Standard Model Higgs Theory in the realm of the LHC

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Outline

The Brout–Englert–Higgs mechanism

- Consider a scalar $SU(2)$–doublet field ϕ, $Y_\phi = 1$, in a ϕ^4 potential:

  $$\mathcal{L}_S = |D_\mu \phi|^2 - V(\phi),\, V(\phi) = -m^2\phi^2 + \lambda\phi^4,\, D_\mu = \partial_\mu - \imath g T_{\mathrm{a}} W_\mu^{\mathrm{a}} - \imath g^{'} \tfrac{Y}{2} B_\mu$$

  T_a as SU(2) generators & W_μ^a SU(2) gauge bosons

  Y hypercharge & B_μ U(1) gauge boson

- Use $W_\mu^\pm \equiv \dfrac{W_\mu^1 \mp \imath W_\mu^2}{\sqrt{2}}$, $Z_\mu = \dfrac{g W_\mu^3 - g^{'} B_\mu}{\sqrt{g^2 + g^{'2}}}$, $A_\mu = \dfrac{g W_\mu^3 + g^{'} B_\mu}{\sqrt{g^2 + g^{'2}}}$

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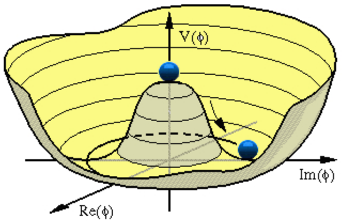
VEV $\langle 0|\phi|0\rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$ and $\phi = \begin{pmatrix} 0 \\ \frac{v + H(x)}{\sqrt{2}} \end{pmatrix}$:

mass terms for weak bosons through v

one Higgs boson in the spectrum

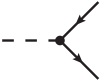


(Imperial College CMS Group)

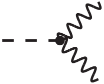
[Higgs (1964); Brout, Englert (1964); Hagen,Kibble,Guralnik (1964)]

Higgs boson couplings

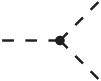
After EWSB: Higgs boson couples to fermions and gauge bosons:



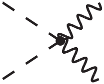
$$g_{Hff} = \frac{M_f}{v} \times (-\imath)$$



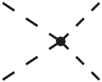
$$g_{HVV} = 2\frac{2M_V^2}{v} \times (\imath g_{\mu\nu})$$



$$g_{HHH} = \frac{3M_H^2}{v} \times (-\imath)$$



$$g_{HHVV} = \frac{2M_V^2}{v^2}$$



$$g_{HHHH} = \frac{3M_H^2}{v^2}$$

Hff $\propto m_f$: Higgs couples mostly to **top** and **bottom** quarks in **fermion loops**
ggH and $\gamma\gamma H$ couplings occur at one-loop level

Theory bounds and precision measurements

Higgs boson mass not predicted by the SM but constrained:

- Triviality and unitarity $\Rightarrow$ upper bound on M_H
  [Marciano *et al* (1989),...; Cabibbo *et al* (1979); Dashen,Neuberger (1983),...]

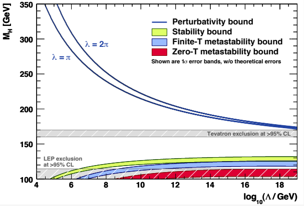
  Stability of the vacuum $\Rightarrow$ lower bound on M_H
  [Lindner, Sher (1989); Casas, Espinosa, Quiros (1995); Hambye, Riesselmann (1996),...]

$$\Lambda_{\rm CUT} = 1\text{ TeV: } 50\text{ GeV} \lesssim M_H \lesssim 750\text{ GeV}$$
$$\Lambda_{\rm CUT} = 10^{16}\text{ GeV: } 130\text{ GeV} \lesssim M_H \lesssim 180\text{ GeV}$$

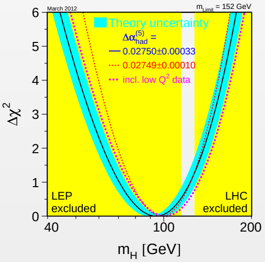
- Precision data fit ($M_Z, \Gamma_Z, M_W, \Delta^{\rm had}\alpha_s$, etc):

$$M_H \leq 152\text{ GeV @ 95\% CL}$$

[Ellis, Espinosa (2009)]



[LEPEWG (2012)]



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Direct searches at LEP and Tevatron

[LEPHWG (2003)]

- Direct LEP2 searches ($\sqrt{s} = 209$ GeV):
  $e^+e^- \to Z(H \to b\bar{b}, \tau^+\tau^-)$

$M_H > 114.4$ GeV @ 95% CL

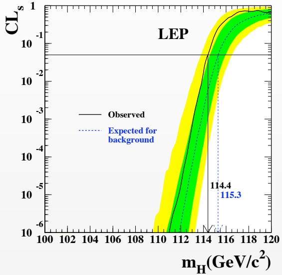
- Latest Tevatron run II result:

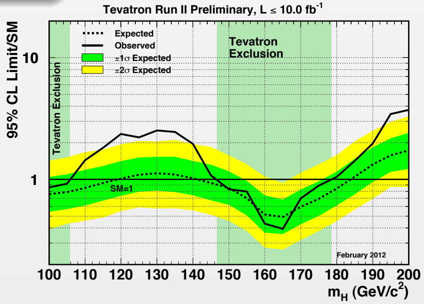
147 GeV $\leq M_H \leq$ 179 GeV excluded @ 95% CL

Broad 2.2σ excess in

$115 \leq M_H \leq 135$ GeV

[TEVNPHWG (2012)]

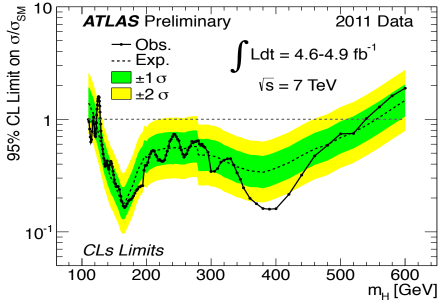


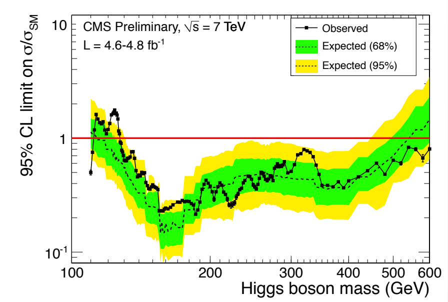


Current status at the LHC

Combined channels:

[CMS-HIG-12-008, ATLAS-CONF-2012-019 (03/2012)]





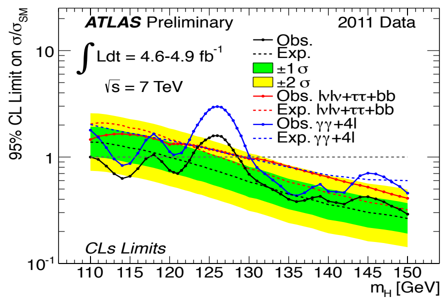
$110\ \text{GeV} \leq M_H \leq 117.5\ \text{GeV}$
$118.5\ \text{GeV} \leq M_H \leq 122.5\ \text{GeV}$
$129\ \text{GeV} \leq M_H \leq 539\ \text{GeV}$
excluded @ 95% CL (ATLAS)

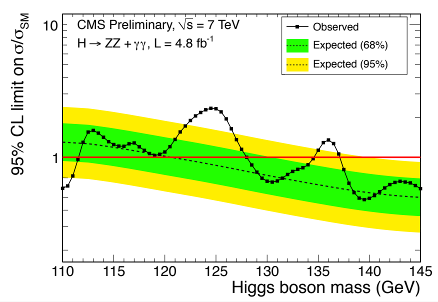
$127.5\ \text{GeV} \leq M_H \leq 600\ \text{GeV}$
excluded @ 95% CL (CMS)

Current status at the LHC

$\mathbf{H} \to \gamma\gamma, \mathbf{H} \to \mathbf{ZZ} \to \mathbf{4}\ell$:

[CMS-HIG-12-008, ATLAS-CONF-2012-019 (03/2012)]





local 2.5σ excess @ $M_H \sim 126$ GeV
local 2.8σ in $H \to \gamma\gamma$,
local 2.1σ in $H \to ZZ \to 4\ell$

local 2.8σ excess @ $M_H \sim 125$ GeV
local 3.1σ in $H \to \gamma\gamma$ @ $M_H = 124$ GeV

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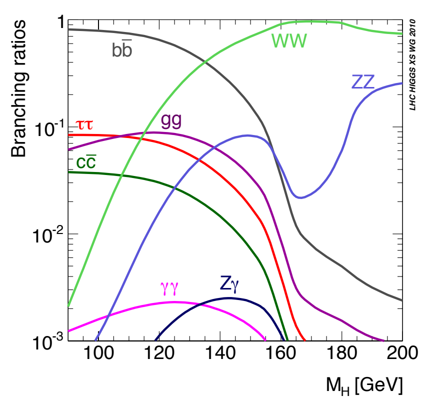
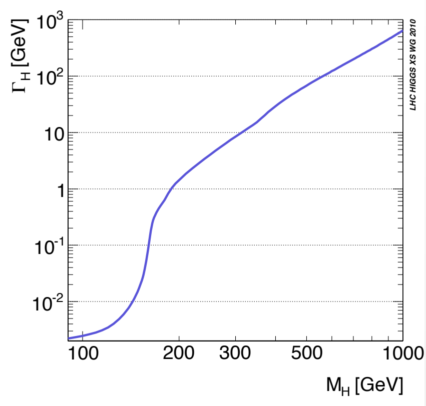
SM Higgs boson decays

Higgs decay channels





[LHC Higgs XS WG (2011)]

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Higgs decay channels

LHC Higgs Cross Section Working Group (LHC Higgs XS WG) calculation based on

- ⋆ HDECAY [Djouadi, Kalinowski, Mühlleitner, Spira (1996,2006)]
- ⋆ PROPHECY4F [Bredenstein, Denner, Dittmaier, Mück, Weber (2010)]

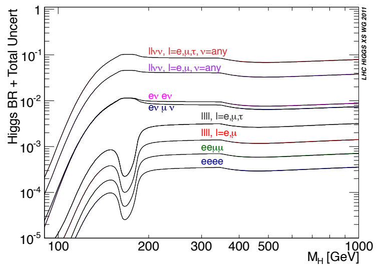
$$\Gamma_{\mathrm{tot}} = \Gamma_{\mathrm{tot}}^{\mathtt{HDECAY}} - \Gamma_{WW}^{\mathtt{HDECAY}} - \Gamma_{ZZ}^{\mathtt{HDECAY}} + \Gamma_{4f}^{\mathtt{PROPHECY4F}}$$

- **HDECAY**

  all relevant higher-order corrections, in particular with NNLO running of α_s and 4–loop QCD corrections to $H \to gg$ [Baikov,Chetyrkin (2012)]

- **PROPHECY4F**

$H \to WW, ZZ \to 4f$ including complete NLO QCD+EW correction and interference effects

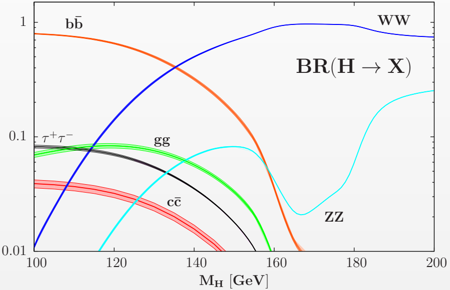


[LHC Higgs XS WG (2012)]

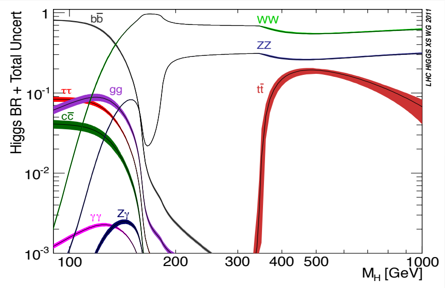
Parameters and uncertainties

Higgs decay branching ratios affected by uncertainties:

- ⋆ parametric: $\bar{m}_b(\bar{m}_b) = (4.16 \pm 0.06)$ GeV, $\bar{m}_c(\bar{m}_c) = (1.27 \pm 0.03)$ GeV, $\alpha_s(M_Z^2) = 0.1171 \pm 0.0014$ [NNLO MSTW] or $\alpha_s(M_Z^2) = 0.118 \pm 0.002$ [LHC Higgs XS WG]
- ⋆ theory: missing higher-order contributions estimated by scale variation



[J. B., Djouadi (2011)]



[LHC Higgs XS WG (2012); Denner *et al* (2011)]

In most relevant channels at $M_H = 120$ GeV:
$\Delta_{\rm BR}(H \to \gamma\gamma) = \pm 5.5\%$, $\Delta_{\rm BR}(H \to WW, ZZ) = \pm 4.8\%$
$\Delta_{\rm BR}(H \to b\bar{b}) = \pm 2.8\%$

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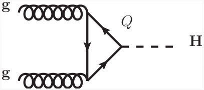
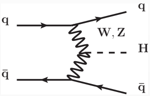
SM Higgs production at the LHC

The four main production channels

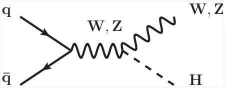
- gluon fusion



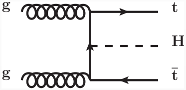
- vector boson fusion

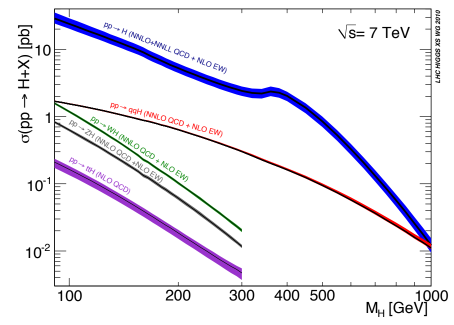


- Higgsstrahlung

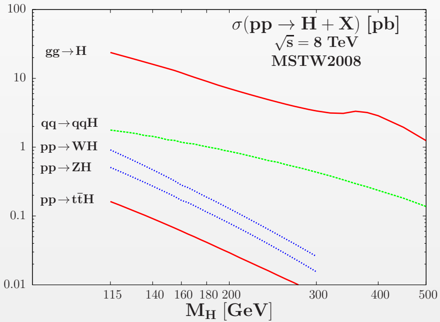


- associated production





[LHC Higgs XS WG (2011)]



[update of J. B., Djouadi (2011)]

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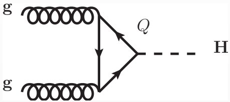
Gluon fusion production: the largest cross section

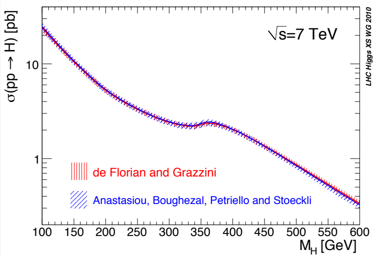
pp → gg → H: the largest production channel at hadron colliders



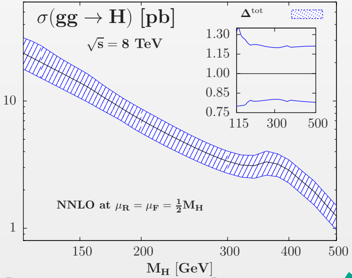
[Georgi, Glashow, Machacek, Nanopoulos (1978)]

Main production channel for many Higgs searches:

- $H \to \gamma\gamma$, $H \to ZZ \to 4\ell$: main detection channels for $M_H \lesssim 140$ GeV (the latter also for $M_H \geq 180$ GeV) [Gunion *et al* (1986); Gunion, Kane, Wudka (1988)]
- $H \to WW \to \ell\nu\ell\nu$: main channel for $M_H \simeq 160$ GeV [Dittmar, Dreiner (1997)]
- Also useful in $H \to \tau\tau$ [J. B., Djouadi (2011)]



[LHC Higgs XS WG (2011)]



[update of J. B., Djouadi (2011)]

Gluon fusion production: the largest cross section

Higher order corrections to inclusive rate:

- NLO QCD corrections: exact for top and bottom loops, $\simeq +100\%$ correction, large scale dependence [Djouadi, Spira, Zerwas; Dawson (1991); Djouadi, Graudenz, Spira, Zerwas (1995)]
- NNLO QCD corrections: only for the top loop where
  - $\simeq +25\%$ in the limit $M_H \ll m_t$
    [Harlander, Kilgore; Anastasiou, Melnikov (2002); Ravindran, Smith, Neerven (2003)]
  - top mass effects negligible for $M_H \lesssim 300$ GeV [Harlander,Ozeren (2009); Pak,Rogal,Steinhauser; Marzani et al. (2010)]
- other QCD corrections:
  - N^3LO estimated in the limit $M_H \ll m_t$ [Moch,Vogt (2005); Ravindran (2006)]
  - NNLL resummation $\Rightarrow +10\%$ [Catani,de Florian,Grazzini,Nason (2003)]; accounted for at NNLO with central scale $\mu_0 = M_H/2$ [Anastasiou, Boughezal, Petriello (2009)]
  - soft gluon at N^3LL and π^2–enhanced terms [Ahrens,Neubert,Becher,Yang (2009)]
- NLO EW corrections: $\simeq \pm 4\%$ [Aglietti *et al*; Degrassi, Maltoni (2004); Actis *et al* (2008)]
- NNLO mixed QCD+EW corrections: in the limit $M_H \ll M_W$ [Anastasiou,Boughezal,Petriello (2009)]

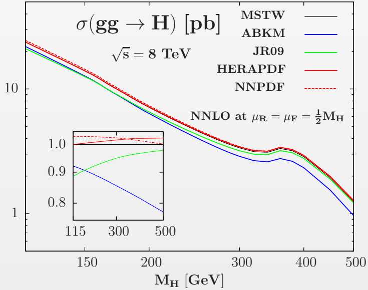
(some) LHC 7 TeV predictions: [LHC Higgs XS WG (2011)]

(some) LHC 8 TeV predictions: [J. B., Djouadi (2011); Anastasiou *et al* (2012)]

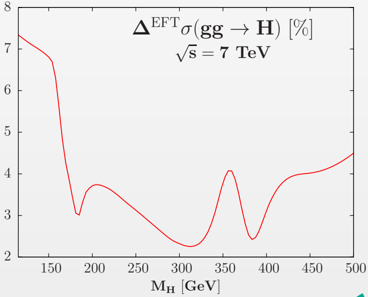
Gluon fusion production: the largest cross section

$gg \to H$ affected by sizeable uncertainties:

- Scale uncertainty: calculated at NNLO with $\frac{1}{2}\mu_0 \leq \mu_R, \mu_F \leq 2\mu_0$, $\mu_0 = \frac{1}{2}M_H$;
  $\Delta_{\rm scale} \simeq \pm 4$ - 8% at $\sqrt{s} = 7, 8$ TeV [LHC Higgs XS WG (2011)]
- PDF uncertainty: gluon PDF at high$-x$ less constrained, $\alpha_s(M_Z^2)$ uncertainty
  $\Rightarrow$ large discrepancy between NNLO PDFs predictions [J. B., Djouadi (2010,2011)]
  PDF4LHC recommandation $\Rightarrow$ $\Delta_{\rm PDF} \simeq \pm 10\%$ [LHC Higgs XS WG (2011)]
- EFT approximation: NNLO calculation without b–loop and with approximate mixed QCD+EW corrections $\Rightarrow$ a few % additional uncertainties [J. B., Djouadi (2011)]



[J. B., Djouadi (2011)]



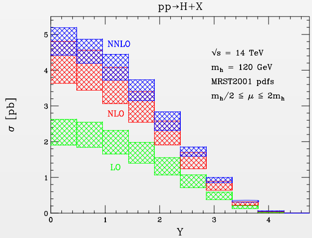
[update of J. B., Djouadi (2011)]

Gluon fusion production: the largest cross section

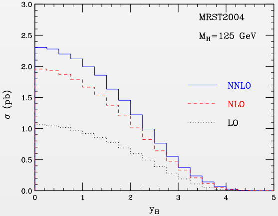
Exclusive studies and differential distributions:

here some highlights, for more see e.g. [LHC Higgs XS WG (2012)] and references therein

- NLO QCD corrections: implemented in HIGLU [Djouadi, Graudenz, Spira, Zerwas (1995)] and Monte Carlo event generators in particular with the subtraction formalism [Catani, Seymour (1996)]
- Fully exclusive NNLO QCD corrections: reduce the scale dependance to $\simeq \pm 20\%$ [Anastasiou, Melnikov, Petriello (2004, 2005); Catani, Grazzini (2007); Grazzini (2008)]
- NNLL resummation in Higgs p_T spectrum: $\simeq +10\%$ enhancement in the distributions [Bozzi, Catani, de Florian, Grazzini (2006); Cao, Chen, Schmidt, Yuan (2009); de Florian, Gerrera, Grazzini, Tommasini (2011);]
- Finite top mass and bottom effects at NNLO: not correctly modeled with effective theory, studies show that at least $\mathcal{O}(10\%)$ distortion of $p_T(H)$ distribution [Bagnaschi, Degrassi, Slavich, Vicini (2011)]



[Anastasiou, Melnikov, Petriello (2004)]



[Catani, Grazzini (2007)]

Gluon fusion production: the largest cross section

Exclusive studies and differential distributions, some issues:

- Scale uncertainties: $gg \to H \to WW$ divided into jet bins to improve background reduction $\Rightarrow$ what is the scale uncertainty in 0, 1, 2 jet bins, what about correlations?
  [Anastasiou, Dissertori, Stöckli, Webber (2007); Grazzini (2008); Stewart, Tackmann (2011); Gerwick, Plehn, Schumann (2012)]

- Jet veto efficiency: ambiguities in the definition of jet-veto efficiency [Berger *et al* (2011)]:

  a) $f_0 = \dfrac{\sigma^{(0)}_{0\text{ jet}}(p_T^{\text{cut}}) + \sigma^{(1)}_{0\text{ jet}}(p_T^{\text{cut}}) + \sigma^{(2)}_{0\text{ jet}}(p_T^{\text{cut}})}{\sigma_{\text{tot}}(\text{NNLO})}$

  b) $f_0 = 1 - \dfrac{\sigma^{NLO}_{1\text{ jet}}(p_T^{\text{cut}})}{\sigma_{\text{tot}}(\text{NLO})}$ (using $f_0(\text{LO}) = 1$)

  c) $f_0 = 1 - \dfrac{\sigma^{NLO}_{1\text{ jet}}(p_T^{\text{cut}})}{\sigma_{\text{tot}}(\text{LO})} + \dfrac{\sigma_{\text{tot}}(NLO)}{(\sigma_{\text{tot}}(\text{LO}))^2}\sigma^{\text{LO}}_{1\text{ jet}}(p_T^{\text{cut}})$ (fixed order expansion to order $\mathcal{O}(\alpha_s^2)$ of method a)

  Poor convergence of total rate $\Rightarrow$ large discrepency between the 3 schemes

- Shape of $p_T(H)$ spectrum and PDF uncertainties [LHC Higgs XS WG (2012)]

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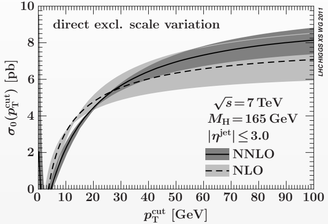
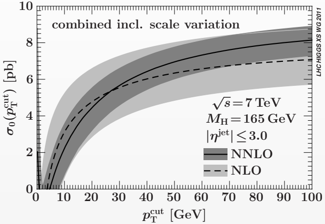
Gluon fusion production: the largest cross section

Exclusive studies and differential distributions, some issues:

- Scale uncertainties:

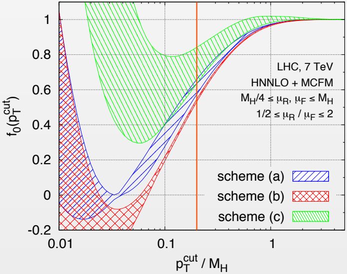


[Stewart, Tackmann (2011); LHC Higgs XS WG (2012)]



[Stewart, Tackmann (2011); LHC Higgs XS WG (2012)]

- Jet veto efficiency:



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Gluon fusion production: the largest cross section

Exclusive studies and differential distributions, some issues:

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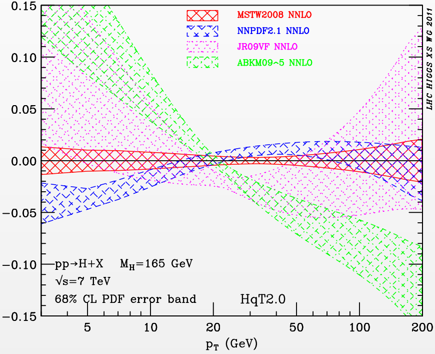
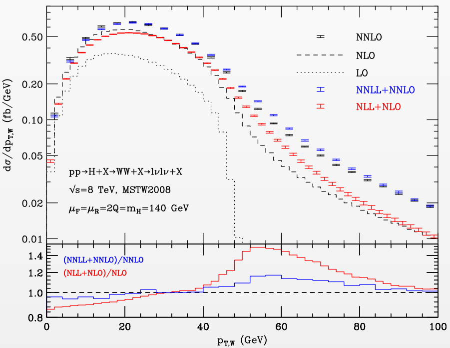


[LHC Higgs XS WG (2012)]



[Grazzini *et al* (2012)]

Gluon fusion production: the largest cross section

Tools:

- **Inclusive cross section:**
  - ⋆ `HIGLU`: version 3.01 including NNLO QCD and mixed EW+QCD corrections, NNLO evolution of α_s [Spira, (2011)]
  - ⋆ `iHixs`: gluon fusion and bottom quarks fusion with NNLO QCD and mixed QCD+EW corrections, finite Γ_H effects [Anastasiou, Bühler, Herzog, Lazopoulos (2011)]
- **Differential distributions and cuts:**
  - ⋆ `POWHEG`: interface NLO Monte Carlo generator with parton shower tools, $gg \to H$ implemented [Bagnaschi, Degrassi, Slavich, Vicini (2011)]
  - ⋆ `MC@NLO`: NLO Monte Carlo event generator [Frixione, Webber (2002)]
  - ⋆ `FEHIP`: full NNLO QCD $gg \to H \to \gamma\gamma$ [Anastasiou, Melnikov, Petriello (2004, 2005)]
  - ⋆ `HNNLO`: full NNLO QCD $gg \to H \to \gamma\gamma$, $H \to WW \to \ell\nu\ell\nu$ and $gg \to H \to ZZ \to 4\ell$ [Grazzini (2008)]
  - ⋆ `HqT`: NLO+NNLL $p_T(H)$ distribution in the large p_T region [de Florian, Ferrera, Grazzini, Tommasini (2011)]
  - ⋆ `HRes`: NNLO+NNLL accuracy in several decay channels [update of HqT (2012)]

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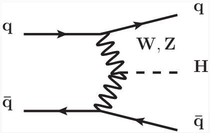
Vector boson fusion: the clean production channel

$\mathbf{pp \to qq \to qq\,WW/ZZ \to qqH}$: clean production channel and second to largest at the LHC



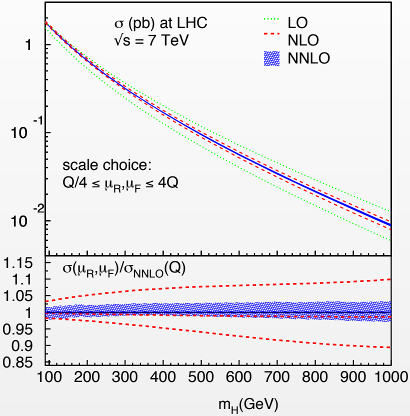
[Cahn, Dawson (1984); Hikasa (1985); Altarelli, Mele, Pitolli (1987)]

Very useful for light Higgs searches in $H \to \tau\tau, WW^*, \gamma\gamma$ channel due to small backgrounds thanks to e.g. jet veto [Barger, Phillips, Zeppenfeld (1995); Rainwater, Zeppenfeld (1997); Eboli *et al* (2000); Plehn, Rainwater, Zeppenfeld (2000); Kauer *et* (2001)]

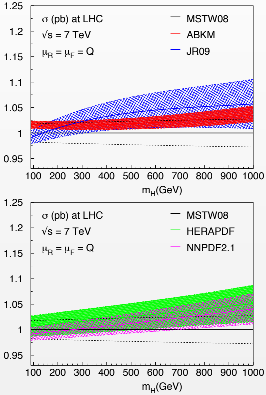
- NLO QCD corrections: $\simeq +10\%$ on total rate, ± 5 - 10% scale dependence [Han, Valencia, Willenbrock (1992)]
- NNLO QCD corrections: we have
  - $\mathcal{O}(\alpha^3\alpha_S^2)$ gluon induced VBF, negligible [Harlander, Vollinga, Weber (2008)]
  - QCD corrections in the structure function approach which barely affect total rate but scale dependence reduced down to $\simeq \pm 2\%$ [Bolzoni, Maltoni, Moch, Zaro (2010)]
- NLO EW corrections: $\simeq +5\%$ shift [Ciccolini, Denner, Dittmaier (2008); Figy, Palmer, Weiglein (2010)]

Vector boson fusion: the clean production channel

Inclusive cross section: central scale chosen as $\mu_R = \mu_F = \mu_0 = Q$ (virtuality of the fusing bosons)



[Bolzoni, Maltoni, Moch, Zaro (2010)]



[Bolzoni, Maltoni, Moch, Zaro (2011)]

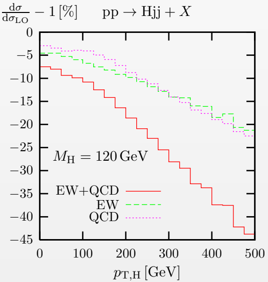
Total uncertainty dominated by PDF

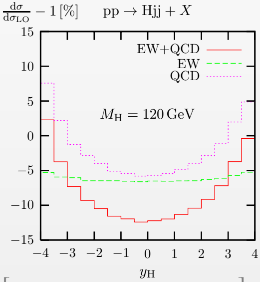
$(\Delta^{\rm tot}\sigma)/\sigma \simeq \pm 6\%$

Vector boson fusion: the clean production channel

Exclusive studies and differential distributions:

- NLO QCD corrections: $\simeq 20\%$ effect [Figy, Oleari, Zeppenfeld (2003); Campbell, Ellis, Berger (2004)]
- dominant NLO $H + 3j$: reduce scale uncertainty $< 5\%$ [Figy, Hankele, Zeppenfeld (2008)]
- 1–loop inteference between gg fusion and WBF: very small effect [Andersen, Binoth, Heinrich, Smillie (2008); Bredenstein, Hagiwara, Jäger (2008)]
- 1–loop QCD+EW corrections: 5% effect [Figy, Palmer, Weiglein (2010)]





[Ciccolini, Denner, Dittmaier (2008)]

Strong effect on the shapes by QCD corrections

EW corrections mostly affect the normalization of distributions

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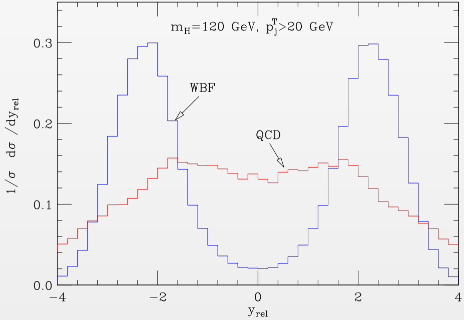
Vector boson fusion: the clean production channel

Exclusive studies and differential distributions:

Major VBF cuts

$$p_T(j) > 20\text{ GeV}, |y_j| < 4.5$$
$$|y_{j1} - y_{j2}| > 4, y_{j1} \cdot y_{j2} < 0$$
$$m_{jj} > 600\text{ GeV}$$

Jet veto very efficient to kill most of QCD background:



[Del Duca, Frizzo, Maltoni (2004)]

Vector boson fusion: the clean production channel

Tools:

- **Inclusive cross section:**
  - ⋆ HAWK, VBFNLO: NLO QCD+EW Monte Carlo event generators (see below)
  - ⋆ VV2H: NLO QCD total cross section [Spira (2000)]
  - ⋆ VBF@NNLO: NNLO QCD total cross section online calculator [Bolzoni, Maltoni, Moch and Zaro (2011)]
- **Differential distributions and cuts:**
  - ⋆ HAWK: NLO Monte Carlo event generator, full 1–loop EW+QCD corrections and interference effects [Denner, Dittmaier, Kallweit, Mück (2010, 2011)]
  - ⋆ POWHEG: interface NLO calculations with parton shower tools, VBF implemented in the POWHEG BOX [Alioli *et al* (2010)]
  - ⋆ VBFNLO: Monte Carlo event generator, full 1–loop EW+QCD corrections, interference effects, Higgs+2j with gg fusion [Arnold *et al* (2008, 2011)]

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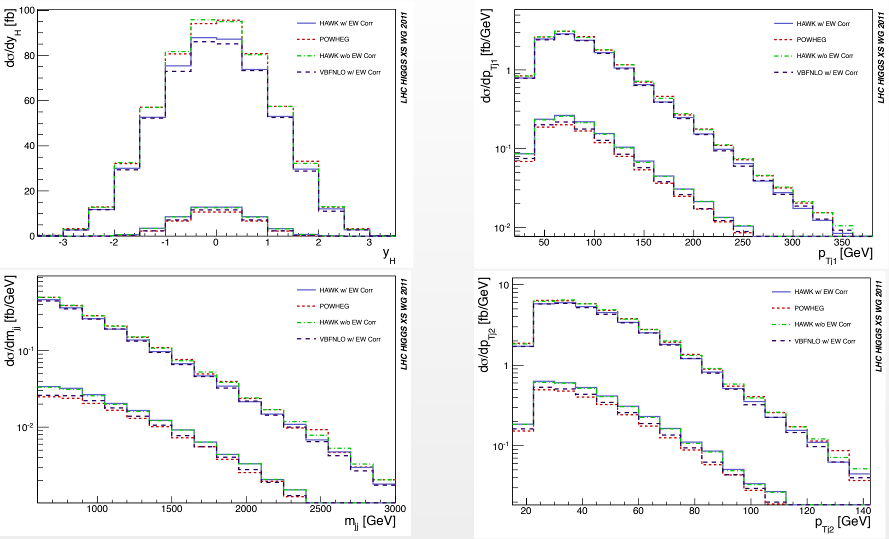
Vector boson fusion: the clean production channel

Recent studies at the LHC with $\sqrt{s} = 7$ TeV:



[LHC Higgs XS WG (2012)]

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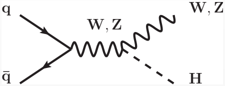
Associated W/Z + Higgs production

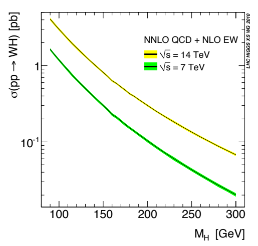
$\mathbf{pp \to Z^*/W^* \to Z/W + H}$: LHC detection channel

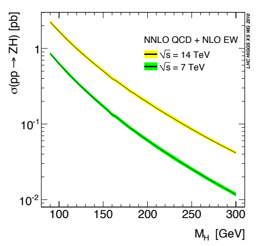
- in $HW \to \ell\nu\gamma\gamma$ with high luminosity (100 fb^{-1}) [Kleiss, Kunszt, Stirling (1991)]
- with $H \to b\bar{b}$ decay in boosted jets regime ($p_T(H) > 200$ GeV) [Butterworth *et al* (2008)]



[Glashow, Nanopoulos, Yildiz (1978)]

- NLO QCD corrections: Drell-Yan $\sigma(pp \to V^*)$ corrections $\simeq +20\%$ [Han, Willenbrock (1991)]
- NNLO QCD corrections: Drell-Yan $\simeq +10\%$ [Hamberg *et al* (1991); Harlander, Kilgore (2002)]; $gg \to ZH \Rightarrow \simeq +5\%$ [Brein, Djouadi, Harlander (2004)]; non Drell-Yan $< 3\%$ [Brein *et al* (2011)]
- Full NLO EW corrections: $\sigma_{WH} = \sigma_{WH}^{\text{QCD NNLO}}(1 + \delta_W^{\text{EW}})$ $+\sigma(gg \to ZH)$ with $\delta_W^{\text{EW}} \simeq -8\%$ [Ciccolini, Dittmaier, Krämer (2003)]





central scale $\mu_0 = M_{HV}$

$(\Delta^{\text{th}}\sigma)/\sigma \simeq \pm 5\%$

[LHC Higgs XS WG (2011)]

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Associated W/Z + Higgs production

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- in $HW \to \ell\nu\gamma\gamma$ with high luminosity (100 fb^{-1}) [Kleiss, Kunszt, Stirling (1991)]
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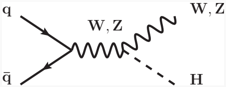

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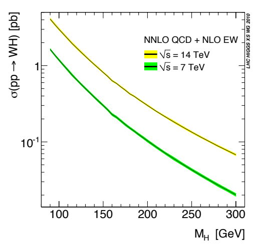
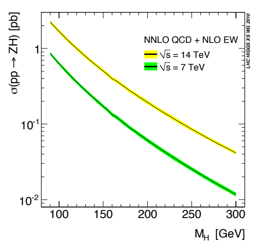
- Full NLO EW corrections: $\sigma_{ZH} = \sigma_{ZH}^{\text{QCD NNLO}}(1 + \delta_Z^{\text{EW}}) + \sigma(gg \to ZH)$ with $\delta_Z^{\text{EW}} \simeq -5\%$ [Ciccolini, Dittmaier, Krämer (2003)]





central scale $\mu_0 = M_{HV}$

$(\Delta^{\text{th}}\sigma)/\sigma \simeq \pm 5\%$

[LHC Higgs XS WG (2011)]

Associated W/Z + Higgs production

Fully exclusive calculation of pp $\to$ HV with $\mu_0 = M_H + M_V$ as central scale

- NLO QCD corrections: $\simeq -40\%$, scale dependence $\simeq \pm 13\%$ [Ciccolini, Denner, Dittmaier (2007)]
- NNLO QCD corrections: $pp \to HW$ exclusive calculation fully at NNLO based on the subtraction formalism, including
  - finite-width effects
  - $W \to \ell\nu$ decay with full spin correlations
  - $H \to b\bar{b}$ decay

  -15% effect; scale dependence reduced to $\simeq \pm 2$ - 6% [Ferrera, Grazzini, Tramontano (2011)]
- Full NLO EW corrections: large effect (e.g. -14% at $M_H = 120$ GeV) [Denner *et al* (2011)]

⋆ Great effort with a fully exclusive NNLO *HW* production: $(\Delta^{\rm tot}\sigma)/\sigma \simeq \pm 7$ - 11%
striking different behaviour compared to Tevatron (+20% NLO, +1% NNLO)

⋆ Perturbative stability worse compared to inclusive production
$\Rightarrow$ ongoing studies to understand why

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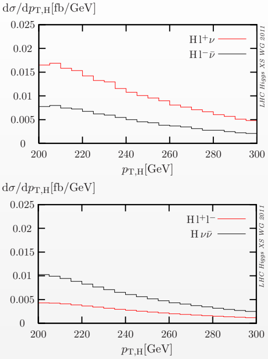
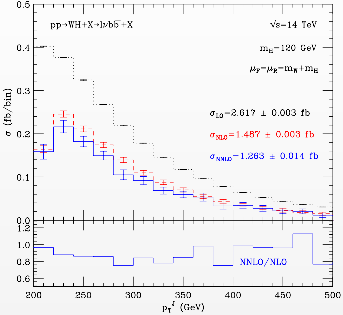
Associated W/Z + Higgs production



[LHC Higgs XS WG (2012)]



[Ferrera, Grazzini, Tramontano (2011)]

- **7 TeV cuts:** $p_T(H) > 200$ GeV, $p_T(V) > 190$ GeV, $p_T(\ell) > 20$ GeV, $|\eta_\ell| < 2.5$, $\not{p}_T > 25$ GeV
- **14 TeV cuts:** $p_T(H) > 200$ GeV, $p_T(W) > 200$ GeV, $p_T(\ell) > 30$ GeV, $|\eta_\ell| < 2.5$, $\not{p}_T > 30$ GeV
- **Tools:** `V2VH` [Spira, NLO; public]; `MCFM` [Campbell, Ellis, Williams, NLO; public]; `VH@NNLO` [Brein, Djouadi, Harlander, NNLO; public]; `HAWK` [Denner, Dittmaier, Mück, NLO; public]

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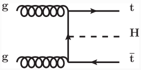
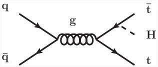
Associated production with a $t\bar{t}$ pair

$\mathbf{pp \to q\bar{q} + gg \to t\bar{t}H}$: smallest of the four main production channels



(dominant)



Useful for $M_H \lesssim 150$ GeV: e.g. top Yukawa coupling in $pp \to t\bar{t}(H \to b\bar{b})$ [Drollinger *et al* (2001)]

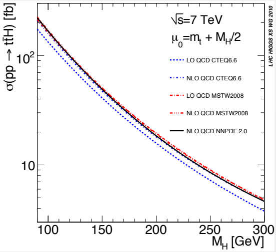
- LO calculation: central scale $\mu_0 = m_t + \frac{1}{2}M_H$, $\mathcal{O}(50\%)$ scale dependence

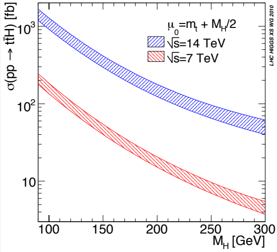
  [Raito, Wada (1979); Ng, Zakarauskas; Kunszt (1984); Gunion; Marciano, Paige (1991)]

- NLO corrections: reduce scale dependence to $\mathcal{O}(10\%)$ with $\frac{1}{2}\mu_0 \leq \mu_R, \mu_F \leq 2\mu_0$

  [Reina, Dawson (2001); Beenakker *et al*; Dawson *et al* (2003)]

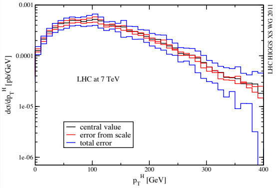
- PDF+α_S uncertainty: $\simeq \pm 4$ - 6% depending on the PDF set chosen

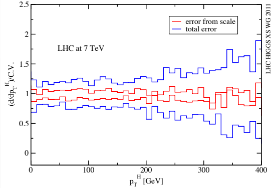




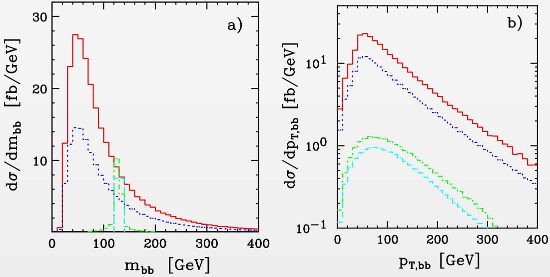
Associated production with a $t\bar{t}$ pair

- Exclusive studies at NLO: $\pm \simeq 20$ - 50% total uncertainty [LHC Higgs XS WG (2012)]





- Main background: $pp \to t\bar{t}b\bar{b}$ known at NLO; central scale choice $\mu^2 = m_t\sqrt{p_{T,b}p_{T,\bar{b}}}$ improves the scale uncertainty to $\ll 30\%$ [Bredenstein *et al* (2008,2009); Bevilacqua *et al* (2009)]



NLO bckgd - LO bckgd

NLO signal - LO signal

[LHC Higgs XS WG (2012)]

- **Tools:** `HQQ` [Spira, LO]; `aMC@NLO` [Frederix *et al*, NLO]; `POWHEL` [Garzelli *et al*, NLO]

Beyond the SM Higgs?

[P. Tanedo, Quantum Diaries blog]

But which Higgs boson may we have?

Summary

Higgs physics in the realm of the LHC:

- Higgs discovery: major LHC goal to

  unravel the electroweak symmetry breaking mechanism

- **A SM Higgs boson discovery may await us:**
  - ATLAS/CMS hints of **3σ excess @ $M_H \sim 125$ GeV**
  - LHC run at 8 TeV for a final answer before end 2012

- **Theory meets high precision accuracy:** up to NNLO in the three main inclusive production channels, huge efforts in exclusive production predictions $\Rightarrow$ **uncertainties from $\sim 100\%$ reduced below $\lesssim 15-20\%$**

- **LHC Higgs Cross Section Working Group**: a collective effort from theorists and experimentalists to give the most up-to-date predictions and assessments on uncertainties

- **Standard Model is not the end of the story! If Higgs boson discovered, what is its nature?** See M. Mühlleitner's talk for SUSY and compositeness examples

Backup

Unitarity bound on the Higgs boson mass

Unitarity: a severe upper constraint on the Higgs boson mass

unitarity $\equiv$ quantum probability $P \leq 1$

Consider scattering of longitudinal Z bosons $Z_L Z_L \to Z_L Z_L$:

$$\mathcal{A} = -\left[3\frac{M_H^2}{v^2} + \left(\frac{M_H^2}{v}\right)^2 \frac{1}{s - M_H^2} + \left(\frac{M_H^2}{v}\right)^2 \frac{1}{t - M_H^2}\right]$$

with $s \gg M_Z^2$ (direct Goldstone scattering), s, t the usual Mandelstam variables

perturbativity unitarity of $J = 0$ partial wave $\Rightarrow \left|\int_{-s}^{0} dt \mathcal{A}(t) dt\right| < 8\pi s$

$$M_H^2 < \frac{8\pi v^2}{3} \Rightarrow M_H \lesssim 710 \text{ GeV}$$