Good News for LHC Analyses

Not a proper unbiased theory overview

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Higgs Workshop, Seattle, 1/2009

Outline

Higgs to bottoms

Gluon fusion rate

Higgs couplings

Minijet veto

SFitter — Higgs couplings at LHC

Weak boson fusion and supersymmetry

Higgs to bottoms

A new channel to detect $H \to bb$ [Butterworth, Davison, Rubin, Salam]

- desperately needed after deceased ttH channel
- one of my personal favorites in 2008
- $q\bar{q} \to V_\ell H_b$ save in boosted regime [$p_T \gtrsim$ 300 GeV, few % of total rate]
- single fat bottom jet $R_{bb} \sim 2m_h/p_T \sim 0.8$
- underlying event challenge: re-define filtered subjets

$\Rightarrow$ difficult as hell, but very serious progress

jet definition	σ_S/fb	σ_B/fb	$S/\sqrt{B}_{30}$
C/A	0.57	0.51	4.4
$k_\perp$	0.19	0.74	1.2
SISCone	0.49	1.33	2.3

Higgs to bottoms

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Parton-level/fast simulation results

- channels combined $V \to \ell\ell, \nu\nu, \ell\nu$
- NLO corrections for signal and backgrounds [bbV notorious]
- H vs Z mass peaks as sanity check
- do-do list:

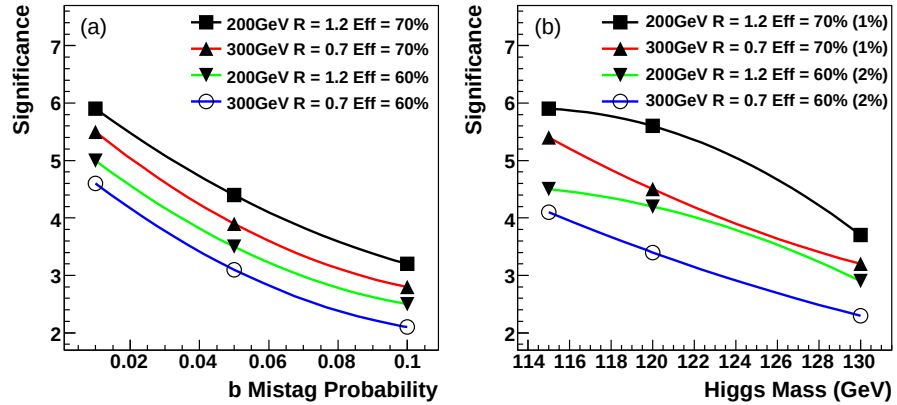
  jet algorithm comparison?

  realistic b tagging?

  detector simulation?

  towards 100 fb^{-1}?

$\Rightarrow$ keep fingers crossed!



Gluon fusion rate

Understanding of $gg \to H$ rate [Ahrens, Becher, Neubert, Yang]

- old problem: corrections large [Dawson; Spira et al; Harlander, Kilgore; Anastasiou, Melnikov,...]
- QCD effects in low-energy Lagrangian $C_t(m_t^2, \mu^2)\, G_{\mu\nu,a} G_a^{\mu\nu}\, H/v$
- Wilson coefficient of QCD part of operator

$$C(\mu^2) = 1 + \sum_n c_n \left(\frac{\alpha_s(\mu^2)}{4\pi}\right)^n \qquad c_1 = N_c \left(-\log^2 \frac{|q^2|}{\mu^2} + \frac{\pi^2}{6}\right)$$

- strong-coupling series of hard function in $\sigma_{gg\to H}$

$$|C(m_H^2, m_H^2)|^2 = 1 + 5.5\alpha_s + 17.2\alpha_s^2 \to |C(-m_H^2, -m_H^2)|^2 = 1 + 0.4\alpha_s + 0.15\alpha_s^2$$

- π^2 terms resummable as part of funny logarithm [not all π^2 terms]
- time-like scale logs general problem of $2 \to 1$ processes [similar for Drell-Yan]
- beneficial effect mostly on error analysis [from scale dependence]

$\Rightarrow$ ask Sally or Michael later

	fixed order	π^2 resummed	+ threshold resummed
LO	$15.2^{+2.3}_{-2.0}$	$26.9^{+3.8}_{-3.7}$	$31.0^{+5.7}_{-4.8}$
NLO	$35.3^{+5.8}_{-4.5}$	$44.9^{+2.9}_{-3.2}$	$46.5^{+2.7}_{-1.2}$
NNLO	$47.5^{+4.6}_{-4.2}$	$51.5^{+1.7}_{-1.5}$	$51.5^{+1.4}_{-0.3}$

Higgs couplings

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

- optimistic LHC scenario: everything working and good data
- motivation: scalar little Higgs axions or radion or 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 masses]
- hope: cancel uncertainties

  $(WBF : H \to WW)/(WBF : H \to \tau\tau)$
  $(WBF : H \to WW)/(GF : H \to WW)...$
- goals: Higgs vs. scalars? SM vs MSSM? doublet vs. general Higgs?

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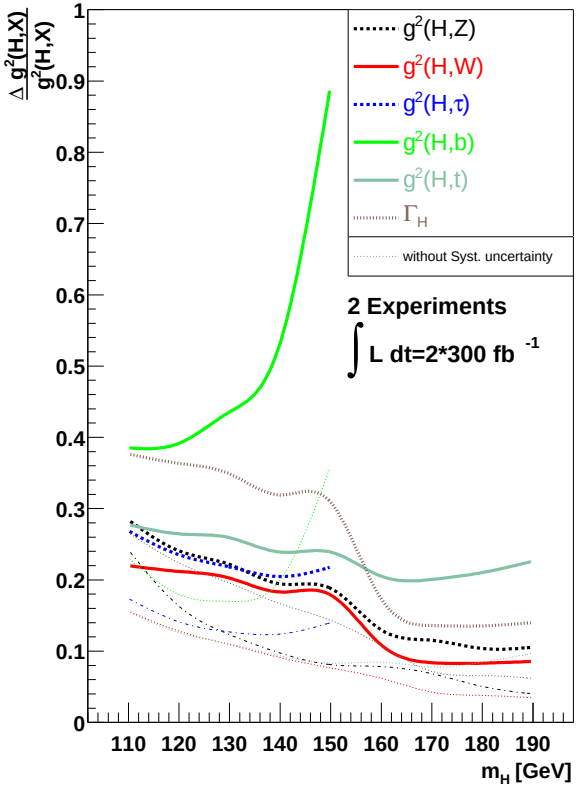
Total width

- 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: $\Gamma_H = \sum_{\text{obs}} \Gamma_j$



Before talking measurements...

...remember minijet veto [Barger, Cheung, Han, Zeppenfeld; Rainwater, Szalapski, Zeppenfeld]

- backgrounds for WBF Higgs production

  $t\bar{t}$ with b tagging jet
  V/VV radiation off QCD 2-jet production
  V/VV radiation off ew 2-jet production
- signal: color/interference structure [disconnected 2-sided DIS; Han, Valencia, Willenbrock]
- veto central jets above $\sim 20 \cdots 30$ GeV [survival probabilities between 25% and 90%]

$\Rightarrow$ will work, don't know how well [or QCD is wrong]

WBF rate measurement

- backbone of Higgs coupling analysis [many channels, clean structure]
- jet veto not used by experiments, lacking error estimate?
- straight-forward comparison between Monte Carlos not useful
  QCD simulation problem: recent progress great news
- large survival probabilities: fixed order [*Hjjj*@NLO: Zeppenfeld and friends]
  small survival probabilities: non-perturbative [jet merging: CKKW, MLM (Madgraph)]
  $W, Z, t\bar{t}$ backgrounds: measurement [Cranmer et al]
- gluon-fusion understood? [Andersen, Del Ducca, White]

$\Rightarrow$ meaningful error estimate on horizon

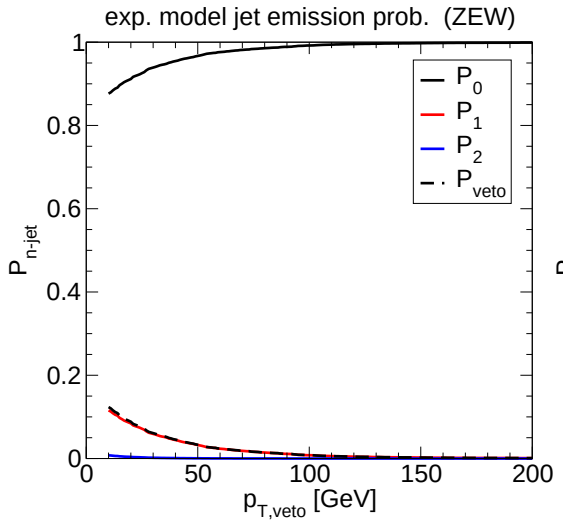
Minijet veto

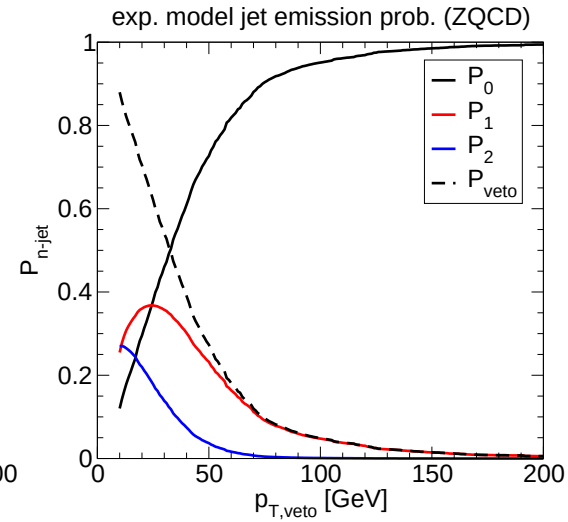
Preliminary (!!!) first study [TP, Schumann, Sherpas]

- first test with (measurable) $Z+$jets channels
- compute jet multiplicities as function of $p_{T,\text{veto}}$

(1) parton level: exponentiation approach [checked with truncated shower approximation]

$$P_n = \frac{\bar{n}^n}{n!} e^{-\bar{n}} \qquad \bar{n} = \frac{1}{\sigma_2} \int_{p_{T,\text{veto}}}^{\infty} \mathrm{d}p_{Tj3} \frac{\mathrm{d}\sigma_3}{\mathrm{d}p_{Tj3}} \qquad \Rightarrow \qquad P_{\text{veto}} = 1 - e^{-\bar{n}}$$





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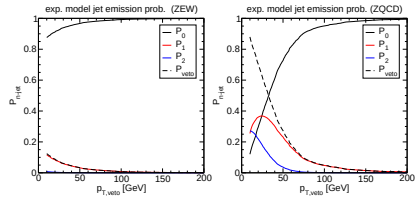
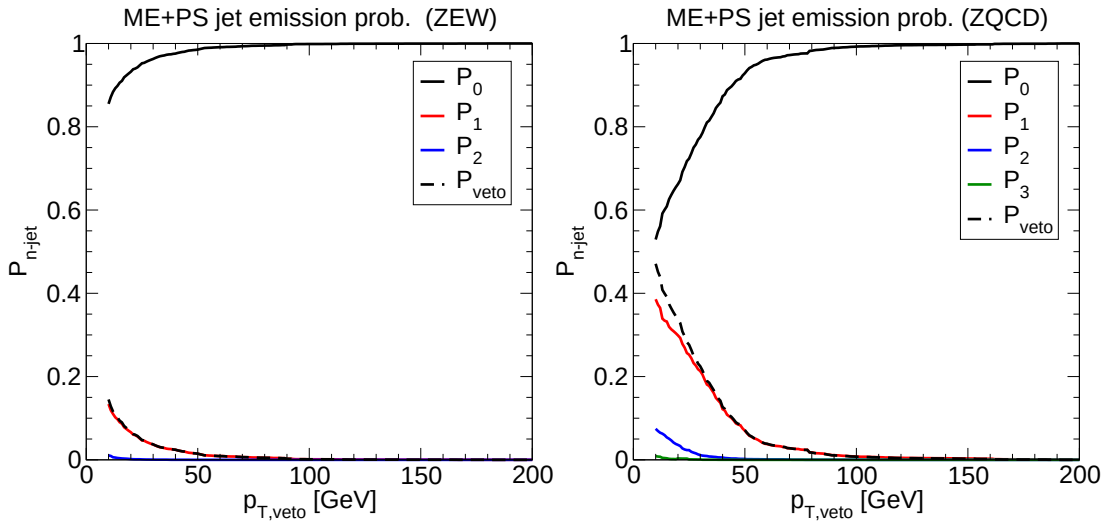


(2) CKKW merging of hard jets and parton shower

- only jet cuts, same renormalization scales,...



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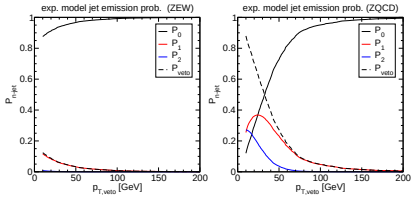

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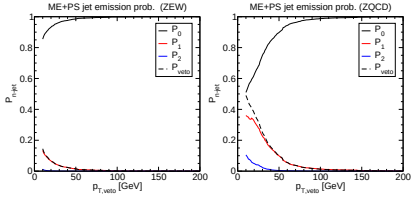

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$\Rightarrow$ give us some time, we'll beat the startup, promised

SFitter — Higgs couplings at LHC

Parameter extraction [Lafaye, TP, Rauch, Zerwas]

- know-how from TeV-scale MSSM analysis [parameters from edges etc]
- parameters: weak-scale Higgs Lagrangian
- measurements: signal+background rates
- errors: statistics & systematics & theory
- questions: global structure of parameter space, secondary minima
  local structure of best points, error bars
  distributions for fewer parameters, correlations

Probability maps [Baltz,...; Roszkowski,...; Allanach,...; Fittino; SFitter]

- fully exclusive likelihood map $p(d|m)$ over model space m
- local and global structure for different hypotheses
- 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

SFitter — Higgs couplings at LHC

Alternative best-fit points and error bars

- all couplings varied around SM values $g_{HXX} = g_{HXX}^{\text{SM}} \, (1 + \delta_{HXX})$
- $\delta_{HXX} \sim -2$ means sign flip [$g_{HWW} > 0$ fixed, only broken by loops]
- alternative solutions for unsmeared data point

observable	1	2	3	4	5
δ_{HWW}	-0.01	0.25	-0.02	0.23	0.39
δ_{HZZ}	0.00	0.25	0.07	0.38	0.49
$\delta_{H\tau\tau}$	-0.00	0.27	0.08	0.21	0.40
δ_{Hbb}	-2.05	0.61	0.06	-2.67	-3.10
δ_{Htt}	-0.03	0.11	-2.07	-2.10	0.19
$\delta_{H\gamma\gamma}$	-2.07	-2.55	-0.48	-0.58	-2.83
δ_{Hgg}	-0.13	-2.27	0.22	2.28	-0.13
$\Delta\chi^2$/dof	0	0.1175	0.342	0.4454	0.7331

- error bars for Standard Model hypothesis [smeared data point, no effective couplings]

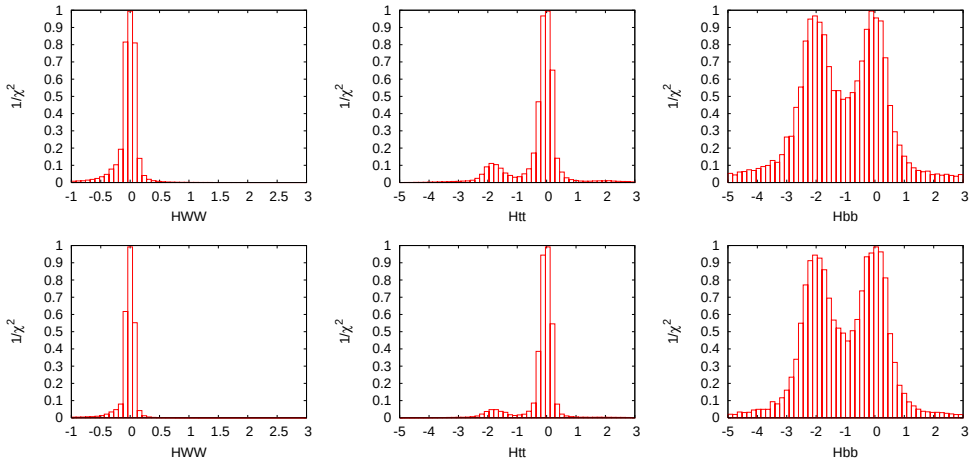
observable	central	error	
δ_{HWW}	-0.18	- 0.22	+ 0.44
δ_{HZZ}	-0.31	- 0.74	+ 0.81
δ_{Htt}	-0.09	- 0.32	+ 0.48
δ_{Hbb}	-0.13	- 0.56	+ 0.76
$\delta_{H\tau\tau}$	-0.11	- 0.24	+ 0.53
m_H	120.00	- 0.27	+ 0.25
χ^2/dof	19.09/10		

$\Rightarrow$ brand new results, only to show it can be done

SFitter — Higgs couplings at LHC

One-dimensional distributions

- limitations of the analysis with all errors included [true data set, no effective couplings]
- 30 vs 300 fb^{-1}: similar cooled profile likelihoods



$\Rightarrow$ pure statistics not the problem

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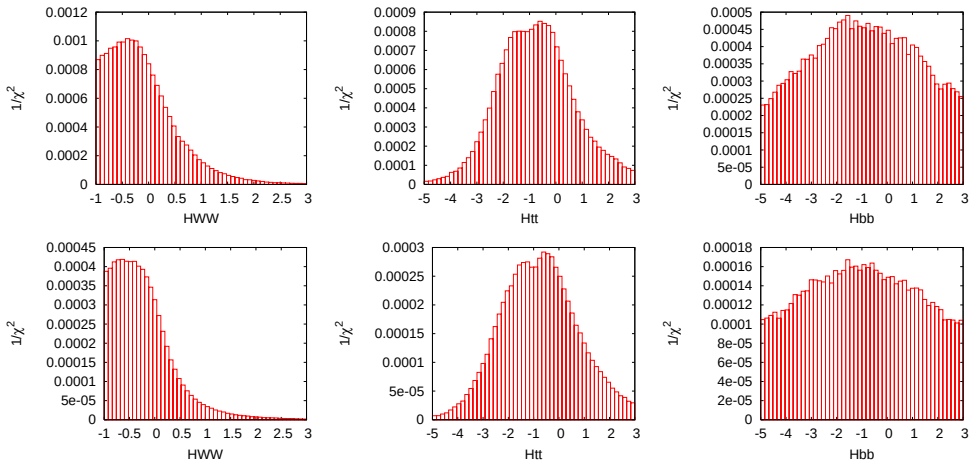

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Simulating theory errors

- for example: scale-dependence on production rate
- (1) likelihood flat in central region [any K factor possible]
  (2) likelihood zero far out [QCD is perturbative!]
  (3) convolution with gaussian errors still flat
- RFit scheme [CKMfitter]

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

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

- error bar still the problem, e.g. $gg \to H$ a la Neubert

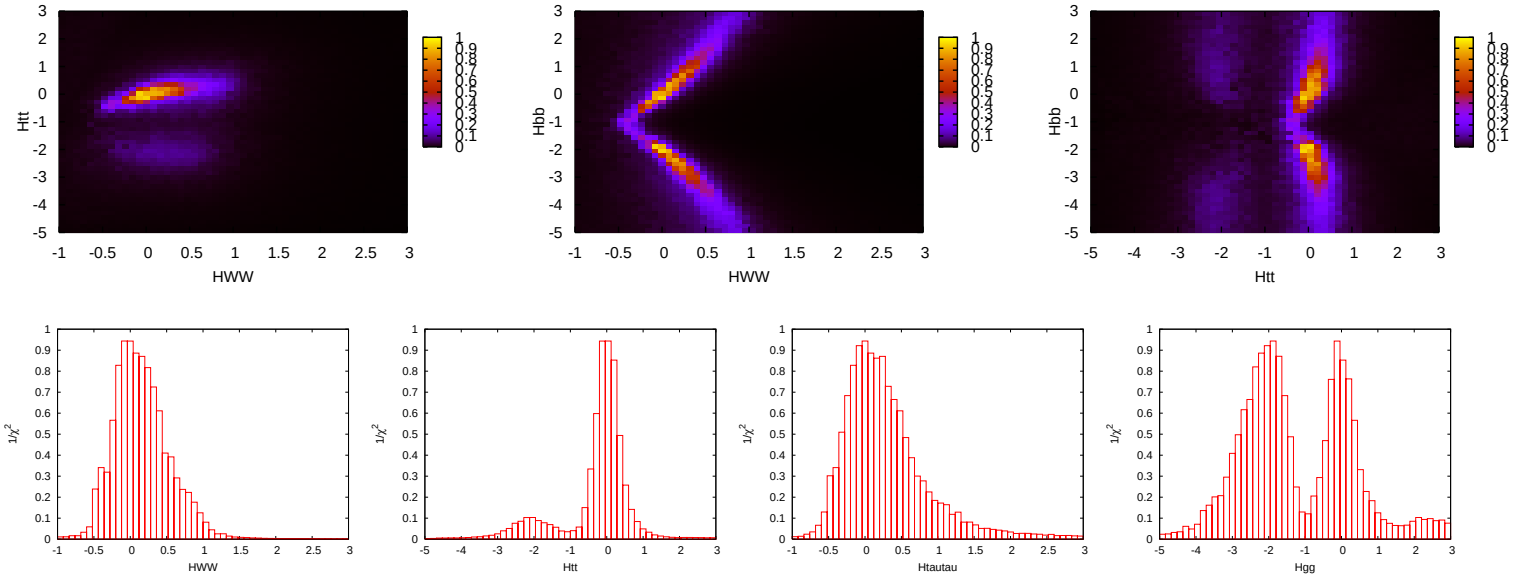
$\Rightarrow$ numerically hard, but possible

SFitter — Higgs couplings at LHC

Two-dimensional correlations and effective coupings

(1) profile likelihoods, including effective g_{Hgg}

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



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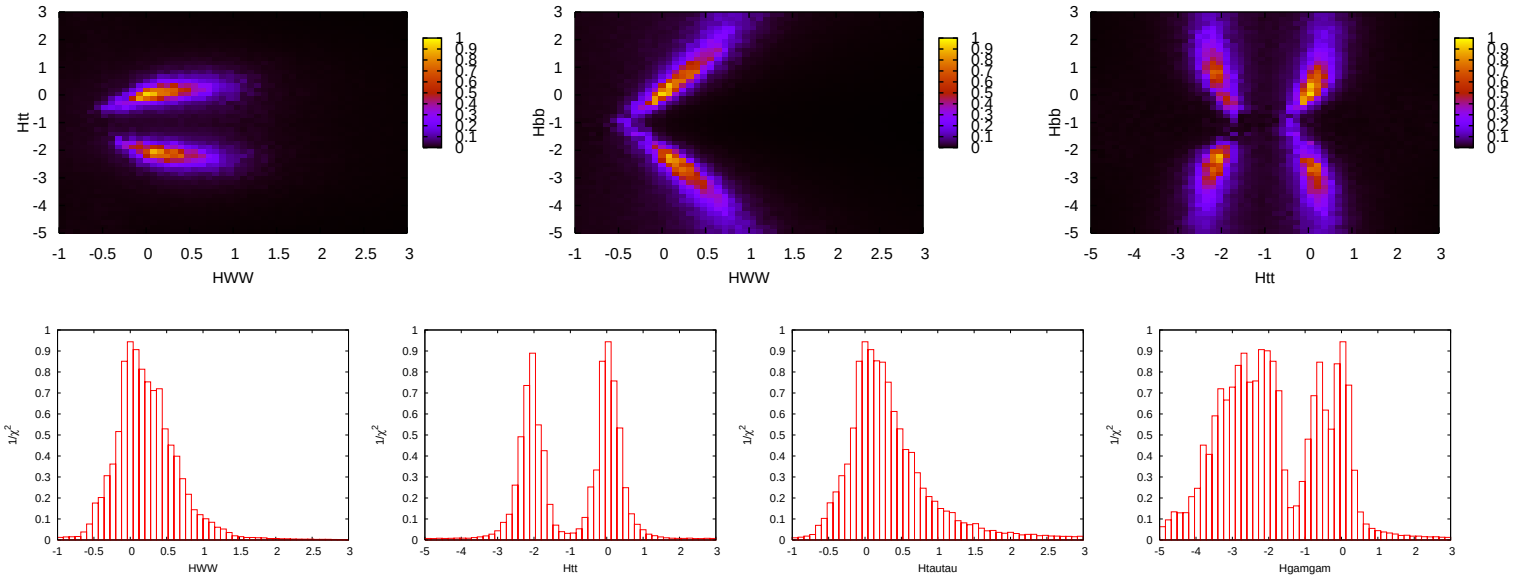
(2) profile likelihoods, including effective $g_{H\gamma\gamma}$
- correlation of g_{Htt} and g_{HWW} on both branches
- still correlation of g_{Hbb} and g_{HWW} [width]
- effective coupling $g_{H\gamma\gamma}$ more noisy



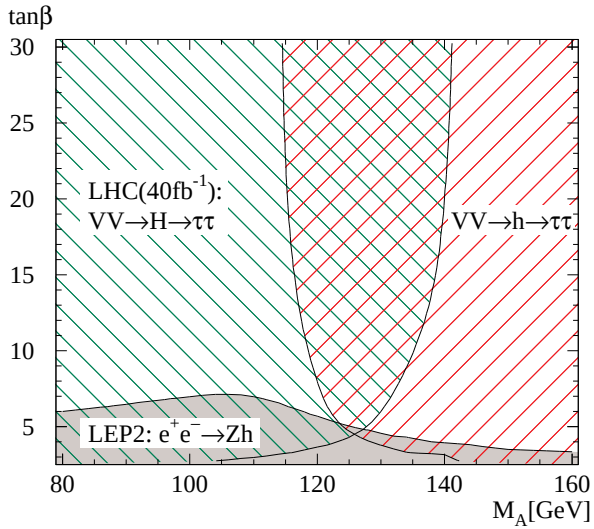
$\Rightarrow$ two-dimensional correlations useful

Weak boson fusion and supersymmetry

Higgs analysis beyond the Standard Model

- extension of Higgs analysis to BSM scenarios
  comparison SM-MSSM [WBF: TP, Rainwater, Zeppenfeld]
- help with MSSM parameters [SFitter+Higgs]
- hypothesis determining theory error
- known particles: corrections included
  new particles: theory error
- general: heavy additional states at one loop
  example: MSSM sectors Higgs–weak–strong

$\Rightarrow$ study for BSM-Higgs analysis



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: show we can do 52504 diagrams [Hadcalc: automized IR-finite one-loop 2 $\longrightarrow$ 3]

$\Rightarrow$ input for MSSM-Higgs analysis

Weak boson fusion and supersymmetry

Higgs sector corrections

- close to decoupling: $\lambda^2_{WWh}\lambda_{hhh}$
- finite momentum, different masses $\longrightarrow$ Feynman diagrams [FeynHiggs]
  consistent self couplings $\longrightarrow$ effective potential [SubH]
- check identical limit: effective angle α_{eff}

	$\Delta\sigma/\sigma(ud \to udh)$	$(\sigma_{\alpha_{\text{eff}}} - \sigma_{\text{full}})/\sigma$
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

Weak boson fusion and supersymmetry

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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 [$m_g / m_{\tilde{g}}$]
  up-down concellation in one-loop $duWh$ vertex [$T_3 - Qs^2_W = -1/3, +5/16$]
- 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

$\Rightarrow$ electroweak corrections dominant

Weak boson fusion and supersymmetry

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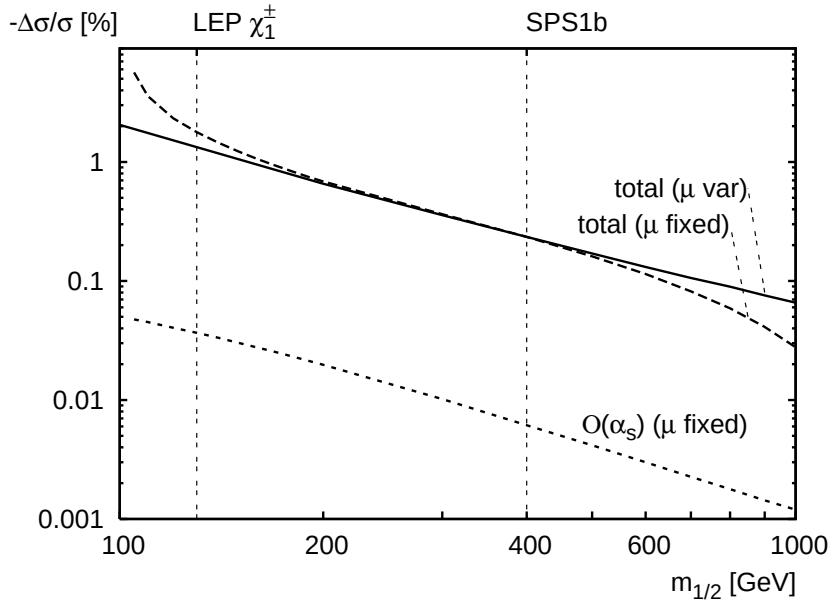
SUSY corrections

- 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

Some ideas trying to understand Higgs@LHC

- relevance of parameter analysis undisputed
- measurement of bottom Yukawa possible?
- large $gg \to H$ corrections understood?
- QCD study of minijet veto overdue
- Bayesian/likelihood parameter extraction promising
- skipping parton densities: ask Wu-Ki
  skipping higher orders: ask Sally
  skipping non-minimal Higgs sectors: ask Tim or Graham
  skipping light-MSSM-Higgs-mass-at-two-loops-with-FeynHiggs: ask Sven
  . . .

$\Rightarrow$ many promising studies in progress

It's great to be back in the U.S. writing talks to the Prairie Home Companion!