# Higgs Couplings at 100 TeV

Tilman Plehn

Universität Heidelberg

Higgs Couplings, October 2015

# Fundamental Higgs physics

## High scales [Lindner etal, Wetterich etal]

– Planck-scale extrapolation

$$\frac{d\,\lambda}{d\,\log Q^2} = \frac{1}{16\pi^2}\left[12\lambda^2 + 6\lambda\lambda_t^2 - 3\lambda_t^4\right]$$

– Landau pole: exploding $\lambda$ for large $Q$, small $\lambda_t$

– stability issue: sign change in $\lambda$ for large $Q$, large $\lambda_t$

– IR fixed point for $\lambda/\lambda_t^2$ fixing $m_H^2/m_t^2$ [with gravity: Shaposhnikov, Wetterich]

$$m_H = 126.3 + \frac{m_t - 171.2}{2.1} \times 4.1 - \frac{\alpha_s - 0.1176}{0.002} \times 1.5$$

# Fundamental Higgs physics

## High scales [Lindner etal, Wetterich etal]

– Planck-scale extrapolation

$$\frac{d\,\lambda}{d\,\log Q^2} = \frac{1}{16\pi^2}\left[12\lambda^2 + 6\lambda\lambda_t^2 - 3\lambda_t^4\right]$$

– Landau pole: exploding $\lambda$ for large $Q$, small $\lambda_t$

– stability issue: sign change in $\lambda$ for large $Q$, large $\lambda_t$

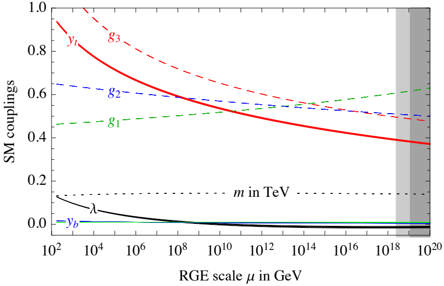
– IR fixed point for $\lambda/\lambda_t^2$ fixing $m_H^2/m_t^2$ [with gravity: Shaposhnikov, Wetterich]

$$m_H = 126.3 + \frac{m_t - 171.2}{2.1} \times 4.1 - \frac{\alpha_s - 0.1176}{0.002} \times 1.5$$

## Vacuum stability [Giudice etal; Eichhorn, Gies, Jaeckel, TP, Scherer, Sondenheimer]

– RG running of Higgs potential

– $\lambda < 0$ at $10^{10}$ GeV? [Buttazo etal]



# Fundamental Higgs physics

## High scales [Lindner etal, Wetterich etal]

– Planck-scale extrapolation

$$\frac{d\,\lambda}{d\,\log Q^2} = \frac{1}{16\pi^2}\left[12\lambda^2 + 6\lambda\lambda_t^2 - 3\lambda_t^4\right]$$

– Landau pole: exploding $\lambda$ for large $Q$, small $\lambda_t$

– stability issue: sign change in $\lambda$ for large $Q$, large $\lambda_t$

– IR fixed point for $\lambda/\lambda_t^2$ fixing $m_H^2/m_t^2$ [with gravity: Shaposhnikov, Wetterich]

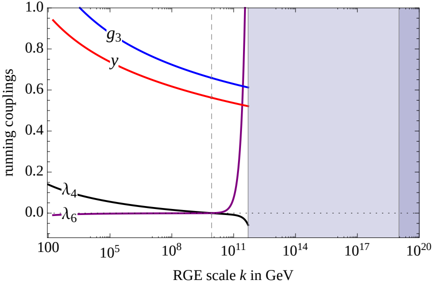
$$m_H = 126.3 + \frac{m_t - 171.2}{2.1} \times 4.1 - \frac{\alpha_s - 0.1176}{0.002} \times 1.5$$

## Vacuum stability [Giudice etal; Eichhorn, Gies, Jaeckel, TP, Scherer, Sondenheimer]

– RG running of Higgs potential

– $\lambda < 0$ at $10^{10}$ GeV? [Buttazo etal]

– new physics at $10^{11}$ GeV?



# Fundamental Higgs physics

## High scales [Lindner etal, Wetterich etal]

– Planck-scale extrapolation

$$\frac{d\,\lambda}{d\,\log Q^2} = \frac{1}{16\pi^2}\left[12\lambda^2 + 6\lambda\lambda_t^2 - 3\lambda_t^4\right]$$

– Landau pole: exploding $\lambda$ for large $Q$, small $\lambda_t$

– stability issue: sign change in $\lambda$ for large $Q$, large $\lambda_t$

– IR fixed point for $\lambda/\lambda_t^2$ fixing $m_H^2/m_t^2$ [with gravity: Shaposhnikov, Wetterich]

$$m_H = 126.3 + \frac{m_t - 171.2}{2.1} \times 4.1 - \frac{\alpha_s - 0.1176}{0.002} \times 1.5$$

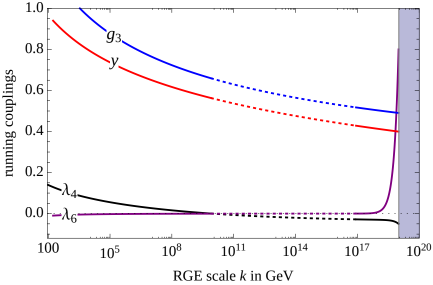
## Vacuum stability [Giudice etal; Eichhorn, Gies, Jaeckel, TP, Scherer, Sondenheimer]

– RG running of Higgs potential

– $\lambda < 0$ at $10^{10}$ GeV? [Buttazo etal]

– new physics at $10^{11}$ GeV?

– new physics at $10^{19}$ GeV?



# Fundamental Higgs physics

## High scales [Lindner etal, Wetterich etal]

– Planck-scale extrapolation

$$\frac{d\,\lambda}{d\,\log Q^2} = \frac{1}{16\pi^2}\left[12\lambda^2 + 6\lambda\lambda_t^2 - 3\lambda_t^4\right]$$

– Landau pole: exploding $\lambda$ for large $Q$, small $\lambda_t$

– stability issue: sign change in $\lambda$ for large $Q$, large $\lambda_t$

– IR fixed point for $\lambda/\lambda_t^2$ fixing $m_H^2/m_t^2$ [with gravity: Shaposhnikov, Wetterich]

$$m_H = 126.3 + \frac{m_t - 171.2}{2.1} \times 4.1 - \frac{\alpha_s - 0.1176}{0.002} \times 1.5$$

## Vacuum stability [Giudice etal; Eichhorn, Gies, Jaeckel, TP, Scherer, Sondenheimer]

– RG running of Higgs potential

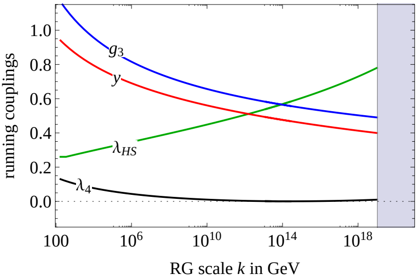
– $\lambda < 0$ at $10^{10}$ GeV? [Buttazo etal]

– new physics at $10^{11}$ GeV?

– new physics at $10^{19}$ GeV?

– TeV-scale DM portal?

$\Rightarrow$ three parameters: $\lambda, y_t, \Lambda_{NP}$



# Self-coupling at 100 TeV

## Really measure $\lambda$ [Glover & v.d.Bij; Baur etal]

- fundamental parameter for ew symmmetry breaking
- $gg \to HH$ leading production process
- rate measurement requiring $y_t$ measurement [use $m_{HH}$, $p_T$]
- $HH \to b\bar{b}\gamma\gamma$ rate-limited
  $HH \to b\bar{b}\tau\tau$ requiring excellent tagging
  $HH \to 4b$ most promising for $HH$ resonances
  $HH \to b\bar{b}WW$ not sure

$\Rightarrow$ $\pm$50% at LHC?

# Self-coupling at 100 TeV

## Really measure $\lambda$ [Glover & v.d.Bij; Baur etal]

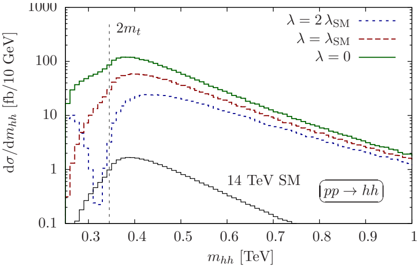
- fundamental parameter for ew symmmetry breaking
- $gg \to HH$ leading production process
- rate measurement requiring $y_t$ measurement [use $m_{HH}$, $p_T$]
- $HH \to b\bar{b}\gamma\gamma$ rate-limited
  $HH \to b\bar{b}\tau\tau$ requiring excellent tagging
  $HH \to 4b$ most promising for $HH$ resonances
  $HH \to b\bar{b}WW$ not sure

$\Rightarrow$ $\pm$50% at LHC?

## 100 TeV Collider [Barr, Dolan, Englert, Ferreira de Lima, Spanno; Azatov, Contino, Panico, Son]

- standard cuts on final state
- add $HHj$ for some improvement

$\Rightarrow$ $\pm$15% at 100 TeV



# Top Yukawa at 100 TeV

Really measure $y_t$

- much more interesting than top mass
- $t\bar{t}H$ leading production process
- $H \to b\bar{b}$ combinatorially hard
  $H \to \gamma\gamma$ rate-limited
  $H \to \tau\tau$ experimentally hard

$\Rightarrow$ $\pm$10% at LHC, neglecting theory uncertainties

# Top Yukawa at 100 TeV

## Really measure $y_t$

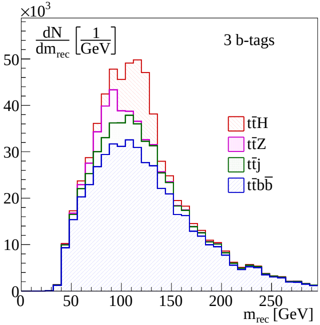
- much more interesting than top mass
- $t\bar{t}H$ leading production process
- $H \to b\bar{b}$ combinatorially hard
  $H \to \gamma\gamma$ rate-limited
  $H \to \tau\tau$ experimentally hard

$\Rightarrow$ $\pm$10% at LHC, neglecting theory uncertainties

## 100 TeV Collider [Mangano, Reimitz, TP, Schell, Shao]

- boosted $t\bar{t}H$, $H \to b\bar{b}$ [TP, Salam, Spanno]
- tagged top, Higgs [state of art taggers]
  $m_{bb}$ side band
  simultaneous fit of $Z, H$ peaks
- theory control from $\dfrac{H \to b\bar{b}}{Z \to b\bar{b}}$

$\Rightarrow$ $\pm$1% at 100 TeV



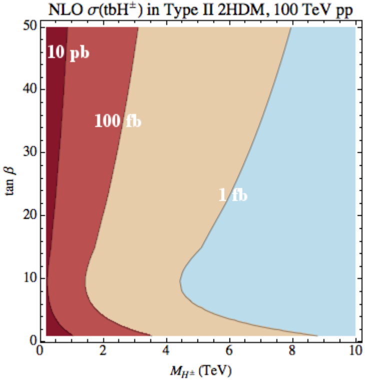
# Heavy Higgs at 100 TeV

## Additional Higgs bosons [Hajer, Ismail, Kling, Li, Liu, Su]

– new charged states
  new neutral states

– production processes known from LHC

⇒ multi-TeV range



# Kappas beyond Run I

Higgs couplings worked great at Run II

They are not sufficient for Run II

There is no updated framework worked out

# Higgs Couplings

## Standard Model operators [SFitter: Gonzalez-Fraile, Klute, TP, Rauch, Zerwas]

– Lagrangian [essentially non-linear sigma model: Buchalla etal]

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \Delta_W \; g m_W H \; W^\mu W_\mu + \Delta_Z \; \frac{g}{2c_w} m_Z H \; Z^\mu Z_\mu - \sum_{\tau,b,t} \Delta_f \; \frac{m_f}{v} H \left( \bar{f}_R f_L + \text{h.c.} \right)$$
$$+ \Delta_g F_G \; \frac{H}{v} \; G_{\mu\nu} G^{\mu\nu} + \Delta_\gamma F_A \; \frac{H}{v} \; A_{\mu\nu} A^{\mu\nu} - \Delta_3 \; \frac{m_H^2}{2v} H^3 + \text{invisible decays}$$

| $gg \to H$ <br> $qq \to qqH$ <br> $gg \to t\bar{t}H$ <br> $qq' \to VH$ | $\longleftrightarrow$ | $g_{HXX} = g_{HXX}^{\text{SM}} \; (1 + \Delta_X)$ | $\longleftrightarrow$ | $H \to ZZ$ <br> $H \to WW$ <br> $H \to b\bar{b}$ <br> $H \to \tau^+\tau^-$ <br> $H \to \gamma\gamma$ <br> $H \to \vec{p}_T$ |
|---|---|---|---|---|

# Higgs Couplings

## Standard Model operators [SFitter: Gonzalez-Fraile, Klute, TP, Rauch, Zerwas]

– Lagrangian [essentially non-linear sigma model: Buchalla etal]

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \Delta_W \; g m_W H \; W^\mu W_\mu + \Delta_Z \; \frac{g}{2c_w} m_Z H \; Z^\mu Z_\mu - \sum_{\tau,b,t} \Delta_f \; \frac{m_f}{v} H \left( \bar{f}_R f_L + \text{h.c.} \right)$$
$$+ \Delta_g F_G \; \frac{H}{v} \; G_{\mu\nu} G^{\mu\nu} + \Delta_\gamma F_A \; \frac{H}{v} \; A_{\mu\nu} A^{\mu\nu} - \Delta_3 \; \frac{m_H^2}{2v} H^3 + \text{invisible decays}$$

$$\begin{array}{|l|}\hline gg \to H \\ qq \to qqH \\ gg \to t\bar{t}H \\ qq' \to VH \\ \hline \end{array} \quad \longleftrightarrow \quad \boxed{g_{HXX} = g_{HXX}^{\rm SM} \; (1 + \Delta_X)} \quad \longleftrightarrow \quad \begin{array}{|l|}\hline H \to ZZ \\ H \to WW \\ H \to b\bar{b} \\ H \to \tau^+\tau^- \\ H \to \gamma\gamma \\ H \to \not{p}_T \\ \hline \end{array}$$

## Executive summary

– couplings fit works great [experimentally]

– offers perfect th-ex interface [Cranmer, Kreiss, Lopez-Val, TP]

(1) has issues with electroweak renormalization

(2) does not describe kinematic distributions

(3) is hard to relate to other sectors

# SFitter D6 fit

## Higgs sector effective field theory [following Corbett, Eboli, Gonzalez-Fraile, Goncales-Garcia]

– set of Higgs-gauge operators

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

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

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

$$\mathcal{O}_{\Phi,3} = \frac{1}{3} \left( \Phi^\dagger \Phi \right)^3 \qquad \mathcal{O}_{\Phi,4} = (D_\mu \Phi)^\dagger \, (D^\mu \Phi) \left( \Phi^\dagger \Phi \right)$$

– relevant part after equation of motion, etc

$$\mathcal{L}^{HVV} = - \frac{\alpha_s v}{8\pi} \frac{f_g}{\Lambda^2} \mathcal{O}_{GG} + \frac{f_{BB}}{\Lambda^2} \mathcal{O}_{BB} + \frac{f_{WW}}{\Lambda^2} \mathcal{O}_{WW} + \frac{f_B}{\Lambda^2} \mathcal{O}_{B} + \frac{f_W}{\Lambda^2} \mathcal{O}_{W} + \frac{f_{\Phi,2}}{\Lambda^2} \mathcal{O}_{\Phi,2}$$

# SFitter D6 fit

## Higgs sector effective field theory [following Corbett, Eboli, Gonzalez-Fraile, Goncales-Garcia]

– set of Higgs-gauge operators

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

$$\mathcal{O}_{\Phi,2} = \frac{1}{2} \partial^\mu \left( \Phi^\dagger \Phi \right) \partial_\mu \left( \Phi^\dagger \Phi \right) \qquad \mathcal{O}_W = (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi) \qquad \mathcal{O}_B = \cdots$$

– relevant part after equation of motion, etc

$$\mathcal{L}^{HVV} = -\frac{\alpha_s v}{8\pi} \frac{f_g}{\Lambda^2} \mathcal{O}_{GG} + \frac{f_{BB}}{\Lambda^2} \mathcal{O}_{BB} + \frac{f_{WW}}{\Lambda^2} \mathcal{O}_{WW} + \frac{f_B}{\Lambda^2} \mathcal{O}_B + \frac{f_W}{\Lambda^2} \mathcal{O}_W + \frac{f_{\Phi,2}}{\Lambda^2} \mathcal{O}_{\Phi,2}$$

– Higgs couplings to SM particles

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

# SFitter D6 fit

## Higgs sector effective field theory [following Corbett, Eboli, Gonzalez-Fraile, Goncales-Garcia]

– set of Higgs-gauge operators

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

$$\mathcal{O}_{\Phi,2} = \frac{1}{2} \partial^\mu \left( \Phi^\dagger \Phi \right) \partial_\mu \left( \Phi^\dagger \Phi \right) \qquad \mathcal{O}_W = (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi) \qquad \mathcal{O}_B = \cdots$$

– relevant part after equation of motion, etc

$$\mathcal{L}^{HVV} = - \frac{\alpha_s v}{8\pi} \frac{f_g}{\Lambda^2} \mathcal{O}_{GG} + \frac{f_{BB}}{\Lambda^2} \mathcal{O}_{BB} + \frac{f_{WW}}{\Lambda^2} \mathcal{O}_{WW} + \frac{f_B}{\Lambda^2} \mathcal{O}_B + \frac{f_W}{\Lambda^2} \mathcal{O}_W + \frac{f_{\Phi,2}}{\Lambda^2} \mathcal{O}_{\Phi,2}$$

– Higgs couplings to SM particles

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

– plus Yukawa structure $f_{\tau,b,t}$

# SFitter D6 fit

## Higgs sector effective field theory [following Corbett, Eboli, Gonzalez-Fraile, Goncales-Garcia]

– set of Higgs-gauge operators

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

$$\mathcal{O}_{\Phi,2} = \frac{1}{2} \partial^\mu \left( \Phi^\dagger \Phi \right) \partial_\mu \left( \Phi^\dagger \Phi \right) \qquad \mathcal{O}_W = (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi) \qquad \mathcal{O}_B = \cdots$$

– relevant part after equation of motion, etc

$$\mathcal{L}^{HVV} = - \frac{\alpha_s v}{8\pi} \frac{f_g}{\Lambda^2} \mathcal{O}_{GG} + \frac{f_{BB}}{\Lambda^2} \mathcal{O}_{BB} + \frac{f_{WW}}{\Lambda^2} \mathcal{O}_{WW} + \frac{f_B}{\Lambda^2} \mathcal{O}_B + \frac{f_W}{\Lambda^2} \mathcal{O}_W + \frac{f_{\Phi,2}}{\Lambda^2} \mathcal{O}_{\Phi,2}$$

– Higgs couplings to SM particles

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

– plus Yukawa structure $f_{\tau,b,t}$

– 7 EFT couplings identical to $\Delta_x$, suppressed by $v^2/\Lambda^2$ [with $\Delta_W = \Delta_Z$]
  4 EFT couplings $g^{(1,2)}_{W,Z}$ in addition, suppressed by $\partial/\Lambda$

⇒ natural extension of $\Delta_j$

# SFitter D6 fit

## Higgs sector effective field theory [following Corbett, Eboli, Gonzalez-Fraile, Goncales-Garcia]

– set of Higgs-gauge operators

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

$$\mathcal{O}_{\Phi,2} = \frac{1}{2} \partial^\mu \left( \Phi^\dagger \Phi \right) \partial_\mu \left( \Phi^\dagger \Phi \right) \qquad \mathcal{O}_W = (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi) \qquad \mathcal{O}_B = \cdots$$

– relevant part after equation of motion, etc

$$\mathcal{L}^{HVV} = -\frac{\alpha_s v}{8\pi} \frac{f_g}{\Lambda^2} \mathcal{O}_{GG} + \frac{f_{BB}}{\Lambda^2} \mathcal{O}_{BB} + \frac{f_{WW}}{\Lambda^2} \mathcal{O}_{WW} + \frac{f_B}{\Lambda^2} \mathcal{O}_B + \frac{f_W}{\Lambda^2} \mathcal{O}_W + \frac{f_{\Phi,2}}{\Lambda^2} \mathcal{O}_{\Phi,2}$$

## SFitter analysis [Corbett, Eboli, Goncalves, Gonzalez-Fraile, TP, Rauch]

– setup and data identical to SFitter $\Delta_x$ fit

– ew-renormalizable: #1

– including $p_{T,V}, \Delta\Phi_{jj}$: #2

– TGVs for $\mathcal{O}_{B,W}$: #3

# SFitter D6 fit

## Higgs sector effective field theory [following Corbett, Eboli, Gonzalez-Fraile, Goncales-Garcia]

– set of Higgs-gauge operators

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

$$\mathcal{O}_{\Phi,2} = \frac{1}{2} \partial^\mu \left( \Phi^\dagger \Phi \right) \partial_\mu \left( \Phi^\dagger \Phi \right) \qquad \mathcal{O}_W = (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi) \qquad \mathcal{O}_B = \cdots$$

– relevant part after equation of motion, etc

$$\mathcal{L}^{HVV} = -\frac{\alpha_s v}{8\pi} \frac{f_g}{\Lambda^2} \mathcal{O}_{GG} + \frac{f_{BB}}{\Lambda^2} \mathcal{O}_{BB} + \frac{f_{WW}}{\Lambda^2} \mathcal{O}_{WW} + \frac{f_B}{\Lambda^2} \mathcal{O}_B + \frac{f_W}{\Lambda^2} \mathcal{O}_W + \frac{f_{\Phi,2}}{\Lambda^2} \mathcal{O}_{\Phi,2}$$

## SFitter analysis [Corbett, Eboli, Goncalves, Gonzalez-Fraile, TP, Rauch]

– setup and data identical to SFitter $\Delta_x$ fit

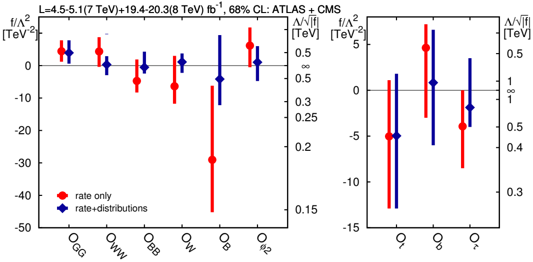
– ew-renormalizable: #1

– including $p_{T,V}, \Delta\Phi_{jj}$: #2

– TGVs for $\mathcal{O}_{B,W}$: #3

(1) D6 fit works

(2) D6 is not EFT



# Limitations of D6 description

## D6 vs EFT breakdown [Brehmer, Freitas, Lopez-Val, TP]

– phenomenology: does D6 capture all model features at LHC?
theory: how do D6 vs EFT differences appear?

# Limitations of D6 description

## D6 vs EFT breakdown [Brehmer, Freitas, Lopez-Val, TP]

– phenomenology: does D6 capture all model features at LHC?
  theory: how do D6 vs EFT differences appear?

– push models to visible deviations at 13 TeV
  Higgs portal, 2HDM, stops, vector triplet [weakly interacting, Knochel etal]

$$\left| \frac{\sigma \times \text{BR}}{(\sigma \times \text{BR})_{\text{SM}}} - 1 \right| = \frac{g^2 m_h^2}{\Lambda^2} \gtrsim 0.1 \qquad \Leftrightarrow \qquad \Lambda \lesssim 280~\text{GeV}$$

# Limitations of D6 description

## D6 vs EFT breakdown [Brehmer, Freitas, Lopez-Val, TP]

– phenomenology: does D6 capture all model features at LHC?
  theory: how do D6 vs EFT differences appear?

– push models to visible deviations at 13 TeV
  Higgs portal, 2HDM, stops, vector triplet [weakly interacting, Knochel etal]

$$\left| \frac{\sigma \times \text{BR}}{(\sigma \times \text{BR})_\text{SM}} - 1 \right| = \frac{g^2 m_h^2}{\Lambda^2} \gtrsim 0.1 \qquad \Leftrightarrow \qquad \Lambda \lesssim 280 \text{ GeV}$$

– construct and match EFT to D6
  coupling modifications $v^2/\Lambda^2$ vs new structures $\partial/\Lambda$?
  matching conditions with $v \lesssim \Lambda$?

# Limitations of D6 description

## D6 vs EFT breakdown [Brehmer, Freitas, Lopez-Val, TP]

- phenomenology: does D6 capture all model features at LHC?
  theory: how do D6 vs EFT differences appear?
- push models to visible deviations at 13 TeV
  Higgs portal, 2HDM, stops, vector triplet [weakly interacting, Knochel etal]

$$\left| \frac{\sigma \times \text{BR}}{(\sigma \times \text{BR})_\text{SM}} - 1 \right| = \frac{g^2 m_h^2}{\Lambda^2} \gtrsim 0.1 \qquad \Leftrightarrow \qquad \Lambda \lesssim 280 \text{ GeV}$$

- construct and match EFT to D6
  coupling modifications $v^2/\Lambda^2$ vs new structures $\partial/\Lambda$?
  matching conditions with $v \lesssim \Lambda$?
- compare LHC simulations: model vs D6
  production: WBF, $VH$, $HH$
  decays: $H \to \gamma\gamma, 4\ell$
- check where differences D6 vs EFT appear

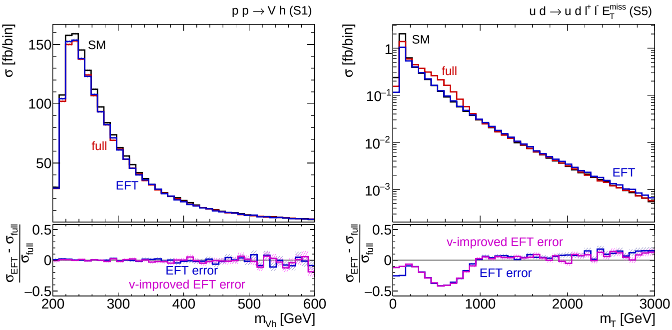
# Limitations of D6 description

## Higgs portal

– testable benchmarks for LHC

| Singlet | | | | EFT | | | EFT ($v$-improved) | |
|---|---|---|---|---|---|---|---|---|
| $m_H$ | $\sin\alpha$ | $v_s/v$ | $\Delta_x^{\text{singlet}}$ | $\Lambda$ | $\bar{c}_H$ | $\Delta_x^{\text{EFT}}$ | $\bar{c}_H$ | $\Delta_x^{\text{EFT}}$ |
| 500 | 0.2 | 10 | −0.020 | 491 | 0.036 | −0.018 | 0.040 | −0.020 |
| 350 | 0.3 | 10 | −0.046 | 336 | 0.073 | −0.037 | 0.092 | −0.046 |
| 200 | 0.4 | 10 | −0.083 | 190 | 0.061 | −0.031 | 0.167 | −0.083 |
| 1000 | 0.4 | 10 | −0.083 | 918 | 0.183 | −0.092 | 0.167 | −0.092 |
| 500 | 0.6 | 10 | −0.200 | 407 | 0.461 | −0.231 | 0.400 | −0.200 |

– LHC effects in $Vh$ and WBF production



# Limitations of D6 description

## Higgs portal

- testable benchmarks for LHC
- LHC effects in *Vh* and WBF production

## 2HDM

- testable benchmarks for LHC

| 2HDM | | | | | | | EFT | | |
|---|---|---|---|---|---|---|---|---|---|
| Type | $\tan\beta$ | $\alpha/\pi$ | $m_{12}$ | $m_{H^0}$ | $m_{A^0}$ | $m_{H^\pm}$ | $\lvert\Lambda\rvert$ [GeV] | $\bar{c}_u$ | $\bar{c}_{d,\ell}$ |
| I | 1.5 | −0.086 | 45 | 230 | 300 | 350 | 100 | −0.744 | −0.744 |
| II | 15 | −0.023 | 116 | 449 | 450 | 457 | 448 | 0.000 | 0.065 |
| II | 10 | 0.032 | 157 | 500 | 500 | 500 | 99 | 0.465 | −46.5 |
| I | 20 | 0 | 45 | 200 | 500 | 500 | 142 | 0.003 | 0.003 |

Higgs Fits

Tilman Plehn

100 TeV

Rant

D6 fit

D6 limitations

# Limitations of D6 description

## Higgs portal

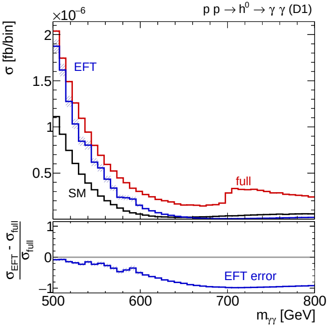
- testable benchmarks for LHC
- LHC effects in *Vh* and WBF production

## 2HDM

- testable benchmarks for LHC

| 2HDM | | | | | | | EFT | | |
|---|---|---|---|---|---|---|---|---|---|
| Type | $\tan\beta$ | $\alpha/\pi$ | $m_{12}$ | $m_{H^0}$ | $m_{A^0}$ | $m_{H^\pm}$ | $\lvert\Lambda\rvert$ [GeV] | $\bar{c}_u$ | $\bar{c}_{d,\ell}$ |
| I | 1.5 | $-0.086$ | 45 | 230 | 300 | 350 | 100 | $-0.744$ | $-0.744$ |
| II | 15 | $-0.023$ | 116 | 449 | 450 | 457 | 448 | 0.000 | 0.065 |
| II | 10 | 0.032 | 157 | 500 | 500 | 500 | 99 | 0.465 | $-46.5$ |
| I | 20 | 0 | 45 | 200 | 500 | 500 | [illegible] | [illegible] | [illegible] |

- LHC effects in $H \to \gamma\gamma$



# Limitations of D6 description

## Higgs portal

– testable benchmarks for LHC
– LHC effects in $Vh$ and WBF production

## 2HDM

– testable benchmarks for LHC
– LHC effects in $H \to \gamma\gamma$

## Top partners

– testable benchmarks for LHC

| Scalar top-partner model | | | | | | EFT | | |
|---|---|---|---|---|---|---|---|---|
| $M$ | $\kappa_{LL}$ | $\kappa_{RR}$ | $\kappa_{LR}$ | $m_{\tilde{t}_1}$ | $m_{\tilde{t}_2}$ | $\bar{c}_H$ | $\bar{c}_W$ | $\bar{c}_{HW}$ |
| 500 | $-1.16$ | 2.85 | 0.147 | 500 | 580 | $6.22 \cdot 10^{-3}$ | $-3.11 \cdot 10^{-7}$ | $3.99 \cdot 10^{-7}$ |
| 350 | $-3.16$ | $-2.82$ | 0.017 | 173 | 200 | $4.30 \cdot 10^{-3}$ | $-2.55 \cdot 10^{-4}$ | $2.55 \cdot 10^{-4}$ |
| 500 | $-7.51$ | $-7.17$ | 0.012 | 173 | 200 | $1.66 \cdot 10^{-2}$ | $-2.97 \cdot 10^{-4}$ | $2.97 \cdot 10^{-4}$ |

# Limitations of D6 description

## Higgs portal

- testable benchmarks for LHC
- LHC effects in $Vh$ and WBF production

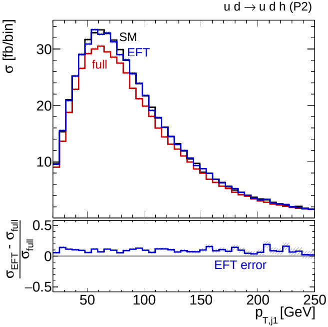
## 2HDM

- testable benchmarks for LHC
- LHC effects in $H \to \gamma\gamma$

## Top partners

- testable benchmarks for LHC

| Scalar top-partner model | | | | | | EFT |
|---|---|---|---|---|---|---|
| $M$ | $\kappa_{LL}$ | $\kappa_{RR}$ | $\kappa_{LR}$ | $m_{\tilde{t}_1}$ | $m_{\tilde{t}_2}$ | |
| 500 | −1.16 | 2.85 | 0.147 | 500 | 580 | 6.22 |
| 350 | −3.16 | −2.82 | 0.017 | 173 | 200 | 4.30 |
| 500 | −7.51 | −7.17 | 0.012 | 173 | 200 | 1.66 |




- LHC effects in WBF

# Limitations of D6 description

## Higgs portal

- testable benchmarks for LHC
- LHC effects in $Vh$ and WBF production

## 2HDM

- testable benchmarks for LHC
- LHC effects in $H \to \gamma\gamma$

## Top partners

- testable benchmarks for LHC
- LHC effects in WBF

## Vector triplet

- testable benchmarks for LHC

| Triplet model | | | | | | EFT | | | |
|---|---|---|---|---|---|---|---|---|---|
| $M_V$ | $g_V$ | $c_H$ | $c_F$ | $c_{VVHH}$ | $m_\xi$ | $\bar{c}_W$ | $\bar{c}_H$ | $\bar{c}_6$ | $\bar{c}_f$ |
| 591 | 3.0 | −0.47 | −5.0 | 2.0 | 1200 | −0.044 | 0.000 | 0.000 | 0.000 |
| 946 | 3.0 | −0.47 | −5.0 | 1.0 | 1200 | −0.017 | 0.000 | 0.000 | 0.000 |
| 941 | 3.0 | −0.28 | 3.0 | 1.0 | 1200 | 0.006 | 0.075 | 0.100 | 0.025 |
| 1246 | 3.0 | −0.50 | 3.0 | −0.2 | 1200 | 0.006 | 0.103 | 0.138 | 0.034 |
| 846 | 1.0 | −0.56 | −1.32 | 0.08 | 849 | −0.007 | −0.020 | −0.027 | −0.007 |

$\Rightarrow$ nothing dramatic except for resonances

# Limitations of D6 description

## Higgs portal

- testable benchmarks for LHC
- LHC effects in *Vh* and WBF production

## 2HDM

- testable benchmarks for LHC
- LHC effects in $H \to \gamma\gamma$

## Top partners

- testable benchmarks for LHC
- LHC effects in WBF

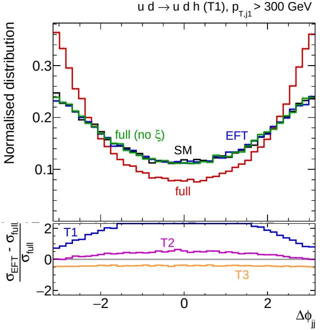
## Vector triplet

- testable benchmarks for LHC

Triplet model

| $M_V$ | $g_V$ | $c_H$ | $c_F$ | $c_{VVHH}$ | $m_\xi$ |
|---|---|---|---|---|---|
| 591 | 3.0 | −0.47 | −5.0 | 2.0 | 1200 |
| 946 | 3.0 | −0.47 | −5.0 | 1.0 | 1200 |
| 941 | 3.0 | −0.28 | 3.0 | 1.0 | 1200 |
| 1246 | 3.0 | −0.50 | 3.0 | −0.2 | 1200 |
| 846 | 1.0 | −0.56 | −1.32 | 0.08 | 849 |

- LHC effects in WBF



# Limitations of D6 description

## Higgs portal

– testable benchmarks for LHC

– LHC effects in *Vh* and WBF production

## 2HDM

– testable benchmarks for LHC

– LHC effects in $H \to \gamma\gamma$

## Top partners

– testable benchmarks for LHC

– LHC effects in WBF

## Vector triplet

– testable benchmarks for LHC

– LHC effects in WBF

$\Rightarrow$ nothing dramatic except for resonances

# Limitations of D6 description

| Model | Process | EFT failure | | |
|---|---|---|---|---|
| | | resonance | kinematics | matching |
| singlet | on-shell $h \to 4\ell$, WBF, *Vh*, ... | | | $\times$ |
| | off-shell WBF, ... | | $(\times)$ | $\times$ |
| | *hh* | $\times$ | $\times$ | $\times$ |
| 2HDM | on-shell $h \to 4\ell$, WBF, *Vh*, ... | | | $\times$ |
| | off-shell $H \to \gamma\gamma$, ... | | $(\times)$ | $\times$ |
| | *hh* | $\times$ | $\times$ | $\times$ |
| top partner | WBF, *Vh* | | | $\times$ |
| vector triplet | WBF | | $(\times)$ | $\times$ |
| | *Vh* | $\times$ | $(\times)$ | $\times$ |

# Higgs couplings at Run II

## D6 Higgs operator fit

– works very well [we did the fit]
  includes $\Delta_x$ as $v^2/\Lambda^2$
  describes distributions though $\partial/\Lambda$
– is easy to simulate through MC [we did it]
  Rosetta to avoid basis choice
– only breaks down in theory land [we tested it]
– can be interpreted in terms of EFT

## Laundry list

– check how non-linear realization works
– combine with triple gauge boson vertices [following Dieter]
– check what we miss without D8 [custodial symmetry]
– anything else?