Measuring Higgs Couplings — Why and How

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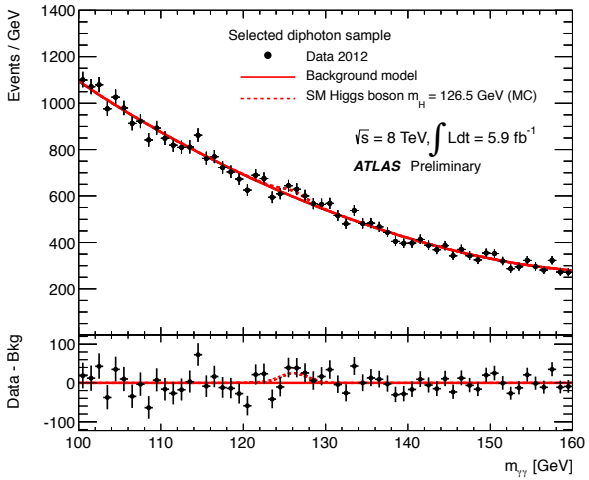
Higgs discovery

Best of ATLAS [and CMS]

– 'silver channel' $H \to \gamma\gamma$

local significance 4.5σ (ATLAS), 4.1σ (CMS)
correct background treatment beneficial



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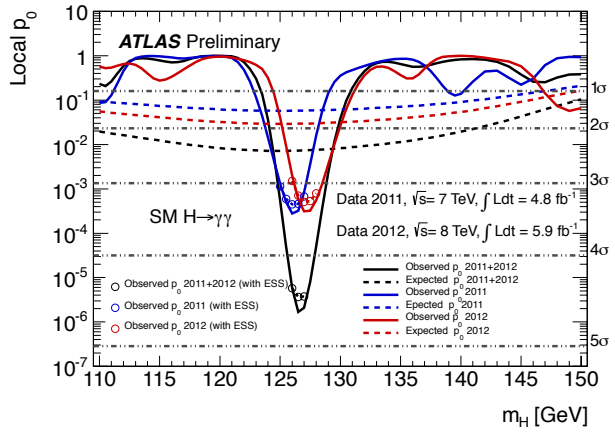

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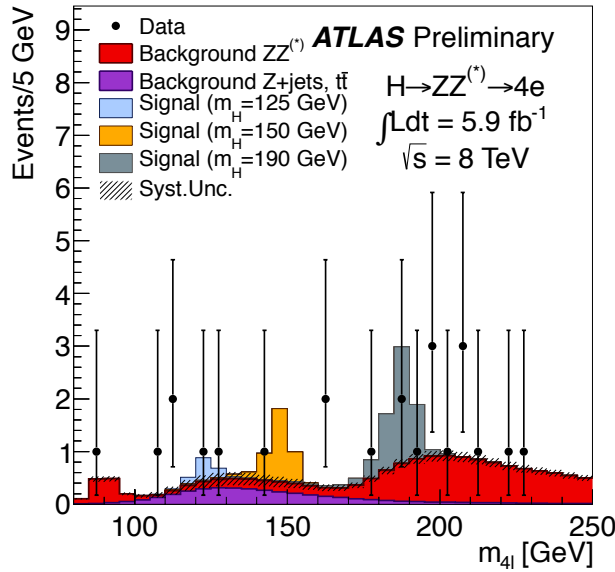

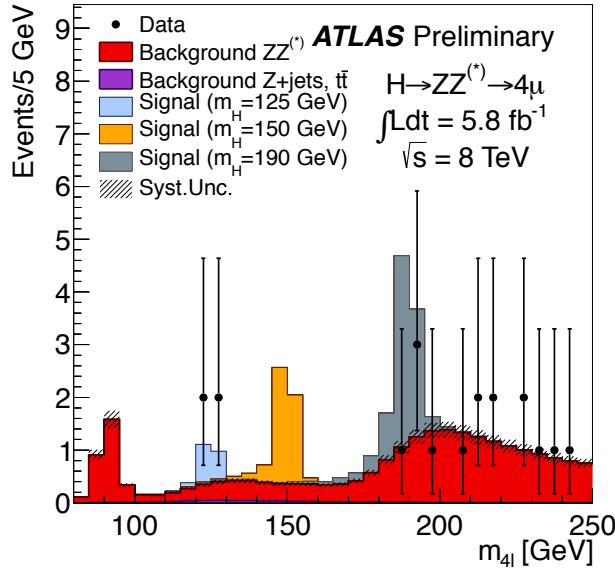

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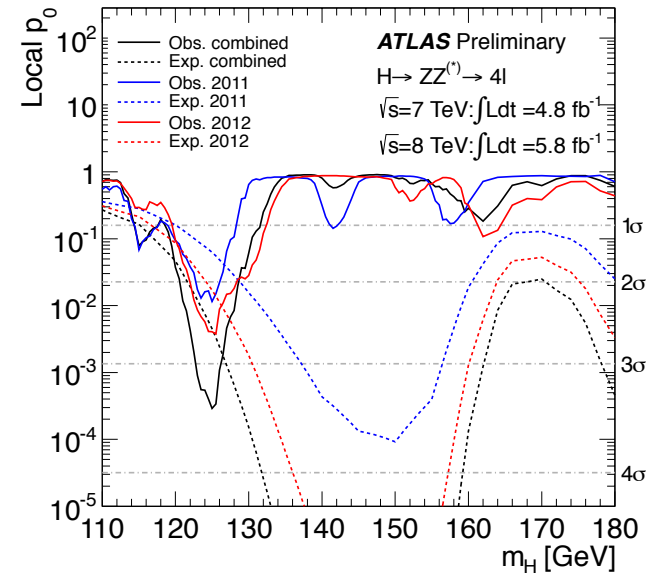

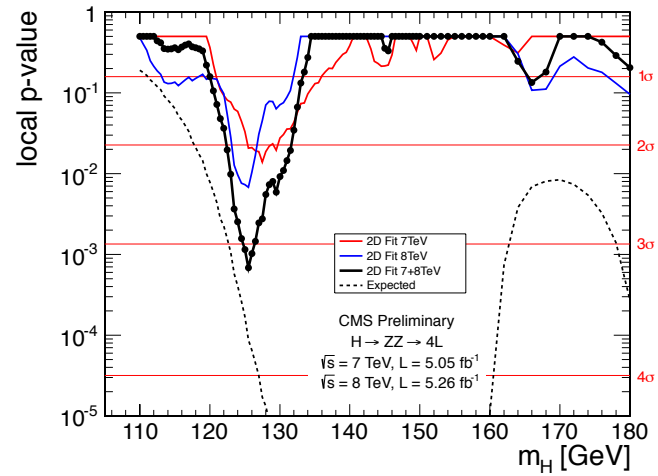

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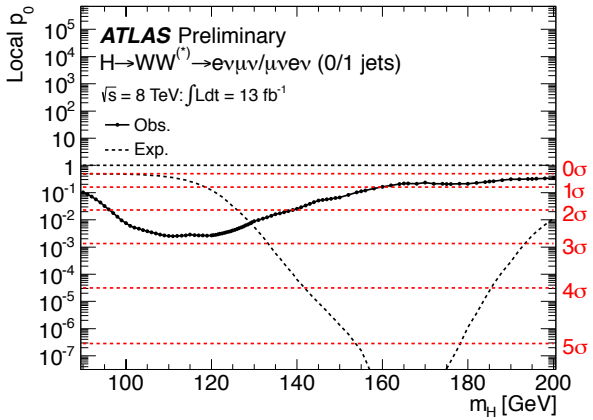
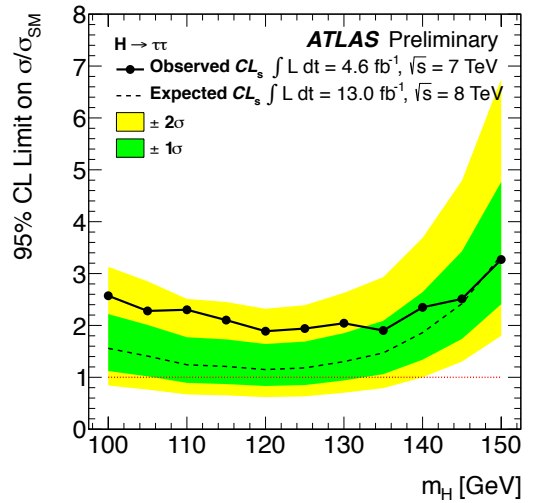
  broad excess, bb not sensitive to SM rates





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Any models ruled out?

- Standard Model fine [Holthausen, Lim, Lindner]
- reasonably decoupling theories all fine

  MSSM one example [tons of papers]
  hypersphere in $m_{\tilde{t}_{L/R}}$, $\tan\beta$, A_t, μ, m_A predicting little $[x_t^2/(m_{\tilde{t}_1} m_{\tilde{t}_2}) \gtrsim 1]$
- strongly interacting light Higgs supposedly fine
- Higgs portal fine

$\Rightarrow$ let's try to make science out of this

Operators

Equivalent questions

- what are the Higgs quantum numbers?
- what is the structure of the Higgs Lagrangian?
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Heavy flavor inspiration

- for any observed Higgs coupling there exists a renormalizable operator
- except Higgs production in gluon fusion
- except Higgs decay to photons
- except g_{WWH} might mean $HW^{\mu\nu} W_{\mu\nu}$
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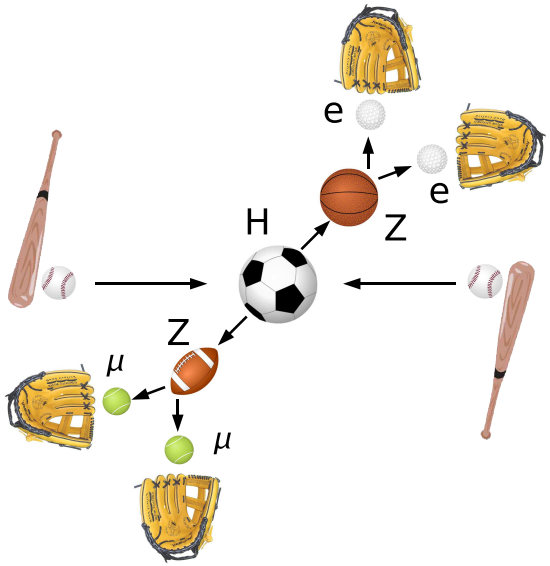
$\Rightarrow$ analyze Higgs kinematics [in as many channels as possible]

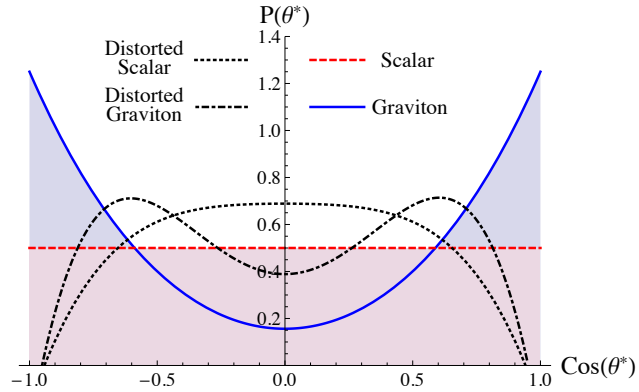


Operators

Model independent angles

– first step: Higgs polar angle for spin-0 vs spin-2 [Alves; Choi etal]

$$\frac{d\Gamma_0}{d\cos\theta^*} \sim P_0(\theta^*) = 1 \qquad P_2(\theta^*) \sim 1+6\cos^2\theta^*+\cos^4\theta^*$$



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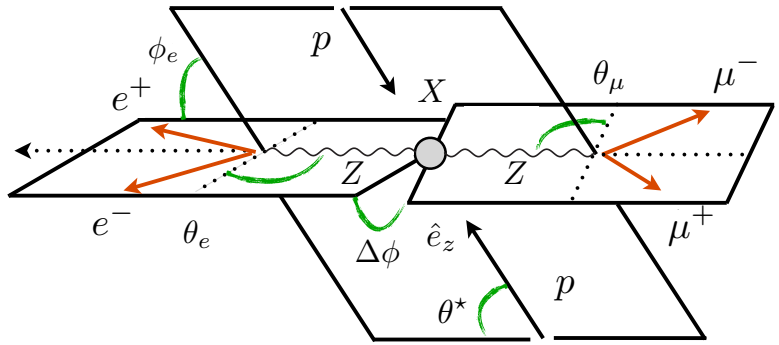
– $H \to ZZ$ decays [Melnikov etal; Lykken etal; v d Bij etal; Englert, Spannowsky, Takeuchi]
classic Cabibbo–Maksymowicz–Dell'Aquila–Nelson angles

$$\cos\theta_e = \hat{p}_{e-} \cdot \hat{p}_{Z_\mu}\Big|_{Z_e} \qquad \cos\theta_\mu = \hat{p}_{\mu-} \cdot \hat{p}_{Z_e}\Big|_{Z_\mu} \qquad \cos\theta^* = \hat{p}_{Z_e} \cdot \hat{p}_{\text{beam}}\Big|_X$$

$$\cos\phi_e = (\hat{p}_{\text{beam}} \times \hat{p}_{Z_\mu}) \cdot (\hat{p}_{Z_\mu} \times \hat{p}_{e-})\Big|_{Z_e}$$

$$\cos\Delta\phi = (\hat{p}_{e-} \times \hat{p}_{e+}) \cdot (\hat{p}_{\mu-} \times \hat{p}_{\mu+})\Big|_X$$



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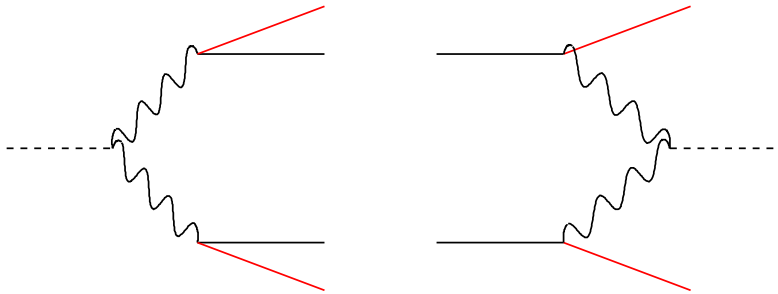
  Breit frame or hadron collider (η, ϕ) [Breit: boost into space-like]



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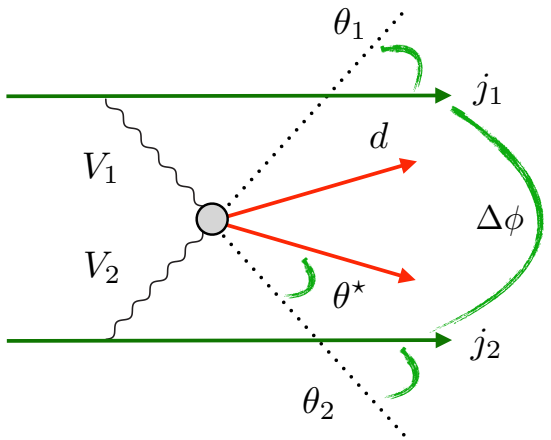

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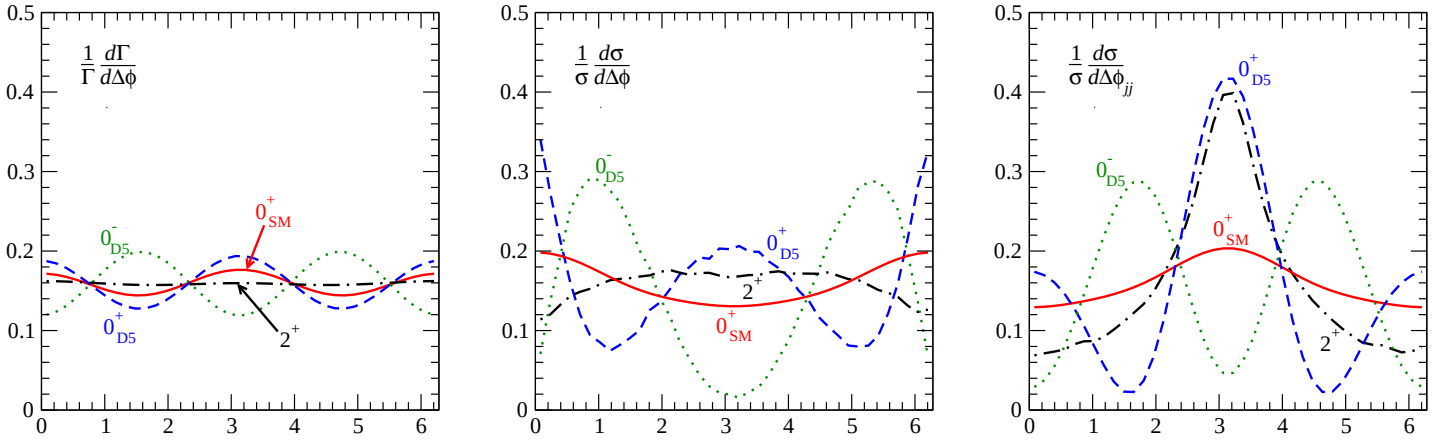
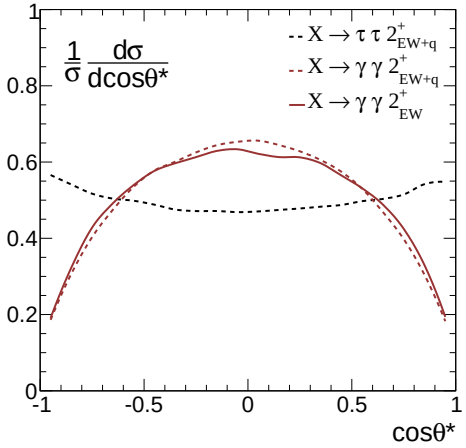


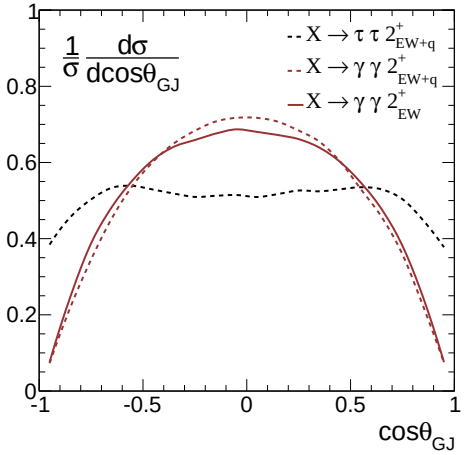
$\Rightarrow$ different approaches with similar physics

Operators

Spin-2 test? [Englert, Mawatari, Netto, TP]

- unitarization affecting all energy variables
- try Gottfried-Jackson angle [$\hat{p}_{X,lab}$ vs $\hat{p}_{d,X}$; Frank, Rauch, Zeppenfeld; Schumi]





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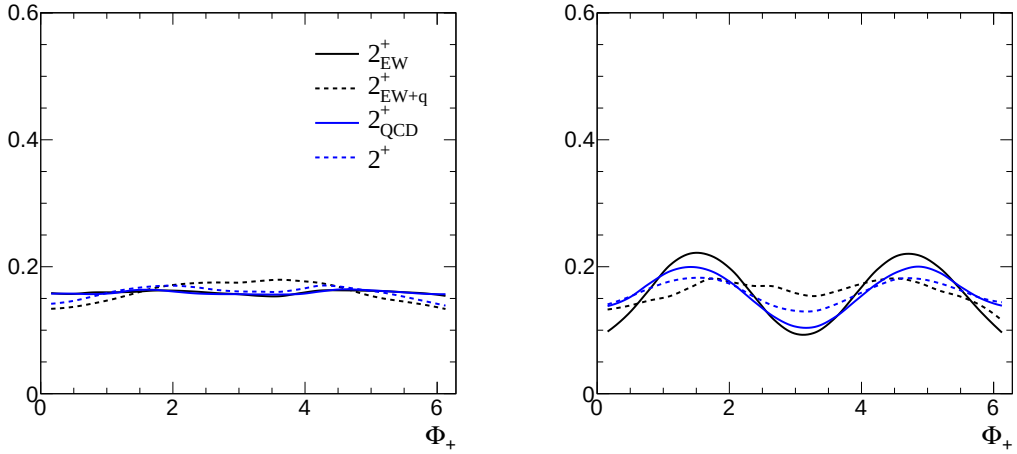
- alternatively $\phi_1 + \phi_2$ [Hagiwara, Li, Mawatari]



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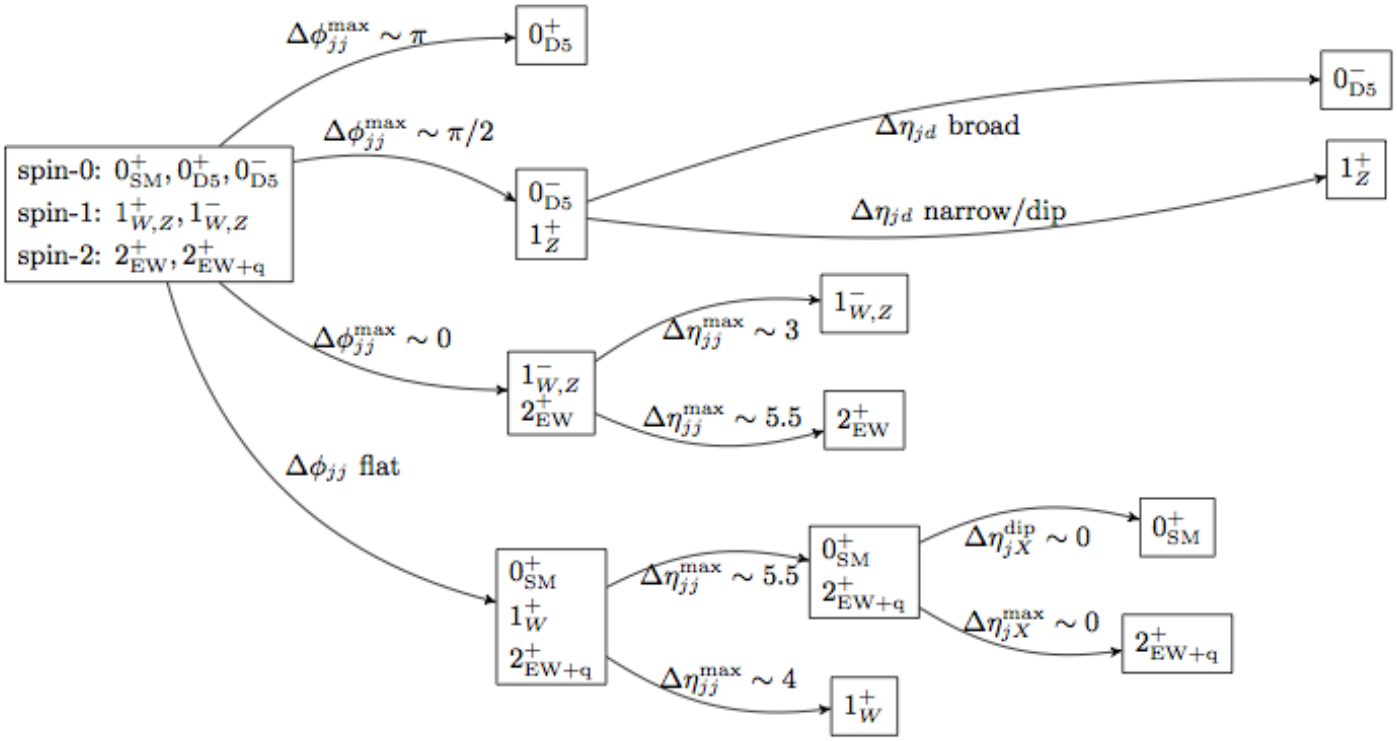
- diagrammatic analysis for WBF [$\Delta\eta_{jj}$ crucial]

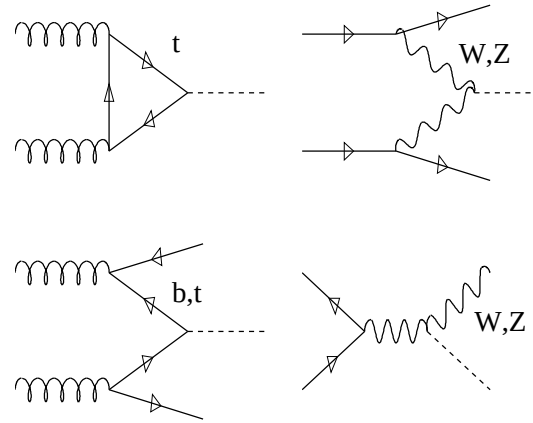


$\Rightarrow$ observables in most channels

Where we are going

The model

- assume: we see a scalar [ZZ and WBF correlations]
  it is a narrow resonance
  SM-like D4 structures
  benchmarks useless
- production & decay combinations
- signal strength vs couplings?



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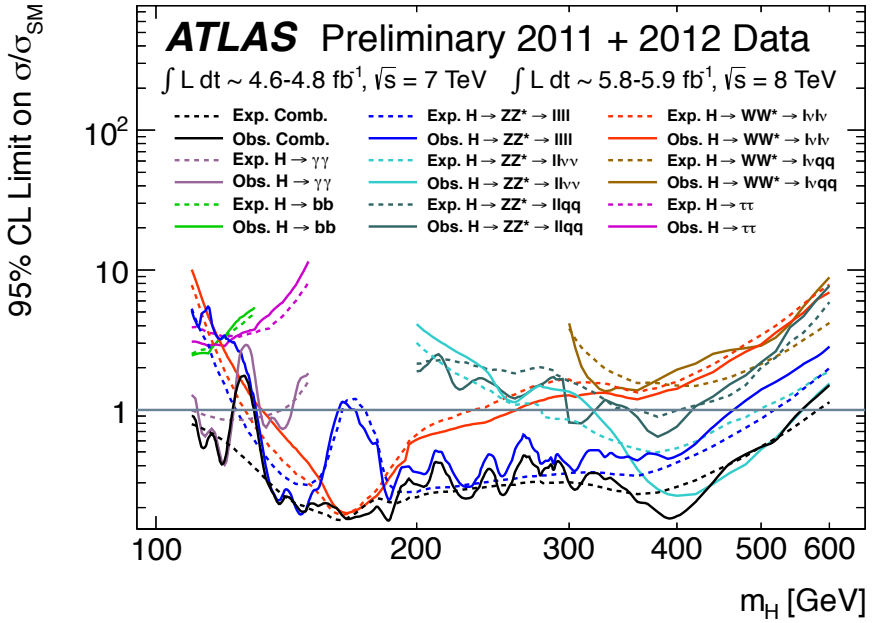

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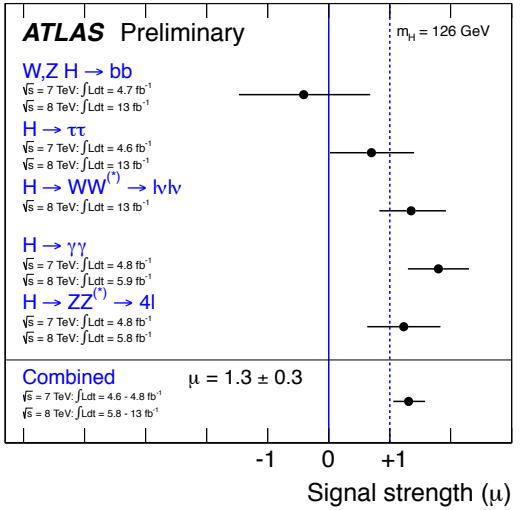

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Why 126 GeV is just perfect [Zeppenfeld et al; Dührssen et al; SFitter 2009/2012]

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

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

- 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

SFitter 1: Markov chains

Probability maps [statistics unexpectedly hard...]

- 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 partitions, numbered by j

$$p(d|m') > p(d|m)\, r^{10/j} \qquad r \epsilon [0,1] \quad \text{random number}$$

- check for parameter coverage with many Markov chains

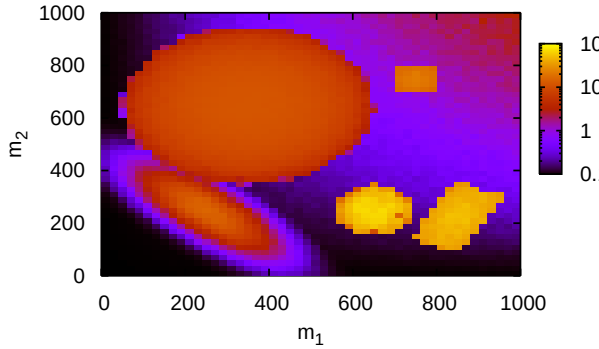
$\Rightarrow$ exclusive likelihood map first result

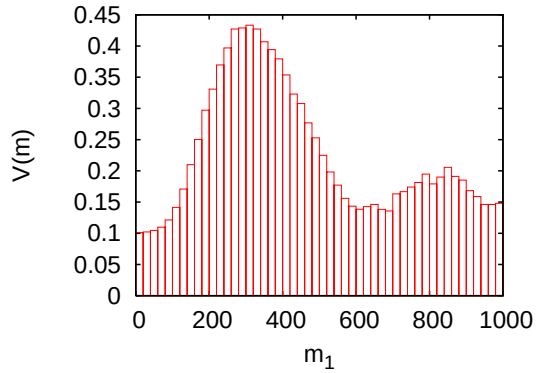
SFitter 2: Frequentist vs Bayesian

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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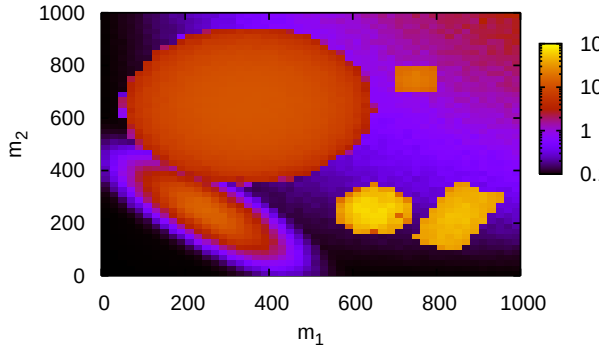
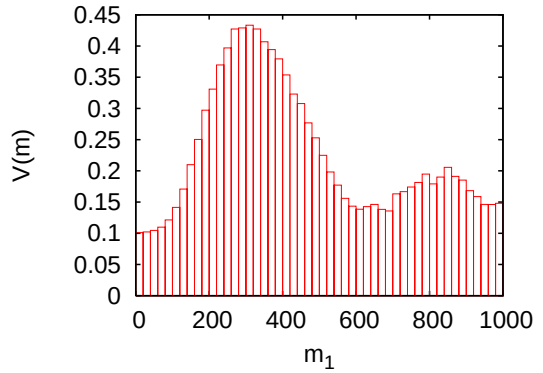
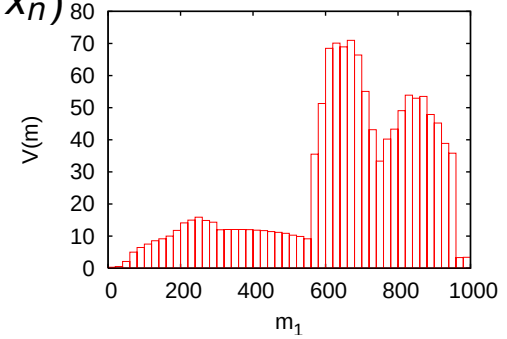




2– profile likelihood $\mathcal{L}(.., x_{j-1}, x_{j+1}....) \equiv \max_{x_j} \mathcal{L}(x_1, ..., x_n)$
no integration needed
no noise accumulation
not normalized, no comparison of structures
classical example: best-fit point



– one-dimensional distributions tricky

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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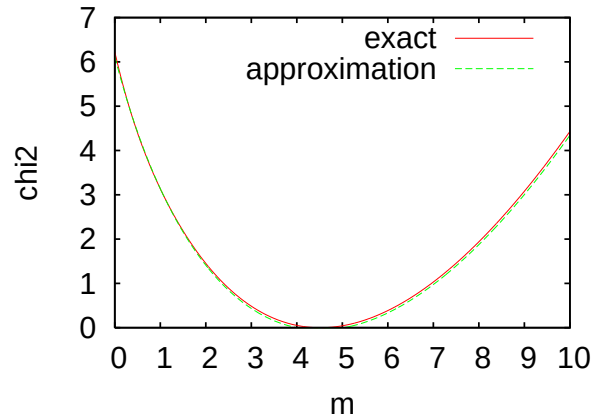
Efficient combination of errors [different from Michael's ATLAS analysis]

- 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

$\Rightarrow$ error bars from toy measurements



Higgs couplings

Higgs sector at LHC [Zeppenfeld et al; Dührssen et al; SFitter 2009/2012; Contino et al]

- light Higgs around 126 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-like analyses only]
  $t\bar{t}H : H \to \gamma\gamma, WW, b\bar{b}...$ [useful but later]
- parameters: couplings $W, Z, t, b, \tau, g, \gamma$ [plus eventually Higgs mass]

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Total width

- myths about scaling

$$N = \sigma\, BR \propto \frac{g_p^2}{\sqrt{\Gamma_{\text{tot}}}}\,\frac{g_d^2}{\sqrt{\Gamma_{\text{tot}}}} \sim \frac{g^4}{g^2\,\dfrac{\sum \Gamma_i(g^2)}{g^2} + \Gamma_{\text{unobs}}} \overset{g^2\to 0}{\longrightarrow} = 0$$

  gives constraint from $\sum \Gamma_i(g^2) < \Gamma_{\text{tot}} \to \Gamma_H|_{\text{min}}$
- $WW \to WW$ unitarity: $g_{WWH} \lesssim g^{\text{SM}}_{WWH} \to \Gamma_H|_{\text{max}}$
- SFitter assumption $\Gamma_{\text{tot}} = \sum_{\text{obs}} \Gamma_j$ [plus generation universality]

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

- couplings measurement $g_{HXX} = g^{\text{SM}}_{HXX} \, (1 + \Delta_X)$
  D5 couplings $g_{ggH}, g_{\gamma\gamma H}$ free?
  electroweak correction currently negligible
- experimental/theory errors on signal and backgrounds
  ATLAS and CMS both included
- exclusive likelihood map
  each coupling from profile likelihoods
  best-fit point with Minuit
  complete error analysis

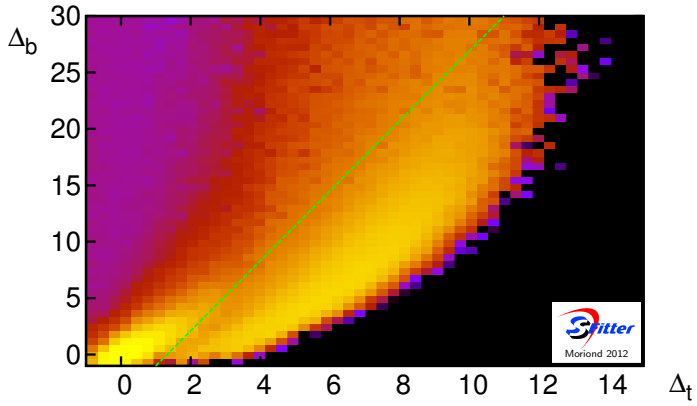
Global/local 7 TeV analysis

Global view on 7 TeV data [Klute, Lafaye, TP, Rauch, Zerwas]

– is there a SM-like solution?
are there alternative solutions?

(1) expected 2011: SM central values, measured error bars

– large-coupling solution separable



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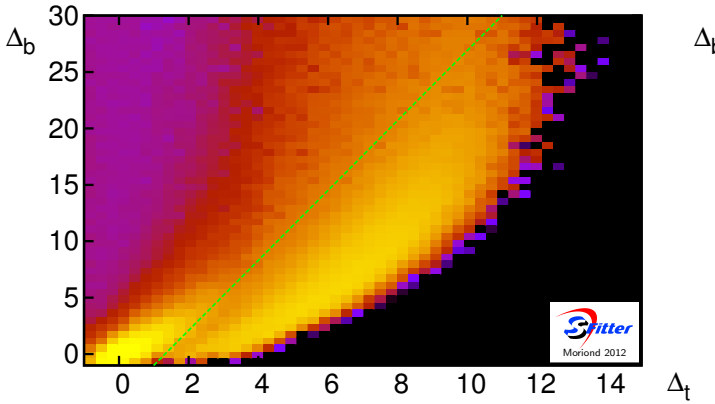
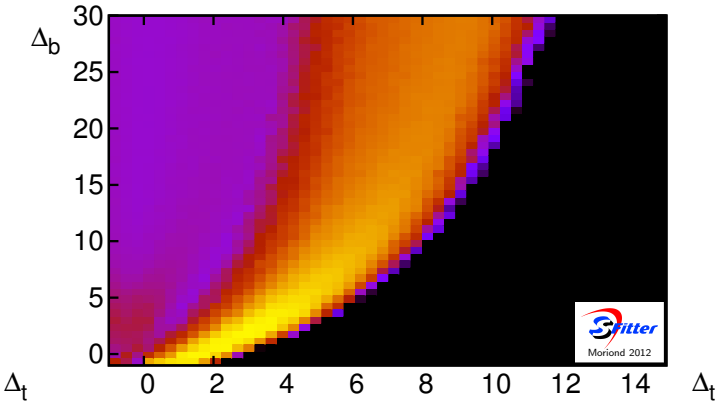
error bars inflated





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Local view on 7 TeV data

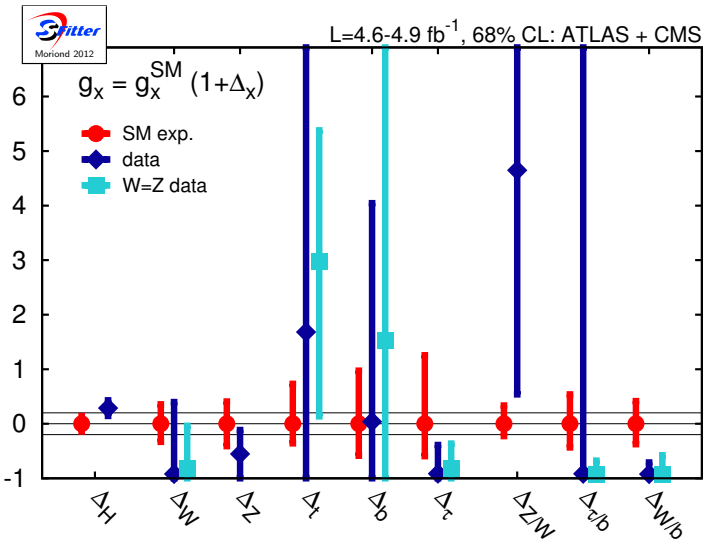
– focus on SM solution where possible

– five couplings from data

$g_W \sim 0$ while g_Z okay
g_b and g_t hurt by secondary solution
g_τ inconclusive in data

– poor man's analysis great: $\Delta_j \equiv \Delta_H$

$\Rightarrow$ pointing towards Standard Model?



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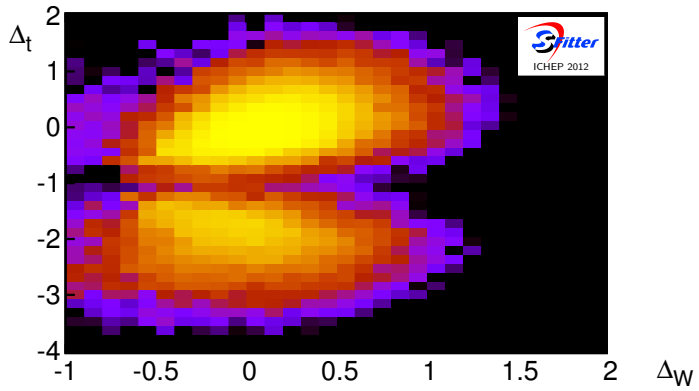
– g_W now improved

(1) expected 2012: SM central values, measured error bars

– two symmetric solutions



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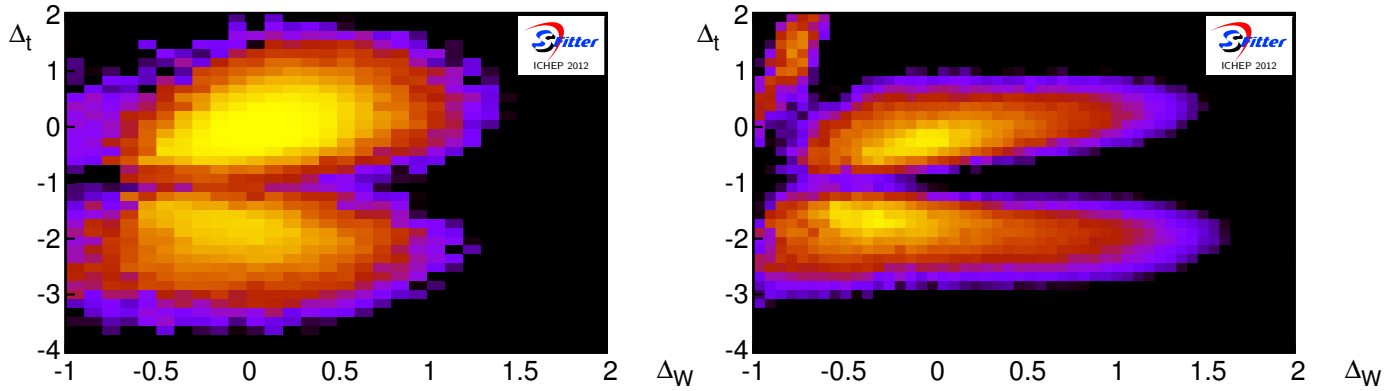

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Local view on 8 TeV data [no change from HCP]

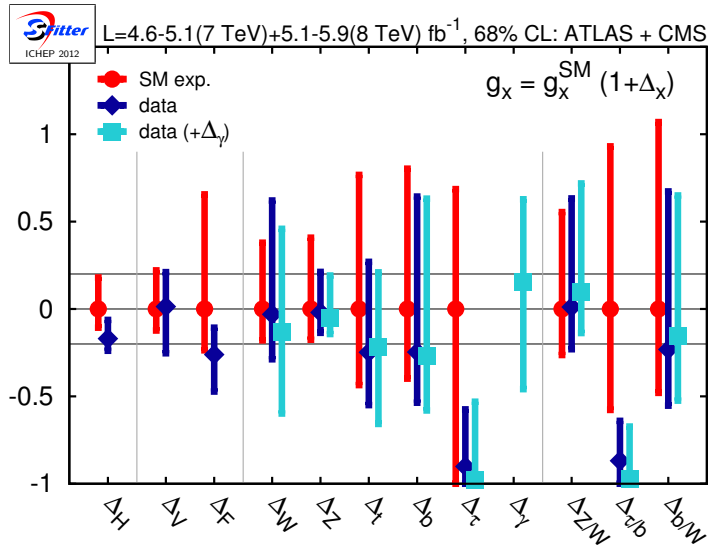
– focus on SM solution

– six couplings from data

$g_{W,Z}$ okay
$g_{t,b}$ indirectly
g_τ poor
g_γ possible

– poor man's analyses great: $\Delta_H, \Delta_V, \Delta_f$

$\Rightarrow$ moving towards Standard Model?



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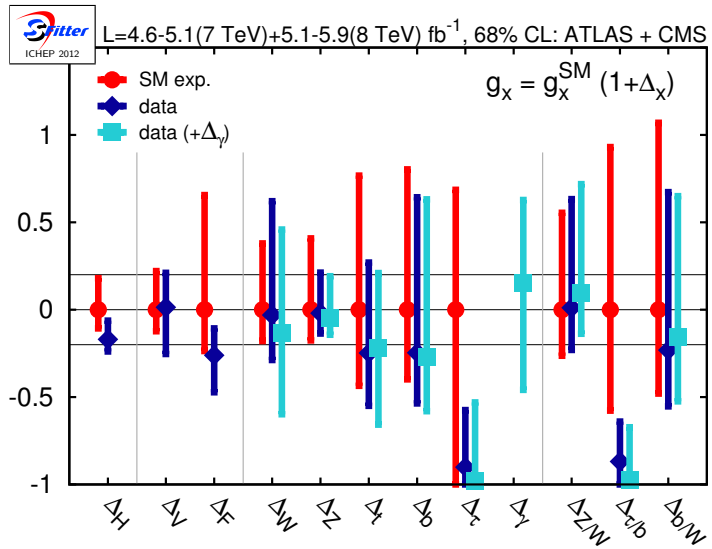
Testing the Higgs

– six couplings determined [g_{ggH} still missing]

– error bars $20 - 50\%$

– central value $\Delta_\gamma = 0.16$

– all good fits



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hypothesis	χ^2_{2012}/dof	solutions
Standard Model	43.3/54	
form factor Δ_H	32.2/53	1
two-parameter $\Delta_{V,f}$	29.0/52	2
independent Δ_x	27.7/49	3
including Δ_γ	27.3/48	2

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$\Rightarrow$ what's next?

Beyond renormalizable couplings

Anomalous Higgs couplings [Corbett, Eboli, Gonzales-Fraile, Gonzales-Garcia]

- anomalous couplings from D6 operators f_j [index '2' for $W_{\mu\nu} W^{\mu\nu}$]

$$g_{Hgg} = -\frac{\alpha_s}{8\pi}\frac{f_g v}{\Lambda^2} \qquad g_{H\gamma\gamma} = -\frac{gM_W}{\Lambda^2}\frac{s^2(f_{BB}+f_{WW}-f_{BW})}{2}$$

$$g^{(1)}_{HZ\gamma} = \frac{gM_W}{\Lambda^2}\frac{s(f_W-f_B)}{2c} \qquad g^{(2)}_{HZ\gamma} = \frac{gM_W}{\Lambda^2}\frac{s[2s^2 f_{BB}-2c^2 f_{WW}+(c^2-s^2)f_{BW}]}{2c}$$

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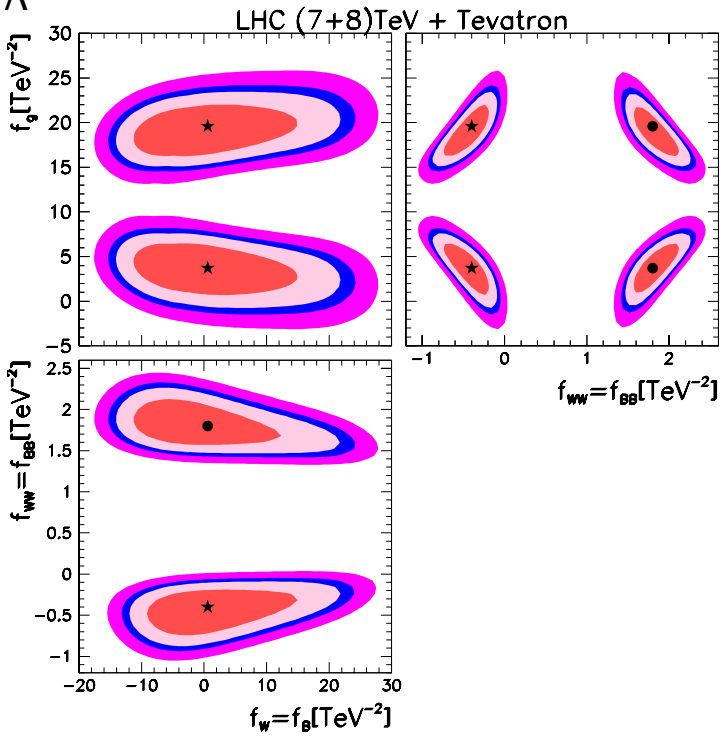
- asume $f_W = f_B$ [otherwise no convergence]
  fit f_{gg}, f_{WW}, f_{BB}
  observe usual sign-flip degeneracy
  compare to $\Delta\kappa$ and Λ in g_{WWV}



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A word on benchmarks

– known to 'say more about authors than about physics'

– bottom-up approach crucial

– theory benchmarks really only interesting for authors [I like the Higgs portal]

Top Yukawa

Direct measurement $t\bar{t}H, H \to b\bar{b}$ [Atlas-Bonn: Jochen Cammin]

- crucial to understand Higgs sector [details later]
- 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]

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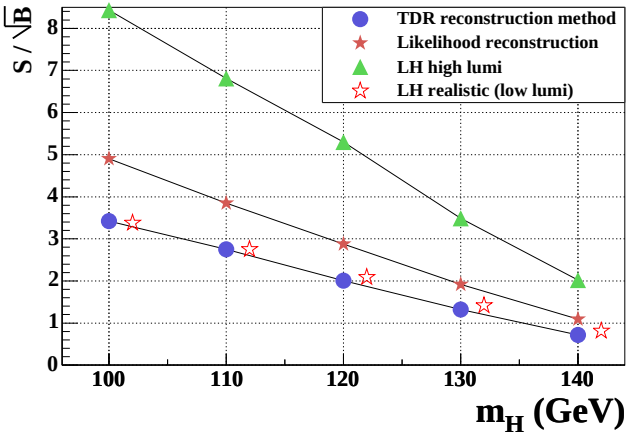
  1– combinatorics: m_H in $pp \to 4b_{tag}\ 2j\ \ell\nu$
  2– kinematics: peak-on-peak
  3– systematics: $S/B \sim 1/9$



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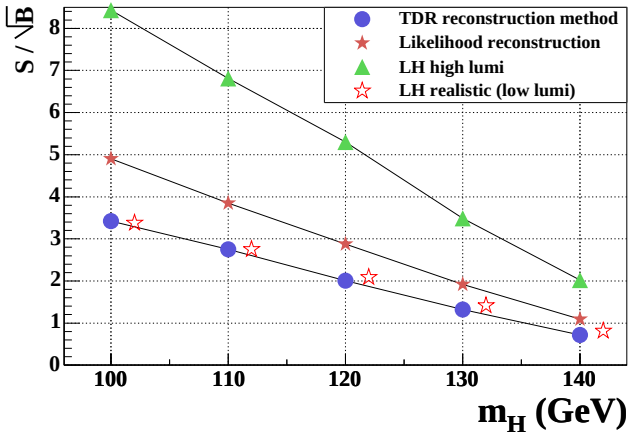

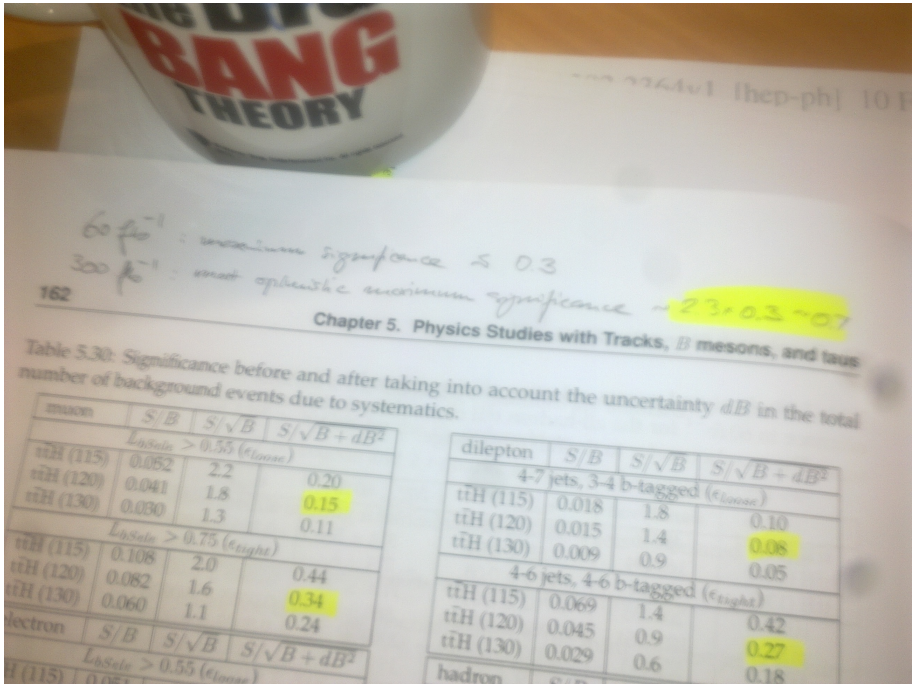

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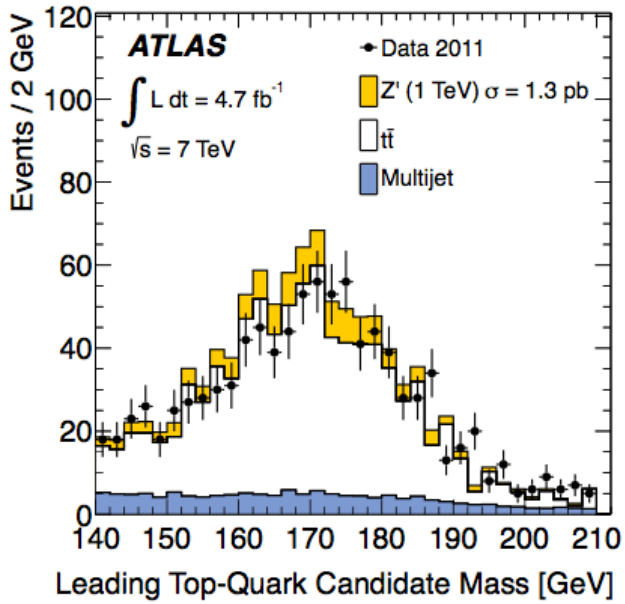
Fat jets analysis [TP, Salam, Spannowsky, Takeuchi]

- require tagged top and Higgs
  trigger on lepton
  only continuum $t\bar{t}b\bar{b}$ left [with sidebands]
- top tagger working [Atlas-Heidelberg]



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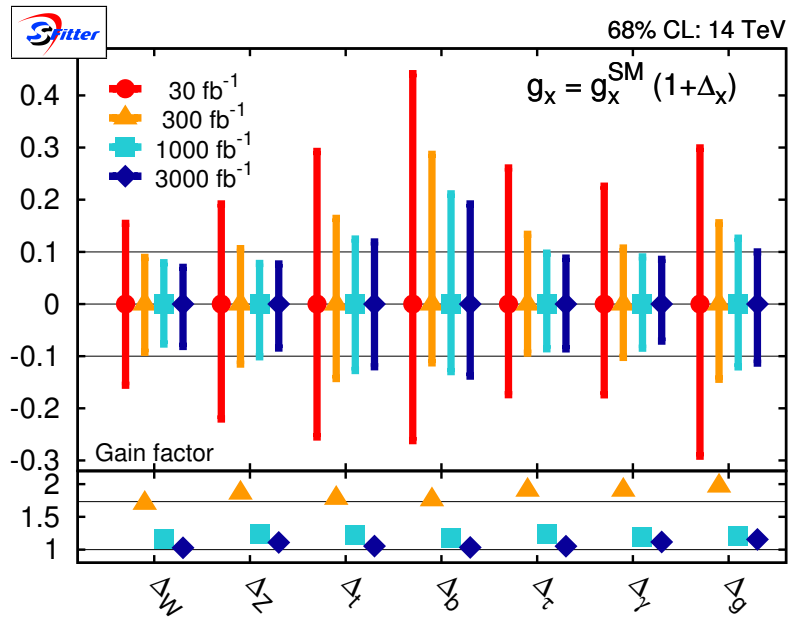


Weak scale models

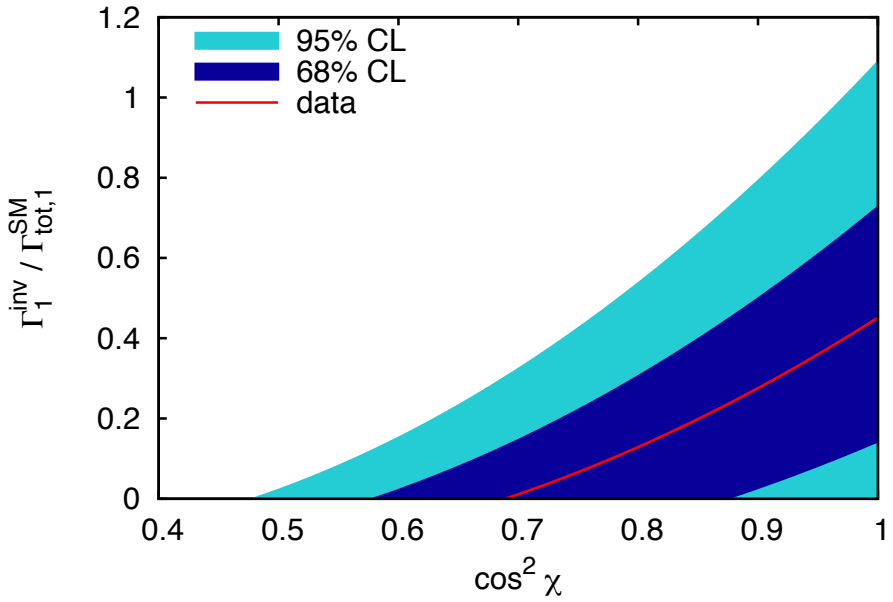
Higgs portal

- only few renormalizable links to a new phyics world
  general standard-hidden ansatz $H_1 = \cos\chi\, H_s + \sin\chi\, H_h$
- 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

$$\frac{\sigma[H_1 \to XX^*]}{\sigma[H_1 \to XX^*]^{\text{SM}}} = \frac{\cos^2\chi}{1 + \tan^2\chi\, \dfrac{\Gamma_1^{\text{hid}}}{\Gamma_{\text{tot},1}^{\text{SM}}}}$$



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Form factor Higgs [Kaplan & Georgi; Contino, Espinosa, Giudice, Grojean, Mühlleitner, Pomarol, Rattazzi]

- simple trick: $\xi \equiv v/f \gtrsim 0.3$ while $m_\rho = g_\rho f \gg f$ [also not calculable]

1– all couplings scaled $g \to g\sqrt{1-\xi}$

- one-parameter fit in SFitter
- from 8 TeV data $\Delta_H = 0 \pm 0.15$

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

Weak scale theory

Non-decoupling D6 operators

- SM: chiral fermions $g_{Hgg} \sim \alpha_s/(12\pi v)$
- new particle with charge Q and SU(3) Casimir $C(R)$ [Reece]

$$R_\gamma = \frac{g_{H\gamma\gamma}}{g^{\text{SM}}_{H\gamma\gamma}} = \left[1 + 0.28\xi \left(1 \mp \sqrt{R_g}\right)\right]^2, \qquad \xi = \frac{3Q^2}{C_2(R)}$$

$\Rightarrow$ end of a fourth chiral generation [Lenz etal]

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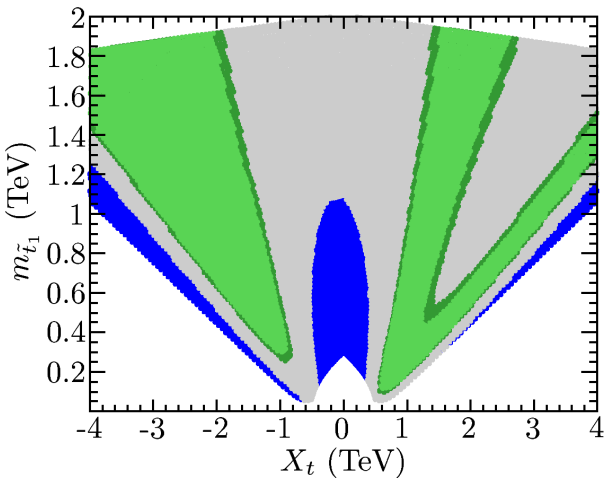
Supersymmetry

- MSSM Higgs mass the best-predicted LHC observable [Hahn etal + Stal]
- production rates mix of form factor and D6 [e.g. Hollik, TP, Rauch, Rzehak]
- stop mass/mixing crucial [$m_A = 1$ TeV, $\tan\beta = 20$]



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- SUSY particles in eff couplings [everyone]
  stop mixing destructive [Reece]

$$\frac{g_{Hgg}}{g^{\text{SM}}_{Hgg}} = 1 + \frac{1}{4}\left(\frac{m_t^2}{m^2_{\tilde{t}_1}} + \frac{m_t^2}{m^2_{\tilde{t}_2}} - \frac{m_t^2 X_t^2}{m^2_{\tilde{t}_1} m^2_{\tilde{t}_2}}\right)$$

- move towards NMSSM always an option...

$\Rightarrow$ no final verdict on the MSSM (ever?)

Weak scale theory

Non-decoupling D6 operators

- SM: chiral fermions $g_{Hgg} \sim \alpha_s/(12\pi v)$
- new particle with charge Q and SU(3) Casimir $C(R)$ [Reece]

$$R_\gamma = \frac{g_{H\gamma\gamma}}{g^{\text{SM}}_{H\gamma\gamma}} = \left[1 + 0.28\xi\left(1 \mp \sqrt{R_g}\right)\right]^2, \qquad \xi = \frac{3Q^2}{C_2(R)}$$

$\Rightarrow$ end of a fourth chiral generation [Lenz etal]

General study [Gupta, Rzehak, Wells]

- modelling Higgs coupling deviations
- deviations allowed by other constraints

	ΔhVV	$\Delta h\bar{t}t$	$\Delta h\bar{b}b$
Mixed-in Singlet	6%	6%	6%
Composite Higgs	8%	tens of %	tens of %
Minimal Supersymmetry	$< 1\%$	3%	$10\%^{(\text{large } \tan\beta)}$, $100\%^{(\text{small } \tan\beta)}$

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$\Rightarrow$ end of a fourth chiral generation [Lenz etal]

General study [Gupta, Rzehak, Wells]

- modelling Higgs coupling deviations
- deviations allowed by other constraints
- correlation of Δ_τ and heavy Higgs states

$\Rightarrow$ no final verdict on (too) many models?

High scale theory

What if it is essentially the Standard Model

- many theories decouple in Higgs sector [custodial symmetry, suppressed D6]
- any handle on high-scale physics needed

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Renormalization group

- Higgs mass related to self coupling: $m_H = v\sqrt{2\lambda}$
  top mass related to Yukawa: $y_t = \sqrt{2} m_t / v$

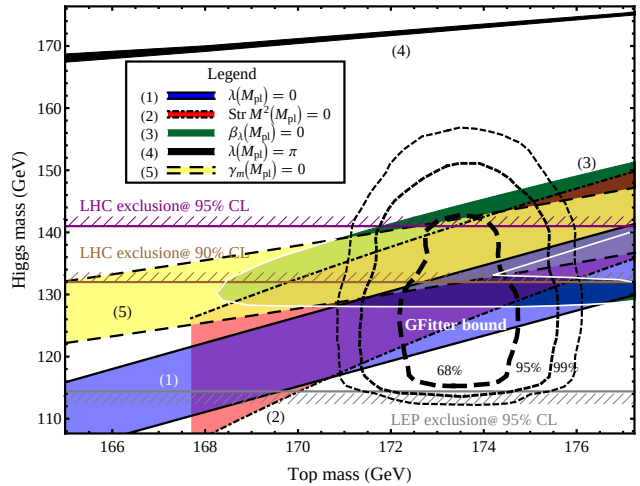
$$\frac{d\,\lambda}{d\,\log Q^2} = \frac{1}{16\pi^2}\left[12\lambda^2 + 6\lambda y_t^2 - 3y_t^4 - \frac{3}{2}\lambda\left(3g_2^2 + g_1^2\right) + \frac{3}{16}\left(2g_2^4 + (g_2^2 + g_1^2)^2\right)\right]$$

- IR fixed point for λ/y_t^2 fixing $m_H^2/m_t^2 = 1/2$ [with gravity: Shaposhnikov, Wetterich]

$$m_H = 126.3 + \frac{m_t - 171.2}{2.1} \times 4.1 - \frac{\alpha_s - 0.1176}{0.002} \times 1.5$$

- Planck-scale conditions [Holthausen, Lim, Lindner]

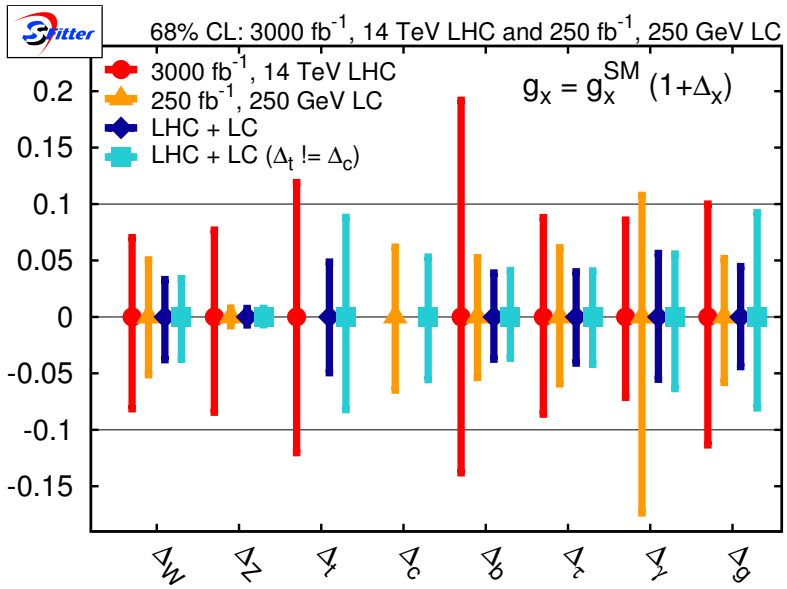
$\Rightarrow$ Higgs and top crucial in combination



Outlook

LHC Higgs program

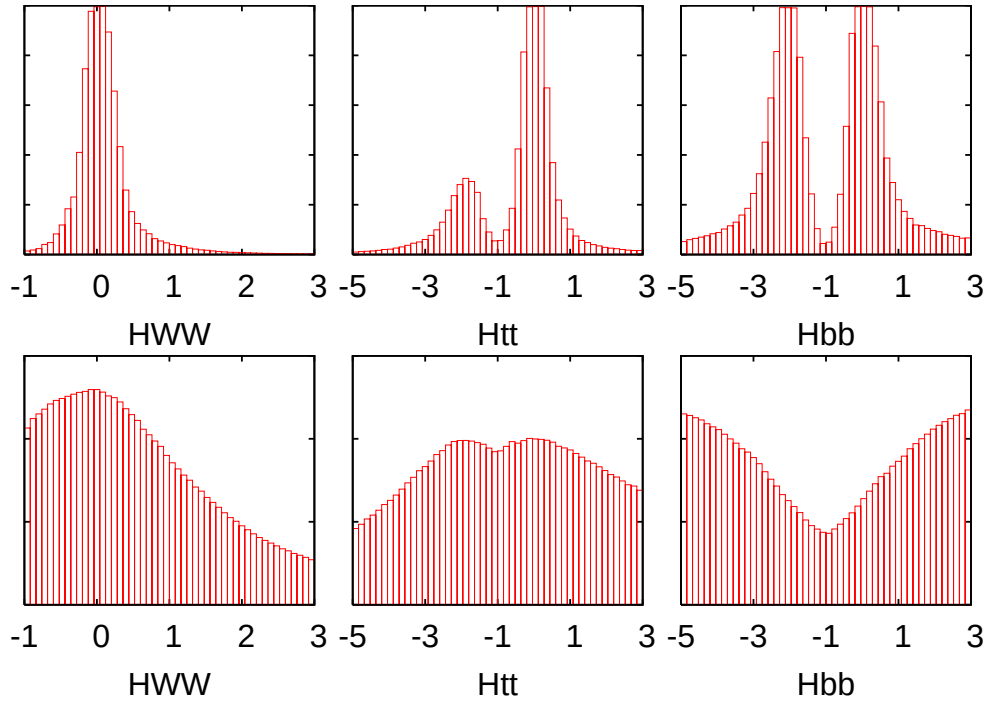
- determine coupling structure
- measure pre-factors (i.e. coupling strengths) [ask me in private why by theorists]
- come up with good ideas for top Yukawa
- search for anomalous Higgs decays
- apply to everyone's favorite models [stop calling them benchmarks]



Basic checks

Marginalization procedures

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



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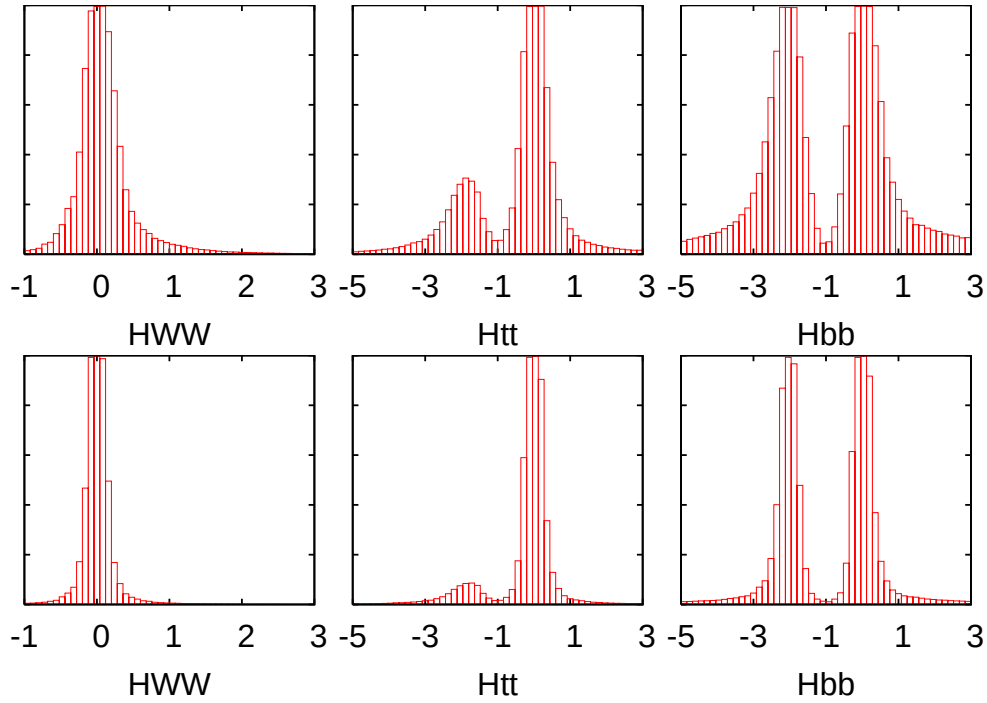
2– higher luminosity quantitatively different [no effective couplings, 30 vs 300 fb^{-1}]



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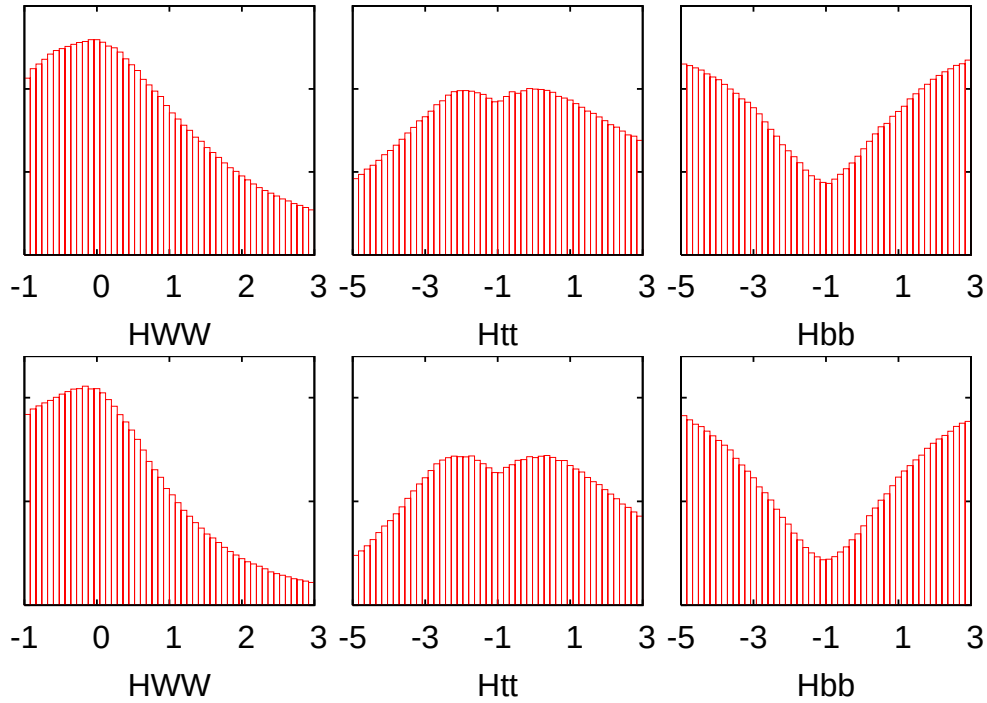

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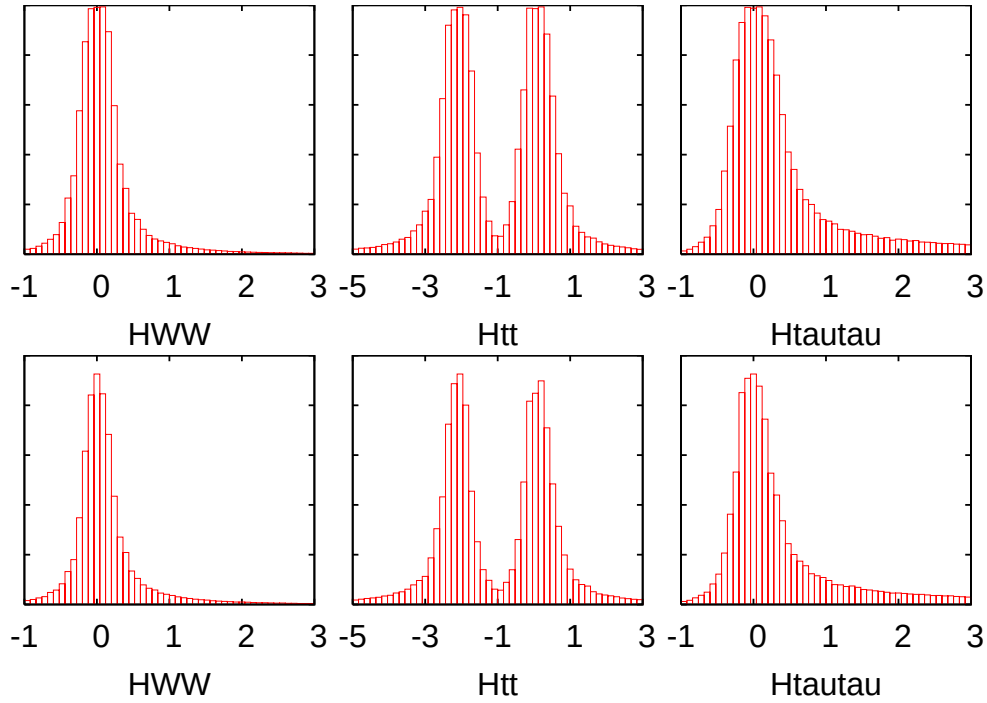
2– higher luminosity quantitatively different [no effective couplings, 30 vs 300 fb^{-1}]

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 [like ATLAS]