



# SM HH production and Higgs self coupling at the LHC and beyond

*SM@LHC 2015*, Galileo Galilei Institute, Florence, Italy

Julien Baglio | 23. 04. 2015

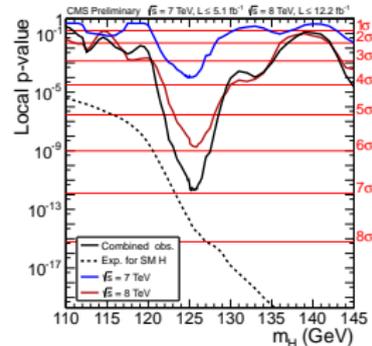
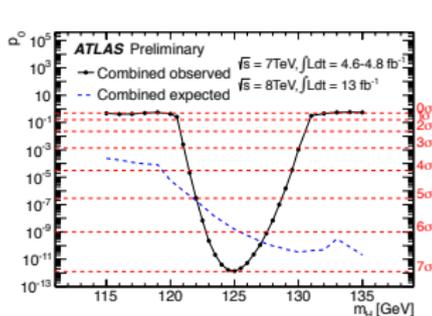
INSTITUT FÜR THEORETISCHE PHYSIK



- 1 Introduction
- 2 SM Higgs pair production at the LHC
- 3 Status of the studies of the triple Higgs coupling in the SM
- 4 Outlook

# Once upon a time...

4/7/2012: CERN presents the discovery of a bosonic particle  
Its properties are compatible with those of the Higgs boson



$$M_H \simeq 125.5 \text{ GeV}$$

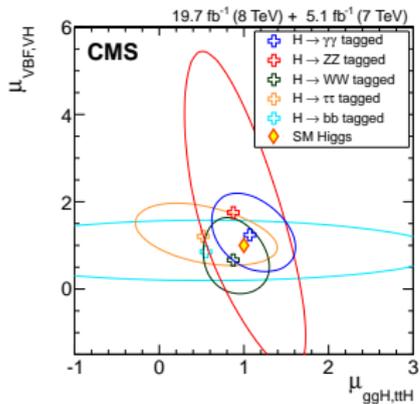
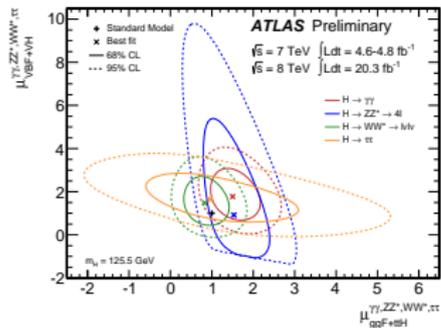
[ATLAS, Phys.Lett. B716 (2012) 1; CMS *ibid* 30]

2013 analyses have confirmed the discovery of a Higgs boson: spin 0, couplings to fermions and bosons as a function of their masses  $\Rightarrow$  2013 Nobel Prize awarded to Englert and Higgs

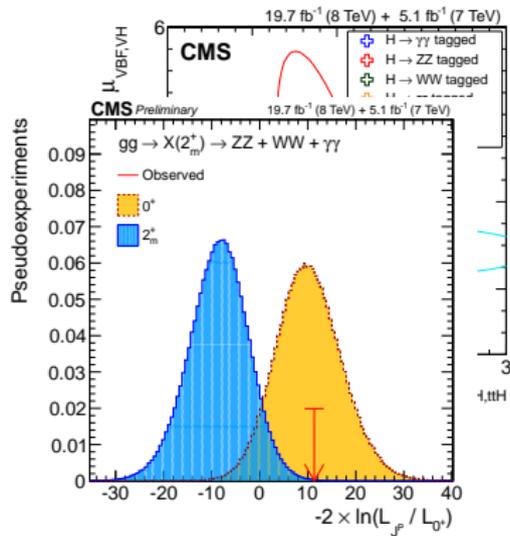
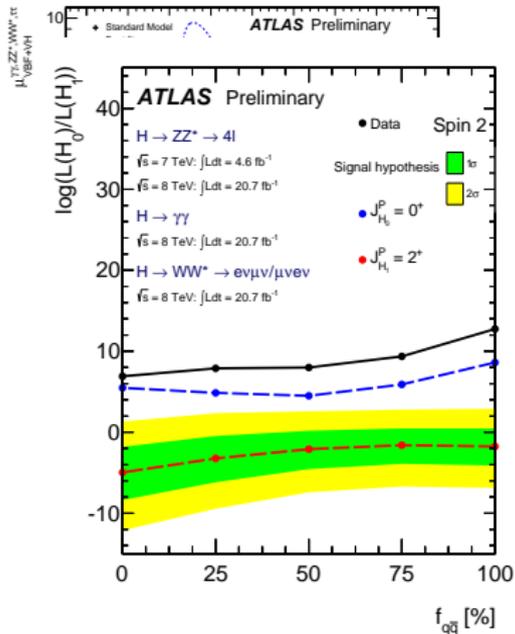


**Key question: what is the exact nature of the observed Higgs boson? Standard Model (SM)-like or more exotics?**

# Coining the scalar boson

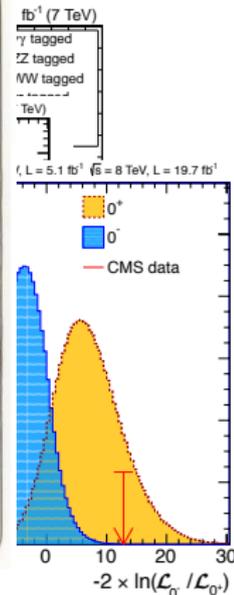
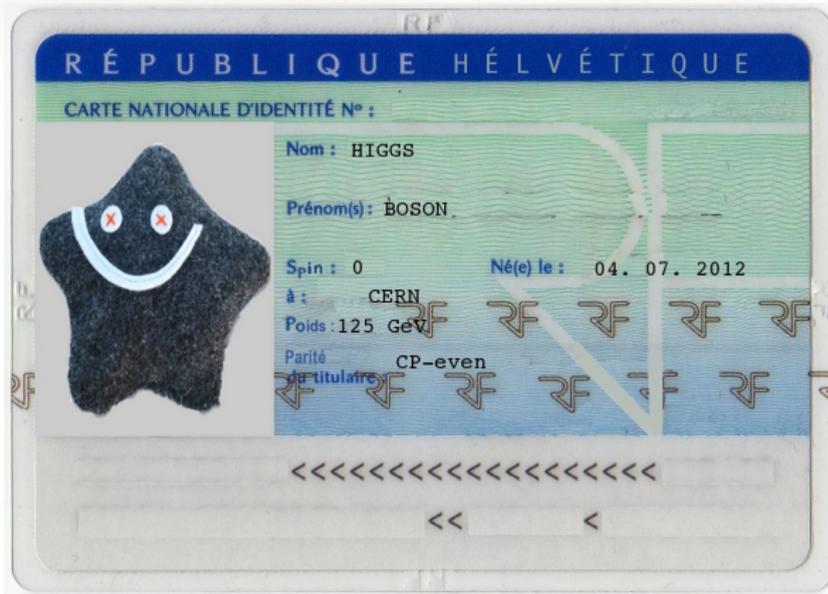


# Coining the scalar boson





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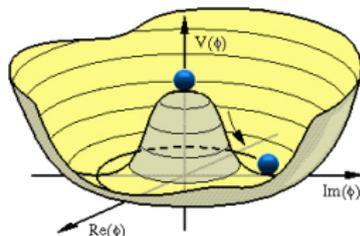
**CP-even spin 0 hypothesis strongly preferred, no significant deviations from SM couplings: data up to now points toward a SM Higgs boson...**

See Rebeca's talk on Wednesday morning about the spin, anomalous couplings, and CP structure of the Higgs boson (and references therein)

# The SM ultimate test: probing the scalar potential

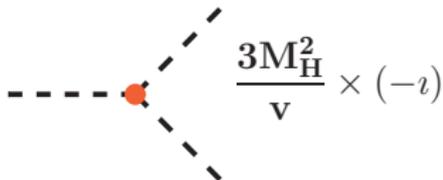
- From the scalar potential before EWSB:

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

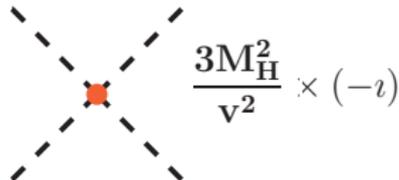


- To  $V(\phi)$  after EWSB, with  $M_H^2 = 2m^2$ ,  $v^2 = m^2/\lambda$ :

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



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

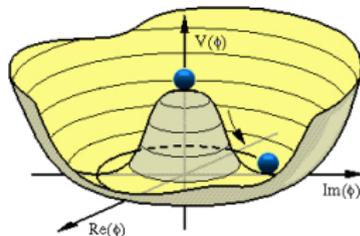


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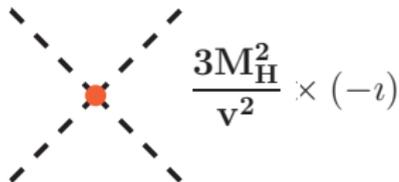
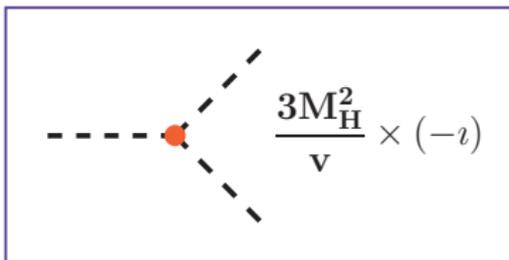
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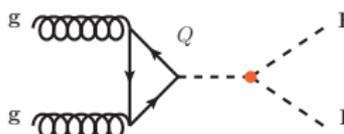


- **Quartic Higgs coupling:** not accessible at current or foreseen collider energies (up to 200 TeV) [Plehn, Rauch, PRD 72 (2005) 053008; Binoth, Karg, Kauer, Ruckl, PRD 74 (2006) 113008]
- **Early studies at lepton colliders:**
  - Studies at a **2 TeV  $e^+e^-$  collider:** SM triple Higgs coupling could be measured with a **10% accuracy** for a light Higgs, in  $\nu_e\bar{\nu}_e HH$  and  $W^+W^- HH$  modes (VBF modes) [Boudjema, Chopin, Z.Phys. C73 (1996) 85]
  - Complementary SM and MSSM studies: in addition to weak boson fusion, associated Higgs production with a weak gauge boson and triple Higgs production; **500 GeV  $e^+e^-$  collider could be enough for a 20% accuracy on the triple Higgs coupling** [Djouadi, Kilian, Muhlleitner, Zerwas, Eur.Phys.J. C10 (1999) 27]
- **Early studies at the LHC:**
  - **First study at the LHC:** theoretical predictions for  $HH$  production in the main channels, in the SM and MSSM [Djouadi, Kilian, Muhlleitner, Zerwas, Eur.Phys.J. C10 (1999) 45]
  - **Comprehensive analysis of the  $b\bar{b}\gamma\gamma$  channel:** with a very high luminosity (6000  $\text{fb}^{-1}$ )  $\lambda = 0$  can be excluded at 90% CL [Baur, Plehn, Rainwater, PRL 89 (2002) 151801; PRD 67 (2003) 033003; PRD 69 (2004) 053004]

# SM Higgs pair production at the LHC

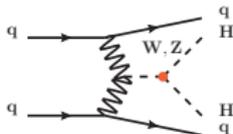
# The main production channels

- gluon fusion



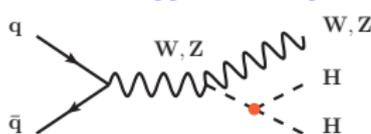
NNLO in QCD  
 (see next slides)

- vector boson fusion

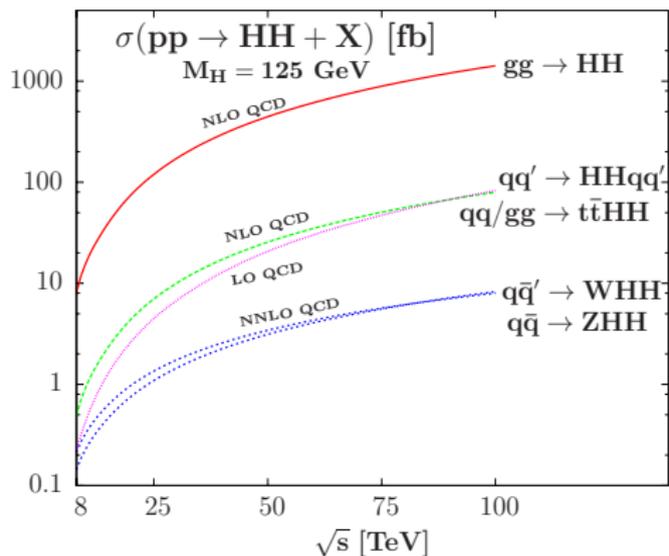


NNLO in QCD  
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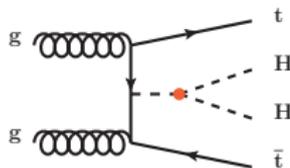
- double Higgs-strahlung



NNLO in QCD  
 [J.B. *et al*, JHEP 1304 (2013) 151]



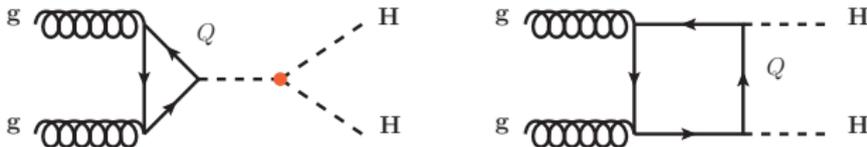
- associated production with top quark



NLO in QCD  
 [Frederix *et al*, Phys.Lett. B732 (2014) 142]

$\sim 1000$  times smaller than  $\sigma(pp \rightarrow H + X)$

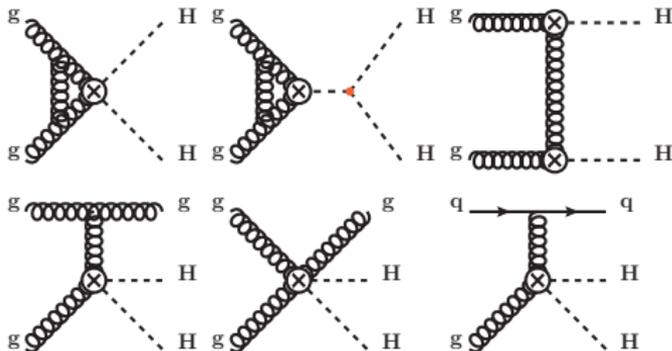
# Gluon fusion: the largest cross section



**LO** inclusive cross section known exactly ( $t + b$  loops) [Eboli *et al*, Phys.Lett. B197 (1987) 269; Glover, v.d. Bij, Nucl.Phys. B309 (1988) 282; Dicus, Kao, Willenbrock, Phys.Lett. B203 (1988) 457; Plehn, Spira, Zerwas, Nucl.Phys. B479 (1996) 46]

**QCD corrections to inclusive rate in the low energy limit  $\sqrt{s} \ll m_t$ : NLO corrections**

[Dawson, Dittmaier, Spira, PRD 58 (1998) 115012] + **NNLO corrections +20% on top of NLO rate** [De Florian, Mazzitelli, Phys.Lett. B724 (2013) 306; PRL 111 (2013) 201801]



**NLO (NNLO)  $K$ -factor  $\simeq 2$  (2.3)**

$\sqrt{s}$ [TeV]	$\sigma^{\text{NLO}}$ [fb]	$\sigma^{\text{NNLO}}$ [fb]
8	8.2	9.8
14	33.9	40.2
33	207.3	242
100	1417.8	1638

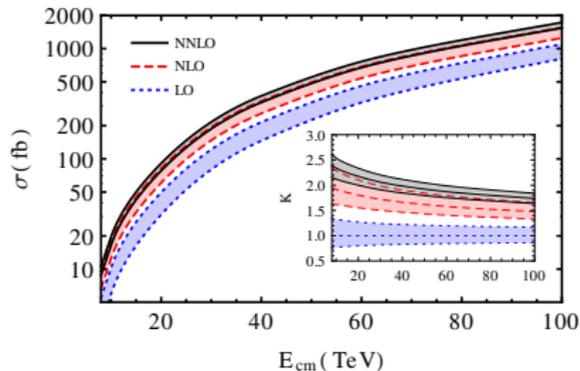
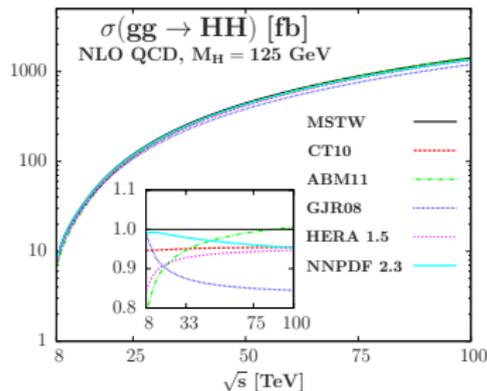
**NNLL resummation:**  $\simeq +20 - 30\%$  on top of NLO cross section, scale dependence stabilized

[Shao, C.S. Li, H.T. Li, Wang, JHEP 1307 (2013) 169]

# Gluon fusion: theoretical uncertainties

$gg \rightarrow HH$  affected by sizable uncertainties:

- Scale uncertainty:** calculated with  $\frac{1}{2}\mu_0 \leq \mu_R, \mu_F \leq 2\mu_0, \mu_0 = M_{HH}$ ;  
 $\Delta^{\text{scale}} \simeq \pm 9\% (\pm 6\%)$  at  $\sqrt{s} = 8(100)$  TeV at NNLO [De Florian, Mazzitelli (2013)]
- PDF uncertainty:** gluon PDF at high- $x$  less constrained,  $\alpha_s(M_Z^2)$  uncertainty  
 $\Rightarrow$  large discrepancy between PDFs predictions  
 $\Delta_{90\%CL}^{\text{PDF}+\alpha_s} \simeq \pm 9\% (\simeq \pm 6\% \text{ at } 100 \text{ TeV})$  uncertainty [J.B. et al (2013)]
- EFT approximation:** NLO correction only known in a top mass expansion  
 $\Rightarrow$  estimate of  $\pm 10\%$  uncertainty (confirmed in [Grigo, Hoff, Melnikov, Steinhauser, Nucl.Phys. B875 (2013) 1])



**Total NLO uncertainty:  $\simeq \pm 40\%$  ( $\simeq \pm 30\%$  at 100 TeV)** [J.B. et al (2013)]

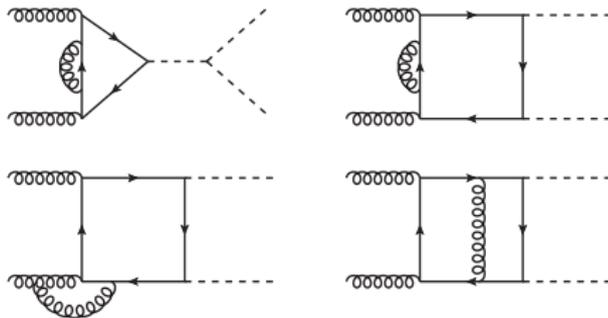
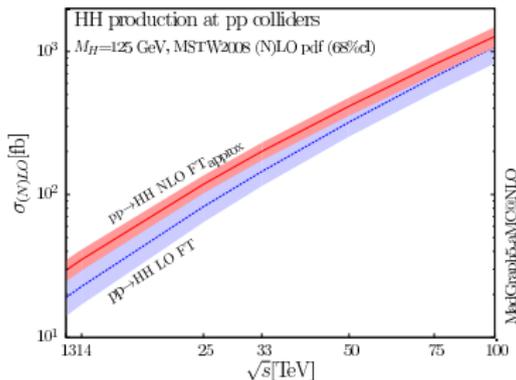
**With NNLO calculation** [De Florian, Mazzitelli (2013)], reduced to  $\pm 30\%$  ( $\pm 20\%$ ) at 8 (100) TeV

# Current issues of the gluon fusion channel

## Big issue in gluon fusion: the effective theory approach

- **Single Higgs production:** works pretty well provided a rescaling to the full Born result
- **Higgs pair production:** approximation worse than for  $\sigma(gg \rightarrow H)$  as  $m_t \gg \sqrt{s} \geq 4M_H^2$  **never** fulfilled (remember the EFT  $\pm 10\%$  uncertainty)
- **Critical: fails for the  $HH$  NLO differential distributions**

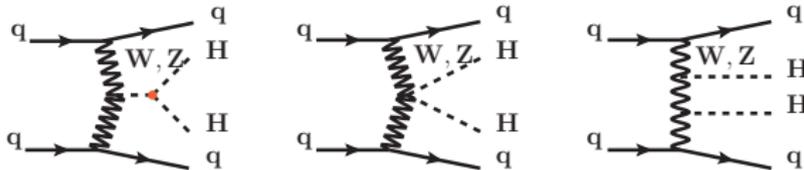
**Status early 2015:** top mass expansion [Grigo, Hoff, Melnikov, Steinhauser, Nucl.Phys. B875 (2013) 1] and improved EFT NLO with exact real corrections and Born reweighting [Maltoni, Vryodinou, Zaro, JHEP 1411 (2014) 079]



**The goal: having the full 2-loop calculation including the yet unknown box contributions**

# Vector boson fusion at NLO

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

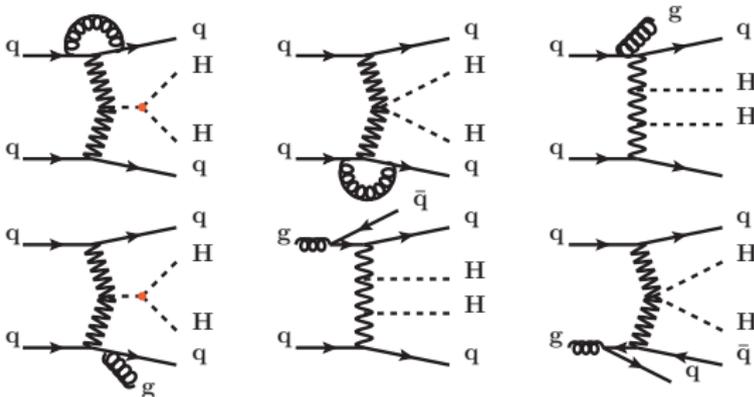


**LO** inclusive cross section known for a while [Keung, Mod.Phys.Lett. A2 (1987) 765; Eboli *et al.*, Phys.Lett. B197 (1987)

269; Dicus, Kao, Willenbrock, Phys.Lett. B203 (1988) 457; Dobrovolskaya, Novikov, Z.Phys. C52 (1991) 427]

**QCD corrections: NLO corrections to inclusive rates and differential distributions** [J.B. *et al.*, JHEP 1304 (2013) 151; Frederix *et al.*, Phys.Lett. B732 (2014) 142] **implemented in VBFNLO (publicly available)**

[Arnold *et al* CPC 180 (2009) 1661; J.B. *et al.*, arXiv:1404.3940]



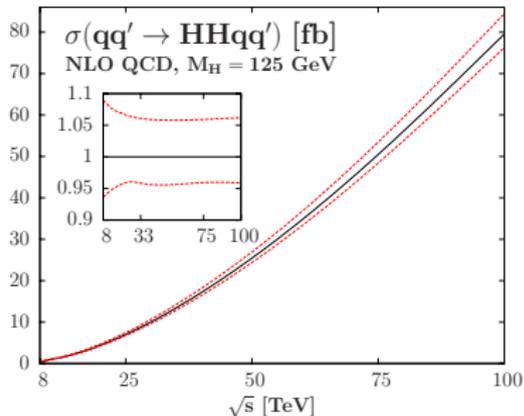
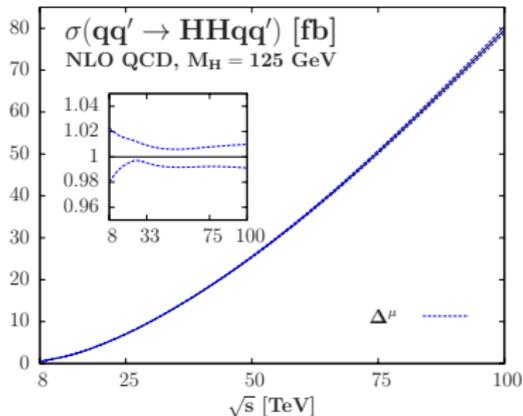
$\simeq +7\%$  correction  
(similar to single Higgs case)

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

# Vector boson fusion: theoretical uncertainties

$qq \rightarrow HHqq$  is a clean process:

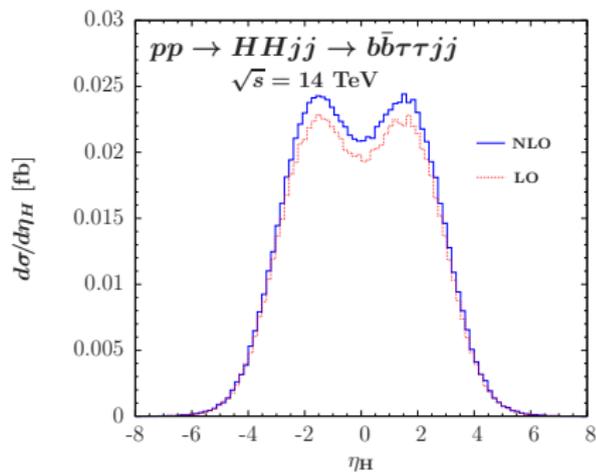
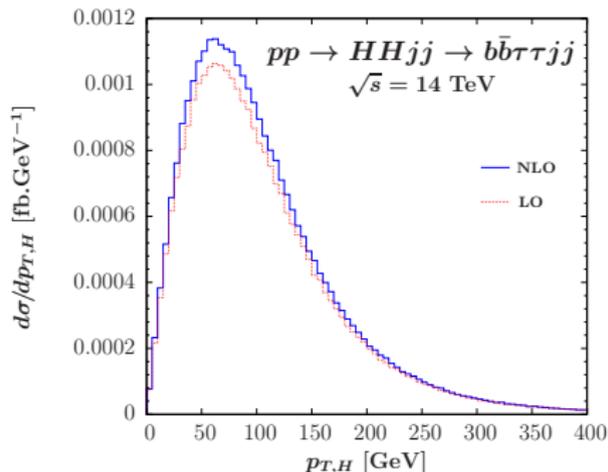
- **Scale uncertainty:** calculated at NLO with  $\frac{1}{2}\mu_0 \leq \mu_R, \mu_F \leq 2\mu_0$ ,  $\mu_0 = Q_{W/Z}$ ;  
 $\Delta^{\text{scale}} \simeq +3\%(+2\%)/-2\%(-1\%)$  at  $\sqrt{s} = 8(33)$  TeV  
Good precision compared to LO  $\Delta^{\text{scale}} \simeq \pm 10\%$
- **PDF uncertainty:**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



**Total uncertainty:**  $\simeq +8\%/-5\%$  (14 TeV)

**NNLO QCD corrections in the structure function approach:**  $+0.5\%$  on top of the NLO result, scale uncertainty at the percent level [L. Liu-Sheng *et al.*, PRD 89 (2014) 073001]

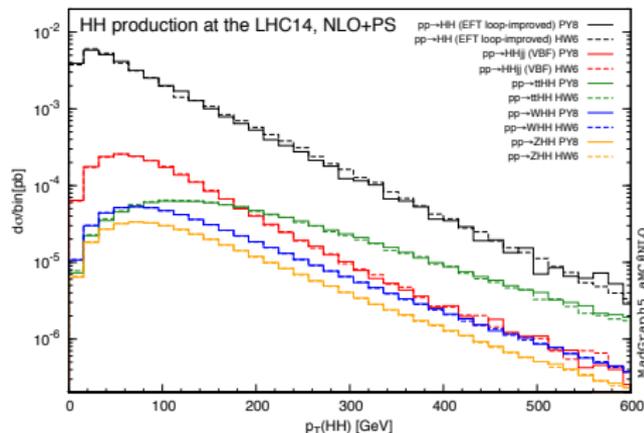
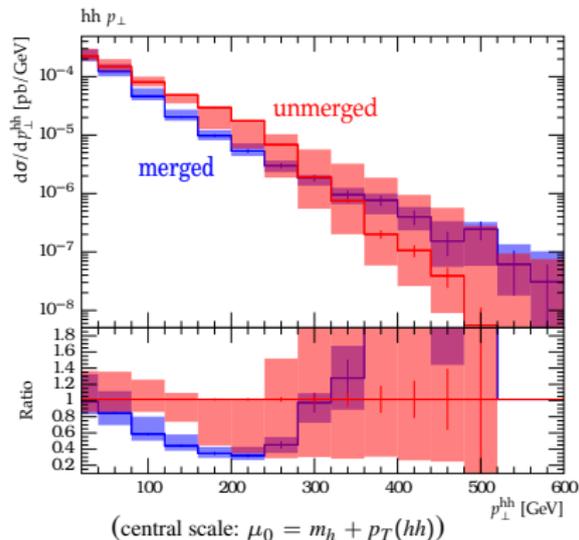
Example of NLO differential distributions with VBFNLO  
in  $VBF \rightarrow H(\rightarrow b\bar{b})H(\rightarrow \tau\tau)jj$ :



Soon to be released in the VBFNLO public version, parton shower with HERWIG is also ready

## Progress in 2014: Monte-Carlo tools including parton shower:

- $gg \rightarrow HH$  merged to 1 jet: **HERWIG++ implementation** of  $HH + 1j$  production with real radiation merged to parton shower  $\Rightarrow$  **10% theoretical uncertainty on the efficiencies of the cuts**, much better than unmerged samples [Maierhöfer, Papaefstathiou, JHEP 1403 (2014) 126]
- All main processes interfaced with parton shower in the ac@NLO framework: fully differential predictions at NLO for all channels** [Frederix *et al.*, Phys.Lett. B732 (2014) 142]

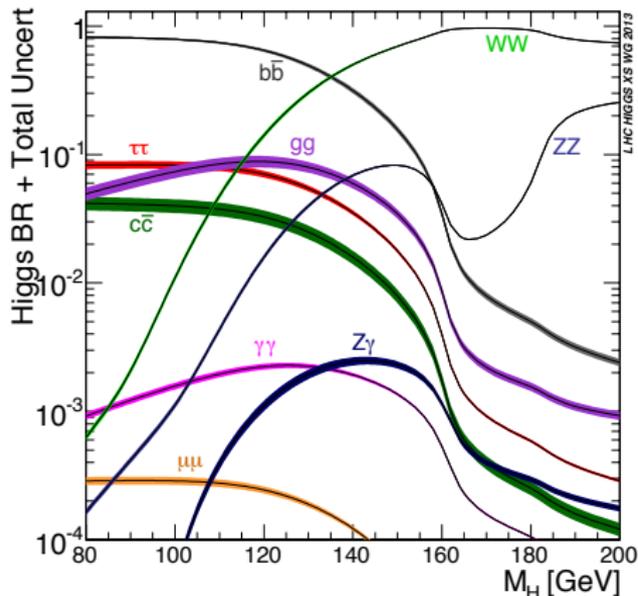


# Status of the studies of the *HHH* coupling in the SM

# Main search channels

Where to look for  $HH$  production? production cross section small

⇒ use min. one  $H \rightarrow b\bar{b}$  decay channel to retain some signal,  $\mathcal{L} = 3000 \text{ fb}^{-1}$



**Remark:**  $gg \rightarrow HH$  production channel mostly used;  $HH + 2j$  (using also VBF process)

analyses have started [Dolan, Englert, Greiner, Spannowsky, PRL 112 (2014) 101802] as well as  $pp \rightarrow t\bar{t}HH$  process

[Englert, Krauss, Spannowsky, Thompson, Phys.Lett. B743 (2015) 93; Liu, Zhang, arXiv:1410.1855]

3 interesting final states *a priori*:

- $b\bar{b}W(\rightarrow \ell\nu)W(\rightarrow 2j)$ : difficult but might be interesting with MVA techniques

[Papaefstathiou, Lin Yang, Zurita, PRD 87 (2013) 011301]

- $b\bar{b}\gamma\gamma$ : rates very small, lots of fake photon identification, but promising!

[Baur, Plehn, Rainwater, PRD 69 (2004) 053004; J.B. *et al*, JHEP 1304 (2013) 151; Barger, Everett, Jackson, Shaughnessy, Phys.Lett. B728 (2014) 433; Azatov, Contino, Panico, Son, arXiv:1502.00539]

- $b\bar{b}\tau\tau$ : rates small, but quite promising

[Barr, Dolan, Englert, Spannowsky, JHEP 1210 (2012) 112, Phys.Lett. B728 (2014) 308; J.B. *et al*, JHEP 1304 (2013) 151; etc.]

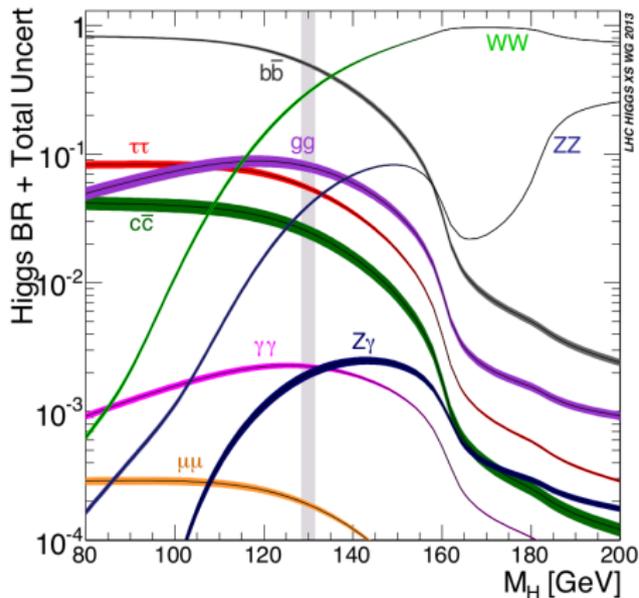
See also ATLAS/CMS first analyses;

ATLAS sees small  $2.4\sigma$  signal at 8 TeV

[ATLAS, PRL 114 (2015) 081802; CMS, arXiv:1503.04114]

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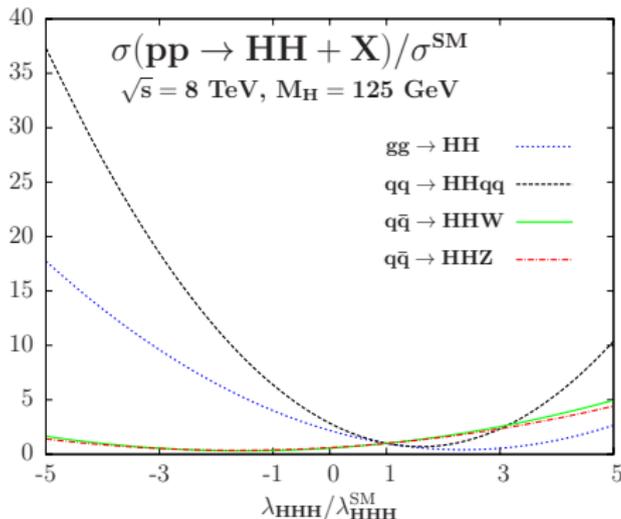
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# Triple Higgs coupling sensitivity in the production channels

## How sensitive are the three main channels to HHH coupling?

- VBF mode is the most sensitive channel
- Identical shape when increasing the energy but **reduced sensibility** (for total Xsec)



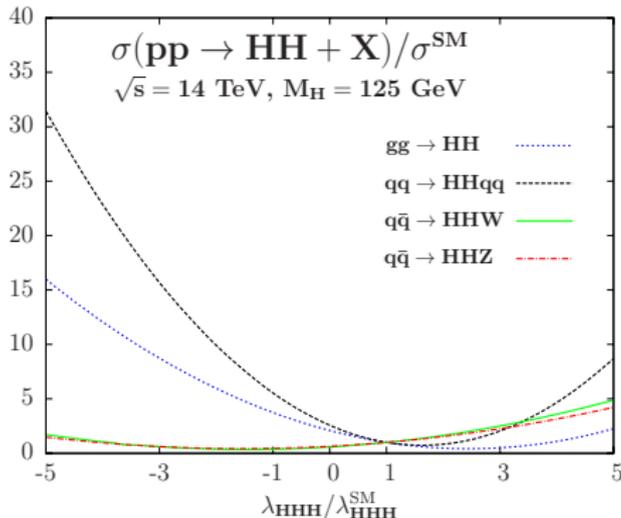
[J.B. et al, JHEP 1304 (2013) 151; see also Djouadi, Kilian, Mühlleitner, Zerwas, Eur.Phys.J. C10 (1999) 45-49]

**In gluon fusion:** interference behavior between triangle and box independent on the collider energy and maximally destructive  $\Rightarrow$  damps the trilinear coupling [Dicus, Kao, Repko, arXiv:1504.0233]

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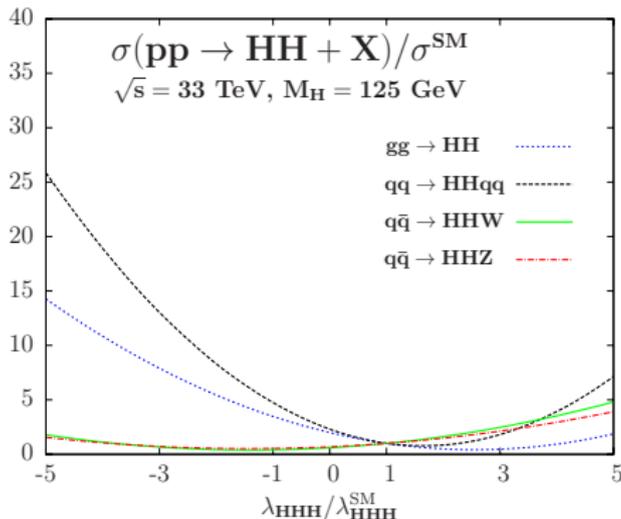
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**Jet substructure analysis, the major improvement :** fatjet analysis with boosted kinematics to distinguish in jet substructure the signal from large QCD backgrounds

[Butterworth, Davison, Rubin, Salam, PRL 100 (2008) 242001]

the idea: define a large cone size (“fatjet”) and then work backward through the jet to define and separate softer subjects

**Cut strategy:** kinematic acceptance cuts + boosted topology cuts + **Fat jet cuts**

**Results with a SHERPA/MADEVENT+HERWIG++ simulation:**

**$S/B \simeq 0.5$ , 95 signal events for  $1000 \text{ fb}^{-1}$**  [Dolan, Englert, Spannowsky, JHEP 1210 (2012) 112]

- **Adding one jet in the final state ( $hhj \rightarrow b\bar{b}\tau\tau j$ ):** with the same techniques,  $S/B \simeq 1.5$
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**Optimistic expected significance at 14 TeV,  $\mathcal{L} = 3000 (300) \text{ fb}^{-1}$ :**  
 **$S/\sqrt{B} = 9.37 (2.97)$ , 330 (33) signal events**

**Jet substructure analysis, the major improvement :** fatjet analysis with boosted kinematics to distinguish in jet substructure the signal from large QCD backgrounds

[Butterworth, Davison, Rubin, Salam, PRL 100 (2008) 242001]

the idea: define a large cone size (“fatjet”) and then work backward through the jet to define and separate softer subjects

**Cut strategy:** kinematic acceptance cuts + boosted topology cuts + **Fat jet cuts**

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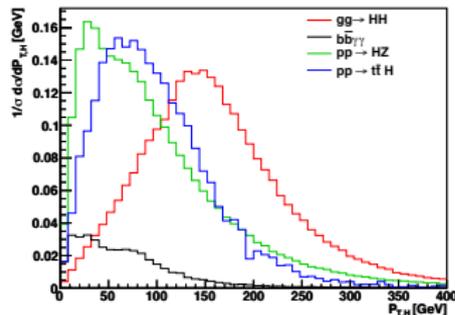
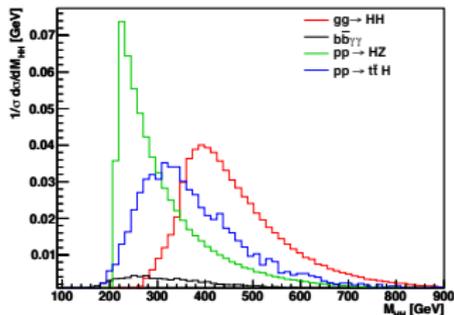
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# Signal analysis in $b\bar{b}\gamma\gamma$ final state

► **Parton level analysis in 2013:** Pythia 6 + rough detector simulation (Delphes) for fake photons, kinematic acceptance cuts + **boosted topology cuts** [J.B. et al, JHEP 1304 (2013) 151]



**Expected significance at 14 TeV,  $\mathcal{L} = 3000 \text{ fb}^{-1}$  :  $S/\sqrt{B} = 6.46$ , 47 signal events; down to 13 events with a 0.64 photon efficiency + more sophisticated evaluation of the background** [Azatov, Contino, Panico, Son, arXiv:1502.00539]

► **BDT analysis in 2014:** improved significance and probe of  $\lambda_{HHH}$  within 40% uncertainty at LHC 14 TeV with  $3 \text{ ab}^{-1}$  [Barger, Everett, Jackson, Shaughnessy, Phys.Lett. B728 (2014) 433]

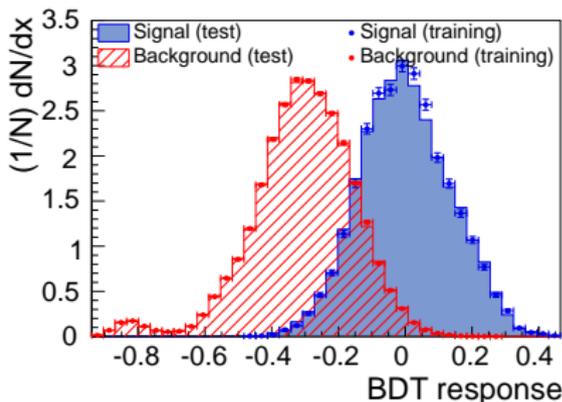
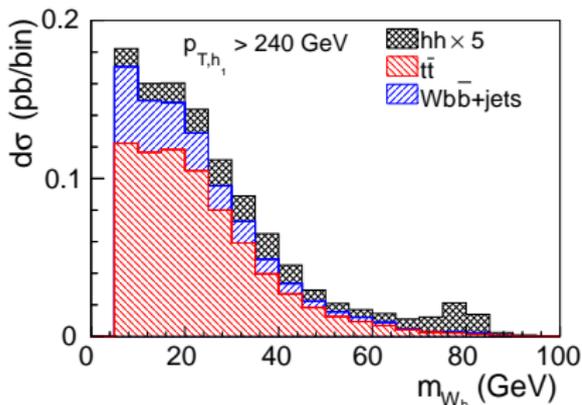
► **Beyond LHC:** at 100 TeV VLHC 40% (10%) accuracy on  $\lambda_{HHH}$  expected with  $\mathcal{L} = 3(30) \text{ ab}^{-1}$  [Barr, Dolan, Englert, de Lima, Spannowsky, arXiv:1412.7174]; see also a Snowmass study at 33 TeV LHC and 100 TeV VLHC [Yao, arXiv:1308.6302] and a very recent study claiming a reduced 30% accuracy on  $\lambda_{HHH}$  at VLHC with  $3 \text{ ab}^{-1}$  [Azatov, Contino, Panico, Son, arXiv:1502.00539]

# Signal analysis in $b\bar{b}W(\rightarrow \ell\nu)W(\rightarrow jj)$ final state

[Papaefstathiou, Yang, Zurita, PRD 87 (2013) 011301]

**Parton level analysis:** MADGRAPH using  $gg \rightarrow HH$  matrix elements from HPAIR, HERWIG++ and ALPGEN for background processes, rates normalized to (N)NLO total cross section

**Cut-based analysis with jet substructure technique, improved with BDT multivariate analysis + specific cuts to this channel, e.g.  $p_{T,H} > 240$  GeV and  $m_{W_h} > 65$  GeV (hadronically decaying W)**



**promising result of  $S/\sqrt{S+B} = 2.4$  with 9 events at  $600 \text{ fb}^{-1}$**

- **Using ratio of cross sections:** similar structure for higher-order corrections in  $\sigma(gg \rightarrow H)$  and  $\sigma(gg \rightarrow HH) \Rightarrow$  **uncertainties on their ratio  $C_{HH}$  much more reduced**  
 $\Delta^\mu C_{HH} \simeq \pm 2\%$ ,  $\Delta^{\text{PDF}} C_{HH} \simeq \pm 2\%$  [Goertz, Papaefstathiou, Yang, Zurita, JHEP 1306 (2013) 016]

Very promising confidence interval of  $\simeq +30\% / -20\%$  on the reduced triple Higgs coupling  $\tilde{\lambda} = \lambda_{HHH} / \lambda_{HHH}^{\text{SM}}$  when the three previous search channels are naively combined

- **New in 2014: 4b analyses!**

- with jet substructure analysis, set a 95% CL limit  $\tilde{\lambda} \leq 1.2$  at  $3 \text{ ab}^{-1}$   
[de Lima, Papaefstathiou, Spannowsky, JHEP 1408 (2014) 030]
- sophisticated BDT analysis including PS  $\Rightarrow$   **$1.8\sigma$  ( $2.1\sigma$ ) significance at  $3 \text{ ab}^{-1}$**   
for an efficiency  $b$ -jet misidentification as  $c/\tau$ -jet of 20% (10%), 240 events  
[Wardrope *et al.*, arXiv:1410.2794]

- **$4W \rightarrow 3\ell 2j + \cancel{E}_T$  channel:** full hadronic study (PS + detector simulation) at **14 (100) TeV,  $1.8\sigma$  ( $13\sigma$ ) sensitivity, 50% accuracy on  $\lambda_{HHH}$  at 95% CL** [Li, Li, Yan, Zhao, arXiv:1503.07611]

- **Rare decay channels at 100 TeV:** newest analysis 3 days ago including notably  $b\bar{b}(ZZ \rightarrow 4\ell)$  and  $b\bar{b}(WW \rightarrow 2\ell 2\nu)$   
 $S/B \simeq 4/O(10)$  at  $3 \text{ ab}^{-1}$  for ZZ,  $S/B \simeq O(10)/O(100)$  for WW [Papaefstathiou, arXiv:1504.0462]

## HH production at hadron colliders: Major goal for the LHC run II and the future VLHC collider

- **Major news since 2012:** a Higgs boson has been observed, now it is time to solve the next big question: **is it standard or a first window on BSM physics?**
- **The SM Higgs frontier at the high luminosity LHC:** the measure of the triple Higgs coupling to probe directly the scalar potential
- **HH production status:** all main inclusive production channels known at least NLO, even NNLO for double Higgsstrahlung and gluon fusion, **theoretical uncertainty in the range 10 – 30%**
- **The big issue in HH gluon fusion:** (N)NLO corrections only in the effective approach, still sizable uncertainties  $\Rightarrow$  **complete 2-loop calculation for  $gg \rightarrow HH$  is awaited (stay tuned!)**
- **HH Parton level analysis: jet substructure technique is the 2013 major improvement**  
 **$b\bar{b}\tau\tau$  channel really promising even already at  $\mathcal{L} = 300 \text{ fb}^{-1}$**   
 **$b\bar{b}\gamma\gamma$  may also be very interesting at  $\mathcal{L} = 3000 \text{ fb}^{-1}$**   
 **$b\bar{b}W(\rightarrow \ell\nu)W(\rightarrow 2j)$  shows good prospects with multivariate analysis at  $600 \text{ fb}^{-1}$**
- **The VLHC search:** 2014 and 2015 have seen analyses for a 100 TeV VLHC machines, rare decay channels may be valuable at such energies for  $3 \text{ ab}^{-1}$

## ■ Signal analysis in $b\bar{b}\tau\tau$ :

### Main backgrounds considered:

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

Define the subjet separation in the fat jet: using mass-drop condition,

$$m_{j_1} \leq 0.66m_j \ \& \ \min(p_{T,j_1}^2, p_{T,j_2}^2) / m_j^2 \Delta R_{j_1 j_2}^2 > 0.09$$

$\tau$  reconstruction efficiency of 80%

## ■ Signal analysis in $b\bar{b}\gamma\gamma$ :

### Main backgrounds considered:

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

Framework: Pythia 6 using  $gg \rightarrow HH$  matrix elements from HPAIR, rates rescaled to (N)NLO through  $K$ -factors, tag efficiency of 70% ( $b$ ), fake photons with a rough detector simulation (Delphes)

## ■ Signal analysis in $b\bar{b}W(\rightarrow \ell\nu)W(\rightarrow jj)$ :

### Main backgrounds considered:

- ▶ largest background:  $pp \rightarrow t\bar{t}$  with semi-leptonic decays
- ▶  $W(\rightarrow \ell\nu)b\bar{b} + 2j$  production,  $H(\rightarrow WW)b\bar{b}$  production and  $H + jj$  with misidentified jets