Once the LHC does Higgs

An incoherent set of high-lumi Higgs ideas

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Outline

Higgs to bottoms

Markov chains

Higgs sector

Weak boson fusion

Higgs to bottoms

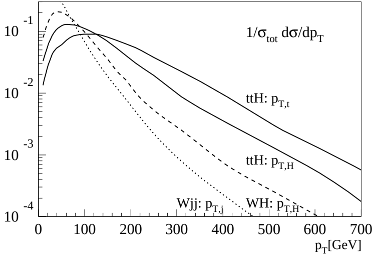
New strategy for $H \rightarrow bb$ [Butterworth, Davison, Rubin, Salam]

– 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: go for large m_{bb} and small R_{bb}, so boost Higgs

– fat Higgs jet $R_{bb} \sim 2m_H/p_T \sim 0.8$

– $q\bar{q} \rightarrow V_\ell H_b$ sizeable in boosted regime [$p_T \gtrsim 300$ GeV, few % of total rate]



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$\Rightarrow$ 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

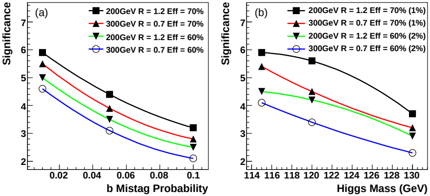
– combined channels $V \rightarrow \ell\ell, \nu\nu, \ell\nu$

– 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



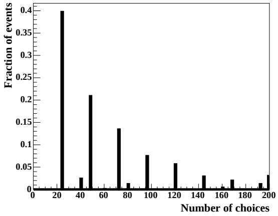
Rescuing $t\bar{t}H$

Traditional $t\bar{t}H$, $H \to b\bar{b}$ [Atlas-Bonn study, CMS-TDR even worse]

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

– continuum background $t\bar{t}b\bar{b}$, $t\bar{t}jj$ [weighted by b-tag]

– no chance:
  1– combinatorics: m_{bb} from $pp \to 4b_{tag}\ 2j\ \ell\nu$



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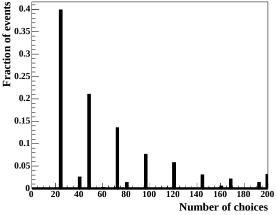

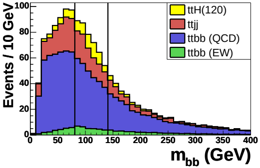

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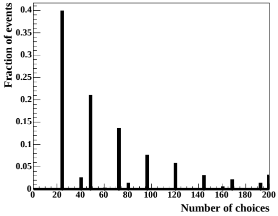

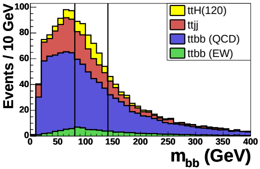

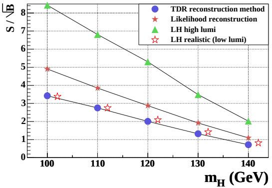

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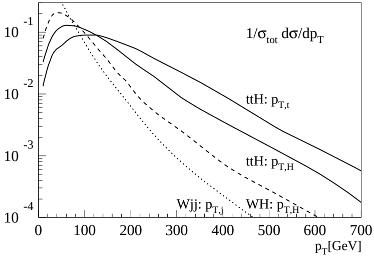
Fat jets analysis [TP, Salam, Spannowsky]

– 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}; correct bottom pair boosted [solves 1]

– $pp \to t_\ell t_h H_b$ even better than VH?
also boost different for S and B [solves 2]

– cool: fat Higgs jet + fat top jet
uncool: QCD [Dittmaier et al: $K = 2.3$ for $t\bar{t}b\bar{b}$]

– see how far we get... [watch S/B for 3]



Rescuing $t\bar{t}H$

Top tag [cf Johns Hopkins, Princeton, Washington]

– start with C/A jet [$R = 1.5$] [Johns Hopkins]

– uncluster one-by-one: $j \to j_1 + j_2$
1– unbalanced $m_{j_1} > 0.8 m_j$ means QCD; discard j_2
2– soft $m_{j_1} < 30$ GeV means QCD; keep j_1

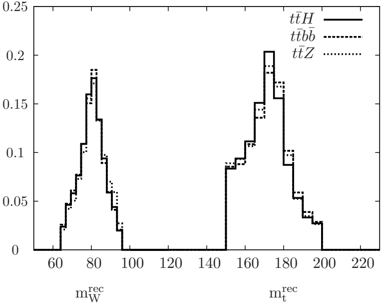
– search for top decay kinematics in relevant substructures
reconstruct $m_W = 60...95$ GeV
reconstruct $m_t = 150...200$ GeV
helicity angle $\cos\theta_{t,j_1} > 0.7$ [not vital]
no b tag needed

– underlying event scaling like R^4
filter reconstruction jets [Butterworth–Salam]
decay plus one add'l jet at $R_{\text{filt}} \sim R_{jj}/2$
reconstruct masses w/ QCD jet

– right now: efficiency 43%; mistag 5%

⇒ only (working) Standard Model top tag

[still working on it, including experimenters...]



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Higgs tag

- same as top tag [stricter mass drop criterion, harder jets]
  but: Higgs mass unknown
- double b tag [$\mathcal{O}(10\%)$ from leptonic top]
  combinations ordered by $J = p_{T,1} p_{T,2} (\Delta R_{12})^4$
  three leading combinations vs m_{bb}^{filt}

$\Rightarrow$ like Butterworth-Salam for busy QCD

Analysis

- require tagged top and Higgs
  trigger on lepton
- remove 'Higgs' as $t_\ell \to b$ plus QCD
  3rd b tag in continuum
  $B = 3.8S \to 2.4S$ [costing $S/\sqrt{B}$]
  only continuum $t\bar{t}b\bar{b}$ left

per 1 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
including a third b tag	0.48	0.03	1.09	0.06

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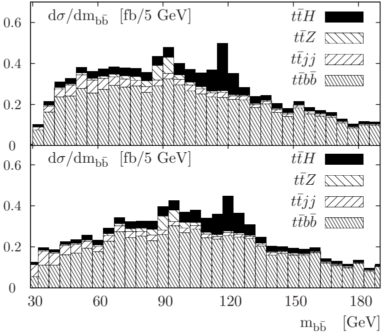
m_H	S	S/B	$S/\sqrt{B}$
115	57	1/2.1	5.2 (5.7)
120	48	1/2.4	4.5 (5.1)
130	29	1/3.6	2.9 (3.0)

$\Rightarrow$ under experimental scrutiny



Markov chains

Probability maps

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

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

– 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]

$\Rightarrow$ given measurements: 1– compute map $p(d|m)$
2– rank local maxima
3– derive probabilities for parameters

Markov chains

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

– BSM physics: map $p(d|m)$ of parameter points
evaluate same probability or additional function

– 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 $p(d|m')/p(d|m) < 1$

Improving 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

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

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

– need to zoom in on peak structures

– modified condition [inspired by simulated annealing]
  Markov chain in 100 partitions, numbered by j

$$\frac{p(m')}{p(m)} > r^{\frac{100}{j\,c}} \qquad \text{with} \quad c \sim 10, \qquad r \epsilon [0,1] \quad \text{random number}$$

– check for parameter coverage with many Markov chains

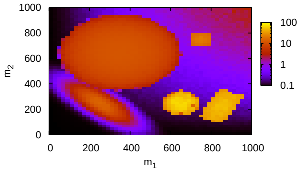
Frequentist vs Bayesian

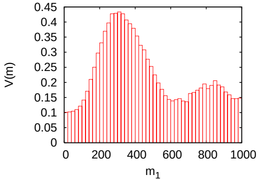
Getting rid of model parameters

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

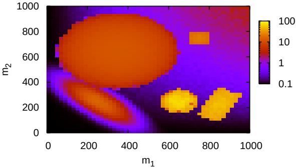
– two ways to marginalize likelihood map

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





Frequentist vs Bayesian



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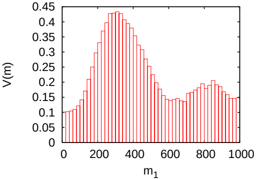
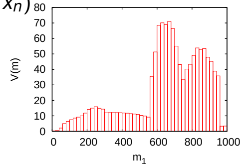


2– profile likelihood $\mathcal{L}(.., x_{j-1}, x_{j+1} ....) \equiv \max_{x_j} \mathcal{L}(x_1, ..., x_n)$
  no integration needed
  no noise accumulation
  not normalized, no comparison of structures
  classical example: best-fit point



– childish civil war if applied to same question
  frequentist: flavor, Higgs,...
  Bayesian: dark matter, new physics,...

– simply: two questions, two answers

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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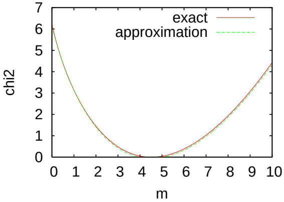
(Inconsistent) combination of errors

– Gaussian $\otimes$ Gaussian: half width added in quadrature
  Gaussian $\otimes$ flat: RFit scheme
  Gaussian $\otimes$ Poisson: ??

– approximate formula

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

– good to 5% for 5 events with 10% Gaussian



Higgs sector

Higgs-sector analysis at the LHC [Zeppenfeld, Kinnunen, Nikitenko, Richter-Was; Dührssen et al.]

– optimistic LHC scenario: everything working and good data

– Higgs vs. scalars? SM vs MSSM? doublet vs. general Higgs?

– 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

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

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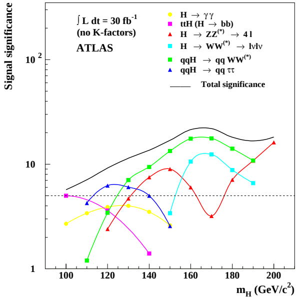

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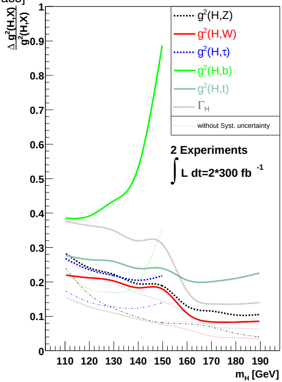

Total width

- degeneracy $\sigma\, BR \propto (g_p^2/\sqrt{\Gamma_H})\ (g_d^2/\sqrt{\Gamma_H}) \equiv C > 0$
- bad scaling
  $$C = \lim_{g^2 \to 0} \frac{g^4}{\Gamma_H} = \lim_{g^2 \to 0} \frac{g^4}{g^2(\Gamma_{\text{vis}}/g^2) + \Gamma_x} = 0$$
  means constraint: $\sum \Gamma_i(g^2) < \Gamma_H \to \Gamma_H|_{\text{min}}$
- $WW \to WW$ unitarity: $g_{WWH} \lesssim g_{WWH}^{\text{SM}} \to \Gamma_H|_{\text{max}}$

Higgs couplings

SFitter analysis [Dührssen, Lafaye, TP, Rauch, Zerwas]

– all couplings varied around SM values $g_{HXX} = g_{HXX}^{\rm SM}\,(1+\delta_{HXX})$
  $\delta_{HXX} \sim -2$ means sign flip [$g_{HWW} > 0$ fixed]
– need assumption about loop-induced couplings $g_{ggH}, g_{\gamma\gamma H}$
– likelihood map and local errors from SFitter
– experimental/theory errors on signal and backgrounds [do not ask theorists!]

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 %

σ (gluon fusion)	13 %
σ (weak boson fusion)	7 %
σ (VH-associated)	7 %
σ ($t\bar{t}$-associated)	13 %

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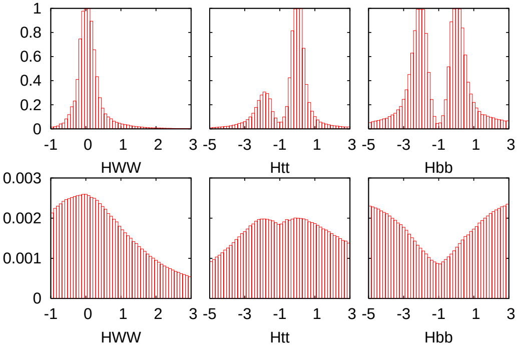
- experimental/theory errors on signal and backgrounds [do not ask theorists!]
- error bars for Standard Model hypothesis [smeared data point, 30fb^{-1}]

coupling	without eff. couplings			including eff. couplings		
	σ_{symm}	σ_{neg}	σ_{pos}	σ_{symm}	σ_{neg}	σ_{pos}
δ_{WWH}	± 0.23	-0.21	$+0.26$	± 0.24	-0.21	$+0.27$
δ_{ZZH}	± 0.50	-0.74	$+0.30$	± 0.44	-0.65	$+0.24$
$\delta_{t\bar{t}H}$	± 0.41	-0.37	$+0.45$	± 0.53	-0.65	$+0.43$
$\delta_{b\bar{b}H}$	± 0.45	-0.33	$+0.56$	± 0.44	-0.30	$+0.59$
$\delta_{\tau\bar{\tau}H}$	± 0.33	-0.21	$+0.46$	± 0.31	-0.19	$+0.46$
$\delta_{\gamma\gamma H}$	—	—	—	± 0.31	-0.30	$+0.33$
δ_{ggH}	—	—	—	± 0.61	-0.59	$+0.62$
m_H	± 0.26	-0.26	$+0.26$	± 0.25	-0.26	$+0.25$
m_b	± 0.071	-0.071	$+0.071$	± 0.071	-0.071	$+0.072$
m_t	± 1.00	-1.03	$+0.98$	± 0.99	-1.00	$+0.98$

Higgs couplings

One-dimensional distributions to check....

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



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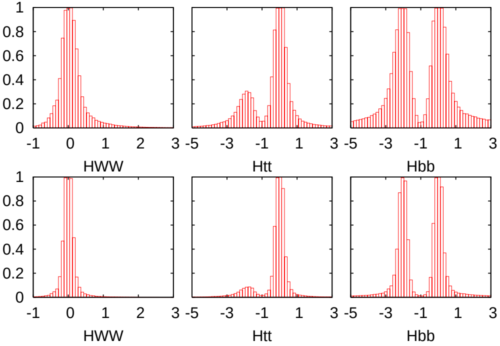
2– higher luminosity quantitatively different [no effective couplings, 30 vs 300 fb^{-1}]



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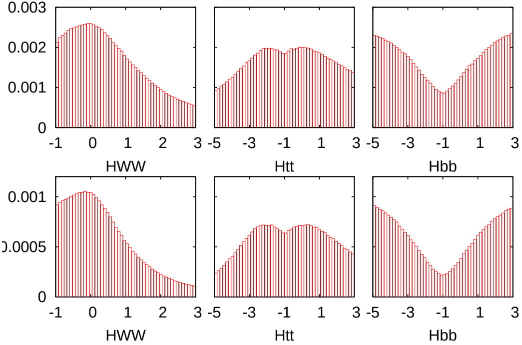

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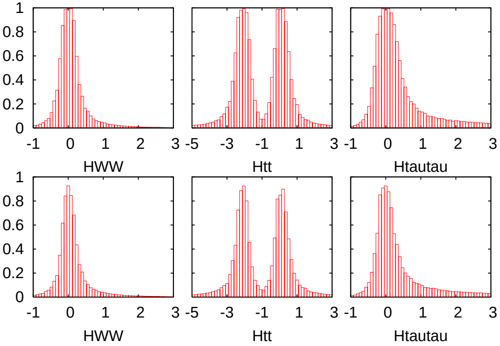
4– theory errors not dominant for 30 fb^{-1} [with effective couplings, 30 fb^{-1}]

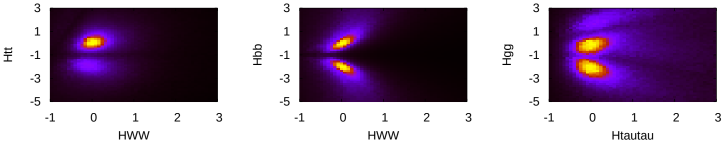


$\Rightarrow$ profile likelihood analysis for 30 fb^{-1} good for local structures

Pretty colorful pictures

Two-dimensional correlations and effective coupings

1– including effective g_{Hgg}
sign of g_{Htt} fixed by $g_{HWW} > 0$
correlation of g_{Hbb} and g_{HWW} [loops and width]
g_{Hgg} accessible



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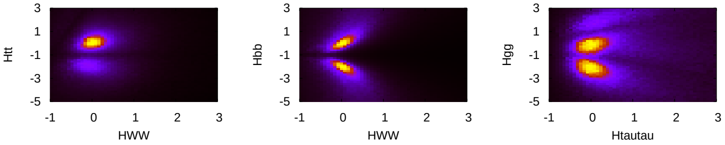

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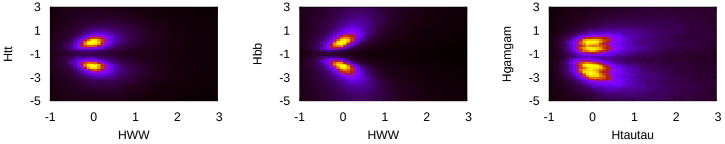

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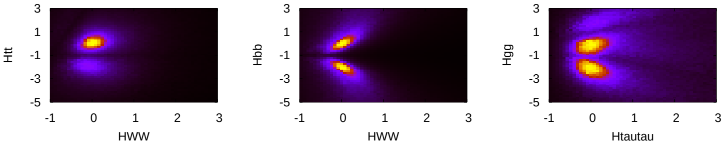

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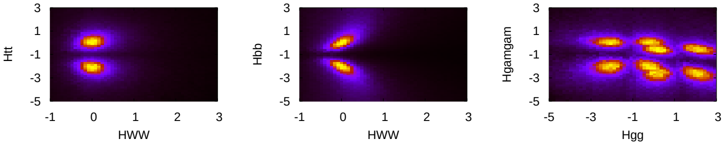
3– both effective couplings
discrete structures getting out of hand



Unobserved vs invisible

Invisible Higgs

– two channels at LHC
  $pp \to qqH$: tagging jets plus nothing [Eboli & Zeppenfeld]
  $pp \to ZH$: recoil against nothing [Atlas CSC notes]

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  naturally occuring in all models [charming buried Higgses]
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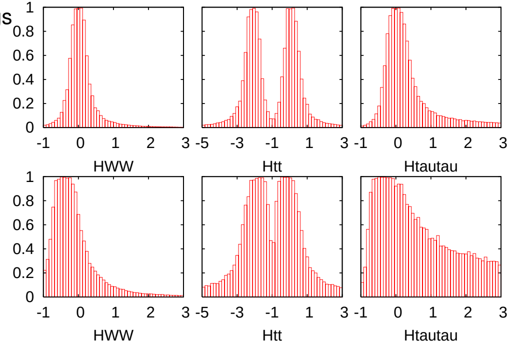

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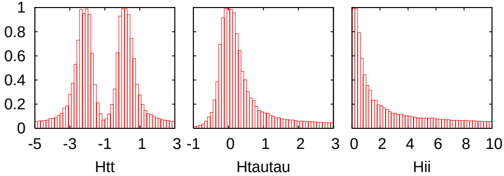
2– include $\Delta\Gamma$ and fix g_{HWW}



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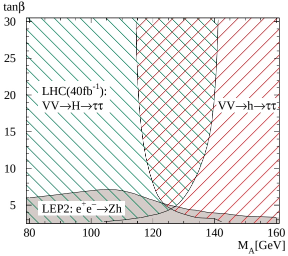
Weak boson fusion and supersymmetry

Higgs analysis beyond the Standard Model



- extension of Higgs analysis to BSM scenarios
  comparison SM-MSSM [no-lose: TP, Rainwater, Zeppenfeld]
- define hypothesis
  known particles: known corrections
  new particles: theory error
- general: heavy additional states at one loop
  example: MSSM sectors Higgs–weak–strong

Technical questions [Hollik, TP, Rauch, Rzehak]

- vertex corrections dominant? [Djouadi & Spira]
- which one larger: QCD vs EW? [similar for Standard Model: Ciccolini, Denner, Dittmaier]
- corrections from Higgs sector? [renormalization scheme/higher orders]
- general phase space generator?
- Germans: we can do 52504 diagrams [Hadcalc: automized IR-finite one-loop $2 \to 3$]

$\Rightarrow$ input for MSSM-Higgs analysis

Weak boson fusion and supersymmetry

Higgs sector corrections

- close to decoupling
- finite momentum, different masses $\rightarrow$ Feynman diagrams [FeynHiggs]
  consistent self couplings $\rightarrow$ effective potential [SubH]
- check identical limit: effective angle α_{eff}

	$\Delta\sigma/\sigma(ud \rightarrow udh)$	$(\sigma_{\alpha_{\text{eff}}} - \sigma_{\text{full}})/\sigma$
effective theory		
α_{eff}	-0.389 %	-0.122 %
full	-0.266 %	
Feynman diagrams		
α_{eff}	-0.393 %	-0.076 %
full	-0.317 %	
Feynman diagrams, loop-improved Z_{FH}		
α_{eff}	-0.343 %	-0.115 %
full	-0.228 %	

$\Rightarrow$ small corrections, even smaller uncertainty

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SUSY corrections

- QCD correstions suppressed:
  color flow and forward jets [no interference, like SM]
  mass suppression of one-loop $q_L q_L W$ vertex [$1/m_{\tilde{g}}$]
  up-down concellation in one-loop $duWh$ vertex [$T_3 - Q s_w^2 = -1/3, +5/16$]
- electroweak corrections as expected

diagram	$\Delta\sigma/\sigma$ [%]	diagram	$\Delta\sigma/\sigma$ [%]
$\Delta\sigma \sim \mathcal{O}(\alpha)$		$\Delta\sigma \sim \mathcal{O}(\alpha_s)$	
self energies	0.199		
$qqW + qqZ$	-0.392	$qqW + qqZ$	-0.0148
qqh	-0.0260	qqh	0.00545
$WWh + ZZh$	-0.329		
box	0.0785	box	-0.00518
pentagon	0.000522	pentagon	-0.000308

⇒ electroweak corrections dominant

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SUSY corrections

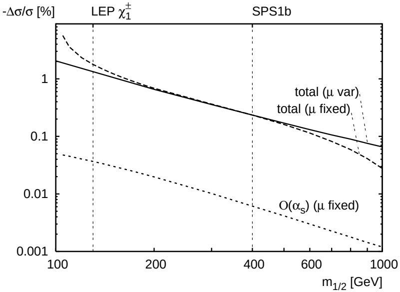
– SPS1b with variable mass scale $m_{1/2}$

– squark/gluino masses from LHC not helpful

– perfect decoupling at one loop

– typical corrections around 1%

$\Rightarrow$ maximum corrections below 4%



Outlook

Trying to understand Higgs@LHC

– decay to bottoms observable

– parameter analysis the final goal

– hiding the Higgs hard

– one-loop corrections sometimes almost irrelevant...

$\Rightarrow$ Higgs phenomenology at LHC still making progress!

Great to be back to the UK!