Higgs Couplings and EFT Fits

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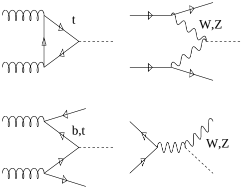
Santander, September 2015

Higgs Couplings



Standard Model operators [SFitter: Gonzalez-Fraile, Klute, TP, Rauch, Zerwas]

- assume: narrow CP-even scalar
  Standard Model operators
- couplings from production & decay rates
- test Lagrangian [essentially non-linear sigma model: Buchalla etal]

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

- electroweak renormalizability through UV completion
- QCD renormalizability not an issue [ask Spirix]
- frequentist likelihood everywhere
- one key issue: theory uncertainties
- total rates only

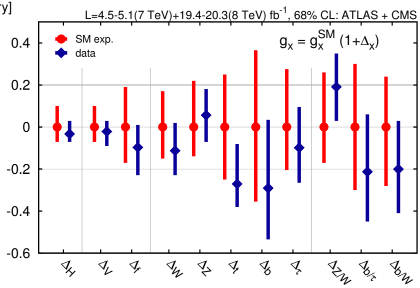
$$\begin{array}{l} gg \to H \\ qq \to qqH \\ gg \to t\bar{t}H \\ qq' \to VH \end{array} \quad \longleftrightarrow \quad g_{HXX} = g_{HXX}^{\text{SM}} \; (1 + \Delta_X) \quad \longleftrightarrow \quad \begin{array}{l} H \to ZZ \\ H \to WW \\ H \to b\bar{b} \\ H \to \tau^+\tau^- \\ H \to \gamma\gamma \\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

SFitter legacy fit

All of Run I [Barca+SFitter: Corbett, Eboli, Goncalves, Gonzalez-Fraile, Lopez-Val, TP, Rauch]

– assume SM-like [secondary solutions secondary]

– ex: extract Δ_H from general fit



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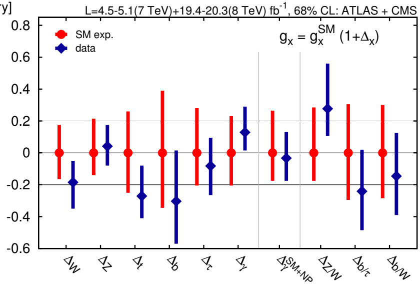

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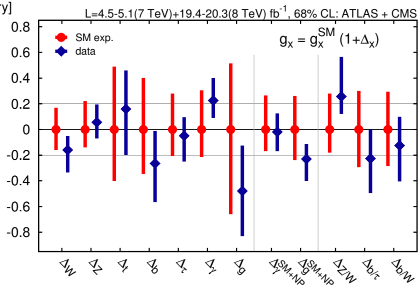

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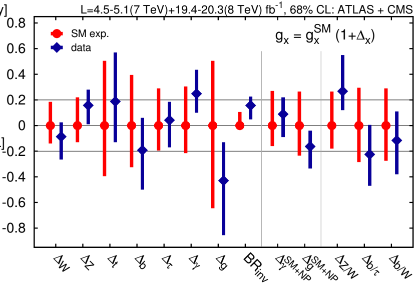
– invisible decays: $\text{BR}_\text{inv} < 31\%$ [95% CL]

– 8 couplings best we can do

$\Rightarrow$ Standard Model within 25%



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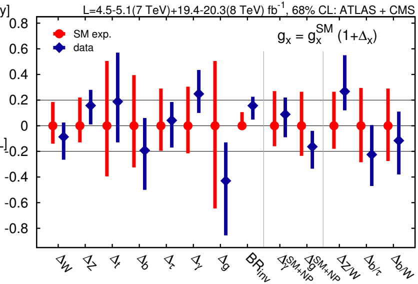


Model for invisible Higgs: Hooperon [SFitter: Butter etal]

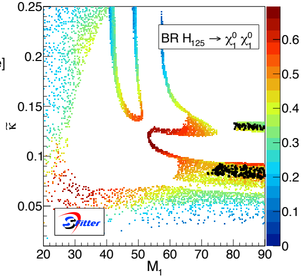
– NMSSM with singlino dark matter [Ellwanger, ask Maggie]

– simplified model: pseudo-scalar mediator
Majorana dark matter

– motivated by Fermi galactic center excess

– different LHC signatures [Cao, Zurek,...]

$\Rightarrow$ BR_inv up to 40%



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Executive summary

– couplings fit works great [experimentally]

– offers perfect th-ex interface [Cranmer, Kreiss, Lopez-Val, TP]

(1) has issues with electroweak renormalization

(2) only describes total rate changes [theory-defined categories]

(3) does not easily replace model fits [correlations]

$\Rightarrow$ obvious answer: fit extended Higgs sectors... [that's for Sven]

D6 operators

Higgs sector effective field theory [following Corbett, Eboli, Gonzalez-Fraile, Goncales-Garcia]

– set of Higgs-gauge operators

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

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

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

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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

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

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

$\Rightarrow$ 9 operators for Run I data

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– 11 Higgs couplings from 9 operators

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

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

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

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

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

– 7 EFT couplings identical to Δ_x, suppressed by v^2/Λ^2

4 EFT couplings $g_{W,Z}^{(1,2)}$ in addition, suppressed by $\partial\partial/\Lambda^2$

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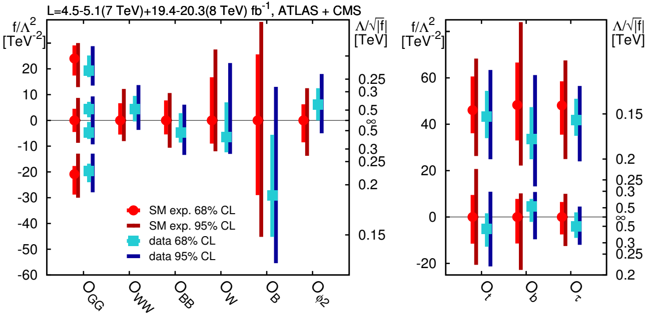
SFitter rate analysis

– setup and data identical to Δ_x fit



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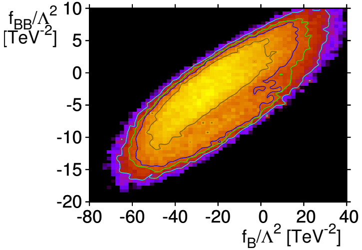
– correlations through larger basis [problem for #3]

– diagonalization essentially means Δ_x

– price to pay for theory issue #1?



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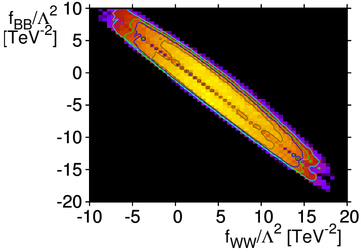

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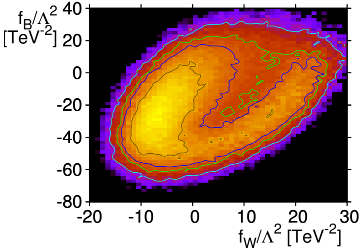

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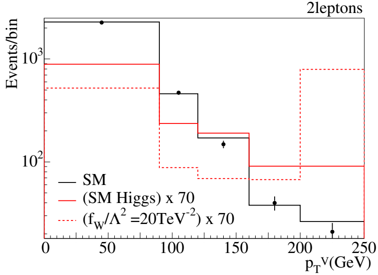
SFitter distributions analysis

– $\mathcal{O} \propto \partial\partial/\Lambda^2$ testing $p_{T,V}$ or $\Delta\Phi_{jj}$, #2 [easy with Madgraph]



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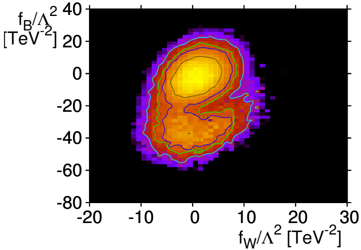

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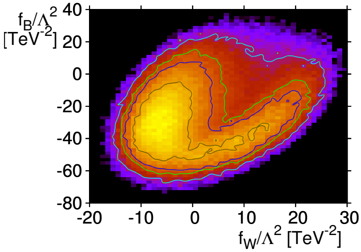

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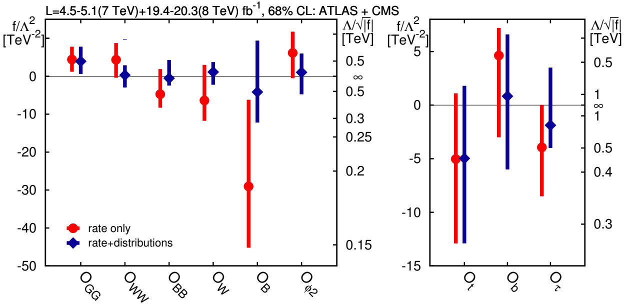

Off-shell Higgs

Width measurements [Kauer & Passarino; Caola & Melnikov; Ellis & Williams]

– peak cross section vs off-shell interference in $H \to ZZ$

$$\sigma_{\text{peak}} \sim \frac{g_g^2 g_Z^2}{(s-m^2)^2 + m^2\Gamma^2} = \frac{g_g^2 g_Z^2}{m^2\Gamma^2} \qquad \sigma_{\text{off}}(g_g g_Z) \sim \sigma_{cont} - \frac{A_{\text{int}}\, g_g g_Z}{s-m^2} + \frac{A_H\, g_g^2 g_Z^2}{(s-m^2)^2}$$

– top–Higgs–gluon sector Δ_t vs Δ_g or f_t vs f_g [$m_{4\ell} \gg m_t > m_H$]

$$\mathcal{M}_{gg\to ZZ} \sim \pm \frac{m_t^2}{m_Z^2} \log^2 \frac{m_{4\ell}^2}{m_t^2}$$

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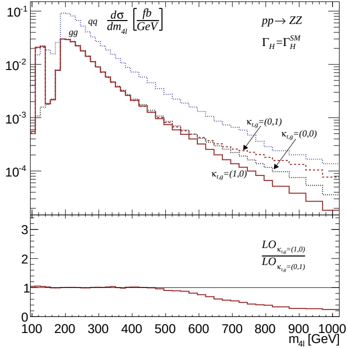

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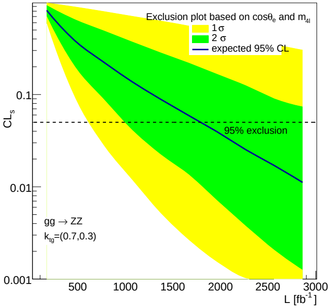
– most optimistic: statistics only
$H \to ee\mu\mu$ analysis
2D likelihood study of $\cos\theta_e, m_{4\ell}$

$\Rightarrow$ $\Delta_t = -0.3$ to 95% CL with 1700 fb^{-1}



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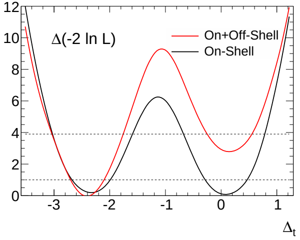

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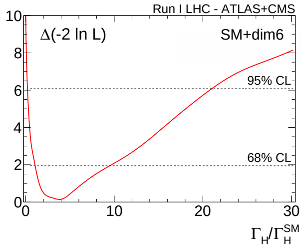
– nothing but a rate measurement...

...either improving Δ_t or f_t measurement

...or measuring unobserved Higgs decays

– eventually a measured distribution



Preview

Complete models vs EFT signatures [Brehmer, Freitas, Lopez-Val, TP]

- push models to visible deviations at 13 TeV
  Higgs portal, 2HDM, stops, vector triplet
- simulate distributions in full models
  $H \to \gamma\gamma, 4\ell$, WBF, VH, HH
- construct and match EFT to each model at D6
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– v^2/Λ^2-operators dominant
– problems arising from resonances, not high-energy tails
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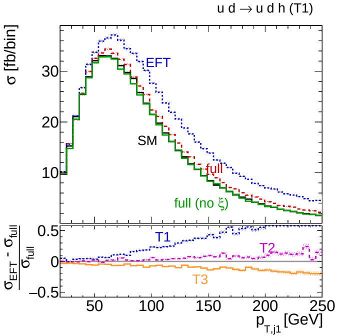

Longitudinal WW scattering

WW scattering at high energies [Han etal; Dawson]

– classic *WW* scattering at high energies

$$g_V \; H \; \left(a_L V_{L\mu} V_L^{\mu} + a_T V_{T\mu} V_T^{\mu} \right)$$

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Tagging jet observables [Brehmer, Jäckel, TP]

- polarization defined in Higgs frame
- transverse momenta

$$P_T(x, p_T) \sim \frac{1+(1-x)^2}{x} \; \frac{p_T^3}{((1-x)m_W^2 + p_T^2)^2}$$

$$P_L(x, p_T) \sim \frac{1-x}{x} \; \frac{2(1-x)m_W^2 p_T}{((1-x)m_W^2 + p_T^2)^2}$$

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$$A_\phi = \frac{\sigma(\Delta\phi_{jj} < \frac{\pi}{2}) - \sigma(\Delta\phi_{jj} > \frac{\pi}{2})}{\sigma(\Delta\phi_{jj} < \frac{\pi}{2}) + \sigma(\Delta\phi_{jj} > \frac{\pi}{2})}$$

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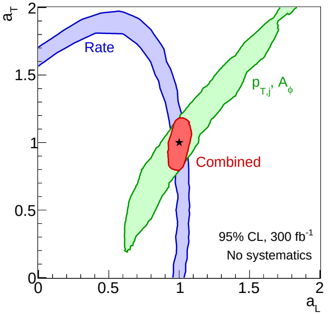
– total rate $\sigma \sim (A_L a_L^2 + A_T a_T^2)$

$\Rightarrow$ simple question, clear answer



Lessons from actually doing fits

Higgs couplings

- couplings fit works great [experimentally]
- offers perfect th-ex interface [Cranmer, Kreiss, Lopez-Val, TP]

(1) has issues with electroweak renormalization

(2) only describes total rate changes [theory-defined categories]

(3) does not easily replace model fits [correlations]

Higgs effective theory

- is harder than Δ_x for v^2/Λ^2
  describes distributions though $\partial\partial/\Lambda^2$
- is easy to simulate through MC
- currently excludes D8 operators ex cathedra
- will hardly replace model fits [correlations and matching]
- explains why nothing new happens with $\Lambda < 400$ GeV

Lectures on LHC Physics, Springer, arXiv:0910.4182 updated under www.thphys.uni-heidelberg.de/~plehn/

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Bundesministerium für Bildung und Forschung