Cincuenta Aniversario
1968
2018
UAM Universidad Autónoma de Madrid

ift Instituto de Física Teórica
UAM-CSIC

elusiVes-inVisiblesPlus
neutrinos, dark matter & dark energy physics

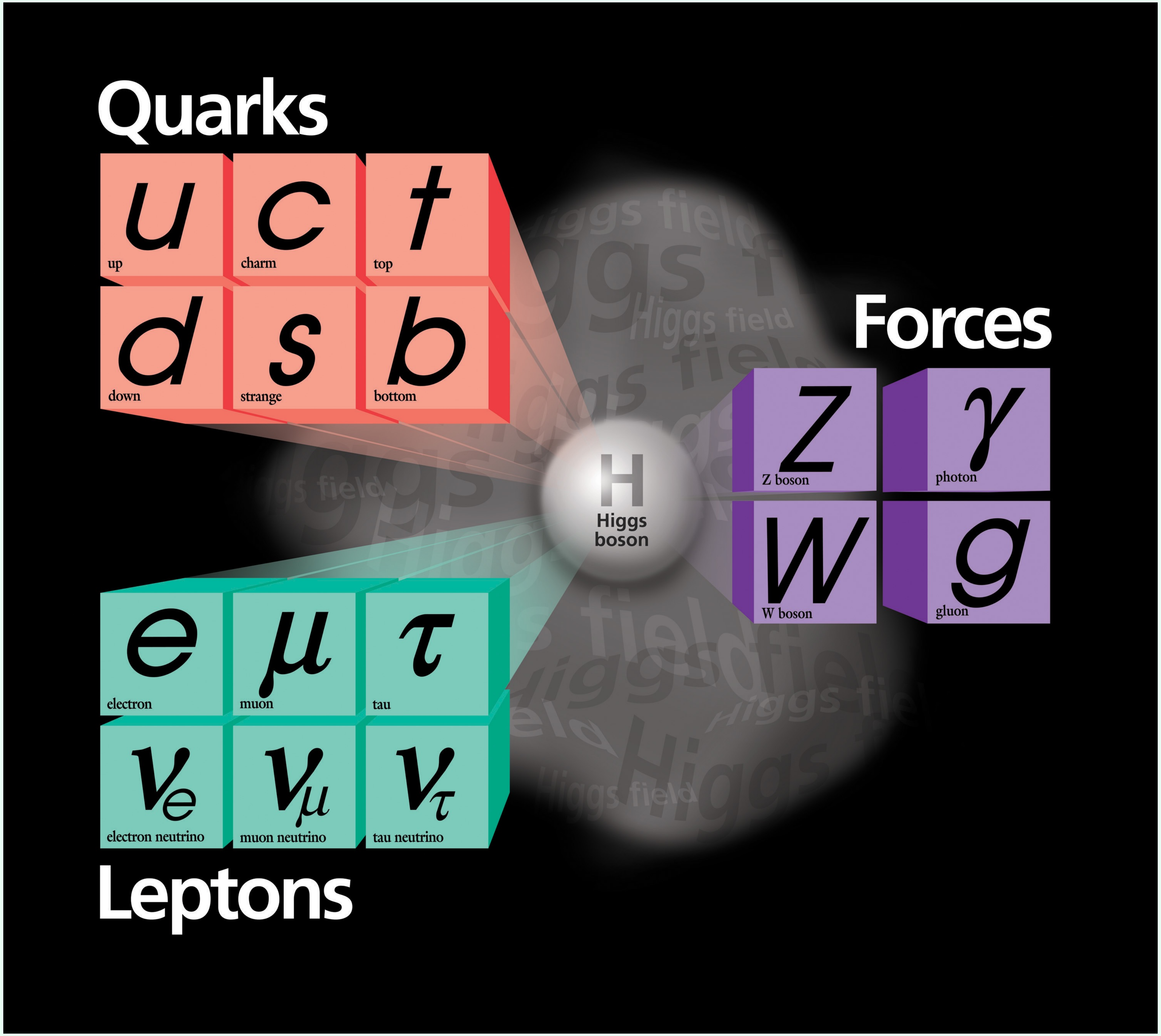
HIGGS EFFECTIVE FIELD THEORIES

Luca Merlo

Milan, 21st of August 2021

Advanced VBS training school

Normal matter



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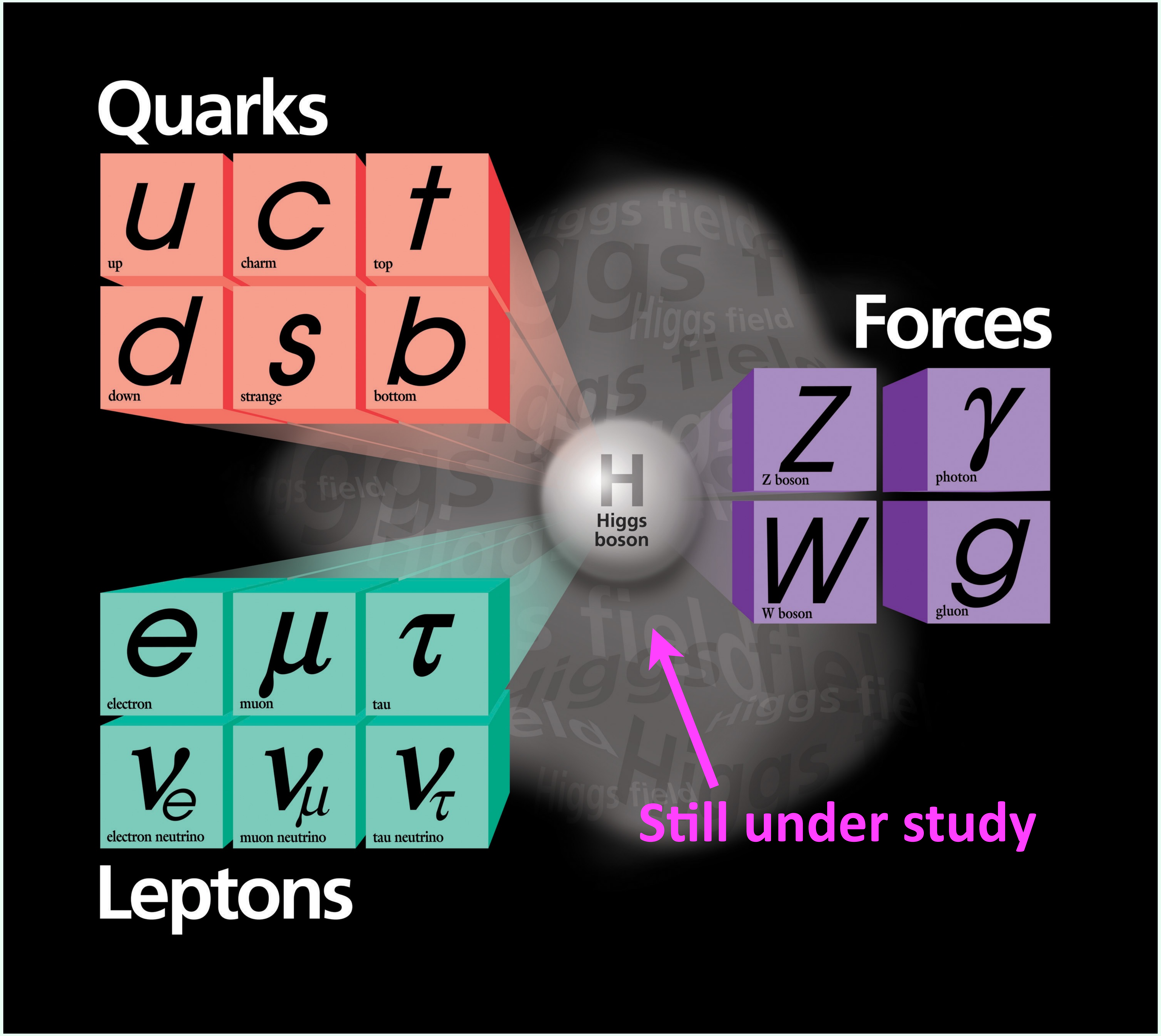
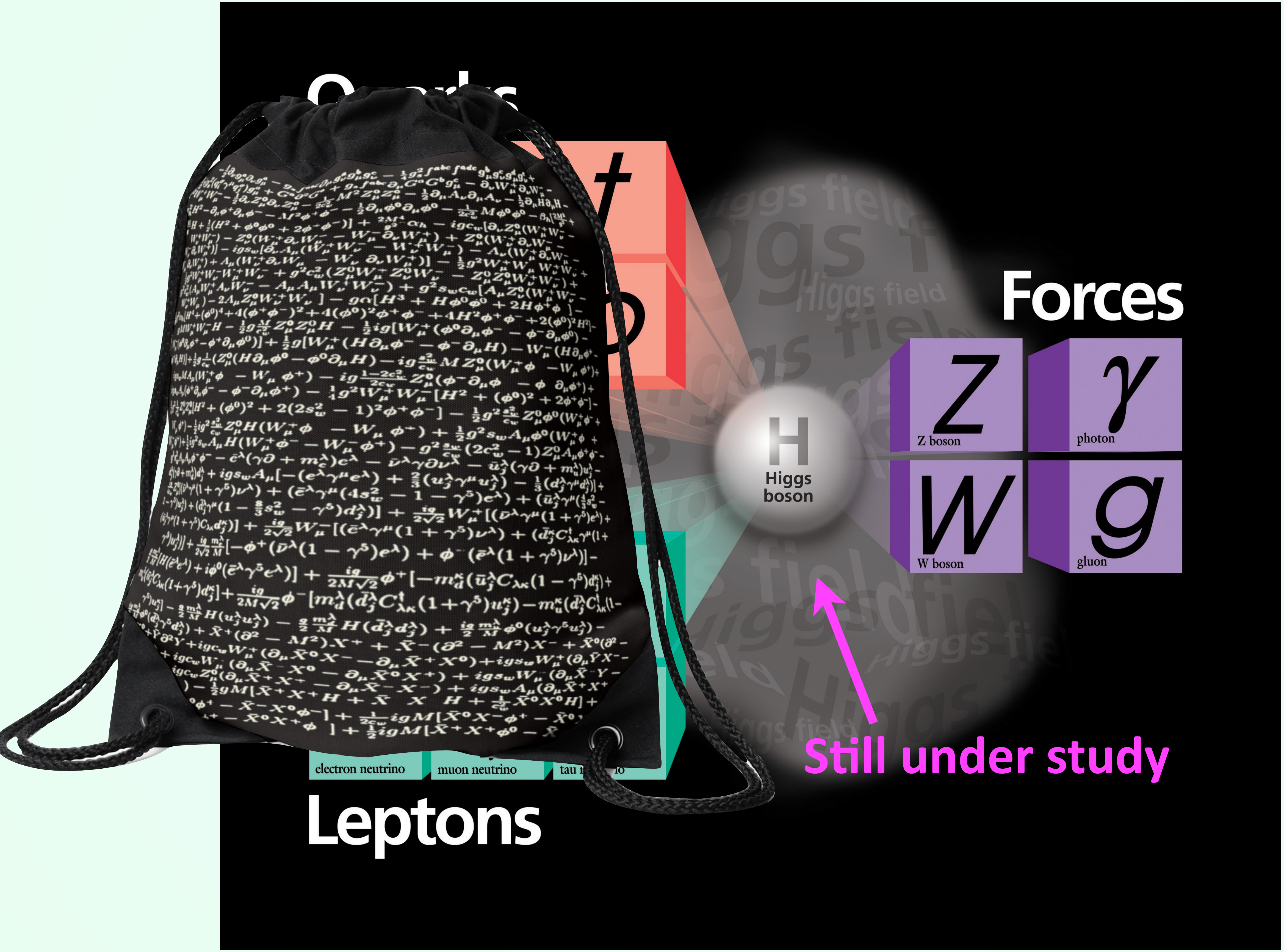


Still under study

Normal matter



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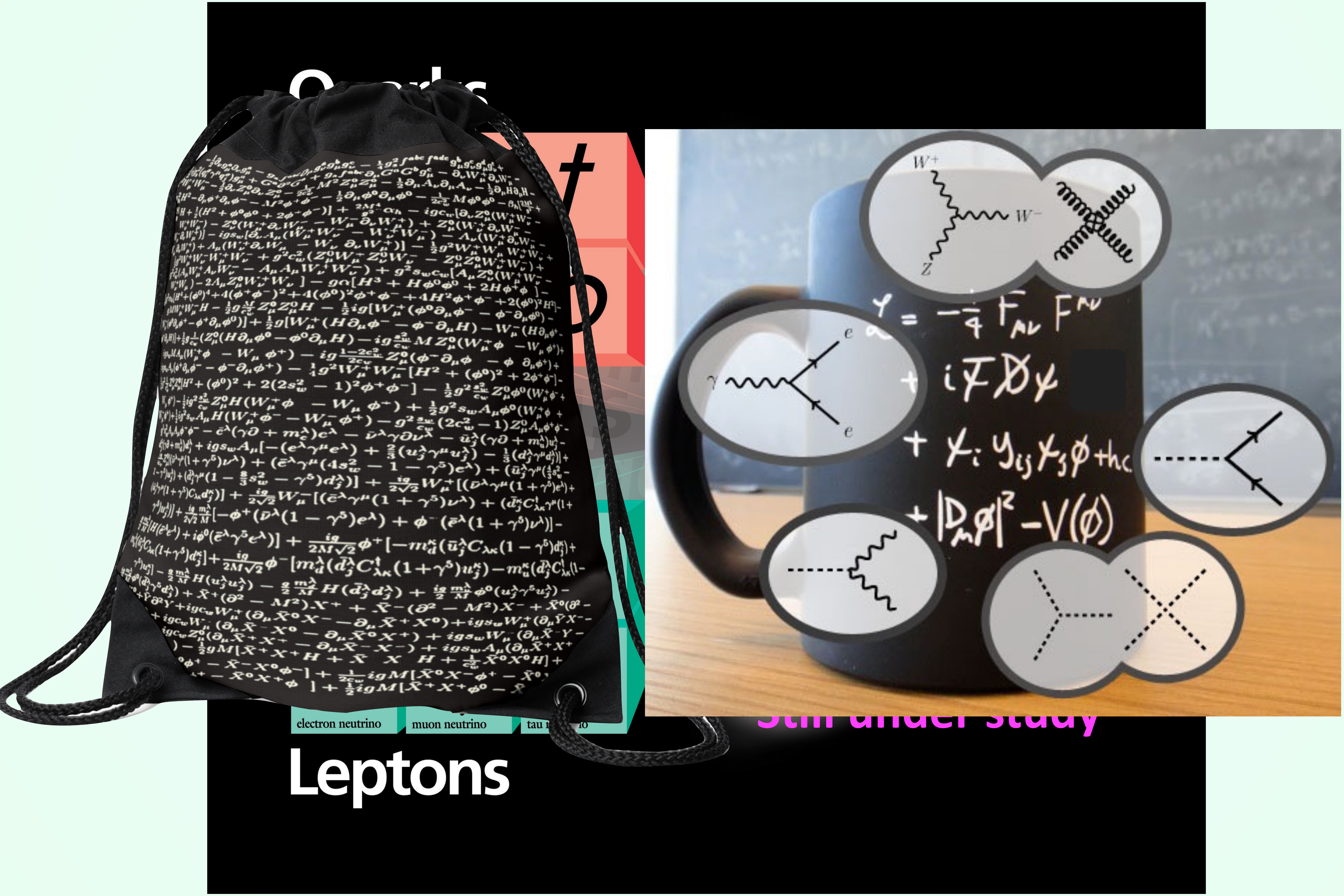

Many questions!

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Experimental Evidences

Theoretical Problems

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- Neutrino Masses

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- Baryon Asymmetry

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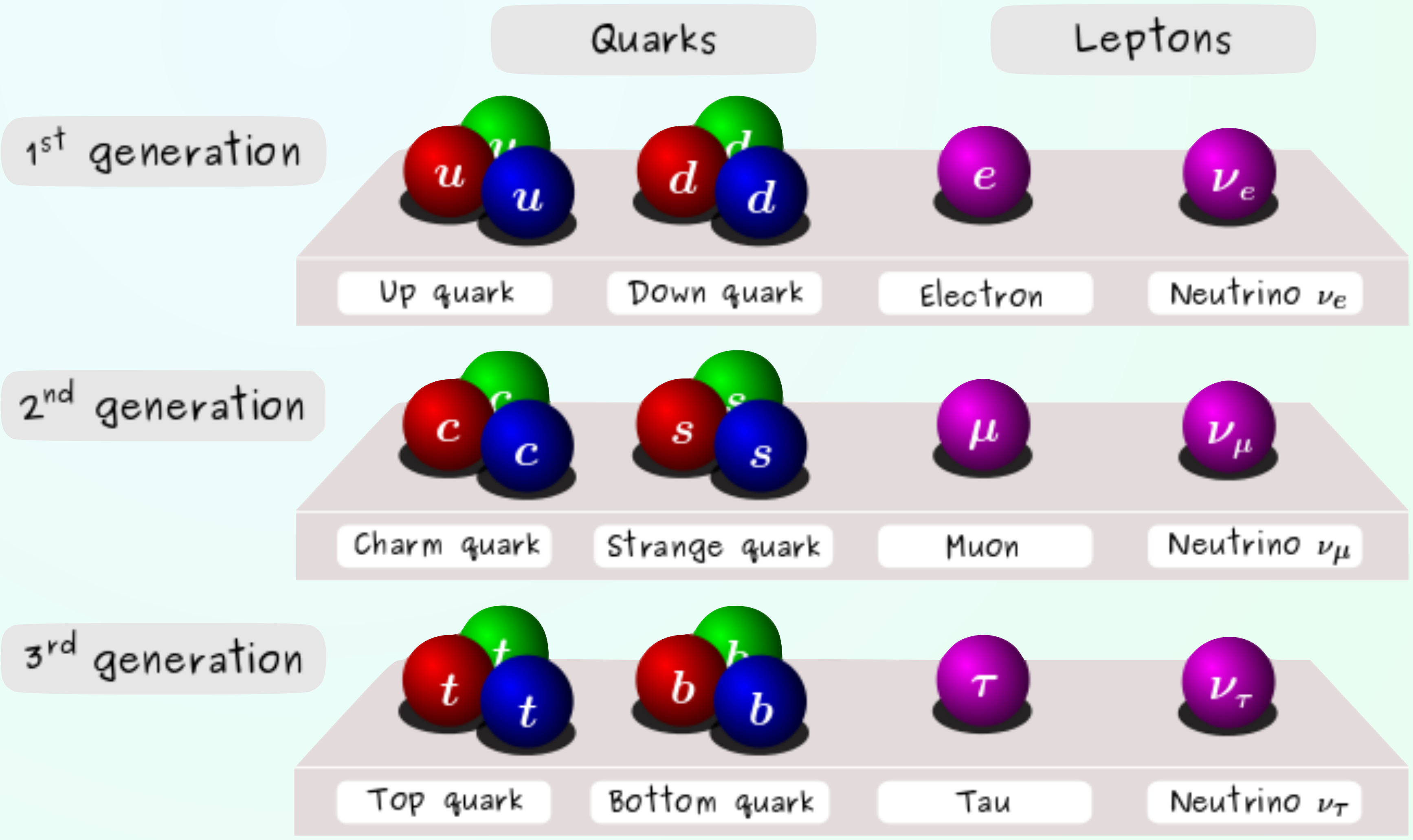
Theoretical Problems

- Why 3 generations?



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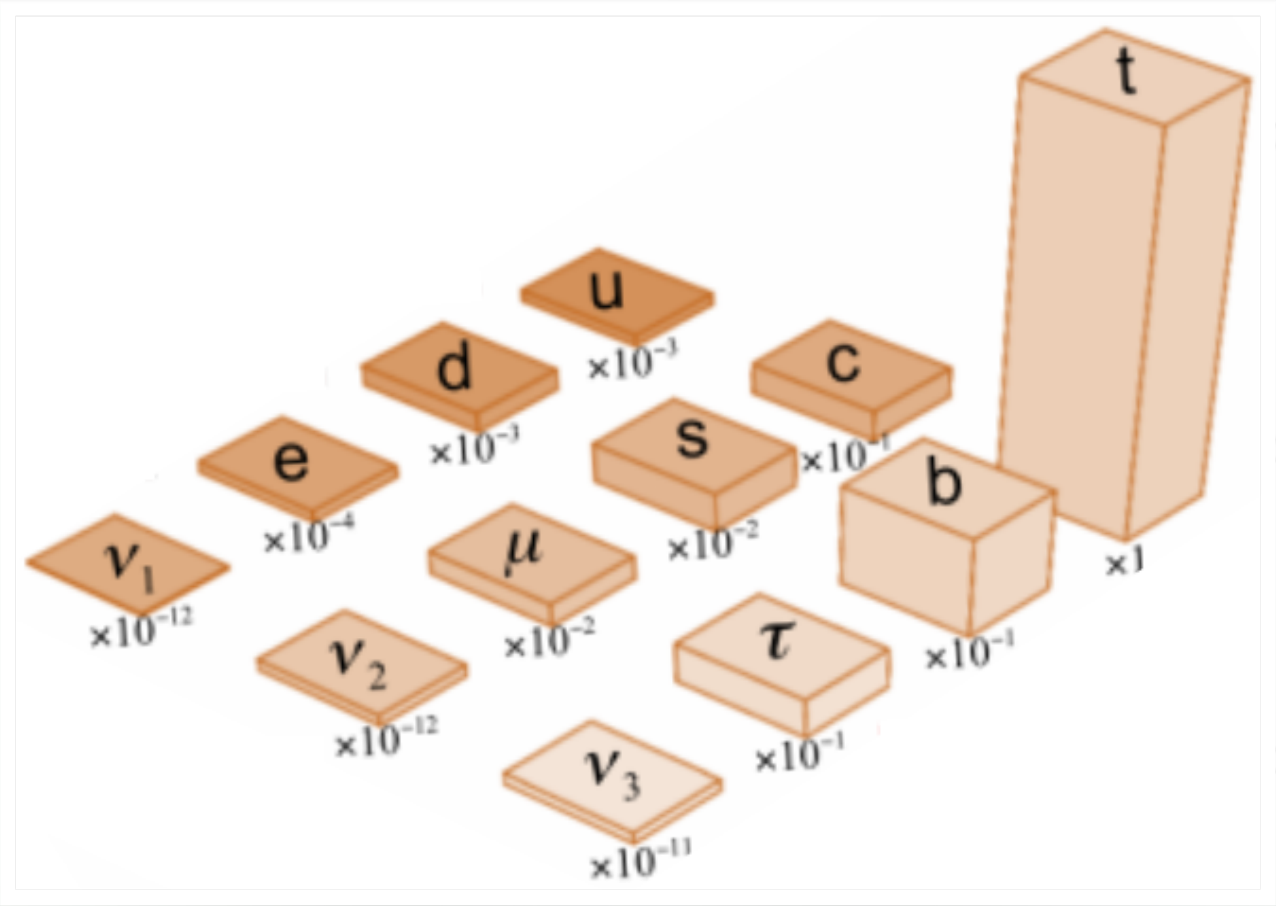
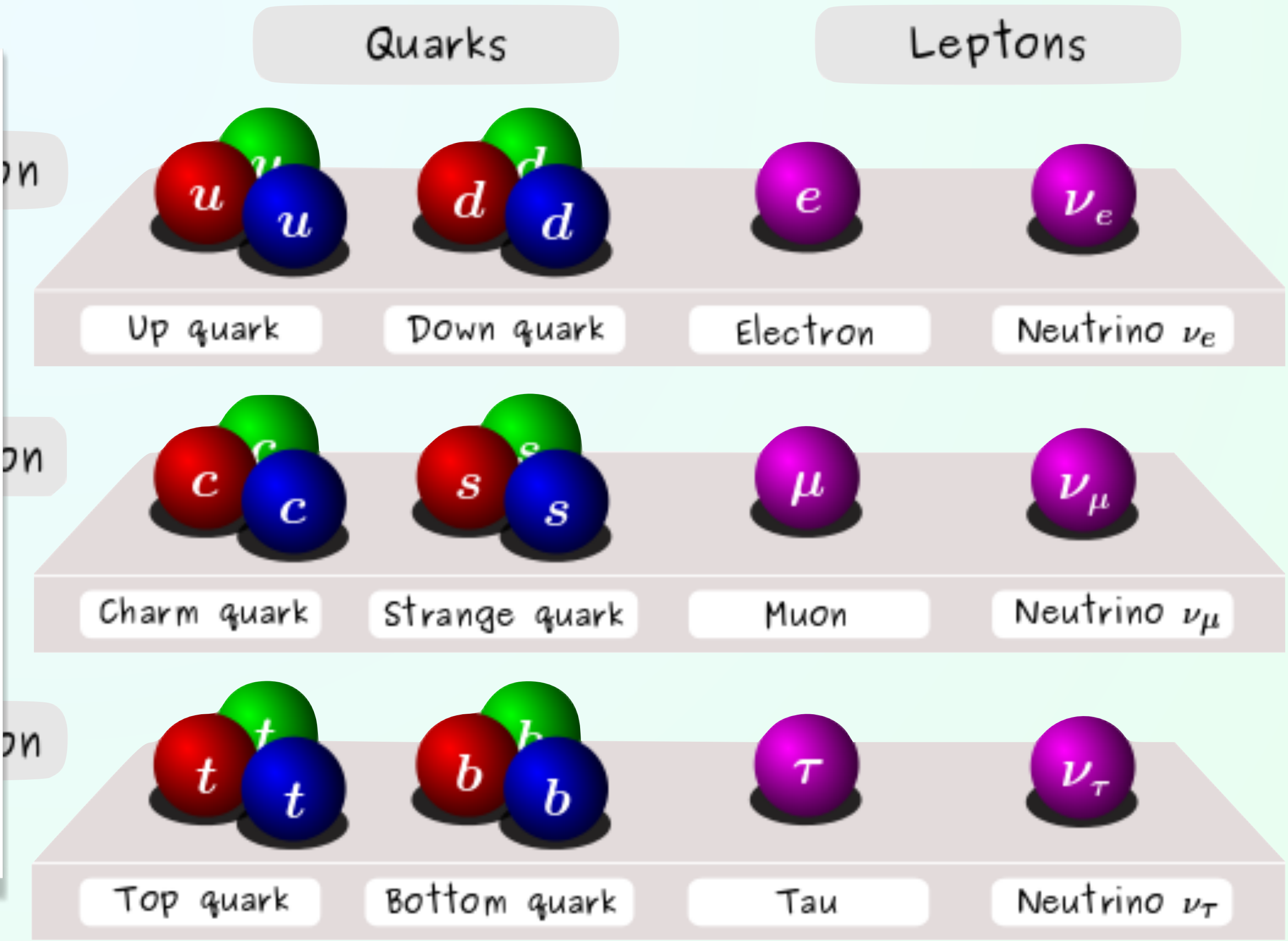


Theoretical Problems

Why 3 generations?

Why so different masses & mixings?



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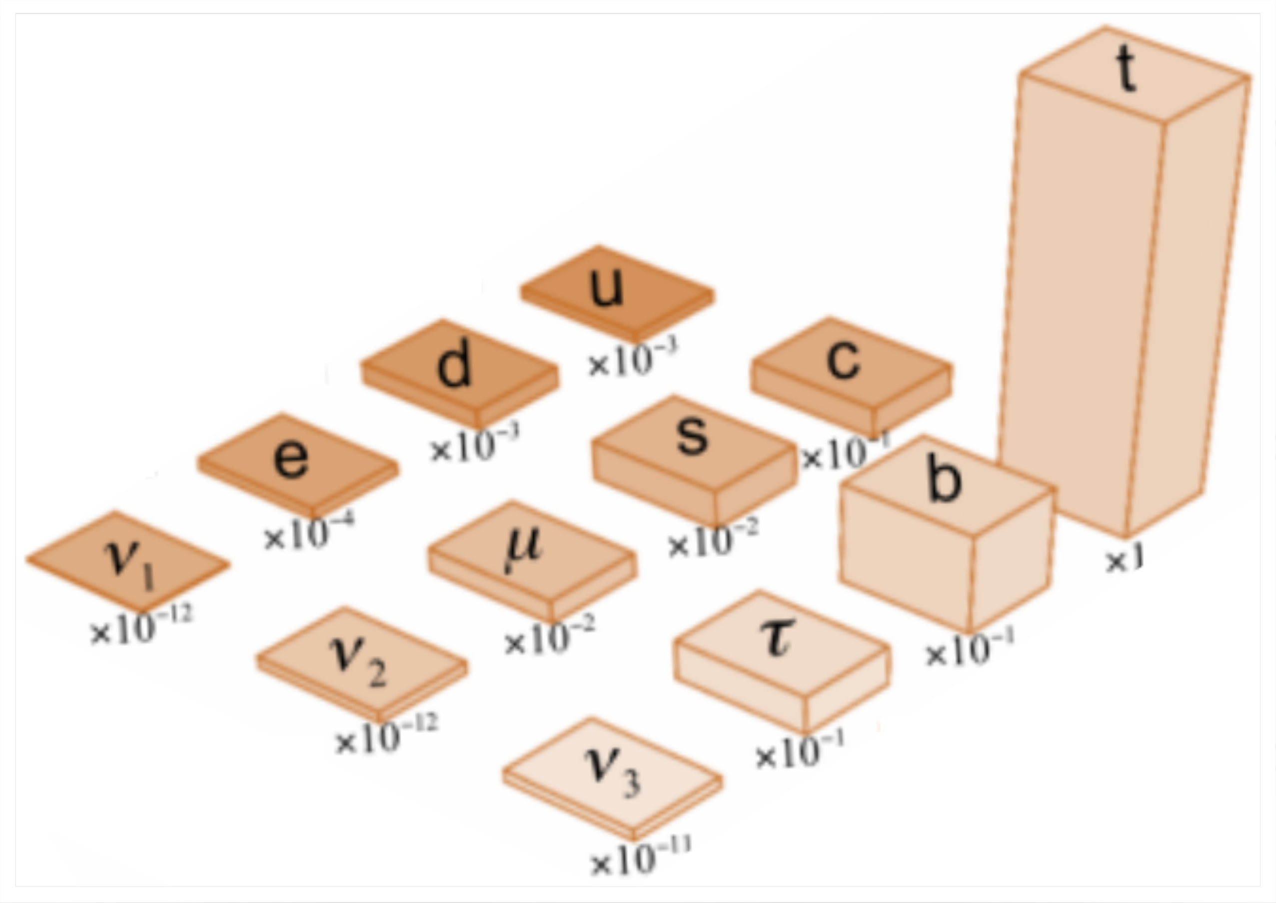
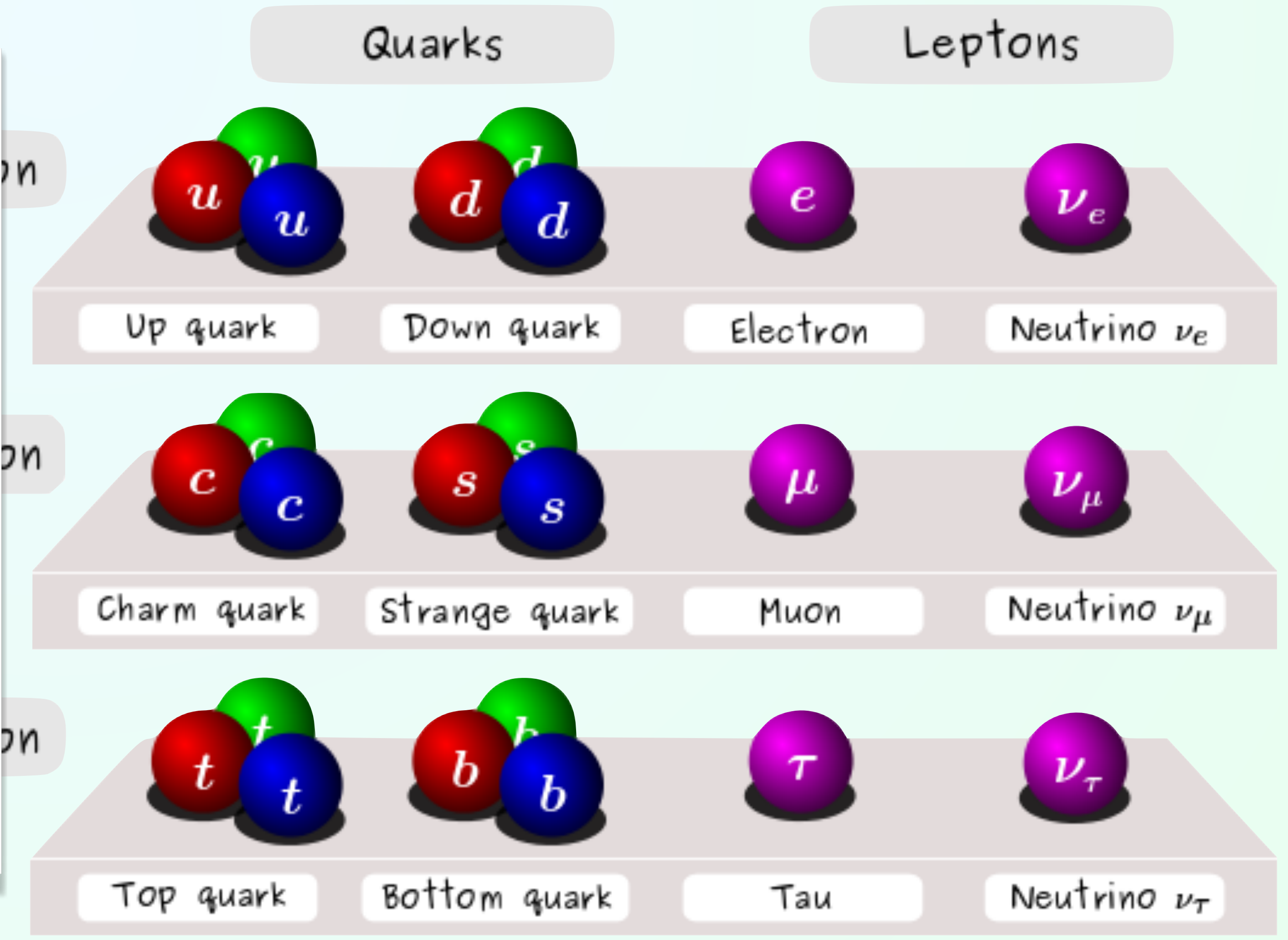
Flavour Puzzle





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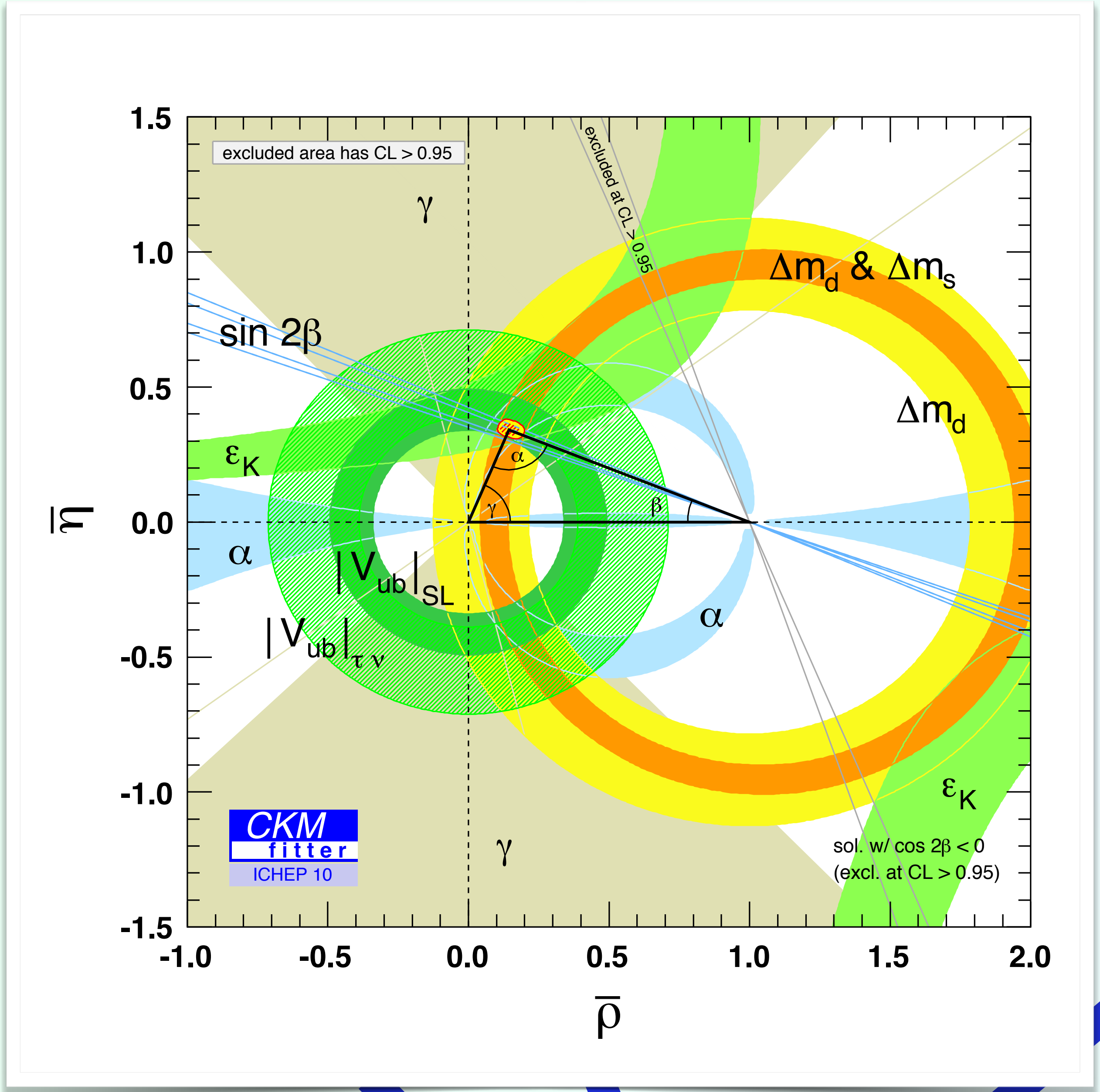

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NP Flavour Problem
(no FCNC in BSM)

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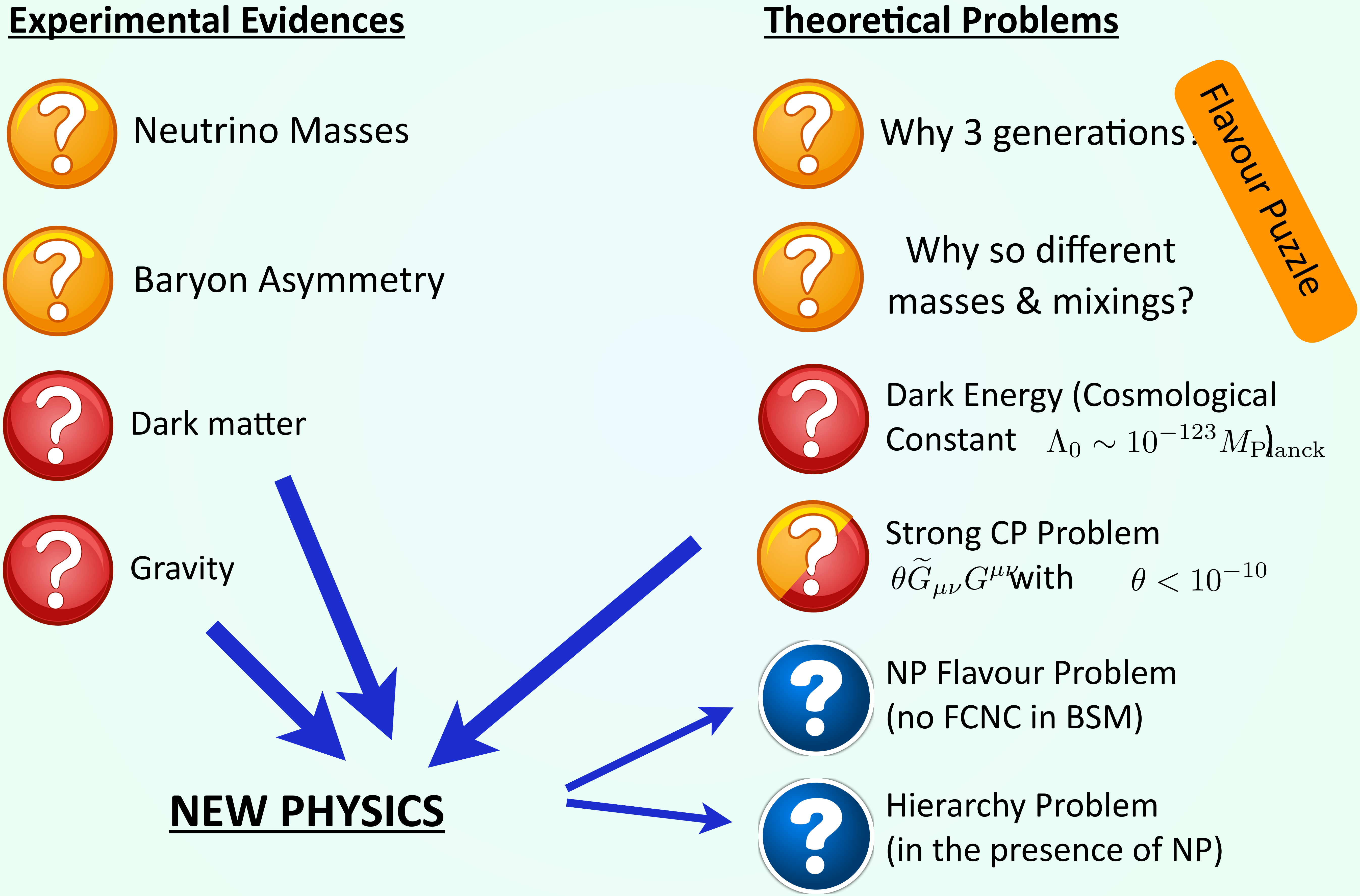

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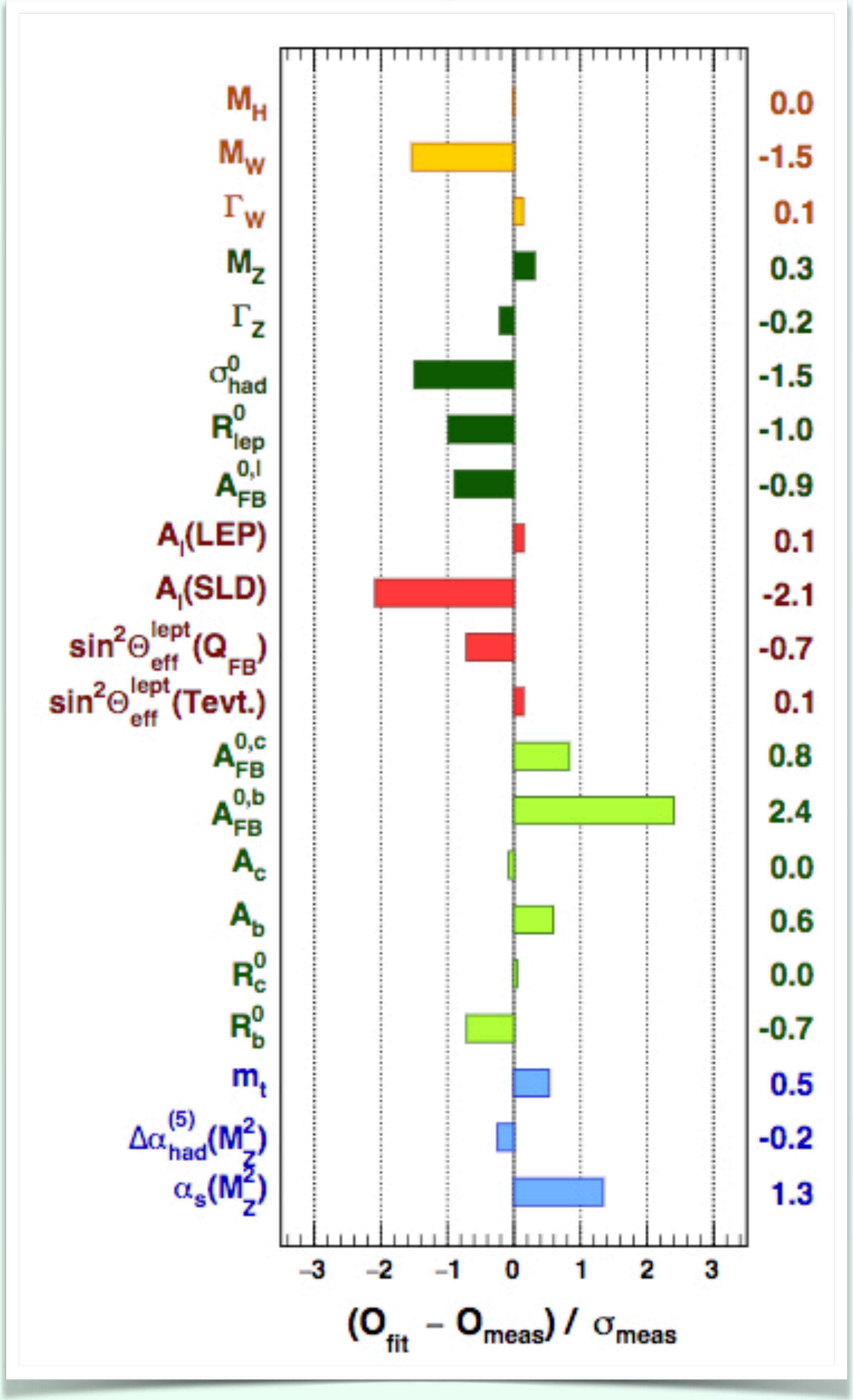
- Hierarchy Problem (in the presence of NP)

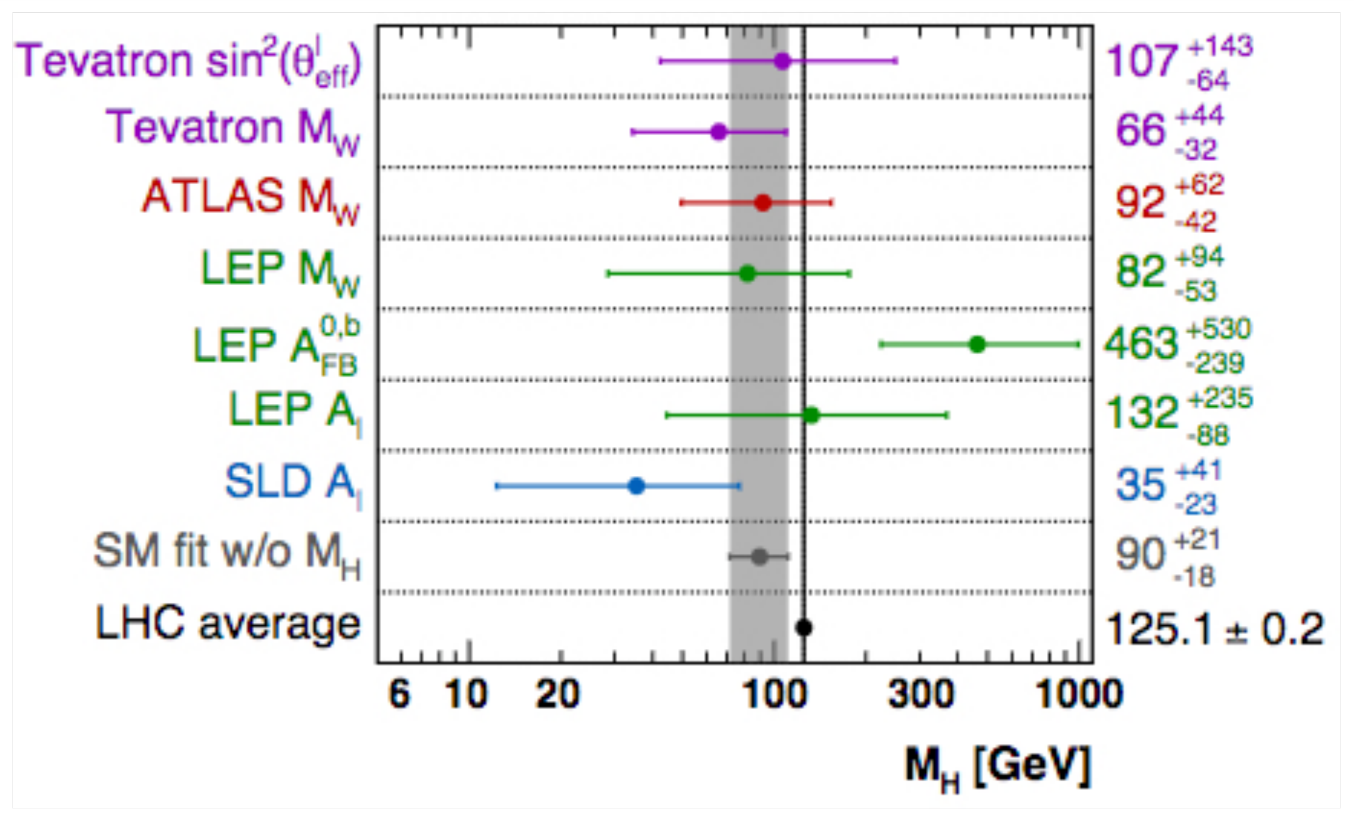
Flavour Puzzle

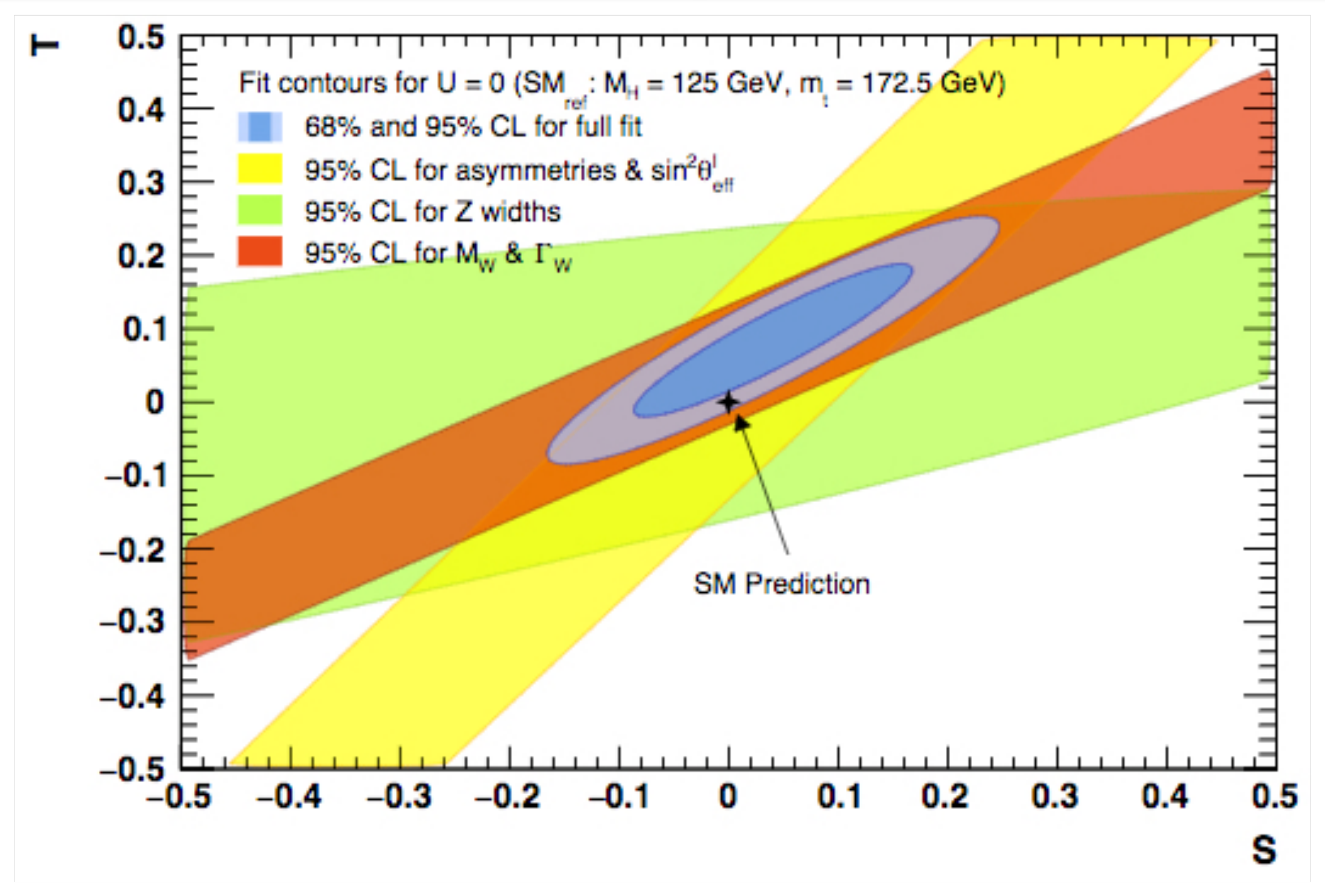
NEW PHYSICS

Amazing Standard Model

[The Gfitter group, 1803.01853]







Indirect Searches

Still no direct signals of New Physics

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Effective Field Theory

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Effective Field Theory

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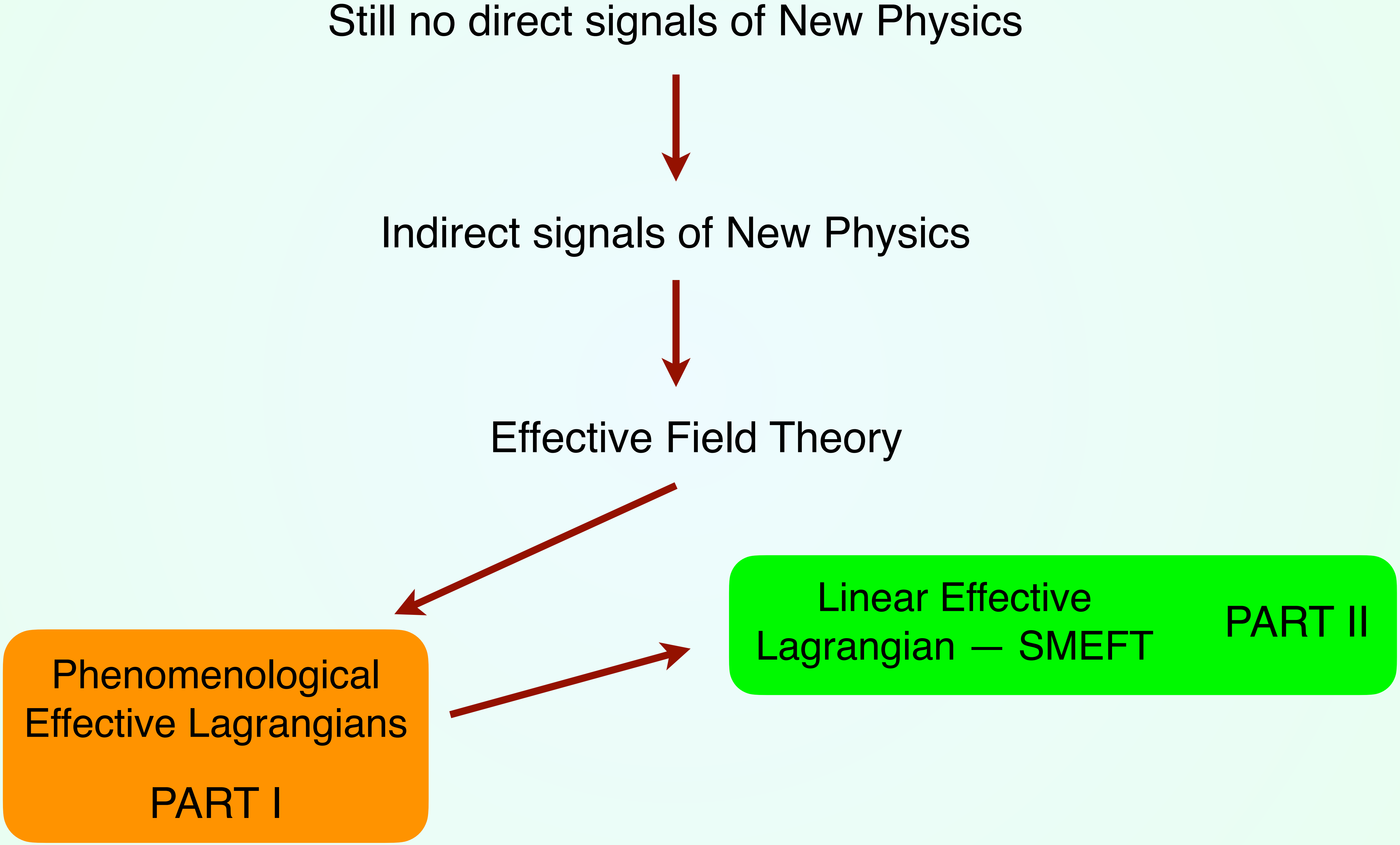
Phenomenological
Effective Lagrangians

PART I

Indirect Searches



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Effective Field Theory

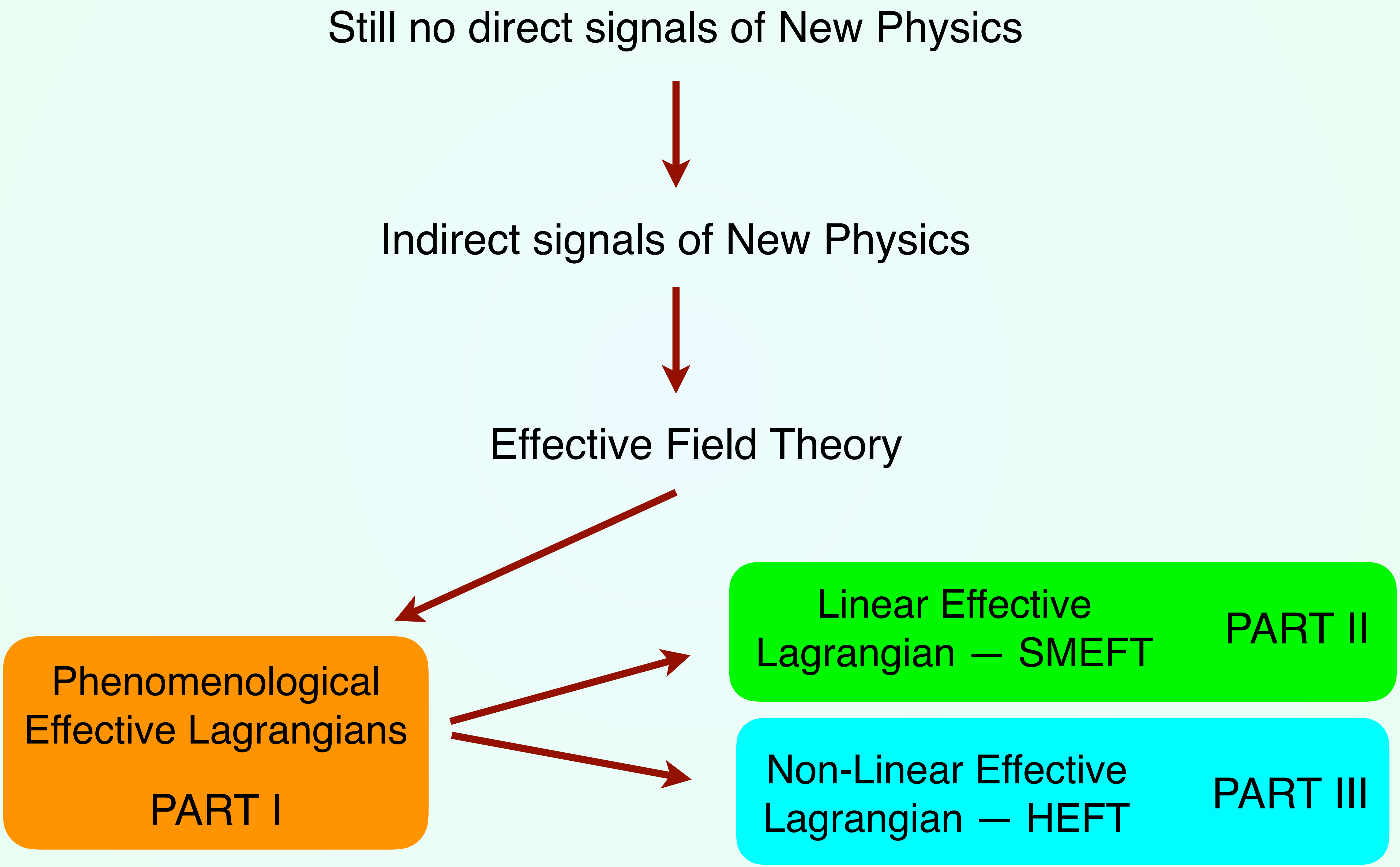
Phenomenological Effective Lagrangians

PART I

Linear Effective Lagrangian — SMEFT

PART II

Indirect Searches



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Effective Field Theory

Phenomenological Effective Lagrangians

PART I

Linear Effective Lagrangian — SMEFT

PART II

Non-Linear Effective Lagrangian — HEFT

PART III

Phenomenological Lagrangians

Collections of a series of couplings that can be used to translate data into Lagrangian parameters:

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Triple Gauge Vertices Lag. [Hagiwara, Peccei, Zeppenfeld & Hikasa, NPB282 (1987)]

$$\mathcal{L}_{WWV} = -\, i g_{WWV} \Big\{ g_1^V \left(W^+_{\mu\nu} W^{-\,\mu} V^\nu - W^+_\mu V_\nu W^{-\,\mu\nu} \right) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu}$$

$$- i g_5^V \epsilon^{\mu\nu\rho\sigma} \left(W^+_\mu \partial_\rho W^-_\nu - W^-_\nu \partial_\rho W^+_\mu \right) V_\sigma + g_6^V \left(\partial_\mu W^{+\mu} W^{-\nu} - \partial_\mu W^{-\mu} W^{+\nu} \right) V_\nu \Big\}$$

$$V \equiv \{\gamma, Z\} \qquad g_{WW\gamma} \equiv e = g s_W \qquad g_{WWZ} = g c_W$$

The SM values are: $g_1^Z = \kappa_\gamma = \kappa_Z = 1$ and $g_5^Z = g_6^\gamma = g_6^Z = 0$

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NOT $SU(2)_L \times U(1)_Y$ invariant, but just $U(1)_{em}$

The gauge bosons are not always written by means of the gauge field strengths

Δ (k) — Formalism

Higgs triple vertices with gauge bosons — HVV

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When considering only the SM couplings:

[Lafaye, Plehn, Rauch, Zerwas & Dührssen, JHEP 0908 (2009)]

SFITTER

$$\left\{\begin{array}{l} g_{xxh} \equiv g_x = g_x^{SM}(1+\Delta_x) \\ \\ g_{\gamma\gamma h} \equiv g_\gamma = g_\gamma^{SM}(1+\Delta_\gamma^{SM}+\Delta_\gamma) \\ \\ g_{ggh} \equiv g_g = g_g^{SM}(1+\Delta_g^{SM}+\Delta_g) \end{array}\right.$$

tree-level couplings

loop-induced couplings

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$$\left(\text{Equivalent parameters} \quad \kappa_x \equiv 1+\Delta_x \right)$$

[LHC Higgs Cross Section Working Group, arXiv:1209.0040]

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→

$$\mathcal{L} = \mathcal{L}_{SM} + \Delta_W g m_W h W^\mu W_\mu + \Delta_Z \frac{g}{2c_W} m_Z h Z^\mu Z_\mu - \sum_{\tau,b,t} \Delta_f \frac{m_f}{v} h \left(\bar{f}_R f_L + \text{h.c.}\right) +$$

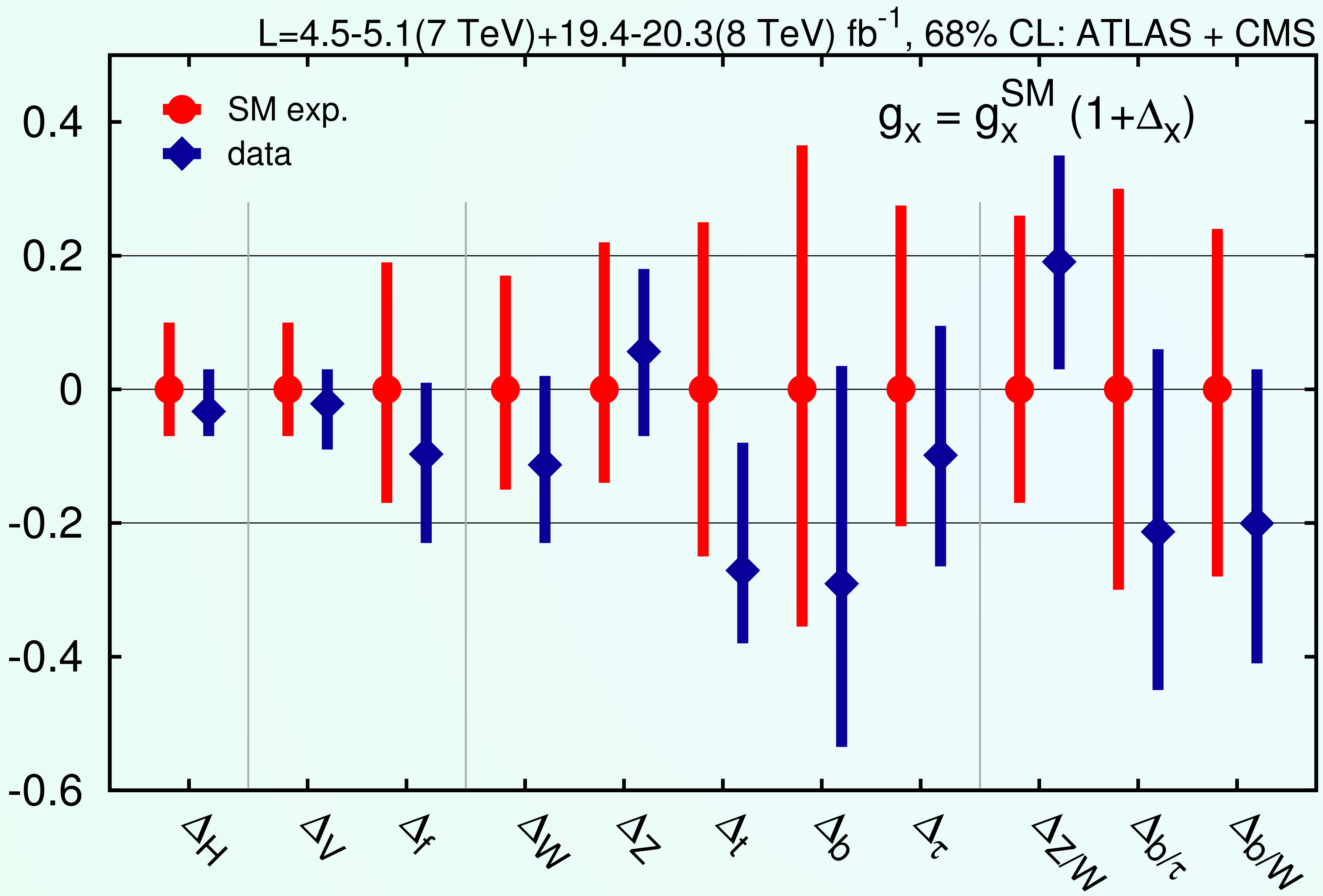
$$+ g_g^{SM} \Delta_g \frac{h}{v} G^{\mu\nu} G_{\mu\nu} + g_\gamma^{SM} \Delta_\gamma \frac{h}{v} A^{\mu\nu} A_{\mu\nu} + \dots$$

Again, NOT $SU(2)_L \times U(1)_Y$ invariant, but just $U(1)_{em}$.

Results with $\Delta_g=0=\Delta_\gamma$

[Corbett, Eboli, Gonçalves, Gonzalez-Fraile, Plehn, & Rauch, JHEP 1508 (2015)]

Analyses based on **event rates** from ATLAS and CMS:



production/decay mode

$H \to WW$

$H \to ZZ$

$H \to \gamma\gamma$

$H \to \tau\bar{\tau}$

$H \to b\bar{b}$

$H \to Z\gamma$

$H \to$ invisible

$t\bar{t}H$ production

kinematic distributions

SM exp. are obtained injecting the SM Higgs signal on top of the background.

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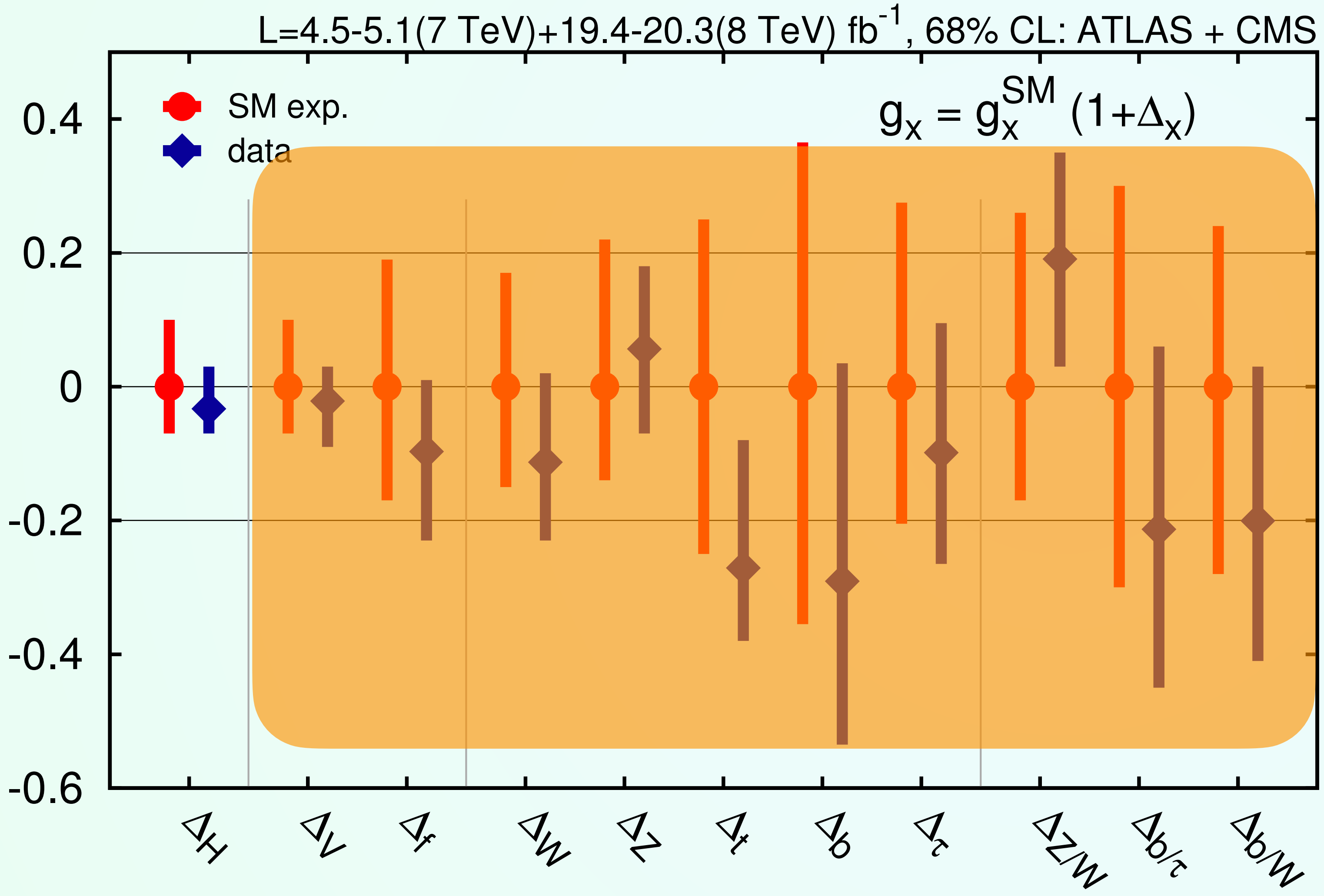

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kinematic distributions

First analysis: universal modifications of *h* couplings

→ Extended Higgs sector, e.g. extra Singlet, $\Delta_H \approx 3\%$

Results with $\Delta_g=0=\Delta_\gamma$

[Corbett, Eboli, Gonçalves, Gonzalez-Fraile, Plehn, & Rauch, JHEP 1508 (2015)]

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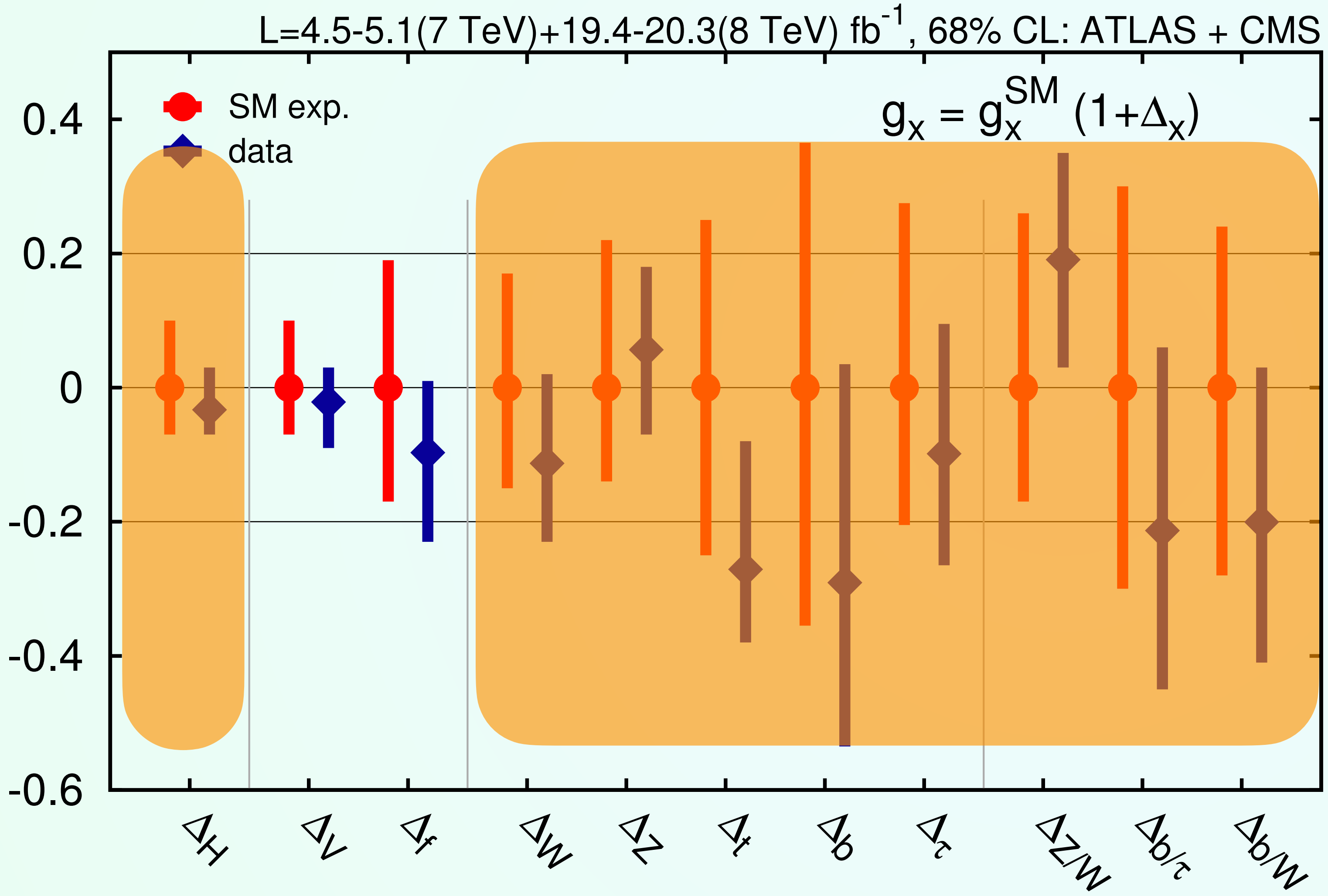

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kinematic distributions

Second analysis: universal modifications with gauge bosons and fermions

→ SU(2)$_L$ scalar triplet or similar:

$\Delta_V \approx \pm 6\%$

$\Delta_f \approx \pm 12\%$

Results with $\Delta_g=0=\Delta_\gamma$

[Corbett, Eboli, Gonçalves, Gonzalez-Fraile, Plehn, & Rauch, JHEP 1508 (2015)]

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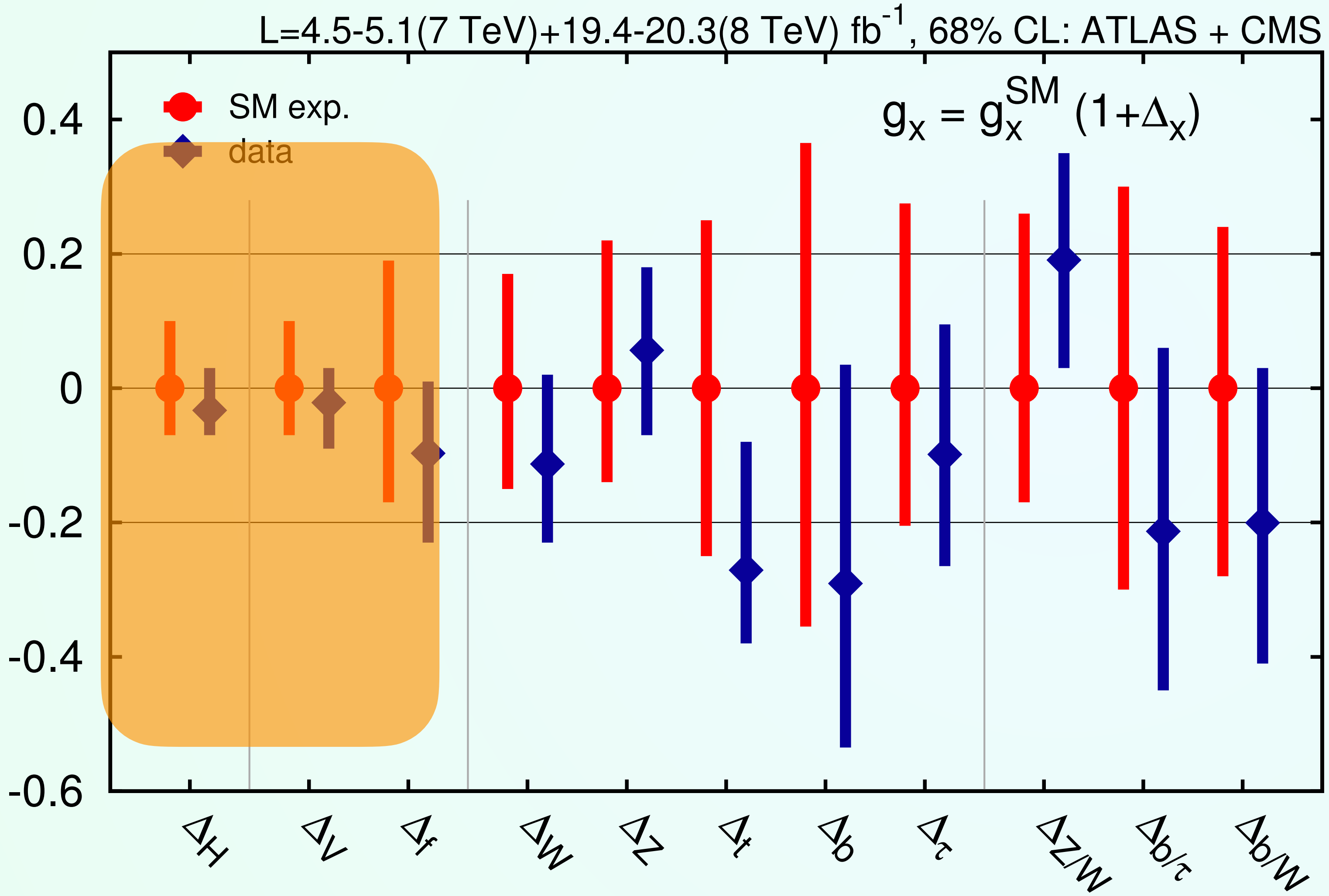

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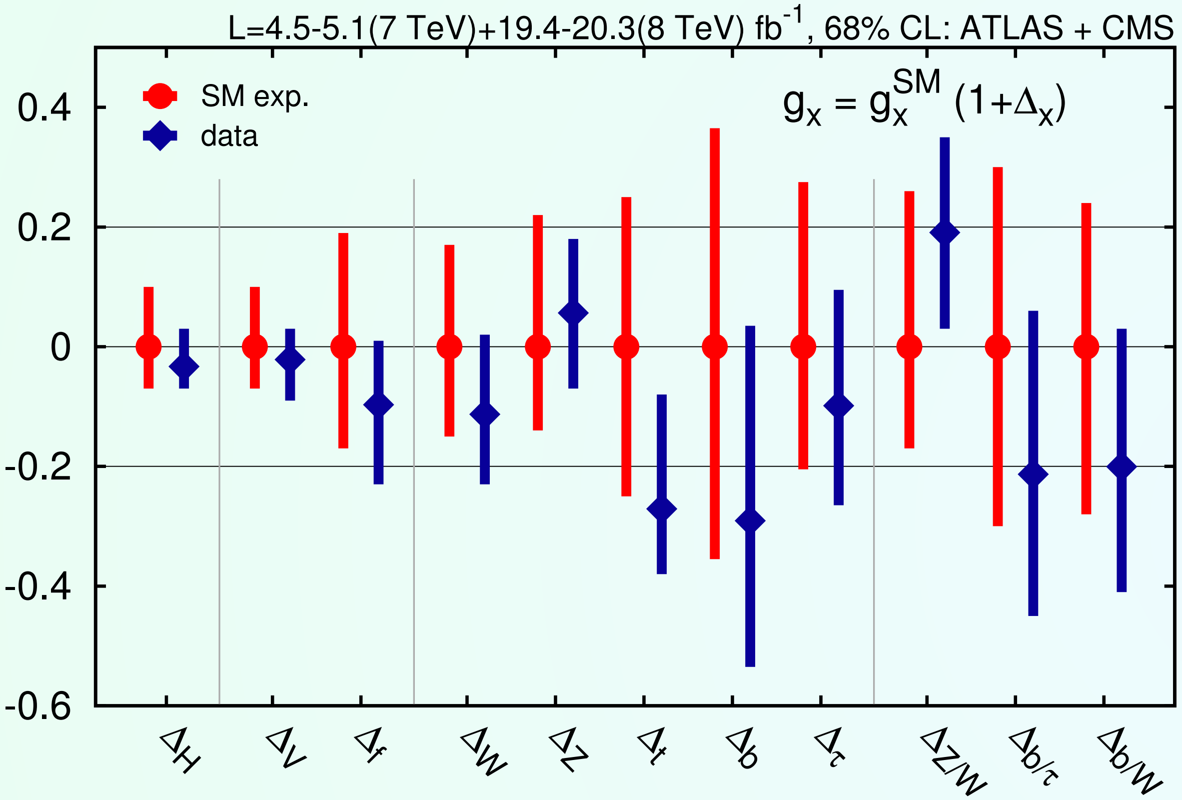
Third analysis: independent modifications of *h* couplings

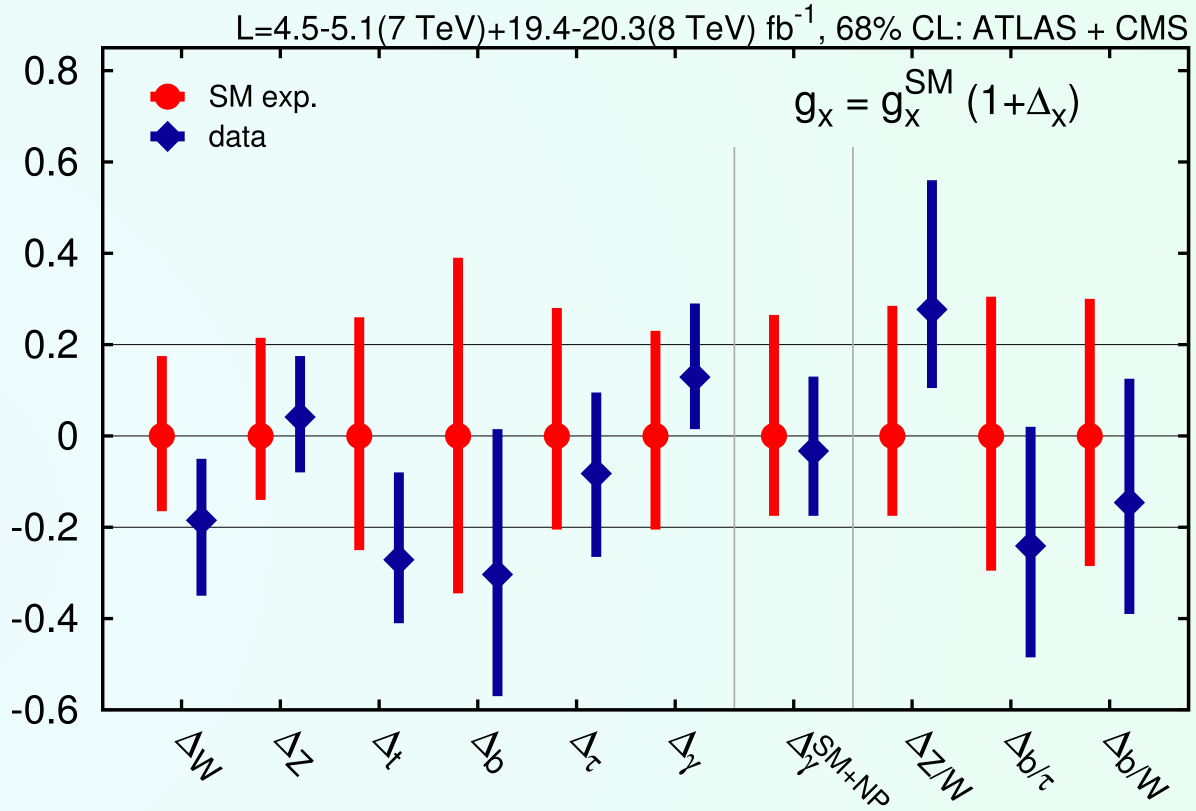
The ratios remove systematic and theo uncertainties

Results with $\Delta_g=0$, $\Delta_\gamma\neq0$

[Corbett, Eboli, Gonçalves, Gonzalez-Fraile, Plehn, & Rauch, JHEP 1508 (2015)]

$h\gamma\gamma$ is well measured: variation of SM couplings (t, b, W) + NP contributions





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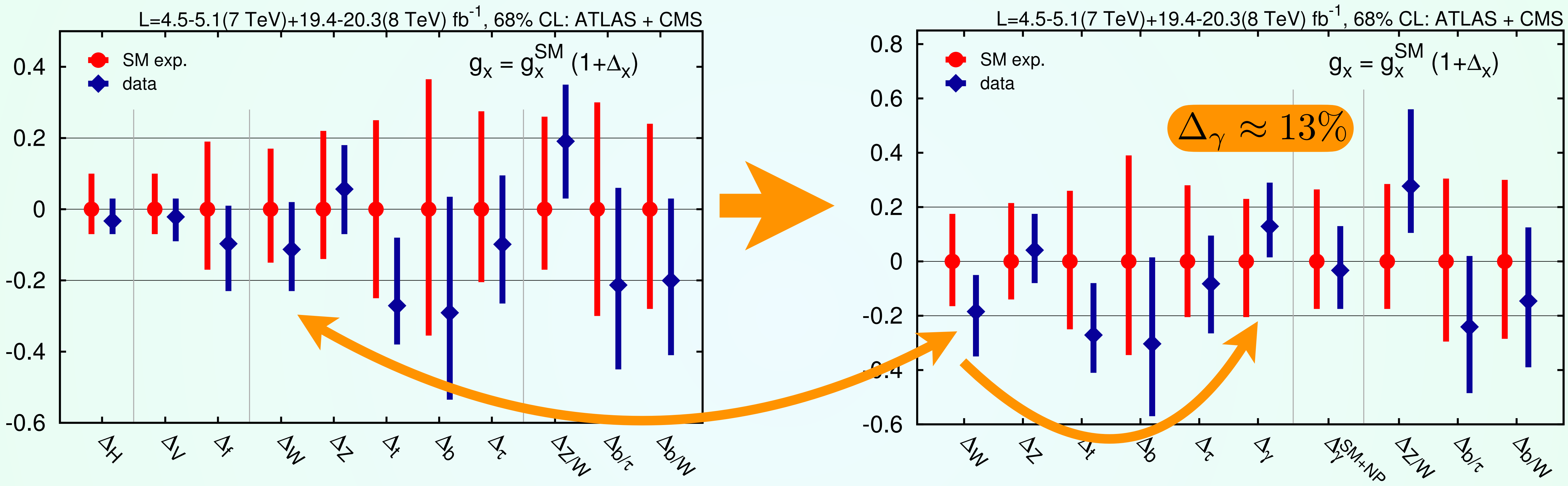

The addition of a new parameter allows larger changes in the SM couplings, but the final combination for hγγ is very compatible with the SM exp.

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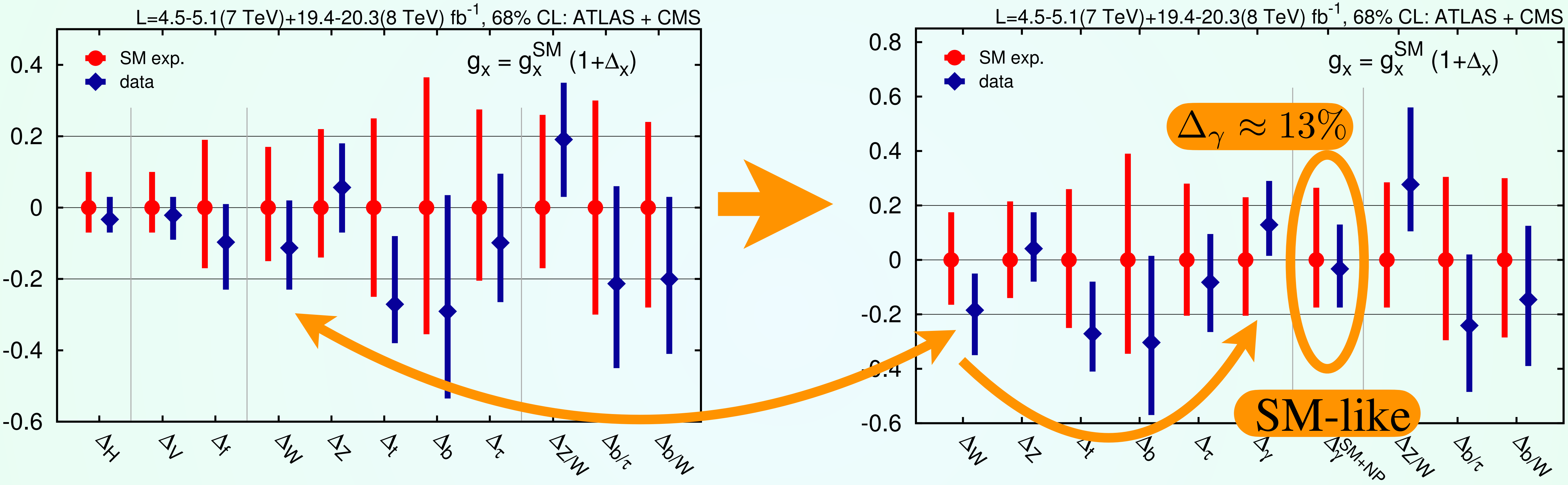

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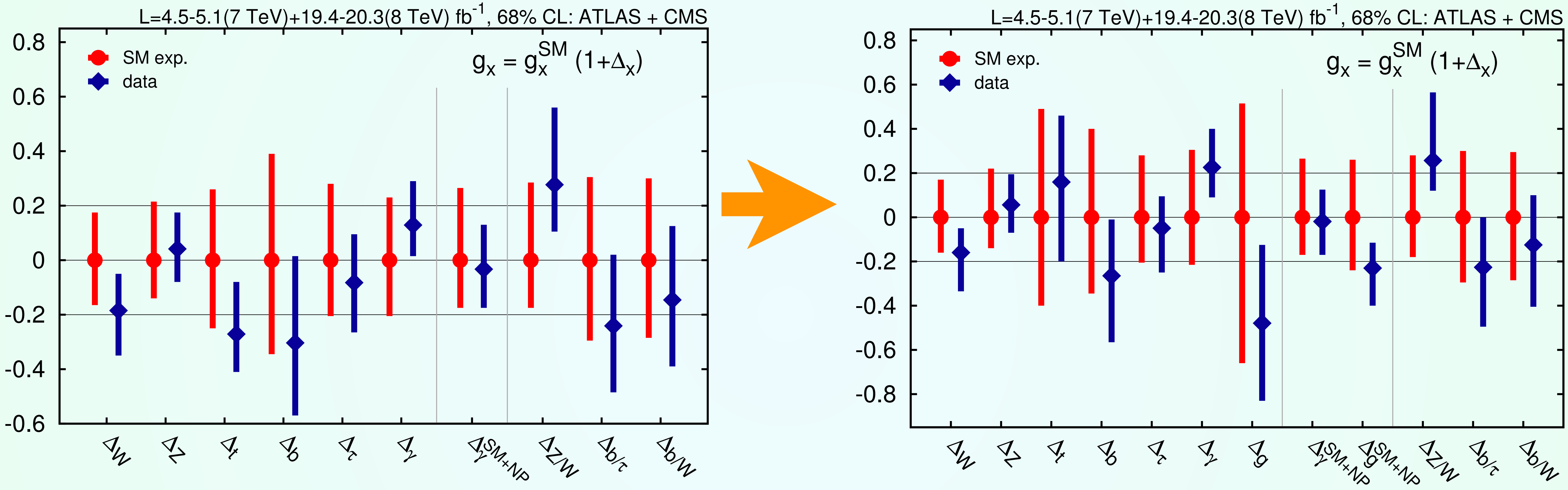

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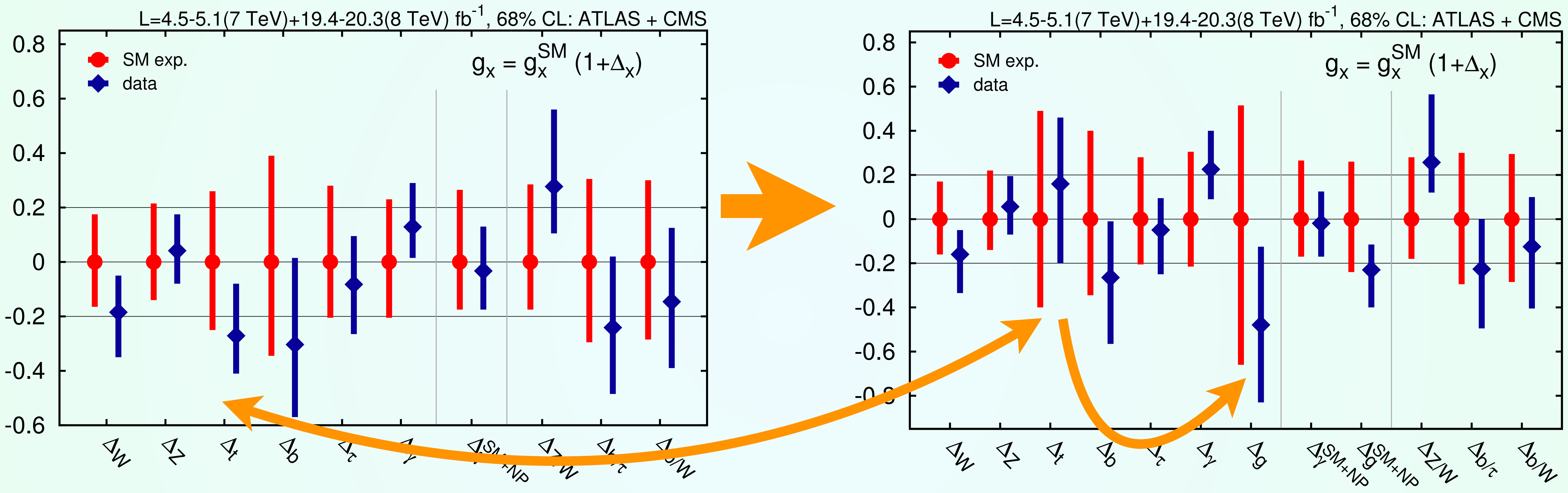

Δ_t has much larger error bar ⟷ large deviation in Δ_g

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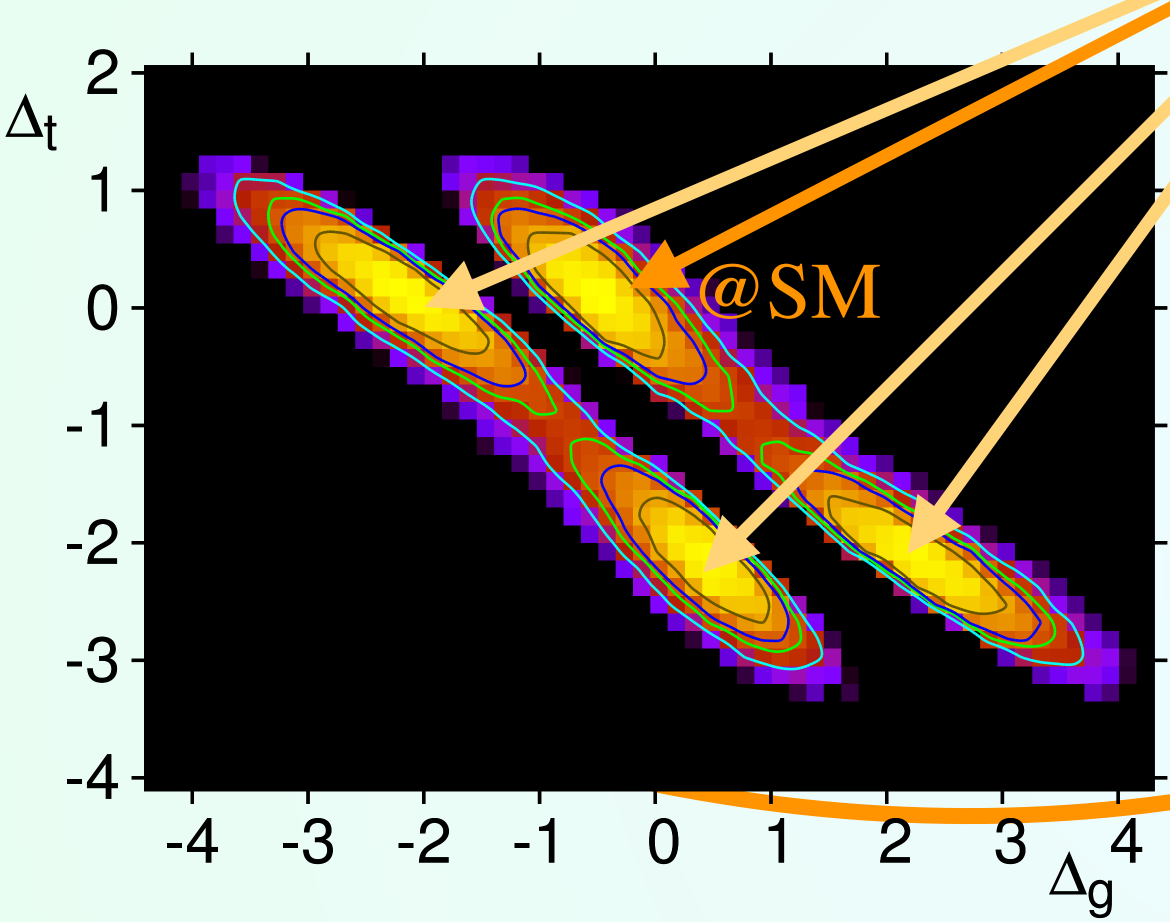
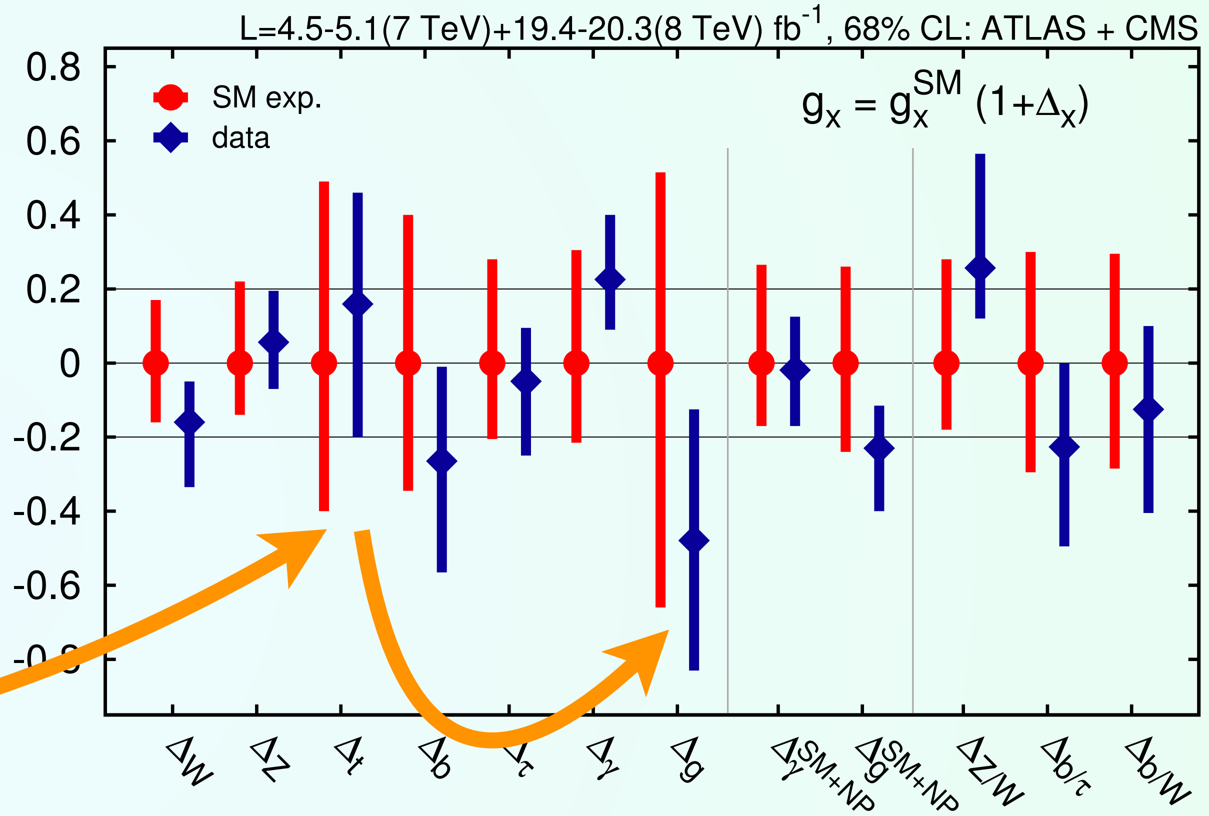
Adding new physics into hgg:

four degenerate vacua!





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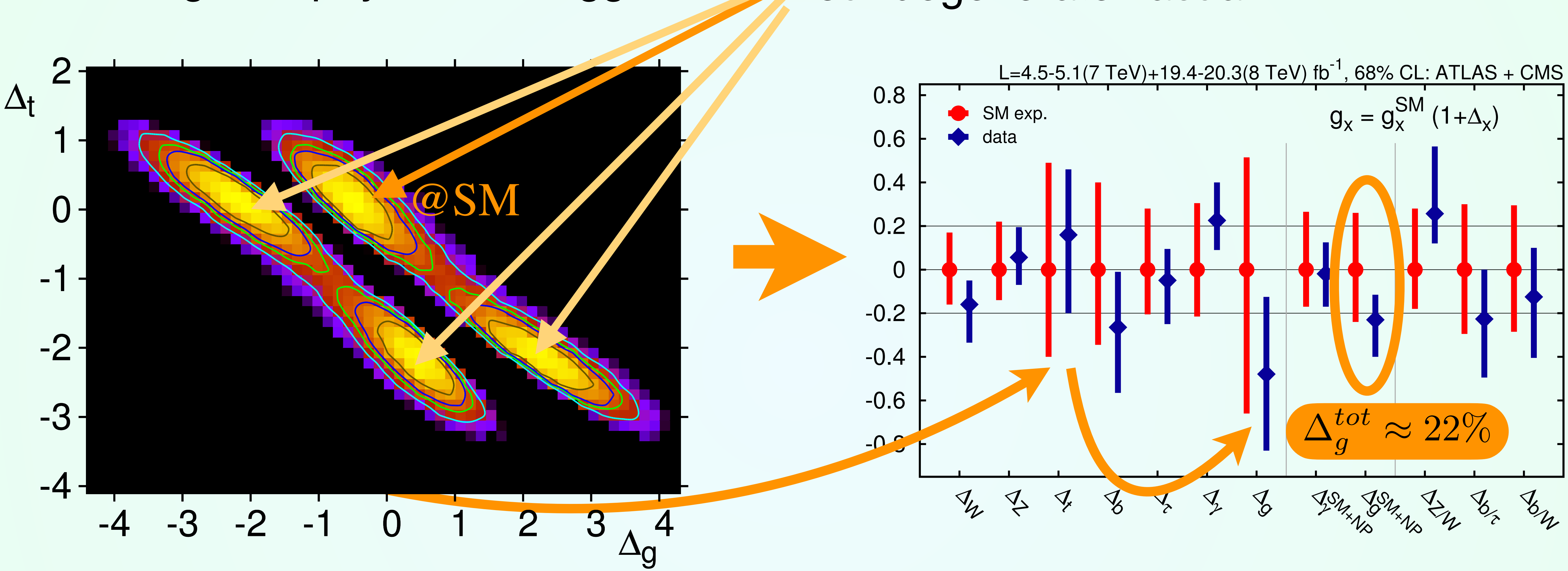

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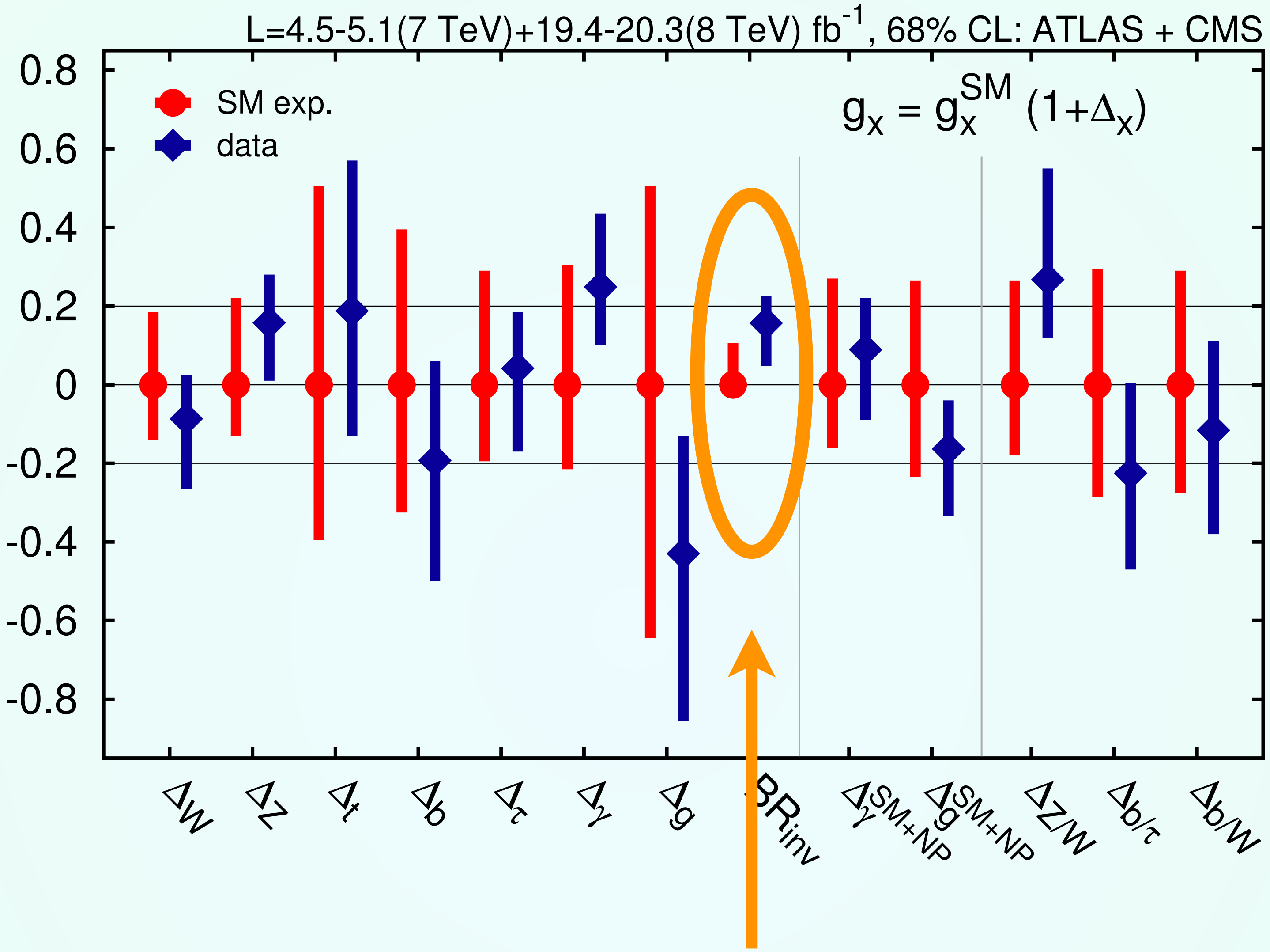
Adding the Higgs invisible BR

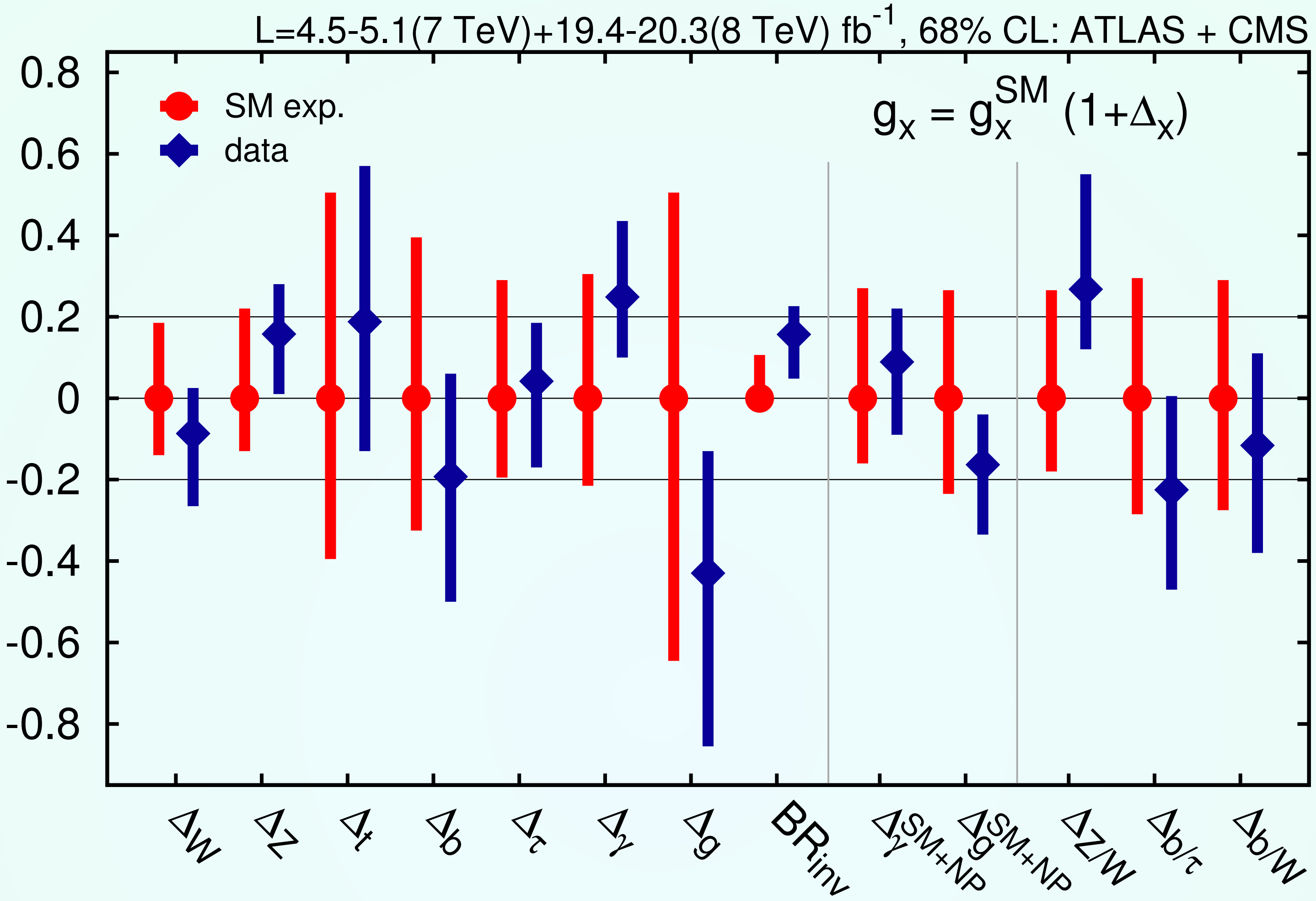
[Corbett, Eboli, Gonçalves, Gonzalez-Fraile, Plehn, & Rauch, JHEP 1508 (2015)]



The SM prediction essentially consists in $h \to ZZ^* \to 4\nu$, $BR(h \to \text{Inv}) \approx 1\%$

The results of the fit gives $BR(h \to \text{Inv}) \approx 10\%$, without affecting much the other couplings.

Final Remarks



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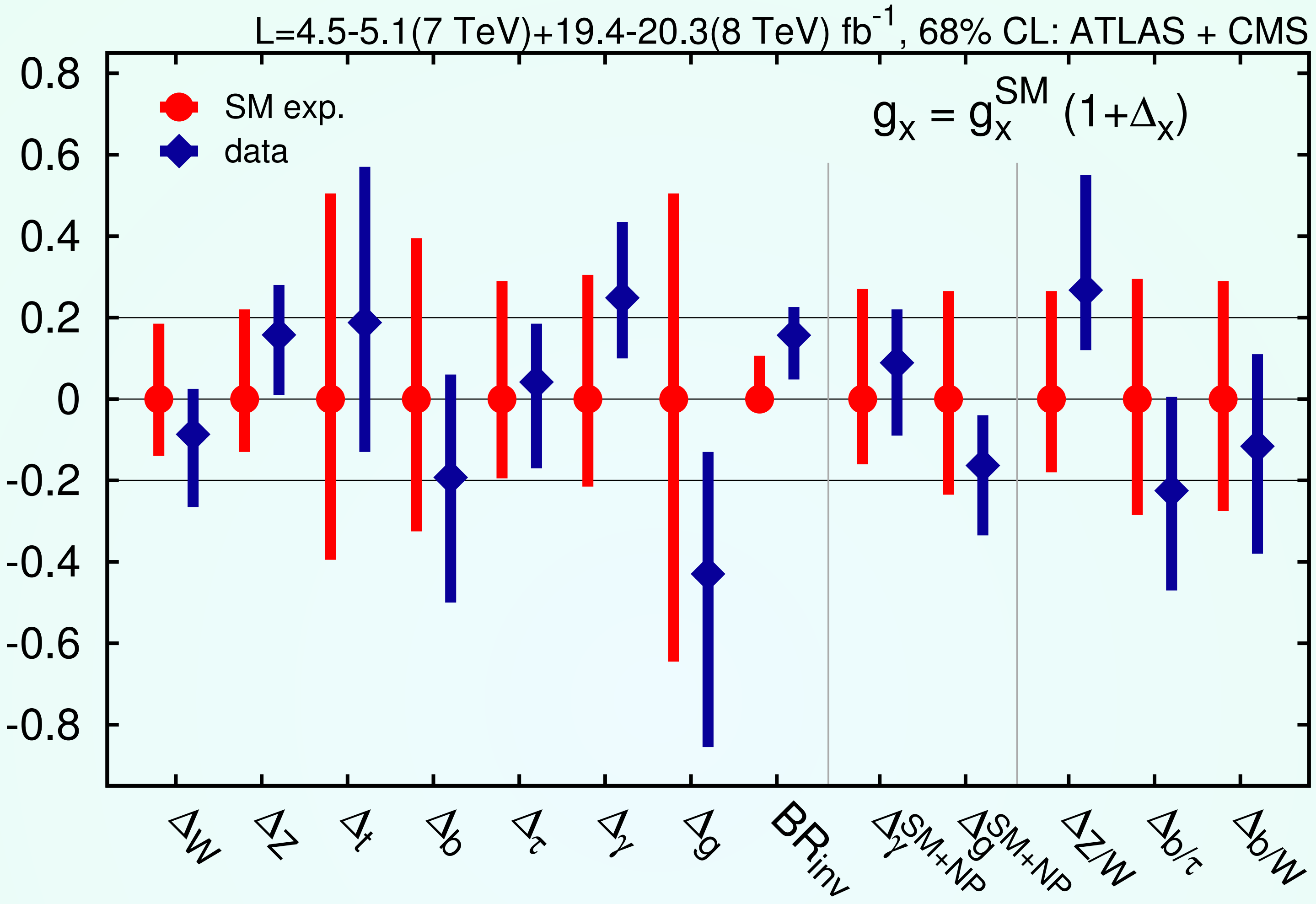

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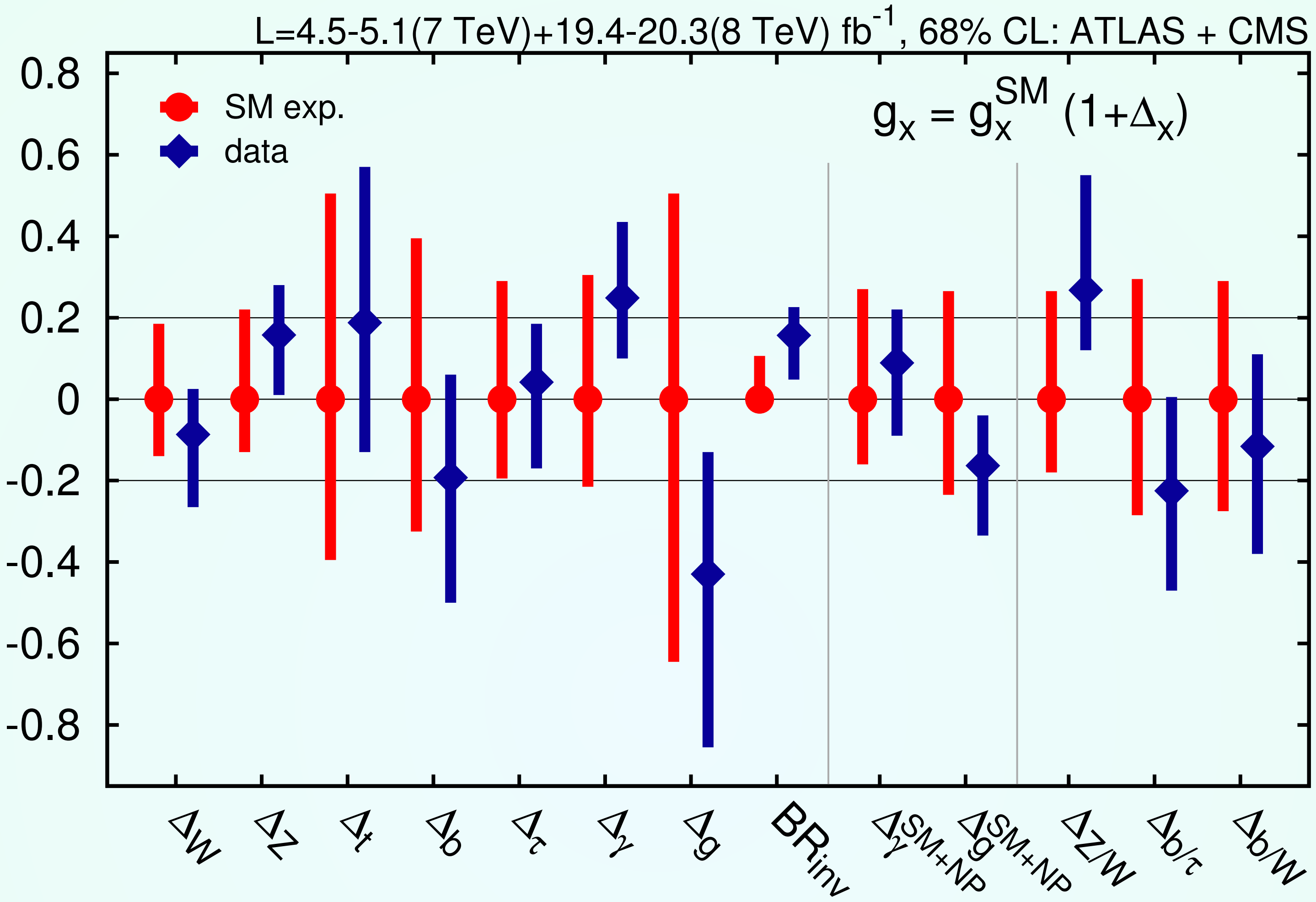
Final Remarks



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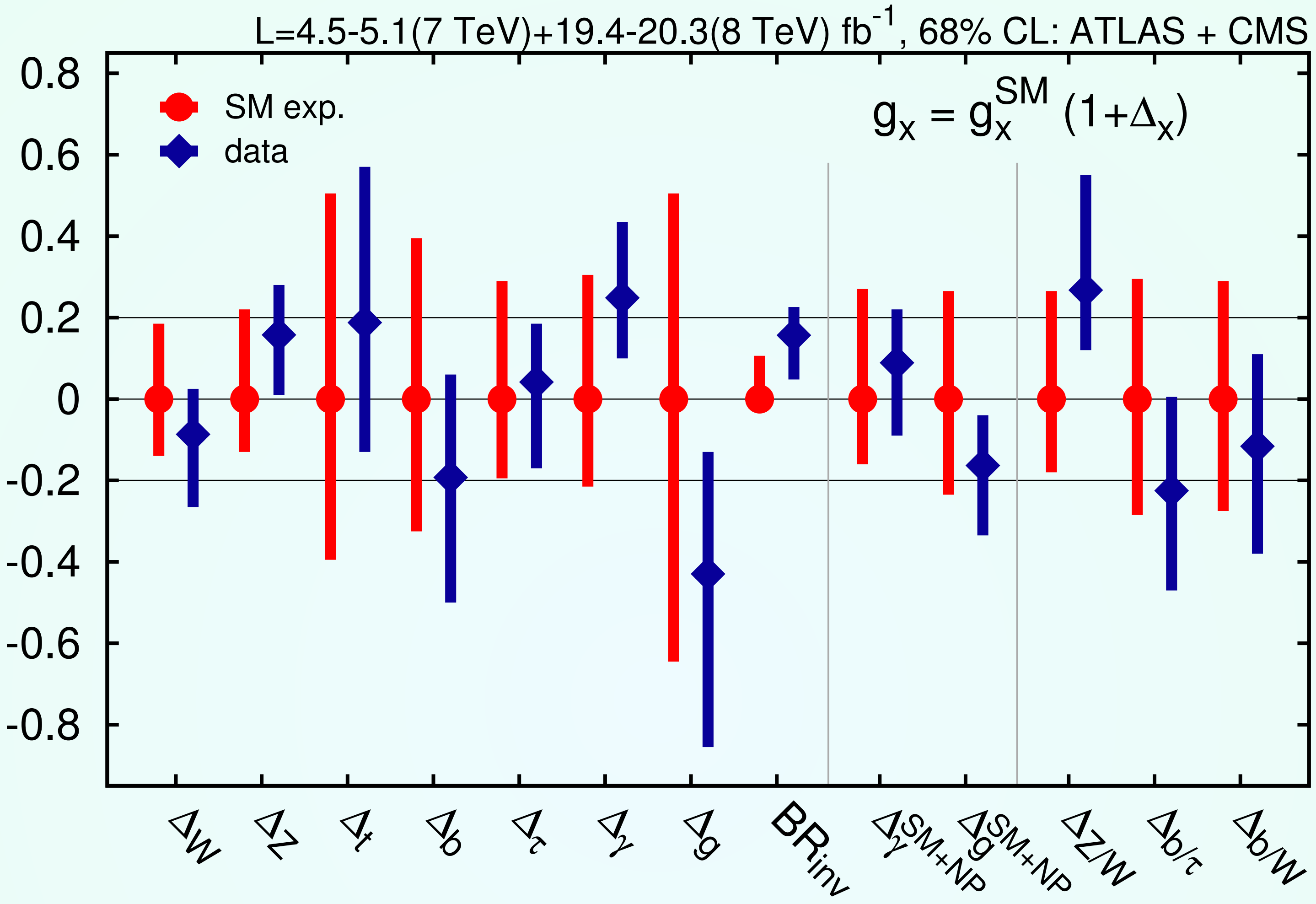

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- We need to go beyond the Δ-framework for EWSB sector

Generic HVV Lagrangian

When considering beyond SM couplings:

[Brivio, Corbett, Eboli, Gavela, Gonzalez-Fraile, Gonzalez-Garcia, LM & Rigolin, JHEP 1403 (2014)]

$$
\begin{aligned}
\mathcal{L}_{\mathrm{HVV}} = \; & g_{Hff} h \left(\bar{f}_R f_L + \mathrm{h.c.}\right) \\
& + g_{Hgg}\, G^a_{\mu\nu} G^{a\mu\nu} h + g_{H\gamma\gamma}\, A_{\mu\nu} A^{\mu\nu} h + g^{(1)}_{HZ\gamma}\, A_{\mu\nu} Z^\mu \partial^\nu h + g^{(2)}_{HZ\gamma}\, A_{\mu\nu} Z^{\mu\nu} h \\
& + g^{(1)}_{HZZ}\, Z_{\mu\nu} Z^\mu \partial^\nu h + g^{(2)}_{HZZ}\, Z_{\mu\nu} Z^{\mu\nu} h + g^{(3)}_{HZZ}\, Z_\mu Z^\mu h + g^{(4)}_{HZZ}\, Z_\mu Z^\mu \Box h \\
& + g^{(5)}_{HZZ}\, \partial_\mu Z^\mu Z_\nu \partial^\nu h + g^{(6)}_{HZZ}\, \partial_\mu Z^\mu \partial_\nu Z^\nu h \\
& + g^{(1)}_{HWW}\, \left(W^+_{\mu\nu} W^{-\,\mu} \partial^\nu h + \mathrm{h.c.}\right) + g^{(2)}_{HWW}\, W^+_{\mu\nu} W^{-\,\mu\nu} h + g^{(3)}_{HWW}\, W^+_\mu W^{-\,\mu} h \\
& + g^{(4)}_{HWW}\, W^+_\mu W^{-\mu} \Box h + g^{(5)}_{HWW}\, + \left(\partial_\mu W^{+\mu} W^-_\nu \partial^\nu h + \mathrm{h.c.}\right) + g^{(6)}_{HWW}\, \partial_\mu W^{+\mu} \partial_\nu W^{-\nu} h
\end{aligned}
$$

$$V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu \qquad V = \{A, Z, W, G\}$$

In general: $g_{Hxy} = g^{SM}_{Hxy} + \Delta g_{Hxy}$ with only non-vanishing SM at tree-level

$$g^{(3)SM}_{HZZ} = \frac{m_Z^2}{v} \qquad g^{(3)SM}_{HZZ} = \frac{m_Z^2}{v} \qquad g^{(3)SM}_{HWW} = \frac{2 m_Z^2 c_W^2}{v}$$

The relation with the Δ formalism is trivial: $\Delta g_{Hxy} = g^{SM}_{Hxy} \Delta_{Hxy}$

Generic HVV Lagrangian

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[Brivio, Corbett, Eboli, Gavela, Gonzalez-Fraile, Gonzalez-Garcia, LM & Rigolin, JHEP 1403 (2014)]

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Too many parameters for a fit now: difficult and probably inconclusive.

EW Effective Lagrangians

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EXACT EW DOUBLET

SM

Hierarchy Problem
(neutrino masses &
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Not exactly an EW doublet, but almost

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Linear Effective Lagrangian SMEFT

$SU(2)_L \times U(1)_Y$ gauge sym

SM spectrum, and in particular exact EW Higgs doublet Φ

Non-Linear Effective Lagrangian HEFT

$SU(2)_L \times U(1)_Y$ gauge sym

SM spectrum, but non-exact EW Higgs doublet h

SMEFT

In 4 traditional space-time dimensions:

Buchmüller & Wyler, NPB 268 (1986)
Grzadkowski, Iskrzynski, Misiak & Rosiek, JHEP 1010 (2010)

$$\mathcal{L}_{\text{linear}} = \mathcal{L}_{SM} + \sum_i \frac{f_i}{\Lambda^2} \mathcal{O}_i + \text{higher orders}$$

with Λ (≥ few TeV) the NP scale

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$$\begin{aligned}\mathcal{L}_{SM} = & -\frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} - V(h) \\ & + (D_\mu \Phi)^\dagger (D^\mu \Phi) + i\bar{Q} \not{D} Q + i\bar{L} \not{D} L \\ & - (\bar{Q}_L \Phi \mathcal{Y}_D D_R + \text{h.c.}) - \left(\bar{Q}_L \tilde{\Phi} \mathcal{Y}_U U_R + \text{h.c.}\right) \\ & - (\bar{L}_L \Phi \mathcal{Y}_L L_R + \text{h.c.})\end{aligned}$$

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- 59 (no flavour) d=6 operators preserving SM, lepton, baryon syms
- Reduction to a minimal independent set of operators: EOMs
- Choice of a suitable basis (data driven): measurable @ LHC

d=6 Basis

[Elias-Miro, Espinosa, Masso & Pomarol, JHEP 1308 (2013), JHEP 1311 (2013)
Jenkins, Manohar & Trott JHEP 1310 (2013), JHEP 1401 (2014)
Alonso, Jenkins, Manohar & Trott JHEP 1404 (2014)]

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Fermionic:

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EOMs remove redondant contributions:

$$2\mathcal{O}_{\Phi,2}+2\mathcal{O}_{\Phi,4}=\sum_{ij}\left(y^e_{ij}(\mathcal{O}_{e\Phi,ij})^\dagger+y^u_{ij}\mathcal{O}_{u\Phi,ij}+y^d_{ij}(\mathcal{O}_{d\Phi,ij})^\dagger+\text{h.c.}\right)-\frac{\partial V(h)}{\partial h}\quad ,$$

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Which operators are the best to keep??

[based on: Corbett, Eboli, Gonzalez-Fraile & Gonzalez-Garcia, PRD87 (2013)]

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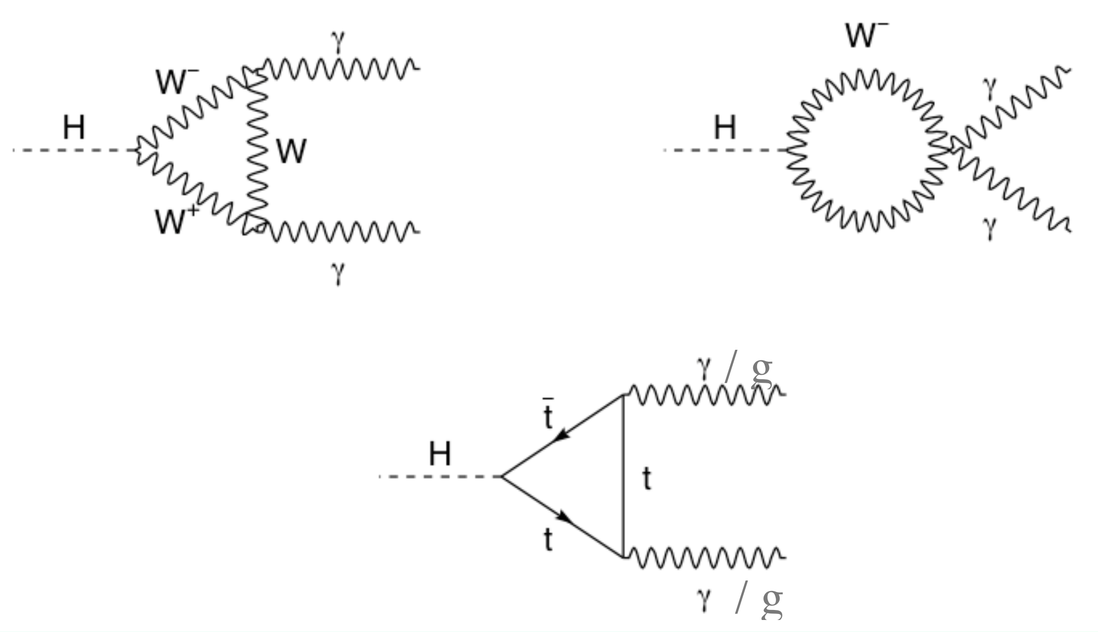
<u>Contribute to:</u> i.e.

HVV

VVV

ΔS



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$$2\mathcal{O}_{\mathcal{B}} + \mathcal{O}_{BW} + \mathcal{O}_{BB} + g'^2\left(\mathcal{O}_{\Phi,1} - \frac{1}{2}\mathcal{O}_{\Phi,2}\right) = -\frac{g'^2}{2}\sum_i\left(-\frac{1}{2}\mathcal{O}^{(1)}_{\Phi L,ii} + \frac{1}{6}\mathcal{O}^{(1)}_{\Phi Q,ii} - \mathcal{O}^{(1)}_{\Phi e,ii} + \frac{2}{3}\mathcal{O}^{(1)}_{\Phi u,ii} - \frac{1}{3}\mathcal{O}^{(1)}_{\Phi d,ii}\right)$$

$$2\mathcal{O}_W + \mathcal{O}_{BW} + \mathcal{O}_{WW} + g^2\left(\mathcal{O}_{\Phi,4} - \frac{1}{2}\mathcal{O}_{\Phi,2}\right) = -\frac{g^2}{4}\sum_i\left(\mathcal{O}^{(3)}_{\Phi L,ii} + \mathcal{O}^{(3)}_{\Phi Q,ii}\right) \quad .$$

Which operators are the best to keep??

[based on: Corbett, Eboli, Gonzalez-Fraile & Gonzalez-Garcia, PRD87 (2013)]

$\mathcal{O}_{GG} = \Phi^\dagger\Phi\, G^a_{\mu\nu}G^{a\mu\nu}$

$\mathcal{O}_{WW} = \Phi^\dagger\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\Phi$

$\mathcal{O}_{BB} = \Phi^\dagger\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\Phi$

$\mathcal{O}_{BW} = \Phi^\dagger\hat{B}_{\mu\nu}\hat{W}^{\mu\nu}\Phi$

$\mathcal{O}_W = (D_\mu\Phi)^\dagger\hat{W}^{\mu\nu}(D_\nu\Phi)$

$\mathcal{O}_B = (D_\mu\Phi)^\dagger\hat{B}^{\mu\nu}(D_\nu\Phi)$

$\boxed{\mathcal{O}_{\Phi,1} = (D_\mu\Phi)^\dagger\,\Phi\,\Phi^\dagger\,(D^\mu\Phi)}$

$\boxed{\mathcal{O}_{\Phi,2} = \frac{1}{2}\partial^\mu\left(\Phi^\dagger\Phi\right)\partial_\mu\left(\Phi^\dagger\Phi\right)}$

$\boxed{\mathcal{O}_{\Phi,4} = (D_\mu\Phi)^\dagger\,(D^\mu\Phi)\left(\Phi^\dagger\Phi\right)}$

$\boxed{\mathcal{O}_{\Phi,3} = \frac{1}{3}\left(\Phi^\dagger\Phi\right)^3}$

Contribute to:

HVV

VVV

VVVV

scalar potential

ΔT

EOMs removes redondant contributions:

$$2\mathcal{O}_{\Phi,2}+2\mathcal{O}_{\Phi,4}=\sum_{ij}\left(y^e_{ij}(\mathcal{O}_{e\Phi,ij})^\dagger+y^u_{ij}\mathcal{O}_{u\Phi,ij}+y^d_{ij}(\mathcal{O}_{d\Phi,ij})^\dagger+\text{h.c.}\right)-\frac{\partial V(h)}{\partial h}\quad ,$$

$$2\mathcal{O}_{\mathcal{B}}+\mathcal{O}_{BW}+\mathcal{O}_{BB}+g'^2\left(\mathcal{O}_{\Phi,1}-\frac{1}{2}\mathcal{O}_{\Phi,2}\right)=-\frac{g'^2}{2}\sum_i\left(-\frac{1}{2}\mathcal{O}^{(1)}_{\Phi L,ii}+\frac{1}{6}\mathcal{O}^{(1)}_{\Phi Q,ii}-\mathcal{O}^{(1)}_{\Phi e,ii}+\frac{2}{3}\mathcal{O}^{(1)}_{\Phi u,ii}-\frac{1}{3}\mathcal{O}^{(1)}_{\Phi d,ii}\right)$$

$$2\mathcal{O}_W+\mathcal{O}_{BW}+\mathcal{O}_{WW}+g^2\left(\mathcal{O}_{\Phi,4}-\frac{1}{2}\mathcal{O}_{\Phi,2}\right)=-\frac{g^2}{4}\sum_i\left(\mathcal{O}^{(3)}_{\Phi L,ii}+\mathcal{O}^{(3)}_{\Phi Q,ii}\right)\quad .$$

Which operators are the best to keep??

$$\mathcal{O}_{e\Phi,ij}=(\Phi^\dagger\Phi)(\bar{L}_i\Phi e_{R_j}),$$
$$\mathcal{O}_{u\Phi,ij}=(\Phi^\dagger\Phi)(\bar{Q}_i\tilde{\Phi}u_{R_j}),$$
$$\mathcal{O}_{d\Phi,ij}=(\Phi^\dagger\Phi)(\bar{Q}_i\Phi d_{Rj}),$$

$$\mathcal{O}^{(1)}_{\Phi L,ij}=\Phi^\dagger(i\overleftrightarrow{D}_\mu\Phi)(\bar{L}_i\gamma^\mu L_j),$$
$$\mathcal{O}^{(1)}_{\Phi Q,ij}=\Phi^\dagger(i\overleftrightarrow{D}_\mu\Phi)(\bar{Q}_i\gamma^\mu Q_j),$$
$$\mathcal{O}^{(1)}_{\Phi e,ij}=\Phi^\dagger(i\overleftrightarrow{D}_\mu\Phi)(\bar{e}_{R_i}\gamma^\mu e_{R_j}),$$
$$\mathcal{O}^{(1)}_{\Phi u,ij}=\Phi^\dagger(i\overleftrightarrow{D}_\mu\Phi)(\bar{u}_{R_i}\gamma^\mu u_{R_j}),$$
$$\mathcal{O}^{(1)}_{\Phi d,ij}=\Phi^\dagger(i\overleftrightarrow{D}_\mu\Phi)(\bar{d}_{R_i}\gamma^\mu d_{R_j}),$$
$$\mathcal{O}^{(1)}_{\Phi ud,ij}=\tilde{\Phi}^\dagger(i\overleftrightarrow{D}_\mu\Phi)(\bar{u}_{R_i}\gamma^\mu d_{R_j}),$$

$$\mathcal{O}^{(3)}_{\Phi L,ij}=\Phi^\dagger(i\overleftrightarrow{D}^a_\mu\Phi)(\bar{L}_i\gamma^\mu\sigma_a L_j),$$
$$\mathcal{O}^{(3)}_{\Phi Q,ij}=\Phi^\dagger(i\overleftrightarrow{D}^a_\mu\Phi)(\bar{Q}_i\gamma^\mu\sigma_a Q_j),$$

EOMs removes redondant contributions:

$$2\mathcal{O}_{\Phi,2} + 2\mathcal{O}_{\Phi,4} = \sum_{ij} \left(y^e_{ij} (\mathcal{O}_{e\Phi,ij})^\dagger + y^u_{ij} \mathcal{O}_{u\Phi,ij} + y^d_{ij} (\mathcal{O}_{d\Phi,ij})^\dagger + \text{h.c.} \right) - \frac{\partial V(h)}{\partial h} \quad ,$$

$$2\mathcal{O}_{\mathcal{B}} + \mathcal{O}_{BW} + \mathcal{O}_{BB} + g'^2 \left(\mathcal{O}_{\Phi,1} - \frac{1}{2}\mathcal{O}_{\Phi,2} \right) = -\frac{g'^2}{2} \sum_i \left(-\frac{1}{2}\mathcal{O}^{(1)}_{\Phi L,ii} + \frac{1}{6}\mathcal{O}^{(1)}_{\Phi Q,ii} - \mathcal{O}^{(1)}_{\Phi e,ii} + \frac{2}{3}\mathcal{O}^{(1)}_{\Phi u,ii} - \frac{1}{3}\mathcal{O}^{(1)}_{\Phi d,ii} \right)$$

$$2\mathcal{O}_{W} + \mathcal{O}_{BW} + \mathcal{O}_{WW} + g^2 \left(\mathcal{O}_{\Phi,4} - \frac{1}{2}\mathcal{O}_{\Phi,2} \right) = -\frac{g^2}{4} \sum_i \left(\mathcal{O}^{(3)}_{\Phi L,ii} + \mathcal{O}^{(3)}_{\Phi Q,ii} \right) \quad .$$

Which operators are the best to keep??

$$\boxed{\begin{aligned} \mathcal{O}_{e\Phi,ij} &= (\Phi^\dagger\Phi)(\bar{L}_i \Phi e_{R_j}), \\ \mathcal{O}_{u\Phi,ij} &= (\Phi^\dagger\Phi)(\bar{Q}_i \tilde{\Phi} u_{R_j}), \\ \mathcal{O}_{d\Phi,ij} &= (\Phi^\dagger\Phi)(\bar{Q}_i \Phi d_{Rj}), \end{aligned}}$$

$$\begin{aligned} \mathcal{O}^{(1)}_{\Phi L,ij} &= \Phi^\dagger (i\overleftrightarrow{D}_\mu \Phi)(\bar{L}_i \gamma^\mu L_j), \\ \mathcal{O}^{(1)}_{\Phi Q,ij} &= \Phi^\dagger (i\overleftrightarrow{D}_\mu \Phi)(\bar{Q}_i \gamma^\mu Q_j), \\ \mathcal{O}^{(1)}_{\Phi e,ij} &= \Phi^\dagger (i\overleftrightarrow{D}_\mu \Phi)(\bar{e}_{R_i} \gamma^\mu e_{R_j}), \\ \mathcal{O}^{(1)}_{\Phi u,ij} &= \Phi^\dagger (i\overleftrightarrow{D}_\mu \Phi)(\bar{u}_{R_i} \gamma^\mu u_{R_j}), \\ \mathcal{O}^{(1)}_{\Phi d,ij} &= \Phi^\dagger (i\overleftrightarrow{D}_\mu \Phi)(\bar{d}_{R_i} \gamma^\mu d_{R_j}), \\ \mathcal{O}^{(1)}_{\Phi ud,ij} &= \tilde{\Phi}^\dagger (i\overleftrightarrow{D}_\mu \Phi)(\bar{u}_{R_i} \gamma^\mu d_{R_j}), \end{aligned}$$

$$\begin{aligned} \mathcal{O}^{(3)}_{\Phi L,ij} &= \Phi^\dagger (i\overleftrightarrow{D}^a_\mu \Phi)(\bar{L}_i \gamma^\mu \sigma_a L_j), \\ \mathcal{O}^{(3)}_{\Phi Q,ij} &= \Phi^\dagger (i\overleftrightarrow{D}^a_\mu \Phi)(\bar{Q}_i \gamma^\mu \sigma_a Q_j), \end{aligned}$$

Contribute to:

Yukawa Couplings

EOMs removes redondant contributions:

$$2\mathcal{O}_{\Phi,2}+2\mathcal{O}_{\Phi,4}=\sum_{ij}\left(y^e_{ij}(\mathcal{O}_{e\Phi,ij})^\dagger+y^u_{ij}\mathcal{O}_{u\Phi,ij}+y^d_{ij}(\mathcal{O}_{d\Phi,ij})^\dagger+\text{h.c.}\right)-\frac{\partial V(h)}{\partial h}\quad,$$

$$2\mathcal{O}_{\mathcal{B}}+\mathcal{O}_{BW}+\mathcal{O}_{BB}+g'^2\left(\mathcal{O}_{\Phi,1}-\frac{1}{2}\mathcal{O}_{\Phi,2}\right)=-\frac{g'^2}{2}\sum_i\left(-\frac{1}{2}\mathcal{O}^{(1)}_{\Phi L,ii}+\frac{1}{6}\mathcal{O}^{(1)}_{\Phi Q,ii}-\mathcal{O}^{(1)}_{\Phi e,ii}+\frac{2}{3}\mathcal{O}^{(1)}_{\Phi u,ii}-\frac{1}{3}\mathcal{O}^{(1)}_{\Phi d,ii}\right)$$

$$2\mathcal{O}_W+\mathcal{O}_{BW}+\mathcal{O}_{WW}+g^2\left(\mathcal{O}_{\Phi,4}-\frac{1}{2}\mathcal{O}_{\Phi,2}\right)=-\frac{g^2}{4}\sum_i\left(\mathcal{O}^{(3)}_{\Phi L,ii}+\mathcal{O}^{(3)}_{\Phi Q,ii}\right)\quad.$$

Which operators are the best to keep??

$$\mathcal{O}_{e\Phi,ij}=(\Phi^\dagger\Phi)(\bar{L}_i\Phi e_{R_j}),$$
$$\mathcal{O}_{u\Phi,ij}=(\Phi^\dagger\Phi)(\bar{Q}_i\tilde{\Phi}u_{R_j}),$$
$$\mathcal{O}_{d\Phi,ij}=(\Phi^\dagger\Phi)(\bar{Q}_i\Phi d_{Rj}),$$

$$\mathcal{O}^{(1)}_{\Phi L,ij}=\Phi^\dagger(i\overleftrightarrow{D}_\mu\Phi)(\bar{L}_i\gamma^\mu L_j),$$
$$\mathcal{O}^{(1)}_{\Phi Q,ij}=\Phi^\dagger(i\overleftrightarrow{D}_\mu\Phi)(\bar{Q}_i\gamma^\mu Q_j),$$
$$\mathcal{O}^{(1)}_{\Phi e,ij}=\Phi^\dagger(i\overleftrightarrow{D}_\mu\Phi)(\bar{e}_{R_i}\gamma^\mu e_{R_j}),$$
$$\mathcal{O}^{(1)}_{\Phi u,ij}=\Phi^\dagger(i\overleftrightarrow{D}_\mu\Phi)(\bar{u}_{R_i}\gamma^\mu u_{R_j}),$$
$$\mathcal{O}^{(1)}_{\Phi d,ij}=\Phi^\dagger(i\overleftrightarrow{D}_\mu\Phi)(\bar{d}_{R_i}\gamma^\mu d_{R_j}),$$
$$\mathcal{O}^{(1)}_{\Phi ud,ij}=\tilde{\Phi}^\dagger(i\overleftrightarrow{D}_\mu\Phi)(\bar{u}_{R_i}\gamma^\mu d_{R_j}),$$

$$\mathcal{O}^{(3)}_{\Phi L,ij}=\Phi^\dagger(i\overleftrightarrow{D}^a_\mu\Phi)(\bar{L}_i\gamma^\mu\sigma_a L_j),$$
$$\mathcal{O}^{(3)}_{\Phi Q,ij}=\Phi^\dagger(i\overleftrightarrow{D}^a_\mu\Phi)(\bar{Q}_i\gamma^\mu\sigma_a Q_j),$$

Contribute to:

Neutral and Charged Weak Currents

A possible choice:

$$\mathcal{O}_{GG} = \Phi^\dagger \Phi \; G^a_{\mu\nu} G^{a\mu\nu} \qquad \mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \qquad \mathcal{O}_{BB} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \Phi$$

$$\mathcal{O}_{BW} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \qquad \mathcal{O}_{W} = (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi) \qquad \mathcal{O}_{B} = (D_\mu \Phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \Phi)$$

$$\mathcal{O}_{\Phi,1} = (D_\mu \Phi)^\dagger \; \Phi \; \Phi^\dagger \; (D^\mu \Phi) \qquad \mathcal{O}_{\Phi,2} = \frac{1}{2} \partial^\mu \left(\Phi^\dagger \Phi\right) \partial_\mu \left(\Phi^\dagger \Phi\right) \qquad \mathcal{O}_{\Phi,4} = (D_\mu \Phi)^\dagger \, (D^\mu \Phi) \left(\Phi^\dagger \Phi\right)$$

$$\mathcal{O}_{\Phi,3} = \frac{1}{3} \left(\Phi^\dagger \Phi\right)^3$$

$$\mathcal{O}_{e\Phi,ij} = (\Phi^\dagger \Phi)(\bar{L}_i \Phi e_{R_j}), \qquad \mathcal{O}^{(1)}_{\Phi L,ij} = \Phi^\dagger (i \overleftrightarrow{D}_\mu \Phi)(\bar{L}_i \gamma^\mu L_j), \qquad \mathcal{O}^{(3)}_{\Phi L,ij} = \Phi^\dagger (i \overleftrightarrow{D}^a_\mu \Phi)(\bar{L}_i \gamma^\mu \sigma_a L_j),$$

$$\mathcal{O}_{u\Phi,ij} = (\Phi^\dagger \Phi)(\bar{Q}_i \tilde{\Phi} u_{R_j}), \qquad \mathcal{O}^{(1)}_{\Phi Q,ij} = \Phi^\dagger (i \overleftrightarrow{D}_\mu \Phi)(\bar{Q}_i \gamma^\mu Q_j), \qquad \mathcal{O}^{(3)}_{\Phi Q,ij} = \Phi^\dagger (i \overleftrightarrow{D}^a_\mu \Phi)(\bar{Q}_i \gamma^\mu \sigma_a Q_j),$$

$$\mathcal{O}_{d\Phi,ij} = (\Phi^\dagger \Phi)(\bar{Q}_i \Phi d_{Rj}), \qquad \mathcal{O}^{(1)}_{\Phi e,ij} = \Phi^\dagger (i \overleftrightarrow{D}_\mu \Phi)(\bar{e}_{R_i} \gamma^\mu e_{R_j}),$$

$$\mathcal{O}^{(1)}_{\Phi u,ij} = \Phi^\dagger (i \overleftrightarrow{D}_\mu \Phi)(\bar{u}_{R_i} \gamma^\mu u_{R_j}),$$

$$\mathcal{O}^{(1)}_{\Phi d,ij} = \Phi^\dagger (i \overleftrightarrow{D}_\mu \Phi)(\bar{d}_{R_i} \gamma^\mu d_{R_j}),$$

$$\mathcal{O}^{(1)}_{\Phi ud,ij} = \tilde{\Phi}^\dagger (i \overleftrightarrow{D}_\mu \Phi)(\bar{u}_{R_i} \gamma^\mu d_{R_j}),$$

A possible choice:

$$\mathcal{O}_{GG} = \Phi^\dagger\Phi\, G^a_{\mu\nu}G^{a\mu\nu} \qquad \mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\Phi \qquad \mathcal{O}_{BB} = \Phi^\dagger \hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\Phi$$

$$\mathcal{O}_{BW} = \Phi^\dagger \hat{B}_{\mu\nu}\hat{W}^{\mu\nu}\Phi \qquad \mathcal{O}_{W} = (D_\mu\Phi)^\dagger \hat{W}^{\mu\nu}(D_\nu\Phi) \qquad \mathcal{O}_{B} = (D_\mu\Phi)^\dagger \hat{B}^{\mu\nu}(D_\nu\Phi)$$

$$\mathcal{O}_{\Phi,1} = (D_\mu\Phi)^\dagger\,\Phi\,\Phi^\dagger\,(D^\mu\Phi) \qquad \mathcal{O}_{\Phi,2} = \frac{1}{2}\partial^\mu\left(\Phi^\dagger\Phi\right)\partial_\mu\left(\Phi^\dagger\Phi\right) \qquad \mathcal{O}_{\Phi,4} = (D_\mu\Phi)^\dagger\,(D^\mu\Phi)\left(\Phi^\dagger\Phi\right)$$

$$\mathcal{O}_{\Phi,3} = \frac{1}{3}\left(\Phi^\dagger\Phi\right)^3$$

$$\mathcal{O}_{e\Phi,ij} = (\Phi^\dagger\Phi)(\bar{L}_i\Phi e_{R_j}),$$
$$\mathcal{O}_{u\Phi,ij} = (\Phi^\dagger\Phi)(\bar{Q}_i\tilde{\Phi} u_{R_j}),$$
$$\mathcal{O}_{d\Phi,ij} = (\Phi^\dagger\Phi)(\bar{Q}_i\Phi d_{Rj}),$$

~~$\mathcal{O}^{(1)}_{\Phi L,ij} = \Phi^\dagger(i\overleftrightarrow{D}_\mu\Phi)(\bar{L}_i\gamma^\mu L_j),$~~

$$\mathcal{O}^{(1)}_{\Phi Q,ij} = \Phi^\dagger(i\overleftrightarrow{D}_\mu\Phi)(\bar{Q}_i\gamma^\mu Q_j),$$
$$\mathcal{O}^{(1)}_{\Phi e,ij} = \Phi^\dagger(i\overleftrightarrow{D}_\mu\Phi)(\bar{e}_{R_i}\gamma^\mu e_{R_j}),$$
$$\mathcal{O}^{(1)}_{\Phi u,ij} = \Phi^\dagger(i\overleftrightarrow{D}_\mu\Phi)(\bar{u}_{R_i}\gamma^\mu u_{R_j}),$$
$$\mathcal{O}^{(1)}_{\Phi d,ij} = \Phi^\dagger(i\overleftrightarrow{D}_\mu\Phi)(\bar{d}_{R_i}\gamma^\mu d_{R_j}),$$
$$\mathcal{O}^{(1)}_{\Phi ud,ij} = \tilde{\Phi}^\dagger(i\overleftrightarrow{D}_\mu\Phi)(\bar{u}_{R_i}\gamma^\mu d_{R_j}),$$

~~$\mathcal{O}^{(3)}_{\Phi L,ij} = \Phi^\dagger(i\overleftrightarrow{D}^a_\mu\Phi)(\bar{L}_i\gamma^\mu\sigma_a L_j),$~~

$$\mathcal{O}^{(3)}_{\Phi Q,ij} = \Phi^\dagger(i\overleftrightarrow{D}^a_\mu\Phi)(\bar{Q}_i\gamma^\mu\sigma_a Q_j),$$

- Remove operators that contribute tree-level to EWPO via EOMs

$$2\mathcal{O}_B + \mathcal{O}_{BW} + \mathcal{O}_{BB} + g'^2\left(\mathcal{O}_{\Phi,1} - \frac{1}{2}\mathcal{O}_{\Phi,2}\right) = -\frac{g'^2}{2}\sum_i\left(-\boxed{\frac{1}{2}\mathcal{O}^{(1)}_{\Phi L,ii}} + \frac{1}{6}\mathcal{O}^{(1)}_{\Phi Q,ii} - \mathcal{O}^{(1)}_{\Phi e,ii} + \frac{2}{3}\mathcal{O}^{(1)}_{\Phi u,ii} - \frac{1}{3}\mathcal{O}^{(1)}_{\Phi d,ii}\right)$$

$$2\mathcal{O}_W + \mathcal{O}_{BW} + \mathcal{O}_{WW} + g^2\left(\mathcal{O}_{\Phi,4} - \frac{1}{2}\mathcal{O}_{\Phi,2}\right) = -\frac{g^2}{4}\sum_i\boxed{\left(\mathcal{O}^{(3)}_{\Phi L,ii}\right.} + \left.\mathcal{O}^{(3)}_{\Phi Q,ii}\right)\ .$$

A possible choice:

$$\mathcal{O}_{GG} = \Phi^\dagger\Phi\, G^a_{\mu\nu}G^{a\mu\nu} \qquad \mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\Phi \qquad \mathcal{O}_{BB} = \Phi^\dagger \hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\Phi$$

$$\mathcal{O}_{BW} = \Phi^\dagger \hat{B}_{\mu\nu}\hat{W}^{\mu\nu}\Phi \qquad \mathcal{O}_{W} = (D_\mu\Phi)^\dagger \hat{W}^{\mu\nu}(D_\nu\Phi) \qquad \mathcal{O}_{B} = (D_\mu\Phi)^\dagger \hat{B}^{\mu\nu}(D_\nu\Phi)$$

$$\mathcal{O}_{\Phi,1} = (D_\mu\Phi)^\dagger\, \Phi\, \Phi^\dagger\, (D^\mu\Phi) \qquad \mathcal{O}_{\Phi,2} = \frac{1}{2}\partial^\mu\left(\Phi^\dagger\Phi\right)\partial_\mu\left(\Phi^\dagger\Phi\right) \qquad \cancel{\mathcal{O}_{\Phi,4} = (D_\mu\Phi)^\dagger\,(D^\mu\Phi)\,(\Phi^\dagger\Phi)}$$

$$\mathcal{O}_{\Phi,3} = \frac{1}{3}\left(\Phi^\dagger\Phi\right)^3$$

$$\mathcal{O}_{e\Phi,ij} = (\Phi^\dagger\Phi)(\bar{L}_i\Phi e_{R_j}), \qquad \cancel{\mathcal{O}^{(1)}_{\Phi L,ij} = \Phi^\dagger(i\overleftrightarrow{D}_\mu\Phi)(\bar{L}_i\gamma^\mu L_j)}, \qquad \cancel{\mathcal{O}^{(3)}_{\Phi L,ij} = \Phi^\dagger(i\overleftrightarrow{D}^a_\mu\Phi)(\bar{L}_i\gamma^\mu\sigma_a L_j)},$$

$$\mathcal{O}_{u\Phi,ij} = (\Phi^\dagger\Phi)(\bar{Q}_i\tilde{\Phi}u_{R_j}), \qquad \mathcal{O}^{(1)}_{\Phi Q,ij} = \Phi^\dagger(i\overleftrightarrow{D}_\mu\Phi)(\bar{Q}_i\gamma^\mu Q_j), \qquad \mathcal{O}^{(3)}_{\Phi Q,ij} = \Phi^\dagger(i\overleftrightarrow{D}^a_\mu\Phi)(\bar{Q}_i\gamma^\mu\sigma_a Q_j),$$

$$\mathcal{O}_{d\Phi,ij} = (\Phi^\dagger\Phi)(\bar{Q}_i\Phi d_{Rj}), \qquad \mathcal{O}^{(1)}_{\Phi e,ij} = \Phi^\dagger(i\overleftrightarrow{D}_\mu\Phi)(\bar{e}_{R_i}\gamma^\mu e_{R_j}),$$

$$\mathcal{O}^{(1)}_{\Phi u,ij} = \Phi^\dagger(i\overleftrightarrow{D}_\mu\Phi)(\bar{u}_{R_i}\gamma^\mu u_{R_j}),$$

$$\mathcal{O}^{(1)}_{\Phi d,ij} = \Phi^\dagger(i\overleftrightarrow{D}_\mu\Phi)(\bar{d}_{R_i}\gamma^\mu d_{R_j}),$$

$$\mathcal{O}^{(1)}_{\Phi ud,ij} = \tilde{\Phi}^\dagger(i\overleftrightarrow{D}_\mu\Phi)(\bar{u}_{R_i}\gamma^\mu d_{R_j}),$$

- Use the last EOM to remove $\mathcal{O}_{\Phi,4}$

$$2\mathcal{O}_{\Phi,2} + \boxed{2\mathcal{O}_{\Phi,4}} = \sum_{ij}\left(y^e_{ij}(\mathcal{O}_{e\Phi,ij})^\dagger + y^u_{ij}\mathcal{O}_{u\Phi,ij} + y^d_{ij}(\mathcal{O}_{d\Phi,ij})^\dagger + \text{h.c.}\right) - \frac{\partial V(h)}{\partial h} \quad ,$$

A possible choice:

$$\mathcal{O}_{GG} = \Phi^\dagger \Phi \, G^a_{\mu\nu} G^{a\mu\nu}$$

$$\mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi$$

$$\mathcal{O}_{BB} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \Phi$$

~~$\mathcal{O}_{BW} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \Phi$~~

$$\mathcal{O}_W = (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi)$$

$$\mathcal{O}_B = (D_\mu \Phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \Phi)$$

~~$\mathcal{O}_{\Phi,1} = (D_\mu \Phi)^\dagger \Phi \, \Phi^\dagger (D^\mu \Phi)$~~

$$\mathcal{O}_{\Phi,2} = \frac{1}{2} \partial^\mu \left(\Phi^\dagger \Phi\right) \partial_\mu \left(\Phi^\dagger \Phi\right)$$

~~$\mathcal{O}_{\Phi,4} = (D_\mu \Phi)^\dagger (D^\mu \Phi) \left(\Phi^\dagger \Phi\right)$~~

$$\mathcal{O}_{\Phi,3} = \frac{1}{3} \left(\Phi^\dagger \Phi\right)^3$$

$$\mathcal{O}_{e\Phi,ij} = (\Phi^\dagger \Phi)(\bar{L}_i \Phi e_{R_j}),$$

$$\mathcal{O}_{u\Phi,ij} = (\Phi^\dagger \Phi)(\bar{Q}_i \tilde{\Phi} u_{R_j}),$$

$$\mathcal{O}_{d\Phi,ij} = (\Phi^\dagger \Phi)(\bar{Q}_i \Phi d_{Rj}),$$

~~$\mathcal{O}^{(1)}_{\Phi L,ij} = \Phi^\dagger (i \overleftrightarrow{D}_\mu \Phi)(\bar{L}_i \gamma^\mu L_j),$~~

~~$\mathcal{O}^{(1)}_{\Phi Q,ij} = \Phi^\dagger (i \overleftrightarrow{D}_\mu \Phi)(\bar{Q}_i \gamma^\mu Q_j),$~~

~~$\mathcal{O}^{(1)}_{\Phi e,ij} = \Phi^\dagger (i \overleftrightarrow{D}_\mu \Phi)(\bar{e}_{R_i} \gamma^\mu e_{R_j}),$~~

~~$\mathcal{O}^{(1)}_{\Phi u,ij} = \Phi^\dagger (i \overleftrightarrow{D}_\mu \Phi)(\bar{u}_{R_i} \gamma^\mu u_{R_j}),$~~

~~$\mathcal{O}^{(1)}_{\Phi d,ij} = \Phi^\dagger (i \overleftrightarrow{D}_\mu \Phi)(\bar{d}_{R_i} \gamma^\mu d_{R_j}),$~~

~~$\mathcal{O}^{(1)}_{\Phi ud,ij} = \tilde{\Phi}^\dagger (i \overleftrightarrow{D}_\mu \Phi)(\bar{u}_{R_i} \gamma^\mu d_{R_j}),$~~

~~$\mathcal{O}^{(3)}_{\Phi L,ij} = \Phi^\dagger (i \overleftrightarrow{D}^a_\mu \Phi)(\bar{L}_i \gamma^\mu \sigma_a L_j),$~~

~~$\mathcal{O}^{(3)}_{\Phi Q,ij} = \Phi^\dagger (i \overleftrightarrow{D}^a_\mu \Phi)(\bar{Q}_i \gamma^\mu \sigma_a Q_j),$~~

- Remove all those operators strongly constrained: Z, W currents and oblique corrections.

A possible choice:

$$\mathcal{O}_{GG} = \Phi^\dagger\Phi \, G^a_{\mu\nu}G^{a\mu\nu}$$

~~$\mathcal{O}_{BW} = \Phi^\dagger \hat{B}_{\mu\nu}\hat{W}^{\mu\nu}\Phi$~~

~~$\mathcal{O}_{\Phi,1} = (D_\mu\Phi)^\dagger \Phi \, \Phi^\dagger (D^\mu\Phi)$~~

$$\mathcal{O}_{e\Phi,ij} = (\Phi^\dagger\Phi)(\bar{L}_i \Phi e_{R_j}),$$

$$\mathcal{O}_{u\Phi,ij} = (\Phi^\dagger\Phi)(\bar{Q}_i \tilde{\Phi} u_{R_j});$$

$$\mathcal{O}_{d\Phi,ij} = (\Phi^\dagger\Phi)(\bar{Q}_i \Phi d_{Rj});$$

$$\mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\Phi$$

$$\mathcal{O}_{W} = (D_\mu\Phi)^\dagger \hat{W}^{\mu\nu}(D_\nu\Phi)$$

$$\mathcal{O}_{\Phi,2} = \frac{1}{2}\partial^\mu\left(\Phi^\dagger\Phi\right)\partial_\mu\left(\Phi^\dagger\Phi\right)$$

~~$\mathcal{O}^{(1)}_{\Phi L,ij} = \Phi^\dagger(i\overleftrightarrow{D}_\mu\Phi)(\bar{L}_i\gamma^\mu L_j),$~~

~~$\mathcal{O}^{(1)}_{\Phi Q,ij} = \Phi^\dagger(i\overleftrightarrow{D}_\mu\Phi)(\bar{Q}_i\gamma^\mu Q_j),$~~

~~$\mathcal{O}^{(1)}_{\Phi e,ij} = \Phi^\dagger(i\overleftrightarrow{D}_\mu\Phi)(\bar{e}_{R_i}\gamma^\mu e_{R_j}),$~~

~~$\mathcal{O}^{(1)}_{\Phi u,ij} = \Phi^\dagger(i\overleftrightarrow{D}_\mu\Phi)(\bar{u}_{R_i}\gamma^\mu u_{R_j}),$~~

~~$\mathcal{O}^{(1)}_{\Phi d,ij} = \Phi^\dagger(i\overleftrightarrow{D}_\mu\Phi)(\bar{d}_{R_i}\gamma^\mu d_{R_j}),$~~

~~$\mathcal{O}^{(1)}_{\Phi ud,ij} = \tilde{\Phi}^\dagger(i\overleftrightarrow{D}_\mu\Phi)(\bar{u}_{R_i}\gamma^\mu d_{R_j}),$~~

$$\mathcal{O}_{BB} = \Phi^\dagger \hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\Phi$$

$$\mathcal{O}_{B} = (D_\mu\Phi)^\dagger \hat{B}^{\mu\nu}(D_\nu\Phi)$$

~~$\mathcal{O}_{\Phi,4} = (D_\mu\Phi)^\dagger (D^\mu\Phi)\left(\Phi^\dagger\Phi\right)$~~

$$\mathcal{O}_{\Phi,3} = \frac{1}{3}\left(\Phi^\dagger\Phi\right)^3$$

~~$\mathcal{O}^{(3)}_{\Phi L,ij} = \Phi^\dagger(i\overleftrightarrow{D}^a_\mu\Phi)(\bar{L}_i\gamma^\mu\sigma_a L_j),$~~

~~$\mathcal{O}^{(3)}_{\Phi Q,ij} = \Phi^\dagger(i\overleftrightarrow{D}^a_\mu\Phi)(\bar{Q}_i\gamma^\mu\sigma_a Q_j),$~~

- Low energy flavour interactions: strong bounds on off-diag Yukawas $(\mathcal{O}_{f\Phi})_{i\neq j}$ (maybe relevant τe and $\tau\mu$, but not for this analysis!)

A possible choice:

$\mathcal{O}_{GG} = \Phi^\dagger\Phi\, G^a_{\mu\nu}G^{a\mu\nu}$

$\mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\Phi$

$\mathcal{O}_{BB} = \Phi^\dagger \hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\Phi$

~~$\mathcal{O}_{BW} = \Phi^\dagger \hat{B}_{\mu\nu}\hat{W}^{\mu\nu}\Phi$~~

$\mathcal{O}_{W} = (D_\mu\Phi)^\dagger \hat{W}^{\mu\nu}(D_\nu\Phi)$

$\mathcal{O}_{B} = (D_\mu\Phi)^\dagger \hat{B}^{\mu\nu}(D_\nu\Phi)$

~~$\mathcal{O}_{\Phi,1} = (D_\mu\Phi)^\dagger\,\Phi\,\Phi^\dagger\,(D^\mu\Phi)$~~

$\mathcal{O}_{\Phi,2} = \frac{1}{2}\partial^\mu\left(\Phi^\dagger\Phi\right)\partial_\mu\left(\Phi^\dagger\Phi\right)$

~~$\mathcal{O}_{\Phi,4} = (D_\mu\Phi)^\dagger\,(D^\mu\Phi)\,(\Phi^\dagger\Phi)$~~

$\mathcal{O}_{\Phi,3} = \frac{1}{3}\left(\Phi^\dagger\Phi\right)^3$

~~$\mathcal{O}_{e\Phi,ij} = (\Phi^\dagger\Phi)(\bar{L}_i\Phi e_{R_j}),$~~

~~$\mathcal{O}_{u\Phi,ij} = (\Phi^\dagger\Phi)(\bar{Q}_i\tilde{\Phi} u_{R_j}),$~~

~~$\mathcal{O}_{d\Phi,ij} = (\Phi^\dagger\Phi)(\bar{Q}_i\Phi d_{R_j}),$~~

↓

$(\mathcal{O}_{f\Phi})_{e\Phi,33}$

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~~$\mathcal{O}^{(1)}_{\Phi L,ij} = \Phi^\dagger(i\overleftrightarrow{D}_\mu\Phi)(\bar{L}_i\gamma^\mu L_j),$~~

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~~$\mathcal{O}^{(1)}_{\Phi ud,ij} = \tilde{\Phi}^\dagger(i\overleftrightarrow{D}_\mu\Phi)(\bar{u}_{R_i}\gamma^\mu d_{R_j}),$~~

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~~$\mathcal{O}^{(3)}_{\Phi Q,ij} = \Phi^\dagger(i\overleftrightarrow{D}^a_\mu\Phi)(\bar{Q}_i\gamma^\mu\sigma_a Q_j),$~~

- $(\mathcal{O}_{f\Phi})_{ii}$ for 1st and 2nd generations only via Hgg and Hγγ loops: negligible!

A possible choice:

$\mathcal{O}_{GG} = \Phi^\dagger \Phi \, G^a_{\mu\nu} G^{a\mu\nu}$

~~$\mathcal{O}_{BW} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \Phi$~~

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$\mathcal{O}_{\Phi,2} = \frac{1}{2} \partial^\mu \left(\Phi^\dagger \Phi\right) \partial_\mu \left(\Phi^\dagger \Phi\right)$

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$\downarrow$

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~~$\mathcal{O}^{(3)}_{\Phi Q,ij} = \Phi^\dagger (i \overleftrightarrow{D}^a_\mu \Phi)(\bar{Q}_i \gamma^\mu \sigma_a Q_j),$~~

- $\mathcal{O}_{\Phi,3}$ only relevant for the scalar potential

A possible choice:

[based on: Corbett, Eboli, Gonzalez-Fraile & Gonzalez-Garcia, PRD87 (2013)]

$\mathcal{O}_{GG} = \Phi^\dagger \Phi \, G^a_{\mu\nu} G^{a\mu\nu}$

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Relevant parameters for Higgs Physics:

$$\frac{f_{GG}}{\Lambda^2}, \frac{f_{WW}}{\Lambda^2}, \frac{f_{BB}}{\Lambda^2}, \frac{f_W}{\Lambda^2}, \frac{f_B}{\Lambda^2}, \frac{f_{\Phi,2}}{\Lambda^2}, \frac{f_\tau}{\Lambda^2}, \frac{f_b}{\Lambda^2}, \frac{f_t}{\Lambda^2}$$

In the unitary gauge:

In the unitary gauge:

$$\begin{aligned}\mathcal{L}_{HVV} = {} & g_{Hgg}\, G^a_{\mu\nu} G^{a\mu\nu} h + g_{H\gamma\gamma}\, A_{\mu\nu} A^{\mu\nu} h + g^{(1)}_{HZ\gamma}\, A_{\mu\nu} Z^\mu \partial^\nu h + g^{(2)}_{HZ\gamma}\, A_{\mu\nu} Z^{\mu\nu} h \\ & + g^{(1)}_{HZZ}\, Z_{\mu\nu} Z^\mu \partial^\nu h + g^{(2)}_{HZZ}\, Z_{\mu\nu} Z^{\mu\nu} h + g^{(3)}_{HZZ}\, Z_\mu Z^\mu h \\ & + g^{(1)}_{HWW}\, \left(W^+_{\mu\nu} W^{-\,\mu} \partial^\nu h + \text{h.c.} \right) + g^{(2)}_{HWW}\, W^+_{\mu\nu} W^{-\,\mu\nu} h + g^{(3)}_{HWW}\, W^+_\mu W^{-\,\mu} h \,,\end{aligned}$$

$$\mathcal{L}_{Hff} = g_f \bar{f}_L f_R h + \text{h.c.}$$

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$$\mathcal{L}_{Hff} = g_f \bar{f}_L f_R h + \text{h.c.}$$

$$g_{Hgg} = -\frac{\alpha_s}{8\pi}\frac{f_{GG}v}{\Lambda^2} \qquad g^{(1)}_{HZ\gamma} = \frac{g^2 v}{2\Lambda^2}\,\frac{s_w(f_W - f_B)}{2c_w}$$

$$g_{H\gamma\gamma} = -\frac{g^2 v s_w^2}{2\Lambda^2}\,\frac{f_{BB}+f_{WW}}{2} \qquad g^{(2)}_{HZ\gamma} = \frac{g^2 v}{2\Lambda^2}\,\frac{s_w(2s_w^2 f_{BB} - 2c_w^2 f_{WW})}{2c_w}$$

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$$g^{(3)}_{HZZ} = m_Z^2(\sqrt{2}G_F)^{1/2}\left(1 - \frac{v^2}{2\Lambda^2}f_{\Phi,2}\right) \quad g^{(3)}_{HWW} = m_W^2(\sqrt{2}G_F)^{1/2}\left(1 - \frac{v^2}{2\Lambda^2}f_{\Phi,2}\right)$$

$$g_f = -\frac{m_f}{v}\left(1 - \frac{v^2}{2\Lambda^2}f_{\Phi,2} - \frac{v^2}{\sqrt{2}\Lambda^2}f_f\right)$$

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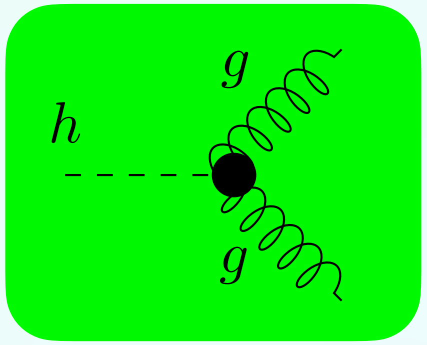
$$+ g^{(1)}_{HZZ}\, Z_{\mu\nu}Z^{\mu}\partial^{\nu}h + g^{(2)}_{HZZ}\, Z_{\mu\nu}Z^{\mu\nu}h + g^{(3)}_{HZZ}\, Z_{\mu}Z^{\mu}h$$
$$+ g^{(1)}_{HWW}\, (W^+_{\mu\nu}W^{-\,\mu}\partial^{\nu}h + \text{h.c.}) + g^{(2)}_{HWW}\, W^+_{\mu\nu}W^{-\,\mu\nu}h + g^{(3)}_{HWW}\, W^+_{\mu}W^{-\,\mu}h\,,$$

$$\mathcal{L}_{Hff} = g_f \bar{f}_L f_R h + \text{h.c.}$$



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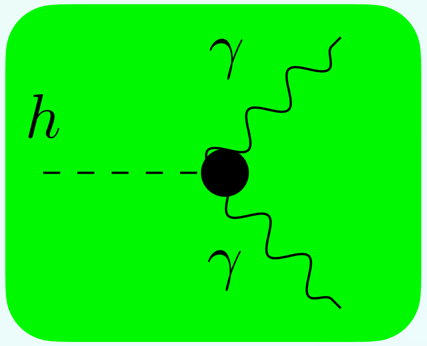
$$\mathcal{L}_{Hff} = g_f \bar{f}_L f_R h + \mathrm{h.c.}$$



$$g_{Hgg} = -\frac{\alpha_s}{8\pi} \frac{f_{GG} v}{\Lambda^2}$$

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→ 13 free coefficients vs. 9 Lagrangian parameters

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- SMEFT is a well defined EFT, invariant under $SU(2)_L \times U(1)_Y$
- Fewer number of parameters in the fit: easier and more constraining
- Correlation between HVV and TGV

$$\mathcal{L}_{WWV} = -ig_{WWV}\Big\{g_1^V\left(W^+_{\mu\nu}W^{-\mu}V^\nu - W^+_\mu V_\nu W^{-\mu\nu}\right) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{m_W^2}W^+_{\mu\nu}W^{-\nu\rho}V^\mu_\rho - g_5^V\epsilon^{\mu\nu\rho\sigma}\left(W^+_\mu\partial_\rho W^-_\nu - \partial_\rho W^+_\mu W^-_\nu\right)V_\sigma\Big\}$$

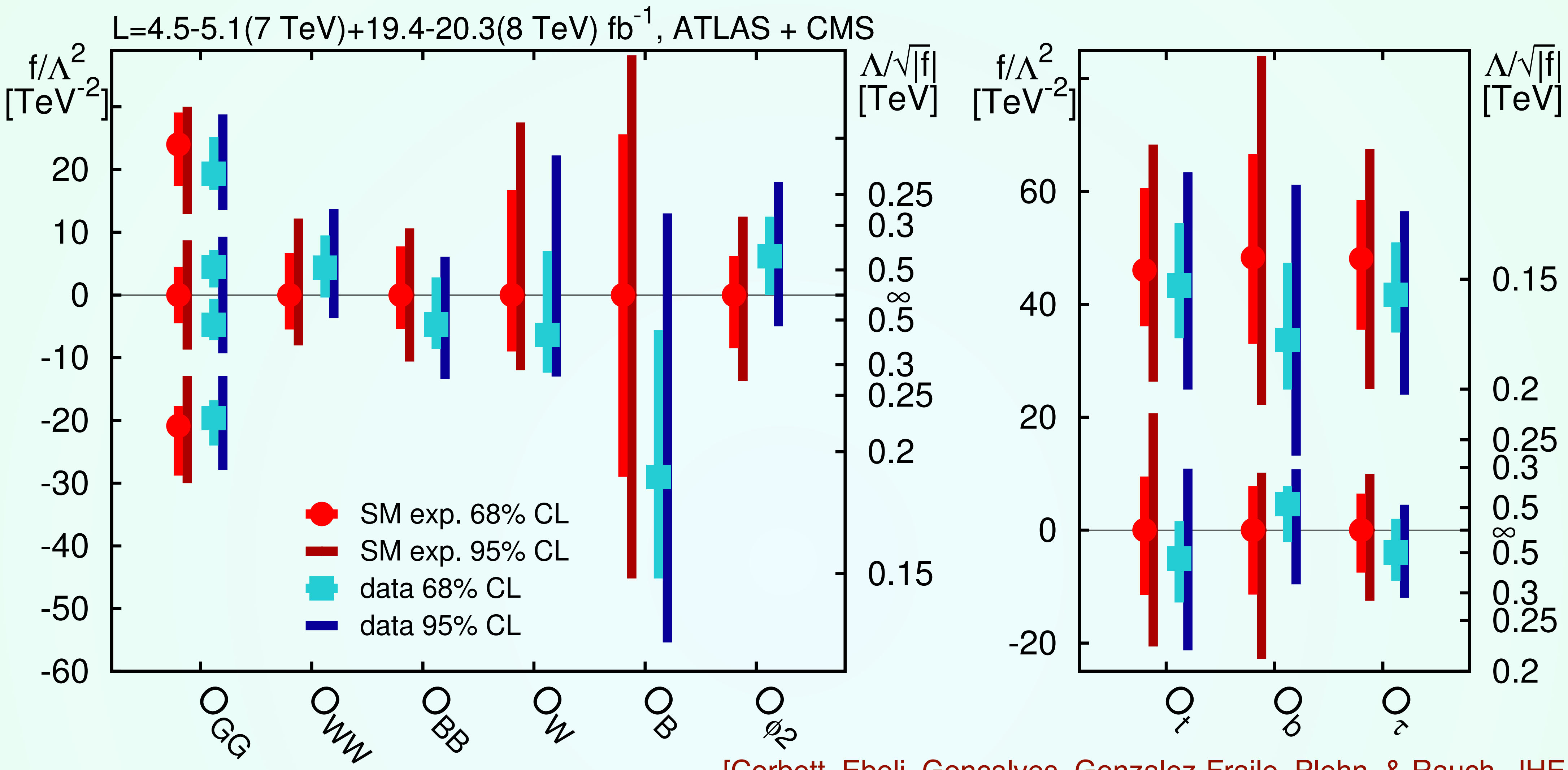
$$\left.\begin{aligned}
\Delta g_1^Z &= g_1^Z - 1 = \frac{g^2v^2}{8c_w^2\Lambda^2}f_W \\
\Delta\kappa_\gamma &= \kappa_\gamma - 1 = \frac{g^2v^2}{8c_w^2\Lambda^2}\left(f_W + f_B\right) \\
\Delta\kappa_Z &= \kappa_Z - 1 = \frac{g^2v^2}{8c_w^2\Lambda^2}\left(c_w^2 f_W - s_w^2 f_B\right)
\end{aligned}\right\}$$

same parameters of HVV Lagrangian

$$\lambda_\gamma = \lambda_Z = \frac{3g^2m_W^2}{\Lambda^2}f_{WWW}$$

$$\mathcal{O}_{WWW} = -ig^3\mathrm{Tr}\left(W^\nu_\mu W^\rho_\nu W^\mu_\rho\right)$$

Results for Rate-Based Analysis



[Corbett, Eboli, Gonçalves, Gonzalez-Fraile, Plehn, & Rauch, JHEP 1508 (2015)]

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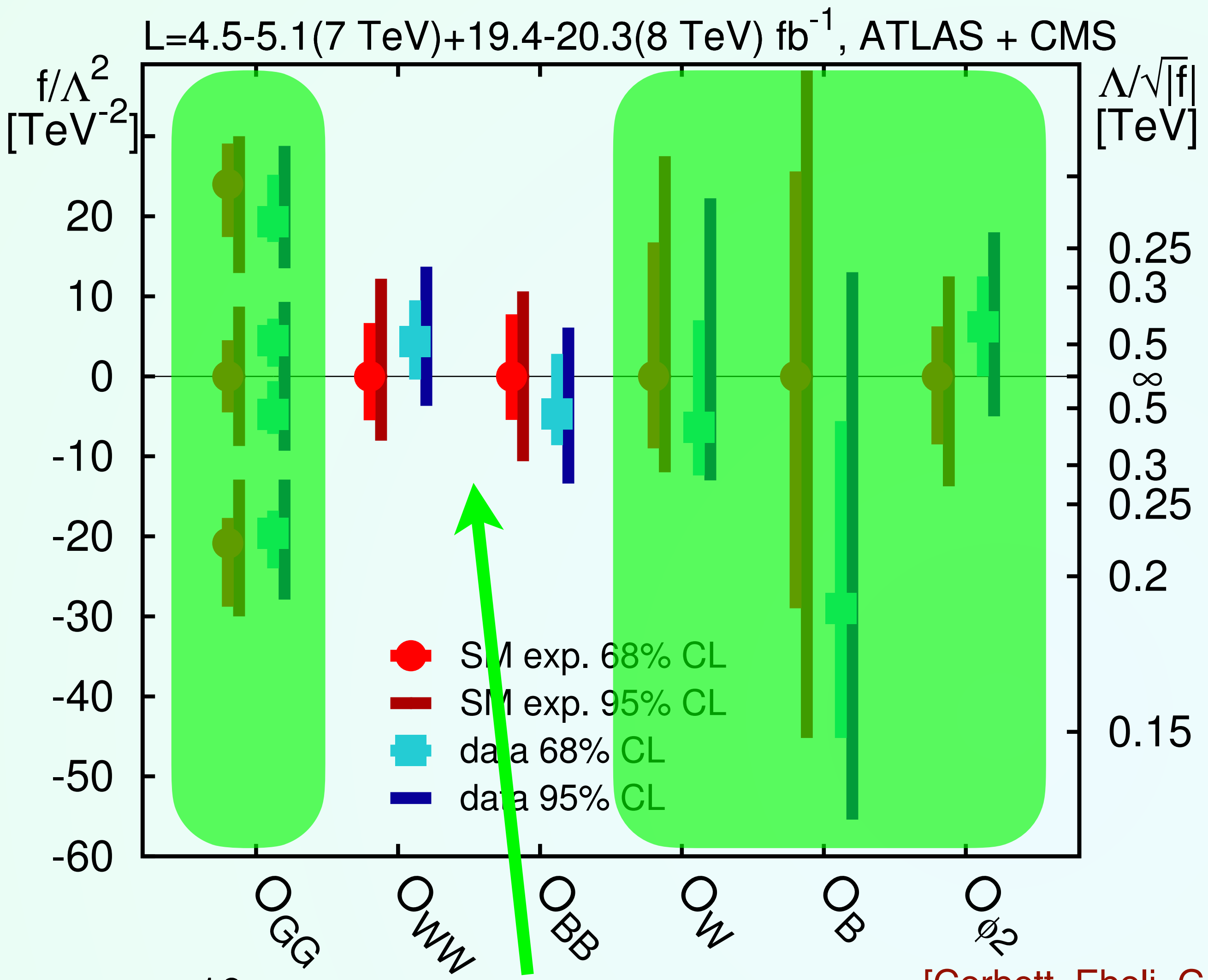

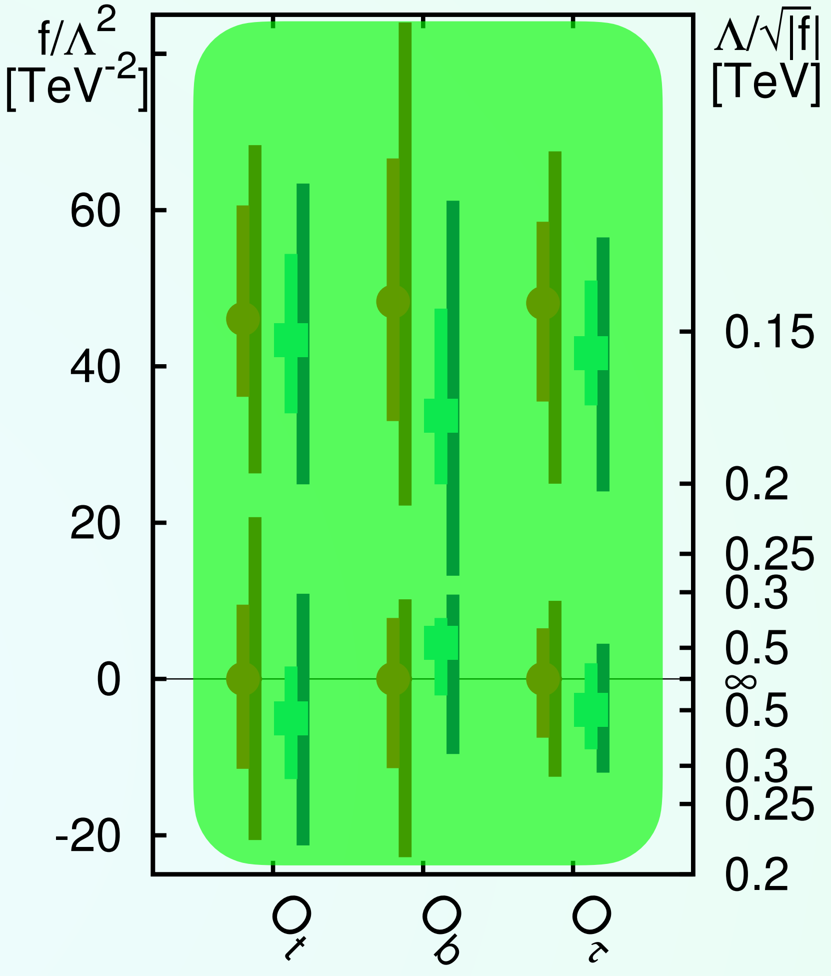

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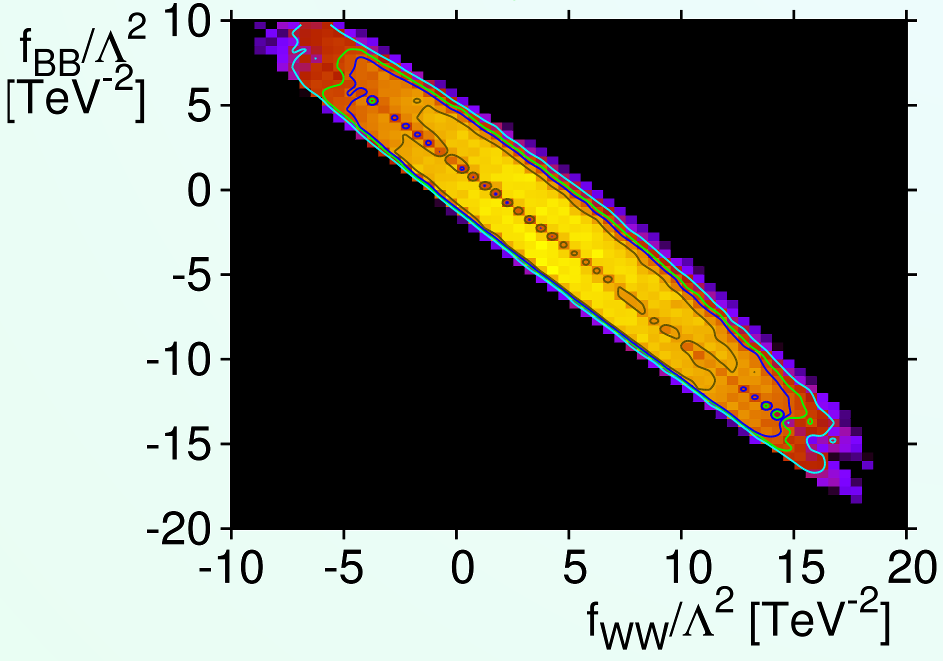
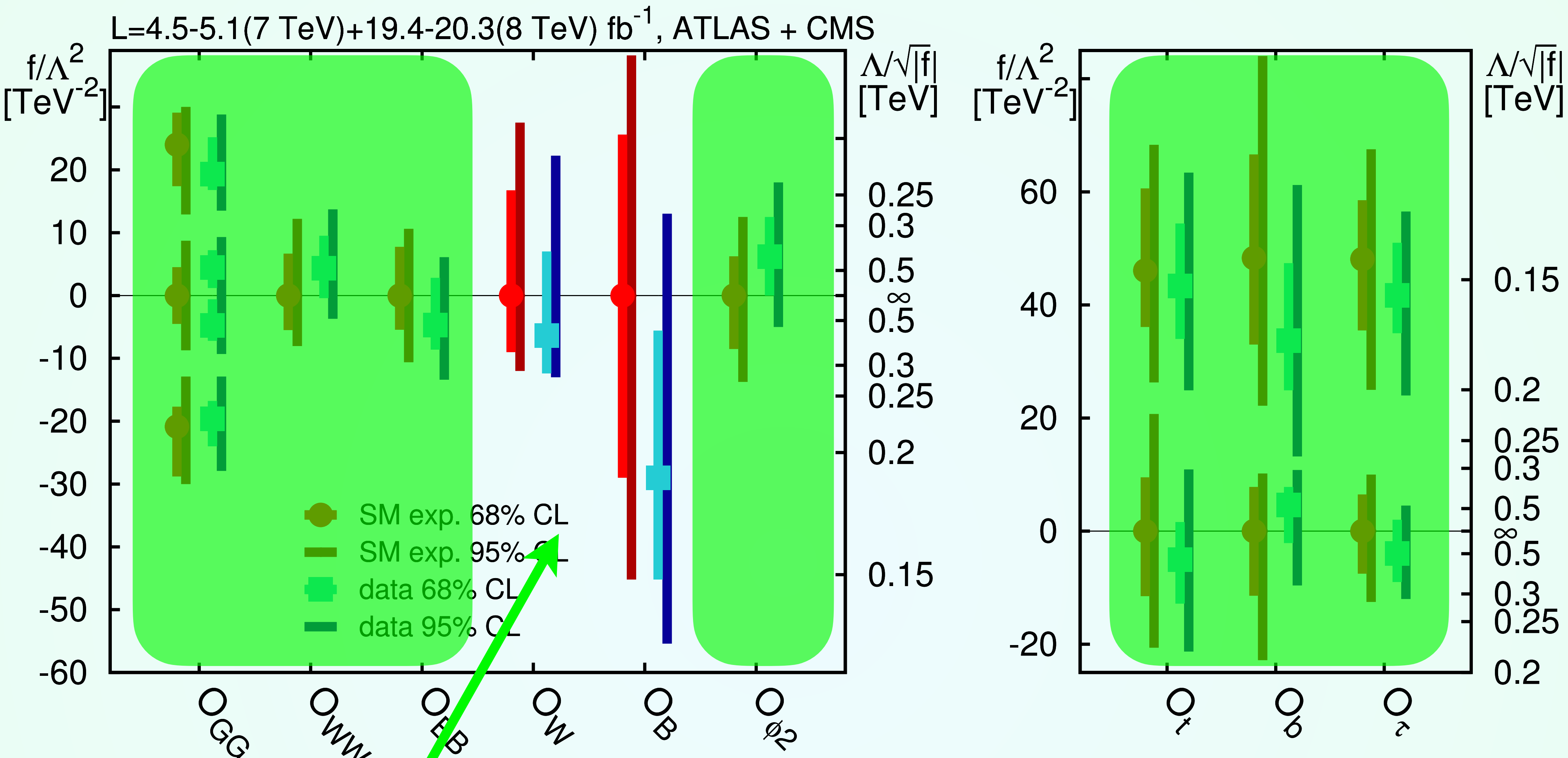


- Best constrained from $h \to \gamma\gamma$
- Strong anti-correlation

Results for Rate-Based Analysis



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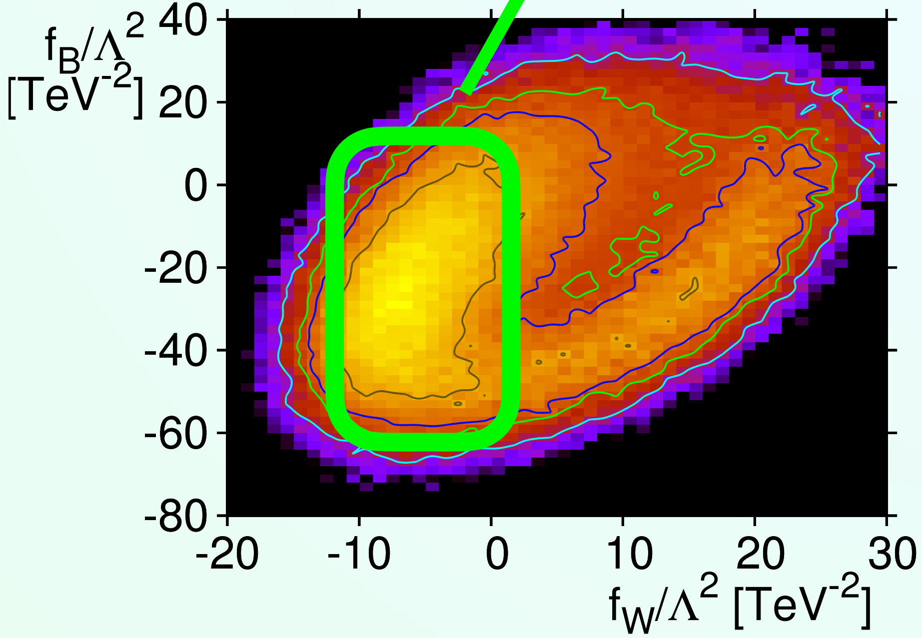
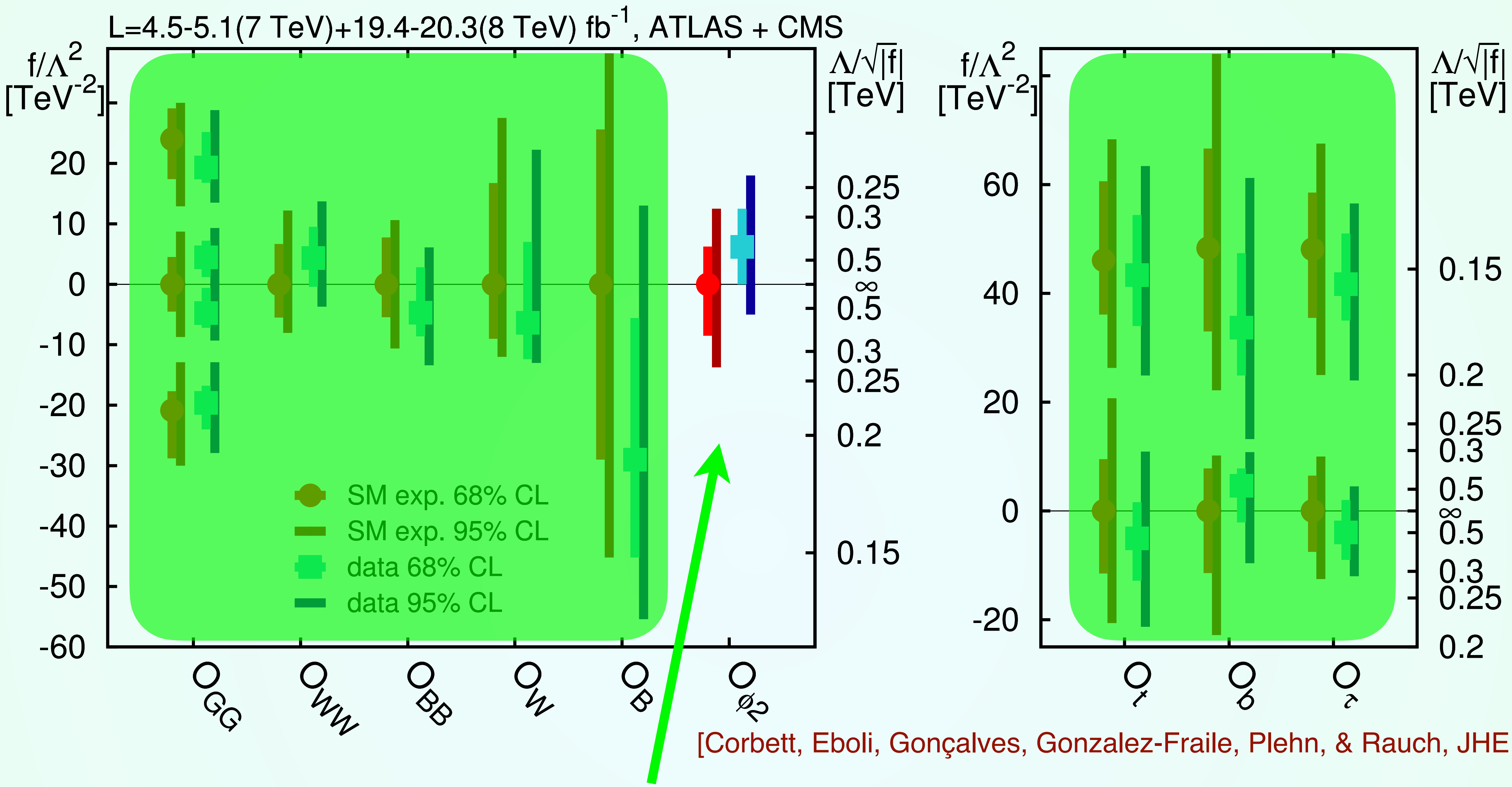


- f_W much better than f_B
- f_W to HVV
- f_B only to HZZ (Weinberg angle supp.)

Results for Rate-Based Analysis



[Corbett, Eboli, Gonçalves, Gonzalez-Fraile, Plehn, & Rauch, JHEP 1508 (2015)]

- $f_{\Phi 2}$ universal mod. of gauge bosons and fermion masses
- enters in many observables

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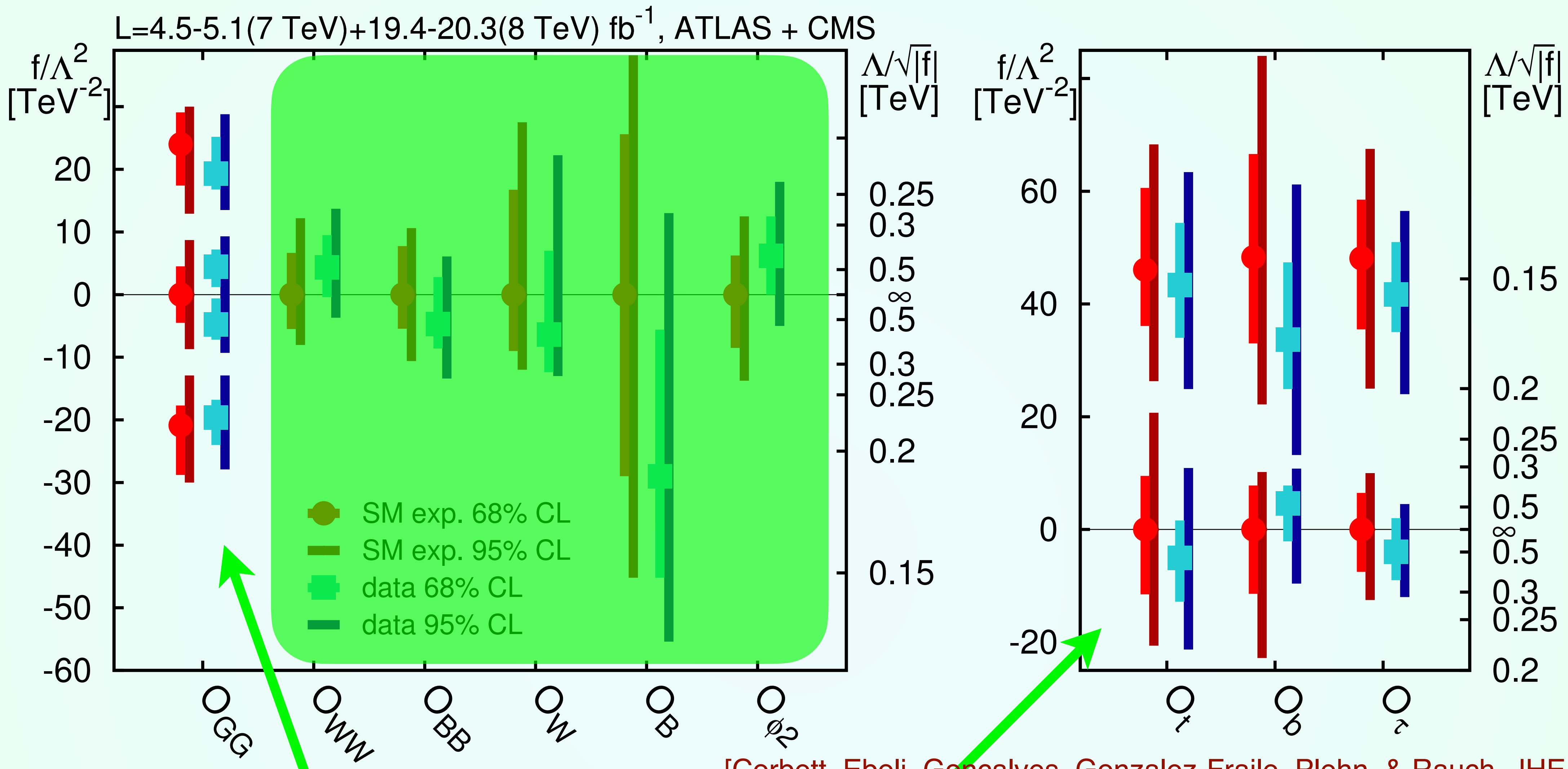

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- O_{GG} has 2x2 degenerate minima
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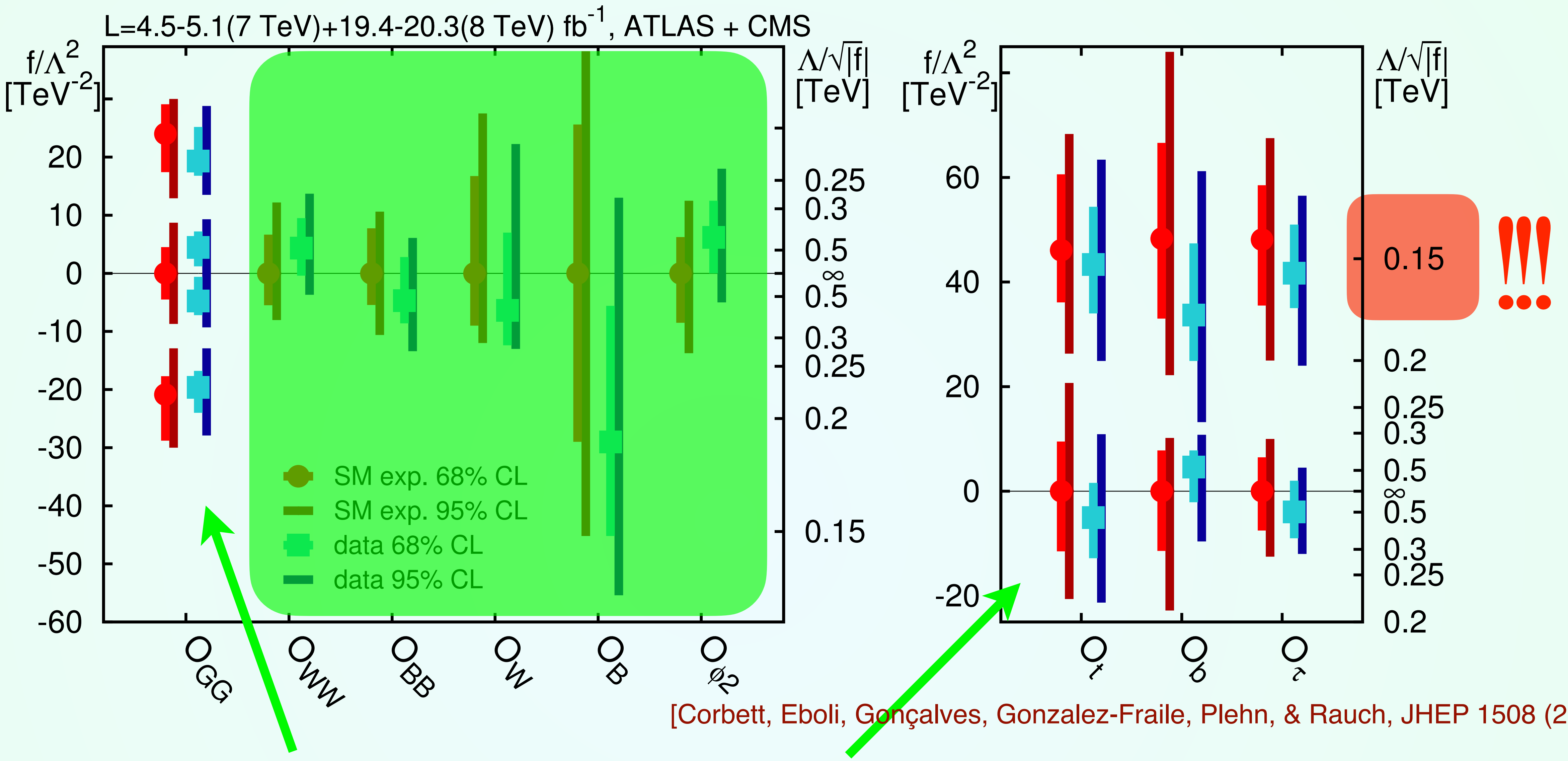

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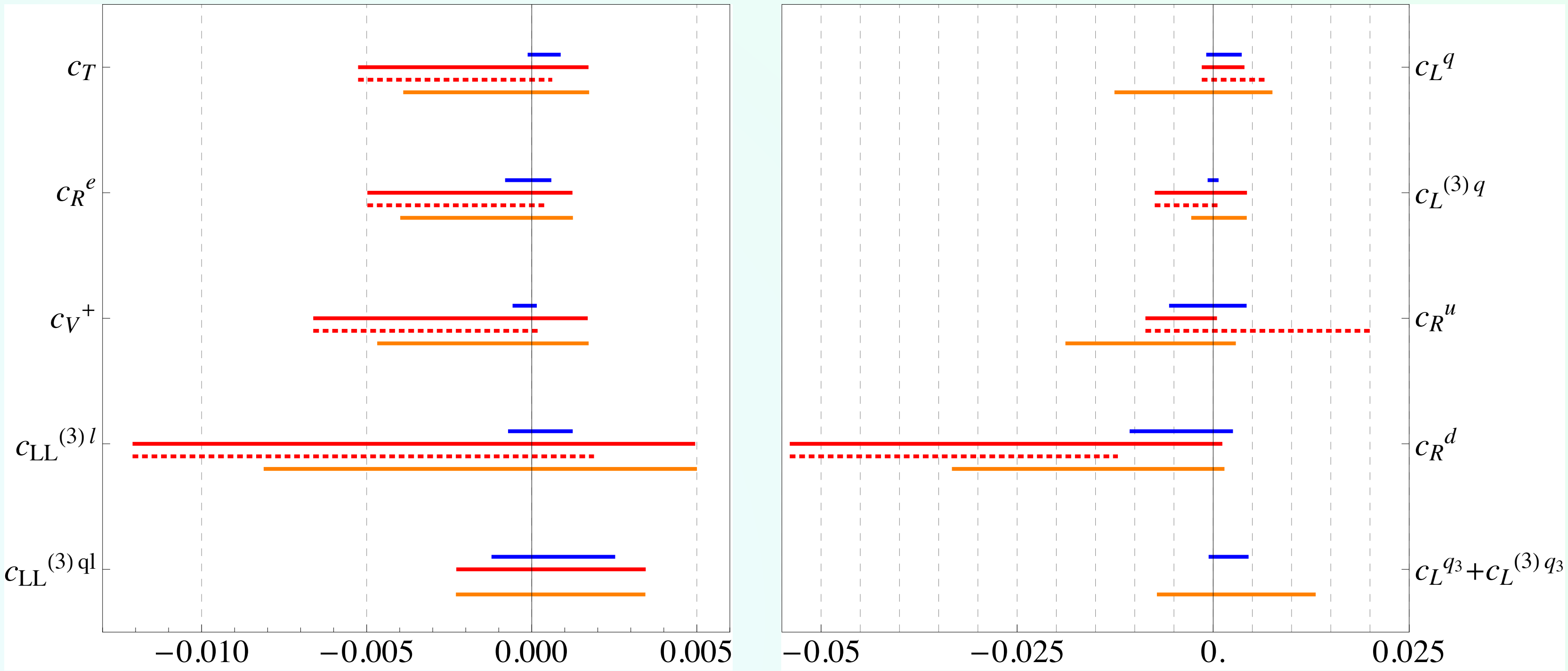
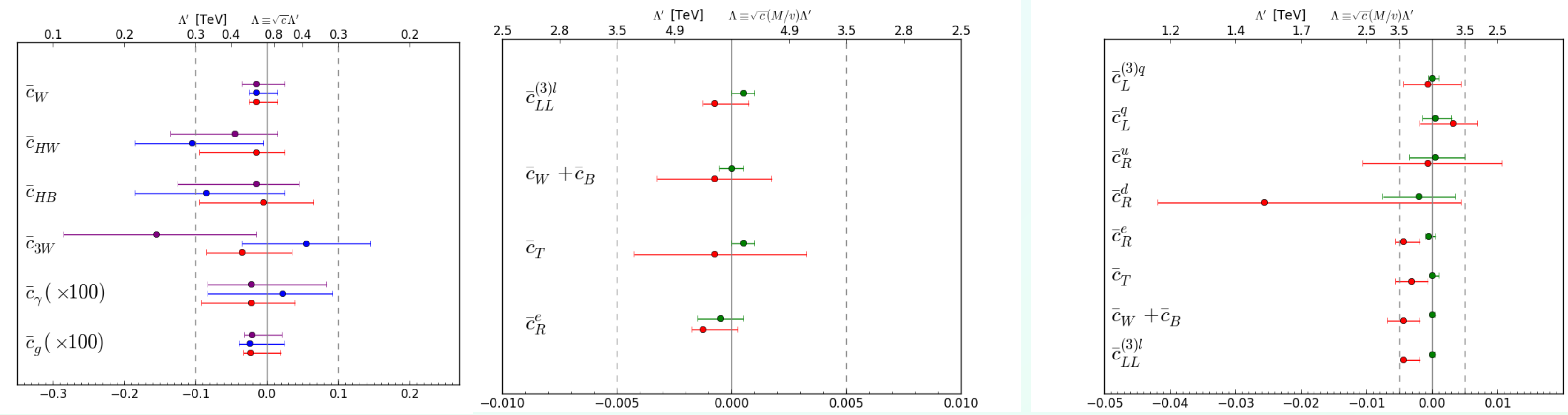
Alternative linear bases and fits

Elias-Miro, Espinosa, Masso & Pomarol, JHEP 1311(2013)
Pomerol & Riva, JHEP 1401 (2014)
Gupta, Pomarol & Riva, PRD91 (2015)
Falkowski & Riva, JHEP 1502 (2015)

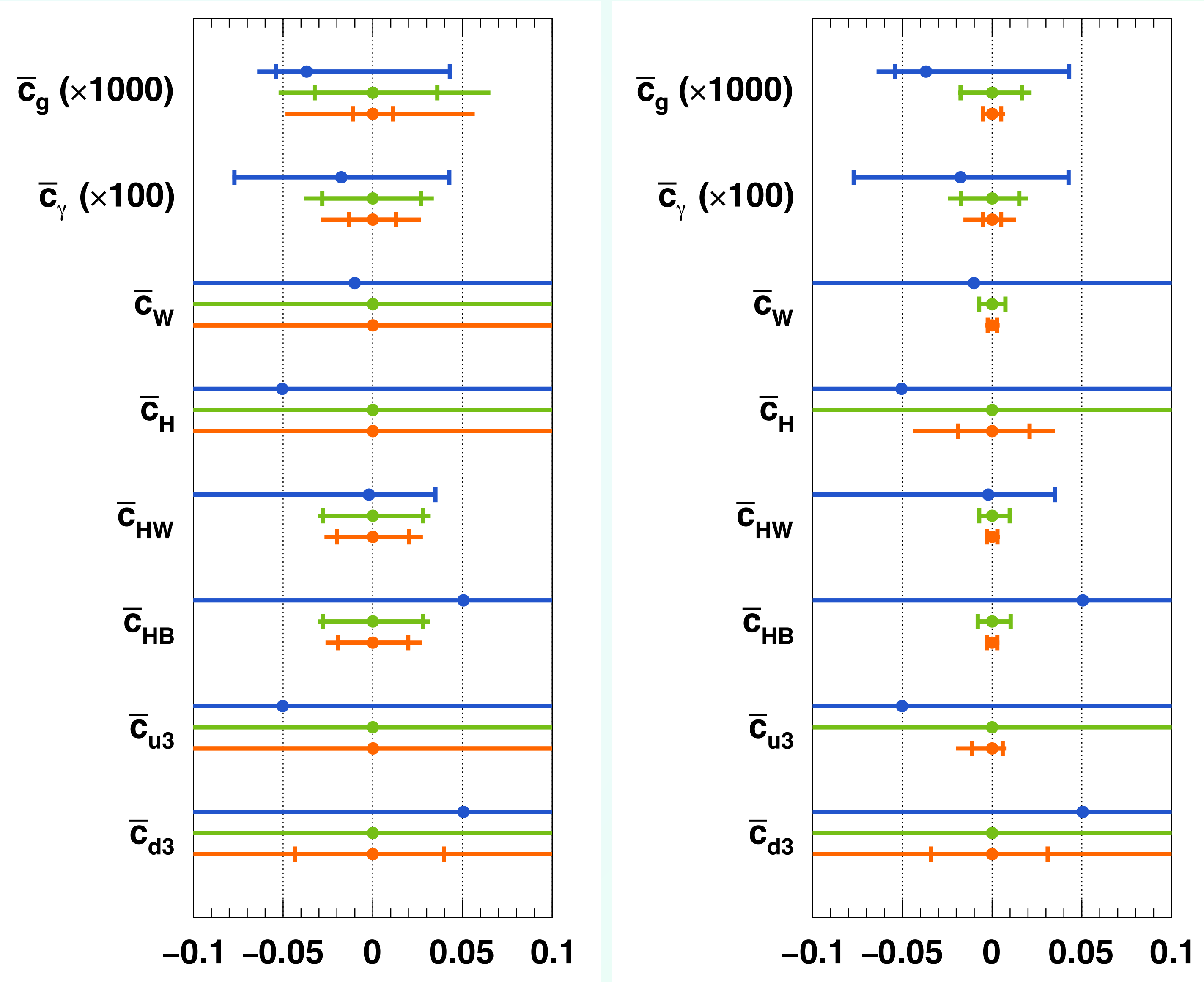


Ellis, Sanz & You, JHEP 1407 (2014)
Ellis, Sanz & You, JHEP 1503 (2015)



Alternative linear bases and fits

Englert, Kogler, Schulz & Spannowsky, arXiv: 1511.05170



Beyond Rate-Based Analysis

Anomalous Lorentz couplings modify the Kinematic distributions:

$$\begin{aligned}\mathcal{L}_{HVV} = {} & \cancel{g_{Hgg}\, G^a_{\mu\nu} G^{a\mu\nu}} h + \cancel{g_{H\gamma\gamma}\, A_{\mu\nu} A^{\mu\nu}} h + \cancel{g^{(1)}_{HZ\gamma}\, A_{\mu\nu} Z^\mu \partial^\nu} h + \cancel{g^{(2)}_{HZ\gamma}\, A_{\mu\nu} Z^{\mu\nu}} h \\ & + g^{(1)}_{HZZ}\, Z_{\mu\nu} Z^\mu \partial^\nu h + g^{(2)}_{HZZ}\, Z_{\mu\nu} Z^{\mu\nu} h + \cancel{g^{(3)}_{HZZ}\, Z_\mu Z^\mu h} \\ & + g^{(1)}_{HWW}\, \left(W^+_{\mu\nu} W^{-\,\mu} \partial^\nu h + \mathrm{h.c.}\right) + g^{(2)}_{HWW}\, W^+_{\mu\nu} W^{-\,\mu\nu} h + \cancel{g^{(3)}_{HWW}\, W^+_\mu W^{-\,\mu}} h\,, \\ \mathcal{L}_{Hff} = {} & g_f \cancel{\bar{f}_L f_R h} + \mathrm{h.c.}\end{aligned}$$

$$g^{(1)}_{HZZ} = \frac{g^2 v}{2\Lambda^2}\,\frac{c_w^2 f_W + s_w^2 f_B}{2c_w^2} \qquad g^{(1)}_{HWW} = \frac{g^2 v}{2\Lambda^2}\,\frac{f_W}{2}$$

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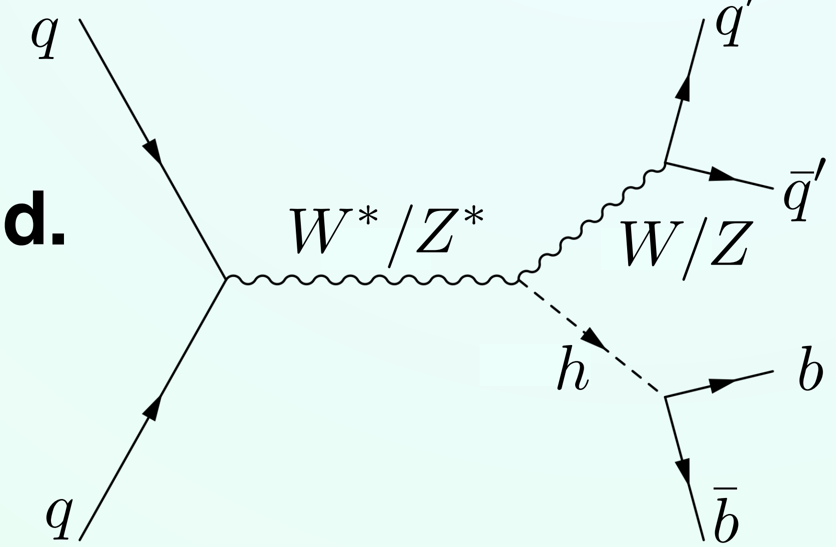
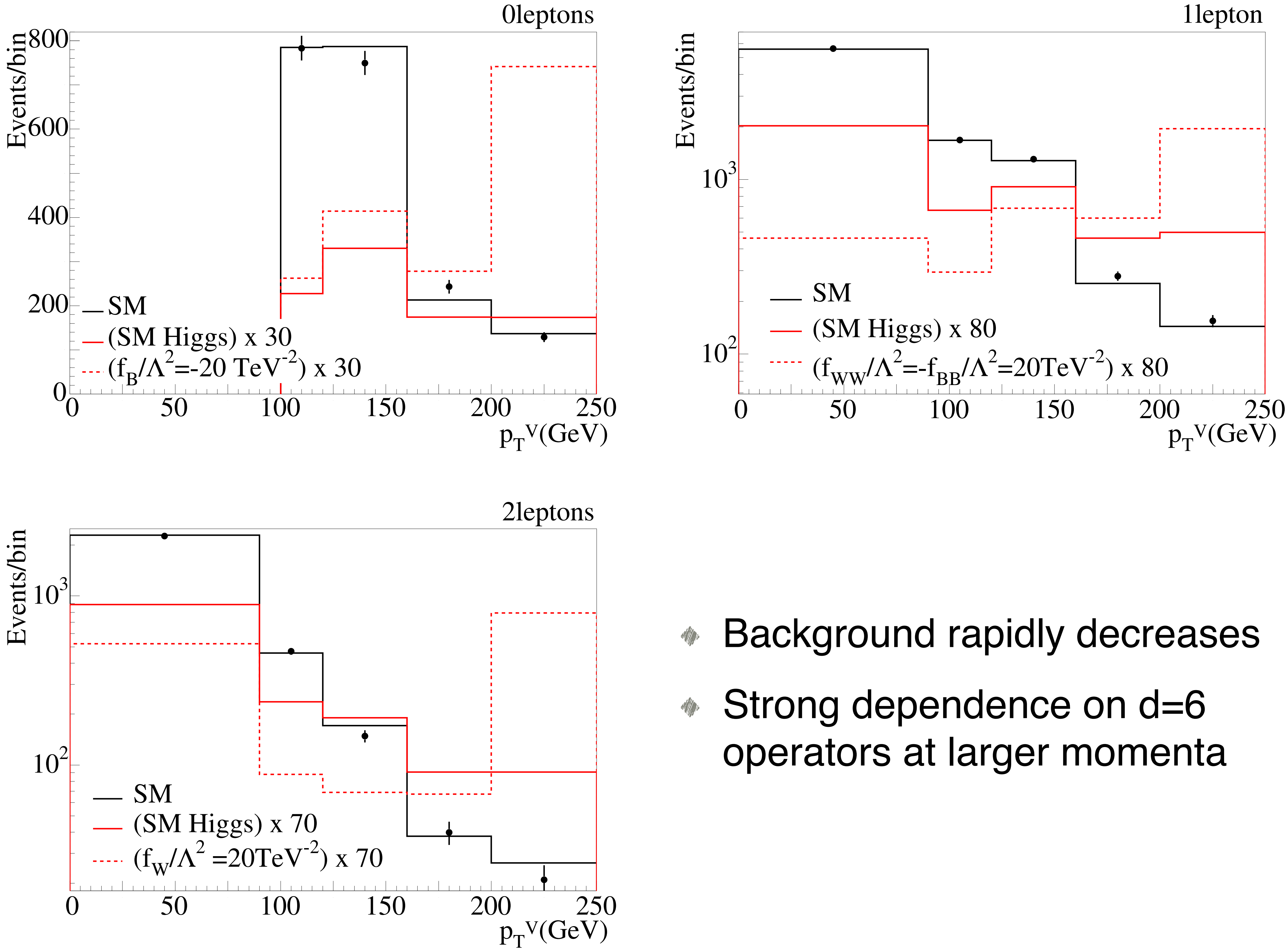
Focus on:

VH Prod.



- variable with large flow in the production vertex: p_T^V
- tagging with 2 b's and 0, 1, 2 leptons



[Corbett, Eboli, Gonçalves, Gonzalez-Fraile, Plehn, & Rauch, JHEP 1508 (2015)]

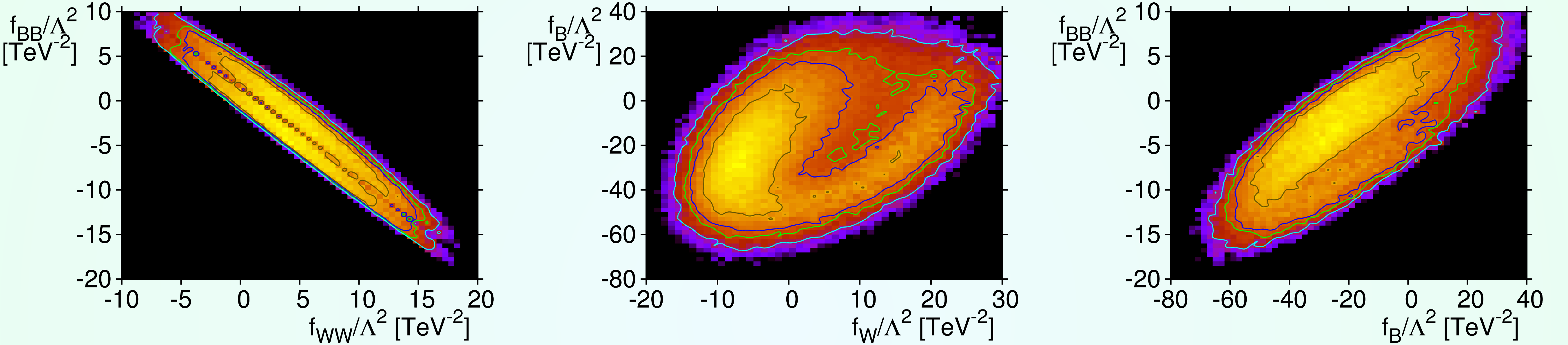
- Background rapidly decreases
- Strong dependence on d=6 operators at larger momenta

Kinematic distributions from ATLAS $h \to \bar{b}b$ (1409.6212)

Results with Kinematics

Corbett, Eboli, Gonçalves, Gonzalez-Fraile, Plehn, & Rauch, JHEP 1508 (201

- **WITHOUT:**



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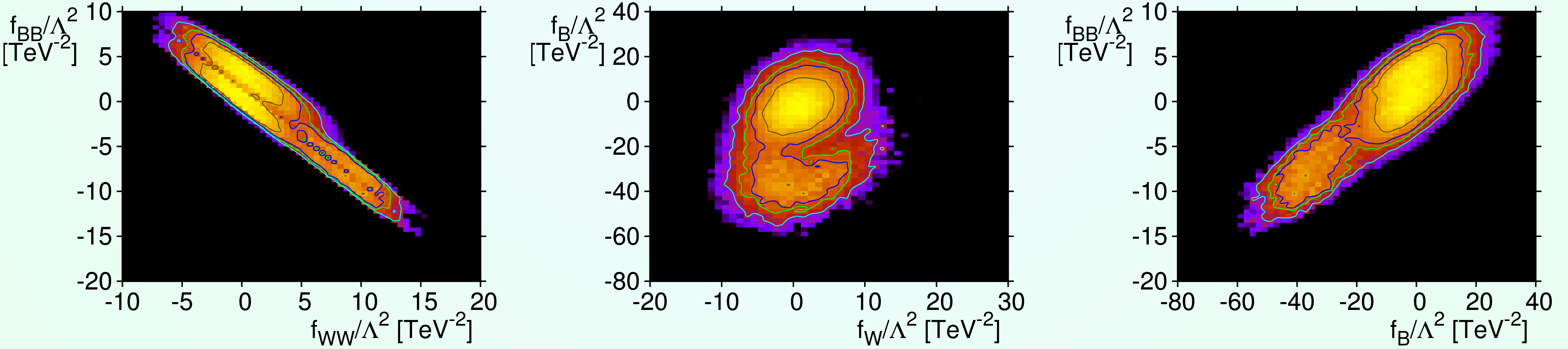

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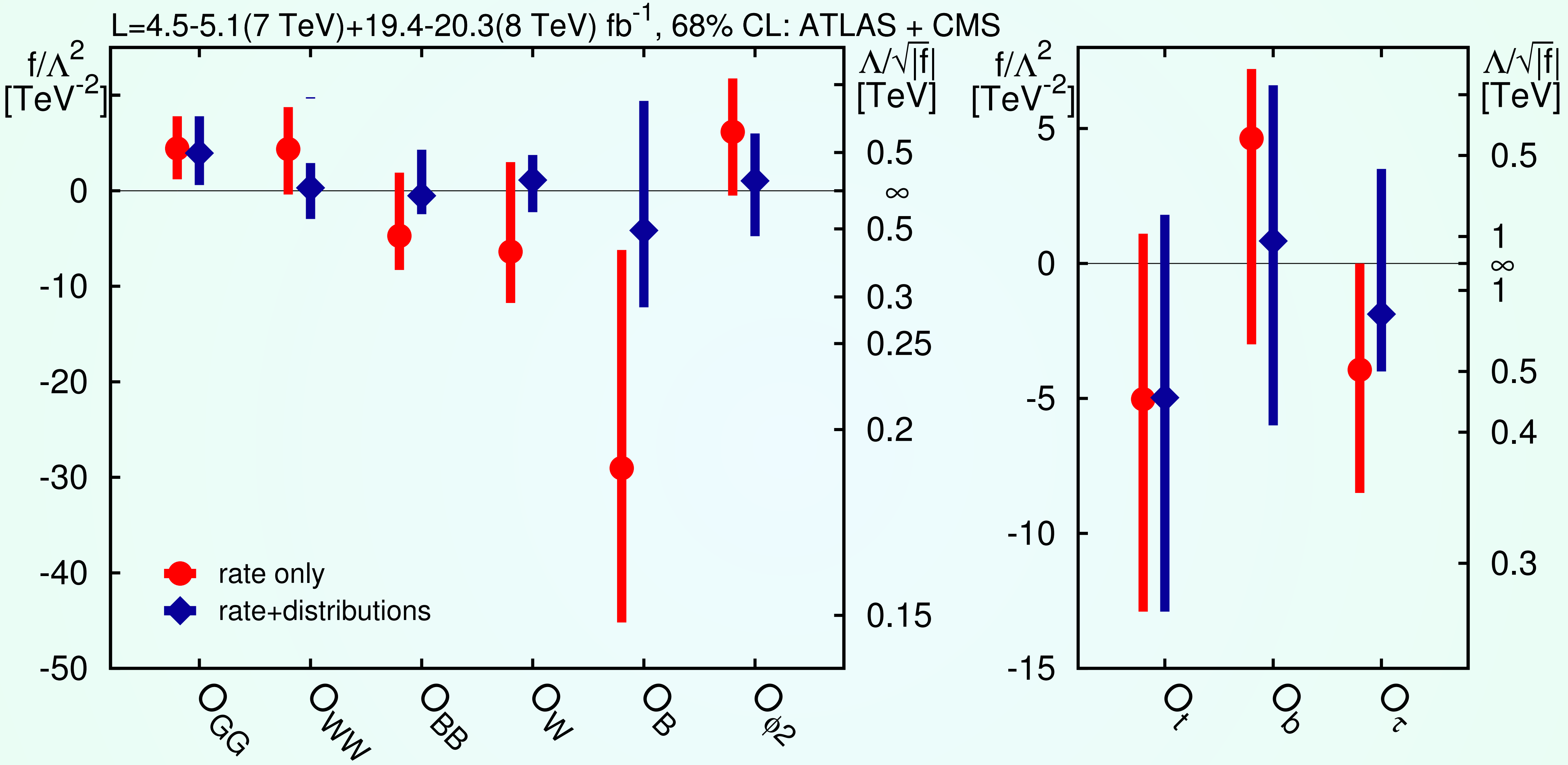

- Biggest impact of Kinematics on O_B, O_W, O_{BB}, O_{WW} , respectively.
- Energy scales probed by Run I are 300-500 GeV (O(1) coeff.)

Interplay HVV and TGV

- Correlation between HVV and TGV: Example

$$\mathcal{O}_B = (D_\mu \Phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \Phi)$$

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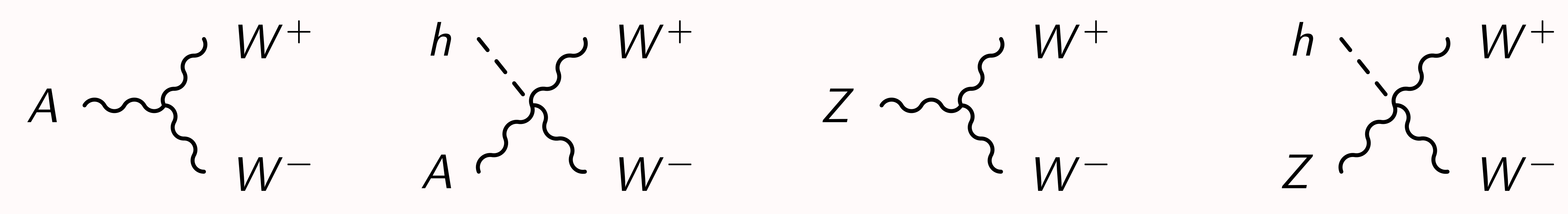
In unitary gauge can be rewritten as:

$$\mathcal{O}_B = \frac{ieg^2}{8} A_{\mu\nu} W^{-\mu} W^{+\nu} (v+h)^2 - \frac{ie^2 g}{8\cos\theta_W} Z_{\mu\nu} W^{-\mu} W^{+\nu} (v+h)^2$$
$$- \frac{eg}{4\cos\theta_W} A_{\mu\nu} Z^\mu \partial^\nu h (v+h) + \frac{e^2}{4\cos^2\theta_W} Z_{\mu\nu} Z^\mu \partial^\nu h (v+h)$$



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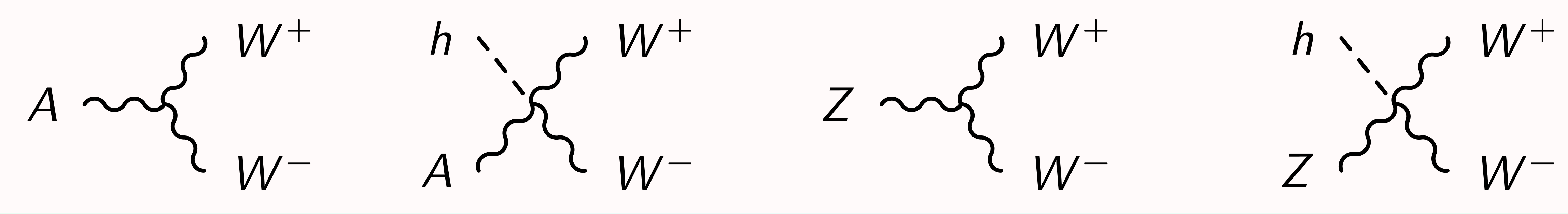
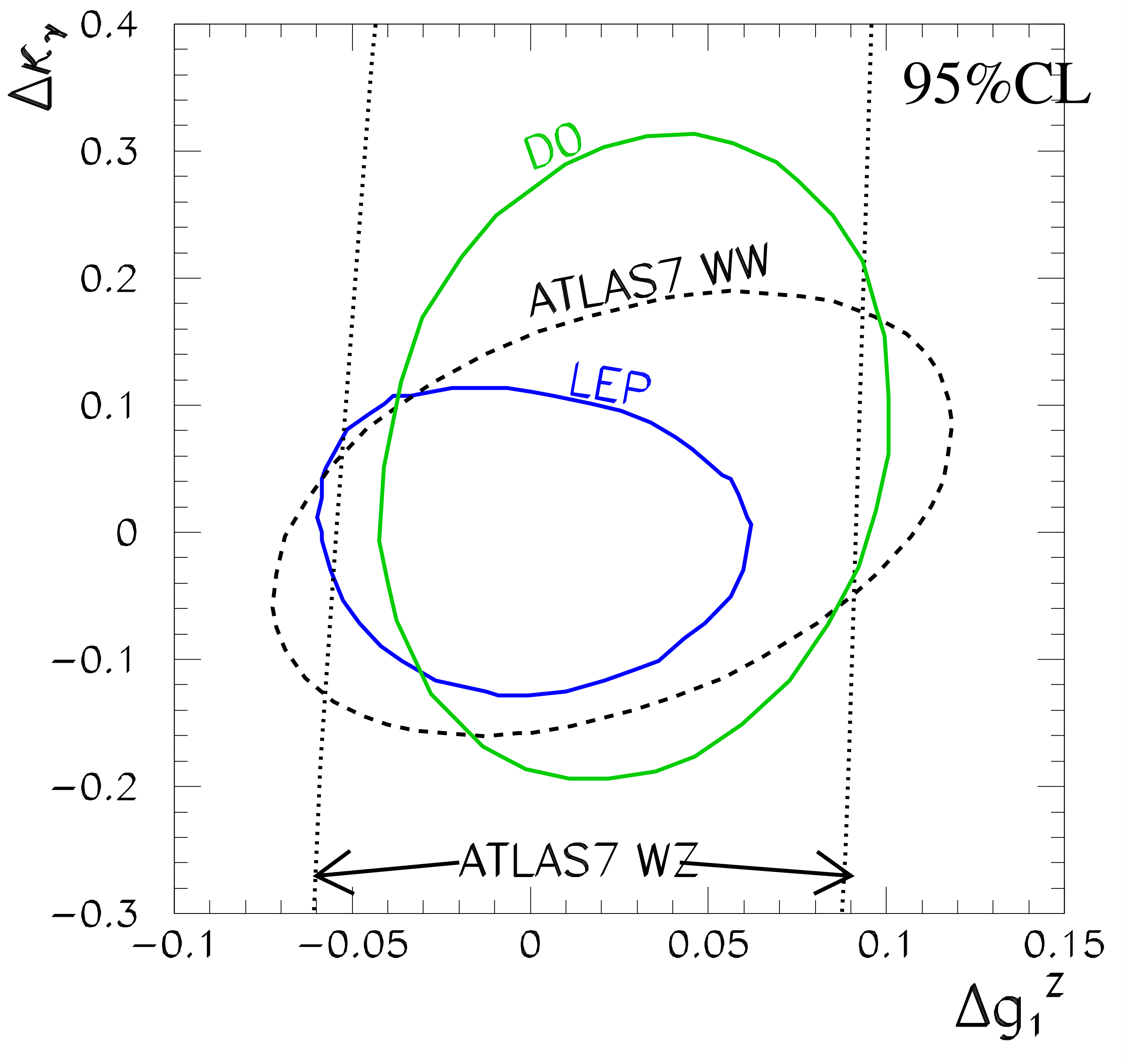


All these couplings are correlated!!

Interplay HVV and TGV

Corbett, Eboli, Gonzalez-Fraile & Gonzalez-Garcia, PRL 111 (2013)



- Assuming

$$f_{WWW} = 0 \rightarrow \lambda_V = 0$$

- Only two independent:

$$\Delta g_1^Z = g_1^Z - 1 = \frac{g^2v^2}{8c_w^2\Lambda^2} f_W$$

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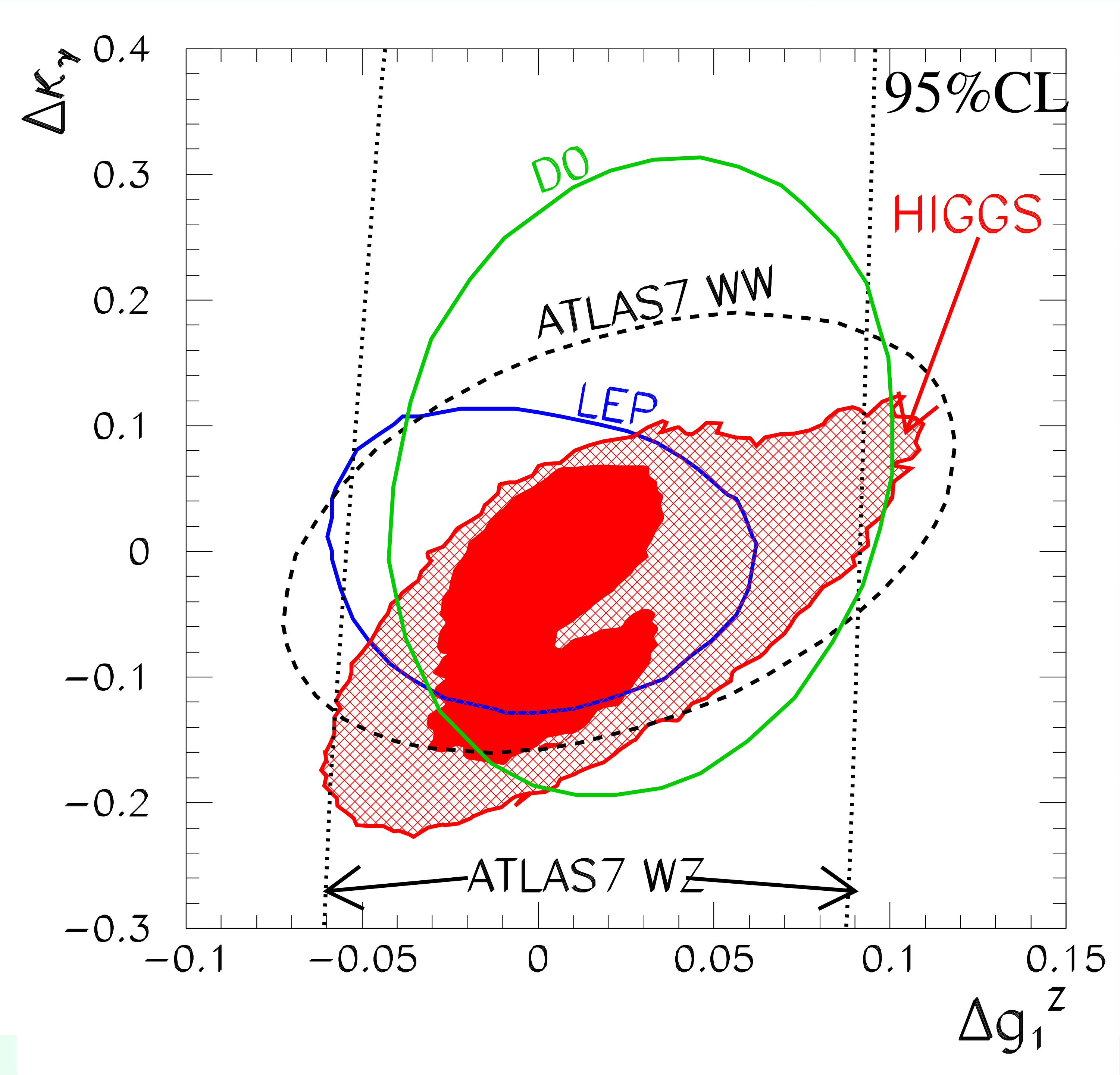

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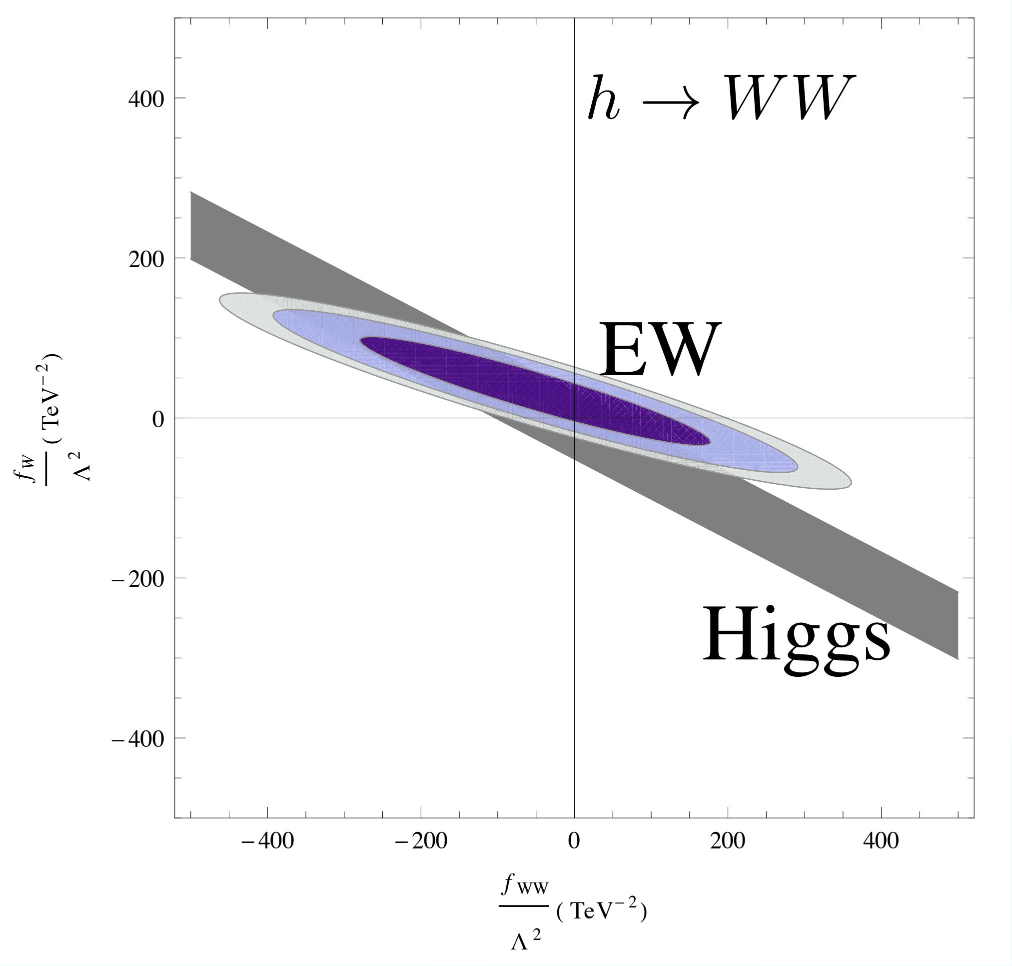
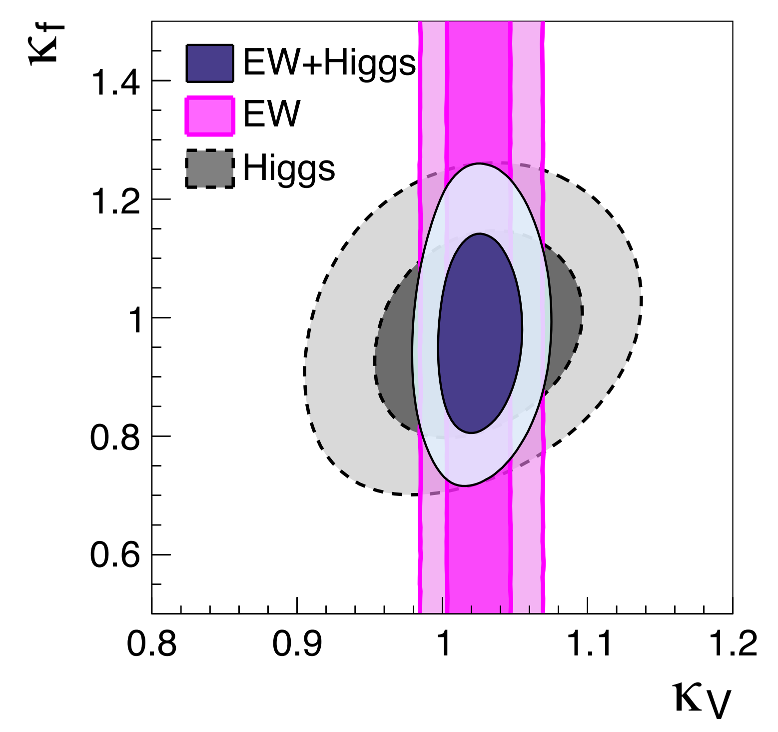
- Higgs data bounds (7+8 TeV data used, including kinematics)

Other similar studies

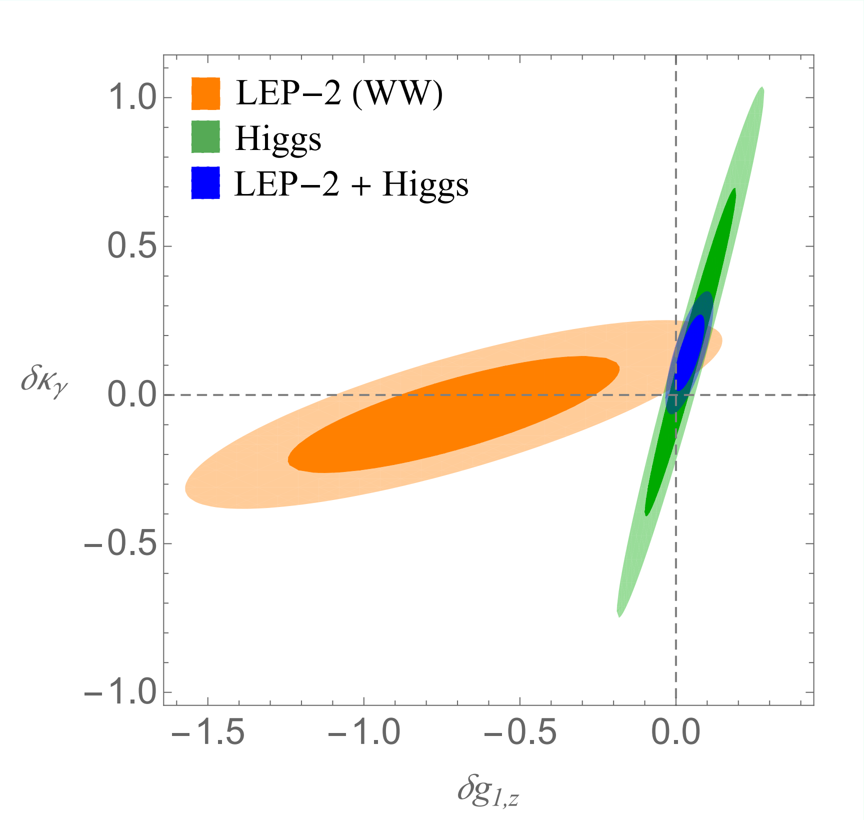
Chen, Dawson & Zhang, PRD89 (2014)



Ciuchini, Franco, Mishima, Pierini, Reina & Silvestrini, arXiv: 1410.4204, 1410.6940



Falkowski, Gonzalez-Alonso, Greljo & Marzocca, PRL 116 (2016)



Which Higgs?

EXACT EW DOUBLET

SM

Hierarchy Problem (neutrino masses & DM & Baryon Asym)

(**SUSY** two $SU(2)_L$ doublets)

NOT NECESSARILY DOUBLET

Composite Higgs Models

Not exactly an EW doublet, but almost

Dilaton or Exotic

EW singlet

Linear Effective Lagrangian SMEFT

$SU(2)_L \times U(1)_Y$ gauge sym

SM spectrum, and in particular exact EW Higgs doublet Φ

Non-Linear Effective Lagrangian HEFT

$SU(2)_L \times U(1)_Y$ gauge sym

SM spectrum, but non-exact EW Higgs doublet h

HEFT

SMEFT: constructed with

$$\Phi(x) = \frac{v+h}{\sqrt{2}} e^{i\sigma_a \pi^a(x)/v} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

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Higgs: h **Singlet**

GBs: $\mathbf{U}(x) = e^{i\sigma_a \pi^a(x)/v}$

$$\mathbf{U}(x) \to L\,\mathbf{U}(x) R^\dagger$$

Independent!!

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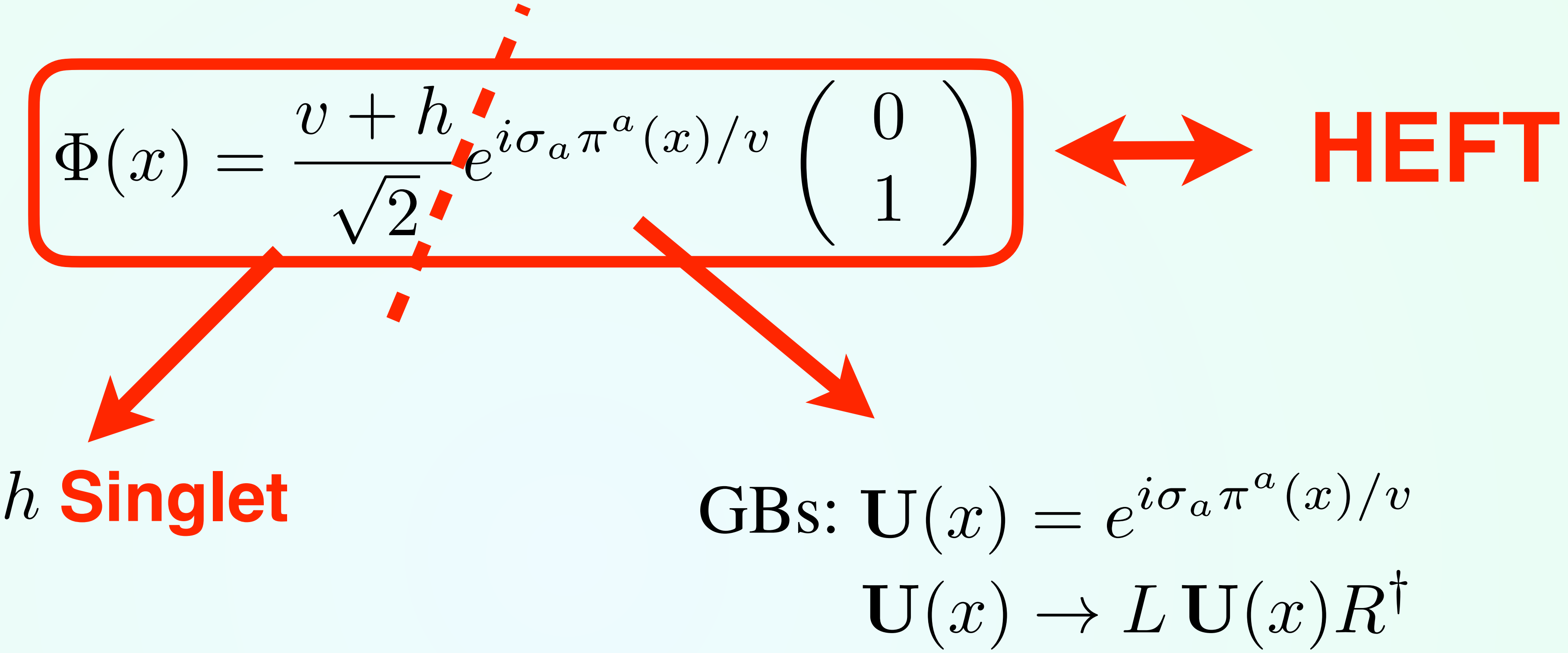

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- Being h a singlet: generic functions of h $\boxed{\mathcal{F}_i(h) = 1 + 2\alpha_i \frac{h}{v} + \beta_i \frac{h^2}{v^2} + \ldots}$
- Being $\boxed{\mathbf{U}(x) \textbf{ vs. } h}$ independent, many more operators can be constructed

Decorrelations & New Signals

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$\mathbf{U}(x)$ is a 2x2 **adimensional** matrix. This leads to a fundamental difference between the linear and chiral Lagrangians:

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SMEFT

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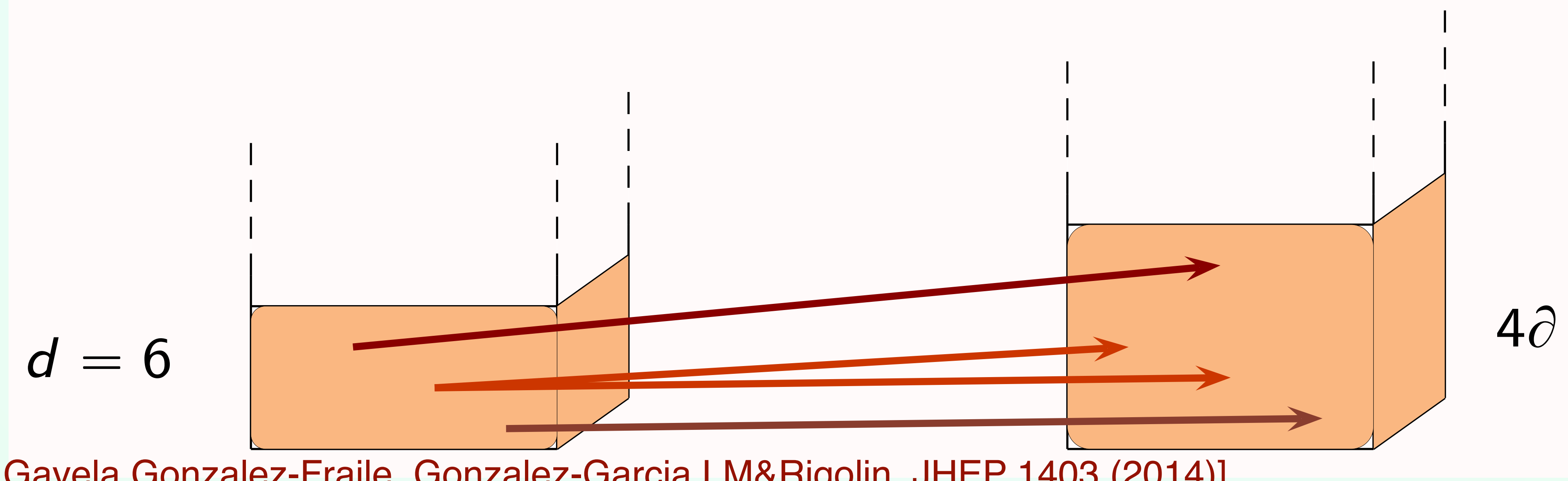
The dimension of the leading low-energy operators differs

- Investigate on the signals of decorrelations: due to the nature of the chiral expansion vs. the linear one, and due to $\mathcal{F}_i(h) \neq \left(1+\frac{h}{v}\right)^2$

SMEFT **HEFT**



[Brivio,Corbett,Eboli,Gavela,Gonzalez-Fraile, Gonzalez-Garcia,LM&Rigolin, JHEP 1403 (2014)]

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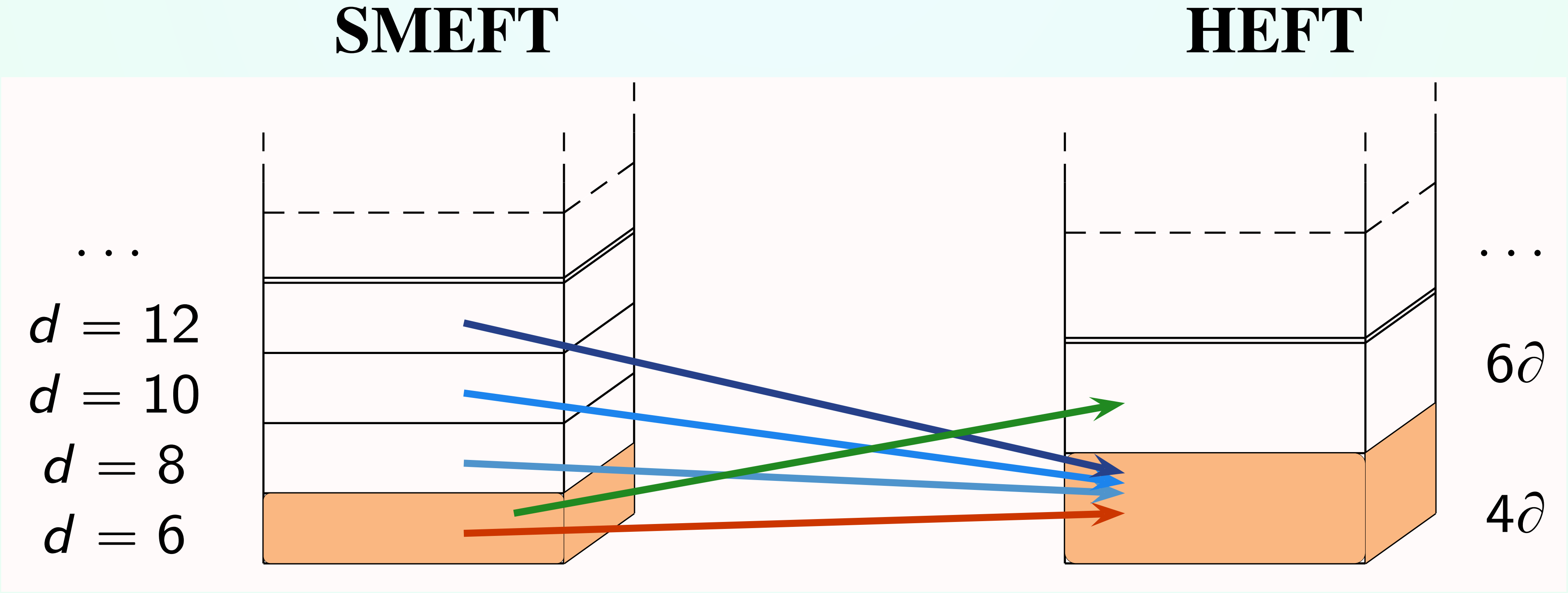
The dimension of the leading low-energy operators differs

- Study the anomalous signals present in the chiral, but absent in the linear



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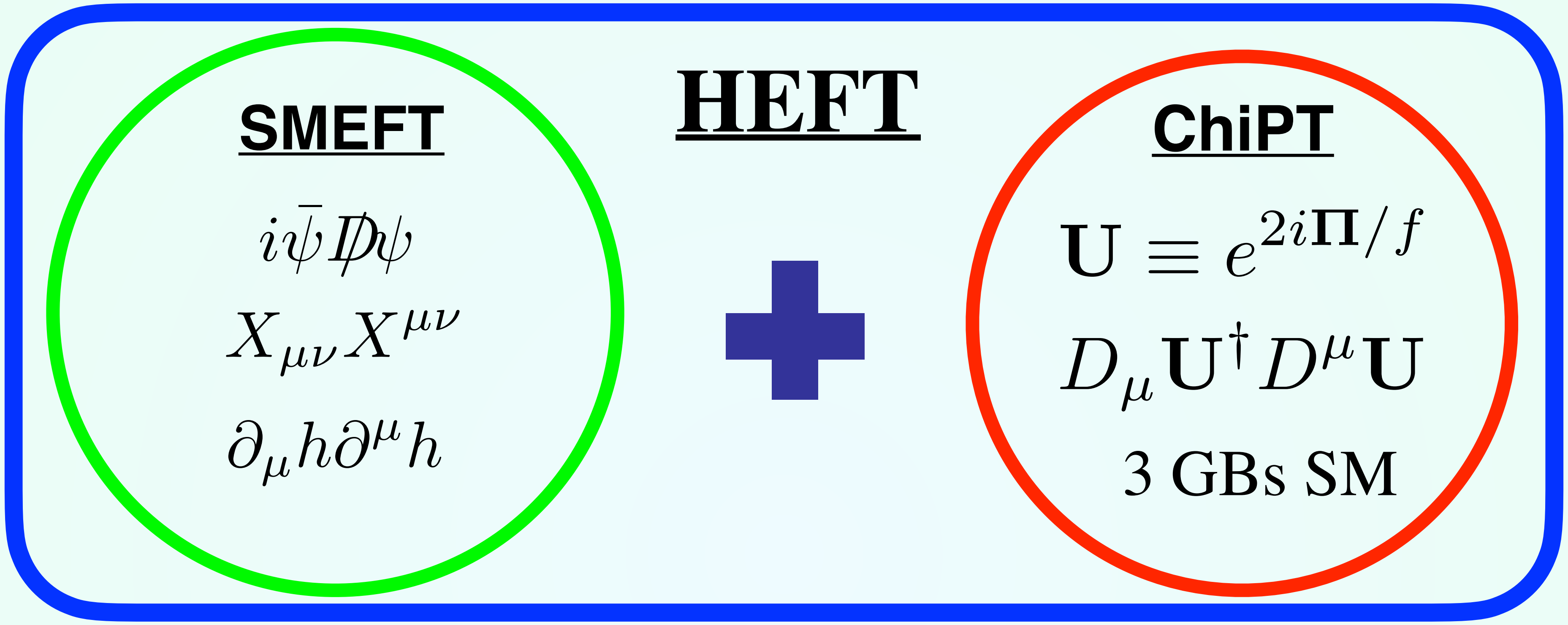
What is HEFT?

The Higgs Effective Field Theory (HEFT) is a fusion of SMEFT and ChiPT



HEFT

SMEFT

$$i\bar{\psi}\not{D}\psi$$

$$X_{\mu\nu}X^{\mu\nu}$$

$$\partial_\mu h \partial^\mu h$$

+

ChiPT

$$\mathbf{U} \equiv e^{2i\mathbf{\Pi}/f}$$

$$D_\mu \mathbf{U}^\dagger D^\mu \mathbf{U}$$

3 GBs SM

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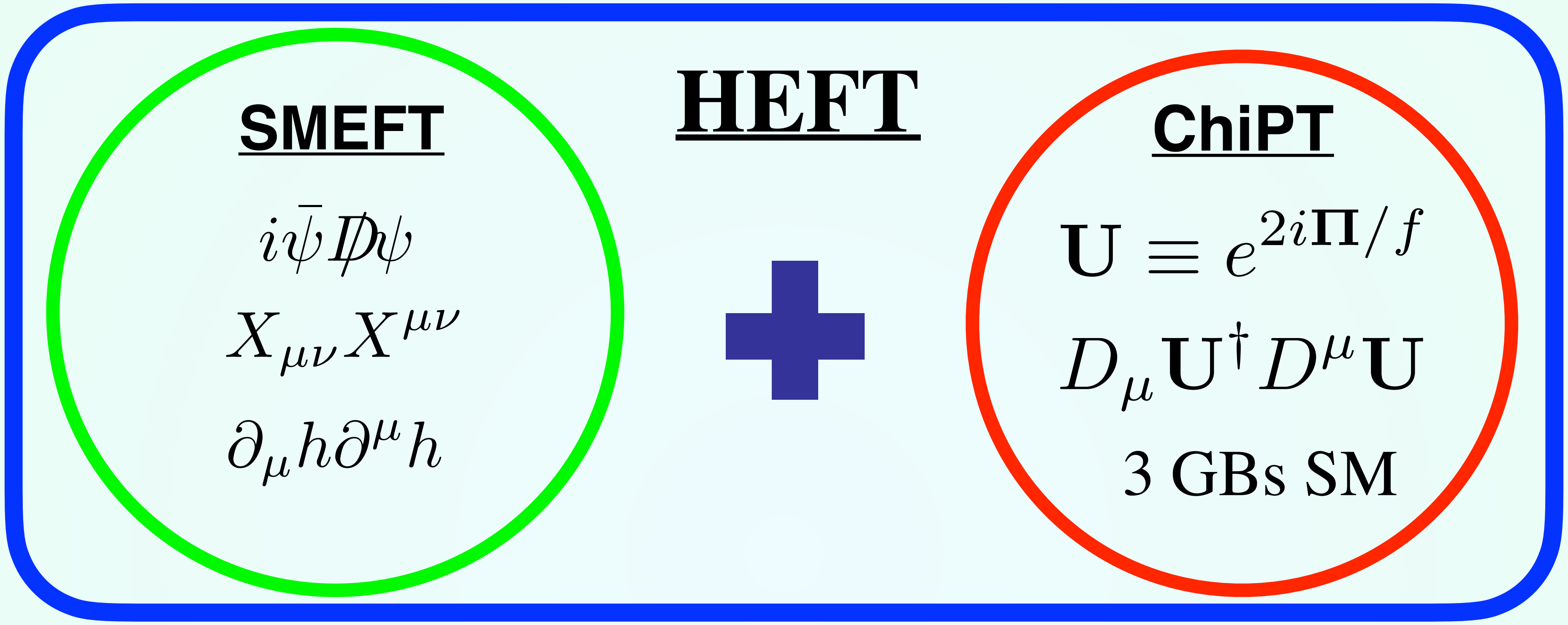

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3 GBs SM

HEFT describes an extended class of “Higgs” models:

$$\left.\begin{array}{l}\text{Standard Model}\\ \text{SMEFT}\\ \text{Technicolor-like ansatz}\\ \text{Dilator-Like models}\\ \text{Composite Higgs models}\end{array}\right\}$$

special limits and fixing the parameters

Alonso,Brivio,Gavela,LM&Rigolin, JHEP **12** (2014) 034
Hierro,LM&Rigolin, arXiv:1510.07899

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3 GBs SM

Building blocks:

$$\mathbf{V}_\mu \equiv (\mathbf{D}_\mu \mathbf{U})\,\mathbf{U}^\dagger \qquad \mathbf{V} \to L\,\mathbf{V}\,L^\dagger$$

$$L \in SU(2)_L$$

$$\mathbf{T} \equiv \mathbf{U}\sigma_3\mathbf{U}^\dagger \qquad \mathbf{T} \to L\,\mathbf{T}\,L^\dagger$$

$$\psi_{L,R}$$

$$A_\mu \qquad X_{\mu\nu}$$

h singlet of SM syms: arbitrary $\mathcal{F}(h) = \sum_{i=0} a_i \left(\frac{h}{f}\right)^i$

The HEFT Lagrangian

Azatov, Contino & Galloway JHEP 1204 (2012)
Alonso, Gavela, LM, Rigolin & Yepes, JHEP 1206 (2012)
Alonso, Gavela, LM, Rigolin & Yepes, PLB 722 (2013)
Alonso, Gavela, LM, Rigolin & Yepes, PRD 87 (2013)
Buchalla, Cata & Krause, NPB 880 (2014)
Gavela, Gonzalez-Fraile, Gonzalez-Garcia, LM, Rigolin & Yepes, JHEP 1410 (2014)

$$\mathcal{L}_{HEFT} = \boxed{\mathcal{L}_0} + \Delta\mathcal{L}$$

$$\begin{aligned}\mathcal{L}_0 = & -\frac{1}{4}G^{\alpha}_{\mu\nu}\mathcal{G}^{\alpha\,\mu\nu} - \frac{1}{4}W^{a}_{\mu\nu}W^{a\,\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \\ & + \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{v^2}{4}\mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}^\mu)\mathcal{F}_C(h) - V(h) + \\ & + i\bar{Q}_L \not{D} Q_L + i\bar{Q}_R \not{D} Q_R + i\bar{L}_L \not{D} L_L + i\bar{L}_R \not{D} L_R + \\ & - \frac{v}{\sqrt{2}}\left(\bar{Q}_L \mathbf{U}\mathcal{Y}_Q(h) Q_R + \mathrm{h.c.}\right) - \frac{v}{\sqrt{2}}\left(\bar{L}_L \mathbf{U}\mathcal{Y}_L(h) L_R + \mathrm{h.c.}\right)\end{aligned}$$

The HEFT Lagrangian

Azatov, Contino & Galloway JHEP 1204 (2012)
Alonso, Gavela, LM, Rigolin & Yepes, JHEP 1206 (2012)
Alonso, Gavela, LM, Rigolin & Yepes, PLB 722 (2013)
Alonso, Gavela, LM, Rigolin & Yepes, PRD 87 (2013)
Buchalla, Cata & Krause, NPB 880 (2014)
Gavela, Gonzalez-Fraile, Gonzalez-Garcia, LM, Rigolin & Yepes, JHEP 1410 (2014)

$$\mathcal{L}_{HEFT} = \boxed{\mathcal{L}_0} + \Delta\mathcal{L}$$

$$\mathcal{L}_0 = -\frac{1}{4}G^{\alpha}_{\mu\nu}\mathcal{G}^{\alpha\,\mu\nu} - \frac{1}{4}W^{a}_{\mu\nu}W^{a\,\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} +$$

$$D_\mu\Phi^\dagger D^\mu\Phi \longrightarrow \boxed{+\frac{1}{2}\partial_\mu h\partial^\mu h - \frac{v^2}{4}\mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}^\mu)\mathcal{F}_C(h)} - V(h) +$$

$$+ i\bar{Q}_L \not{D} Q_L + i\bar{Q}_R \not{D} Q_R + i\bar{L}_L \not{D} L_L + i\bar{L}_R \not{D} L_R +$$

$$- \frac{v}{\sqrt{2}}\left(\bar{Q}_L\mathbf{U}\mathcal{Y}_Q(h)Q_R + \mathrm{h.c.}\right) - \frac{v}{\sqrt{2}}\left(\bar{L}_L\mathbf{U}\mathcal{Y}_L(h)L_R + \mathrm{h.c.}\right)$$

The HEFT Lagrangian

Alonso, Gavela, LM, Rigolin & Yepes, PLB 722 (2013)
Alonso, Gavela, LM, Rigolin & Yepes, PRD 87 (2013)
Gavela, Gonzalez-Fraile, Gonzalez-Garcia, LM, Rigolin & Yepes, JHEP 1410 (2014)
Gavela, Kanshin, Machado & Saa, JHEP 1503 (2015)
Brivio, Gonzalez-Fraile, Gonzalez-Garcia & LM, Eur.Phys.J. **C76** (2016) 416

$$\mathcal{L}_{HEFT} = \mathcal{L}_0 + \boxed{\Delta\mathcal{L}}$$

- 145 (no flavour) operators preserving SM, lepton, baryon syms, up to NLO in the renormalisation procedure (4 derivatives & d=6)
- Reduction to a minimal independent set of operators: EOMs
- Choice of a suitable basis (data driven): measurable @ LHC.
- Analysis on similar lines as for SMEFT

HVV

$$\begin{aligned}\mathcal{L}_{HVV} &= g_{Hgg}\, G^a_{\mu\nu} G^{a\mu\nu} h + g_{H\gamma\gamma}\, A_{\mu\nu} A^{\mu\nu} h + g^{(1)}_{HZ\gamma}\, A_{\mu\nu} Z^{\mu} \partial^{\nu} h + g^{(2)}_{HZ\gamma}\, A_{\mu\nu} Z^{\mu\nu} h \\ &\quad + g^{(1)}_{HZZ}\, Z_{\mu\nu} Z^{\mu} \partial^{\nu} h + g^{(2)}_{HZZ}\, Z_{\mu\nu} Z^{\mu\nu} h + g^{(3)}_{HZZ}\, Z_{\mu} Z^{\mu} h \\ &\quad + g^{(1)}_{HWW}\, \left(W^{+}_{\mu\nu} W^{-\,\mu} \partial^{\nu} h + \text{h.c.} \right) + g^{(2)}_{HWW}\, W^{+}_{\mu\nu} W^{-\,\mu\nu} h + g^{(3)}_{HWW}\, W^{+}_{\mu} W^{-\,\mu} h \,,\end{aligned}$$

$$\mathcal{L}_{Hff} = g_f \bar{f}_L f_R h + \text{h.c.}$$

HVV

$$\mathcal{L}_{HVV} = g_{Hgg}\; G^a_{\mu\nu} G^{a\mu\nu} h + g_{H\gamma\gamma}\; A_{\mu\nu} A^{\mu\nu} h + g^{(1)}_{HZ\gamma}\; A_{\mu\nu} Z^{\mu} \partial^{\nu} h + g^{(2)}_{HZ\gamma}\; A_{\mu\nu} Z^{\mu\nu} h$$
$$+ g^{(1)}_{HZZ}\; Z_{\mu\nu} Z^{\mu} \partial^{\nu} h + g^{(2)}_{HZZ}\; Z_{\mu\nu} Z^{\mu\nu} h + g^{(3)}_{HZZ}\; Z_{\mu} Z^{\mu} h$$
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$$\mathcal{L}_{Hff} = g_f \bar{f}_L f_R h + \text{h.c.}$$

SMEFT

$$g_{Hgg} = -\frac{\alpha_s}{8\pi} \frac{f_{GG} v}{\Lambda^2}$$

$$g_{H\gamma\gamma} = -\frac{g^2 v s_w^2}{2\Lambda^2} \frac{f_{BB} + f_{WW}}{2}$$

$$g^{(1)}_{HZZ} = \frac{g^2 v}{2\Lambda^2} \frac{c_w^2 f_W + s_w^2 f_B}{2c_w^2}$$

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$$+ g^{(1)}_{HZZ}\, Z_{\mu\nu}Z^{\mu}\partial^{\nu}h + g^{(2)}_{HZZ}\, Z_{\mu\nu}Z^{\mu\nu}h + g^{(3)}_{HZZ}\, Z_{\mu}Z^{\mu}h$$

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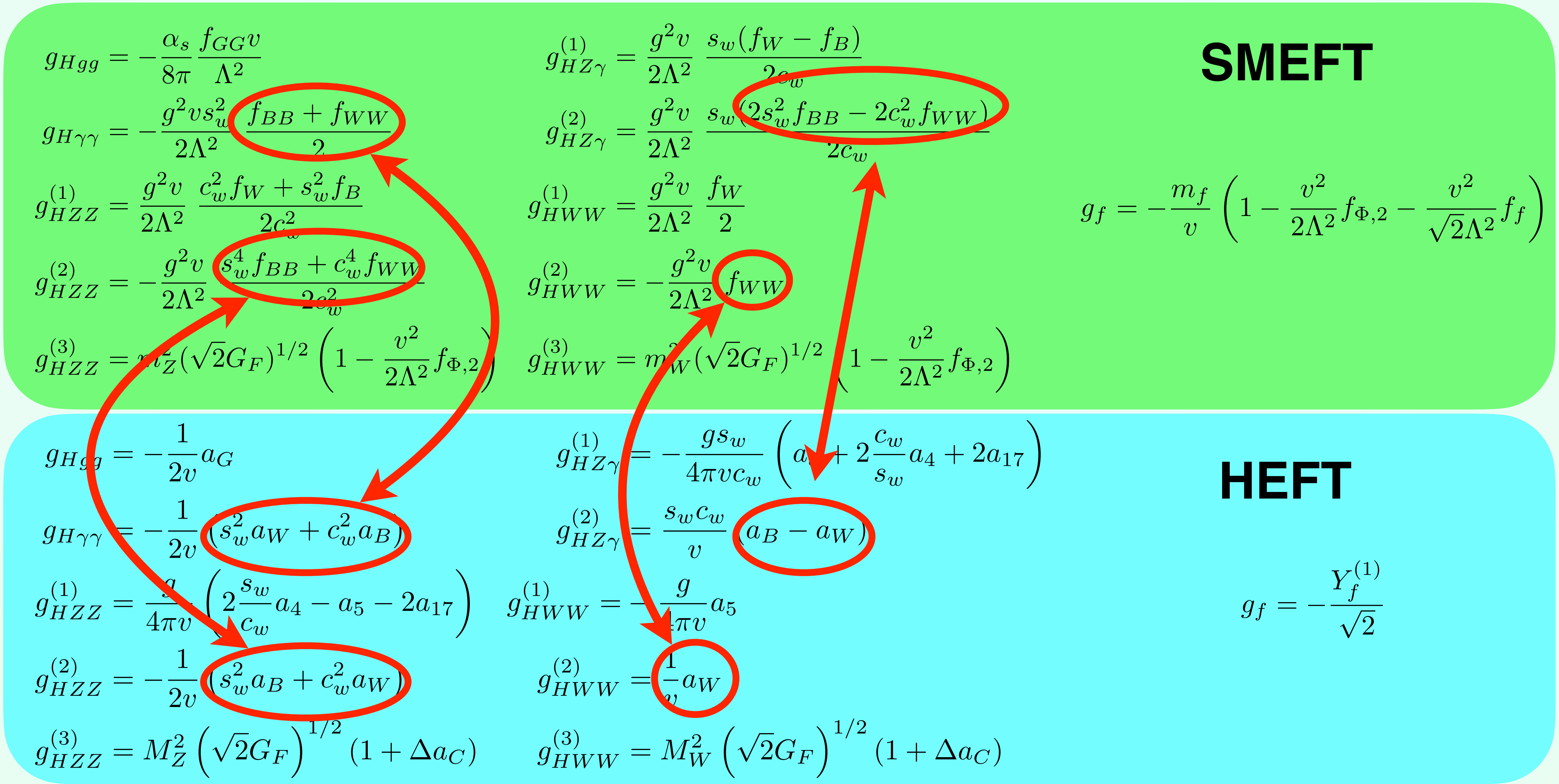
$$\mathcal{L}_{Hff} = g_f \bar{f}_L f_R h + \mathrm{h.c.}$$



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$$g^{(2)}_{HZZ} = -\frac{1}{2v}\left(s_w^2 a_B + c_w^2 a_W\right)$$
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$$g^{(1)}_{HZ\gamma} = -\frac{g s_w}{4\pi v c_w}\left(a_5 + 2\frac{c_w}{s_w}a_4 + 2a_{17}\right)$$
$$g^{(2)}_{HZ\gamma} = \frac{s_w c_w}{v}(a_B - a_W)$$
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$$g_f = -\frac{Y_f^{(1)}}{\sqrt{2}}$$

HVV

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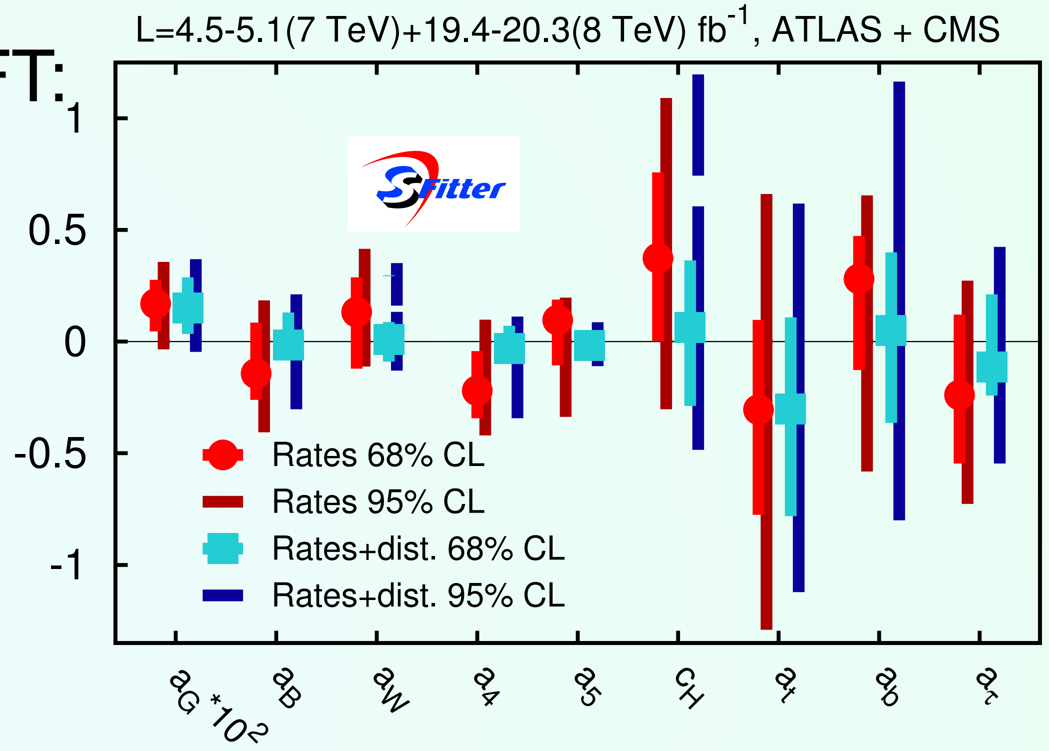
- The fit WITHOUT a_{17} is the same as for SMEFT:

Corbett, Eboli, Gonçalves, Gonzalez-Fraile, Plehn, & Rauch arXiv: 1511.08188

<u>Kinematics are important in several couplings</u>



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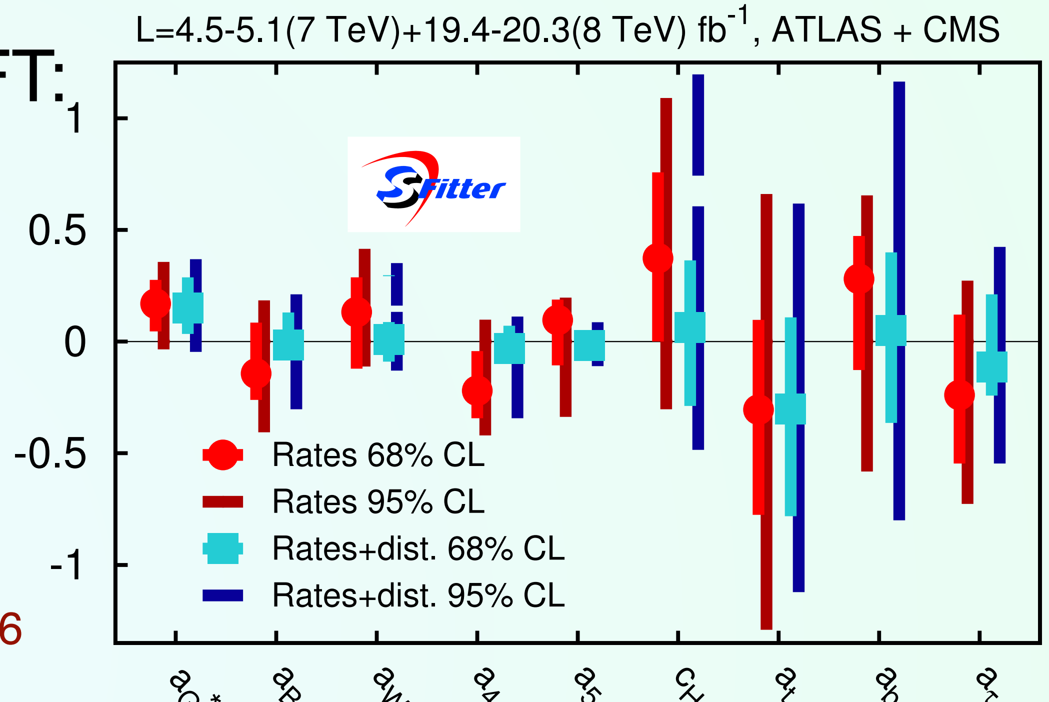
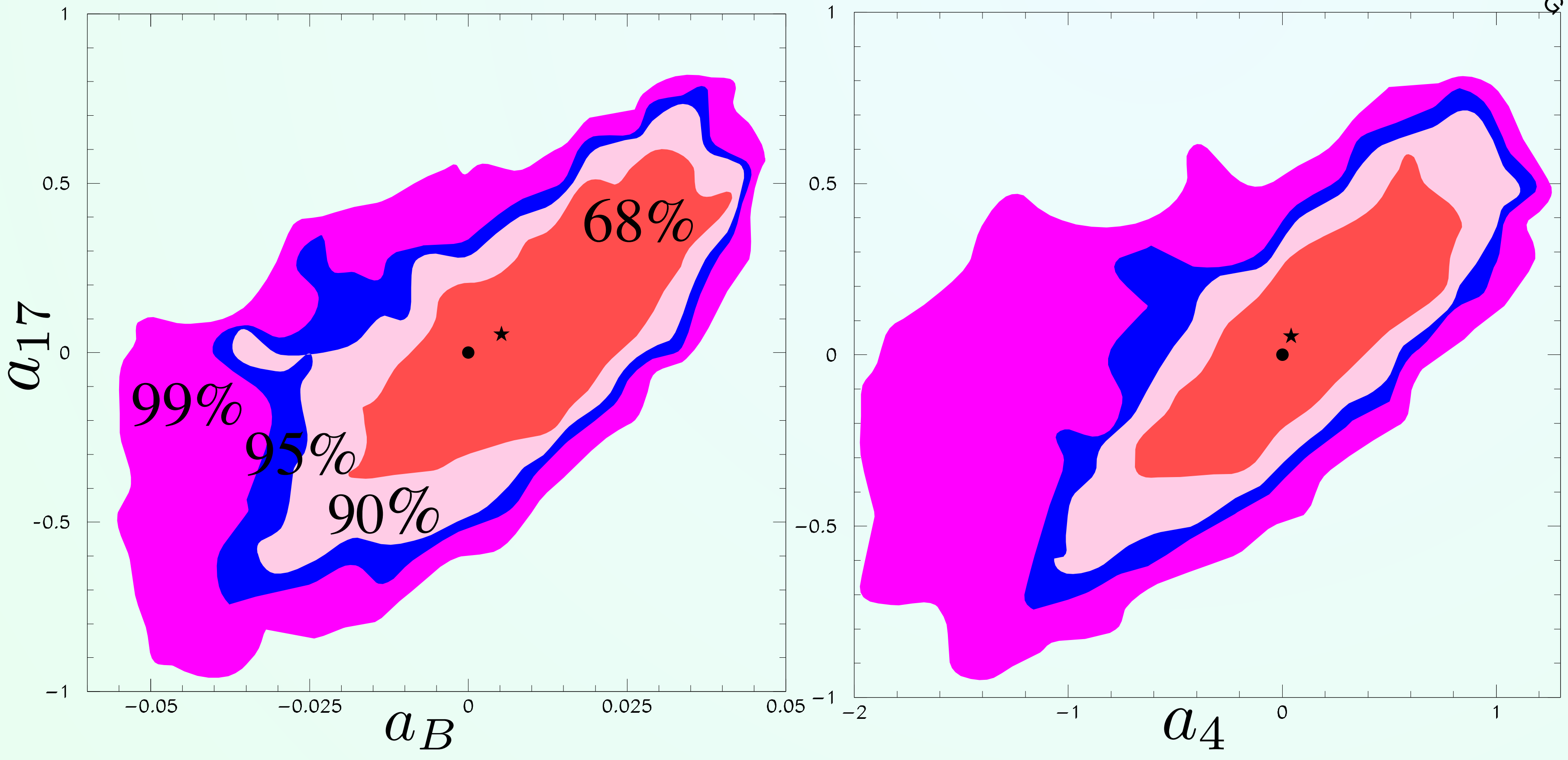


- Adding a_{17} : correlation with a_4 and a_B

Brivio, Gonzalez-Fraile, Gonzalez-Garcia & LM, Eur.Phys.J. **C76** (2016) 416



<ins>Minor impact on the fit results</ins>

The h functions

The functions $\mathcal{F}_i(h) \equiv g(h, f)$ are generic functions of *h/f* (and can be derived only once a fundamental model is chosen). It is common to write,

$$\mathcal{F}_i(h) = 1 + 2\alpha_i \frac{h}{v} + \beta_i \frac{h^2}{v^2} + \ldots$$

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If we consider the SM as a reference, the combinations $c_i \mathcal{F}_i(h)$ become:

$$\Phi(x) = \frac{v+h}{\sqrt{2}} \mathbf{U} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$\begin{aligned} \frac{f_{BW}}{f^2} \mathcal{O}_{BW} &= \frac{f_{BW}}{f^2} \Phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \\ &= f_{BW} \frac{gg'}{8} B_{\mu\nu} \mathrm{Tr}(\mathbf{T} W^{\mu\nu}) \left(\frac{v+h}{f} \right)^2 \\ &= f_{BW}\, \xi\, \frac{gg'}{8} B_{\mu\nu} \mathrm{Tr}(\mathbf{T} W^{\mu\nu}) \left(1 + \frac{h}{v} \right)^2 \\ &= c_1\, gg' B_{\mu\nu} \mathrm{Tr}(\mathbf{T} W^{\mu\nu}) \mathcal{F}_1(h) = c_1 \mathcal{P}_1(h) \end{aligned}$$

with $c_1 = \frac{f_{BW}}{8} \xi$ $\alpha_1 = 1$ $\beta_1 = 1$

Decorrelations

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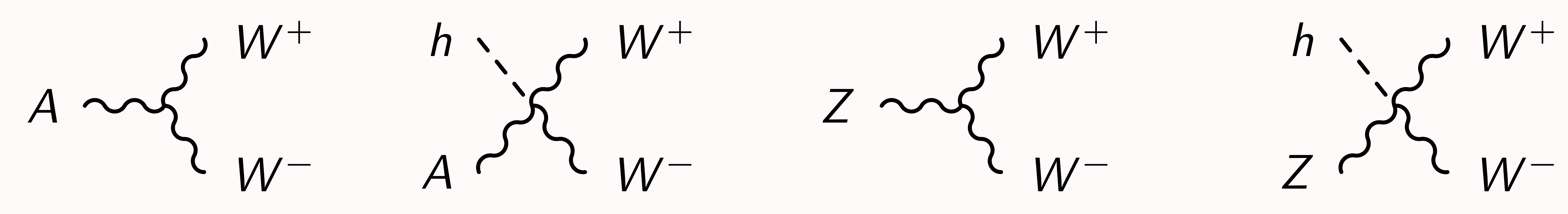

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$$\Rightarrow \quad \mathcal{O}_B = \frac{v^2}{16} \mathcal{P}_2(h) + \frac{v^2}{8} \mathcal{P}_4(h) \quad \text{with} \quad \mathcal{F}_i(h) = \left(1 + \frac{h}{v}\right)^2$$

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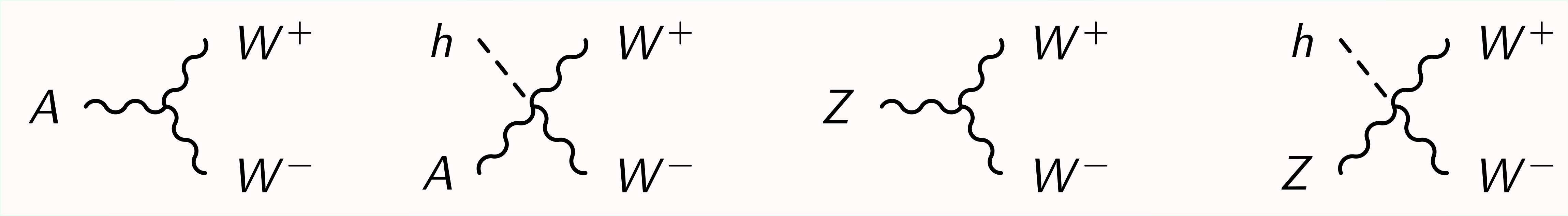

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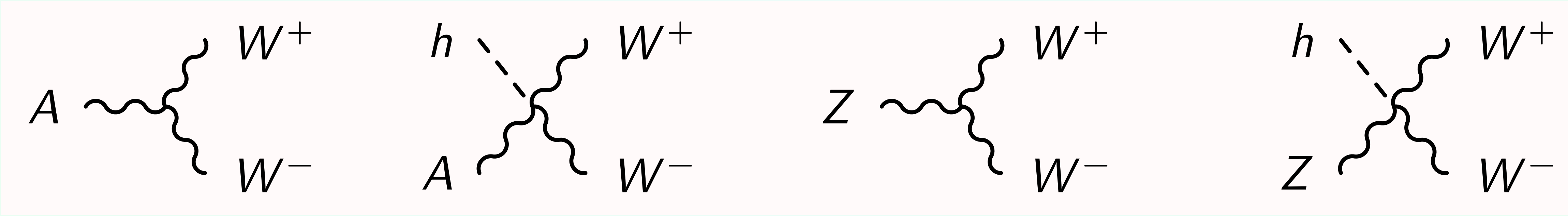

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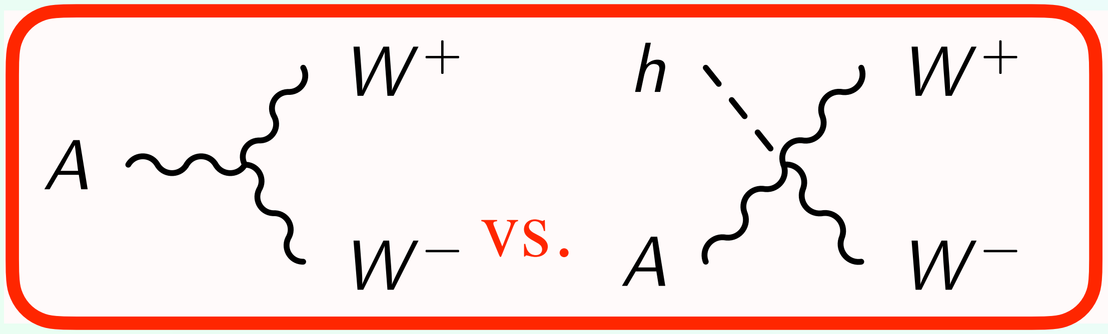
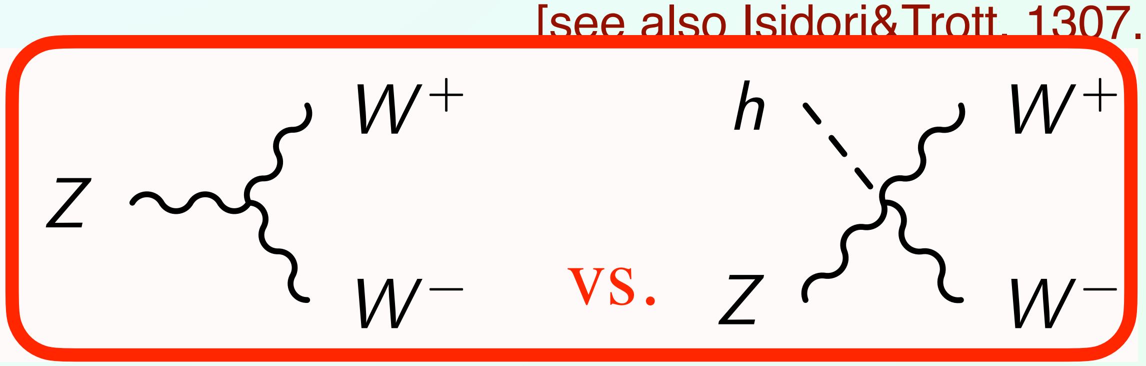
due to the decorrelation in the $\mathcal{F}_i(h)$ functions: i.e.

[see also Isidori&Trott, 1307.4051]





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$$\begin{aligned}\mathcal{O}_B =& \frac{ieg^2}{8} A_{\mu\nu} W^{-\mu} W^{+\nu} (v+h)^2 - \frac{ie^2 g}{8\cos\theta_W} Z_{\mu\nu} W^{-\mu} W^{+\nu} (v+h)^2 \\ &- \frac{eg}{4\cos\theta_W} A_{\mu\nu} Z^\mu \partial^\nu h (v+h) + \frac{e^2}{4\cos^2\theta_W} Z_{\mu\nu} Z^\mu \partial^\nu h (v+h)\end{aligned}$$

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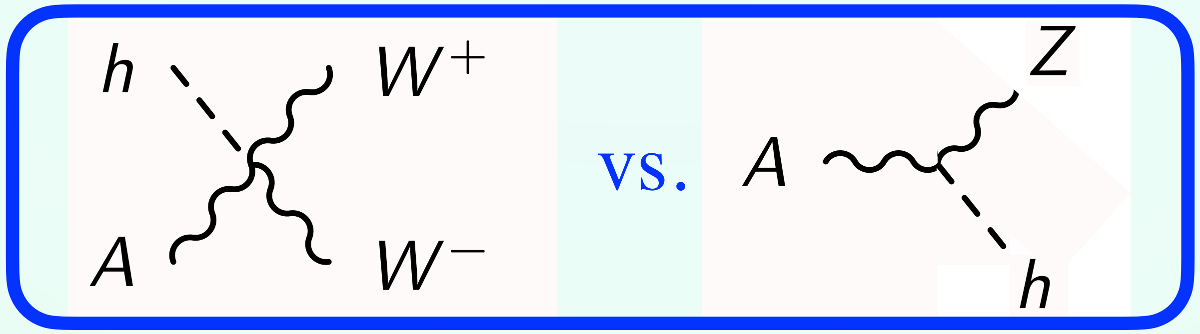
due to the nature of the chiral operators (different c_i coefficients): i.e.



HEFT (bosonic) basis

$$\mathcal{P}_B(h) = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu}\mathcal{F}_B \qquad \mathcal{P}_W(h) = -\frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu}\mathcal{F}_W$$

$$\mathcal{P}_G(h) = -\frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu}\mathcal{F}_G \qquad \mathcal{P}_{DH}(h) = (\partial_\mu\mathcal{F}_{DH}(h)\partial^\mu\mathcal{F}'_{DH}(h))^2$$

$$\mathcal{P}_1(h) = B_{\mu\nu}\mathrm{Tr}(\mathbf{T}W^{\mu\nu})\mathcal{F}_1 \qquad \mathcal{P}_2(h) = \frac{i}{4\pi}B_{\mu\nu}\mathrm{Tr}(\mathbf{T}[\mathbf{V}^\mu,\mathbf{V}^\nu])\mathcal{F}_2$$

$$\mathcal{P}_3(h) = \frac{i}{4\pi}\mathrm{Tr}(W_{\mu\nu}[\mathbf{V}^\mu,\mathbf{V}^\nu])\mathcal{F}_3 \qquad \mathcal{P}_4(h) = \frac{i}{4\pi}B_{\mu\nu}\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_4$$

$$\mathcal{P}_5(h) = \frac{i}{4\pi}\mathrm{Tr}(W_{\mu\nu}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_5 \qquad \mathcal{P}_6(h) = \frac{1}{(4\pi)^2}(\mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}^\mu))^2\mathcal{F}_6$$

$$\mathcal{P}_8(h) = \frac{1}{(4\pi)^2}\mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}_\nu)\partial^\mu\mathcal{F}_8\partial^\nu\mathcal{F}'_8 \qquad \mathcal{P}_{11}(h) = \frac{1}{(4\pi)^2}(\mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}_\nu))^2\mathcal{F}_{11}$$

$$\mathcal{P}_{12}(h) = (\mathrm{Tr}(\mathbf{T}W_{\mu\nu}))^2\mathcal{F}_{12} \qquad \mathcal{P}_{13}(h) = \frac{i}{4\pi}\mathrm{Tr}(\mathbf{T}W_{\mu\nu})\mathrm{Tr}(\mathbf{T}[\mathbf{V}^\mu,\mathbf{V}^\nu])\mathcal{F}_{13}$$

$$\mathcal{P}_{14}(h) = \frac{\varepsilon^{\mu\nu\rho\lambda}}{4\pi}\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\mathrm{Tr}(\mathbf{V}_\nu W_{\rho\lambda})\mathcal{F}_{14} \qquad \mathcal{P}_{17}(h) = \frac{i}{4\pi}\mathrm{Tr}(\mathbf{T}W_{\mu\nu})\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_{17}$$

$$\mathcal{P}_{18}(h) = \frac{1}{(4\pi)^2}\mathrm{Tr}(\mathbf{T}[\mathbf{V}_\mu,\mathbf{V}_\nu])\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_{18} \qquad \mathcal{P}_{20}(h) = \frac{1}{(4\pi)^2}\mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}^\mu)\partial_\nu\mathcal{F}_{20}\partial^\nu\mathcal{F}'_{20}$$

$$\mathcal{P}_{21}(h) = \frac{1}{(4\pi)^2}(\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu))^2\partial_\nu\mathcal{F}_{21}\partial^\nu\mathcal{F}'_{21} \qquad \mathcal{P}_{22}(h) = \frac{1}{(4\pi)^2}\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu)\partial^\mu\mathcal{F}_{22}\partial^\nu\mathcal{F}'_{22}$$

$$\mathcal{P}_{23}(h) = \frac{1}{(4\pi)^2}\mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}^\mu)(\mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu))^2\mathcal{F}_{23} \qquad \mathcal{P}_{24}(h) = \frac{1}{(4\pi)^2}\mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}_\nu)\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\mathrm{Tr}(\mathbf{T}\mathbf{V}^\nu)\mathcal{F}_{24}$$

$$\mathcal{P}_{26}(h) = \frac{1}{(4\pi)^2}(\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu))^2\mathcal{F}_{26}$$

Alonso, Gavela, LM, Rigolin & Yepes, PRD 87 (2013)

Connection with the Linear Basis

We can repeat the previous exercise and see the connection among the bases:

$$\mathcal{O}_{BB}/f^2 = \frac{\xi}{2}\mathcal{P}_B(h) \qquad \mathcal{O}_{WW}/f^2 = \frac{\xi}{2}\mathcal{P}_W(h)$$

$$\mathcal{O}_{GG}/f^2 = -\frac{2\xi}{g_s^2}\mathcal{P}_G(h) \qquad \mathcal{O}_{BW}/f^2 = \frac{\xi}{8}\mathcal{P}_1(h)$$

$$\mathcal{O}_B/f^2 = \frac{\xi}{16}\mathcal{P}_2(h) + \frac{\xi}{8}\mathcal{P}_4(h) \qquad \mathcal{O}_W/f^2 = \frac{\xi}{8}\mathcal{P}_3(h) - \frac{\xi}{4}\mathcal{P}_5(h)$$

$$\mathcal{O}_{\Phi,1}/f^2 = \frac{\xi}{2}\mathcal{P}_H(h) - \frac{\xi}{4}\mathcal{F}(h)\mathcal{P}_T(h) \qquad \mathcal{O}_{\Phi,2}/f^2 = \xi\mathcal{P}_H(h)$$

$$\mathcal{O}_{\Phi,4}/f^2 = \frac{\xi}{2}\mathcal{P}_H(h) + \frac{\xi}{2}\mathcal{F}(h)\mathcal{P}_C(h)$$

$$\mathcal{O}_{\Box\Phi}/f^2 = \frac{\xi}{2}\mathcal{P}_{\Box H}(h) + \frac{\xi}{8}\mathcal{P}_6(h) + \frac{\xi}{4}\mathcal{P}_7(h) - \xi\mathcal{P}_8(h) - \frac{\xi}{4}\mathcal{P}_9(h) - \frac{\xi}{2}\mathcal{P}_{10}(h)$$

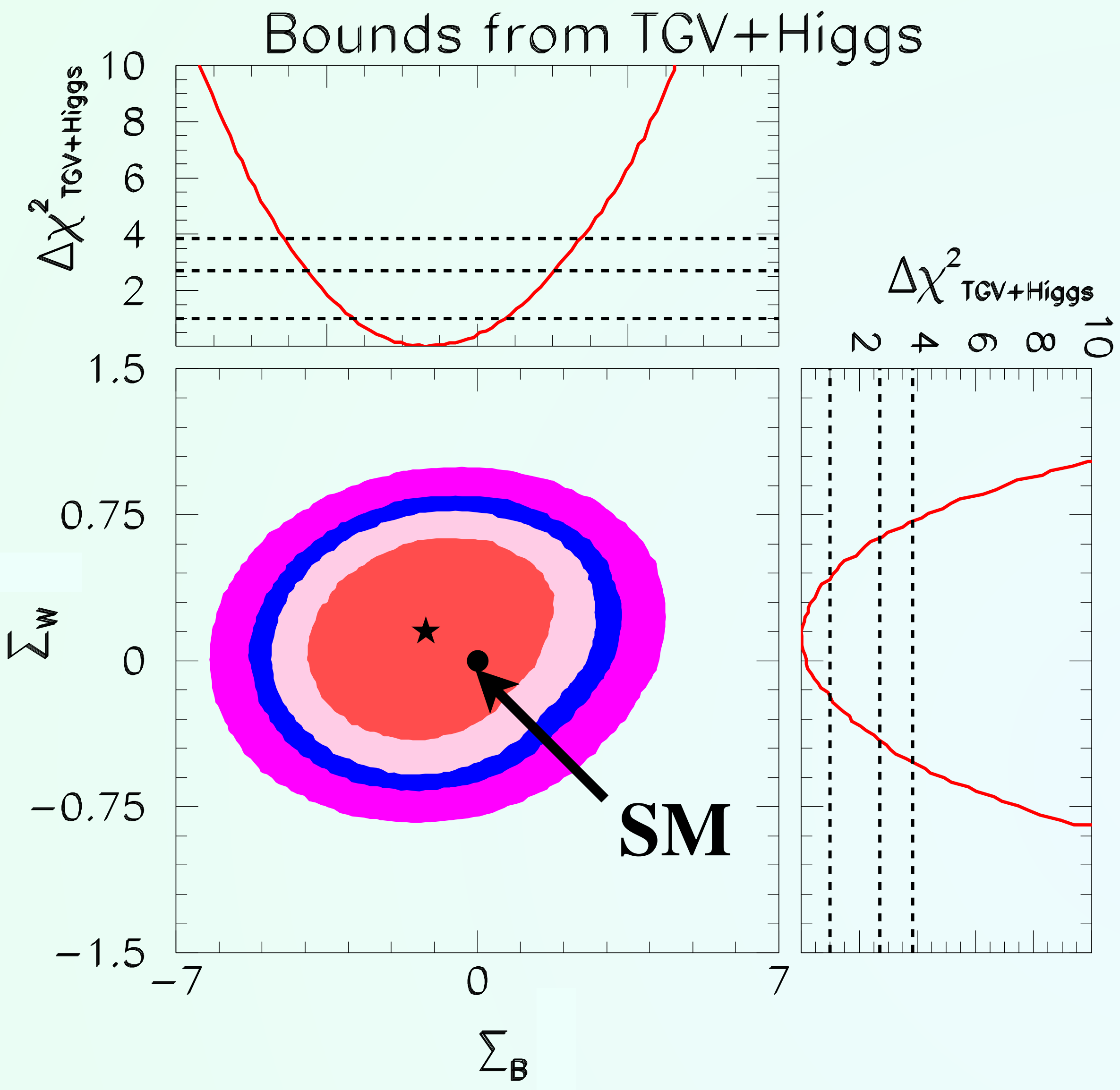
with in general $\mathcal{F}(h) = 1 + 2\frac{h}{v} + \frac{h^2}{v^2}$

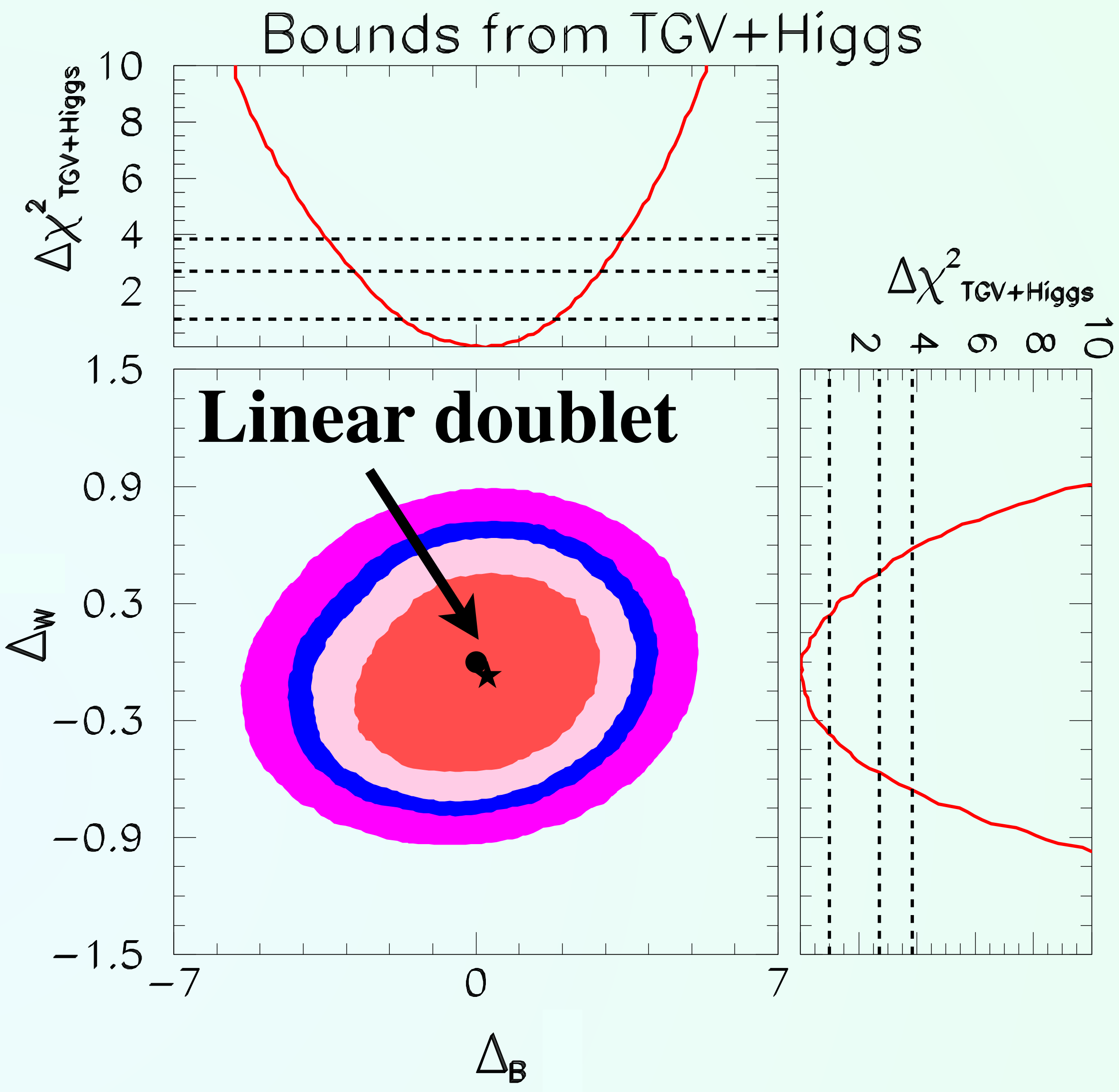
We added two pure-*h* operators:

$$\mathcal{P}_H(h) = \frac{1}{2}(\partial_\mu h)(\partial^\mu h)\mathcal{F}_H(h) \qquad \mathcal{P}_{\Box H} = \frac{1}{v^2}(\partial_\mu\partial^\mu h)^2\mathcal{F}_{\Box H}(h)$$

Brivio,Corbett,Eboli,Gavela,Gonzalez-Fraile, Gonzalez-Garcia,LM&Rigolin, JHEP 1403 (2014)

- Considering all the couplings together:





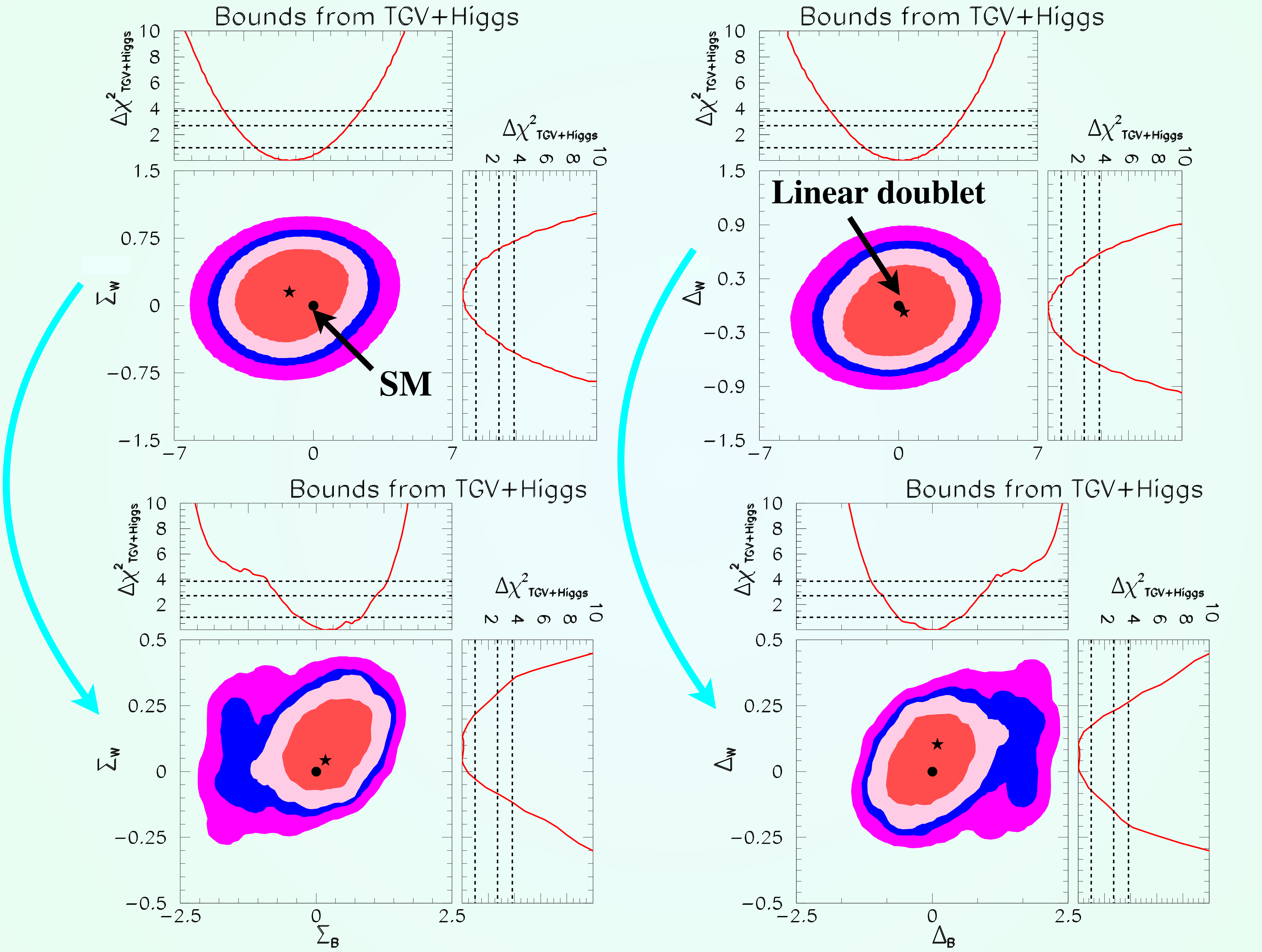
$$\Sigma_B = 4(2c_2 + a_4) \to f_B \qquad \Delta_B = 4(2c_2 - a_4) \to 0$$

$$\Sigma_W = 2(2c_3 - a_5) \to f_W \qquad \Delta_W = 2(2c_3 + a_5) \to 0$$

Data: Tevatron D0 and CDF Collaborations and LHC, CMS, and ATLAS Collaborations at 7 TeV and 8 TeV for final states γγ, W^+W^-, ZZ, Zγ, $b\bar{b}$, and $\tau\bar{\tau}$

Brivio, Gonzalez-Fraile, Gonzalez-Garcia & LM, Eur.Phys.J. **C76** (2016) 416

- Adding the data from kinematic distributions:



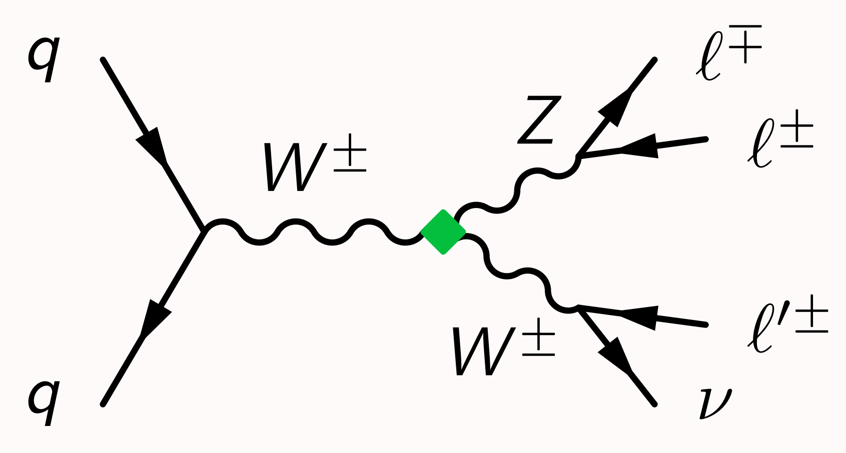
New Signals

Brivio,Corbett,Eboli,Gavela,Gonzalez-Fraile, Gonzalez-Garcia,LM&Rigolin, JHEP 1403 (2014)

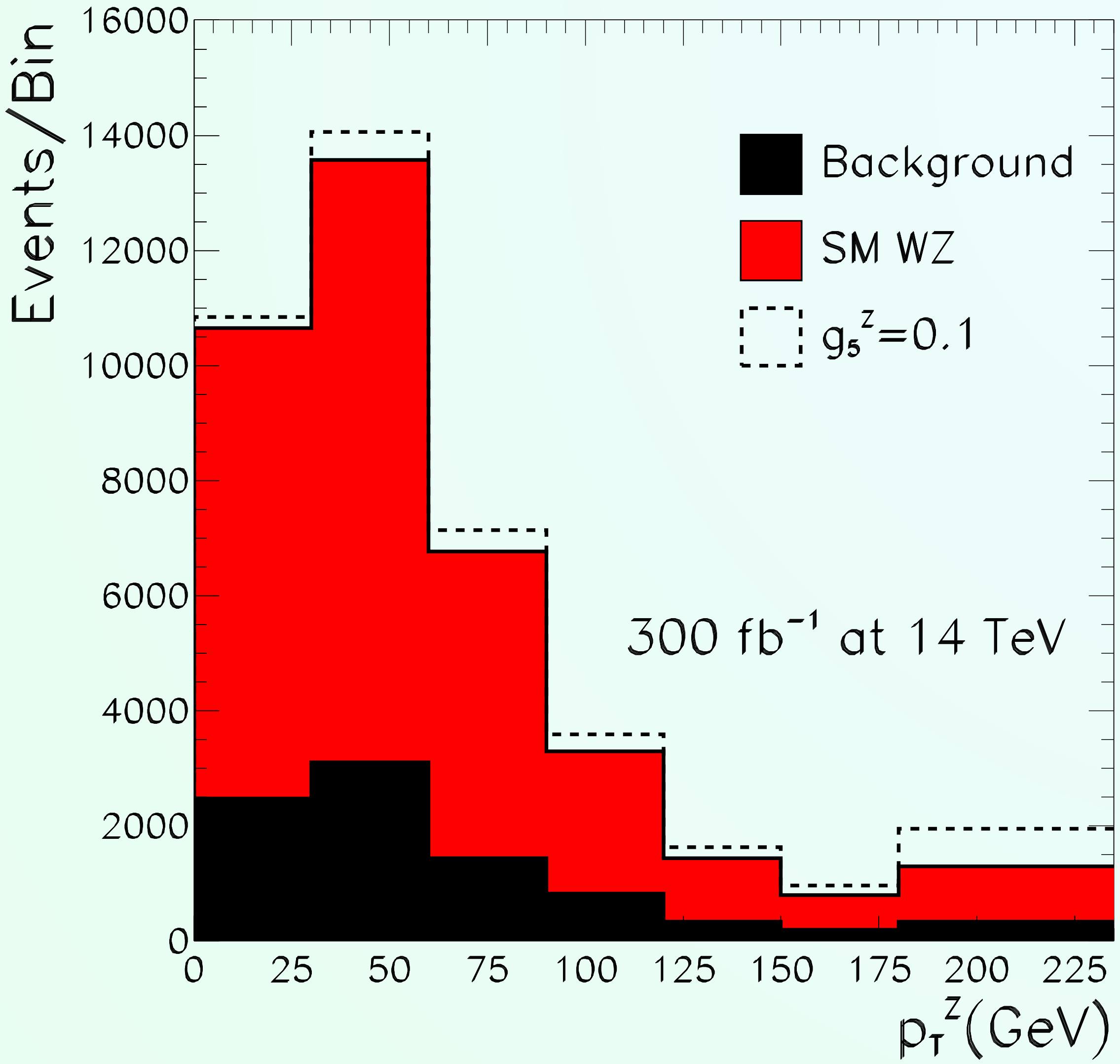
Signals expected in the chiral basis, but not in the linear one (d=8)

$$\mathcal{P}_{14}(h) = \varepsilon^{\mu\nu\rho\lambda}\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\mathrm{Tr}(\mathbf{V}_\nu W_{\rho\lambda})\mathcal{F}_{14}(h)$$

$$\hookrightarrow \quad g_5^Z\, \varepsilon^{\mu\nu\rho\lambda}\partial_\mu W_\nu^+ W_\rho^- Z_\lambda \mathcal{F}_{14}(h)$$



number of expected events (WZ production) with respect to the Z p_T



@95% CL:

present $g_5^Z \in [-0.08, 0.04]$

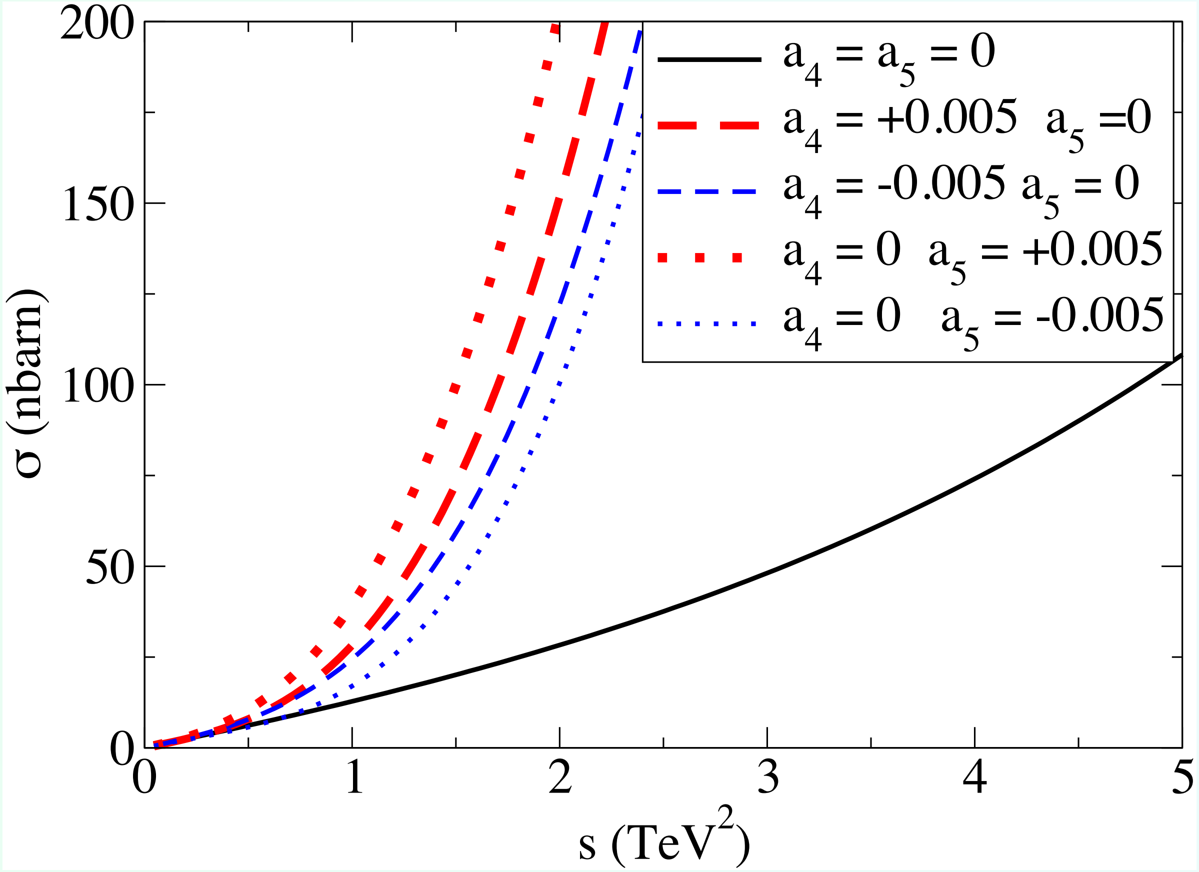
LHC(7+8+14) $g_5^Z \in [-0.033, 0.028]$

Longitudinal Gauge Bosons

As **U** is so special in HEFT, why don't study the physics associated to the SM GBs

Scattering of $W_L W_L$ and $Z_L Z_L$

Delgado, Dobado & Llanes-Estrada, JHEP 1402 (2014)

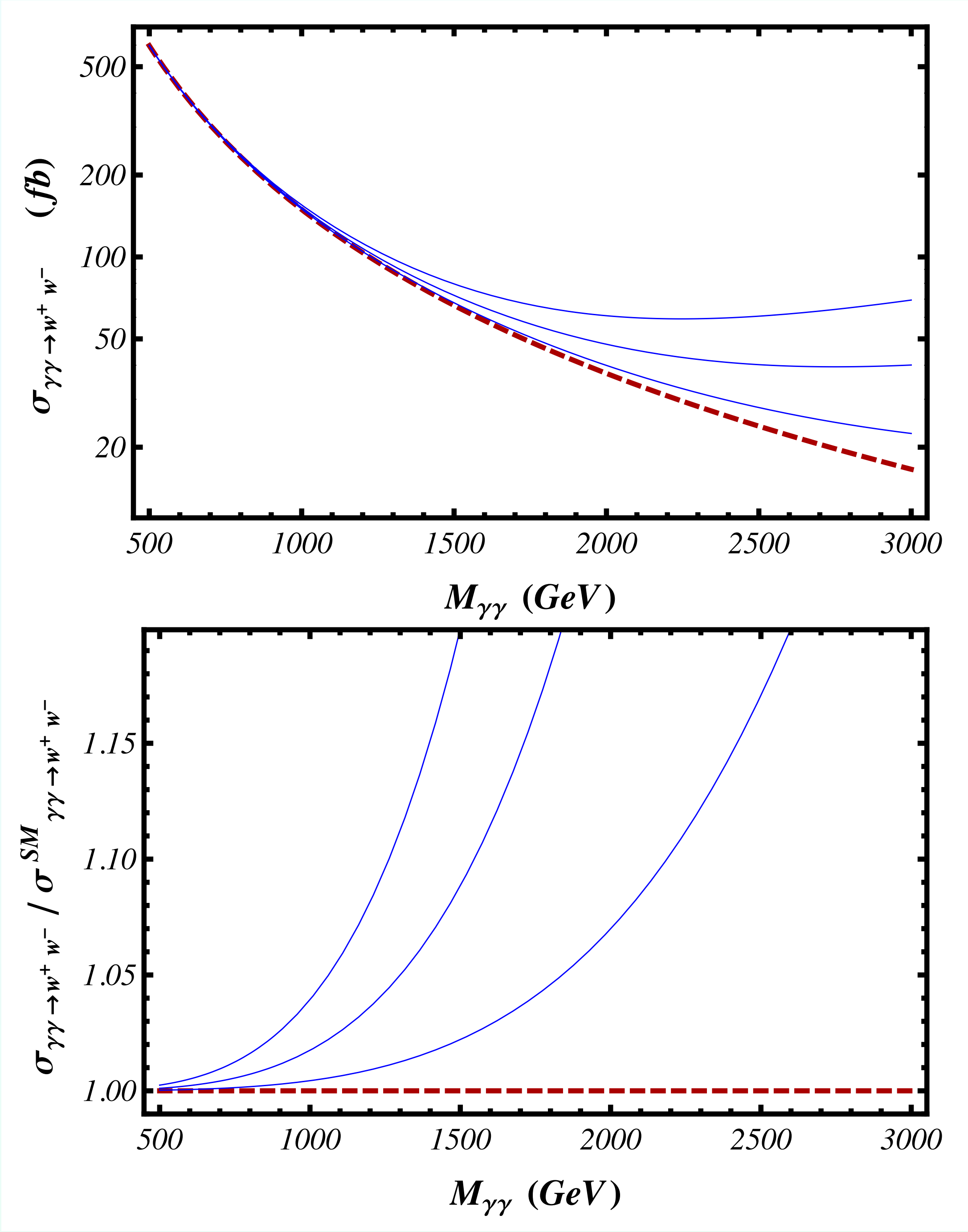


Similar studies in:

Espriu & Yencho, PRD87 (2013)
Espriu, Mescia & Yencho, PRD88 (2013)

Cross section for $\gamma\gamma \to W_L^+ W_L^-$

Delgado, Dobado, Herrero & Sanz-Cillero, JHEP 1407 (2014)



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  - New Signals in HEFT wrt SMEFT
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- Dis

Thanks

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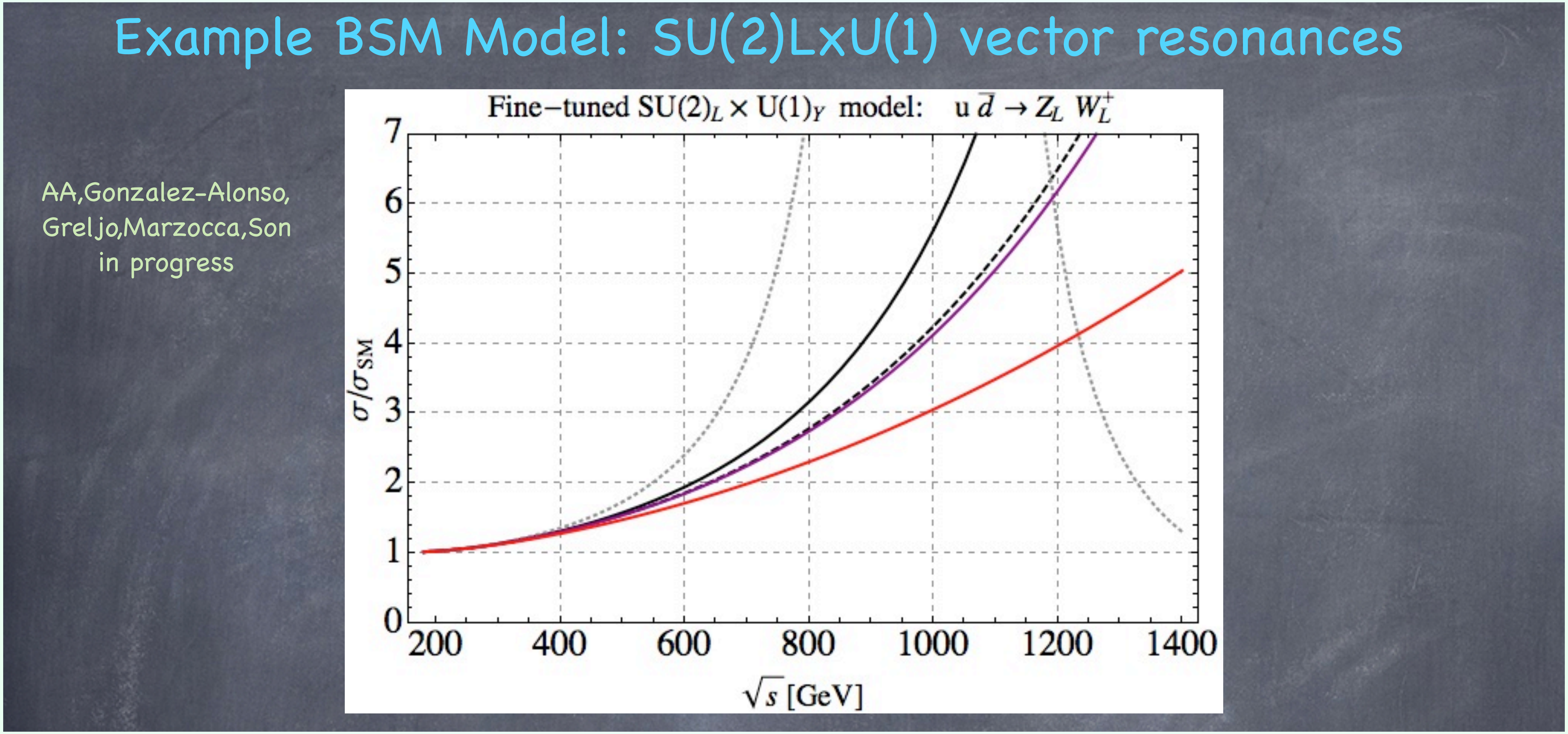
Backup

Validity of SMEFT

From Falkowski's talk at ATLAS meeting



Example BSM Model: SU(2)LxU(1) vector resonances

AA,Gonzalez-Alonso,
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in progress

Fine−tuned $SU(2)_L \times U(1)_Y$ model: $u\,\bar{d} \to Z_L\, W_L^+$

HEFT basis

Gavela, Jenkins, Manohar & LM, arXiv: 1601.0755

Assuming B and L conservation, and no BSM custodial breaking

Operator	d_p	N_χ	NDA form
$\psi^2\mathbf{U}$	3	1	$\Lambda\,\psi^2\mathbf{U}\,\mathcal{F}_{\psi^2\mathbf{U}}(h)$
X^2	4	2	$X^2\,\mathcal{F}_{X^2}(h)$
$\psi^2 D$	4	2	$\psi^2 D$
$(\partial h)^2$	4	2	$(\partial h)^2$
$\mathbf{V}^2$	4	2	$\frac{\Lambda^2}{(4\pi)^2}\,\mathbf{V}^2\,\mathcal{F}_{\mathbf{V}^2}(h)$
$\psi^2\mathbf{V}$	5	2	$\psi^2\mathbf{V}\,\mathcal{F}_{\psi^2\mathbf{V}}(h)$
$\psi^2 X\mathbf{U}$	5	2	$\frac{4\pi}{\Lambda}\,\psi^2 X\mathbf{U}\,\mathcal{F}_{\psi^2 X\mathbf{U}}(h)$
ψ^4	6	2	$\frac{(4\pi)^2}{\Lambda^2}\,\psi^4\,\mathcal{F}_{\psi^4}(h)$
$X\mathbf{V}^2$	6	3	$\frac{1}{4\pi}\,X\mathbf{V}^2\,\mathcal{F}_{X\mathbf{V}^2}(h)$
X^3	6	3	$\frac{(4\pi)}{\Lambda^2}\,X^3\,\mathcal{F}_{X^3}(h)$
$X\mathbf{V}\partial$	6	3	$\frac{1}{4\pi}\,X\mathbf{V}\,\partial\mathcal{F}_{X\mathbf{V}\partial}(h)$
$\psi^2\mathbf{V}\mathbf{U}\partial$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{V}\mathbf{U}\,\partial\mathcal{F}_{\psi^2\mathbf{V}\mathbf{U}\partial}(h)$
$\psi^2\mathbf{V}^2\mathbf{U}$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{V}^2\mathbf{U}\,\mathcal{F}_{\psi^2\mathbf{V}^2\mathbf{U}}(h)$
$\psi^2\mathbf{U}\partial^2$	7	3	$\frac{1}{\Lambda}\,\psi^2\mathbf{U}\,\partial^2\,\mathcal{F}_{\psi^2\mathbf{U}\partial^2}(h)$
$\mathbf{V}^2\partial^2$	8	4	$\frac{1}{(4\pi)^2}\,\mathbf{V}^2\,\partial^2\mathcal{F}_{\mathbf{V}^2\partial^2}(h)$
$\mathbf{V}^4$	8	4	$\frac{1}{(4\pi)^2}\,\mathbf{V}^4\,\mathcal{F}_{\mathbf{V}^4}(h)$

$$\longleftrightarrow \quad \Lambda\bar\psi_L\mathbf{U}\psi_R\mathcal{F}_{\psi^2\mathbf{U}}(h)$$

$$\longleftrightarrow \quad i\bar\psi\not{D}\psi$$

$$\longleftrightarrow \quad \frac{\Lambda^2}{(4\pi)^2}\mathrm{Tr}\,\left(\mathbf{V}_\mu\mathbf{V}^\mu\right)\mathcal{F}_{\mathbf{V}^2}(h)$$

$$\longleftrightarrow \quad \frac{1}{4\pi}\mathrm{Tr}\,\left(W_{\mu\nu}\left[\mathbf{V}^\mu,\mathbf{V}^\nu\right]\right)\mathcal{F}_{X\mathbf{V}^2}(h)$$

$$\longleftrightarrow \quad \frac{1}{(4\pi)^2}\mathrm{Tr}\,\left(\mathbf{V}^\mu\mathbf{V}^\mu\right)^2\mathcal{F}_{\mathbf{V}^4}(h)$$

HEFT (bosonic) basis

$$\mathcal{P}_B(h) = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu}\mathcal{F}_B$$

$$\mathcal{P}_G(h) = -\frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu}\mathcal{F}_G$$

$$\mathcal{P}_1(h) = B_{\mu\nu}\mathrm{Tr}(\mathbf{T}W^{\mu\nu})\mathcal{F}_1$$

$$\mathcal{P}_3(h) = \frac{i}{4\pi}\mathrm{Tr}(W_{\mu\nu}[\mathbf{V}^\mu, \mathbf{V}^\nu])\mathcal{F}_3$$

$$\mathcal{P}_5(h) = \frac{i}{4\pi}\mathrm{Tr}(W_{\mu\nu}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_5$$

$$\mathcal{P}_8(h) = \frac{1}{(4\pi)^2}\mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}_\nu)\partial^\mu\mathcal{F}_8\partial^\nu\mathcal{F}'_8$$

$$\mathcal{P}_{12}(h) = (\mathrm{Tr}(\mathbf{T}W_{\mu\nu}))^2\mathcal{F}_{12}$$

$$\mathcal{P}_{14}(h) = \frac{\varepsilon^{\mu\nu\rho\lambda}}{4\pi}\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\mathrm{Tr}(\mathbf{V}_\nu W_{\rho\lambda})\mathcal{F}_{14}$$

$$\mathcal{P}_{18}(h) = \frac{1}{(4\pi)^2}\mathrm{Tr}(\mathbf{T}[\mathbf{V}_\mu, \mathbf{V}_\nu])\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_{18}$$

$$\mathcal{P}_{21}(h) = \frac{1}{(4\pi)^2}(\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu))^2\partial_\nu\mathcal{F}_{21}\partial^\nu\mathcal{F}'_{21}$$

$$\mathcal{P}_{23}(h) = \frac{1}{(4\pi)^2}\mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}^\mu)(\mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu))^2\mathcal{F}_{23}$$

$$\mathcal{P}_{26}(h) = \frac{1}{(4\pi)^2}(\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu))^2\mathcal{F}_{26}$$

$$\mathcal{P}_W(h) = -\frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu}\mathcal{F}_W$$

$$\mathcal{P}_{DH}(h) = (\partial_\mu\mathcal{F}_{DH}(h)\partial^\mu\mathcal{F}'_{DH}(h))^2$$

$$\mathcal{P}_2(h) = \frac{i}{4\pi}B_{\mu\nu}\mathrm{Tr}(\mathbf{T}[\mathbf{V}^\mu, \mathbf{V}^\nu])\mathcal{F}_2$$

$$\mathcal{P}_4(h) = \frac{i}{4\pi}B_{\mu\nu}\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_4$$

$$\mathcal{P}_6(h) = \frac{1}{(4\pi)^2}(\mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}^\mu))^2\mathcal{F}_6$$

$$\mathcal{P}_{11}(h) = \frac{1}{(4\pi)^2}(\mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}_\nu))^2\mathcal{F}_{11}$$

$$\mathcal{P}_{13}(h) = \frac{i}{4\pi}\mathrm{Tr}(\mathbf{T}W_{\mu\nu})\mathrm{Tr}(\mathbf{T}[\mathbf{V}^\mu, \mathbf{V}^\nu])\mathcal{F}_{13}$$

$$\mathcal{P}_{17}(h) = \frac{i}{4\pi}\mathrm{Tr}(\mathbf{T}W_{\mu\nu})\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\partial^\nu\mathcal{F}_{17}$$

$$\mathcal{P}_{20}(h) = \frac{1}{(4\pi)^2}\mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}^\mu)\partial_\nu\mathcal{F}_{20}\partial^\nu\mathcal{F}'_{20}$$

$$\mathcal{P}_{22}(h) = \frac{1}{(4\pi)^2}\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)\mathrm{Tr}(\mathbf{T}\mathbf{V}_\nu)\partial^\mu\mathcal{F}_{22}\partial^\nu\mathcal{F}'_{22}$$

$$\mathcal{P}_{24}(h) = \frac{1}{(4\pi)^2}\mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}_\nu)\mathrm{Tr}(\mathbf{T}\mathbf{V}^\mu)\mathrm{Tr}(\mathbf{T}\mathbf{V}^\nu)\mathcal{F}_{24}$$

Alonso, Gavela, LM, Rigolin & Yepes, PRD 87 (2013)

Connection with the Linear Basis

We can repeat the previous exercise and see the connection among the bases:

$$\mathcal{O}_{BB}/f^2 = \frac{\xi}{2}\mathcal{P}_B(h) \qquad \mathcal{O}_{WW}/f^2 = \frac{\xi}{2}\mathcal{P}_W(h)$$

$$\mathcal{O}_{GG}/f^2 = -\frac{2\xi}{g_s^2}\mathcal{P}_G(h) \qquad \mathcal{O}_{BW}/f^2 = \frac{\xi}{8}\mathcal{P}_1(h)$$

$$\mathcal{O}_{B}/f^2 = \frac{\xi}{16}\mathcal{P}_2(h) + \frac{\xi}{8}\mathcal{P}_4(h) \qquad \mathcal{O}_{W}/f^2 = \frac{\xi}{8}\mathcal{P}_3(h) - \frac{\xi}{4}\mathcal{P}_5(h)$$

$$\mathcal{O}_{\Phi,1}/f^2 = \frac{\xi}{2}\mathcal{P}_H(h) - \frac{\xi}{4}\mathcal{F}(h)\mathcal{P}_T(h) \qquad \mathcal{O}_{\Phi,2}/f^2 = \xi\mathcal{P}_H(h)$$

$$\mathcal{O}_{\Phi,4}/f^2 = \frac{\xi}{2}\mathcal{P}_H(h) + \frac{\xi}{2}\mathcal{F}(h)\mathcal{P}_C(h)$$

$$\mathcal{O}_{\Box\Phi}/f^2 = \frac{\xi}{2}\mathcal{P}_{\Box H}(h) + \frac{\xi}{8}\mathcal{P}_6(h) + \frac{\xi}{4}\mathcal{P}_7(h) - \xi\mathcal{P}_8(h) - \frac{\xi}{4}\mathcal{P}_9(h) - \frac{\xi}{2}\mathcal{P}_{10}(h)$$

with in general $\mathcal{F}(h) = 1 + 2\frac{h}{v} + \frac{h^2}{v^2}$

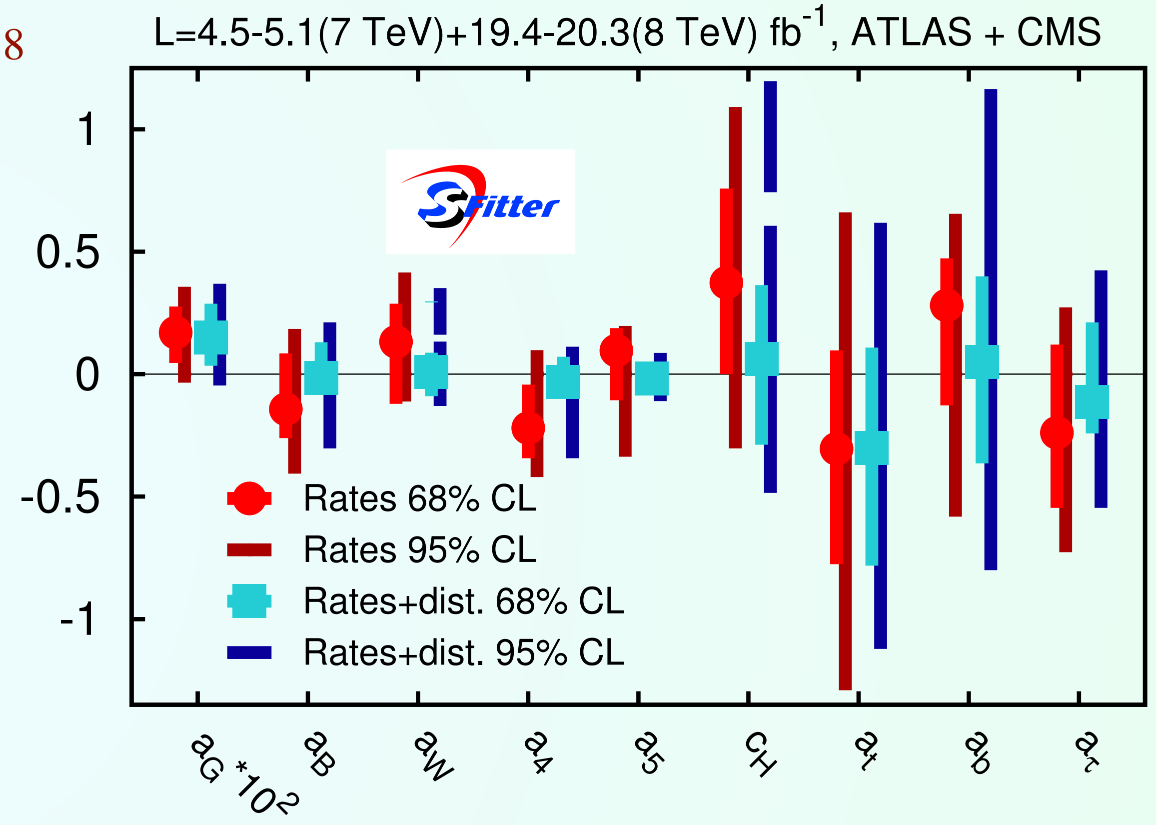
We added two pure-*h* operators:

$$\mathcal{P}_H(h) = \frac{1}{2}(\partial_\mu h)(\partial^\mu h)\mathcal{F}_H(h) \qquad \mathcal{P}_{\Box H} = \frac{1}{v^2}(\partial_\mu \partial^\mu h)^2\mathcal{F}_{\Box H}(h)$$

HVV FIT

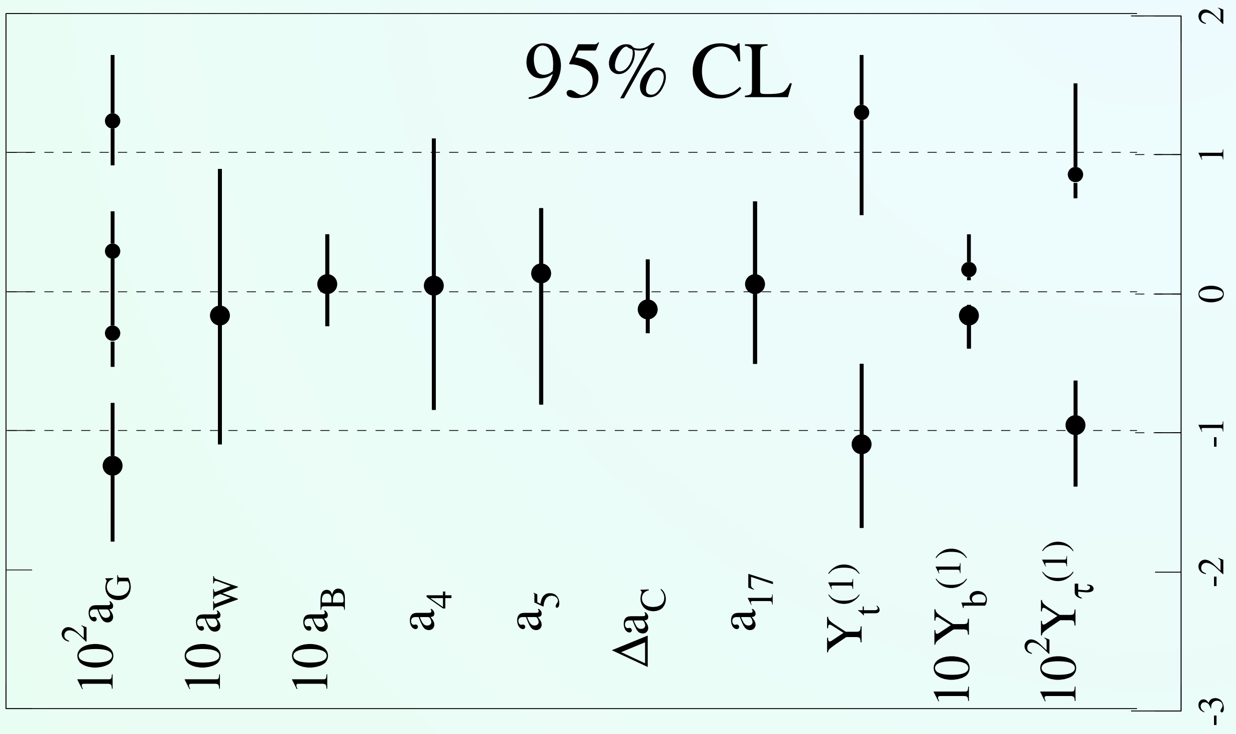
- The HVV analysis for HEFT has 10 parameters vs 9 in SMEFT:
- The fit WITHOUT a_{17} is the same as for SMEFT:

Corbett, Eboli, Gonçalves, Gonzalez-Fraile, Plehn, & Rauch arXiv: 1511.08188



- Adding a_{17} : correlation with a_4 and a_B

Brivio, Gonzalez-Fraile, Gonzalez-Garcia & LM, to appear



The differences are due to different definitions and normalisations

New Signals

Brivio,Corbett,Eboli,Gavela,Gonzalez-Fraile, Gonzalez-Garcia,LM&Rigolin, JHEP 1403 (2014)

The simulation for LHC (7 TeV, 14 TeV) has been done taking cuts and precautions:

- Focused on WZ production, considering leptonic decays of W and Z (background)

$$pp \to \ell'^{\pm}\ell^{+}\ell^{-}\mathrm{E}^{\mathrm{miss}} \qquad \ell^{(\prime)} = e \text{ or } \mu$$

- Main background: SM production of WZ pairs; W and Z production with jets; ZZ production with one Z in leptons with one charged in missing E, the other in tt pair.
- Detection efficiencies rescaled to the one by ATLAS for TGV$\Delta K_Z\ ,\ g_1^Z\ ,\ \lambda_Z$.
- We closely follow the TGV analysis performed by ATLAS (cuts on transverse momentum and pseudorapidity).
- The cross section in the presence of an anomalous g_5^Z is then given by

$$\sigma \;=\; \sigma_{\text{bck}} + \sigma_{SM} \;+\; \sigma_{\text{int}}\, g_5^Z \;+\; \sigma_{\text{ano}}\left(g_5^Z\right)^2$$

In the SM, Vff contain a CP odd component. The amplitude for any subprocess $q\bar{q} \to WZ$ contains SM contributions that are both C and P odd and that interfere with the contribution from the anomalous.

	68% CL range		95% CL range	
Data sets used	Counting $p_T^Z > 90$ GeV	p_T^Z binned analysis	Counting $p_T^Z > 90$ GeV	p_T^Z binned analysis
7+8 TeV (4.64+19.6 fb^{-1})	$(-0.066,\ 0.058)$	$(-0.057,\ 0.050)$	$(-0.091,\ 0.083)$	$(-0.080,\ 0.072)$
7+8+14 TeV (4.64+19.6+300 fb^{-1})	$(-0.030,\ 0.022)$	$(-0.024,\ 0.019)$	$(-0.040,\ 0.032)$	$(-0.033,\ 0.028)$

- Counting $p_T^Z > 90$ GeV
  - Simple even counting analysis, assuming that the observed events are SM and looking for values of g_5^Z inside the 68% and 95% CL allowed regions. The restriction to $p_T^Z > 90$ GeV increases the sensitivity.

- p_T^Z binned analysis
  - Simple χ^2 based on the contents of the different p_T^Z distributions with no cuts. Same conditions of the previous method.

So far we have compared the phenomenology of the Higgs being a

linear $SU(2)_L$ doublet vs. generic $SU(2)_L$ singlet

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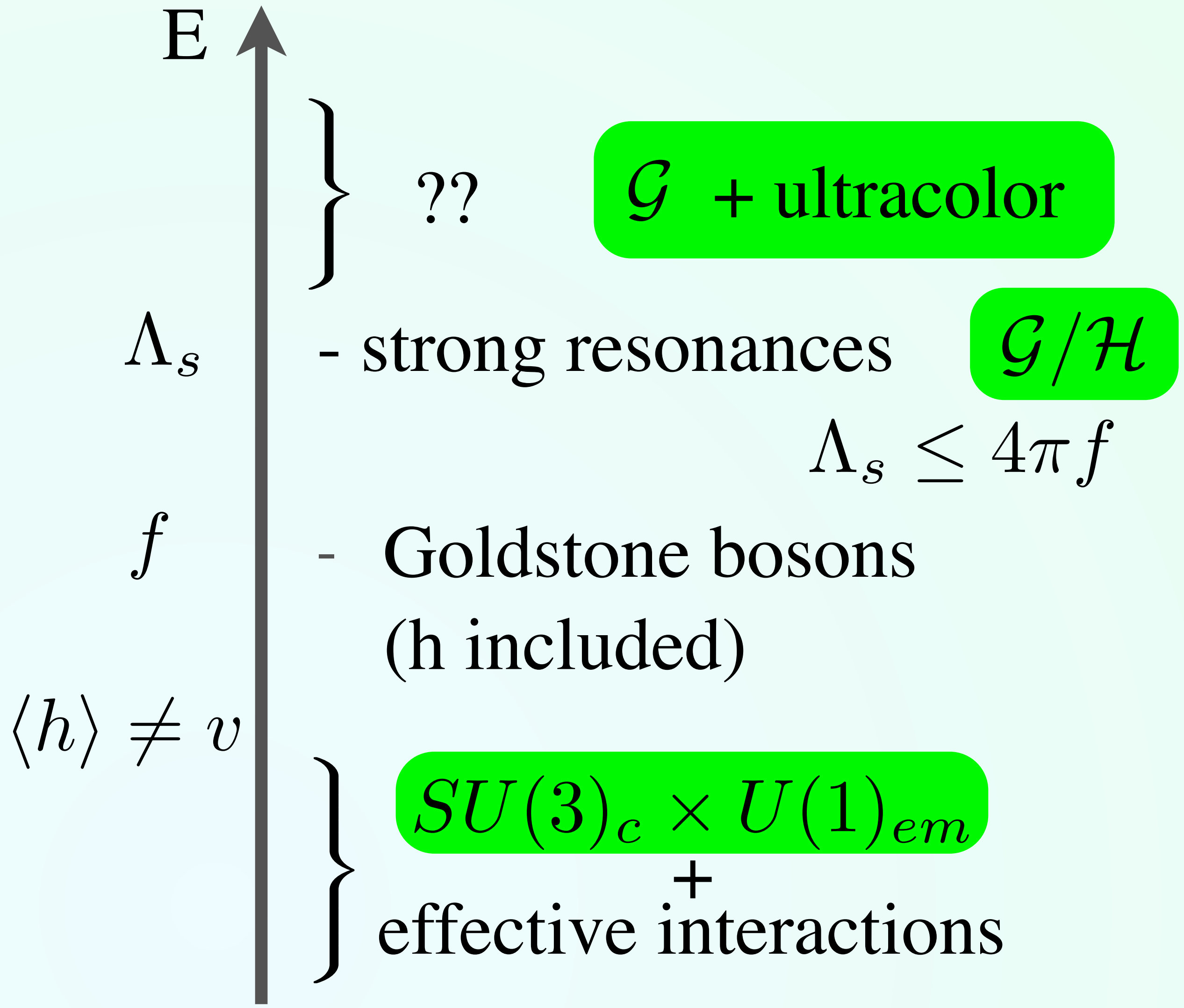
What if the Higgs is a non elementary - doublet?

Alonso,Brivio,Gavela,LM&Rigolin, JHEP 1412 (2014)
Hierro,LM&Rigolin, 1510.07899

Generic Composite Higgs Models



E

?? $\mathcal{G}$ + ultracolor

Λ_s - strong resonances $\mathcal{G}/\mathcal{H}$

$\Lambda_s \leq 4\pi f$

f - Goldstone bosons (h included)

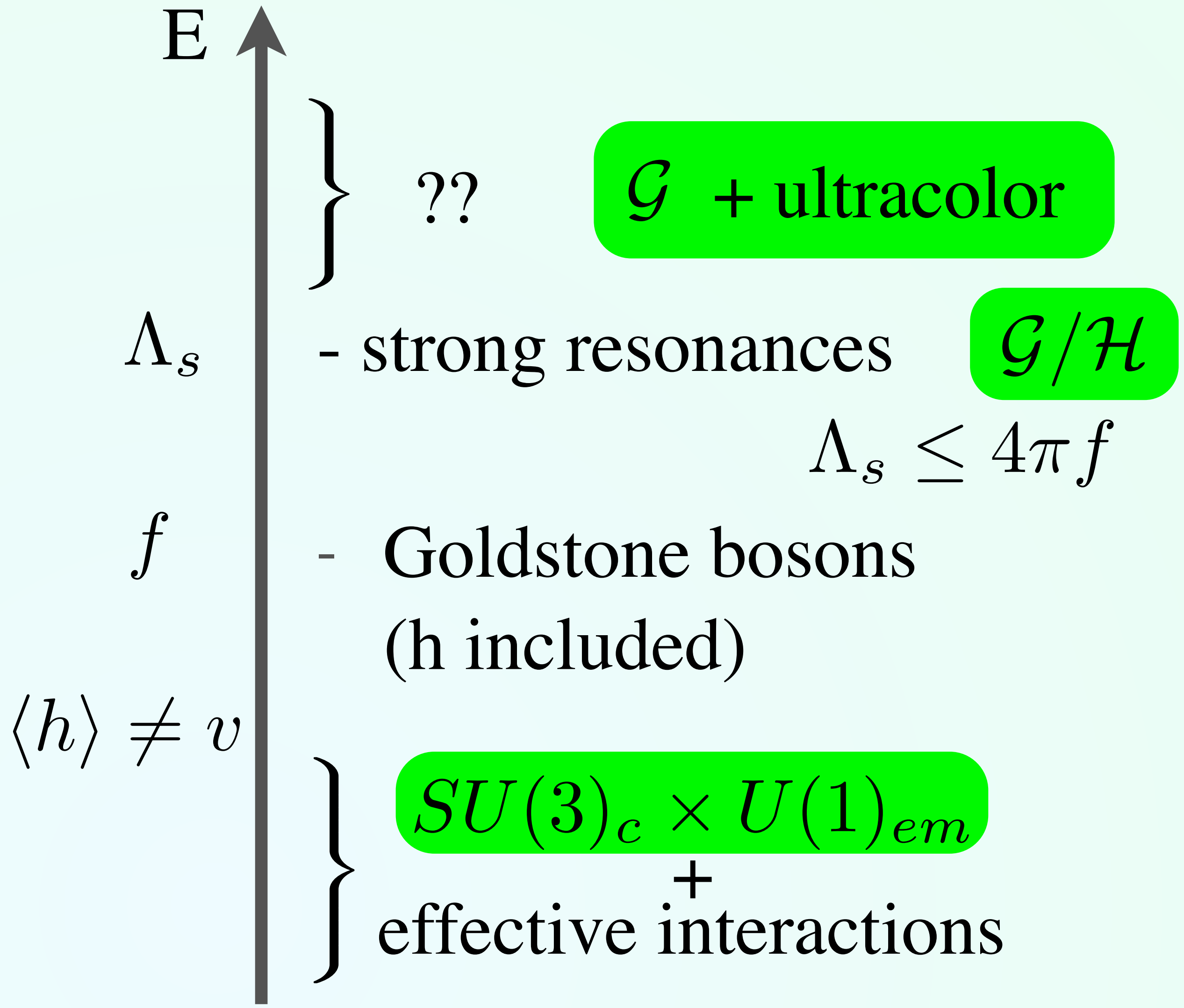
$\langle h \rangle \neq v$

$SU(3)_c \times U(1)_{em}$

\+

effective interactions

Generic Composite Higgs Models



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effective interactions

- h is embedded in a doublet of $SU(2)_L$ (reducible rep of $\mathcal{G}$)

- $\mathcal{F}_i(h) = 1 + 2\alpha_i \frac{h}{v} + \beta_i \frac{h^2}{v^2} + \ldots$ not generic but specific

- If the number of operators at the high-energy is smaller than the generic basis at low-energy, there must be <u>correlations among operators</u>

At the high-scale: *h* still a GB together to all the others generated by $\mathcal{G}/\mathcal{H}$, the most generic effective Lagrangian (with same Custodial breaking on SM)

$$\mathcal{L}_{\rm high} = \mathcal{L}^{p^2}_{\rm high} + \mathcal{L}^{p^4}_{\rm high}$$

$$\mathcal{L}^{p^2}_{\rm high} = \widetilde{\mathcal{A}}_C$$

$$\mathcal{L}^{p^4}_{\rm high} = \widetilde{\mathcal{A}}_B + \widetilde{\mathcal{A}}_W + \tilde{c}_{B\Sigma}\widetilde{\mathcal{A}}_{B\Sigma} + \tilde{c}_{W\Sigma}\widetilde{\mathcal{A}}_{W\Sigma} + \sum_{i=1}^{8} \tilde{c}_i \, \widetilde{\mathcal{A}}_i$$

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$$\widetilde{\mathcal{A}}_C = -\frac{f^2}{4}{\rm Tr}\left(\widetilde{\mathbf{V}}_\mu \widetilde{\mathbf{V}}^\mu\right)$$

$$\widetilde{\mathcal{A}}_B = -\frac{1}{4}{\rm Tr}\left(\widetilde{\mathbf{B}}_{\mu\nu}\widetilde{\mathbf{B}}^{\mu\nu}\right)$$

$$\widetilde{\mathcal{A}}_W = -\frac{1}{4}{\rm Tr}\left(\widetilde{\mathbf{W}}_{\mu\nu}\widetilde{\mathbf{W}}^{\mu\nu}\right)$$

$$\widetilde{\mathcal{A}}_{B\Sigma} = g'^2{\rm Tr}\left(\mathbf{\Sigma}\widetilde{\mathbf{B}}_{\mu\nu}\mathbf{\Sigma}^{-1}\widetilde{\mathbf{B}}^{\mu\nu}\right)$$

$$\widetilde{\mathcal{A}}_{W\Sigma} = g^2{\rm Tr}\left(\mathbf{\Sigma}\widetilde{\mathbf{W}}_{\mu\nu}\mathbf{\Sigma}^{-1}\widetilde{\mathbf{W}}^{\mu\nu}\right)$$

$$\widetilde{\mathcal{A}}_1 = g\, g'\, {\rm Tr}\left(\mathbf{\Sigma}\widetilde{\mathbf{B}}_{\mu\nu}\mathbf{\Sigma}^{-1}\widetilde{\mathbf{W}}^{\mu\nu}\right)$$

$$\widetilde{\mathcal{A}}_2 = i\, g'\, {\rm Tr}\left(\widetilde{\mathbf{B}}_{\mu\nu}\left[\widetilde{\mathbf{V}}^\mu, \widetilde{\mathbf{V}}^\nu\right]\right)$$

$$\widetilde{\mathcal{A}}_3 = i\, g\, {\rm Tr}\left(\widetilde{\mathbf{W}}_{\mu\nu}\left[\widetilde{\mathbf{V}}^\mu, \widetilde{\mathbf{V}}^\nu\right]\right)$$

$$\widetilde{\mathcal{A}}_4 = {\rm Tr}\left(\widetilde{\mathbf{V}}_\mu\, \widetilde{\mathbf{V}}^\mu\right){\rm Tr}\left(\widetilde{\mathbf{V}}_\mu\, \widetilde{\mathbf{V}}^\mu\right)$$

$$\widetilde{\mathcal{A}}_5 = {\rm Tr}\left(\widetilde{\mathbf{V}}_\mu\, \widetilde{\mathbf{V}}_\nu\right){\rm Tr}\left(\widetilde{\mathbf{V}}^\mu\, \widetilde{\mathbf{V}}^\nu\right)$$

$$\widetilde{\mathcal{A}}_6 = {\rm Tr}\left((\mathcal{D}_\mu \widetilde{\mathbf{V}}^\mu)^2\right)$$

$$\widetilde{\mathcal{A}}_7 = {\rm Tr}\left(\widetilde{\mathbf{V}}_\mu\, \widetilde{\mathbf{V}}^\mu \widetilde{\mathbf{V}}_\nu\, \widetilde{\mathbf{V}}^\nu\right)$$

$$\widetilde{\mathcal{A}}_8 = {\rm Tr}\left(\widetilde{\mathbf{V}}_\mu\, \widetilde{\mathbf{V}}_\nu \widetilde{\mathbf{V}}^\mu\, \widetilde{\mathbf{V}}^\nu\right)$$

Let's concentrate on $\widetilde{\mathcal{A}}_2 = i\, g' \,\mathrm{Tr}\left(\widetilde{\mathbf{B}}_{\mu\nu}\left[\widetilde{\mathbf{V}}^{\mu}, \widetilde{\mathbf{V}}^{\nu}\right]\right)$

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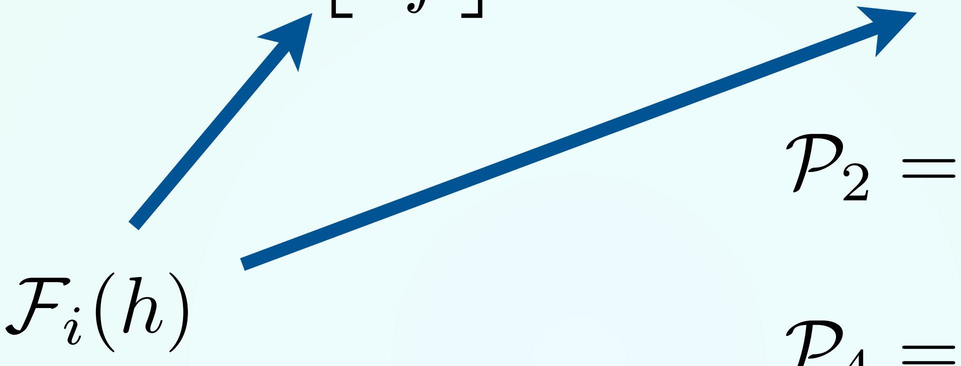
distinguishing the *h* from the others GBs: $\varphi \equiv h + \langle\varphi\rangle$

$$\widetilde{\mathcal{A}}_2 \to \sin^2\left[\frac{\varphi}{2f}\right]\mathcal{P}_2 + \sqrt{\xi}\sin\left[\frac{\varphi}{f}\right]\mathcal{P}_4$$



$\mathcal{F}_i(h)$

$$\mathcal{P}_2 = ig' B_{\mu\nu}\mathrm{Tr}(\mathbf{T}[\mathbf{V}^\mu, \mathbf{V}^\nu])$$

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going to the limit of small ξ

$$\widetilde{\mathcal{A}}_2 \to \mathcal{O}_B + \mathcal{O}(\xi^2)$$

$$\mathcal{O}_B = (D_\mu\Phi)^\dagger\, \hat{B}^{\mu\nu}\,(D_\nu\Phi)$$

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distinguishing the *h* from the others GBs: $\varphi \equiv h + \langle\varphi\rangle$

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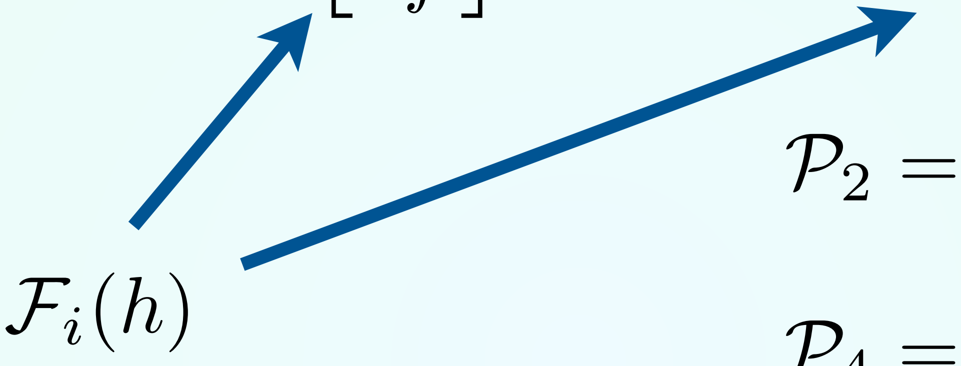

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going to the limit of small ξ

$$\widetilde{\mathcal{A}}_2 \to \mathcal{O}_B + \mathcal{O}(\xi^2)$$

$$\mathcal{O}_B = (D_\mu\Phi)^\dagger\, \hat{B}^{\mu\nu}\, (D_\nu\Phi)$$

We recover the linear expansion, with corrections in higher powers of ξ.

$$\widetilde{\mathcal{A}}_C = -\frac{f^2}{4}\mathrm{Tr}\left(\widetilde{\mathbf{V}}_\mu \widetilde{\mathbf{V}}^\mu\right) \longrightarrow \left(D_\mu \Phi\right)^\dagger \left(D^\mu \Phi\right)$$

$$\widetilde{\mathcal{A}}_B = -\frac{1}{4}\mathrm{Tr}\left(\widetilde{\mathbf{B}}_{\mu\nu} \widetilde{\mathbf{B}}^{\mu\nu}\right) \longrightarrow B_{\mu\nu} B^{\mu\nu}$$

$$\widetilde{\mathcal{A}}_W = -\frac{1}{4}\mathrm{Tr}\left(\widetilde{\mathbf{W}}_{\mu\nu} \widetilde{\mathbf{W}}^{\mu\nu}\right) \longrightarrow W^a_{\mu\nu} W^{a\mu\nu}$$

$$\widetilde{\mathcal{A}}_{B\Sigma} = g'^2 \mathrm{Tr}\left(\mathbf{\Sigma}\widetilde{\mathbf{B}}_{\mu\nu}\mathbf{\Sigma}^{-1}\widetilde{\mathbf{B}}^{\mu\nu}\right) \longrightarrow \Phi^\dagger B_{\mu\nu} B^{\mu\nu}\Phi$$

$$\widetilde{\mathcal{A}}_{W\Sigma} = g^2 \mathrm{Tr}\left(\mathbf{\Sigma}\widetilde{\mathbf{W}}_{\mu\nu}\mathbf{\Sigma}^{-1}\widetilde{\mathbf{W}}^{\mu\nu}\right) \longrightarrow \Phi^\dagger W_{\mu\nu} W^{\mu\nu}\Phi$$

$$\widetilde{\mathcal{A}}_1 = g\, g' \,\mathrm{Tr}\left(\mathbf{\Sigma}\widetilde{\mathbf{B}}_{\mu\nu}\mathbf{\Sigma}^{-1}\widetilde{\mathbf{W}}^{\mu\nu}\right) \longrightarrow \Phi^\dagger B_{\mu\nu} W^{\mu\nu}\Phi$$

$$\widetilde{\mathcal{A}}_2 = i\, g' \,\mathrm{Tr}\left(\widetilde{\mathbf{B}}_{\mu\nu}\left[\widetilde{\mathbf{V}}^\mu, \widetilde{\mathbf{V}}^\nu\right]\right) \longrightarrow \left(\mathbf{D}_\mu \Phi\right)^\dagger B^{\mu\nu} \left(\mathbf{D}_\nu \Phi\right)$$

$$\widetilde{\mathcal{A}}_3 = i\, g \,\mathrm{Tr}\left(\widetilde{\mathbf{W}}_{\mu\nu}\left[\widetilde{\mathbf{V}}^\mu, \widetilde{\mathbf{V}}^\nu\right]\right) \longrightarrow \left(\mathbf{D}_\mu \Phi\right)^\dagger W^{\mu\nu} \left(\mathbf{D}_\nu \Phi\right)$$

$$\widetilde{\mathcal{A}}_6 = \mathrm{Tr}\left(\left(\mathcal{D}_\mu \widetilde{\mathbf{V}}^\mu\right)^2\right) \longrightarrow \left(\mathbf{D}_\mu \mathbf{D}^\mu \Phi\right)^\dagger \left(\mathbf{D}_\nu \mathbf{D}^\nu \Phi\right)$$

$$\widetilde{\mathcal{A}}_4 \quad \widetilde{\mathcal{A}}_5 \quad \widetilde{\mathcal{A}}_7 \quad \widetilde{\mathcal{A}}_8$$

irrelevant: redundant or contribute to d>6 linear ops.

$$\mathcal{O}_{\Phi,1} \quad \mathcal{O}_{\Phi,2} \quad \mathcal{O}_{\Phi,3} \quad \mathcal{O}_{\Phi,4}$$

irrelevant: custodial breaking or pure Higgs corrections deviations from $(v+h)^2$ → elementary vs. composite

other type of deviations i.e.

$$\widetilde{\mathcal{A}}_2 \to \sin^2\left[\frac{\varphi}{2f}\right]\mathcal{P}_2 + \sqrt{\xi}\sin\left[\frac{\varphi}{f}\right]\mathcal{P}_4$$

→ doublet vs. singlet