Higgs pair production in the bbWW channel

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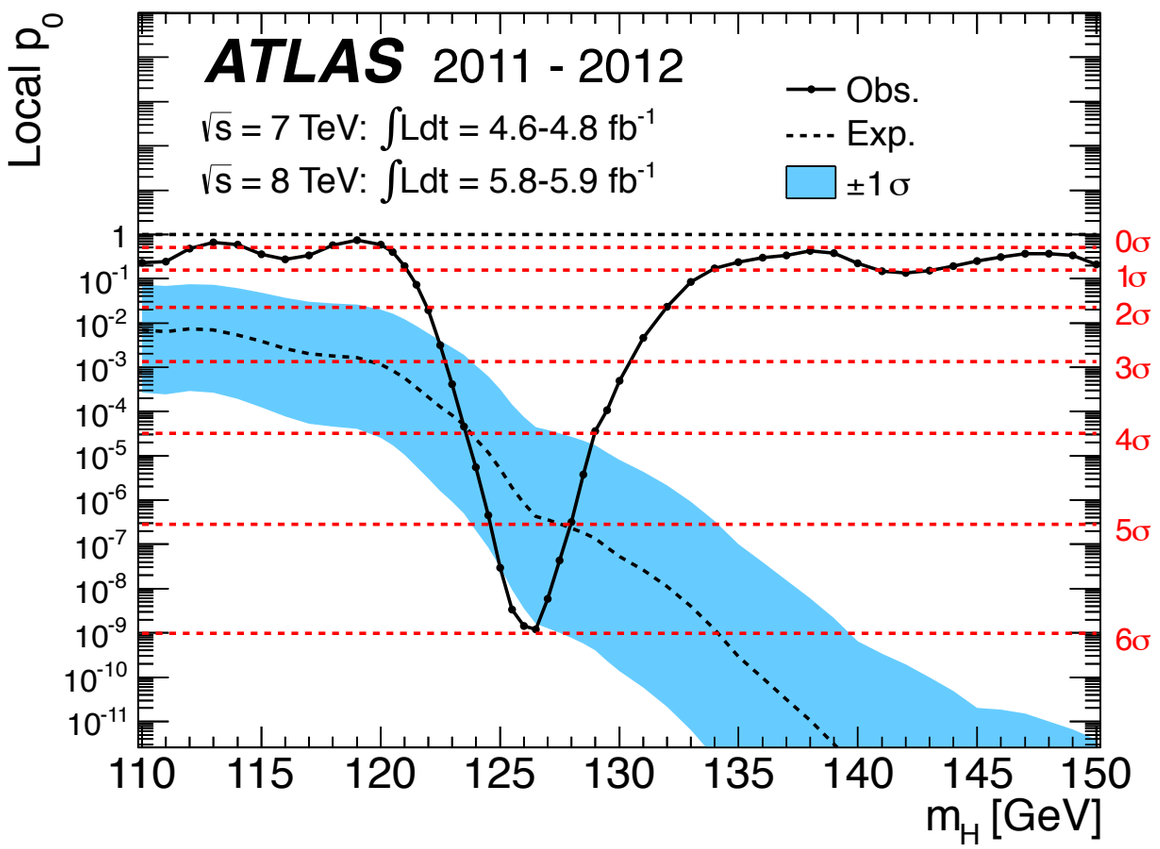
In collaboration with Andreas Papaefstathiou and José Zurita
arXiv:1209.1489

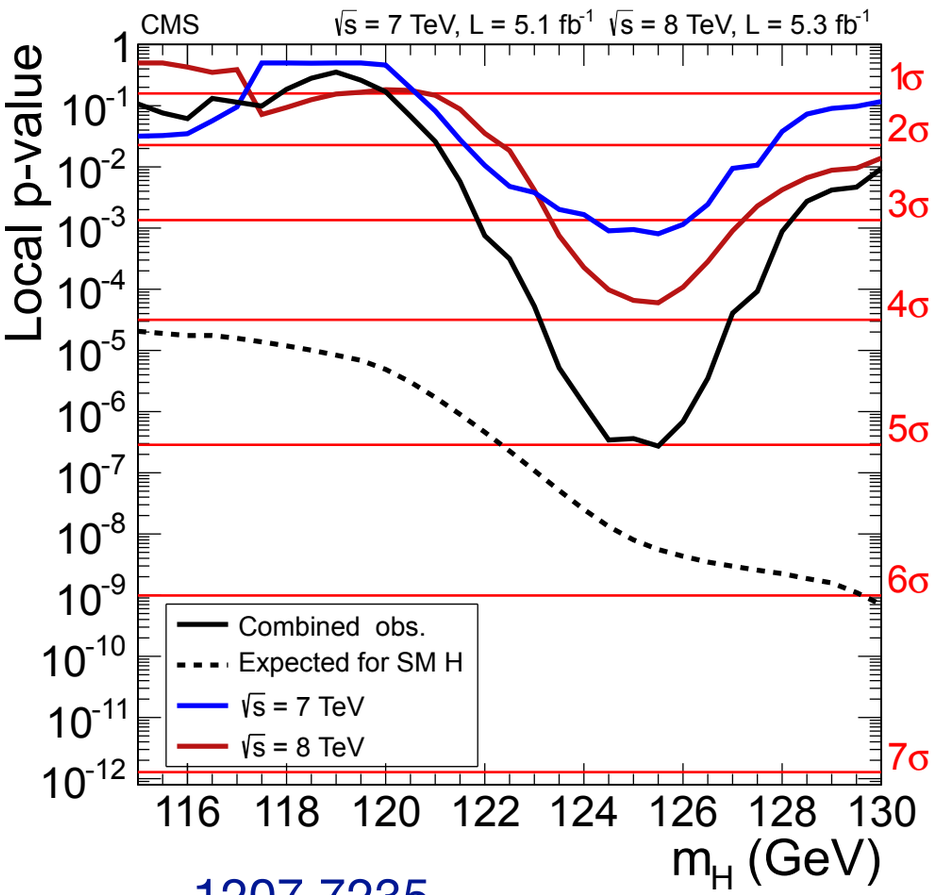
Outline

- Higgs discovery and coupling measurement
- Higgs self-coupling and Higgs pair production
- Higgs pair in the bbWW channel
- Summary and Outlook

Higgs day



1207.7214

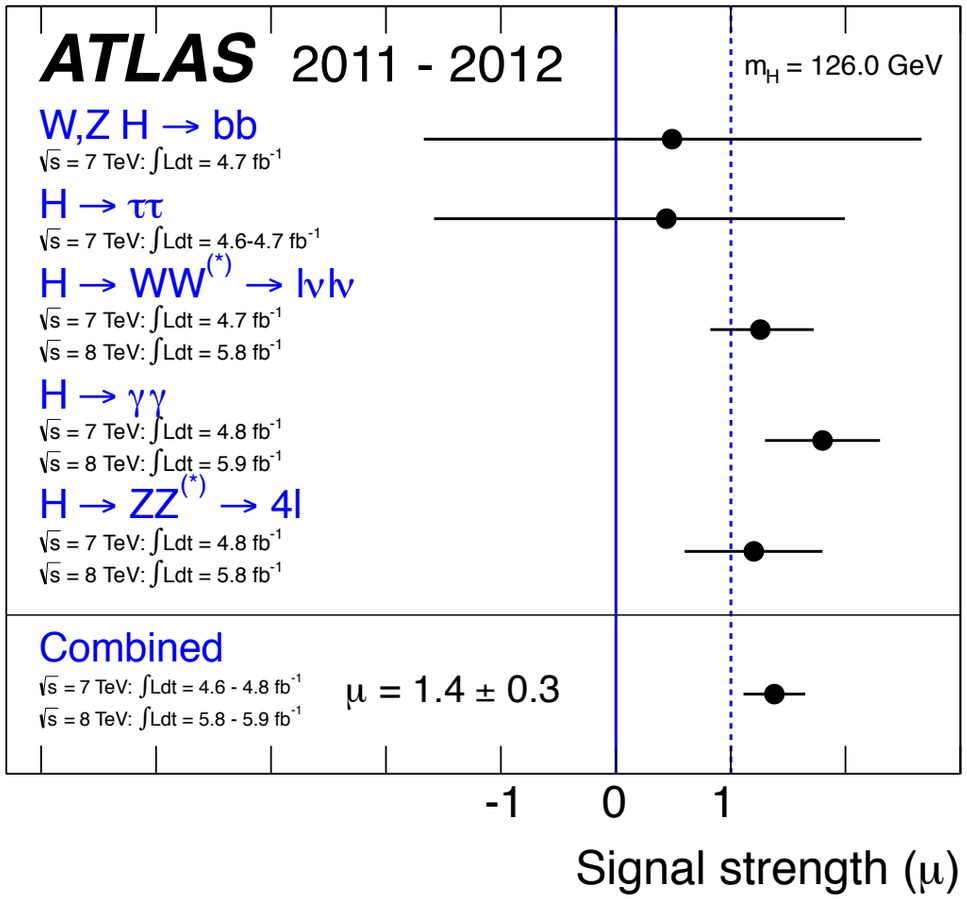


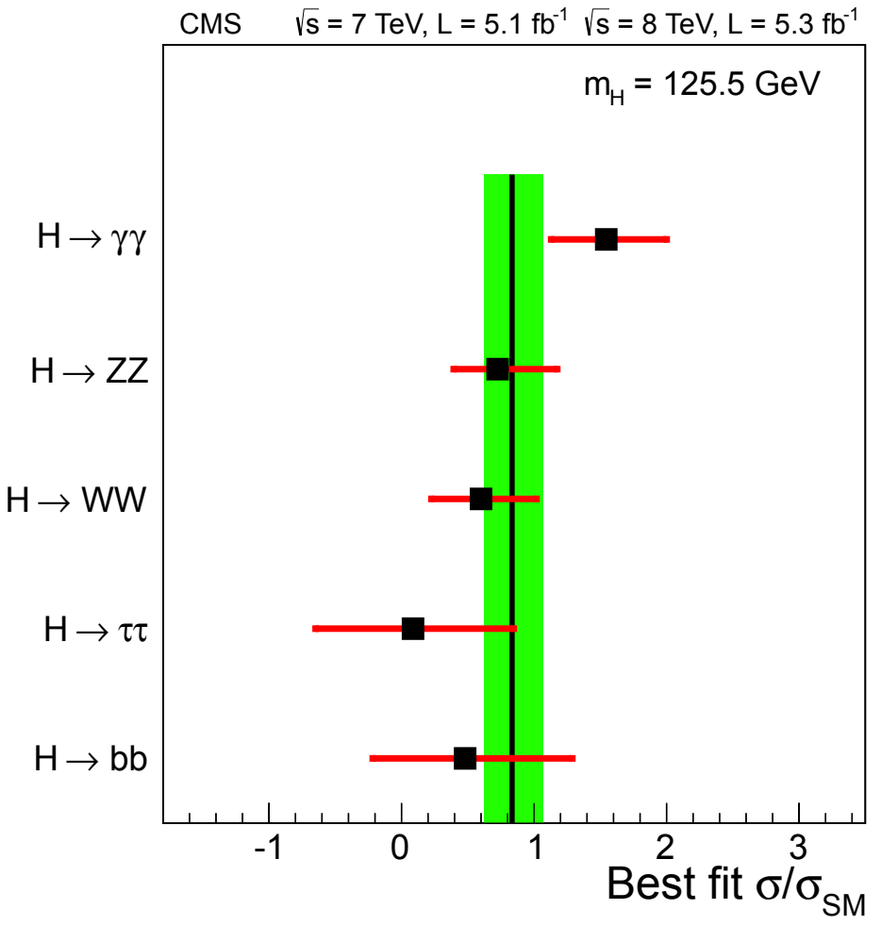
1207.7235

4th July 2012: observation of a Higgs-like boson by ATLAS and CMS

Is it the SM Higgs? ⇨ We need to measure its couplings!

Higgs couplings to gauge bosons and fermions





- Production rates consistent with SM within 2 sigma

- Di-photon rate a bit higher than SM. New physics? Waiting for more data!

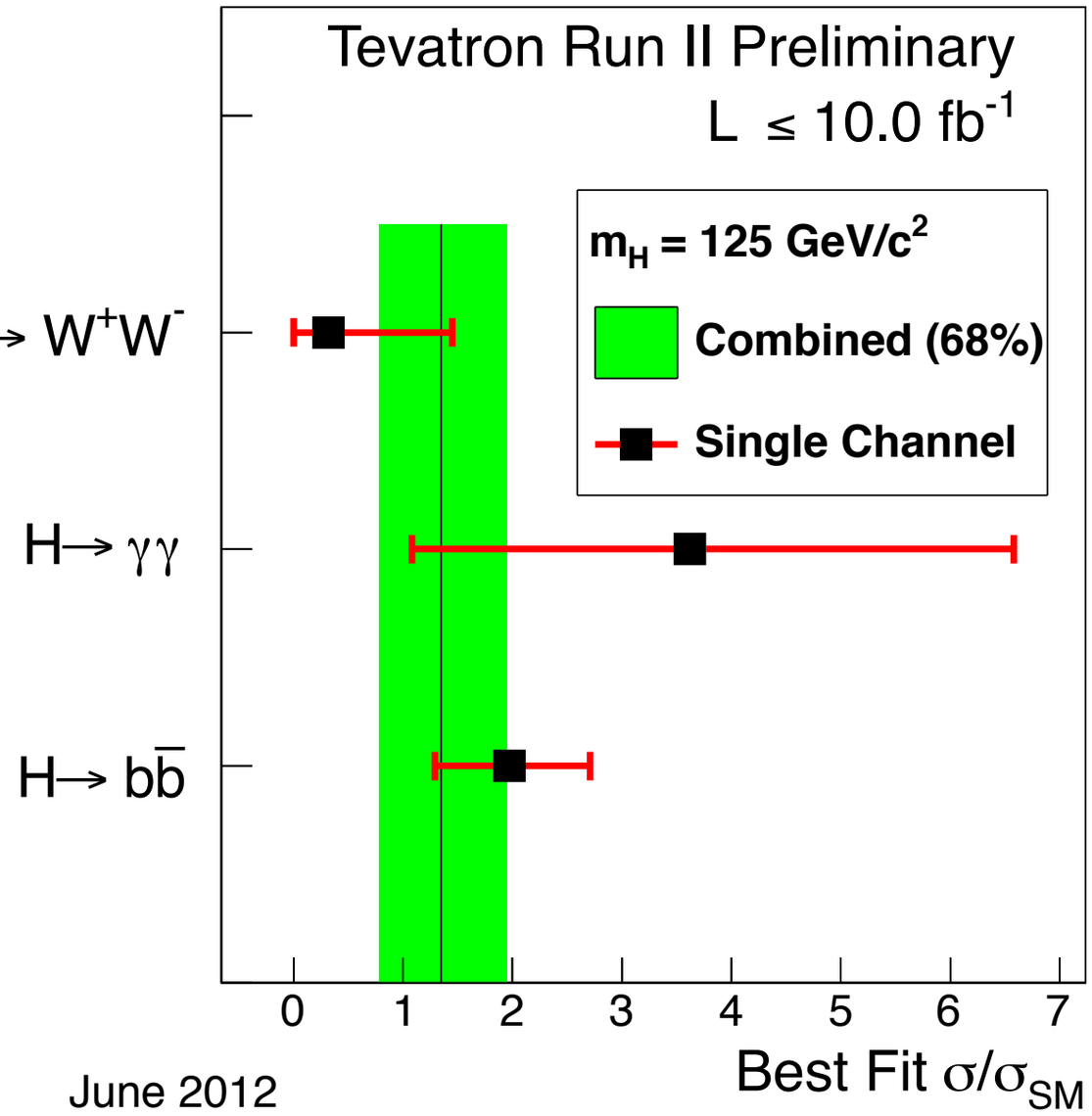
Today and Tomorrow
HCP2012@Tokyo

See also talks by Ren-Yuan Zhu and Xin Chen

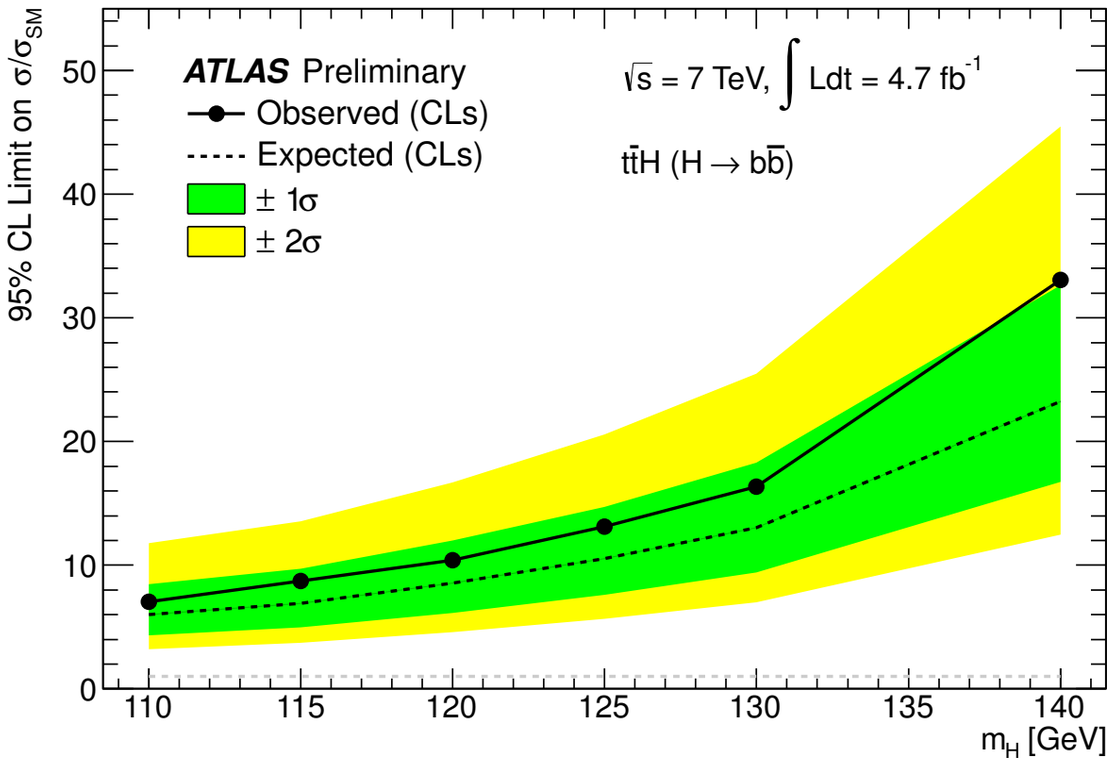
H→bb at Tevatron

Talk by Weiming Yao

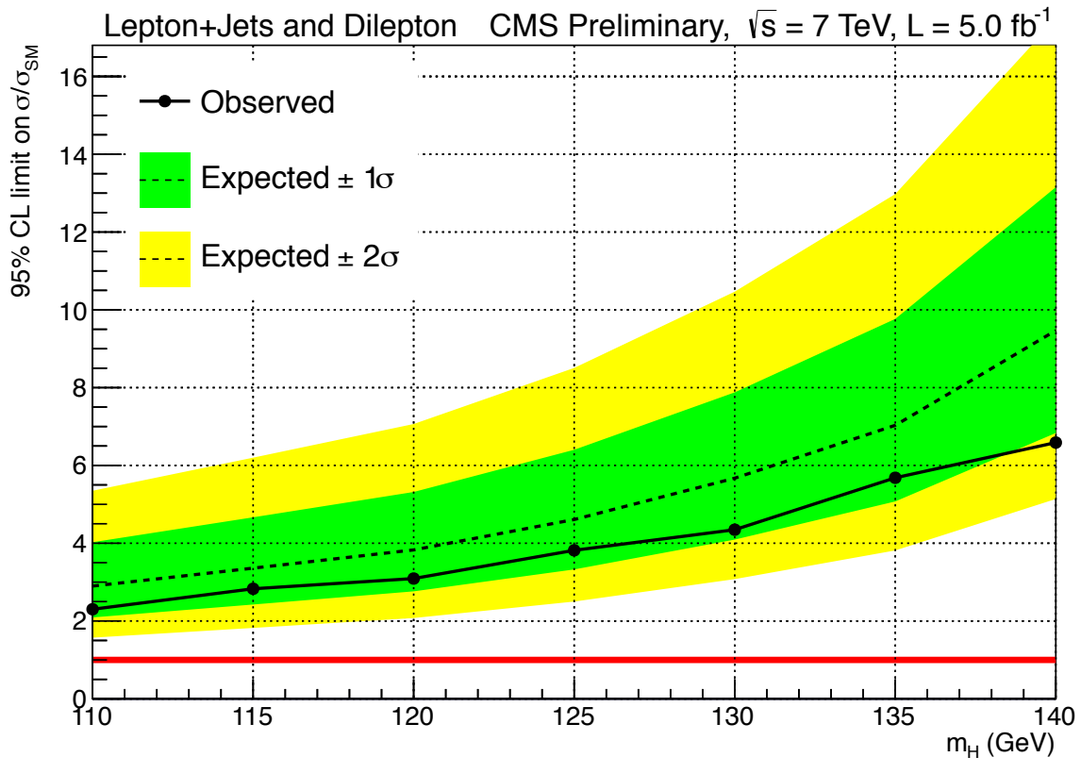
- Consistent with SM



ttH production: yet to be discovered



ATLAS-CONF-2012-135



CMS PAS HIG-12-025

- Measurable at the upgraded LHC? Linear collider required?

- Htt coupling also probed in gg→H **assuming no new particles in the loop**

Higgs potential: self-couplings

Direct verification of the Higgs mechanism

After EWSB: $V = \frac{1}{2} m_h^2 h^2 + \lambda v h^3 + \frac{1}{4} \tilde{\lambda} h^4$

probed by single Higgs production
well-measurable @ 7–8 TeV LHC

probed by Higgs pair production
discovery @ 14 TeV LHC?

probed by triple Higgs production
difficult @ LHC

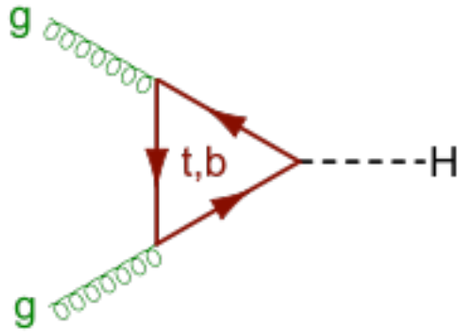
In the SM $\tilde{\lambda} = \lambda = \frac{m_h^2}{2v^2} \approx 0.13$

$m_h = 125 \text{ GeV}$

Higgs production: single vs. double vs. triple

Main production mechanism similar: gluon fusion

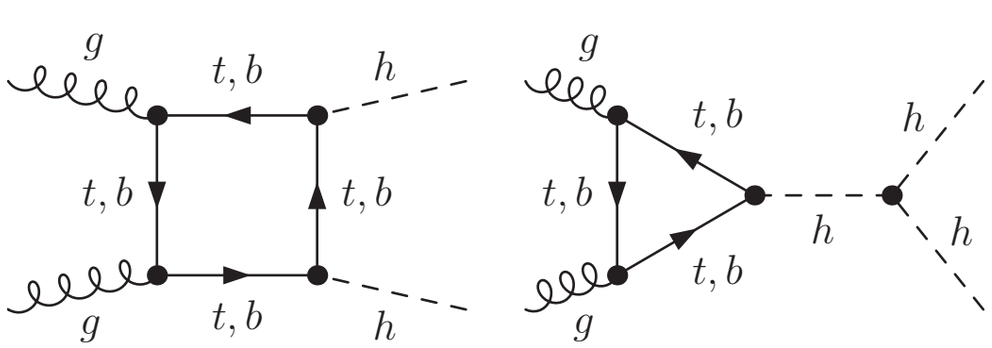
$$m_h = 125 \text{ GeV}$$



$$\sigma_h(7 \text{ TeV}) = 15.43^{+0.44+1.23}_{-0.12-1.18} \text{ pb}$$

NNLO+NNNLL QCD + NLO EW

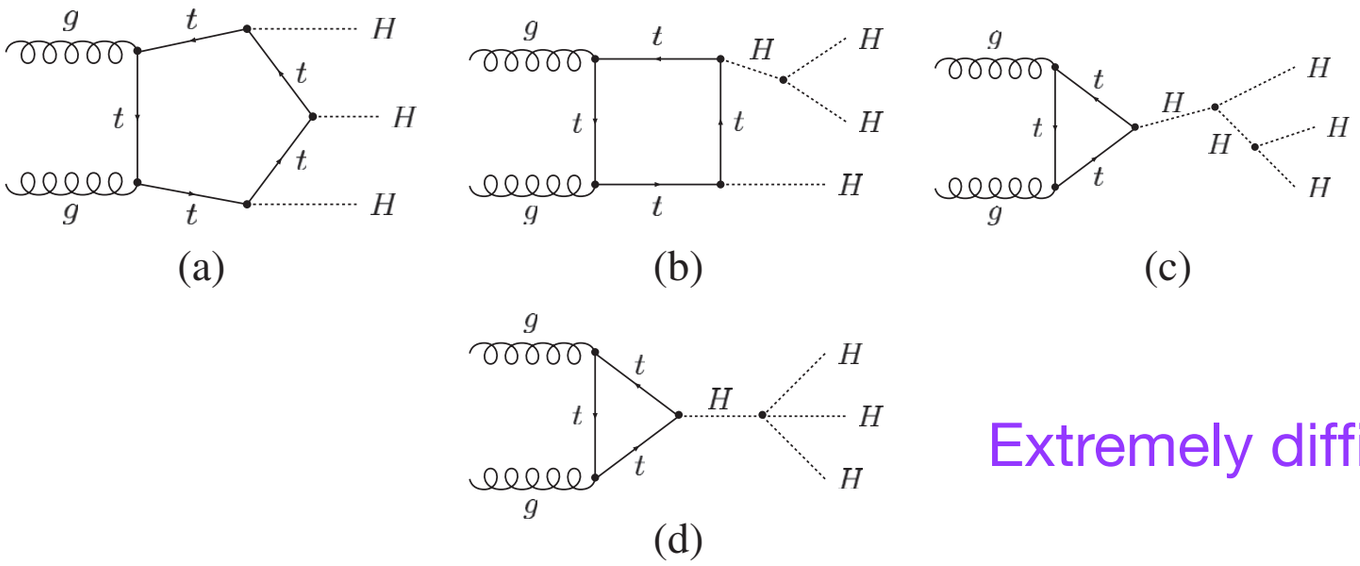
Ahrens, Becher, Neubert, LLY: 0808.3008, 0809.4283, 1008.3162



$$\sigma_{hh}(14 \text{ TeV}) \approx 34 \text{ fb}$$

NLO QCD

Dawson, Dittmaier, Spira: hep-ph/9805244



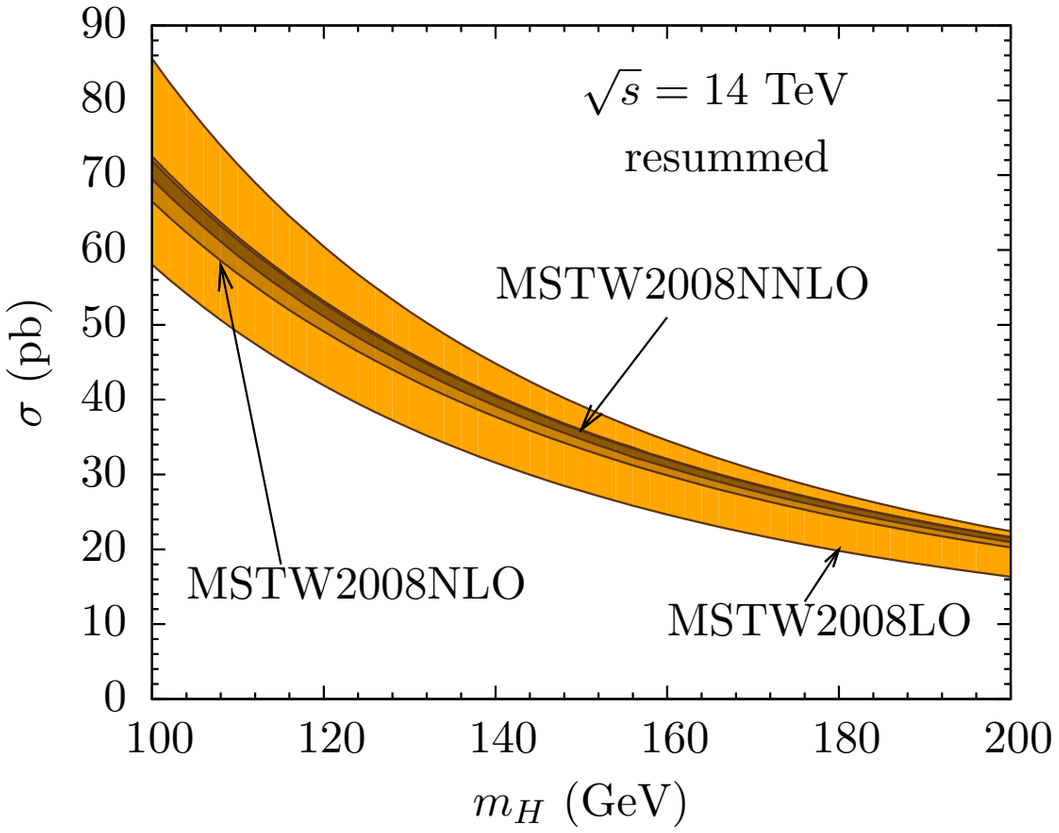
$$\sigma_{hhh}(14 \text{ TeV}) \approx 0.05 \text{ fb}$$

LO only

Plehn, Rauch: hep-ph/0507321

Extremely difficult @ LHC. Linear collider? VLHC?

Perturbative behavior



Ahrens, Becher, Neubert, LLY: 0809.4283

Single Higgs
NNLO+NNNLL
good convergence
small uncertainty

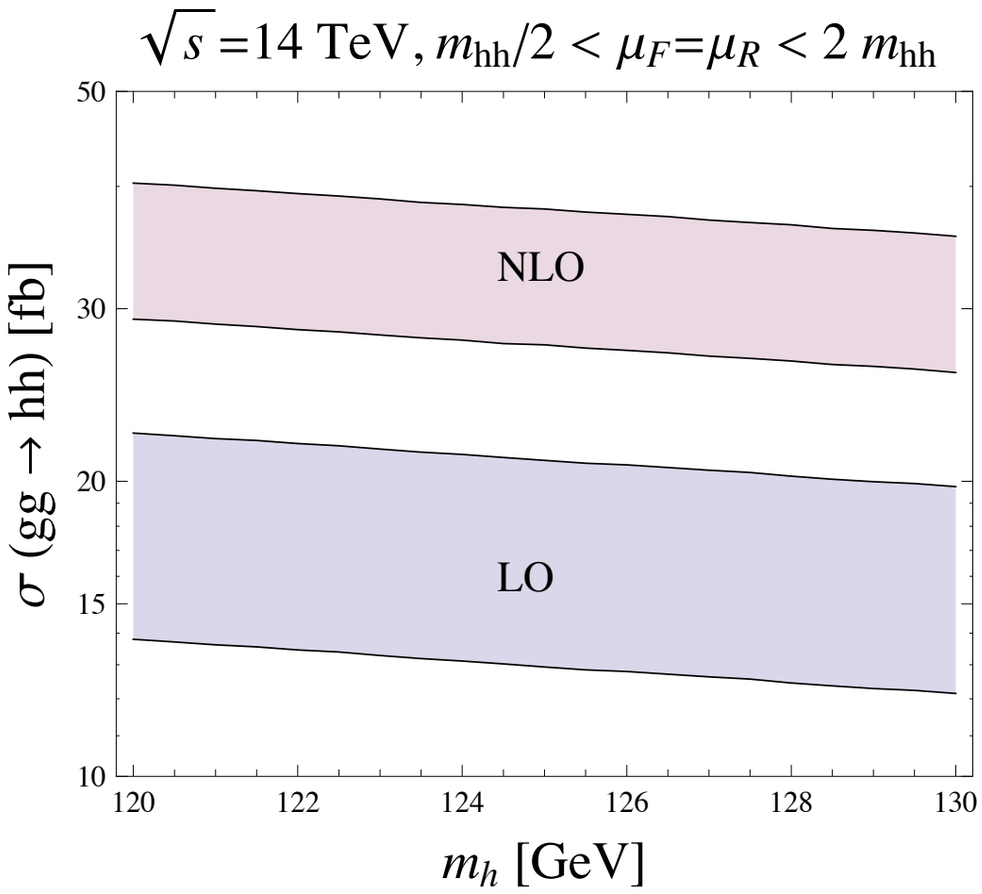
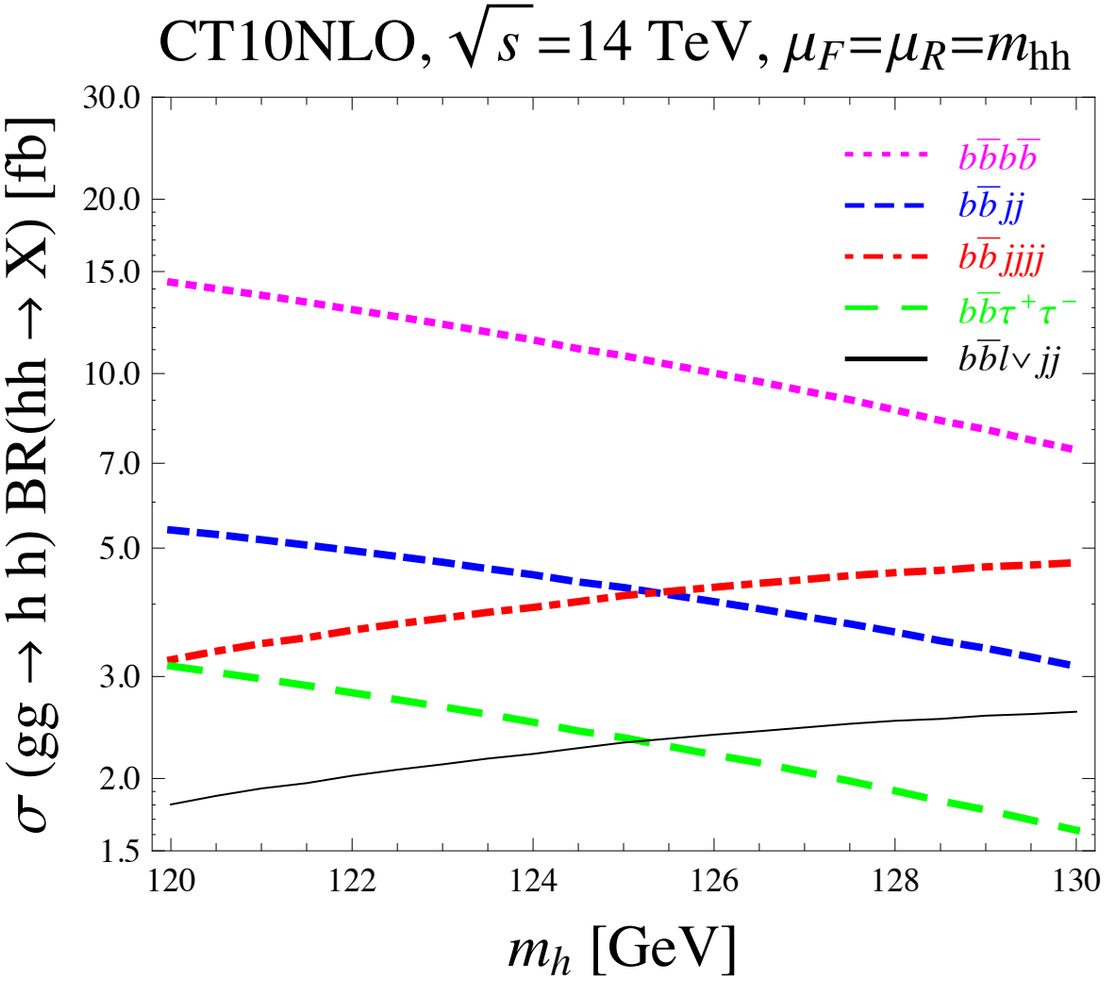


Figure from Papaefstathiou, LLY, Zurita: 1209.1489

Higgs pair
huge correction
large uncertainty
higher order desirable

Higgs pair production and decay



$l = e, \mu$

- Channels with biggest rates overwhelmed by QCD backgrounds
- First channel containing leptons: bbWW→bblνjj This talk

τ decays hadronically

Papaefstathiou, LLY, Zurita: 1209.1489

Previous studies

- Baur, Plehn, Rainwater: hep-ph/0310056
  - bbγγ most promising, S ~ 6 and B ~ 11 @ 600/fb
- Dolan, Englert, Spannowsky (DES): 1206.5001
  - bbττ best channel assuming excellent τ-jet tagging
- Both studies concluded that bbWW channel is impossible due to large backgrounds from top-quark pair production

Signal and backgrounds

Process	σ_{initial} (fb)
$hh \to b\bar{b}\ell\nu jj$	2.34
$t\bar{t} \to b\bar{b}\ell\nu jj$	240×10^3
$W(\to \ell\nu)b\bar{b}$+jets	2.17×10^3
$W(\to \ell\nu)$+jets	2.636×10^6
$h(\to \ell\nu jj)$+jets	36.11
$h(\to \ell\nu jj)b\bar{b}$	6.22
$h(\to b\bar{b}) + WW(\to \ell\nu jj)$	0.0252

Generated with MG/ME
(custom model file from R. Frederix)
Normalized to NLO

Generated with Herwig++
Normalized to approx. NNLO

Ahrens, Ferroglia, Neubert, Pecjak, LLY: 1005.5824

Generated with ALPGEN

Shower/Hadronization with Herwig++

- Backgrounds 5 orders-of-magnitude larger than signal!
  - Require clever ideas to suppress the backgrounds
  - Require huge amount of MC events — huge computational resource

Signal and backgrounds

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Shower/Hadronization with Herwig++

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Boosted jet techniques
Event reconstruction

Top quark pair production

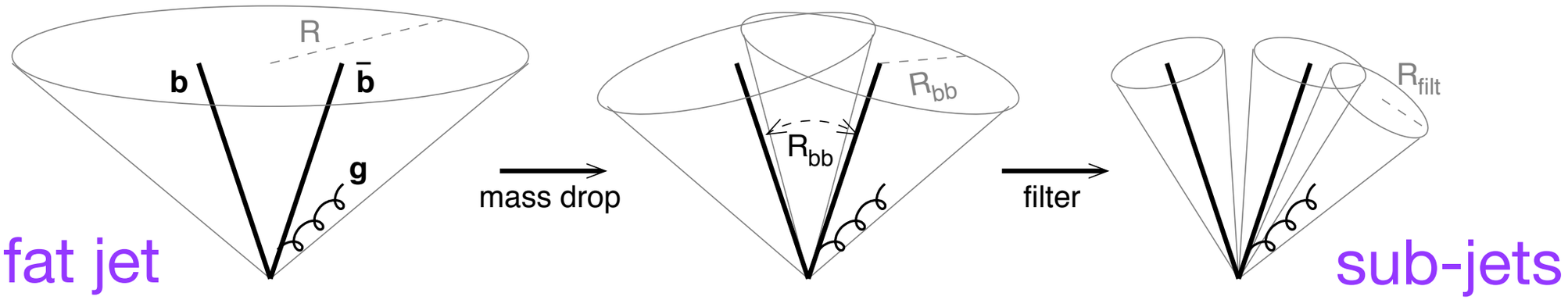
- Main background: precise knowledge important! (total cross section and distributions)

- Our works: NLO+NNLL and/or approximate NNLO

  - Invariant mass distribution
    Ahrens, Ferroglia, Neubert, Pecjak, LLY: 1003.5827
  - Transverse momentum and rapidity distributions
    Ahrens, Ferroglia, Neubert, Pecjak, LLY: 1103.0550
  - Total cross section
    Ahrens, Ferroglia, Neubert, Pecjak, LLY: 1105.5824
  - Forward-backward asymmetry
    Ahrens, Ferroglia, Neubert, Pecjak, LLY: 1106.6051
  - Transverse momentum of tt system
    Zhu, Li, Li, Shao, LLY: 1208.5774

Boosted jet techniques

Butterworth, Davison, Rubin, Salam (BDRS): 0802.2470



- Designed for H+V@LHC, capturing high-pT Higgs decaying to two b-quarks

saved this channel
(disregarded by earlier studies)

applying to hh→bbWW
also employed by DES in hh→bbττ

- Mass drop: fight against QCD initiated jets

- Filtering: fight against underlying events

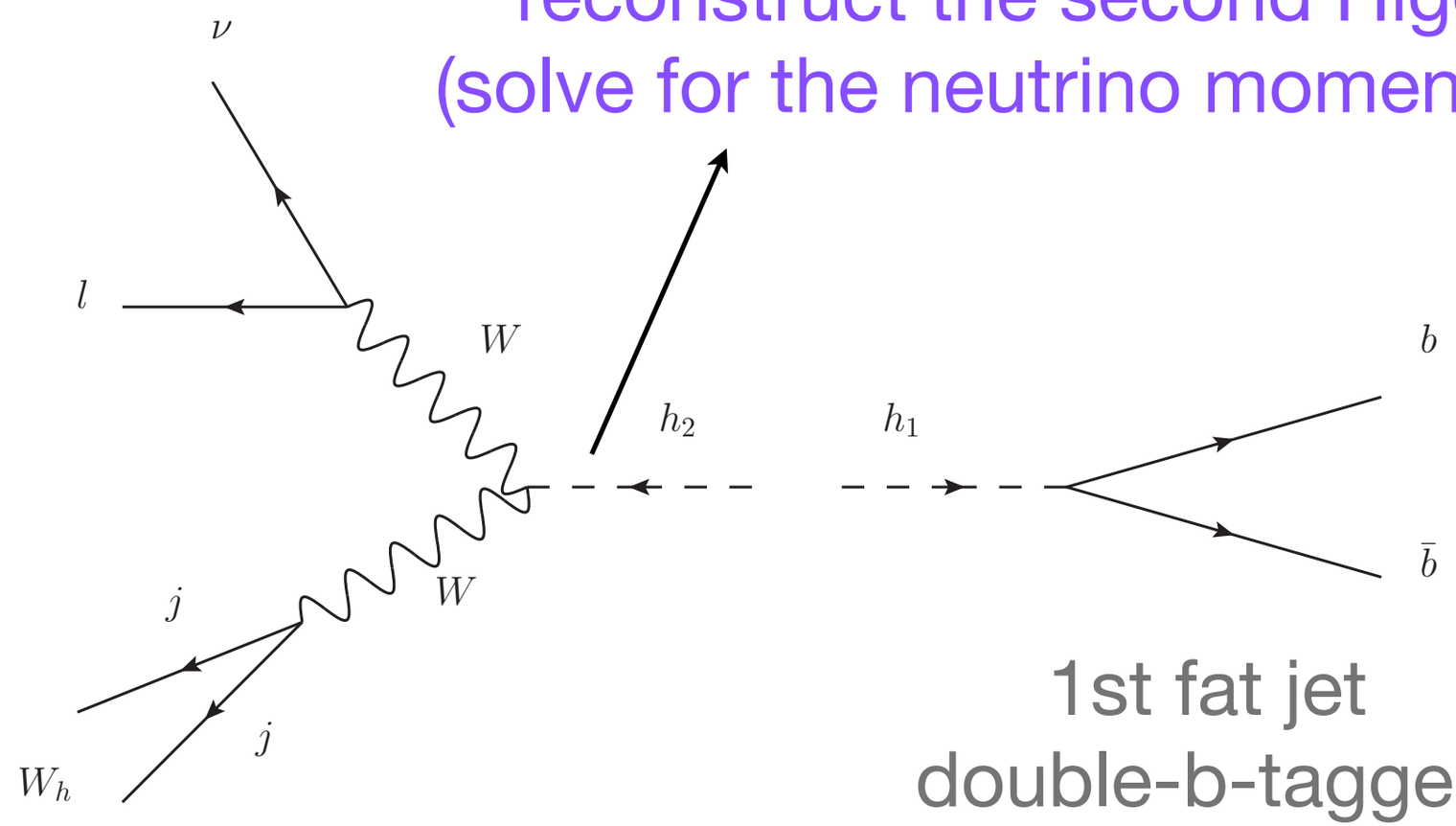
- We use it also for capturing the hadronic decaying W boson

NEW!

Event topology & basic selection cuts

$\not{E}_T > 10$ GeV

reconstruct the second Higgs
(solve for the neutrino momentum)



isolated lepton

$p_T > 10$ GeV

2nd fat jet

$p_T > 40$ GeV, $m > 5$ GeV

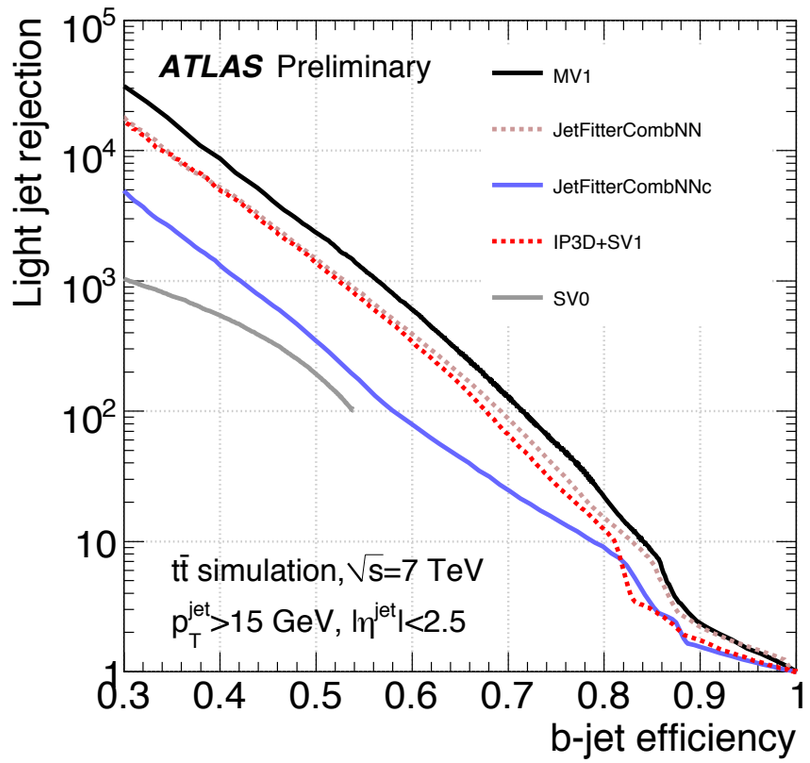
1st fat jet
double-b-tagged

$p_T > 180$ GeV

highly boosted

After the basic cuts

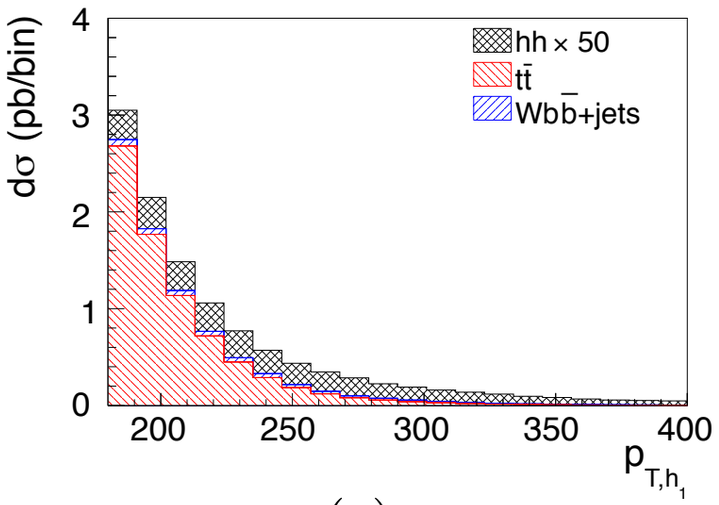
Process	σ_{initial} (fb)	$\sigma_{\textbf{basic}}$ (fb)
$hh \to b\bar{b}\ell\nu jj$	2.34	0.134
$t\bar{t} \to b\bar{b}\ell\nu jj$	240×10^3	15.5
$W(\to \ell\nu)b\bar{b}$+jets	2.17×10^3	0.97
$W(\to \ell\nu)$+jets	2.636×10^6	$\mathcal{O}(0.01)$
$h(\to \ell\nu jj)$+jets	36.11	$\mathcal{O}(0.0001)$
$h(\to \ell\nu jj)b\bar{b}$	6.22	$\mathcal{O}(0.001)$
$h(\to b\bar{b}) + WW(\to \ell\nu jj)$	0.0252	-



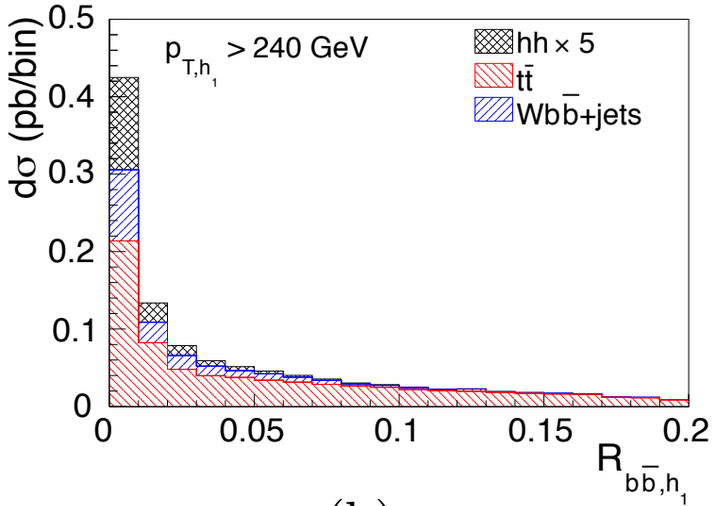
ATLAS-CONF-2012-043

- B-tagging efficiency 70%, light jet fake rate 1%
- h+jets and W+jets backgrounds can be safely neglected
- Basic cuts great performance: keep 5% signal, 0.05% Wbbj and 0.005% tt
- Backgrounds still 100 times bigger, further analysis needed

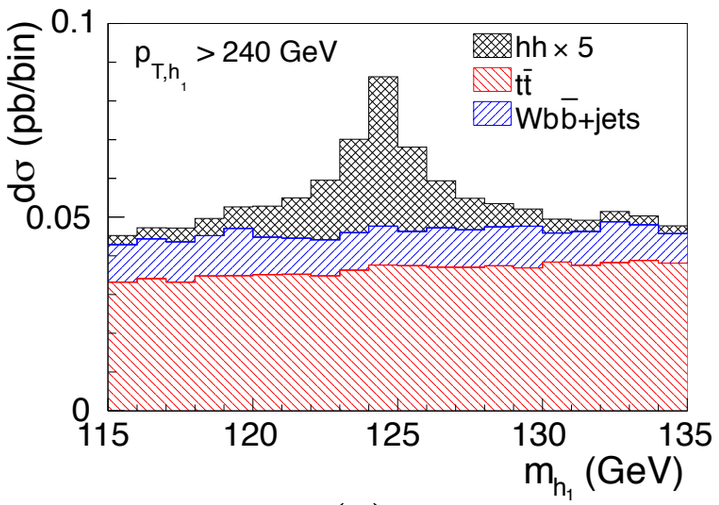
Further analysis



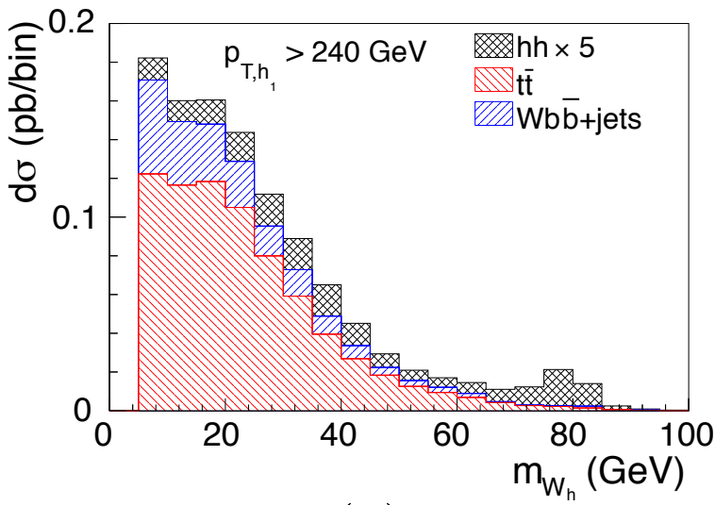
(a)



(b)



(c)



(d)

- **Further cuts**

$$p_{T,h_1} > 240 \text{ GeV}$$

$$R_{b\bar{b},h_1} < 0.06$$

$$m_{h_1} \in [120 - 130] \text{ GeV}$$

$$m_{W_h} > 65 \text{ GeV}$$

- **S ~ 4.5, B ~ 2.4 @ 600/fb**

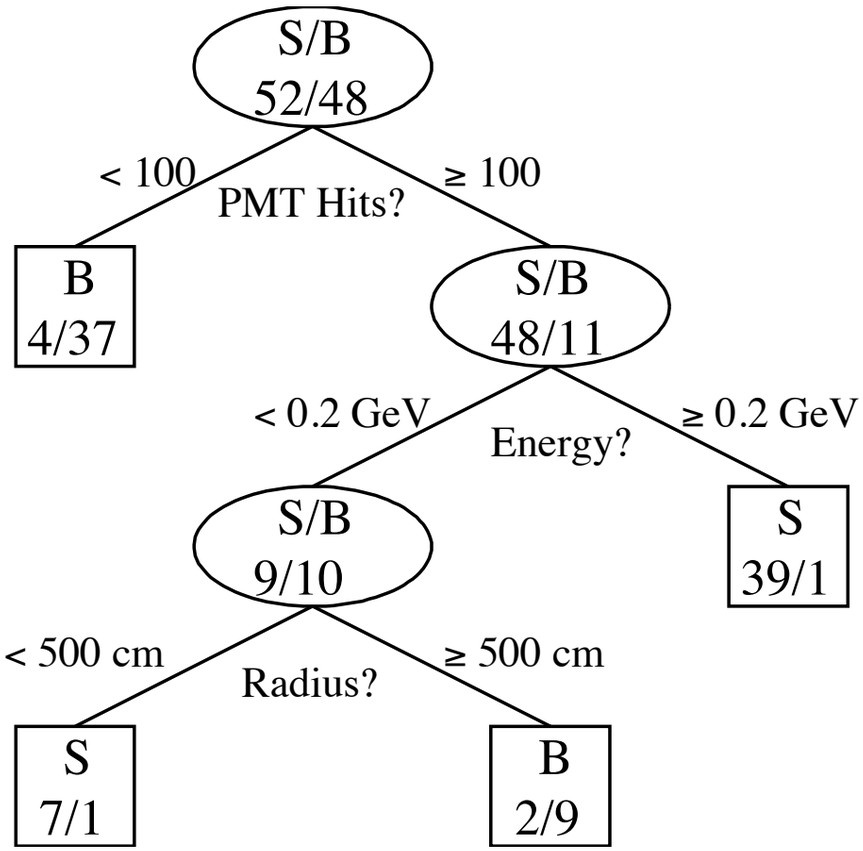
Further improvement requires more kinematic variables

➥ multivariate analysis: Boosted Decision Trees (BDT)

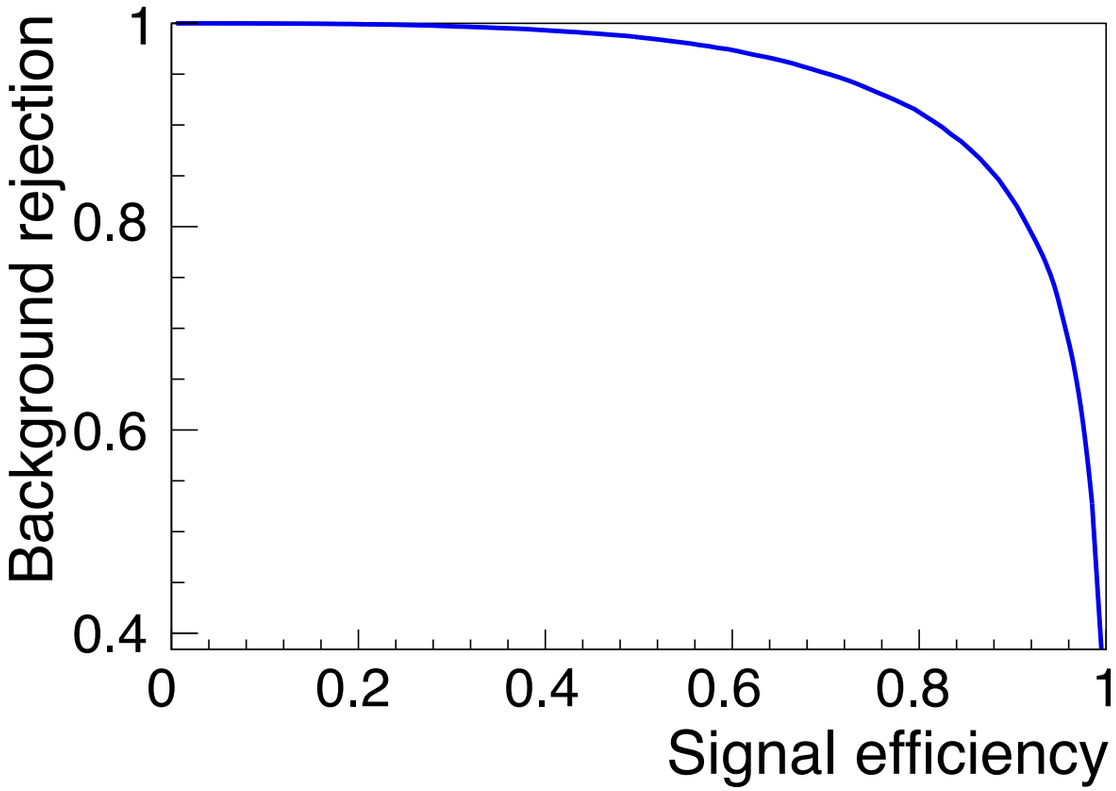
Boosted Decision Trees

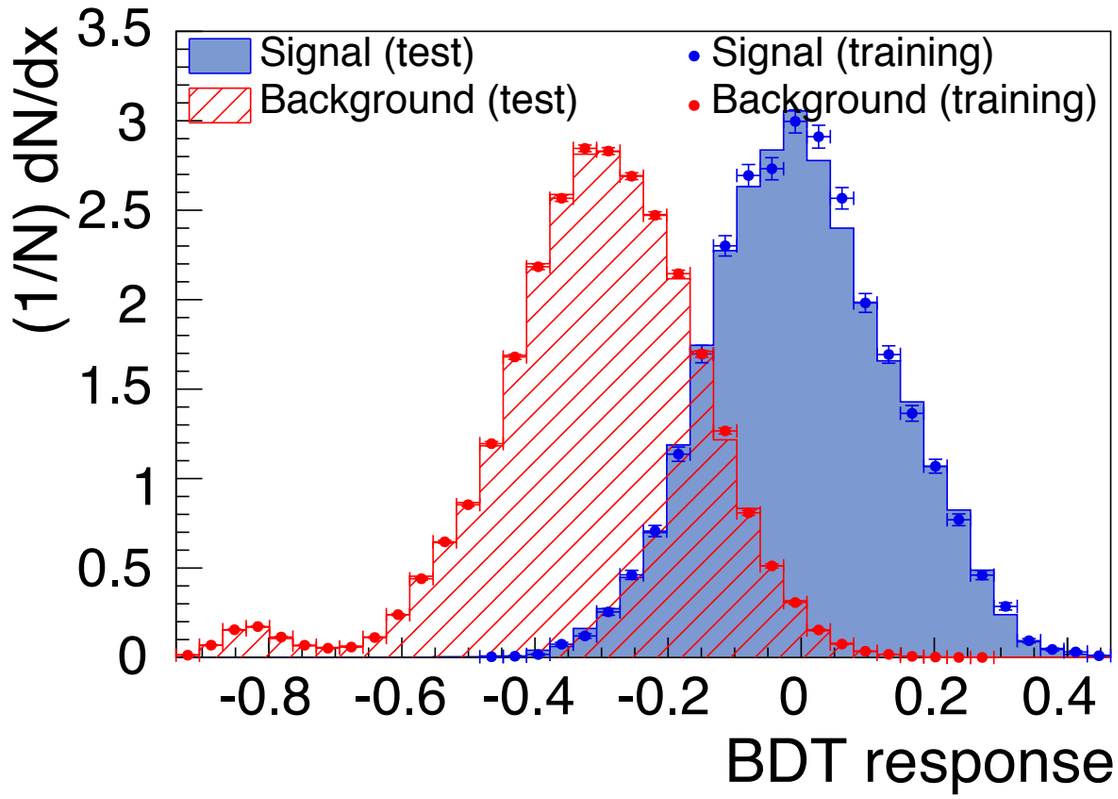
Roe, Yang, Zhu, Liu, Stancu, McGregor: physics/0408124

- Greater power to distinguish signal and background than simple cuts
- Widely used in modern HEP experiments (alternative to neural networks)
- Implemented in ROOT TMVA package
- Boosting: stability against training-sample-dependence



BDT output





- Good separation between signal and background
- Optimal point: S ~ 9, B ~ 5 @ 600/fb, about 3.1σ evidence!
- Including $W \to \tau\nu_\tau$ $(\epsilon_\tau = 0.7)$ increases significance to 3.6σ

DES assumed 0.8 for bbττ

Summary

- Higgs coupling measurements crucial to finally establish the SM, or provide hints to new physics

- Higgs self-couplings: direct probe of the Higgs potential

- Probe Higgs trilinear coupling via Higgs pair production in the bbWW channel (disregarded in previous studies due to large background)

- Employ jet substructure techniques, event reconstruction and multivariate analysis to enhance sensitivity

- Can achieve 3.6σ evidence at the 14 TeV LHC with 600/fb

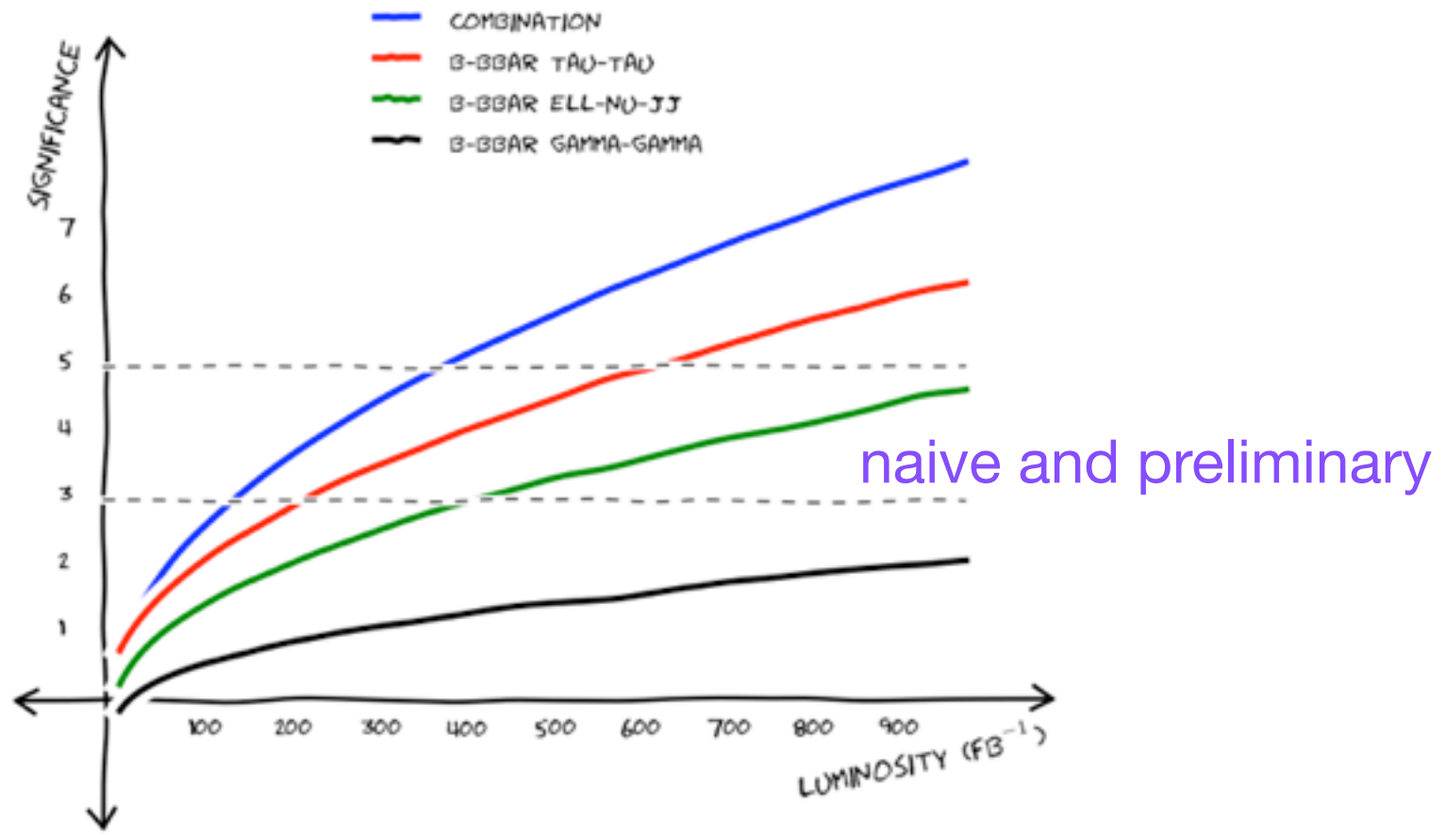
Future prospects

works in progress

- Improved analysis: detector effects, underlying events, hh+jet and tt+jet
  Change of energy? 13 TeV or 14 TeV?

- Combination of channels

aiming for discovery at 300/fb!



naive and preliminary

- New physics effects (may enhance the signal)

Possible improvements in pQCD

- NLO QCD corrections only available in the heavy top quark limit (not a very good approximation, especially for distributions)
  - Exact NLO very difficult
  - May attempt an expansion in $1/m_t$

Done for single Higgs at NNLO

Harlander, Ozeren: 0909.3420
Pak, Rogal, Steinhauser: 0911.4662

- Higher orders: resummation and/or NNLO (of course in the heavy top limit)
  - Will bring down the scale uncertainty