New Physics Results from the LHC: boosted multi-boson signatures

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MBI2018, Aug 28-30, 2018

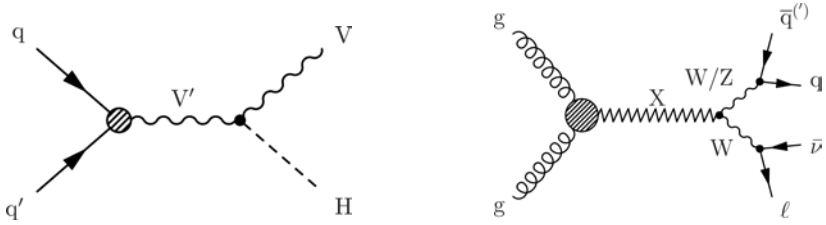
Heavy resonance searches at LHC

The search for new heavy particles is an integral part of the physics program at LHC

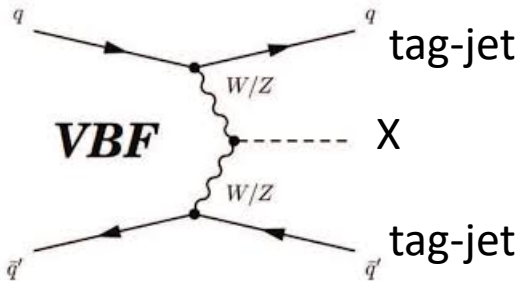
Using generalized models as a benchmarks in **diboson resonance searchers**

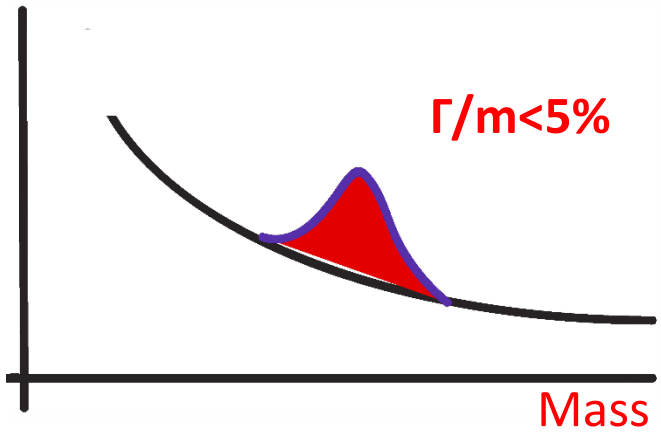
- ❖ 2 Higgs-doublet model (2HDM)
- ❖ Heavy Vector Triplet (W', Z')
- ❖ Warped extra dimensions

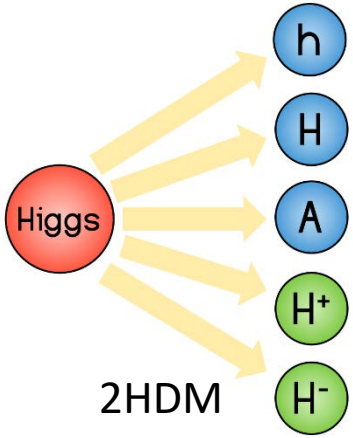
Narrow width resonances

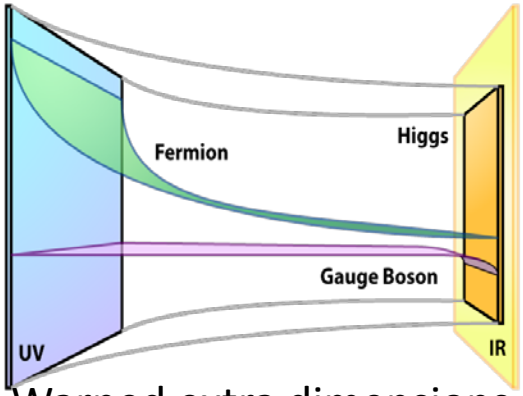


Reconstruction of **boosted V(W,Z,H)** is critical for heavy (TeV scale) diboson resonance searches





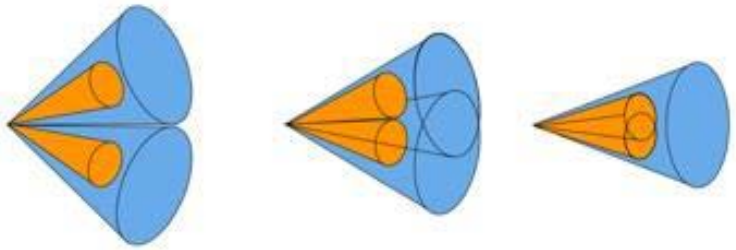




Warped extra dimensions

Boosted hadronic decays

$$R_{qq} \approx 2\frac{M_V}{p_T^V}$$

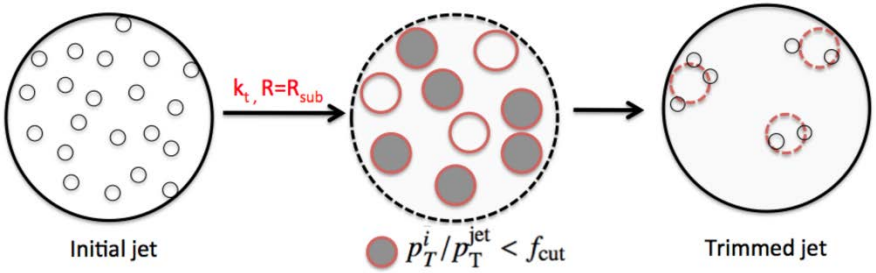


Large-*R* jet: anti-k_T R = 1.0

Track-CaloClusters ATL-PHYS-PUB-2017-015

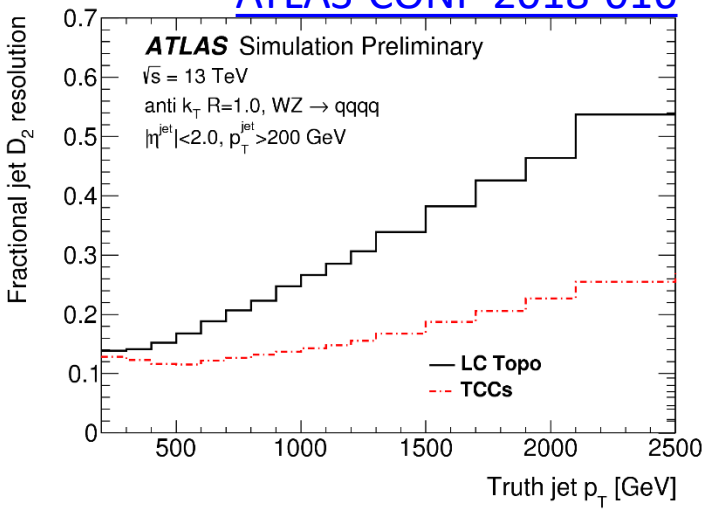
Jet grooming technique: *trimming*

- To remove the effects of pile-up and underlying event
- Trimming parameters: R_{sub} = 0.2 and f_{cut} = 0.05

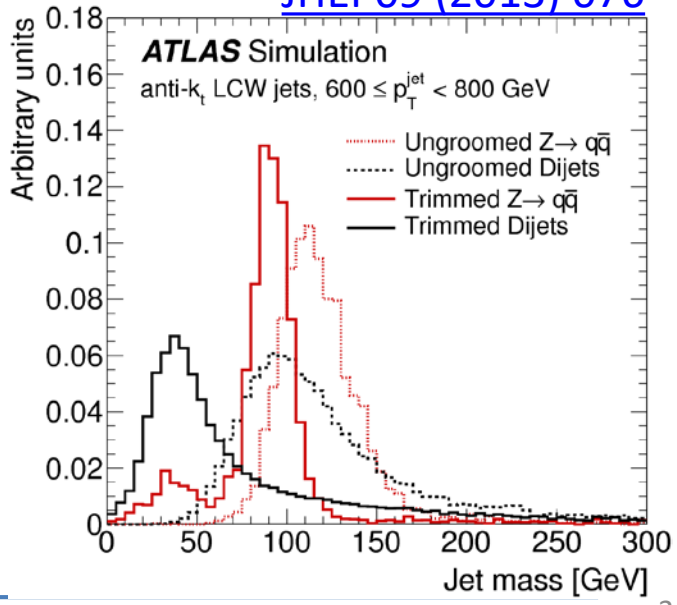


minimum transverse momentum fraction > f_{cut}

ATLAS-CONF-2018-016



JHEP09 (2013) 076



V/H-tagging

ATLAS-CONF-2018-016
ATLAS-CONF-2016-039

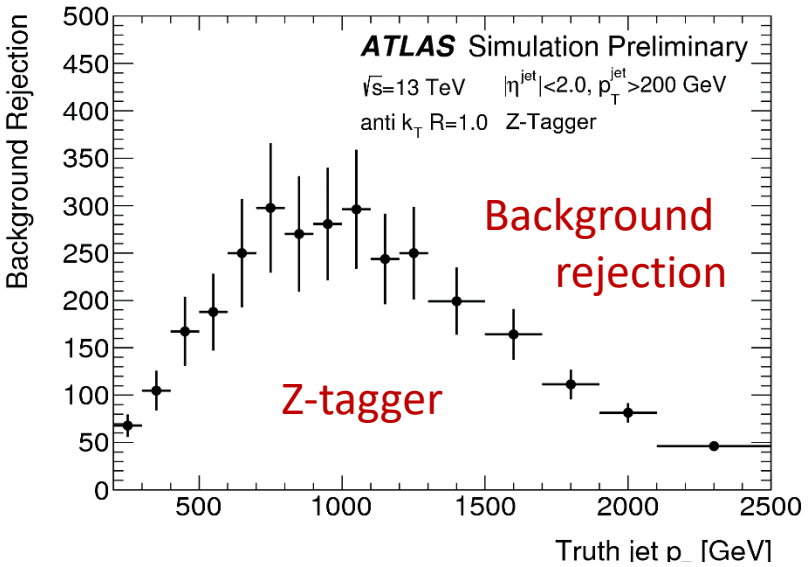
Jet substructure: energy correlation D_2

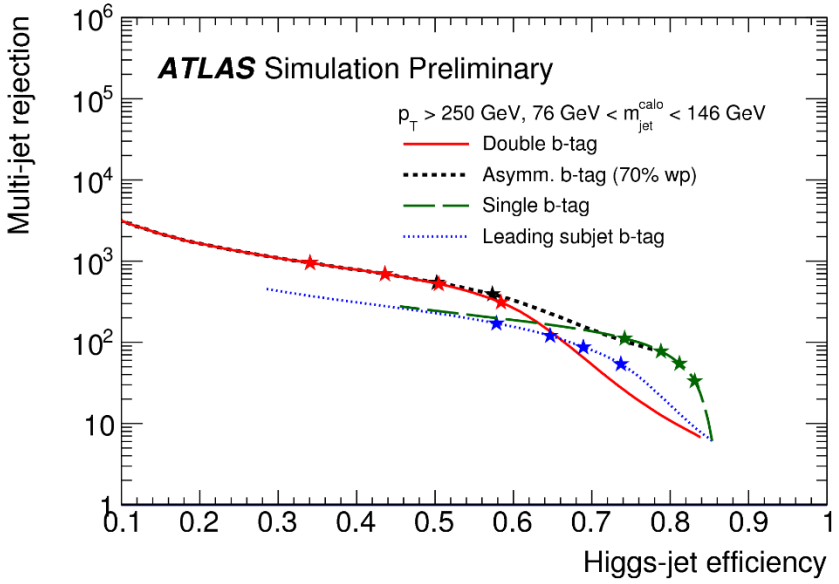
***W/Z-jet* tagger:**

- Large-R jet **mass window and D_2** selection (p_T dependent)
- **Working points**: *50%* and *80%* constant signal efficiency in wide range: 200-2500 GeV

Higgs-jet tagger:

- Large-*R* jet **mass window** cut
- ***b*-tagging** of track jet (R=0.2), MV2c10 algorithm





The stars correspond to the 60%, 70%, 77% and 85% b-tagging WPs (from left to right).

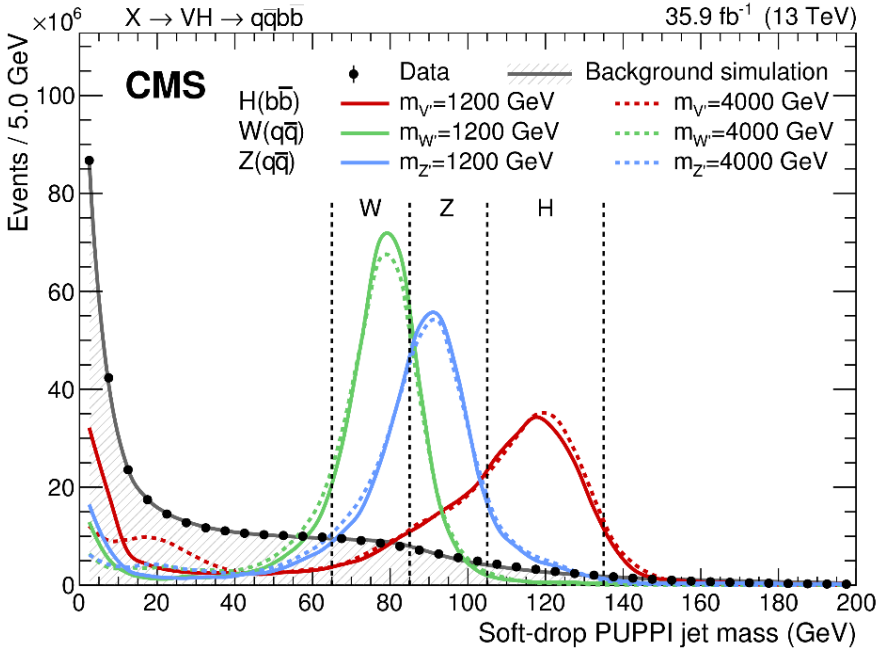
Boosted hadronic decays

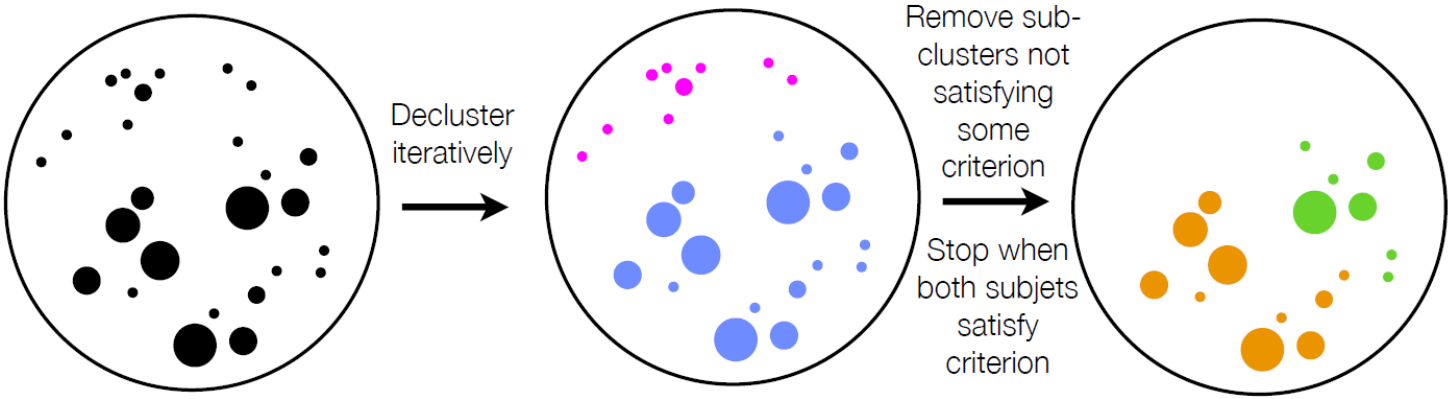
Eur. Phys. J. C 77 (2017) 636

Large-R jets : anti-k_T, R = 0.8 with **p**ileup **p**er **p**article **i**dentification (PUPPI)

Jet mass — **soft-drop** algorithm:

➢ Recursively removes soft wide-angle radiation from a jet





V/H-tagging

[Eur. Phys. J. C 77 (2017) 636]

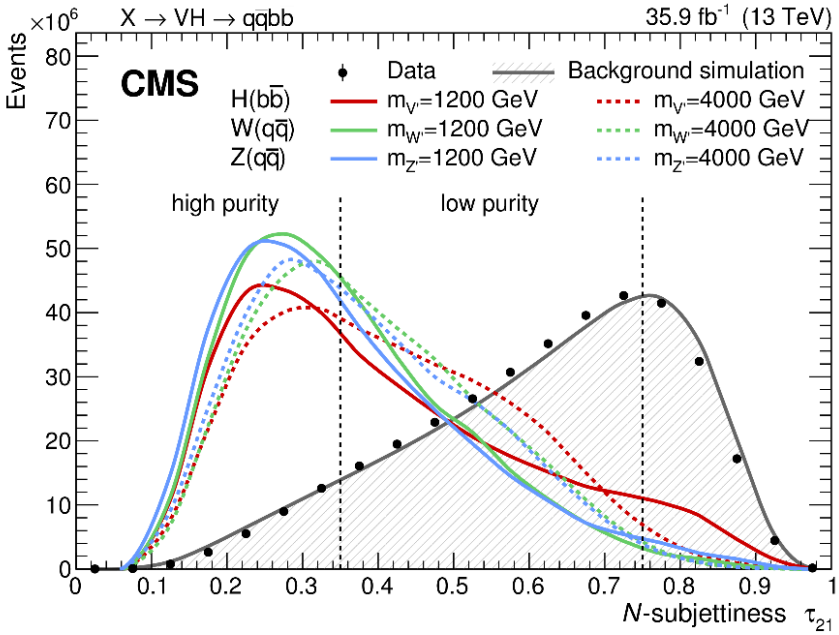
Jets substructure :

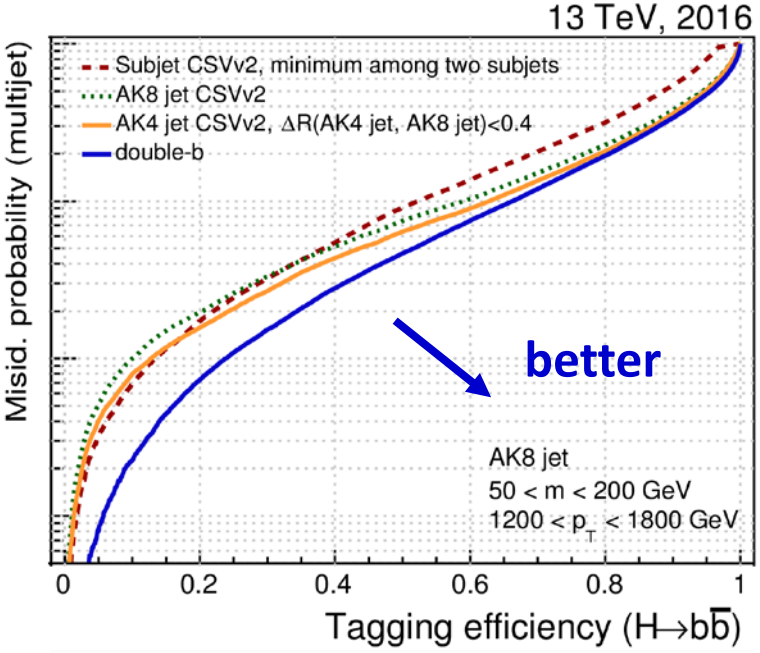
- ***N*-subjettiness** : $\tau_{21} = \tau_2/\tau_1$ separating bosons jets from q/g jets;
  - ✓ high- and low-purity regions based on the value of τ_{21}

W/Z-jet tagging: mass window, τ_{21} selection

Higgs-jet tagging: mass window, τ_{21} selection

- **double-*b* tagger:** MVA discriminant. “loose” and “tight” working point





All Hadronic decays

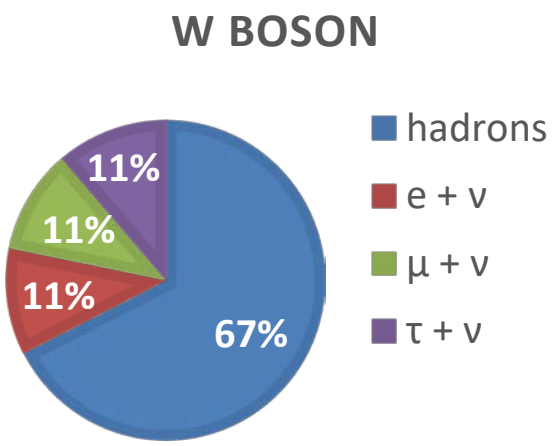
All-hadronic decays

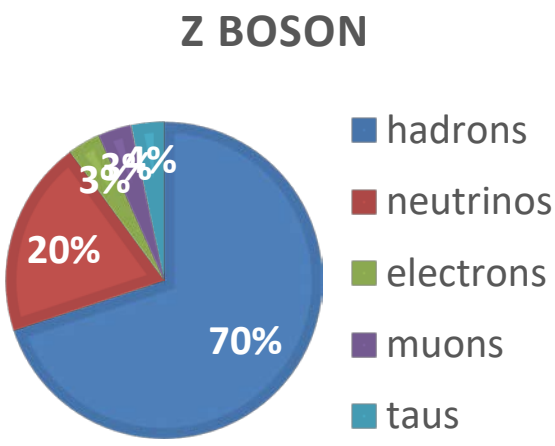
The advantage:

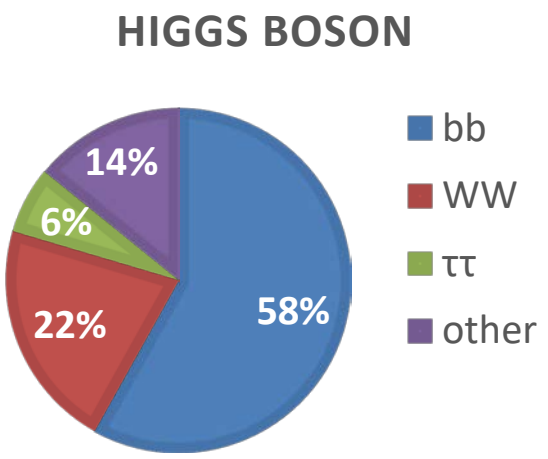
- Largest **branching fraction**.
- Simpler background composition – **mostly QCD multijets**(>90%).
- Smoothly falling $\mathbf{m_{VV}}$ spectra – well **modeled by parametric functions**

Challenges:

- Overwhelming **multijet background**
- Lower mass searches limited by **triggers** (higher pt thresholds)

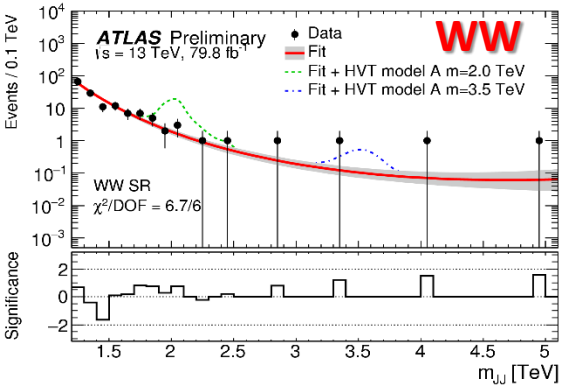


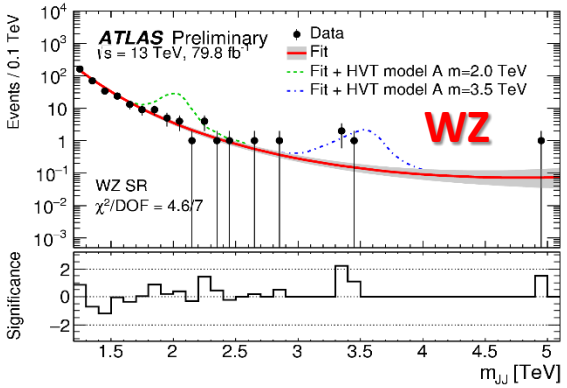


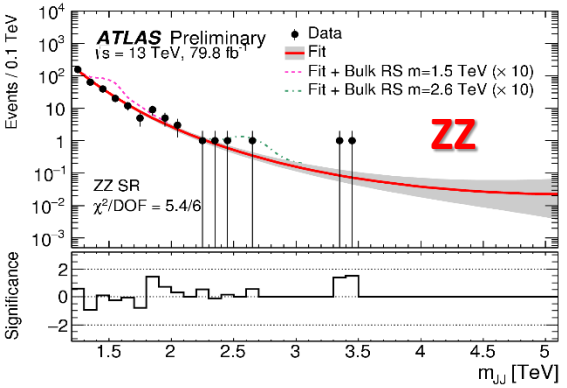


X→VV→qqqq

ATLAS-CONF-2018-016
PRD 97 (2018) 072006

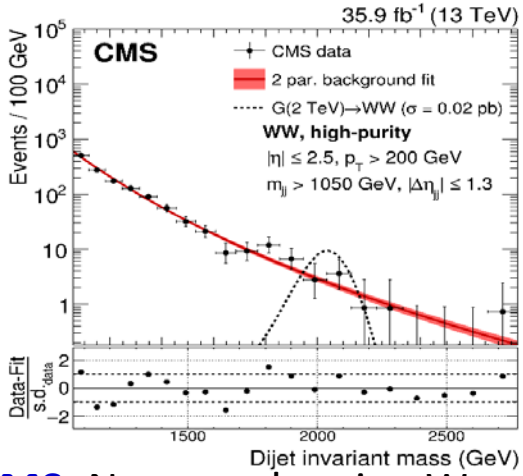


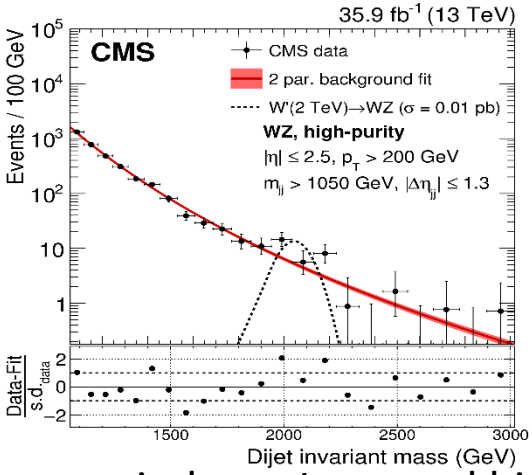


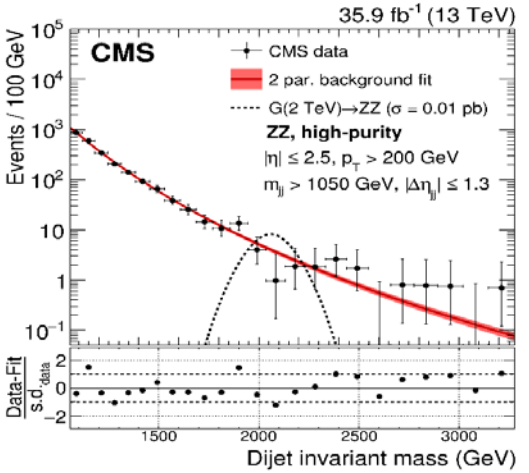


ATLAS: $W \to qq \to J$ and $Z \to qq \to J$ mass windows partially overlap; 50% efficiency WP

Background Modeling : $\frac{dn}{dx} = p_1(1-x)^{p_2-\xi p_3} x^{-p_3}$



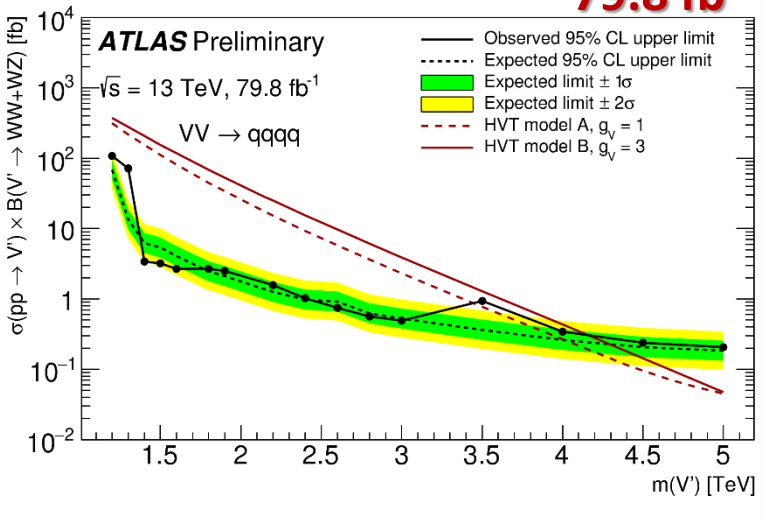




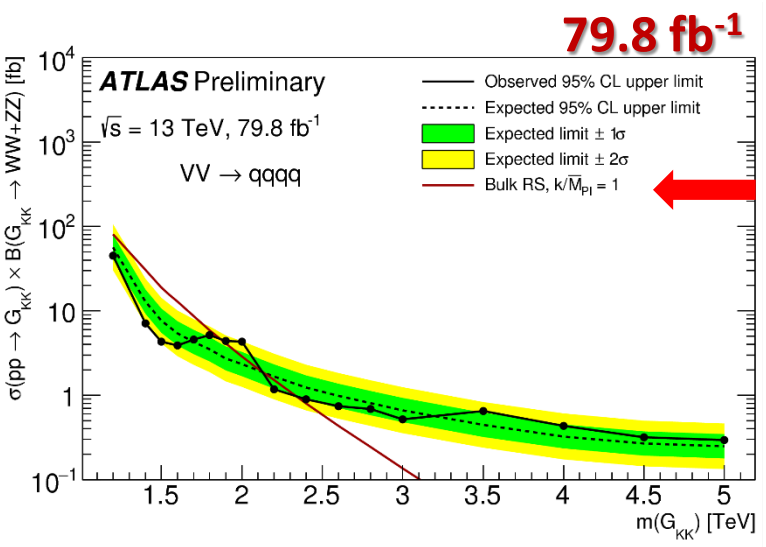
CMS: Non-overlapping W and Z mass windows. Low- and high-purity categories in N-subjetiness. Background Modeling : $\frac{dN}{dm_{jj}} = \frac{P_0}{(m_{jj}/\sqrt{s})^{P_1}}$

X→VV→qqqq

79.8 fb^{-1}



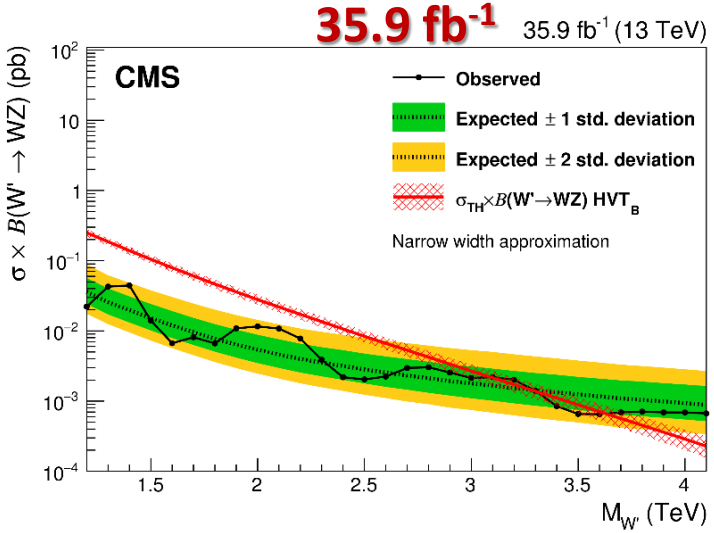
79.8 fb^{-1}



k/MPl =1

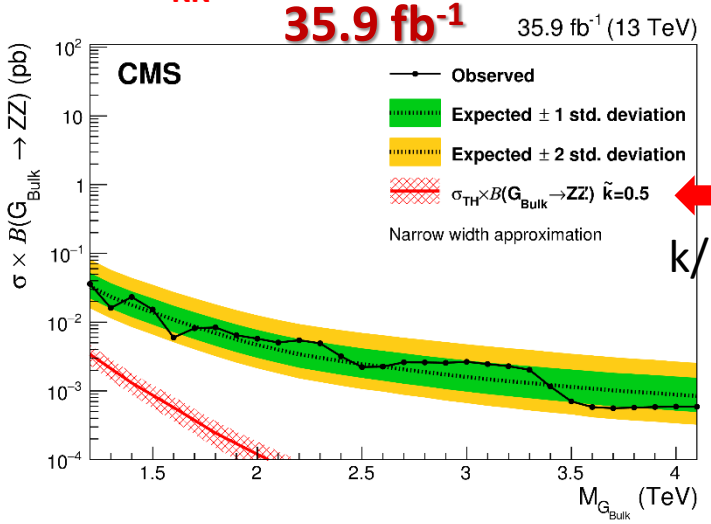
HVT model A and/or B

35.9 fb^{-1}



G_{KK} → WW and/or ZZ

35.9 fb^{-1}



k/MPl =0.5

X→VH→qqbb

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Signature: 2 large-R jets
W/Z and Higgs bosons decay hadronically
Dominant background: multi-jets
Additional handle: b-tag for H->bb

ATLAS:

Categorize according the **number of b-tag track jets (1 and 2)** associated with the Higgs candidate. 1-tag is more efficient from m_{VV}>2.5 TeV when the two track jets merge into one.

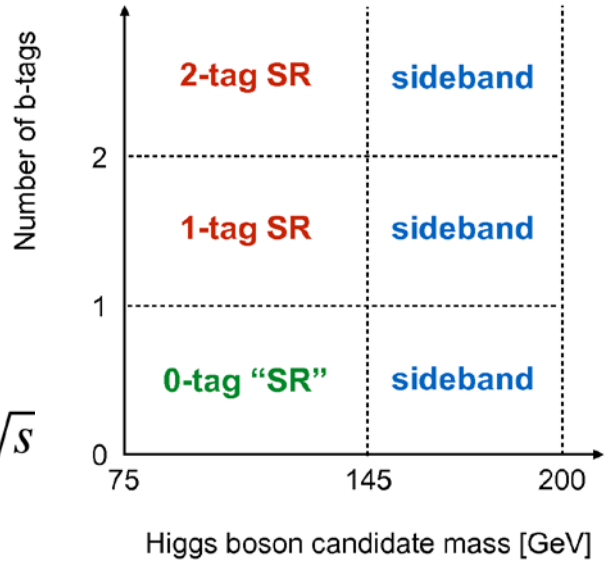
CMS:

Signal regions with **loose and tight double-b tag** for the Higgs candidate.
Low- and high-purity in N-subjetiness. Loose b-tag and low-purity help with sensitivity of the search at higher resonance mass.
W mass and Z mass categories.

X→VH→qqbb

ATLAS:

- 0-tag sample(99% multijet) is used to **model the kinematics** in the signal regions (1-,2-tags).
- high-mass sideband in $m_{J,H}$ is used for the **normalization**
- The **background modeling is validated** in sideband region for the V-jet mass.
- $f_{\text{Multijet}}(x) = p_a(1-x)^{p_b}(1+x)^{p_c x}$, $x = m_{JJ}/\sqrt{s}$
- **tt and V+jets** are also modeled with parametric function



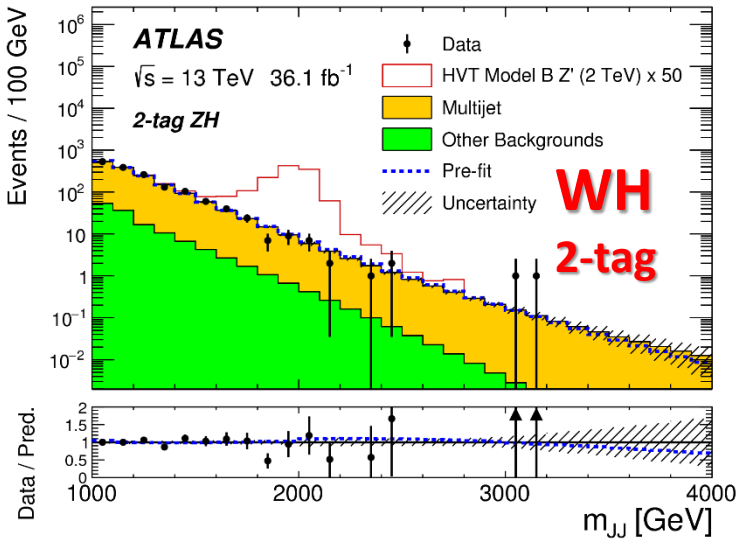
CMS:

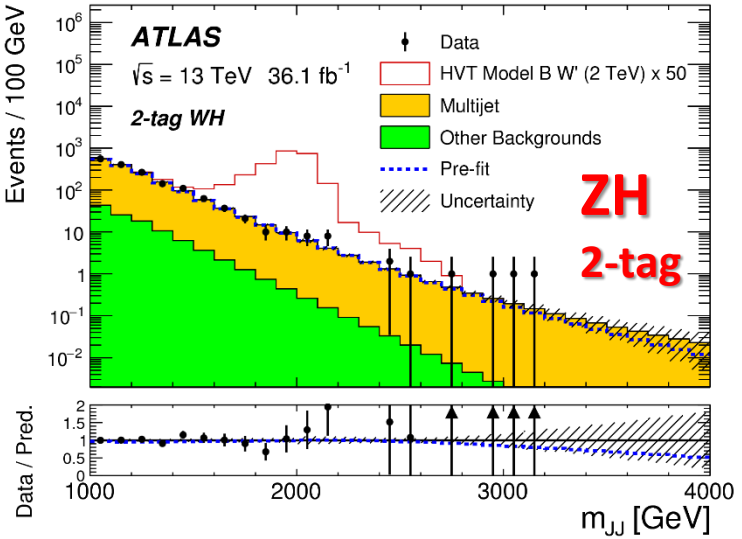
- Background (>95% multijets) is estimated directly from data using smooth, monotonic **parametric functions**. **Validated** in V-jet mass sideband and on simulation.

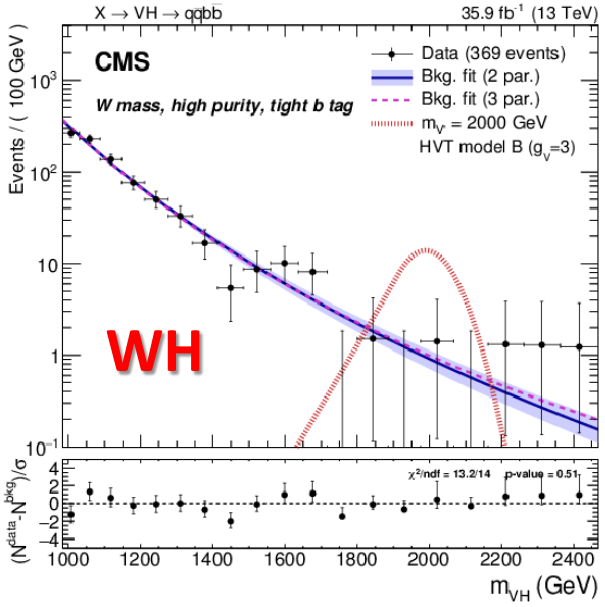
$$\frac{p_0}{x^{p_1}}, \quad \frac{p_0\,(1-x)^{p_1}}{x^{p_2}}, \quad \frac{p_0\,(1-x)^{p_1}}{x^{p_2+p_3\,\log(x)}}, \qquad x = m_{\text{VH}}/\sqrt{s}$$

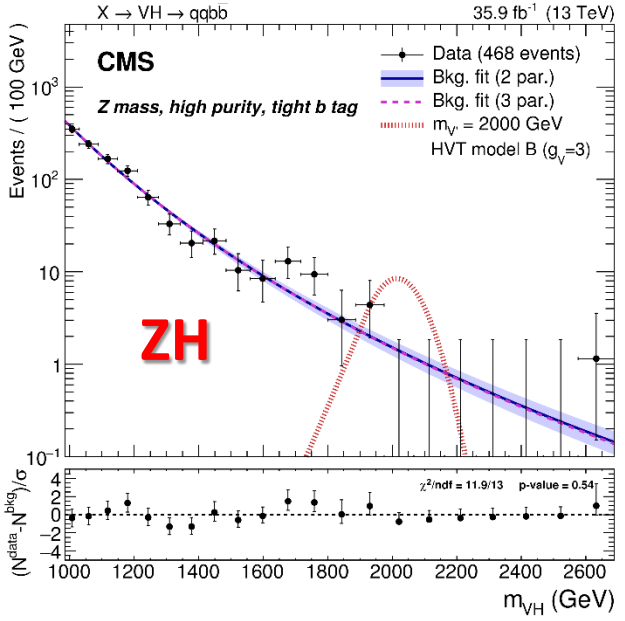
Preferred for low-purity and loose b-tag categories

X→VH→qqbb

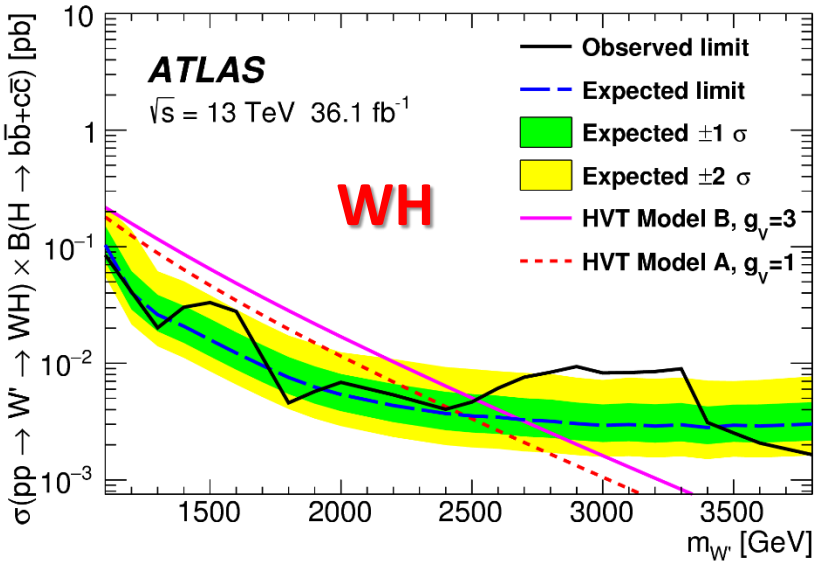

ATLAS
√s = 13 TeV 36.1 fb-1
2-tag ZH
Data
HVT Model B Z' (2 TeV) x 50
Multijet
Other Backgrounds
Pre-fit
Uncertainty
WH
2-tag
Events / 100 GeV
Data / Pred.
mJJ [GeV]

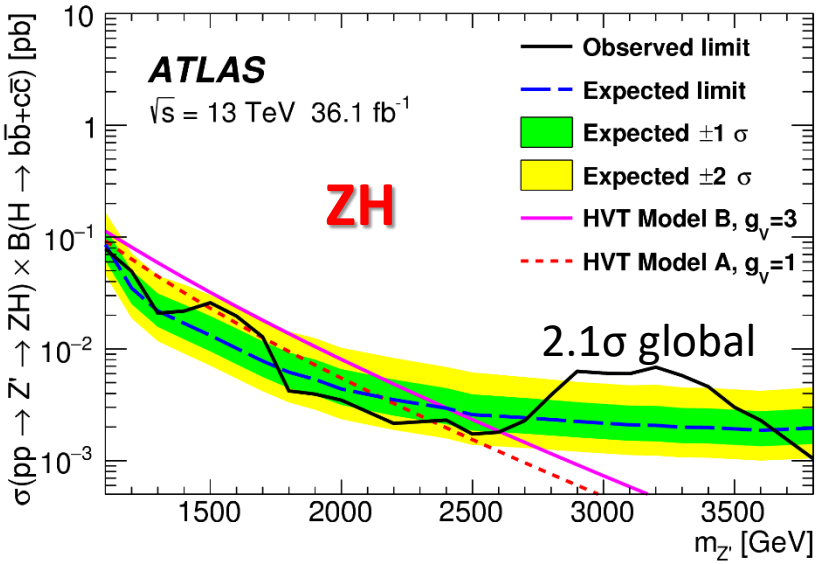

ATLAS
√s = 13 TeV 36.1 fb-1
2-tag WH
Data
HVT Model B W' (2 TeV) x 50
Multijet
Other Backgrounds
Pre-fit
Uncertainty
ZH
2-tag
Events / 100 GeV
Data / Pred.
mJJ [GeV]

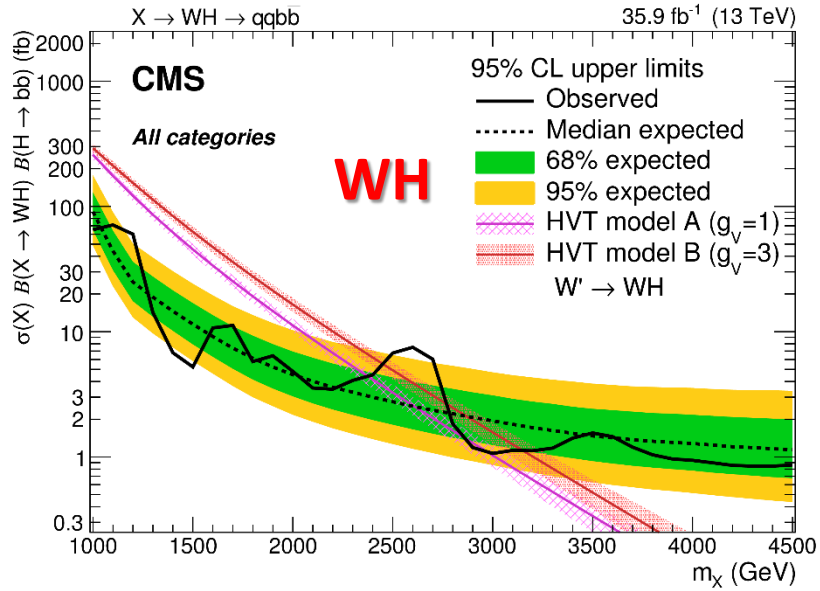

X → VH → qqbb
35.9 fb-1 (13 TeV)
CMS
W mass, high purity, tight b tag
Data (369 events)
Bkg. fit (2 par.)
Bkg. fit (3 par.)
mV' = 2000 GeV
HVT model B (gV=3)
WH
χ2/ndf = 13.2/14
p-value = 0.51
Events / (100 GeV)
(Ndata-Nbkg)/σ
mVH (GeV)

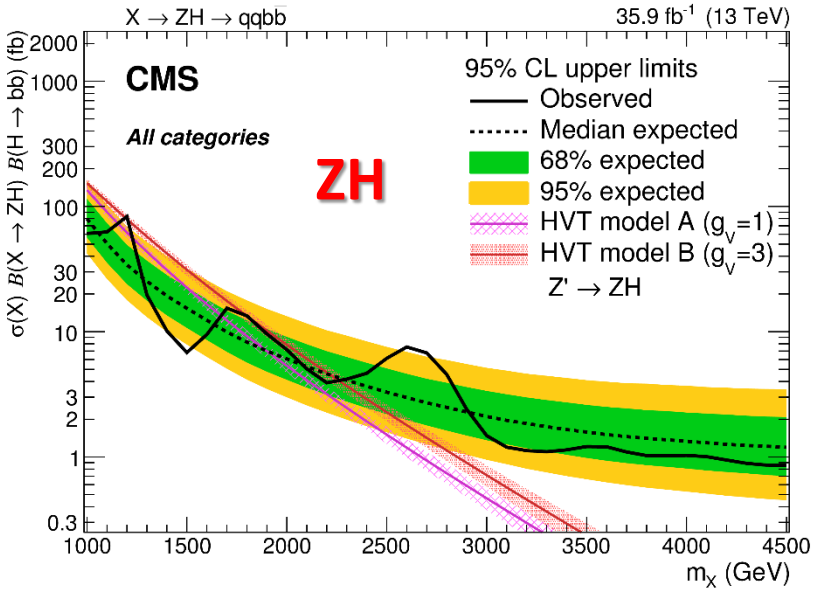

X → VH → qqbb
35.9 fb-1 (13 TeV)
CMS
Z mass, high purity, tight b tag
Data (468 events)
Bkg. fit (2 par.)
Bkg. fit (3 par.)
mV' = 2000 GeV
HVT model B (gV=3)
ZH
χ2/ndf = 11.9/13
p-value = 0.54
Events / (100 GeV)
(Ndata-Nbkg)/σ
mVH (GeV)

X→VH→qqbb


ATLAS
√s = 13 TeV 36.1 fb-1
WH
Observed limit
Expected limit
Expected ±1 σ
Expected ±2 σ
HVT Model B, gV=3
HVT Model A, gV=1
σ(pp → W' → WH) × B(H → bb̄+cc̄) [pb]
mW' [GeV]


ATLAS
√s = 13 TeV 36.1 fb-1
ZH
Observed limit
Expected limit
Expected ±1 σ
Expected ±2 σ
HVT Model B, gV=3
HVT Model A, gV=1
2.1σ global
σ(pp → Z' → ZH) × B(H → bb̄+cc̄) [pb]
mZ' [GeV]


X → WH → qqbb
35.9 fb-1 (13 TeV)
CMS
All categories
WH
95% CL upper limits
Observed
Median expected
68% expected
95% expected
HVT model A (gV=1)
HVT model B (gV=3)
W' → WH
σ(X) B(X → WH) B(H → bb) (fb)
mX (GeV)


X → ZH → qqbb
35.9 fb-1 (13 TeV)
CMS
All categories
ZH
95% CL upper limits
Observed
Median expected
68% expected
95% expected
HVT model A (gV=1)
HVT model B (gV=3)
Z' → ZH
σ(X) B(X → ZH) B(H → bb) (fb)
mX (GeV)

X→HH→bbbb

arXiv:1804.06174

Phys. Lett. B 781 (2018) 244

arXiv:1808.01473

ATLAS:

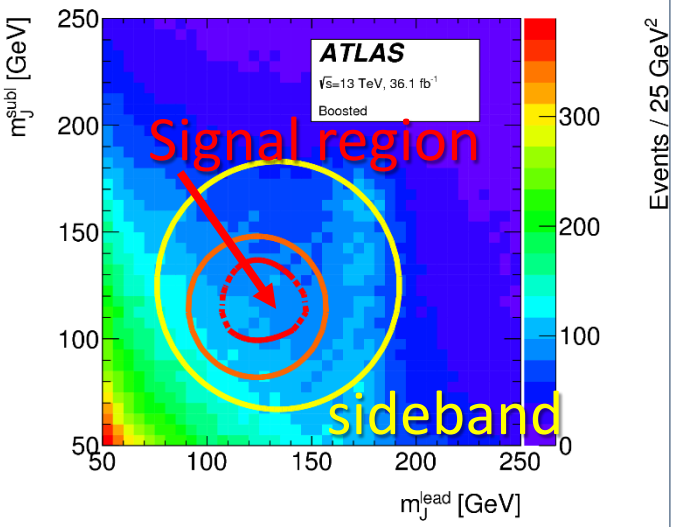
Categorize according the **number of b-tag track jets (2,3 and 4)** associated with the Higgs candidates

Multijet background (80-95%) modeled from data

- **Shape** – the same selection, but has one track jet failing b-tag.
- **Normalization** – signal free sideband region in m_J.

Includes resolved jets topology

- ✓ Extends to lower masses (~200GeV)

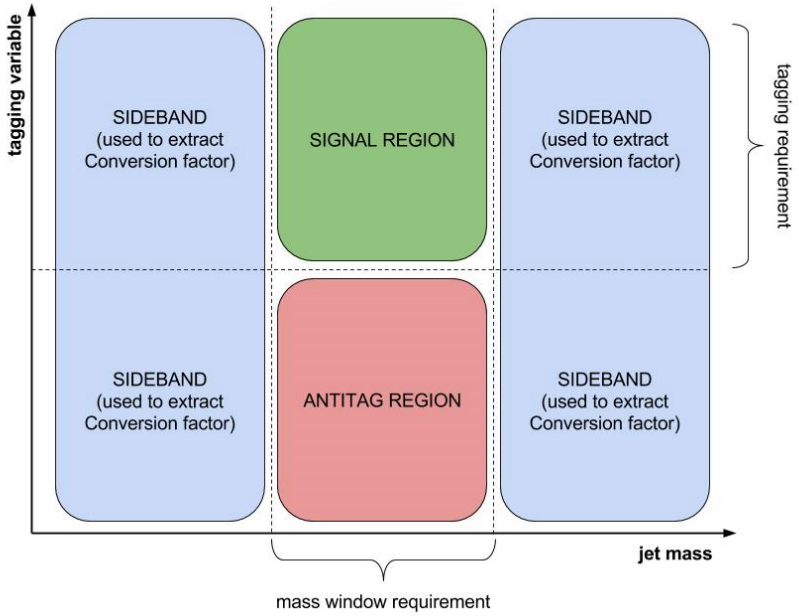


CMS:

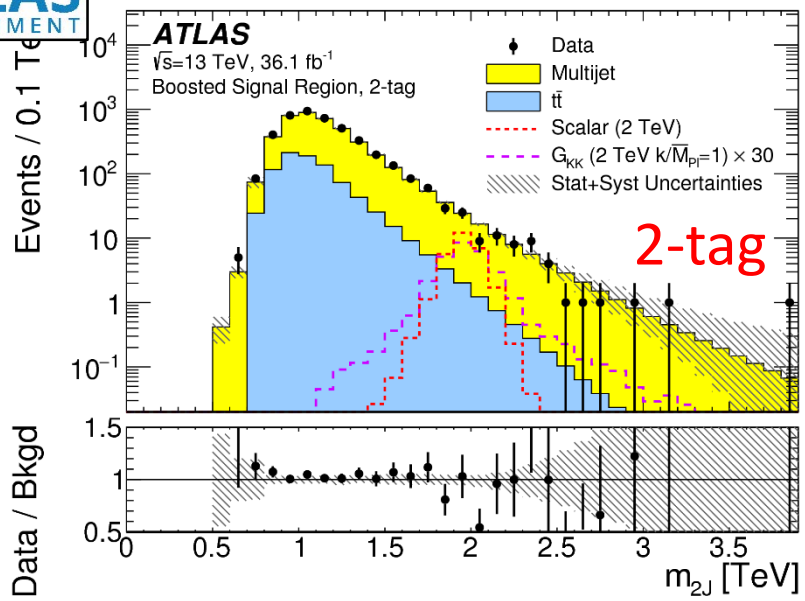
Two complementary searches:

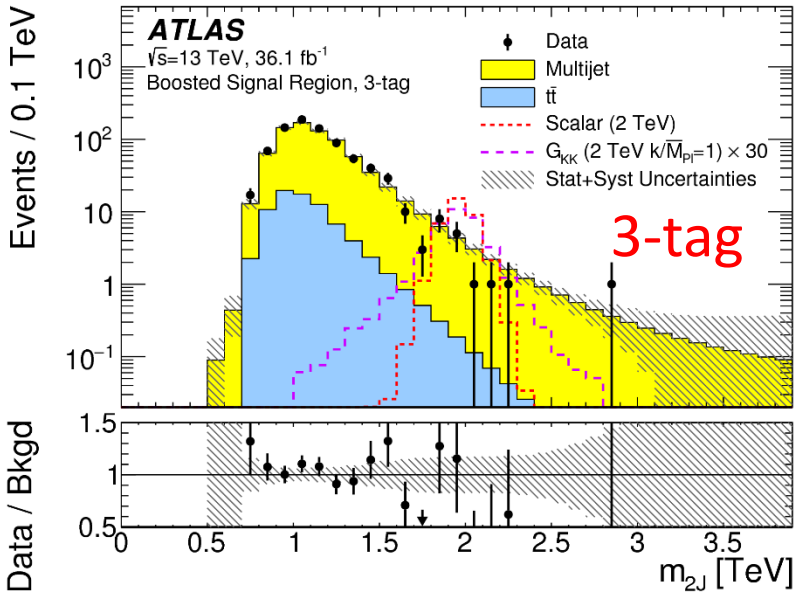
- **merged** – two large-R jets with double-b tag
- **partially merged**: one large-R jet and 2 resolved

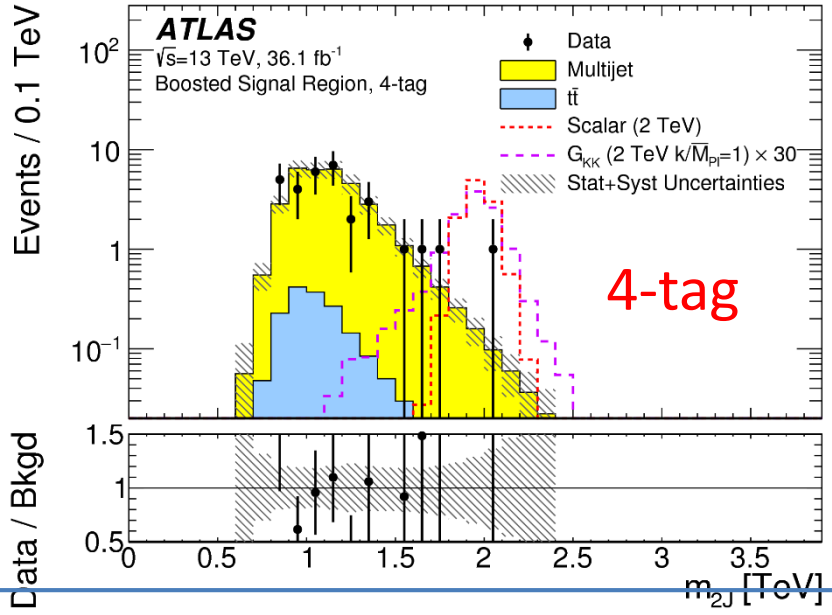
Background estimation – multiple sidebands



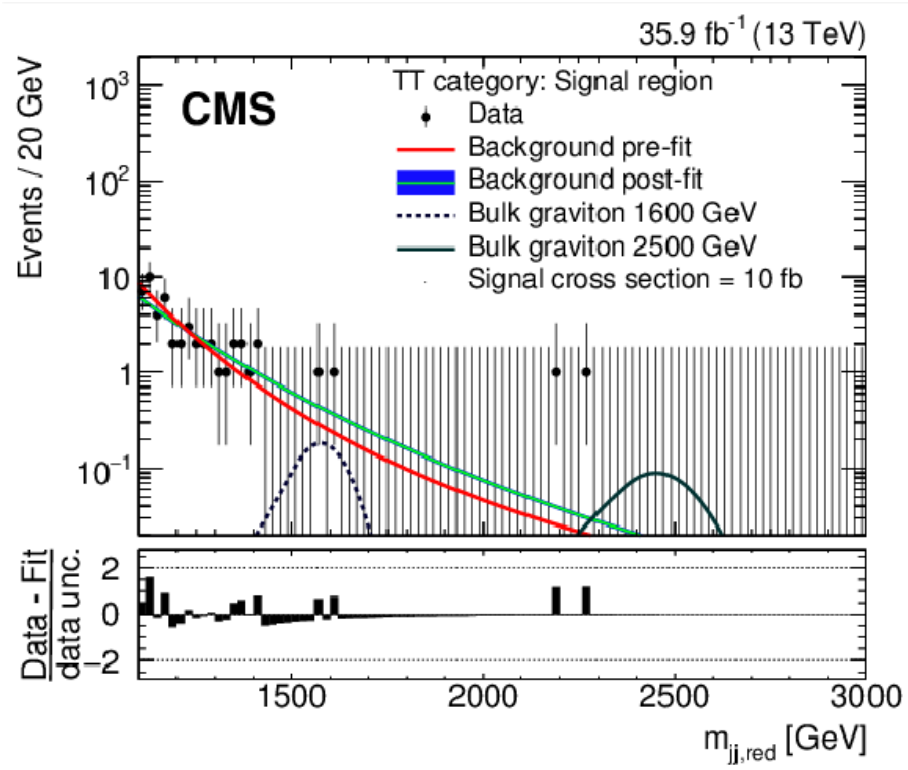
X→HH→bbbb

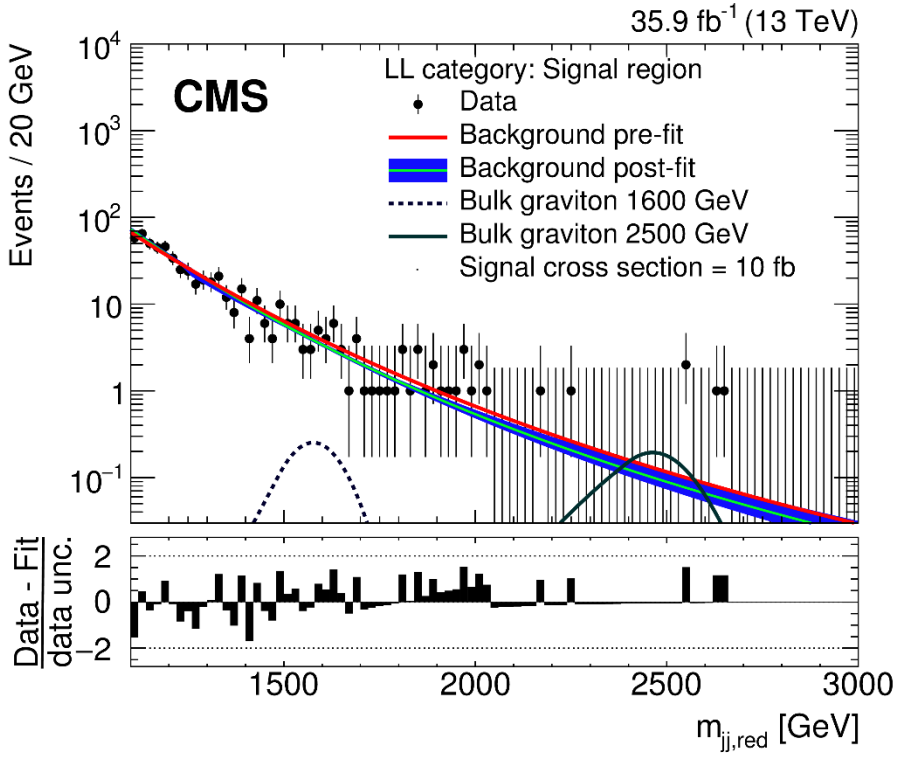

ATLAS
√s=13 TeV, 36.1 fb-1
Boosted Signal Region, 2-tag
Data
Multijet
tt̄
Scalar (2 TeV)
GKK (2 TeV k/M̄Pl=1) × 30
Stat+Syst Uncertainties
2-tag
Events / 0.1 TeV
Data / Bkgd
m2J [TeV]


ATLAS
√s=13 TeV, 36.1 fb-1
Boosted Signal Region, 3-tag
Data
Multijet
tt̄
Scalar (2 TeV)
GKK (2 TeV k/M̄Pl=1) × 30
Stat+Syst Uncertainties
3-tag
Events / 0.1 TeV
Data / Bkgd
m2J [TeV]


ATLAS
√s=13 TeV, 36.1 fb-1
Boosted Signal Region, 4-tag
Data
Multijet
tt̄
Scalar (2 TeV)
GKK (2 TeV k/M̄Pl=1) × 30
Stat+Syst Uncertainties
4-tag
Events / 0.1 TeV
Data / Bkgd
m2J [TeV]

X→HH→bbbb

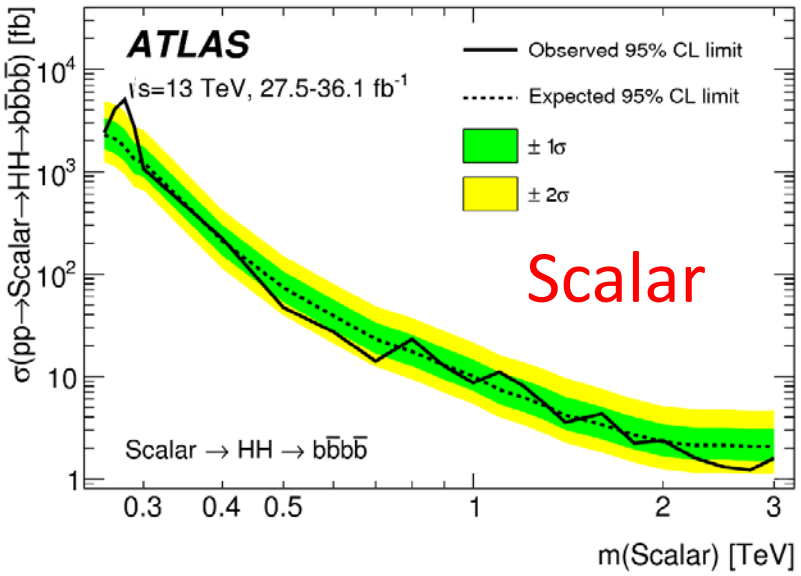


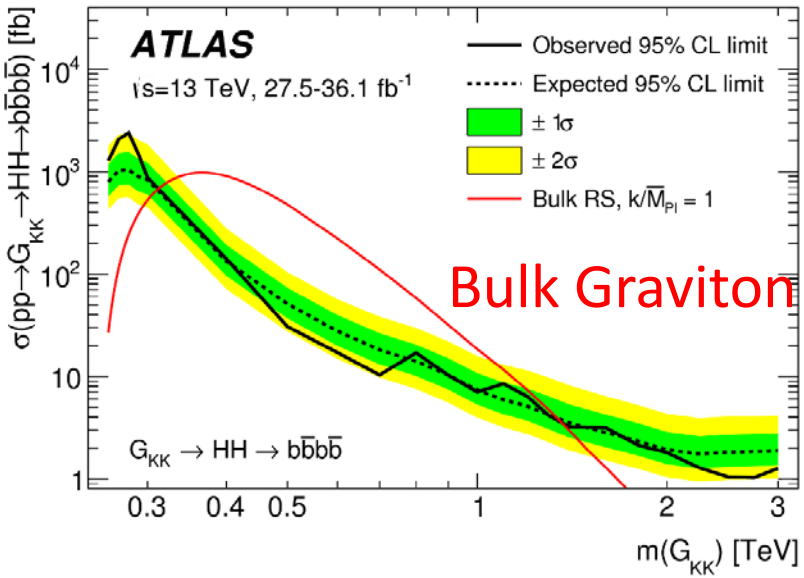


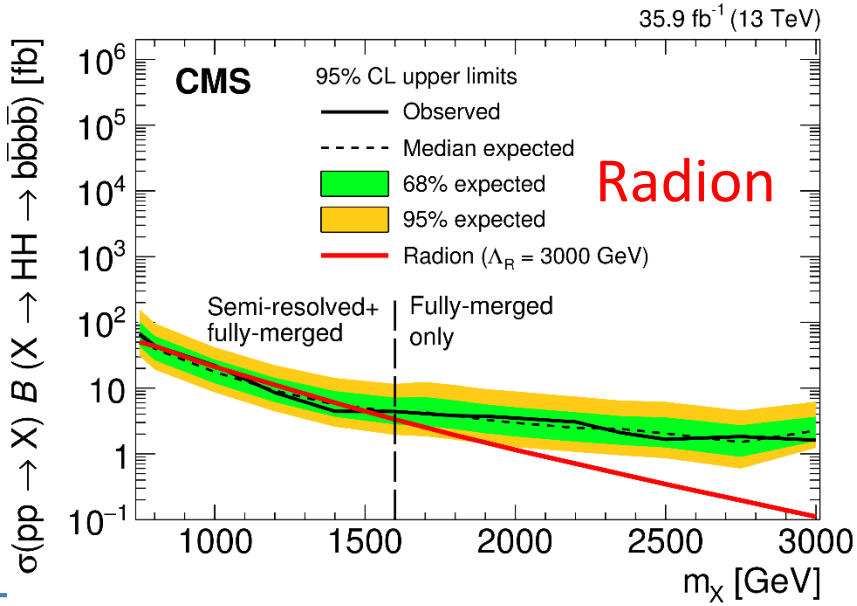
Fit **reduced mass** $m_{Jjj,red} \equiv m_{Jjj} - (m_J - m_H) - (m_{jj}(j_1, j_2) - m_H)$

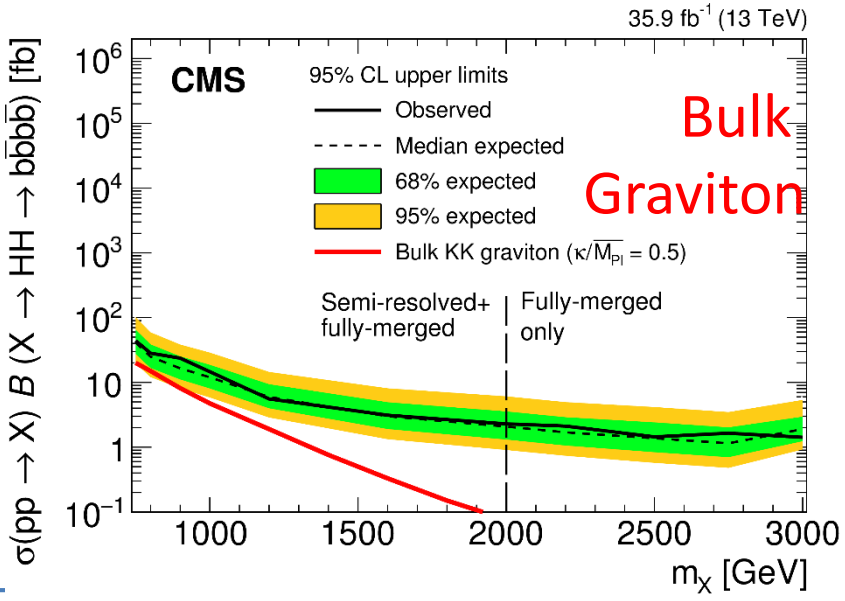
- **8-10% improvement** on HH mass resolution

X→HH→bbbb: limits









Semi-leptonic decays

X→WV→lvqq: ATLAS

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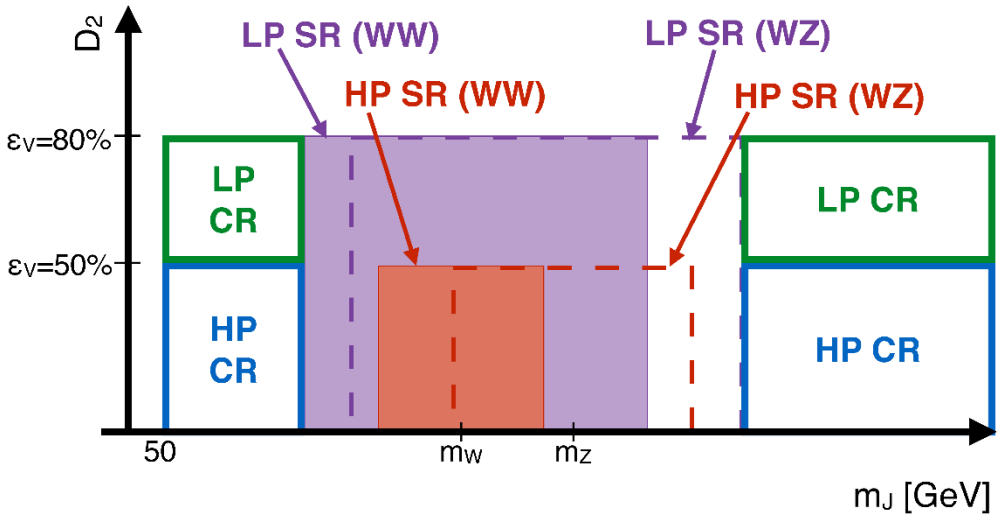
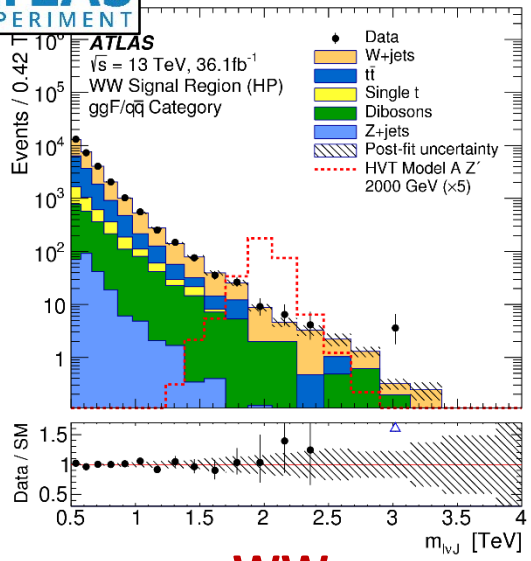
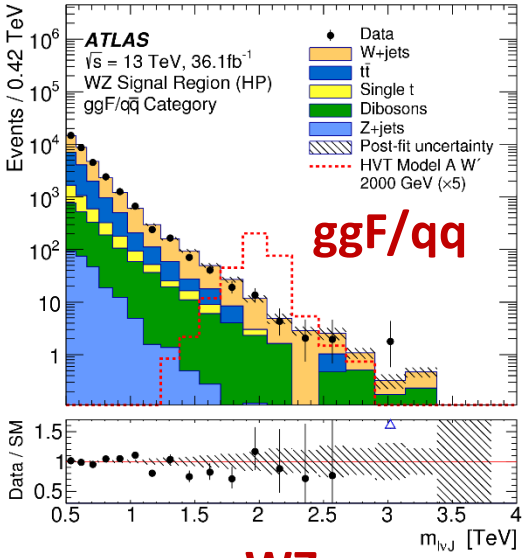
- Using h**igh-purity** (50% WP) and **low-purity** (80% WP) – improves sensitivity
- **Dominant background**: W+jets, tt
  - ✓ **Shape** from the simulation
  - ✓ **Normalization** estimated from combined **fit in signal and control regions**
    - W+jet: mass sidebands of V→qq
    - tt: requires b-jets
- Consider **resolved jets** topologies to extend the search to **lower resonance masses**
- Consider excusive **VBF category**: $m_{tag}(j,j) > 770$GeV, $|\Delta\eta_{tag}(j,j)| > 4.7$



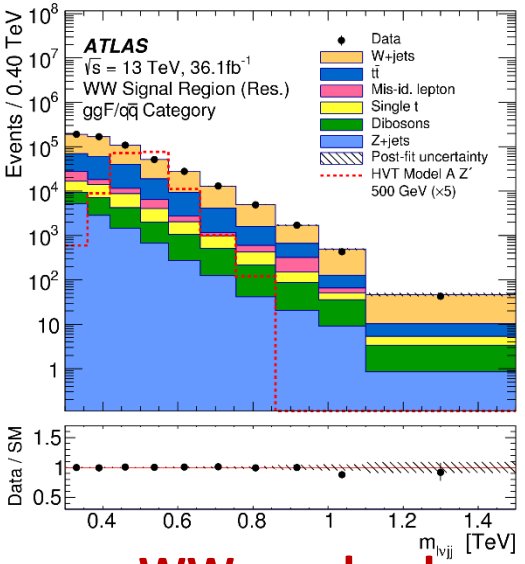
X→WV→lvqq



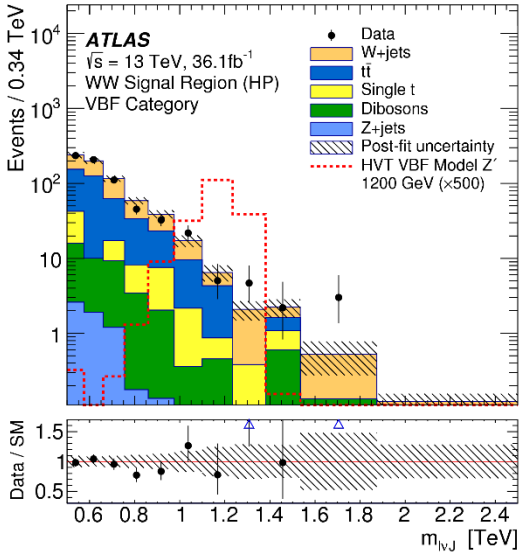
WW

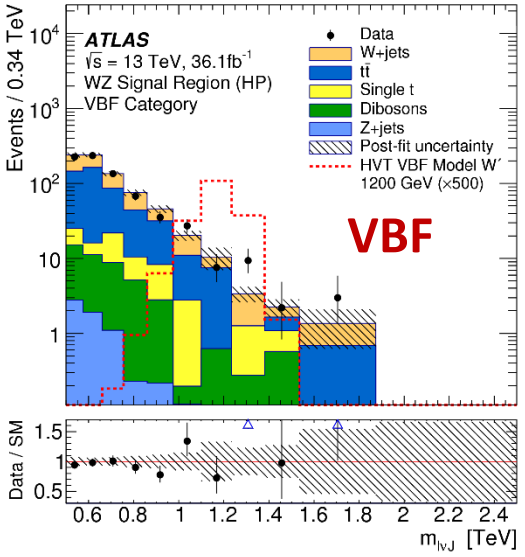


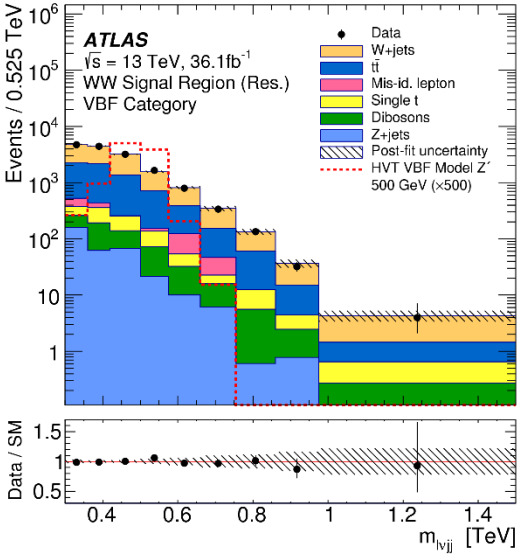
WZ



WW resolved







X→WV→lvqq: CMS

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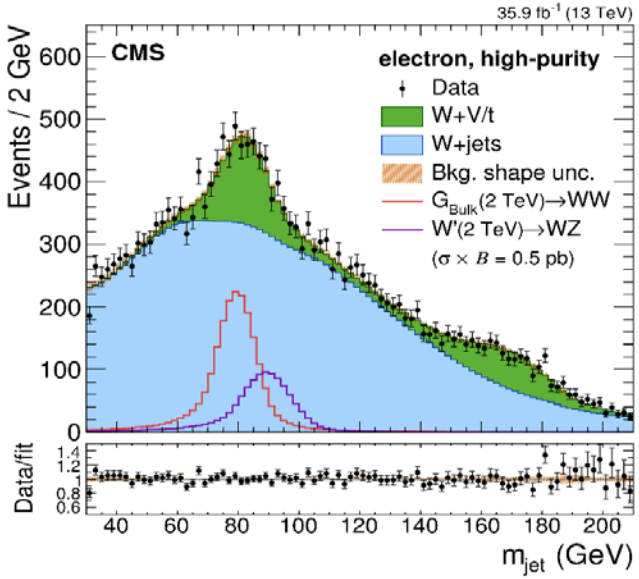
2D bump hunt in the (m_{WV}, m_{jet}) plane, where m_{jet} is the soft-drop jet mass.

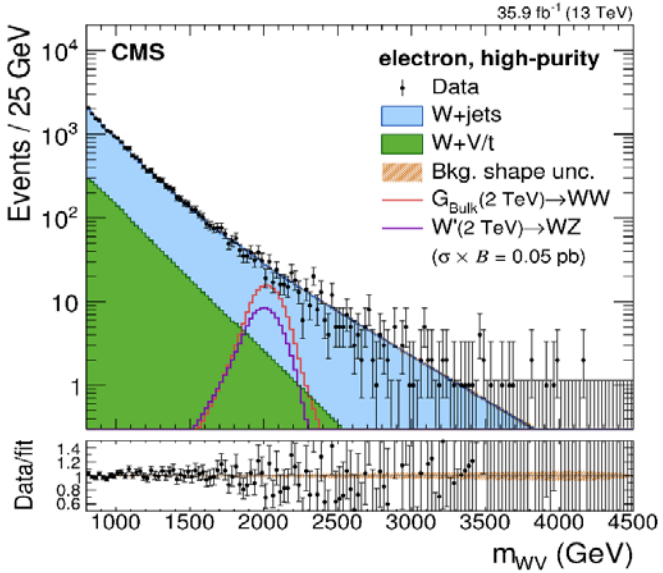
Takes advantage of 2D sidebands to constraint the backgrounds:

- **resonant** in m_{jet} - "**W+V/t**" (tt-dominated)
- **non-resonant** in m_{jet} - "**W+jets**" (W+jets, mis-assigned tt)

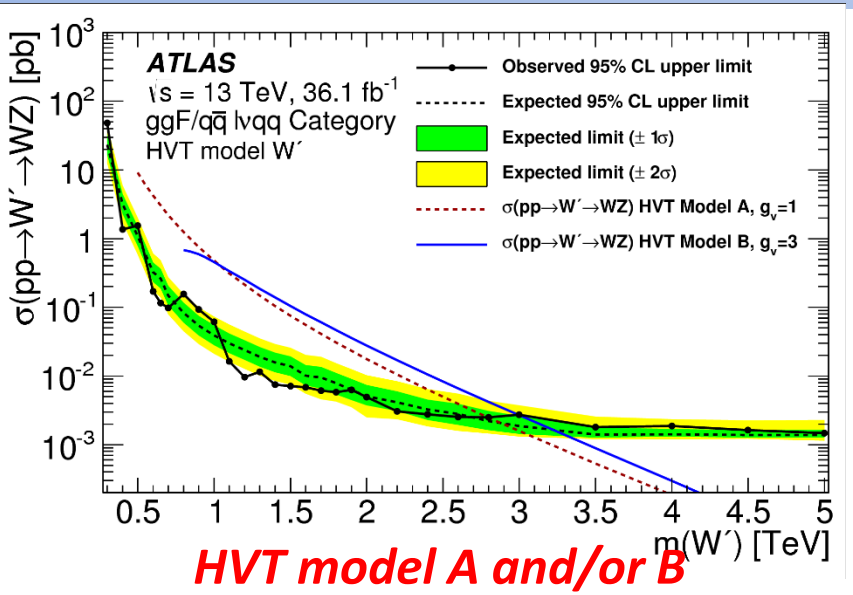
Kernel approach in building of smooth 2D templates

- Each gen.-level event contributes a gaussian, according to **scale & resolution model**.
- Performs loosely constraint fit to the data

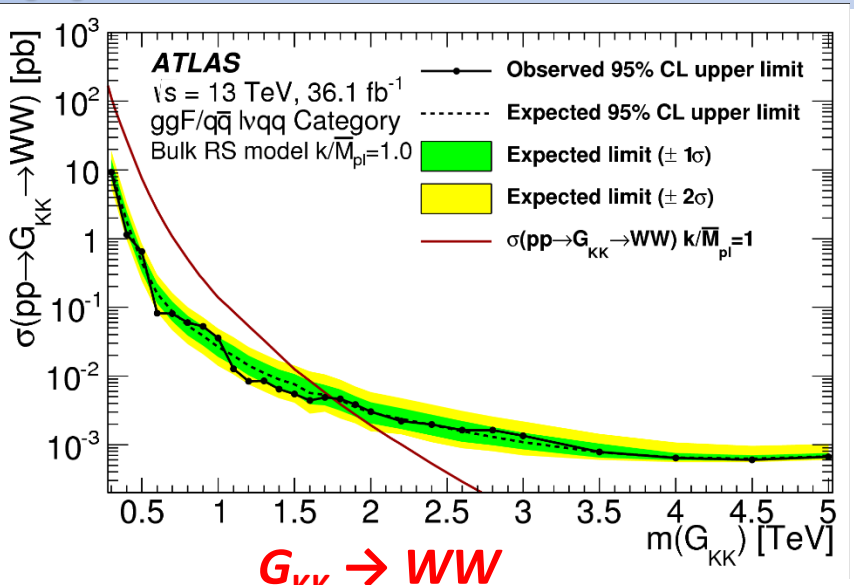




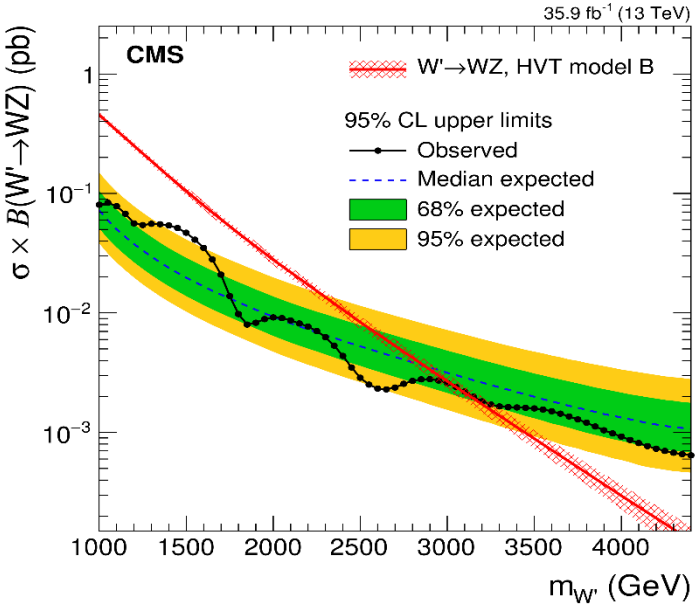
X→WV→lvqq: Limits

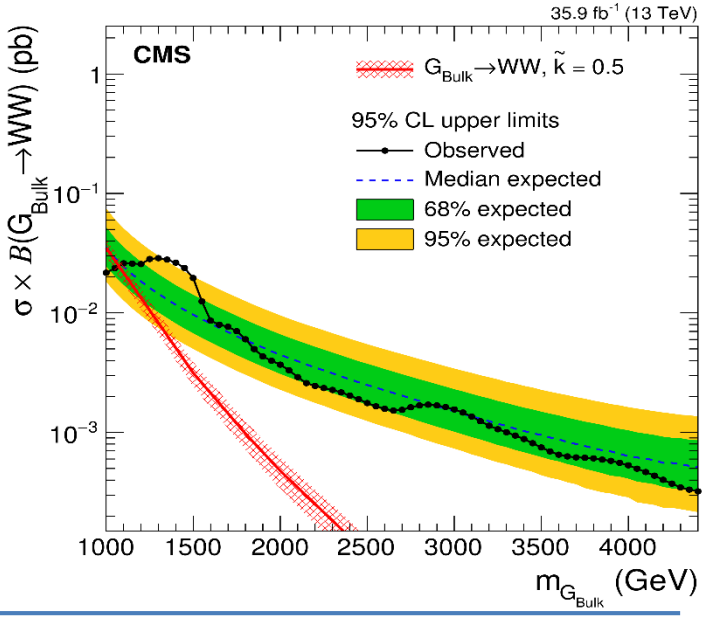


HVT model A and/or B

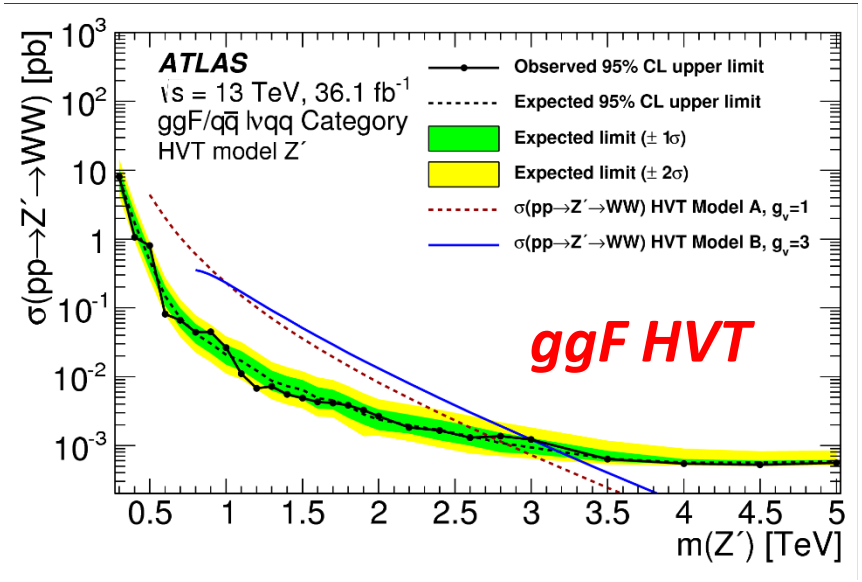


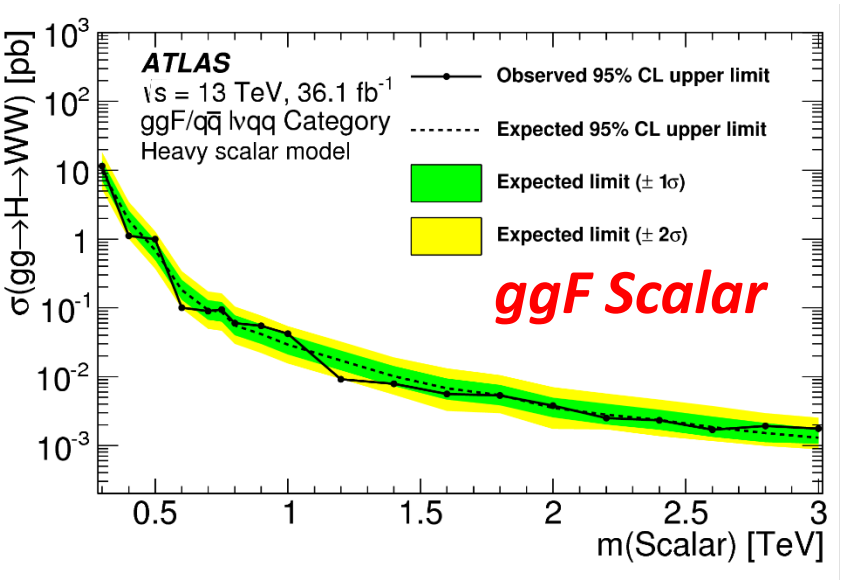
$G_{KK} \rightarrow WW$

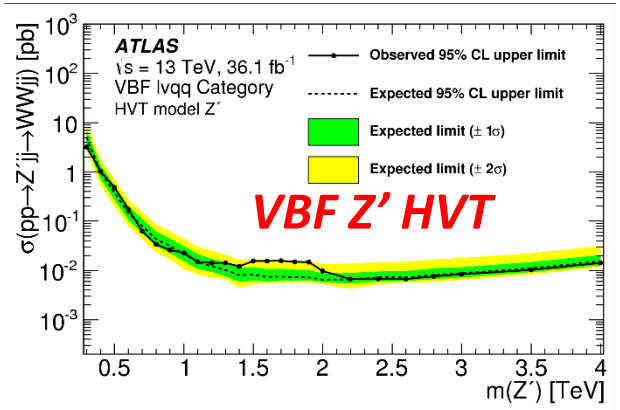


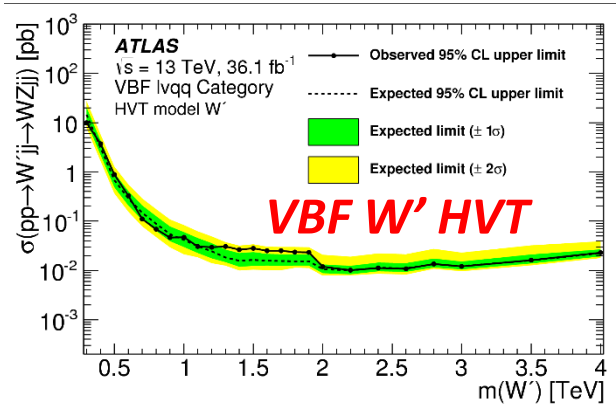


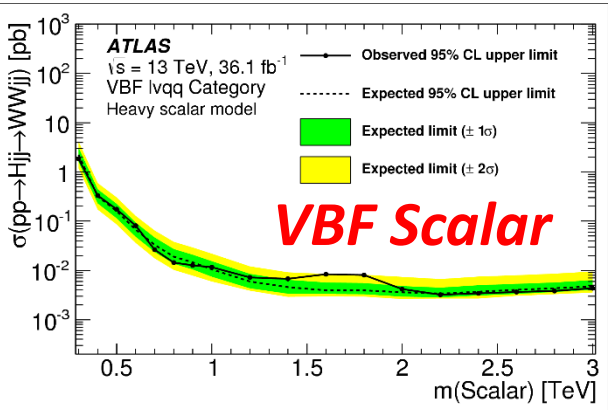
X→WV→lvqq: Limits











X→ZV→llqq, vvqq

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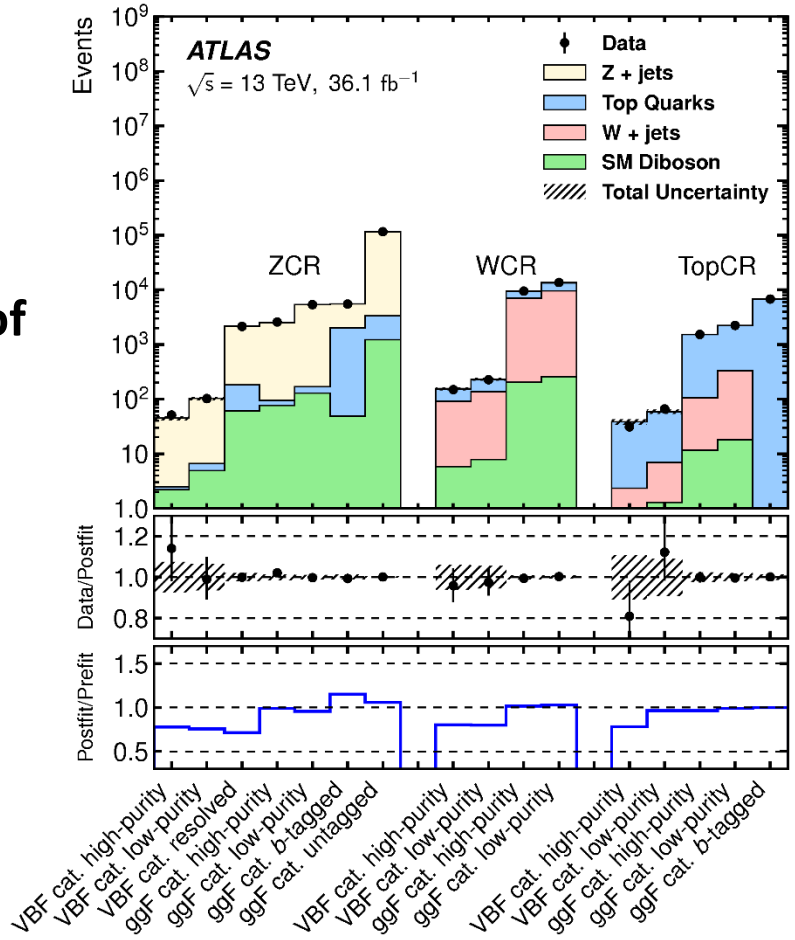
The analyses considers

- resolved and **merged V->qq decays**
- **ggF/DY** and **VBF** categories ($m_{tag}(j,j)$ >770GeV, $|\Delta\eta_{tag}(j,j)|$ >4.7)
- categorization according to the **number of b-tags** (two or less than two)

Background modeling

- The **shape** of kinematic distribution is taken from the simulation
- **Normalization** is constrained from simultaneous fit in signal and control regions (outside of m_J/m_{jj} window).



Backgrounds normalization in the control regions

The vvqq search uses the transverse mass instead.

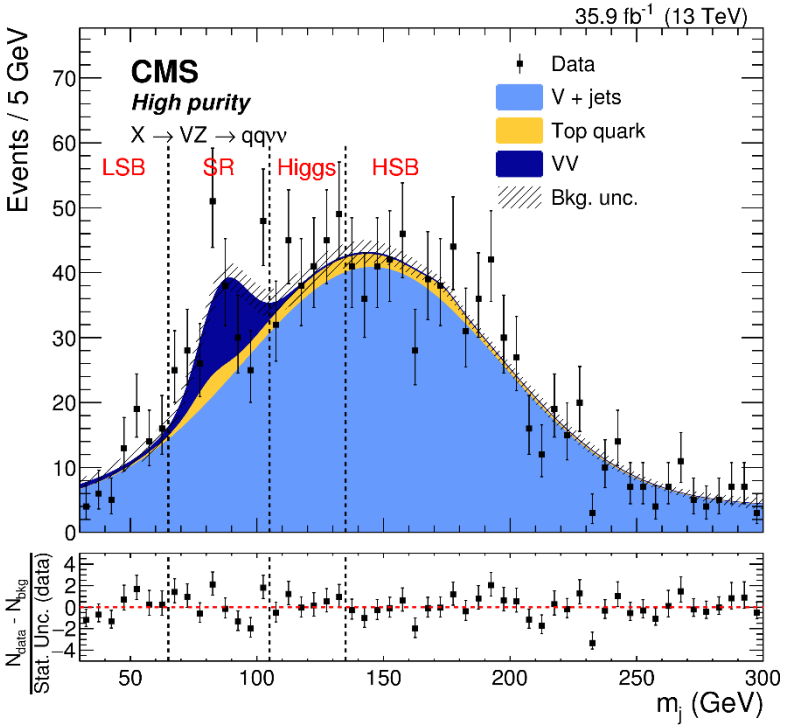
X→ZV→llqq, vvqq: CMS

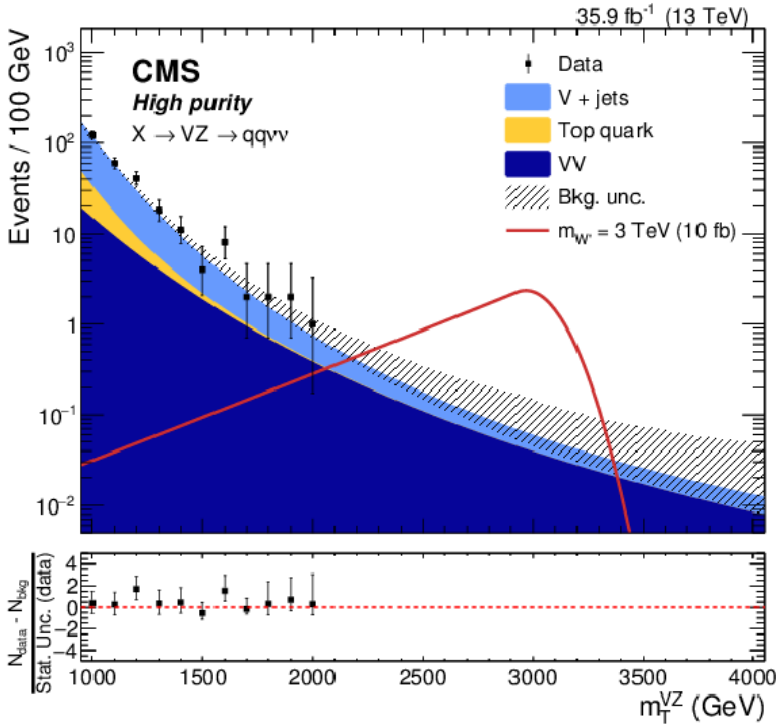
arXiv:1803.03838
arXiv:1803.10093

Both analyses perform high-mass resonance search with **merged V->qq decay**
The Z->ll also performs "low-mass" and covers 400<m_{ZV}<850 GeV mass range
Modify lepton reconstruction is used for boosted Z->ll

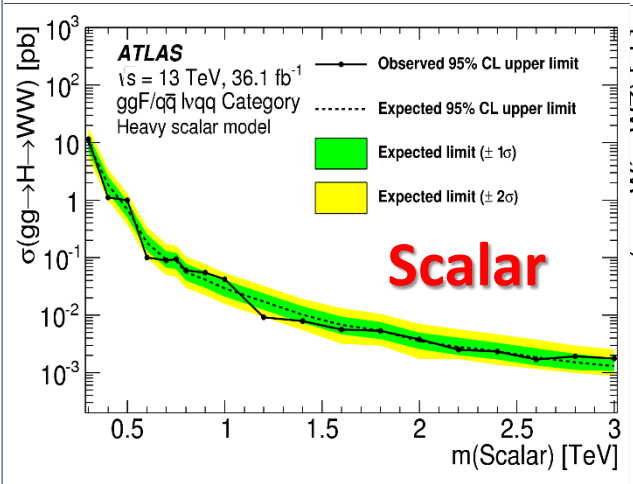
Dominant backgrounds are Z+jets (irreducible) and W+jets.

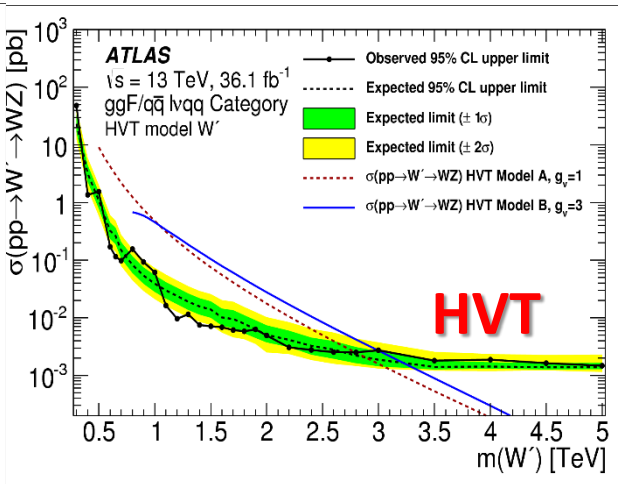
- Using m_J sideband to estimate the background (normalization and shape)
- Transfer function of the shape (CR->SR) is derived from the simulation.

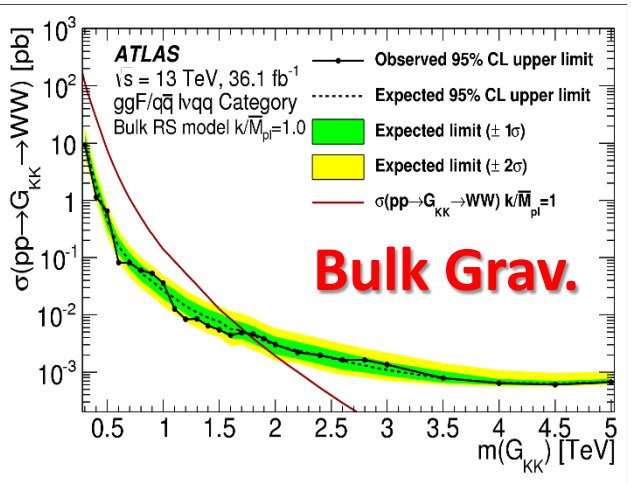


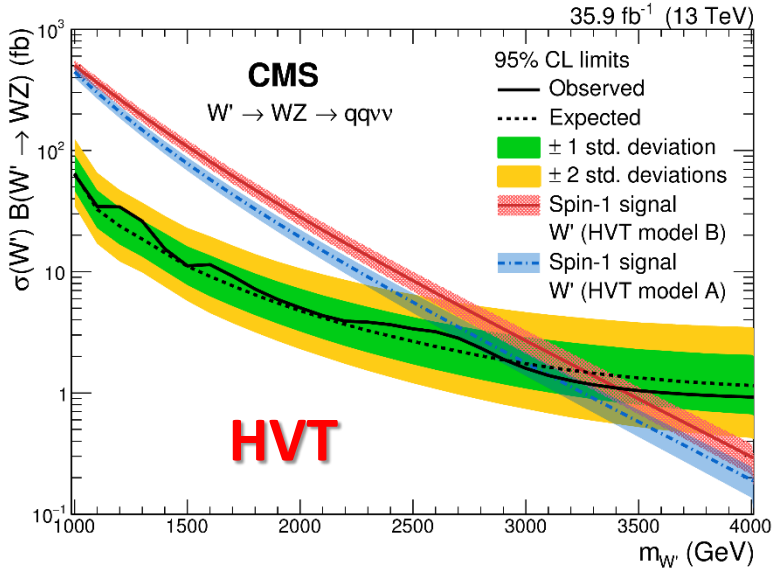


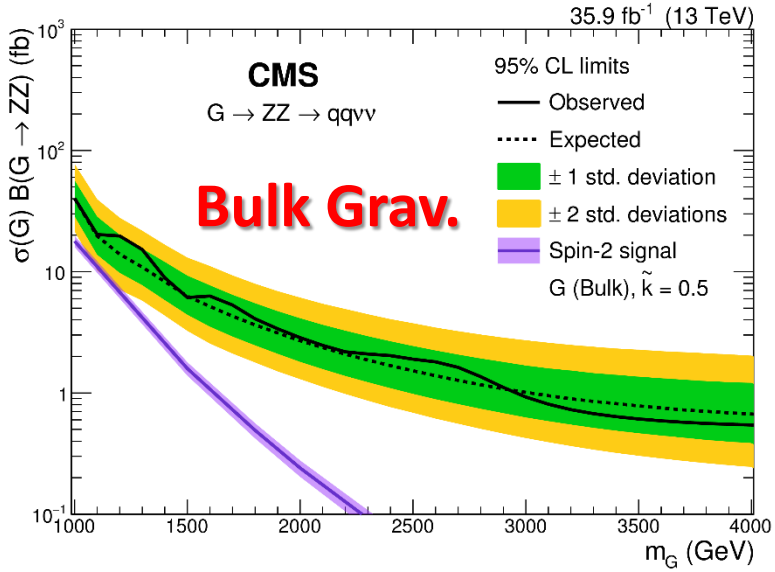
X→ZV→llqq, vvqq: limits











X→ZH→llbb, vvbb; WH→lvbb: ATLAS

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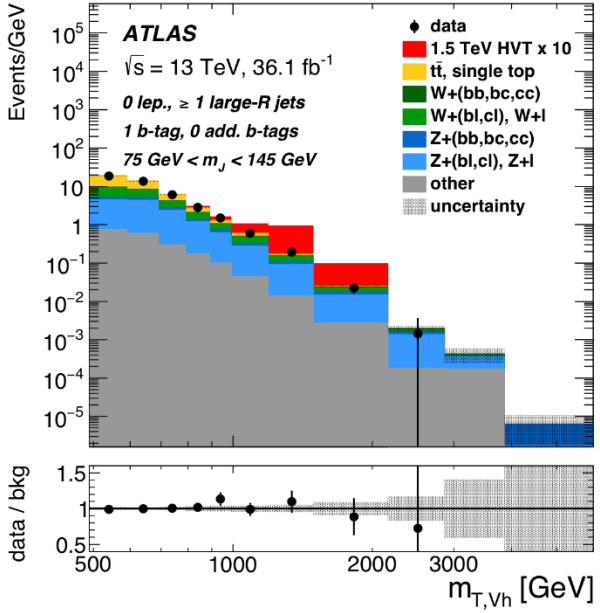
Searches in mass range 220 – 5000 GeV

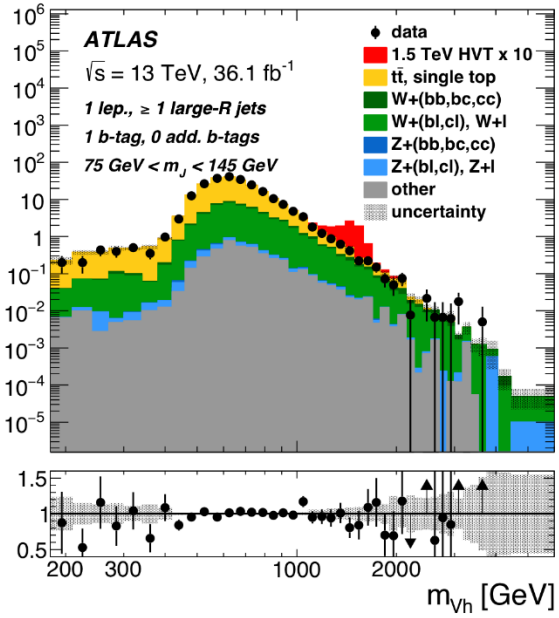
- resolved and **merged H→bb**.

Using **1 and 2 b-tag categories** for the merged H→bb

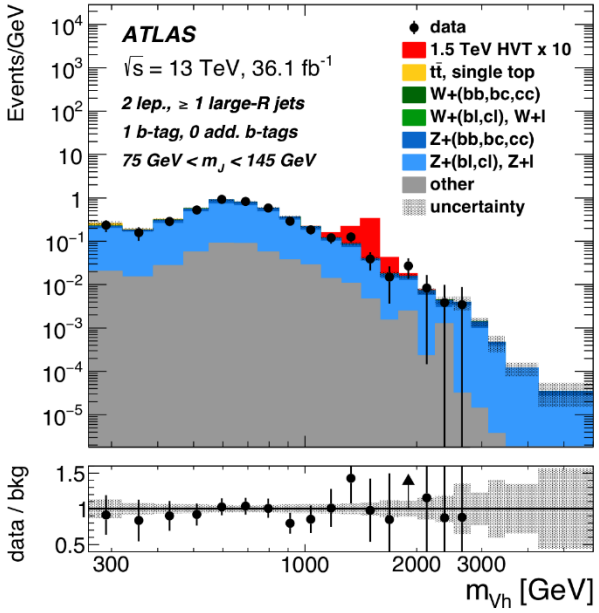
Backgrounds estimation: shape from the simulation, **normalization** from fit to data



0 lep,1 b-tag
large-R jets



1 lep,1 b-tag
large-R jets



2 lep,1 b-tag
large-R jets

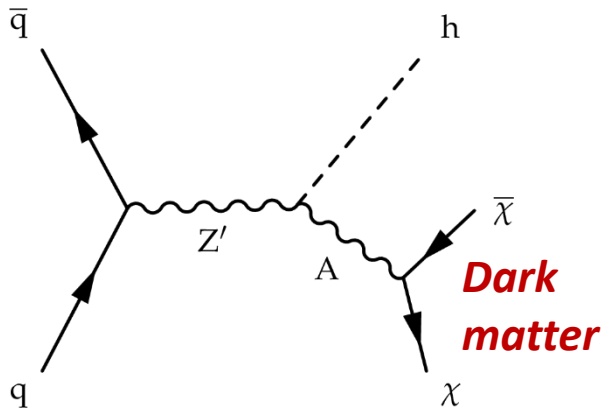
X→ZH→llbb, vvbb; X→WH→lvbb: CMS

arXiv:1807.02826

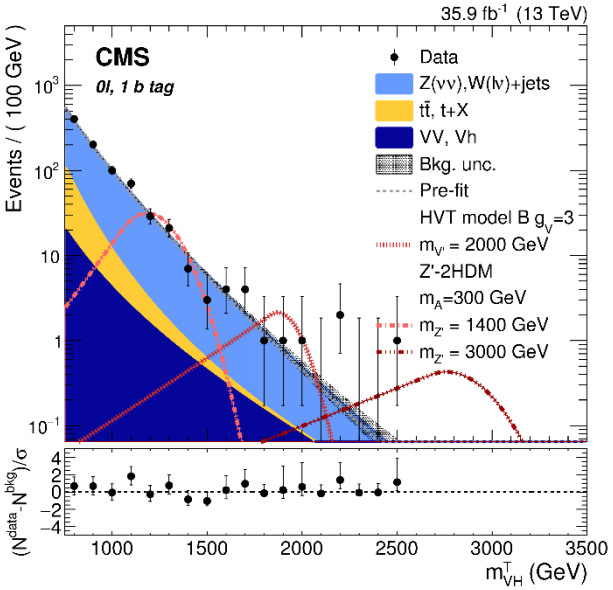
Searches in mass range 850 – 4500 GeV

New interpretation with **dark matter** production

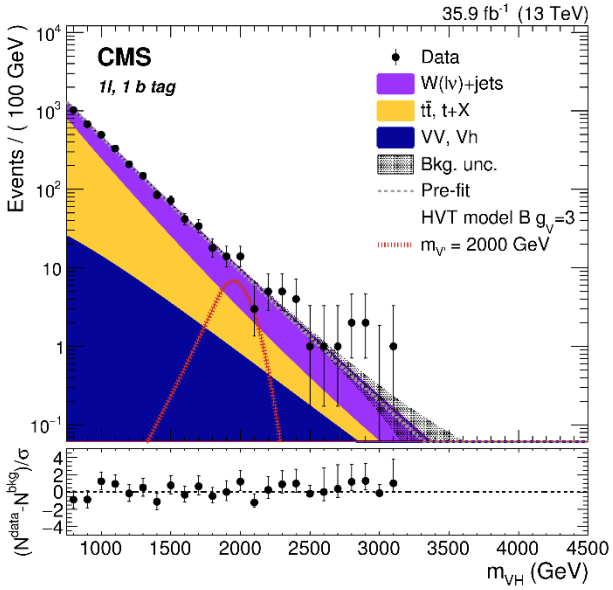
Sub-jets b-tag: **1-b-tag and 2-b-tag categories**
Major backgrounds estimated from data in sidebands



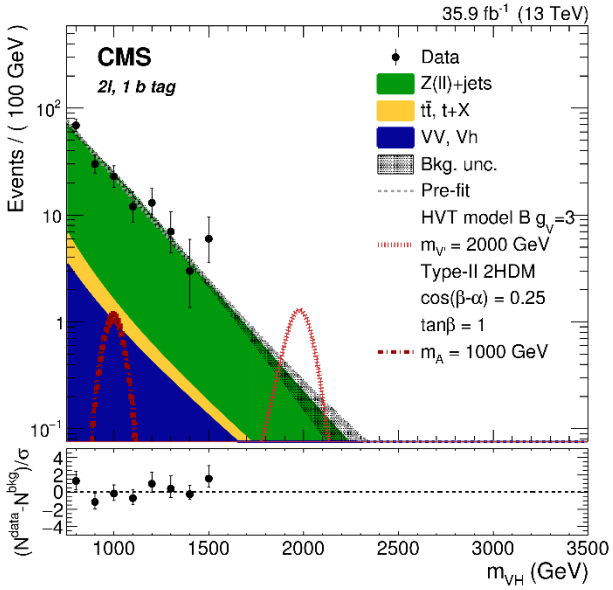
0 lep,1 b-tag



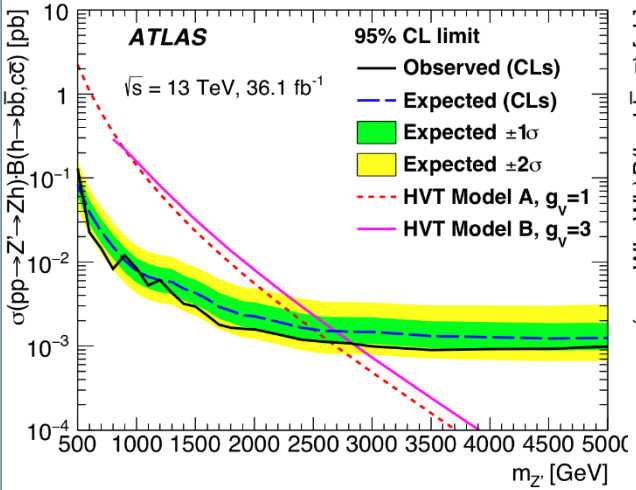
1 lep,1 b-tag

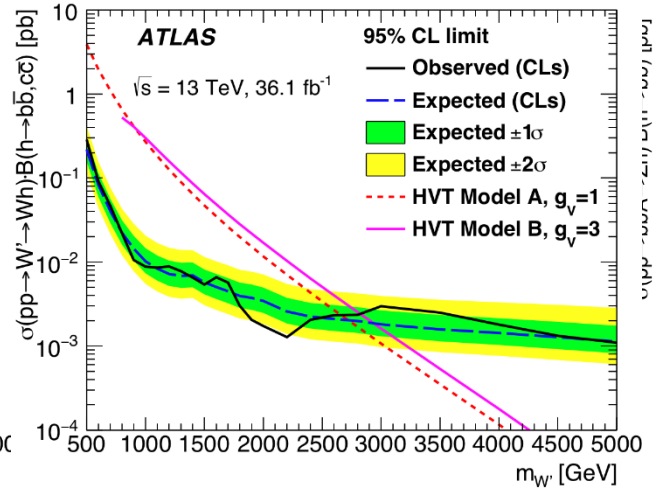


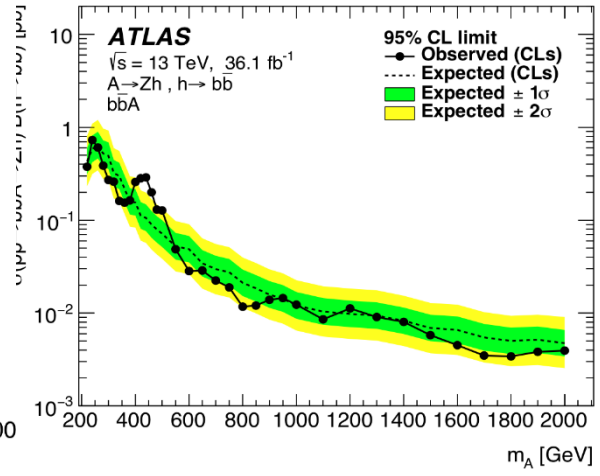
2 lep,1 b-tag



X→ZH→llbb, vvbb; X→WH→lvbb: limits



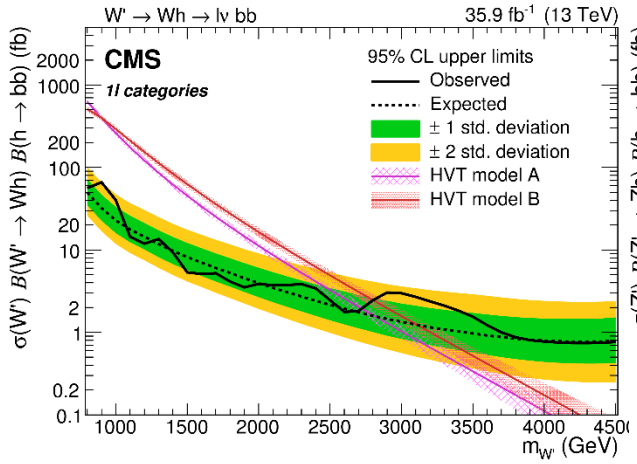


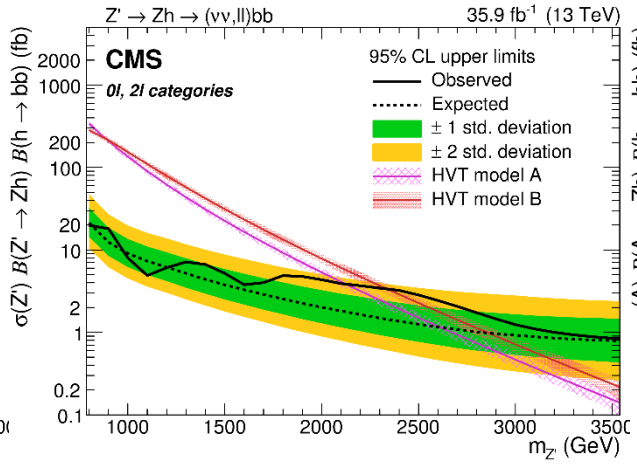


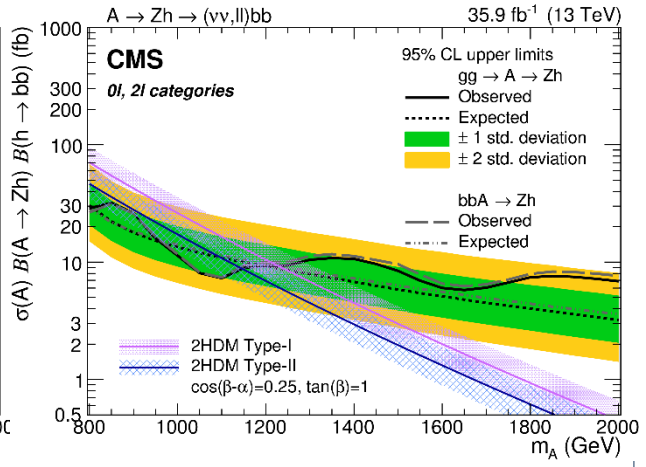
Z' HVT model A, B

W' HVT model A, B

2HDM

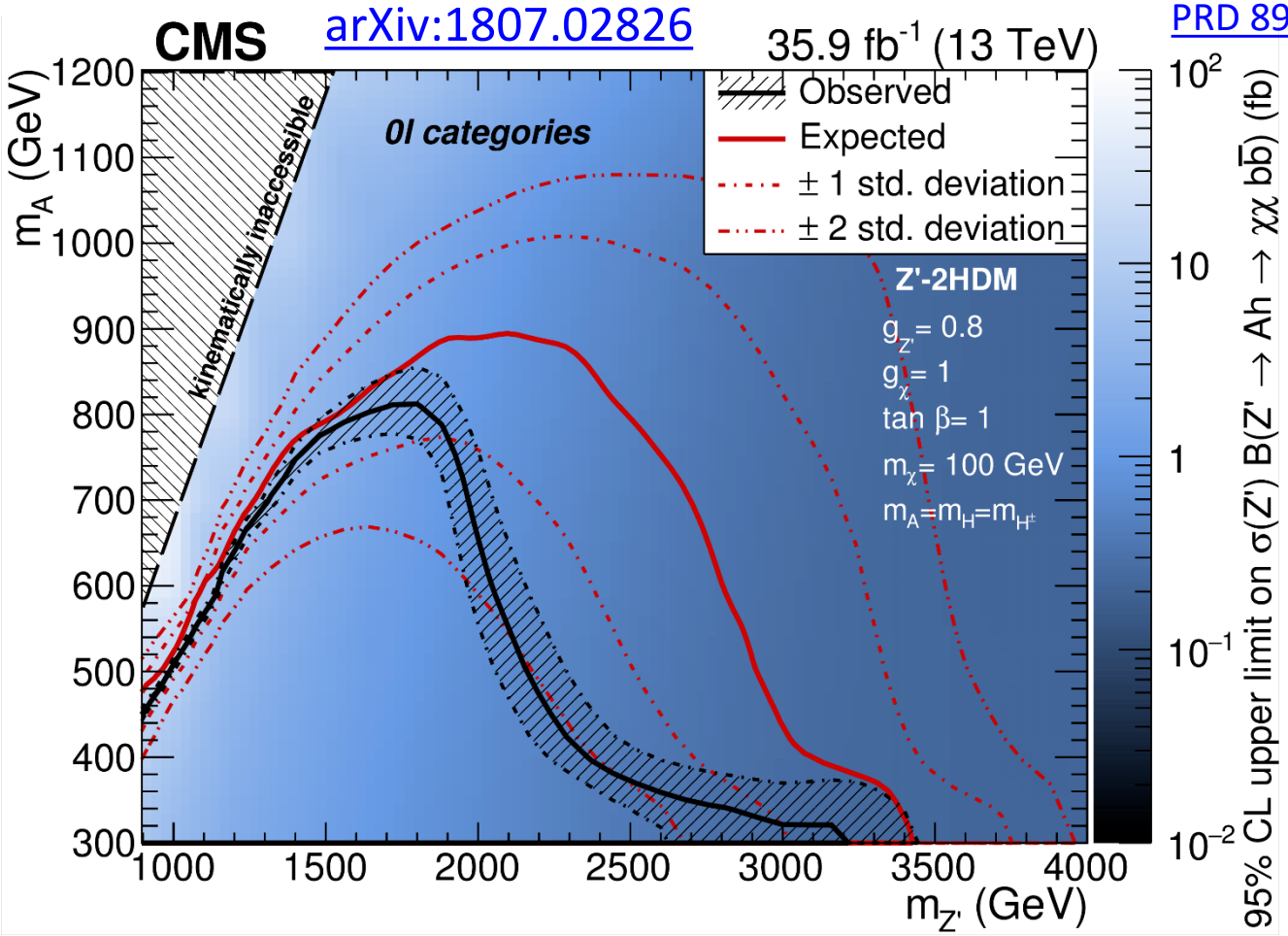






Dark matter interpretation (Z'-2HDM)

JHEP 06 (2014) 078
PRD 89 (2014) 075017

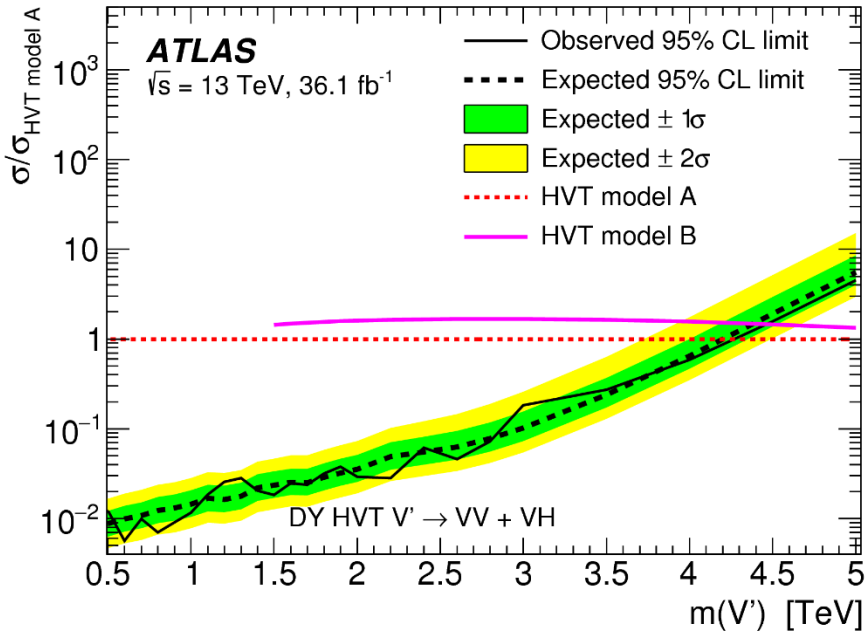


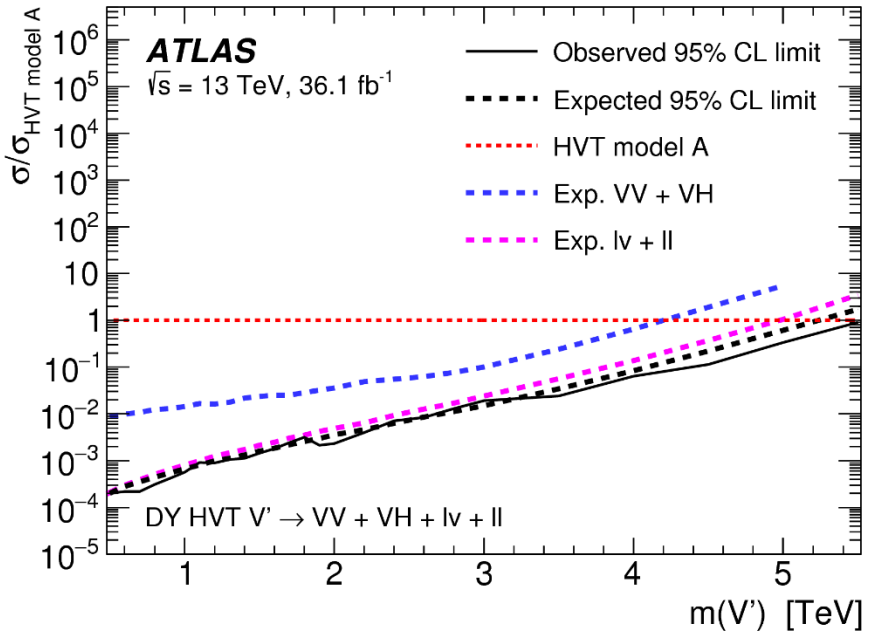
The excluded regions in the considered benchmark scenario ($g_{Z'}$=0.8, g_χ=1, tanβ=1, m_χ= 100 GeV, and m_A=m_H=$m_{H^\pm}$) are represented by the areas below the curve. The hatched band relative to the observed limit represents the uncertainty on the signal cross section.

Combinations and summaries

ATLAS combinations

arXiv:1808.02380





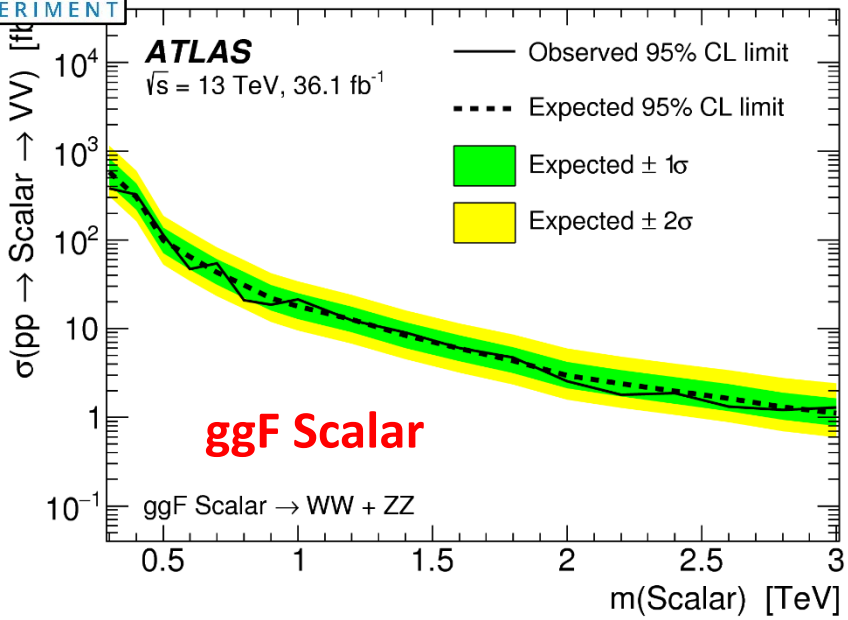
Exclusion limits (VV+VH):

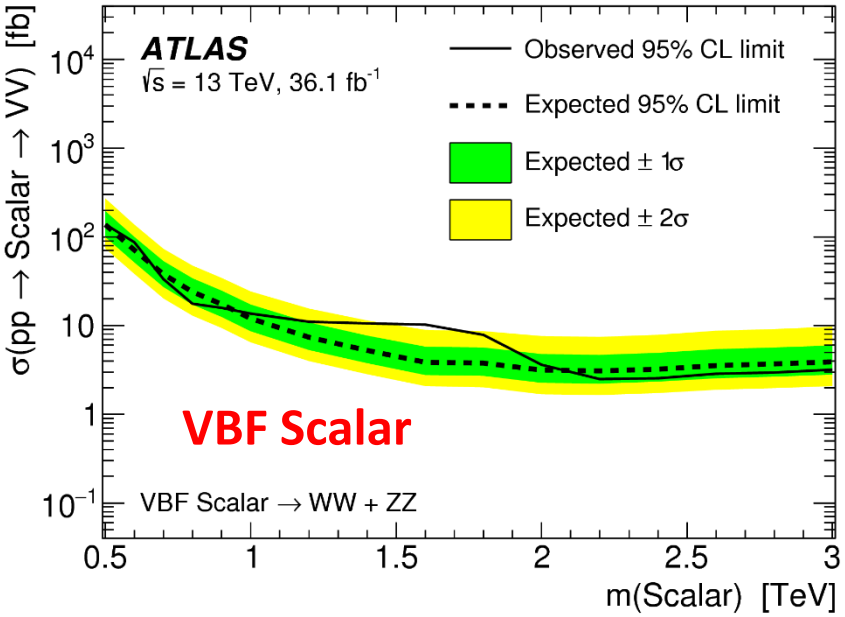
- ***HVT model B*** **at about 4.5 TeV**
- ***HVT model A*** **at about 4.3 TeV**

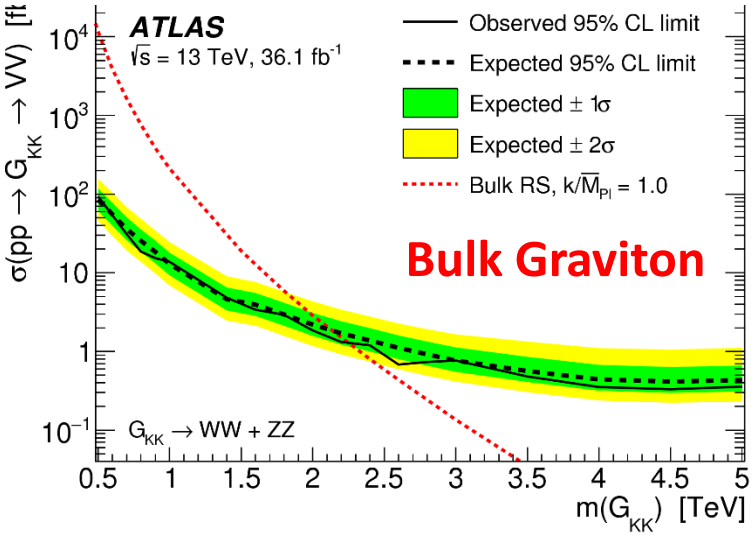
Exclusion limits for *HVT model A* benefits from additional channels:
X→ll and X→lv : 5.5 GeV

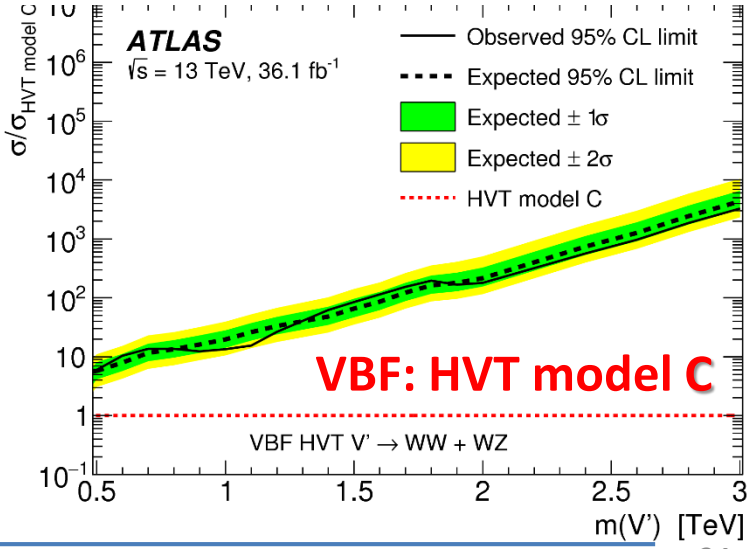
ATLAS combinations

arXiv:1808.02380



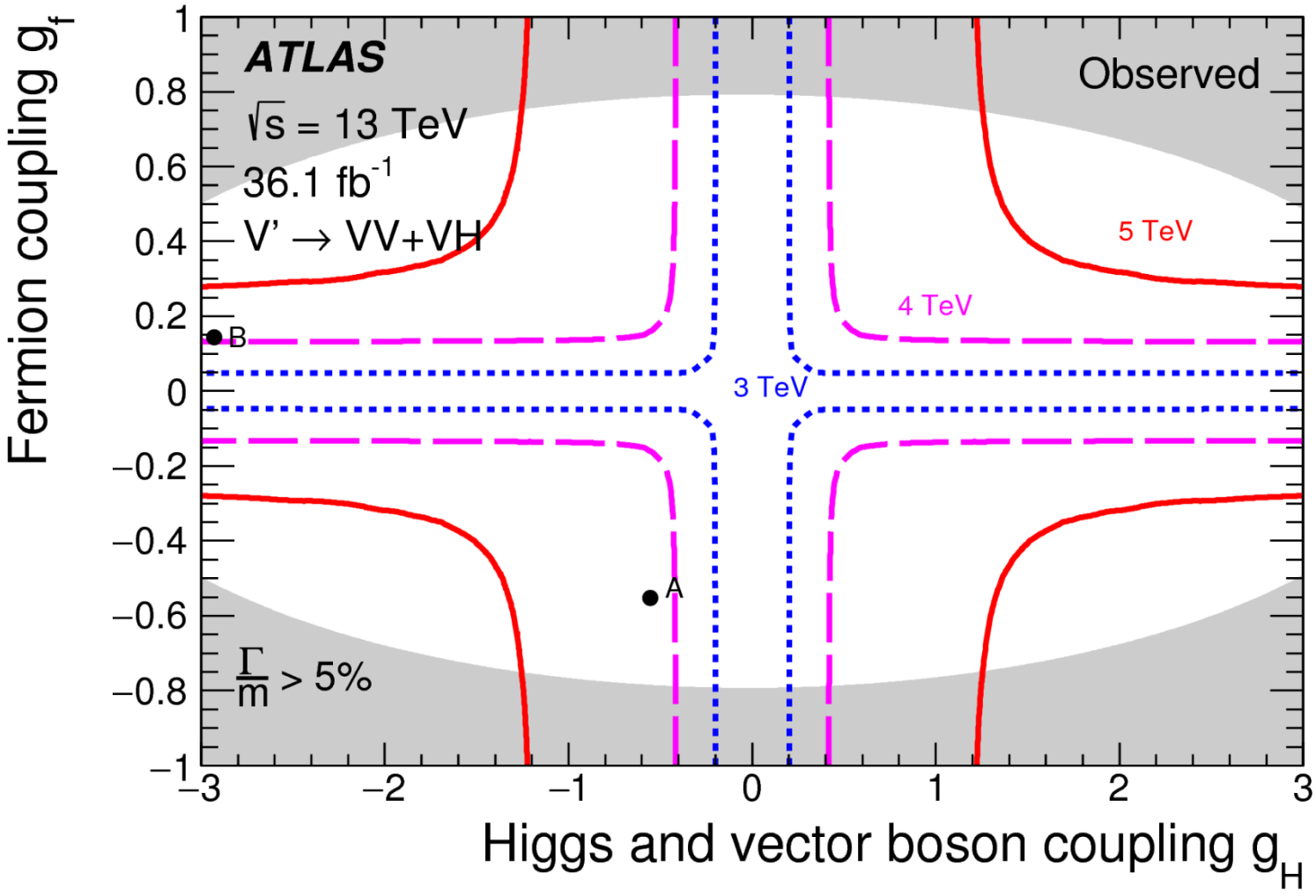






ATLAS combinations

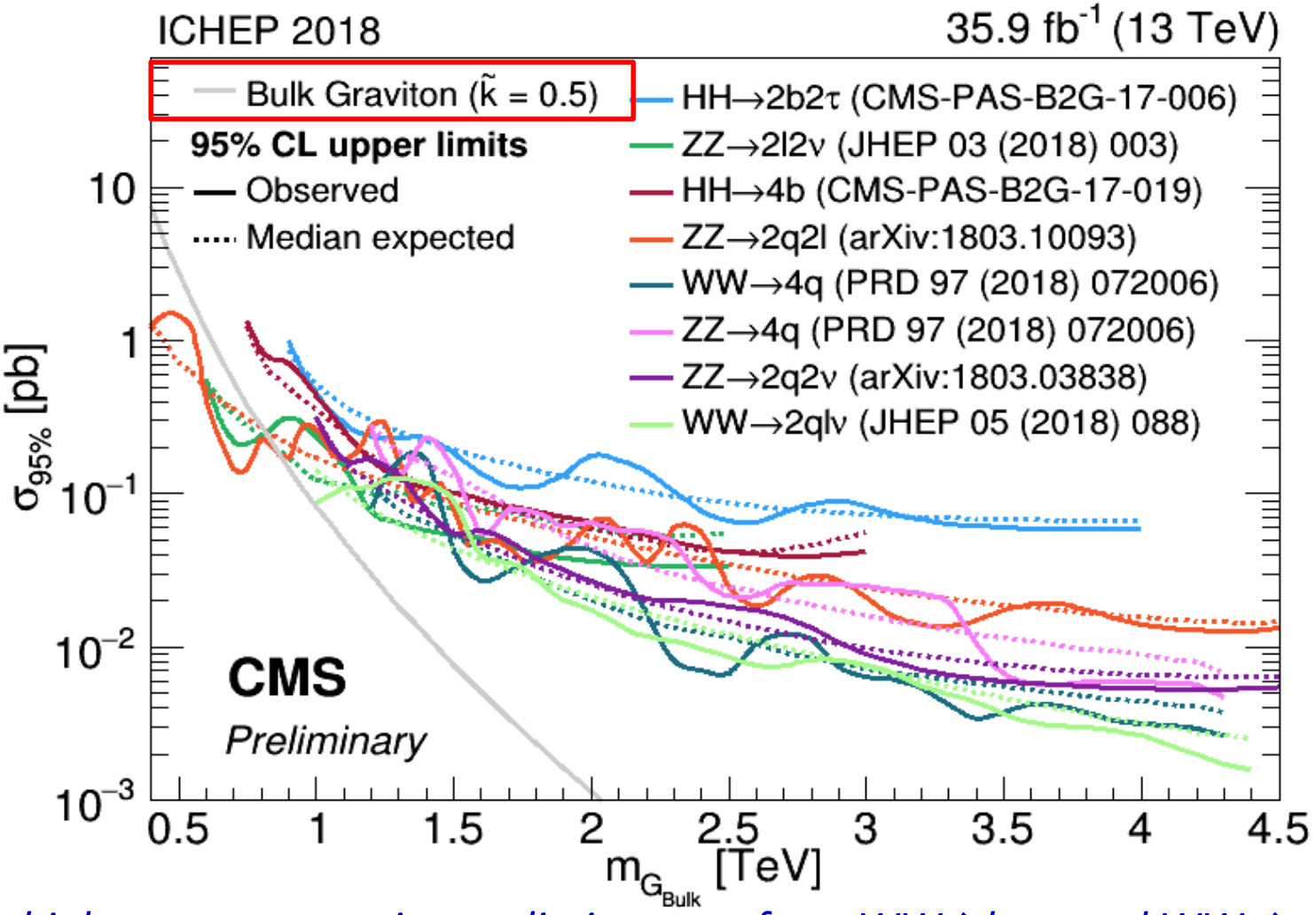
arXiv:1808.02380



CMS summaries

PhysicsResultsB2GDibosons

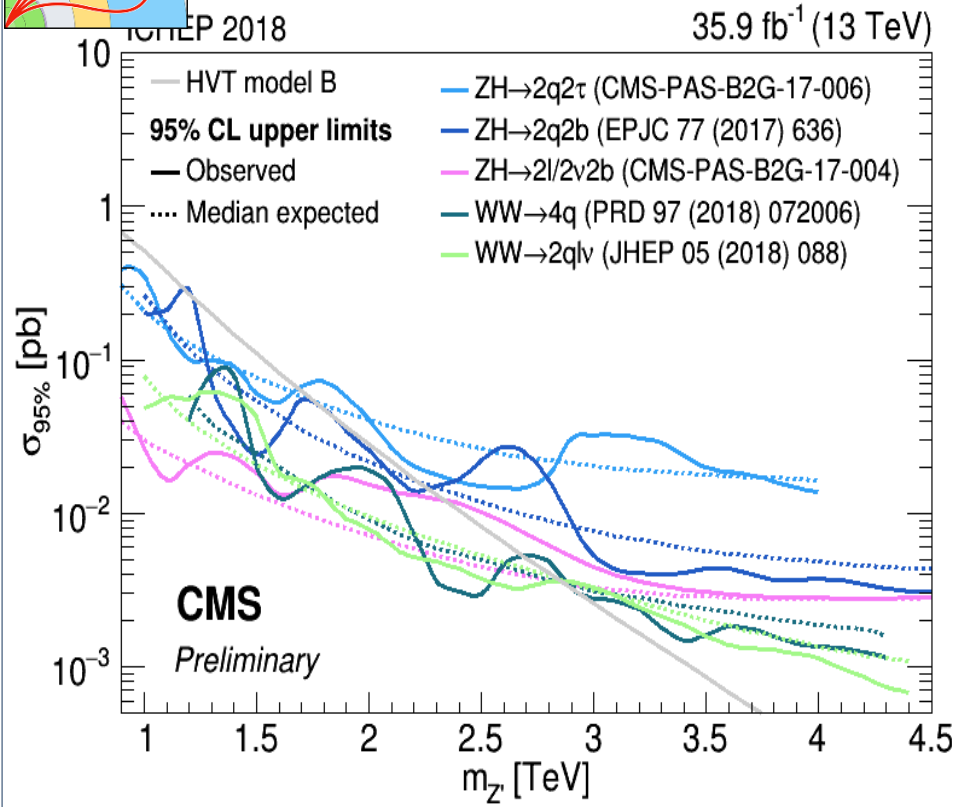
Combination of all the channels is being work on.

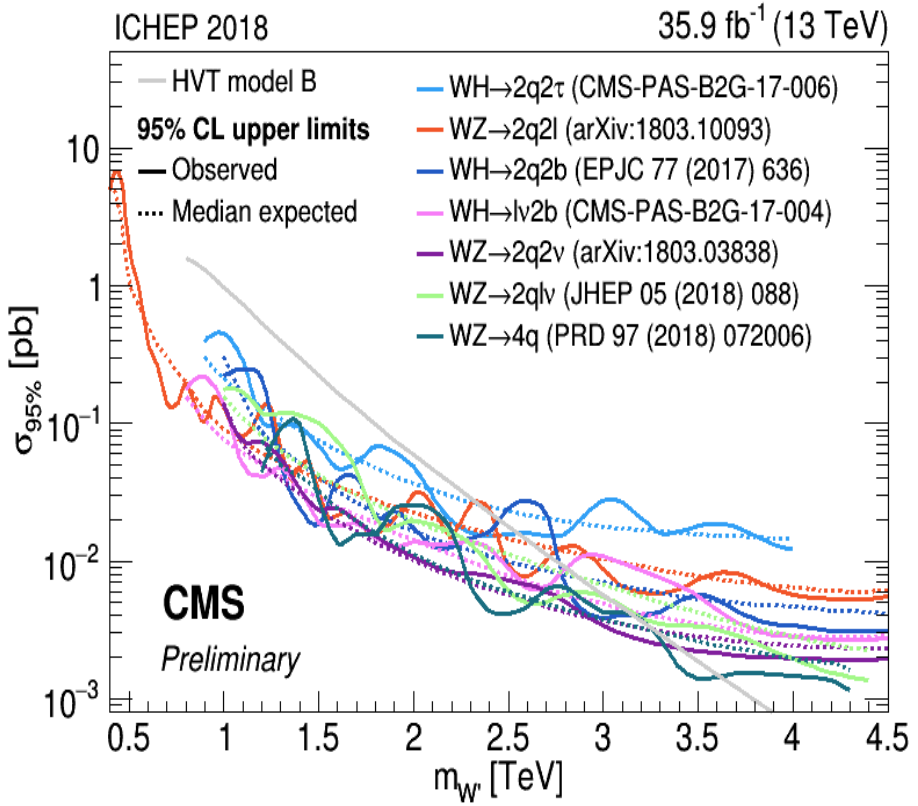


At high mass, most stringent limits come from WW→lvqq and WW → 4q.

CMS summaries

PhysicsResultsB2GDibosons





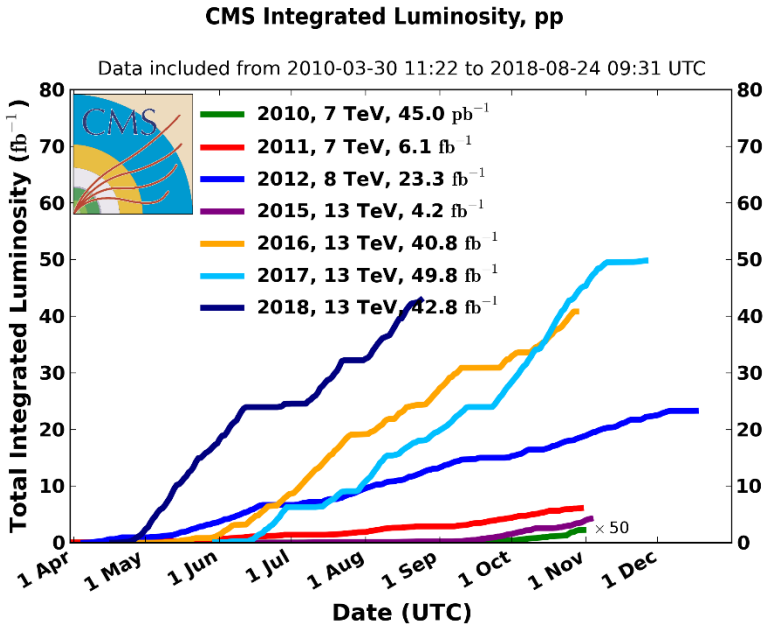
- 95% CL upper limits on cross sections of WZ, WH, and ZH resonances,
  - W' and Z' bosons in ***HVT model B***.

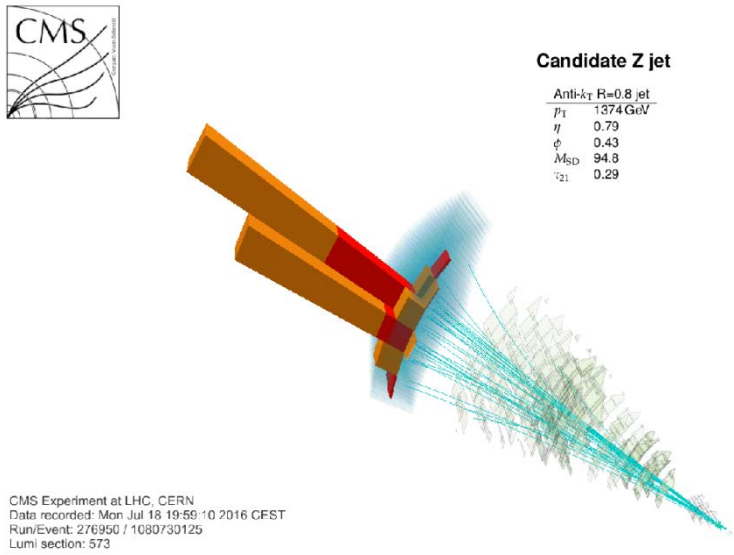
- **Several channels with similar sensitivity – will benefit from combination.**

Summary

- **Most recent results for diboson resonance searches are presented (boosted signature)**
  - No significant deviations from Standard Model observed.

- **Looking forward to take advantage of the full Run 2 dataset**
  - and take advantage of the advancements in the reconstruction of events with boosted topologies

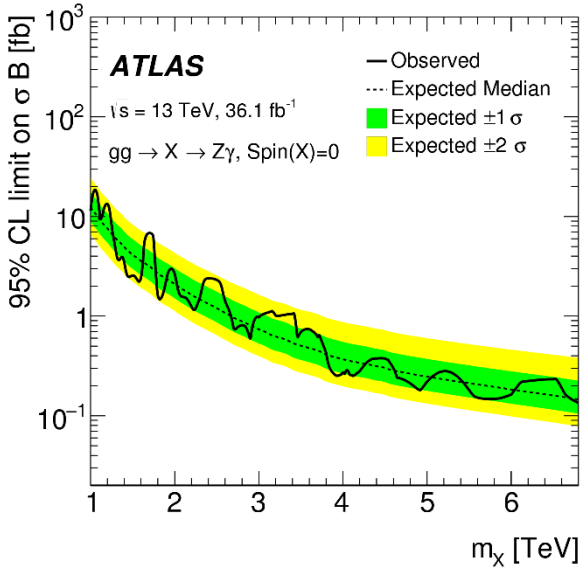


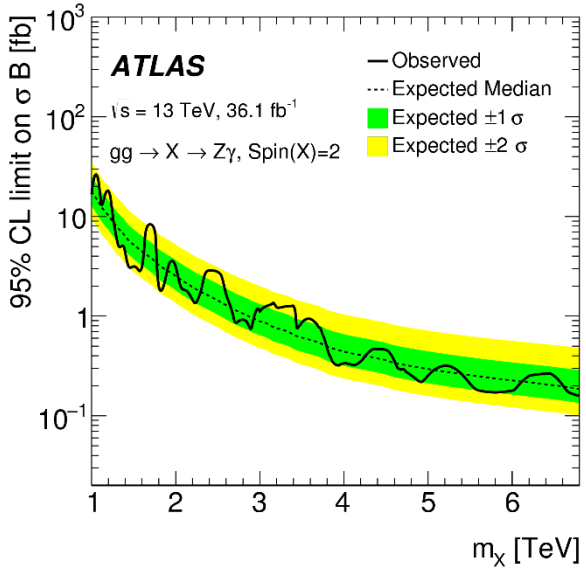


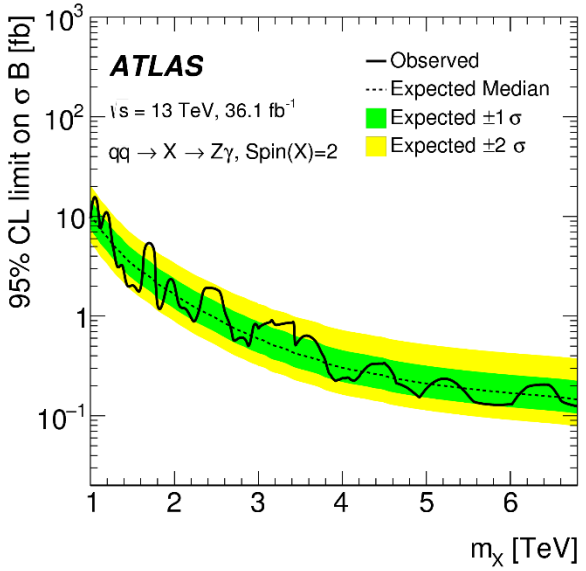
BACKUP

ATLAS:X→Vγ→qqγ, X→Hγ→bbγ

arXiv:1805.01908







narrow-width approximation