The effective electroweak Lagrangian

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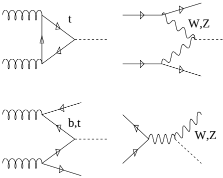
Higgs couplings



How the LHC became a precision Higgs machine

- assume: narrow *CP*-even scalar
  Standard Model operators
- Lagrangian like non-linear symmetry breaking

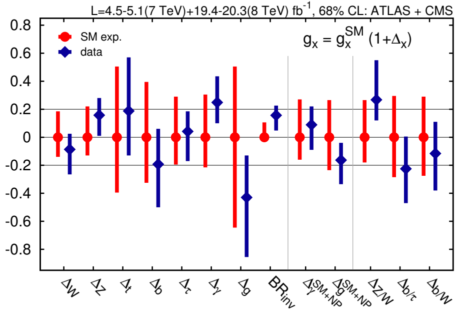
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \Delta_W \; g m_W H \; W^\mu W_\mu + \Delta_Z \; \frac{g}{2c_w} m_Z H \; Z^\mu Z_\mu - \sum_{\tau,b,t} \Delta_f \; \frac{m_f}{v} H \left(\bar{f}_R f_L + \text{h.c.} \right)$$

$$+ \Delta_g F_G \; \frac{H}{v} \; G_{\mu\nu} G^{\mu\nu} + \Delta_\gamma F_A \; \frac{H}{v} \; A_{\mu\nu} A^{\mu\nu} + \text{invisible} + \text{unobservable}$$

Brilliant Run I legacy, but issues...

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

1. renormalizability broken
2. total rates only
3. hard to extend to full SM



Higgs operators

D6 Lagrangian [SMEFT, introducing Ilaria Brivio]

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

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

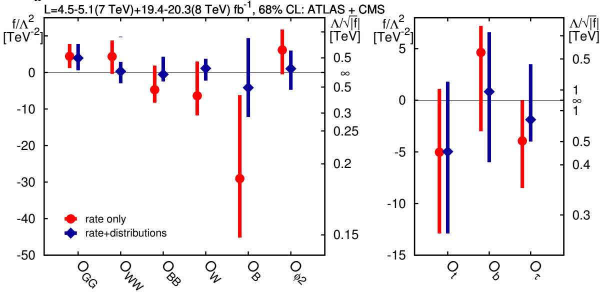
$$\mathcal{O}_{BW} = \phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \phi \qquad \mathcal{O}_{W} = (D_\mu \phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \phi) \qquad \mathcal{O}_{B} = \cdots$$

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

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

Improved Run I legacy

$\Rightarrow$ kinematics $p_{T,V}, \Delta\phi_{jj}$ [#2 solved, A1a, A1b]



Higgs-gauge operators

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

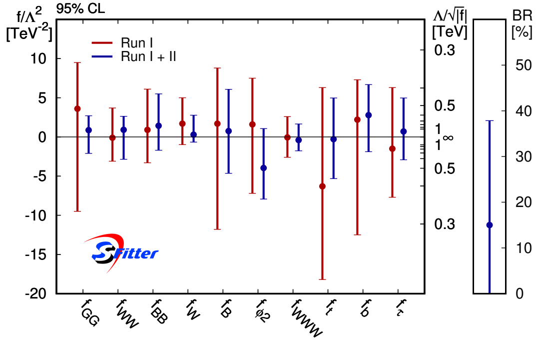
– one more operator for TGV [#3 solved]

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

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

– removing correlations

⇒ Higgs-gauge analysis at Run II [Biekötter, Corbett, TP (2018), invisible Higgs decays: B3a]



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LHC vs LEP

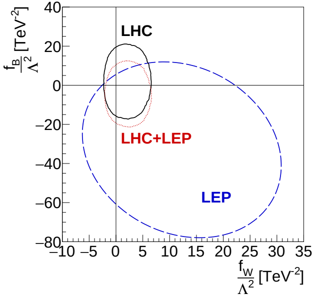
– triple vertices g_1, κ, λ vs gauge-invariant operators

– generic EFT feature:

LEP driven by precision
LHC driven by energy

– LHC/energy wins

⇒ E^2/Λ^2 limiting validity?



Fermionic operators

After beating LEP once... [Biekötter, Corbett, TP (2018)]

– gauge-fermion operators visible

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

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

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

– bosonic operators bounded by EWPD

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

– after equations of motions, etc

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

Fermionic operators

After beating LEP once... [Biekötter, Corbett, TP (2018)]

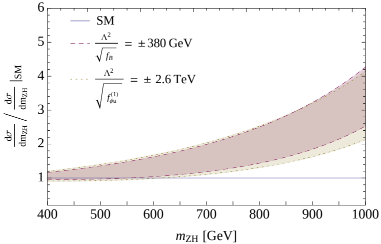
– after equations of motions, etc

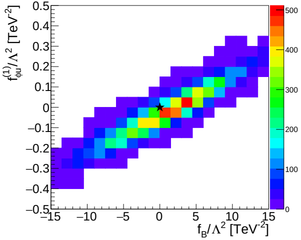
$$\mathcal{L}_{\rm eff} = -\frac{\alpha_s v}{8\pi}\frac{f_g}{\Lambda^2}\mathcal{O}_{GG} + \frac{f_{BB}}{\Lambda^2}\mathcal{O}_{BB} + \frac{f_{WW}}{\Lambda^2}\mathcal{O}_{WW} + \frac{f_B}{\Lambda^2}\mathcal{O}_B + \frac{f_W}{\Lambda^2}\mathcal{O}_W + \frac{f_{\phi,2}}{\Lambda^2}\mathcal{O}_{\phi,2}$$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

Side remark: being tricked by LHC kinematics

– m_{ZH} probed to 1.2 TeV by exotics search

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





More operators

Ubiquitous QCD operator [TP, Krauss, Kuttimalai]

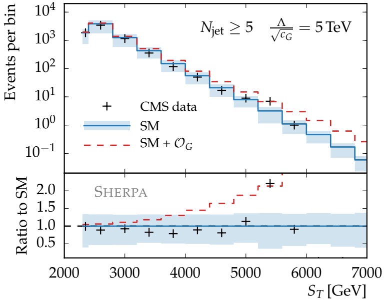
- anomalous gluon coupling

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

- multi-jet production [black hole search]

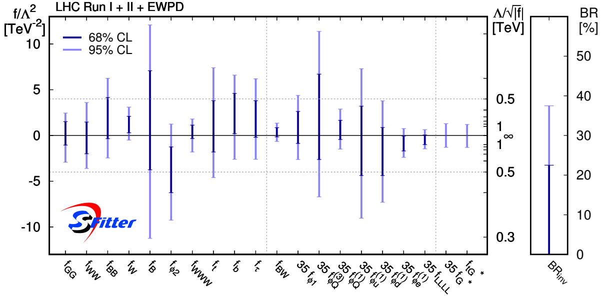
  4-fermion operator for $N_{\text{jets}} = 2, 3$
  gluon operator for $N_{\text{jets}} \geq 5$

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



Run II legacy [Biekötter, Corbett, TP]

- LHC data & EWPD
- quote multi-jet
- quote tops [B2b]



Questions

Ideal LEP and flavor worlds vs rotten LHC world [A2b]

– SMEFT Lagrangian: linear realization matching unbroken phase but $v \sim E_\text{LHC}$

– no chain of well separated energy scales at LHC [H+jets, WBF,...]

– low precision, reach from energy

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

⇒ systematic expansion in E/Λ and α? [examples: ew precision data, HQET]

SMEFT representing full models [Aachen plan, A3a]

– fully automatic 1-loop matching to UV model

1- calculation of 1-loop Wilson coefficients for general models

2- computer program to apply the general result to concrete UV models

3- phenomenological study of UV models...

SMEFT fit [Heidelberg plan, B2b]

– more operators, better uncertainty treatment [Axy, B2b]

– Bayesian analysis

– ML methods in the fit... [B3a]

Symmetries of the effective Lagrangian

Learning from flavor: C and P and T and $\hat{T}$ [Cxy]

– transformations on state with spin/momentum

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

– genuine CP-odd is what we want

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

CP-odd is what we get, but genuine CP-odd under conditions

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

– CPT symmetry assumed, T proxy for CP
naive time reversal $\hat{T}$ avoiding inital $\leftrightarrow$ final state

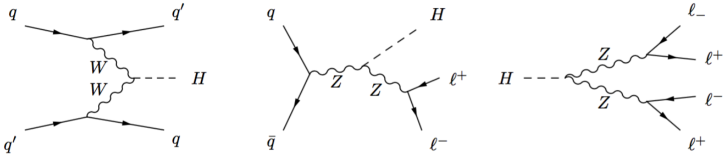
$$\hat{T}\,|\phi(p,s)\rangle = |\phi(-p,-s)\rangle$$

$\Rightarrow$ non-zero genuine $\hat{T}$-odd observable means 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

Ways to test *CP*

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



- four 4-momenta, so 10+1 observables [Levi-Civita tensor]

  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 [flavor]
  for symmetric initial state also genuine *CP*-odd
  for *CP*-violating theory, *CP*-expectation value non-zero
  but $\hat{T}$-expectation value zero
  need re-scattering/complex phase for $\langle O \rangle$ to match symmetry
- one *C*-even, *P*-odd, and $\hat{T}$-odd observable
  for symmetric initial state also genuine *CP*-odd and genuine $\hat{T}$-odd
  non-zero $\langle O \rangle$ means *CP* violation

$\Rightarrow$ single *CP*-odd and $\hat{T}$-odd observable vs kinematic analysis?

Quantifying the available information

Information geometry for LHC [Brehmer, Cranmer, Kling, TP (2017); A3a]

– 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 and additive over phase space

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

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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 [Dieter, A1c]

– C-even, P-odd, $\hat{T}$-odd observable known

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

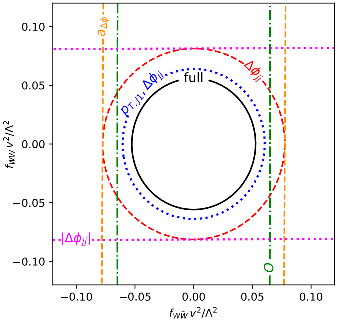
– azimuthal angle difference [lab frame]

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

– 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 [Dieter, A1c]

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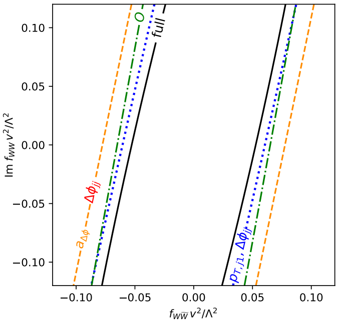
– difference from dimension-6 kinematics

– 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

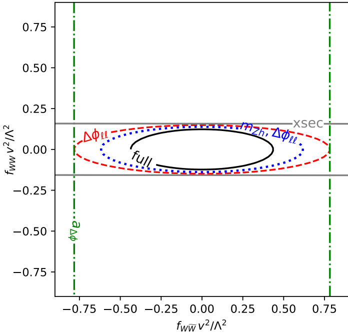
$$O_1 = \epsilon_{\mu\nu\rho\sigma} \, k_1^\mu k_2^\nu q_{\ell+}^\rho q_{\ell-}^\sigma \; \text{sign}((k_1 - k_2) \cdot (q_1 - q_2)) \quad \to \quad \sin \Delta\phi_{\ell\ell}$$

– *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

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



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

– difference from dimension-6 kinematics

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

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

– same 10 scalar products

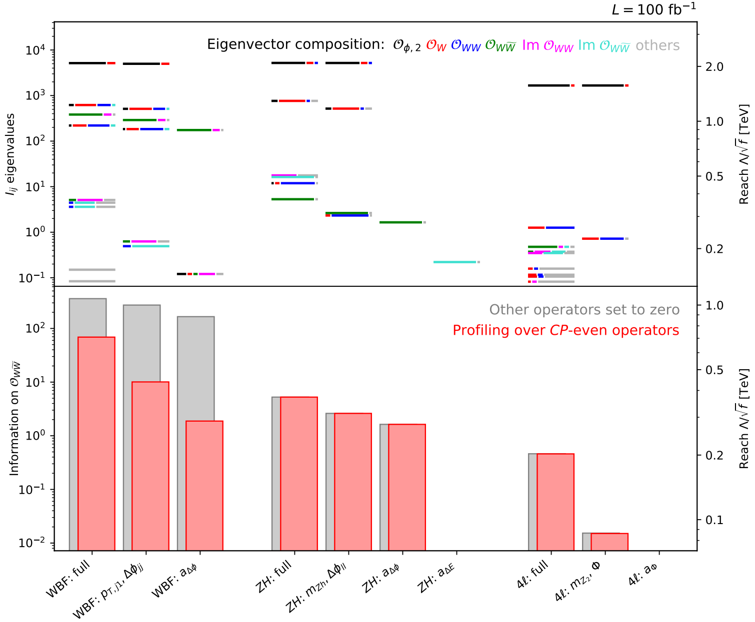
– momentum flow limited by m_H

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

– even showing plots is waste of time

⇒ what's the point...

Comparison of CP sensitivity



Let’s make it work!