LHC Physics in a Data-Driven Era

Tilman Plehn

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Theory in a data-driven era

Same old theory motivation

– dark matter still not understood [WIMP still best choice]

– hierarchy problem (probably) a problem

– but: data in driving seat [remember 750]

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Theory tool box

– Lagrangian language obvious after Higgs discovery
1 full new physics model [built to solve problems, last lecture]
2 simplified models [Feynman diagrams for experimental features, theoretically poor at best]
3 effective Lagrangians [symmetries and particles fixed, non-renormalizable operators, SMEFT]
⇒ matter of experimental needs, convenience and taste

	effective Lagrangian	simplified models	full models
agnostic	$(\times)$		
data-driven		$(\times)$	$(\times)$
theory-driven		$(\times)$	

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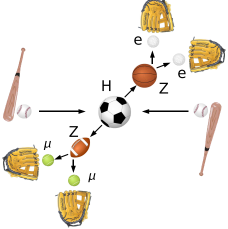
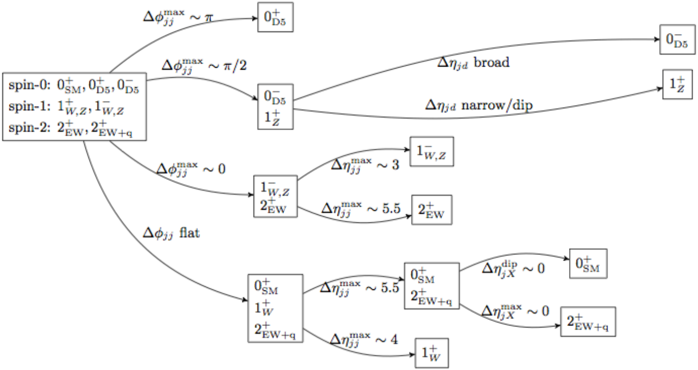
data-driven	boring	$(\times)$	$(\times)$
theory-driven	pointless	$(\times)$	pre-LHC

Higgs questions



1. What is the 'Higgs' field?

- psychologically: looked for Higgs, so found a Higgs
- CP-even spin-0 scalar expected, which operators?
  spin-1 vector unlikely
  spin-2 graviton unexpected
- ask LHCb [Cabibbo–Maksymowicz–Dell'Aquila–Nelson angles, not part of lecture]



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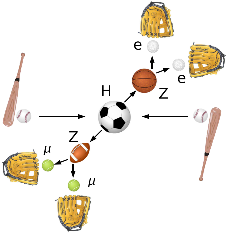

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- naive-but-useful: set of 'couplings' given Lagrangian
- bottom-up: effective theory [simplified models?]
- top-down: modified Higgs sectors

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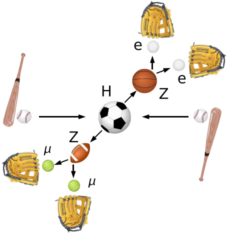

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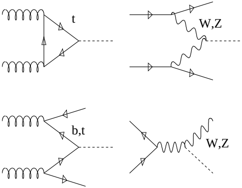
3. What does all this tell us? [not part of lecture]

- strongly interacting models?
- weakly interacting extensions?
- TeV-scale physics, hierarchy problem, vacuum stability, Higgs inflation, etc

Higgs Couplings



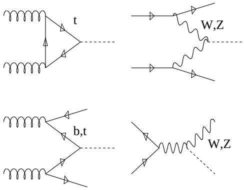
Standard Model operators [historic slide]

- assume: narrow CP-even scalar
  Standard Model operators
- couplings proportional to masses?
- fundamental physics in terms of Lagrangian

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

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

Higgs Couplings



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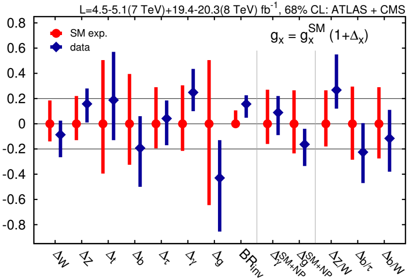
Great Run I results, but issues... [Corbett, Eboli, Goncalves, Gonzalez-Fraile, TP, Rauch]

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]

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– actual basis after equation of motion, etc

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

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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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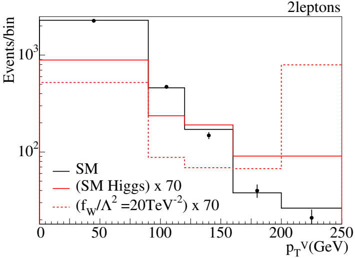
Run 1 legacy

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



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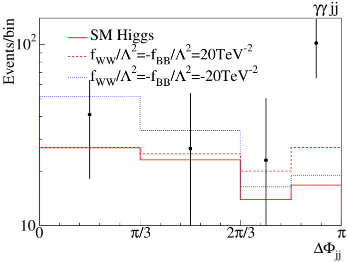

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Higgs Coupl's
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Consistency
QCD EFT
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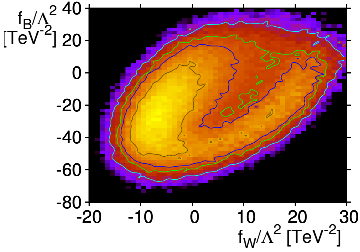

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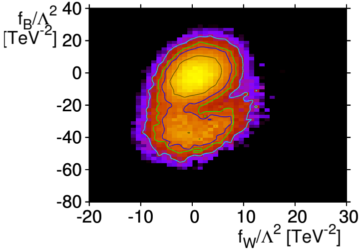
...in last bin



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

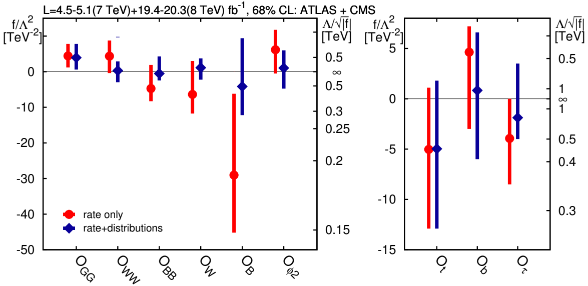
Run 1 legacy

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

– with impact...

...in last bin

– Run I limits



Exercise: higher-dimensional operators

Higgs sector including dimension-6 operators

$$\mathcal{L}_{D6} = \sum_{i=1}^{2} \frac{f_i}{\Lambda^2} \mathcal{O}_i \quad \text{with} \quad \mathcal{O}_{\phi,2} = \frac{1}{2} \partial_\mu (\phi^\dagger \phi) \, \partial^\mu (\phi^\dagger \phi) \; , \quad \mathcal{O}_{\phi,3} = -\frac{1}{3} (\phi^\dagger \phi)^3$$

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first operator, wave function renormalization

$$\mathcal{O}_{\phi,2} = \frac{1}{2} \partial_\mu (\phi^\dagger \phi) \, \partial^\mu (\phi^\dagger \phi) = \frac{1}{2} \, (\tilde{H} + v)^2 \, \partial_\mu \tilde{H} \, \partial^\mu \tilde{H}$$

proper normalization of combined kinetic term [LSZ]

$$\mathcal{L}_{\text{kin}} = \frac{1}{2} \partial_\mu \tilde{H} \, \partial^\mu \tilde{H} \left(1 + \frac{f_{\phi,2} v^2}{\Lambda^2} \right) \stackrel{!}{=} \frac{1}{2} \partial_\mu H \, \partial^\mu H \quad \Leftrightarrow \quad H = \tilde{H} \sqrt{1 + \frac{f_{\phi,2} v^2}{\Lambda^2}}$$

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second operator, minimum condition giving v

$$v^2 = -\frac{\mu^2}{\lambda} - \frac{f_{\phi,3} \mu^4}{4 \lambda^3 \Lambda^2}$$

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both operators contributing to Higgs mass

$$\mathcal{L}_{\text{mass}} = -\frac{\mu^2}{2} \tilde{H}^2 - \frac{3}{2} \lambda v^2 \tilde{H}^2 - \frac{f_{\phi,3}}{\Lambda^2} \frac{15}{24} v^4 \tilde{H}^2 \stackrel{!}{=} -\frac{m_H^2}{2} H^2$$

$$\Leftrightarrow \qquad m_H^2 = 2 \lambda v^2 \left(1 - \frac{f_{\phi,2} v^2}{\Lambda^2} + \frac{f_{\phi,3} v^2}{2 \Lambda^2 \lambda} \right)$$

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Higgs self couplings momentum dependent

$$\begin{aligned} \mathcal{L}_{\text{self}} = &- \frac{m_H^2}{2v} \left[\left(1 - \frac{f_{\phi,2} v^2}{2\Lambda^2} + \frac{2 f_{\phi,3} v^4}{3 \Lambda^2 m_H^2} \right) H^3 - \frac{2 f_{\phi,2} v^2}{\Lambda^2 m_H^2} H \, \partial_\mu H \, \partial^\mu H \right] \\ &- \frac{m_H^2}{8v^2} \left[\left(1 - \frac{f_{\phi,2} v^2}{\Lambda^2} + \frac{4 f_{\phi,3} v^4}{\Lambda^2 m_H^2} \right) H^4 - \frac{4 f_{\phi,2} v^2}{\Lambda^2 m_H^2} H^2 \, \partial_\mu \, H \partial^\mu H \right] \end{aligned}$$

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alternatively, strong multi-Higgs interactions

$$H = \left(1 + \frac{f_{\phi,2} v^2}{2\Lambda^2} \right) \tilde{H} + \frac{f_{\phi,2} v}{2\Lambda^2} \tilde{H}^2 + \frac{f_{\phi,2}}{6\Lambda^2} \tilde{H}^3 + \mathcal{O}(\tilde{H}^4)$$

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$\Rightarrow$ operators and distributions linked to (poor) UV behavior

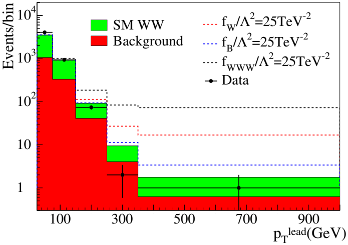
D6 Higgs-gauge operators

Triple gauge couplings

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

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

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



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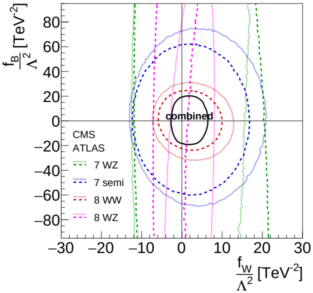

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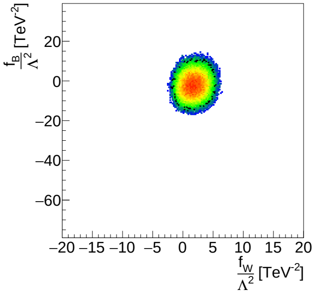

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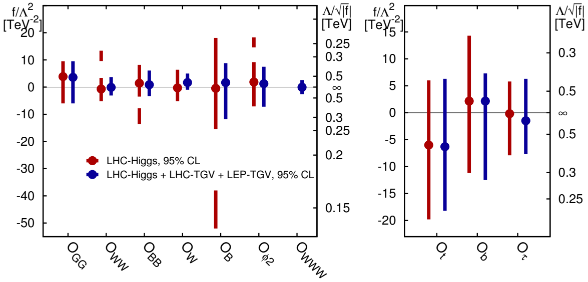

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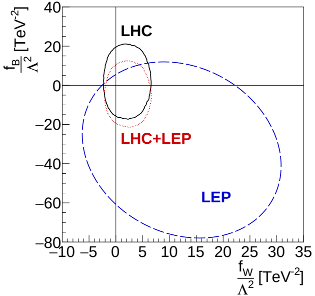
LHC vs LEP

– triple gauge vertices g_1, κ, λ vs operators

– LEP limits from precision
LHC limits from energy

– semileptonic analyses missing for 8 TeV

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



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 [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

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

$\Rightarrow$ D8 operators not obviously suppressed

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Task for LHC theory

– develop a working D6 framework
– keep theorist's self respect
– validate as representation of full models [forget D8 estimates]

Matching matters

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

– 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 with $\mathcal{O}_H$

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

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

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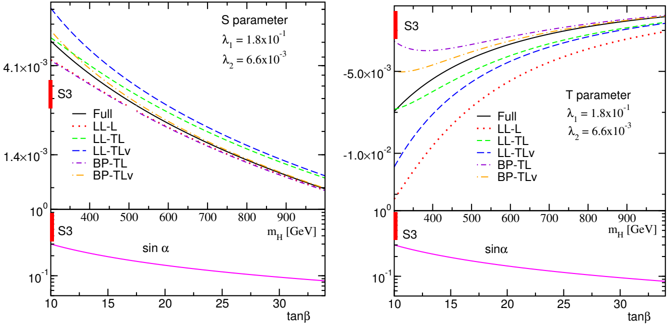
– numerical comparison [$\tan\beta = v/v_S$]



– similar analysis for loop-induced $H \to \gamma\gamma$ [Trott etal]

$\Rightarrow$ D6 Lagrangian systematically improved

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

Model by model...

Higgs singlet/doublet extensions [Higgs portal]

– mixing with SM-like Higgs, not too interesting

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Triplet gauge extension [Brehmer, Biekötter, TP]

– 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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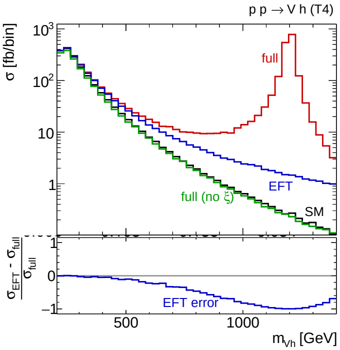
– effects in Vh and WBF



Model by model...

Higgs singlet/doublet extensions [Higgs portal]

– mixing with SM-like Higgs, not too interesting

Scalar top partners [simplified supersymmetry]

– loop contributions everywhere, small, not too interesting

Triplet gauge extension [Brehmer, Biekötter, TP]

– additional vector triplet field V_μ

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

Triplet model					
M_V	g_V	c_H	c_F	c_{VVHH}	m_ξ
591	3.0	-0.47	-5.0	2.0	1200
946	3.0	-0.47	-5.0	1.0	1200
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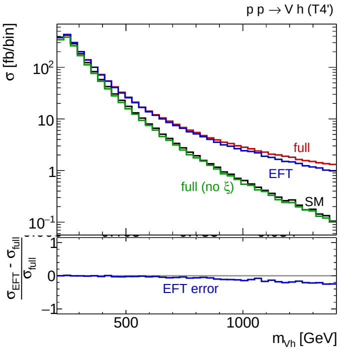

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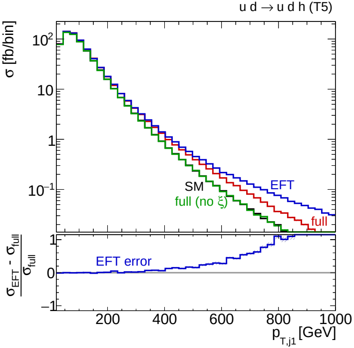

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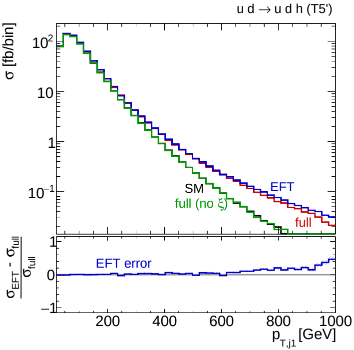

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DUH!

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]

$$S_T = \sum_{j=1}^{N_\text{jets}} E_{T,j} + (\not{p}_T > 50 \ \text{GeV})$$

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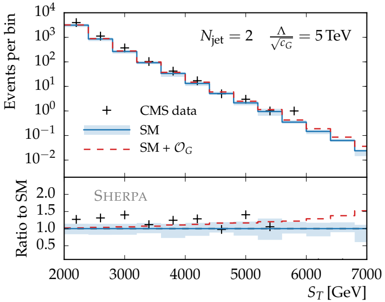
gluon operator for $N_\text{jets} \geq 5$ [Sherpa]



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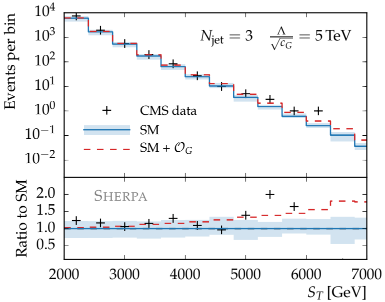

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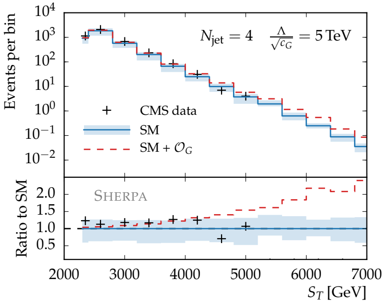

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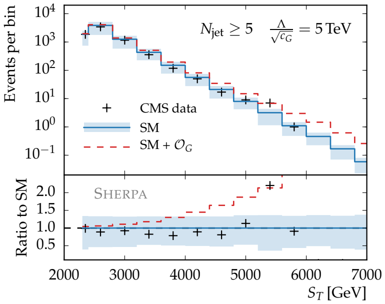

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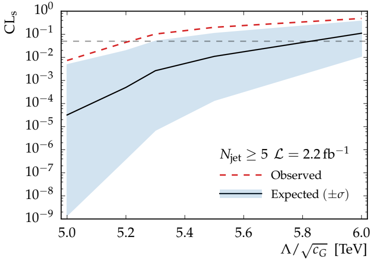
– 4-fermion operators from ATLAS $\Lambda/\sqrt{c} > 4.8 \ldots 6.8$ TeV

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



YEAH!

D6 top operators

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

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

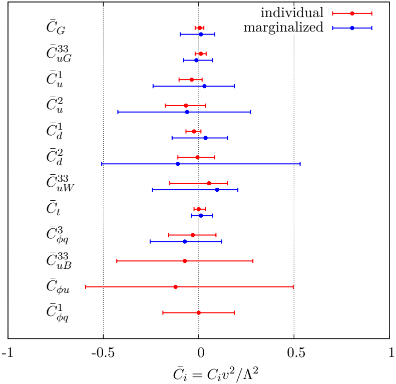
– including anomalous A_{FB} from Tevatron

– 4-quark, Yang-Mills, electroweak operators

$$\mathcal{O}_{qq} = \bar{q}\gamma_\mu q \; \bar{t}\gamma^\mu t \qquad \mathcal{O}_G = f_{ABC} G_\mu^{A\nu} G_\nu^{B\lambda} G_\lambda^{C\mu} \qquad \mathcal{O}_{\phi G} = \phi^\dagger \phi G^a_{\mu\nu} G^{a\mu\nu} \cdots$$

– profile likelihoods and individual limits

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



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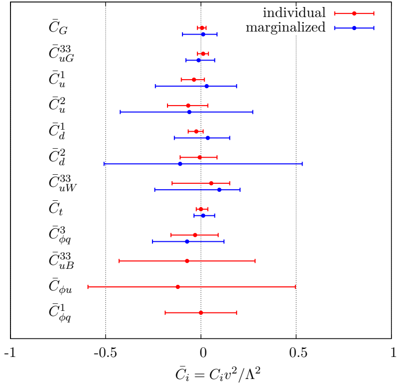

For theorists: in terms of models

– axigluon: $M_A > 1.4$ TeV [$t\bar{t}$ resonance]

– SM-like W': $M_{W'} > 1.2$ TeV [t-channel,...]

$\Rightarrow$ models less sensitive to correlations

D6 dark matter operators

Combining direct, indirect, collider results for WIMPs [Tait etal]

- choose dark matter candidate [Majorana/Dirac fermion, scalar, dark photon]
- consider D6 scattering process $\chi\chi \to$ SM SM
- relic density from annihilation [$m_\chi / T \sim 30$]
- indirect detection even later
- direct detection non-relativistic [$E \sim 10$ MeV]
- LHC tricky: single scale $m_\chi \ll m_{\text{mediator}}$?
- example: scalar dark matter

Label	Coefficient	Operator	σ_{SI}	$\langle \sigma_{\text{ann}} v \rangle$
		Real scalar		
R1	$\lambda_1 \sim 1/(2M^2)$	$m_q \chi^2 \bar{q} q$	✓	s-wave
R2	$\lambda_2 \sim 1/(2M^2)$	$i m_q \chi^2 \bar{q} \gamma^5 q$		s-wave
R3	$\lambda_3 \sim \alpha_s/(4M^2)$	$\chi^2 G_{\mu\nu} G^{\mu\nu}$	✓	s-wave
R4	$\lambda_4 \sim \alpha_s/(4M^2)$	$i \chi^2 G_{\mu\nu} \tilde{G}^{\mu\nu}$		s-wave
		Complex scalar		
C1	$\lambda_1 \sim 1/(M^2)$	$m_q \chi^\dagger \chi \bar{q} q$	✓	s-wave
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C6	$\lambda_6 \sim \alpha_s/(8M^2)$	$i \chi^\dagger \chi G_{\mu\nu} \tilde{G}^{\mu\nu}$		s-wave

D6 dark matter operators

Relic density plus Hooperon [Liem, Bertone, Calore, Ruiz de Austri, Tait, Trotta, Weniger]

– default input: relic density

– scalar dark matter

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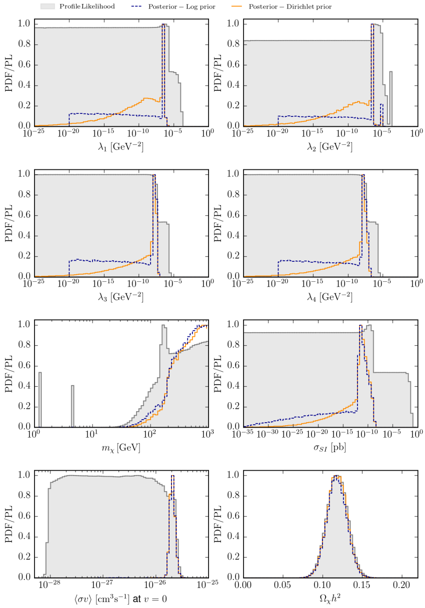
– profile likelihood

– flat prior on log λ_i [prior $1/\lambda_i$]

– Dirichlet prior prefering similar-sized Wilson coefficients



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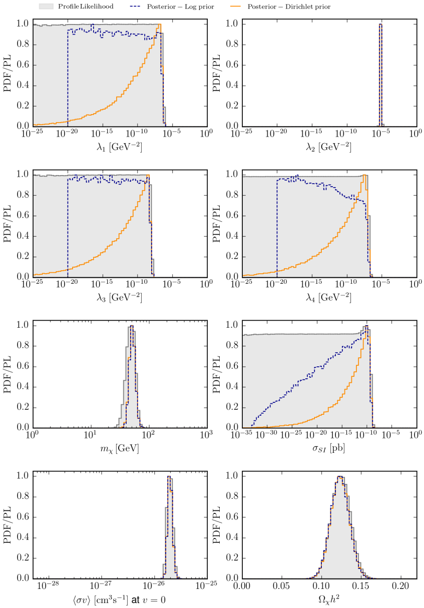
– Fermi: GCE plus dwarf galaxies

$\Rightarrow$ working in practice...



Towards a global analysis?

Combination of measurements [Bauer, Butter, Desai, Gonzalez-Fraile, TP]

– relic density, annihilation in early universe [non-relativistic]

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Representing models?

– relic density only actual measurement
typical mass scales $m_{\text{med}}^2/(g^2 m_\chi) \sim 8$ TeV
– tree-level colored t-channel mediator [squark-neutralino in MSSM]
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$\Rightarrow$ relic density and LHC combination the challenge

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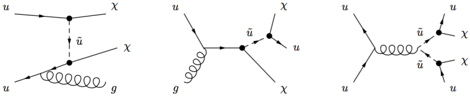
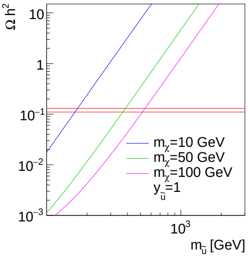


Tree-level scalar in t-channel [squarks]

– relic density for $m_\chi < m_{\tilde{u}}$



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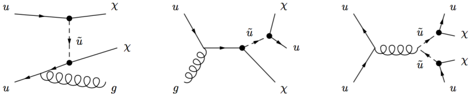

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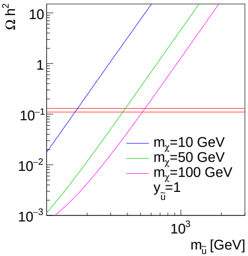
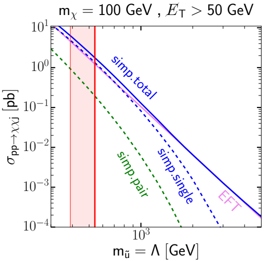
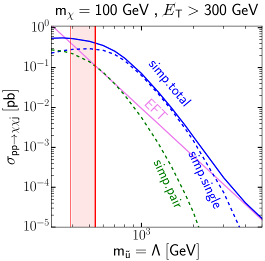
- not valid for correct relic density...







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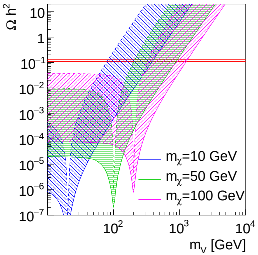
Tree-level vector in s-channel

- relic density for $m_\chi < m_V$



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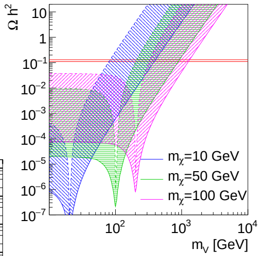
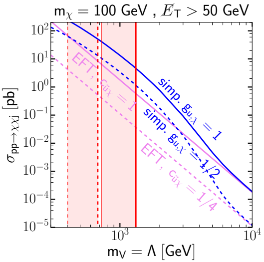
Tree-level vector in s-channel

- relic density for $m_\chi < m_V$
- only 4-fermion operator
- not valid for correct relic density...





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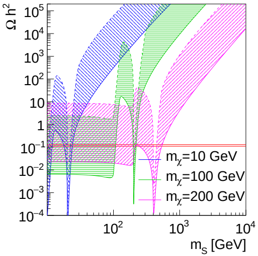
– not valid for correct relic density...



Loop-mediated scalar in s-channel

– relic density for $m_\chi < m_S$

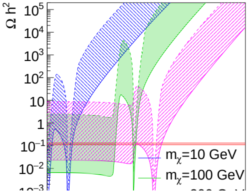
Model by model...

Tree-level scalar in t-channel [squarks]

- relic density for $m_\chi < m_{\tilde{u}}$
- two effective Lagrangians

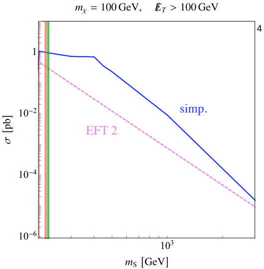
$$\mathcal{L}_{\text{eff}} \supset \frac{c_{u\chi}}{\Lambda^2} \; (\bar{u}_R \chi) \; (\bar{\chi} u_R) \qquad \mathcal{L}_{\text{eff}} \supset \frac{c}{\Lambda^3} (\bar{\chi}\chi) \, G_{\mu\nu} \, G^{\mu\nu}$$

- not valid for correct relic density...



Tree-level vector in s-channel

- relic density for $m_\chi < m_V$
- only 4-fermion operator
- not valid for correct relic density...



Loop-mediated scalar in s-channel

- relic density for $m_\chi < m_S$
- two good effective Lagrangians

$$\mathcal{L}_{\text{eff}} \supset \frac{c_S^t}{\Lambda^2} (\bar{t}t) \; (\bar{\chi}\chi) \qquad \mathcal{L}_{\text{eff},3} \supset \frac{c_\chi^g}{\Lambda^3} (\bar{\chi}\chi) \; G_{\mu\nu} \, G^{\mu\nu}$$

- not valid for correct relic density...

SIGH...

Bottom line

Describing LHC data using effective Lagrangians

dimension-6 Higgs-gauge Lagrangian working
dimension-6 QCD Lagrangian excellent
dimension-6 top Lagrangian like Higgs
dark matter EFT not for global analyses

validation through full models
uncertainties part of matching
mostly tool for limit setting
$\Rightarrow$ Welcome to a data-driven era!

Lectures on LHC Physics and dark matter updated under `www.thphys.uni-heidelberg.de/~plehn/`

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