Diboson searches and VBS studies in ATLAS

Francesco Cirotto
Università degli studi Napoli Federico II and INFN sezione di Napoli

on behalf of the ATLAS Collaboration

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Why study diboson processes

- Why study di-boson processes at the LHC?
  - Stringent test of the standard model non-abelian character of the SU(2)L x U(1) gauge group at TeV scale

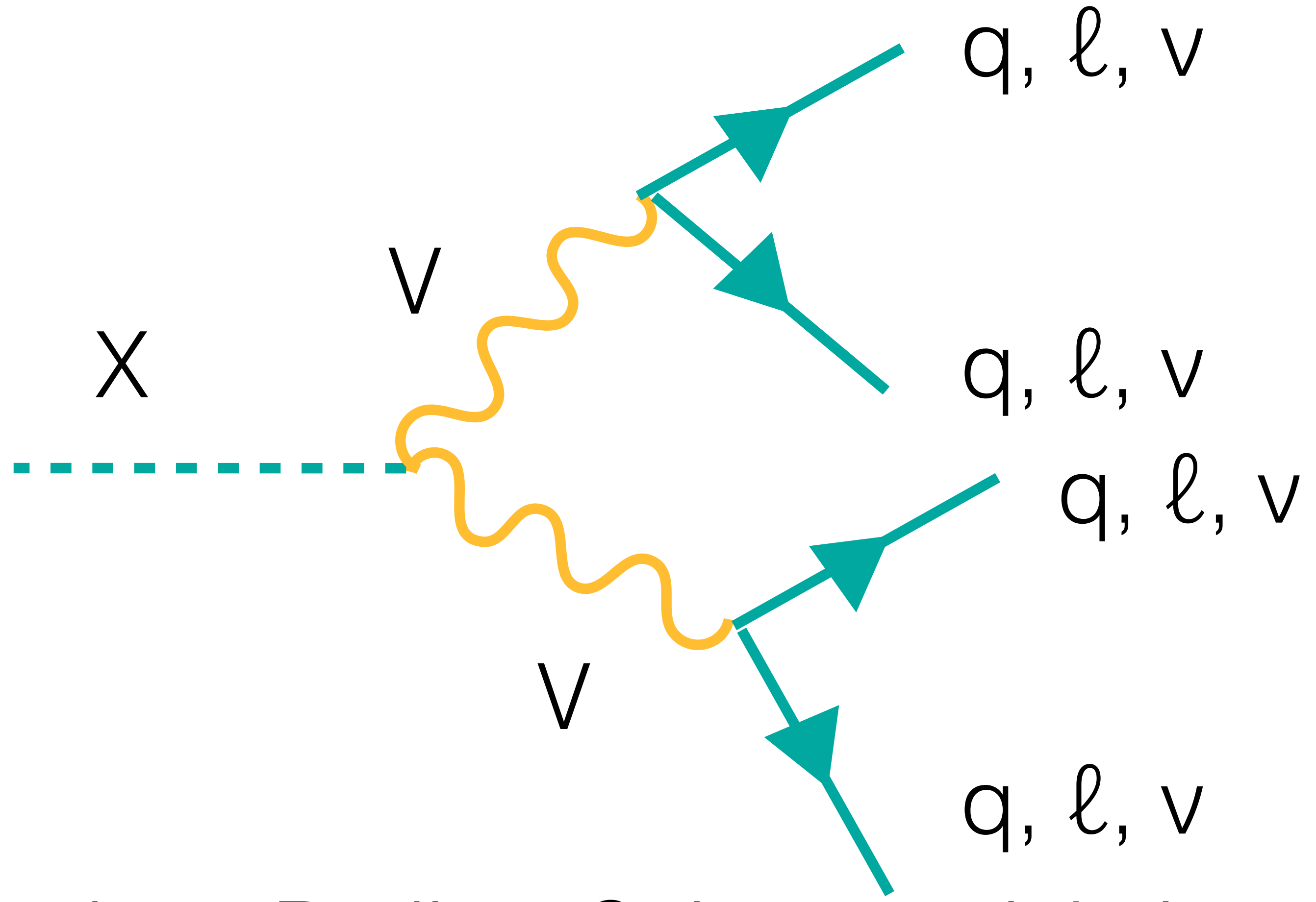
- Precision test of:
  - sensitive to higher order QCD / EW corrections at TeV scale
  - New physics

- Model-independent means to search for new physics at the TeV scale.
  - Allow for the possibility of new physics with mass scales very close to the Electroweak Scale
  - Growing interest in indirect searches at LHC

- Precise measurements help to constrain Standard Model contribution (background) in searches of many new physics models and Higgs analysis.

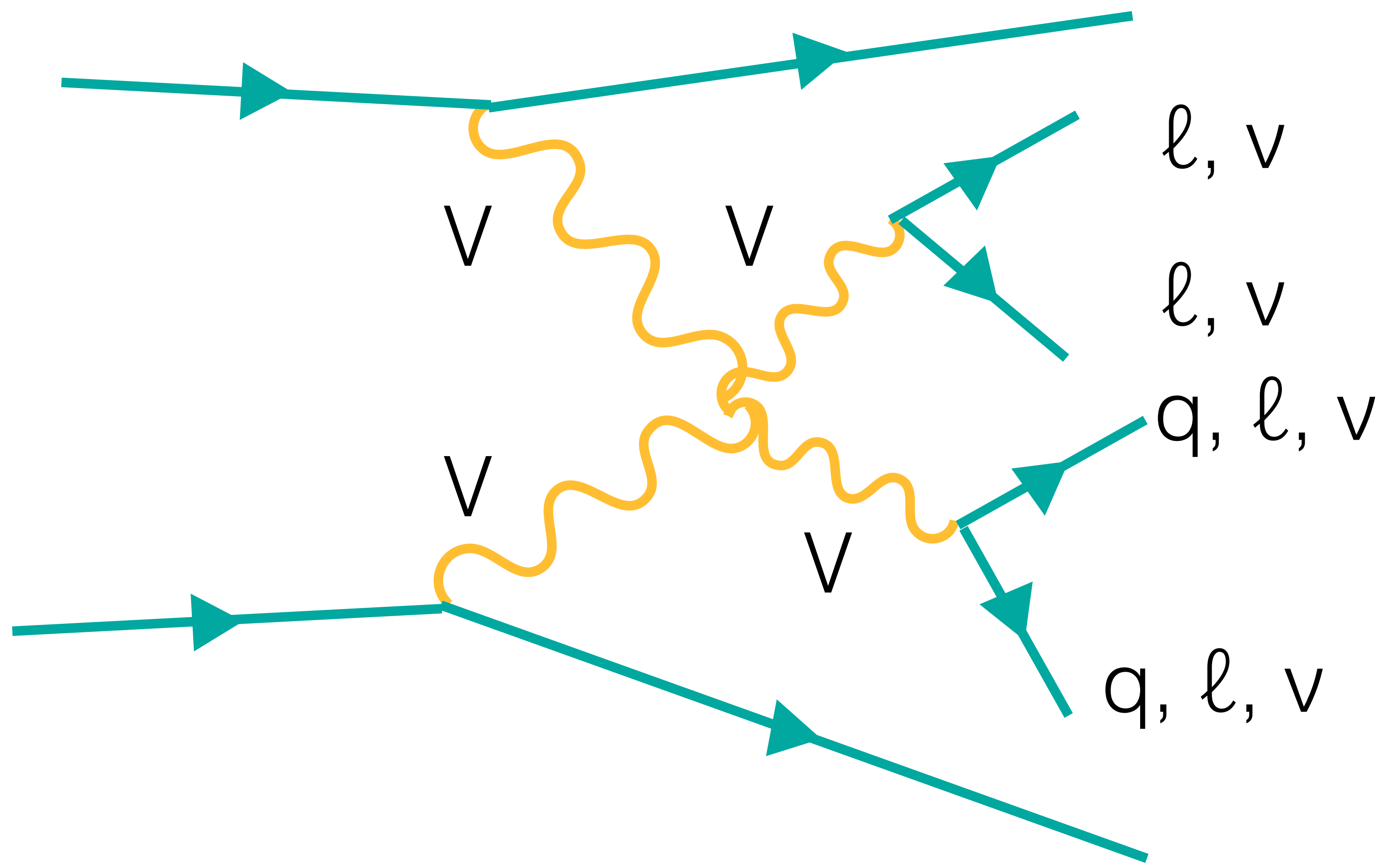
Searches covered in this talk

Exotic diboson searches



- Randall-Sundrum Radion: Spin-0 particle in models with warped extra dimension
- Extended Higgs sector (2HDM): 5 Higgs bosons H, h, $H^{\pm}$, A. (spin0)
- Spin-1 Heavy Vector Triplet
  - ↪2 charge W' boson,1 neural Z' boson
  - ↪Model A (g_V=1), Model B (gv=3)
- Bulk Randall-Sundrum Graviton: Spin-2 particle, excitement of Kaluza-Klein graviton, in models with warped extra dimension.

Vector boson scattering searches



- Rare process in SM
- Indirect search of new Physics by studying anomalous couplings

Analysis strategy

① Definition of a set of **signal region**(s) **(SR)**

  ↪ Find the best cuts to optimize signal over background

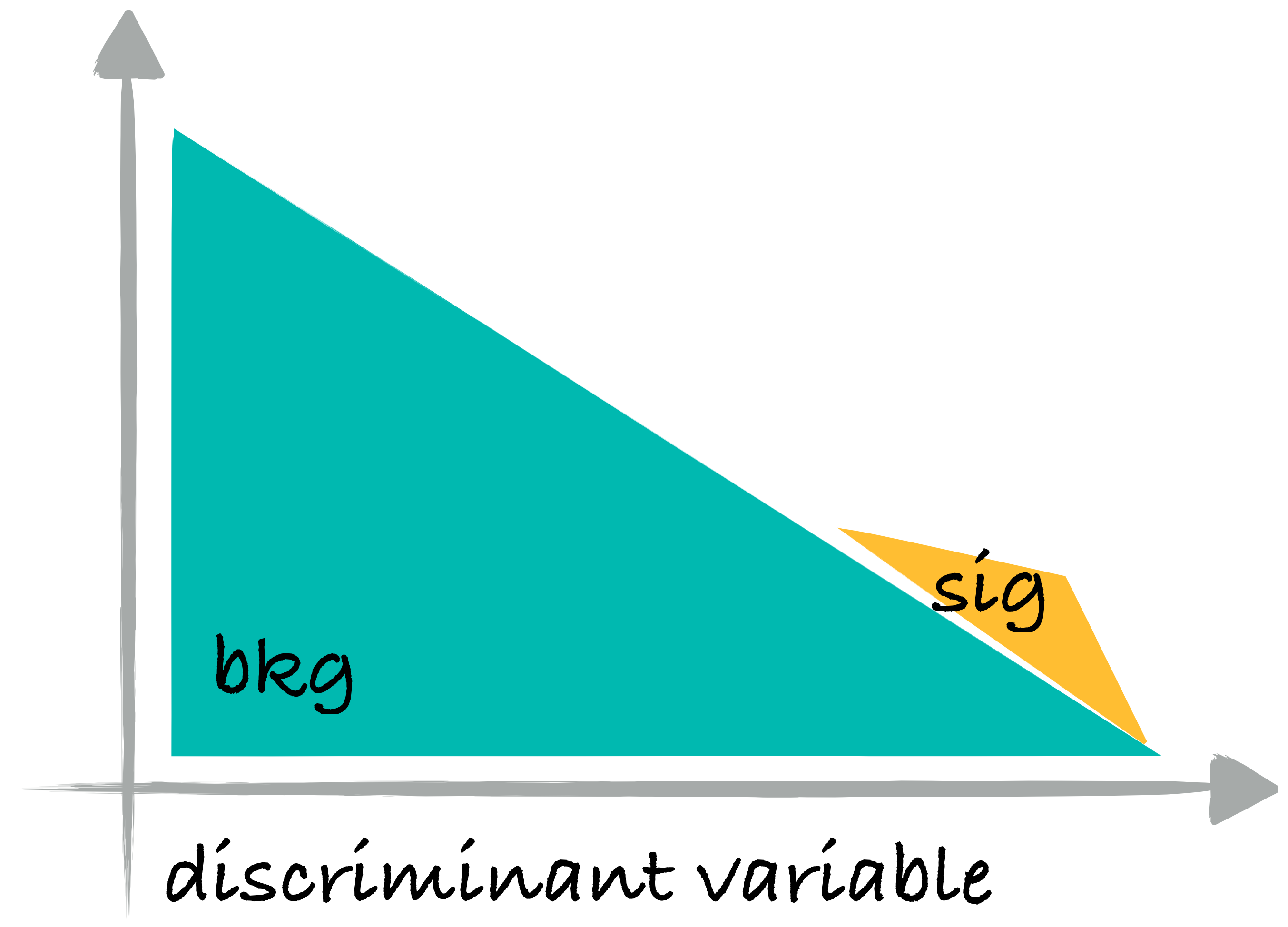
② Definition of a set of **control regions (CR)** to estimate backgrounds

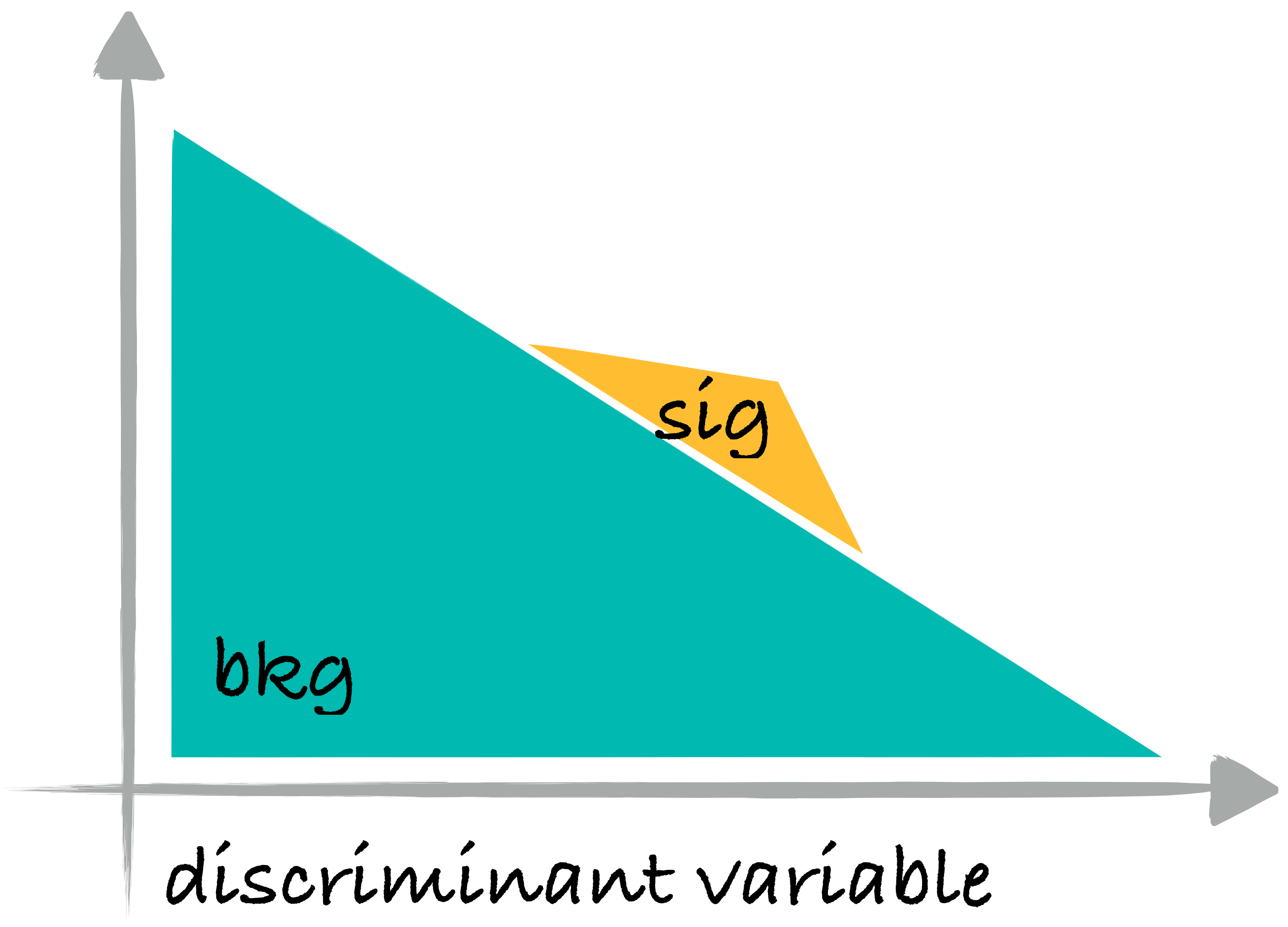
  ↪ Define a region with a high purity of a specific background

  ↪ Estimate background with data-driven techniques

③ Unblinding ➜ Is there an excess?

④ Results are interpreted in terms of limits on models under study





Analysis strategy

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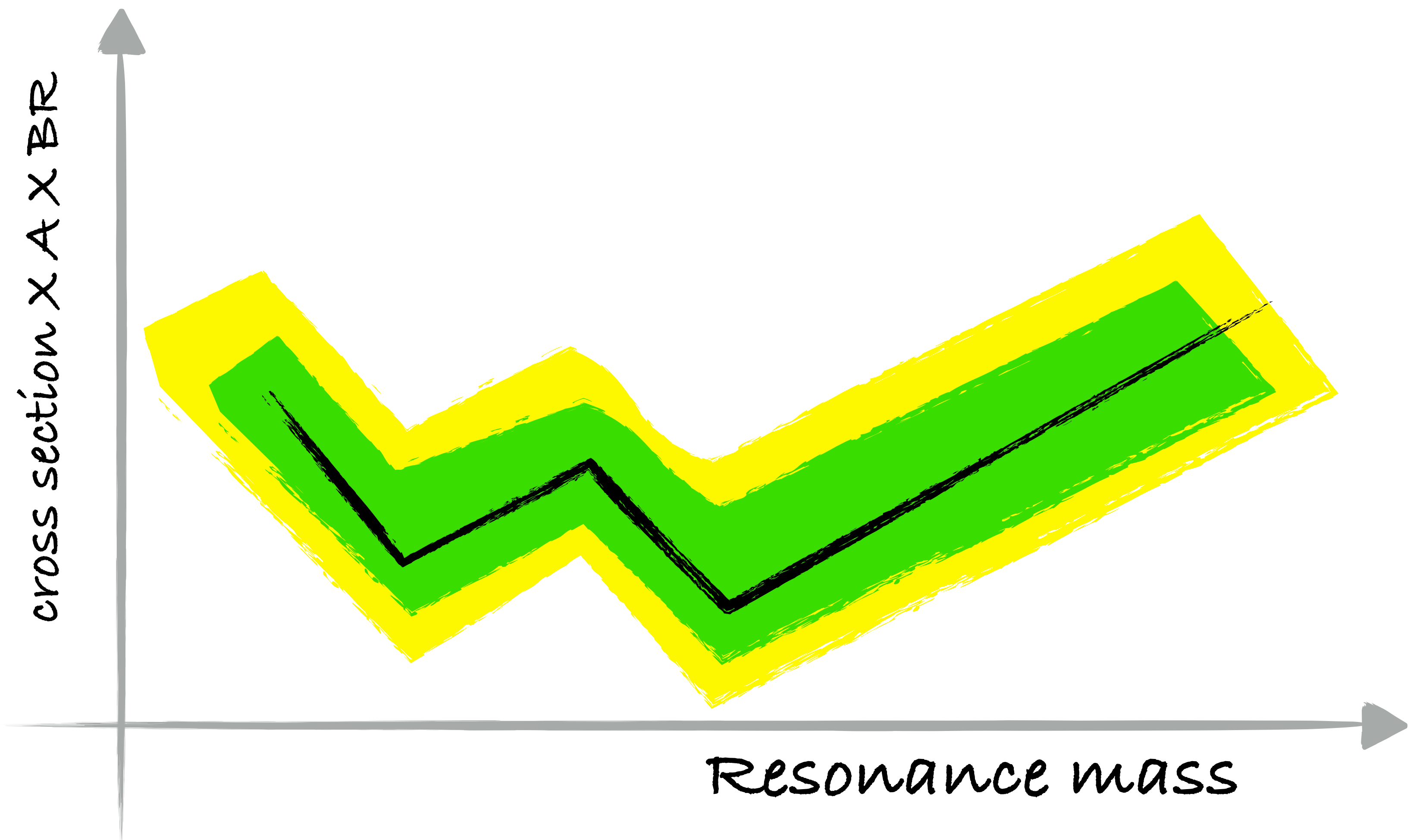
Typically a cut&count analysis

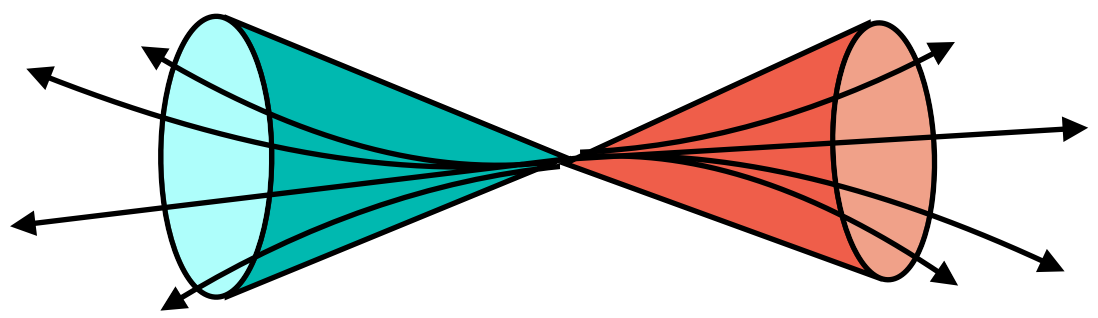
Estimated with data-driven techniques

$$\sigma = \frac{N_{selected} - N_{background}}{A \cdot \epsilon \cdot \int \mathcal{L} dt}$$

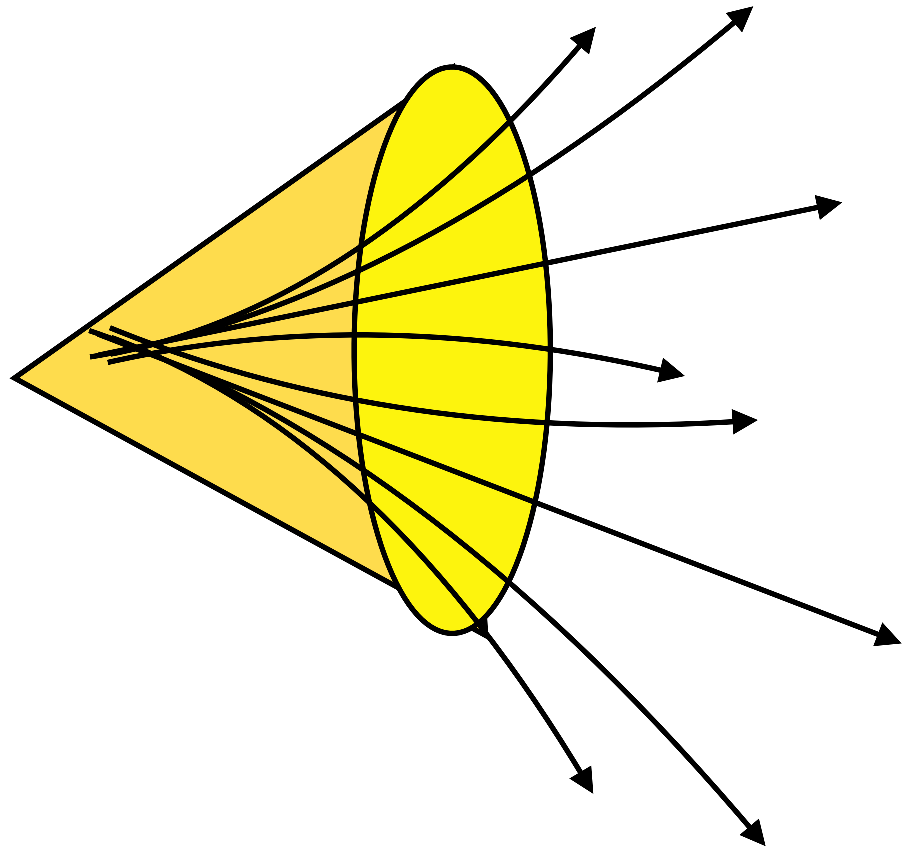
Include acceptance, efficiency and branching ratio



How to reconstruct hadronic V?

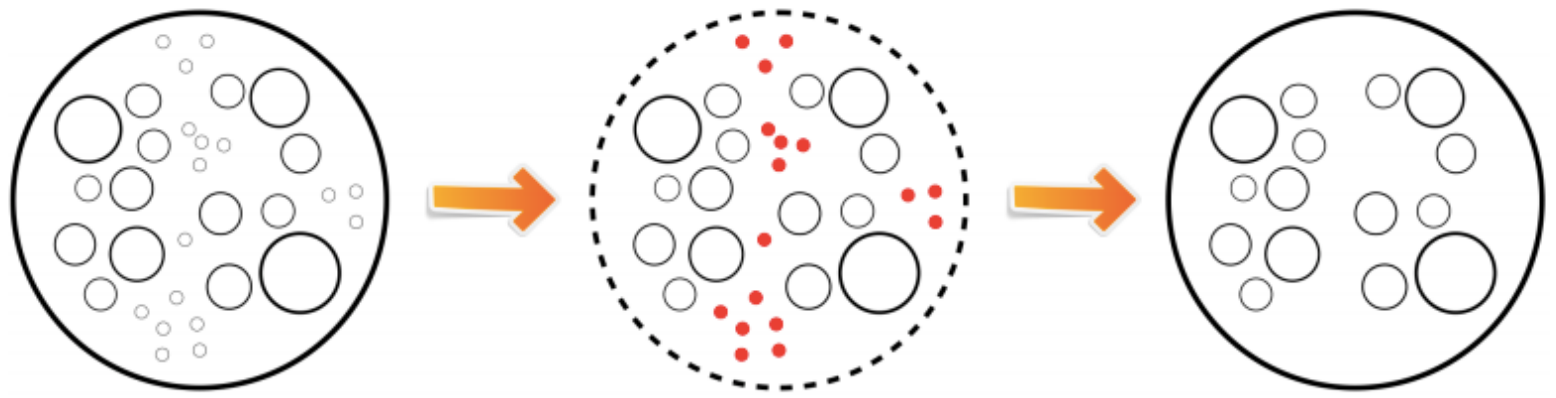


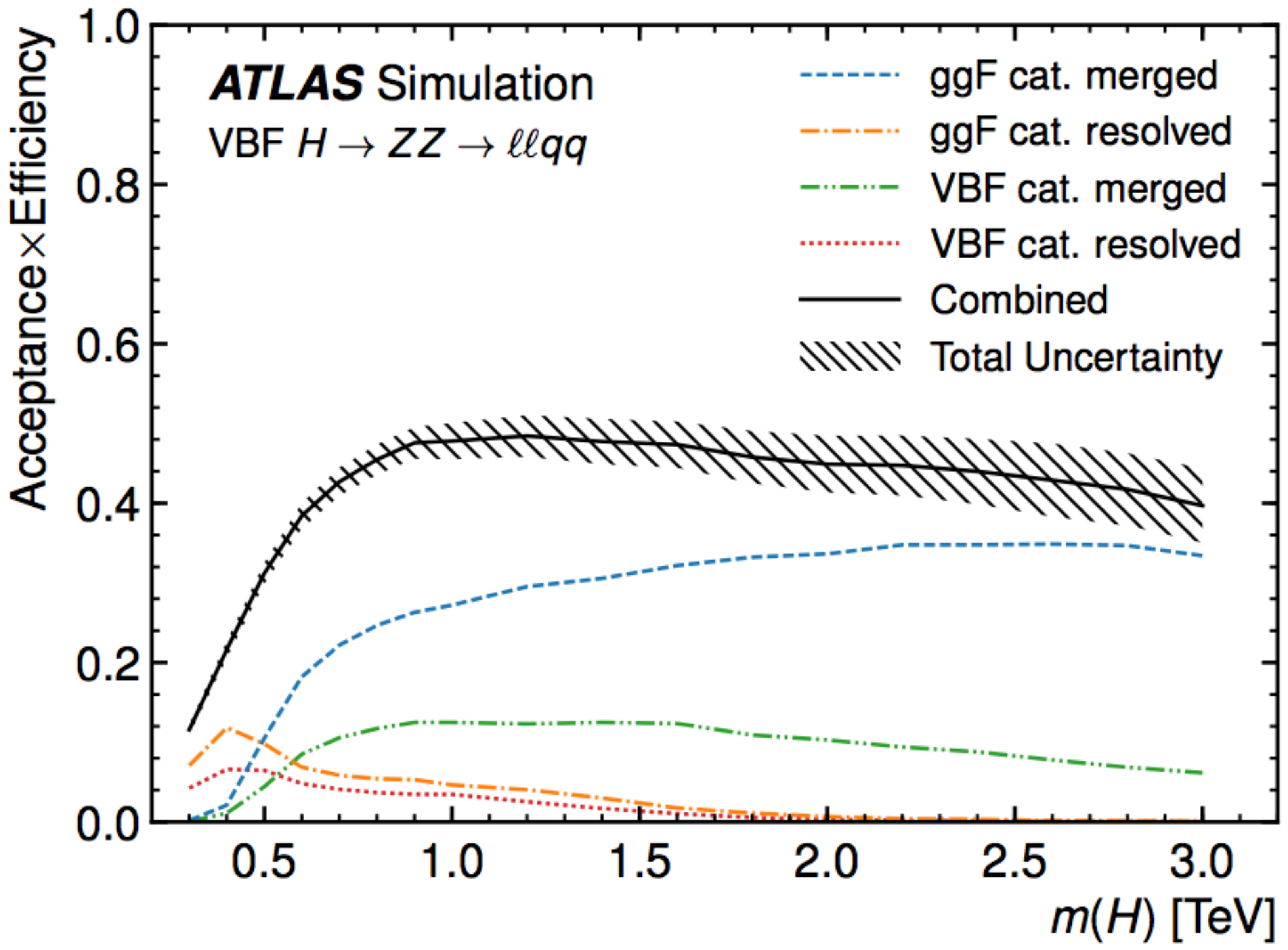
Resolving individual decay products become more difficult at high mass (boosted objects)



Reconstruct a single large-R jet (R=1.0) and investigate its substructure

- Recover signal efficiency for merged decays
- Use tracking information
- **Jet Grooming**: remove unwanted jet soft-component, initial state radiation, multi-parton interaction, pile-up in jet reconstruction;



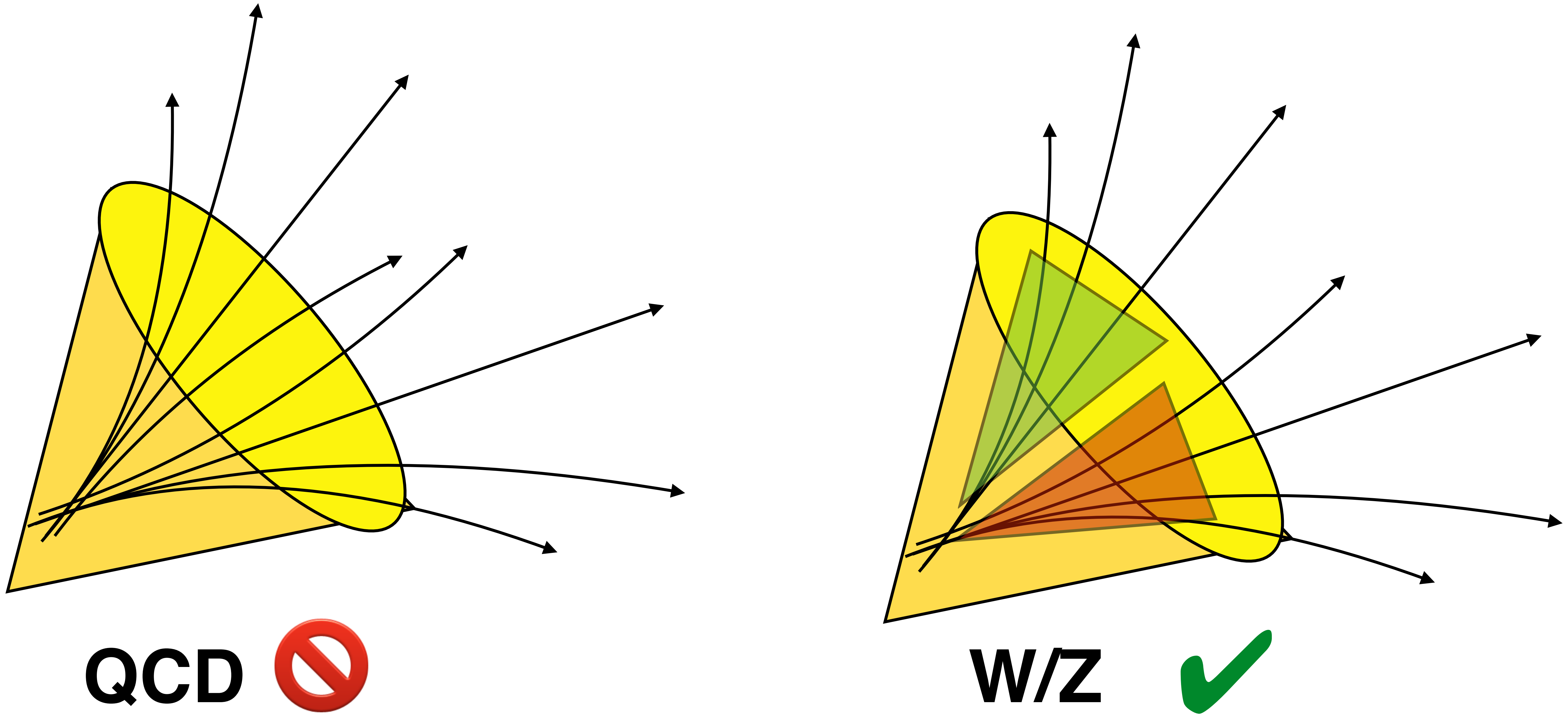


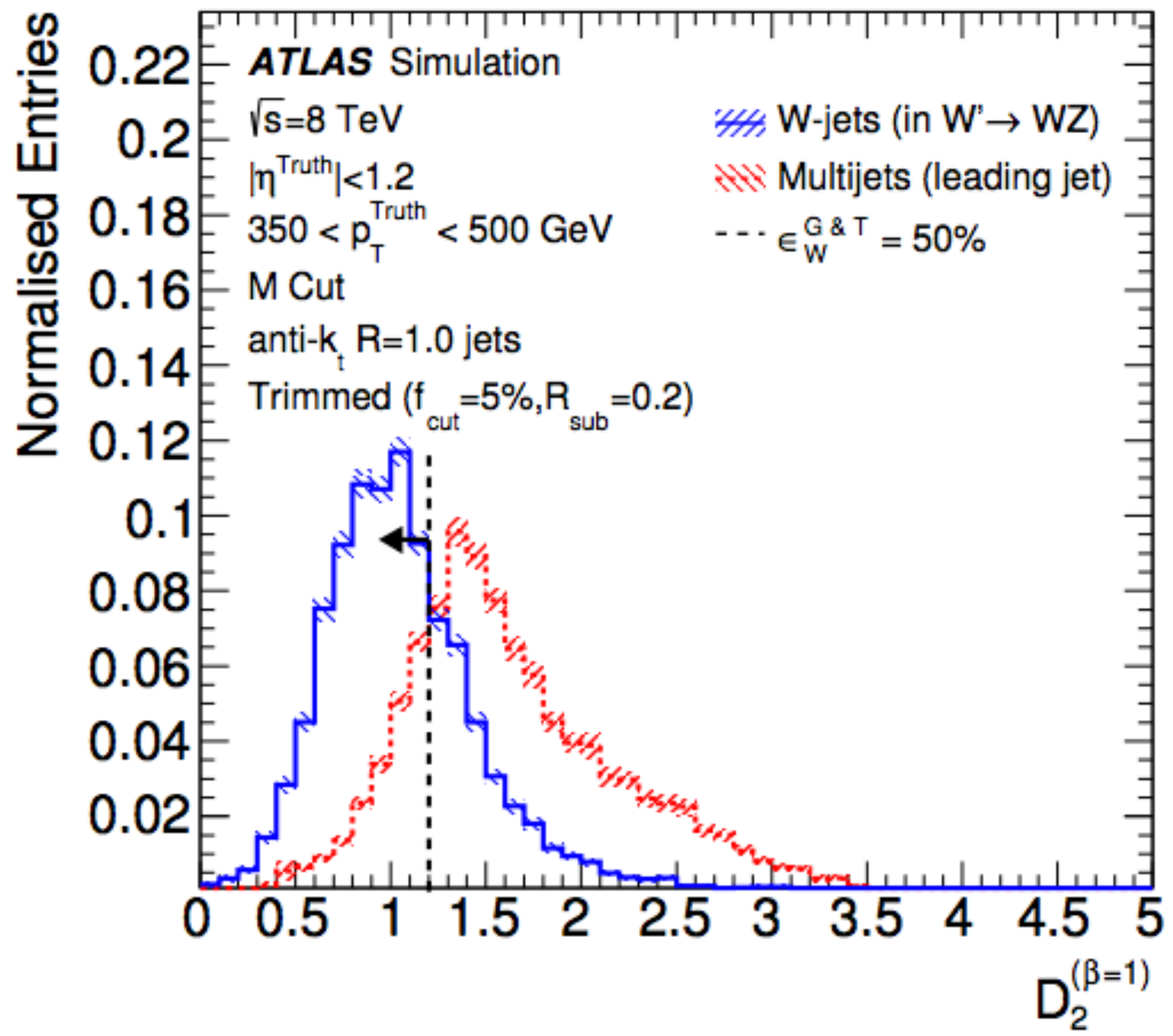
$$\Delta R(q_1, q_2) \sim \frac{2M(V)}{p_T(V)}$$

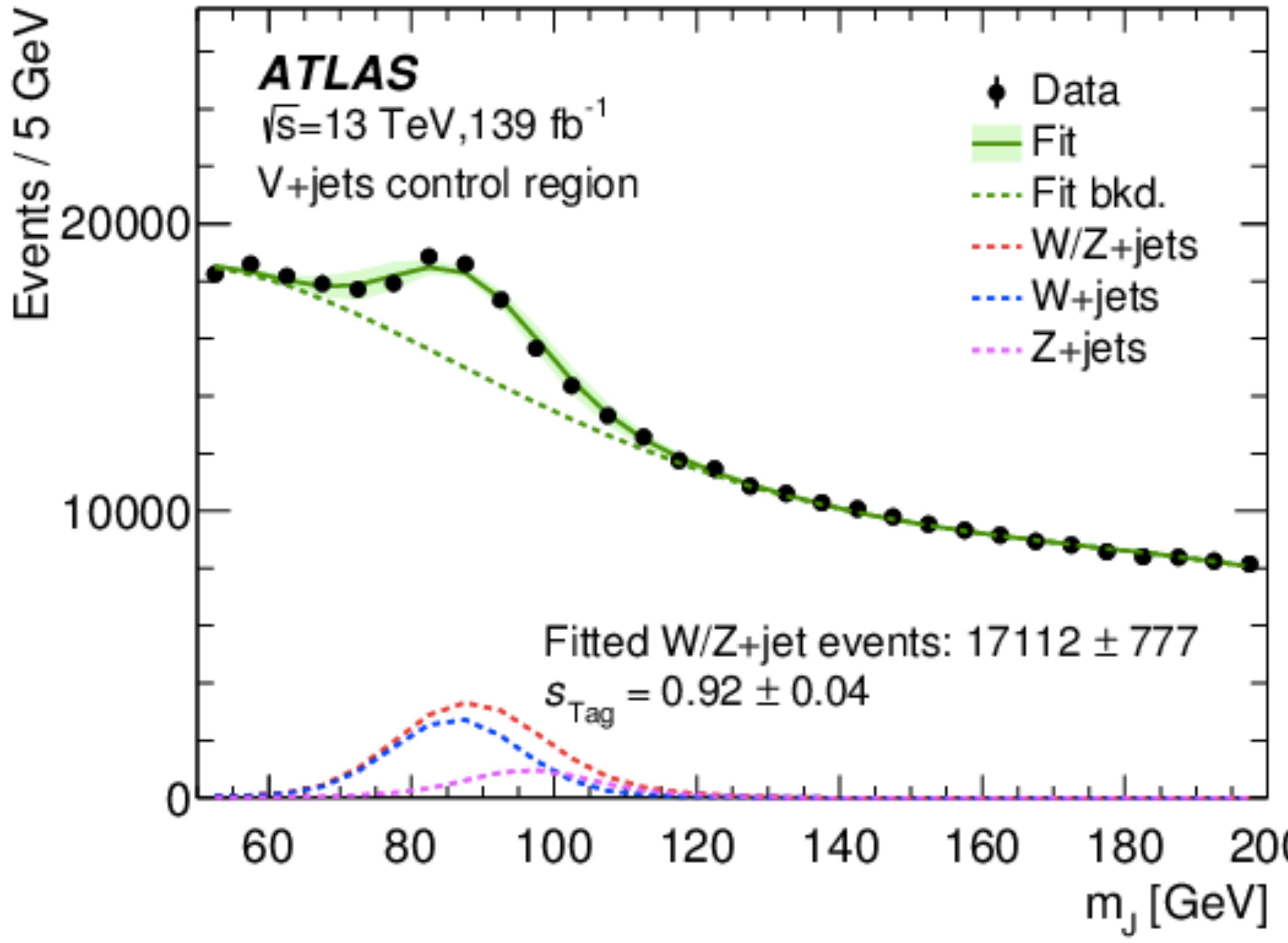
How to distinguish QCD and W/Z jets?

- **Boson Tagging**: discrimination between signal merged jets and soft radiation merged jets;
  - ↪Identify 2 core substructure jets due to boson decays and reject single core substructure jets.

- Background rejection optimized inside merged jet windows mass and combining cuts on the $\mathbf{D_2}$ variable (built from information on the merged jet constituent)





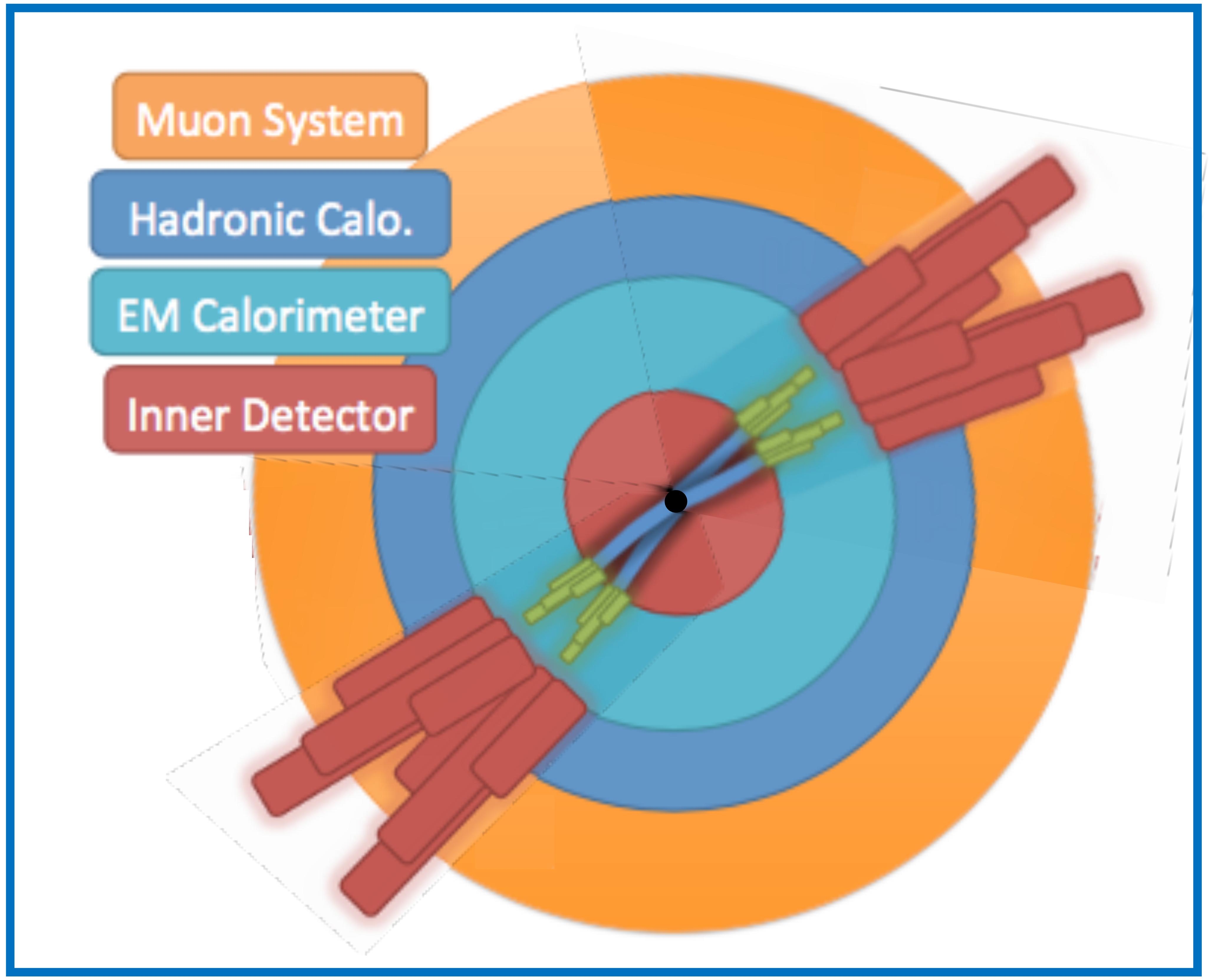


Exotics diboson searches

VV→JJ analysis

139 fb^{-1}

- Channel with the highest diboson branching ratio BR(VV—>had) ~50%
- Only merged region selection
- 5 signal regions (WW, ZZ, WZ, WZ+WW, WW+ZZ)
- Main background: multijets (~85%); diboson production, W/Z+jets, ttbar
  - ↪ 1D parametric function
  - ↪ Test & validation of the fit in data CRs



HDBS-2018-31

VV→JJ analysis improvements: Track-Calo Cluster Jets

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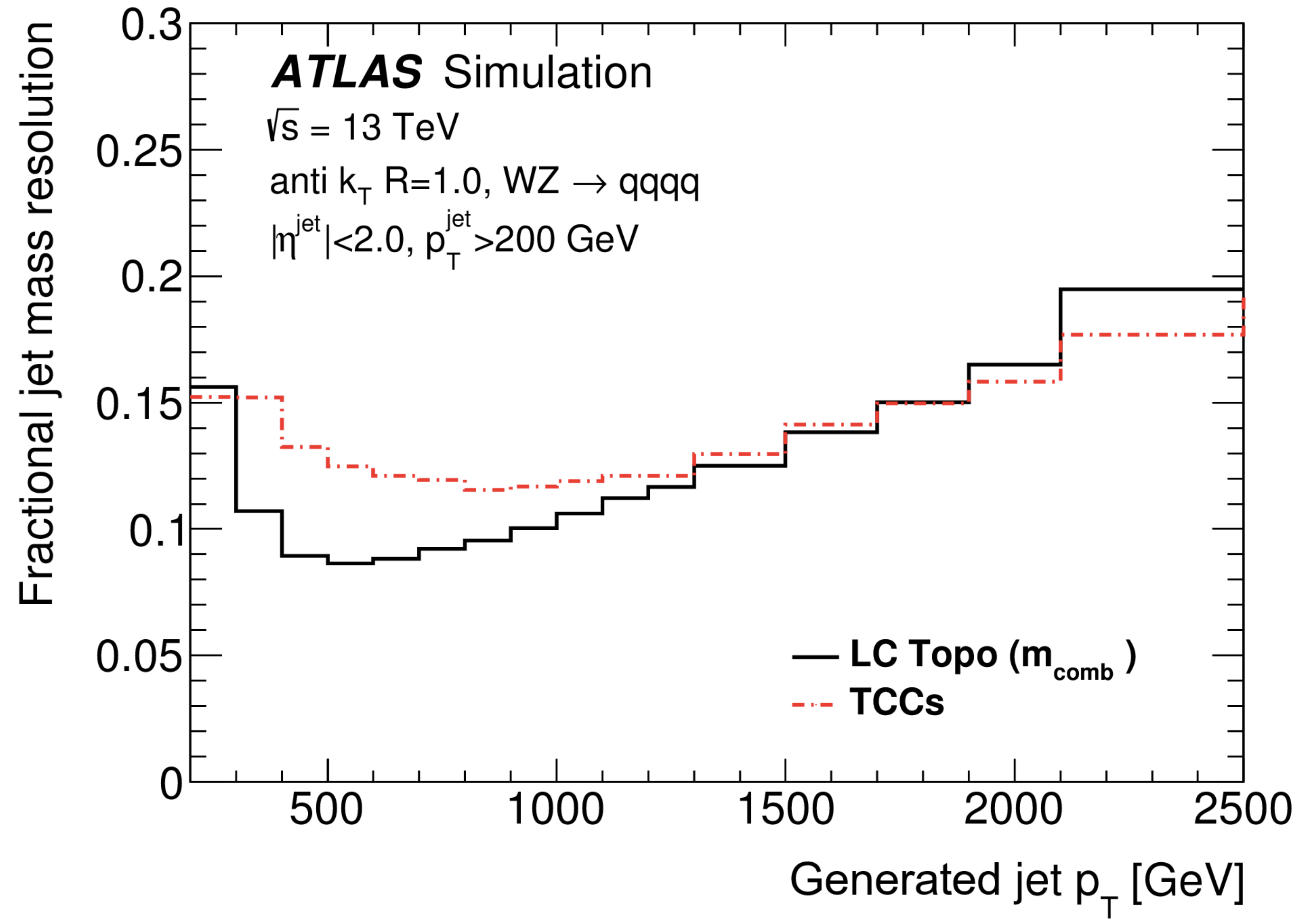
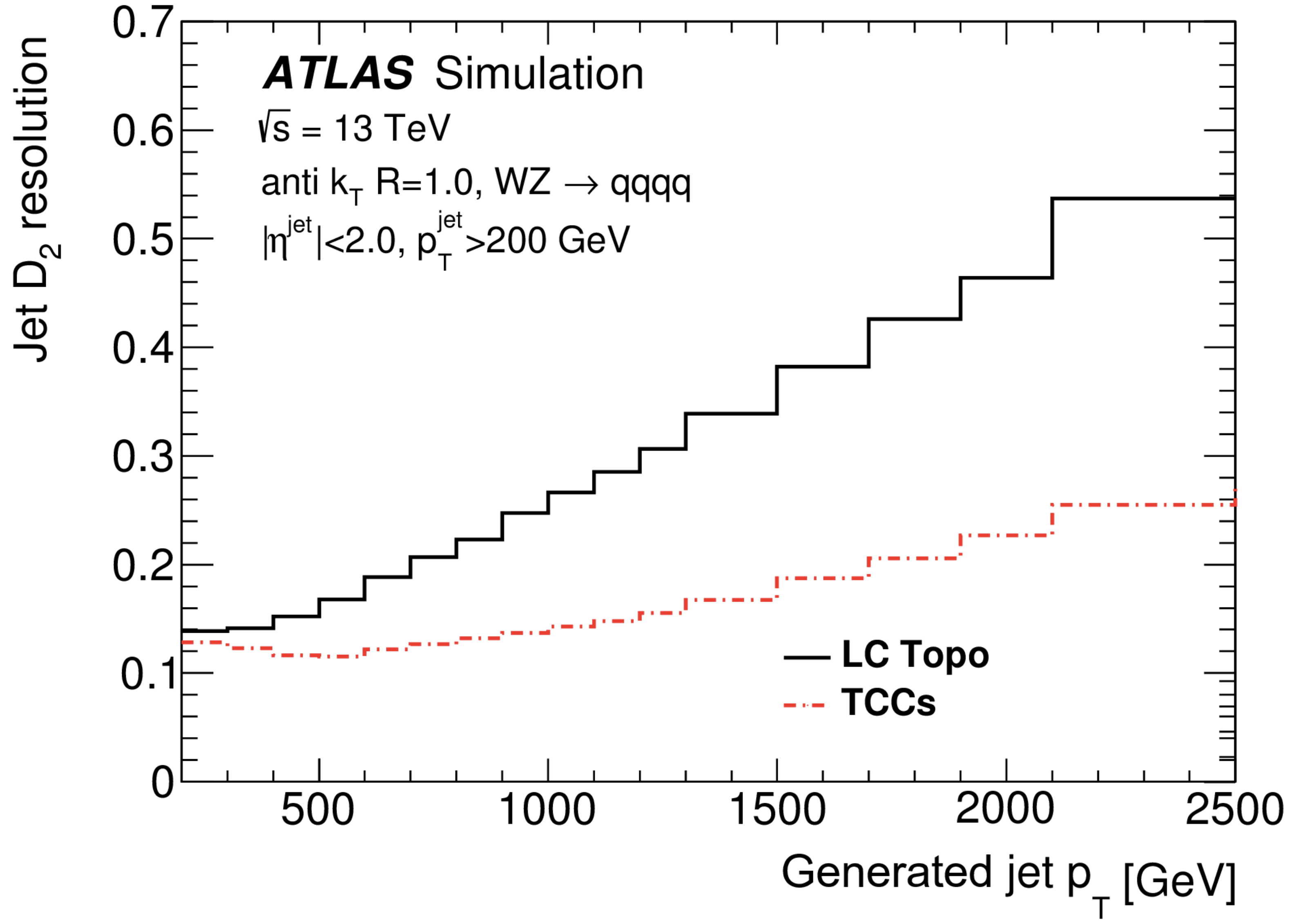
- In the previous analyses calorimeter-clusters for large-R jets used (exploits the exceptional energy resolution of the ATLAS calorimetry);
- When p_T >1 TeV, only a handful of calorimeter-cell clusters are created, each with limited angular resolution, but excellent energy resolution.
- Combining information from the calorimeter and tracking detectors, the precision of jet substructure techniques can be improved for a wide range of energies.





VV→JJ analysis

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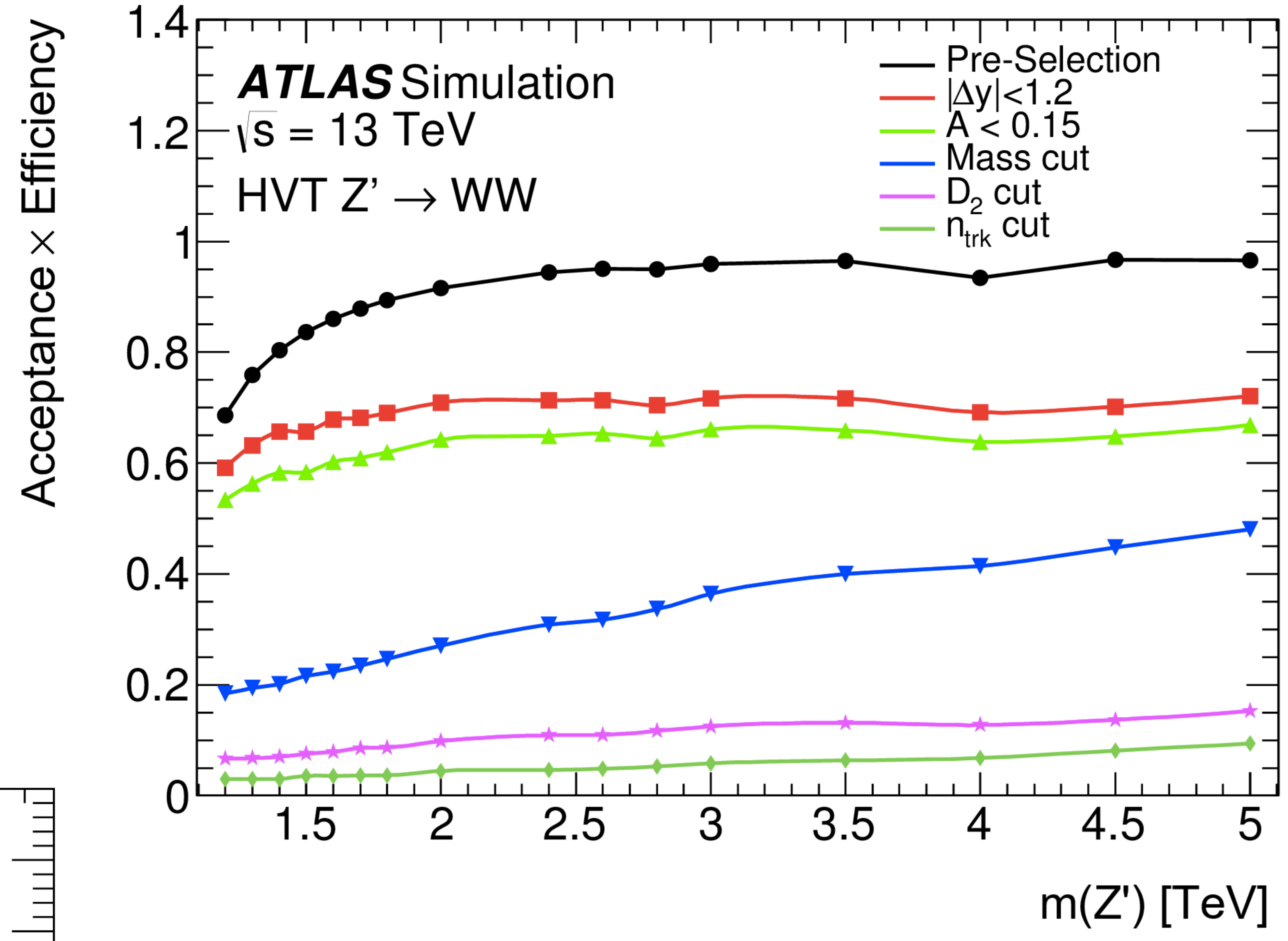
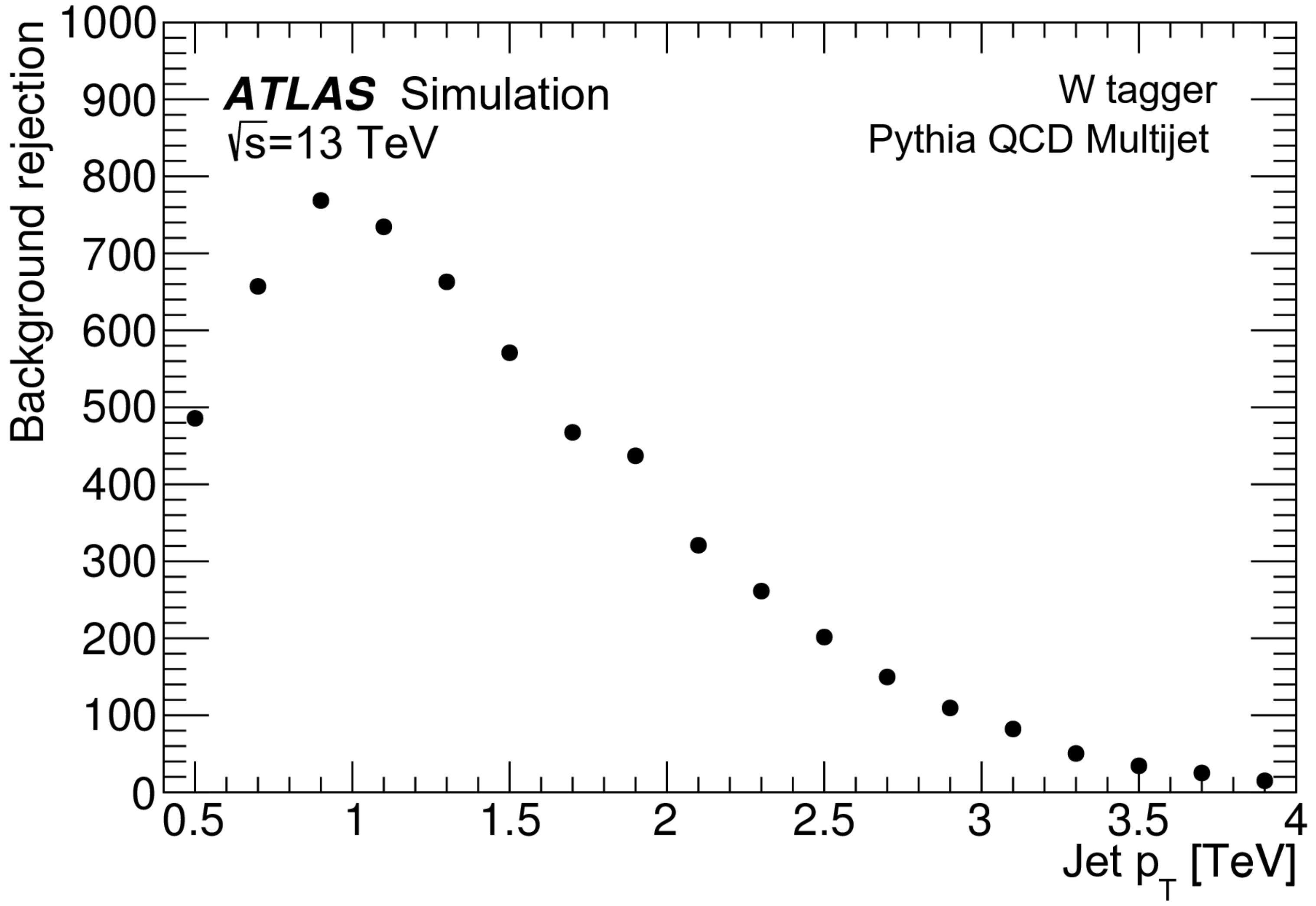
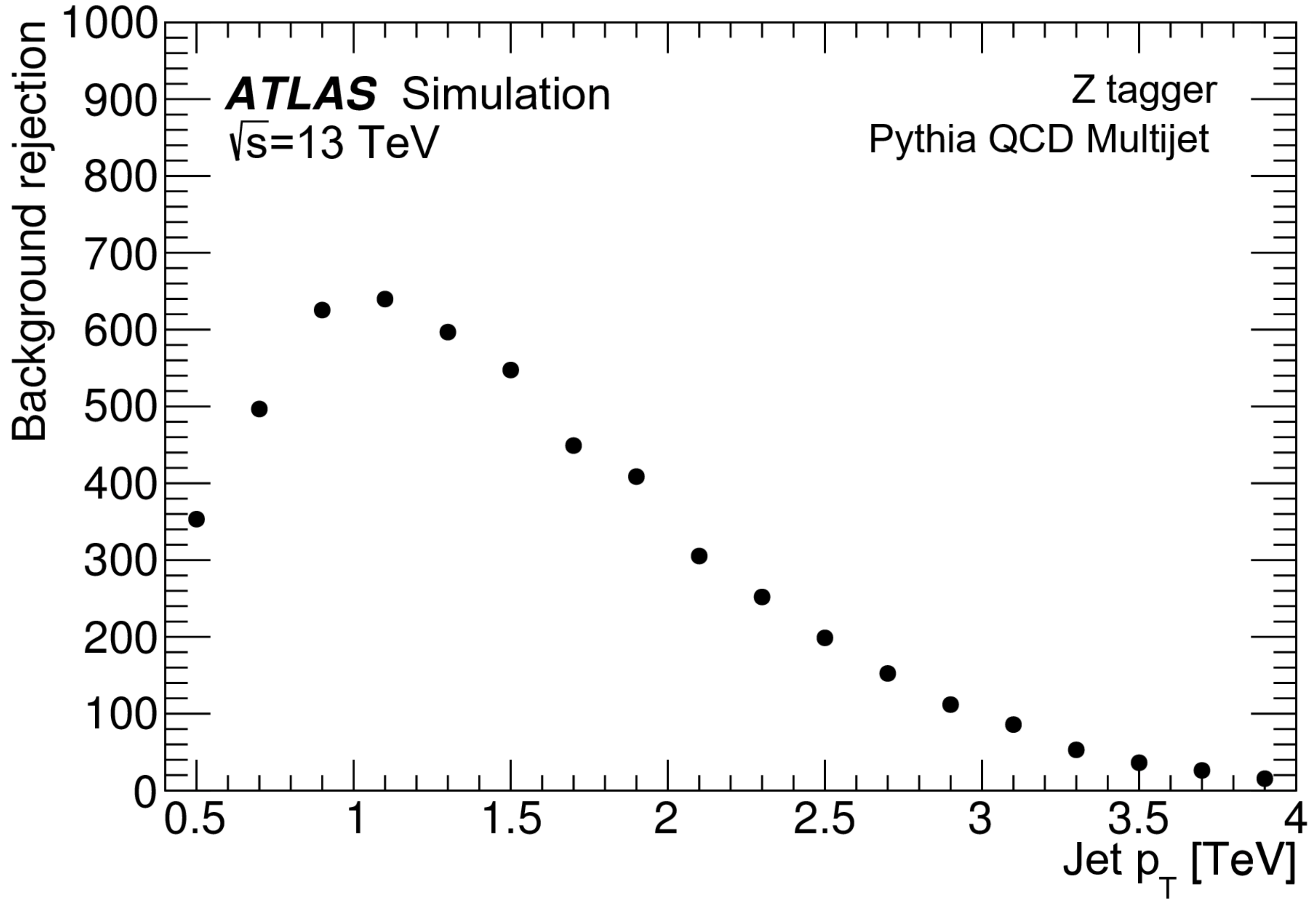
- Very "simple" selection
  - 2 large-R jets required with p_T>500 GeV and p_T>200 GeV
  - m_{JJ}>1.3 TeV
  - Small separation, Δy_{12}<1.2 allows to reject QCD background
  - p_T asymmetry to reject events with badly reconstructed jets



- 3-dimensional tagger (jet mass, D_2, n track) using TCC jets properly optimized





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VV→JJ: results

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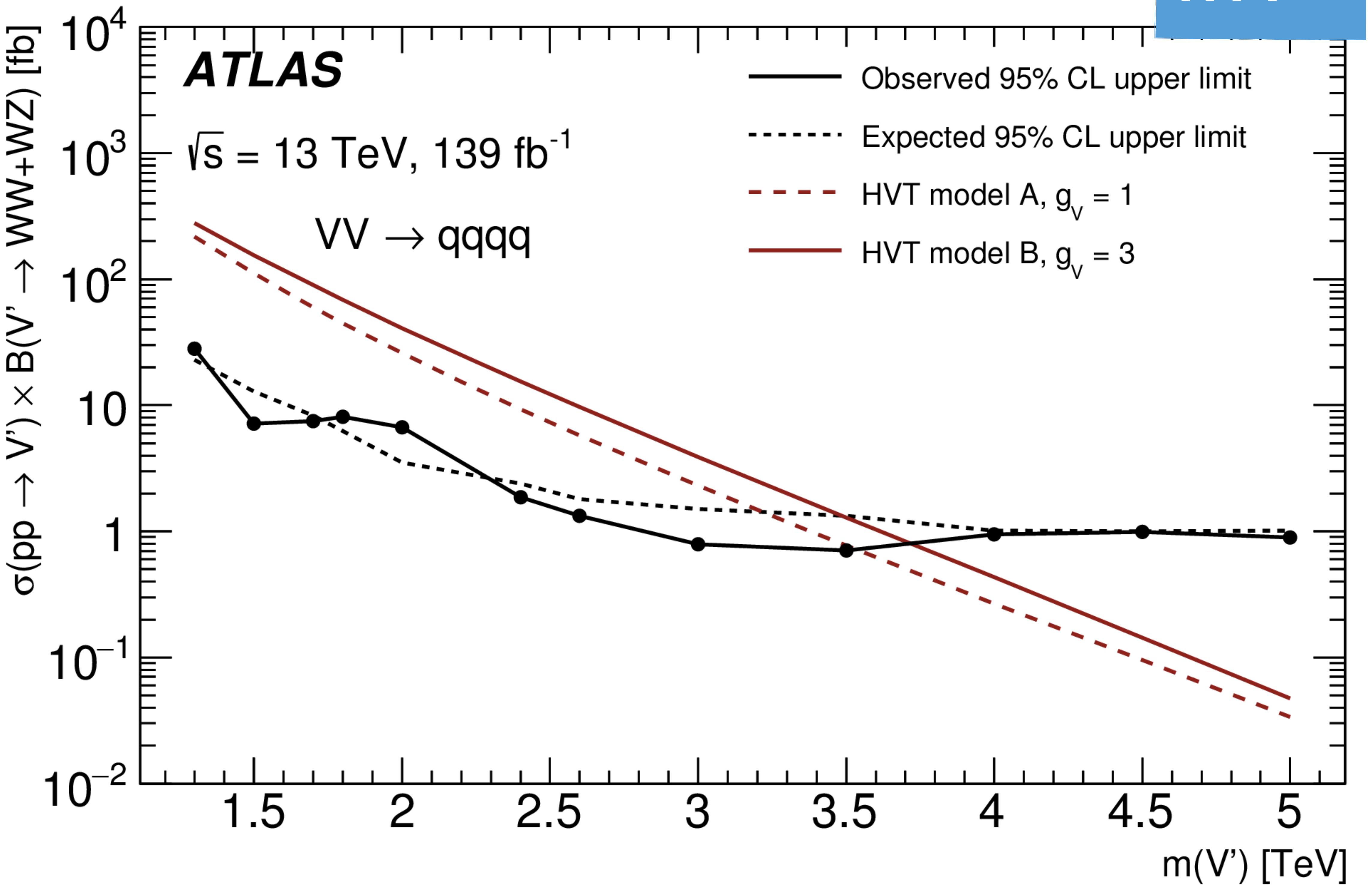
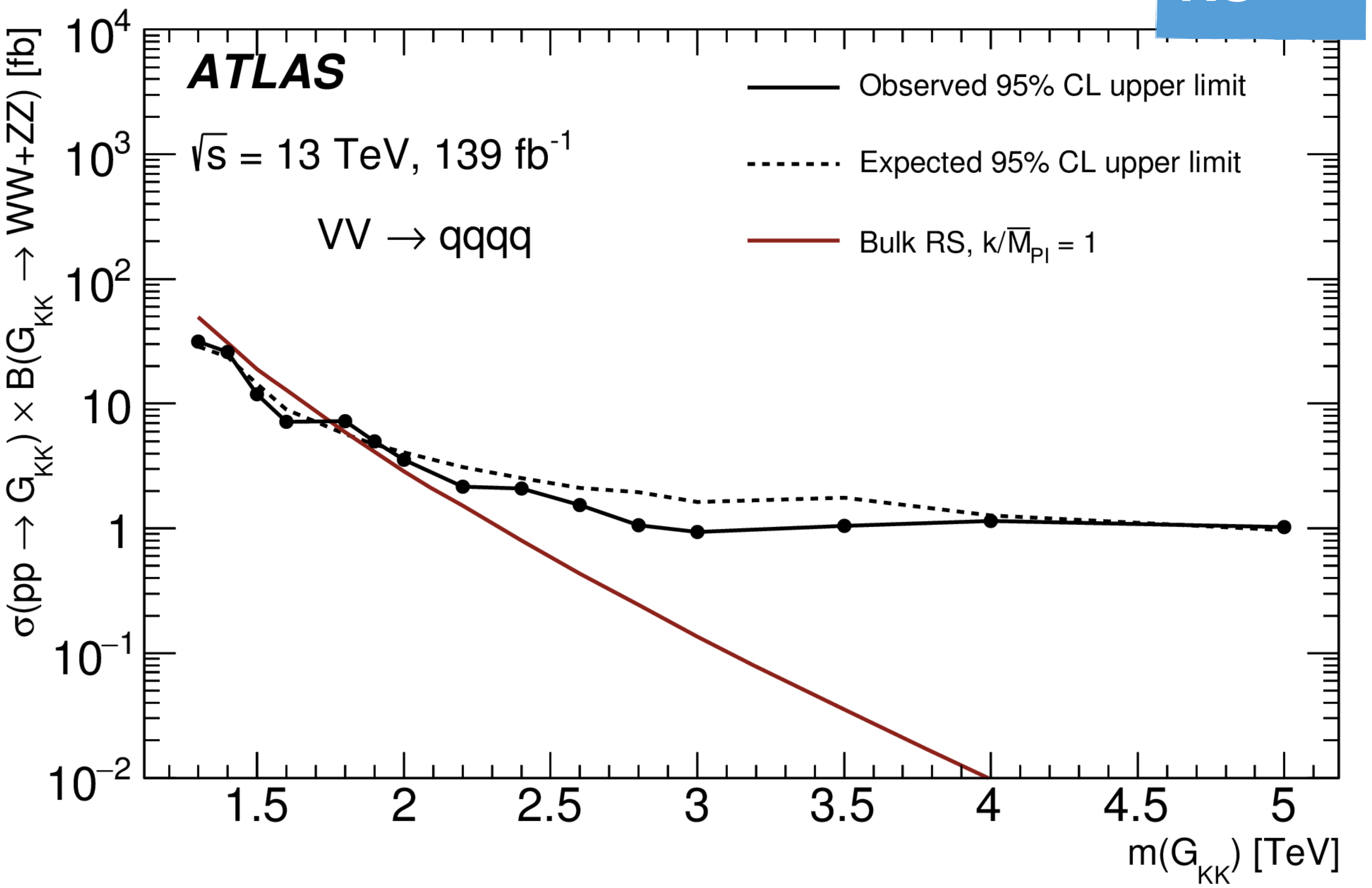
HVT



RS



HVT model A, $g_V = 1$	WW	1.3–2.9
	WZ	1.3–3.4
	$WW + WZ$	1.3–3.5
HVT model B, $g_V = 3$	WW	1.3–3.1
	WZ	1.3–3.6
	$WW + WZ$	1.3–3.8

Bulk RS, $k/\overline{M}_{\rm Pl} = 1$	WW	1.3–1.6
	ZZ	none
	$WW + ZZ$	1.3–1.8

HDBS-2018-31

VV semileptonic analysis

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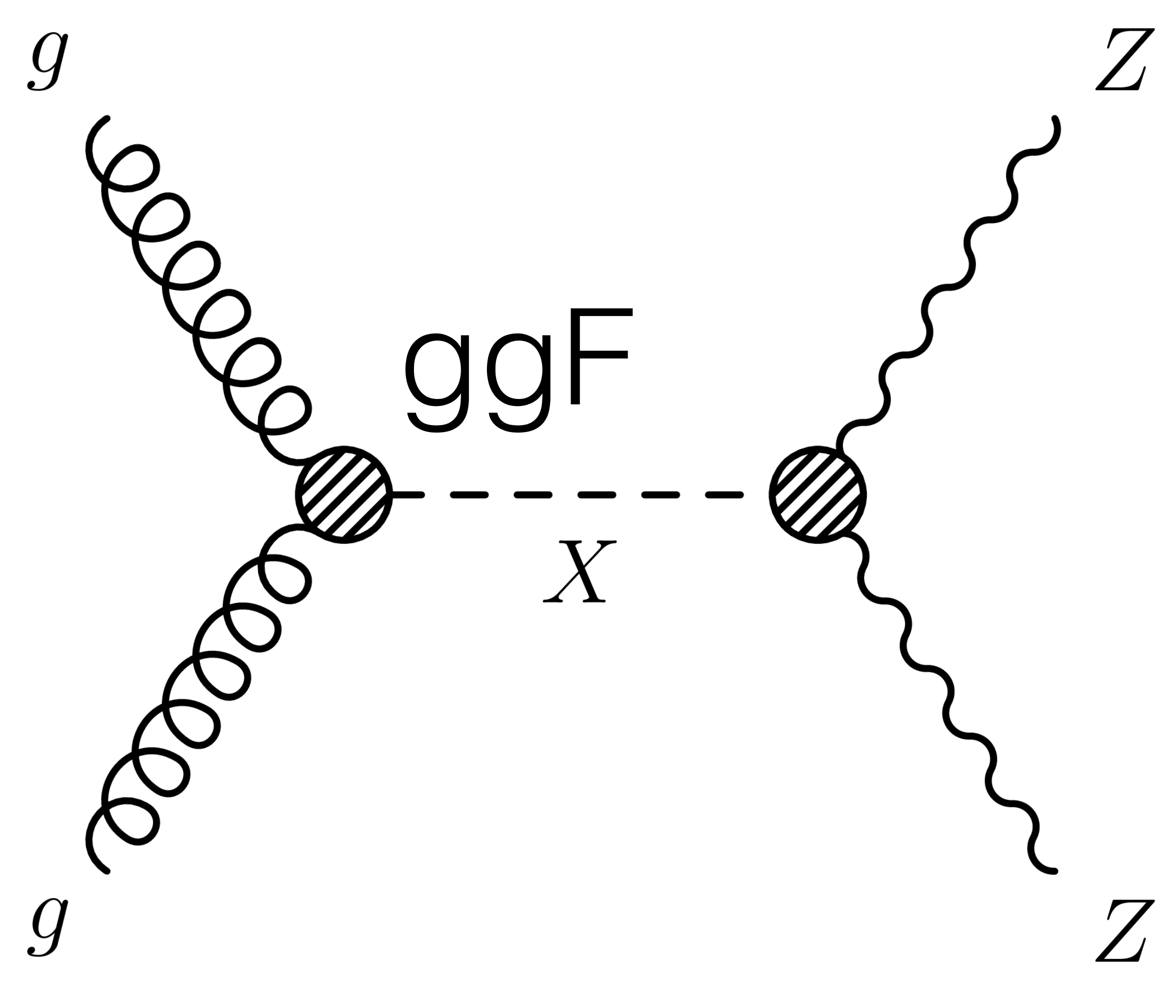
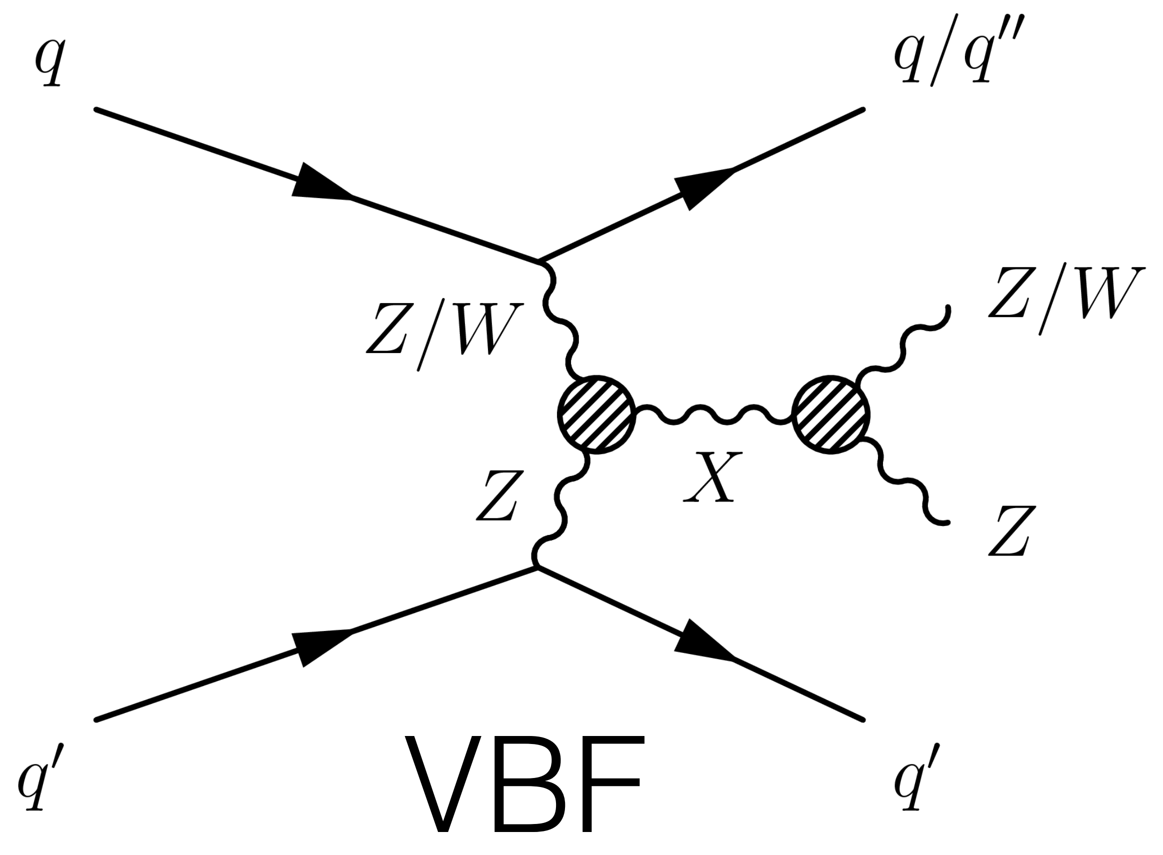
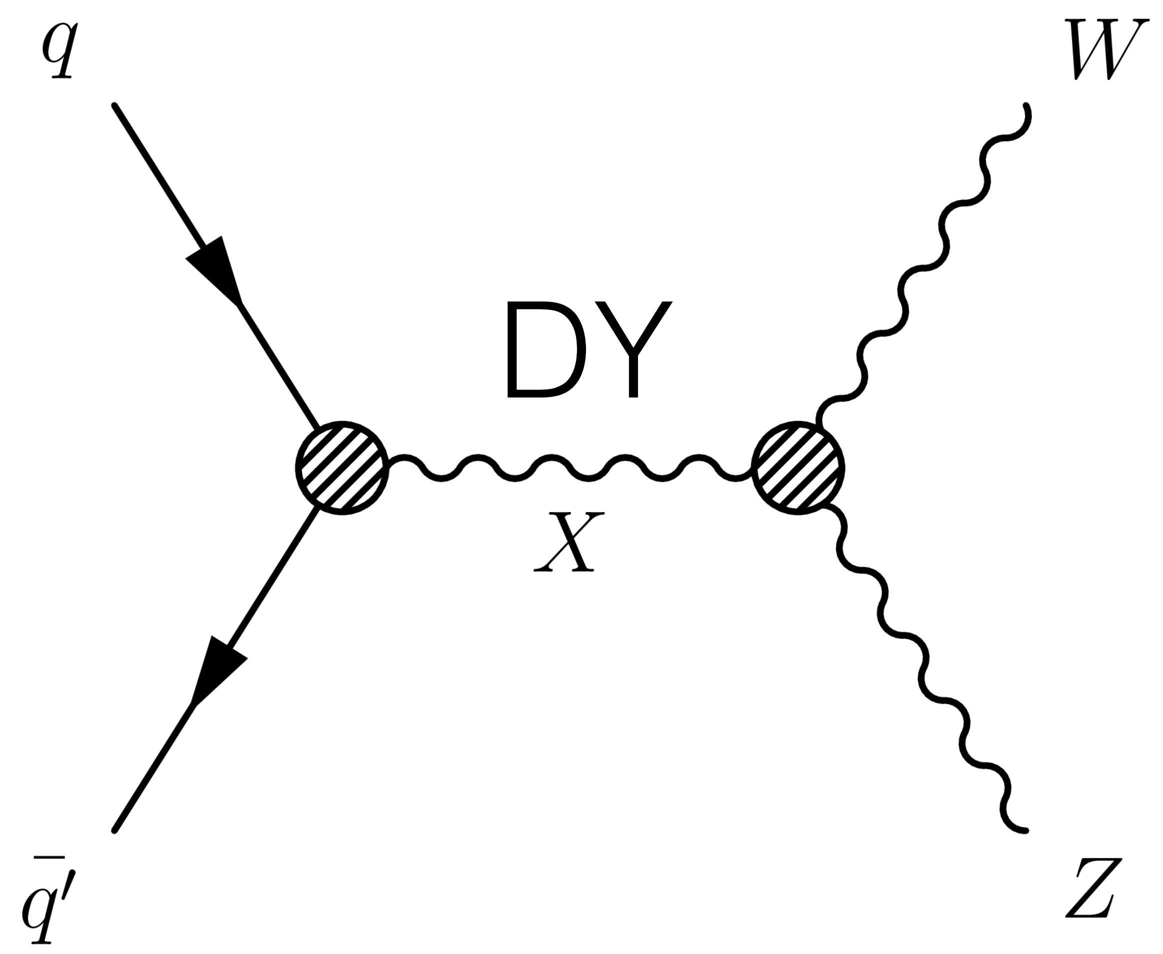
- Model interpretation:
  - ↪ Spin-0: Heavy Higgs/Radion
  - ↪ Spin-1: HVT Z',W'
  - ↪ Spin-2: Graviton
- 3 channel (0/1/2 leptons)
- 2 category (ggF-DY/VBF)
  - ↪ VBF: two additional jets with large separation in pseudorapidity and a large dijet invariant mass
- 2 regimes (resolved/merged)
- B-tagging categorization
- High/Low Purity categorization in merged regime



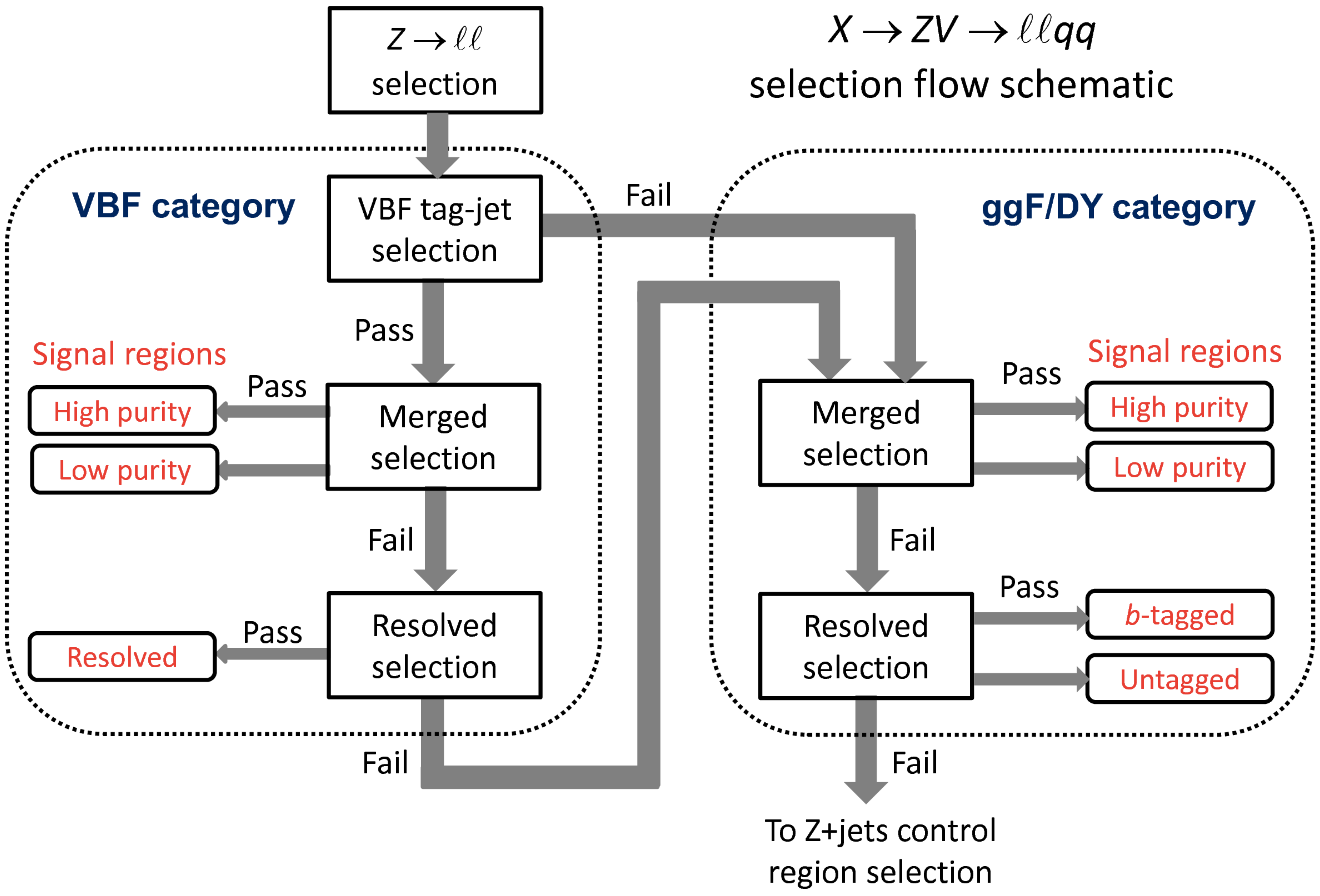




EXOT-2016-28
EXOT-2016-29

VV semileptonic analysis

- Lepton requirements:
  - 0 lep: Lepton veto (loose lepton) and E_T^{miss}>250 GeV;
  - 1 lep: exactly 1 lepton (tight) and E_T^{miss}>100(60) and GeV $p_T(l\nu)$ > 200(75) GeV in merged (resolved);
  - 2 lep: exactly 2 same flavor lepton (loose) in the Z mass range and with p_T > 30 GeV



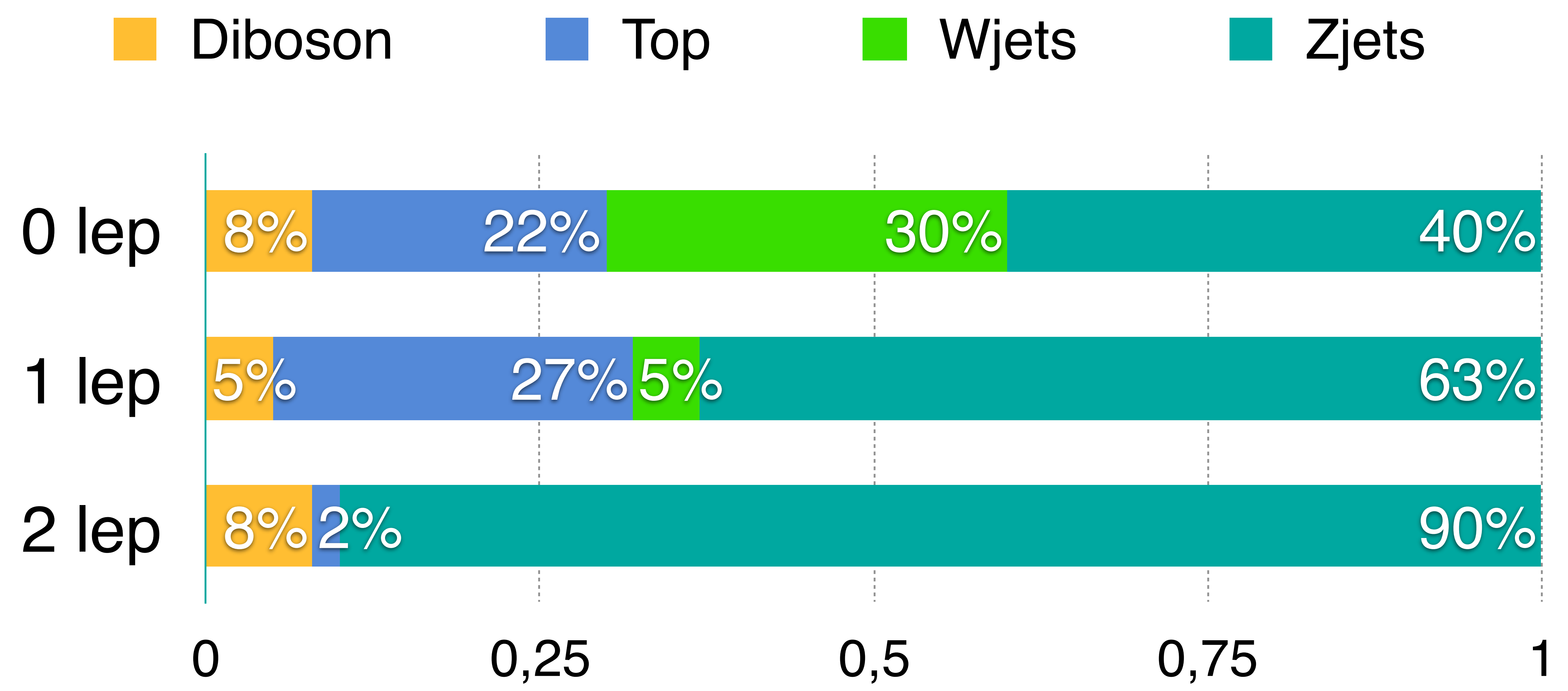
- Jet requirements:
  - merged regime: Selection of a merged jet that pass one of the two WP of the boson tagger
  - resolved regime: Selection of two small-R jets in the region |ηj| <2.5 and with invariant mass compatible with Z or W boson.

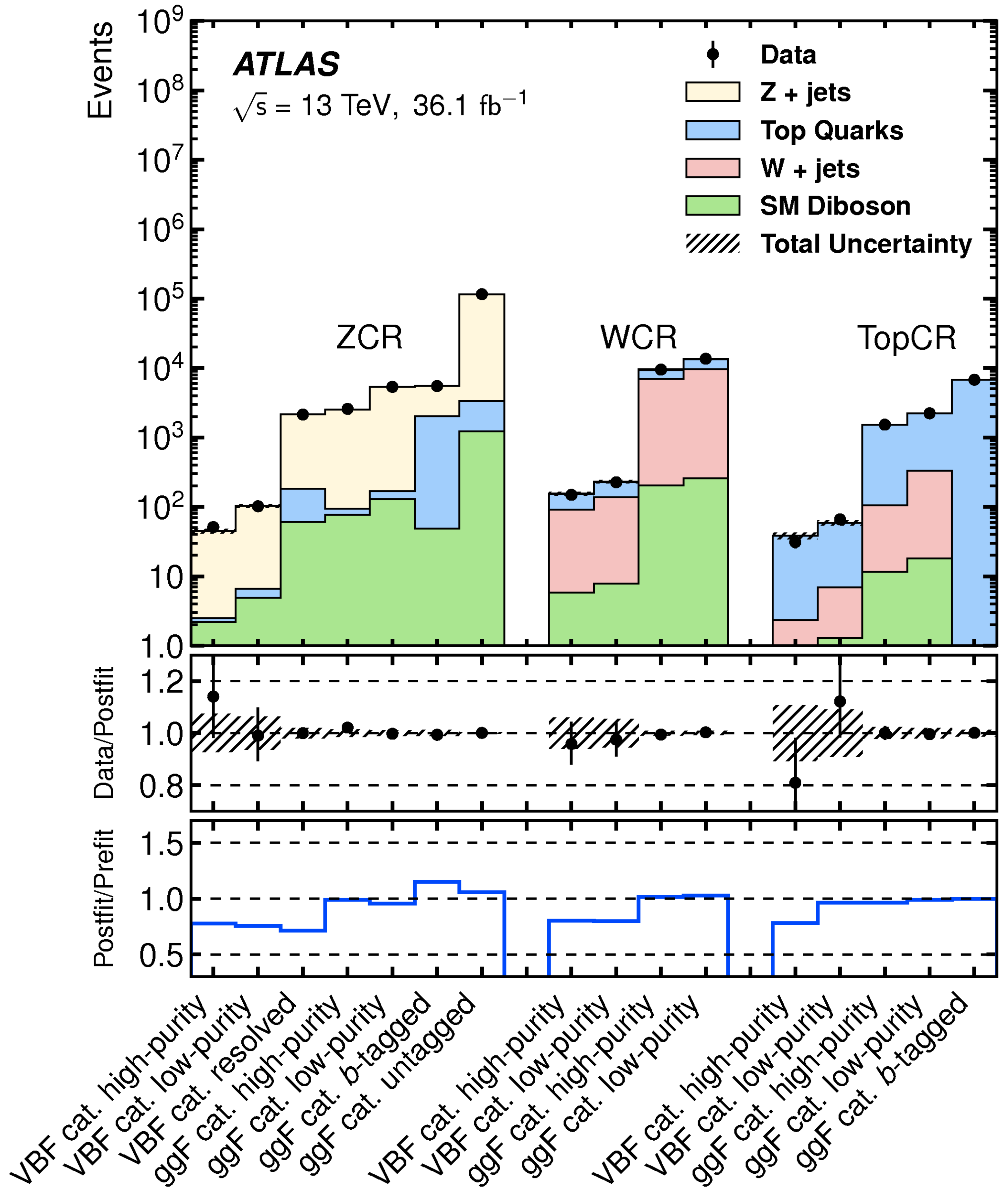
EXOT-2016-28
EXOT-2016-29

VV semileptonic analysis

36 fb^{-1}

- W+jets (W) and Z+jets (Z) Control Regions:
  - 1 and 2 lep: same selections as the SR but using mass sidebands of the W/Z tagger
- Top CR:
  - 1 lep: at least one b-jet instead of b-veto;
  - 2 lep: two different-flavour leptons
- Validation region:
  - 0 lep: Mass sideband of the W/Z tagger



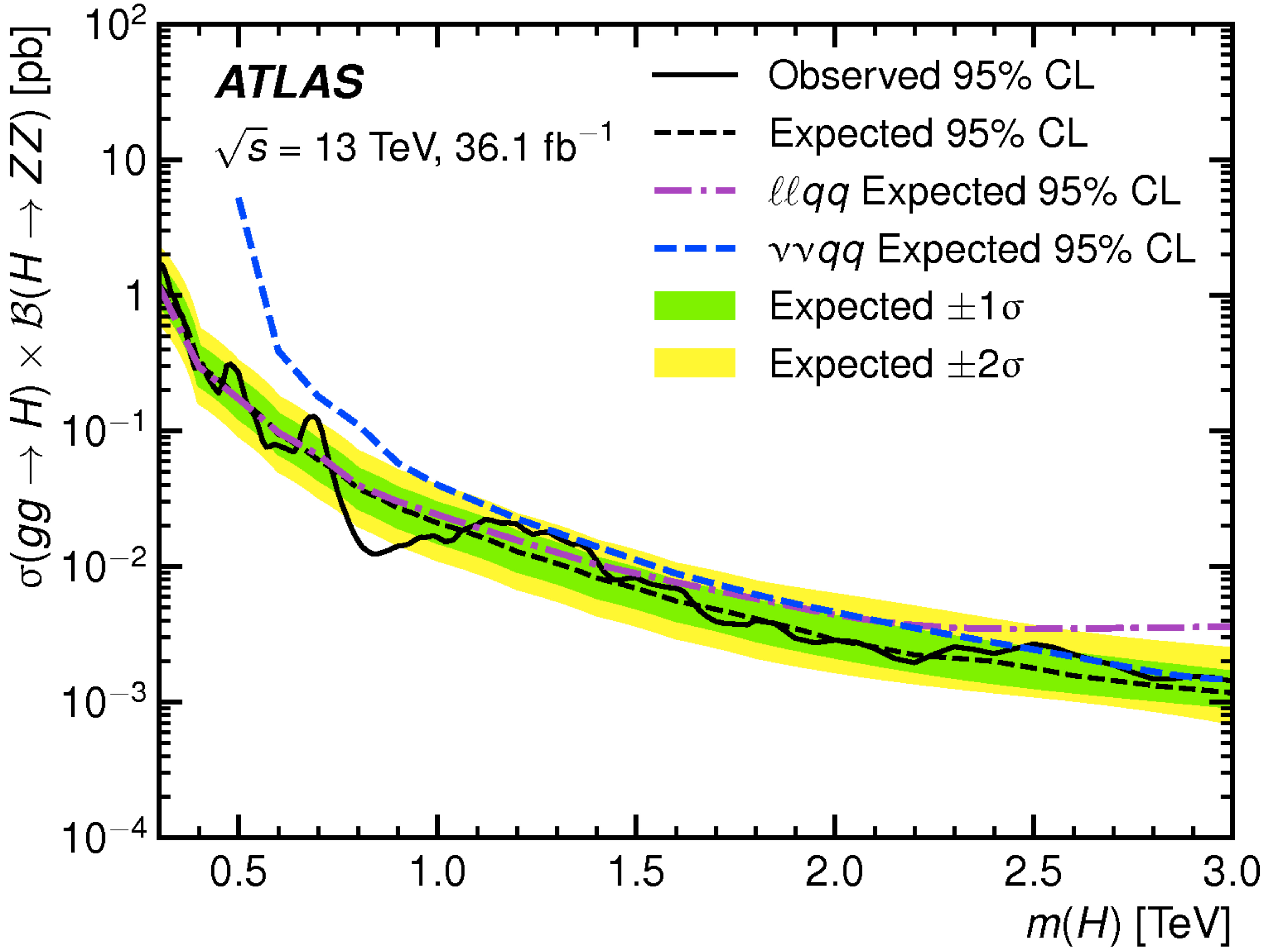


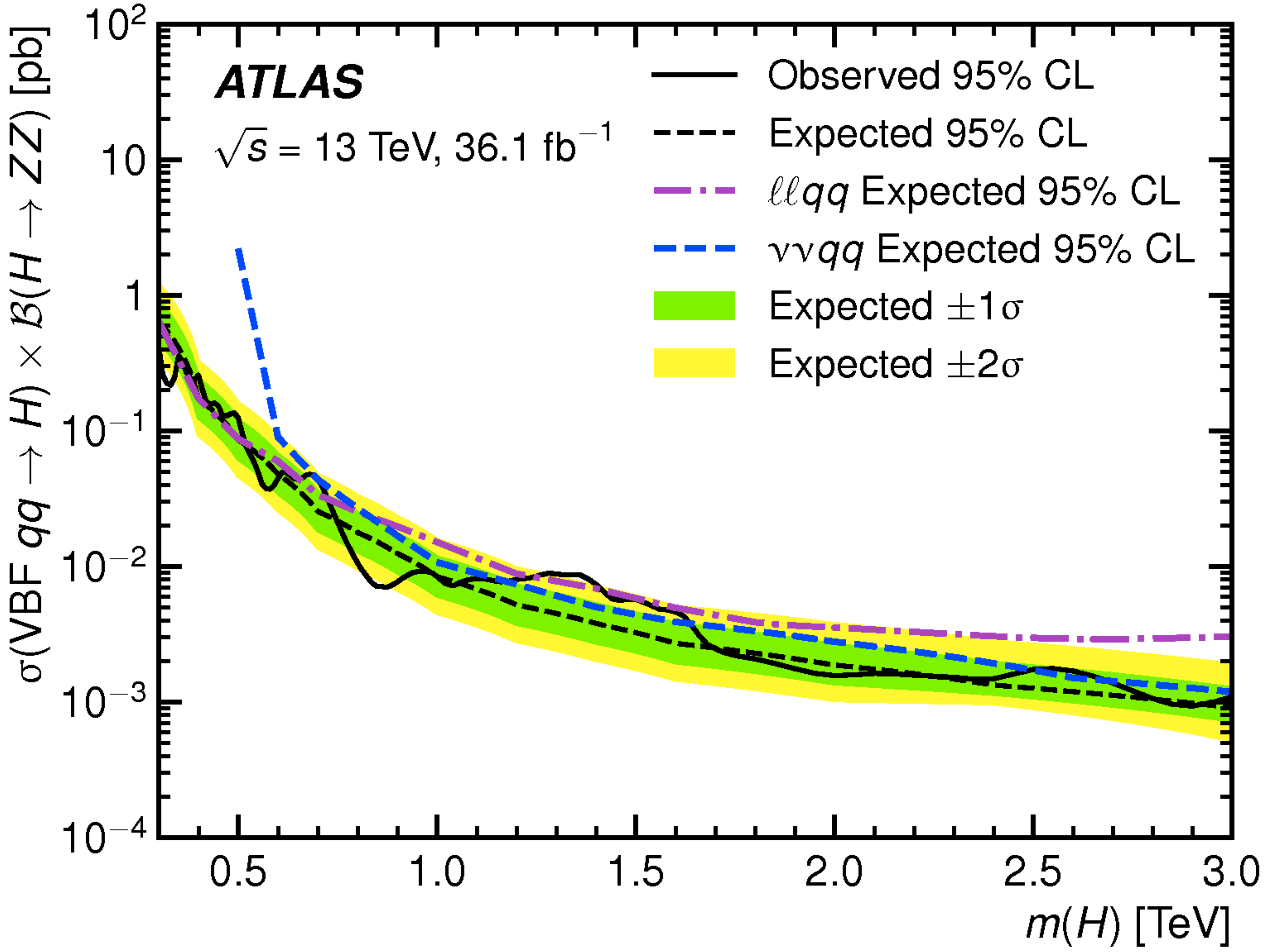
1D cut and count fit

- 0 lep: Transverse mass (mT)
- 1-2 lep: Invariant mass (mlljj/mllJ - mljj/mlJ)

VV semileptonic analysis — Heavy Higgs

36 fb^{-1}





m(*H*) from 300 GeV to 1.4

EXOT-2016-29

VV semileptonic analysis — HVT

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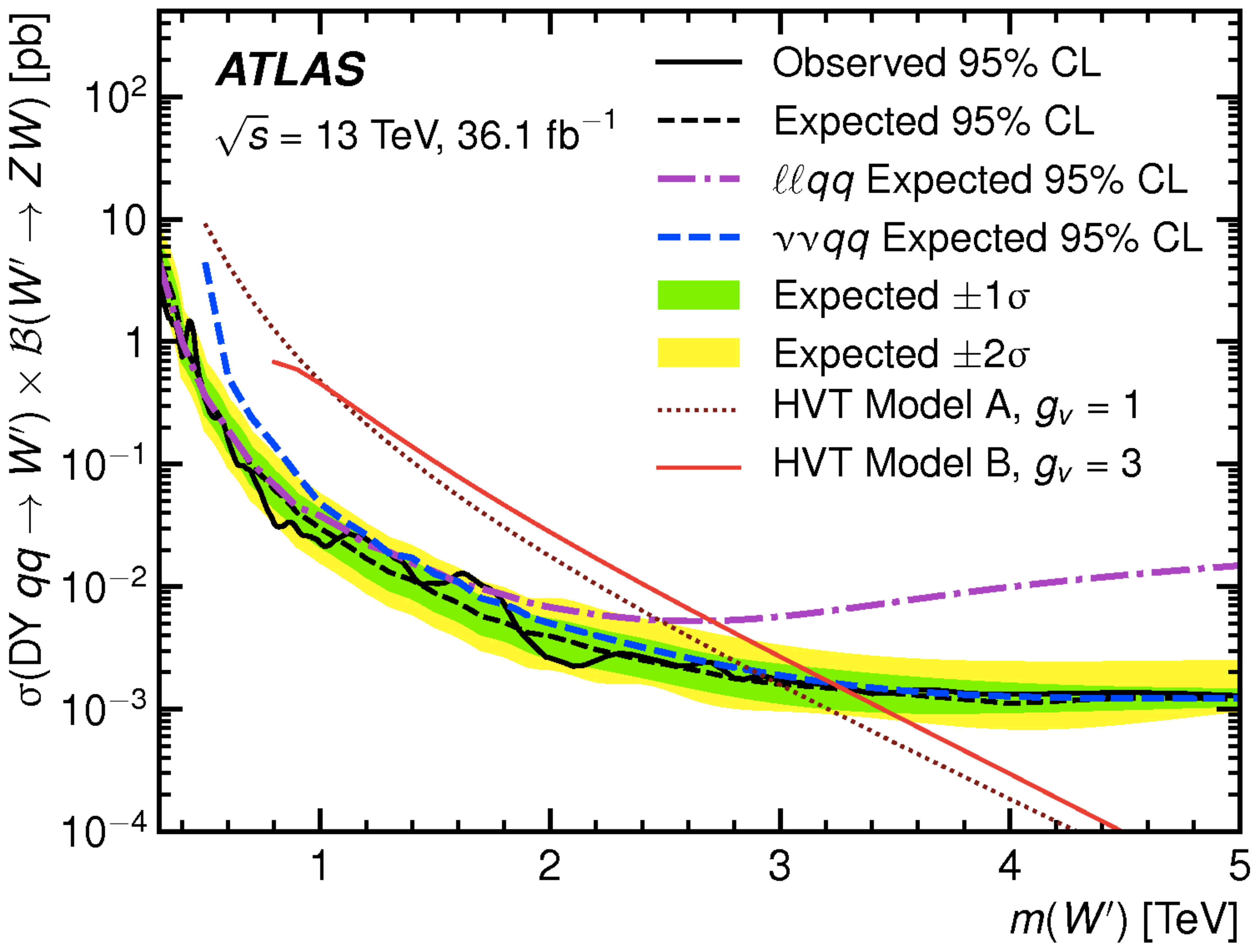

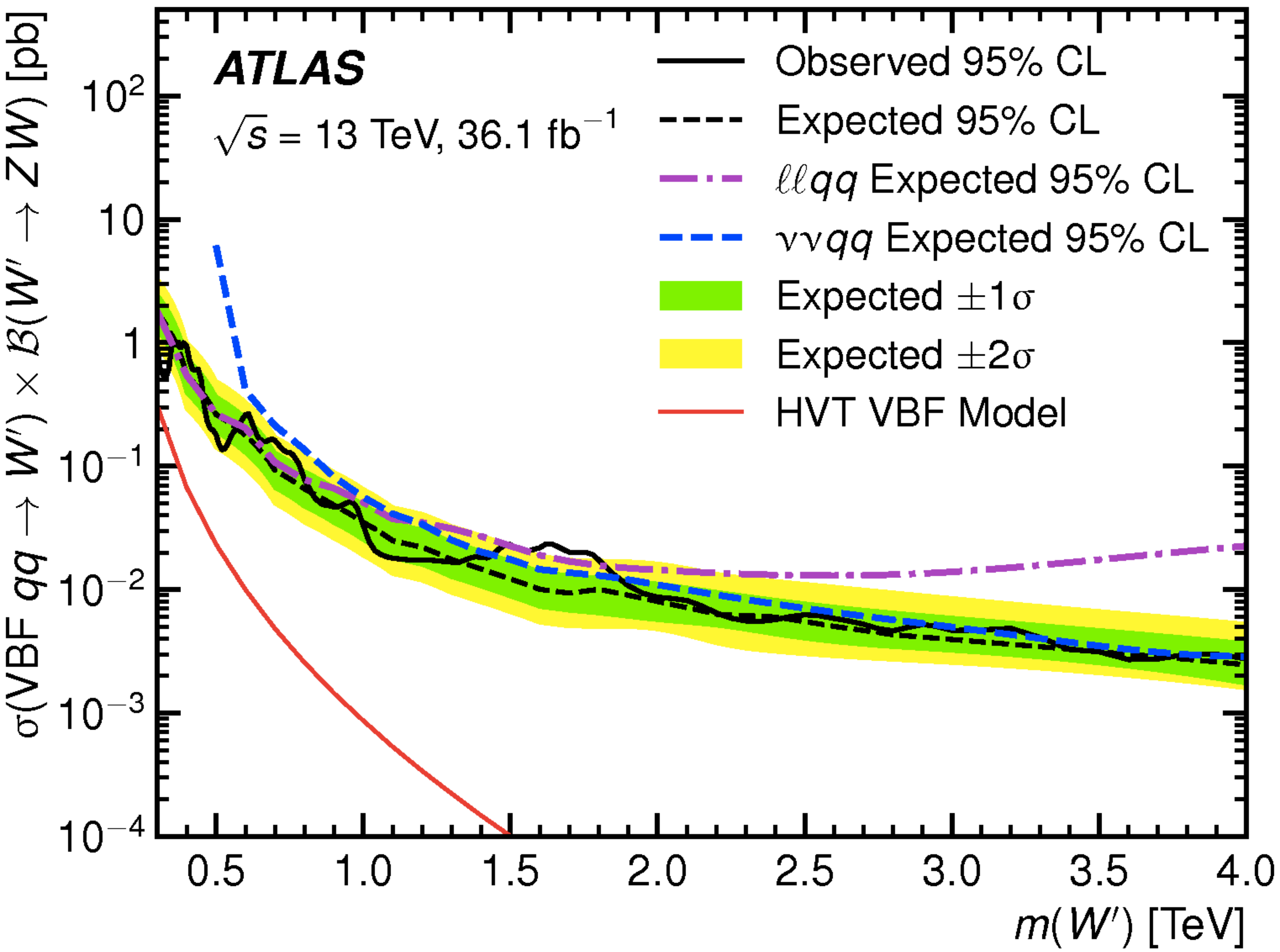

HVT A, g_V=1 < 2.9 TeV

HVT B, g_V=3 < 3.2 TeV

EXOT-2016-29

VV semileptonic analysis — Graviton

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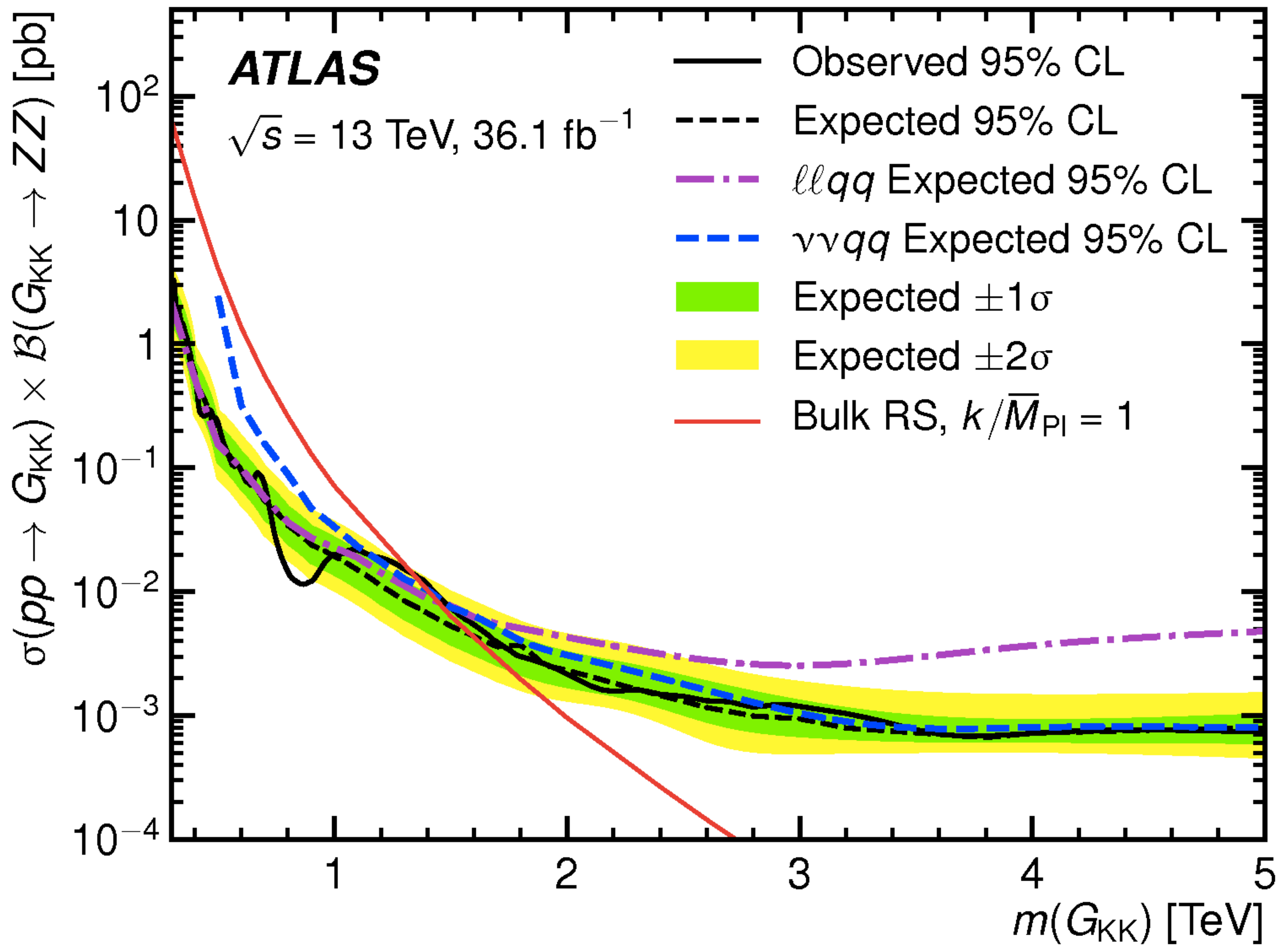
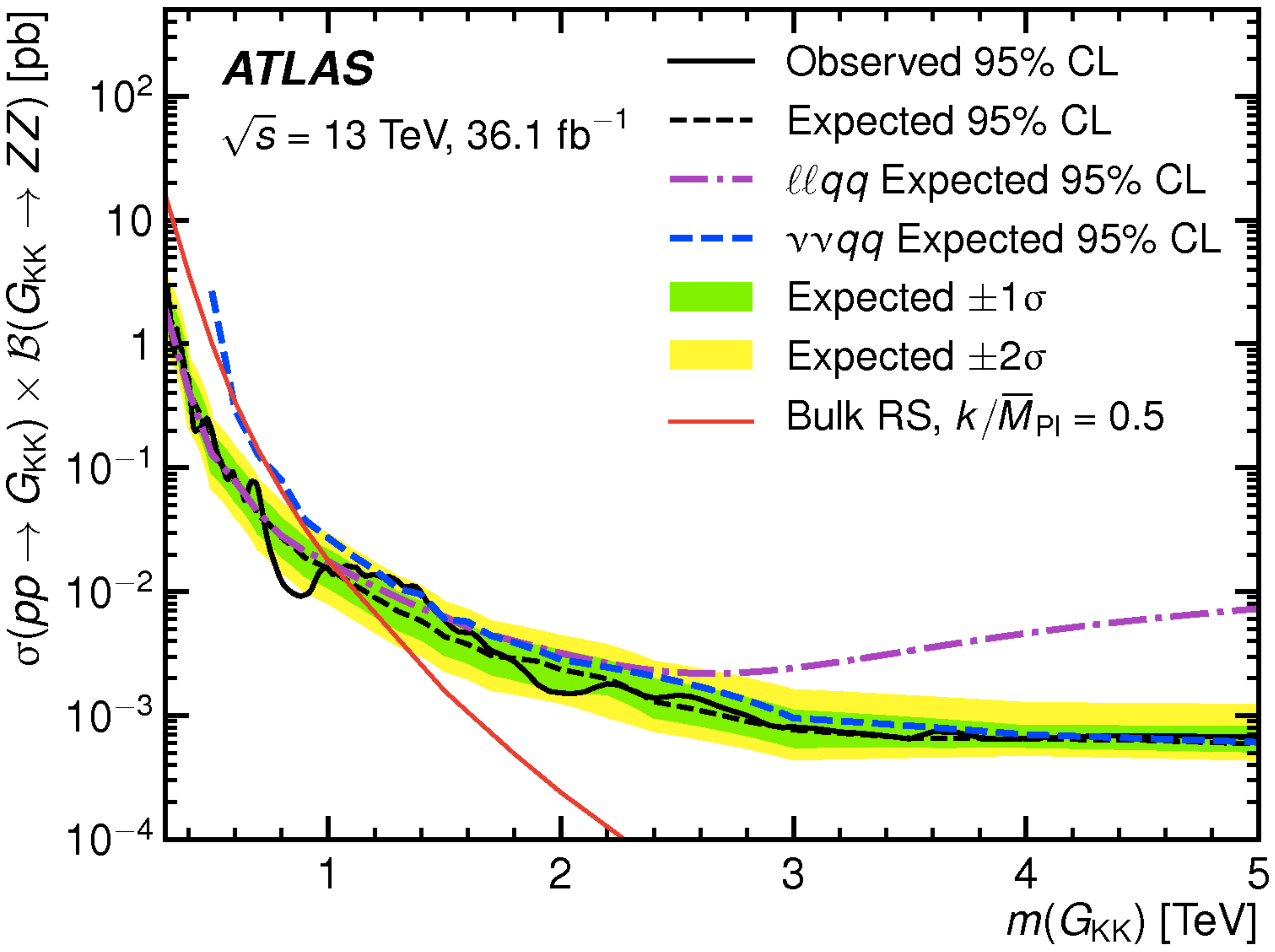


$m(G\mathrm{KK}) < 1.3$ TeV



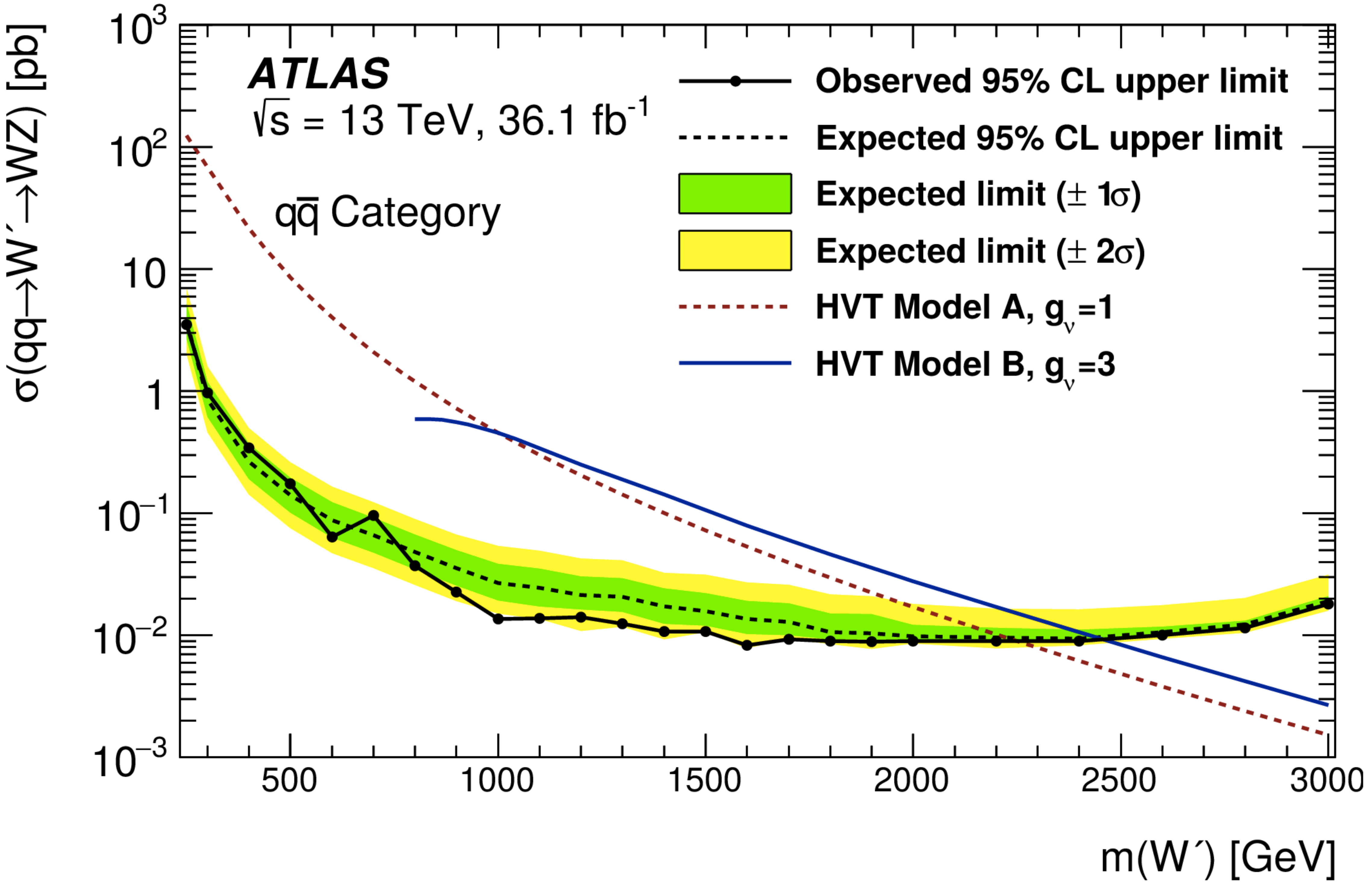
$m(G\mathrm{KK}) < 1$ TeV

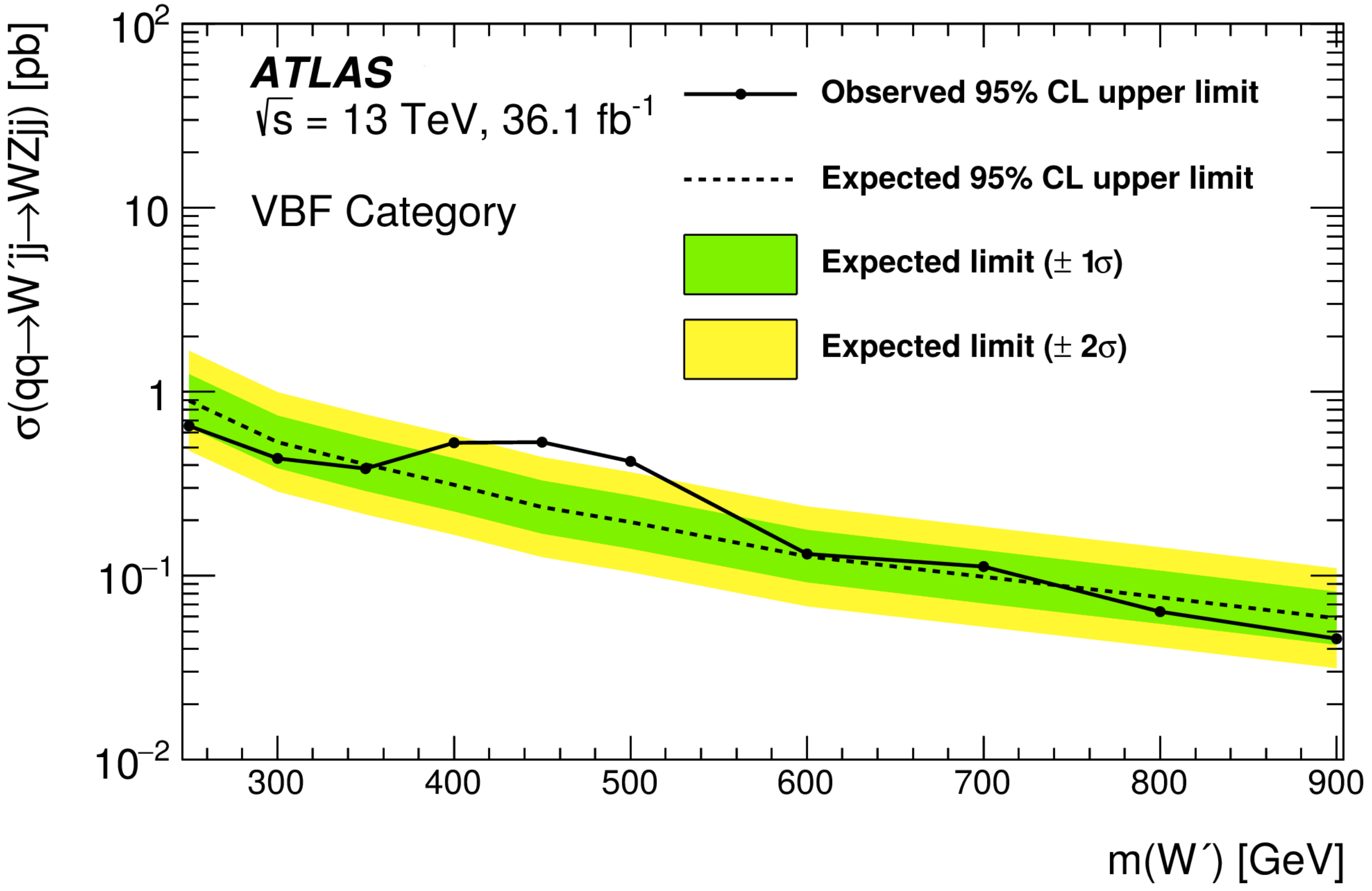
EXOT-2016-29

WZ full leptonic analysis

- Lower branching ratio with respect to other channels
  - ↪ Expected to be particularly sensitive to low-mass resonances as it has lower background

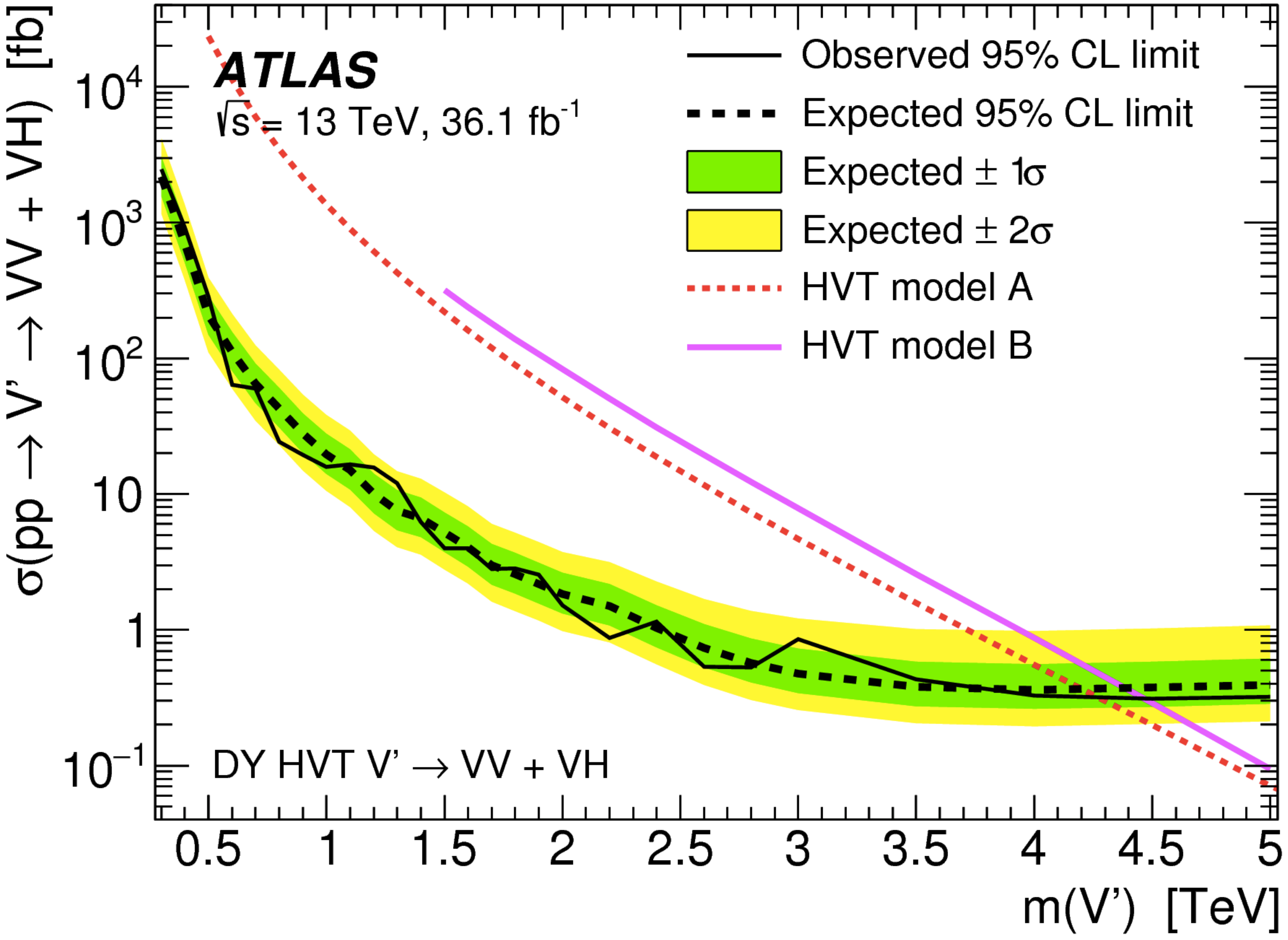
- Drell Yan/VBF categorization





EXOT-2016-11

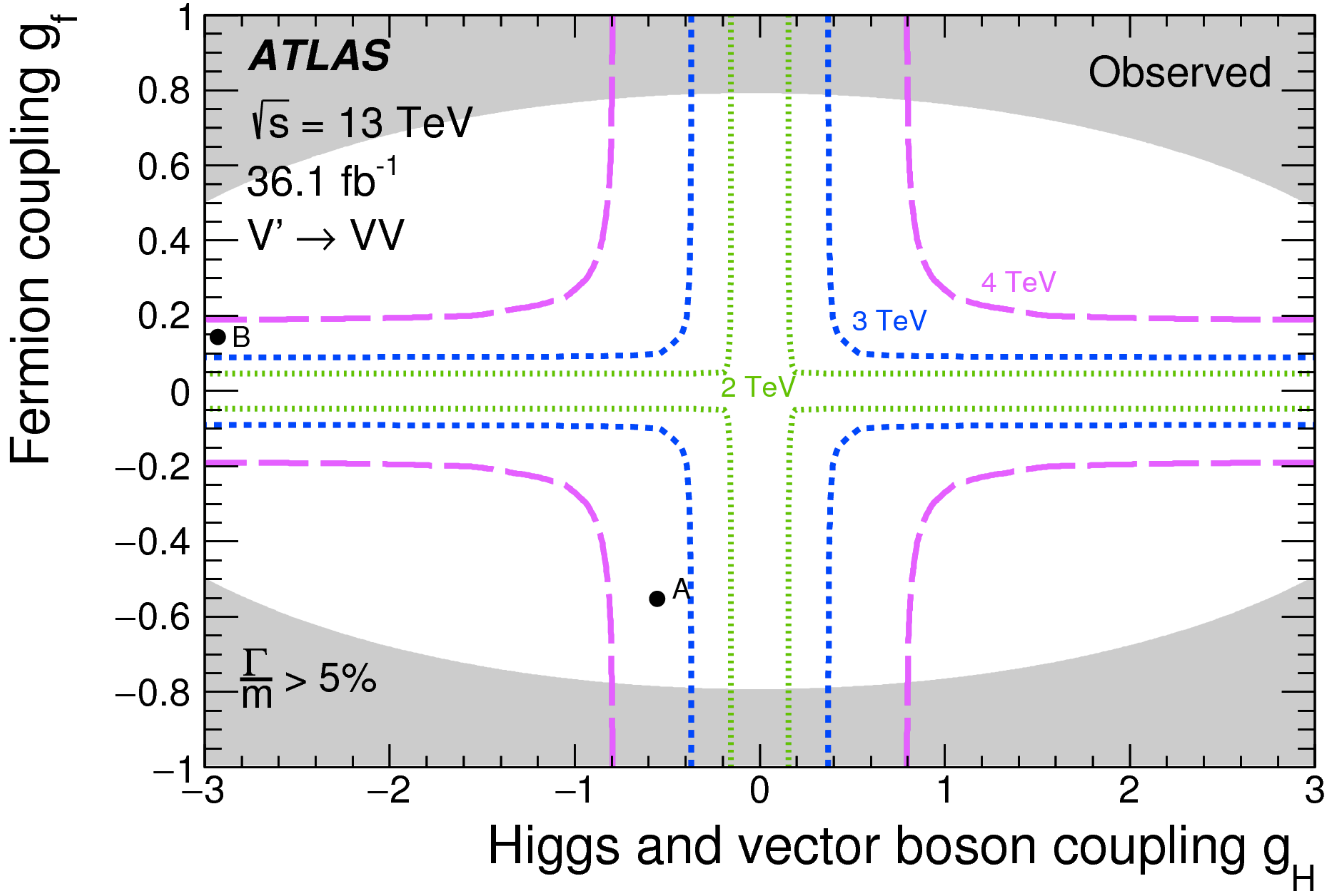
Combination VV + VH



Channel	Lower limits on resonance mass [TeV]					
	HVT model A		HVT model B		Bulk RS	
	Obs	Exp	Obs	Exp	Obs	Exp
WW	2.9	3.1	3.6	3.5	1.7	1.9
WZ	3.6	3.6	3.9	3.9	-	-
ZZ	-	-	-	-	1.5	1.7
VV	3.7	3.7	4.0	3.9	2.3	2.2
WH	2.6	2.8	2.8	3.1	-	-
ZH	2.7	2.5	2.8	2.8	-	-
VH	2.8	3.1	3.0	3.4	-	-
$\ell\nu$	4.6	4.6	-	-	-	-
$\ell\ell$	4.5	4.4	-	-	-	-
$\ell\nu/\ell\ell$	5.0	5.0	-	-	-	-
VV/VH	4.3	4.3	4.5	4.4	-	-
$VV/VH/\ell\nu/\ell\ell$	5.5	5.3	-	-	-	-

EXOT-2017-31

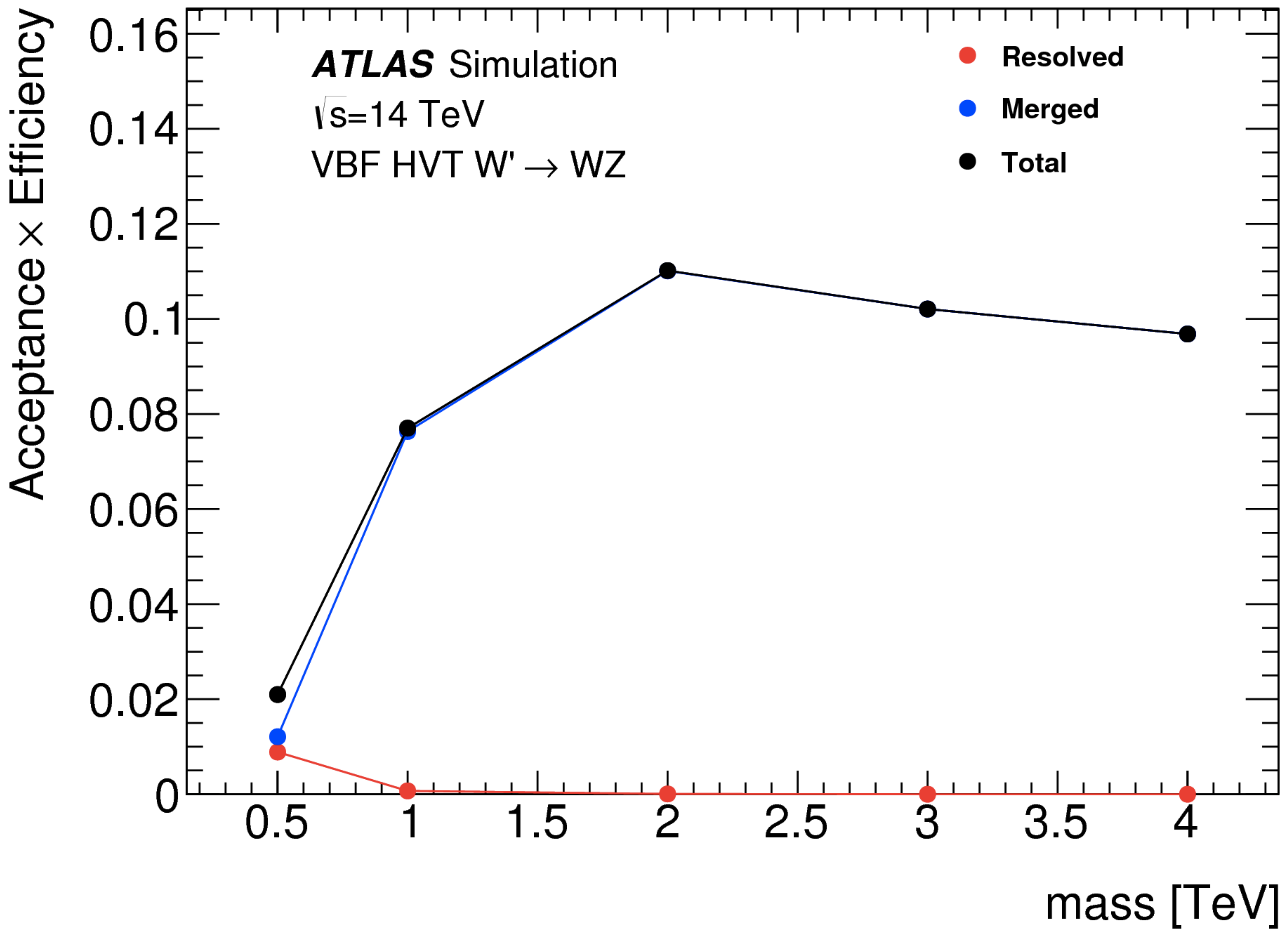
Combination VV + VH



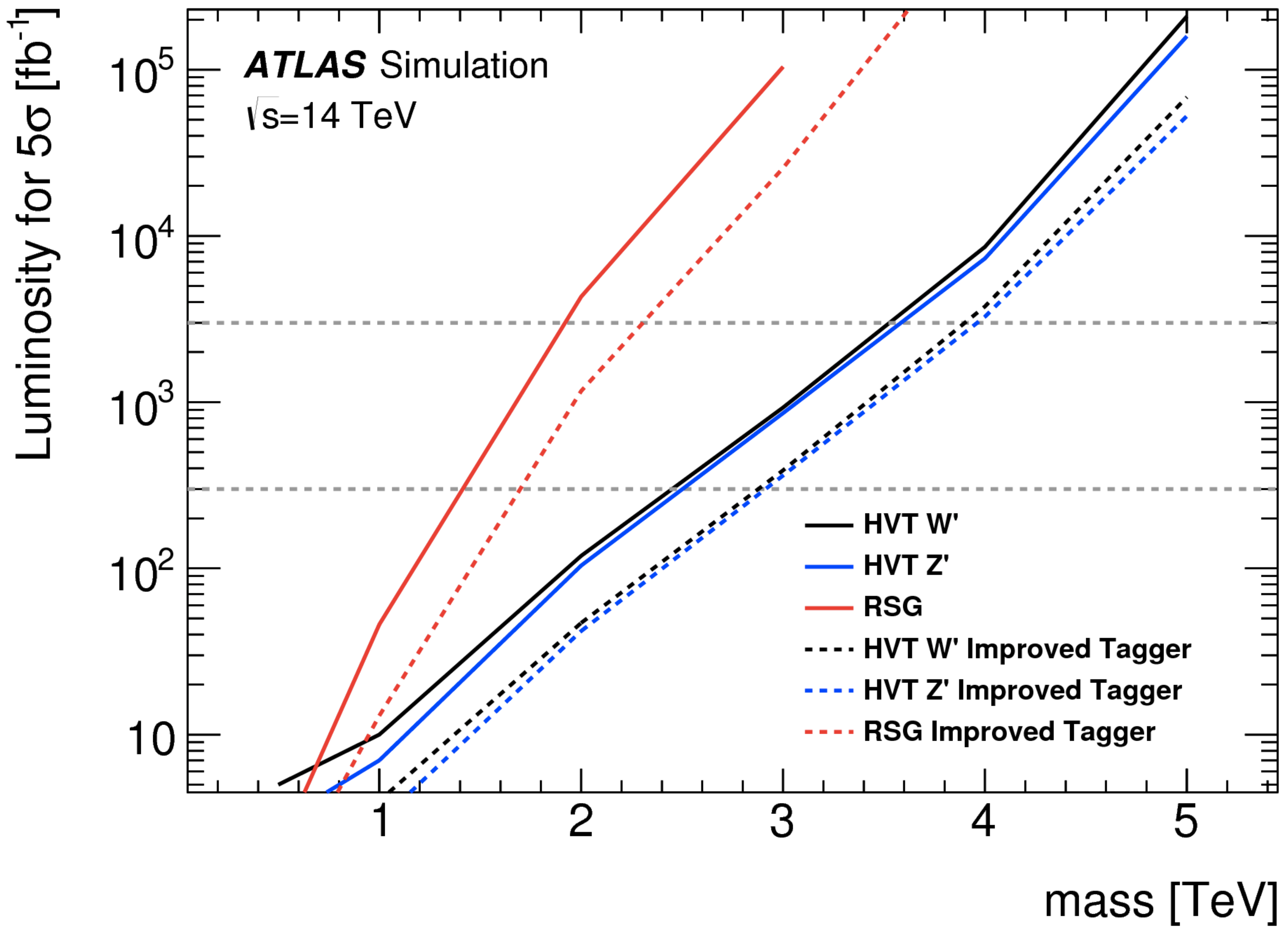
EXOT-2017-31

VV: future studies

HL-LHC



Merged regime dominant



Discovery potential if excess is observed

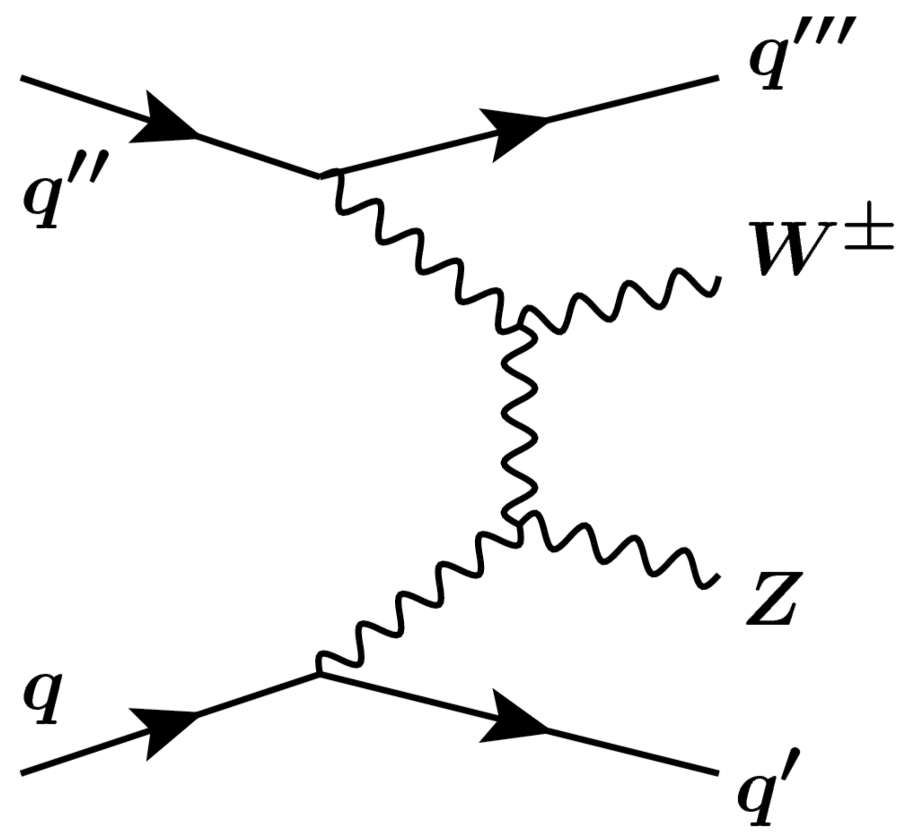
ATL-PHYS-PUB-2018-022

Vector Boson Scattering

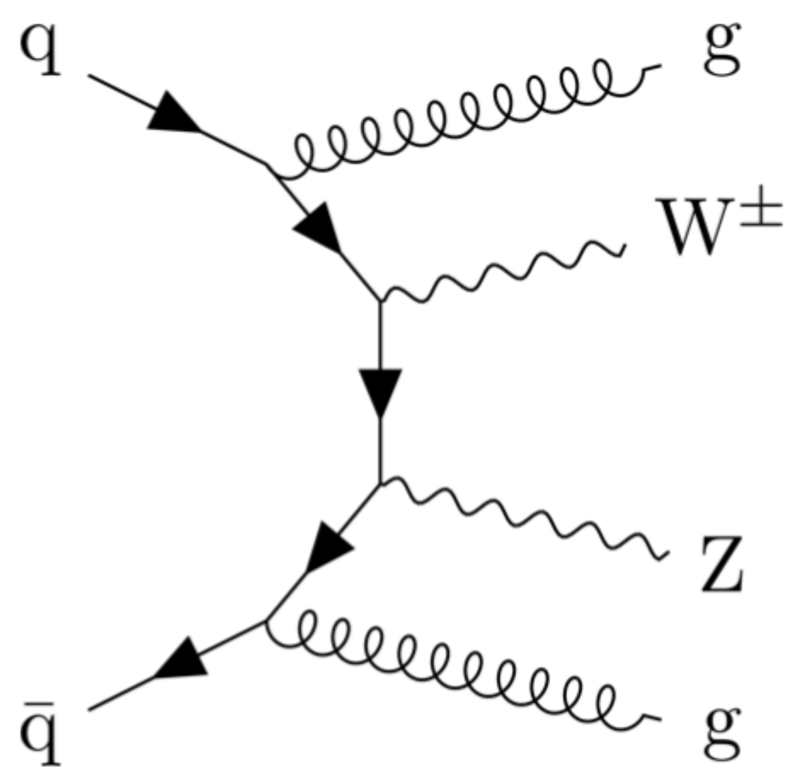
VBS: Motivation

- Vector Boson Scattering is important for understanding EW symmetry breaking
- Without the SM Higgs, longitudinal VV scattering cross section ($\sigma_{VV\rightarrow VV}$) increases as center-of-mass energy and violates unitarity at high energy
- Can be solved by adding contributions from Higgs
- VBS allows indirect search of New Physics by studying anomalous quartic gauge couplings (aQGC)

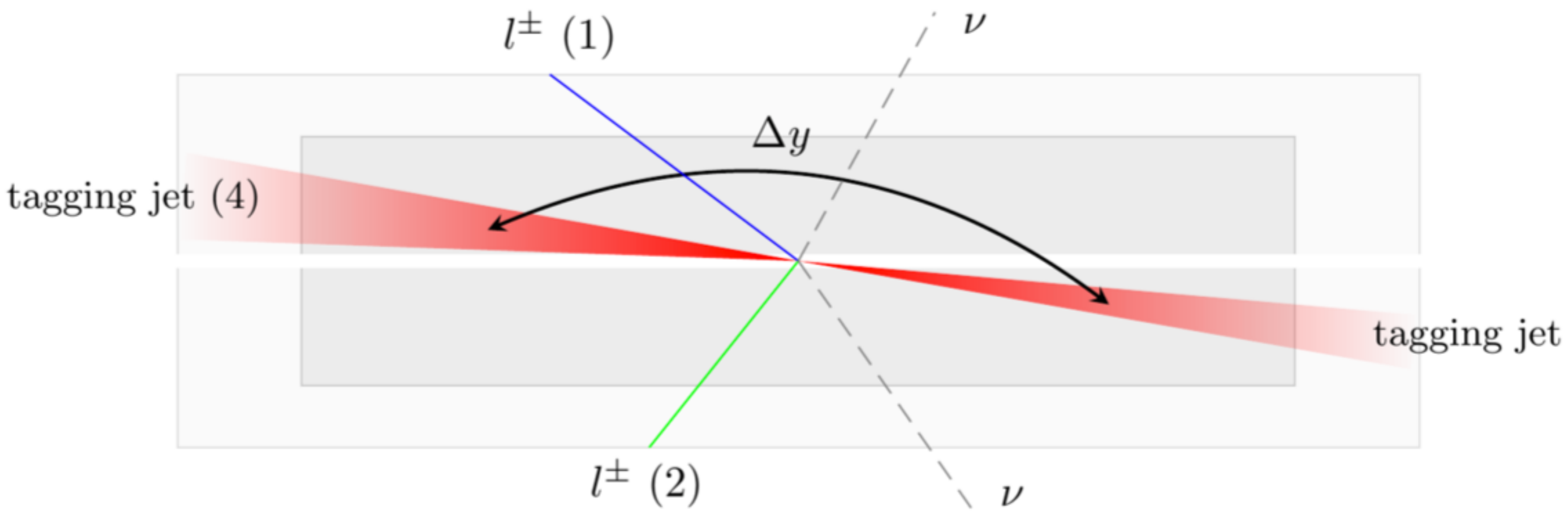
EW production $\mathcal{O}(\alpha^4)$

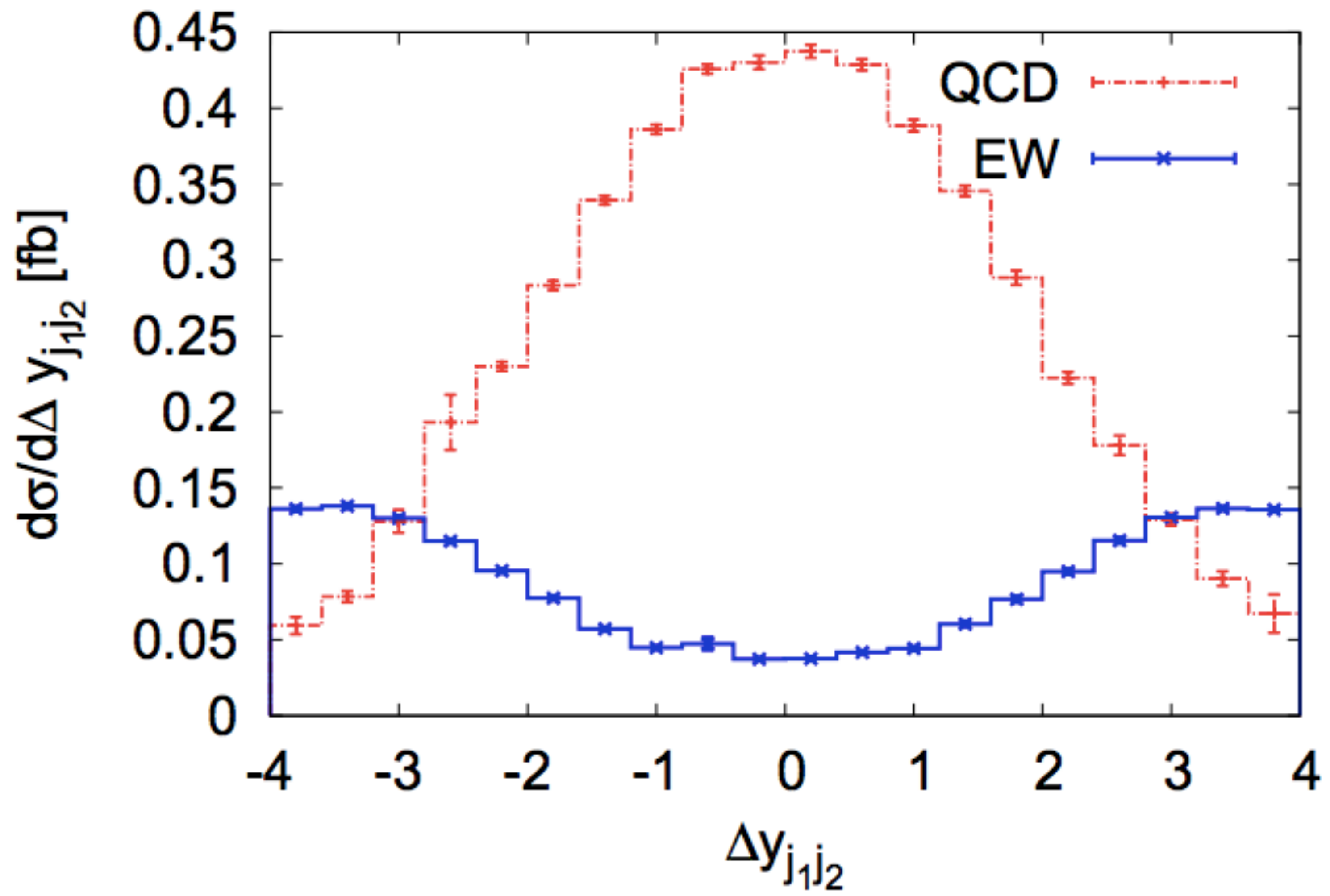


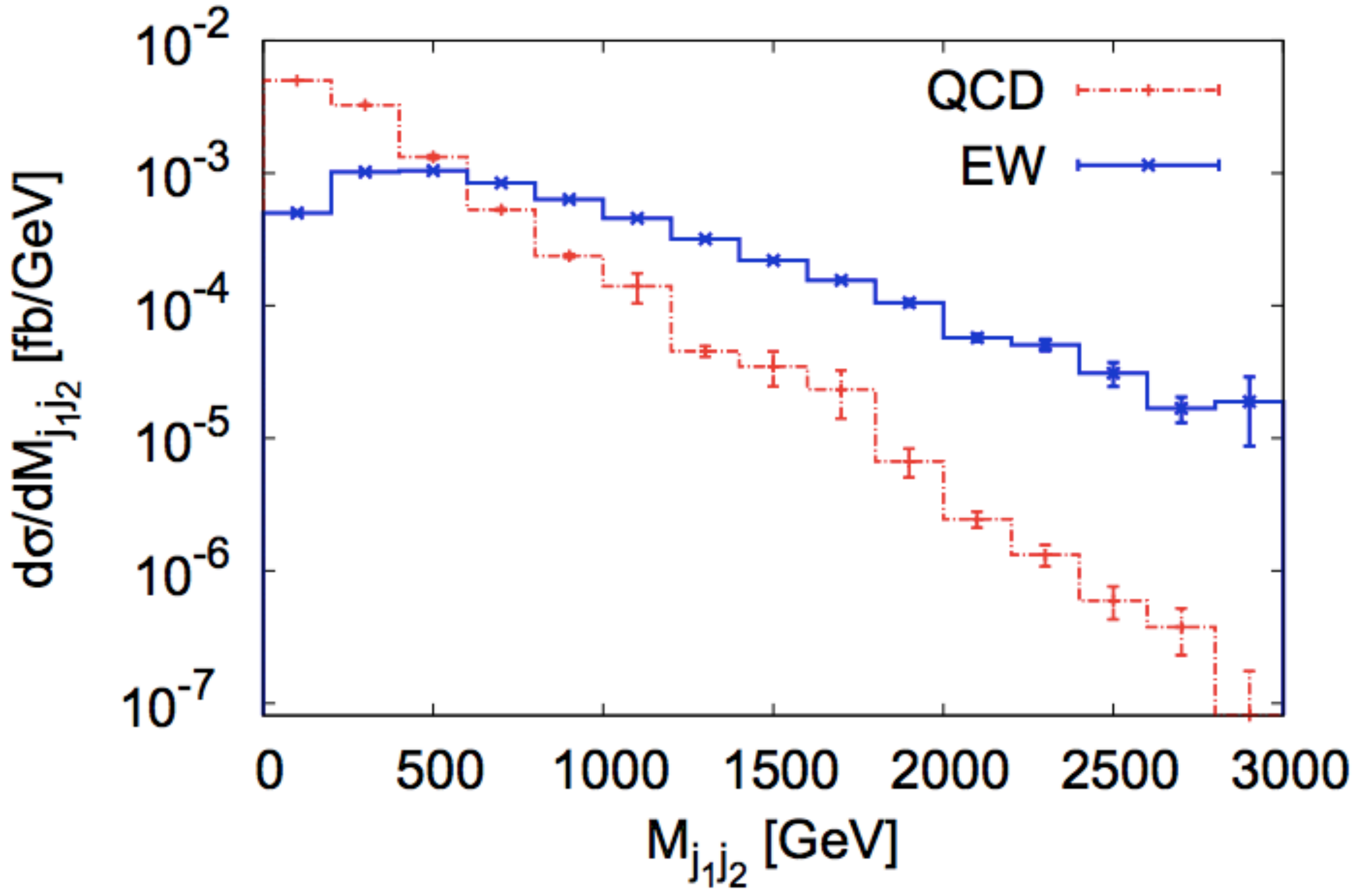
QCD-induced production $\mathcal{O}(\alpha^2\alpha_S^2)$



VBS: phenomenology







arXiv:1108.0864

- VBS has distinctive final states topology
  - Two hadronic jets in forward and backward regions with very high energy (tagging jets)
  - Hadronic activity suppressed between the two jets (rapidity gap) due to absence of color flow between. interacting partons.
  - Boson pair more central than in QCD processes

VBS: EW WZjj

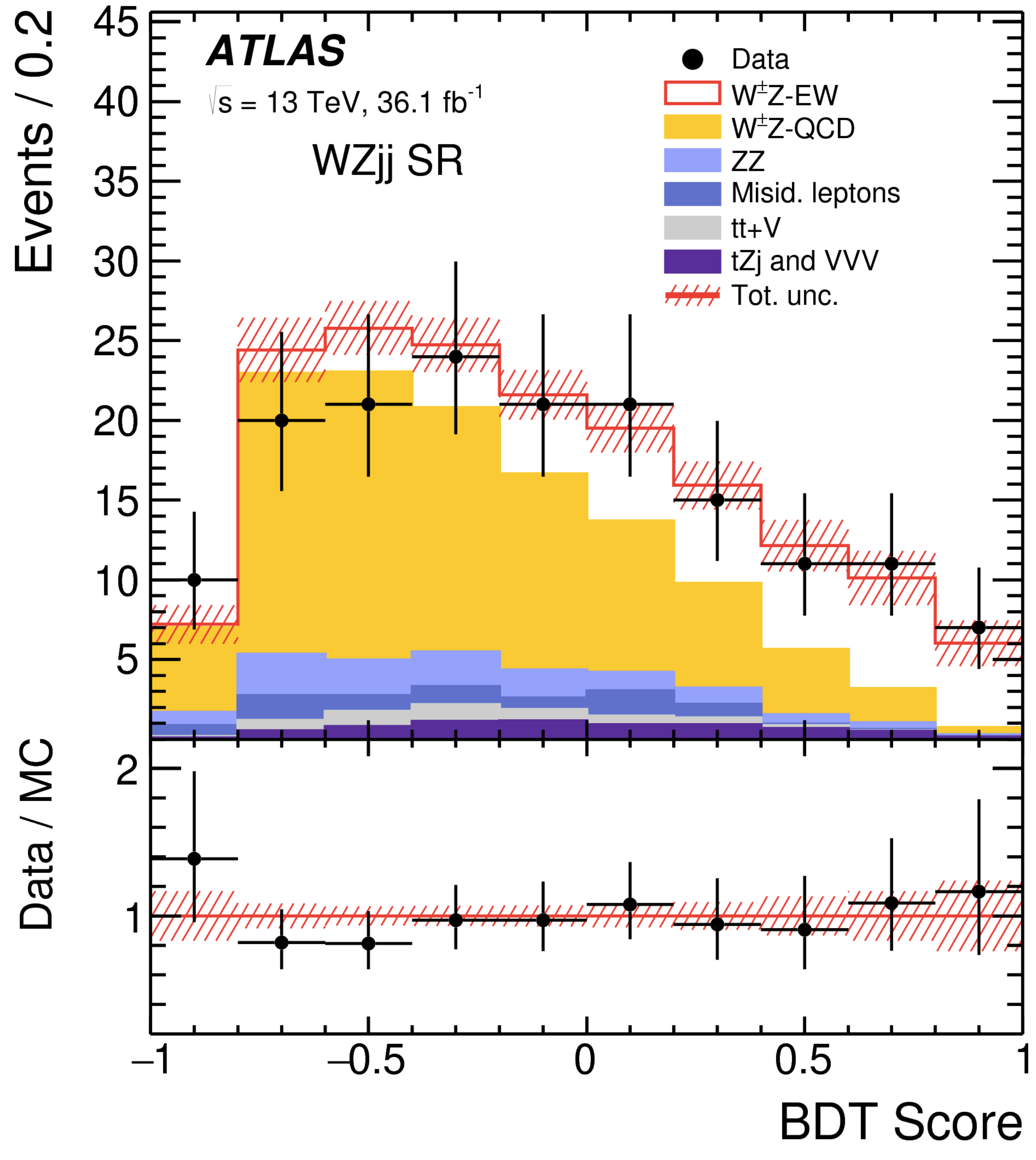
36 fb^{-1}

- Fully leptonic final state (ℓℓℓν)

- A BDT is trained in signal region to separate WZjj-EW signal from WZjj-QCD and other backgrounds
  - ↪BDT build from 15 discriminant variables
  - ↪Variables related to the kinematics of tagging jets
  - ↪Variables related to the kinematics of vector bosons
  - ↪Variables related to both leptons and jets kinematics

- Irreducible background: All candidates are prompt leptons or produced in the decay of tau (Main sources of backgrounds)
  - ↪ $W^{\pm}$Zjj QCD, ZZ, tt + V, tZj, VVV

- Reducible background: at least one of the candidate leptons is not a prompt lepton
  - ↪Z+j, Zγ, tt, Wt and WW
  - ↪Data driven matrix method



STDM-2017-23

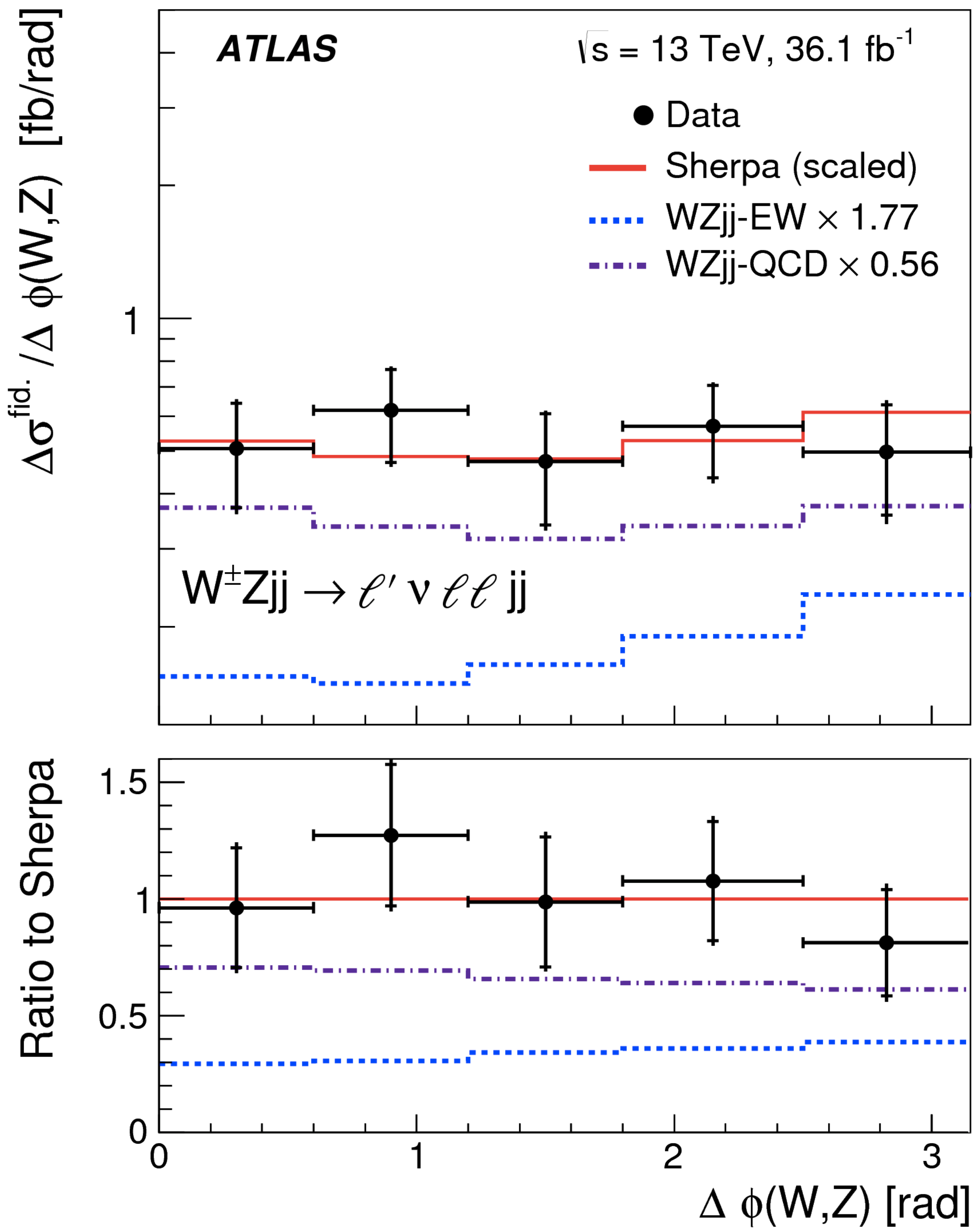
VBS: EW WZjj

36 fb^{-1}

- Signal is extracted with a maximum-likelihood fit of BDT score distribution in SR
- 5.3σ observed
- Fiducial cross section

$$\sigma_{WZjj\text{-EW}} = 0.57\ ^{+0.14}_{-0.13}\,(\text{stat.})\ ^{+0.05}_{-0.04}\,(\text{exp. syst.})\ ^{+0.05}_{-0.04}\,(\text{mod. syst.})\ ^{+0.01}_{-0.01}\,(\text{lumi.})\ \text{fb}$$

- Differential cross section for 8 variables
  - ↪Variables sensitive to anomalous quartic gauge coupling
  - ↪Variables for model constrains:

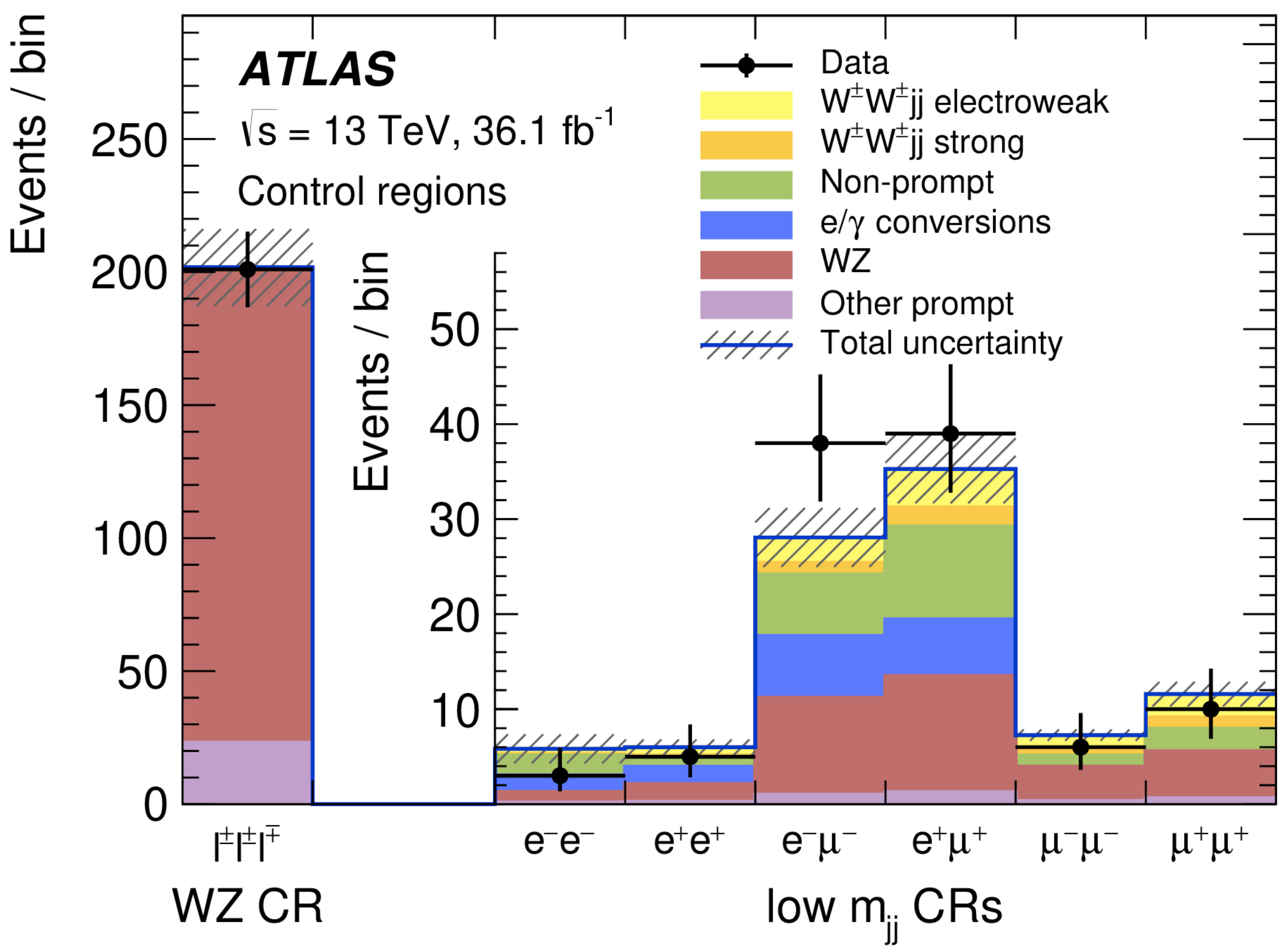


STDM-2017-23

VBS: EW $W^{\pm}W^{\pm}jj$

36 fb^{-1}

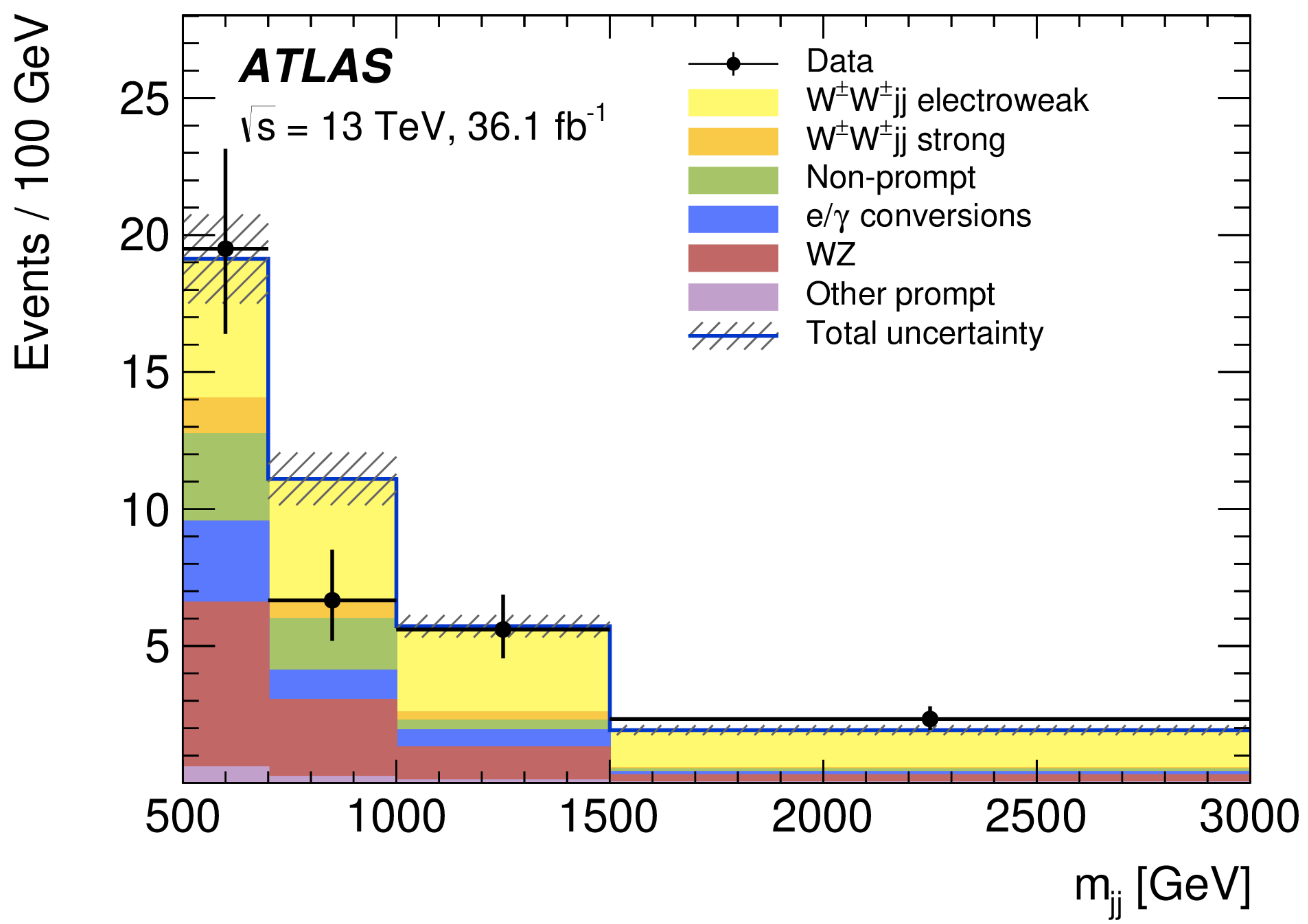
- Channel with largest ratio of electroweak to strong production cross sections compared to other VBS diboson processes
  - ↪ quark-gluon and gluon-gluon initiated diagrams are absent and contributions from quark and (anti-)quark annihilation diagrams are suppressed
- Fully leptonic final state
- Main background contributions:
  - ↪ Processes with two real prompt same-charge leptons, mainly W±Z+jets
  - ↪ Experimental backgrounds: Processes with non-prompt ("fake") leptons from mis-identified jets, or leptons from hadron decays
  - ↪ Processes with electron charge mis-identification



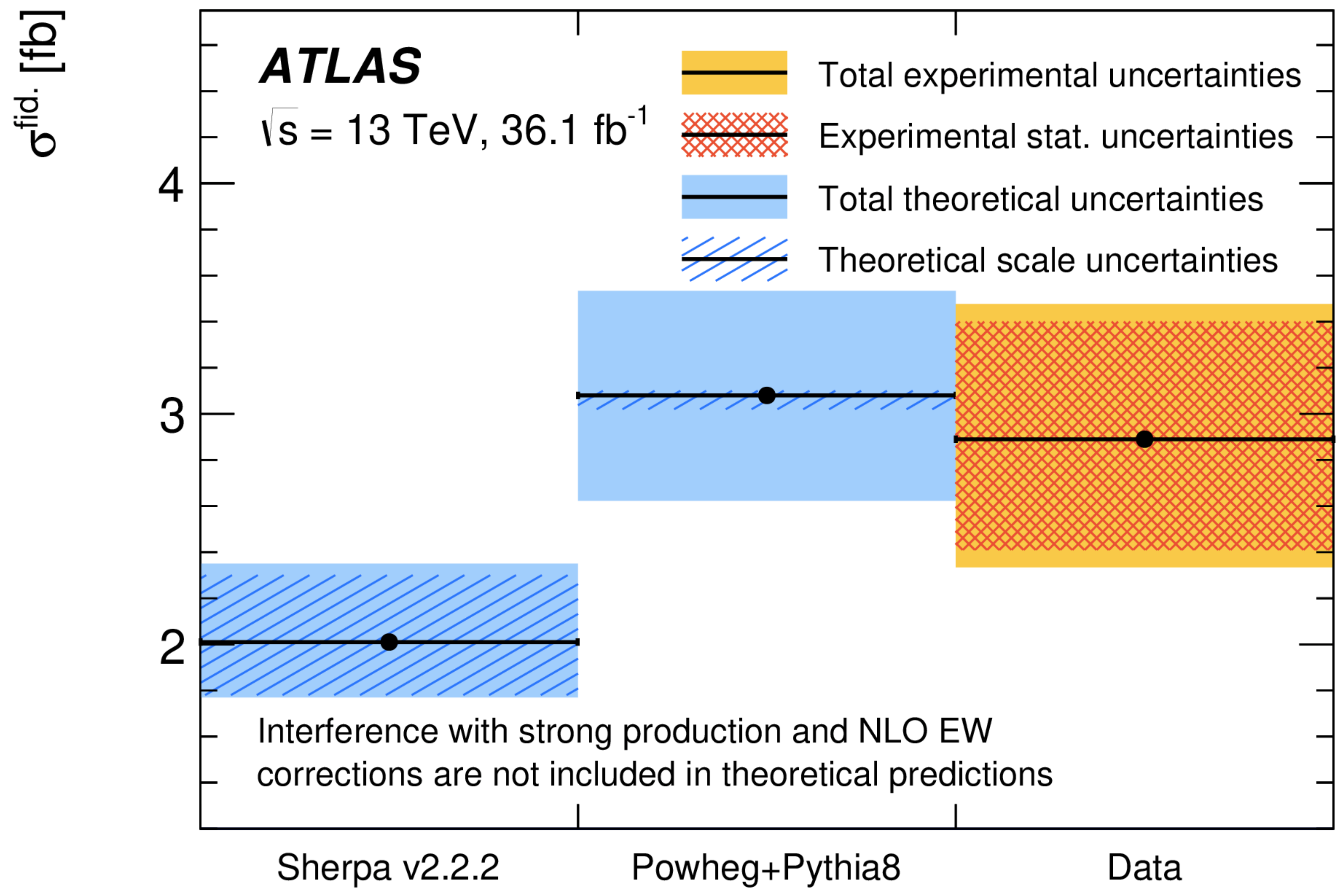
STDM-2017-06

VBS: EW W±W±jj

36 fb^{-1}



6.5σ observed



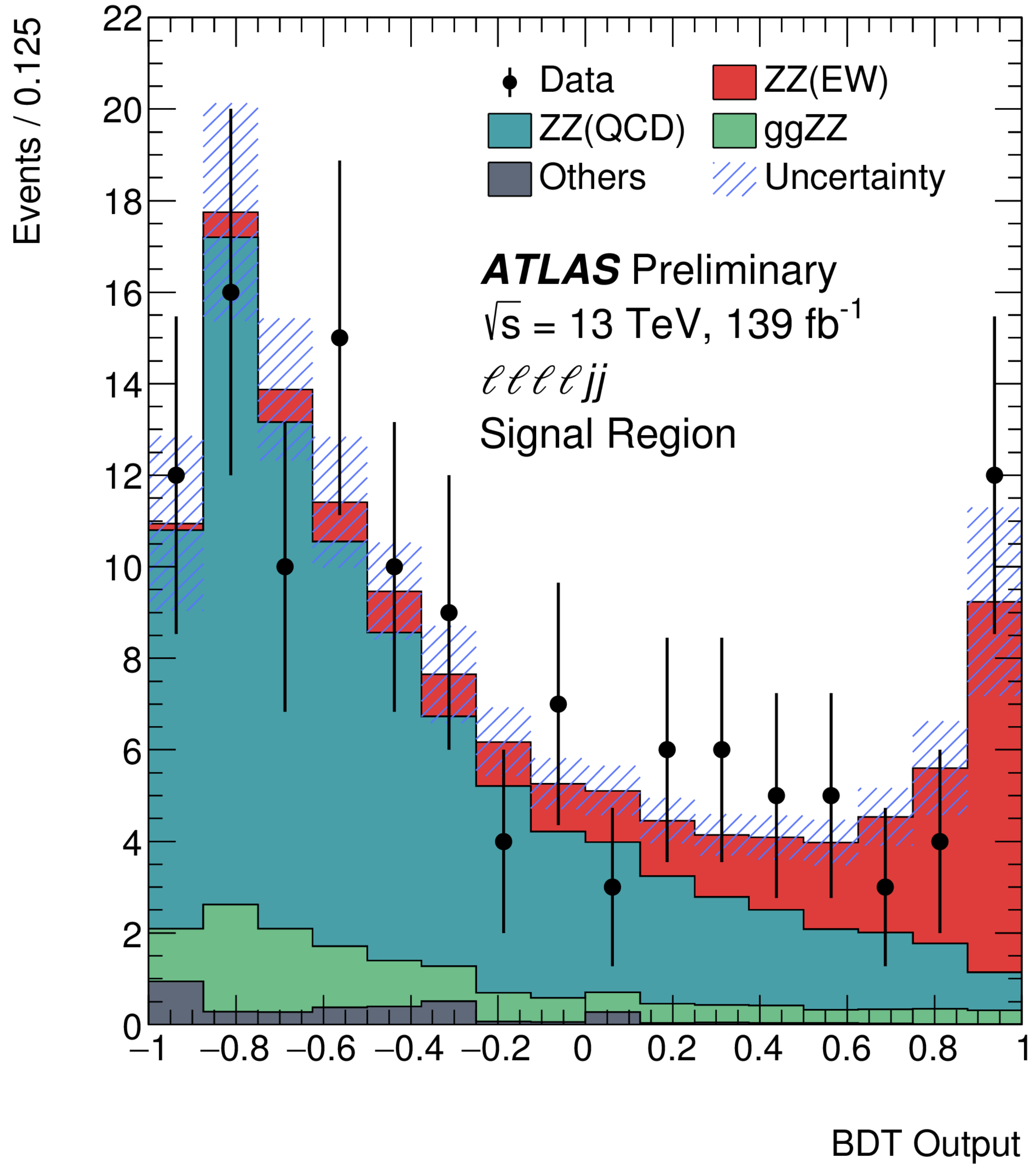
$\sigma^{fid} = 2.91^{+0.51}_{-0.47}$(stat.) ± 0.27(sys.) fb

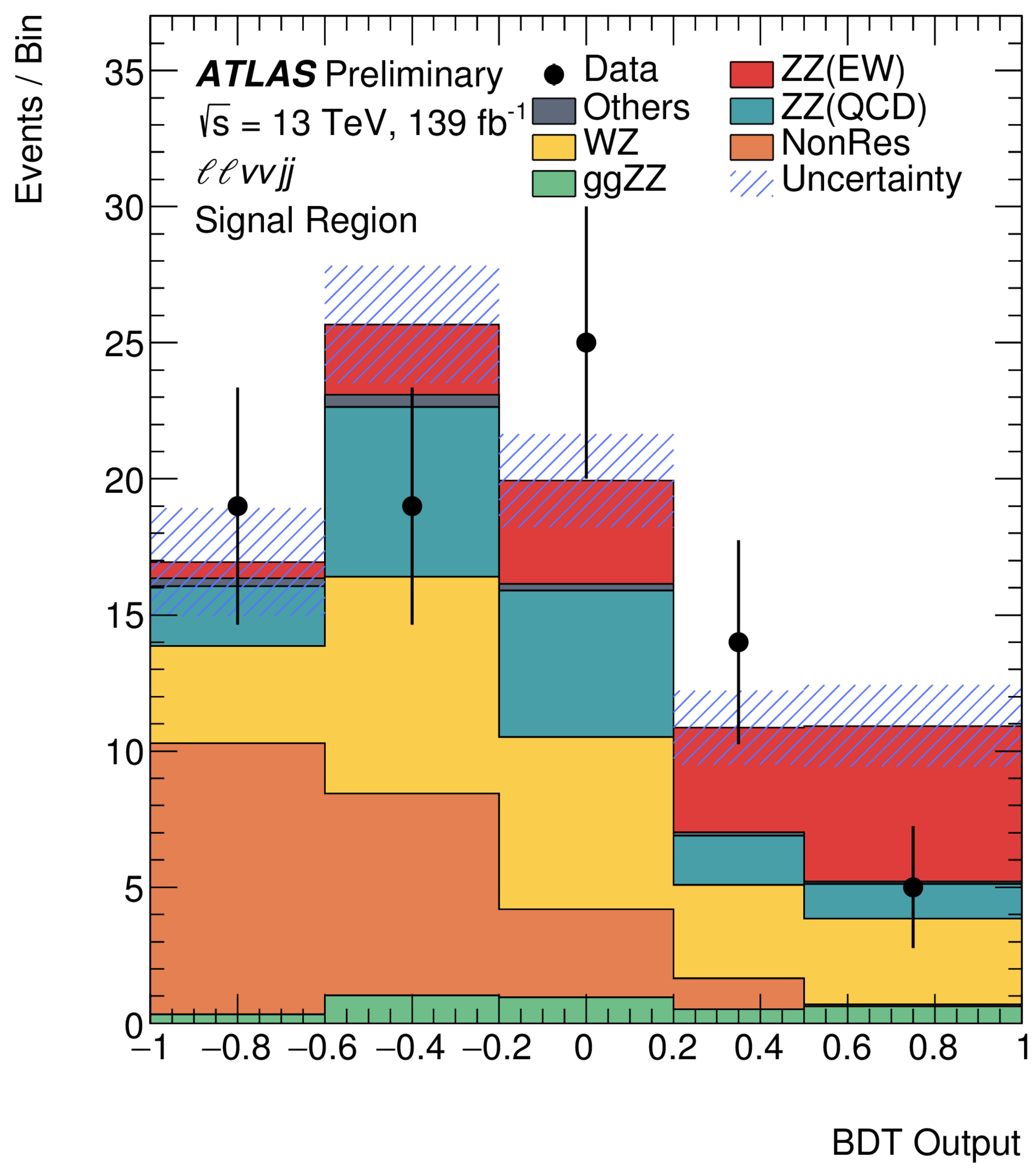
STDM-2017-06

VBS: EW ZZjj

139 fb^{-1}

- Based on full Run-2 dataset
- Includes 4ℓ and 2ℓ2ν channels
- BDT trained to distinguish the kinematic differences between signal and backgrounds
  - ↪ 12 input variables in the 4ℓ channel
  - ↪ 13 input variables in the 2ℓ2ν channel
  - ↪ Simultaneous fit in the two channels
- 5.52σ observed when combining channels





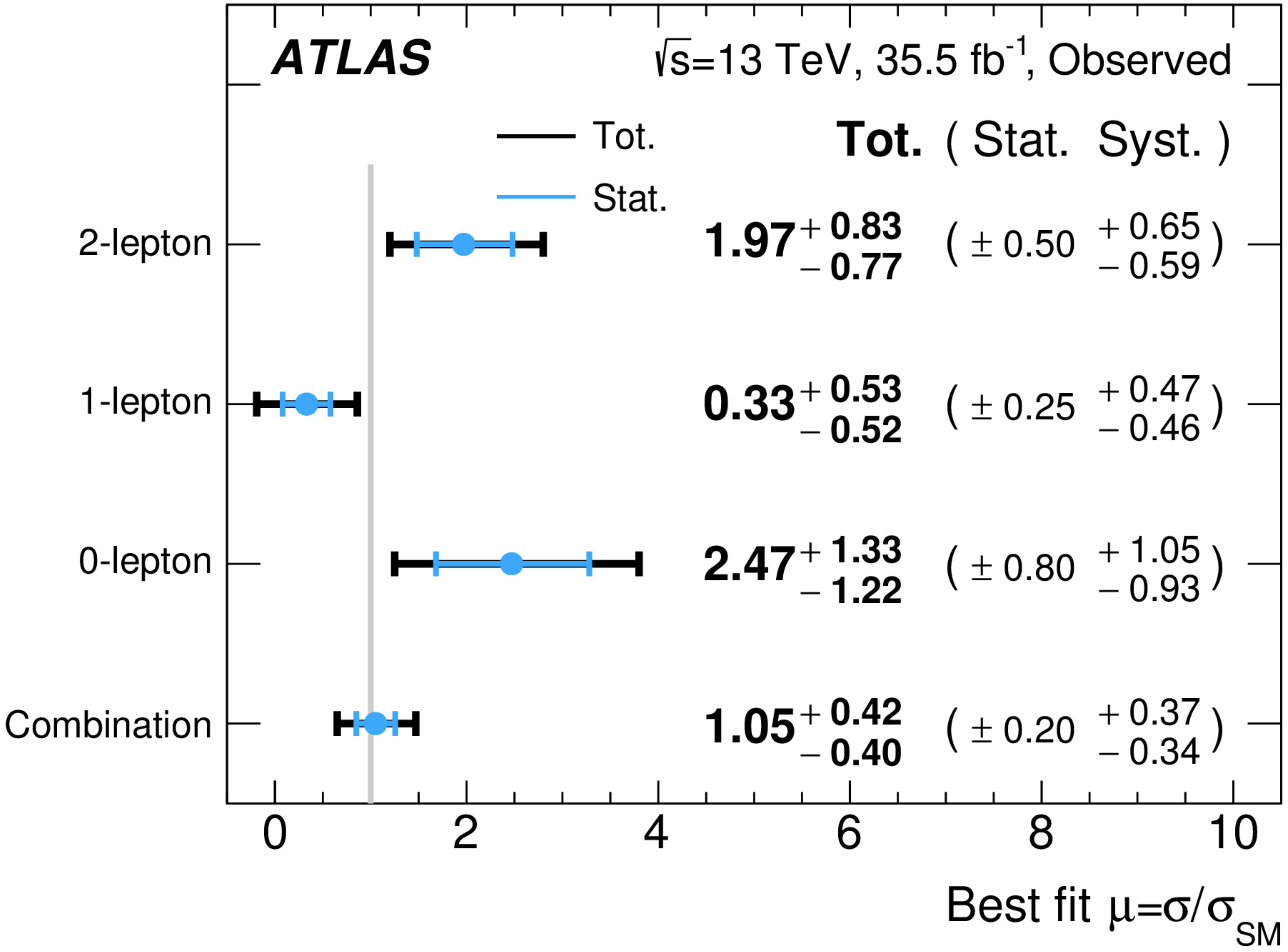
	μ_{EW}	$\mu_{\text{QCD}}^{\ell\ell\ell\ell jj}$	Significance Obs. (Exp.)
$\ell\ell\ell\ell jj$	1.54 ± 0.42	0.95 ± 0.22	$5.48\ (3.90)\ \sigma$
$\ell\ell\nu\nu jj$	0.73 ± 0.65	-	$1.15\ (1.80)\ \sigma$
Combined	1.35 ± 0.34	0.96 ± 0.22	$5.52\ (4.30)\ \sigma$

ATLAS-CONF-2019-033

VBS: EW VVjj semileptonic

36 fb^{-1}

- 3 channels explored
  - ↪ 0 lepton: Z(→νν)jj
  - ↪ 1 lepton: W(→ℓν)jj
  - ↪ 2 lepton: Z(→ℓℓ)jj
- Resolved and merged region definitions
- Multivariate approach: BDTs are constructed, trained and evaluated in each lepton channel and analysis region separately
- 2.7σ observed when combining channels

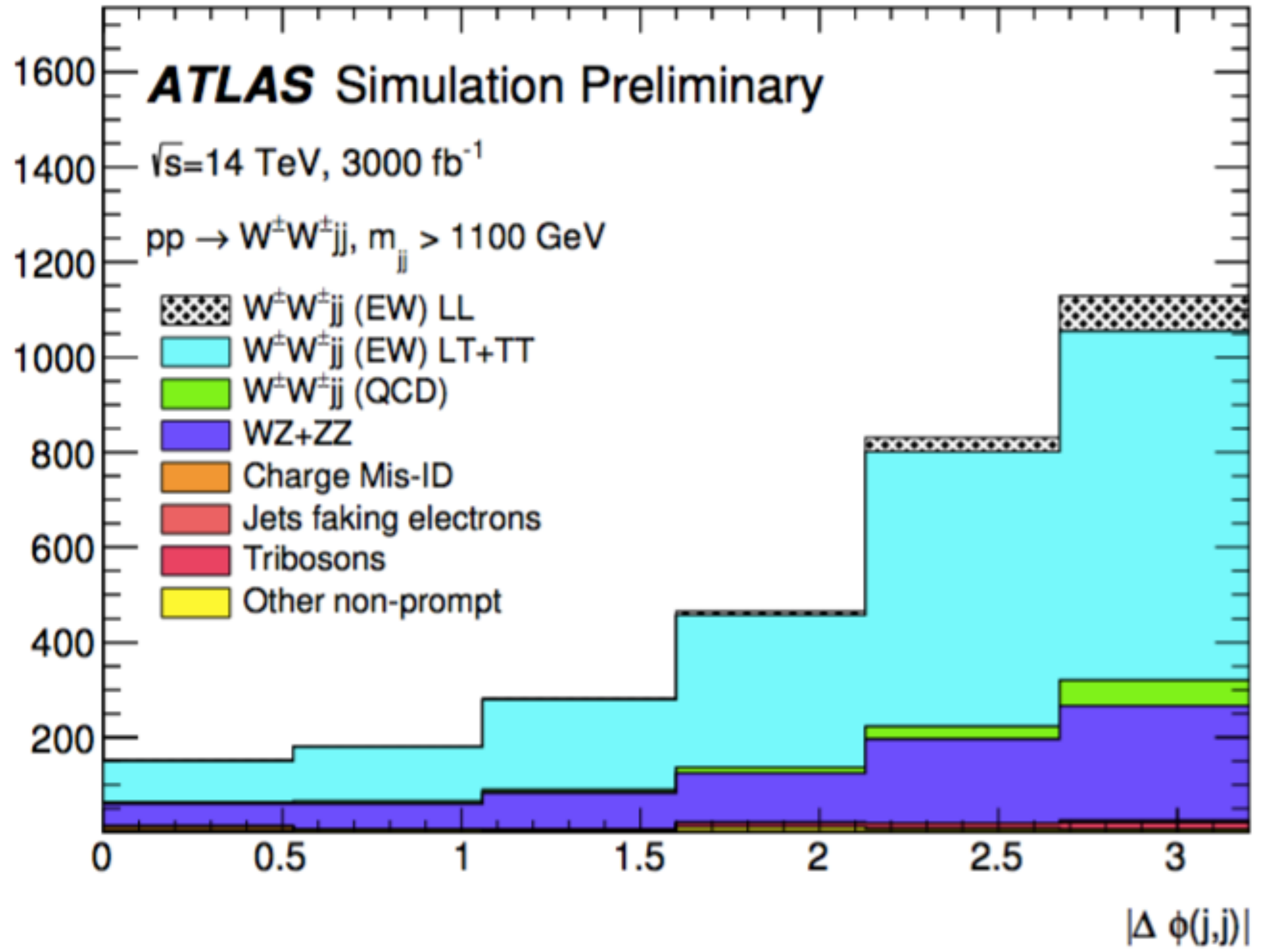


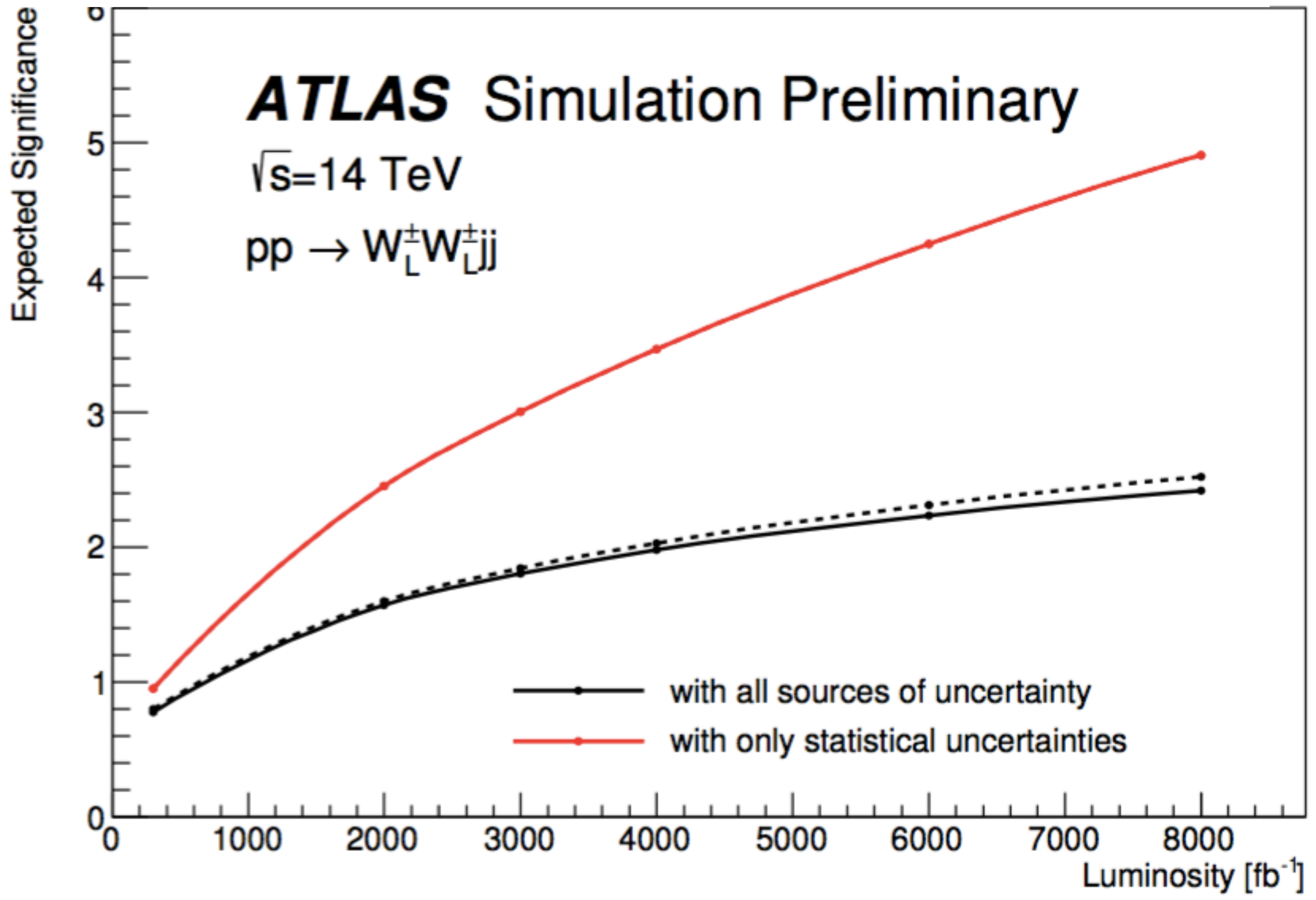
STDM-2017-20

VBS: future studies

HL-LHC

- The total $W^{\pm}W^{\pm}jj$ VBS cross section can be decomposed into the polarized components based on the decays of the individual W bosons
- $W_L^{\pm}W_L^{\pm}jj$ is expected to be only about 6-7% of the total VBS cross sections
  - ↪ W_LW_L diverges if there is no Higgs boson or the Higgs boson is too heavy
- Theoretical models with composite Higgs bosons
  - ↪ measurement of the longitudinal polarization will tell us the 125 GeV boson unitarizes scattering fully or only partially
- $\Delta\phi_{jj}$ difference between the two leading jets able to discriminate the LL component from TT and LT contributions
- 2.7σ for 3000 fb-1
  - ↪ A combination between ATLAS and CMS could reach 3σ with 2000 fb-1
  - ↪ Machine Learning techniques could improve the prospects

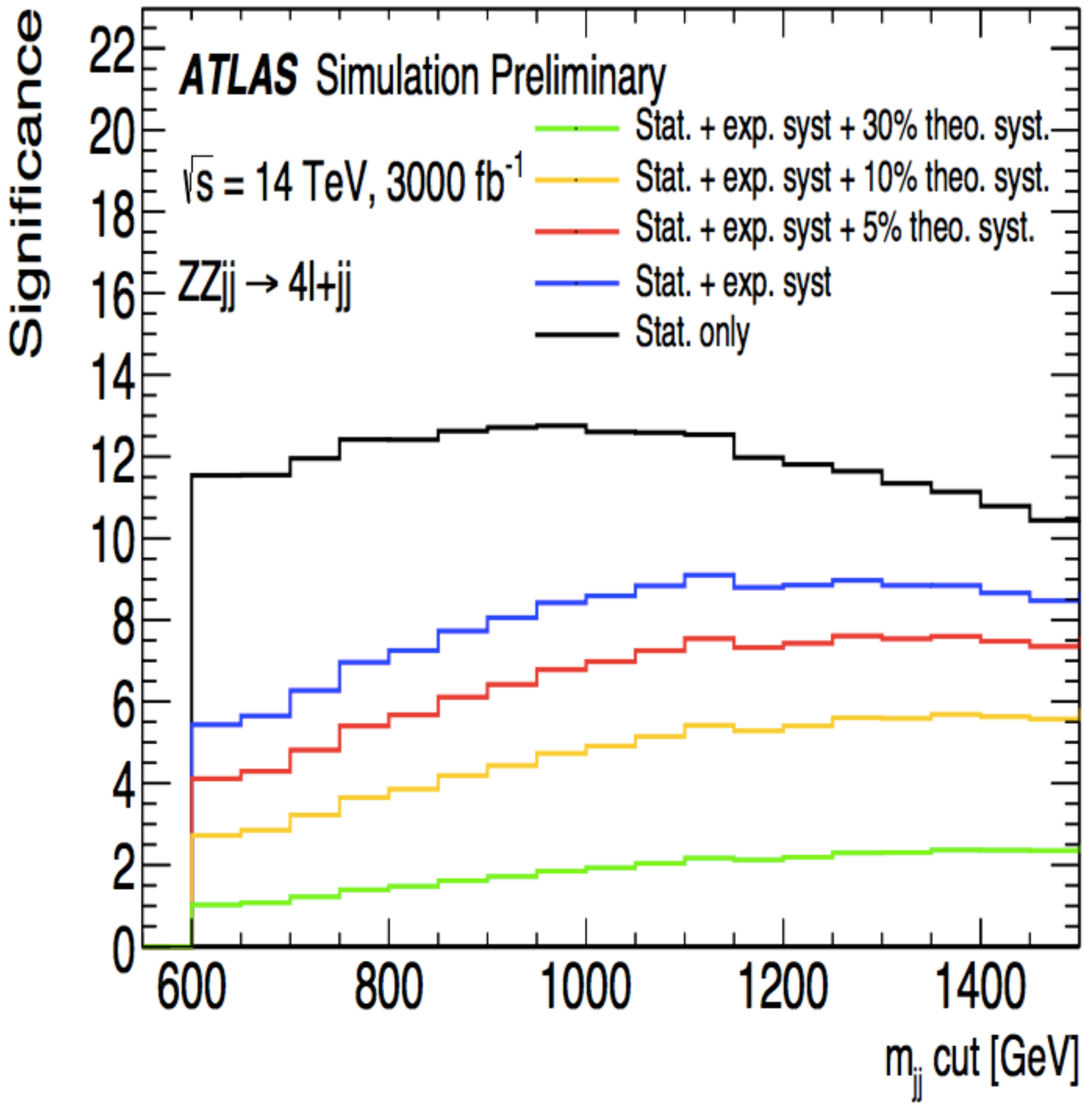




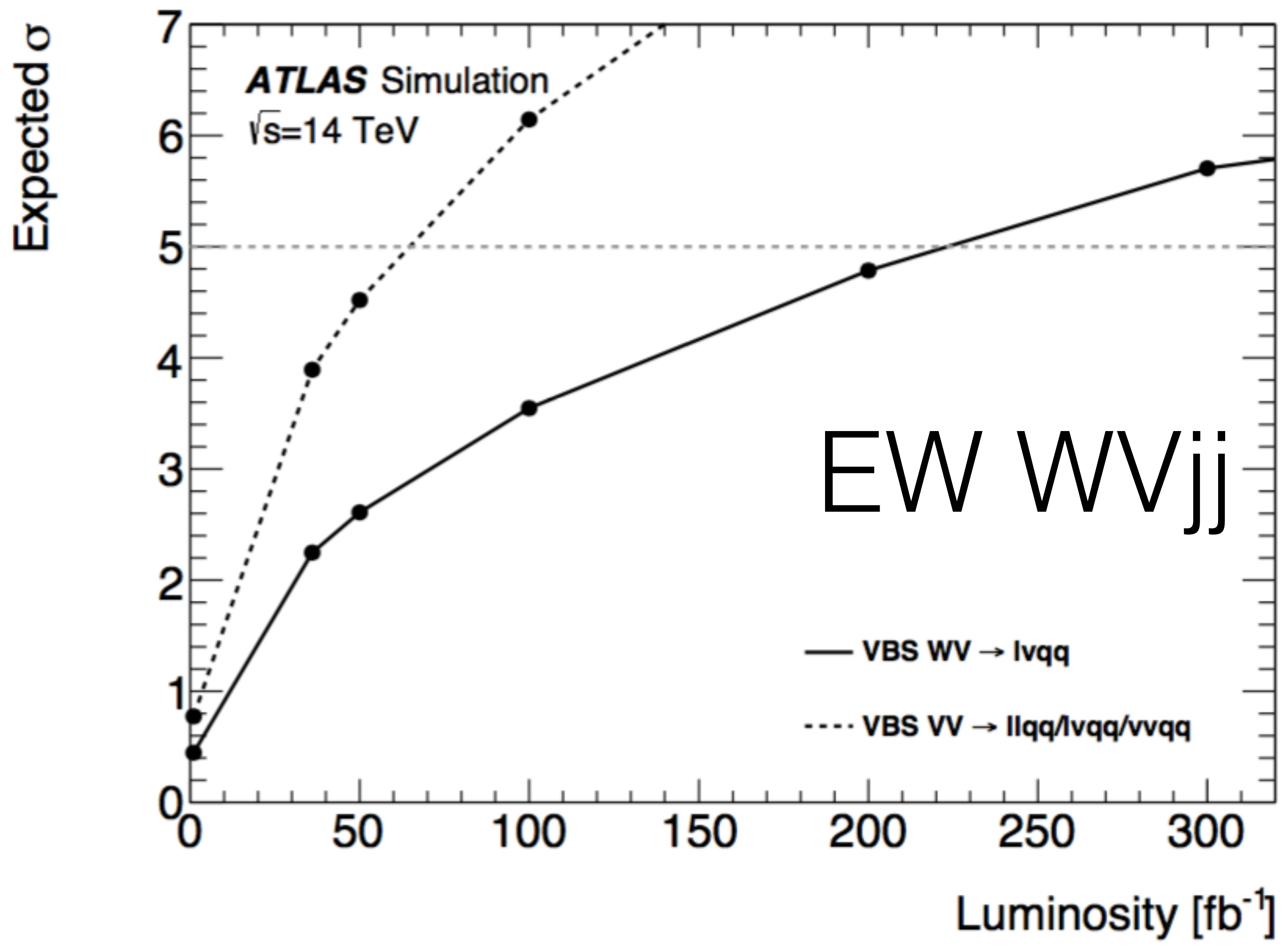
ATL-PHYS-PUB-2018-022

VBS: future studies

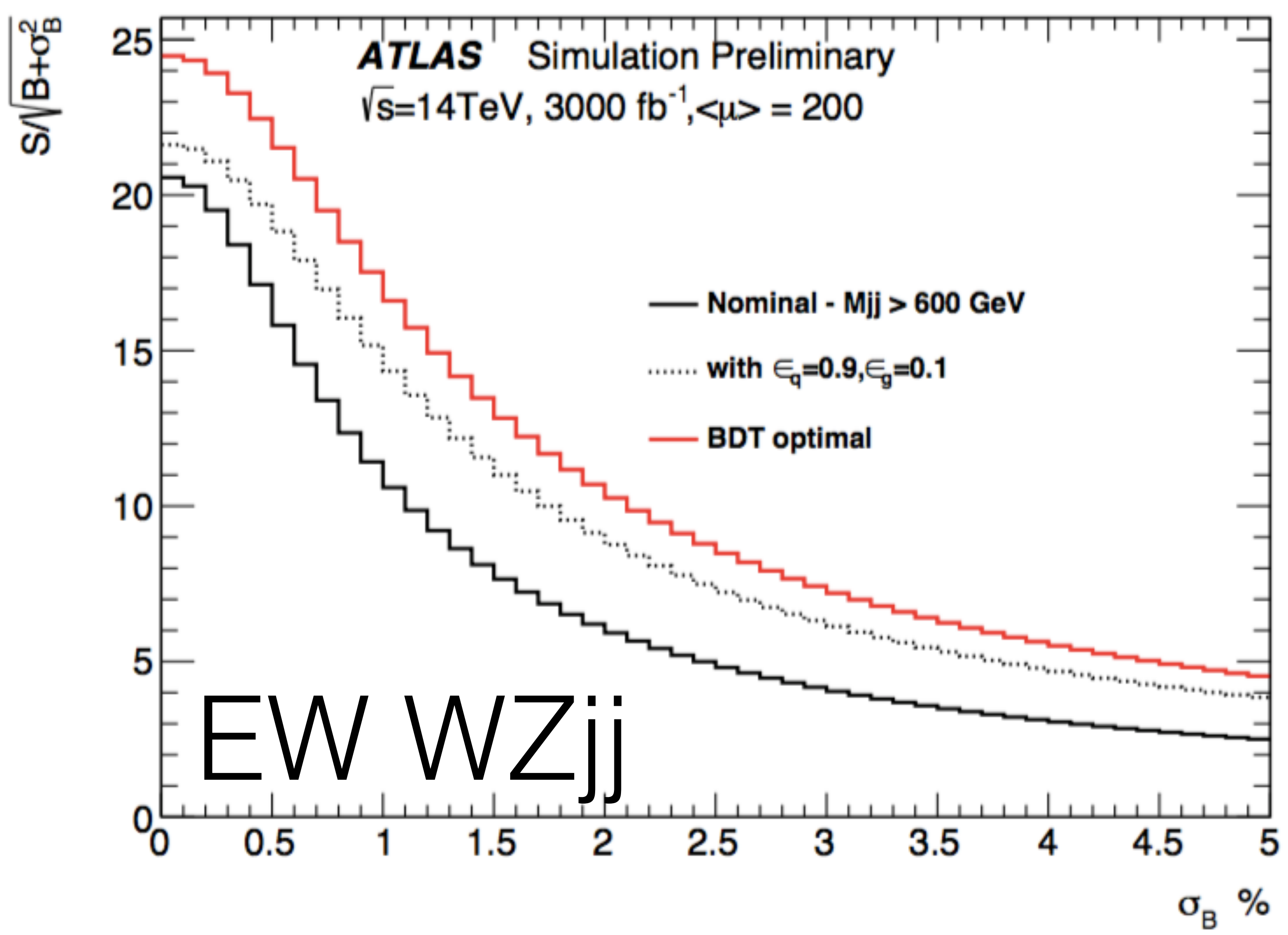
HL-LHC



EW ZZjj



EW WVjj



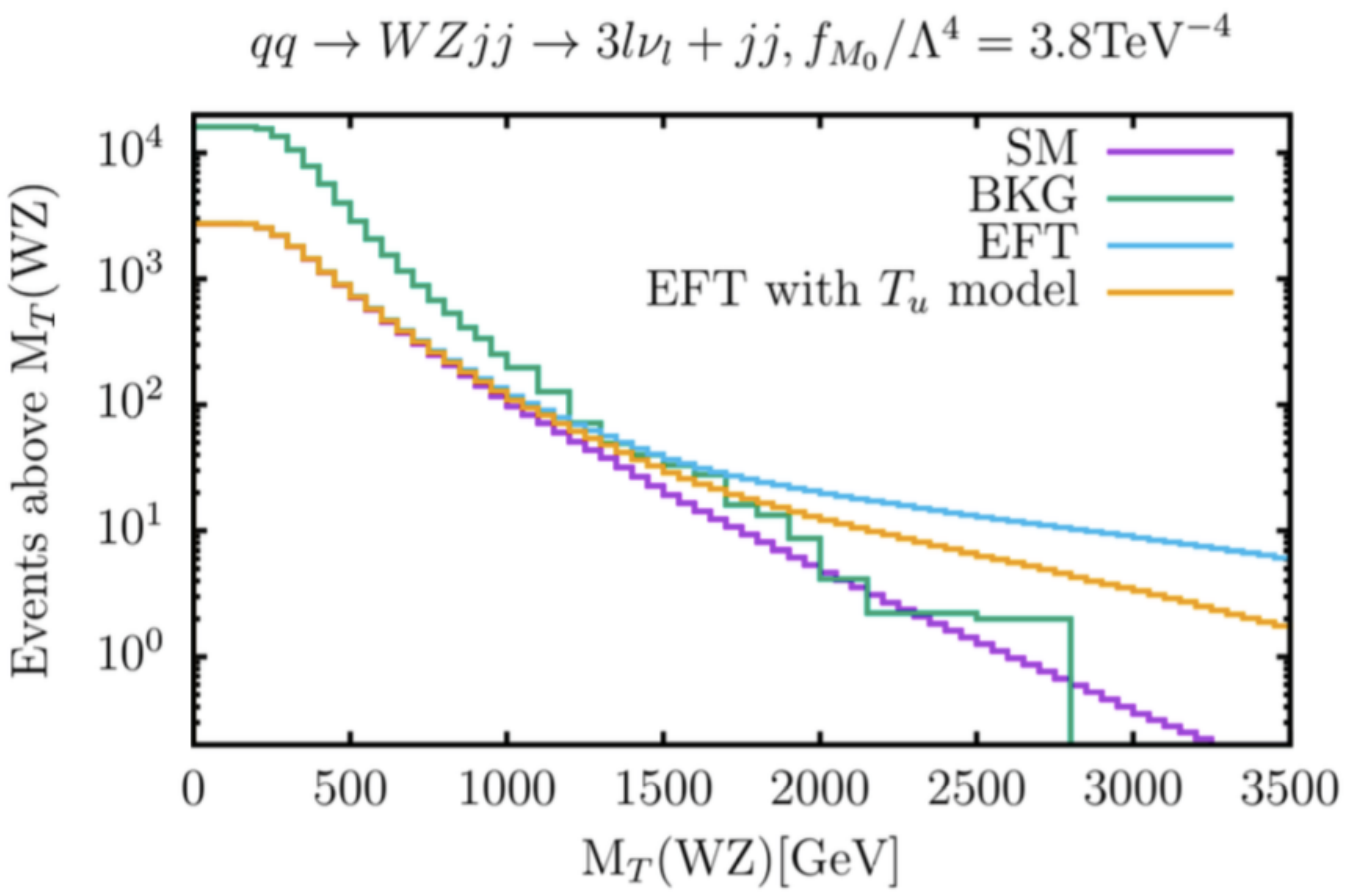
EW WZjj

ATL-PHYS-PUB-2018-022

anomalous Quartic Gauge Coupling (aQCG)

HL-LHC

- VBS provides excellent probes for the structure of gauge boson interaction, in particular for quartic gauge couplings
- Anomalous quartic couplings predicted in new physics models and effective field theories would enhance cross sections
  - ↪ Quantify deviations from the Standard Model in a general or model independent way
- Deviations from SM are parametrized by an effective Lagrangian $\mathscr{L}_{EFT}=\sum_i f_i/\Lambda^{d_i-4}\,\mathcal{O}_i^{(d_i)}$ with 8D operator for aQCG
- In the presence of aQGC which signify strong interactions in the bosonic sector, VBS cross sections are enhanced at high VV invariant masses
  - ↪ Observables correlated to m_{VV}



	14 TeV	
	$WZjj$	$W^\pm W^\pm jj$
f_{S_0}/Λ^4	[-8,8]	[-6,6]
f_{S_1}/Λ^4	[-18,18]	[-16,16]
f_{T_0}/Λ^4	[-0.76,0.76]	[-0.6,0.6]
f_{T_1}/Λ^4	[-0.50,0.50]	[-0.4,0.4]
f_{M_0}/Λ^4	[-3.8,3.8]	[-4.0,4.0]
f_{M_1}/Λ^4	[-5.0,5.0]	[-12,12]

ATLAS Run-2 results will come soon

ATL-PHYS-PUB-2018-022

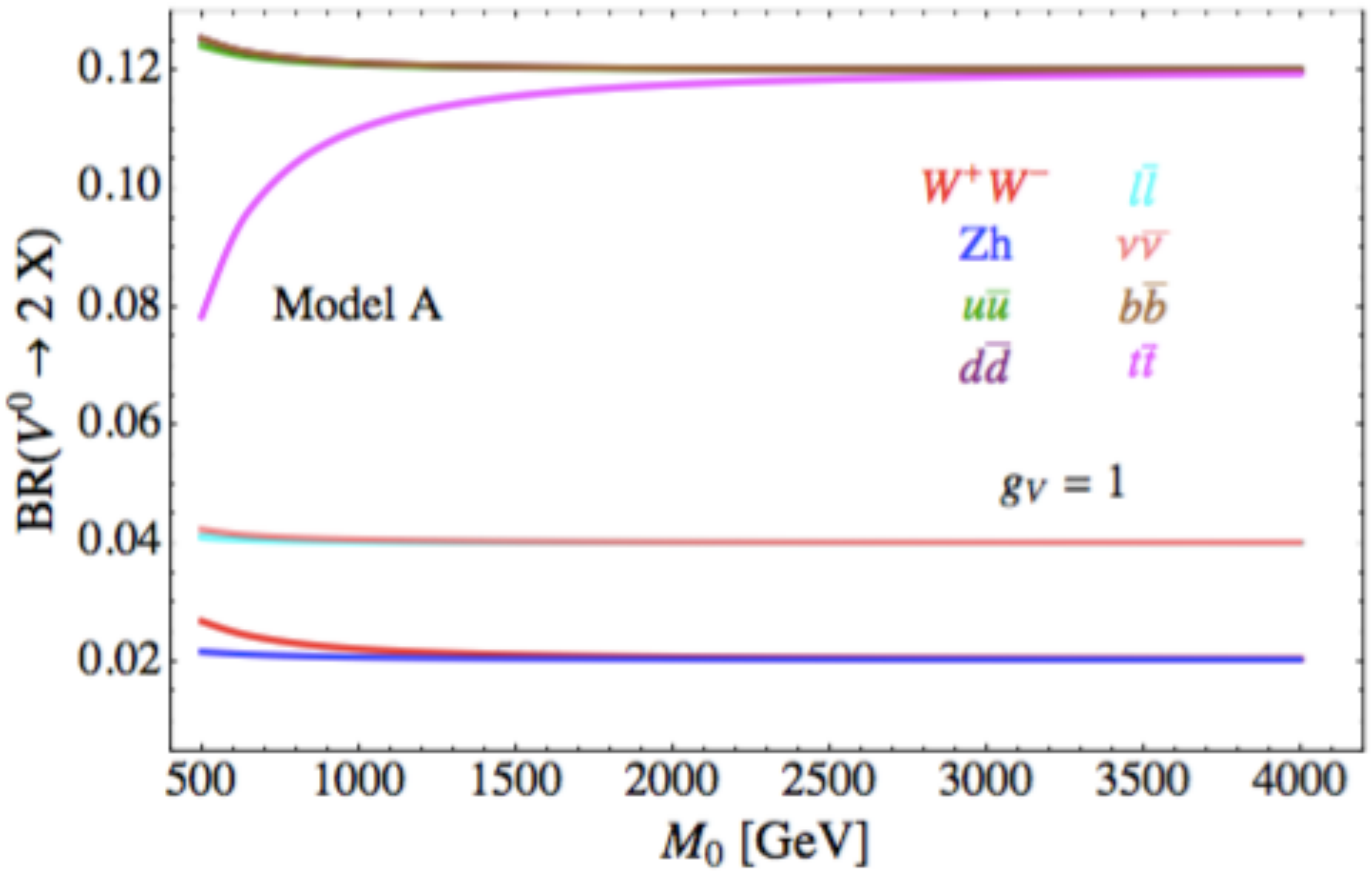
Conclusions

- Diboson searches have a great importance for SM and BSM searches
- Sophisticated object taggers are designed and applied to distinguish W/Z from SM background
  - ↪ Taggers are a very hot R&D topic now!
  - ↪ Machine learning approach
- No evidence for New Physics
  - ↪ Limits push G_{KK}, V', W' masses higher
  - ↪ Full Run-2 dataset analyses ongoing

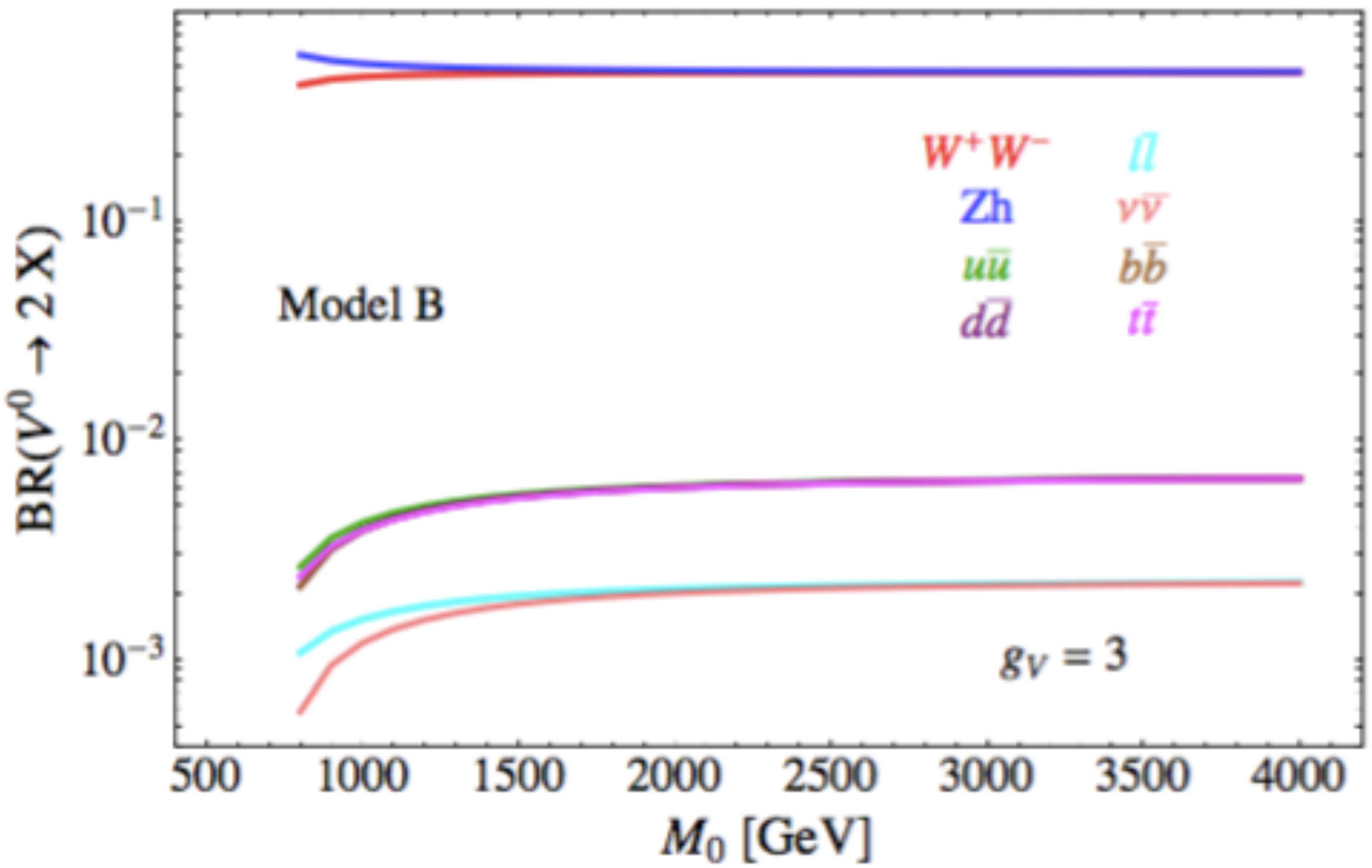
- ATLAS has published result on VBS measurements using 36.1 fb^{-1} or 139 fb^{-1}
  - ↪ Run 2 of the LHC has revealed access to further exploration of final states in VBS
  - ↪ Observation of electro-weak production in $W^{\pm}W^{\pm}jj$, WZjj, ZZjj
  - ↪ Measurement of fiducial cross sections for these final states
- With more data being collected for the full Run2 higher order theoretical computations are becoming more important
- Improving sensitivity for BSM
- VBS final states continue to be a playground for exciting physics to be explored!

Backup

HVT

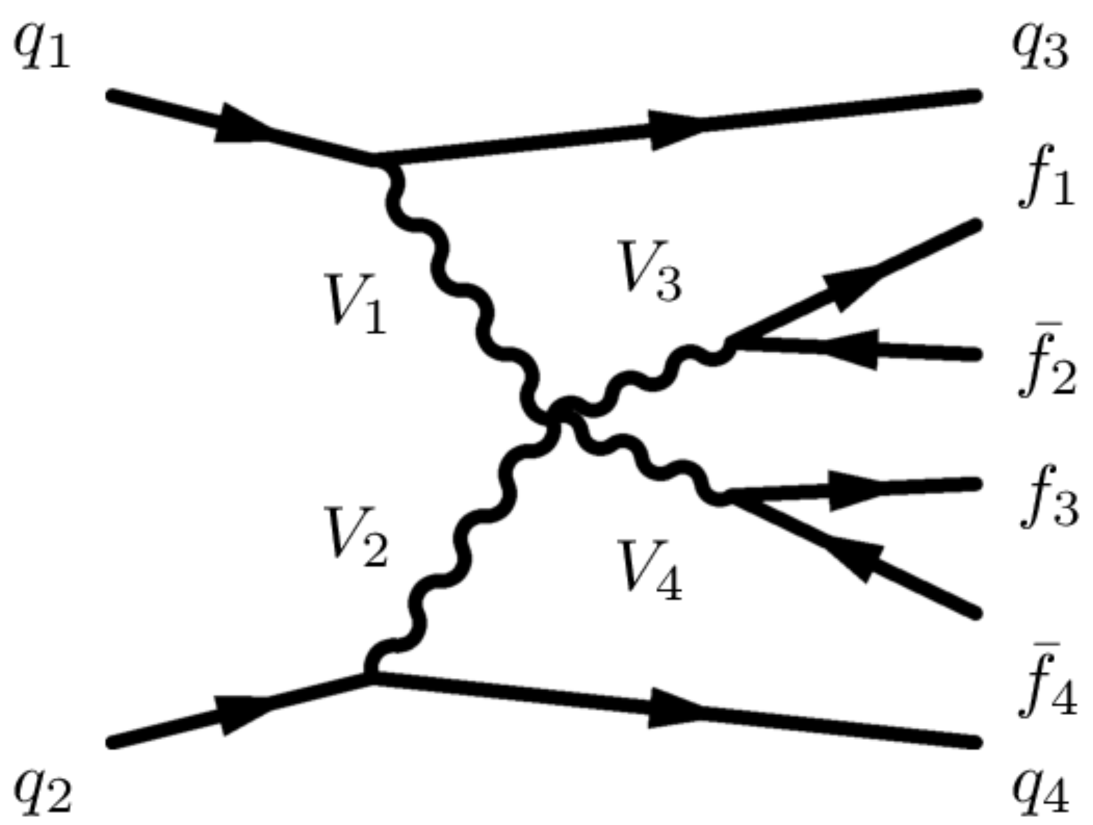


Model A
W^+W^-
Zh
$u\bar{u}$
$d\bar{d}$
$l\bar{l}$
$\nu\bar{\nu}$
$b\bar{b}$
$t\bar{t}$
$g_V = 1$
$BR(V^0 \to 2\ X)$
M_0 [GeV]



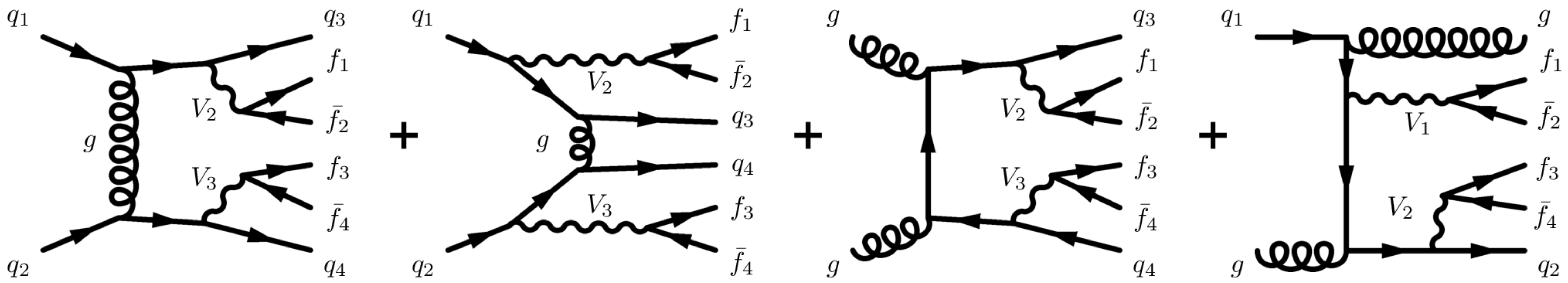
Model B
W^+W^-
Zh
$u\bar{u}$
$d\bar{d}$
$l\bar{l}$
$\nu\bar{\nu}$
$b\bar{b}$
$t\bar{t}$
$g_V = 3$
$BR(V^0 \to 2\ X)$
M_0 [GeV]

VBS: Motivation



VVjj EWK VBS

VVjj QCD



VVjj EWK non VBS

All EW-induced processes (only EW interaction vertices) treated as signal

An interference occurs between electroweak and QCD production

VV→JJ analysis

139 fb^{-1}

Signal region	Veto events with leptons:
	No e or μ with $p_T > 25$ GeV and $\|\eta\| < 2.5$
	Event pre-selection:
	≥ 2 large-R jets with $\|\eta\| < 2.0$ and mass > 50 GeV
	$p_{T1} > 500$ GeV and $p_{T2} > 200$ GeV
	$m_{JJ} > 1.3$ TeV
	Topology and boson tag:
	$\|\Delta y\| = \|y_1 - y_2\| < 1.2$
	$A = (p_{T1} - p_{T2}) / (p_{T1} + p_{T2}) < 0.15$
	Boson tag with D_2 variable, n_{trk} variable, and W or Z mass window
V+jets control region	Veto events with leptons:
	No e or μ with $p_T > 25$ GeV and $\|\eta\| < 2.5$
	V+jets selection:
	≥ 2 large-R jets with $\|\eta\| < 2.0$
	$p_{T1} > 600$ GeV and $p_{T2} > 200$ GeV
	Boson tag with D_2 and n_{trk} variables on either jet
	Anti-boson tag with D_2 variable on other jet

HDBS-2018-31

VV→JJ analysis

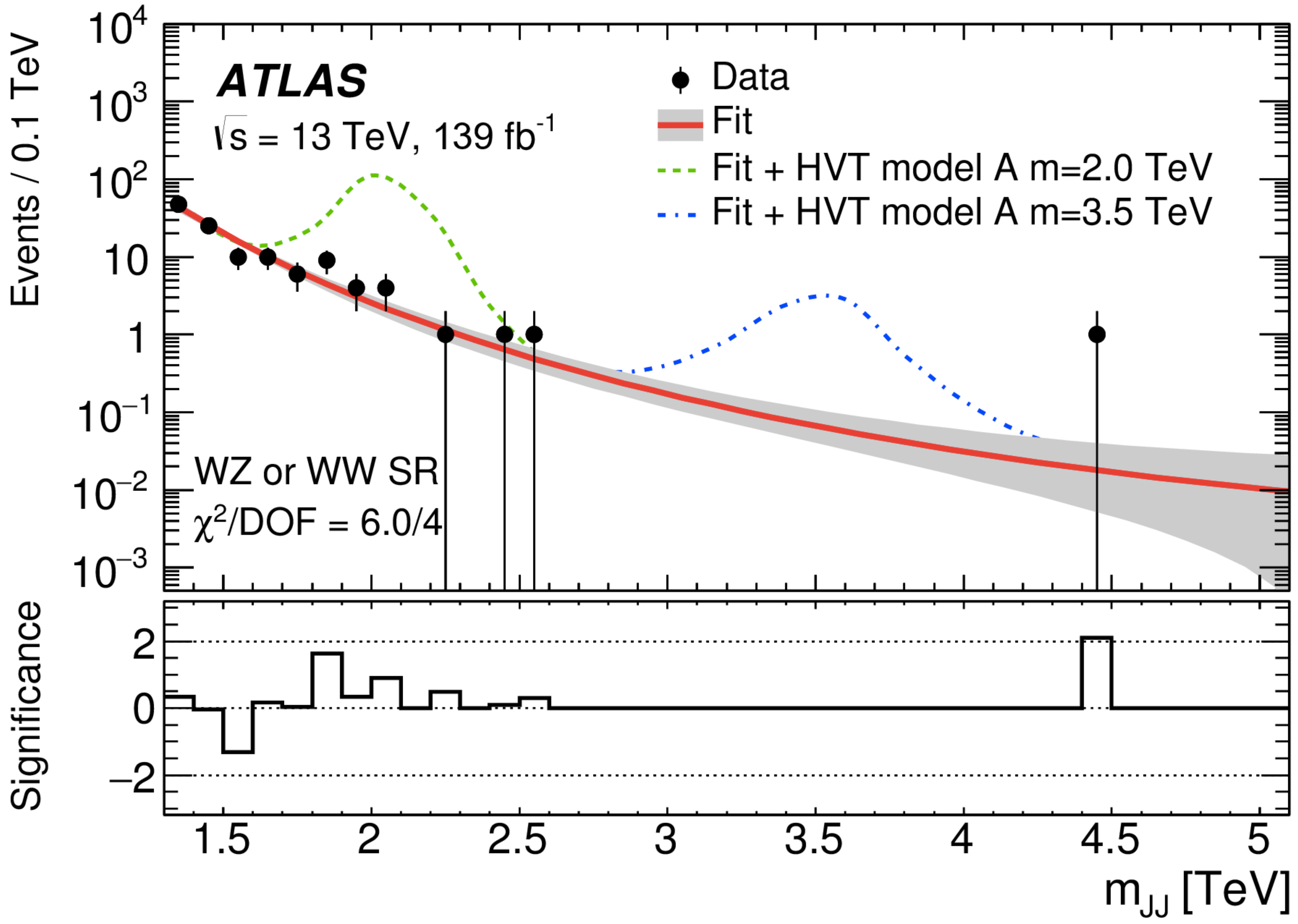
139 fb^{-1}

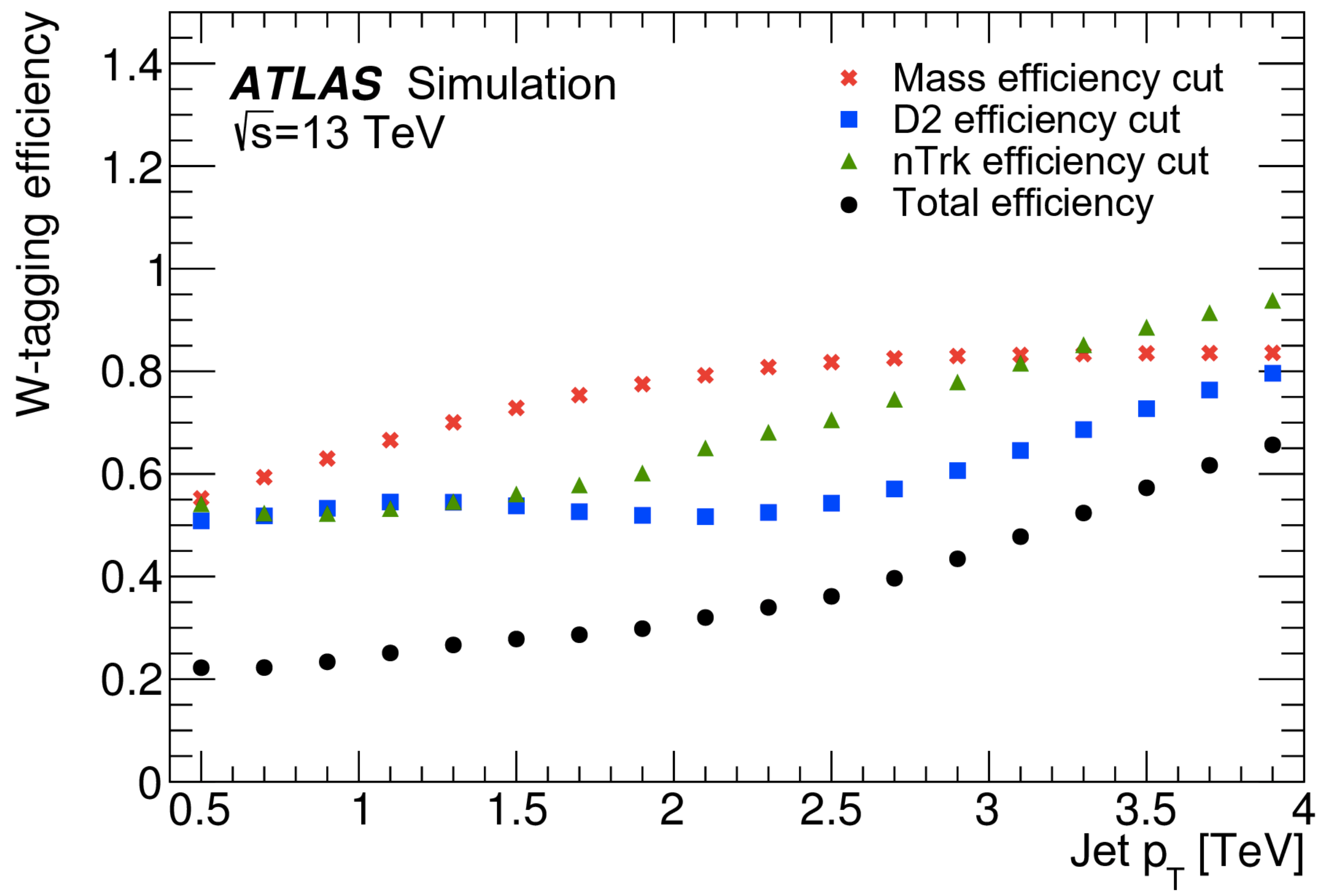
Model	Signal Region	Excluded mass range [TeV]
Radion	WW	none
	ZZ	none
	$WW + ZZ$	none
HVT model A, $g_V = 1$	WW	1.3–2.9
	WZ	1.3–3.4
	$WW + WZ$	1.3–3.5
HVT model B, $g_V = 3$	WW	1.3–3.1
	WZ	1.3–3.6
	$WW + WZ$	1.3–3.8
Bulk RS, $k/\overline{M}_{\text{Pl}} = 1$	WW	1.3–1.6
	ZZ	none
	$WW + ZZ$	1.3–1.8

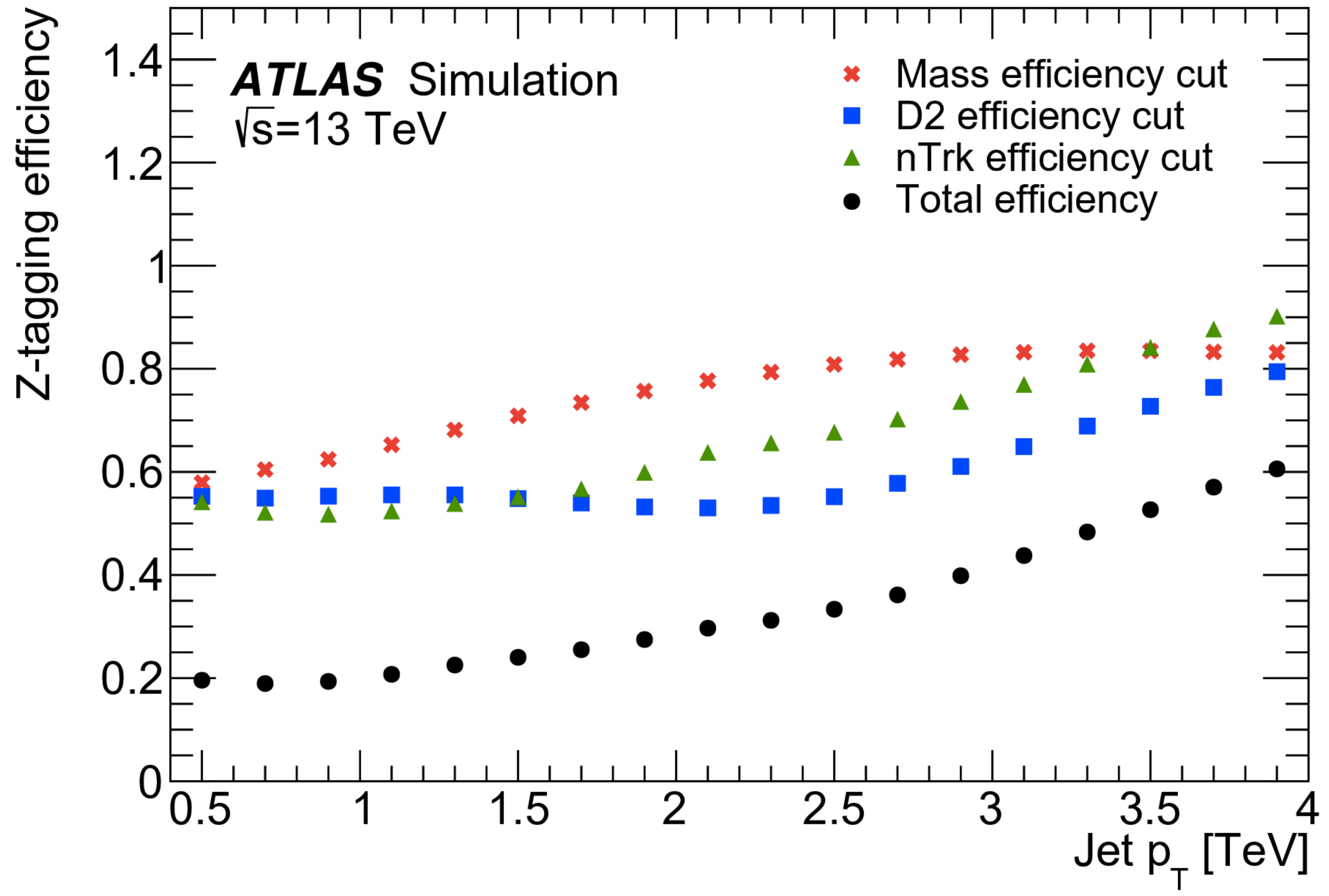
HDBS-2018-31

VV→JJ analysis

139 fb^{-1}



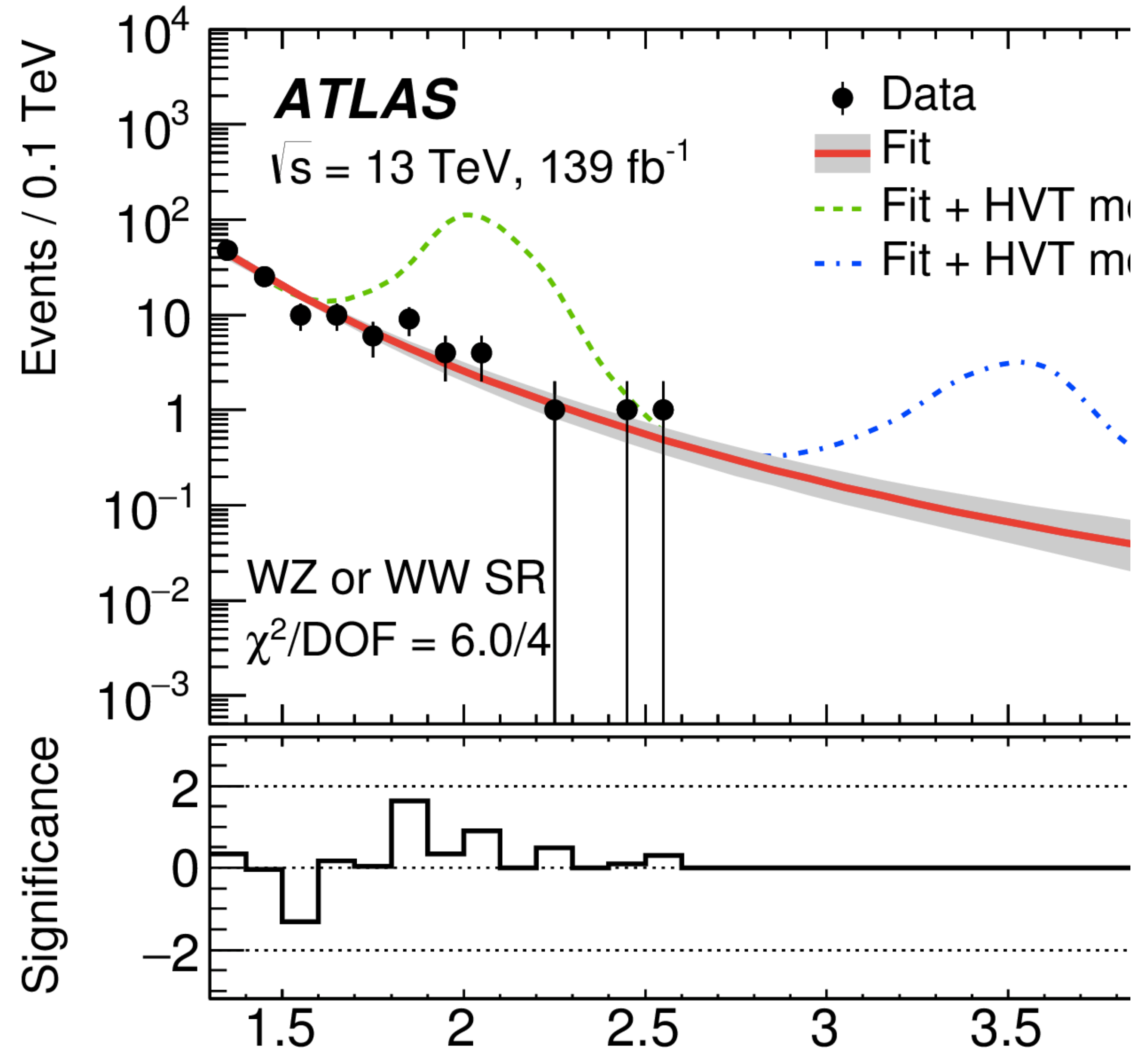


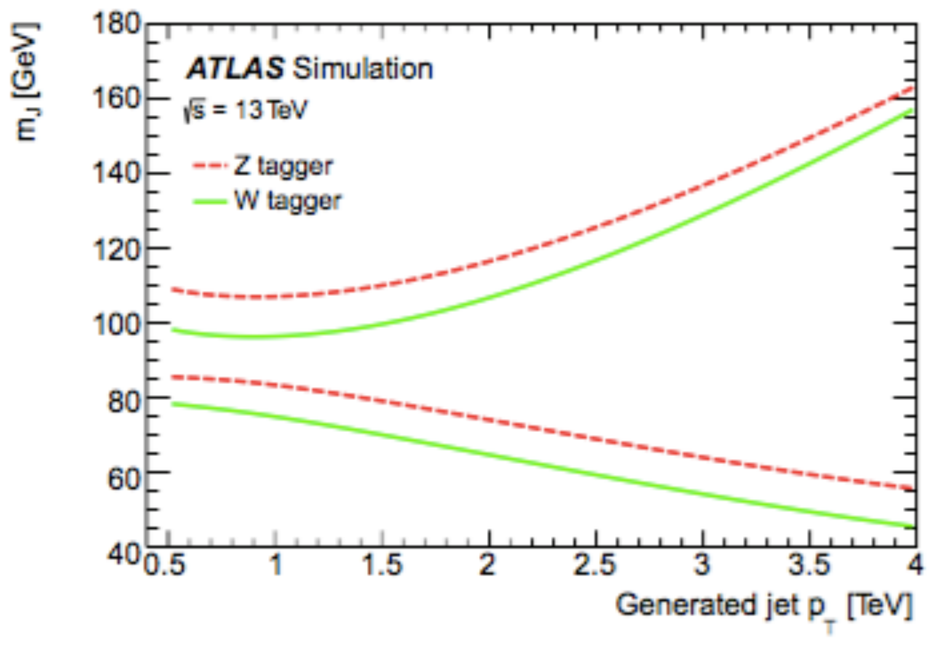


HDBS-2018-31

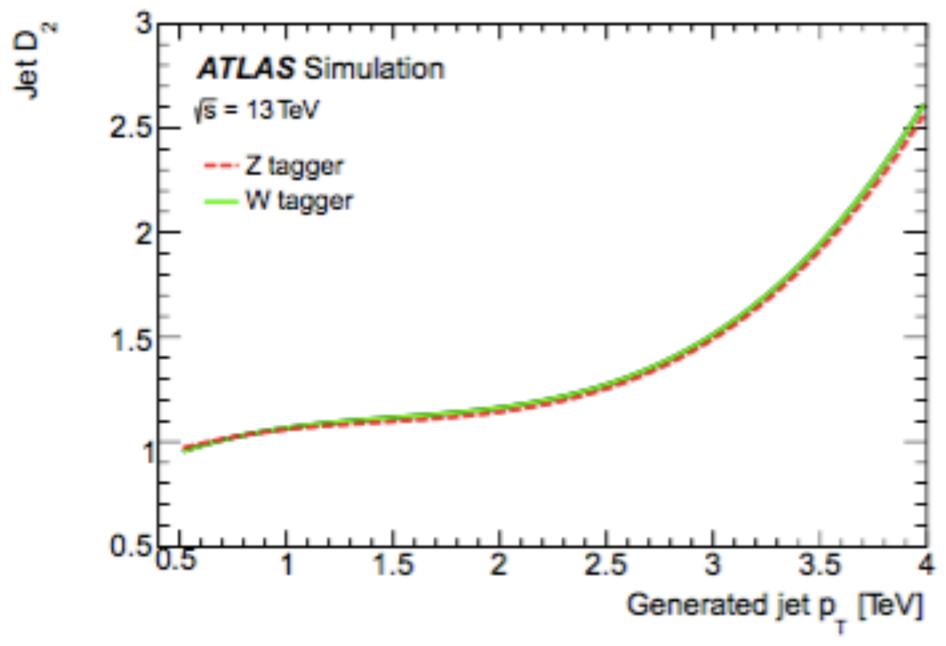
VV→JJ analysis

139 fb^{-1}

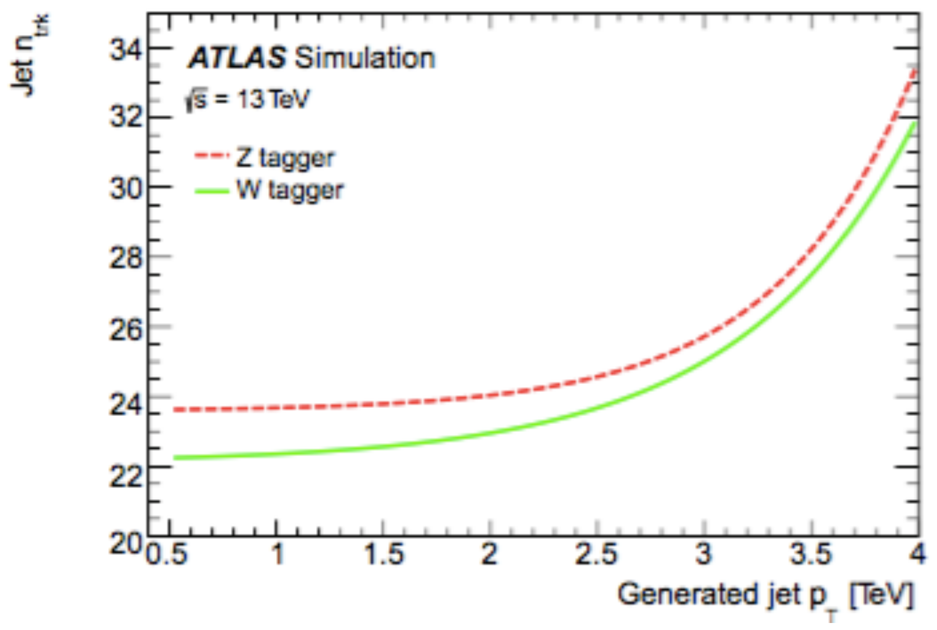


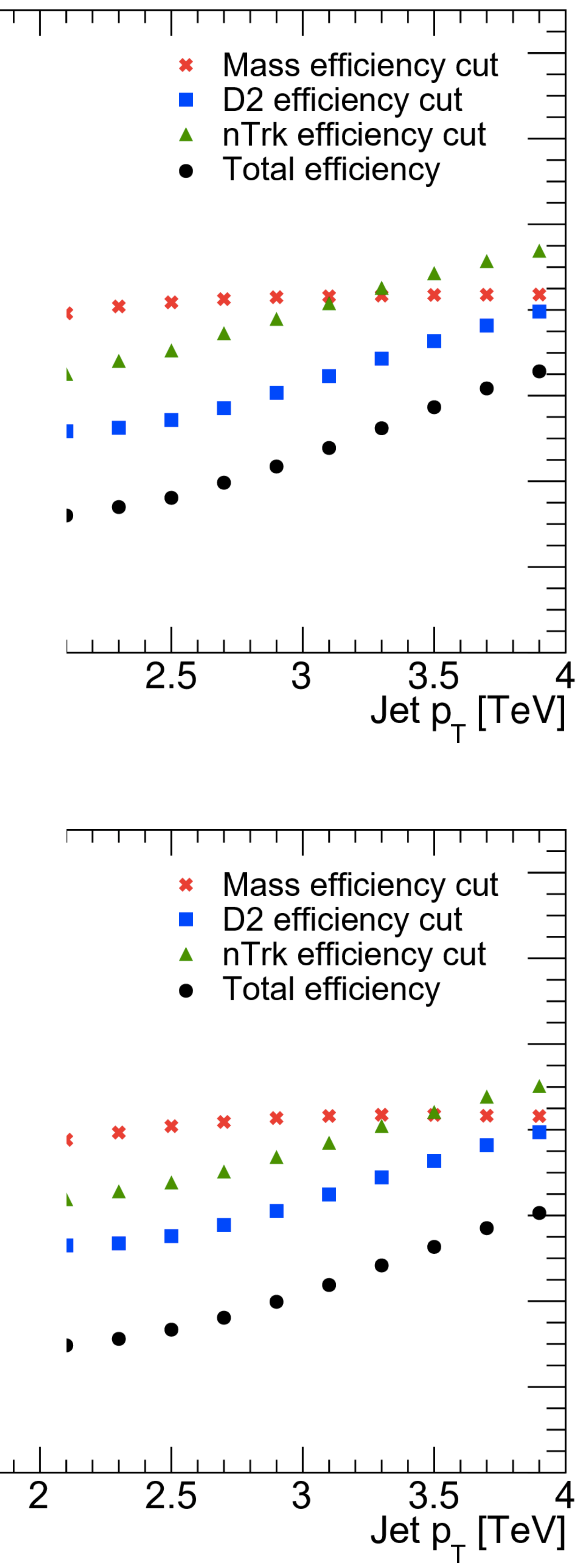


(a)



(b)

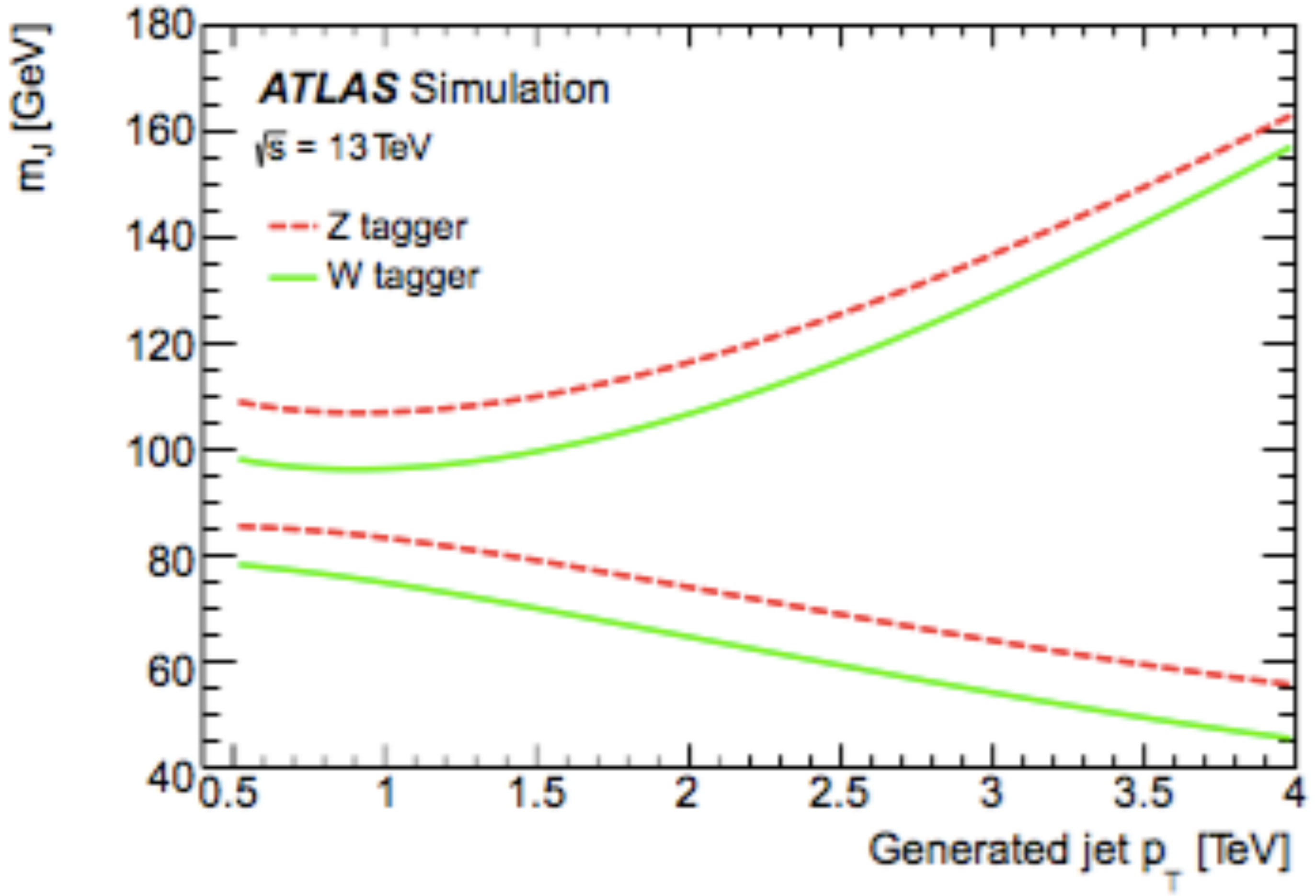




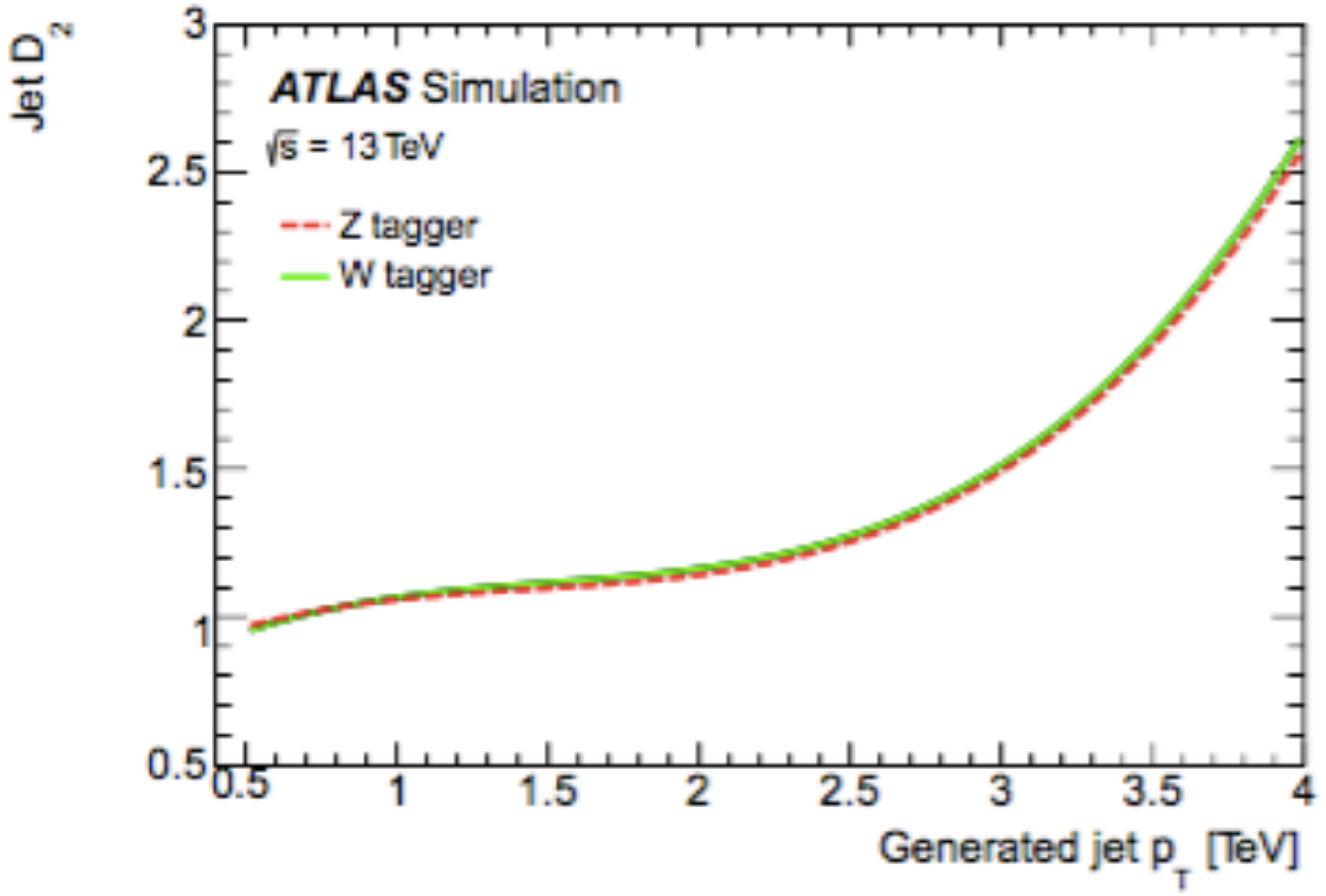
HDBS-2018-31

VV→JJ analysis

139 fb^{-1}



(a)



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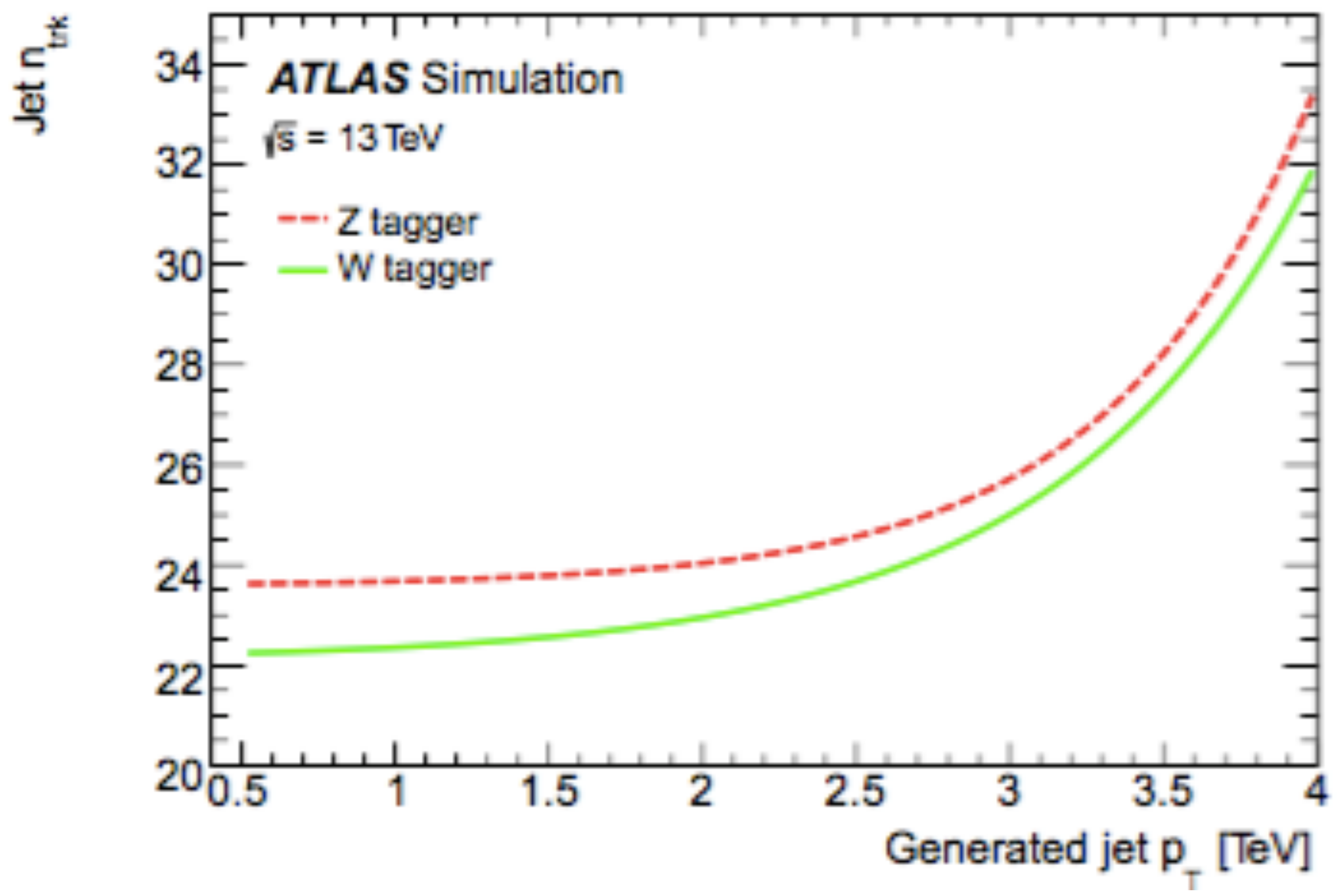


HDBS-2018-31

VV semileptonic

Selection	$ZV \rightarrow \ell\ell J$	$ZV \rightarrow \ell\ell jj$
$Z \rightarrow \ell\ell$	Two opposite-flavour leptons with $p_{\mathrm{T}}(E_{\mathrm{T}}) > 7$ GeV leading lepton with $p_{\mathrm{T}}(E_{\mathrm{T}}) > 28$ GeV $83 < m_{ee} < 99$ GeV $85.6\,\mathrm{GeV} - 0.0117^{\ell\ell}_{\mathrm{T}} < m_{\mu\mu} < 94.0\,\mathrm{GeV} + 0.0185^{\ell\ell}_{\mathrm{T}}$	
Tag-jet selection for VBF category	Two non-b-tagged small-R jets with $\eta_1 \cdot \eta_2 < 0$, $\lvert\Delta\eta^{\mathrm{tag}}_{jj}\rvert > 4.7$ and $m^{\mathrm{tag}}_{jj} > 770$ GeV	
Jet requirements	≥ 1 large-R jet with $p_{\mathrm{T}} > 200$ GeV	≥ 2 'signal' jets with $p_{\mathrm{T}} > 30$ GeV $p_{\mathrm{T}} > 60$ GeV for the leading jet no events with $> 2\,b$-tagged jets
Kinematic criteria	$\min(p^{\ell\ell}_{\mathrm{T}}, p^{J}_{\mathrm{T}})\,/m_{\ell\ell J}$	$\sqrt{(p^{\ell\ell}_{\mathrm{T}})^2 + \left(p^{jj}_{\mathrm{T}}\right)^2}\,/m_{\ell\ell jj}$
H	> 0.3	> 0.4
W' or G_{KK}	> 0.35	> 0.5
V boson tagging	p_{T}-dependent criteria in D_2 and m_J	$70 < m_{jj} < 105$ GeV $(V = Z)$ $62 < m_{jj} < 97$ GeV $(V = W)$

VV semileptonic

$Z \to \nu\nu$	$E_{\mathrm{T}}^{\mathrm{miss}} > 250$ GeV
Multijet removal	$p_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV $\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}) < 1$ $\min[\Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \text{small-}R\text{ jet})] > 0.4$
Tag-jet selection for VBF category	Two non-b-tagged small-R jets with $\eta_1 \cdot \eta_2 < 0$, $\lvert\Delta\eta_{jj}^{\mathrm{tag}}\rvert > 4.7$ and $m_{jj}^{\mathrm{tag}} > 630$ GeV
Jet requirements	≥ 1 large-R jet with $p_{\mathrm{T}} > 200$ GeV
V boson tagging	p_{T}-dependent criteria on D_2 and m_J

VV semileptonic ($\ell\ell qq$)

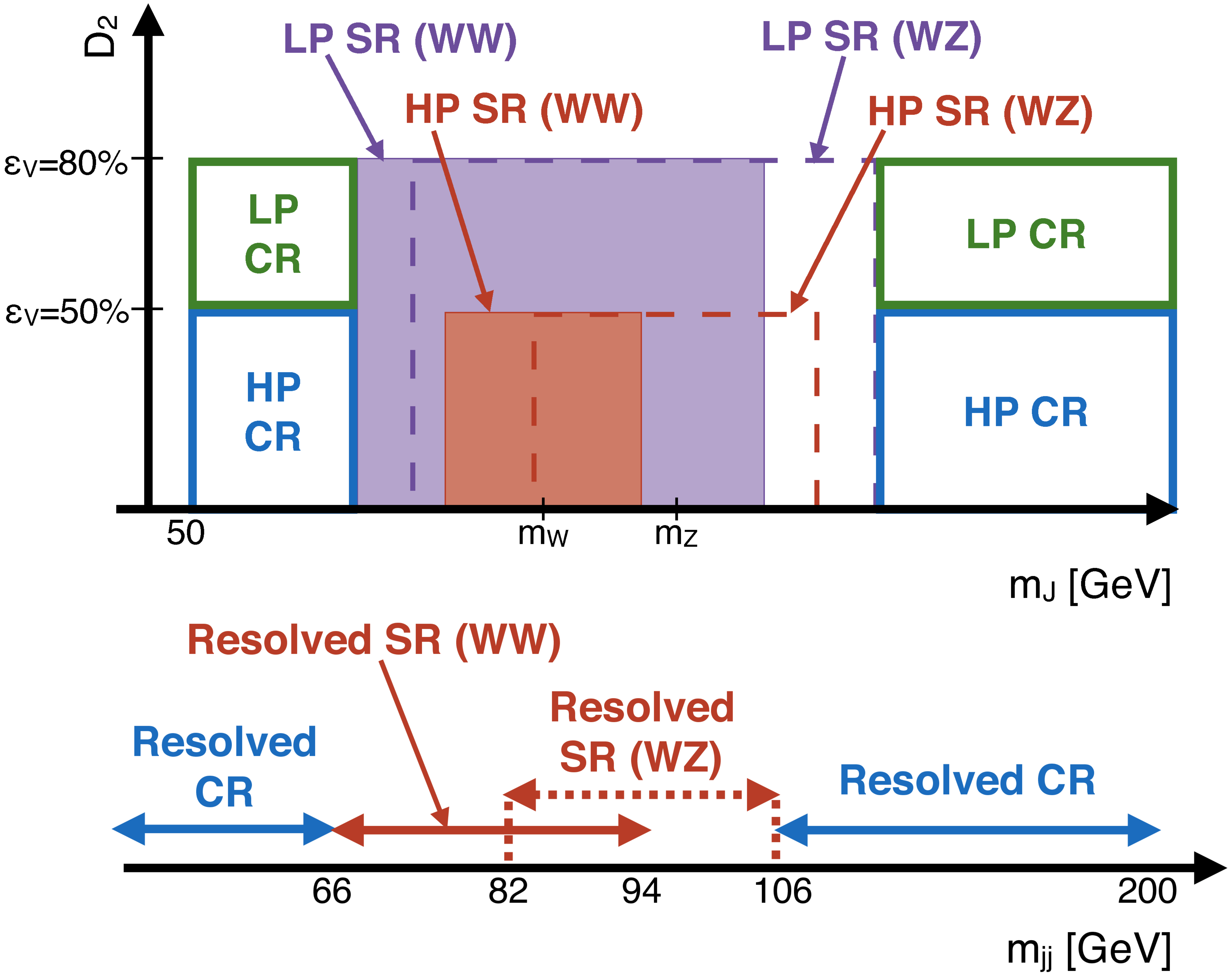
Selection	$ZV \to \ell\ell J$	$ZV \to \ell\ell jj$
$Z \to \ell\ell$	Two opposite-flavour leptons with $p_{\mathrm{T}}(E_{\mathrm{T}}) > 7$ GeV leading lepton with $p_{\mathrm{T}}(E_{\mathrm{T}}) > 28$ GeV $83 < m_{ee} < 99$ GeV $85.6\,\mathrm{GeV} - 0.0117^{\ell\ell}_{\mathrm{T}} < m_{\mu\mu} < 94.0\,\mathrm{GeV} + 0.0185^{\ell\ell}_{\mathrm{T}}$	
Tag-jet selection for VBF category	Two non-b-tagged small-R jets with $\eta_1 \cdot \eta_2 < 0$, $\lvert\Delta\eta^{\mathrm{tag}}_{jj}\rvert > 4.7$ and $m^{\mathrm{tag}}_{jj} > 770$ GeV	
Jet requirements	≥ 1 large-R jet with $p_{\mathrm{T}} > 200$ GeV	≥ 2 'signal' jets with $p_{\mathrm{T}} > 30$ GeV $p_{\mathrm{T}} > 60$ GeV for the leading jet no events with $> 2\,b$-tagged jets
Kinematic criteria	$\min(p^{\ell\ell}_{\mathrm{T}}, p^{J}_{\mathrm{T}})\,/m_{\ell\ell J}$	$\sqrt{\left(p^{\ell\ell}_{\mathrm{T}}\right)^2 + \left(p^{jj}_{\mathrm{T}}\right)^2}\,/m_{\ell\ell jj}$
H	> 0.3	> 0.4
W' or G_{KK}	> 0.35	> 0.5
V boson tagging	p_{T}-dependent criteria in D_2 and m_J	$70 < m_{jj} < 105$ GeV ($V = Z$) $62 < m_{jj} < 97$ GeV ($V = W$)

VV semileptonic ($\ell\nu$)

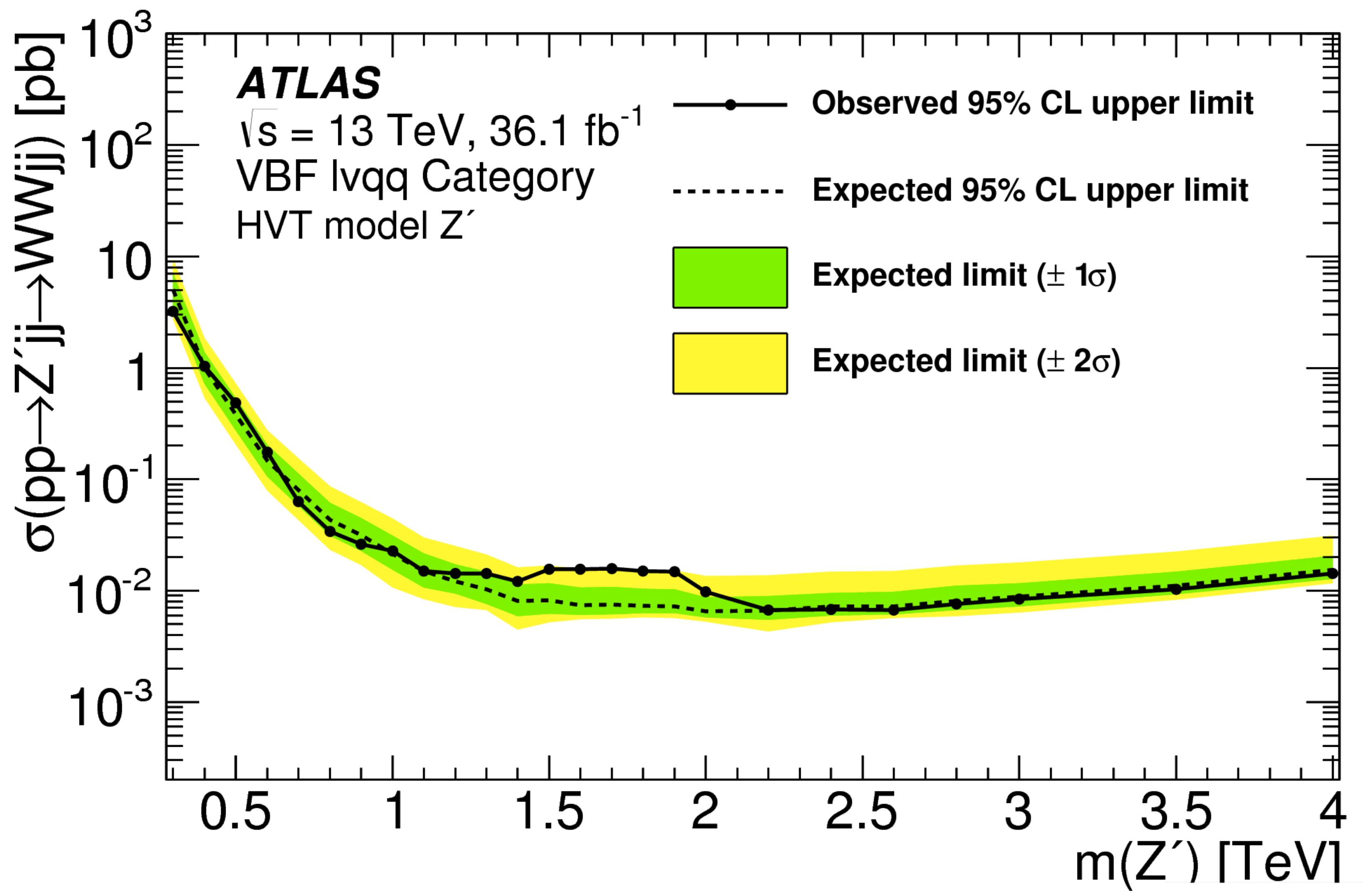
Selection		WW (WZ) SR	W CR	$t\bar{t}$ CR
Production category	VBF	$m^{\text{tag}}(j,j) > 770$ GeV and $\lvert\Delta\eta^{\text{tag}}(j,j)\rvert > 4.7$		
	ggF/$q\bar{q}$	Fails VBF selection		
$W \to \ell\nu$ selection	Num. of signal leptons	1		
	Num. of veto leptons	0		
	$E_{\text{T}}^{\text{miss}}$	> 60 GeV		
	$p_{\text{T}}(\ell\nu)$	> 75 GeV		
	$E_{\text{T}}^{\text{miss}}/p_{\text{T}}(e\nu)$	> 0.2		
$V \to jj$ selection	Num. of small-R jets	≥ 2		
	$p_{\text{T}}(j_1)$	> 60 GeV		
	$p_{\text{T}}(j_2)$	> 45 GeV		
	$m(jj)$ [GeV]	[66, 94] ([82, 106])	< 66 or [106, 200]	[66, 106]
Topology criteria	$\Delta\phi(j,\ell)$	> 1.0		
	$\Delta\phi(j, E_{\text{T}}^{\text{miss}})$	> 1.0		
	$\Delta\phi(j,j)$	< 1.5		
	$\Delta\phi(\ell, E_{\text{T}}^{\text{miss}})$	< 1.5		
	$p_{\text{T}}(\ell\nu)/m(WV)$ $p_{\text{T}}(jj)/m(WV)$	> 0.3 for VBF and 0.35 for ggF/$q\bar{q}$ category		
Num. of b-tagged jets	$j_1 \equiv b$ or $j_2 \equiv b$ where $V \to j_1 j_2$	$\leq 1(2)$	≤ 1	> 0 (for jets other than j_1 orj_2)
	$j_1 \neq b$ and $j_2 \neq b$ where $V \to j_1 j_2$	0		

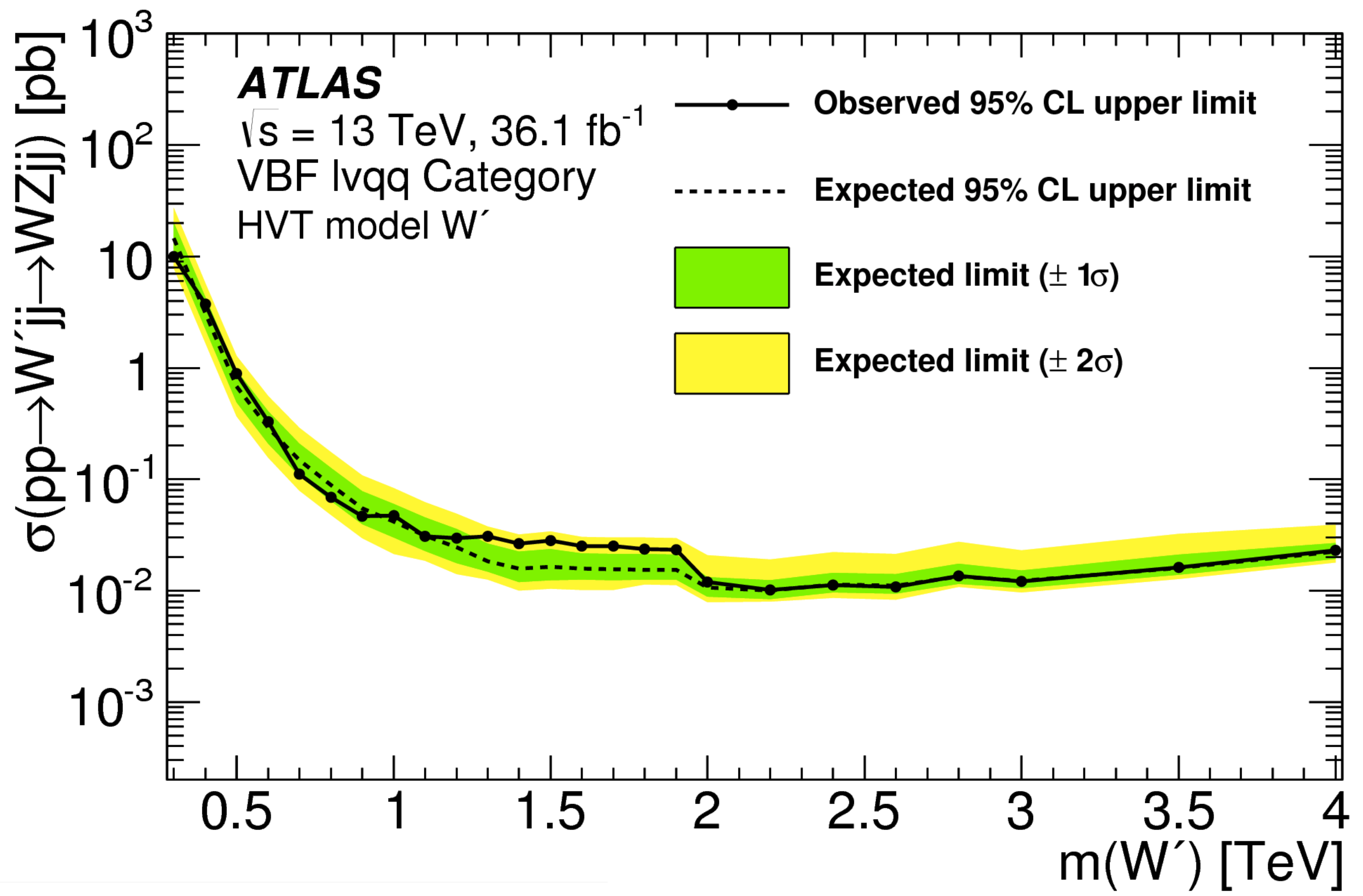
Selection		SR: HP (LP)	W CR: HP (LP)	$t\bar{t}$ CR: HP (LP)
Production category	VBF	$m^{\text{tag}}(j,j) > 770$ GeV and $\lvert\Delta\eta^{\text{tag}}(j,j)\rvert > 4.7$		
	ggF/$q\bar{q}$	Fails VBF selection		
$W \to \ell\nu$ selection	Num. of signal leptons	1		
	Num. of veto leptons	0		
	$E_{\text{T}}^{\text{miss}}$	> 100 GeV		
	$p_{\text{T}}(\ell\nu)$	> 200 GeV		
	$E_{\text{T}}^{\text{miss}}/p_{\text{T}}(e\nu)$	> 0.2		
$V \to J$ selection	Num. of large-R jets	≥ 1		
	D_2 eff. working point (%)	Pass 50 (80)	Pass 50 (80)	Pass 50 (80)
	Mass window Eff. working point (%)	Pass 50 (80)	Fail 80 (80)	Pass 50 (80)
Topology criteria	$p_{\text{T}}(\ell\nu)/m(WV)$ $p_{\text{T}}(J)/m(WV)$	> 0.3 for VBF and > 0.4 for ggF/$q\bar{q}$ category		
Num. of b-tagged jet	excluding b-tagged jets with $\Delta R(J,b) \leq 1.0$	0		≥ 1

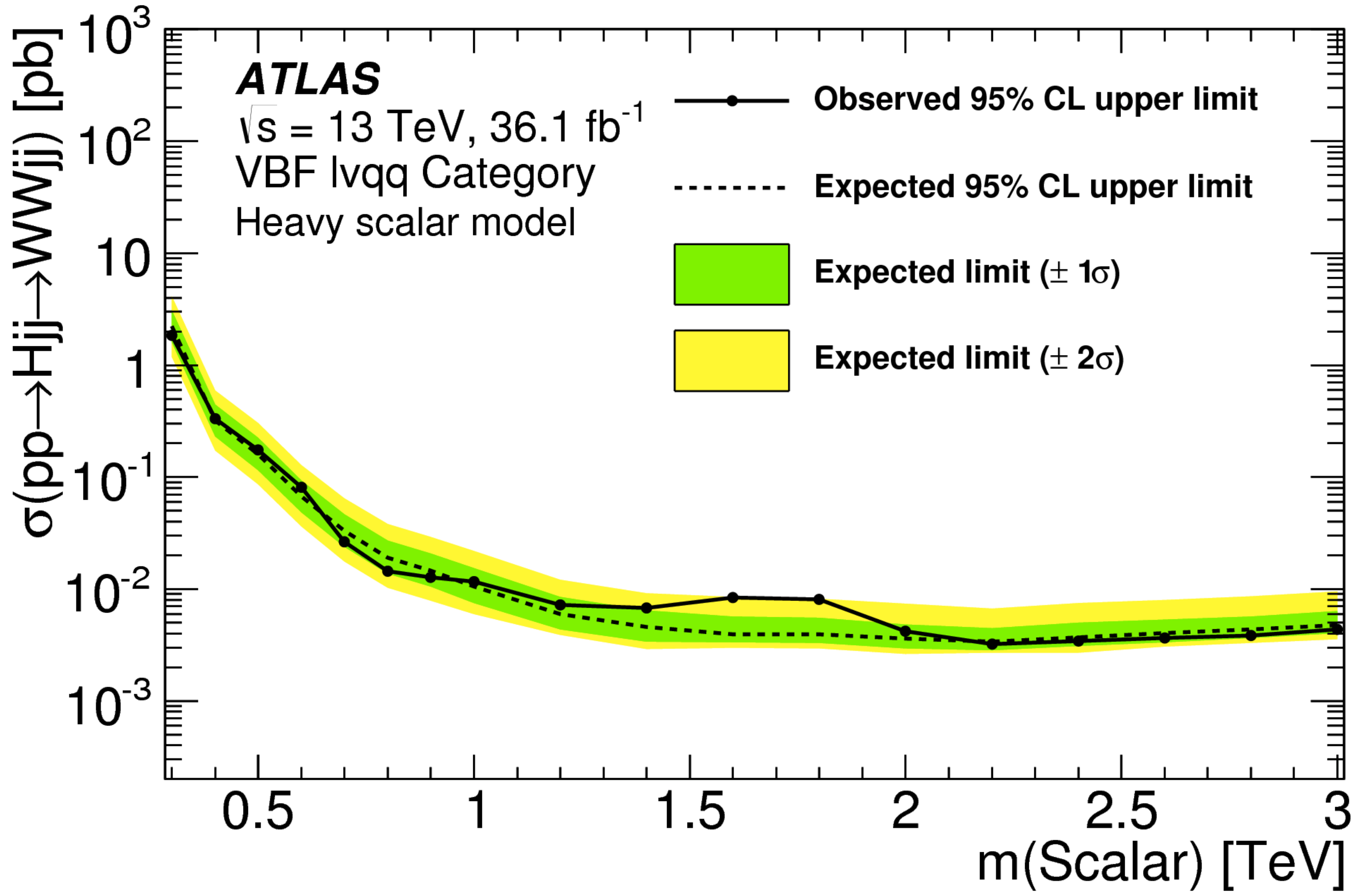
VV semileptonic



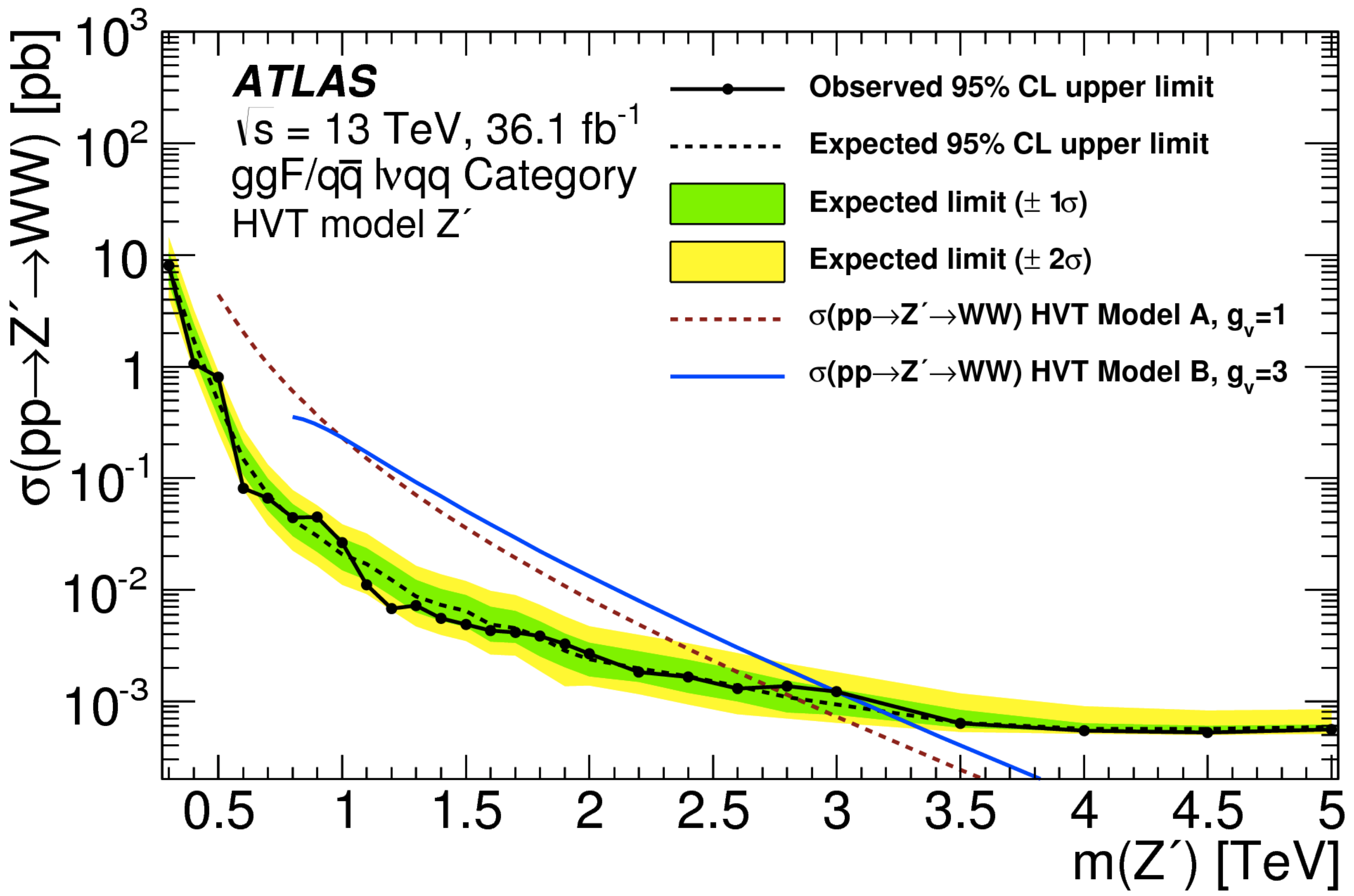
VV semileptonic

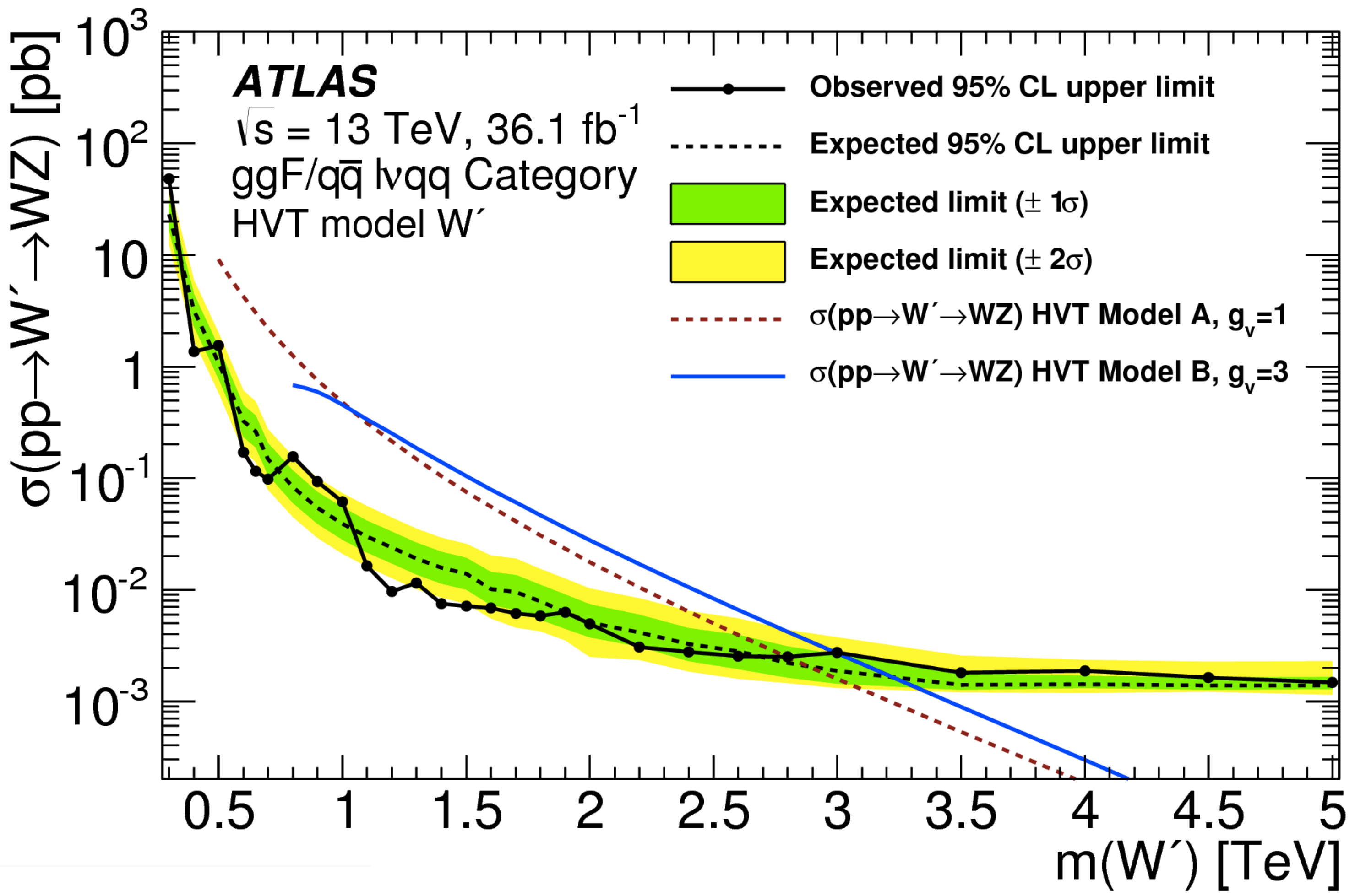


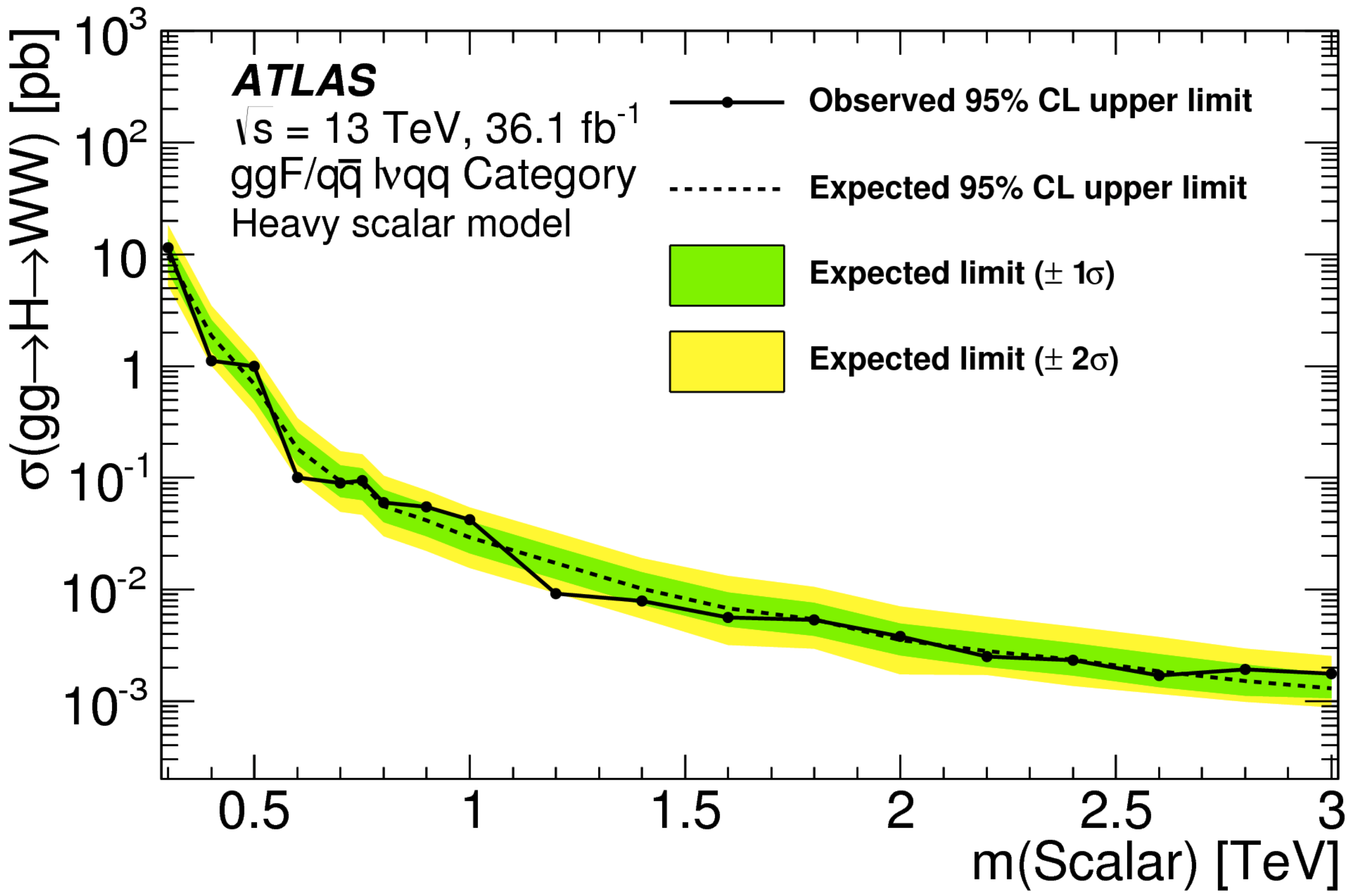




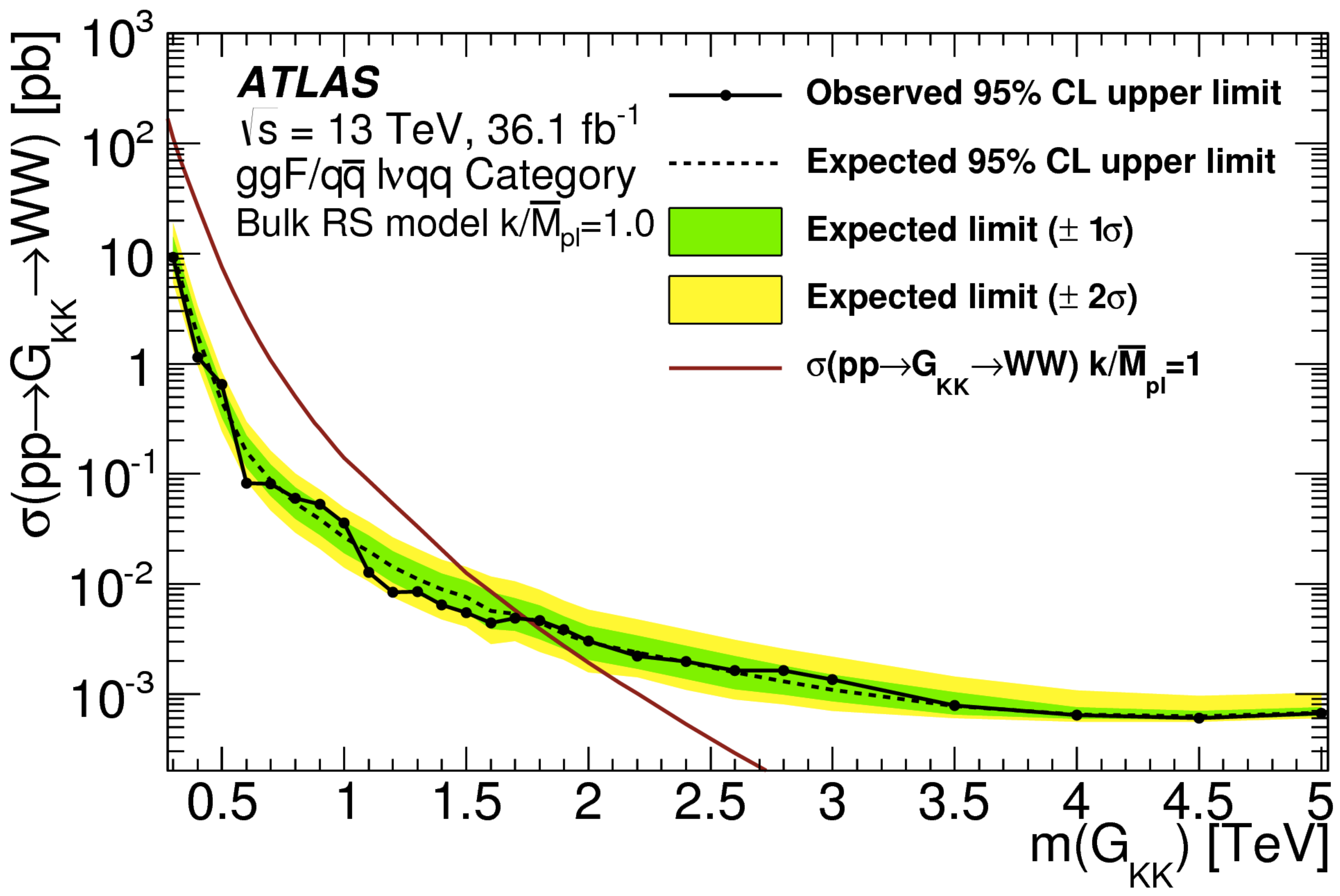
VV semileptonic



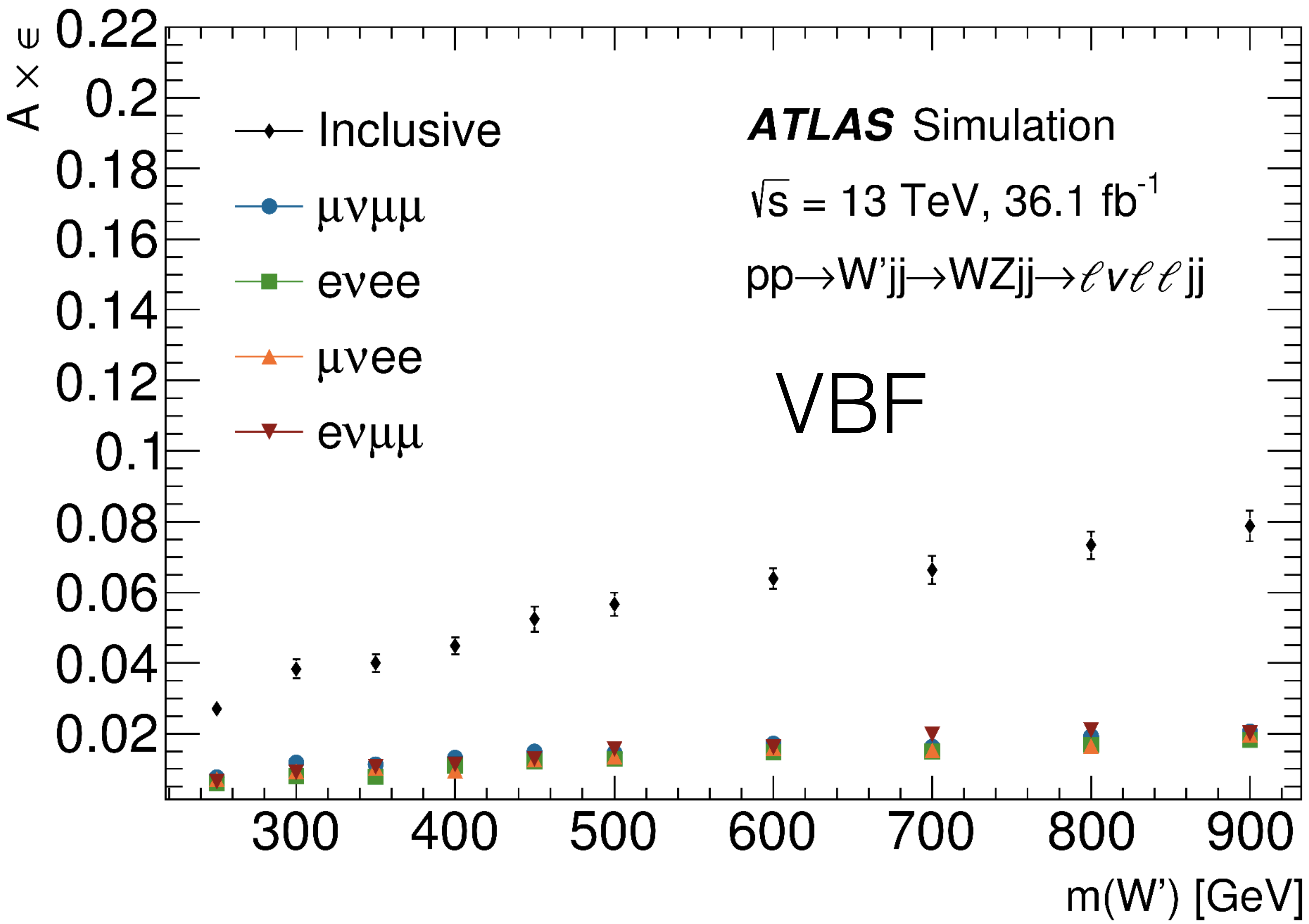


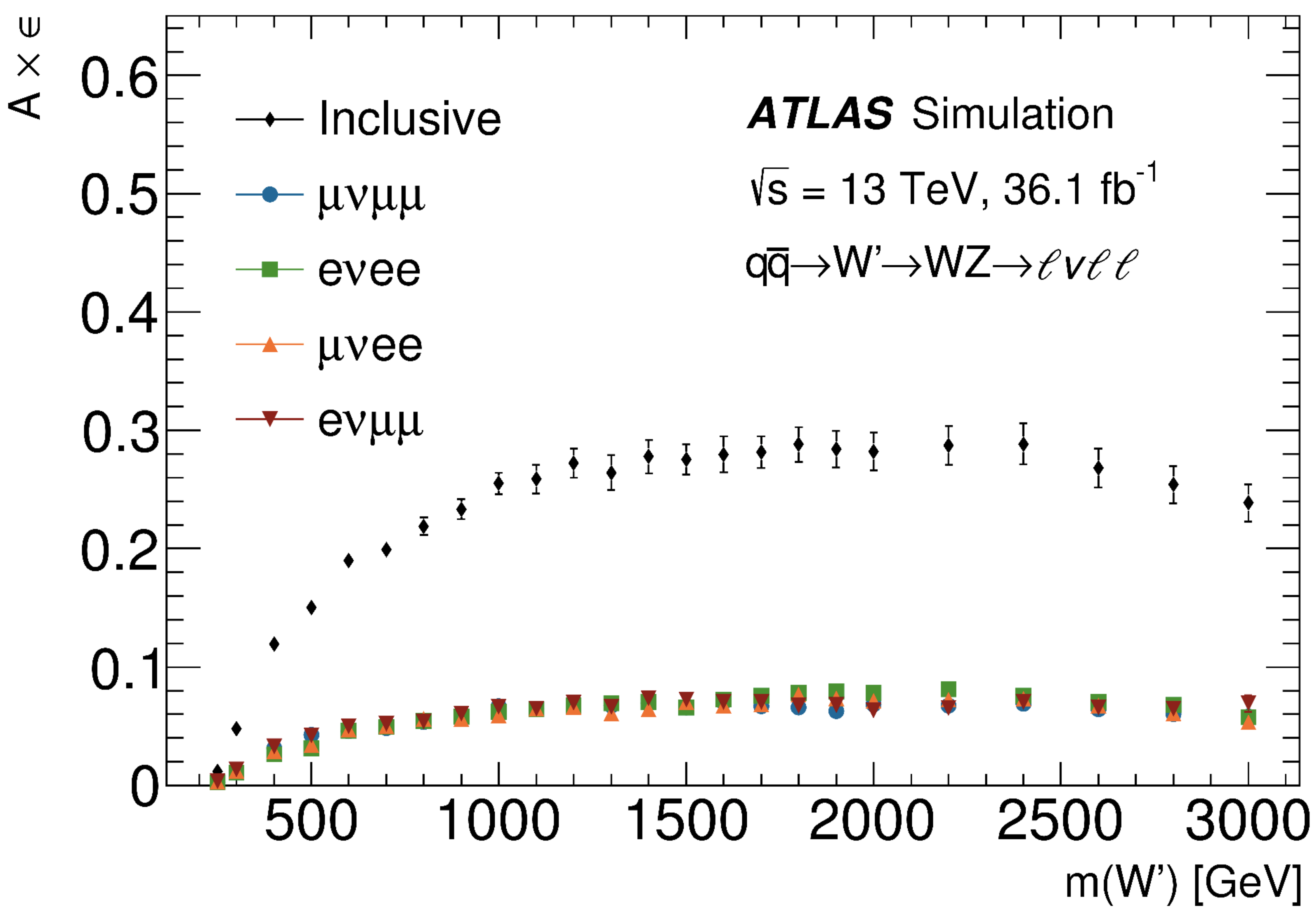


VV semileptonic

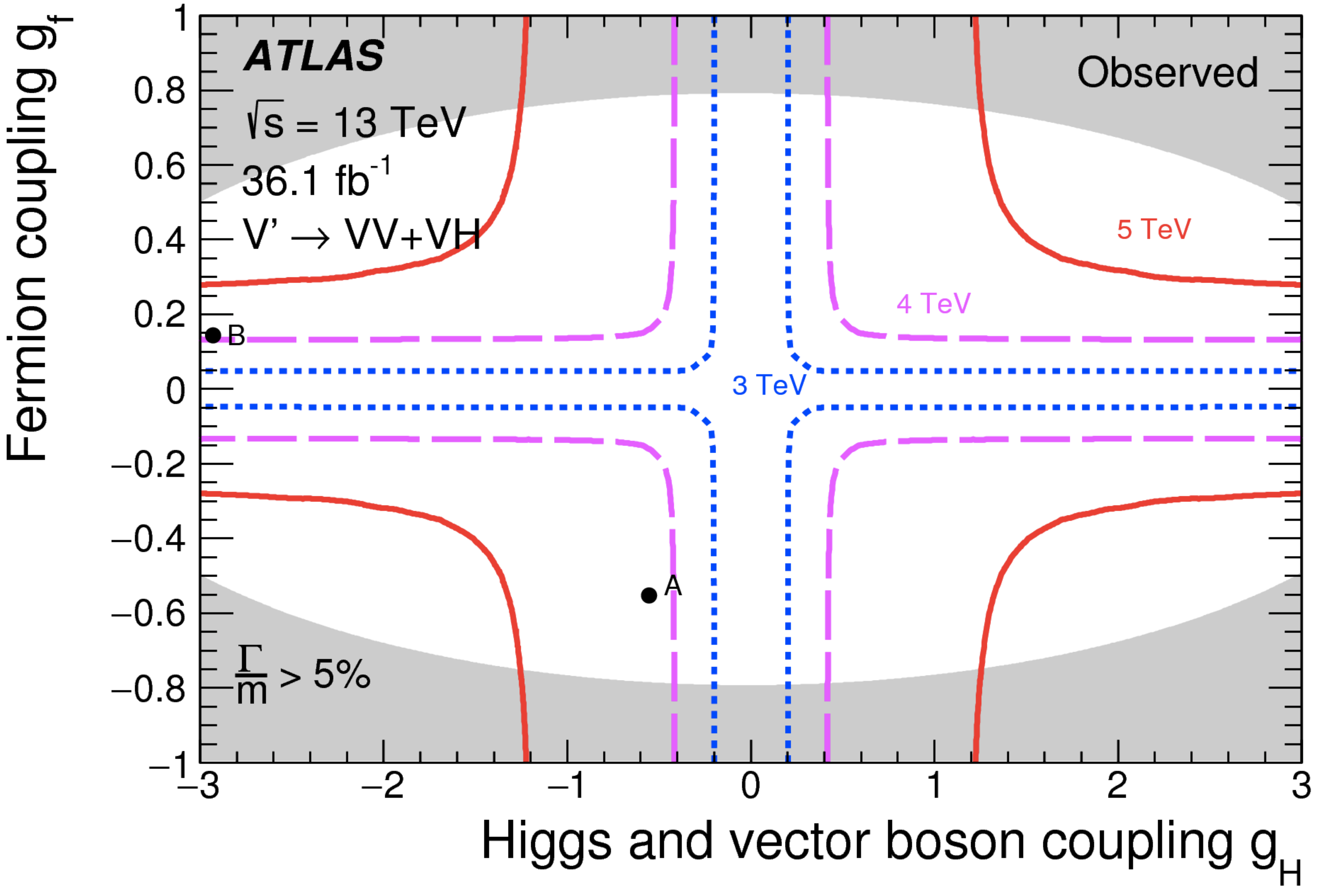


VZ


A × ε
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
Inclusive
μνμμ
evee
μvee
eνμμ
ATLAS Simulation
√s = 13 TeV, 36.1 fb-1
pp→W'jj→WZjj→ℓνℓℓjj
VBF
300
400
500
600
700
800
900
m(W') [GeV]


A × ε
0.6
0.5
0.4
0.3
0.2
0.1
0
Inclusive
μνμμ
evee
μvee
eνμμ
ATLAS Simulation
√s = 13 TeV, 36.1 fb-1
qq̄→W'→WZ→ℓνℓℓ
500
1000
1500
2000
2500
3000
m(W') [GeV]

VV Combination



Channel	Diboson state	Selection				VBF cat.
		Leptons	E_T^{miss}	Jets	b-tags	
$qqqq$	$WW/WZ/ZZ$	0	veto	2J	–	–
$\nu\nu qq$	WZ/ZZ	0	yes	1J	–	yes
$\ell\nu qq$	WW/WZ	$1e, 1\mu$	yes	2j, 1J	–	yes
$\ell\ell qq$	WZ/ZZ	$2e, 2\mu$	–	2j, 1J	–	yes
$\ell\ell\nu\nu$	ZZ	$2e, 2\mu$	yes	–	0	yes
$\ell\nu\ell\nu$	WW	$1e+1\mu$	yes	–	0	yes
$\ell\nu\ell\ell$	WZ	$3e$, $2e+1\mu$, $1e+2\mu$, 3μ	yes	–	0	yes
$\ell\ell\ell\ell$	ZZ	$4e$, $2e+2\mu$, 4μ	–	–	–	yes
$qqbb$	WH/ZH	0	veto	2J	1, 2	–
$\nu\nu bb$	ZH	0	yes	2j, 1J	1, 2	–
$\ell\nu bb$	WH	$1e, 1\mu$	yes	2j, 1J	1, 2	–
$\ell\ell bb$	ZH	$2e, 2\mu$	veto	2j, 1J	1, 2	–
$\ell\nu$	–	$1e, 1\mu$	yes	–	–	–
$\ell\ell$	–	$2e, 2\mu$	–	–	–	–

VBS: EW VVjj

139 fb^{-1}

Selection	0-lepton	1-lepton	2-lepton
Trigger	$E_{\text{T}}^{\text{miss}}$ triggers	Single-electron triggers Single-muon or $E_{\text{T}}^{\text{miss}}$ triggers	Single-lepton triggers
Leptons	0 'loose' leptons with $p_{\text{T}} > 7$ GeV	1 'tight' lepton with $p_{\text{T}} > 27$ GeV 0 'loose' leptons with $p_{\text{T}} > 7$ GeV	2 'loose' leptons with $p_{\text{T}} > 20$ GeV ≥ 1 lepton with $p_{\text{T}} > 28$ GeV
$E_{\text{T}}^{\text{miss}}$	> 200 GeV	> 80 GeV	–
$m_{\ell\ell}$	–	–	$83 < m_{ee} < 99$ GeV $-0.0117 \times p_{\text{T}}^{\mu\mu} + 85.63 < m_{\mu\mu} < 0.0185 \times p_{\text{T}}^{\mu\mu} + 94$ GeV
Small-R jets	$p_{\text{T}} > 20$ GeV if $\lvert\eta\rvert < 2.5$, and $p_{\text{T}} > 30$ GeV if $2.5 < \lvert\eta\rvert < 4.5$		
Large-R jets	$p_{\text{T}} > 200$ GeV, $\lvert\eta\rvert < 2$		
$V_{\text{had}} \to J$ $V_{\text{had}} \to jj$	V boson tagging, $\min(\lvert m_J - m_W\rvert, \lvert m_J - m_Z\rvert)$ $64 < m_{jj} < 106$ GeV, jj pair with $\min(\lvert m_{jj} - m_W\rvert, \lvert m_{jj} - m_Z\rvert)$, leading jet with $p_{\text{T}} > 40$ GeV		
Tagging-jets	$j \notin V_{\text{had}}$, not b-tagged, $\Delta R(J, j) > 1.4$ $\eta_{\text{tag},j_1} \cdot \eta_{\text{tag},j_2} < 0$, $m_{jj}^{\text{tag}} > 400$ GeV, $p_{\text{T}} > 30$ GeV		
Num. of b-jets	–	0	–
Multijet removal	$p_{\text{T}}^{\text{miss}} > 50$ GeV $\Delta\phi(\vec{E}_{\text{T}}^{\text{miss}}, \vec{p}_{\text{T}}^{\text{miss}}) < \pi/2$ $\min[\Delta\phi(\vec{E}_{\text{T}}^{\text{miss}}, \text{small-}R\text{ jet})] > \pi/6$ $\Delta\phi(\vec{E}_{\text{T}}^{\text{miss}}, V_{\text{had}}) > \pi/9$	–	–