Ideas on Electroweak Fit

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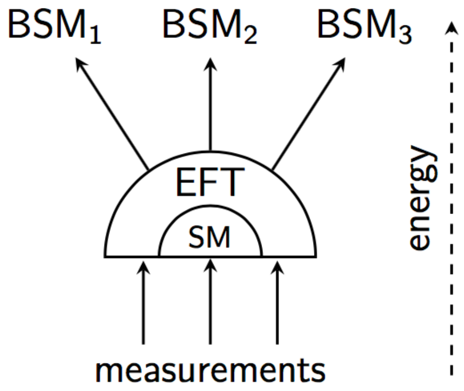
- Not an expert of EW
    - Not exactly sure why this topic was assigned…
- Will present a mixture of
    - Some results form past works
    - Some very preliminary results from an ongoing fit
    - A collection of ideas on EW measurements, from other people's work
        - Some are not related to the CEPC, but could important for a comprehensive understanding of the current status, which provides input for future strategies.

Global SMEFT fit

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 colliders and scenarios, HL/HE-LHC, CEPC/SppC, ILC, FCC, …
- **Investigate new observables/techniques** and their impacts.



Global SMEFT fit can be conveniently organized by different sectors:
Higgs, Top, Electroweak, Flavor… (but situation might change in the future)

Higgs + EW fit

<u>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</u>. 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].

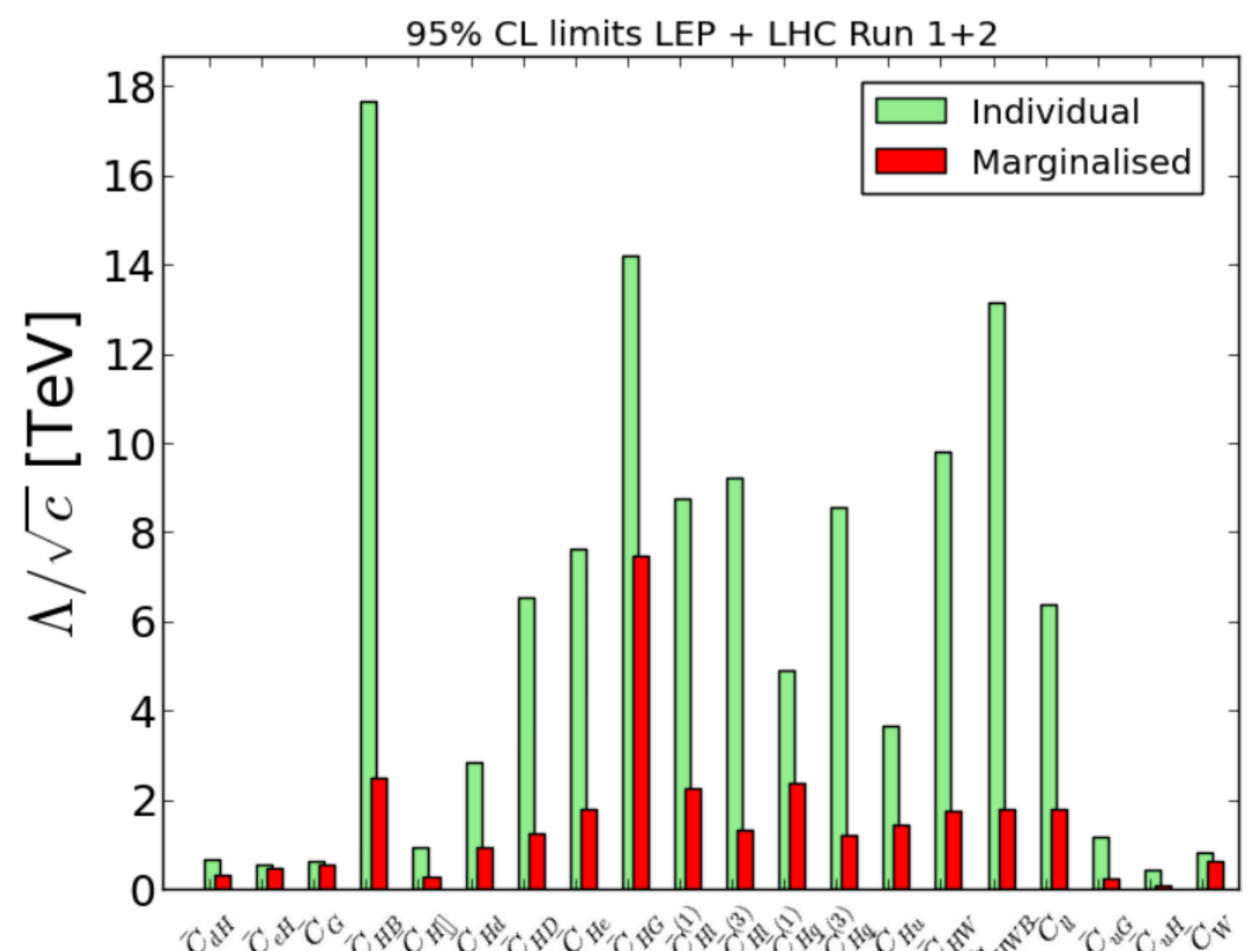
50 [Z. Zhang 1610.01618]

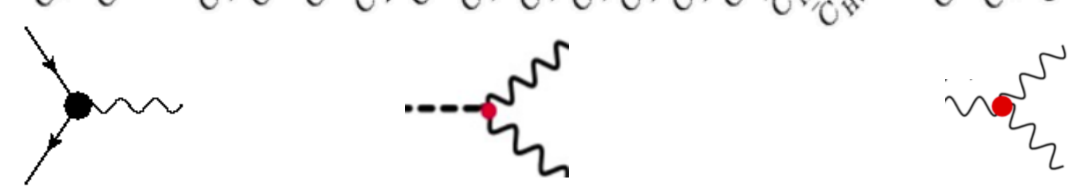
51 [Baglio, Dawson, Lewis 1708.03332]

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

[J. Ellis et al. 1803.03252]

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

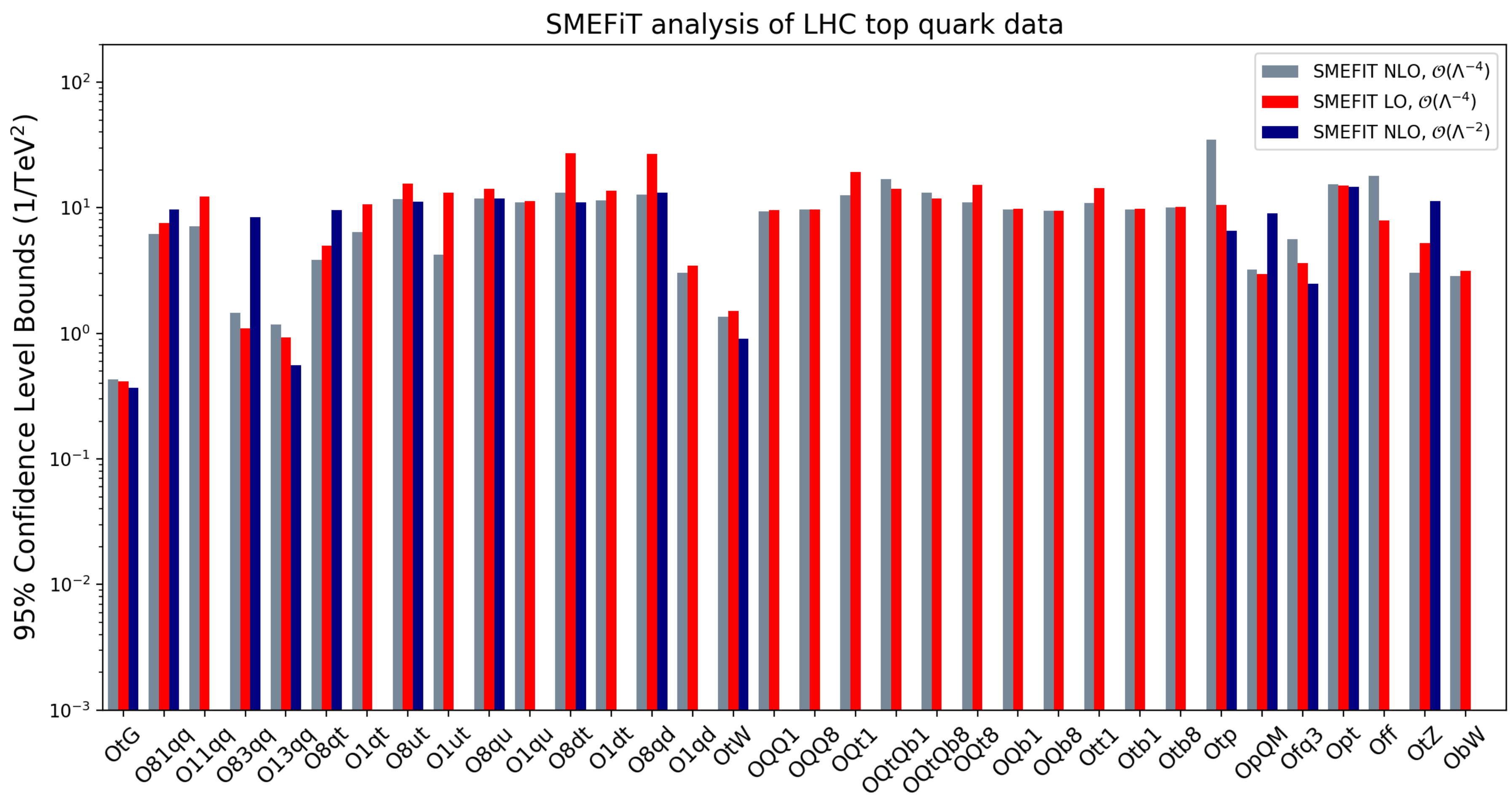




Top fit: SMEFiT

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

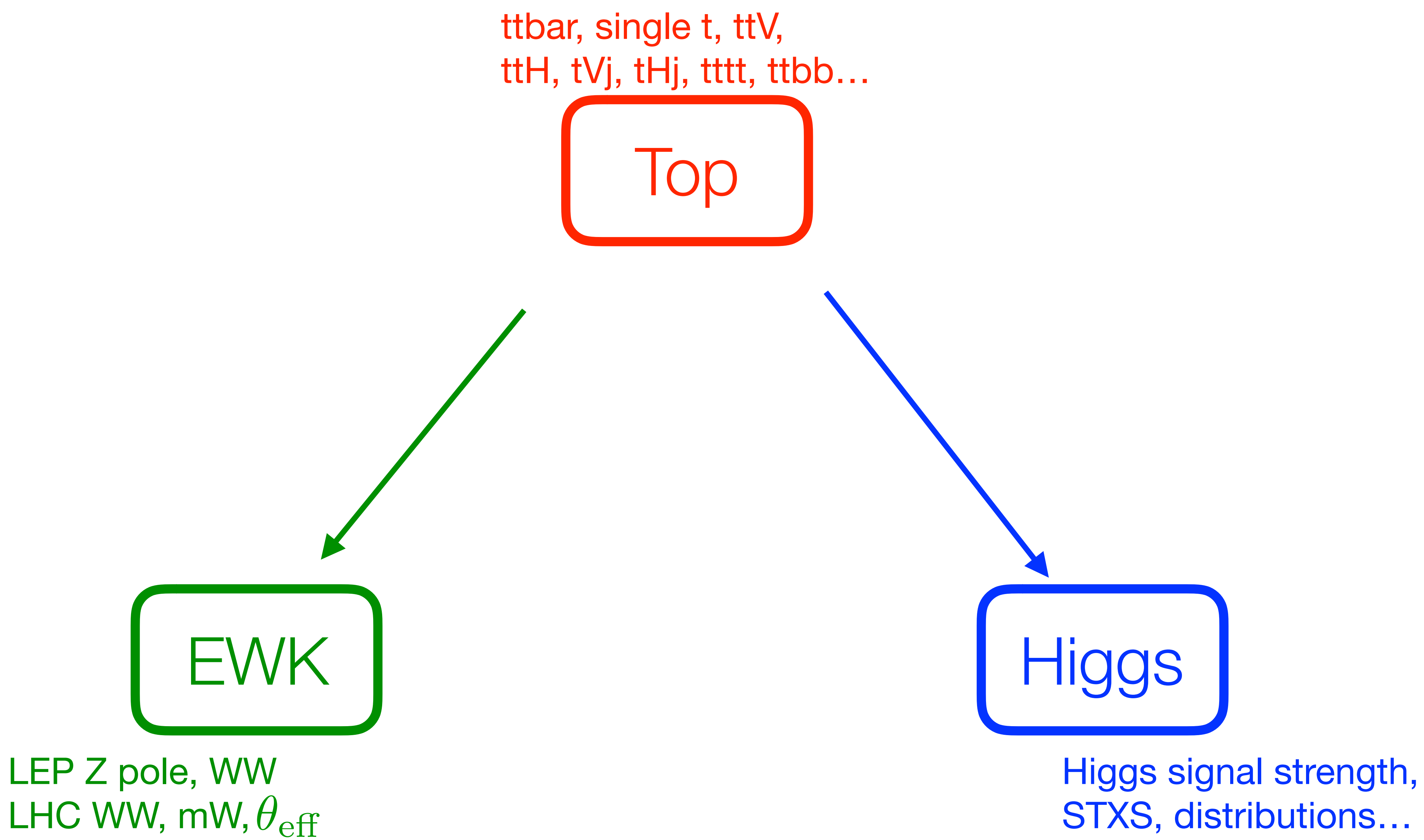
- Fitting approach based on NNPDF: MC replicas + cross validation and closure test
- Theory predictions from MG5_aMC@NLO, i.e. operator contributions are at NLO in QCD
- Parametrization & operator basis etc. are consistent with TOP working group EFT recommendation



Next step: to extend and include EW and Higgs data

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

Global EFT fit at the LHC era



Global EFT fit at the LHC era

ttbar, single t, ttV,
ttH, tVj, tHj, tttt, ttbb…

Top/Higgs operators entering
ttH and top-loop induced channels
[F. Maltoni, E. Vryonidou, CZ ’16]

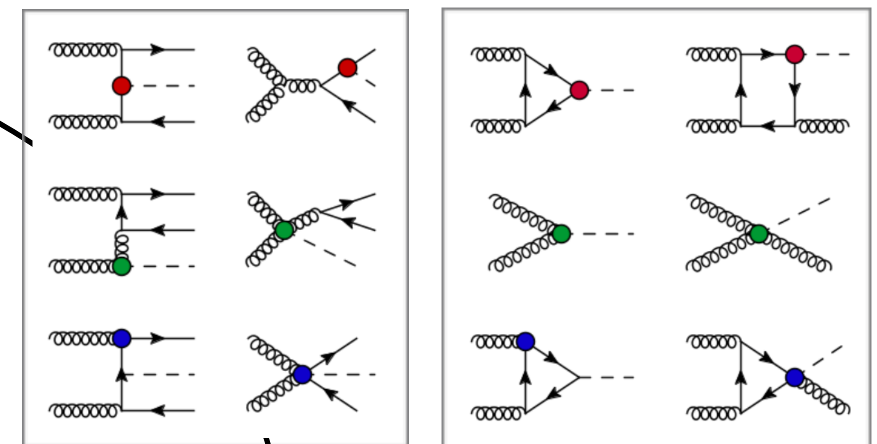
Z>bb leads to correlation between
neutral and charged top EW couplings

$$\begin{pmatrix} O_{\varphi q}^{1(33)} \\ O_{\varphi q}^{3(33)}\end{pmatrix} = \begin{pmatrix} (\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_3 \gamma^\mu q_3) \\ (\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_3\gamma^\mu \tau^I q_3)\end{pmatrix} = \begin{pmatrix} -1 & 1\\ 1 & 1 \\ 0 & 1 \\ 0 & 1\end{pmatrix}^T \begin{pmatrix} \frac{+e}{2s_w c_w}\ (\bar t\gamma^\mu P_L t)\ Z_\mu\ (v+h)^2 \\ \frac{-e}{2 s_w c_w}\ (\bar b \gamma^\mu P_L b)\ Z_\mu\ (v+h)^2 \\ \frac{g}{\sqrt{2}}\ (\bar t\gamma^\mu P_L b)\ W^+_\mu\ (v+h)^2 \\ \frac{g}{\sqrt{2}}\ (\bar b\gamma^\mu P_L t)\ W^-_\mu\ (v+h)^2\end{pmatrix}$$

$c_{\varphi Q}^{-} \equiv C_{\varphi q}^{1(33)} - C_{\varphi q}^{3(33)}$ enters in $pp \to t\bar{t}Z$

$c_{\varphi Q}^{3} \equiv C_{\varphi q}^{3(33)}$ enters in $t \to bW^+$

$c_{\varphi Q}^{+} \equiv C_{\varphi q}^{1(33)} + C_{\varphi q}^{3(33)}$ enters in $e^+e^- \to b\bar{b}$ (or $pp \to b\bar{b}Z$)



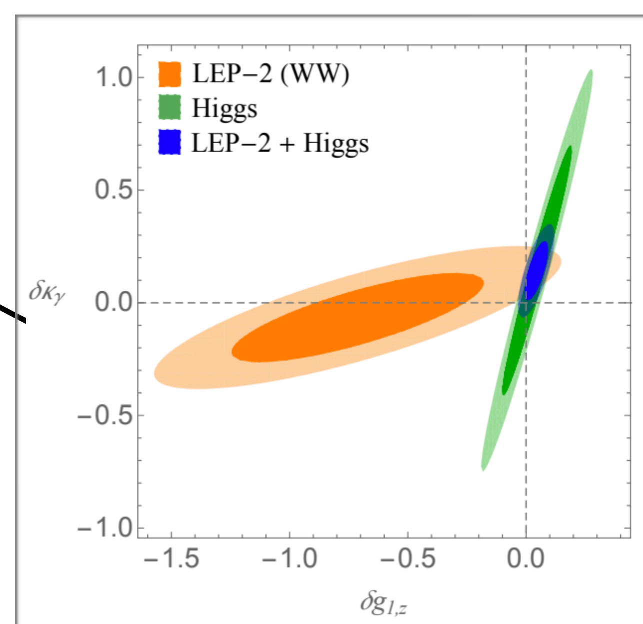
Top

EWK

Higgs

LEP Z pole, WW
LHC WW, mW, $\theta_{\rm eff}$

Higgs signal strength,
STXS, distributions…



Higgs measurements help
to determine TGC
[A. Falkowski et al. ’16]

New ideas are changing this picture

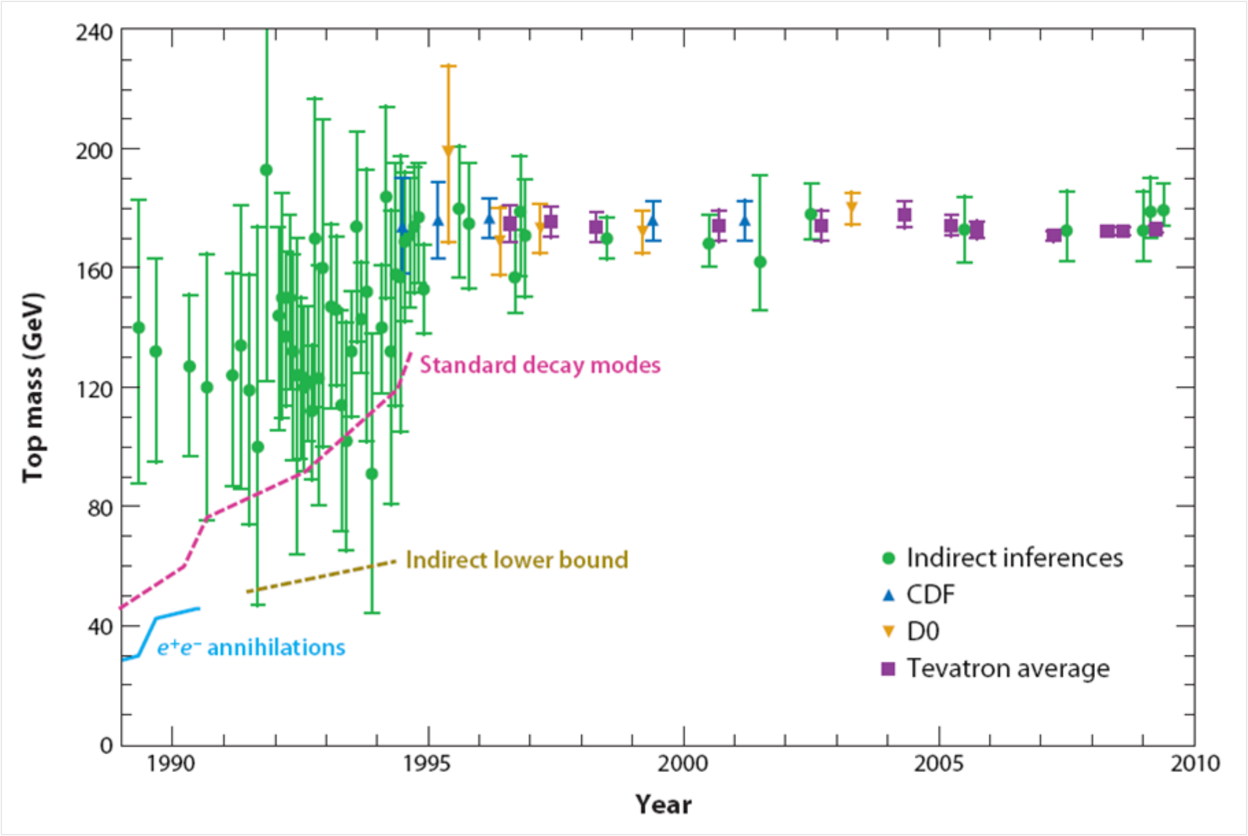
There are more to implement:

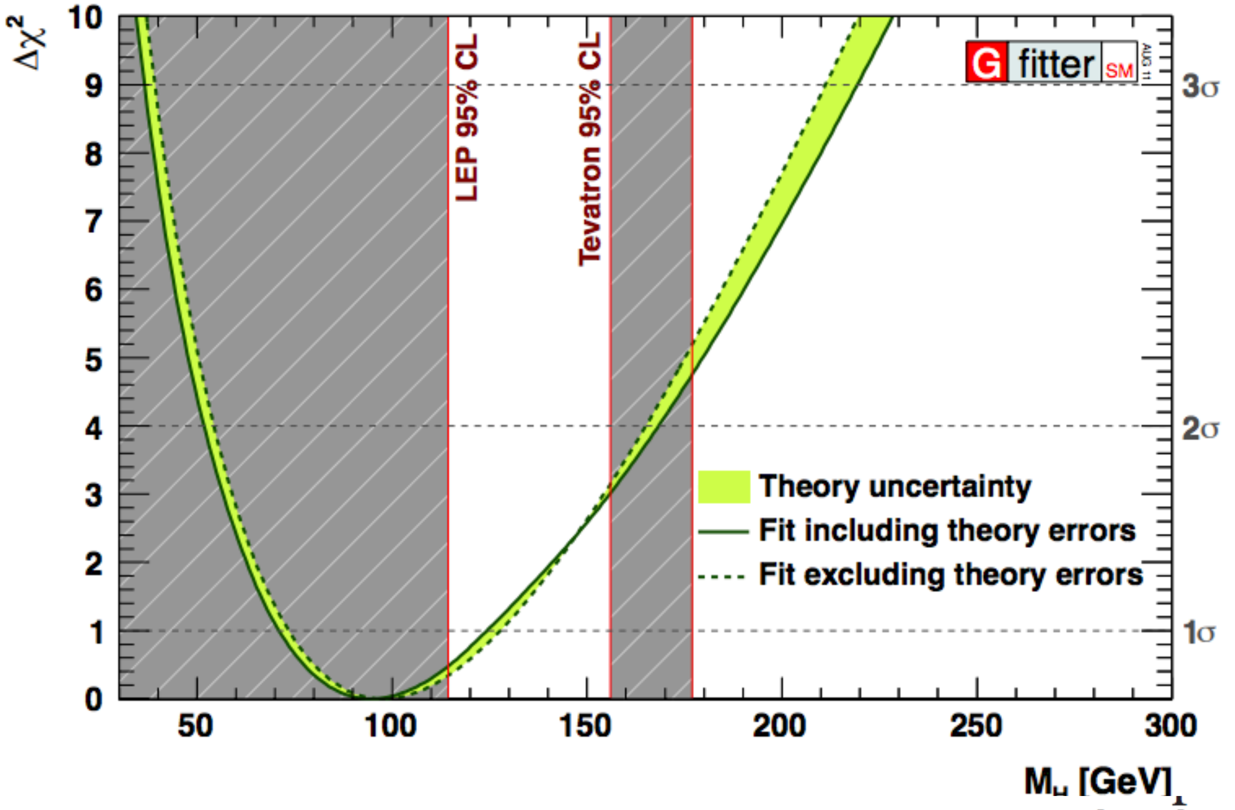
- At LEP1/2, low-energy precision measurements, and ee collider in the future:
  - Excellent precision, limited energy and channels
  - Use loops to open up more possibilities. Loop factor suppression will be compensated for by the precision.

- At the LHC, and future HL/HE upgrades:
  - Large energy, but precision limited by large systematic effects.
  - Use energy-growth effects to avoid the precision "floor", i.e. same precision but at larger energy means much better constraining power.

- People have explored different ideas that in the above 2 categories, with limited channels/scenarios, to demonstrate their usefulness.
- Still, **the ultimate reach should be assessed with a global fit with these new observables/ideas/calculations implemented.**

Precision with loops



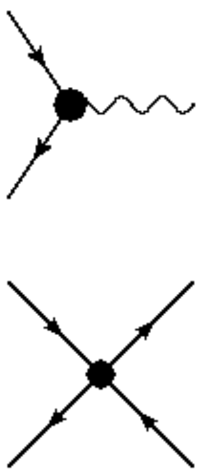


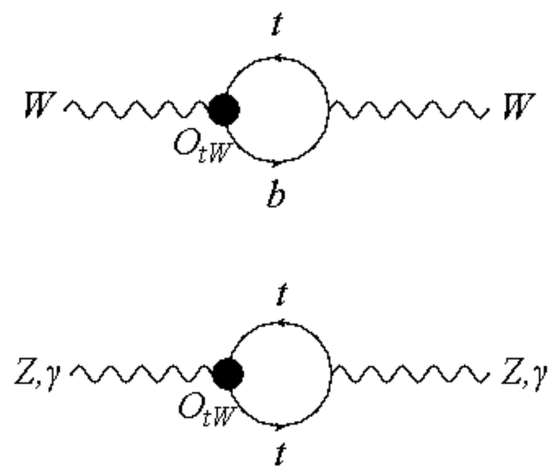
$$M_H = 125^{+8[+21]}_{-10[-11]}$$

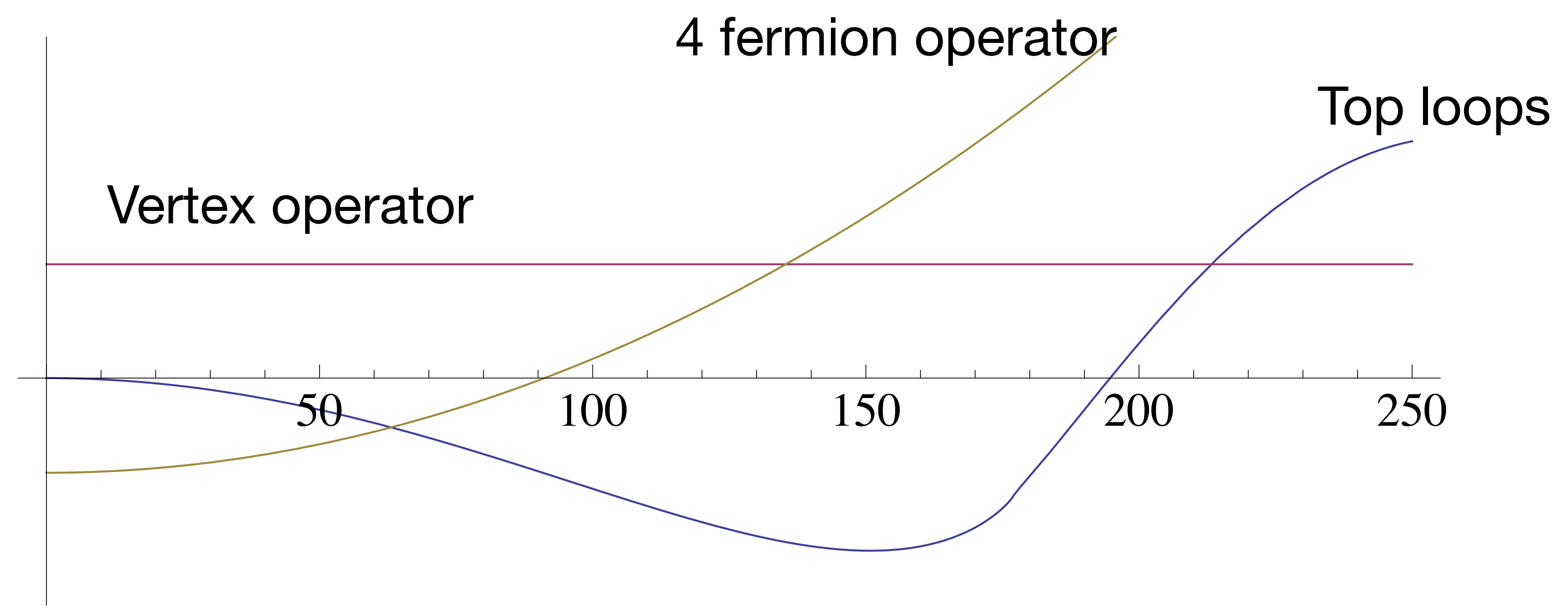
EW fit: top couplings enter through loops

$$\frac{c_i v^2}{\Lambda^2}$$

$$\frac{c_i E^2}{\Lambda^2}$$







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

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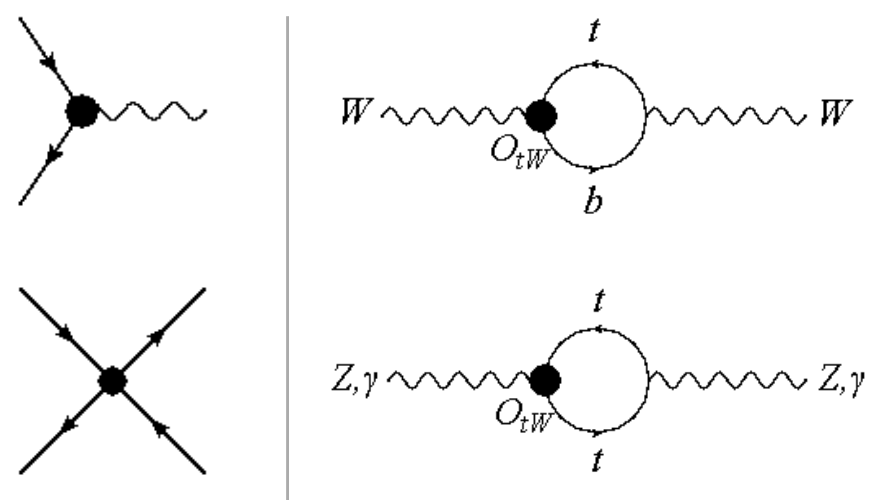

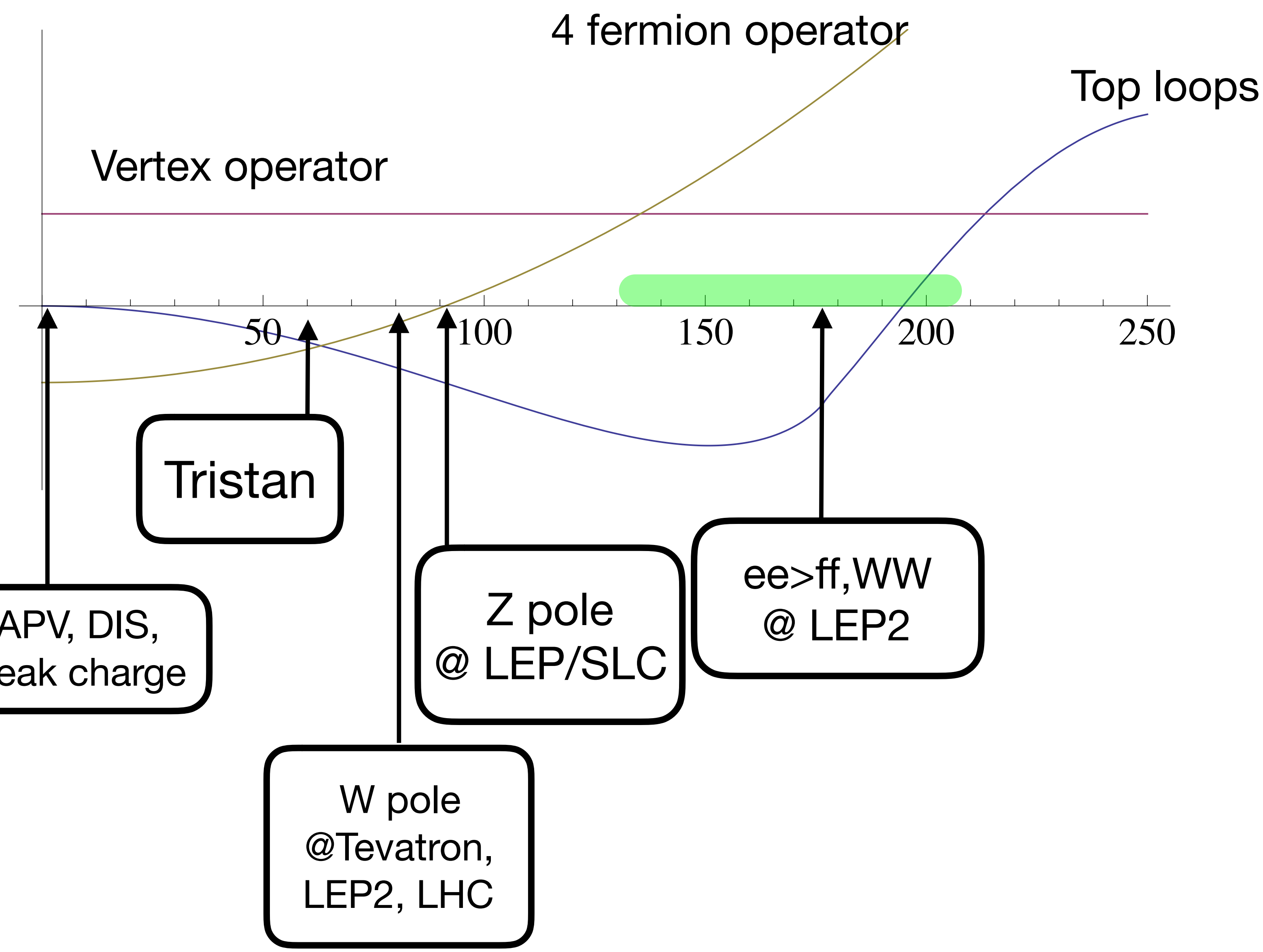

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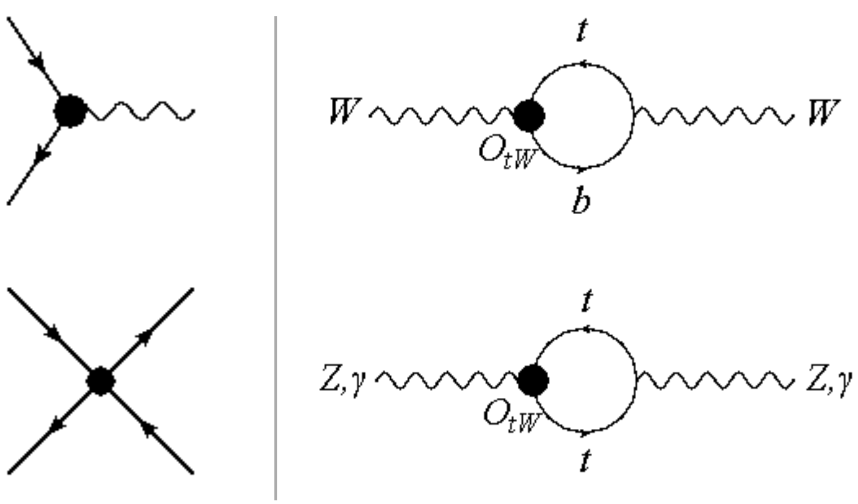

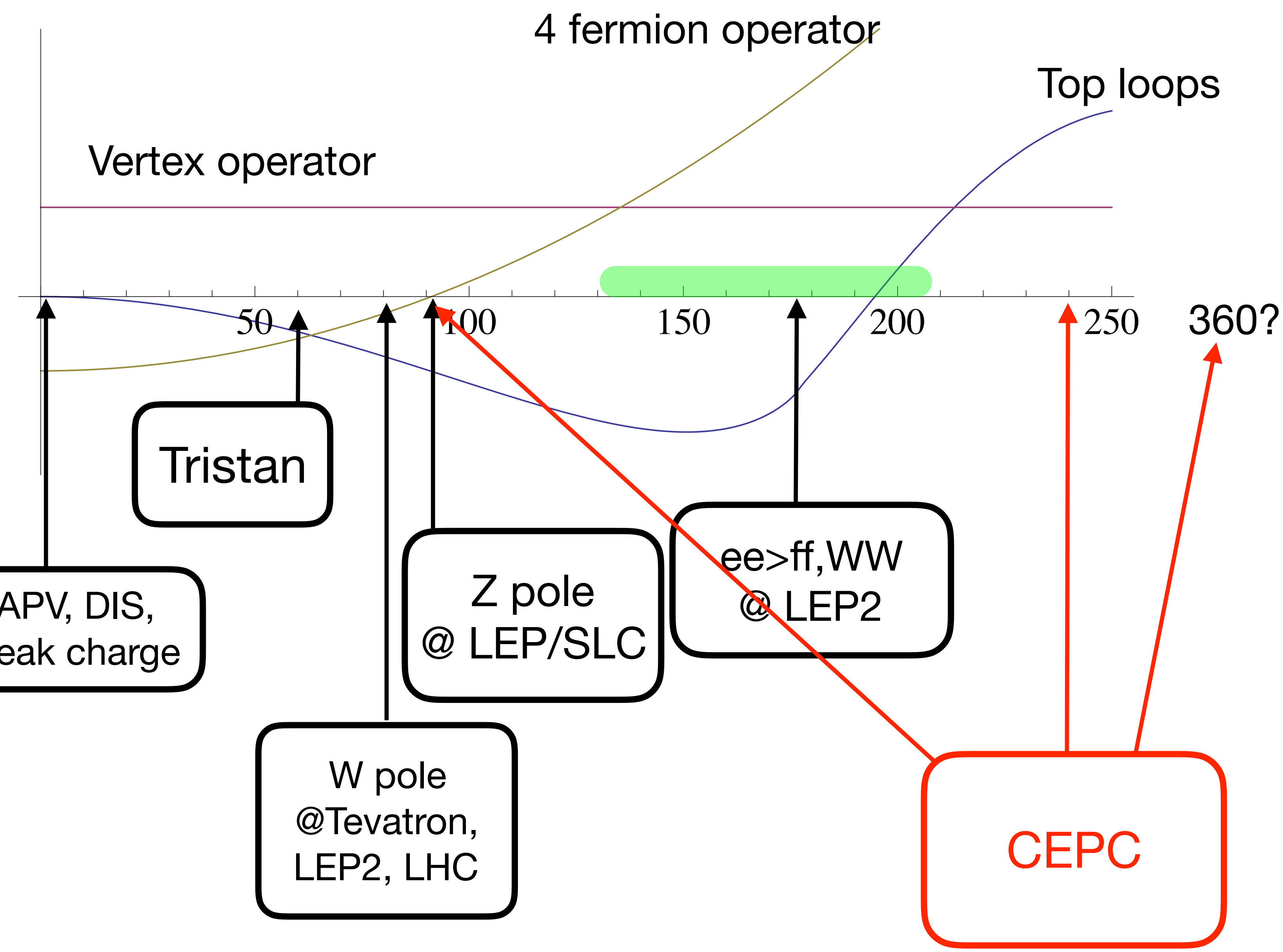

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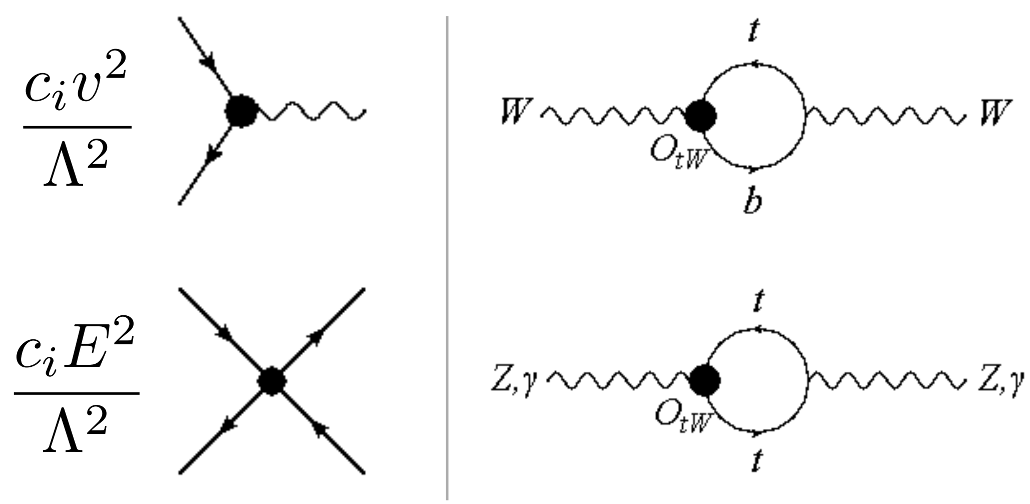

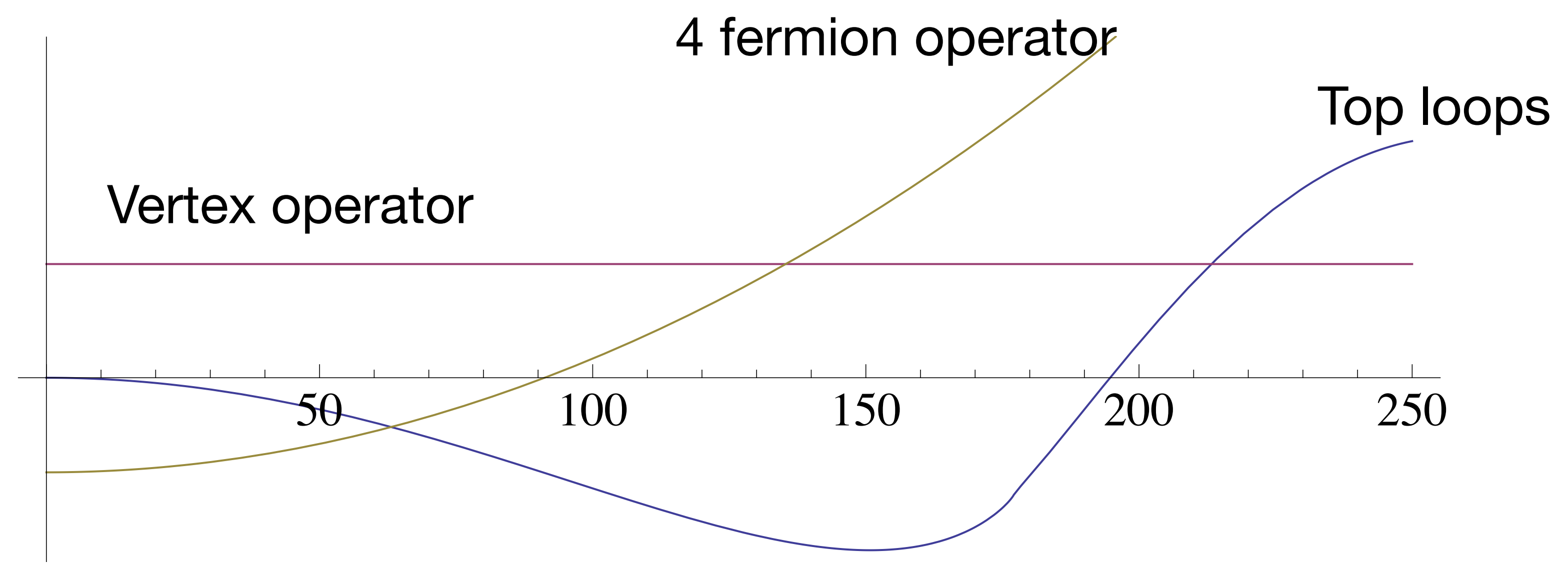

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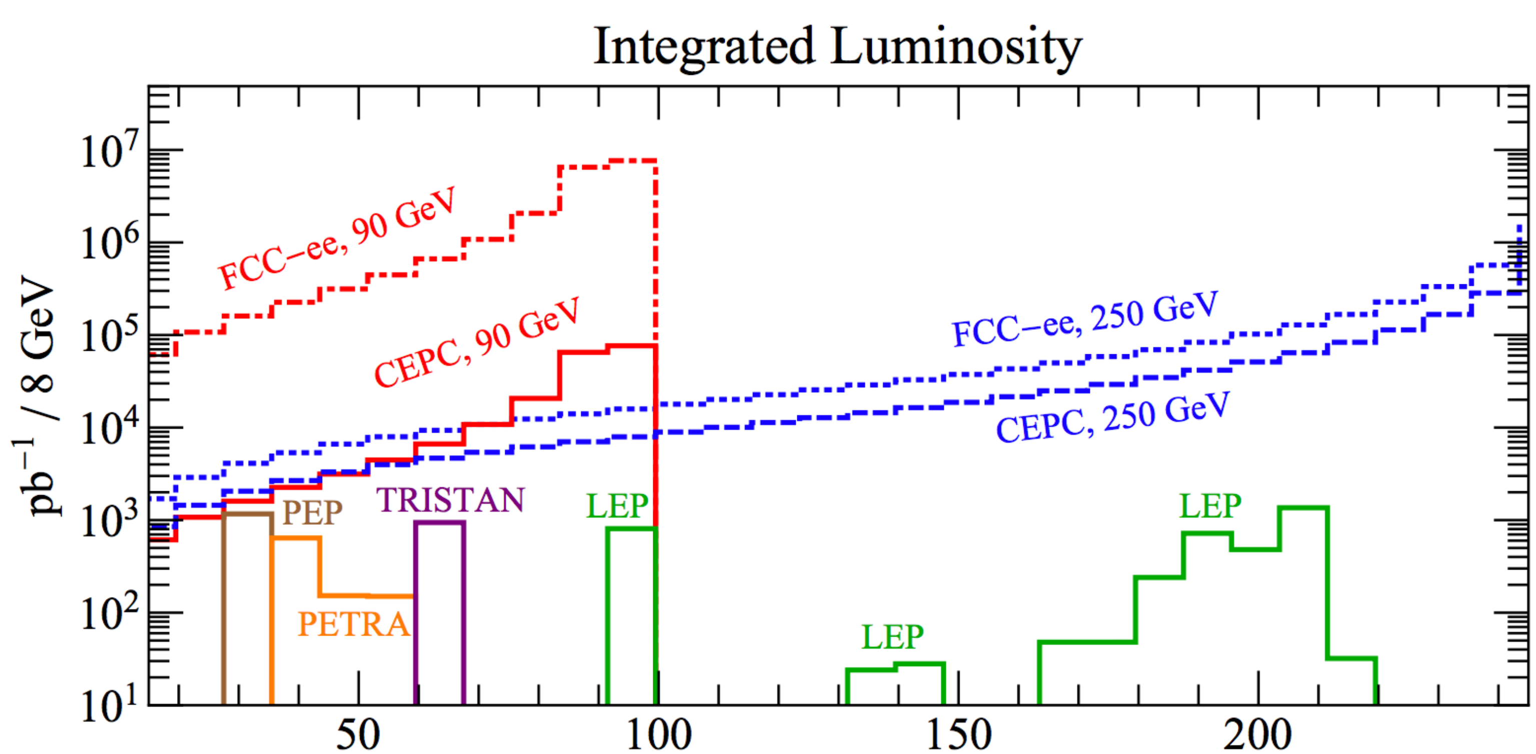


[M. Karliner 1503.07209]

EW fit: top couplings enter through loops

[CZ, Greiner, Willenbrock 1201.6670]

$$
\begin{pmatrix}
-0.702 & -0.701 & -0.000 & +0.128 & -0.003 & +0.000 & -0.000 & -0.000 \\
-0.094 & -0.087 & -0.002 & -0.992 & -0.019 & +0.001 & -0.001 & -0.000 \\
-0.342 & +0.349 & -0.398 & +0.017 & -0.761 & +0.056 & -0.136 & -0.039 \\
-0.326 & +0.323 & -0.591 & -0.009 & +0.632 & -0.065 & -0.191 & +0.015 \\
+0.137 & -0.137 & +0.128 & -0.000 & -0.003 & +0.138 & -0.935 & -0.229 \\
+0.034 & -0.034 & +0.039 & +0.001 & -0.094 & -0.745 & -0.244 & +0.610 \\
-0.003 & +0.003 & +0.007 & -0.000 & +0.025 & +0.646 & -0.090 & +0.757 \\
+0.505 & -0.505 & -0.689 & -0.000 & -0.108 & +0.014 & +0.054 & +0.009
\end{pmatrix}
\times \frac{1}{\Lambda^2}
\begin{pmatrix}
C_{\phi q}^{(3)} \\ C_{\phi q}^{(1)} \\ C_{\phi t} \\ C_{\phi b} \\ C_{tW} \\ C_{bW} \\ C_{tB} \\ C_{bB}
\end{pmatrix}
=
\begin{pmatrix}
-0.011 & \pm 0.014 \\
+0.59 & \pm 0.27 \\
-0.23 & \pm 1.10 \\
-1.75 & \pm 1.62 \\
-2.2 & \pm 11.9 \\
-9.2 & \pm 21.1 \\
+102.4 & \pm 50.4 \\
-1.36\mathrm{e}{+3} & \pm 1.38\mathrm{e}{+3}
\end{pmatrix}
\mathrm{TeV}^{-2}.
$$

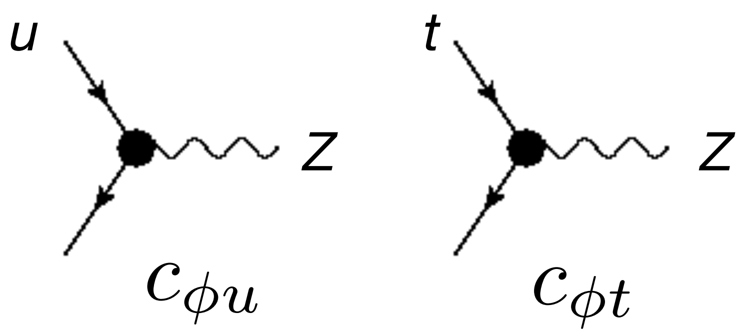
Top operators — 1 sigma limits

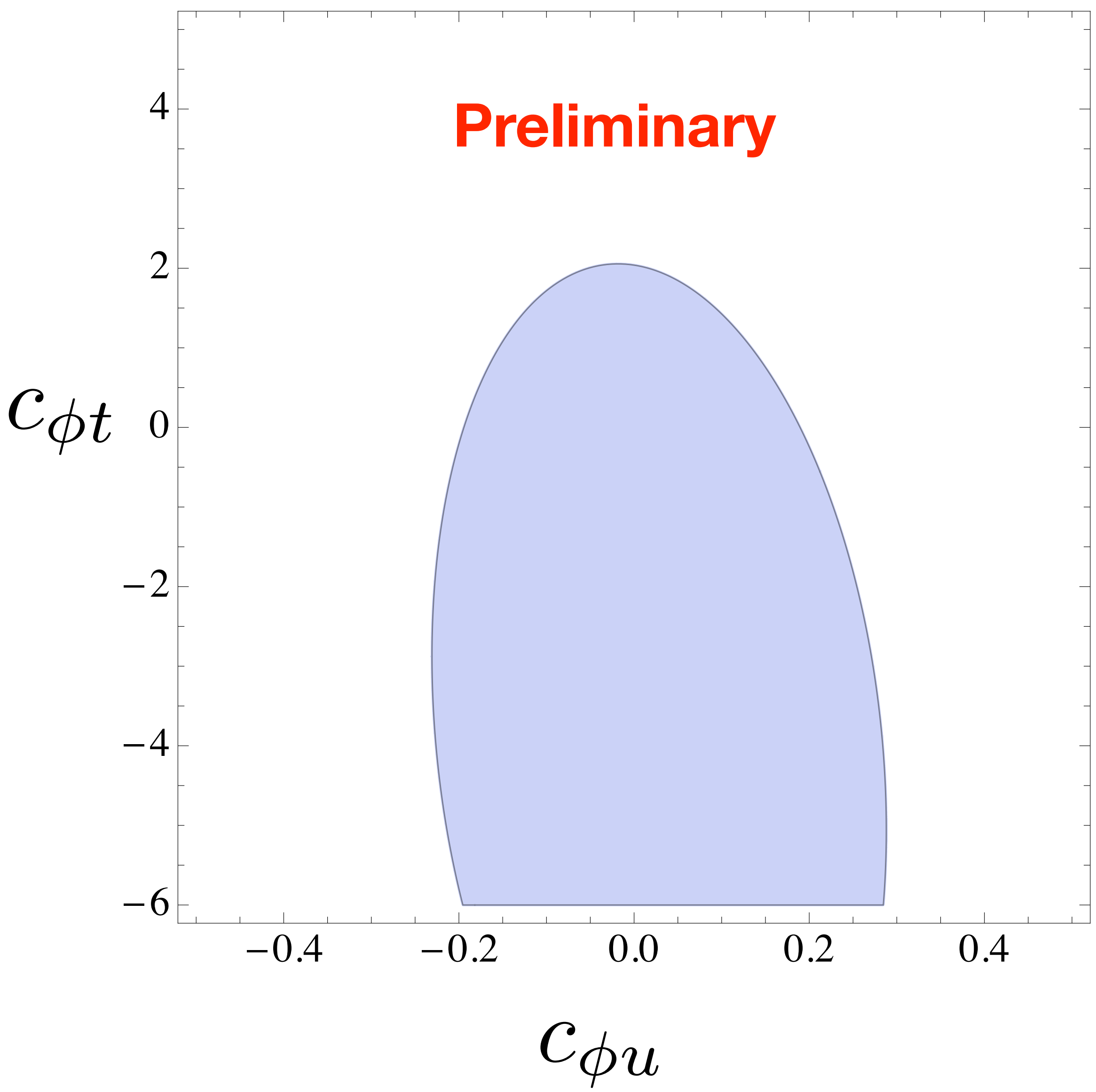
[SMEFiT 1901.05965]

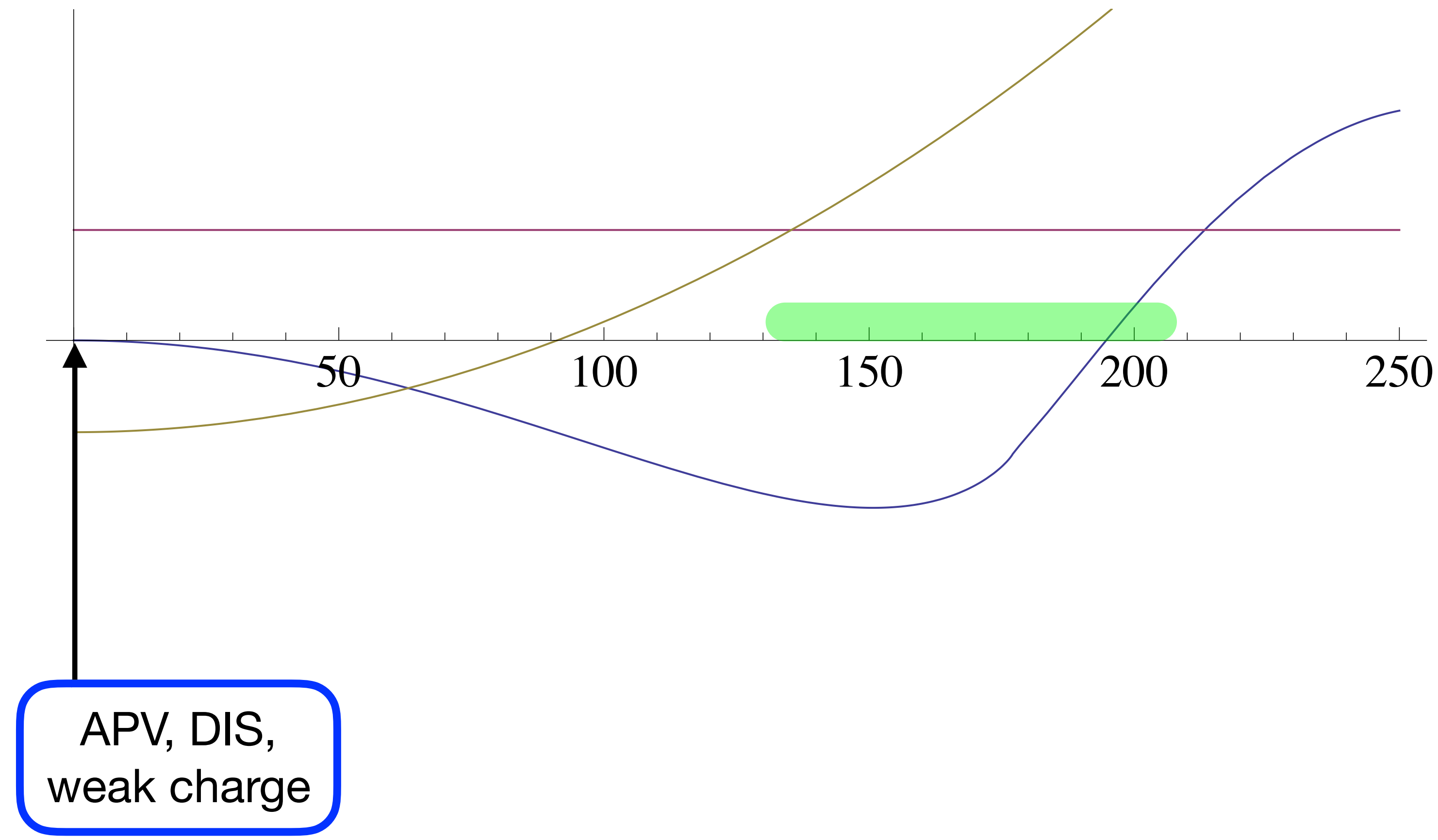
	Direct LHC	Indirect EW
c_{tG}	$[-0.4, 0.4]$	
c_{tW}	$[-1.8, 0.9]$	$[-2.8, 2.0]$ (EW)
c_{bW}	$[-2.6, 3.1]$	$[-15, 37]$ (EW)
c_{tZ}	$[-2.1, 4.0]$	c_{tB}: $[-5.8, 15.4]$ (EW)
$c_{\varphi tb}$	$[-27, 8.7]$	
$c^{3}_{\varphi Q}$	$[-5.5, 5.8]$	
$c^{-}_{\varphi Q}$	$[-3.5, 3]$	$[-3.4, 7.4]$ (EW)
$c_{\varphi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

Interplay of Top & EW sectors
due to precision loop effects

95% limits on $(c_{\phi u}, c_{\phi t})$, marginalized over $c_{\phi e}, c_{\phi WB}$ $(\Lambda = 1\ \text{TeV})$







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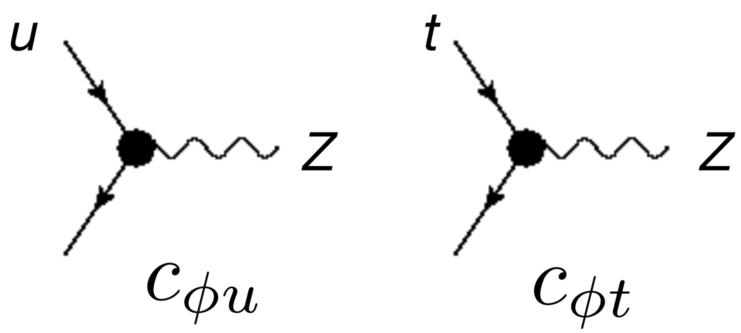

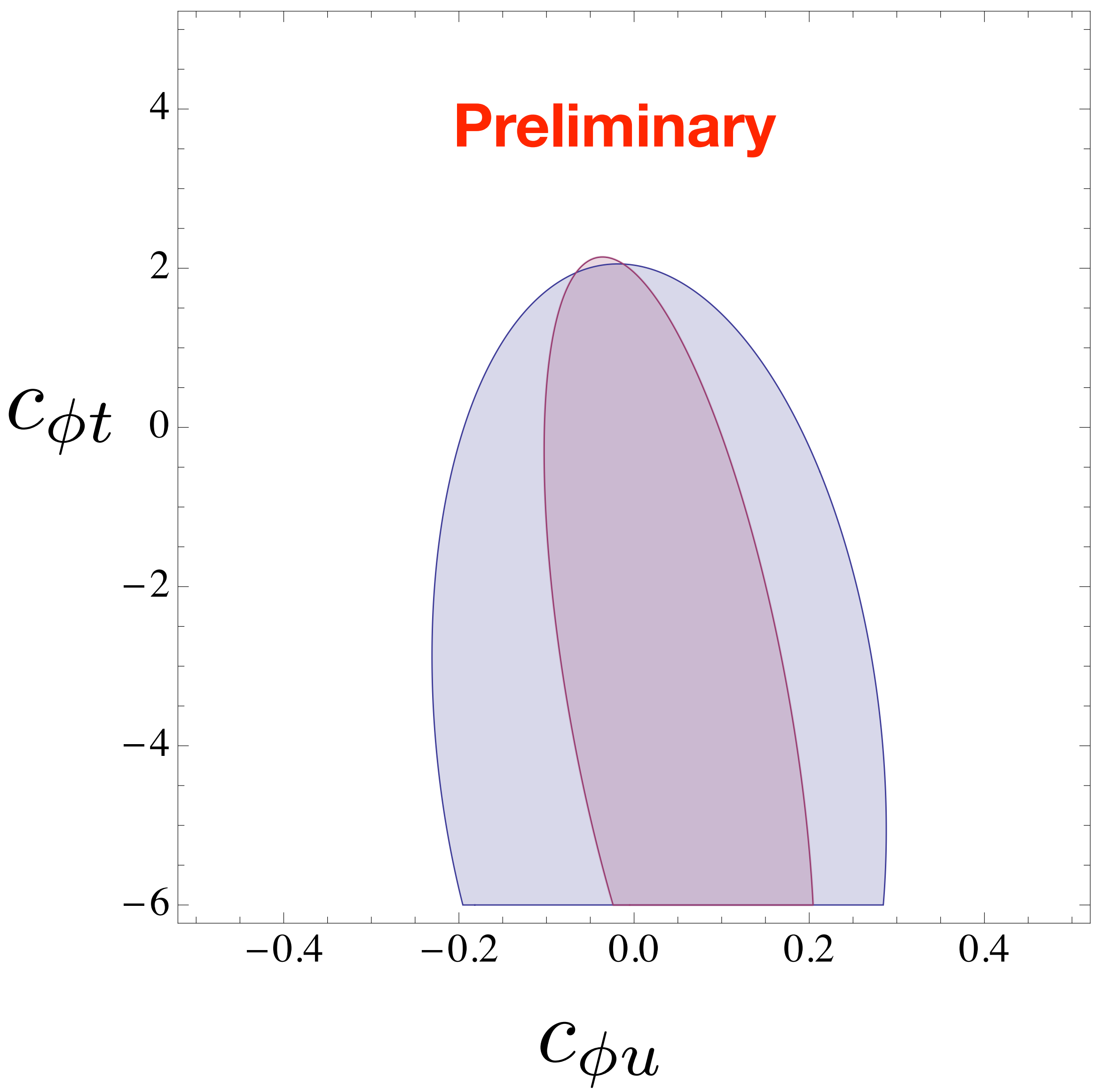

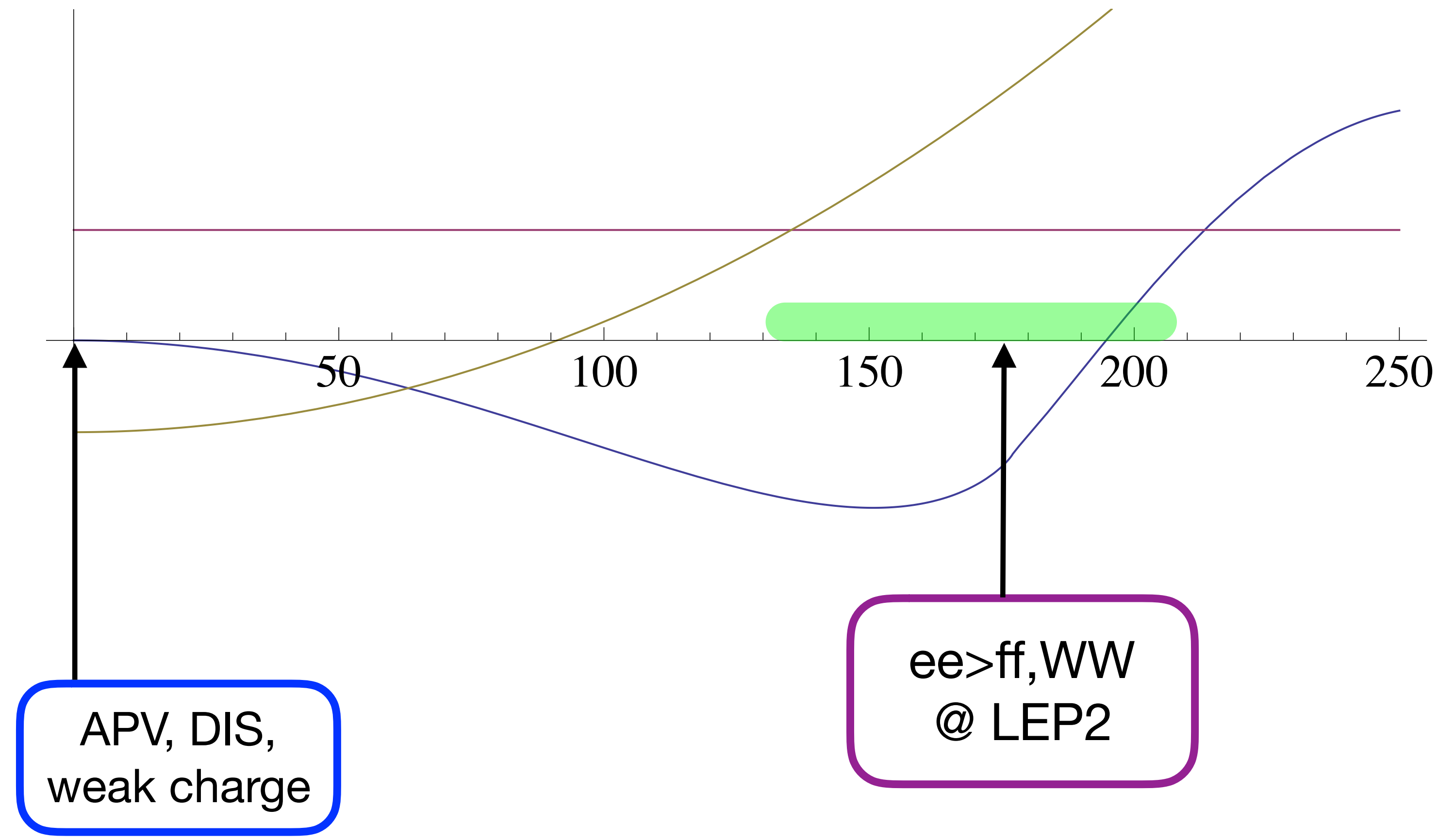

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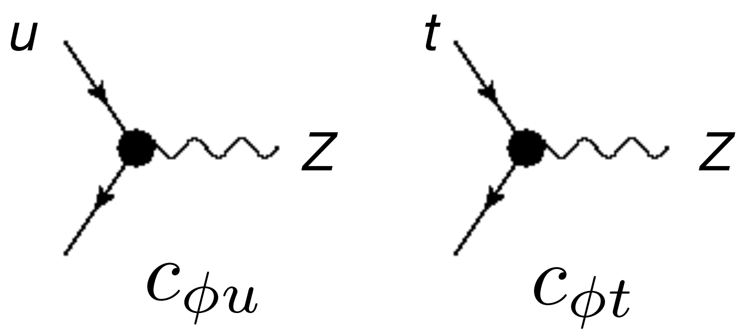
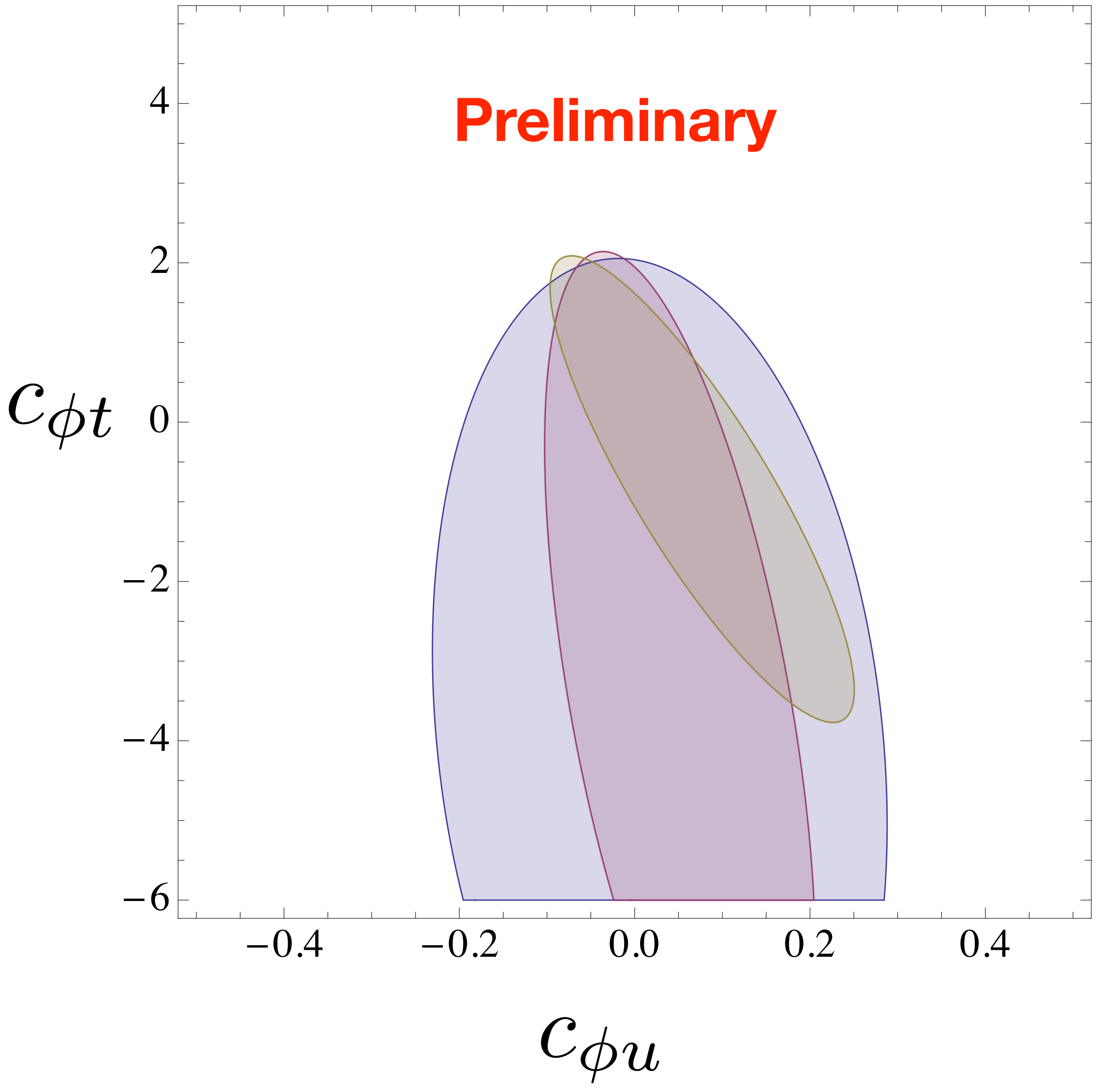
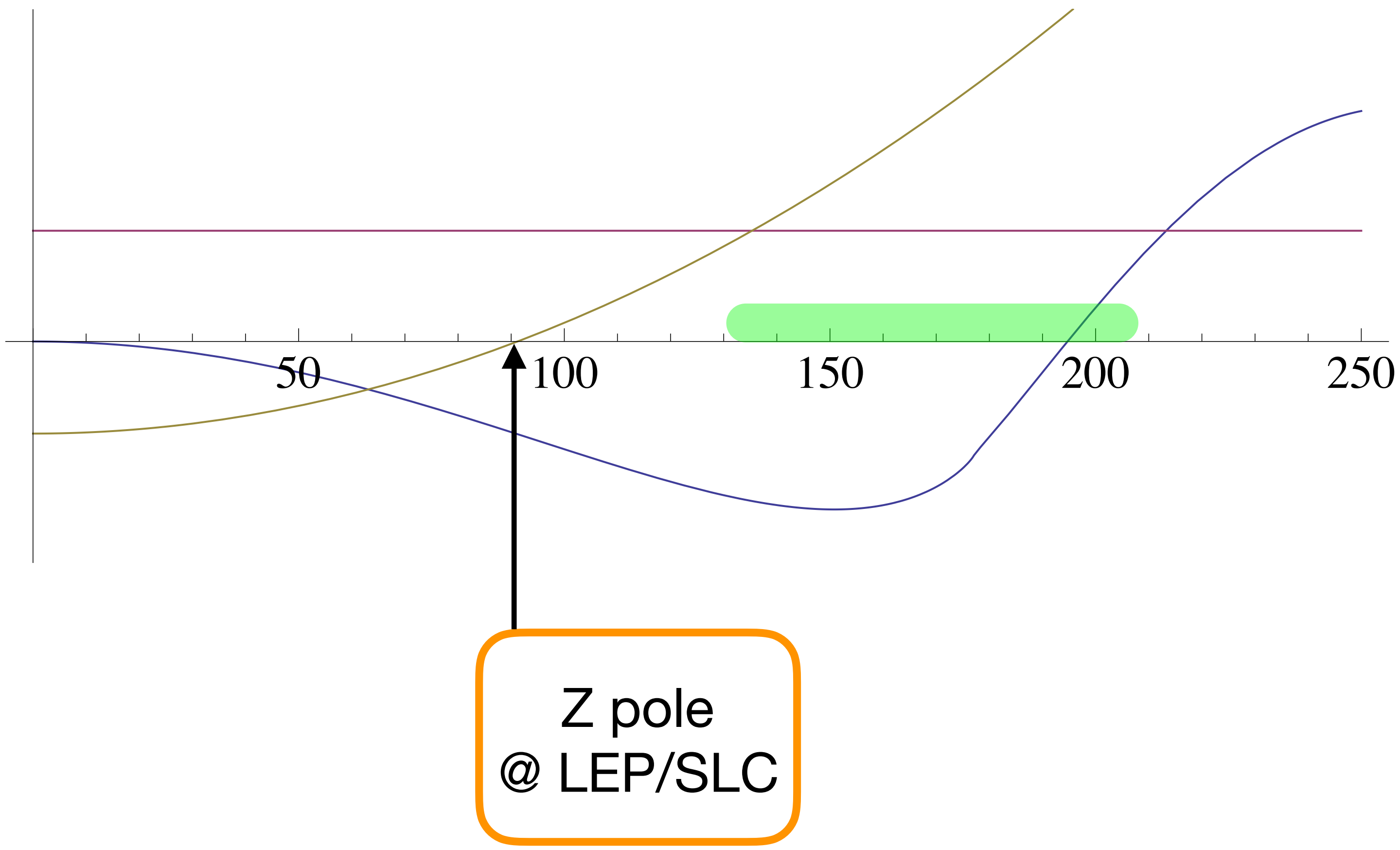
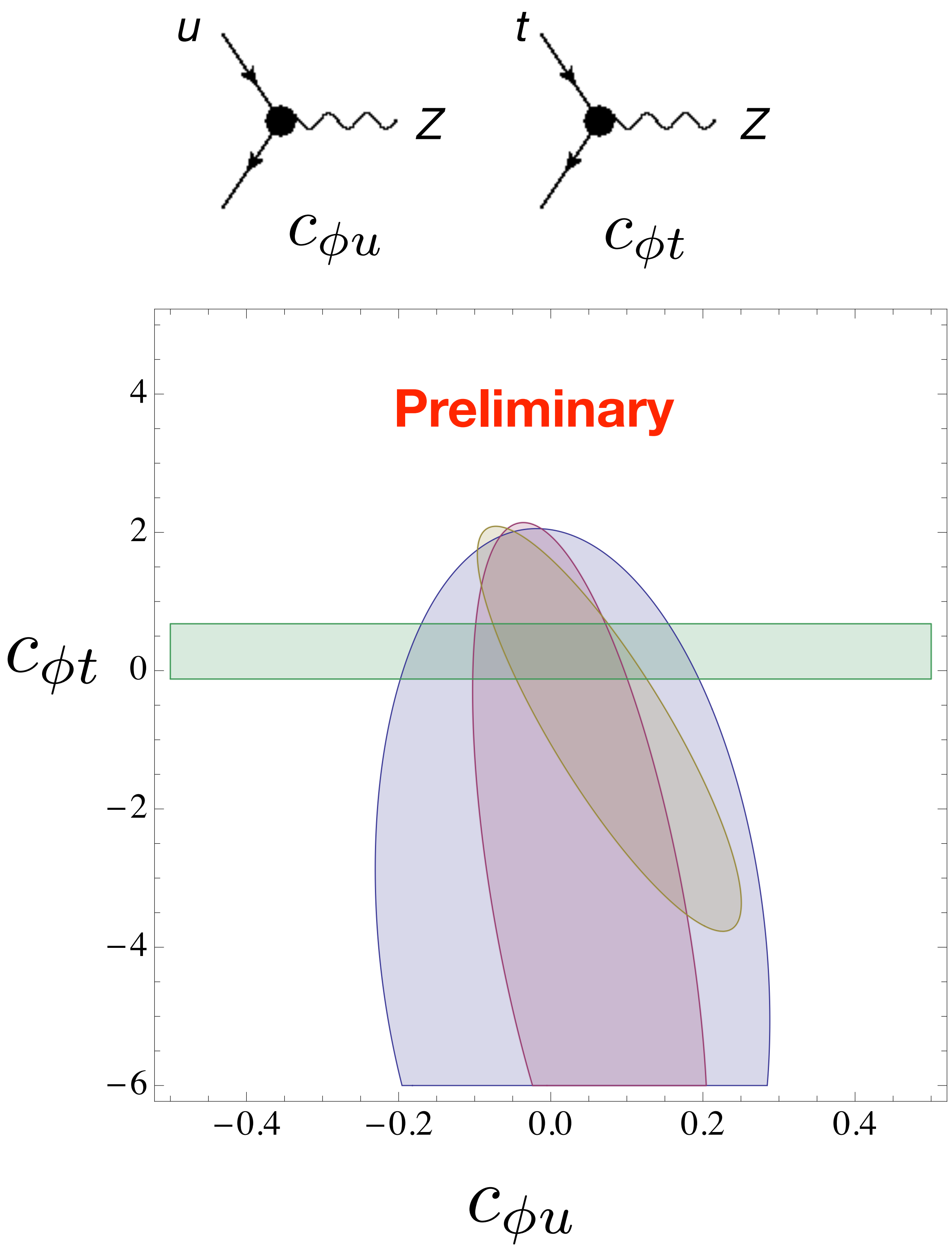
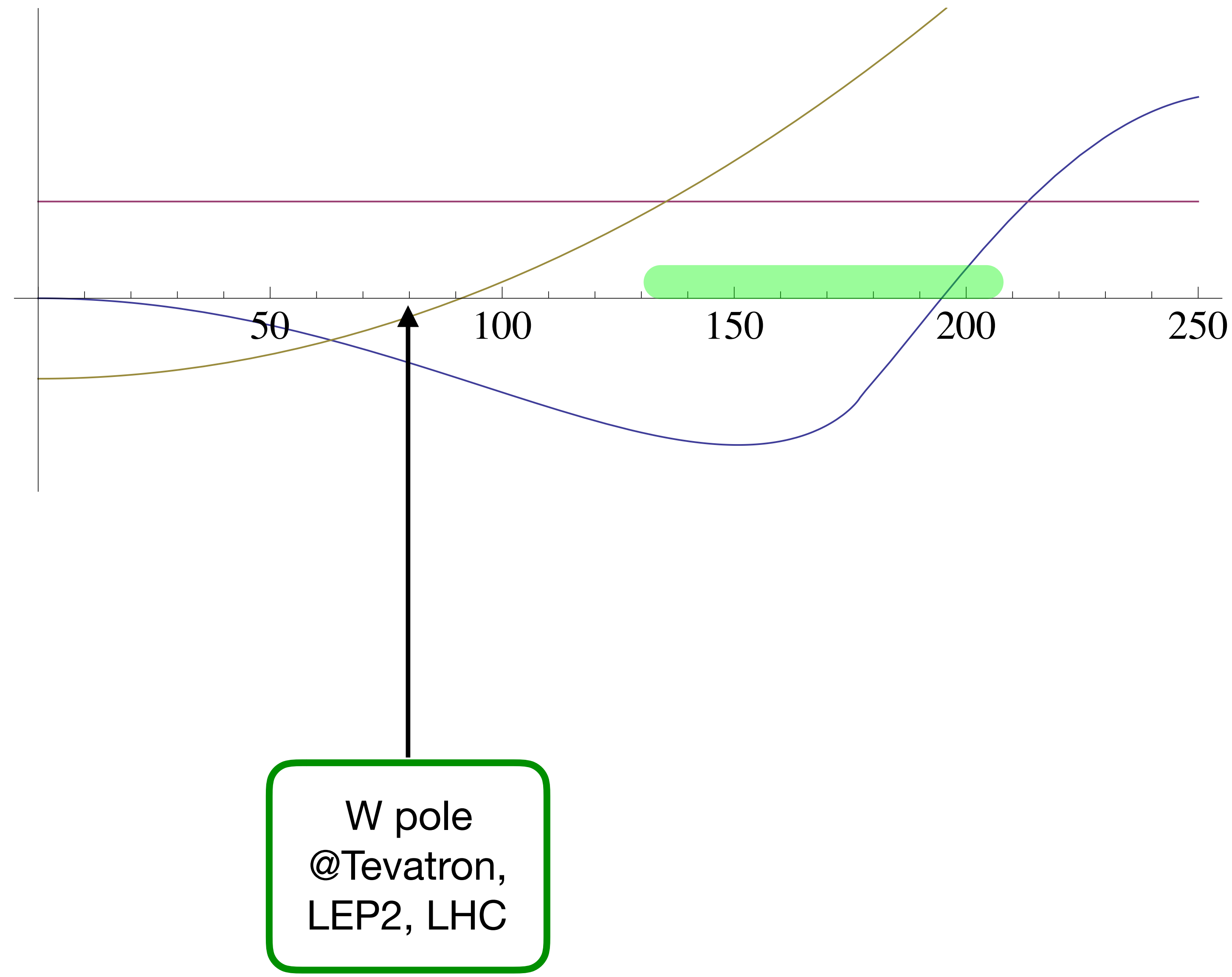




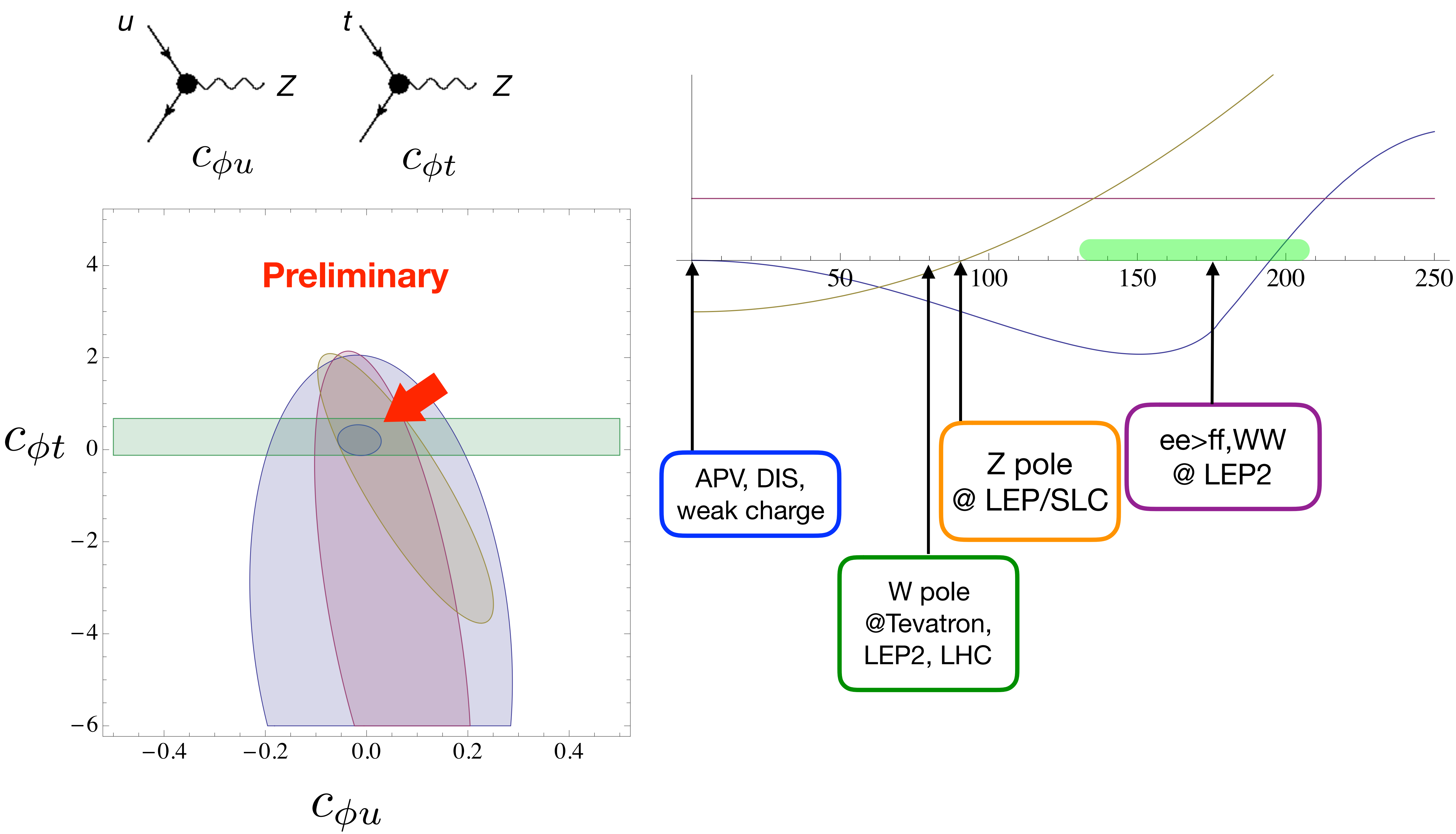


95% limits on $(c_{\phi u}, c_{\phi t})$, marginalized over $c_{\phi e}, c_{\phi WB}$ $(\Lambda = 1\ \text{TeV})$





95% limits on $(c_{\phi u}, c_{\phi t})$, marginalized over $c_{\phi e}, c_{\phi WB}$ $(\Lambda = 1$ TeV$)$



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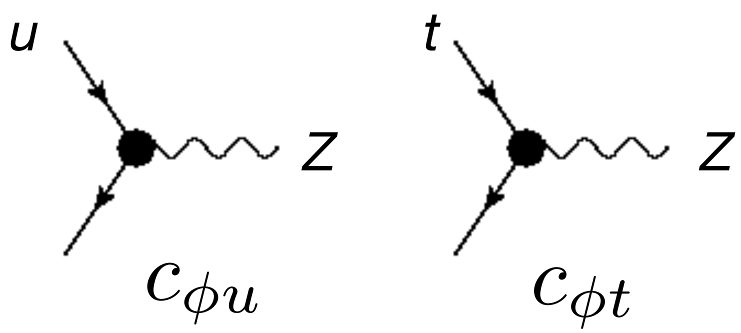
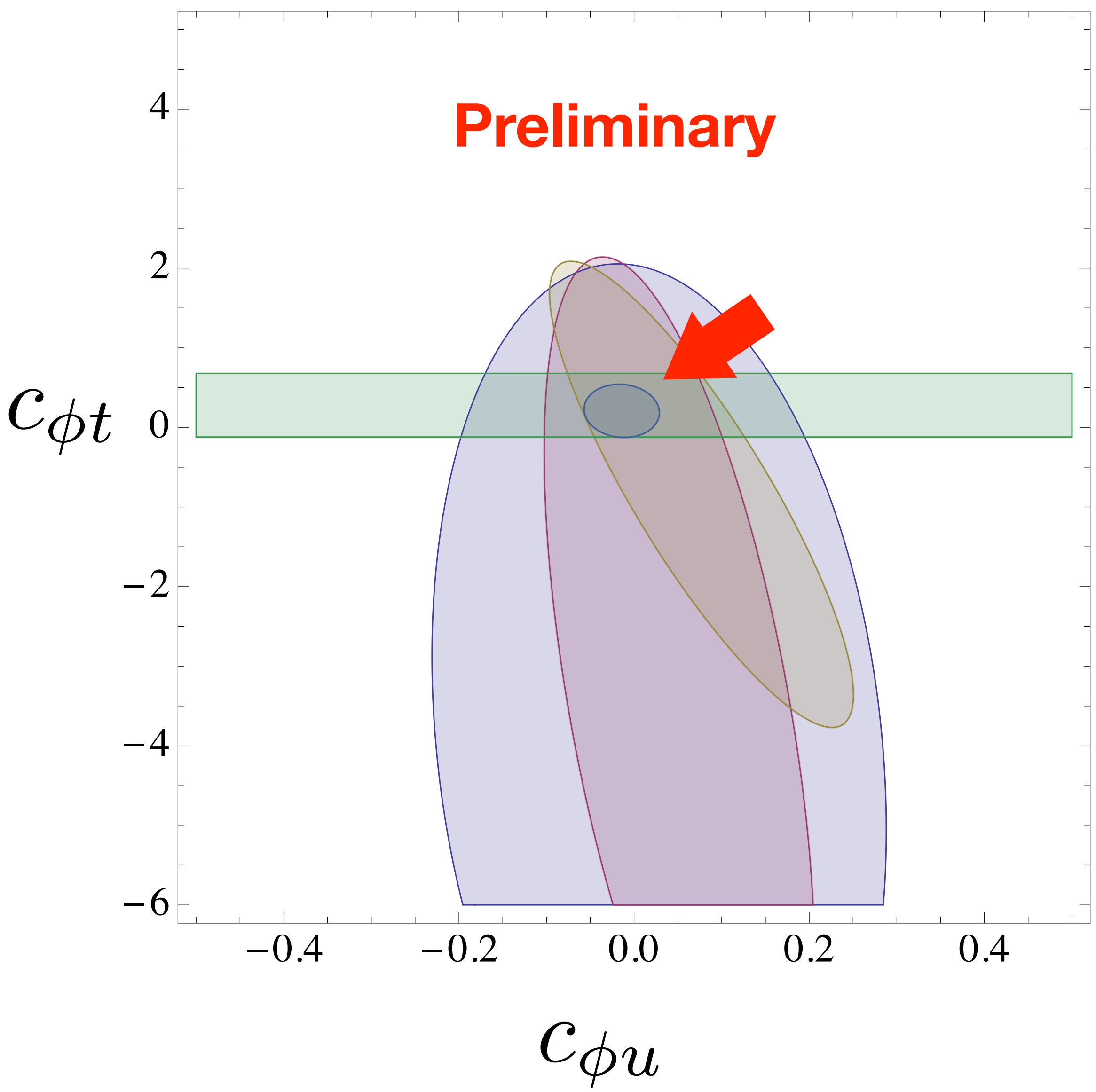
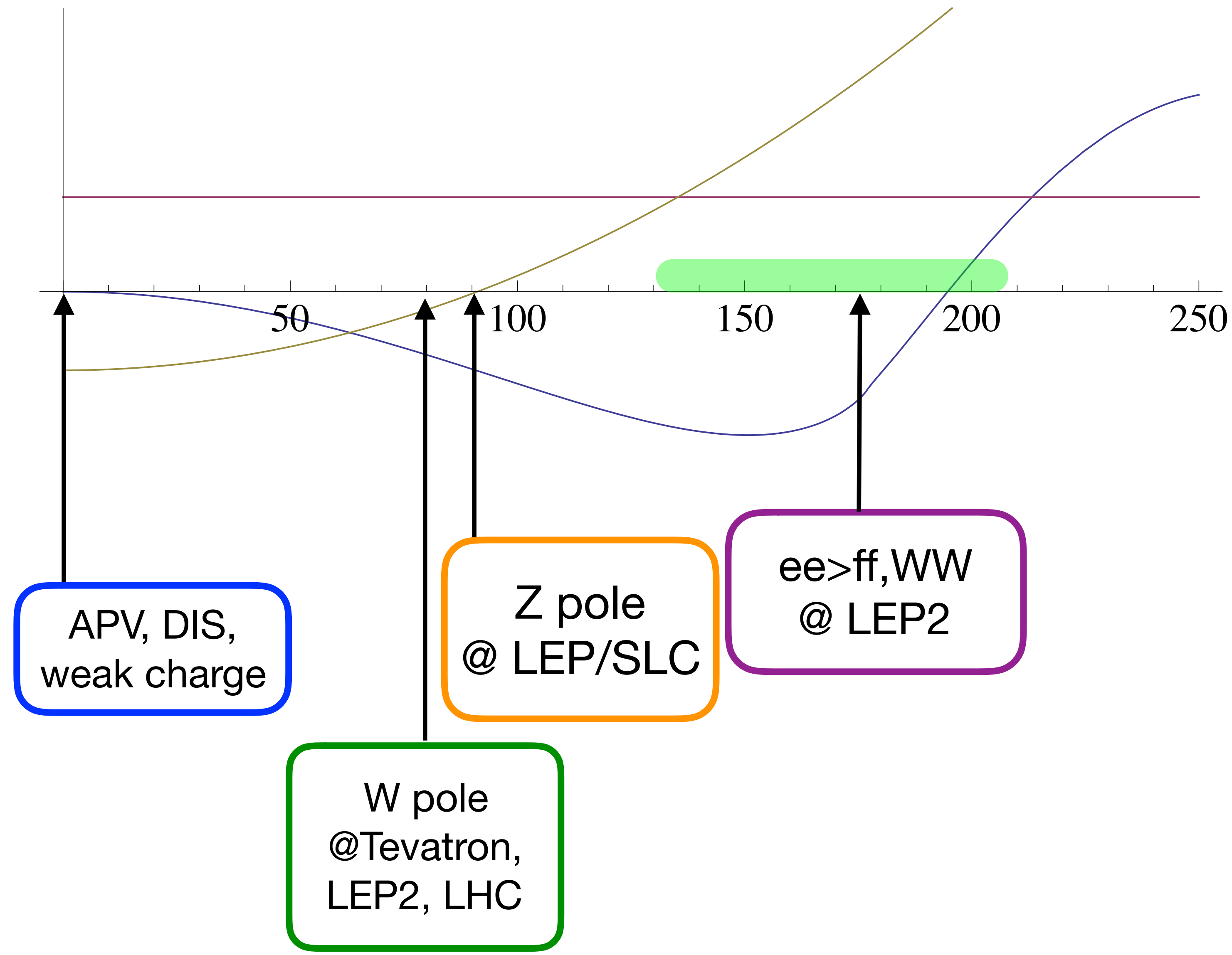






Further improvement at CEPC with the “radiative return”?

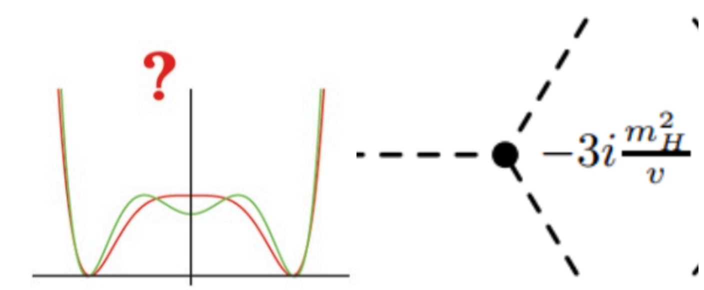
EW fit: going to two loop

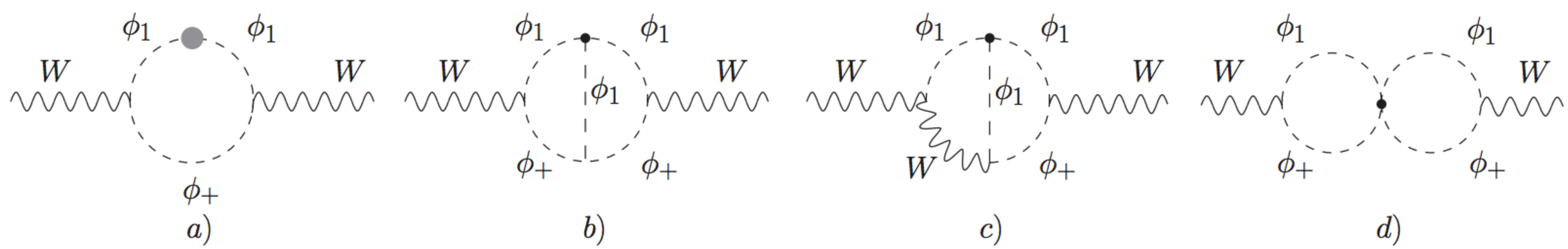
[Degrassi, Fedele, Giardino 1702.01737]

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

But: Higgs trilinear coupling

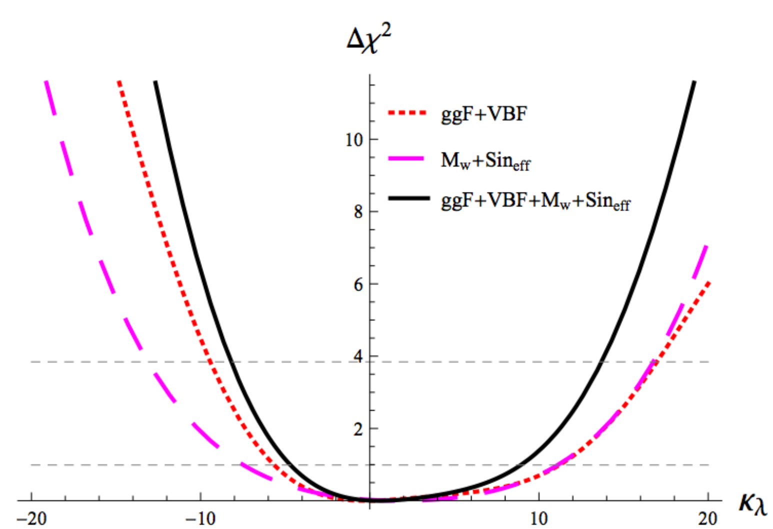
- Direct probe via di-Higgs at LHC
- One loop effect with single Higgs
- **Two loop effects in EWPO: through W/Z self energies**





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

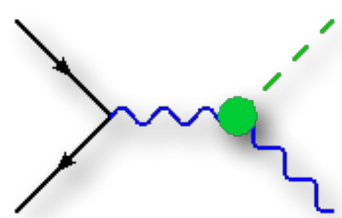
	C_1	C_2
m_W	6.27×10^{-6}	-1.72×10^{-6}
$\sin^2\theta_{\rm eff}^{\rm lep}$	-1.56×10^{-5}	4.55×10^{-6}



Currently O(10) bound.
~10 improvement with
CEPC Z/W pole projection

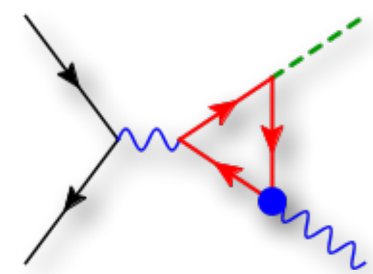
Higgs fit with loops

- **Higgs/diboson channels can reach ~5% precision at HL-LHC, and even better with future lepton collider. When this happens, we want to be able to disentangle**



Dim-6 tree

and



Dim-6 top loops

- **NLO EW in SMEFT may not be small:**

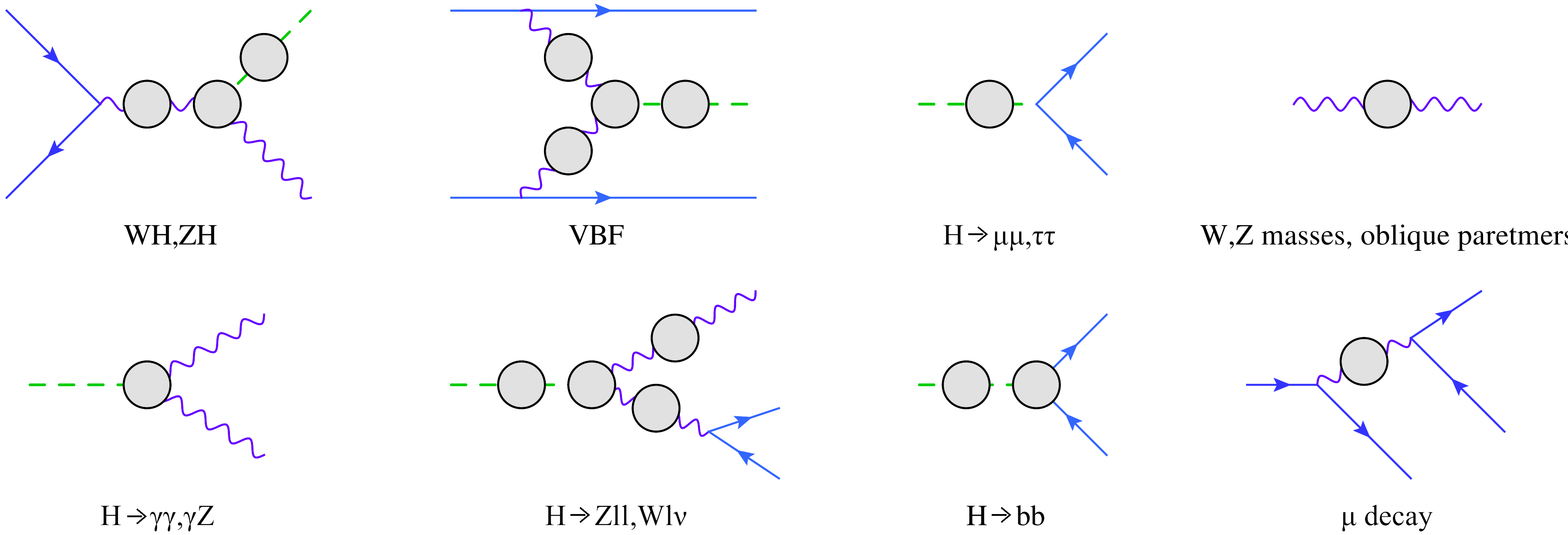
$$\mathcal{O}(\alpha_{EW}/\pi \cdot C_t/C_H) \quad \text{instead of} \quad \mathcal{O}(\alpha_{EW}/\pi)$$

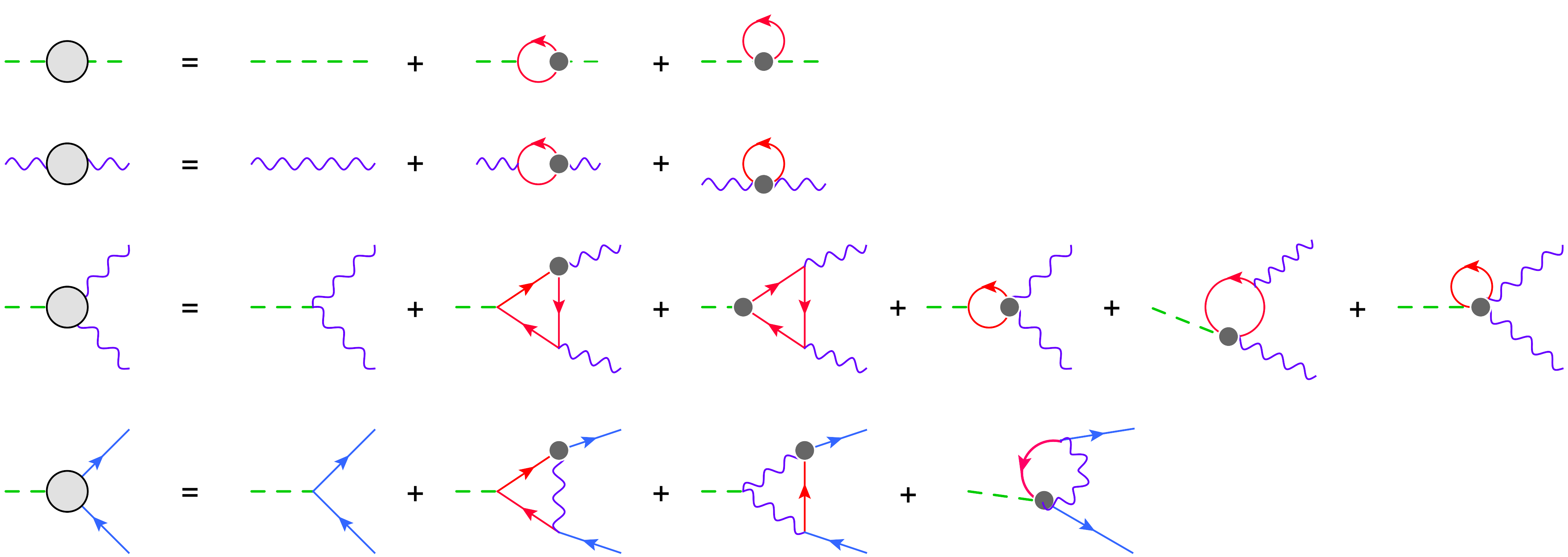
given that in general C_t is less constrained than C_H.

All dim-6 top loop contributions in Higgs

Automated with MG5_aMC@NLO

[Vryonidou, CZ '18]

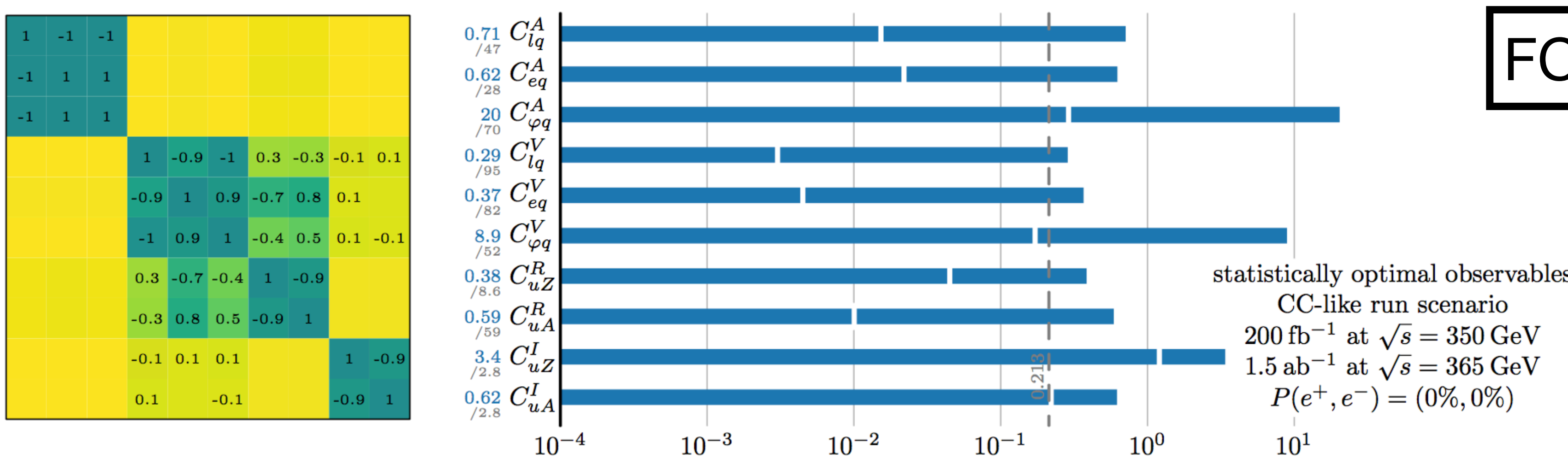




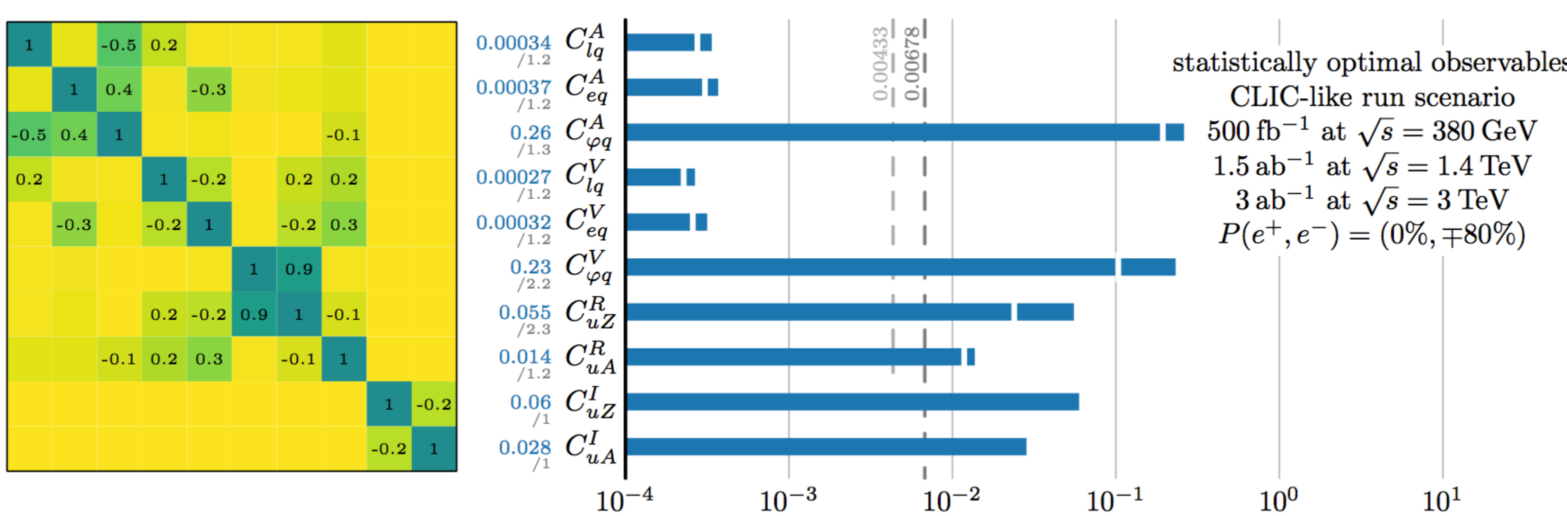
Top loops at CEPC

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



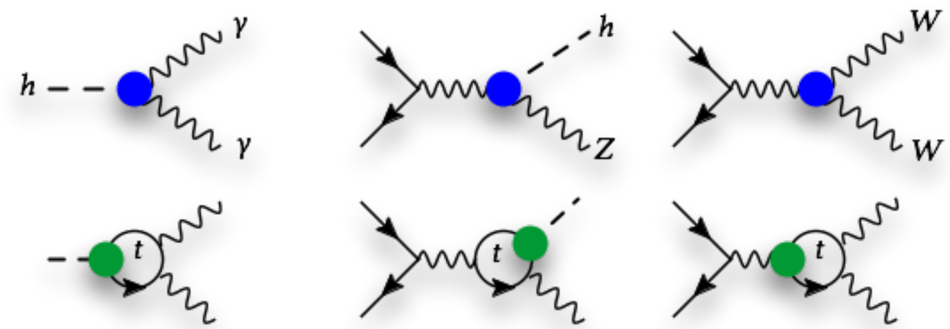
CLIC

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

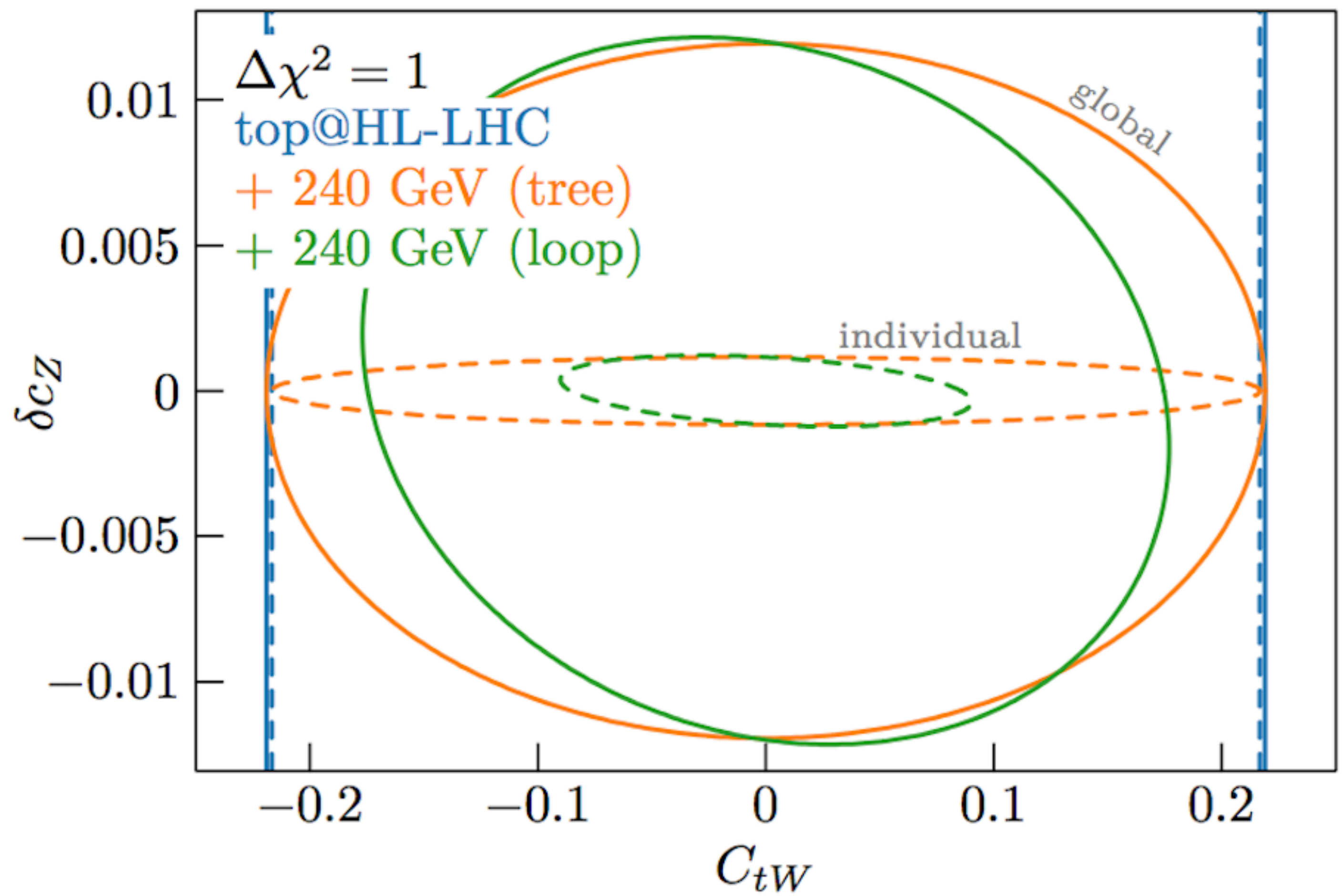
Top loops at CEPC

[Durieux, Gu, Vryonidou, CZ ’18]

Probing the tops below ttbar threshold:



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



- extra parameter space covered thanks to loop sensitivity

Important information to add in a global top & Higgs fit

Talk by G. Durieux at HC2018

Higgs trilinear couplings in loops

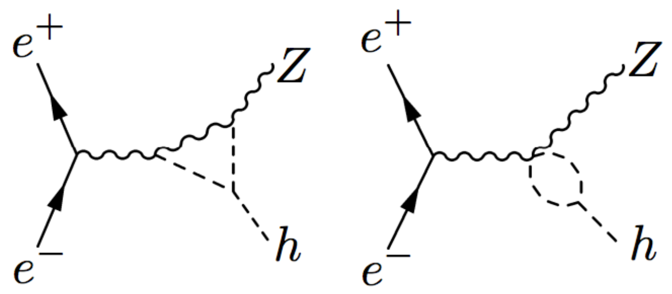


FIG. 1: NLO vertex corrections to the associated production cross section which depend on the Higgs self-coupling. These terms lead to a linear dependence on modifications of the self-coupling δ_h.

[M. McCullough 1312.3322]

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

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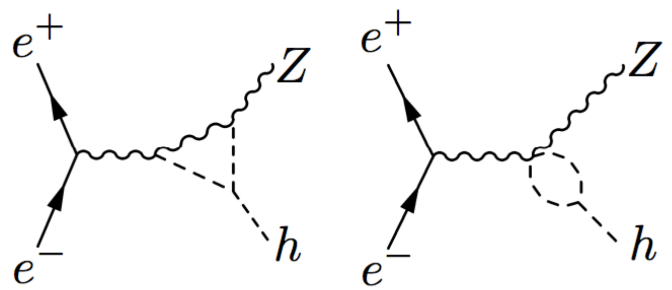

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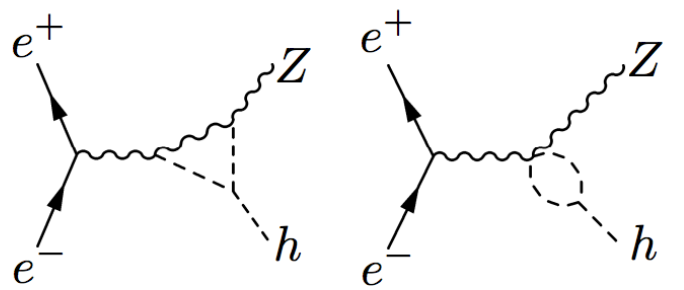

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[S. Di Vita et al. 1711.03978]

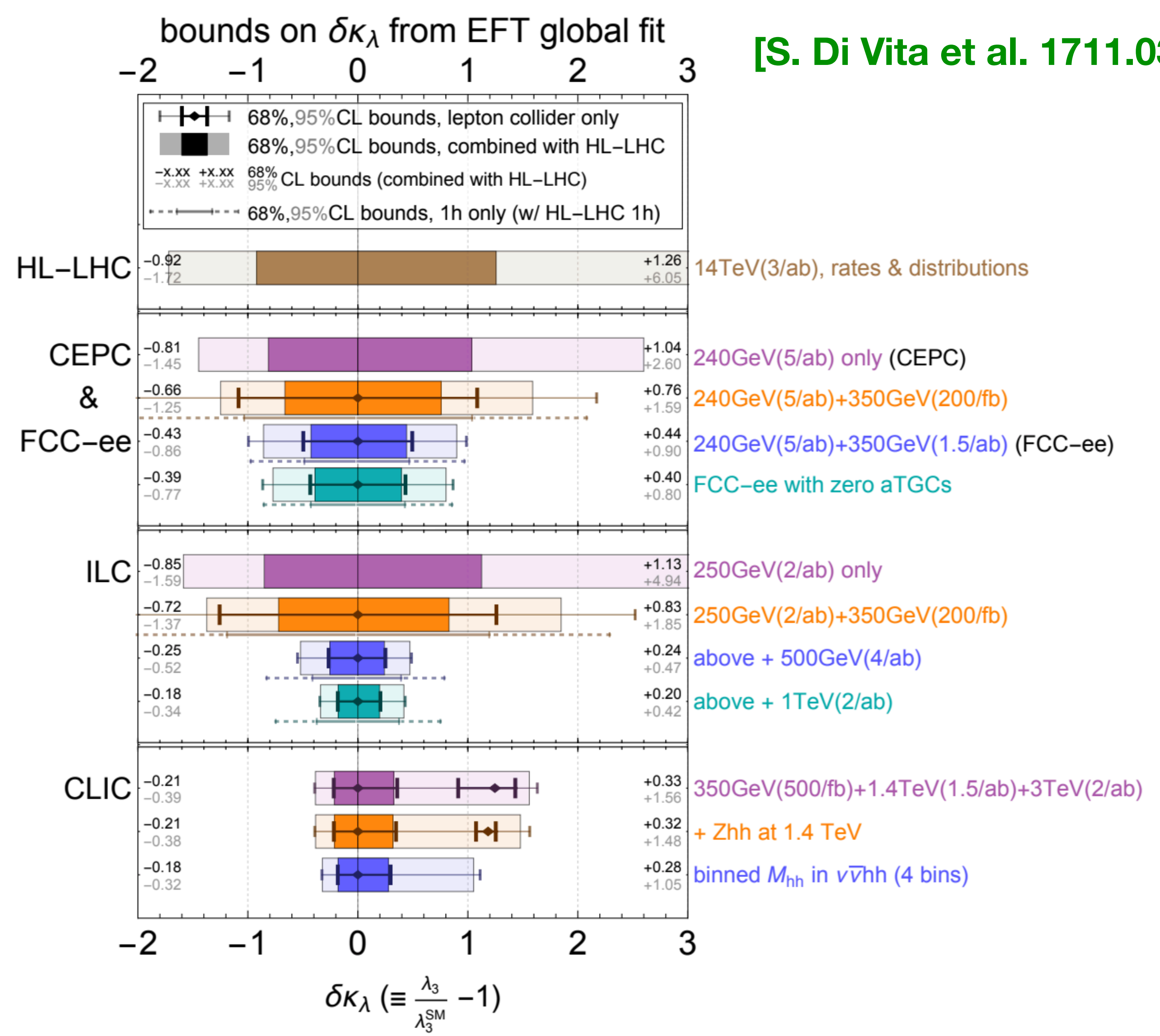


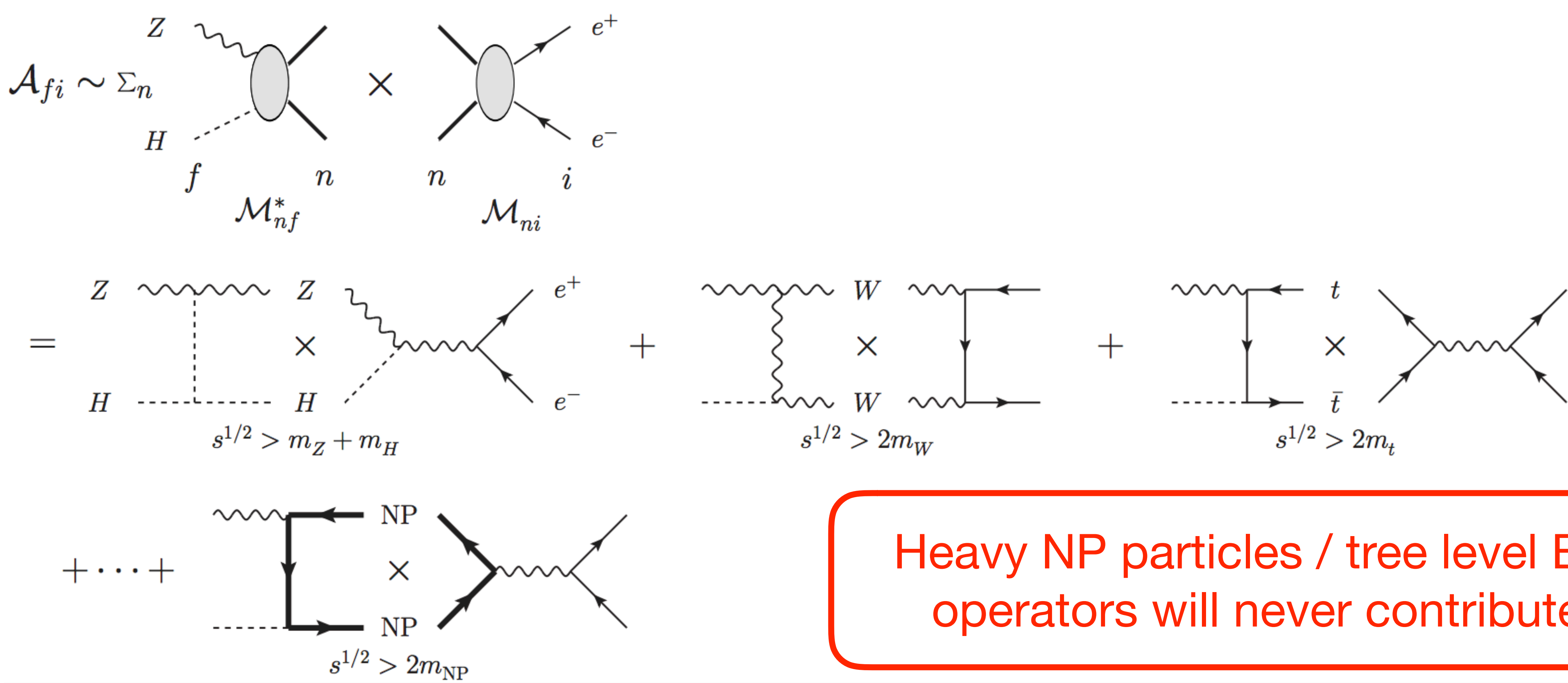
Figure 12: A summary of the bounds on $\delta\kappa_\lambda$ from global fits for various future collider scenarios. For the "1h only" scenario, only single Higgs measurements at lepton colliders are included.

Another solution: loops as “direct” probes

[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



Heavy NP particles / tree level EFT operators will never contribute!

Loops as “direct” probes

[J. Nakamura & A. Shivaji 1812.01576]

- **Consider Z(->ll) + H**

Under T transformation without interchanging the initial and final states,

$$\frac{d^3\sigma}{d\cos\Theta\, d\cos\theta\, d\phi} \to \underbrace{F_1(1+\cos^2\theta) + F_2(1-3\cos^2\theta) + F_3\sin 2\theta\cos\phi + F_4\sin^2\theta\cos 2\phi}_{\text{T-even}}$$

$$+ \underbrace{F_5\cos\theta + F_6\sin\theta\cos\phi}_{\text{T-even}} \underbrace{-F_7\sin\theta\sin\phi - F_8\sin 2\theta\sin\phi - F_9\sin^2\theta\sin 2\phi}_{\text{T-odd}},$$

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

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

8/11

Loops as "direct" probes

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Define T-odd asymmetries $(A_7, A_8, A\ldots$

$$A_{(7,8,9)} \equiv \frac{F_{(7,8,9)}}{F_1},$$

$N(\sin\phi > 0) + N(\sin\phi < 0)$

8/11

$$\begin{aligned}
\mathcal{J}(q^2,\theta_1,\theta_2,\phi) &= J_1(1+\cos^2\theta_1\cos^2\theta_2+\cos^2\theta_1+\cos^2\theta_2)\\
&+ J_2\sin^2\theta_1\sin^2\theta_2 + J_3\cos\theta_1\cos^2\theta_2\\
&+ (J_4\sin^2\theta_1\sin^2\theta_2 + J_5\sin 2\theta_1\sin 2\theta_2)\sin\phi\\
&+ (J_6\sin\theta_1\sin\theta_2 + J_7\sin 2\theta_1\sin 2\theta_2)\cos\phi\\
&+ J_8\sin^2\theta_1\sin^2\theta_2\sin 2\phi + J_9\sin^2\theta_1\sin^2\theta_2\cos 2\phi
\end{aligned}$$

See talk by Abdualazem Fadol

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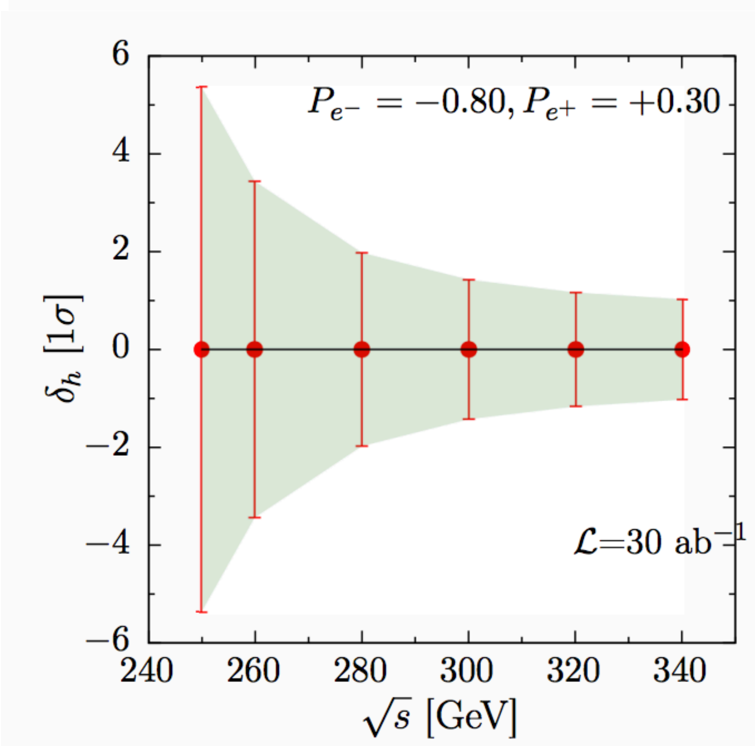
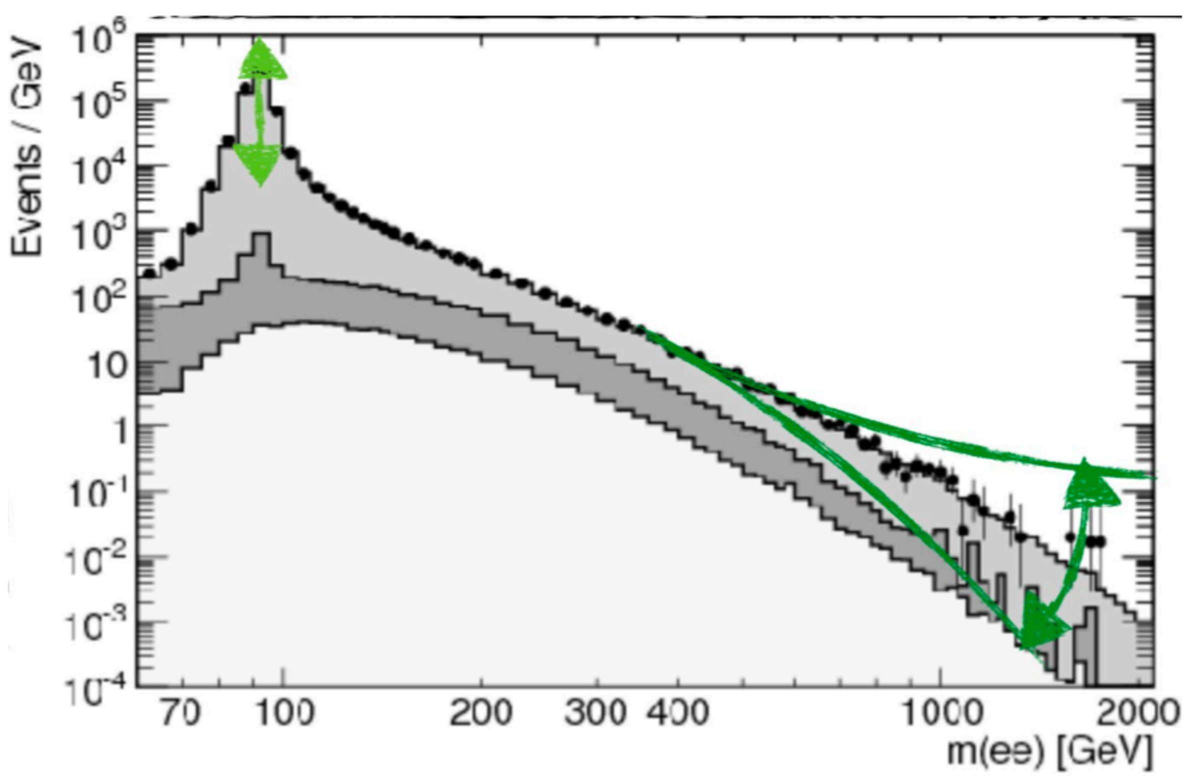


Difficult method, but

- Useful method to constrain HHH below 340
- Provide additional observable to isolate HHH from other couplings, should be added to a global H/EW fit
- May trigger other ideas in different channels

EW at large energy



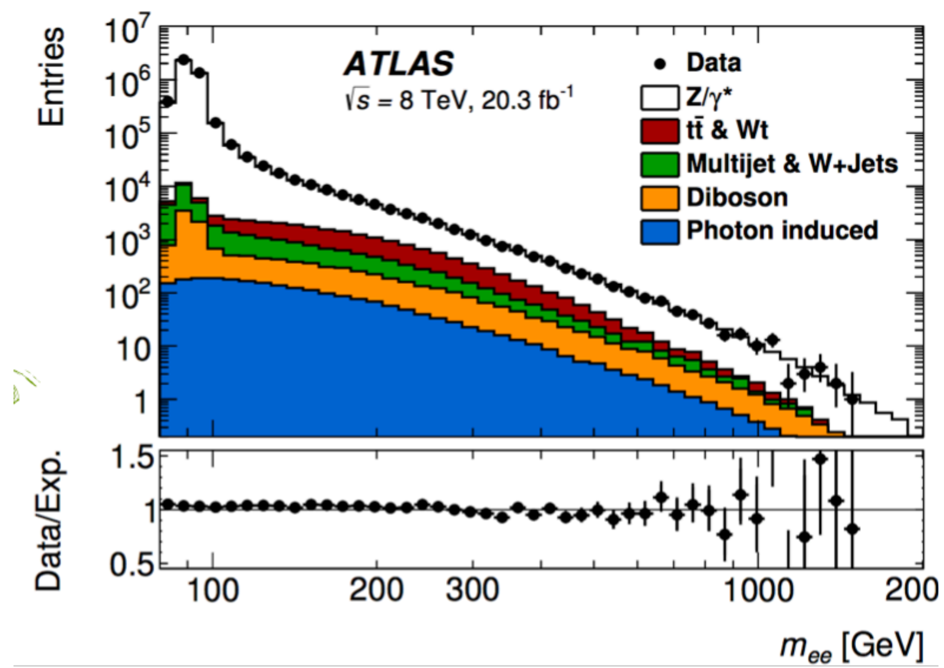
DY at the LHC

Drell-Yan ~5% precision, the quark couplings cannot compete with LEP

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

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

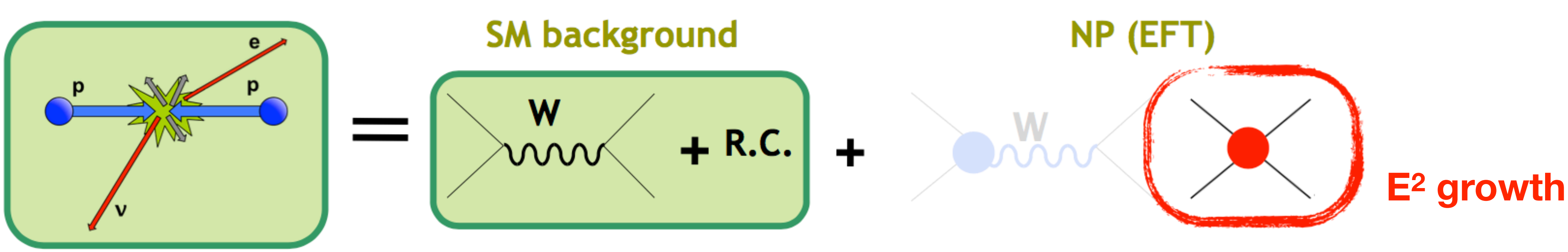
pp→e⁺e⁻



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

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

$$30\%\ \text{in}\ \delta\sigma \ \Rightarrow 0.3\%\ \text{in couplings}$$

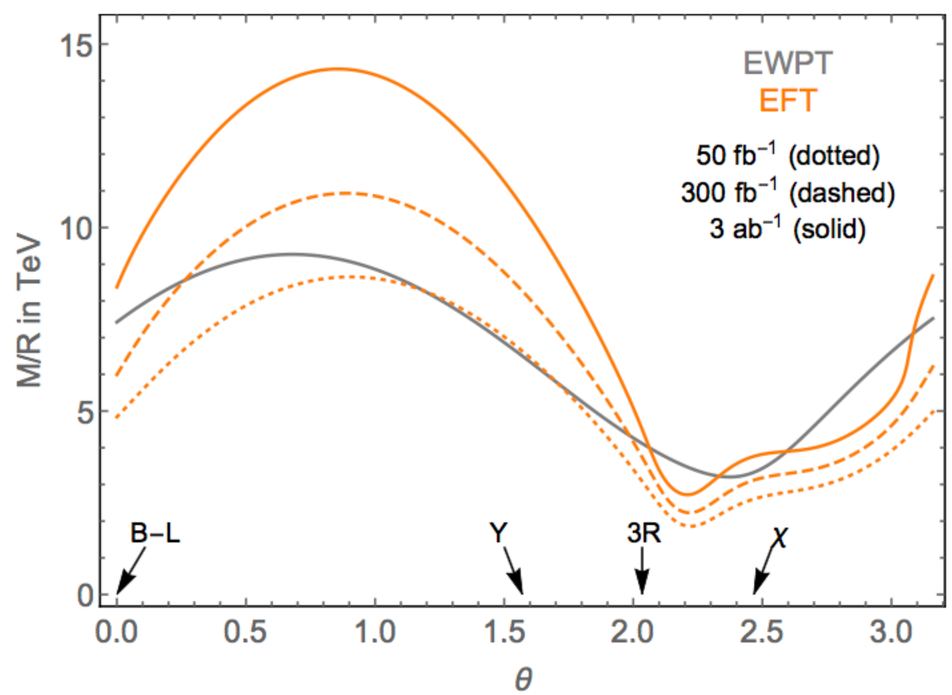


Talk by Martín González-Alonso, Moriond 18

DY at the LHC: LHC is now competing with PEWO

[S. Alioli et al., 1712.02347]

Z’ model



[Falkowski, González-Alonso, Mimouni 1706.03783]

SMEFT 4-f operators

$(ee)(qq)$

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

$(\mu\mu)(qq)$

	$[c^{(3)}_{\ell q}]_{2211}$	$[c_{\ell q}]_{2211}$	$[c_{\ell u}]_{2211}$	$[c_{\ell d}]_{2211}$	$[c_{eq}]_{2211}$	$[c_{eu}]_{2211}$	$[c_{ed}]_{2211}$
Low-energy	-0.2 ± 1.2	4 ± 21	18 ± 19	-20 ± 37	40 ± 390	-20 ± 190	40 ± 390
$\mathrm{LHC}_{1.5}$	$-1.22^{+0.62}_{-0.70}$	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
$\mathrm{LHC}_{1.0}$	$-0.72^{+0.81}_{-0.87}$	$3.2^{+4.0}_{-3.5}$	$3.9^{+4.8}_{-4.4}$	$-2.3^{+4.9}_{-4.7}$	$2.3^{+3.1}_{-3.2}$	$1.6^{+2.3}_{-1.8}$	-4.4 ± 5.3
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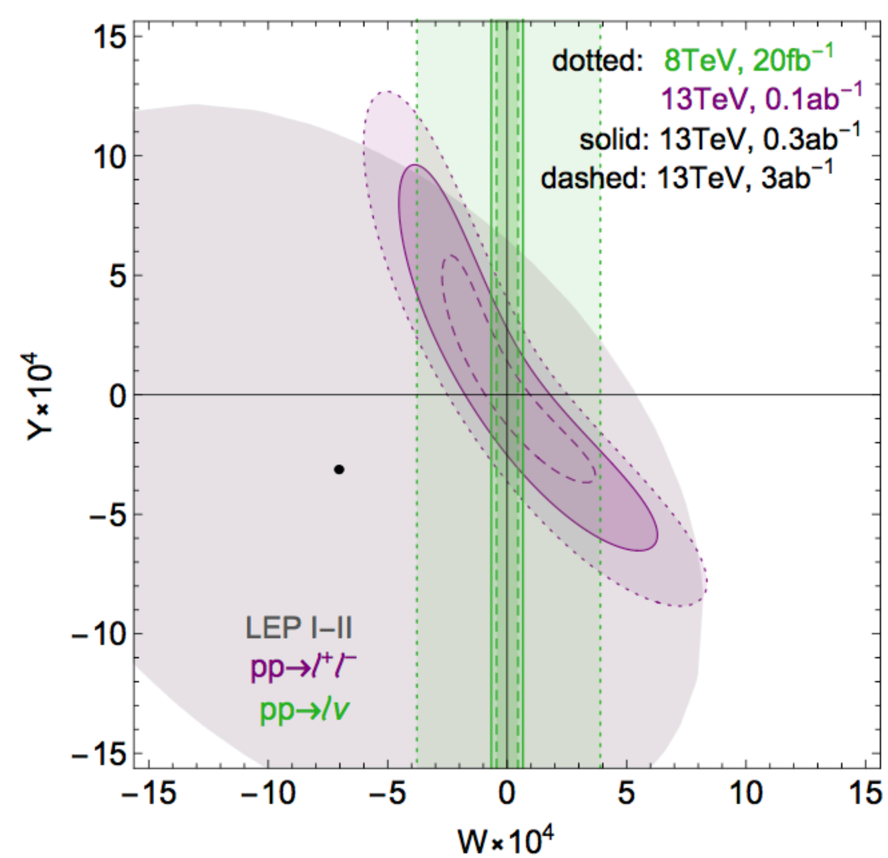
[M. Farina et al. 1609.08157]

Oblique parameters W and Y

	universal form factor ($\mathcal{L}$)	contact operator ($\mathcal{L}'$)
W	$-\frac{\mathrm{W}}{4m_W^2}(D_\rho W^a_{\mu\nu})^2$	$-\frac{g_2^2 \mathrm{W}}{2m_W^2} J_L{}^a_\mu J_L{}^\mu_a$
Y	$-\frac{\mathrm{Y}}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$	$-\frac{g_1^2 \mathrm{Y}}{2m_W^2} J_Y{}_\mu J_Y{}^\mu$



DY at the LHC: LHC is now competing with PEWO

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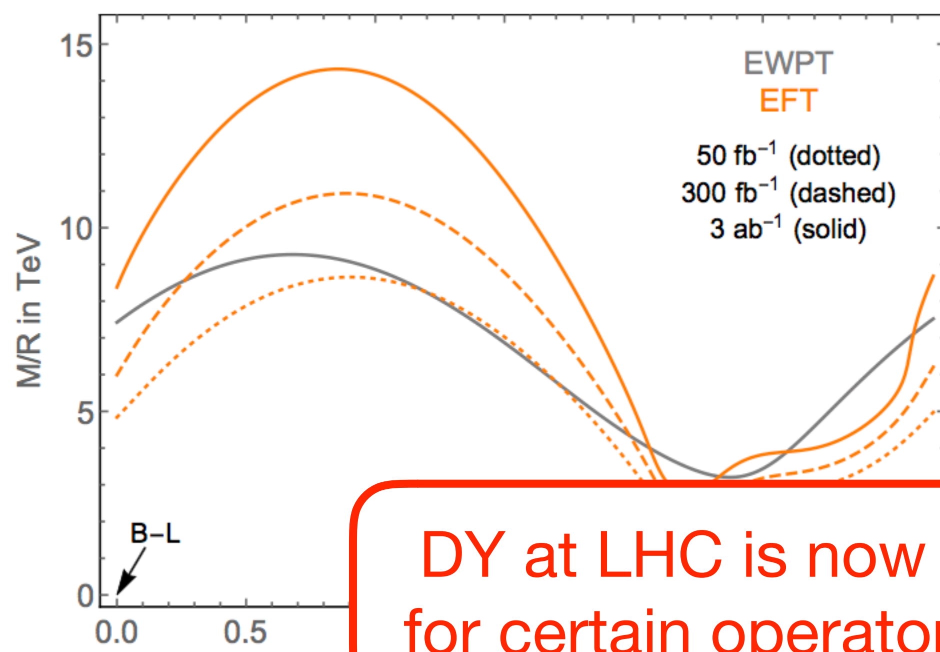

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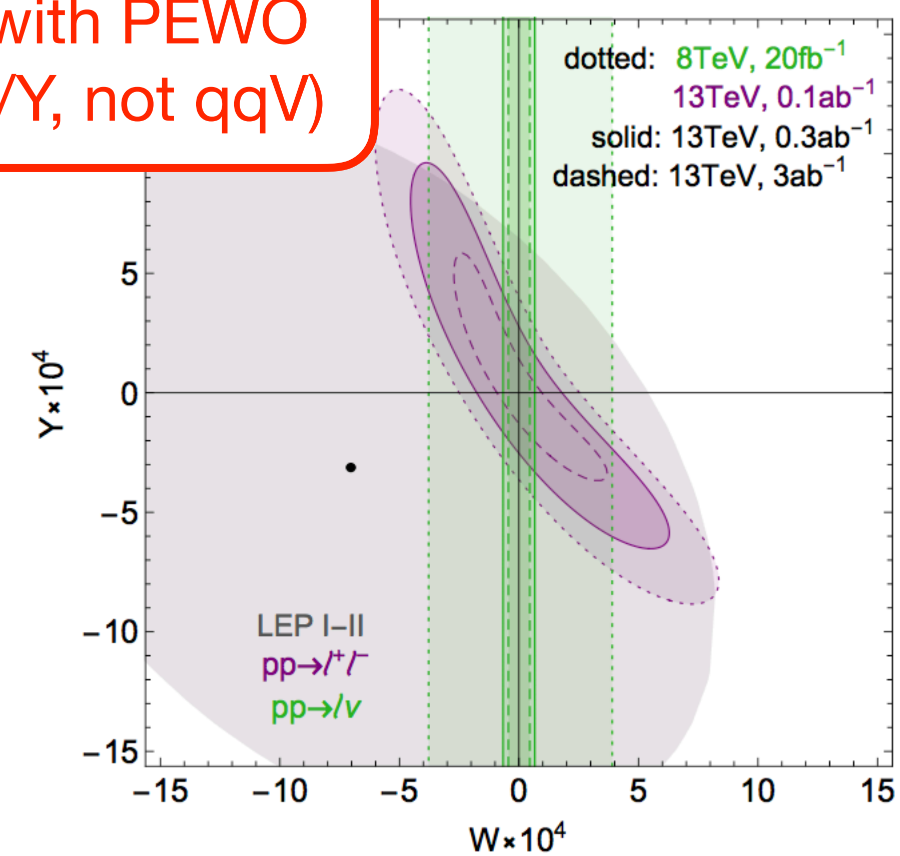
DY at LHC is now competing with PEWO
for certain operators (4f and W/Y, not qqV)



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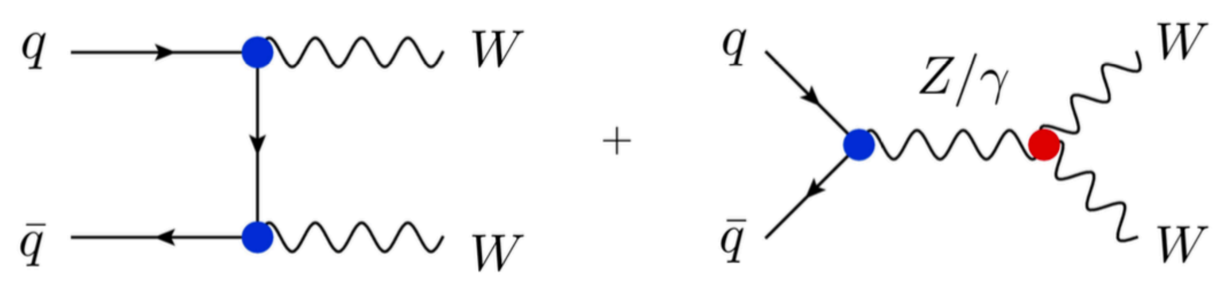
Diboson at the LHC

The most constraining limits on quark EW couplings are given by diboson at LHC, instead of DY



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

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

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

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

- The quark couplings are well constrained by LEP. Lets focus on TGC…
- The LEP constraints on δg_L^Z are not strong enough to make them negligible…

[Z. Zhang 1610.01618]

- In fact, at large energy, WW/WZ/WH/ZH give the best bounds on $\delta g_L^{Zu},\ \delta g_R^{Zu},\ \delta g_L^{Zd},\ \delta g_R^{Zd}$

“High Energy Primaries”

[R. Franceschini et al. 1712.01310]

- The E^2-growth piece that interferes with the SM can only come from the longitudinal amplitude
- The high energy behavior of $qq > V_L V_L$, $V_L H$ are related
- They determined only by 4 parameters

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

Non-interference of transversal V

[A. Azatov et al. 1607.05236]

Amplitude	High-energy primaries	Low-energy primaries
$\bar{u}_L d_L \to W_L Z_L, W_L h$	$\sqrt{2} a_q^{(3)}$	$\sqrt{2}\frac{g^2}{m_W^2}\left[c_{\theta_W}(\delta g_{uL}^Z - \delta g_{dL}^Z)/g - c_{\theta_W}^2 \delta g_1^Z\right]$
$\bar{u}_L u_L \to W_L W_L$ $\bar{d}_L d_L \to Z_L h$	$a_q^{(1)} + a_q^{(3)}$	$-\frac{2g^2}{m_W^2}\left[Y_L t_{\theta_W}^2 \delta\kappa_\gamma + T_Z^{u_L}\delta g_1^Z + c_{\theta_W}\delta g_{dL}^Z/g\right]$
$\bar{d}_L d_L \to W_L W_L$ $\bar{u}_L u_L \to Z_L h$	$a_q^{(1)} - a_q^{(3)}$	$-\frac{2g^2}{m_W^2}\left[Y_L t_{\theta_W}^2 \delta\kappa_\gamma + T_Z^{d_L}\delta g_1^Z + c_{\theta_W}\delta g_{uL}^Z/g\right]$
$\bar{f}_R f_R \to W_L W_L, Z_L h$	a_f	$-\frac{2g^2}{m_W^2}\left[Y_{f_R} t_{\theta_W}^2 \delta\kappa_\gamma + T_Z^{f_R}\delta g_1^Z + c_{\theta_W}\delta g_{fR}^Z/g\right]$

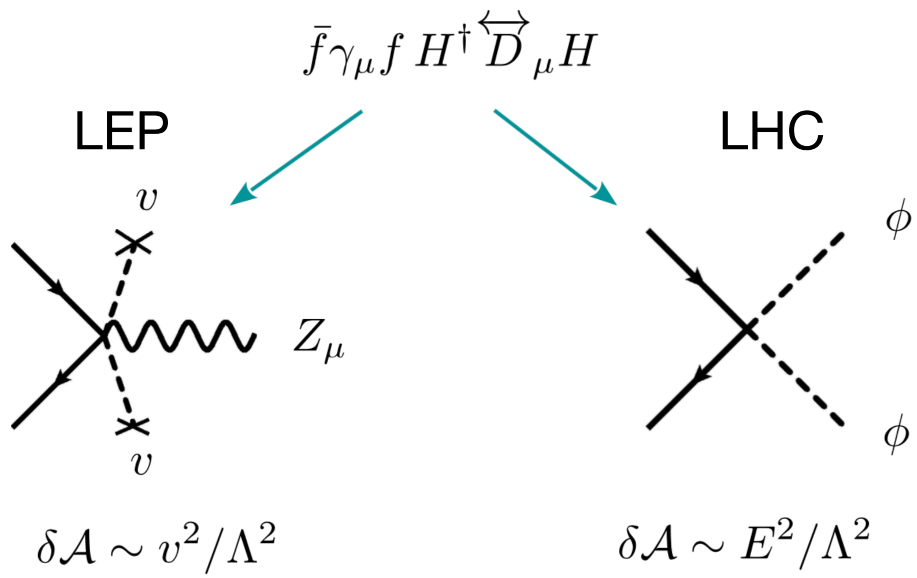
Warsaw Basis

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

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

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

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



“High Energy Primaries”

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

Leptonic WZ and Zh(->bb), W,Y<<1

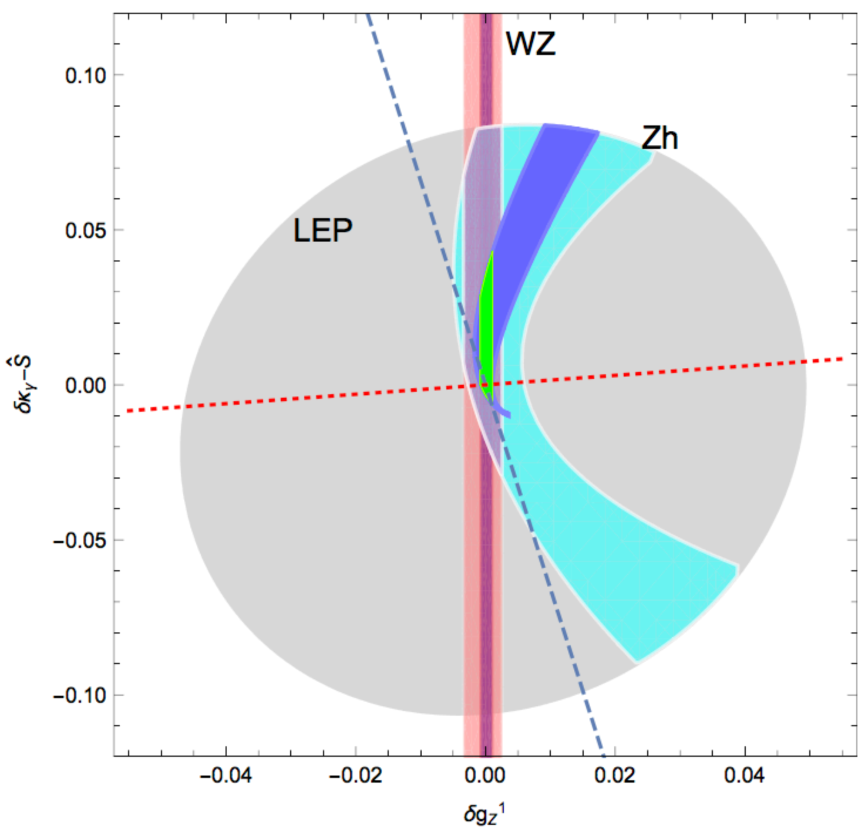
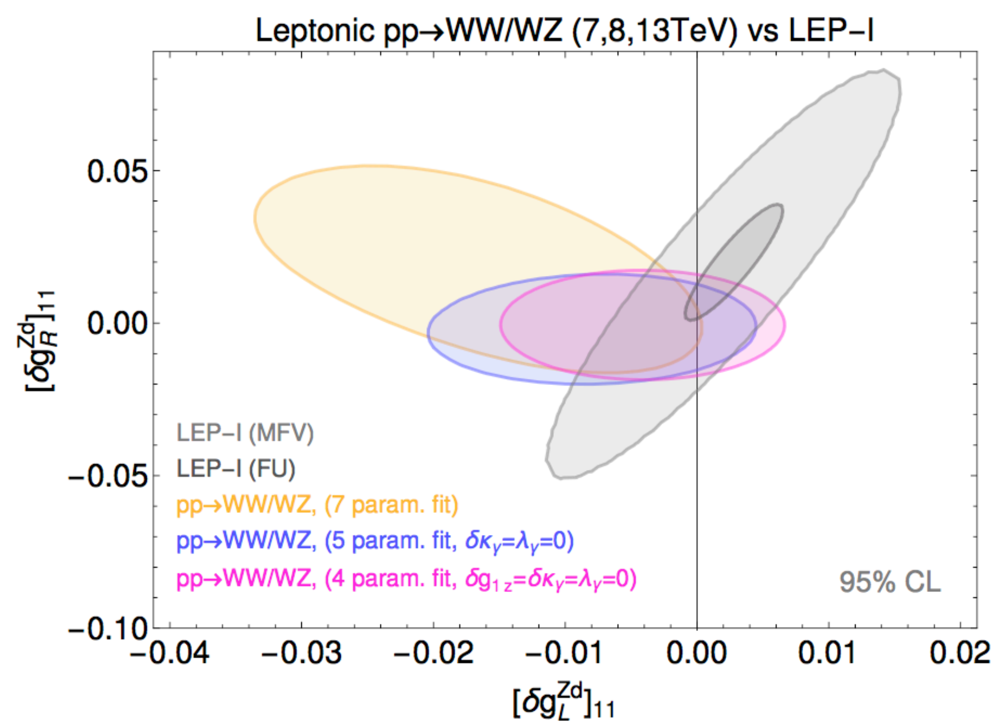
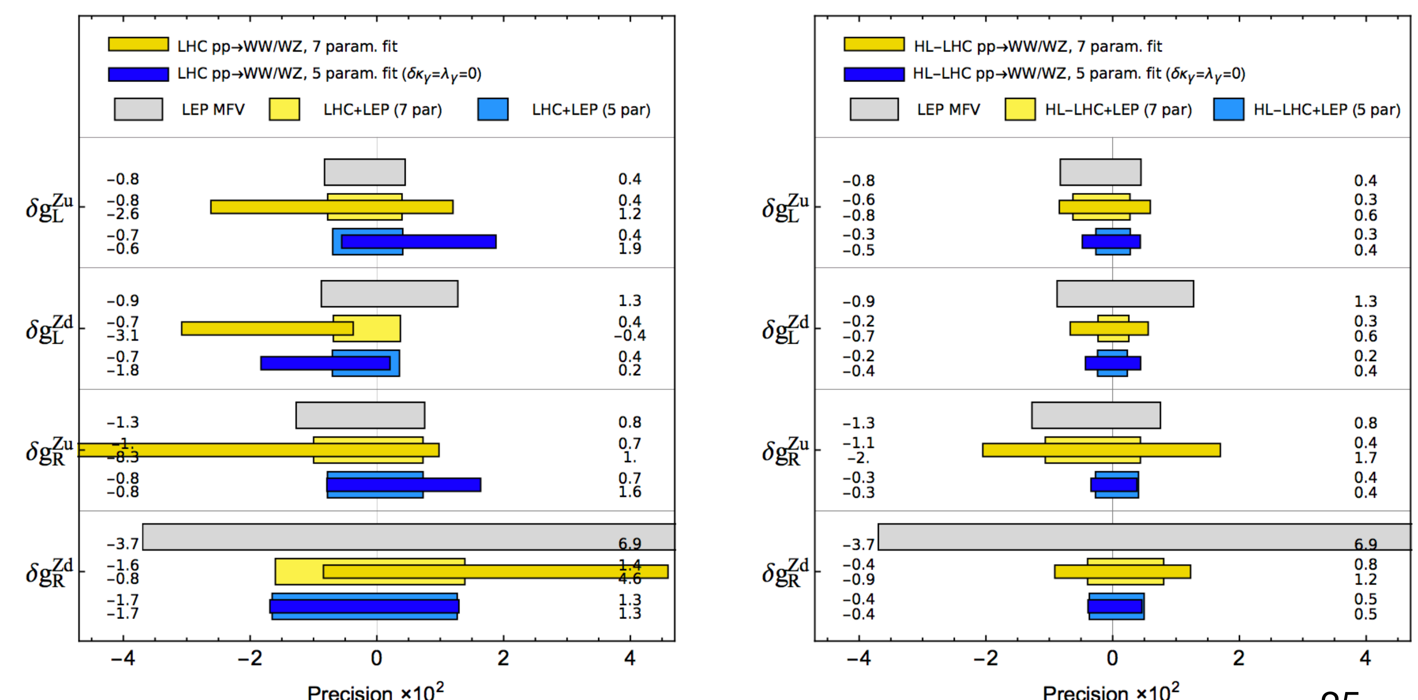


FIG. 2: We show in light blue (dark blue) the projection for the allowed region with 300 fb^{-1} (3 ab^{-1}) data from the $pp \to Zh$ process for universal models in the $\delta\kappa_\gamma - \hat{S}$ vs δg_1^Z plane. The allowed region after LEP bounds (taking the TGC $\lambda_\gamma = 0$, a conservative 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 Zh process is combined with the above WZ projections with 300 fb^{-1} (3 ab^{-1}) data.





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

Leptonic WZ and Zh(->bb), W,Y<<1

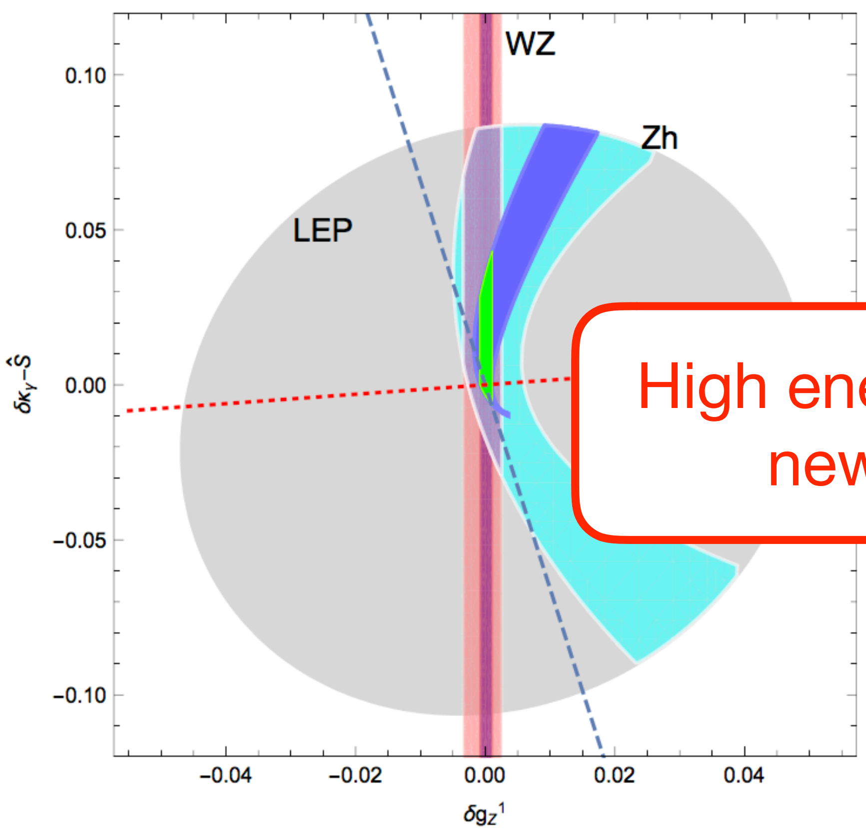
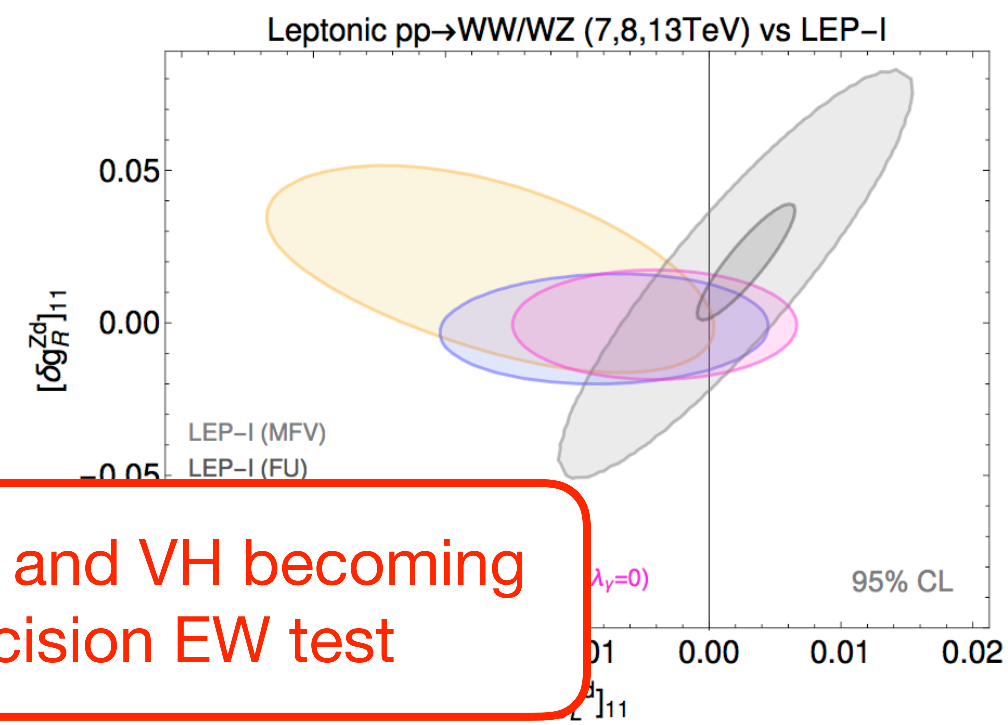
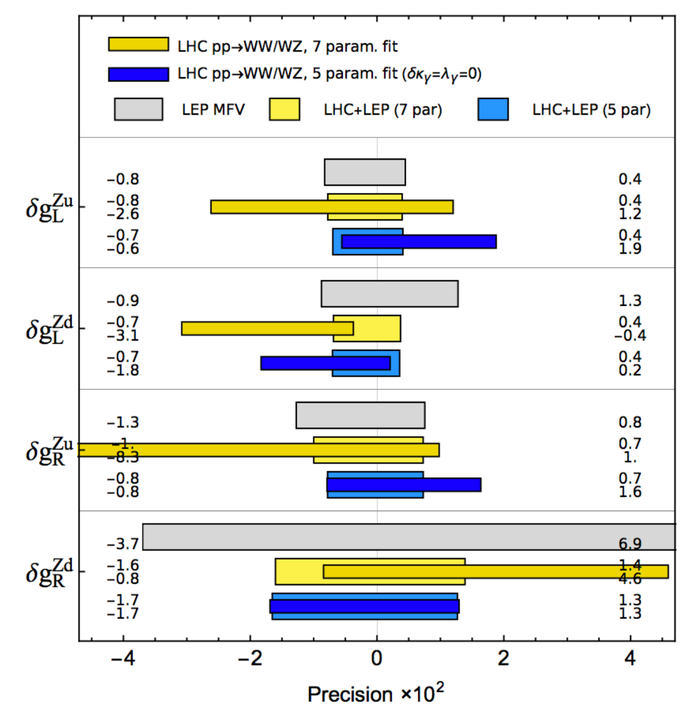
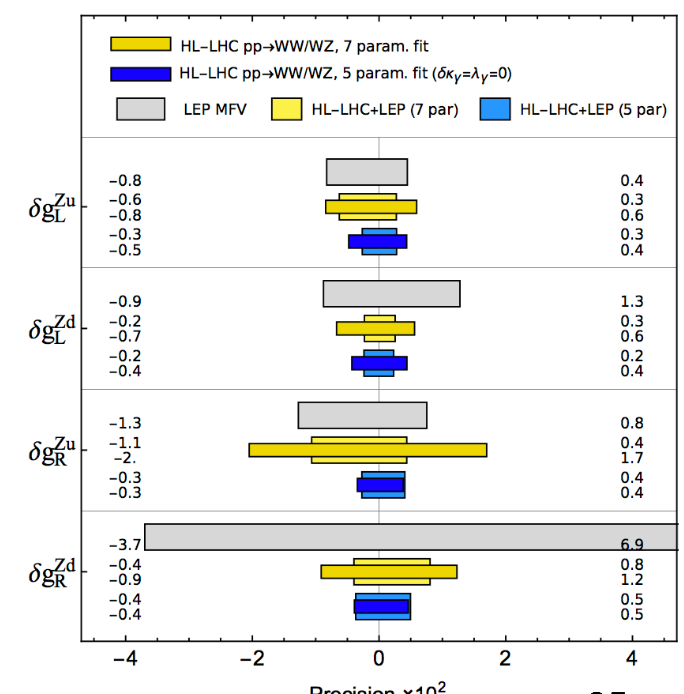


FIG. 2: We show in light blue (dark blue) the projection for the allowed region with 300 fb^{-1} (3 ab^{-1}) data from the $pp \to Zh$ process for universal models in the $\delta\kappa_\gamma - \hat{S}$ vs δg_1^Z plane. The allowed region after LEP bounds (taking the TGC $\lambda_\gamma = 0$, a conservative 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 Zh process is combined with the above WZ projections with 300 fb^{-1} (3 ab^{-1}) data.



High energy diboson and VH becoming new tools in precision EW test



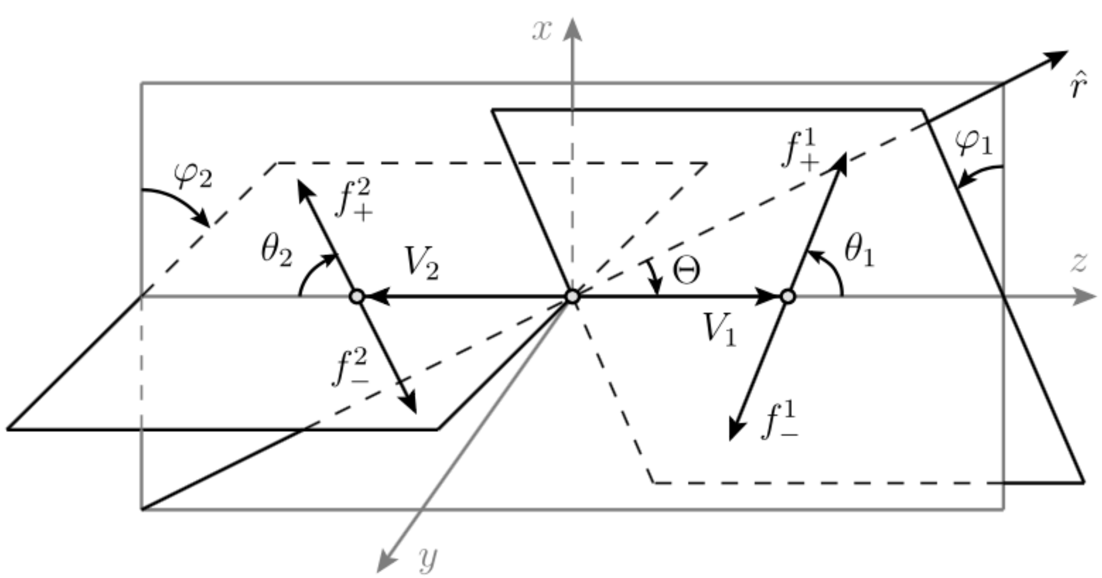


Interference resurrection

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

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

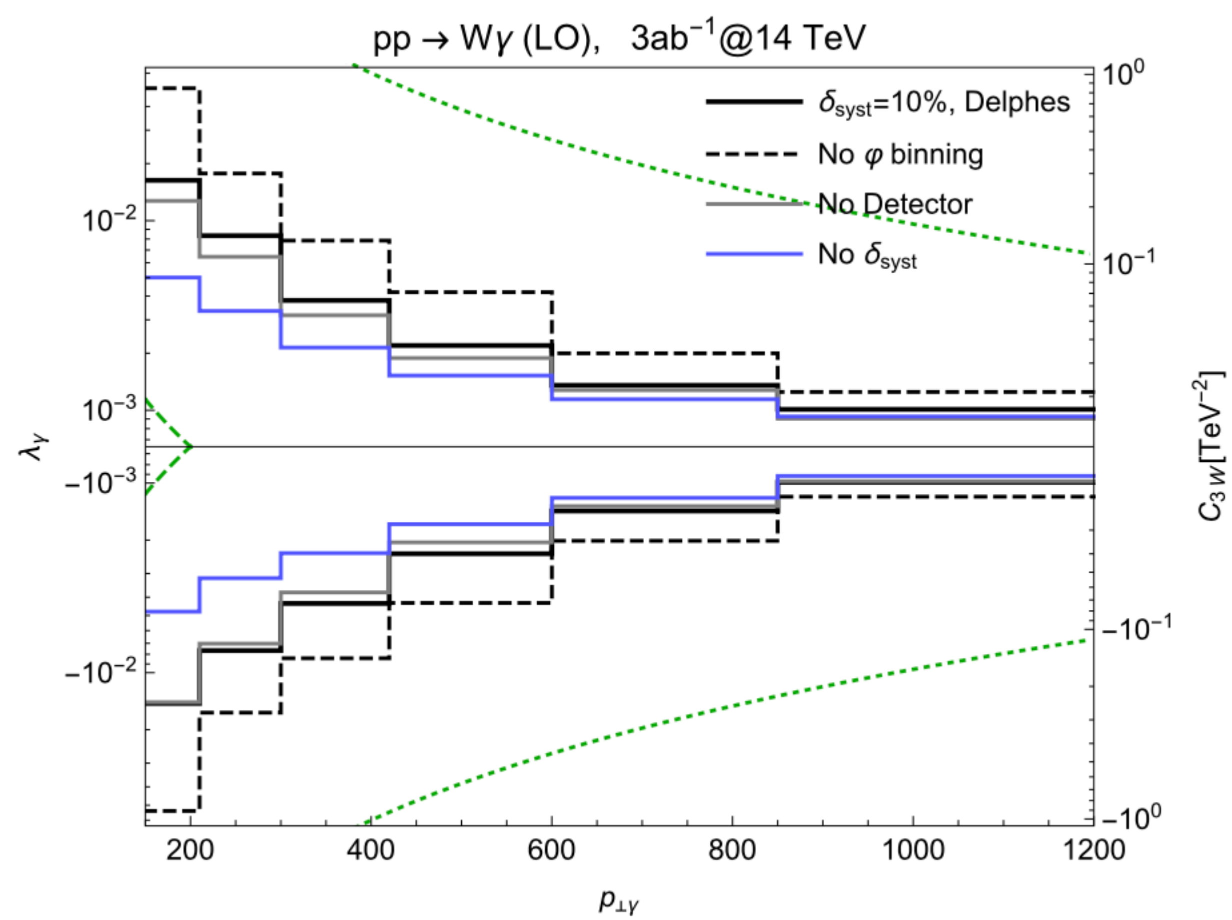
Interfering the V with different helicities will recover the E² energy growth



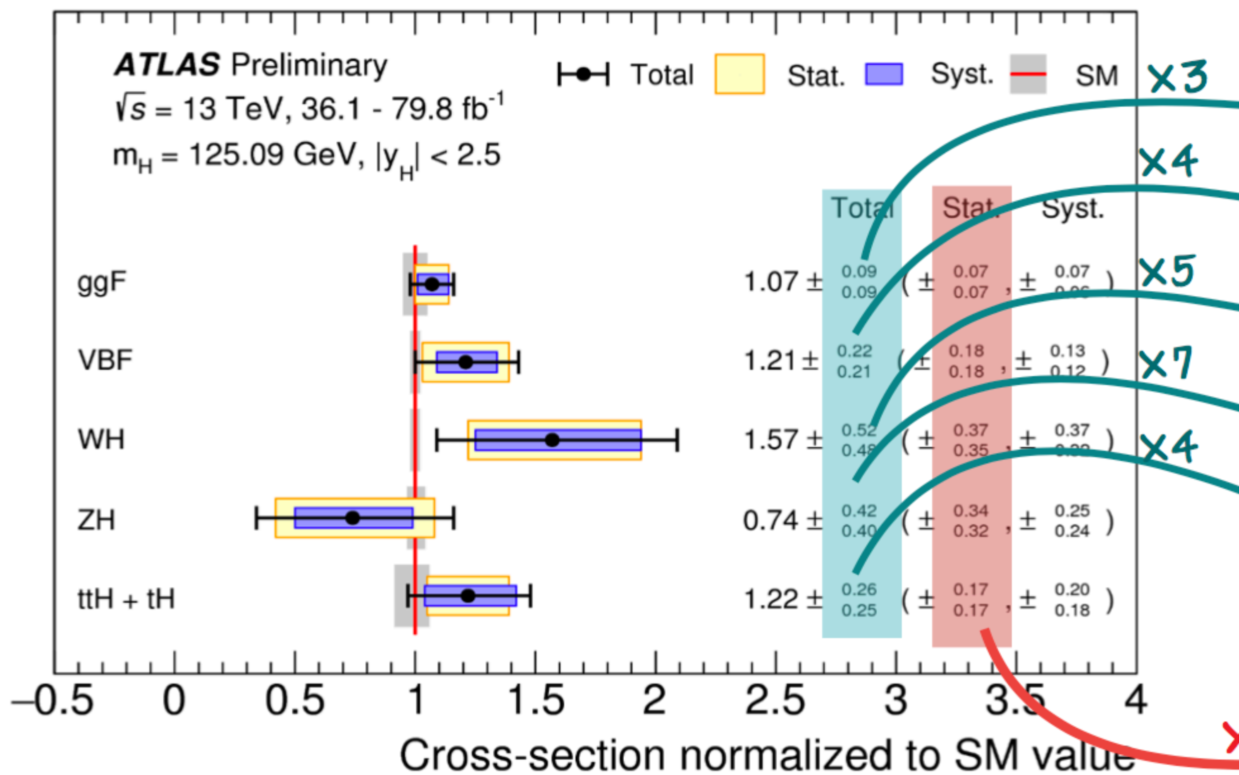
$$\mathbf{h} = (h_1, h_2) \qquad \boldsymbol{\varphi} = (\varphi_1, \varphi_2)$$

$$I^{V_1V_2}_{\mathbf{h}\otimes\mathbf{h}'} = T^{V_1V_2}_{\mathbf{h}\mathbf{h}'}\left[\mathcal{A}^{\rm SM}_{\mathbf{h}}\mathcal{A}^{\rm BSM+}_{\mathbf{h}'} + \mathcal{A}^{\rm BSM+}_{\mathbf{h}}\mathcal{A}^{\rm SM}_{\mathbf{h}'}\right]\cos\left[\boldsymbol{\Delta}\mathbf{h}\cdot\boldsymbol{\varphi}\right],$$

$$I^{V_1V_2}_{\mathbf{h}\otimes\mathbf{h}'} = iT^{V_1V_2}_{\mathbf{h}\mathbf{h}'}\left[\mathcal{A}^{\rm SM}_{\mathbf{h}}\mathcal{A}^{\rm BSM-}_{\mathbf{h}'} - \mathcal{A}^{\rm BSM-}_{\mathbf{h}}\mathcal{A}^{\rm SM}_{\mathbf{h}'}\right]\sin\left[\boldsymbol{\Delta}\mathbf{h}\cdot\boldsymbol{\varphi}\right],$$



Higgs at high energy: off shell measurements



HL-LHC projections:

		ATLAS				
		3000 fb^{-1} uncertainty [%]				
		Total	Stat	Exp	SigTh	BkgTh
σ_{ggH}	S1	3.5	0.8	2.1	2.1	1.6
	S2	2.4	0.8	1.7	1.2	1.0
σ_{VBF}	S1	5.5	2.0	2.7	3.7	2.1
	S2	4.2	2.0	2.3	2.2	1.7
σ_{WH}	S1	9.3	4.0	4.0	5.1	5.4
	S2	7.7	4.0	3.4	3.3	4.5
σ_{ZH}	S1	6.2	3.4	2.4	3.4	3.0
	S2	4.8	3.4	1.8	2.0	2.1
σ_{ttH}	S1	6.7	1.9	3.1	3.7	4.3
	S2	5.3	1.9	2.8	2.4	3.3

On shell Higgs measurements will be saturated by systematics.

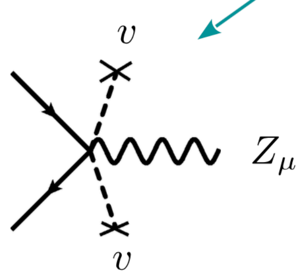
Will not benefit from either
1) higher luminosity
2) higher energy

Off shell Higgs measurements are the opposite:

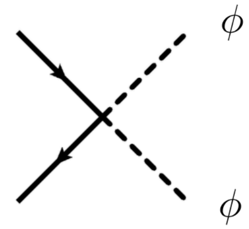
1) limited by statistics
2) Benefit from higher-energy colliders, HE-LHC/CLIC/SppC

The same logic that applied to diboson also apply here

$\bar{f}\gamma_\mu f\, H^\dagger \overleftrightarrow{D}_\mu H$



$\delta\mathcal{A} \sim v^2/\Lambda^2$

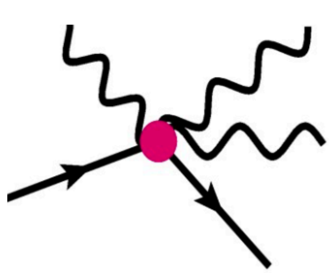


$\delta\mathcal{A} \sim E^2/\Lambda^2$

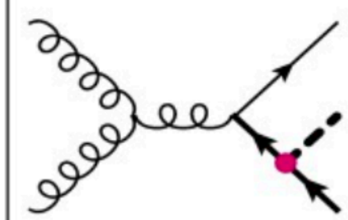
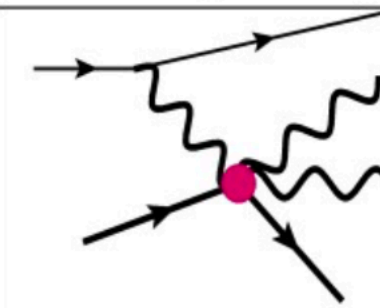
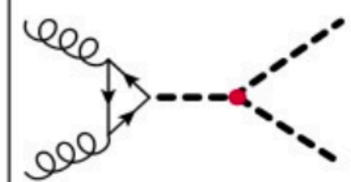
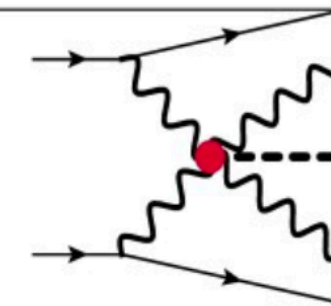
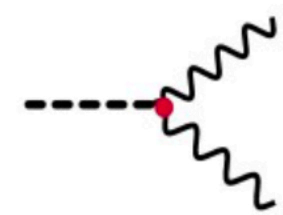
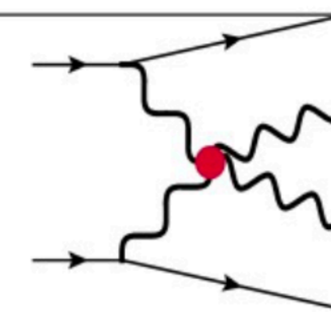
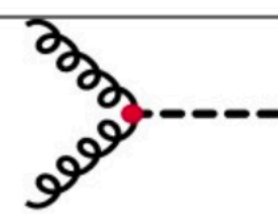
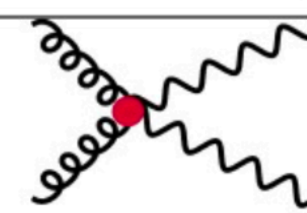
$\delta\mathcal{A}/\mathcal{A} \sim v^2/\Lambda^2$

$|H|^2 \bar{f}_L H f_R$

unanchor the Higgs from its vev

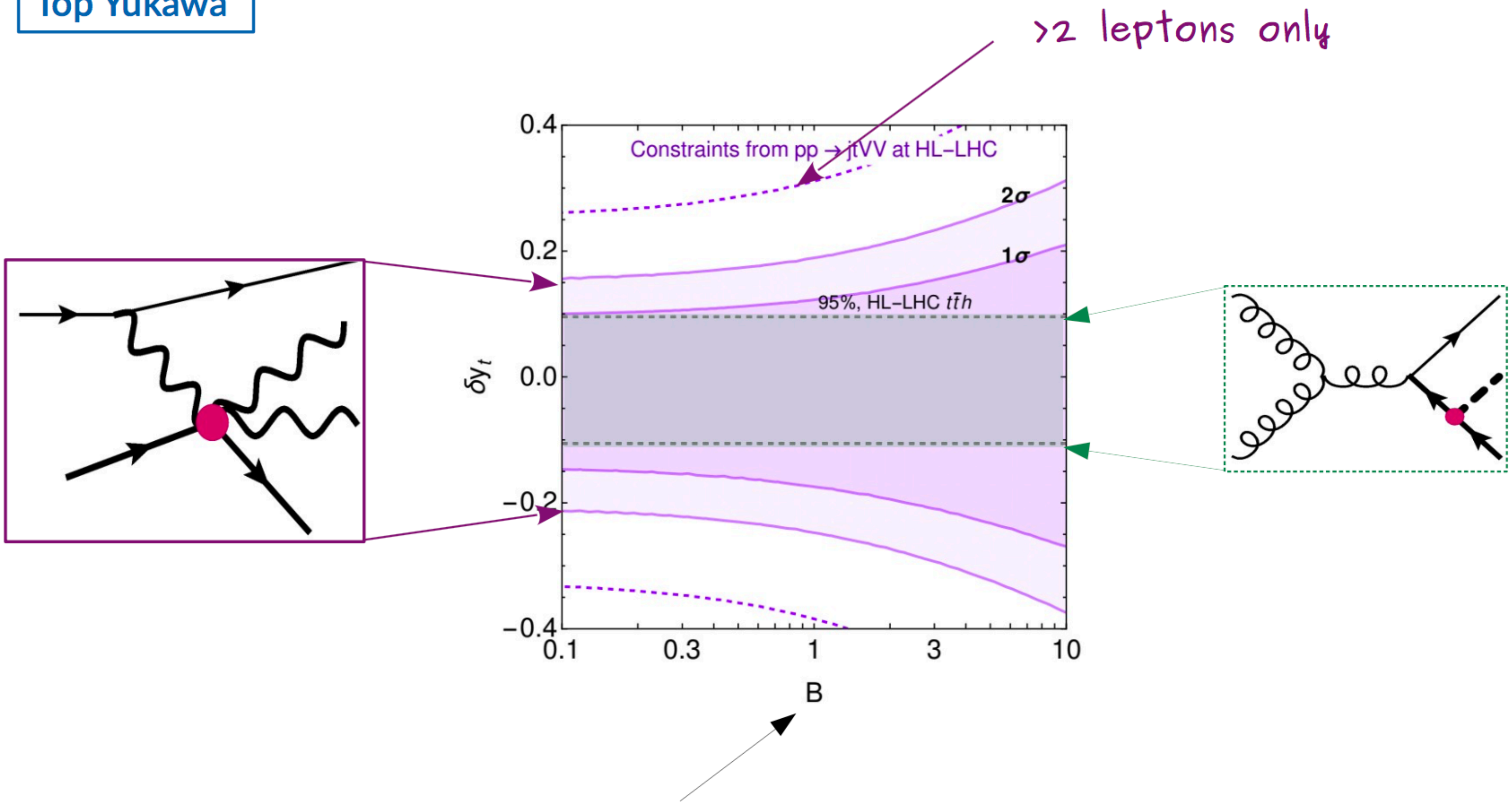


$\delta\mathcal{A}/\mathcal{A} \sim E^2/\Lambda^2$

		HC	HwH	Growth
κ_t	$\mathcal{O}_{y_t}$			$\sim \frac{E^2}{\Lambda^2}$
κ_λ	$\mathcal{O}_6$			$\sim \frac{vE}{\Lambda^2}$
$\kappa_{Z\gamma}$ $\kappa_{\gamma\gamma}$ κ_V	$\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$ $\mathcal{O}_r$			$\sim \frac{E^2}{\Lambda^2}$
κ_g	$\mathcal{O}_{gg}$			$\sim \frac{E^2}{\Lambda^2}$

[Henning, Lombardo, Riembau, Riva 1812.09299]

Top Yukawa



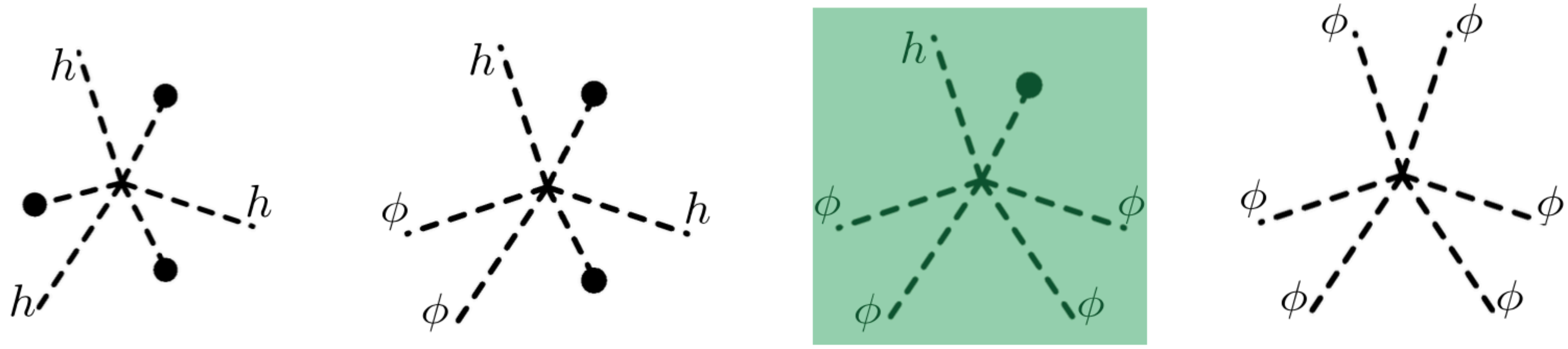
Again, we parametrize background with B x signal

Competitive with on-shell Higgs measurements

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

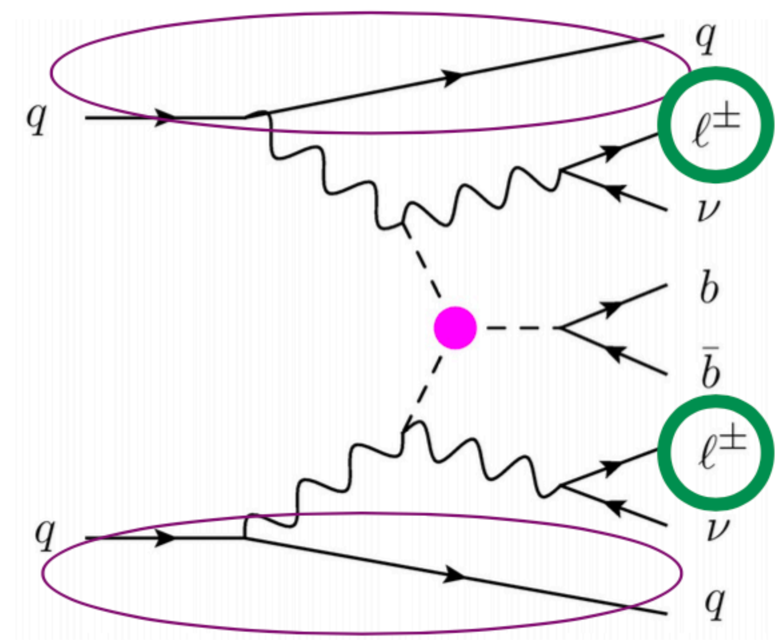
Higgs self-coupling

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



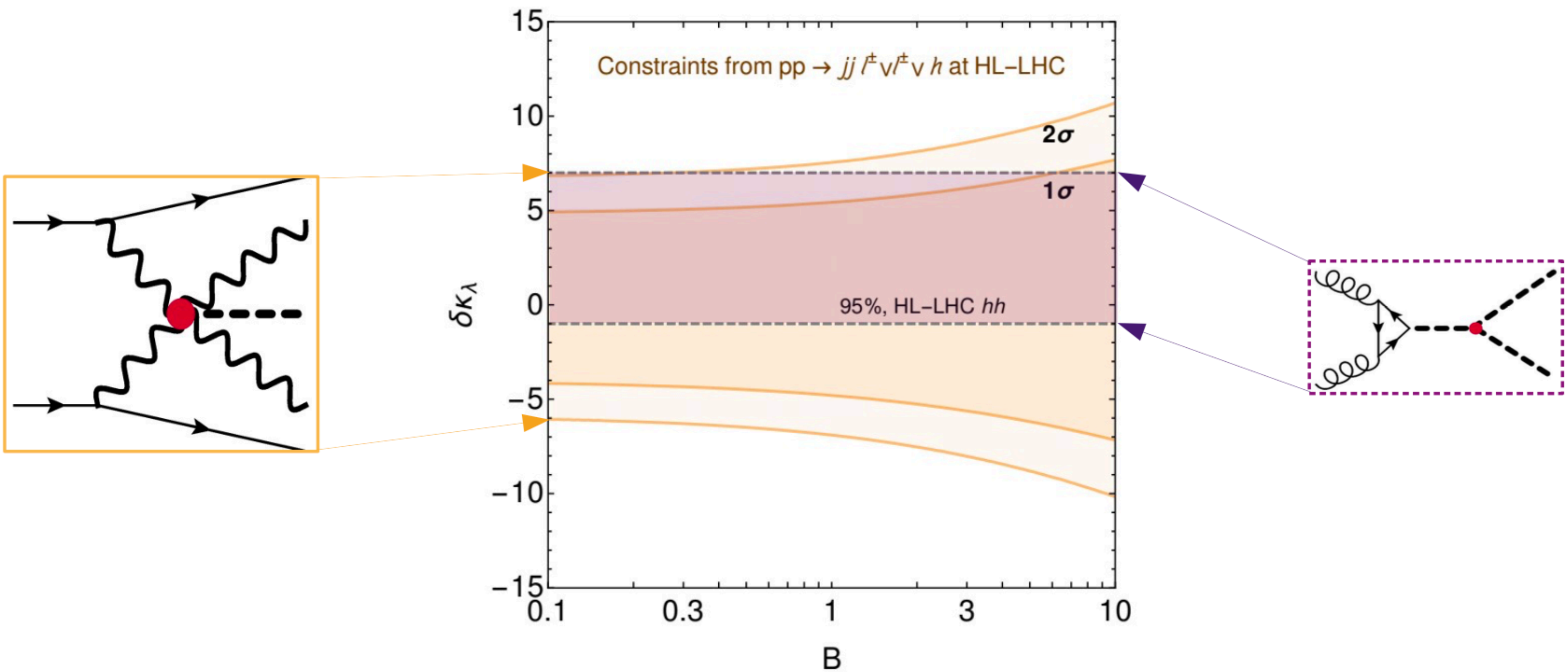
Signal enhanced only with a single power of energy,
but extremelly attractive and clean process experimentally!

VBF topology



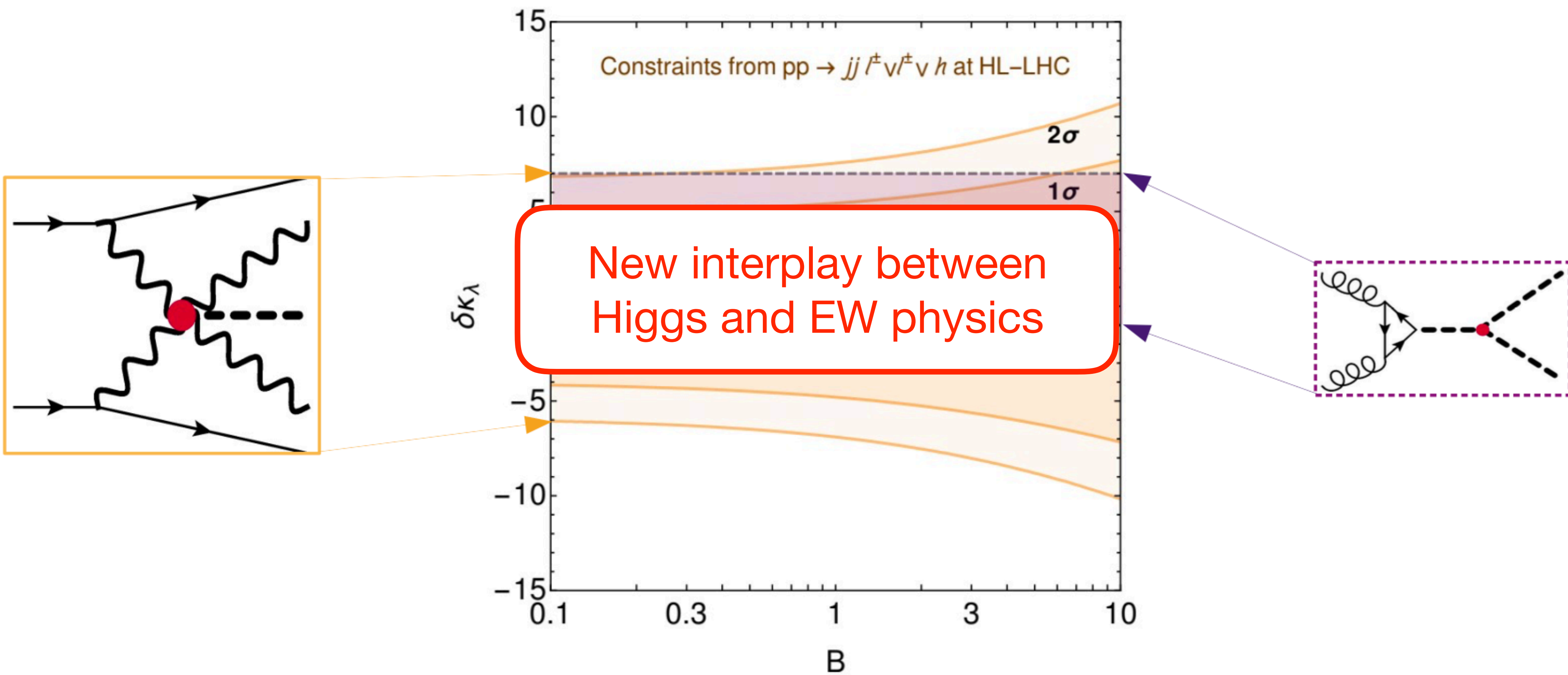
Same sign leptons!

Higgs self-coupling



- 50-ish events in the SM
- Irreducible background negligible
- Background from ttjj with lepton misidentification under control
- Backgorund from fake leptons is potentially the dominant one.
  We parametrize it with #back = B x #signal.
- Rough cut-and-count analysis gives competitive results with double higgs production

Higgs self-coupling



- 50-ish events in the SM
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Talk by M. Riembau

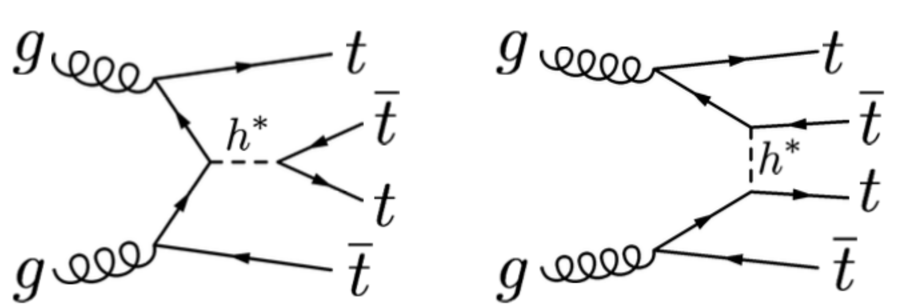
A different off-shell perspective: the oblique H parameter

[Englert, Giudice, Greljo, McCullough 1903.07725]

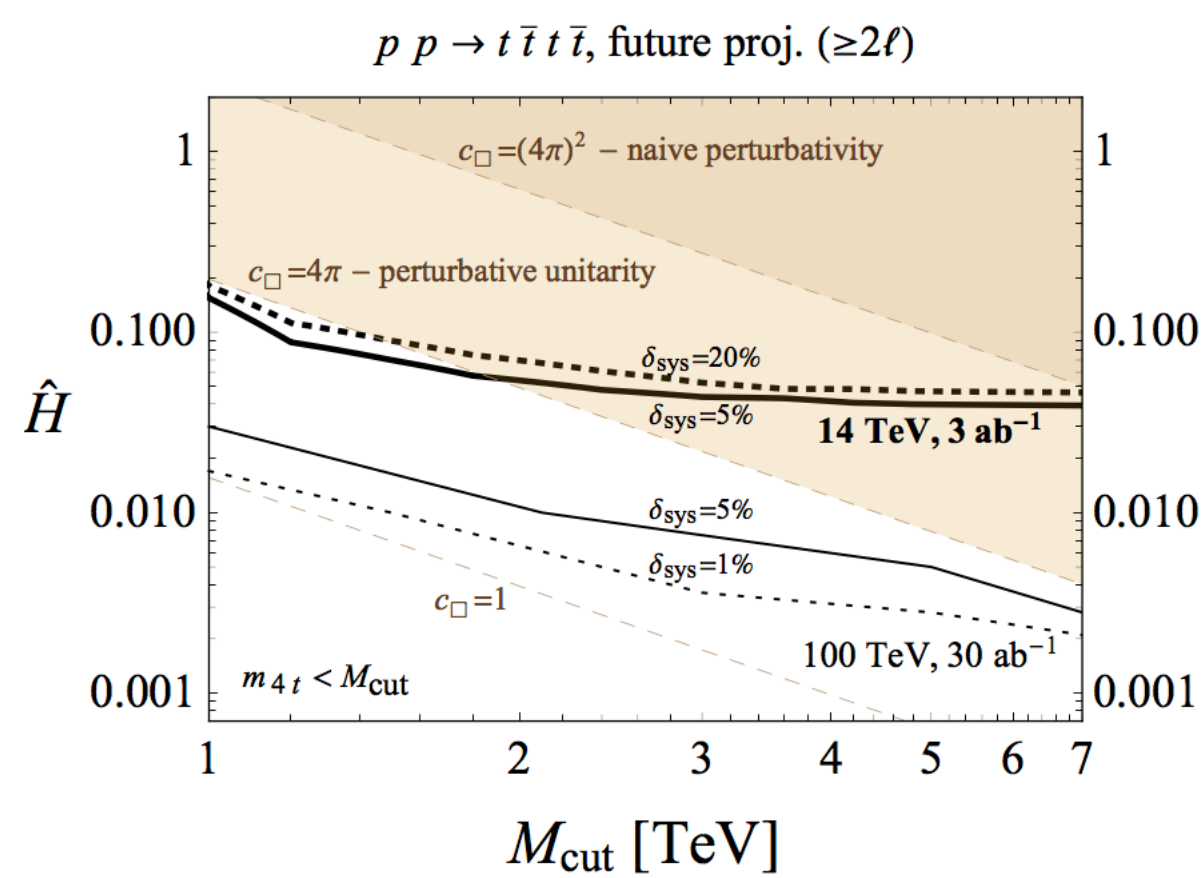
In universal theories, the $\mathcal{O}(q^4)$ terms in EW boson self-energy can be parametrized by

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

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



Top measurements revealing the off-shell propagation of the H



Summary

- Precision loop measurements:
  - **Top couplings** can be measured via loops in EW observables and in Higgs factory. **Complementary with direct top measurement**.
  - **Higgs self couplings** enters EWPO at two loop, and Higgs production at one-loop. **Complementary to di-Higgs at LHC**.
    - **The Naive T-odd observable** makes the indirect measurement direct.
- Use large energy to amplify BSM and to improve precision:
  - Drell-Yan: **4-fermion / W,Y. Complementary with LEP 1&2**
  - Diboson: **"High energy primaries" / quark EW couplings. Complementary with LEP Z-pole.**
    - **Diboson interference resurrection:** more energy dependence.
  - Off shell Higgs: **all Higgs couplings with the form HH*dim4. Complementary to standard HC measurements**.
- Need a real global fit, with the above implemented, to assess the physical improvements.

Backups

Top

LHC Drell-Yan

Higgs off shell (VVH,VVt...)

Higgs on-shell

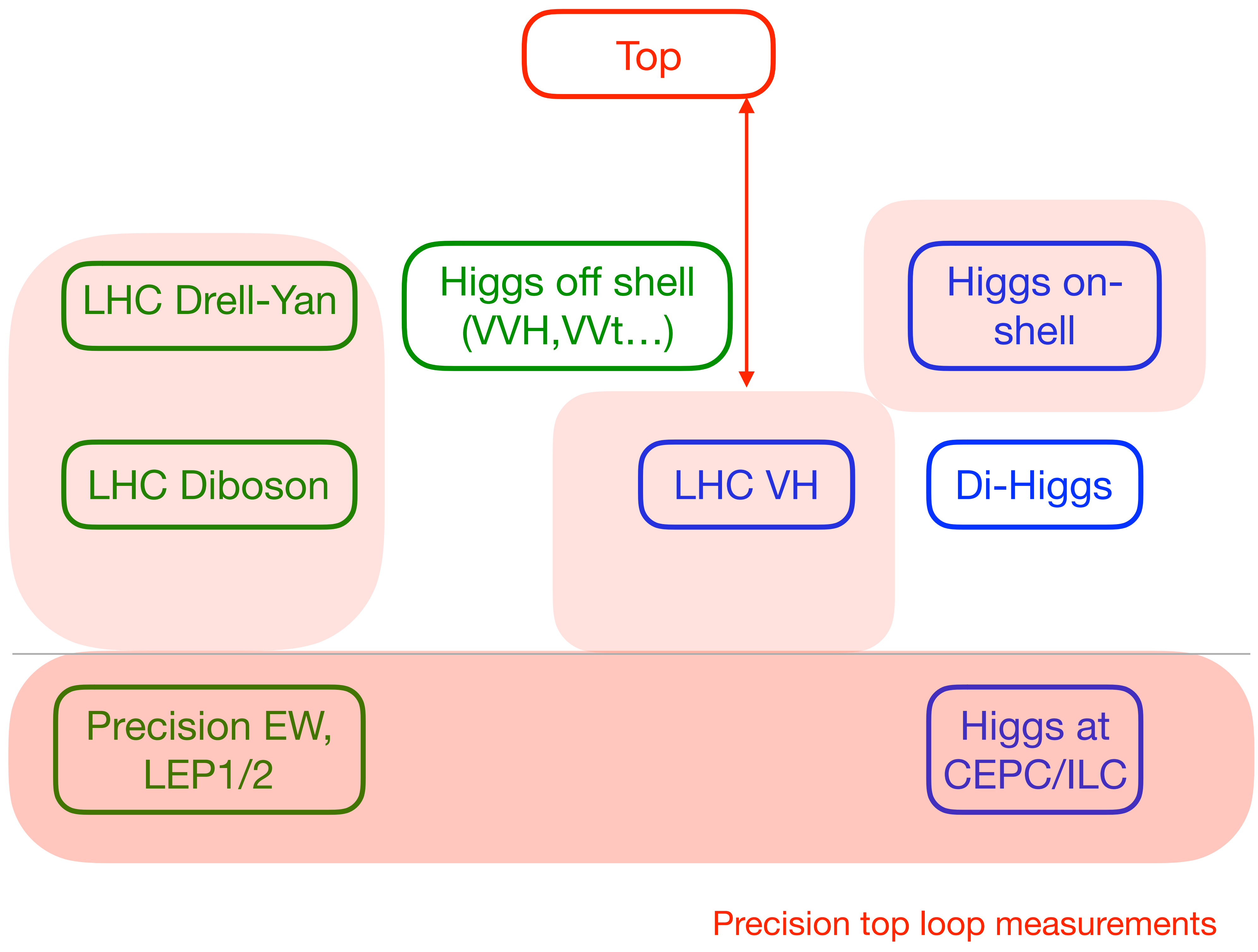
LHC Diboson

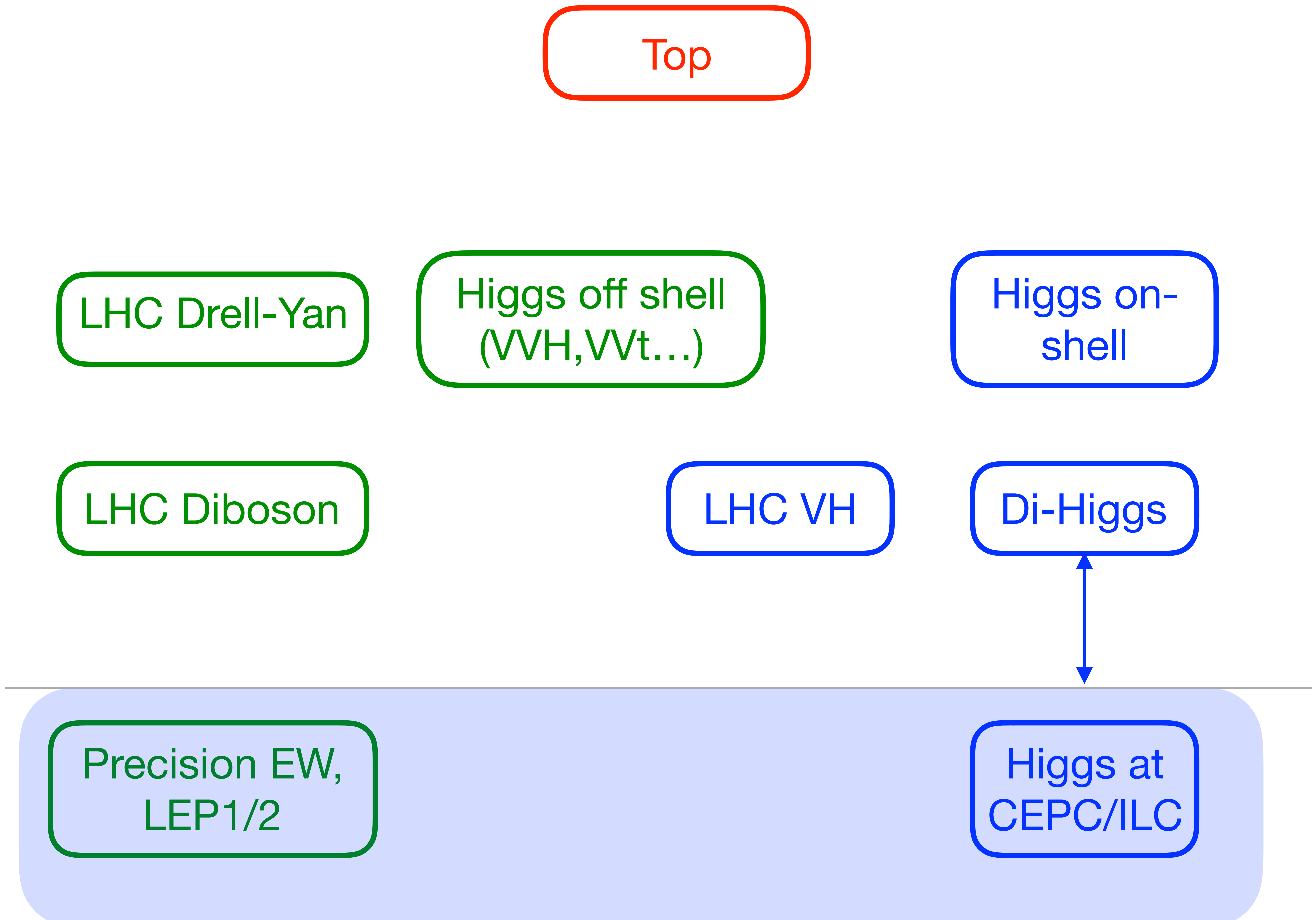
LHC VH

Di-Higgs

Precision EW, LEP1/2

Higgs at CEPC/ILC

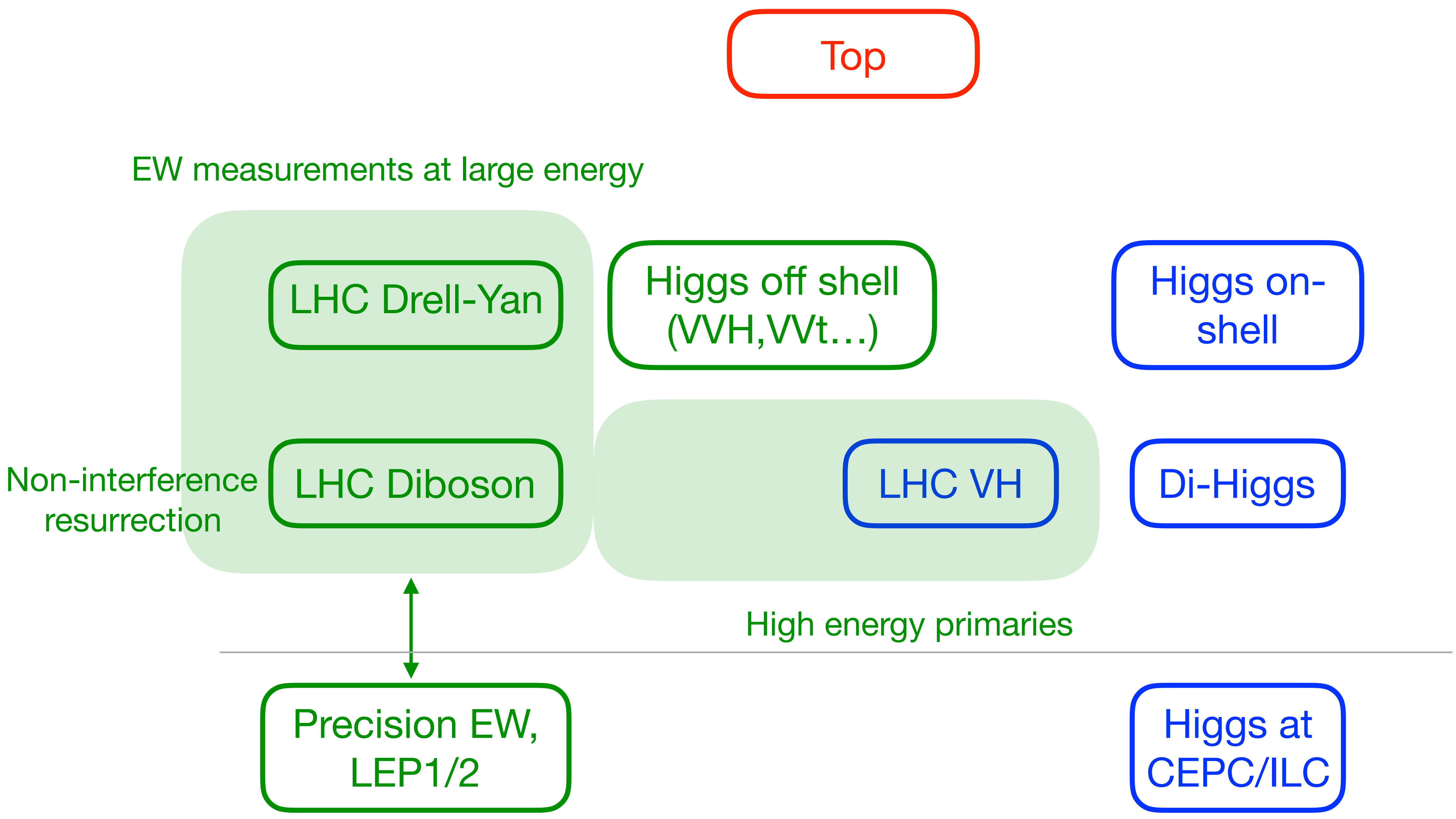

Top
LHC Drell-Yan
Higgs off shell
(VVH,VVt…)
Higgs on-
shell
LHC Diboson
LHC VH
Di-Higgs
Precision EW,
LEP1/2
Higgs at
CEPC/ILC
Precision top loop measurements



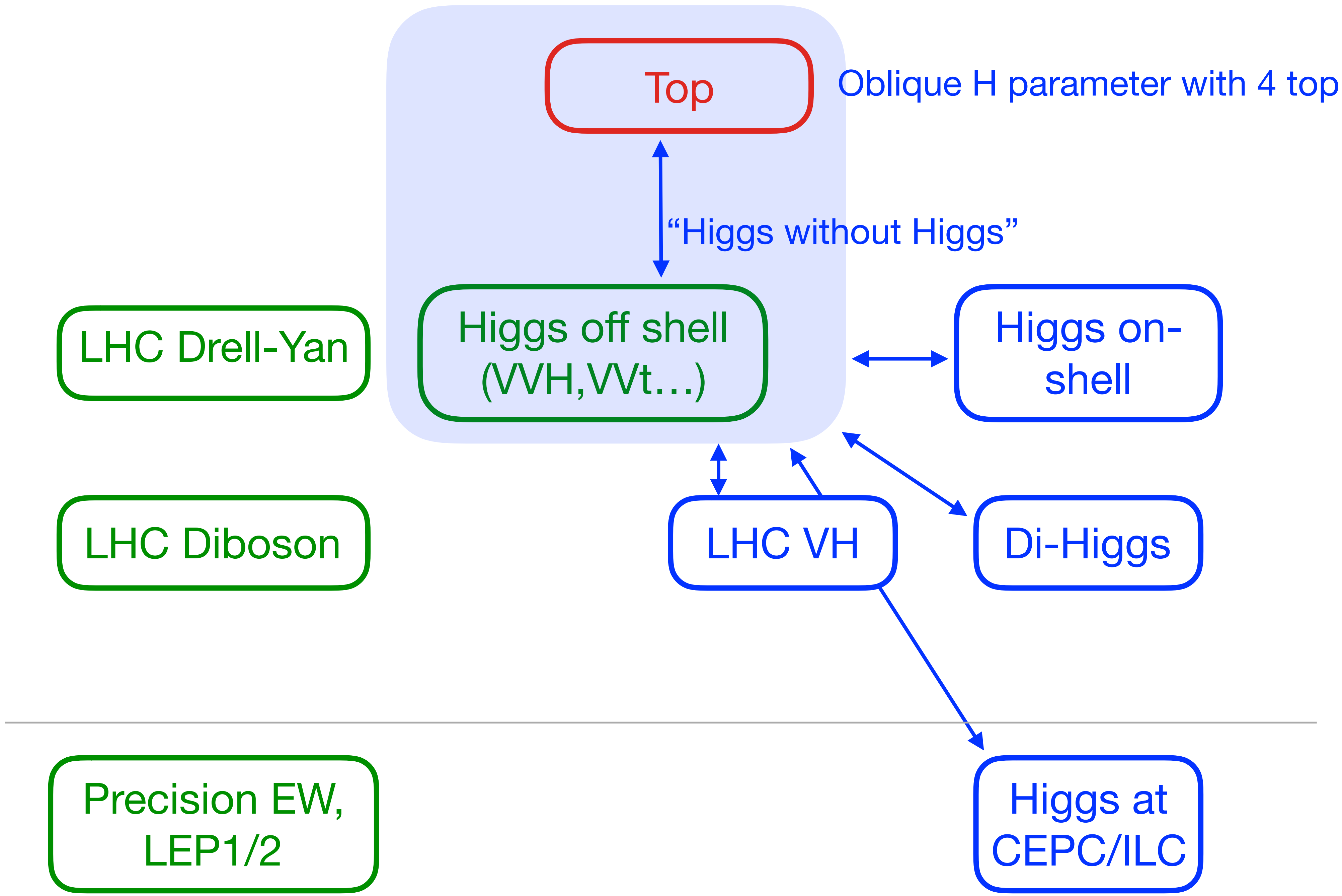
H trilinear at two loop

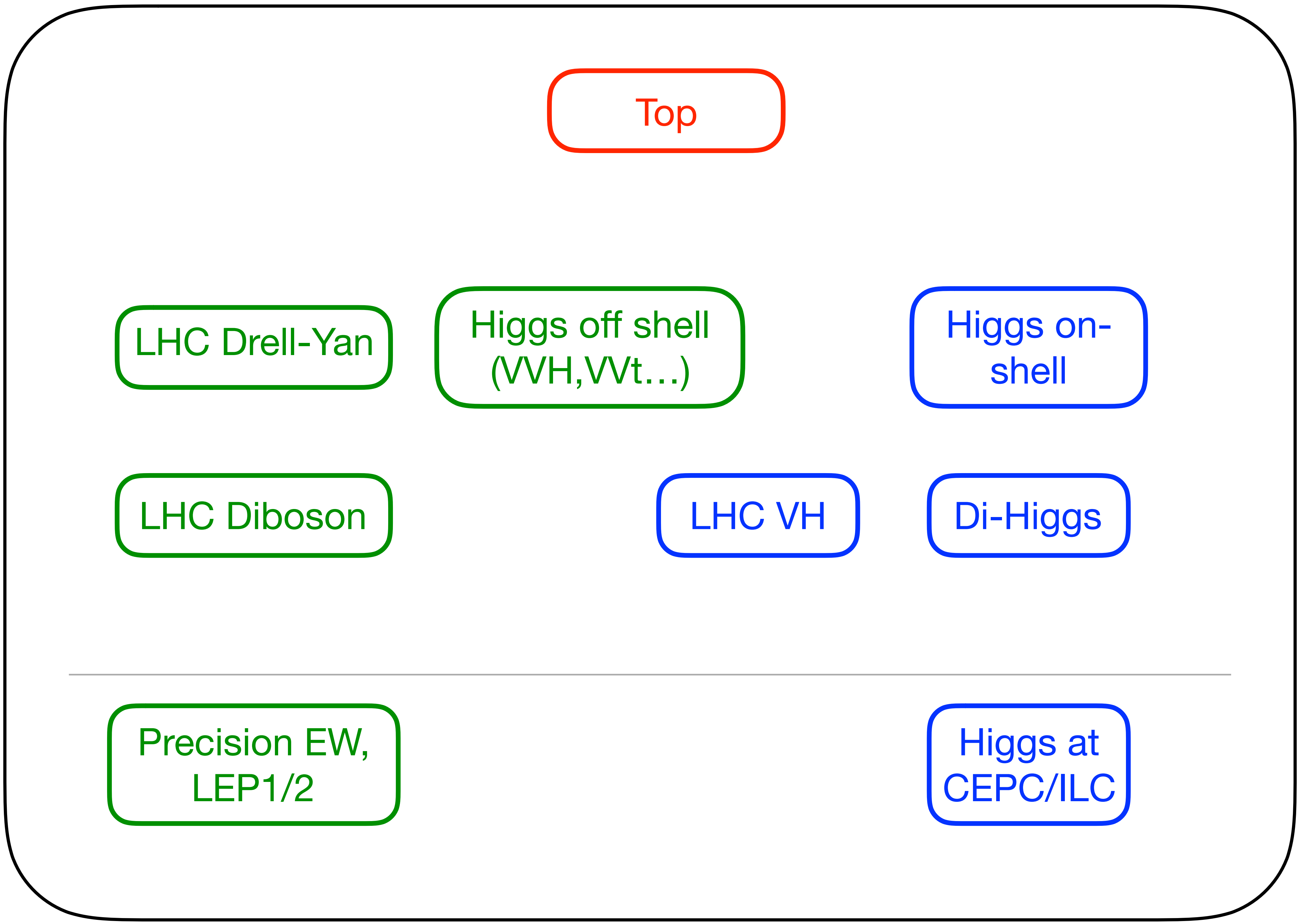
H trilinear at one loop

T-odd asymmetry as a direct loop probe



Top
EW measurements at large energy
LHC Drell-Yan
Higgs off shell (VVH,VVt…)
Higgs on-shell
Non-interference resurrection
LHC Diboson
LHC VH
Di-Higgs
High energy primaries
Precision EW, LEP1/2
Higgs at CEPC/ILC


Top
Oblique H parameter with 4 top
"Higgs without Higgs"
LHC Drell-Yan
Higgs off shell (VVH,VVt…)
Higgs on-shell
LHC Diboson
LHC VH
Di-Higgs
Precision EW, LEP1/2
Higgs at CEPC/ILC



Final goal: the global Top+EW+Higgs SMEFT fit

Thank you