di-Higgs
searches and prospects
CMS and ATLAS experiments

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on behalf of CMS and ATLAS collaborations

International Symposium on Higgs Boson and Beyond Model Physics
Shandong University - Weihai, August 17th 2016

* Università di Padova

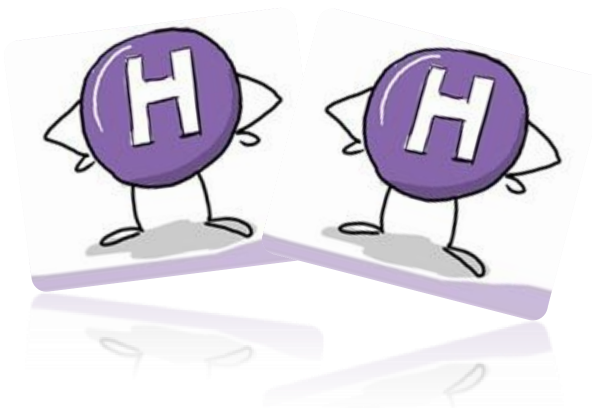
OUTLINE

1. Why and which Higgs pair (di-Higgs) productions?
    - resonant
    - non-resonant

2. Searches status per decay channel (focus on Run 2 results):
    - bb bb
    - bb WW
    - bb ττ
    - bb γγ
    - γγ WW

3. BSM in non-resonant hh searches

4. Future prospects

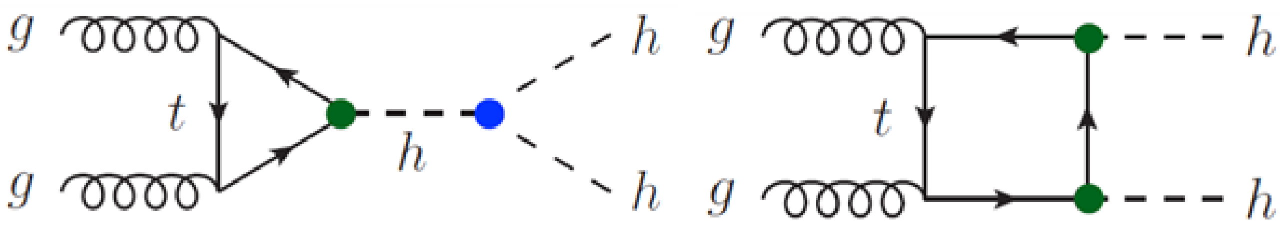


Results from CMS and ATLAS collaborations.
New analysis shown at ICHEP 2016 plus two brand new results.

MOTIVATIONS

Search for Standard Model (SM) di-Higgs (hh) production at LHC is:

- a baseline SM topic.
- *important for measuring Higgs self-coupling (λ_{hhh}).*



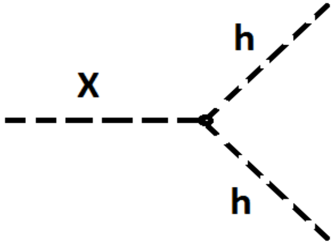
➢ Di-Higgs are produced mainly via **gluon-gluon fusion** at LHC.
Destructive interference among diagrams leads to **small prod. cross section**:

$$\sigma^{SM}_{hh}(\text{p-p 8 TeV}) = 10.16\ \text{fb}\ ^{[1]}$$
$$\sigma^{SM}_{hh}(\text{p-p 13 TeV}) = 33.45\ \text{fb}\ ^{[2]}$$

➢ Measurements possible starting from 3 ab^{-1}.
However, **BSM effects lead to**:
- the presence of **resonant** hh process.
- the enhancement of the **non-resonant** hh production cross section.

[1] +4.1% -5.7% (scale unc.) ± 4.0% (PDF+α_S unc) -- NNLO+NNLL.
[2] +4.3% -6.0% (scale unc.) ± 3.1% (PDF+α_S unc) -- NNLO+NNLL.
LHCHXSWG Yellow Report 4

MOTIVATIONS



RESONANT

Resonant di-Higgs predicted in at least three possible BSM models:

- **MSSM/2HDM** (250-400 GeV) -> additional Higgs doublet → CP-even scalar H.

  *see Ning Chen's talk

- **Singlet model** (250-1000 GeV) **->** Additional Higgs singlet with an extra scalar H.
  Sizeable BR beyond 2xm_{top}, non negligible width at high m_H.

- **Warped Extra Dimensions** (250-3000 GeV) **->**
  spin-2 (KK-graviton) [1] *and spin-0 (radion)* [2] *resonances*.
  Different phenomenology if SM particles are allowed (bulk RS) or not (RSI model) in the extra dimensional bulk.

➢ Searches for resonant di-Higgs production at LHC cover a wide resonance mass range. Above 1 TeV performed on bbbb channel only.

➢ Different analysis techniques depending on the mass region.

➢ Results usually compared with prediction from spin-2 and spin-0 scenarios.

[1] Goldberger-Wise mechanism
[2] Radion phenomenology, Csaba Csaki et al

SEARCHES

RESONANT | NON-RESONANT

di-Higgs searches can be performed looking at different final states

Considering the low production cross section,

one Higgs is mainly searched for in bb decay to exploit the higher branching ratio.

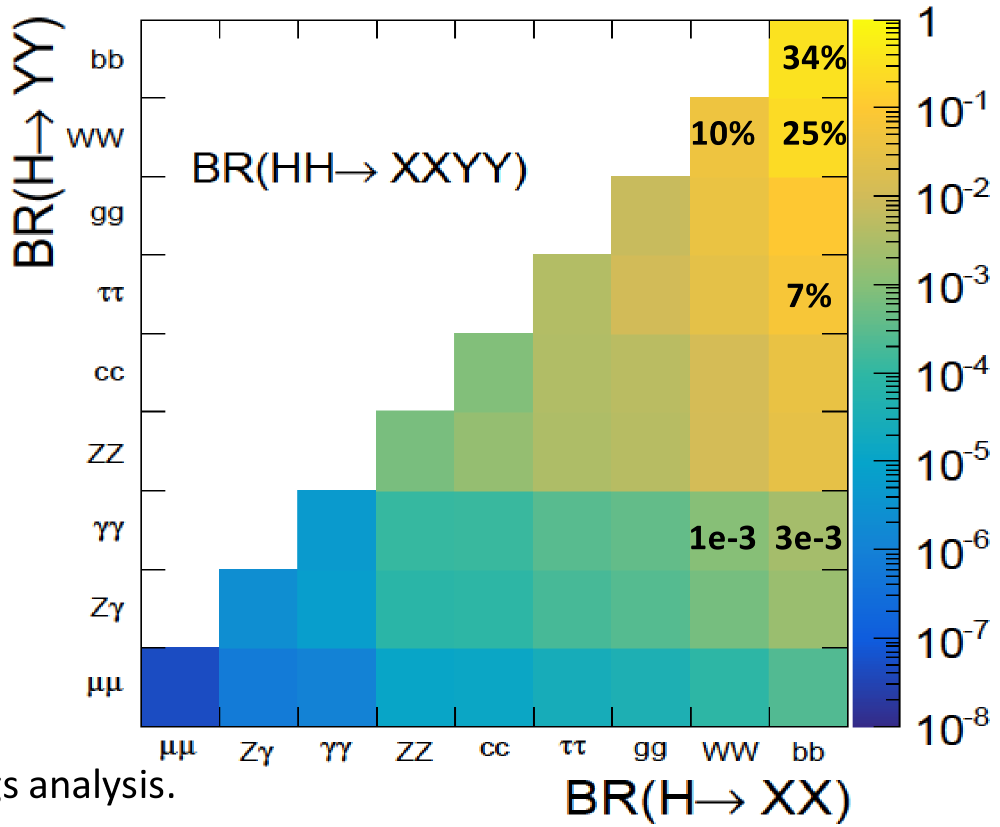
<u>**Four main decay channels**</u>**:**

- **bb bb** -> highest BR, high QCD/tt bkg
- **bb WW** -> high BR, large irreducible tt
- **bb ττ** -> relatively low background
- **bb γγ** -> high purity, very low BR

In addition:

- **γγ WW** -> studied by ATLAS.
- **WW WW** -> first studies done.

See Maosen Zhou's talk



All challenging searches →

'add' one more Higgs to 'standard' single Higgs analysis.

SEARCHES

RESONANT | NON-RESONANT

LHC Run1 (8 TeV, ~20 fb^{-1}):

	ATLAS resonant && non- res	CMS resonant	non- res
hh-> bbbb	10.1103/PhysRevD.92.092004	PLB 749 (2015) 560, arXiv:1602:08762	-
hh-> bbWW	-	-	-
hh-> bbττ	10.1103/PhysRevD.92.092004	PLB 755 (2016) 217, PAS-EXO-15-008, PAS-HIG-15-013	PAS-HIG-15-013
hh-> bbγγ	10.1103/PhysRevD.92.092004	arxiv:1603.06896	arxiv:1603.06896
hh-> γγWW	10.1103/PhysRevD.92.092004	-	-

- channels combination performed by Atlas producing: 10.1103/PhysRevD.92.092004.
- bbWW channel not exploited by any experiment in Run 1.
- BSM effects on non-resonant hh studied by CMS in bbγγ channel.

No excess observed for resonant searches,
upper limit set on SM non-resonant hh production:
best observed limit: ATLAS (hh->bbbb) > 63 X σ_{SM}

SEARCHES

RESONANT | NON-RESONANT

LHC Run2 (13 TeV):

	ATLAS resonant	ATLAS non- res	CMS resonant	CMS non- res
hh-> bbbb	arXiv:1606.04782* ATLAS-CONF-2016-049_***		CMS-PAS-HIG-16-002*, CMS-PAS-B2G-16-008*	CMS-PAS HIG-16- 026*
hh-> bbWW	-		CMS-PAS-HIG-16-011_*	CMS-PAS-HIG-16-024_*
hh-> bbττ	-		CMS-PAS-HIG-16-029_**	CMS-PAS-HIG-16-028_**
hh-> bbγγ	ATLAS-CONF-2016-004*		CMS-PAS HIG-16-032_*	
hh-> γγWW	ATLAS-CONF-2016-071_**		-	

* 2015 data (~ 3 fb^{-1})
** 2016 data (~ 13 fb^{-1})
*** 2015+2016 data combination (~ 13 fb^{-1})

New results:
Green -> shown at ICHEP2016
Red -> shown here for the first time

- Details of these analysis in next slides.

SEARCHES

LHC Run2 (13 TeV):

RESONANT
hh

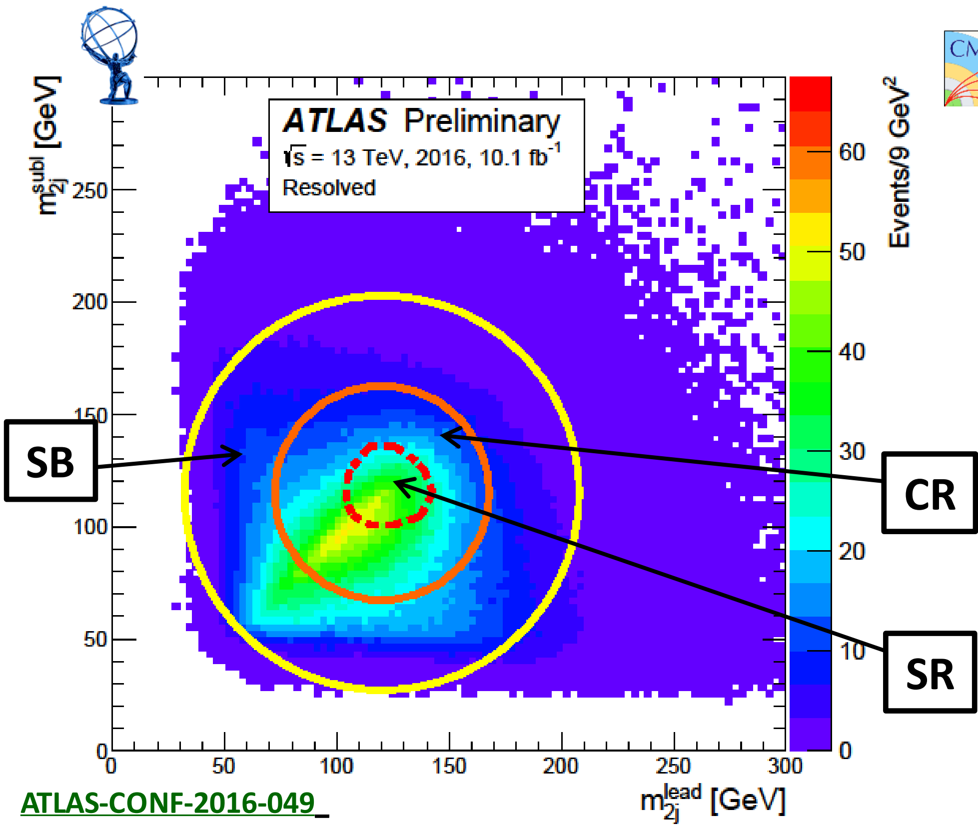
SEARCHES - hh>bbbb

RESONANT

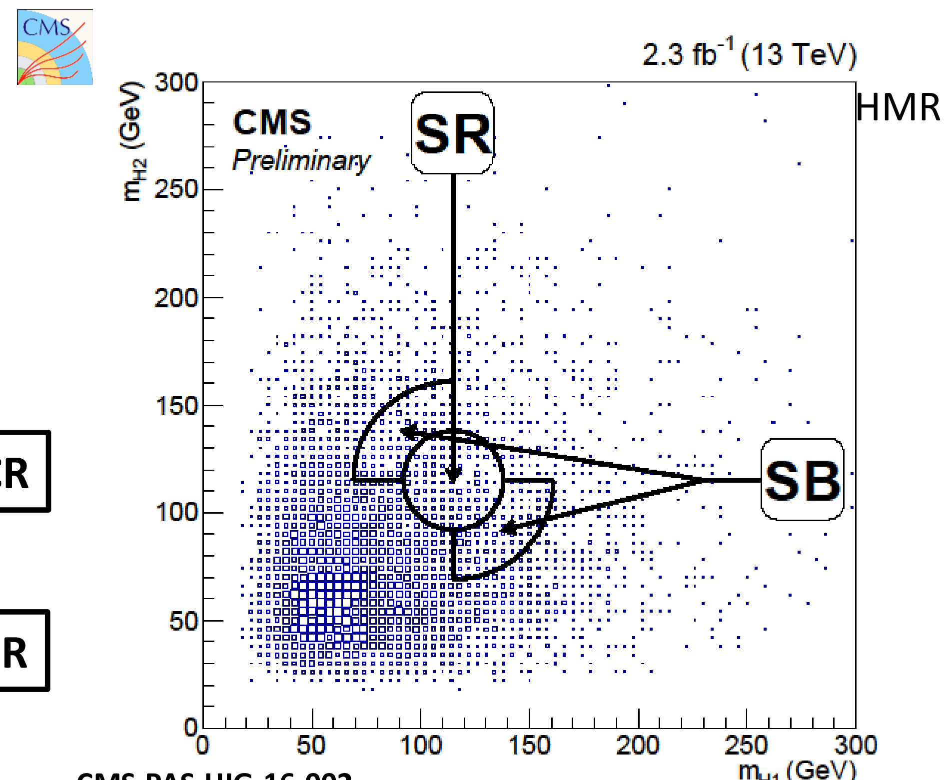
RESOLVED ANALYSIS:

- Resolve all decay products
- 2 strategy for CMS:
  Low mass (m_H<400 GeV) and
  High mass (m_H<1200 GeV) regions.

- Exploit b-tagging → off-line cut: >= 4 b-tagged jets per event.
  on-line cut: >= 2 (3) b-tagged anti-k_T R=0.4 jets for ATLAS (CMS)
- High QCD and tt contamination (2-10%).
- First 4 jets sorted in bTag + selection on jet/di-jet ΔR/Δm.
- Bkg shape extracted from sidebands on data in 2D mass plane (with request of >=2 b-tag for ATLAS).
- **Limit extraction on m_{4j} distribution.**



ATLAS-CONF-2016-049



CMS-PAS-HIG-16-002

SEARCHES - hh>bbbb

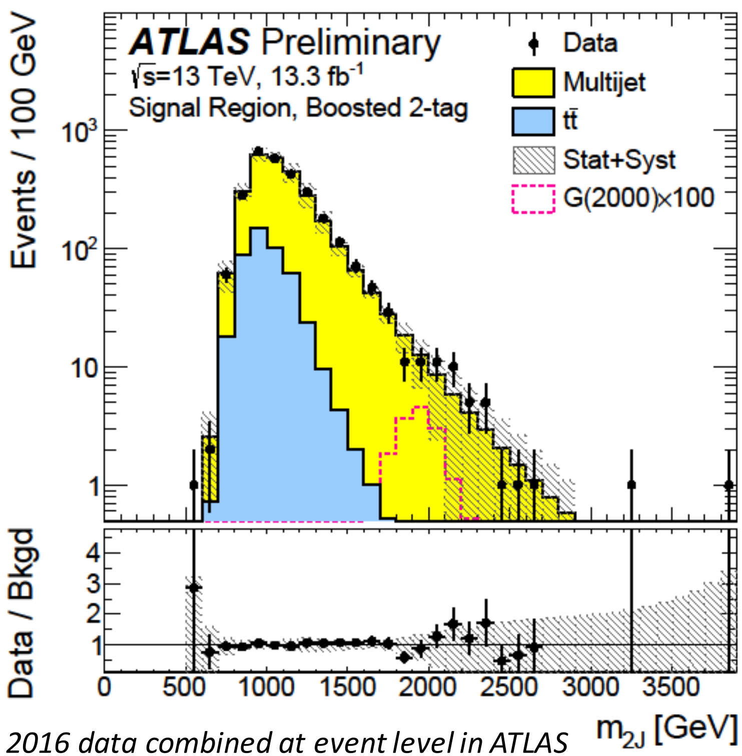
ATLAS-CONF-2016-049
CMS-PAS-B2G-16-008

RESONANT

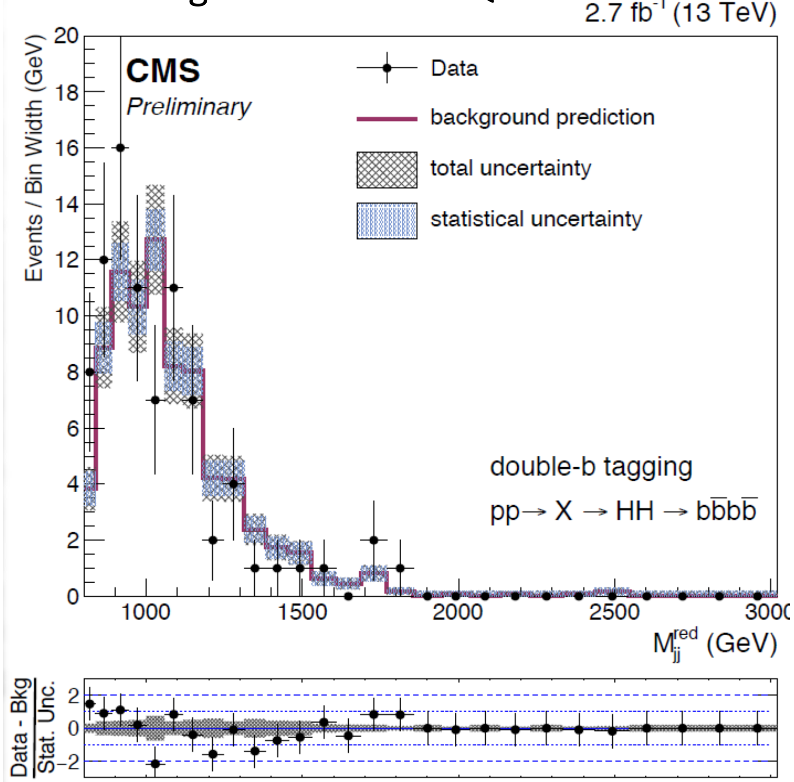
BOOSTED ANALYSIS:

- Optimised for higher mass (**m_{hh}>1TeV**) resonant hh.
- high-momentum Higgs bosons-> high boosted 2 b-jets are in a 'large' jet.
- Apply substructure techniques.
- Limit extracted on M of 2 'large' jets.

- *For CMS -> 2 complementary techinques:*
  double b-tagger: BDT from jet properties + bkg estimation from multiple sidebands.
  subjet b-tag: bkg fit + 3 categories based on number of b-tagged sub-jets.
- *For ATLAS ->*
  >=2 anti-k_t jet (R=0.1) with p_T>250 per event
  >=1 b-tagged anti-k_t jet (R=0.2) 'inside' each large jet
  data-driven bkg extraction for QCD and tt in sidebands.



2015 and 2016 data combined at event level in ATLAS



SEARCHES - hh>bbbb

ATLAS-CONF-2016-049
CMS-PAS-HIG-16-002
CMS-PAS-B2G-16-008

RESONANT

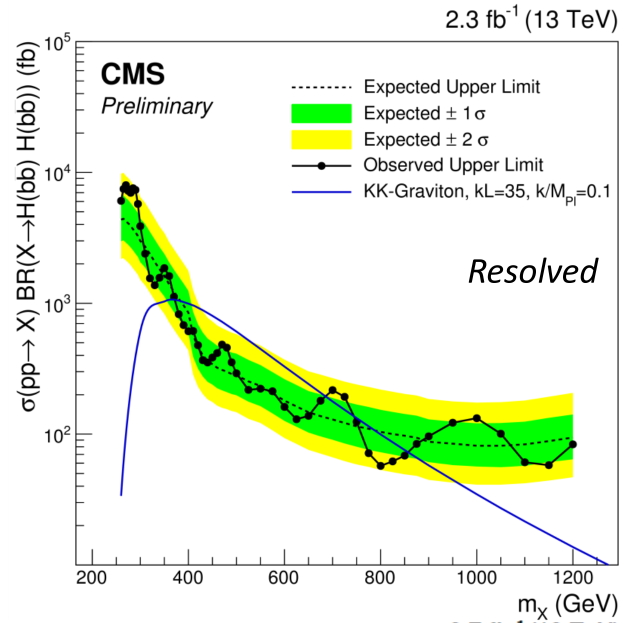
Unique channel which covers mass range above 1TeV.
No evidence of new resonance over large mass range.

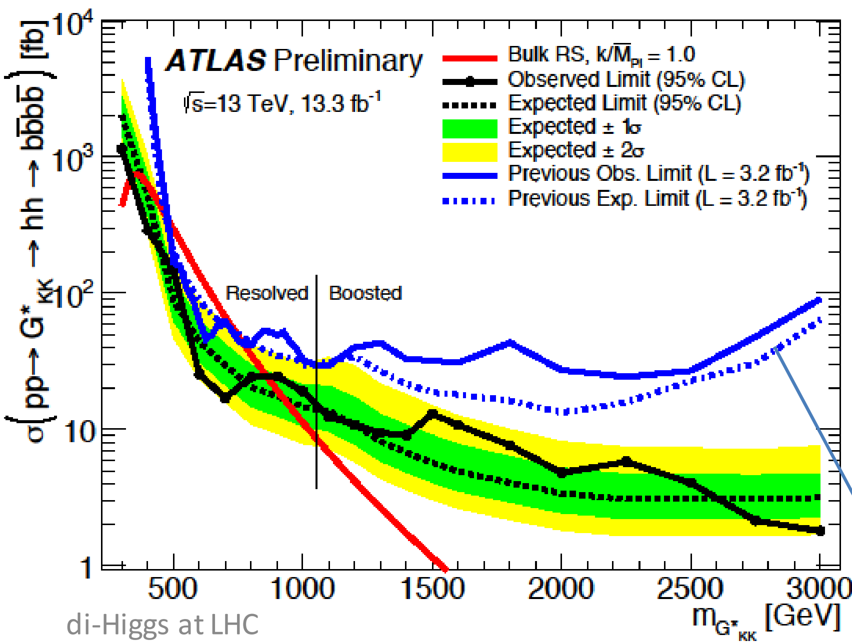
***Exclusion** at 95% CL :*

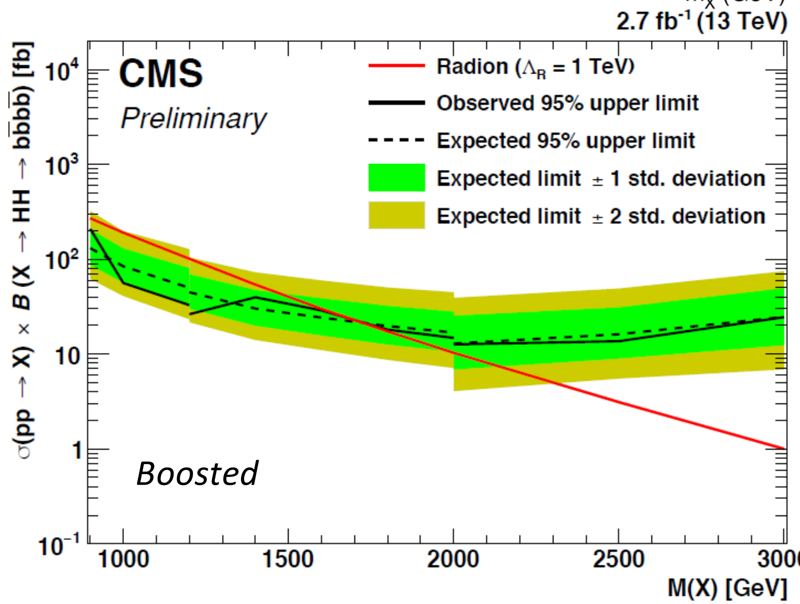
CMS: $1000 < M_H < 1720$ GeV for Radion (Λ_R = 1 TeV) -boosted.
$350 < M_H < 725$ GeV and $M_H > 850$ GeV for Graviton.

ATLAS: $360 < M_H < 869$ GeV for Radion.

CMS on 2015 data, ATLAS on 2015+2016 data.







With 2015 data

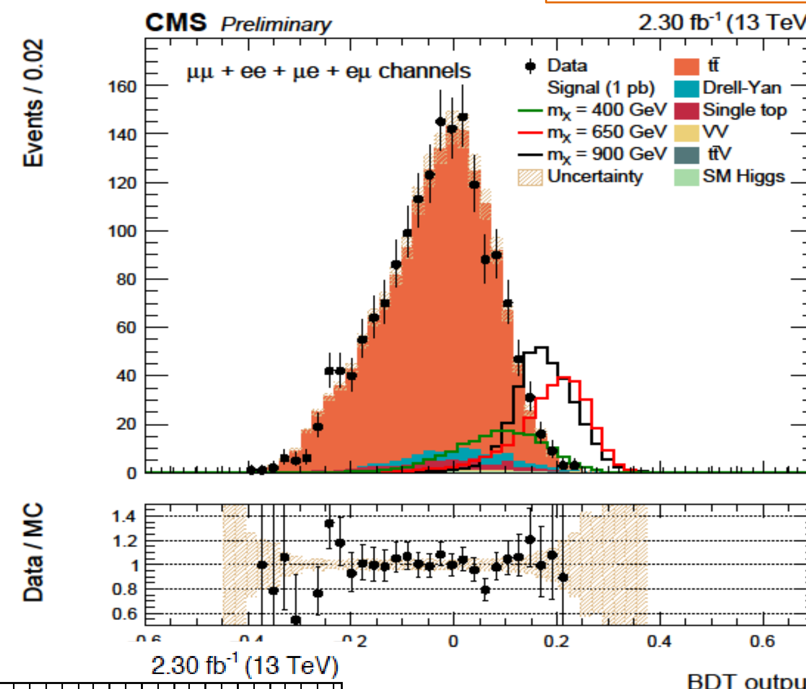
RESONANT

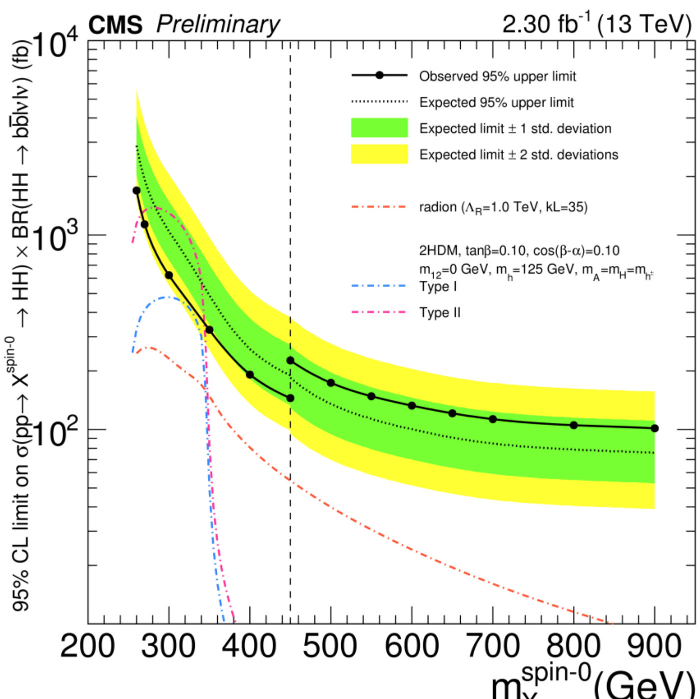
SEARCHES – hh>bbWW

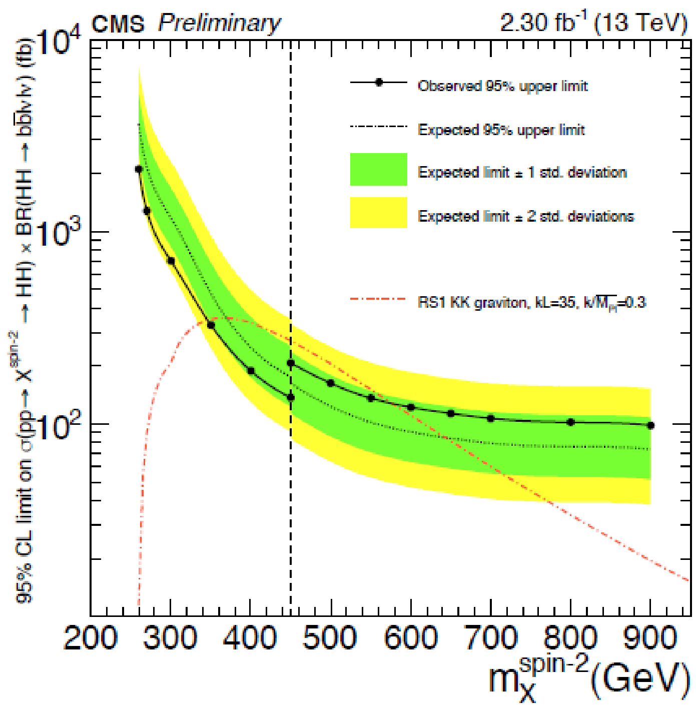
IN THIS CHANNEL CMS SEARCHES ONLY.

Search for hh→bbWW→bb2l2ν

- 2 isolated OS leptons + 2 b-jets in the final state
- Cuts on m_z-m_{ll}, ΔR_{ll}, ΔR_{jj}, $\Delta\Phi_{lljj}$.
- Main backgrounds: tt, DY, single top
- 2 BDT discriminants low (m_H<450) and high (m_H >450) mass trained on MC bkgs.
- **Cut&count experiment**
- 4 categories: (m_{bb}-peak, m_{bb}-SB) x (low BDT, high BDT).







Exclusions:
Spin-2 RS1
KK-graviton
m_H < 600 GeV

CMS-PAS-HIG-16-011

SEARCHES – hh>bbττ

CMS-PAS-HIG-16-029

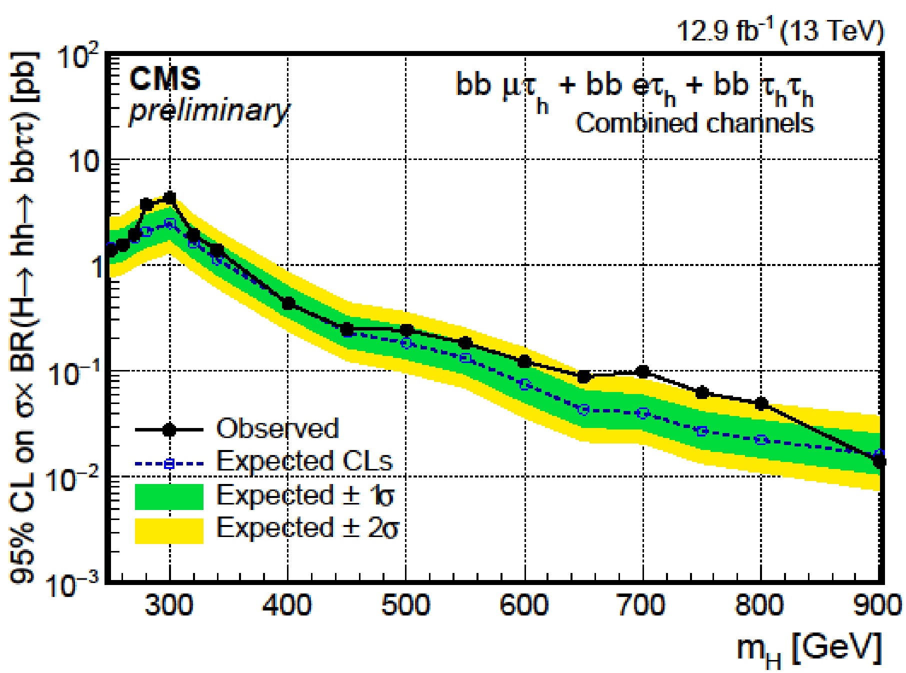
RESONANT

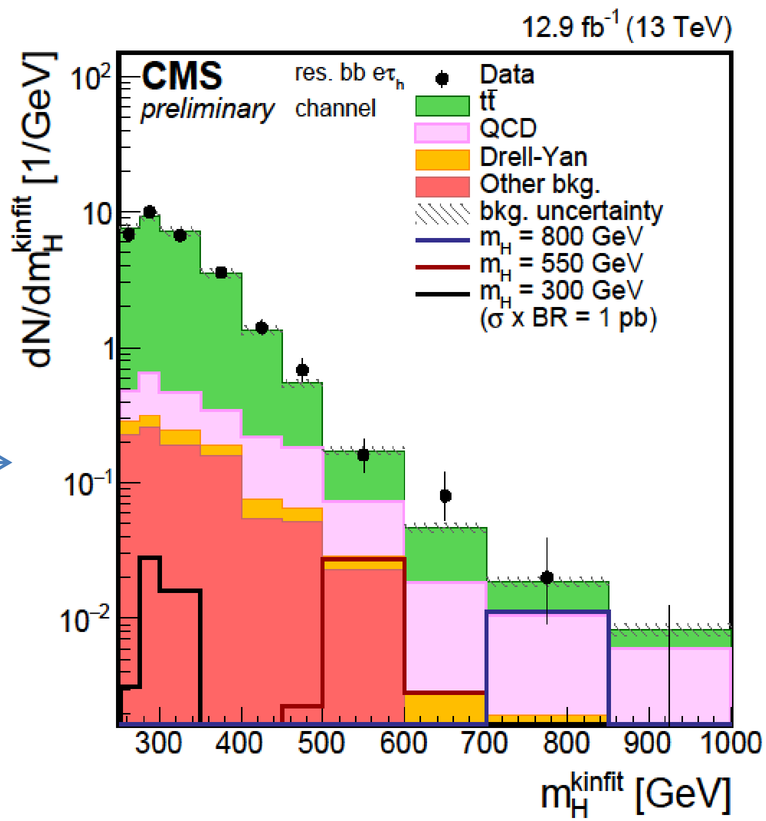
IN THIS CHANNEL IN RUN2, CMS SEARCHES ONLY.

3 final states: $e\tau_H$, $\mu\tau_H$, $\tau_H\tau_H$

- Final state: $1\tau_H$ + 1 isolated leptons (e, μ, τ_H) + 2 b-jets
- Main bkgs: $t\bar{t}$ (from MC),
  QCD multijet (from data in control regions).
- BDT to enrich signal region.

- **Limit extraction on kinematic fit of the resonant m_H**
- 3 categories: 1b-jet, 2 b-jet, boosted b-jets category.





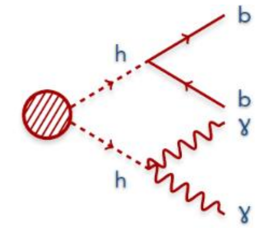
- Range of m_H up to 900 GeV covered.
- No significant excess.
- Improvement wrt Run1 limits.
- Th. interpretation not computed yet.

Results on 2016 datasets.

SEARCHES – hh>bbγγ

ATLAS-CONF-2016-004
CMS-PAS HIG-16-032

RESONANT



- Lowest BR among all channels, but excellent resolution on $m_{\gamma\gamma}$

Main backgrounds:

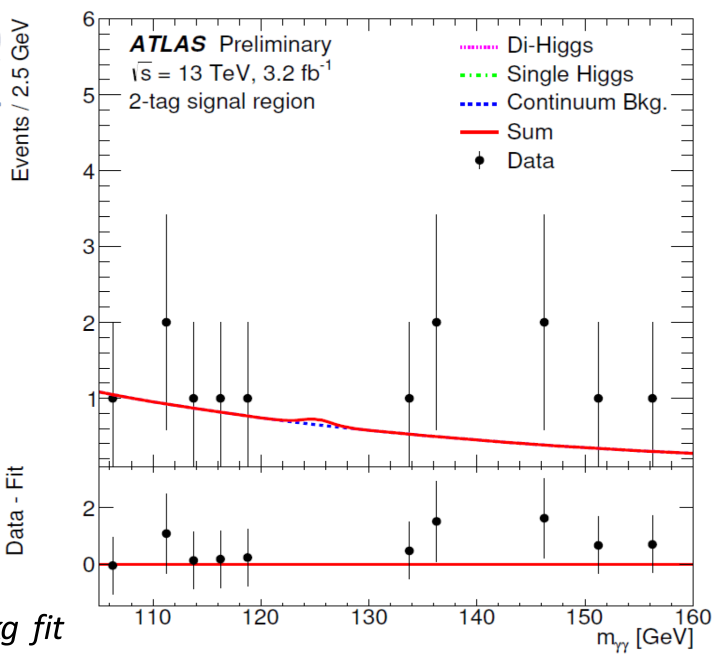
- SM γγ+Jets production
- SM γ+Jets (one jet identified as a photon)
- Multijet (two jets identified as photons)

Similar event selection both for CMS and ATLAS ->

Accordingly to signal hypothesis, select mass window in M(jjγγ) around resonance mass.
Two categories based on b-tagging (one for high mass region).

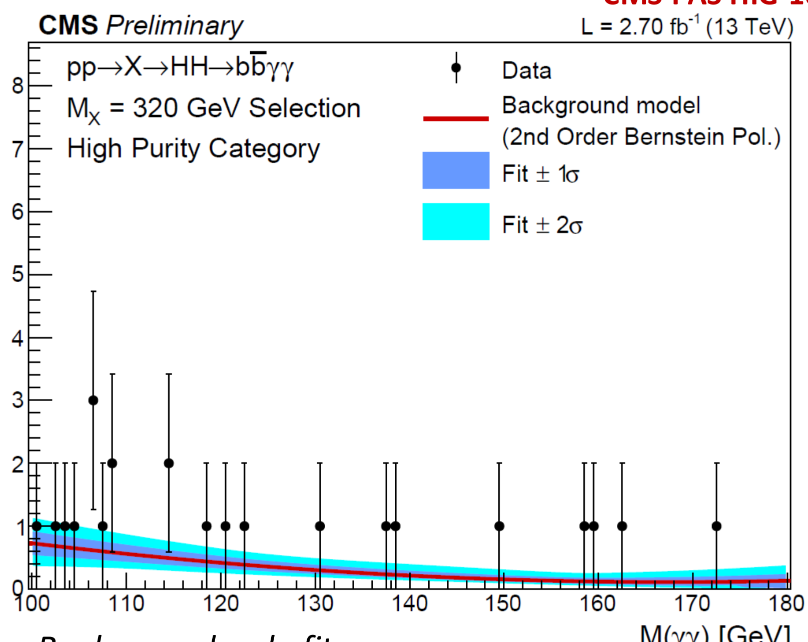
Different Signal Extraction -> **2D unbinned fit in m_{jj} and $m_{\gamma\gamma}$ for CMS → selection on m_H region**
Counting experiment with fit on $m_{\gamma\gamma}$ for ATLAS.

ATLAS-CONF-2016-004



Sig+Bkg fit

CMS-PAS HIG-16-032



Background-only fit

SEARCHES – hh>bbγγ

RESONANT

- ATLAS search stop at low mass regime.
- CMS search divided into low and high mass regime with different b-tag categorization.

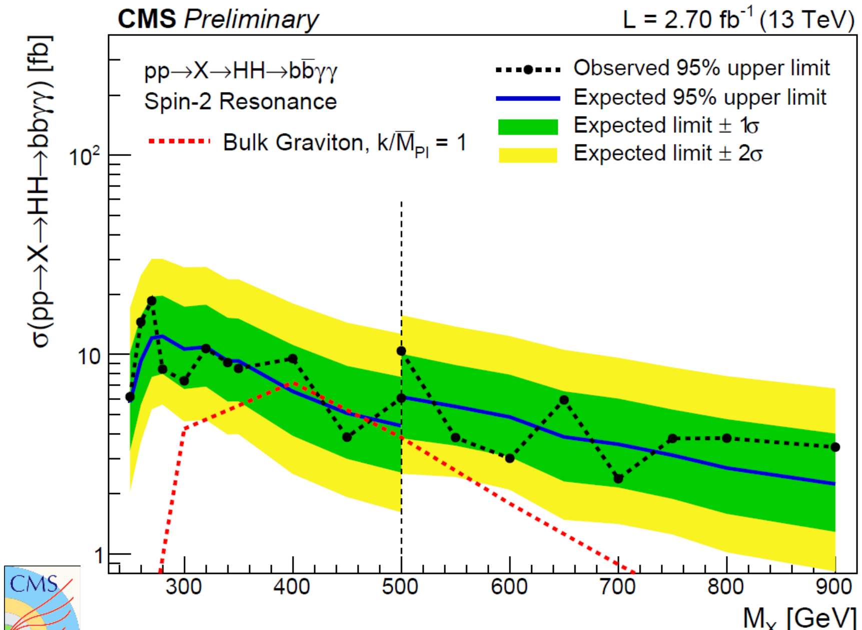
No significant excess in both CMS and ATLAS.

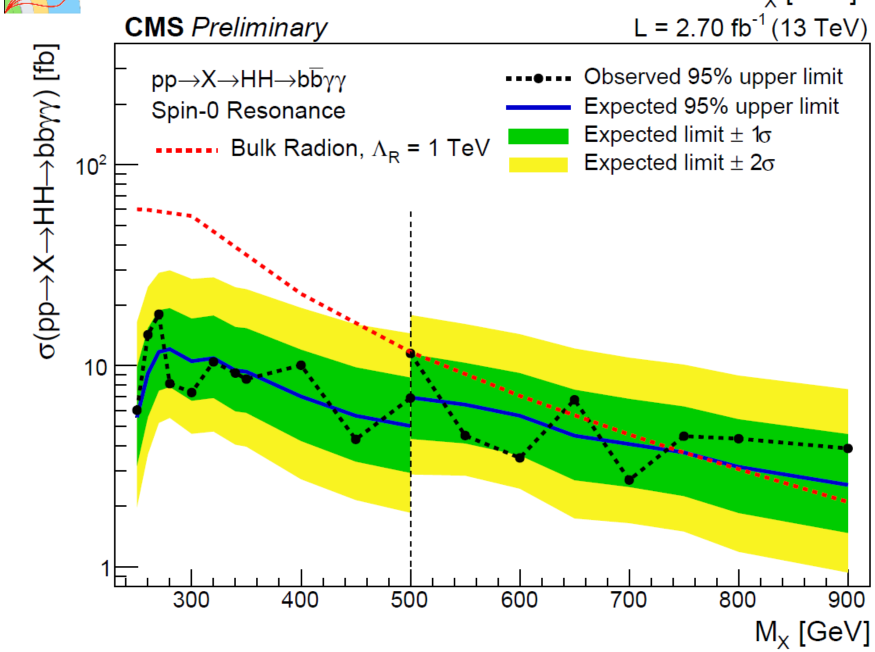
Exclusions at 95%:

CMS-> Spin-0 Radion below 750 GeV (except 650 GeV vicinity)

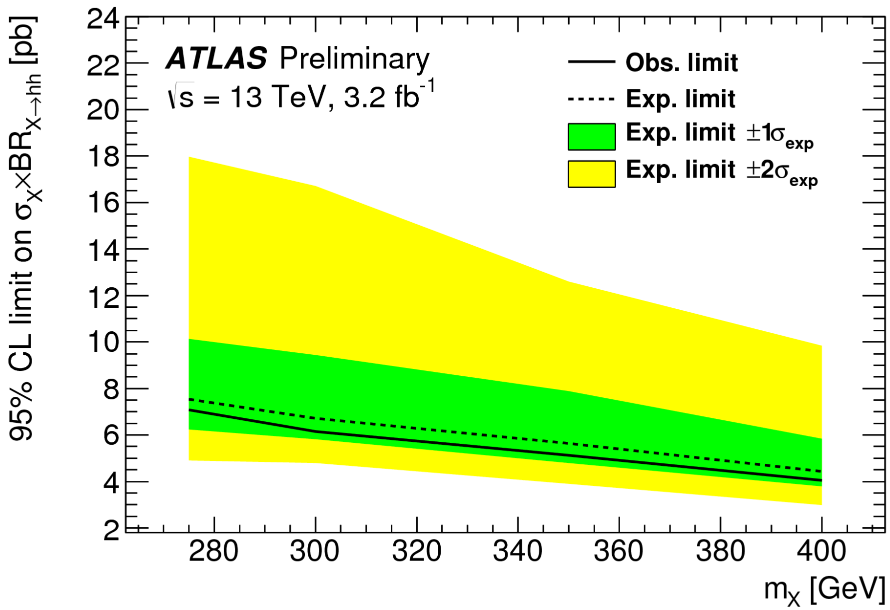
Atlas-> no th interpretation

CMS-PAS HIG-16-032





ATLAS-CONF-2016-004



SEARCHES – hh>γγWW

ATLAS-CONF-2016-071

See Qi Li's talk this afternoon

RESONANT

IN THIS CHANNEL ATLAS SEARCHES ONLY.

Large h->WW BR -- Clean h-> signature

Final state γγlνqq'

- Events with 2 photons, at least 2 jets and no b-jet
- 105 GeV< $m_{\gamma\gamma}$ < 160 GeV

Signal Region:

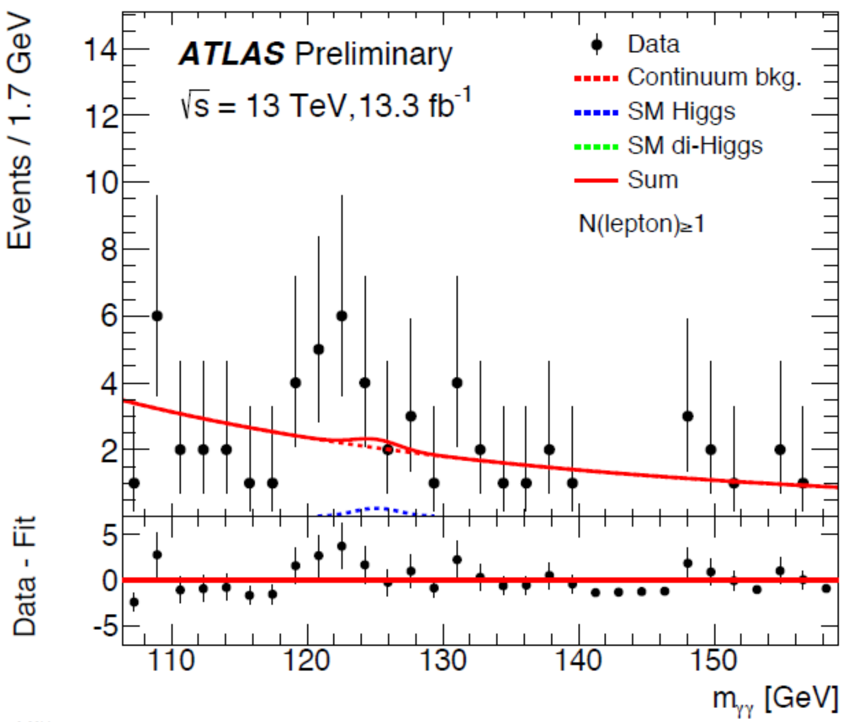
- One lepton region - requiring at least one lepton
- The diphoton mass $m_{\gamma\gamma}$ to be within a 2σ window of the Higgs boson mass ($\sigma_{\gamma\gamma}$ = 1.7 GeV)

Control Region:

- Zero lepton region - requiring no lepton

Side-Band Region:

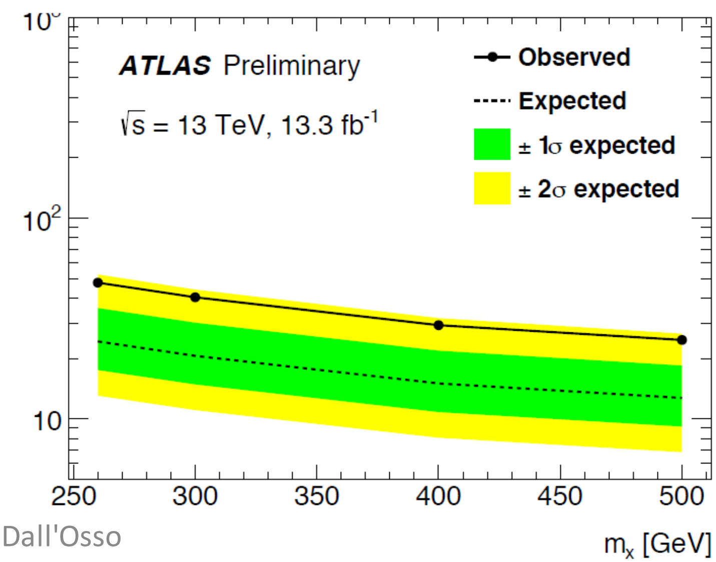
- Reversing the tight mass window in either the one-lepton region or the zero-lepton region
- Used for the data-driven estimation of the continuum diphoton background



Limits on σ(pp→X→hh)

47.7 pb (expected 24.3 pb) at m_X= 260 GeV

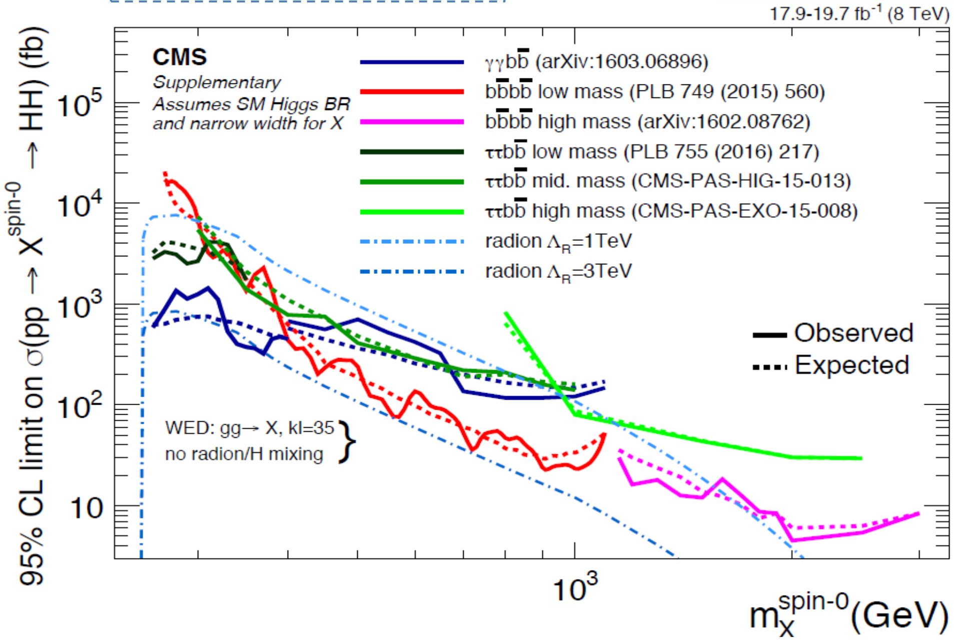
24.7 pb (expected 12.7 pb) at m_X = 500 GeV



SEARCHES – hh>ALL

LHC Run1 (8 TeV):

RESONANT

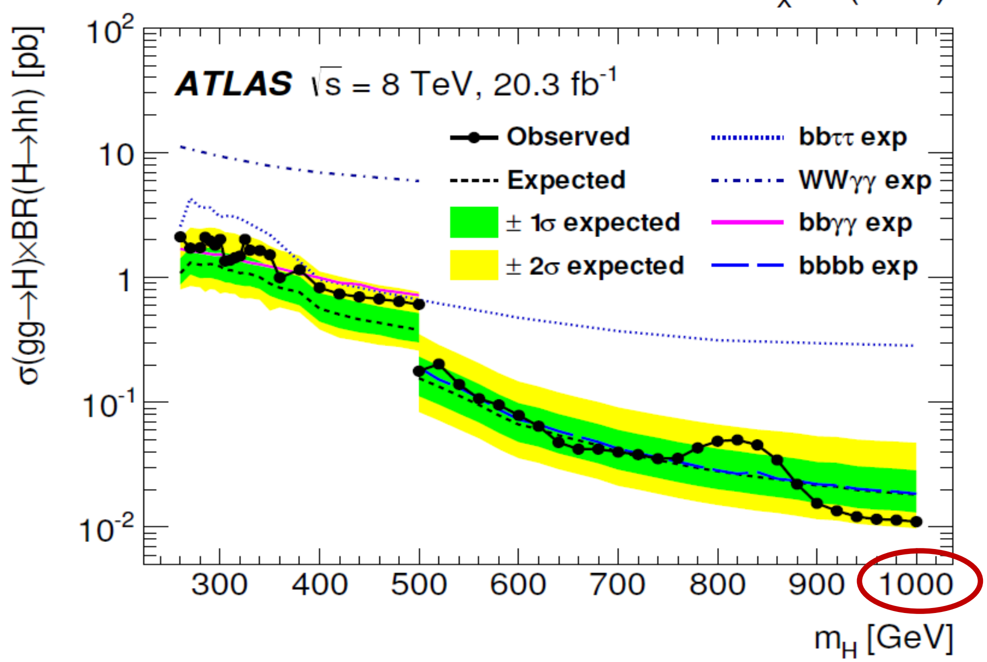


CMS -> Summary plot of limit on spin-0 resonant including all the results performed on 8 TeV:

- Coverage ranges from 2 x m_H to few TeVs.
- 4b channel provides tighter limit for high mass

ATLAS -> combination of all the analysis performed on 8TeV.

- Combination improves each single AN limit.
- No boosted regime in the combination. ATLAS search in hh->4b above 1 TeV also do not provide any excess.



SEARCHES – hh>ALL

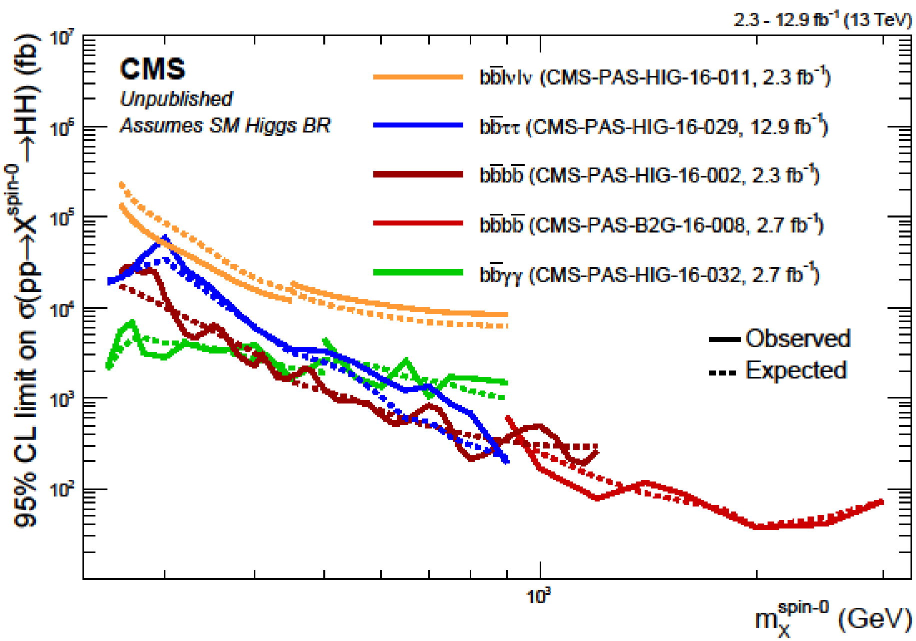
LHC Run2 (13 TeV):

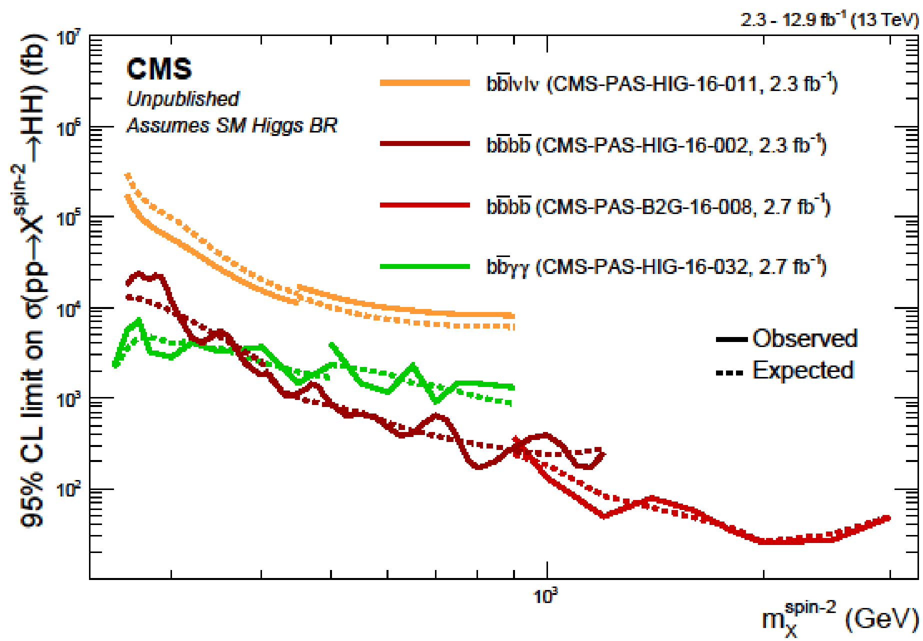
RESONANT

ATLAS -> no excess in each channel. No official combination yet.

CMS -> Summary plots including all the latest results:

- Range from 2 x m_H to few TeVs covered.
- hh->4b still provides best limit in a wide mass range.
- hh->bbγγ has strong power in low mass regions.





SEARCHES

LHC Run2 (13 TeV):

NON-RESONANT
hh

BSM non-resonant hh

NON-RESONANT

The non-resonant Higgs bosons pair is a golden channel to study the **Higgs potential.**

It allows to directly probe the Higgs trilinear coupling (λ_{hhh}). No sensitivity to measure SM λ_{hhh} in Run2.

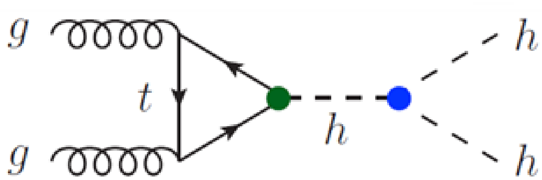
- Variation of λ_{hhh} wrt to SM value can be investigated with di-Higgs.
- A more general extension to **BSM effects** is modelled in EFT adding dim-6 operators[2].

The physics can be described with **5 parameters** following this Lagrangian: λ_{HHH} y_T C_2 C_g C_{2g}

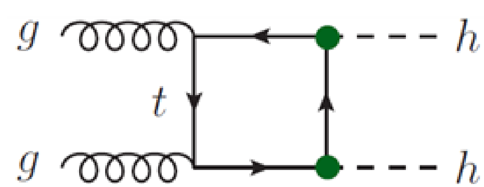
$$\mathcal{L}_h = \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{1}{2}m_h^2 h^2 - \boxed{\kappa_\lambda}\lambda_{SM} v h^3 - \frac{m_t}{v}\left(v + \boxed{\kappa_t} h + \boxed{\frac{c_2}{v}} h h\right)\left(\bar{t}_L t_R + h.c.\right) + \frac{1}{4}\frac{\alpha_s}{3\pi v}\left(\boxed{c_g} h - \boxed{\frac{c_{2g}}{2v}} h h\right) G^{\mu\nu} G_{\mu\nu} .$$

where $k_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$; $k_t = y_T/y_T^{SM}$;
$\lambda_{SM} = m^2_H/(2v^2) = 0.129$.

SM processes:

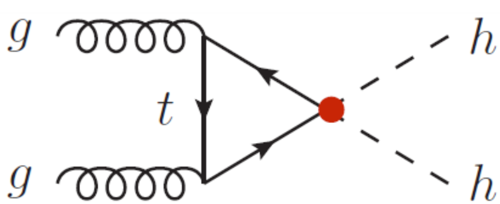


Tri-linear coupling

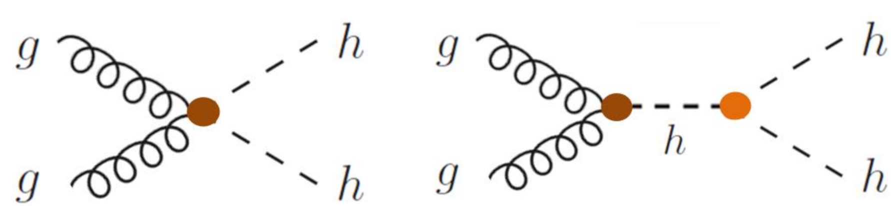


Yukawa interaction

BSM processes:



ttHH interaction



Higgs-gluon contact interactions

[2] *Phys. Rev.* **D91** (2015), no. 11, 115008

BSM non-resonant hh

NON-RESONANT

The previous parametrization leads to 5-dimensional space

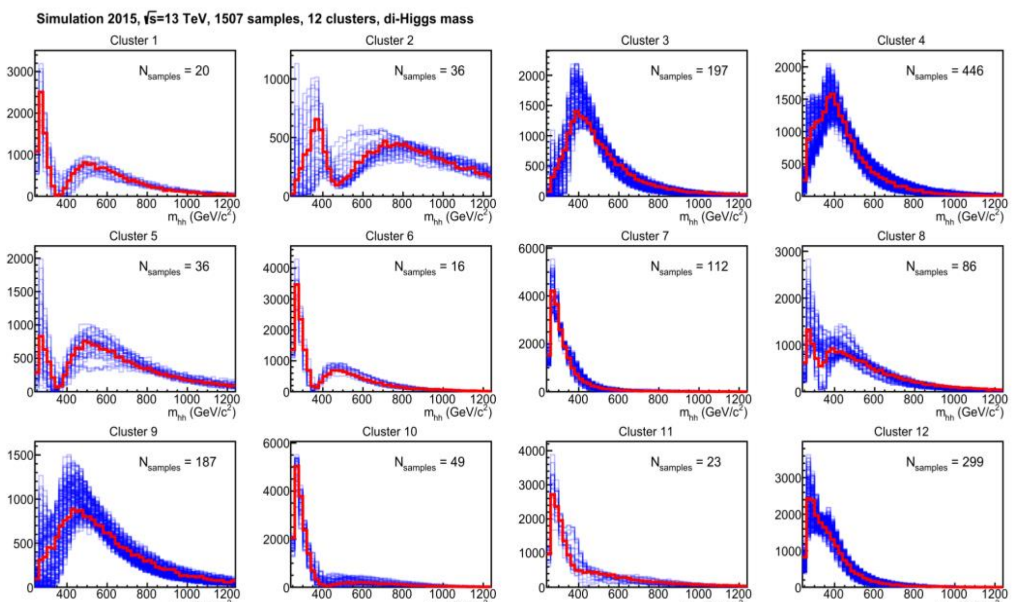
-> Need to identify benchmarks to be analyzed.

Variation of the 5 parameters (couplings) implies a variation of the di-higgs kinematics.

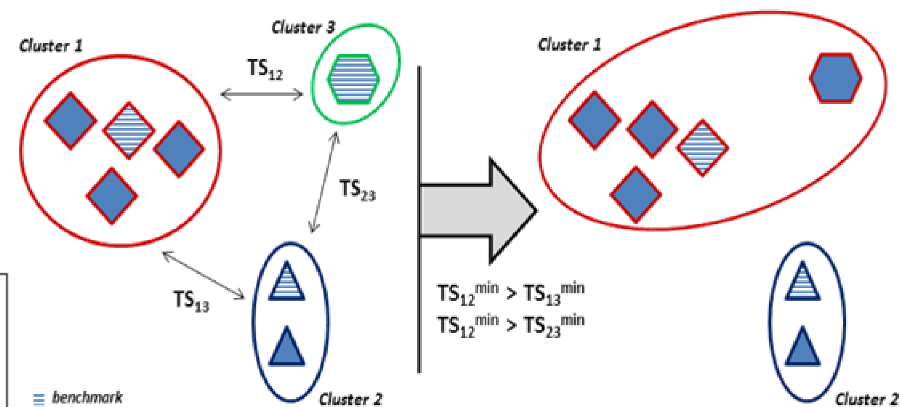
Developed a technique based on test statistic (TS) to group parameters space points and to identify benchmarks of each cluster based on final state kinematics.

Study performed on 1500 initial points:

- compute TS for each sample.
- use TS to group samples in clusters.
- iterate procedure to get 12 final clusters.



di-higgs mass for each cluster – red==benchmark



Run 2 CMS searches have been based on this parametrization.

Result published on JHEP and LHCXSWG note:

http://arxiv.org/abs/1507.02245

http://cds.cern.ch/record/2199287

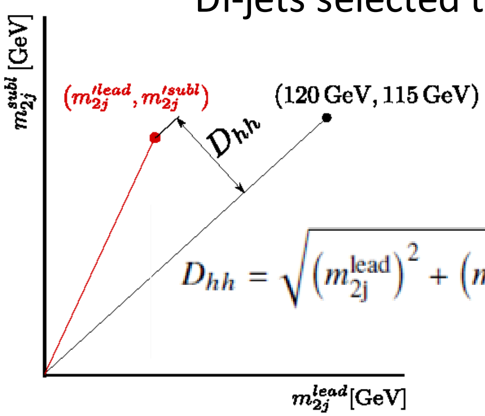
SEARCHES – hh>bbbb

NON-RESONANT

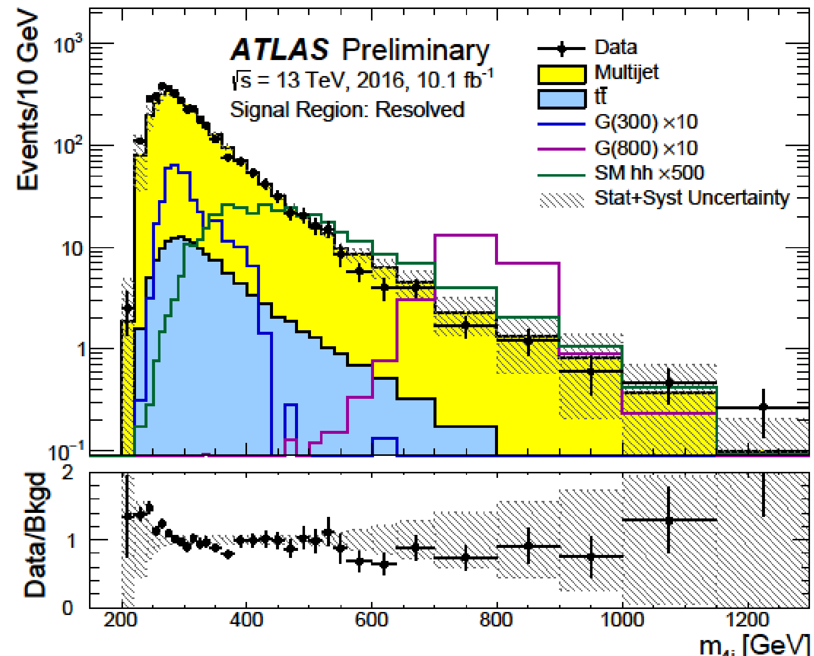
- *In hh->bbbb channel studied only the SM production so far.*
  - First CMS result in this channel approved yesterday.
  - Tighten upper limit set by Atlas looking at 2015+2016 data.

ATLAS -> same analysis strategy of the low mass resonant hh search.

Peculiar jets selection looking at jets ΔR:
requirement on ΔR_{jj} as a function of m_{4j} value.
Di-jets selected to minimise distandce D_{hh}:



$$D_{hh} = \sqrt{\left(m_{2j}^{\text{lead}}\right)^2 + \left(m_{2j}^{\text{subl}}\right)^2}\left|\sin\left(\tan^{-1}\left(\frac{m_{2j}^{\text{subl}}}{m_{2j}^{\text{lead}}}\right) - \tan^{-1}\left(\frac{115}{120}\right)\right)\right|$$



Observed limit on 2015+2016 data:

σ(pp→hh→bbbb) < 330 fb to be compared with SM prediction = 11.3 fb

-> upper limit equal to 29 X σ_{SM}

ATLAS-CONF-2016-049

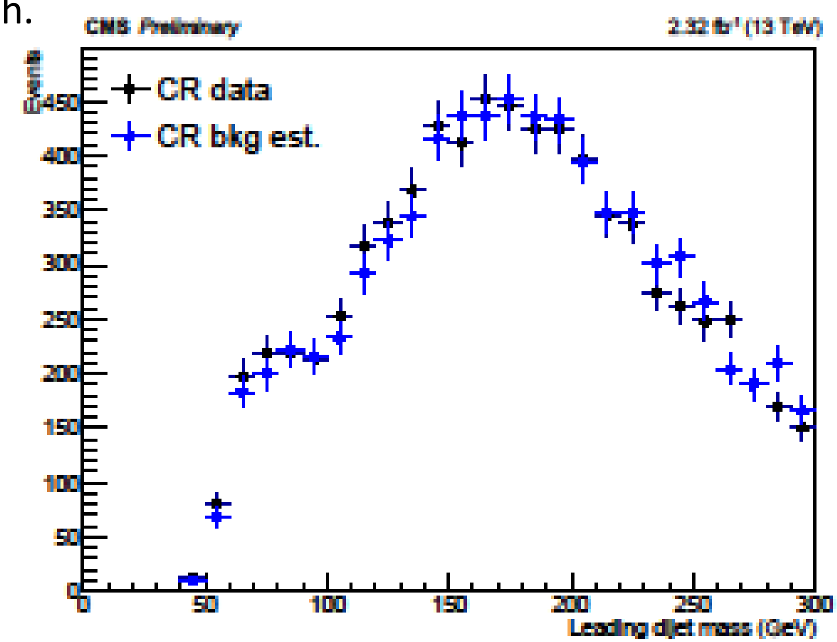
Sensible changes in the analysis strategy wrt 2015 data analysis -> Limit was 108 X σ_{SM}.

SEARCHES – hh>bbbb

CMS-PAS HIG-16- 026

NON-RESONANT

CMS -> dedicated analysis to the non-resonant search.
Preliminary result performed on 2015 data.



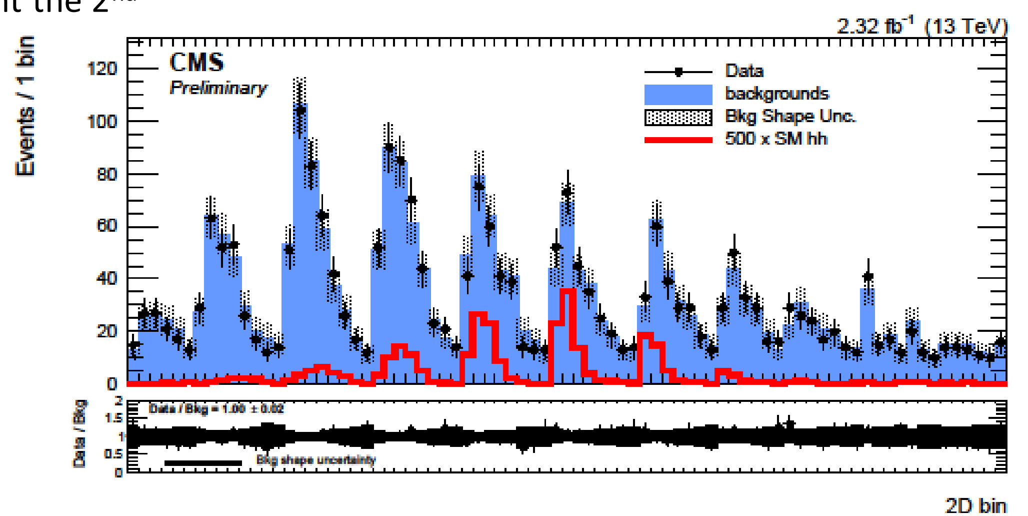
- Same trigger as resonant (3b-tag).
- First 4 jets sorted in b-tag.
- BDT trained on QCD and tt (di-jet kinematics).
- **2D fit in [m(bb), m(bb)] plane to extract the limit.**
- **Background extraction** based on data-driven method:
  hemisphere mixing technique
  -> *divide data events into two parts and get new events (bkg template) from them*

1. Fill hemisphere library from data dividing each events ⊥ to the transverse thrust axis (max of Σ p_T projections).
2. Create new events dataset choosing per each event the 2nd nearest neighbour* hemispheres from library.

Background shape well reproduced and not dependent on small signal contaminations.
→ no sidebands, extracted from whole 2D plane.

SM Observed (exp) limit on 2015 data:

σ(pp→hh→bbbb) < 3880 (3490) fb
-> equal to 342 X σ_{SM}



*kin variables: #jets, #b-tag, ΣpTcosθ, ΣpTsinθ, Σpz, hemisphere mass.

SEARCHES – hh>bbWW

CMS-PAS-HIG-16-024

NON-RESONANT

IN THIS CHANNEL CMS SEARCHES ONLY.

Search for hh→bbWW→bb2l2ν

- 2 isolated OS leptons + 2 b-jets in the final state
- Main backgrounds: tt, DY, single top

Differences wrt resonant search:

- 1 single BDT trained for non-resonant searches.
- **2D fit in [m(bb), BDT score] to extract the limits**

SM observed (exp) LIMIT:

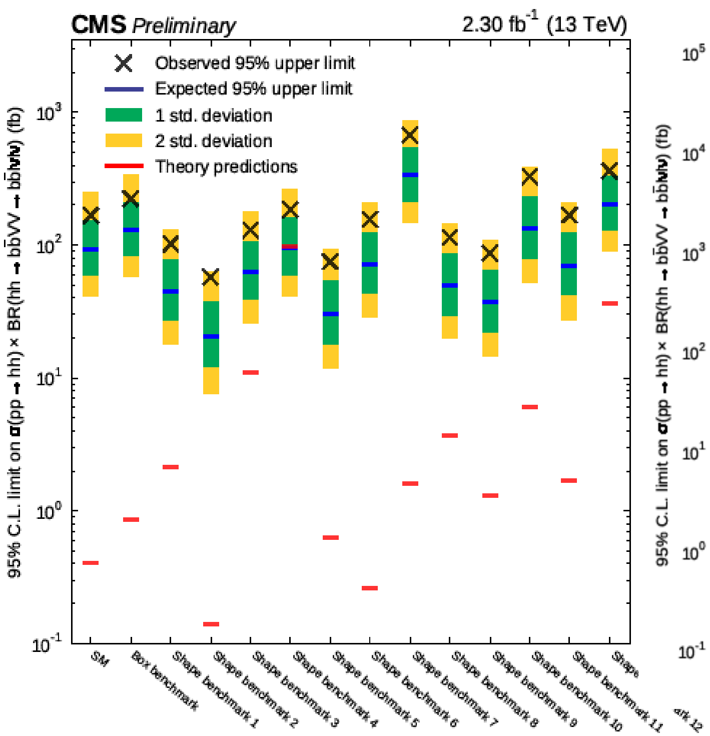
σ(pp→hh→bb2l2ν) < 166.7 (92.8) fb

-> equal to ~ 400 x σ_{SM}.

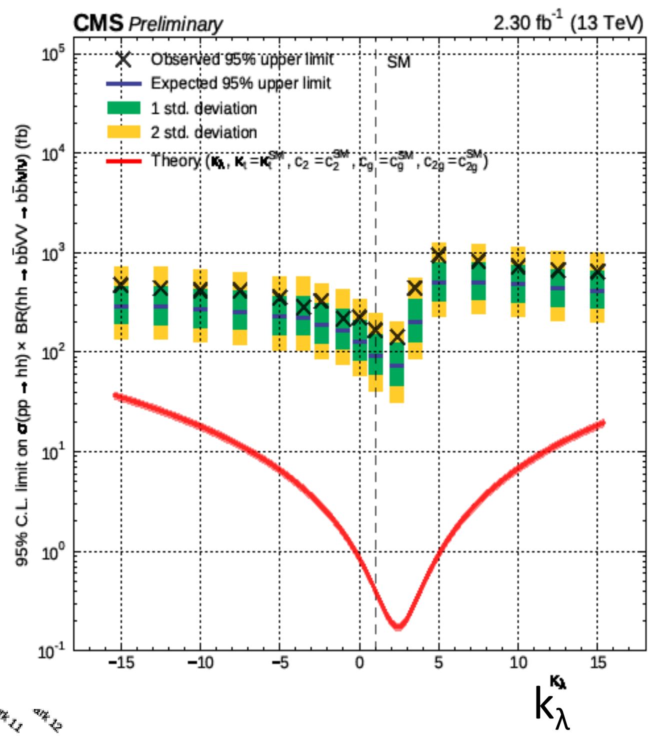
BSM SEARCHES:

Performed on 12 benchmarks and then extended to the 5-D parameter space →excl. limit in some k_λ k_t combinations.

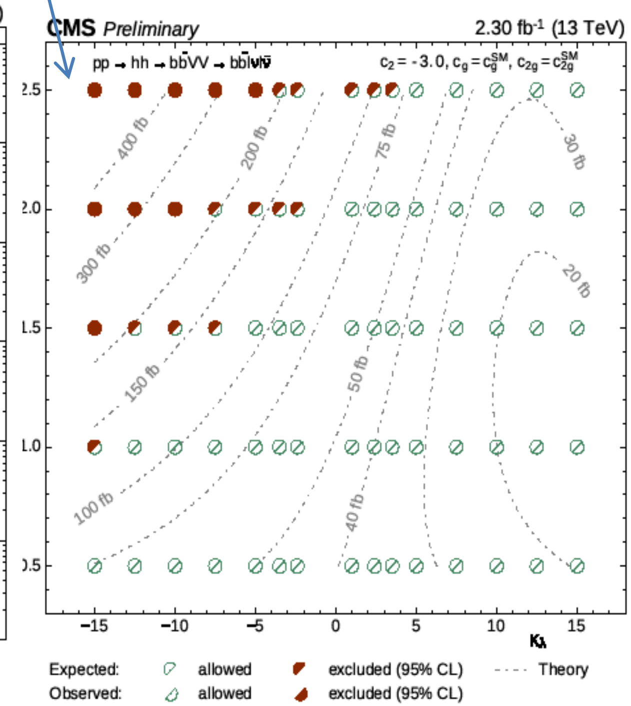
12 Benchmarks



Limit on different K_λ



Limit on K_λ K_t plane



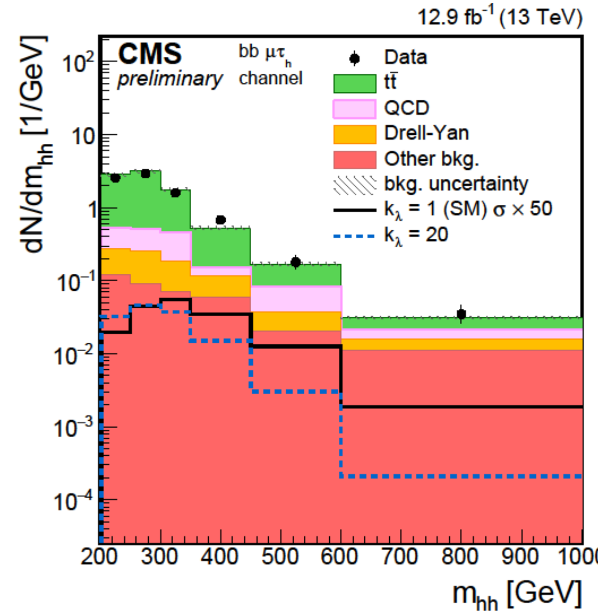
NON-RESONANT

SEARCHES – hh>bbττ

IN THIS CHANNEL IN RUN2, CMS SEARCHES ONLY.

3 final states: $e\tau_H$, $\mu\tau_H$, $\tau_H \tau_H$

- Final state: 1τ_H + 1 isolated leptons + 2 b-jets
- Main bkgs: tt (from MC),
  QCD multijet (from data in control regions).
- BDT discriminant to reduce tt, only angular information.
- BDT trained on the SM sample has good performances on BSM samples ($k_\lambda \neq 1$) too.
- limit extracted on four body mass.



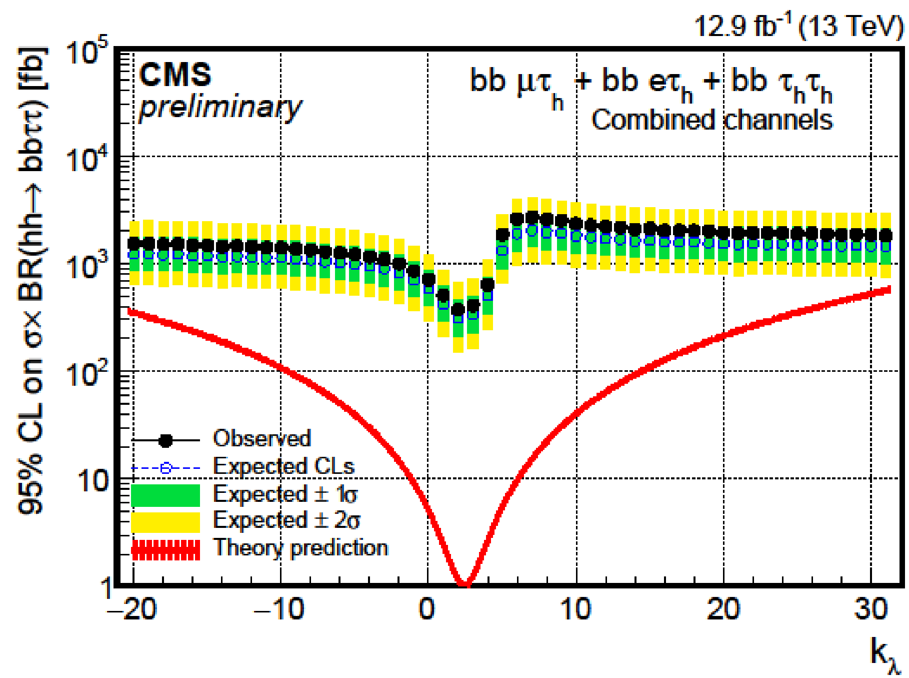
SM observed (exp) LIMIT:

σ(pp→hh→bbττ) < 508 (420) fb

-> equal to ~ 200 x σ_{SM}.

BSM SEARCHES:

- k_λ variations investigated (k_t, c_2, c_g, c_{2g} = SM value). Still not enough sensitivity.
- Extension to the 5-D parameter space will be performed soon.



Results on 2016 datasets.

CMS-PAS-HIG-16-028

SEARCHES – hh>bbγγ

NON-RESONANT

- Almost same strategy of resonant search for both ATLAS and CMS.

ATLAS - SM observed (exp) LIMIT:

σ(pp→hh→bbγγ) < 10 (14) fb

-> equal to ~ 115 x $\sigma_{SM.}$

ATLAS-CONF-2016-004

CMS - SM observed (exp) LIMIT:

σ(pp→hh→bbγγ) < 7.90 (7.85) fb

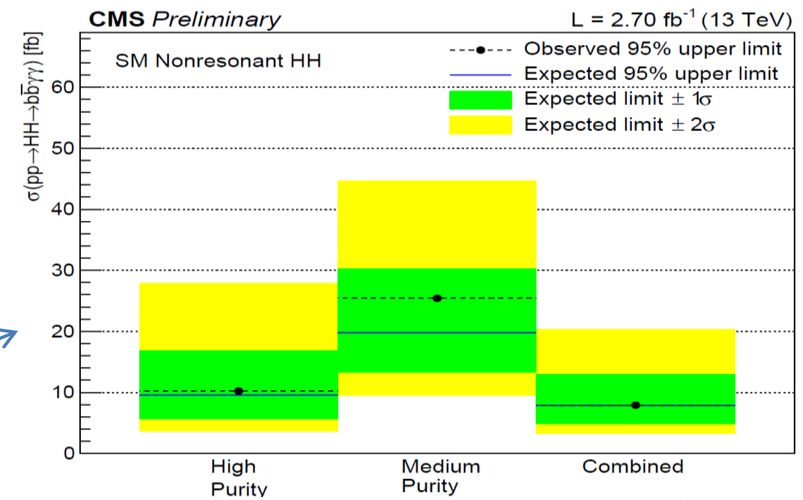
-> equal to ~ 91 x $\sigma_{SM.}$

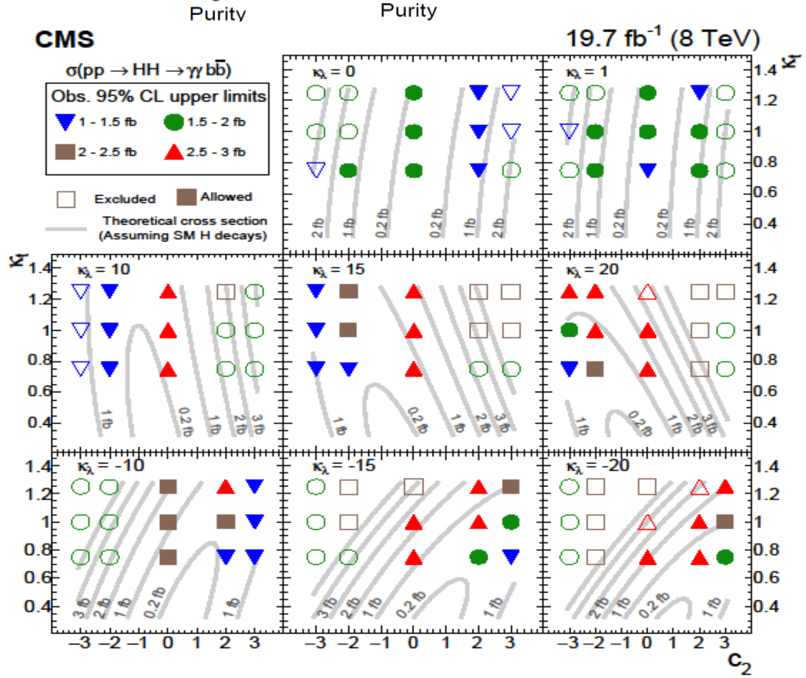
BSM SEARCHES:

- Interpretation with BSM samples still not performed on 13 TeV data.
- Previously done on 8 TeV data →exclusion limit set in some k_λ k_t combinations.

CMS-PAS HIG-16-032

arxiv:1603.06896 (8TeV)





RESULTS

LHC Run2 (13 TeV):

NON-RESONANT

SM – Observed upper limit on $\sigma(pp\to hh)_{SM}$ x BR:

	ATLAS SM	CMS SM	CMS BSM searches
hh-> bbbb	**29 X σ_{SM}** (13.3 fb^{-1})**	**342 X σ_{SM}** (2.32 fb^{-1})	-
hh-> bbWW	-	**410 X σ_{SM}** (2.3 fb^{-1})	DONE
hh-> bbττ	-	**200 X σ_{SM}** (12.9 fb^{-1}) **	DONE
hh-> bbγγ	**115 X σ_{SM}** (3.2 fb^{-1})	**91 X σ_{SM}** (2.7 fb^{-1})	DONE
hh-> γγWW	**700 X σ_{SM}** (13.3 fb^{-1}) **	-	-

Assuming $\sigma(pp\to hh)_{SM}$ =33.45 fb [1], values are indicatives for channels comparisons. ** 2016 data

[1] LHCHXSWG Yellow Report 4.

green -> shown at ICHEP2016
red -> shown here for the first time

- **No excess even in Run 2 searches.**
- Upper limits on SM prod. cross section extracted on 2015 data only are compatible with Run1.
- Result on hh->bbbb from ATLAS, based on 2016 data, set tighter limit on SM process.
- **CMS started searches to BSM effects**, looking at Higgs anomalous couplings.
  No excess seen but exclusion limit set to points of the parameters space,
  mainly on point with 'high' k_λ and k_t values -- far from 1 (SM).

PROSPECTS

CMS-FTR-15-002

What can we expect from HL-LHC (>2024)?

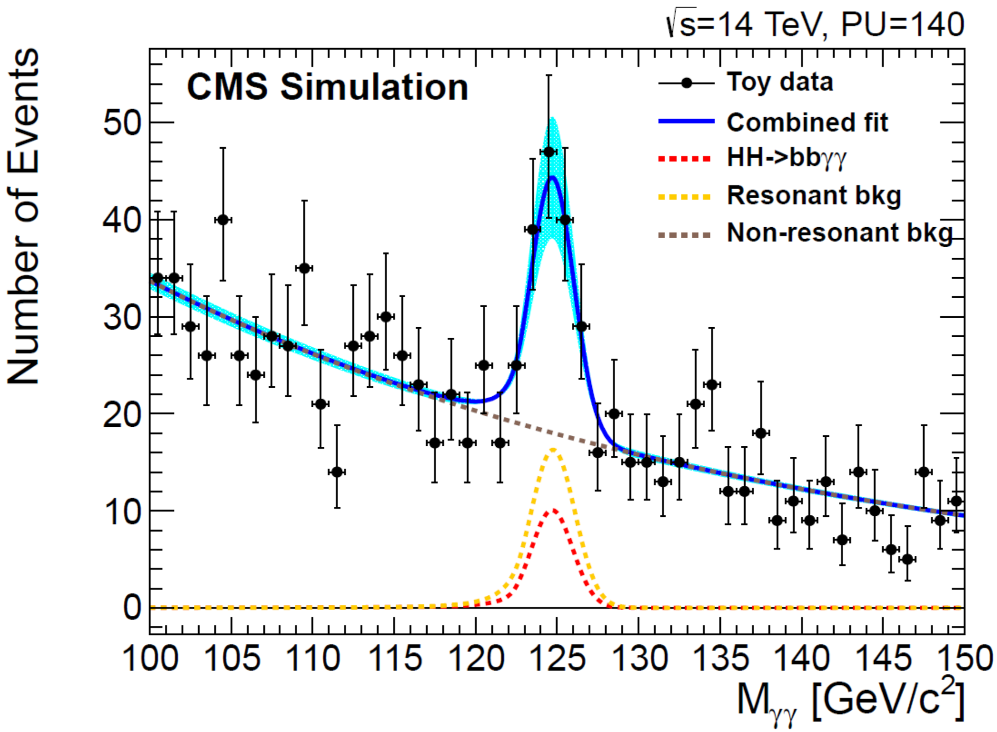
Main focus is on SM non-resonant production since most the BSM should be already constrained.

- **Study performed by CMS on bbττ, bbγγ and bbWW channels**

  HL-LHC operating condition assumed → 3000 fb^{-1}
  Delphes simulation used.
  Simplified Run1 analysis flow followed.
  Phase II Upgrade conditions included.

Combining **bbττ and bbγγ:** the expected significance for Higgs boson pair production is 1.9 standard deviation.

The bbbb final state promises the largest potential for improvement but still not investigated → waiting for first result on 13TeV data.



PROSPECTS

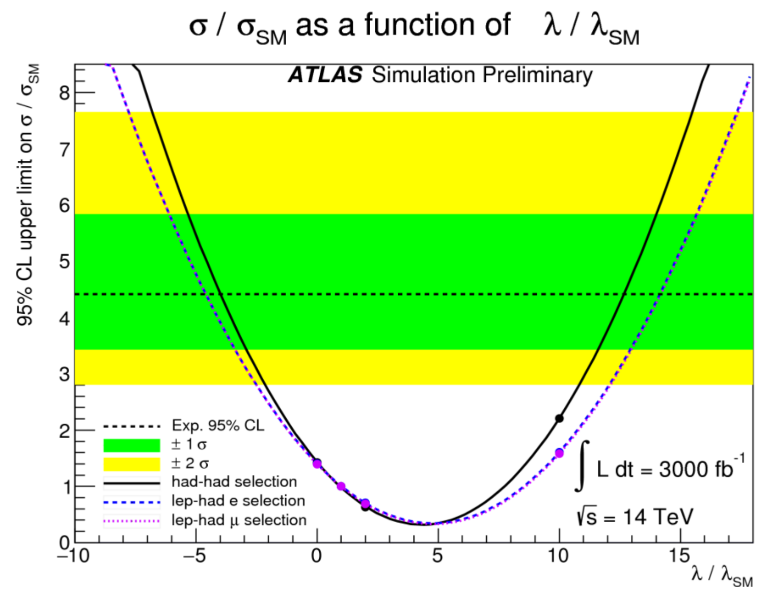
ATL-PHYS-PUB-2015-046
ATL-PHYS-PUB-2014-019

What can we expect from HL-LHC (>2024)?

HL-LHC operating condition assumed → 3000 fb^{-1}

- **bbττ channel:**
  Simple cut based analysis.
  Assuming SM background and SM signal,
  set an upper limit of the cross section for
  di-Higgs production of **4.3 x σ(hh->bbττ)** at 95% CL.

  BSM →using an effective Lagrangian
  for the Higgs potential,
  exclusion of k_λ<-4 and k_λ>12 *

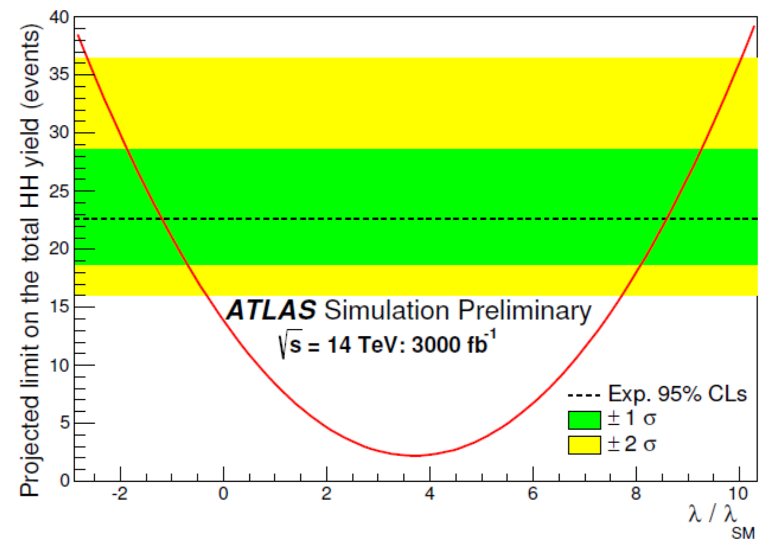


- **bbγγ channel:**

  Gen-level MC used. Simple cut based analysis.

  8 events expected → **significance = 1.3 std dev.**

  BSM → exclusion of k_λ<-1.3 and k_λ>8.7 *



j j j j, j j j, bc, b j j, ttH(→ bb), H(→ bb), H(→ bb) j, H(→ bb) j j,
fully hadronic *tt* decays, *Z*(→ *bb*), also considered but
almost zero events expected.

*different notation/parametrization wrt the one previously shown.

CONCLUSIONS

LHC Run 2:

- di-Higgs searches at LHC started to be an interesting topic.
- Several final states lead to competing analysis within each experiment and provide excellent coverage in different decay modes.
- SM process still not accessible but tight limit set by ATLAS with 2016 dataset.
- Higgs anomalous couplings -> 5-D parameter space. Developed a cluster technique to identify benchmarks. First exclusion limits set by CMS searches.
- No excess seen in BSM resonant di-Higgs searches.

Prospects:

- Considering current LHC performances, whole 2016 dataset will provide a strong improvements in each final state searches.
- Deep investigation of BSM effects on non-resonant hh production using Run2 data.
- Update of HL-LHC prediction is planned for ECFA based on 2015-2016 experience.

*see also DongMing Zhan's talk

Thank you

BACK-UP

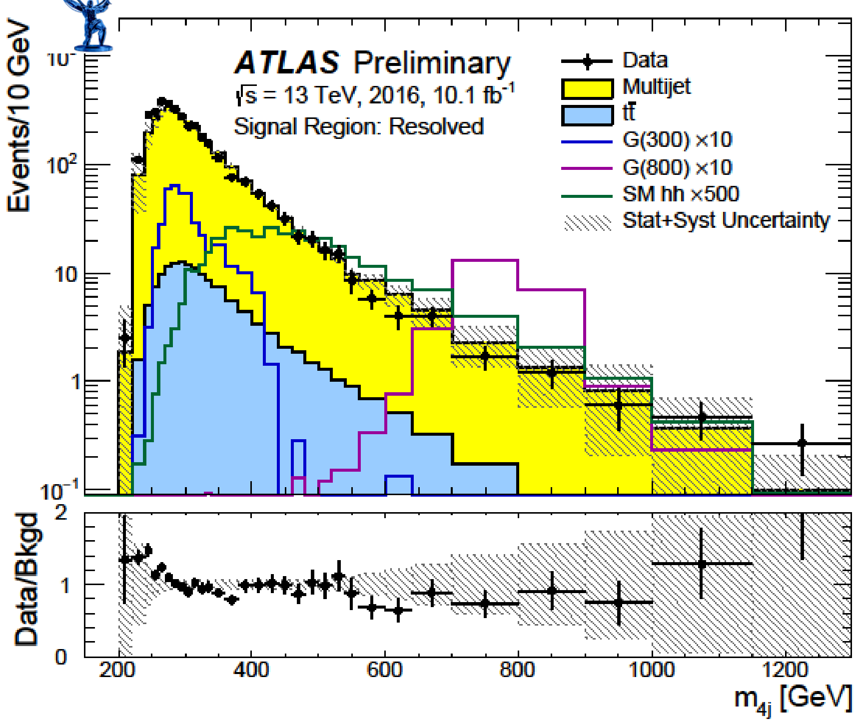
SEARCHES - hh>bbbb

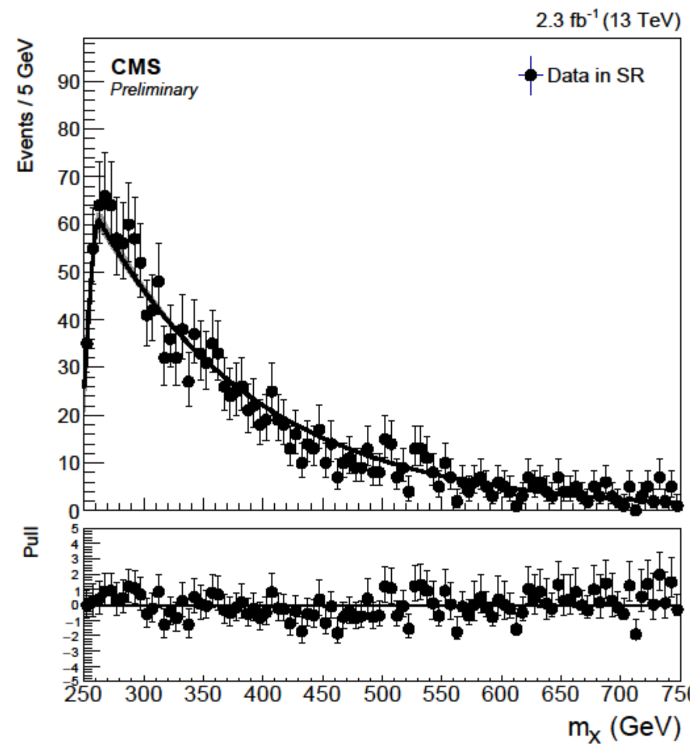
RESONANT

RESOLVED ANALYSIS:

- Resolve all decay products
- 2 strategy for CMS:
  Low mass (m_H<400 GeV) and
  High mass (m_H<1200 GeV) regions.

- Exploit b-tagging → off-line cut: >= 4 b-tagged jets per event.
  on-line cut: >= 2 (3) b-tagged anti-k_T R=0.4 jets for ATLAS (CMS)
- High QCD and tt contamination (2-10%).
- Additional selection on jet ΔR in ATLAS (see later).
- Bkg shape extracted from sidebands on data in 2D mass plane with request on 2 b-tag only.
- Limit extraction on m_{4j} distribution.





ATLAS-CONF-2016-049

CMS-PAS-HIG-16-002

SEARCHES - hh>bbbb

RESONANT

ATLAS – RESOLVED

Thanks to Tülin Varol @ICHEP2016

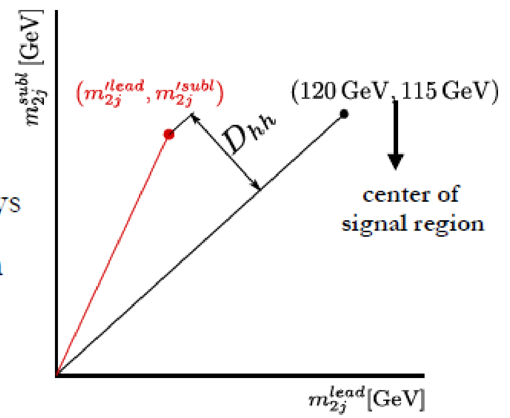
- *Large $h \rightarrow bb$ branching fraction*
- *High statistics control regions*
- *Suffers from large multi-jet background*

ATLAS-CONF-2016-049

RESOLVED ANALYSIS

- ***Optimised for non-resonant or low-mass hh systems***
- ***Resolve all decay products***

- **Four anti-kt jets with R=0.4 selected**
  - Each b-tagged (70% working point),
  - With $p_T > 30$ GeV and $|\eta| < 2.5$
- **Forming di-jets with selected jets**
  - Three possible ways to build two Higgs candidates out of the four jets
  - m_{4j}-dependent requirements applied on the Higgs candidate $\Delta R(j,j)$
  - Minimising the distance D_{hh}
  - (120 GeV, 115 GeV) - account for energy losses through semi-leptonic decays
    - Correspond to the median values of the narrowest intervals that contain 90% of the signal in simulation



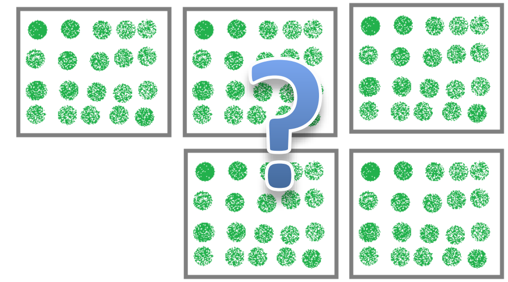
- **Mass dependent cuts as a function of m_{4j} applied on the three variables;** Leading and sub-leading Higgs candidate p_T & $|\Delta\eta_{hh}|$

$$D_{hh} = \sqrt{\left(m_{2j}^{\text{lead}}\right)^2 + \left(m_{2j}^{\text{subl}}\right)^2}\left|\sin\left(\tan^{-1}\left(\frac{m_{2j}^{\text{subl}}}{m_{2j}^{\text{lead}}}\right) - \tan^{-1}\left(\frac{115}{120}\right)\right)\right|$$

- **Vetoing events with $\Delta R(h,h) < 1.5$**

SEARCHES

BSM non-resonant hh
--- cluster analysis



2. Define a Test Statistic to identify kinematical similarities:

- A 2-D binned histogram created on m_{HH} and $\cos\theta^*$ (i == bin).
- If 2 samples share the same parent distribution, the likelihood function is the product over the bins of probability to observe $n_{i,1}$ and $n_{i,2}$ events (1,2 == samples).

→ product of two Poisson distributions (*P*P*) with estime: $\hat{\mu}_i = (n_{i,1} + n_{i,2})/2$

All information on samples diversity are contained in this binomial (factorized out from *P*P*):

$$Binomial(n_{i,1}/(n_{i,1}+n_{i,2})) = \frac{(n_{i,1}+n_{i,2})!}{n_{i,1}!n_{i,2}!}\left(\frac{1}{2}\right)^{n_{i,1}}\left(\frac{1}{2}\right)^{n_{i,2}}$$

Considering L_s the *Binom.* with sample1 = sample2 (*saturated hypothesis*), we got:

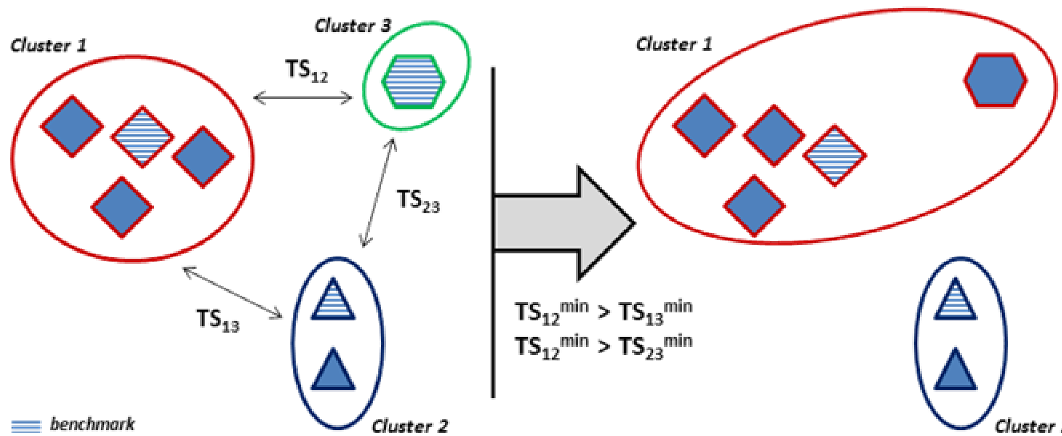
$$\boxed{TS = -2\,log\left(\frac{L}{L_S}\right) = 2\sum_{i=1}^{N_{bins}} log(n_{i,1}!) + log(n_{i,2}!) - 2log\left(\frac{n_{i,1}+n_{i,2}}{2}!\right)}$$

TS does not depend on the sample under test.

3. Clustering algorithm:

- TS used as distance parameter.
- Iterative procedure. →
- Unique free parameter:

    final number of clusters.



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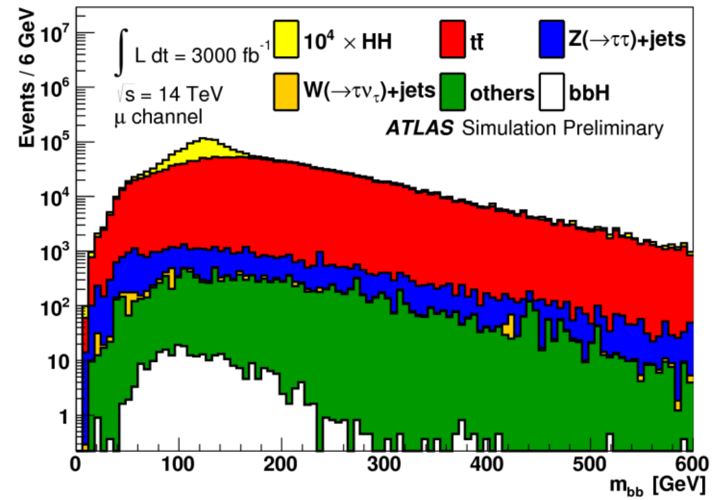
PROSPECTS

ATL-PHYS-PUB-2015-046
ATL-PHYS-PUB-2014-019

What can we expect from HL-LHC (>2024)?

HL-LHC operating condition assumed → 3000 fb^{-1}

- **bbττ channel:**



- **bbγγ channel:**