Silvia Auricchio, on behalf of ATLAS Collaboration

ATLAS EXPERIMENT

Università degli Studi di Napoli Federico II

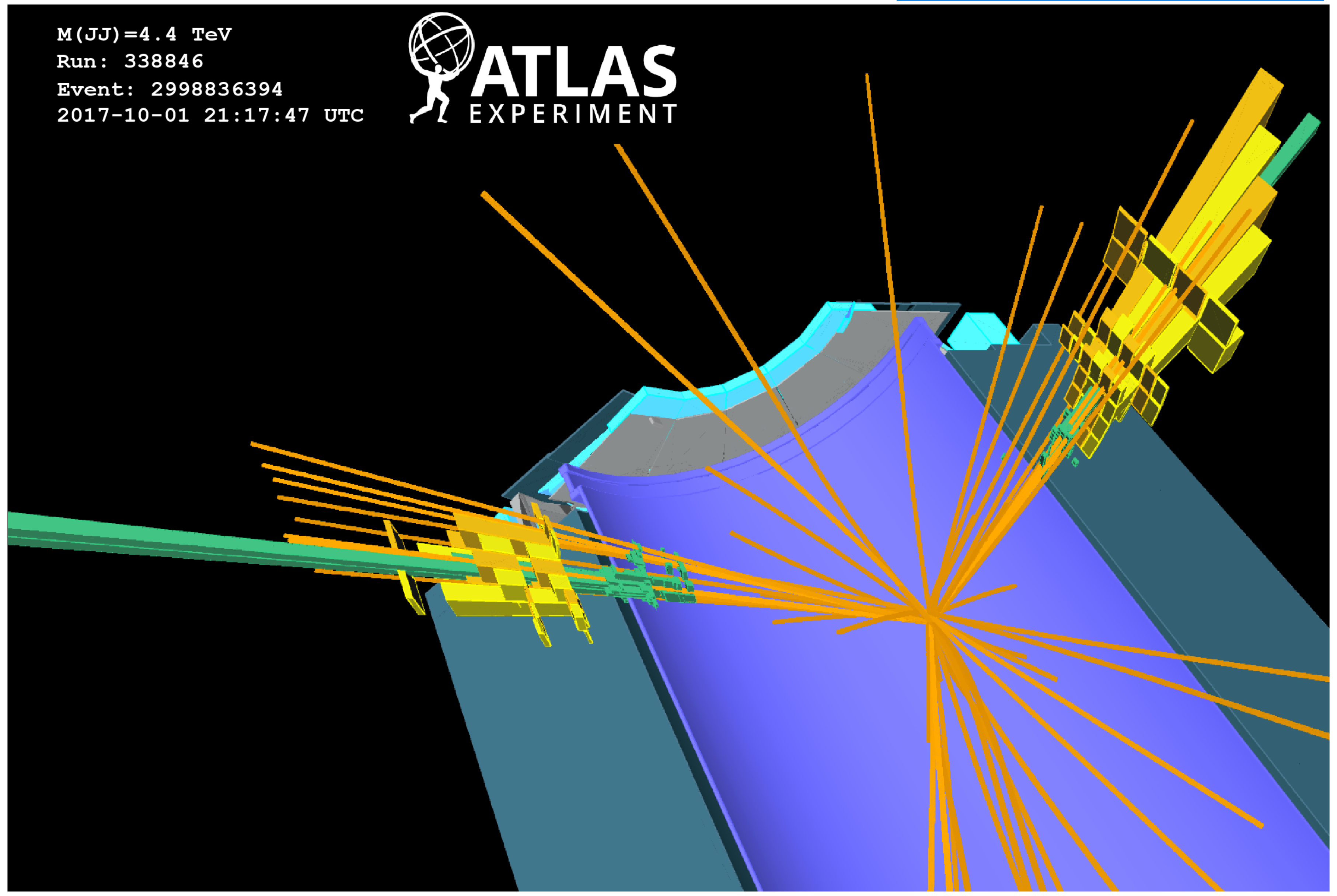
Searches for resonances decaying to pairs of heavy bosons in ATLAS

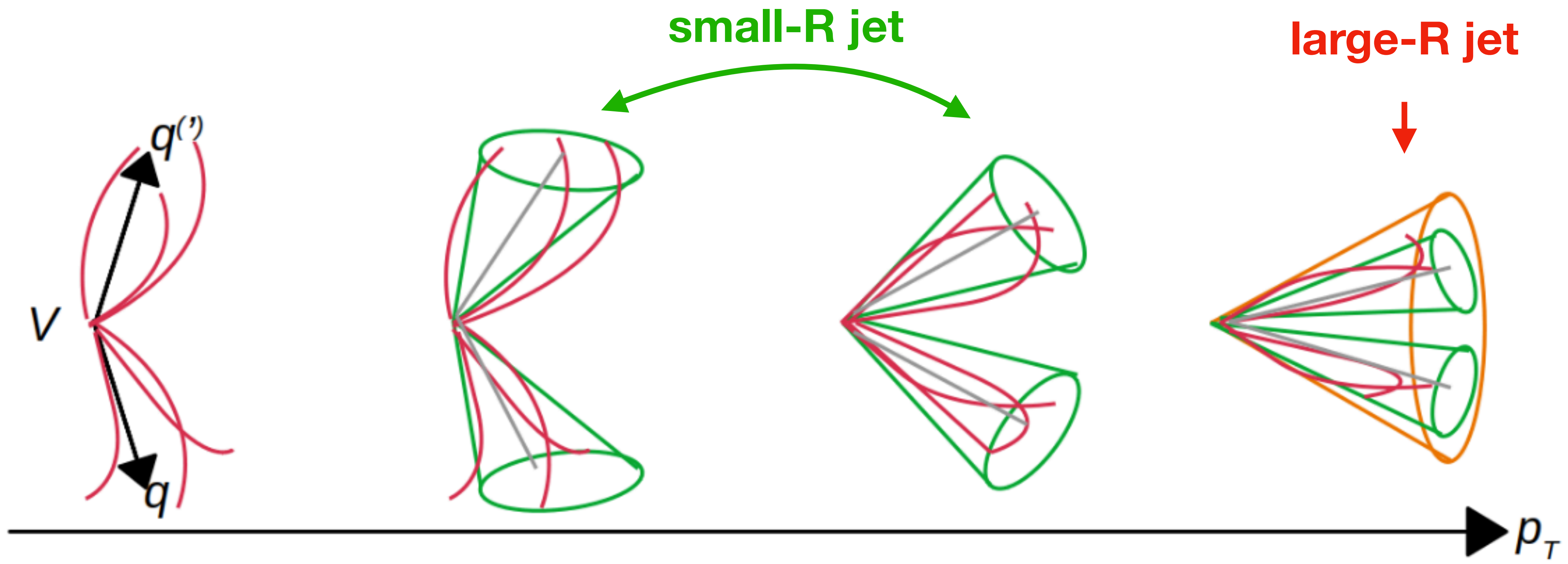
CIPANP, 29 August - 4 September 2022

Diboson Resonances Searches in ATLAS

arXiv:1906.08589

- Several Beyond Standard Model (BSM) theories predict the existence of new heavy resonances X decaying into pairs of SM bosons $X \rightarrow VV',\ X \rightarrow hV$ or $X \rightarrow \gamma V$ (V=W, Z)
- Hadronic boson decays can be reconstructed:
  - with two small-R jets (**resolved**)
  - with a large-R jet (**merged**)
- Improvements in jet substructure identification techniques significantly enhanced the sensitivity in boosted final states





- Models mentioned in this talk are:
  - Heavy Vector Triplet (HVT): simplified model with an additional SU(2) field in the SM lagrangian
  - Several models with extended Higgs sector (2HDM, MSSM, Georgi–Machacek (GM))
  - Kaluza-Klein model with spin-2 graviton

Outline

- Jets reconstruction techniques & performances overview (arXiv:2009.04986, arXiv:1703.10485, arXiv:0802.1189, ATL-PHYS-PUB-2017-015)
- Boson tagging in ATLAS (arXiv:1808.07858 , ATL-PHYS-PUB-2020-008)
- b-jets identification (arXiv:1907.05120)
- Diboson physics results performed with $139\ fb^{-1}$ of pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector:

Hadronic (& with photons) :

- Search for high-mass $W\gamma$ and $Z\gamma$ resonances using $139\ fb^{-1}$ of pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector (ATLAS-CONF-2021-041)
- Anomaly detection search for new resonances decaying into a Higgs boson and a generic new particle X in hadronic final states using $\sqrt{s} = 13$ pp collisions with the ATLAS detector (ATLAS-CONF-2022-045)

Semi-leptonic:

- Search for heavy resonances decaying into a Z or W boson and a Higgs boson in final states with leptons and b-jets in $139\ fb^{-1}$ of pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector (arXiv:2207.00230)
- Search for Higgs boson pair production in association with a vector boson in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector (ATLAS-CONF-2022-043) <— backup

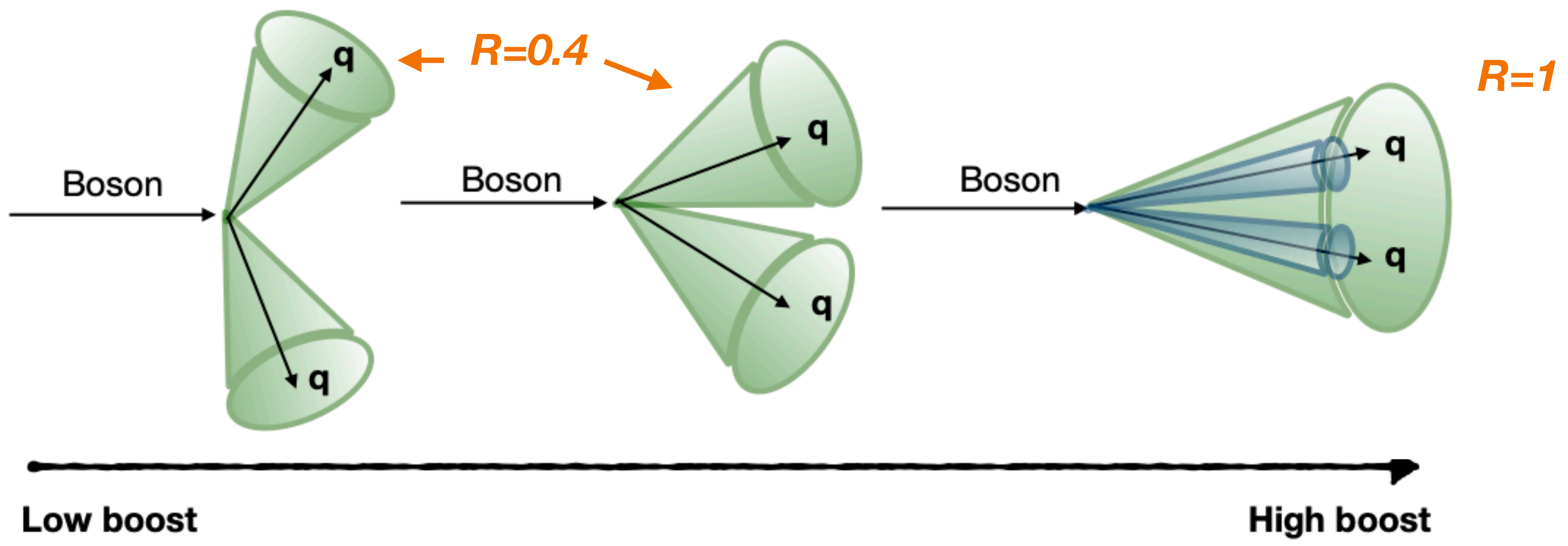
Fully-leptonic:

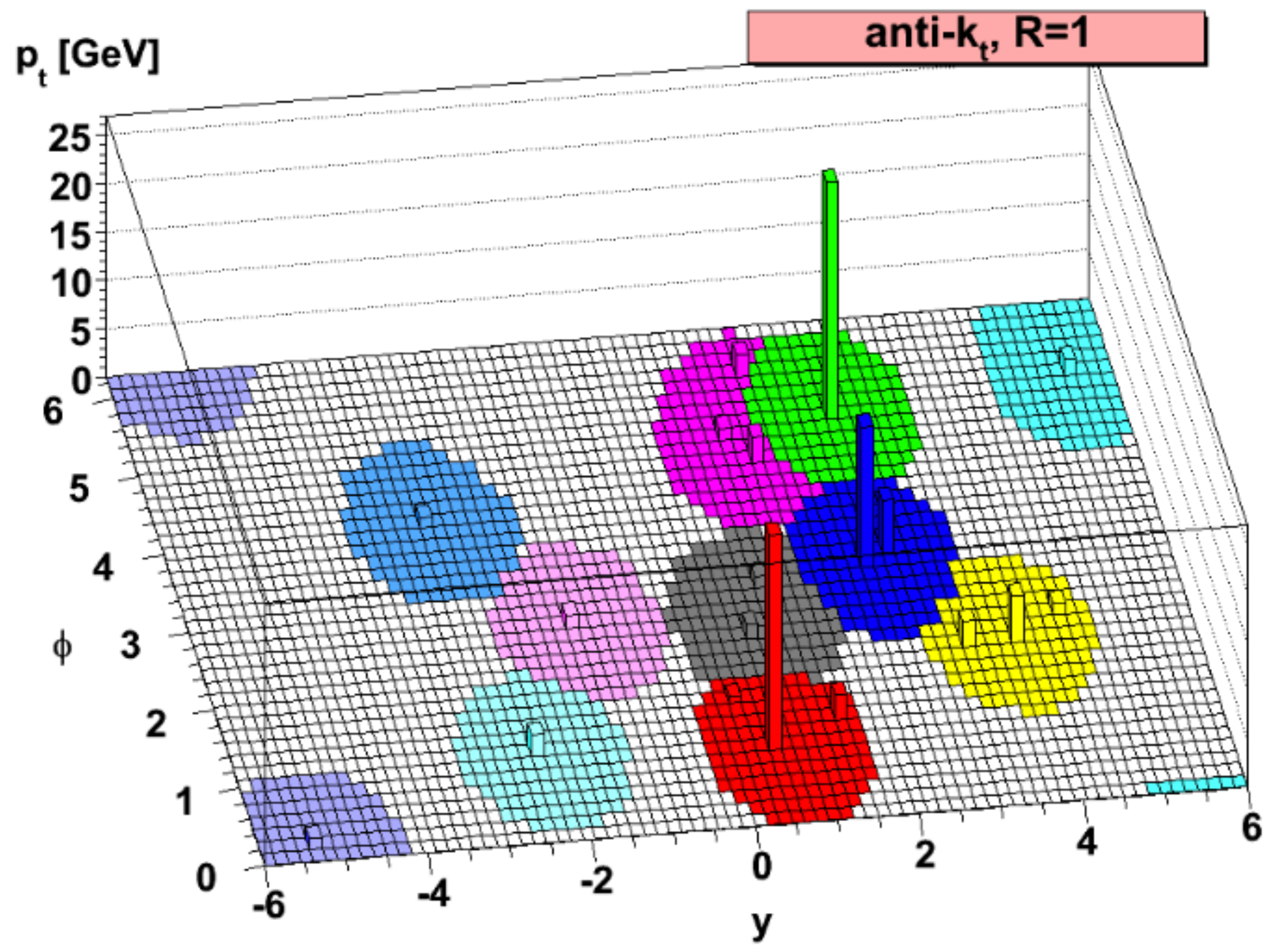
- Search for resonant $WZ \to l\nu l'l'$ production in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector (arXiv:2207.03925)
- Search for heavy resonances decaying into a pair of Z bosons in the $l^+l^-l^+l^-$ and $l^+l^-\nu\bar{\nu}$ final states using $139\ fb^{-1}$ of proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector (arXiv:2009.14791) <— backup

Introduction to Jets

arXiv:0802.1189
arXiv:2009.04986

- Jets are objects reconstructed using deposits of energy inside the calorimeter and tracks from the inner detector
- In ATLAS they are typically reconstructed from a set of input objects using a sequential recombination algorithm (anti-k_t) with a user-specified R parameter
    - R=0.4 for small-R jets
    - R=1 for large-R jets





- Topoclusters uses a combination of calorimeter cells calibrated to the electromagnetic scale
- All clusters are taken to be massless
- Grooming algorithms (Trimming, Pruning, Soft Drop..) are used to remove undesirable radiation (pile-up, initial state radiation…) from jets after they have been reconstructed

Track-CaloCluster

arXiv:2009.04986

ATL-PHYS-PUB-2017-015

- By combining track- and calorimeter-based measurements it is possible to improve jet energy, mass resolution and pile-up stability
- Particle-flow (PFlow) and Track-CaloClusters (TCCs) jets reconstruction algorithms are born from this idea
- TCCs use the energy information from topoclusters and angular information from tracks
  - Track p_T is used to determine shared fraction of calo clusters
- Improvements are particularly at high transverse momentum

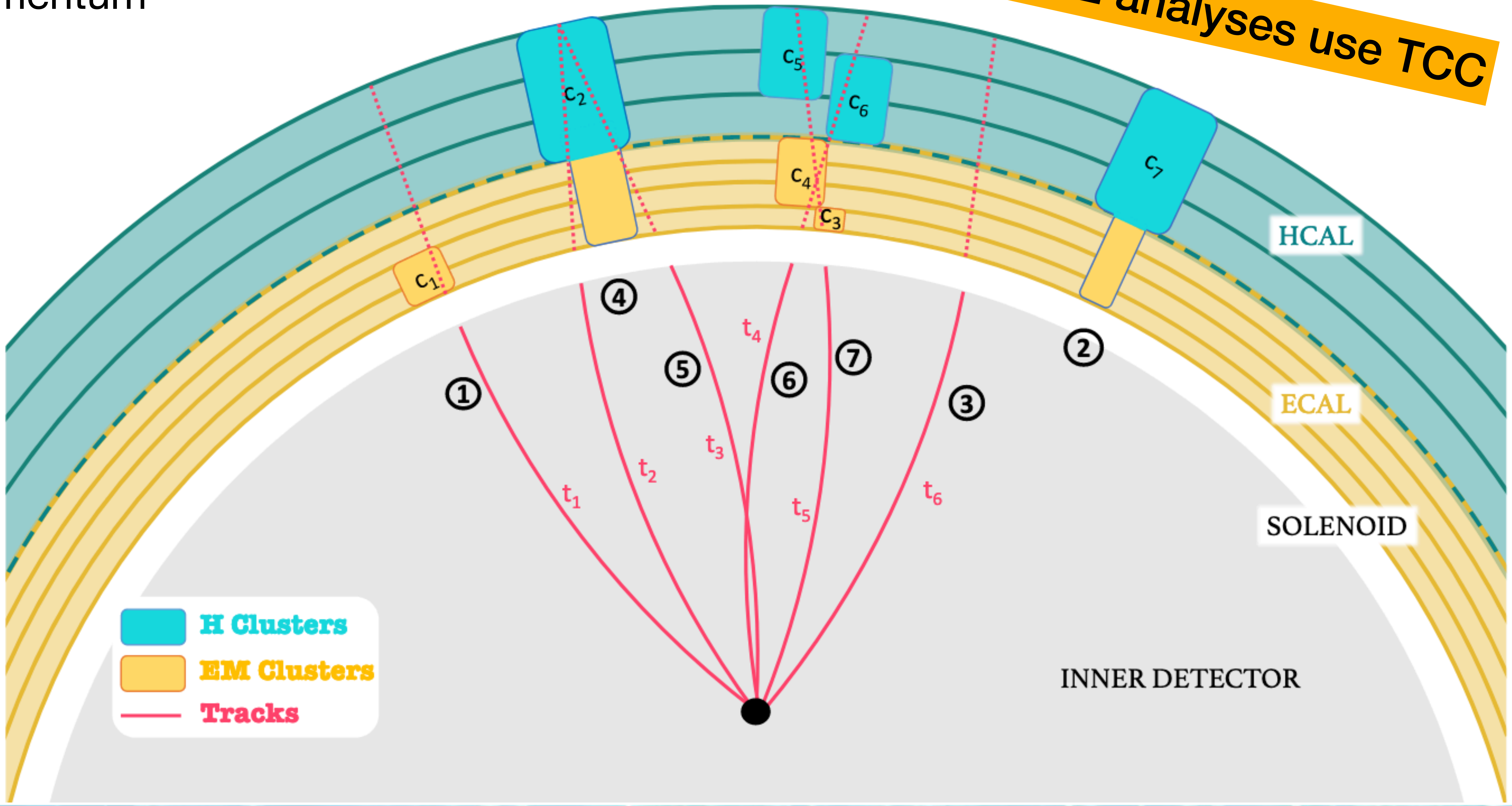
Most of Run-2 analyses use TCC

$$\mathrm{TCC}_{①} = (p_{\mathrm{T}}^{c_1}, \eta^{t_1}, \phi^{t_1}, m^{c_1} = 0)$$

$$\mathrm{TCC}_{②} = (p_{\mathrm{T}}^{c_7}, \eta^{c_7}, \phi^{c_7}, m^{c_7} = 0)$$

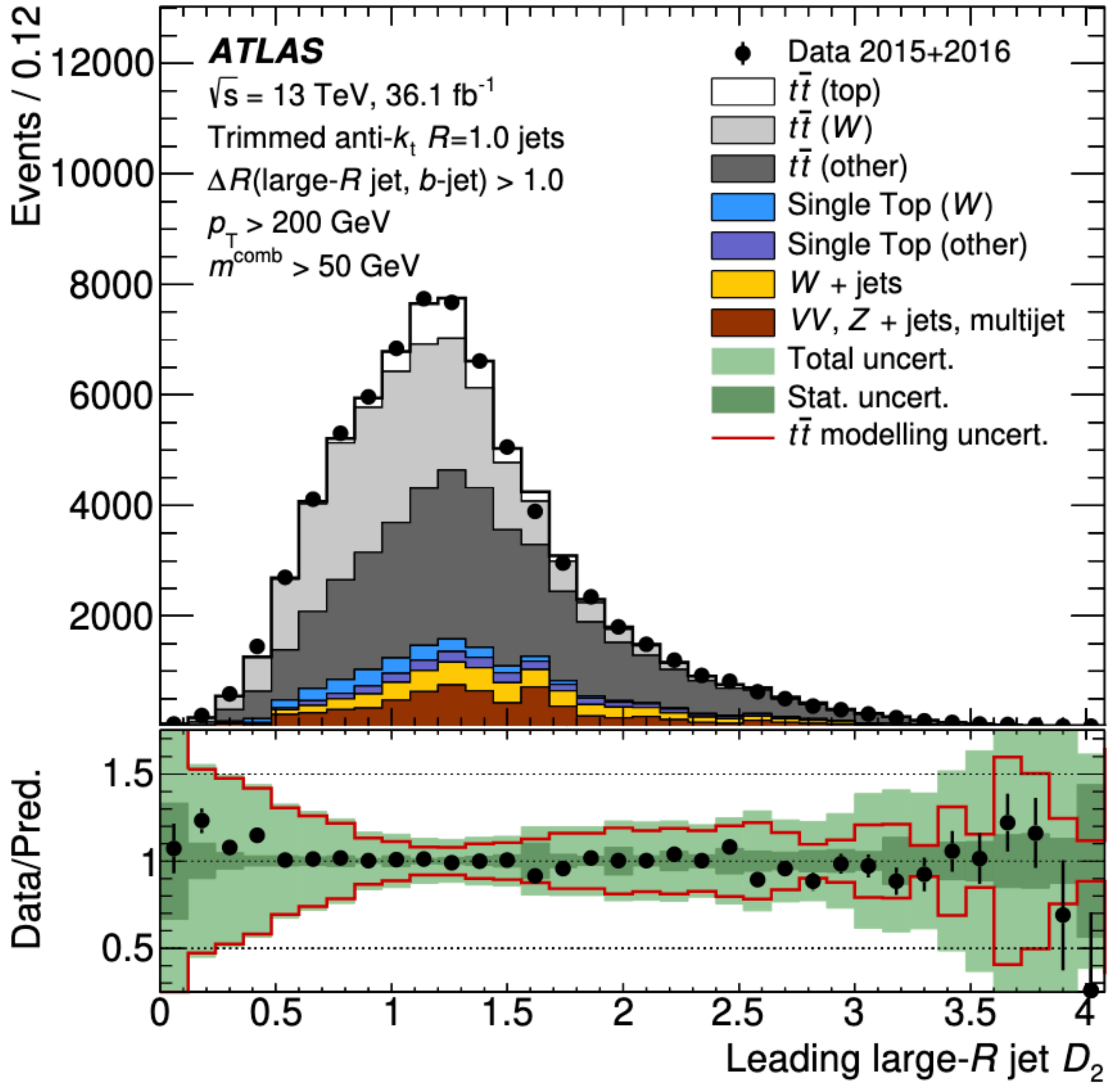
$$\mathrm{TCC}_{③} = (p_{\mathrm{T}}^{t_6}, \eta^{t_6}, \phi^{t_6}, m^{t_6} = 0)$$

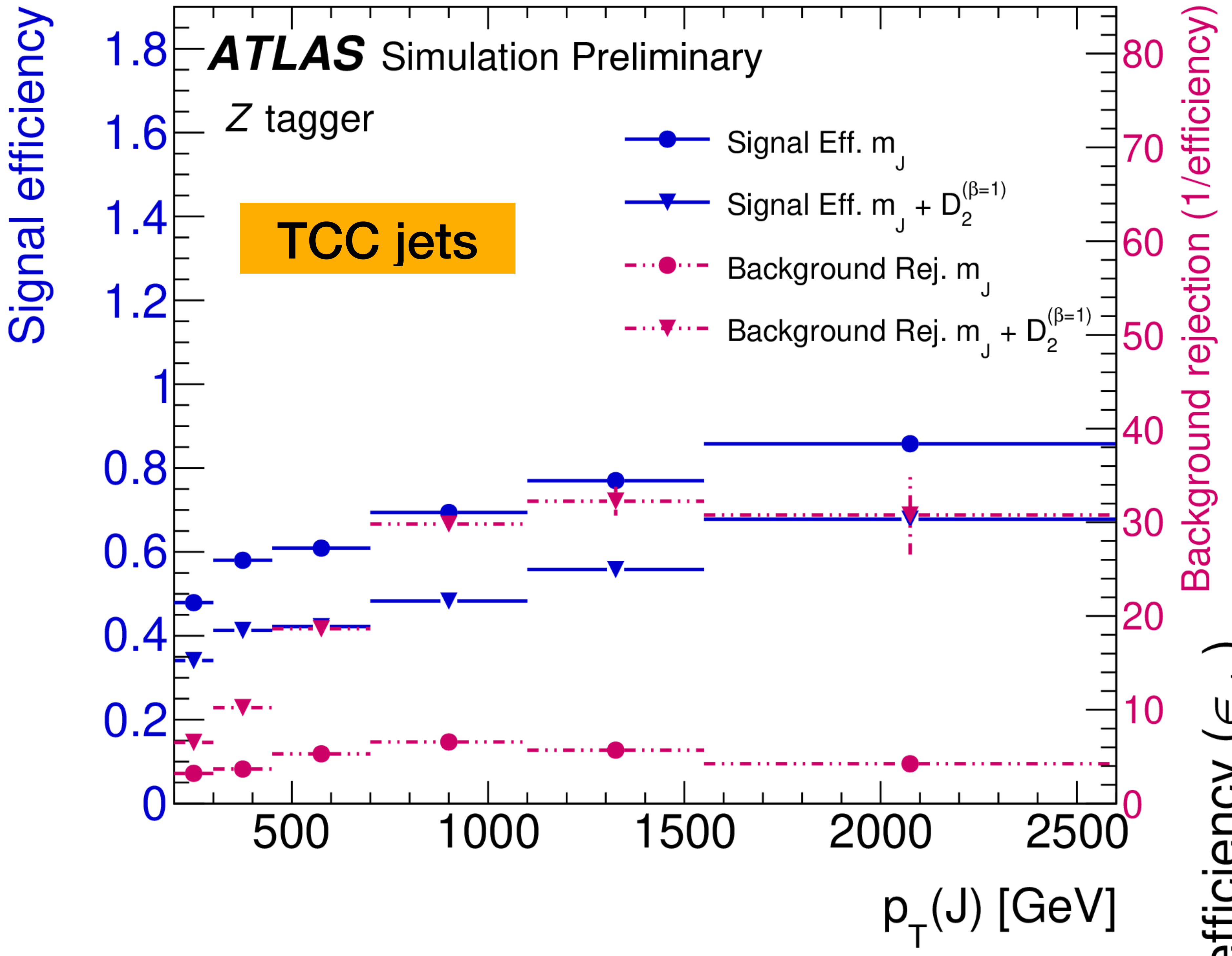
$$\mathrm{TCC}_{④} = \left(p_{\mathrm{T}}^{c_2}\frac{p_{\mathrm{T}}^{t_2}}{p_{\mathrm{T}}\left[\mathbf{p}^{t_2}+\mathbf{p}^{t_3}\right]}, \eta^{t_2}, \phi^{t_2}, m^{c_2}\frac{p_{\mathrm{T}}^{t_2}}{p_{\mathrm{T}}\left[\mathbf{p}^{t_2}+\mathbf{p}^{t_3}\right]} = 0\right)$$



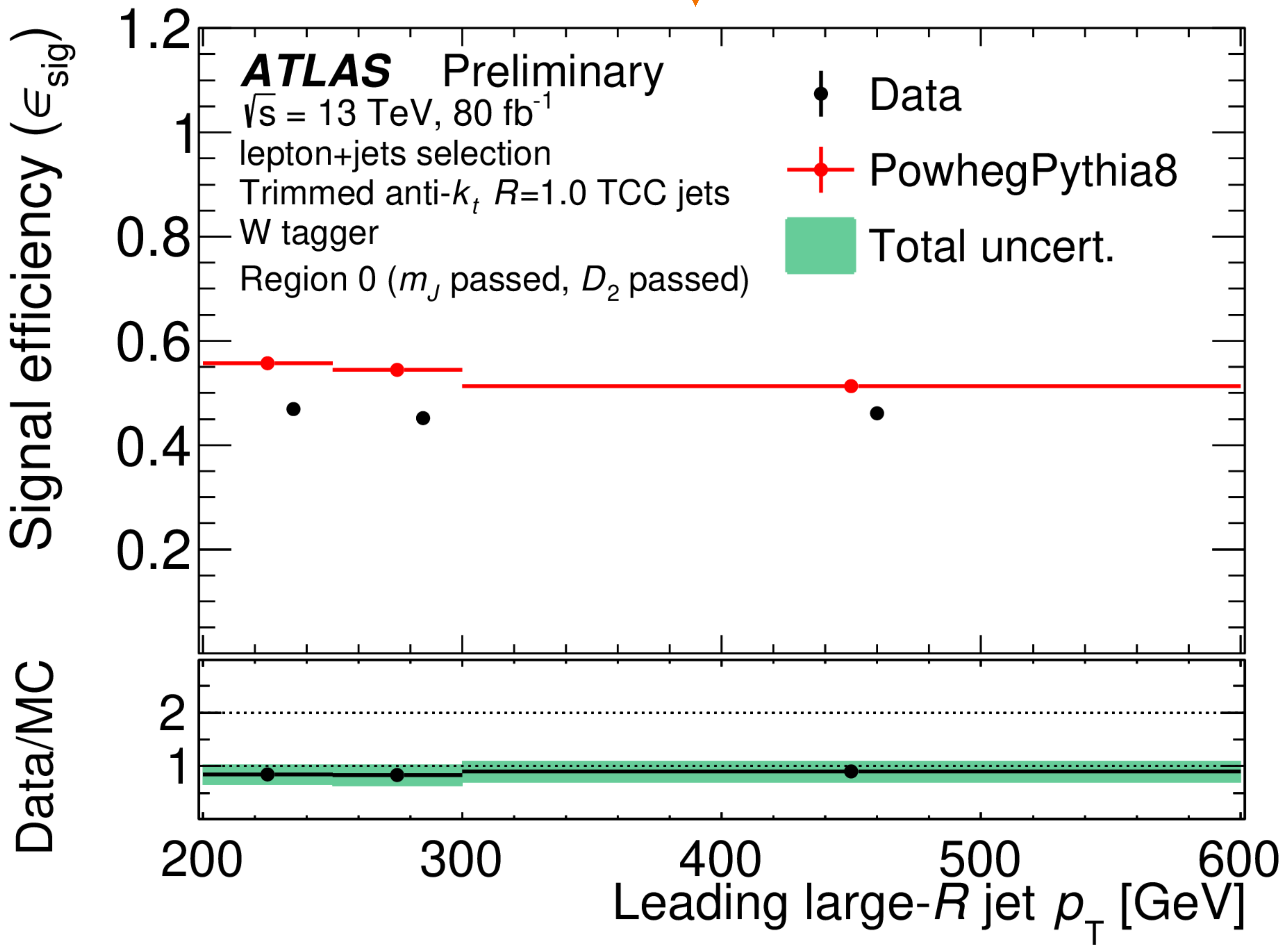
Boson Tagging

arXiv:1808.07858
ATL-PHYS-PUB-2020-008





- Performance of taggers evaluated in MC simulation and data to derive dedicated scale factors on the signal efficiency

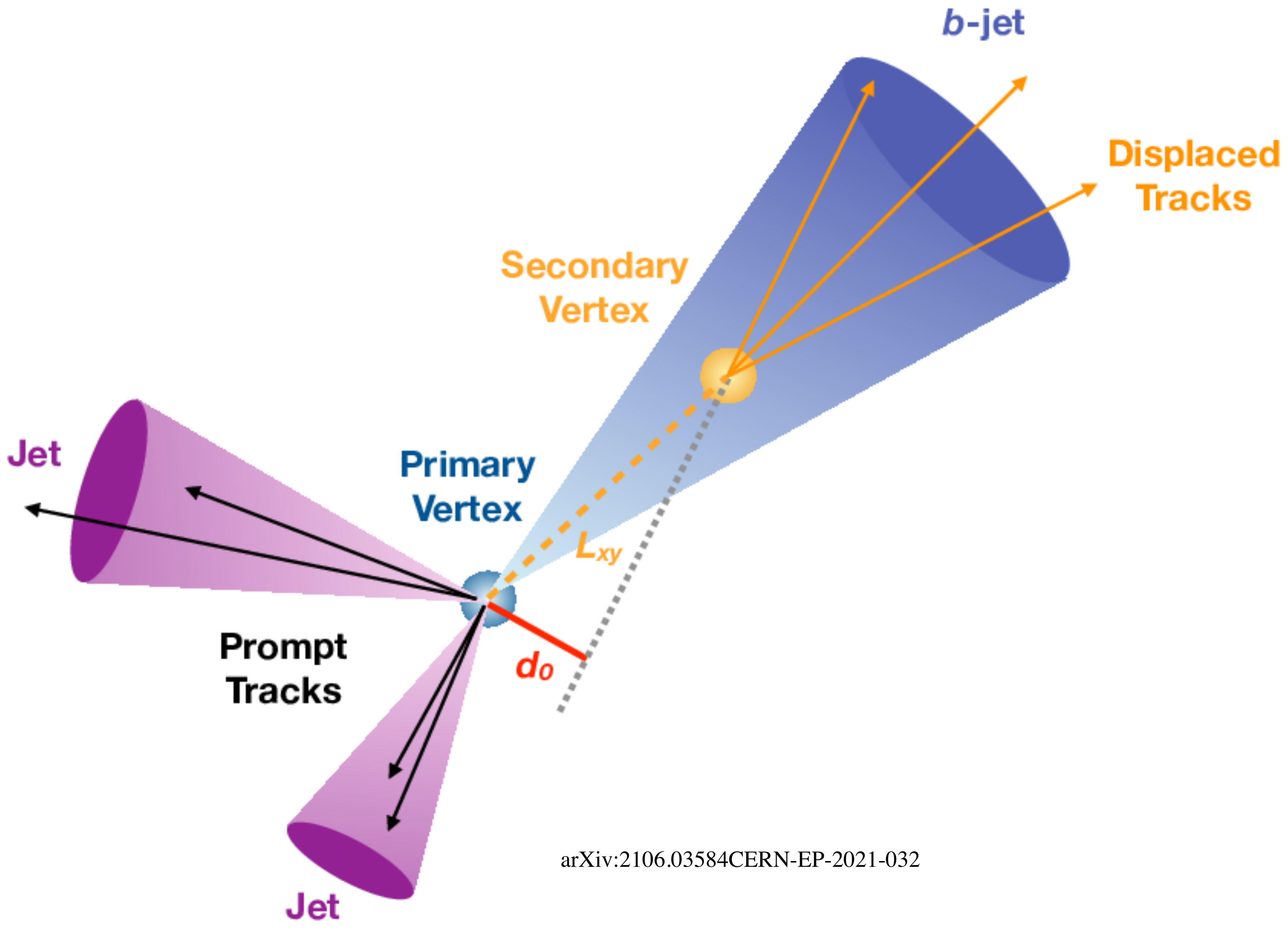


- Boson tagging for boosted decays is performed by exploring jet substructure variables
  - Most commonly used W and Z taggers are based on selection requirements on jet mass and the two-prong substructure variable D2
  - The optimal thresholds are chosen such that they optimise the sensitivity in each p_T bin

Identifying b-jets

arXiv:1907.05120

- The identification of jets containing b-hadrons, referred to as b-jets, is vital for a large part of the physics program of the ATLAS experiment
- b-tagging algorithms exploit the relatively long b-hadron lifetime



arXiv:2106.03584CERN-EP-2021-032

- **For boosted regimes** b-tagging algorithm is applied on variable-R (VR) track jets matched with large-R jets:
  - They are built by clustering Inner Detector tracks using the anti-k_t algorithm adopting a p_T-dependent cone size with radius:

$$R = \frac{\rho}{p_{\mathrm{T}}}$$

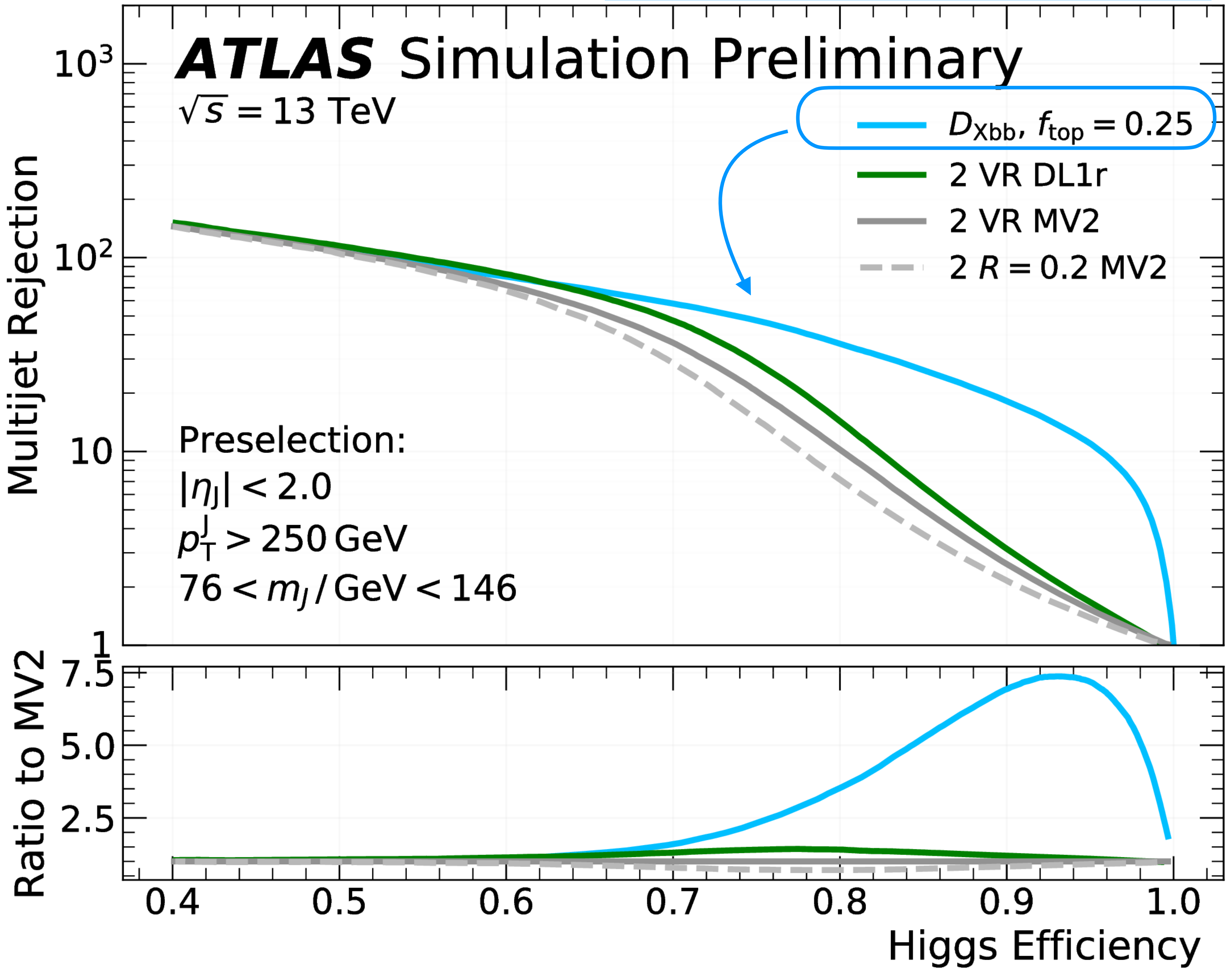
← ρ: dimensionful constant

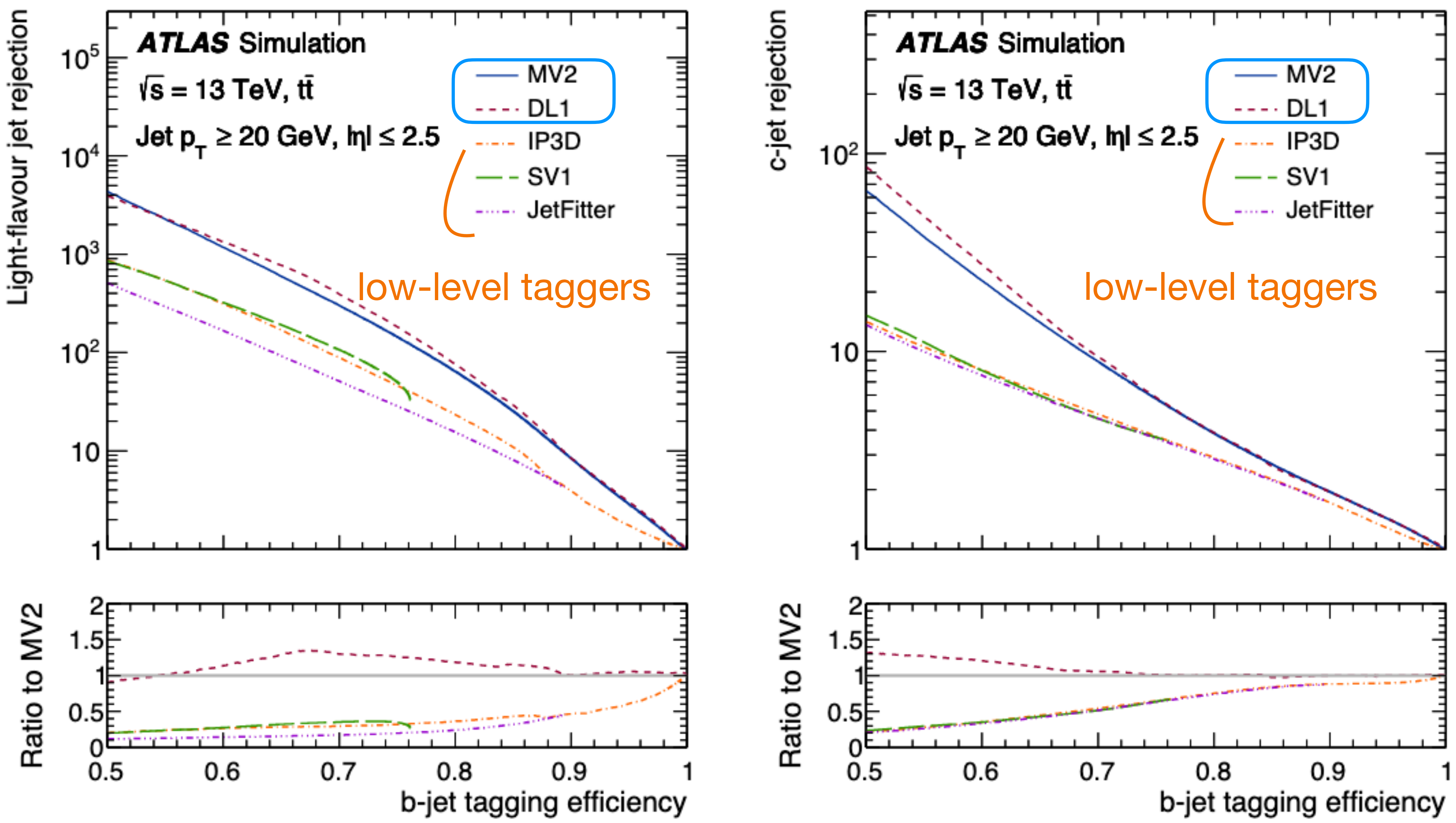
b-taggers & Xbb

arXiv:1907.05120

- MV2c10 and DL1 (or DL1r trained on VR track jets) algorithms are high-level taggers obtained by combining the outputs (probability of being b-jets, c-jets and light-flavour jets) of a boosted decision tree and a deep feed-forward neural network respectively, both trained on simulated $t\bar{t}$ events

ATLAS-PHYS-PUB-2020-019





- A new algorithm to select boosted Higgs boson $h \to b\bar{b}$ and separate it from top quark and QCD jets has been developed
  - It combines flavor discriminants (from DL1r) from up to three subjets using a feed-forward neural network along with p_T and η of the large-R jet
- This Xbb tagger is defined as:

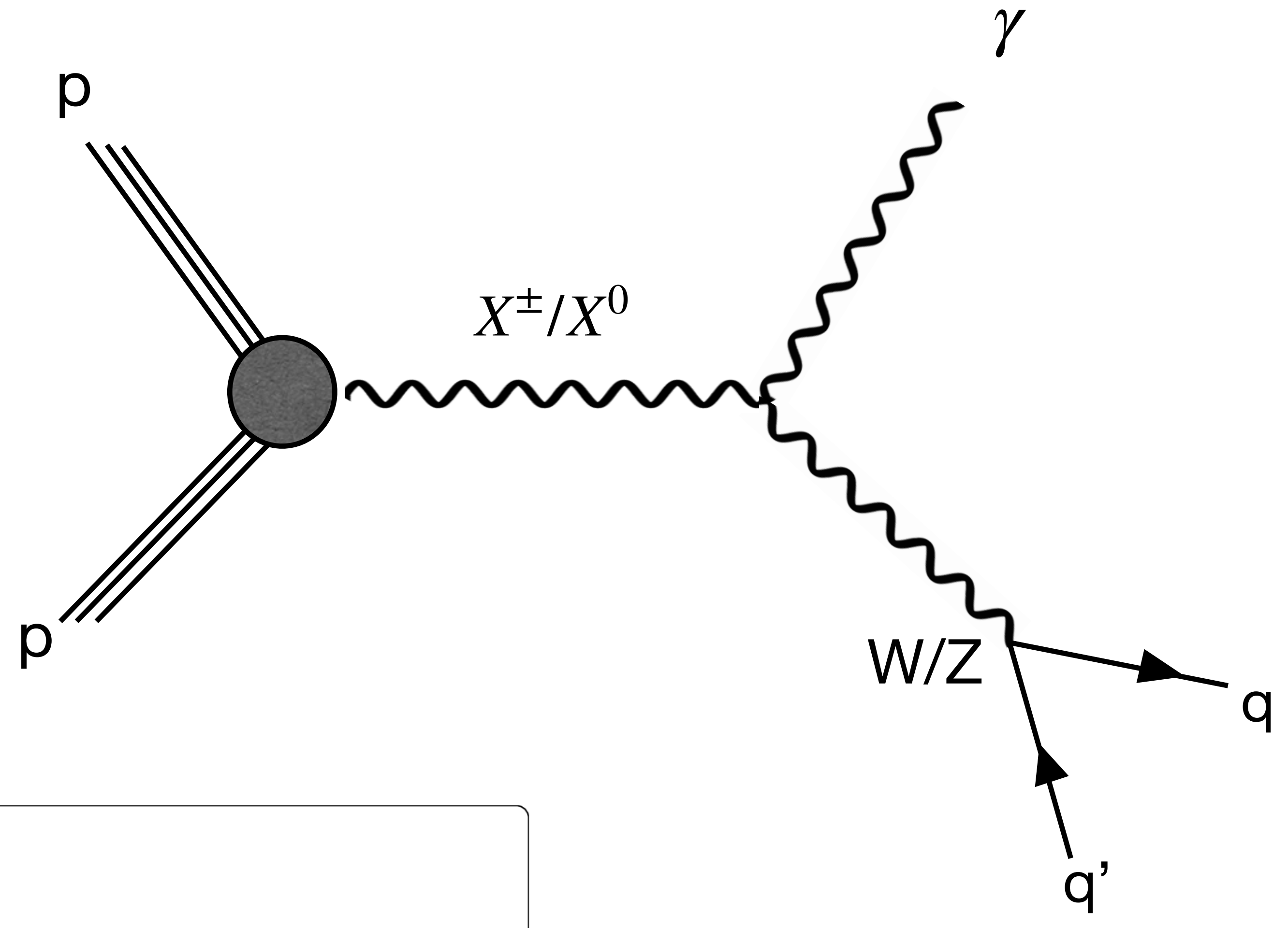
$$D_{X_{b\bar{b}}} = ln \frac{p_{Higgs}}{f_{top} \cdot p_{top} + (1 - f_{top}) \cdot p_{multijet}}$$

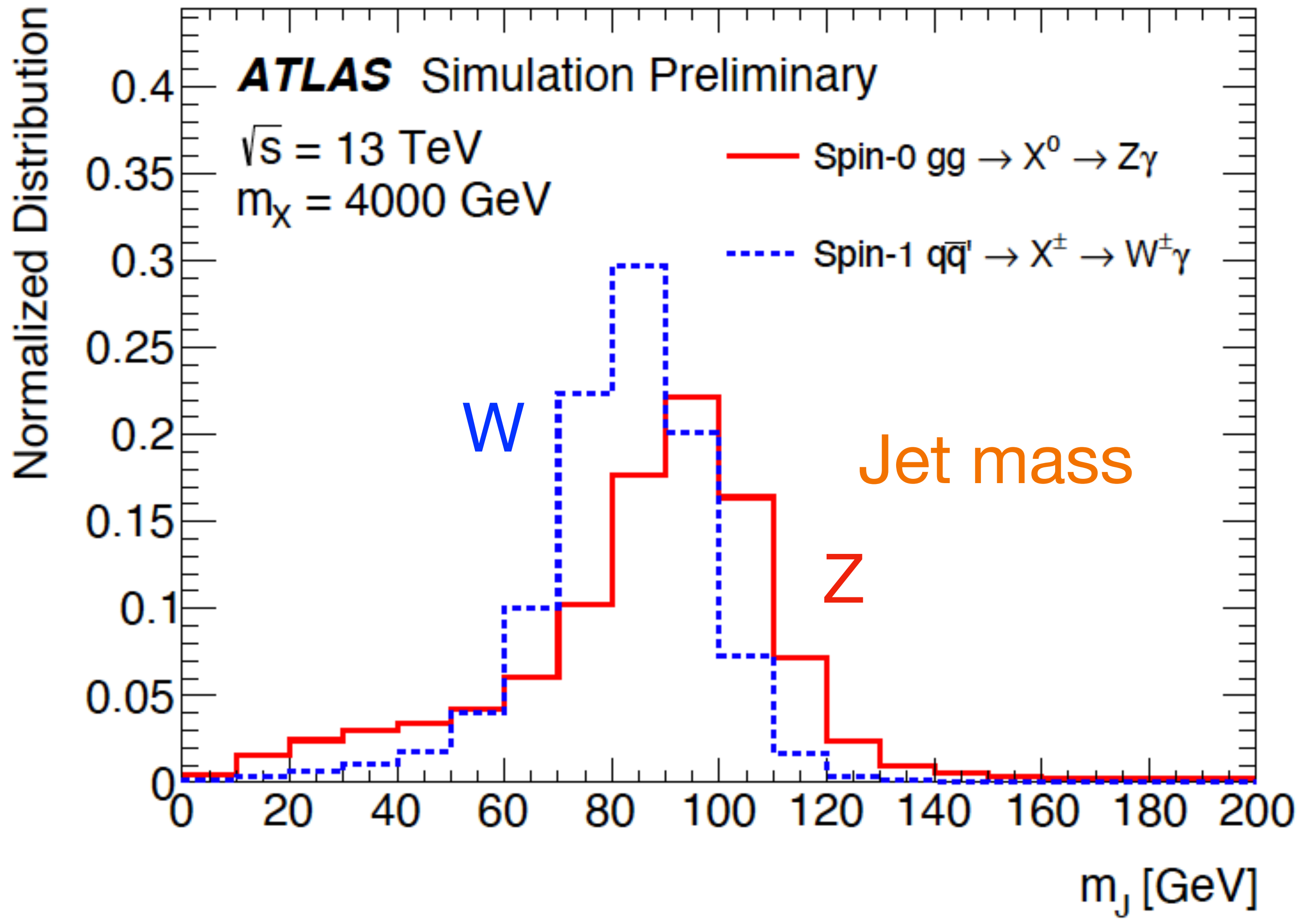
*Already adopted from YXH analysis (described later in this talk)

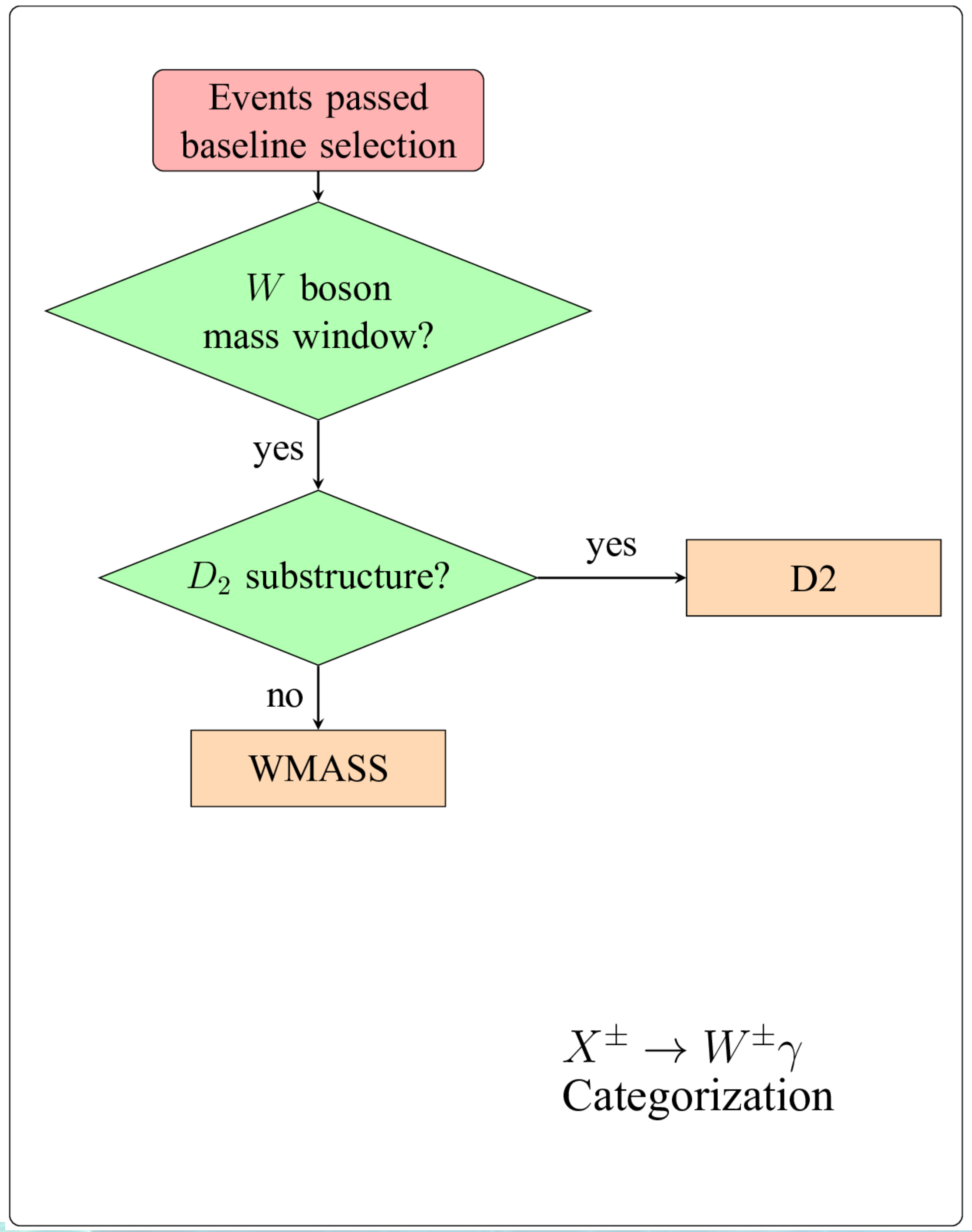
Hadronic W/Z + γ

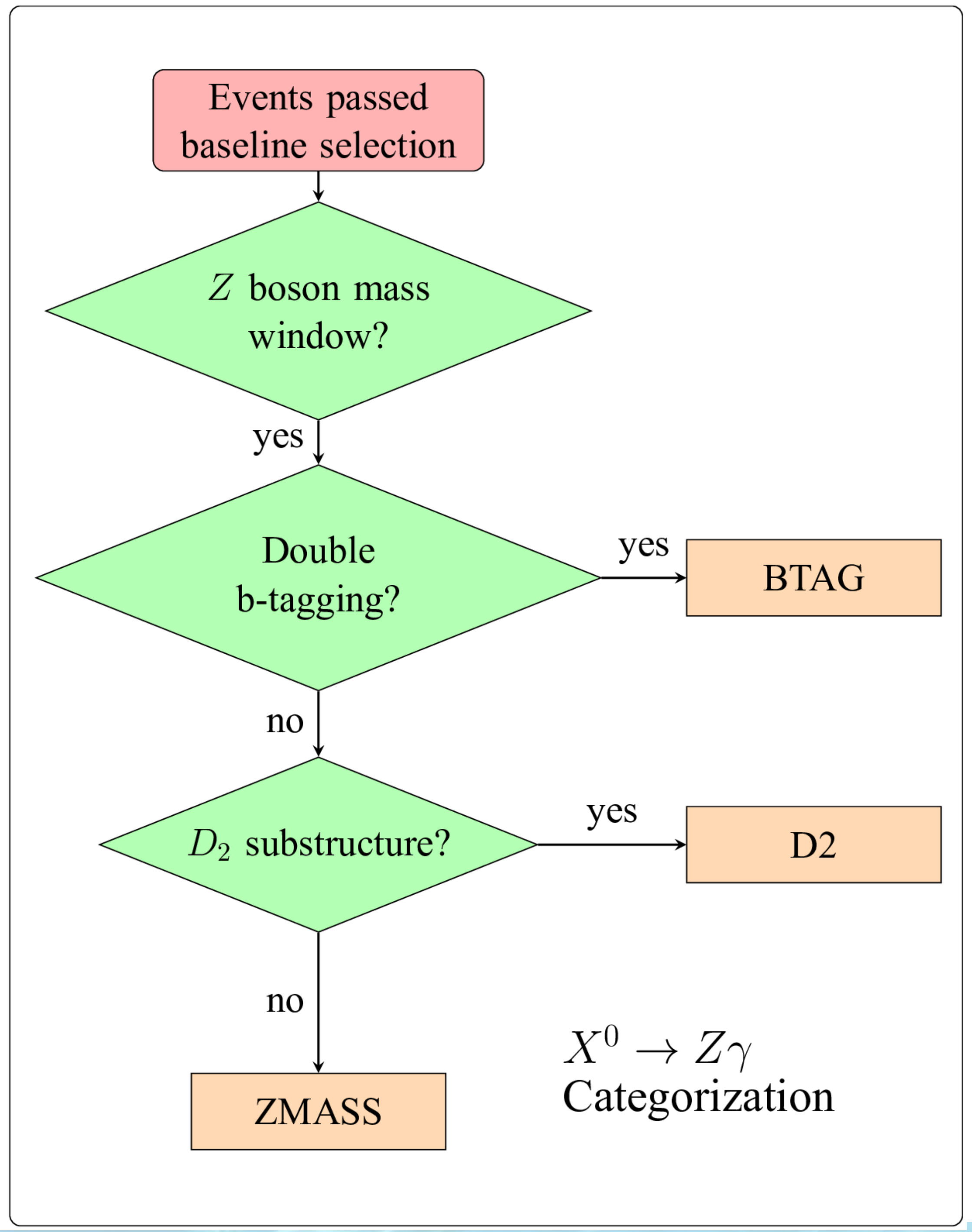
ATLAS-CONF-2021-041

- Search for high-mass resonances decaying to W+γ or Z+γ, with hadronic W/Z decays
- Narrow-width signal interpretations:
  - spin-1 $X^{\pm} \rightarrow W^{\pm}\gamma$ from Heavy-Vector-Triplet (HVT) model
  - spin-0/spin-2 $X^{0} \rightarrow Z\gamma$ from MSSM and Kaluza-Klein models





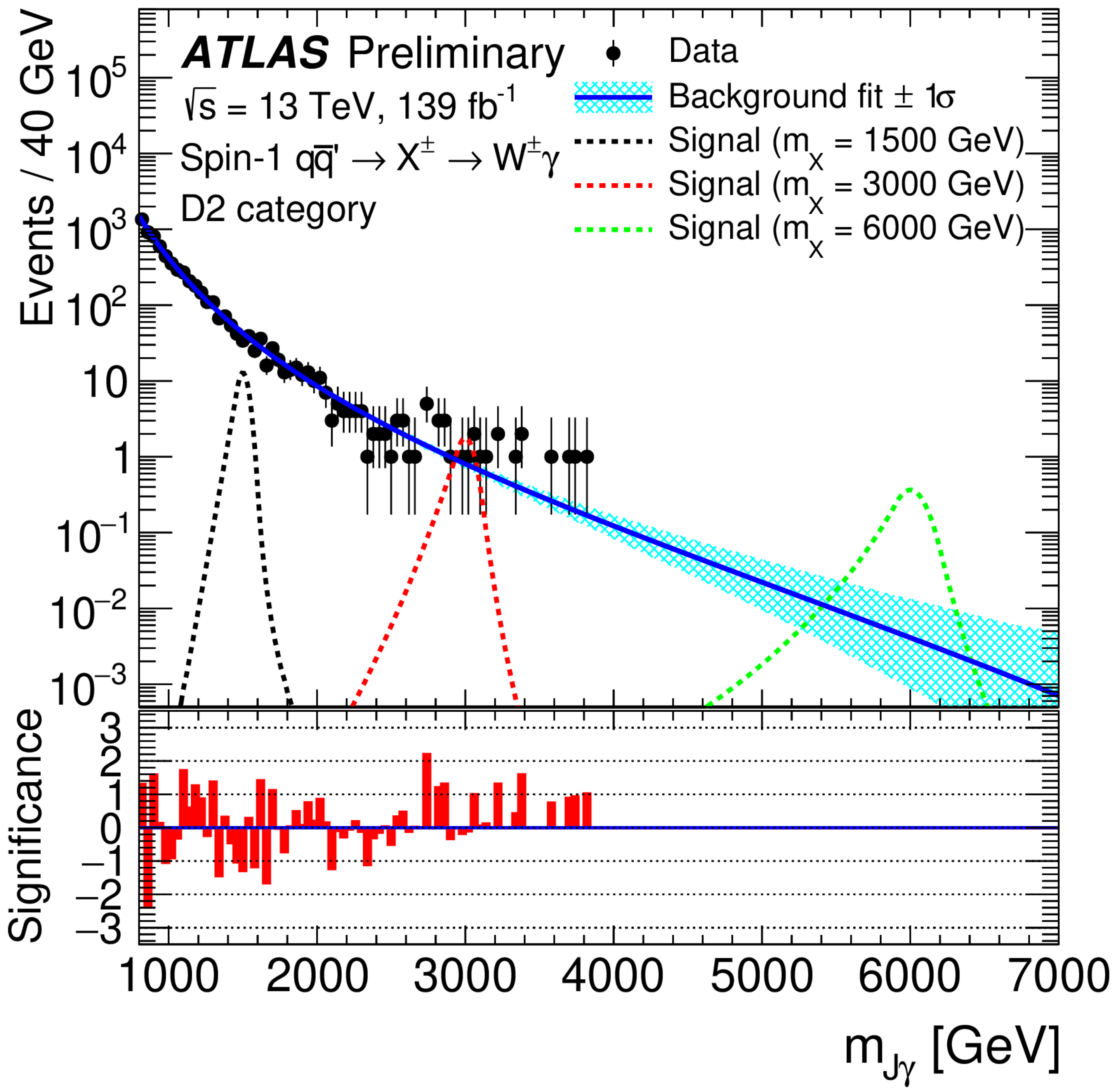


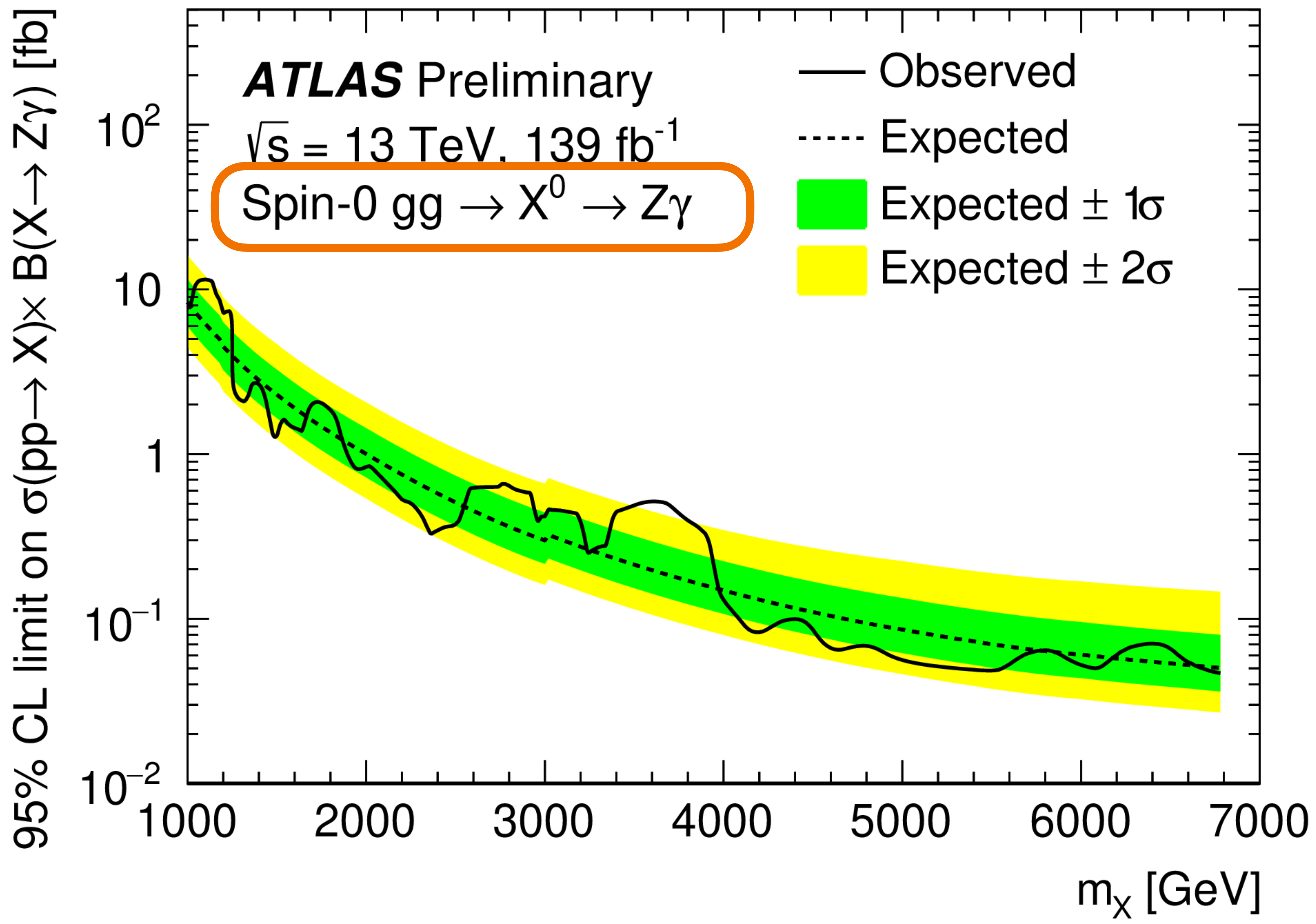


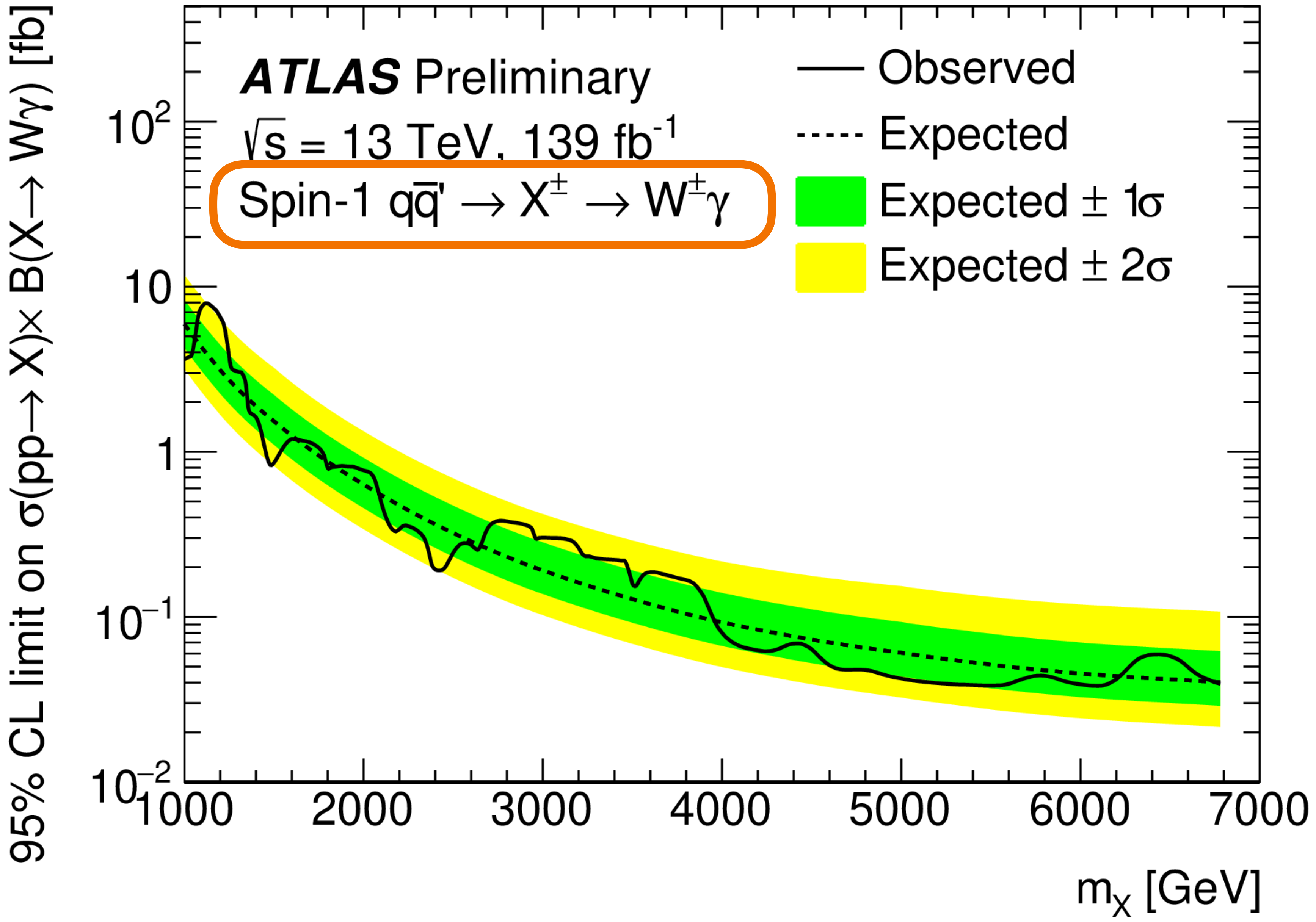
- Single-photon trigger, TCC jets (R=1) for the reconstruction of boosted W/Z decays
- W/Z boson identified by a cut-based tagger based on the jet mass and the two-prong substructure variable D2
- To improve Z boson selection, b-tagging is applied on VR track-jets (with MV2c10)

Hadronic W/Z + γ results

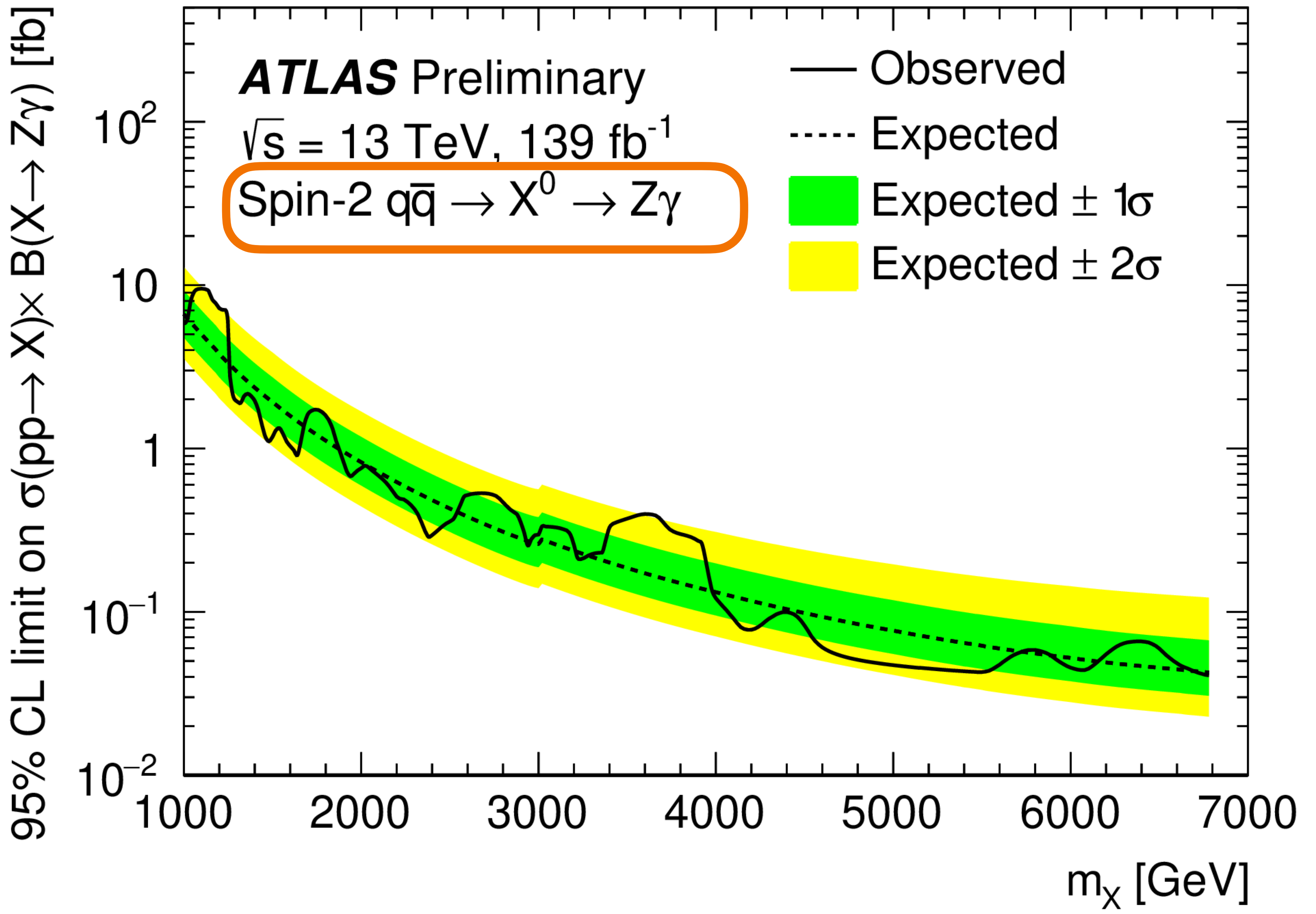
ATLAS-CONF-2021-041







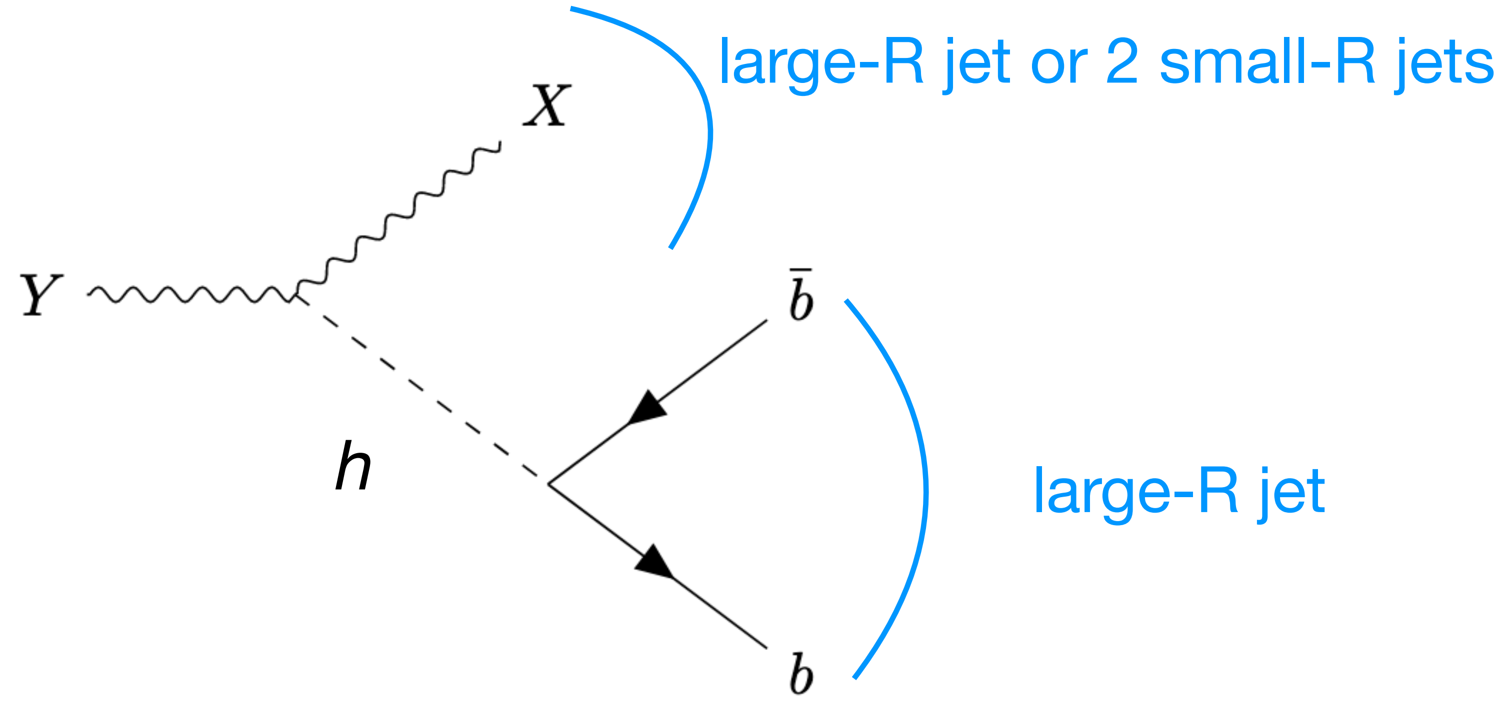
- SM Background, modeled with a parametric function, is dominated by γ+jets and non-resonant W/Z+γ processes
- No significant deviation in data with respect to SM background predictions:
  - the largest local signal significance (2.5σ) is found for spin-0 $gg \to X^0 \to Z\gamma$ production from gluon-gluon fusion at M_X = 3640 GeV
- 95% CLs upper limits calculated on signal cross-sections have been extracted



Fully-hadronic Xh

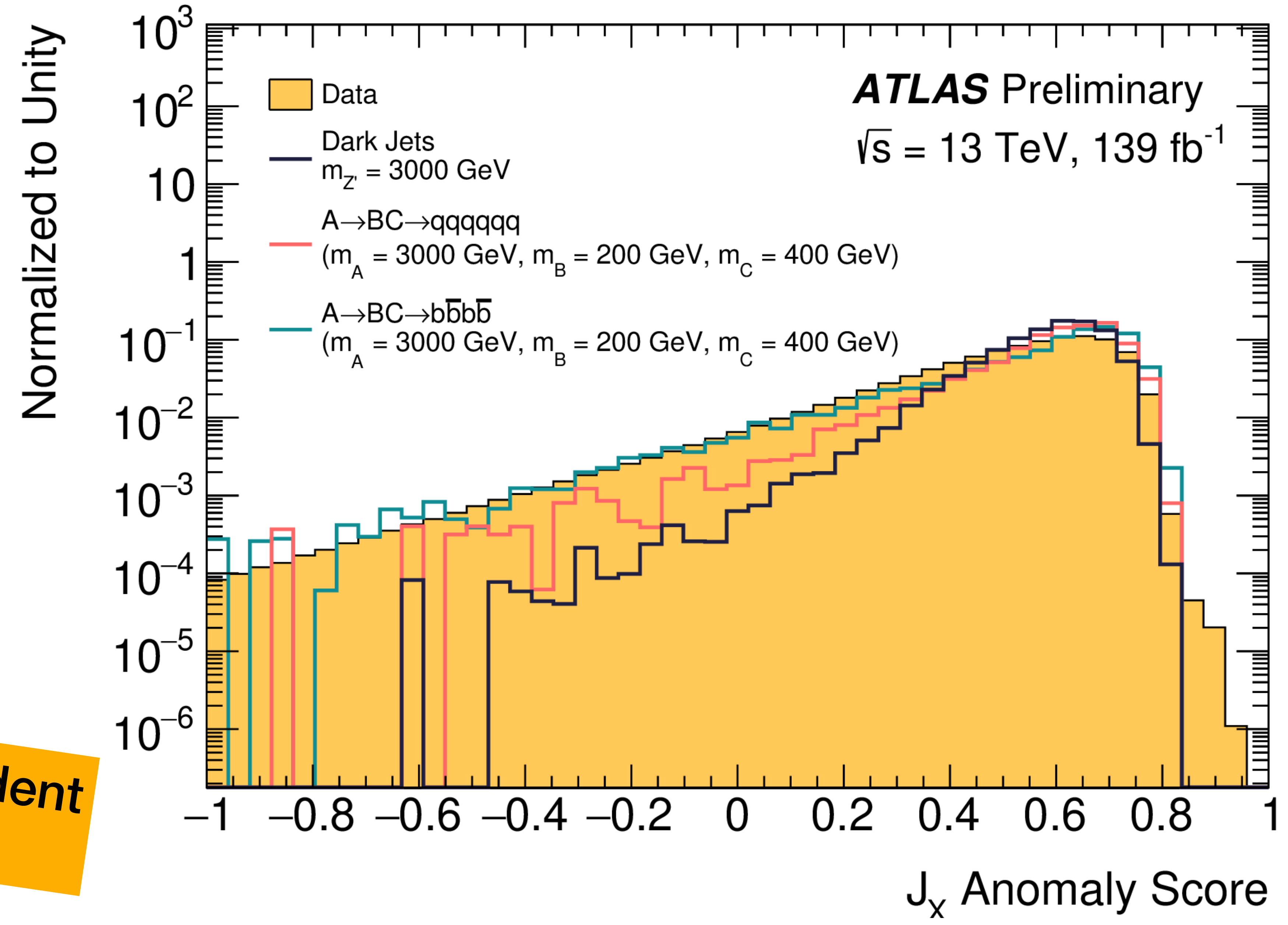
ATLAS-CONF-2022-045

- Search for a narrow-width heavy resonance (Y) decaying into a SM Higgs h($b\bar{b}$) and a new particle X in a fully hadronic final state
- Mass ranges investigated: m_Y in (1500-6000) GeV, m_X in (65-3000) GeV
- Model-independent search, HVT model used as a benchmark for $Y \to Xh \to q\bar{q}b\bar{b}$ decay



- Single large-R jet trigger (large-R jet collection TCC R=1)
- **Higgs candidate** tagged with an η reweighted version of Xbb tagger
- **For X candidate** two tagging approaches are carried out:
  1. Discovery Region based on a jet-level anomaly score (from a variational Recurrent-Neural-Network **trained on jets collection in data** at preselection level)
     - sensitive to an X with any hadronic decay, model-independence assessed

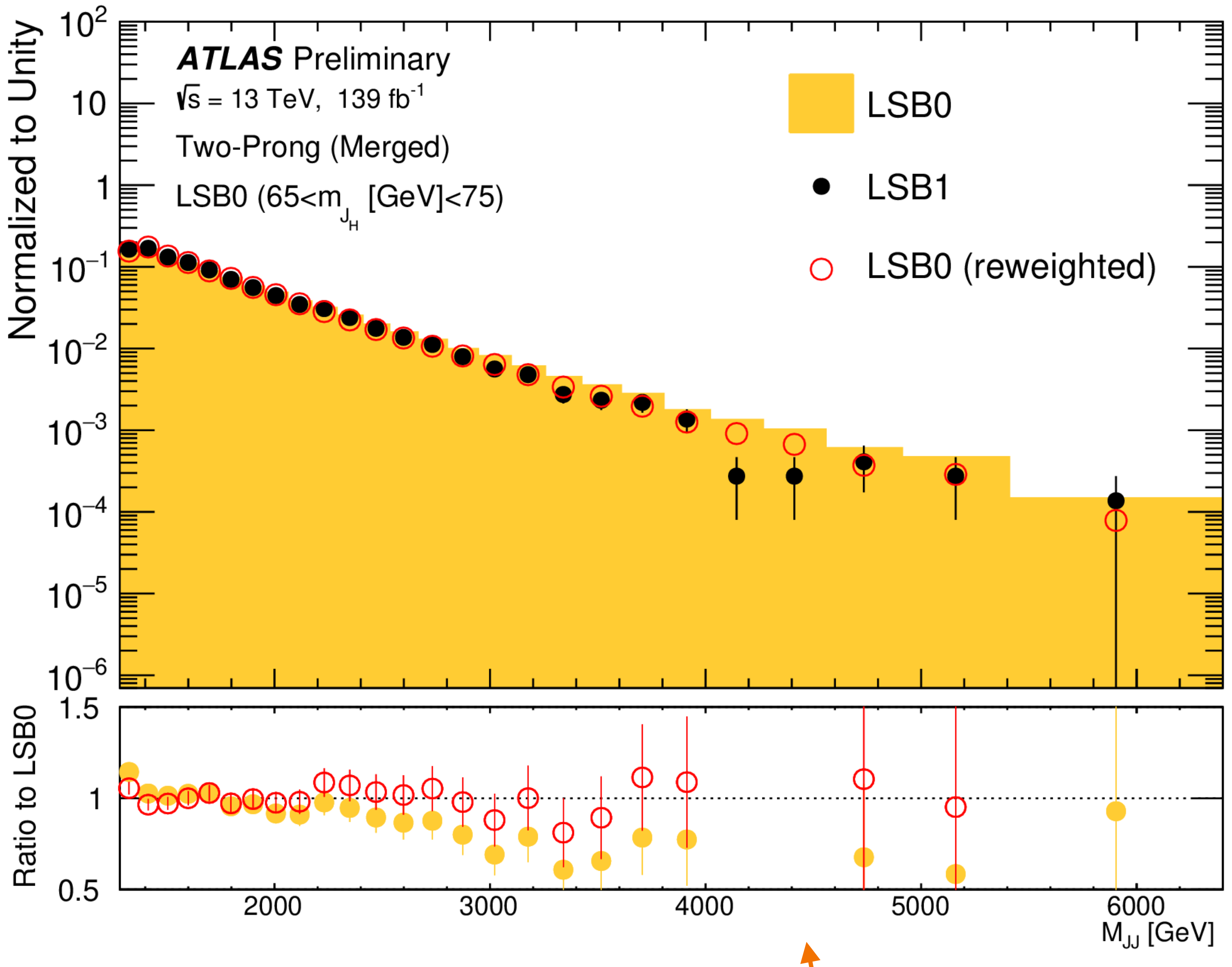
1st ATLAS analysis with a model independent (unsupervised) autoencoder!

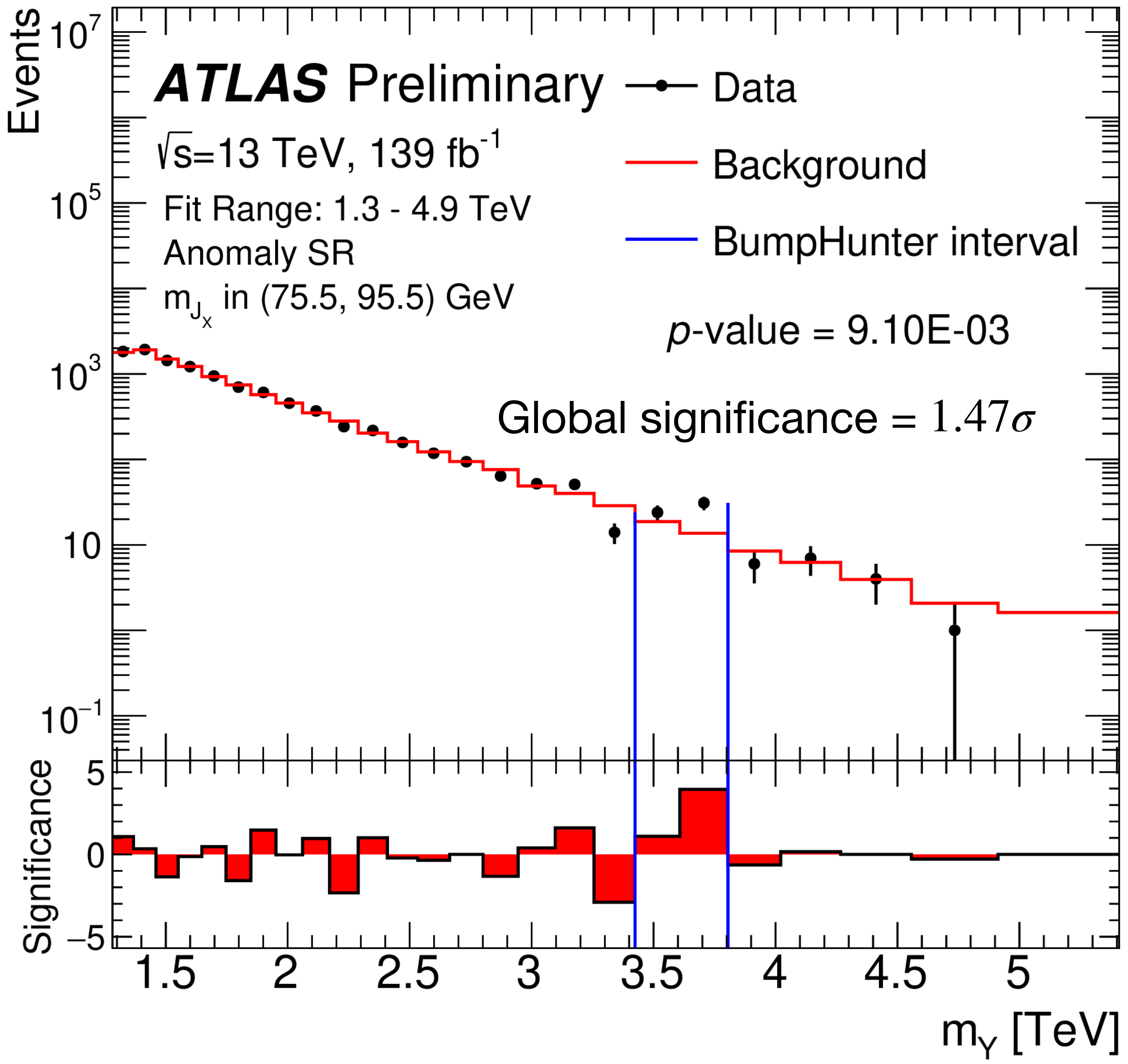


  2. Exclusion Regions for two-prong jets $X \to q\bar{q}$

Fully-hadronic Xh results

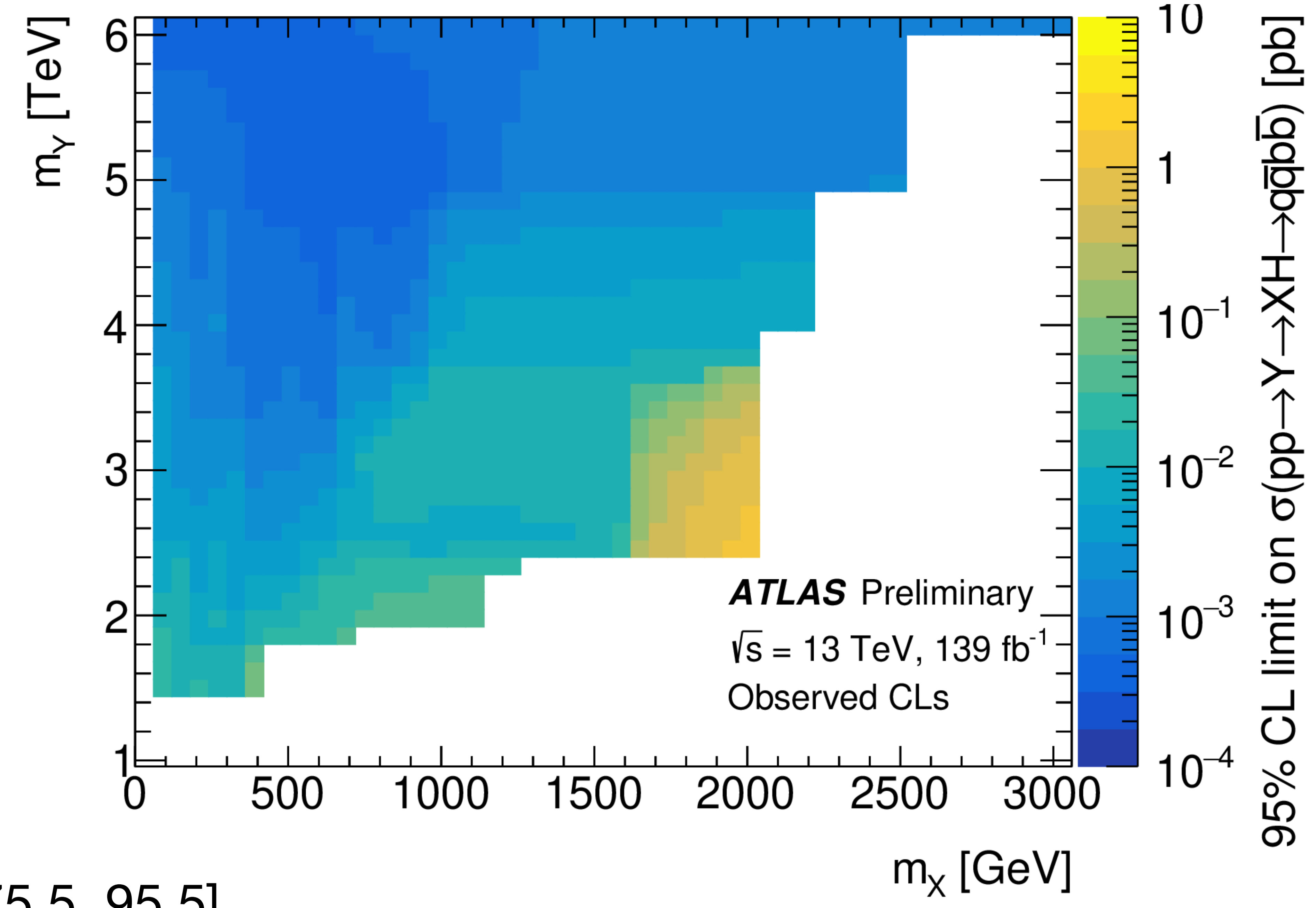
ATLAS-CONF-2022-045





Model independent search

HVT upper limits

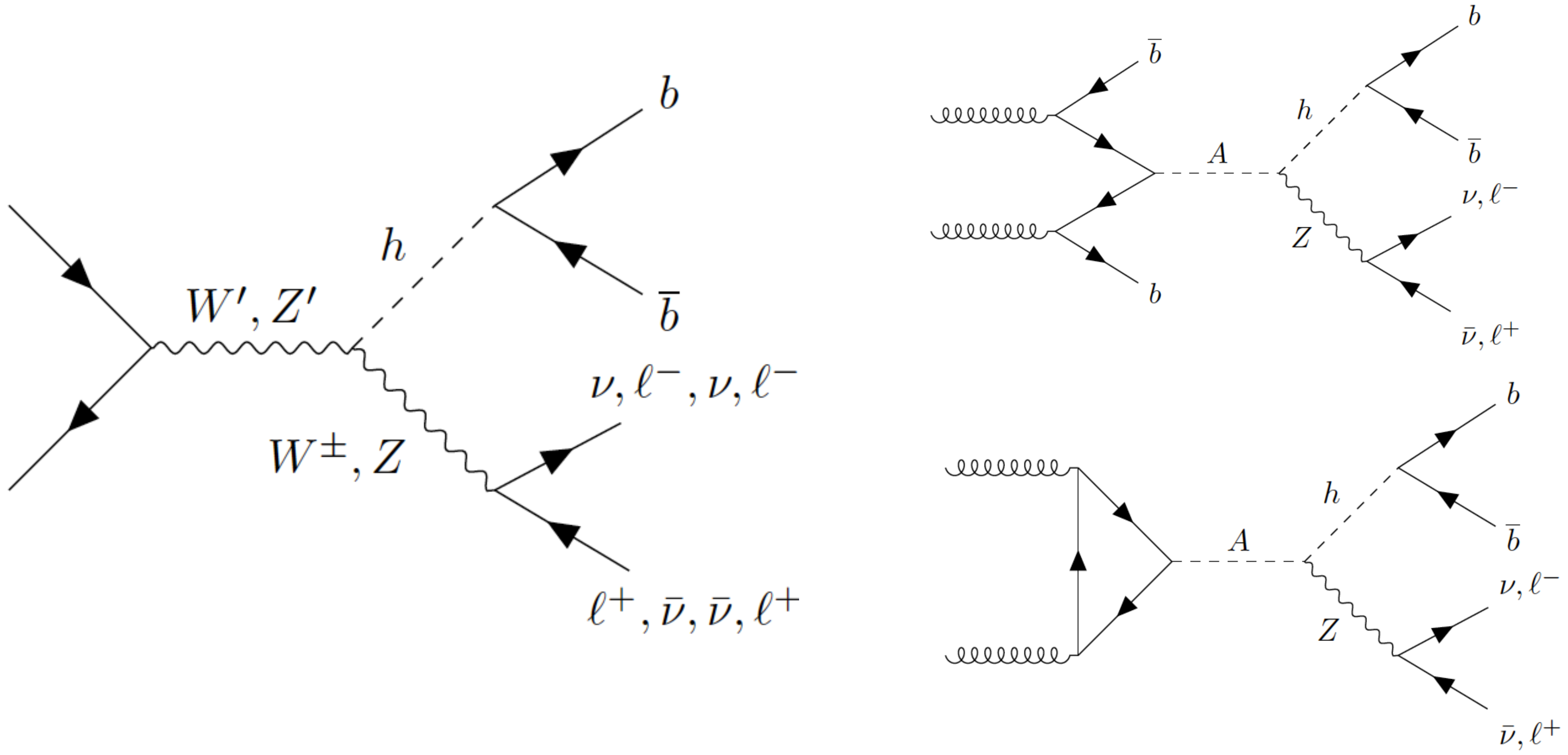


- Deep Neural Network (DNN)-based data-driven background reweighting
- The m_{JJ} distribution is fitted in overlapping bins of the X candidate mass
- A BumpHunter search for excesses of data over the expected background is performed
  - Good compatibility found for background-only fit, largest excess in the m_X window [75.5, 95.5] GeV with a local p-value 0.0091 (corresponding to a global significance of 1.47σ)
- Two-dimensional 95%CLs upper limit on the cross section of the $Y \to Xh \to q\bar{q}b\bar{b}$ HVT process of HVT signals have been calculated in the plane $\{m_Y, m_X\}$

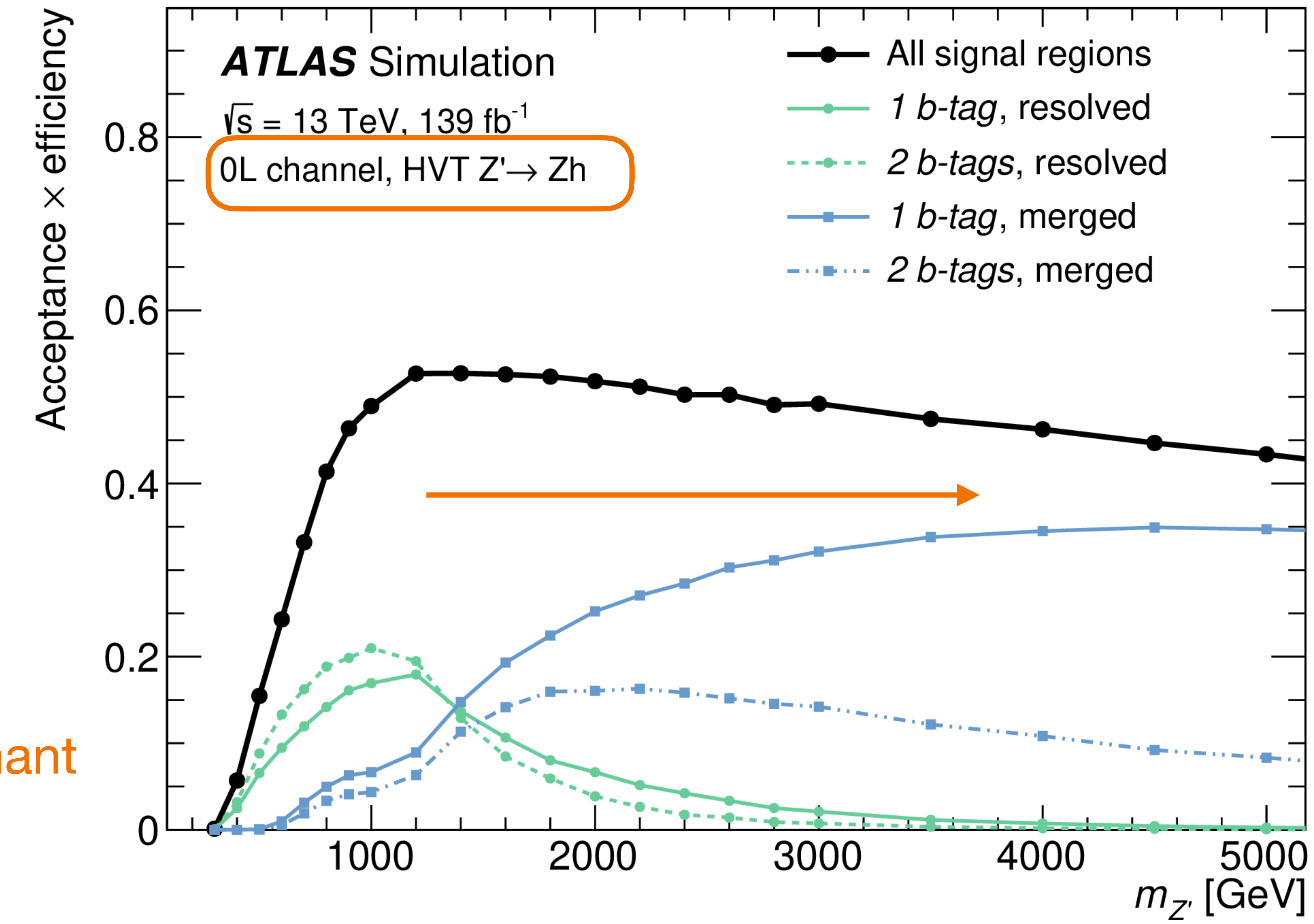
Semi-leptonic Z/W + h

arXiv:2207.00230

- Search for new resonances decaying into a Z or a W and a 125 GeV Higgs boson in the $\nu\nu b\bar{b}$, $llb\bar{b}$ and $l\nu b\bar{b}$ final states
- Results are interpreted in terms of a HVT Z' or W' and a heavy CP-odd scalar boson A, from a generic two-Higgs-doublet model (2HDM)



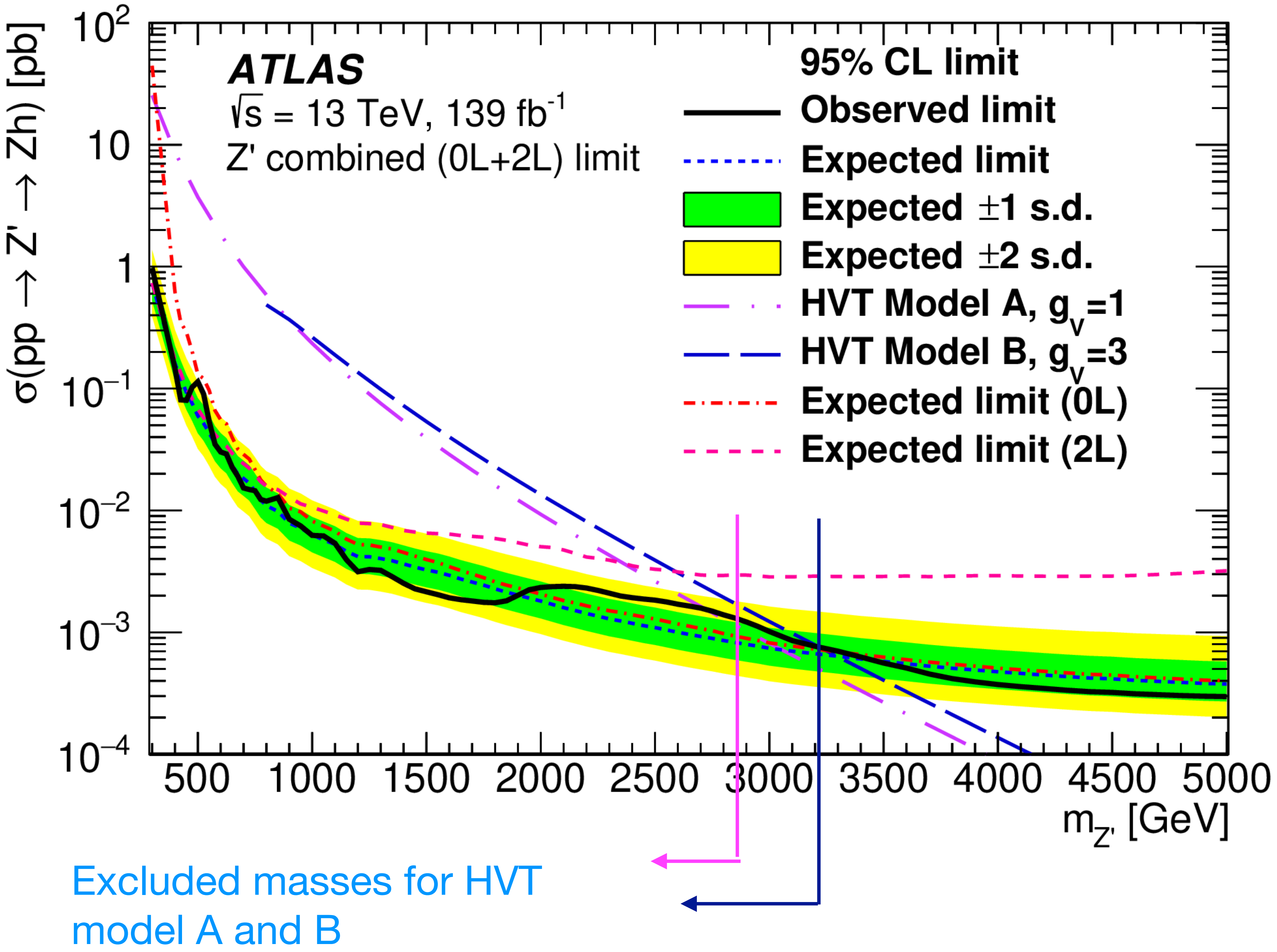
- Events with exactly 0, 1 or 2 charged leptons are selected with a E_T^{miss} or a combination of single-lepton triggers
- Higgs decay products (bb) are reconstructed either as two small-R jets (LCTopo, R=0.4, **resolved category**) or as a single large-R jet (TCC, R=1, **merged category**)
- 1 and 2 b-tags categories for $h \to b\bar{b}$ are defined (Small-R jets and VR track-jets containing b-hadrons are identified using the MV2c10 b-tagging algorithm)

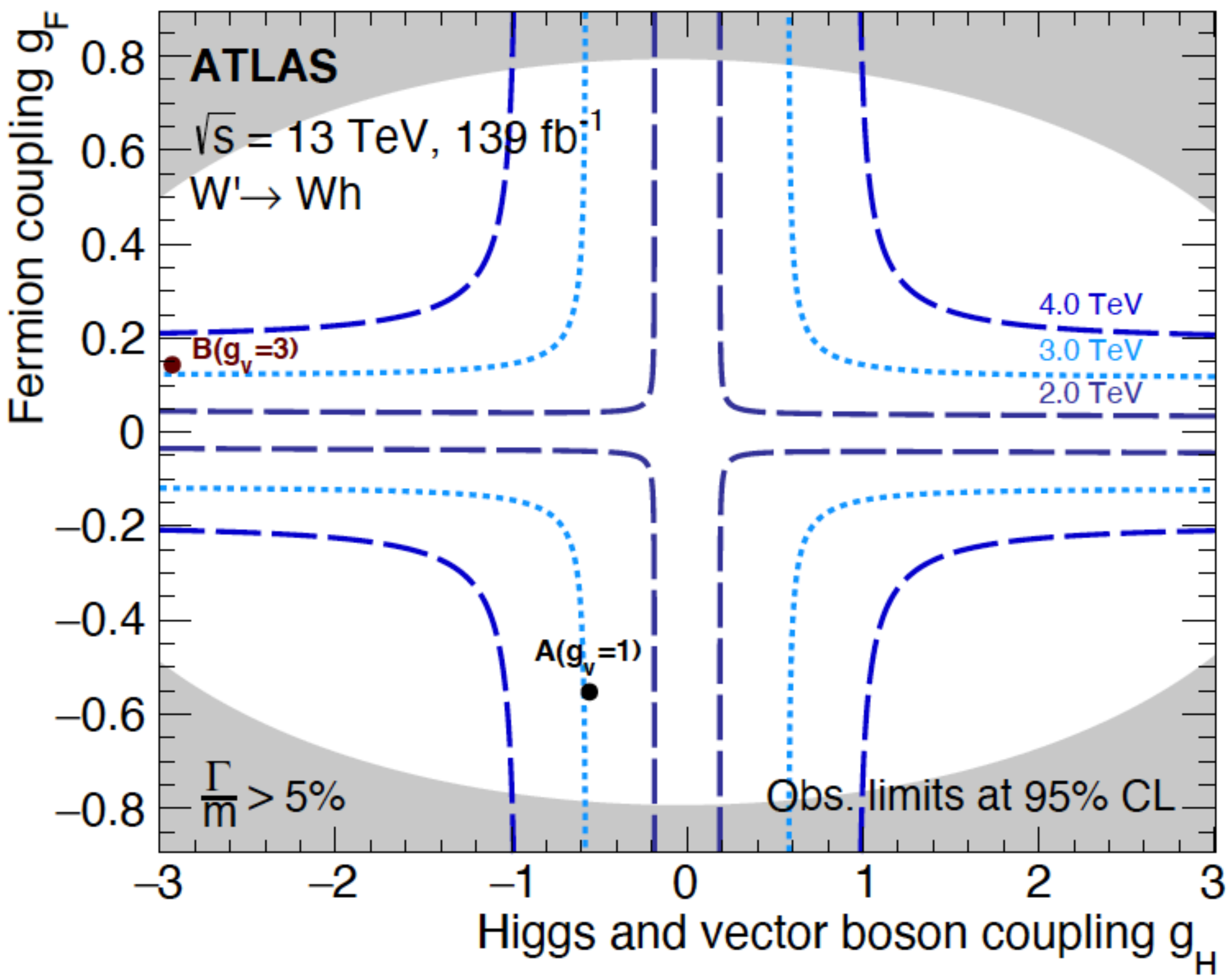


At high mass values merged category becomes predominant

Semi-leptonic Z/W + h results

arXiv:2207.00230

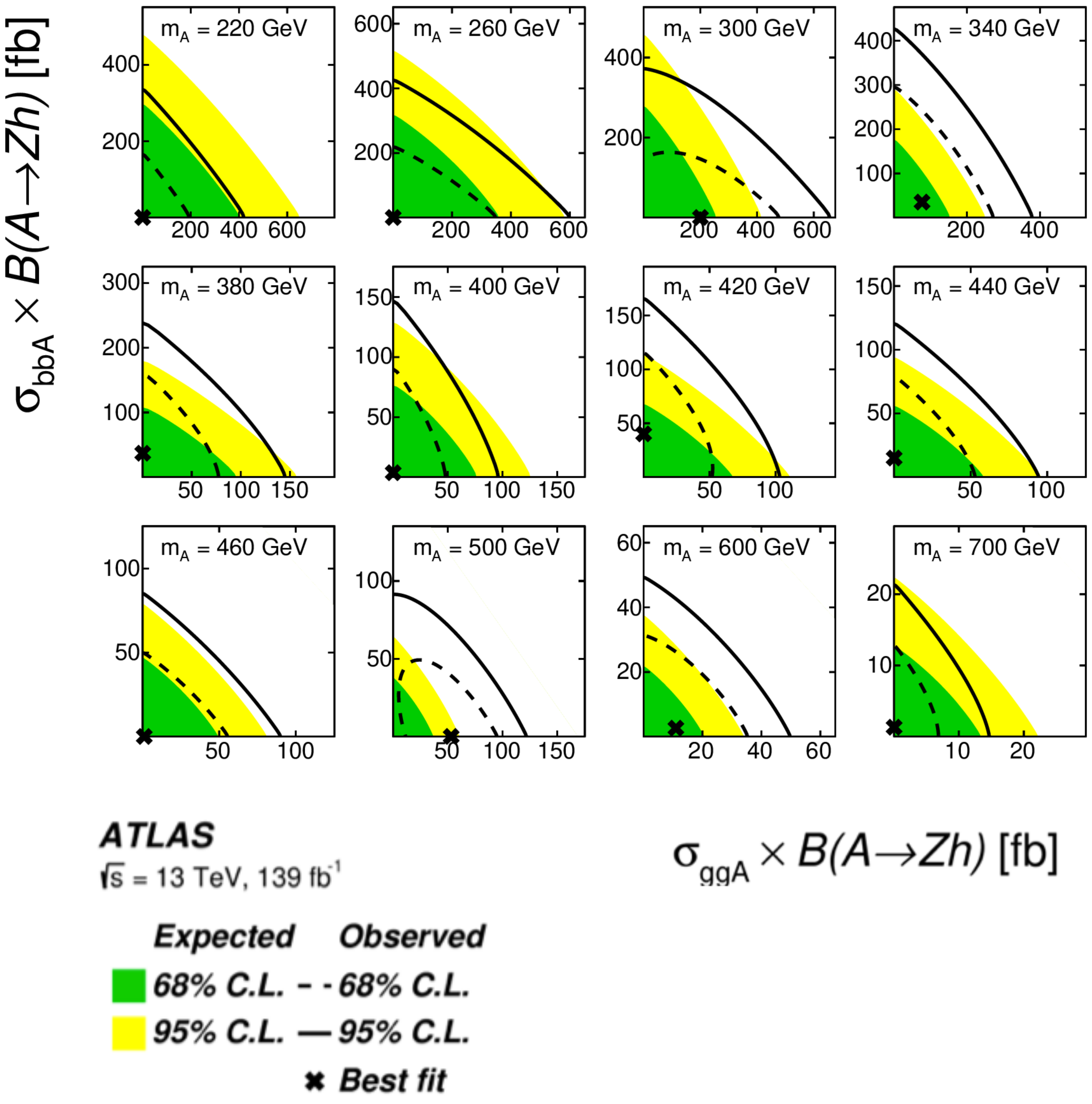




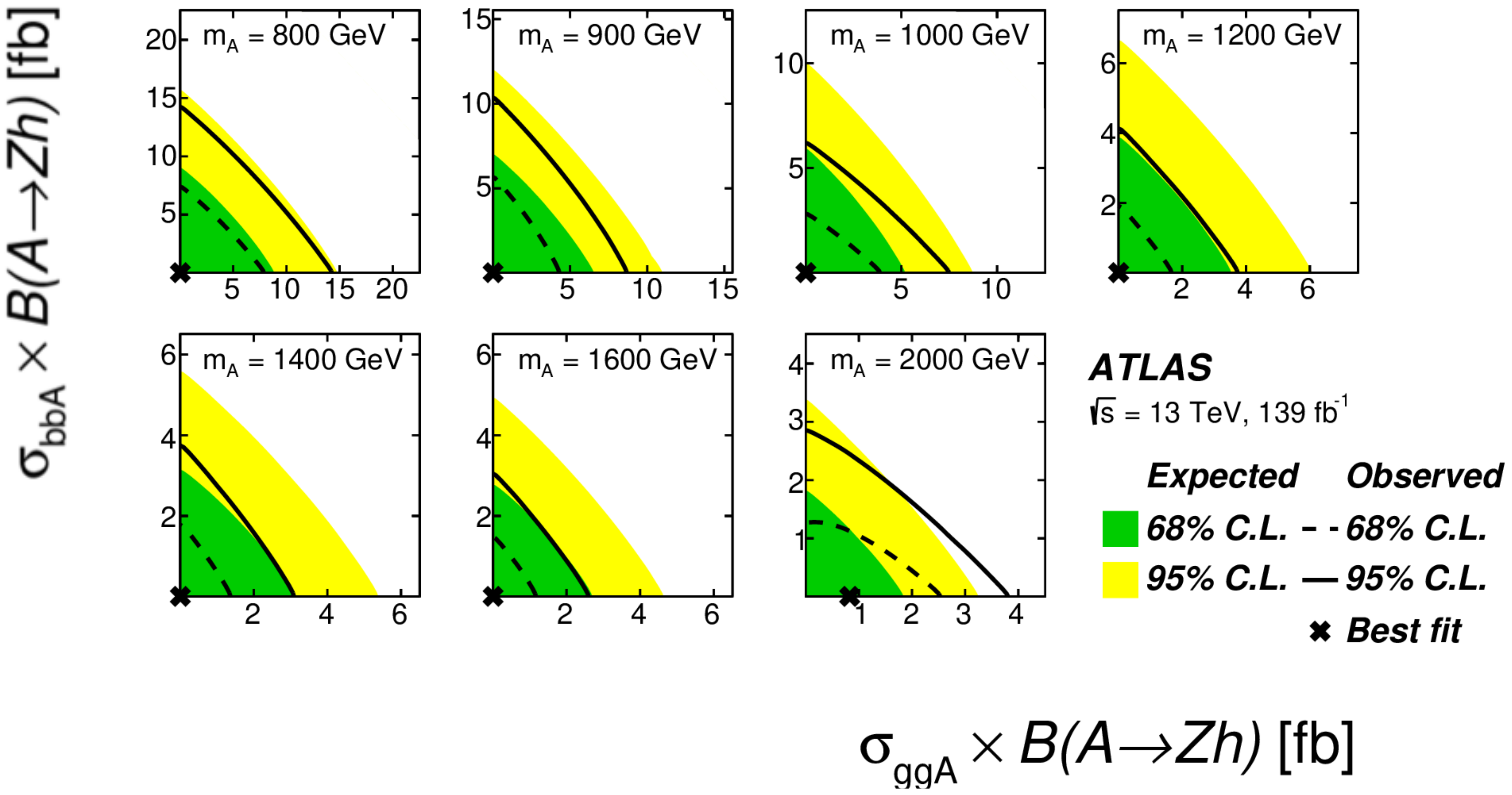
- Major background ($t\bar{t}$ and W/Z+jets) contributions estimated from MC simulations and with normalization taken from data
- The largest deviation from the standard model expectations is found in the Z' and ggA searches for a mass of 500 GeV with a local (global) significance of 2.1σ (1.1σ)
- Limits on xsec translated into 95% CL exclusion contours in the HVT parameter plane $\{g_F, g_H\}$ for resonance masses of 2, 3 and 4 TeV

Semi-leptonic Z/W + h results

arXiv:2207.00230



- Two-dimensional likelihood scans of the b-associated production cross section $\sigma_{bbA} \times BR(A \to ZH)$ vs the gluon-gluon cross section $\sigma_{ggA} \times BR(A \to ZH)$ for a given m_A
- The best-fit point and the preferred 68% and 95% CL boundaries are found at $2\Delta(NLL)$ values of 0.0, 2.30 and 5.99, respectively
- For each mass hypothesis the best-fit value is compatible with the absence of a signal
- The largest difference between the observed and expected best-fit values is found for m_A = 500 GeV



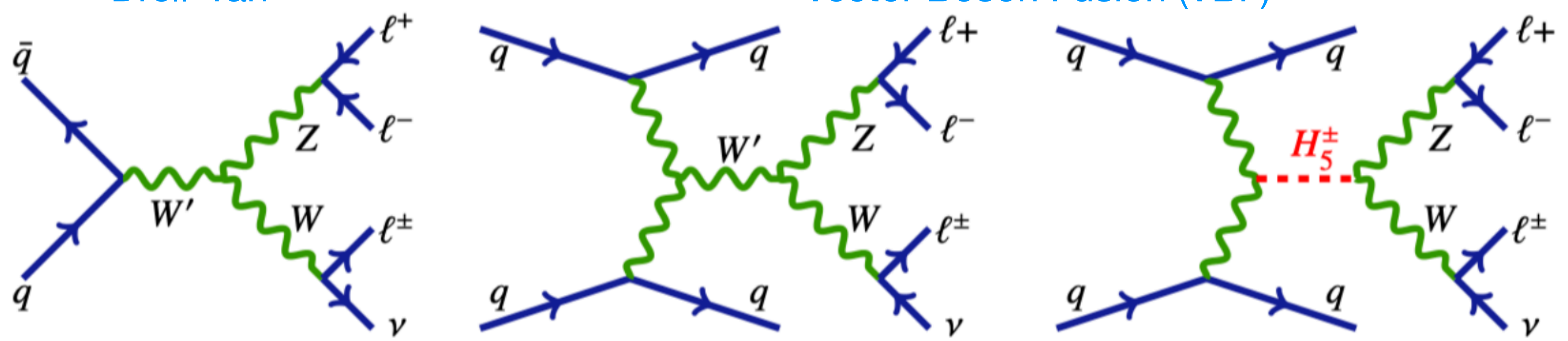
Fully-leptonic WZ

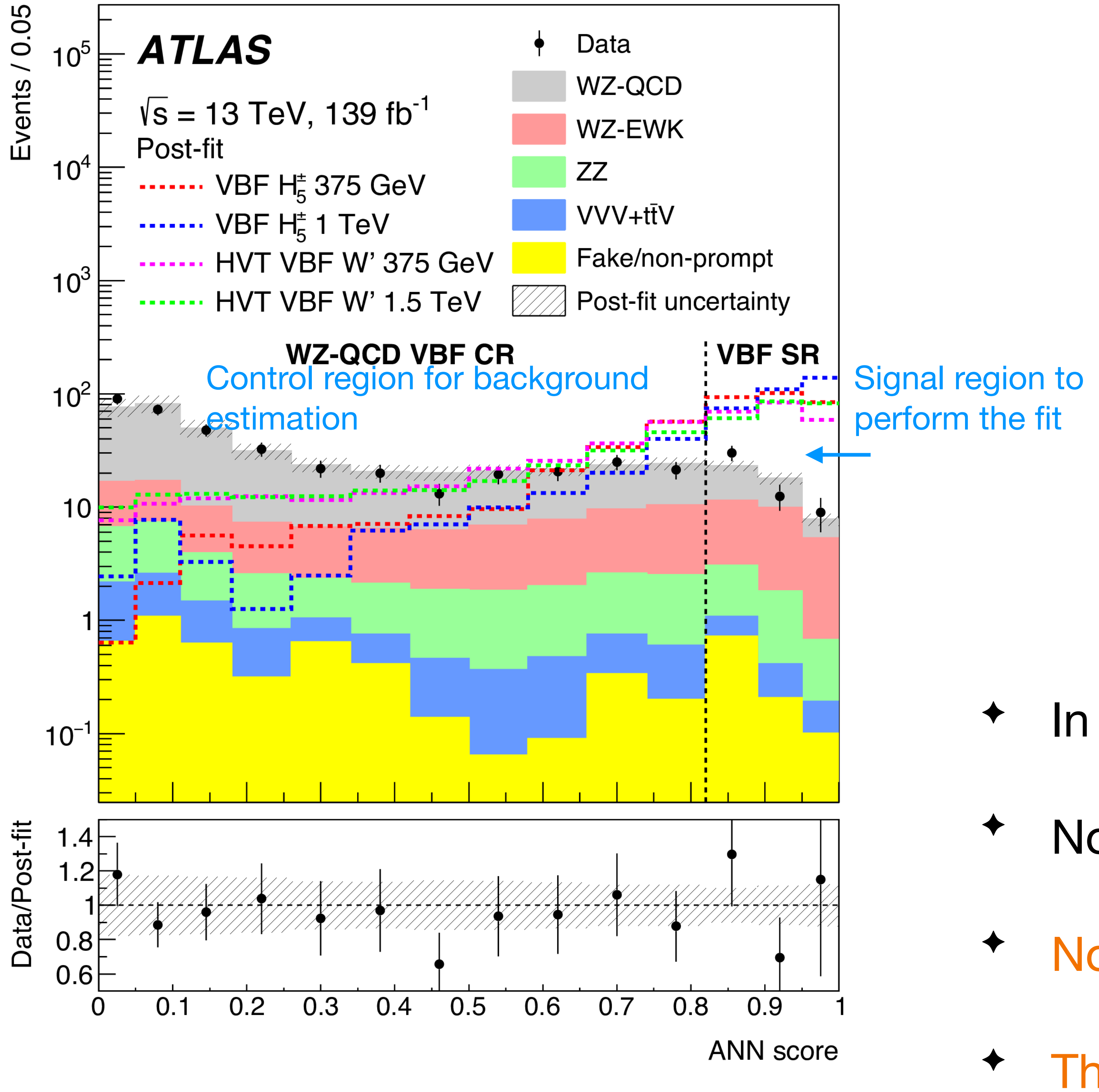
arXiv:2207.03925

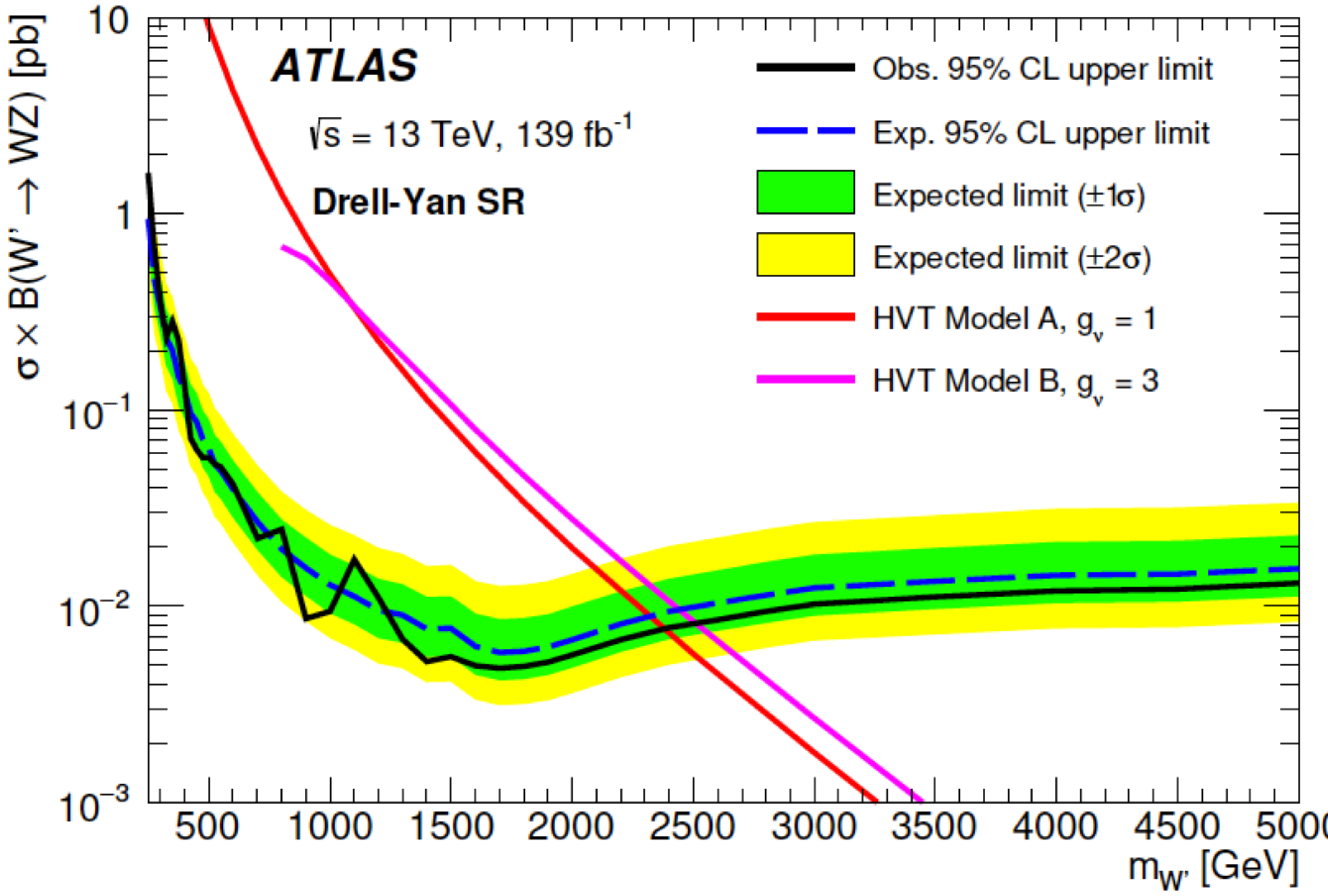
- A search for a WZ resonance is performed in the $ll l\nu$ final state
- Results are interpreted in the context of a HVT W' or a Georgi–Machacek (GM) charged Higgs boson from the fiveplet $(H_5^{++}, H_5^{+}, H_5^{0}, H_5^{-}, H_5^{--})$

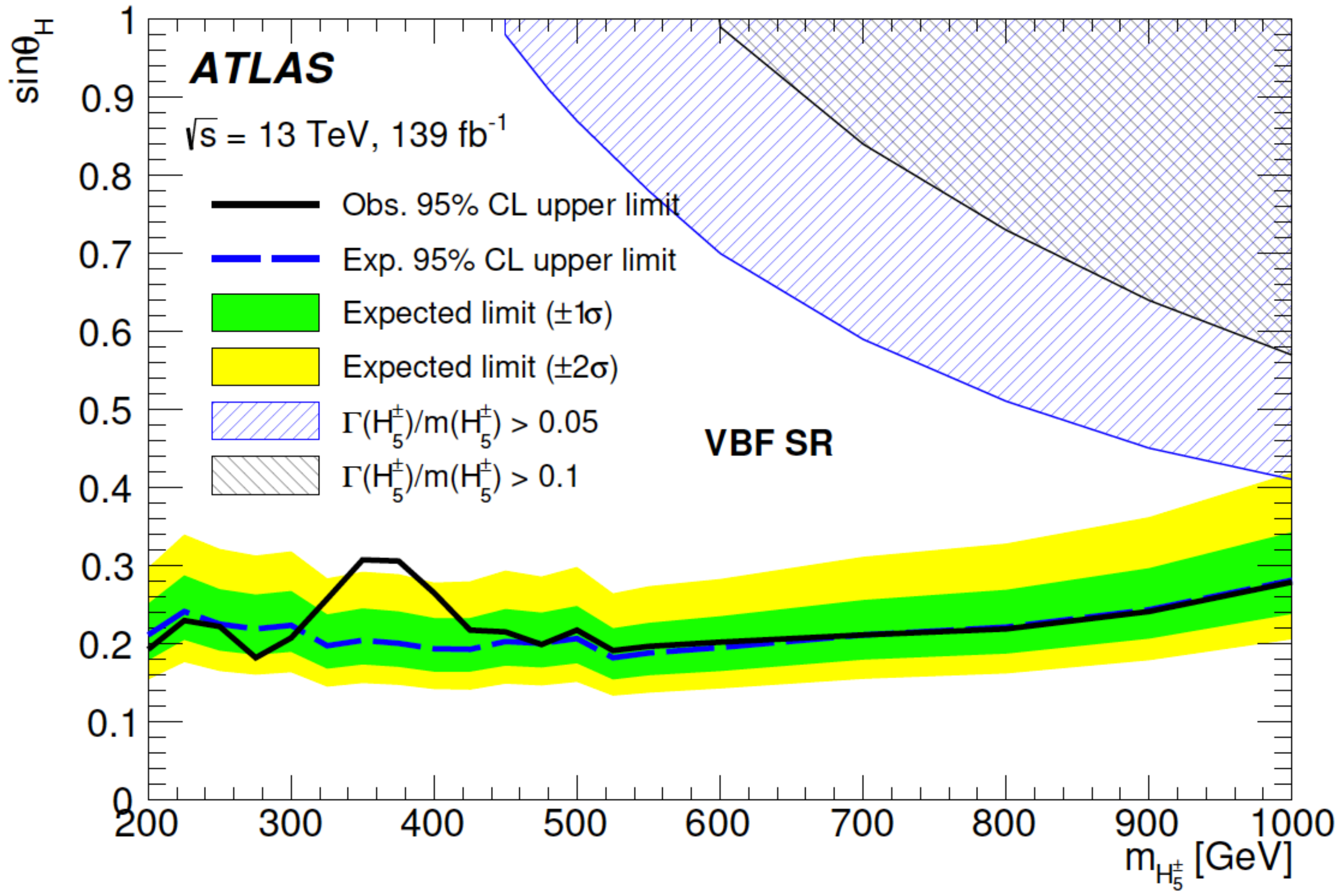
Drell-Yan

Vector Boson Fusion (VBF)







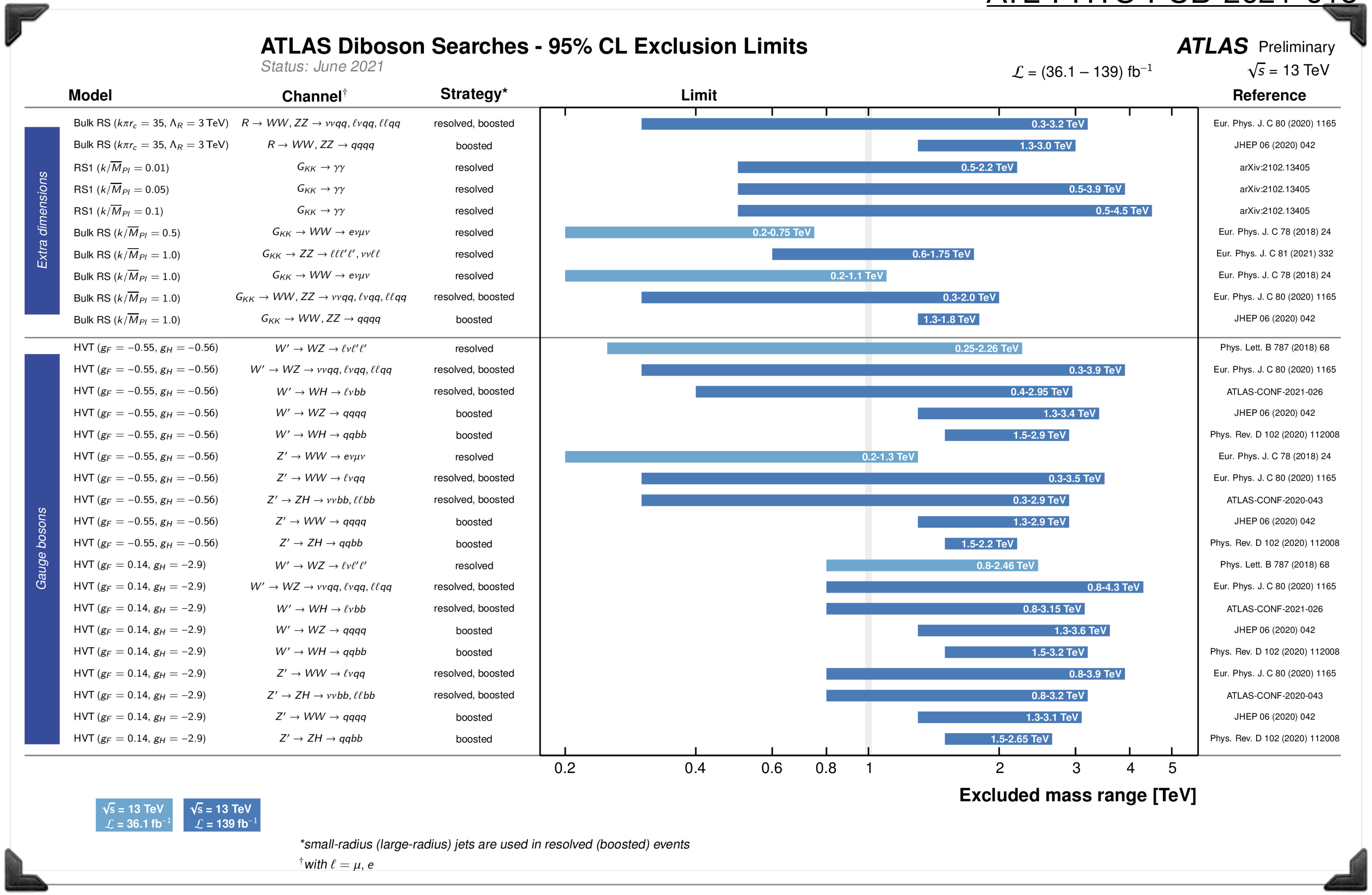


- In VBF category ($N_{jets} \geq 2$ with $m_{jj} > 100$ GeV) a NN is adopted to enhance signal sensitivity
- No significant excess with respect to SM background has been found
- No evidence of HVT for masses below 2.4 (2.5 for Model B) TeV in the DY production channel
- The ratio of vacuum expectation values ($sin\theta_H$) of GM Higgs excluded above 0.3 for masses in (200, 1000) GeV

Conclusions

- ✦ Many BSM theories predict new resonances that decay to boson pairs
- ✦ Lot of heavy resonance searches have been published and many are still ongoing in ATLAS
  - ✦ mainly 'legacy' round of analyses already published with Run-2 data but exploiting new objects reconstructions and/or novel ML techniques
- ✦ The novel jet reconstruction and tagging techniques are crucial to enhance search sensitivity
- ✦ Ongoing effort on optimizing tools performances for Run-3

ATL-PHYS-PUB-2021-018

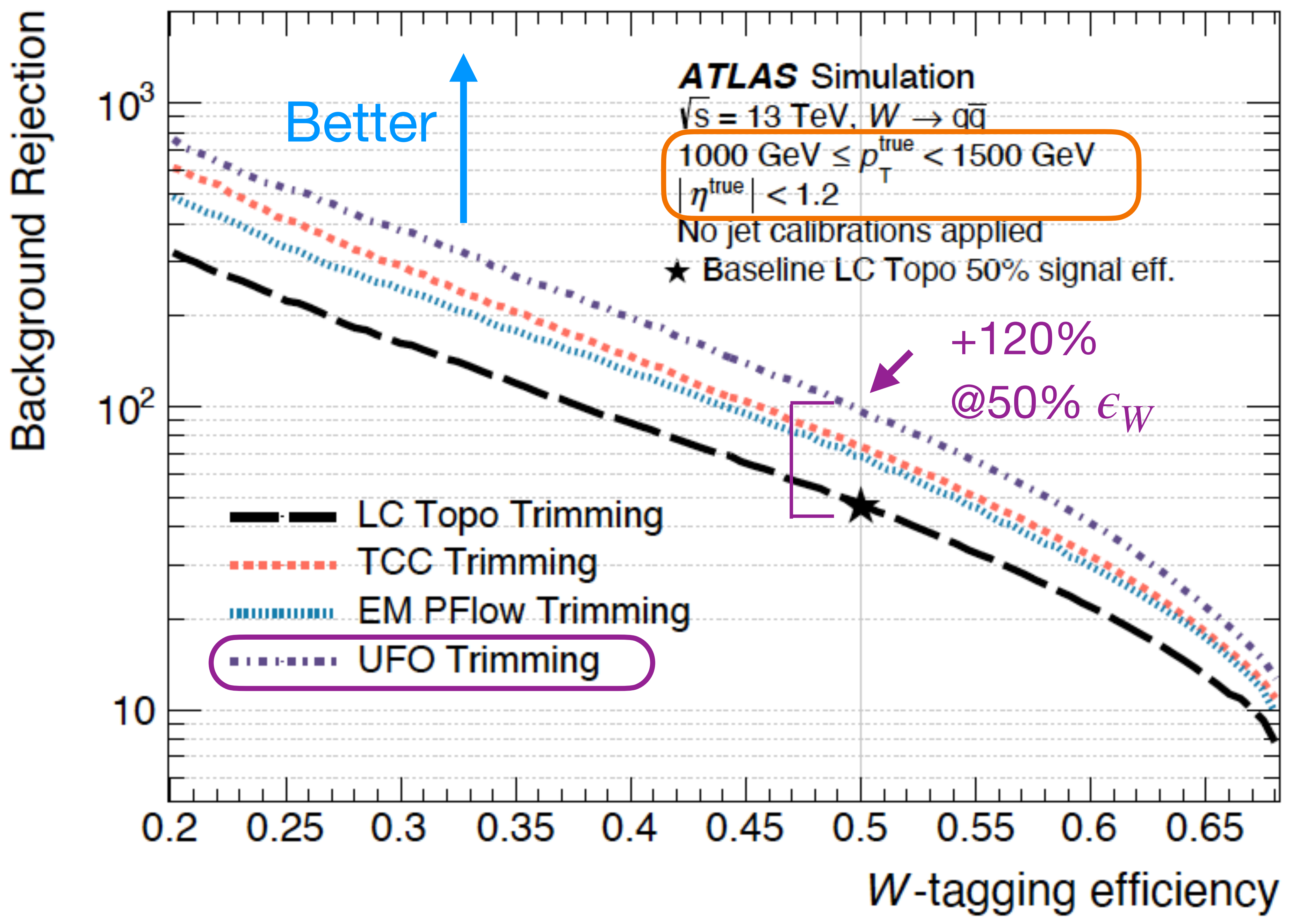


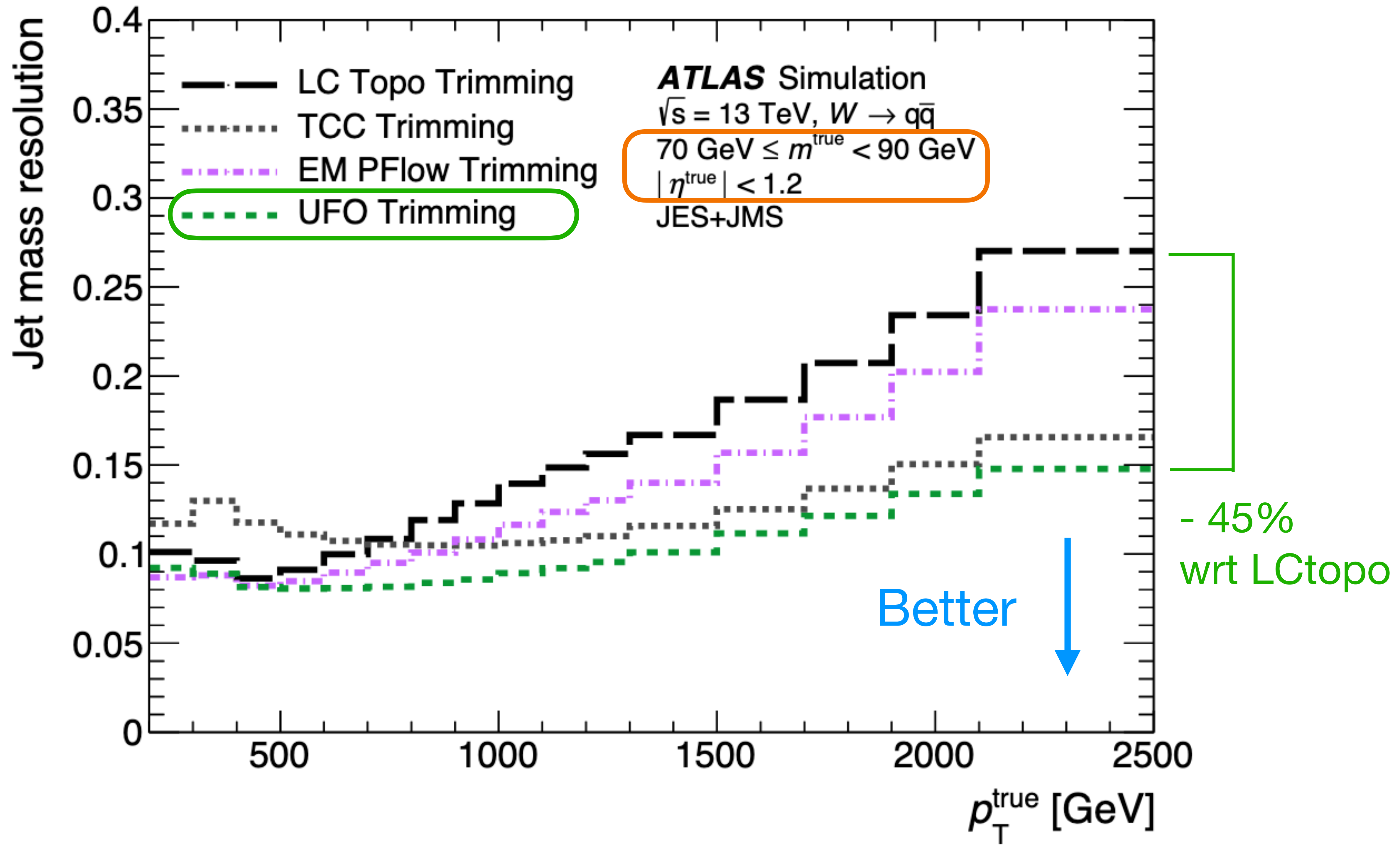
Backup

UFO jets

arXiv:2009.04986

- New jets reconstruction algorithm: Unified Flow Objects (UFOs) combines PFlow and TCC algorithms
  - already used from some late Run-2 analyses
- The increased tagging performance of UFOs is demonstrated across both the low and high p_T ranges, where their performance is superior to that of TCC jets at high p_T and becomes similar to that of PFlow jets as p_T decreases
- Jet mass resolution is improved up to 45% above a p_T of 500 GeV when compared with other large-R jet types

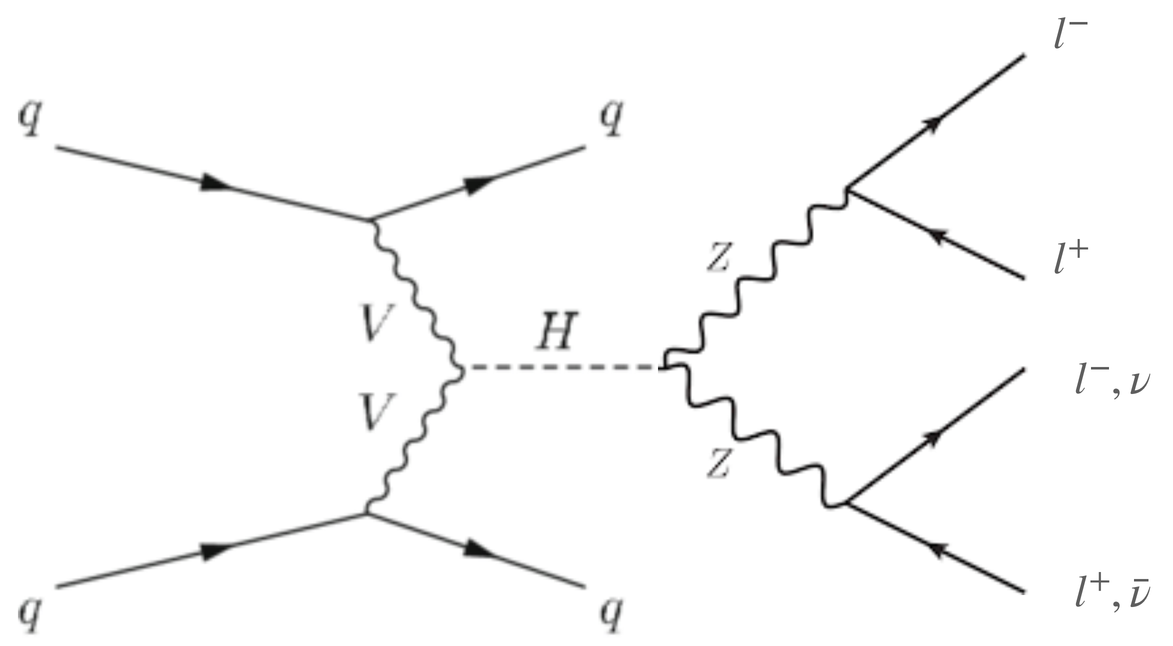


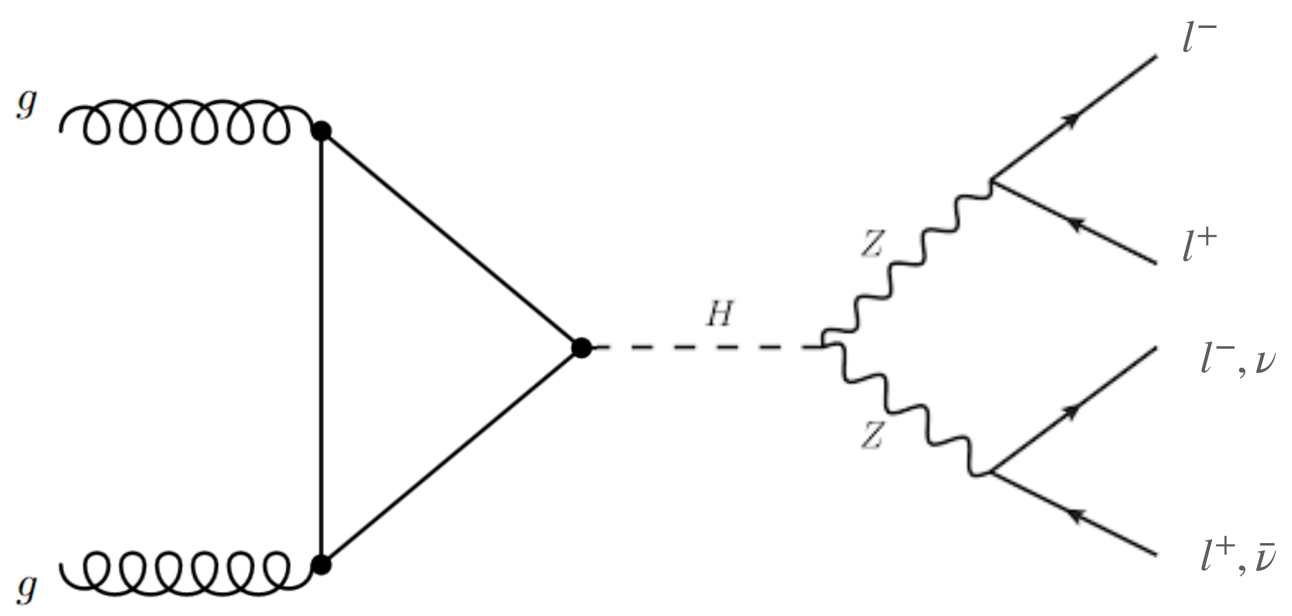


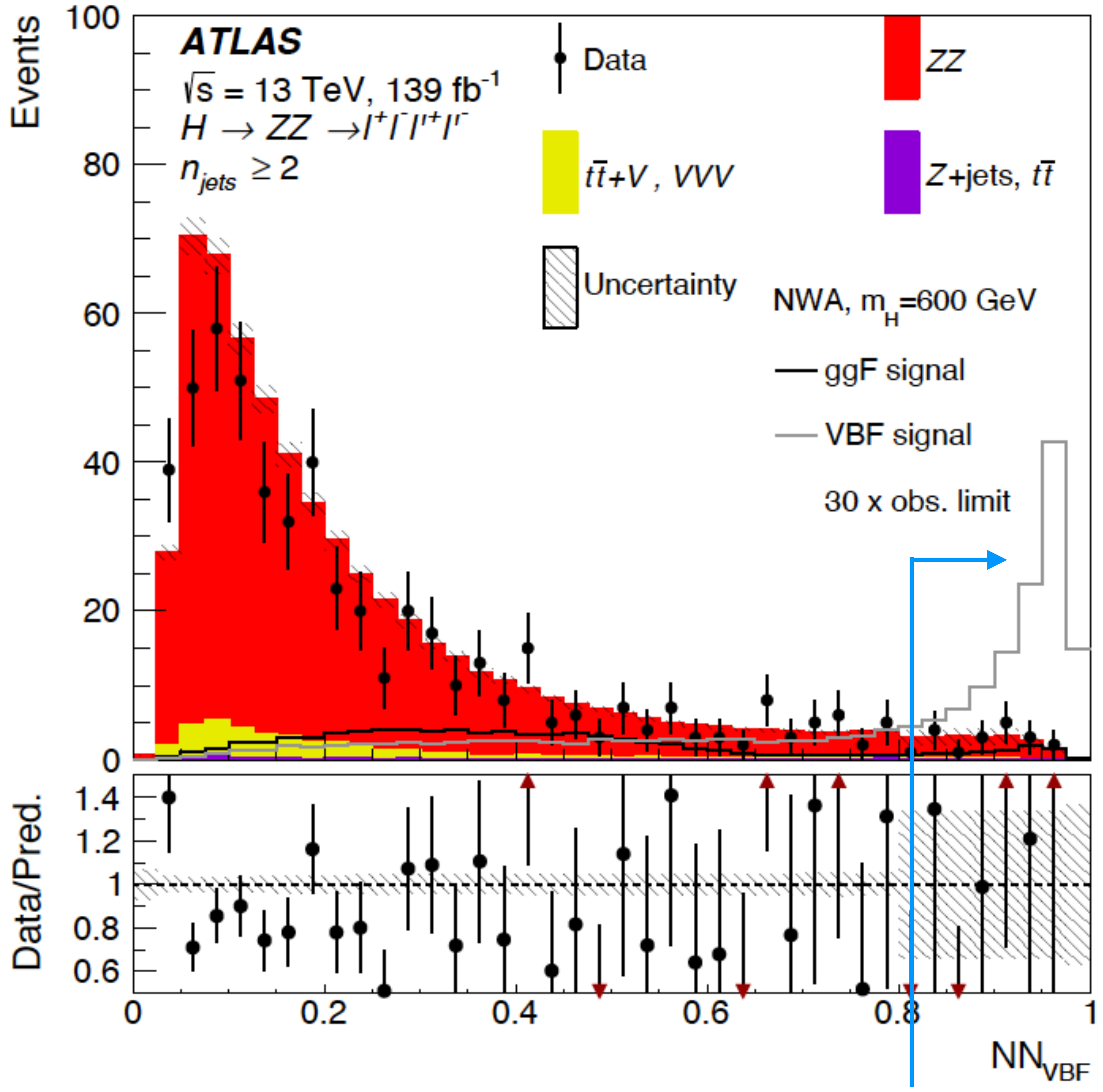
Fully-leptonic ZZ

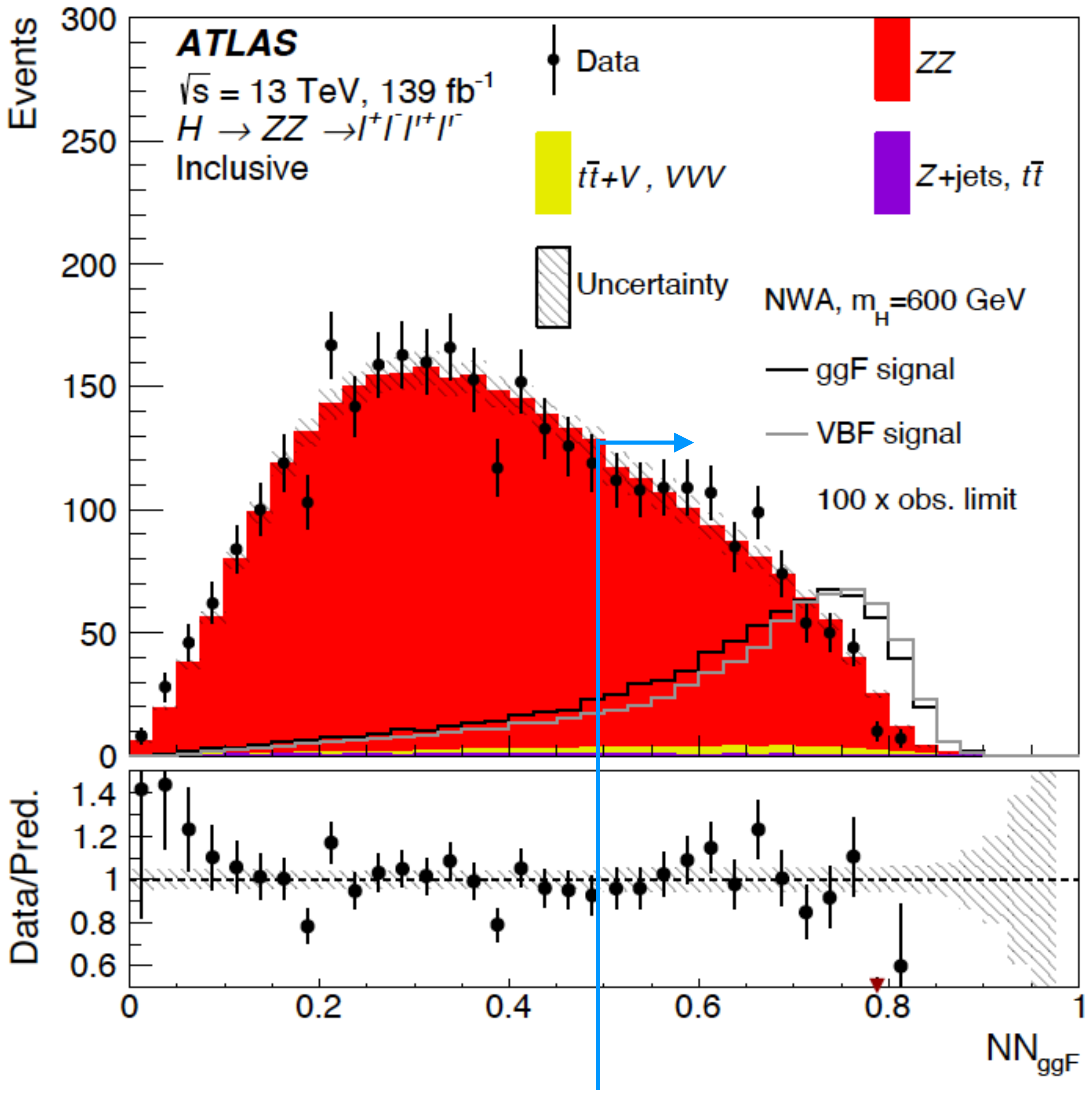
arXiv:2009.14791

- Search for heavy resonances decaying into a pair of Z bosons, in $l^+l^-l^+l^-$ and $l^+l^-\nu\bar{\nu}$ final states
  - Investigated mass range: 200 - 2000 GeV
- Production of a spin-0 heavier H or a spin-2 Kaluza-Klein Graviton G_{KK}, considering both ggF and VBF production modes
  - Both Narrow Width (NWA) and Large Width Approximation (LWA), with width 1%, 5%, 10% and 15% of the resonance mass
- Combination of single-lepton, dilepton and trilepton trigger used
- Both cut-based and MVA (in 4 lep) performed:
  - DNN discriminants (recurrent NNs + Multi Layer Perceptron (MLP)) for VBF and ggF categories, optimized for NWA searches
  - Cut-based VBF categories defined with the two leading jets $\Delta\eta_{jj} > 3.3\ (4.4)$ and $m_{jj} > 400$ (550) GeV









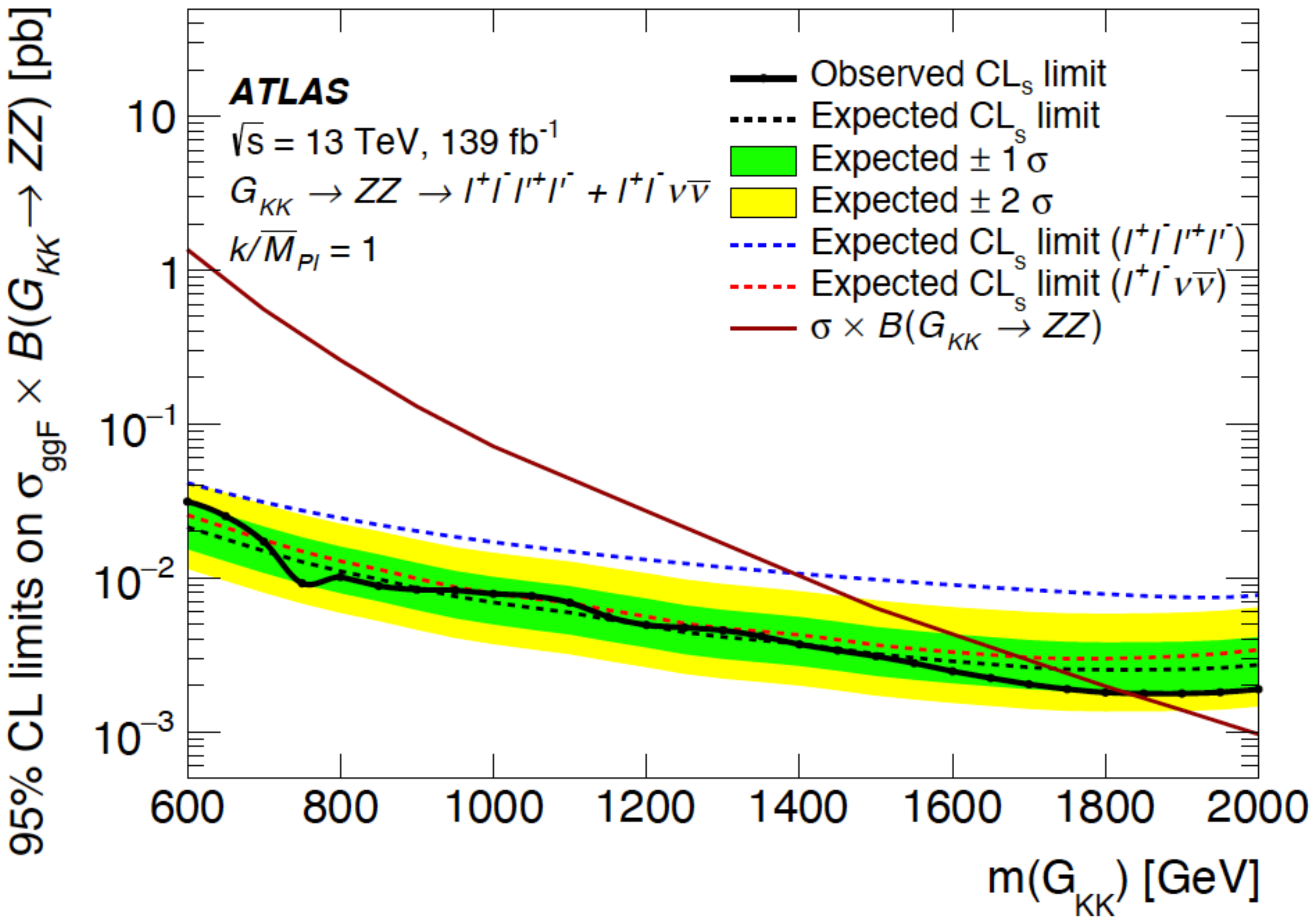
VBF-MVA-enriched: $n_{jets} \geq 2$ && $NN_{VBF} > 0.8$

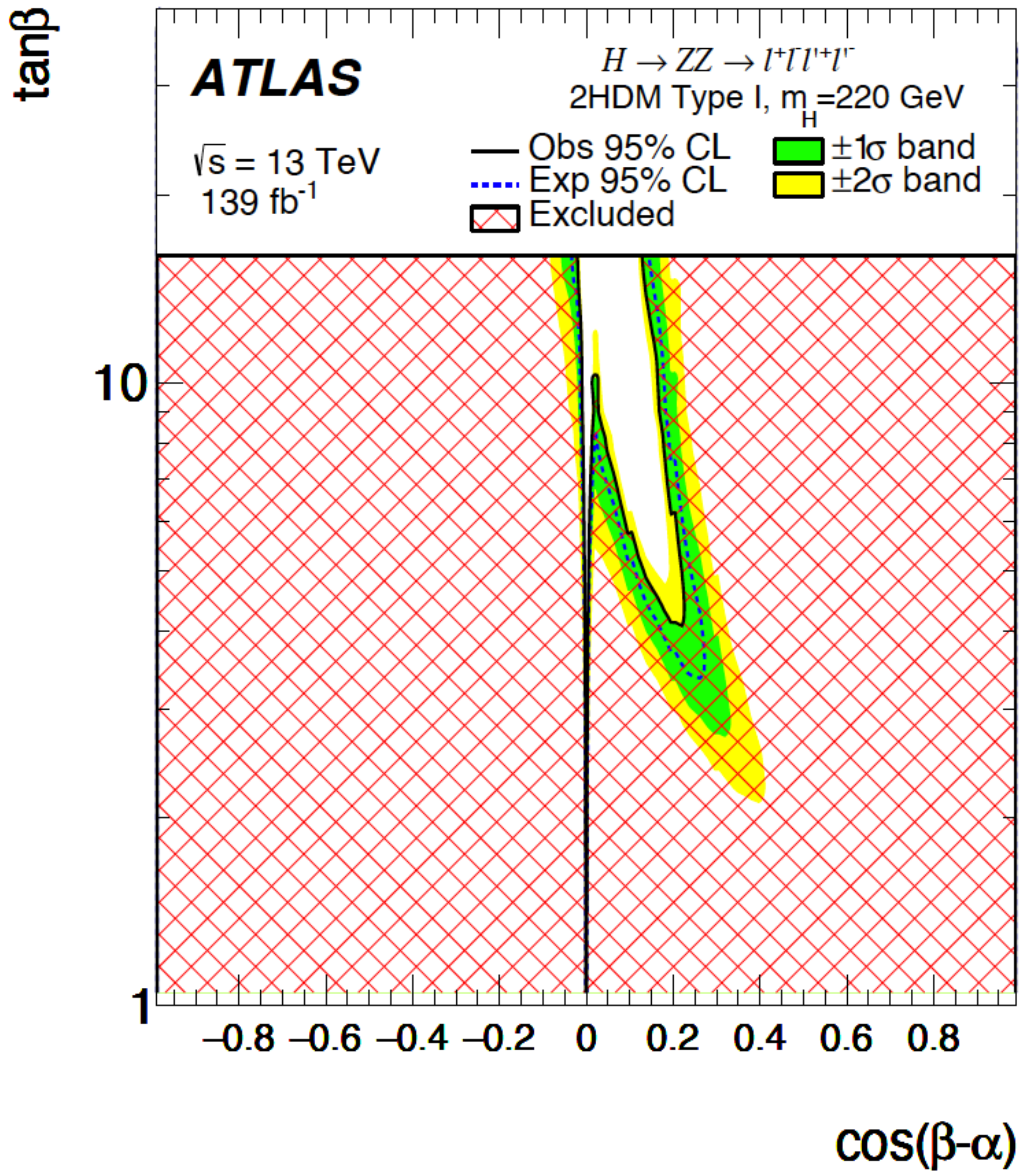
ggF-MVA-high: not VBF && $NN_{ggF} > 0.5$

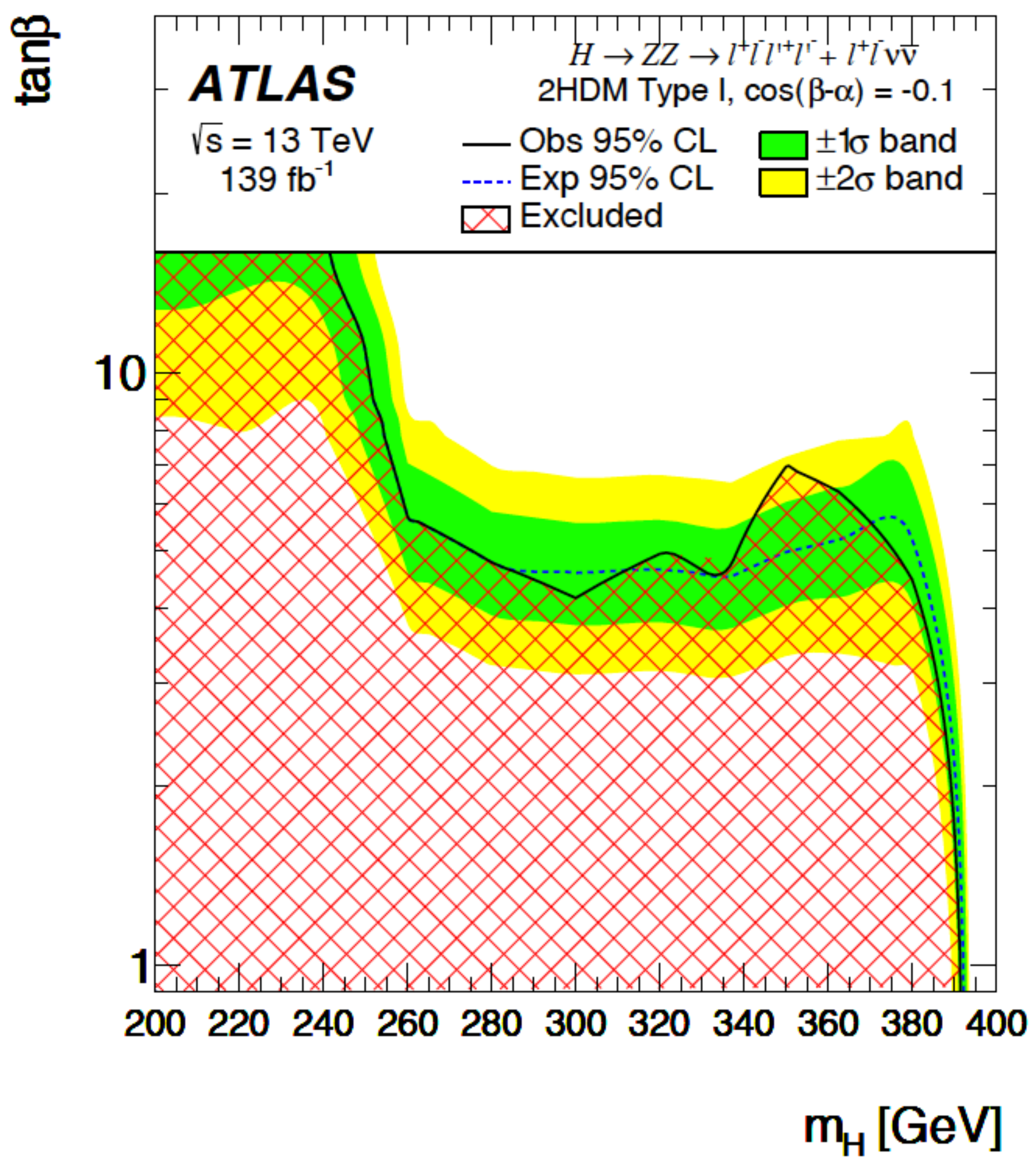
ggF-MVA-low for events failing both categories

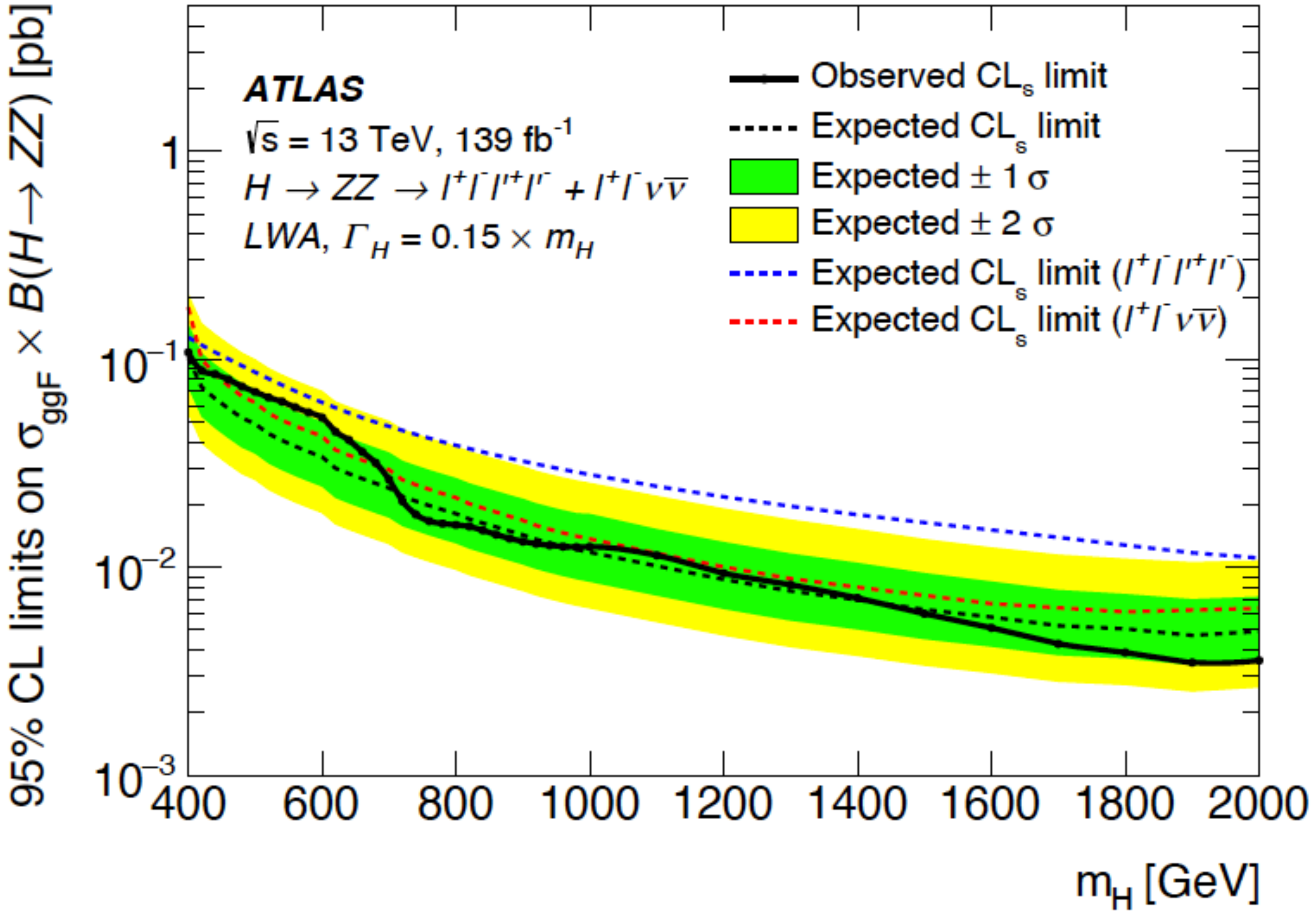
Fully-leptonic ZZ

arXiv:2009.14791









- Main background contributions (normalization estimated from data): non-resonant ZZ and WZ production, Z+jets and $t\bar{t}$
- No excesses on data wrt background-only hypothesis found on m_{4lep} (m_T), 95% CLs upper limits on signal cross section are extracted
- Exclusion limits in the $tan\beta$ vs $cos(\beta - \alpha)$ and m_H plane
  - $tan\beta$: ratio of the vacuum expectation values of the two Higgs doublets
  - α: the mixing angle between the CP-even Higgs bosons

Semi-leptonic Z/W + hh

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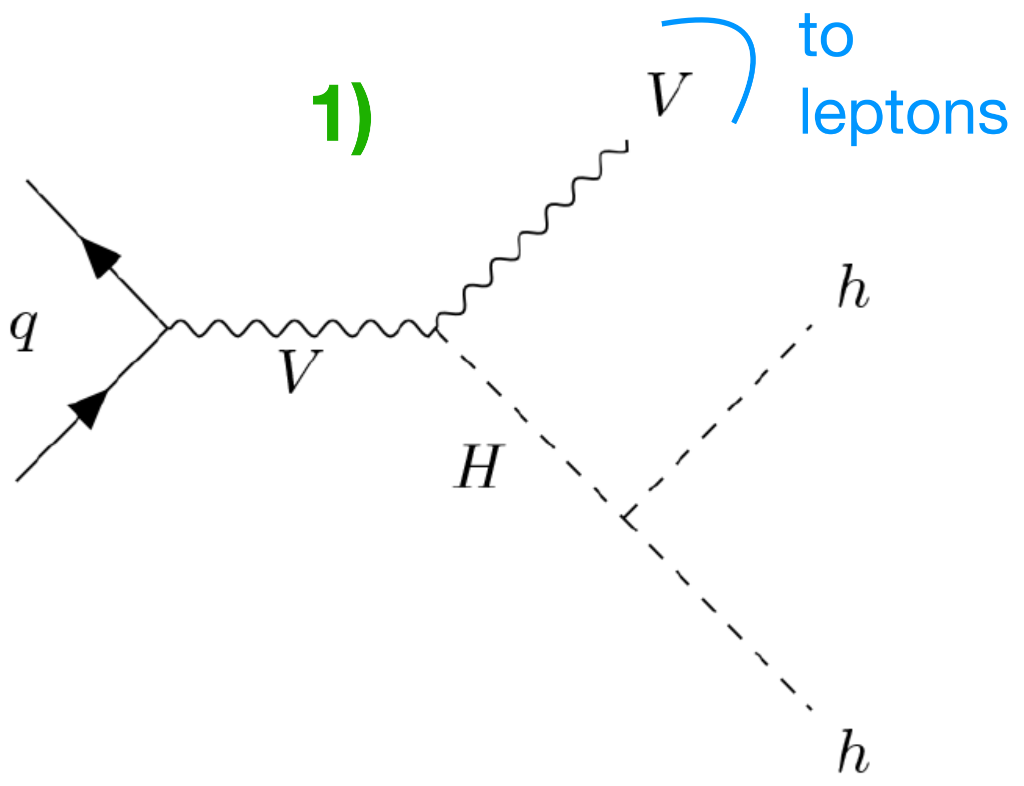
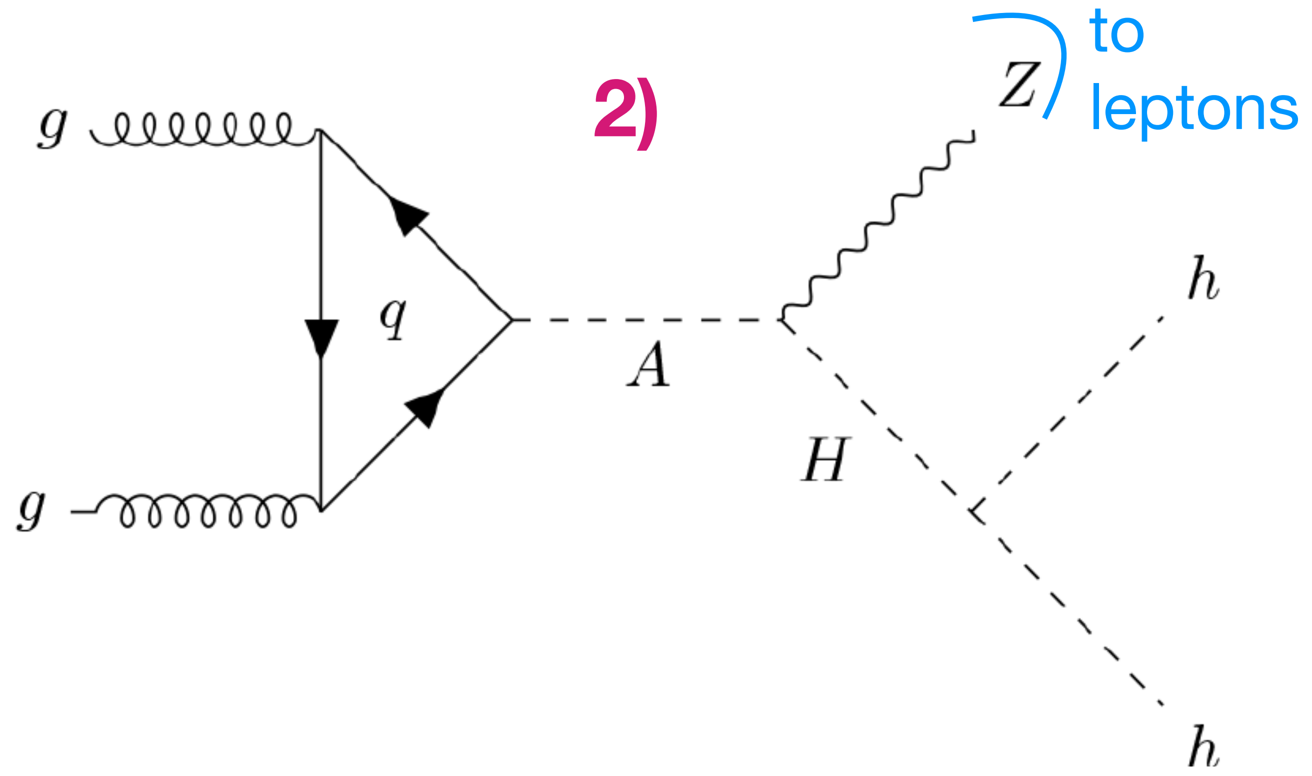
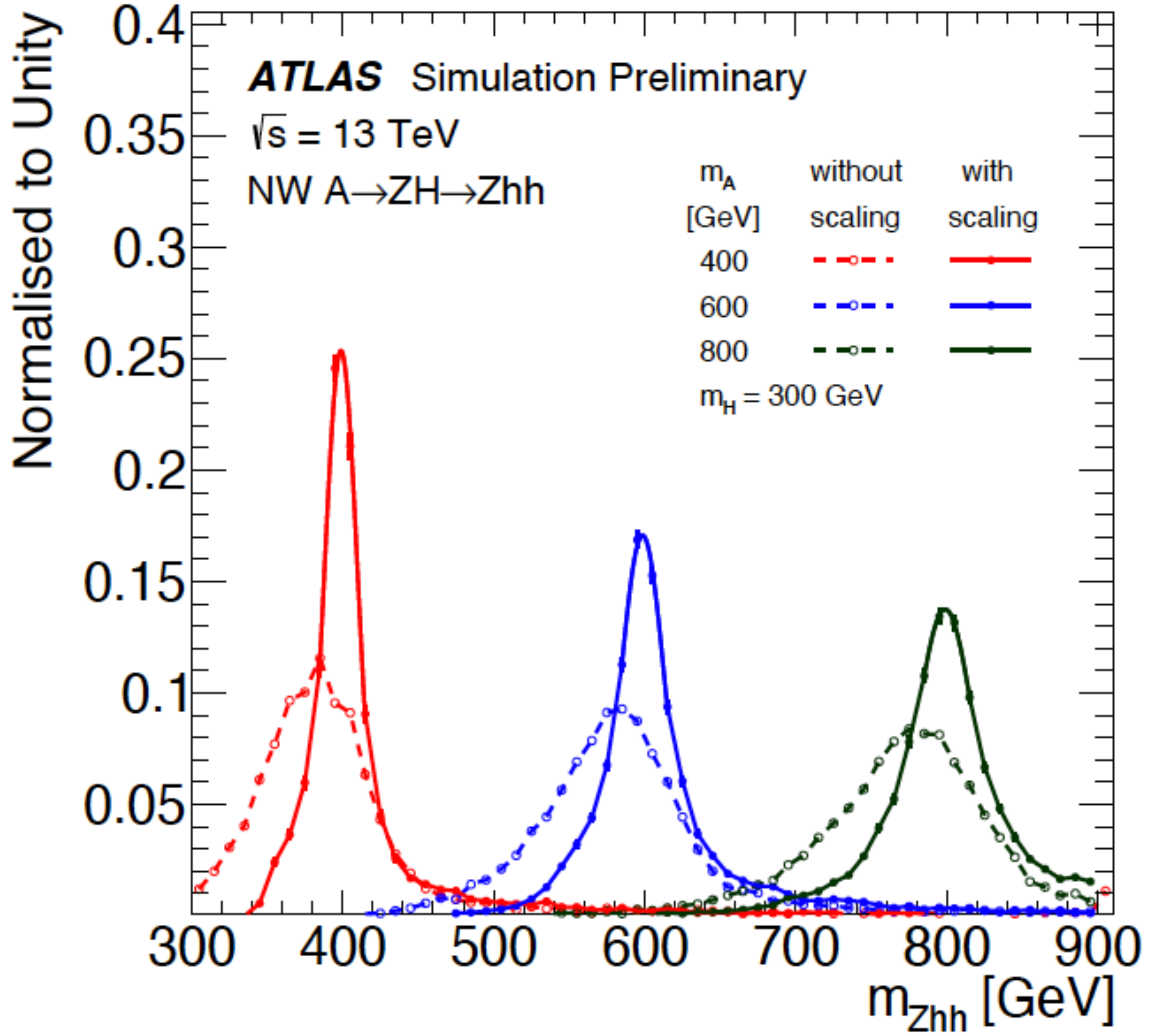
- A search for Higgs boson pairs produced in association with a vector boson in the semi-leptonic final states $Zhh \rightarrow \nu\nu bbbb$ (0-lep), $Whh \rightarrow l\nu bbbb$ (1-lep) and $Zhh \rightarrow llbbbb$ (2-lep)
- Two BSM scenarios are considered:
  - 1) a generic neutral CP-even scalar H (investigated mass range 260-1000 GeV)
  - 2) a CP-odd scalar A (with mass between 360-800 GeV) decaying into Z and a CP-even scalar H (with mass in 260-400 GeV) in the 2HDM model, separately for the NWA and LWA of the A boson
- single-lepton trigger, $N_{bjets} \geq 4$ (DL1r b-tag) for the two $h \rightarrow b\bar{b}$ decays, each reconstructed with two small-R jets (PFlow with R=0.4)
- Mass resolution is improved by constraining the measured masses of the two Higgs boson to their expected value of 125 GeV by scaling the b-jet momenta with the ratio between the measured di-b-jet mass and 125 GeV

1)



2)





Semi-leptonic Z/W + hh results

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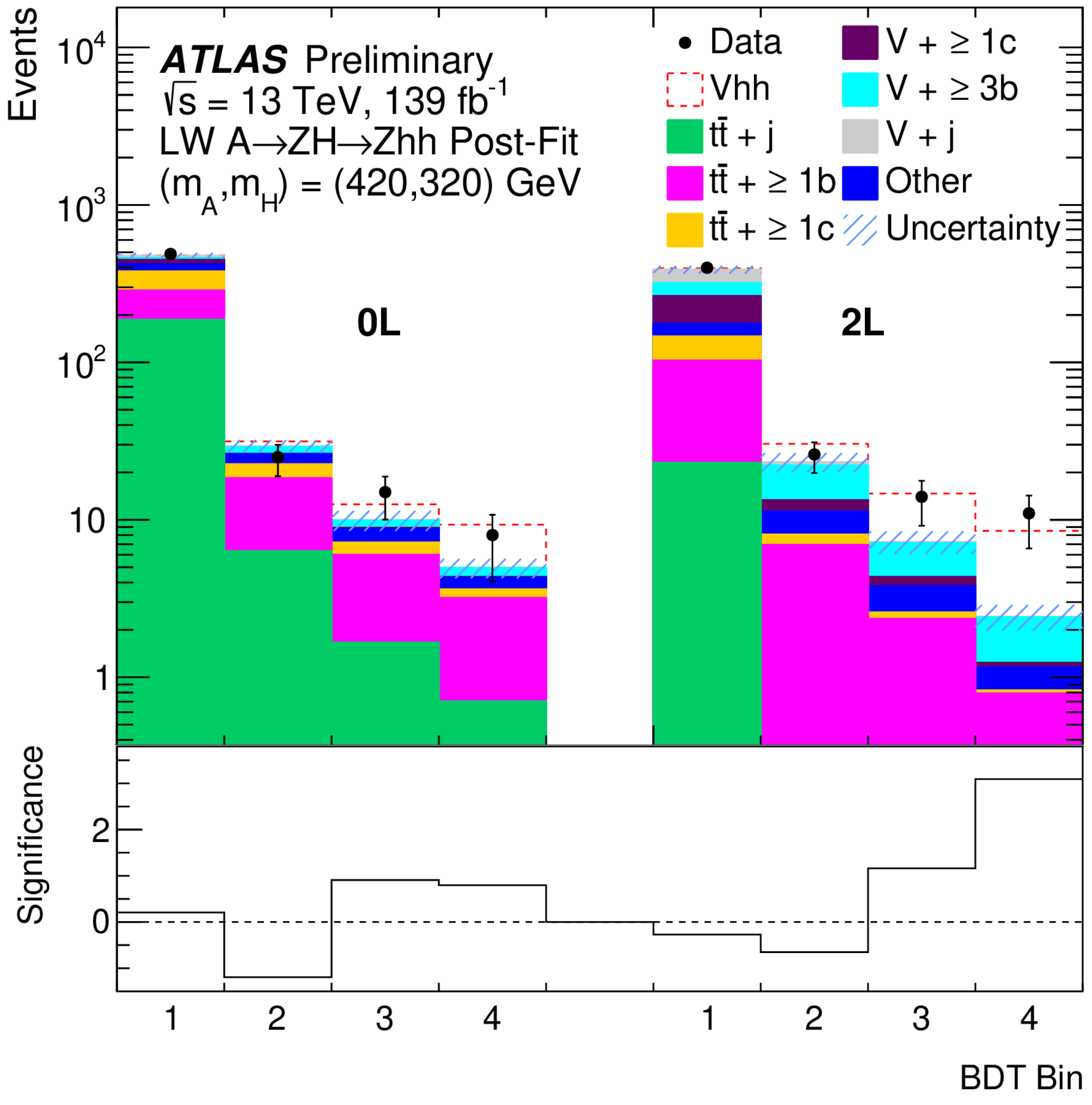

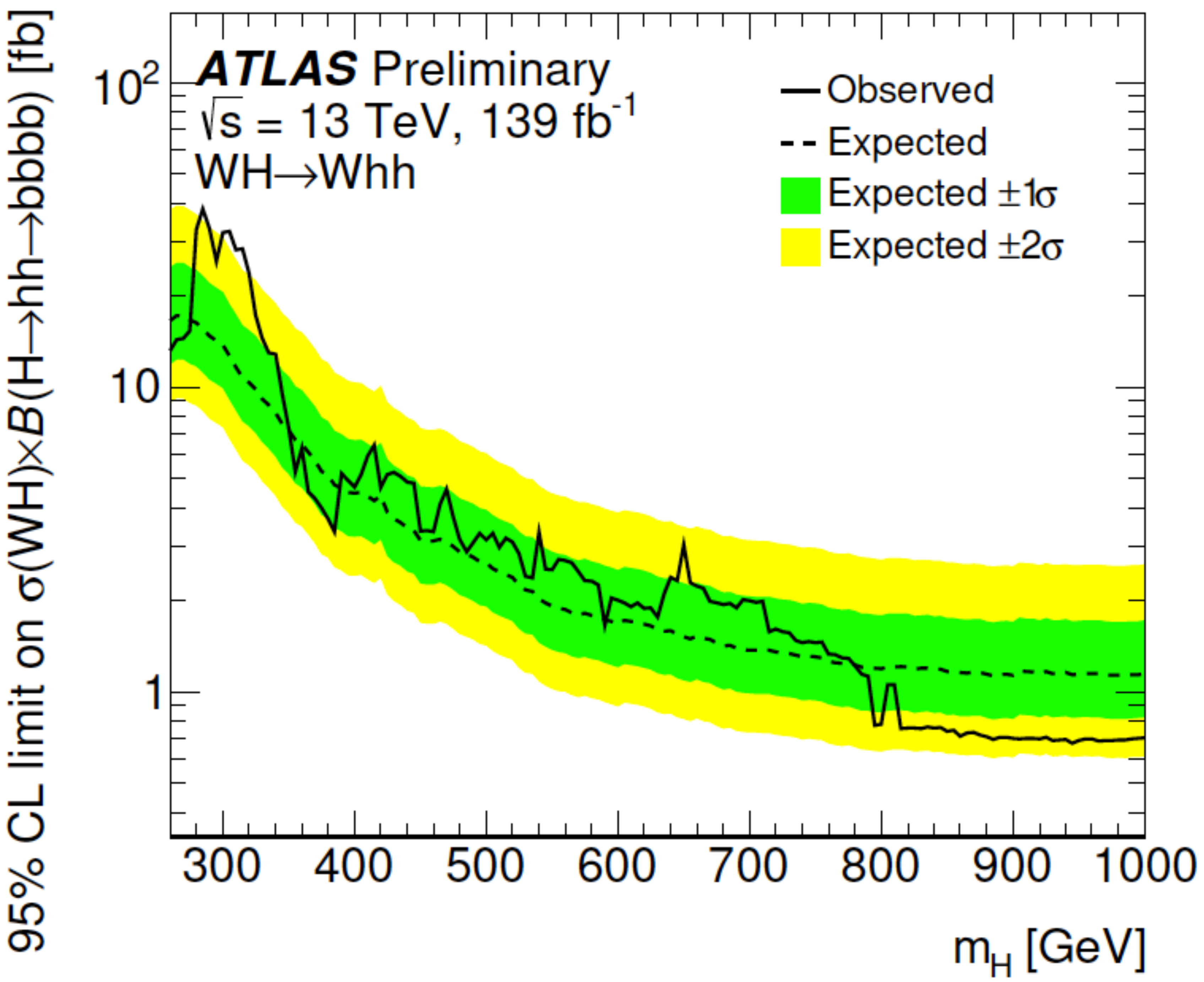

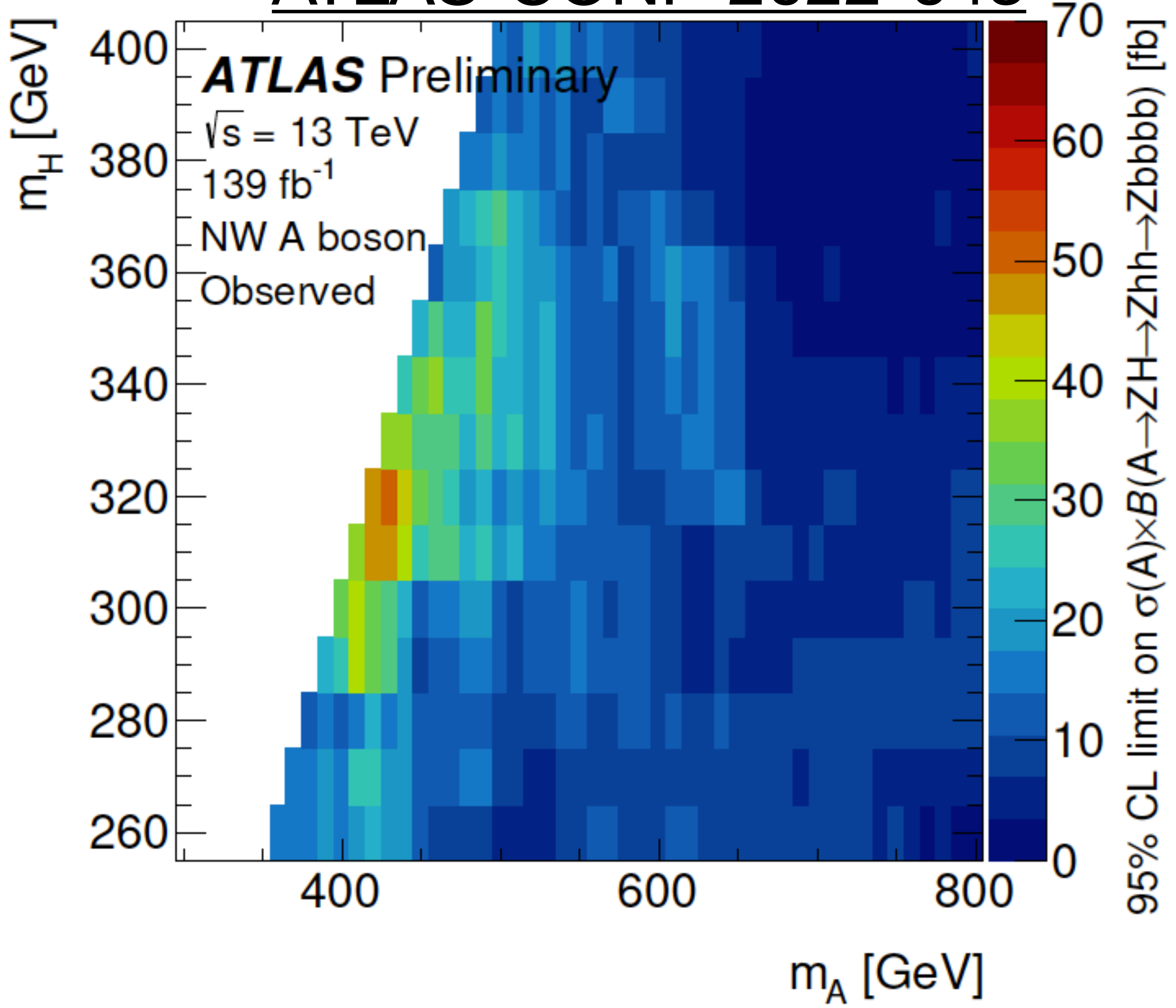

- BDTs used as final discriminants trained with jets kinematic information, to distinguish signal and background events in each SR and for each signal model
- Major background sources: $t\bar{t}$, single top, V+jets, di- and multi-bosons (from MC) and multi-jets (data-driven estimated)
- The most significant excess of data over background is observed in the $gg \to A \to ZH \to Zhh$ search for $(m_A, m_H) = (420, 320)$ GeV with a local (global) significance of 3.8 (2.8) σ. More data are needed to ascertain the nature of this excess
- Upper bounds on the cross-sections of the resonances production are derived

Semi-leptonic Z/W + hh

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- The constraints on $A \rightarrow ZH$ production are also interpreted in the $cos(\beta - \alpha)$ vs m_A parameter space of type-I and lepton-specific two-Higgs doublet models