Search for HH production at the LHC

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on Behalf of CMS and ATLAS collaborations

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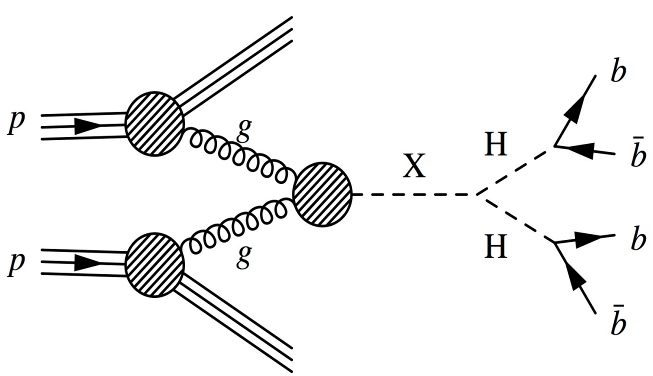
HH search at LHC

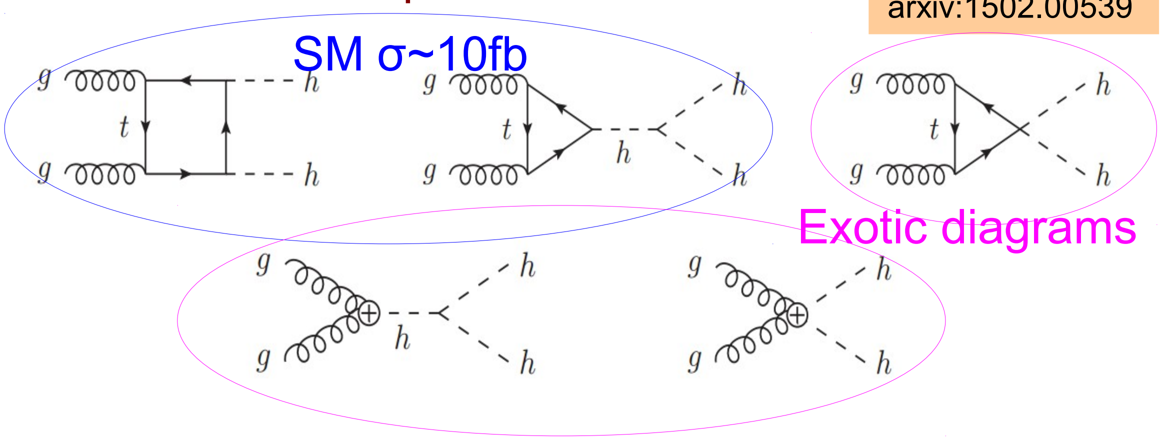
- The just discovered Higgs boson can be already used as a “tool” to tag new physics
- An easy pattern is to look for pairs of Higgses
  - Resonant production from decay of new exotic particles
  - Non-resonant production from SM (beyond reach with current luminosity) or from new diagrams increasing the production cross section
- Models predicting enhanced or resonant HH production can be found in several context such as supersymmetry, extra dimensions, 2HDM, etc..
  - Assuming $gg \rightarrow X$ production (with $X \rightarrow HH$)
  - Separate spin-0 vs spin-2 case due to different kinematics of decay product

Resonant



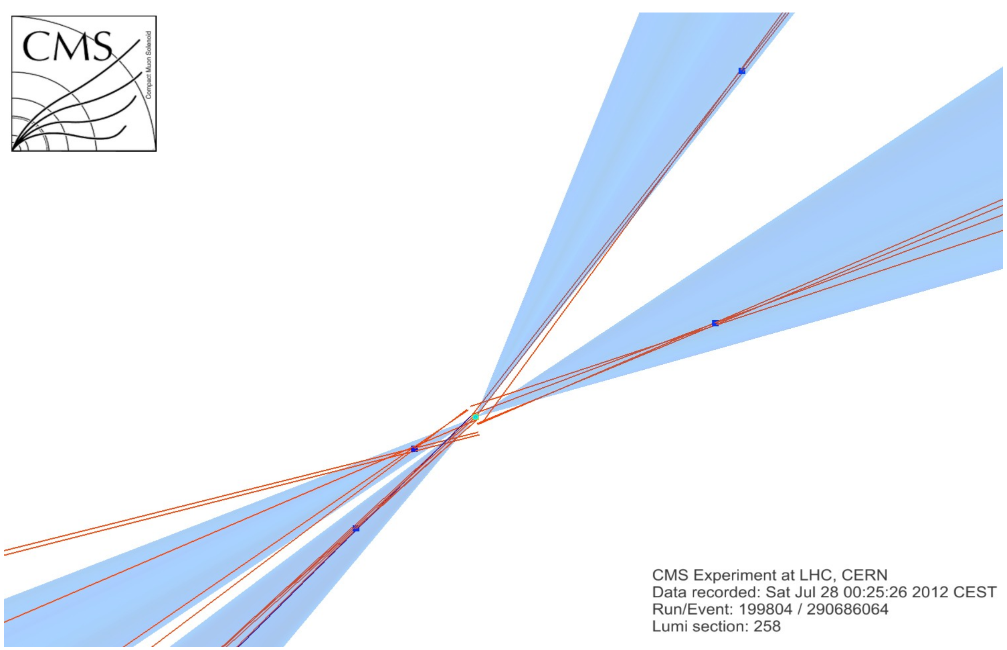
Example non resonant

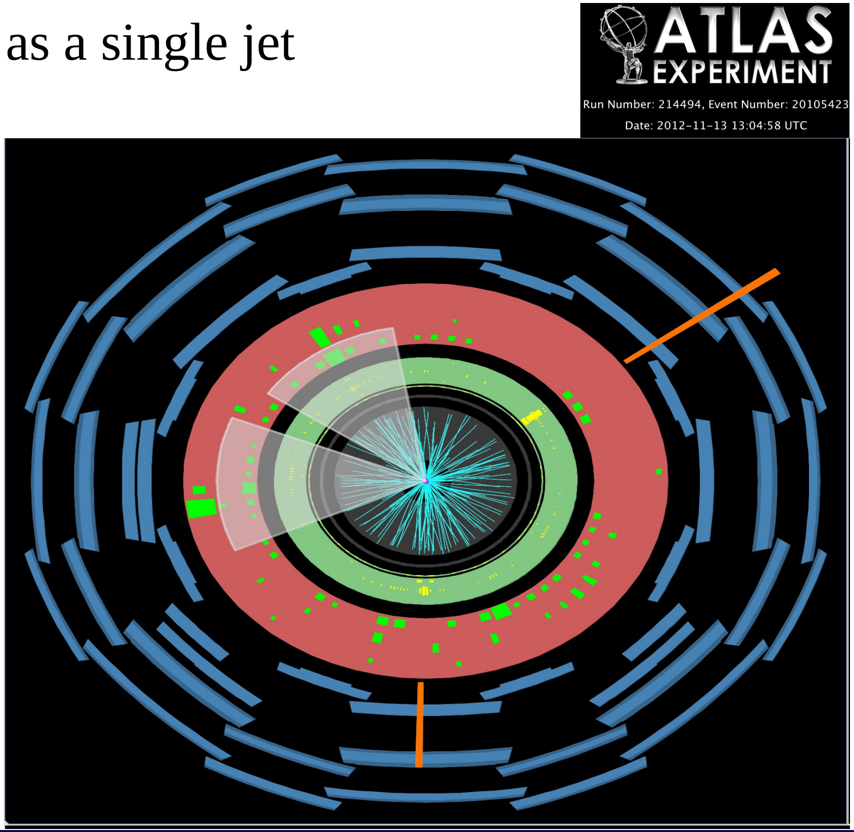
arxiv:1502.00539



HH signatures

- Each of the two H can decay to different particles pairs
  - Analyses divided by final states
  - 4b (largest BR), bbγγ, bbττ, etc...
- Given the high LHC energy heavy (> 1TeV) resonances can be produced
  - the pair of H bosons may have pT >~500 GeV
  - decay products of the H could be very collimated
  - H → bb decay would show up in the detector as a single jet

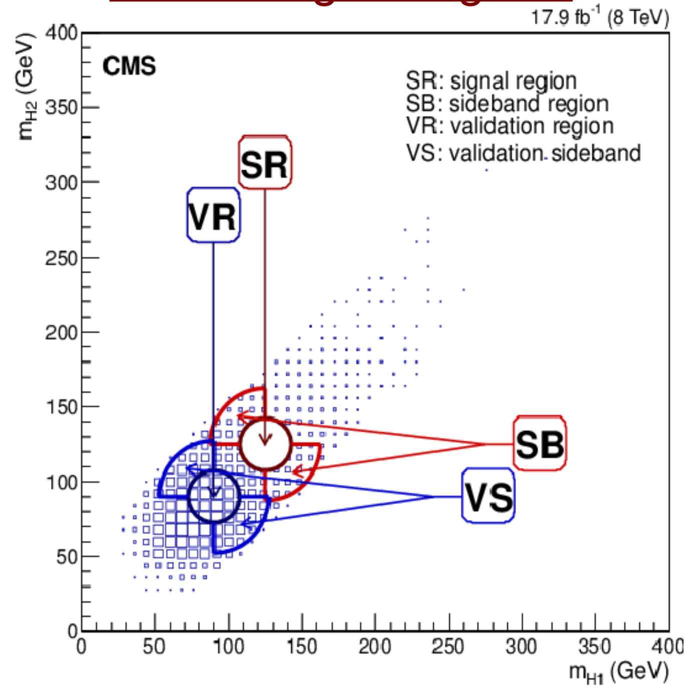




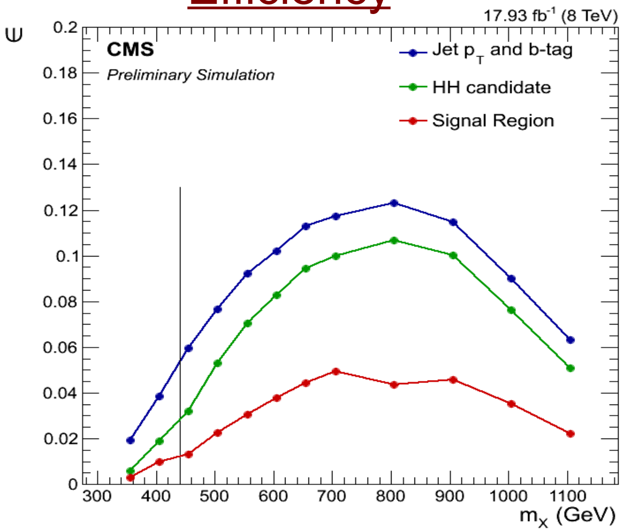
CMS 4b resolved

- Events with 4 b-tagged jets are selected
- Largest backgrounds are QCD multijet and ttbar production
- Modeling of background based on fits in several control regions and sidebands (mass sidebands and b-tag sidebands)
- Use kinematic fit to known H mass to improve 4j mass resolution
- Efficiency limited by trigger at low mass and by merging of jets at higher mass

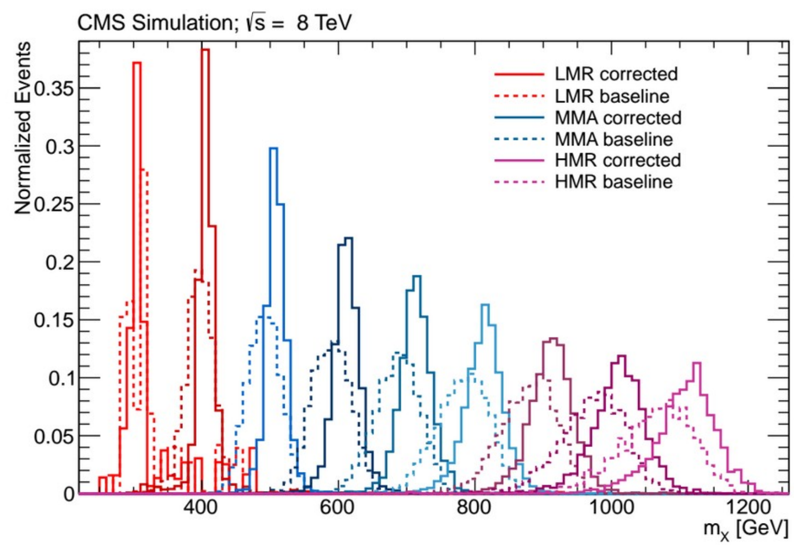
Control/signal regions



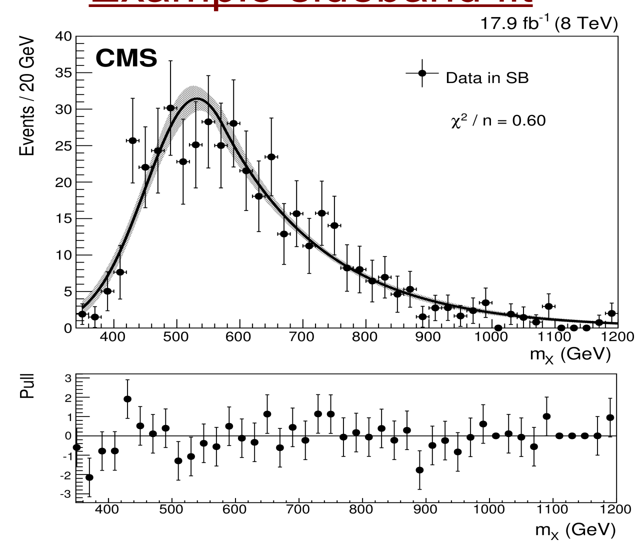
Efficiency



Effect of kin-fit



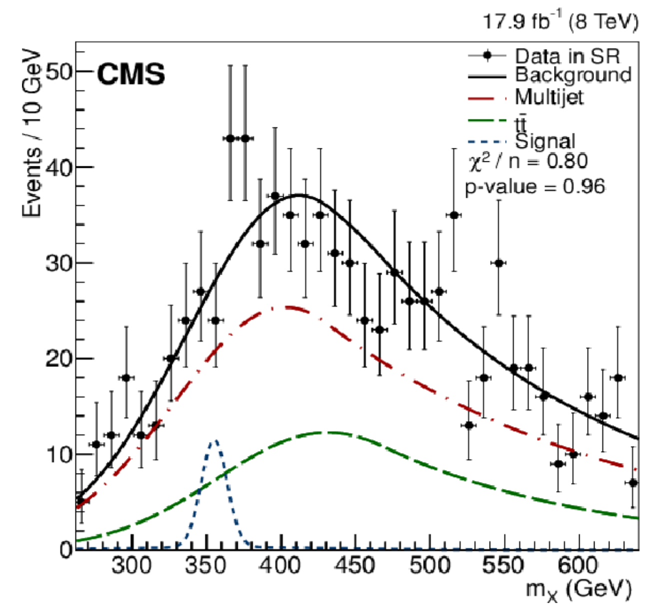
Example sideband fit



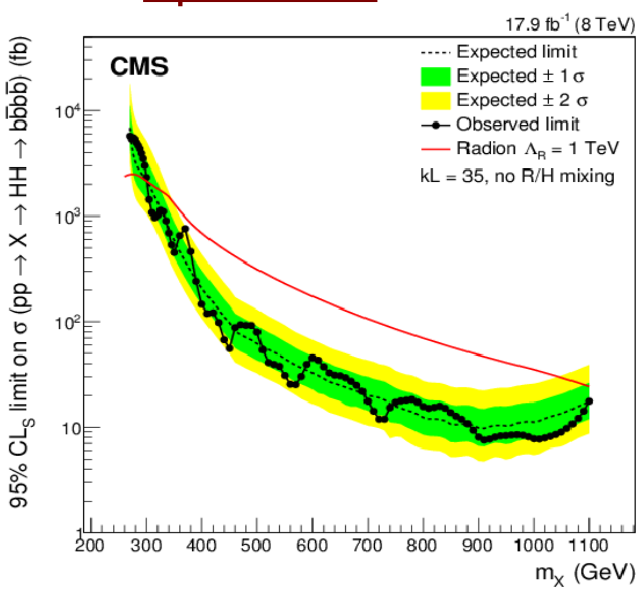
CMS 4b resolved

- The analysis is split in 3 mass regions and optimized selections are applied
- A fit including for a narrow peak signal on top of multijet+tt background is performed in each region
- Results are interpreted in spin-0 and spin-2 hypothesis (slightly different acceptance) and compared to some benchmarks (Radion, KK graviton)
- No significant excess observed

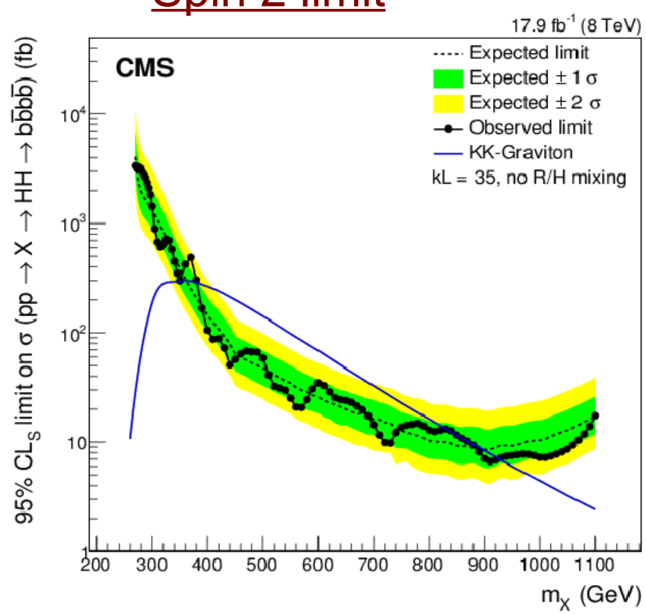
Example fit



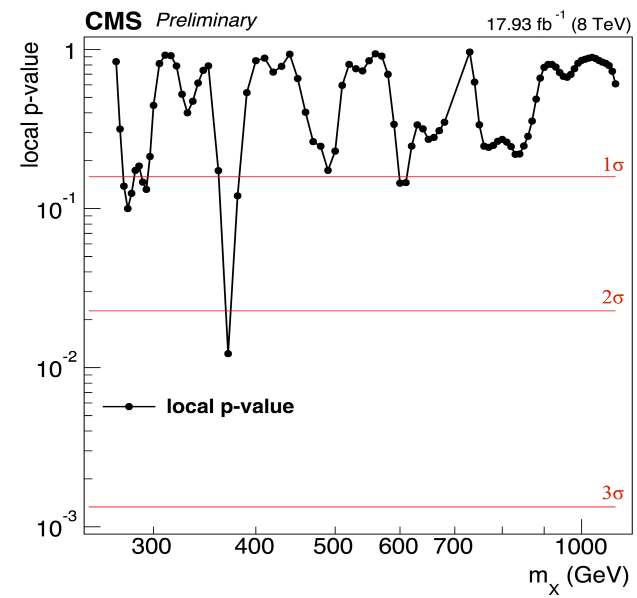
Spin 0 limit



Spin 2 limit



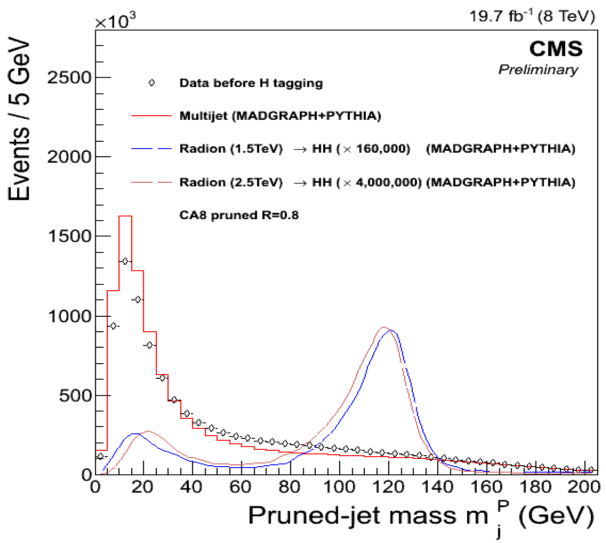
Significance of excess



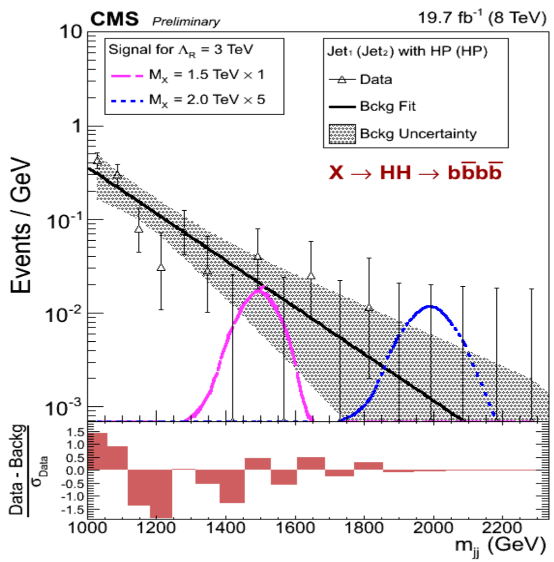
CMS 4b boosted

- Above ~1TeV significant merging takes place (one fat jet instead of two resolved b jets)
- Using substructures techniques to tag H-jets
  - Pruned mass
  - N-subjetiness ratio
- No significant excess in the range 1-3 TeV

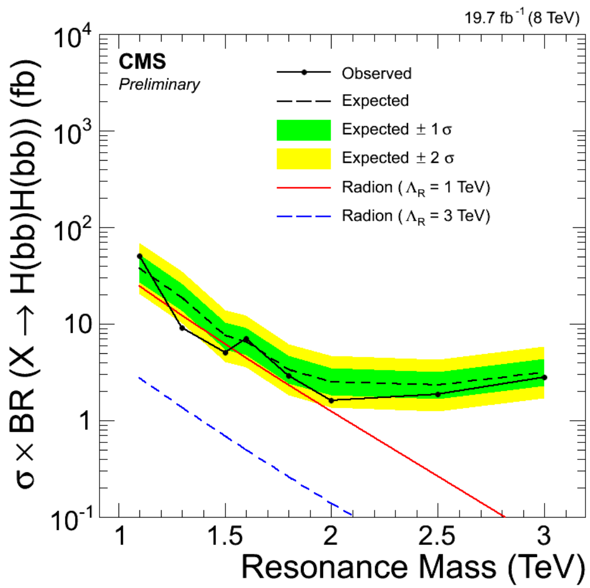
Substructs: pruned jet mass



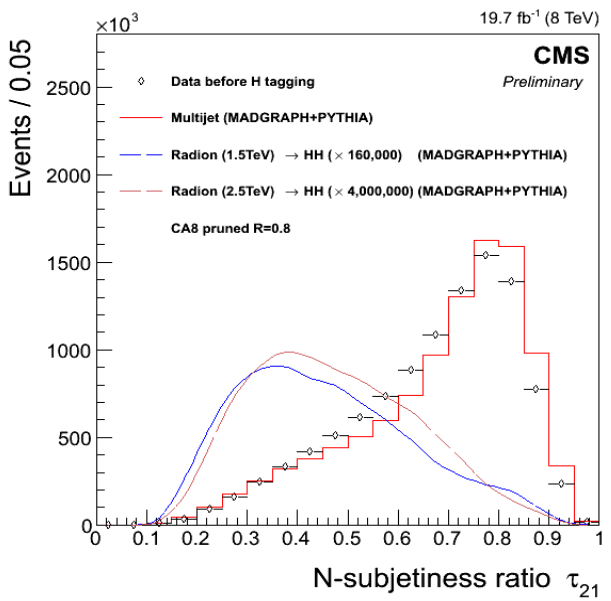
2-fatjets mass



Excl. Limits (including H BR)



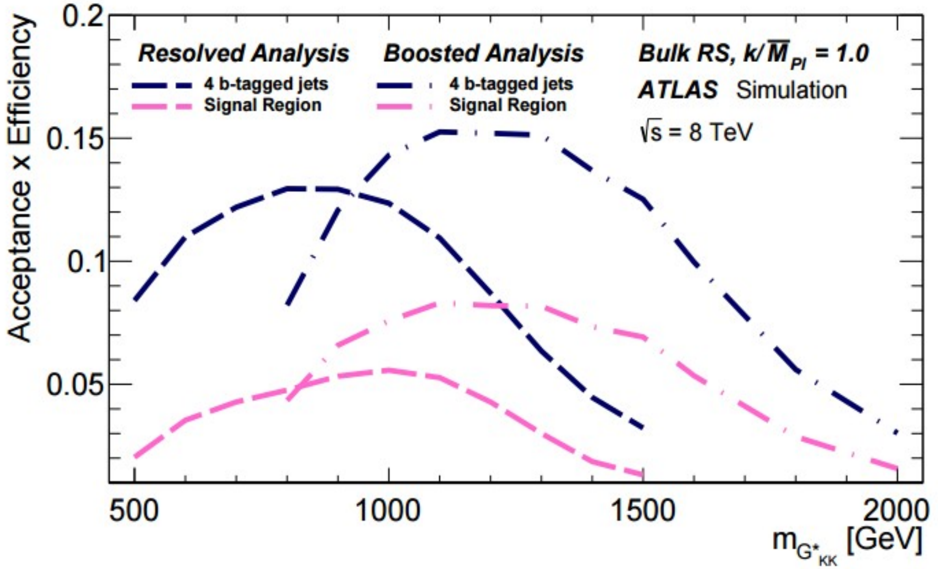
Substructs: N-subjetiness



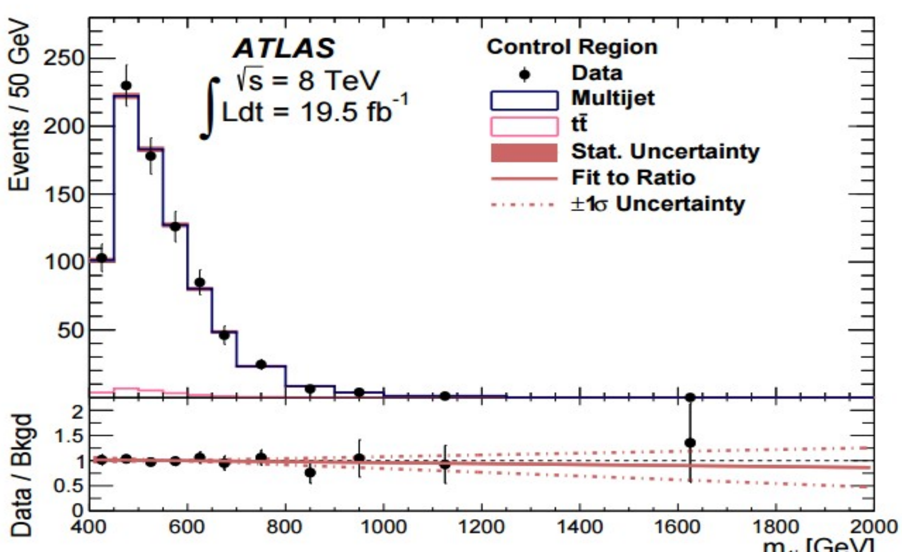
ATLAS 4b

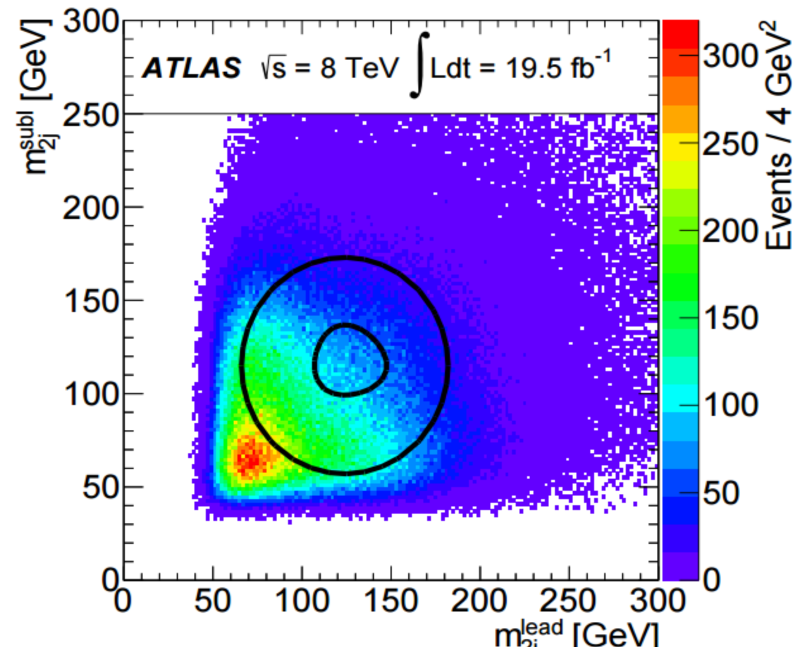
- Resolved analysis: 4 Jets, pt > 40, b-tag
  - Top background rejection cuts 90% eff, x2 reject
  - Background model built from sidebands
  - Cuts optimized in 3 mass regions
- Boosted analysis: 2 Jets(R=1.0), pt>250
  - Trimming to remove pile-up effects
  - Track jets b-tag (R=0.3)
  - Use jet mass to test Higgs mass compatibility

Coverage resolved vs boosted



Background model from control region





ATLAS 4b results

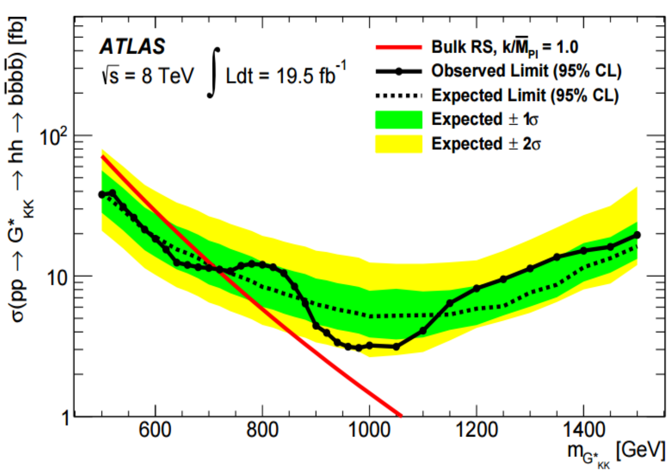
- Resolved and boosted analysis have large overlapping phase space, performance crossing around 1TeV
- No significant excess observed in [500 GeV, 2 TeV]
- Systematics dominated by b-tagging and Jet uncertainties

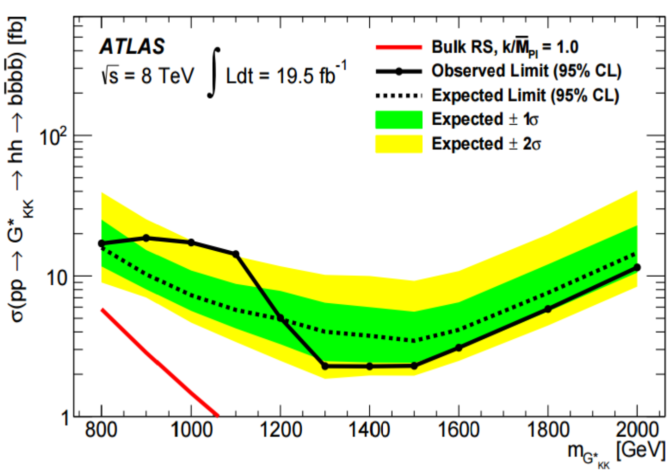
Resolved

Source	Bkgd	SM hh	G^*_{KK} $\frac{k}{\bar{M}_{\mathrm{Pl}}}=1$	G^*_{KK} $\frac{k}{\bar{M}_{\mathrm{Pl}}}=2$	H
Luminosity	–	2.8	2.8	2.8	2.8
JER	–	4.5	1.1	1.1	2.0
JES	–	7	1.8	1.3	3.4
b-tagging	–	12	22	21	22
Theoretical	–	1.0	1.1	1.1	1.1
Multijet	5.6	–	–	–	–
$t\bar{t}$	3.0	–	–	–	–
Total	6.4	15	22	22	23

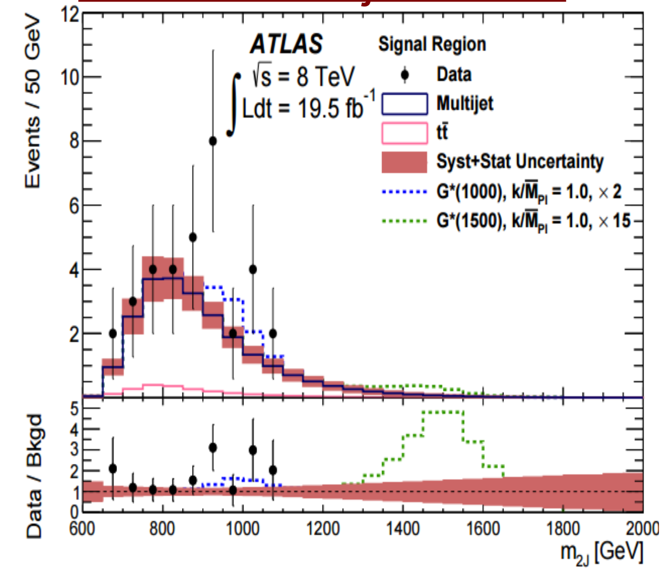
Boosted

Source	Bkgd	G^*_{KK} $k/\bar{M}_{\mathrm{Pl}}=1$	G^*_{KK} $k/\bar{M}_{\mathrm{Pl}}=2$	H
Luminosity	0.2	2.8	2.8	2.8
JER	0.9	0.1	0.2	0.1
JES	0.4	0.1	2.5	0.1
JMR	4.3	13	13	12
JMS	1.3	18	17	16
b-tagging	-	21	20	21
Theoretical	-	2.0	2.0	2.0
Multijet	12	-	-	-
$t\bar{t}$	2.5	-	-	-
Bkgd stat.	8.9	-	-	-
Total	15.9	33	28	30

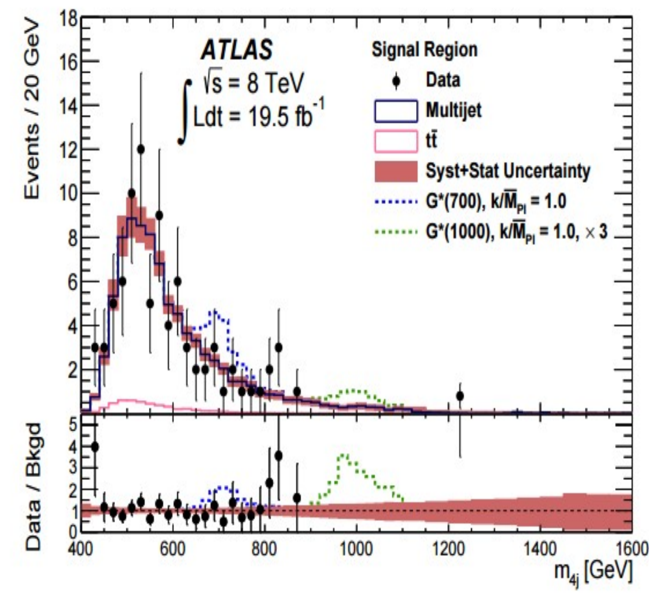




Boosted 2-fatjets mass



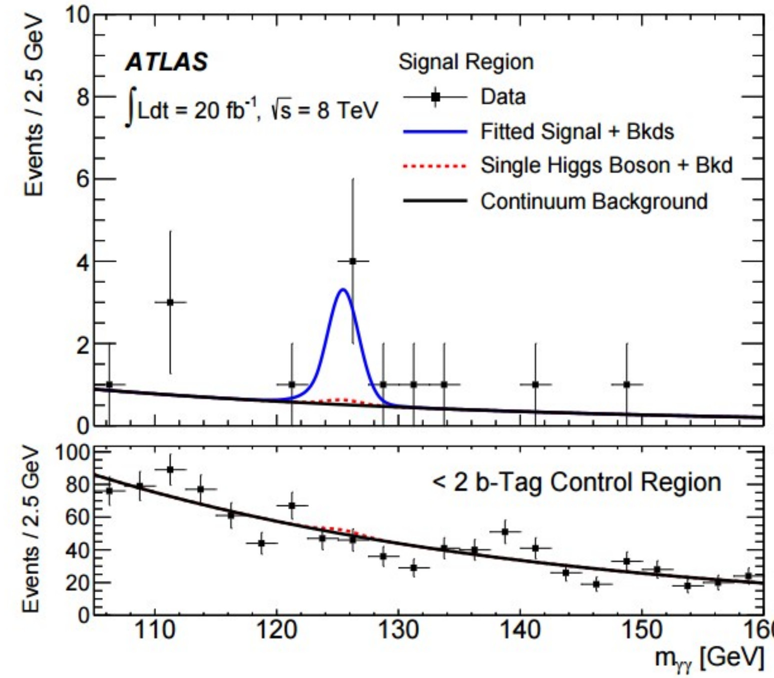
Resolved 4-jets mass



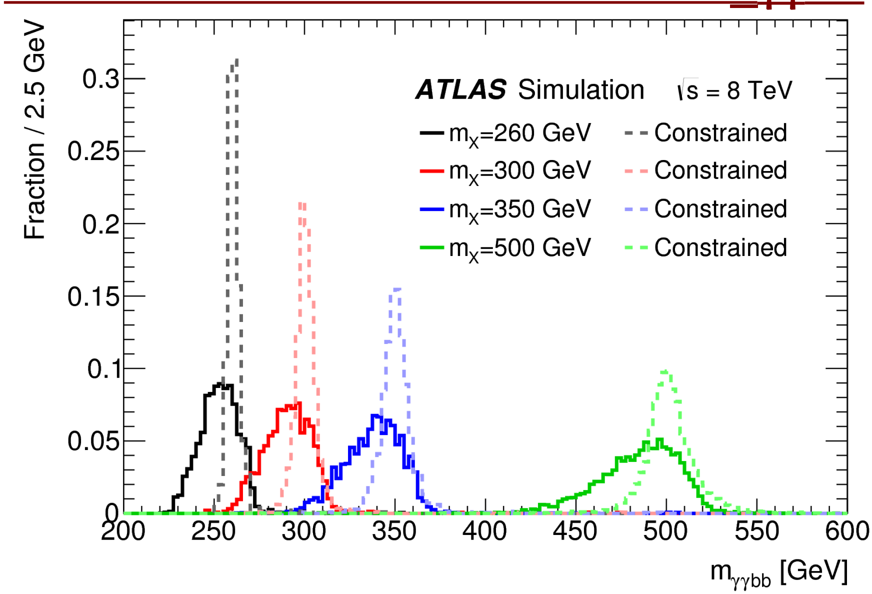
ATLAS bbγγ

- Cleaner channel than 4b final state
  - Less background
  - Better resolution
  - Easier trigger
- Limited by small BR
- Nicely complement the hadronic search in the low mass or non-resonant regime
- ATLAS analysis:
  - Analysis largely based on SM $H \rightarrow \gamma\gamma$ selection
  - Use <=1 b-tag $\gamma\gamma$+jj as control region
  - Scale energy to nominal m_bb in m_γγbb calculation
  - Fit continuum background from data
  - Estimate SM H+jets from simulation

di-photon mass



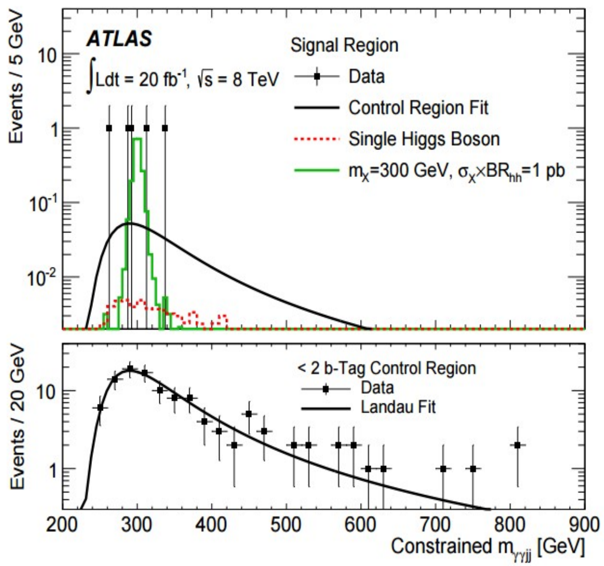
Effect of hadronic mass corr. on m_γγbb



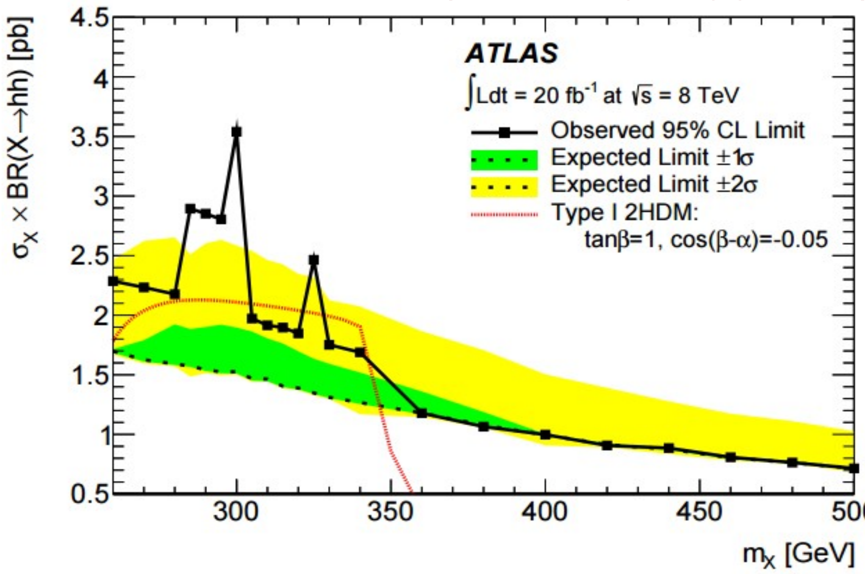
ATLAS bbγγ

- Limit on non resonant production:
  - Expected: 1.0 +0.2 -0.5 pb
  - Observed: 2.2 pb (2.4σ)
- Resonant analysis sets limit around 1pb in the higher mass region
- Local excesses below 350 GeV raising the observed limits to up to 3.5pb

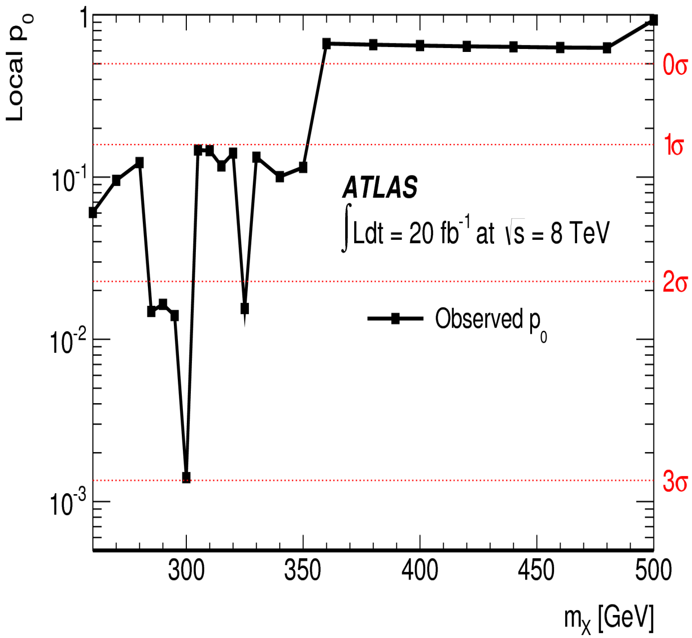
HH mass spectrum



Exclusion limits (including Higgs BR)



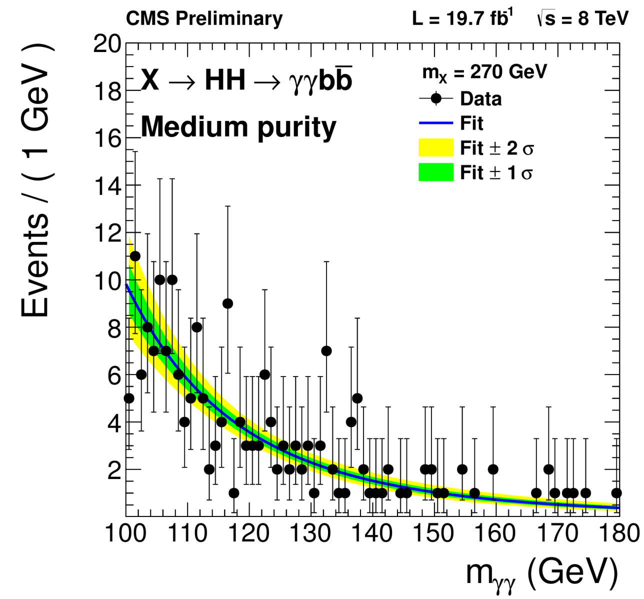
Significance of the excess



CMS bbγγ

- Follow SM H → gg measurement analysis
  - No Primary Vertex efficiency issue thanks to the hadronic H
- Three categories of events
  - 0 b-tags: used as control region
  - 1 and >=2 b-tags: medium and high purity region
- Dominant syst: b-tag eff and high pt photons uncert
- Background model bias negligible

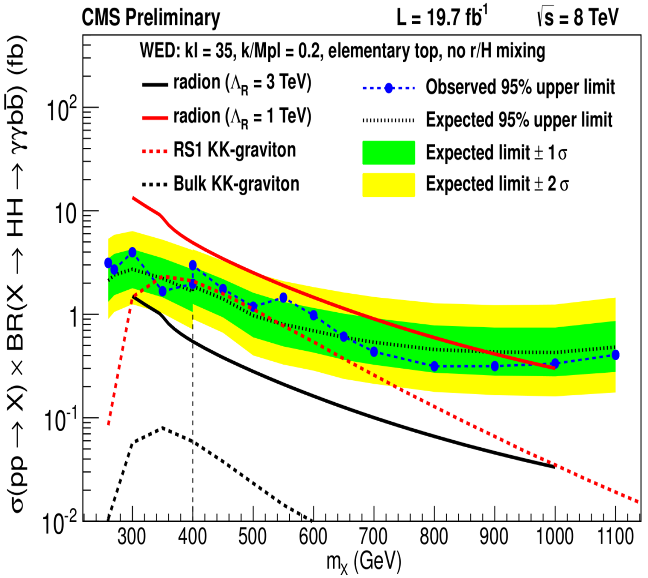
Diphoton mass (medium purity)



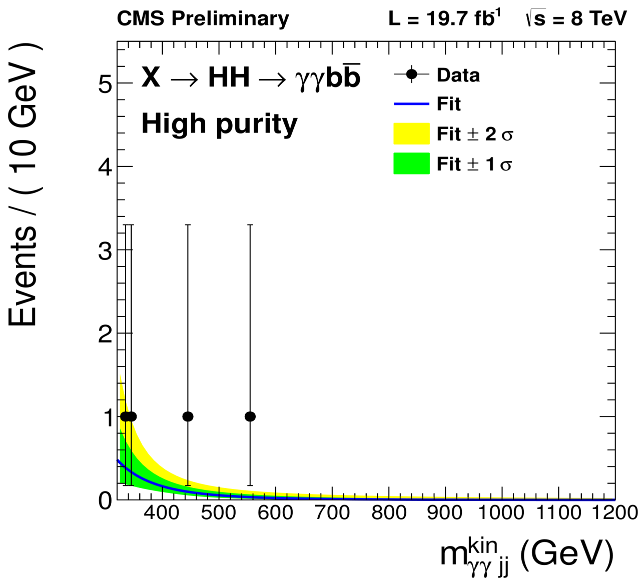
Systematic uncertainties

High mass analysis: fit to $m^{kin}_{\gamma\gamma jj}$	
Normalization uncertainties	
Photons selection acceptance	1.0%
"b-tag" eff. uncertainty 2 btag cat	5.3%
"b-tag" eff. uncertainty 1 btag cat	-1.8%
m_{jj} and $p_{T,j}$ cut acceptance (JES & JER)	1.5%
$m_{\gamma\gamma}$ cut acceptance (PES & PER)	0.5%
Extra High pt norm. uncertainty	5.0%
Shape uncertainties	
Parametric abs. shift (PES ⊕ JES)	$\frac{\Delta m_{\gamma\gamma jj}}{m_{\gamma\gamma jj}} = 0.45 \oplus (0.8 \oplus 1.0) = 1.4\%$
Parametric shift (PER ⊕ JER)	$\frac{\Delta\sigma}{\sigma_{\gamma\gamma jj}} = 10\%$

Exclusion limits (no Higgs BR)

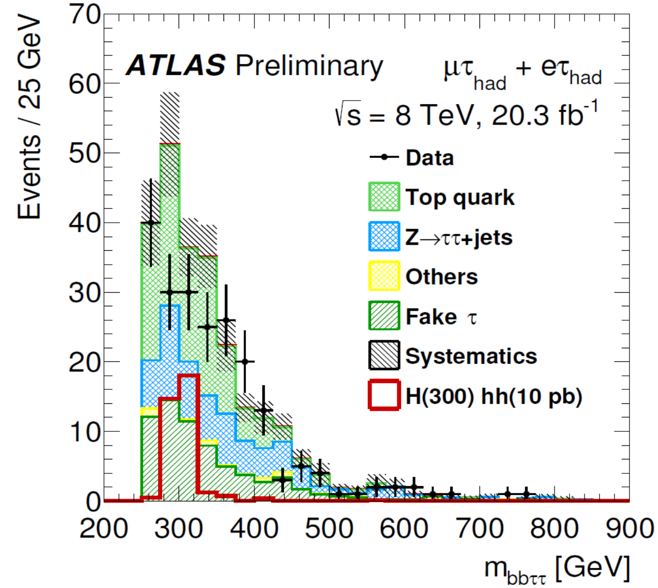


HH mass (high purity region)

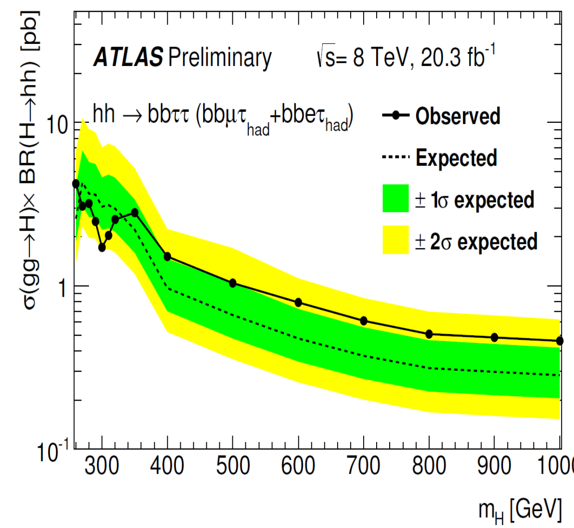


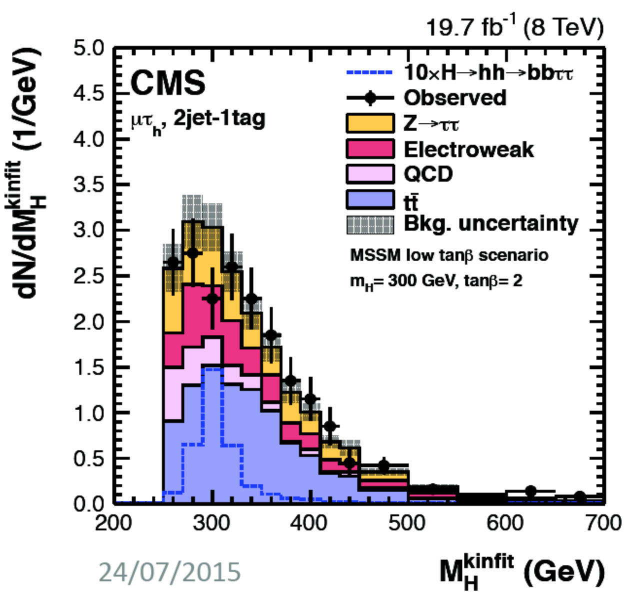
HH → bbττ

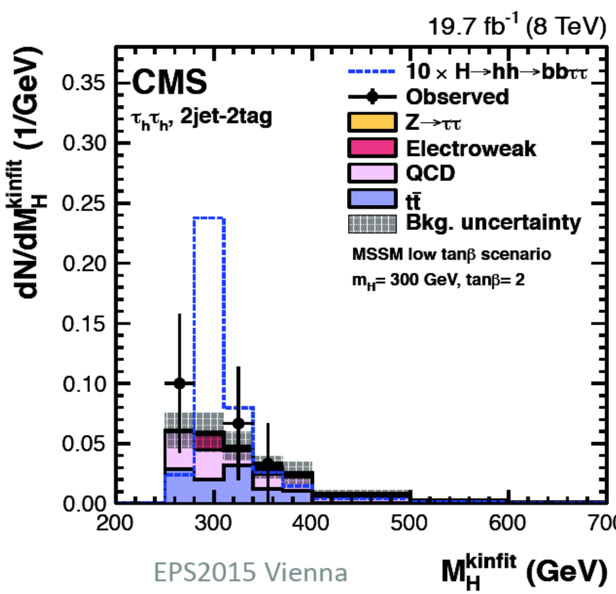
- bb+ττ final state:
  - CMS: 2had and 1had+1lep
  - ATLAS: 1had+1lep
- Separate by number of b-tags
- Selection largely following the H → ττ analysis
- Good sensitivity at low mass



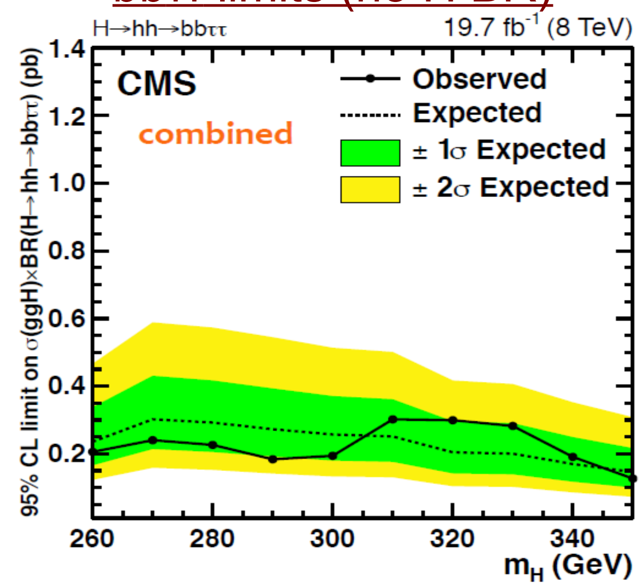
bbττ limits (w/ H BR)







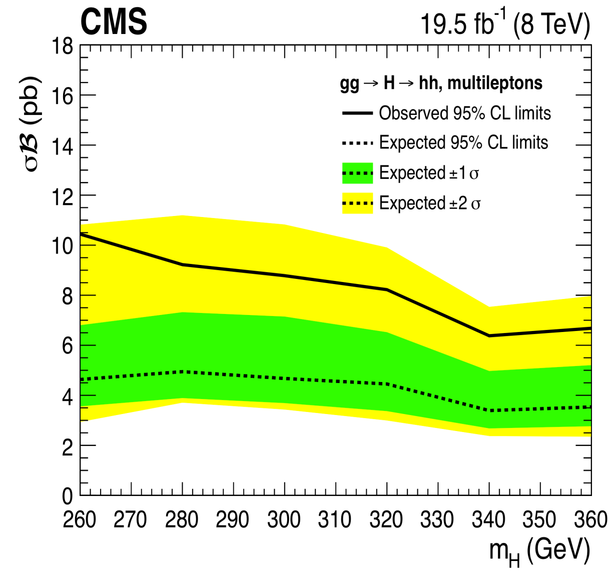
bbττ limits (no H BR)



Other final states

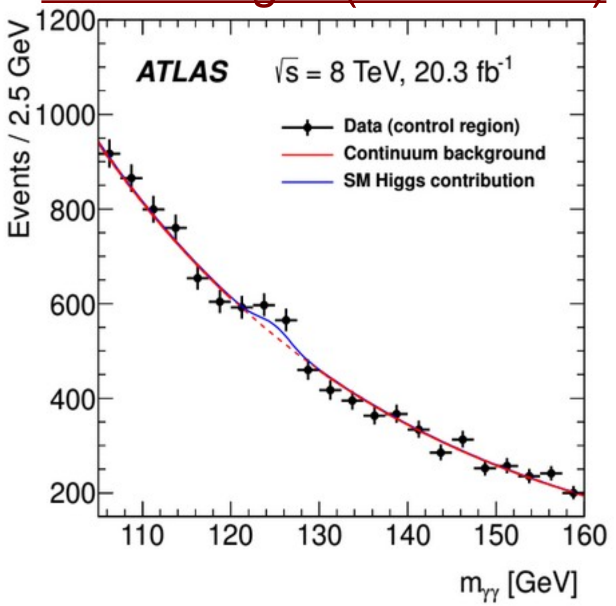
- CMS implemented a multilepton and lepton plus photon analysis
  - >=3 leptons or 2 photons plus >=1 lepton
  - Cover several final states WWγγ, WWWW, WWZZ, WWττ, etc...
- ATLAS analysis focused on WWγγ
  - H→γγ side following single H analysis
  - Additional lepton+jets (b-tag veto) for WW side

Multi lepton limits (include H BR)

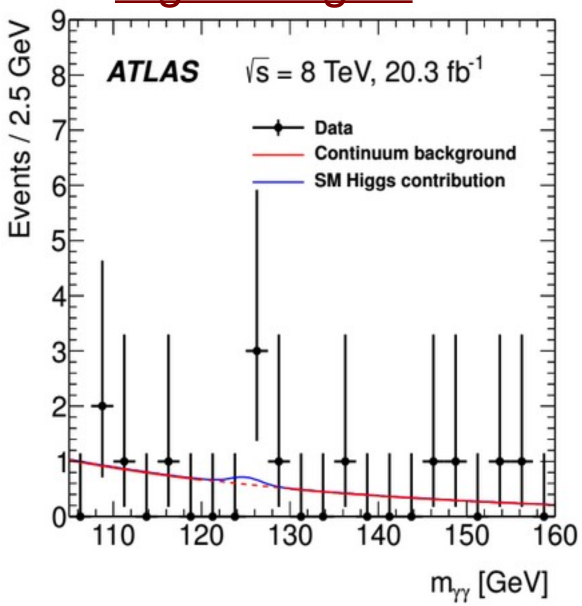


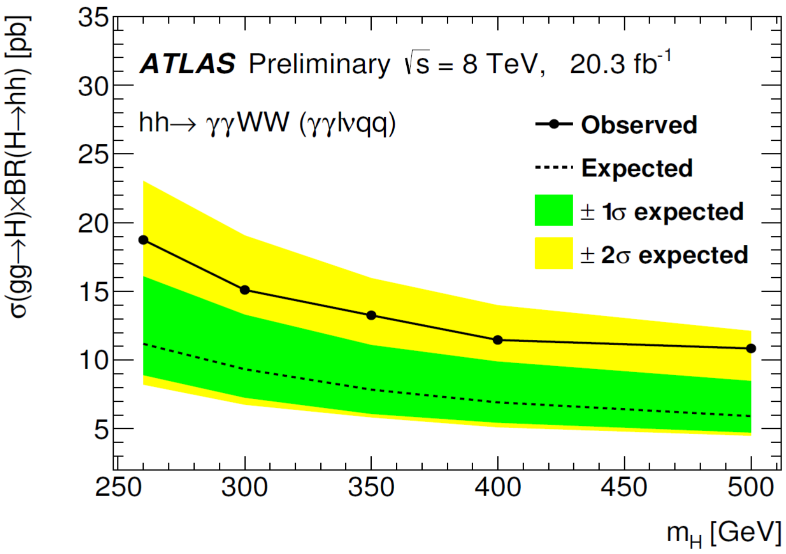
WWγγ (include H BR)

Control region(no WW sel)



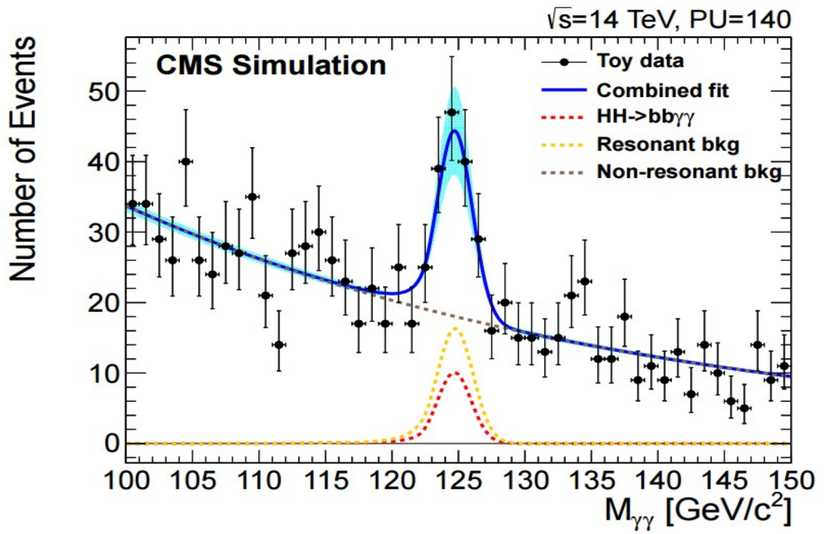
Signal Region



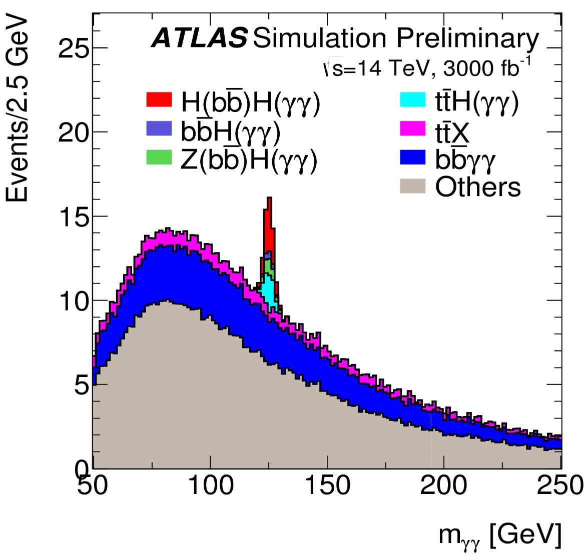


HH in LHC upgrade

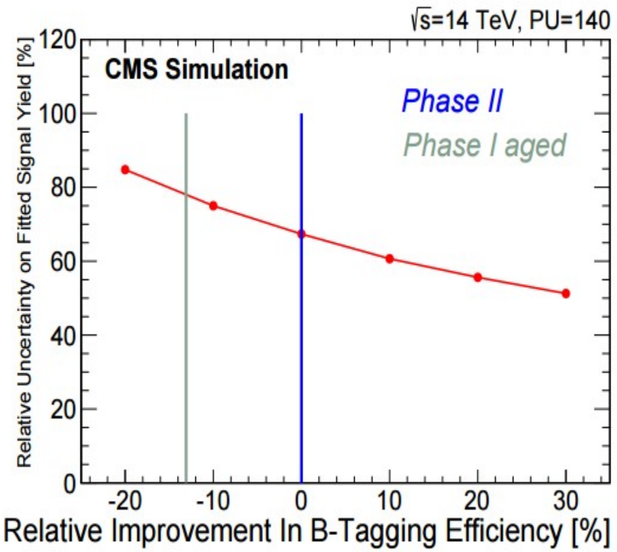
- Very preliminary studies are being performed in the context of LHC and experiment upgrades
- bbγγ can reach ~1.5σ per experiment
- Sensitivity to non resonant HH in the SM can be reached combining different channels and possibly the two experiments



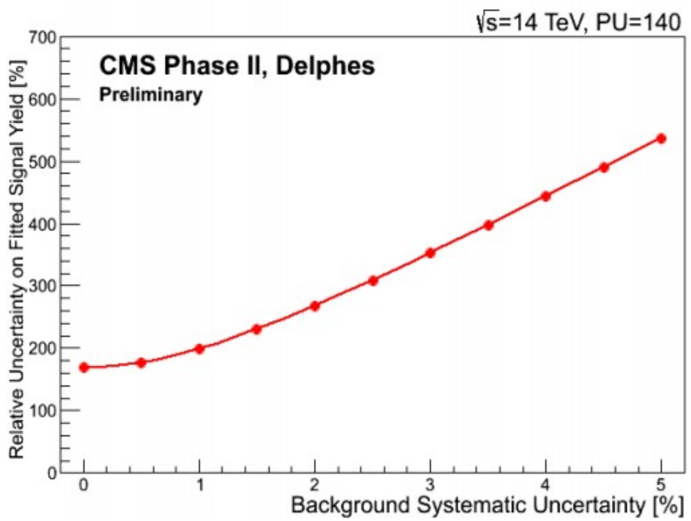
γγ mass plot on 3000/fb



bbγγ performance

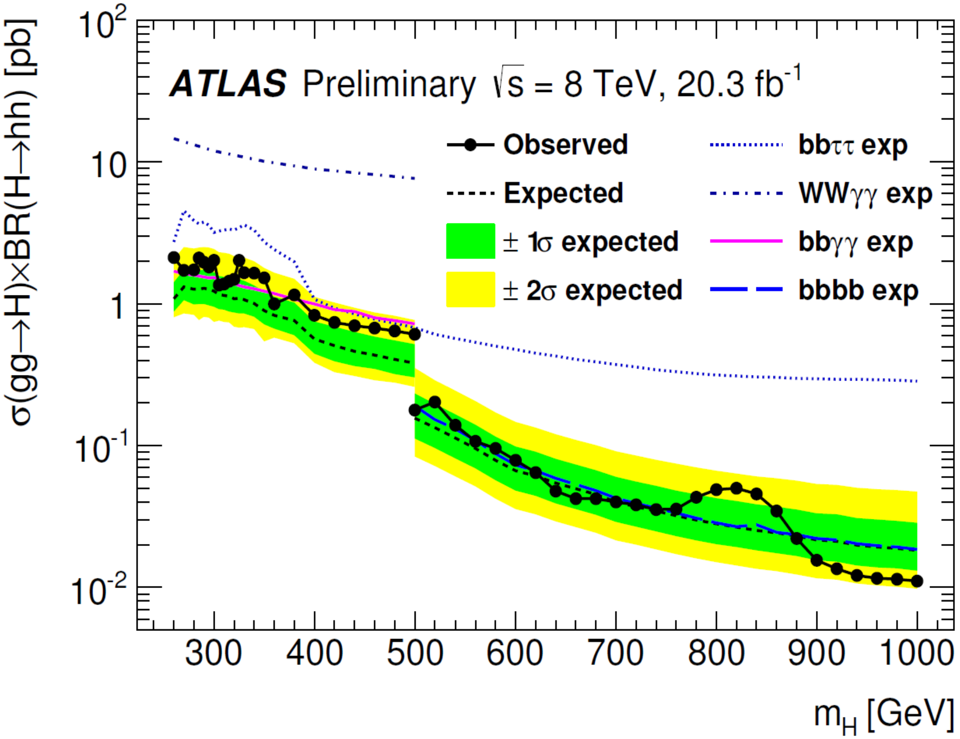


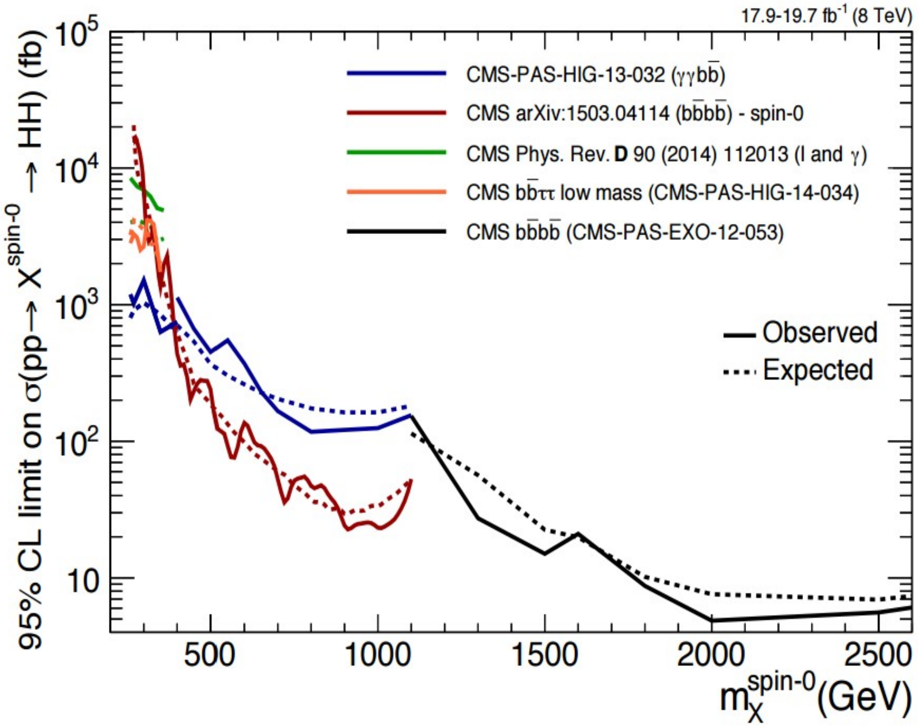
bbWW performance



Summary

- Search for HH final state in Run1 performed by both LHC experiments
- While the non-resonant search are far from SM sensitivity (>50x SM) new physics can be probed
- Limits on resonant HH are set on wide mass range



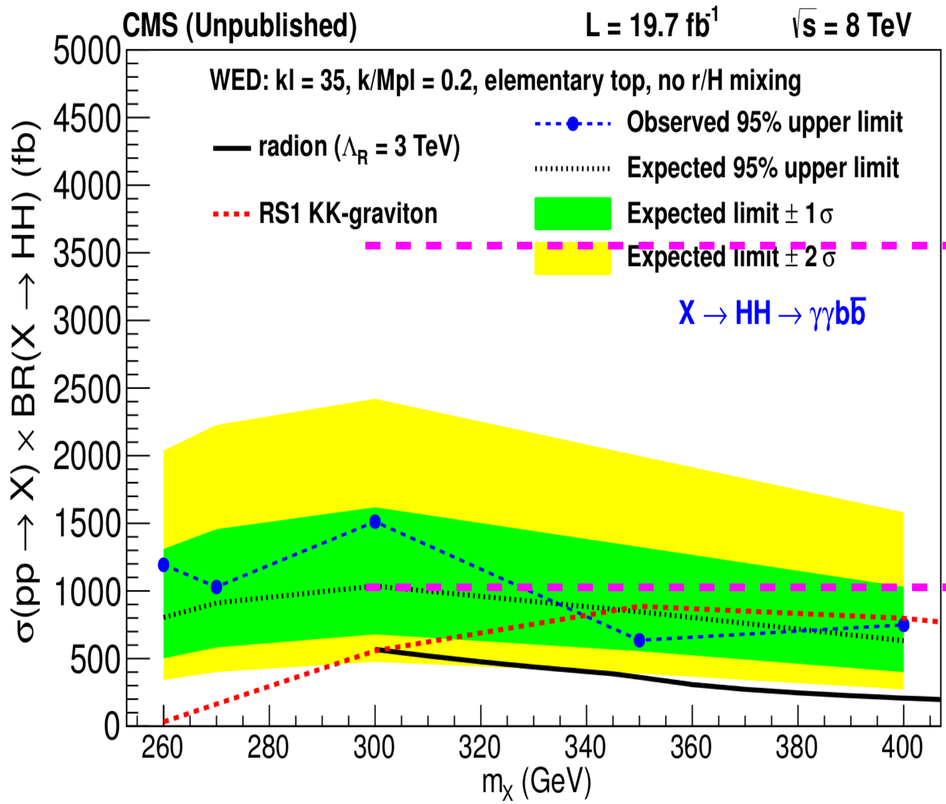


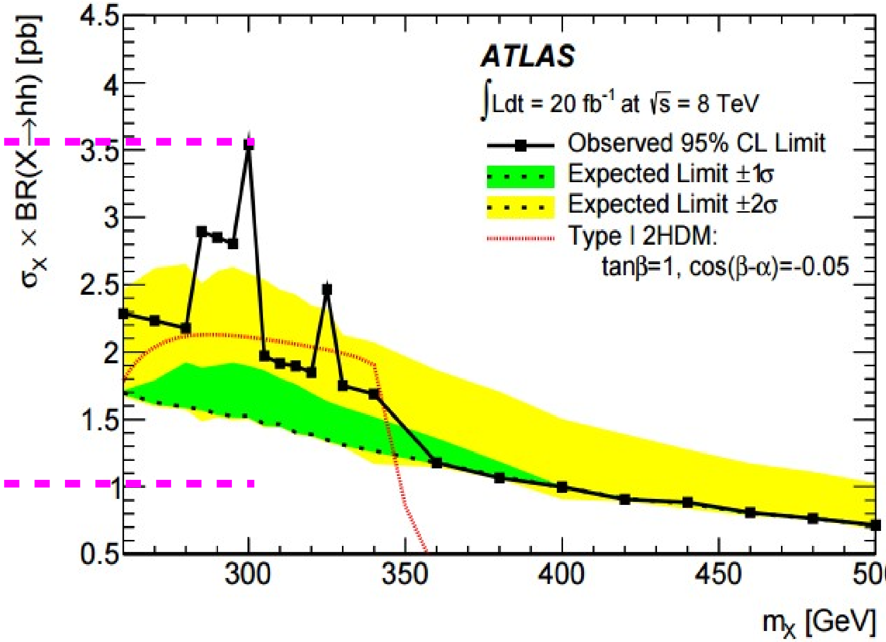
Backup

Bibliography

- ATLAS HIGGS-2013-33 (ATLAS bbττ,WWγγ) - to be published
- Arxiv:1406.5053 (ATLAS bbγγ, incl. non-reson.)
- Arxiv:1506.00285 (ATLAS 4b boosted and resolved)
- HIG-14-013/arxiv:1503.04114 (CMS 4b below ~1TeV)
- HIG-14-034 (CMS bbττ) – to be published
- HIG-13-032 (CMS bbγγ)
- EXO-12-053 (CMS 4b boosted)
- HIG-13-025/arxiv:1410.2751 (CMS leptonic and lept+photon final states)
- CERN-LHCC-2015-010 (CMS Upgrade studies)
- ATL-PHYS-PUB-2014-019 (ATLAS Upgrade)

Low mass bbgammagamma





CMS bbgg – all regions