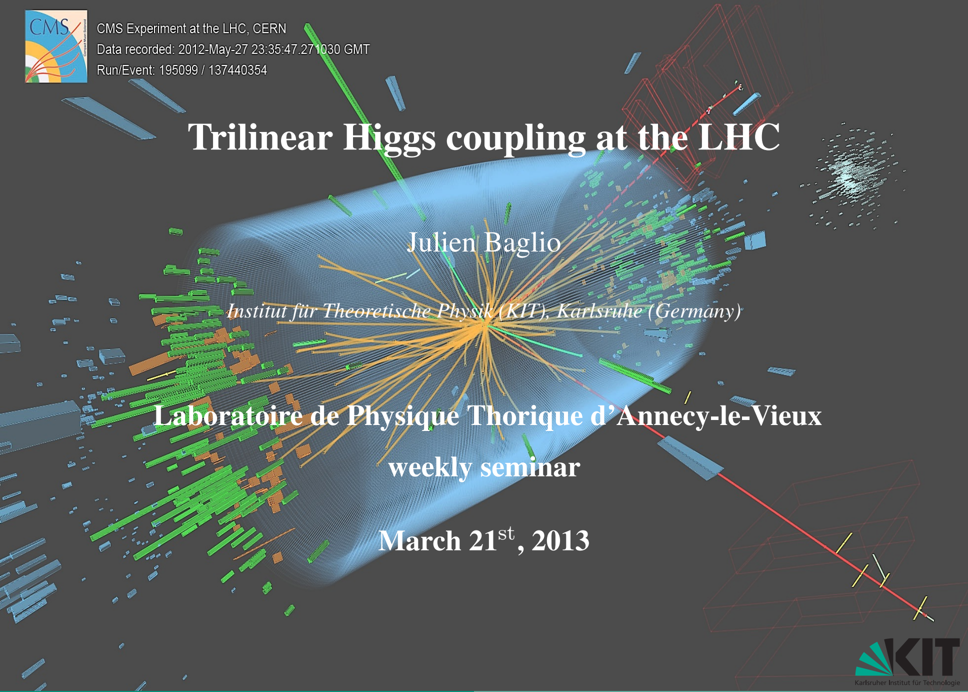

Trilinear Higgs coupling at the LHC

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Laboratoire de Physique Thorique d'Annecy-le-Vieux

weekly seminar

March 21st, 2013

Outline

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Electroweak symmetry breaking: why do we need the Higgs?

Weak bosons masses

Weak bosons massive, but mass terms breaks explicitely gauge symmetry:

how to produce weak bosons masses without spoiling gauge invariance?

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Unitarity in weak processes

WW, ZZ scattering (and others) $\propto s^2$ without a scalar field

Restore unitarity $\Rightarrow$ something exactly like the Higgs boson required

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Simplest solution is a complex scalar field which sponteanously breaks the SM $SU(3) \times SU(2) \times U(1)$: the Brout-Englert-Higgs-Kibble field

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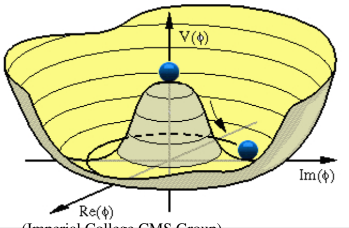
VEV $\langle 0|\phi|0\rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$ and $\phi = \begin{pmatrix} 0 \\ \frac{v + H(x)}{\sqrt{2}} \end{pmatrix}$:

mass terms for weak bosons through v

one Higgs boson in the spectrum

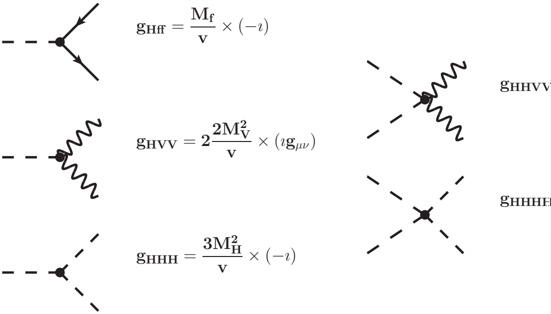
[Higgs (1964); Brout, Englert (1964); Hagen,Kibble,Guralnik (1964)]



(Imperial College CMS Group)

Higgs boson couplings

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



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 ⇒ upper bound on M_H

  [Marciano *et al* (1989),...; Cabibbo *et al* (1979); Dashen,Neuberger (1983),...]

  Stability of the vacuum ⇒ lower bound on M_H

  [Lindner, Sher (1989); Casas, Espinosa, Quiros (1995); Hambye, Riesselmann (1996),...]

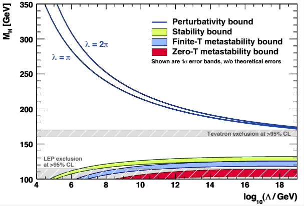
$\Lambda_{\mathrm{CUT}} = 1$ TeV: $50\ \mathrm{GeV} \lesssim M_H \lesssim 750\ \mathrm{GeV}$

$\Lambda_{\mathrm{CUT}} = 10^{16}$ GeV: $130\ \mathrm{GeV} \lesssim M_H \lesssim 180\ \mathrm{GeV}$

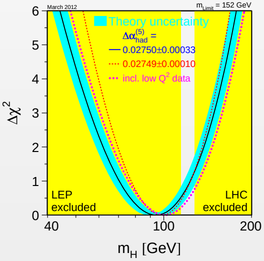
- Precision data fit ($M_Z, \Gamma_Z, M_W, \Delta^{\mathrm{had}}\alpha_s$, etc):

$M_H \leq 152$ GeV @ 95% CL

[Ellis, Espinosa (2009)]



[LEPEWG (2012)]



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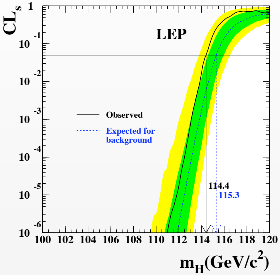
Direct searches at LEP and Tevatron

[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

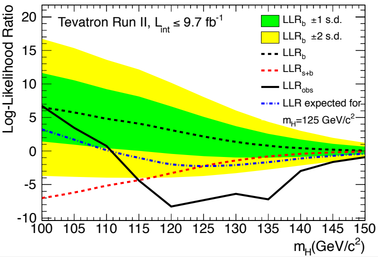


- Latest Tevatron run II result:

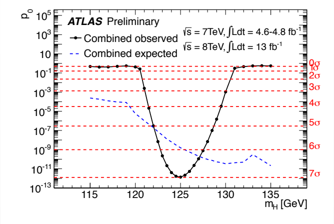
Broad $\geq 2\sigma$ excess in $115 \leq M_H \leq 140$ GeV

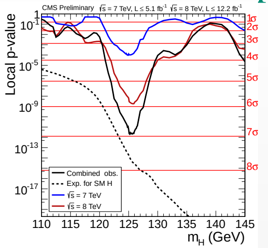
[TEVNPHWG, Phys.Rev.Lett. 109, 071804 (2012)]

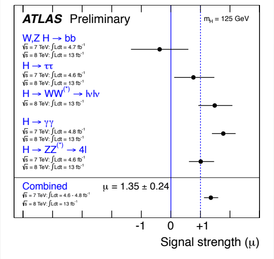
(not updated since HCP 2012)

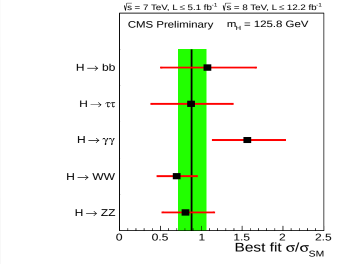


Higgs status at the LHC: observation of a scalar particle









$$M_H = 125.5 \pm 0.2(\text{stat}) \pm 0.6(\text{sys})\ [\text{ATLAS}]$$
$$M_H = 125.8 \pm 0.4(\text{stat}) \pm 0.4(\text{sys})\ [\text{CMS}]$$

[ATLAS, Phys.Lett. B716 (2012) 1-29; CMS *ibid* 30-61; ATLAS-CONF-2013-014; CMS-HIG-12-045]

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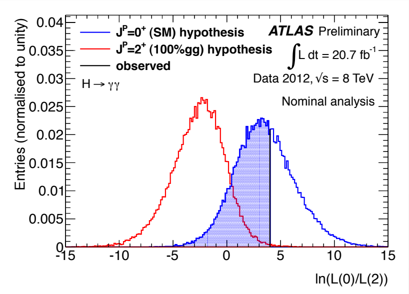
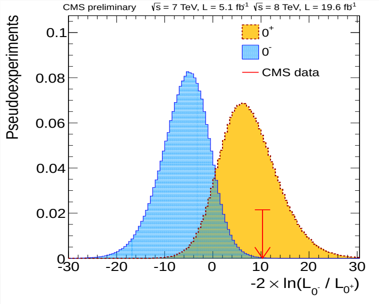
Higgs status at the LHC: spin/parity early measurments

Spin/parity measured through angular correlations in $H \to \gamma\gamma$ and $H \to ZZ \to 4\ell$ channels



$H \to \gamma\gamma$ analysis [ATLAS-CONF-2013-029]



$H \to ZZ \to 4\ell$ analysis [CMS PAS HIG-13-002]

Latest results point towards the observation of 0^+ boson with couplings to fermions and gauge bosons $\Leftrightarrow$ **SM Higgs boson**

SM Higgs pair production at the LHC

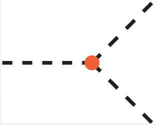
Motivation: probing the Higgs potential

- **From the scalar potential before EWSB:** with a scalar $SU(2)$–doublet field ϕ, $Y_\phi = 1$:

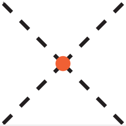
$$V(\phi) = -m^2|\phi|^2 + \lambda|\phi|^4$$

- **$\mathbf{V(\phi)}$ after EWSB, with $\mathbf{M_H^2 = 2m^2}$, $\mathbf{v^2 = m^2/\lambda}$:**

$$\phi = \begin{pmatrix} 0 \\ \frac{v + H(x)}{\sqrt{2}} \end{pmatrix} \Rightarrow V(H) = \frac{1}{2}M_H^2 H^2 + \frac{1}{2}\frac{\mathbf{M_H^2}}{\mathbf{v}}\mathbf{H^3} + \frac{1}{8}\frac{M_H^2}{v^2}H^4 + \text{constant}$$



$$\frac{3\mathbf{M_H^2}}{\mathbf{v}} \times (-\imath)$$



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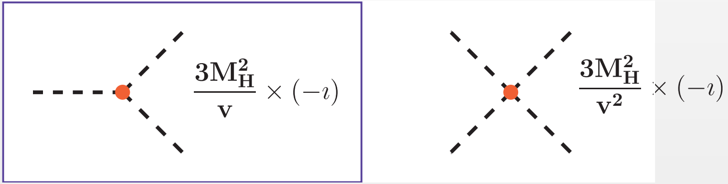
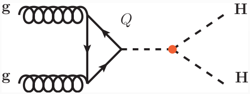


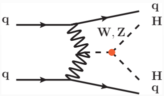
The main production channels

- gluon fusion



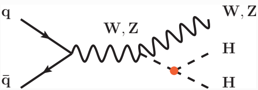
NLO in QCD

- vector boson fusion



NLO in QCD (new!)

- double Higgs–strahlung



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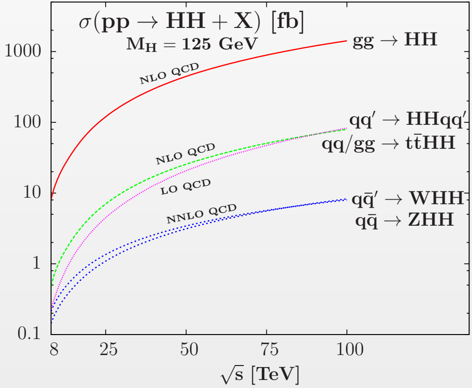
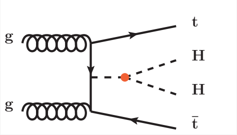


- associated production with top quark



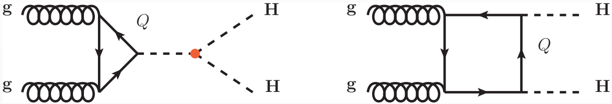
LO in QCD

$\sim$ 1000 times smaller than single Higgs cross section

[J.B., Djouadi, Gröber, Mühlleitner, Quevillon, Spira (2012)]

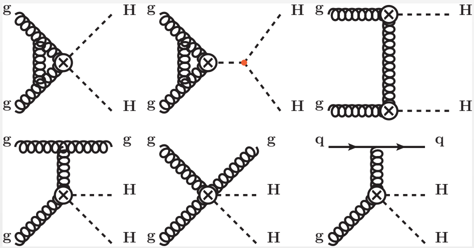
Gluon fusion: the largest cross section

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



LO inclusive cross section known exactly ($t + b$ loops) [Eboli *et al* (1987); Glover, v.d. Bij (1988); Dicus, Kao, Willenbrock (1988); Jikia (1994)]

QCD corrections to inclusive rate: NLO corrections in the low energy limit $\sqrt{\hat{s}} \ll m_t$ [Dawson, Dittmaier, Spira (1998)]



K–factor $\simeq 2$

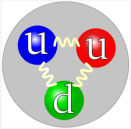
$\sqrt{s}$ [TeV]	$\sigma^{\rm NLO}$ [fb]
8	8.2
14	33.9
33	207.3
100	1417.8

Interlude: parton distribution functions (PDF)

Parton Distribution Functions (PDFs)

Probability density of a given parton (quarks, gluons) to be extracted from the (anti)proton with a fraction x of the (anti)proton momentum

Non–perturbative quantity, fitted on data by different collaborations
$\Rightarrow$ different sets on the market: MSTW, CTEQ, ABKM, HERA, etc



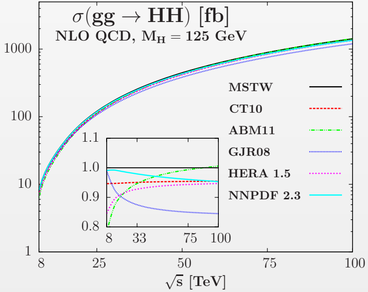
Hadronic cross section

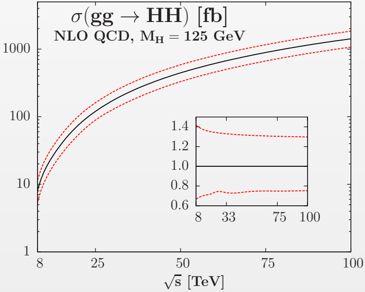
$$\sigma\left(pp \to A\, B\right) = \sum_{i,j=g,q} \int_0^1 dx_1 \int_0^1 dx_2 f_i(x_1) f_j(x_2) \hat{\sigma}_{ij}\left(\hat{s} = x_1 x_2 S\right) \Theta\left(\hat{s} \geq \left(M_A + M_B\right)^2\right)$$

Gluon fusion: theoretical uncertainties

$gg \to$ HH affected by sizeable uncertainties:

- Scale uncertainty: calculated at NLO with $\frac{1}{2}\mu_0 \leq \mu_R, \mu_F \leq 2\mu_0$, $\mu_0 = M_{HH}$;
  $\Delta^{\rm scale} \simeq +20\%(+12\%)/-17\%(-10\%)$ at $\sqrt{s} = 8(100)$ TeV
- PDF uncertainty: gluon PDF at high$-x$ less constrained, $\alpha_s(M_Z^2)$ uncertainty
  $\Rightarrow$ large discrepancy between PDFs predictions
  $\Delta^{\rm PDF+\alpha_s}_{90\%{\rm CL}} \simeq \pm 9\%$ ($\simeq \pm 6\%$ at 100 TeV) uncertainty
- EFT approximation: NLO correction only known in the $\sqrt{\hat{s}} \ll m_t$ approximation
  conservative estimate of $\Rightarrow \pm 10\%$ uncertainty





Total uncertainty: $\simeq \pm 40\%$ ($\simeq \pm 30\%$ at 100 TeV)

[J. B., Djouadi, Gröber, Mühlleitner, Quevillon, Spira (2012)]

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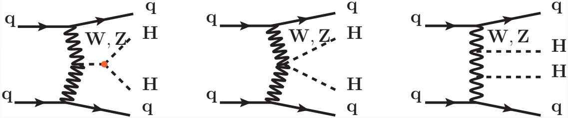
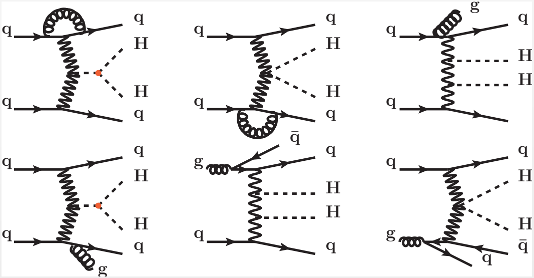
Vector boson fusion at NLO

$pp \to qq \to qq\,WW/ZZ \to qqHH$: the second production channel at the LHC



LO inclusive cross section known for a while [Keung (1987); Eboli *et al* (1987); Dicus, Kao, Willenbrock (1988); Dobrovolskaya, Novikov (1991)]

QCD corrections to inclusive rate: **new NLO corrections in the structure function approach** [J.B., Djouadi, Gröber, Mühlleitner, Quevillon, Spira (2012)] **implemented in `VBFNLO`** [Zeppenfeld *et al* (2008)]



$\simeq +7\%$ correction
(similar to single Higgs case)

$\sqrt{s}$ [TeV]	$\sigma^{\rm NLO}$ [fb]
8	0.49
14	2.01
33	12.05
100	79.55

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Interlude: handling infrared singularities in VBFNLO

- How to handle singularities in cross–section calculation? UV divergences treated with renormalization, e.g. usually $\overline{\text{MS}}$–scheme for QCD corrections
- What about Infrared singularities? Soft and collinear singularies may arise, notabely cumbersome as arising in different phase–spaces ⇒ substraction method to handle them!

$$\sigma^{\text{NLO}} = \int_{\phi_n} d\sigma^{\text{Born}} + \int_{\phi_n} d\sigma^{\text{virt}} + \int_{\phi_{n+1}} d\sigma^{\text{real}}$$

with each contribution divergent ⇒ cancel soft & collinear singularities before Monte-Carlo integration:

$$\sigma^{\text{NLO}} = \int_{\phi_n+1} \left(d\sigma^{\text{real}}|_{\varepsilon=0} - d\sigma^{A}|_{\varepsilon=0} \right) + \int_{\phi_n} \left(d\sigma^{\text{Born}} + d\sigma^{\text{virt}} + \int_{\phi_1} d\sigma^{\text{A}} \right) |_{\varepsilon=0}$$

where $d\sigma^{\text{A}}$ a substraction term with the following properties:

- $d\sigma^{\text{A}}$ cancels soft & collinear divergences of $d\sigma^{\text{real}}$
- $\int_{\phi_1} d\sigma^{\text{A}}$ done (partially) analytically in d dimensions ⇒ I, P, K operators,left–over collinear singularities absorbed into PDFs

The calculation has been done in VBFNLO with Catani-Seymour dipoles

[Catani, Seymour, Nucl.Phys. B485 (1997) 291]

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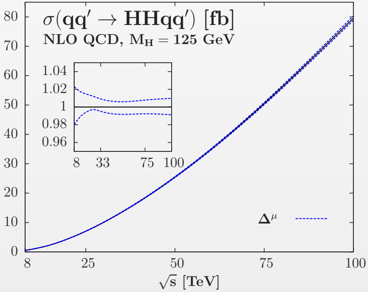
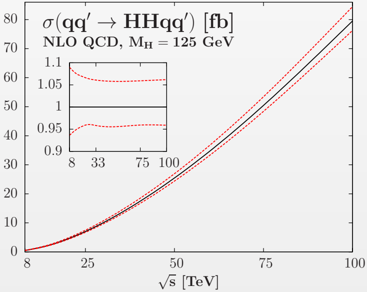
Vector boson fusion: theoretical uncertainties

$qq \to HHqq$ is a clean process:

- Scale uncertainty: calculated at NLO with $\frac{1}{2}\mu_0 \leq \mu_R, \mu_F \leq 2\mu_0$, $\mu_0 = Q_{W/Z}$;
  $\Delta^{\rm scale} \simeq +3\%(+2\%)/-2\%(-1\%)$ at $\sqrt{s} = 8(33)$ TeV
  Good precision compared to LO $\Delta^{\rm scale} \simeq \pm 10\%$
- PDF uncertainty: total $\Delta^{\rm PDF+\alpha_s}_{90\%\rm CL} \simeq +7\%/-4\%$
  ($\simeq +5\%/-4\%$ at 33 TeV)





Total uncertainty: $\simeq +8\%/-5\%$ (14 TeV) [J. B., Djouadi, Gröber, Mühlleitner, Quevillon, Spira (2012)]

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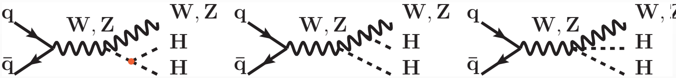
Associated W/Z + Higgs pair production

$\mathbf{pp \to Z^*/W^* \to Z/W + HH}$: clean but very small rates



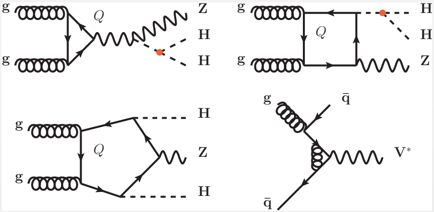
[Barger, Han, Phillips (1988)]

- NLO QCD corrections: Drell-Yan $\sigma(pp \to V^*)$ corrections $\simeq +20\%$

  [J.B., Djouadi, Gröber, Mühlleitner, Quevillon, Spira (2012)]

- **new** NNLO QCD corrections: Drell-Yan $\simeq +4\%$ [J.B., Djouadi, Gröber, Mühlleitner, Quevillon, Spira (2012)]

- **new** NNLO QCD corrections (II): specific $gg \to ZHH$ channel $\Rightarrow \simeq +20$ - 30%, sharp contrast with $\simeq +5\%$ in ZH production [J.B., Djouadi, Gröber, Mühlleitner, Quevillon, Spira (2012)]



$\sqrt{s}$ [TeV]	$\sigma^{\rm NNLO}_{WHH}$ [fb]	$\sigma^{\rm NNLO}_{ZHH}$ [fb]
8	0.21	0.14
14	0.57	0.42
33	1.99	1.68
100	8.00	8.27

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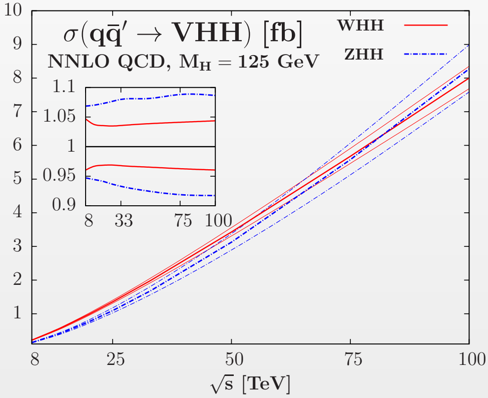
Theoretical uncertainties in double Higgs–strahlung

pp → VHH is also a very clean process:

- Scale uncertainty: calculated at NNLO with $\frac{1}{2}\mu_0 \le \mu_R, \mu_F \le 2\mu_0$, $\mu_0 = M_{VHH}$;
  $\Delta^{\rm scale} < 1\%$ in *WHH* channel
  In *ZHH* channel, worse due to $gg \to ZHH$: $\Delta^{\rm scale}_{ZHH} \simeq \pm 3\%$

- PDF uncertainty: total $\Delta^{\rm PDF+\alpha_s}_{\rm 90\%CL} \simeq \pm 4\%$ ($\simeq \pm 3\%$ at 100 TeV)



Total uncertainty:

$\Delta^{\rm tot}_{\rm WHH} \simeq \pm 4\%$, $\Delta^{\rm tot}_{\rm ZHH} \simeq \pm 7\%$

[J. B., Djouadi, Gröber, Mühlleitner, Quevillon, Spira (2012)]

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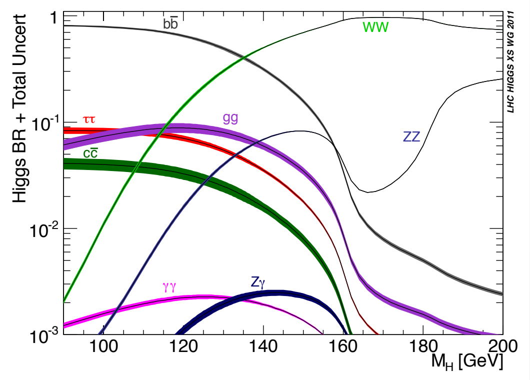
Parton level analysis at the 14 TeV LHC

Parton level analysis: overview of the main channels

Where to look for HH production? production cross section small $\Rightarrow$ use $H \to b\bar{b}$ decay channel at least once to retain some signal



3 interesting final states *a priori*:

- $b\bar{b}W(\to \ell\nu)W(\to \ell\nu)$: difficult because of MET, not promising [J. B., Djouadi, Gröber, Mühlleitner, Quevillon, Spira (2012)]
- $b\bar{b}\gamma\gamma$: rates very small, lots of fake photon identification, still promising?
- $b\bar{b}\tau\tau$: clean leptonic channel, rates small, but promising

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Signal analysis in $b\bar{b}\tau\tau$ final state

Our parton level analysis: `Pythia 6` using $gg \to HH$ matrix elements from `HPAIR`, rates rescaled to (N)NLO through K–factors, tag efficiency of 70% (b) and 50% (τ)

	HH	$b\bar{b}\tau\tau$	$t\bar{t}$	ZH [NNLO]
LHC 14 TeV K–factor	1.88	1.21	1.35	1.33

Main backgrounds considered:

- continuum production: $pp \to b\bar{b}\tau\tau$; $b\tau^+\nu_\tau\, \bar{b}\tau^-\bar{\nu}_\tau$ (mainly from $t\bar{t}$ production)
- $ZH \to b\bar{b}\tau\tau$ production

Cut strategy: kinematic acceptance cuts + boosted topology cuts:

- $p_T(b/\tau) > 30$ GeV, $|\eta(b/\tau)| < 2.4$, $112.5 \text{ GeV} < M_{b\bar{b}} < 137.5$ GeV
- $M_{HH} > 350$ GeV, $p_T(H) > 100$ GeV, $100 \text{ GeV} < M_{\tau\tau} < 150$ GeV
- Optimistic scenario: $112.5 \text{ GeV} < M_{\tau\tau} < 137.5$ GeV

	HH	$b\bar{b}\tau\bar{\tau}$	$b\bar{b}\tau\bar{\tau}\nu_\tau\bar{\nu}_\tau$	ZH	S/B	$S/\sqrt{B}$
$\sigma_{\text{(N)NLO}}$ [fb]	2.47	2.99×10^{4}	8.17×10^{3}	2.46×10^{1}	6.48×10^{-5}	6.93×10^{-1}
Higgs from $\tau\tau$	2.09×10^{-1}	8.35×10^{1}	1.58×10^{2}	5.70×10^{-1}	8.63×10^{-4}	7.36×10^{-1}
Higgs from $b\bar{b}$	1.46×10^{-1}	6.34×10^{-1}	1.43×10^{1}	3.75×10^{-2}	9.75×10^{-3}	2.07
Cut on M_{HH}	1.30×10^{-1}	1.37×10^{-1}	1.74	1.26×10^{-2}	6.88×10^{-2}	5.18
Cut on $p_T(H)$	1.10×10^{-1}	7.80×10^{-2}	7.17×10^{-1}	1.15×10^{-2}	1.36×10^{-1}	**6.71**
Optimistic	1.10×10^{-1}	3.41×10^{-2}	3.76×10^{-1}	3.15×10^{-3}	2.67×10^{-1}	**9.37**

Optimistic expected significance at 14 TeV, $\mathcal{L} = 3000\ (300)\ \text{fb}^{-1}$:
$S/\sqrt{B} = 9.37\ (2.97)$, 330 (33) signal events

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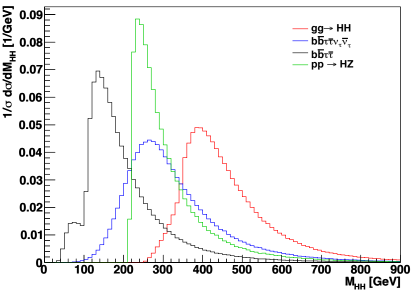

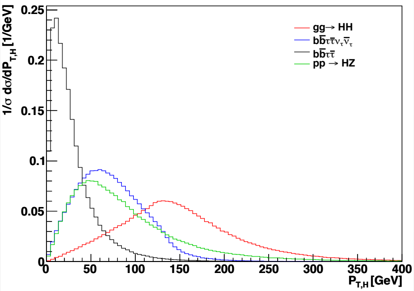

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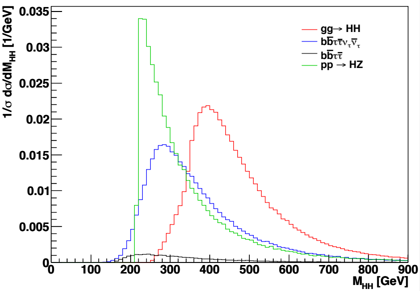

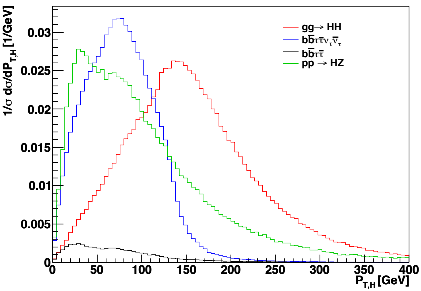

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Signal analysis in $b\bar{b}\gamma\gamma$ final state

Our parton level analysis: same set-up, ignore fake photon identification in a first step

	HH	$b\bar{b}\gamma\gamma$	$t\bar{t}H$	ZH [NNLO]
LHC 14 TeV K–factor	1.88	1.0	1.10	1.33

Main backgrounds considered:

- continuum production: $pp \to b\bar{b}\gamma\gamma$
- $t\bar{t}H$ production with $H \to \gamma\gamma$ and $t \to W^+ b$ decays, $ZH \to b\bar{b}\gamma\gamma$ production

Cut strategy: kinematic acceptance cuts + boosted topology cuts:

- $p_T(b/\gamma) > 30$ GeV, $|\eta(b/\gamma)| < 2.4$, $\Delta R(b/\gamma, b/\gamma) > 0.4$
- $120 \text{ GeV} < M_{\gamma\gamma} < 130$ GeV, $112.5 \text{ GeV} < M_{b\bar{b}} < 137.5$ GeV
- $M_{HH} > 350$ GeV, $p_T(H) > 100$ GeV, $|\eta_H| < 2$, $\Delta R(b,b) < 2.5$

	HH	$b\bar{b}\gamma\gamma$	$t\bar{t}\gamma\gamma$	ZH	S/B	$S/\sqrt{B}$
$\sigma_{\text{(N)NLO}}$ [fb]	8.92×10^{-2}	5.05×10^{3}	1.39	3.33×10^{-1}	1.77×10^{-5}	6.87×10^{-2}
Higgs from $b\bar{b}$	4.37×10^{-2}	4.01×10^{2}	8.70×10^{-2}	1.24×10^{-3}	1.09×10^{-4}	1.20×10^{-1}
Higgs from $\gamma\gamma$	3.05×10^{-2}	1.78	2.48×10^{-2}	3.73×10^{-4}	1.69×10^{-2}	1.24
Cut on M_{HH}	2.73×10^{-2}	3.74×10^{-2}	7.45×10^{-3}	1.28×10^{-4}	6.07×10^{-1}	7.05
Cut on $p_T(H)$	2.33×10^{-2}	3.74×10^{-2}	5.33×10^{-3}	1.18×10^{-4}	5.44×10^{-1}	6.17
Cut on η_H	2.04×10^{-2}	1.87×10^{-2}	3.72×10^{-3}	9.02×10^{-5}	9.06×10^{-1}	7.45
Cut on $\Delta R(b,b)$	1.71×10^{-2}	0.00	3.21×10^{-3}	7.44×10^{-5}	5.21	16.34
"Detector level"	1.56×10^{-2}	0.00	8.75×10^{-3}	8.74×10^{-3}	8.92×10^{-1}	6.46

Rough detector level expected significance at 14 TeV, $\mathcal{L} = 3000$ fb^{-1}:
$S/\sqrt{B} = 6.46$, 47 signal events

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	HH	$b\bar{b}\gamma\gamma$	$t\bar{t}H$	ZH [NNLO]
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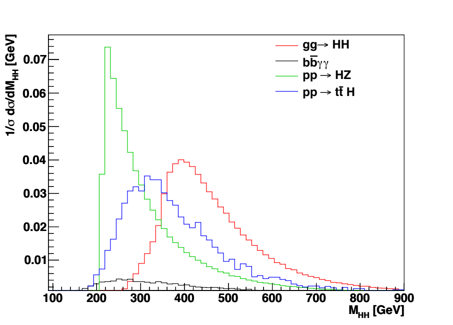

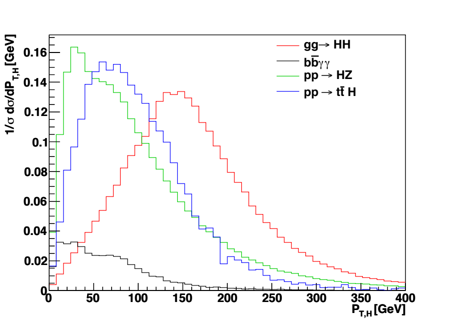

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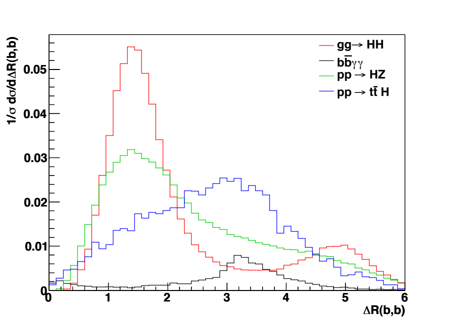

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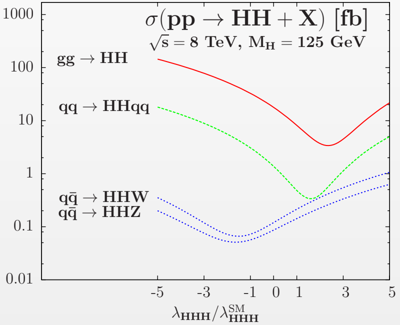
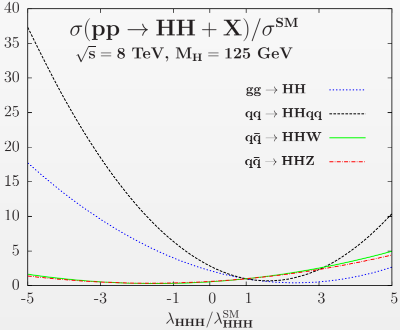
Triple Higgs coupling sensitivity in the production channels

How sensitive are the three main channels to HHH coupling?

Update of a study done in [Djouadi, Kilian, Mühlleitner, Zerwas, Eur.Phys.J. C10 (1999) 45-49]

- VBF mode is the most sensitive channel
- Identical shape when increasing the center–of–mass energy but reduced sensibility





[J. B., Djouadi, Gröber, Mühlleitner, Quevillon, Spira (2012)]

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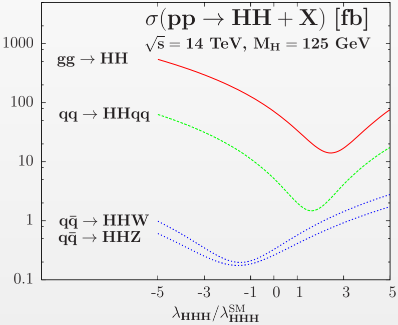

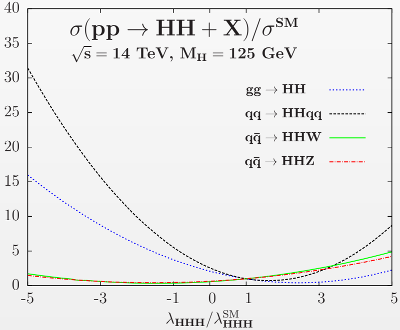

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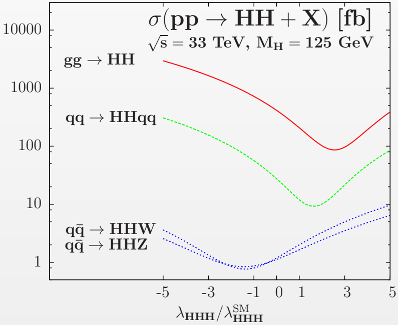
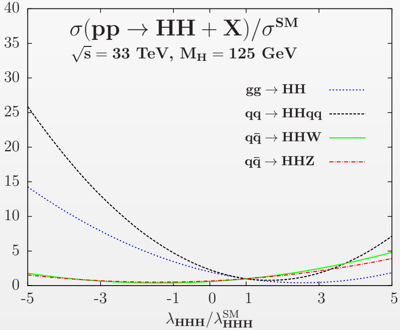




[J. B., Djouadi, Gröber, Mühlleitner, Quevillon, Spira (2012)]

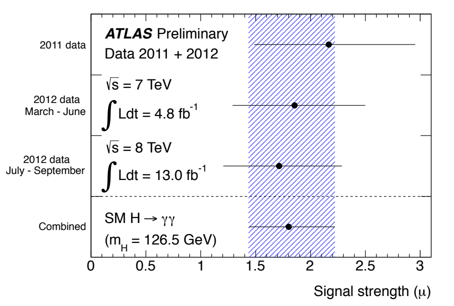
Beyond the SM Higgs?

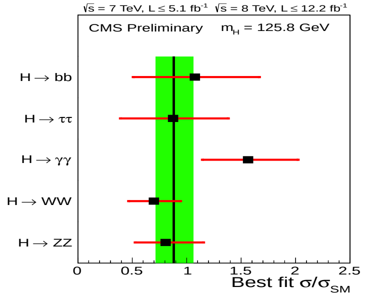
[P. Tanedo, Quantum Diaries blog]

But which Higgs boson have been observed?

Beyond the SM Higgs?

The observed scalar particle is fairly SM–like, but...

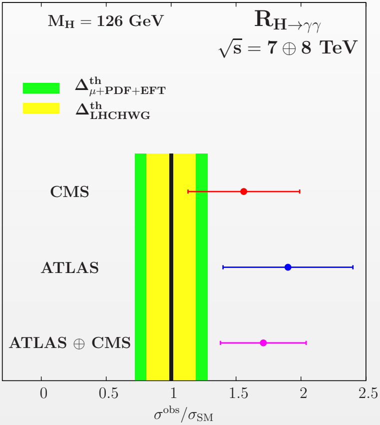


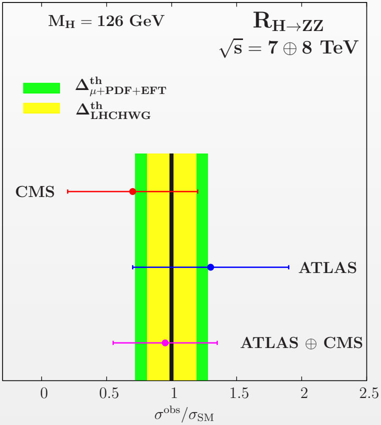


Data seems to indicate a **2σ deviation** w.r.t SM Higgs boson expectation in $H \to \gamma\gamma$ channel

Beyond the SM Higgs?

What about QCD uncertainties? Compare data with theoretical prediction including theoretical uncertainty:





Deviation **reduced** to **1**σ level, still there though... [J.B., Djouadi, Godbole (2012)]

Beyond the SM Higgs?

Summary and outlook

Trilinear Higgs coupling at the LHC:

- **Major news from 2012: the observation of a scalar particle at the LHC compatible with the SM Higgs boson**
- After the Higgs discovery, the next step is the Higgs couplings measurements:

  HHH coupling of utmost importance for the scalar potential measurement
- **Update of the major *HH* production channels to include higher order effects in the inclusive calculations:** VBF process now at NLO, Higgs–strahlung at NNLO

  $\Rightarrow$ **uncertainties $<$ 10% in VHH and VBF channels**

  a thorough analysis of **gg $\rightarrow$ HH** NLO uncertainties leads to

  $+40\%/-30\%$ total error at 14 TeV
- **HH Parton level analysis: $b\bar{b}\tau\tau$ channel really promising even already at $\mathcal{L} = 300$ fb^{-1}, $b\bar{b}\gamma\gamma$ may also be interesting at $\mathcal{L} = 3000$ fb^{-1}** $\Rightarrow$ more studies needed!

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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 $\Rightarrow \left|\int_{-s}^{0} dt \mathcal{A}(t) dt\right| < 8\pi s$

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

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