Higgs Physics after the Discovery

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Universität Heidelberg

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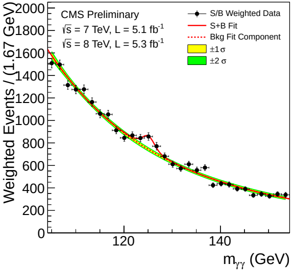
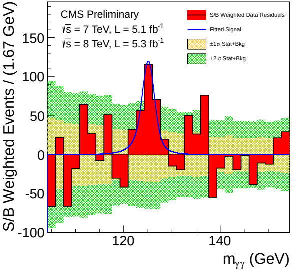
Higgs discovery

Best of ATLAS and CMS [together over 100 subchannels]

– ‘silver channel’ $H \to \gamma\gamma$
  local significance 4.5σ (ATLAS), 4.1σ (CMS)





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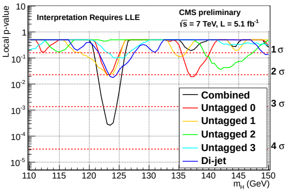

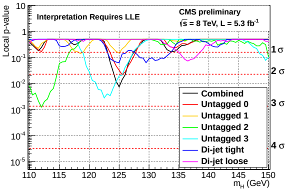

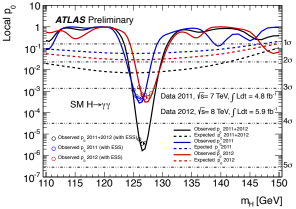

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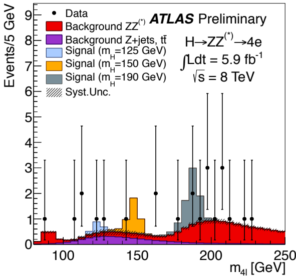

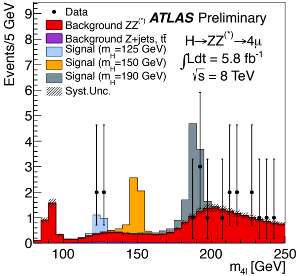

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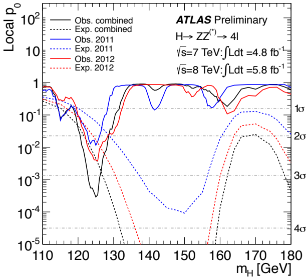

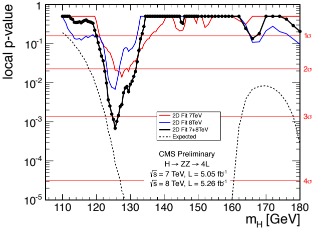

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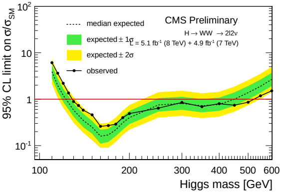

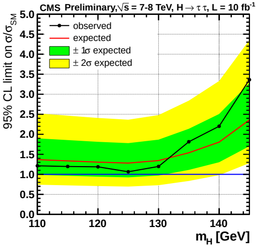

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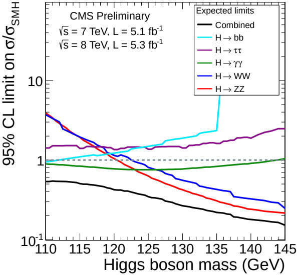
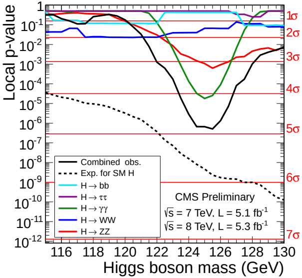
$\Rightarrow$ resonance at $m_H = 125.5$ GeV discovered





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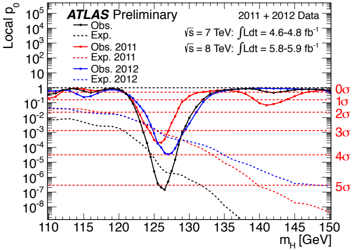

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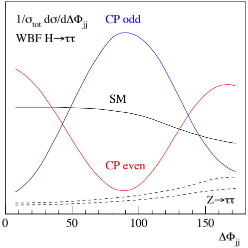
So, what is this bump?

– spin-0 scalar likely and expected [P even?]
– spin-1 vector unlikely with $V \to \gamma\gamma$ [Landau-Yang]
– spin-2 graviton unexpected

$\Rightarrow$ quantum numbers analysis needed

[TP, Rainwater, Zeppenfeld; Lykken etal; Melnikov etal]



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Any models ruled out?

- Standard Model fine [Holthausen, Lim, Lindner]
- reasonably decoupling theories all fine
  MSSM one example [tons of papers]
  hypersphere in $m_{\tilde{t}_{L/R}}$, $\tan\beta$, A_t, μ, m_A predicting little [$X_t^2/(m_{\tilde{t}_1} m_{\tilde{t}_2}) \gtrsim 1$]
- strongly interacting light Higgs supposedly fine
- Higgs portal fine

$\Rightarrow$ coupling measurement the key

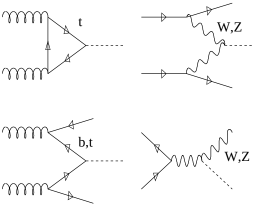
Where we are going

The model

– assume: we see a scalar [*ZZ* and WBF correlations]
  it is a narrow resonance
  SM-like D4 structures
  self coupling out of reach [Baur et al]

– 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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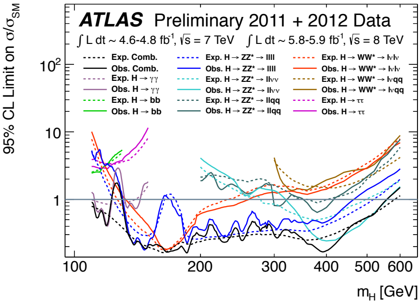

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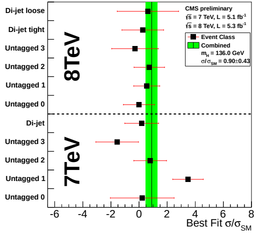

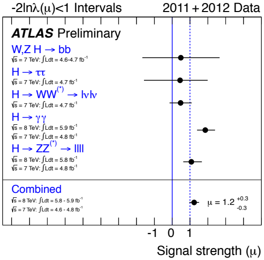

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Why 126 GeV is just perfect [Zeppenfeld et al; Dührssen et al; SFitter 2009/2012]

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

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

– 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

SFitter 1: 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 $p(d|m')/p(d|m) < 1$

SFitter 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

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

- check for parameter coverage with many Markov chains

$\Rightarrow$ exclusive likelihood map first result

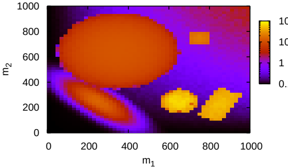
SFitter 2: Frequentist vs Bayesian

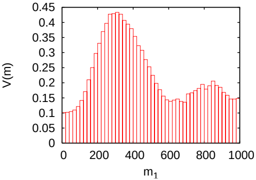
Getting rid of model parameters

– poorly constrained parameters
uninteresting parameters
unphysical parameters [JES part of m_t extraction]

– two ways to marginalize likelihood map

1– integrate over probabilities
normalization etc mathematically correct
integration measure unclear
noise accumulation from irrelevant regions
classical example: convolution of two Gaussians





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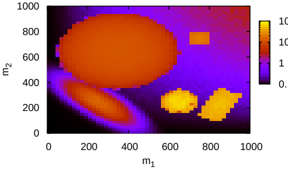

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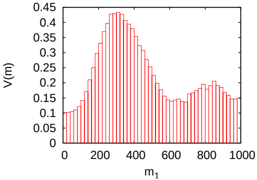
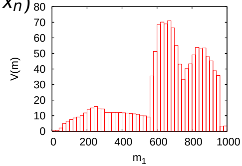


1– integrate over probabilities
  normalization etc mathematically correct
  integration measure unclear
  noise accumulation from irrelevant regions
  classical example: convolution of two Gaussians

2– profile likelihood $\mathcal{L}(.., x_{j-1}, x_{j+1} \dots) \equiv \max_{x_j} \mathcal{L}(x_1, \dots, x_n)$
  no integration needed
  no noise accumulation
  not normalized, no comparison of structures
  classical example: best-fit point



– one-dimensional distributions tricky

SFitter 3: 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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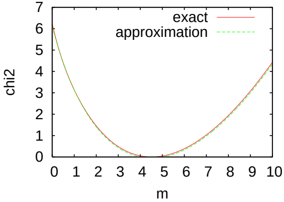
Combination of errors

- 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



Higgs couplings

Higgs-sector analysis [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 crucial]
$t\bar{t}H: H \to \gamma\gamma, WW, b\bar{b}$... [useful but later]

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

– hope: cancel uncertainties

$(WBF:\ H \to WW)/(WBF:\ H \to \tau\tau)$
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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]

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$(WBF: H \to WW)/(GF: H \to WW)$...

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

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

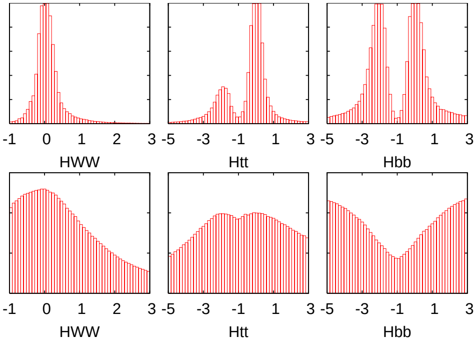
– experimental/theory errors on signal and backgrounds
ATLAS and CMS both included

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

Basic checks

Marginalization procedures

1– noisy environment preferring profile likelihoods [no effective couplings, 30 fb^{-1}]



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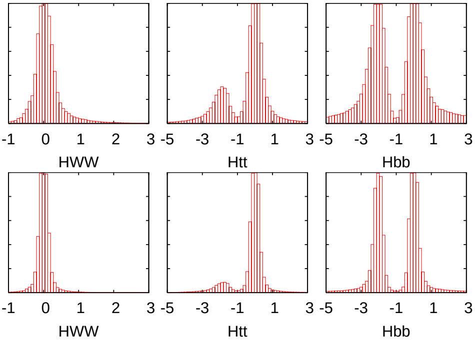
2– higher luminosity quantitatively different [no effective couplings, 30 vs 300 fb^{-1}]



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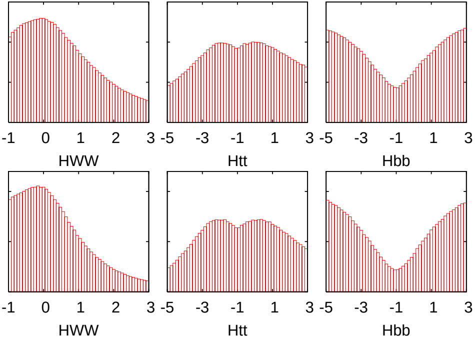
3– but not saving Bayesian statistics [no effective couplings, 300 fb^{-1}]



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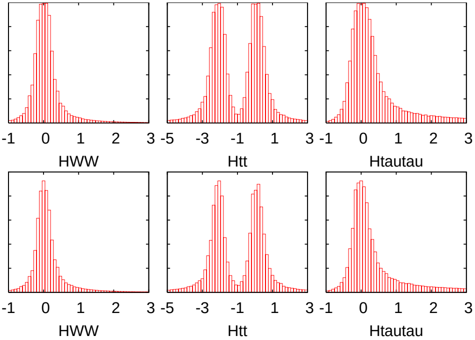
1– noisy environment preferring profile likelihoods [no effective couplings, 30 fb^{-1}]

2– higher luminosity quantitatively different [no effective couplings, 30 vs 300 fb^{-1}]

3– but not saving Bayesian statistics [no effective couplings, 300 fb^{-1}]

4– theory errors not dominant for 30 fb^{-1} [with effective couplings, 30 fb^{-1}]



$\Rightarrow$ profile likelihood for now

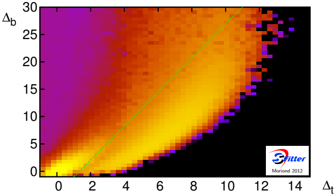
7 TeV and 8 TeV results

Global view on 7 TeV data [Klute, Lafaye, TP, Rauch, Zerwas, Dührssen]

– is there a SM-like solution?
are there alternative solutions?

(1) expected 2011 results: SM central values, measured error bars

– large-coupling solution separable



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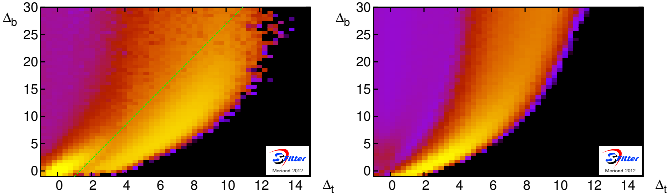
(2) measured 2011 results: measured central values and error bars

– both solutions overlapping



7 TeV and 8 TeV results

Global view on 7 TeV data [Klute, Lafaye, TP, Rauch, Zerwas, Dührssen]

– is there a SM-like solution?
  are there alternative solutions?

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– large-coupling solution separable

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Local view on 7 TeV/8 TeV data [Klute, Lafaye, TP, Rauch, Zerwas, Dührssen]

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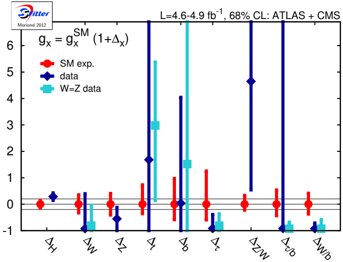
– poor man's analysis great: $\Delta_j \equiv \Delta_H$

$\Rightarrow$ moving toward Standard Model?



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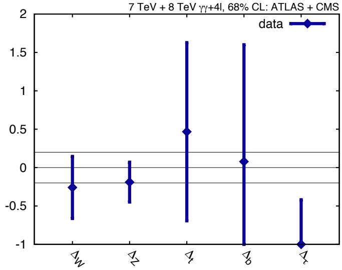

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2012, 2014, etc

– specifically Higgs:

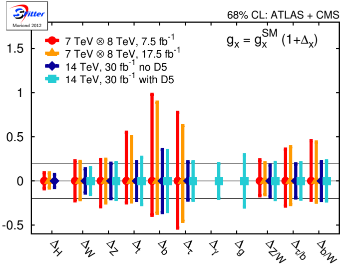
  dark side of the Higgs portal?
  new states in effective couplings?

– 2012: meaningful WBF measurements
  g_W and g_τ accessible

– 2014: $t\bar{t}H$ and $H \to b\bar{b}$ measurements
  g_g and g_γ accessible

– upgrades: systematics critical

$\Rightarrow$ exciting prospects!



Specific Higgs hypotheses

Status of the Higgs portal

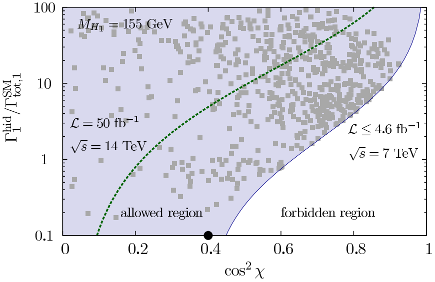
– visible and hidden decays [plus $H_2 \to H_1 H_1$ cascade decays]

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

– constraints on event rate

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

– two scenarios: $(m_H = 125, \mathcal{R} \sim 1)$ and $(m_H = 155, \mathcal{R} \sim 0.4)$



$\Rightarrow$ invisible Higgs needed for final answer [Eboli & Zeppenfeld]

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Strongly interacting Higgs at LHC [Espinosa, Grojean, Mühlleitner; SFitter; Ellis & You]

– pretty much fundamental Higgs

– coupling analysis technically simple

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

– one-parameter fit in SFitter

– from 7 TeV data $\Delta_H = 0 \pm 0.20$

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

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Hypotheses vs 7 TeV data [SFitter 2012]

– start from general analysis

– pick your favorite model as constraint

	χ^2_{2011}/dof
independent Δ_x	9.3/22
$\Delta_W = \Delta_Z$	12.3/23
$\Delta_W = \Delta_Z$ and $\Delta_b = \Delta_t = \Delta_\tau$	18.0/24
$\Delta_x \equiv \Delta_H$	18.6/26
gaugephobic	13.2/24
fermiophobic	16.0/25

$\Rightarrow$ easy once the general fit is done

To-do list

Problems in Higgs sector analyses

1– pile-up in Higgs analyses
nothing I can do

2– channels for *bbH* and *ttH* couplings
Higgs and top tagging: tools in good hands [thank you to Higgs workshop in 2009!]

3– N^{∞}LO cross section predictions
maybe I am not German enough

4– analyses not organized by production channels
count recoil jets instead, jet vetos

To-do list

Higgs searches by recoil jets, not production processes

- 'soft' gluon radiation infinitely likely [like soft photons]
- parton densities including 'collinear' jets [intro: arXiv:0910.4182, Springer Lecture Notes]
- many analyses at odds with DGLAP [hard to predict at fixed order]

$\Rightarrow$ study exclusive n_{jets} distributions

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Poisson scaling [Peskin & Schroeder]

– example: photons off hard electron

$$\sigma_n = \frac{\bar{n}^n e^{-\bar{n}}}{n!} \qquad \Longleftrightarrow \qquad R^{\text{excl}}_{(n+1)/n} \equiv \frac{\sigma_{n+1}}{\sigma_n} = \frac{\bar{n}}{n+1}$$

1– radiation matrix element $\bar{n}^n$ [abelian fine, non-abelian for leading log and color]

2– phase space factor $1/n!$ [only combinatorics effect, matrix element ordered]

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Staircase scaling [Ellis, Kleiss, Stirling]

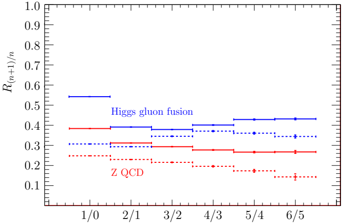
- observed since UA2
- same for inclusive and exclusive rates

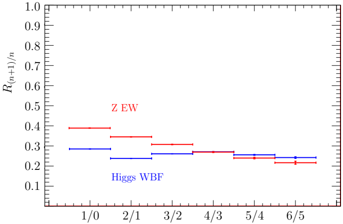
$$R^{\text{incl}}_{(n+1)/n} = \frac{\sum_{j=n+1}^{\infty} \sigma_j^{(\text{excl})}}{\sigma_n^{(\text{excl})} + \sum_{j=n+1}^{\infty} \sigma_j^{(\text{excl})}} = R^{\text{excl}}_{(n+1)/n} = \text{const}$$

Jet veto

Example: WBF $H \to \tau\tau$ [Englert, Gerwick, TP, Schichtel, Schumann]

- staircase scaling before WBF cuts [QCD and e-w processes]
- e-w Zjj production with too many structures





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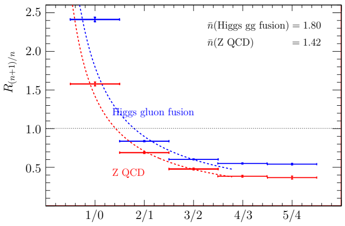
Understanding a jet veto

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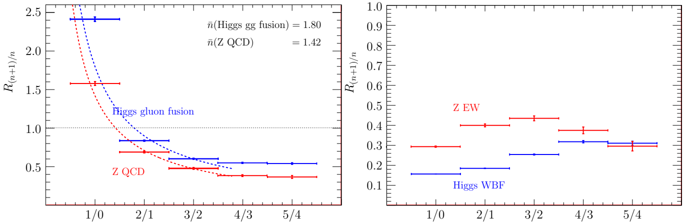
– (fairly) staircase for e-w processes [cuts keeping signal]

– QCD and n_{jets} at work



Outlook

Higgs@LHC

– discovery from successful bump hunt

– many open questions in the details

– coupling analysis a major LHC goal

– naive guesstimate misleading

– many technical issues

– SFitter update imminent

$\Rightarrow$ for Manfred: a case for a 250 GeV linear collider?

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