UNIVERSIDAD AUTONOMA DE MADRID

inVisibles
neutrinos, dark matter & dark energy physics

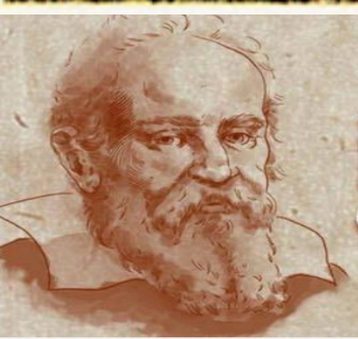
elusives
neutrinos, dark matter & dark energy physics

ift Instituto de Física Teórica UAM-CSIC

CSIC

HIGGS EFFECTIVE FIELD THEORIES

Luca Merlo



inVisibles 16 Workshop
Orto Botanico Padova 12-16 September 2016

Going Beyond the SM

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Experimental Evidences

Neutrino Masses

Baryon Asymmetry

Dark matter

Gravity

Going Beyond the SM

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- Neutrino Masses
- Baryon Asymmetry
- Dark matter
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Theoretical Problems

- Why 3 generations?
- Why so different masses & mixings?

} Flavour Puzzle

- Dark Energy (Cosmological Constant $\Lambda_0 \sim 10^{-123} M_{\rm Planck}$)
- Strong CP Problem $\theta \widetilde{G}_{\mu\nu} G^{\mu\nu}$ with $\theta < 10^{-10}$

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NEW PHYSICS

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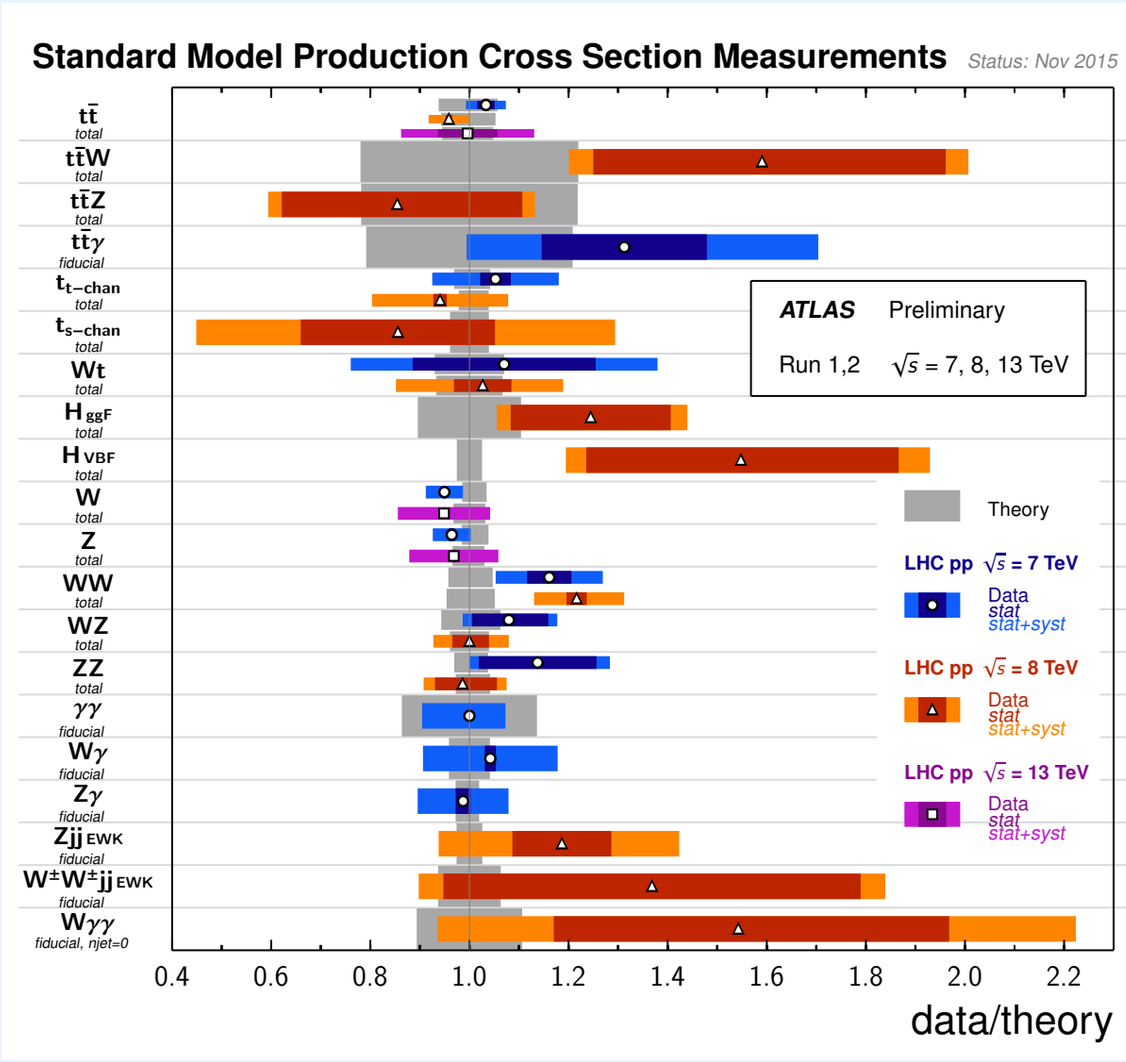
- Dark Energy (Cosmological Constant $\Lambda_0 \sim 10^{-123} M_{\rm Planck}$)
- Strong CP Problem $\theta \widetilde{G}_{\mu\nu} G^{\mu\nu}$ with $\theta < 10^{-10}$
- NP Flavour Problem (no FCNC in BSM)
- Hierarchy Problem (in the presence of NP)

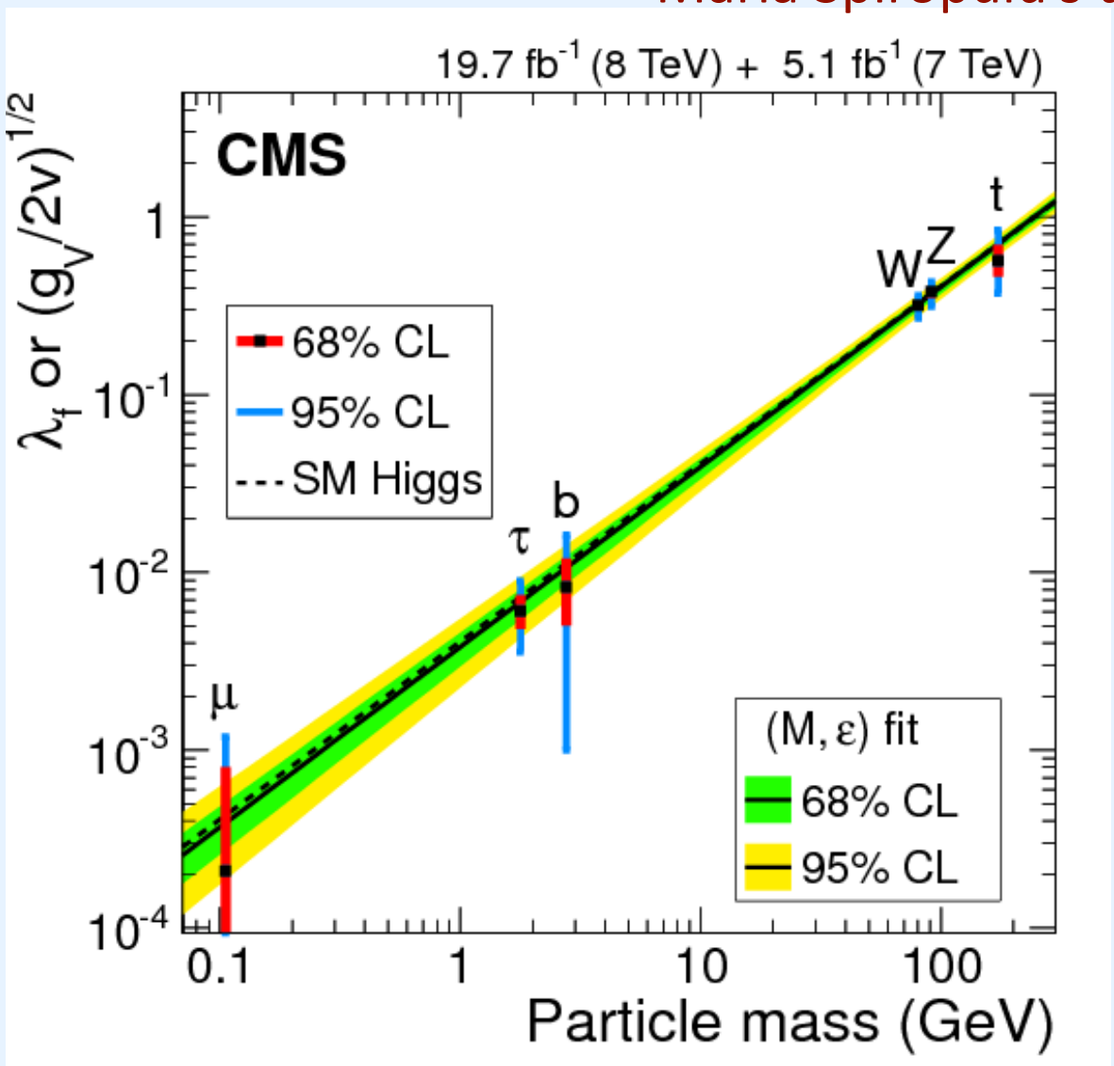
NEW PHYSICS

SM Higgs or not?

SM Higgs or not?

Maria Spiropulu's talk





If it is not the SM Higgs, it is very similar!

SM Higgs or not?

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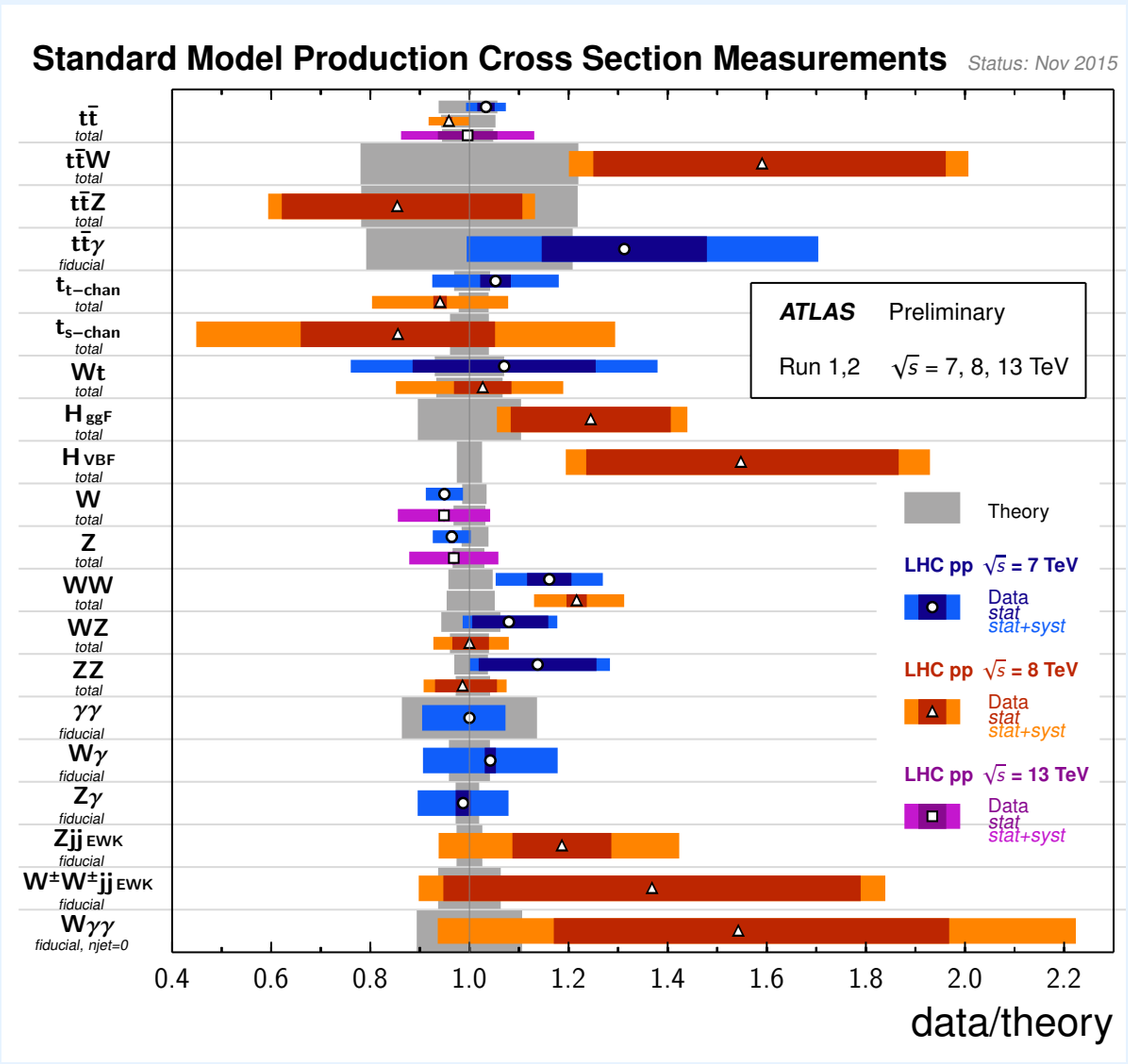

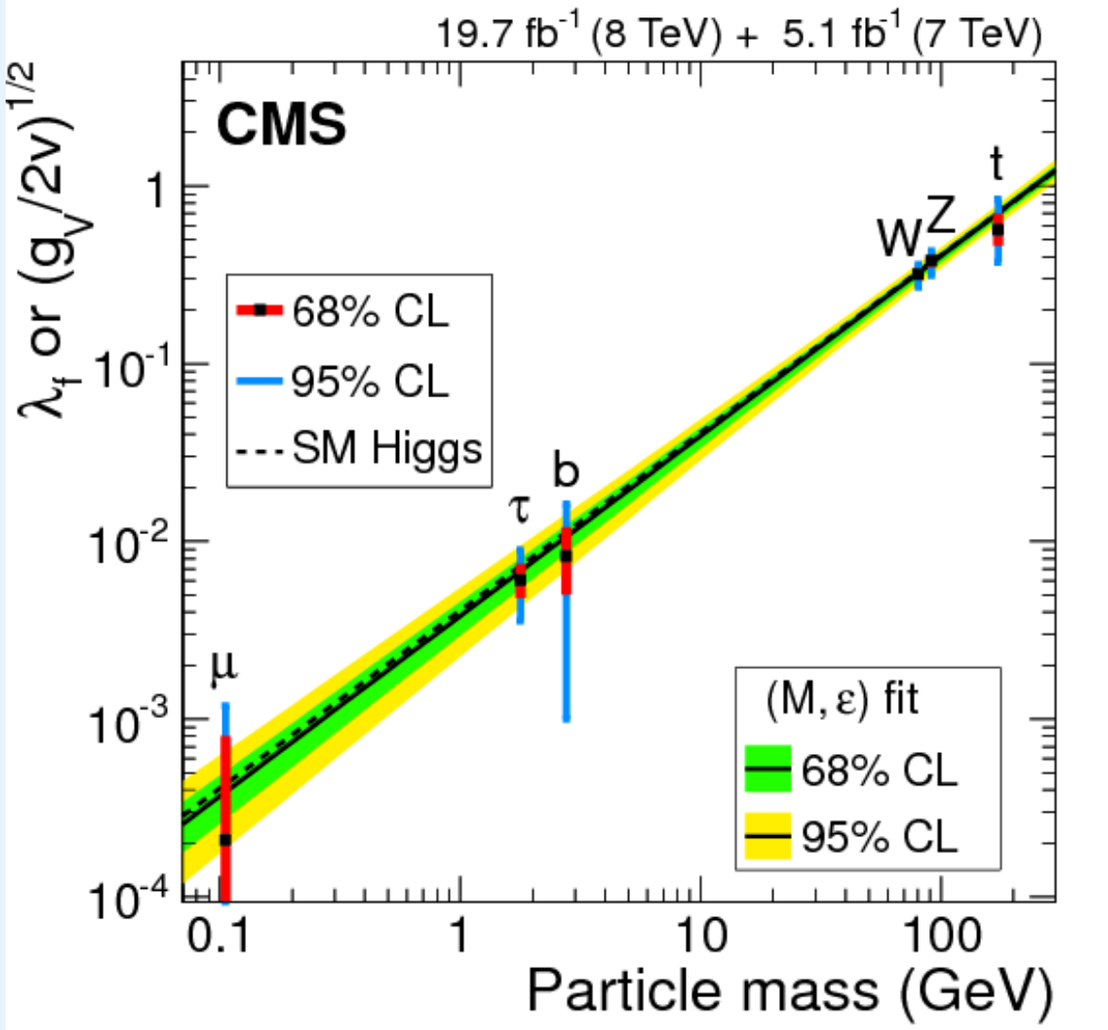

If it is not the SM Higgs, it is very similar!

Uncertainties leave space to alternatives to SM EWSB sector!

SM Higgs or not?

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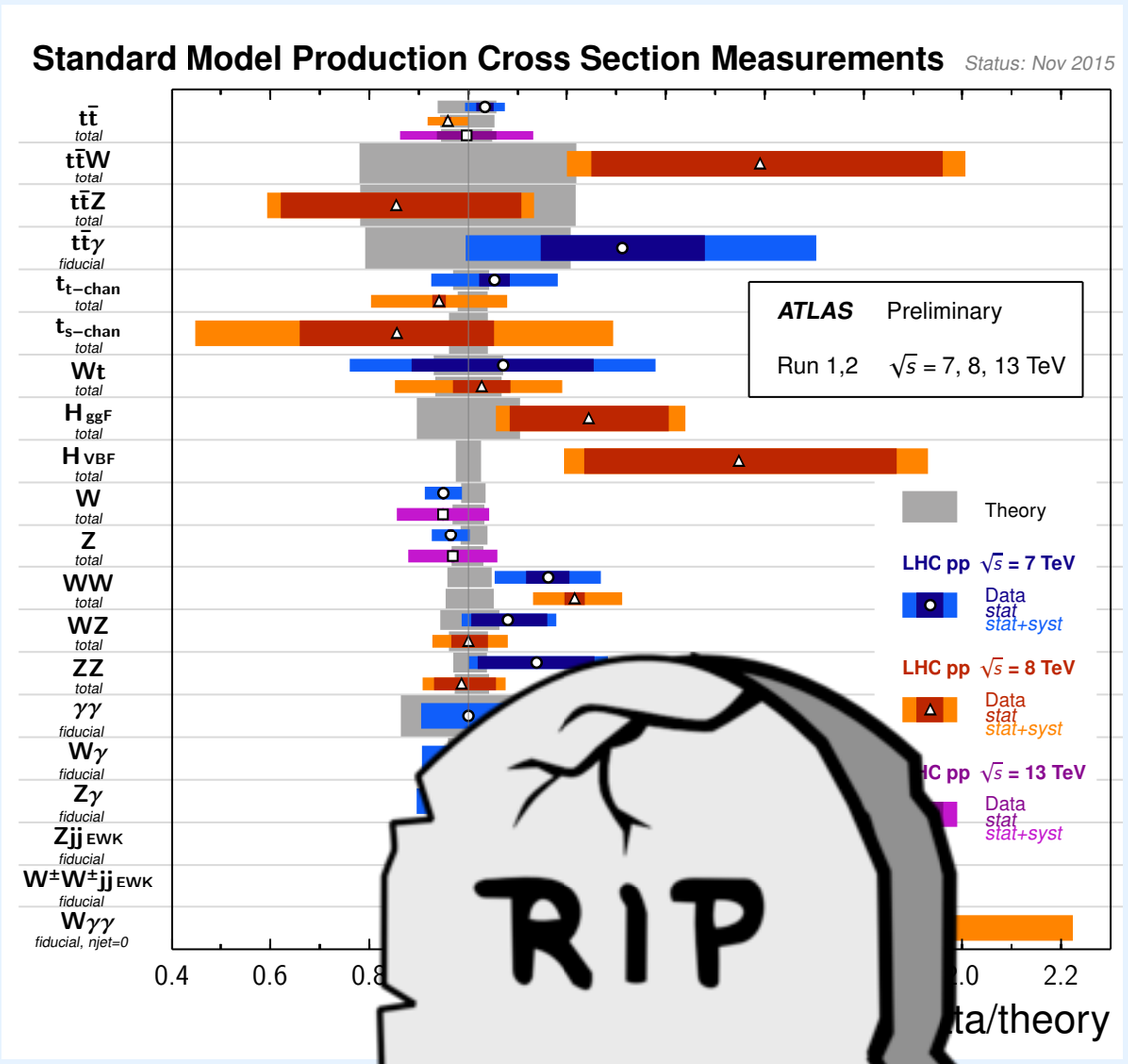

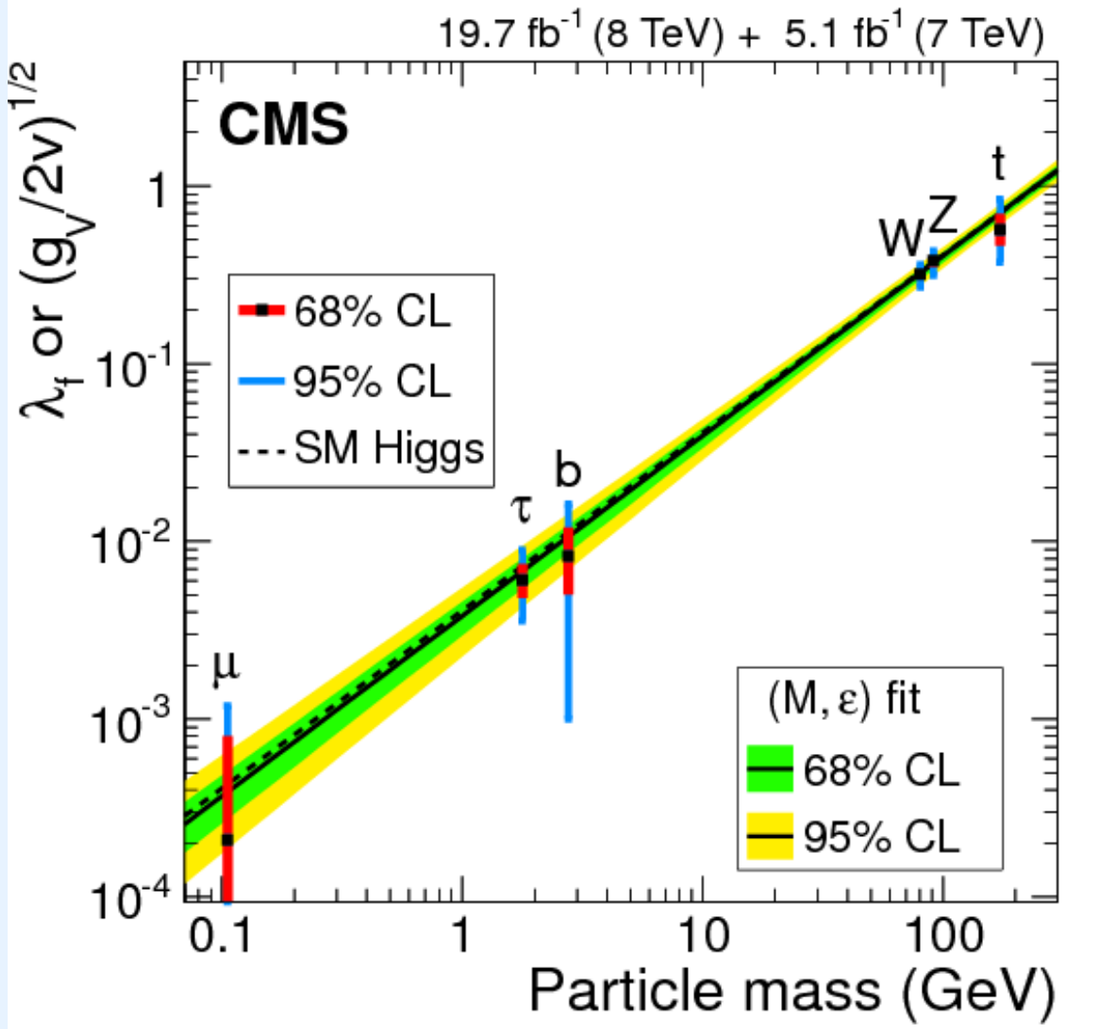

M Higgs, it is very similar!

Uncertain e to alternatives to SM EWSB sector!

Without any hint of NP → indirect signals!

Indirect Searches by EFTs

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EXACT EW DOUBLET

SM

Hierarchy Problem
(neutrino masses &
DM & Baryon Asym)

Indirect Searches by EFTs

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SUSY

two $SU(2)_L$ doublets
(Solution for HP)

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Composite Higgs Models

Not exactly an EW doublet, but almost (Solution for HP)

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→ **Effective Field Theory**

- Only on relevant contributions at that energy (LHC)
- Calculations are easier
- Benefits in the renormalisation procedure
- Accidental (approximate) symmetries

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Needs only:

- **Spectrum**
- **Symmetry**
- **Expansion rule**

Indirect Searches by EFTs

EXACT EW DOUBLET

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(**SUSY** — two $SU(2)_L$ doublets (Solution for HP))

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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

The SMEFT Lagrangian

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

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

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$$- \left(\bar{L}_L\Phi\mathcal{Y}_L L_R + \text{h.c.}\right)$$

59 (no flavour) d=6 operators preserving SM, lepton, baryon syms

(2499 including flavour Alonso, Jenkins, Manohar & Trott, JHEP **1404** (2014) 159)

Higgs Physics in SMEFT

e.g.: Corbett, Eboli, Gonzalez-Fraile & Gonzalez-Garcia, PRD87 (2013)

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

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

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NOT REALLY IMPORTANT

- Contribute to:

  HVV VVV VVVV

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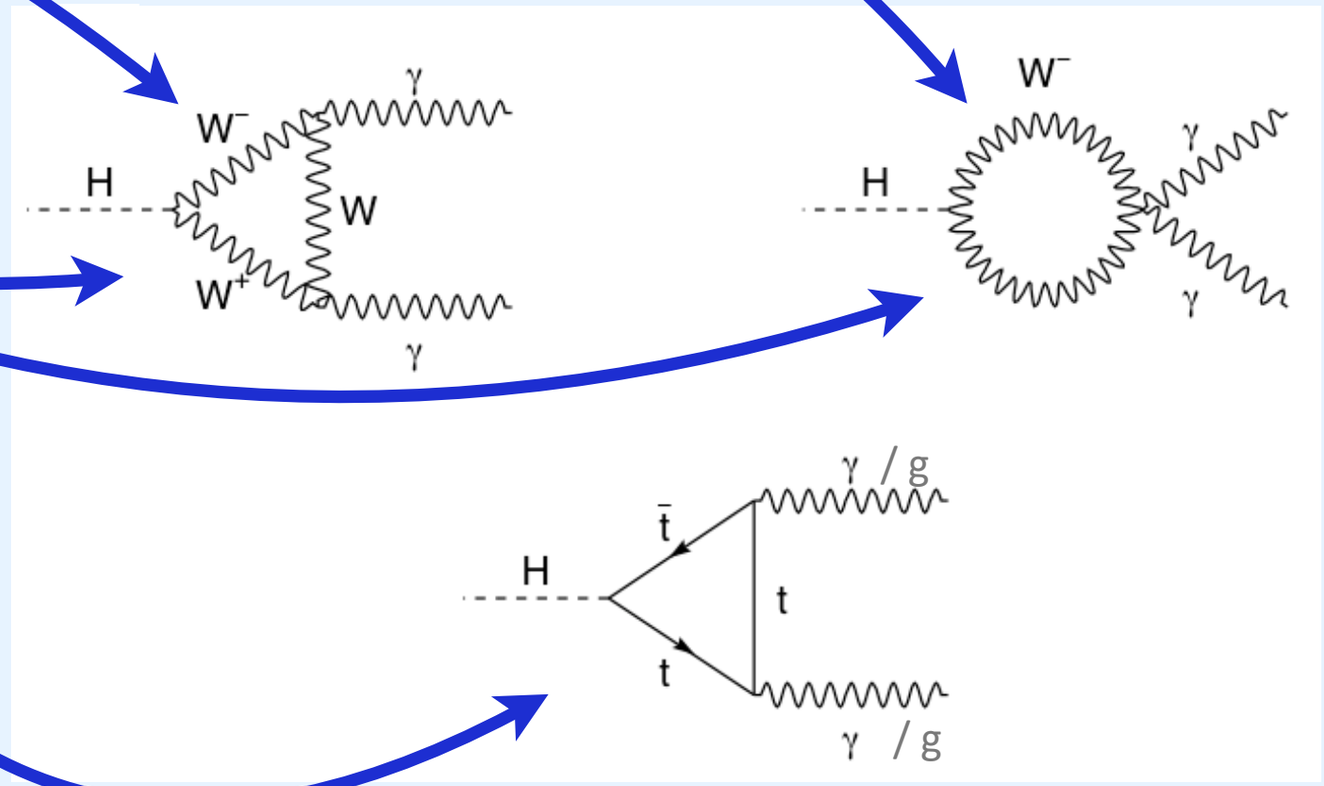

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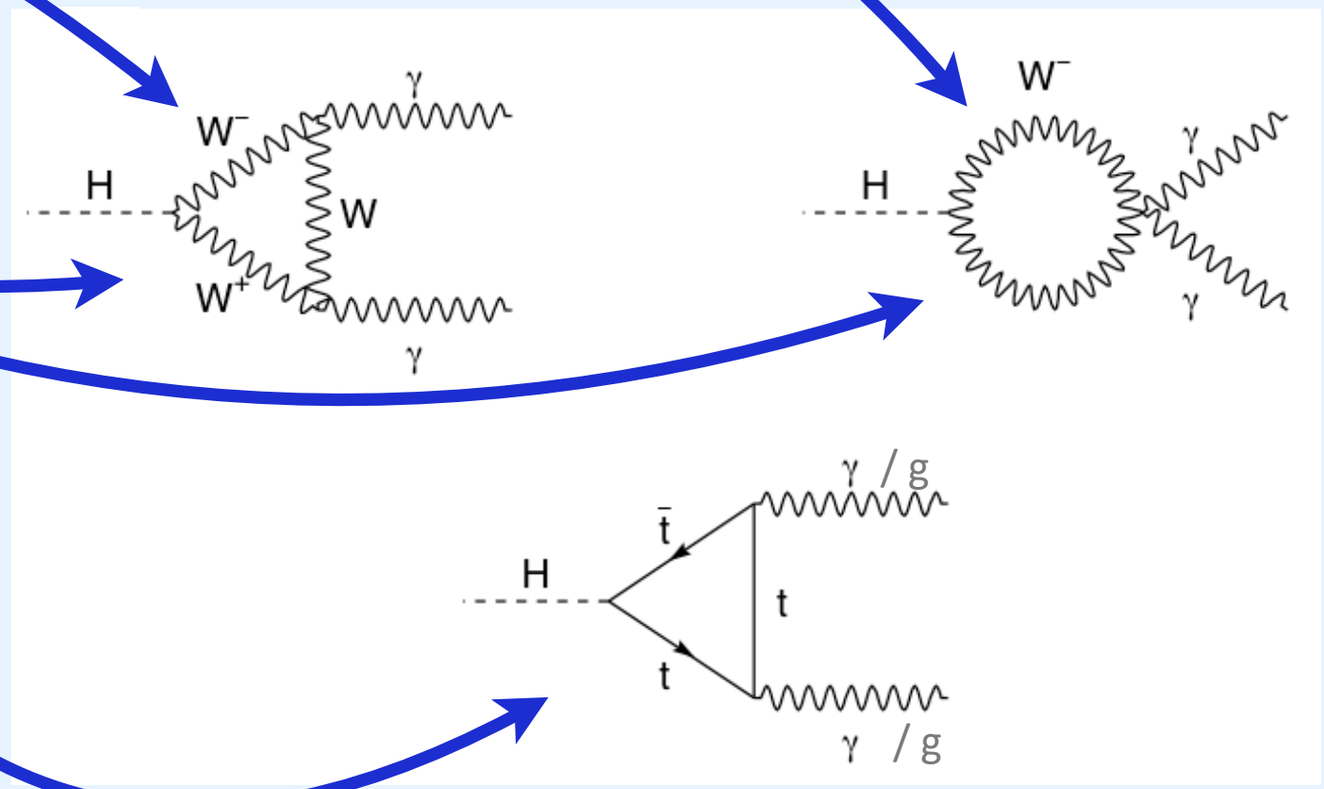

- Gauge Invariance (absent in k-formalism)

→ correlations between VVV and HVV

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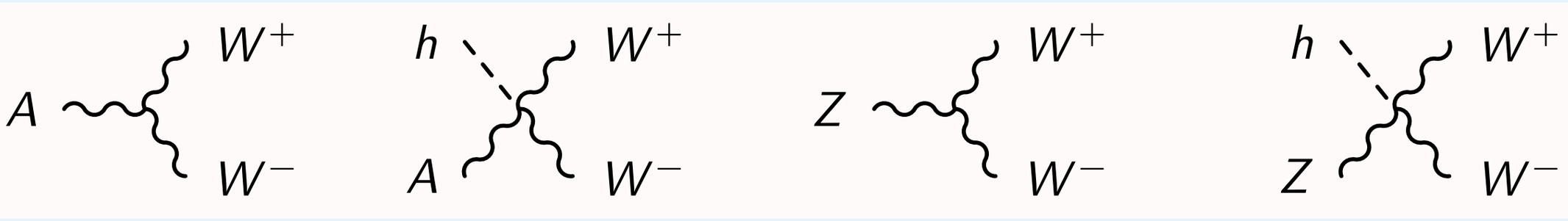

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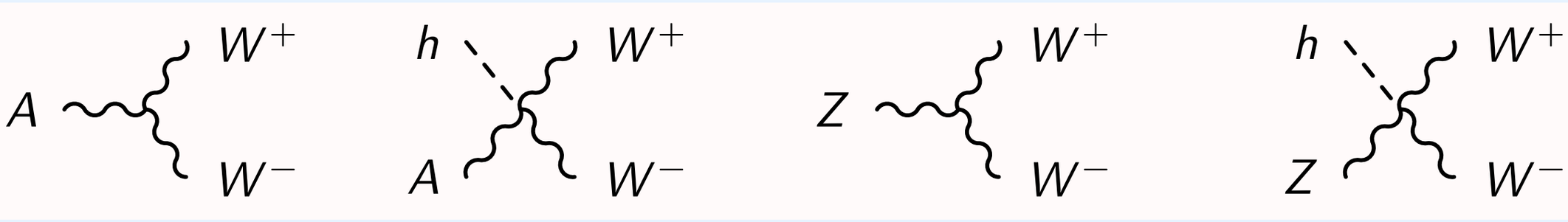

All these couplings are correlated!!

Interplay HVV and TGV

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

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

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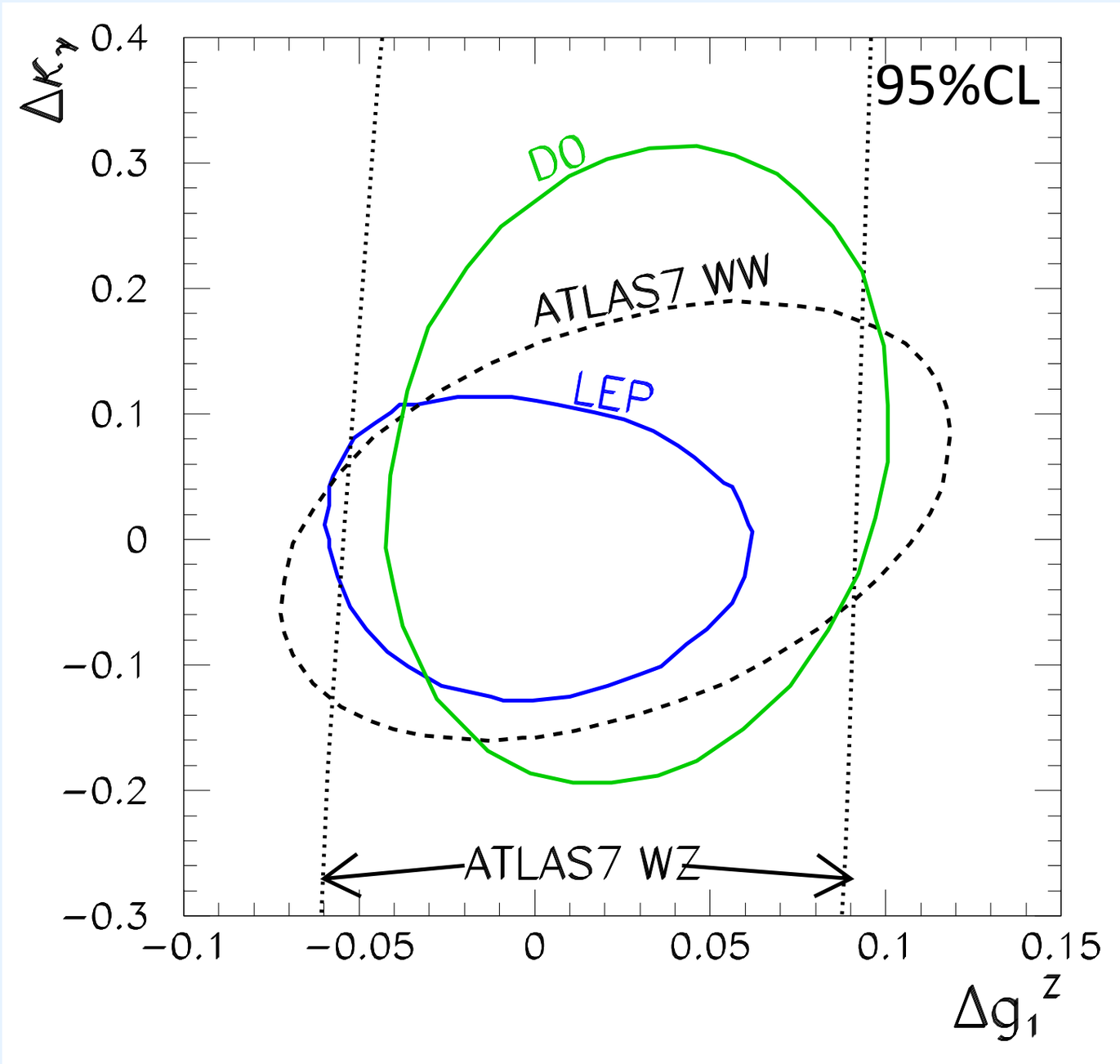

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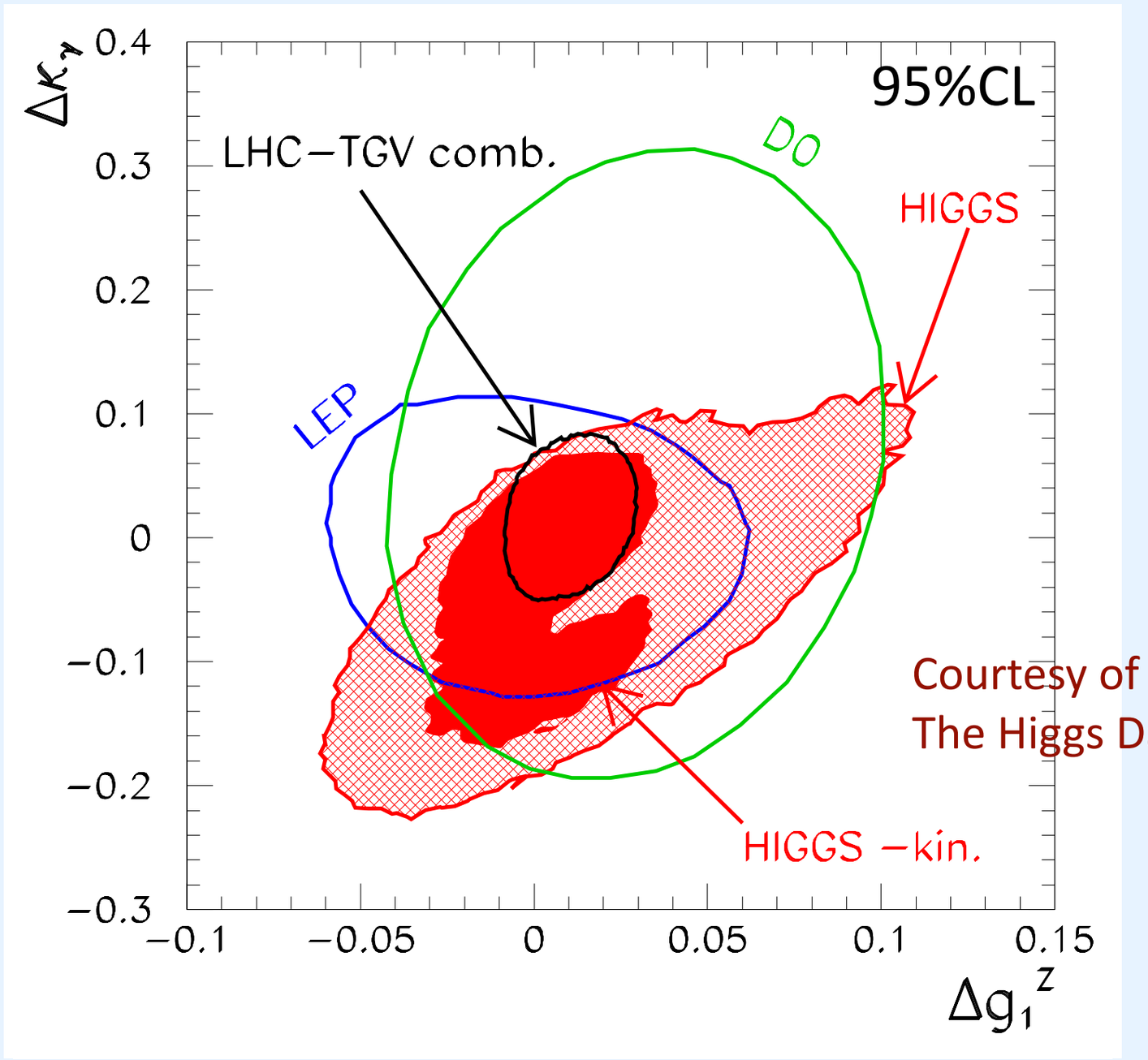


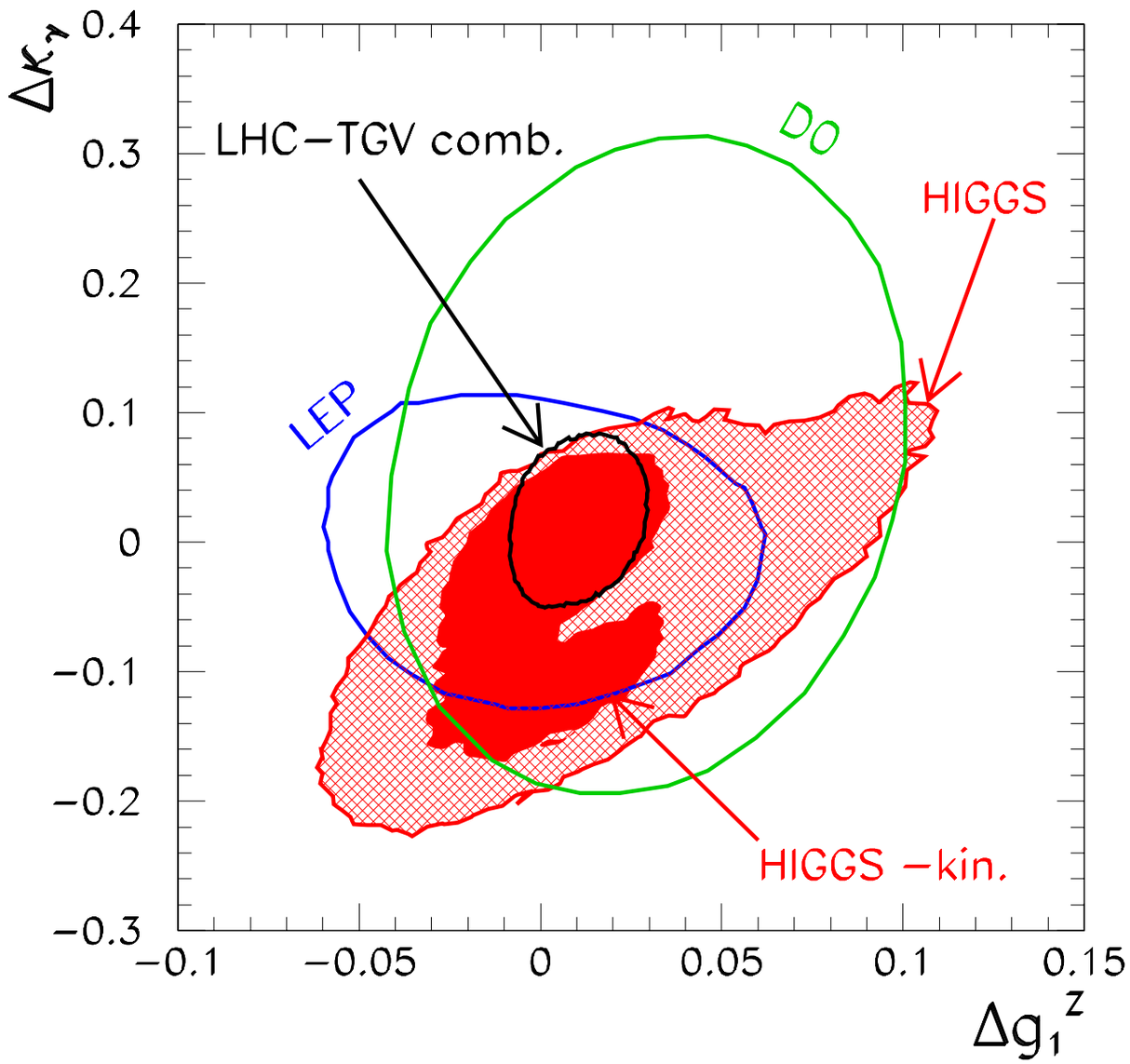
Courtesy of Juan Gonzalez-Fraile, The Higgs Days at Santander 2016

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

The impact of kinematic distributions

With

2016



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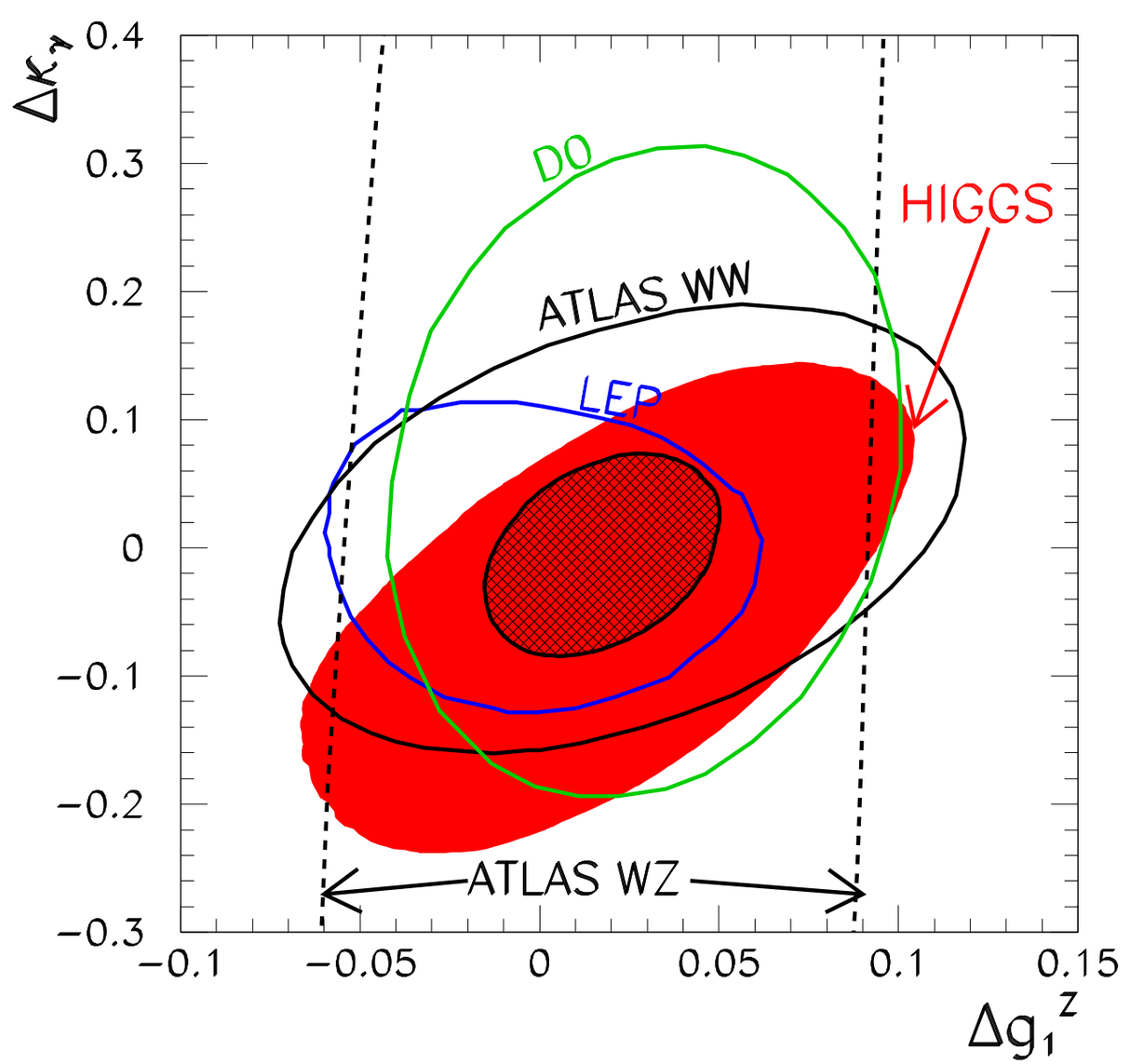
(based on Butter et al., JHEP **1607** (2016) 152)

Without

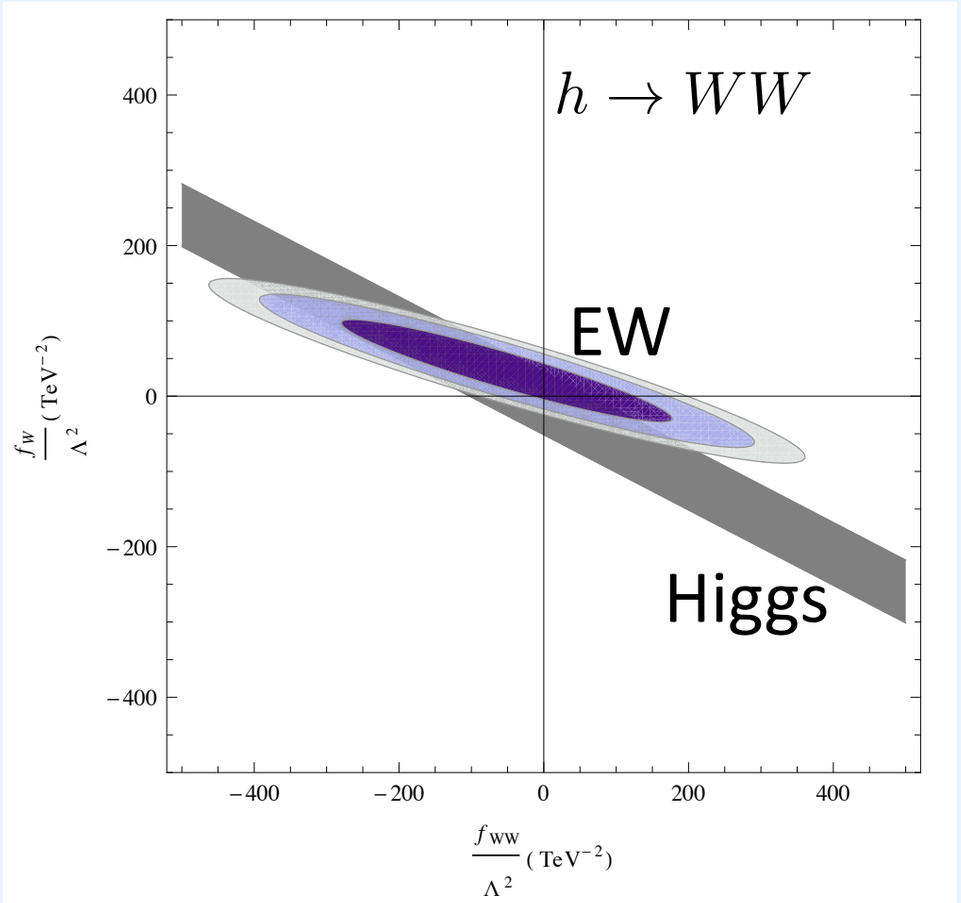
2013



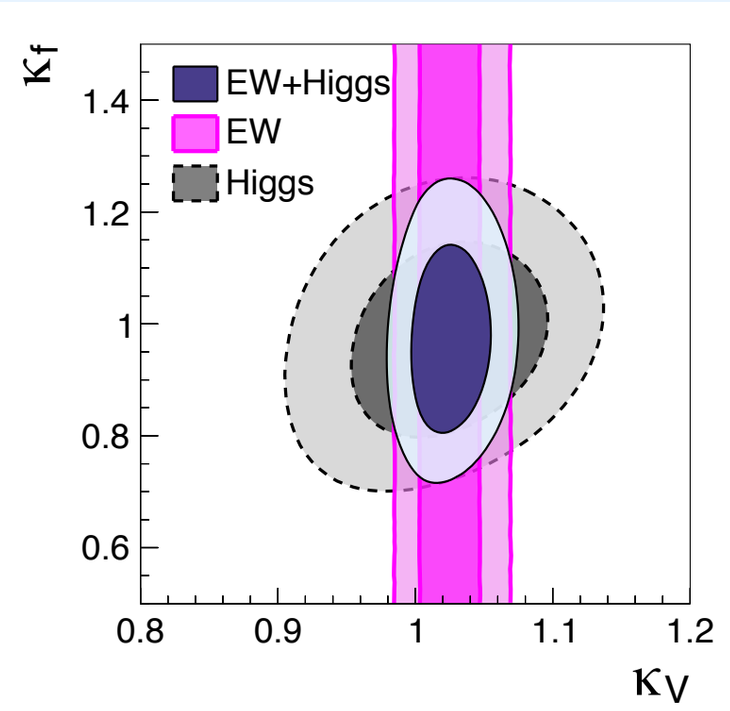
Corbett, Eboli, Gonzalez-Fraile &
Gonzalez-Garcia, PRL 111 (2013)

Other similar studies

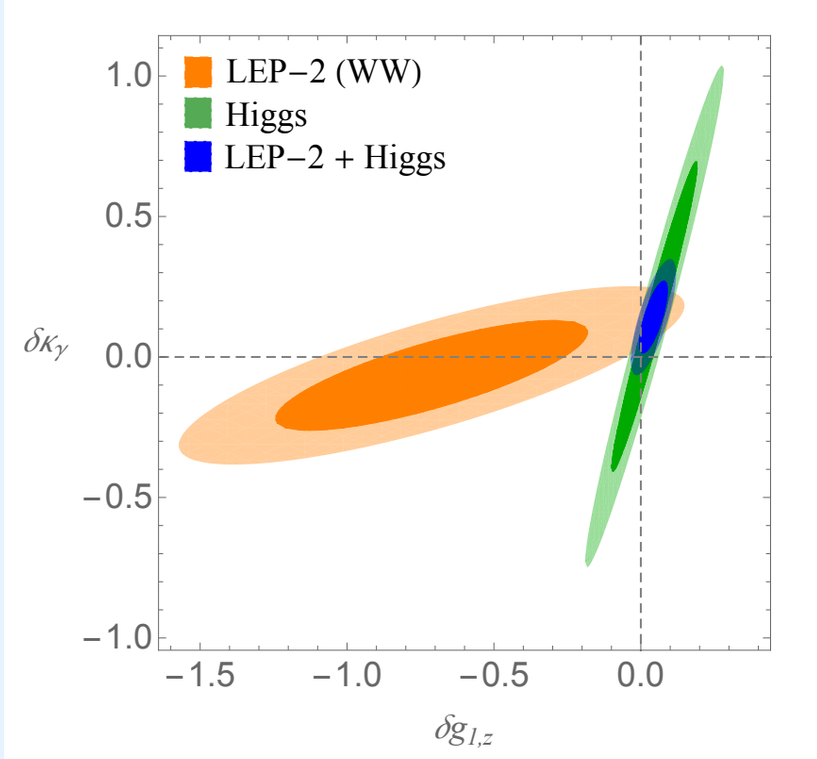
Chen, Dawson & Zhang, PRD89 (2014)



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



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



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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HEFT

Rocio del Rey's talk

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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Independent!!

- Being h a singlet: generic functions of h $\mathcal{F}_i(h) = 1 + 2\alpha_i \frac{h}{v} + \beta_i \frac{h^2}{v^2} + \dots$

HEFT

SMEFT: constructed with

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

Rocio del Rey's talk

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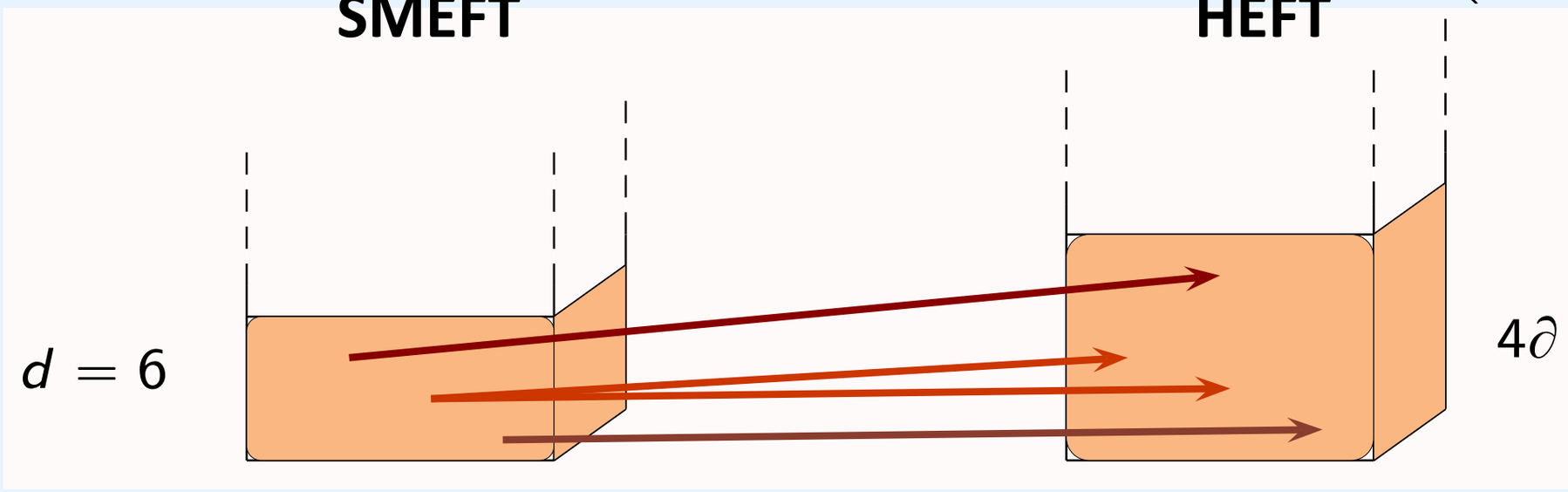
- Being $\mathbf{U}(x)$ **vs.** h independent, many more operators can be constructed

Decorrelations & New Signals

Brivio,Corbett,Eboli,Gavela,Gonzalez-Fraile, Gonzalez-Garcia,LM&Rigolin, JHEP 1403 (2014) 024

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



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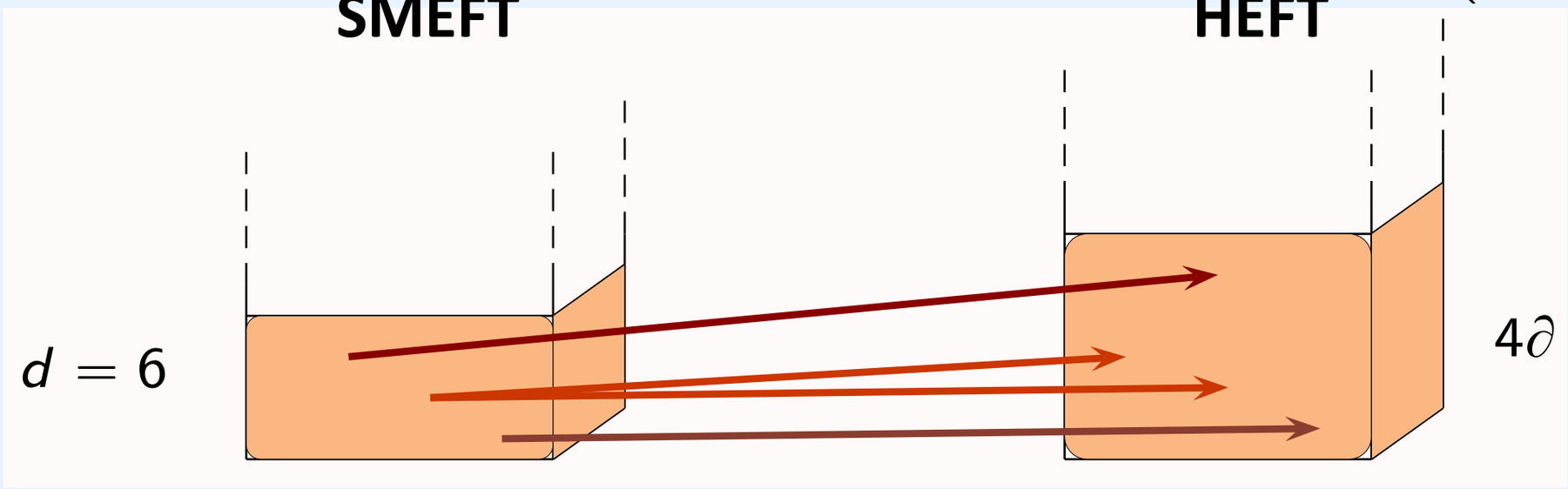
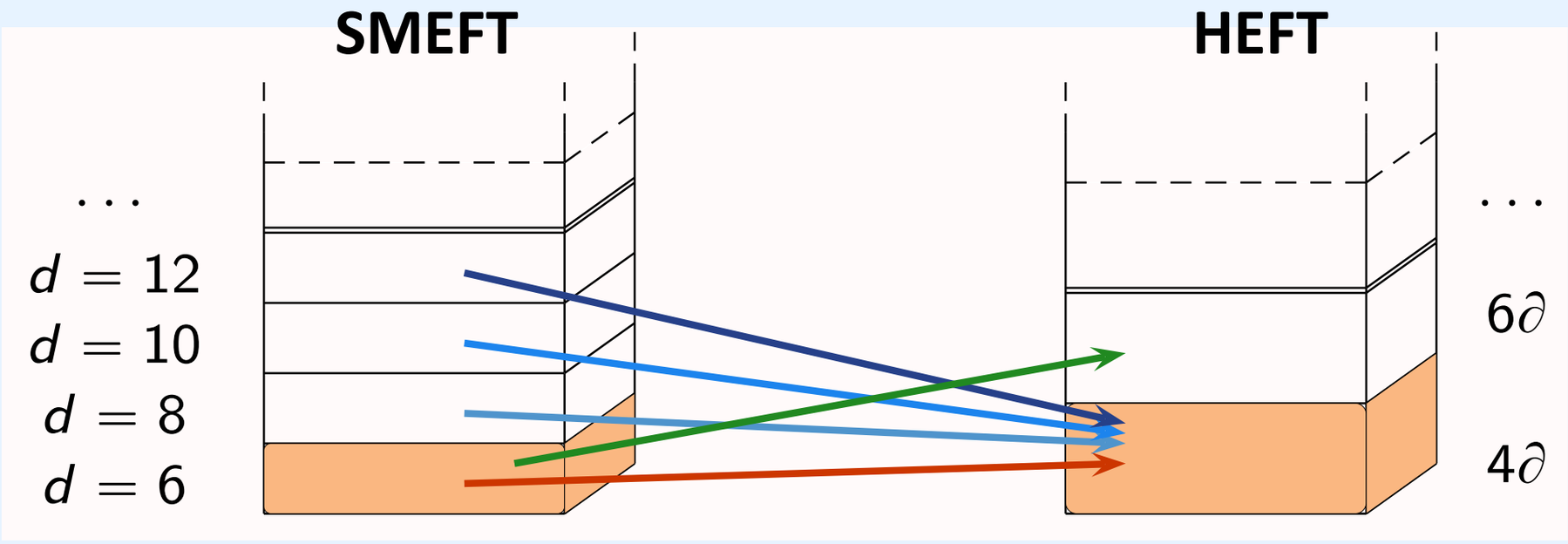
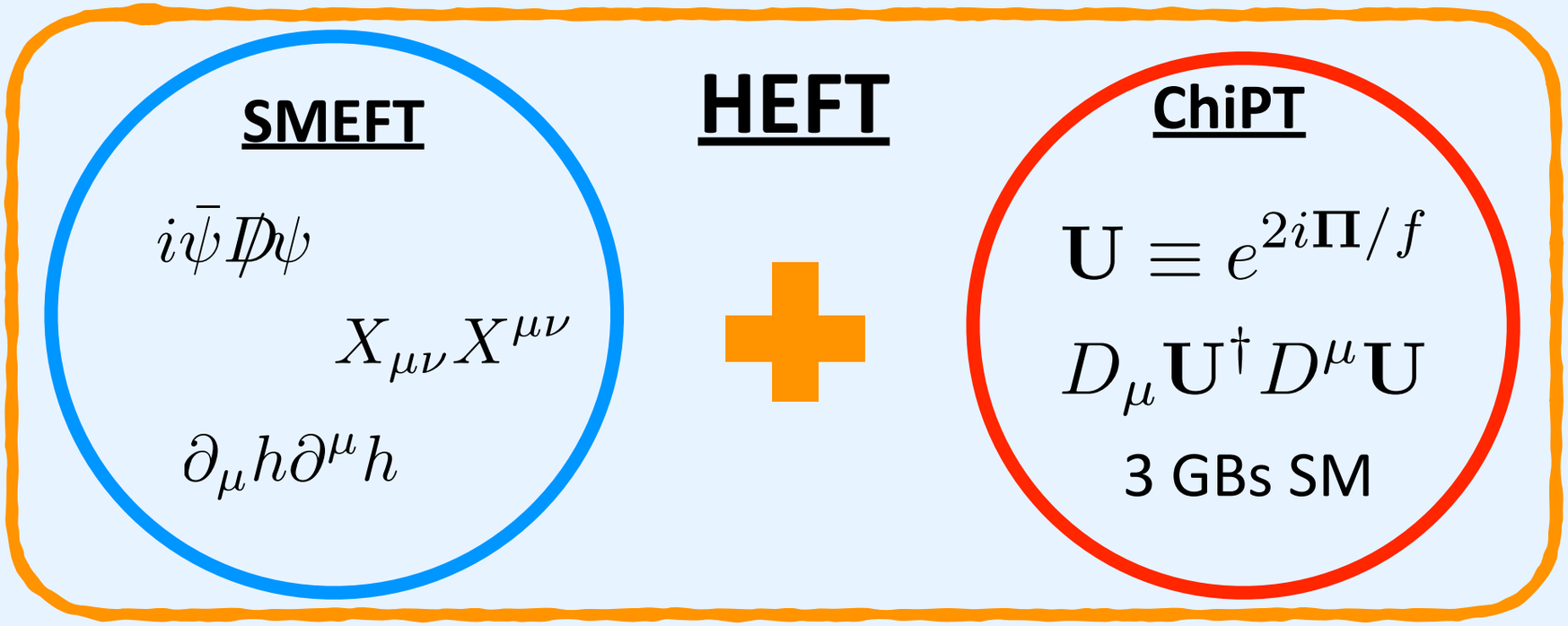


- Study the **anomalous signals** present in the chiral, but absent in the linear



What is HEFT?

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



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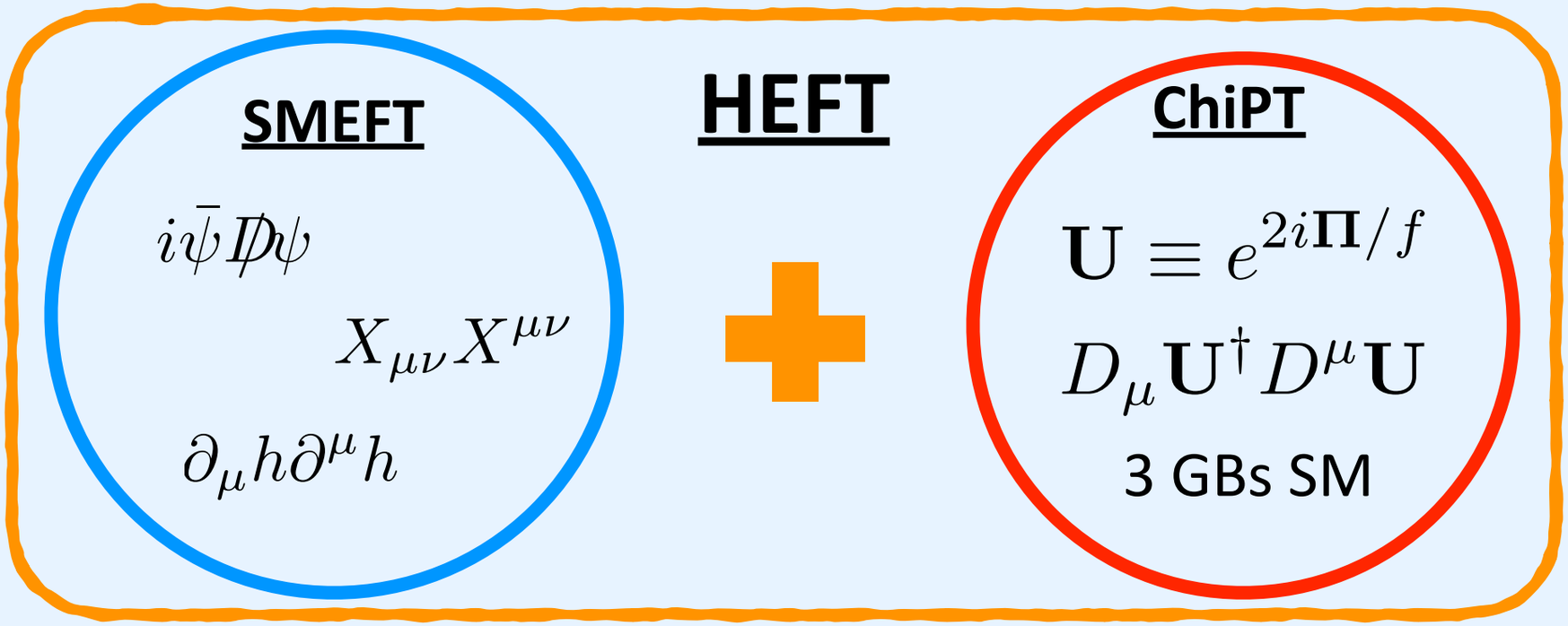

HEFT describes an extended class of "Higgs" models:

- Standard Model
- SMEFT
- Technicolor-like ansatz
- Dilator-Like models
- Composite Higgs models

} special limits and fixing the parameters

Alonso,Brivio,Gavela,LM&Rigolin, JHEP **12** (2014) 034
Hierro,LM&Rigolin, JHEP 1604 (2016) 016
Feruglio,Gavela,Kanshin,Machado,Rigolin&Saa, JHEP **1606** (2016) 038

What is HEFT?

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

SMEFT

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

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

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

HEFT

ChiPT

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

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

3 GBs SM

Building blocks:

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

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

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

$\psi_{L,R}$

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

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

The HEFT Lagrangian

Feruglio, Int.J.Mod.Phys. **A8** (1993) 4937-4972
Azatov, Contino & Galloway JHEP 1304 (2013) 140
Alonso, Gavela, LM, Rigolin & Yepes, JHEP 1206 (2012) 076, PLB 722 (2013) 926, PRD 87 (2013) 055019
Buchalla, Cata & Krause, NPB 880 (2014) 552-573
Gavela, Gonzalez-Fraile, Gonzalez-Garcia, LM, Rigolin & Yepes, JHEP 1410 (2014) 043

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

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

$$\mathcal{F}_i(h) \neq \left(1 + \frac{h}{v}\right)^2$$

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$D_\mu\Phi^\dagger D^\mu\Phi \rightarrow$

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

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

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

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The HEFT Lagrangian

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

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

- 148 (no flavour) operators preserving SM, lepton, baryon syms, up to NLO in the renormalisation procedure

  Gavela, Jenkins, Manohar & LM, Eur.Phys.J. C76 (2016) 485

  (see Buchalla, Cata & Krause, NPB 880 (2014) 552-573 for an alternative basis)

- Higgs analysis similar to SMEFT: 10 parameters wrt 9 of SMEFT

  → The fit on the Higgs is very close to the SMEFT one!

Decorrelations

- More important effects when comparing TGV and HVV: for example

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

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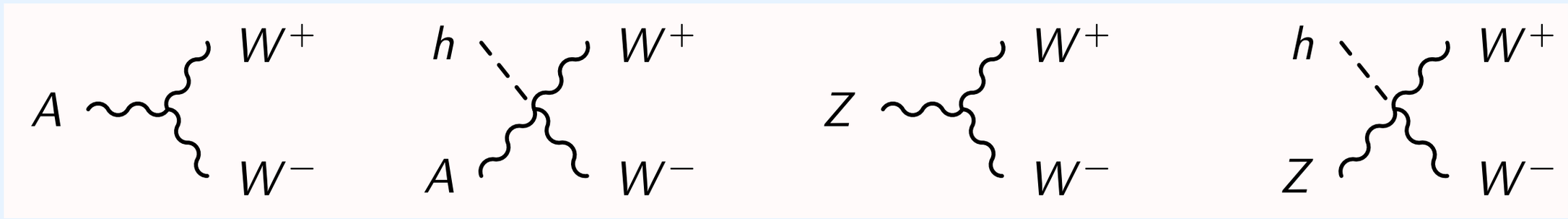

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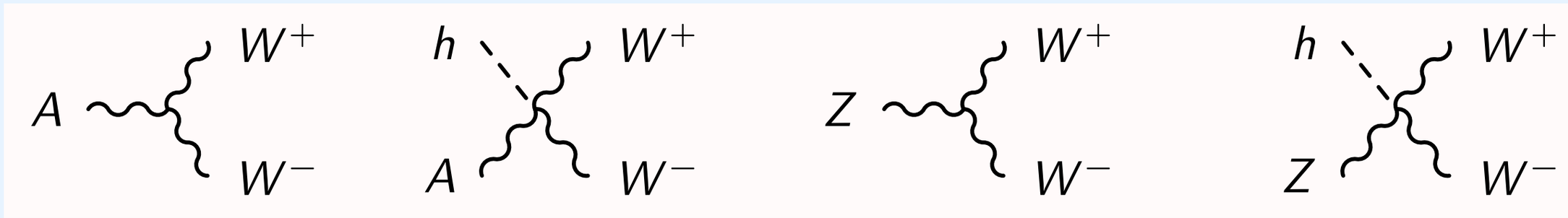
$$\mathcal{O}_B = \frac{v^2}{16} \mathcal{P}_2(h) + \frac{v^2}{8} \mathcal{P}_4(h) \quad \text{with} \quad \mathcal{F}_i(h) = \left(1 + \frac{h}{v}\right)^2$$

$$\mathcal{P}_2(h) = iB_{\mu\nu} \mathrm{Tr}\left(\mathbf{T}\left[\mathbf{V}^{\mu}, \mathbf{V}^{\nu}\right]\right) \mathcal{F}_2(h)$$

$$\mathcal{P}_4(h) = iB_{\mu\nu} \mathrm{Tr}\left(\mathbf{T}\mathbf{V}^{\mu}\right) \partial^{\nu} \mathcal{F}_4(h)$$



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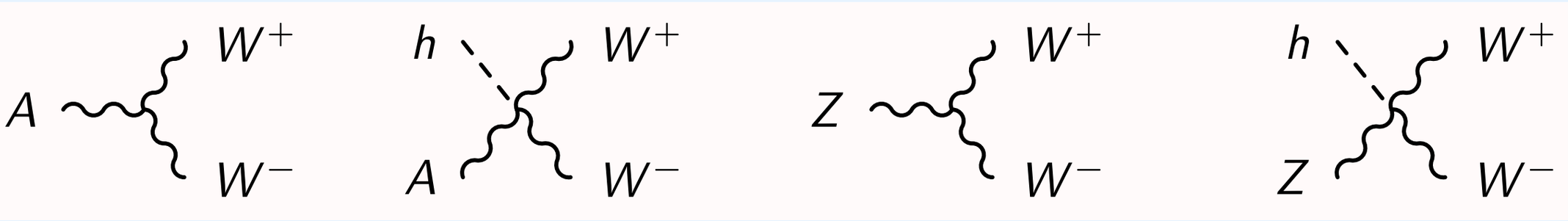

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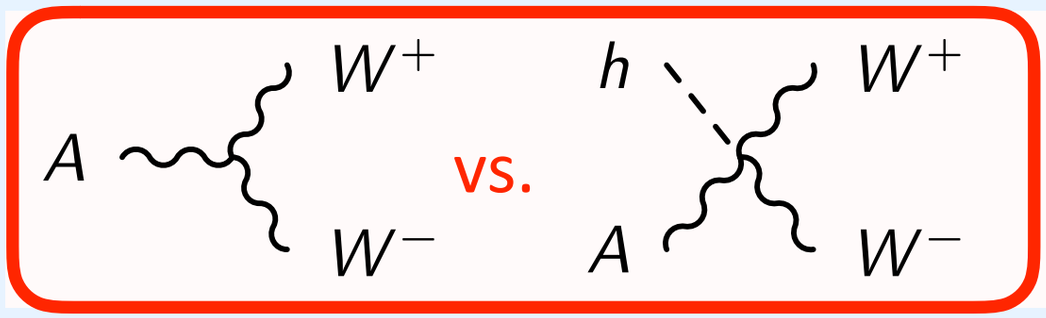
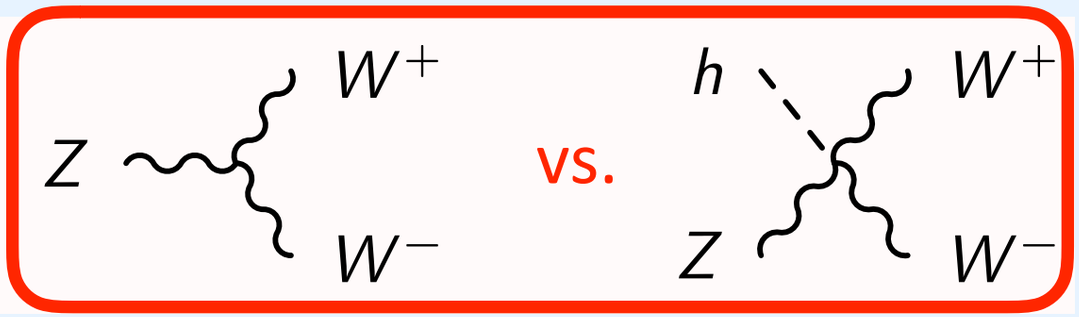
due to the decorrelation in the $\mathcal{F}_i(h)$ functions: i.e.

[see also Isidori&Trott, 1307.4051]





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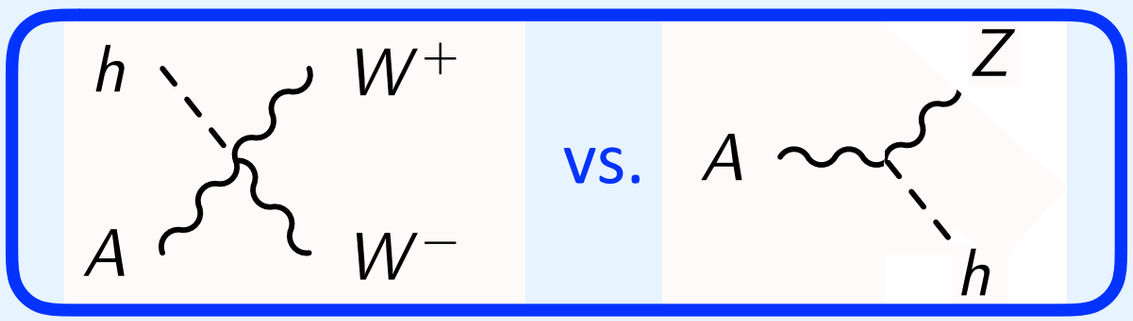
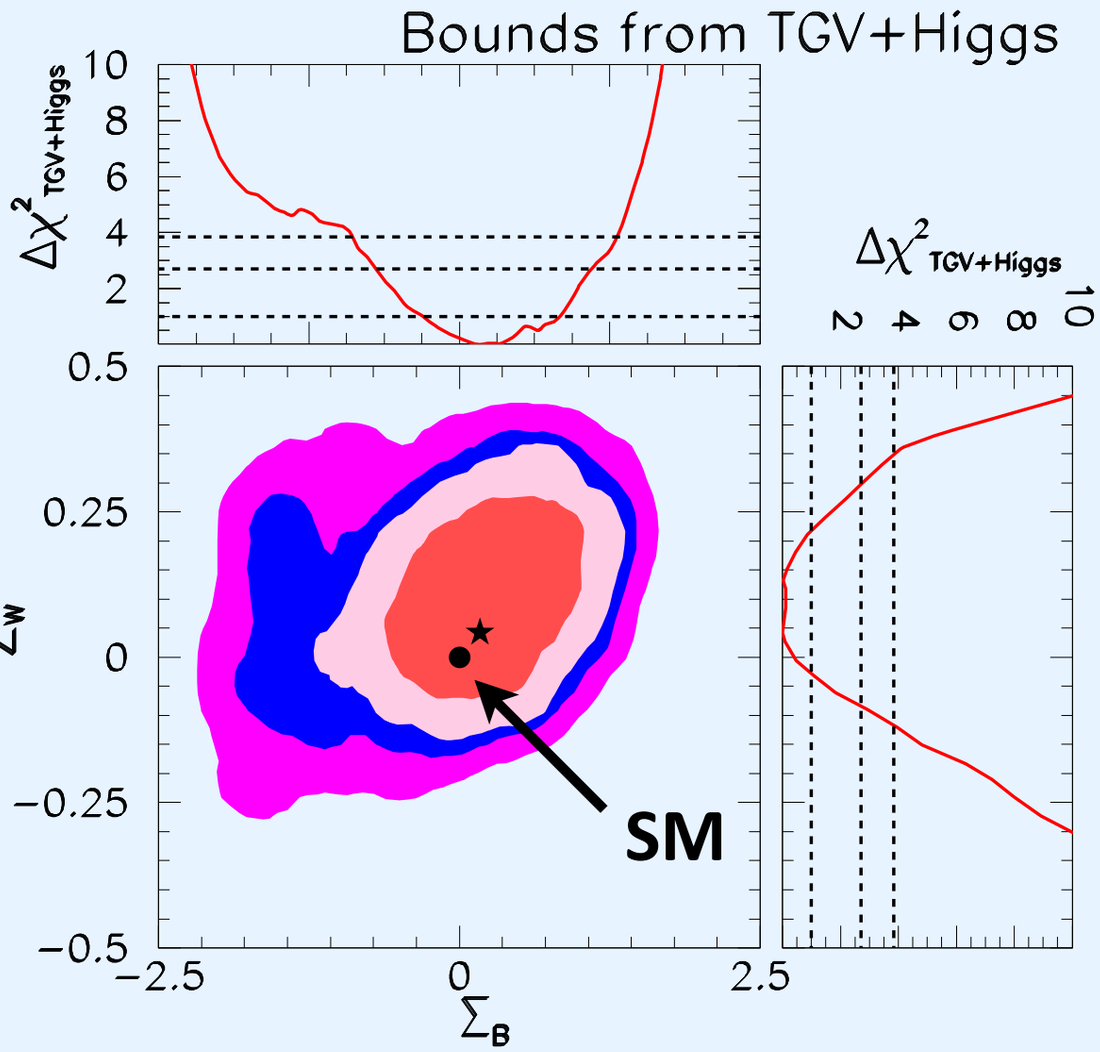
due to the nature of the chiral operators (different c_i coefficients): i.e.



SM vs. BSM



$$\Sigma_B = 4(2c_2 + a_4) \rightarrow f_B \; v^2/\Lambda^2$$

$$\Sigma_W = 2(2c_3 - a_5) \rightarrow f_W \, v^2/\Lambda^2$$

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 $\tau\tau^-$

Brivio,Corbett,Eboli,Gavela,Gonzalez-Fraile, Gonzalez-Garcia,LM&Rigolin, JHEP 1403 (2014) 024

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

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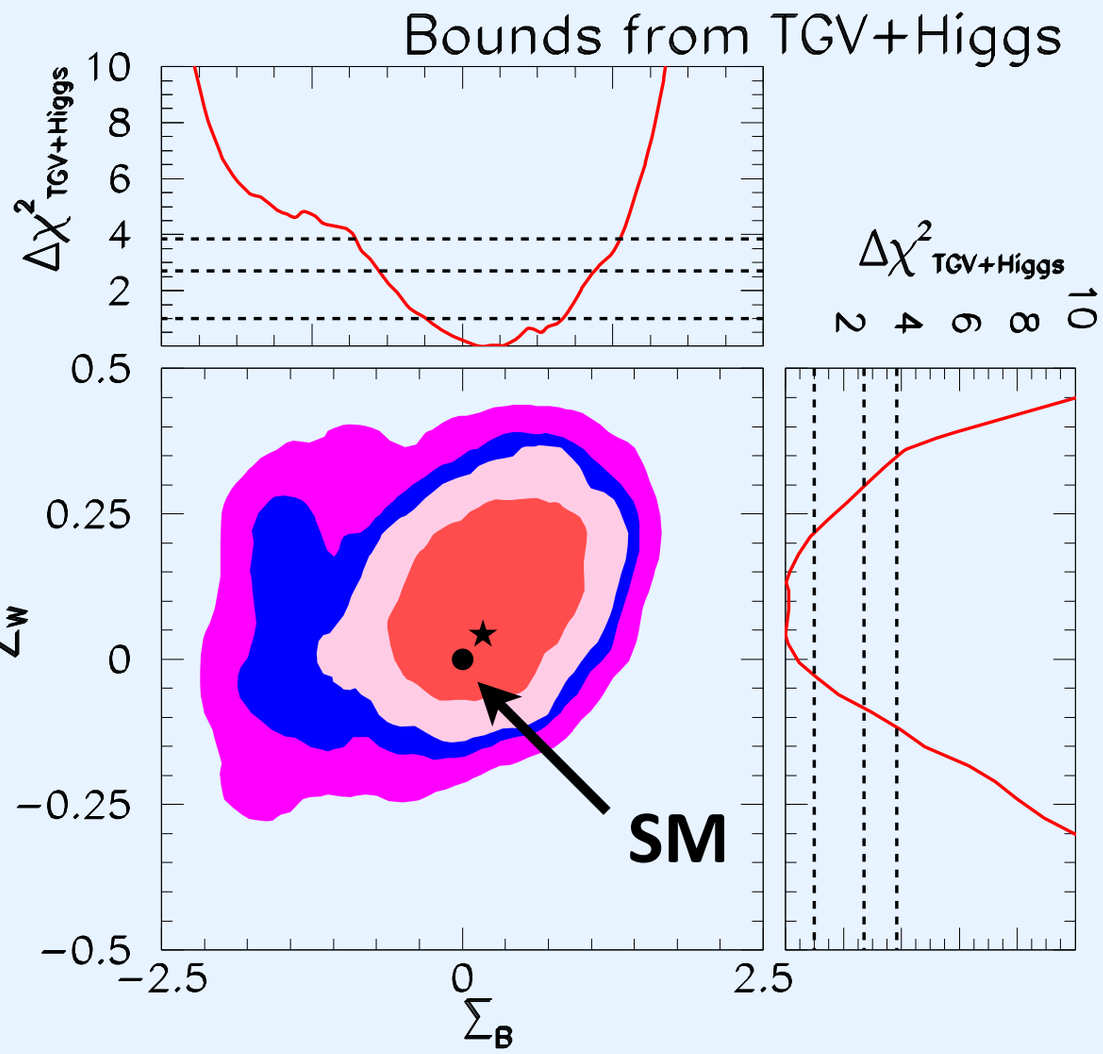

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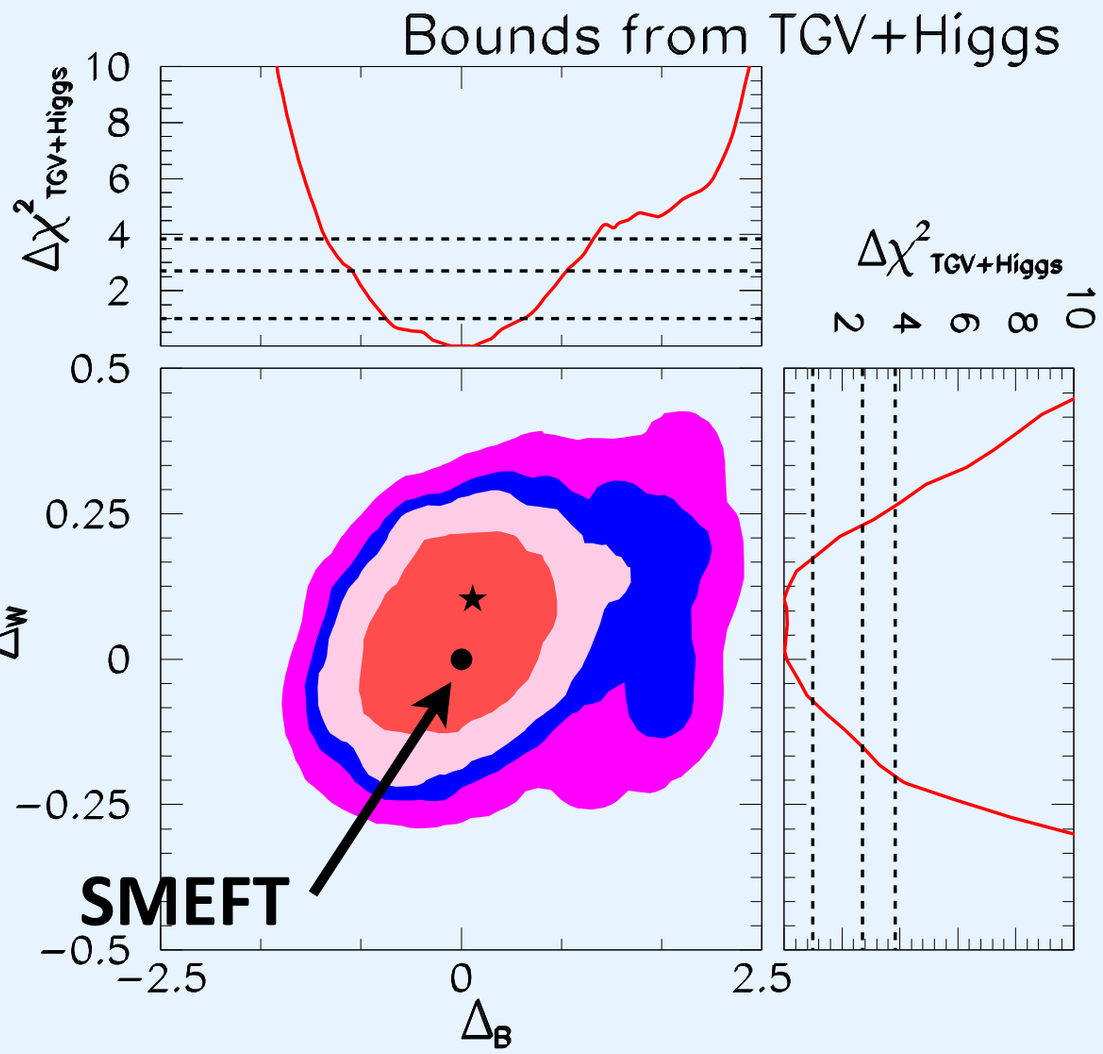
SMEFT vs. HEFT



$$\Delta_B = 4(2c_2 - a_4) \to 0$$

$$\Delta_W = 2(2c_3 + a_5) \to 0$$

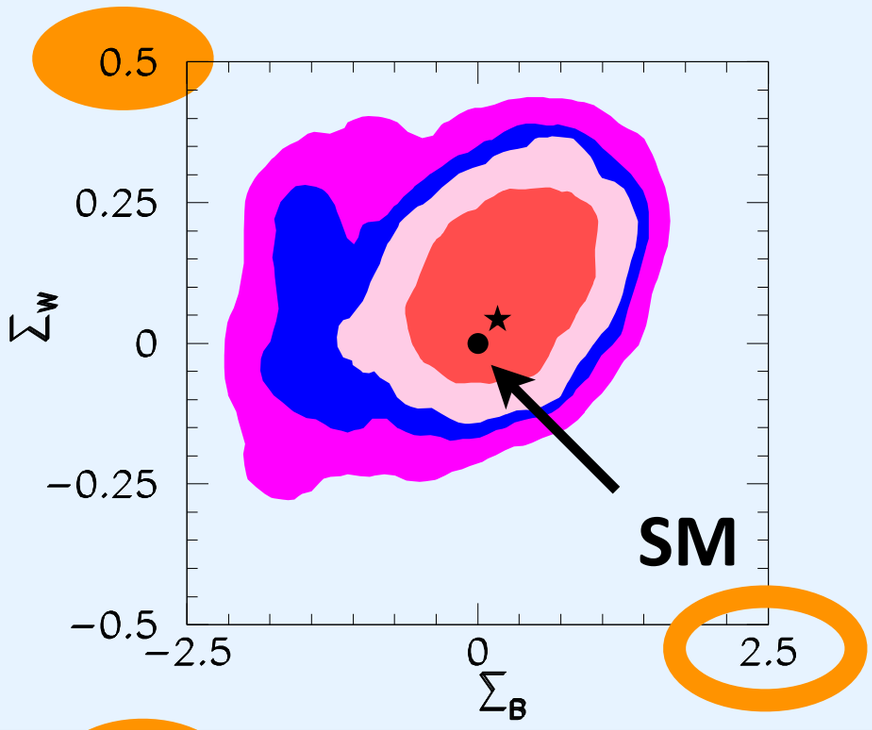
Data: Tevatron D0 and CDF Collaborations and LHC, CMS, and ATLAS Collaborations at 7 TeV and 8 TeV for final states $\gamma\gamma$, W^+W^-, ZZ, $Z\gamma$, $b\bar{b}$, and $\tau\tau^-$

The impact of kinematic distributions

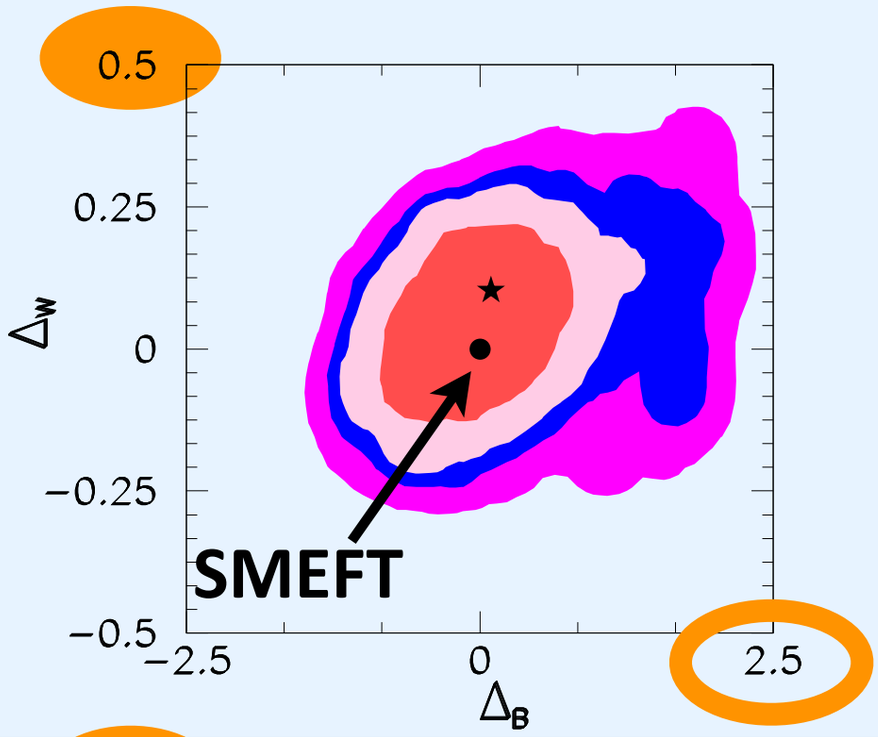
With

2016

SM vs. BSM



SMEFT vs. HEFT



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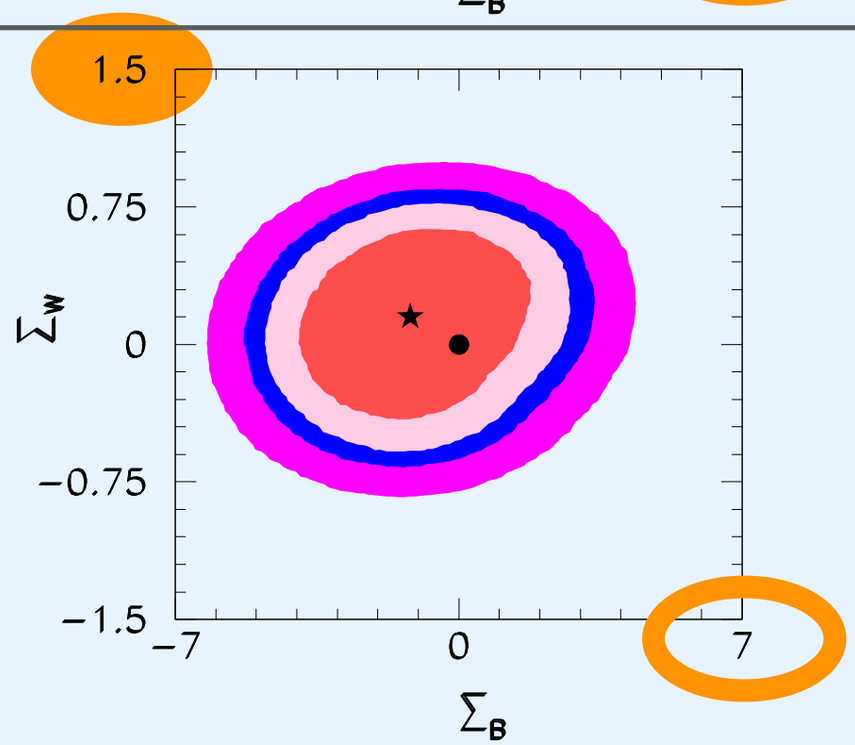
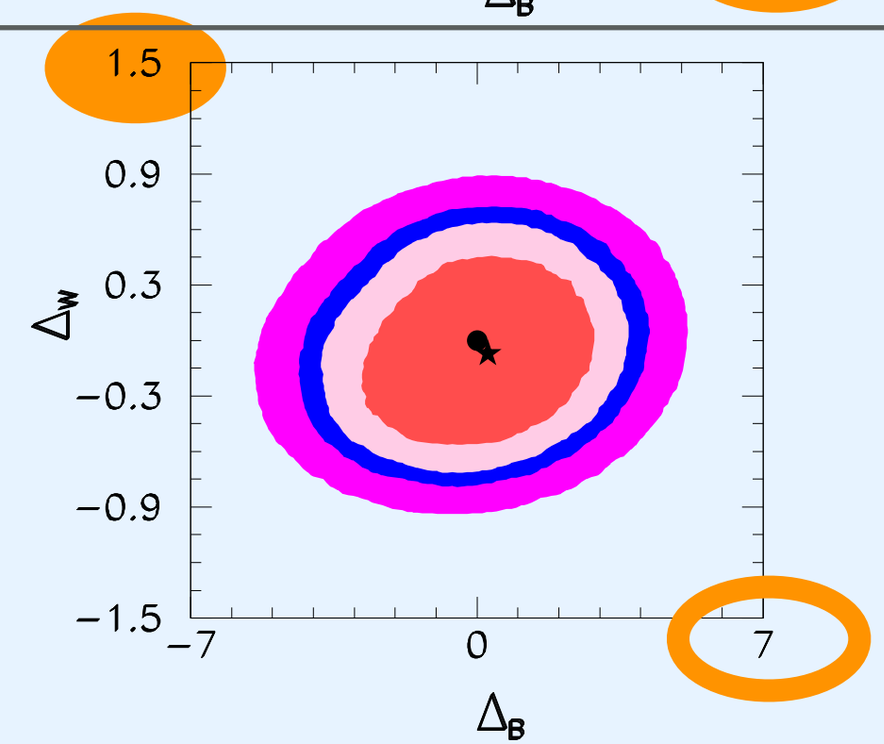
2014





New Signals

Brivio,Corbett,Eboli,Gavela,Gonzalez-Fraile, Gonzalez-Garcia,LM&Rigolin, JHEP 1403 (2014) 024

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

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

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

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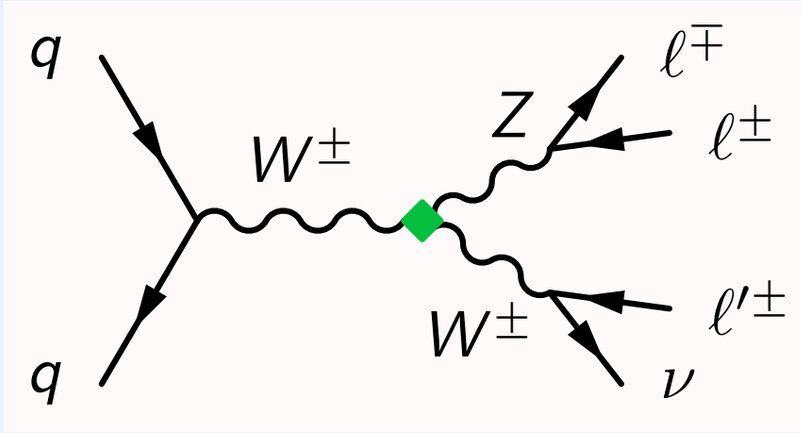

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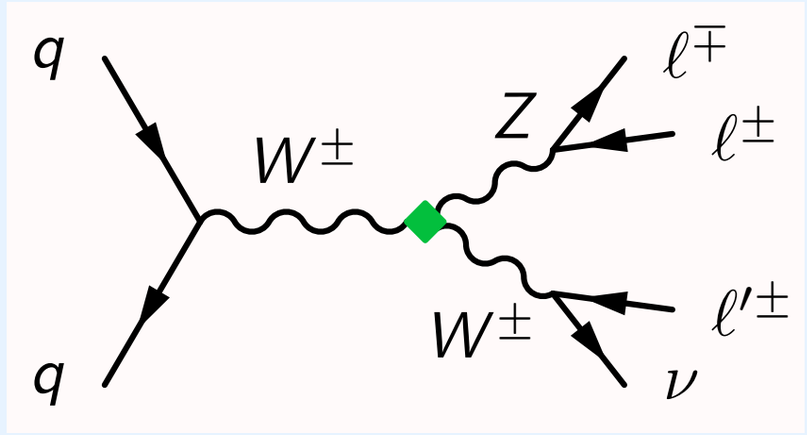
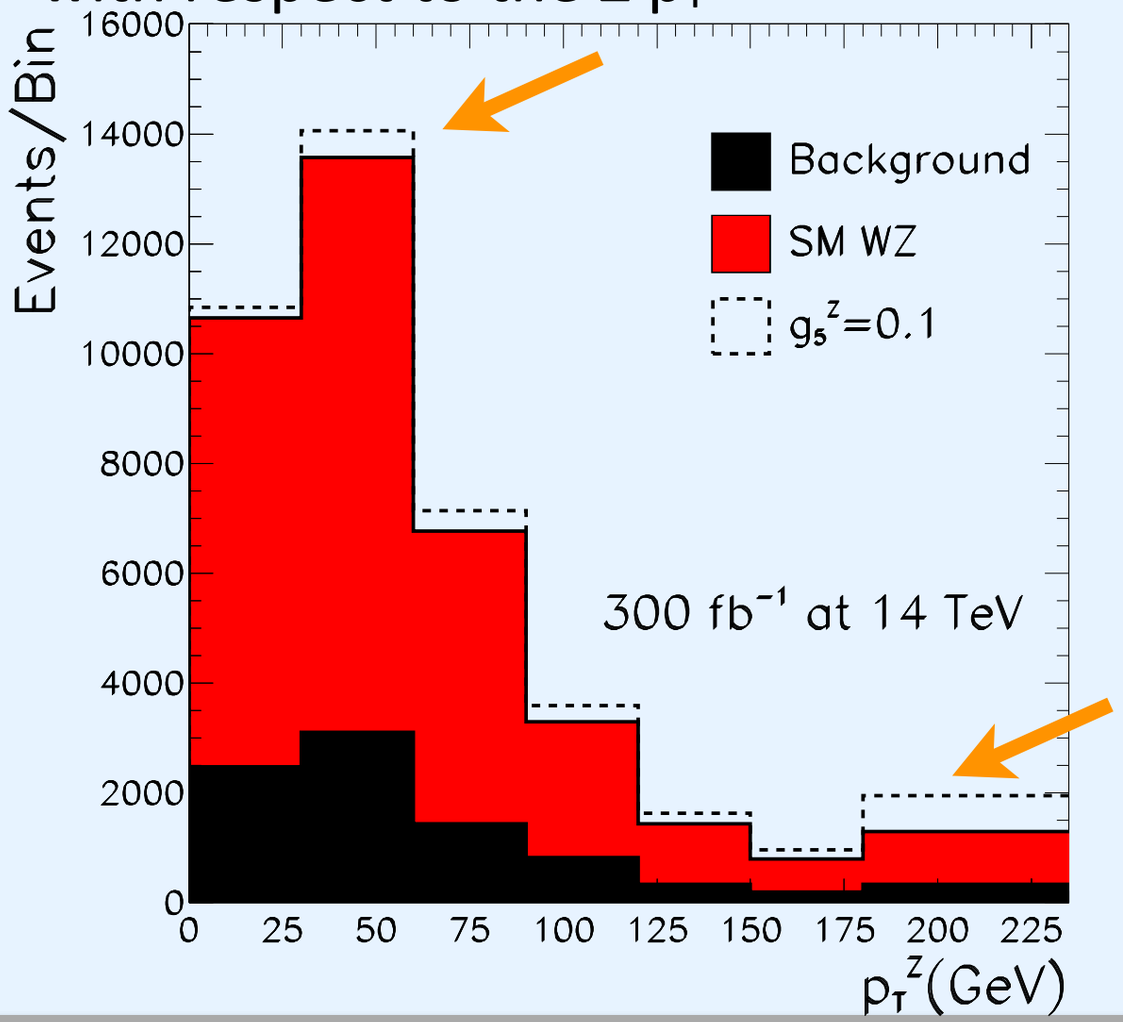


number of expected events (WZ production) with respect to the Z p_T



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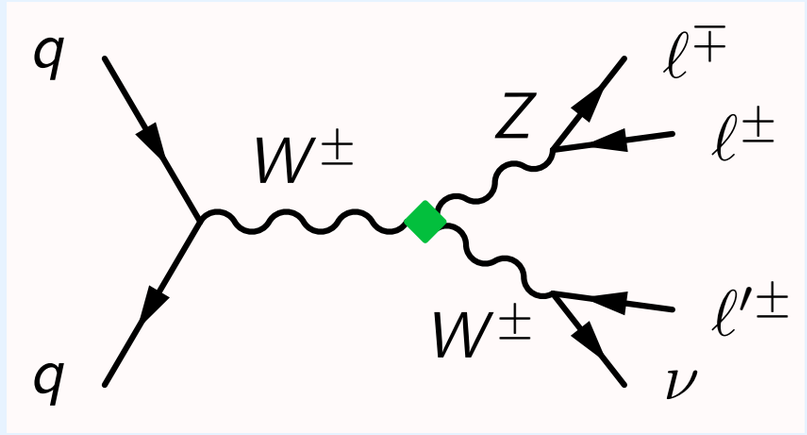

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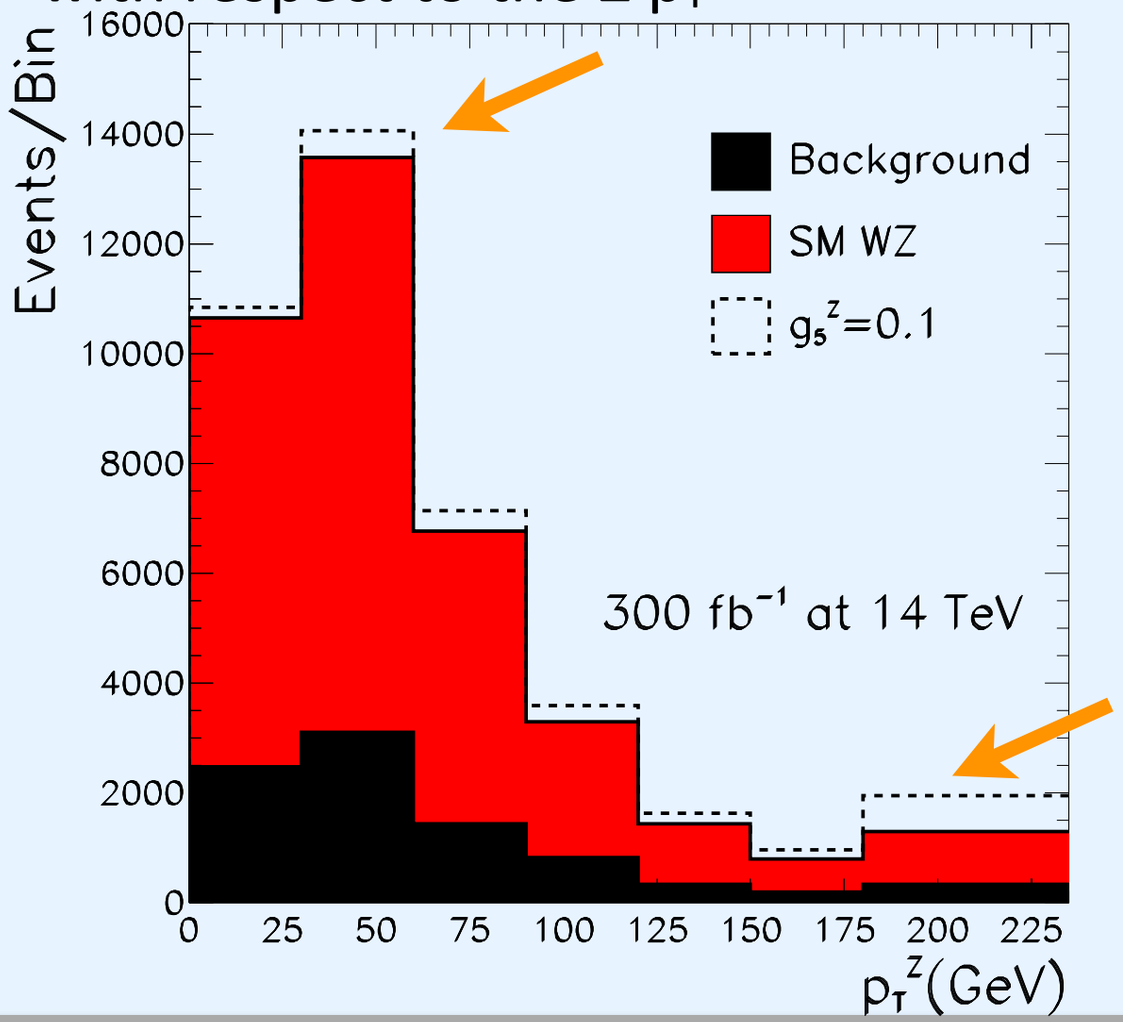


@95% CL:

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

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

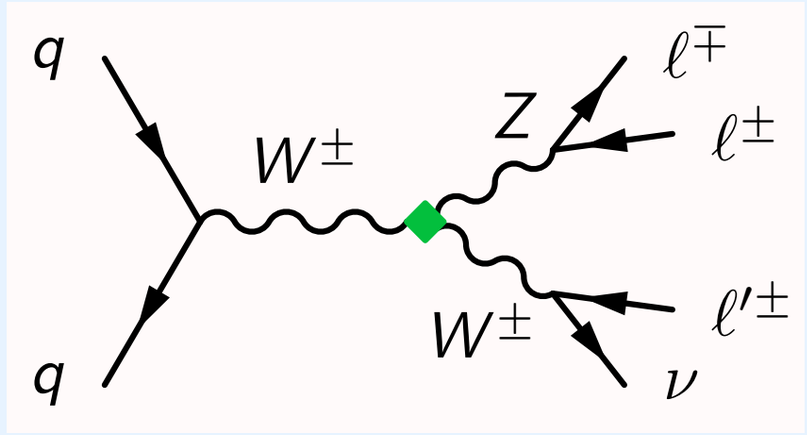
New Signals

Brivio,Corbett,Eboli,Gavela,Gonzalez-Fraile, Gonzalez-Garcia,LM&Rigolin, JHEP 1403 (2014) 024

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

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

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



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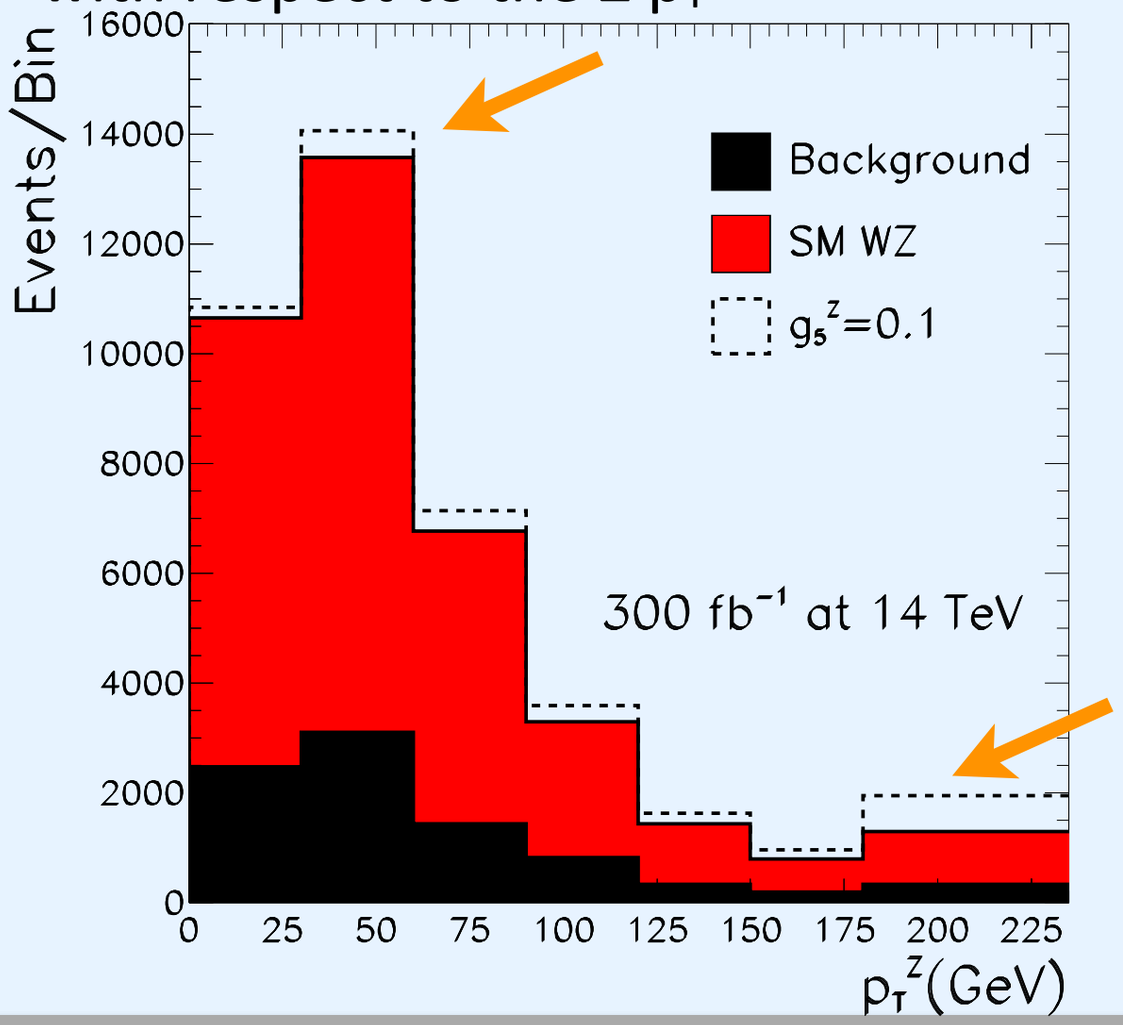

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Message to Experimental Collaborations: please, do this dedicate analysis!

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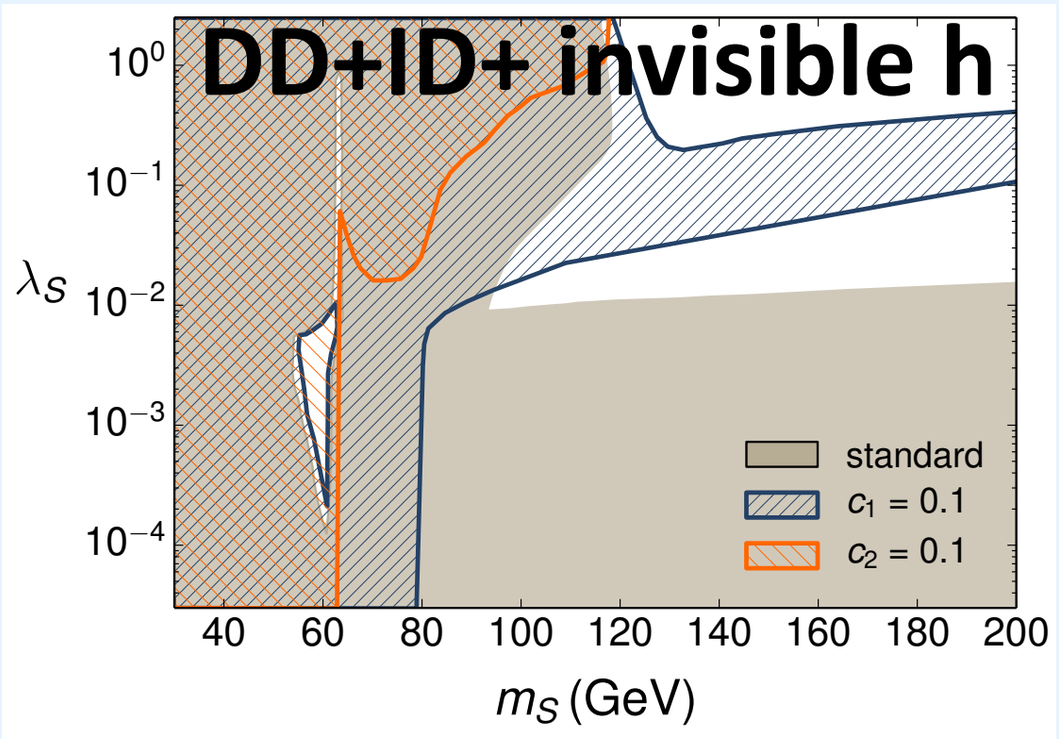
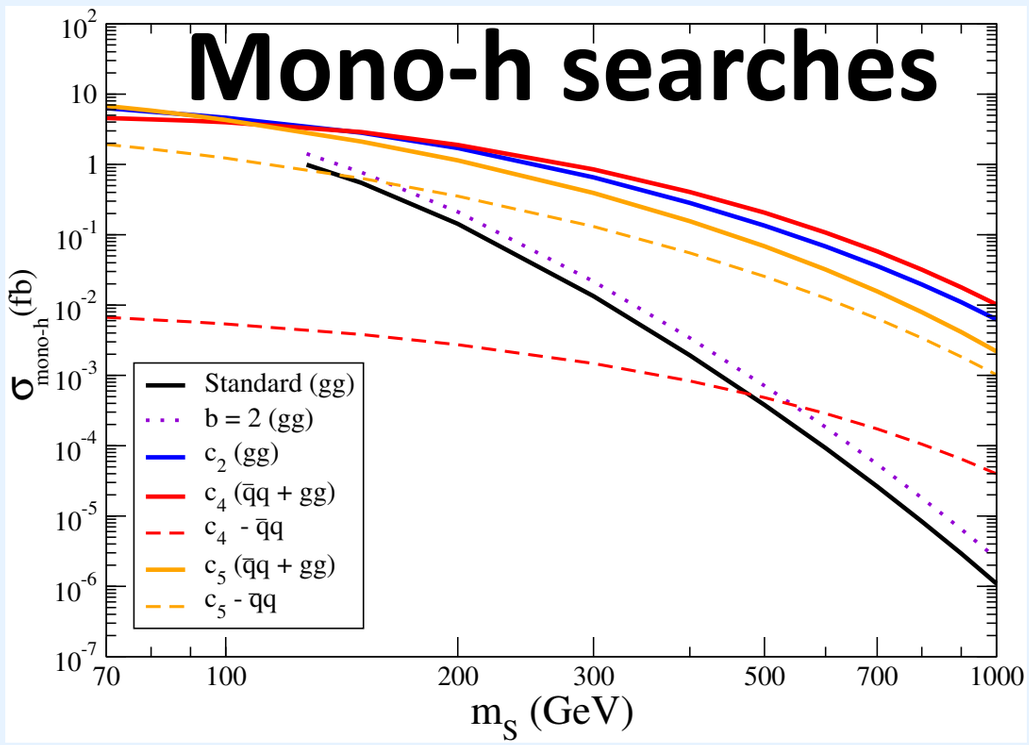
- If the Higgs is found to deviate from a pure doublet, then many other consequences: for example, the scalar DM Higgs portal!

Brivio, Gavela, LM, Mimasu, No, Rey & Sanz, JHEP 1604 (2016) 141 Rocio del Rey's talk