Karlsruher Institut für Technologie

Higgs and gauge boson physics for the LHC

Michael Rauch | May 14, 2014

INSTITUTE FOR THEORETICAL PHYSICS

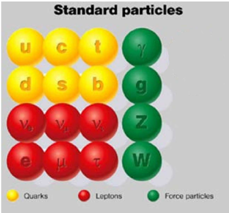
Outline

- Introduction
- Higgs physics
  - Determination of spin
  - Fit of couplings
  - Interpretation in new-physics models
- Gauge boson physics
  - Anomalous gauge couplings
  - Precise predictions for WW

Standard Model of Particle Physics

Status of a few years ago:

- matter particles: quarks, leptons
- force particles: photon, W/Z boson, gluon



mathematical description:
gauge theory ($SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$)

$$\mathcal{L} = \sum_L \bar\psi_L i \not{D}_L \psi_L + \sum_R \bar\psi_R i \not{D}_R \psi_R - \frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu} - \frac{1}{4} W^a_{\mu\nu} W^{a,\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$

where

$$D^\mu_L = \partial^\mu + i g_s t^a G^{a,\mu} + i g' \frac{Y}{2} B^\mu - i g t^a W^{a,\mu}$$

$$D^\mu_R = \partial^\mu + i g_s t^a G^{a,\mu} + i g' \frac{Y}{2} B^\mu$$

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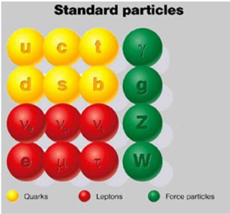

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left-handed fermions   right-handed fermions

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gluon   elektro-weak gauge bosons

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weak interaction
maximally parity-violating   [Wu]

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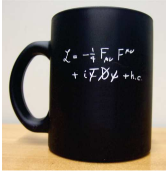

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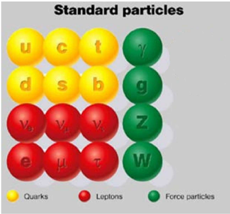

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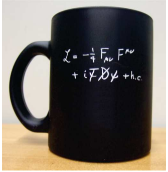

no mass terms fermion: $\mathcal{L}_{\text{mass},f} = -m_f(\bar\psi_L \psi_R + \bar\psi_R \psi_L)$

gauge boson: $\mathcal{L}_{\text{mass},V} = -\frac{m_V^2}{2} V_\mu V^\mu$

→ violate gauge invariance

Spontaneous Symmetry Breaking

Solution: spontaneous symmetry breaking

idea: additional field Φ such that $\mathcal{L}$ invariant under gauge transformations
but ground state not invariant
$\Rightarrow$ non-vanishing vacuum expectation value of Φ

Ex. ferro-magnetism:
$T > T_c$: no magnetisation → rotational symmetry
$T < T_c$: spontaneous magnetisation → preferred direction, symmetry broken

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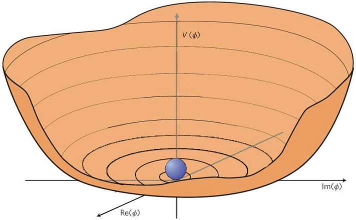
field theory:

- global continuous symmetry:
  massless Goldstone boson
  for every broken generator
- local gauge symmetry:
  eliminated by gauge transformations
  (*would-be goldstone bosons*)
  longitudinal modes of gauge bosons

$$\mathcal{L} \propto -\mu^2(\Phi^\dagger\Phi) - \lambda(\Phi^\dagger\Phi)^2$$

$\underline{\mu^2 > 0}$



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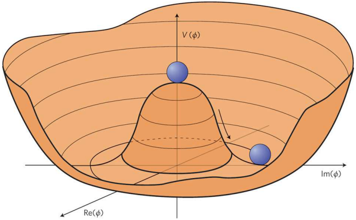
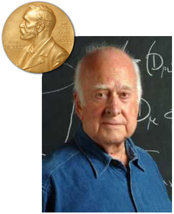


Higgs Mechanism in the Standard Model

Standard Model: Higgs Mechanism [Higgs; Guralnik, Hagen, Kibble; Englert, Brout 1964]

(based on similar ideas in solid state physics) [Anderson 1963]

→ Nobel prize 2013



- Add Higgs field as $SU(2)$ doublet with hypercharge $+1$:

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

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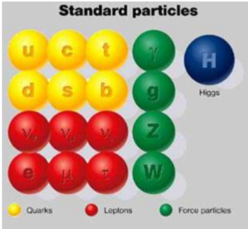

- Breaks $SU(2)_L \otimes U(1)_Y \to U(1)_{\text{em}}$ (→ photon massless)
- $G^\pm$, G^0 → longitudinal modes of $W^\pm$, Z
- H real scalar field → Higgs boson
- $v = \frac{2M_W}{e\sqrt{1-\frac{M_W^2}{M_Z^2}}} \simeq 246\,\mathrm{GeV}$ vacuum expectation value
- Contribution to Lagrangian:

$$\begin{aligned} \mathcal{L}_H = {} & (D_{L,\mu}\Phi)^\dagger (D_L^\mu \Phi) && \text{kinetic term} \\ & + \frac{m_H^2}{2}\Phi^\dagger\Phi - \frac{m_H^2}{2v^2}(\Phi^\dagger\Phi)^2 && \text{Higgs potential} \\ & - (\lambda_\ell \bar{L}\Phi e_R + \lambda_u \bar{Q}\Phi^c u_R + \lambda_d \bar{Q}\Phi d_R + h.c.) && \text{Yukawa coupling to fermions} \end{aligned}$$

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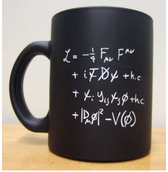
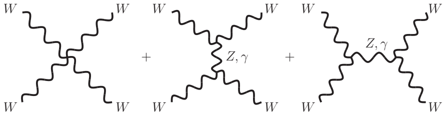
mass term ($m_f = \frac{\lambda_f v}{\sqrt{2}}$) fermion-Higgs coupling



Unitarity Violation

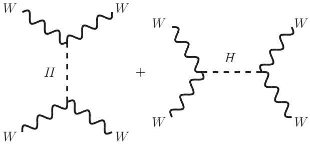
Higgs solves further problem:

- longitudinal W scattering without Higgs



high energy limit: centre-of-mass energy $\sqrt{S} \to \infty$
cross section diverges $\sigma \propto S \to \infty$

- additional Higgs diagrams



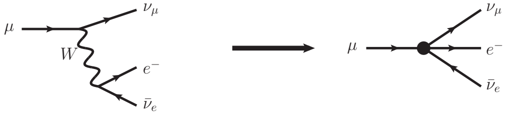
remove divergence exactly $\sigma \propto 1/S \to 0$

Appearance of unitarity violation $\mathcal{O}(1\ \text{TeV}) \Rightarrow$ accessible at LHC energies

Effective Field Theory

Assumption: new physics is heavy

Classic example: μ decay → Fermi theory (t-channel W integrated out)



$$G_F = \frac{\sqrt{2}}{8} \frac{g^2}{m_W^2}$$

⇒ Effective Lagrangian

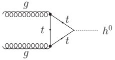
$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_{d>4} \sum_{i} \frac{f_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

- operators $\mathcal{O}$ contain SM fields only
- respect SM gauge symmetries
- suppressed by $1/\Lambda^{d-4}$ (Λ: scale of new physics)
  → keep only leading order (lowest dimension $d = 6$)
- building blocks:
  - Higgs field Φ
  - (covariant) derivative ∂^μ, D^μ
  - field strength tensors $G^{\mu\nu}$, $W^{\mu\nu}$, $B^{\mu\nu}$
  - fermion fields ψ

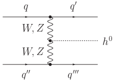
Higgs Production Channels

Main production channels of Higgs boson:

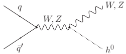
- gluon gluon fusion



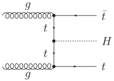
- vector boson fusion

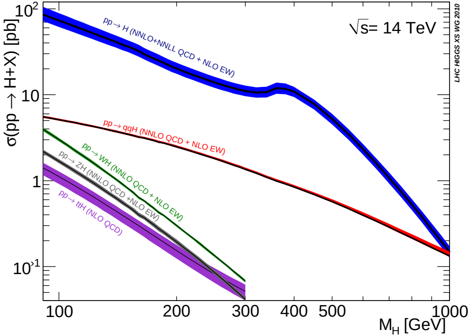


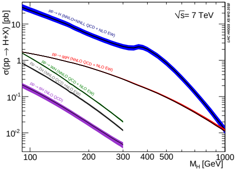
- associated production with gauge bosons



- associated production with top-quark–anti-quark pair



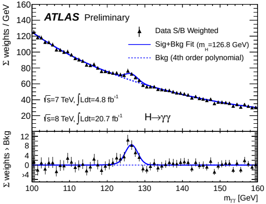


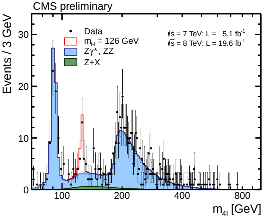


Higgs decay modes

- $H \to \gamma\gamma$
  - 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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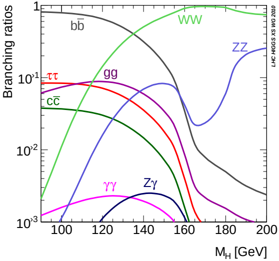
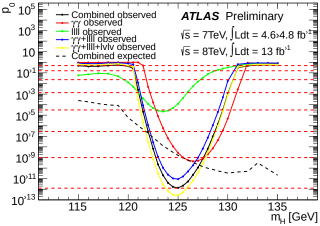


→ 126 GeV ideal value for testing different modes

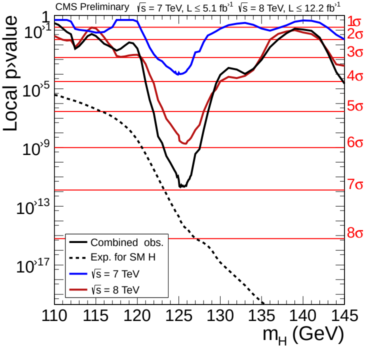
Higgs discovery

Clear resonance observed in both LHC experiments

ATLAS: 7.0 σ (Dec 2012)

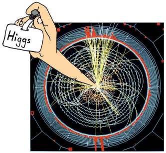


CMS: 6.9 σ (Nov 2012)



"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
↔ "Higgs" properties

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

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

- Spin-2 singlet $T_{\mu\nu}$ 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

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

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

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

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

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

- Experiments: mostly only graviton scenario studied: $f_1 = f_2 = f_5 = f_9$
  $\leftrightarrow$ impact of varying relative strength of K_1 and K_2 unclear

Observables for Distinction

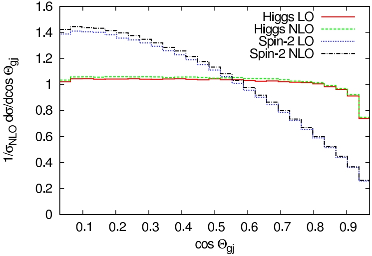
p_T distributions (e.g. of VBF tagging jets) can be made SM-like by form factors
$\rightarrow$ not sufficient to look at

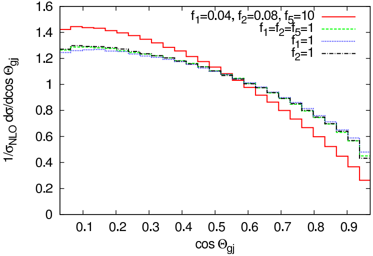
Observables left for distinction:

- 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 θ^* in Collins-Soper frame)

Example: Diphoton production in VBF



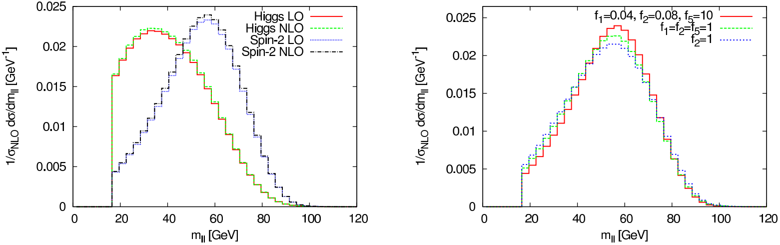


$\Rightarrow$ Good distinction power independent of parameter choice

Spin properties of resonance

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

Spin-0 nature of Higgs forces leptons parallel



ATLAS & CMS: Spin-2 currently disfavoured at $2-3\sigma$ level

- $\Rightarrow$ also valid for other spin-2 scenarios
- model implemented in program package VBFNLO

[Zeppenfeld, MR, . . .]

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.* ; . . .]

↔ New-physics models modifying Higgs couplings

- Additional Higgs particles (Higgs portal, 2HDM, . . .)
- Composite Higgs models
- Supersymmetry

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 $x = W, Z, t, b, \tau$
  $g_{xxH} \equiv g_x \longrightarrow g_x^{\text{SM}} \; (1 + \Delta_x) \equiv g_x^{\text{SM}} \; \kappa_x$ $\quad (\rightarrow \Delta = -2$ 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_μ, $g^{\text{eff}}_{HZ\gamma}$, 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 (∼ simulated annealing)
- Modified gradient fit (Minuit)
- Grid scan
- Nested Sampling [Skilling; Feroz, Hobson]

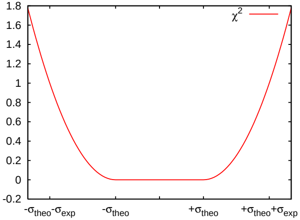
[Lafaye, Plehn, MR,Zerwas]

[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 (→ systematic errors)
  - Poisson
  - box-shaped (RFit) [CKMFitter]
- assignment as in exp. studies
- adaption to likelihood input easy



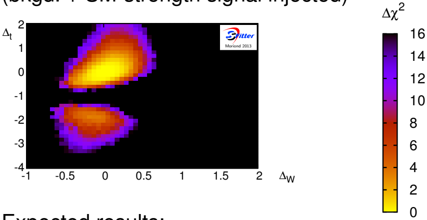
Output of SFitter:

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

Global view

Δ_W vs. Δ_t

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



Expected results:

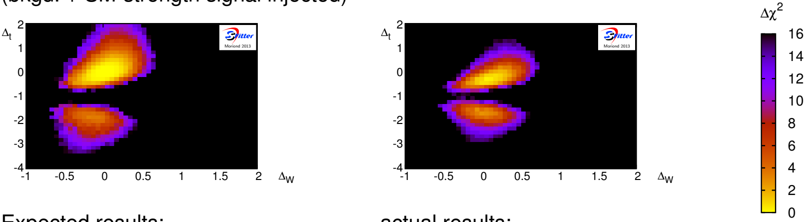
- Correct solution around SM value
- Secondary solution
  for flipped top Yukawa coupling
  $\rightarrow$ photon coupling enhanced

Global view

Δ_W vs. Δ_t

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

measured data



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actual results:

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

Global view

Δ_W vs. Δ_t

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

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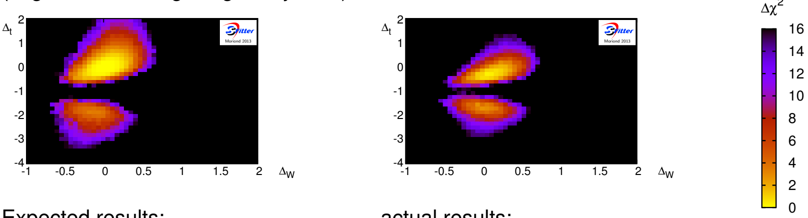


Expected results:

- Correct solution around SM value
- Secondary solution
  for flipped top Yukawa coupling
  → photon coupling enhanced

actual results:

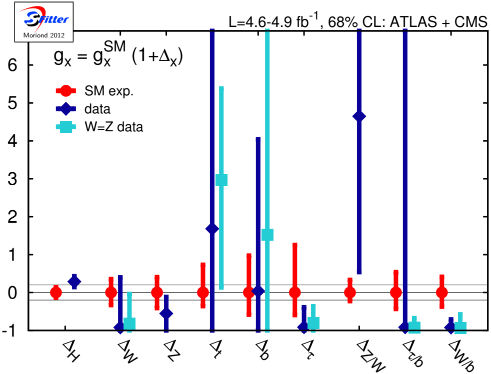
- similar to expectation
- flipped-top coupling disfavoured by $\sim 1\sigma$

Best-fitting solutions:

Δ_W	Δ_Z	Δ_t	Δ_b	Δ_τ	$-2\log L$/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

$-2\log L(\mathrm{SM}) = 16.4$

Local View on data

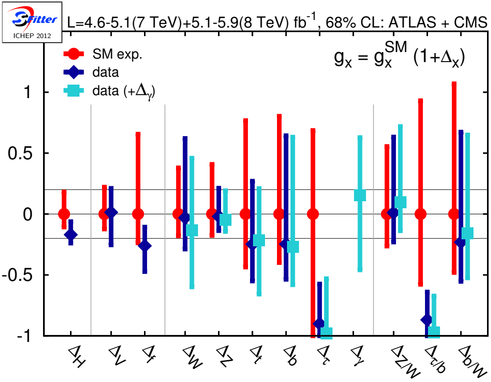


- Two years ago ... (Moriond 2012)

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

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

Local View on data



- Discovery ...
  (ICHEP 2012)

- best-fit point from Markov-chain Monte Carlo
- Error bars: 5000 toy MC, 68% CL coverage
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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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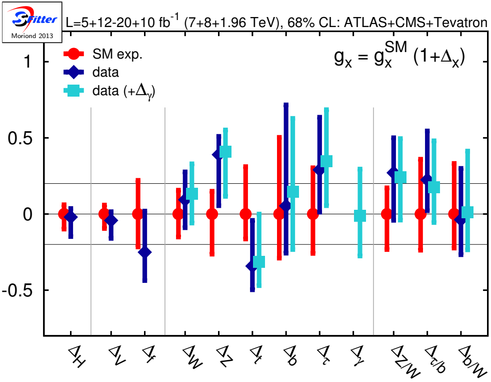

- Δ_H already very precise
- Δ_V-Δ_f also well determined

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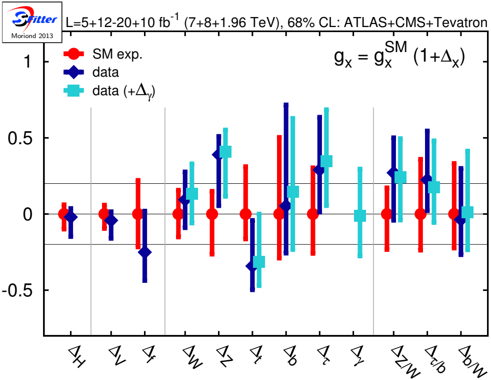

- Δ_H already very precise
- Δ_V-Δ_f also well determined
- g_W, g_Z, g_b, g_t okay
- g_τ now SM-like as well
- ratios:
  no improvement over direct measurements but less assumptions

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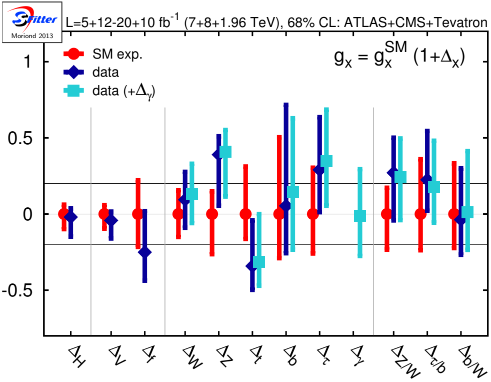

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  $\Delta_\gamma \sim 0$

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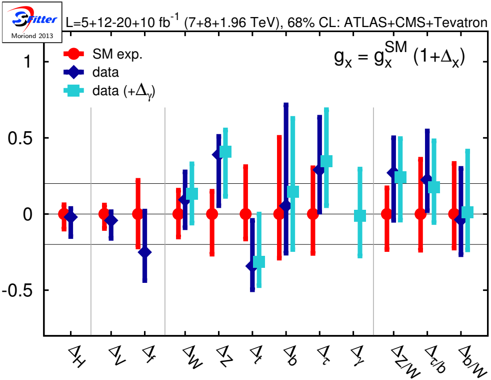

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- g_τ now SM-like as well
- ratios:
  no improvement over direct measurements but less assumptions
- g_γ possible
  $\Delta_\gamma \sim 0$

Standard Model-like Higgs

- best-fit point from Markov-chain Monte Carlo
- Error bars: 5000 toy MC, 68% CL coverage
- horizontal lines: ±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 Effective Operators

Interpret coupling deviations in terms of new physics

Assumptions:

[Bonnet, Ota, MR, Winter]

- new physics in Higgs sector only
- operators generated at tree level

→ Relevant operators and contributions of mediators

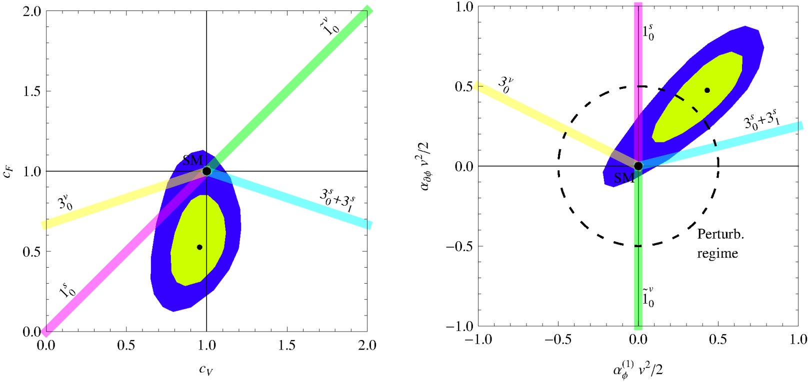
SU(2)→ X^L_Y ←spin (**S**calar,**V**ector)
←hypercharge

Coeff.	Participating in	$\mathbf{1}^s_0$	$\mathbf{3}^s_0$	$\mathbf{3}^s_1$	Gauge $\mathbf{1}^v_0$	Gauge $\mathbf{3}^v_0$	Non-gauge $\tilde{\mathbf{1}}^v_0$	Non-gauge $\tilde{\mathbf{3}}^v_0$
$\alpha_\phi^{(1)}$	*HWW*, *HZZ*	0	$2\,\frac{\mu_\Delta^2}{m_\Delta^4}$	$4\,\frac{\lvert\mu_{\Delta_1}\rvert^2}{m_{\Delta_1}^4}$	0	$-\,\frac{g_U^2}{2m_U^2}$	0	$-2\,\frac{\lambda_U^2}{m_U^2}$
$\alpha_\phi^{(3)}$	EWPT!	0	$-2\,\frac{\mu_\Delta^2}{m_\Delta^4}$	$4\,\frac{\lvert\mu_{\Delta_1}\rvert^2}{m_{\Delta_1}^4}$	$-2\,\frac{g_V^2}{m_V^2}$	0	0	$2\,\frac{\lambda_U^2}{m_U^2}$
$\alpha_{\partial\phi}$	*HWW*, *HZZ*, $H\bar{f}f$	$\frac{\mu_S^2}{m_S^4}$	$\frac{\mu_\Delta^2}{m_\Delta^4}$	0	$\frac{g_V^2}{m_V^2}$	$\frac{g_U^2}{4m_U^2}$	$-\,\frac{\lambda_V^2}{m_V^2}$	$-\,\frac{\lambda_U^2}{m_U^2}$

strong constraints from electro-weak precision tests
effective contribution must sum up to ~ 0
↔ beware of flat directions

Higgs Effective Operators

[Bonnet, Ota, MR, Winter 2012]

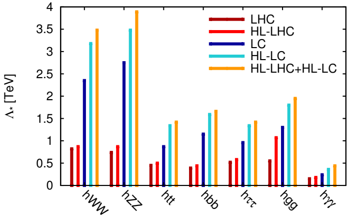


- Correlations between operators unique to model
- Deviations from tree-level mediators orthogonal to less constrained exp. combination
- → Good constraining power of Higgs measurements

Scale of New Physics

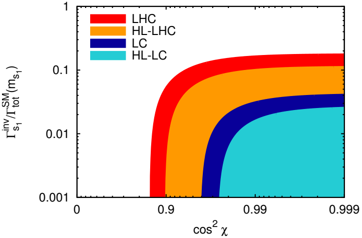
[plots from review: Englert, Freitas, Plehn, MR, Spira, Walz]

Effective new physics scale



- convert coupling precision into new-physics scale
- probes between 0.5 TeV and 4 TeV possible

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



- model-specific fit
- mixing angle vs. invisible width

2HDM interpretation

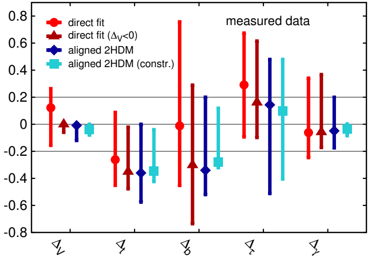
Δ not only scaling factors

$\Rightarrow$ Interpretation of Δ in terms of 2HDM

[Lopez-Val,Plehn,MR]

Yukawa-aligned 2HDM – 5 relevant parameters: $\sin\alpha$, $\tan\beta$, γ_b, γ_τ, M_H

$1+\Delta_V$	$\sin(\beta-\alpha)$
$1+\Delta_t$	$\frac{\cos\alpha}{\sin\beta}$
$1+\Delta_b$	$-\frac{\sin(\alpha-\gamma_b)}{\cos(\beta-\gamma_b)}$
$1+\Delta_\tau$	$-\frac{\sin(\alpha-\gamma_\tau)}{\cos(\beta-\gamma_\tau)}$
$1+\Delta_\gamma^{\text{tot}}$	$f(\sin\alpha, \tan\beta, \gamma_b, \gamma_\tau, M_H)$



Direct mapping between 2HDM parameters and Δ possible

Constraints:

- $|1+\Delta_V| < 1$
  due to sum rule $\sum_i g^2_{VVh_i^0} = g^2_{VVH_{\text{SM}}}$
  → BSM loop corrections
- $\Delta_W = \Delta_Z$
  Breaking possible by adding Higgs triplet
  → custodial symmetry breaking
  ↔ strong experimental constraints
- no invisible decays
  → add dark singlet
- ignore model-specific exp. limits

→ Good agreement between constrained Δ fit and 2HDM interpretation

$\Rightarrow$ can serve as consistent model for fully flexible fit of Higgs couplings

Gauge-boson Physics

NLO QCD vs. anomalous couplings

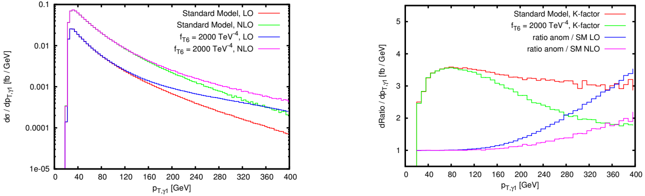
Anomalous couplings also testable in multi-gauge boson production

Example: $W\gamma\gamma$ with VBFNLO, $\frac{f_{T,6}}{\Lambda^4} = 2000\ \text{TeV}^{-4}$, $\Lambda_{\text{FF}} = 1606$ GeV, $n_{\text{FF}} = 4$

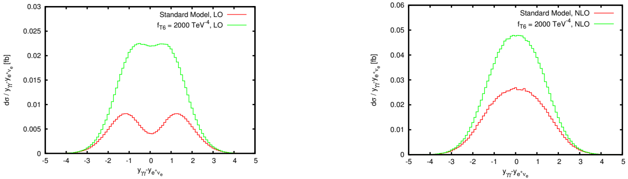
[SM: Bozzi, Campanario, MR, Zeppenfeld; aQGC: Feigl; plots from D. Wackeroth (ed.), MR *et al.*]

somewhat extreme example: radiation zero at tree-level leads to huge K factors

Transverse momentum distribution of the hardest photon



Rapidity difference photon pair – W for $p_{T,\gamma_1} > 200$ GeV



aQGC break radiation zero already at tree-level ⇒ different NLO K-factors

WW pair production

→ need precise predictions for LHC

WW pair production

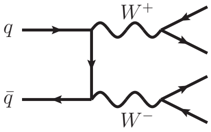
→ need precise predictions for LHC

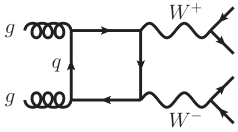
Start with simpler process (higher c.s., relevant already now):

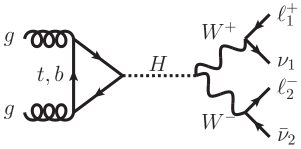
WW pair production at the LHC

$$pp \to W^+W^- + X \to \ell_1^+ \nu_1 \ell_2^- \bar{\nu}_2 + X$$

- Neutrinos in the final state → invariant *W* mass cannot be reconstructed
- → background for many LHC measurements:
  Higgs searches/measurements,
  BSM physics (often contains light stable particle → missing energy)
- signal process in its own right: anomalous triple gauge couplings
- Experiment: exclusive cross section measurements
  from ATLAS (7 TeV run only) and CMS (7 TeV and 8 TeV, 5 fb^{-1})
  → reasonable agreement, ∼ 2σ excess observed







State of the Art

Available higher-order corrections:

- *WW*
  - NLO QCD: $\mathcal{O}(50\%)$ for inclusive cuts, phase-space dependent [Dixon, Kunszt, Signer; Campbell, Ellis, Williams]
  - soft-gluon resummation of threshold logarithms [Dawson, Lewis, Zeng]
  - NNLO QCD: work started [Gehrmann, Tancredi, Weihs; Chachamis]
  - NLO EW up to double-pole approximation [Bierweiler, Kasprzik, Kühn, Uccirati, Gieseke; Baglio, Ninh, Weber; Billoni, Dittmaier, Jäger, Speckner]
  - gluon-initiated contributions: [Ametller, Gava, Paver, Treleani; Dicus, Kao, Repko; Glover, van der Bij; Binoth, Ciccolini, Kauer, Krämer; Bonvini, Caola, Forte, Melnikov, Ridolfi]
    formally NNLO, numerically enhanced due to large gluon PDFs:
    3-5% inclusive, 10% in Higgs analyses
- *WWj*
  - NLO QCD plus gluon-initiated contributions [Dittmaier, Kallweit, Uwer; Melia, Melnikov, Rontsch, Schulze, Zanderighi]
    $\mathcal{O}(40\%)$ for inclusive cuts, phase-space dependent
- *WWjj*
  - NLO QCD: $\mathcal{O}(10\%)$, greatly reduced scale dependence [Greiner, Heinrich, Mastrolia, Ossola, Reiter, Tramontano]

Large QCD corrections for *WW* and *WWj*
→ assess size of NNLO QCD corrections ↔ lack of explicit calculation
→ combine *WW* and *WWj* consistently with simulated 2-loop contributions

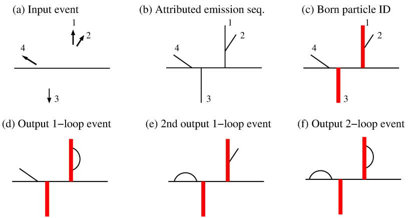
(see also [Cascioli, Hoeche, Krauss, Maierhöfer, Pozzorini, Siegert]
for similar approach with different physics focus)

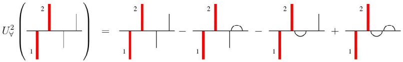
LoopSim

LoopSim approach

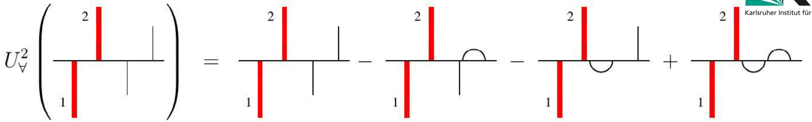
[Rubin, Salam, Sapeta]

- based on unitarity
- assign angular-ordered branching structure to each event (C/A algorithm with radius R_{LS}) until number of particles identical to Born number
- hard structure of event determined $\rightarrow$ remaining particles marked as "Born"
- construct virtual "loop" events: recombine particles *j* not marked as "Born":
    - clustered with particle *i*: spread *j* momentum over *i* and all particles emitted after *j*
    - clustered with beam: remove *j* and apply transverse boost
    - no secondary emitters looped (particles which emit another particle) $\leftrightarrow$ no divergence for emission from internal line


(a) Input event
(b) Attributed emission seq.
(c) Born particle ID
(d) Output 1−loop event
(e) 2nd output 1−loop event
(f) Output 2−loop event



LoopSim (cont.)



- weight for each loop diagram: $(-1)^{\text{number of loops}}$
- double counting from exact 1-loop diagrams removed
- fully inclusive: cross section unmodified
- also electro-weak particles looped → removed by final-state requirements
- cuts applied to each (simulated) part separately → integrated cross sections differ

$\Rightarrow$ Exact tree-level and one-loop parts, singular part of two-loop diagrams
$\leftrightarrow$ constant term of two-loop diagrams missing

Cross-checks:

- $\bar{n}$LO vs. NLO calculation
- Drell-Yan: $\bar{n}$*NLO* vs. NNLO calculation

→ good agreement

Generation of $WW + X$ events: VBFNLO
(NLO QCD *WW*, NLO QCD *WWj*, LO GF-*WW*)

[Zeppenfeld, MR *et al.*]

Numerical Results

Integrated cross sections for LHC 8 TeV

$$\mu_{F,R} = \mu_0 = \frac{1}{2}\left(\sum p_{T,\text{partons}} + \sqrt{p_{T,W^+}^2 + m_{W^+}^2} + \sqrt{p_{T,W^-}^2 + m_{W^-}^2}\right),\ R_{LS} = 1$$

MSTW NNLO 2008 PDF for all cross sections used

	c.s. [fb] without jet veto	c.s. [fb] with jet veto
σ_{LO}	$247.49\ ^{+5.40}_{-7.60}$	$247.49\ ^{+5.40}_{-7.60}$
$\sigma_{\text{box+Higgs}}$	$19.02\ ^{-3.70}_{+4.86}$	$19.02\ ^{-3.70}_{+4.86}$
$\sigma_{\text{pure-NLO}}$	$334.64\ ^{-6.36}_{+6.49}$	$253.05\ ^{+2.98}_{-4.75}$
$\sigma_{\text{pure-}\bar{n}\text{NLO}}$	$345.17\ ^{-7.06}_{+7.03}\ (\mu)\ ^{+5.24}_{-3.33}\ (R_{\text{LS}})$	$236.63\ ^{-1.16}_{+1.45}\ (\mu)\ ^{+5.31}_{-3.27}\ (R_{\text{LS}})$
σ_{NLO}	$353.67\ ^{-10.06}_{+11.35}$	$272.07\ ^{-8.45}_{+7.84}$
$\sigma_{\bar{n}\text{NLO}}$	$364.19\ ^{-10.76}_{+11.89}\ (\mu)\ ^{+5.24}_{-3.33}\ (R_{\text{LS}})$	$255.72\ ^{-4.86}_{+6.31}\ (\mu)\ ^{+5.31}_{-3.27}\ (R_{\text{LS}})$

- scale variation between $2\mu_0$ (upper value) and $\mu_0/2$ (lower value)
- R_{LS} variation between 1.5 (upper) and 0.5 (lower)
- σ_{NLO}, $\sigma_{\bar{n}\text{NLO}}$ contains gluon-fusion (box+Higgs) part (errors added linearly)
- → Large negative corrections for vetoed results (Sudakov logarithms)
- ↔ Missing finite part of 2-loop virtuals

Cuts:
(follows CMS analysis)

- $p_{T,\ell} > 20$ GeV
- $|\eta_\ell| < 2.5$
- different-flavour: $E_{T,\text{miss}}^{\text{projected}} > 20$ GeV
- same-flavour:
  $E_{T,\text{miss}}^{\text{projected}} > 45$ GeV
  $m_{\ell\ell} > 12$ GeV
  $|m_{\ell\ell} - m_Z| > 15$ GeV
  $p_{T,\ell\ell} > 45$ GeV
  $\Delta\phi(\ell\ell, j_1) < 165^\circ$

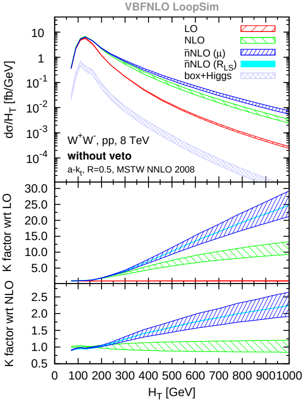
Jet veto: no jets with

- $p_{T,\text{jet}} > 30$ GeV
- $|\eta_{\text{jet}}| < 4.7$

Distributions

Effective mass observable H_T (commonly used in new-physics searches)

$$H_T = \sum p_{T,\text{jets}} + \sum p_{T,\ell} + E_{T,\text{miss}}$$

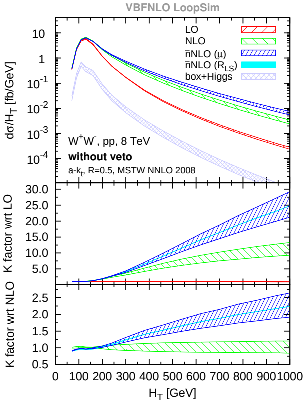


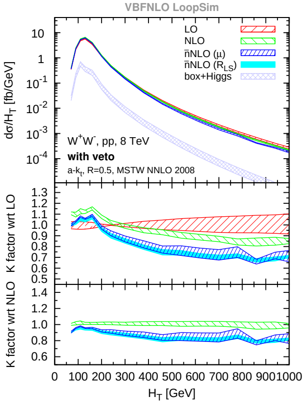
- very sensitive to additional radiation from further partons and soft or collinear emission of the W bosons
- → giant K factors for large H_T
- → well described by LoopSim method
- ↔ small dependence on R_{LS} parameter
- cross-check:
  comparison of $\bar{n}$LO and NLO results
  → very close for $H_T \gtrsim 200$ GeV

Distributions

Effective mass observable H_T (commonly used in new-physics searches)

$$H_T = \sum p_{T,\text{jets}} + \sum p_{T,\ell} + E_{T,\text{miss}}$$





- large negative corrections when applying jet veto (Sudakov logs)
  $\mathcal{O}(-15\%)$ for NLO compared to LO, $\mathcal{O}(-20\%)$ for $\bar{n}$NLO compared to NLO
- $\leftrightarrow$ finite two-loop contributions missing
- $\leftrightarrow$ same effect in WH@NNLO: $\mathcal{O}(-15\%)$ for NNLO/NLO [Ferrera, Grazzini, Tramontano]

Conclusions

- Higgs boson at 126 GeV discovered
  - spin-0 particle; spin-1 and spin-2 disfavoured
    generic spin-2 model: graviton-inspired results stay valid in more general scenarios
  - couplings equal to SM expectation (within errors)
    approach of free SM couplings well defined (→ 2HDM)

  → SM complete

- Interpretation in terms of new-physics models

  from generic (effective field theory)
  to specific models (2HDM, Higgs portal)

- ⇒ precise predictions for SM processes
  to distinguish new physics from higher-order corrections

- Example: *WW* production
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    for observables sensitive to QCD radiation (like H_T or $E_{T,\text{miss}}$)

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  - spin-0 particle; spin-1 and spin-2 disfavoured
    generic spin-2 model: graviton-inspired results stay valid in more general scenarios
  - couplings equal to SM expectation (within errors)
    approach of free SM couplings well defined (→ 2HDM)

  → SM complete

- Interpretation in terms of new-physics models

  from generic (effective field theory)
  to specific models (2HDM, Higgs portal)

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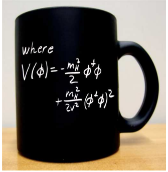

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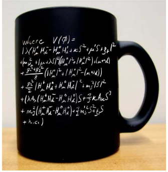


Effective Operators for Higgs

Relevant operators for Higgs physics

[Buchmuller, Wyler; Hagiwara *et al.* ; Grzadkowski *et al.* ; Corbett *et al.* ; Pomarol *et al.* ; . . .]

[recent reviews: Wackeroth (ed.), MR *et al.* ; Englert, Freitas, Muhlleitner, Plehn, MR, Walz]

Higgs–gluon	$\mathcal{O}_{GG} = \phi^\dagger \phi \, \mathrm{tr}\{G^2\}$	SM Higgs phenomenology
Higgs–vector boson (1)	$\mathcal{O}_{\phi 1} = (D\phi)^\dagger \phi \phi^\dagger (D\phi)$ $\mathcal{O}_{\phi 4} = (D\phi)^\dagger (D\phi) \phi^\dagger \phi$	custodial symmetry violation
Higgs–vector boson (2)	$\mathcal{O}_{WW} = \phi^\dagger W^2 \phi, \quad \mathcal{O}_{BB}$ $\mathcal{O}_{BW} = \phi^\dagger B W \phi$ $\mathcal{O}_{W} = (D\phi)^\dagger W (D\phi), \quad \mathcal{O}_{B}$	SM Higgs decays $h \to \gamma\gamma, \gamma Z$ custodial symmetry violation
Higgs–fermion (1)	$\mathcal{O}_{LR} = (\phi^\dagger \phi)(\bar{L} \phi R)$ $\mathcal{O}_{LL1} = \phi^\dagger (i \overleftrightarrow{D} \phi)(\bar{L} \gamma L), \quad \mathcal{O}_{RR1}$ $\mathcal{O}_{LL3} = \phi^\dagger (i \overleftrightarrow{D}^a \phi)(\bar{L} \gamma \tau^a L)$	corrections to Yukawa couplings neutral current contributions neutral/charged current contributions
Higgs–fermion (2)	$\mathcal{O}_{\phi B} = \phi \bar{L} (\sigma B) R, \quad \mathcal{O}_{\phi W}, \quad \mathcal{O}_{\phi G}$	electric/magnetic moments
Higgs self-coupling	$\mathcal{O}_{\phi 2} = \frac{1}{2} \lvert \partial (\phi^\dagger \phi) \rvert^2$ $\mathcal{O}_{\phi 3} = \frac{1}{3} \lvert \phi^\dagger \phi \rvert^3$	weak boson fusion, decays $h \to VV$ Higgs self-interactions

↔ equations of motion

→ different operators may lead to same physics

↔ electro-weak precision observables from LEP

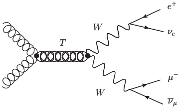
→ some operators strongly constrained

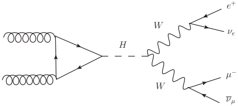
→ relevant operator basis

$$\mathcal{O}_{GG}, \quad \mathcal{O}_{WW}, \quad \mathcal{O}_{BB}; \quad \mathcal{O}_{\phi 2}, \quad \mathcal{O}_{\phi 3}; \quad \mathcal{O}_{LR}$$

Spin-2: Considered processes

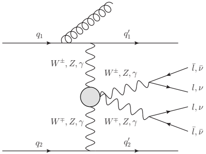
- Gluon-fusion

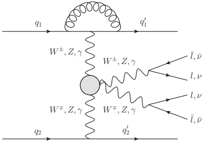




Calculation at LO, higher-orders up to known NNLL included as constant K factors
Assume same factor for Higgs and spin-2 (↔ different operator structure)

- 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 → interference small
→ non-resonant graphs and SM background omitted

Spin-2: Feynman Rules

$$
\begin{aligned}
TW^+W^- &: \ \frac{2if_2}{\Lambda} K_1^{\alpha\beta\mu\nu} + \frac{if_5 g^2 v^2}{2\Lambda} K_2^{\alpha\beta\mu\nu} \\
TZZ &: \ \frac{2i}{\Lambda}(f_2 c_w^2 + f_1 s_w^2) K_1^{\alpha\beta\mu\nu} + \frac{if_5 v^2}{2\Lambda}(g^2 + g'^2) K_2^{\alpha\beta\mu\nu} \\
T\gamma\gamma &: \ \frac{2i}{\Lambda}(f_1 c_w^2 + f_2 s_w^2) K_1^{\alpha\beta\mu\nu} \\
T\gamma Z &: \ \frac{2i}{\Lambda} c_w s_w (f_2 - f_1) K_1^{\alpha\beta\mu\nu} \\
Tgg &: \ \frac{2if_9}{\Lambda} K_1^{\alpha\beta\mu\nu}
\end{aligned}
$$

$$
\begin{aligned}
\text{with } K_1^{\alpha\beta\mu\nu} &= p_1^\nu\, p_2^\mu\, g^{\alpha\beta} - p_1^\beta\, p_2^\nu\, g^{\alpha\mu} - p_2^\alpha\, p_1^\nu\, g^{\beta\mu} + p_1 \cdot p_2\, g^{\alpha\nu} g^{\beta\mu} \\
K_2^{\alpha\beta\mu\nu} &= g^{\alpha\nu} g^{\beta\mu}
\end{aligned}
$$

f_i, Λ free coupling parameters

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

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

Spin-2: 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.]

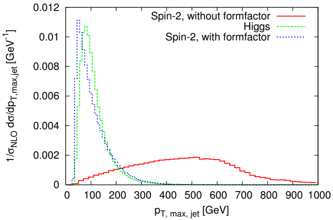
Formfactor multiplying amplitude:

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

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, $n_{ff} = 3$)

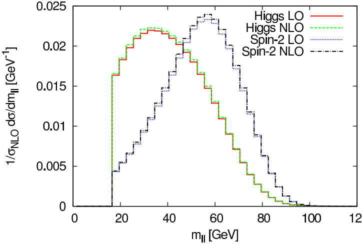


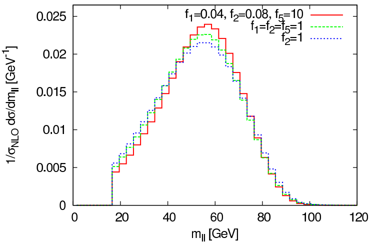
⇒ p_T-distributions not sufficient for distinction

Spin-2: Spin properties

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

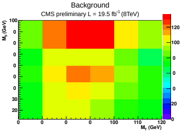
Spin-0 nature of Higgs forces leptons parallel



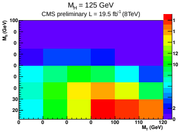


CMS *WW* 0-jet analysis, $m_{\ell\ell}$-m_T-plane

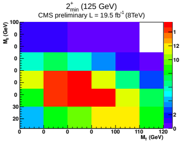
background



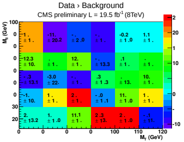
Higgs signal



Spin-2 signal



data



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

Higgs Couplings after Moriond 2013

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

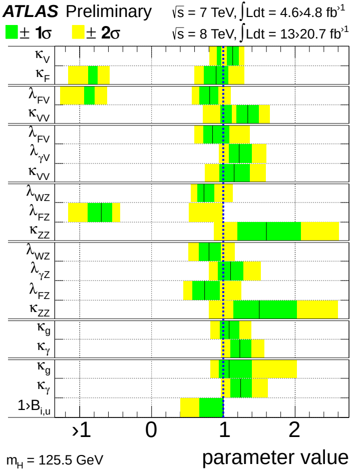
ATLAS		CMS	
$\gamma\gamma$		$\gamma\gamma$	
ZZ (4ℓ)		$\gamma\gamma$	di-jet
WW	0-jet	ZZ (4ℓ)	
WW	1-jet	WW	0-jet
WW	2-jet	WW	1-jet
$\tau\tau$	0-jet	WW	2-jet
$\tau\tau$	1-jet	$\tau\tau$	0/1-jet
$\tau\tau$	VBF	$\tau\tau$	Boosted
$\tau\tau$	VH	$\tau\tau$	VBF
$b\bar{b}$	WH	$b\bar{b}$	WH
$b\bar{b}$	Z_ℓH	$b\bar{b}$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

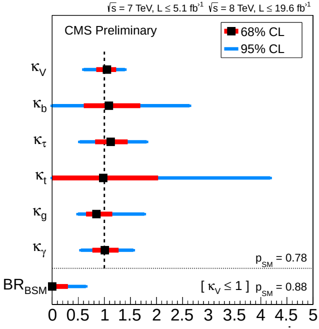
⊗ 8 TeV $\mathcal{L}$ = 12-21 fb^{-1}

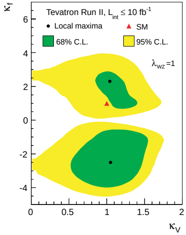
ATLAS		CMS	
$\gamma\gamma$	low-p_T	$\gamma\gamma$	Cat0
$\gamma\gamma$	high-p_T	$\gamma\gamma$	Cat1
$\gamma\gamma$	di-jet lml	$\gamma\gamma$	Cat2+3
$\gamma\gamma$	di-jet hml	$\gamma\gamma$	di-jet tight
$\gamma\gamma$	di-jet tight	$\gamma\gamma$	di-jet loose
$\gamma\gamma$	E_T(miss)	ZZ $\to 4\ell$	
$\gamma\gamma$	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

Experimental Results . . .



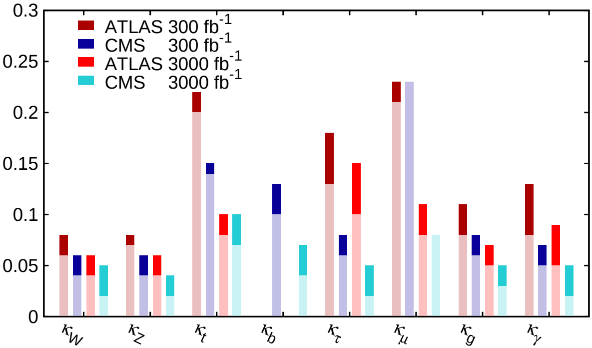




Extrapolations – LHC

What to expect from the LHC in the future?

Precision on κ:



[ATLAS/CMS; own compilation]

dark shading:
current syst/theo unc.

light shading:
ATLAS: no theo unc.
CMS: theo unc./2,
syst unc./$\sqrt{L}$

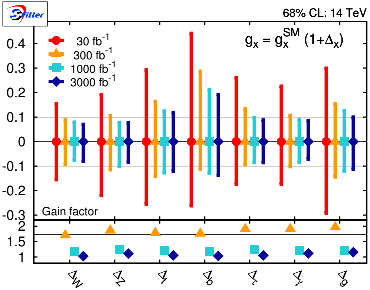
Difficult question – requires many assumptions:

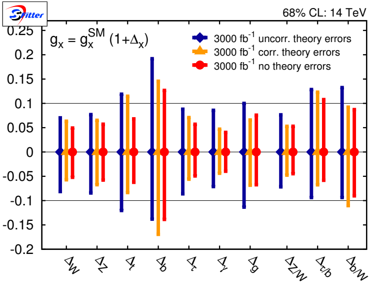
- detector performance – pile-up, efficencies, . . .
- theory progress – higher-order corrections, PDFs, . . .
- new analysis channels

Extrapolations – LHC

Tests from the theory side

(based on naive extrapolation of ATLAS 14 TeV, 30 fb^{-1} MC study)
Theory errors implemented as box-shaped following LHC HXSWG recommendations
↔ ATLAS/CMS Gauss-shaped

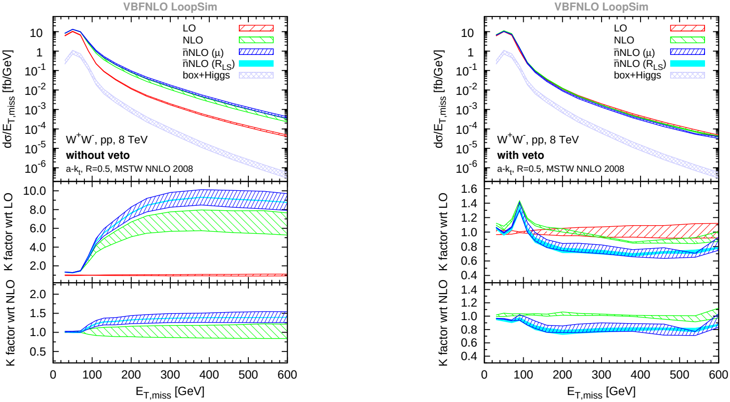




- gain from higher statistics alone small after 300 fb^{-1}
- exploiting correlations between theory errors helps
  ↔ How large are they? (different cuts, inclusive vs. n-jet exclusive)

Distributions (cont.)

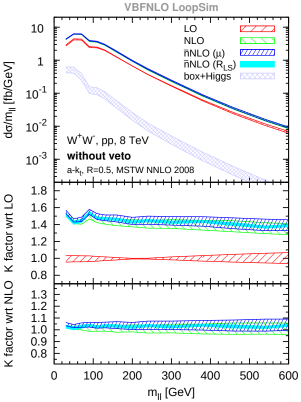
Missing transverse energy $E_{T,\text{miss}}$

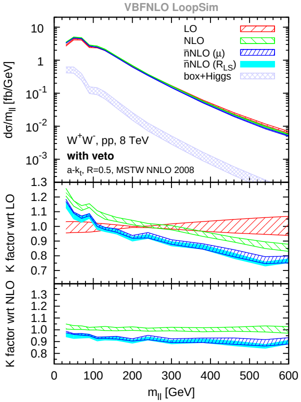


- large K factors for unvetoed results
- negative $\mathcal{O}(-20\%)$ correction for vetoed results
- outside scale variation bands

Distributions (cont.)

Invariant mass of the lepton pair $m_{\ell\ell}$





- shape unchanged by $\bar{n}$NLO effects, normalization differs for vetoed case
- large $m_{\ell\ell}$ ↔ back-to-back leptons dominate
  → not particularly sensitive to new topologies opening up