Higgs Properties at the LHC and beyond

Michael Rauch | Bonn, Jun 2013

INSTITUTE FOR THEORETICAL PHYSICS

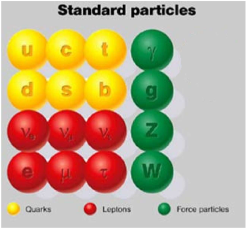
The Higgs Boson

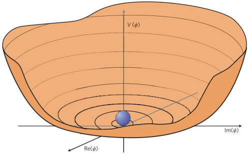
[Andersen; Englert, Brout; Higgs; Hagen, Guralnik, Kibble]

Standard Model of Elementary Particle Physics

Gauge theory $(SU(3)_c \otimes SU(2)_L \otimes U(1)_Y)$

Direct mass terms for elementary particles forbidden by gauge invariance





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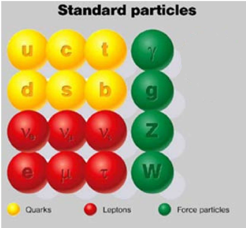
forbidden by gauge invariance

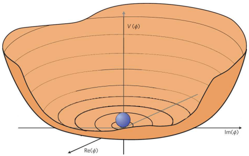
$\rightarrow$ Use trick: Spontaneous Symmetry Breaking

Introduce scalar $SU(2)$ doublet Φ (Higgs field)

- $\mathcal{L}$ invariant under gauge transformations
- but ground state not $\rightarrow$ vacuum expectation value v

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + H + iG^0) \end{pmatrix}$$





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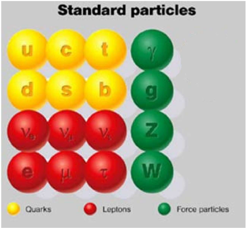

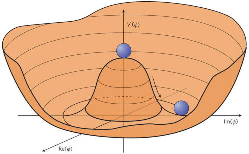

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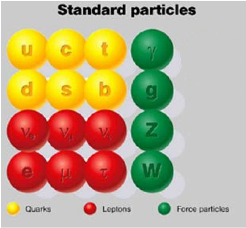
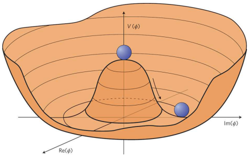
$G^\pm$, G^0 $\rightarrow$ longitudinal modes of $W^\pm$, Z
H real scalar field $\rightarrow$ Higgs boson





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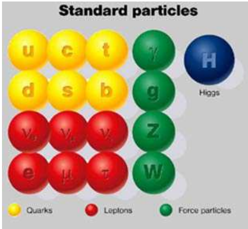
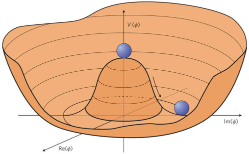
masses of fermions via Yukawa couplings
$\mathcal{L}_{\text{Yukawa}} = -\lambda_f \bar{\psi}_L \Phi \psi_R + \text{h.c.}$

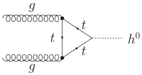




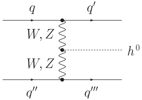
Higgs production modes

Main Higgs-boson production modes:

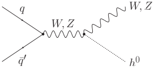
- gluon-gluon fusion



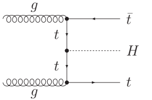
- vector-boson fusion

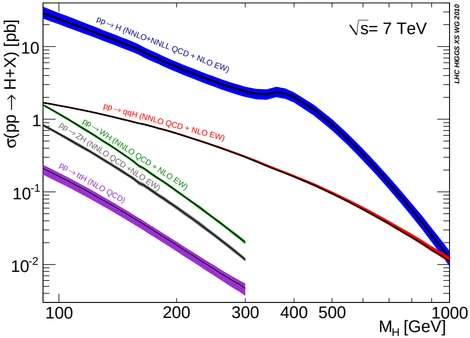


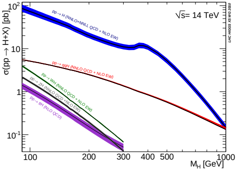
- associated production with gauge bosons



- associated production with top-quark–antiquark pair



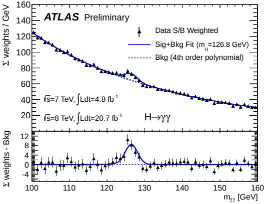


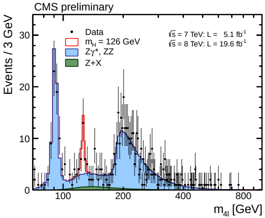


Higgs decay modes

- $H \to \gamma\gamma$
  - loop-induced coupling by (mainly) W and t
  - small branching ratio ($\lesssim 0.2\%$)
  - clear peak, background can be subtracted via sidebands
  - Higgs mass measurement up to 100 MeV
- $H \to ZZ$
  - "Golden Channel" due to four-lepton final state
- $H \to WW$
- $H \to \tau\bar{\tau}$
  - need to reconstruct invariant mass of the two taus $\to$ most sensitivity from vector-boson fusion
- $H \to b\bar{b}$
  - main decay mode for light Higgs bosons
  - hard to extract from QCD backgrounds
  - WH/ZH production with boosted kinematics plus possibly jet substructure analysis looks promising

[Butterworth, Davison, Rubin, Salam]





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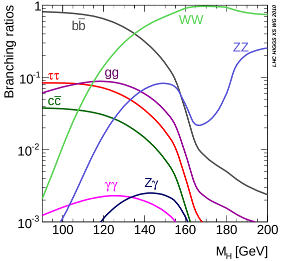
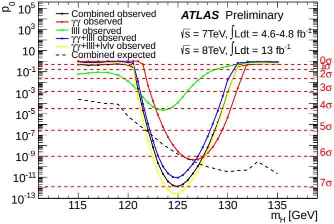


$\to$ 126 GeV ideal value for testing different modes

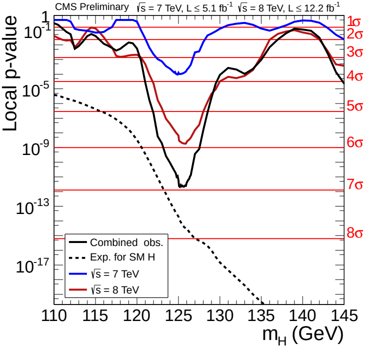
Higgs discovery

Clear resonance observed in both LHC experiments

ATLAS: 7.0 σ (Dec 2012)

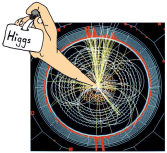


CMS: 6.9 σ (Nov 2012)



“Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC”

Higgs properties



Verify nature of observed resonance
$\leftrightarrow$ "Higgs" properties

- spin-0 particle
  spin-1 excluded by $H \to \gamma\gamma$ [Landau-Yang theorem]
  spin-2: look at angular correlations
- CP-nature
  SM-Higgs CP-even; extended Higgs sectors also CP-odd or mixed states
  look at angular correlations

[Zeppenfeld *et al.* ; Choi *et al.* ; Godbole *et al.* ; Hagiwara, Mawatari, Li; Englert *et al.* ; Ellis *et al.* ; Frank, MR, Zeppenfeld; Alves; Boughezal *et al.* ; . . .]

Spin-2 Particle

Effective model for interaction of spin-2 particle with bosons [Frank, MR, Zeppenfeld]

- Start from effective Lagrangian approach $\mathcal{L}_{\text{eff}} = \sum_i \frac{f_i}{\Lambda} T_{\mu\nu} O_i^{\mu\nu}$
- construct all possible operators of dimension 5

SU(2) singlet $T_{\mu\nu}$

$$\mathcal{L}_{\text{singlet}} = \frac{1}{\Lambda} T_{\mu\nu} \left(f_1 B^{\alpha\nu} B^{\mu}{}_{\alpha} + f_2 W_i^{\alpha\nu} W^{i,\mu}{}_{\alpha} + 2 f_5 (D^\mu \Phi)^\dagger (D^\nu \Phi) + f_9 G_a^{\alpha\nu} G^{a,\mu}{}_{\alpha} \right)$$

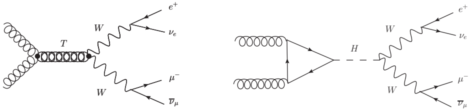
SU(2) triplet $T_{\mu\nu,j}$ (3 particles T^0, $T^\pm$ with same mass)

$$\mathcal{L}_{\text{triplet}} = \frac{1}{\Lambda} T_{\mu\nu,j} \left(f_6 (D^\mu \Phi)^\dagger \sigma^j (D^\nu \Phi) + f_7 W^{j,\mu}{}_{\alpha} B^{\alpha\nu} \right)$$

- Spin-2 field $T_{\mu\nu}$ symmetric, transverse, $T^\mu_\mu = 0$.
- Terms with dual field strength tensors do not contribute for on-shell T
- $\Rightarrow$ Occurring vertices: TW^+W^-, TZZ, $T\gamma Z$, $T\gamma\gamma$, Tgg
- implemented in program package VBFNLO [Zeppenfeld, MR, ...]
- Results in the following for singlet case

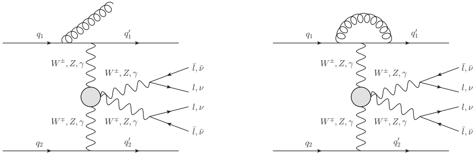
Considered processes

- Gluon-fusion



Calculation at LO, higher-orders up to known NNLL included as constant K factors
Assume same factor for Higgs and spin-2 ($\leftrightarrow$ different operator structure)

- Vector-boson fusion



Calculation at NLO QCD
can be adapted from SM case, spin-2 only affects electro-weak part

- final states: $W^+W^- \to 2\ell 2\nu$, $ZZ \to 4\ell$, $\gamma\gamma$
- Spin-2 resonance narrow $\to$ interference small
  $\to$ non-resonant graphs and SM background omitted

Feynman Rules

$$TW^+W^- : \frac{2if_2}{\Lambda} K_1^{\alpha\beta\mu\nu} + \frac{if_5 g^2 v^2}{2\Lambda} K_2^{\alpha\beta\mu\nu}$$

$$TZZ : \frac{2i}{\Lambda}(f_2 c_w^2 + f_1 s_w^2) K_1^{\alpha\beta\mu\nu} + \frac{if_5 v^2}{2\Lambda}(g^2 + g'^2) K_2^{\alpha\beta\mu\nu}$$

$$T\gamma\gamma : \frac{2i}{\Lambda}(f_1 c_w^2 + f_2 s_w^2) K_1^{\alpha\beta\mu\nu}$$

$$T\gamma Z : \frac{2i}{\Lambda} c_w s_w (f_2 - f_1) K_1^{\alpha\beta\mu\nu}$$

$$Tgg : \frac{2if_9}{\Lambda} K_1^{\alpha\beta\mu\nu}$$

$$\text{with } K_1^{\alpha\beta\mu\nu} = p_1^\nu\, p_2^\mu\, g^{\alpha\beta} - p_1^\beta\, p_2^\nu\, g^{\alpha\mu} - p_2^\alpha\, p_1^\nu\, g^{\beta\mu} + p_1 \cdot p_2\, g^{\alpha\nu} g^{\beta\mu}$$

$$K_2^{\alpha\beta\mu\nu} = g^{\alpha\nu} g^{\beta\mu}$$

f_i, Λ free coupling parameters

$g_{HWW}, g_{HZZ} \gg g_{H\gamma\gamma}, g_{H\gamma Z}$ $\leftrightarrow$ measured rates approx. SM-like

$\Rightarrow f_5 \gg f_1, f_2, f_9$

Cross sections

⇒ Can adjust couplings such that SM-Higgs-like cross sections can be obtained

Final State	Production mode	Higgs cross sec. [fb]	Spin-2 cross sec. [fb]
$\gamma\gamma$	VBF	0.7448	0.8780
	Gluon Fusion	14.273	13.942
$W^+W^- \to e^+ \nu_e \mu^- \overline{\nu}_\mu$	VBF	0.3887	0.4108
	Gluon Fusion	11.918	11.575
$ZZ \to e^+ e^- \mu^+ \mu^-$	VBF	$1.639 \cdot 10^{-3}$	$2.453 \cdot 10^{-3}$
	Gluon Fusion	0.2565	0.2194

using $f_1 = 0.04$, $f_2 = 0.08$, $f_5 = 10$, $f_9 = 0.04$, $\Lambda = 6.4$ TeV
not possible in Graviton-like models [Ellis et al.]

Formfactor multiplying amplitude:

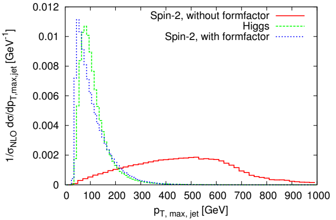
$$f_{\text{Spin-2}} = \left(\frac{\Lambda_{ff}^2}{|p_1^2| + \Lambda_{ff}^2} \cdot \frac{\Lambda_{ff}^2}{|p_2^2| + \Lambda_{ff}^2} \cdot \frac{\Lambda_{ff}^2}{|k_{\text{sp2}}^2| + \Lambda_{ff}^2} \right)^{n_{ff}}$$

p_1, p_2: momenta of vector bosons

solves unitarity violation at high energies

can be used to make p_T distributions SM-like (e.g. of VBF-tagging jets)
(here: $\Lambda_{ff} = 400$ GeV, $n_{ff} = 3$)

⇒ p_T-distributions not sufficient for distinction



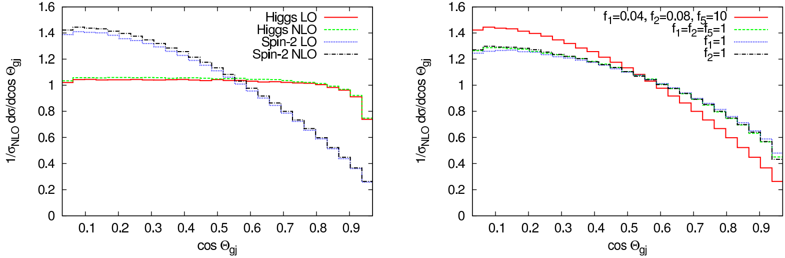
Observables for Distinction

Observables left for distinction:

- angular distributions
- invariant-mass distributions

Gottfried-Jackson angle:
angle between momentum of resonance in lab frame and final-state photon in rest frame of resonance
(for gluon-fusion equal to $\cos\theta^*$ in Collins-Soper frame)

Example: Diphoton production in VBF

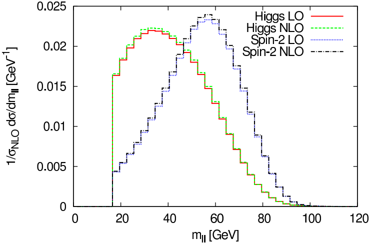


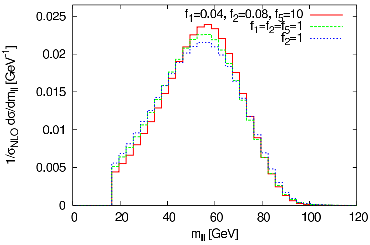
$\Rightarrow$ Good distinction power independent of parameter choice

Higgs properties

Invariant $\ell\ell$ mass in WW decay mode

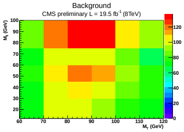
Spin-0 nature of Higgs forces leptons parallel



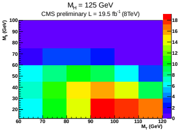


CMS WW 0-jet analysis, $m_{\ell\ell}$-m_T-plane

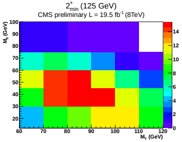
background



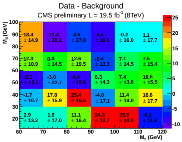
Higgs signal



Spin-2 signal



data



$\Rightarrow$ CP-odd and spin-2 currently disfavoured at $2-3\sigma$ level

Higgs properties – couplings

Couplings:

SM prediction fixed by already known quantities

- unitarity in $W_L W_L \to W_L W_L$ scattering
  $\longrightarrow$ fixed coupling $g_{WWH} \propto m_W$
- fermion masses
  $\longrightarrow g_{f\bar{f}H} \propto m_f$
- Higgs self-couplings
  determine shape of Higgs potential via trilinear and quartic couplings
  SM: $V = \mu^2|\Phi|^2 + \lambda|\Phi|^4 + \text{const.}$
  new scale Λ: $V = \sum_{n\geq 0} \frac{\lambda^n}{\Lambda^{2n}} \left(|\Phi|^2 + \frac{v^2}{2}\right)^{2+n}$
  $\longrightarrow$ very challenging for LHC (and ILC)

[Djouadi *et al.* ; Plehn *et al.* ; Baur *et al.* ; MR *et al.* ; Binoth *et al.* ; Englert *et al.* ; Baglio *et al.* ; ...]

$\leftrightarrow$ New-physics models modifying Higgs couplings

- Additional Higgs particles (Higgs portal, THDM, ...)
- Composite Higgs models
- Supersymmetry

$\to$ Expected deviations: $\mathcal{O}(10\%)$ [Gupta, Rzehak, Wells]

Generalized Higgs sector

How well can we determine the SM Higgs couplings?
Can we distinguish a non-Standard-Model-like Higgs sector?

- Theory: Standard Model plus free Higgs couplings
  Couplings from modified version of HDecay [Djouadi, Kalinowski, Mühlleitner, Spira]
- For Higgs couplings present in the Standard Model $x = W, Z, t, b, \tau$
  $g_{xxH} \equiv g_x \longrightarrow g_x^{\text{SM}} \; (1 + \Delta_x) \equiv g_x^{\text{SM}} \; \kappa_x$ ($\rightarrow \Delta = -2$ means sign flip)
- For loop-induced Higgs couplings $x = \gamma, g$
  $$g_x \longrightarrow g_x^{\text{SM}} \left(1 + \Delta_x^{\text{SM}} + \Delta_x\right) \equiv \kappa_x g_x^{\text{SM}}$$
  where g_x^{SM}: (loop-induced) coupling in the Standard Model
  Δ_x^{SM}: contribution from modified tree-level couplings to Standard-Model particles
  Δ_x : additional (dimension-five) contribution
- Ratios $\frac{g_x}{g_y} = \frac{g_x^{\text{SM}}}{g_y^{\text{SM}}}(1 + \Delta_{x/y}) \equiv \frac{g_x^{\text{SM}}}{g_y^{\text{SM}}}\lambda_{xy}$
- Neglecting couplings only available from high-luminosity analyses
  $(g_\mu, g_{HZ\gamma}^{\text{eff}}, g_{HHH}, g_{HHHH})$
- Δ_H: single parameter modifying all (tree-level) couplings
- Total width
  $$\Gamma_{\text{tot}} = \Sigma_{\text{obs}} \Gamma_x < 2 \text{ GeV} \quad \text{(plus generation universality)}$$
- Electro-weak corrections not yet relevant
  for later consistency: QCD corrections scale with couplings, EW ones not

SFitter

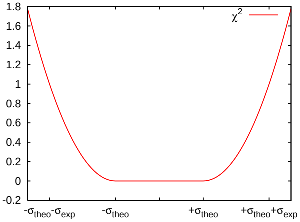
Algorithms:

- Weighted Markov chain
- Cooling Markov chain ($\sim$ simulated annealing)
- Modified gradient fit (Minuit)
- Grid scan
- Nested Sampling [Skilling; Feroz, Hobson]

[Lafaye, Plehn, MR,Zerwas]
[Eur.Phys.J.C54:617-644,2008, [arXiv:0709.3985 [hep-ph]]]
[JHEP08(2009)009 [arXiv:0904.3866 [hep-ph]]]

Errors:

- three types:
  - Gaussian – arbitrary correlations possible ($\rightarrow$ systematic errors)
  - Poisson
  - box-shaped (RFit) [CKMFitter]
- assignment as in exp. studies
- adaption to likelihood input easy



Output of SFitter:

- fully-dimensional log-likelihood map
- one- and two-dimensional distributions via
  - marginalization (Bayesian)
  - profile likelihood (Frequentist)
- list of best points

Higgs Couplings after Moriond 2013

7 TeV $\mathcal{L}$ = 4.6-5.1 fb^{-1}

ATLAS		CMS	
$\gamma\gamma$		$\gamma\gamma$	
ZZ (4ℓ)		$\gamma\gamma$	di-jet
WW	0-jet	ZZ (4ℓ)	
WW	1-jet	WW	0-jet
WW	2-jet	WW	1-jet
$\tau\tau$	0-jet	WW	2-jet
$\tau\tau$	1-jet	$\tau\tau$	0/1-jet
$\tau\tau$	VBF	$\tau\tau$	Boosted
$\tau\tau$	VH	$\tau\tau$	VBF
$b\bar{b}$	WH	$b\bar{b}$	WH
$b\bar{b}$	Z_ℓH	$b\bar{b}$	Z_ℓH
$b\bar{b}$	Z_νH	$b\bar{b}$	Z_νH
		$b\bar{b}$	$t\bar{t}$H

$\otimes$ 8 TeV $\mathcal{L}$ = 12-21 fb^{-1}

ATLAS		CMS	
$\gamma\gamma$	low-p_T	$\gamma\gamma$	Cat0
$\gamma\gamma$	high-p_T	$\gamma\gamma$	Cat1
$\gamma\gamma$	di-jet lml	$\gamma\gamma$	Cat2+3
$\gamma\gamma$	di-jet hml	$\gamma\gamma$	di-jet tight
$\gamma\gamma$	di-jet tight	$\gamma\gamma$	di-jet loose
$\gamma\gamma$	E_T(miss)	ZZ $\to 4\ell$	
$\gamma\gamma$	1ℓ	WW	0-jet
ZZ $\to 4\ell$		WW	1-jet
WW	0-jet	WW	2-jet
WW	1-jet	$\tau\tau$	0/1-jet
WW	2-jet	$\tau\tau$	Boosted
$\tau\tau$	0-jet	$\tau\tau$	VBF
$\tau\tau$	1-jet	$b\bar{b}$	Z_ℓH low-p_T
$\tau\tau$	Boosted	$b\bar{b}$	Z_ℓH high-p_T
$\tau\tau$	VBF	$b\bar{b}$	Z_νH low-p_T
$\tau\tau$	VH	$b\bar{b}$	Z_νH high-p_T
$b\bar{b}$	WH	$b\bar{b}$	WH low-p_T
$b\bar{b}$	Z_ℓH	$b\bar{b}$	WH high-p_T
$b\bar{b}$	Z_νH		

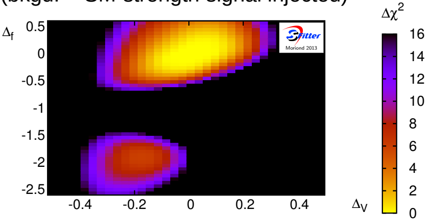
- background expectations, exp. errors, etc. from analyses
- cross-checked with exclusion and signal-strength plots

Global view

[Plehn, MR]

Δ_V vs. Δ_f

SM hypothesis
(bkgd. + SM-strength signal injected)



Expected 2012 results:

- Correct solution around SM value $\Delta = 0$
- Secondary solution for opposite fermion coupling $\rightarrow$ photon coupling enhanced
- $\sim 2.5\sigma$ discrimination power between both signs

Global view

[Plehn, MR]

Δ_V vs. Δ_f

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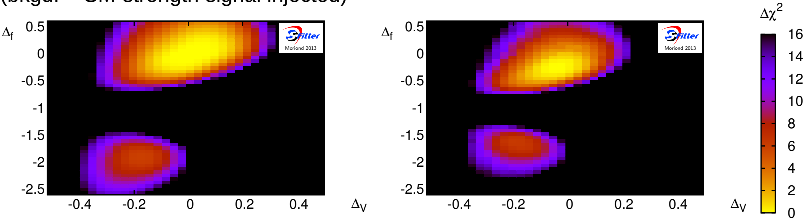
measured data



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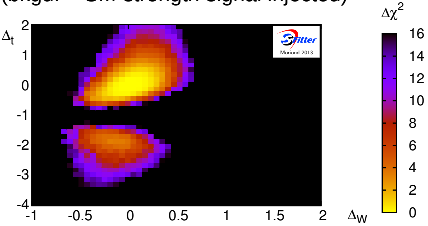
2012 results:

- similar to expectation
- opposite-sign solution clearly disfavoured

Global view

Δ_W vs. Δ_t

SM hypothesis
(bkgd. + SM-strength signal injected)



Expected 2012 results:

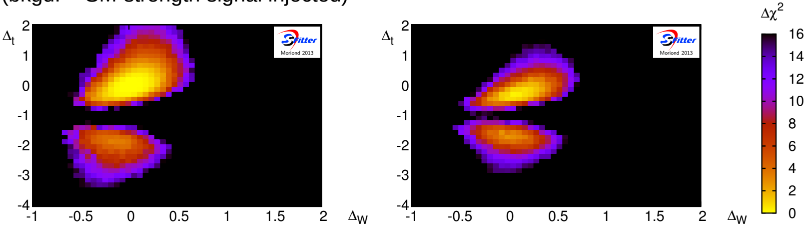
- Correct solution around SM value $\Delta = 0$
- Secondary solution for flipped top Yukawa coupling $\to$ photon coupling enhanced
- Large-Δ_t solution of 2011 killed by $t\bar{t}H$, $H \to b\bar{b}$ measurement

Global view

Δ_W vs. Δ_t

SM hypothesis
(bkgd. + SM-strength signal injected)

measured data



Expected 2012 results:

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  for flipped top Yukawa coupling
  $\rightarrow$ photon coupling enhanced
- Large-Δ_t solution of 2011 killed by $t\bar{t}H$, $H \rightarrow b\bar{b}$ measurement

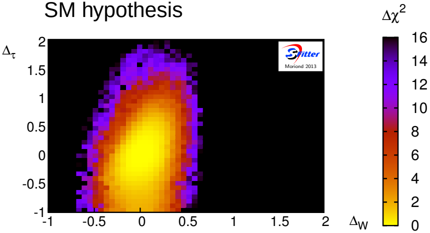
2012 results:

- similar to expectation
- flipped-top coupling disfavoured by $\sim 1\sigma$

Global view

Δ_W vs. Δ_τ

SM hypothesis



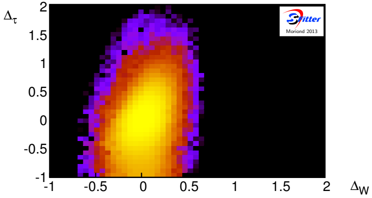
Expected 2012 results:

- Clear indication of non-vanishing $H\tau\tau$ coupling

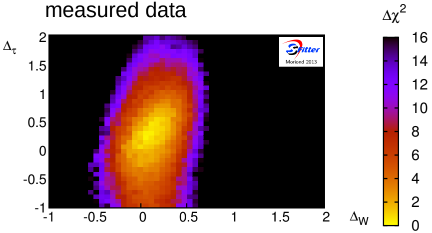
Global view

Δ_W vs. Δ_τ

SM hypothesis



measured data



Expected 2012 results:

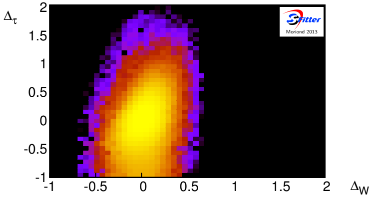
- Clear indication of non-vanishing $H\tau\tau$ coupling

- Finally seen
- First direct evidence for coupling to fermions!

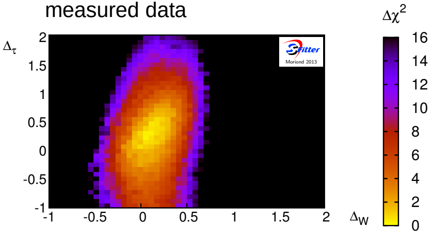
Global view

Δ_W vs. Δ_τ

SM hypothesis



measured data



Expected 2012 results:

- Clear indication of non-vanishing $H\tau\tau$ coupling

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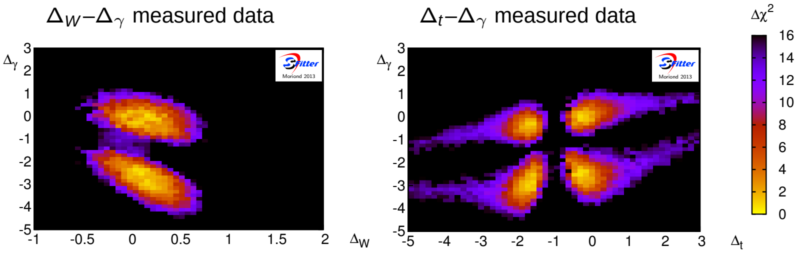
Best-fitting solutions:

Δ_W	Δ_Z	Δ_t	Δ_b	Δ_τ	χ^2/d.o.f.
-0.11	-0.04	-0.20	-0.27	-0.04	15.8/58
-0.26	-0.02	-1.70	-0.30	0.03	16.8/58

χ^2(SM) = 16.4

Global view

Independent contribution to photon coupling Δ_γ

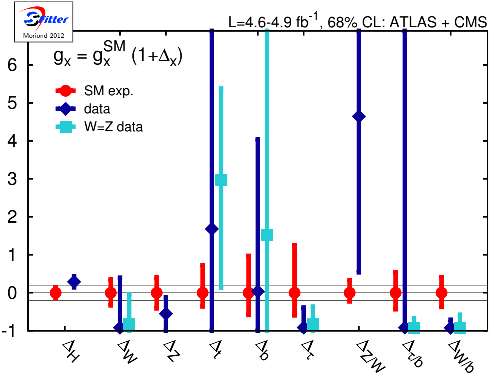


Standard Model-like solution plus secondary flipped-sign solutions

(Anti-)correlations between parameters as expected

No surprising new features

Local View on data



- One year ago ... (Moriond 2012)

- best-fit point from Markov-chain Monte Carlo
- Error bars: 5000 toy MC, 68% CL coverage
- horizontal lines: $\pm 20\%$

[see also Carmi *et al.* ; Asatov *et al.* ; Espinosa *et al.* ; Giardino *et al.* ; Ellis *et al.* ; Farina *et al.* ; Bechtle *et al.* ; . . .]

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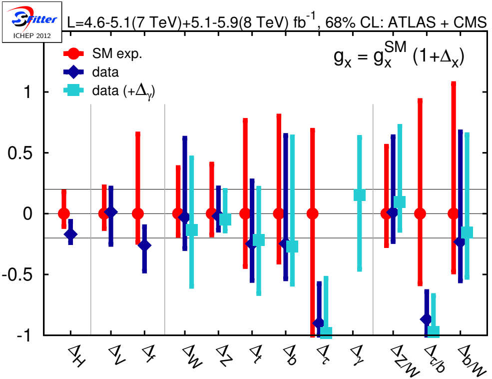

- Discovery ... (ICHEP 2012)

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[see also Carmi *et al.* ; Asatov *et al.* ; Espinosa *et al.* ; Giardino *et al.* ; Ellis *et al.* ; Farina *et al.* ; Bechtle *et al.* ; . . .]

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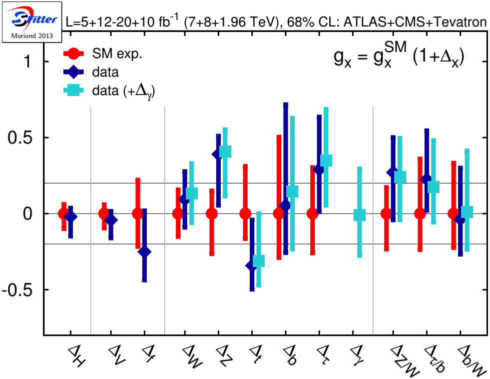

- Δ_H already very precise
- Δ_V-Δ_f also well determined

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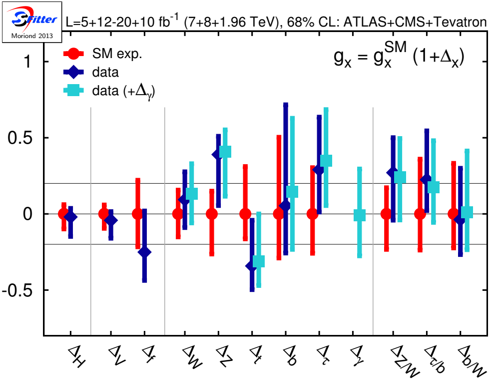

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- g_W, g_Z, g_b, g_t okay
- g_τ now SM-like as well
- ratios:
  no improvement over direct measurements but less assumptions

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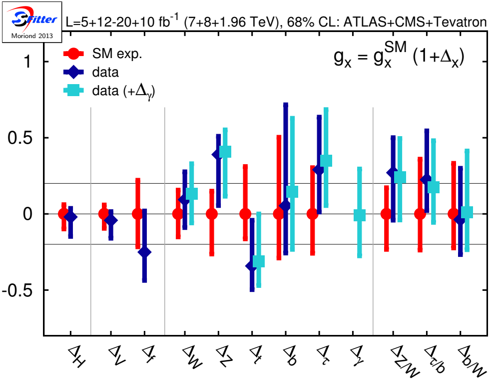

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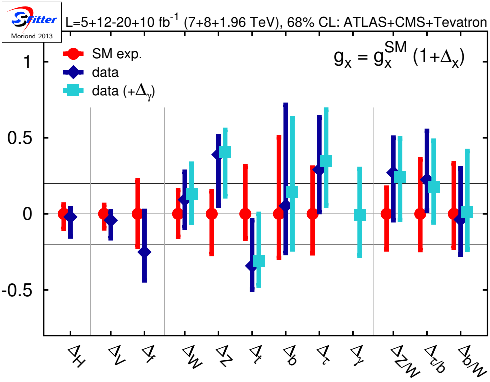

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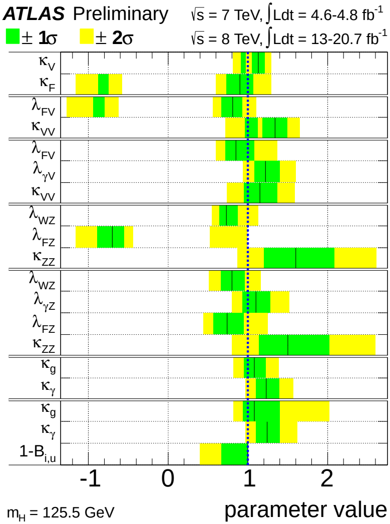
Standard Model-like Higgs

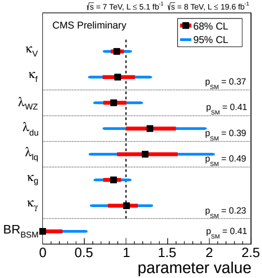
- best-fit point from Markov-chain Monte Carlo
- Error bars: 5000 toy MC, 68% CL coverage
- horizontal lines: $\pm 20\%$

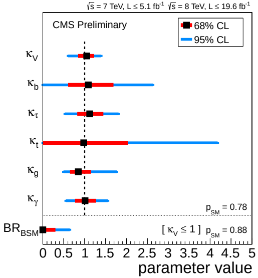
[see also Carmi *et al.* ; Asatov *et al.* ; Espinosa *et al.* ; Giardino *et al.* ; Ellis *et al.* ; Farina *et al.* ; Bechtle *et al.* ; . . .]

Higgs Couplings – ATLAS & CMS

Karlsruher Institut für Technologie







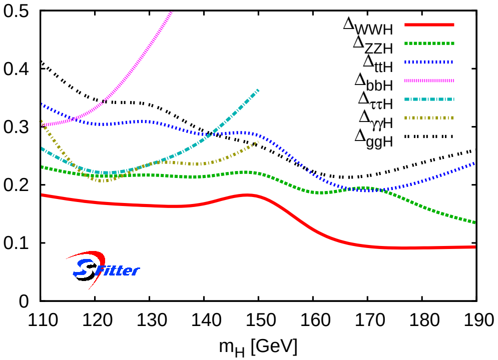
Higgs at the LHC

14 TeV expectations (30 fb^{-1}) [Zeppenfeld, Kinnunen, Nikitenko, Richter-Was; Dührssen *et al.*]

(Standard Model hypothesis)

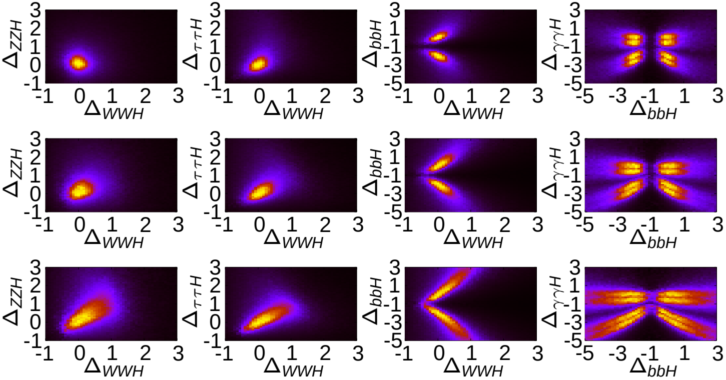
[Lafaye, Plehn, MR, Zerwas, Dührssen 2009]

production	decay
$gg \to H$	ZZ
qqH	ZZ
$gg \to H$	WW
qqH	WW
$t\bar{t}H$	$WW(3\ell)$
$t\bar{t}H$	$WW(2\ell)$
inclusive	$\gamma\gamma$
qqH	$\gamma\gamma$
$t\bar{t}H$	$\gamma\gamma$
WH	$\gamma\gamma$
ZH	$\gamma\gamma$
qqH	$\tau\tau(2\ell)$
qqH	$\tau\tau(1\ell)$
$t\bar{t}H$	$b\bar{b}$
WH/ZH	$b\bar{b}$ (subjet)



Impact of subjet analysis

[SFitter]



Top to bottom: VH, $H \to b\bar{b}$ subjet analysis with full strength

[Butterworth, Davison, Rubin, Salam; ATLAS-MC]

- sensitivity reduced by 50%
- subjet analysis removed

$\leftrightarrow$ No test of subjet analysis with data yet

$\leftrightarrow$ Recent ATLAS study on boosted W, Z, $t\bar{t}$ in 7 TeV data very promising

Invisible vs. Unobserved

Additional decays into "invisible" final states possible

$$\Gamma_{\text{tot}} = \Gamma_{\text{tot}}^{SM} + \Gamma_{\text{inv}} \equiv \Gamma_{\text{tot}}^{SM}\,(1 + \Delta_\Gamma)$$

Can be compensated by global scaling of couplings

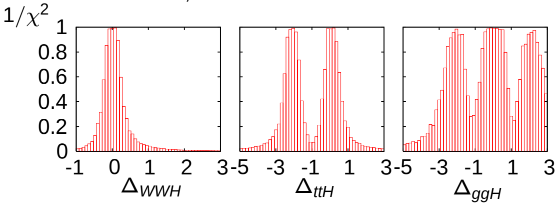
$$\sigma \cdot BR = \frac{\Delta_H^2}{1 + \frac{\Delta_\Gamma}{\Delta_H^2}}\,(\sigma \cdot BR)_{\text{SM}}$$

- Invisible Higgs decays actually observable
  - Vector-Boson Fusion: tagging jets plus missing E_T [Eboli, Zeppenfeld]
  - WH/ZH: recoil against nothing
    [Choudhury, Roy; Godbole, Guchait, Mazumdar, Moretti, Roy; Englert, Spannowsky, Wymant]

- Unobservable decays into particles with large backgrounds (like $H \to$ jets)
  e.g. increased ccH coupling (corresponding to 15.4 GeV Yukawa coupling)

Invisible vs. Unobserved

- Unobservable decays into particles with large backgrounds (like $H \to$ jets)
  e.g. increased *ccH* coupling (corresponding to 15.4 GeV Yukawa coupling)
  $\mathcal{L} = 30\ \text{fb}^{-1}$, SM data / increased *ccH* / increased *ccH* plus free width



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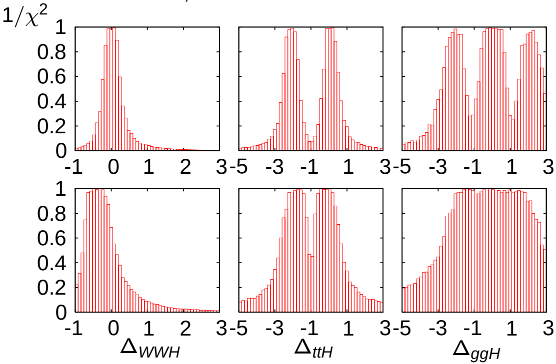

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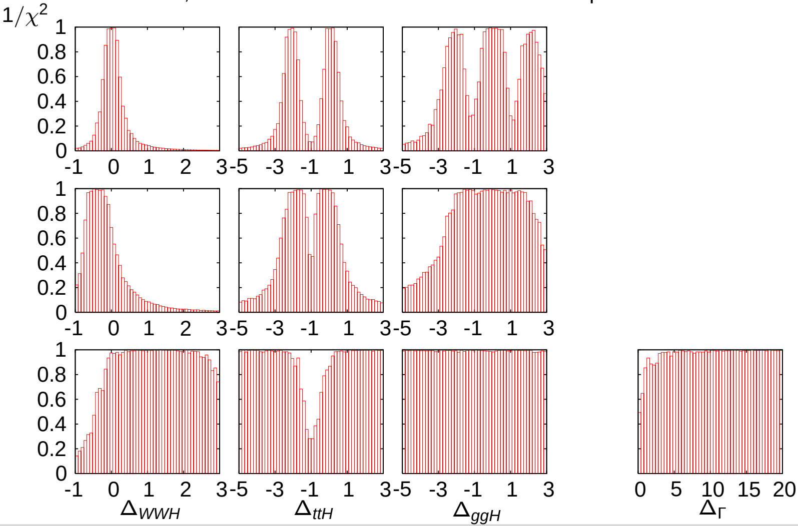

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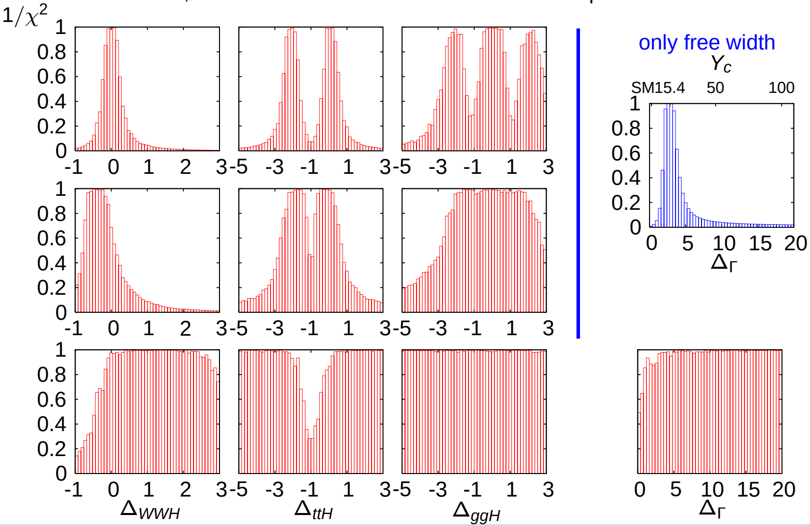
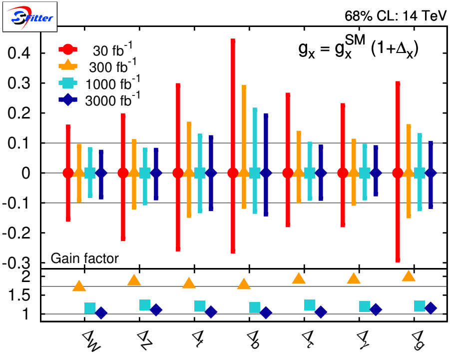


LHC in the future

LHC high-luminosity run: 14 TeV, 3000 fb^{-1}
Standard Model hypothesis



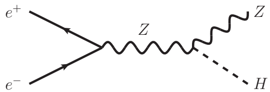
- extrapolation done blindly (only stat. improvements) starting from MC expectation at 14 TeV, 30 fb^{-1}
- full set including effective couplings

- gain factor less than 3 (30→300 fb^{-1}), $\sqrt{3}$ (300→1000 fb^{-1}, 1000→3000 fb^{-1})
- ⇒ statistical scaling does not apply any longer
- best obtainable precision $\simeq$ 10%
- all couplings limited by systematic and theory error

Linear Collider

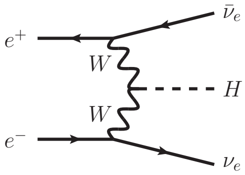
Linear Collider:
proposed first run: $\sqrt{S} = 250$ GeV, $L = 250$ fb^{-1},
upgrade to $\sqrt{S} = 500$ GeV, $L = 500$ fb^{-1}
ILC measurements (from ILC DBD draft) [Peskin (ed.) *et al.*]

Main production mode *ZH*



Allows measuring inclusive *ZH* cross section via recoil technique
(use all events where *Z* decay products kinematically compatible with *ZH* production; *H* decay products stay unobserved)

WW-fusion channel



Important ingredient to reconstruct total width

Combine four measurements

1. Higgs-strahlung inclusive (σ_{ZH})
2. Higgs-strahlung, $H \to b\bar{b}$ (σ_{Zbb})
3. Higgs-strahlung, $H \to WW$ (σ_{ZWW})
4. *WW*-fusion with $H \to b\bar{b}$ ($\sigma_{\nu\nu bb}$)

[Dürig, Desch, Bechtle]

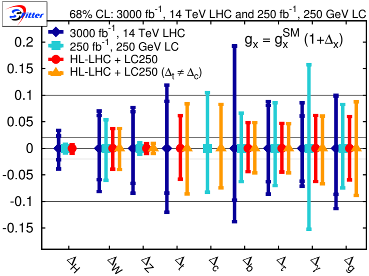
and four unknowns Δ_W, Δ_Z, Δ_b, and Γ_{tot}:

$$\Gamma_{\text{tot}} \leftarrow \frac{\sigma_{\nu\nu bb} / \sigma_{Zbb}}{\sigma_{ZWW} / \sigma_{ZH}} \times \sigma_{ZH}$$

LHC-ILC interplay

[Klute, Lafaye, Plehn, MR, Zerwas]

$\sqrt{S} = 250$ GeV, $L = 250$ fb^{-1}



- reminder: $\Delta_t = \Delta_c$ (generation universality)
- LHC: no Δ_c (no obs. channel)
- ILC: no Δ_t (below $t\bar{t}H$ threshold)

- dramatic improvement on Δ_Z, Δ_b
- complementary: combination better than each alone
- testing $\Delta_t \stackrel{?}{=} \Delta_c$ possible

LHC-ILC interplay

[Klute, Lafaye, Plehn, MR, Zerwas]

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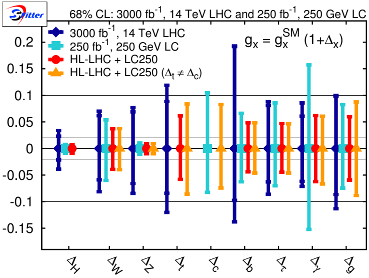
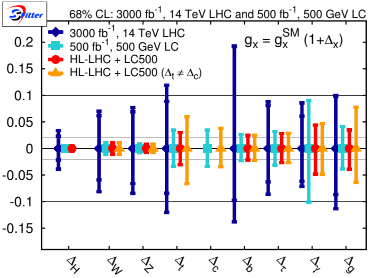


$+\sqrt{S} = 500$ GeV, $L = 500$ fb^{-1}

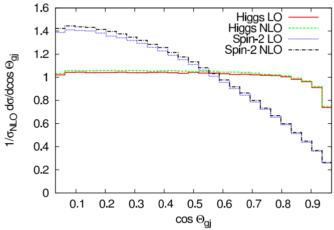


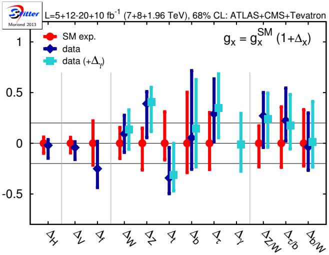
- dramatic improvement on Δ_Z, Δ_b
- complementary: combination better than each alone
- testing $\Delta_t \stackrel{?}{=} \Delta_c$ possible

+ 500 GeV run: ILC precision surpasses LHC everywhere

Conclusions & Outlook

- Determining the Higgs-boson properties important for our understanding of electroweak symmetry breaking
- Angular and invariant-mass distributions can distinguish spin and CP
  - Minimal graviton-like couplings already excluded at $> 99\%$ CL
  - Cross sections and p_T distributions not sufficient can be made SM-Higgs-like
  - task left: exclude general spin-2 scenarios
- Standard Model with effective Higgs couplings
  - All errors including correlations fully implemented
  - Already wealth of measurements from LHC
  - Precision on single-parameter modifier $\Delta_H \simeq 10\%$ already now
- SM Higgs Boson good explanation of observed resonance





SFitter

- Need to scan high-dimensional parameter space
- $\Rightarrow$ SFitter [Lafaye, Plehn, MR, Zerwas]
- General Higgs couplings from modified version of HDecay [Djouadi, Kalinowski, Spira]
- Three scanning techniques:
  - Weighted Markov Chain
  - Cooling Markov Chain (equivalent to simulated annealing)
  - Gradient Minimisation (Minuit)
  - Nested Sampling [Skilling; Feroz, Hobson]
- 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
- Also successfully used for SUSY parameter extraction studies

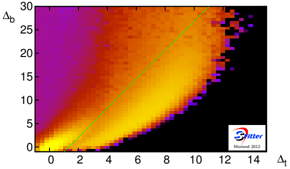
[partly in coll. with Adam, Kneur; Turlay]

The 7 TeV Case

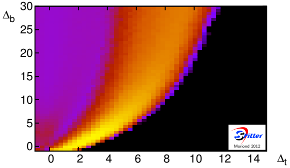
Higgs boson channels, $\mathcal{L}$ = 4.6-4.9 fb^{-1}

ATLAS		CMS	
$\gamma\gamma$		$\gamma\gamma$	
ZZ $\to 4\ell$		$\gamma\gamma$	di-jet
WW	0-jet	ZZ $\to 4\ell$	
WW	1-jet	WW	0-jet
WW	2-jet	WW	1-jet
$\tau\tau$	0-jet	WW	2-jet
$\tau\tau$	1-jet	$\tau\tau$	0/1-jet
$\tau\tau$	VBF	$\tau\tau$	Boosted
$\tau\tau$	VH	$\tau\tau$	VBF
$b\bar{b}$	WH	$b\bar{b}$	WH
$b\bar{b}$	Z($\to \ell\bar{\ell}$)H	$b\bar{b}$	Z($\to \ell\bar{\ell}$)H
$b\bar{b}$	Z($\to \nu\bar{\nu}$)H	$b\bar{b}$	Z($\to \nu\bar{\nu}$)H

SM hypothesis Δ_t vs. Δ_b



7 TeV data Δ_t vs. Δ_b



- background expectations, exp. errors, etc. from analyses
- cross-checked with exclusion and signal-strength plots

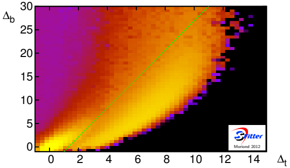
The 7 TeV Case

Higgs boson channels, $\mathcal{L}$ = 4.6-4.9 fb^{-1}

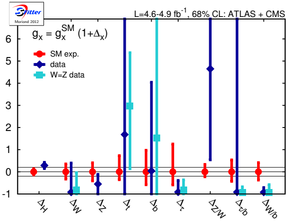
ATLAS		CMS	
$\gamma\gamma$		$\gamma\gamma$	
ZZ $\to 4\ell$		$\gamma\gamma$	di-jet
WW	0-jet	ZZ $\to 4\ell$	
WW	1-jet	WW	0-jet
WW	2-jet	WW	1-jet
$\tau\tau$	0-jet	WW	2-jet
$\tau\tau$	1-jet	$\tau\tau$	0/1-jet
$\tau\tau$	VBF	$\tau\tau$	Boosted
$\tau\tau$	VH	$\tau\tau$	VBF
$b\bar{b}$	WH	$b\bar{b}$	WH
$b\bar{b}$	Z($\to \ell\bar{\ell}$)H	$b\bar{b}$	Z($\to \ell\bar{\ell}$)H
$b\bar{b}$	Z($\to \nu\bar{\nu}$)H	$b\bar{b}$	Z($\to \nu\bar{\nu}$)H

- background expectations, exp. errors, etc. from analyses
- cross-checked with exclusion and signal-strength plots

SM hypothesis Δ_t vs. Δ_b

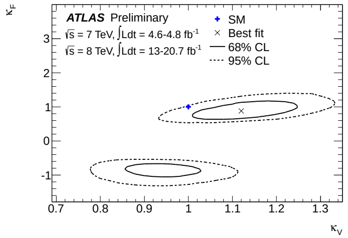


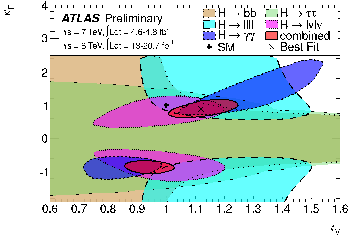
Higgs couplings 7 TeV data



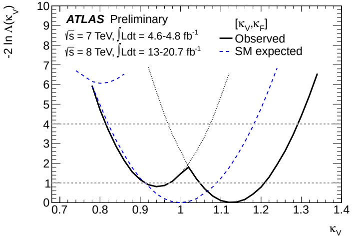
Higgs Couplings – ATLAS

Correlation of the coupling scale factors κ_F and κ_V

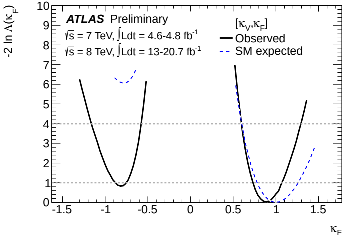




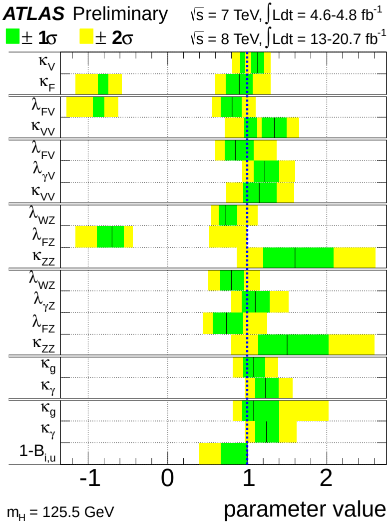
Coupling scale factor κ_V



Coupling scale factor κ_F



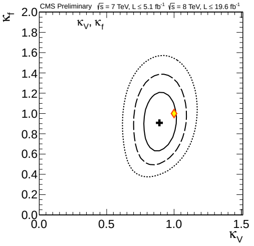
Higgs Couplings – ATLAS

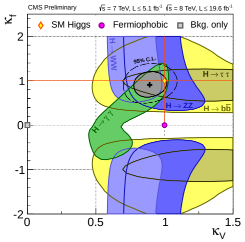


$$\kappa_{XX} = \frac{\kappa_X \cdot \kappa_X}{\kappa_H}$$

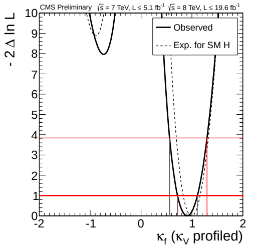
Higgs Couplings – CMS

Correlation of the coupling scale factors κ_F and κ_V

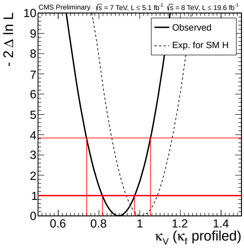




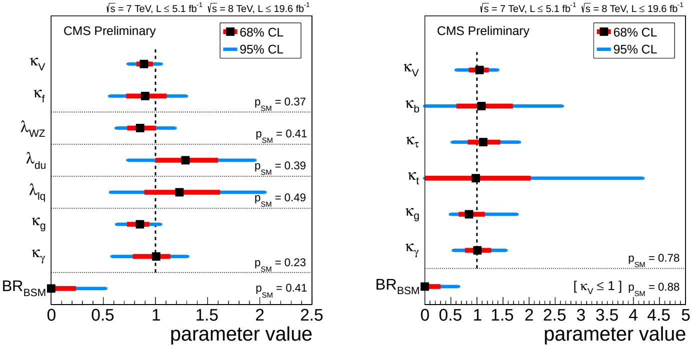
Coupling scale factor κ_V



Coupling scale factor κ_F



Higgs Couplings – CMS



Higgs at the LHC

Input data [Dührssen (ATL-PHYS-2002-030), ATLAS CSC Note; CMS results comparable]
$m_H = 120$ GeV; $\mathcal{L} = 30$ fb^{-1}

production	decay	$S+B$	B	S	$\Delta S^{(\text{exp})}$	$\Delta S^{(\text{theo})}$
$gg \to H$	ZZ	13.4	6.6 ($\times$ 5)	6.8	3.9	0.8
qqH	ZZ	1.0	0.2 ($\times$ 5)	0.8	1.0	0.1
$gg \to H$	WW	1019.5	882.8 ($\times$ 1)	136.7	63.4	18.2
qqH	WW	59.4	37.5 ($\times$ 1)	21.9	10.2	1.7
$t\bar{t}H$	$WW(3\ell)$	23.9	21.2 ($\times$ 1)	2.7	6.8	0.4
$t\bar{t}H$	$WW(2\ell)$	24.0	19.6 ($\times$ 1)	4.4	6.7	0.6
inclusive	$\gamma\gamma$	12205.0	11820.0 ($\times$ 10)	385.0	164.9	44.5
qqH	$\gamma\gamma$	38.7	26.7 ($\times$ 10)	12.0	6.5	0.9
$t\bar{t}H$	$\gamma\gamma$	2.1	0.4 ($\times$ 10)	1.7	1.5	0.2
WH	$\gamma\gamma$	2.4	0.4 ($\times$ 10)	2.0	1.6	0.1
ZH	$\gamma\gamma$	1.1	0.7 ($\times$ 10)	0.4	1.1	0.1
qqH	$\tau\tau(2\ell)$	26.3	10.2 ($\times$ 2)	16.1	5.8	1.2
qqH	$\tau\tau(1\ell)$	29.6	11.6 ($\times$ 2)	18.0	6.6	1.3
$t\bar{t}H$	$b\bar{b}$	244.5	219.0 ($\times$ 1)	25.5	31.2	3.6
WH/ZH	$b\bar{b}$	228.6	180.0 ($\times$ 1)	48.6	20.7	4.0

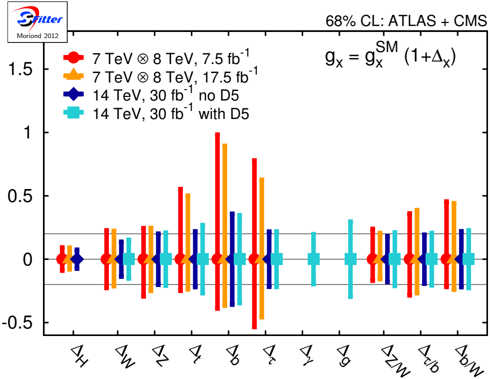
Last line obtained using subjet techniques ([Butterworth, Davison, Rubin, Salam]),
theoretical results confirmed by ATLAS ([ATL-PHYS-PUB-2009-088])
(stricter cuts, statistical significance basically unchanged)

In the future

2012, 2014, . . . (assuming m_H = 125 GeV)

Scenarios: 2012_{low}: $(7.5\ \text{fb}^{-1}, 8\ \text{TeV}) \otimes (5\ \text{fb}^{-1}, 7\ \text{TeV})$
2012_{high}: $(17.5\ \text{fb}^{-1}, 8\ \text{TeV}) \otimes (5\ \text{fb}^{-1}, 7\ \text{TeV})$
2014: $(30\ \text{fb}^{-1}, 14\ \text{TeV})$

Standard Model hypothesis
Extrapolation 7→8 TeV done blindly
(only statistical improvements, based on 2011 measurements)



- VBF measurements giving important information
- $t\bar{t}H$ and $H \to b\bar{b}$ measurements
- g_g and g_γ accessible independently

⇒ exciting prospects

The Higgs Portal

Additional hidden sector as singlet under SM gauge groups

[Binoth, van der Bij; Hill, van der Bij; Schabinger, Wells; Patt, Wilczek; . . .]

Only possible connection to SM:

$\mathcal{L} \propto \Phi_s^\dagger \Phi_s \Phi_h^\dagger \Phi_h$

$\Phi_{s/h}$: Higgs field of SM/hidden sector

Electro-weak symmetry breaking:
$\phi_{s/h} \to (v_{s/h} + H_{s/h})/\sqrt{2}$

H_s and H_h mix into mass eigenstates:
$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} \cos\chi & \sin\chi \\ -\sin\chi & \cos\chi \end{pmatrix} \begin{pmatrix} H_s \\ H_h \end{pmatrix}$

Modifications for H_1: ($\cos\chi \,\widehat{=}\, \Delta_H$)

$\sigma = \cos^2\chi \cdot \sigma^{\text{SM}}$
$\Gamma_{\text{vis}} = \cos^2\chi \cdot \Gamma^{\text{SM}}_{\text{vis}}$
$\Gamma_{\text{inv}} = \cos^2\chi \cdot \Gamma^{\text{SM}}_{\text{inv}} + \Gamma_{\text{hid}}$

($\Gamma^{\text{SM}}_{\text{inv}}$: Decay $H \to ZZ \to 4\nu$ (negligible))

similarly for H_2 with $\cos\chi \leftrightarrow \sin\chi$ plus possibly Γ_2^{HH} : $H_2 \to H_1 H_1$

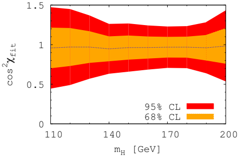
The Higgs Portal

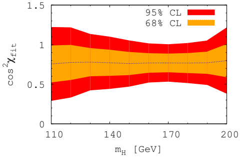
Fit of $\cos^2\chi_{\text{fit}}$ without constraints (14 TeV, 30 fb^{-1})

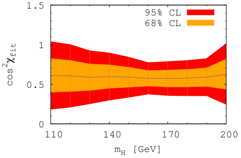
[Bock, Lafaye, Plehn, MR, D. Zerwas, P.M. Zerwas]

- No invisible decay modes

$\cos^2\chi_{\text{th}} = 1.0$ $\quad$ $\cos^2\chi_{\text{th}} = 0.8$ $\quad$ $\cos^2\chi_{\text{th}} = 0.6$





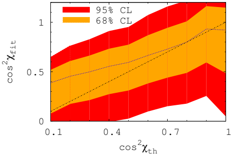


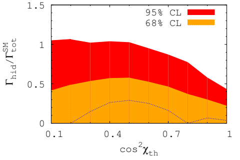
$\Rightarrow$ If $\cos^2\chi_{\text{th}} < 0.6$ can exclude SM at the 95% CL with 30 fb^{-1}

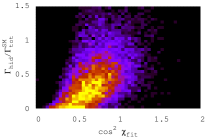
- Measuring invisible decays in VBF-Higgs production
  Signature: Two VBF-jets plus missing E_T

[Eboli, Zeppenfeld; MC-study: ATLAS]

$\Gamma_{\text{hid}} = \sin^2\chi \cdot \Gamma^{\text{SM}}_{\text{tot}}$ $\quad$ (rhs: $\cos^2\chi_{\text{th}} = 0.6$)







The Higgs Portal

[C. Englert, Plehn, Rauch, D. Zerwas, P.M. Zerwas]

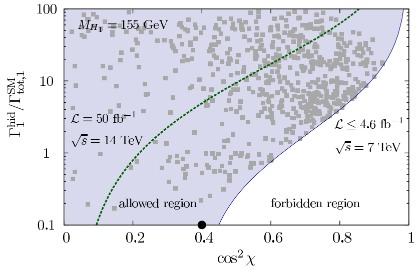
- bounds are determined by measurement of twin ratios

$$\left(\frac{\Gamma_p \Gamma_d}{\Gamma_{\text{tot}}}\right) / \left(\frac{\Gamma_p \Gamma_d}{\Gamma_{\text{tot}}}\right)^{\text{SM}} = (\sigma_p \times \text{BR}_d)/(\sigma_p \times \text{BR}_d)^{\text{SM}}$$

$$\frac{\sigma(pp \to H_1 \to F)}{\sigma(pp \to H_1 \to F)^{\text{SM}}} = \frac{\cos^2\chi}{1 + \tan^2\chi(\Gamma_1^{\text{hid}}/\Gamma_{\text{tot},1}^{\text{SM}})} \leq \mathcal{R}$$

$$\frac{\sigma(pp \to H_1 \to inv)}{\sigma(pp \to H_1)^{\text{SM}}} = \frac{\sin^2\chi(\Gamma_1^{\text{hid}}/\Gamma_{\text{tot},1}^{\text{SM}})}{1 + \tan^2\chi(\Gamma_1^{\text{hid}}/\Gamma_{\text{tot},1}^{\text{SM}})} \leq \mathcal{J}$$

- additional constraint: electroweak precision data (dots: compatible points)



Example: $M_{H_1} = 155$ GeV
$\Rightarrow \mathcal{R} \lesssim 0.4$ @ 95% CL

- bound weakened by invisible decays
- whole area left of it still possible
- significant improvement with higher statistics

The Higgs Portal

[C. Englert, Plehn, Rauch, D. Zwerwas, P.M. Zerwas]

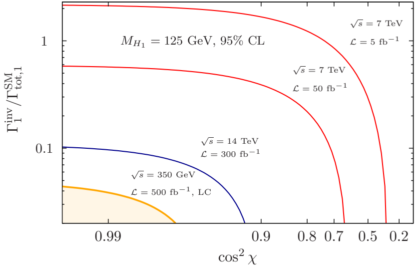
- bounds are determined by measurement of twin ratios

$$\left(\frac{\Gamma_p \Gamma_d}{\Gamma_{\text{tot}}}\right) / \left(\frac{\Gamma_p \Gamma_d}{\Gamma_{\text{tot}}}\right)^{\text{SM}} = (\sigma_p \times \text{BR}_d)/(\sigma_p \times \text{BR}_d)^{\text{SM}}$$

$$\frac{\sigma(pp \to H_1 \to F)}{\sigma(pp \to H_1 \to F)^{\text{SM}}} = \frac{\cos^2\chi}{1 + \tan^2\chi(\Gamma_1^{\text{hid}}/\Gamma_{\text{tot},1}^{\text{SM}})} \leq \mathcal{R}$$

$$\frac{\sigma(pp \to H_1 \to inv)}{\sigma(pp \to H_1)^{\text{SM}}} = \frac{\sin^2\chi(\Gamma_1^{\text{hid}}/\Gamma_{\text{tot},1}^{\text{SM}})}{1 + \tan^2\chi(\Gamma_1^{\text{hid}}/\Gamma_{\text{tot},1}^{\text{SM}})} \leq \mathcal{J}$$

- additional constraint: electroweak precision data (dots: compatible points)



- Standard Model: limit $\mathcal{R} \to 1$
- quantify coincidence by possible deviations left
- (invisible decays hard at LHC: $\to$ Linear Collider)

Strongly-Interacting Light Higgs

[Giudice, Grojean, Pomarol, Rattazzi; Espinosa, Grojean, Mühlleitner]

Higgs pseudo-Goldstone boson of new strongly interacting sector
Modifications parametrized by $\xi = (v/f)^2$ *(f: Goldstone scale)*

- MCHM4:

  Scaling of all couplings with $\sqrt{1-\xi}$
  $\Rightarrow$ Identify $\cos^2\chi = 1-\xi$
  $\Gamma_{\text{hid}} = 0$

- MCHM5:

  Scaling:

  $g_{VVH} = g_{VVH}^{\text{SM}} \cdot \sqrt{1-\xi}$

  $g_{f\bar{f}H} = g_{f\bar{f}H}^{\text{SM}} \cdot \frac{1-2\xi}{\sqrt{1-\xi}}$

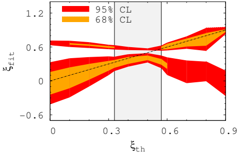
Significant and observable deviations also in Higgs self-couplings [Gröber, Mühlleitner]

MCHM5

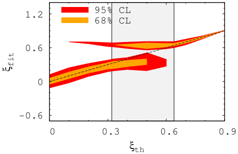
[Bock, Lafaye, Plehn, MR, D. Zerwas, P.M. Zerwas]

Secondary solutions appear (sign of $f\bar{f}H$ coupling)

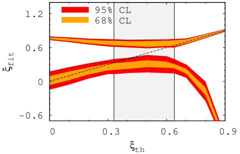
$m_H = 120$ GeV



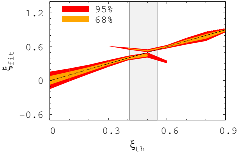
$m_H = 160$ GeV



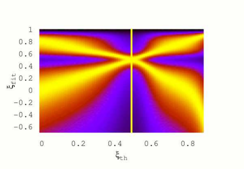
$m_H = 200$ GeV



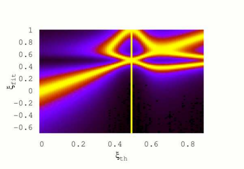
$\mathcal{L} = 300$ fb^{-1}



Gluon fusion $H \to \gamma\gamma$



WH/ZH, $H \to b\bar{b}$



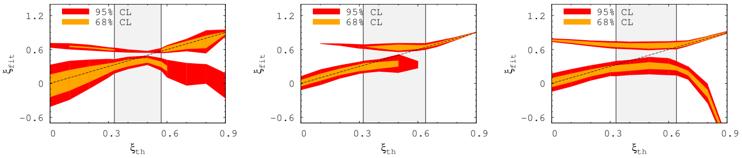
Not a true degeneracy
$\to$ Each (smeared) toy experiment has unique solution

MCHM5

[Bock, Lafaye, Plehn, MR, D. Zerwas, P.M. Zerwas]

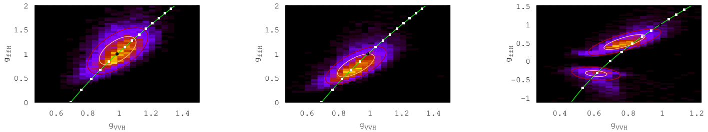
Secondary solutions appear (sign of $f\bar{f}H$ coupling)

$m_H = 120$ GeV $\quad m_H = 160$ GeV $\quad m_H = 200$ GeV



Independent fit of common vector and fermion couplings

$\xi_{\text{th}} = 0 \quad \xi_{\text{th}} = 0.2 \quad \xi_{\text{th}} = 0.6$



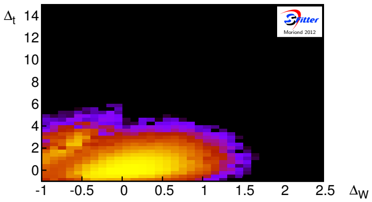
Not a true degeneracy
$\rightarrow$ Each (smeared) toy experiment has unique solution

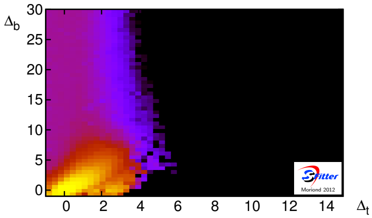
Top-associated Higgs Subjets

Add additional measurement for $t\bar{t}H$, $H \to b\bar{b}$ using subjet techniques

[Plehn, Salam, Spannowsky]

extrapolated to 7 TeV
SM hypothesis





$\Rightarrow$ Secondary solution strongly suppressed
$\to$ large g_t disfavoured by new measurement