How to Measure Higgs Couplings

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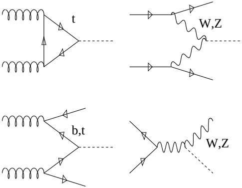
Universität Heidelberg

Irvine, March 2017

A Butter... 1604.03105, A Freitas... 1607.08251, A Biekotter... 1602.05202

Higgs couplings



Standard Model operators [historic slide]

– assume: narrow CP-even scalar
  Standard Model operators

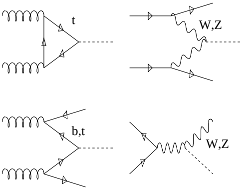
– couplings proportional to masses?

– fundamental physics in terms of Lagrangian

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

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

Higgs couplings



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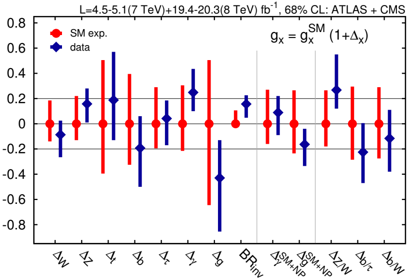
Great Run I results, but issues... [Corbett, Eboli, Goncalves, Gonzalez-Fraile, TP, Rauch]

1 electroweak renormalizability broken

2 total rates only

3 hard to relate to gauge, flavor sectors



D6 Higgs operators

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

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

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

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

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

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

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

– 7 Δ-like coupling modifications

4 new Lorentz structures

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– linking couplings and operators

$$g_g = \frac{f_{GG} v}{\Lambda^2} \equiv -\frac{\alpha_s}{8\pi} \frac{f_g v}{\Lambda^2} \qquad g_\gamma = -\frac{g^2 v s_w^2}{2\Lambda^2} \frac{f_{BB} + f_{WW}}{2}$$

$$g_Z^{(1)} = \frac{g^2 v}{2\Lambda^2} \frac{c_w^2 f_W + s_w^2 f_B}{2 c_w^2} \qquad g_W^{(1)} = \frac{g^2 v}{2\Lambda^2} \frac{f_W}{2}$$

$$g_Z^{(2)} = -\frac{g^2 v}{2\Lambda^2} \frac{s_w^4 f_{BB} + c_w^4 f_{WW}}{2 c_w^2} \qquad g_W^{(2)} = -\frac{g^2 v}{2\Lambda^2} f_{WW}$$

$$g_Z^{(3)} = \frac{g^2 v}{4 c_w^2} \left(1 - \frac{v^2}{2\Lambda^2} f_{\phi,2}\right) \qquad g_W^{(3)} = \frac{g^2 v}{4} \left(1 - \frac{v^2}{2\Lambda^2} f_{\phi,2}\right)$$

$$g_f = -\frac{m_f}{v} \left(1 - \frac{v^2}{2\Lambda^2} f_{\phi,2}\right) + \frac{v^2}{\sqrt{2}\Lambda^2} f_f$$

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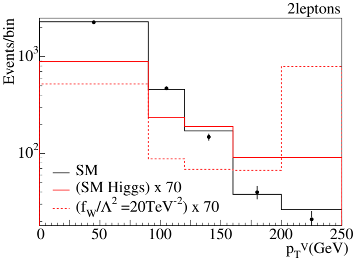
Run 1 legacy

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



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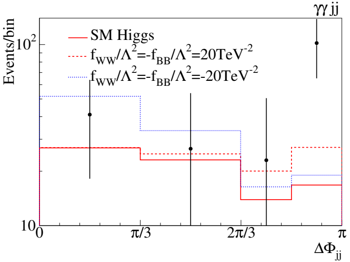

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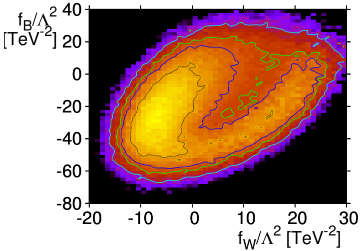
– with impact...



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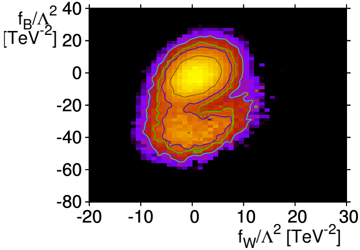
...in last bin



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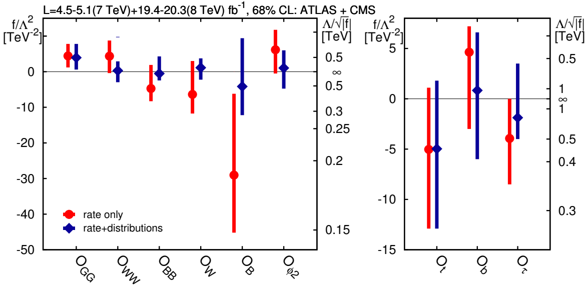

D6 Higgs-gauge operators

Triple gauge couplings

– one more Higgs-gauge operator [#3 solved]

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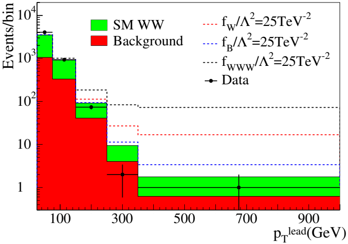

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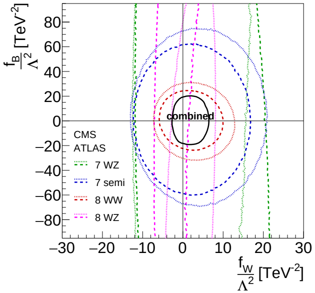

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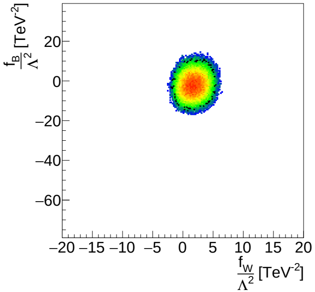

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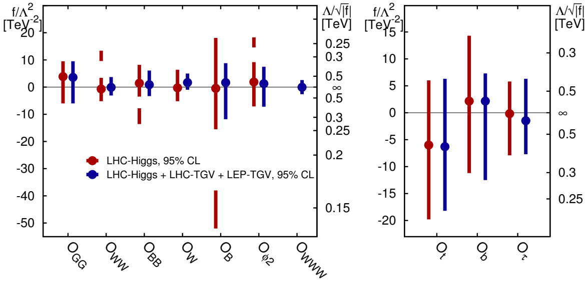
⇒ complete Higgs-gauge analysis



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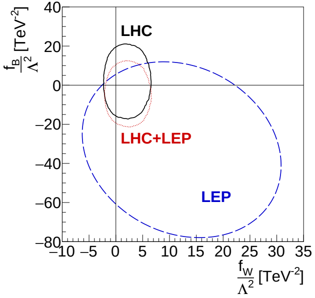
LHC vs LEP

– triple gauge vertices g_1, κ, λ vs operators

– LEP limits from precision
LHC limits from energy

– semileptonic analyses missing for 8 TeV

⇒ LHC beating LEP, but what does it mean?



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

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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

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

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Task for LHC theory

– develop a working D6 framework
or find a better approach, test it, include in Monte Carlos...

– keep theorist's self respect

– remember we really care about UV models

EFT strategy at LHC

What does the D6 analysis at LHC mean? [Brehmer, Freitas, Lopez-Val, TP]

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

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?
v-improved and broken phase matching

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

$\Rightarrow$ check for differences
kinematic distributions like $p_{T,j}$ or m_{VH}?
resonance peaks of new states?

$\Rightarrow$ consider uncertainties as matching uncertainties

Matching matters

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

– operators

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

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

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

– including weak-scale loops including $\mathcal{O}_H$

$$\frac{c_H}{\Lambda^2} = \frac{\lambda_3^2}{2\lambda_2\Lambda^2}\ .$$

– v-improvement: $\Lambda = m_H$ and full model in terms of c_α [resumming VEV insertions]

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

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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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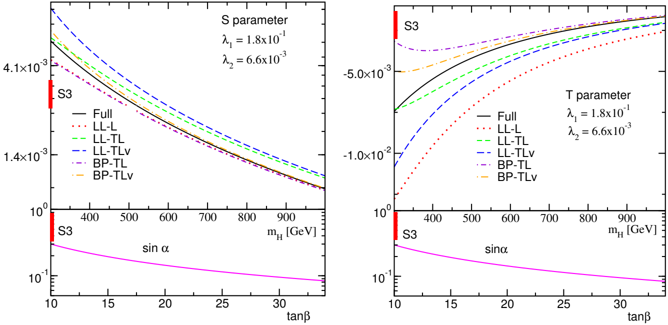
– numerical comparison [$\tan\beta = v/v_s$]



– similar analysis for loop-induced $H \to \gamma\gamma$

$\Rightarrow$ D6 Lagrangian systematically improved

EFT representing models

Higgs singlet/doublet extensions [Higgs portal]

– mixing with SM-like Higgs, not too interesting

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– additional vector triplet field V_μ

– Lagrangian modulo UV completion

$$\mathcal{L} \supset -\frac{1}{4}\tilde{V}^a_{\mu\nu}\tilde{V}^{\mu\nu a} + \frac{M^2_{\tilde{V}}}{2}\tilde{V}^a_\mu \tilde{V}^{\mu a} + i\frac{g_V}{2}c_H \tilde{V}^a_\mu \left[\phi^\dagger \sigma^a \overleftrightarrow{D}^\mu \phi\right] + \frac{g_w^2}{2g_V}\tilde{V}^a_\mu \sum_{\text{fermions}} c_F \overline{F}_L \gamma^\mu \sigma^a F_L$$
$$+ \frac{g_V}{2}c_{VVV}\epsilon_{abc}\tilde{V}^a_\mu \tilde{V}^b_\nu D^{[\mu}\tilde{V}^{\nu]c} + g_V^2 c_{VVHH}\tilde{V}^a_\mu \tilde{V}^{\mu a}(\phi^\dagger\phi) - \frac{g_w}{2}c_{VVW}\epsilon_{abc}W^{\mu\nu}\tilde{V}^b_\mu \tilde{V}^c_\nu$$

– new states, mixing with $W^\pm$ and Z
weak gauge coupling to W, Z mass eigenstates

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Triplet model						EFT			
M_V	g_V	c_H	c_F	c_{VVHH}	m_ξ	$\bar{c}_W$	$\bar{c}_H$	$\bar{c}_6$	$\bar{c}_f$
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

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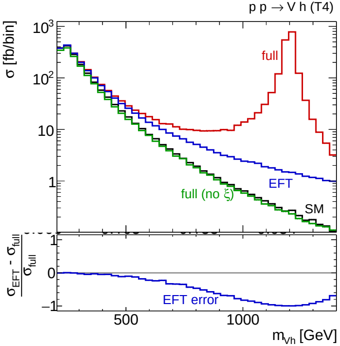
– effects in Vh and WBF



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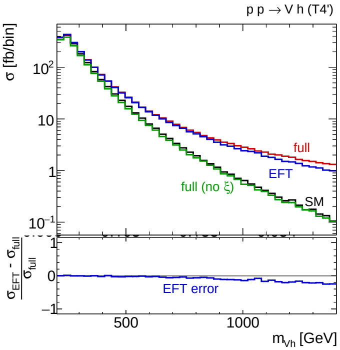

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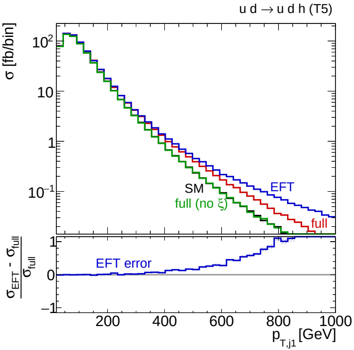
$\Rightarrow$ D6 Lagrangian okay, if away from poles



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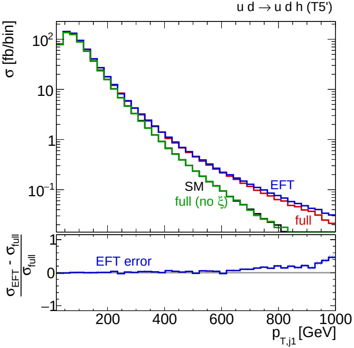

DUH!

D6 QCD operators

Ubiquitous QCD operator [TP, Krauss, Kuttimalai]

– anomalous gluon coupling

$$c_G \mathcal{O}_G = \frac{g_s\, c_G}{\Lambda^2}\, f_{abc} G^{\rho}_{a\nu} G^{\nu}_{b\lambda} G^{\lambda}_{c\rho} \qquad \text{with} \quad G^{\rho\nu}_a = \partial^\rho G^\nu_a - \partial^\nu G^\rho_a - i g_s f_{abc} G^{b\rho} G^{c\nu}$$

– affecting multi-jet production [CMS black hole search]

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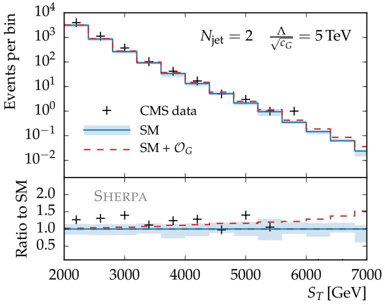

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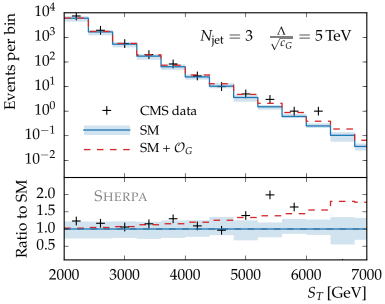

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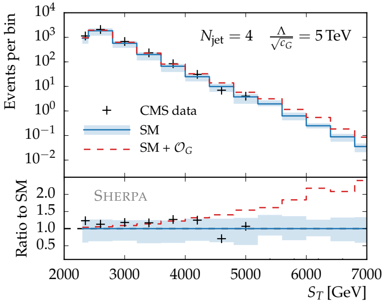

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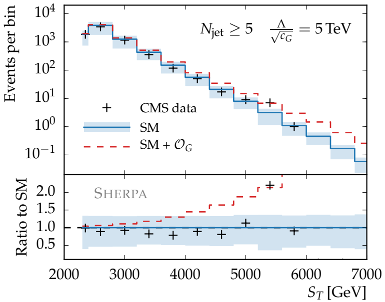

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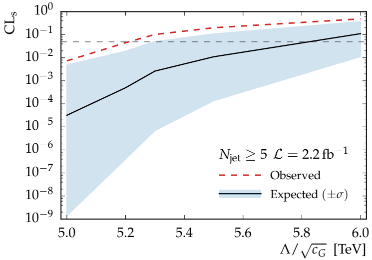
– 4-fermion operators from ATLAS $\Lambda/\sqrt{c} > 4.8 \ldots 6.8$ TeV

$\Rightarrow$ gluon operator $\Lambda/\sqrt{c} > 5.2$ TeV $\sim S_\text{max}$



D6 top operators

EFT for tops@LHC [TopFitter: Buckley, Englert, Ferrando, Miller, Moore, Russell, White]

– single, pair-wise, and associated top production [plus decays]

– including anomalous A_{FB} from Tevatron

– 4-quark, Yang-Mills, electroweak operators

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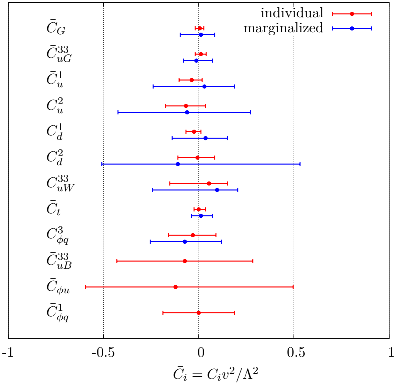
– profile likelihoods and individual limits

⇒ generic D6 reach $\sim$ 500 GeV [$C = 1$]



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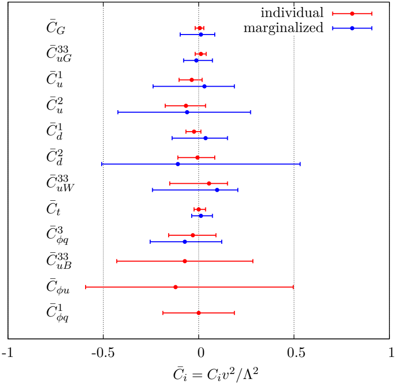

For theorists: in terms of models

– axigluon: $M_A > 1.4$ TeV [$t\bar{t}$ resonance]
– SM-like W': $M_{W'} > 1.2$ TeV [t-channel,...]
⇒ models less sensitive to correlations

Questions

Where we stand with LHC theory

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]

Can we use first-principle EFT at LHC? [no]

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

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

$\Rightarrow$ Welcome to a data-driven era! [it sucks]

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Bundesministerium für Bildung und Forschung