Running away from the T-parameter solution to the W mass anomaly

Physics beyond the Standard Model in light of the CDF W boson mass anomaly

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The CDF W-mass anomaly

- The CDF collaboration has made the most precise measurement of the W-mass

$$\boxed{m_W^{\text{CDF}} = (80.433 \pm 0.0064_{\text{stat}} \pm 0.0069_{\text{syst}})\ \text{GeV}}$$

CDF collaboration (2022)

- This is inconsistent with the SM at a 7σ level !

$$\boxed{m_W = (80.357 \pm 0.004_{\text{inputs}} \pm 0.004_{\text{theory}})\ \text{GeV}}$$

PDG (2020)

- It also disagrees with the global average of all other measurements, given by,

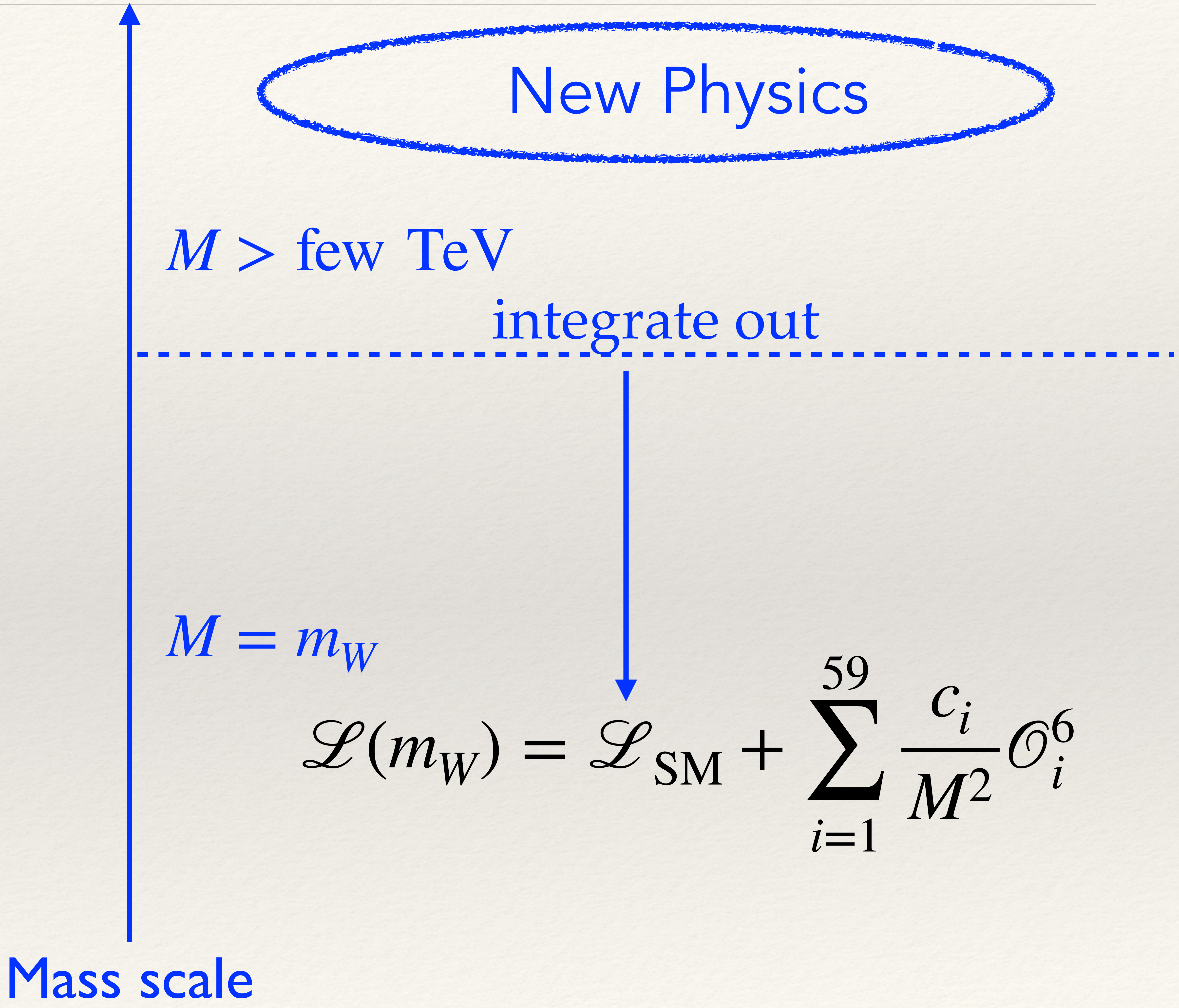
$$\boxed{m_W = (80.379 \pm 0.012)\ \text{GeV}.}$$

PDG (2020)

EFT approach

- Assuming CDF result to be correct many BSM interpretations have been proposed.
- Frequently utilised methodology (for heavy new physics models):

1. A SMEFT fit (eg. *S*-*T* parameter fits)
2. Exploration of UV complete models that can generate the observed low energy pattern of operators.



EFT approach

Z′,Leptoquarks,
Little Higgs

New Physics

$M = \text{few TeV}$

integrate out

integrate out

$$\mathcal{O}_{WB} = gg' H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}$$

$$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$$

$$\hat{T} = \frac{v^2}{\Lambda^2} c_T(m_W)\ , \quad \hat{S} = \frac{g^2 v^2}{4\Lambda^2} 4 c_{WB}(m_W),$$

$M = m_W$

$$\mathscr{L}(m_W) = \mathscr{L}_{\mathrm{SM}} + \sum_{i=1}^{59} \frac{c_i}{M^2} \mathcal{O}_i^6$$

Mass scale

Peskin & Takeuchi (1990)

EFT approach

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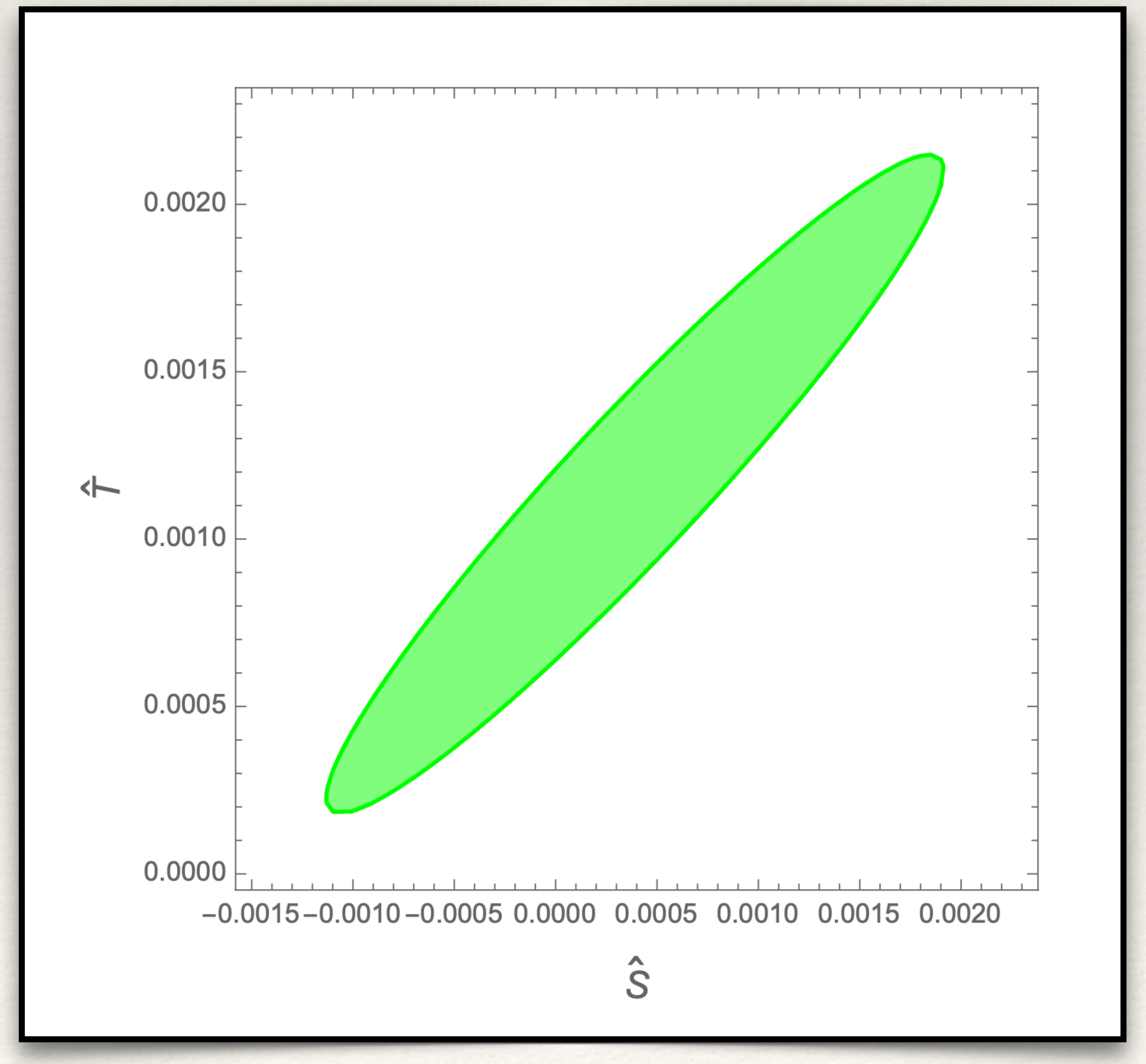

Strumia (2022)

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Mass scale

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EFT approach: What about running ?

New Physics

$M = \text{few TeV}$

What about running ??

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$M = m_W$

Mass scale

EFT approach: isn't running subdominant?

Naively, yes because it is loop suppressed.

0.01

$$c_T(m_W) = c_T(\Lambda) - \boxed{\frac{1}{16\pi^2}\log\left(\frac{\Lambda}{m_W}\right)}\sum_i \gamma_T^i c_i$$

$$c_{WB}(m_W) = c_{WB}(\Lambda) - \boxed{\frac{1}{16\pi^2}\log\left(\frac{\Lambda}{m_W}\right)}\sum_i \gamma_{WB}^i c_i$$

But what if operators contributing to the RG are much less constrained than operators on the LHS ?

EFT approach: isn't running subdominant?

Naively, yes because it is loop suppressed.

0.01 0.01 0.01 1

$$\boxed{c_T(m_W)} = c_T(\Lambda) - \boxed{\frac{1}{16\pi^2}\log\left(\frac{\Lambda}{m_W}\right)} \sum_i \boxed{\gamma_T^i c_i}$$

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If all Wilson coefficients are of the same order, indeed we can neglect RG effects and this gives us the solutions to the CDF anomaly considered so far in the literature. These are only subset of all possible solutions including running.

EFT approach: What about running ?

New Physics

$M = \text{few TeV}$

$\mathcal{O}_{WB}(M), \mathcal{O}_T(M), \mathcal{O}_{HW}(M), \mathcal{O}_{HB}(M), \mathcal{O}_{H-}(M) \ldots$

We will find much larger parameter space consistent with CDF anomaly at the matching scale M !

Running

$\mathcal{O}_{WB}(m_W), \mathcal{O}_T(m_W)$

$M = m_W$

Mass scale

We will consider in detail the case of **universal new physics** and then argue that our main observations will hold also for the general case.

Universal new physics

16 operators can completely parametrise universal theories:

$$
\begin{aligned}
\mathcal{O}_H &= \tfrac{1}{2}(\partial^\mu |H|^2)^2 \\
\mathcal{O}_T &= \tfrac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2 \\
\mathcal{O}_r &= |H|^2 |D_\mu H|^2 \\
\mathcal{O}_{K4} &= |D^2 H|^2 \\
\mathcal{O}_6 &= \lambda |H|^6 \\
\mathcal{O}_{HW} &= ig(D^\mu H)^\dagger \sigma^a D^\nu H D^\nu W^a_{\mu\nu} \\
\mathcal{O}_{HB} &= ig'(D^\mu H)^\dagger D^\nu \partial^\nu B_{\mu\nu}
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{O}_{2W} &= -\tfrac{1}{2}(D^\mu W^a_{\mu\nu})^2 \\
\mathcal{O}_{2B} &= -\tfrac{1}{2}(\partial^\mu B_{\mu\nu})^2 \\
\mathcal{O}_{2G} &= -\tfrac{1}{2}(D^\mu G^A_{\mu\nu})^2 \\
\mathcal{O}_{BB} &= g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu} \\
\mathcal{O}_{WB} &= gg' H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu} \\
\mathcal{O}_{WW} &= g^2 |H|^2 W^a_{\mu\nu} W^{a\mu\nu} \\
\mathcal{O}_{GG} &= g_s^2 |H|^2 G^A_{\mu\nu} G^{A\mu\nu} \\
\mathcal{O}_{3W} &= \tfrac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_{\mu} W^b_{\nu\rho} W^{c\,\rho\mu} \\
\mathcal{O}_{3G} &= \tfrac{1}{3!} g_s f_{ABC} G^{A\,\nu}_{\mu} G^B_{\nu\rho} G^{C\,\rho\mu}
\end{aligned}
$$

Wells and Zhang (2015)

Which operators contribute to running of S & T?

6 Operators contributing to running of $\mathcal{O}_T$

	c_{H-}	c_T
$\gamma^i_{c_T}$	$\frac{3}{2}g'^2$	$\frac{9}{2}g^2 + 12\lambda + 12y_t^2$
$\gamma^i_{c_{WB}}$	$-\frac{1}{6}$	$-\frac{1}{2}$

	c_{2B}	c_{2W}	c_{HB}	c_{HW}
$\gamma^i_{c_T}$	$3g'^4 + \frac{9}{8}g'^2g^2 + 3\lambda g'^2$	$\frac{9}{8}g'^2g^2$	$-\frac{9}{4}g'^2g^2 - 6\lambda g'^2$	$-\frac{9}{4}g'^2g^2$
$\gamma^i_{c_{WB}}$	$\frac{1}{4}\left(\frac{147}{8} - \frac{53}{4}t^2_{\theta_W}\right)g'^2$	$\frac{77}{32}g^2 + \frac{29}{16}g'^2$	$-\frac{9}{8}g^2 - \frac{7}{24}g'^2 - \lambda$	$\frac{5}{8}g^2 + \frac{1}{8}g'^2 - \lambda$

	c_{BB}	c_{WW}	c_{WB}	c_{3W}
$\gamma^i_{c_T}$	0	0	0	0
$\gamma^i_{c_{WB}}$	$2g'^2$	$2g^2$	$\frac{9g^2}{2} - \frac{g'^2}{2} + 6y_t^2 + 4\lambda$	$-\frac{g^2}{2}$

Elias-miro, Gupta, Grojean, Marzocca (2014)

Which operators contribute to running of S & T?

10 Operators contributing to running of $\mathcal{O}_{WB}$

	c_{H-}	c_T
$\gamma^i_{c_T}$	$\frac{3}{2}g'^2$	$\frac{9}{2}g^2 + 12\lambda + 12y_t^2$
$\gamma^i_{c_{WB}}$	$-\frac{1}{6}$	$-\frac{1}{2}$

	c_{2B}	c_{2W}	c_{HB}	c_{HW}
$\gamma^i_{c_T}$	$3g'^4 + \frac{9}{8}g'^2g^2 + 3\lambda g'^2$	$\frac{9}{8}g'^2g^2$	$-\frac{9}{4}g'^2g^2 - 6\lambda g'^2$	$-\frac{9}{4}g'^2g^2$
$\gamma^i_{c_{WB}}$	$\frac{1}{4}\left(\frac{147}{8} - \frac{53}{4}t^2_{\theta_W}\right)g'^2$	$\frac{77}{32}g^2 + \frac{29}{16}g'^2$	$-\frac{9}{8}g^2 - \frac{7}{24}g'^2 - \lambda$	$\frac{5}{8}g^2 + \frac{1}{8}g'^2 - \lambda$

	c_{BB}	c_{WW}	c_{WB}	c_{3W}
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Elias-miro, Gupta, Grojean, Marzocca (2014)

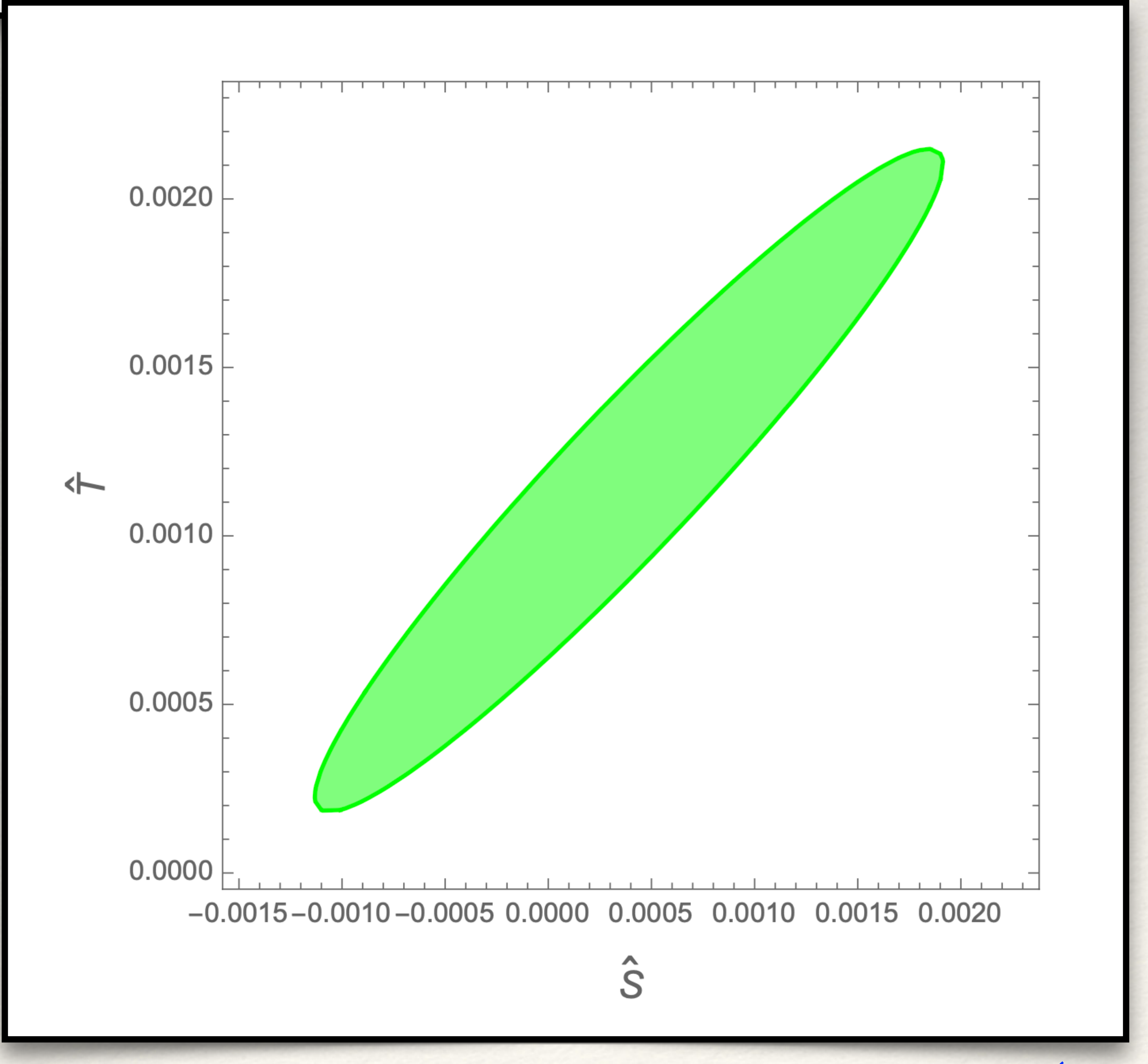
Electroweak precision observables

- Measurements including Z-pole measurements, $ee \to ff$ at LEP-1, $pp \to ll$ at LEP-2 can constrain the following:

$$\Delta\mathcal{L}_{\rm EWPT} = -\frac{\hat{T}}{2}\frac{m_Z^2}{2}Z_\mu Z^\mu - \frac{\hat{S}}{4m_W^2}\frac{gg'v^2}{2}(W^3_{\mu\nu}B^{\mu\nu}) - \frac{W}{2m_W^2}(\partial^\mu W^3_{\mu\nu})^2 - \frac{Y}{2m_W^2}(\partial^\mu B_{\mu\nu})^2.$$

$$\hat{T} = \frac{v^2}{\Lambda^2}c_T(m_W)\ , \quad \hat{S} = \frac{g^2v^2}{4\Lambda^2}4c_{WB}(m_W),$$
$$Y = \frac{g^2v^2}{4\Lambda^2}c_{2B}(p)\ , \quad W = \frac{g^2v^2}{4\Lambda^2}c_{2W}(p)\ .$$

$$|W|,|Y| \lesssim 10^{-4}$$



Peskin & Takeuchi (1990)
Barbieri, Pomarol, Rattazzi & Strumia (2004)

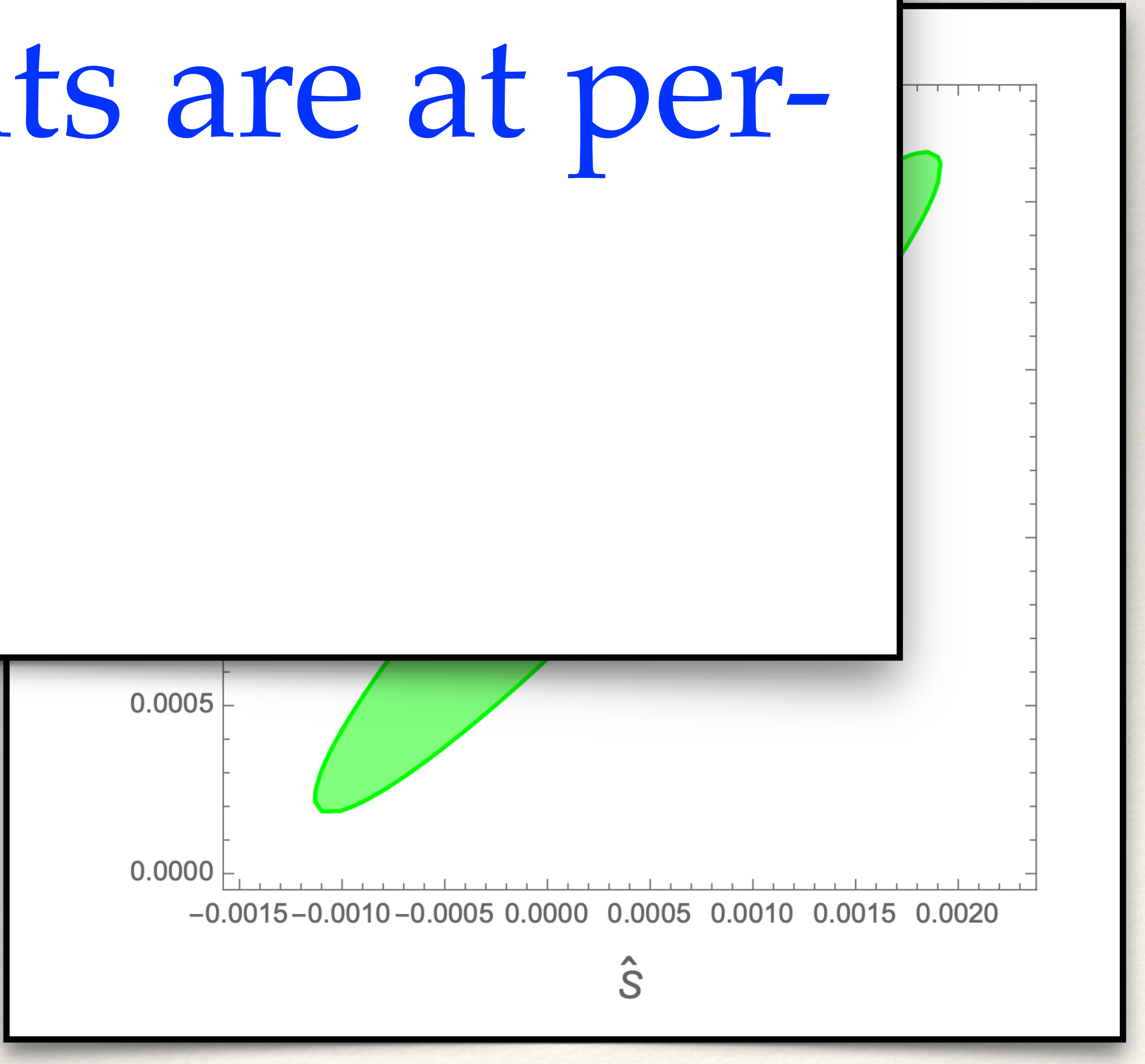
Strumia (2022)

Electroweak precision observables

- Measurements including Z-pole measurements, $ee \to ff$ at LEP-1, $pp \to ll$ at LEP-2 ca

$\Delta\mathcal{L}$

Most precisely constrained in electroweak sector 'observables'. Constraints are at per-mille level or less.



Diboson Production

- LEP-2 and LHC diboson data can constrain modifications of WWZ and $WW\gamma$ vertices

$$\Delta\mathcal{L}_{3V} = ig\, g_1^Z c_{\theta_W} Z^\mu \left(W^{+\nu}\hat{W}^-_{\mu\nu} - W^{-\nu}\hat{W}^+_{\mu\nu}\right) + ig\left(\kappa_z c_{\theta_W}\hat{Z}^{\mu\nu} + \kappa_\gamma s_{\theta_W}\hat{A}^{\mu\nu}\right) W^+_\mu W^-_\nu + \frac{ig}{m_W^2}\left(\lambda_Z c_{\theta_W}\hat{Z}^{\mu\nu} + \lambda_\gamma s_{\theta_W}\hat{A}^{\mu\nu}\right)\hat{W}^{-\rho}_\mu \hat{W}^+_{\rho\nu},$$

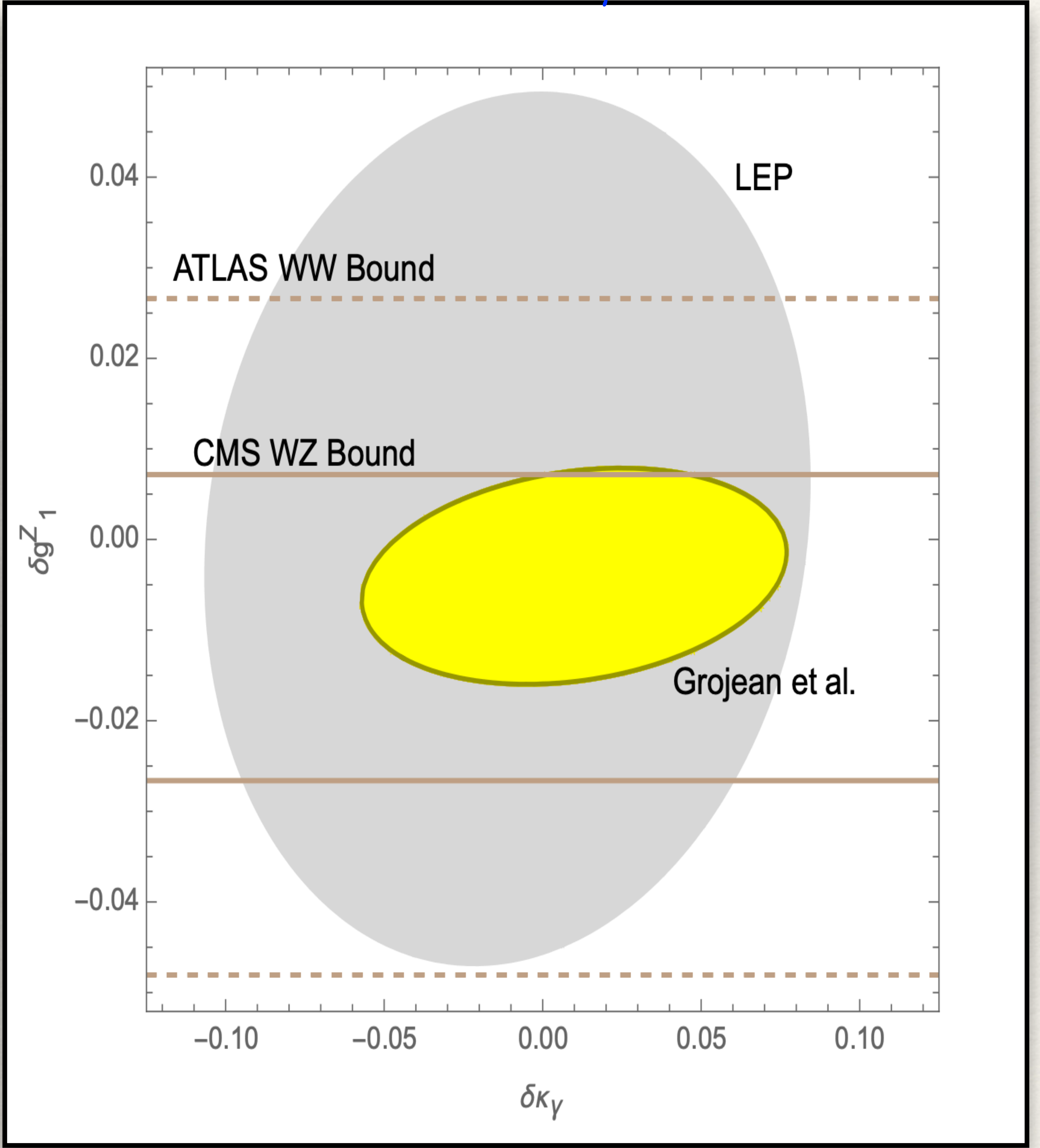
Hagiwara et al (1986)

- These anomalous Triple gauge coupling modifications probe $\mathcal{O}_{WB}$, $\mathcal{O}_{HW}$, $\mathcal{O}_{HB}$ and $\mathcal{O}_{3W}$.

$$\delta g_1^Z = -\frac{g^2v^2}{4\Lambda^2}\frac{1}{c^2_{\theta_W}} c_{HW}(p)\,, \qquad \delta\kappa_\gamma = -\frac{g^2v^2}{4\Lambda^2}\left(c_{HW}(p) + c_{HB}(p) - 4c_{WB}(p)\right),$$

$$\lambda_\gamma = \frac{g^2v^2}{4\Lambda^2} c_{3W}(p).$$

λ_γ marginalised over



Grojean, Montull & Riembau (2019)

Diboson Production

- LEP-2 and LHC diboson data can constrain modifications of WWZ and $WW\gamma$ vertices

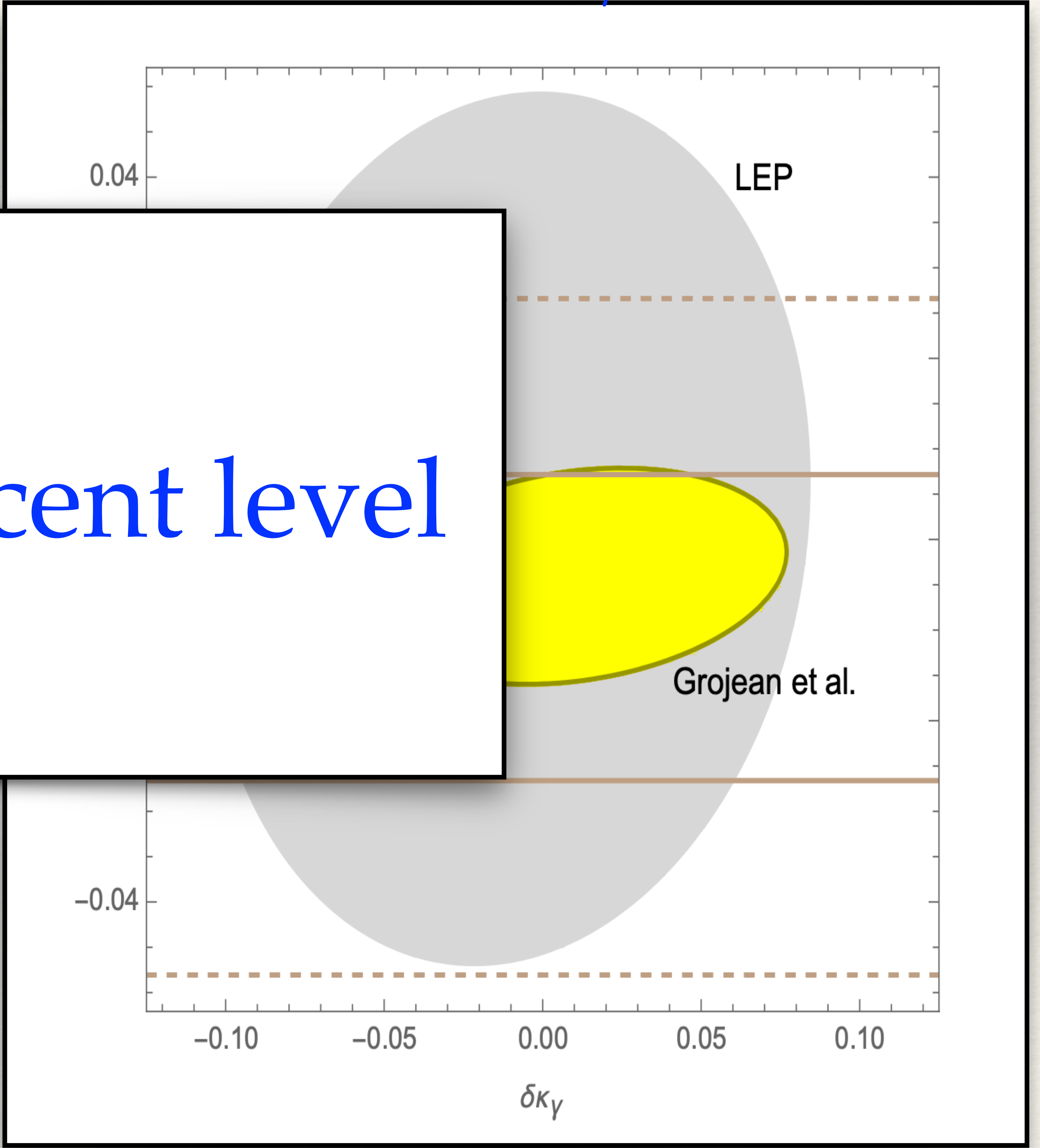
$$\Delta\mathcal{L}_{3V} = ig\, g_1^Z c_{\theta_W} \ldots$$
$$+ \frac{ig}{m_W^2}\Big(\lambda_Z \ldots$$

Constrained are at few per-cent level

- These ano...
modificati...

$$\delta g_1^Z = -\frac{g^2 v^2}{4\Lambda^2}\frac{1}{c_{\theta_W}^2} c_{HW}(p)\,, \qquad \delta\kappa_\gamma = -\frac{g^2 v^2}{4\Lambda^2}\left(c_{HW}(p) + c_{HB}(p) - 4c_{WB}(p)\right)\,,$$
$$\lambda_\gamma = \frac{g^2 v^2}{4\Lambda^2} c_{3W}(p).$$

λ_γ marginalised over



Grojean, Montull & Riembau (2019)

Rewriting Higgs operators

$$\boxed{\frac{c_H}{\Lambda^2}\mathcal{O}_H + \frac{c_r}{\Lambda^2}\mathcal{O}_r = \frac{c_{H+}}{\Lambda^2}\mathcal{O}_{H+} + \frac{c_{H-}}{\Lambda^2}\mathcal{O}_{H-}}$$

$$\boxed{\mathcal{O}_{H\pm} = \frac{1}{2}(\mathcal{O}_H \pm \mathcal{O}_r)}$$

- It is the operator $\mathcal{O}_{H-}$ that contributes to running of $\hat{S}$ and $\hat{T}$. It is constrained by deviations in hVV vertex.

Higgs physics constraints

- Finally operators that generate the following anomalous couplings can be constrained by Higgs physics processes

$$\Delta\mathcal{L}_H = \delta\kappa_V \frac{g^2 v}{2} h \left(W_\mu^+ W^{-\mu} + \frac{Z_\mu Z^\mu}{2c_{\theta_W}} \right) - \delta\kappa_f \sum_f \frac{m_f}{v} h \bar{f} f + \frac{\kappa_{gg} h}{2v} G_{\mu\nu} G^{\mu\nu}$$
$$+ \frac{\kappa_{\gamma\gamma} h}{2v} A_{\mu\nu} A^{\mu\nu} + \frac{\kappa_{\gamma Z}\, h}{v} A_{\mu\nu} Z^{\mu\nu}.$$

$$-0.03 \leq \delta\kappa_V \leq 0.13$$
$$-0.13 \leq \delta\kappa_f \leq 0.23,$$

$$\begin{aligned}
\delta\kappa_V &= -\frac{c_{H-}(m_h)\, v^2}{2\Lambda^2} \\
\delta\kappa_f &= \left(-c_{H+}(m_h) - 2\lambda c_{K4}(m_h)\right) \frac{v^2}{2\Lambda^2} \\
\kappa_{\gamma\gamma} &= 2g^2 s_{\theta_W}^2 \left(c_{WW}(m_h) + c_{BB}(m_h) - c_{WB}(m_h)\right) \frac{v^2}{\Lambda^2} \\
\kappa_{Z\gamma} &= g^2 t_{\theta_W} \left(2c_{\theta_W}^2 c_{WW}(m_h) - 2s_{\theta_W}^2 c_{BB}(m_h) - (c_{\theta_W}^2 - s_{\theta_W}^2) c_{WB}(m_h)\right) \frac{v^2}{\Lambda^2} \\
\kappa_{GG} &= 2g_s^2 \frac{c_{GG}(m_h)\, v^2}{\Lambda^2}
\end{aligned}$$

ATLAS collaboration (2020)

Higgs physics constraints

- Finally operators that generate the following anomalous couplings can be constrained by Higgs physics processes

$$\Delta\mathcal{L}_H = \delta\kappa_V \frac{g^2 v}{2} h \left(W_\mu^+ W^- \right.$$

$$+ \frac{\kappa_{\gamma\gamma} h}{2v} A_{\mu\nu} A^{\mu\nu} + \kappa_\gamma$$

Only $\mathcal{O}(1)$ level constraints.

$$3 \leq \delta\kappa_V \leq 0.13$$

$$3 \leq \delta\kappa_f \leq 0.23,$$

$$\delta\kappa_V = -\frac{c_{H-}(m_h)\, v^2}{2\Lambda^2}$$

$$\delta\kappa_f = \left(-c_{H+}(m_h) - 2\lambda c_{K4}(m_h)\right) \frac{v^2}{2\Lambda^2}$$

$$\kappa_{\gamma\gamma} = 2g^2 s_{\theta_W}^2 \left(c_{WW}(m_h) + c_{BB}(m_h) - c_{WB}(m_h)\right) \frac{v^2}{\Lambda^2}$$

$$\kappa_{Z\gamma} = g^2 t_{\theta_W} \left(2c_{\theta_W}^2 c_{WW}(m_h) - 2s_{\theta_W}^2 c_{BB}(m_h) - (c_{\theta_W}^2 - s_{\theta_W}^2) c_{WB}(m_h)\right) \frac{v^2}{\Lambda^2}$$

$$\kappa_{GG} = 2g_s^2 \frac{c_{GG}(m_h)\, v^2}{\Lambda^2}$$

ATLAS collaboration (2020)

RG contribution due to well constrained operators can be ignored

- From $\mathcal{O}_{BB}$, $\mathcal{O}_{WW}$, $\mathcal{O}_{2B}$ and $\mathcal{O}_{2W}$ we get $\Delta\hat{S}, \Delta\hat{T} \simeq 0.00001 \ll 0.001$.

$$\text{For eg. } \Delta\hat{T} = -\underbrace{\boxed{\frac{\gamma_T^{2W}}{16\pi^2}\log(\Lambda/m_W)}}_{<0.01}\underbrace{\boxed{\frac{c_{2W}v^2}{\Lambda^2}}}_{<0.001} \lesssim 10^{-5}$$

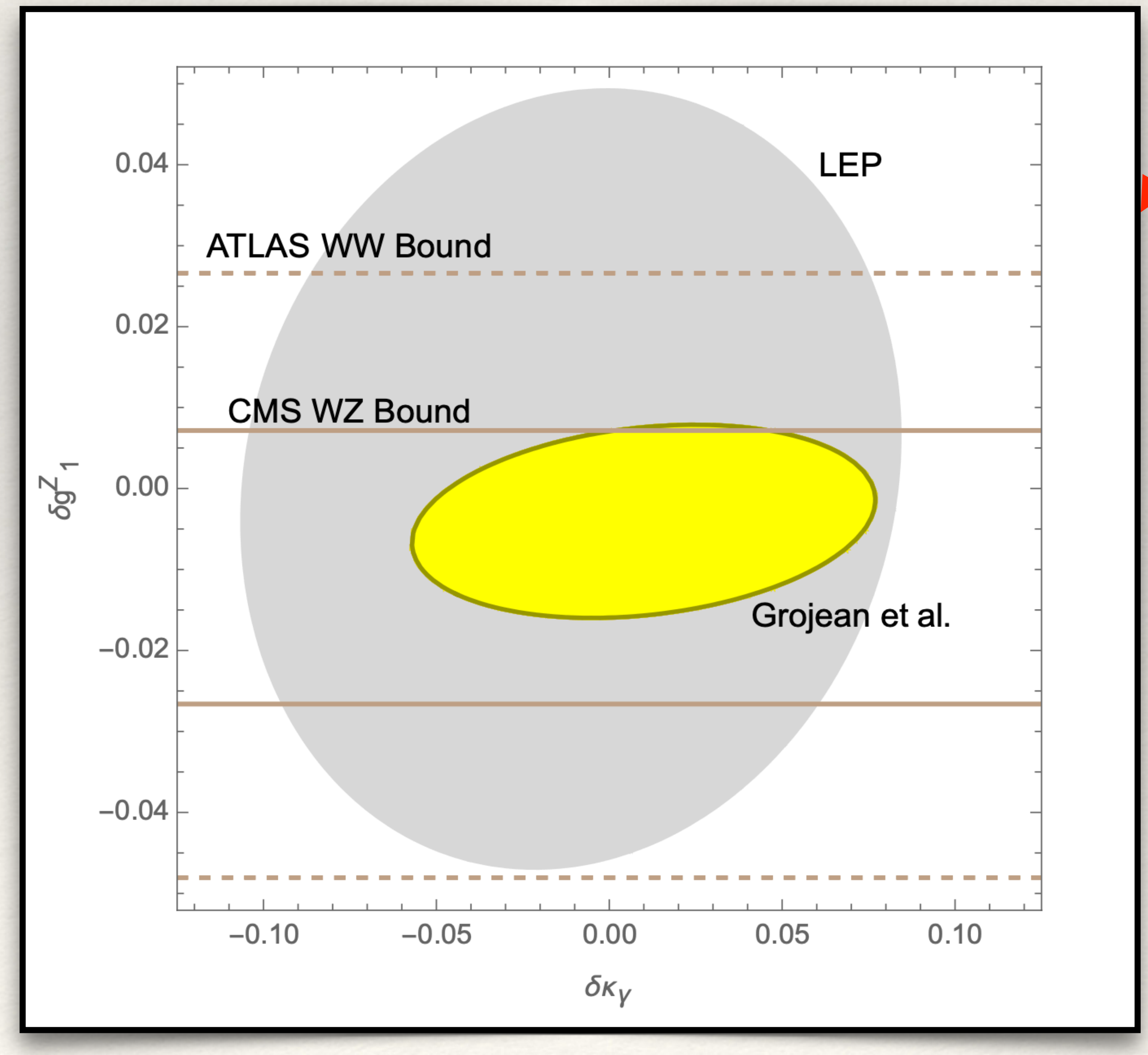
$= \frac{4}{g^2}\hat{W}$ and $\hat{W} \lesssim 10^{-4}$

- From $\mathcal{O}_{3W}$ we get $\Delta\hat{S}, \Delta\hat{T} \simeq 0.0001 \ll 0.001$.

Poorly constrained operators

- We will thus consider only the three poorly constrained operators:

$$\{\boxed{\mathcal{O}_{HW}, \mathcal{O}_{HB}}, \boxed{\mathcal{O}_{H-}}\}$$



$$\boxed{-0.03 \leq \delta\kappa_V \leq 0.13}$$

RG contribution due to $\mathcal{O}_{H-}$

- Contribution of $\mathcal{O}_{H-}$:

$$\boxed{\Delta\hat{S} = \frac{c_H v^2}{6\Lambda^2}\frac{g^2}{16\pi^2}\log\left(\frac{\Lambda}{m_W}\right), \qquad \Delta\hat{T} = -\frac{3c_H v^2}{2\Lambda^2}\frac{g'^2}{16\pi^2}\log\left(\frac{\Lambda}{m_W}\right).}$$

- This is equivalent to the contribution of a modified hVV vertex considered in Cacciapaglia et al.

Cacciapaglia and Sannino (2022)

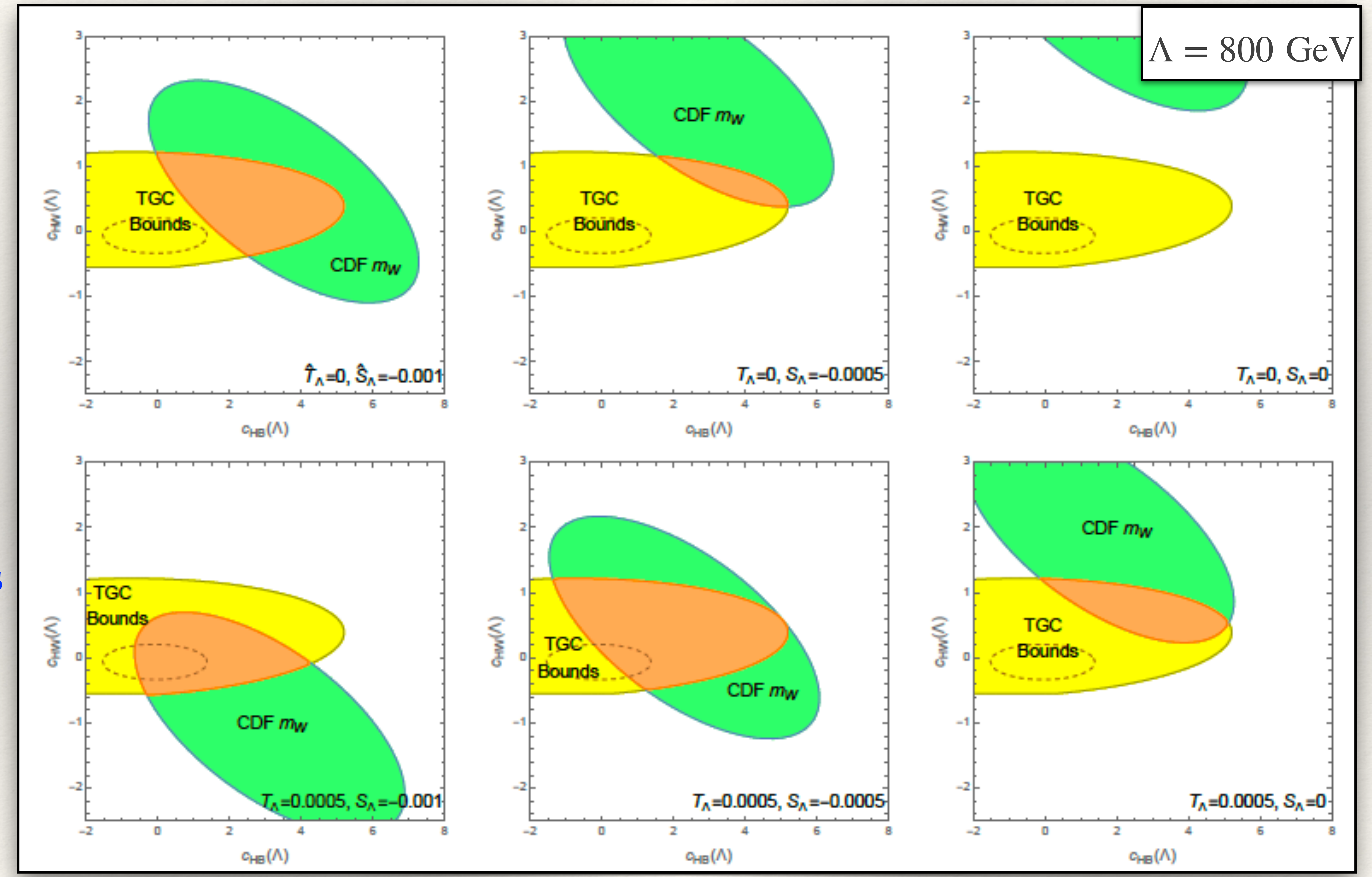
- It requires $-2.5 \leq c_{H-} \leq -1.4$ to fit the CDF measurement
- This is problematic within SMEFT because $c_{H-} \geq 0$ on general grounds.

Rattazzi, Low and Vichi (2010)

Explaining CDF anomaly

Region of overlap is parameter space at matching scale consistent with both CDF anomaly and TGC constraints

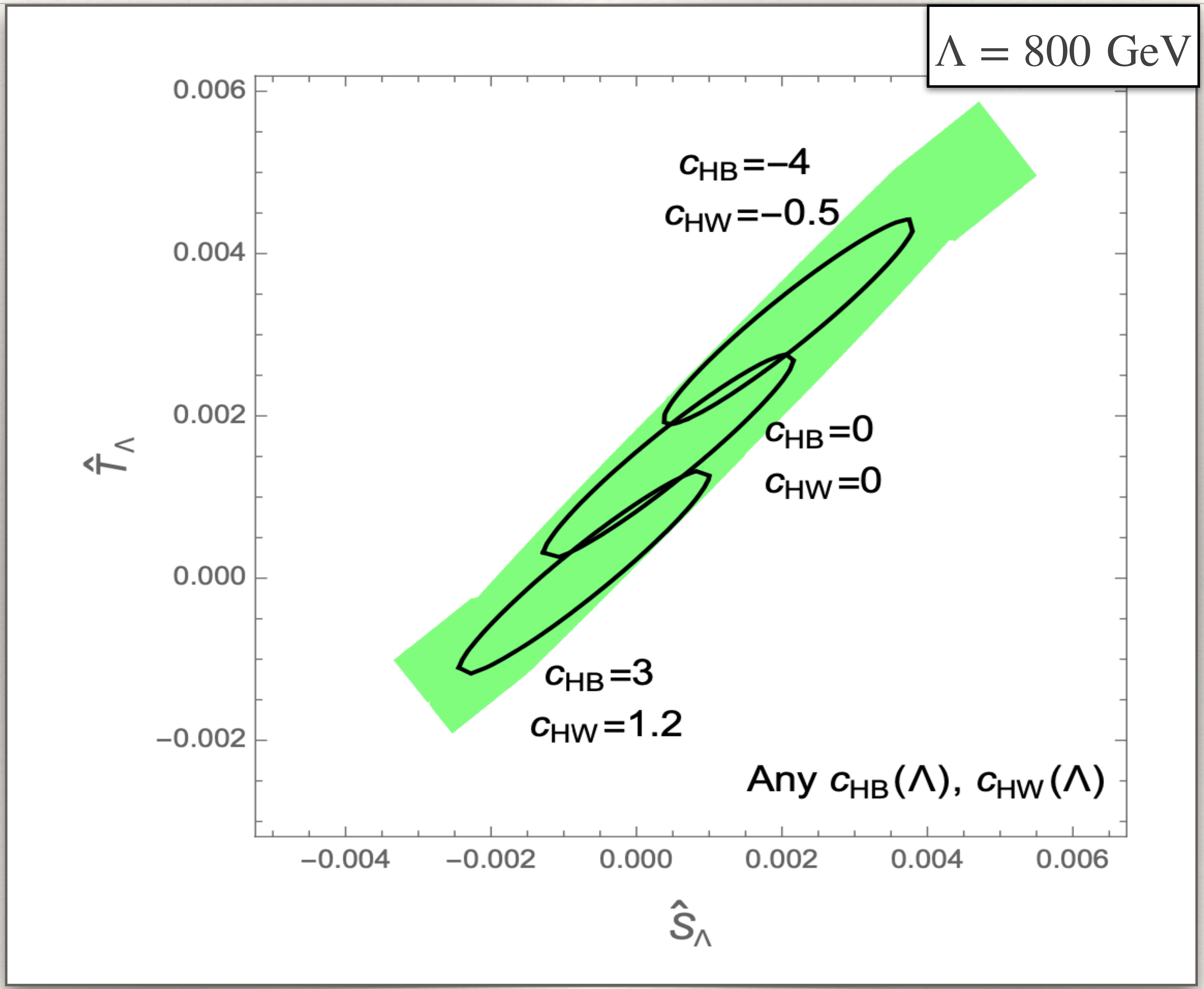
Dotted line: projected HL-LHC Constraints. Large deviations in TGCs due to smaller scale of new physics



Gupta (2022)

Explaining CDF anomaly

Parameter space at matching scale consistent with CDF anomaly after marginalising over TGC constraints



Gupta (2022)

Generalising to non universal case

- Analysis for universal new physics carried out only for practical reasons. Analysis involving all the dimension 6 operators far more elaborate.
- We will have to augment the 16 bosonic operators shown before by adding 43 dimension 6 operators to obtain a complete 59 dimensional basis (for a single generation of fermions).
- There would be 4 operators that give tree level contribution to the W mass.many more operators that contribute to these 4 operators via RG effects
- Including all these operators can result in the discovery of many new allowed regions in the SMEFT parameter space at the matching scale.
- The regions shown in previous Figures would still exist in the limit that the 43 new Wilson coefficients vanish. If these new Wilson coefficients are marginalised over, the regions will only become larger.

Conclusions

- Renormalisation gauge (RG) effects can be crucial in determining the SMEFT parameter space consistent with the CDF W-mass anomaly at the matching scale.
- This is because operators are only weakly constrained by diboson and Higgs data can have a large contribution to the W-boson mass via one-loop RG effects.
- This effect is comparable to the tree-level contribution of the much more strongly constrained operators related to electroweak precision observables.
- We find that it is possible to have a vanishing or even negative T-parameter at the matching scale. This will hopefully lead to a larger set of UV completions that can explain the anomaly.
- For the one-loop contributions to be important a relatively low new physics scale around 800 GeV is required. This enhances the possibility of probing this new physics in direct and indirect searches in the recent future.