Search for a pair of BEH production with ATLAS

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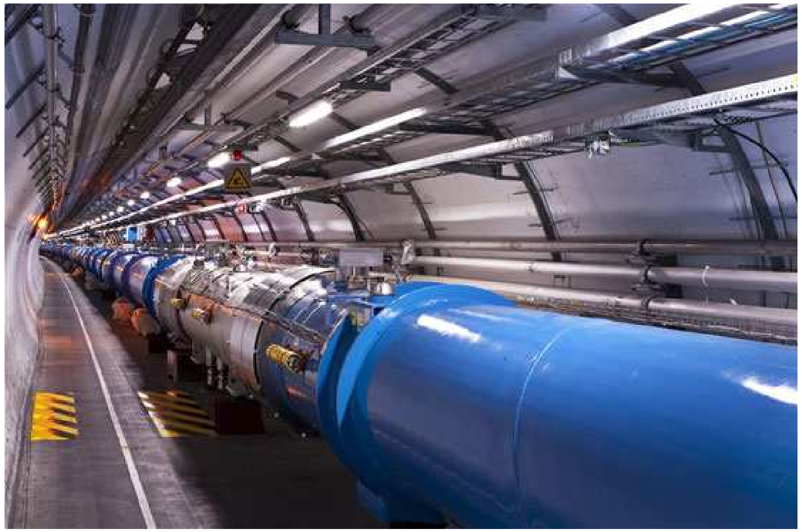
Large Hadron Collider

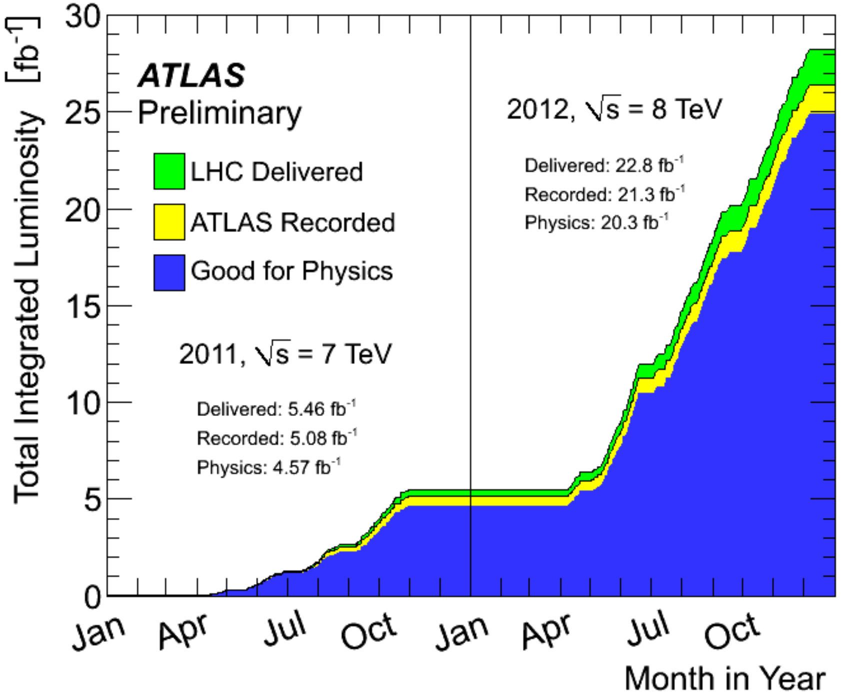
pp collider, designed for $\sqrt{s}$ = 14 TeV (7 TeV in 2011, 8 TeV in 2012, 13 TeV in 2015)

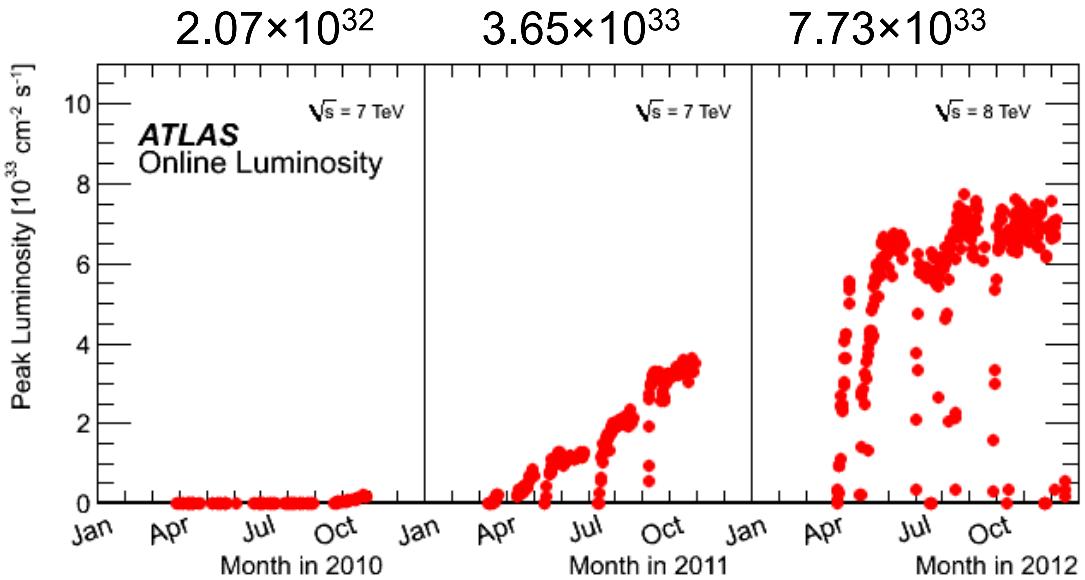
- 27 km circumference, 100 m underground, 1232 superconducting dipole magnets, magnetic field nominally 8.3 T, max instantaneous luminosity $10^{34} cm^{-2}s^{-1}$

- 4 detectors at collision points: **ATLAS, CMS, LHCb, ALICE** (TOTEM and LHCf)

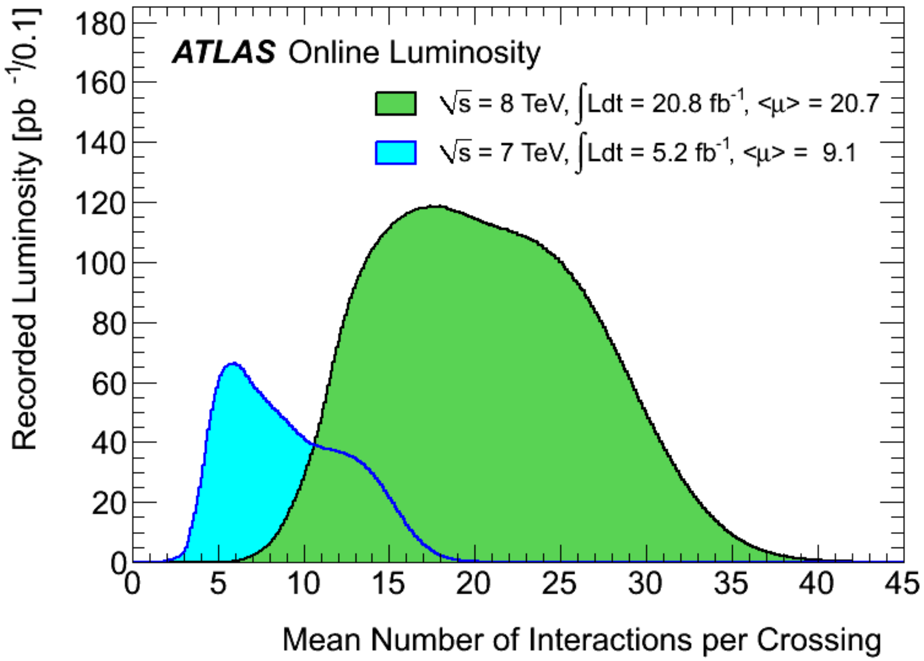


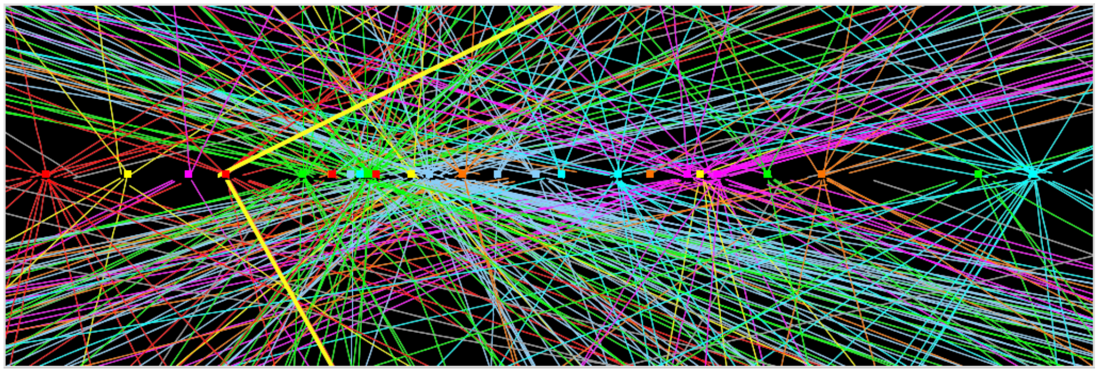
Run I (2009-2012) data taking





~20 fb-1 of 8 TeV + 5 fb-1 of 7 TeV used for Run I analyses





$Z \rightarrow \mu^+\mu^-$ candidate with 25 reconstructed vertices

Higgs boson discovery

The Nobel Prize in Physics 2013

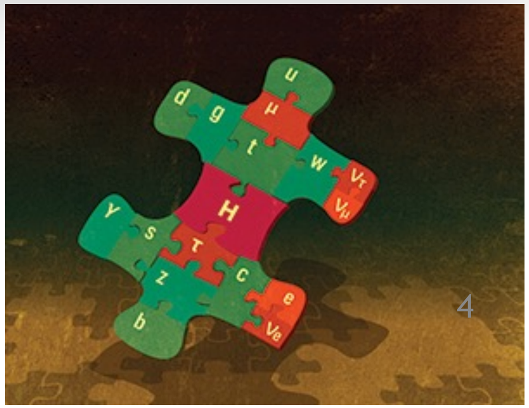
The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2013 to

François Englert
Université Libre de Bruxelles, Brussels, Belgium

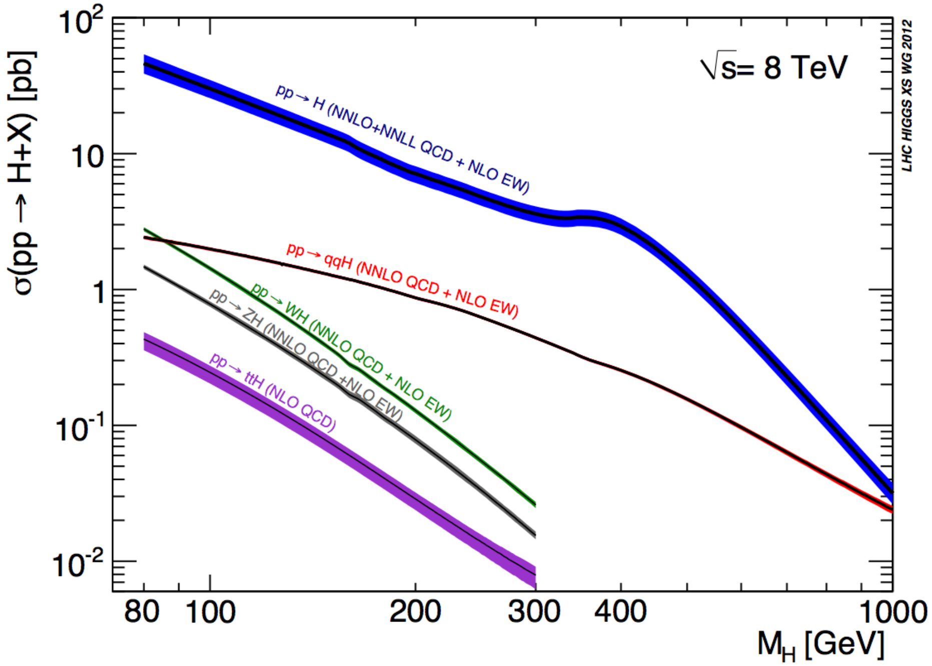
Peter W. Higgs
University of Edinburgh, UK

"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

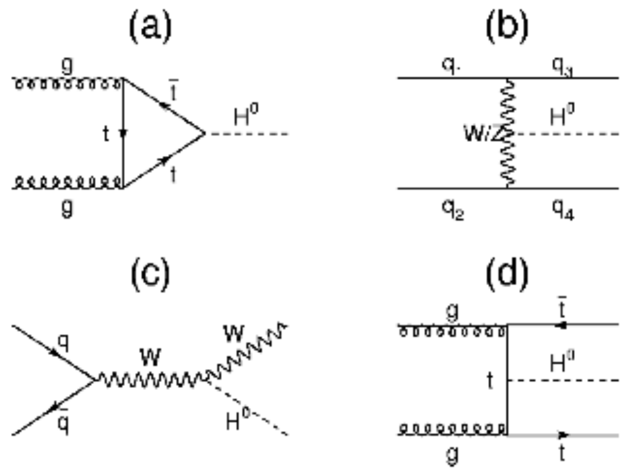
The puzzle being completed, the two experiments ATLAS and CMS enter the era of properties measurement of the newly discovered particle and the search for New Physics beyond the Standard Model.

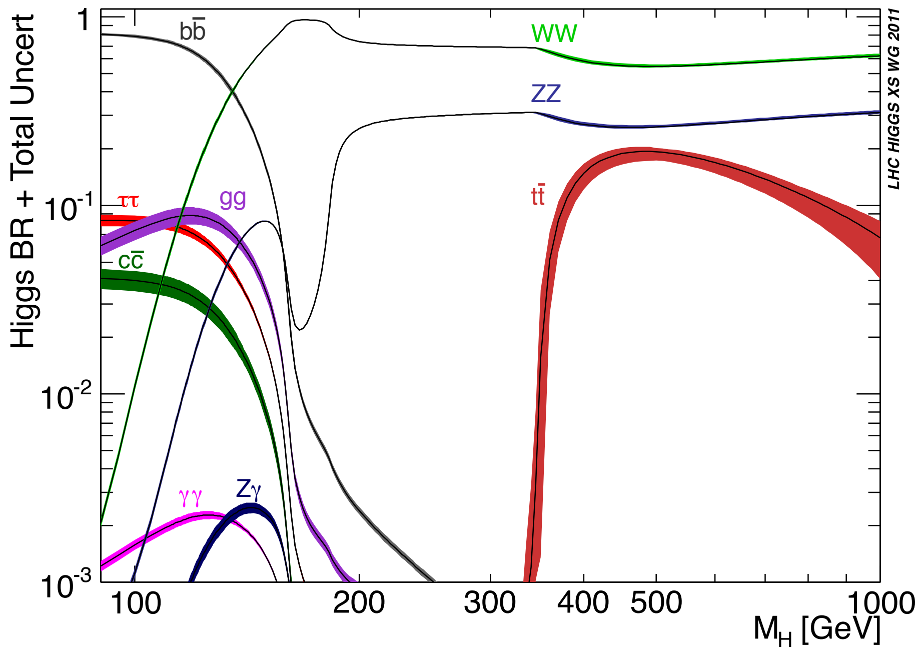


Higgs production at the LHC



a) Gluon-gluon fusion (ggH)
b) Vector boson fusion (VBF)
c) Associated V=W,Z production (VH)
d) Associated tt production (ttH)



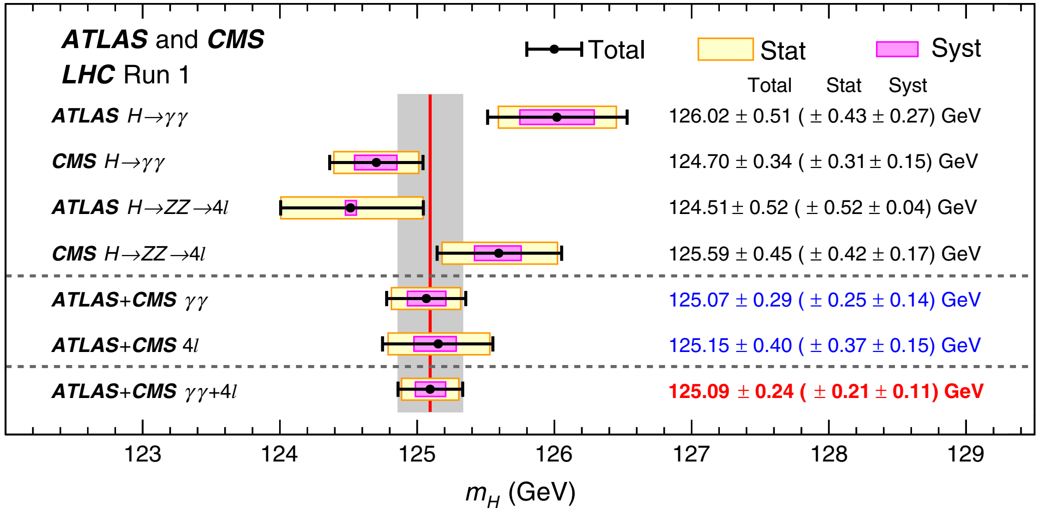


- H-->bb: high BR but suffers from large QCD background
- H--> ττ: sensitivity enhanced in VBF production
- H-->γγ: narrow resonance over a continuum background
- H-->ZZ: -->4l golden channel excellent mass resolution and S/B --> llqq and llvv
- H-->WW: -->lvlv and lvqq

Properties measurement

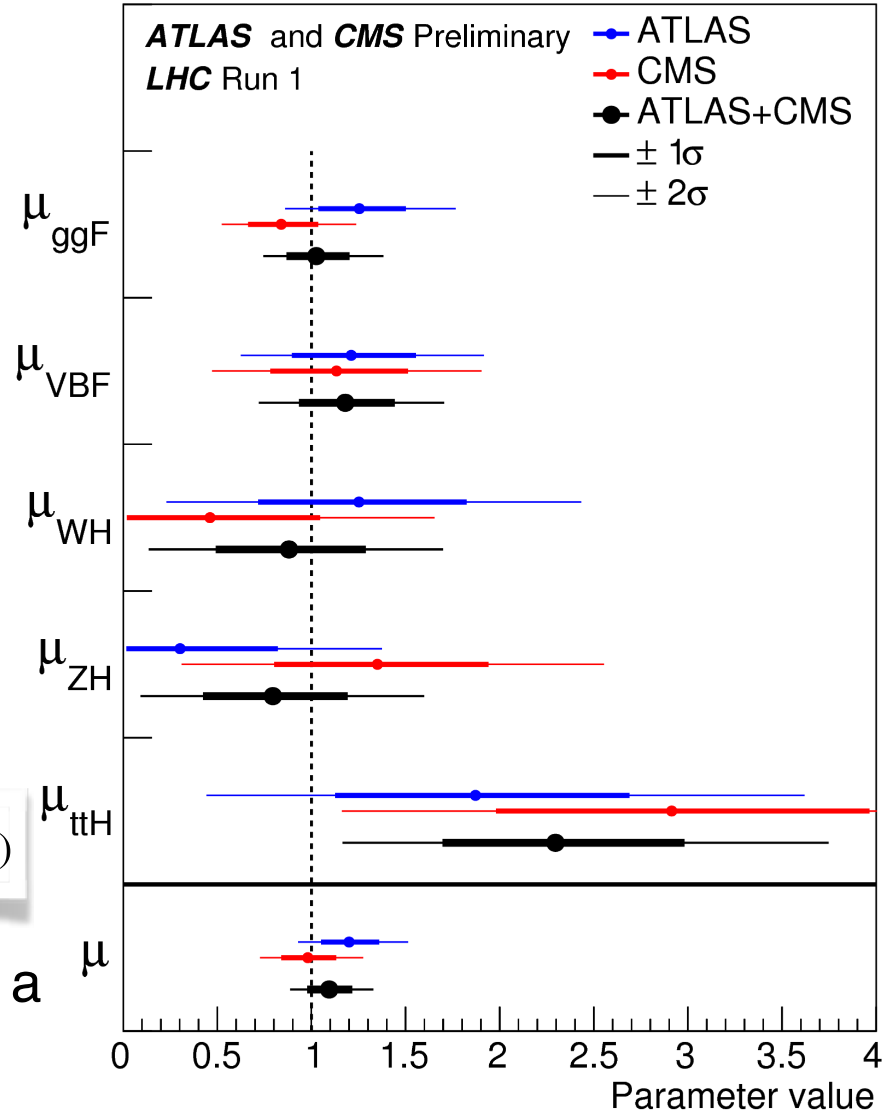
ATLAS-CONF-2015-044
CMS-PAS-HIG-15-002

PRL **114,** 191803 (2015)



$$m_H = 125.09 \pm 0.24 \text{ GeV}$$
$$= 125.09 \pm 0.21\,(\text{stat}) \pm 0.11\,(\text{syst})\ \text{GeV}$$

$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}\,(\text{stat})\ ^{+0.04}_{-0.04}\,(\text{expt})\ ^{+0.03}_{-0.03}\,(\text{thbgd})^{+0.07}_{-0.06}\,(\text{thsig})$$



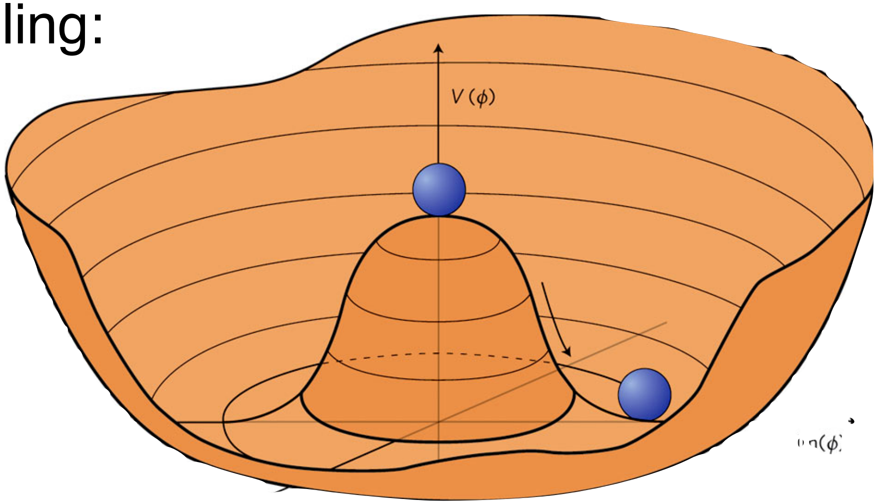
The exclusion of all non-SM spin hypotheses at a more than 99.9% CL in favour of the SM 0^+

arXiv:1506.05669, Phys. Rev. D 92, 012004

So far, compatibility with the SM properties —> SM Higgs boson discovered

Higgs self-coupling

The Higgs potential is directly to its self-coupling:



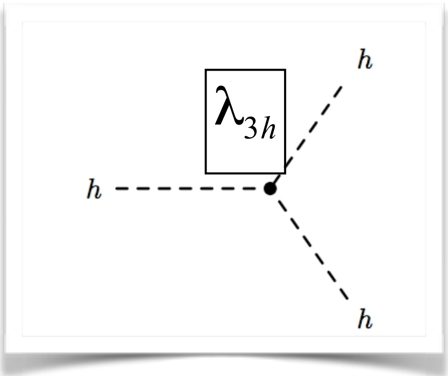
$$V(H) = \mu^2 |H|^2 + \lambda |H|^4 + \ldots$$

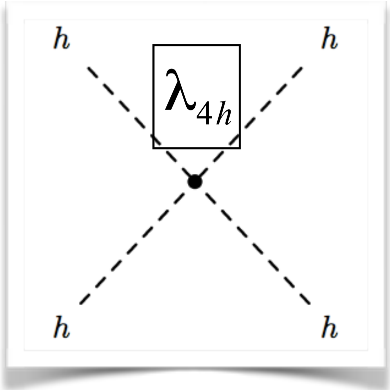
$$H \rightarrow \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \upsilon + h \end{pmatrix}$$

Expressed in terms of mass, trilinear and quartic couplings:

$$V(h) = \frac{1}{2} m_h^2 h^2 + \lambda_{3h} \upsilon h^3 + \frac{\lambda_{4h}}{4} h^4 + \ldots$$

$$\lambda_{3h} = \lambda_{4h} = m_h^2 / 2\upsilon^2$$



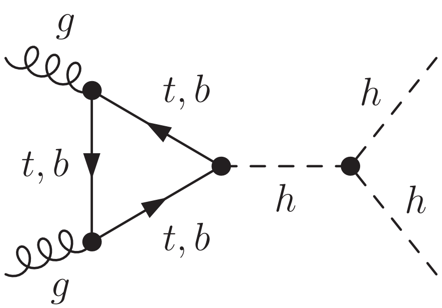


Accessible in Higgs pair production

Extremely challenging

SM Higgs pair production

SM hh production: destructive interference between the trilinear coupling diagram and the box diagram



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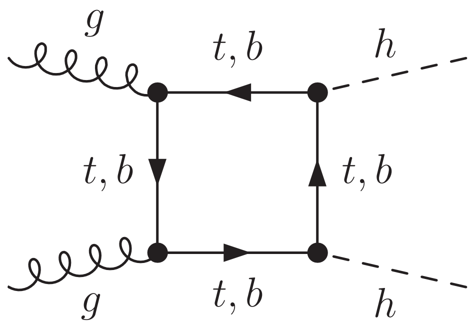
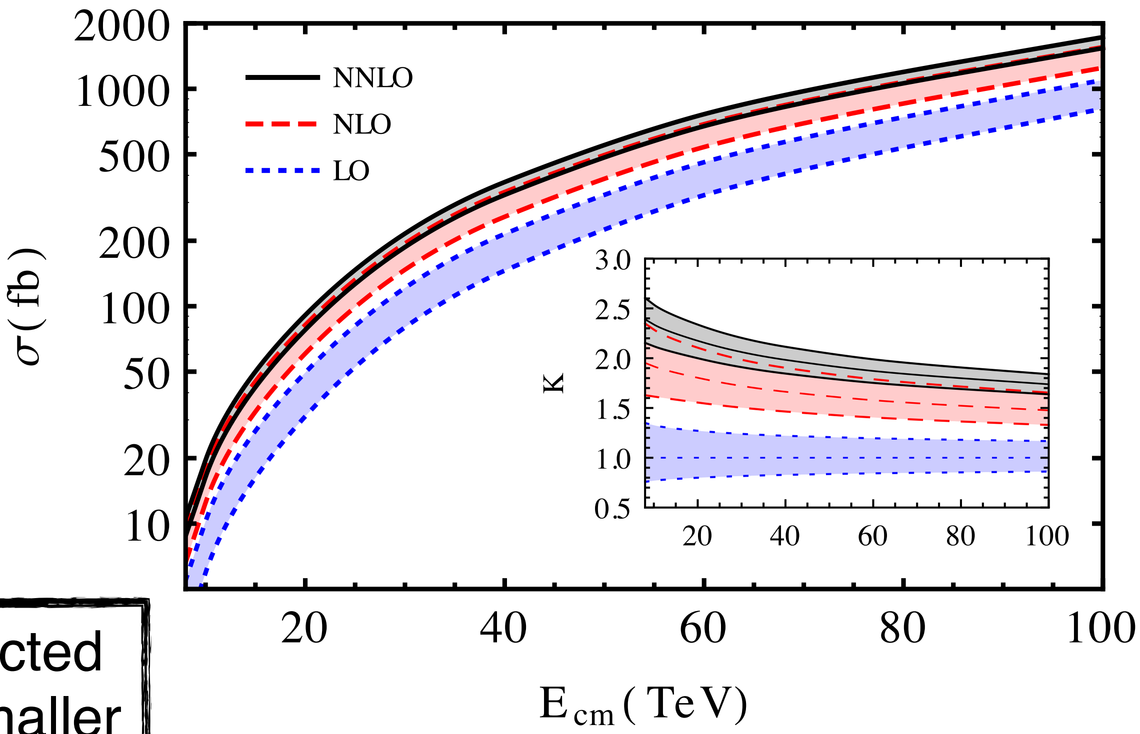


Cross sections computed at NNLO

E_{cm}	8 TeV	14 TeV	100 TeV
$\sigma_{\rm NNLO}$	9.76 fb	40.2 fb	1638 fb
Scale [%]	$+9.0-9.8$	$+8.0-8.7$	$+5.9-5.8$
PDF [%]	$+6.0-6.1$	$+4.0-4.0$	$+2.3-2.6$
PDF+α_S [%]	$+9.3-8.8$	$+7.2-7.1$	$+5.8-6.0$

arXiv:1309.6594v2



Difficult to probe due to the low predicted rate ~ several order of magnitudes smaller than the single h

HL-LHC prospects

Decay Channel	Branching Ratio	Total Yield (3000 fb^{-1})
$b\bar{b} + b\bar{b}$	33%	40,000
$b\bar{b} + W^+W^-$	25%	31,000
$b\bar{b} + \tau^+\tau^-$	7.3%	8,900
$ZZ + b\bar{b}$	3.1%	3,800
$W^+W^- + \tau^+\tau^-$	2.7%	3,300
$ZZ + W^+W^-$	1.1%	1,300
$\gamma\gamma + b\bar{b}$	0.26%	320
$\gamma\gamma + \gamma\gamma$	0.0010%	1.2

Considering **bbγγ** decay channel in ATLAS:

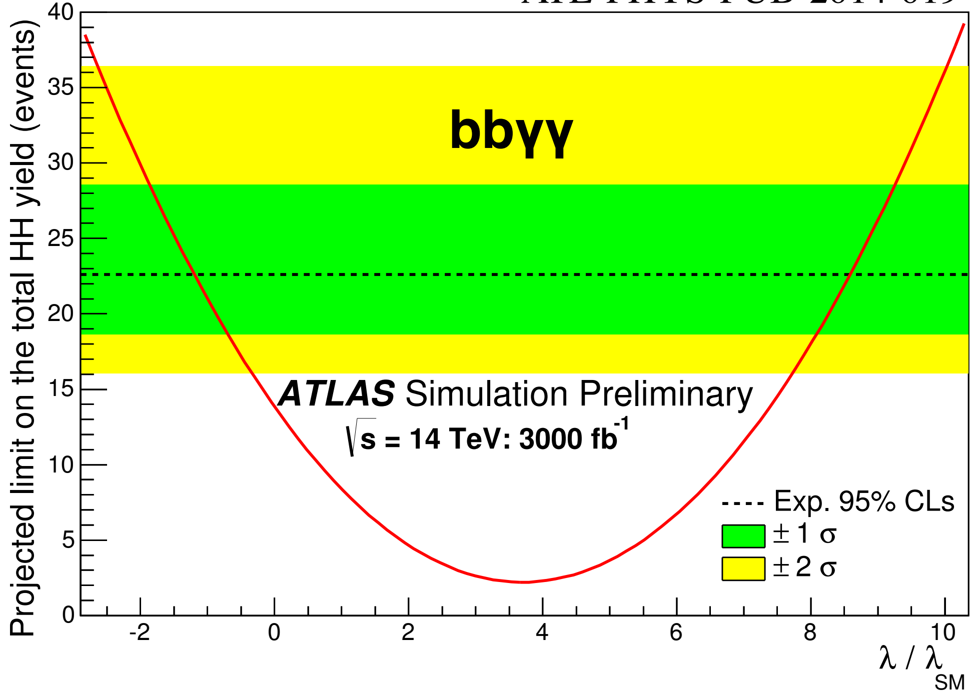
S/√B ~ 1.3 in the full 3000fb^{-1} dataset

An exclusion of 95%CL of BSM models with values **<~ -1.3SM and >~8.7SM**

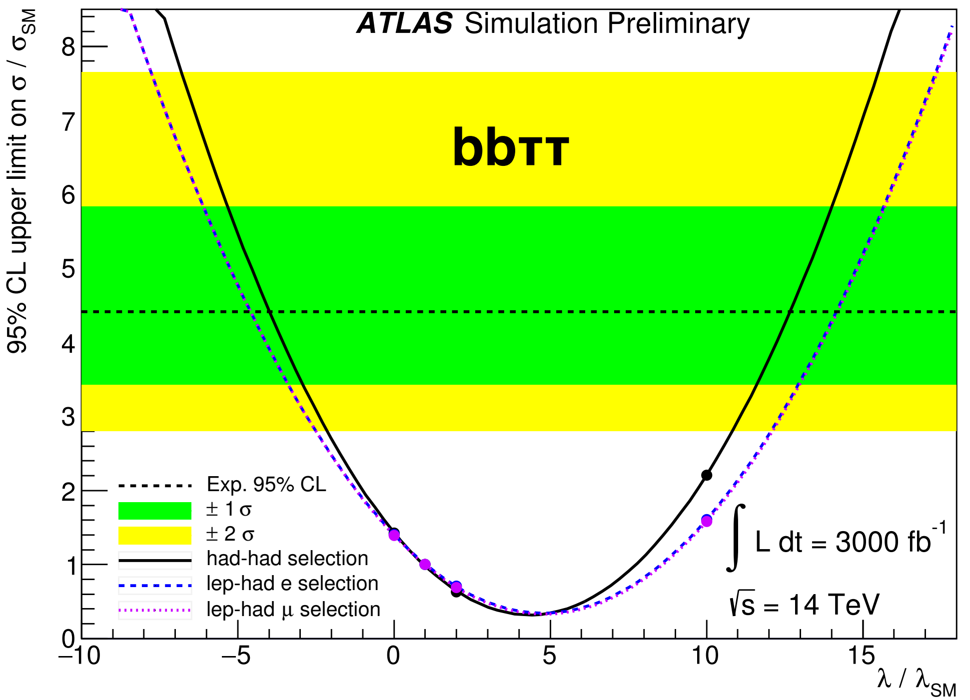
Expected 0.6σ for bbττ and exclusions of <-4SM and >12SM

The CMS collaboration showed *(CMS-PAS FTR-15-002)* that combining the bbγγ and the bbττ decay channels, the expected significance of a Higgs pair production is **1.9σ**

ATL-PHYS-PUB-2014-019



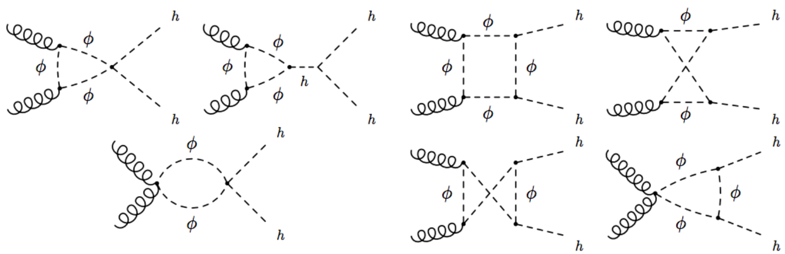
ATL-PHYS-PUB-2015-046



A variety of extensions of the SM would enhance Higgs boson pair production

Non resonant production

- non SM Yukawa couplings
- direct tthh vertex (composite models)
- addition of light colored scalars
- dimension-6 gluon Higgs operators …



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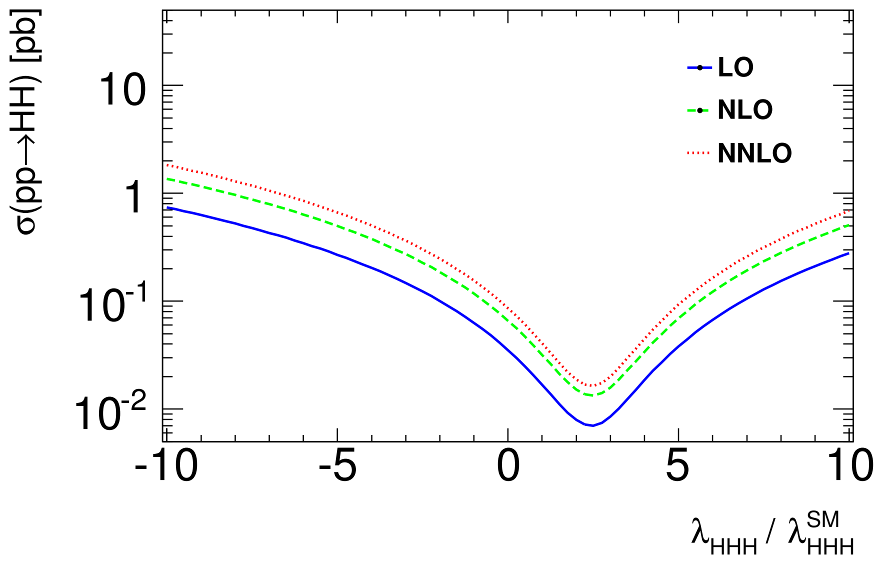
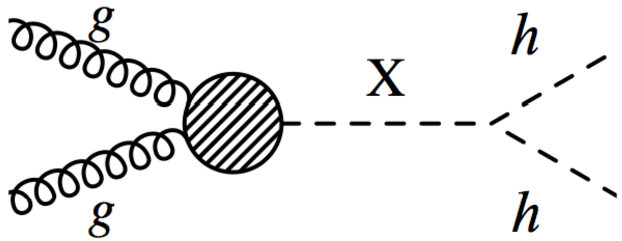


Resonant production



- SUSY: 2HDM the heavier H —>hh (—>1pb)
- Production and decay of exotic particles: graviton, radion or stoponium..
- Hidden sector mixing with the observed h

Search for hh in Run I

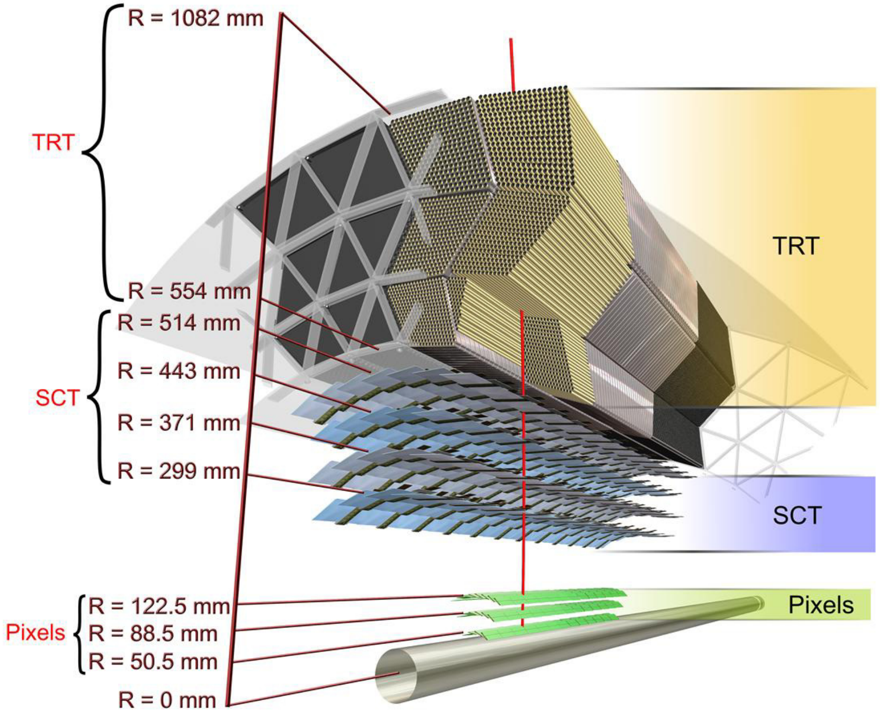
ATLAS Collaboration

- Searches for Higgs boson pair production in the $hh \rightarrow bb\tau\tau, \gamma\gamma WW^{*}, \gamma\gamma bb, bbbb$ channels with the ATLAS detector *Phys. Rev. D 92, 092004 (2015)*
- Search for Higgs boson pair production in the $b\bar{b} b\bar{b}$ final state from pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector *Eur. Phys. J. C (2015) 75:412*
- Search For Higgs Boson Pair Production in the $\gamma\gamma bb$ Final State using pp Collision Data at $\sqrt{s}=8$ TeV from the ATLAS Detector *Phys. Rev. Lett. 114, 081802 (2015)*

CMS Collaboration

- Search for the resonant production of two Higgs bosons in the final state with two photons and two bottom quarks *CMS PAS HIG-13-032*
- Search for resonant pair production of Higgs bosons decaying to two bottom quark-antiquark pairs in proton-proton collisions at 8 TeV, *CMS-HIG-14-013*
- Searches for a heavy scalar boson H decaying to a pair of 125 GeV Higgs bosons hh or for a heavy pseudoscalar boson A decaying to Zh, in the final states with h to tautau, *CMS-HIG-14-034*

Inner Detector

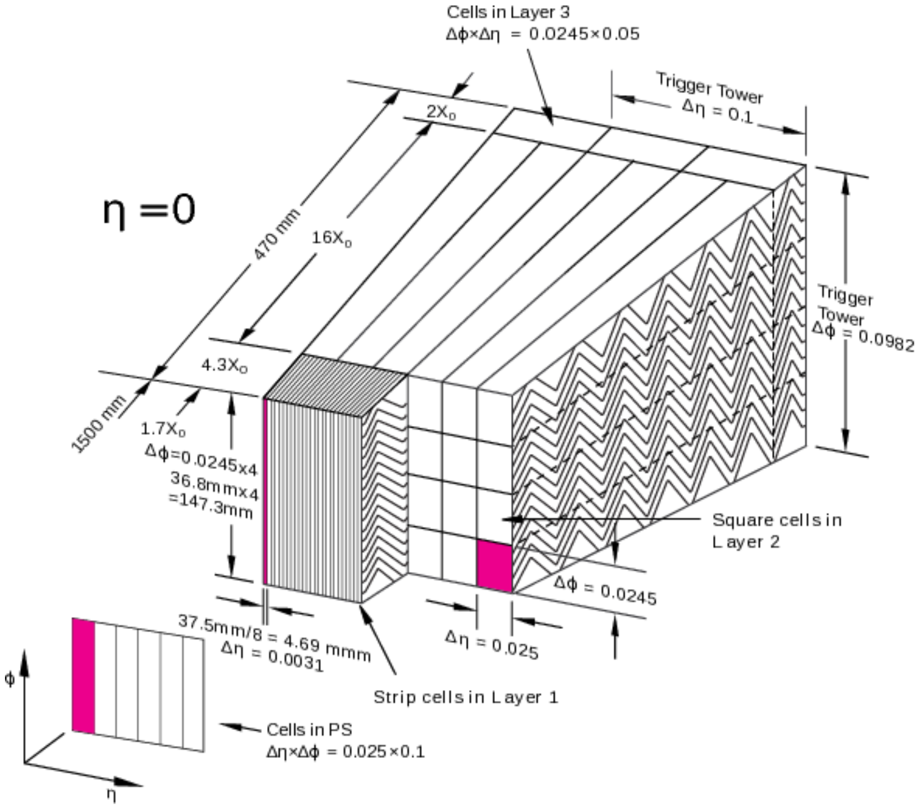


Three subdetectors (B=2T)

- Pixel detector
- Semi-Conductor Tracker
- Transition Radiation Tracker

Reconstruct charged particles

EM Calorimeter



Sampling calorimeter Pb-LAr

Three longitudinal layers:

- layer 1: very fine segmentation along η allowing γ/π^0 discrimnation
- layer 2: bulk of the EM shower deposited
- layer 3: tail of the EM shower

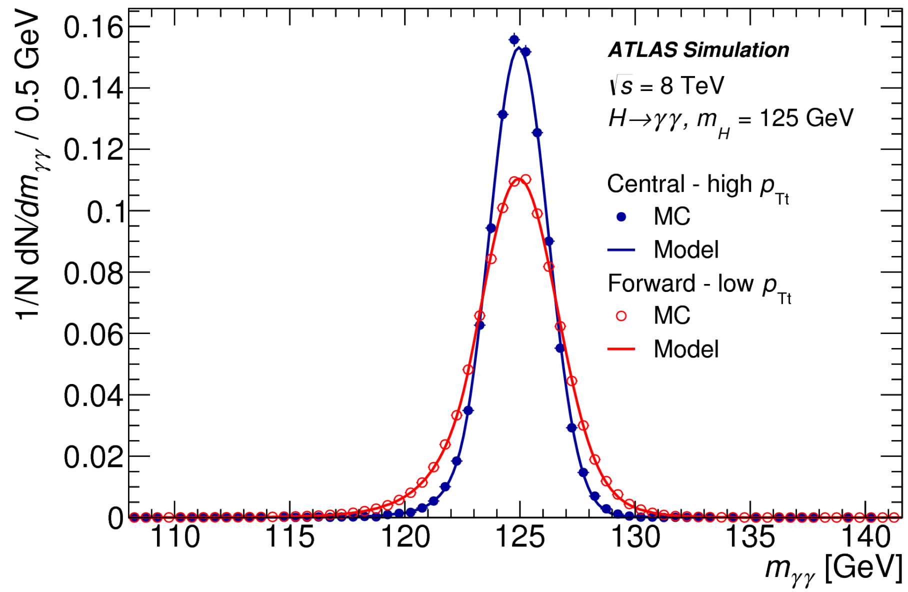
A presampler up to $|\eta|<1.8$ corrects for losses upstream the calorimeter

hh—>bbγγ

hh—>bbγγ

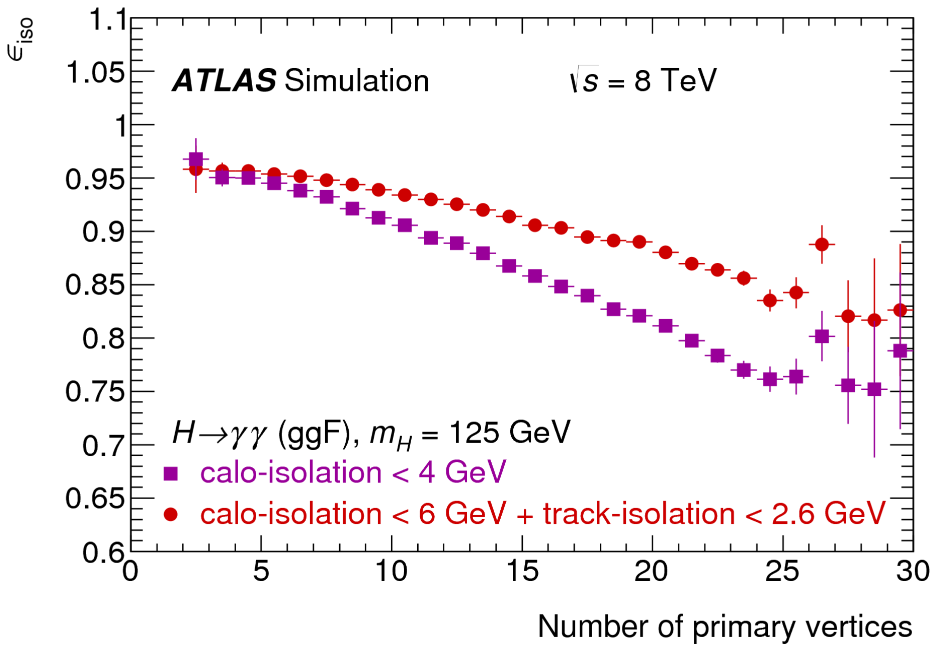
Powerful final state:

- large h—>bb branching ratio
- excellent diphoton invariant mass resolution
- low backgrounds
- clean diphoton trigger



H—>γγ selection

- Loose diphoton trigger ~ 100% efficient
- pT>0.35 (0.25) mγγ for leading (subleading) photon
- lηl<2.37 excluding 1.37<lηl<1.56
- Tight identified photons
- Track isolation (ΔR<0.2) < 2.6 GeV
- Calorimetric isolation (ΔR<0.4) <6 GeV corrected for γ energy leakage and pileup
- 105< mγγ<160 GeV



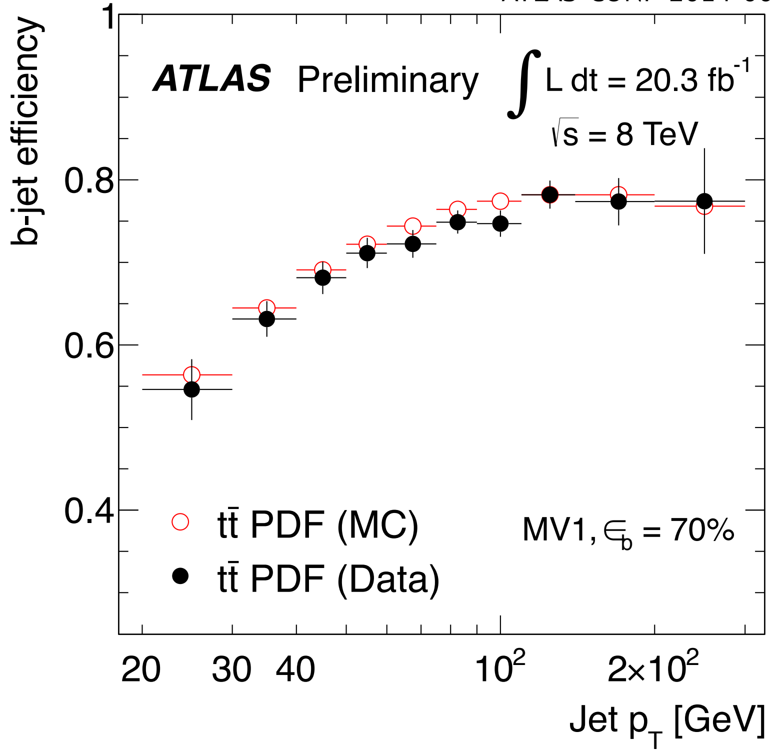
hh—>bbγγ

Anti-kT jets (R=0.4) satisfy:
- pT>55 (35) GeV for leading (subleading) jets
- |eta|<2.5

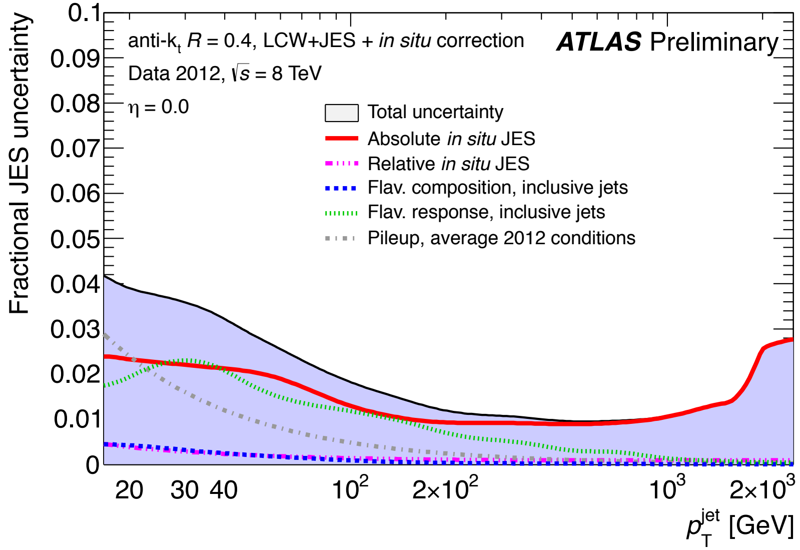
b-tagging use multivariate algorithm with an 70% efficiency for jets from b fragmentation in simulated ttbar events: rejection factor of ~ 130 (4) for light quark (charm) jets

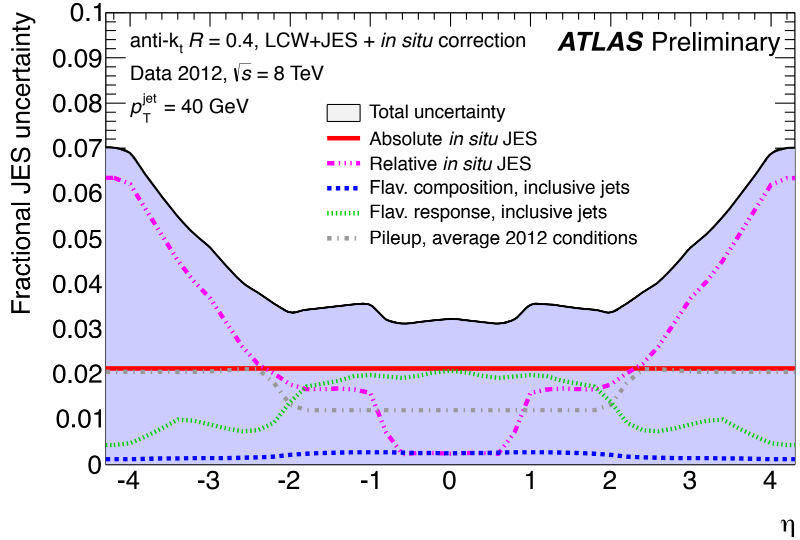
Calibrate b-tag scale using dilepton ttbar events

ATLAS-CONF-2014-004



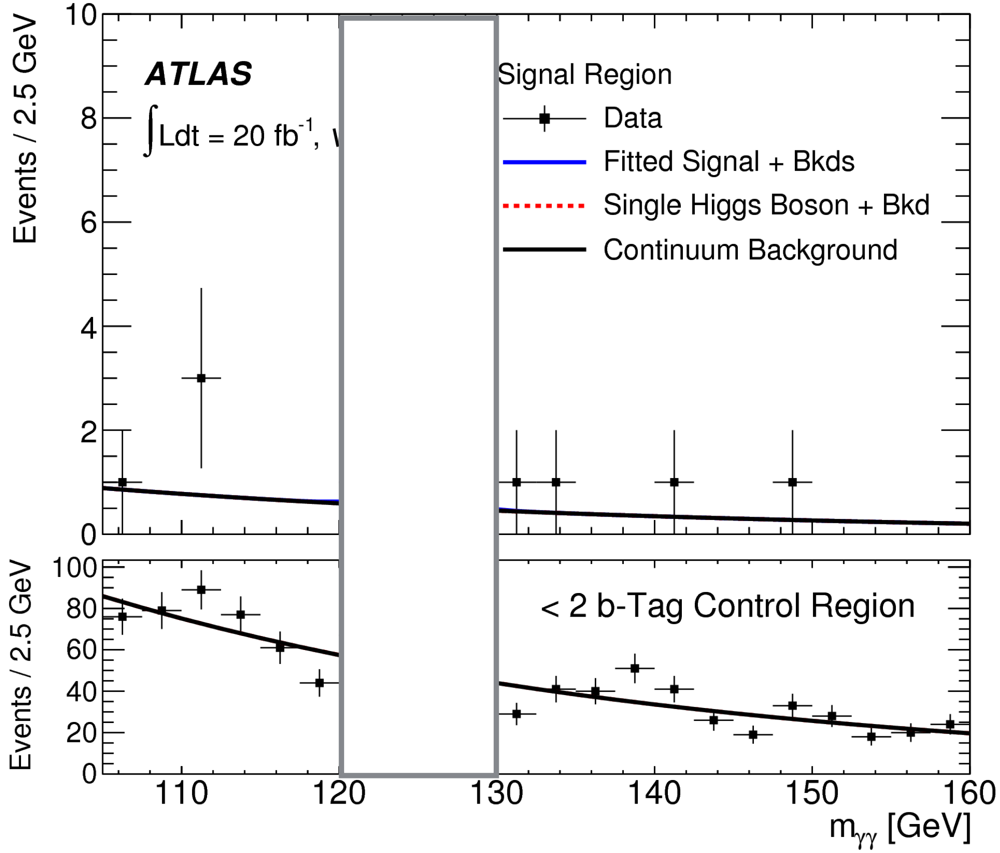
95< m_{jj} < 135 GeV: mass resolution ~ 13 GeV asymmetric cut since neutrinos from semileptonic b-decays are not measured





Signal parameterisation: Crystal Ball+gaussian fit to SM dihiggs sample
The combined acceptance and selection efficiency for SM hh signal **= 7.4 %**

Continuum background Modelling:
determined from data sidebands
An exponential function is used to fit the data in the sidebands in a **control region <2b-tag**. The slope is shared with the **signal region i.e >=2b-tag** to constrain the bkg shape.



Its composition is checked using truth smeared samples
bbγγ, bbγj, γγbj, γγjj, bγjj, bbjj
The contribution from ttbar where 2 electrons fake the 2 photons is roughly 10% of the total bkg.

Single Higgs background modelling: determined from simulation (dominated by ttH and ZH processes). A CB+gauss fit is used.

Systematic uncertainties: non-resonant search

The systematic uncertainties are small compared to the statistical uncertainty: 30-35%

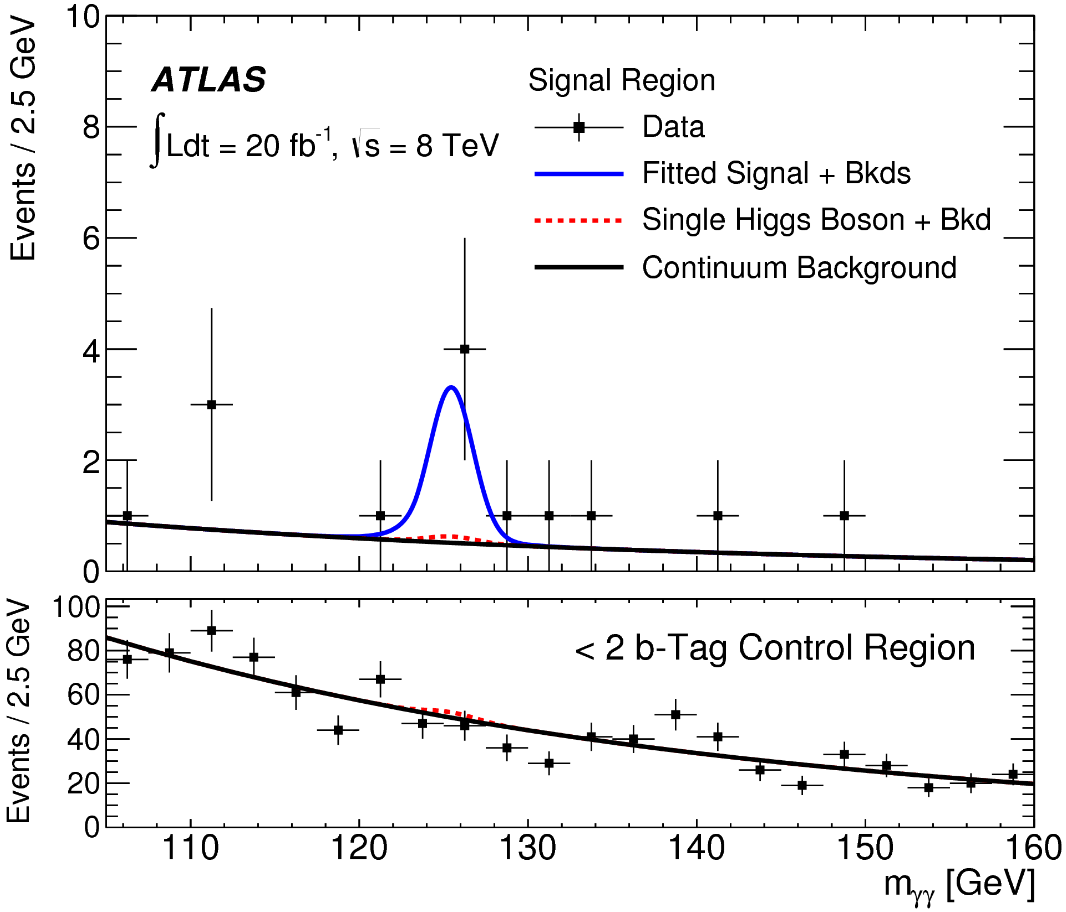
Systematic uncertainty		Non-Resonance Analysis: Single h Bkgd	Non-Resonance Analysis: hh Signal	Non-Resonance Analysis: Continuum
Trigger	[%]	0.5		–
Luminosity	[%]	2.8		–
Photon	Identification [%]	2.4		–
	Isolation [%]	2		–
Mass	Resolution [%]	Resolution: 13		–
	Position	Value: +0.5/-0.6 GeV		–
Shape	$m_{\gamma\gamma}$ Continuum Shape [%]	–		11
	$m_{\gamma\gamma b\bar{b}}$: Statistical [%]	–		–
	$m_{\gamma\gamma b\bar{b}}$: jj vs bb [%]	–		–
	$m_{\gamma\gamma b\bar{b}}$: Fit Model [%]	–		–
Jets	b-Tagging [%]	3.3	1.8	–
	Energy Scale [%]	6.5	1.4	–
	b-jet Energy Scale [%]	2.6	0.3	–
	Energy Resolution [%]	4.8	6.3	–
Theory	PDF+Scale [%]	8.4	–	–
	Single h+HF [%]	14	–	–

Largest uncertainty coming from bkg shape determination 11%:
fit sidebands to 0-tag data, 1-tag, data with reversed photon identification and using flat function to fit

Non resonant search

Predicted number of events in SR for SM single Higgs background

Process	Fraction of total
ggH	11%
qqH	2%
WH	1%
ZH	17%
$t\bar{t}H$	69%
Total	0.17 ± 0.04 Events



Fitted number of continuum background in the SR coming from data sidebands : **1.3 events**

Total expected SM hh signal is **0.04 events**

5 events are observed

2.4σ from background-only hypothesis
95% CL upper limit (using CLs) is **2.2 pb** (expected **1.0 pb**)

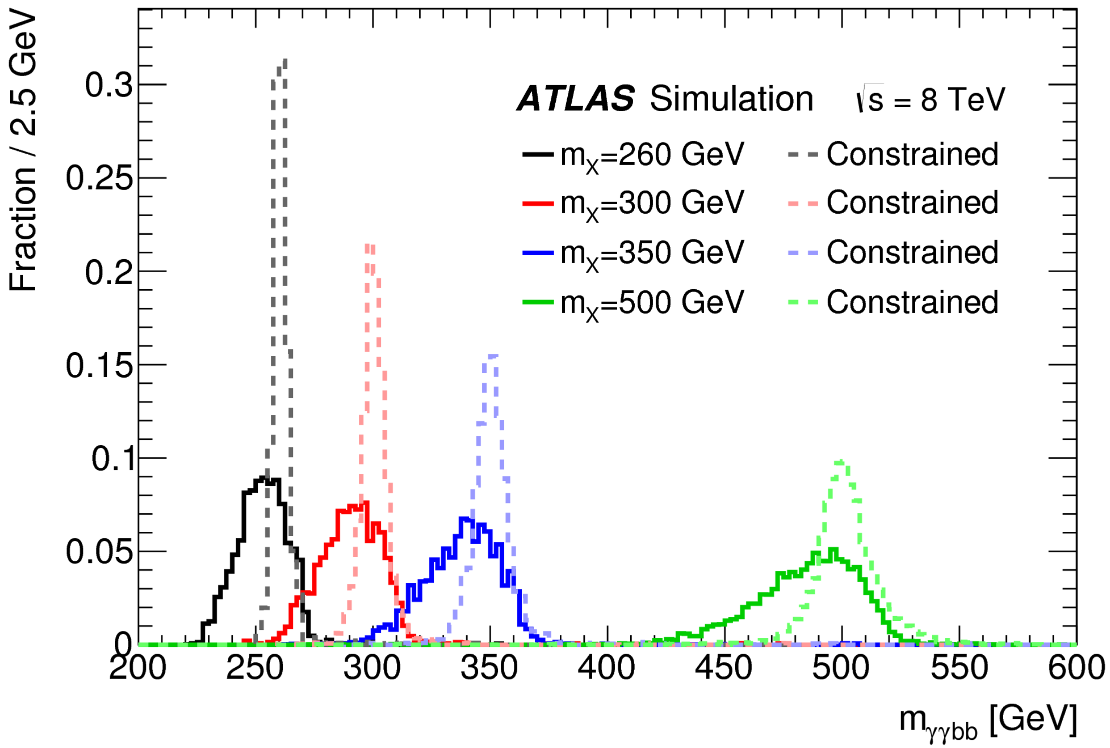
Resonant search

Resonant hh production modeled with a gluon-initiated spin-0 resonant state in a narrow-width approximation (NWA) —> signal simulation

Same analysis as non-resonant but require m_{bb} to be 125 GeV: scaling the combined bb 4-vector multiplying it by m_H/m_{bb} —> improve 4-object invariant mass resolution $m_{\gamma\gamma bb}$ by 30-60% depending on the mass hypothesis

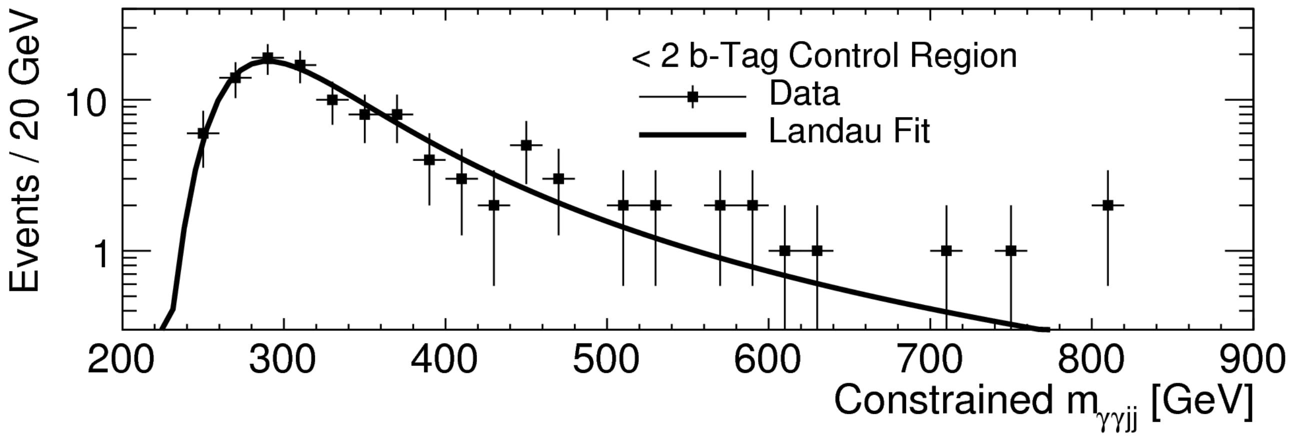
The impact of the mass constraint was checked not to alter significantly the shape of the background

Require $m_{\gamma\gamma bb}$ to be within window selecting 95% signal efficiency in simulation
Window varies from 17 GeV (mX=260 GeV) to 60 GeV (mX = 500 GeV)



Resonant search: bkg

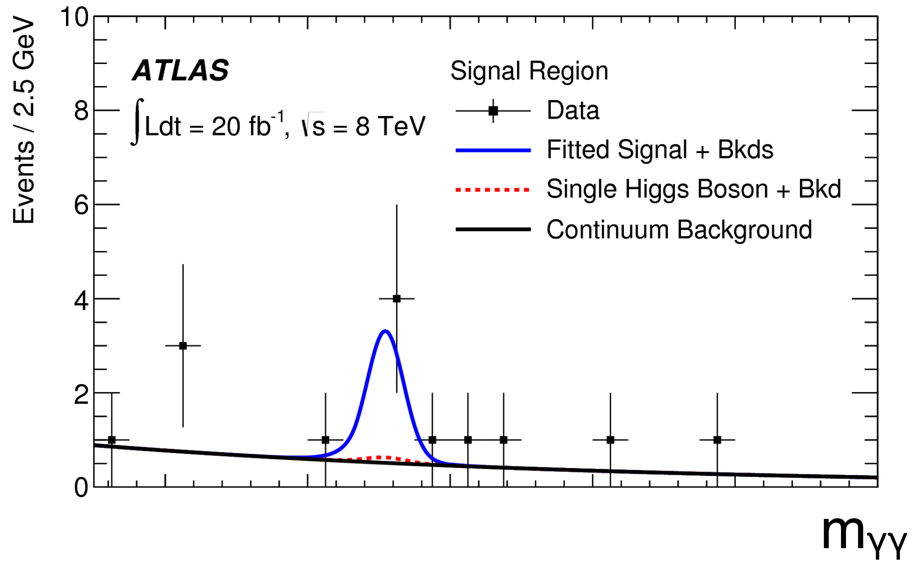
Continuum background: take the shape from a <2b-tag control region
Fit with a Landau function



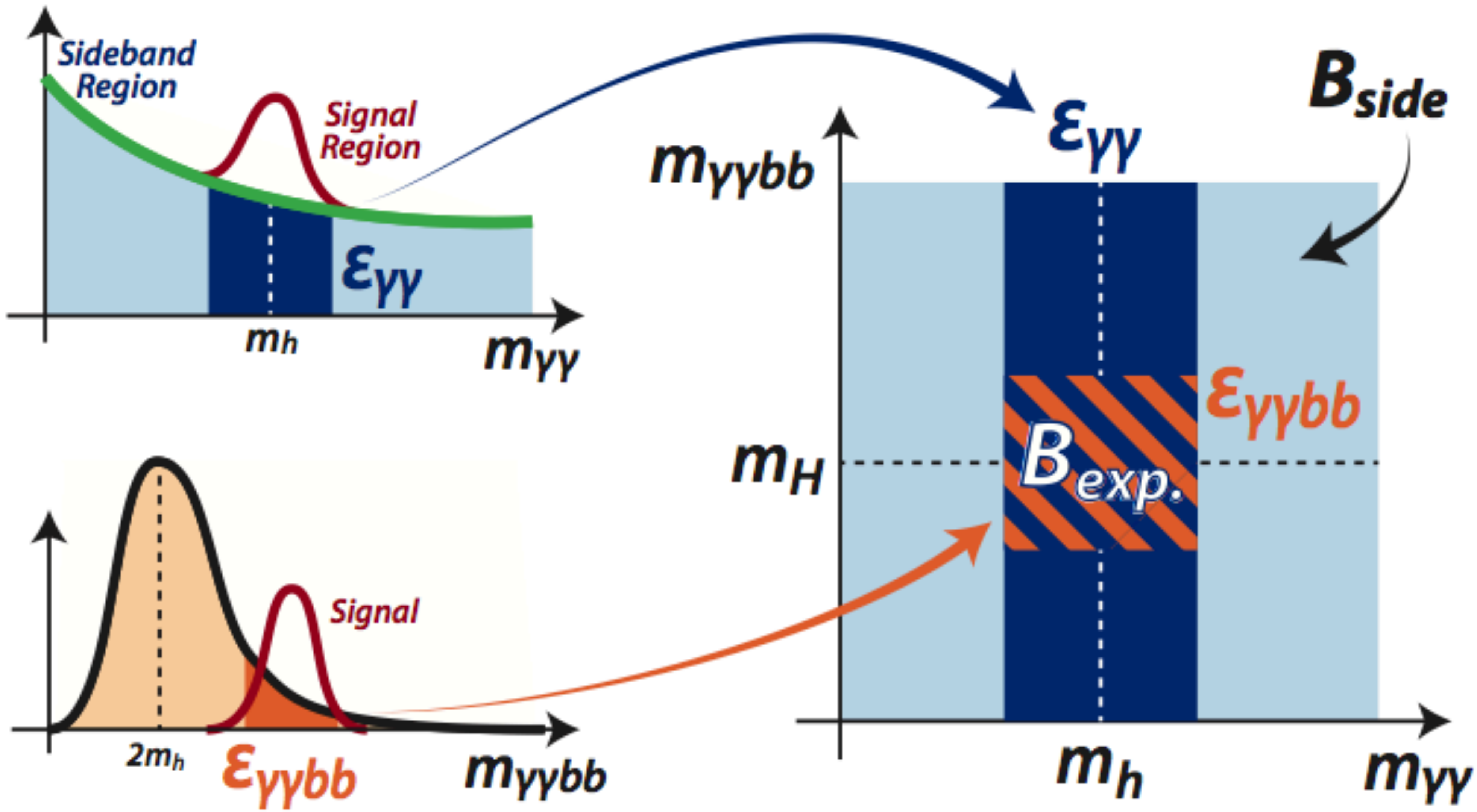
Measure the efficiency of continuum to pass the cut on $m_{\gamma\gamma bb}$ with $|m_{\gamma\gamma}-m_h|<2\sigma_{\mu\gamma\gamma}$
For mX low (260 GeV) and high (500 GeV), efficiency for continuum <8%
For mX= 300 GeV, 18% of continuum

$$N^{SR}_{\text{Continuum}} = N^{\text{Sideband}}_{\text{Continuum}} \times \frac{\varepsilon^{B}_{\gamma\gamma}}{1-\varepsilon^{B}_{\gamma\gamma}} \varepsilon^{B}_{\gamma\gamma bb}$$

Nb of bkg in $|m_{\gamma\gamma}-m_h|<2\sigma_{\mu\gamma\gamma}$
and $N^{\text{sideband}}_{\text{continuum}}$ is the number of observed events in the sidebands of $m_{\gamma\gamma}$



Resonant search: bkg



Resonant search

Not enough statistics to perform robust fit sidebands after resonance selection

Perform instead cut-and-count analysis

$$N^{SR}_{\text{Continuum}} = N^{\text{Sideband}}_{\text{Continuum}} \times \frac{\varepsilon^{B}_{\gamma\gamma}}{1-\varepsilon^{B}_{\gamma\gamma}} \varepsilon^{B}_{\gamma\gamma bb}$$

$$N^{\text{Sideband}}_{\text{SM}} = N_{SM} \times (1-\varepsilon^{S}_{\gamma\gamma})$$

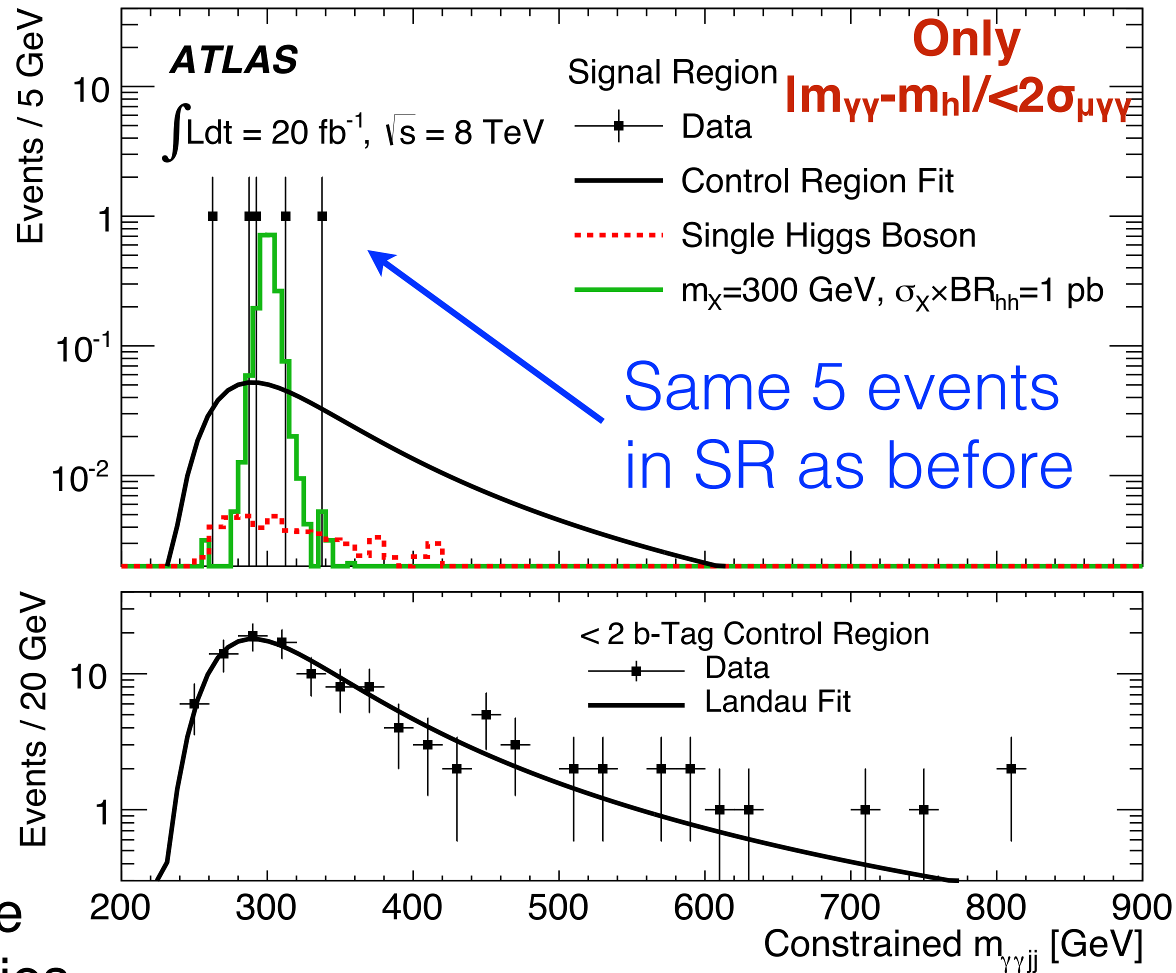
$$N^{\text{SR}}_{\text{SM}} = N_{SM} \times \varepsilon^{S}_{\gamma\gamma} \times \varepsilon^{\text{SM}}_{\gamma\gamma bb}$$

$$N^{\text{Sideband}}_{\text{BSM}} = N_{BSM} \times (1-\varepsilon^{S}_{\gamma\gamma})$$

$$N^{\text{SR}}_{\text{BSM}} = N_{BSM} \times \varepsilon^{S}_{\gamma\gamma} \times \varepsilon^{\text{BSM}}_{\gamma\gamma bb}$$

$$N^{\text{Sideband}} = N^{\text{Sideband}}_{\text{Continuum}} + N^{\text{Sideband}}_{\text{SM}} + N^{\text{Sideband}}_{\text{BSM}}$$

$$N^{SR} = N^{SR}_{\text{Continuum}} + N^{\text{SR}}_{\text{SM}} + N^{\text{SR}}_{\text{BSM}}$$



The combined acceptance and selection efficiency for a resonance signal to pass all requirements varies from 3.8% at mX=260 GeV to 8.2% at mX=500 GeV

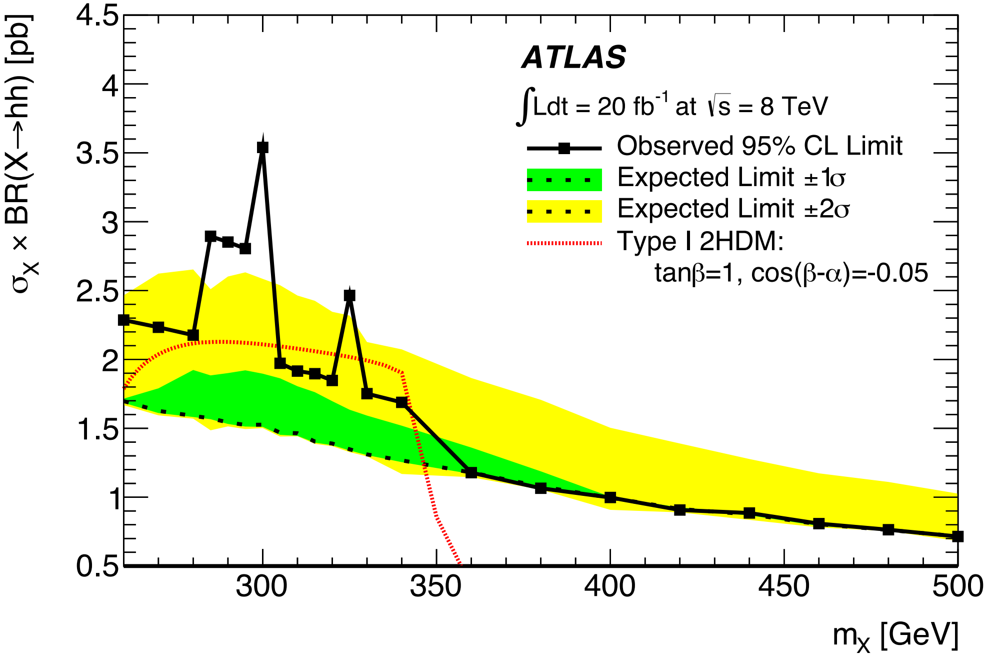
Resonant search: systematics

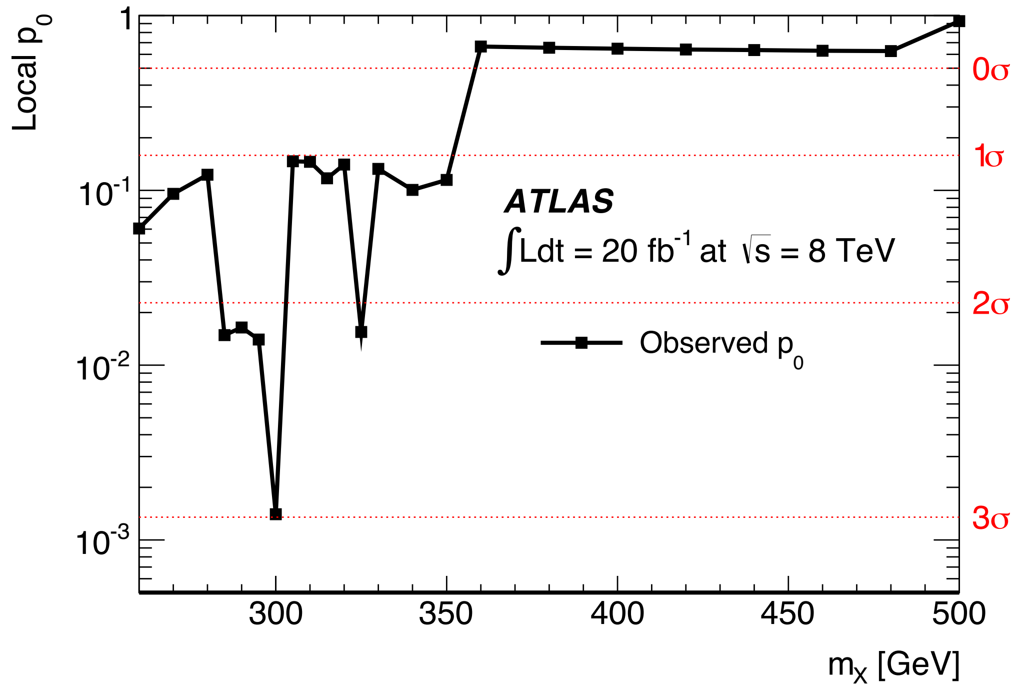
Systematic uncertainty		Resonance Analysis		
		SM $h + hh$ Bkgd	$H \to hh$ Signal	Continuum
Trigger [%]		0.5		–
Luminosity [%]		2.8		–
Photon	Identification [%]	2.4		–
	Isolation [%]	2		–
Mass	Resolution [%]	Migration: 1.6		–
	Position	Migration: 1.7%		–
Shape	$m_{\gamma\gamma}$ Continuum Shape [%]	–		11
	$m_{\gamma\gamma b\bar{b}}$: Statistical [%]	–		3-18
	$m_{\gamma\gamma b\bar{b}}$: jj vs bb [%]	–		0-30
	$m_{\gamma\gamma b\bar{b}}$: Fit Model [%]	–		16-30
Jets	b-Tagging [%]	3.4	2.4	–
	Energy Scale [%]	19	3.8	–
	b-jet Energy Scale [%]	6.5	2.2	–
	Energy Resolution [%]	15	9.3	–
Theory	PDF+Scale [%]	+18/-15	–	–
	Single h+HF [%]	14	–	–

Use simulation to evaluate differences in shape between γγbb and γγjj

Use alternative fit functions to Landau distribution

Resonant search: results





The observed exclusion ranges from 3.5 to 0.8 pb

The expected exclusion improves from 1.8 to 0.8 pb

Also shown the expectation from a sample type I 2HDM with cos(β-α)=-0.05 and tanβ=1.

The max local significance is **3σ** at mX=300 GeV

*The global probability of such an excess occurring at any mass in the range studied is **2.1σ***

hh—>bbbb

hh—>bbbb

Despite the fully hadronic final state being subject to large multijet background, searches for hh—>bbbb have good sensitivity for both the resonant and non-resonant searches —> high BR for h—>bb

It is a much more sensitive analysis at high mX where the bkg can be controlled to a manageable rate

Start the search at mX = 500 GeV

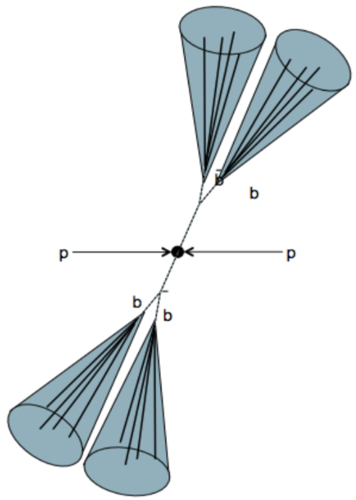
Combination of 5 unprescaled triggers —> 99.5% efficiency

Two Higgs boson reconstruction techniques which are complementary in their acceptance are performed.

hh—>bbbb

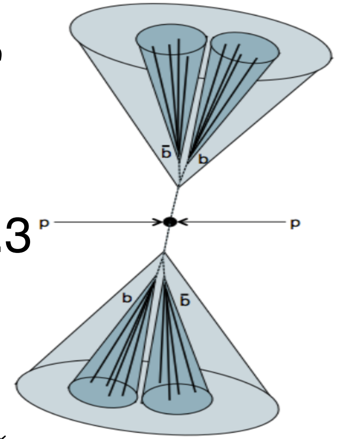
Resolved analysis

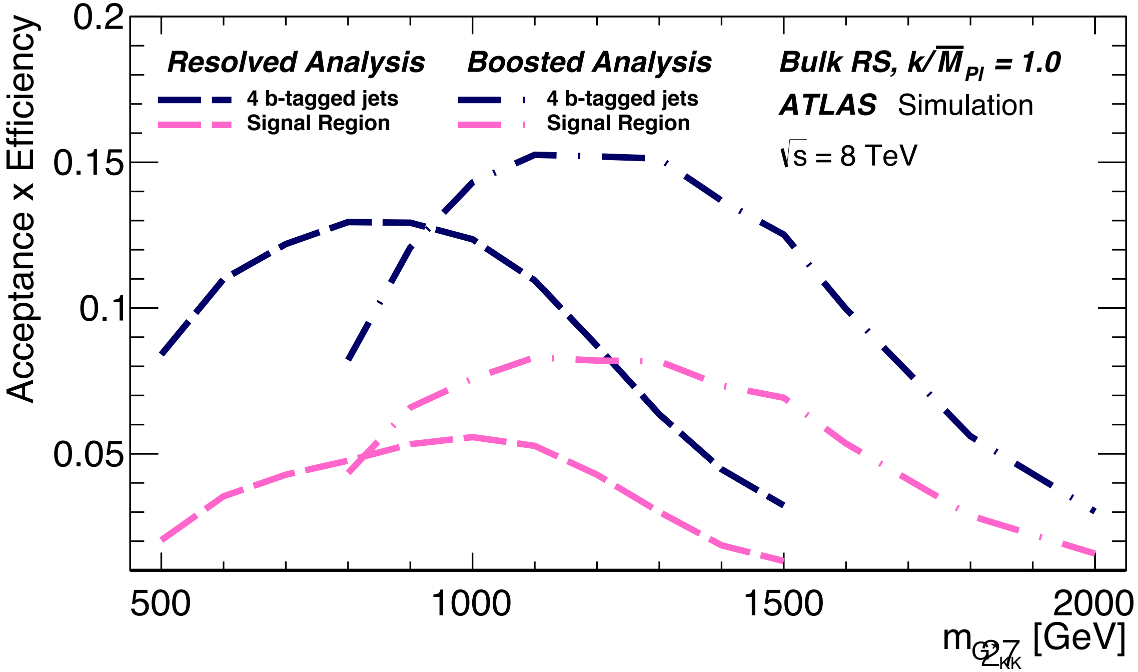
4 b-tagged anti-kT R=0.4 jets,
b-tagging efficiency 70%
pT>40 GeV
2 dijet systems each with the
2 jets separated by ΔR<1.5
pT and Δη cuts mass
dependent
tt veto

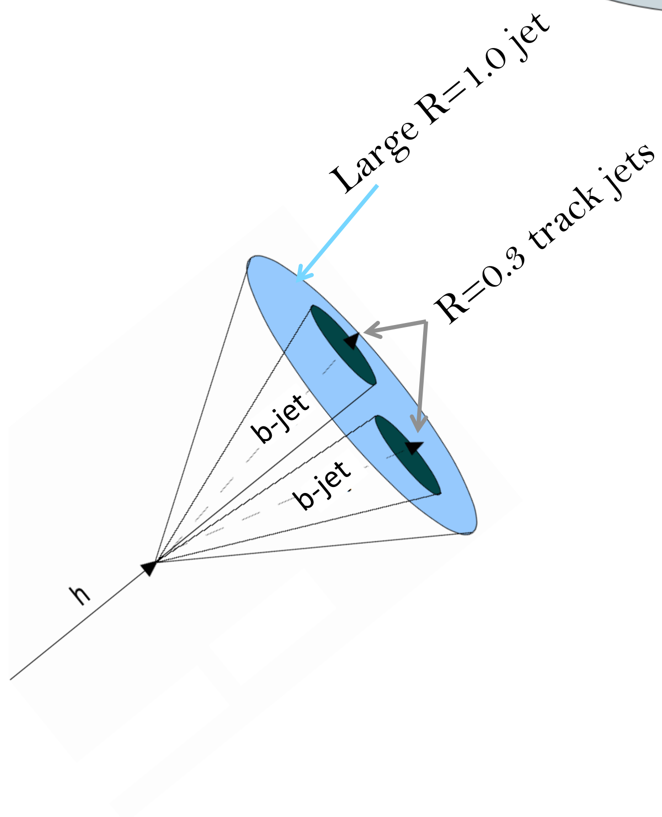


Boosted analysis

jet substructure technique
2 anti-kT R=1 jets with
pT>350 GeV (250 GeV)
Each with 2b-tagged R=0.3
track jets
pT and Δη cuts







hh—>bbbb

Form X_{hh} from pairs of jets

$$X_{hh} = \sqrt{\left(\frac{m_{2j}^{lead} - 124\ \text{GeV}}{0.1\, m_{2j}^{lead}}\right)^2 + \left(\frac{m_{2j}^{subl} - 115\ \text{GeV}}{0.1\, m_{2j}^{subl}}\right)^2}$$

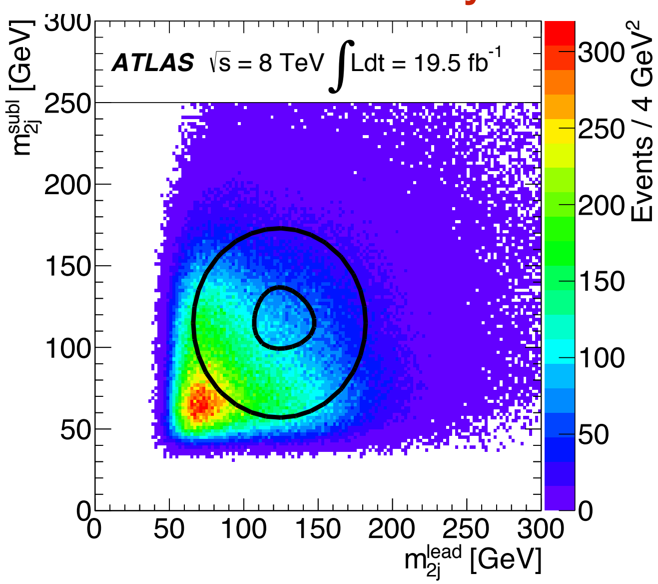
124 and 115 are the expected peak values from simulation for the leading and subleading dijet pair as well as 10% the estimated dijet mass resolutions

Require **$X_{HH} < 1.6$** to define the signal region, then constrain dijet systems mass to 125 GeV for the resonant analysis (improvement of ~30% in the m_{4j} resolution)

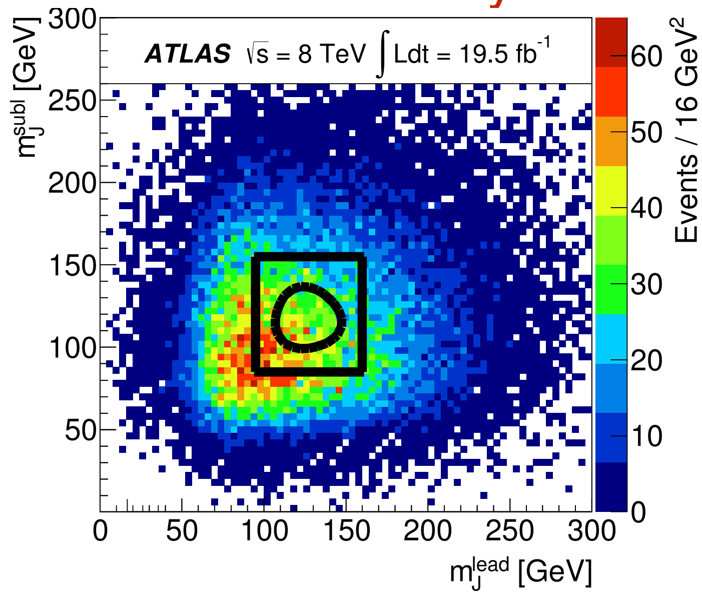
Dominant background: multijet events estimated using a 2-tag region (one dijet system b-tagged):

$$\mu_{QCD} = \frac{N_{QCD}^{4-tag}}{N_{QCD}^{2-tag}} = \frac{N_{data}^{4-tag} - N_{t\bar{t}}^{4-tag} - N_{Z}^{4-tag}}{N_{data}^{2-tag} - N_{t\bar{t}}^{2-tag} - N_{Z}^{2-tag}}$$

Resolved analysis

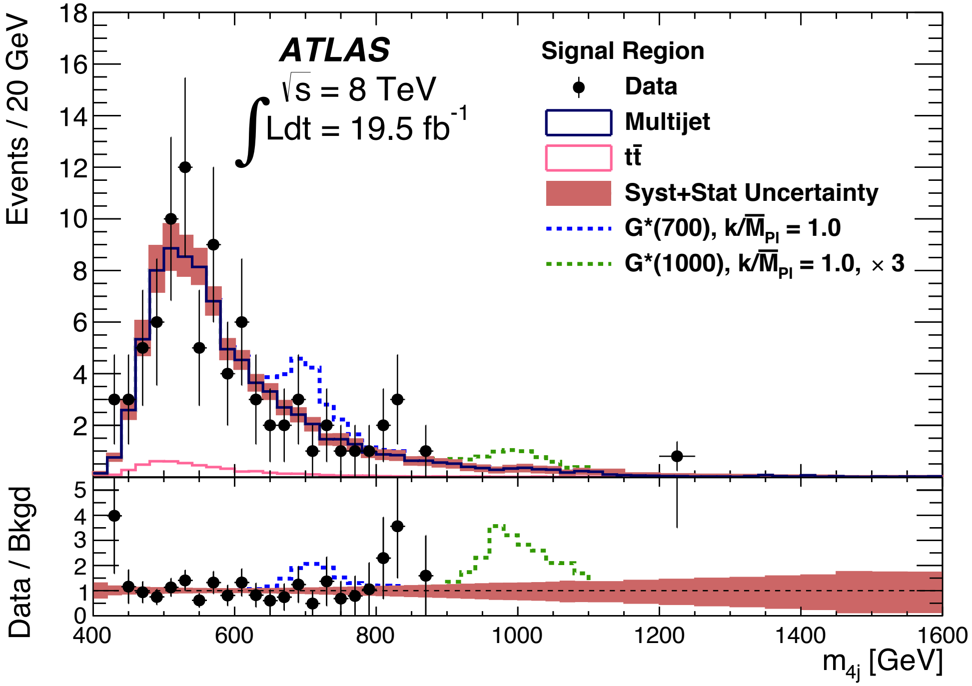


Boosted analysis



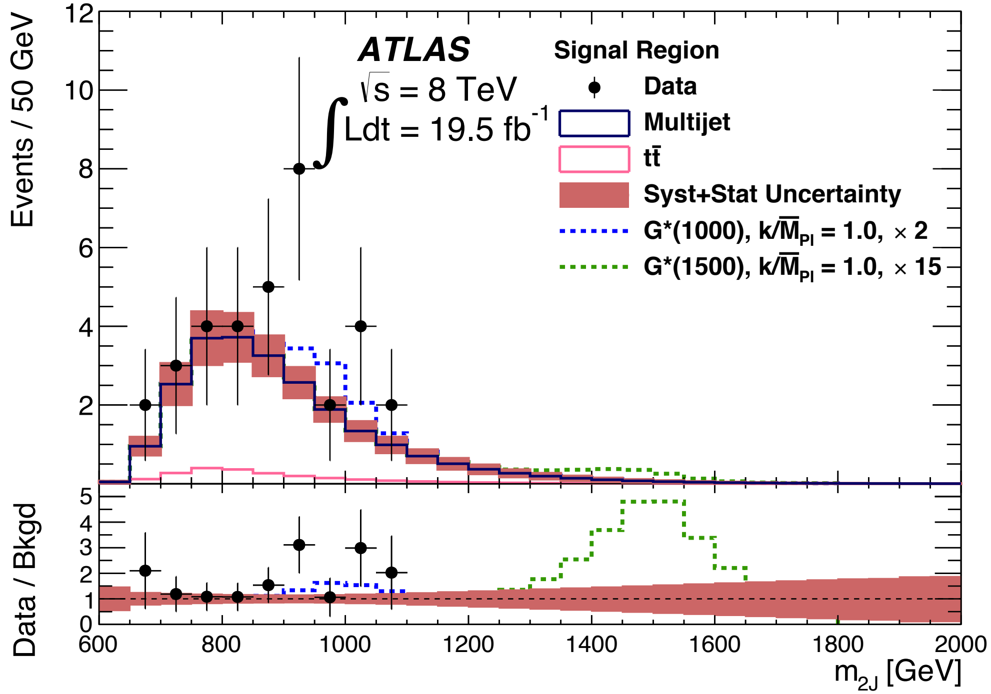
hh—>bbbb

Resolved analysis



Sample	Signal Region Yield
Multijet	81.4 ± 4.9
$t\bar{t}$	5.2 ± 2.6
Z+jets	0.4 ± 0.2
Total	87.0 ± 5.6
Data	87
SM hh	0.34 ± 0.05
G^*_{KK} (500 GeV), $k/\bar{M}_{Pl} = 1$	27 ± 5.9

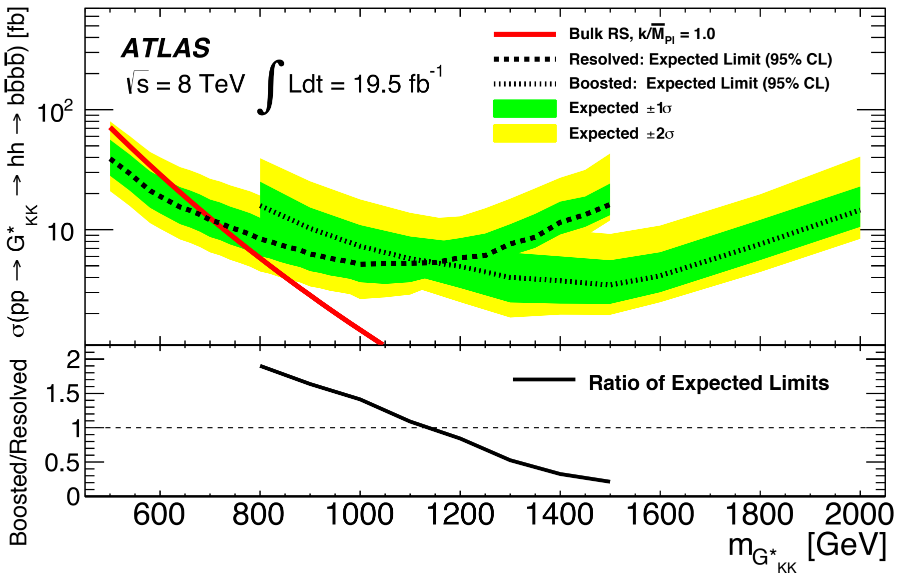
Boosted analysis



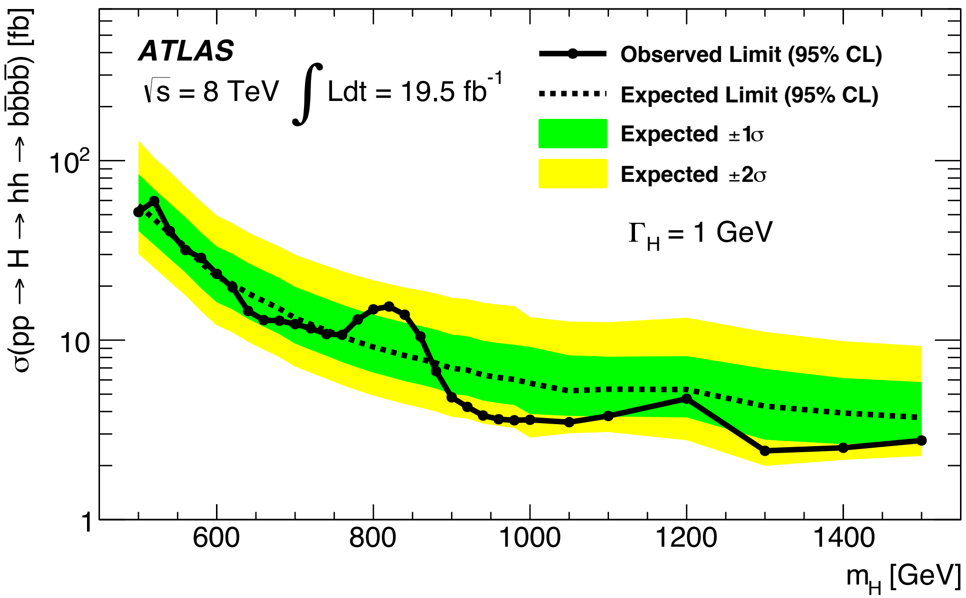
Sample	Signal Region Yield
Multijet	23.5 ± 4.1
$t\bar{t}$	2.2 ± 0.9
Z+jets	0.14 ± 0.06
Total	25.7 ± 4.2
Data	34
G^*_{KK} (1000 GeV), $k/\bar{M}_{Pl} = 1$	2.1 ± 0.6

hh—>bbbb

pp—>G^*_{kk}—>hh—>bbbb



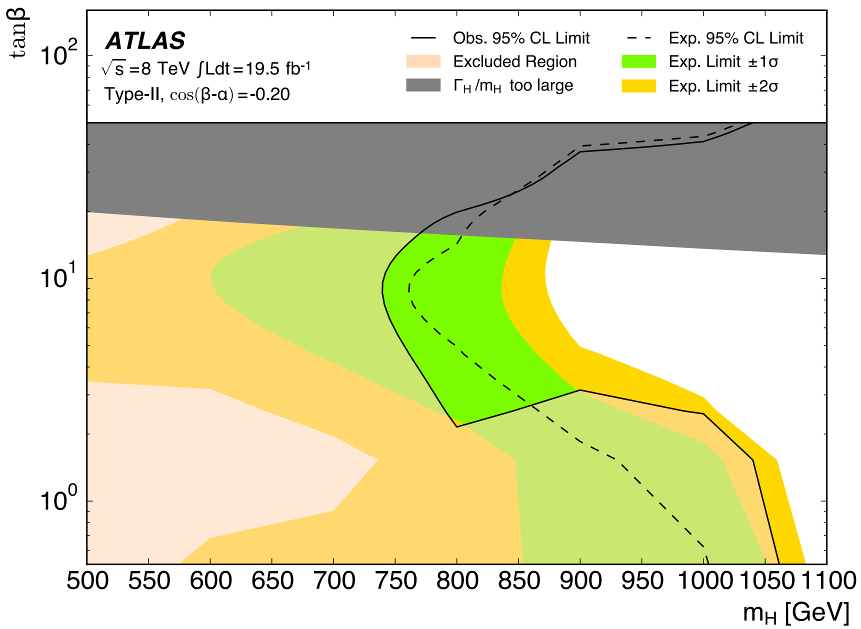
pp—>H(1 GeV)—>hh—>bbbb



Boosted analysis offers large gain at resonance high mass

500-720 GeV is excluded at 95%CL

Non resonant search performed using resolved analysis, upper limit of 202 fb is set (compared to 3.6+/-0.5 fb)



(b) Type-II 2HDM, $\cos(\beta - \alpha) = -0.2$

hh—>bbττ

hh—>bbττ

$bb\tau_l\tau_{had}$ final state considered

Trigger requires at least one lepton pT>24 GeV —>~ 100% efficient

Requiring one lepton pT>26 GeV, one hadronically decaying tau lepton with pT>20 GeV and meeting medium criteria and two or more jets with pT>30 GeV. Between 1 and 3 of the selected jets must be b-tagged. 90< m_{bb}< 160 GeV

Four categories are considered in the analysis: $p_T^{\tau\tau}$<100 GeV, $pT^{\tau\tau}$>100 GeV, number of b-tagged jets (n_b=1 or >=2)

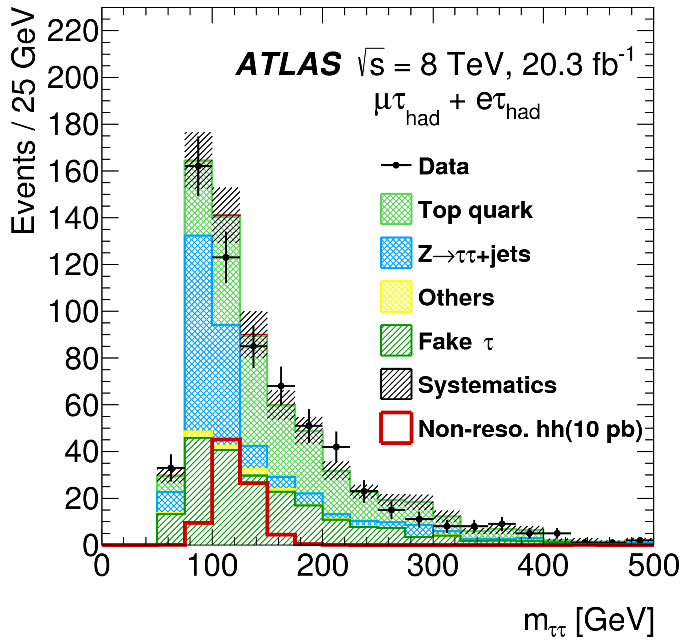
Background: W+jets, Z—>ττ, diboson, top and fake τ

	Process	$n_b \geq 2$	
		$p_T^{\tau\tau} < 100$ GeV	$p_T^{\tau\tau} > 100$ GeV
Simulation	SM Higgs	0.1 ± 0.1	0.2 ± 0.1
	Top quark	30.9 ± 3.0	23.6 ± 2.5
Embedded	$Z \to \tau\tau$	6.8 ± 1.8	2.6 ± 1.0
"Fake-factor" method	Fake τ_{had}	13.7 ± 1.9	5.4 ± 1.0
	Others	0.7 ± 1.6	0.2 ± 0.7
	Total background	52.2 ± 8.2	32.1 ± 5.4
	Data	35	35
	Signal m_H = 300 GeV	1.5 ± 0.3	0.9 ± 0.2

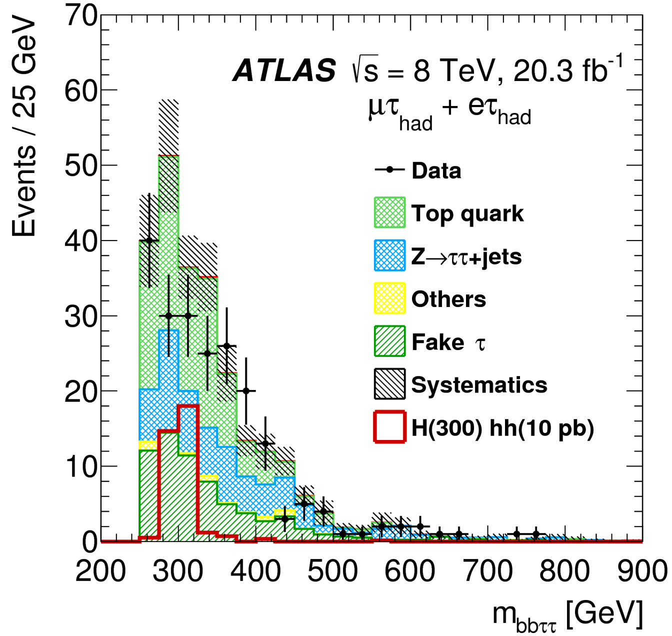
Numbers of events predicted from background and observed in the data

hh—>bbττ

Non resonant



Resonant

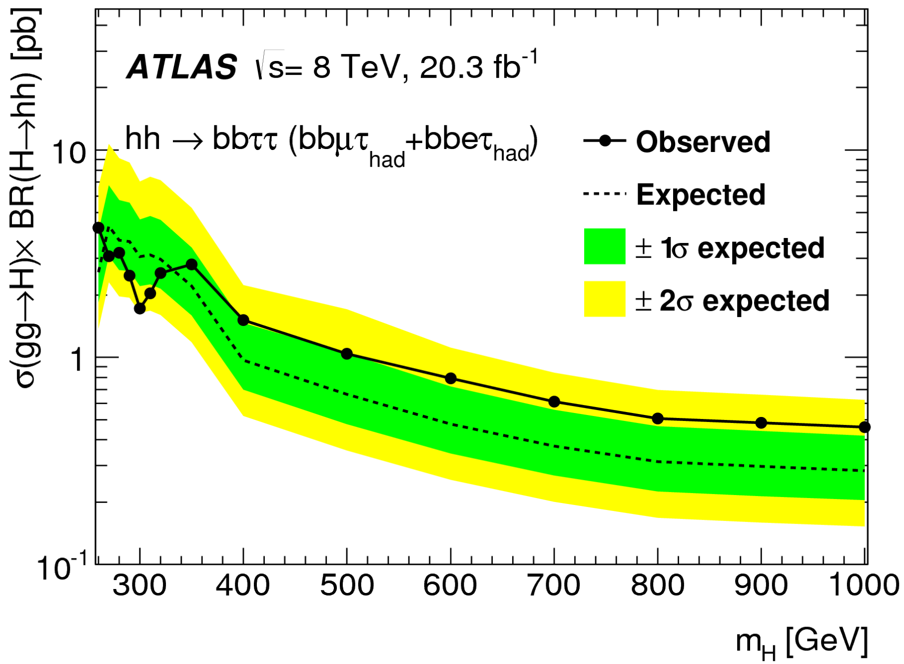


For the non resonant search, $m_{\tau\tau}$ is used as a final discriminant

For the resonant search, $m_{bb\tau\tau}$ is used as a discriminant and $100 < m_{\tau\tau} < 150$ GeV

Non resonant observed limit = 1.6 pb (expected 1.3pb)

Small deficit ~2sigma at 300 GeV in the resonant analysis



hh—>γγWW*

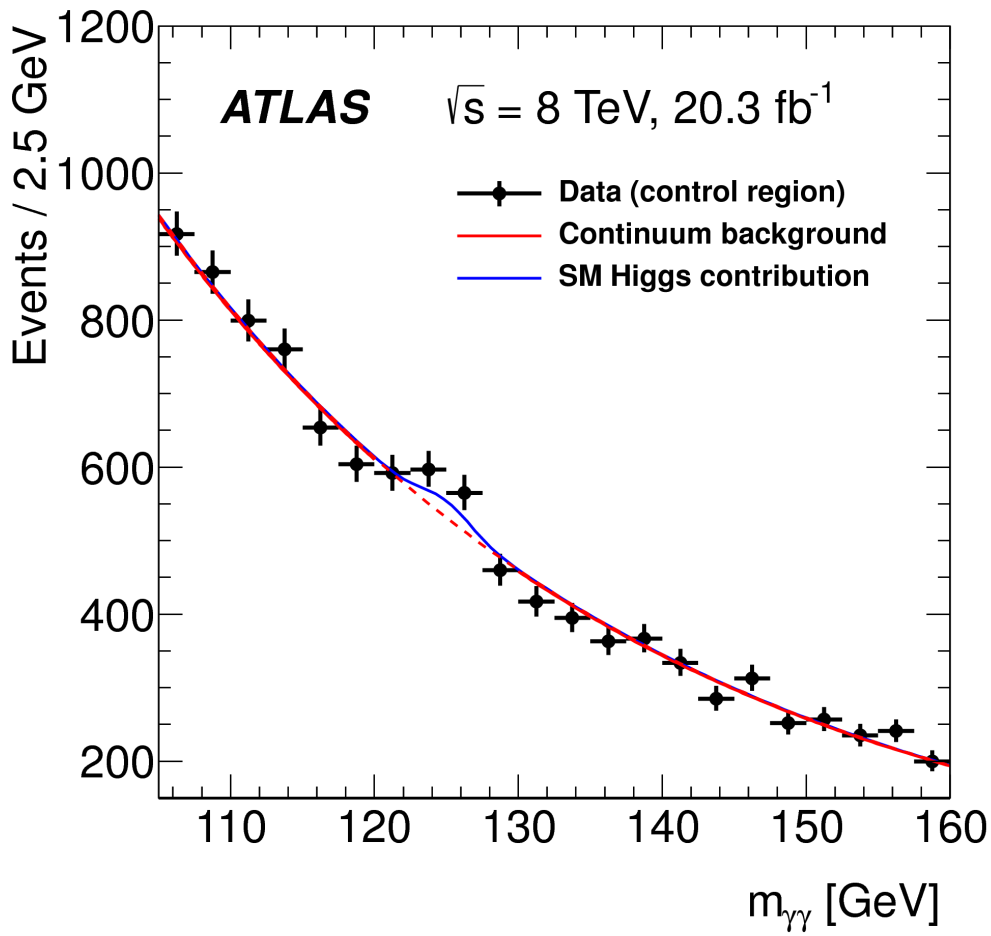
hh—>γγWW*

WW*—>lvqq' final state considered to reduce mulitjet bkg

Events are recorded with diphoton triggers, efficiency close to 100%

Same diphoton selection as for hh—>γγbb, in addition to require >=2 jets and exactly 1 lepton, any b-tagged jet is vetoed to reduce bkg from top, and large E_T^{miss}

Require $m_{\gamma\gamma}$ to be within 2σ from the Higgs mass.

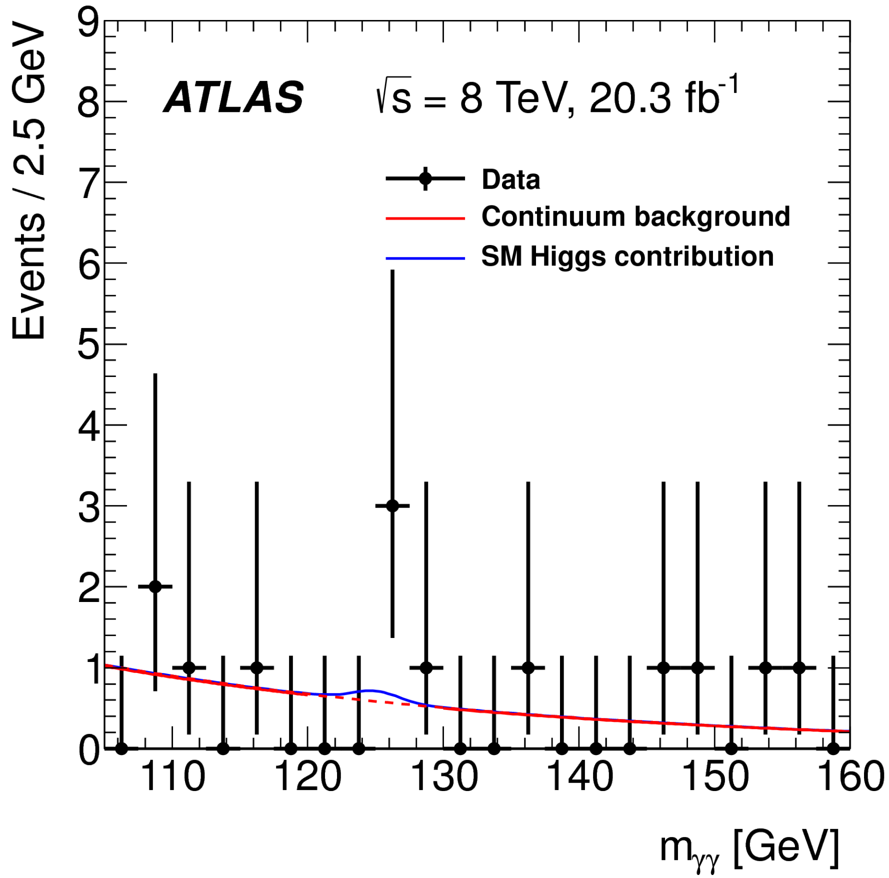


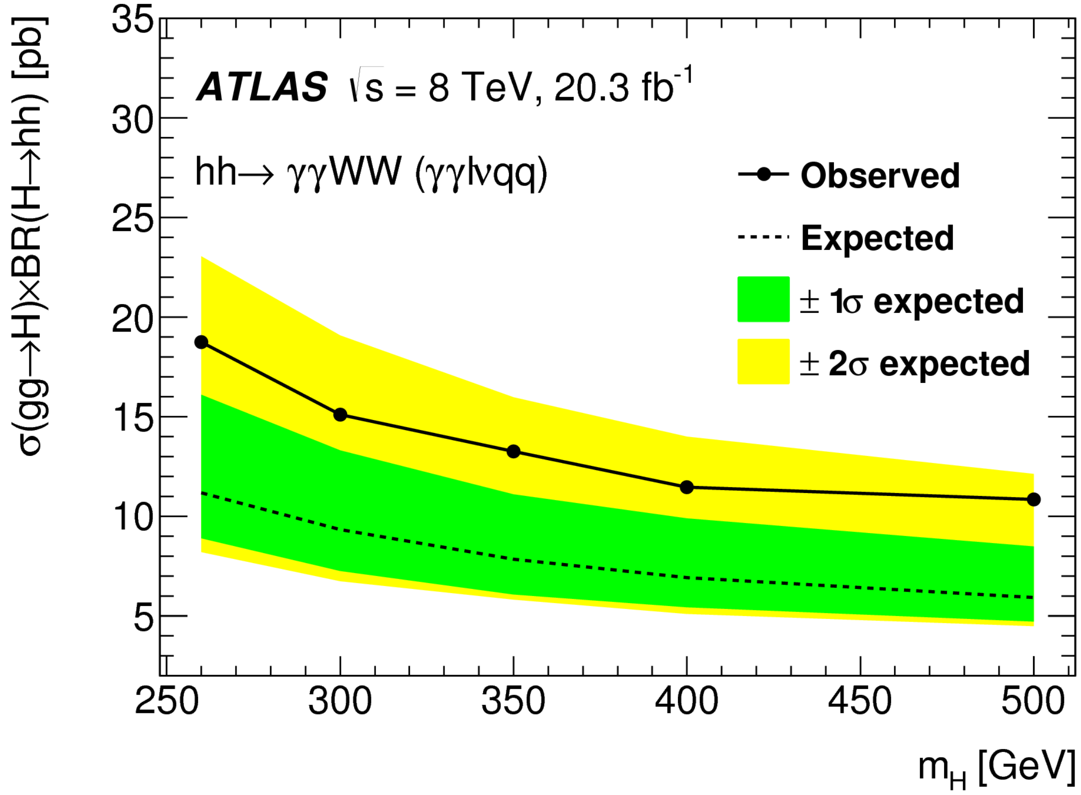
Background: - single SM h (*dominated by Wh, tth and Zh*) = 0.25+/-0.07

- continuum bkg (*Wγγ+jets*) estimated from $m_{\gamma\gamma}$ sidebands in data

A control region selected as the signal sample without the lepton and E_T^{miss} requirements, fit with an exponential function excluding 5 GeV around m_h

hh—>γγWW*





Non resonant: The observed (expected) exclusion is 11.4 (6.7) pb

Small nb of events—>cut-and-count method

Selection efficiency for signal of SM non-resonant = 2.9% and for resonant is =1.7% for mX=260 GeV and 3.3% at 500 GeV.

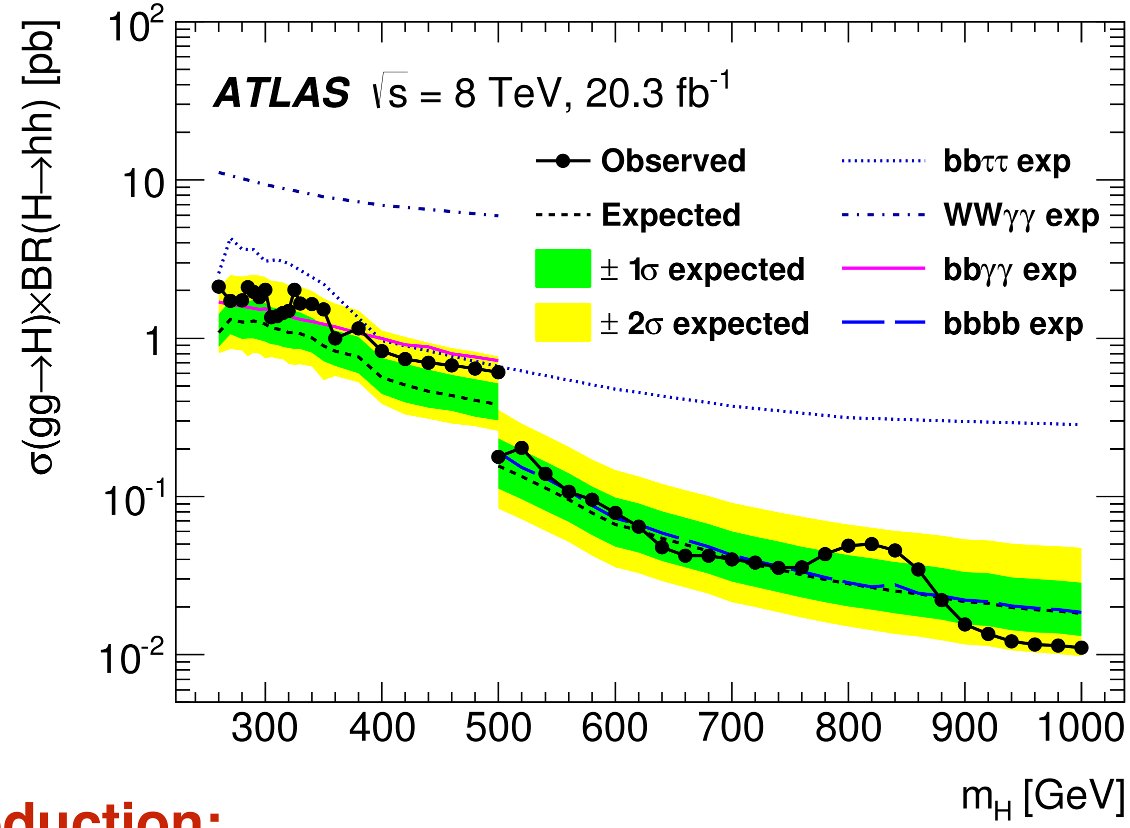
Number of background events =1.40+/-0.47

4 events are observed in the signal window, **significance = 1.8σ**

Combination

Combined channels

Resonant production:



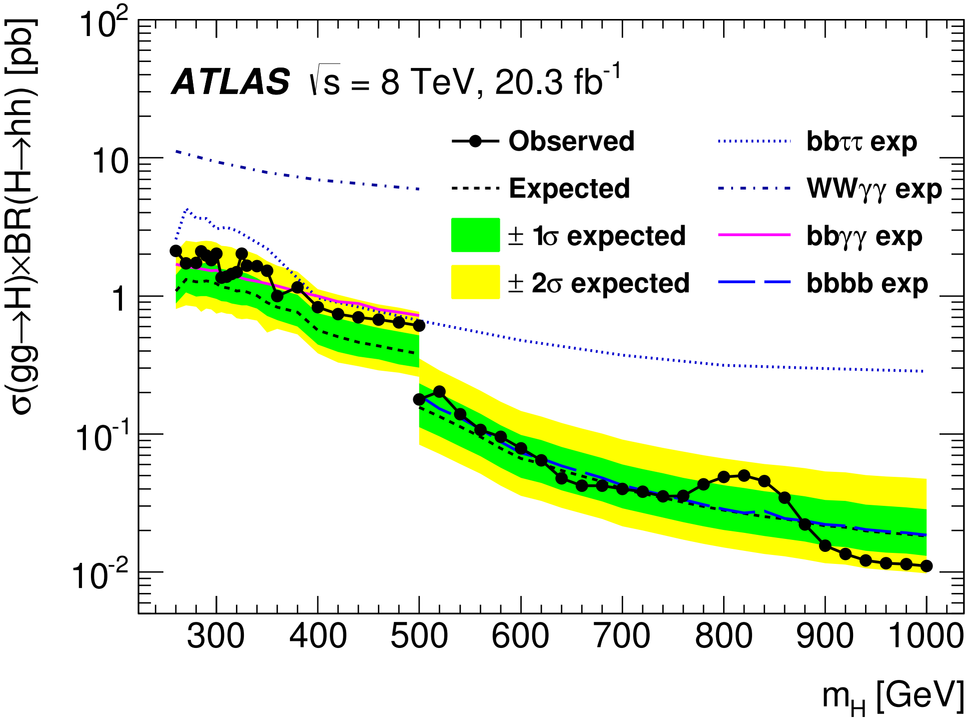
2.5σ excess at 300 GeV

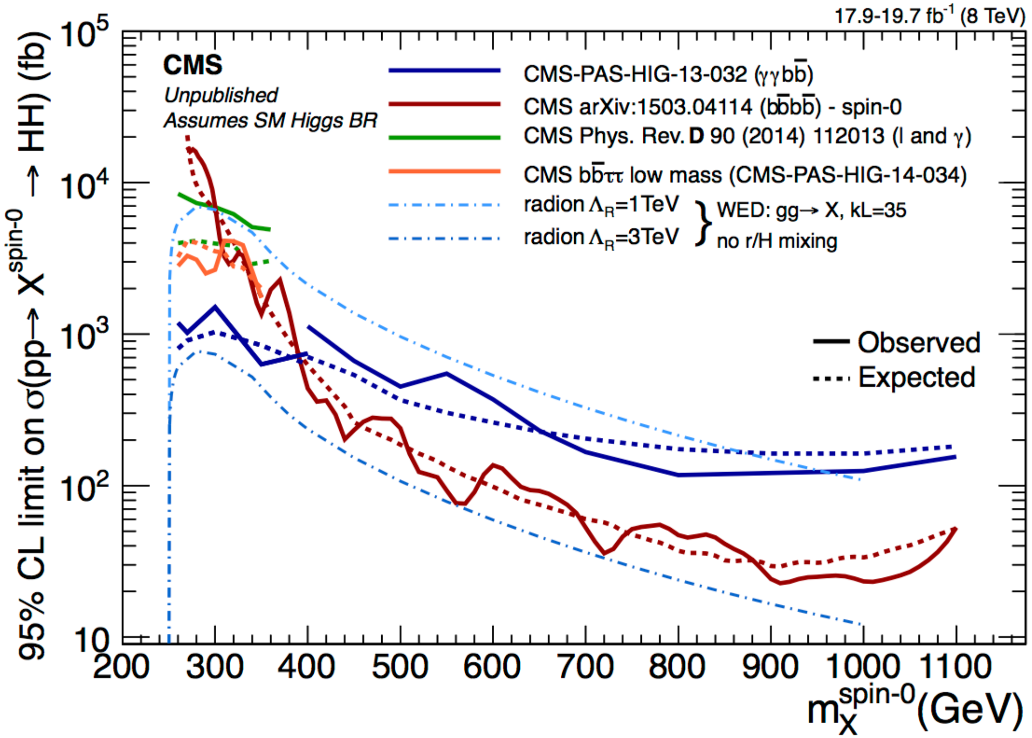
Non resonant production:

Analysis	$\gamma\gamma bb$	$\gamma\gamma WW^*$	$bb\tau\tau$	$bbbb$	Combined
		Upper limit on the cross section [pb]			
Expected	1.0	6.7	1.3	0.62	0.47
Observed	2.2	11	1.6	0.62	0.69
		Upper limit on the cross section relative to the SM prediction			
Expected	100	680	130	63	48
Observed	220	1150	160	63	70

combined significance = 1.7σ

Comparison with CMS results

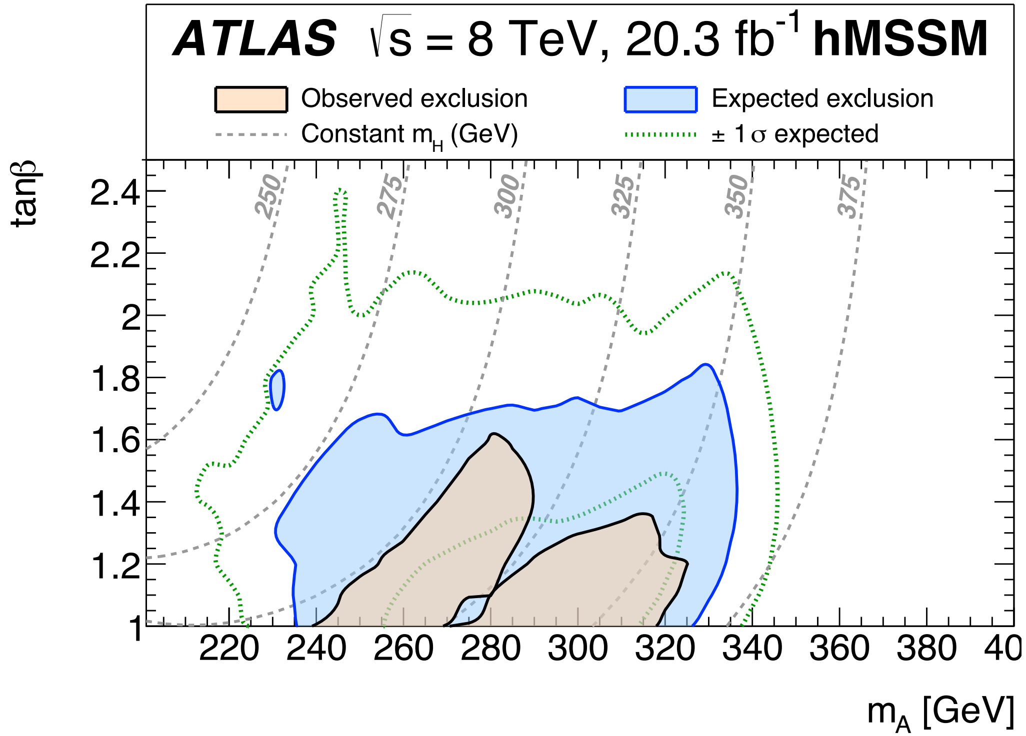


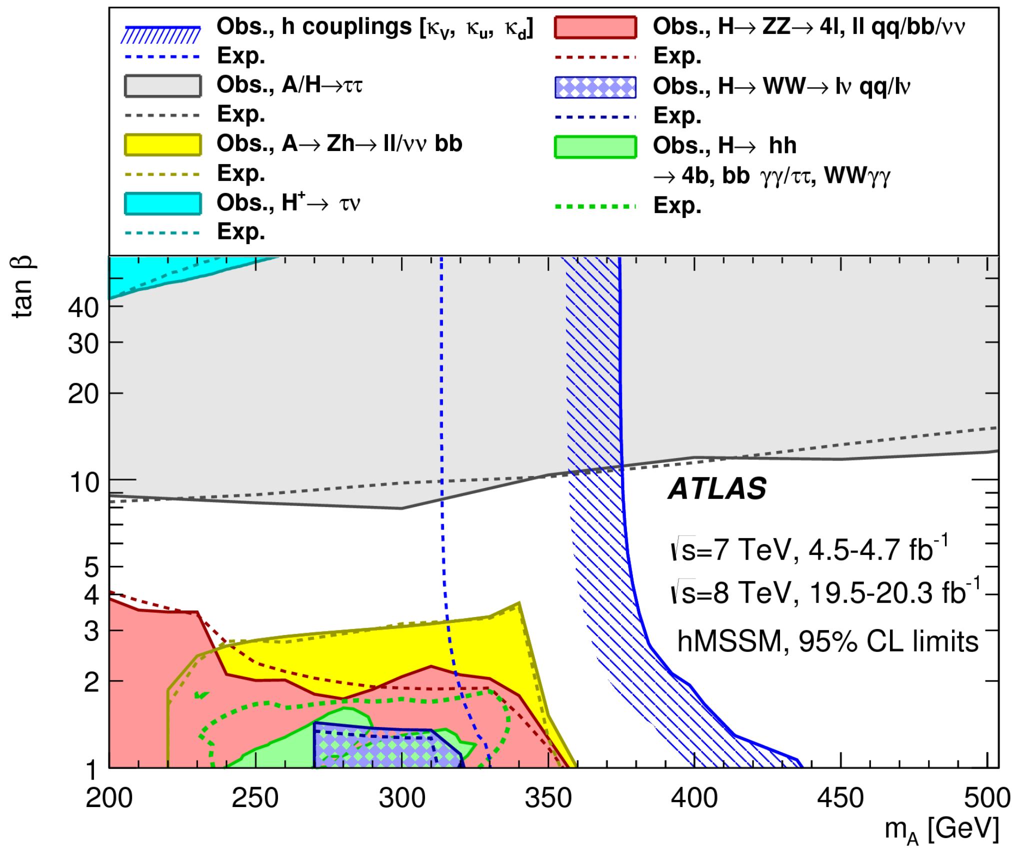


Results look quite consistent, no combination is yet performed for CMS.
The expected limit in the case of bbγγ is slightly better in CMS due to looser jet pT cuts and to an addition of 1b-tag category

Interpretation in hMSSM

hMSSM: the mass of the light CP-even h = 125 GeV. SUSY-breaking scale allowed to be very large —> model dependent on 2 parameters: mA and tanβ

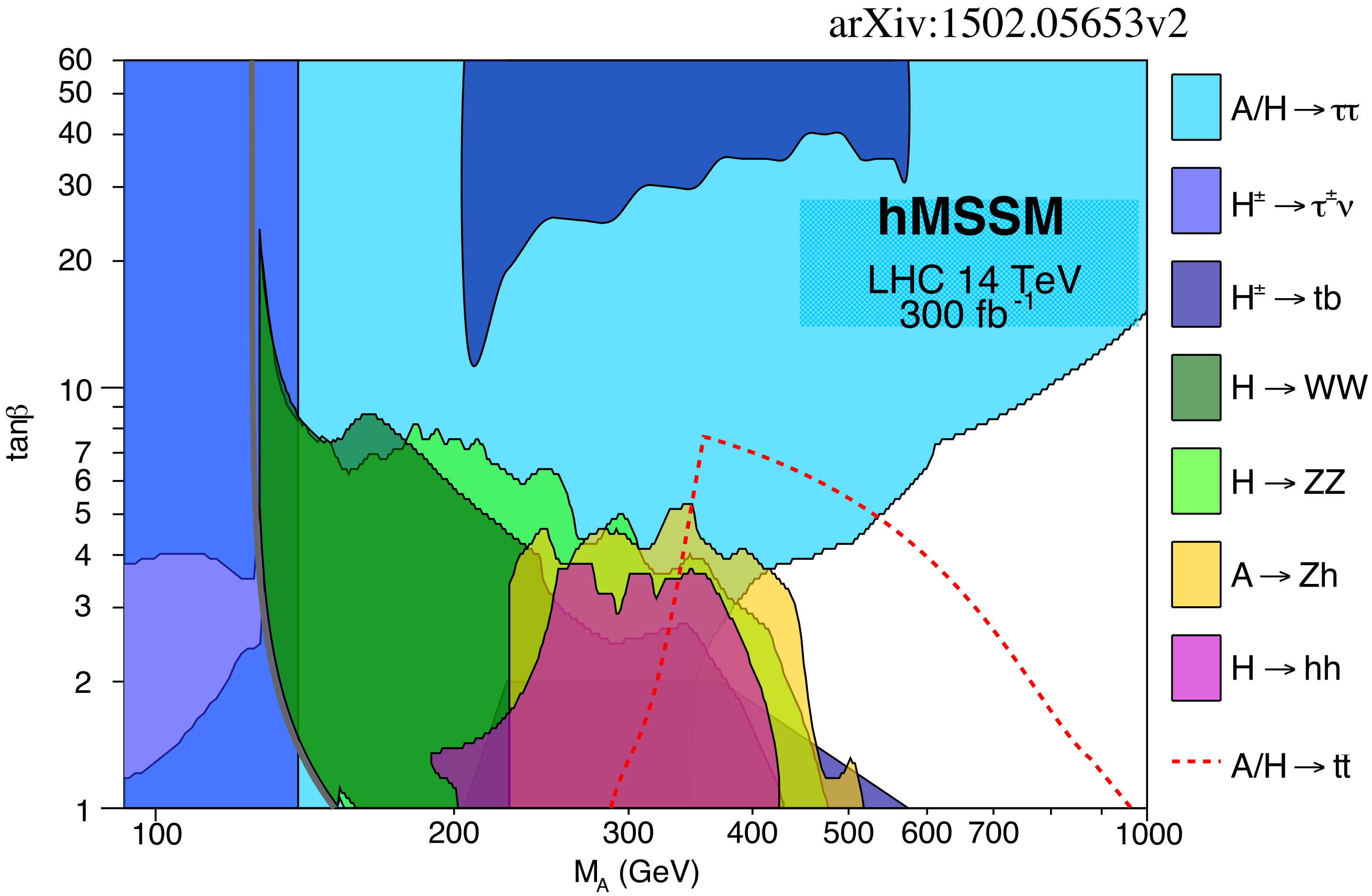




The observed exclusion is smaller than the expectation reflecting the small excess observed in the data

Exclusion in the hMSSM model via direct searches for heavy H and fits to the measured rates of h production and decays.

Further on hMSSM



Expectations for 2σ sensitivity in the hMSSM for the forthcoming 300 fb^{-1} data

The entire parameter space can be probed, any value of tanβ can be probed up to m_A~400 GeV

**hh in this plot considers only results of bbγγ, better limits expected using the combined channels.*

Perspectives

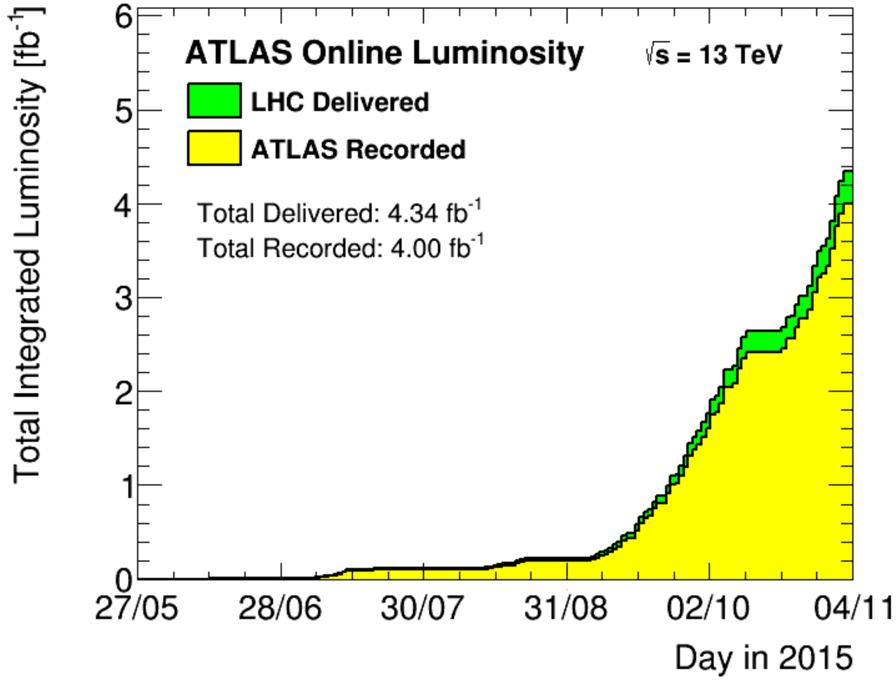
Run II already started ~ 3.5 fb^{-1} to be used for physics analyses

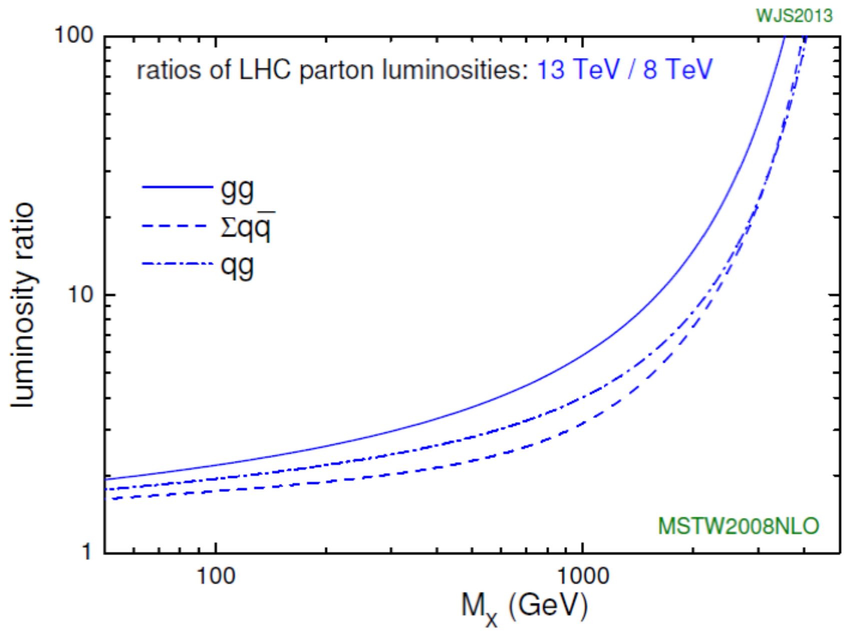
Higher instantaneous luminosities (25 vs 50 ns bunch spacing)

13 vs 8 TeV allows to explore new phase space for BSM physics

An increase in cross section going from 13 to 8 TeV

Very naive estimation:
To reach the same sensitivity for bbγγ (assuming a real 3σ excess) we therefore need 2.5 less luminosity with 13 TeV . To have 5σ—> 21fb^{-1} at 13 TeV (assuming bkg and signal behave the same with √s)



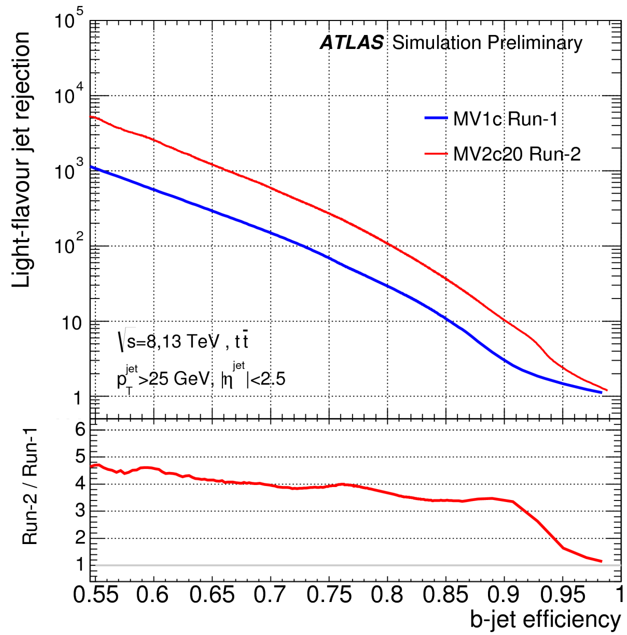


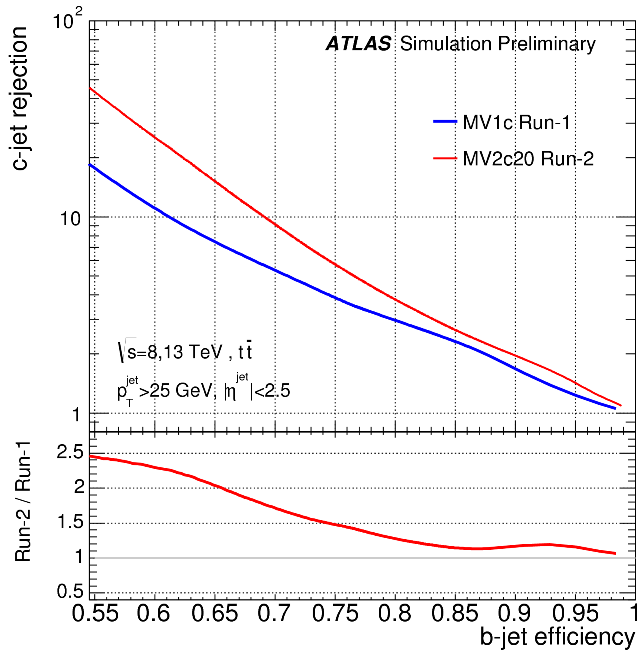
Perspectives

ATL-PHYS-PUB-2015-022

Experimental improvements:

A new pixel layer (Insertable b-layer IBL) mounted on beam pipe allows a much better b-tagging





BSM Physics is one of the most important searches to perform in the coming Run II and Run III of LHC data taking as well as beyond that.

Stay tuned for further results !

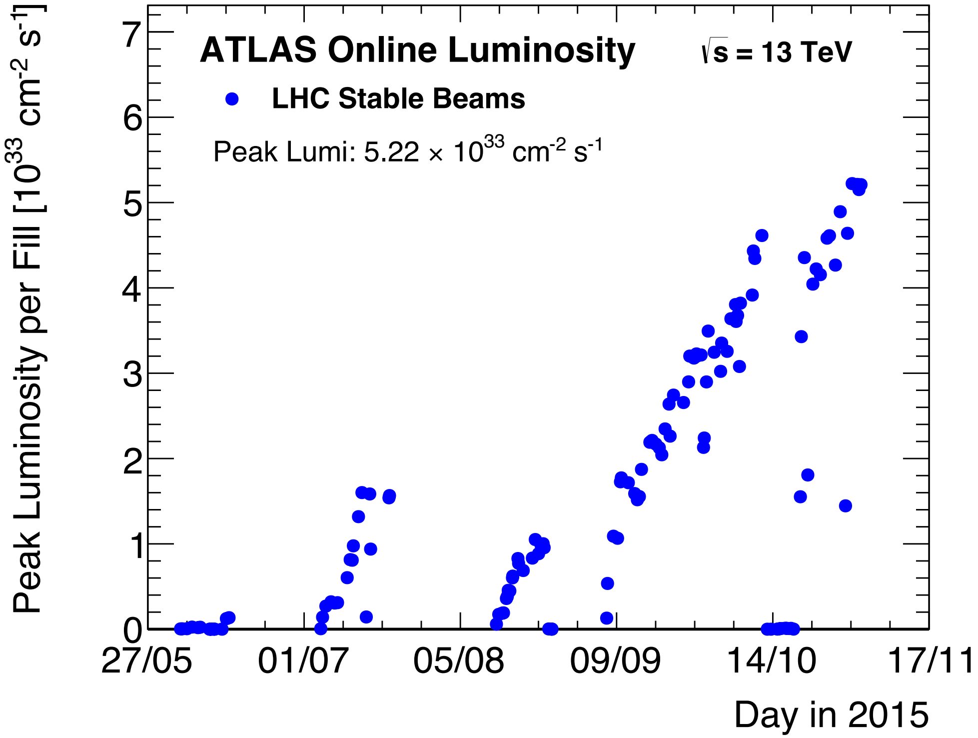
Thanks for your attention!

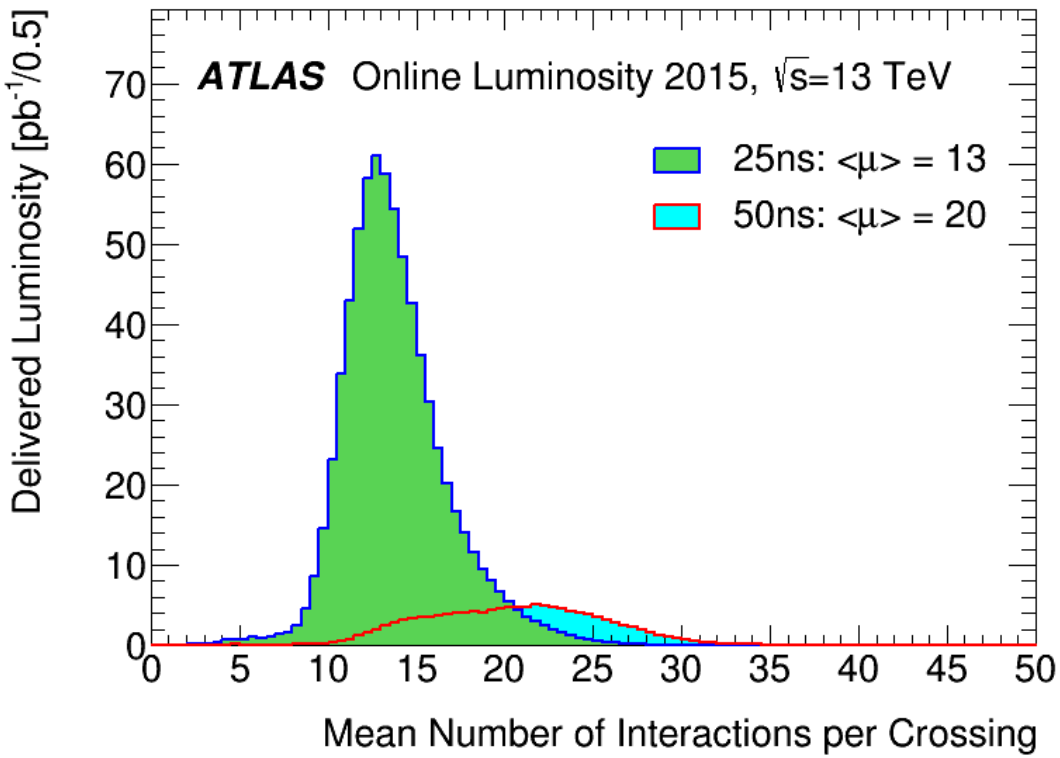
Backup Slides

Nonresonant search		Resonant search			
		m_H = 300 GeV		m_H = 600 GeV	
Source	$\Delta\mu/\mu$ [%]	Source	$\Delta\mu/\mu$ [%]	Source	$\Delta\mu/\mu$ [%]
Background model	11	Background model	15	b-tagging	10
b-tagging	7.9	Jet and E_T^{miss}	9.9	h BR	6.3
h BR	5.8	Lepton and τ_{had}	6.9	Jet and E_T^{miss}	5.5
Jet and E_T^{miss}	5.5	h BR	5.9	Luminosity	2.7
Luminosity	3.0	Luminosity	4.0	Background model	2.4
Total	16	Total	21	Total	14

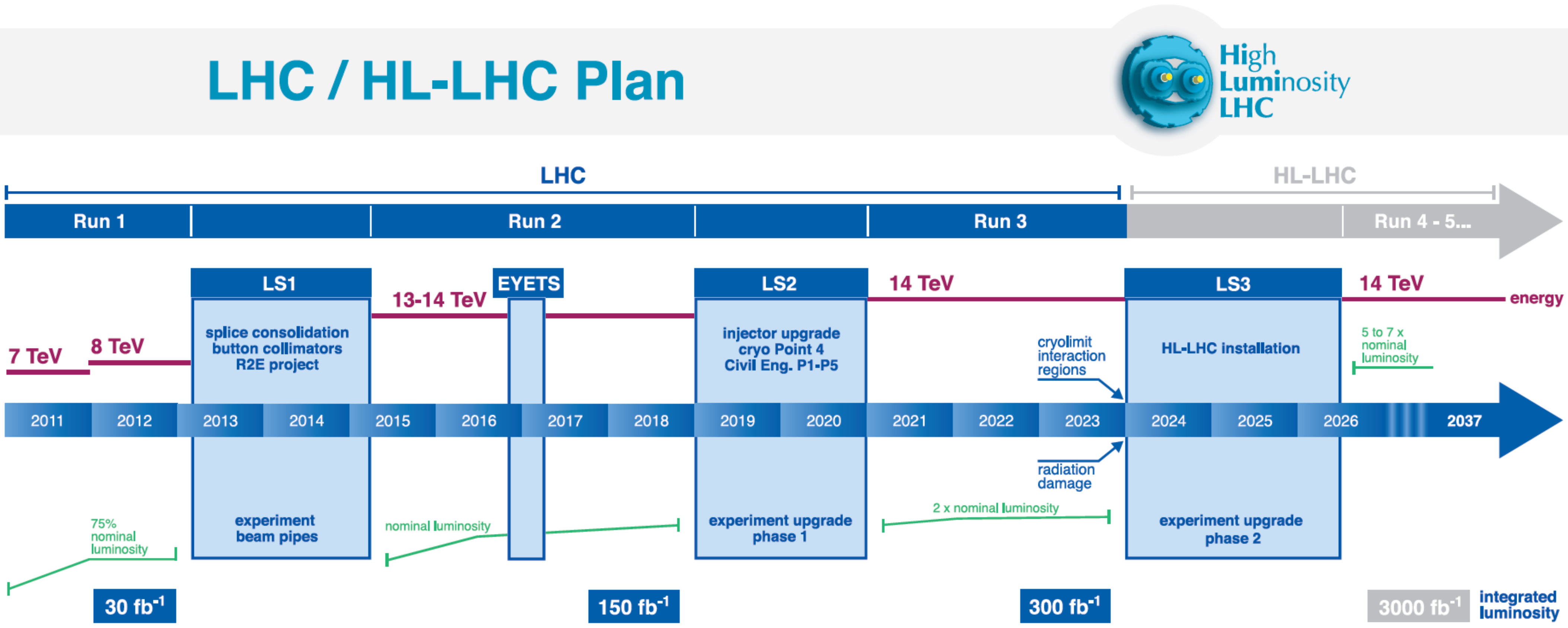
Table 5: The impact of the leading systematic uncertainties on the signal-strength parameter μ of a hypothesized signal for both the nonresonant and resonant (m_H = 300, 600 GeV) searches. For the signal hypothesis, a Higgs boson pair production cross section ($\sigma(gg \to hh)$ or $\sigma(gg \to H) \times \text{BR}(H \to hh)$) of 1 pb is assumed.

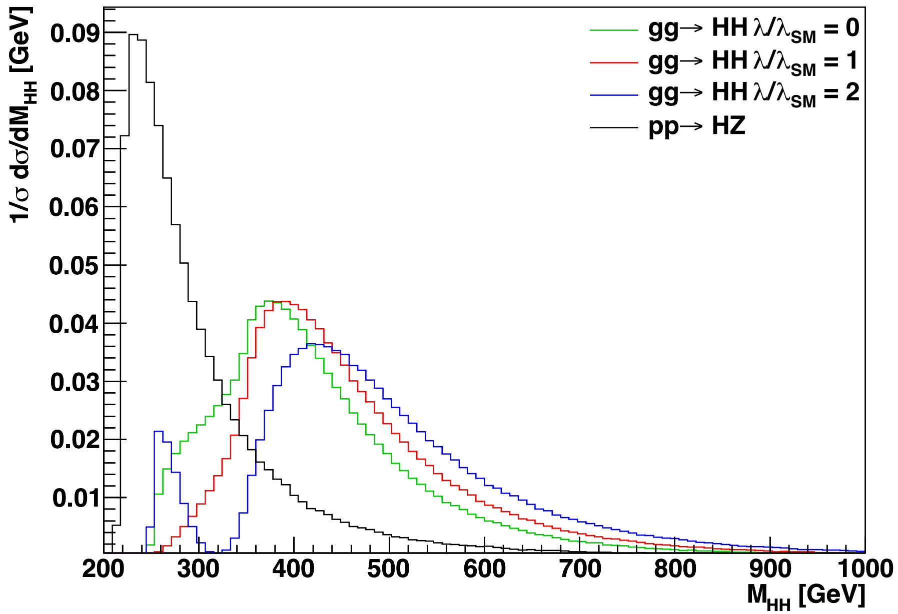
hh	Nonresonant search		Resonant search		
final state	Categories	Discriminant	Categories	Discriminant	m_H [GeV]
$\gamma\gamma b\bar{b}$	1	$m_{\gamma\gamma}$	1	event yields	260–500
$\gamma\gamma WW^*$	1	event yields	1	event yields	260–500
$b\bar{b}\tau\tau$	4	$m_{\tau\tau}$	4	$m_{bb\tau\tau}$	260–1000
$b\bar{b}b\bar{b}$	1	event yields	1	m_{bbbb}	500–1500

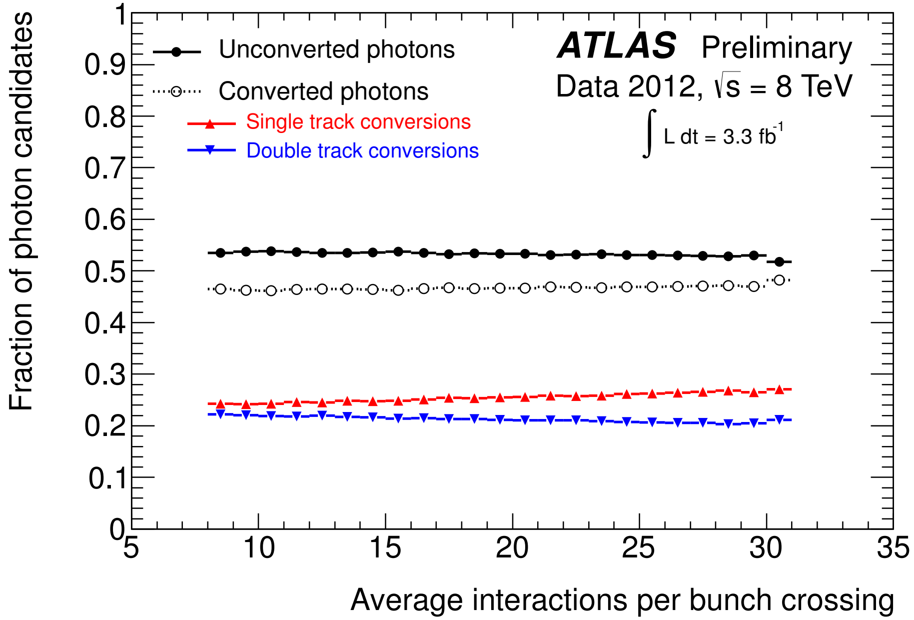

ATLAS Online Luminosity
√s = 13 TeV
LHC Stable Beams
Peak Lumi: 5.22 × 10^33 cm^-2 s^-1
Peak Luminosity per Fill [10^33 cm^-2 s^-1]
0
1
2
3
4
5
6
7
27/05
01/07
05/08
09/09
14/10
17/11
Day in 2015


ATLAS Online Luminosity 2015, √s=13 TeV
25ns: <μ> = 13
50ns: <μ> = 20
Delivered Luminosity [pb^-1/0.5]
0
10
20
30
40
50
60
70
0
5
10
15
20
25
30
35
40
45
50
Mean Number of Interactions per Crossing

LHC / HL-LHC Plan




gg→ HH λ/λ_SM = 0
gg→ HH λ/λ_SM = 1
gg→ HH λ/λ_SM = 2
pp→ HZ
1/σ dσ/dM_HH [GeV]
M_HH [GeV]


Unconverted photons
Converted photons
Single track conversions
Double track conversions
ATLAS Preliminary
Data 2012, √s = 8 TeV
∫ L dt = 3.3 fb⁻¹
Fraction of photon candidates
Average interactions per bunch crossing

pp Higgs factories

LHC is the 1st Higgs factory!
E_{CM}=8-14 TeV, $\hat{L}\sim10^{34}cm^{-2}s^{-1}$

1 M Higgs produced so far – more to come!
15 H bosons / min – and more to come

HL-LHC (~2022-2030):
E_{CM}=14 TeV, $L\sim5x10^{34}cm^{-2}s^{-1}$ (leveled)

10x more Higgs

HE-LHC: in LHC tunnel (2035-?)
E_{CM}=33 TeV, $L = 5x10^{34}cm^{-2}s^{-1}$

6x higher cross section for *H* self coupling

VHE-LHC in new 80-100 km tunnel (2040?)
E_{CM}=84-104 TeV,$L = 5x10^{34}cm^{-2}s^{-1}$

42x higher cross section for *H* self coupling

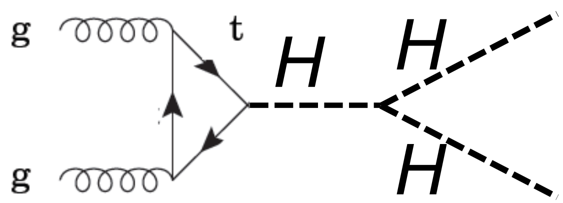
pp Higgs coupling cross sections vs c.m. energy

M. Mangano

HE-LHC   VHE-LHC

	σ(14 TeV)	R(33)	R(40)	R(60)	R(80)	R(100)
ggH	50.4 pb	3.5	4.6	7.8	11.2	14.7
VBF	4.40 pb	3.8	5.2	9.3	13.6	18.6
WH	1.63 pb	2.9	3.6	5.7	7.7	9.7
ZH	0.90 pb	3.3	4.2	6.8	9.6	12.5
ttH	0.62 pb	7.3	11	24	41	61
HH	33.8 fb	6.1	8.8	18	29	42

➔ high statistics studies of ttH
… and, at long last, HHH couplings



VHE-LHC is ultimate machine to measure Higgs self coupling! (~2-5% level)

Higgs selfcouplings: pp→HH

- gg→HH (most promising?) , qq→HHqq (via VBF)
- Reference benchmark process: HH→bb γγ
- Goal: 5% (or better) precision for SM selfcoupling

$HH \to b\bar{b}\gamma\gamma$	Barr,Dolan,Englert,Lima, Spannowsky JHEP 1502 (2015) 016	Contino, Azatov, Panico, Son arXiv:1502.00539	He, Ren, Yao (follow-up of Snowmass study)
$\mathrm{FCC}_{@100\mathrm{TeV}}$ 3/ab	30~40%	30%	15%
$\mathrm{FCC}_{@100\mathrm{TeV}}$ 30/ab	10%	10%	5%
$S/\sqrt{B}$	8.4	15.2	16.5
Details	✓ λ_{HHH} modification only ✓ $c \to b$ & $j \to \gamma$ included ✓ Background systematics ○ $b\bar{b}\gamma\gamma$ not matched ✓ $m_{\gamma\gamma} = 125 \pm 1$ GeV	✓ Full EFT approach ○ No $c \to b$ & $j \to \gamma$ ✓ Marginalized ✓ $b\bar{b}\gamma\gamma$ matched ✓ $m_{\gamma\gamma} = 125 \pm 5$ GeV ✓ Jet $/W_{had}$ veto	✓ λ_{HHH} modification only ✓ $c \to b$ & $j \to \gamma$ included ○ No marginalization ✓ $b\bar{b}\gamma\gamma$ matched ✓ $m_{\gamma\gamma} = 125 \pm 3$ GeV

Work in progress to compare studies, harmonize performance assumptions, optimize, etc
⇒ ideal benchmarking framework

M.Son, HH summary at FCC week

Units are %

Coupling	LHC	CepC	FCC-ee	ILC	CLIC	FCC-hh
√s (TeV) →	14	0.24	0.24 +0.35	0.25+0.5	0.38+1.4+3	100
L (fb^{-1}) →	3000(1 expt)	5000	13000	6000	4000	40000
K_W	2-5	1.2	0.19	0.4	0.9	
K_Z	2-4	0.26	0.15	0.3	0.8	
K_g	3-5	1.5	0.8	1.0	1.2	
K_γ	2-5	4.7	1.5	3.4	3.2	< 1
K_μ	~8	8.6	6.2	9.2	5.6	
K_c	--	1.7	0.7	1.2	1.1	
K_τ	2-5	1.4	0.5	0.9	1.5	
K_b	4-7	1.3	0.4	0.7	0.9	
$K_{Z\gamma}$	10-12	n.a.	n.a.	n.a.	n.a.	
Γ_h	n.a.	2.8	1%	1.8	3.4	
BR_{invis}	<10	<0.28	<0.19%	<0.29	<1%	
K_t	7-10	--	13% ind. tt scan	6.3	<4	~ 1 ?
K_{HH}	?	35% from K_Z model-dep	20% from K_Z model-dep	27	11	5-10

Few preliminary estimates available
SppC : similar reach

from K_γ/K_Z, using K_Z from FCC-ee

rare decays → pp competitive/better

from ttH/ttZ, using ttZ and H BR from FCC-ee

- LHC: ~20% today → ~ 10% by 2023 (14 TeV, 300 fb^{-1}) → ~ 5% HL-LHC
- HL-LHC: -- first direct observation of couplings to 2nd generation (H→ μμ)
  -- model-independent ratios of couplings to 2-5%
- Best precision (few 0.1%) at FCC-ee (luminosity !), except for heavy states (ttH and HH) where high energy needed → linear colliders, high-E pp colliders
- Complementarity/synergies between ee and pp