The Rise of Effective Lagrangians at the LHC

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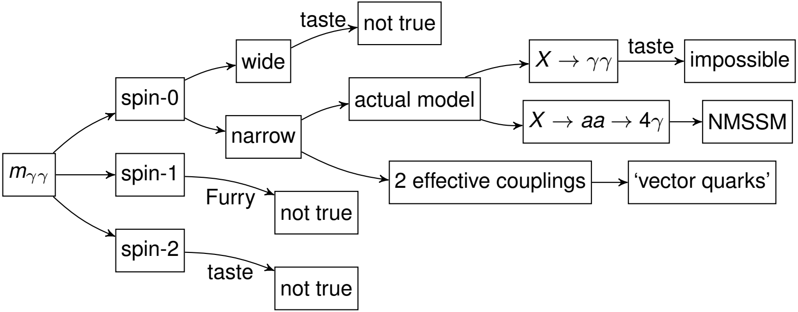
Brookhaven, May 2016

750 GeV — the finger to particle theory



A 750 GeV elefant in the Higgs room

– key question: another Higgs scalar? [Dawson & Lewis]
– largely EFT exercise [problem: large signal rate]
– dimension-5 operators $XG^{\mu\nu}G_{\mu\nu}$ and $XA^{\mu\nu}A_{\mu\nu}$ $\longrightarrow$ avoid di-jet constraints
– gauge invariant $XB^{\mu\nu}B_{\mu\nu}$ and $XW^{\mu\nu}W_{\mu\nu}$ $\longrightarrow$ avoid VV constraints
– no clear link to other data

$\Rightarrow$ great to play with, but only for fun, please

Theory in data-driven era

Same old theory motivation

- WIMP dark matter still best choice [Hooperon@Fermi]
- hierarchy problem (probably) a problem
- but: data in driving seat

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Theory tool box

– Lagrangian language established by Higgs discovery
1- full new physics model [built to solve problems]
2- simplified models [capturing experimental features, theoretically poor]
3- effective field theory [symmetries and particles fixed, non-renormalizable operators]
$\Rightarrow$ matter of convenience and taste

	bottom-up EFT	simplified models	full models
agnostic	$(\times)$		
data-driven		$(\times)$	$(\times)$
theory-driven		$(\times)$	

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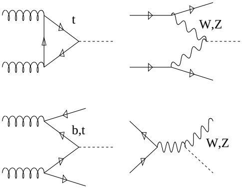
	bottom-up EFT	simplified models	full models
agnostic	$(\times)$	dishonest	pre-LHC
data-driven	boring	$(\times)$	$(\times)$
theory-driven	pointless	$(\times)$	pre-LHC

Higgs couplings



Agnostic: why super-simple SM-Higgs sector? [SFitter]

– or: all couplings proportional to masses?

– assume: narrow CP-even scalar
Standard Model operators

– total production/decay rates only

– Lagrangian

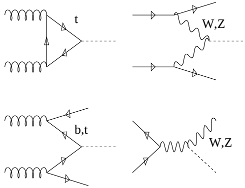
$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \Delta_W \; g m_W H \; W^\mu W_\mu + \Delta_Z \; \frac{g}{2c_w} m_Z H \; Z^\mu Z_\mu - \sum_{\tau,b,t} \Delta_f \; \frac{m_f}{v} H \left(\bar{f}_R f_L + \text{h.c.} \right)$$
$$+ \Delta_g F_G \; \frac{H}{v} \; G_{\mu\nu} G^{\mu\nu} + \Delta_\gamma F_A \; \frac{H}{v}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

– electroweak renormalizability through some UV completion

– QCD renormalizability not an issue

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

Higgs couplings



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Total width

- coupling extraction impossible without width assumption
- observed partial widths:

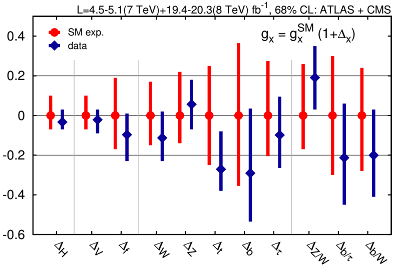
$$N = \sigma \, BR \propto \frac{g_p^2}{\sqrt{\Gamma_{\rm tot}}} \; \frac{g_d^2}{\sqrt{\Gamma_{\rm tot}}} \sim \frac{g^4}{g^2 \sum \dfrac{\Gamma_i(g^2)}{g^2} + \Gamma_{\rm unobs}} \stackrel{g^2 \to 0}{\longrightarrow} = 0$$

  gives constraint from $\sum \Gamma_i(g^2) < \Gamma_{\rm tot} \quad \to \Gamma_H|_{\rm min}$
- $WW \to WW$ unitarity: $g_{WWH} \lesssim g_{WWH}^{\rm SM} \quad \to \Gamma_H|_{\rm max}$ [HiggsSignals]
- our assumption $\Gamma_{\rm tot} = \sum_{\rm obs} \Gamma_j$ [plus generation universality]

Higgs couplings after Run I

Run I legacy [Corbett, Eboli, Goncalves, Gonzalez-Fraile, Lopez-Val, TP, Rauch]

- assume SM-like [secondary solutions possible]
- SFitter: correct theory uncertainties



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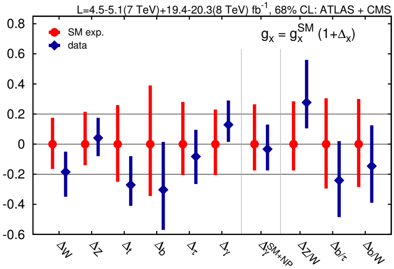

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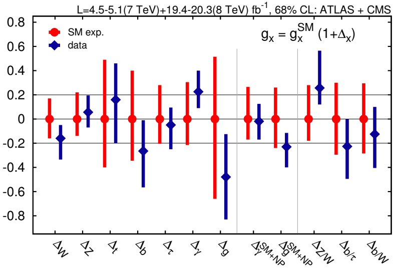

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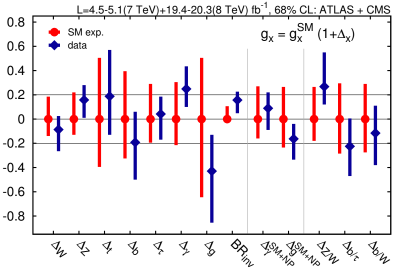
– including invisible decays

$\Rightarrow$ Standard Model within 25%



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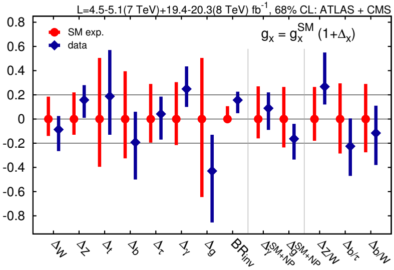
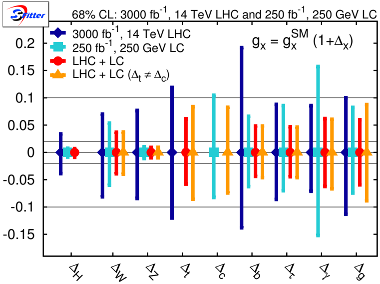


Future [SFitter; Cranmer, Kreiss, Lopez-Val, TP]

- LHC extrapolations unclear
- systematic/theory uncertainties large
- e^+e^- linear collider much better

  unobserved decays avoided
  width measured from σ_{ZH}
  $H \to c\bar{c}$ accessible
  invisible decays hugely improved
  QCD theory error bars avoided



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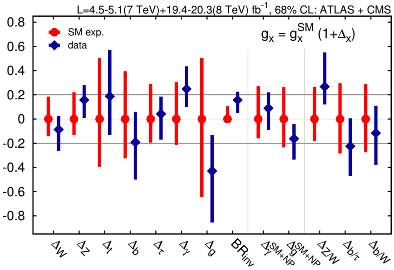

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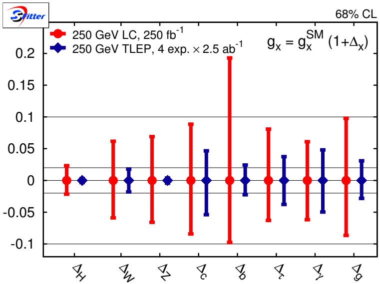
$\Rightarrow$ Higgs factory case obvious



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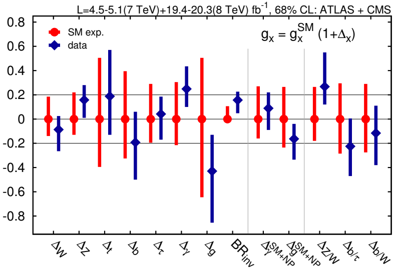

Three major problems with approach

1– theory: no electroweak renormalizability

2– experiment: no kinematic distributions

3– phenomenology: no link to other sectors

D6 Higgs operators

Higgs sector effective field theory [Eboli, Goncales-Garcia,...]

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

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

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

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– relevant part 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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– Higgs couplings to SM particles [derivatives = momentum, #2 solved]

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

– 9 operators for Run I data

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– linked to Higgs couplings

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

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

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

$$g_Z^{(3)} = M_Z^2 (\sqrt{2} G_F)^{1/2} \left(1 - \frac{v^2}{2\Lambda^2} f_{\phi,2}\right) \qquad g_W^{(3)} = M_W^2 (\sqrt{2} G_F)^{1/2} \left(1 - \frac{v^2}{2\Lambda^2} f_{\phi,2}\right)$$

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

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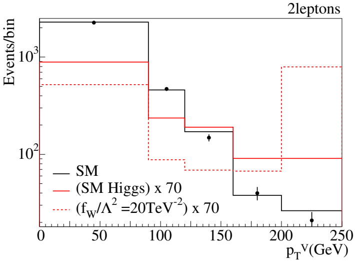
– kinematics: $p_{T,V}, \Delta\phi_{jj}$ [remember #2]



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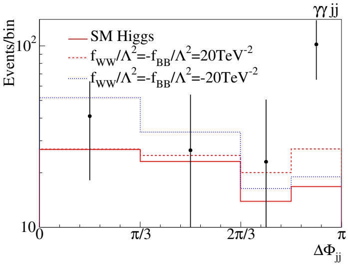

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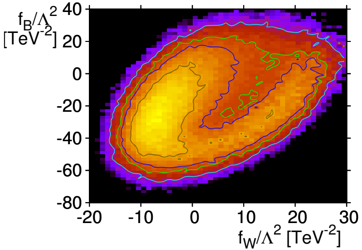
Run 1 legacy

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

– with impact...



D6 Higgs operators

Higgs sector effective field theory [Eboli, Goncales-Garcia,...]

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

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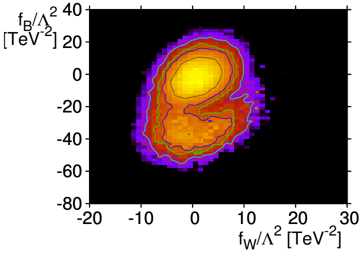
...in last bin



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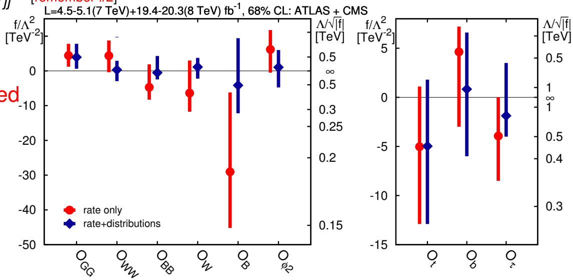
$\Rightarrow$ Run I sensitivity limited



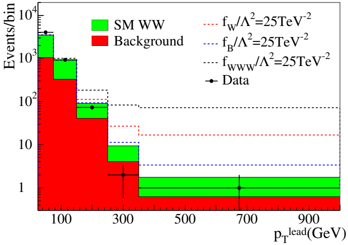
D6 Higgs-gauge operators

Triple gauge couplings

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

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

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



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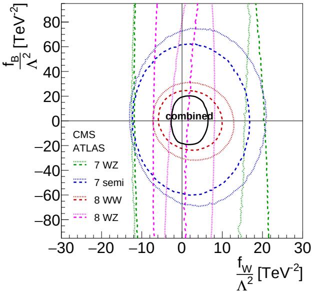
– combined LHC channels



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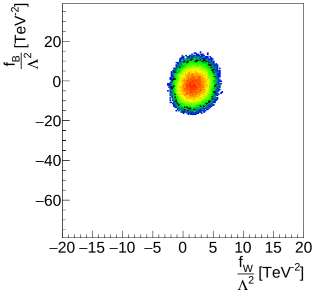

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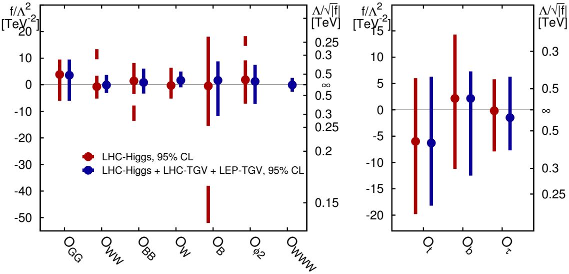
$\Rightarrow$ complete Higgs-gauge analysis



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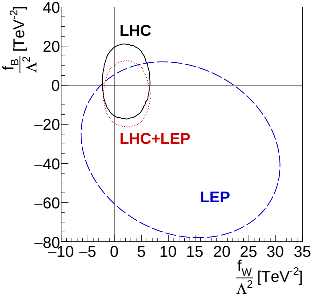
⇒ complete Higgs-gauge analysis

LHC vs LEP

- triple gauge vertices g_1, κ, λ vs operators
- semileptonic analyses missing for 8 TeV

⇒ Run I LHC beating LEP



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

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

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alternatively, strong multi-Higgs interactions

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

D6 top operators

Same for tops [TopFitter: Buckley, Englert, Ferrando, Miller, Moore, Russell, White]

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

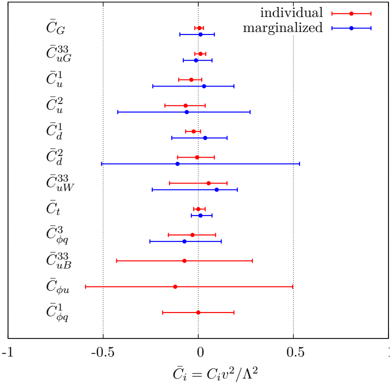
– including anomalous A_{FB} from Tevatron

– 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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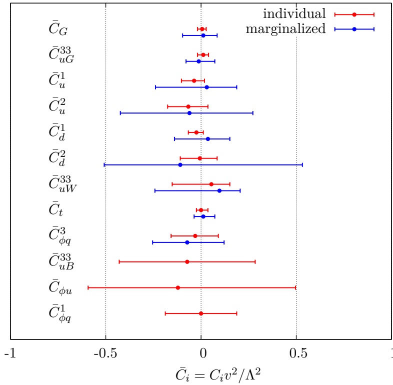

For theorists: in terms of models

– 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}	$\langle\sigma_{ann} v\rangle$
		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		
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C3	$\lambda_3 \sim 1/(M^2)$	$\chi^\dagger \partial_\mu \chi \bar{q} \gamma^\mu q$	✓	p-wave
C4	$\lambda_4 \sim 1/(M^2)$	$\chi^\dagger \partial_\mu \chi \bar{q} \gamma^\mu \gamma^5 q$		p-wave
C5	$\lambda_5 \sim \alpha_s/(8M^2)$	$\chi^\dagger \chi G_{\mu\nu} G^{\mu\nu}$	✓	s-wave
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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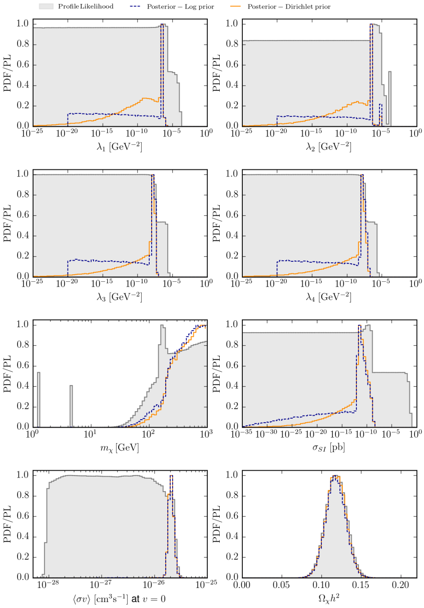
– profile likelihood

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

– Dirichlet prior prefering similar-sized Wilson coefficients



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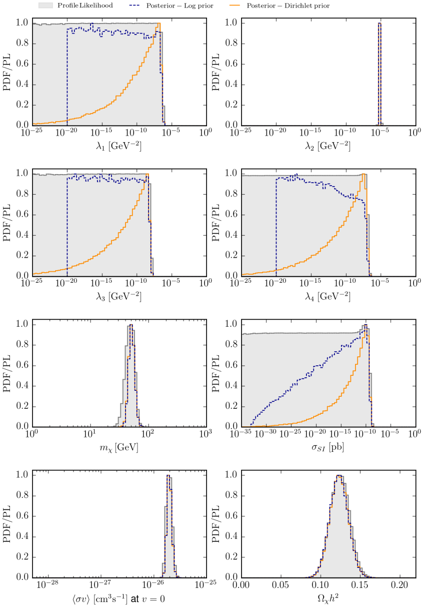
– profile likelihood

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

– Dirichlet prior prefering similar-sized Wilson coefficients

– Fermi: GCE plus dwarf galaxies

$\Rightarrow$ with data, the method hardly matters



(Simplified) scalar/gauge extensions

Higgs singlet/doublet extensions [Higgs portal]

– one or more new (pseudo-) scalars
– mixing with SM-like Higgs

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Scalar top partners, non-Higgs [simplfied supersymmetry]

– Lagrangian with scalar top partner, singlet plus doublet

$$
\begin{aligned}
\mathcal{L} \supset & (D_\mu \tilde{\ })^\dagger (D^\mu \tilde{Q}) + (D_\mu \tilde{t}_R)^* (D^\mu \tilde{t}_R) - \tilde{Q}^\dagger M^2 \tilde{Q} - M^2 \tilde{t}_R^* \tilde{t}_R \\
& - \kappa_{LL} (\phi \cdot \tilde{Q})^\dagger (\phi \cdot \tilde{Q}) - \kappa_{RR} (\tilde{t}_R^* \tilde{t}_R)(\phi^\dagger \phi) - \left[\kappa_{LR} M \tilde{t}_R^* (\phi \cdot \tilde{Q}) + \text{h.c.} \right]
\end{aligned}
$$

– contribution through loops all over Higgs-gauge sector

(Simplified) scalar/gauge extensions

Higgs singlet/doublet extensions [Higgs portal]

– one or more new (pseudo-) scalars
– mixing with SM-like Higgs

Scalar top partners, non-Higgs [simplfied supersymmetry]

– Lagrangian with scalar top partner, singlet plus doublet

$$\mathcal{L} \supset (D_\mu \tilde{)}^\dagger (D^\mu \tilde{Q}) + (D_\mu \tilde{t}_R)^* (D^\mu \tilde{t}_R) - \tilde{Q}^\dagger M^2 \tilde{Q} - M^2 \tilde{t}_R^* \tilde{t}_R$$
$$- \kappa_{LL} (\phi \cdot \tilde{Q})^\dagger (\phi \cdot \tilde{Q}) - \kappa_{RR} (\tilde{t}_R^* \tilde{t}_R)(\phi^\dagger \phi) - \left[\kappa_{LR} M \tilde{t}_R^* (\phi \cdot \tilde{Q}) + \text{h.c.} \right]$$

– contribution through loops all over Higgs-gauge sector

Triplet gauge extension [whatever that becomes in the UV]

– additional vector triplet field V_μ

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

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

Higgs D6 breakdown

D6-Lagrangian breakdown [Brehmer, Freitas, Lopez-Val, TP]

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

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– push (simplified) models to visible deviations at 13 TeV
  Higgs portal, 2HDM, stops, vector triplet [weakly interacting, Eq.(2)]

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

no scale hierarchy for testable models?!

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  coupling modifications v^2/Λ^2 vs new kinematics ∂/Λ?
  matching conditions with $v \lesssim \Lambda$, v-improved matching

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  matching conditions with $v \lesssim \Lambda$, v-improved matching

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

– check where differences appear at 13 TeV
  kinematic distributions like $p_{T,j}$ or m_{VH}?
  resonance peaks of new states?

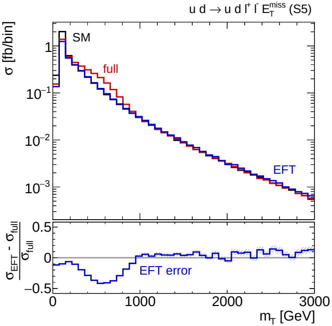
Higgs D6 breakdown

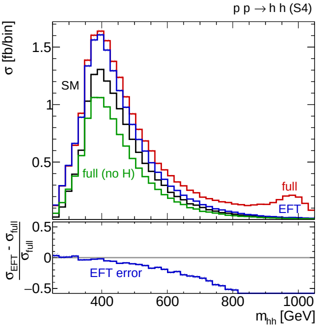
Higgs portal

– testable benchmarks for LHC

Singlet				EFT			EFT (v-improved)	
m_H	$\sin\alpha$	v_s/v	$\Delta_x^{\text{singlet}}$	Λ	$\bar{c}_H$	Δ_x^{EFT}	$\bar{c}_H$	Δ_x^{EFT}
500	0.2	10	-0.020	491	0.036	-0.018	0.040	-0.020
350	0.3	10	-0.046	336	0.073	-0.037	0.092	-0.046
200	0.4	10	-0.083	190	0.061	-0.031	0.167	-0.083
1000	0.4	10	-0.083	918	0.183	-0.092	0.167	-0.092
500	0.6	10	-0.200	407	0.461	-0.231	0.400	-0.200

– effects in WBF and hh





Higgs D6 breakdown

Higgs portal

– testable benchmarks for LHC

– effects in WBF and *hh*

2HDM

– testable benchmarks for LHC

2HDM							EFT		
Type	$\tan\beta$	α/π	m_{12}	m_{H^0}	m_{A^0}	$m_{H^\pm}$	$\lvert\Lambda\rvert$ [GeV]	$\bar{c}_u$	$\bar{c}_{d,\ell}$
I	1.5	-0.086	45	230	300	350	100	-0.744	-0.744
II	15	-0.023	116	449	450	457	448	0.000	0.065
II	10	0.032	157	500	500	500	99	0.465	-46.5
I	20	0	45	200	500	500	142	0.003	0.003

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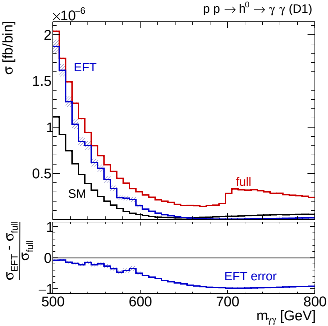
I	20	0	45	200	500	500	[illegible]	[illegible]	[illegible]

- effects in $H \to \gamma\gamma$



Higgs D6 breakdown

Higgs portal

- testable benchmarks for LHC
- effects in WBF and hh

2HDM

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- effects in $H \to \gamma\gamma$

Top partners

- testable benchmarks for LHC

Scalar top-partner model						EFT		
M	κ_{LL}	κ_{RR}	κ_{LR}	$m_{\tilde{t}_1}$	$m_{\tilde{t}_2}$	$\bar{c}_H$	$\bar{c}_W$	$\bar{c}_{HW}$
500	-1.16	2.85	0.147	500	580	$6.22 \cdot 10^{-3}$	$-3.11 \cdot 10^{-7}$	$3.99 \cdot 10^{-7}$
350	-3.16	-2.82	0.017	173	200	$4.30 \cdot 10^{-3}$	$-2.55 \cdot 10^{-4}$	$2.55 \cdot 10^{-4}$
500	-7.51	-7.17	0.012	173	200	$1.66 \cdot 10^{-2}$	$-2.97 \cdot 10^{-4}$	$2.97 \cdot 10^{-4}$

Higgs D6 breakdown

Higgs portal

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- effects in WBF and *hh*

2HDM

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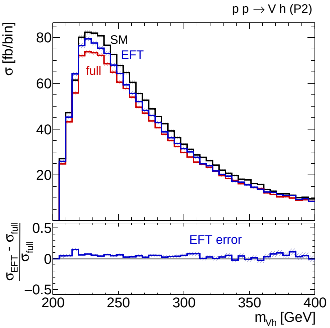
350	-3.16	-2.82	0.017	173	200	4.30
500	-7.51	-7.17	0.012	173	200	1.66

- effects in WBF and *Vh*



Higgs D6 breakdown

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2HDM

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- effects in $H \to \gamma\gamma$

Top partners

- testable benchmarks for LHC
- effects in WBF and *Vh*

Vector triplet [Brehmer, Biekötter, Krämer, TP]

- testable benchmarks for LHC

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

Higgs D6 breakdown

Higgs portal

- testable benchmarks for LHC
- effects in WBF and *hh*

2HDM

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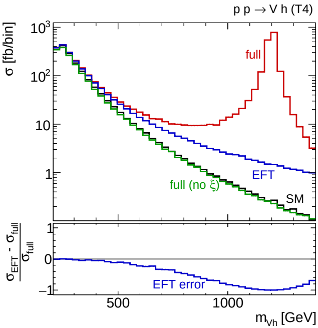
Triplet model						
M_V	g_V	c_H	c_F	c_{VVHH}	m_ξ	
591	3.0	-0.47	-5.0	2.0	1200	–
946	3.0	-0.47	-5.0	1.0	1200	–
941	3.0	-0.28	3.0	1.0	1200	
1246	3.0	-0.50	3.0	-0.2	1200	
846	1.0	-0.56	-1.32	0.08	849	–

- effects in *Vh* and WBF



Higgs D6 breakdown

Higgs portal

– testable benchmarks for LHC

– effects in WBF and *hh*

2HDM

– testable benchmarks for LHC

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Top partners

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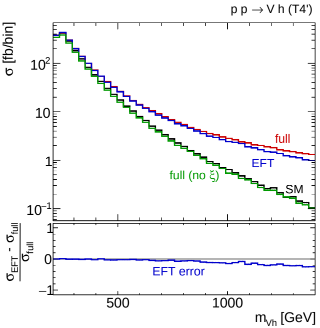

Higgs D6 breakdown

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- testable benchmarks for LHC
- effects in WBF and *hh*

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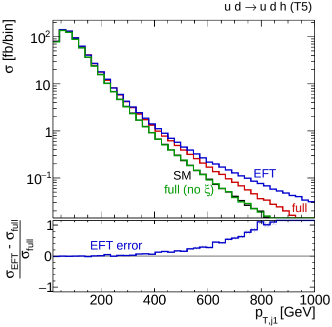

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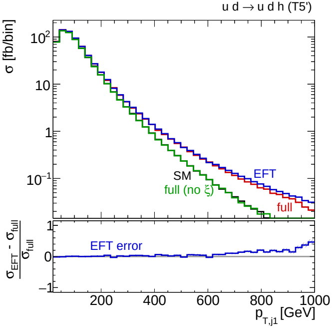

Higgs D6 breakdown

Reasons for D6-breakdown in Higgs sector at LHC

Model	Process	EFT failure		
		resonance	kinematics	matching
singlet	on-shell $h \to 4\ell$, WBF, *Vh*, ...			$\times$
	off-shell WBF, ...		$(\times)$	$\times$
	hh	$\times$	$\times$	$\times$
2HDM	on-shell $h \to 4\ell$, WBF, *Vh*, ...			$\times$
	off-shell $H \to \gamma\gamma$, ...		$(\times)$	$\times$
	hh	$\times$	$\times$	$\times$
top partner	WBF, *Vh*			$\times$
vector triplet	WBF		$(\times)$	$\times$
	Vh	$\times$	$(\times)$	$\times$

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	hh	$\times$	$\times$	$\times$
2HDM	on-shell $h \to 4\ell$, WBF, Vh, ...			$\times$
	off-shell $H \to \gamma\gamma$, ...		$(\times)$	$\times$
	hh	$\times$	$\times$	$\times$
top partner	WBF, Vh			$\times$
vector triplet	WBF		$(\times)$	$\times$
	Vh	$\times$	$(\times)$	$\times$

Lessons from Higgs sector

- start with D6 description [data-driven era of particle physics]
- EFT expansion in E/Λ known to be dodgy
- test D6 in comparison to (simplified) models
- all relevant effect at tree level
- resonance peaks the key feature

Questions

Questions waiting to be answered

– 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 boring? [Yes]

– will we stop EFT analyses once we find new states [Hopefully]

$\Rightarrow$ 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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