# Prospects for Higgs Self Coupling measurements with ATLAS and CMS

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**(Tufts University)**
**On behalf of the ATLAS and CMS Collaborations**

**"Higgs Quo Vadis", March 10th -15th 2013**

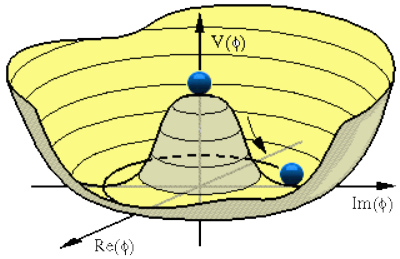
A·S·P·E·N
Center for Physics

# Introduction

- In July 2012, ATLAS and CMS discovered a SM Higgs-like particle: final nature of the particle to be established

- For the next round, at HL-LHC, crucial to precisely assess the properties on the new particle to measure the details of the electroweak symmetry breaking mechanism: spin, CP, couplings and self coupling measurements

- The Higgs self couplings measurements one of key topics in this new challenge:
  - only way to reconstruct the Higgs potential
  - deviation from the SM expectations are hint of new physics




→ SM Higgs self coupling measurements not accessible at LHC, in this talk prospect for future HL-LHC measurements

# Outline

- LHC and Higgs: today and tomorrow
- Higgs self couplings:

  - theory predictions

  - interesting channels and measurement strategies:

  - $HH \rightarrow bb\gamma\gamma$ , $HH \rightarrow bbWW$, $HH \rightarrow bb\tau\tau$ and others

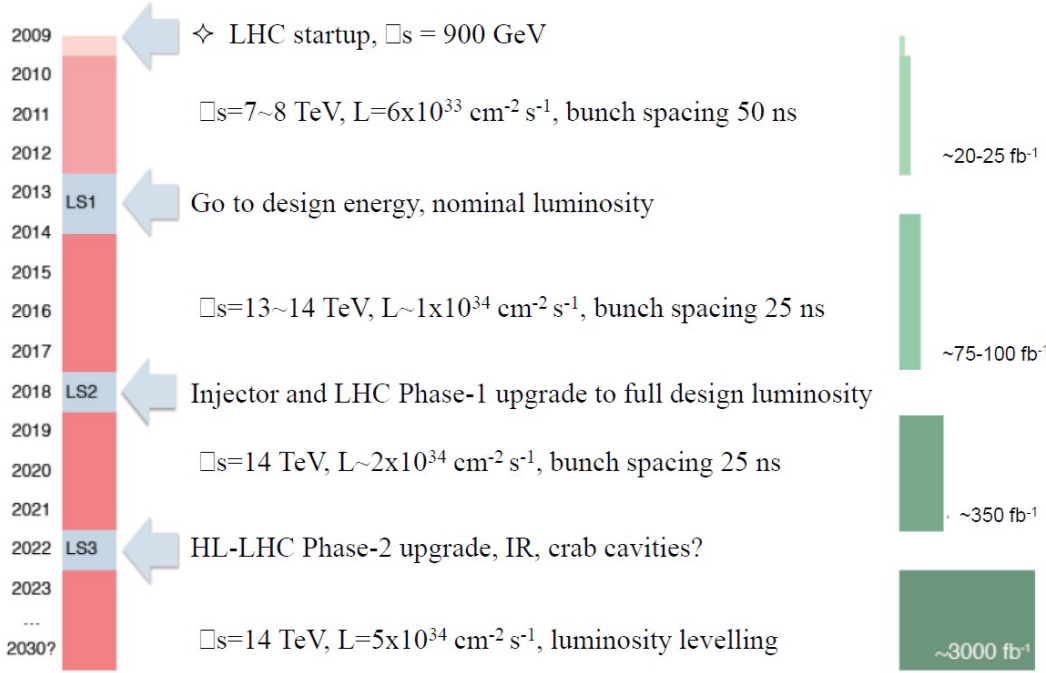
  - Boosted objects techniques

- Conclusions

# LHC tomorrow

ATLAS and CMS recorded: ~5 $fb^{-1}$ at 7 TeV and ~20 $fb^{-1}$ at 8 TeV
- Mean number of interactions per crossing: <μ>~ 20 (35 maximum)
  → Physics objects stable against pileup

*See talks:*
*M. Shapiro " **ATLAS Physics results review**"*
*G. Dissertori , **"CMS Physics results review"***




Higgs self coupling measurements feasible only at HL-LHC

→More challenging environment (<μ> ~ 140):

Major detectors upgrades to cope with higher radiation levels, higher occupancy and required data rates:
-Replacement of critical components,
-Upgrades to trigger and electronics

→ LH LHC Goal: the same or better detector performances than the present ones

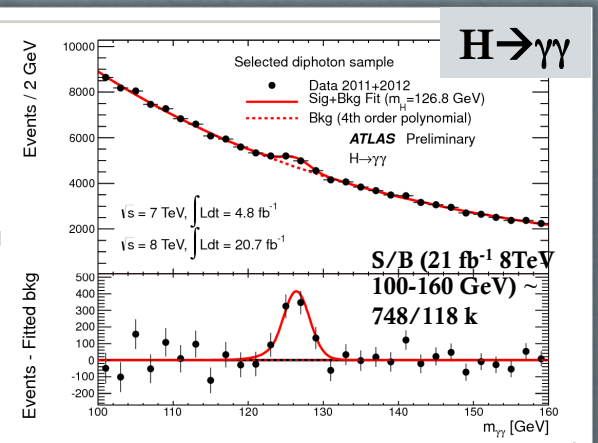
# Higgs-like boson today

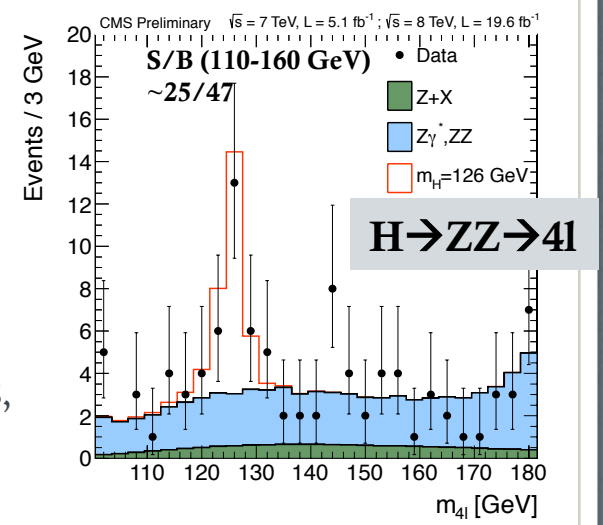
**ATLAS** **ATLAS-CONF-2013-014 (last week)**

$m_H$ = 125.5 ± 0.2 (stat) +0.5/-0.6 (syst) GeV
Signal strength μ = 1.43 ± 0.16 (stat) ± 0.14 (sys) (SM units)

**CMS** **CMS PAS HIG-12-045 ( December 2012)**

$m_H$ = 125.8 ± 0.4 (stat) ± 0.4 (syst) GeV
Obs. Sig. significance = 6.9 σ at 125.8 GeV
Sig. strength μ = 0.88 ± 0.21 at 125.8 GeV (SM units)




This week all the most recent updates will be shown (cross sections, mass, spin, CP, couplings):

almost the best extractible with current statistics and detectors (some updates in Summer)

*J. Alison,"**Results of H->WW from ATLAS**"*
*A. Ambruster, "**Combined Higgs couplings from ATLAS**"*
*M. Delmastro, "**Results of H→γγ and Z-γ from ATLAS** "*
*K. Grimm, "**Searches for 2-doublet Higgs from ATLAS**"*
*G. Pasztor, **"Results of H→ZZ from ATLAS"***
*E.Strauss,**" Results of the search for Heavy Higgs and BSM Higgs Bosons from ATLAS"***
*S. Tsuno, **"Results of H->TauTau from ATLAS"***
*C. Weiser, **"Results of H->bb from ATLAS"***

*M. Takahashi"**Results of H->WW from CMS**"*
*N. Wardle," **Combined Higgs couplings from CMS**"*
*R. Volpe,"**Results of H→γγ at CMS**"*
*S. Xie **"Results of H->ZZ from CMS"***
*P.Harris, **"Results of H->TauTau from CMS"***
*M.Gallinaro,**" Results of the search for Heavy Higgs and BSM Higgs Bosons from CMS"***
*A. Rizzi, **"Results of H->bb from CMS"***

# Higgs boson tomorrow

LHC is going to provide constraints on the properties of the new particles but not final answers on the nature of this particle

Goals for the next Higgs measurements:
- improved sensitivity of current measurements
  → soon after the shutdown
- measurement of the low BR channels → for HL-LHC
- Higgs self couplings → for HL-LHC

See in this conference:
*A Nisati,"* ***Report back from the European Strategy for Particle Physics"***
*J. Groth-Jensen "****Rare Higgs decays with ATLAS and CMS****"*

ATLAS and CMS have initial results on the prospects of the future measurements:

**ATL-PHYS-PUB-2012-004**

ATLAS approach:
- studies at generator-level
- detector performance extrapolated by the current ones, smearing applied to the physics objects to mimic detector effects (resolutions, efficiencies, fake rates)

**CMS NOTE -2012/006**

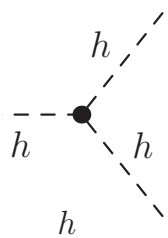
CMS approach: detector upgrade will compensate pile-up effects, assumed 3 scenarios:
Scenario 1: systematic uncertainties equal to current ones
Scenario 2: theoretical uncertainties scaled by 1/2,
other systematic uncertainties scaled by $\sqrt{L}$
Scenario 3: zero theoretical uncertainties (to demonstrate interplay with the experimental uncertainties)

# Higgs self coupling predictions

- In SM, Higgs self couplings follow from the Higgs potential after expanding the Higgs doublet field Φ around the electroweak symmetry breaking vacuum expectation :

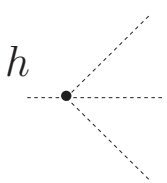
$$V_H = \mu^2 \Phi^+ \Phi + \eta (\Phi^+ \Phi)^2 \rightarrow \frac{1}{2} m_H^2 h^2 + \sqrt{\frac{\eta}{2}} m_H h^3 + \frac{\eta}{4} h^4 \text{ with : } m_H^2 = \eta v^2 / 2 \text{ and } v^2 = -\mu^2 / \eta$$

To fully reconstruct the Higgs potential one should have to:



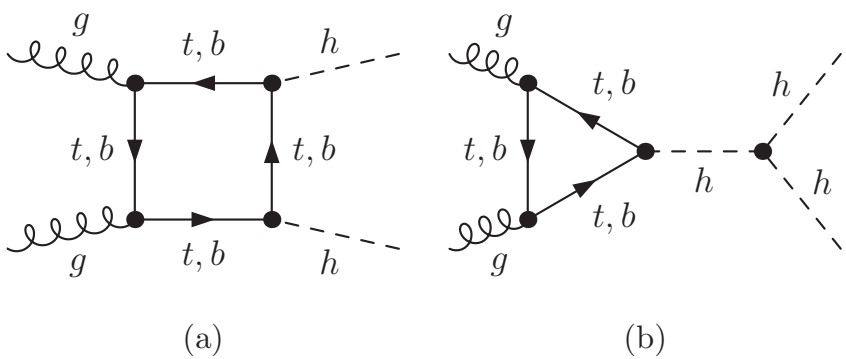

Measure the 3 linear Higgs vertex,
via measurement on double Higgs production

$$\lambda_{SM} = \sqrt{\frac{\eta}{2}} m_H$$

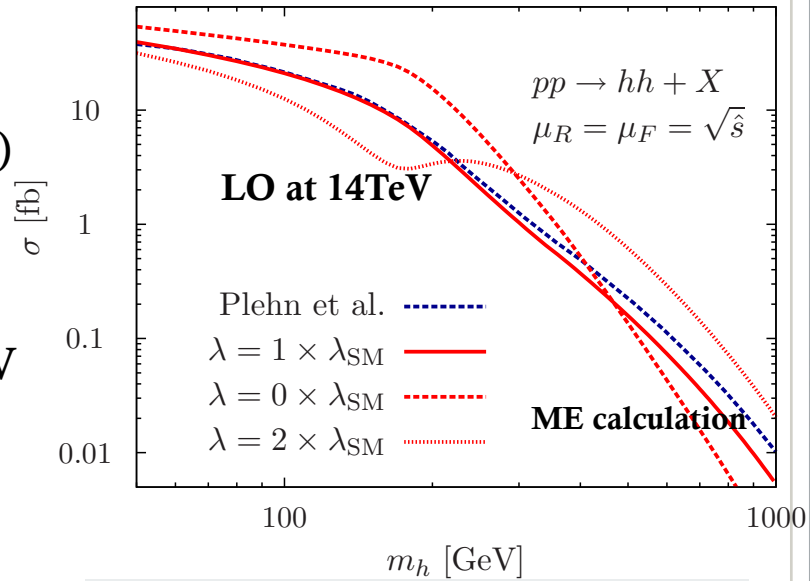



Measure the quadratic Higgs vertex:
more challenging, not accessible to HL-LHC

# Higgs self coupling predictions




**M. J. Dolan, C. Englert ,M. Spannowsky, *Higgs self-coupling measurements at the LHC*, JHEP 10 (2012) 112**




Destructive interference between diagram (a) and (b)

→ σ(hh) depends on $\lambda$ :

- diagram (b) resonantly enhanced when $m_h \cong m_{top}$
- large dependence on $\lambda$ at $m_h \leq m_{top}$ :

  relatively large dependence at $m_h \approx 125$ GeV

- NLO cross-section at $m_h$=125 GeV:

$$34\,fb^{+18\%}_{-15\%}(QDC\ scale) \pm 7\%(PDF + \alpha_s) \pm 10\%(EFT)$$

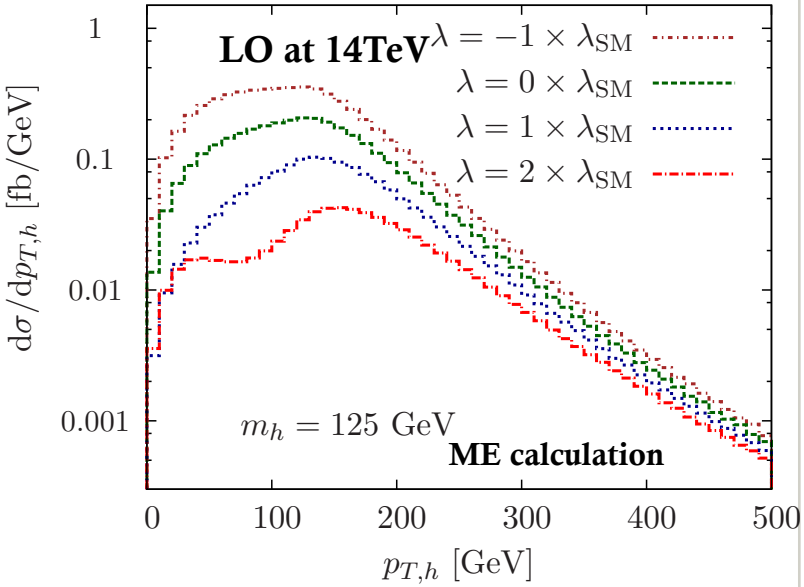
**http://people.web.psi.ch/spira/proglist.html**
**Baglio, et al, arXiv:1212.5581v1 [hep-ph]**

# Higgs self coupling predictions

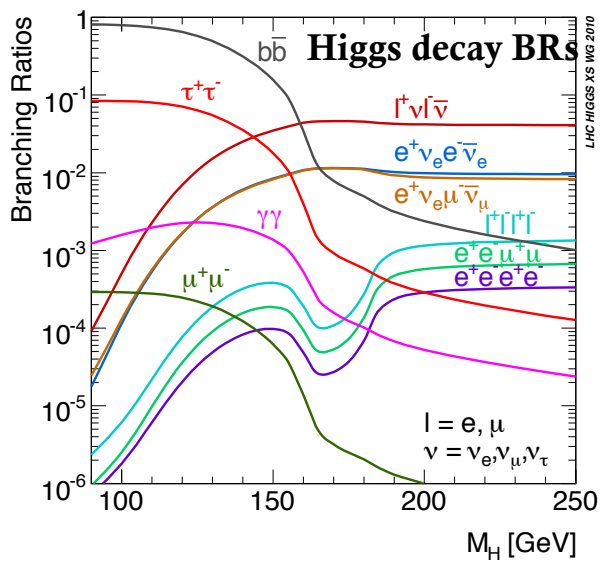
**M. J. Dolan, C. Englert ,M. Spannowsky,**
***Higgs self-coupling measurements at the LHC*,**
**JHEP 10 (2012) 112**

$p_{T,h}$ good observable to identify kinematical region sensitive to different $\lambda$ :

- naturally boosted $p_{T,h} \geq 100$ GeV
- max sensitivity around 100 GeV



# Interesting channels




| Channel | BR(%) | σ x BR (fb) | Events @ 14 TeV (L=3000 fb$^{-1}$) |
|---|---|---|---|
| **bb+bb** | 33.41 | 11.33 | 34 k |
| **bb+WW** | 24.97 | 8.36 | 26 k |
| **bb+ττ** | 7.36 | 2.50 | 7.5 k |
| WW+WW | 4.67 | 1.58 | 4.7 k |
| ZZ+bb: (ZZ+bb →4l+bb) | 3.09 | 1.03 | 3.1 k (→13.9) |
| ZZ+WW | 1.15 | 0.39 | 1.2 k |
| **γγ+bb** | 0.27 | 0.09 | 270 |
| **bb+μμ** | 0.013 | 0.004 | 12.8 |

Focus of channels with larger BR or favorable S/B and allowing a precision $m_H$ measurement of one of the 2 Higgs.

Today:

**bbγγ** and **bbWW**: studied by ATLAS

**bbbb** and **bbττ**: studied in recent phenomenological papers

**bbμμ**:CMS showed the perspective for bbμμ for a $\sqrt{s}$ = 33 TeV energy upgraded LHC (HE-LHC)

# HH→ bbγγ

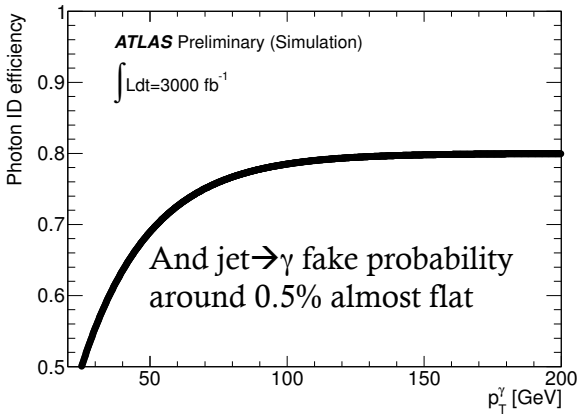
ATLAS-PHYS-PUB-2013-001

Study done at generator level applying object smearing and id/reconstruction efficiency

**Photons**

-Performance of the current full simulation and reconstructions codes with μ=46 (detector performances improvement will mitigate higher pileup)

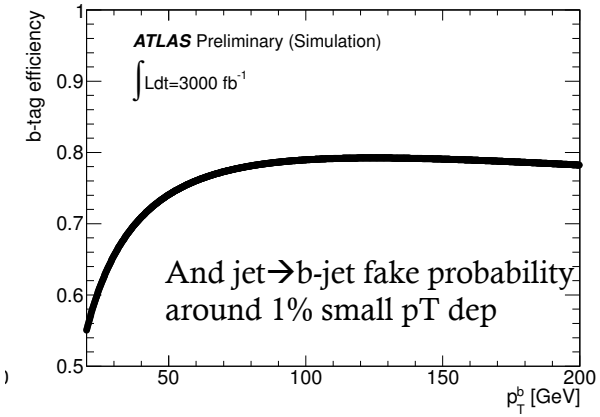
-Energy smearing around 2.5% ($p_T$ and η dep)




**B-Jets**

Fit of the parameters (b-tag eff. and light jet rej.) at low pileup extrapolated at high pileup (μ=140)

-Energy smearing around 20% ($p_T$ and η dep)




Peak of signal $p_{T\gamma}$ and $p_{T,b\text{-}jet}$ distributions ($m_H$=125 GeV) ~ 60 GeV

# HH→bb γγ

ATLAS-PHYS-PUB-2013-001

| sample | $\sigma\times$BR (fb) |
|---|---|
| $HH \to b\bar{b}\gamma\gamma$ ($\lambda_{HHH}$ = 1) | 0.09 |
| $HH \to b\bar{b}\gamma\gamma$ ($\lambda_{HHH}$ = 0) | 0.19 |
| $HH \to b\bar{b}\gamma\gamma$ ($\lambda_{HHH}$ = 2) | 0.04 |
| $\gamma\gamma b\bar{b}$ | 111 |
| $ZH(Z \to b\bar{b}, H \to \gamma\gamma)$ | 0.04 |
| $b\bar{b}H(H \to \gamma\gamma)$ | 0.124 |
| $\gamma\gamma jj$ | $2 \times 10^3$ |
| $jjjj$ | $1.8 \times 10^8$ |
| $t\bar{t}H(H \to \gamma\gamma)$ | 1.71 |
| $t\bar{t}$ ($\geq$ 1 leptonic W decay) | $5.0 \times 10^5$ |

BR=0.27% → 270 HH evt at 3000 fb$^{-1}$ at 14 TeV

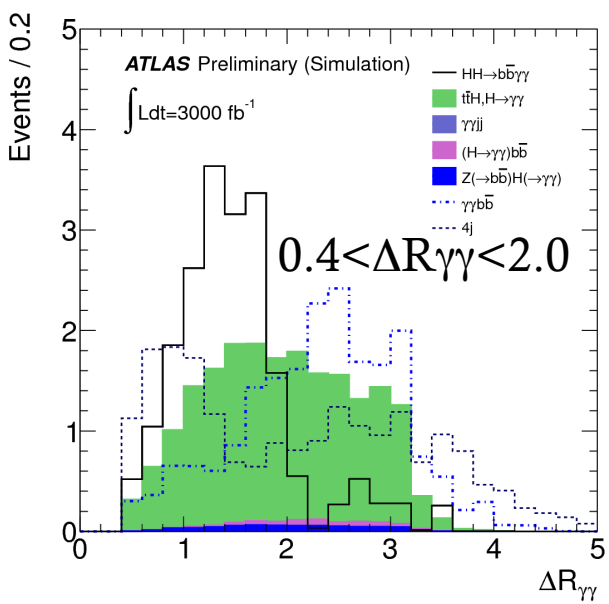
**Main bkg sources:**
bbγγ , jjγγ, jjjj, ttbar → huge production
associated H productions → ttbarH dominant

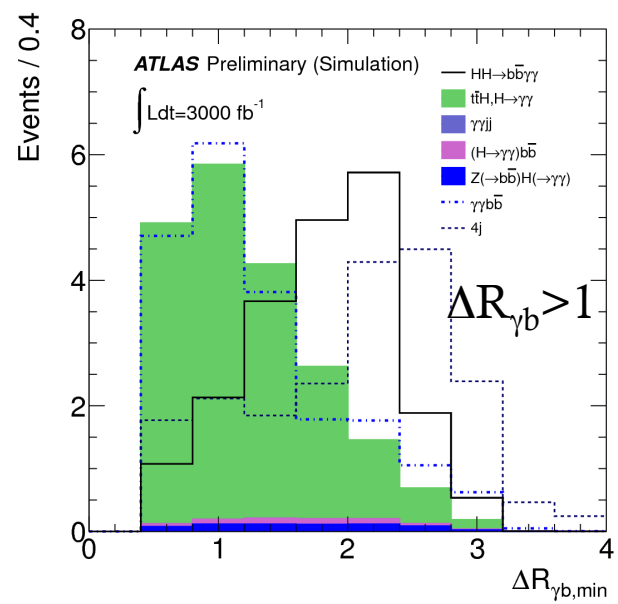
**Event selection**
-events with 2b-jets and 2 γ, where b-jets: $p_T$>40/25 GeV;
γ: $p_T$>25 GeV, isolated, and $\Delta R_{\gamma b}$>0.4

**MC samples production**: MadGraph 5 showered with Pythia 6 expect ttbarH (Pythia 8) and ttbar(MC@NLO/JIMMY)

bbγγ and jjjj dominant before angular cuts

Sum of ttH, ZH, bbH, γγ jj normalized to the signal, bbγγ and jjjj normalized to the signal separately

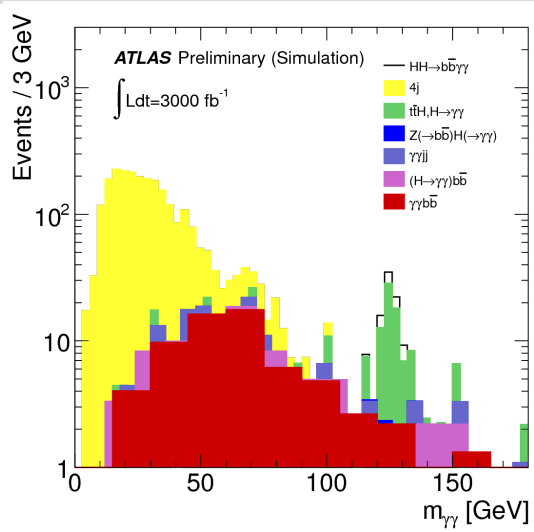


# HH→ bb γγ

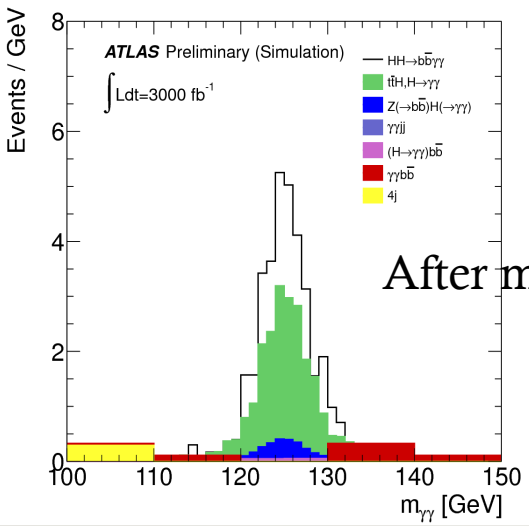
ATLAS-PHYS-PUB-2013-001

After angular cuts
(and $N_{jets}$<=4 to reject ttbar and ttbarH):
jjjj and bbγγ still dominant,
but mainly at low $m_{\gamma\gamma}$

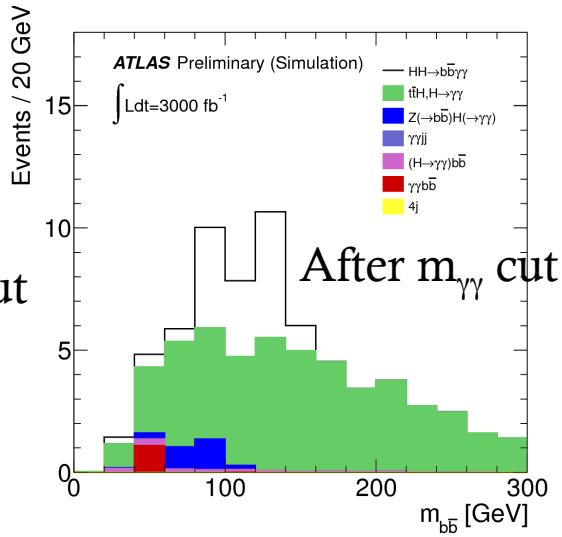



Final cuts:

$120<m_{\gamma\gamma}<130$ GeV
$50<m_{bb}<130$ GeV




After $m_{bb}$ cut




After $m_{\gamma\gamma}$ cut

# HH→ bb γγ

ATLAS-PHYS-PUB-2013-001

| sample | $\sigma\times$BR (fb) | simulated events | events passing selection | events expected in 3000 fb$^{-1}$ |
|---|---|---|---|---|
| $HH \to b\bar{b}\gamma\gamma$ ($\lambda_{HHH}=1$) | 0.09 | 1020 | 42 | 10.7 |
| $HH \to b\bar{b}\gamma\gamma$ ($\lambda_{HHH}=0$) | 0.19 | 1020 | 32 | 17.9 |
| $HH \to b\bar{b}\gamma\gamma$ ($\lambda_{HHH}=2$) | 0.04 | 1230 | 66 | 6.4 |
| $\gamma\gamma b\bar{b}$ | 111 | $3.1\times10^4$ | 1 | 1.1 |
| $ZH(Z\to b\bar{b}, H\to\gamma\gamma)$ | 0.04 | $5\times10^5$ | 11600 | 2.8 |
| $b\bar{b}H(H\to\gamma\gamma)$ | 0.124 | $5\times10^4$ | 71 | 0.5 |
| $\gamma\gamma jj$ | $2\times10^3$ | $5\times10^5$ | 0.004 | 0.1 |
| $jjjj$ | $1.8\times10^8$ | $4.6\times10^6$ | 0 | 0 |
| $t\bar{t}H(H\to\gamma\gamma)$ | 1.71 | $1.2\times10^5$ | 379 | 13.6 |
| $t\bar{t}$ ($\geq$ 1 leptonic W decay) | $5.0\times10^5$ | $1\times10^7$ | $74^\dagger$ | 1.1 |
| Total Background | - | - | - | 19.2 |

Final results after full selection:

Large rejection of γγbb and jjjj , ttH dominant and competitive with the signal, followed by ZH

**S/B = 0.6** and **S/sqrt(B)= 2.4** (λ=1)

- What about the potential of observing or excluding different λ hypothesis?

  Evidence is possible for λ=0 and λ=1, but no significant discrimination allowed
  → Combining with another channel with similar sensitivity and with CMS results, feasible a measurement of the Higgs self coupling with an accuracy of ~30%

# HH→bbWW→bblνjj

BR=25% (all possible W decays)→ 26k HH evt at 3000 $fb^{-1}$ at 14 TeV

**Main bkg source:** ttbar

**ATLAS-PHYS-PUB-2013-001**

**Event selection**

-events with 1 lepton with $p_T$>25 GeV $|\eta|$<2.5 ( veto on a second lepton) and at least 4 jets with $p_T$>25 GeV $|\eta|$<4.5 at least 1 b-jet

-MET> 30 (20) GeV electron (muon) ch

**Measurement strategy**

- Reconstruction of $W_{lep}$→lν imposing: $m_W=m_{l\nu}$

$$\frac{m_W^2 - m_\ell^2}{2} = E_\ell \sqrt{p_{\nu_x}^2 + p_{\nu_y}^2 + p_{\nu_z}^2} - p_{\ell_x} p_{\nu_x} - p_{\ell_y} p_{\nu_y} - p_{\ell_z} p_{\nu_z}.$$

- Reconstruction of the system bb(=$j_1$+$j_2$) and WW(=$j_3$+$j_4$+$W_{lep}$) via $\chi^2$ fit :

$$\chi^2 = ((m_{b\bar{b}} - m_H)/\sigma)^2 + ((m_{W^+W^-} - m_H)/\sigma)^2$$

- Higgs mass cut (on both Higgs): 100GeV <$m_H$<150 GeV

**Results**

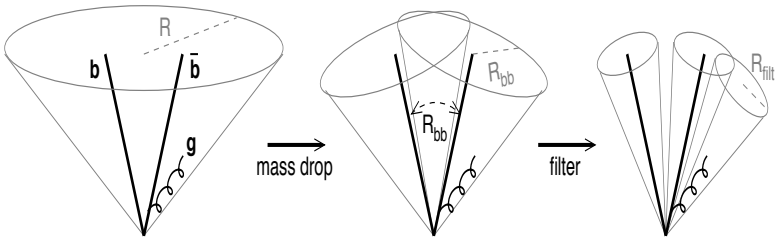
| Sample | σxBR (fb) | Events expected after selection in 3000 $fb^{-1}$ |
|---|---|---|
| HH→bbWW | 8.7 | 441 (318) |
| ttbar | $8.33\ 10^5$ | $3.5\ 10^6$ ($6.3\ 10^6$) |

S/B ≈$10^{-5}$ → Very challenging to constrain Higgs self coupling with this channel

# Boosted object for Higgs self couplings

Higgs in di-Higgs production naturally boosted → explore high $p_T$ regime to gain in sensitivity against bkgs, even if poor discriminating power in modifications of the Higgs self couplings

Build Higgs (H→bb) as a fat jet and apply jet substructure techniques to discriminate between a jet containing the Higgs decay products and a jet from a single quark or gluon.




Jet substructure procedures relatively new fertile ground in collision data:

- Important to understand whether the jets substructure are well modelled by MC and the detector simulation.
- Refined techniques could come in the next

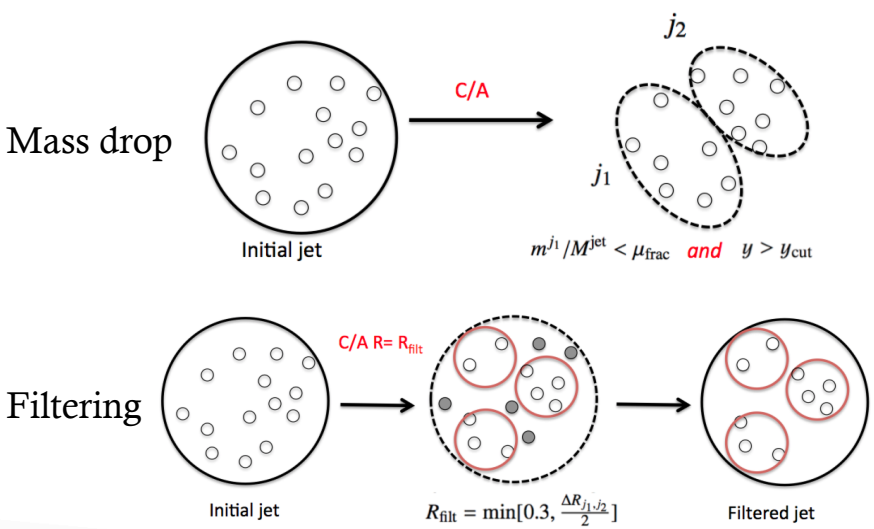
ATLAS and CMS haven't yet specific studies on Higgs self coupling with boosted objects, but they are moving in this direction → after the shutdown , they will be the daily-life

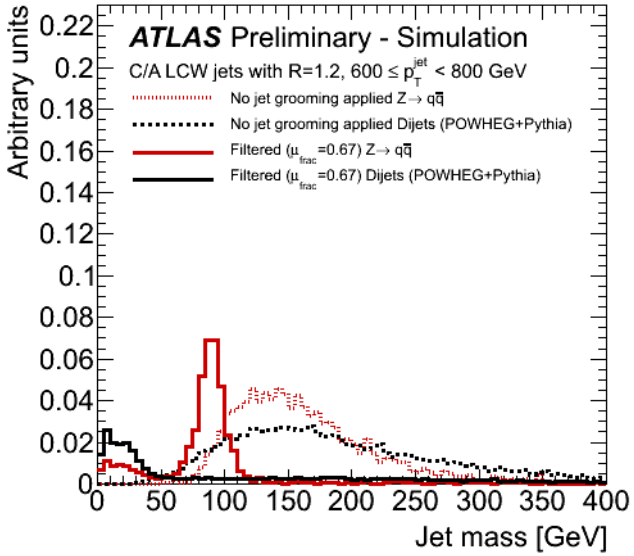
# Boosted object for Higgs self couplings

→ Jet algorithm with R-large (anti-kt or Cambridge-Aachen (C/A) algorithm): larger PU and UE
→ Jet grooming techniques to reduce these components (mass drop/filtering, trimming, pruning)
→ Look at jet structures as discriminating variables: jet mass (simplest one) or more complex (splitting scale, N/subjettiness,…)

**C/A algorithm with mass drop/filtering** optimized for two-body hadronic decay (W/Z → qq, H → bb)

**Original idea on :J. Butterworth et al, Phys.Rev.Lett 100 (2008) 242001**
**Example in ATLAS : ATLAS-CONF-2012-065**



# Boosted object for Higgs self couplings

## HH→bbbb

BR=33.4%→ 34k HH events
Triggerable thanks to the naturally boosted b-jets, but limited options against the huge QCD bbbb bkg.
In boosted scenario analysis (trigger, lepton veto, 2 fat jets with $m_J$ close to $m_H$ , 2 hardest sub-jets tagged as b-jet) : S/B around $10^{-2}$ → this channel seems currently not promising.

**M. J. Dolan, C. Englert ,M. Spannowsky,** ***Higgs self-coupling measurements at the LHC,*** **JHEP 10 (2012) 112**

## HH→bbττ

BR=7.36% (all possible τ decay)→7.5k HH events
Assumed τ reconstruction efficiency 80% with negligible fake rate and b-tag efficiency of 60% with a fake rate of 2%

Two of the most delicate objects at HL-LHC
τ–jets and b-jets

**Event selection**: 2 τ-jets $p_T$>20 GeV $m_{\tau\tau}=m_H \pm 25$ GeV ; >=1 fat jet (C/A R=1.5) $p_{T,j}$ > 150 GeV; the 2 hardest sub-jets both b-jets with $m_H \pm 10$ GeV

| cross sections in fb | $\xi=0$ | $\xi=1$ | $\xi=2$ | $b\bar{b}\tau\tau$ | $b\bar{b}\tau\tau$ [ELW] | $b\bar{b}W^+W^-$ | ratio to $\xi=1$ |
|---|---|---|---|---|---|---|---|
| cross section before cuts | 59.48 | 28.34 | 13.36 | 67.48 | 8.73 | 873000 | $3.2 \cdot 10^{-5}$ |
| reconstructed Higgs from $\tau$s | 4.05 | 1.94 | 0.91 | 2.51 | 1.10 | 1507.99 | $1.9 \cdot 10^{-3}$ |
| fatjet cuts | 2.27 | 1.09 | 0.65 | 1.29 | 0.84 | 223.21 | $4.8 \cdot 10^{-3}$ |
| kinematic Higgs reconstruction ($m_{b\bar{b}}$) | 0.41 | 0.26 | 0.15 | 0.104 | 0.047 | 9.50 | $2.3 \cdot 10^{-2}$ |
| Higgs with double $b$-tag | 0.148 | 0.095 | 0.053 | 0.028 | 0.020 | 0.15 | 0.48 |

After full selection S/B ≈0.5 for λ=1 (285 signal evts at 3000 $fb^{-1}$)

**J.Baglio et al,arXiv:1212.5581v1[hep-ph]** with different analysis and more conservative assumptions: S/B = 0.3

→ Promising channel, but ATLAS and CMS have to reassess results in a more realistic scenario

# Rare di-Higgs decay

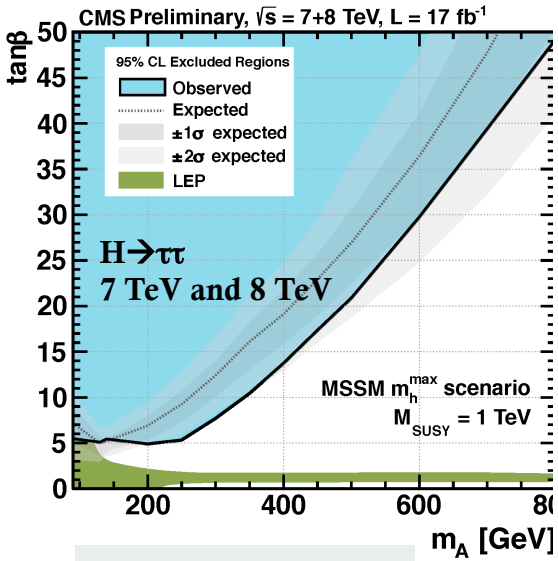
CMS prospects in addition to HH→bbγγ also HH→bbμμ for feasibility studies of Higgs multiple production at √s = 33 TeV (HE-LHC)

σ( HH→bbμμ) about one order of magnitude less than HH→ bbγγ but smaller level of background, mainly constituted by Z+bb, Z+cc,Z+(light) jets dominant on Hjj . Anyhow challenging and less favorable than HH→bbγγ

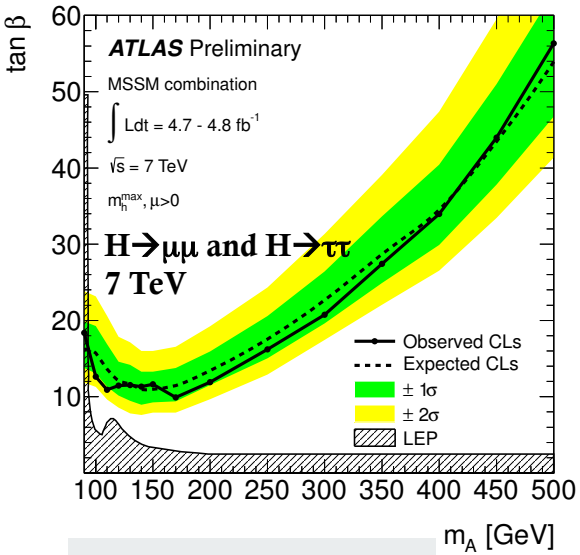
**U. Baur, "*Probing the Higgs self-coupling at hadron colliders using rare decays*", Phys. Rev. D 69, 053004 (2004)**

HH→bbμμ production as in general Multiple Higgs ones can be increased in scenarios beyond SM, e.g. MSSM
→ Some studies done in the past

ATLAS and CMS excluded a significant fraction of the MSSM parameter space, new feasibility studies should be done in the light of these limits




**CMS-PAS-HIG-12-050**




**ATLAS-CONF-2012-094**

# Conclusions

Higgs-like particle discovered at LHC:
-ATLAS and CMS are completing the analyses with the full dataset

HL-LHC and following projects will have the important task of measuring the properties of the new particle:
- Higgs self-coupling measurements are the only way to measure the Higgs potential

ATLAS and CMS started first feasibility studies in this direction:
- $HH \rightarrow bb\gamma\gamma$ seems a promising channel
- Combining with another channel and the 2 experiments, we should be able to measure the Higgs self coupling with an accurancy of 30% at HL-LHC:
  - $HH \rightarrow bb\tau\tau$ seems a good candidate in this effort
  - boosted object techniques can help

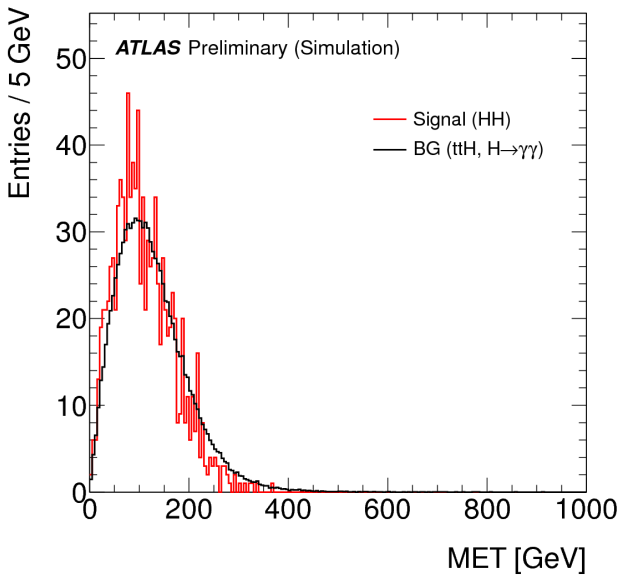
- In the next future needed more refined studies based on full simulation of the upgraded detectors, appropriate levels of pile-up, updated reconstruction tools and optimized selections and analysis strategies.

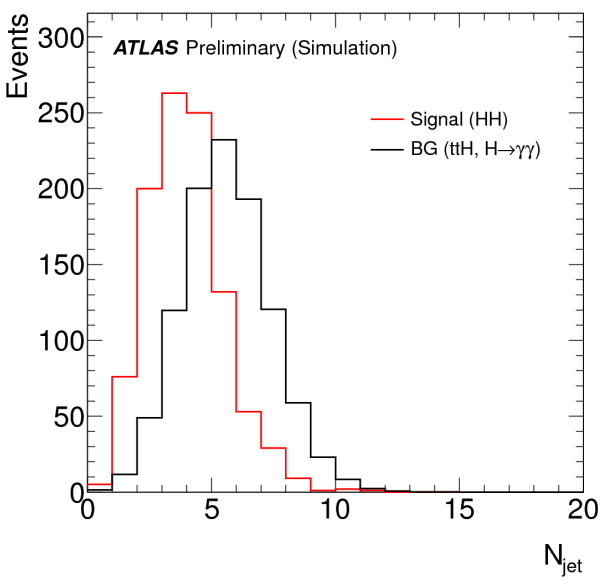
# Backup slides

# HH→bb γγ

ATLAS-PHYS-PUB-2013-001

To reject ttH bkgs investigated MET and Njets



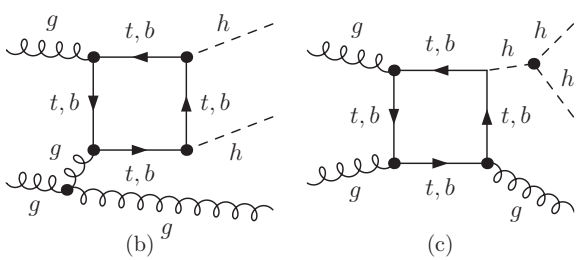



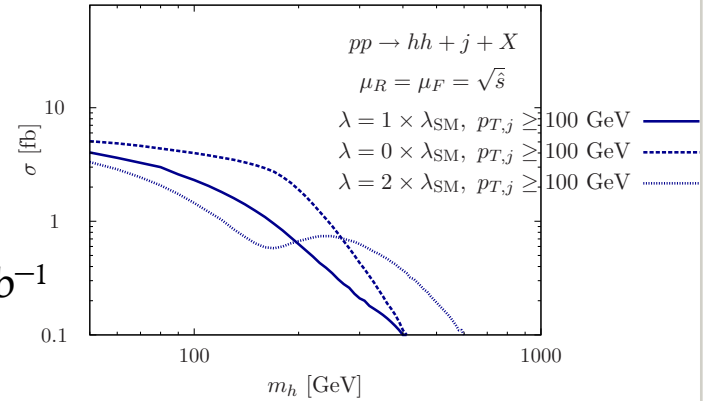

Little separation in MET after pre-selection and proper objects smearing

# HH+1jet

**M. J. Dolan, C. Englert ,M. Spannowsky,**
***Higgs self-coupling measurements at the LHC,***
**JHEP 10 (2012) 112**

What is the impact of (hard) initial state radiation (or radiation from the virtual loop) on dihiggs production and on the sensitivity to Higgs trilinear couplings variations?




- Again large dependence on λ but $\sigma(pp \to hh + j) \simeq$ few $fb^{-1}$
- Dihiggs system less back to back at increasing of jet $p_T$: decay products likely overlap → rely on jet substructures

**HH→bbττ:**

2 $\tau$ -jets with $m_{\tau\tau}=m_H \pm 25$ GeV
1 fat jet, Higgs-tagger:
$m_H \pm 10$ GeV, $p_{T,H}>150$ GeV
$m_{HH} > 400$ GeV
associated jet $p_{Tjet}>100$ GeV

| cross sections in fb | $\xi=0$ | $\xi=1$ | $\xi=2$ | $b\bar{b}\tau^+\tau^- j$ | $b\bar{b}\tau^+\tau^- j$ [ELW] | $t\bar{t}j$ | ratio to $\xi=1$ |
|---|---|---|---|---|---|---|---|
| cross section before cuts | 6.45 | 3.24 | 1.81 | 66.0 | 1.67 | 106.7 | $1.9 \cdot 10^{-2}$ |
| 2 $\tau$s | 0.44 | 0.22 | 0.12 | 37.0 | 0.94 | 7.44 | $4.8 \cdot 10^{-3}$ |
| Higgs rec. from taus + fatjet cuts | 0.29 | 0.16 | 0.10 | 2.00 | 0.150 | 0.947 | $5.1 \cdot 10^{-2}$ |
| kinematic Higgs rec. | 0.07 | 0.04 | 0.02 | 0.042 | 0.018 | 0.093 | 0.26 |
| $2b + hh$ invariant mass + $p_{T,j}$ cut | 0.010 | 0.006 | 0.004 | <0.0001 | 0.0022 | 0.0014 | 1.54 |

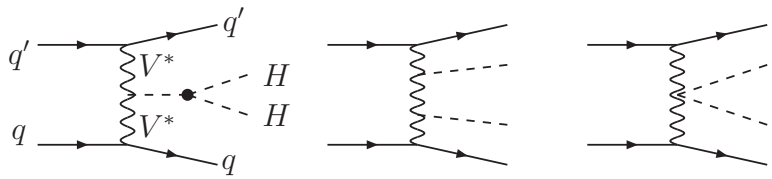
Final S/B=1.5 (18 signal evts at 3000 $fb^{-1}$) → Promising channel
Note: VBF di-higgs production not accounted (~10% contribution)

# Higgs self coupling predictions: other production mechanisms

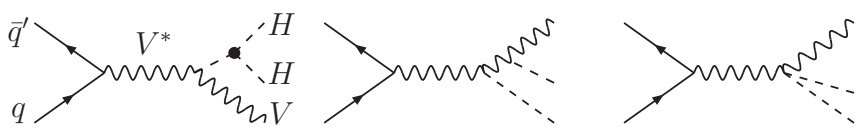
gg-fusion is not the only possibility for HH in a similar way of the single H production

**J.Baglio et al,"** ***The measurement of the Higgs self-coupling at the LHC: theoretical status"*****, arXiv:1212.5581v1[hep-ph]**

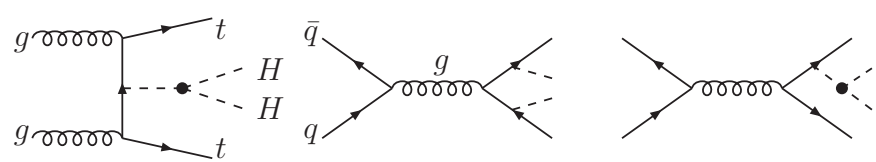
(b) $WW/ZZ$ double-Higgs fusion: $qq' \to HHqq'$

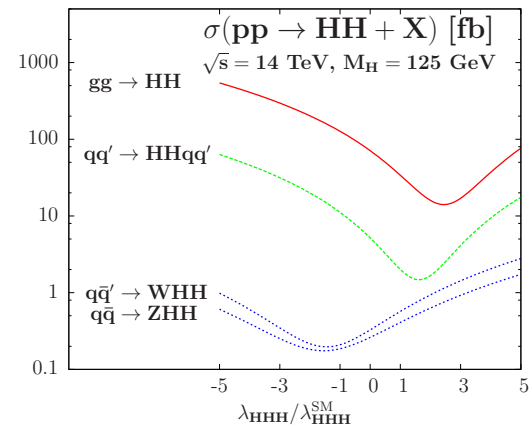


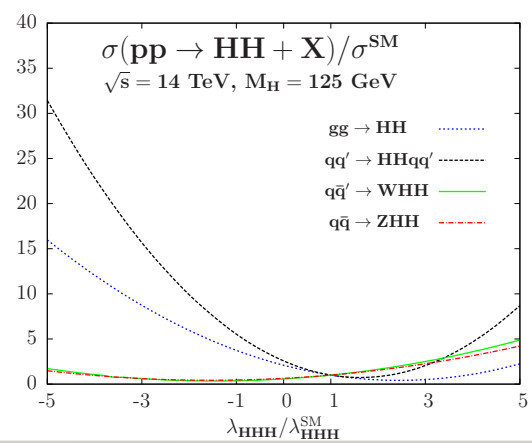

(c) Double Higgs-strahlung: $q\bar{q}' \to ZHH/WHH$




(d) Associated production with top-quarks: $q\bar{q}/gg \to t\bar{t}HH$




VBF is the most sensitive channel to SM λ deviations, but $\sigma_{VBF}$ very low (after considering H decay BR)
→ No feasibility studies so far