Determination of Higgs Couplings at the LHC

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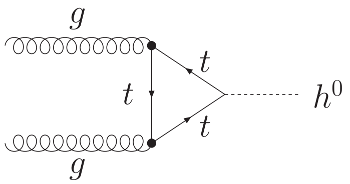
Outline

- Production and Decay of Higgs Bosons
- Higgs Channels at the LHC
- Analysis of Effective Higgs Couplings
- Combining Poisson and Gaussian Errors
- Determining Errors on Couplings

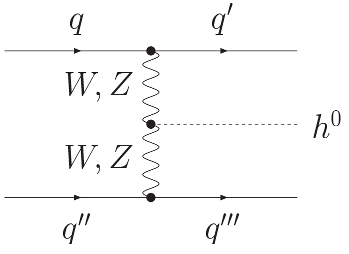
Production Modes

Main Higgs-boson production modes:

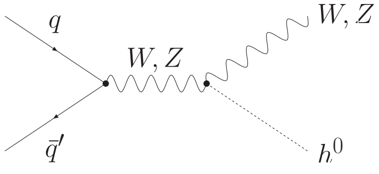
- Gluon-Gluon Fusion



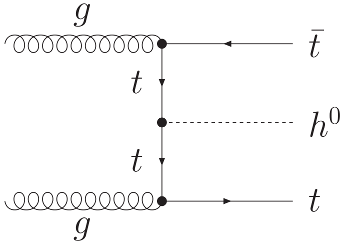
- Vector-Boson Fusion

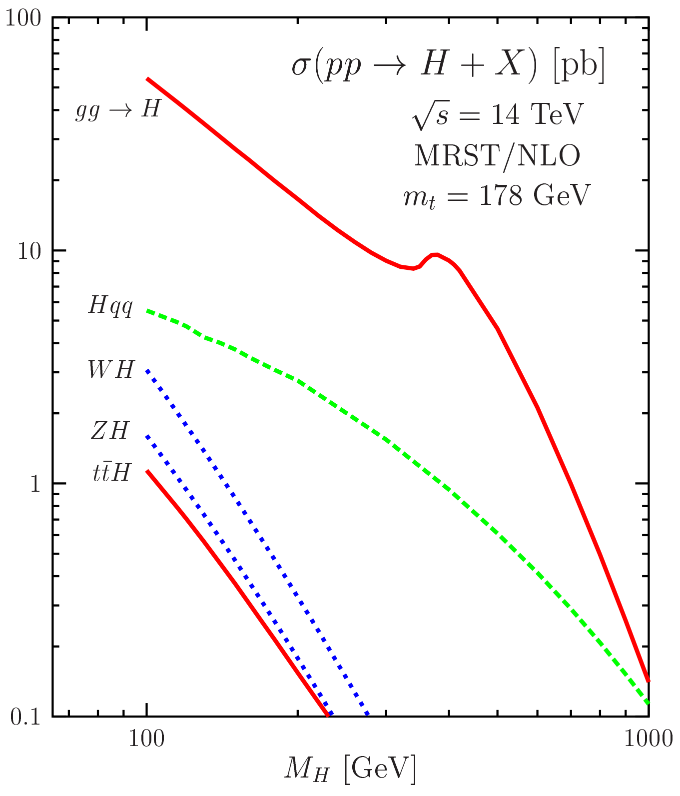


- Associated Production with a Gauge Boson



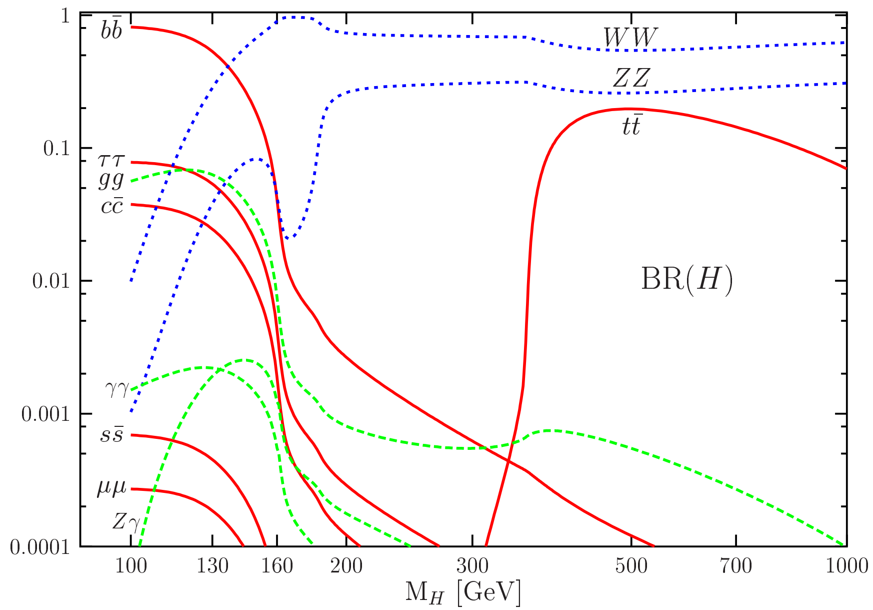
- Associated Production with Top-Quark–Antiquark Pair





Higgs-Boson Decays

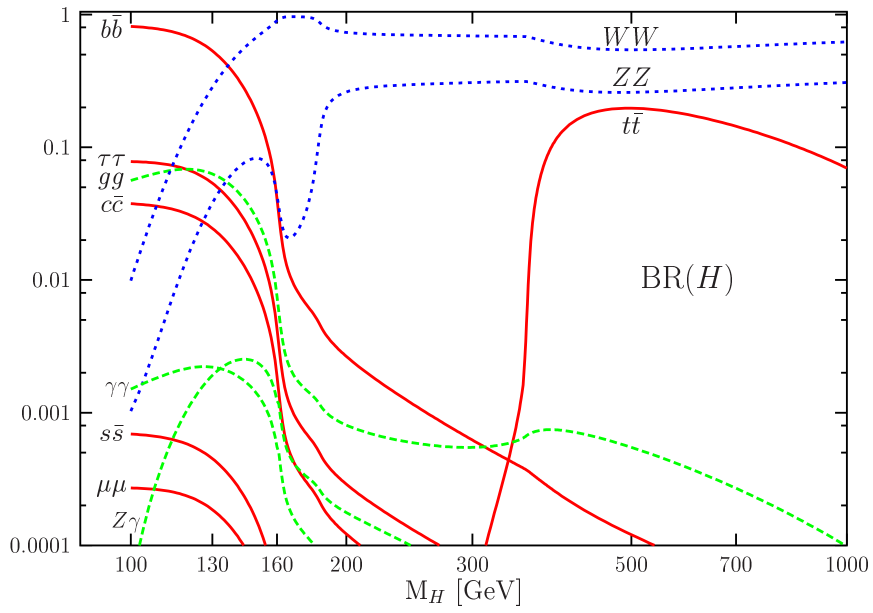
- $H \longrightarrow b\bar{b}$
  - Main decay mode ($\sim 90\%$) for light Higgs bosons, as suggested by electroweak precision data
  - Hard to extract from QCD backgrounds
  - Combination with ttH production hard to observe because of combinatorial background (4 bottom quarks in final state)
  - Recent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



[CMS-TDR]

Higgs-Boson Decays

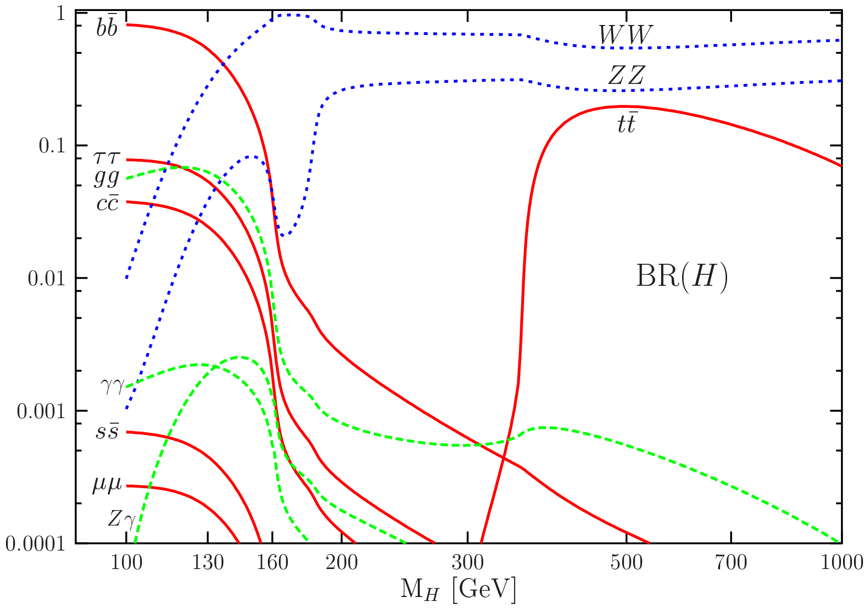
- $H \to WW$
  - Main decay mode for heavier Higgs bosons ($m_H \gtrsim 140$ GeV)
  - Two leptonic decays of the W allow only reconstruction of transverse mass of the WW pair
  - Gluon and vector-boson fusion relevant even if Ws are off-shell
  - Associated WH/ZH and $t\bar{t}H$ production only for heavier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



[CMS-TDR]

Higgs-Boson Decays

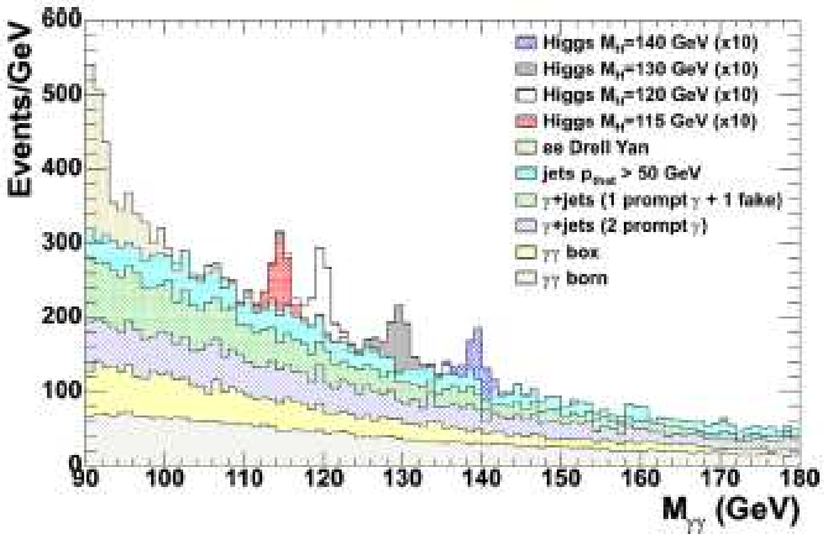
- $H \to ZZ$
  - “Golden Channel” due to four-lepton final state
  - Combination with gluon and vector-boson fusion production
  - Statistically limited to larger Higgs masses
- $H \to \tau\tau$
  - Need to reconstruct invariant mass of the two taus
  - Limits production channel to vector-boson fusion
  - One of the discovery channels for light Higgs bosons



[CMS-TDR]

Higgs-Boson Decays

- $H \to \gamma\gamma$
  - 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]

Higgs-Boson Decays

Decays not considered in our analysis:

- $H \to Z\gamma$
  - Similar features to the two-photon channel
  - Reduced branching ratio (phase-space suppression)
  - Additional leptonic branching ratio of the Z
- $H \to \mu\mu$
  - Excellent $\mu\mu$ invariant mass reconstruction
  - Might be observable similar to two-photon decay
  - Combination with vector-boson fusion production mode
- $H \to invisible$
  - Important for new physics
  - Best seen in combination with vector-boson fusion
    (Two tagging jets recoiling against missing energy)
- $H^* \to HH, HHH$
  - Triple Higgs coupling can in principle be seen at the LHC
  - Relies on precision measurement of all other parameters
  - Quartic Higgs coupling not measurable at any considered collider

[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

$$g_{Hjj} \quad \to \quad g_{Hjj}(1 + \frac{\Delta_{Hjj}}{g_{Hjj}}) \quad \equiv \quad g_{Hjj}(1 + \delta_{Hjj})$$

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

$$g^{\text{SM}}_{Hjj} \quad \to \quad g_{Hjj}(1 + \frac{\Delta_{Hjj}}{g_{Hjj}}) \quad \equiv \quad g_{Hjj} + \delta_{Hjj} \cdot g^{\text{SM}}_{Hjj}$$

  where g_{Hjj}: Using general couplings of loop particles
  g^{SM}_{Hjj}: Using Standard Model couplings of loop particles
- 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]

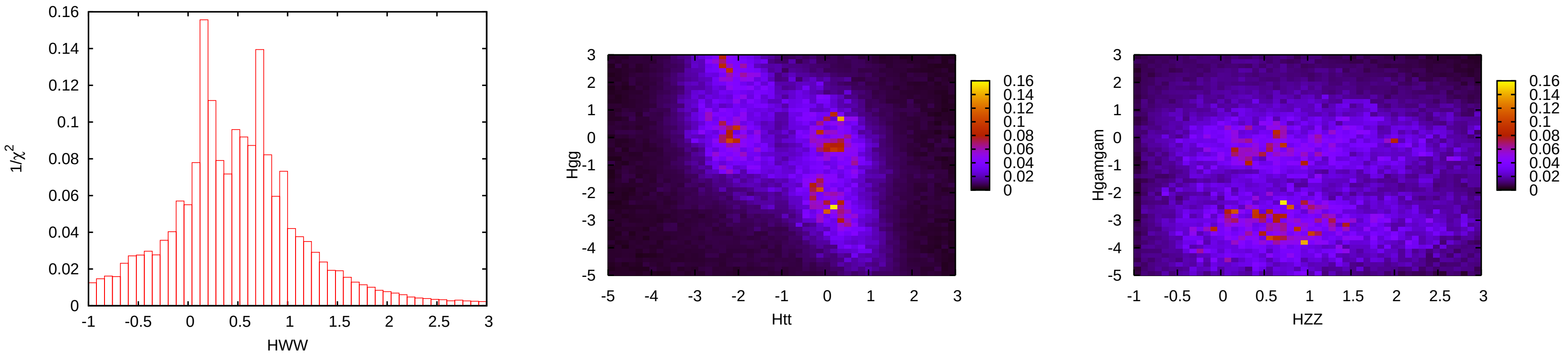
SFitter

- Need to scan high-dimensional parameter space
- $\Rightarrow$ SFitter [Lafaye, Plehn, MR, Zerwas]
- General Higgs couplings from modified version of HDecay [Spira]
- Three scanning techniques:
  - Gradient Minimisation (Minuit)
  - Grid scan
  - Weighted Markov Chain
- 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

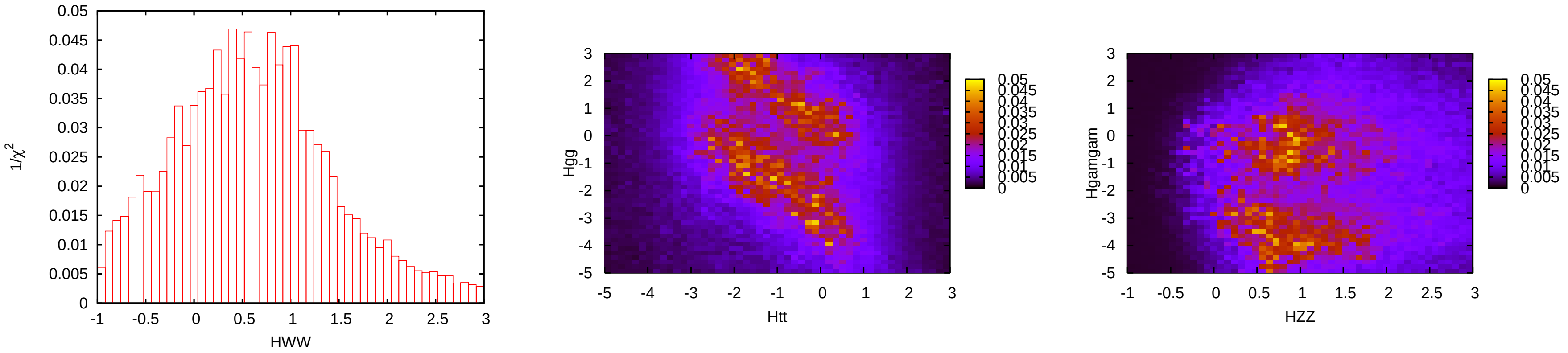
Results

LHC data set with 30 fb^{-1}:

Frequentist: True data set



Smeared data set



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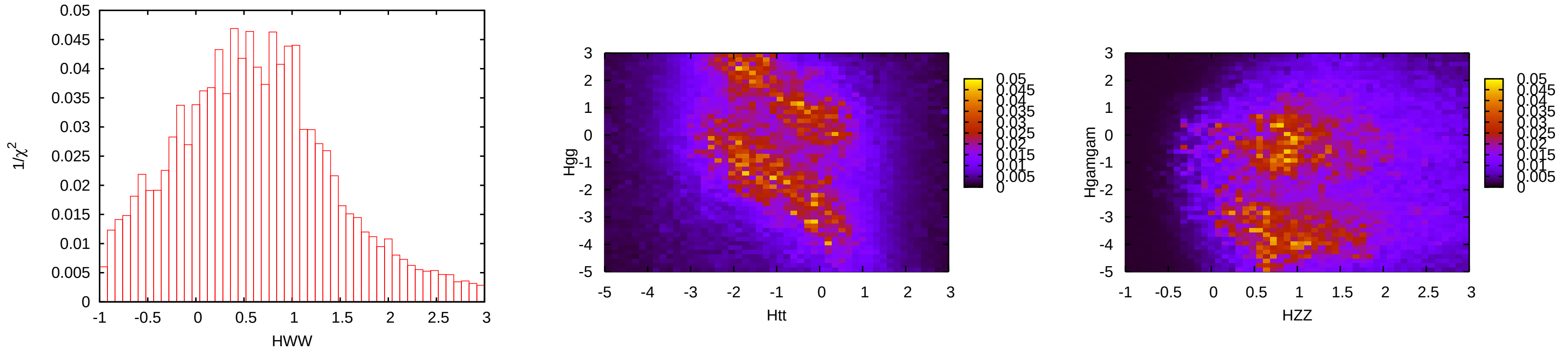
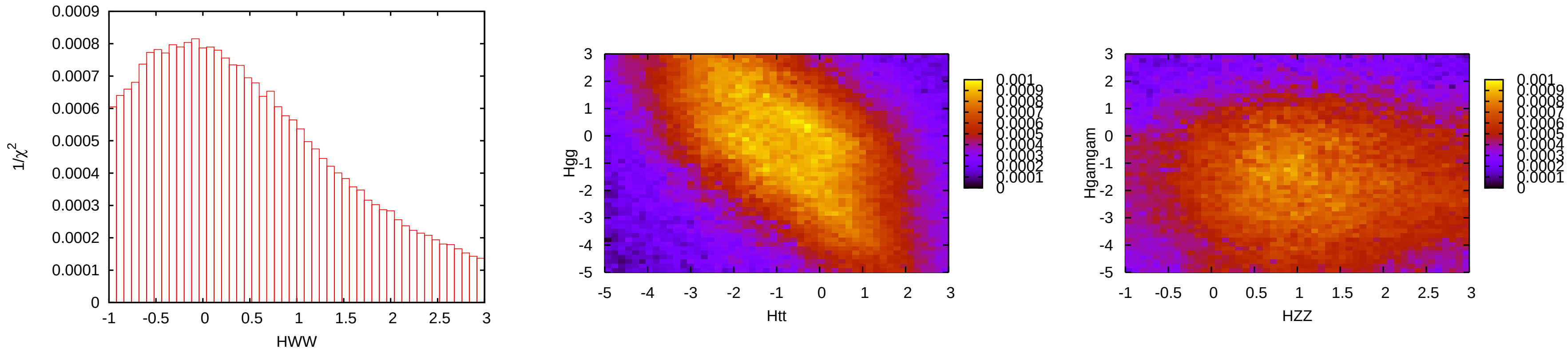


Bayesian:



Smeared dataset leads to shifted best–fitting points

Can see expected correlations between Higgs couplings

Results(2)

List of best points: True data set

HWW	HZZ	$Ht\bar{t}$	$Hb\bar{b}$	$H\tau\bar{\tau}$	$H\gamma\gamma$	Hgg	m_H	m_b	m_t	χ^2
0.06	0.06	0.02	0.18	0.03	-2.16	-2.00	120.00	4.20	171.40	0.00
0.08	0.04	-2.04	-2.18	0.07	-2.74	-0.05	120.00	4.20	171.40	0.00
0.19	0.13	0.06	-2.43	0.22	-2.42	-2.38	120.00	4.20	171.39	0.01
0.30	0.19	0.12	0.71	0.29	-2.66	0.21	120.00	4.20	171.41	0.15
0.36	0.46	0.16	-2.97	0.28	-2.76	-2.49	120.00	4.20	171.35	0.56

Smeared data set

HWW	HZZ	$Ht\bar{t}$	$Hb\bar{b}$	$H\tau\bar{\tau}$	$H\gamma\gamma$	Hgg	m_H	m_b	m_t	χ^2
0.46	0.39	-1.91	-3.37	0.39	-0.62	-0.99	119.54	4.12	169.98	10.53
0.56	0.48	-0.05	-3.73	0.48	-0.13	0.76	119.54	4.12	169.96	10.60
0.68	0.60	-2.01	-4.22	0.60	-0.70	3.00	119.54	4.12	169.98	10.78
0.77	0.68	-0.02	-4.54	0.66	-0.20	-3.37	119.52	4.12	169.98	10.90

Results(2)

List of best points: Smeared data set

HWW	HZZ	$Ht\bar{t}$	$Hb\bar{b}$	$H\tau\bar{\tau}$	$H\gamma\gamma$	Hgg	m_H	m_b	m_t	χ^2
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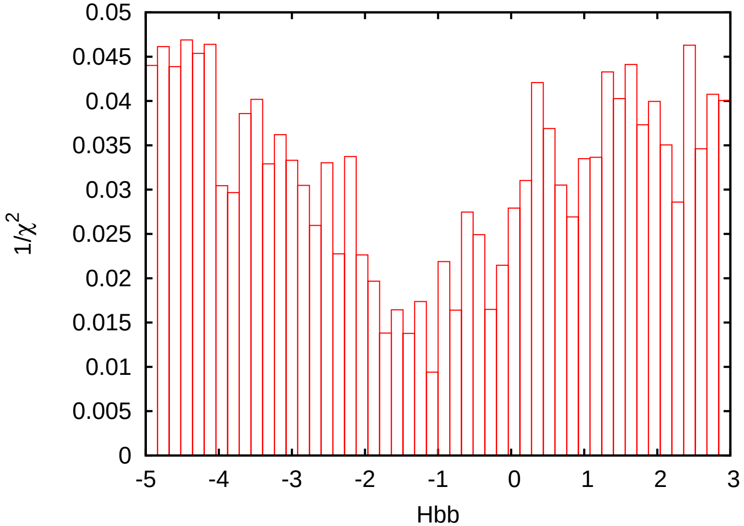
0.68	0.60	-2.01	-4.22	0.60	-0.70	3.00	119.54	4.12	169.98	10.78
0.77	0.68	-0.02	-4.54	0.66	-0.20	-3.37	119.52	4.12	169.98	10.90

Looking at the $Hb\bar{b}$ coupling:

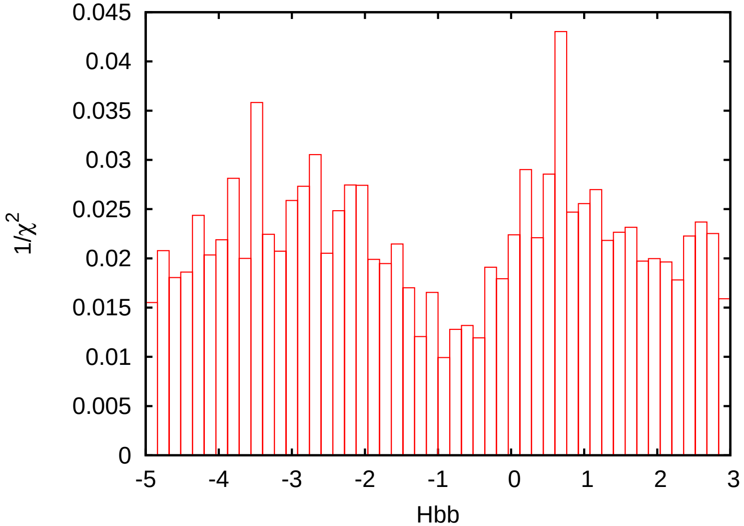
Channel ttH, $H \to b\bar{b}$ significantly degraded in performance when including NLO results

Recent jet substructure analysis looks promising [Butterworth, Davison, Rubin, Salam]

without jet substructure analysis



including jet substructure analysis



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:

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

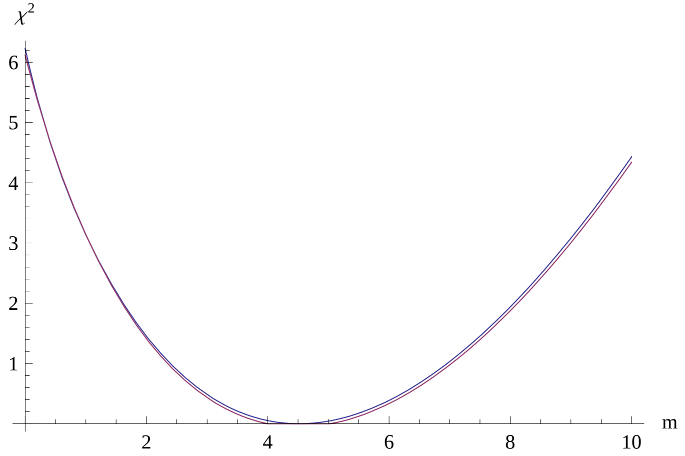
  - Yields exact formula for Gaussian-only (adding errors in quadrature)
  - Gives correct result when one error approaches 0 or ∞

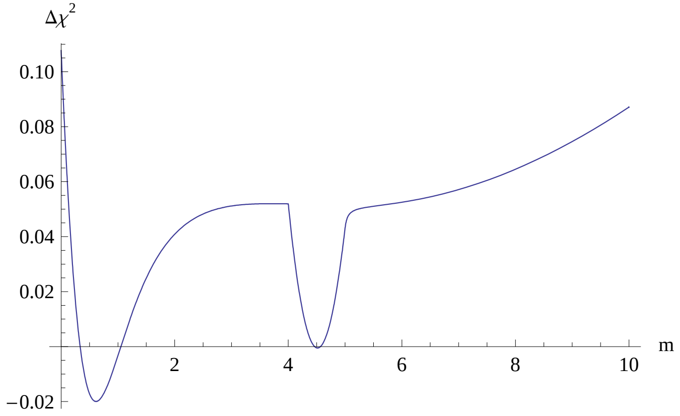
Errors

- Approximate formula for Gauss and Poisson errors:

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

- 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!)

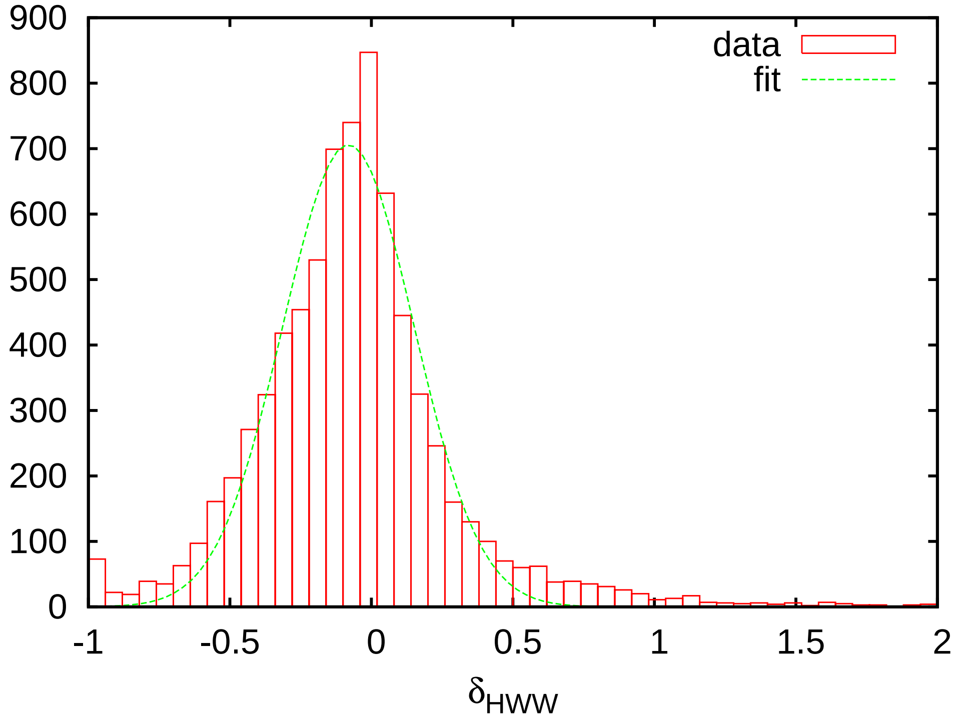
Determination of errors on couplings

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 with Gaussian

Results:

Coupling	$\delta_{\text{coupling}} \pm \Delta_\delta$
$H \to WW$	-0.08 $\pm$ 0.23
$H \to ZZ$	-0.08 $\pm$ 0.43
$H \to t\bar{t}$	0.09 $\pm$ 0.48
$H \to b\bar{b}$	-0.01 $\pm$ 0.33
$H \to \tau\bar{\tau}$	-0.03 $\pm$ 0.30
$H \to \gamma\gamma$	0.07 $\pm$ 0.36
$H \to gg$	-0.24 $\pm$ 0.63
m_H [GeV]	120.07 $\pm$ 0.34
m_b [GeV]	4.20 $\pm$ 0.07
m_t [GeV]	171.40 $\pm$ 0.98



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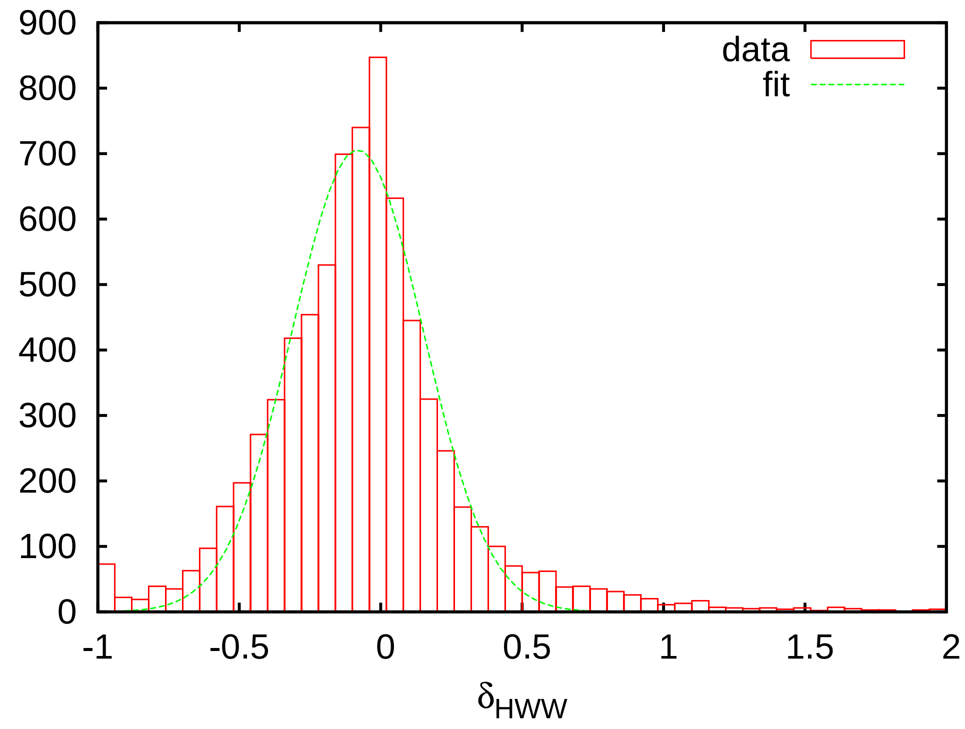
Preliminary



Summary & Outlook

- 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 for true data
- For smeared data result shifted within errors
- Observe expected correlations between Higgs couplings
- Recently suggested jet substructure analysis can improve result on bottom-quark coupling

- Analysis of errors on couplings
- Supersymmetric scenario with non-SM couplings