Measuring Higgs Couplings

Tilman Plehn

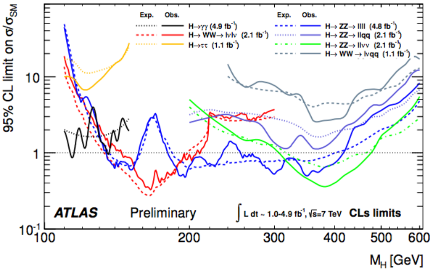
Universität Heidelberg

Eugene, 4/2012

Where we stand

Around Moriond 2012

- ATLAS and CMS results published
- official line: ‘exclusion gone wrong’ [in many channels]



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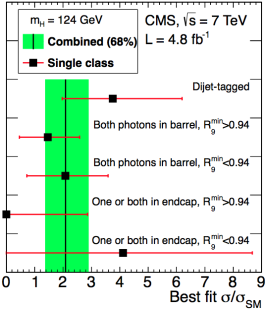

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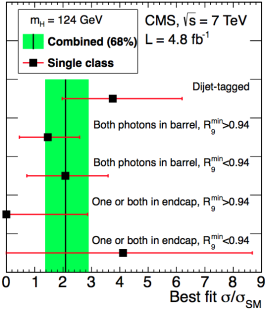

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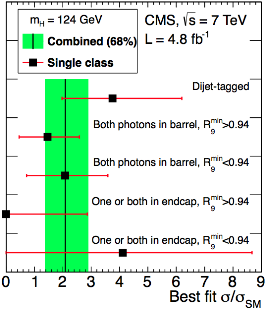

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  UV/IR fixed points right there

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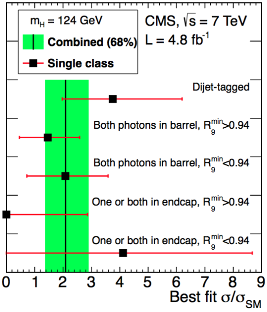

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- reasonably decoupling theories all fine
  MSSM one example [tons of papers]
  hypersphere in $m_{\tilde{t}_{L/R}}$, $\tan\beta, A_t, \mu, m_A$ predicting little [$X_t^2/(m_{\tilde{t}_1} m_{\tilde{t}_2}) \gtrsim 1$]

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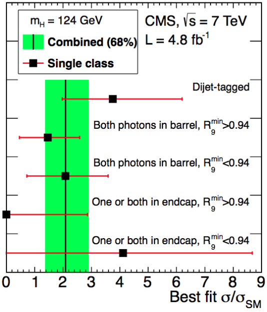

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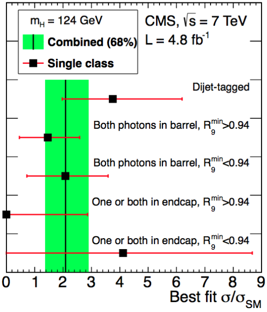

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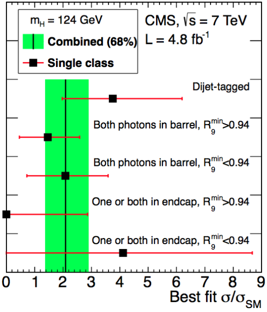

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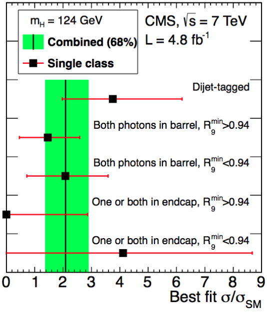

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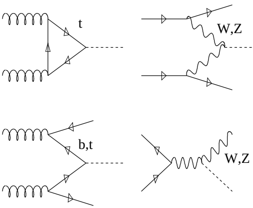
⇒ but Graham wants technical details [skipping references, wrote the talk on plane]

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

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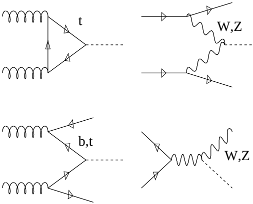

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Why 125 GeV is just perfect [Zeppenfeld et al; Dührssen et al; SFitter 2009]

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

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

– 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

Markov chains

Probability maps [statistics questions go to Kyle]

- 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 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

$\Rightarrow$ exclusive likelihood map first result

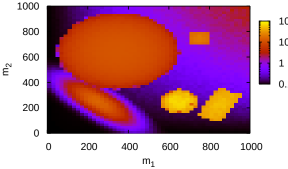
SFitter 2: Frequentist vs Bayesian

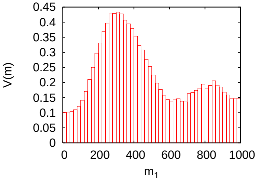
Getting rid of model parameters

– 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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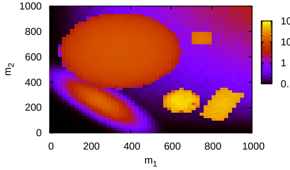

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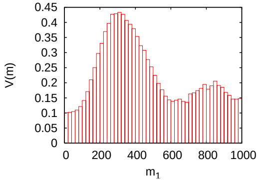
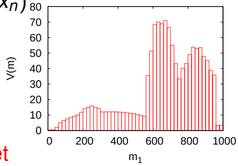


2– profile likelihood $\mathcal{L}(.., x_{j-1}, x_{j+1} ....) \equiv \max_{x_j} \mathcal{L}(x_1, ..., x_n)$
  no integration needed
  no noise accumulation
  not normalized, no comparison of structures
  classical example: best-fit point



– one-dimensional parameter distributions second target

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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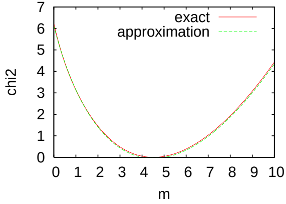
Combination of errors

- 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



Higgs couplings

Higgs-sector analysis [Zeppenfeld et al; Dührssen et al; SFitter 2009; Contino et al]

– light Higgs around 125 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

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

– all wrong because of exclusive $H + n$ jets... [later]

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

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

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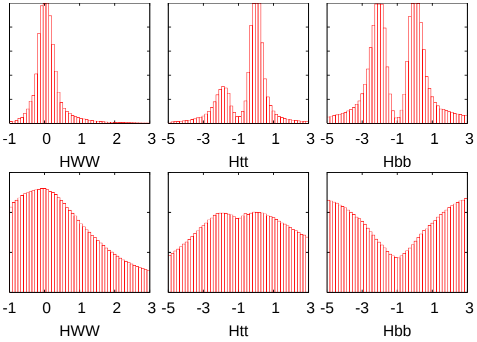
SFitter ansatz [Dührssen, Klute, Lafaye, TP, Rauch, Zerwas]

- couplings measurement $g_{HXX} = g_{HXX}^{\mathrm{SM}} (1 + \Delta_X)$
  D5 couplings $g_{ggH}, g_{\gamma\gamma H}$ free?
- experimental/theory errors on signal and backgrounds
  ATLAS and CMS both included
- exclusive likelihood map
  individual coupling measurements
- alternative parameters, e.g. coupling ratios?

Basic checks

Marginalization procedures

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



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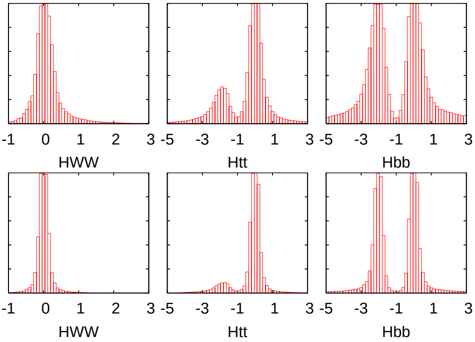

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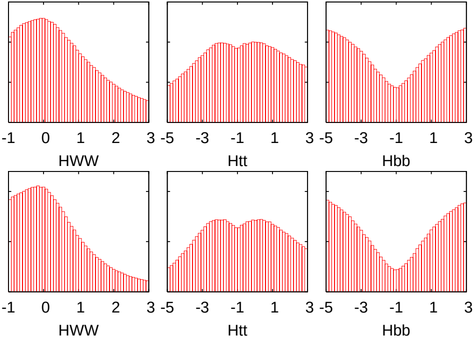

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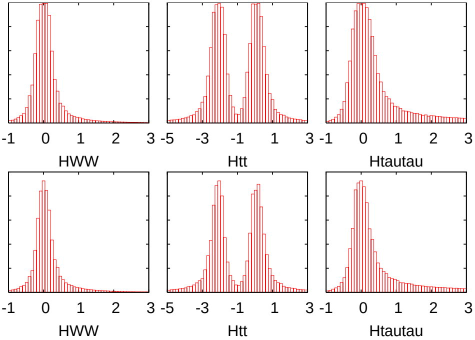
3– but not saving Bayesian statistics [no effective couplings, 300 fb^{-1}]

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



$\Rightarrow$ profile likelihood for now

Results after Moriond

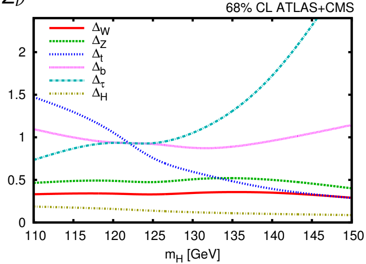
ATLAS and CMS data well documented [Dührssen, Klute, Lafaye, TP, Rauch, Zerwas]

– ATLAS: $\gamma\gamma$, $Z_\ell Z_\ell$, $WW + 0/1$ jets

– CMS: $\gamma\gamma + 0/2$ jets, $Z_\ell Z_\ell$, $WW + 0/1/2$ jets
CMS: $\tau\tau + 0/1/2$ jets, $b\bar{b}$ with W_ℓ, Z_ℓ, Z_ν

– central points on SM values
everything preliminary

– (7 TeV, $2.1 - 4.9$ fb^{-1})



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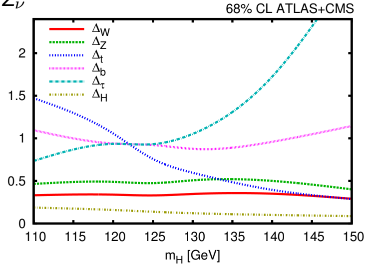
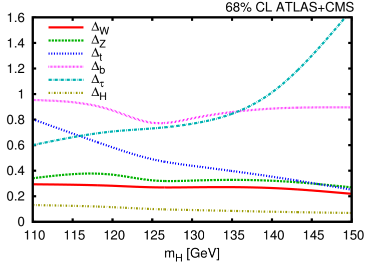
– $(7\ \text{TeV}, 2.1 - 4.9\ \text{fb}^{-1})$

$(7\ \text{TeV}, 20\ \text{fb}^{-1})$





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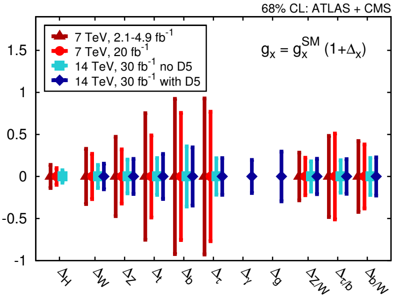
– $(7\ \text{TeV}, 2.1 - 4.9\ \text{fb}^{-1})$
$(7\ \text{TeV}, 20\ \text{fb}^{-1})$

– different projections 2012-2014

form factor already constrained
gauge boson couplings promising
fermion couplings a problem
D5 operators wide open
ratios actually better

– comments welcome!

technical screwups?
experimental misunderstandings?
proper operator basis?
...



Specific Higgs hypotheses

Status of the Higgs portal

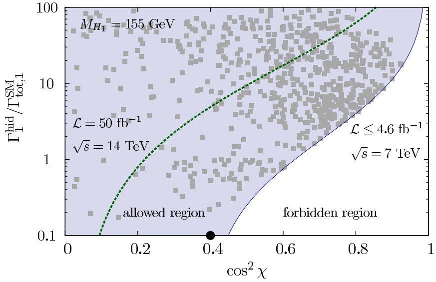
– visible and hidden decays [plus $H_2 \to H_1 H_1$ cascade decays]

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

– constraints on event rate

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

– 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

Specific Higgs hypotheses

Status of the Higgs portal

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

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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

– $(14\ \text{TeV}, 30\ \text{fb}^{-1})$ and 120 GeV Higgs: $\Delta g/g \sim 10\%$

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

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 vs number of recoil jets?? [for Dave and Steve]

– ‘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]
3– normalization factor $e^{-\bar{n}}$

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Staircase scaling [Ellis, Kleiss, Stirling]

- observed since UA2
- same for inclusive and exclusive rates

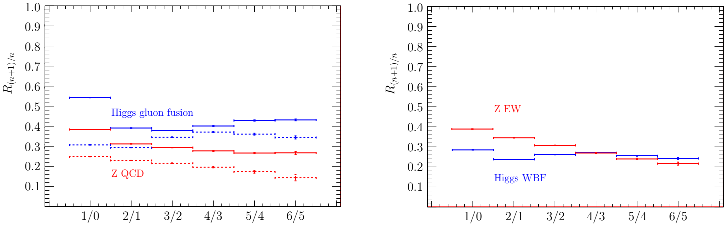
$$R^{\text{incl}}_{(n+1)/n} = \frac{\sum_{j=n+1}^{\infty} \sigma_j^{(\text{excl})}}{\sigma_n^{(\text{excl})} + \sum_{j=n+1}^{\infty} \sigma_j^{(\text{excl})}} = R^{\text{excl}}_{(n+1)/n} = \text{const}$$

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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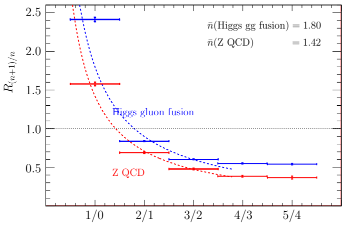
Understanding a jet veto

– 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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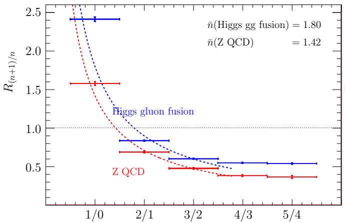
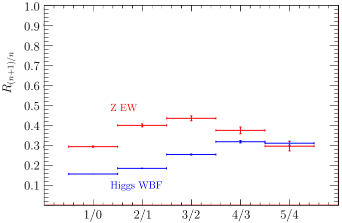
- Poisson for QCD processes ['radiation' pattern]
- (fairly) staircase for e-w processes [cuts keeping signal]
- n_{jets} features understood, go from here...





Outlook

Confirming Higgs@LHC

– hope there were enough details, you can wake up now

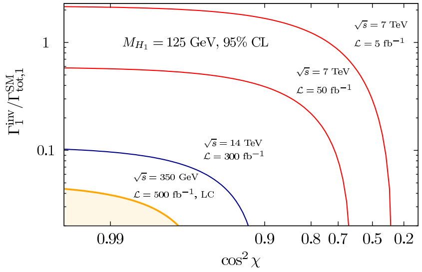
– coupling analysis the main LHC goal

– many technical issues

– Higgs tagger vital

– SFitter paper imminent

$\Rightarrow$ case for a 250 GeV linear collider



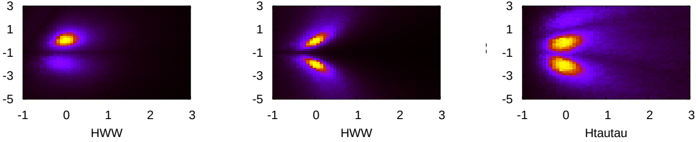
Much of this work was funded by the BMBF Theorie-Verbund which is ideal for hard and relevant LHC work

Bundesministerium für Bildung und Forschung

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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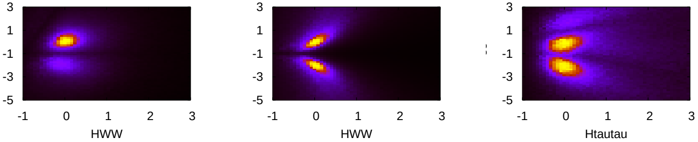
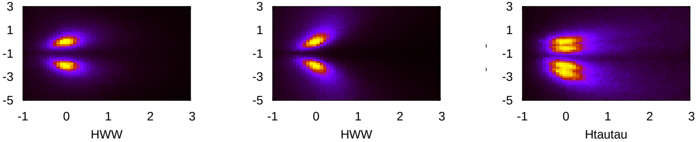


2– only effective $g_{H\gamma\gamma}$
correlated g_{Htt} and g_{HWW} on both branches
$g_{H\gamma\gamma}$ structure more complex



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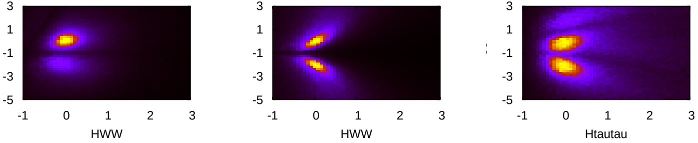

2– only effective $g_{H\gamma\gamma}$
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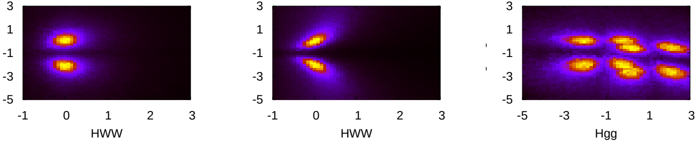
3– both effective couplings
discrete structures getting out of hand



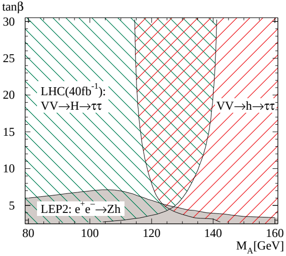
Weak boson fusion and supersymmetry

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 $\longrightarrow$ 3]

$\Rightarrow$ input for MSSM-Higgs analysis

Weak boson fusion and supersymmetry

Higgs sector corrections

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

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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 [$T_3 - Qs_w^2 = -1/3, +5/16$]
- 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

$\Rightarrow$ electroweak corrections dominant

Weak boson fusion and supersymmetry

Higgs sector corrections

– finite momentum, different masses $\longrightarrow$ Feynman diagrams [FeynHiggs]
  consistent self couplings $\longrightarrow$ effective potential [SubH]

– check identical limit: effective angle α_{eff}

SUSY corrections

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

– perfect decoupling at one loop

– typical corrections around 1%
  maximum corrections below 4%