Determination of Higgs Couplings at the LHC

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https://trac.lal.in2p3.fr/SFitter

(in collaboration with Michael Dührssen, Rémi Lafaye, Tilman Plehn, Dirk Zerwas)

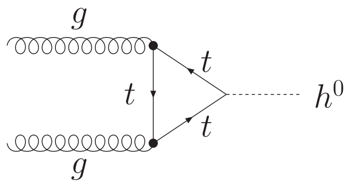
Outline

- Production and Decay of Higgs Bosons
- Analysis of Effective Higgs Couplings
- Supersymmetric Scenario
- Combining Poisson and Gaussian Errors
- Determination of Errors on Couplings

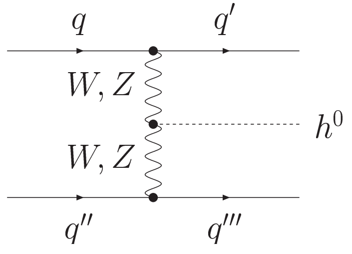
Production Modes

Main Higgs-boson production modes:

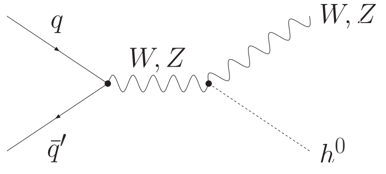
- Gluon-Gluon Fusion



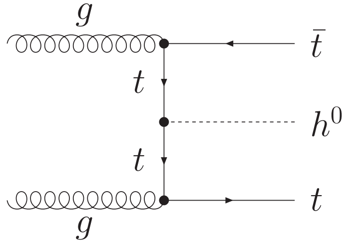
- Vector-Boson Fusion

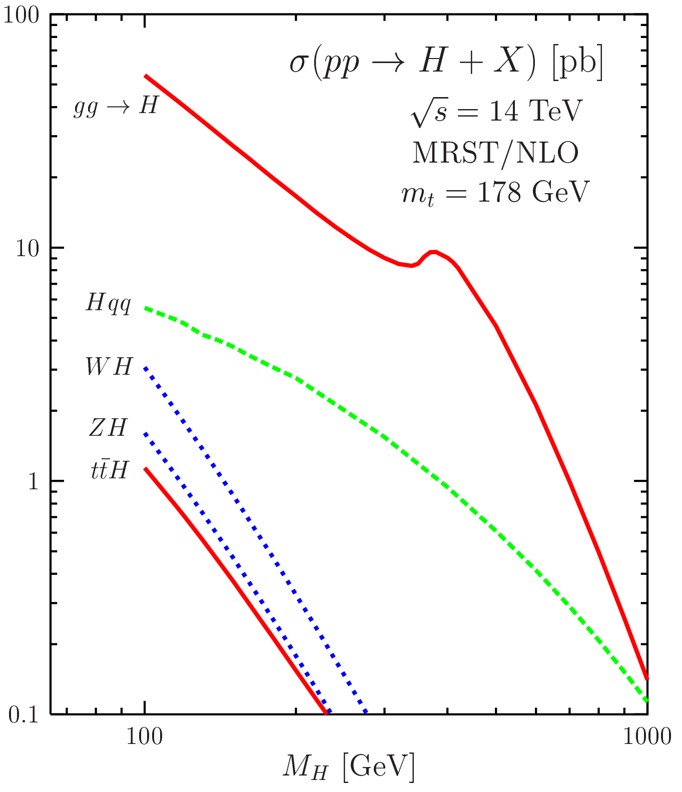


- Associated Production with a Gauge Boson



- Associated Production with Top-Quark–Antiquark Pair

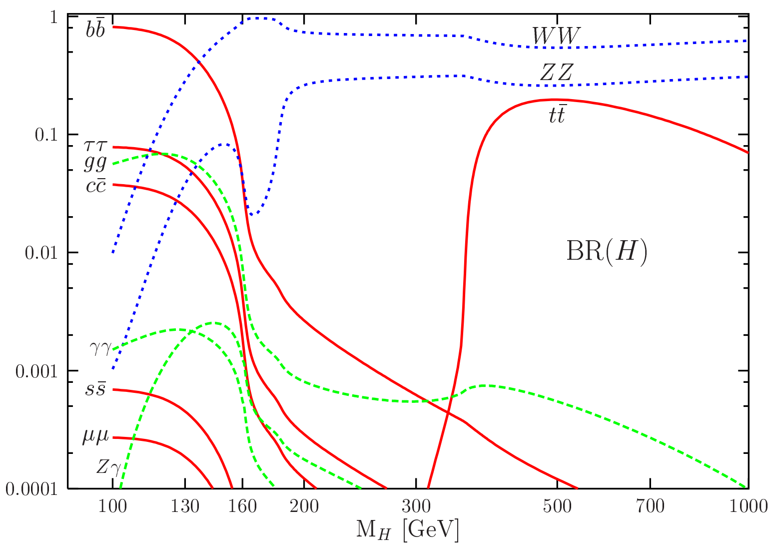




Higgs-Boson Decays

- $H \rightarrow b\bar{b}$
  - Main decay mode ($\sim 90\%$) for light Higgs bosons, as suggested by electroweak precision data
  - Hard to extract from QCD backgrounds
  - Combination with ttH production difficult to observe because of combinatorial background (4 bottom quarks in final state)
  - Recent suggestion of WH/ZH production plus jet substructure analysis looks promising (3.7σ)

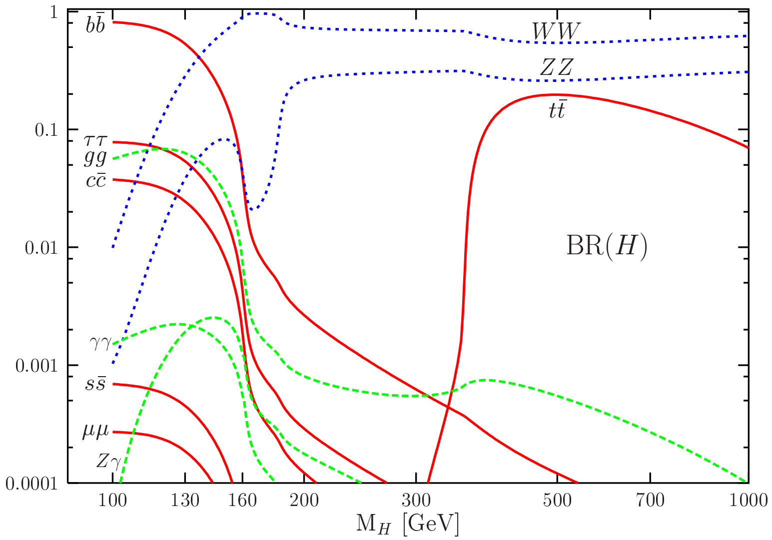
    [Butterworth, Davison, Rubin, Salam; ATL-PHYS-PUB-088]



[CMS-TDR]

Higgs-Boson Decays

- $H \to b\bar{b}$
- $H \to WW$
  - Main decay mode for heavier Higgs bosons ($m_H \gtrsim 140$ GeV)
  - Two leptonic decays of the W allow only reconstruction of transverse mass of the WW pair
  - Gluon and vector-boson fusion relevant even if Ws are off-shell

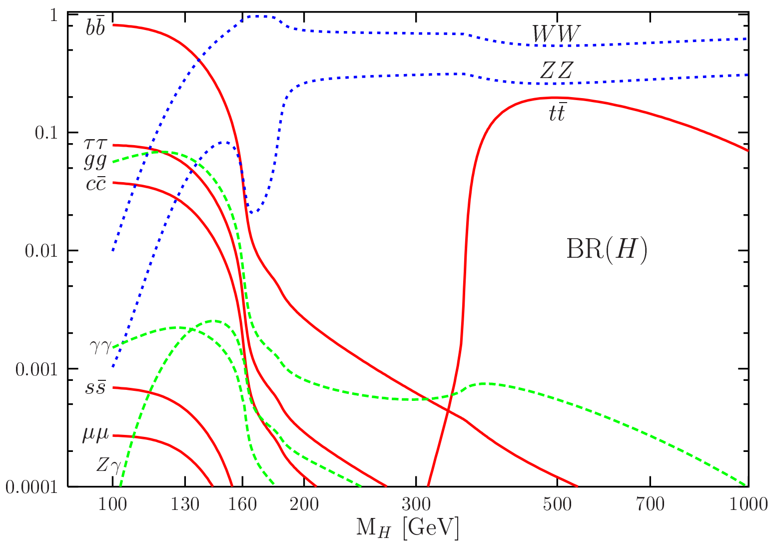


[CMS-TDR]

Higgs-Boson Decays

- $H \to b\bar{b}$
- $H \to WW$
- $H \to ZZ$
  - "Golden Channel" due to four-lepton final state
  - Statistically limited to larger Higgs masses
- $H \to \tau\tau$
  - Need to reconstruct invariant mass of the two taus
  - Limits production channel to vector-boson fusion
  - One of the discovery channels for light Higgs bosons

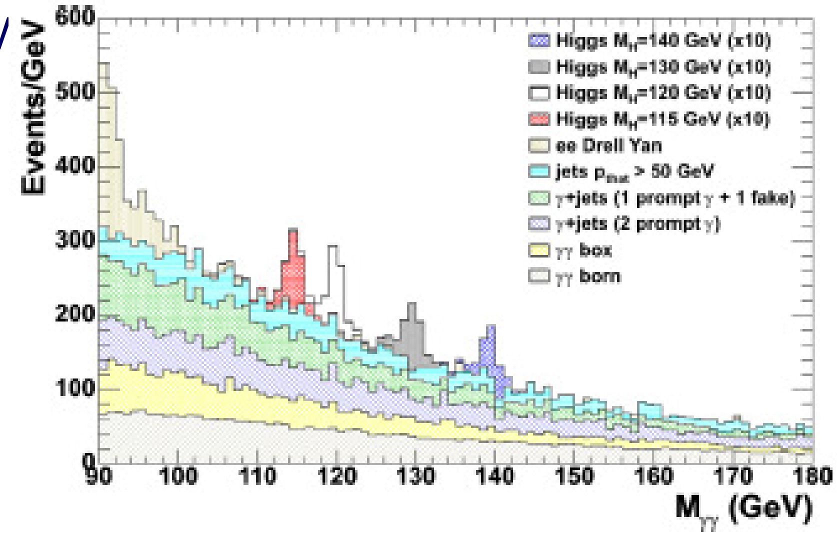
[Plehn, Rainwater, Zeppenfeld]



[CMS-TDR]

Higgs-Boson Decays

- $H \to b\bar{b}$
- $H \to WW$
- $H \to ZZ$
- $H \to \tau\tau$
- $H \to \gamma\gamma$
  - Loop-induced coupling by (mainly) W and t
  - Only fully reconstructable channel for a light Higgs boson
  - Small branching ratio ($\lesssim 0.2\%$)
  - Promising discovery channel for light Higgs bosons, background can be subtracted via sidebands
  - Higgs mass measurement up to 100 MeV



[CMS-TDR]

General Higgs Sector

- Theory: Standard Model plus general Higgs sector
- For Higgs couplings present in the Standard Model $j = W, Z, t, b, \tau$ replace general couplings by

$$g_{jjH} \longrightarrow g_{jjH}^{\text{SM}} \ \left(1 + \Delta_{jjH}\right)$$

- For loop-induced Higgs couplings $j = \gamma, g$ replace by

$$g_{jjH} \longrightarrow g_{jjH}^{\text{SM}} \ \left(1 + \Delta_{jjH}^{\text{SM}} + \Delta_{jjH}\right)$$

  where g_{jjH}^{SM}: (loop-induced) coupling in the Standard Model
  Δ_{jjH}^{SM}: contribution from modified tree-level couplings to Standard-Model particles
  Δ_{jjH}: additional (dimension-five) contribution

- Additional free parameters:
  - Higgs boson mass m_H
  - Top-quark mass m_t
  - Bottom-quark mass m_b
- Experimental input:
  - ATLAS study on Higgs couplings [Dührssen, references therein; ATLAS & CMS-TDR]
  - Jet substructure analysis for WH/ZH, $H \to b\bar{b}$ [Butterworth, Davison, Rubin, Salam]

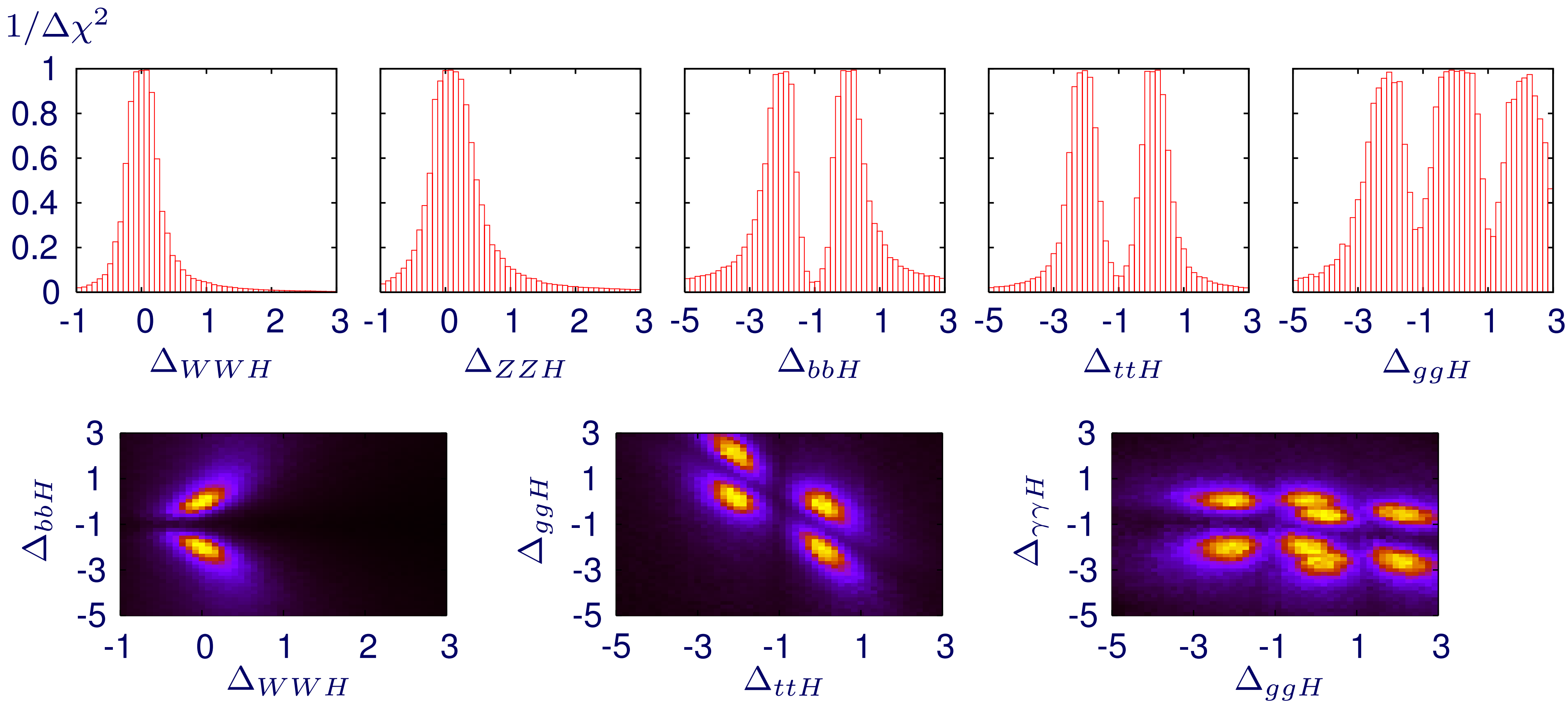
SFitter

- Need to scan high-dimensional parameter space
- ⇒ SFitter [Lafaye, Plehn, MR, Zerwas]
- General Higgs couplings from modified version of HDecay [Spira]
- Three scanning techniques:
  - Weighted Markov Chain
  - Cooling Markov Chain (equivalent to simulated annealing)
  - Gradient Minimisation (Minuit)
- Output of SFitter:
  - Fully-dimensional log-likelihood map
  - Reduction to plotable one- or two-dimensional distributions via both
    - Bayesian (marginalisation) or
    - Frequentist (profile likelihood) techniques
  - List of best points

Results

LHC data set with $30\ \text{fb}^{-1}$, $m_H = 120$ GeV , Profile likelihood

True data set

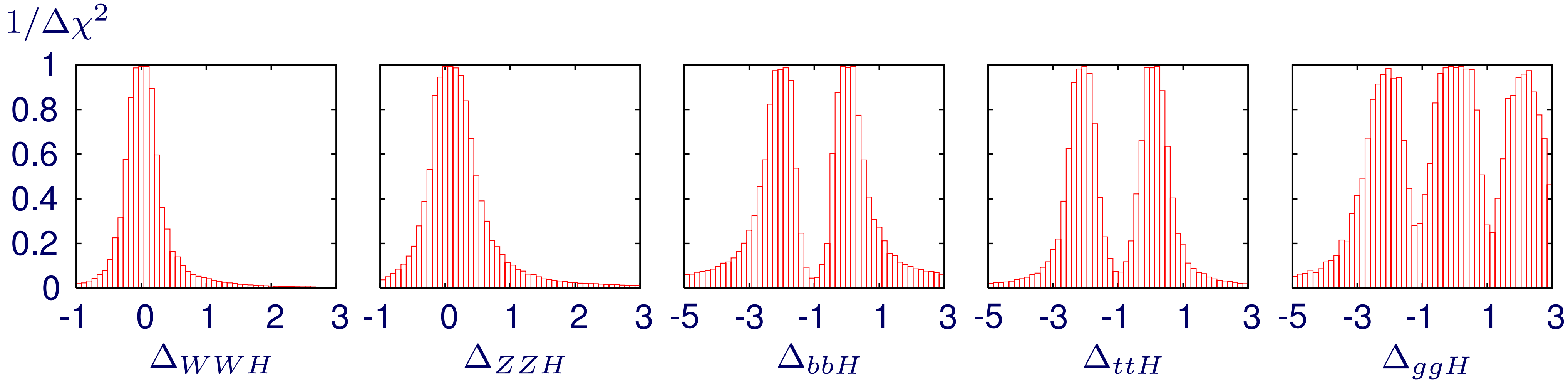


- Can reconstruct Standard Model solution, alternative solutions due to sign degeneracy
- See expected correlations (e.g. Δ_{ttH} vs Δ_{ggH})

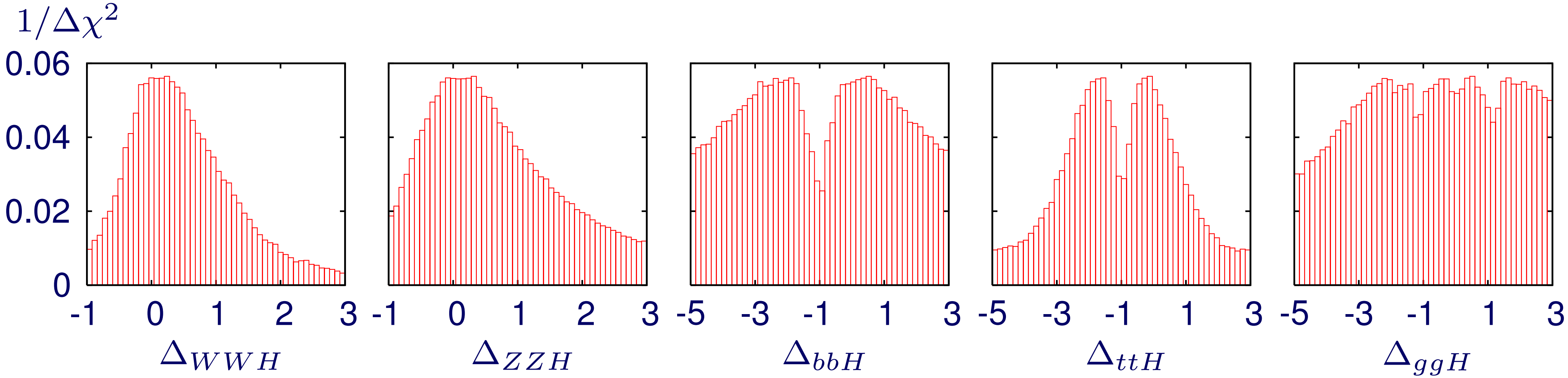
Results

LHC data set with 30 fb^{-1}, $m_H = 120$ GeV , Profile likelihood

True data set

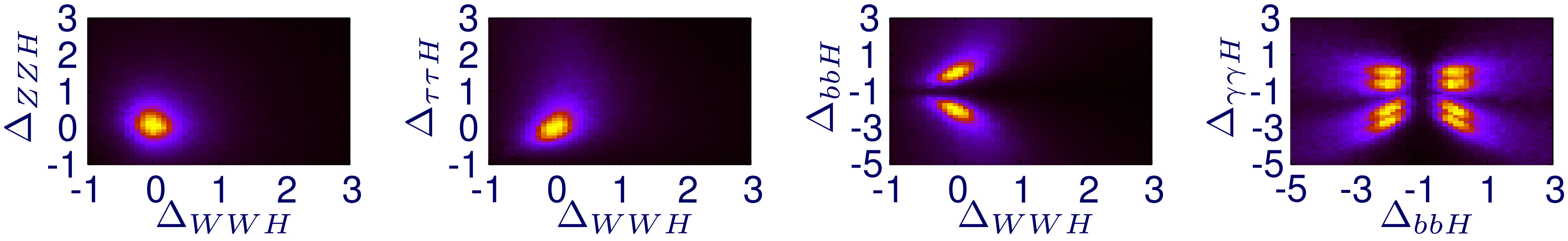


Smeared data set

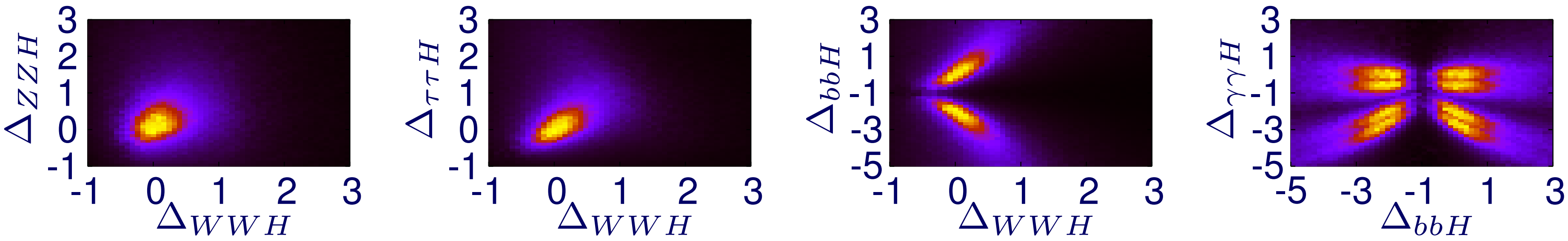


Impact of subjet analysis

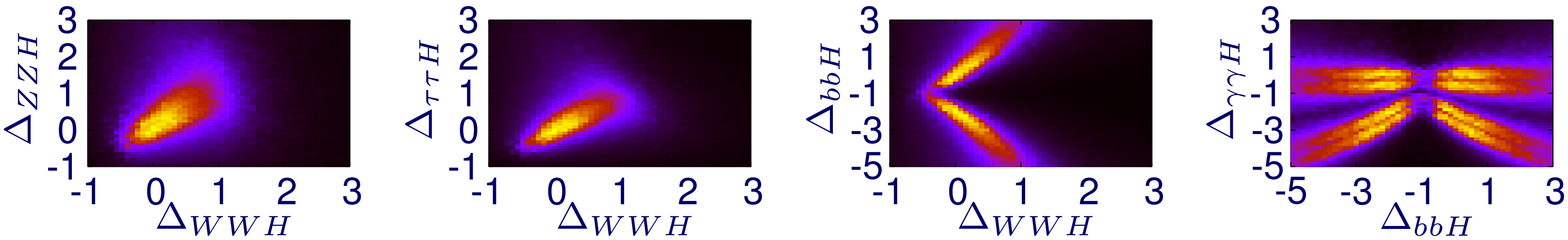
Nominal sensitivity on subjet analysis:



Reduced sensitivity on subjet analysis ($50\ \%$ of signal events):



Subjet analysis removed from dataset:

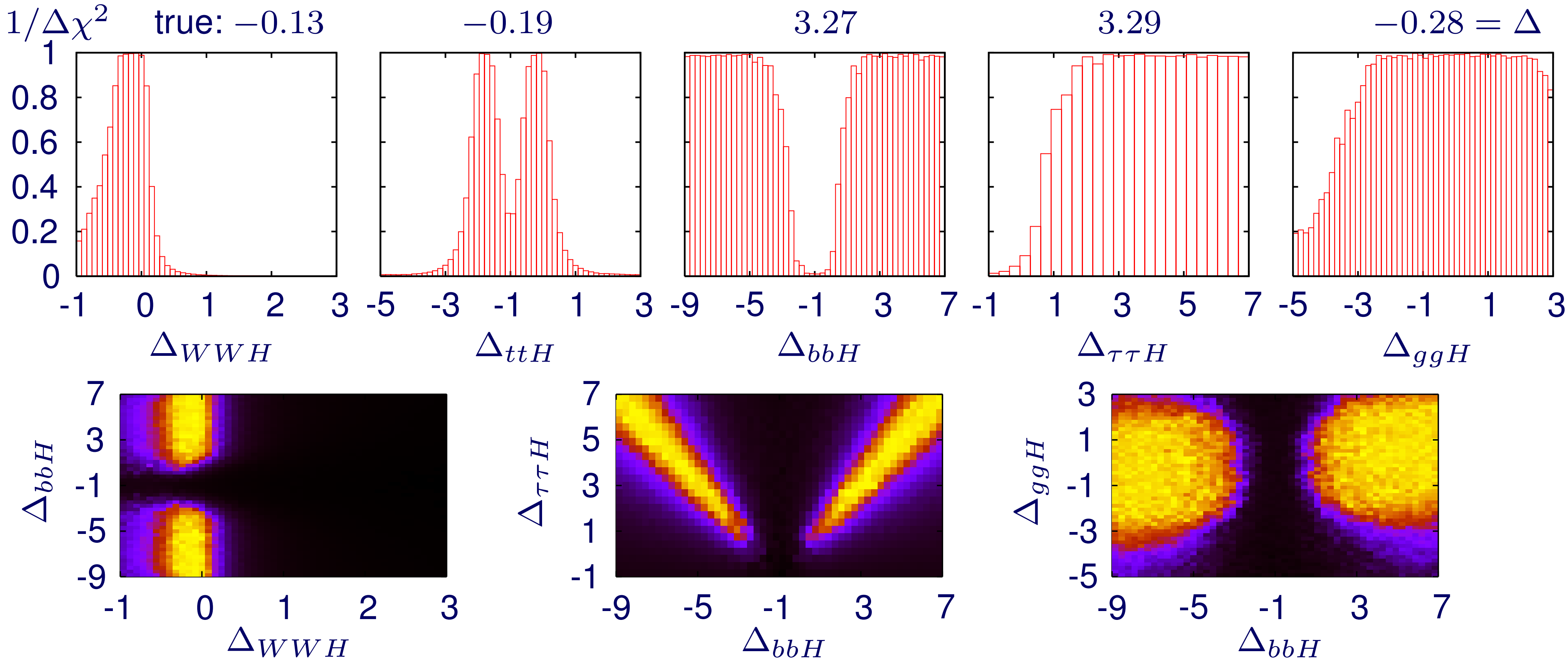


- Subjet analysis crucial for precise determination of g_{bbH}
- Accuracy on g_{bbH} feeds back into all other couplings via total width
- ATLAS study: Experimental sensitivity between $50\ \%$ and full (tending towards full side)

Non-decoupling Supersymmetric Higgs

SPS1a-inspired scenario with $t_\beta = 7$, $A_t = -1100$ GeV , $m_A = 151$ GeV , $m_{h^0} = 120$ GeV

LHC data set with 30 fb^{-1}, Profile likelihood, true data set



- Clear deviation from Standard Model: $q(d_{\text{SUSY}}|m_{\text{SM}}) < q(d_{\text{SM}}|m_{\text{SM}})$: 77% at 90% CL
- Favouring of new physics more difficult: only 4% better described by SUSY model
- Strong correlation between Δ_{bbH} and $\Delta_{\tau\tau H}$ via total width
- No upper limit on g_{bbH} as $BR \simeq 1$ compatible with data

Errors

- Statistical errors on individual channels of Poisson type
- Systematic errors (luminosity, tagging efficiency, ...) extracted from large event samples $\Rightarrow$ Gaussian
- Need to combine
  - Poisson $P_P(d,m) = \frac{\exp(-m)m^d}{\Gamma(d+1)}$ and
  - Gaussian $P_G(d,m,\sigma) = \frac{1}{\sqrt{2\pi}\sigma}\exp(-\frac{(d-m)^2}{2\sigma^2})$ errors
- Mathematically correct way: convolution
- No analytic solution, numerical integration too time-consuming
- $\Rightarrow$ Approximate formula:

$$\frac{1}{\tilde{\chi}^2} \equiv \frac{1}{-2\log L} = \sum_i \frac{1}{-2\log L_i}$$

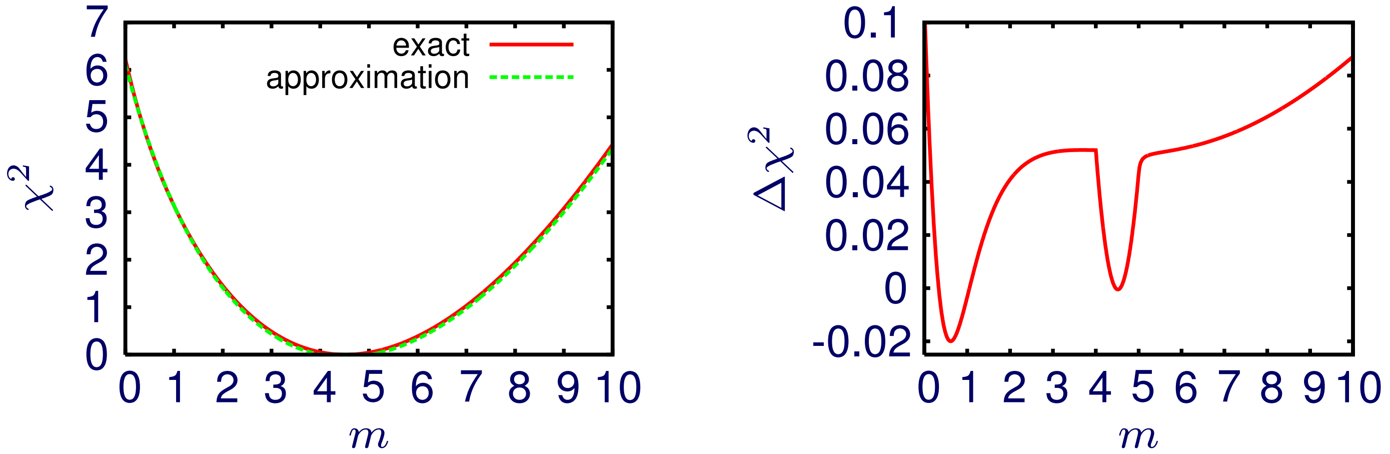
  - Yields exact formula for Gaussian-only (adding errors in quadrature)
  - Gives correct result when one error approaches 0 or ∞

Errors

- Approximate formula for Gauss and Poisson errors:

$$\frac{1}{\tilde{\chi}^2} = \frac{1}{-2\log L} = \sum_i \frac{1}{-2\log L_i}$$
$$\to \frac{1}{-2\log L_P} + \frac{1}{-2\log L_G}$$
$$= \frac{1}{-2\log P_P(d,m)/P_P(m,m)} + \frac{\sigma^2}{-2(d-m)^2}$$

- Example: Poisson($d = 5$), Gauss($\sigma = 0.5$)



- $\Rightarrow$ Very good agreement with exact convolution
- Difference almost always positive $\Rightarrow$ slight overestimation of Higgs-coupling errors (good!)

Determination of errors on couplings

Determination of errors on Higgs couplings:

- Perform 10,000 toy experiments with measurements smeared around correct value
- Minimise each toy experiment
- Plot resulting distribution of parameter points and fit central peak with Gaussian

	no effective couplings				with effective couplings				ratio $\Delta_{jjH/WWH}$		
	RMS	σ_{symm}	σ_{neg}	σ_{pos}	RMS	σ_{symm}	σ_{neg}	σ_{pos}	σ_{symm}	σ_{neg}	σ_{pos}
Δ_{WWH}	± 0.31	± 0.23	-0.21	$+0.26$	± 0.29	± 0.24	-0.21	$+0.27$	—	—	—
Δ_{ZZH}	± 0.49	± 0.36	-0.40	$+0.35$	± 0.46	± 0.31	-0.35	$+0.29$	± 0.41	-0.40	$+0.41$
Δ_{ttH}	± 0.58	± 0.41	-0.37	$+0.45$	± 0.59	± 0.53	-0.65	$+0.43$	± 0.51	-0.54	$+0.48$
Δ_{bbH}	± 0.53	± 0.45	-0.33	$+0.56$	± 0.64	± 0.44	-0.30	$+0.59$	± 0.31	-0.24	$+0.38$
$\Delta_{\tau\tau H}$	± 0.47	± 0.33	-0.21	$+0.46$	± 0.57	± 0.31	-0.19	$+0.46$	± 0.28	-0.16	$+0.40$
$\Delta_{\gamma\gamma H}$	—	—	—	—	± 0.55	± 0.31	-0.30	$+0.33$	± 0.30	-0.27	$+0.33$
Δ_{ggH}	—	—	—	—	± 0.80	± 0.61	-0.59	$+0.62$	± 0.61	-0.71	$+0.46$

- Can determine all couplings with accuracy of about 20-$50\ \%$ for $30\ \text{fb}^{-1}$
- ZZH coupling more precise including effective couplings
- Forming ratios can slightly improve precision

Summary

- Determining the Higgs-boson couplings next step after discovery
  Important for our understanding of electroweak symmetry breaking
- Independent of explicit realisation of new physics (if any):
  Standard Model with effective Higgs couplings
- Problem of high-dimensional parameter space with correlated measurements
  $\Rightarrow$ Dedicated tool: SFitter

- Obtain Standard Model couplings within errors for SM scenario
- Alternative solutions due to sign degeneracy of couplings
- Clear deviation for non-degenerate SPS1a-inspired scenario

- Analysis of errors on couplings
- Recent jet substructure analysis significantly improves result on bottom-quark coupling
- Influences accuracy of all other couplings via total width