Higgs Physics after the Discovery

Tilman Plehn [and lots of Karlsruhe people]

Universität Heidelberg

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Immediate questions

1. What is the 'Higgs' Lagrangian?

   – psychologically: looked for Higgs, so found a Higgs

   – CP-even spin-0 scalar expected
   spin-1 vector unlikely
   spin-2 graviton unexpected

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   – requires fixed operator basis

   – Standard Model structure?

   – anomalous couplings?

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   - Standard Model structure?
   - anomalous couplings?

3. What can we expect in the future?
   - WBF analyses still sub-leading
   - VH and $t\bar{t}H$ missing
   - self coupling not accessible?

Lagrangian

Equivalent questions

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- what is the structure of the Higgs Lagrangian?
- can the Higgs give mass to heavy states?

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Heavy flavor inspiration

- for any observed Higgs coupling there exists a renormalizable operator
- 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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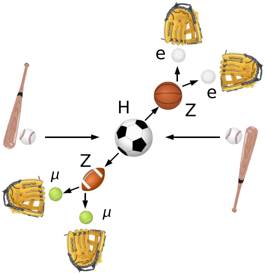
$\Rightarrow$ analyze Higgs kinematics [in as many channels as possible]

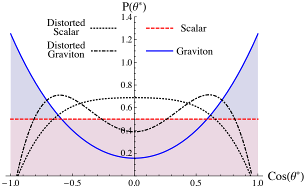


Lagrangian

Model independent angles

– first step: Higgs polar angle for spin-0 vs spin-2

$$\frac{d\Gamma_0}{d\cos\theta^*} \sim P_0(\theta^*) = 1 \qquad\qquad P_2(\theta^*) \sim 1 + 6\cos^2\theta^* + \cos^4\theta^*$$



Lagrangian

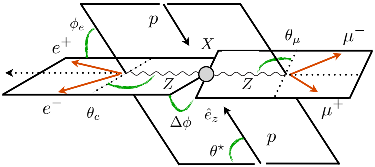
Model independent angles

– $H \to ZZ$ decays [Choi etal; Melnikov etal; Lykken etal; v d Bij etal; Englert, Spannowsky, Takeuchi]
classic Cabibbo–Maksymowicz–Dell'Aquila–Nelson angles [all over LHCb]

$$\cos\theta_e = \hat{p}_{e^-} \cdot \hat{p}_{Z_\mu}\Big|_{Z_e} \qquad \cos\theta_\mu = \hat{p}_{\mu^-} \cdot \hat{p}_{Z_e}\Big|_{Z_\mu} \qquad \cos\theta^* = \hat{p}_{Z_e} \cdot \hat{p}_{\text{beam}}\Big|_X$$

$$\cos\phi_e = (\hat{p}_{\text{beam}} \times \hat{p}_{Z_\mu}) \cdot (\hat{p}_{Z_\mu} \times \hat{p}_{e^-})\Big|_{Z_e}$$

$$\cos\Delta\phi = (\hat{p}_{e^-} \times \hat{p}_{e^+}) \cdot (\hat{p}_{\mu^-} \times \hat{p}_{\mu^+})\Big|_X$$



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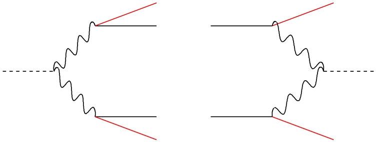
  Breit frame or hadron collider (η, ϕ) [Breit: boost into space-like]



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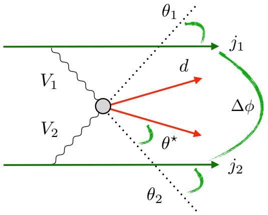

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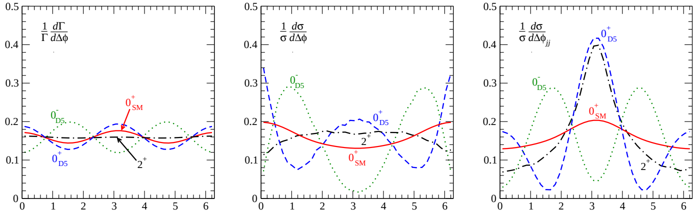


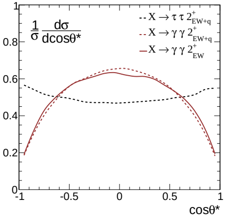
⇒ different approaches with similar physics

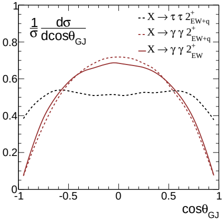
Lagrangian

Spin-2 test? [Englert, Mawatari, Netto, TP]

– unitarization affecting all energy variables

– try Gottfried-Jackson angle [$\hat{p}_{X,lab}$ vs $\hat{p}_{d,X}$; Frank, Rauch, Zeppenfeld; Schumi]





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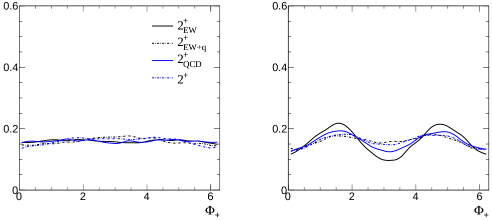
– alternatively $\phi_1 + \phi_2$ [Hagiwara, Li, Mawatari]



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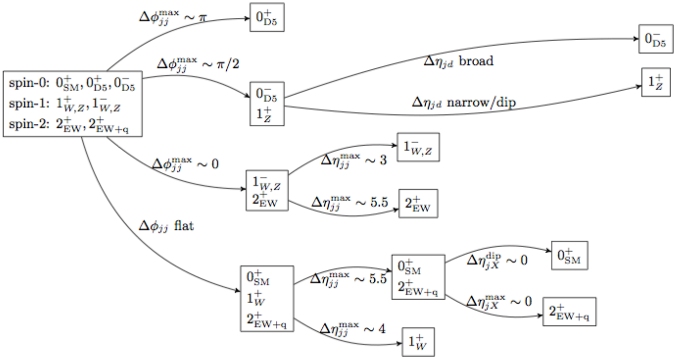
- diagrammatic analysis for WBF [$\Delta\eta_{jj}$ crucial]



$\Rightarrow$ angular observables in most channels

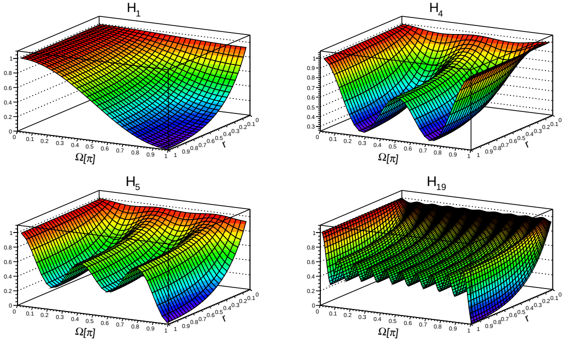
Fox-Wolfram moments

Series in spherical harmonics [Field, Kanev, Tayebnejad; BaBar; Bernaciak, Buschmann, Butter, TP]

– originally alternative to event shapes

$$H_\ell^T = \frac{4\pi}{2\ell+1} \sum_{m=-\ell}^{\ell} \left| \sum_{i=1}^{N} Y_\ell^m(\Omega_i) \, \frac{p_{T,i}}{p_{T,\text{tot}}} \right|^2 = \sum_{i,j=1}^{N} \frac{p_{T,i} p_{T,j}}{p_{T,\text{tot}}^2} P_\ell(\cos\Omega_{ij}) \, ,$$

– defined on separated jets for a start



	$H_\ell < 0.3$	$0.3 < H_\ell < 0.7$	$0.7 < H_\ell < 1$
even ℓ	forbidden	democratic	ordered, collinear, back-to-back
odd ℓ	back-to-back	democratic	collinear, ordered

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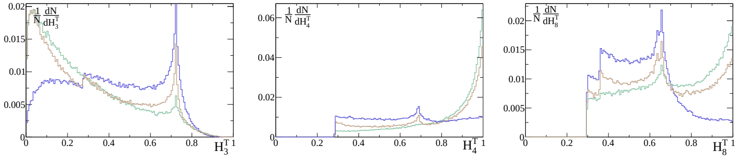
– applied to tagging jets in WBF [$m_{jj} > 600$ GeV]



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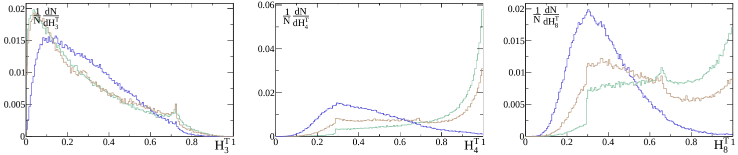

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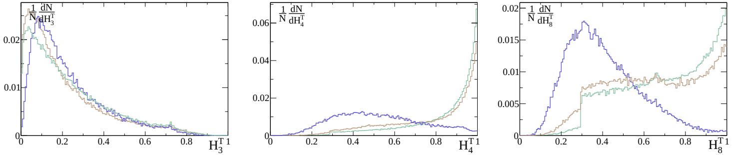

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– useful information left
tuned resolution via variable ℓ [not too correlated]

– adjust weight factor?
adjust objects entering FWMs?

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⇒ might be useful eventually

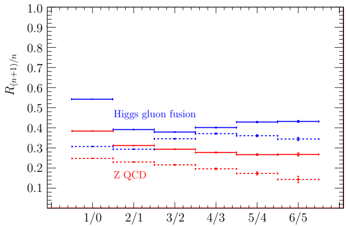
Jet counting

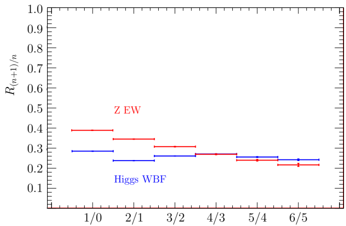
Jets with Higgs [Englert, Gerwick, TP, Schichtel, Schumann]

– 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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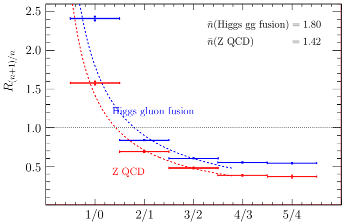
Understanding a jet veto from QCD [simulated with SHERPA, also ask Stefan Gieseke]

- count add'l jets to reduce backgrounds

$$p_T^{\text{veto}} > 20 \text{ GeV} \qquad \min y_{1,2} < y^{\text{veto}} < \max y_{1,2}$$

- Poisson for QCD processes ['radiation' pattern]



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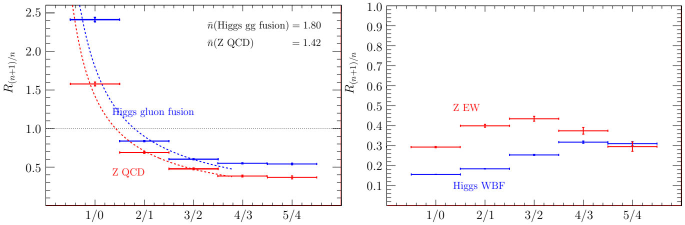
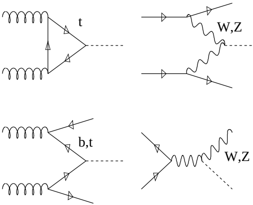
– (fairly) staircase for e-w processes [cuts keeping signal]

– distribution of number of jets understood



Higgs rates

The model



– assume: we see a scalar [*ZZ* and WBF correlations]
  it is a narrow resonance
  SM-like D4 structures
  benchmarks useless
– production & decay combinations
– signal strength vs couplings?

$gg \to H$ $qq \to qqH$ $gg \to t\bar{t}H$ $q\bar{q}' \to WH$ plus a little problem	$\leftrightarrow$	$H \to ZZ$ $H \to WW$ $H \to b\bar{b}$ $H \to \tau^+_{\ell h}\tau^-_\ell$ $H \to \gamma\gamma$ $H \to Z\gamma$ ...	$\leftrightarrow$	signal $\times$ trigger backgrounds Gauss/Poisson statistics systematics theory errors

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Why 126 GeV is just perfect [Zeppenfeld et al; Dührssen et al; SFitter 2009/2012]

- because is wants a weakly interacting top partner

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Why 126 GeV is just perfect [Zeppenfeld et al; Dührssen et al; SFitter 2009/2012]

– parameters: Higgs couplings to $W, Z, t, b, \tau, g, \gamma$ [SM-like D4 operators]

$$g_{HXX} = g_{HXX}^{\text{SM}} \; (1 + \Delta_X) \qquad\qquad g_{HWW} > 0$$

– measurements: $GF : H \to ZZ, WW, \gamma\gamma$
$WBF : H \to ZZ, WW, \gamma\gamma, \tau\tau$
$VH : H \to b\bar{b}$
$t\bar{t}H : H \to \gamma\gamma, b\bar{b}$

$\Rightarrow$ perfect application for SFitter

Error analysis

Sources of uncertainty

- statistical error: Poisson
  systematic error: Gaussian, if measured
  theory error: not Gaussian
- simple argument
  LHC rate 10% off: no problem
  LHC rate 30% off: no problem
  LHC rate 300% off: Standard Model wrong
- theory likelihood flat centrally and zero far away
- profile likelihood construction: RFit [CKMFitter]

$$-2 \log \mathcal{L} = \chi^2 = \vec{\chi}_d^T \; C^{-1} \; \vec{\chi}_d$$

$$\chi_{d,i} = \begin{cases} 0 & |d_i - \bar{d}_i| < \sigma_i^{\text{(theo)}} \\ \dfrac{|d_i - \bar{d}_i| - \sigma_i^{\text{(theo)}}}{\sigma_i^{\text{(exp)}}} & |d_i - \bar{d}_i| > \sigma_i^{\text{(theo)}} \end{cases}$$

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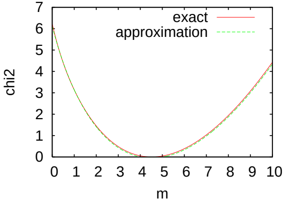
Efficient combination of errors [different from Michael's ATLAS analysis]

- Gaussian $\otimes$ Gaussian: half width added in quadrature
  Gaussian/Poisson $\otimes$ flat: RFit scheme
  Gaussian $\otimes$ Poisson: ??
- approximate formula

$$\frac{1}{\log\mathcal{L}_{\text{comb}}} = \frac{1}{\log\mathcal{L}_{\text{Gauss}}} + \frac{1}{\log\mathcal{L}_{\text{Poisson}}}$$

- modified Minuit gradient fit last step

$\Rightarrow$ error bars from toy measurements



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Systematic uncertainties

luminosity measurement	5 %
detector efficiency	2 %
lepton reconstruction efficiency	2 %
photon reconstruction efficiency	2 %
WBF tag-jets / jet-veto efficiency	5 %
b-tagging efficiency	3 %
τ-tagging efficiency (hadronic decay)	3 %
lepton isolation efficiency ($H \to 4\ell$)	3 %

	$\Delta B^{\text{(syst)}}$
$H \to ZZ$	1%
$H \to WW$	5%
$H \to \gamma\gamma$	0.1%
$H \to \tau\tau$	5%
$H \to b\bar{b}$	10%

Higgs couplings

Higgs sector at LHC [Zeppenfeld et al; Dührssen et al; SFitter 2009/2012; Contino et al]

– light Higgs around 126 GeV: over 10 channels ($\sigma \times BR$)

– measurements: $GF : H \to ZZ, WW, \gamma\gamma$ [first analyses]
$WBF : H \to ZZ, WW, \gamma\gamma, \tau\tau$ [just starting]
$VH : H \to b\bar{b}$ [BDRS-like analyses only]
$t\bar{t}H : H \to \gamma\gamma, WW, b\bar{b}$... [useful but later]

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

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Total width

– myths about scaling

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

gives constraint from $\sum \Gamma_i(g^2) < \Gamma_\text{tot} \to \Gamma_H|_\text{min}$

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

– SFitter assumption $\Gamma_\text{tot} = \sum_\text{obs} \Gamma_j$ [plus generation universality]

Higgs couplings

Higgs sector at LHC [Zeppenfeld et al; Dührssen et al; SFitter 2009/2012; Contino et al]

– light Higgs around 126 GeV: over 10 channels ($\sigma \times BR$)

– measurements: $GF : H \to ZZ, WW, \gamma\gamma$ [first analyses]
$WBF : H \to ZZ, WW, \gamma\gamma, \tau\tau$ [just starting]
$VH : H \to b\bar{b}$ [BDRS-like analyses only]
$t\bar{t}H : H \to \gamma\gamma, WW, b\bar{b}...$ [useful but later]

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

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

– SM operators $g_{HXX} = g_{HXX}^{\text{SM}} \, (1 + \Delta_X)$
D5 couplings $g_{ggH}, g_{\gamma\gamma H}$ free?
electroweak correction currently negligible

– experimental/theory errors on signal and backgrounds
ATLAS and CMS both included

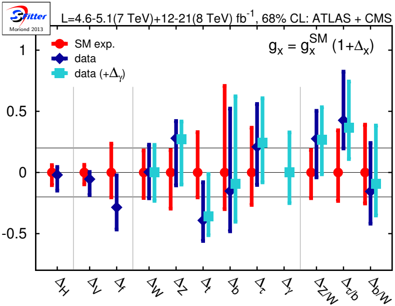
– exclusive likelihood map
each coupling from profile likelihoods
best-fit point with Minuit
complete error analysis

SFitter results

LHC including Moriond/Aspen data [SFitter: Klute, Lafaye, TP, Rauch, Zerwas]

- focus SM-like [secondary solutions possible]
- six couplings and ratios from data
  g_b from width
  g_g vs g_t not yet possible

  [similar: Ellis etal, Djouadi etal, Strumia etal, Grojean etal]
- poor man's analyses: $\Delta_H, \Delta_V, \Delta_f$
- Tevatron $H \to b\bar{b}$ with little impact



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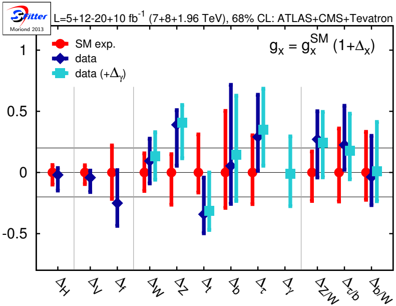

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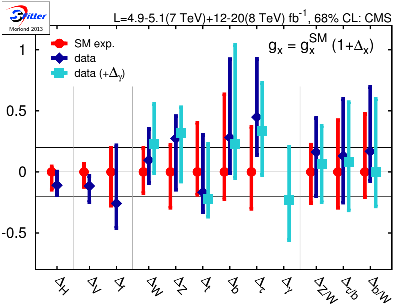

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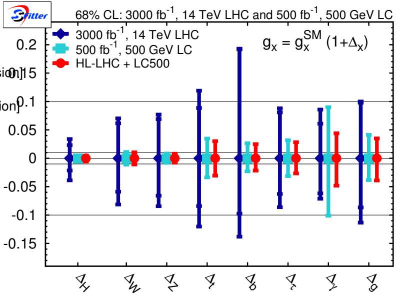
Future dinosaurs

- LHC extrapolations unclear [SFitter version]
- theory extrapolations tricky [SFitter version]
- ILC case obvious [500 GeV for now]
- interplay in loop-induced couplings



Theorists ideas

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]

– interesting if $v \ll f < 4\pi f$ [little Higgs $v \sim g^2 f/(2\pi)$]

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\begin{aligned}
\mathcal{L}_{\text{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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- collider phenomenology of mostly $(H^\dagger H)$ terms [Mühlleitner etal]

$\Rightarrow$ remember what your operators are!

Anomalous couplings

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

– assume Higgs is largely Standard Model

– additional higher-dimensional couplings

$$\begin{aligned}\mathcal{L}_{\text{eff}} = &-\frac{\alpha_s v}{8\pi}\frac{f_g}{\Lambda^2}(\Phi^\dagger\Phi)G_{\mu\nu}G^{\mu\nu} + \frac{f_{WW}}{\Lambda^2}\Phi^\dagger W_{\mu\nu}W^{\mu\nu}\Phi \\ &+ \frac{f_W}{\Lambda^2}(D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi) + \frac{f_B}{\Lambda^2}(D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi) + \frac{f_{WWW}}{\Lambda^2}\text{Tr}(W_{\mu\nu}W^{\nu\rho}W_\rho^\mu) \\ &+ \frac{f_b}{\Lambda^2}(\Phi^\dagger\Phi)(\overline{Q}_3\Phi d_{R,3}) + \frac{f_\tau}{\Lambda^2}(\Phi^\dagger\Phi)(\overline{L}_3\Phi e_{R,3})\end{aligned}$$

– plus e-w precision data and triple gauge couplings

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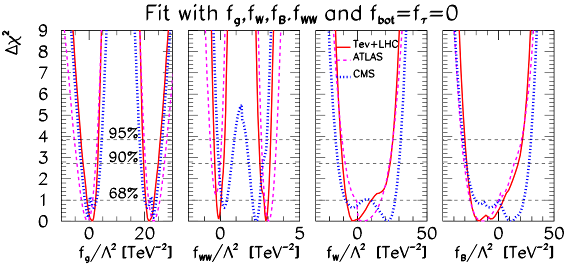

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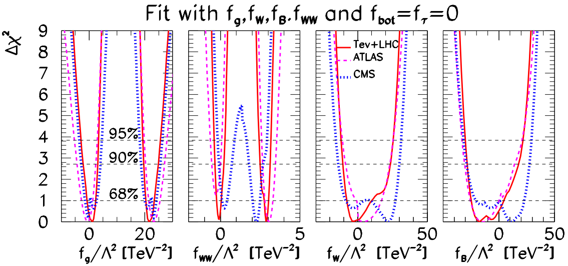

⇒ remember what your operators are!

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: $t \to bW^+ \to b\ell^+\nu$
reconstruction and rate: $\bar{t} \to \bar{b}W^- \to \bar{b}jj$

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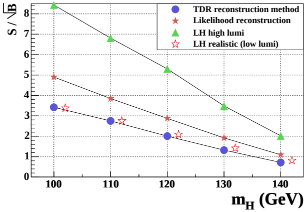
1– combinatorics: m_H in $pp \to 4b_{tag}\, 2j\, \ell\nu$
2– kinematics: peak-on-peak
3– systematics: $S/B \sim 1/9$



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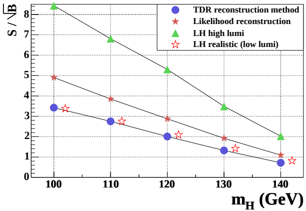

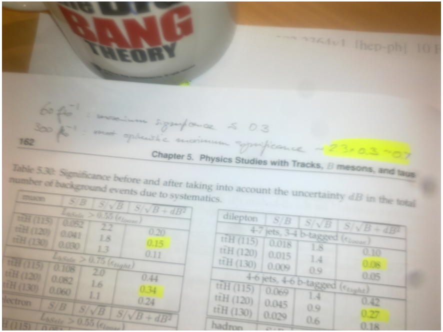

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– semi-leptonic fat jets analysis [TP, Salam, Spannowsky]
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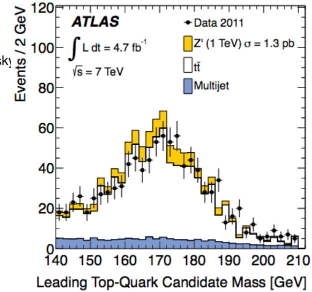

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$4b$–2ℓ–MET final state
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$\Rightarrow$ good ideas welcome

Weak scale models

Higgs portal [Englert, TP, Rauch, Zerwas, Zerwas]

– only few renormalizable links to a new phyics world
general standard-hidden ansatz $H_1 = \cos\chi\, H_s + \sin\chi\, H_h$

– visible and hidden decays [plus $H_2 \to H_1 H_1$ cascade decays]

$$\Gamma_1^{\text{tot}} = \cos^2\chi\, \Gamma_{\text{tot};1}^{\text{SM}} + \sin^2\chi\, \Gamma_1^{\text{hid}}$$

– constraints on event rate

$$\frac{\sigma[H_1 \to XX^*]}{\sigma[H_1 \to XX^*]^{\text{SM}}} = \frac{\cos^2\chi}{1 + \tan^2\chi\, \dfrac{\Gamma_1^{\text{hid}}}{\Gamma_{\text{tot},1}^{\text{SM}}}}$$

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Form factor Higgs [Kaplan & Georgi; Contino, Espinosa, Giudice, Grojean, Mühlleitner, Pomarol, Rattazzi]

– simple trick: $\xi \equiv v/f \gtrsim 0.3$ while $m_\rho = g_\rho f \gg f$ [also not calculable]

1– all couplings scaled $g \to g\sqrt{1-\xi}$

– one-parameter fit in SFitter

– from 8 TeV data $\Delta_H = 0 \pm 0.15$

2– gauge couplings $g \to g\sqrt{1-\xi}$
  Yukawas $g \to g(1-2\xi)/\sqrt{1-\xi}$

– sign change of Yukawas, $g_{\gamma\gamma H}$ correlated

Weak scale theory

Non-decoupling D6 operators

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

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

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

$\Rightarrow$ end of a fourth chiral generation [Lenz etal]

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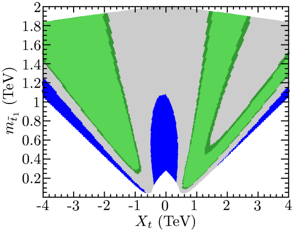
Supersymmetry

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

– production rates mix of form factor and D6 [e.g. Hollik, TP, Rauch, Rzehak]

– stop mass/mixing crucial [m_A = 1 TeV, tan β = 20]



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⇒ end of a fourth chiral generation [Lenz etal]

Supersymmetry

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

– production rates mix of form factor and D6 [e.g. Hollik, TP, Rauch, Rzehak]

– stop mass/mixing crucial [$m_A = 1$ TeV, $\tan\beta = 20$]

– SUSY particles in eff couplings [everyone]
stop mixing destructive [Reece]

$$\frac{g_{Hgg}}{g^{\text{SM}}_{Hgg}} = 1 + \frac{1}{4}\left(\frac{m_t^2}{m_{\tilde{t}_1}^2} + \frac{m_t^2}{m_{\tilde{t}_2}^2} - \frac{m_t^2 X_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}\right)$$

– move towards NMSSM always an option...

⇒ no final verdict on the MSSM (ever?)

Weak scale theory

Non-decoupling D6 operators

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Moving towards the Standard Model?

– should we worried by SM $\pm 20\%$?

– what is expected in BSM models [Gupta, Rzehak, Wells]

	ΔhVV	$\Delta h\bar{t}t$	$\Delta h\bar{b}b$
mixed-in singlet	6%	6%	6%
composite Higgs	8%	tens of %	tens of %
MSSM	$< 1\%$	3%	depends...

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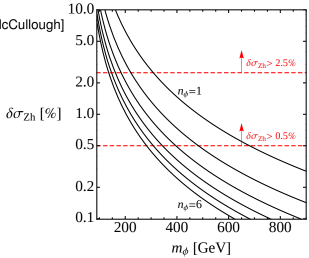
– contributing to σ_{ZH} through self energy



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$\Rightarrow$ trivial: want best possible precision

High scale theory

What if it is essentially the Standard Model

– many theories decouple in Higgs sector [custodial symmetry, suppressed D6]

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Renormalization group

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

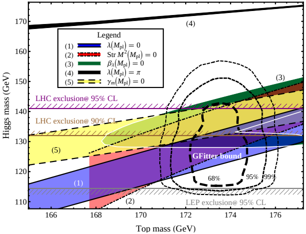
$$\frac{d\,\lambda}{d\,\log Q^2} = \frac{1}{16\pi^2}\left[12\lambda^2 + 6\lambda y_t^2 - 3y_t^4 - \frac{3}{2}\lambda\left(3g_2^2 + g_1^2\right) + \frac{3}{16}\left(2g_2^4 + (g_2^2 + g_1^2)^2\right)\right]$$

- IR fixed point for λ/y_t^2 fixing $m_H^2/m_t^2 = 1/2$ [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]

$\Rightarrow$ Higgs and top crucial in combination



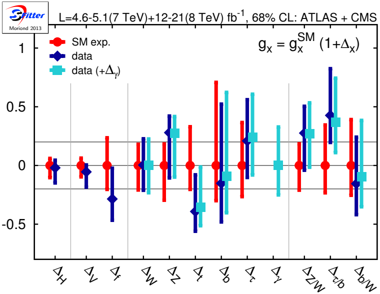
Outlook

LHC Higgs program

– experimentalists: do not listen to theorists

– phenomenologists: enjoy fun problems

– theorists: give us some fun interpretations



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

Markov chains

Probability maps [statistics unexpectedly hard...]

– honest LHC parameters: weak-scale Lagrangean [Higgs, MSSM, dark matter,...]

– likelihood map: data given a model $p(d|m) \sim |\mathcal{M}|^2(m)$

– Bayes' theorem: $p(m|d) = p(d|m)\ p(m)/p(d)$ [$p(d)$ normalization, $p(m)$ prejudice]

Markov chains

– problem in grid: huge phase space, find local best points?
problem in fit: domain walls, find global best points?

– construct 'representative' poll

– classical: representative set of spin states
compute average energy on this reduced sample

– BSM or Higgs: map $p(d|m)$ of parameter points
evaluate whatever you want

– Metropolis-Hastings
starting probability $p(d|m)$ vs suggested probability $p(d|m')$
1– accept new point if $p(d|m') > p(d|m)$
2– or accept with $p(d|m')/p(d|m) < 1$

Markov chains

Weighted Markov chains [Lafaye, TP, Rauch, Zerwas; Ferrenberg, Swendsen]

- special situation
  measure of 'representative': probability itself
- example with 2 bins, probability 9:1
  10 entries needed for good Markov chain
  2 entries needed if weight kept
- binning with weight would double count
  bin with inverse averaging

$$P_{\text{bin}}(p \neq 0) = \frac{\text{bincount}}{\sum_{i=1}^{\text{bincount}} p^{-1}}$$

- good choice for $\mathcal{O}(6)$ dimensions

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Cooling Markov chains [Lafaye, TP, Rauch, Zerwas]

– zoom in on peak structures [inspired by simulated annealing]

– modified condition
Markov chain in partitions, numbered by j

$$p(d|m') > p(d|m)\; r^{10/j} \qquad r\epsilon[0,1] \quad \text{random number}$$

– check for parameter coverage with many Markov chains

⇒ exclusive likelihood map first result