BSM Searches using Golden Gate of Higgs or di-Higgs

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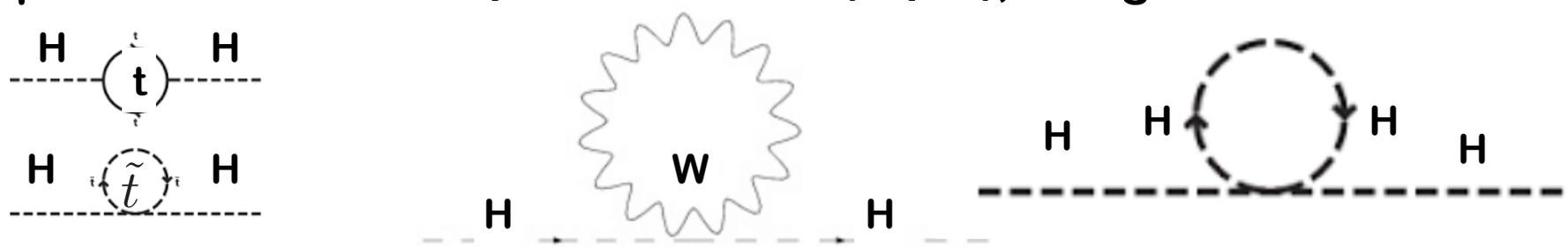
of behalf of the ATLAS and CMS Collaborations

11/11/2016

Run-2, new era for Physics?

- Impact of 125 H on our measurements and searches strategy?
- SM Higgs related measurements:
  - Measure everything: mass, width and BR to SM particles
  - Look for other decay channels and measure their BR
  - Measure its spin (angular distributions)…
- Exotics decays, does it couple to new particles??
  - ➡ Invisible Higgs ➔ (MonoX analyses..)
  - ➡ Higgs to Exotics objects, e.g. Hidden valley to dark photons (LLP or lepton jets)
  - ➡ Other Higgses? might (should?) be several (2HDM, triplet, MSSM, nMSSM)…
- As the Higgs acquires mass from loops of fermions (tops!), Gauge bosons and itself..



  - ➡ New physics may appear close to the Higgs mass
  - ➡ Look for new physics in top related, or diboson physics.
  - ➡ BSM Higgs (LFV..)
  - ➡ **Use higgs to search for BSM phenomena!**

BSM + Higgs tags new results (ICHEP++)

➡ Higgs in EXOT/SUSY cascades

- CMS EW prod. of charginos and neutralinos in the WH
- CMS SUSY with a Higgs to γγ (razor)
- ATLAS Res. to W/Z + H in qqbb, in llbb, lvbb,vvbb

➡ Vector like quarks

- ATLAS VLQ T'->Zt , T'->Wb
- CMS VLQ single T'->tH (l+H) , T'->tH (hadronic)
- CMS VLQ pair T->boosted tH (leptonic)

➡ DM searches

- CMS DM + jet / hadronically decaying W/Z
- ATLAS DM association with a hadronically decaying W/Z
- ATLAS DM with b quarks, with top quarks …

➡ Mono Higgs

- ATLAS DM + H(γγ)
- ATLAS DM + H(bb)
- CMS DM + H(γγ), DM + H(bb)

➡ DiHiggs

- ATLAS hh the bbbb final
- ATLAS hh in the γγWW*
- CMS hh in 4b resonance and non resonance
- CMS hh in bbττ resonance and non resonance
- CMS hh in bbγγ, hh in bbℓνℓν

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- CMS VLQ single T'->tH (l+H) B2G-15-008, T'->tH (hadronic) B2G-16-005
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- ATLAS DM association with a hadronically decaying W/Z arxiv:1608.02372
- ATLAS DM with b quarks, with top quarks ATLAS-CONF-2016-086 top quarks ATLAS-CONF-2016-050 …

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- ATLAS DM + H(γγ) ATLAS-CONF-2016-087
- ATLAS DM + H(bb) arxiv:1608.04572
- CMS DM + H(γγ), CMS-PAS-EXO-16-011, DM + H(bb) CMS-PAS-EXO-16-012

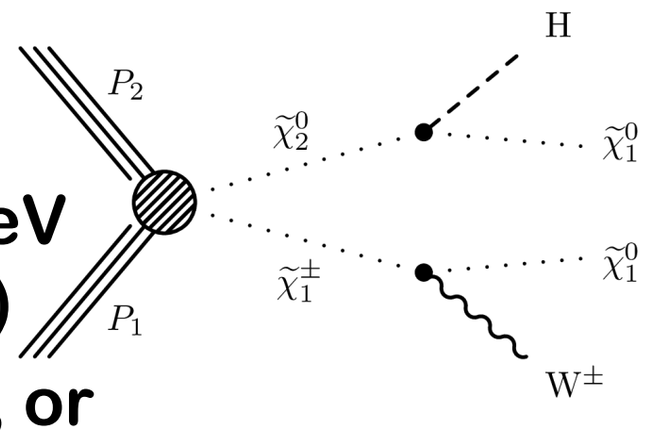
➡ DiHiggs

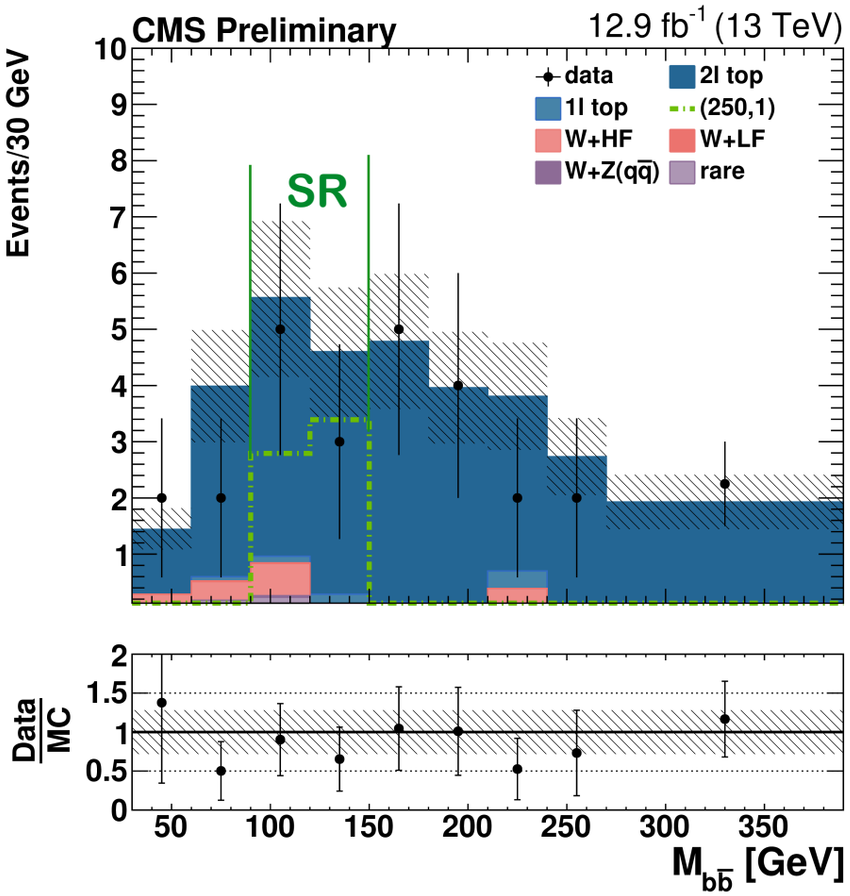
- ATLAS hh the bbbb final PRD 94 (2016) 052002
- ATLAS hh in the γγWW* ATLAS-CONF-2016-071
- CMS hh in 4b resonance B2G-16-008, non res. CMS-PAS-HIG-16-026
- CMS hh in bbττ resonance CMS-PAS-HIG-16-029, non res. CMS-PAS-HIG-16-028
- CMS hh in bbγγ, hh in bbℓνℓν

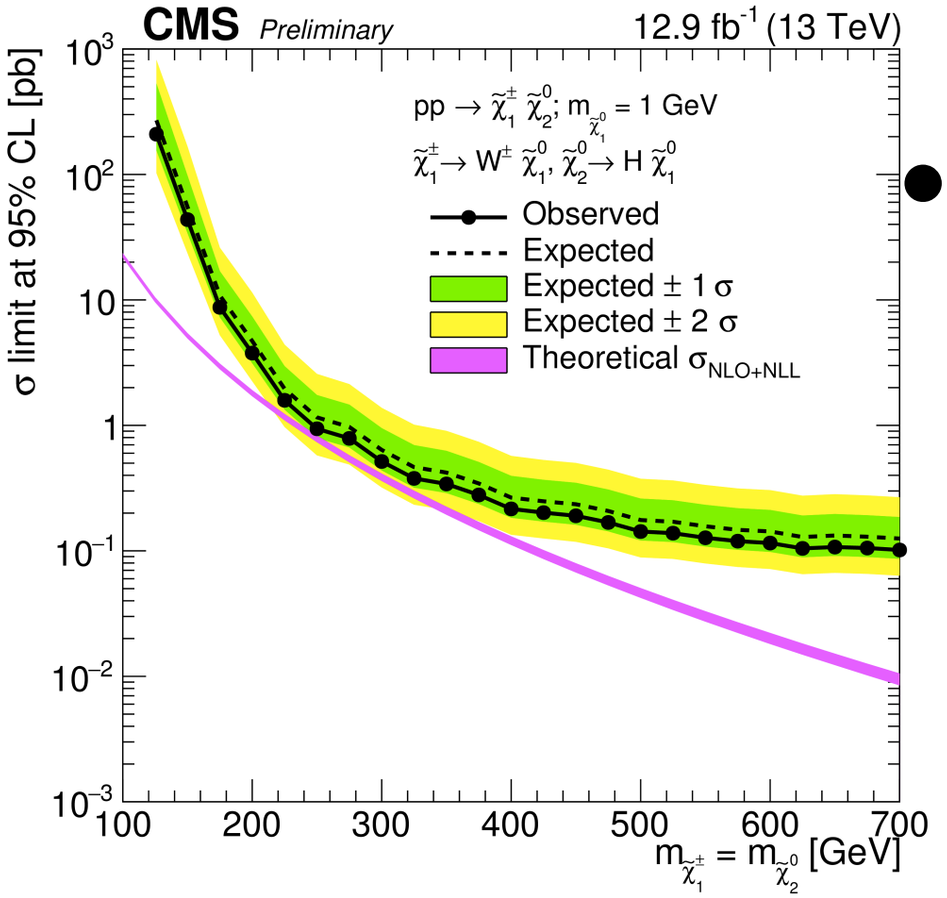
EW production of charginos and neutralinos in WH

- Can occur e.g in EW gaugino production
- While strong SUSY might be heavy, $\tilde{\chi}^{\pm}$ and $\tilde{\chi}^{0}$ may have escaped detection (no color charge)..
- Selection require 1 isolated lepton (p_T>25), MET>100 GeV and 2 b-tagged jets (b-tag efficiency ~65%, purity ~99%)
- SR: 90 <M_{bb}< 150 GeV, Main BG tt->ll, t+W->ll, W+light q, or W+HF, W+Z, modelled with MC tested in three CRs.

SUS-16-026



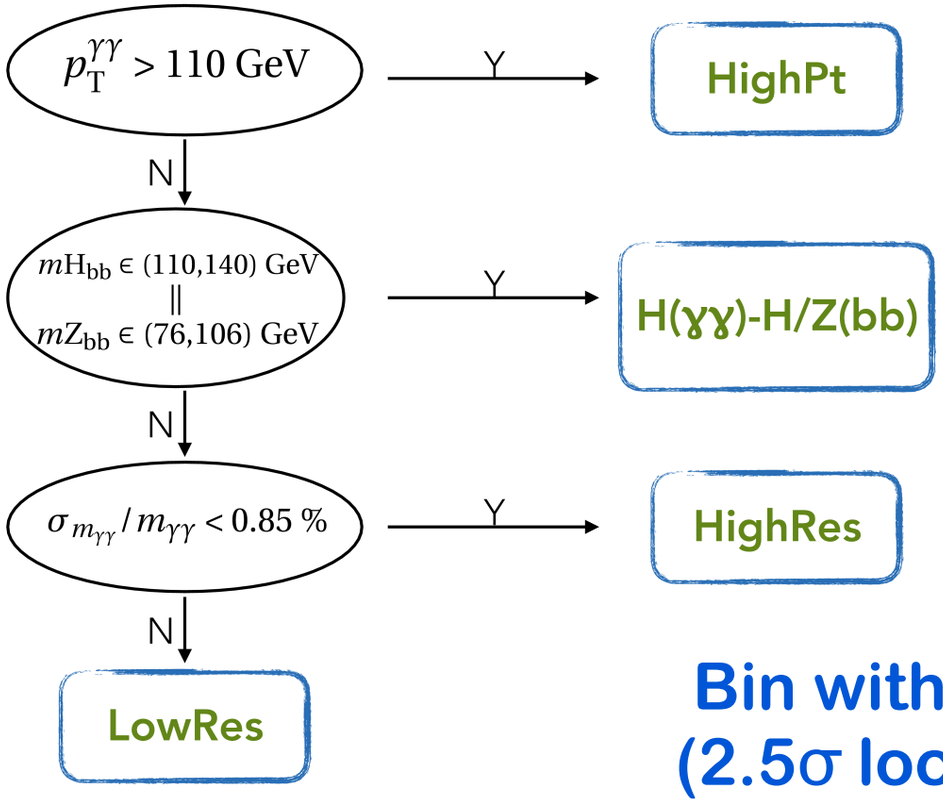


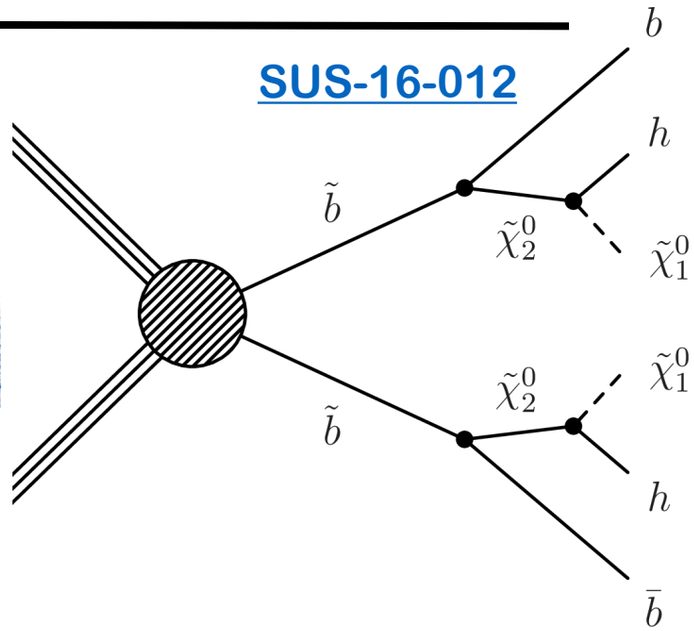


- Exclude chargino-neutralino production in a simplified model of SUSY with the decays $\tilde{\chi}^{\pm}_1 \to W\tilde{\chi}^{0}_1$ and $\tilde{\chi}^{0}_2 \to H\tilde{\chi}^{0}_1$

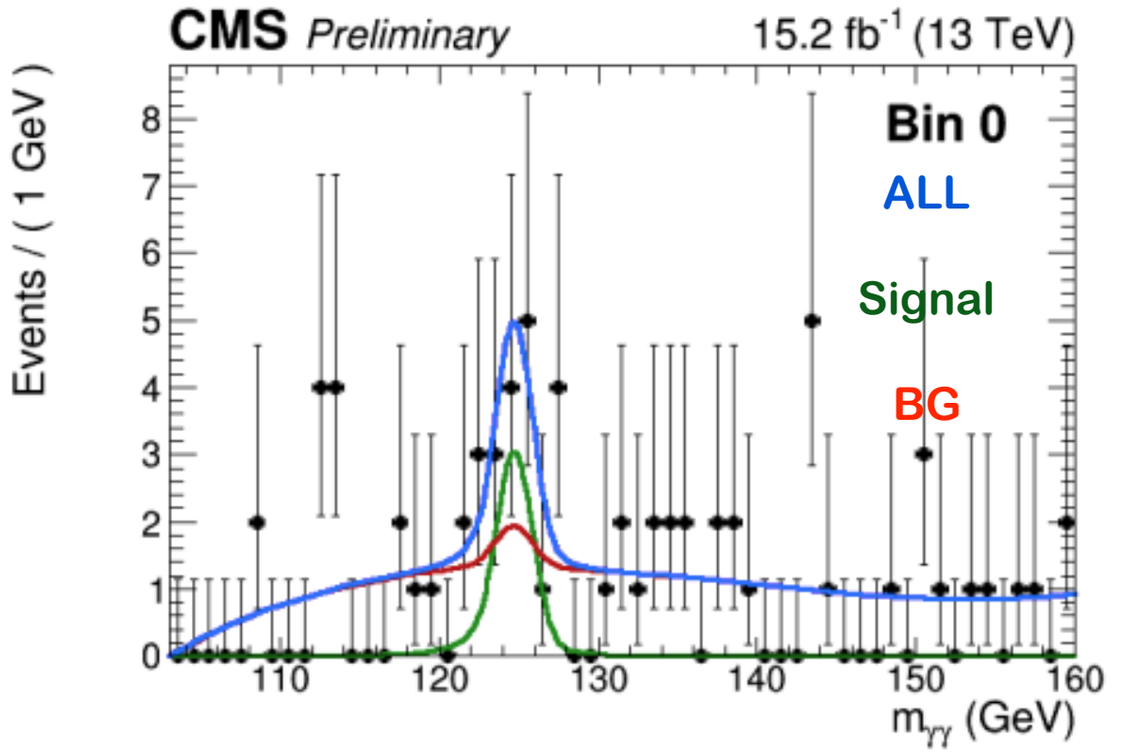
SUSY with a Higgs to γγ (razor)

- Excess in run-1…
- Four analysis categories:
- “Razor” variables suppress SM (+ Higgs production)
- Fit to γγ dist. in bins in each category
- BG: non-res (QCD estimates with the fit) and SM Higgs (estimated with MC)
- Exclude sbottom pair prod. (each ->Higgs, b-quark, and LSP) with mass below 350 GeV.





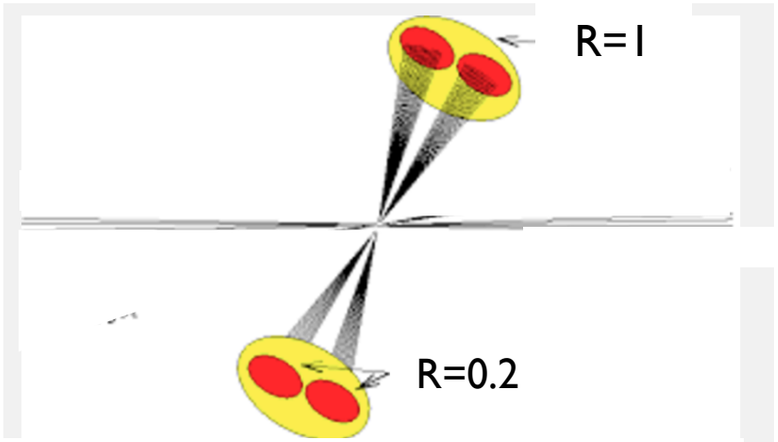
Bin with highest excess (2.5σ local->1.4σ global)

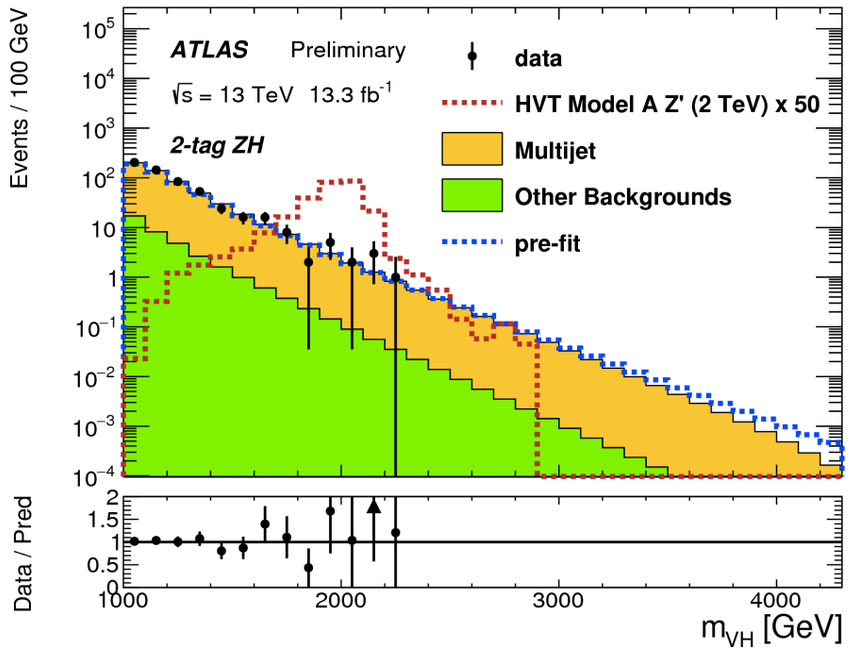


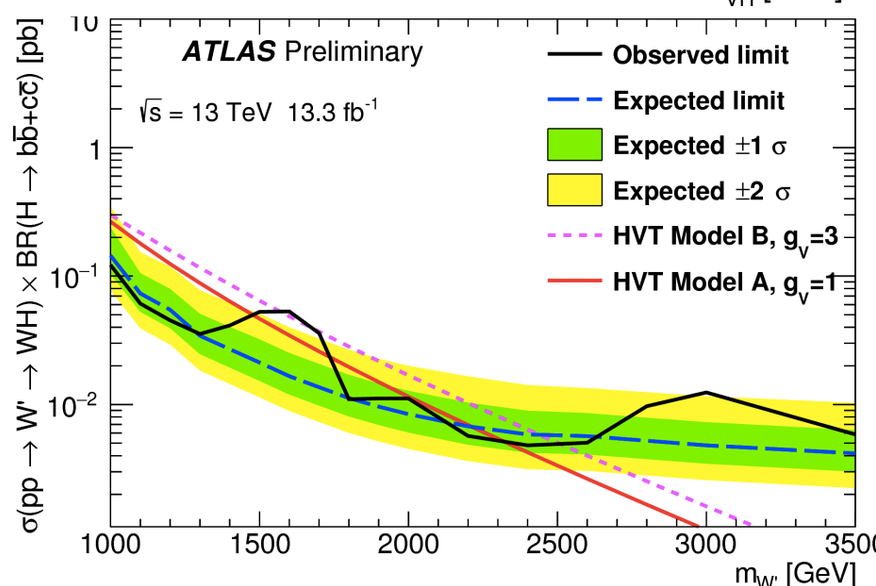
Exotic resonance decaying to W/Z + H in qqbb

ATLAS-CONF-2016-083

- V+H resonance decay to two merged jets (anti-Kt R=1)
- Heavy Vector Triplet (HVT) Simplified model:
  - Model A (comparable fermions boson couplings)
  - Model B (fermion coupling is suppressed)
- b-tag efficiency. ~ 77% fake ~2% (24%) light (charm)
- Veto leptons for orthogonality with VV analyses or events with MET> 150GeV against HZ->vv events.
- Largest mass jet =Higgs candidate. $75<m_H<145$ GeV
- Higgs tag effi. double- (single-) b-tag H-jets 25-40% (65-75%)
- m_W (m_Z) 83 (93) +/-15 GeV
- Sensitivity of 2 b-tag is dominant below 2.5 TeV
- Dominant BG - multijets (DD estimate in -0 b-tag)
- Largest local deviation (3σ) WH ~ 3 TeV (2.5σ global)
- Exclude Xsec X Br to qqbb or in HVT B 1000 - 1570 and 1680 - 2520 (1070 - 1580) GeV for WH (ZH) resonances.





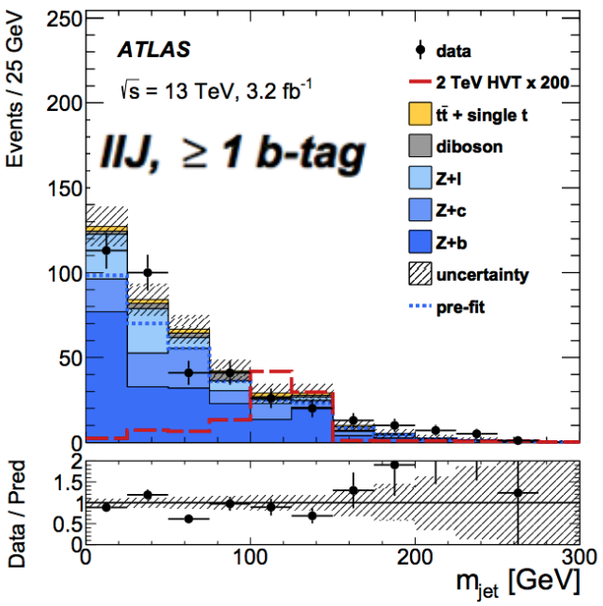


Higgs couplings 2016

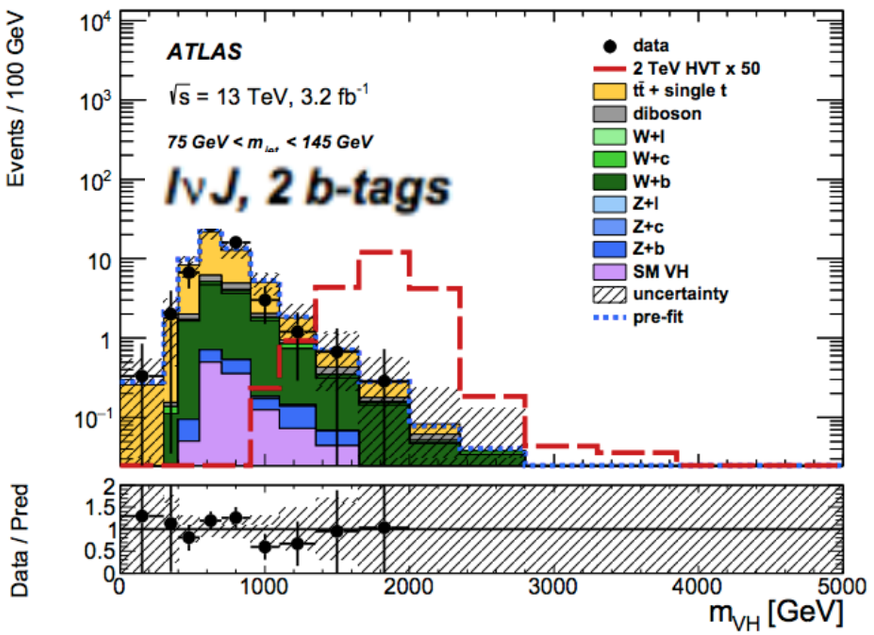
W/Z + H in $\ell\ell$bb, $\ell\nu$bb, and $\nu\nu$bb channels (2015 data)

- Three categories for the V:
  - Z' →ZH →$\ell\ell$bb (2 OS SF ℓ)
  - Z' →ZH →$\nu\nu$bb (MET)
  - W' →WH→$\ell\nu$bb (single lepton)
- Higgs tagging: large (R=1) jets with >= 1 b-subjet.

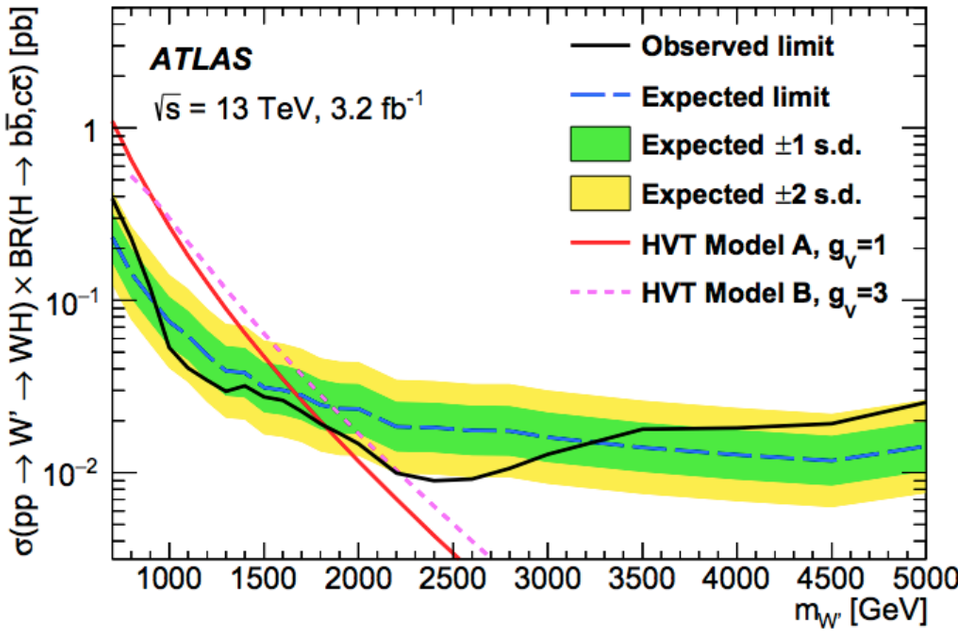
75<m_H<145 GeV



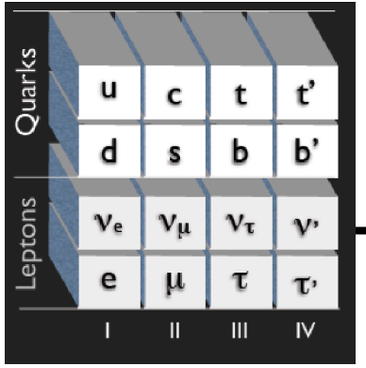
(c) 2-lepton, ≥ 1 *b*-tag



(d) 1-lepton, 2-*b*-tag



(b) $W'^{\pm} \to WH, H \to b\bar{b}/c\bar{c}$



4th Generation and Heavy Quarks

"Standard" SM4

- t't'->WbWb: like heavier $t\bar{t}$
- b'b'->WtWt

- 4th generation would significantly enhance Higgs production cross section

➡ (almost) excluded by direct searches and observed Higgs cross-section

- Beyond 4th generation: Vector-like quarks (VLQ) in composite Higgs theories
  - diverse phenomenology
  - The left– & right handed components of VLQs transform the same way under SU(2)

➡ Allows for a gauge invariant mass term independent of the Higgs and of some unspecified BSM origin.

- VLQ appear in many BSM theories, mainly with strong EWSB.
  - Loose constraints on CKM4

➡ decays to light quarks possible!

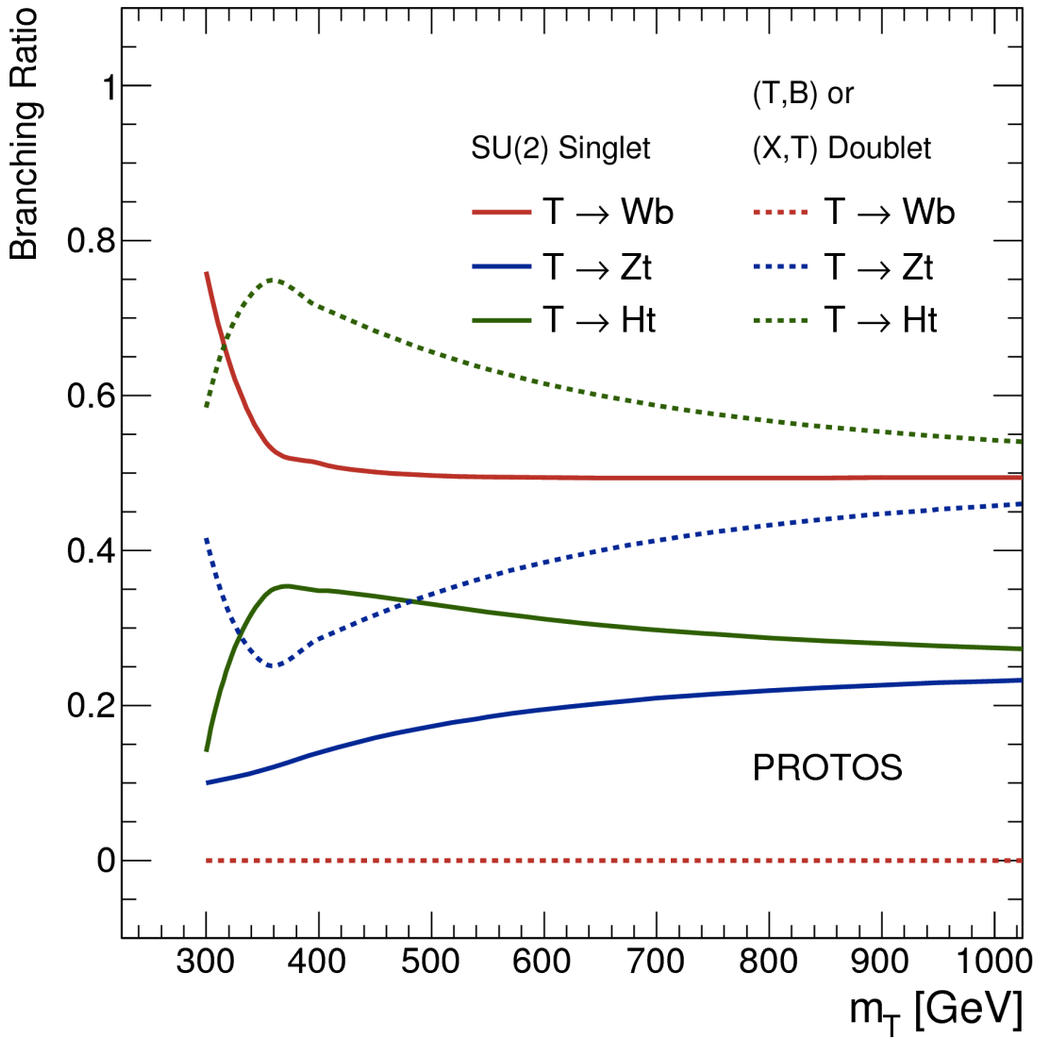
$T_L\ ,\ T_R$

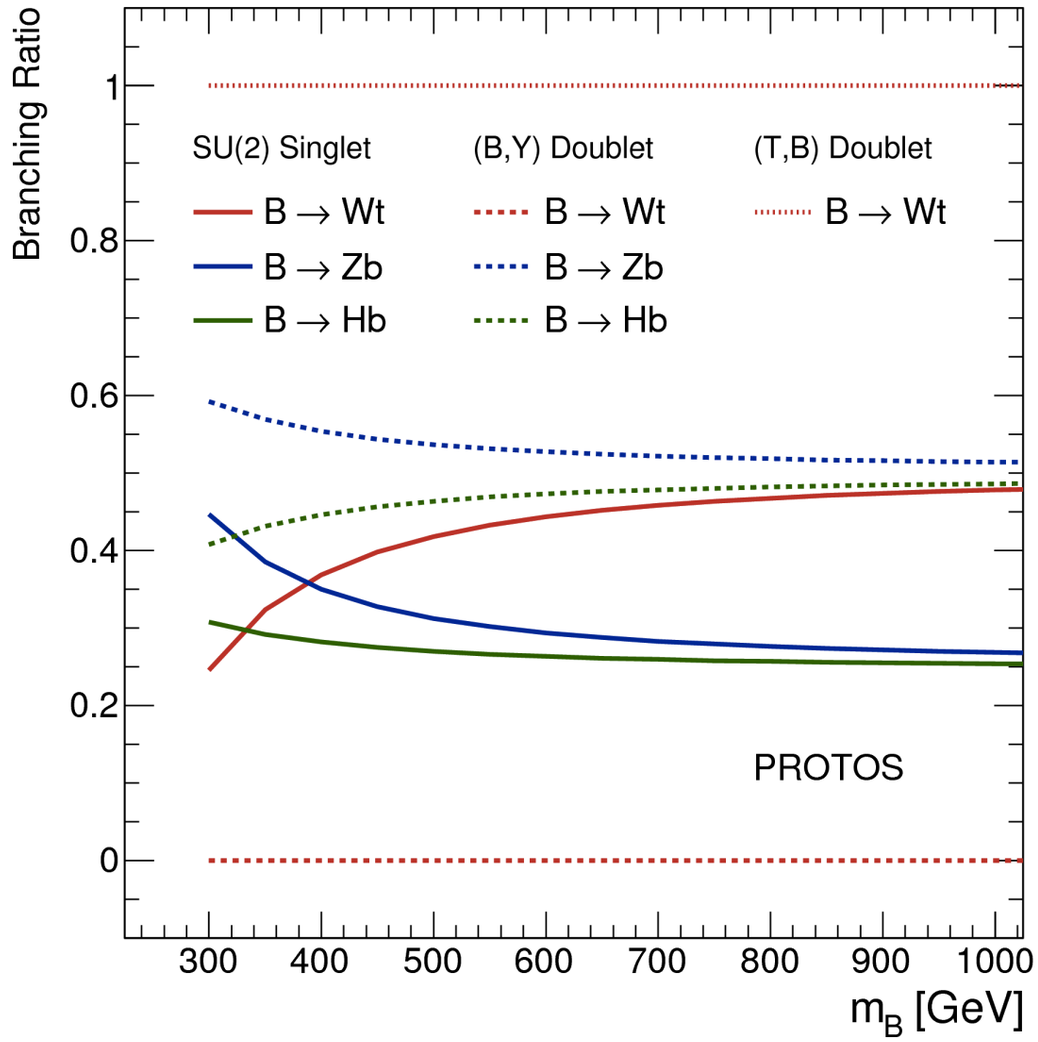
$\begin{pmatrix} T_L \\ B_L \end{pmatrix}, \begin{pmatrix} T_R \\ B_R \end{pmatrix}$

$M\bar{Q}Q$

Vector Like Quarks

- GIM mechanism is broken, tree level FCNC arises.
- Vector like multiplets with charge quarks (+5/3 X, 4/3 Y)
- Mixing primarily with third generation, but not required.





VL-top

JHEP 08 (2015) 105

VL-B

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- ATLAS new phenomena with tt (T' → tH) ATLAS-CONF-2016-104
- CMS VLQ single T' → tH (l+H) B2G-15-108, T' → tH (hadronic) B2G-16-005
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➡ Mono Higgs

- ATLAS Searches for new physics in the γγ+MET ATLAS-CONF-2016-087
- ATLAS DM + H(bb) arxiv:1608.04572
- CMS DM + H(γγ) CMS-PAS-EXO-16-011, DM + H(bb) CMS-PAS-EXO-16-012

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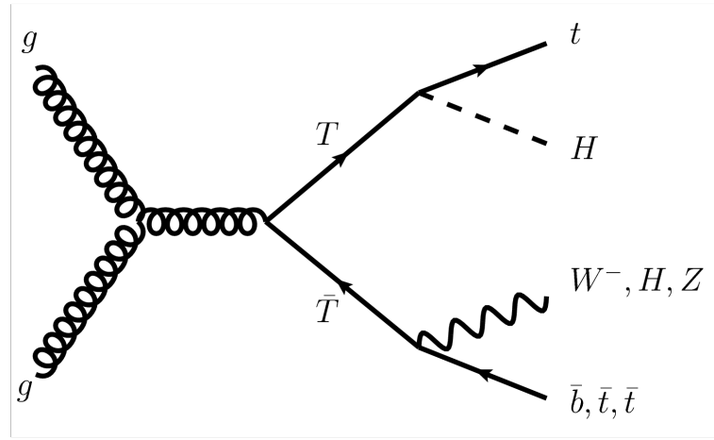
VLQ pair T → boosted Ht (leptonic)

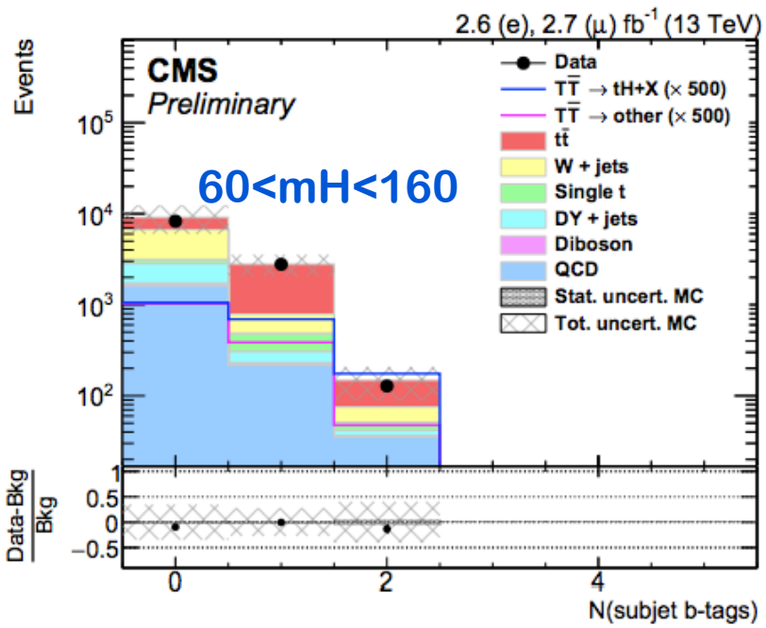
B2G-16-011

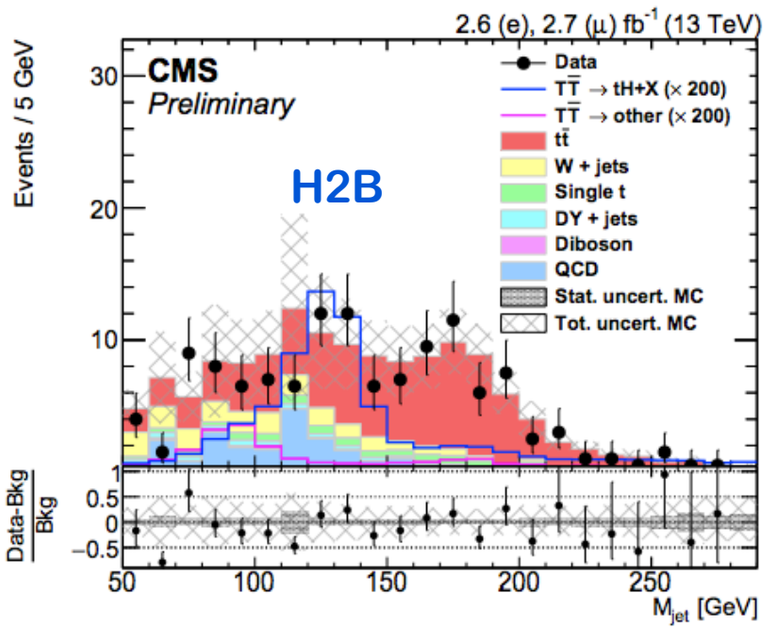
- Searches for $T\bar{T}$ where the BF of T $\rightarrow tH, bW, tZ$ is a free parameter designed to be sensitive to the tH decay case.
- Masses below 700 GeV were excluded, hence focus on boosted T.
- Study anti-K$_t$4 (R=0.4) ($p_T > 30$) jets and merged anti-K$_t$8 ($p_T > 200$) after "soft drop" of soft and wide angle radiation and identifying the merged subjets.
- CSV (combined secondary vertex) algorithm used for b-tagging with efficiency $\sim 80\%$, miss id 1%.
- Require 1 high p_T lepton, two anti-K$_t$8, three anti-K$_t$4 at least one b-tagged anti-K$_t$4 jet.
- Higgs tagging: $p_T > 300$, $60 < M_{jet} < 160$ with at least one b-tagged subject. Distinguish between **H2B, H1b** and **H0b** (no Higgs) cases.

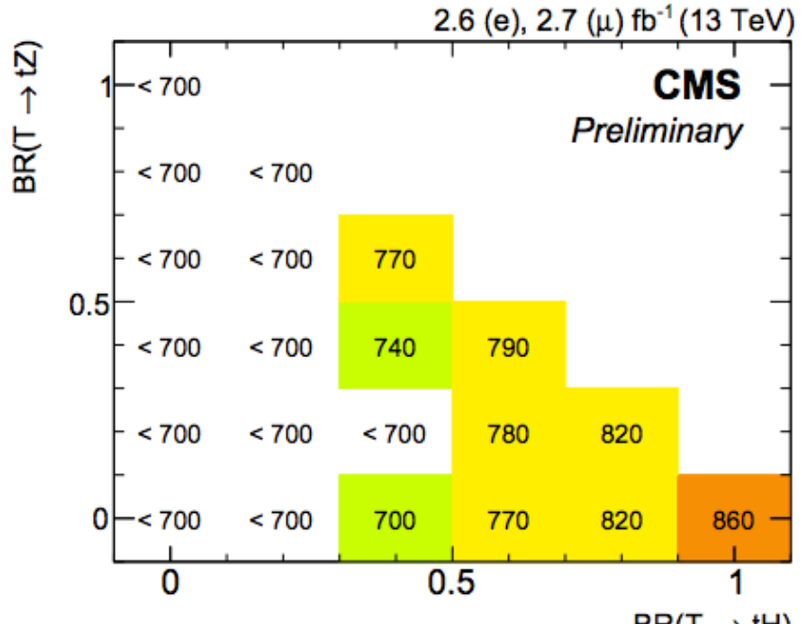


Exclusion mass limit:

$BR(T \rightarrow bW)$
$= 1 - BR(T \rightarrow tH) - BR(T \rightarrow tZ)$



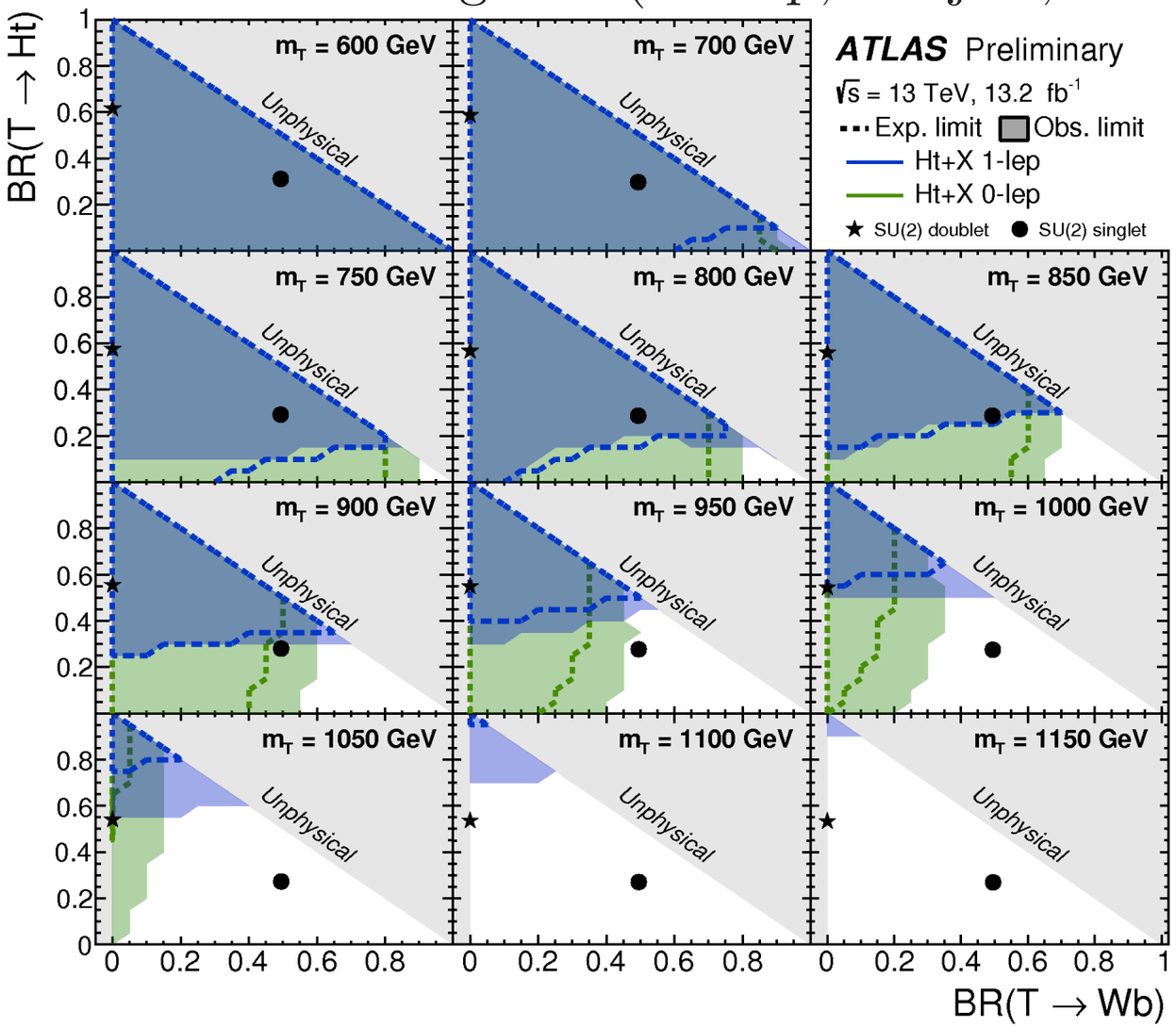


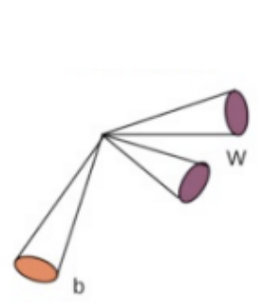


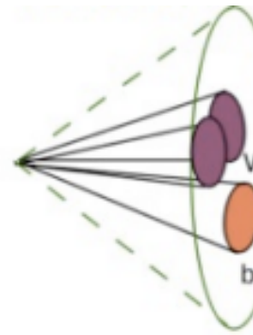
VLQ T' → Ht and more ..

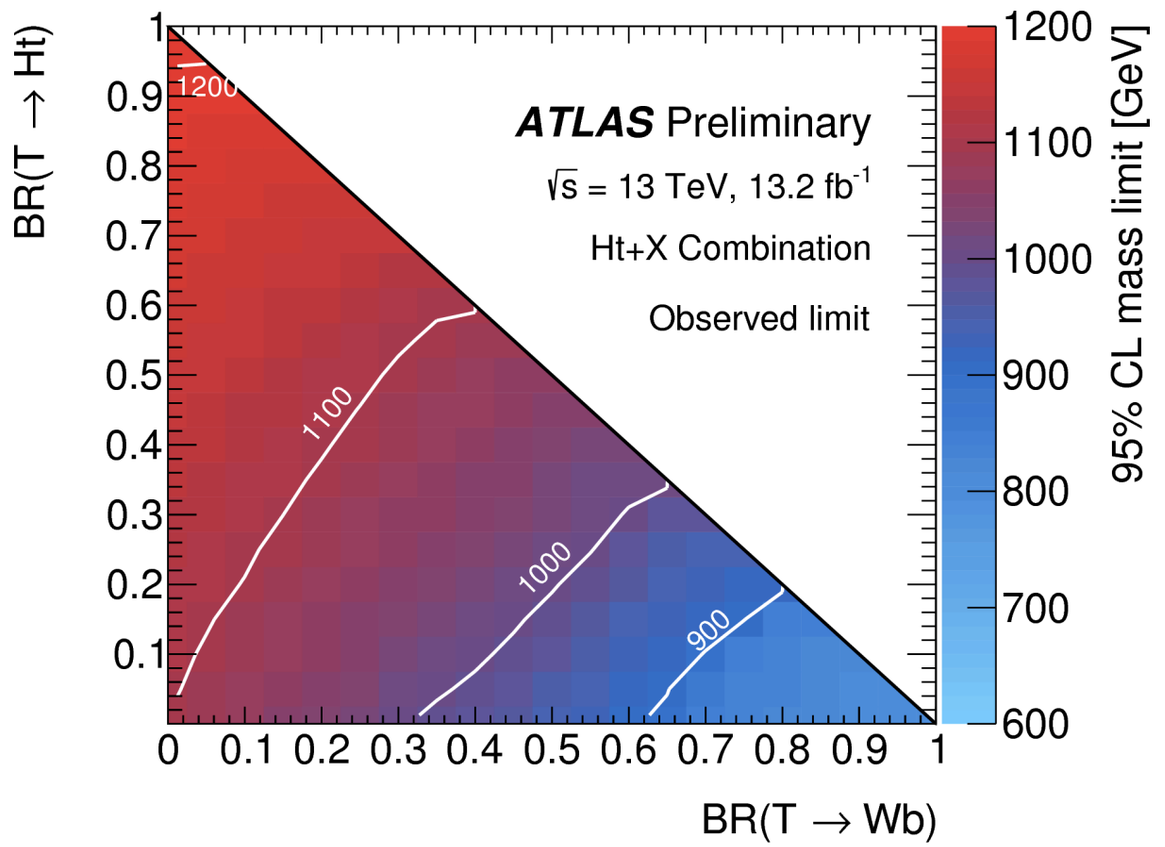
ATLAS-CONF-2016-104

- Searches in $t\bar{t}$+HF from $T\bar{T}$ ($\rightarrow tZ, tH$), $t\bar{t}t\bar{t}$ (SM and BSM), $t\bar{t}H \rightarrow t\bar{t}t\bar{t}$, $b\bar{b}H/A \rightarrow b\bar{b}t\bar{t}$ and $tbH^{\pm} \rightarrow$ tbtb, combining single lepton (+jets) and fully hadronic channels.
- Resolved (anti-K_t R=0.4) jets and boosted (R=1.0) for boosted top and Higgs jets.
- 20 SR categories (0-1 lep, 6-7 jets, 3-4 btag, Low/Hige mass)





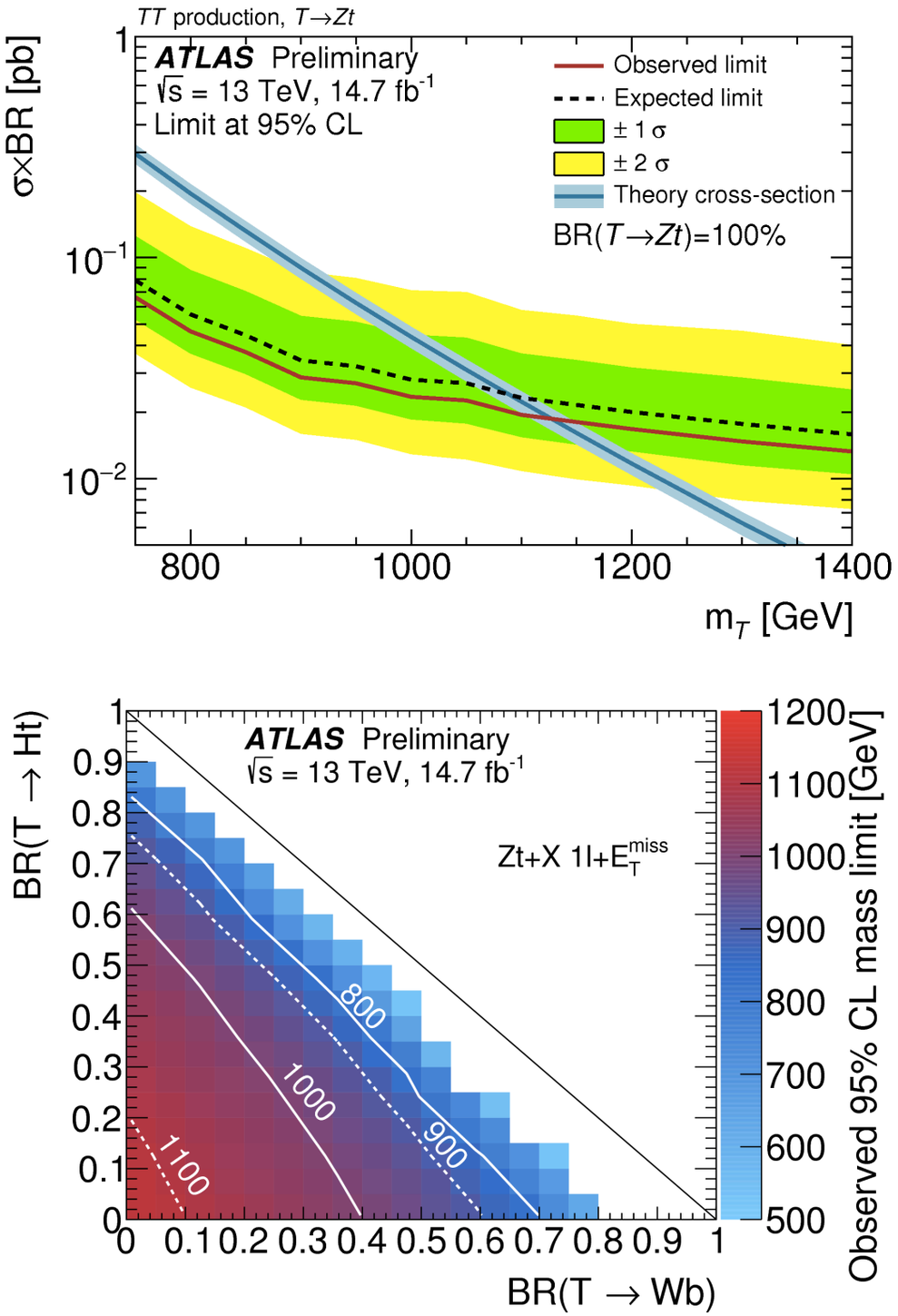


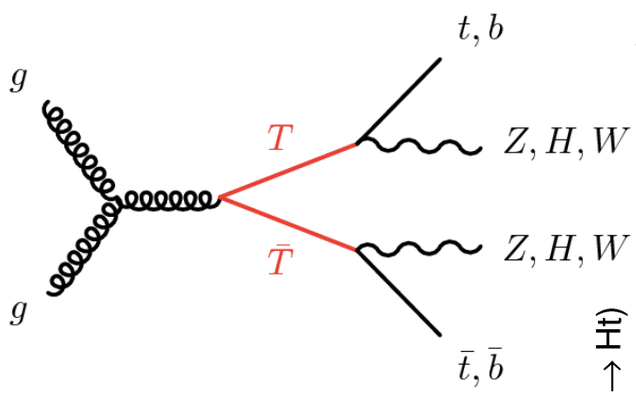


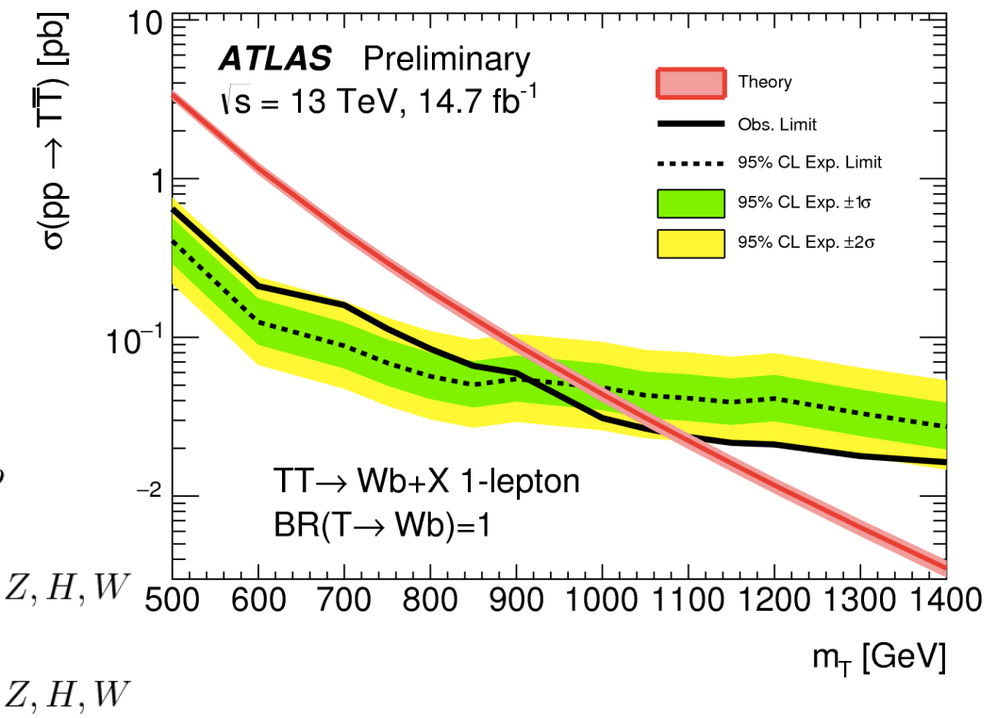
VLQ T’ → Zt , T’ → Wb

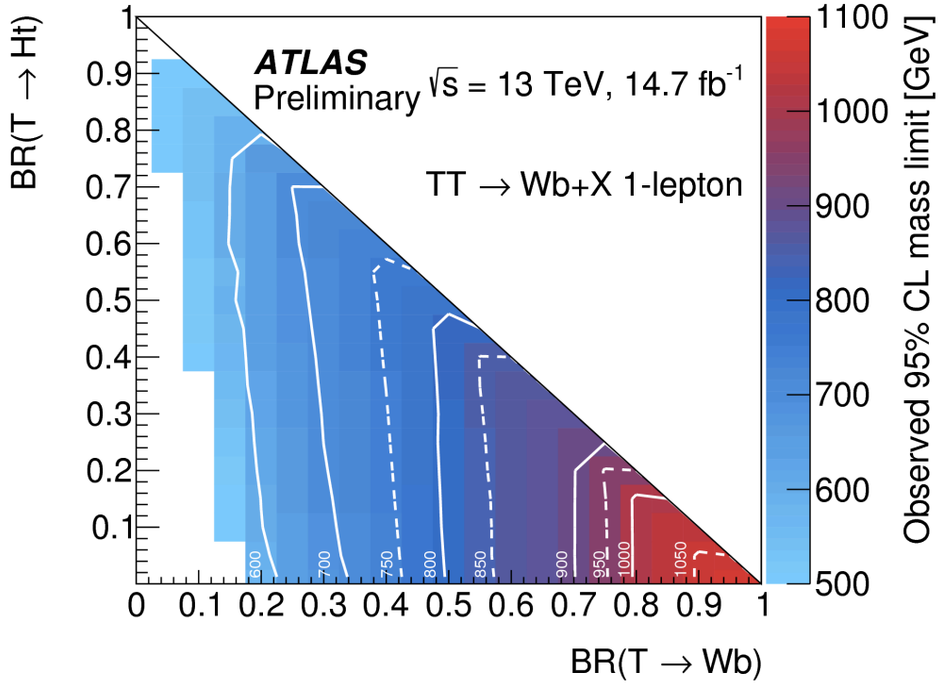
ATLAS-CONF-2016-101

ATLAS-CONF-2016-102



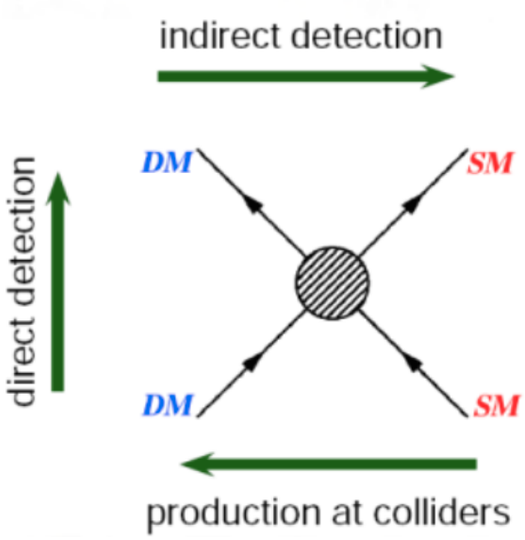




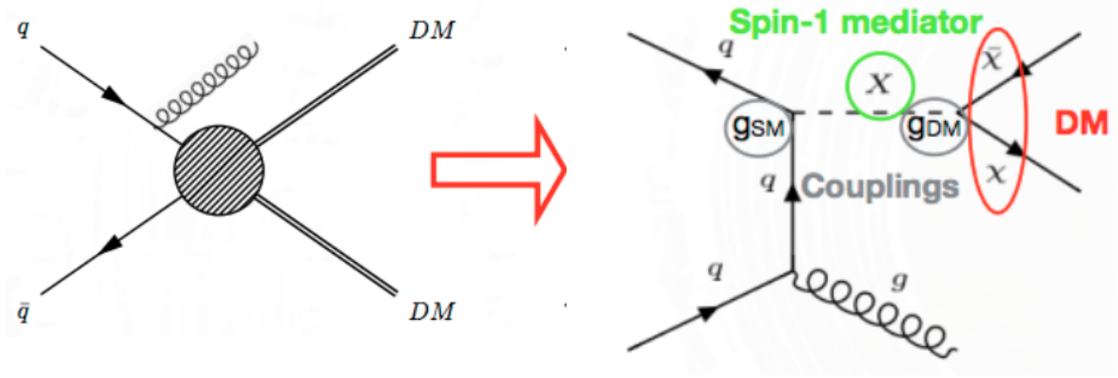


DM at LHC X+MET searches

arXiv:1409.2893, 1506.03116



- From **cosmological observations,** 85% of the matter comprised of dark matter (**DM**)
- Collider approach: DM production by colliding SM particles at high energies



From EFT to Simplified Models

- EFT - contact interaction with mediator too heavy to be generated
- EFT has limited validity when mediator mass is light ->Simplified models

BSM + Higgs tags new results (ICHEP++)

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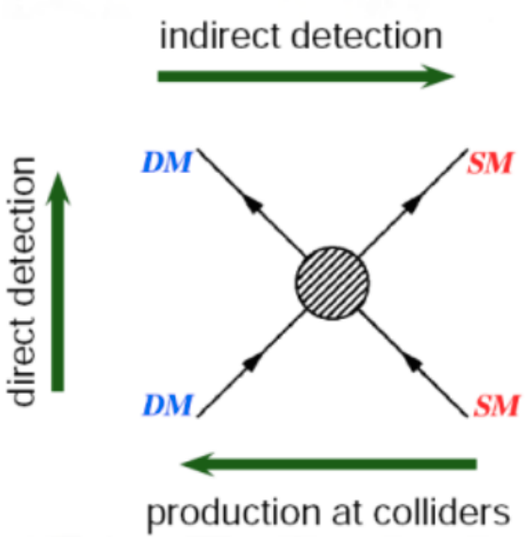

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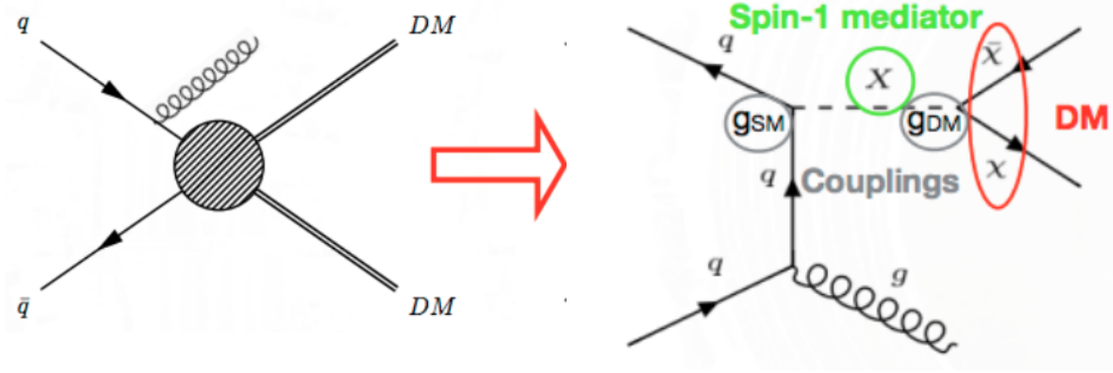

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- EFT has limited validity when mediator mass is light ->Simplified models

➡ **DM searches**

- **CMS DM + jet / hadronically decaying W/Z** CMS PAS EXO-16-037
- **ATLAS DM association with a hadronically decaying W/Z** arxiv:1608.02372
- **ATLAS DM with b quarks** ATLAS-CONF-2016-086 **top quarks** ATLAS-CONF-2016-050 **…**

➡ **Mono Higgs**

- **ATLAS DM + H(γγ)** ATLAS-CONF-2016-087, **DM + H(bb)** arxiv:1608.04572
- **CMS DM + H(γγ)** CMS-PAS-EXO-16-011, **DM + H(bb)** CMS-PAS-EXO-16-012

➡ **DiHiggs**

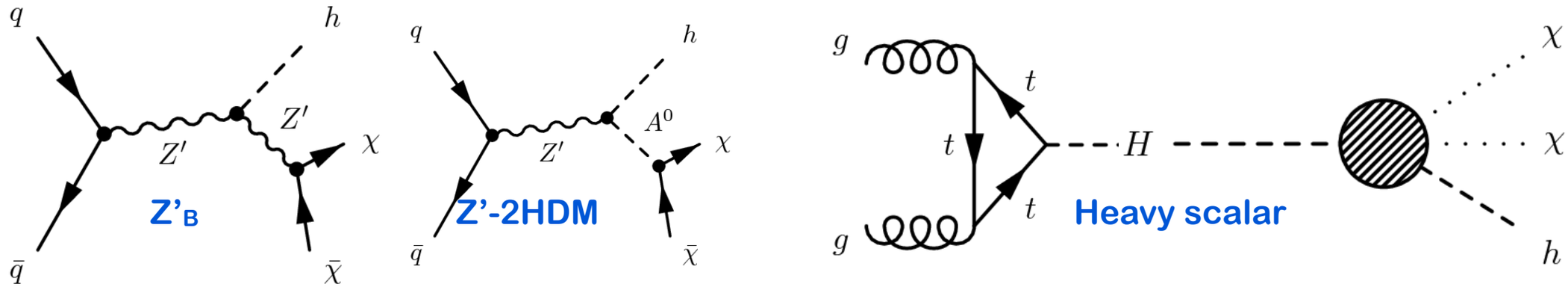
- **ATLAS hh the bbbb final**

Search for DM in H(γγ)+MET (mono Higgs)

ATLAS-CONF-2016-087

- MonoX the X is ISR from SM or BSM where in monoH mass coupling suppress the ISR from partons ⇒ H is directly involved in the BSM DM production

- Simplified models SM–DM mediated by Z' emitting h decaying directly or through intermediate state to two DM, or $H \to h$ + two DM



- At least two γ $p_T > 25$ GeV. $E_T^{\gamma}/m_{\gamma\gamma} > 0.25(0.35)$ (sub)leading photon.

- Mass requirement: $105 < m_{\gamma\gamma} < 160$ GeV

- Z'_B and $Z' - 2HDM$ have large MET, while *Heavy Scalar* model MET and $p_T^{\gamma\gamma}$ span through wide range.

- Events in the $m_{\gamma\gamma}$ window are divided into four SR kinematic regions

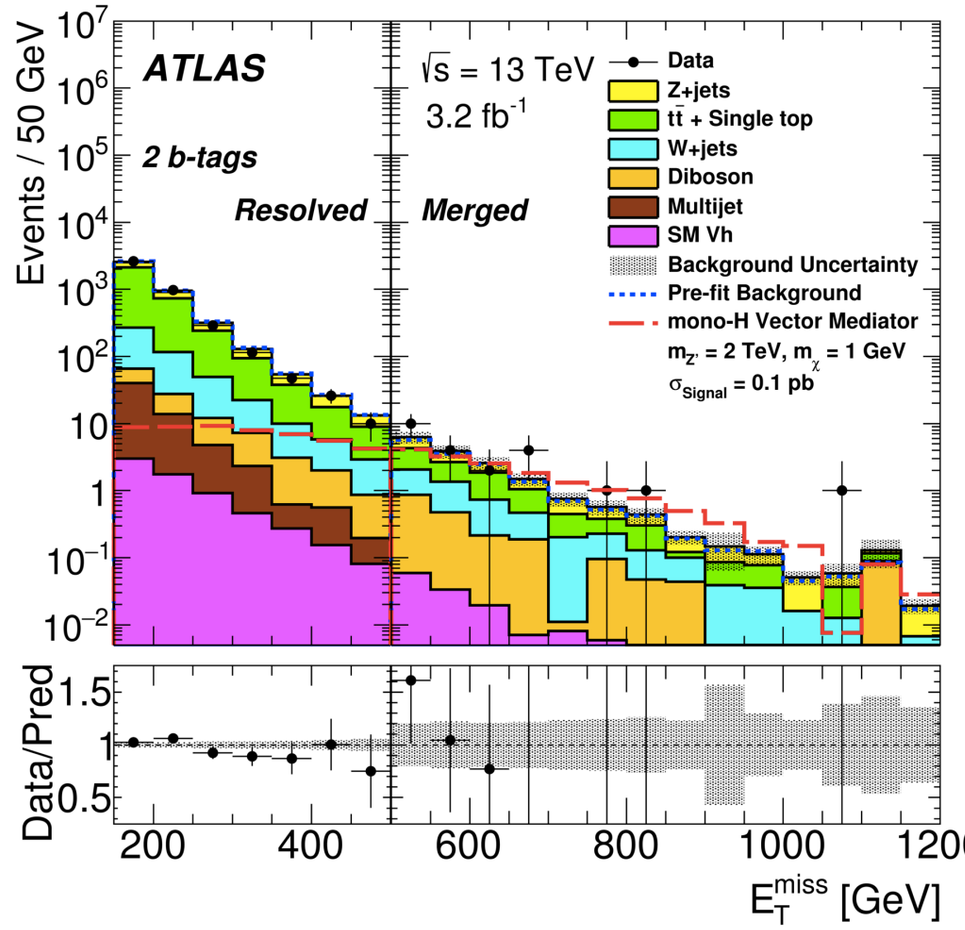
- No deviation in all four categories .. exclusion limits ..

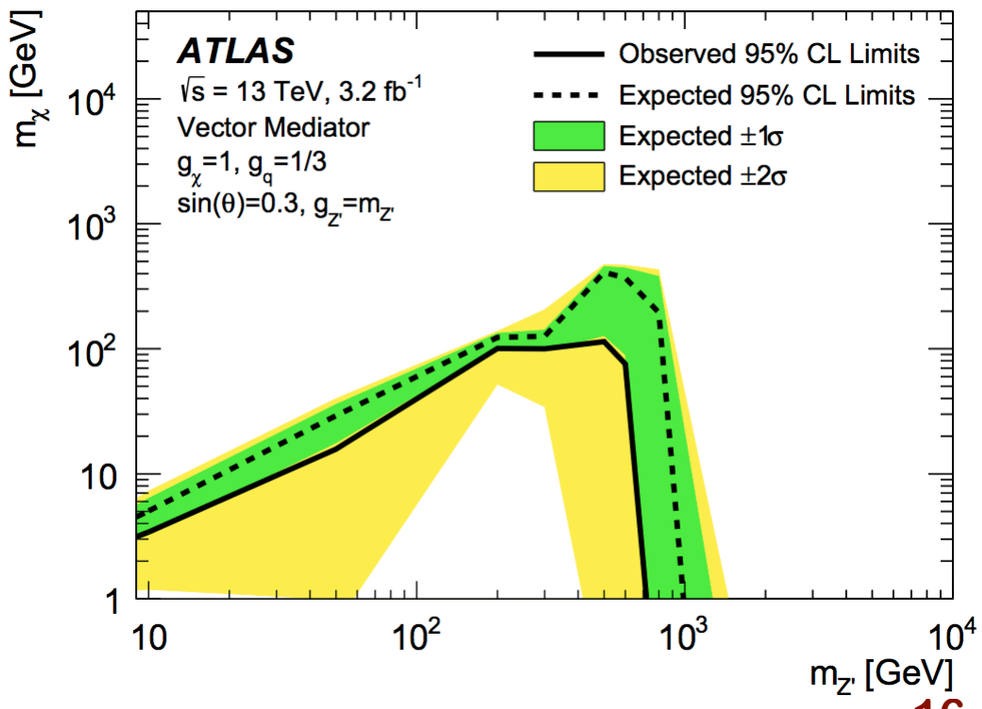
arxiv:1608.04572

Search for DM in H(bb)+MET (mono Higgs)

Reconstructed MET in the resolved and merged two-b-tag SR.

* The SM prediction shown pre (post) the profile likelihood fit
* The various components of the W/Z+jets (bb, bc, bl, cc, cl, ll) BG merged and labelled W+jets and Z+jets.
* The multijet BG is negligible in the merged region.
* The expected signal assumes mZ'=2 TeV and m_x=1 GeV, normalised with a cross-section of 0.1 pb.





Results by profile likelihood fit to the reconstructed invariant mass distribution in all SR and CR

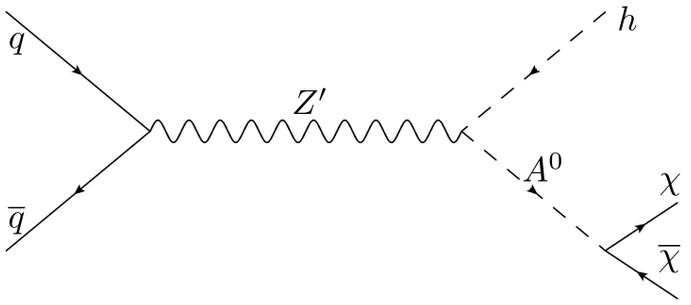
Exclude vector mediators with masses up to 700 GeV (most sensitive monoH analysis)

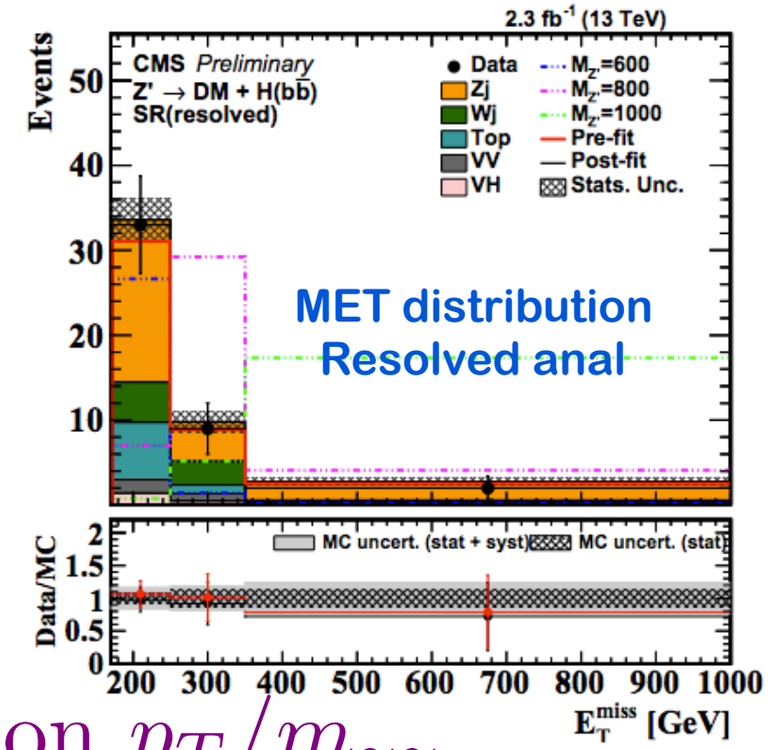
DM in H(bb)/H(γγ)+MET (mono Higgs)

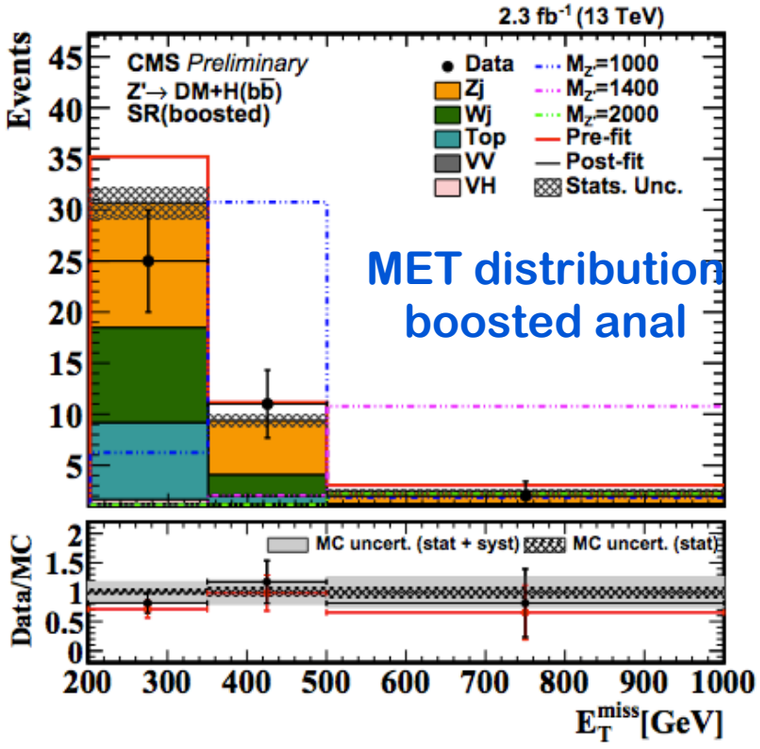
CMS-PAS-EXO-16-012

CMS-PAS-EXO-16-011

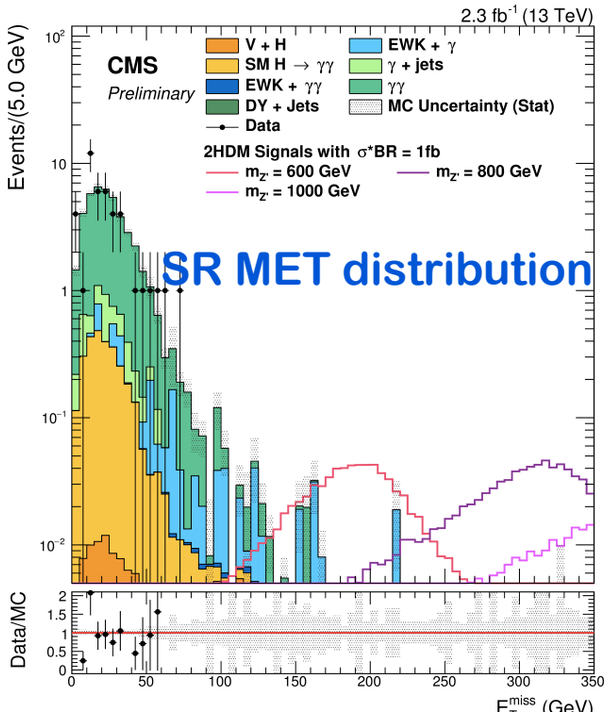
- **H(bb)** use the Z'-2HDM model, 2 AK4 (1 AK8), exactly 2 b-tagged, $MET > 150$ ($MET > 200$), mass between 100-150 GeV for resolved (merged) analysis
- CR for W or $Z \to \nu\nu$+jets and top



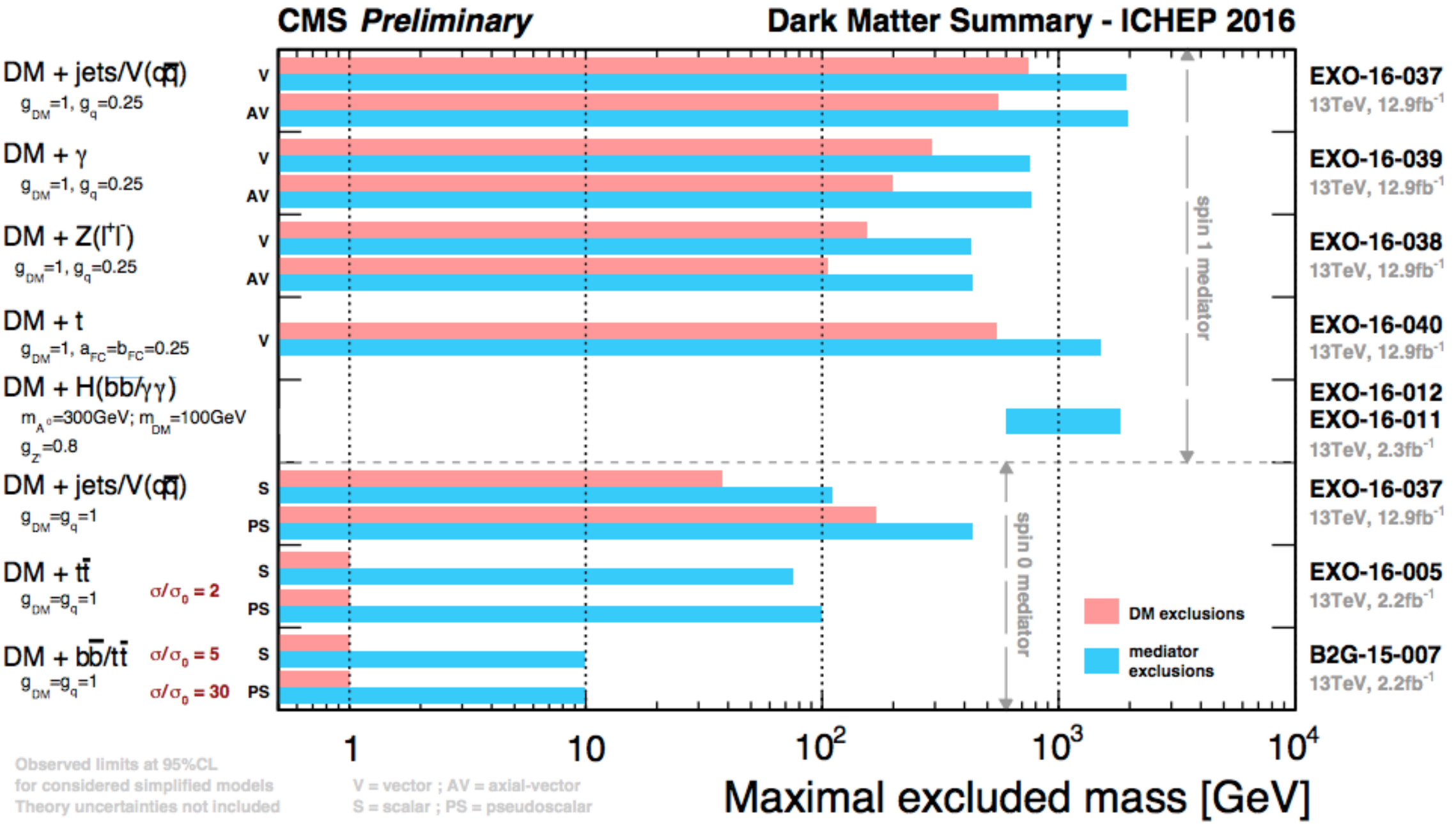




- **H(γγ)** Requirements on $p_T/m_{\gamma\gamma}$, MET and $p_T^{\gamma\gamma}$..
- A lepton veto reduces the EW BG
- $120 < m_{\gamma\gamma} < 130$ tested with 122-128
- Search between $m_{Z'}$ 600 to 2500 GeV



CMS reach of DM searches



BSM + Higgs tags new results (ICHEP++)

➡ Higgs in EXOT/SUSY cascades

- CMS EW prod. of charginos and neutralinos in the WH SUS-16-026
- CMS SUSY with a Higgs to γγ (razor) SUS-16-012
- ATLAS Exot res. decaying to W/Z + H in qqbb ATLAS-CONF-2016-083

➡ Vector like quarks

- ATLAS VLQ T'->Zt ATLAS-CONF-2016-101, T'->Wb ATLAS-CONF-2016-102
- CMS VLQ single T'->tH (l+H) B2G-15-108, T'->tH (hadronic) B2G-16-005
- CMS VLQ pair T->boosted tH (leptonic) B2G-16-011

➡ DM searches

- CMS DM + jet / hadronically decaying W/Z CMS PAS EXO-16-037
- ATLAS DM association with a hadronically decaying W/Z arxiv:1608.02372
- ATLAS DM with b quarks ATLAS-CONF-2016-086 top quarks ATLAS-CONF-2016-050 …

➡ Mono Higgs

- ATLAS Searches for new physics in the γγ+MET ATLAS-CONF-2016-087
- ATLAS DM + H(bb) arxiv:1608.04572
- CMS DM + H(γγ) CMS-PAS-EXO-16-011, DM + H(bb) CMS-PAS-EXO-16-012

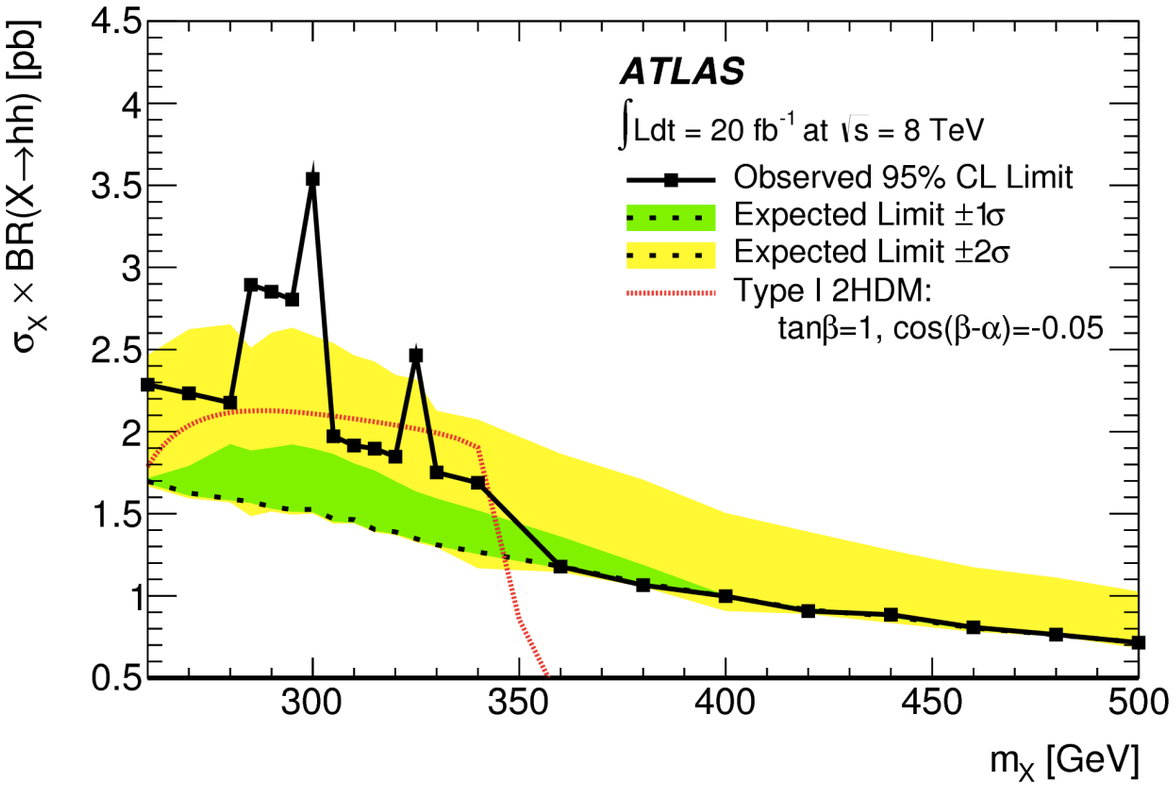
➡ DiHiggs

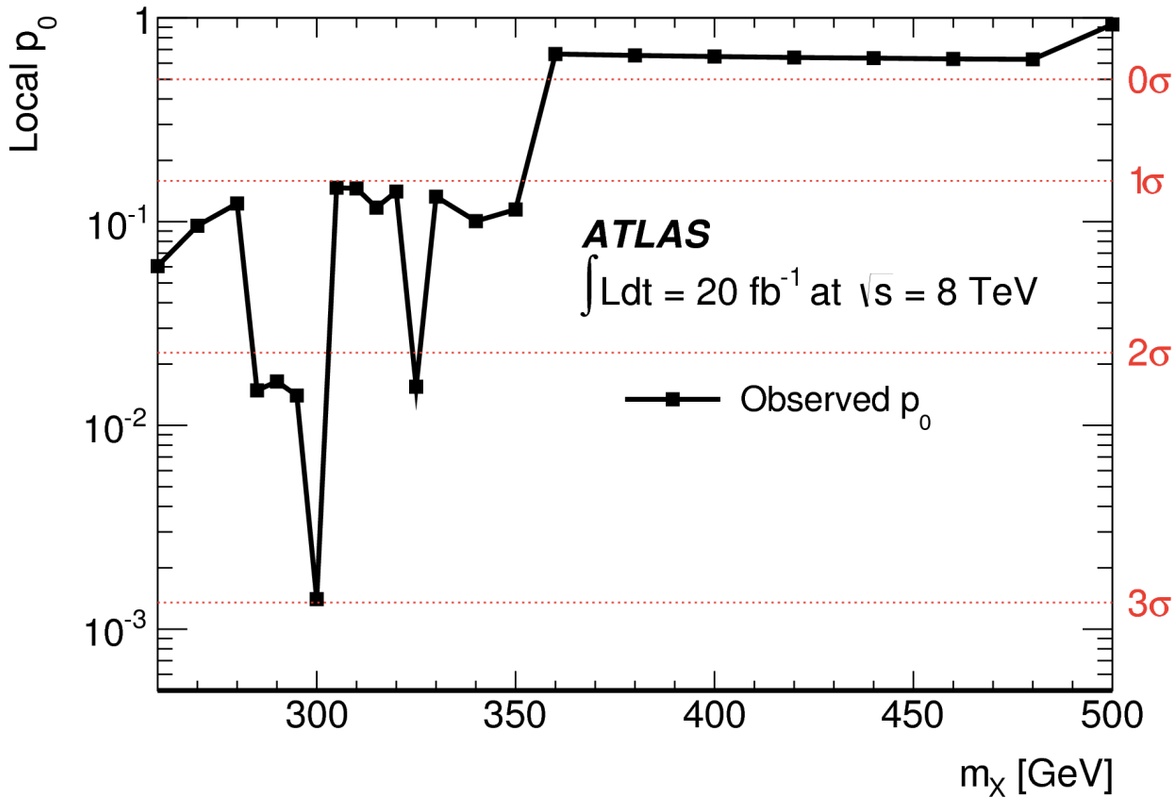
- ATLAS hh the bbbb final ATLAS-CONF-2016-049
- ATLAS hh in the γγWW* ATLAS-CONF-2016-071
- CMS hh in 4b resonance B2G-16-008, non res. CMS-PAS-HIG-16-026
- CMS hh in bbττ res. CMS-PAS-HIG-16-029, non res. CMS-PAS-HIG-16-028
- CMS hh in bbγγ CMC-PAS-HIG-16-032 hh in bbℓνℓν CMS-PAS-HIG-16-024

hh

You surely remember the Run-1 excess ..

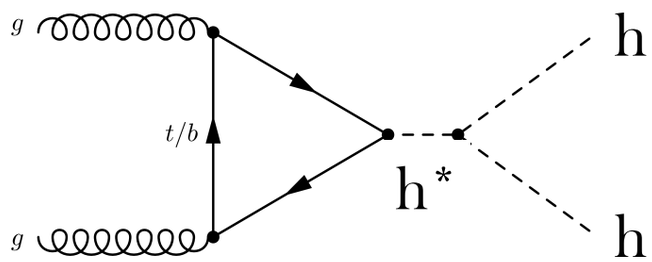
$$hh \to b\bar{b}\gamma\gamma \qquad ATLAS$$

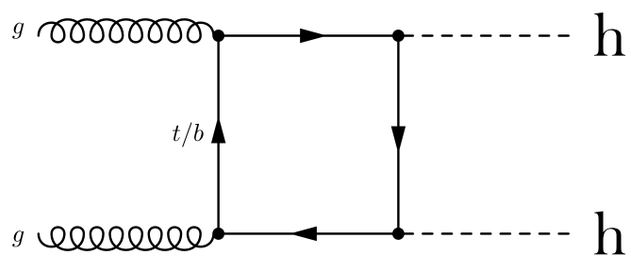




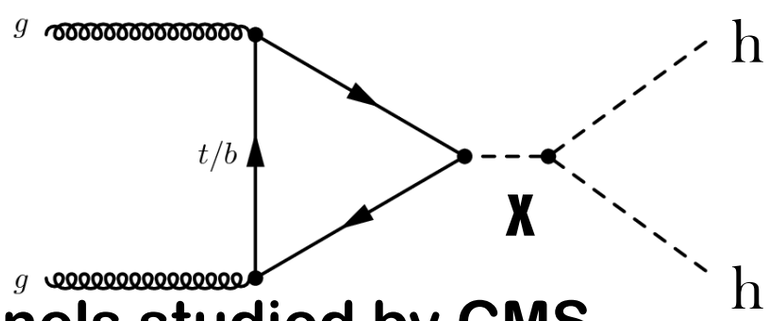
hh

- **SM HH** pair production small (~33 fb) due to interference. Probe the Higgs trilinear self couplings, enhancement may provide a **hint for BSM.**
  Dominant production: ggF (VBF, Higgsstrahlung, associated ttH are order of magnitude smaller)





- **BSM HH** resonance can be the sign for heavy neutral Higgs (e.g. 2HDM), or others (e.g. RS graviton, radions, stoponium)



- Channels studied by ATLAS

	Run 1	2015	2015+16
hh→bbbb	☺	☺	☺
*hh→γγWW**	☺		☺
hh→bbγγ	☺	☺	
hh→bbττ	☺		

Combined Run 1

arXiv:1509.04670v2

- Channels studied by CMS

	Run 1	2015	2016
hh→bbbb		☺	
hh→bbVV		☺	
hh→bbγγ	☺	☺	
hh→bbττ	☺	☺	☺

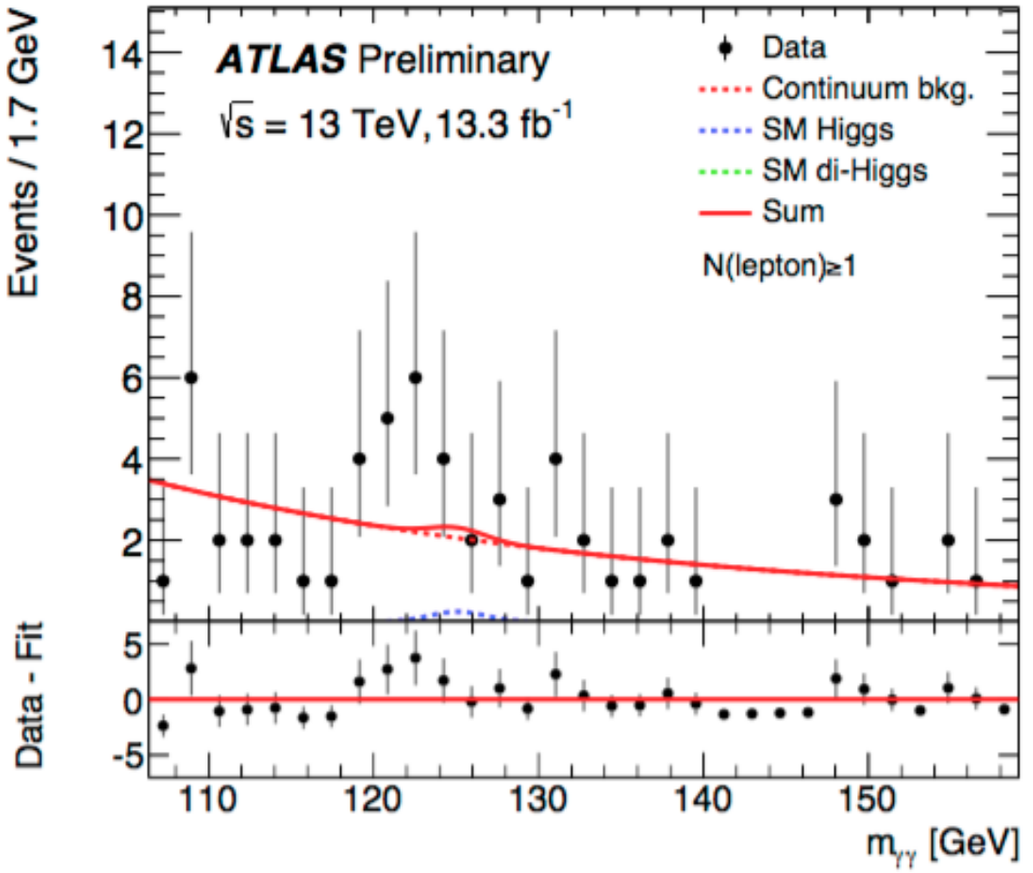
$hh \to \gamma\gamma WW^* \to \gamma\gamma l\nu qq'$

ATLAS-CONF-2016-071

- Large Br($h \to WW$) and clean ($h \to \gamma\gamma$)
- Select $\gamma\gamma$, >=2jets, w/o b-jets, 105 <$m_{\gamma\gamma}$<160 GeV
- SR: 1 lepton, CR: 0 leptons, Sidebands: reverse mass requirements on 0 and 1 lepton regions.
- Selection efficiency ~10%
- BG: SM single h (MC), diphotons (data driven)

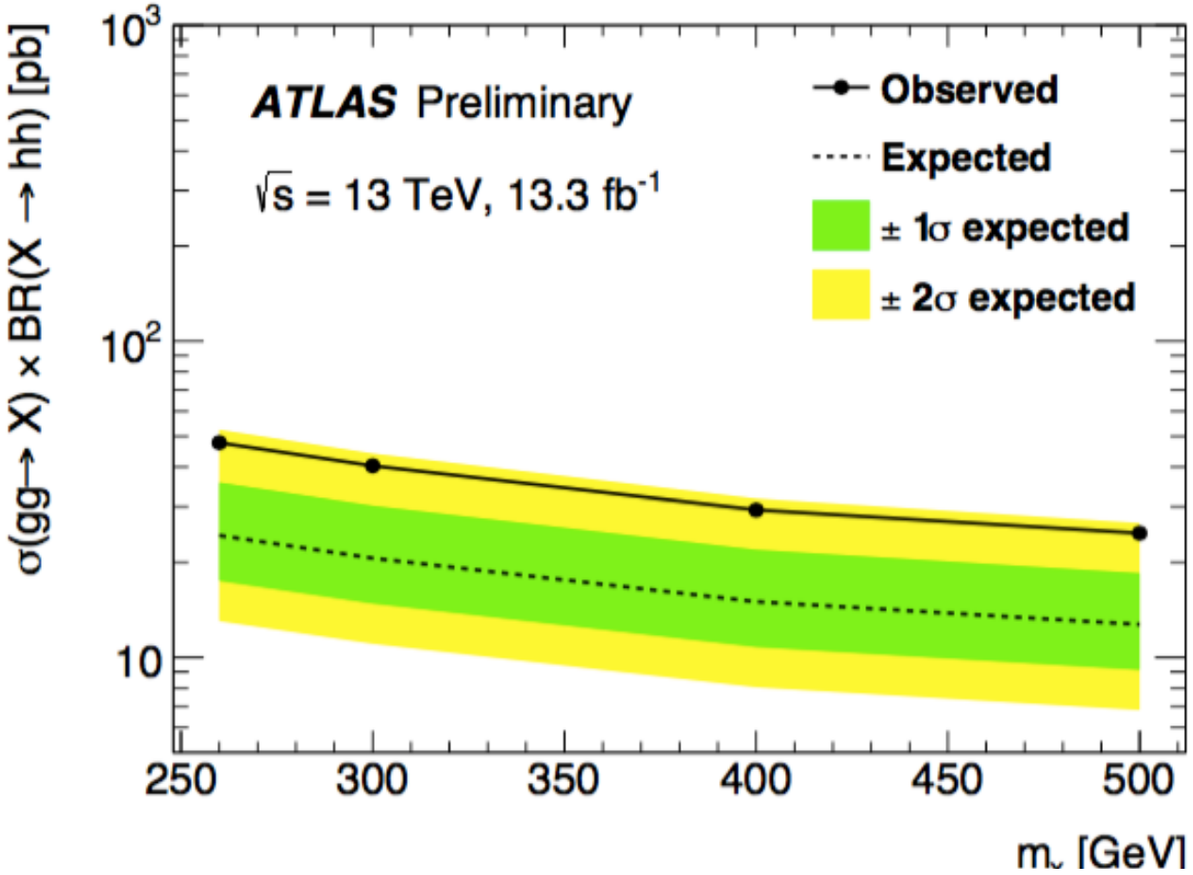
Process	Number of events	$m_h \pm 2\,\sigma_{m_{\gamma\gamma}}$ s
Continuum background	7.26	± 1.23
SM single-Higgs	0.616	± 0.115
SM di-Higgs	0.0187	± 0.00224
Observed		15

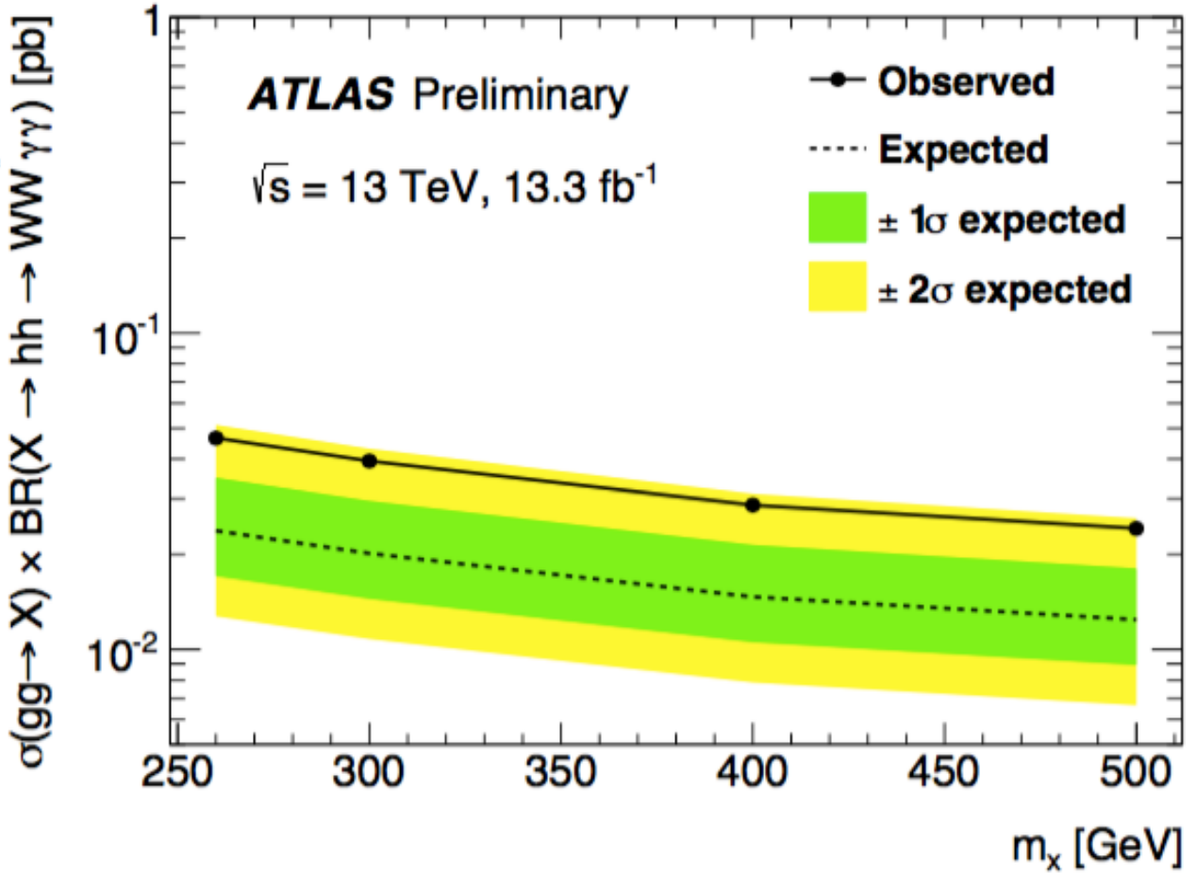
Exclusions	observed	expected
non resonant	25 pb	12.9 pb
resonance m=260GeV	47.7 pb	24.3 pb
resonance m=500GeV	24.7 pb	12.7 pb



hh → γγWW* → γγlνqq’

ATLAS-CONF-2016-071





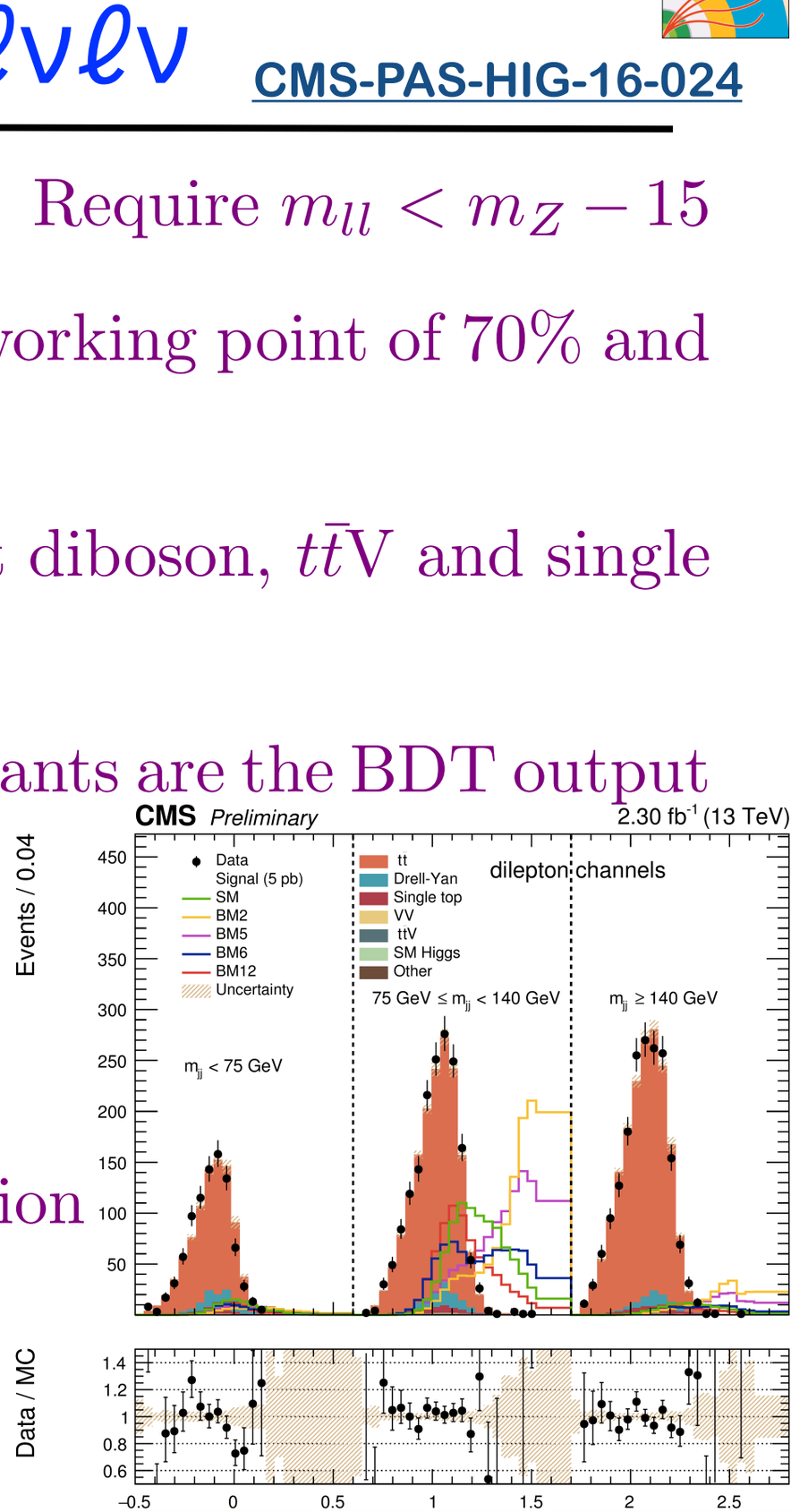
7.88 ± 1.24 events expected

Observed	15

Exclusions	observed	expected
non resonant	25 pb	12.9 pb
resonance m=260GeV	47.7 pb	24.3 pb
resonance m=500GeV	24.7 pb	12.7 pb

hh → bbVV → bb$\ell\nu\ell\nu$ CMS-PAS-HIG-16-024

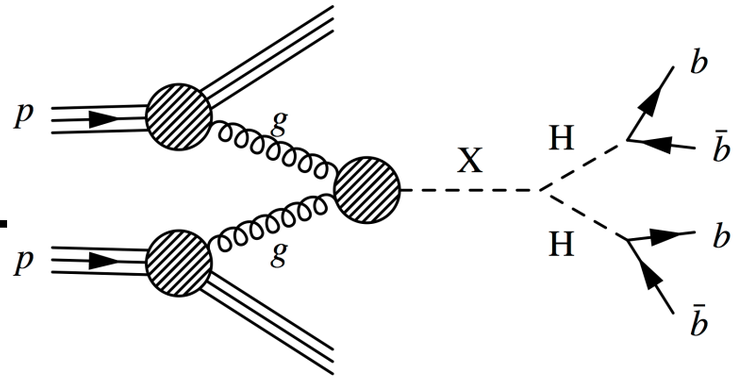
- Trigger on leptons, select events with OS leptons. Require $m_{ll} < m_Z - 15$
- Require $anti-K_t4$ jets, two b-tagged with CSV working point of 70% and fake rate of 1%
- Main BG: $t\bar{t}$, Drell-Yan, single top, sub dominant diboson, $t\bar{t}$V and single SM Higgs → VV or $b\bar{b}$
- Use BDT to improve signal to BG. Final discriminants are the BDT output and m_{jj}
- Binned ML extract best-fit signal cross section
- Upper limit on SM hh → bbVV → bb$l\nu l\nu$ cross section 166.7 fb, about 400 times the SM prediction
- Starts to exclude parts of BSM coupling values



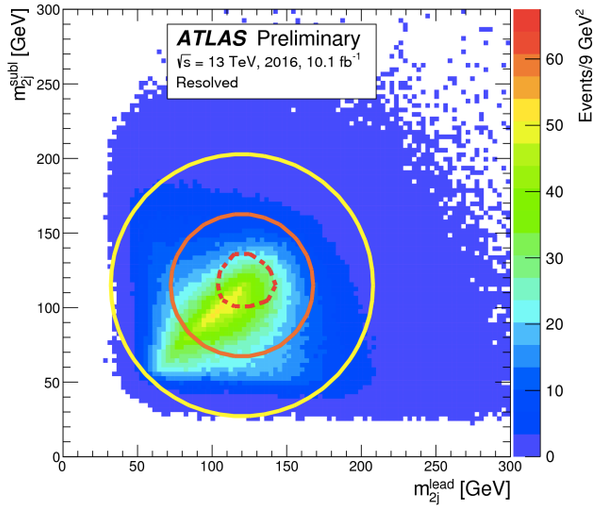
BDT Output in Mjj bins

hh → bb bb

ATLAS-CONF-2016-049



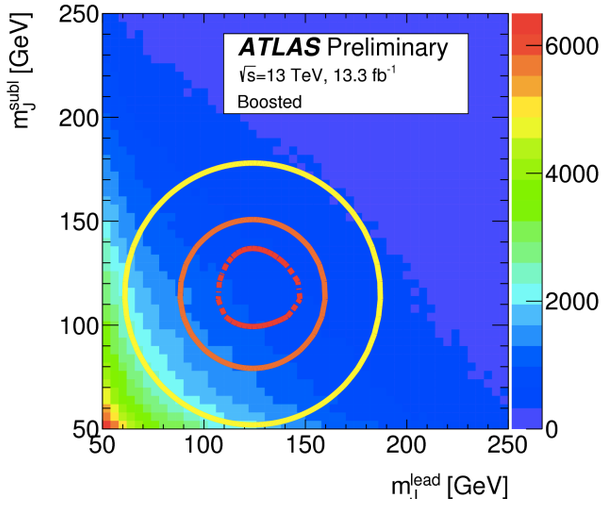
- Highest sensitivity beyond 500 GeV
- Resolved (mH<1 TeV) followed by boosted. Improve acceptance from 2015 by not requiring 2 narrow track jets in the boosted case.
- b-tagging efficiency 70% (77%) c-7.8% (24%) light-0.4%(1.7%)
- Large (95%) multijet BG (data driven estimate). ttbar (MC)

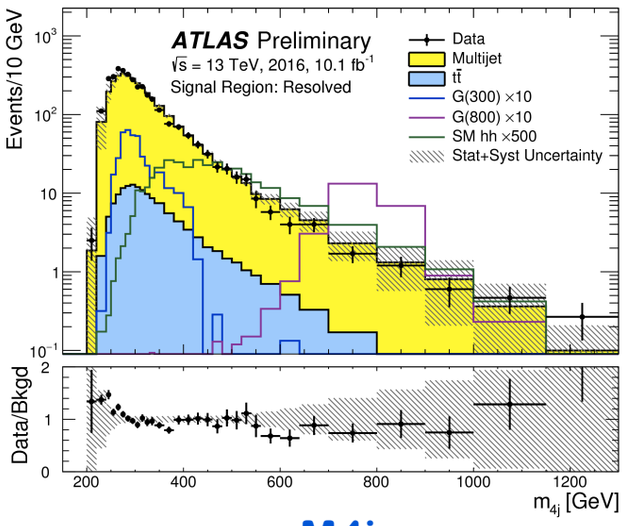


<- resolved

boosted->

multijet bg: subleading, vs the leading dijet mass. **SR** surrounded by the inner black contour line. **CR** inside the outer black contour line, excluding the SR. **Sideband** outside the outer contour line.

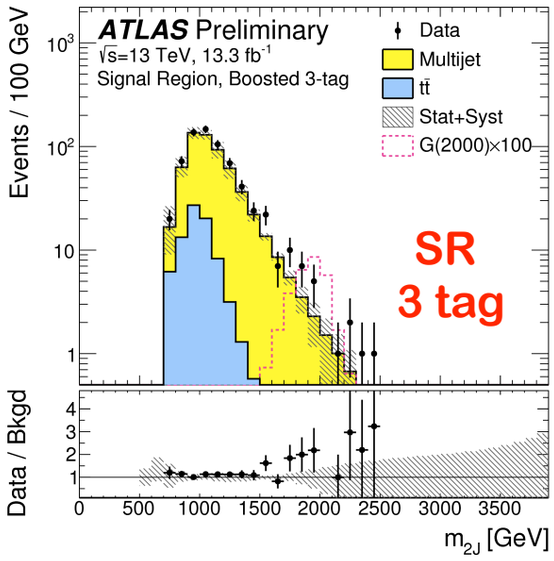


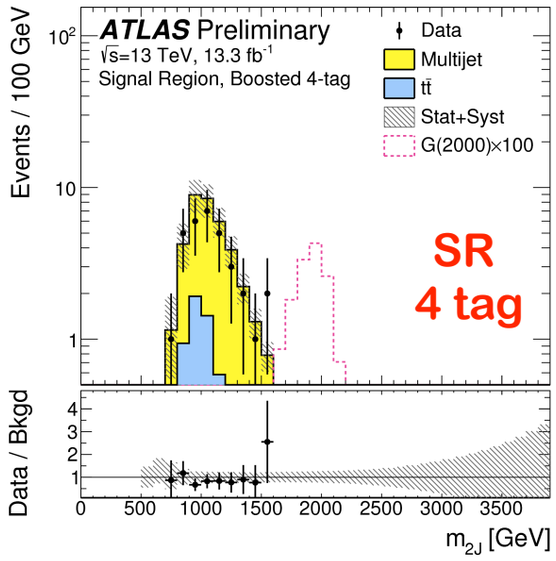


<- (2016)resolved

boosted->

M4j





M2j

ATLAS-CONF-2016-049

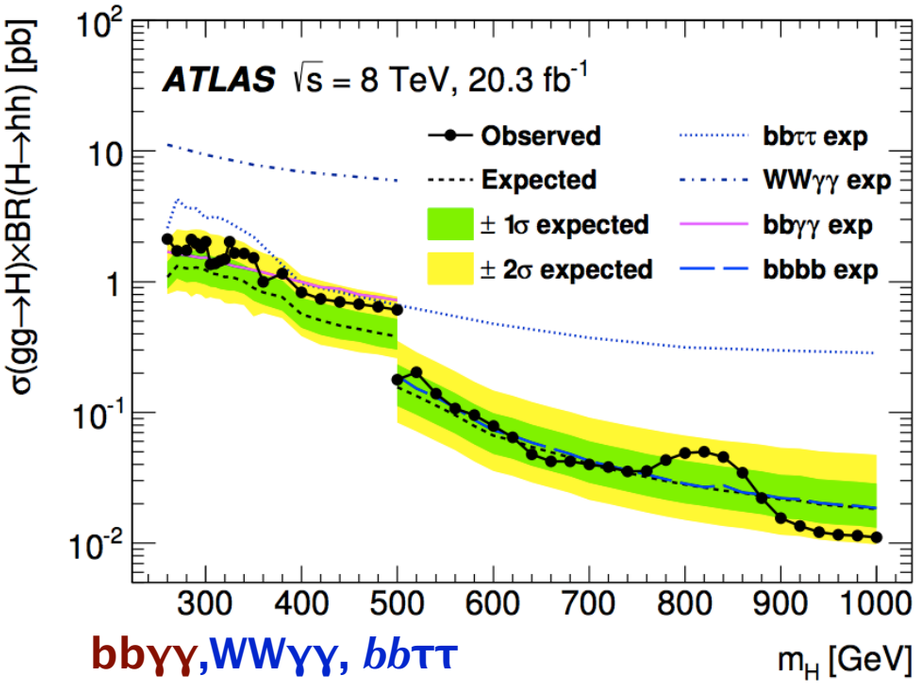
hh → bb bb

<- resolved boosted->

Sample	2015 Signal Region	2016 Signal Region
Multijet	$1\,131 \pm 68$	$3\,670 \pm 200$
$t\bar{t}$	57 ± 34	190 ± 110
Total	$1\,189 \pm 76$	$3\,860 \pm 230$
Data	1 231	3 990
SM hh	0.47 ± 0.12	1.5 ± 0.4
G^*_{KK} (80(	8 ± 3	24 ± 8

Sample	2-tag-split	3-tag	4-tag
Multijet	$2\,310 \pm 240$	515 ± 41	32.6 ± 7.6
$t\bar{t}$	460 ± 170	81 ± 37	5.7 ± 5.2
Total	$2\,770 \pm 130$	596 ± 39	38.3 ± 9.0
Data	2 813	671	32
G^*_{KK} (2 TeV), $k/\bar{M}_{\mathrm{Pl}} = 1$	0.17 ± 0.10	0.31 ± 0.06	0.15 ± 0.06

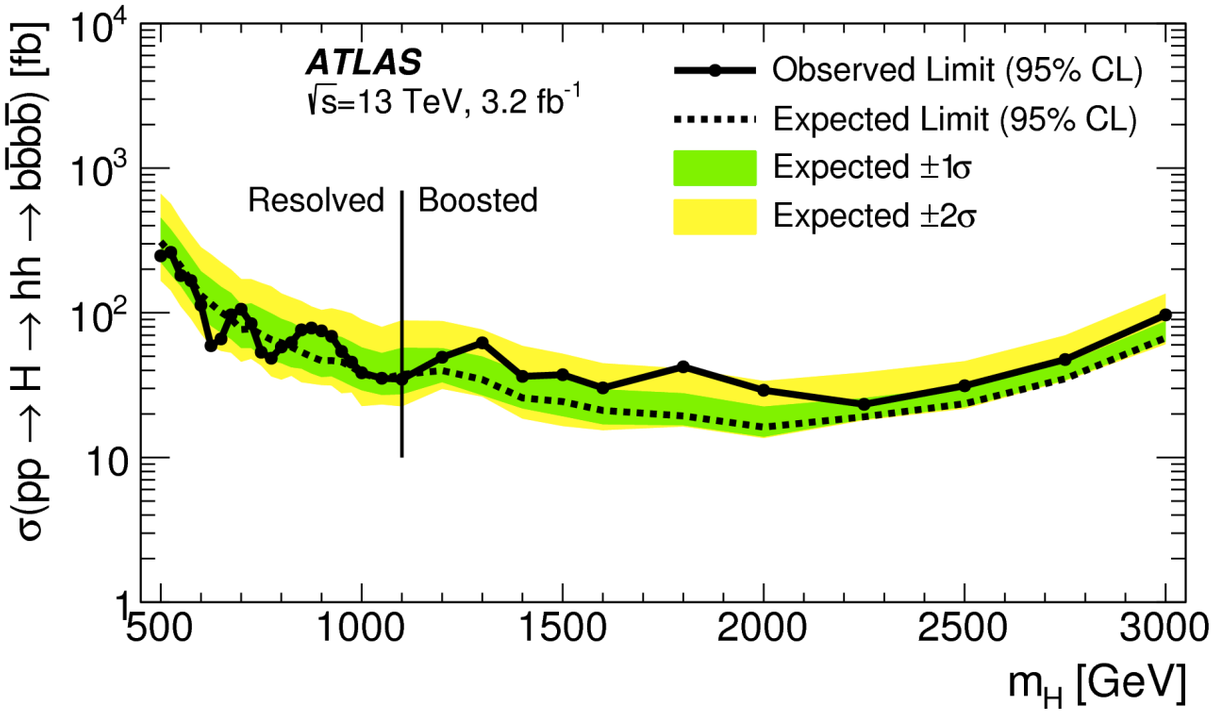
Run-1 combined



bbγγ,WWγγ, *bb*ττ

*bb*bb, *bb*ττ

Run-2, first analysis



ATLAS-CONF-2016-049

hh → bb bb

<- resolved boosted->

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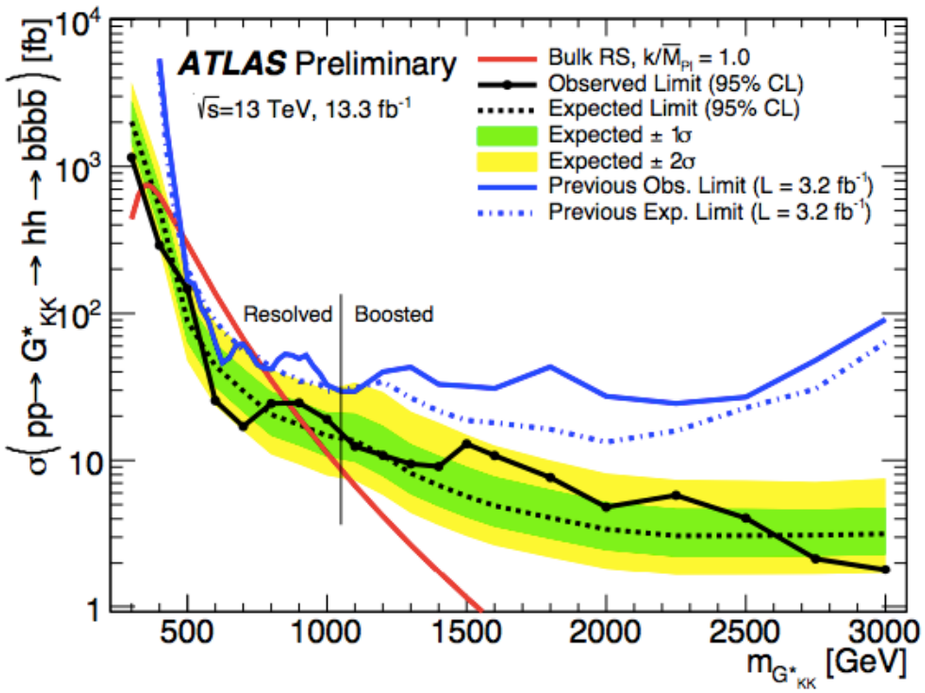
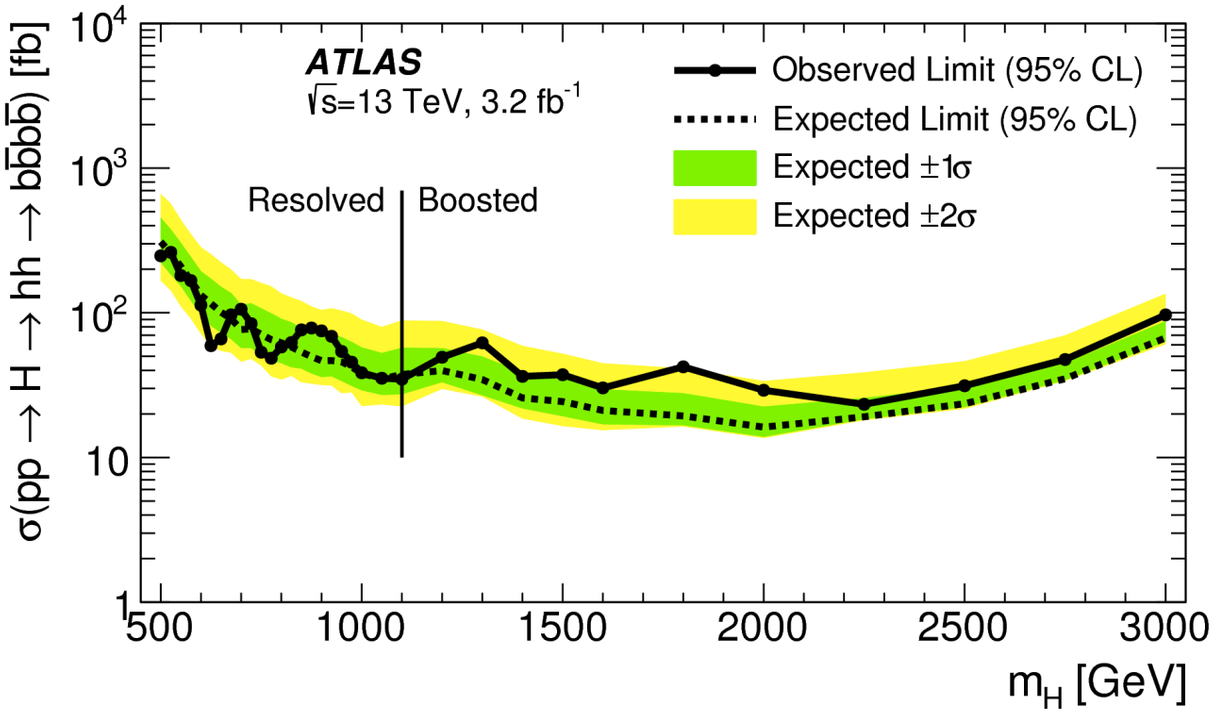
Data	2 813	671	32
G^*_{KK} (2 TeV), $k/\bar{M}_{Pl} = 1$	0.17 ± 0.10	0.31 ± 0.06	0.15 ± 0.06

new bbbb analysis



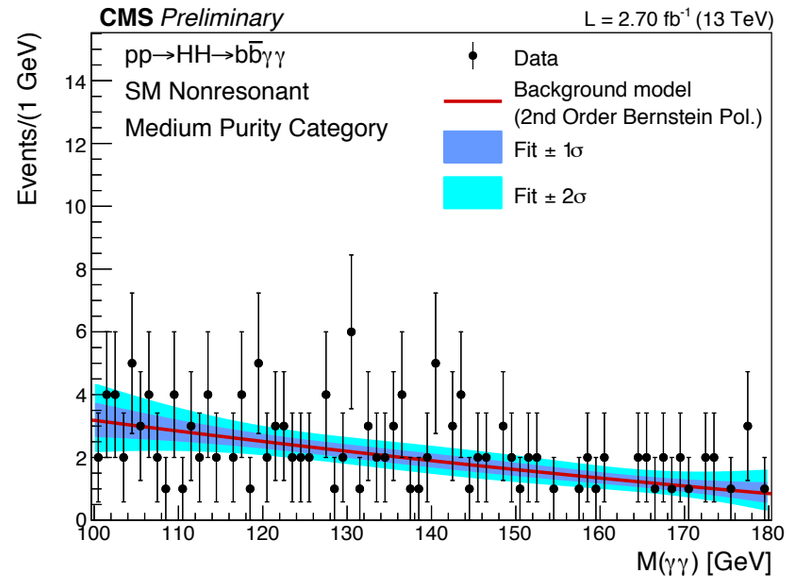
Run-2, first analysis



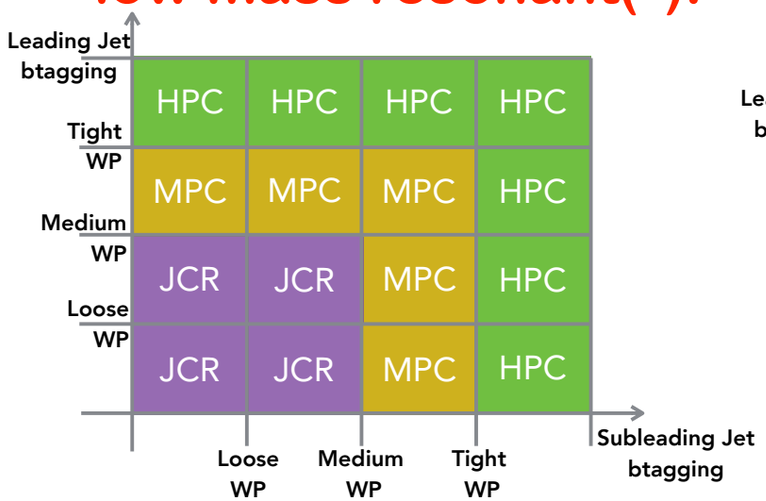
hh → bbγγ

CMS-PAS-HIG-16-032

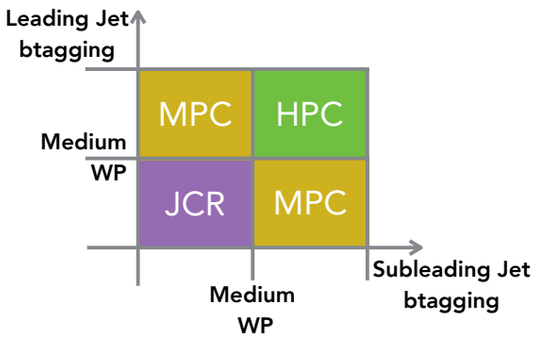
- Separated into low and high mass regions
- Conditions on m_{jj} and $m_{\gamma\gamma}$ around 125 GeV and 4-body mass.
- Perform kinematic fit
- Selection criteria and signal extraction variable optimised very specifically for type of signal
  - Use 2.7/fb of 2015 data
  - Includes both resonant and non resonant interpretations
  - Use of several b-tagging working points to increase sensitivity:



low mass resonant(*):

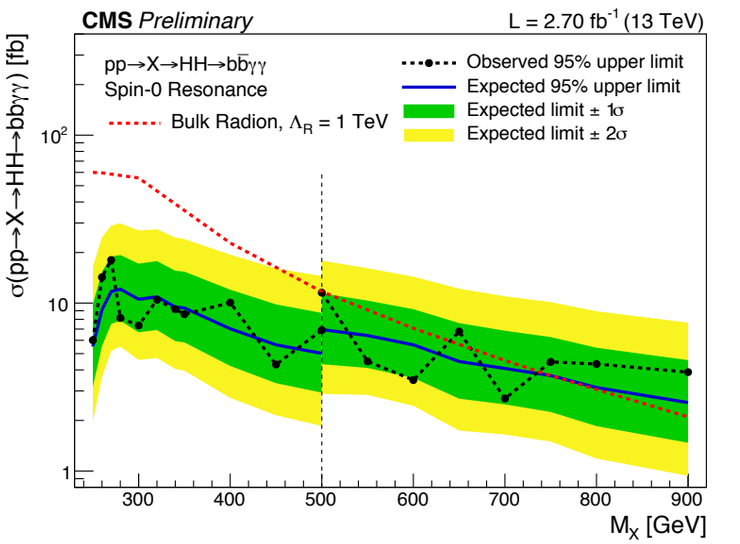


non resonant:



(*) HPC (high purity) and MPC (medium purity) merged for high mass resonant

Still slightly less sensitive than Run 1 even at the highest masses



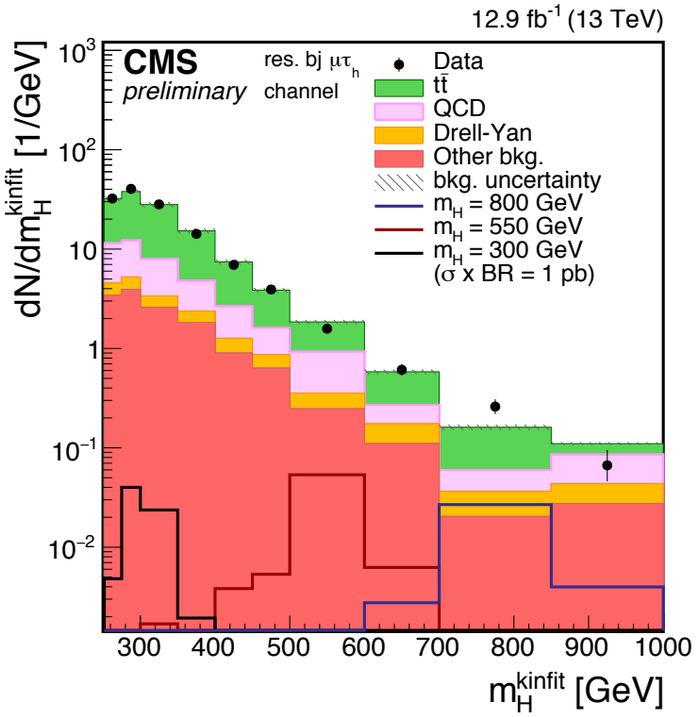
hh → bbττ

CMS-PAS-HIG-16-029

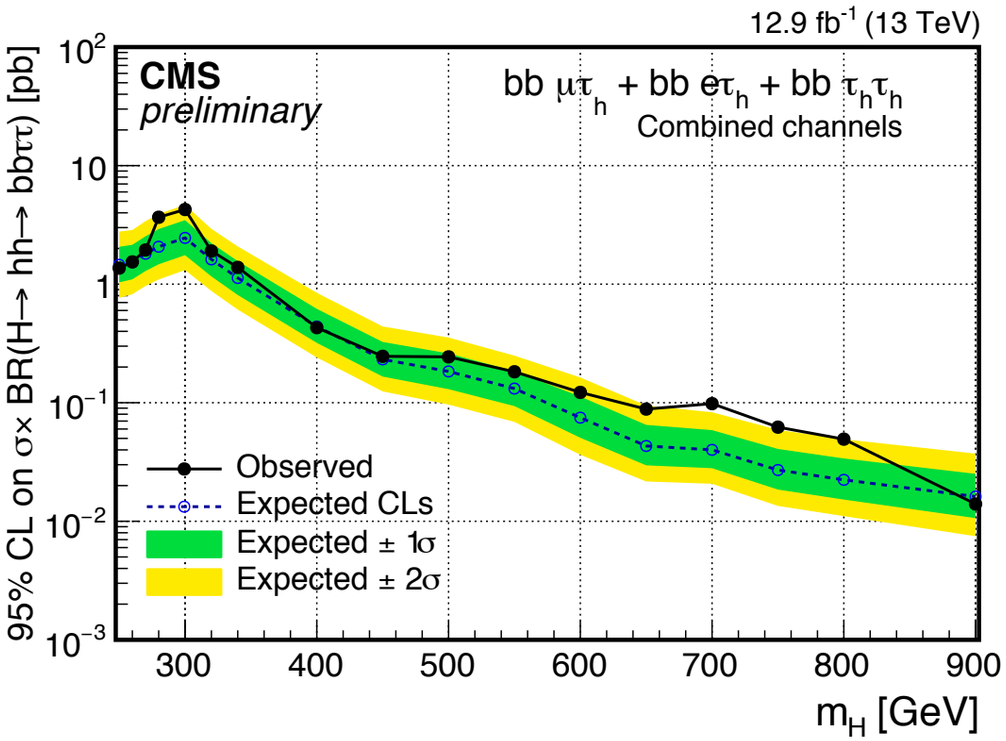
(Non-resonant **CMS-PAS-HIG-16-028**)

Use of h(125) condition:

- **4 body mass reconstructed with kinematic fit**
- **Cuts placed in windows around 125 GeV on m_{bb} and $m_{\tau\tau}$**
- **Extending to higher signal masses - not just MSSM targeted**

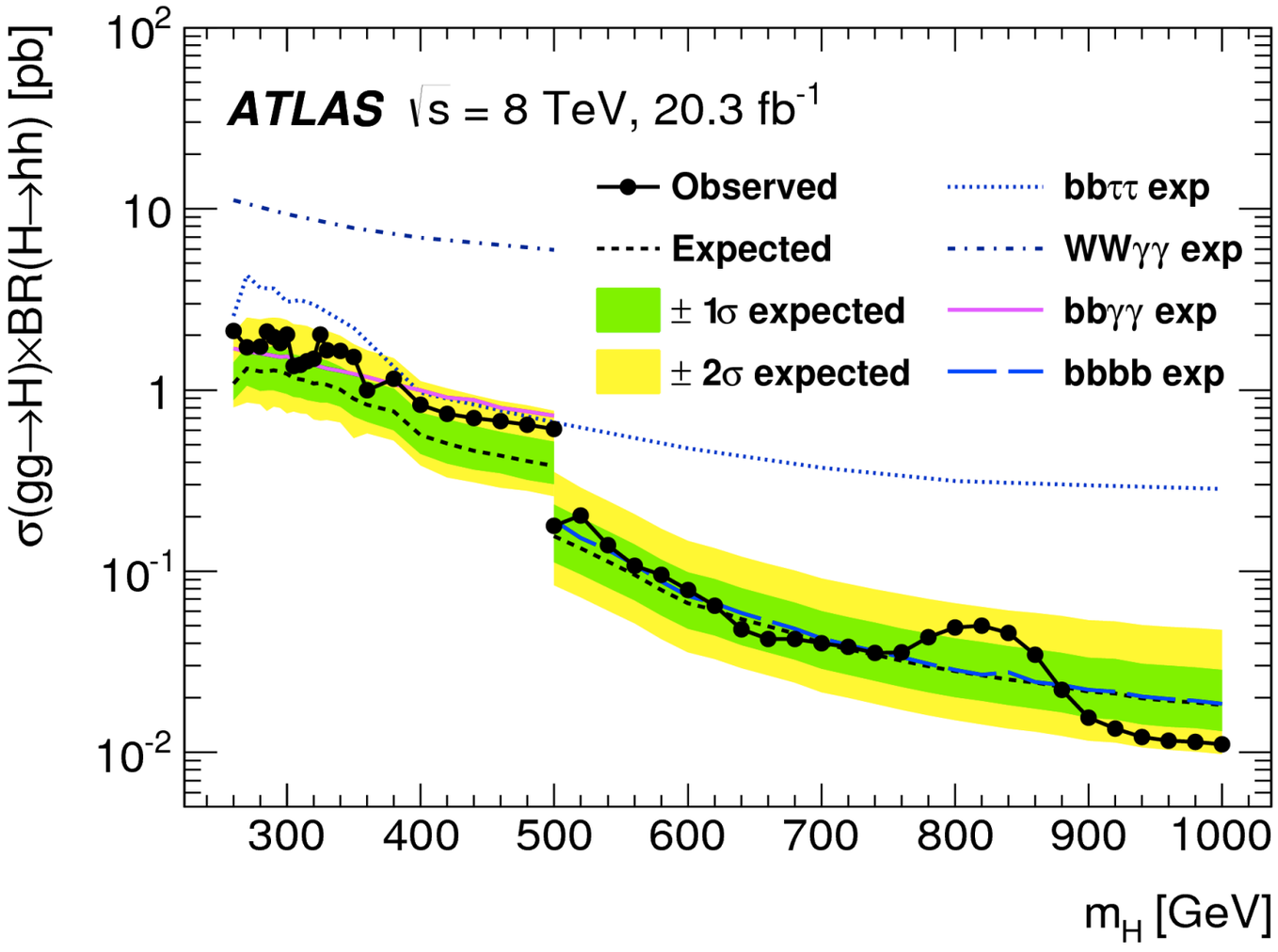


Combine $e\tau_h$ $\mu\tau_h$ $\tau_h\tau_h$ 1tag and 2tag (split into boosted and non boosted)



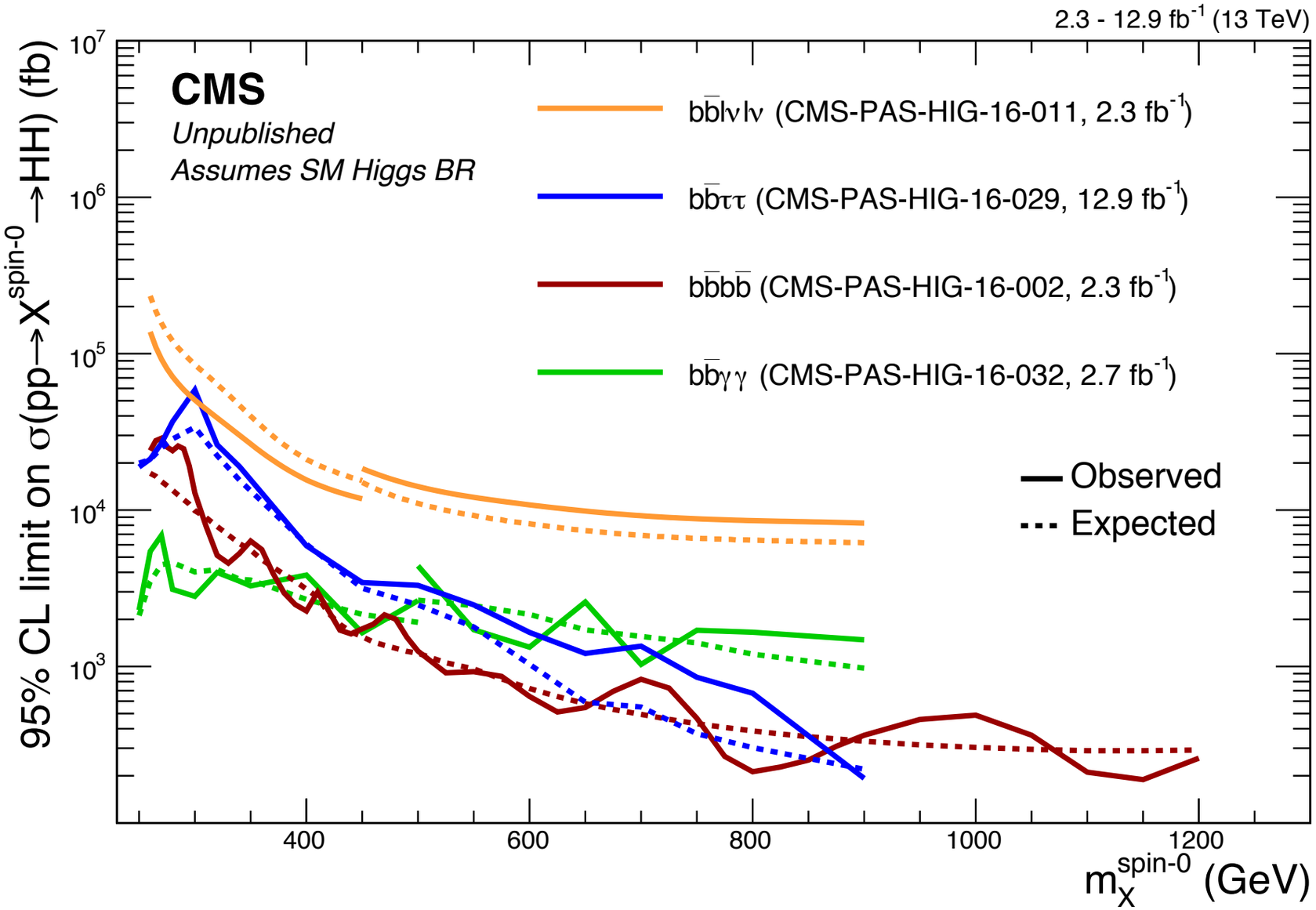
Less sensitive than 8 TeV result in low mass region still (even taking into account 8->13 TeV signal XS enhancement), so no new low-tanβ exclusion yet

Contribution of various channels



Assuming the SM h BRs, can compare the sensitivity of the different channels of the resonant analysis. ATLAS 8 TeV and CMS early 13 TeV

Contribution of various channels



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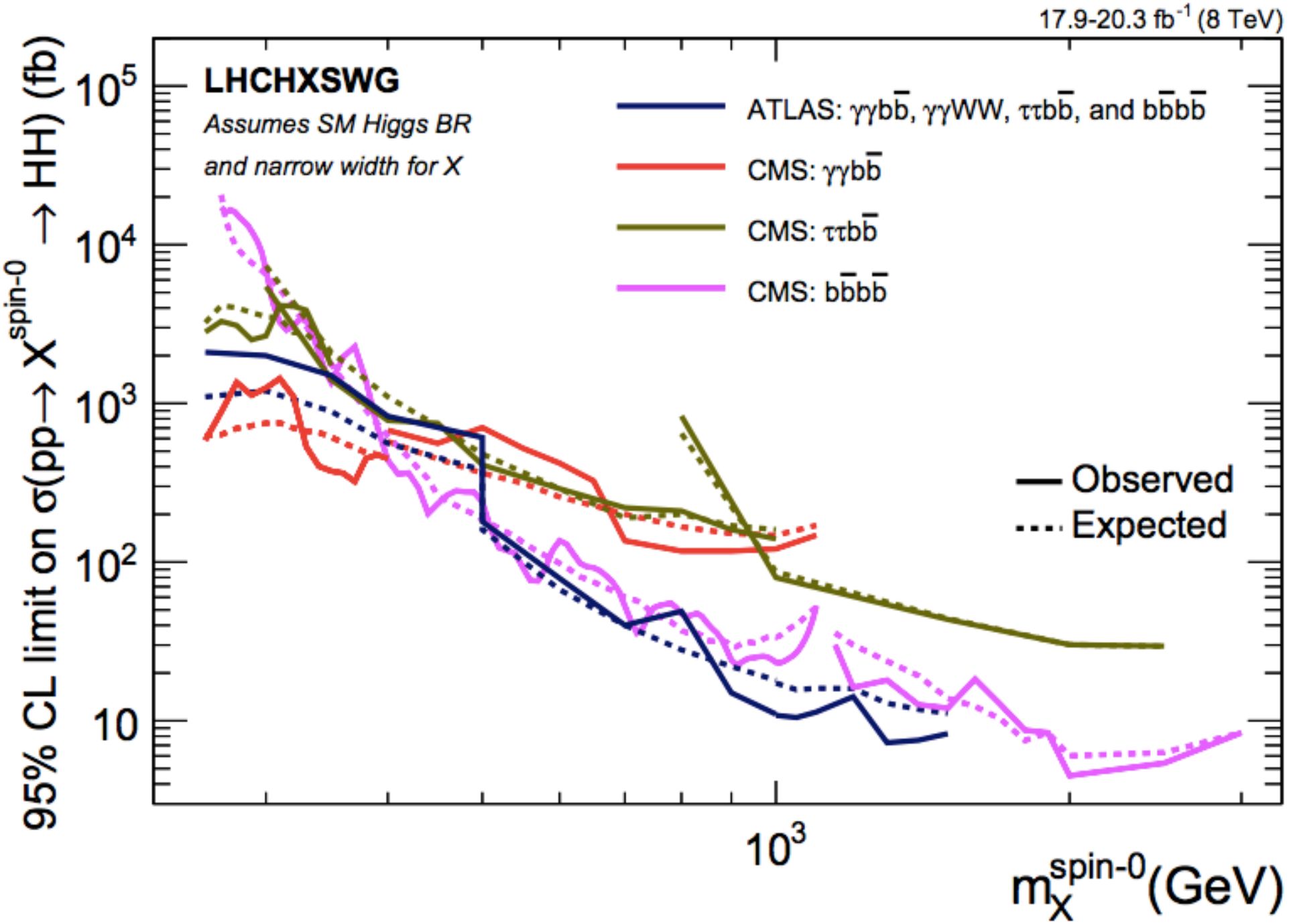
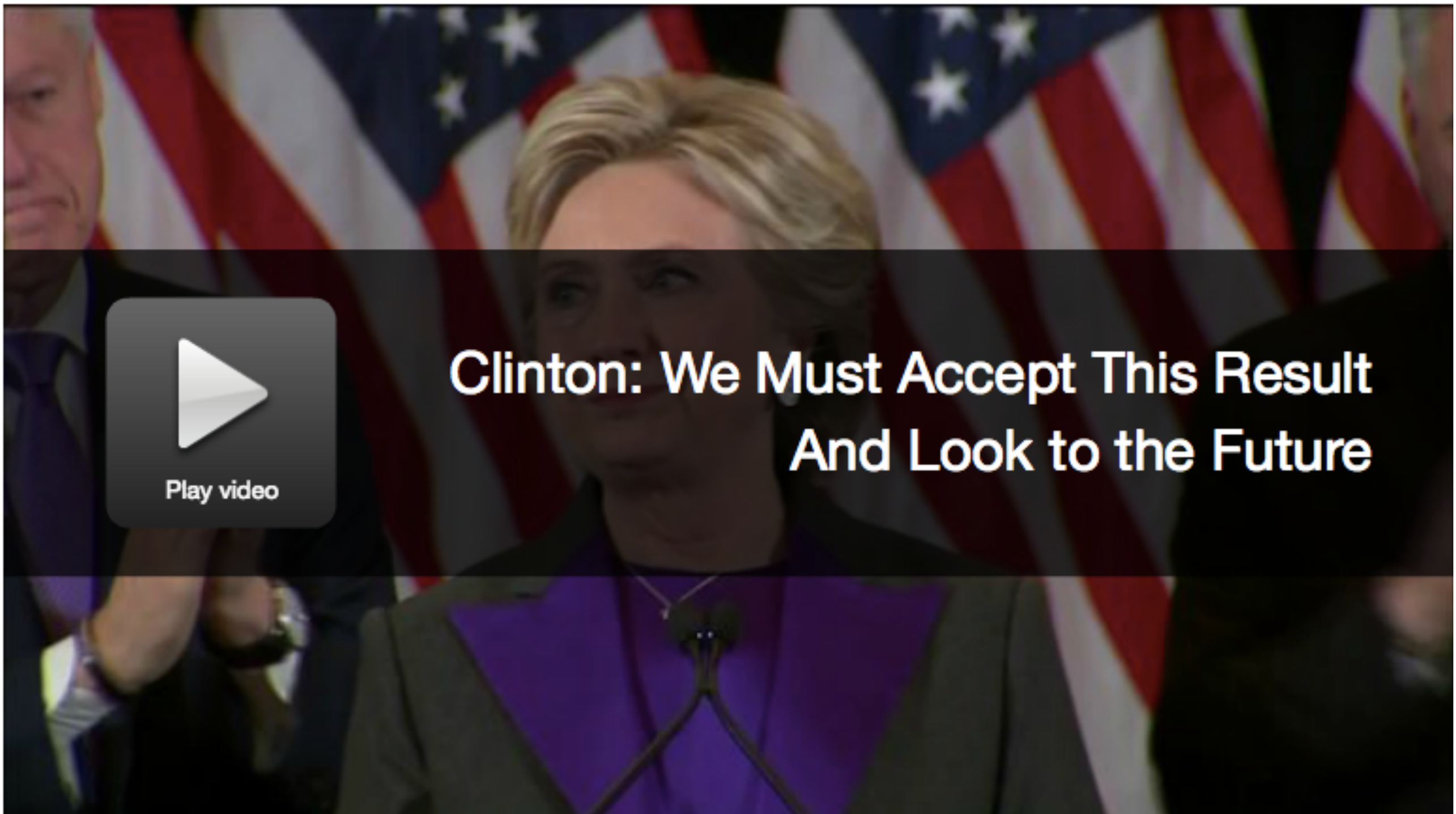


Assuming the SM h BRs, can compare the sensitivity of the different channels of the resonant analysis. ATLAS 8 TeV and CMS early 13 TeV

Some final remarks

- The workshop focuses on measurements of Higgs characteristic as a SM particle or searches for exotic Higgs decays. However, some measurements already use the Higgs as a SM particle to search for other BSM signals!
  - ➡ Benefit from the SM small Higgs Xsec, use the Higgs mass to suppress SM BG.
  - ➡ Prefered channels bb (Br-57.7+/-3.3%), γγ (Br=0.228+5-4.8%), ττ (Br=6.32+/-5.7%), WW & ZZ (lep & had).
- ATLAS and CMS continue with searches for VLT(B), excluding masses ~1 TeV utilising improved boosted top reconstruction techniques.
- Rich search for non resonance HH aiming at (B)SM couplings and BSM resonances searches in the various decay channels.
- Lots of data to come.. Higgs related or not, DM .. any BSM signal is most welcome!

HC delivers final remarks to supporters



BSM + Higgs tags new results (ICHEP++)

➡ Higgs in EXOT/SUSY cascades

- CMS EW prod. of charginos and neutralinos in the WH SUS-16-026
- CMS SUSY with a Higgs to γγ (razor) SUS-16-012
- ATLAS Res. to W/Z + H in qqbb ATLAS-CONF-2016-083 in llbb, lvbb,vvbb arXiv:1607.05621

➡ Vector like quarks

- ATLAS VLQ T' → Zt ATLAS-CONF-2016-101, T'->Wb ATLAS-CONF-2016-102
- ATLAS new phenomena with tt (T' → tH) ATLAS-CONF-2016-104
- CMS VLQ single T' → tH (l+H) B2G-15-108, T' → tH (hadronic) B2G-16-005
- CMS VLQ pair T → boosted tH (leptonic) B2G-16-011

➡ DM searches

- CMS DM + jet / hadronically decaying W/Z CMS PAS EXO-16-037
- ATLAS DM association with a hadronically decaying W/Z arxiv:1608.02372
- ATLAS DM with b quarks ATLAS-CONF-2016-086 top quarks ATLAS-CONF-2016-050 …

➡ Mono Higgs

- ATLAS DM in H(γγ)+MET ATLAS-CONF-2016-087
- ATLAS DM in H(bb)+MET arxiv:1608.04572
- CMS DM in H(γγ)+MET CMS-PAS-EXO-16-011, DM in H(bb)+MET CMS-PAS-EXO-16-012

➡ DiHiggs

- ATLAS hh → bbbb ATLAS-CONF-2016-049 hh → bbyy ATLAS-CONF-2016-004
- ATLAS hh → γγWW* ATLAS-CONF-2016-071
- CMS hh → bbbb resonance B2G-16-008, non res. CMS-PAS-HIG-16-026
- CMS hh → bbττ res. CMS-PAS-HIG-16-029, non res. CMS-PAS-HIG-16-028
- CMS hh → bbγγ CMC-PAS-HIG-16-032 hh in bbℓνℓν CMS-PAS-HIG-16-024