EFT Framework for the LHC

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Theory for the LHC

All this 'field in crisis' bullshit

1- particle physics has plenty of data
2- our standard theory works, if anything, too well
3- we have a big goal: dark matter
4- dead new physics models are fun
– but we should fight for the best students
let young people with new ideas run
become inventive again ourselves
stop defending physics by committee

Combining experiment and theory helps

– simulation tools [amazing progress]
– precision predictions [more amazing progress]
– interpretation frameworks [not model preaching; not amazing progress]
– analysis ideas [our future; not enough progress]

$\Rightarrow$ hard work, but students love working together

D6 Higgs operators

D6 Lagrangian at face value [HISZ, Warsaw, Trott etal, Goncales-Garcia etal]

- assume Higgs-Goldstone connection [rather than κ framework/non-linear EFT]
- set of Higgs doublet operators [linear realization]

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

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

- actual basis 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 [plus 3 Yukawa structures and γZH]

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

- 4+3 κ-modifiers plus new Lorentz structures

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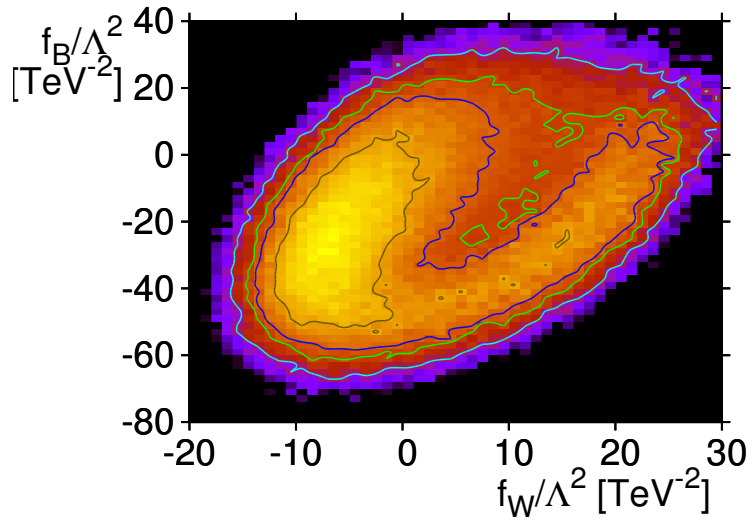
Global Higgs analysis

- SFitter interested in data
- correlations nasty



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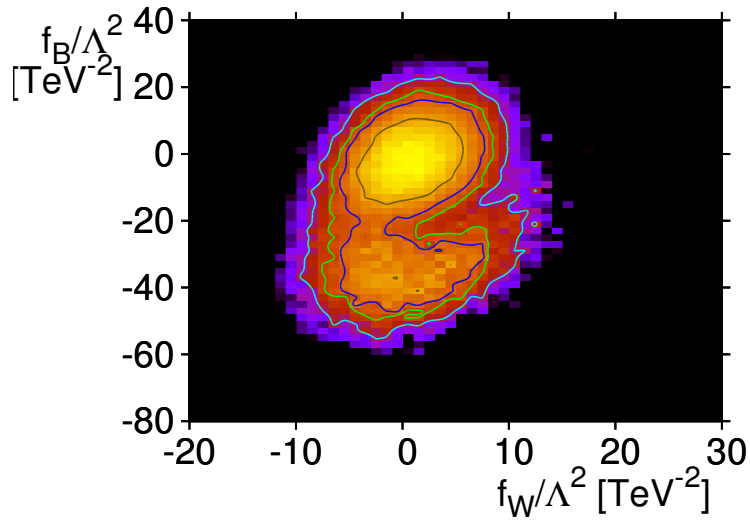

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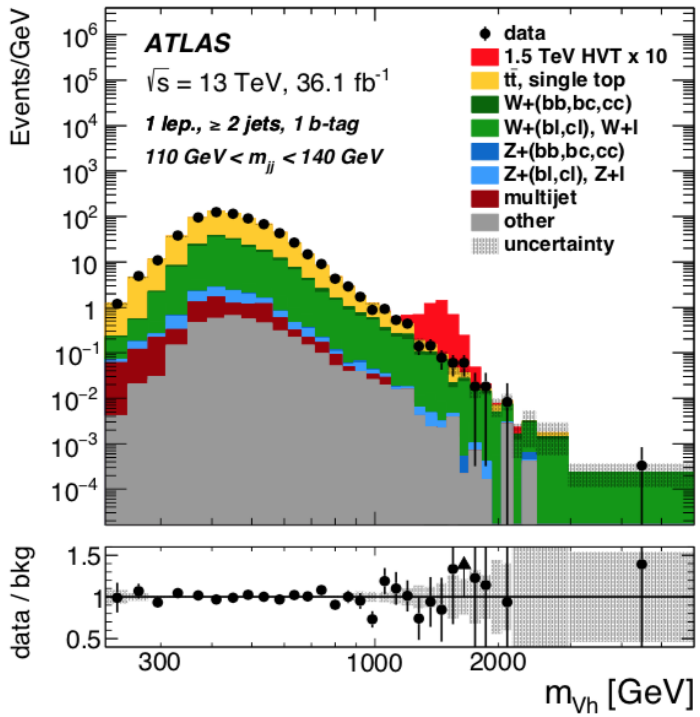
- my favorite Run II input



D6 Higgs-gauge operators

Triple gauge couplings [Butter, Eboli, Gonzalez-Fraile, Gonzalez-Garcia, TP, Rauch]

- adding one more gauge operator

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

- pre-gauge-invariance known as DeltaKappaLambda

$$\begin{aligned}\Delta\mathcal{L}_{\text{TGV}} = &- ie\,\Delta\kappa_\gamma\, W_\mu^+ W_\nu^- \gamma^{\mu\nu} - \frac{ie\lambda_\gamma}{m_W^2}\, W_{\mu\nu}^+ W^{-\nu\rho}\gamma_\rho^\mu - \frac{ig_Z\lambda_Z}{m_W^2}\, W_{\mu\nu}^+ W^{-\nu\rho} Z_\rho^{\ \mu} \\ &- ig_Z\,\Delta\kappa_Z\, W_\mu^+ W_\nu^- Z^{\mu\nu} - ig_Z\,\Delta g_1^Z \left(W_{\mu\nu}^+ W^{-\mu} Z^\nu - W_\mu^+ Z_\nu W^{-\mu\nu}\right)\end{aligned}$$

$$\Delta\kappa_Z \sim \frac{v^2}{\Lambda^2}\left(c_w^2 f_W - s_w^2 f_B\right) \qquad \Delta g_1^Z \sim \frac{v^2}{\Lambda^2} f_W \qquad \lambda_Z \sim \frac{m_W^2}{\Lambda^2} f_{WWW}$$

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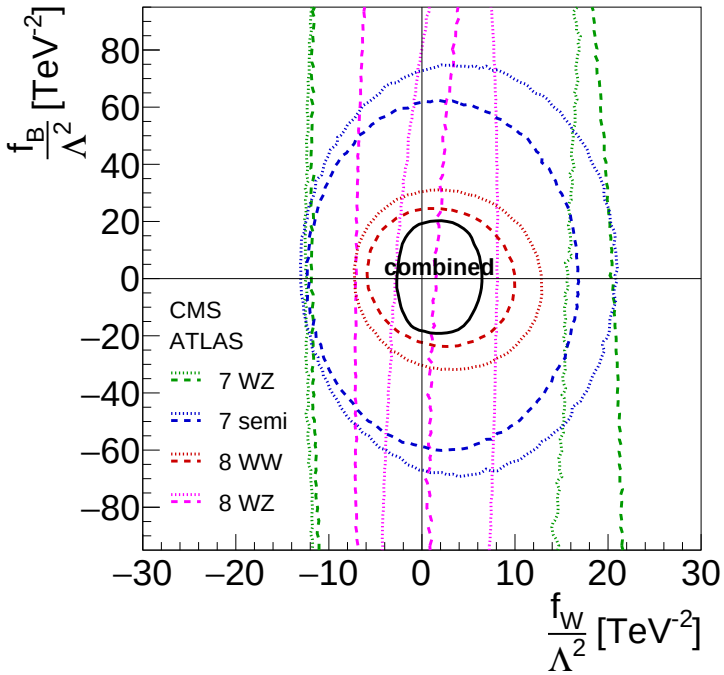
- VV combination [by theorists??]



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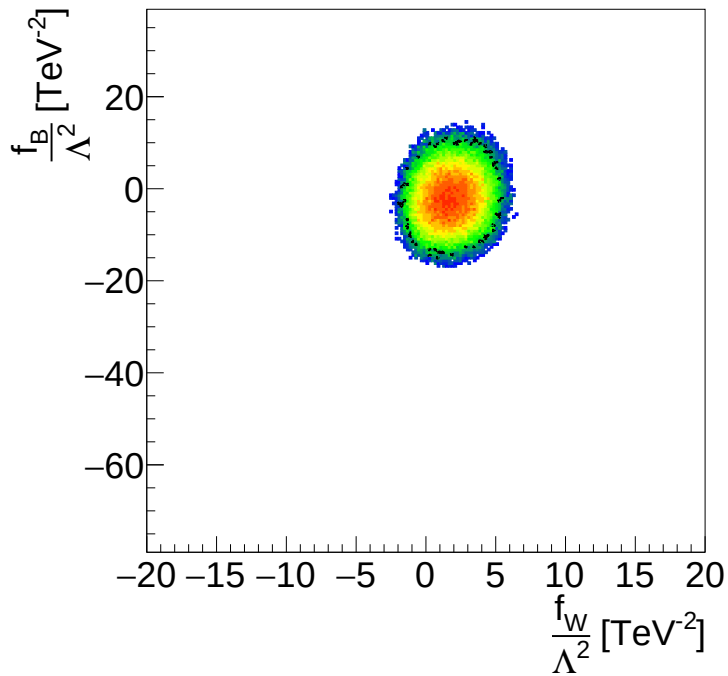
- perfect correlations



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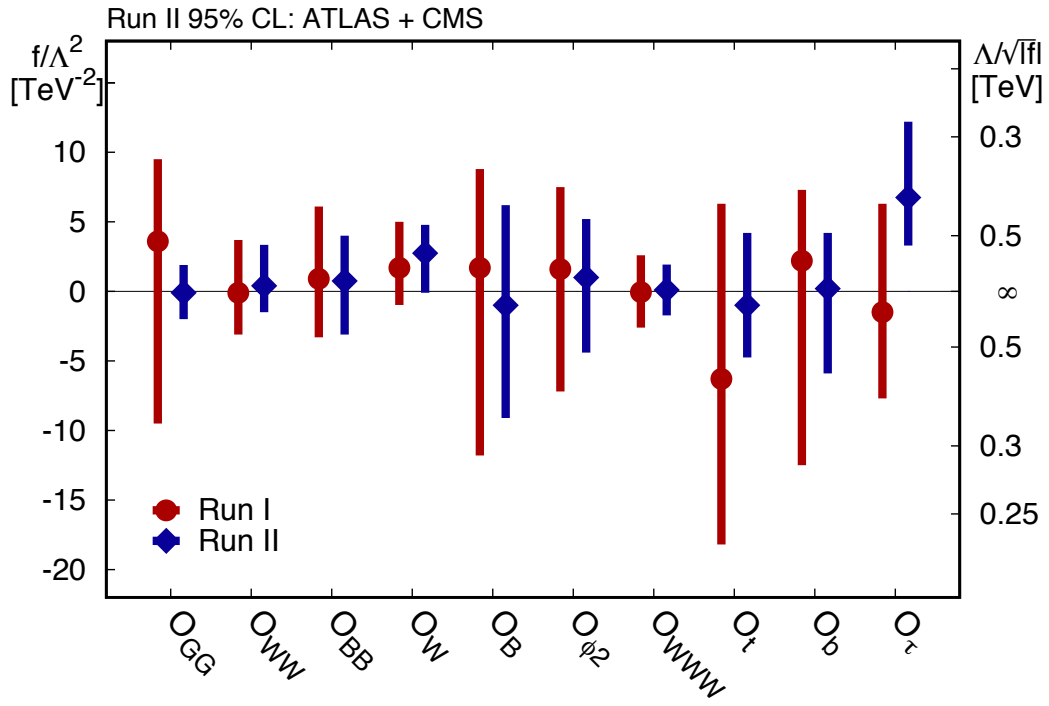
- preliminary 13 TeV update
  game changer: $t\bar{t}H$ rates



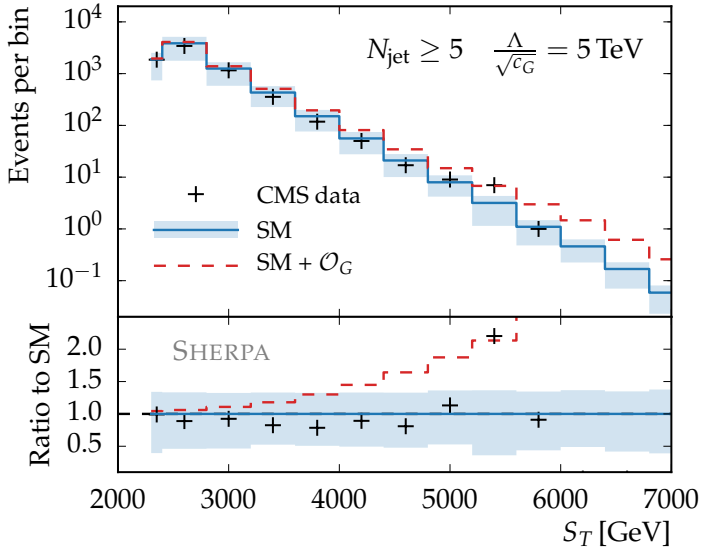
More D6 operators at LHC

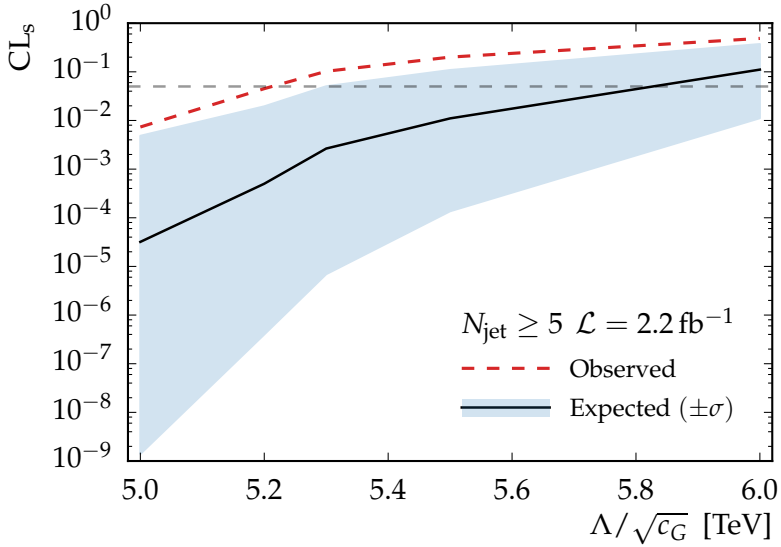
QCD@D6: the most nasty D6 operator [Krauss, Kuttimalai, TP]

- the real reason to do black hole searches: $S_T \approx \sum_{\text{jets}} E_T$
- dimension-6 operators

$$\underbrace{\mathcal{O}_{qq} = \bar{q}\gamma_\mu q\, \bar{q}'\gamma^\mu q'}_{2-3 \text{ jets}} \qquad \underbrace{\mathcal{O}_G = f_{abc} G_\mu^{a\nu} G_\nu^{b\lambda} G_\lambda^{c\mu}}_{\gtrsim 5\text{jets}}$$

$\Rightarrow$ beating Higgs by a mile: $\Lambda/\sqrt{c} \gtrsim 5$ TeV [still needs update]





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top@D6: connecting Higgs to flavor

- Run I limits similar to Higgs-gauge EFT
- for news wait for Kevin

Finding information in phase space

Parameter dependence of kinematics [Brehmer, Cranmer, Kling, TP]

1– Fisher information calculable starting point
additive for phase space integration

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

2– Cramer-Rao bound [(co-)variance $>$ 1/Fisher information]
linking information to ideal analysis outcomes
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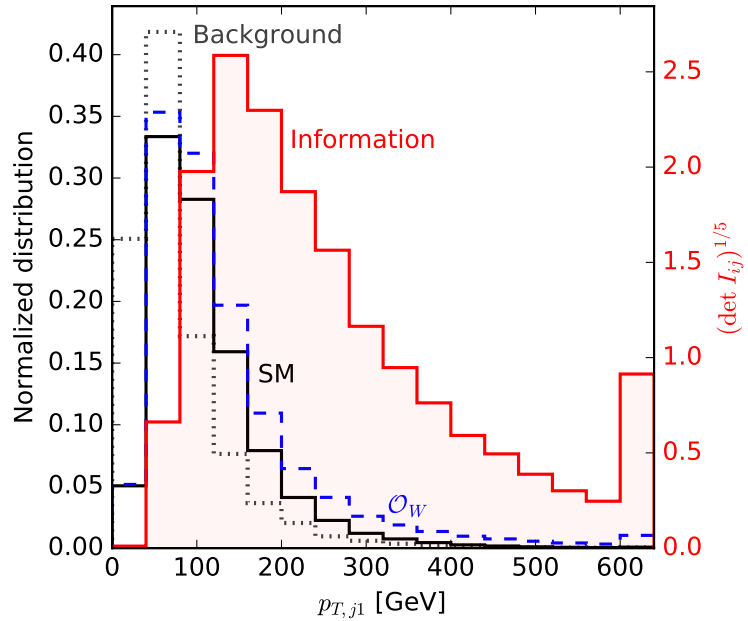
Applied to D6 in WBF $H \to \tau\tau$

– information distribution



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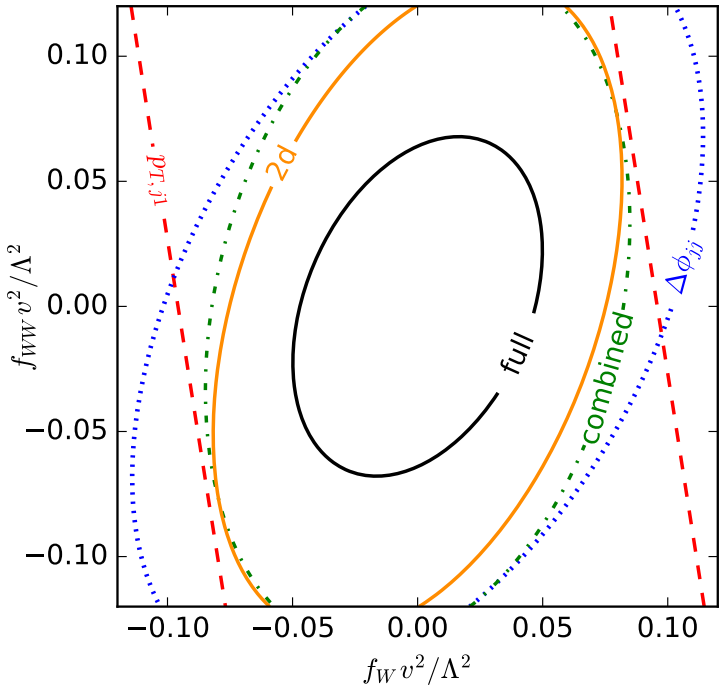
– distributions vs full phase space



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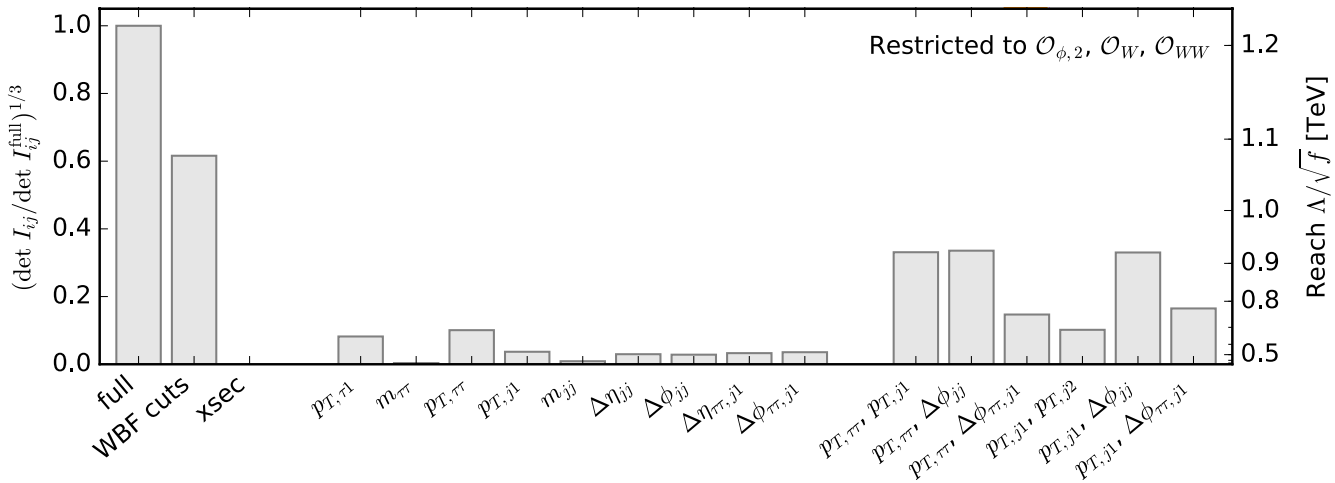
$\Rightarrow$ full statistical analysis



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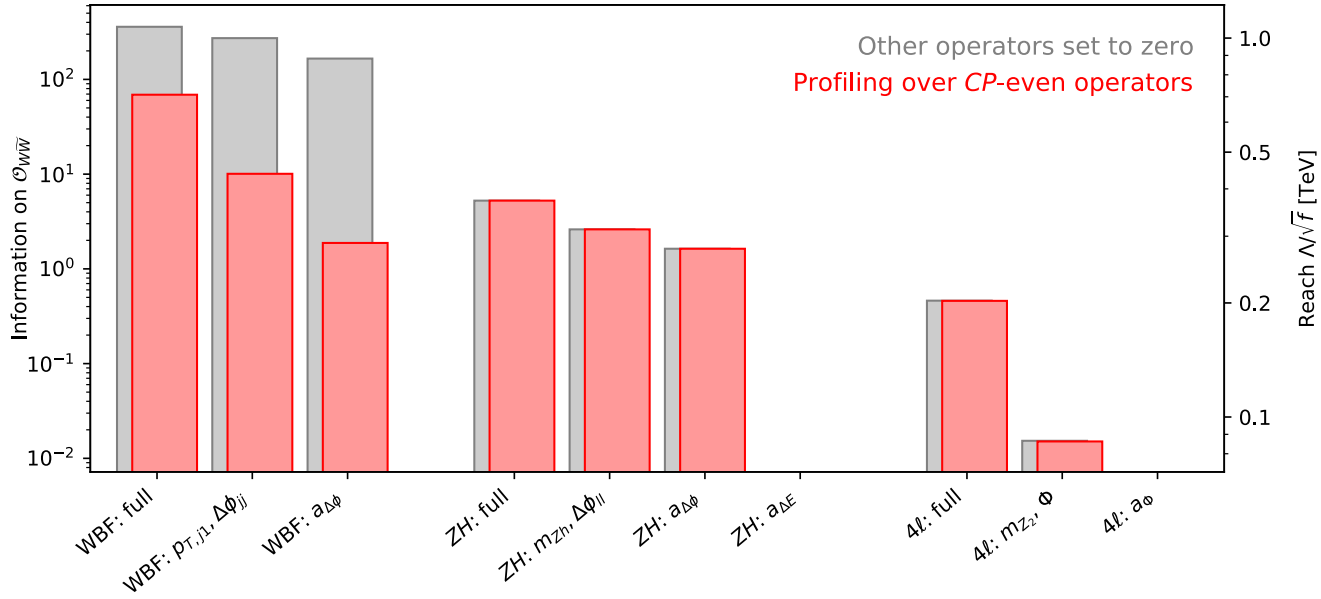
$\Rightarrow$ comparison of channels [CP-measurements]



More questions than answers

EFT consistency?

- UV-models predict patterns in D4-D6-D8, problem for matching@D6
- missing D8-operators, theory error for matching@D6
- but: limits on single Wilson coefficients make no sense

Fundamental physics from EFTs?

- symmetries assumed, not derived [better CP-tests before]
- EFT good for measurements [this is what hurts DM-EFT]
- nobody uses an EFT for an anomaly

Where are we going?

- global SMEFT analysis? [Sanz...]
- where data takes us
- for a drink [Kevin and Sandra first]

Coefficient	Z-pole + m_W	WW at LEP2	Higgs Run1	Higgs Run2	LHC WW high-p_T
$\bar{C}_{dH}$	×	×	36	64	×
$\bar{C}_{eH}$	×	×	49.6	50.4	×
$\bar{C}_G$	×	×	2.3	97.7	×
$\bar{C}_{HB}$	×	×	19	81	×
$\bar{C}_{H\Box}$	×	×	19.7	80.3	0.01
$\bar{C}_{Hd}$	99.88	×	0.04	0.07	×
$\bar{C}_{HD}$	99.92	0.06	×	×	×
$\bar{C}_{He}$	99.99	0.01	×	×	×
$\bar{C}_{HG}$	×	×	34	66	0.02
$\bar{C}^{(1)}_{H\ell}$	99.97	0.03	×	×	×
$\bar{C}^{(3)}_{H\ell}$	99.56	0.41	×	×	0.01
$\bar{C}^{(1)}_{Hq}$	99.98	×	0.01	0.01	×
$\bar{C}^{(3)}_{Hq}$	98.6	0.96	0.19	0.23	0.07
$\bar{C}_{Hu}$	99.5	×	0.2	0.3	0.04
$\bar{C}_{HW}$	×	×	18	82	×
$\bar{C}_{HWB}$	57.9	0.02	8.2	33.9	×
$\bar{C}_{\ell\ell}$	99.66	0.32	×	0.01	0.01
$\bar{C}_{uG}$	×	×	7.8	92.2	×
$\bar{C}_{uH}$	×	×	9.5	90.5	×
$\bar{C}_W$	×	96.2	×	×	3.8

Table 5: *Impact of different sets of measurements on the fit to individual Wilson coefficients in the Warsaw basis as measured by the Fisher information contained in a given dataset for each coefficient. A cross indicates no (current) sensitivity.*