Higgs Physics

Revolution vs Evolution

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Outline

Higgs to bottoms

Fundamental Higgs or What?

Higgs couplings

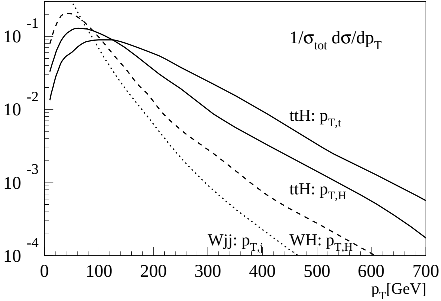
Exotic Higgs

Fixed-point gravity

Higgs to bottoms: Revolution

A new strategy for $H \to bb$ [Butterworth, Davison, Rubin, Salam]

- desperately needed for light Higgs [2/3 of all Higgses; inclusive CMS $S/B \sim 1/80$]
- S: large m_{bb}, boost-dependent R_{bb}
  B: large m_{bb} only for large R_{bb}
  S/B: large m_{bb} and small R_{bb}
- $q\bar{q} \to V_\ell H_b$ sizeable in boosted regime [$p_T \gtrsim 300$ GeV, few % of total rate]



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- fat Higgs jet $R_{bb} \sim 2m_H/p_T \sim 0.8$
- underlying event: 2+1 filtered subjets

⇒ non-trivial challenge to jet algorithms

jet definition	σ_S/fb	σ_B/fb	$S/\sqrt{B}_{30}$
C/A, $R = 1.2$, MD-F	0.57	0.51	4.4
$k_\perp$, $R = 1.0$, y_{cut}	0.19	0.74	1.2
SISCone, $R = 0.8$	0.49	1.33	2.3

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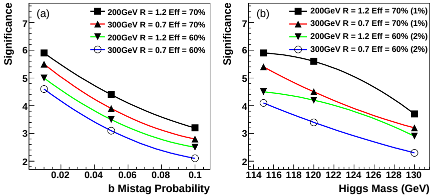
Results and checks

- combined channels $V \to \ell\ell, \nu\nu, \ell\nu$
- NLO rates [bbV notorious, not from data alone]
- Z peak as sanity check
- checked by Freiburg [Piquadio]
  subjet b tag excellent [70%/1%]
  charm rejection challenging
  $m_H \pm 8$ GeV tough

$\Rightarrow$ confirmed at 20% level



Higgs to bottoms: Evolution

Tackling ttH, $H \to bb$ [TP, Salam, Spannowsky]

- traditional analysis dead [$S/B \sim 1/9$]
  killed by indistinguishable background
  killed by bottom combinatorics
- S: large m_{bb}, boost-dependent R_{bb}
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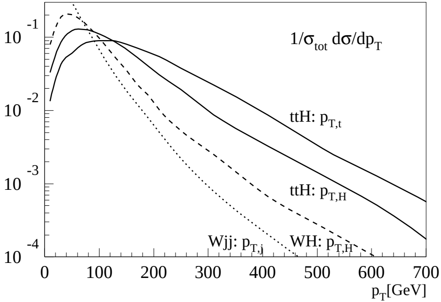
- $pp \to t_\ell t_h H_b$ even larger in boosted regime



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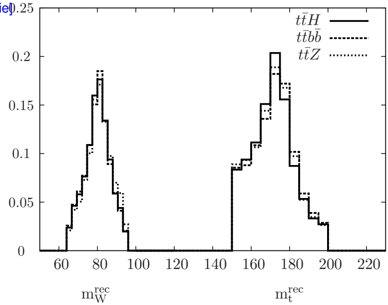
- $pp \to t_\ell t_h H_b$ even larger in boosted regime
- cool: fat Higgs jet + fat top jet + trigger lepton
- uncool: QCD activity [Dittmaier et al: $K = 2.3$ for $t\bar{t}b\bar{b}$]

Top tag [cf Johns Hopkins, Princeton, Washington, talk by Jessie]

- C/A algorithm [$R = 1.5$]
  mass drop criterion
- reconstruct m_W and m_t
  cut on helicity angle
- filtering against underlying event
- efficiency 43%; mistag 5%

$\Rightarrow$ working Standard Model top tag



Higgs to bottoms: Evolution

Higgs tag

- same as top [stricter mass drop criterion, harder jets]
- QCD activity: one or two QCD jets inside fat Higgs jet
- Higgs mass unknown
  subjet combinations ordered by $J = p_{T,1} p_{T,2} (\Delta R_{12})^4$
  three leading combinations vs m_{bb}
- events in 1 fb^{-1} [5.1σ for $m_H = 120$ *GeV* and 100 fb^{-1}]

	signal	$t\bar{t}Z$	$t\bar{t}b\bar{b}$	$t\bar{t}$+jets
events after acceptance	24.1	6.9	191	4160
events with one top tag	10.2	2.9	70.4	1457
events with $m_{bb} = 110 - 130$ GeV	2.9	0.44	12.6	116
corresponding to subjet pairings	3.2	0.47	13.8	121
subjet pairings two b tags	1.0	0.08	2.3	1.4

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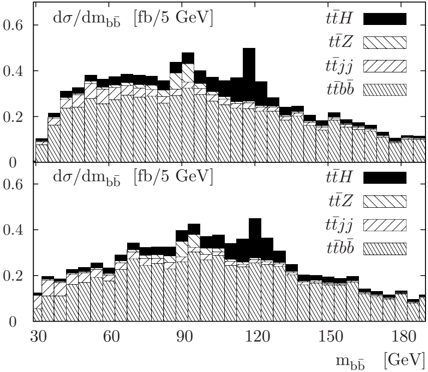
  subjet combinations ordered by $J = p_{T,1} p_{T,2} (\Delta R_{12})^4$
  three leading combinations vs m_{bb}
- $t\bar{t}jj$ background: 'Higgs' as b from t_ℓ plus QCD jet
  additional isolated b tag, only continuum $t\bar{t}b\bar{b}$ left
  missing energy cut?
  jet patterns? [TP, Rauch, Spannowsky]

m_H	S	S/B	$S/\sqrt{B}$
115	57	1/2.1	5.2 (5.7)
120	48	1/2.4	4.5 (5.1)
130	29	1/3.6	2.9 (3.0)

$\Rightarrow$ under experimental scrutiny



Fundamental Higgs or What?

Higher-dimensional Higgs operators [Low, Rattazzi, Vicchi]

- 'strongly interacting light Higgs' [Giudice, Grojean, Pomarol, Rattazzi]
- most relevant for LHC [WBF?]

$$\mathcal{O}_H = \partial^\mu (H^\dagger H) \partial_\mu (H^\dagger H) \qquad \mathcal{O}_y = (H^\dagger H)\, \bar{f}_L H f_R + \text{h.c.}$$
$$\mathcal{O}_g = (H^\dagger H)\, G_{\mu\nu} G^{\mu\nu} \qquad \mathcal{O}_\gamma = (H^\dagger H)\, B_{\mu\nu} B^{\mu\nu}$$

- Standard Model: no decoupling in presence of chiral fermions etc.
- fundamental Higgs:
  $c_H > 0$ unless triplet scalar contribute [Higgs couplings reduced]
  $c_H + 2c_y > 0$ from heavy scalars and vectors [reduced coupling to fermions]
  $c_g < 0$; $c_\gamma > 0$ from top partner solving hierarchy problem
  $c_g < 0$ in SUSY only for large mixing
- composite Higgs [non-linear σ model]:
  $c_H, c_y > 0$
- little Higgs:
  $c_{H,y}$ large, $c_{g,\gamma}$ suppressed

$\Rightarrow$ study Higgs couplings at the LHC

Higgs couplings

Coupling extraction at the LHC [Zeppenfeld, Kinnunen, Nikitenko, Richter-Was; Dührssen et al.]

– optimistic LHC scenario: everything working and good data

– light Higgs around 120 GeV: 10 main channels ($\sigma \times BR$) [*bb* channel new]

– measurements: $GF : H \to ZZ, WW, \gamma\gamma$
$WBF : H \to ZZ, WW, \gamma\gamma, \tau\tau$
$VH : H \to b\bar{b}$ [Butterworth, Davison, Rubin, Salam]
$t\bar{t}H : H \to \gamma\gamma, WW, (b\bar{b})$...

– parameters: couplings $W, Z, t, b, \tau, g, \gamma$ [plus Higgs mass]

– hope: cancel uncertainties
$(WBF :\ H \to WW)/(WBF :\ H \to \tau\tau)$
$(WBF :\ H \to WW)/(GF :\ H \to WW)$...

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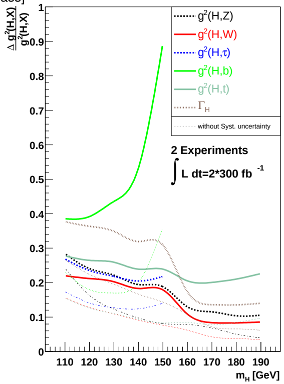


Total width

– degeneracy: $\sigma\, BR \propto (g_p^2/\sqrt{\Gamma_H})\, (g_d^2/\sqrt{\Gamma_H})$

– additional constraint: $\sum \Gamma_i(g^2) < \Gamma_H \to \Gamma_H|_{\text{min}}$

– $WW \to WW$ unitarity: $g_{WWH} \lesssim g_{WWH}^{\text{SM}} \to \Gamma_H|_{\text{max}}$

– width extraction hard

$\Rightarrow$ this analysis: $\Gamma_H = \sum_{\text{obs}} \Gamma_j$

SFitter — Higgs couplings at LHC

Know-how from TeV-scale MSSM analysis [SFitter]

- parameters: weak-scale Higgs Lagrangian
  measurements: signal+background rates
  errors: statistics & systematics & theory [RFit from CKMFitter]
- fully exclusive likelihood map $p(d|m)$ over model space m
- Bayesian: $p(m|d) \sim p(d|m)\, p(m)$ with theorists' bias $p(m)$ [cosmo, BSM]
  frequentist: best–fitting point $\max_m p(d|m)$ [flavor, here: cooling Markov chains]
- LHC aim: compute high-dimensional map $p(d|m)$
  find and rank local maxima in $p(d|m)$
  Bayesian–frequentist dance to reduce dimensions

Alternative best-fit points and error bars [Dührssen, Lafaye, TP, Rauch, Zerwas]

- all couplings varied around SM values $g_{HXX} = g_{HXX}^{SM}\,(1+\delta_{HXX})$
- $\delta_{HXX} \sim -2$ means sign flip [$g_{HWW} > 0$ fixed]
- error bars for Standard Model hypothesis [smeared data point, $30\,\mathrm{fb}^{-1}$]

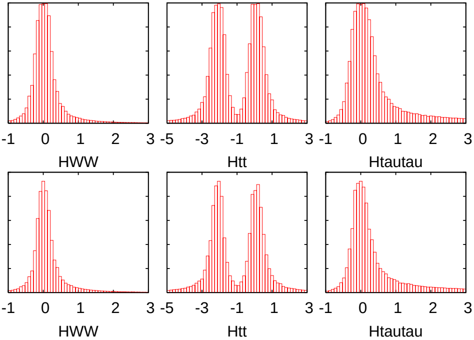
	σ_{symm}	σ_{neg}	σ_{pos}	σ_{symm}	σ_{neg}	σ_{pos}
δ_{WWH}	$\pm\,0.23$	$-\,0.21$	$+\,0.26$	$\pm\,0.24$	$-\,0.21$	$+\,0.27$
δ_{ZZH}	$\pm\,0.50$	$-\,0.74$	$+\,0.30$	$\pm\,0.44$	$-\,0.65$	$+\,0.24$
$\delta_{t\bar{t}H}$	$\pm\,0.41$	$-\,0.37$	$+\,0.45$	$\pm\,0.53$	$-\,0.65$	$+\,0.43$
$\delta_{b\bar{b}H}$	$\pm\,0.45$	$-\,0.33$	$+\,0.56$	$\pm\,0.44$	$-\,0.30$	$+\,0.59$
$\delta_{\tau\bar{\tau}H}$	$\pm\,0.33$	$-\,0.21$	$+\,0.46$	$\pm\,0.31$	$-\,0.19$	$+\,0.46$
$\delta_{\gamma\gamma H}$	—	—	—	$\pm\,0.31$	$-\,0.30$	$+\,0.33$
δ_{ggH}	—	—	—	$\pm\,0.61$	$-\,0.59$	$+\,0.62$

SFitter — Higgs couplings at LHC

One-dimensional distributions

– 30 fb^{-1} with vs without theory error [with effective couplings]

⇒ theory errors there but not dominant for 30 fb^{-1}



SFitter — Higgs couplings at LHC

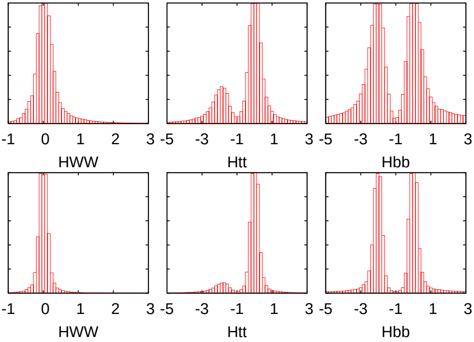
One-dimensional distributions

– 30 fb^{-1} with vs without theory error [with effective couplings]

⇒ theory errors there but not dominant for 30 fb^{-1}

– 30 fb^{-1} vs 300 fb^{-1} [without effective couplings]

⇒ higher luminosity quantitatively different

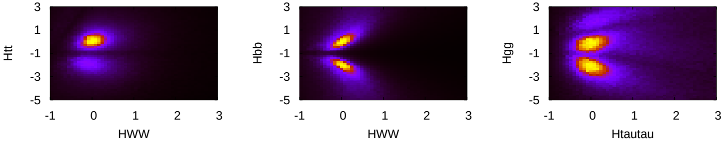


SFitter — Higgs couplings at LHC

Two-dimensional correlations and effective coupings

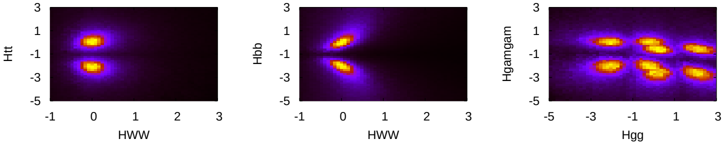
(1) including effective g_{Hgg}

- sign of g_{Htt} fixed, correlated with g_{HWW}
- correlation of g_{Hbb} and g_{HWW} [loops and width]
- effective coupling g_{Hgg} accessible



(2) also effective $g_{H\gamma\gamma}$

- correlation of g_{Htt} and g_{HWW} on both branches
- still correlation of g_{Hbb} and g_{HWW} [width]
- effective coupling $g_{H\gamma\gamma}$ more complex



Bowing to the Organizers

Higgs in Space! [Jackson, Servant, Shaughnessy, Tait, Taoso; talk by Gabe]

– best paper title in 2009

– simple model:
Dirac fermion dark matter [somehow massive]
Z' portal to Standard Model [kinetic mixing and ttZ' coupling]
lots of anomalies cancelled by whatever

– WIMP annihilation to γH with γ lines [$E_\gamma / M = 1 - m_H^2/(4M^2)$]

$\Rightarrow$ LHC signature $pp \to t\bar{t}H\gamma$ with monoenergetic γ [good for $t\bar{t}H$ search]

Higgs in model space [Kribs, Martin, Roy, Spannowsky; talk by Adam]

– showing the QCD animal in Graham

– assume new physics samples with Higgs and without backgrounds

– generic for GMSB with higgsino NLSP and gravitino LSP
non-negligible for bino NLSP

– mixed $\gamma + \widetilde{G}$ and $h + \widetilde{G}$ decays

$\Rightarrow$ reconstruct H just like γ as fat jet

Fixed-point gravity

UV-save gravity as its own UV completion [Weinberg; Reuter; Wetterich; Percacci; Litim...]

– truly minimal model

– dimensionless gravitational coupling $g(\mu) = G(\mu)\mu^2 = G_0\, Z_G^{-1}(\mu)\, \mu^2$

– IR — no gravitational running
M_Planck — anomalous dimensions change
UV — finite gravity fixed point

Gravitational effects on Standard Model [Shaposhnikov, Wetterich]

– dominant in the UV regime

$$\beta = \frac{a}{8\pi}\,\frac{k^2}{M_\text{Planck}(k)^2}\,\{g_1, g_2, g_3, y_t, \lambda\} \qquad \text{means} \qquad \{g_1, g_2, g_3, y_t, \lambda\} \sim k^a$$

– IR fixed point for λ/y_t^2

– IR and UV behavior

$a_{1,2,3} \lesssim -0.013$	asymptotically free, not relevant in UV
$a_t < a_t^\text{crit} < 0$	fixed by finite top mass, avoid Gaussian IR fixed point
$a_\lambda \sim 3$	no Landau pole and $\lambda > 0$ below M_Planck

– $m_H = (128 \pm 2)$ GeV means no physics to the Planck scale

Outlook

Higgs@LHC amazingly still showing progress

1. we can see $H \to b\bar{b}$!
2. Higgs sector analyses will work...
3. cool guys like Graham dig jet algorithms!

$\Rightarrow$ revolution ranking: (3) ahead of (1) ahead of (2)

and tell your students there is no such thing as a completely worked-out field