Effective Higgs-Gauge Analyses

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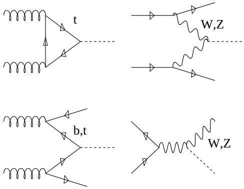
Higgs Couplings



Standard Model operators

– assume: narrow CP-even scalar
  Standard Model operators

– fundamental physics in terms of Lagrangian

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

– non-linear EWSB, no link to gauge sector

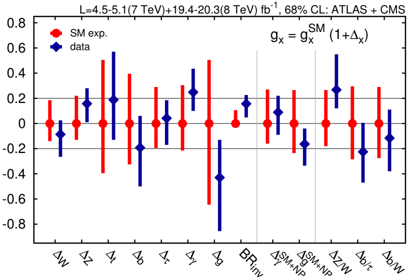
Only Run I results, not enough 13 TeV data...

[Corbett, Eboli, Goncalves, Gonzalez-Fraile, TP, Rauch]

1 electroweak renormalizability broken

2 total rates only

3 hard to relate to electroweak sector



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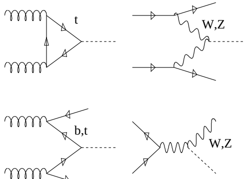

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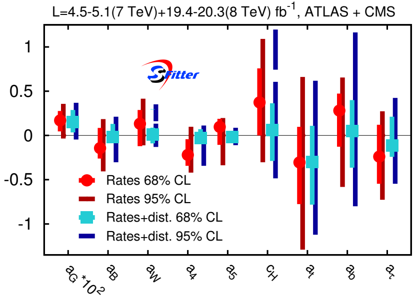

D6 Higgs operators

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

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

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

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

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

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

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– 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 Yukawa structures, #2 solved]

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

– 7 Δ-like coupling modifications

extended by 4 new Lorentz structures

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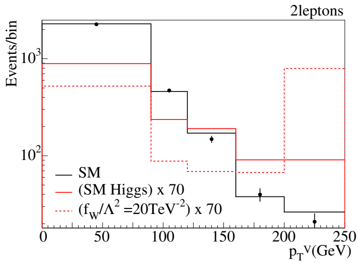
Run I legacy

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



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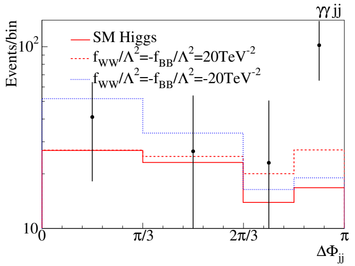

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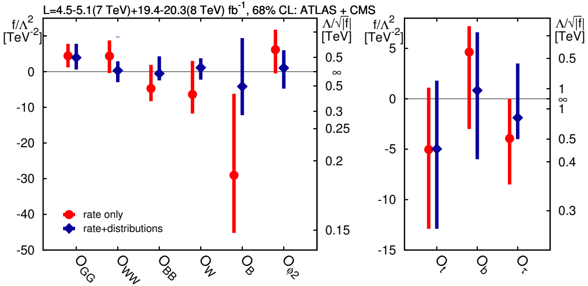

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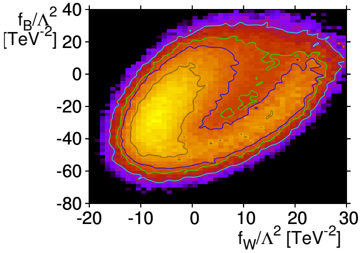

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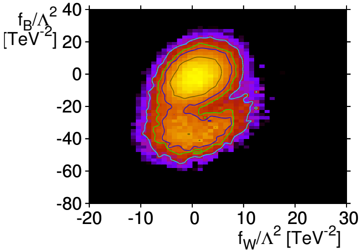

D6 Higgs-gauge operators

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

– just one more gauge operator [#3 solved]

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– pre-gauge invariance known as DeltaKappaLambda

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

$$\Delta\kappa_Z = \frac{g^2 v^2}{8 c_w^2 \Lambda^2} \left(c_w^2 f_W - s_w^2 f_B \right) \qquad \Delta g_1^Z = \frac{g^2 v^2}{8 c_w^2 \Lambda^2} f_W \qquad \lambda_Z = \frac{3 g^2 M_W^2}{2\Lambda^2} f_{WWW}$$

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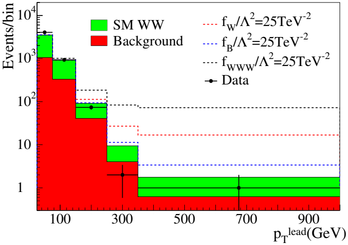

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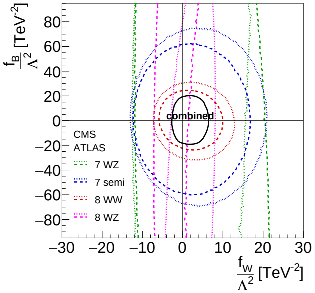

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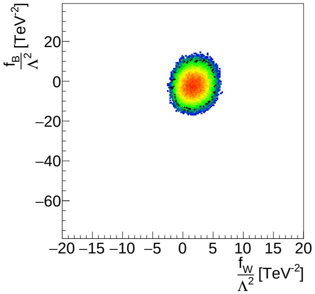

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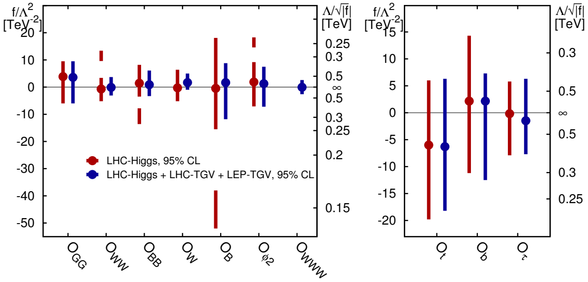
$\Rightarrow$ complete Higgs-gauge analysis



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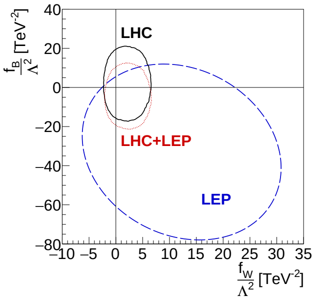
LHC vs LEP [AdamF, FrancescoR,...]

– triple gauge vertices g_1, κ, λ vs operators

– LEP limits from precision
LHC limits from energy

– semileptonic analyses missing for 8 TeV

$\Rightarrow$ LHC beating LEP, but what does it mean?



D6 Higgs-gauge operators

Example of combined Higgs+diboson fit

Fit to LHC Higgs signal strengths in Run-1 and -2 and to LEP-2 WW data

1σ constraints

$$
\begin{aligned}
\delta y_u &= -0.037 \pm 0.13 \\
\delta y_d &= -0.24 \pm 0.25 \\
\delta y_e &= -0.11 \pm 0.14 \\
c_{gg} &= -0.0006 \pm 0.001 \\
c_{\gamma\gamma} &= 0.0076 \pm 0.0072 \\
c_{z\gamma} &= -0.034 \pm 0.054 \\
\delta c_z &= -0.001 \pm 0.11 \\
\delta g_{1z} &= 0.027 \pm 0.023 \\
\delta\kappa_\gamma &= 0.11 \pm 0.07 \\
\lambda_z &= -0.13 \pm 0.061
\end{aligned}
$$

I fit previous 9 parameters affecting single Higgs production + 1 parameter (λz) affecting only diboson production. Thus 10 parameter fit in total

Correlation matrix

$$
\begin{pmatrix}
1. & 0.48 & 0.3 & -0.61 & -0.23 & -0.02 & 0.38 & 0.18 & 0.01 & -0.08 \\
0.48 & 1. & 0.73 & 0.24 & -0.04 & -0.04 & 0.84 & 0.26 & -0.19 & 0.01 \\
0.3 & 0.73 & 1. & 0.22 & -0.18 & -0.06 & 0.55 & 0.04 & -0.28 & 0.14 \\
-0.61 & 0.24 & 0.22 & 1. & 0.29 & 0. & 0.13 & 0.08 & 0. & -0.03 \\
-0.23 & -0.04 & -0.18 & 0.29 & 1. & 0.09 & 0.35 & 0.54 & 0.54 & -0.51 \\
-0.02 & -0.04 & -0.06 & 0. & 0.09 & 1. & -0.01 & 0.16 & 0.03 & -0.07 \\
0.38 & 0.84 & 0.55 & 0.13 & 0.35 & -0.01 & 1. & 0.5 & 0.06 & -0.22 \\
0.18 & 0.26 & 0.04 & 0.08 & 0.54 & 0.16 & 0.5 & 1. & 0.79 & -0.82 \\
0.01 & -0.19 & -0.28 & 0. & 0.54 & 0.03 & 0.06 & 0.79 & 1. & -0.87 \\
-0.08 & 0.01 & 0.14 & -0.03 & -0.51 & -0.07 & -0.22 & -0.82 & -0.87 & 1.
\end{pmatrix}
$$

- Under MFV assumption, current Higgs signal strength measurements together with LEP-2 WW data simultaneously constrain all 10 linear combinations of CP-even dimension-6 operators contributing to single Higgs and diboson observables at leading order and not contributing to electroweak precision observables at this order
- Combining LHC and LEP-2 leads to better constraints on 3 CP-even ATGCs and reduced correlations

[AdamF]

That other gauge theory

The most nasty D6 operator [Krauss, Kuttimalai, TP; ChrisH]

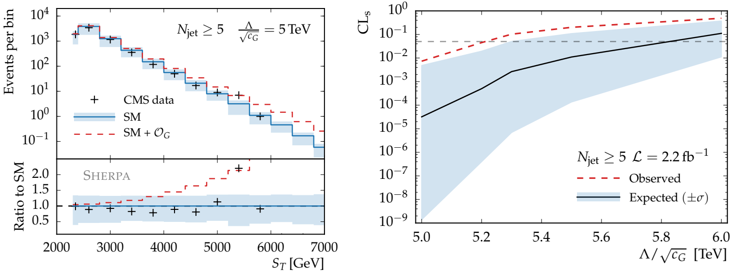
– making sense of black hole searches

$$S_T \approx \sum_{\text{jets}} E_T$$

– dimension-6 operators [MichelangeloM: check more 4-fermions]

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

$\Rightarrow$ new physics $M \gtrsim 5$ TeV



Self consistency

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 expansions in E/Λ and α [example: ew precision data]

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Rotten LHC world

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

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

– low precision, reach from energy

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

$$\stackrel{g=\sqrt{4\pi}}{\Longleftrightarrow} \quad \Lambda \approx 1.4 \text{ TeV}$$

$\Rightarrow$ systematic EFT probably not valid

cutoff scale dependent on UV completion [FrancescoR]

Matching matters

Example: oblique parameters from Higgs portal vs D6 [Freitas, Lopez-Val, TP; Trott etal]

$$\mathcal{L}_{\text{EFT}} \supset \frac{c_H}{2\Lambda^2} \partial^\mu (\phi^\dagger \phi) \partial_\mu (\phi^\dagger \phi) + \frac{c_T}{2\Lambda^2} (\phi^\dagger \overleftrightarrow{D}^\mu \phi)(\phi^\dagger \overleftrightarrow{D}_\mu \phi) + \frac{igc_W}{2\Lambda^2} (\phi^\dagger \sigma^k \overleftrightarrow{D}^\mu \phi) D^\nu W^k_{\mu\nu}$$

– predictions of Higgs portal model [$m_H \approx 2\lambda_2 v_s^2,\ s_\alpha^2 \approx \lambda_3^2 v^2/(2\lambda_2 m_H^2)$]

$$S \approx \frac{\lambda_3^2}{24\pi\lambda_2} \frac{v^2}{m_H^2} \log \frac{m_H^2}{m_h^2} \qquad T \approx \frac{-3\lambda_3^2 v^2}{32\pi\, s_w^2\, \lambda_2\, m_W^2} \left(\frac{m_Z^2}{m_H^2} - \frac{m_W^2}{m_H^2} \right) \log \frac{m_H^2}{m_h^2}$$

– leading log for tree-insertion of loop operators $\mathcal{O}_{T,B,W}$ [$\Lambda^2 = 2\lambda_2 v_s^2$]

$$\frac{c_H}{\Lambda^2} = \frac{\lambda_3^2}{2\lambda_2\Lambda^2} \qquad \frac{c_T}{\Lambda^2} = -\frac{3\alpha_{\text{ew}} s_w^2 \lambda_3^2}{32\pi c_w^2 \lambda_2 \Lambda^2} \log \frac{\Lambda^2}{\mu^2} \qquad \frac{c_{B,W}}{\Lambda^2} = \frac{\lambda_3^2}{192\pi^2 \lambda_2 \Lambda^2} \log \frac{\Lambda^2}{\mu^2}$$

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$$\mathcal{L}_{\text{EFT}} \supset \frac{c_H}{2\Lambda^2}\partial^\mu(\phi^\dagger\phi)\partial_\mu(\phi^\dagger\phi) + \frac{c_T}{2\Lambda^2}(\phi^\dagger \overleftrightarrow{D}^\mu \phi)(\phi^\dagger \overleftrightarrow{D}_\mu \phi) + \frac{igc_W}{2\Lambda^2}(\phi^\dagger \sigma^k \overleftrightarrow{D}^\mu \phi) D^\nu W^k_{\mu\nu}$$

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– leading log for tree-insertion of loop operators $\mathcal{O}_{T,B,W}$ $[\Lambda^2 = 2\lambda_2 v_s^2]$

$$\frac{c_H}{\Lambda^2} = \frac{\lambda_3^2}{2\lambda_2\Lambda^2} \qquad \frac{c_T}{\Lambda^2} = -\frac{3\alpha_{\text{ew}} s_w^2 \lambda_3^2}{32\pi c_w^2 \lambda_2 \Lambda^2}\log\frac{\Lambda^2}{\mu^2} \qquad \frac{c_{B,W}}{\Lambda^2} = \frac{\lambda_3^2}{192\pi^2\lambda_2\Lambda^2}\log\frac{\Lambda^2}{\mu^2}$$

– v-improvement: $\Lambda = m_H$ and full model in terms of c_α

$$\frac{c_H}{\Lambda^2} = \frac{2(1-c_\alpha)}{v^2} \qquad \frac{c_T}{\Lambda^2} = -\frac{3\alpha_{\text{ew}} s_w^2 (1-c_\alpha)}{8\pi c_w^2\, v^2}\log\frac{m_H^2}{\mu^2} \qquad \frac{c_{B,W}}{\Lambda^2} = \frac{1-c_\alpha}{48\pi^2 v^2}\log\frac{m_H^2}{\mu^2}$$

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– broken-phase matching: systematically all terms v/Λ

$$\frac{c_T}{\Lambda^2} = -\frac{\alpha_{\text{ew}} s_w^2(1-c_\alpha)}{8\pi c_w^2 v^2}\left(-\frac{5}{2} + 3\log\frac{m_H^2}{\mu^2}\right) \qquad \frac{c_{B,W}}{\Lambda^2} = \frac{1-c_\alpha}{144\pi^2 v^2}\left(-\frac{5}{2} + 3\log\frac{m_H^2}{\mu^2}\right)$$

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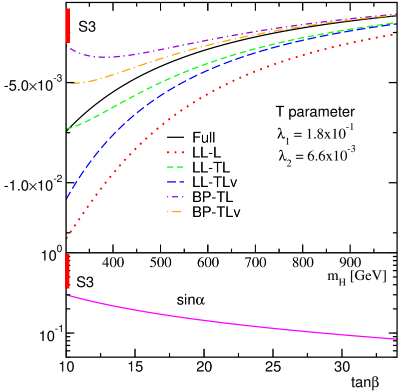
– broken-phase matching: systematical

$$\frac{c_T}{\Lambda^2} = -\frac{\alpha_{\text{ew}} s_w^2 (1-c_\alpha)}{8\pi c_w^2 v^2}\left(-\frac{5}{2} + 3\log\frac{m_H^2}{\mu^2}\right.$$



⇒ D8 effects testing what?

Self consistency at LHC

D6 Lagrangian at face value [Brehmer, Freitas, Lopez-Val, TP]

1 push (simplified) models to visible deviations at LHC
Higgs portal, 2HDM, stops, vector triplet [weakly interacting]

2 construct and match D6-Lagrangian to model
coupling modifications v^2/Λ^2 vs new kinematics ∂/Λ?

3 LHC simulations: D6-Lagrangian vs full model
production: WBF, VH, HH
decays: $H \to \gamma\gamma, 4\ell$

$\Rightarrow$ check for peaks in $p_{T,j}$ or m_{VH},...

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Ensuring self consistency [Monday discussion]

– not use high-virtuality data [Mawatari]
psychologically bad for sensitive experimentalists

– define theory hypothesis with form factors [cutoff?]
not the theory we want to test

– D6 Lagrangian at face value, but matching uncertainties
well-defined, complete, just a little more work for theorists

Kinematic distributions

Kinematical information for example on effective Lagrangian

– simple p_T, m_{ij}, ϕ_{ij} trivially included [Butter etal]

– correlations hard, check impact

– full phase space: BDT/NN-variable-weighting

$\Rightarrow$ phase space patterns understood?

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Kinematics for gauge boson production [Panico, Pomarol, Riva, Wulzer]

Extracting the longitudinal channel

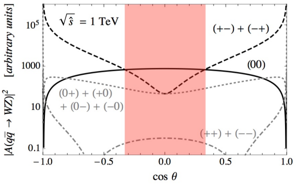
Transverse amplitudes vanish for (nearly) central scattering

[Baur, Han, Ohnemus '94]

$$A_{(+-)}(u\bar{d} \to WZ)\,, \quad A_{(-+)}(u\bar{d} \to WZ) \propto \cos\theta - \frac{1}{3}\tan\theta_W$$

✦ longitudinal amplitude dominates for $\theta \sim 90°$

✦ cuts in $\hat{s}$ and $\cos\theta$ can be used to isolate the longitudinal channel



13 TeV		σ_{tot}	σ_{LL}	σ_{LL}/σ_{tot}
$\lvert\cos\theta\rvert < 0.5$	$\sqrt{\hat{s}} > 300$ GeV	630 fb	230 fb	37%
$\lvert\cos\theta\rvert < 0.5$	$\sqrt{\hat{s}} > 500$ GeV	80 fb	34 fb	42%

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Beyond distributions [That was 90s]

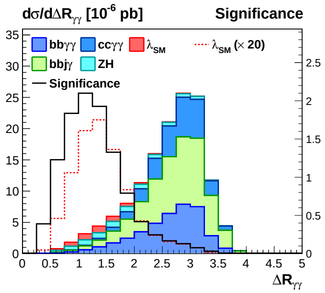
– Log-likelihood estimator for hypothesis testing [MadMax: Cranmer, Kling, TP, Schichtel, Wiegand]

$\rightarrow$ Neyman-Pearson lemma

$\rightarrow$ phase space integration

$\rightarrow$ statistics limiting factor

$\rightarrow$ significance distribution [$HH \to b\bar{b}\gamma\gamma$]



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$\rightarrow$ significance distributions

– Fisher information for parameter estimate [MadFisher: Brehmer, Cranmer, Kling, TP]

$\rightarrow$ Cramer-Rao bound

$\rightarrow$ phase space integration

$\rightarrow$ statistics limiting factor

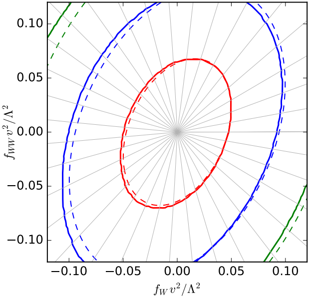
$\rightarrow$ information distributions

$\Rightarrow$ LHC theorists: smell the coffee...

Information geometry

Applied to D6 in WBF $H \to \tau\tau$ [Brehmer, Cranmer, Kling, T

– correlations in Wilson coefficient space



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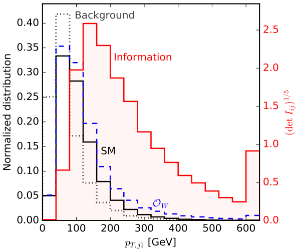

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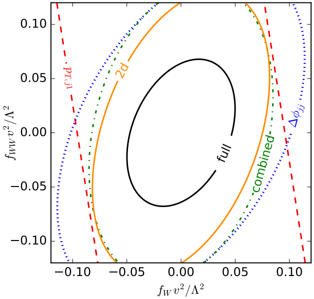
– 1D, 2D distributions vs full phase space



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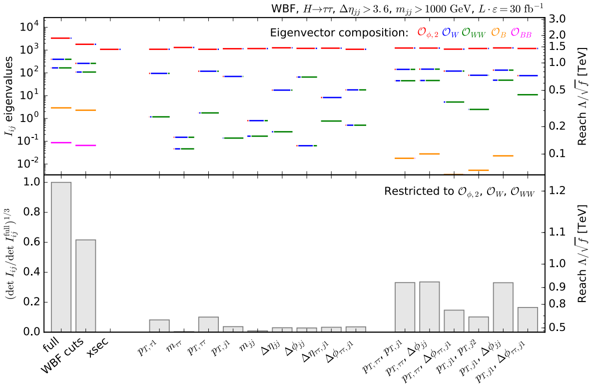
$\Rightarrow$ full statistical analysis: multi-variate wins



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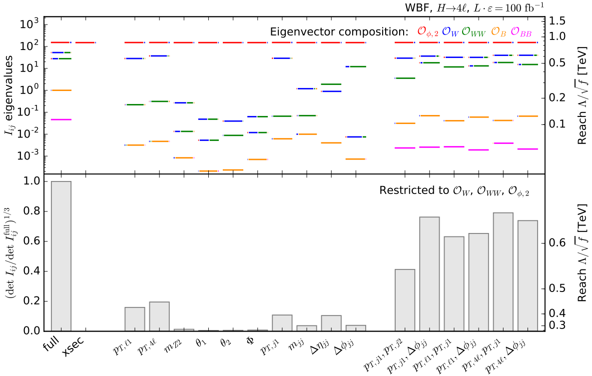
Combined with decay $H \to 4\ell$

– precision vs energy

$\Rightarrow$ energy wins



Bottom line

Higgs and electroweak sectors same thing [linear representation]

dimension-6 Higgs-gauge LHC analysis working [Butter etal, Falkowski etal]

effective Lagrangian validated through full models

uncertainties part of matching

distributions the key, not obviously easy...