

# Searches for resonances decaying to pairs of heavy (massive) bosons in ATLAS

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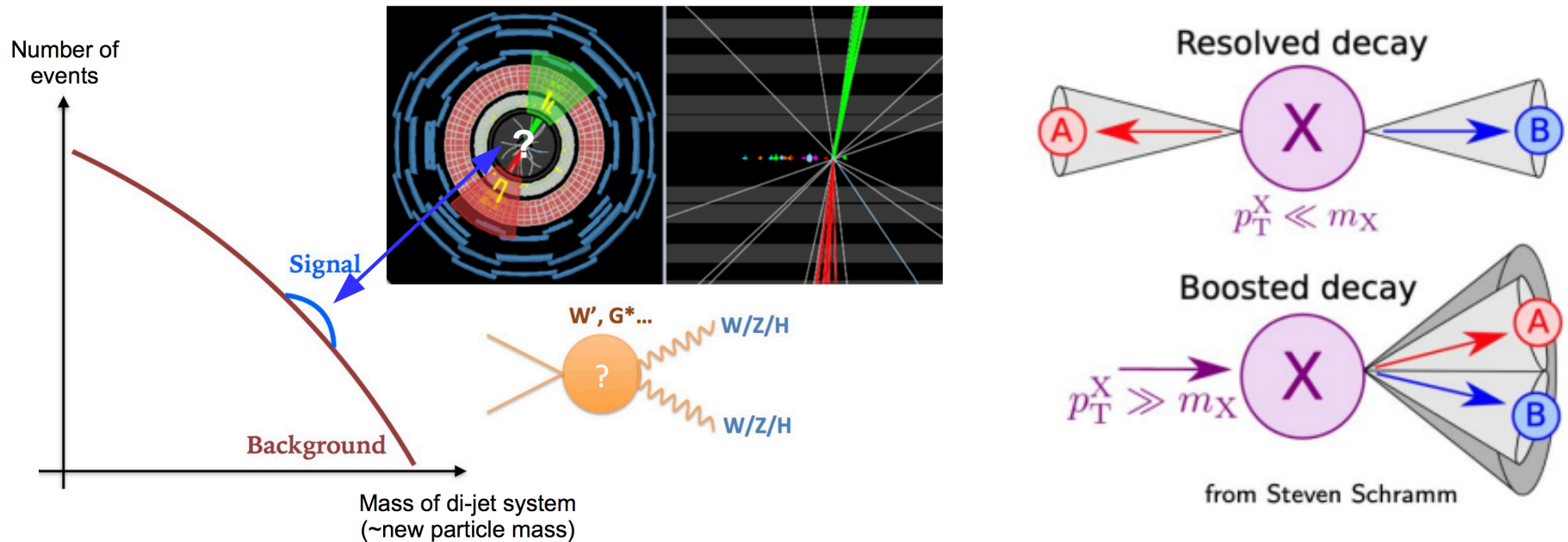
On behalf of

ATLAS Collaboration



上海交通大学  
SHANGHAI JIAO TONG UNIVERSITY

# DiBoson Resonance search in a nutshell



- Diboson process, being the Higgs 1<sup>st</sup> observation channel, still plays the role to probe BSM new physics in LHC Run2 and beyond
- Unique advantage for BSM hunting
  - Experimental signatures easy to identify via clean leptonic decays and boosted hadron final state boson tagging
  - Window to new physics inspire by many BSM hypothesis: HVT, technicolor, RS extra dimension, KK gravitons, 2HDM, MSSM
  - Technical feasible for many ways of searches: model independent bump hunting, LWA/NWA, EFT, anomalous gauge couplings, .



# Outline

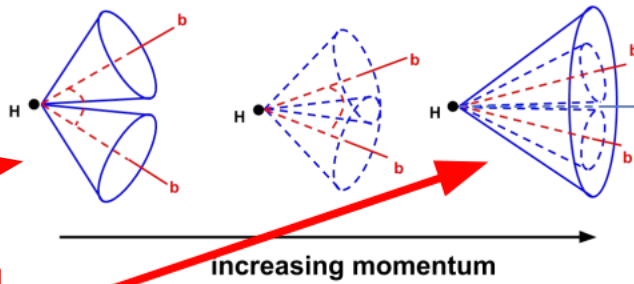
## Physics results shown:

- $X \rightarrow VH$  resonances (semileptonic channel)
  - [ATLAS-CONF-2020-043](#)
  - [ATLAS-CONF-2021-026](#)
- $X \rightarrow H\gamma$  resonances (hadron channels): [Phys. Rev. Lett. 125 \(2020\) 251802](#)
- $X \rightarrow W/Z+\gamma$  resonances (hadron channels): [ATLAS-CONF-2021-041](#)
- $X \rightarrow WZ$  ( $\rightarrow |vll$ ): [Phys. Lett. B 787 \(2018\) 68](#)
- $X \rightarrow ZZ$  ( $\rightarrow 4l/2l2\nu$ ): [Eur. Phys. J. C 81 \(2021\) 332](#)

## Experimental methods and performance results shown:

- [ATL-PHYS-PUB-2020-008](#): A W/Z-boson tagger using Track-CaloCluster jets with ATLAS (TCC jets)
- [ATL-PHYS-PUB-2021-029](#): Advanced W/Z tagging techniques for UFO jets
- [ATL-PHYS-PUB-2021-035](#):  $X \rightarrow bb$  tagger calibration
- [ATL-PHYS-PUB-2020-017](#): Boosted hadronic vector boson and top quark tagging with ATLAS using Run 2 data (LCTopo jets)
- [Eur. Phys. J. C 81 \(2021\) 334](#): UFO paper for future tagging improvements
- [Eur. Phys. J. C 79 \(2019\) 375](#): Performance of top-quark and W-boson tagging with ATLAS in Run 2 of the LHC

# Search for ZH resonances w/ leptons and b-jets



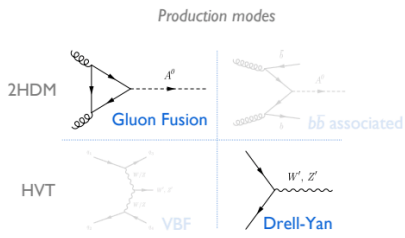
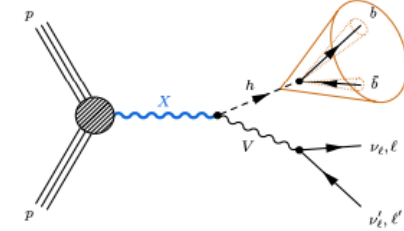
**Resolved:** use two small-R jets

**Merged:** use a large-R jet to reconstruct Higgs bosons with around  $p_T > 250\text{GeV}$

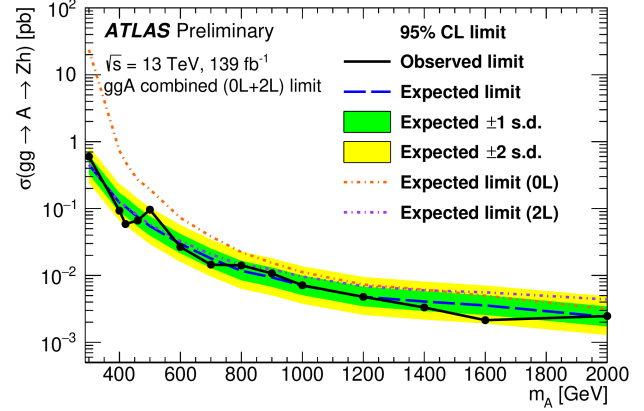
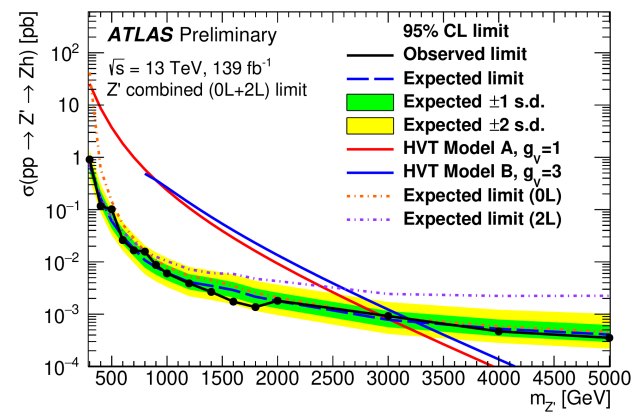
**for  $m_h = 125\text{ GeV}$**

Small-R = 0.4, Large-R = 1.0

$$\Delta R \approx \frac{2m}{p_T}$$

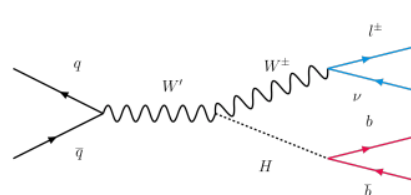
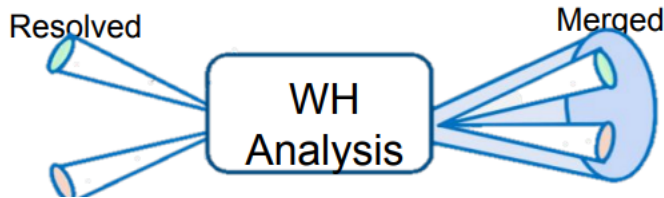


- Search for BSM resonances decaying into  $\nu\nu b\bar{b}$  and  $\ell\ell b\bar{b}$  final states via  $Z_h(125)$
- 0-lep/2-lep channels, resolved and boosted jet schemes, 1/2 b-tag categories are combined to enhance full mass range sensitivity, using TCC jets
- Survey BSM signatures via discriminants of  $m_{T,Zh}$  and  $m_{Zh}$  spectra
- Exclusion limits on x-sec times BR of  $Z'$  resonances in heavy-vector-triplet (model-A/B interpreted) and the CP-odd scalar boson A in 2HDM

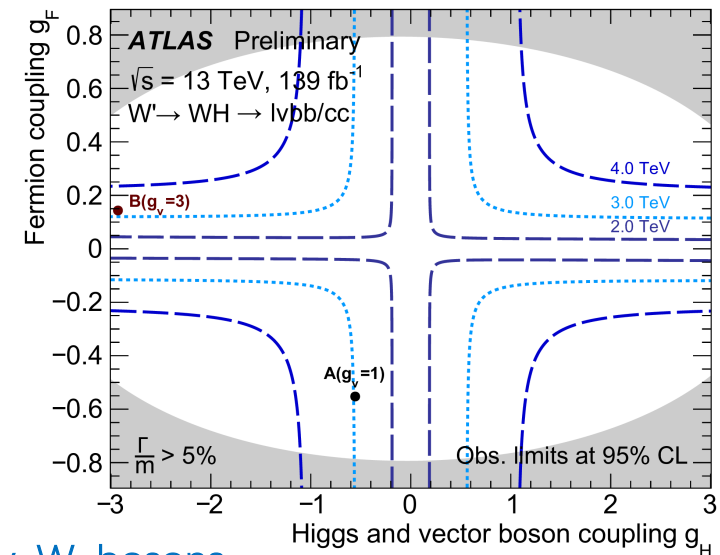
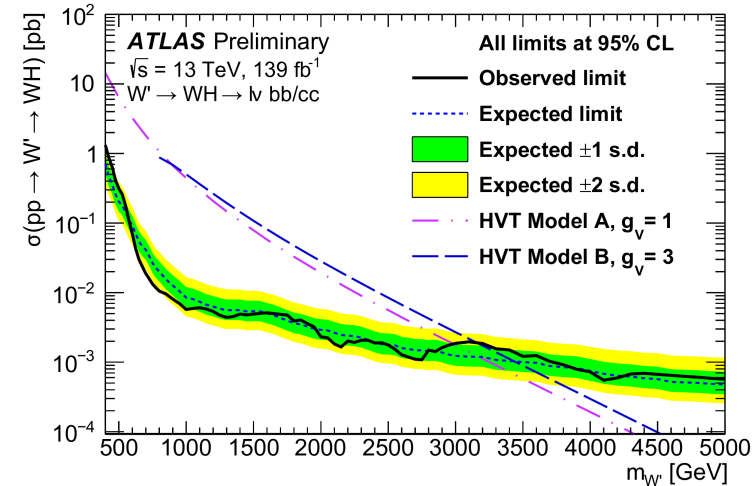


***ATLAS-CONF-2021-026***

# Search for WH resonances w/ leptons and b-jets



- Search for resonances decaying into  $WH(125) \rightarrow l\nu b\bar{b}$
- Resolved/boosted, 1/2 b-tag categories, combined, using TCC jets
- No significant excess is observed
- 95 % CL exclusion limits on x-sec times BR of  $W'$  bosons in Heavy-Vector-Triplet models with  $m_{W'}$  excluded up to  $\sim 3.5\text{TeV}$

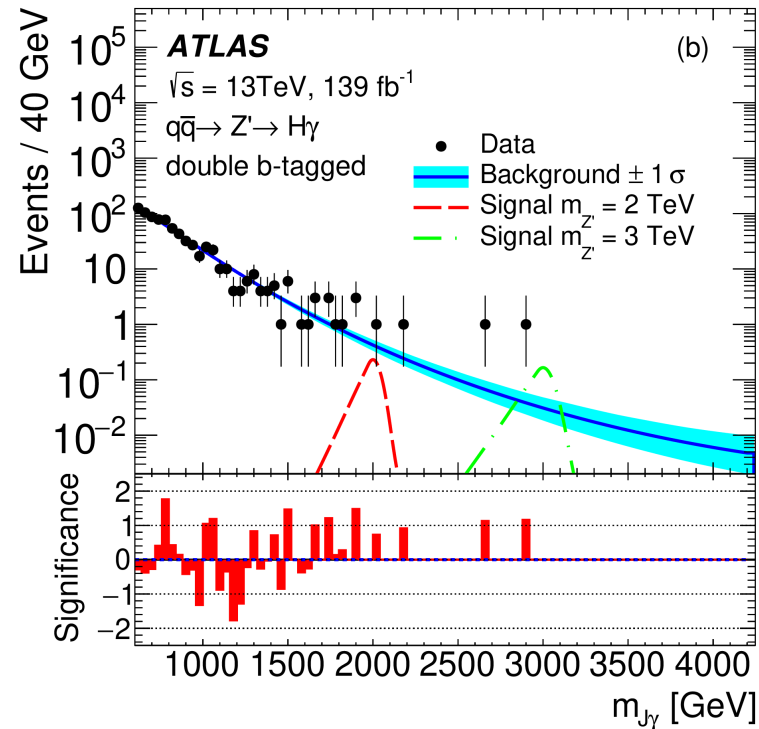
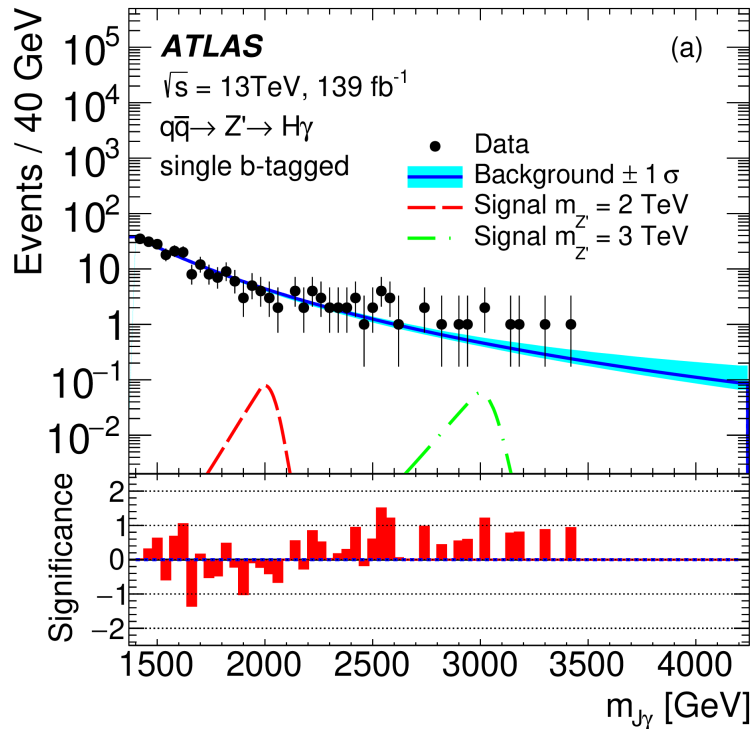


Region	signal regions	control regions
	Resolved	
$b$ -tags	1, 2 $b$ -tag	1, 2 $b$ -tag
Mass window	$110 < m_{jj} < 140 \text{ GeV}$	$50 < m_{jj} < 110 \text{ GeV} \parallel 140 < m_{jj} < 200 \text{ GeV}$
	Merged	
$b$ -tags	1, 2 $b$ -tag	1, 2 $b$ -tag
Mass window	$75 < m_J < 145 \text{ GeV}$	$50 < m_J < 75 \text{ GeV} \parallel 145 < m_J < 200 \text{ GeV}$

<https://atlas.cern/updates/briefing/search-heavy-W-bosons>

# H+ $\gamma$ resonance search

*Phys. Rev. Lett. 125 (2020) 251802*

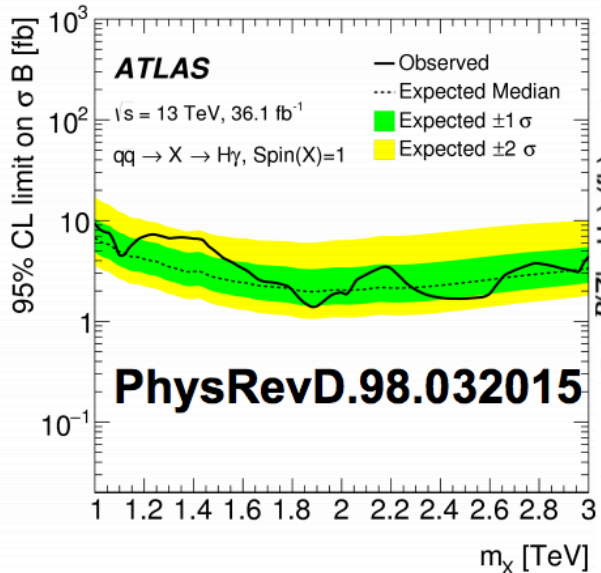


- Heavy resonance search for spin-1  $X \rightarrow H + \gamma$  process with toy model:
  - start from  $Z'$  benchmark, add a contact interaction  $Z' \rightarrow H + \gamma$ , i.e. at the level of the FeynRules, add in a new U(1) symmetry, and then a dim-6 term
- Boosted large-R LCTopo jet for SM Higgs boson candidate: 1/2 b-tag categories
- Novel methodology: based on information about the jet constituents calculated in the center-of-mass frame of the jet (CoM Jet)

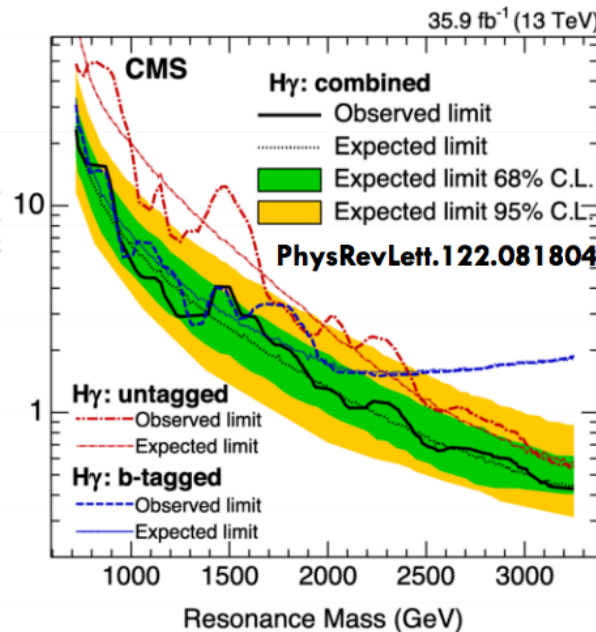
# H+ $\gamma$ resonance search

*Phys. Rev. Lett. 125 (2020) 251802*

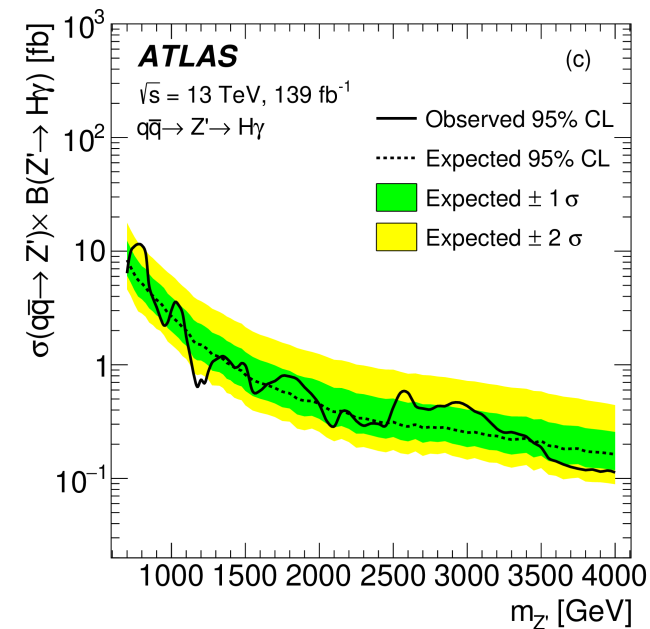
Previous ATLAS result



Previous CMS result



*This work*



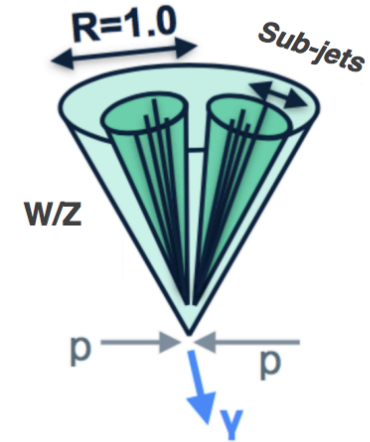
## Limit ratio comparison:

- ATLAS: new result / previous result  $\sim 1/15$  ( $\sim 1/3$ ) for  $M(Z') = 2.5(1.2)\text{TeV}$
- CMS: partial dataset with TMVA treatment applied, based on BDT for  $H \rightarrow b\bar{b}$  + fatjet substructure information, ratio of ATLAS new results/CMS =  $2/5 \sim 1/3$  below 2.5TeV while lumi. projection gives 1/2 (so further improvements thanks to CoM techniques)

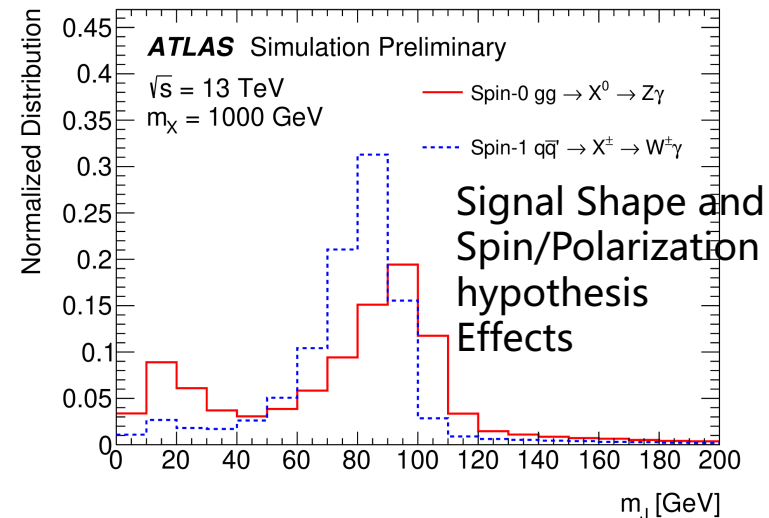
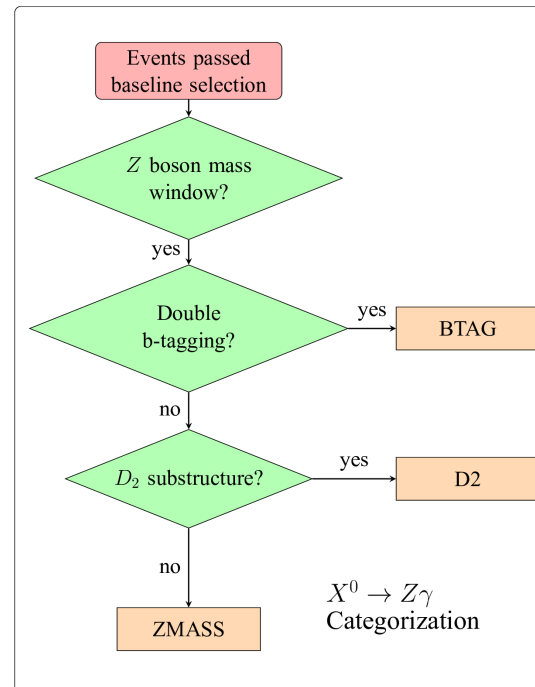
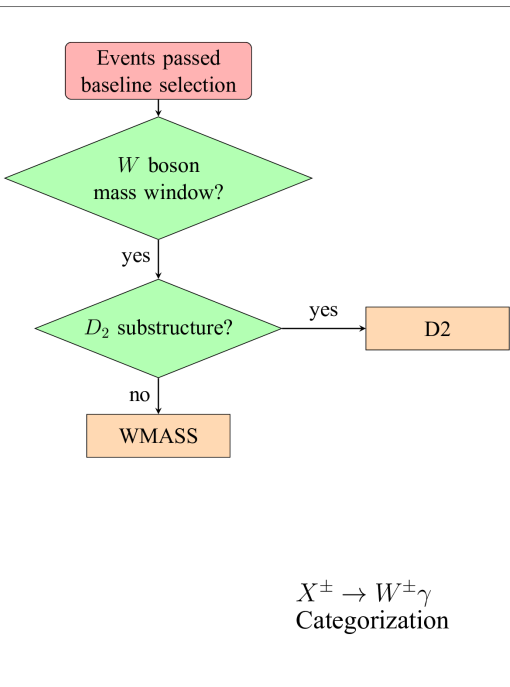
**ATLAS-CONF-2021-041**

# W/Z+ $\gamma$ resonance search

- Search for heavy resonances decaying into W/Z+ $\gamma$  in full hadron final states of W/Z decays, using TCC jets
- Single photon trigger,  $p_T(j/\gamma) > 200\text{GeV}$ , barrel photon only
- Jet substructure based D2 variable to tag large radius jets ( $R = 1.0$ ) containing the W/Z decay products,  $p_T$  dependent optimization to maintain sensitivity across the whole mass range, plus categorization which provide further complementary sensitivities



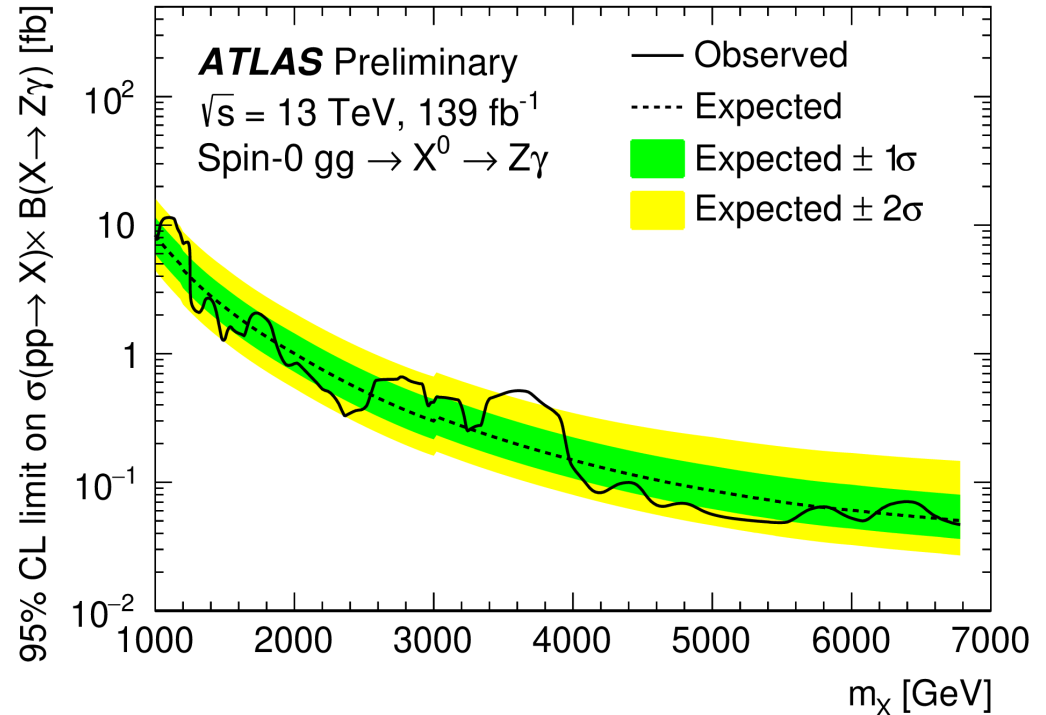
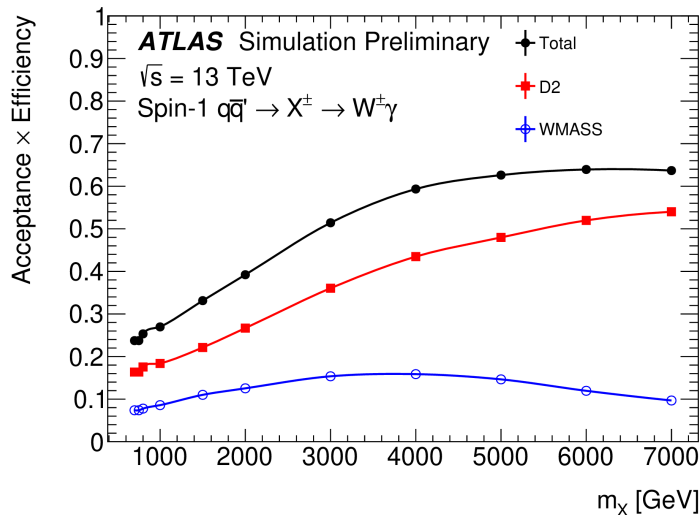
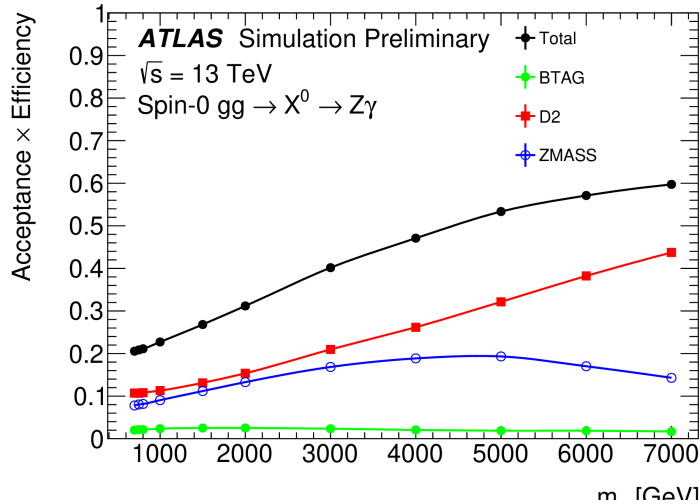
Physics objects:  
1 high energy photon  
1 large-Radius jet (fat-jet)





## ATLAS-CONF-2021-041

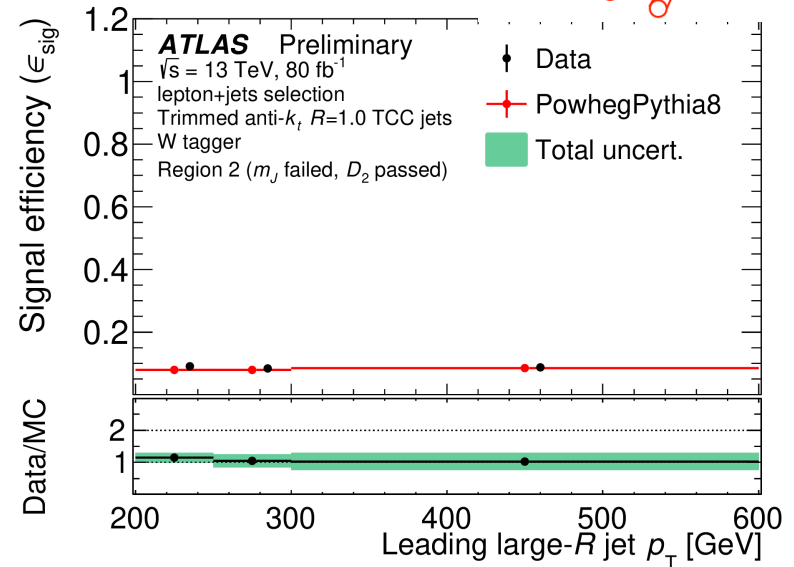
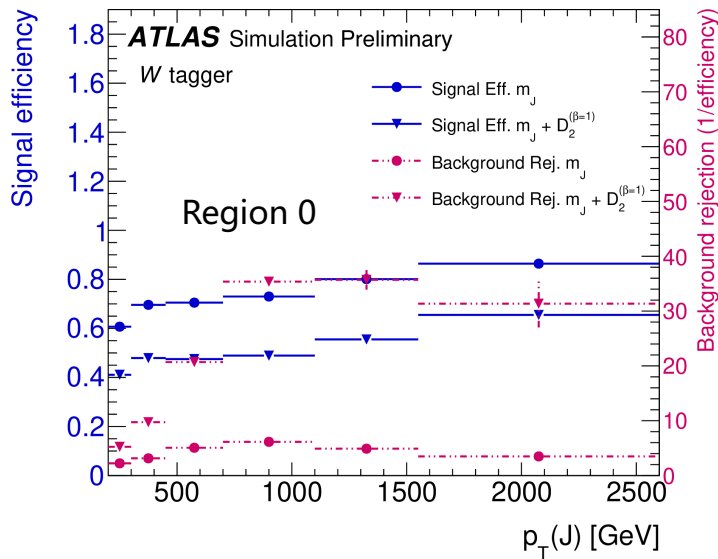
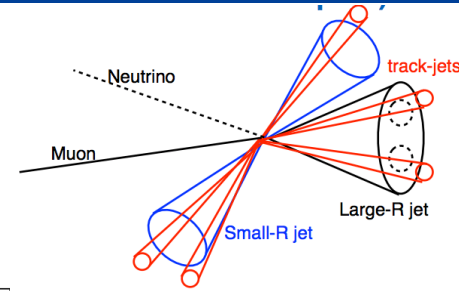
# W/Z+ $\gamma$ resonance search



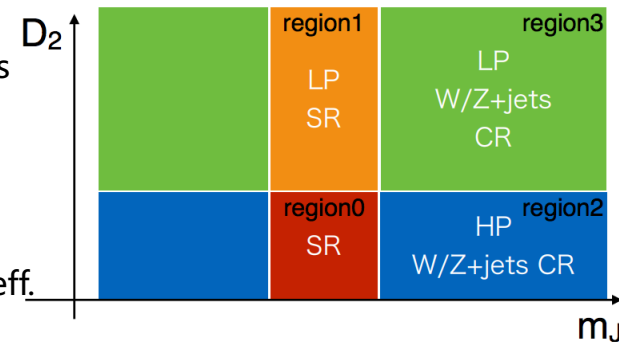
gg/qq induced spin-0/2  $Z+\gamma$  and Spin-1  $W+\gamma$  BSM heavy resonance signals are investigated with combined categories to recover efficiency at high mass, Narrow-Width Approximation is used and Crystal Ball+Gaussian Tail for signal modeling

Limits are set up to 7TeV on x-sec times BR, for the 1<sup>st</sup> time up to this upper mass bound in diboson heavy resonances

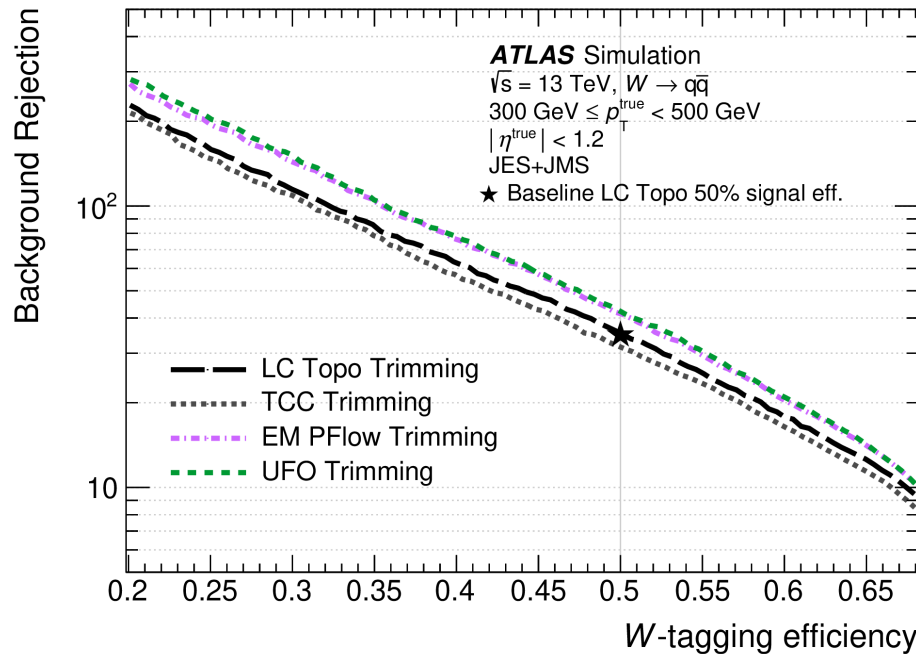
# Novel developments of boosted boson tagging: Track-CaloCluster Jets for W/Z tagging



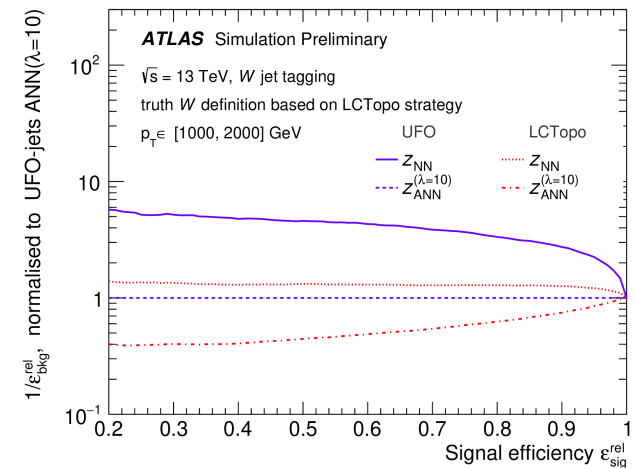
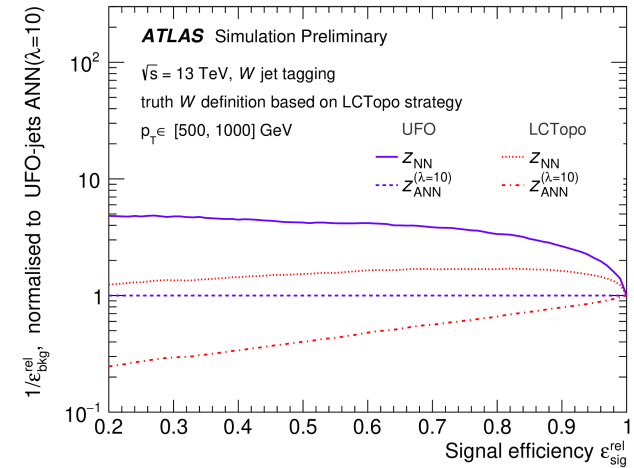
- Novel PFA dedicated to high  $p_T$  jets , Track-CaloClusters, to improve the resolution of the jet substructure variable w.r.t. calorimeter-only jets
- W/Z-boson tagger optimized esp. for diboson res. search in semilep final states
- Template fit to extract signal efficiency in 4-regions
- Calibrated for signal eff. and bgd rej. with better JSS observable  $D_2$
- Can afford 70% eff. with comparable bgd rej. perf. Compared to previous 50% eff.



# DNN tagger with UFO jets for boosted boson tagging

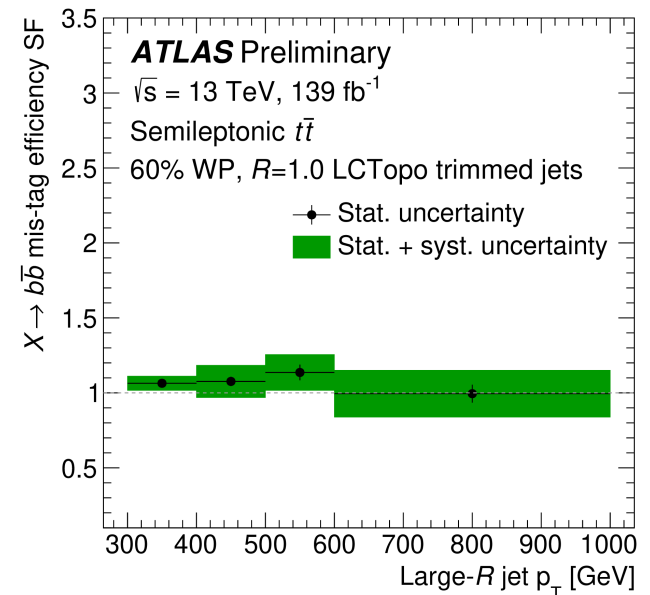
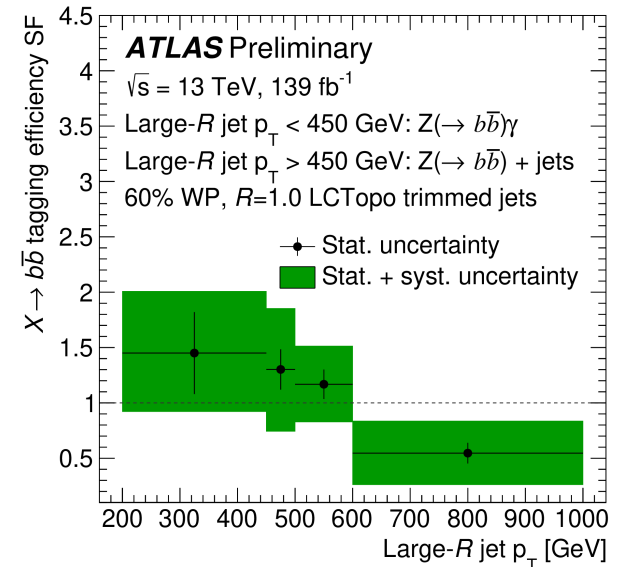


- New large-radius jet collection reconstructed from Unified Flow Objects (UFOs), a new particle-flow like algorithm being the merger of PFlow and TCCs, improve the reconstruction of jet substructure variables used in boosted W/Z/Top tagging
- Bgd rej. found to be improved by a factor~3 for both the low- and high-pT range for the DNN taggers, and a factor~2.5 for the ANN taggers, for a fixed signal efficiency of 50%. Significantly better perf. for cut-based tagger, too
- Also developed mass-correlation treatment for the taggers to enable more robust bgd estimation strategy



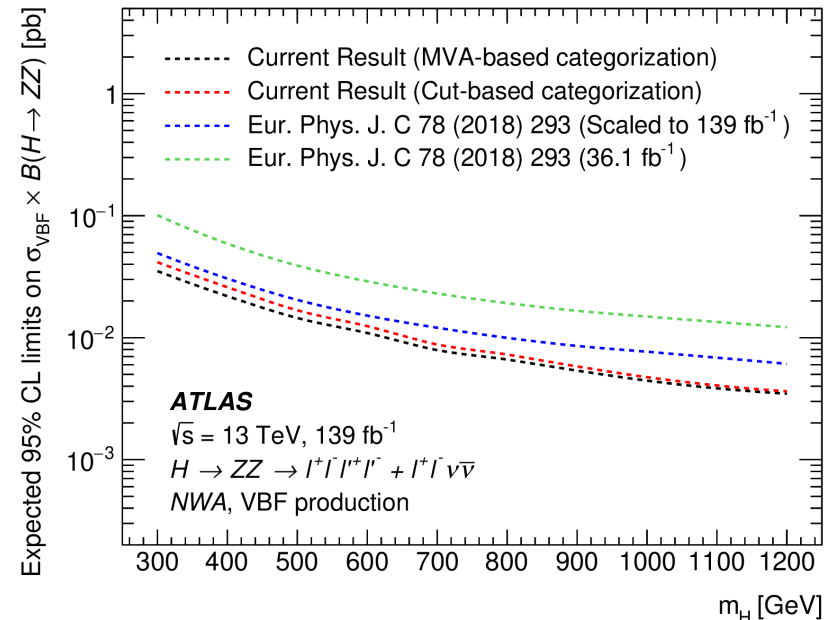
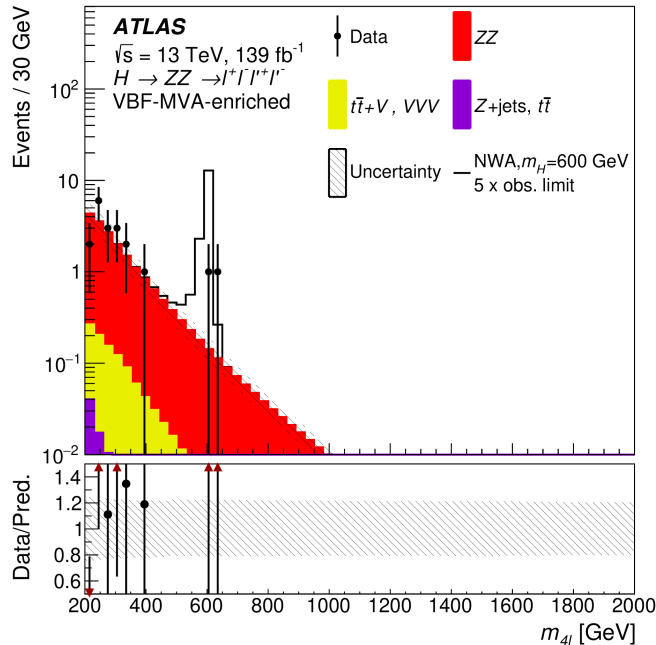
# Boosted $Xbb$ tagger calibration

- Dedicated double  $b$ -tagging algorithm based on a neural network (NN), the  $X \rightarrow bb$  tagger: ATL-PHYS-PUB-2020-019
- Applied on large- $R$  jet, which combines the flavour information of up to three subjets (variable radius) within the large- $R$  jet along with the large- $R$  jet  $p_T$  and  $\eta$
- The signal efficiency is calibrated using  $Z(\rightarrow bb)+jets$  and  $Z(\rightarrow bb)\gamma$  events. The background efficiency is calibrated using  $t\bar{t}$  events.
- Data-to-Monte-Carlo efficiency scale factors are measured as a function of the large- $R$  jet  $p_T$
- Modelling of large- $R$  jet kinematics in Monte Carlo simulation is checked after the application of the  $X \rightarrow bb$  tagger using multijet events enriched in  $g \rightarrow bb$  splitting



*Eur. Phys. J. C 81 (2021) 332*

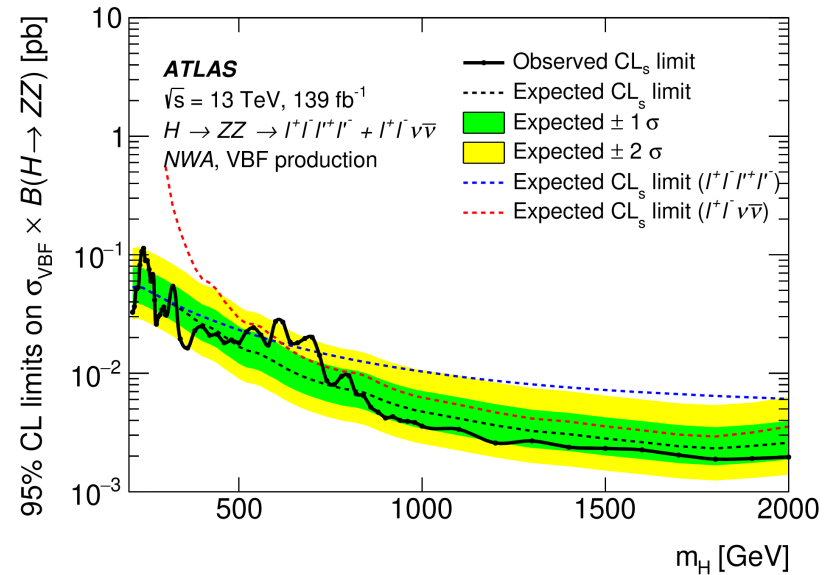
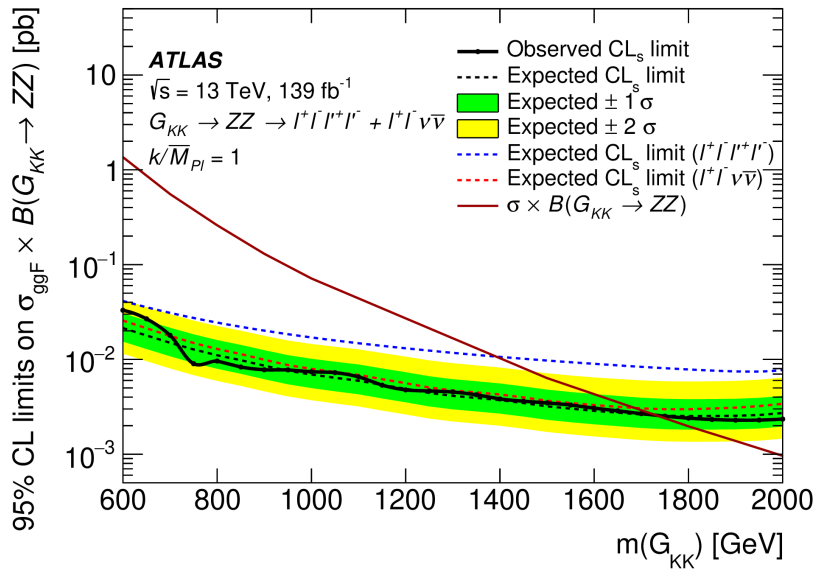
# Towards lower mass region: Search for $ZZ(\rightarrow 4l/2l2\nu)$ heavy resonances



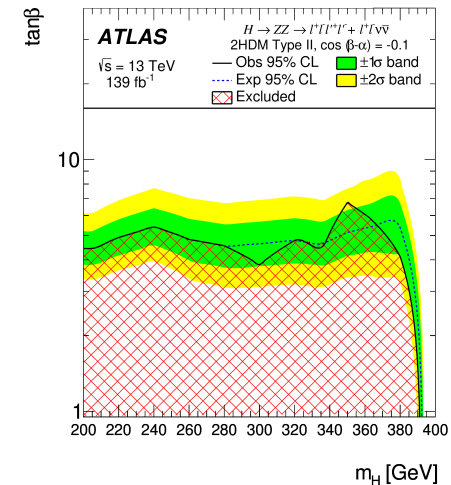
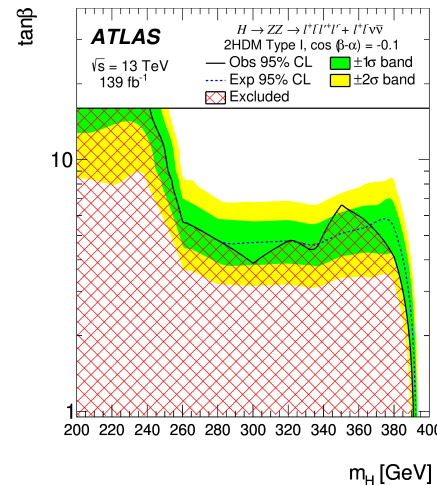
	$4l$	$ll\nu$
Extend range from 1.2 TeV to 2 TeV	✓	✓
ZZ bkg normalization constrained by data	✓	✓
Use PFlow MET, jet & lepton isolation WP	✓	✓
Reoptimize event selection	•	✓
Reoptimize event categorization	✓ MVA	✓ Cut-based

- Revisited Analysis w.r.t.  $36\text{fb}^{-1}$  with significance optimization: cut-based  $\rightarrow$  MVA for  $4l$ , big mass range extension with full run2 dataset, dramatic improvements
- Thorough BSM survey: ggF/VBF, spin-0/spin-1, NWA/LWA, ...

# Search for $ZZ(\rightarrow 4l/2l2\nu)$ heavy resonances



- No significant observed excess
- Results are interpreted as upper limits on the x-sec of spin-0/spin-2 resonance, in ggF/VBF production modes.
- Spin-0 resonance interpretation: exclusion contours in the context of Type-I and Type-II 2HDM,
- Spin-2 resonance interpretation: constraint of the Randall-Sundrum model with an extra dimension giving rise to spin-2 graviton excitations.





# Summary

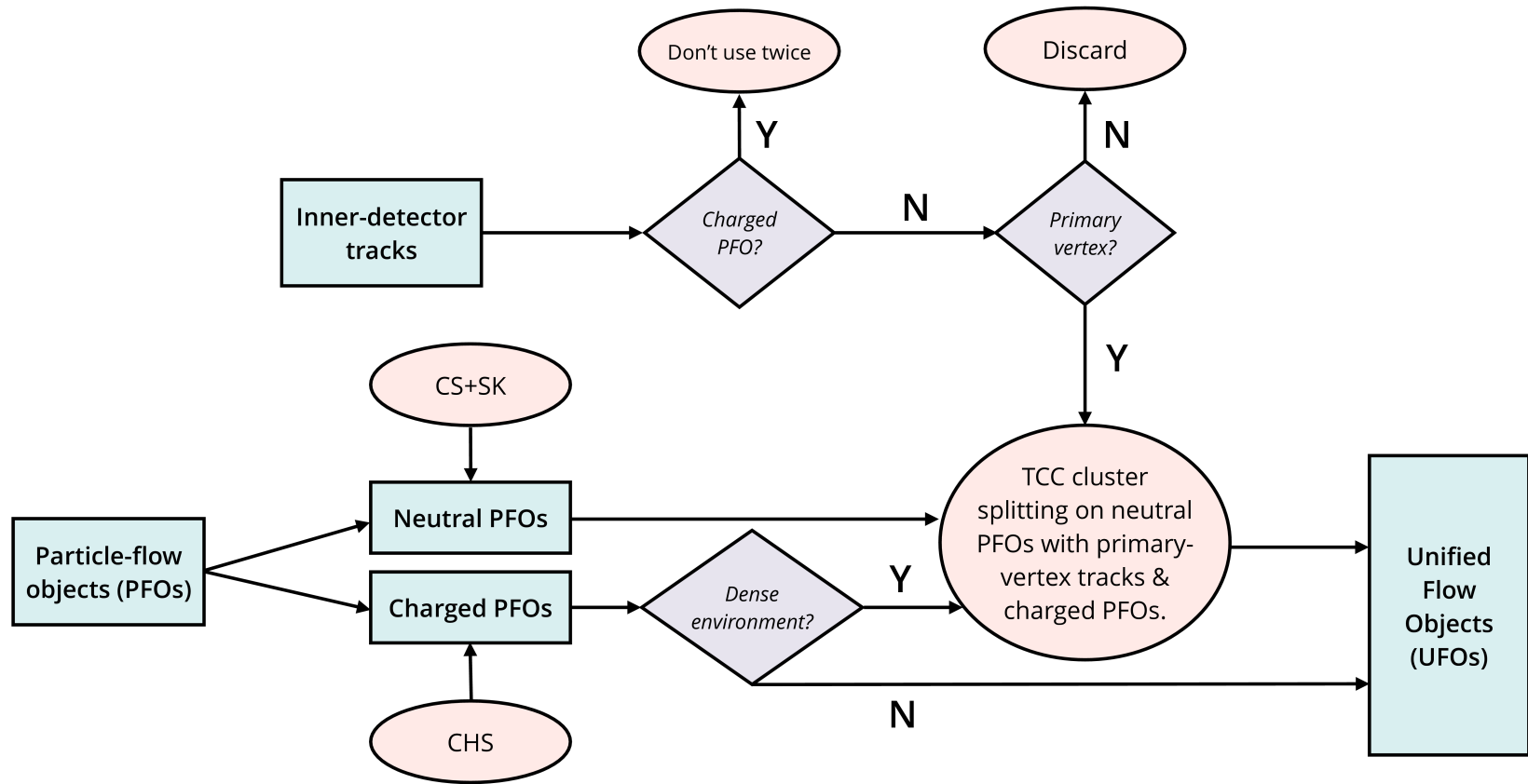
- ATLAS keeps exploring new physics after the discovery of Higgs boson with special focus on new physics inducing Higgs and gauge vector boson productions
- Boosted tagging techniques are essential to enhance the search sensitivities in the high mass regime, a lot of new technical breakthroughs as well as solid calibrations, more sophisticated but effective
  - Large-Radius Jets, Variable Radius subjets, Track-CaloCluster, UFO, ...
  - W/Z tagger, Xbb tagger, (Top tagger), ... and ongoing ML-based studies to improve the tagger perf. even more
- Fully hadron, semi-leptonic, fully leptonic final states of VH, VV are being thoroughly scanned for new resonance signatures. So far, no hints of new physics but the full Run-2 dataset is still being analysed, and more insights will be provided with the upcoming Run-3!



# Backup

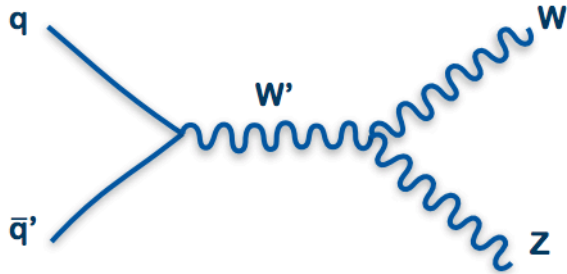


# ATLAS UFO Jet Algo

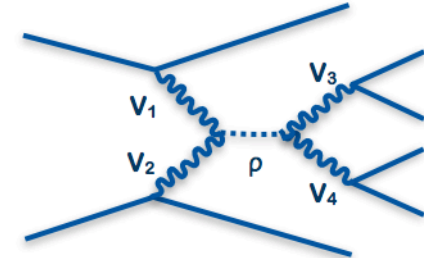
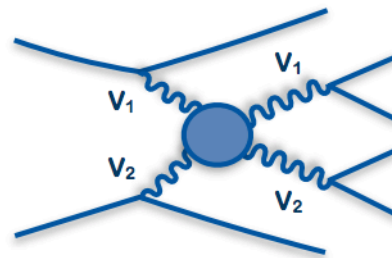


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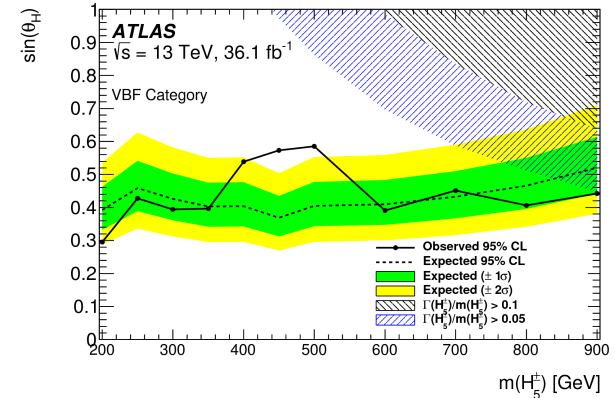
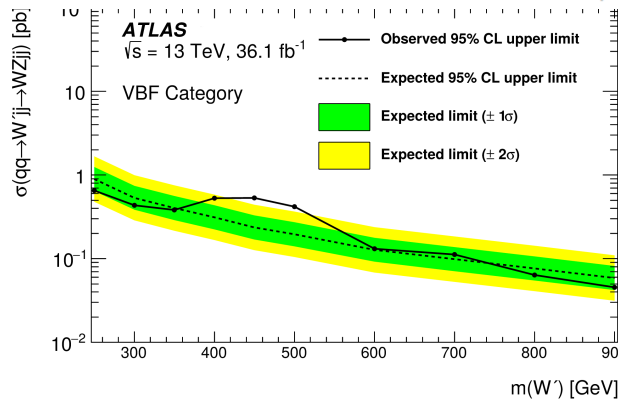
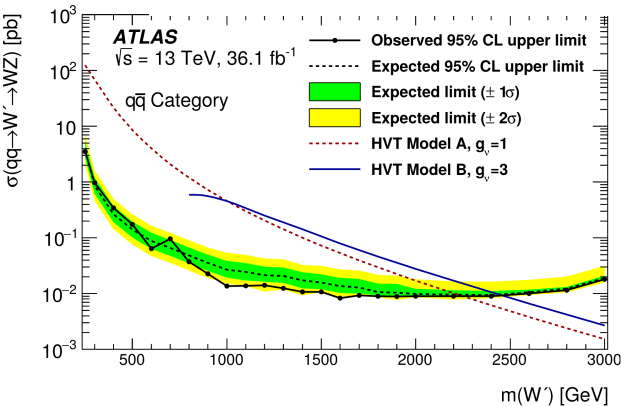
# Search for $WZ(\rightarrow 3l1\nu)$ heavy resonances



$q\bar{q}$  production mode



VBF production mode



- Heavy resonance search in  $WZ$  fully leptonic final states
- BSM survey using both  $q\bar{q}$  annihilation and VBF production modes
- New Physics Interpretation w/ Heavy Vector Triplet and the fiveplet scalar in the Georgi-Machacek (GM) model
- Local/global 3.1/1.9  $\sigma$  excess at 450GeV, to be revisited with full run2 analysis