcal{O}_R^d = (\bar{d}_R \gamma^\mu d_R)(iH^\dagger \overset{\leftrightarrow}{D}_\mu H)$$

“High energy primaries”

(with the caveat of “interference resurrection”, see [G. Panico, F. Riva, A. Wulzer 1708.07823])

“High Energy Primaries”

[R. Franceschini et al. 1712.01310] [S. Banerjee et al. 1807.01796] [Grojean, Montull, Riembau 1810.05149]

Leptonic WZ and Zh($\rightarrow bb$), $W, Y \ll 1$

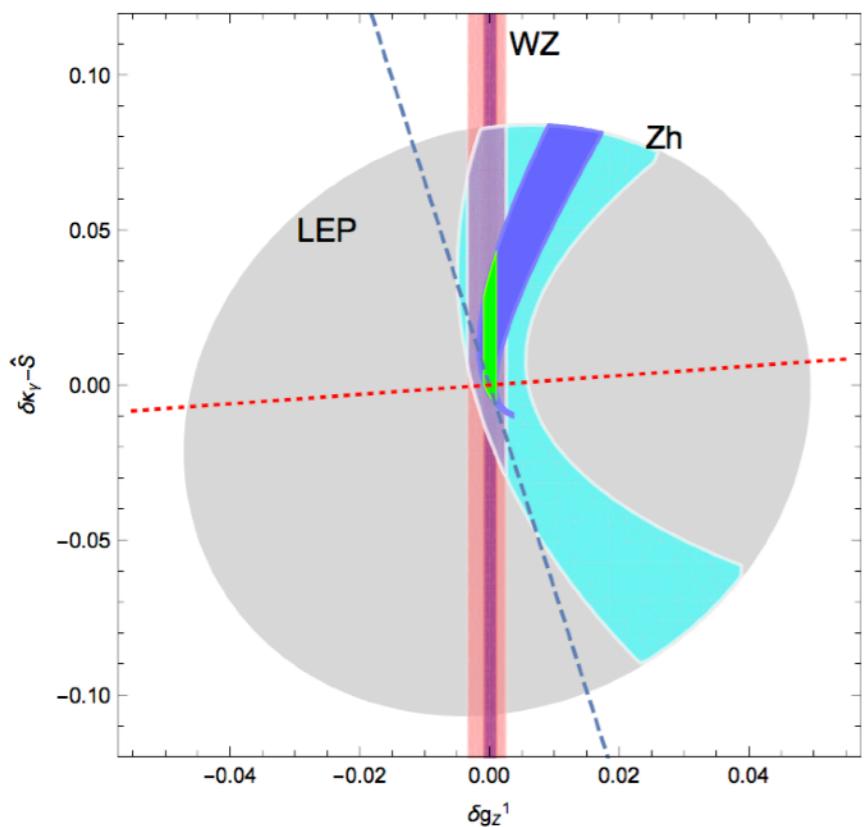
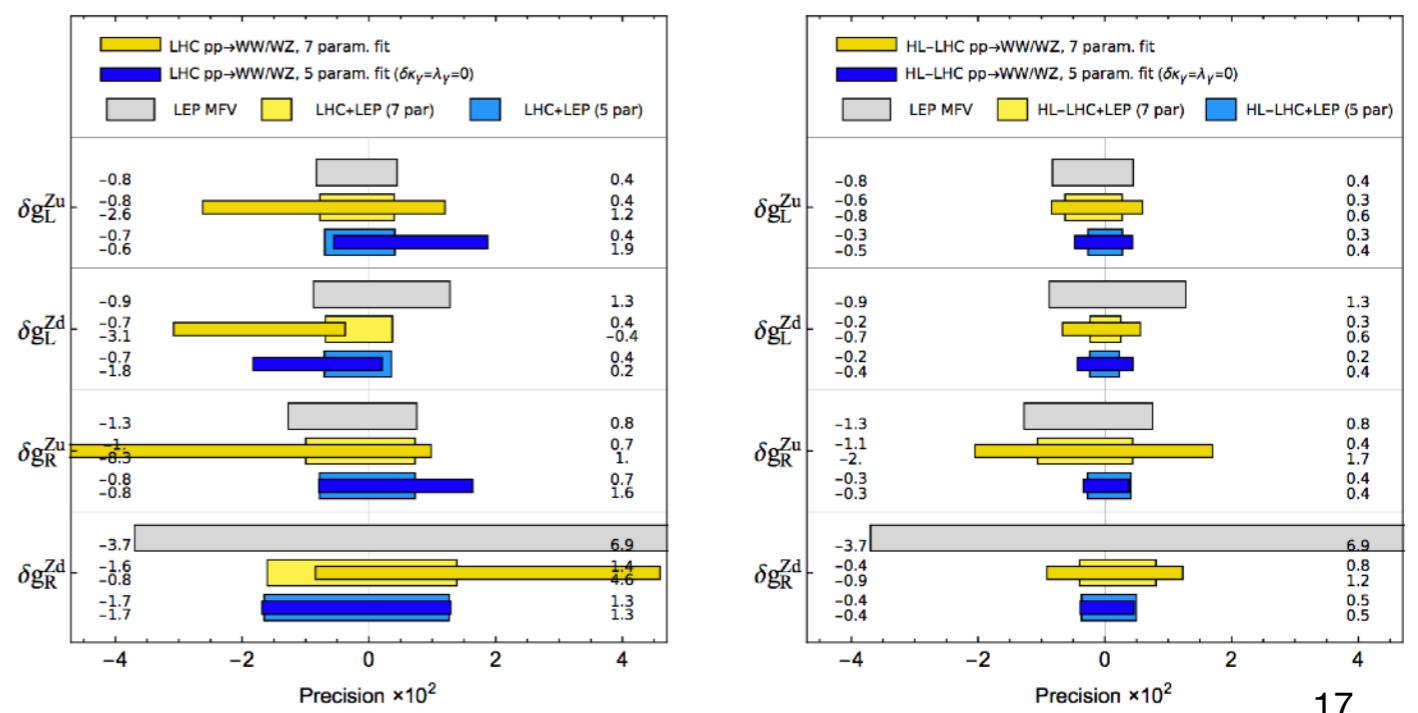
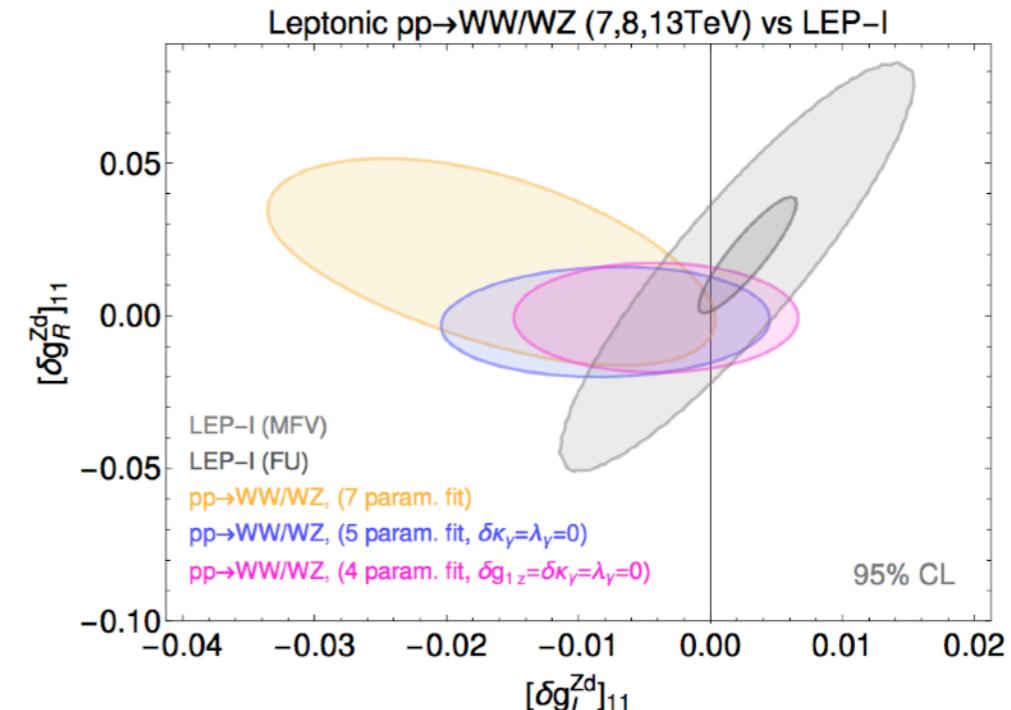


FIG. 2: We show in light blue (dark blue) the projection for the allowed region with 300 fb^{-1} (3 ab^{-1}) data from the $pp \rightarrow Z h$ process for universal models in the $\delta\kappa_\gamma - \hat{S}$ vs δg_1^Z plane. The allowed region after LEP bounds (taking the TGC $\lambda_\gamma = 0$, a conservative choice) are imposed is shown in grey. The pink (dark pink) region corresponds to the projection from the WZ process with 300 fb^{-1} (3 ab^{-1}) data derived in Ref. [20] and the purple (green) region shows the region that survives after our projection from the $Z h$ process is combined with the above WZ projections with 300 fb^{-1} (3 ab^{-1}) data.



“High Energy Primaries”

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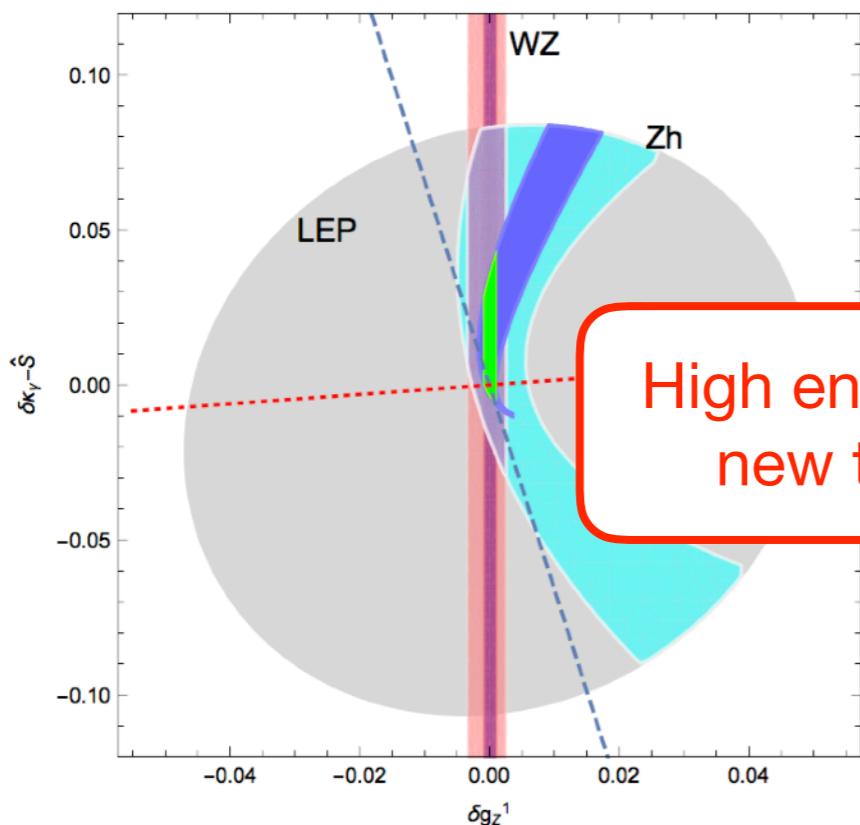
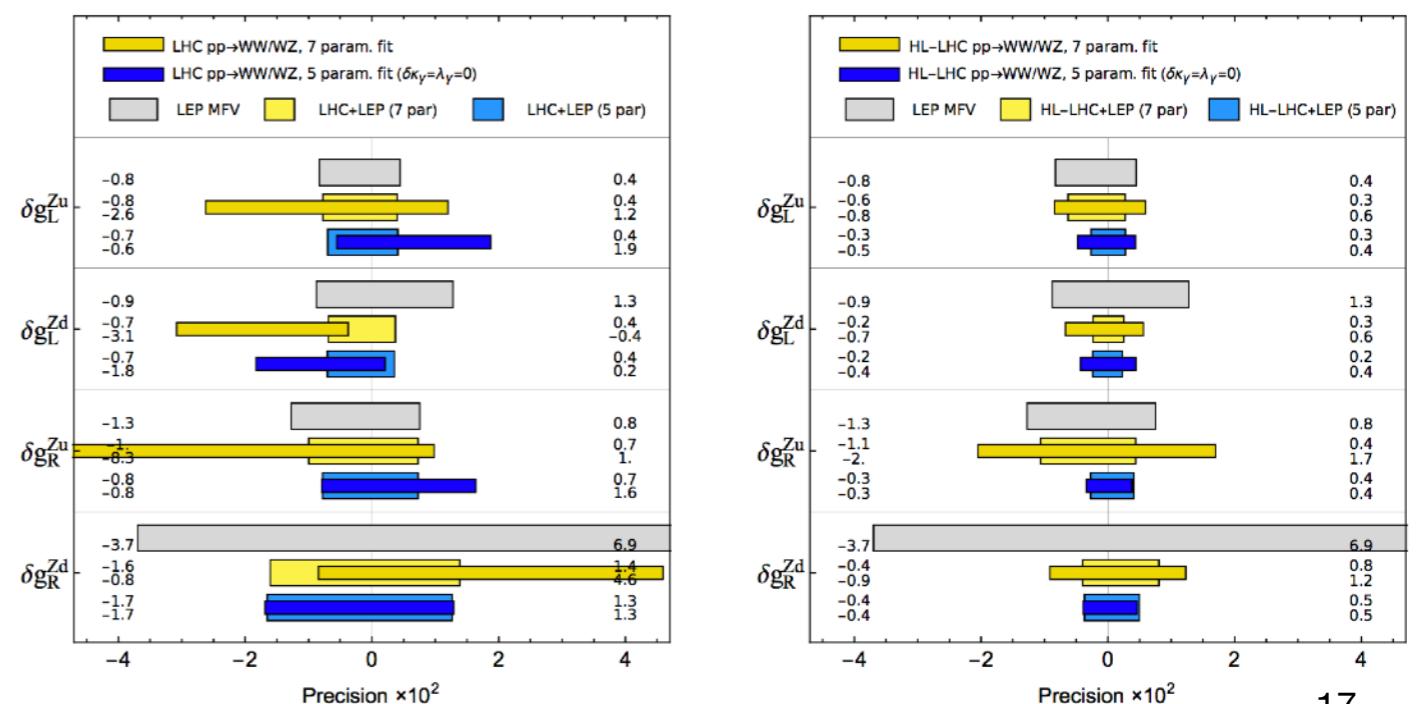
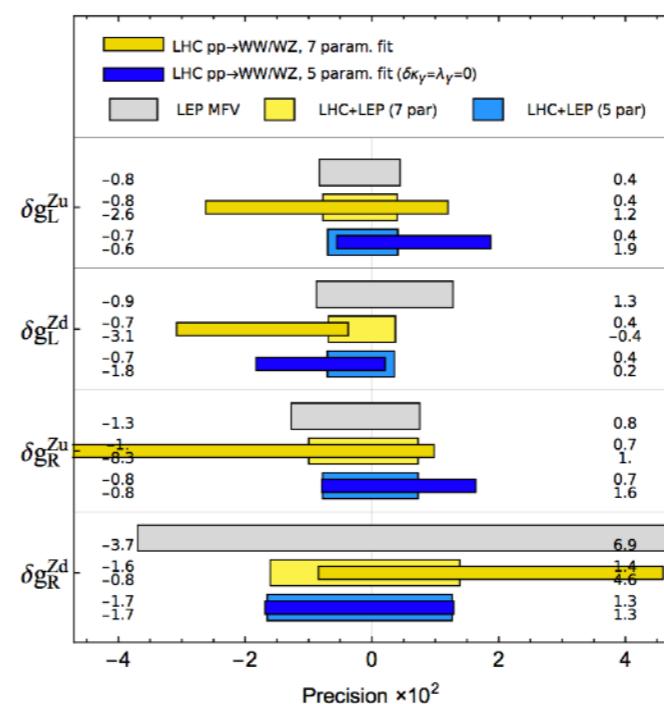
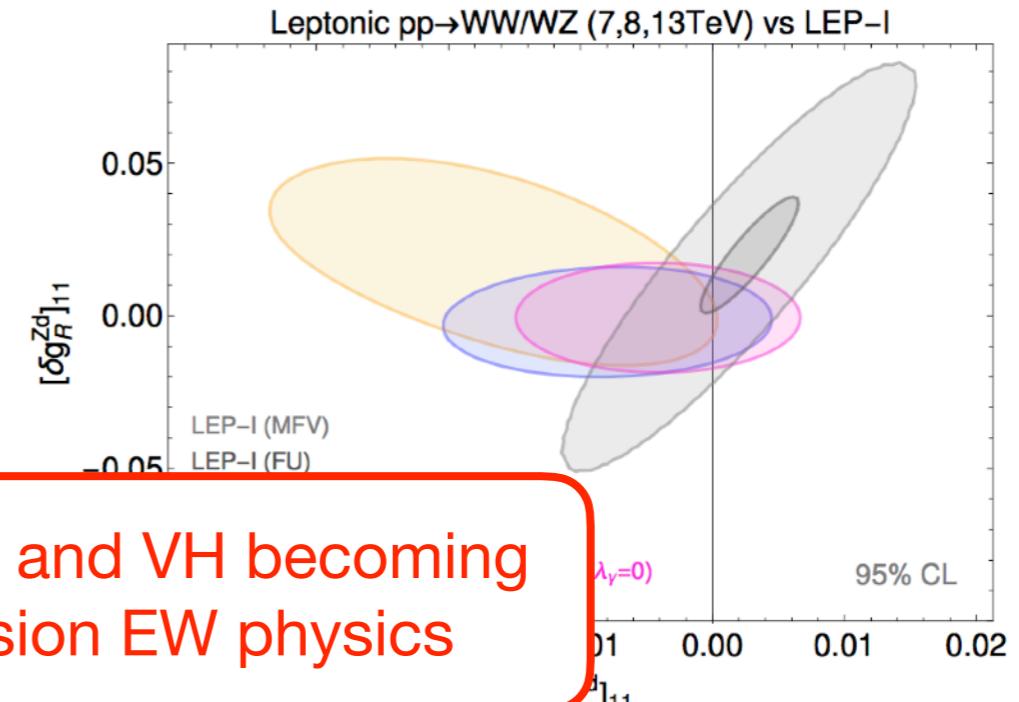
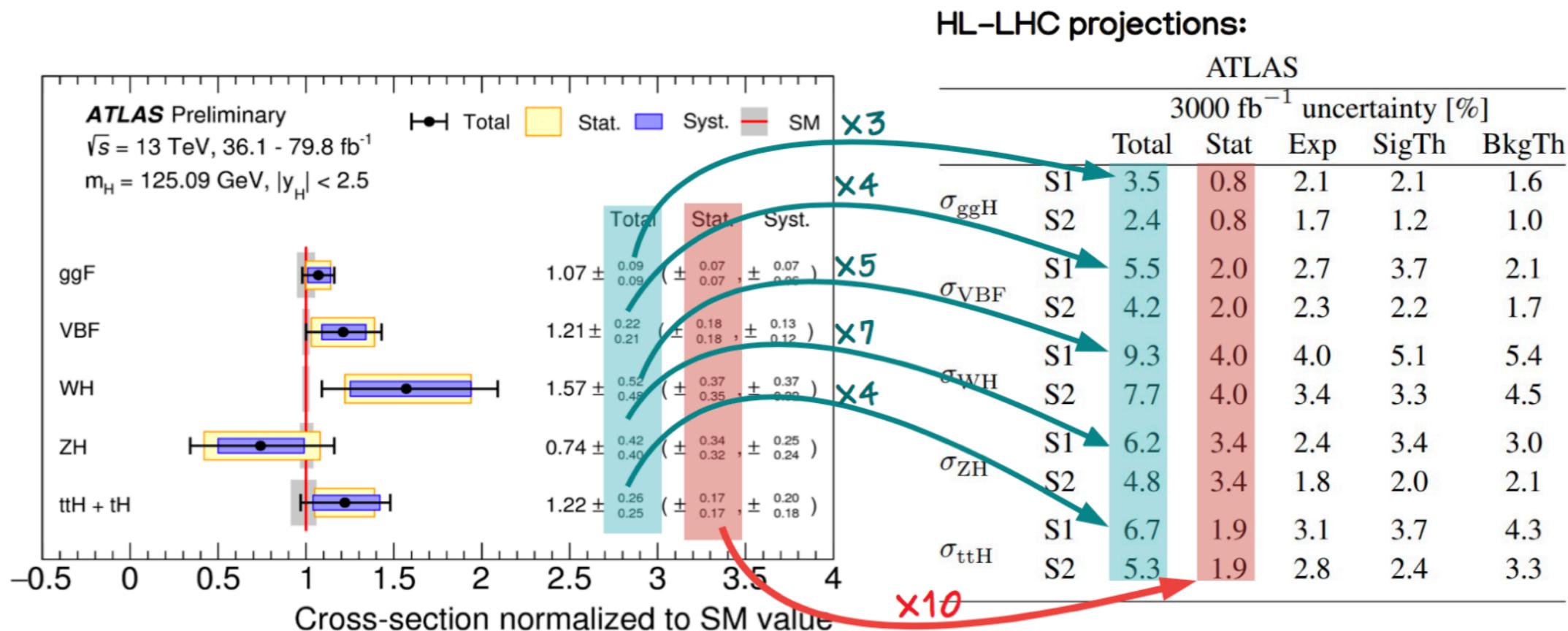


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Higgs at high energy: off shell measurements



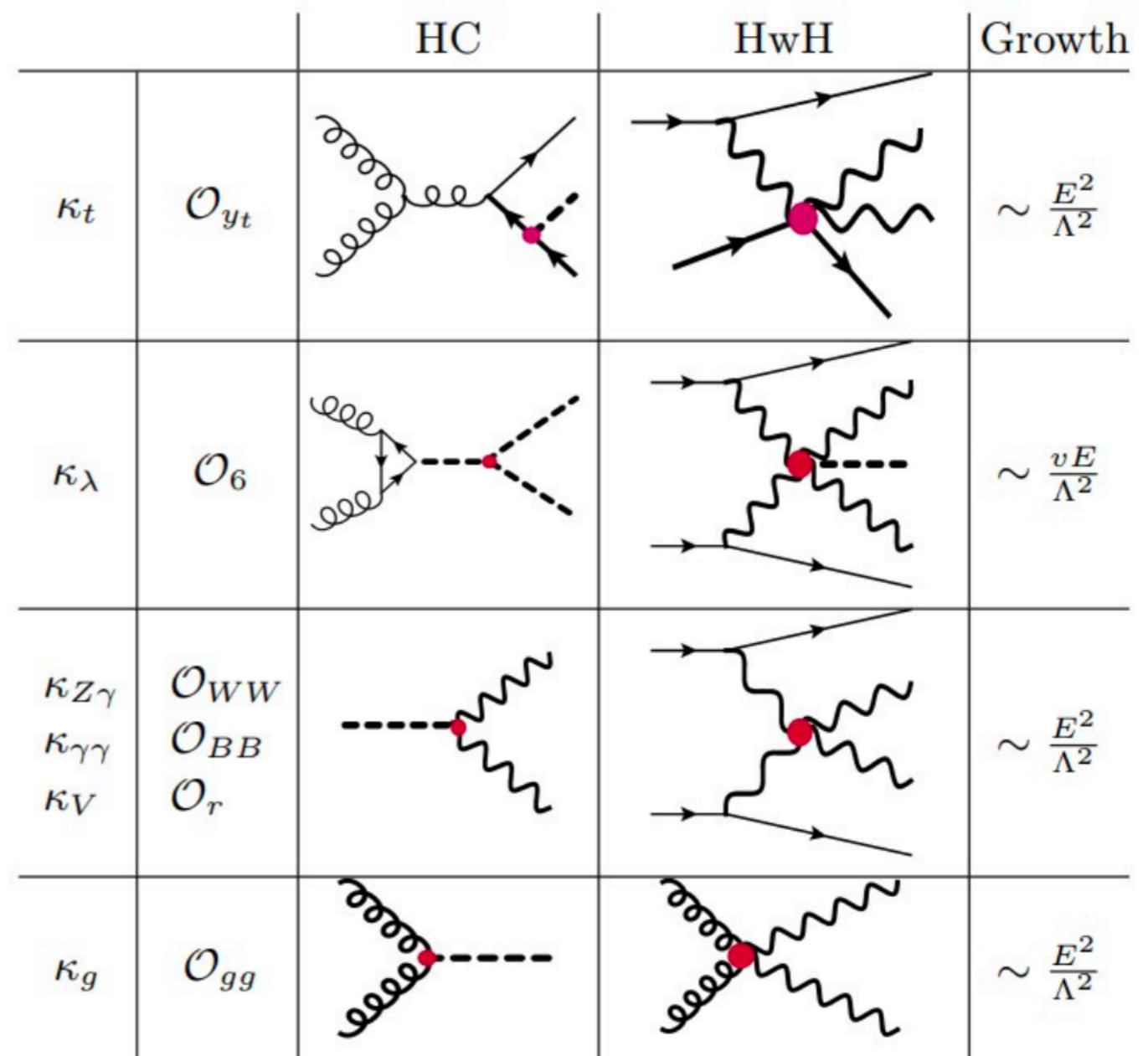
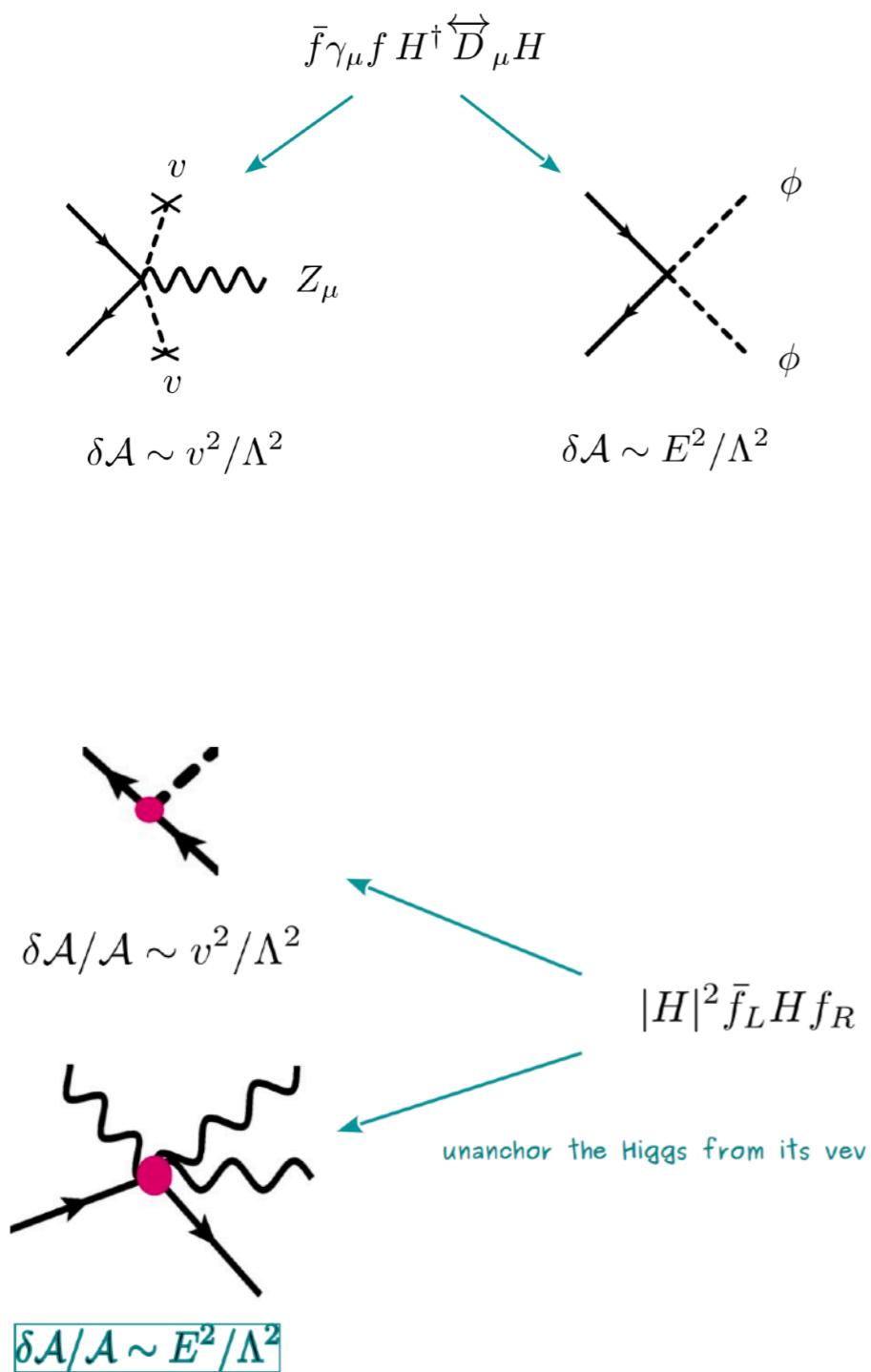
On shell Higgs measurements will be saturated by systematics.

- Will not benefit from either
- 1) higher luminosity
 - 2) higher energy

Off shell Higgs measurements are the opposite:

- 1) limited by statistics
- 2) benefit from higher-energy colliders, HE-LHC/CLIC/SppC

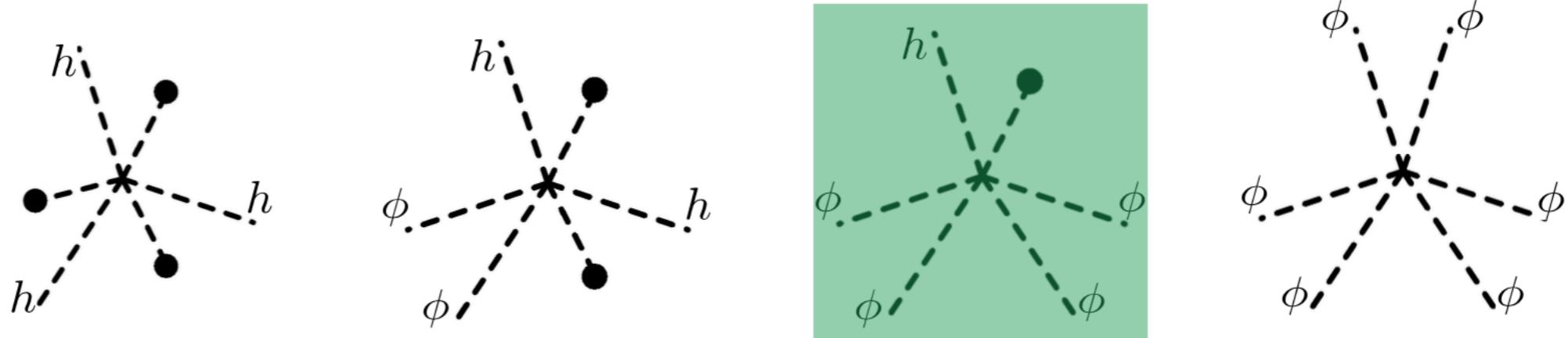
The same logic that applied to diboson also applies here



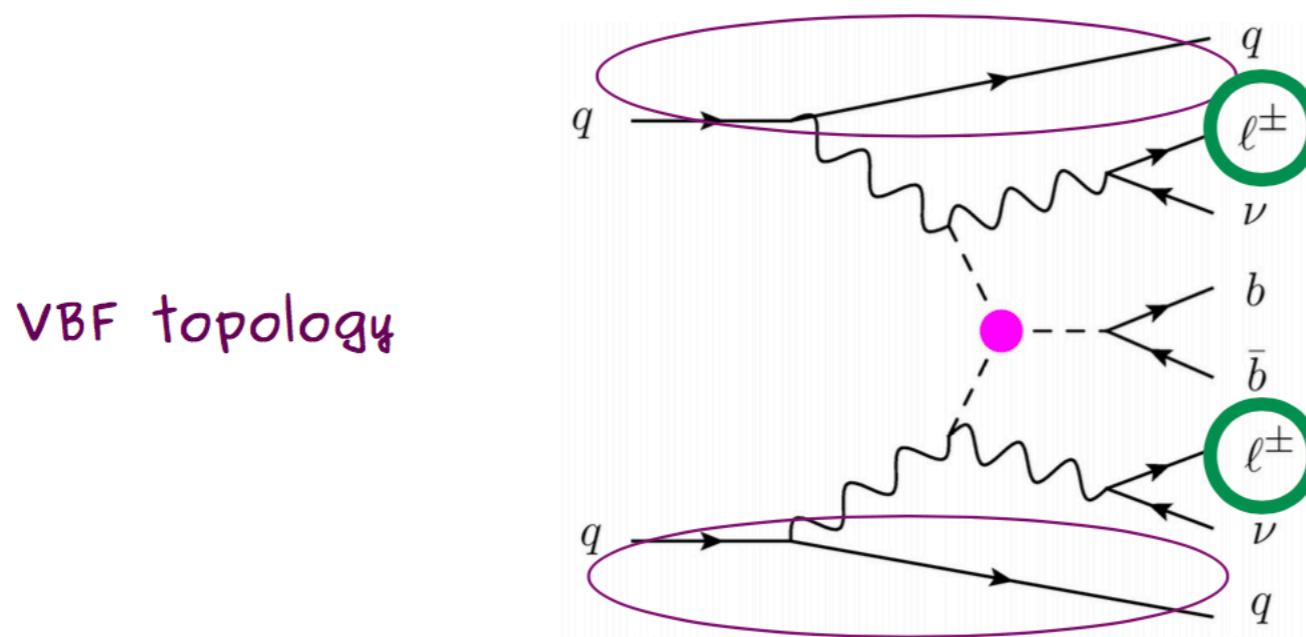
[Henning, Lombardo, Riembau, Riva 1812.09299]

Higgs self-coupling

$$\frac{1}{\Lambda^2} |H|^6 \supset \frac{1}{\Lambda^2} (v^3 h^3 + 3v^2 h^2 \phi^2 + [3vh\phi^4] + \phi^6 + \dots)$$



Signal enhanced only with a single power of energy,
but extremely attractive and clean process experimentally!

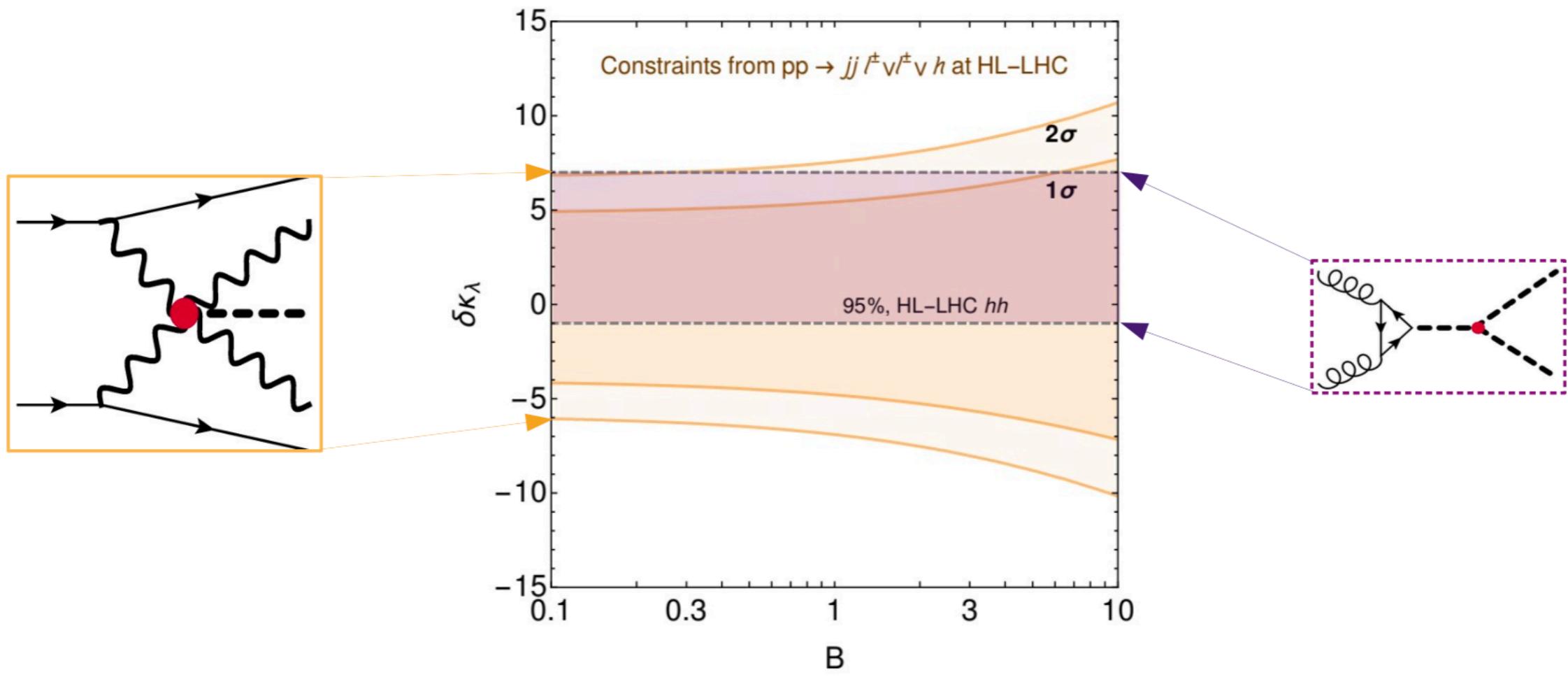


VBF topology

Same sign
leptons!

Talk by M. Riembau

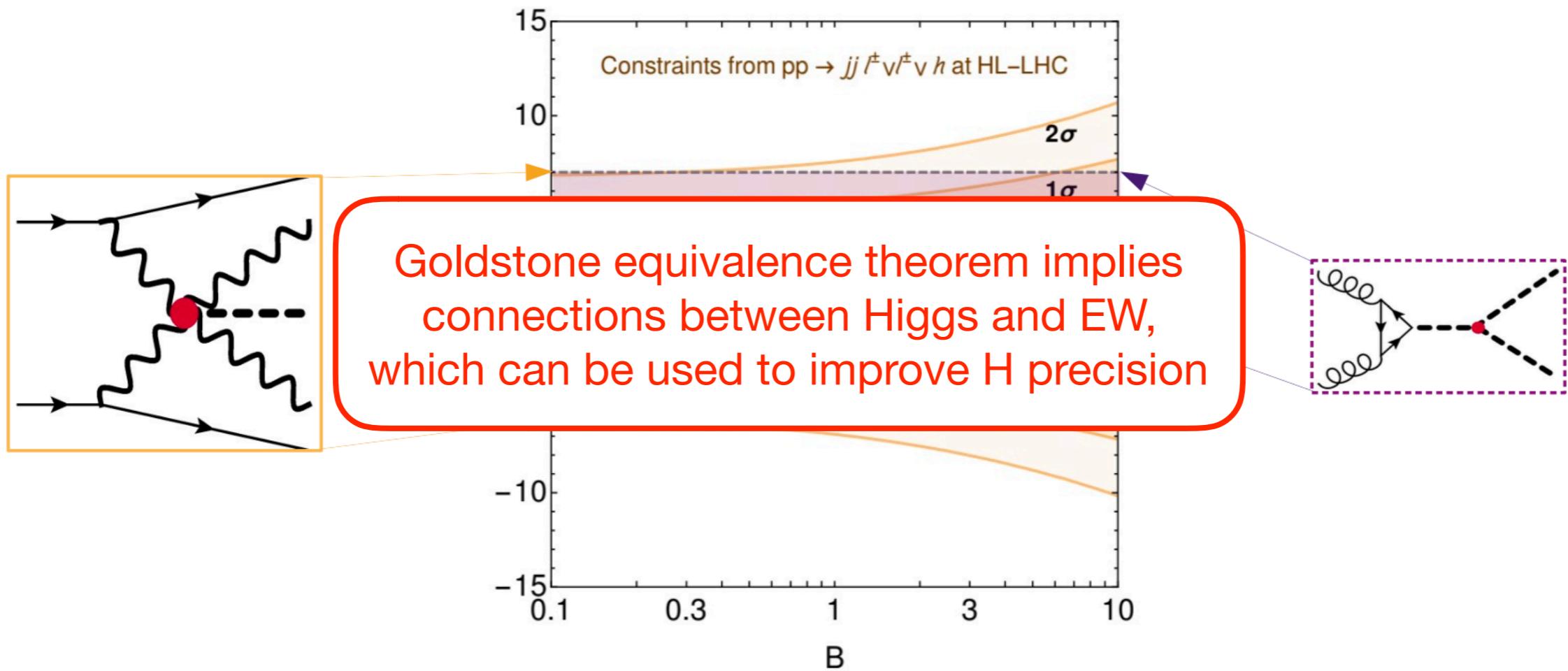
Higgs self-coupling



- 50-ish events in the SM
- Irreducible background negligible
- Background from $t\bar{t}jj$ with lepton misidentification under control
- Background from fake leptons is potentially the dominant one.
We parametrize it with $\#back = B \times \#signal$.
- Rough cut-and-count analysis gives competitive results with double higgs production

Talk by M. Riembau

Higgs self-coupling



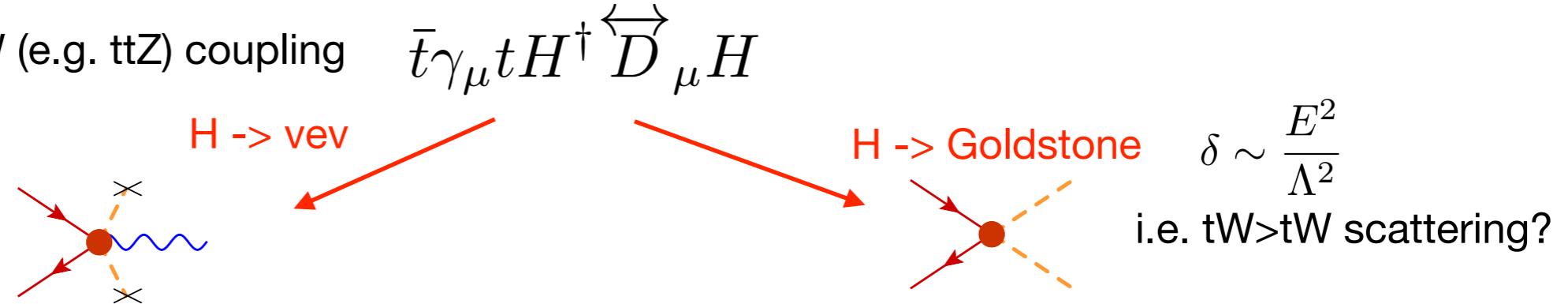
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Talk by M. Riembau

What about top?

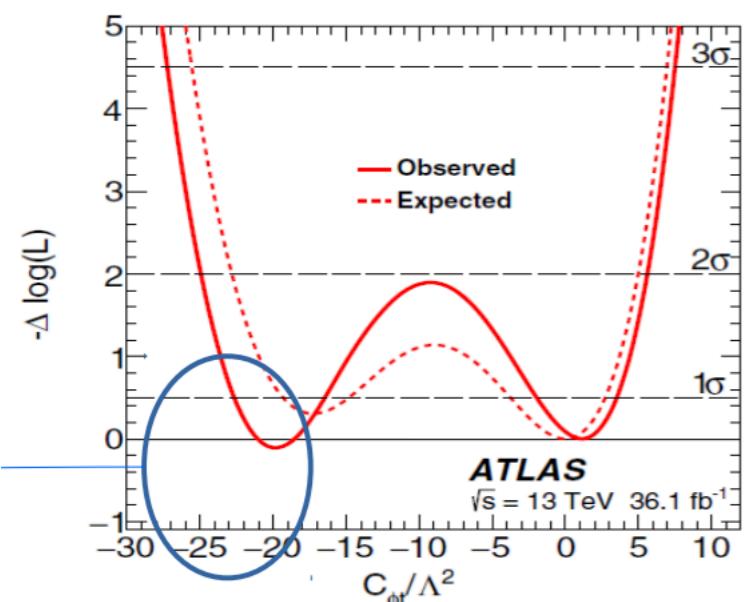
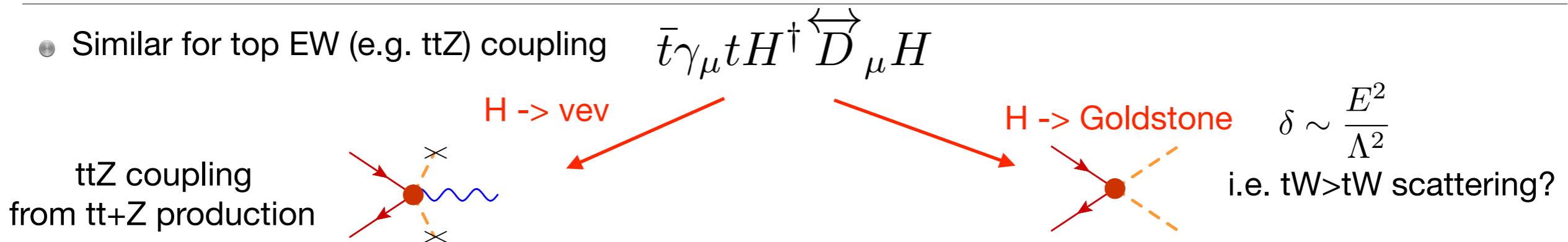
- Similar for top EW (e.g. ttZ) coupling

ttZ coupling
from tt+Z production



What about top?

- Similar for top EW (e.g. ttZ) coupling

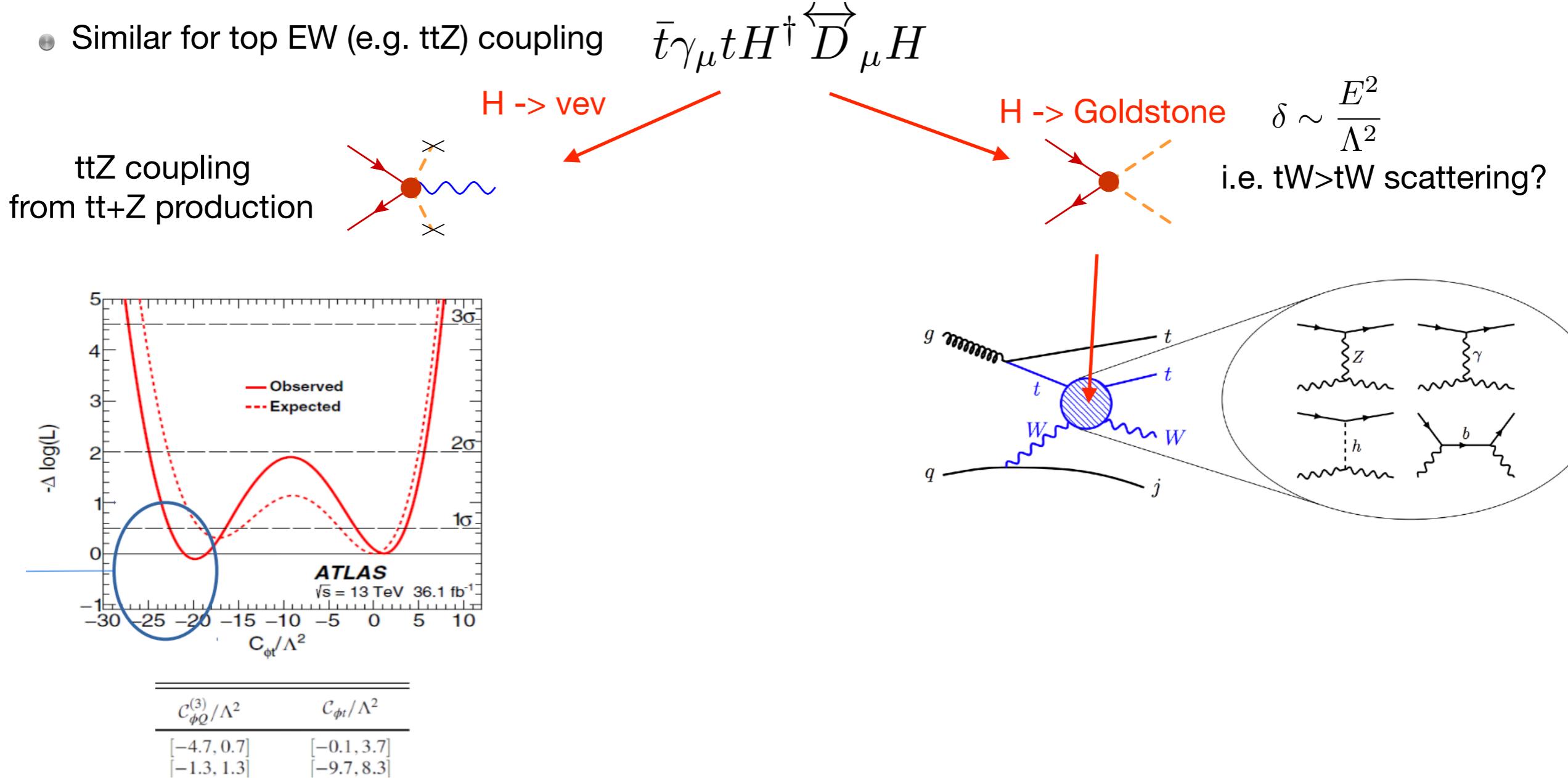


$\mathcal{C}_{φQ}^{(3)} / \Lambda^2$	$\mathcal{C}_{φt} / \Lambda^2$
$[-4.7, 0.7]$	$[-0.1, 3.7]$
$[-1.3, 1.3]$	$[-9.7, 8.3]$

A. Lopez Solis, EPSHEP 2019

What about top?

- Similar for top EW (e.g. ttZ) coupling

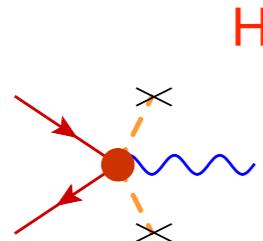


A. Lopez Solis, EPSHEP 2019

What about top?

- Similar for top EW (e.g. $t\bar{t}Z$) coupling

$t\bar{t}Z$ coupling
from $t\bar{t}+Z$ production

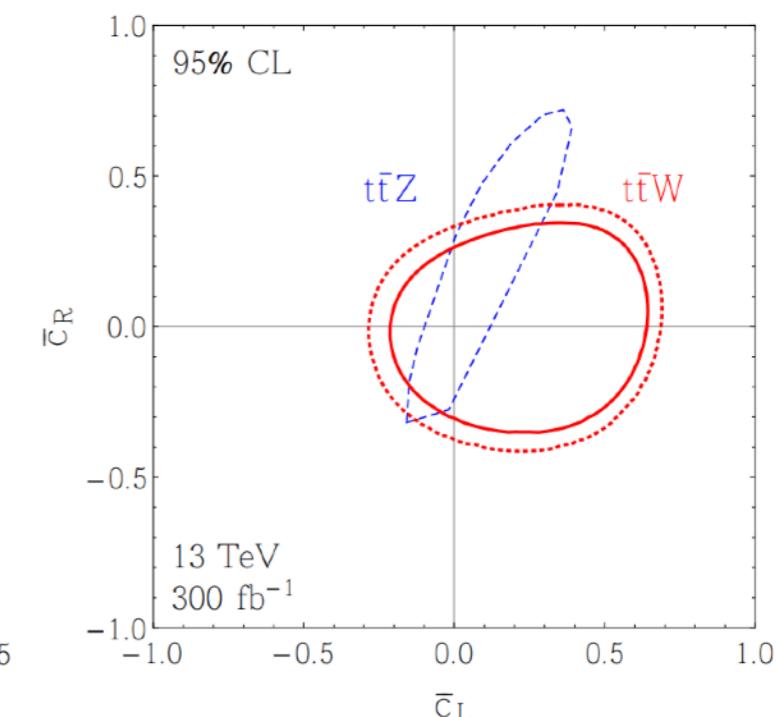
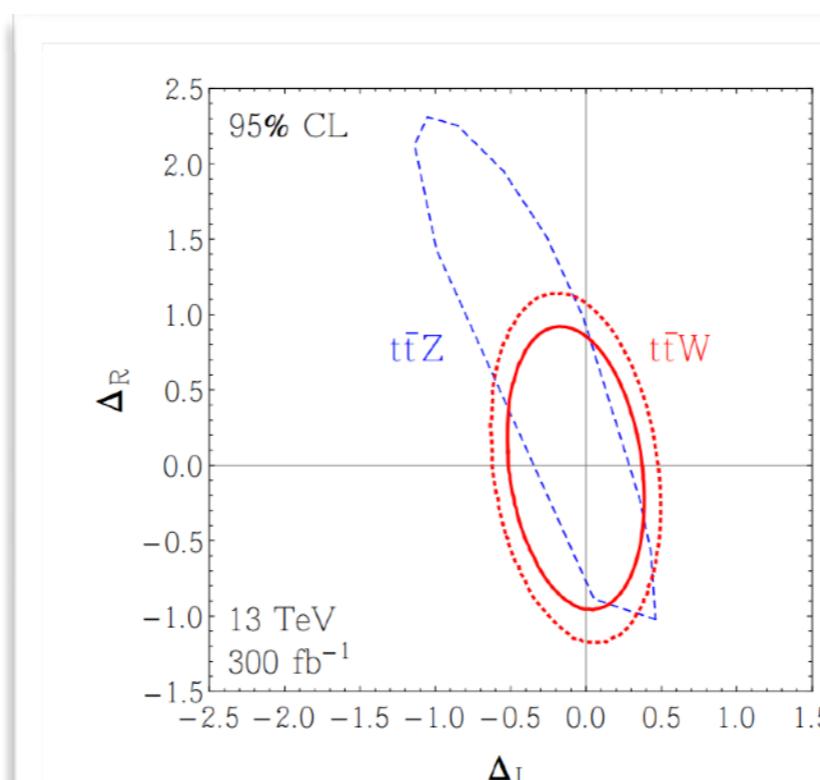
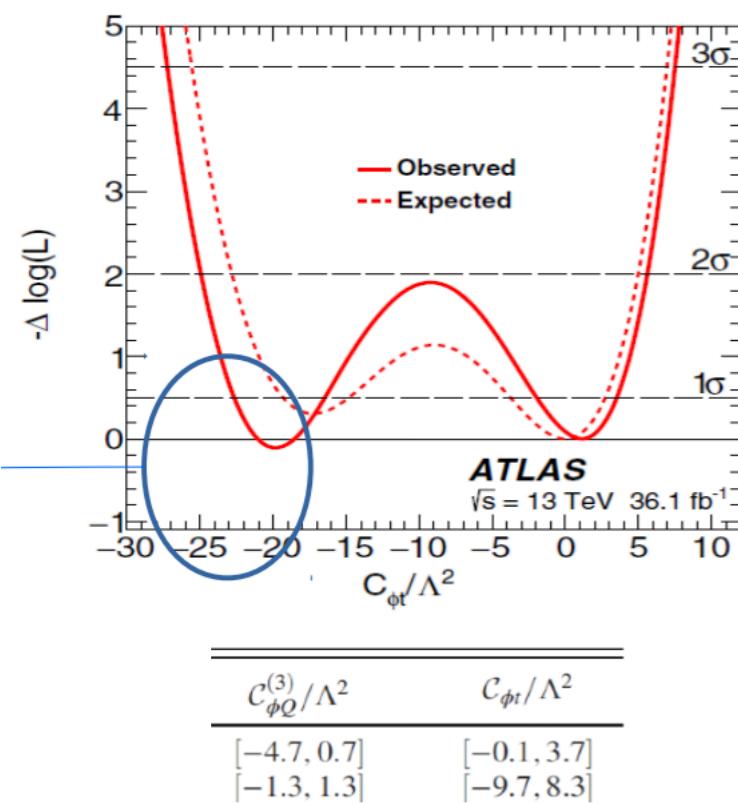


$H \rightarrow vev$

$$\bar{t}\gamma_\mu t H^\dagger \leftrightarrow D_\mu H$$

$H \rightarrow$ Goldstone

$\delta \sim \frac{E^2}{\Lambda^2}$
i.e. $tW>tW$ scattering?



A. Lopez Solis, EPSHEP 2019

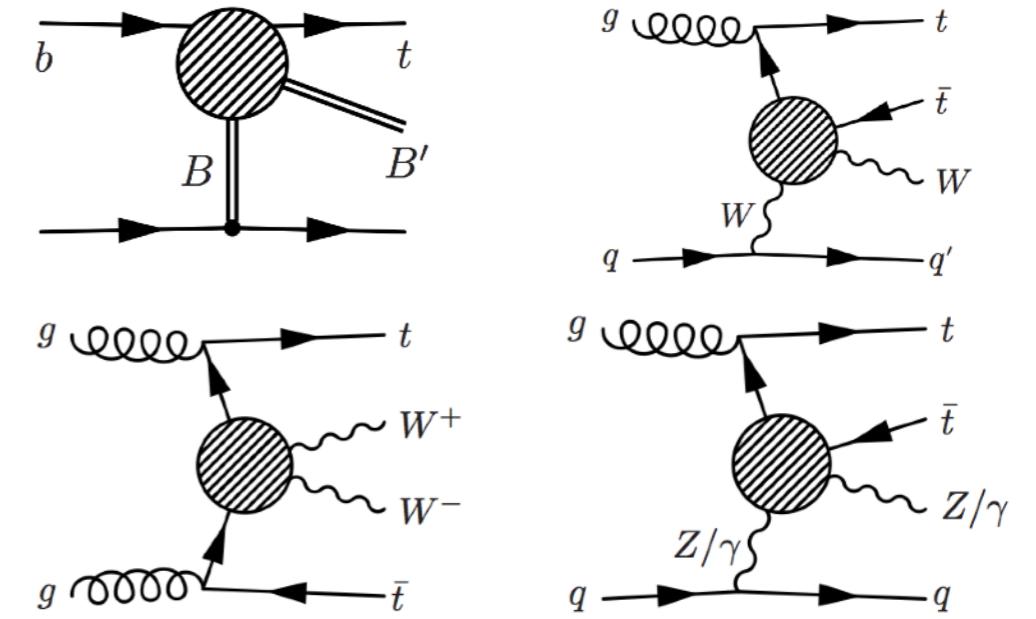
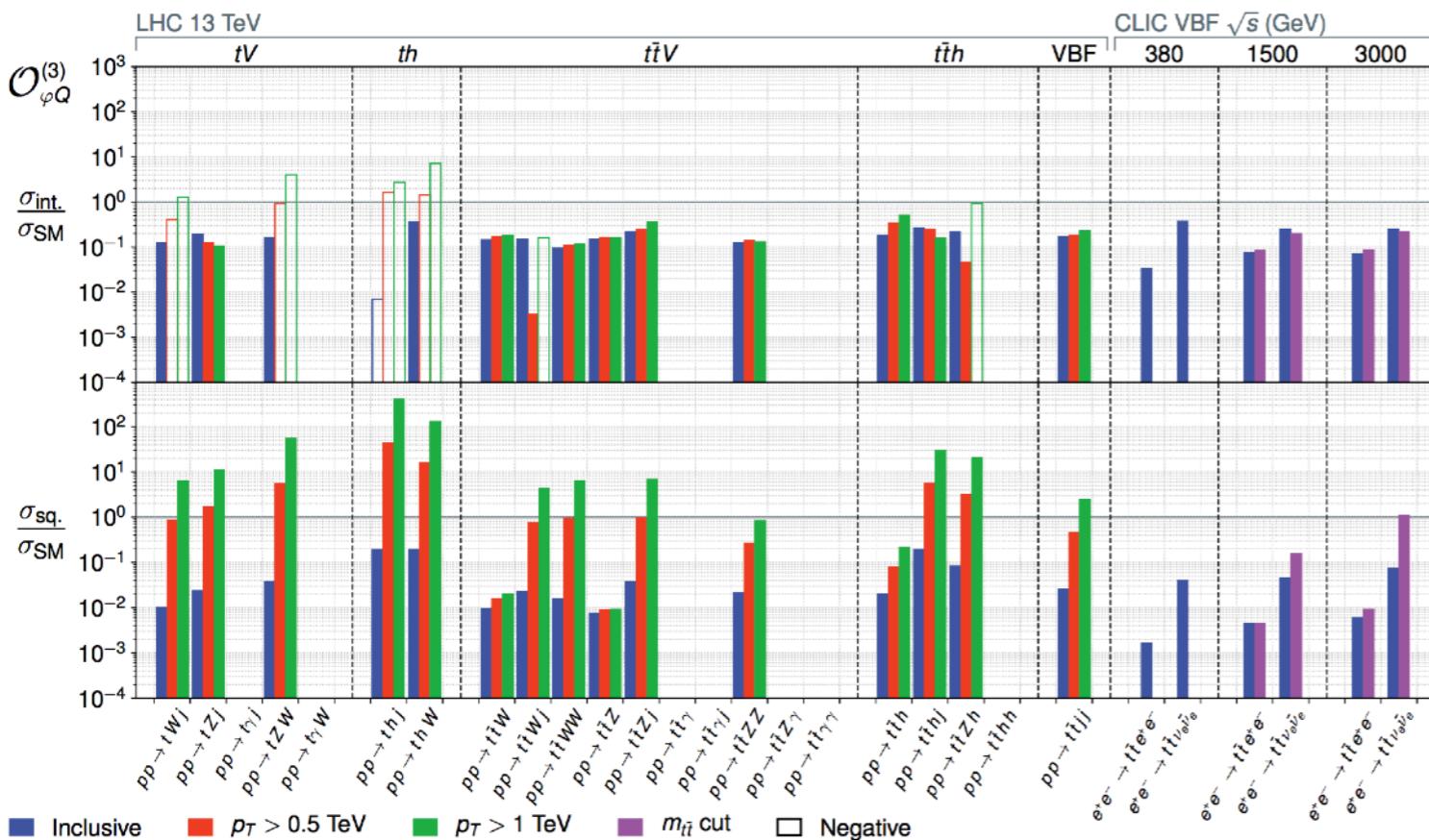
[J. Dror et al., 1511.03674]

More high energy tops

[Maltoni, Mantani, Mimasu, 1904.05637]

	Single-top	Two-top ($t\bar{t}$)
w/o Higgs	$bW \rightarrow t(Z/\gamma)$ (4.1.1)	$tW \rightarrow tW$ (5.1.1) $t(Z/\gamma) \rightarrow t(Z/\gamma)$ (5.1.4)
w/ Higgs	$bW \rightarrow th$ (4.2.1)	$t(Z/\gamma) \rightarrow th$ (5.2.1) $th \rightarrow th$ (5.2.4)

Helicity amplitudes computed, and energy-growing channels identified



- ❖ tZW and tZj optimal to access b W to t Z.
- ❖ tHW and tHj optimal for b W to t H.
- ❖ ttX processes are challenging because suppressed by s-channel propagator.
- ❖ Adding a jet increase the sensitivity (J. A. Dror et al. arXiv:1511.03674).
- ❖ ttXY and VBF-tt are promising but rate-limited (e+ e- collider for VBF).
- ❖ t Z to t H and t H to t H are the most difficult (future colliders).

Mantani, talk at EPSHEP 2019

Validity and dim-8

Beyond dim-6

- By using energy growing effect, we are pushing the EFT over its edge.
Should be careful about higher order dim-8 effects.

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Should be careful about higher order dim-8 effects.
- Assessing EFT validity?
 - Conservative limits obtained by imposing cuts, depending on the expected scale Lambda.
[Contino, Falkowski, Goertz, Grojean, Riva '16]

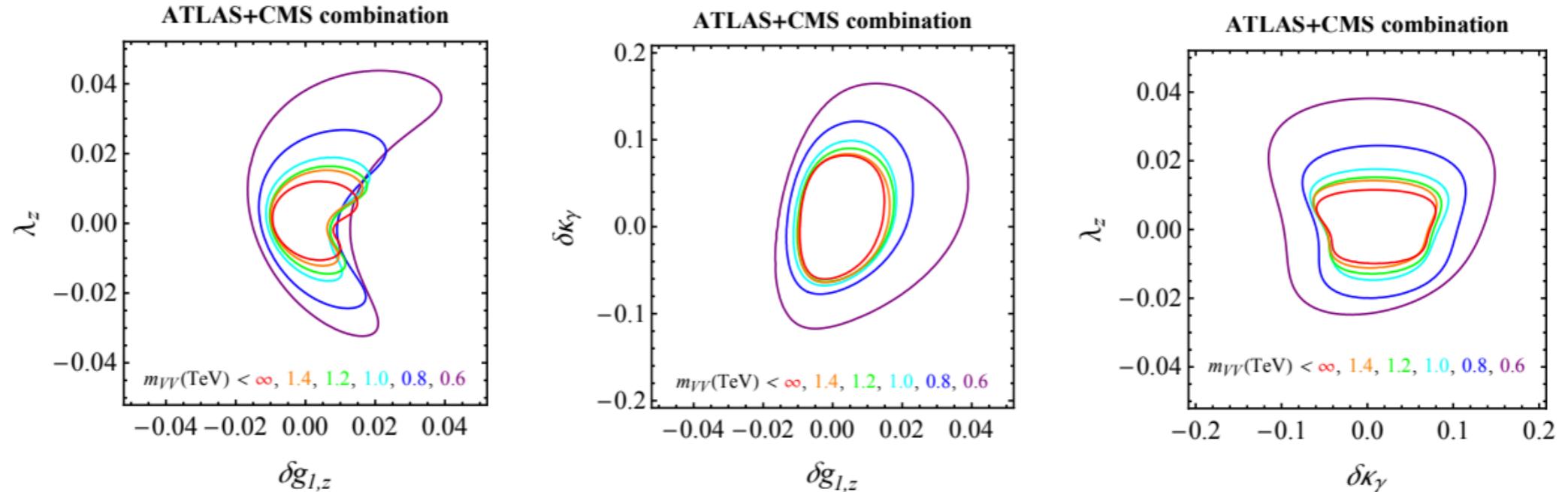


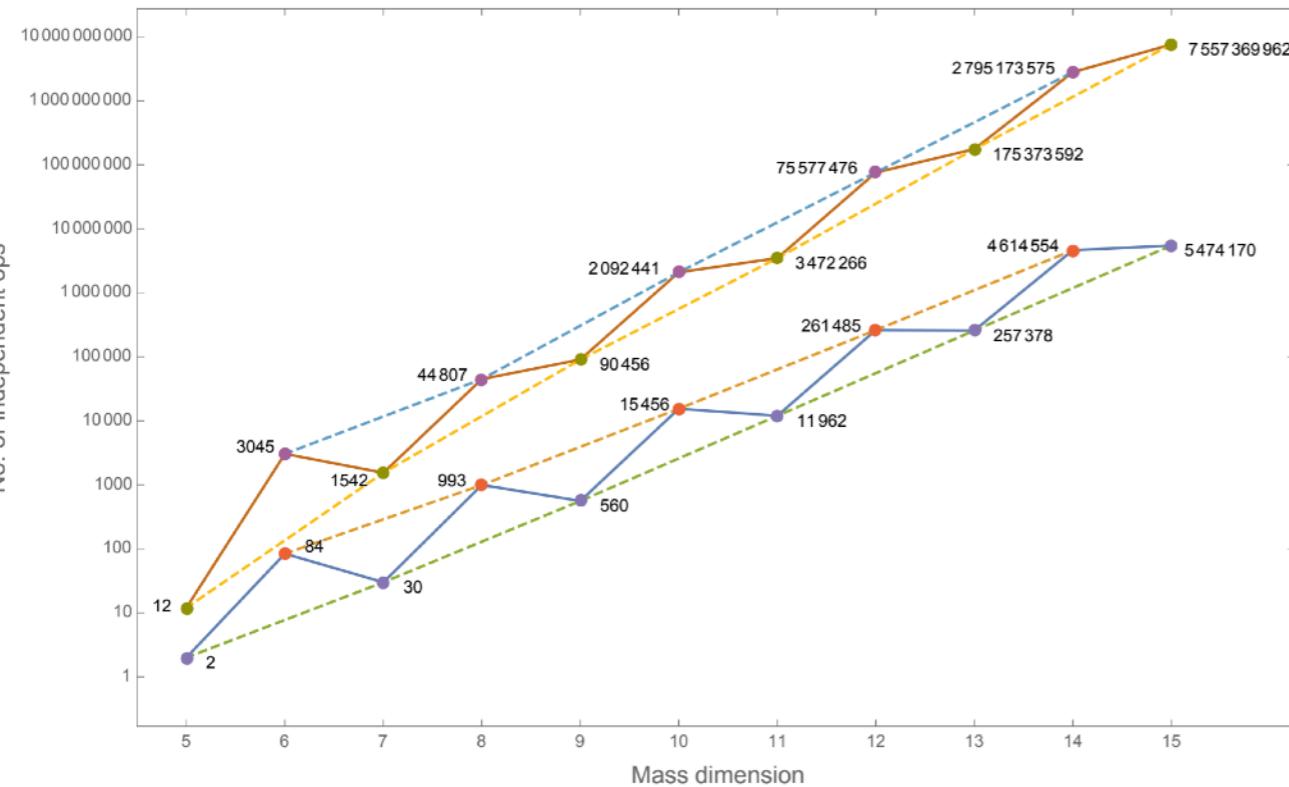
Figure 7: Combined 68% CL region from CMS WW (8 TeV) and ATLAS WZ (8+13 TeV) searches for different m_{VV} cuts.

[A. Falkowski et al. 1609.06312]

Beyond dim-6

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Should be careful about higher order dim-8 effects.
- Assessing EFT validity?
 - Conservative limits obtained by imposing cuts, depending on the expected scale Lambda. **[Contino, Falkowski, Goertz, Grojean, Riva '16]**
 - or, explicit study of TH uncertainties, requires knowledge of dim-8 EFT

[L. Lehman, A. Marin, '15]



[B. Henning et al., '15]

DEFT

[B. Gripaios, D. Sutherland '18]

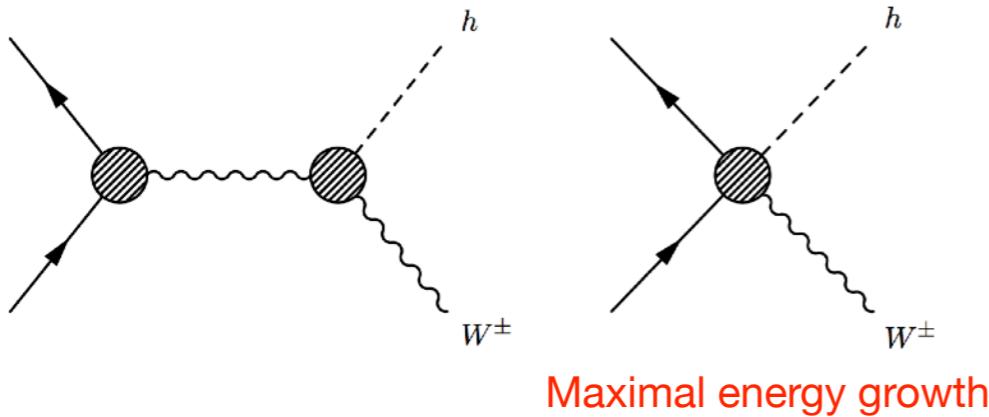
DEFT takes as input a set of fields and their irreps under a set of $SU(N)$ -like symmetries. *In principle*, it can output:

- ▶ a list of all the contractions of products of these fields which are invariant under the symmetries, to a given order;
- ▶ a list of the redundancies between these operators (Fierz, IBPs, EOMs, &c.);
- ▶ an arbitrary operator basis;
- ▶ a matrix to convert into and between arbitrary operator bases.

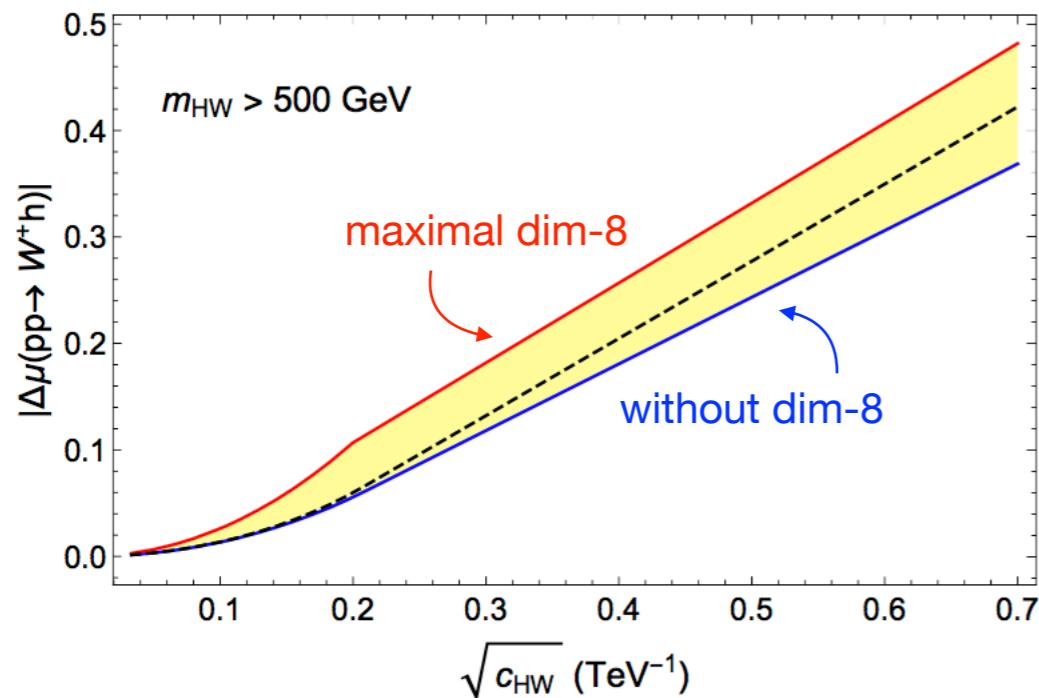
Talk by D. Sutherland, SMEFT tools workshop

Dim-8 in high energy: case study

[Hays, Martin, Sanz, Setford, '18]



$$\hat{\sigma}(pp \rightarrow W^+ h) \sim \left(\frac{e^2}{4608 \pi \sin^4 \hat{\theta}} \right) \frac{\hat{v}^2}{m_W^2 \Lambda^4} \hat{s} \left(e^2 (c_{8,3Q1} - c_{8,3Q2} + c_{8,3Q3} + c_{8,3Q4}) + 8 \sin^2 \theta (c_{Hq}^{(3)})^2 \right) + \mathcal{O}(\hat{s}^0).$$



$\mathcal{O}_{8,QW1}$	$\delta_{IJ} (Q^\dagger \bar{\sigma}^\nu Q) D^\mu (H^\dagger \tau^I H) W_{\mu\nu}^J$	$\mathcal{O}_{8,Q1}$	$i (Q^\dagger \bar{\sigma}^\mu Q) (H^\dagger \overleftrightarrow{D}^\mu H) (H^\dagger H)$
$\mathcal{O}_{8,Q\tilde{W}1}$	$\delta_{IJ} (Q^\dagger \bar{\sigma}^\nu Q) D^\mu (H^\dagger \tau^I H) \tilde{W}_{\mu\nu}^J$	$\mathcal{O}_{8,Q2}$	$i \delta_{IJ} (Q^\dagger \bar{\sigma}^\mu \tau^I Q) \left((\overleftrightarrow{D}_\mu H^\dagger \tau^J H) (H^\dagger H) + (\overleftrightarrow{D}_\mu H^\dagger H) (H^\dagger \tau^J H) \right)$
$\mathcal{O}_{8,QW2}$	$i \delta_{IJ} (Q^\dagger \bar{\sigma}^\nu Q) (H^\dagger \overleftrightarrow{D}^\mu \tau^I H) W_{\mu\nu}^J$	$\mathcal{O}_{8,Q3}$	$i \epsilon_{IJK} (Q^\dagger \bar{\sigma}^\mu \tau^I Q) (H^\dagger \overleftrightarrow{D}^\mu \tau^J H) (H^\dagger \tau^K H)$
$\mathcal{O}_{8,Q\tilde{W}2}$	$i \delta_{IJ} (Q^\dagger \bar{\sigma}^\nu Q) (H^\dagger \overleftrightarrow{D}^\mu \tau^I H) \tilde{W}_{\mu\nu}^J$	$\mathcal{O}_{8,Q4}$	$\epsilon_{IJK} (Q^\dagger \bar{\sigma}^\mu \tau^I Q) (H^\dagger \tau^J H) D_\mu (H^\dagger \tau^K H)$
$\mathcal{O}_{8,QW3}$	$\delta_{IJ} (Q^\dagger \bar{\sigma}^\nu \tau^I Q) D^\mu (H^\dagger H) W_{\mu\nu}^J$	$\mathcal{O}_{8,3Q1}$	$i (Q^\dagger \bar{\sigma}^\mu D^\nu Q) (D_{(\mu\nu)}^2 H^\dagger H) + h.c.$
$\mathcal{O}_{8,Q\tilde{W}3}$	$\delta_{IJ} (Q^\dagger \bar{\sigma}^\nu \tau^I Q) D^\mu (H^\dagger H) \tilde{W}_{\mu\nu}^J$	$\mathcal{O}_{8,3Q2}$	$i \delta_{IJ} (Q^\dagger \bar{\sigma}^\mu \tau^I D^\nu Q) (D_{(\mu\nu)}^2 H^\dagger \tau^J H) + h.c.$
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$\mathcal{O}_{8,Q\tilde{W}4}$	$i \delta_{IJ} (Q^\dagger \bar{\sigma}^\nu \tau^I Q) (H^\dagger \overleftrightarrow{D}^\mu H) \tilde{W}_{\mu\nu}^J$	$\mathcal{O}_{8,3Q4}$	$i \delta_{IJ} (Q^\dagger \bar{\sigma}^\mu \tau^I D^\nu Q) (H^\dagger \tau^J D_{(\mu\nu)}^2 H) + h.c.$
$\mathcal{O}_{8,QW5}$	$\epsilon_{ABC} (Q^\dagger \bar{\sigma}^\nu \tau^A Q) D^\mu (H^\dagger \tau^B H) W_{\mu\nu}^C$		
$\mathcal{O}_{8,Q\tilde{W}5}$	$\epsilon_{ABC} (Q^\dagger \bar{\sigma}^\nu \tau^A Q) D^\mu (H^\dagger \tau^B H) \tilde{W}_{\mu\nu}^C$		
$\mathcal{O}_{8,QW6}$	$i \epsilon_{ABC} (Q^\dagger \bar{\sigma}^\nu \tau^A Q) (H^\dagger \overleftrightarrow{D}^\mu \tau^B H) W_{\mu\nu}^C$		
$\mathcal{O}_{8,Q\tilde{W}6}$	$i \epsilon_{ABC} (Q^\dagger \bar{\sigma}^\nu \tau^A Q) (H^\dagger \overleftrightarrow{D}^\mu \tau^B H) \tilde{W}_{\mu\nu}^C$		

$$|\Delta\mu(pp \rightarrow h W^+)|_{m_{HW}>500\text{ GeV}} = 0.2$$

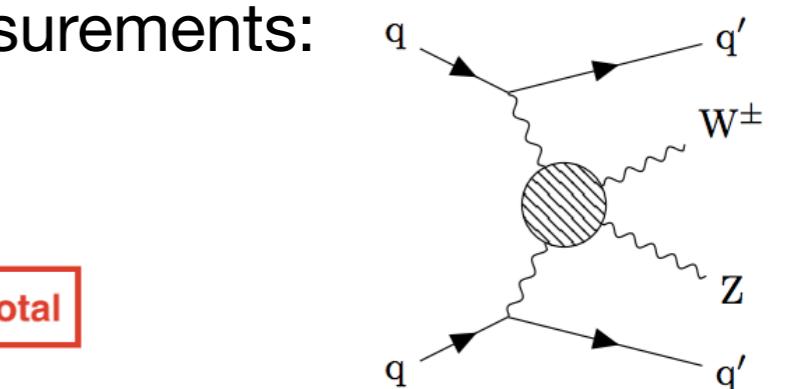
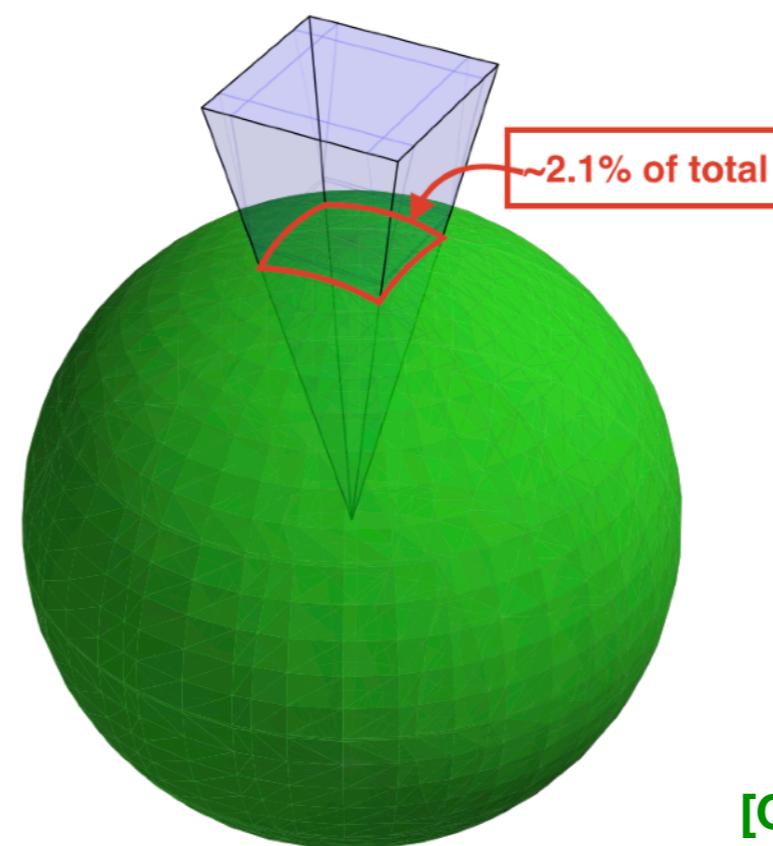
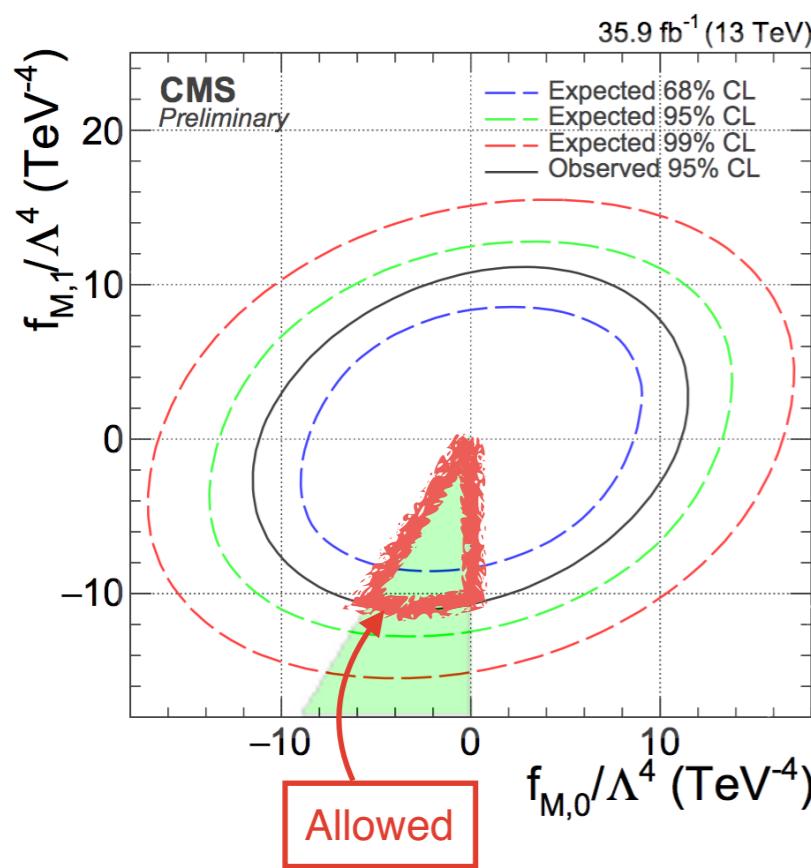
$$\sqrt{c_{HW}} = 1/(2.32 \text{ TeV}) \quad \text{without dim-8}$$

$$\sqrt{c_{HW}} = 1/(3.59 \text{ TeV}) \quad \text{maximal dim-8}$$

55% difference in scale

Dim-8: be careful about signs

- Not every EFT can be UV completed!
[Adams, Arkani-Hamed, Dubovsky, Nicolis, Rattazzi, JHEP 06]
- For SMEFT @ dim-8, the fundamental QFT principles of the UV completion fixes the sign of dim-8 coefficients (or their combinations), i.e. **positivity bounds**
- Important consequence, e.g. for the usual aQGC measurements:



More generally, 98% of the dim-8 QGC parameters being used currently is “redundant”.

[Q. Bi, CZ, S.-Y. Zhou, JHEP 19]

Precision with loops

Top loops at LHC

Recall the $t\bar{t}\phi\phi$ term from opening the $t\bar{t}Z$ operator:

$$\bar{t}\gamma_\mu t H^\dagger \overleftrightarrow{D}_\mu H \rightarrow \text{Feynman diagram}$$

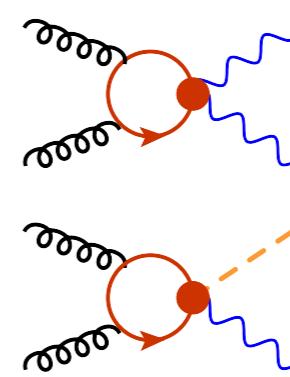
The Feynman diagram shows a central orange dot representing a vertex. Two solid red arrows point towards the vertex from the left, representing incoming top quark lines. From the vertex, two dashed orange lines extend to the right, representing outgoing particles.

Top loops at LHC

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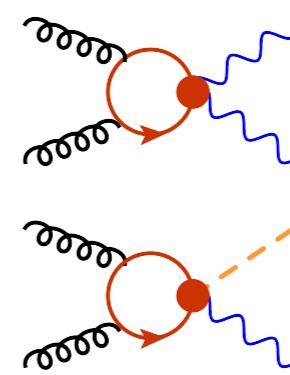

Instead of embedding in $pp>ttWj$, could also use loops:



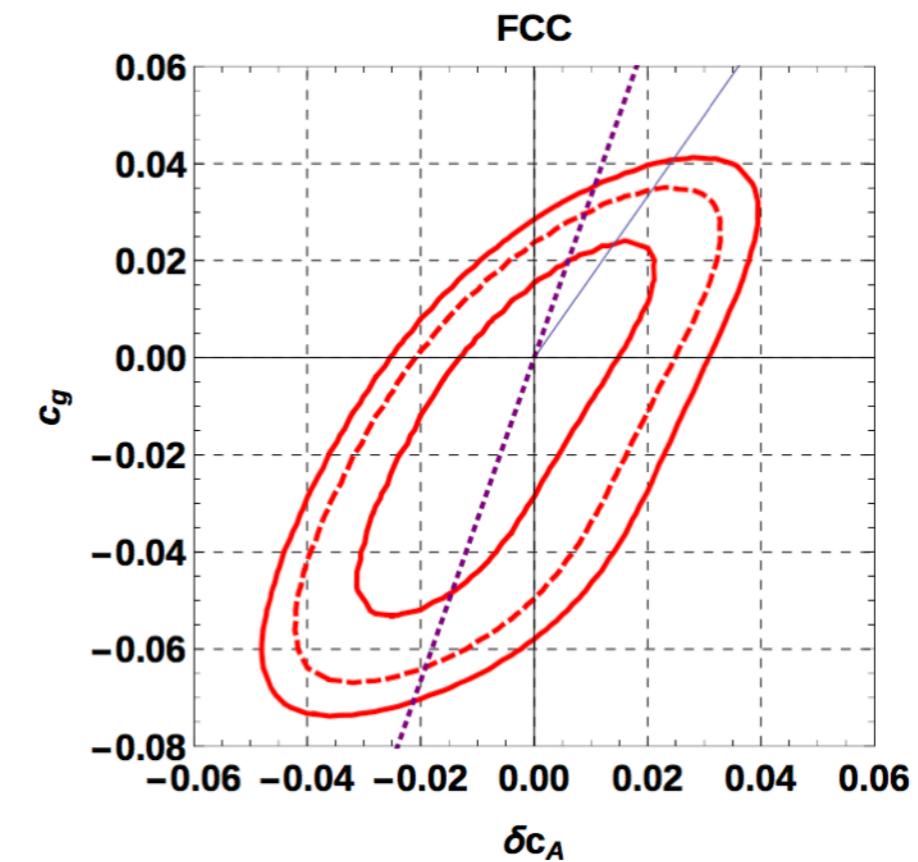
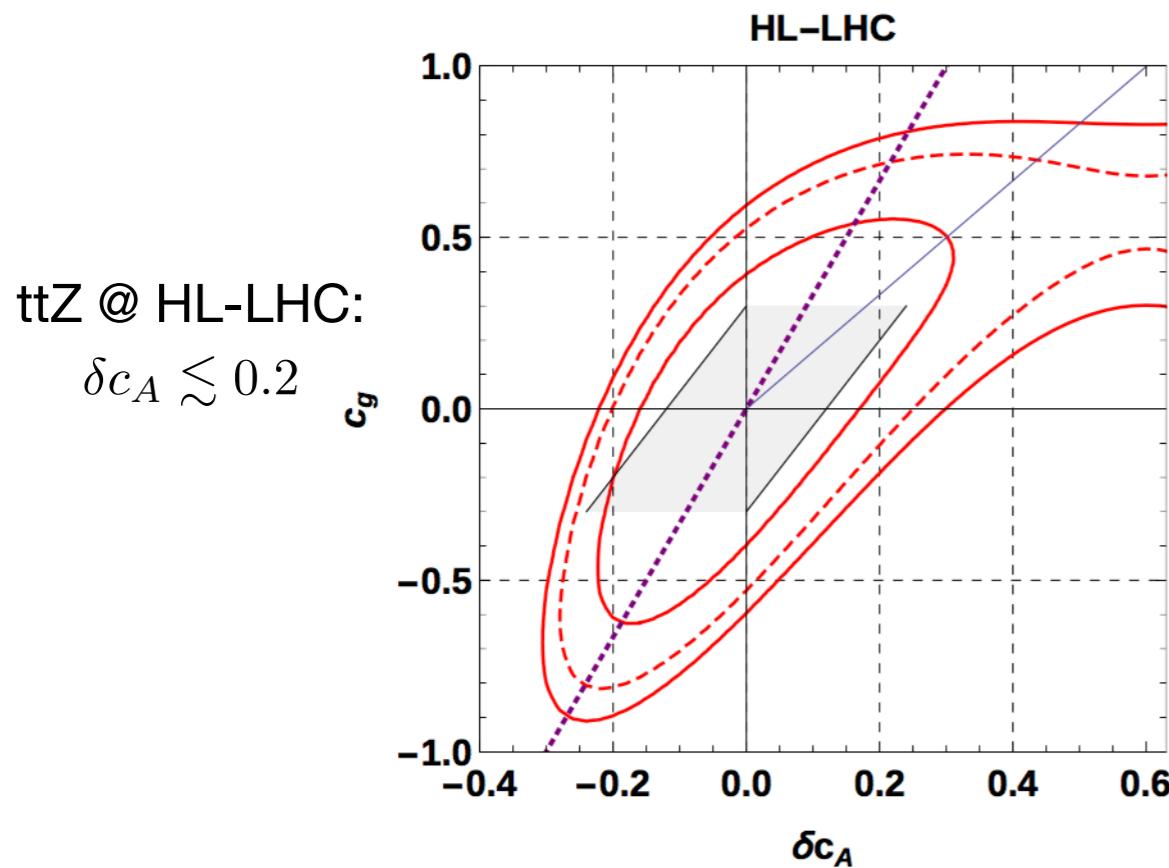
Top loops at LHC

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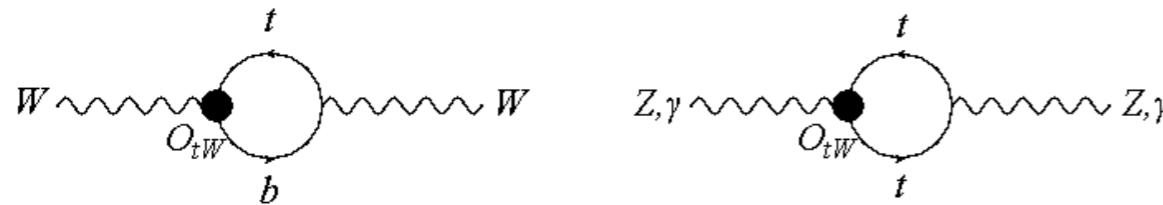


Instead of embedding in $pp>ttWj$, could also use loops:



[Azatov, Grojean, Paul, Salvioni '16], [Englert, Rosenfeld, Spannowsky, Tonero '16]

Top loops in EWPO



[CZ, Greiner, Willenbrock 1201.6670]

$$\begin{pmatrix} -0.702 & -0.701 & -0.000 & +0.128 & -0.003 & +0.000 & -0.000 & -0.000 \\ -0.094 & -0.087 & -0.002 & -0.992 & -0.019 & +0.001 & -0.001 & -0.000 \\ -0.342 & +0.349 & -0.398 & +0.017 & -0.761 & +0.056 & -0.136 & -0.039 \\ -0.326 & +0.323 & -0.591 & -0.009 & +0.632 & -0.065 & -0.191 & +0.015 \\ +0.137 & -0.137 & +0.128 & -0.000 & -0.003 & +0.138 & -0.935 & -0.229 \\ +0.034 & -0.034 & +0.039 & +0.001 & -0.094 & -0.745 & -0.244 & +0.610 \\ -0.003 & +0.003 & +0.007 & -0.000 & +0.025 & +0.646 & -0.090 & +0.757 \\ +0.505 & -0.505 & -0.689 & -0.000 & -0.108 & +0.014 & +0.054 & +0.009 \end{pmatrix}$$

$$\times \frac{1}{\Lambda^2} \begin{pmatrix} C_{\phi q}^{(3)} \\ C_{\phi q}^{(1)} \\ C_{\phi t} \\ C_{\phi b} \\ C_{tW} \\ C_{bW} \\ C_{tB} \\ C_{bB} \end{pmatrix} = \begin{pmatrix} -0.011 & \pm 0.014 \\ +0.59 & \pm 0.27 \\ -0.23 & \pm 1.10 \\ -1.75 & \pm 1.62 \\ -2.2 & \pm 11.9 \\ -9.2 & \pm 21.1 \\ +102.4 & \pm 50.4 \\ -1.36e+3 & \pm 1.38e+3 \end{pmatrix} \text{TeV}^{-2}.$$

Top operators

1 sigma limits

[SMEFiT 1901.05965]

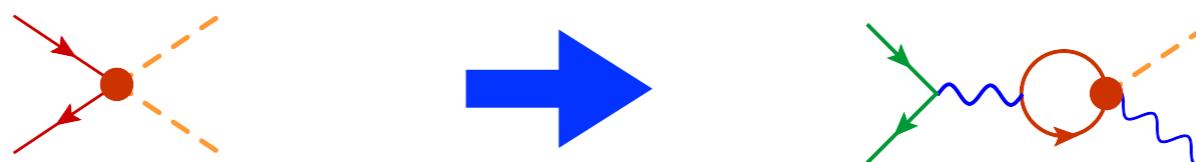
	Direct LHC	Indirect EW
c_{tG}	$[-0.4, 0.4]$	
c_{tW}	$[-1.8, 0.9]$	$[-2.8, 2.0]$ (EW)
c_{bW}	$[-2.6, 3.1]$	$[-15, 37]$ (EW)
c_{tZ}	$[-2.1, 4.0]$	$c_{tB}: [-5.8, 15.4]$ (EW)
$c_{\varphi tb}$	$[-27, 8.7]$	
$c_{\varphi Q}^3$	$[-5.5, 5.8]$	
$c_{\varphi Q}^-$	$[-3.5, 3]$	$[-3.4, 7.4]$ (EW)
$c_{\varphi t}$	$[-13, 18]$	$[-2.0, 5.6]$ (EW)
$c_{t\varphi}$	$[-60, 10]$	

Interplay of Top & EW sectors
due to precision loop effects

Top loops at future H factory

[Durieux, Gu, Vryonidou, CZ '18]

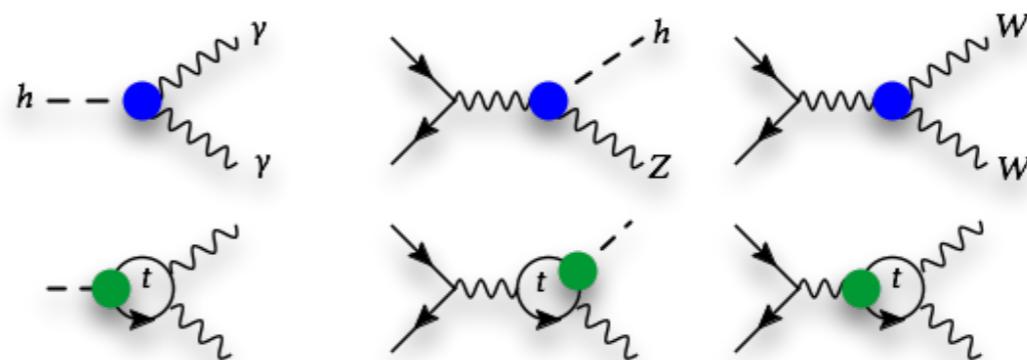
Alternatively



Leads to complication in future H measurements

- Higgs/diboson channels can reach $\sim 1\%$ or even better precision with future lepton collider. When this happens, we want to be able to disentangle

- **H coupling tree level** and
- **Top coupling loop level?**



- At future CC even below ttbar threshold, it's possible to probe top EW couplings with good precision (better than HL-LHC).
- Strong correlation between top/H couplings \rightarrow top uncertainty will downgrade precision on H couplings.
- Once above 350: top Yukawa $\sim 30\%$ marginalized.

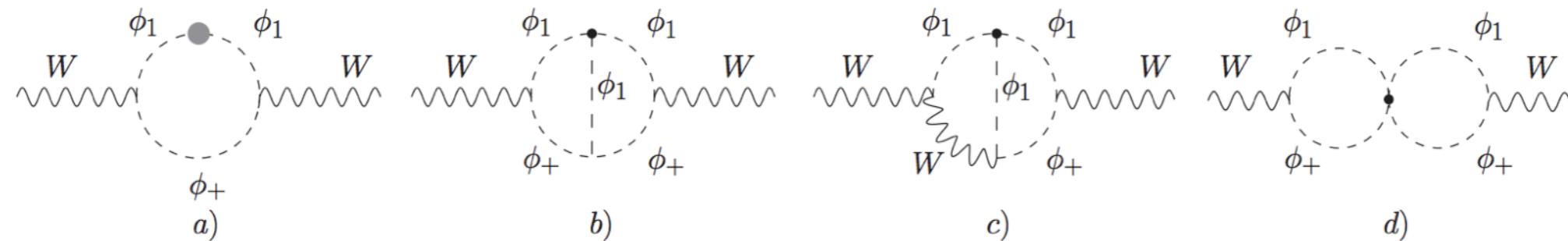
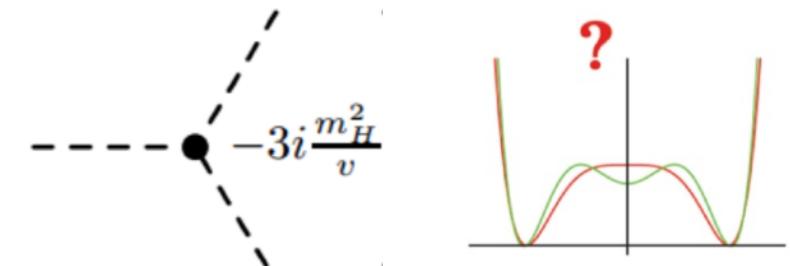
EW fit: going to two loop

[Degrassi, Fedele, Giardino 1702.01737]

H couplings at one-loop are less interesting [Chen, Dawson, CZ '13]

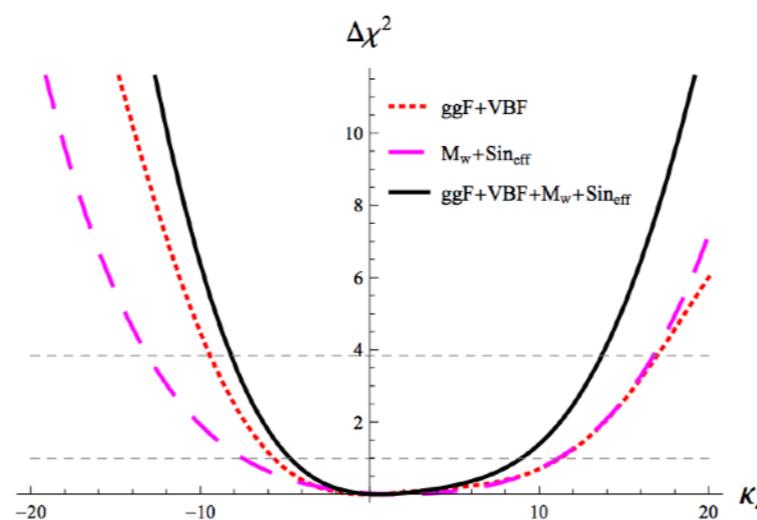
But: **Higgs trilinear coupling**

- Direct probe via di-Higgs at LHC
- One loop effect with single Higgs
- **Two loop effects in EWPO: through W/Z self energies**



$$O = O^{\text{SM}} [1 + (\kappa_\lambda - 1)C_1 + (\kappa_\lambda^2 - 1)C_2] ,$$

	C_1	C_2
m_W	6.27×10^{-6}	-1.72×10^{-6}
$\sin^2 \theta_{\text{eff}}^{\text{lep}}$	-1.56×10^{-5}	4.55×10^{-6}



Currently O(10) bound.
~10 improvement with future CC

Loop measurement: from indirect to direct?

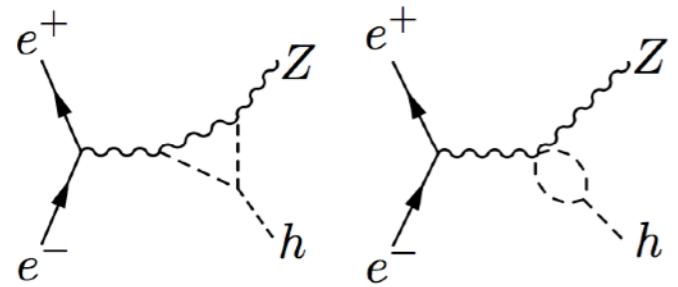


FIG. 1: NLO vertex corrections to the associated production cross section which depend on the Higgs self-coupling. These terms lead to a linear dependence on modifications of the self-coupling δ_h .

[M. McCullough 1312.3322]

- **Problem:** loop probes are “indirect”, i.e. rely on assumptions that other BSM effects are not present.

Loop measurement: from indirect to direct?

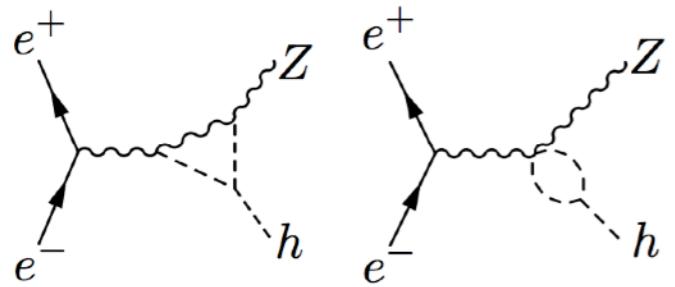


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Loop measurement: from indirect to direct?

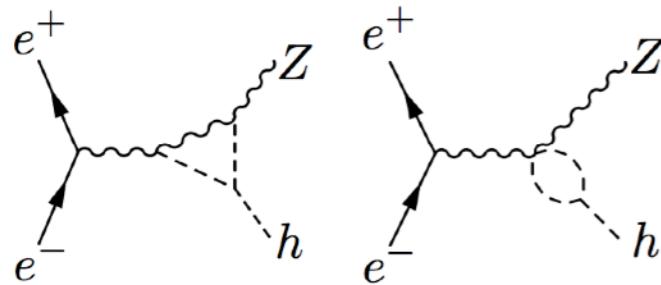


FIG. 1: NLO vertex corrections to the associated production cross section which depend on the Higgs self-coupling. These terms lead to a linear dependence on modifications of the self-coupling δ_h .

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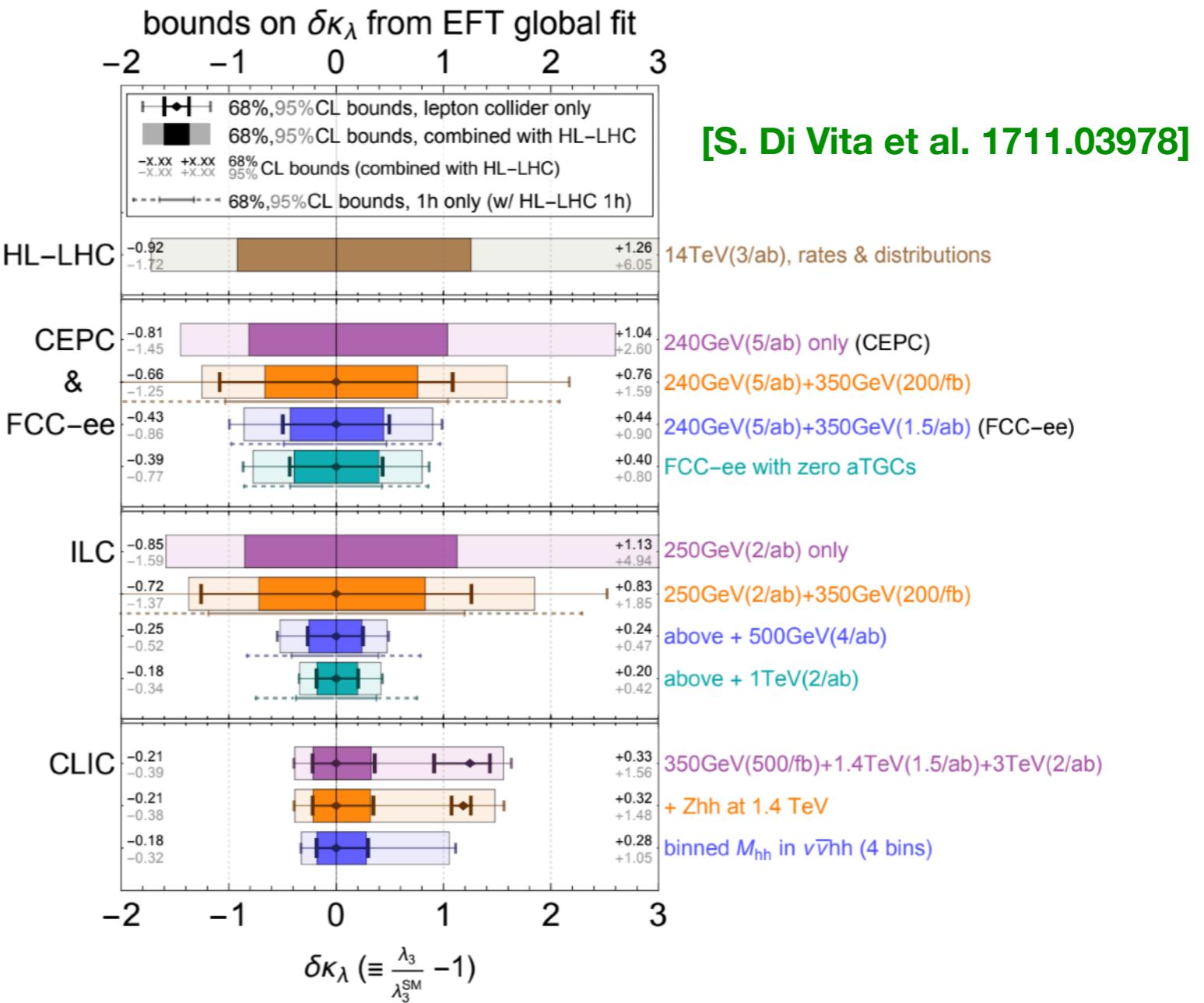


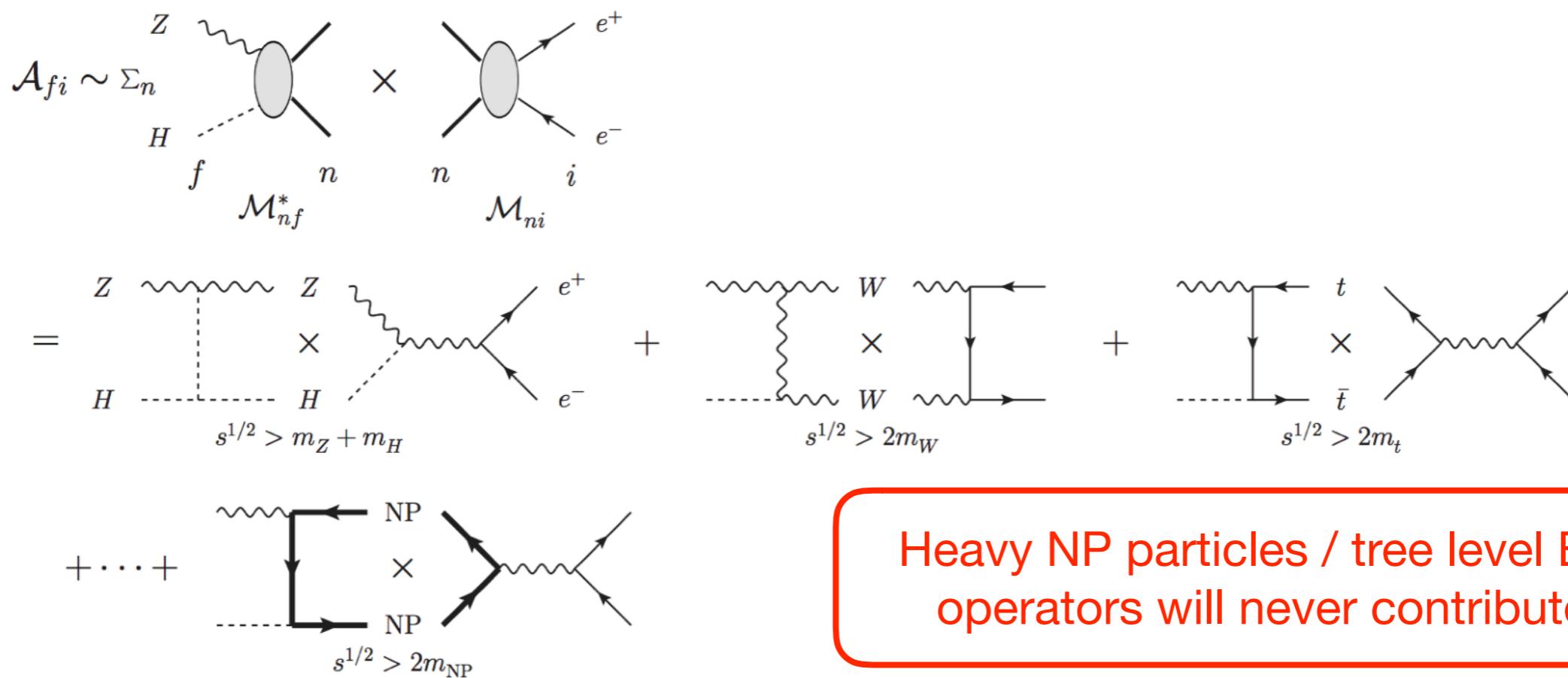
Figure 12: A summary of the bounds on $\delta\kappa_\lambda$ from global fits for various future collider scenarios. For the “1h only” scenario, only single Higgs measurements at lepton colliders are included.

Loop measurement: from indirect to direct?

[J. Nakamura & A. Shivaji 1812.01576]

- New idea: choose the “right” observable (**naive time-reversal odd**) and turn the loop effects into “direct” measurement.

If T (or equally CP) is conserved, T-odd observables
are proportional to the absorptive part



Loop measurement: from indirect to direct?

[J. Nakamura & A. Shivaji 1812.01576]

- Consider $Z(-\rightarrow ll) + H$

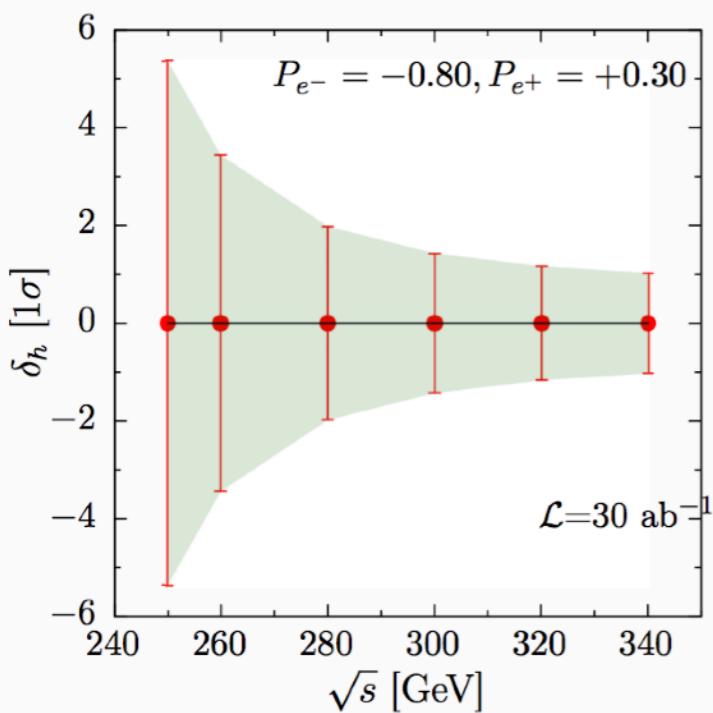
Under T transformation without interchanging the initial and final states,

$$\frac{d^3\sigma}{d\cos\Theta d\cos\theta d\phi} \rightarrow \underbrace{F_1(1 + \cos^2\theta) + F_2(1 - 3\cos^2\theta) + F_3 \sin 2\theta \cos\phi + F_4 \sin^2\theta \cos 2\phi}_{T\text{-even}} + \underbrace{F_5 \cos\theta + F_6 \sin\theta \cos\phi - F_7 \sin\theta \sin\phi - F_8 \sin 2\theta \sin\phi - F_9 \sin^2\theta \sin 2\phi}_{T\text{-odd}}$$

Define T-odd asymmetries (A_7, A_8, A_9) by

$$A_{(7,8,9)} \equiv \frac{F_{(7,8,9)}}{F_1}, \quad A_7 \propto \frac{N(\sin\phi > 0) - N(\sin\phi < 0)}{N(\sin\phi > 0) + N(\sin\phi < 0)} \text{ etc}$$

8/11



Difficult method, but

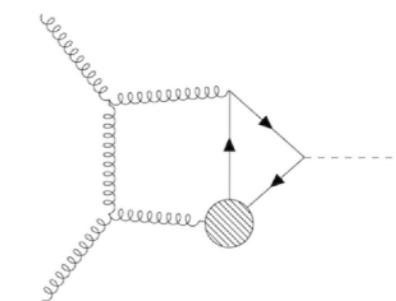
- Useful method to directly constrain HHH below 340
- Provide additional observable to isolate HHH from other couplings, should be added to a global H/EW fit

SMEFT @ NLO?

Status of NLO

Some recent progresses (past two years):

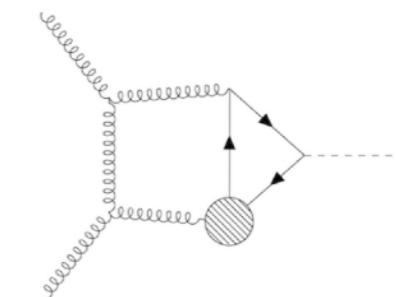
- Higgs decay: $\gamma\gamma$ [A. Dedes et al. '18], γZ [Dedes, Suxho, Trifyllis '19],
 ZZ [Dawson, Giardino '18], WW [Dawson, Giardino '18], bb [Cullen, Pecjak, Scott '19]
- HZ production (QCD): $vh@nnlo$ [R. Harlander et al. '18]
- WW production: [Balio, Dawson, Lewis '19]
- gg to H , **two loop**: [Deutschmann, Duhr, Maltoni, Vryonidou '18]
- Top production NLO+PS, automated with MadGraph5_aMC@NLO:
[Degrande, Maltoni, Mimasu, Vryonidou, CZ '18]
- Loop induced $HH/Hj/HZ/\dots$ based on same framework:
[Bylund, Maltoni, Tsinikos, Vryonidou, CZ '16], [Maltoni, Vryonidou, CZ '16],
- Single top, fNLO QCD production+decay, off shell: [Neumann, Sullivan, '19]
- Top decay @ NLO, including 4-fermion OPs: [Boughezal, Chen, Petriello, Wiegand '19]
- **EW:** H trilinear couplings in single Higgs: [Maltoni, Pagani, Shivaji, Zhao, '17]
- **EW:** top loops in Higgs processes: [Vryonidou, CZ '18]



Status of NLO

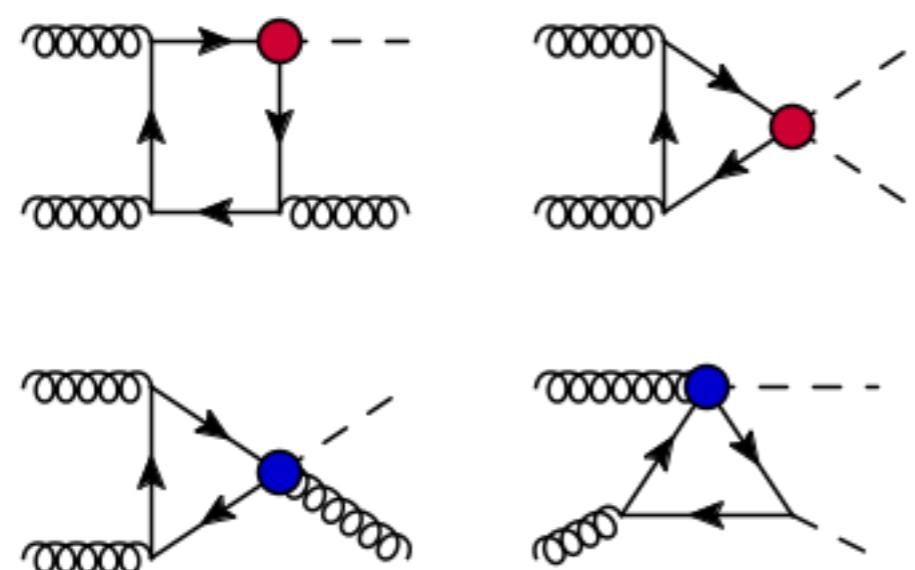
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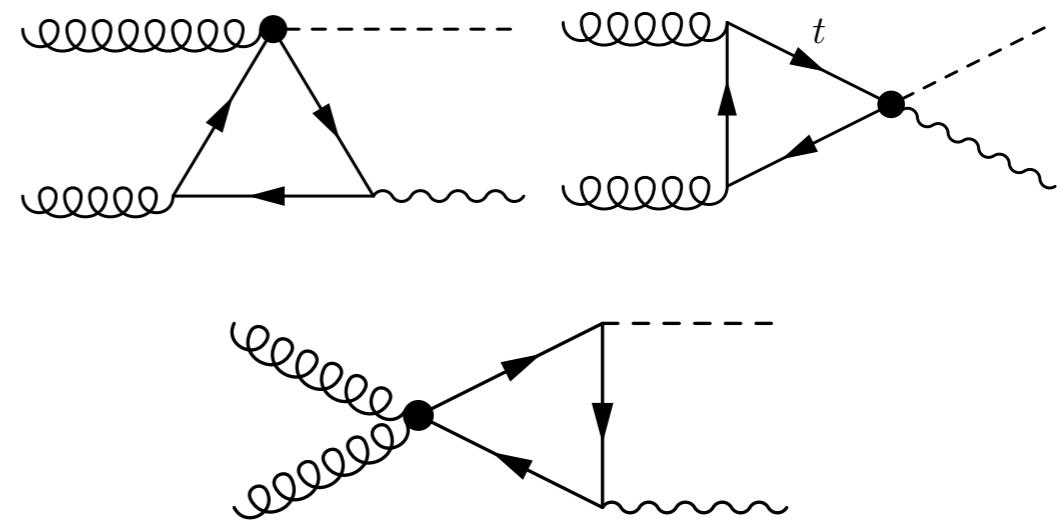
	ttg	ttZ/ γ , tbW	ttH qqttggH
Process	O_{tG}	$O_{tB} O_{tW} O_{\varphi Q}^{(3)} O_{\varphi Q}^{(1)} O_{\varphi t}$	$O_{t\varphi} O_{4f} O_{\varphi G}$
$t \rightarrow bW \rightarrow bl^+ \nu$	✓	✓ ✓	✓
$pp \rightarrow t\bar{q}$	✓	✓ ✓	✓
$pp \rightarrow tW$	✓	✓ ✓	✓
$pp \rightarrow t\bar{t}$	✓		✓
$pp \rightarrow t\bar{t}\gamma$	✓ ✓ ✓		✓
$pp \rightarrow t\gamma j$	✓ ✓ ✓ ✓		✓
$pp \rightarrow t\bar{t}Z$	✓ ✓ ✓ ✓ ✓ ✓		✓
$pp \rightarrow tZj$	✓ ✓ ✓ ✓ ✓ ✓		✓
$pp \rightarrow t\bar{t}W$	✓		✓
$e^+e^- \rightarrow t\bar{t}$	✓ ✓ ✓ ✓ ✓ ✓		✓
$pp \rightarrow t\bar{t}H$	✓		✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ (✓)
$pp \rightarrow tHj$	✓	✓ ✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓ ✓ ✓
$gg \rightarrow H, Hj, Hz$	✓	✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓ ✓ ✓

Coupling measurements



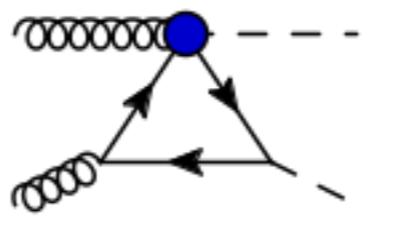
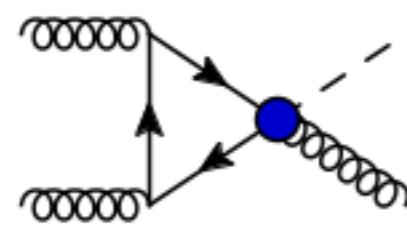
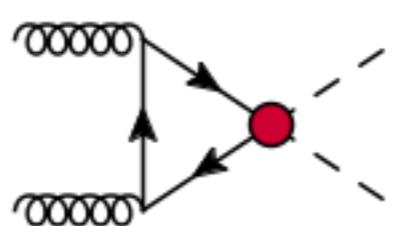
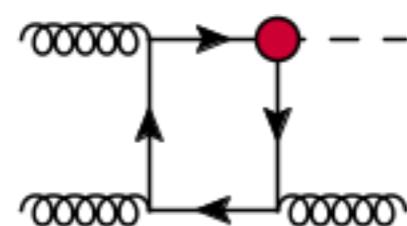
	ttZ/ γ	tqg tqH II tq
Process	$O_{\phi q}^{(3)} O_{\phi q}^{(1)} O_{\phi u}^{(1)} O_{uW} O_{uB}$	$O_{uG} O_{u\phi} O_{4f}$
$t \rightarrow ql^+l^-$	✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓ ✓ ✓
$t \rightarrow q\gamma$		✓ ✓ ✓
$t \rightarrow qH$		✓ ✓
$pp \rightarrow t$		✓
$pp \rightarrow tl^+l^-$	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	(✓)
$pp \rightarrow t\gamma$		✓ ✓ ✓
$pp \rightarrow tH$		✓ ✓ ✓

FCNC searches



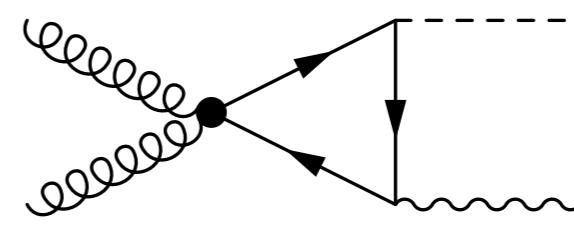
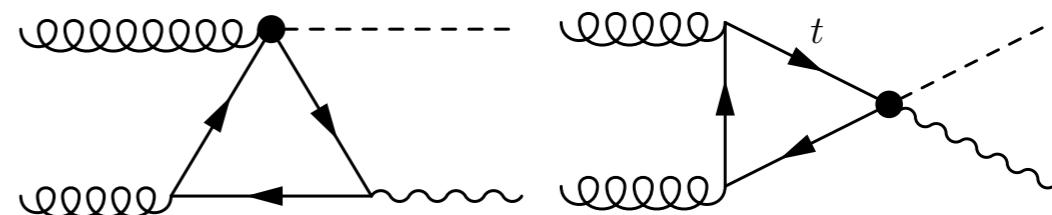
	ttg	ttZ/ γ , tbW				ttH qqttggH			
Process	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{4f}	$O_{\varphi G}$
$t \rightarrow bW \rightarrow bl^+\nu$	✓		✓	✓				✓	
$pp \rightarrow t\bar{q}$	✓		✓	✓				✓	
$pp \rightarrow tW$	✓		✓	✓					
$pp \rightarrow t\bar{t}$	✓							✓	
$pp \rightarrow t\bar{t}\gamma$	✓	✓	✓					✓	
$pp \rightarrow t\gamma j$	✓	✓	✓	✓				✓	
$pp \rightarrow t\bar{t}Z$	✓	✓	✓	✓	✓	✓		✓	
$pp \rightarrow tZj$	✓	✓	✓	✓	✓	✓		✓	
$pp \rightarrow t\bar{t}W$	✓						✓		
$e^+e^- \rightarrow t\bar{t}$	✓	✓	✓						
$pp \rightarrow t\bar{t}H$	✓								
$pp \rightarrow tHj$	✓			✓					
$gg \rightarrow H, Hj, Hz$	✓								

Coupling measurements



	tqZ/ γ					tqg tqH II tq		
Process	$O_{\phi q}^{(3)}$	$O_{\phi q}^{(1)}$	$O_{\phi u}^{(1)}$	O_{uW}	O_{uB}	O_{uG}	$O_{u\phi}$	O_{4f}
$t \rightarrow ql^+l^-$	✓	✓	✓	✓	✓	✓	✓	✓
$t \rightarrow q\gamma$						✓	✓	✓
$t \rightarrow qH$								✓
								✓
								(✓)
								✓
								✓
								✓

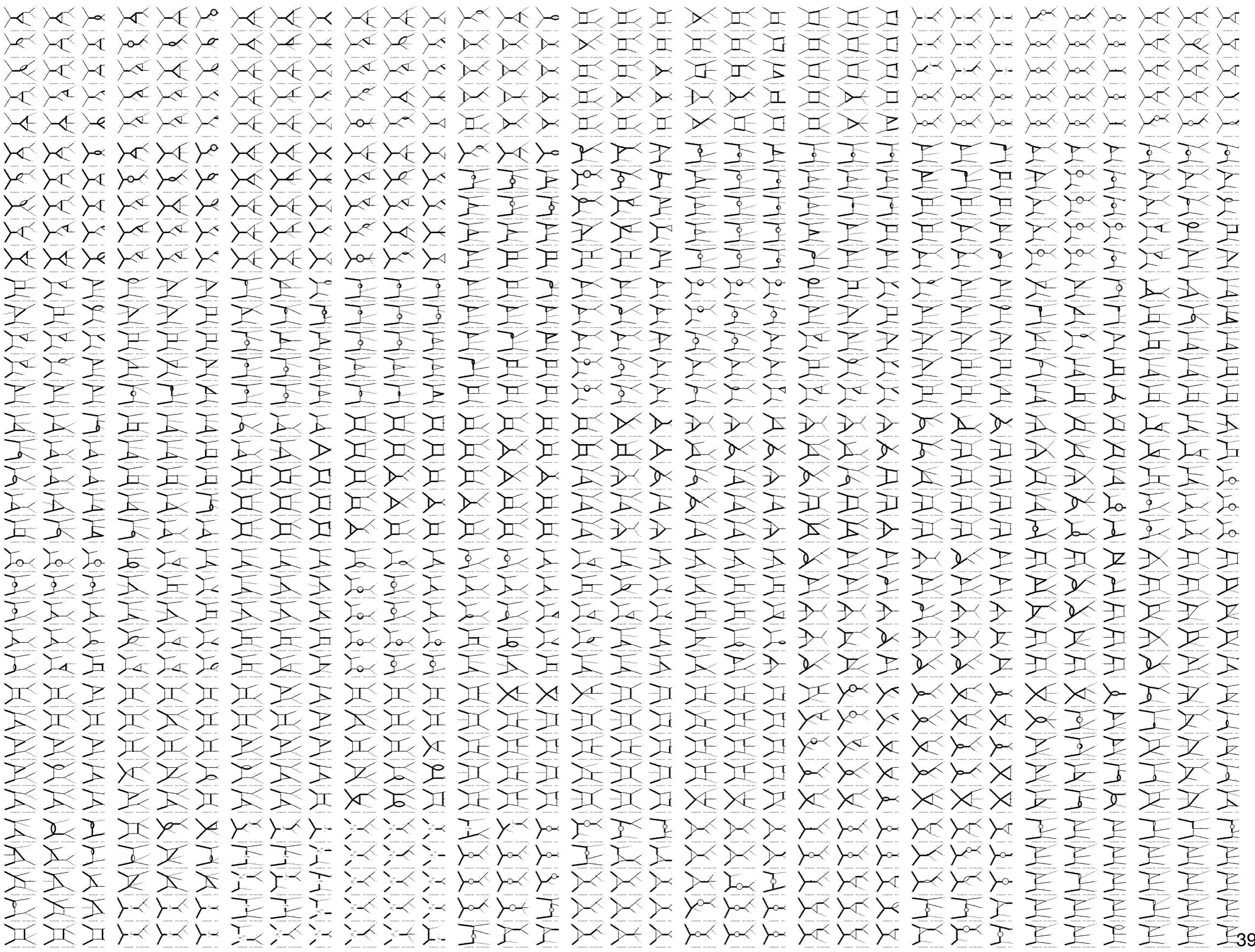
FCNC searches

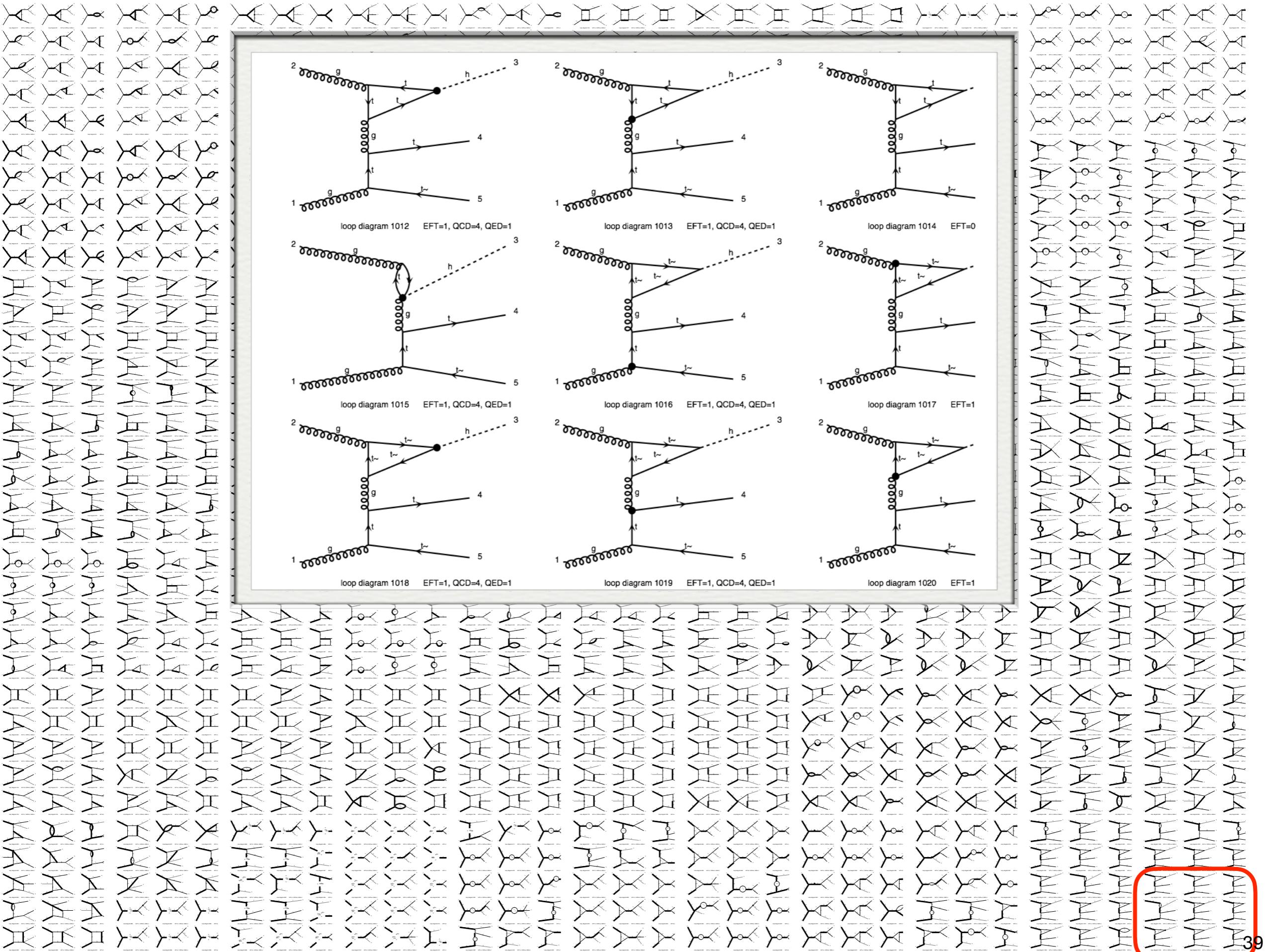


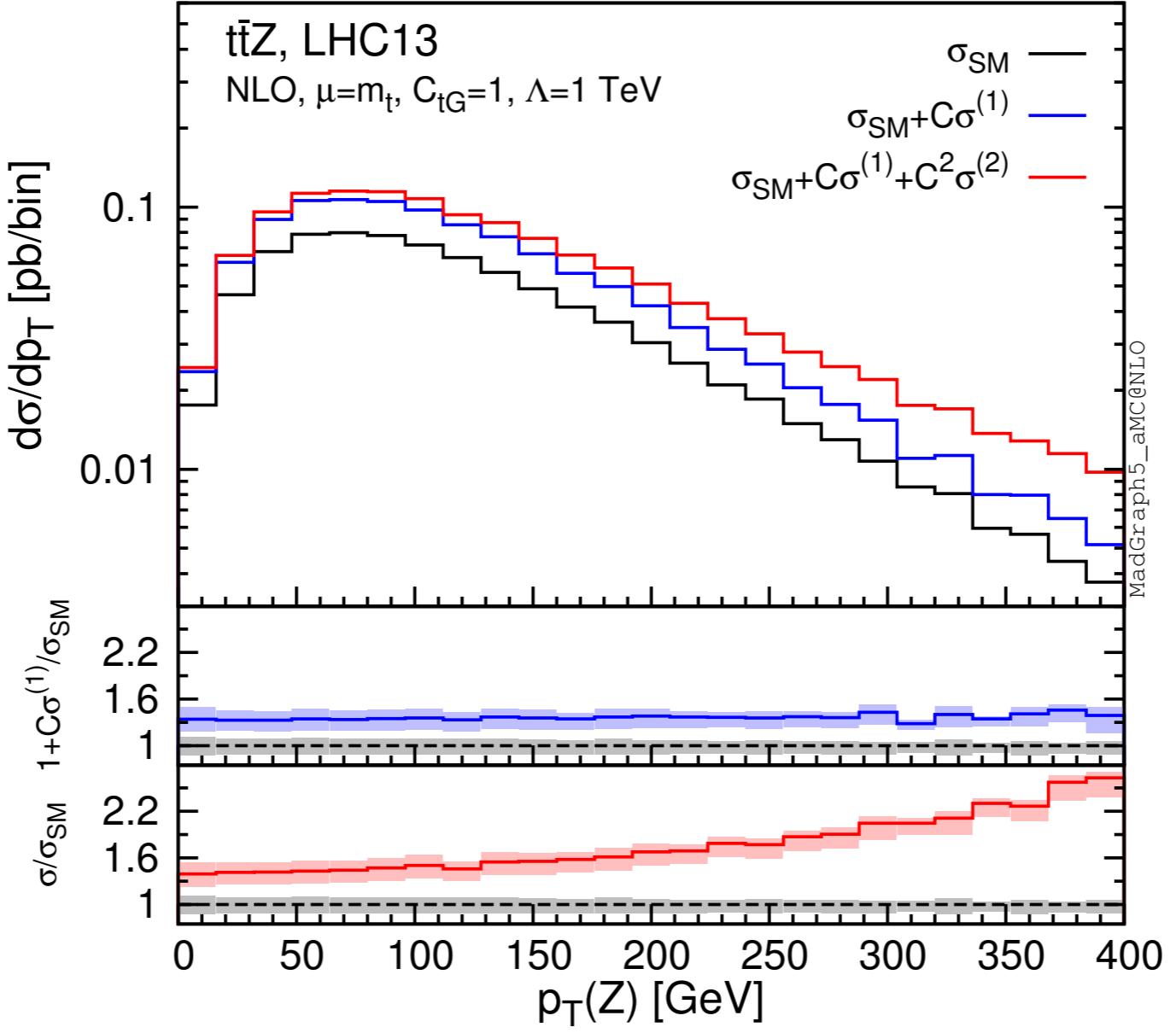
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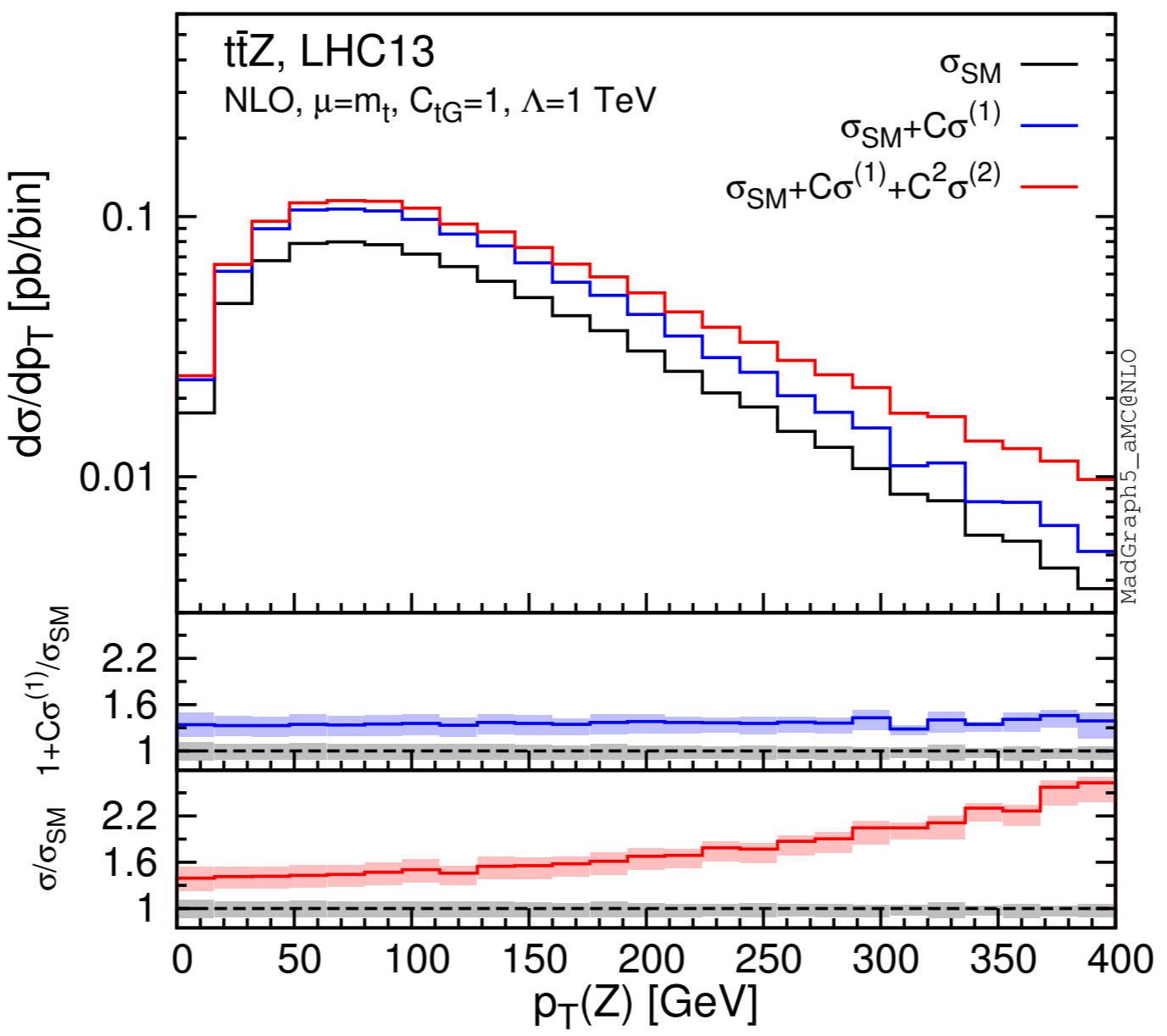
shell> ./bin/mg5
MG5_aMC> import model TopEFT
MG5_aMC> generate p p > t t~ Z EFT=1 [QCD]
MG5_aMC> output some_DIR
MG5_aMC> launch

```









Top/H/EW operators implemented (Degrande, Maltoni, Mimasu, Vryonidou, **CZ '18**)
single top + H/Z studied. Working on four fermion operators...

Full SMEFT@NLO on the way

Automatic EW NLO based on reweighting

H trilinear coupling at one loop:

<https://cp3.irmp.ucl.ac.be/projects/madgraph/wiki/HiggsSelfCoupling>

Higgs Trilinear self-coupling determination through one-loop effects

Authors : Xiaoran Zhao [✉ email](#) and Ambresh Shivaji [✉ email](#)

Proposals have been made to access information on the Higgs self-coupling by accurately measuring cross sections and distributions using single-Higgs processes, see for instance [arXiv:1607.04251](#).

This page contains the codes for generating events in processes **p p > VH, VBF, tHj and ttH** and **H > 4l** including the effect of trilinear Higgs self coupling at one-loop.

Please cite: Fabio Maltoni, Davide Pagani, Ambresh Shivaji and Xiaoran Zhao [arXiv:1709.08649](#)

trilinear-FF (The Form-factor code to run VH, VBF and Hto4l) FF [Download](#)

In this folder we provide:

- 'loop_hvv' : the UFO model folder with modified VVH vertices due to trilinear couplings at one-loop
- "hvvcoef.cpp": C++ implementation of form factors
- "Makefile" : to generate static library (libhvvcoef.a) which is used during event generation
- "ReadMe.txt" : explains how to use the code step by step and benchmarking for HZ process

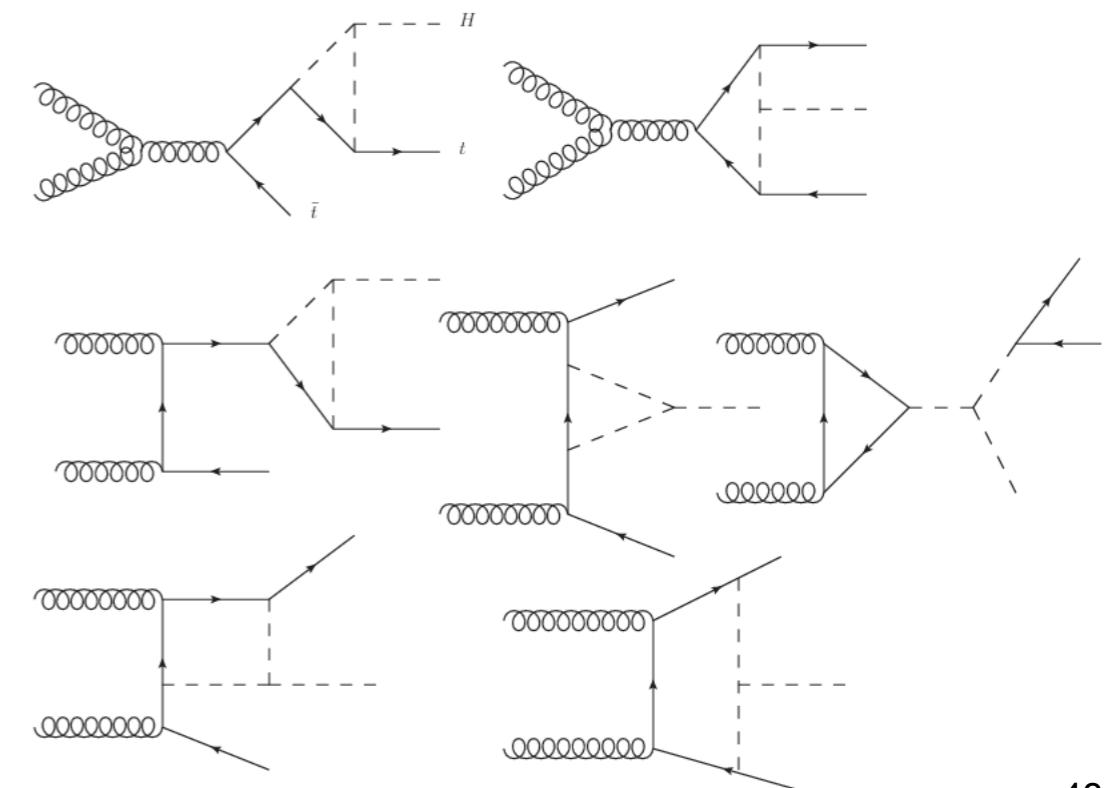
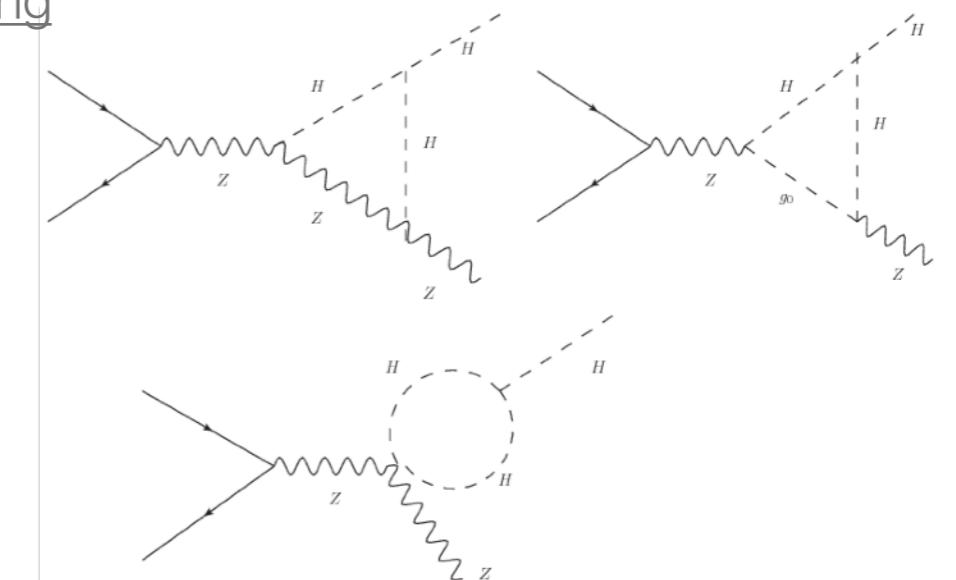
trilinear-RW (The Reweighting code to run VH, VBF, tHj and ttH) RW [Download](#)

In this folder we provide:

- 'hhh-model': the UFO model file to be used
- "gevirt.sh": auxiliary script to generate virtual EW subprocesses
- "vvh-loop_diagram_generation.py" : to select right set of one-loop diagrams in VH, VBF and tHj
- "tth-loop_diagram_generation.py" : to select right set of one-loop diagrams in ttH
- "check_OLP.f": reweighting code
- "makefile" : makefile for reweighting code
- "ReadMe.txt" : explains how to use the code step by step and benchmarking for HZ process
- we also provide 'example_hz' folder which contains a simple script to build the reweighting code for HZ as an example

(All calculations are done in G/μ scheme and benchmarking is done with MG5_aMC_v2_5_5)

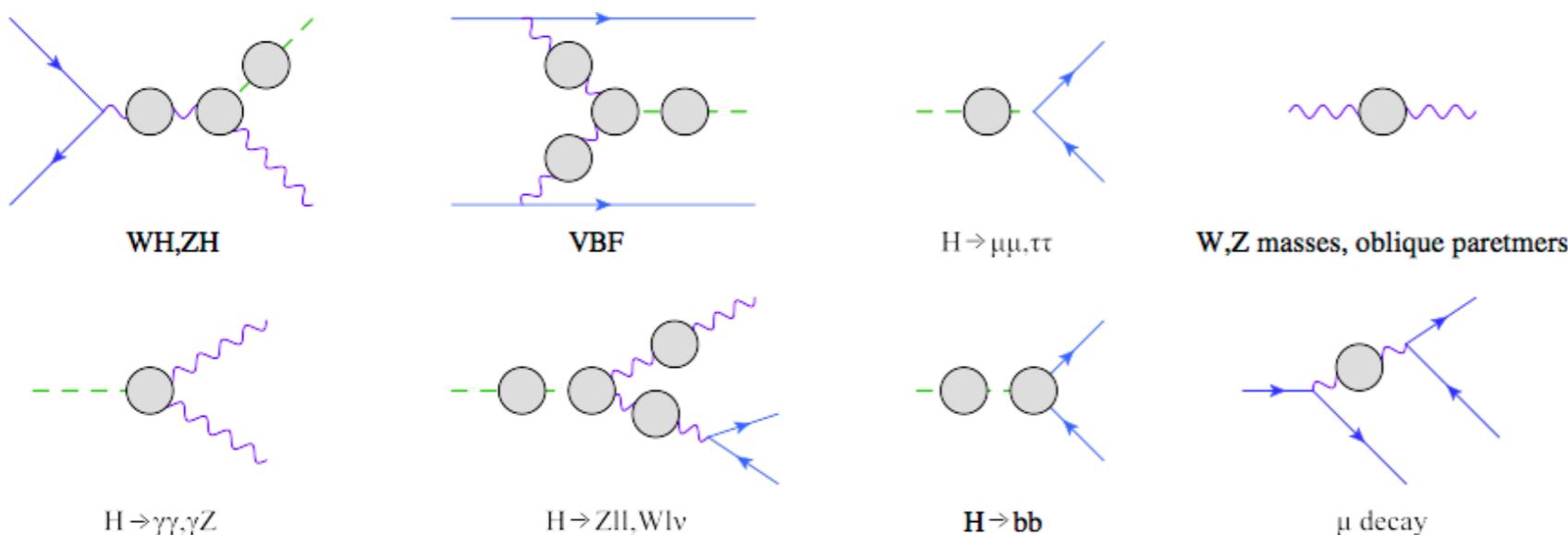
[Maltoni, Pagani, Shivaji, Zhao 1709.08649]



Automatic EW NLO based on reweighting

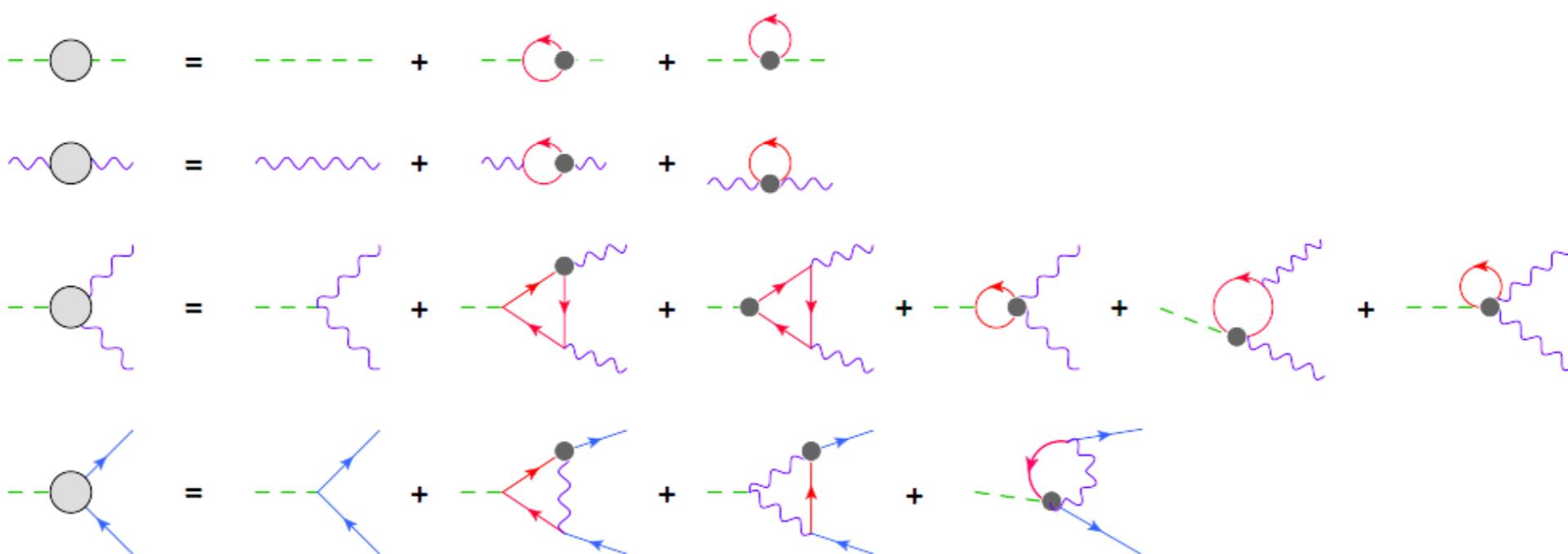
Top coupling at one loop:

[Vryonidou, CZ '18]



All dim-6 top loop contributions in Higgs

Automated with
MG5_aMC@NLO



Global Fits

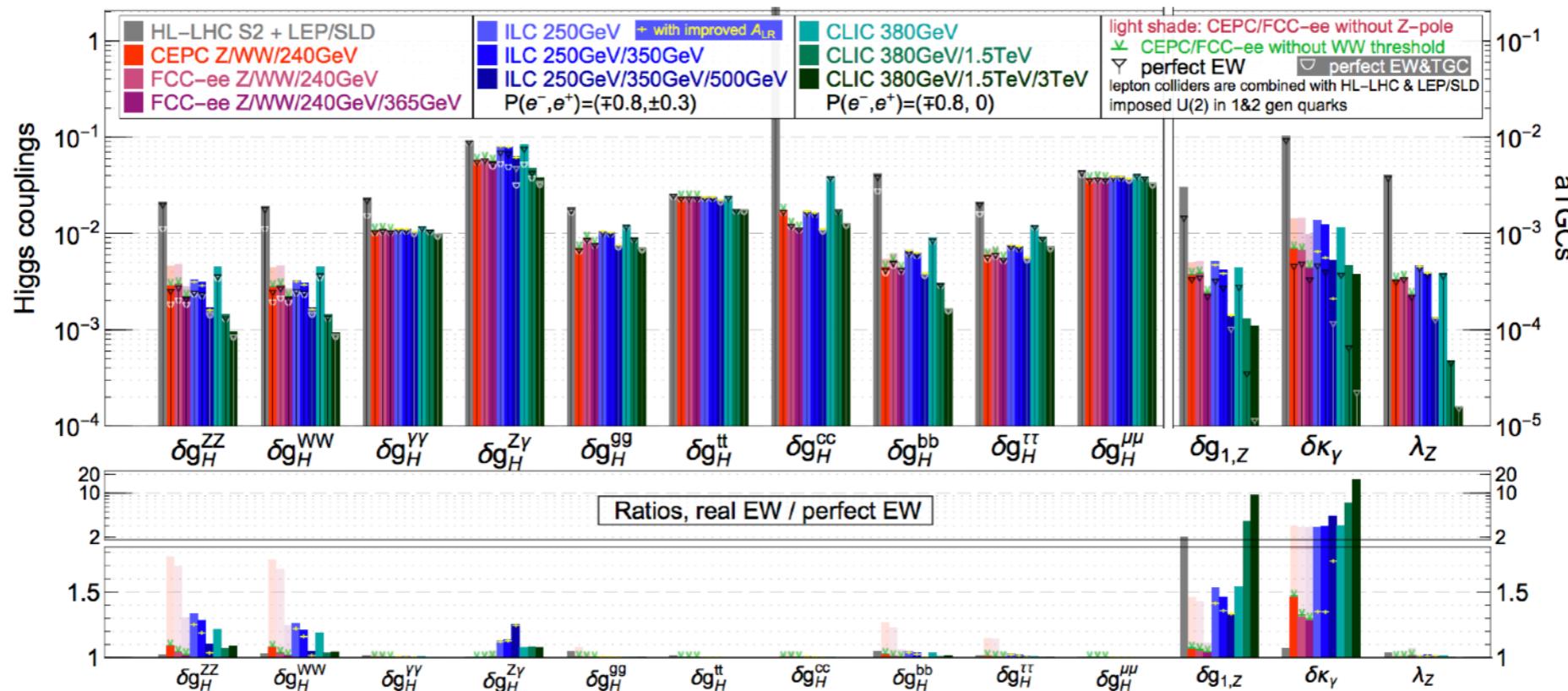
Need for global analysis

- I've showed that the underlying connection behind the H/EW/Top sectors provide new opportunities to improve our precision.
- Ideas have been explored, but often with limited channels, physical cases, theory assumptions, etc.
- The ultimate consequence will always need be quantified with global fits.
- In particular, given that more and more connections between different types of measurements are becoming relevant, it's important to always keep a global perspective.

Future lepton collider: H/EW interplay

[de Blas, Durieux, Grojean, Gu, Paul, '19]

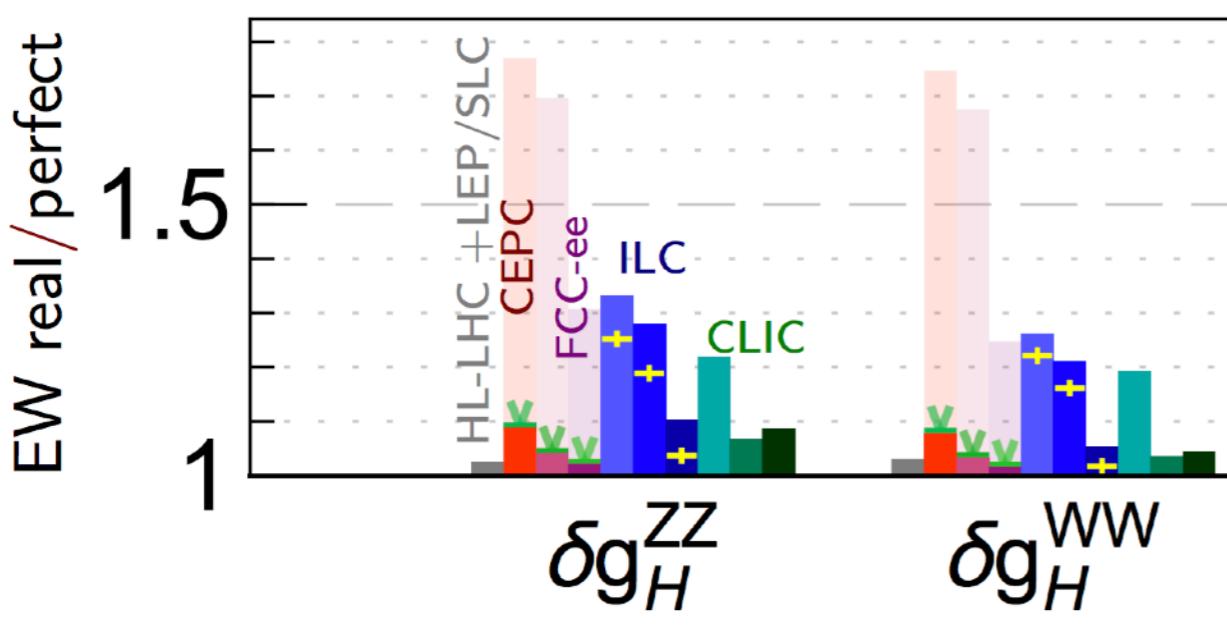
- What's the deterioration in Higgs coupling determinations incurred from EW uncertainties?
- How important are Z-pole and WW-threshold runs for Higgs physics?
- Can Higgs measurements help constraining EW parameters?



15 EW param. also marginalized over / assumed perfectly constrained

Future lepton collider: H/EW interplay

[de Blas, Durieux, Grojean, Gu, Paul, '19]

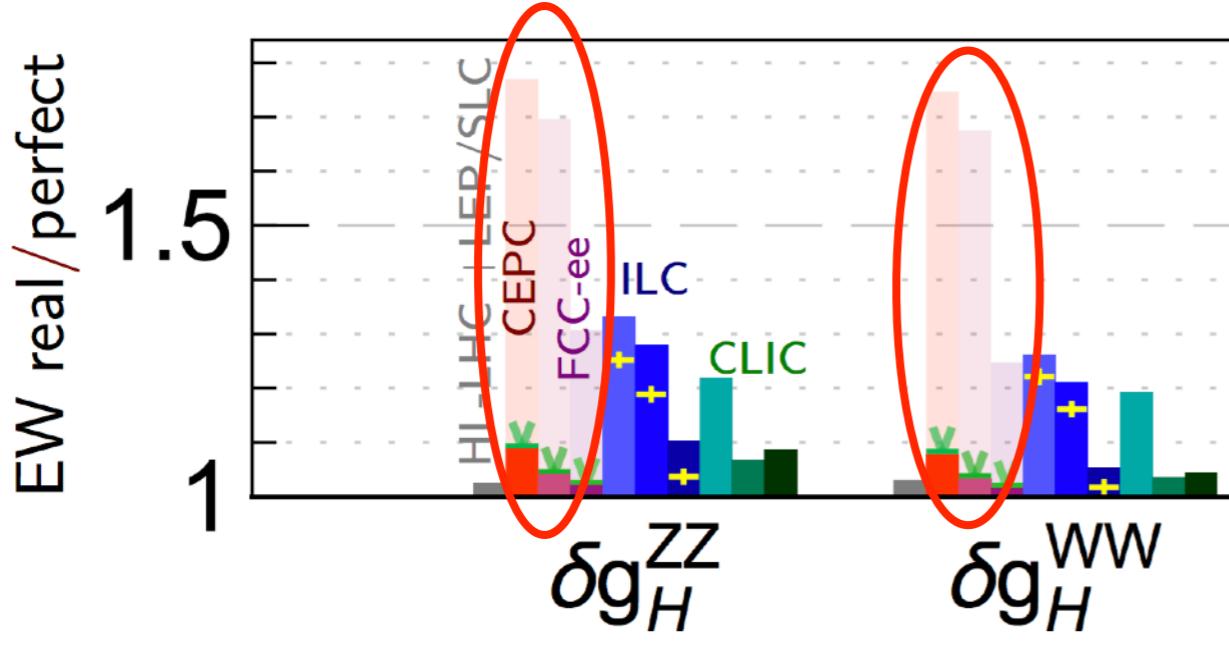


$$\delta g_H^{ZZ} \equiv \sqrt{\frac{\text{Br}(H \rightarrow ZZ^* \rightarrow \text{all})}{\text{Br}(H \rightarrow ZZ^* \rightarrow \text{all})^{\text{SM}}} - 1}$$

$$\delta g_H^{WW} \equiv \sqrt{\frac{\text{Br}(H \rightarrow WW^* \rightarrow \text{all})}{\text{Br}(H \rightarrow WW^* \rightarrow \text{all})^{\text{SM}}} - 1}$$

Future lepton collider: H/EW interplay

[de Blas, Durieux, Grojean, Gu, Paul, '19]



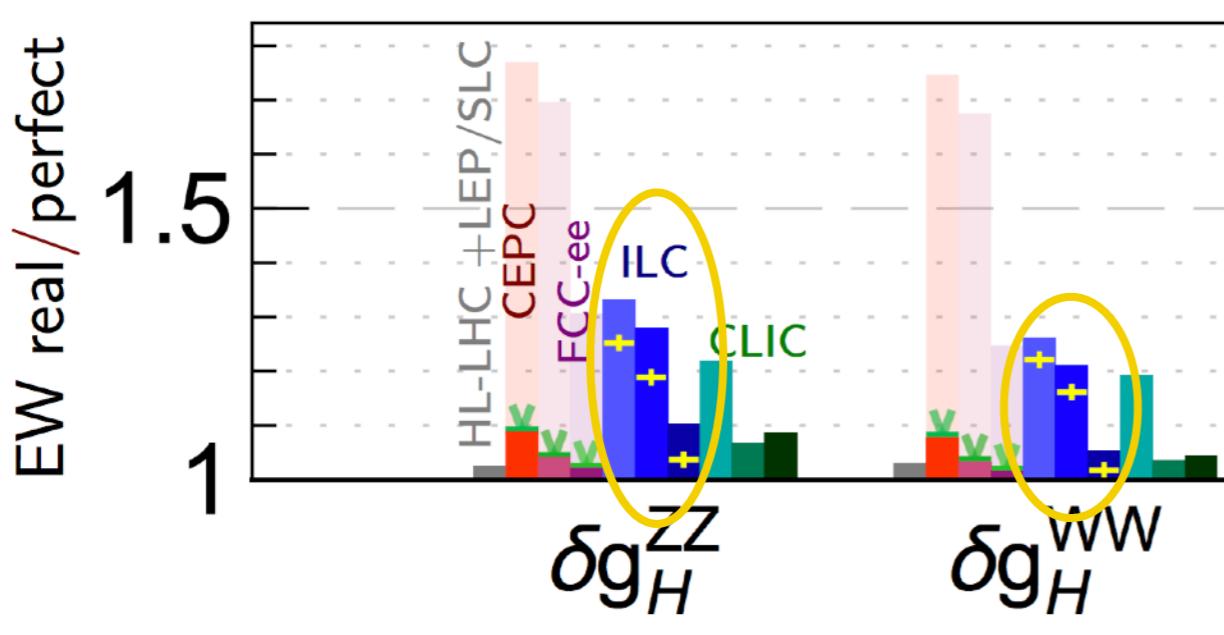
$$\delta g_H^{ZZ} \equiv \sqrt{\frac{\text{Br}(H \rightarrow ZZ^* \rightarrow \text{all})}{\text{Br}(H \rightarrow ZZ^* \rightarrow \text{all})^{\text{SM}}} - 1}$$

$$\delta g_H^{WW} \equiv \sqrt{\frac{\text{Br}(H \rightarrow WW^* \rightarrow \text{all})}{\text{Br}(H \rightarrow WW^* \rightarrow \text{all})^{\text{SM}}} - 1}$$

Z-pole run has a big impact

Future lepton collider: H/EW interplay

[de Blas, Durieux, Grojean, Gu, Paul, '19]



$$\delta g_H^{ZZ} \equiv \sqrt{\frac{\text{Br}(H \rightarrow ZZ^* \rightarrow \text{all})}{\text{Br}(H \rightarrow ZZ^* \rightarrow \text{all})^{\text{SM}}} - 1}$$

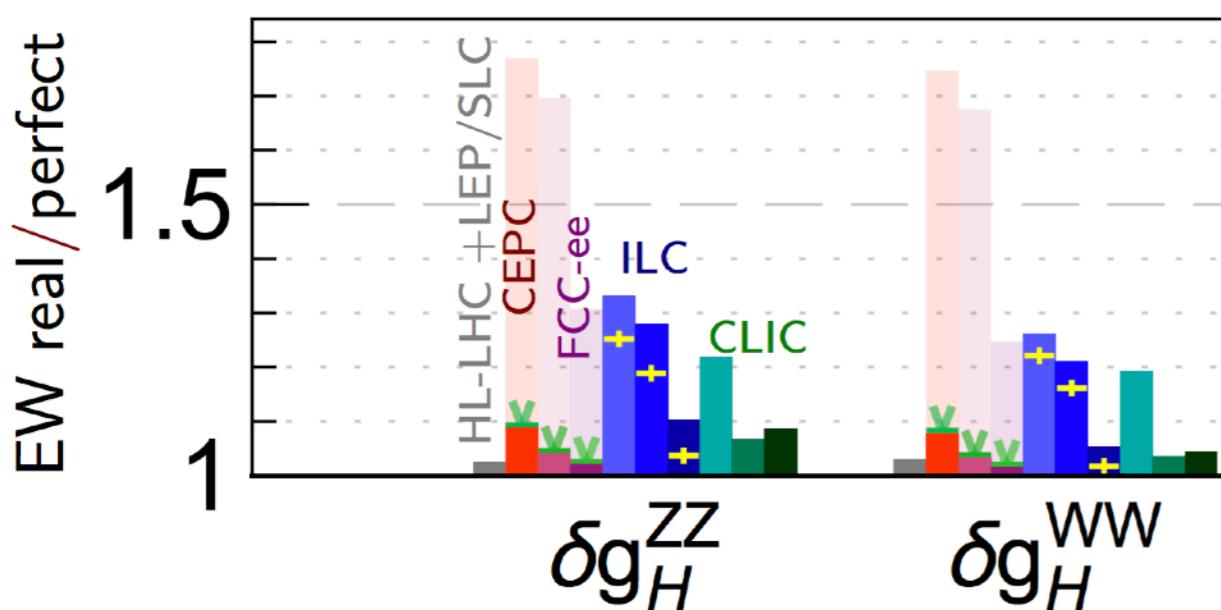
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Z-pole run has a big impact

New electroweak measurement help (e.g. A_{LR} in radiative Z-pole return)

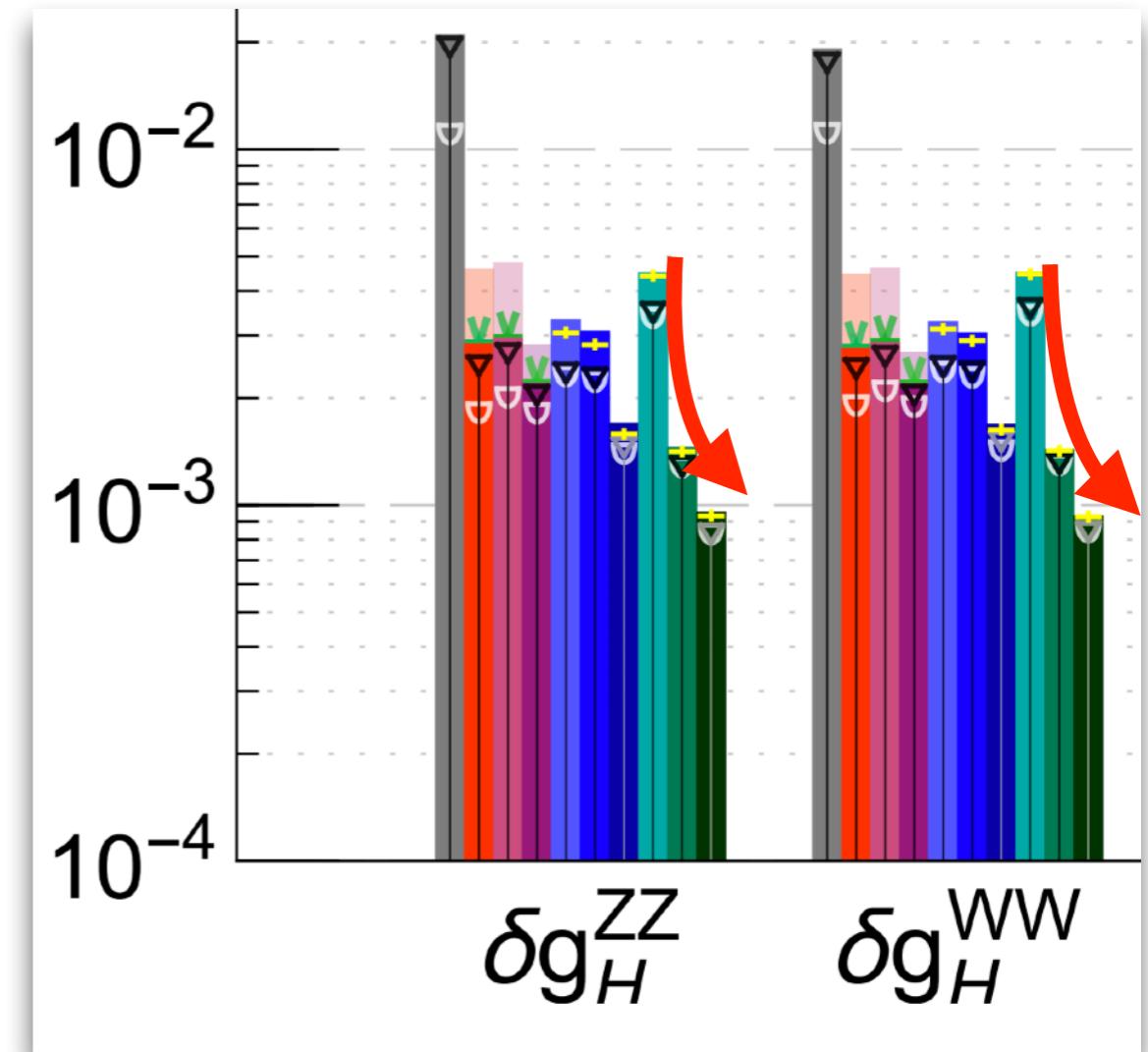
Future lepton collider: H/EW interplay

[de Blas, Durieux, Grojean, Gu, Paul, '19]



$$\delta g_H^{ZZ} \equiv \sqrt{\frac{\text{Br}(H \rightarrow ZZ^* \rightarrow \text{all})}{\text{Br}(H \rightarrow ZZ^* \rightarrow \text{all})^{\text{SM}}} - 1}$$

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Z-pole run has a big impact

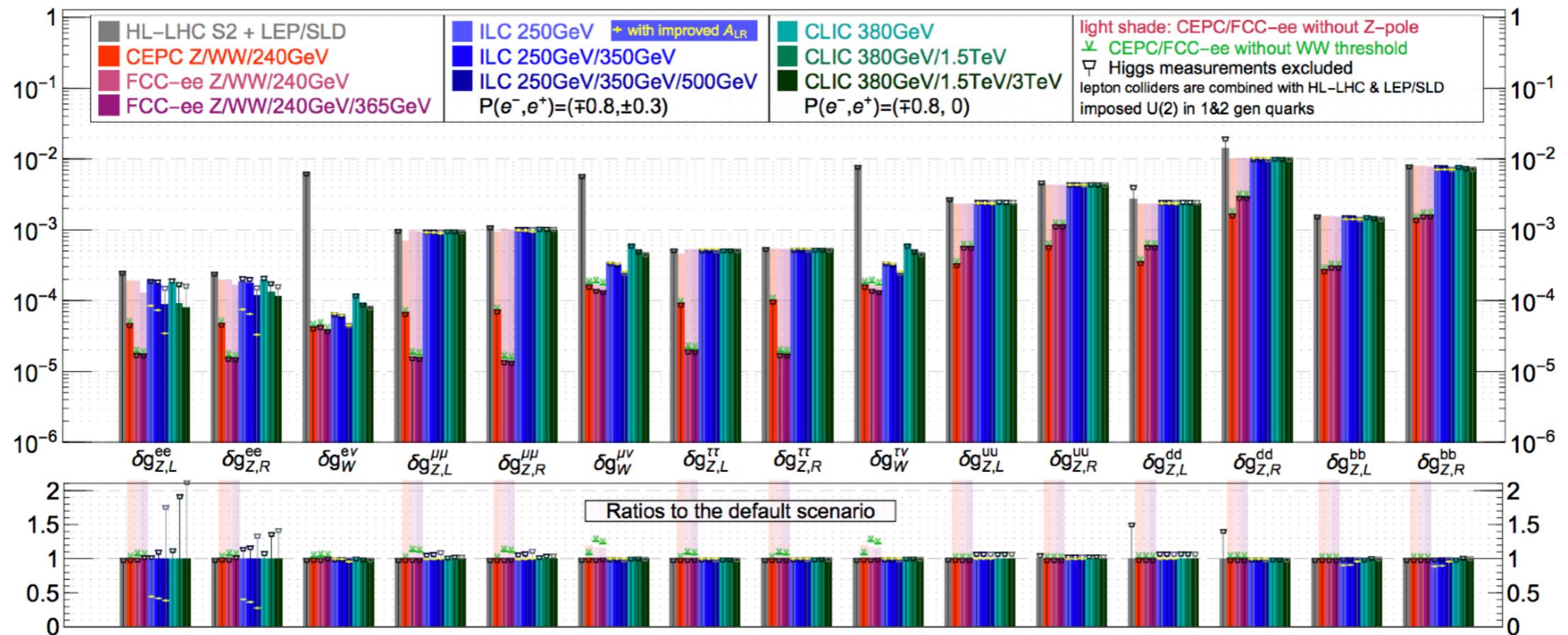
New electroweak measurement help (e.g. A_{LR} in radiative Z-pole return)

Higher energy runs help (in specific directions)

Future lepton collider: H/EW interplay

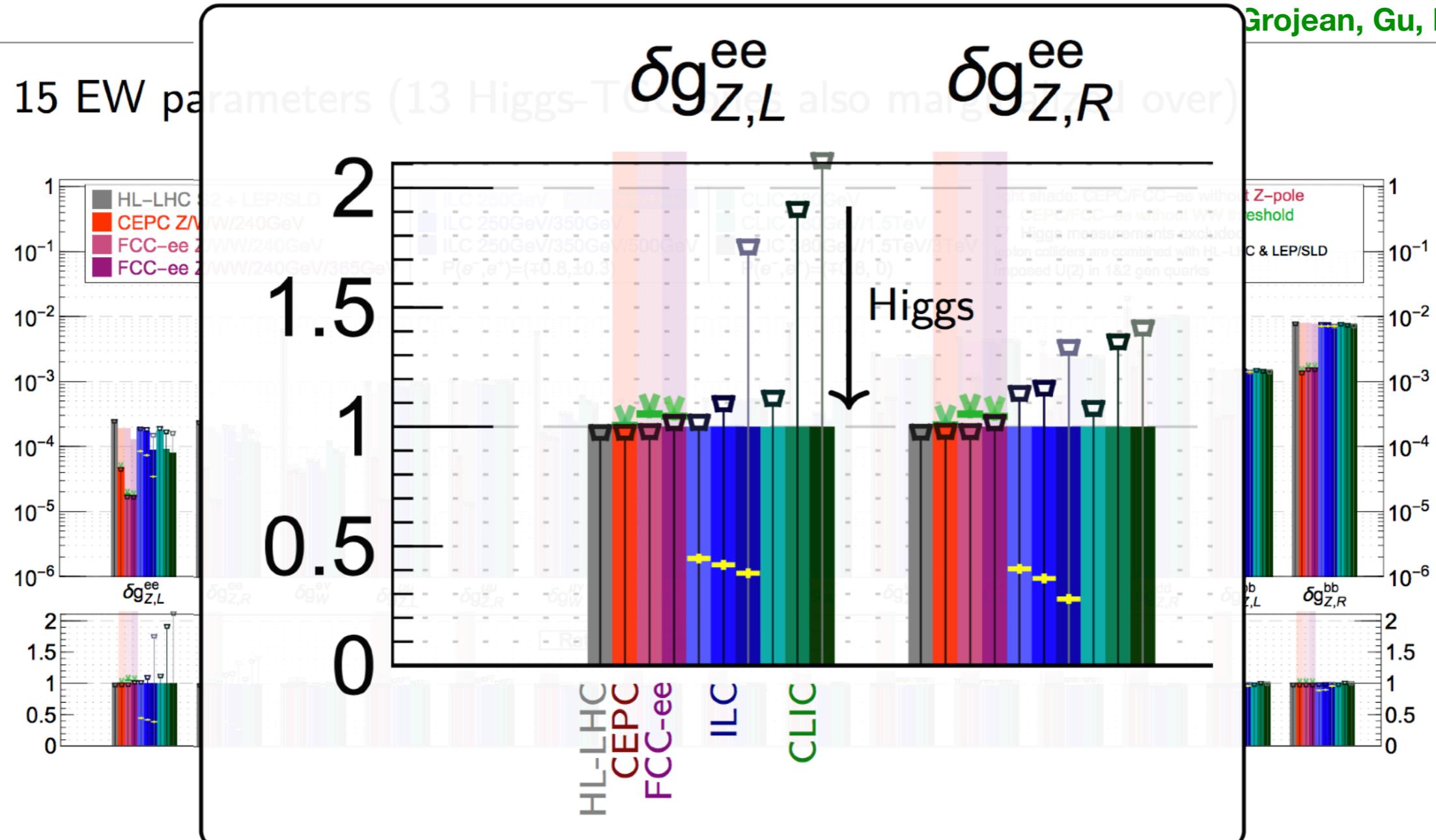
[de Blas, Durieux, Grojean, Gu, Paul, '19]

15 EW parameters (13 Higgs-TGC ones also marginalized over)



Future lepton collider: H/EW interplay

Grojean, Gu, Paul, '19]



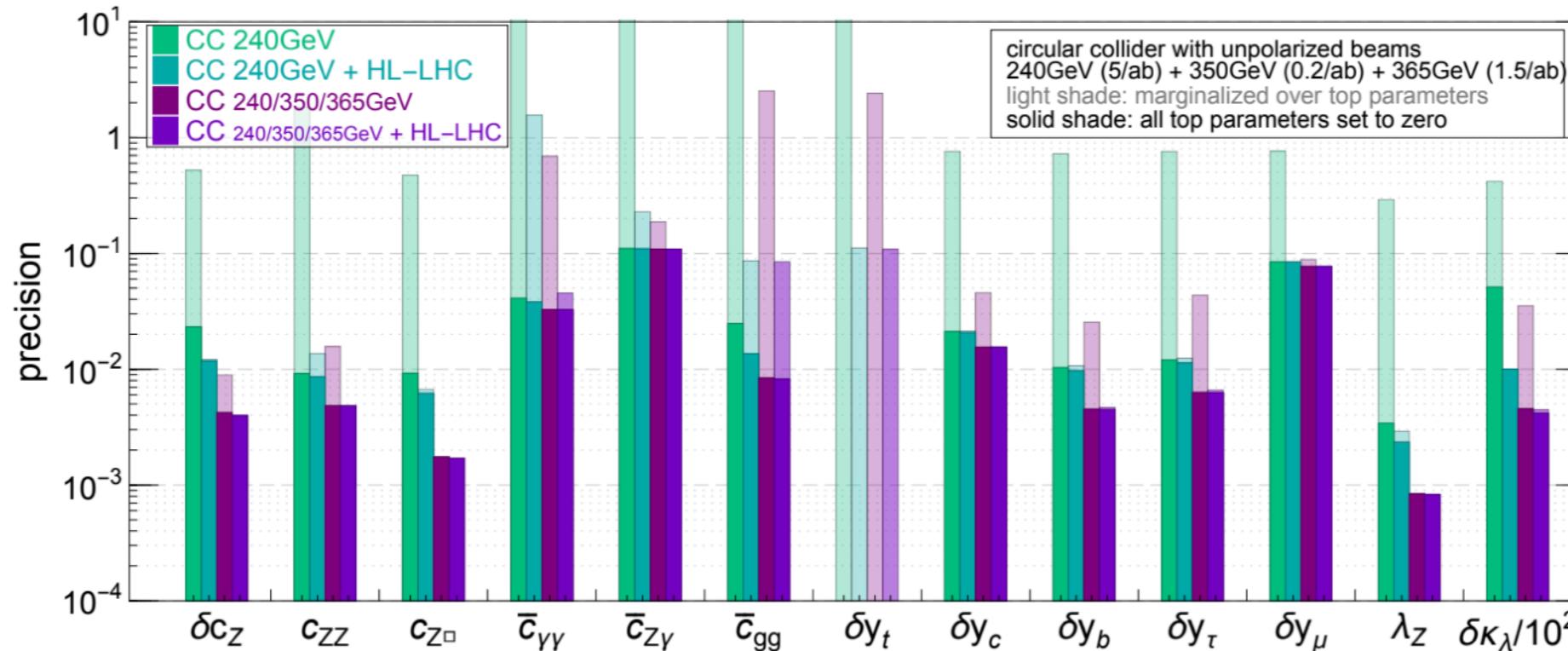
Higgs measurements could help constraining Zee at linear colliders

Future lepton collider: H/top interplay

[Durieux, Gu, Vryonidou, CZ '18]

- How does the top-coupling uncertainties downgrade the H precision at future CC?
- Global H + top loop fit, with TH results based on [Vryonidou, CZ '18]

light shades: 12 Higgs op. floated + 6 top op. floated
dark shades: 12 Higgs op. floated + 6 top op. $\rightarrow 0$



Uncertainties on the top have a big effect on the Higgs

- Higgsstr. run: insufficient
- Higgsstr. run $\oplus e^+e^- \rightarrow t\bar{t}$: large y_t contaminations in various coefficients
- Higgsstr. run \oplus top@HL-LHC: large top contaminations in $\bar{c}_{\gamma\gamma, gg, Z\gamma, ZZ}$
- Higgsstr. run $\oplus e^+e^- \rightarrow t\bar{t} \oplus$ top@HL-LHC: top contam. in \bar{c}_{gg} only

Summary

- With Run II finished, and Run III, HL/HE-LHC, future CC/LC waiting ahead, we are entering a phase where we can better see how the H is connected with the rest of the SM, even in the context of searching for BSM.
- High energy and high precision allow us to benefit from making use of these connections, including but not limited to:
 - Exploring the E^2/Λ^2 effects by activating H/Goldstone fields, and embedding the core process in multi particle production and/or loop induced process.
 - Loop corrections in precision machines open up new possibilities.
 - Be aware of the truncated dim-8 effects.
- TH framework well understood, tools being developed, with which many new ideas/observables/calculations have been proposed and investigated, in case studies, with TH assumptions or restrictions, to demonstrate that how and what we can learn by connecting different sectors in the SMEFT.
- Yet, we should keep in mind that a global perspective is very important in such a situation, and we need it to quantify the actual benefit, to answer more realistic questions, and to provide useful inputs for future strategies.

Thank you for your attention!

Backups

- First SMEFT EW fit, assuming $U(3)^5$ flavor symmetry
(21 coefs)

[Han and Skiba, hep-ph/0412166]

- “Flavorful” version, flavor assumption removed. W/Z-pole
(52 coefs)

[Efrati, Falkowski, Soreq, 1503.07872]

- Change of input scheme (m_Z , m_W , G_F), careful treatment of
 $ee \rightarrow WW \rightarrow 4f$

[Brivio and Trott 1701.06424]

- Flavorful, all $2f$, $2/2q$, and $4l$ operators, adding low-energy
measurements (61 coef combinations) [Falkowski, Gonzalez-Alonso, Mimouni, 1706.03783]

$$\begin{pmatrix} \delta g_L^{We} \\ \delta g_L^{W\mu} \\ \delta g_L^{W\tau} \\ \delta g_L^{Ze} \\ \delta g_L^{Z\mu} \\ \delta g_L^{Z\tau} \\ \delta g_R^{Ze} \\ \delta g_R^{Z\mu} \\ \delta g_R^{Z\tau} \\ \delta g_L^{Zu} \\ \delta g_L^{Zc} \\ \delta g_L^{Zt} \\ \delta g_R^{Zu} \\ \delta g_R^{Zc} \\ \delta g_L^{Zd} \\ \delta g_L^{Zs} \\ \delta g_L^{Zb} \\ \delta g_R^{Zd} \\ \delta g_R^{Zs} \\ \delta g_R^{Zb} \\ \delta g_R^{Wq_1} \\ \delta g_R \end{pmatrix} = \begin{pmatrix} -1.00 \pm 0.64 \\ -1.36 \pm 0.59 \\ 1.95 \pm 0.79 \\ -0.023 \pm 0.028 \\ 0.01 \pm 0.12 \\ 0.018 \pm 0.059 \\ -0.033 \pm 0.027 \\ 0.00 \pm 0.14 \\ 0.042 \pm 0.062 \\ -0.8 \pm 3.1 \\ -0.15 \pm 0.36 \\ -0.3 \pm 3.8 \\ 1.4 \pm 5.1 \\ -0.35 \pm 0.53 \\ -0.9 \pm 4.4 \\ 0.9 \pm 2.8 \\ 0.33 \pm 0.17 \\ 3 \pm 16 \\ 3.4 \pm 4.9 \\ 2.30 \pm 0.88 \\ -1.3 \pm 1.7 \end{pmatrix} \times 10^{-2}.$$

$$\delta g_R^{Zs} = (3.4 \pm 4.9) \times 10^{-2}$$



$$\begin{pmatrix} [c_{\ell q}]_{1111}^{(3)} \\ [\hat{c}_{eq}]_{1111} \\ [\hat{c}_{\ell u}]_{1111} \\ [\hat{c}_{\ell d}]_{1111} \\ [\hat{c}_{eu}]_{1111} \\ [\hat{c}_{ed}]_{1111} \\ [\hat{c}_{\ell q}]_{1122} \\ [c_{\ell u}]_{1122} \\ [\hat{c}_{\ell d}]_{1122} \\ [c_{eq}]_{1122} \\ [c_{eu}]_{1122} \\ [\hat{c}_{ed}]_{1122} \\ [\hat{c}_{\ell q}]_{1133} \\ [c_{\ell d}]_{1133} \\ [c_{eq}]_{1133} \\ [c_{ed}]_{1133} \\ [c_{\ell q}]_{2211} \\ [c_{\ell q}]_{2211} \\ [c_{\ell u}]_{2211} \\ [c_{\ell d}]_{2211} \\ [\hat{c}_{eq}]_{2211} \\ [c_{\ell equ}]_{1111} \\ [c_{\ell edq}]_{1111} \\ [c_{\ell equ}]_{1111}^{(3)} \\ \epsilon_P^{d\mu}(2 \text{ GeV}) \end{pmatrix} = \begin{pmatrix} -2.2 \pm 3.2 \\ 100 \pm 180 \\ -5 \pm 11 \\ -5 \pm 23 \\ -1 \pm 12 \\ -4 \pm 21 \\ -61 \pm 32 \\ 2.4 \pm 8.0 \\ -310 \pm 130 \\ -21 \pm 28 \\ -87 \pm 46 \\ 270 \pm 140 \\ -8.6 \pm 8.0 \\ -1.4 \pm 10 \\ -3.2 \pm 5.1 \\ 18 \pm 20 \\ -1.2 \pm 3.9 \\ 1.3 \pm 7.6 \\ 15 \pm 12 \\ 25 \pm 34 \\ 4 \pm 41 \\ -0.080 \pm 0.075 \\ -0.079 \pm 0.074 \\ -0.02 \pm 0.19 \\ -0.02 \pm 0.15 \end{pmatrix} \times 10^{-2}.$$



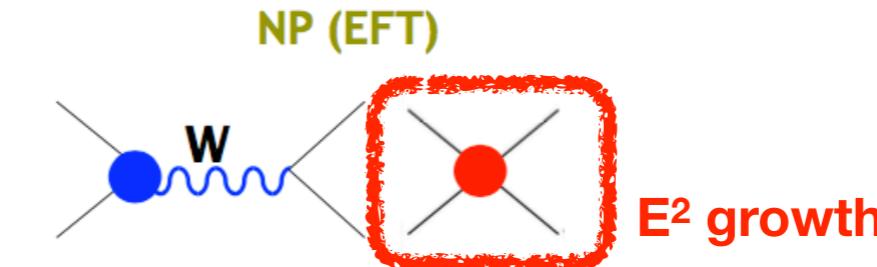
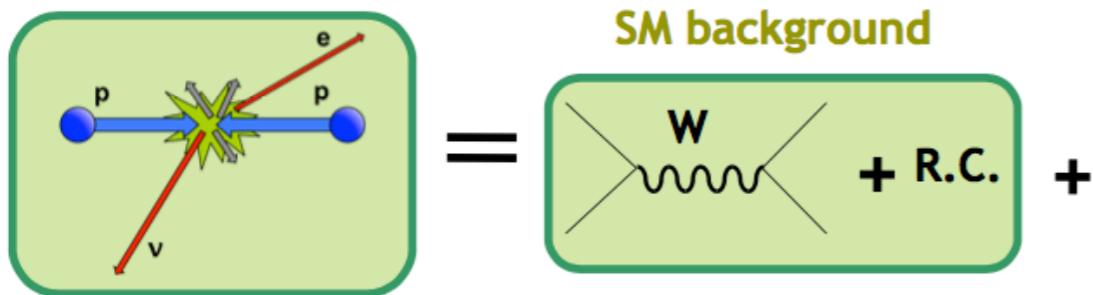
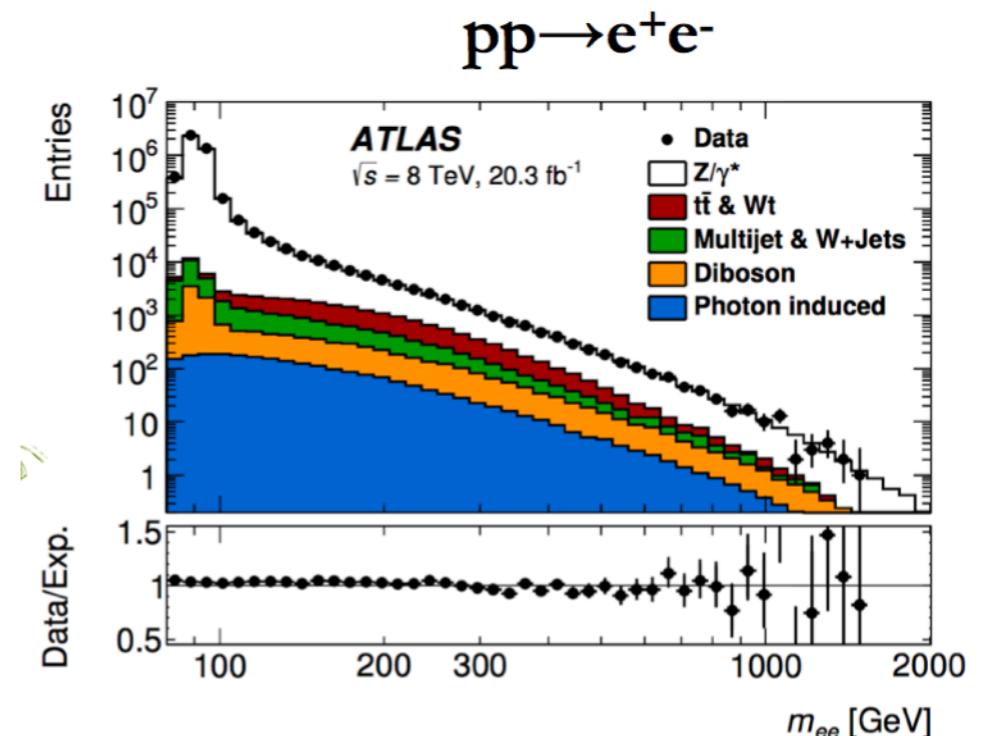
DY at the LHC

Drell-Yan $\sim 5\%$ precision, the **quark couplings** cannot compete with LEP

$$\frac{\sigma_{LO}(pp \rightarrow Z)}{\sigma_{SM, LO}(pp \rightarrow Z)} = 1 + 2.20 \delta g_L^{Zu} - 1.01 \delta g_R^{Zu} - 1.89 \delta g_L^{Zd} + 0.34 \delta g_R^{Zd},$$

$$\frac{\sigma_{LO}(pp \rightarrow W)}{\sigma_{SM, LO}(pp \rightarrow W)} = 1 + 1.73 (\delta g_L^{Zu} - \delta g_L^{Zd}),$$

However, at the LHC we play with the energy lever arm:



$$\frac{\delta\sigma(\hat{s})}{\sigma_{SM}(\hat{s})} \sim \delta g_i \frac{\hat{s}}{m_Z^2}.$$

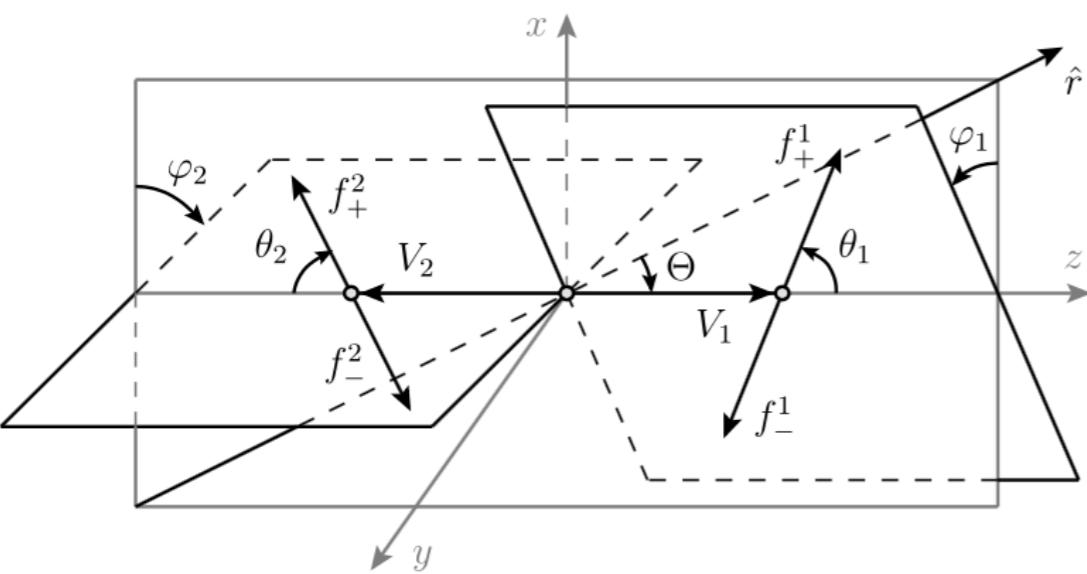
30% in $\delta\sigma \Rightarrow 0.3\%$ in couplings

Talk by Martín González-Alonso, Moriond 18

Interference resurrection

[G. Panico, F. Riva, A. Wulzer 1708.07823]

	SM	BSM
$q_{L,R}\bar{q}_{L,R} \rightarrow V_L V_L(h)$	~ 1	$\sim E^2/M^2$
$q_{L,R}\bar{q}_{L,R} \rightarrow V_\pm V_L(h)$	$\sim m_W/E$	$\sim m_W E/M^2$
$q_{L,R}\bar{q}_{L,R} \rightarrow V_\pm V_\pm$	$\sim m_W^2/E^2$	$\sim E^2/M^2$
$q_{L,R}\bar{q}_{L,R} \rightarrow V_\pm V_\mp$	~ 1	~ 1

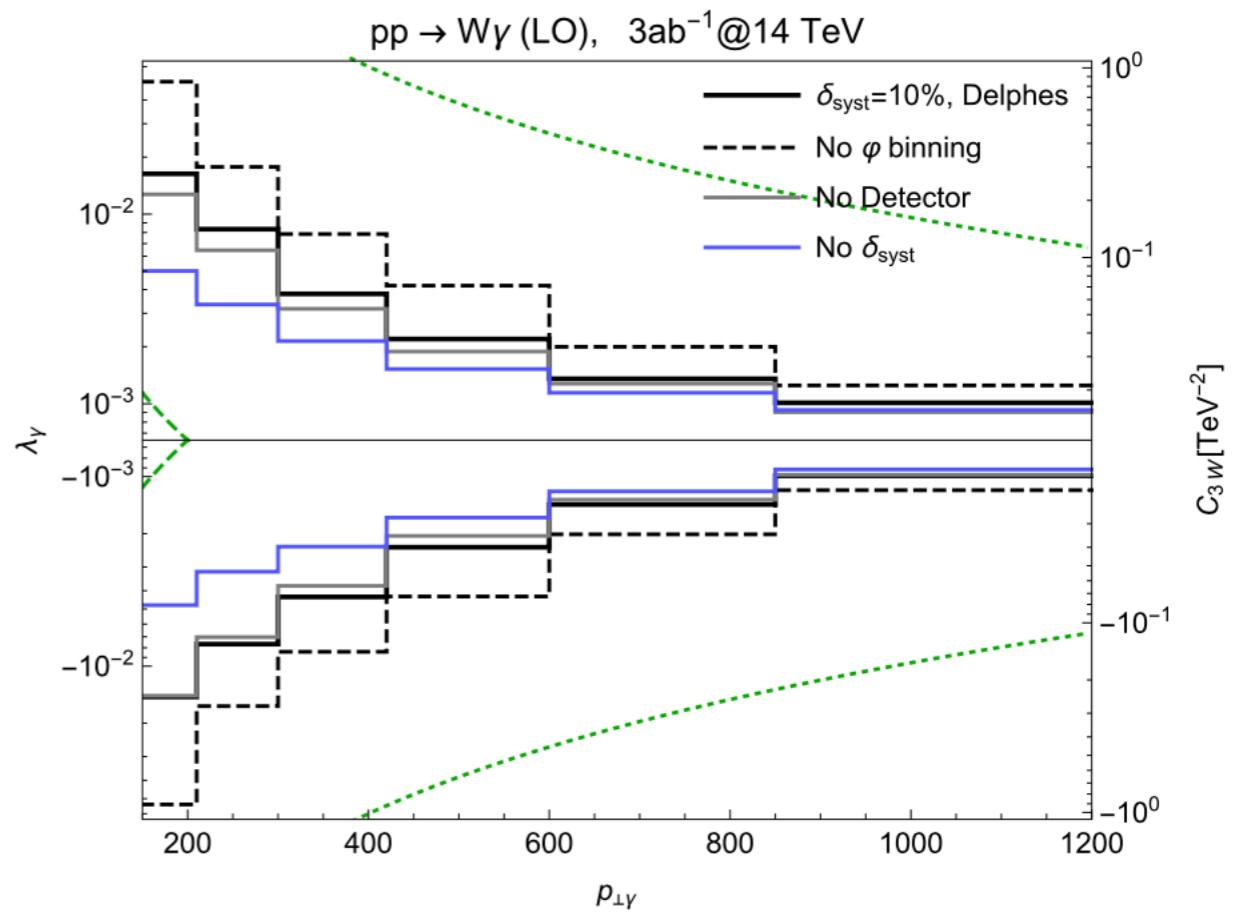


$$\mathbf{h} = (h_1, h_2) \quad \boldsymbol{\varphi} = (\varphi_1, \varphi_2)$$

$$I_{\mathbf{h} \otimes \mathbf{h}'}^{V_1 V_2} = T_{\mathbf{h} \mathbf{h}'}^{V_1 V_2} \left[\mathcal{A}_{\mathbf{h}}^{\text{SM}} \mathcal{A}_{\mathbf{h}'}^{\text{BSM+}} + \mathcal{A}_{\mathbf{h}}^{\text{BSM+}} \mathcal{A}_{\mathbf{h}'}^{\text{SM}} \right] \cos [\Delta \mathbf{h} \cdot \boldsymbol{\varphi}],$$

$$I_{\mathbf{h} \otimes \mathbf{h}'}^{V_1 V_2} = i T_{\mathbf{h} \mathbf{h}'}^{V_1 V_2} \left[\mathcal{A}_{\mathbf{h}}^{\text{SM}} \mathcal{A}_{\mathbf{h}'}^{\text{BSM-}} - \mathcal{A}_{\mathbf{h}}^{\text{BSM-}} \mathcal{A}_{\mathbf{h}'}^{\text{SM}} \right] \sin [\Delta \mathbf{h} \cdot \boldsymbol{\varphi}],$$

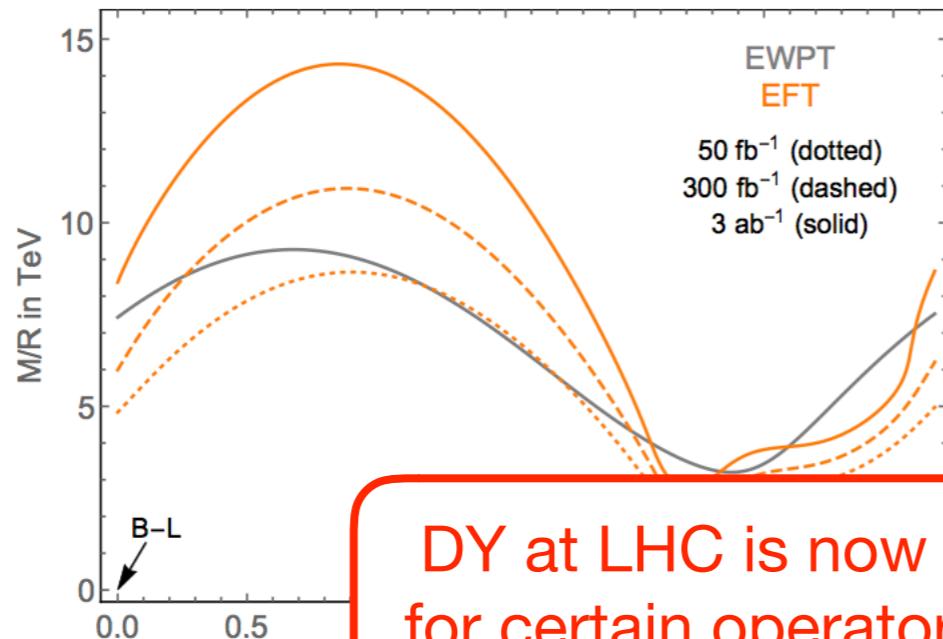
Interfering the V with different helicities will recover the E^2 energy growth



DY at the LHC: LHC is now competing with PEWO

[S. Alioli et al., 1712.02347]

Z' model



[M. Farina et al. 1609.08157]

Oblique parameters W and Y

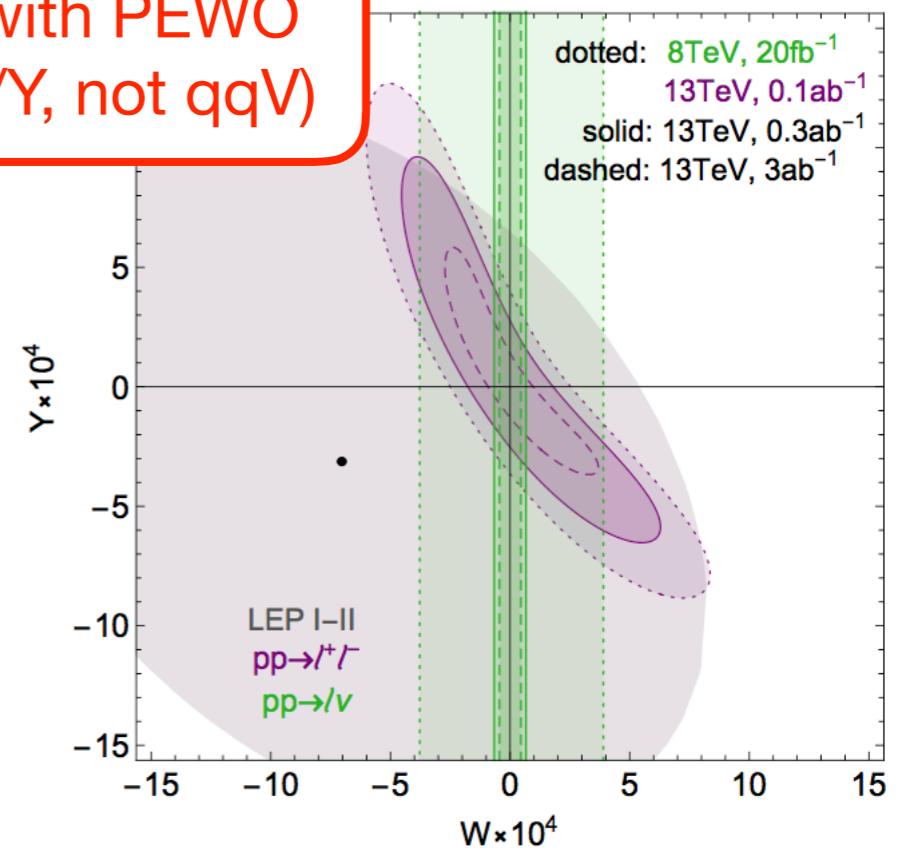
	universal form factor (\mathcal{L})	contact operator (\mathcal{L}')
W	$-\frac{W}{4m_W^2}(D_\rho W_{\mu\nu}^a)^2$	$-\frac{g_2^2 W}{2m_W^2} J_{L\mu}^a J_{L\mu}^a$
Y	$-\frac{Y}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$	$-\frac{g_1^2 Y}{2m_W^2} J_{Y\mu} J_{Y\mu}$

[Falkowski, González-Alonso, Mimouni 1706.03783]

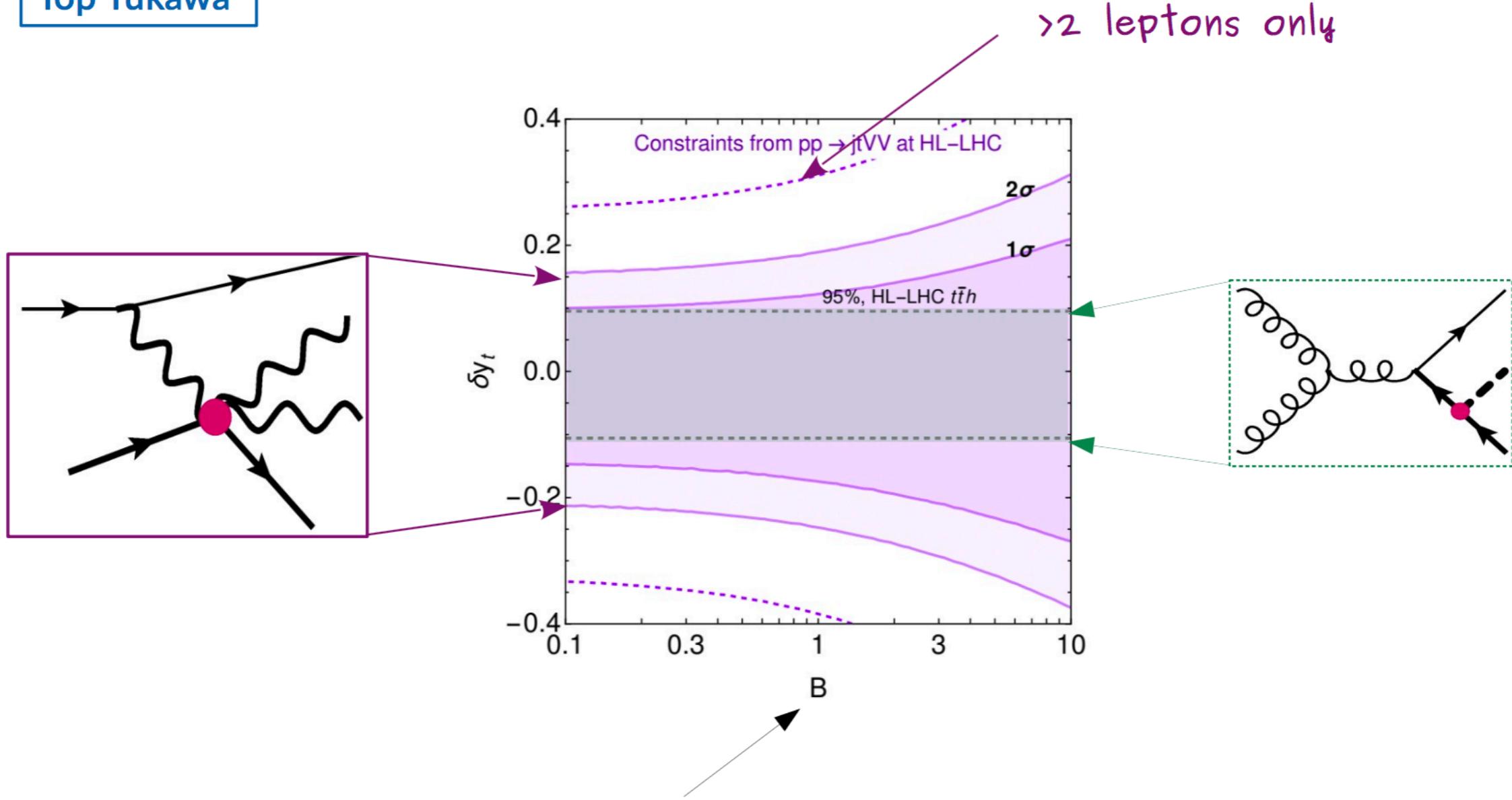
SMEFT 4-f operators

	(ee)(qq)						
	$[c_{\ell q}^{(3)}]_{1111}$	$[c_{\ell q}]_{1111}$	$[c_{\ell u}]_{1111}$	$[c_{\ell d}]_{1111}$	$[c_{eq}]_{1111}$	$[c_{eu}]_{1111}$	$[c_{ed}]_{1111}$
Low-energy	0.45 ± 0.28	1.6 ± 1.0	2.8 ± 2.1	3.6 ± 2.0	-1.8 ± 1.1	-4.0 ± 2.0	-2.7 ± 2.0
LHC _{1.5}	$-0.70^{+0.66}_{-0.74}$	$2.5^{+1.9}_{-2.5}$	$2.9^{+2.4}_{-2.9}$	$-1.6^{+3.4}_{-3.0}$	$1.6^{+1.8}_{-2.2}$	$1.6^{+2.5}_{-1.5}$	$-3.1^{+3.6}_{-3.0}$
LHC _{1.0}	$-0.84^{+0.85}_{-0.92}$	$3.6^{+3.6}_{-3.7}$	$4.4^{+4.4}_{-4.7}$	$-2.4^{+4.8}_{-4.7}$	$2.4^{+3.0}_{-3.2}$	$1.9^{+2.5}_{-1.9}$	$-4.6^{+5.4}_{-4.1}$
LHC _{0.7}	$-1.0^{+1.4}_{-1.5}$	5.9 ± 7.2	7.4 ± 9.0	-3.6 ± 8.7	3.8 ± 5.9	$2.1^{+3.8}_{-2.9}$	-8 ± 10

	$(\mu\mu)(qq)$						
	$[c_{\ell q}^{(3)}]_{2211}$	$[c_{\ell q}]_{2211}$	$[c_{\ell u}]_{2211}$	$[c_{\ell d}]_{2211}$	$[c_{eq}]_{2211}$	$[c_{eu}]_{2211}$	$[c_{ed}]_{2211}$
Low-energy	-0.2 ± 1.2	4 ± 21	18 ± 19	-20 ± 37	40 ± 390	-20 ± 190	40 ± 390
LHC _{1.5}	$-1.22^{+0.62}_{-0.70}$	1.8 ± 1.3	2.0 ± 1.6	-1.1 ± 2.0	1.1 ± 1.2	$2.5^{+1.8}_{-1.4}$	-2.2 ± 2.0
LHC _{1.0}	$-0.72^{+0.81}_{-0.87}$	$3.2^{+4.0}_{-3.5}$	$3.9^{+4.8}_{-4.4}$	$-2.3^{+4.9}_{-4.7}$	$2.3^{+3.1}_{-3.2}$	$1.6^{+2.3}_{-1.8}$	-4.4 ± 5.3
LHC _{0.7}	$-0.7^{+1.3}_{-1.4}$	$3.2^{+10.3}_{-4.8}$	$4.3^{+12.5}_{-6.4}$	-3.6 ± 9.0	3.8 ± 6.2	$1.6^{+3.4}_{-2.7}$	-8 ± 11



Top Yukawa



Again, we parametrize background with $B \times$ signal

Competitive with on-shell Higgs measurements

Further improvements: background characterization, specially for hadronic,
differential information, larger E^2 ,
get rid of transverse polarizations

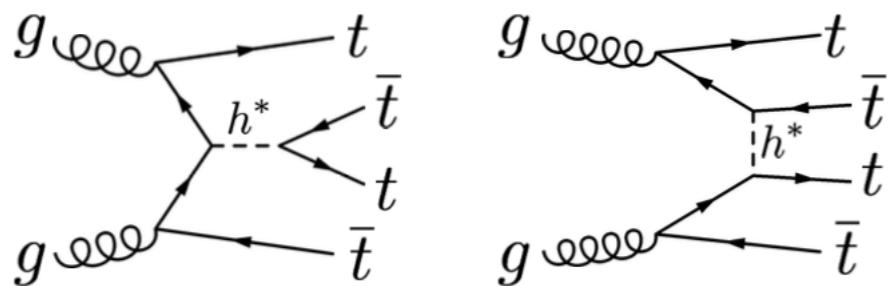
A different off-shell perspective: the oblique H parameter

[Englert, Giudice, Greljo, McCullough 1903.07725]

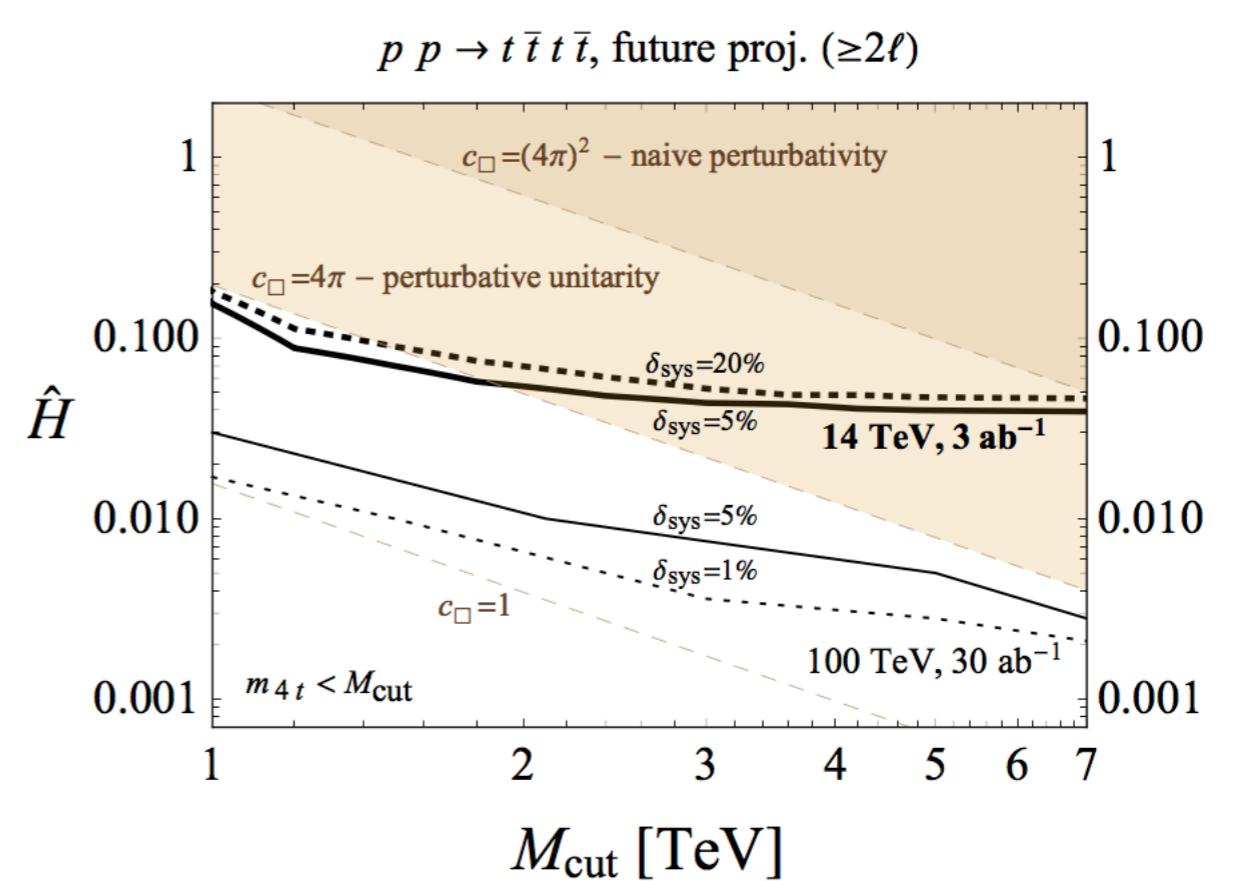
In universal theories, the $\mathcal{O}(q^4)$ terms in EW boson self-energy can be parametrized by

$$\mathcal{L}_{\hat{W}} = -\frac{\hat{W}}{4m_W^2} (D_\rho W_{\mu\nu}^a)^2 , \quad \mathcal{L}_{\hat{Y}} = -\frac{\hat{Y}}{4m_W^2} (\partial_\rho B_{\mu\nu})^2 , \quad \mathcal{L}_{\hat{H}} = \frac{\hat{H}}{m_h^2} |\square H|^2$$

- it is not possible to unambiguously determine \hat{H} by combining on-shell Higgs coupling measurements and a measurement of the trilinear coupling. \rightarrow Need off shell probe
- Best off-shell turns out to be four top



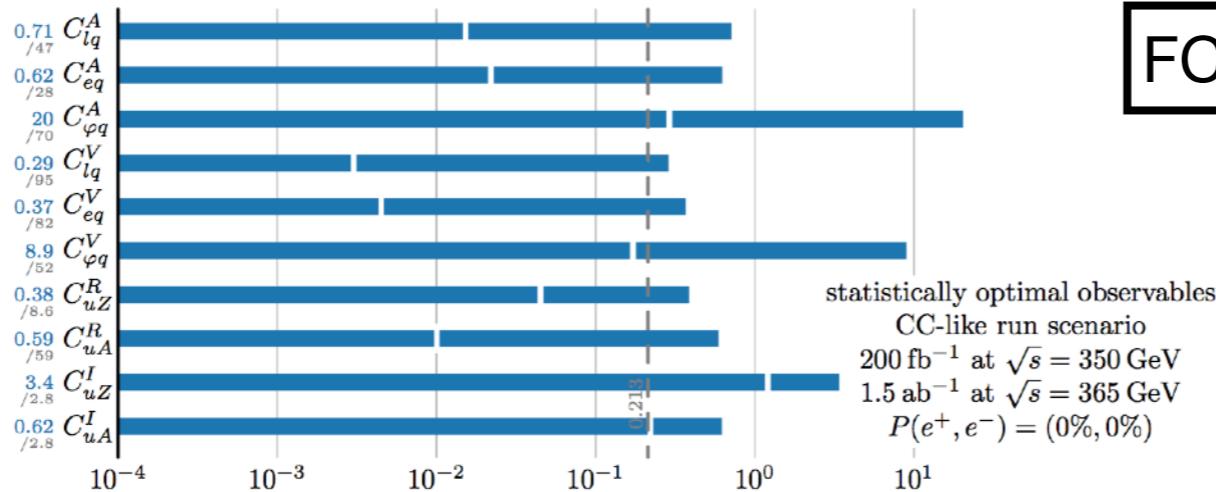
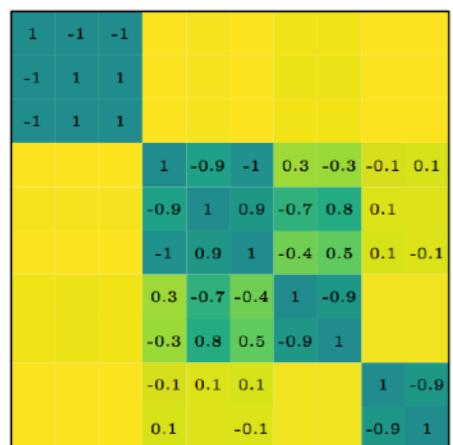
Top measurements revealing the off-shell propagation of the H



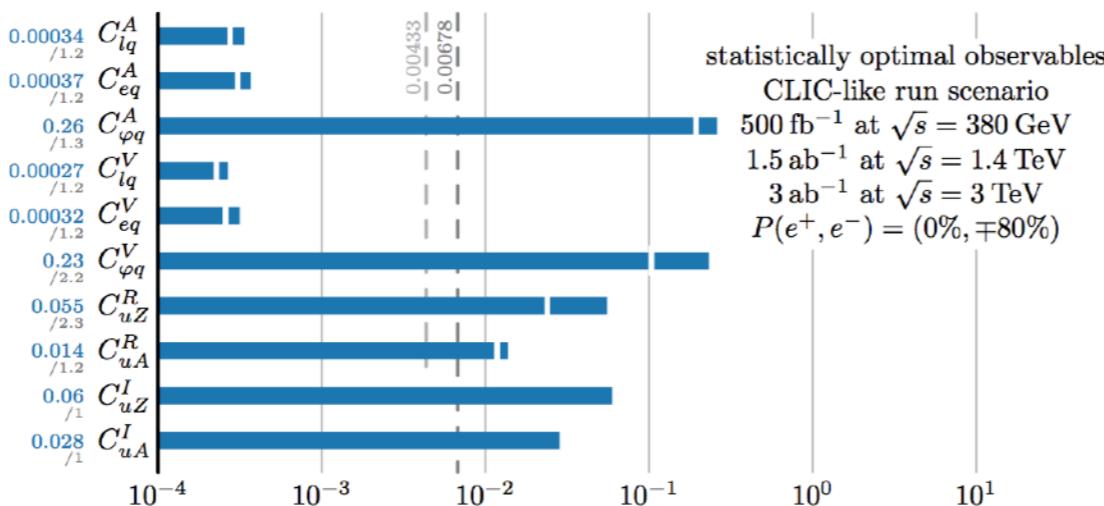
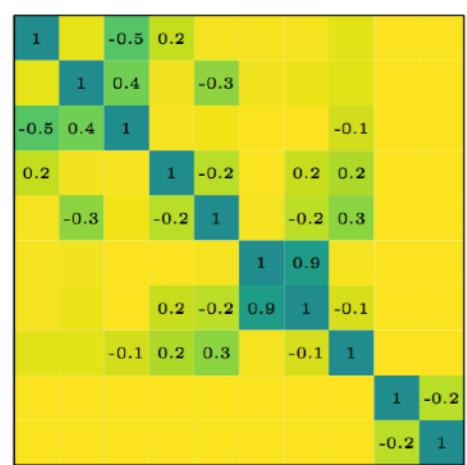
Top loops at CEPC

This is useful for CEPC because

- The 240 GeV run cannot access top couplings (except for FCNC couplings)
- A single 350 GeV run only adds 2 additional DoFs and is not enough to disentangle 10 operators:



FCC-ee



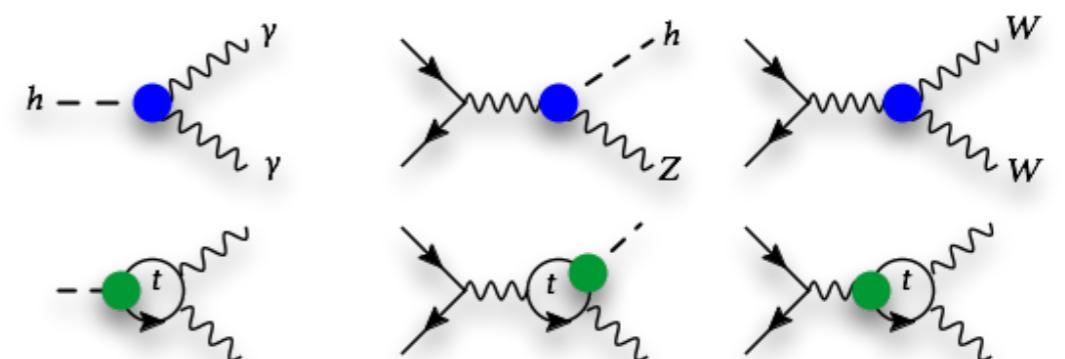
CLIC

[G. Durieux, M. Perello, M. Vos, CZ '18]

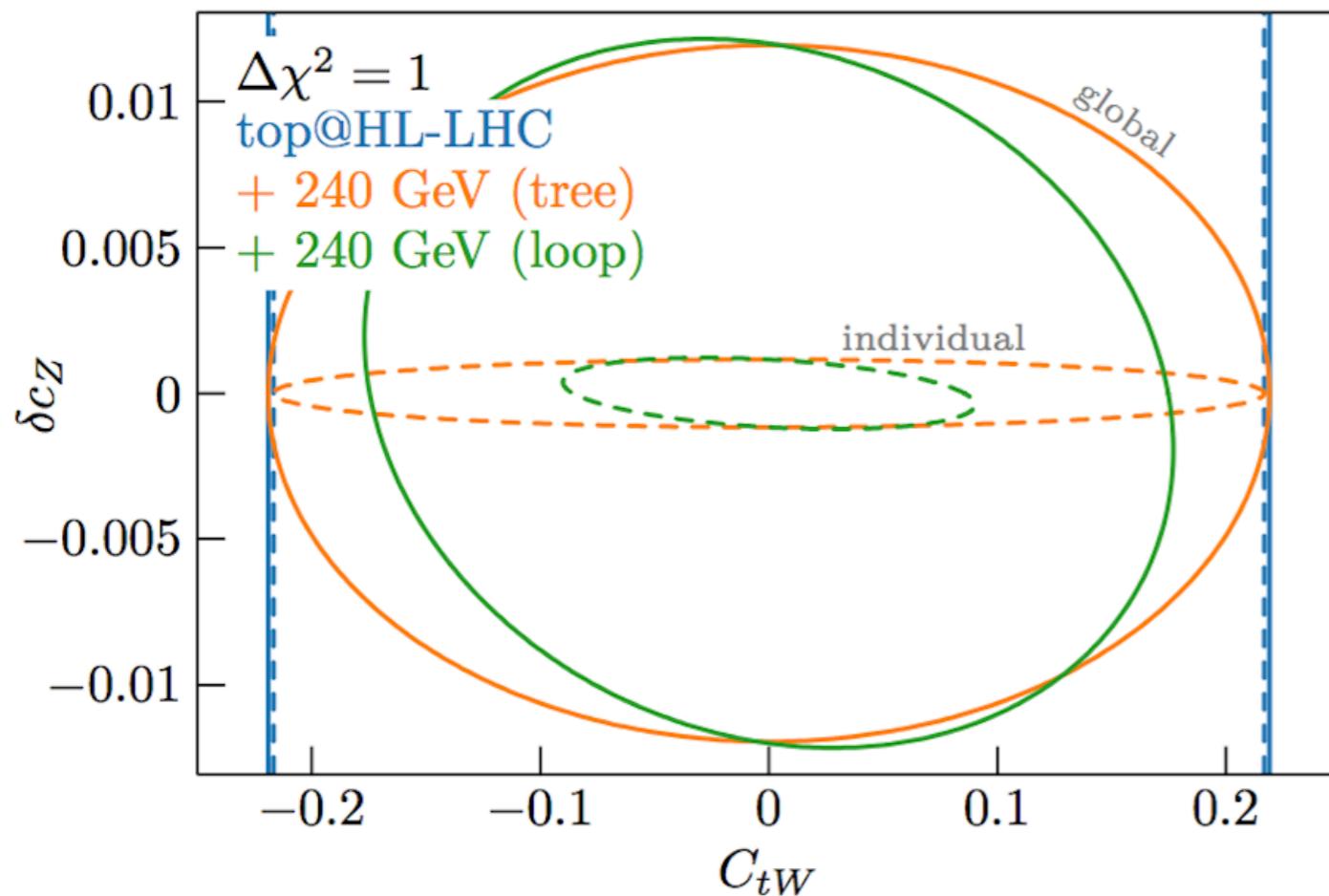
Top loops at CEPC

[Durieux, Gu, Vryonidou, CZ '18]

Probing the tops below ttbar threshold:



On a linear scale, in the $(C_{tW}, \delta c_Z)$ plane:

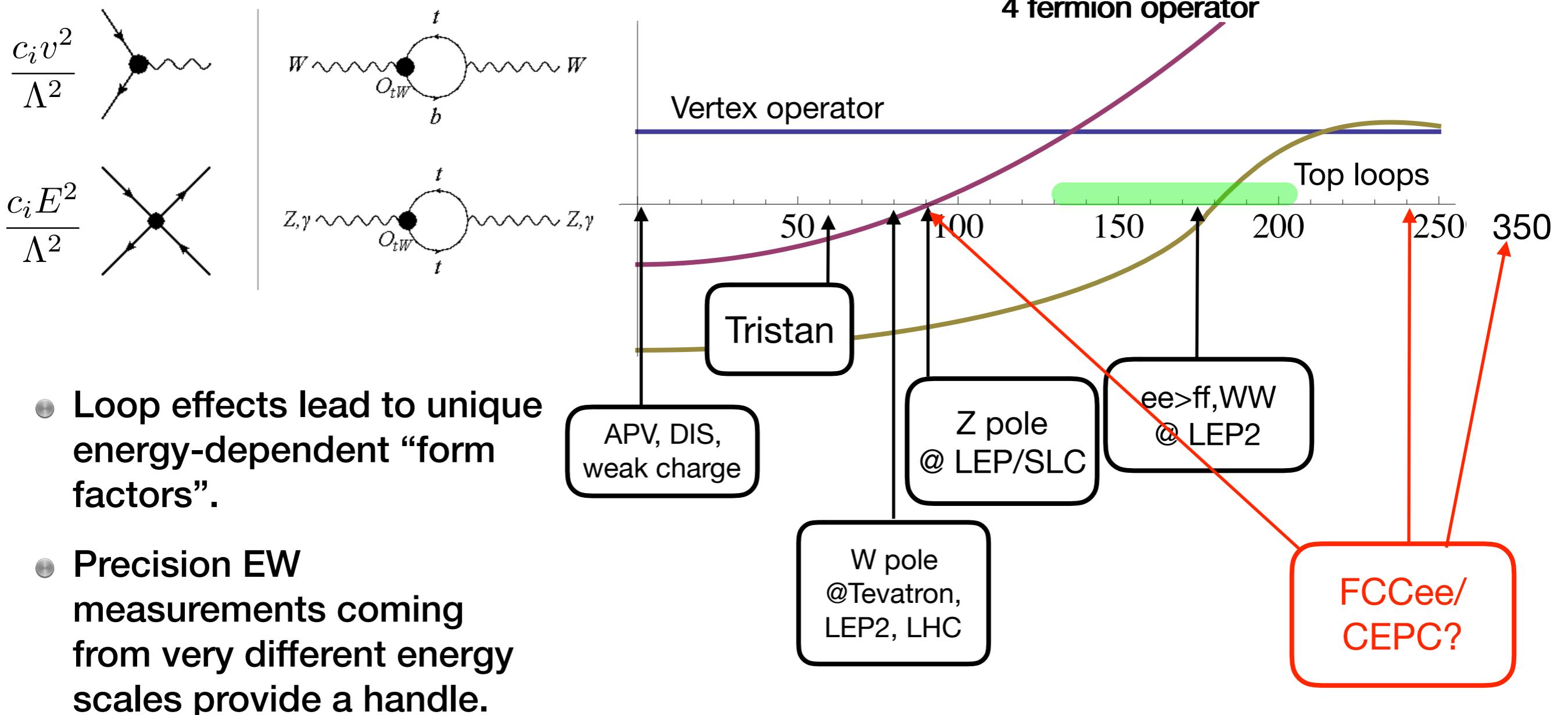


Important information to add
in a global top & Higgs fit
for future colliders

- extra parameter space covered thanks to loop sensitivity

Talk by G. Durieux at HC2018

EW fit: top couplings enter through loops



- Loop effects lead to unique energy-dependent “form factors”.
- Precision EW measurements coming from very different energy scales provide a handle.