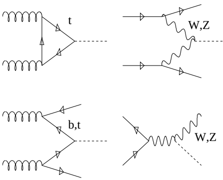
The Higgs Bottom Line of Run II

Tilman Plehn

Universität Heidelberg

Lund, October 2019

1– Higgs couplings



How the LHC became a precision Higgs machine

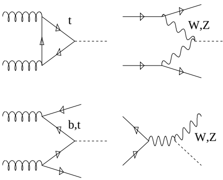
– assume: narrow *CP*-even scalar
  Standard Model operators

– Lagrangian like non-linear symmetry breaking

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

$$\boxed{\begin{array}{l} gg \to H \\ gg \to H+j \quad \text{(boosted)} \\ gg \to H^* \quad \text{(off-shell)} \\ qq \to qqH \\ gg \to t\bar{t}H \\ qq' \to VH \end{array}} \quad \longleftrightarrow \quad \boxed{g_{HXX} = g_{HXX}^{\rm SM} \; (1 + \Delta_X)} \quad \longleftrightarrow \quad \boxed{\begin{array}{l} H \to ZZ \\ H \to WW \\ H \to b\bar{b} \\ H \to \tau^+\tau^- \\ H \to \gamma\gamma \\ H \to \text{invisible} \end{array}}$$

1– Higgs couplings



How the LHC became a precision Higgs machine

– assume: narrow *CP*-even scalar
  Standard Model operators

– Lagrangian like non-linear symmetry breaking

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

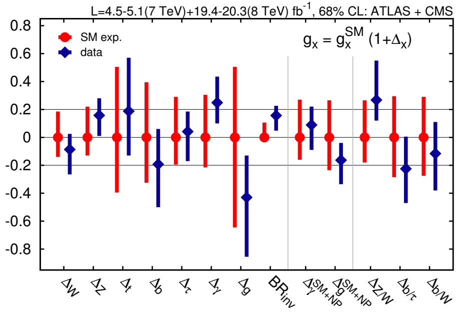
Brilliant Run I analyses, but issues...

[Corbett, Eboli, Goncalves, Gonzalez-Fraile, TP, Rauch (2015)]

1 renormalizability broken

2 total rates only

3 hard to extend to full SM



2– Effective Higgs operators

D6 Lagrangian [SMEFT; review Brivio & Trott]

– set of Higgs operators [renormalizable, #1 solved]

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

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

$$\mathcal{O}_{\phi,1} = (D_\mu \phi)^\dagger \phi \, \phi^\dagger \left(D^\mu \phi\right) \qquad \mathcal{O}_{\phi,2} = \frac{1}{2} \partial^\mu \left(\phi^\dagger \phi\right) \partial_\mu \left(\phi^\dagger \phi\right) \qquad \mathcal{O}_{\phi,3} = \frac{1}{3} \left(\phi^\dagger \phi\right)^3$$

2– Effective Higgs operators

D6 Lagrangian [SMEFT; review Brivio & Trott]

– set of Higgs operators [renormalizable, #1 solved]

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

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

$$\mathcal{O}_{\phi,1} = (D_\mu \phi)^\dagger \phi \, \phi^\dagger \, (D^\mu \phi) \qquad \mathcal{O}_{\phi,2} = \frac{1}{2} \partial^\mu \left(\phi^\dagger \phi\right) \partial_\mu \left(\phi^\dagger \phi\right) \qquad \mathcal{O}_{\phi,3} = \frac{1}{3} \left(\phi^\dagger \phi\right)^3$$

– actual basis after equation of motion, field re-definition, integration by parts

$$\mathcal{L}_{\text{D6}} = -\frac{\alpha_s v}{8\pi} \frac{f_g}{\Lambda^2} \mathcal{O}_{GG} + \frac{f_{BB}}{\Lambda^2} \mathcal{O}_{BB} + \frac{f_{WW}}{\Lambda^2} \mathcal{O}_{WW} + \frac{f_B}{\Lambda^2} \mathcal{O}_B + \frac{f_W}{\Lambda^2} \mathcal{O}_W + \frac{f_{\phi,2}}{\Lambda^2} \mathcal{O}_{\phi,2}$$

2– Effective Higgs operators

D6 Lagrangian [SMEFT; review Brivio & Trott]

– set of Higgs operators [renormalizable, #1 solved]

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

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

$$\mathcal{O}_{\phi,1} = (D_\mu \phi)^\dagger \, \phi \, \phi^\dagger \, (D^\mu \phi) \qquad \mathcal{O}_{\phi,2} = \frac{1}{2} \partial^\mu \left(\phi^\dagger \phi\right) \partial_\mu \left(\phi^\dagger \phi\right) \qquad \mathcal{O}_{\phi,3} = \frac{1}{3} \left(\phi^\dagger \phi\right)^3$$

– actual basis after equation of motion, field re-definition, integration by parts

$$\mathcal{L}_{\text{D6}} = -\frac{\alpha_s v}{8\pi} \frac{f_g}{\Lambda^2} \mathcal{O}_{GG} + \frac{f_{BB}}{\Lambda^2} \mathcal{O}_{BB} + \frac{f_{WW}}{\Lambda^2} \mathcal{O}_{WW} + \frac{f_B}{\Lambda^2} \mathcal{O}_B + \frac{f_W}{\Lambda^2} \mathcal{O}_W + \frac{f_{\phi,2}}{\Lambda^2} \mathcal{O}_{\phi,2}$$

– Higgs couplings to SM particles [derivatives = momentum, #2 solved]

$$\begin{aligned}\mathcal{L}_{\text{D6}} &= g_g \; H G^a_{\mu\nu} G^{a\mu\nu} + g_\gamma \; H A_{\mu\nu} A^{\mu\nu} \\ &\quad + g_Z^{(1)} \; Z_{\mu\nu} Z^\mu \partial^\nu H + g_Z^{(2)} \; H Z_{\mu\nu} Z^{\mu\nu} + g_Z^{(3)} \; H Z_\mu Z^\mu \\ &\quad + g_W^{(1)} \; \left(W^+_{\mu\nu} W^{-\,\mu} \partial^\nu H + \text{h.c.} \right) + g_W^{(2)} \; H W^+_{\mu\nu} W^{-\,\mu\nu} + g_W^{(3)} \; H W^+_\mu W^{-\,\mu} + \cdots\end{aligned}$$

2– Effective Higgs operators

D6 Lagrangian [SMEFT; review Brivio & Trott]

– set of Higgs operators [renormalizable, #1 solved]

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

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

$$\mathcal{O}_{\phi,1} = (D_\mu \phi)^\dagger \, \phi \, \phi^\dagger \, (D^\mu \phi) \qquad \mathcal{O}_{\phi,2} = \frac{1}{2} \partial^\mu \left(\phi^\dagger \phi\right) \partial_\mu \left(\phi^\dagger \phi\right) \qquad \mathcal{O}_{\phi,3} = \frac{1}{3} \left(\phi^\dagger \phi\right)^3$$

– actual basis after equation of motion, field re-definition, integration by parts

$$\mathcal{L}_{\text{D6}} = - \frac{\alpha_s v}{8\pi} \frac{f_g}{\Lambda^2} \mathcal{O}_{GG} + \frac{f_{BB}}{\Lambda^2} \mathcal{O}_{BB} + \frac{f_{WW}}{\Lambda^2} \mathcal{O}_{WW} + \frac{f_B}{\Lambda^2} \mathcal{O}_B + \frac{f_W}{\Lambda^2} \mathcal{O}_W + \frac{f_{\phi,2}}{\Lambda^2} \mathcal{O}_{\phi,2}$$

– Higgs couplings to SM particles [derivatives = momentum, #2 solved]

$$\begin{aligned} \mathcal{L}_{\text{D6}} &= g_g \; H G^a_{\mu\nu} G^{a\mu\nu} + g_\gamma \; H A_{\mu\nu} A^{\mu\nu} \\ &+ g_Z^{(1)} \; Z_{\mu\nu} Z^\mu \partial^\nu H + g_Z^{(2)} \; H Z_{\mu\nu} Z^{\mu\nu} + g_Z^{(3)} \; H Z_\mu Z^\mu \\ &+ g_W^{(1)} \; \left(W^+_{\mu\nu} W^{-\,\mu} \partial^\nu H + \text{h.c.} \right) + g_W^{(2)} \; H W^+_{\mu\nu} W^{-\,\mu\nu} + g_W^{(3)} \; H W^+_\mu W^{-\,\mu} + \cdots \end{aligned}$$

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

– 7 Δ-like coupling modifications plus 4 new Lorentz structures

2– Effective Higgs operators

D6 Lagrangian [SMEFT; review Brivio & Trott]

– set of Higgs operators [renormalizable, #1 solved]

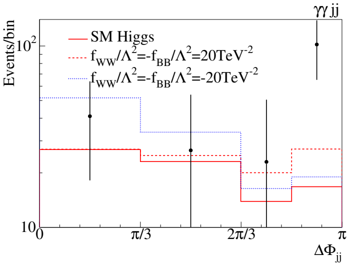
$$\mathcal{O}_{GG} = \phi^\dagger \phi G^a_{\mu\nu} G^{a\mu\nu} \qquad \mathcal{O}_{WW} = \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi \qquad \mathcal{O}_{BB} = \cdots$$

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

$$\mathcal{O}_{\phi,1} = (D_\mu \phi)^\dagger \phi \, \phi^\dagger \, (D^\mu \phi) \qquad \mathcal{O}_{\phi,2} = \frac{1}{2} \partial^\mu \left(\phi^\dagger \phi\right) \partial_\mu \left(\phi^\dagger \phi\right) \qquad \mathcal{O}_{\phi,3} = \frac{1}{3} \left(\phi^\dagger \phi\right)^3$$

Improved Run I legacy [Corbett, Eboli, Goncalves, Gonzalez-Fraile, TP, Rauch (2015)]

– kinematics: $p_{T,V}, \Delta\phi_{jj}$ [#2 solved]



2– Effective Higgs operators

D6 Lagrangian [SMEFT; review Brivio & Trott]

– set of Higgs operators [renormalizable, #1 solved]

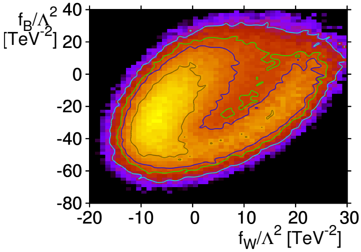
$$\mathcal{O}_{GG} = \phi^\dagger \phi G^a_{\mu\nu} G^{a\mu\nu} \qquad \mathcal{O}_{WW} = \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi \qquad \mathcal{O}_{BB} = \cdots$$

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

$$\mathcal{O}_{\phi,1} = (D_\mu \phi)^\dagger \phi \, \phi^\dagger \left(D^\mu \phi\right) \qquad \mathcal{O}_{\phi,2} = \frac{1}{2} \partial^\mu \left(\phi^\dagger \phi\right) \partial_\mu \left(\phi^\dagger \phi\right) \qquad \mathcal{O}_{\phi,3} = \frac{1}{3} \left(\phi^\dagger \phi\right)^3$$

Improved Run I legacy [Corbett, Eboli, Goncalves, Gonzalez-Fraile, TP, Rauch (2015)]

– kinematics: $p_{T,V}, \Delta\phi_{jj}$ [#2 solved]



2– Effective Higgs operators

D6 Lagrangian [SMEFT; review Brivio & Trott]

– set of Higgs operators [renormalizable, #1 solved]

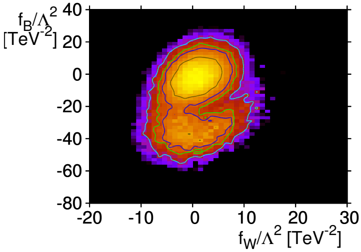
$$\mathcal{O}_{GG} = \phi^\dagger \phi G^a_{\mu\nu} G^{a\mu\nu} \qquad \mathcal{O}_{WW} = \phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \phi \qquad \mathcal{O}_{BB} = \cdots$$

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

$$\mathcal{O}_{\phi,1} = (D_\mu \phi)^\dagger \phi \, \phi^\dagger \left(D^\mu \phi\right) \qquad \mathcal{O}_{\phi,2} = \frac{1}{2} \partial^\mu \left(\phi^\dagger \phi\right) \partial_\mu \left(\phi^\dagger \phi\right) \qquad \mathcal{O}_{\phi,3} = \frac{1}{3} \left(\phi^\dagger \phi\right)^3$$

Improved Run I legacy [Corbett, Eboli, Goncalves, Gonzalez-Fraile, TP, Rauch (2015)]

– kinematics: $p_{T,V}, \Delta\phi_{jj}$ [#2 solved]



2– Effective Higgs operators

D6 Lagrangian [SMEFT; review Brivio & Trott]

– set of Higgs operators [renormalizable, #1 solved]

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

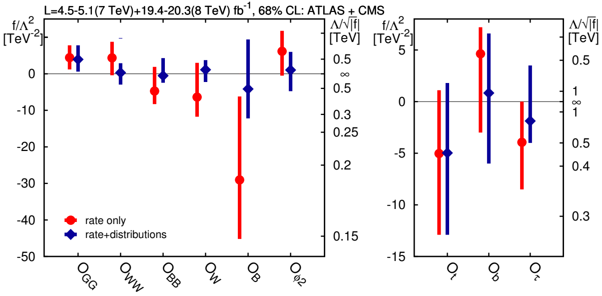
$$\mathcal{O}_{BW} = \phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \phi \qquad \mathcal{O}_{W} = (D_\mu \phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \phi) \qquad \mathcal{O}_{B} = \cdots$$

$$\mathcal{O}_{\phi,1} = (D_\mu \phi)^\dagger \, \phi \, \phi^\dagger \, (D^\mu \phi) \qquad \mathcal{O}_{\phi,2} = \frac{1}{2} \partial^\mu \left(\phi^\dagger \phi \right) \partial_\mu \left(\phi^\dagger \phi \right) \qquad \mathcal{O}_{\phi,3} = \frac{1}{3} \left(\phi^\dagger \phi \right)^3$$

Improved Run I legacy [Corbett, Eboli, Goncalves, Gonzalez-Fraile, TP, Rauch (2015)]

– kinematics: $p_{T,V}, \Delta\phi_{jj}$ [#2 solved]

– key observable



3– Effective Higgs-gauge operators

Higgs-Goldstone doublets [Falkowski etal; Butter, Eboli, Gonzalez-Fraile, Gonzales-Garcia, TP, Rauch (2016)]

– one more operator for TGV [#3 solved]

$$\mathcal{O}_W = (D_\mu \phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \phi) \qquad \cdots \qquad \mathcal{O}_{WWW} = \text{Tr}\left(\hat{W}_{\mu\nu} \hat{W}^{\nu\rho} \hat{W}_\rho^\mu \right)$$

– kinematics: $p_{T,\ell}$ in VV production

3– Effective Higgs-gauge operators

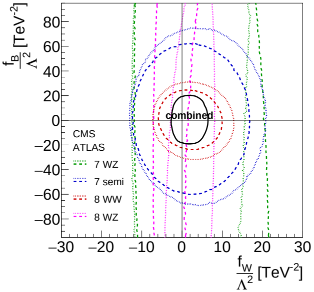
Higgs-Goldstone doublets [Falkowski etal; Butter, Eboli, Gonzalez-Fraile, Gonzales-Garcia, TP, Rauch (2016)]

– one more operator for TGV [#3 solved]

$$\mathcal{O}_W = (D_\mu \phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \phi) \qquad \cdots \qquad \mathcal{O}_{WWW} = \mathrm{Tr}\left(\hat{W}_{\mu\nu} \hat{W}^{\nu\rho} \hat{W}_\rho^\mu \right)$$

– kinematics: $p_{T,\ell}$ in VV production

– smoothing correlations



3– Effective Higgs-gauge operators

Higgs-Goldstone doublets [Falkowski etal; Butter, Eboli, Gonzalez-Fraile, Gonzales-Garcia, TP, Rauch (2016)]

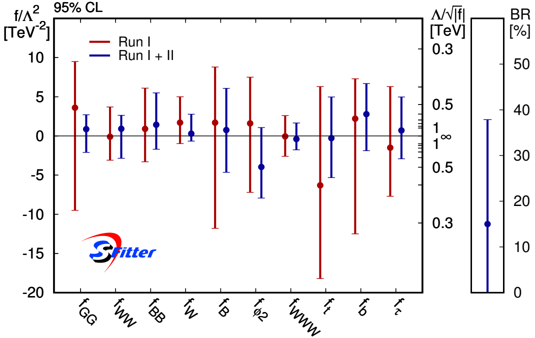
– one more operator for TGV [#3 solved]

$$\mathcal{O}_W = (D_\mu \phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \phi) \qquad \cdots \qquad \mathcal{O}_{WWW} = \text{Tr}\left(\hat{W}_{\mu\nu} \hat{W}^{\nu\rho} \hat{W}^{\mu}_{\rho} \right)$$

– kinematics: $p_{T,\ell}$ in VV production

– smoothing correlations

$\Rightarrow$ Higgs-gauge analysis at Run II [Biekötter, Corbett, TP (2018)]



3– Effective Higgs-gauge operators

Higgs-Goldstone doublets [Falkowski etal; Butter, Eboli, Gonzalez-Fraile, Gonzales-Garcia, TP, Rauch (2016)]

– one more operator for TGV [#3 solved]

$$\mathcal{O}_W = (D_\mu \phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \phi) \qquad \cdots \qquad \mathcal{O}_{WWW} = \text{Tr}\left(\hat{W}_{\mu\nu} \hat{W}^{\nu\rho} \hat{W}^\mu_\rho \right)$$

– kinematics: $p_{T,\ell}$ in VV production

– smoothing correlations

⇒ Higgs-gauge analysis at Run II [Biekötter, Corbett, TP (2018)]

LHC vs LEP [Grojean, Montull, Riembau; Butter, Eboli, Gonzalez-Fraile, Gonzales-Garcia, TP, Rauch (2016)]

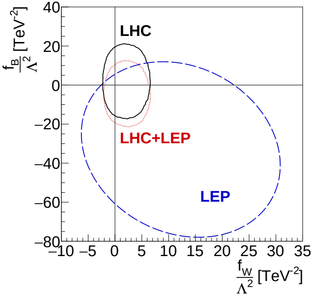
– triple vertices g_1, κ, λ vs gauge-invariant operators

– generic EFT feature:

LEP driven by precision

LHC driven by energy

⇒ LHC the leading precision machine



4– Electroweak fermion couplings

After beating LEP once... [Biekötter, Corbett, TP (2018); also Alves etal]

– gauge-fermion operators visible [Zhang; Baglio, Dawson, Lewis]

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

$$\mathcal{O}_{\phi Q}^{(1)} = \cdots \qquad \mathcal{O}_{\phi d}^{(1)} = \cdots \qquad \mathcal{O}_{\phi Q}^{(3)} = \cdots$$

$$\mathcal{O}_{\phi ud}^{(1)} = \tilde{\phi}^\dagger \overleftrightarrow{D}_\mu \phi (\bar{u}_{R,i} \gamma^\mu d_{R,i}) \qquad \mathcal{O}_{\phi u}^{(1)} = \cdots \qquad \mathcal{O}_{LLLL} = (\bar{L}_1 \gamma_\mu L_2)\ (\bar{L}_2 \gamma^\mu L_1)$$

– bosonic operators bounded by EWPD

$$\mathcal{O}_{\phi,1} = (D_\mu \phi)^\dagger\ \phi \phi^\dagger\ (D^\mu \phi) \qquad \mathcal{O}_{BW} = \phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \phi$$

4– Electroweak fermion couplings

After beating LEP once... [Biekötter, Corbett, TP (2018); also Alves etal]

– gauge-fermion operators visible [Zhang; Baglio, Dawson, Lewis]

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

$$\mathcal{O}^{(1)}_{\phi Q} = \cdots \qquad \mathcal{O}^{(1)}_{\phi d} = \cdots \qquad \mathcal{O}^{(3)}_{\phi Q} = \cdots$$

$$\mathcal{O}^{(1)}_{\phi ud} = \tilde{\phi}^\dagger \overleftrightarrow{D}_\mu \phi (\bar{u}_{R,i} \gamma^\mu d_{R,i}) \qquad \mathcal{O}^{(1)}_{\phi u} = \cdots \qquad \mathcal{O}_{LLLL} = (\bar{L}_1 \gamma_\mu L_2)\, (\bar{L}_2 \gamma^\mu L_1)$$

– bosonic operators bounded by EWPD

$$\mathcal{O}_{\phi,1} = (D_\mu \phi)^\dagger \; \phi \phi^\dagger \; (D^\mu \phi) \qquad \mathcal{O}_{BW} = \phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \phi$$

– after equations of motions, etc

$$\begin{aligned}
\mathcal{L}_\text{eff} = & - \frac{\alpha_s v}{8\pi} \frac{f_g}{\Lambda^2} \mathcal{O}_{GG} + \frac{f_{BB}}{\Lambda^2} \mathcal{O}_{BB} + \frac{f_{WW}}{\Lambda^2} \mathcal{O}_{WW} + \frac{f_B}{\Lambda^2} \mathcal{O}_B + \frac{f_W}{\Lambda^2} \mathcal{O}_W + \frac{f_{\phi,2}}{\Lambda^2} \mathcal{O}_{\phi,2} \\
& + \sum_{\tau bt} \frac{m_f}{v} \frac{f_f}{\Lambda^2} \mathcal{O}_f + \frac{f_{\phi,1}}{\Lambda^2} \mathcal{O}_{\phi 1} + \frac{f_{BW}}{\Lambda^2} \mathcal{O}_{BW} + \frac{f_{LLLL}}{\Lambda^2} \mathcal{O}_{LLLL} \\
& + \frac{f^{(1)}_{\phi Q}}{\Lambda^2} \mathcal{O}^{(1)}_{\phi Q} + \frac{f^{(1)}_{\phi d}}{\Lambda^2} \mathcal{O}^{(1)}_{\phi d} + \frac{f^{(1)}_{\phi u}}{\Lambda^2} \mathcal{O}^{(1)}_{\phi u} + \frac{f^{(1)}_{\phi e}}{\Lambda^2} \mathcal{O}^{(1)}_{\phi e} + \frac{f^{(3)}_{\phi Q}}{\Lambda^2} \mathcal{O}^{(3)}_{\phi Q}
\end{aligned}$$

4– Electroweak fermion couplings

After beating LEP once... [Biekötter, Corbett, TP (2018); also Alves etal]

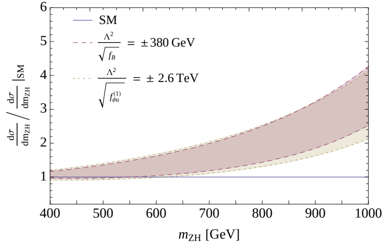
– after equations of motions, etc

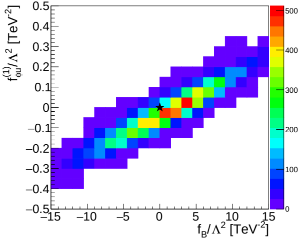
$$\mathcal{L}_{\text{eff}} = -\frac{\alpha_s v}{8\pi}\frac{f_g}{\Lambda^2}\mathcal{O}_{GG} + \frac{f_{BB}}{\Lambda^2}\mathcal{O}_{BB} + \frac{f_{WW}}{\Lambda^2}\mathcal{O}_{WW} + \frac{f_B}{\Lambda^2}\mathcal{O}_B + \frac{f_W}{\Lambda^2}\mathcal{O}_W + \frac{f_{\phi,2}}{\Lambda^2}\mathcal{O}_{\phi,2}$$
$$+ \sum_{\tau bt}\frac{m_f}{v}\frac{f_f}{\Lambda^2}\mathcal{O}_f + \frac{f_{\phi,1}}{\Lambda^2}\mathcal{O}_{\phi 1} + \frac{f_{BW}}{\Lambda^2}\mathcal{O}_{BW} + \frac{f_{LLLL}}{\Lambda^2}\mathcal{O}_{LLLL}$$
$$+ \frac{f^{(1)}_{\phi Q}}{\Lambda^2}\mathcal{O}^{(1)}_{\phi Q} + \frac{f^{(1)}_{\phi d}}{\Lambda^2}\mathcal{O}^{(1)}_{\phi d} + \frac{f^{(1)}_{\phi u}}{\Lambda^2}\mathcal{O}^{(1)}_{\phi u} + \frac{f^{(1)}_{\phi e}}{\Lambda^2}\mathcal{O}^{(1)}_{\phi e} + \frac{f^{(3)}_{\phi Q}}{\Lambda^2}\mathcal{O}^{(3)}_{\phi Q}$$

Side remark: being tricked by LHC kinematics

– m_{ZH} perfect, exotics search to 1.2 TeV

– scale hierarchy $\mathcal{O}^{(1)}_{\phi u} \to g_{qqZH}$ vs $\mathcal{O}_W \to g_{ZZH}$ broken by 4-point vertex





5– More effective couplings

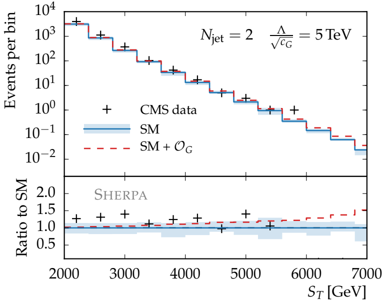
Ubiquitous QCD operator [Simmons etal; Dixon etal; TP, Krauss, Kuttimalai]

– anomalous gluon coupling

$$\mathcal{O}_G = g_s\, f_{abc} G^{\rho}_{a\nu} G^{\nu}_{b\lambda} G^{\lambda}_{c\rho}$$

– multi-jet production [black hole search]

4-fermion operator for $N_{\text{jets}} = 2, 3$
gluon operator for $N_{\text{jets}} \geq 5$



5– More effective couplings

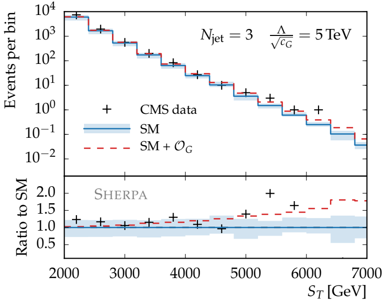
Ubiquitous QCD operator [Simmons etal; Dixon etal; TP, Krauss, Kuttimalai]

– anomalous gluon coupling

$$\mathcal{O}_G = g_s\, f_{abc} G^{\rho}_{a\nu} G^{\nu}_{b\lambda} G^{\lambda}_{c\rho}$$

– multi-jet production [black hole search]

4-fermion operator for $N_{\text{jets}} = 2, 3$
gluon operator for $N_{\text{jets}} \geq 5$



5– More effective couplings

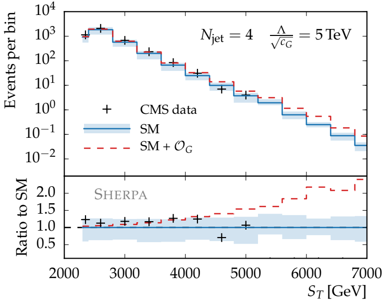
Ubiquitous QCD operator [Simmons etal; Dixon etal; TP, Krauss, Kuttimalai]

– anomalous gluon coupling

$$\mathcal{O}_G = g_s \, f_{abc} G^{\rho}_{a\nu} G^{\nu}_{b\lambda} G^{\lambda}_{c\rho}$$

– multi-jet production [black hole search]

4-fermion operator for $N_\text{jets} = 2, 3$
gluon operator for $N_\text{jets} \geq 5$



5– More effective couplings

Ubiquitous QCD operator [Simmons etal; Dixon etal; TP, Krauss, Kuttimalai]

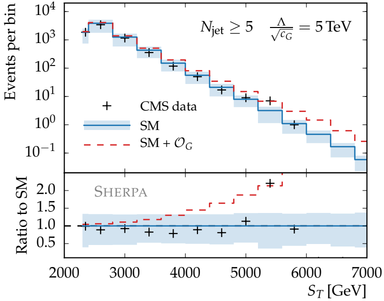
– anomalous gluon coupling

$$\mathcal{O}_G = g_s \, f_{abc} G^{\rho}_{a\nu} G^{\nu}_{b\lambda} G^{\lambda}_{c\rho}$$

– multi-jet production [black hole search]

4-fermion operator for $N_{\text{jets}} = 2, 3$
gluon operator for $N_{\text{jets}} \geq 5$

– input to Higgs analysis $\Lambda/f_G > 5.2$ TeV



5– More effective couplings

Ubiquitous QCD operator [Simmons etal; Dixon etal; TP, Krauss, Kuttimalai]

– anomalous gluon coupling

$$\mathcal{O}_G = g_s \, f_{abc} G^{\rho}_{a\nu} G^{\nu}_{b\lambda} G^{\lambda}_{c\rho}$$

– multi-jet production [black hole search]

4-fermion operator for $N_{\text{jets}} = 2, 3$
gluon operator for $N_{\text{jets}} \geq 5$

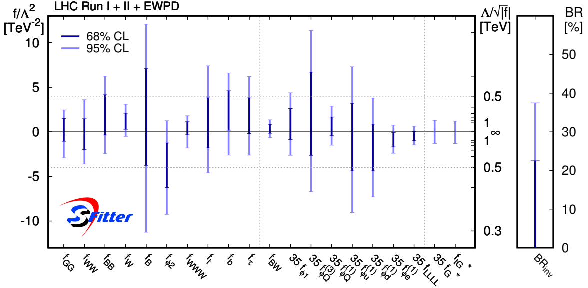
– input to Higgs analysis $\Lambda/f_G > 5.2$ TeV

Combined Run II analysis [Biekötter, Corbett, TP]

– including LHC and EWPD

– quote multi-jet

– quote tops (Scots)



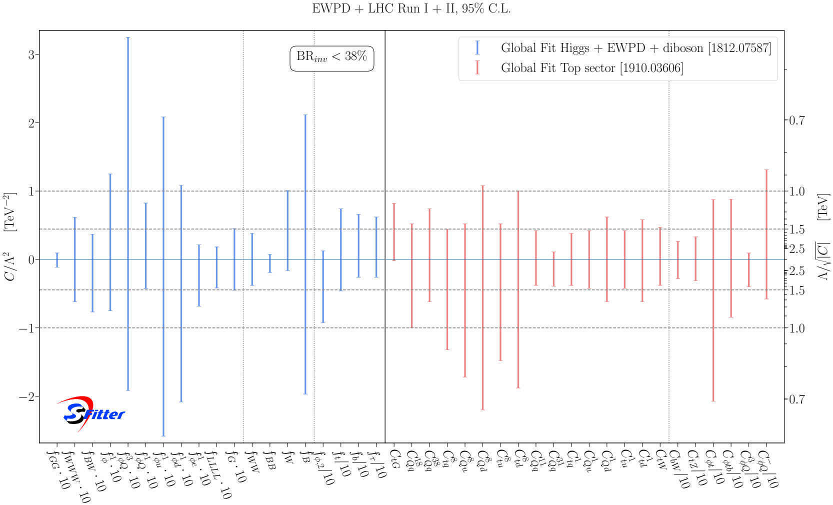
5– More effective couplings

Totally combined Run II analysis [Brivio etal]

– including Higgs–gauge sector and top sector

– interesting physics of four-fermion operators

⇒ closing in on SMEFT fit



Symmetries of the effective Lagrangian

Recap: C and P and T and $\hat{T}$

– transformations on state with spin/momentum [review: Valencia]

$$C\,|\phi(p,s)\rangle = |\phi^*(p,s)\rangle \qquad P\,|\phi(p,s)\rangle = \eta_\phi\,|\phi(-p,s)\rangle \qquad T\,|\phi(p,s)\rangle = \langle\phi(-p,-s)|$$

CPT symmetry generally assumed, T proxy for CP

Symmetries of the effective Lagrangian

Recap: C and P and T and $\hat{T}$

– transformations on state with spin/momentum [review: Valencia]

$$C\,|\phi(p,s)\rangle = \left|\phi^*(p,s)\right\rangle \quad P\,|\phi(p,s)\rangle = \eta_\phi\,|\phi(-p,s)\rangle \quad T\,|\phi(p,s)\rangle = \langle\phi(-p,-s)|$$

CPT symmetry generally assumed, *T* proxy for *CP*

– genuine U-odd is what we want [$U = C, P, T$, Atwood, Bar-Shalom, Eilam]

$$\langle O\rangle_{\mathcal{L}=U\mathcal{L}U^{-1}} = 0\;.$$

U-odd is what we usually get, but genuine U-odd under conditions

$$O(U\,|i\rangle \to U\,|f\rangle) \stackrel{\text{odd}}{=} -O\,(|i\rangle \to |f\rangle) \quad \stackrel{p(|i\rangle)=p(U|i\rangle)}{\Longrightarrow} \quad \langle O\rangle_{\mathcal{L}=U\mathcal{L}U^{-1}} = 0\;.$$

Symmetries of the effective Lagrangian

Recap: C and P and T and $\hat{T}$

– transformations on state with spin/momentum [review: Valencia]

$$C\,|\phi(p,s)\rangle = \left|\phi^*(p,s)\right\rangle \qquad P\,|\phi(p,s)\rangle = \eta_\phi\,|\phi(-p,s)\rangle \qquad T\,|\phi(p,s)\rangle = \langle\phi(-p,-s)|$$

CPT symmetry generally assumed, T proxy for CP

– genuine U-odd is what we want [$U = C, P, T$, Atwood, Bar-Shalom, Eilam]

$$\langle O\rangle_{\mathcal{L}=U\mathcal{L}U^{-1}} = 0 \; .$$

U-odd is what we usually get, but genuine U-odd under conditions

$$O(U\,|i\rangle \to U\,|f\rangle) \overset{\text{odd}}{=} -O\,(|i\rangle \to |f\rangle) \quad \overset{p(|i\rangle)=p(U|i\rangle)}{\Longrightarrow} \quad \langle O\rangle_{\mathcal{L}=U\mathcal{L}U^{-1}} = 0 \; .$$

– naive time reversal $\hat{T}$ avoiding inital $\leftrightarrow$ final state

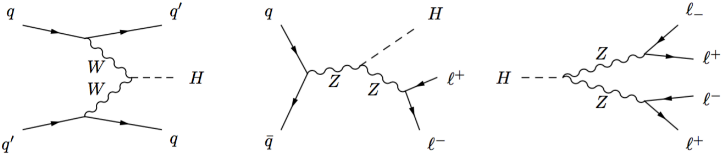
$$\hat{T}\,|\phi(p,s)\rangle = |\phi(-p,-s)\rangle$$

genuine $\hat{T}$-odd observable implies CP-violating theory, provided

1- phase space $\hat{T}$-symmetric
2- initial state distribution invariant under $\hat{T}$
3- no re-scattering, means no imaginary parts

Two ways to test *CP* at the LHC

Identical amplitudes with $\mathcal{O}_{W\tilde{W}}$



– four 4-momenta defining 10+1 observables [Han, Li,...]

four external masses
four *C*-even, *P*-even, and $\hat{T}$-even scalar products
two *C*-odd, *P*-even, and $\hat{T}$-even scalar products
one *C*-even, *P*-odd, and $\hat{T}$-odd observable with Levi-Civita-tensor

1– *CP*-odd and $\hat{T}$-odd
for symmetric initial state also genuine *CP*-odd and genuine $\hat{T}$-odd
non-zero expectation value means *CP* violation

2– *CP*-odd and $\hat{T}$-even [for our LHCb friends]
for symmetric initial state also genuine *CP*-odd
for *CP*-violating theory, *CP*-expectation value non-zero
but without re-scattering, $\hat{T}$-expectation value zero
need complex phase for $\langle O \rangle$ to match symmetry

⇒ so: single *CP*-odd and $\hat{T}$-odd observable or kinematic analysis?

Quantifying available information

Information geometry for LHC [Brehmer, Cranmer, Kling, TP (2017)]

– covariance matrix [measurement error in model space **g**]

$$C_{ij}(\mathbf{g}) \equiv E\left[(\hat{g}_i - \bar{g}_i)(\hat{g}_j - \bar{g}_j)\middle|\mathbf{g}\right]$$

– Fisher information [sensitivity in model space]

$$I_{ij}(\mathbf{g}) \equiv -E\left[\frac{\partial^2 \log f(\mathbf{x}|\mathbf{g})}{\partial g_i\,\partial g_j}\middle|\mathbf{g}\right]$$

– Cramèr-Rao bound defining best measurement [lowest possible covariance]

$$C_{ij}(\mathbf{g}) \geq (I^{-1})_{ij}(\mathbf{g})$$

– computable over phase space [phase space **x**, additive]

$$I_{ij} = \frac{L}{\sigma}\,\frac{\partial\sigma}{\partial g_i}\,\frac{\partial\sigma}{\partial g_j} - L\,\sigma\;E\left[\frac{\partial^2 \log f^{(1)}(\mathbf{x}|\mathbf{g})}{\partial g_i\,\partial g_j}\right]$$

Quantifying available information

Information geometry for LHC [Brehmer, Cranmer, Kling, TP (2017)]

– covariance matrix [measurement error in model space **g**]

$$C_{ij}(\mathbf{g}) \equiv E\left[(\hat{g}_i - \bar{g}_i)(\hat{g}_j - \bar{g}_j)\middle|\mathbf{g}\right]$$

– Fisher information [sensitivity in model space]

$$I_{ij}(\mathbf{g}) \equiv -E\left[\frac{\partial^2 \log f(\mathbf{x}|\mathbf{g})}{\partial g_i\, \partial g_j}\middle|\mathbf{g}\right]$$

– Cramèr-Rao bound defining best measurement [lowest possible covariance]

$$C_{ij}(\mathbf{g}) \geq (I^{-1})_{ij}(\mathbf{g})$$

– computable over phase space [phase space **x**, additive]

$$I_{ij} = \frac{L}{\sigma}\,\frac{\partial\sigma}{\partial g_i}\,\frac{\partial\sigma}{\partial g_j} - L\,\sigma\,E\left[\frac{\partial^2 \log f^{(1)}(\mathbf{x}|\mathbf{g})}{\partial g_i\, \partial g_j}\right]$$

1– parametrization-invariant elipses of constant distance/reach in model space

2– diagonalize I_{ij}, define model-space eigenvectors

3– compute information in distributions or phase space regions

⇒ tool to compare analysis ideas [MadMiner: Brehmer, Cranmer, Kling]

WBF production

Testing *CP* in WBF

- four external 4-momenta $\to$ 10 scalar products
  one C-even, P-odd, $\hat{T}$-odd [yeah]

$$\epsilon_{\mu\nu\rho\sigma}\; k_1^\mu\; k_2^\nu\; q_1^\rho\; q_2^\sigma \quad \to \quad O \equiv \epsilon_{\mu\nu\rho\sigma}\; k_1^\mu\; k_2^\nu\; q_1^\rho\; q_2^\sigma\; \text{sign}\left[(k_1 - k_2)\cdot(q_1 - q_2)\right]$$

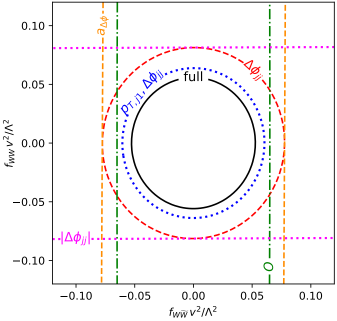
- azimuthal angle difference [lab frame]

$$O = 2E_-(\vec{q}_- \times \vec{q}_+)\cdot\vec{k}_+ \quad \to \quad \sin\Delta\phi_{jj}$$

- *CP* asymmetry

$$a_{\Delta\phi_{jj}} \equiv \frac{\mathrm{d}\sigma(\Delta\phi_{jj}) - \mathrm{d}\sigma(-\Delta\phi_{jj})}{\mathrm{d}\sigma(\Delta\phi_{jj}) + \mathrm{d}\sigma(-\Delta\phi_{jj})}$$

- difference from dimension-6 kinematics



WBF production

Testing *CP* in WBF

– four external 4-momenta → 10 scalar products
one *C*-even, *P*-odd, $\hat{T}$-odd [yeah]

$$\epsilon_{\mu\nu\rho\sigma}\, k_1^\mu\, k_2^\nu\, q_1^\rho\, q_2^\sigma \quad\to\quad O \equiv \epsilon_{\mu\nu\rho\sigma}\, k_1^\mu\, k_2^\nu\, q_1^\rho\, q_2^\sigma\; \text{sign}\left[(k_1 - k_2)\cdot(q_1 - q_2)\right]$$

– azimuthal angle difference [lab frame]

$$O = 2E_-(\vec{q}_- \times \vec{q}_+)\cdot\vec{k}_+ \quad\to\quad \sin\Delta\phi_{jj}$$

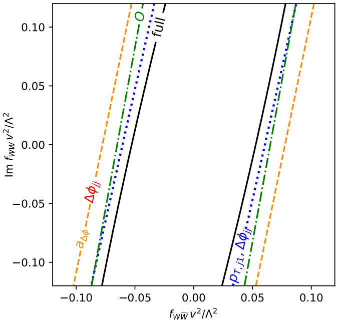
– *CP* asymmetry

$$a_{\Delta\phi_{jj}} \equiv \frac{\mathrm{d}\sigma(\Delta\phi_{jj}) - \mathrm{d}\sigma(-\Delta\phi_{jj})}{\mathrm{d}\sigma(\Delta\phi_{jj}) + \mathrm{d}\sigma(-\Delta\phi_{jj})}$$

– difference from dimension-6 kinematics

– check with imaginary Wilson coefficients

⇒ testing *CP*, but assuming no re-scattering



ZH production

Testing *CP* in *ZH* production

– same 10 scalar products

one *CP*-odd and $\hat{T}$-odd angle as for WBF

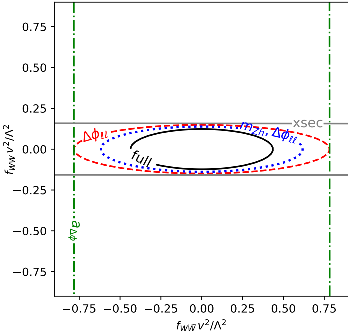
$$O_1 = \epsilon_{\mu\nu\rho\sigma}\ k_1^\mu k_2^\nu q_{\ell+}^\rho q_{\ell-}^\sigma\ \text{sign}((k_1 - k_2)\cdot(q_1 - q_2)) \quad \to \quad \sin\Delta\phi_{\ell\ell}$$

– *CP* asymmetry as for WBF

$$a_{\Delta\phi_{\ell\ell}} \equiv \frac{\mathrm{d}\sigma(\Delta\phi_{\ell\ell}) - \mathrm{d}\sigma(-\Delta\phi_{\ell\ell})}{\mathrm{d}\sigma(\Delta\phi_{\ell\ell}) + \mathrm{d}\sigma(-\Delta\phi_{\ell\ell})}$$

– difference from dimension-6 kinematics

$\Rightarrow$ testing *CP* without assumtions [to leading order]



ZH production

Testing *CP* in *ZH* production

– same 10 scalar products

one *CP*-odd and $\hat{T}$-odd angle as for WBF

$$O_1 = \epsilon_{\mu\nu\rho\sigma} \, k_1^\mu k_2^\nu q_{\ell+}^\rho q_{\ell-}^\sigma \; \text{sign}((k_1 - k_2) \cdot (q_1 - q_2)) \quad \to \quad \sin \Delta\phi_{\ell\ell}$$

– *CP* asymmetry as for WBF

$$a_{\Delta\phi_{\ell\ell}} \equiv \frac{\mathrm{d}\sigma(\Delta\phi_{\ell\ell}) - \mathrm{d}\sigma(-\Delta\phi_{\ell\ell})}{\mathrm{d}\sigma(\Delta\phi_{\ell\ell}) + \mathrm{d}\sigma(-\Delta\phi_{\ell\ell})}$$

– difference from dimension-6 kinematics

⇒ testing *CP* without assumtions [to leading order]

Testing *CP* in $H \to 4\ell$ decays

– same 10 scalar products

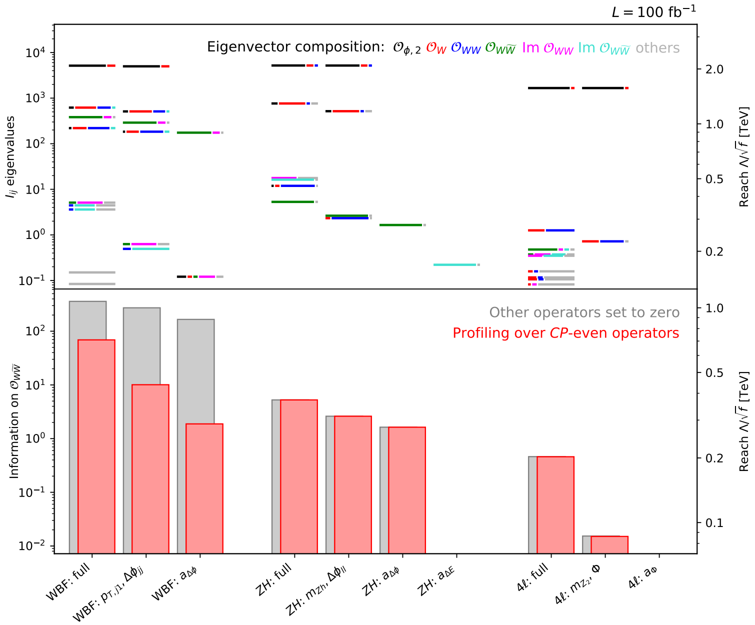
– momentum flow limited by m_H

– reach for *CP*-even operators shit [Brehmer, Cranmer, Kling, TP (2016)]

– even showing plots is waste of time

⇒ what's the point...

Outcome: comparison of *CP* tests



Questions

Theory contribution to bottom-up precision physics at the LHC

Is it really the Standard Model Higgs? [no]

Is there WIMP dark matter? [yes]

Is there TeV-scale physics beyond the Standard Model? [yes]

Are EFT analyses un-inspired? [totally]

Are there nice theory aspects to work on? [plenty]

Are there nice statistics aspects to work on? [always]

Will I stop doing EFT once we find new physics? [definitely]

$\Rightarrow$ Welcome to a data-driven era!

EFT musings

Ideal LEP and flavor worlds

– unique EFT Lagrangian: linear realization matching unbroken phase

– chain of well separated energy scales $E \ll \Lambda_1 \ll ... \ll \Lambda_N$

$\Rightarrow$ systematic expansion in E/Λ and α [example: ew precision data]

Rotten LHC world [Brehmer, Freitas, Lopez-Val, TP]

– range of (partonic) energy scales [H+jets production]

– electroweak symmetry breaking at $v \sim E_{\text{LHC}}$

– low precision, reach from energy

$$\left| \frac{\sigma \times \text{BR}}{(\sigma \times \text{BR})_{\text{SM}}} - 1 \right| = \frac{g^2 m_h^2}{\Lambda^2} \approx 10\% \qquad \stackrel{g=1}{\Longleftrightarrow} \qquad \Lambda \approx 400 \quad \text{GeV}$$

$\Rightarrow$ D8 operators not obviously suppressed

Task for LHC theory

– develop a working D6 framework

– keep theorist's self respect

– remember we really care about UV models

– truncation uncertainties as matching uncertainties