Higgs Physics

Tilman Plehn

Universität Heidelberg

IPPP Christmas Meeting, 12/2012

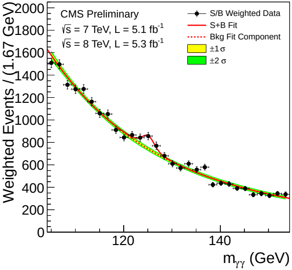
Higgs discovery

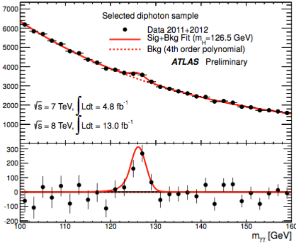
4th of July fireworks and on

– 'silver channel' $H \to \gamma\gamma$

local significance 4.5σ (ATLAS), 4.1σ (CMS)

ATLAS update 12/13/12





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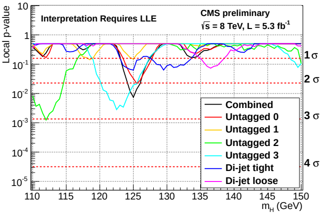

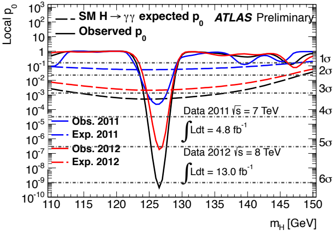

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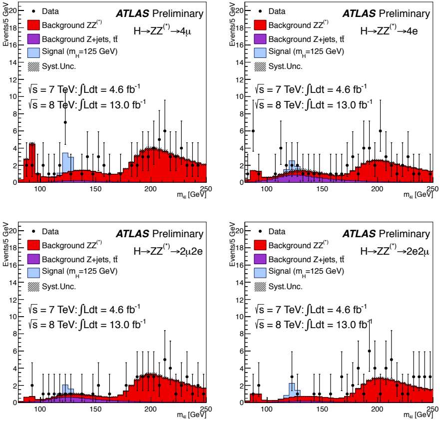

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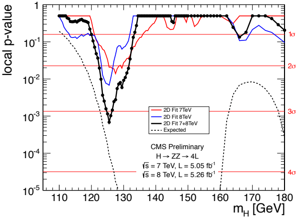

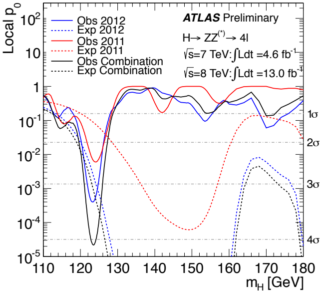

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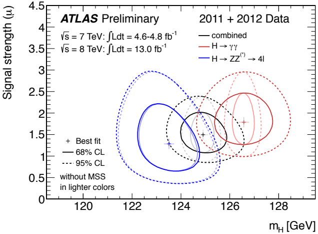

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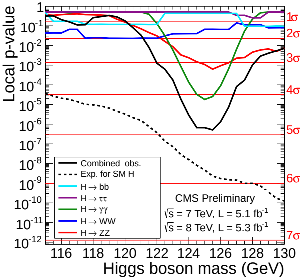
adding little to discovery
ATLAS *WW* post-ICHEP



$\Rightarrow$ narrow light resonance around $m_H = 126$ GeV discovered

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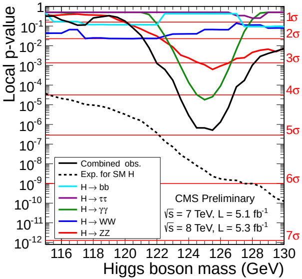

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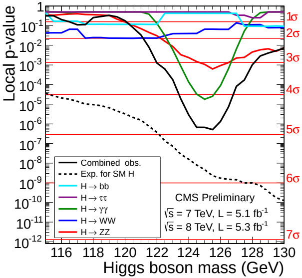

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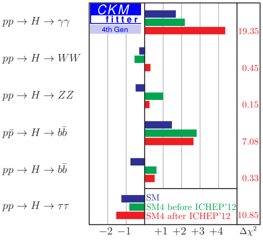
Any models ruled out?

- Standard Model fine [Holthausen, Lim, Lindner]
- reasonably decoupling theories all fine [like MSSM]
- strongly interacting light Higgs supposedly fine
- Higgs portal fine
- fourth chiral generation dead [Lenz etal]



Immediate questions

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   – VH and $t\bar{t}H$ missing

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4. What does all this tell us?
   - models predicting weak-scale modifications
   - renormalization group based Hail-Mary passes

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– except Higgs production in gluon fusion

– except Higgs decay to photons

– except g_{WWH} might mean $HW^{\mu\nu}W_{\mu\nu}$

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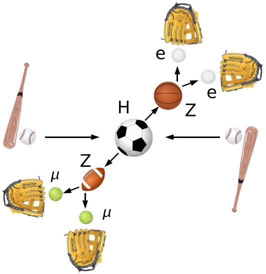
$\Rightarrow$ analyze Higgs kinematics [in as many channels as possible]



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– first step: Higgs polar angle for spin-0 vs spin-2 [Alves; ATLAS/CMS]

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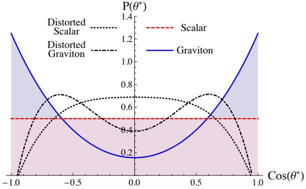

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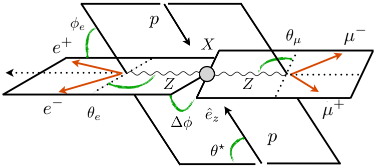

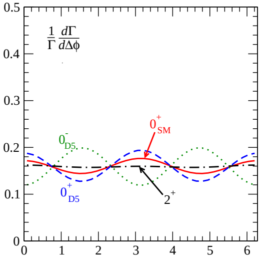

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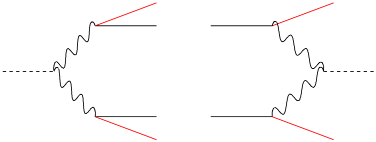

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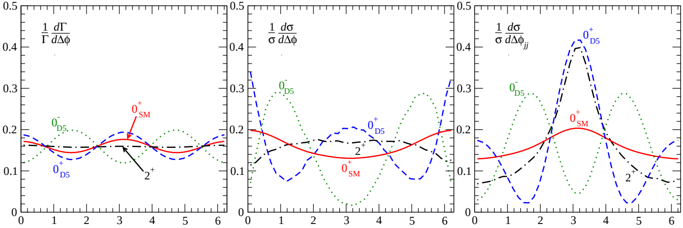

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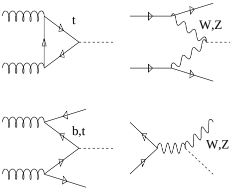
– Higgs operators testable in almost all channels [MC: Madgraph, etc]

$\Rightarrow$ will this work?

Couplings



Current model [guessing answer to question One]

– assume: narrow CP-even scalar
  SM-like D4 structures
  SM-induced D6 structures

– couplings from production & decay combinations?

$gg \to H$
$qq \to qqH$
$gg \to t\bar{t}H$
$qq' \to VH$

$\longleftrightarrow$

$$g_{HXX} = g_{HXX}^{\text{SM}} \; (1 + \Delta_X)$$

$\longleftrightarrow$

$H \to ZZ$
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Similar analyses

– Higgs cross section group: $\kappa_X \equiv (1 + \Delta_X)$

– indicating that Δ_X is a deviation from the Standard Model

– induced couplings with parametrical dependence and new physics

$$g_\gamma = g_\gamma^{\text{SM}} \left(1 + \Delta_\gamma^{\text{SM}} + \Delta_\gamma\right) \equiv g_\gamma^{\text{SM}} \kappa_\gamma$$

– it really is couplings, not ‘scaling factors’

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Why 126 GeV is perfect [Dührssen et al; SFitter 2009/2012; Contino etal; Grojean etal]

- measurements: GF : $H \to ZZ, WW, \gamma\gamma$ [2011]
  WBF : $H \to ZZ, WW, \gamma\gamma, \tau\tau$ [2012]
  VH : $H \to b\bar{b}$ [2015: BDRS?]
  $t\bar{t}H$: $H \to b\bar{b}$... [2015: boosted?]
- parameters: g_{HXX} with $X = W, Z, t, b, \tau, g, \gamma$ [plus Higgs mass, maybe $Z\gamma$]
- correlations: $N_{\text{ev}} \propto \dfrac{g_p^2 g_d^2}{\Gamma_{\text{tot}}(\{g_X^2\})}$

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SFitter ansatz [(Dührssen), Klute, Lafaye, TP, Rauch, Zerwas]

– experimental/theory errors on signal and backgrounds [RFit]
  Atlas and CMS both included
  total width from observed partial widths [most general ansatz now]
  electroweak corrections still not relevant

– starting point: exclusive likelihood map
  individual coupling: profile likelihood
  best fit: Minuit
  errors: toy measurements

$\Rightarrow$ global and local analysis possible

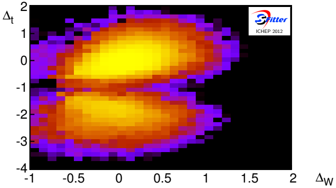
Global/local analysis

Global view on 8 TeV data [Klute, Lafaye, TP, Rauch, Zerwas; TP & Rauch]

– g_W included post-ICHEP

(1) expected 2012: SM central values, measured error bars

– two symmetric solutions $\Delta_t = 0, -2$



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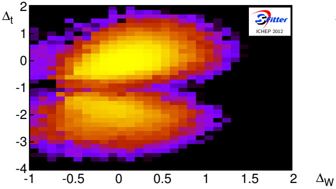
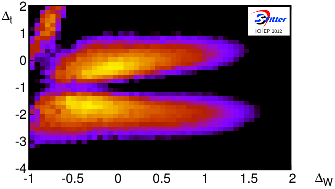
weak third solution with large quark Yukawas





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Local view on 7 TeV data

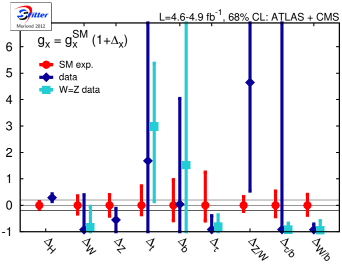
– focus on SM solution where possible

– five couplings from data

$g_W \sim 0$ while g_Z okay
g_b and g_t hurt by secondary solution
g_τ inconclusive in data

– poor man's analysis great: $\Delta_j \equiv \Delta_H$

⇒ pointing towards Standard Model?



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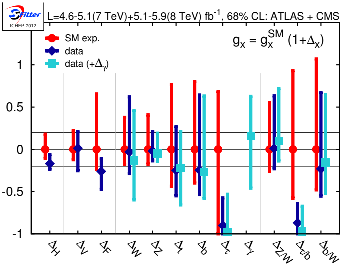
– six couplings from data [errors 20 — 50%]

$g_{W,Z}$ fine
$g_{t,b}$ indirectly
g_τ poor
g_γ now possible



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– all hypotheses great: $\Delta_H, \Delta_V, \Delta_f, \dots$

$\Rightarrow$ moving towards Standard Model?

hypothesis	χ^2_{2012}/dof	sol's
Standard Model	43.3/54	
form factor Δ_H	32.2/53	1
two-parameter $\Delta_{V,f}$	29.0/52	2
independent Δ_x	27.7/49	3
including Δ_γ	27.3/48	2

Anomalous couplings

Anomalous Higgs couplings [Hagiwara etal; Corbett, Eboli, Gonzales-Fraile, Gonzales-Garcia]

– assume Higgs is largely Standard Model and renormalizable

– effective *HVV* Lagrangian

$$\begin{aligned}\mathcal{L}_{\text{eff}}^{HVV} =& g_{Hgg}\; HG^a_{\mu\nu}G^{a\mu\nu} + g_{H\gamma\gamma}\; HA_{\mu\nu}A^{\mu\nu} + g^{(1)}_{HZ\gamma}\; A_{\mu\nu}Z^{\mu}\partial^{\nu}H + g^{(2)}_{HZ\gamma}\; HA_{\mu\nu}Z^{\mu\nu} \\ &+ g^{(1)}_{HZZ}\; Z_{\mu\nu}Z^{\mu}\partial^{\nu}H + g^{(2)}_{HZZ}\; HZ_{\mu\nu}Z^{\mu\nu} + g^{(3)}_{HZZ}\; HZ_{\mu}Z^{\mu} \\ &+ g^{(1)}_{HWW}\; \left(W^+_{\mu\nu}W^{-\,\mu}\partial^{\nu}H + \text{h.c.}\right) + g^{(2)}_{HWW}\; HW^+_{\mu\nu}W^{-\,\mu\nu} + g^{(3)}_{HWW}\; HW^+_{\mu}W^{-\,\mu}\end{aligned}$$

– related to D6 operators

$$\mathcal{L}_{\text{eff}} = \sum_j \frac{f_j\,\mathcal{O}_j}{\Lambda^2}$$

$$\begin{aligned} g_{Hgg} &= -\frac{\alpha_s}{8\pi}\frac{f_g v}{\Lambda^2} & g_{H\gamma\gamma} &= -\frac{gM_W}{\Lambda^2}\frac{s_w^2(f_{BB}+f_{WW}-f_{BW})}{2} \\ g^{(1)}_{HZ\gamma} &= \frac{gM_W}{\Lambda^2}\frac{s_w(f_W-f_B)}{2c_w} & g^{(2)}_{HZ\gamma} &= \frac{gM_W}{\Lambda^2}\frac{s_w[2s_w^2 f_{BB}-2c_w^2 f_{WW}+(c_w^2-s_w^2)f_{BW}]}{2c_w} \\ g^{(1)}_{HZZ} &= \frac{gM_W}{\Lambda^2}\frac{c_w^2 f_W+s_w^2 f_B}{2c_w^2} & g^{(2)}_{HZZ} &= -\frac{gM_W}{\Lambda^2}\frac{s_w^4 f_{BB}+c_w^4 f_{WW}+c_w^2 s_w^2 f_{BW}}{2c_w^2} \\ g^{(1)}_{HWW} &= \frac{gM_W}{\Lambda^2}\frac{f_W}{2} & g^{(2)}_{HWW} &= -\frac{gM_W}{\Lambda^2}f_{WW} \quad \text{etc} \end{aligned}$$

– analysis is terms of f_j [careful with minimal basis]

Anomalous couplings

Anomalous Higgs couplings [Hagiwara etal; Corbett, Eboli, Gonzales-Fraile, Gonzales-Garcia]

– assume Higgs is largely Standard Model and renormalizable

– effective *HVV* Lagrangian

$$\begin{aligned}\mathcal{L}_{\text{eff}}^{HVV} =& g_{Hgg}\; HG^a_{\mu\nu}G^{a\mu\nu} + g_{H\gamma\gamma}\; HA_{\mu\nu}A^{\mu\nu} + g^{(1)}_{HZ\gamma}\; A_{\mu\nu}Z^{\mu}\partial^{\nu}H + g^{(2)}_{HZ\gamma}\; HA_{\mu\nu}Z^{\mu\nu} \\ &+ g^{(1)}_{HZZ}\; Z_{\mu\nu}Z^{\mu}\partial^{\nu}H + g^{(2)}_{HZZ}\; HZ_{\mu\nu}Z^{\mu\nu} + g^{(3)}_{HZZ}\; HZ_{\mu}Z^{\mu} \\ &+ g^{(1)}_{HWW}\; \left(W^+_{\mu\nu}W^{-\,\mu}\partial^{\nu}H + \text{h.c.}\right) + g^{(2)}_{HWW}\; HW^+_{\mu\nu}W^{-\,\mu\nu} + g^{(3)}_{HWW}\; HW^+_{\mu}W^{-\,\mu}\end{aligned}$$

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– also include e-w precision data

$$\alpha\Delta T = \frac{3}{4c^2}\frac{e^2}{16\pi^2}\left[f_B\frac{m_H^2}{\Lambda^2}\log\frac{\Lambda^2}{m_H^2} + (c_w^2 f_W + f_B)\frac{m_Z^2}{\Lambda^2}\log\frac{\Lambda^2}{m_H^2} + \left(2c_w^2 f_W + (3c_w^2 - 1)f_B\right)\frac{m_Z^2}{\Lambda^2}\log\frac{\Lambda^2}{m_Z^2}\right]$$

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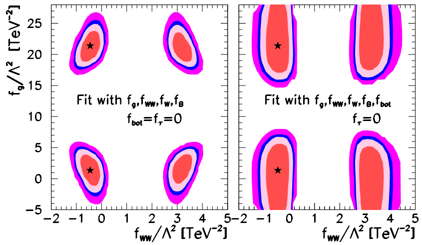

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Light Higgs as a Goldstone boson [Giudice, Grojean, Pomarol, Rattazzi]

– strongly interacting models predicting heavy broad resonance(s)

– light state if protected by Goldstone's theorem [Georgi & Kaplan]

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- postulate new $f \gtrsim v$ and $m_\rho \to 4\pi f$ [$c_j \sim 1$] [assume custodial symmetry]

$$\begin{aligned}
\mathcal{L}_{\rm SILH} = & \frac{c_H}{2f^2} \partial^\mu \left(H^\dagger H \right) \partial_\mu \left(H^\dagger H \right) + \frac{c_T}{2f^2} \left(H^\dagger \overleftrightarrow{D^\mu} H \right) \left(H^\dagger \overleftrightarrow{D}_\mu H \right) \\
& - \frac{c_6 \lambda}{f^2} \left(H^\dagger H \right)^3 + \left(\frac{c_y y_f}{f^2} H^\dagger H \bar{f}_L H f_R + \text{h.c.} \right) \\
& + \frac{i c_W g}{2 m_\rho^2} \left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H \right) (D^\nu W_{\mu\nu})^i + \frac{i c_B g'}{2 m_\rho^2} \left(H^\dagger \overleftrightarrow{D^\mu} H \right) (\partial^\nu B_{\mu\nu}) \\
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- leading terms in wave function renormalization and H^n

$\Rightarrow$ collider phenomenology of mostly $(H^\dagger H)$ terms [Mühlleitner etal]

Future: top Yukawa

Direct measurement $t\bar{t}H$, $H \to b\bar{b}$ [Atlas-Bonn: Jochen Cammin]

– crucial to understand Higgs sector [details later]

– trigger: $t \to bW^+ \to b\ell^+\nu$
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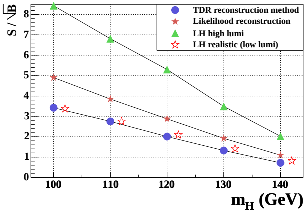

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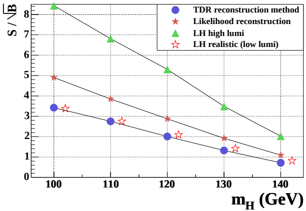

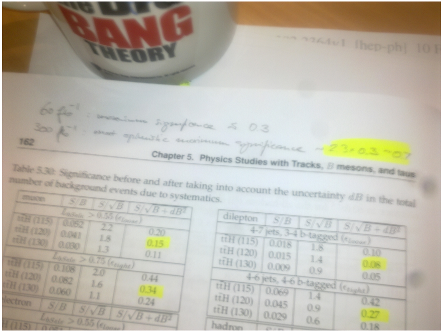

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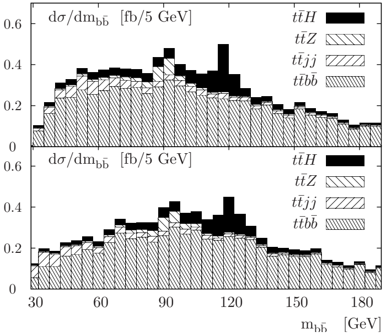

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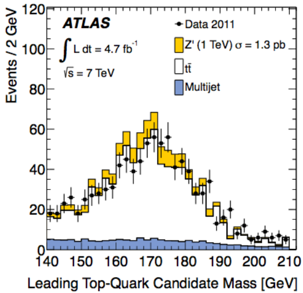
$\Rightarrow$ how do we find this channel?



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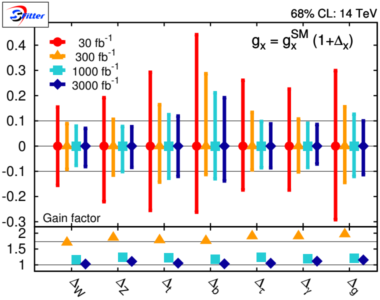

Weak scale theory

D6 operators

– SM: non-decoupling chiral fermions $g_{Hgg} \sim \alpha_s/(12\pi v)$

– new particle with charge Q and SU(3) Casimir $C(R)$ [Reece]

$$R_\gamma = \frac{g_{H\gamma\gamma}}{g_{H\gamma\gamma}^{\rm SM}} = \left[1 + 0.28\xi \left(1 \mp \sqrt{R_g} \right) \right]^2 , \qquad \xi = \frac{3Q^2}{C_2(R)}$$

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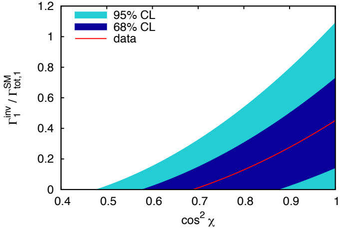
Higgs portal [e.g. Englert, Plehn, Rauch, Zerwas, Zerwas]

- renormalizable mixing $\mathcal{L} \sim (S^\dagger S)\,(H^\dagger H)$
- form-factor correction to SM Higgs [cos χ] plus invisible decays

$\Rightarrow$ invisible Higgs possible?



Weak scale

Supersymmetry

– MSSM Higgs mass the best-predicted LHC observable? [Hahn etal + Stal]

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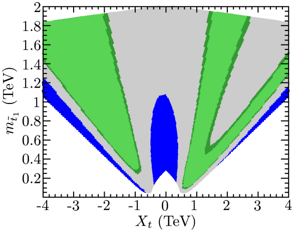

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More general [Gupta, Rzehak, Wells]

- modelling Higgs coupling deviations
- deviations allowed by other constraints

	ΔhVV	$\Delta h\bar{t}t$	$\Delta h\bar{b}b$
Mixed-in Singlet	6%	6%	6%
Composite Higgs	8%	tens of %	tens of %
Minimal Supersymmetry	$< 1\%$	3%	$10\%^{(\text{large }\tan\beta)}$, $100\%^{(\text{small }\tan\beta)}$

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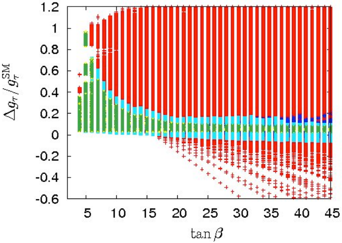
More general [Gupta, Rzehak, Wells]

- modelling Higgs coupling deviations
- deviations allowed by other constraints
- correlation of Δ_τ and heavy Higgs states

$\Rightarrow$ no final verdict on (too) many models?



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What if it is essentially the Standard Model

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High-scale effects

– Higgs mass related to self coupling: $m_H = v\sqrt{2\lambda}$
top mass related to Yukawa: $y_t = \sqrt{2} m_t / v$

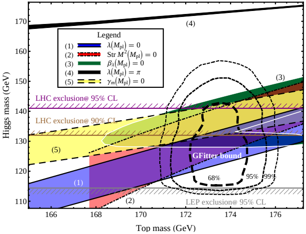
$$\frac{d\,\lambda}{d\,\log Q^2} = \frac{1}{16\pi^2}\left[12\lambda^2 + 6\lambda y_t^2 - 3y_t^4 - \frac{3}{2}\lambda\left(3g_2^2 + g_1^2\right) + \frac{3}{16}\left(2g_2^4 + (g_2^2 + g_1^2)^2\right)\right]$$

– IR fixed point for λ / y_t^2 fixing m_H^2 / m_t^2 [with gravity: Shaposhnikov, Wetterich]

$$m_H = 126.3 + \frac{m_t - 171.2}{2.1} \times 4.1 - \frac{\alpha_s - 0.1176}{0.002} \times 1.5$$

– Planck-scale conditions [Holthausen, Lim, Lindner]

⇒ Higgs and top strongly linked



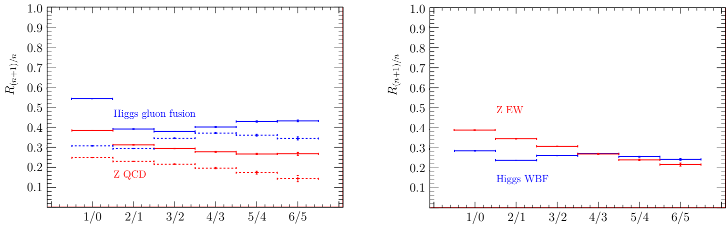
Jet counting

Jets with Higgs [Englert, Gerwick, TP, Schichtel, Schumann]

– example: WBF $H \to \tau\tau$

– staircase scaling before WBF cuts [QCD and e-w processes]

– e-w *Zjj* production with too many structures



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Understanding a jet veto from QCD [simulated with SHERPA]

– count add'l jets to reduce backgrounds

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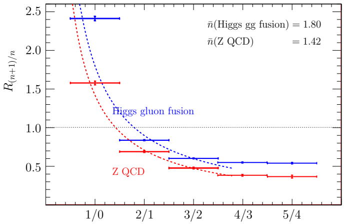

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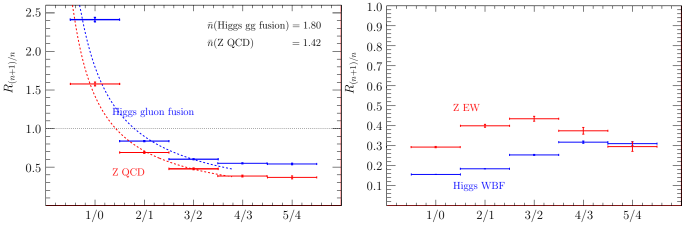
– distribution of number of jets understood



Jet geometry

Fox–Wolfram moments [Bernaciak, Buschmann, Butter, TP]

- jets as part of siagnatures becoming more relevant
- jet counting understood from QCD [Gerwick, TP, Schichtel, Schumann]
- event shapes waiting [Banfi, Salam, Zanderighi]
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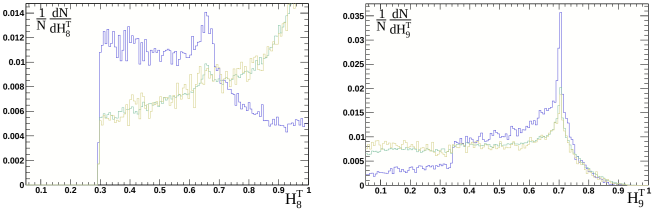

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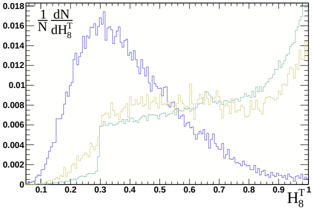

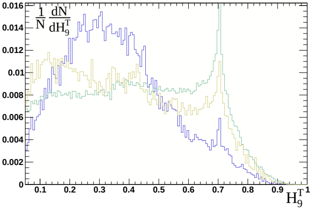

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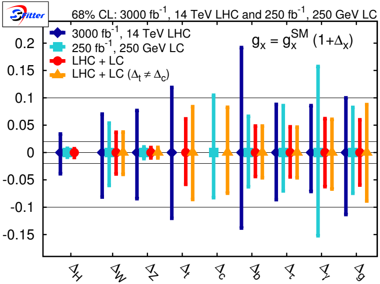

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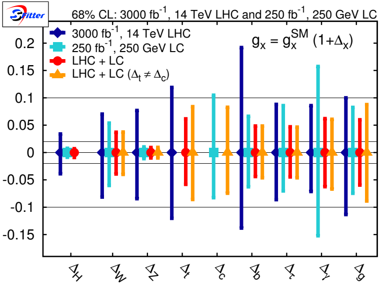

Future: bottom Yukawa

Towards 14 TeV

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Best channel $q\bar{q} \to VH, H \to b\bar{b}$

– let me comment on CMS analysis

– focus on boosted regime $p_{T,V} \gtrsim 120$ GeV
  fudge factor Data/MC=$1.91 \pm 0.14 \pm 0.31$ for $Wb\bar{b}$
  data-estimated background $\Delta\sigma/\sigma \sim 10\%$
  12 observables in BDT [most of them work and are understood]
  no side bands with any S/B

$\Rightarrow$ how will this ever work?

[my hopes rest on BDRS and jet substructure]