ATLAS Searches for Diboson Resonances

Gabriele Chiodini - *INFN Lecce and Università del Salento*

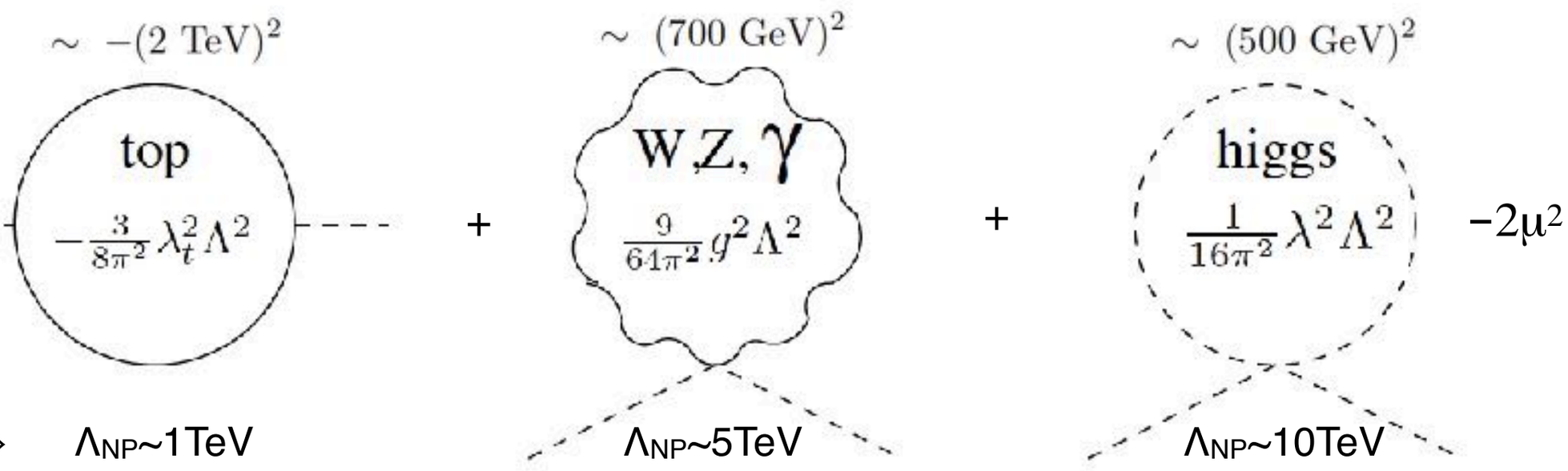
on behalf of ATLAS collaboration

Outline and motivations

The most compelling argument of New Physics at TeV scale is the extreme fine tuning of quantum corrections involving t, γ, W, Z and H in order to keep the observed Higgs mass close to the electroweak scale.

Tuning for $\Lambda_{cut\text{-}off}$=10TeV ⇒

$M_H^2=(125GeV)^2=$



Fine tuning < 10% ⇒ Λ_{NP}~1TeV Λ_{NP}~5TeV Λ_{NP}~10TeV

New resonances coupled to γ/W/Z/H generally expected at multi-TeV scale. The Higgs itself could be the first of a series of di-boson resonances waiting discovery at LHC

Benchmark models

Three models differing from new boson(s) spin:

Spin 0: **Extended Higgs sector** (2HDM, ectroweak-singlet model ……..SUSY, …)

- Heavy scalars H'

Spin 1: **Heavy Vector Triplets** (HVT)→W'$^-$W'$^+$Z'

- Additional SU(2) symmetry
- Small set of parameters:
  - Mass $M_{V'}$
  - Coupling to Bosons and Higgs g_V (enable VV, VH, HH decays)
  - Universal coupling to fermions $g_F=g^2_{EW}/g_F$
- Model A: equal BRs to fermions and bosons (g_V=1)→Extended Gauge Symm.
- Model B: couplings to fermions suppressed (g_V=3) →Minimal Composite Higgs

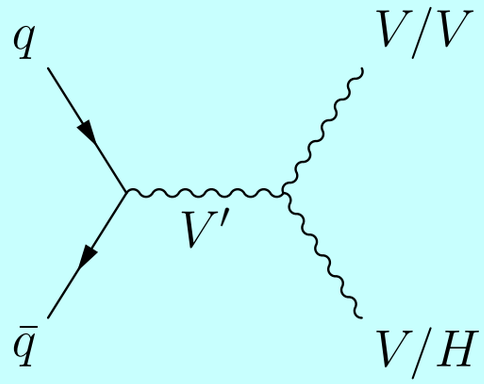
Spin 2: **KK graviton** from bulk Randall-Sundrum model → G*

- KK graviton in 5D warped ADS space with SM particles on 1 TeV brane extending into the "bulk".
- Couplings to light fermions and VBF production suppressed

Production mechanisms

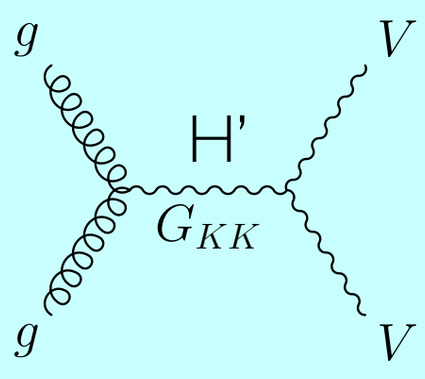
Categorization in production mechanisms increases sensitivity

Drell-Yan



Heavy Vector Triplet W'

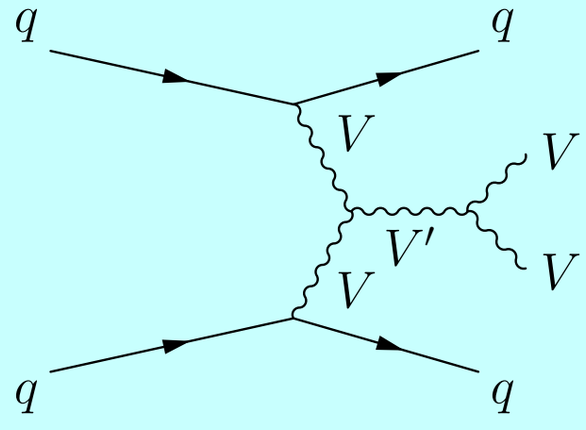
gluon-gluon fusion



Heavy scalar - RS bulk G*

ggF/DY

Vector Boson Fusion



Heavy scalar/vector

VBF

Two opposite hemisphere jets, j1 and j2, with large rapidity separation and large invariant mass

Ex. VV→llqq:

- $\eta_{j1} \cdot \eta_{j2} < 0$
- $|\Delta\eta_{j1j2}| > 4.7$
- $m_{j1j2} > 770$ GeV

Current status of VV searches in ATLAS

- ☑ 2015-2016-2017 @ 13 TeV pp
- ☑ 35-79.8 fb^{-1}

		W→		Z→			H→
		qq'	lν	qq	νν	ll	bb
W→	qq'	ATLAS-CONF-2018-16	arXiv: 1710.07235	arXiv: 1708.04445	arXiv: 1708.09638	arXiv: 1708.09638	arXiv: 1707.06958
	lν			arXiv: 1710.07235		arXiv: 1806.01532	arXiv: 1712.06518
Z→	qq			arXiv: 1708.04445	arXiv: 1708.09638	arXiv: 1708.09638	arXiv: 1707.06958
	νν						arXiv: 1712.06518
	ll						arXiv: 1712.06518
H→	bb						arXiv: 1804.06174

Combination increases sensitivity

THIS TALK: hadronic and semileptonic

- qqqq ~ 45%
- qql(ν)ν ~ 15%
- qqll, lνlν lνν ~ 5%
- llνν ~ 1%
- llll ~0.5%

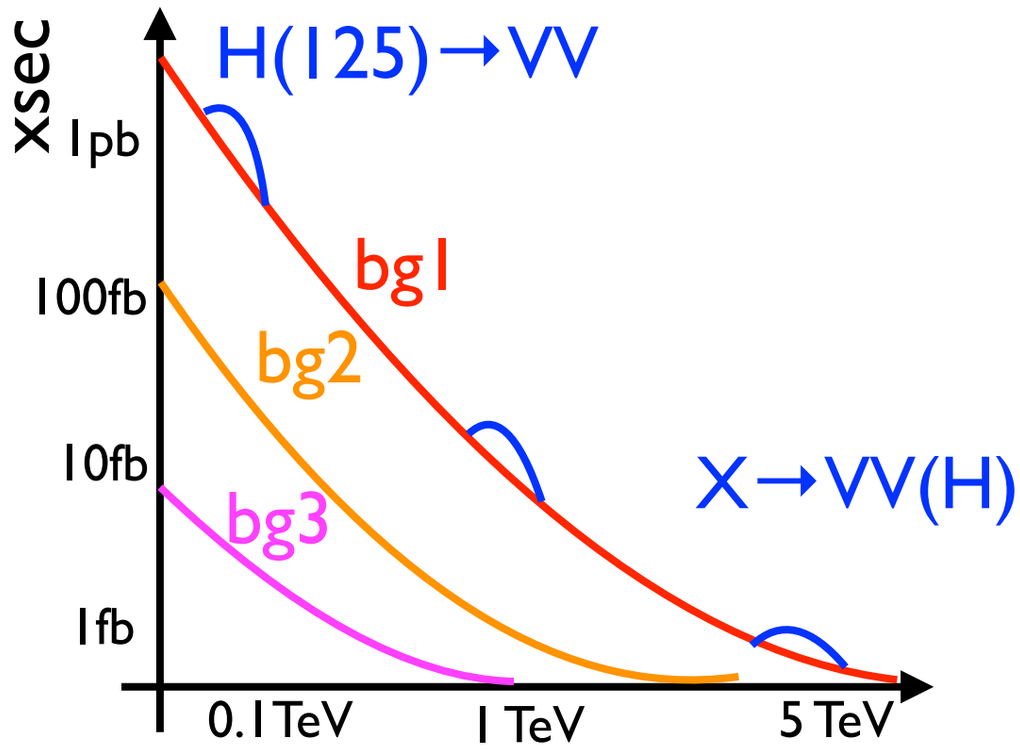
See P.J.Falke and V. Pascuzzi

Not treated here : Search for X→ γ+W/Z/H→γ+fat jet (arxiv:1805.01908) NEW

See plenary X.C.Vidal "Exotic searches - prompt signatures"

Analysis strategy

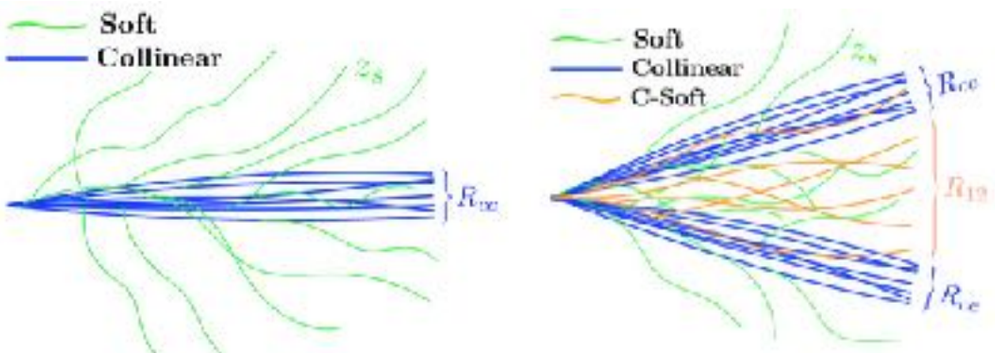
1. Search for a resonant structure into invariant mass or broad enhancement into transverse mass
2. Background estimation: full data-driven or/and MC based.

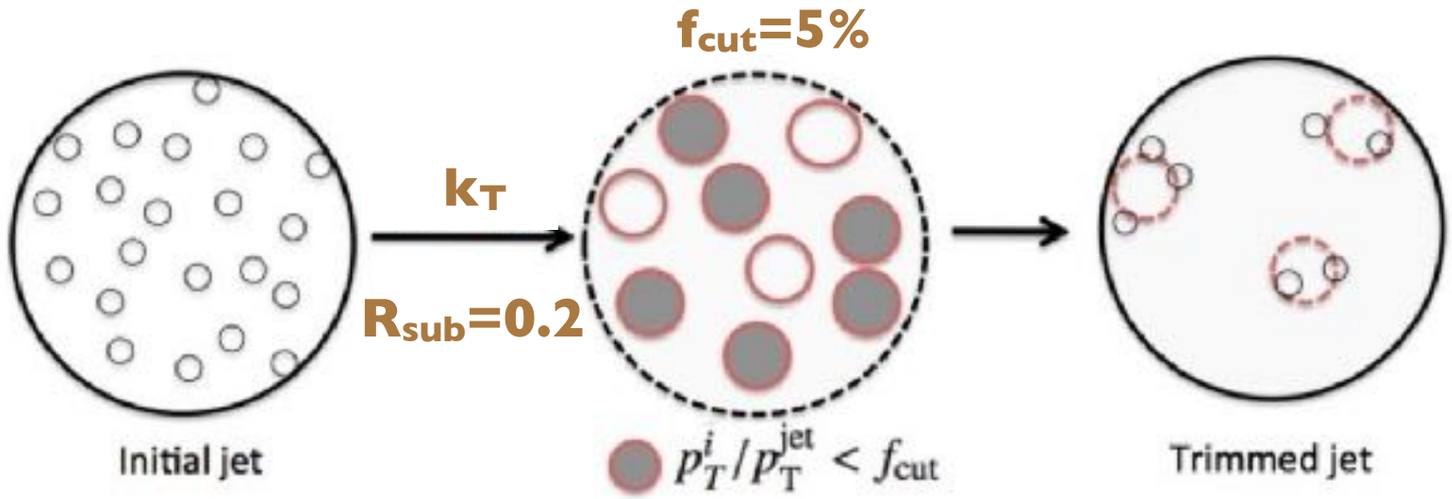


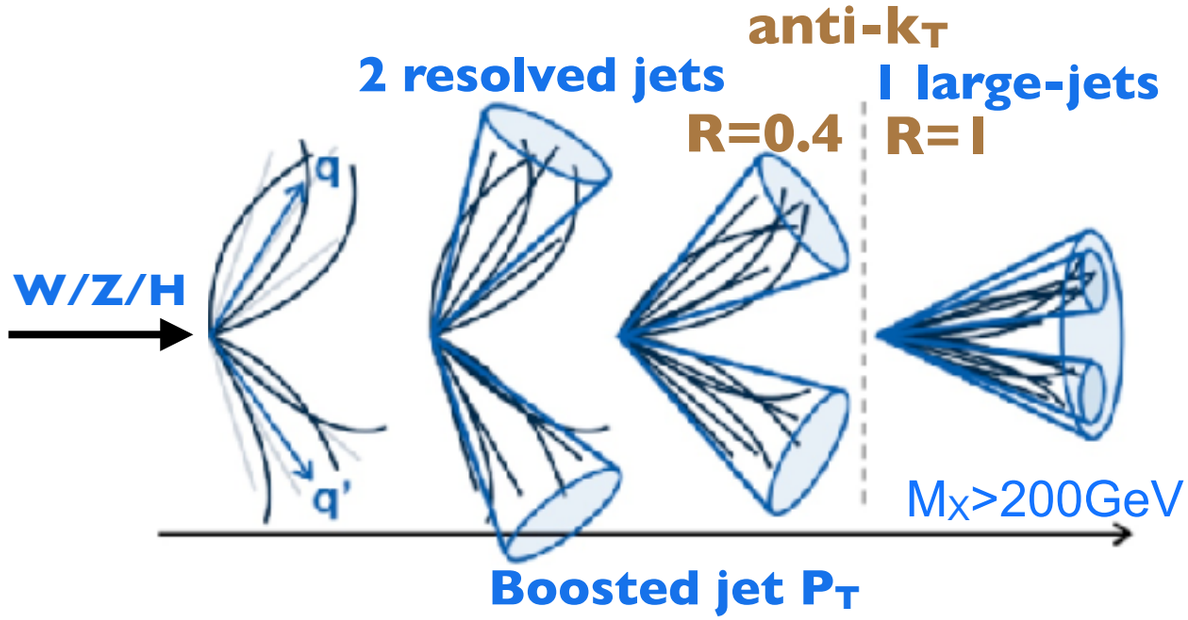
Best performance at high masses where BG is smaller.

Jet trimming and boosted objects

Trimming removes soft QCD and pile-up and leave collinear radiation in jets.







ATLAS-CONF-2017-064

M_J from combined calo and track information

$$D_2^{(\beta)} = \frac{\overbrace{\sum_{i<j<k\in J} p_{T_i} p_{T_j} p_{T_k} (\Delta R_{ij} \Delta R_{ik} \Delta R_{jk})^{\beta}}^{\text{3-prong}}}{\underbrace{\sum_{i<j\in J} p_{T_i} p_{T_j} (\Delta R_{ij})^{\beta}}_{\text{2-prong}}} \quad \text{1-prong: } \sum_{i\in J} p_{T_i}$$

A. Boosted W/Z tagging with $D_2^{\beta=1}$
B. Boosted H tagging with sub-jets b-tag

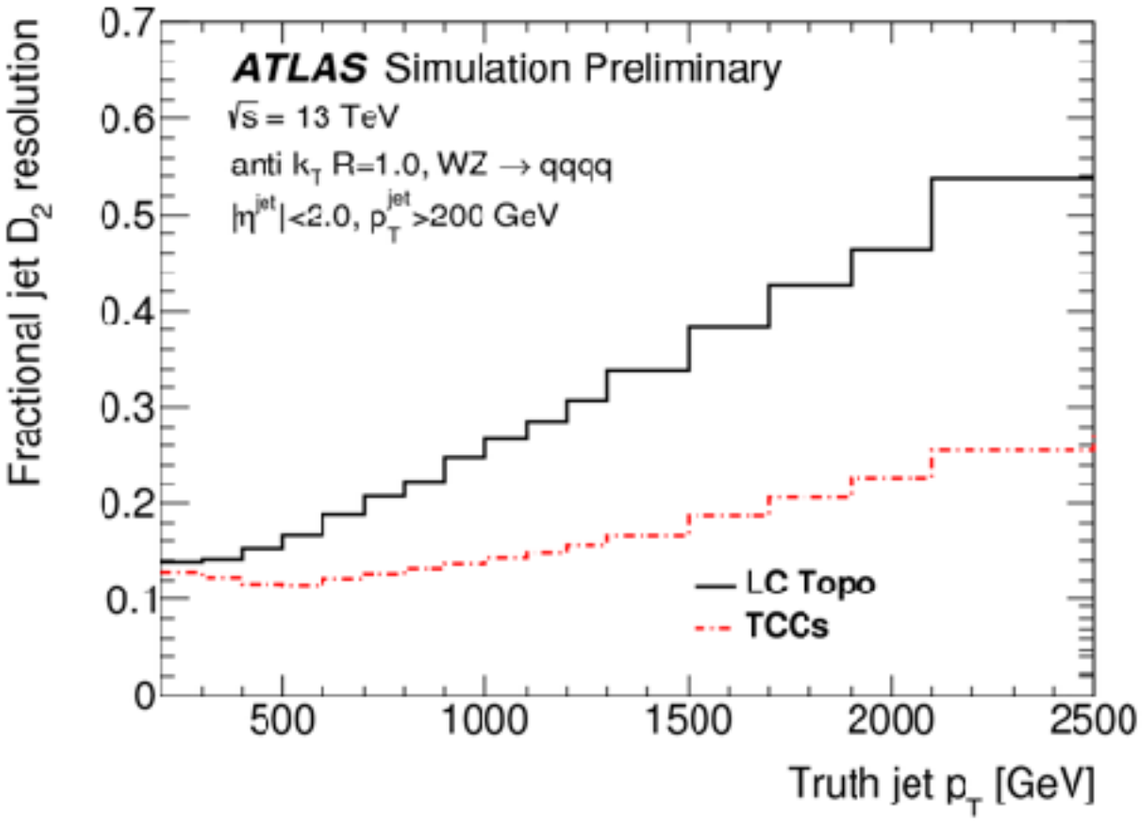
+ M_J

V and H tagging performance

ATLAS-CONF-2018-016

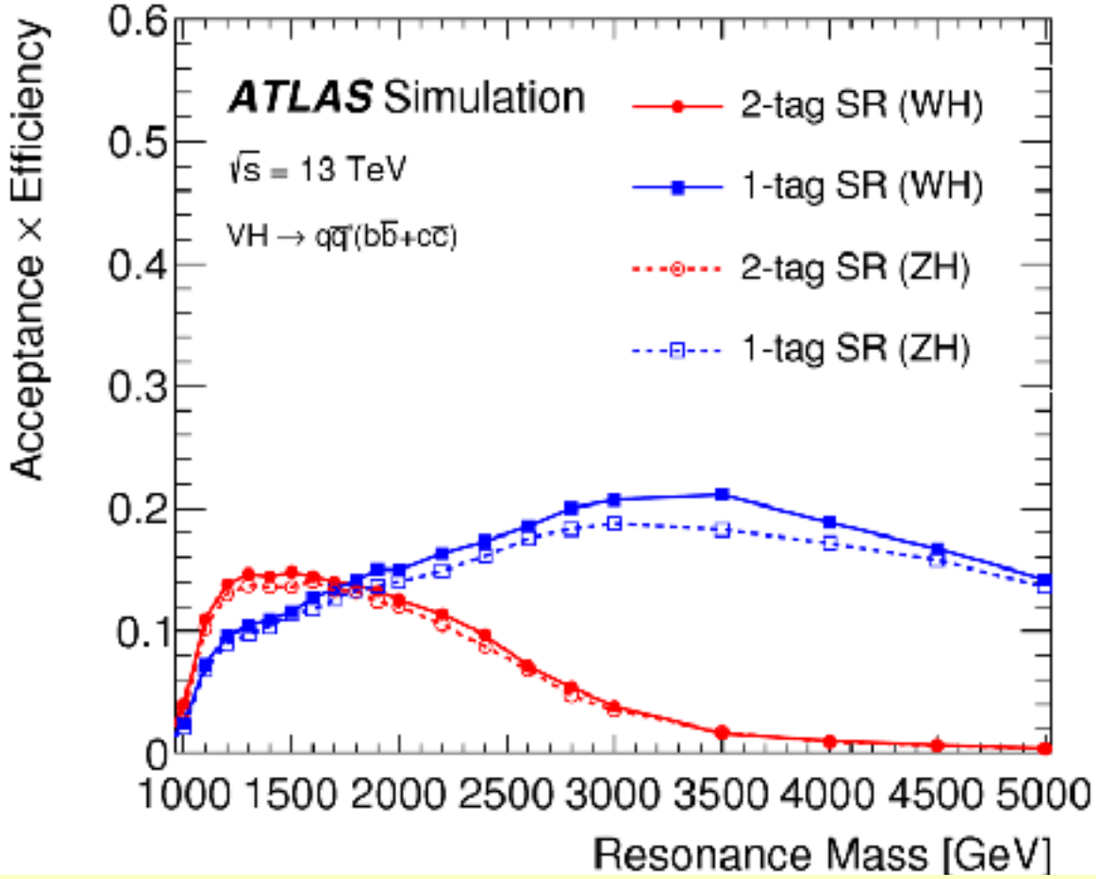
arXiv:1707.06958

ATLAS search of X→VV→JJ @ 13 TeV 79.8fb^{-1}



D_2 resolution for topo-cluster jets and jets built using combined and neutral Track CaloClusters.

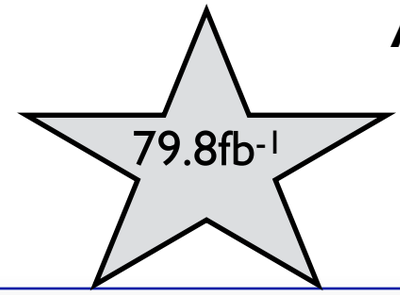
ATLAS search of X → VH → qqbb/qqcc



VH signal acceptance × efficiency including trigger, reconstruction and selection

VV fully hadronic: VV→JJ

ATLAS-CONF-2018-16

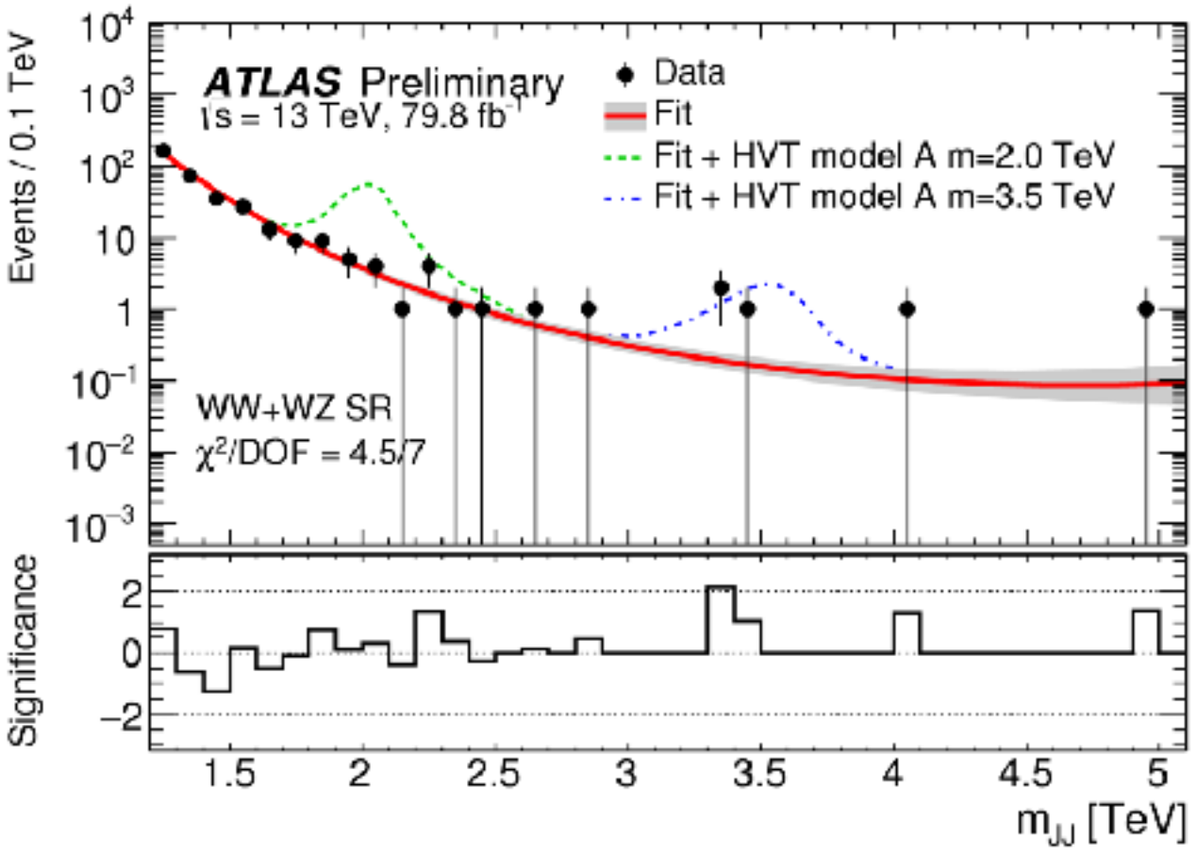


Selection:

- Highest BR ~ 50%
- Merged regime only: 2 large-R jets
- 5 non exclusive SR: WW, ZZ, WZ, WW+WZ,WW+ZZ

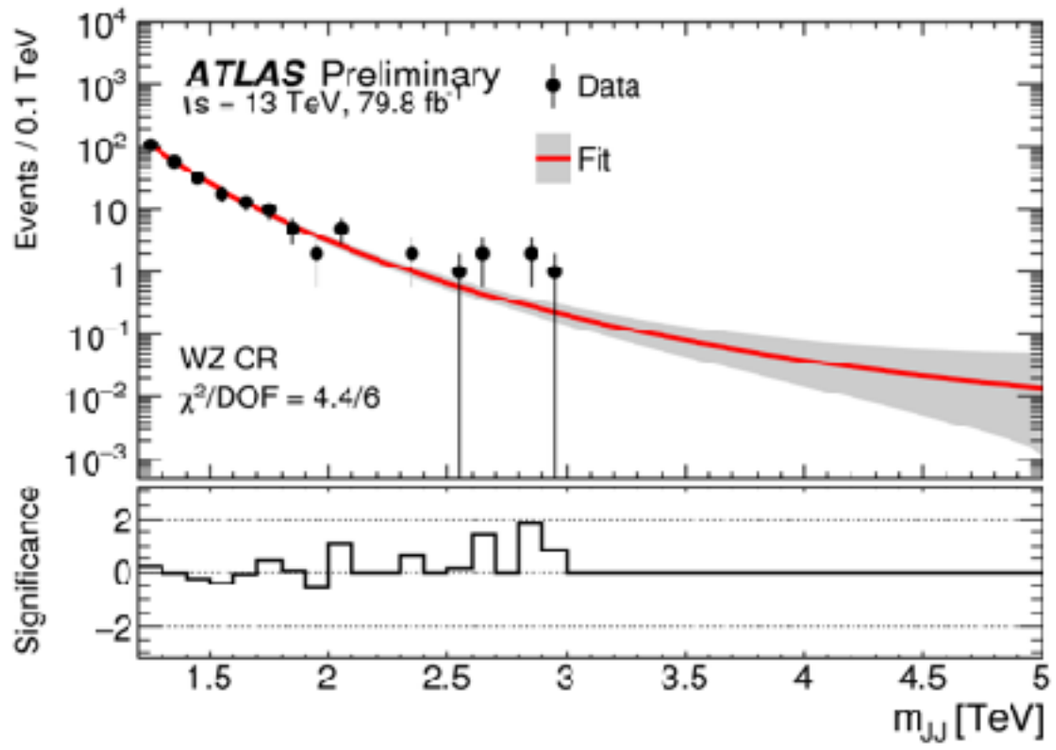
BG evaluation fully data-driven:

- Multi-jets QCD (~85%), diboson, V+j, ttbar.
- Binned ML fit to m_{JJ} spectrum assuming a smoothly falling distribution
- 3 VR inverting $|\Delta y_{JJ}|$ cut and V-tag of WZ SR



WW+WZ signal region

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



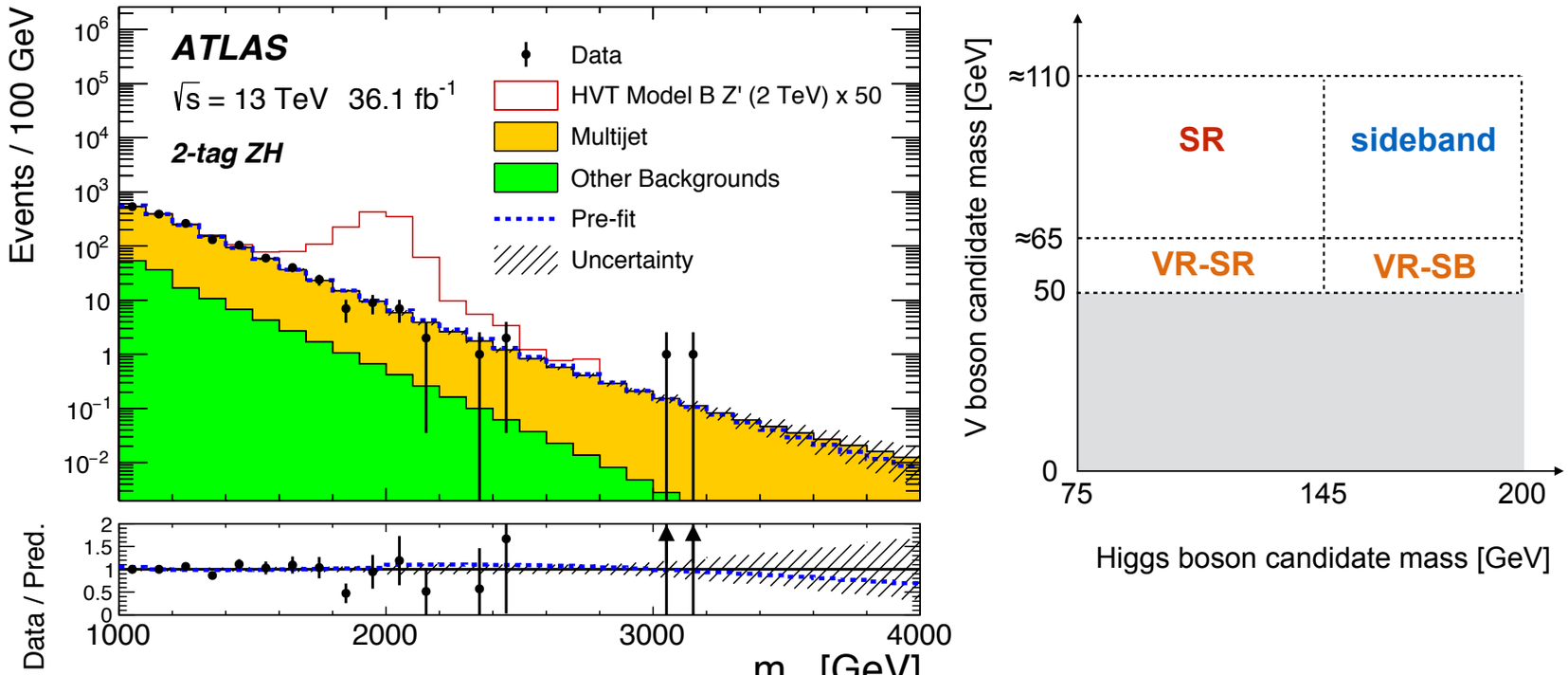
WZ validation region

VH fully hadronic: VH→JJ

arXiv:1707.06958

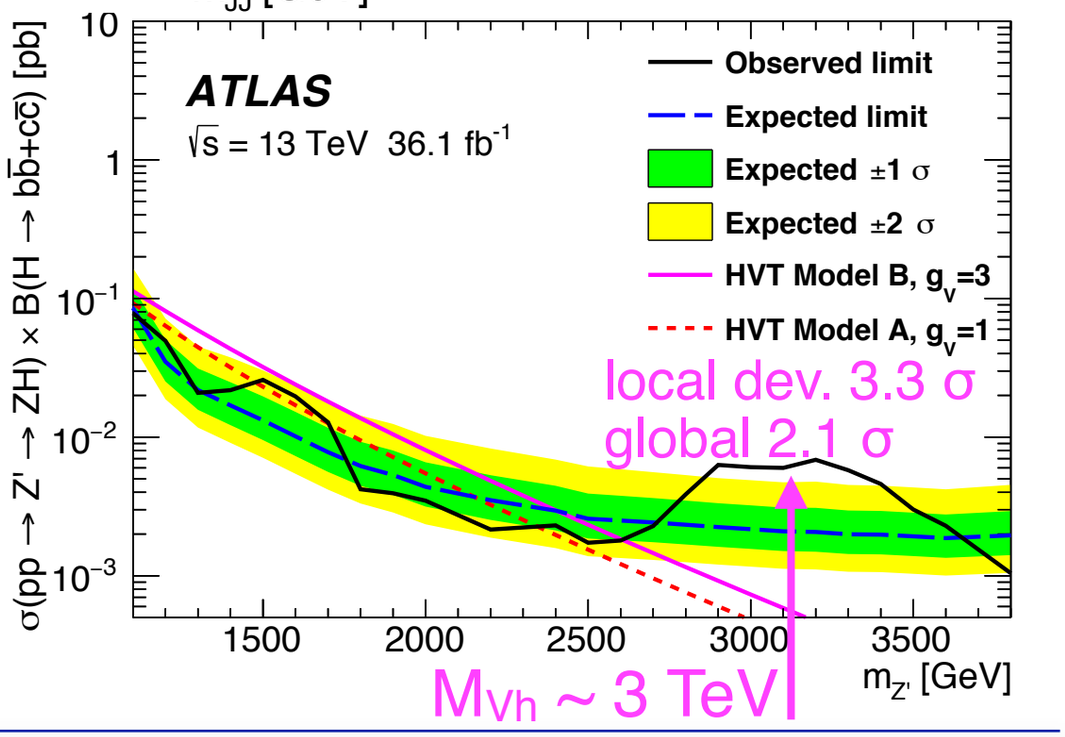
Selection:

- 2 large-R jets
- Higher mass jet is the H candidate and the other is W/Z tagged.
- WH/ZH overlap by ~60%.
- Signal regions with 1-2 b-tags.



BG estimation:

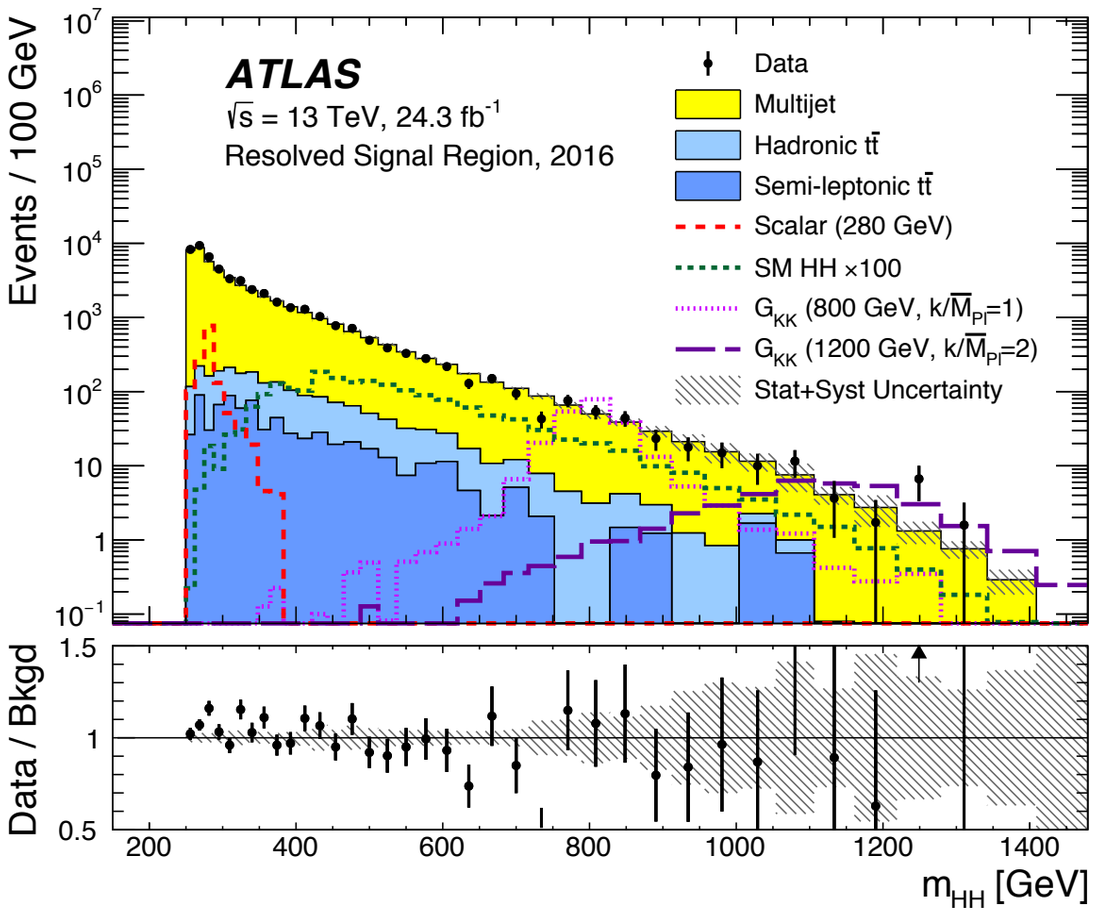
- Multi-jets QCD >90%.
- Data-driven estimation:
  - functional form from CR with 0-tags.
  - normalization and corrections from high SB mass of the Higgs.



HH fully hadronic: HH→bbbb, HH→JJ

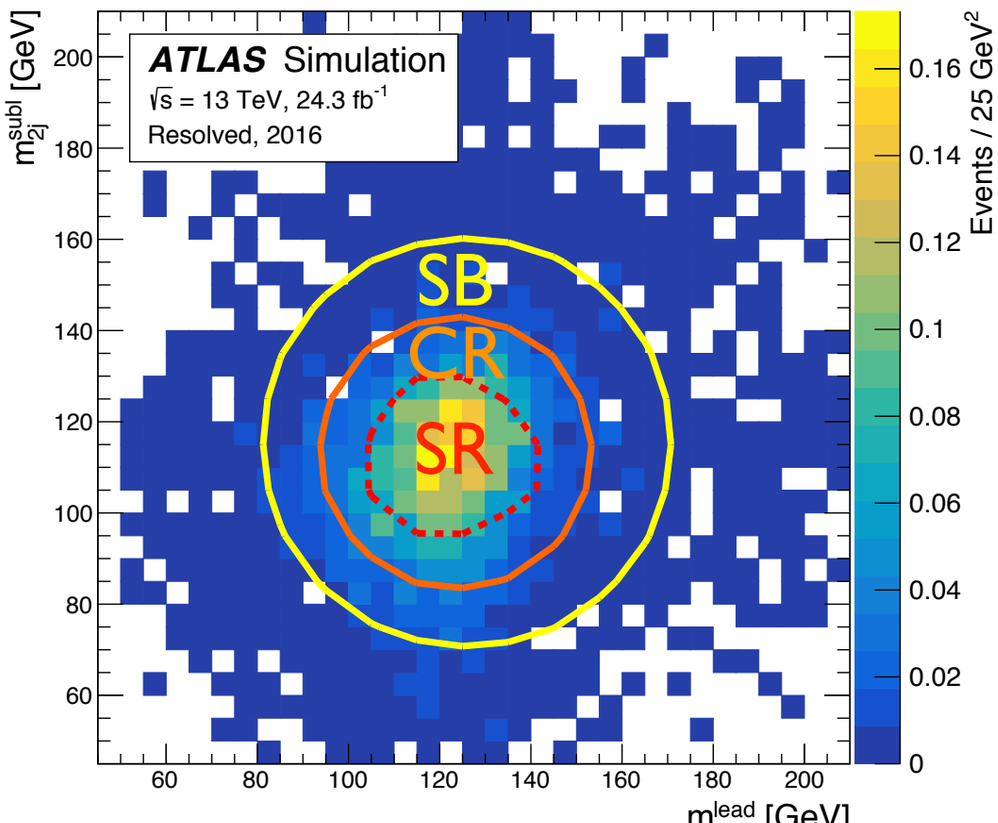
Boosted selection:
- 36.1 fb-1 from fat-jet trigger
- Categorise into 2,3,4 b-tagged track-jets

Resolved selection:
- 27.5 fb-1 from b-jet trigger
- Pair highest score b-jets based on ΔR_{jj} and Δm_{2j}



BG evalutation:
- Multi-jets QCD shape from lower b-tag data and ttbar shape from MC.
- Correct iteratively multi-jets QCD kinematics to higher b-tag data by reweights derived from SB data
- BG's normalisation from simultaneous fit to 3 BG enriched regions and Higgs SB

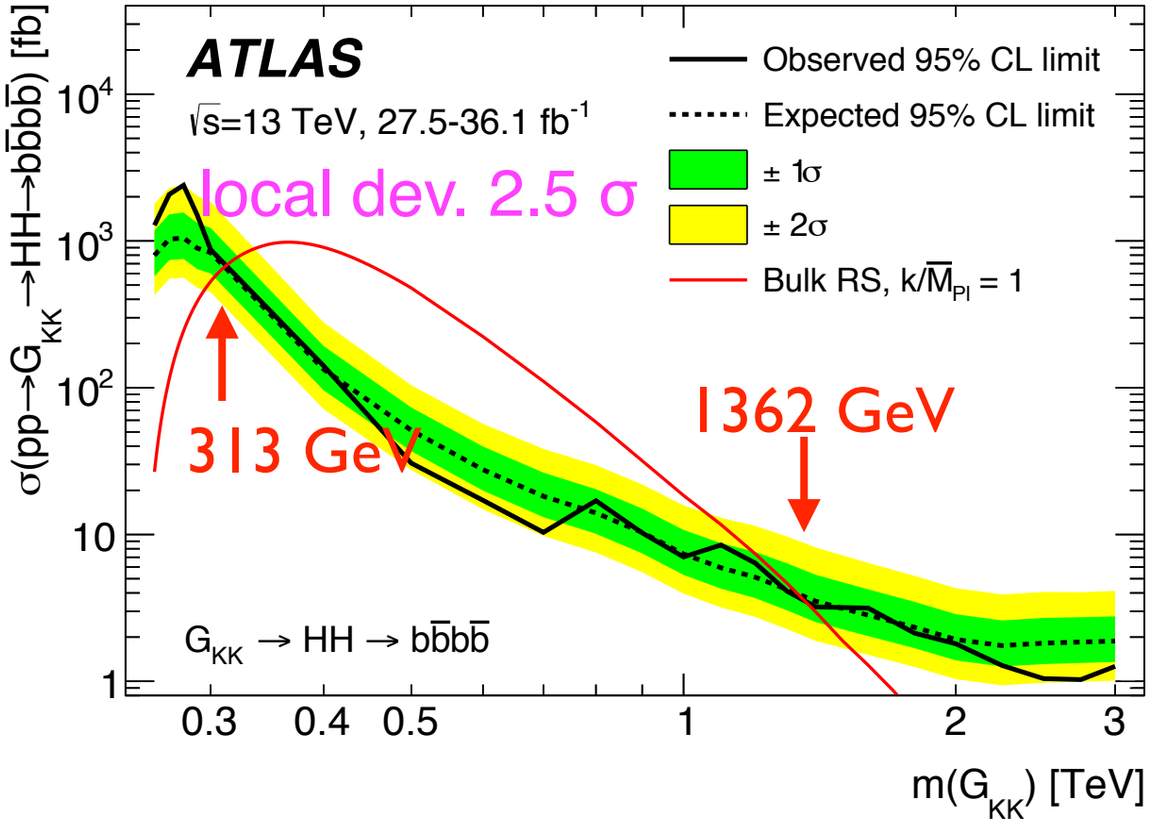
arXiv:1804.06174

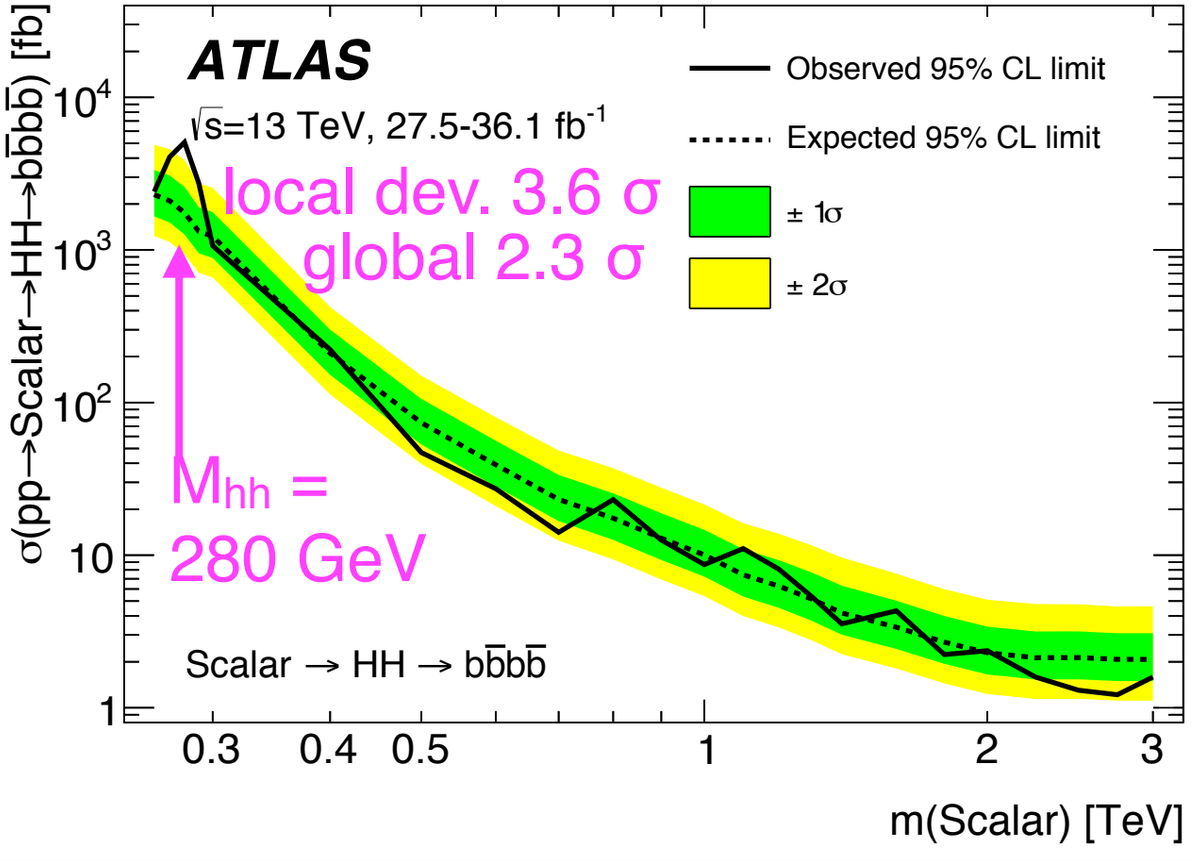


HH fully hadronic: HH→bbbb, HH→JJ

Results:

- Simultaneous fit to resolved and boosted discriminant M_{4j} and M_{2J}
- Limits on mass range: 260–1400 GeV for resolved and 800–3000 GeV for boosted
- Set limits on heavy scalar and spin-2 bulk RS graviton





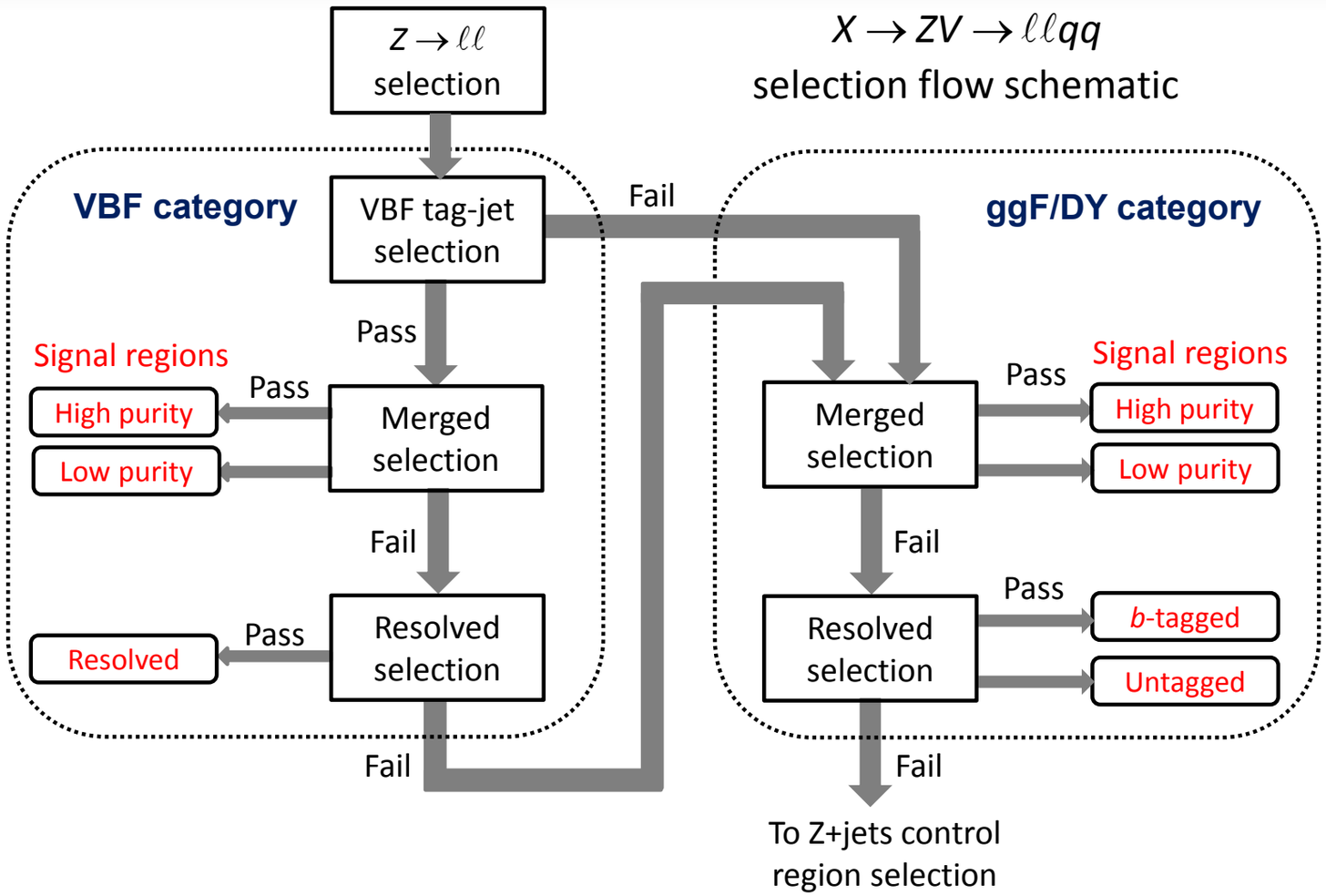
ZV→*llqq, νqq* semi-leptonic

arXiv:1708.09638

ZV→llqq selection:

7 signal regions to increase sensitivity:

- Merged: one large R jet W/Z tagged (dominant above 800 GeV)
  - splitted in High and Low Purity SR defined by <50% and 50-80% of W/Z tagger Work Point.
- Resolved: two small radius jets with invariant mass compatible to W/Z
  - ggF/DY splitted in untag and b-tag



ZV→νvqq selection:

similar to ZV→llqq but:

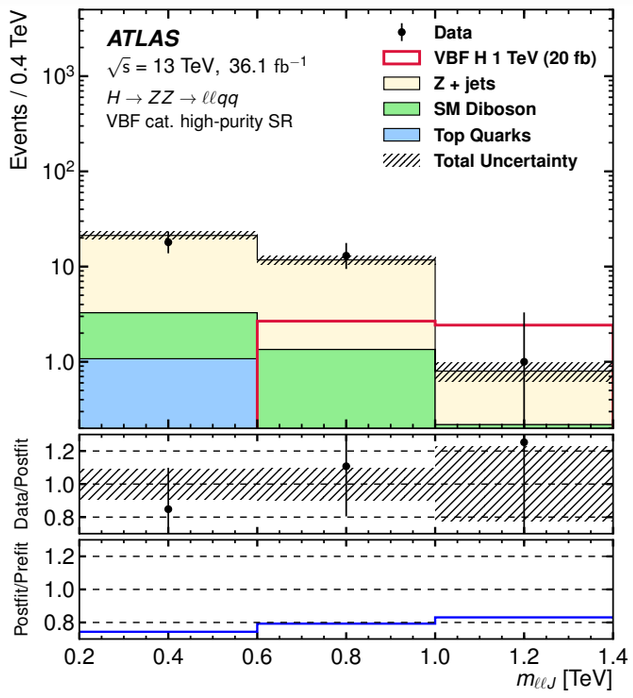
- Only Merged selection
- VBF looser cut $m_{j1j2} > 630$ GeV
- No leptons and $E_T^{miss} > 250$ GeV
- Topological cuts to suppress multi-jets

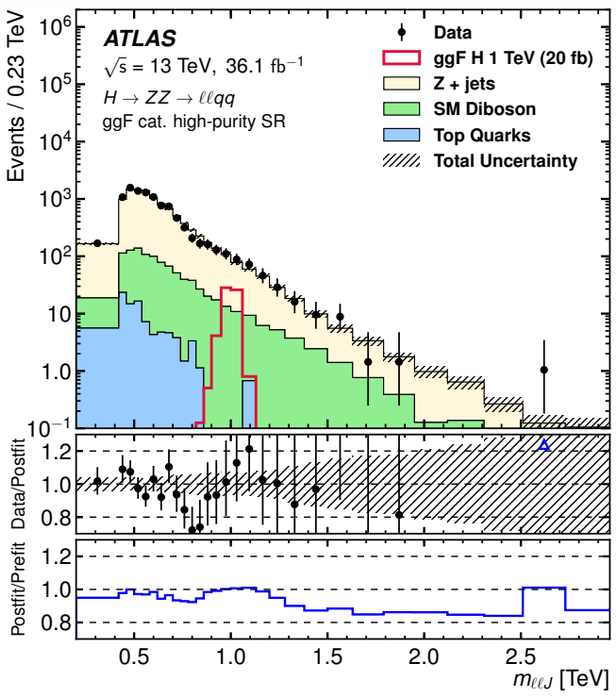
BG evaluation data-driven:

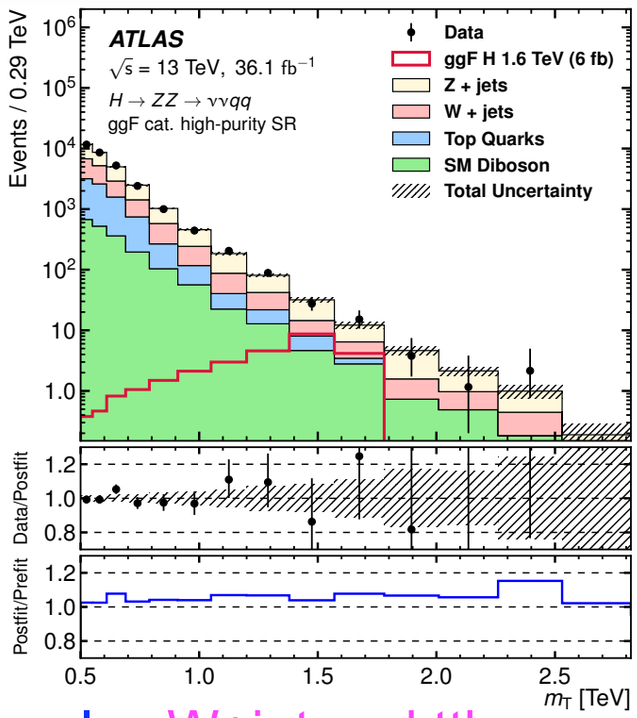
- 7 CR for Z+jets (from qq SB)
- 4 CR for W+jets (from qq SB)
- 5 CR for ttbar (from eu selection)

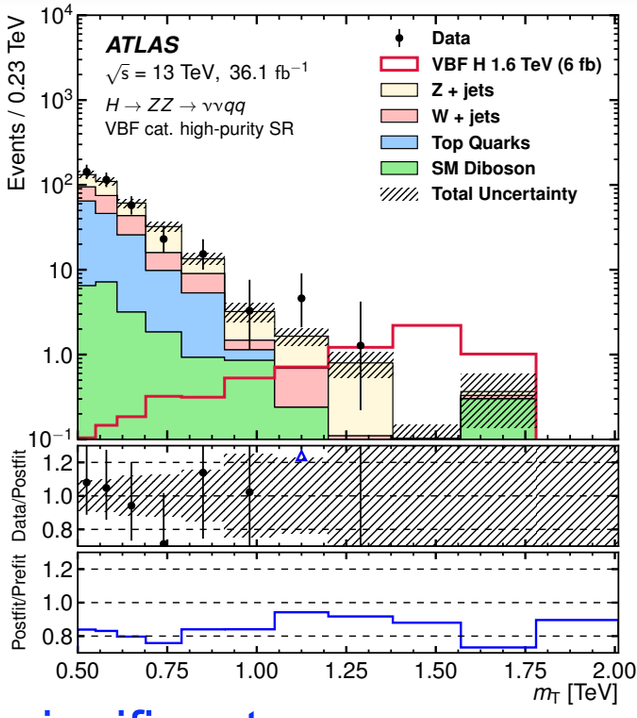
ZV→*llqq, νqq* semi-leptonic

VBF merged llqq | ggF/DY merged llqq | VBF merged νqq | ggF/DY merged νqq

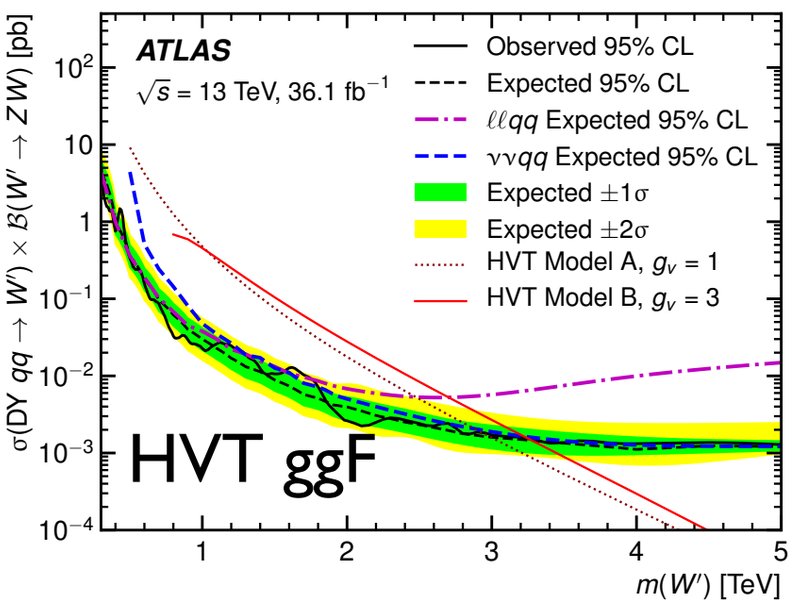


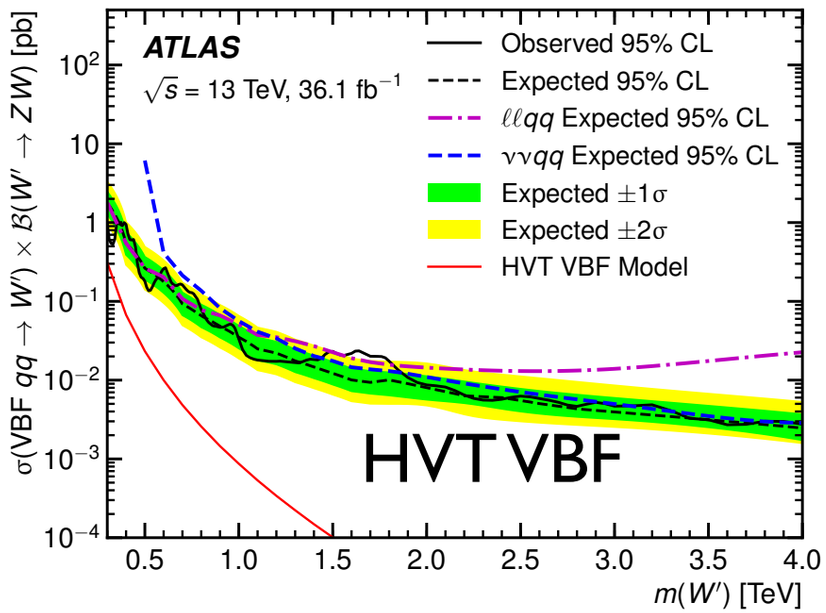






- Dominant BG is Z+jet for both but for llνν also W+jet and ttbar are significant
- V+jets and ttbar normalization from CR, di-boson from MC





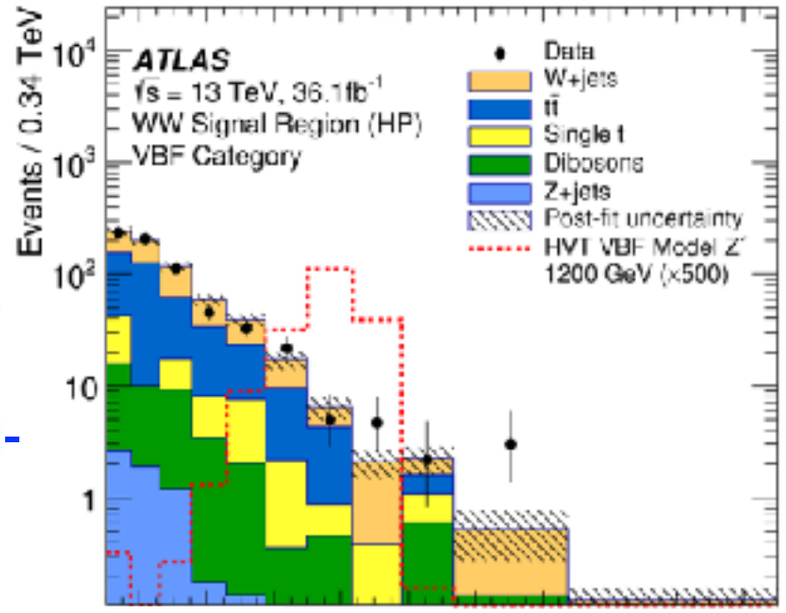
VBF xsec smaller than ggF
Sensitivity often larger for VBF than ggF

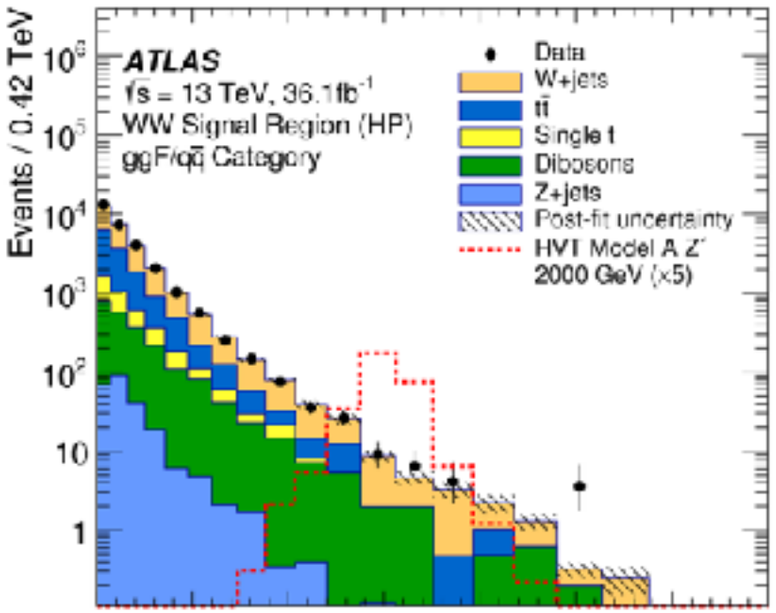
WV→*lνqq* semi-leptonic

arXiv:1710.07235

Selection:

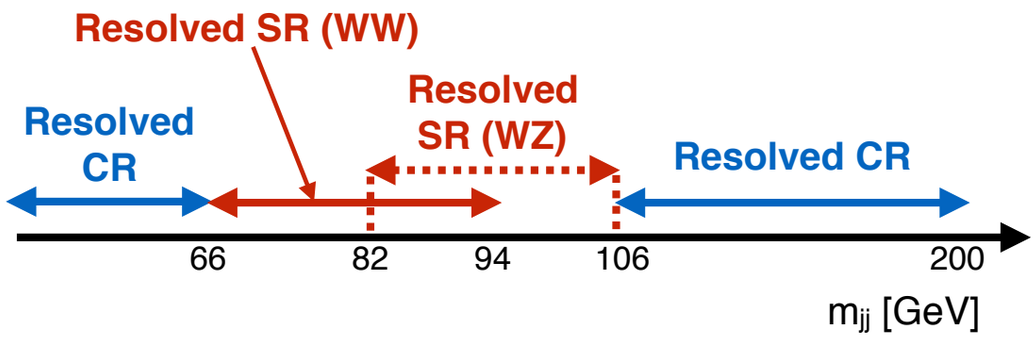
- VBF and ggF/DY categorization
- Merged and Resolved selections
- 1 lepton+ E_T^{miss}
- $E_T^{miss}/p_T(l\nu) > 0.2$ suppress Multi-jets QCD Background



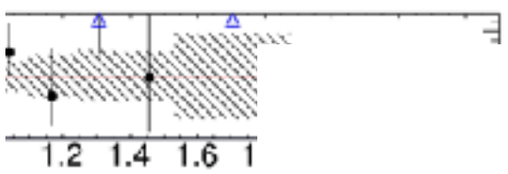


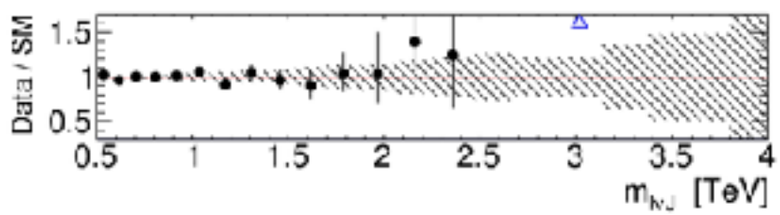
BG evaluation:

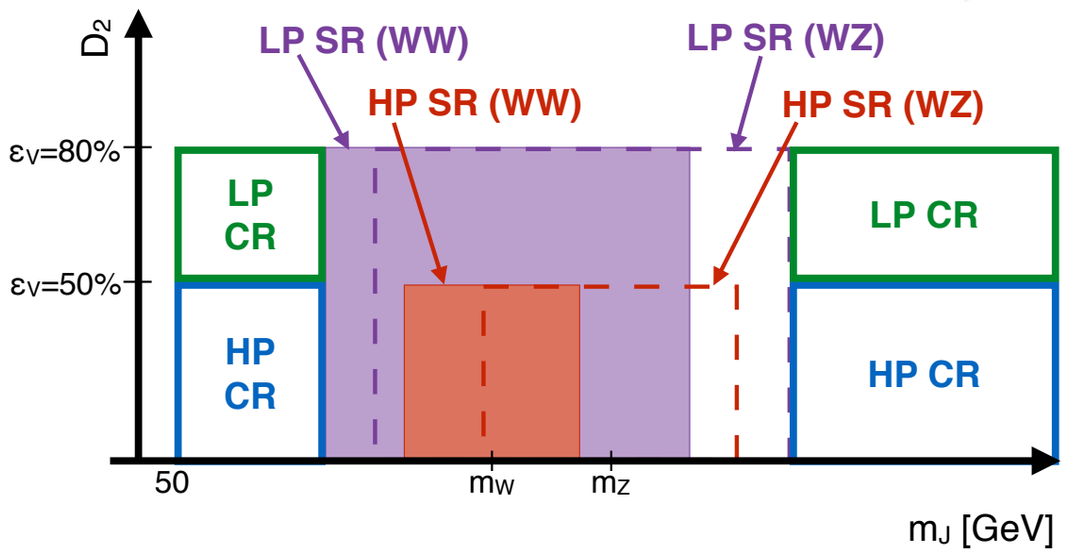
- 50-70% W+jets, 20-30% ttbar
- 5% Z+jets+di-boson+single t
- Multi-jets <1% for Merged and 5% for Resolved



RESOLVED CR and SR







MERGED CR and SR

$VH \to \ell\ell bb/\ell\nu bb/\nu\nu bb$ semi-leptonic

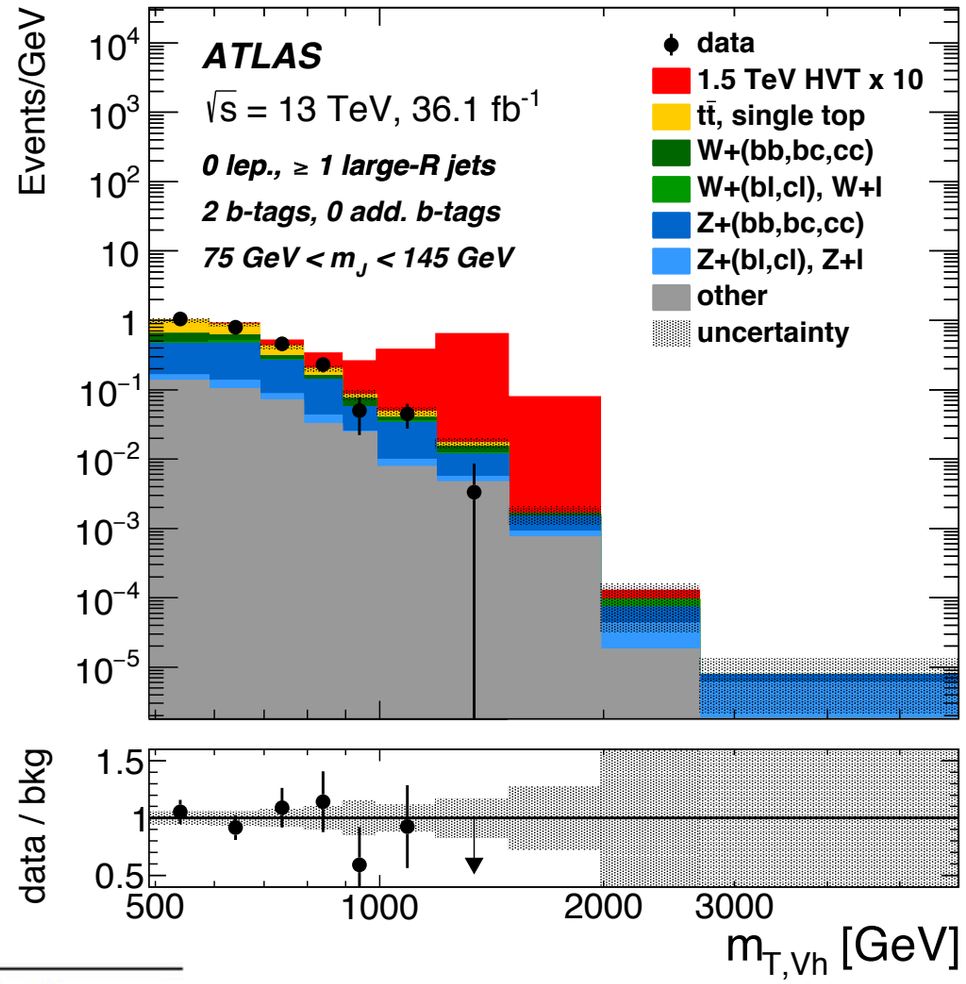
arXiv:1712.06518

Selection:

- Resolved and Merged selections for H→bb with priority to resolved for better invariant mass resolution and less BG
- Signal discriminant:
  - 0-lepton is ZH transverse mass
  - 1-lepton WH mass with two-fold ambiguity
  - 2-leptons ZH invariant mass.
- Many cuts to remove Multi-jets QCD and non-collision BG to 10^{-4} negligible level.

BG evaluation:

- 0(2)-lepton: Z+jets, tt, W+jets
- 1-lepton: tt, single t, W+jets



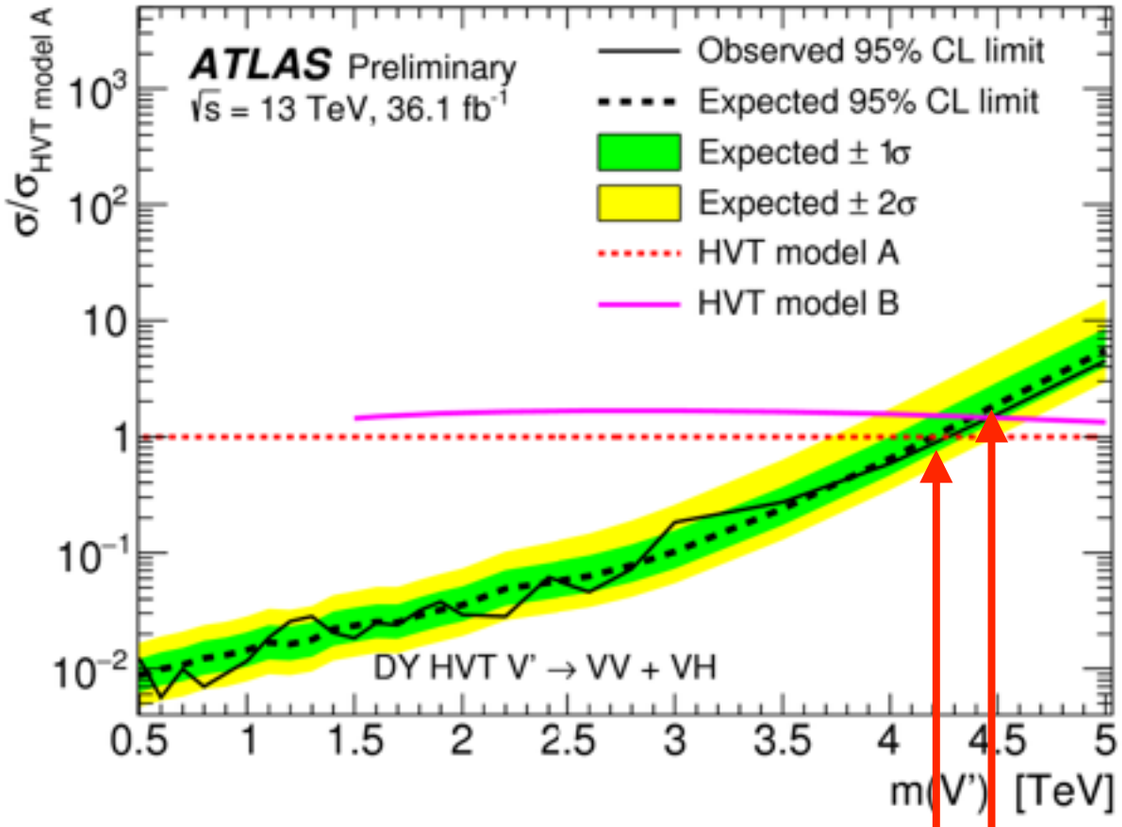
Fit		Channel	Resolved signal regions	Merged signal regions	Resolved control regions
A		0-lepton	1, 2, 3+ b-tag	1, 2 b-tag, and 1, 2 b-tag add. b-tag	–
		2-lepton	1, 2, 3+ b-tag	1, 2 b-tag, and 1+2 b-tag add. b-tag	1+2 b-tag , 3+ b-tag $e\mu$
HVT	Z', W'	0-lepton	1, 2 b-tag	1, 2 b-tag	–
	W'	1-lepton	1, 2 b-tag	1, 2 b-tag	1, 2 b-tag m_{jj} sideband
	Z'	2-lepton	1, 2 b-tag	1, 2 b-tag	1+2 b-tag $e\mu$

- CP-odd scalar boson A →ZHbb

Definition of SR and CR different for V decay mode and model hypotesis

Combination at 36.1fb^{-1}

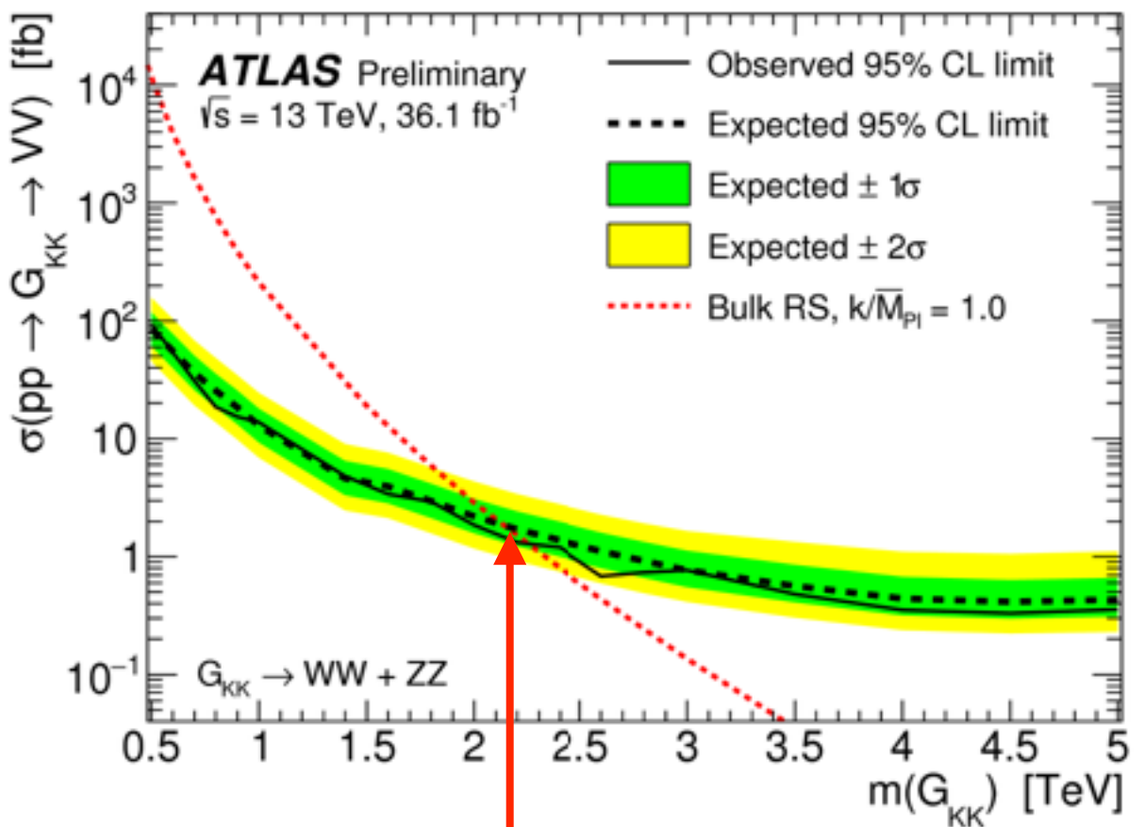
HVT V' → VV+VH



HVT A 4.2 TeV

HVT B 4.5 TeV

G_{KK} → WW+ZZ



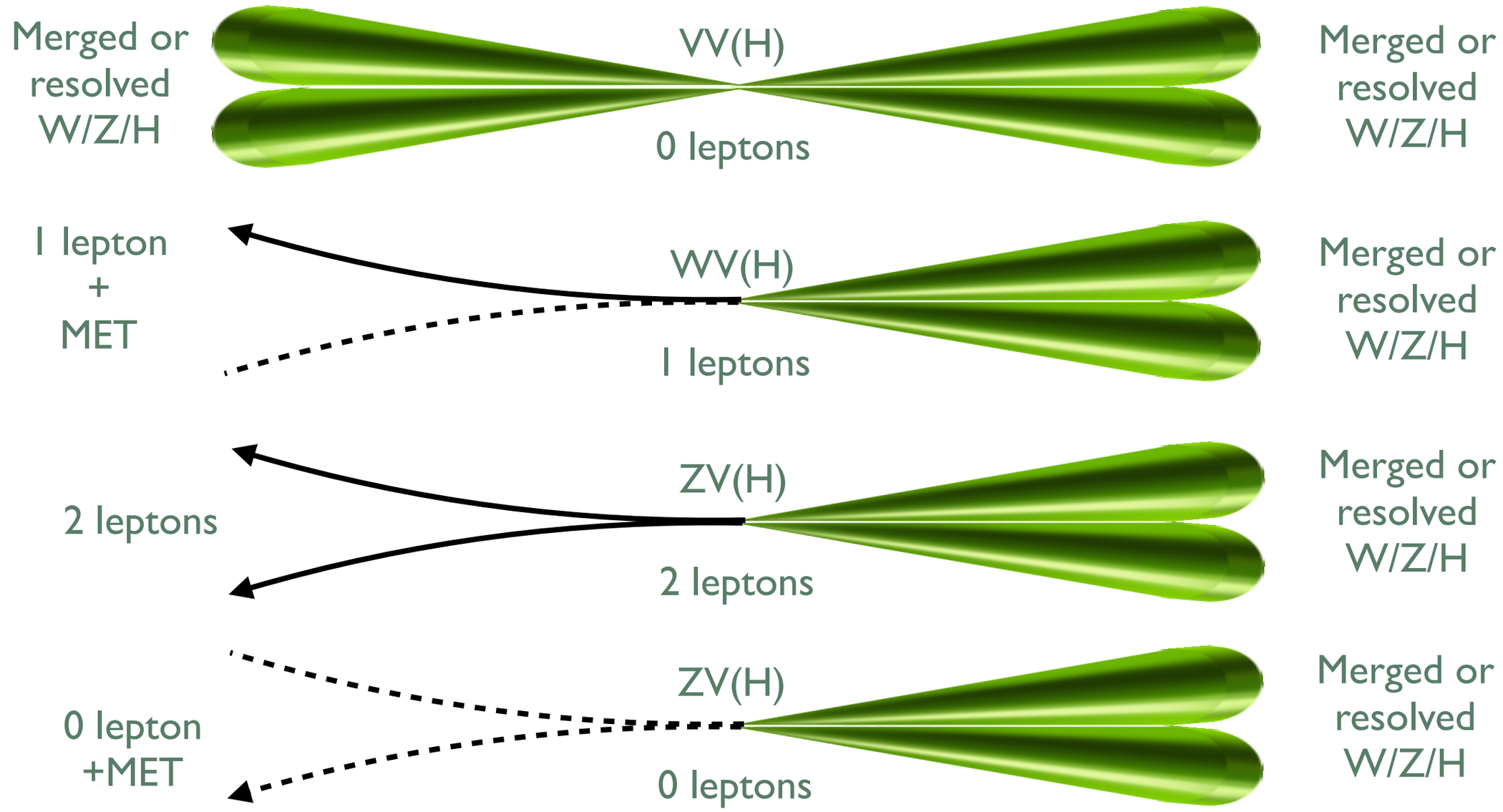
2.2 TeV

Conclusions

- Di-boson resonances searches at TeV scale are strongly motivated by naturalness principle
- Improving reconstruction and advanced analyses techniques we can get the most out of the data:
  - Boosted object tagging
  - New techniques in jet reconstruction and b-tagging
  - Machine learning methods applied to object definition and analysis selection
  - Statistical combinations of different decay modes
- With 2018 data an integrated luminosity of 140 fb^{-1} is expected

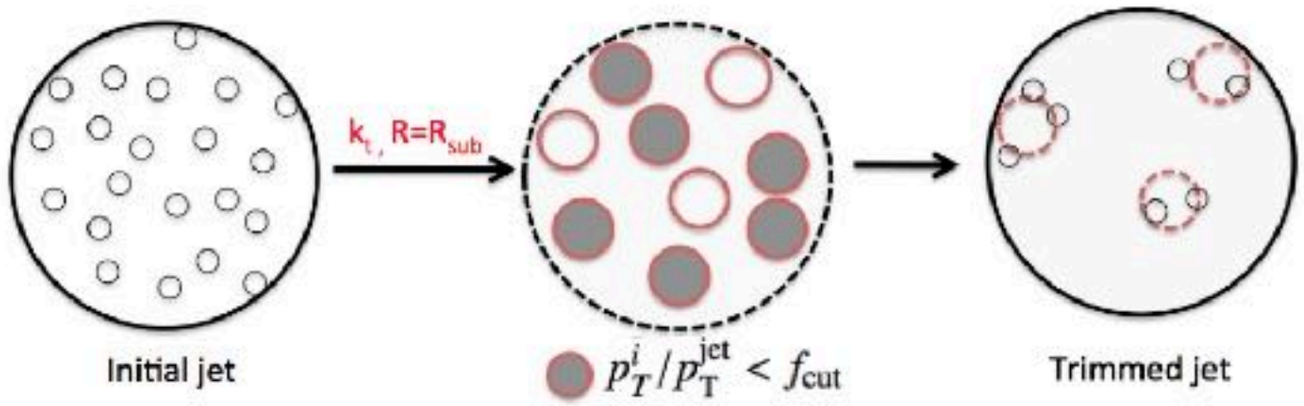
A bright future in front of us with full run II, run III and HL-LHC

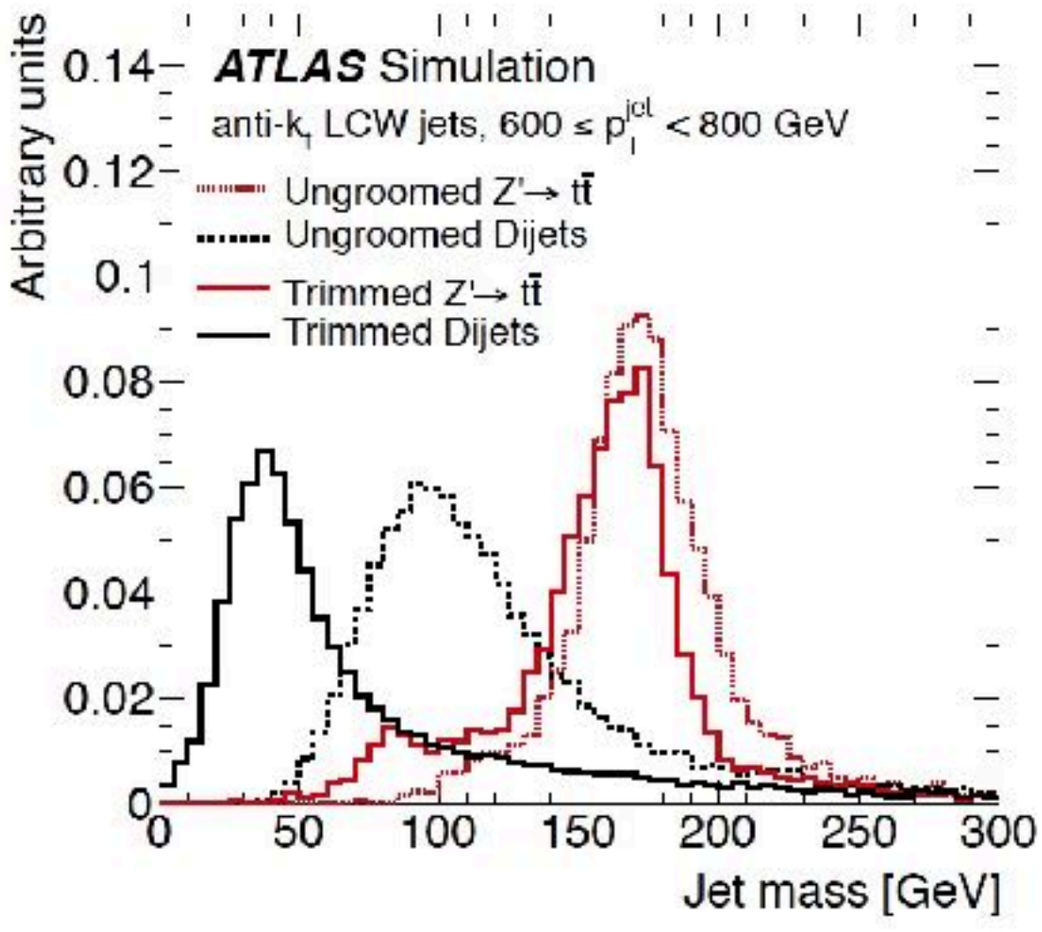
Event topology



Jet trimming

Jet trimming





JHEP 1309 (2013) 076

Jet substructure

Jet substructure

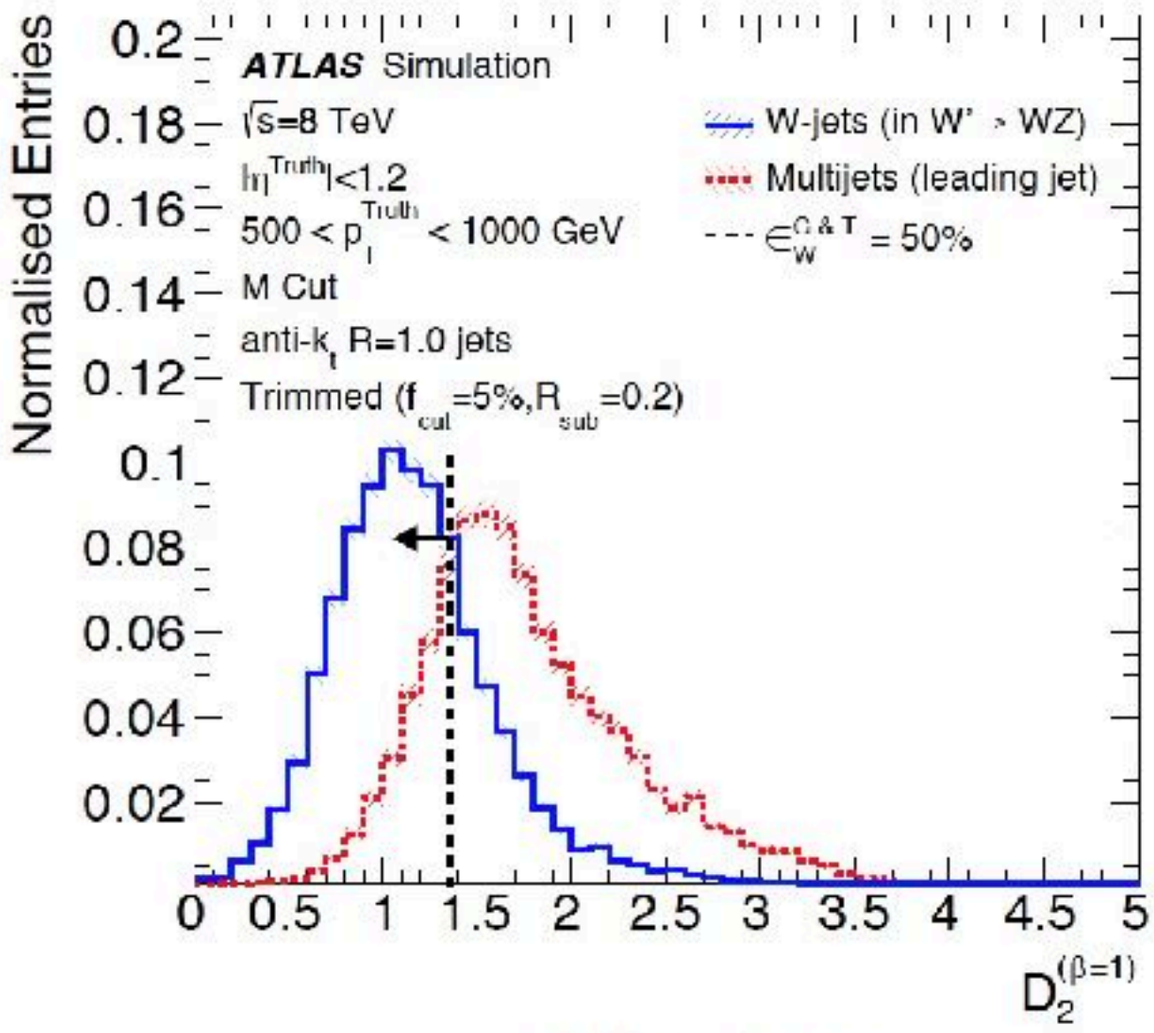
- The $D_2^{\beta=1}$ variable is useful in identifying jets with two-prong substructures.
- Defined from n-point energy correlation functions:

$$E_{CF1}(\beta) = \sum_{i \in J} p_{T_i},$$

$$E_{CF2}(\beta) = \sum_{i<j \in J} p_{T_i} p_{T_j} \left(\Delta R_{ij}\right)^{\beta},$$

$$E_{CF3}(\beta) = \sum_{i<j<k \in J} p_{T_i} p_{T_j} p_{T_k} \left(\Delta R_{ij} \Delta R_{ik} \Delta R_{jk}\right)^{\beta}$$

$$D_2^{\beta=1} = E_{CF3} \left(\frac{E_{CF1}}{E_{CF2}}\right)^3$$



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Combined jet mass

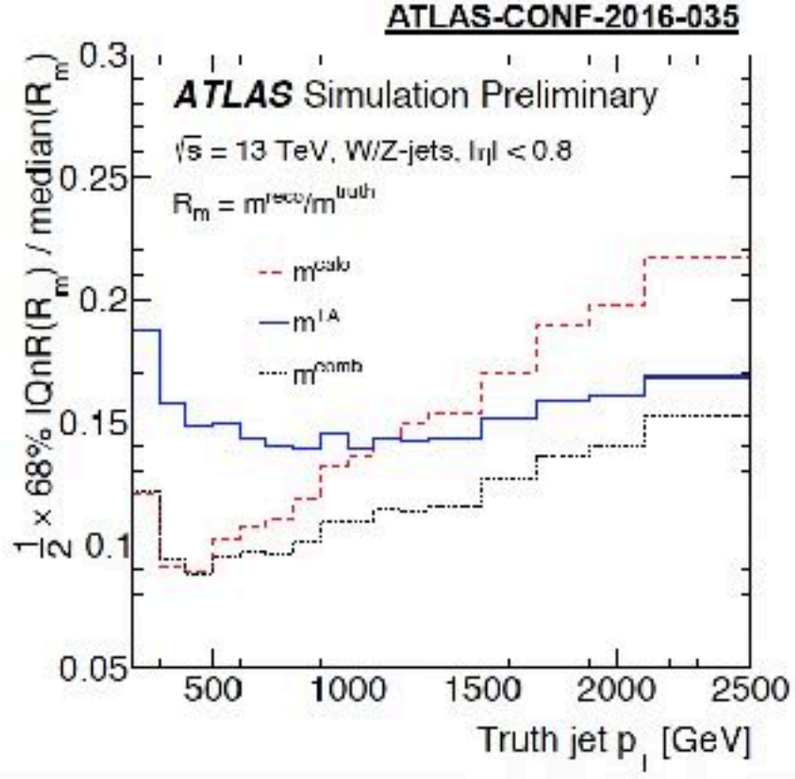
- The jet mass resolution is further improved by combining calorimeter and tracking information:

$$m_J \equiv w_{\text{calo}} \times m_J^{\text{calo}} + w_{\text{track}} \times \left(m_J^{\text{track}} \frac{p_{\text{T}}^{\text{calo}}}{p_{\text{T}}^{\text{track}}} \right)$$

- w_{calo} and w_{track} are inversely proportional to the square of the resolution of each mass term and are optimized to minimize the combined jet mass resolution.

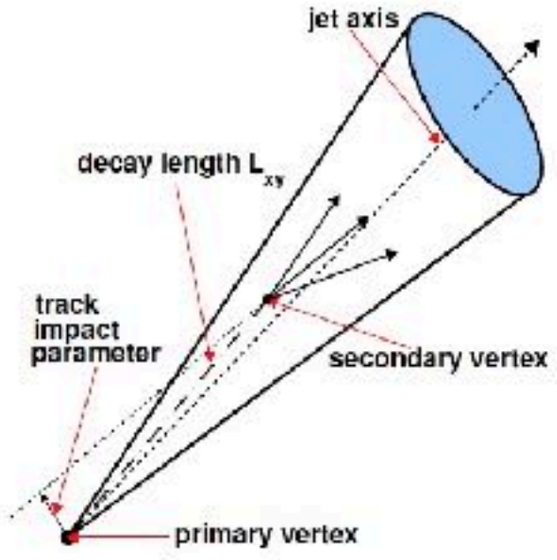
- Resolution is improved especially at high jet p_T, due to the coarser angular resolution of the calorimeter.

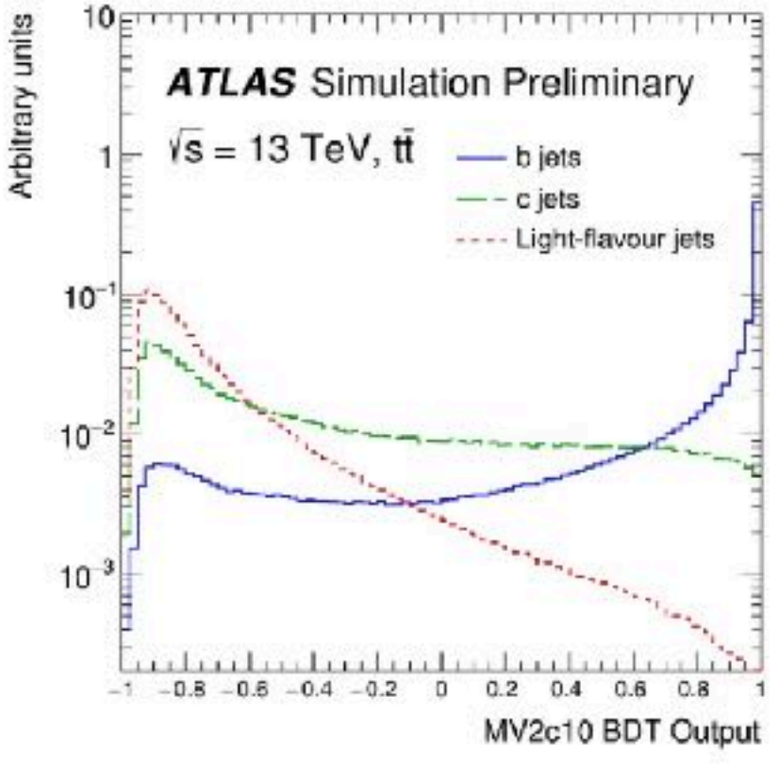
- For Higgs boson reconstruction in the bb decay channel, the mass resolution can also be improved by correcting for semi-leptonic decays of the b-hadrons.



b-tagging

- Crucial for reconstructing Higgs to bb-bar decays but also for rejecting top backgrounds.
- A b-hadron decay in the detector provides a measurable displaced secondary vertex.
- A multivariate tagging algorithm combines information from vertexing and impact parameter tagging algorithms to a set of tracks associated to a jet/track-jet, in order to identify jets containing b-hadrons.





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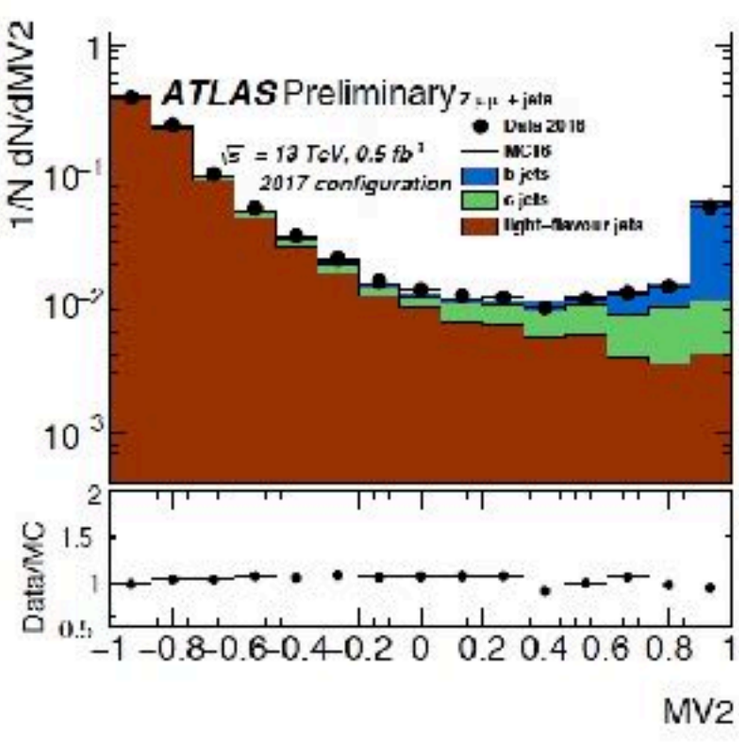

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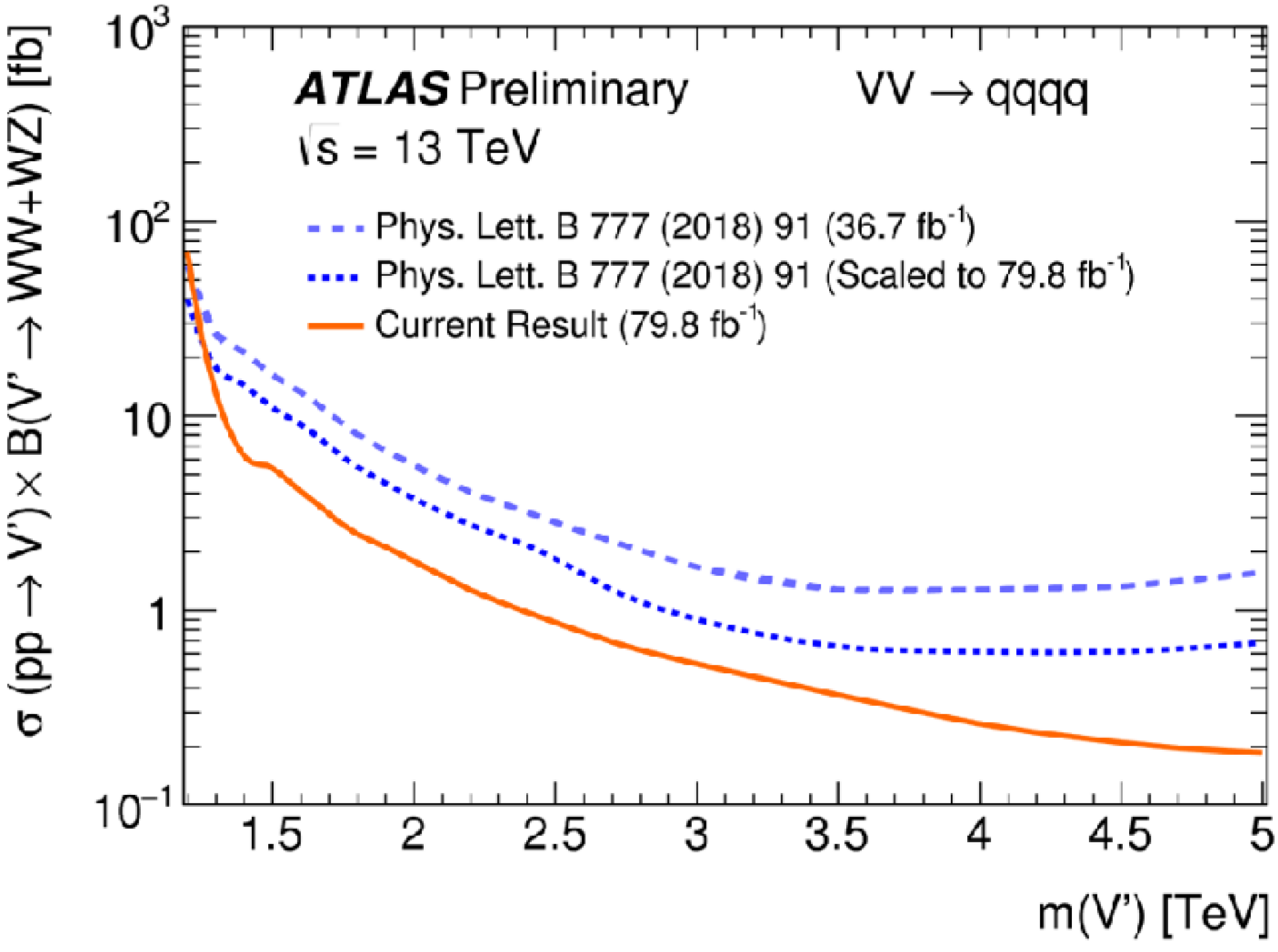
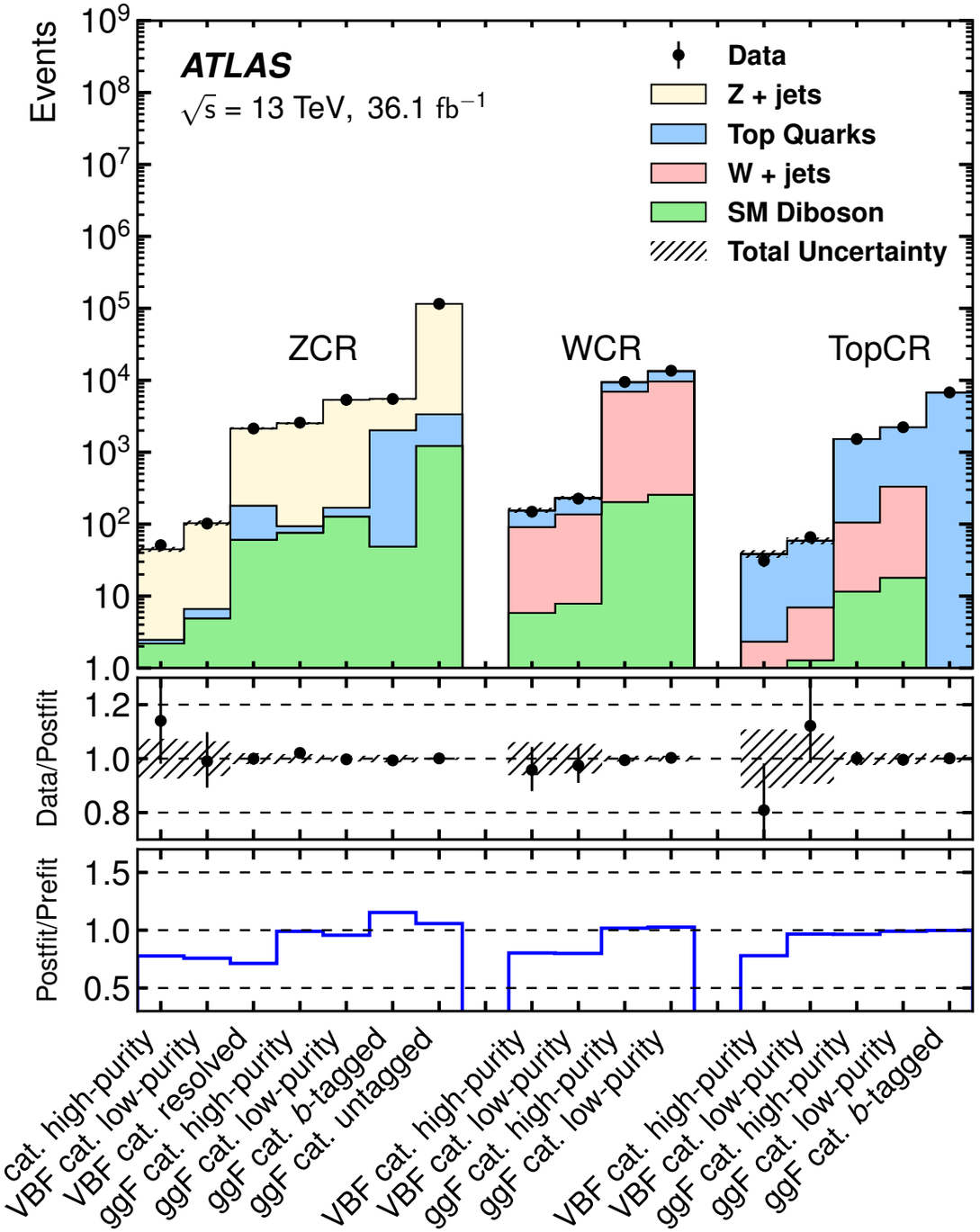
VV fully hadronic: VV→JJ

ATLAS-CONF-2018-16



ZV→*llqq, νqq* semi-leptonic

arXiv:1708.09638



from qq SideBand from eu selection