Inclusive results for diboson in semi-leptonic channels

Semi-leptonic decay channels in multi-boson production: joint WG1+WG3 meeting

20th November 2024
https://indico.cern.ch/event/1473356/

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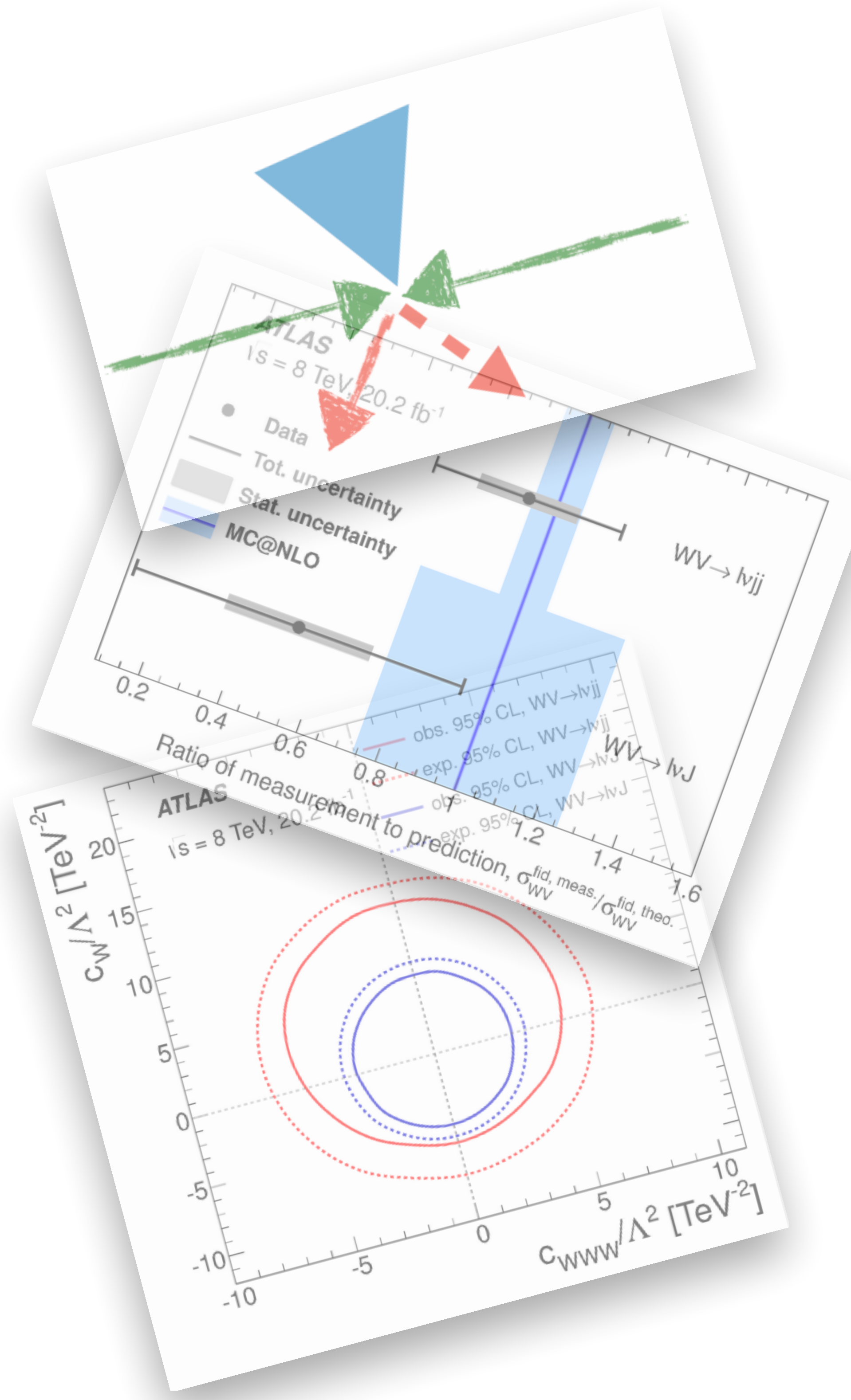
Today menu

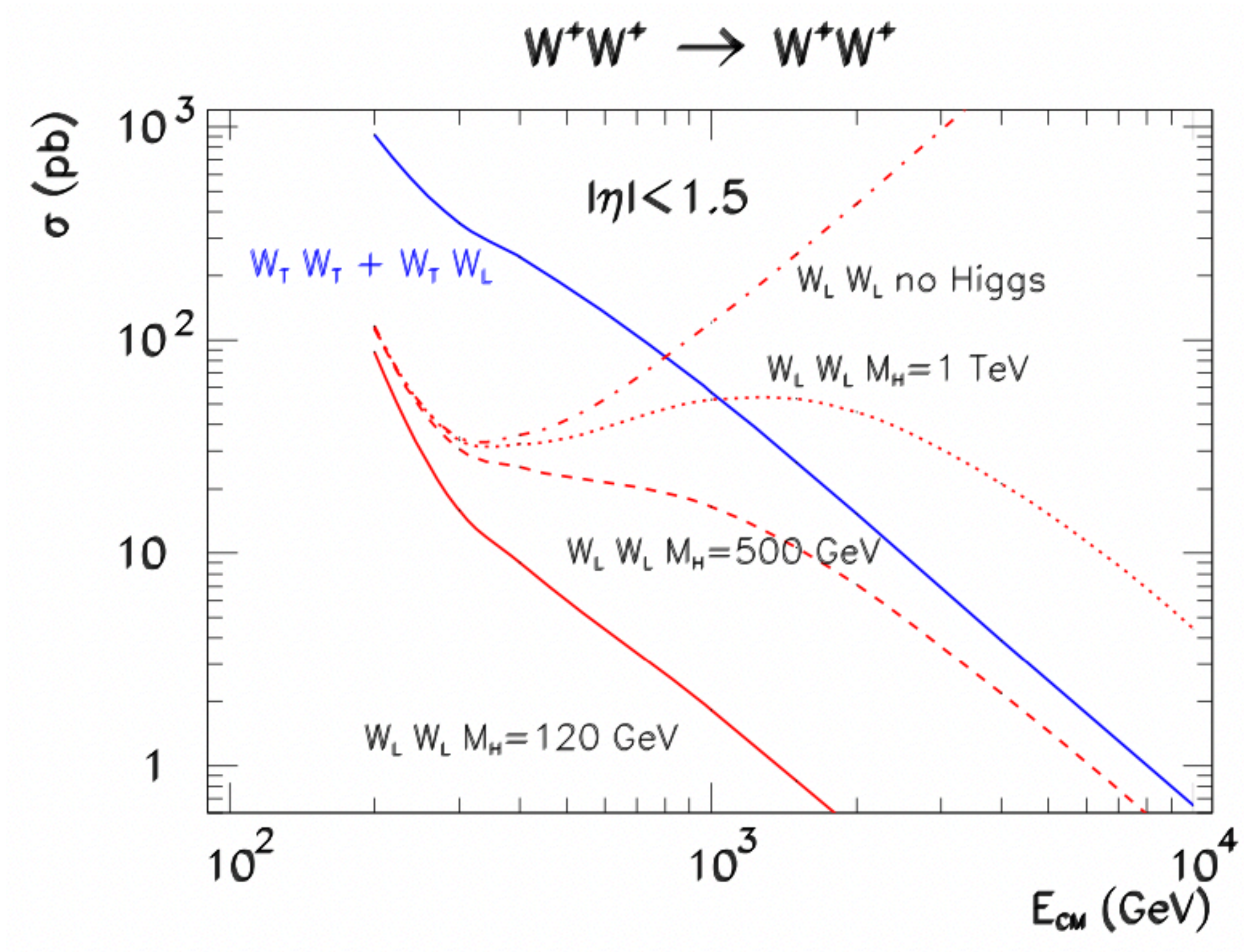
VV semi-leptonic channel

- ***Introduction***
  - motivation and definition
- ***Latest available experimental results***
  - WV in Run-1!!!
  - VZ (heavy flavour) in Run-2
- ***What if…we would like to do a VV semi-leptonic measurement today***
  - walk through what has been done in Run-1 with future perspectives
- ***Wrap-up***
  - EFT and polarisation considerations
  - Conclusions



Why diboson Physics?

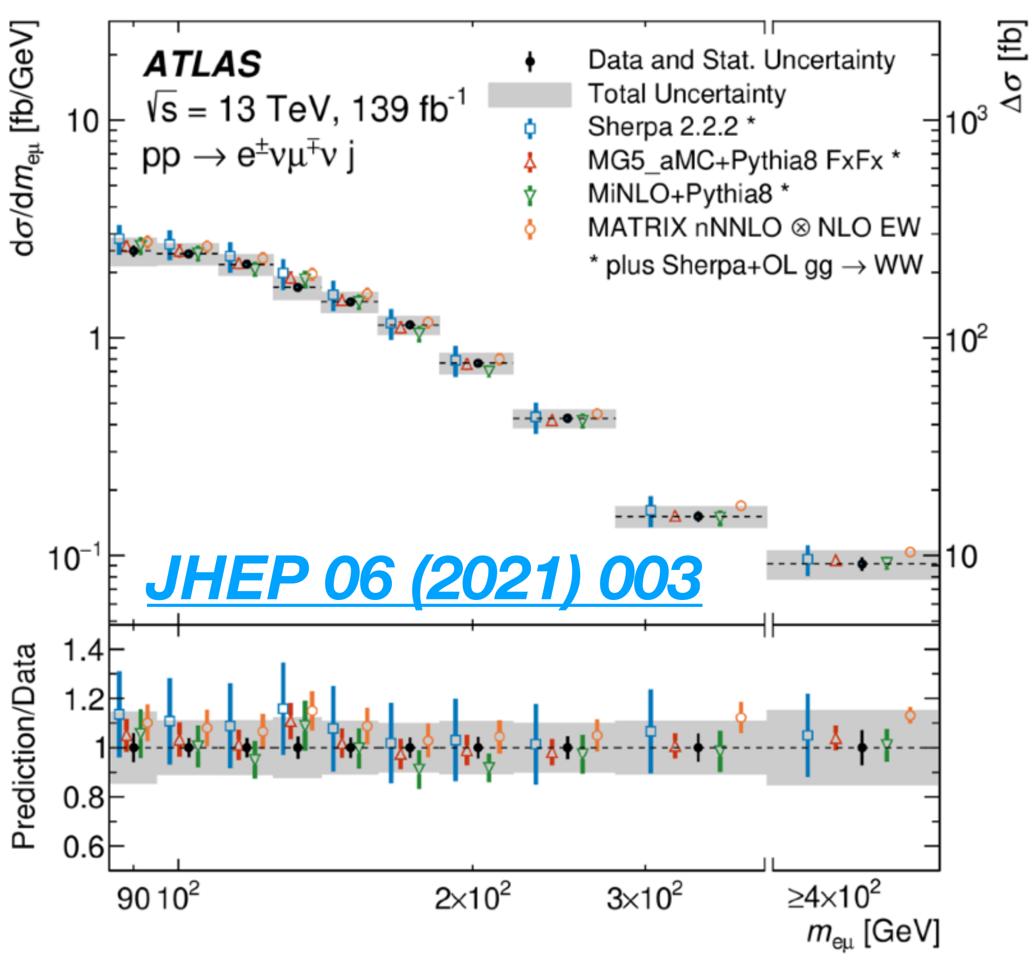
- Diboson interactions are a key process in the LHC program
  - according to the EWK sector the $W_L W_L$ scattering is violating the unitarity at the TeV scale
  - we expected something to happen with the LHC era
- After the Higgs discovery, we can say that the Higgs+EWK sector can mitigate this
  - however, this still needs to be directly confirmed at very high energy
- ***High-energy diboson interactions may still hide new physics!***



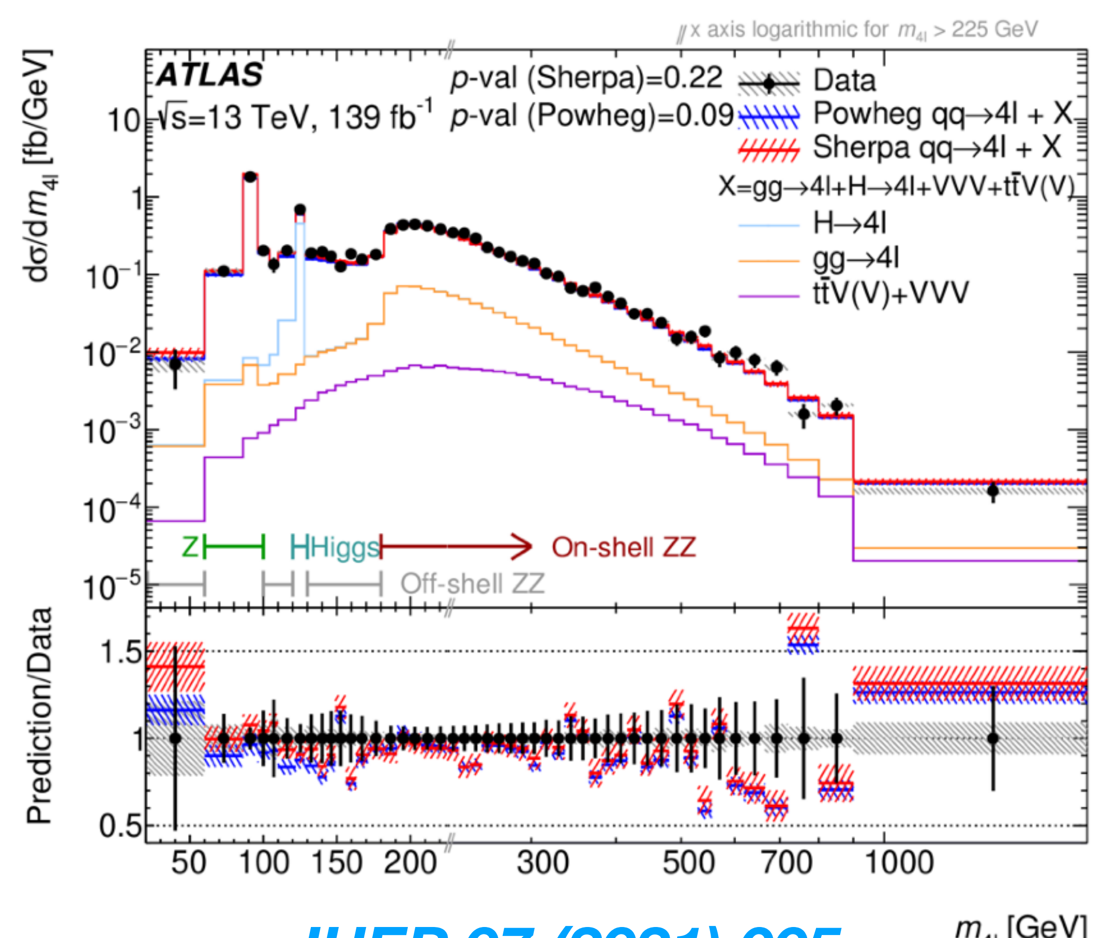
arxiv.1412.8367

Usual (run-2) practice

- During the Run-2 data analyses
  - VV cross section measurements
  - differential measurements
  - EFT interpretation in several channels
- All of this using leptonic channels
  - WW (lνlν), WZ (lνll), …



JHEP 06 (2021) 003



JHEP 07 (2021) 005

Semi-leptonic channel definition

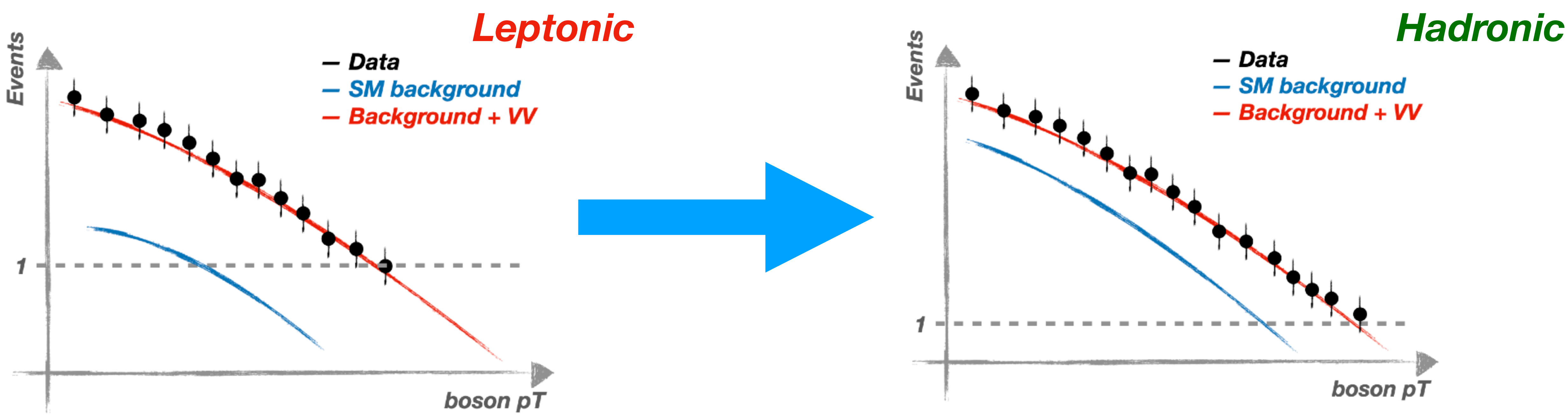
- First, we need to define what is a semi-leptonic diboson channel
  - one of the two bosons decays ***leptonically*** and one ***hadronically***
- In other terms (0-/1-/2-lepton)
  - WV —> lνqq, ZV —> $\nu\nu$qq/llqq
  - with V = W, Z
- ATLAS tried to harmonise and merge all the channels together during Run-2 (resonant searches and VBS measurements); CMS usually considers the channels separated

BR(VV—>1234)		**W lν**	**Z $\nu\nu$**	**Z ll**	**W qq**	**Z qq**
		21,6	**20,5**	**6,8**	**67,6**	**69,2**
W lν	**21,6**	*4,7*	*4,4*	*1,5*	*14,6*	*14,9*
Z $\nu\nu$	**20,5**	-	*4,2*	*1,4*	*13,9*	*14,2*
Z ll	**6,8**	-	-	*0,5*	*4,6*	*4,7*
W qq	**67,6**	-	-	-	*45,7*	*46,8*
Z qq	**69,2**	-	-	-	-	*47,9*

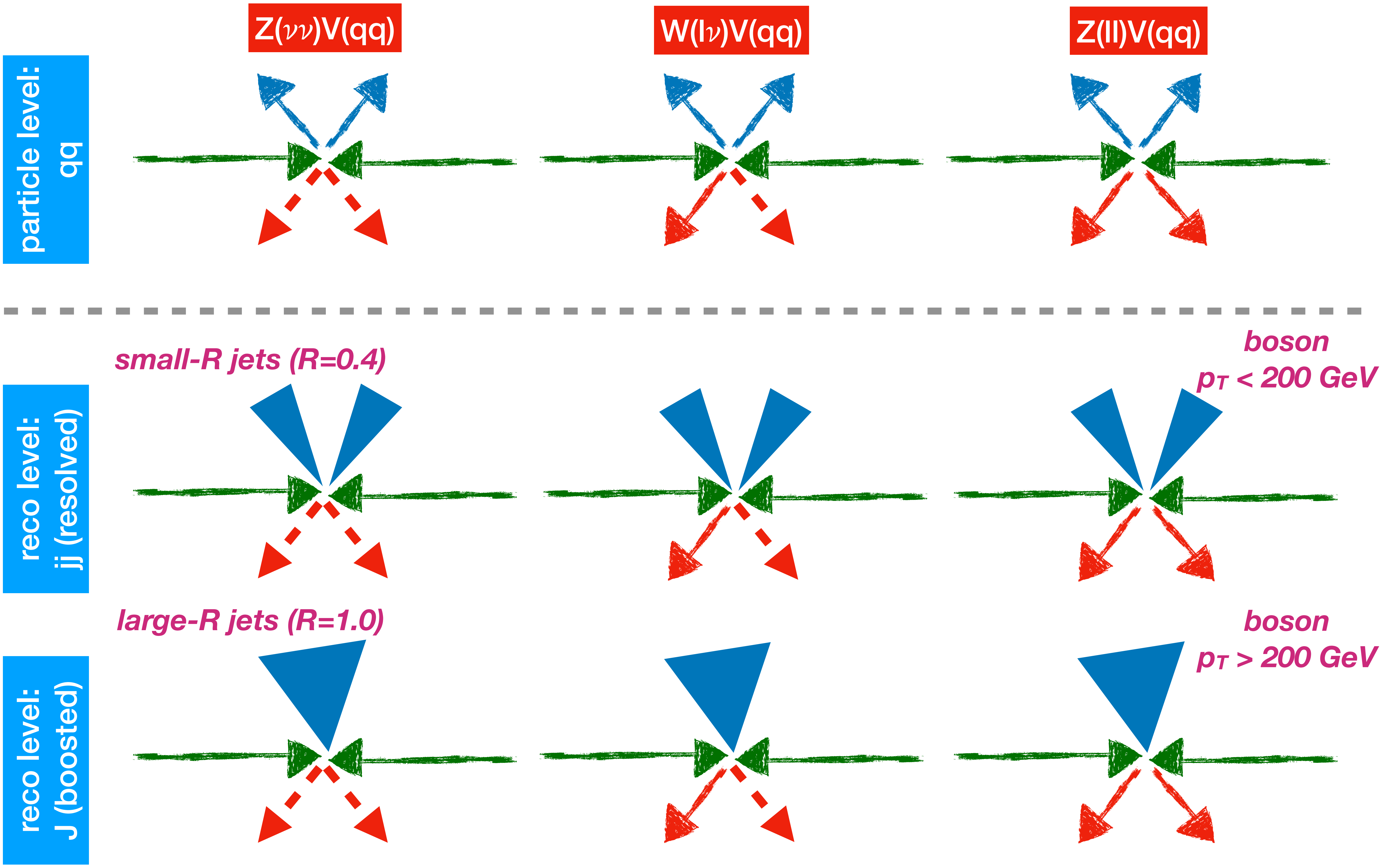
fully-leptonic
semi-leptonic
fully-hadronic

Why semi-leptonic channel?

- There are remarkable cross section measurements in leptonic channels, why should we consider semi-leptonic?
    - *these decay channels are not covered, is this enough to motivate analyses?*
- There are actually other interesting/motivating physics considerations:
    - ***more signal events (higher BRs) potentially accessible***
    - ***higher boson p_T (m_{VV}) phase space can be accessed***
    - ***channels with higher cross section with fully reconstructed final states,***
        - Z(ll)W(qq) + Z(ll)Z(qq) vs Z(ll)Z(ll)



Experimental signature



Experimental results

Reference = [ATLAS, CMS]

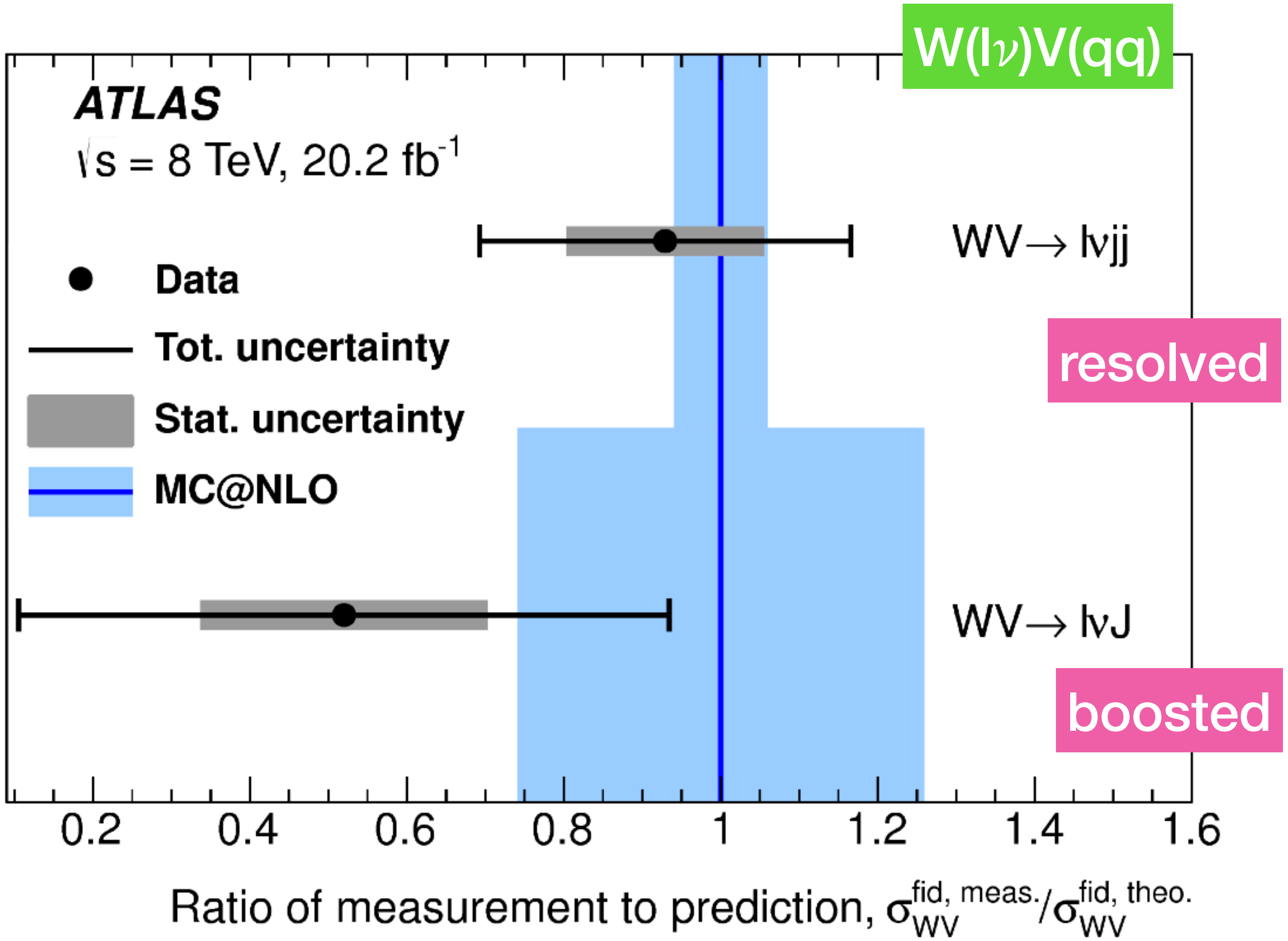
- ***Inclusive VV measurements (+ EFT)***
  - 7 TeV cross section, WW/WZ lνjj [1, 2]
  - 8 TeV cross section + aTGC, WW/WZ lνjj/J [3, 4]
  - 8 TeV cross section, VZ(bb) ($\nu\nu$/lν/ll jj) [5]
- ***VBS VV measurements***
  - 13 TeV, cross section 36/fb VV semi-leptonic [6]
  - 13 TeV, evidence 139/fb WV semi-leptonic [7]
- ***VV searches***
  - a bunch during run-2, both inclusive and VBF phase space, llqq [8, 9], lνqq [8, 10], $\nu\nu$qq [8, 11]
- ***Vh(bb/cc) measurement***
  - 13 TeV, observation 140/fb Vh semi-leptonic [12, 13]

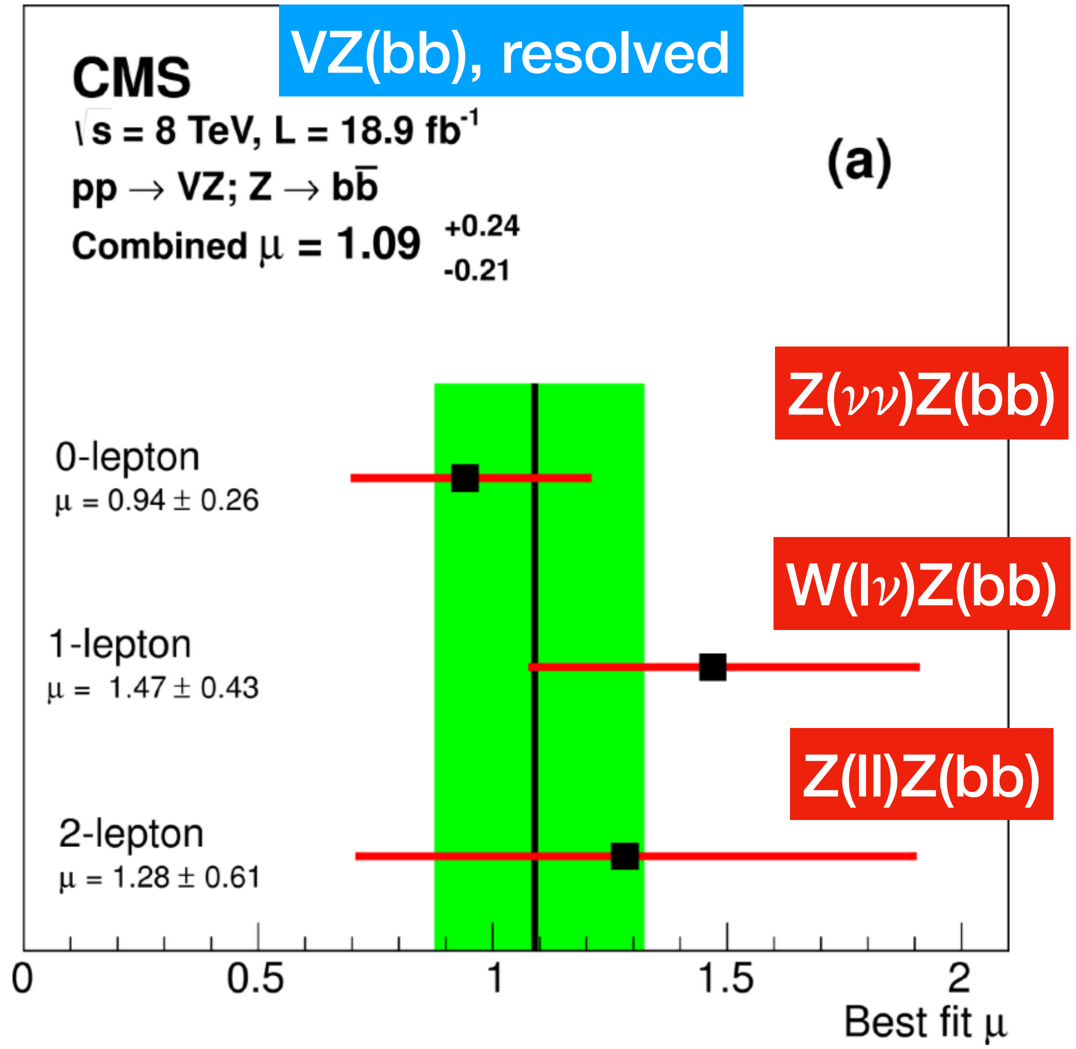
Giacomo's talk

Andrea's talk

Current cross section results

- ***ATLAS and CMS measured the cross section in Run-1 last time***
- Complementary results
  - agreement with SM with relative large uncertainties
  - ***WV: 4.5σ (5.2σ) observed (expected)***
  - ***VZ: 4.1σ (4.6σ) observed (expected)***

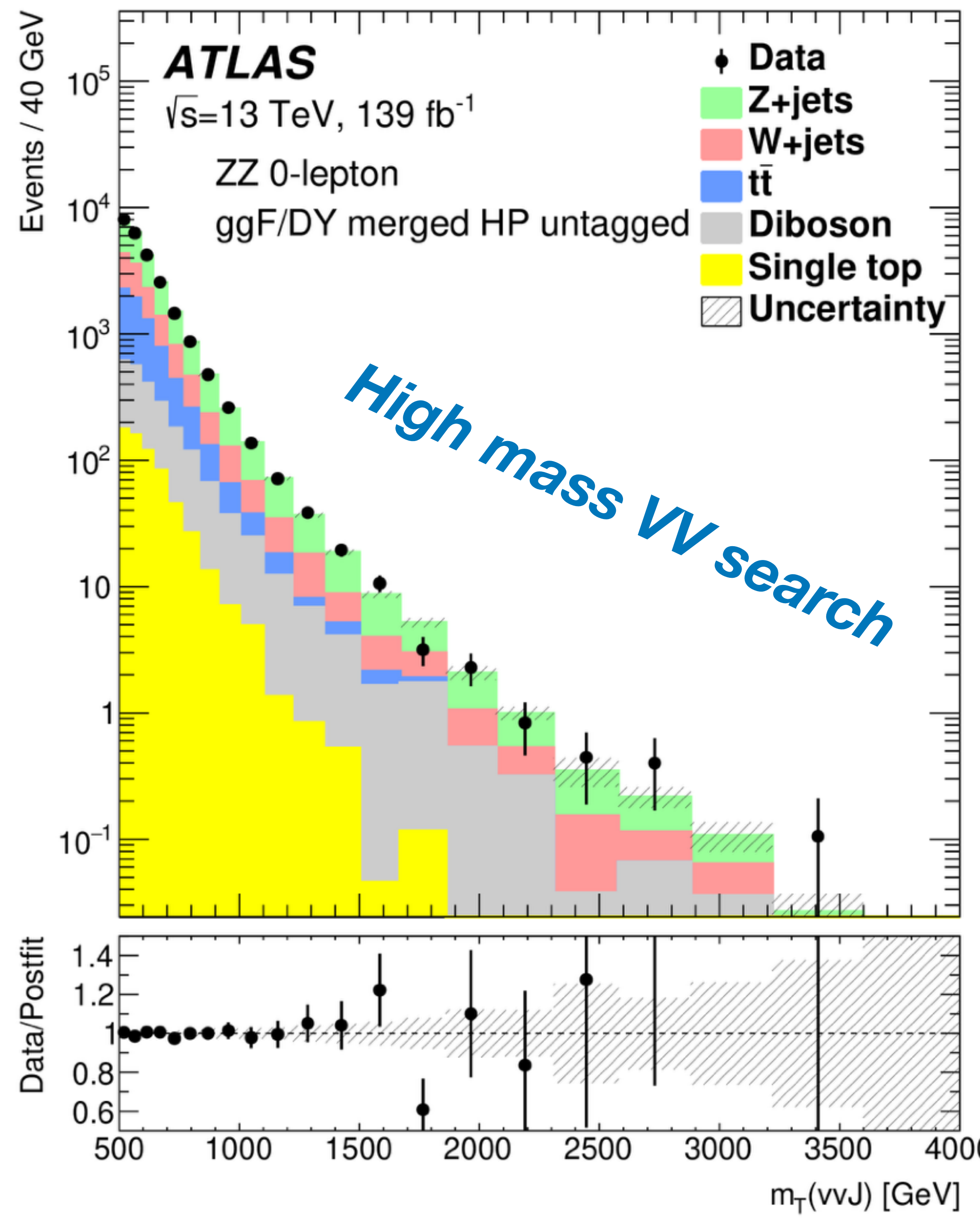




What did we learn so far?

- SM VV semi-leptonic process has been explored already at the time of Run-1
  - very close to the observation (not all the VV channels were combined…)
- ***It has been somehow forgotten during Run-2…***
- Nevertheless, it has been always at our hand since it represents a significant background in
  - ***high mass VV searches***
  - ***Vh(bb/cc) measurements***

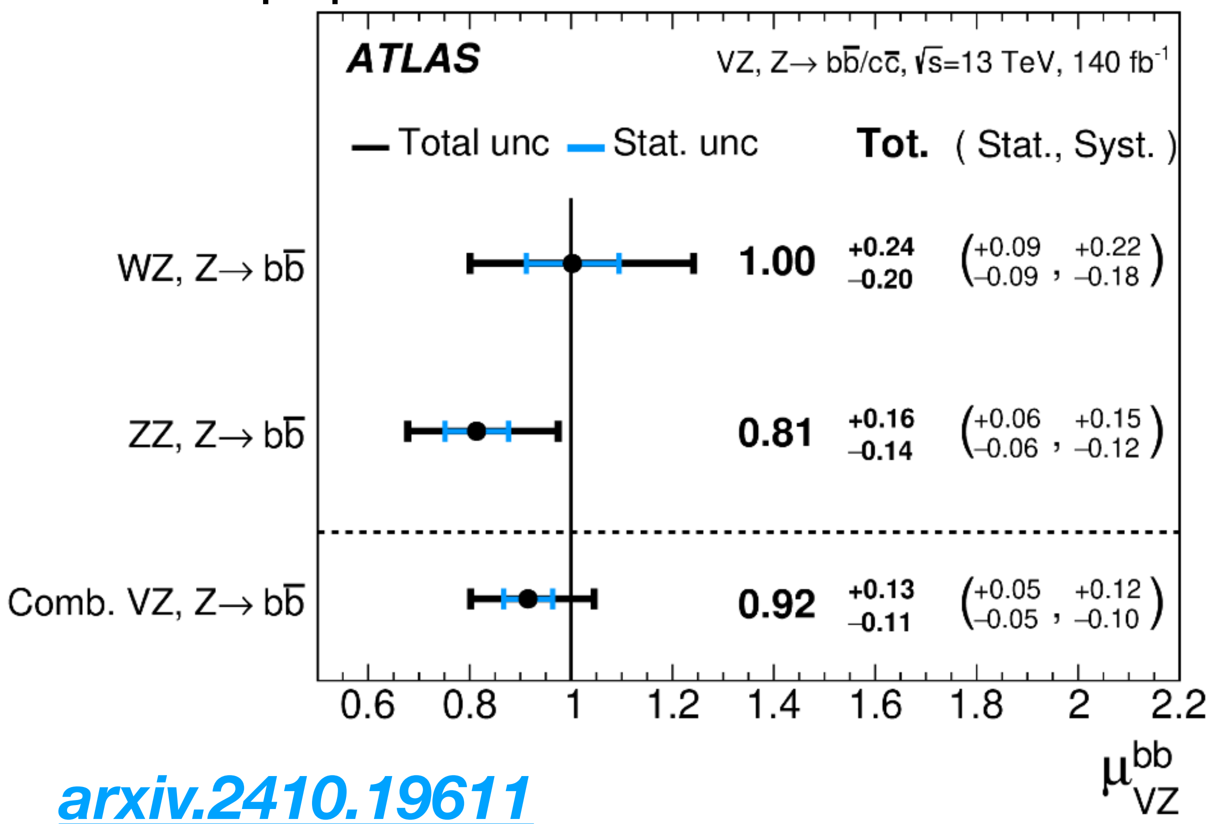
Eur. Phys. J. C 80 (2020) 1165

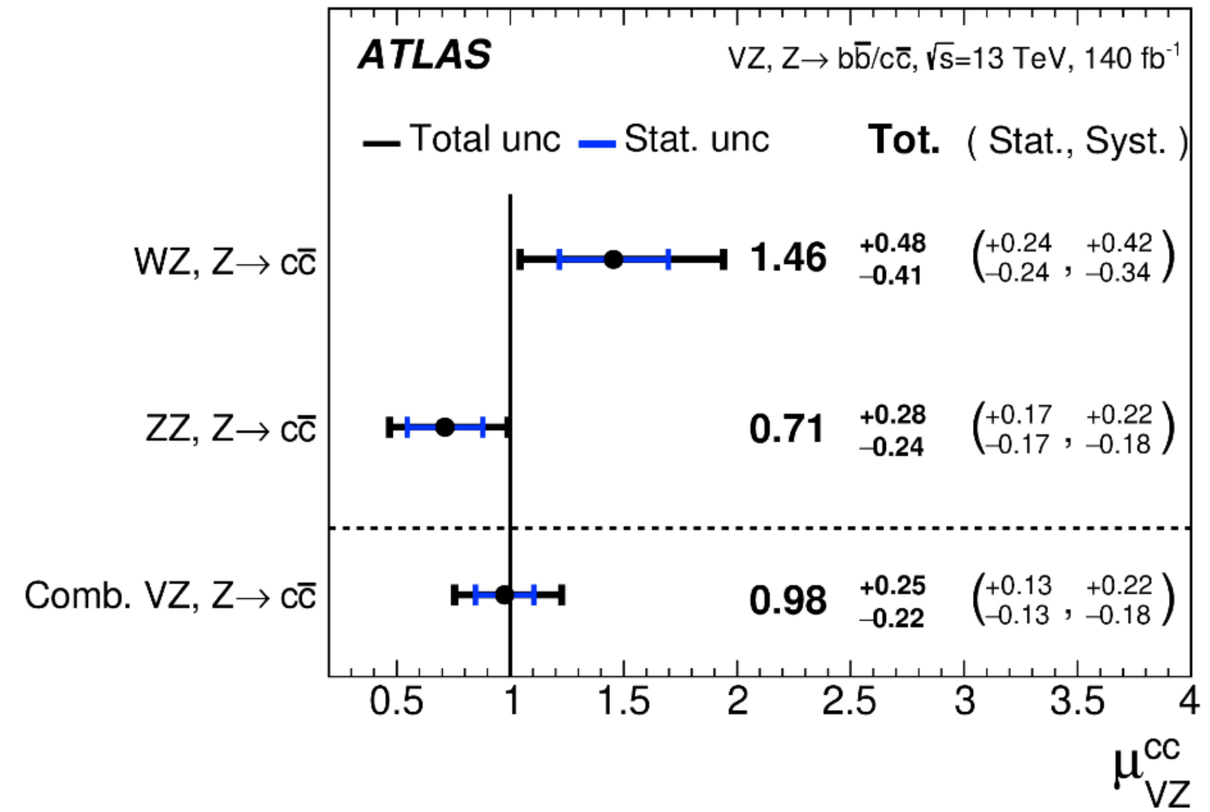


Observation in VZ channels

- ***ATLAS Run-2 Vh semi-leptonic measurement***
  - *V decaying leptonically*
  - *h(bb) resolved/boosted, h(cc) resolved*
- The diboson process represents a background to the Vh production and it is used as a validation
  - a side measurement has been done in the paper

	bb		cc	
	obs	exp	obs	exp
WZ	6.4σ	6.5σ	3.9σ	2.7σ
ZZ	>10σ		3.1σ	4.3σ
VZ	>10σ		5.2σ	5.3σ





arxiv.2410.19611

What if…

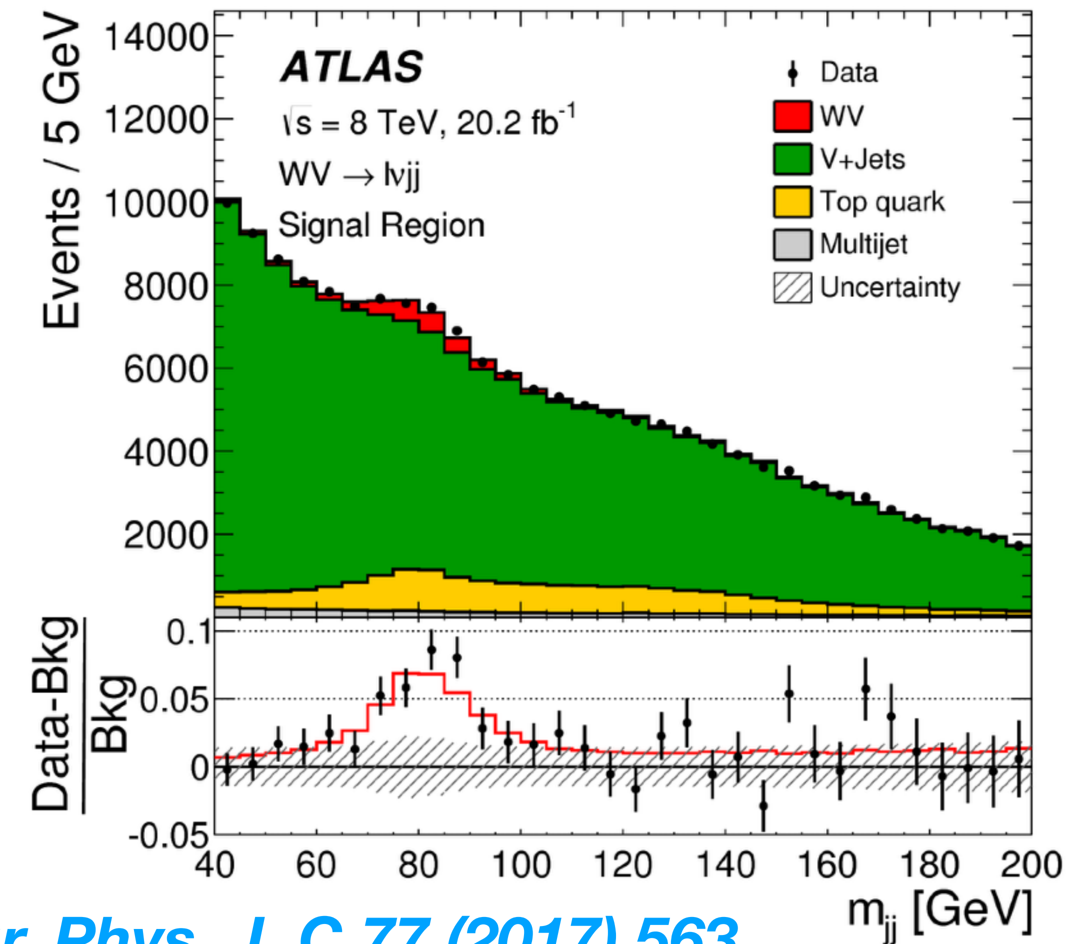
- All right, this channel has been somehow forgotten during Run-2
- ***What if…*** "I would like to do the analysis with Run-2/-3/HL"?
  - "can you guide us through the challenges?" yes, let's do that
- How to…***semi-leptonic***
  - SM background contribution and estimation
  - MC predictions
  - analyses techniques
  - fiducial phase space definition
  - …

Background composition and prediction

- ***How to save events? Trigger selection***
  - data recorded using single-lepton and MET triggers
- ***SM background processes***
  - data dominated by V+jets events
  - ttbar also contributes, according to the lepton channel, suppressed in Z(ll)

- ***Theory predictions***

	Run-1	*On the market*
VV	MC@NLO v4 + Hw6	Sherpa 2.2.11+
V+jets	Sherpa 1.4.1	Sherpa 2.2.11+



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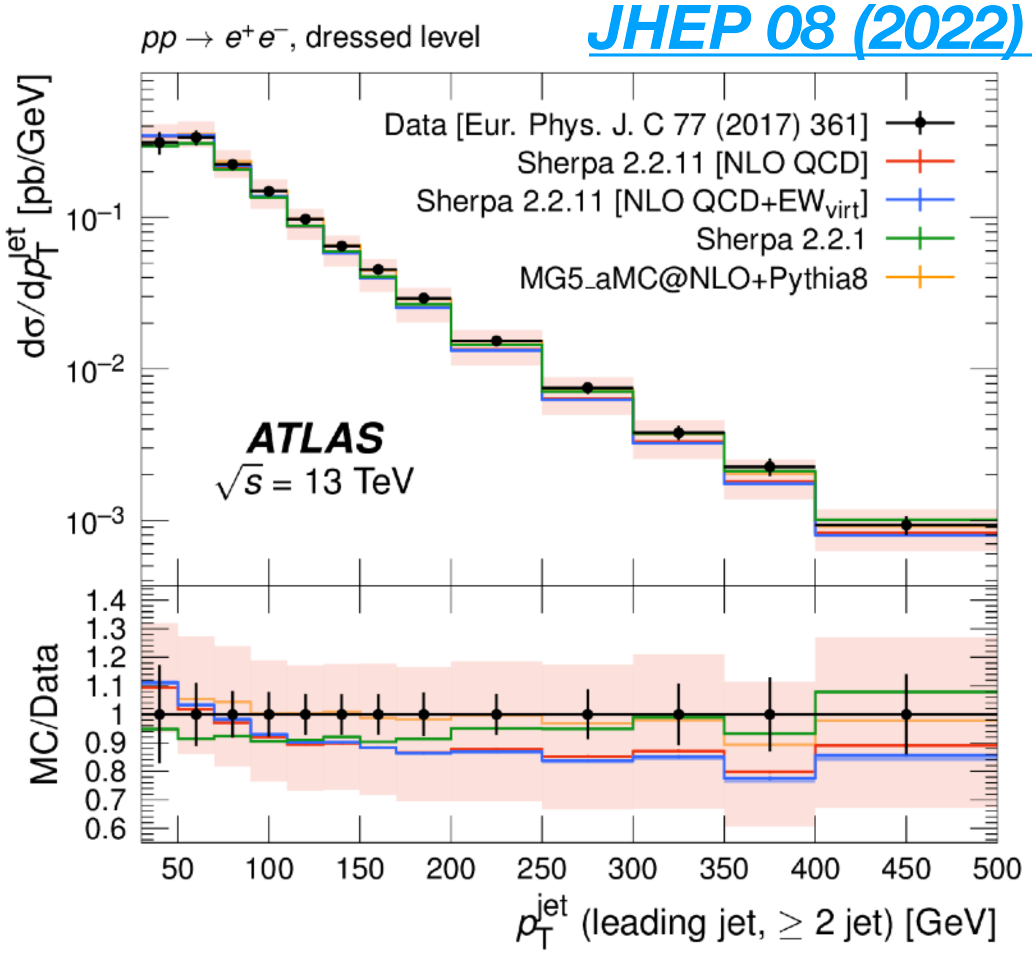
JHEP 08 (2022) 089

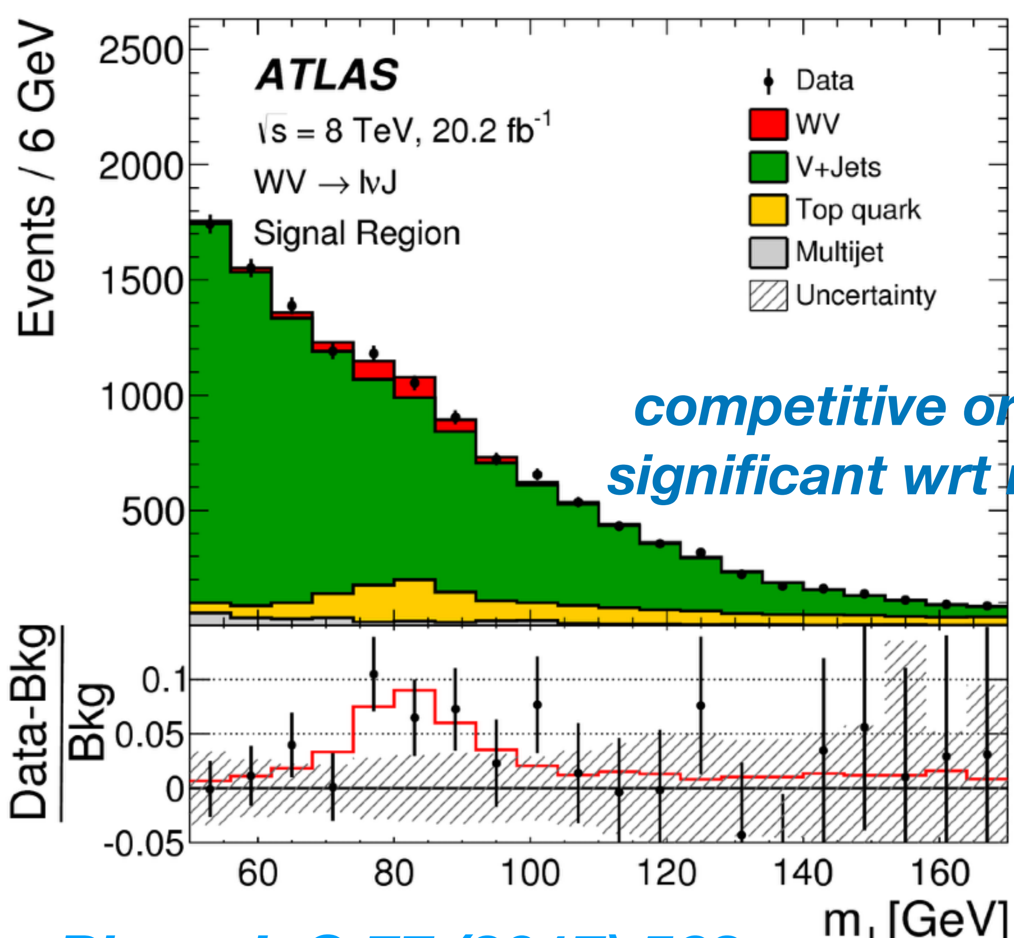


Analysis techniques

- The ability of the jets reconstruction can affect these channels
  - ***significant improvement in jets reconstruction and calibration***

> - small-R jets: EMTopo —> ParticleFlow (PFlow)
> - large-R jets: LCTopo —> Track Calo Clusters (TCC) —> Unified Flow Objects (UFO)

- ***Boosted regime***
  - crucial to exploit the potentiality of these channel in higher p_T/m_{VV} regimes
  - lower signal efficiency but also much lower background



competitive or higher significant wrt resolved

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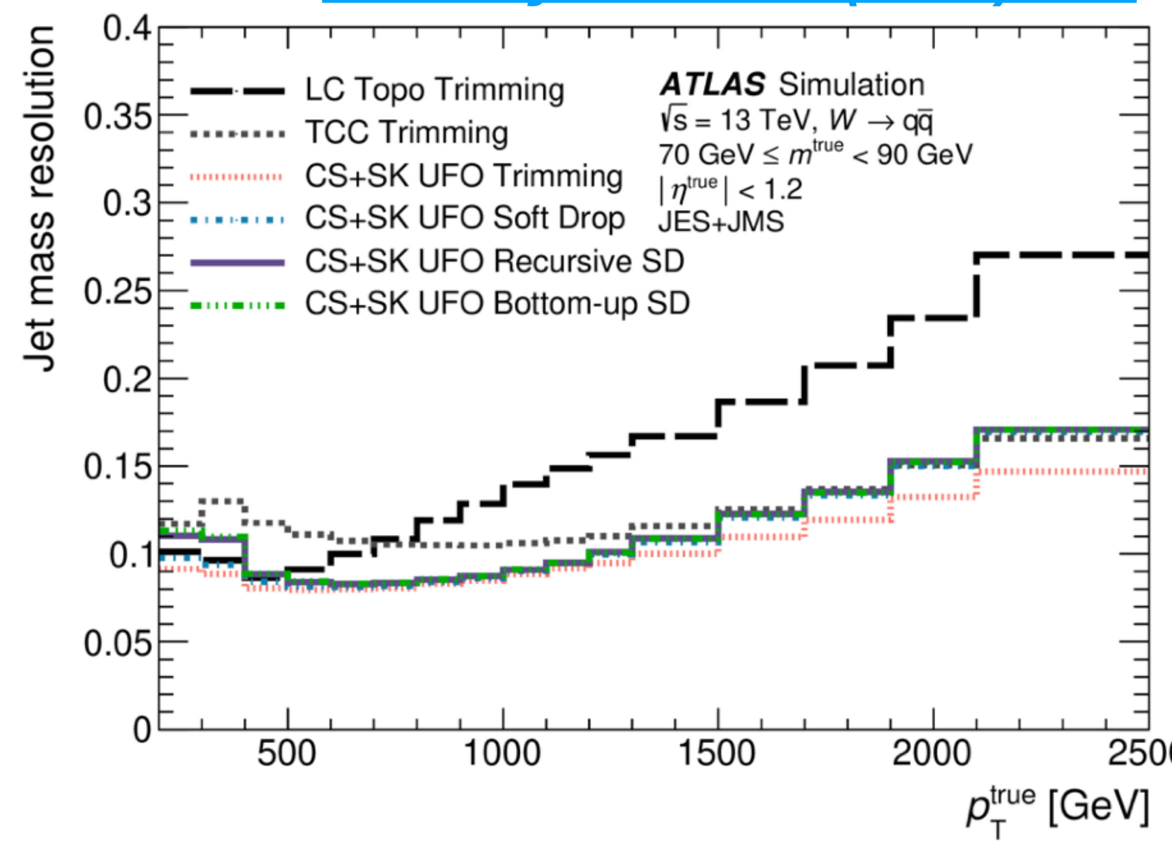
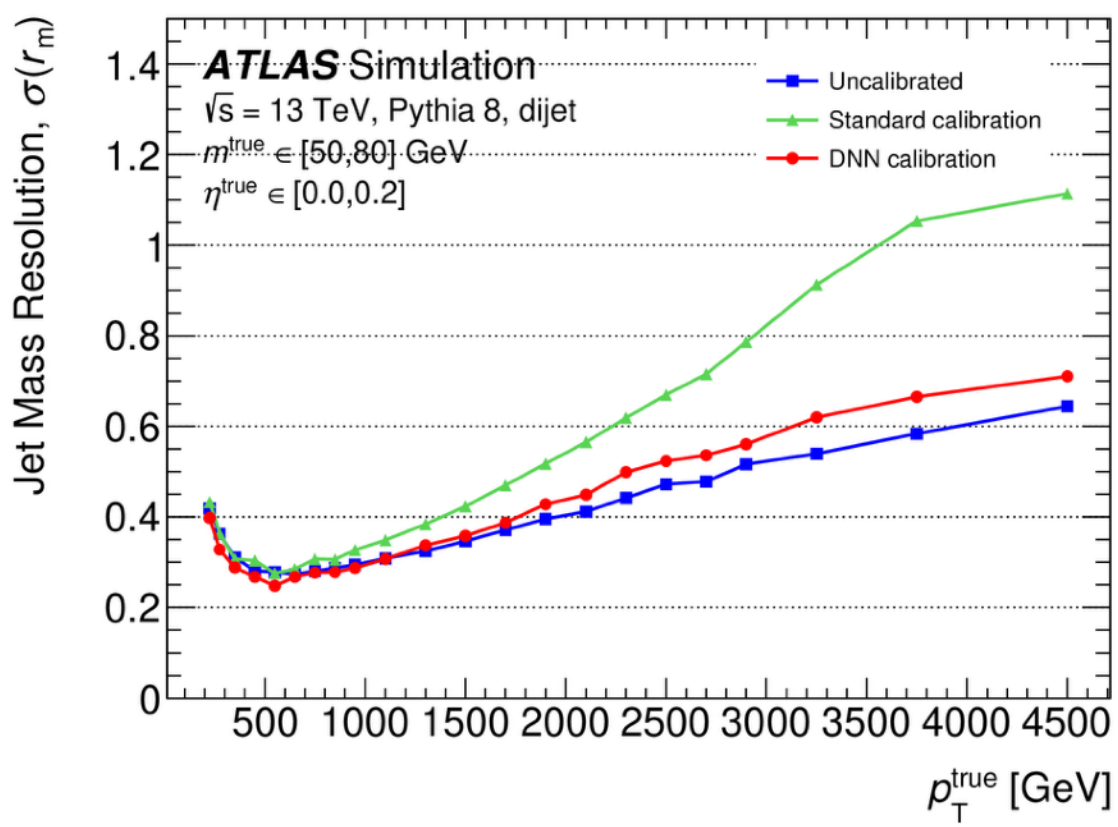


More on boson tagging

- ***UFO jets reconstructions***
  - optimal reconstruction combining calorimetric information to track information both at low and high-p_T
  - new calibration techniques
- ***Machine learning and jet sub-structure***
  - tag 2-prong like jets, i.e. boson tagging W/Z vs q/g
  - huge progress during Run-2 thanks to new techniques

Mach. Learn. Sci. Technol. 5 035051 (2024)



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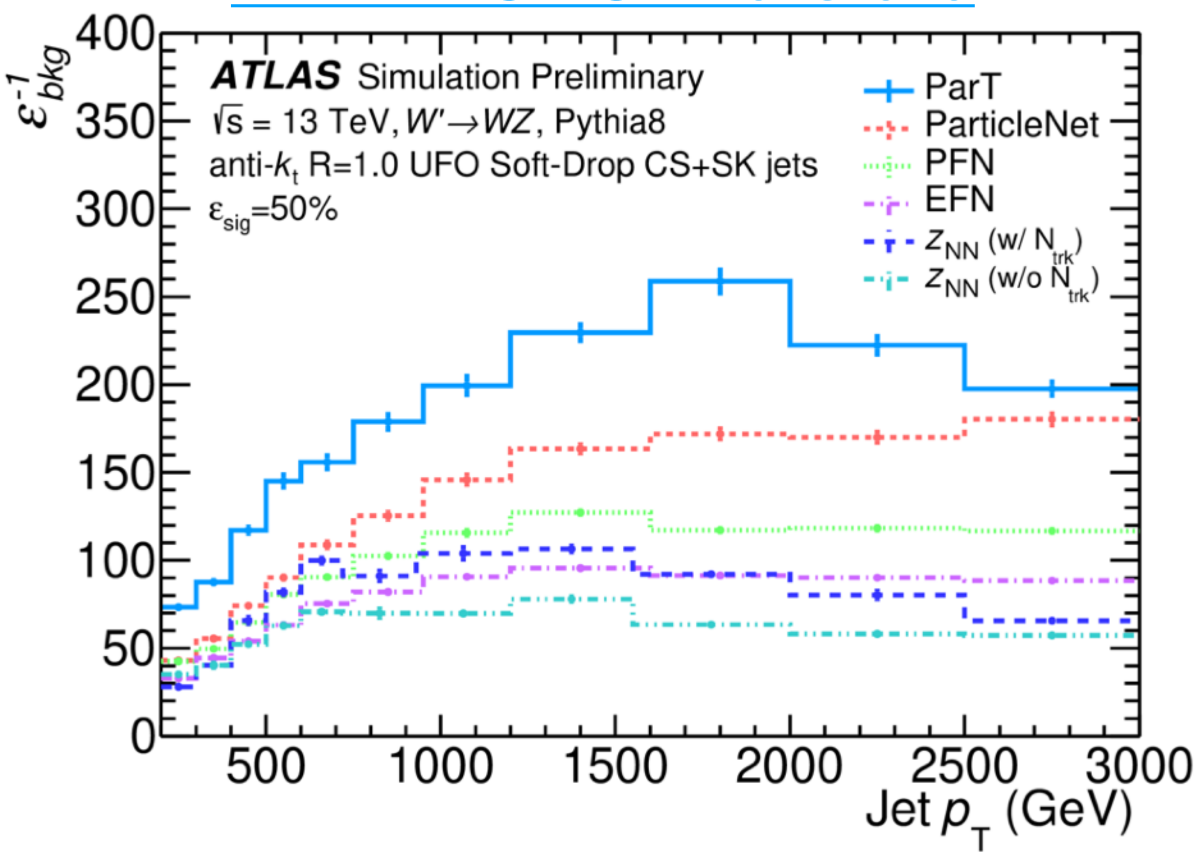

Background estimation

- ***Control regions***
  - dedicated Top-CR and Vjets-CR to constraint the backgrounds
- ***MC modelling***
  - modelling uncertainties are significant
  - V+jets mis-modelling, ad-hoc MC-to-data reweighing to improve predictions (same also in VBS phase space in Run-2)
- ***New techniques for data-driven estimations?***

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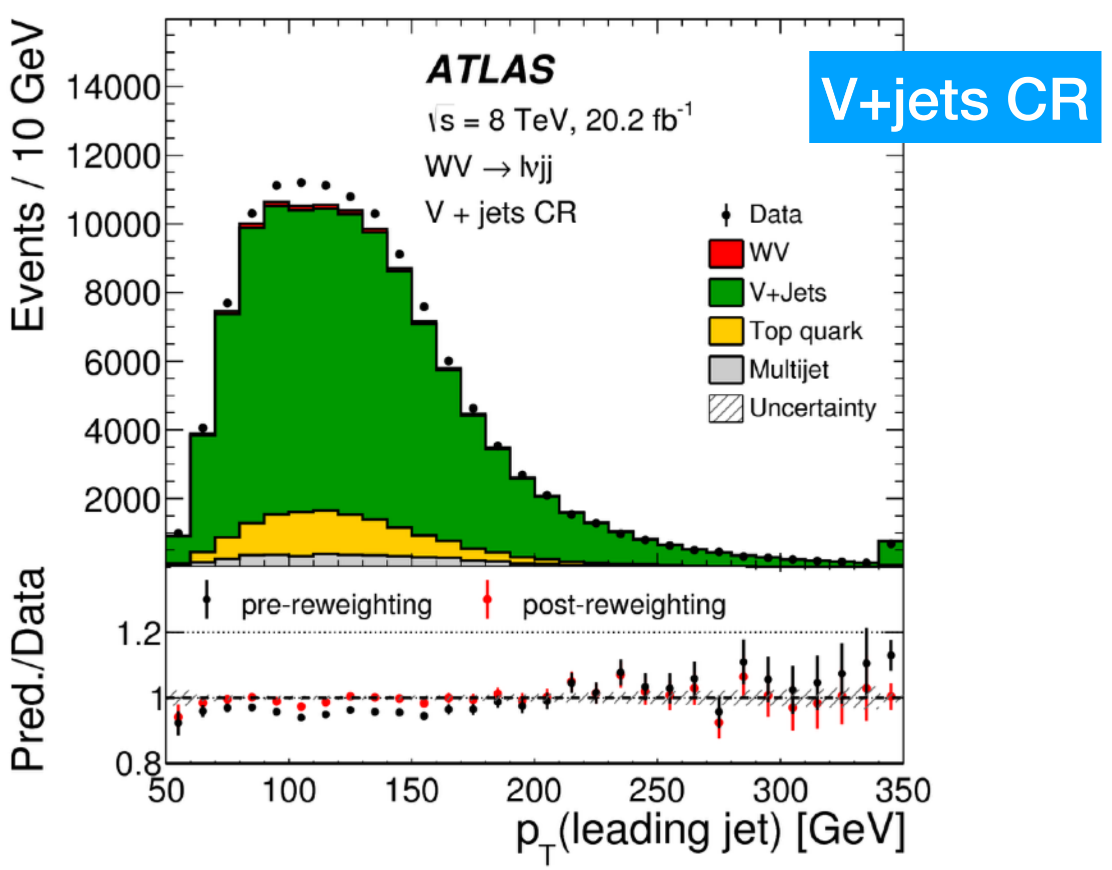
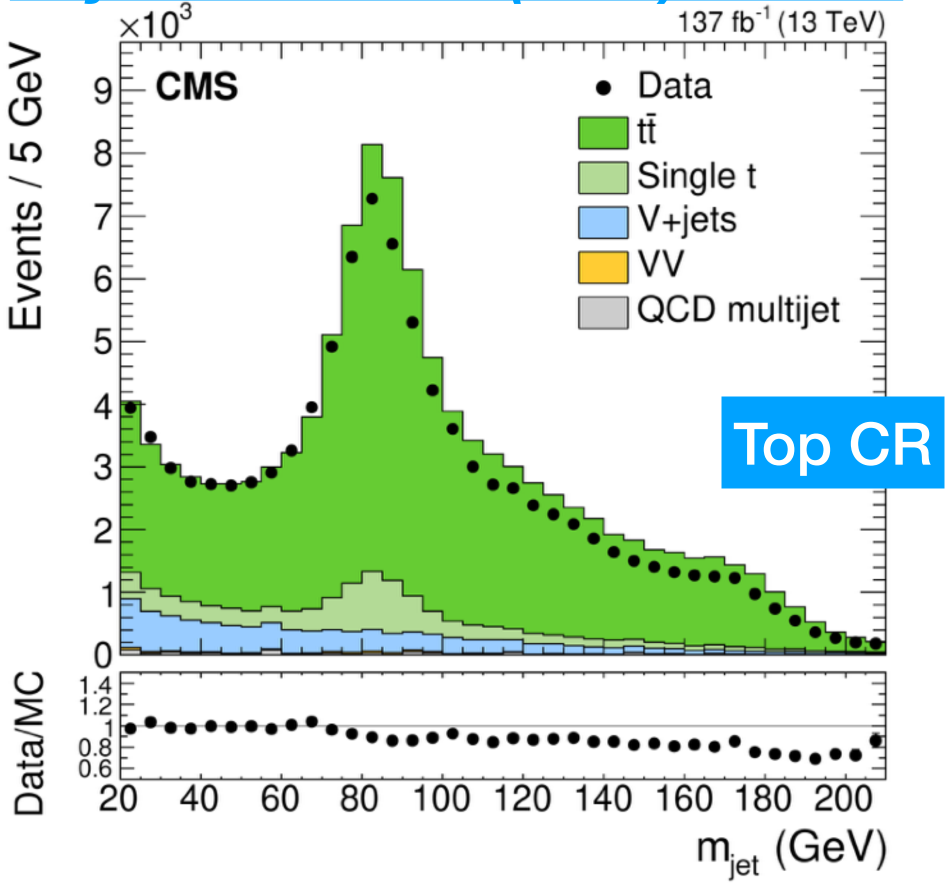


Phys. Rev. D 105 (2022) 032008



Other analysis features

Fiducial phase space definition

- A fiducial phase space at the particle level is an usual method to extract the measurement
- Defined to mimic the reconstruction level definition
    - might not be trivial to mimic the sub-structure information for boosted regimes

$$\sigma_{\text{fid}} = \frac{N^{WV}}{\mathcal{L} \cdot D_{\text{fid}}},$$

Final discriminant

- The Run-1 analyses used the reconstructed boson mass to extract the signal strength
    - modern SM measurement usually relies on Machine Learning discriminants to exploit the full event information

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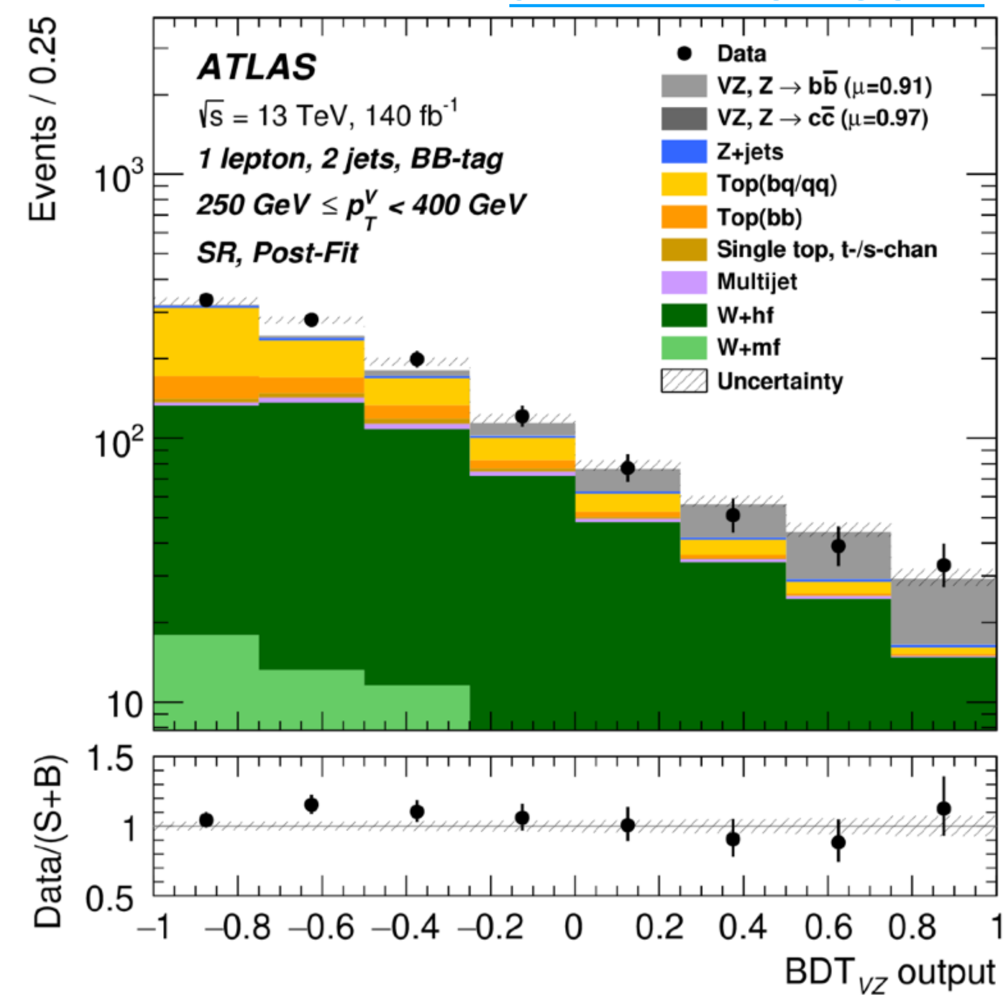

EFT interpretation

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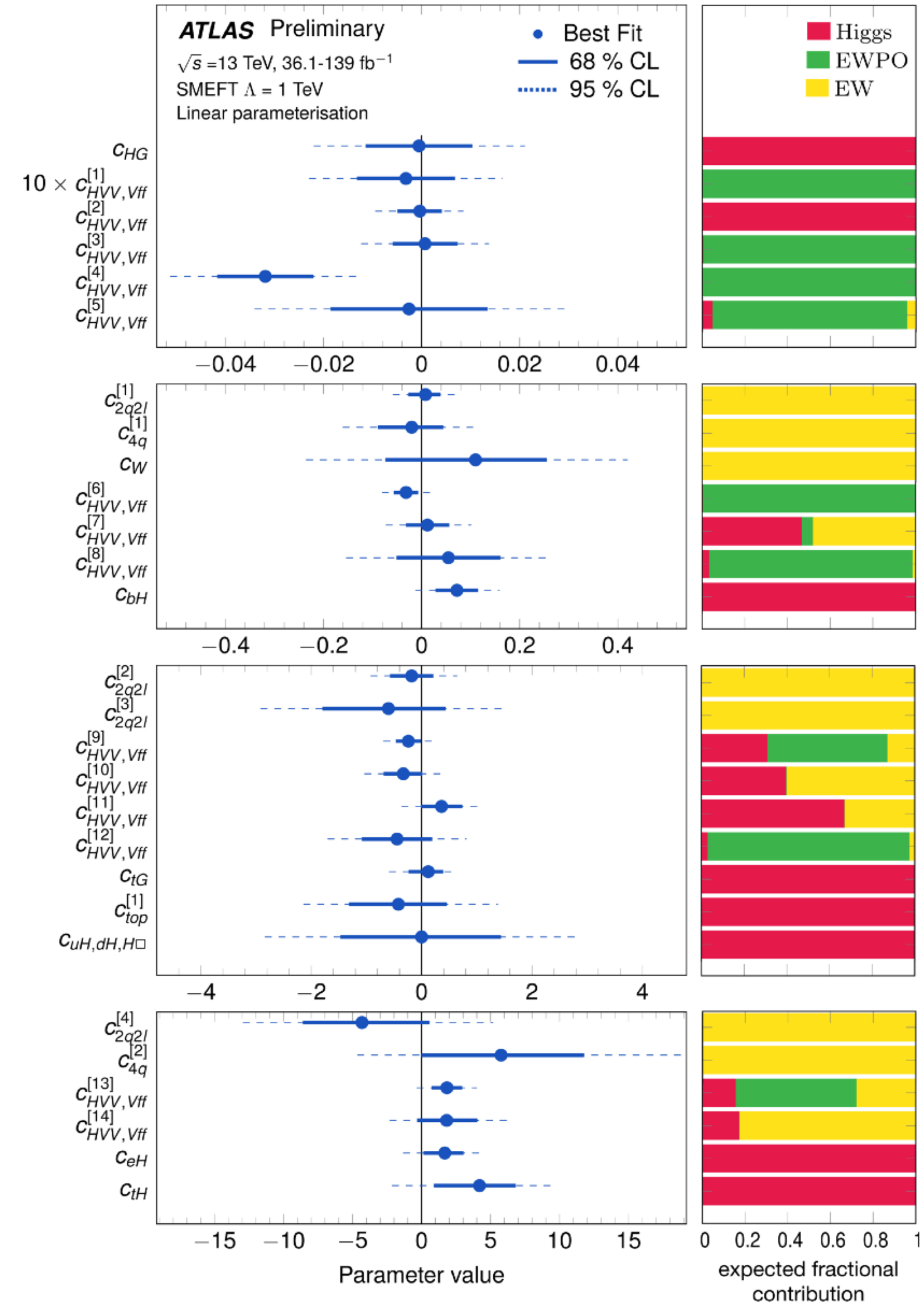
- Data can be interpreted in terms of Beyond SM effects
  - extend the SM Lagrangian using an ***Effective Fields Theory***
  - BSM effects are parametrised as higher dimension operators

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i^{(5)}}{\Lambda} \mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \ldots .$$

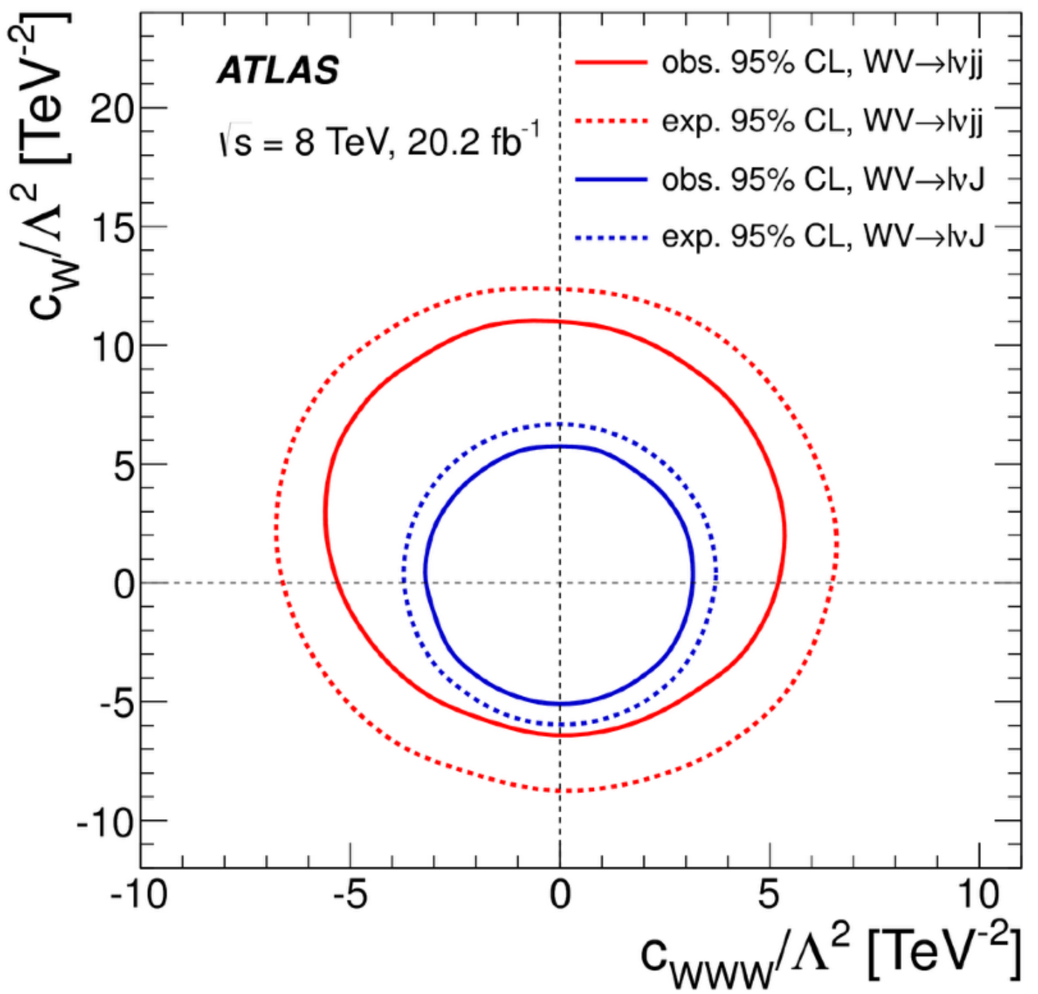
- Several operators can appear
  - they can manifest at high $p_T \sim m_{VV}$ phase space
- Run-2 results cover a good range of phase spaces and operators



The latest results on semi-leptonic

- As for the cross section measurement, the latest results for semi-leptonic channels are from Run-1
  - using also the LEP-constrain aTGC parameters
  - the two schemes can be translated
- ***We now have much higher luminosity and much more advanced analyses techniques!!***

$$\mathcal{O}_W = (D_\mu\Phi)^\dagger W^{\mu\nu}(D_\nu\Phi)\,,$$
$$\mathcal{O}_B = (D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi)\,,$$
$$\mathcal{O}_{WWW} = Tr[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}]\,.$$



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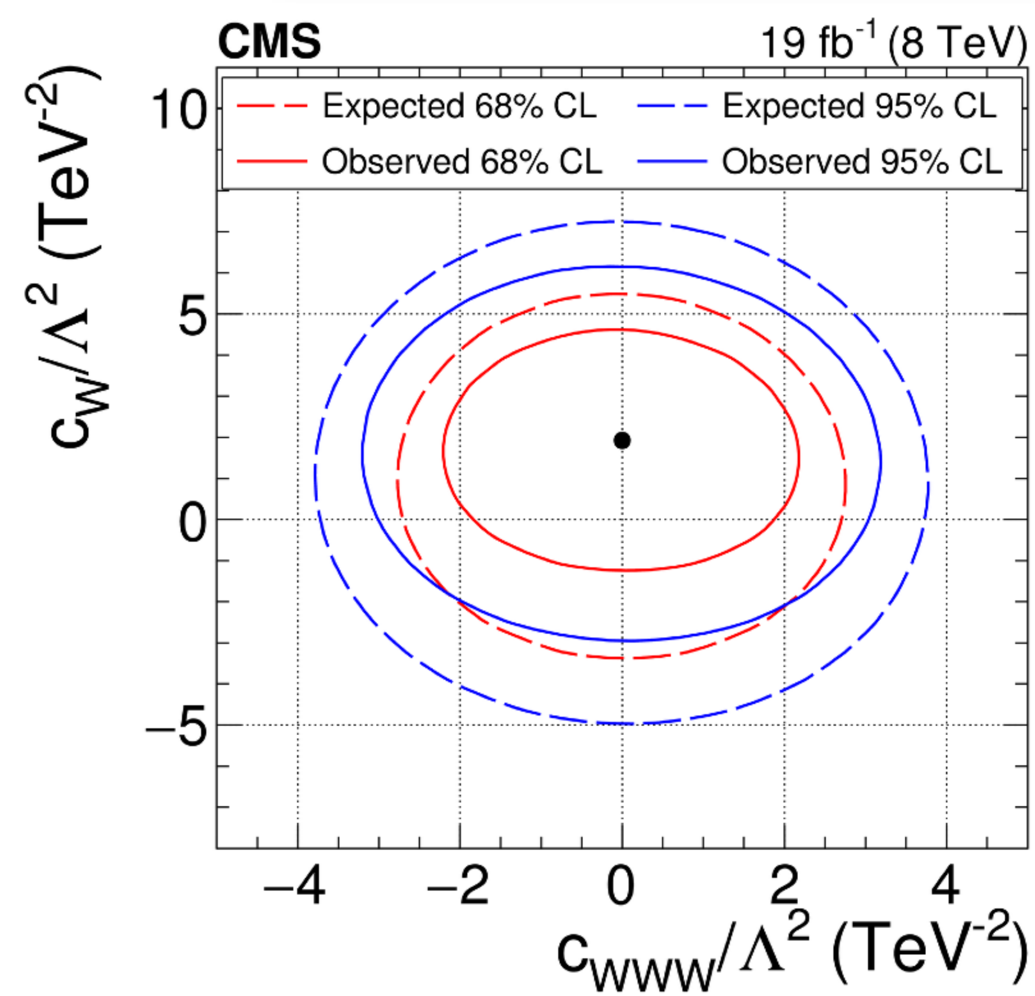
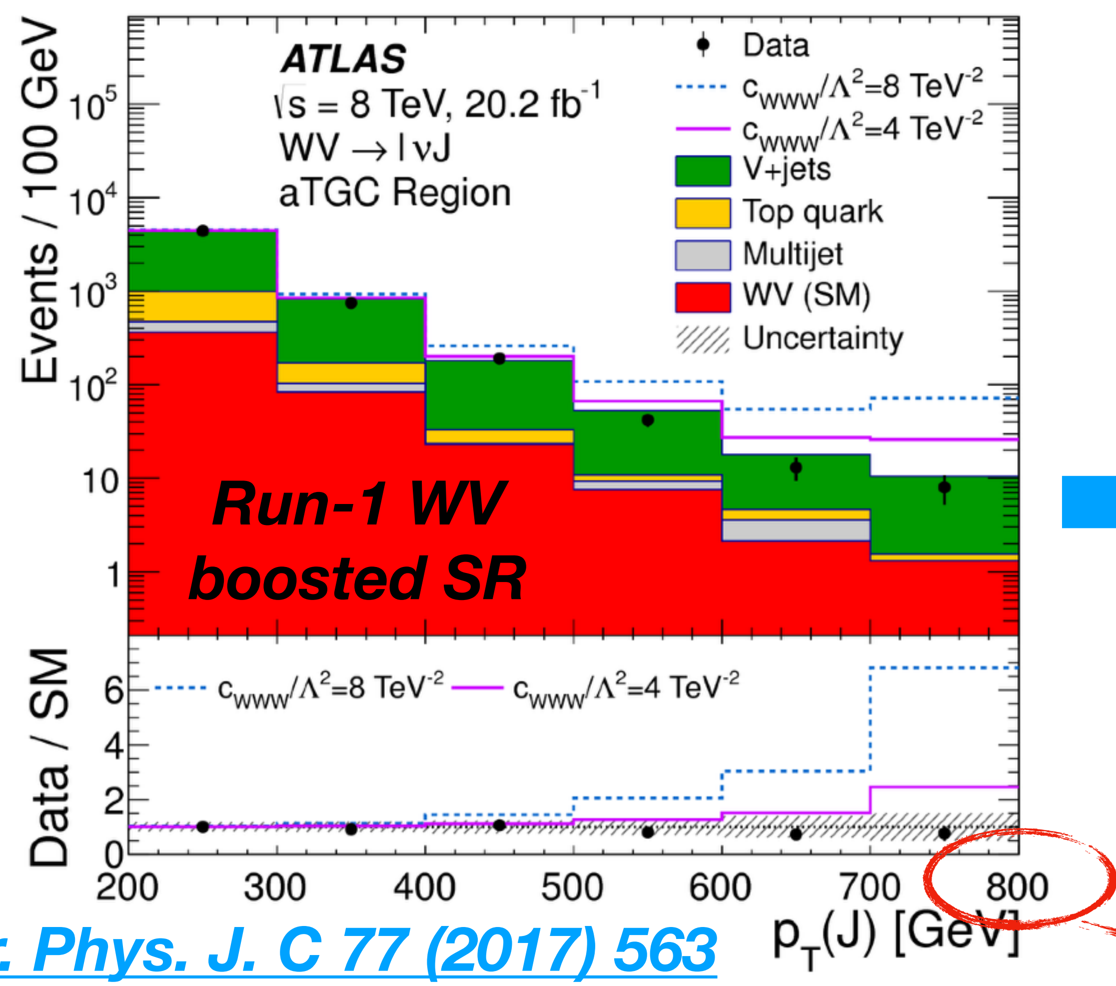


Phys. Lett. B 772 (2017) 21

Can we go further?

- As mentioned already, this channel has been one of the leading channel for BSM searches during Run-2
  - best compromise between BR and background contamination
- ***What can we do more?***
  - probe high-p_T tails
- This means we can use this large amount of data to constraint EFT effects



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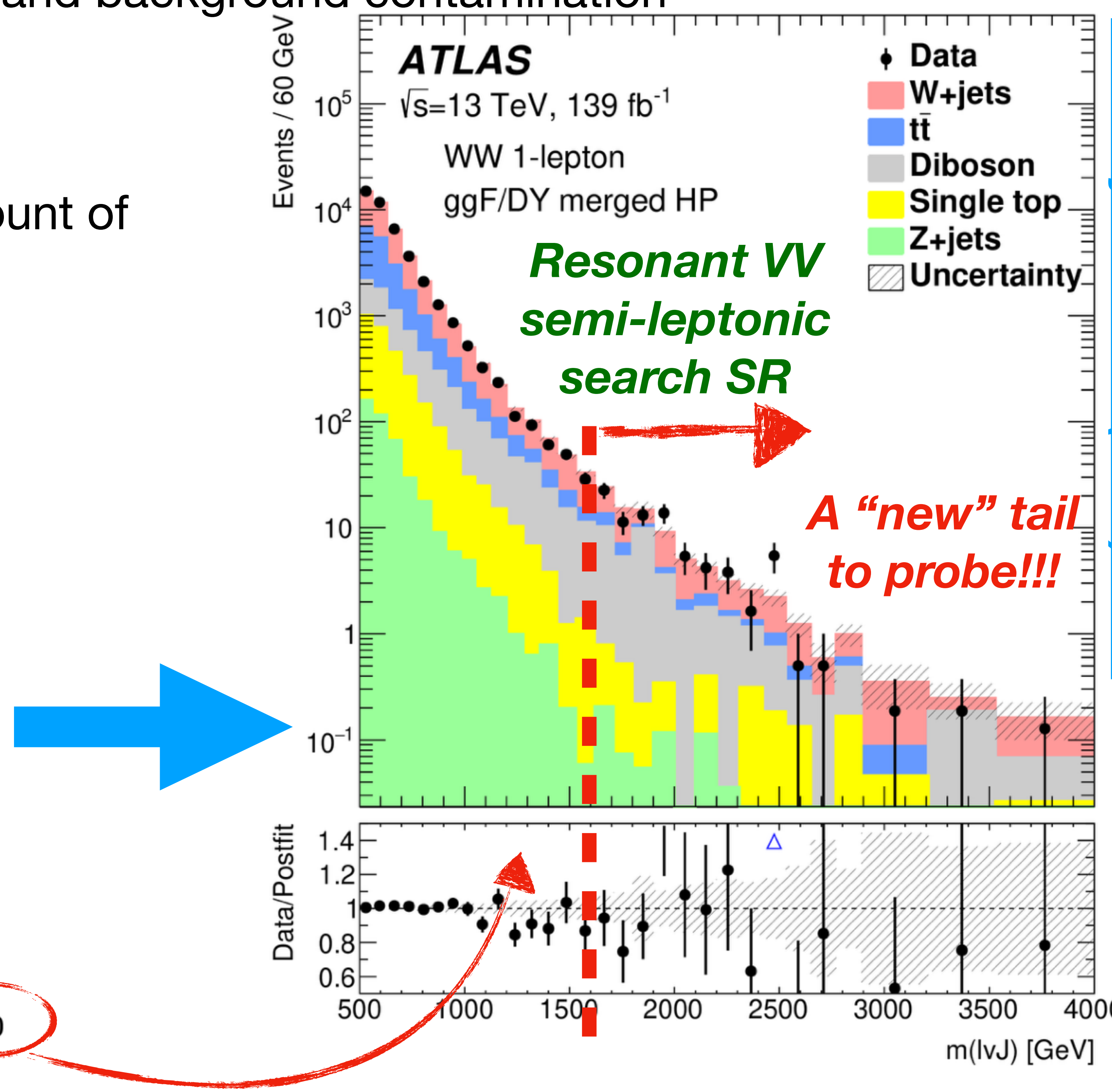

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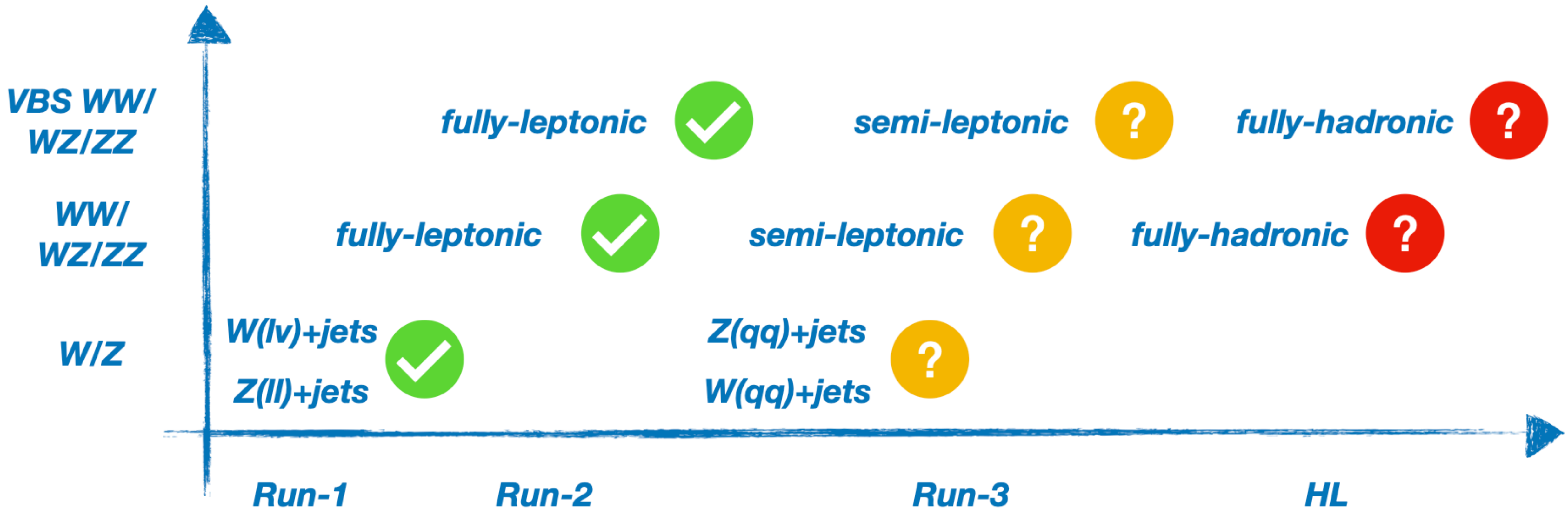
Last but not least…boson polarisation

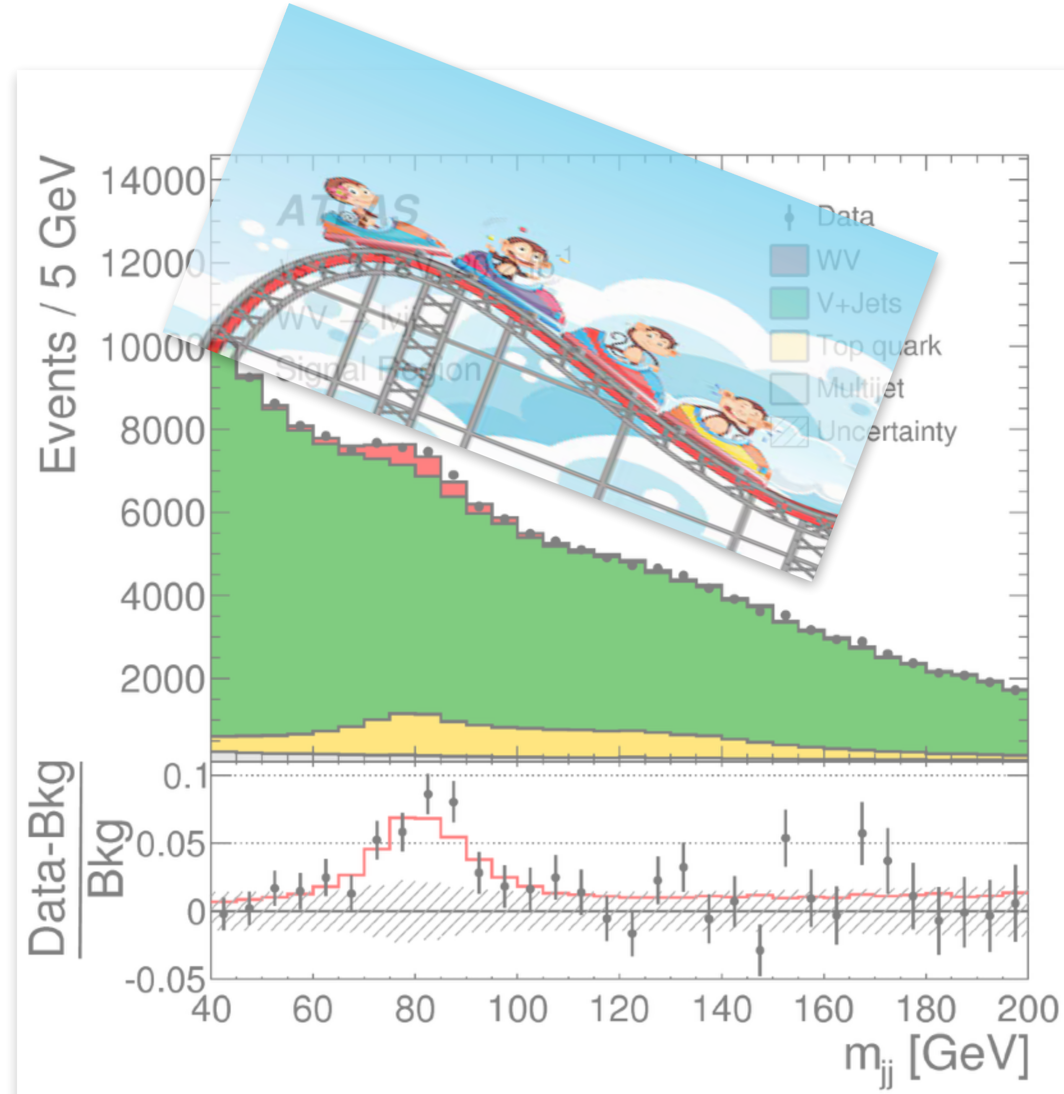
- We have been discussed already the role of hadronic boson decay and interest/ motivations for measurements in diboson channels
  - [Polarisation tagging, COMETA workshop Toulouse](#)
- Polarisation measurements
  - the feasibility in different channels runs with our ability to well measure the not-polarised channels first



Conclusions

VV semi-leptonic channel

- ***Close to the observation in Run-1***
  - both WV(qq) and VZ(bb)
- ***Forgotten channel during Run-2***
  - the events are there, it has not never claimed!
  - side measurement of VZ(bb/cc) in the Vh measurement
- ***Walk through the (ancient) results + future perspective***
  - a huge set of new technologies might help in studying this process further
- ***The era of semi-leptonic is now!***
  - enough luminosity to perform SM measurements
  - stay tuned!!!



backup

How do we measure boson polarisation today?

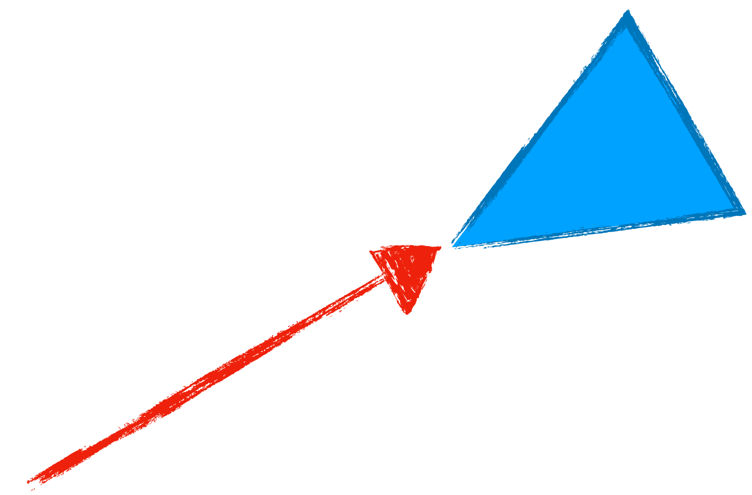
ATLAS link
CMS link

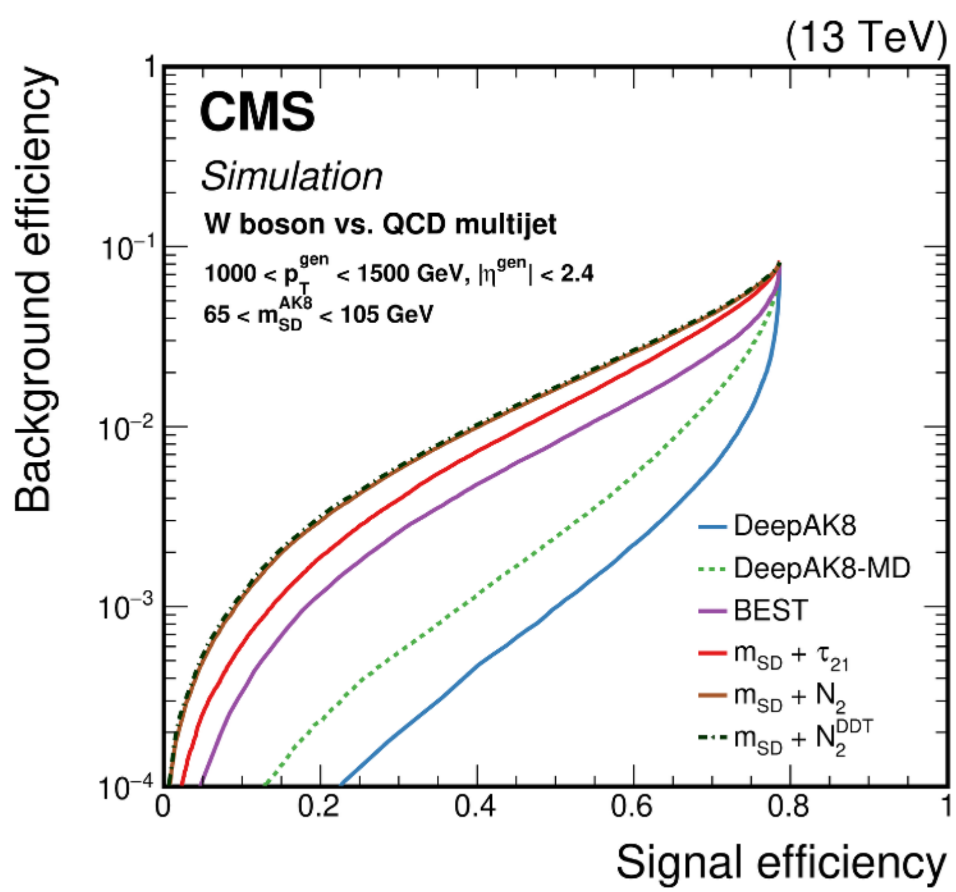
- Boson polarisation has been measured in single W or Z production:
  - W+jets: JHEP 72 (2012) 2001, Phys. Lett. B 107 (2011) 021802
  - Z+ jets: JHEP 08 (2016) 159, Phys. Lett. B 750 (2015) 154
- Also W polarisation in ttbar events
  - ATLAS: Eur. Phys. J. C 79 (2019) 19
  - CMS: Phys. Lett. B 762 (2016) 512
  - Combo: JHEP 08 (2020) 051
- Currently, the experimental interest is about measuring it in diboson events
  - both single and joint boson polarisation has been measured in several final states
  - all of them using leptonic final states

	inclusive	high-p_T	VBS
WW	-	-	-
	-	-	Phys.Lett. B 812 2021
WZ	Phys. Lett. B 843 2023	Phys. Rev. Lett. 133	-
	JHEP 07 (2022) 032	-	-
ZZ	JHEP 12 (2023) 107	-	-
	-	-	-

How to at high p_T boson regime?

- For high-p_T bosons, > 200 GeV, the 2 bodies decay can not be resolved at the detector level
  - it seems we can not use the discriminating information of ϑ_1
- ***What can we do?***
  - look at the jet sub-structure
- ***How?***
  - well known solution in the general boson tagging problem, i.e. W/Z vs q/g initiated jets





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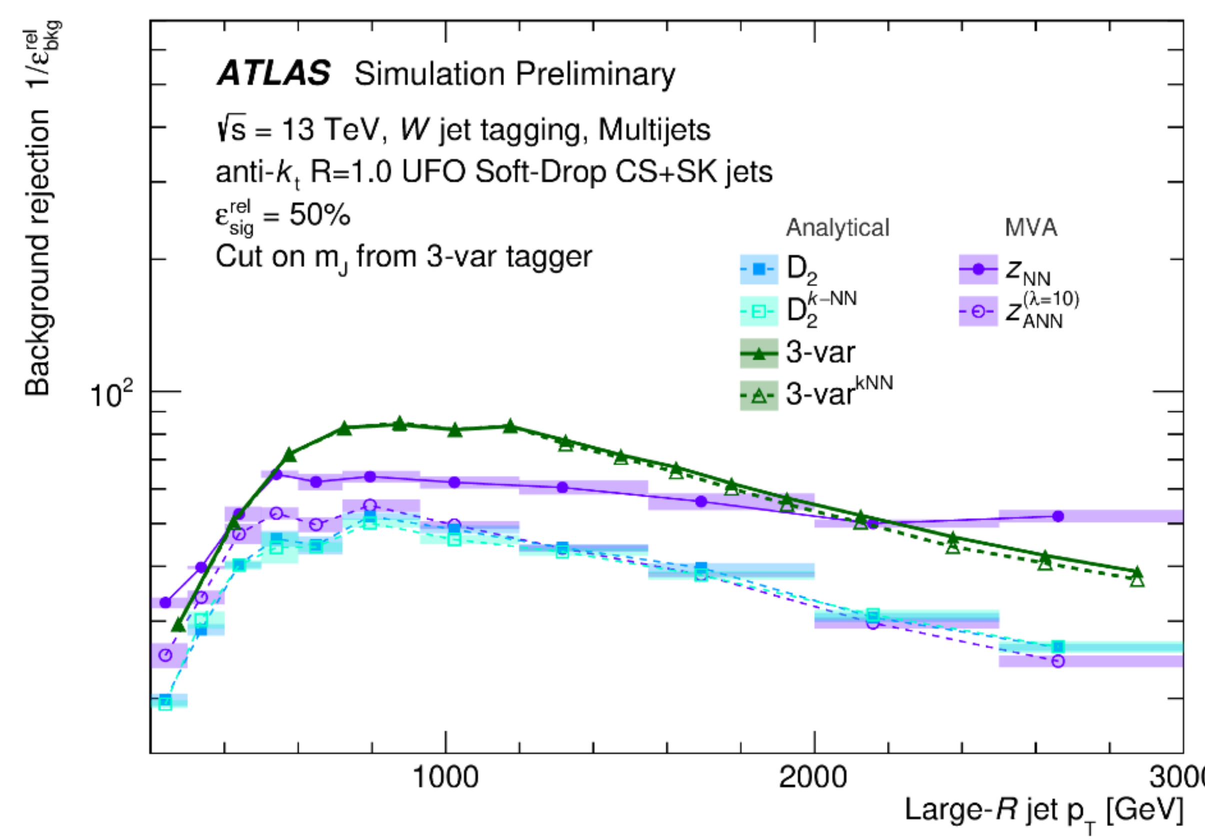

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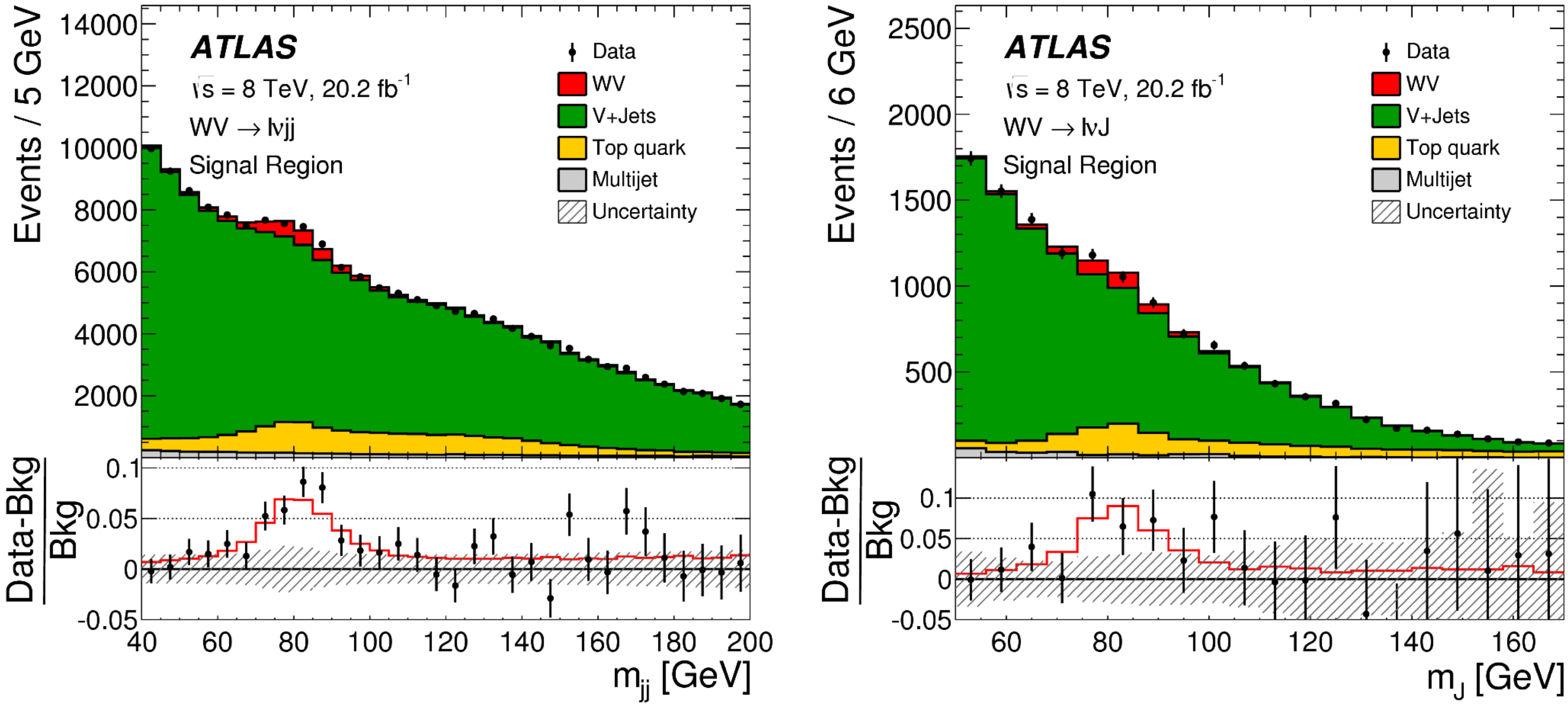
Fiducial phase space definition

- A fiducial phase space at the particle level is an usual method to extract the measurement
- Defined to mimic the reconstruction level definition
  - with the huge progress of boson tagging techniques, it might not be trivial to mimic the sub-structure information

	$WV \to \ell\nu jj$	$WV \to \ell\nu J$
Lepton	$N_\ell = 1$ with $p_T > 30$ GeV and $\lvert\eta\rvert < 2.47$ $\Delta R(\ell, j) > 0.4$	
$W \to \ell\nu$	$p_T(\ell\nu) > 100$ GeV $m_T > 40$ GeV	– –
E_T^{miss}	$E_T^{miss} > 40$ GeV	$E_T^{miss} > 50$ GeV
Jet	$N_j = 2$ with $p_T > 25$ GeV, $\lvert\eta\rvert < 2.5$, $\Delta R(j, e) > 0.2$ $40 < m_{jj} < 200$ GeV $p_T(jj) > 100$ GeV $\Delta\eta(j, j) < 1.5$	$N_J = 1$ with $p_T > 200$ GeV, $\lvert\eta\rvert < 2.0$, $\Delta R(J, \ell) > 1.0$ No small-R jets with $p_T > 25$ GeV, $\lvert\eta\rvert < 4.5$, $\Delta R(j, J) > 1.0$, $\Delta R(j, e) > 0.2$ $50 < m_J < 170$ GeV – –
Global	$\Delta\phi(j_1, E_T^{miss}) > 0.8$	–


ATLAS
√s = 8 TeV, 20.2 fb-1
WV → lvjj
Signal Region
Data
WV
V+Jets
Top quark
Multijet
Uncertainty
Events / 5 GeV
Data-Bkg / Bkg
m_jj [GeV]
ATLAS
√s = 8 TeV, 20.2 fb-1
WV → lvJ
Signal Region
Data
WV
V+Jets
Top quark
Multijet
Uncertainty
Events / 6 GeV
Data-Bkg / Bkg
m_J [GeV]

The fiducial cross-section for the signal process is extracted from the fit as described in Section 8, and the result is

$$\sigma_{\text{fid}}(WV \to \ell\nu\text{jj, observed}) = 209 \pm 28(\text{stat}) \pm 45(\text{syst})\ \text{fb}\,.$$

The impacts of the various systematic uncertainties on the cross-section measurement are shown in Table 3. The measurement can be compared to the theoretical prediction of

$$\sigma_{\text{fid}}(WV \to \ell\nu\text{jj, theory}) = 225 \pm 13\ \text{fb}\,.$$

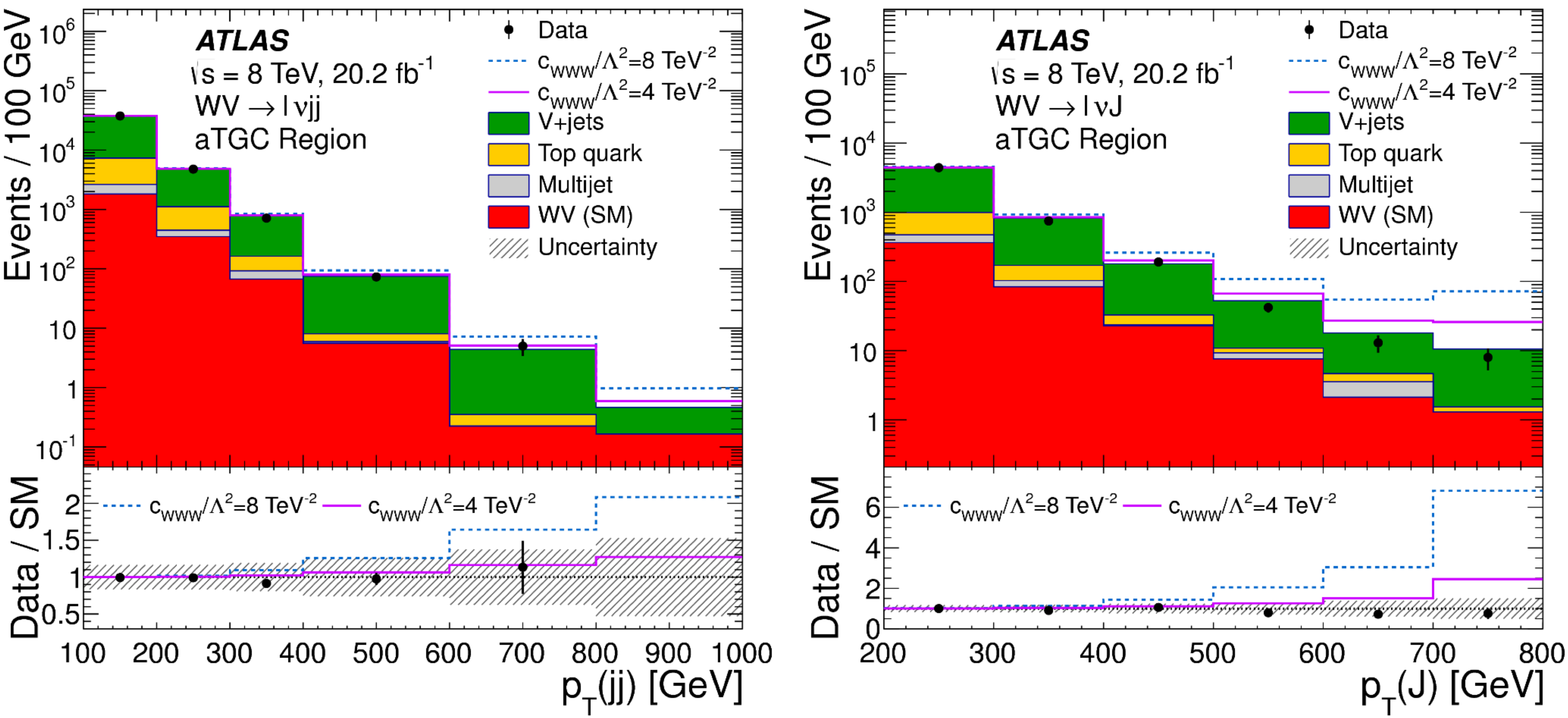
The extracted fiducial cross-section for the signal process is

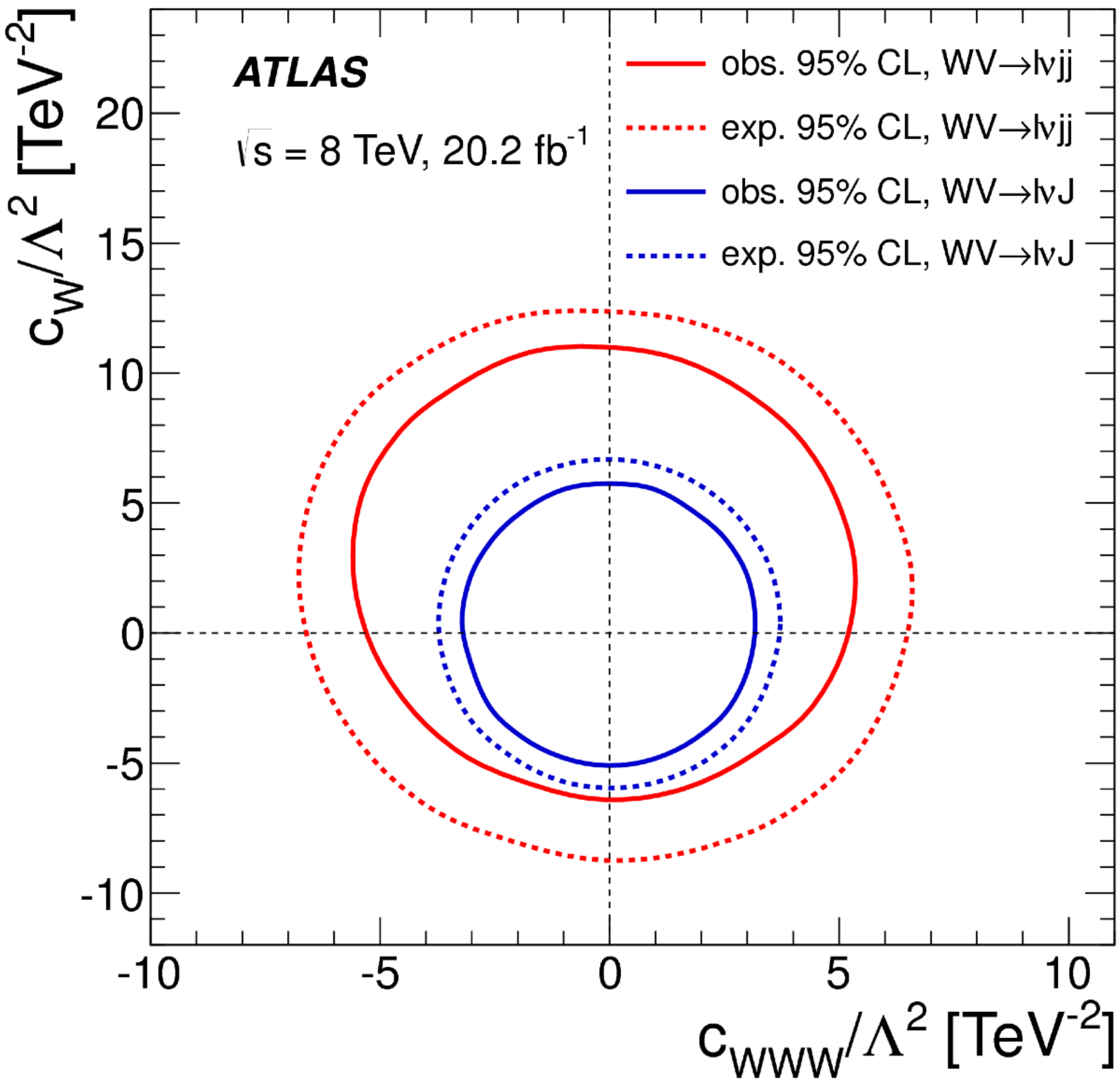
$$\sigma_{\text{fid}}(WV \to \ell\nu\text{J, observed}) = 30 \pm 11(\text{stat}) \pm 22(\text{syst})\ \text{fb}\,,$$

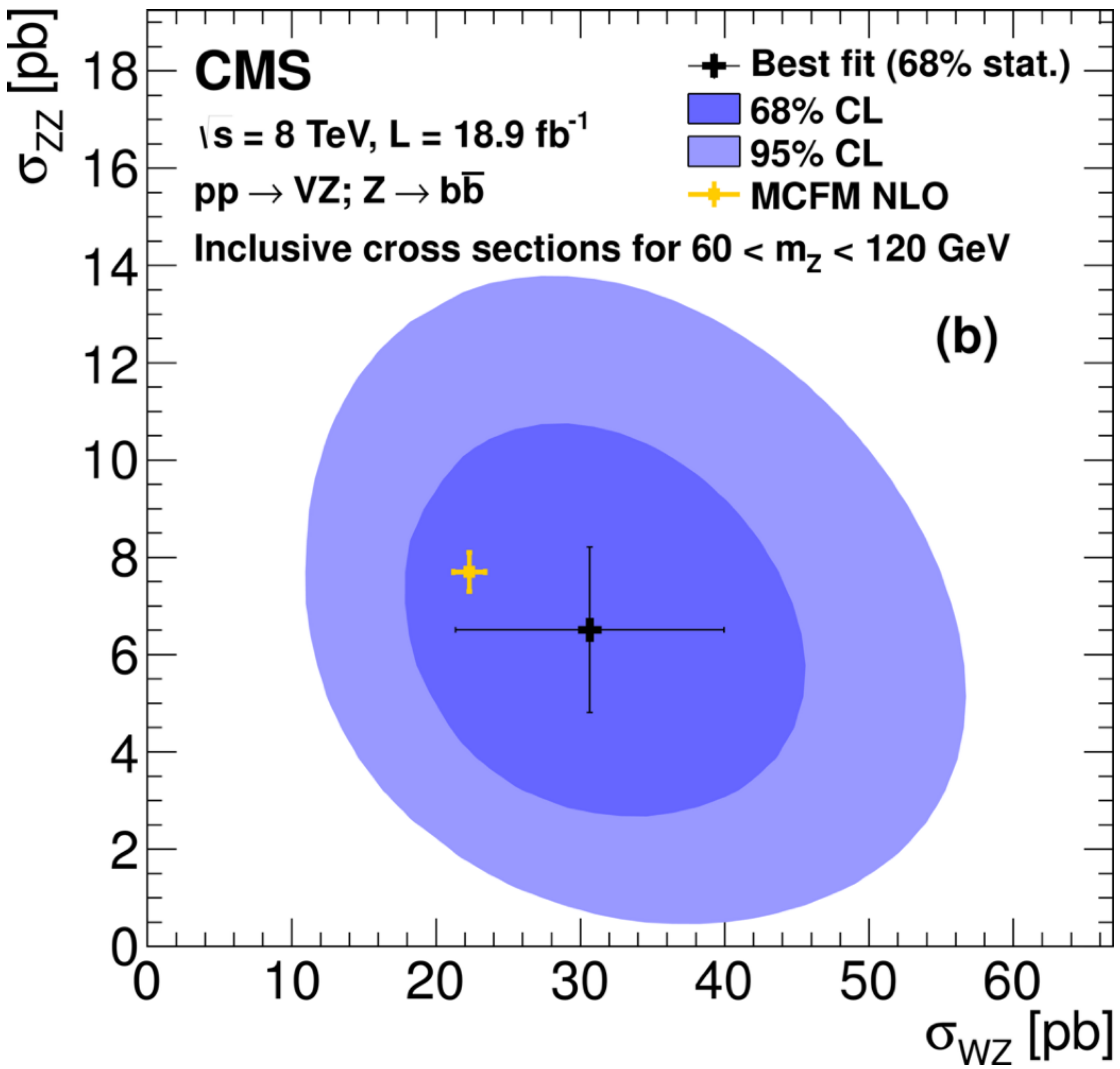
which is compatible with the theoretical prediction of

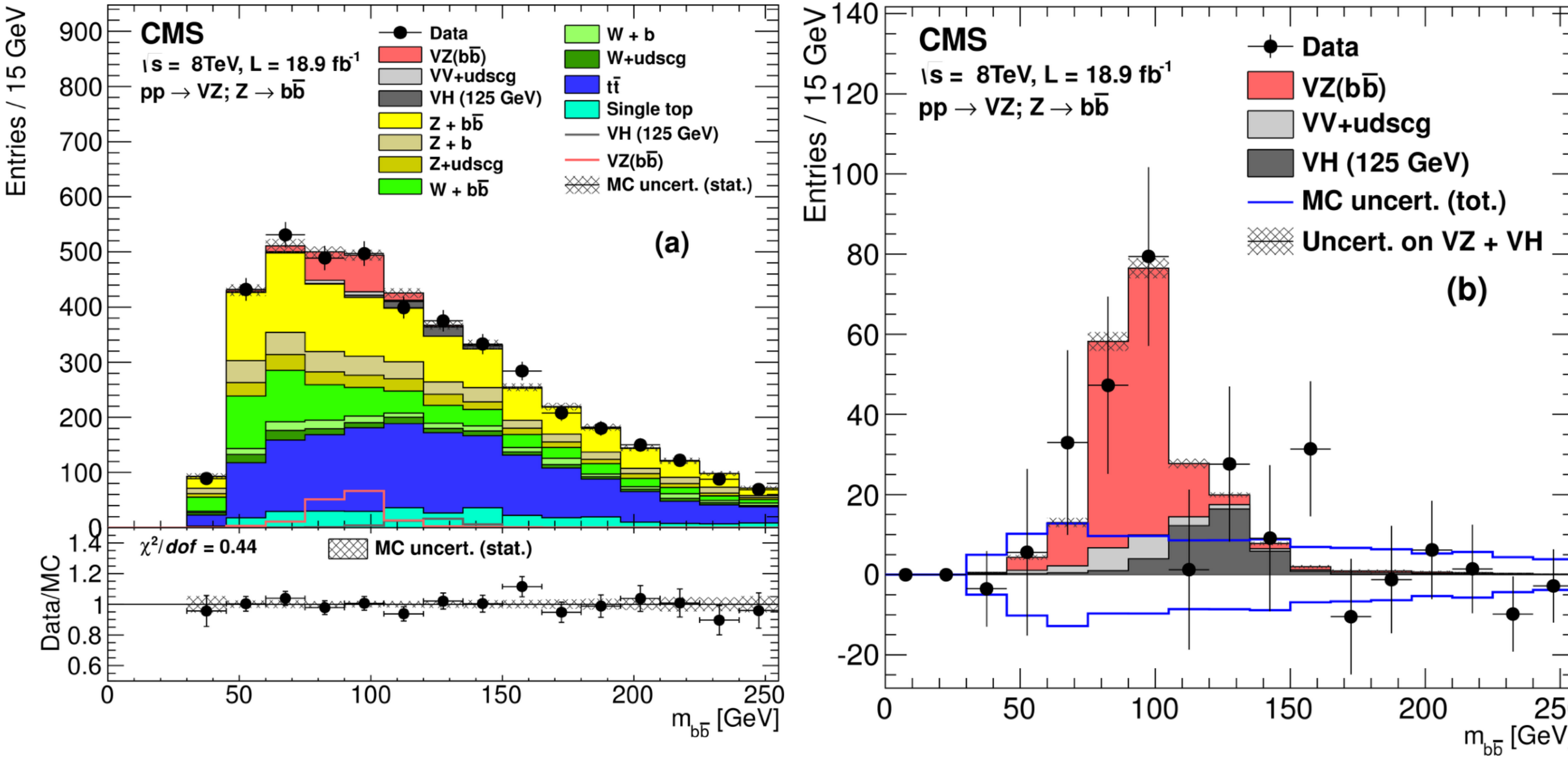
$$\sigma_{\text{fid}}(WV \to \ell\nu\text{J, theory}) = 58 \pm 15\ \text{fb}\,.$$

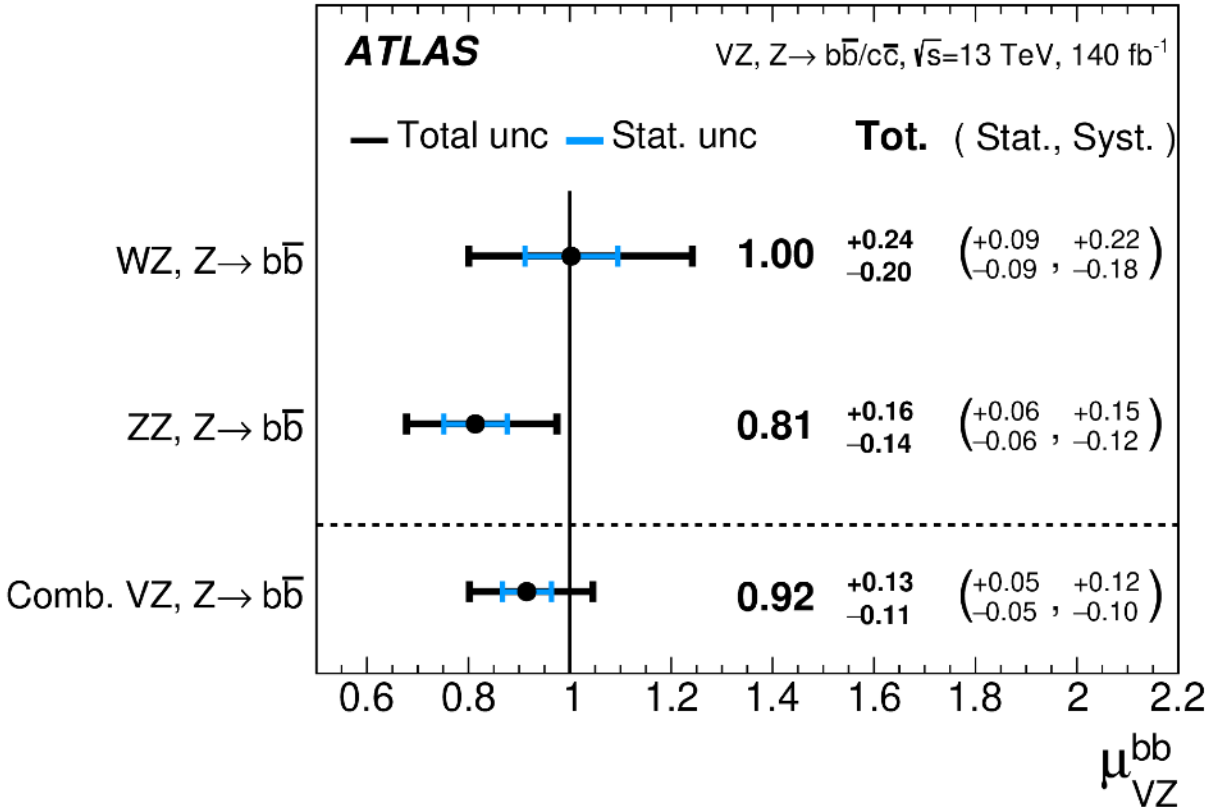
Source of uncertainty	Relative uncertainty for σ_{fid}
V + jets modelling	60%
Top-quark background modelling	32%
Signal modelling	15%
Multijet background modelling	13%
Large-R jet energy/resolution	45%
Small-R jet energy/resolution	16%
Other experimental (leptons, pile-up)	3%
Luminosity	2%
MC statistics	19%
Data statistics	33%

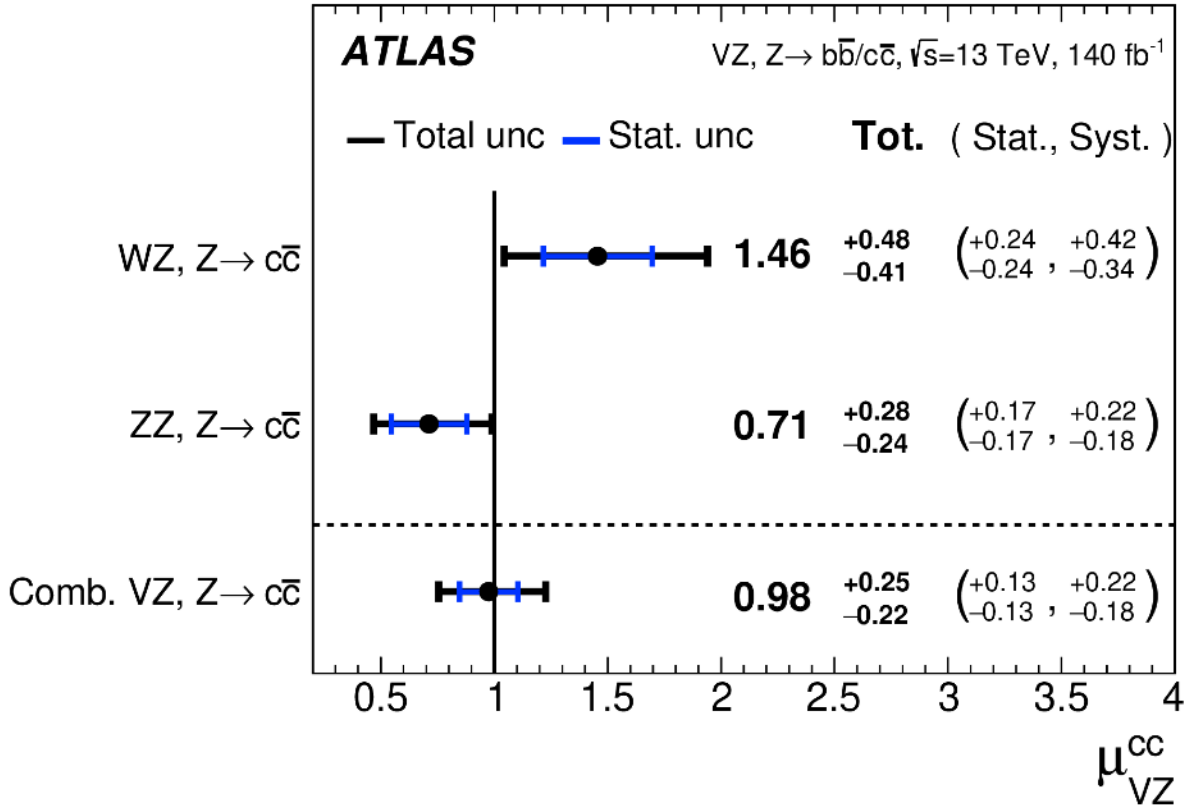

ATLAS
√s = 8 TeV, 20.2 fb⁻¹
WV → l νjj
aTGC Region
Data
c_WWW/Λ²=8 TeV⁻²
c_WWW/Λ²=4 TeV⁻²
V+jets
Top quark
Multijet
WV (SM)
Uncertainty
Events / 100 GeV
Data / SM
p_T(jj) [GeV]
ATLAS
√s = 8 TeV, 20.2 fb⁻¹
WV → l νJ
aTGC Region
p_T(J) [GeV]

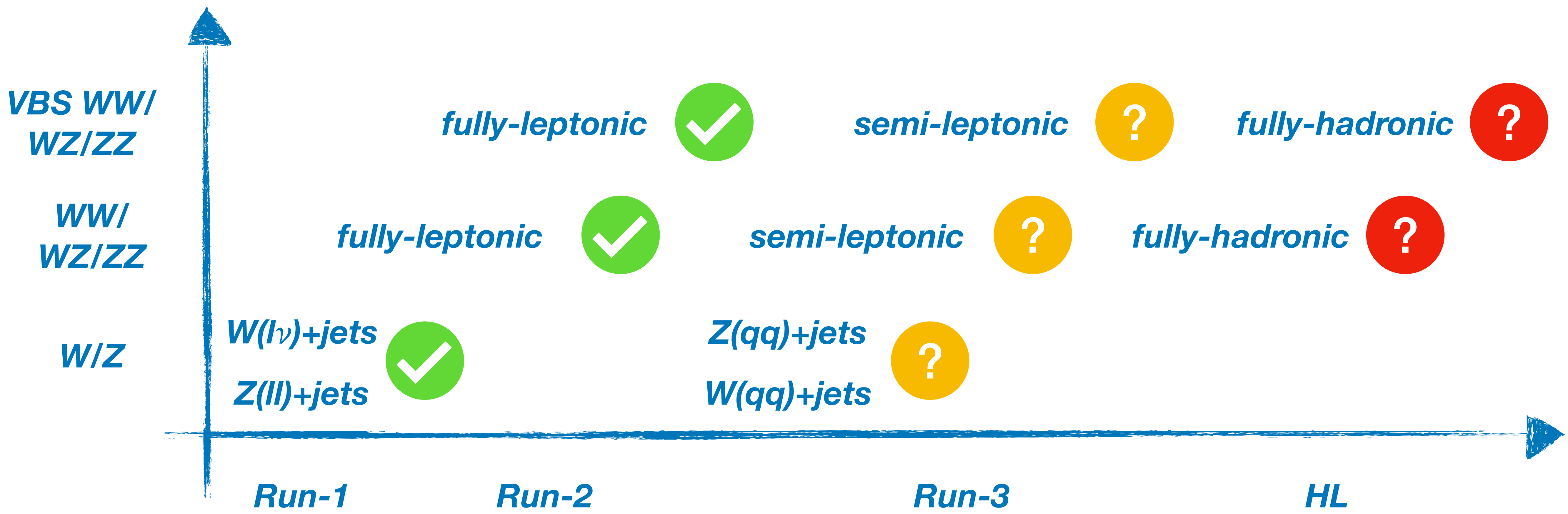

ATLAS
√s = 8 TeV, 20.2 fb-1
obs. 95% CL, WV→lνjj
exp. 95% CL, WV→lνjj
obs. 95% CL, WV→lνJ
exp. 95% CL, WV→lνJ
c_W/Λ^2 [TeV^{-2}]
c_{WWW}/Λ^2 [TeV^{-2}]
-10
-5
0
5
10
15
20


CMS
\s = 8 TeV, L = 18.9 fb-1
pp → VZ; Z → bb̄
Inclusive cross sections for 60 < mZ < 120 GeV
Best fit (68% stat.)
68% CL
95% CL
MCFM NLO
(b)
σZZ [pb]
σWZ [pb]
0
2
4
6
8
10
12
14
16
18
0
10
20
30
40
50
60


CMS
√s = 8TeV, L = 18.9 fb-1
pp → VZ; Z → bb̄
Data
VZ(bb̄)
VV+udscg
VH (125 GeV)
Z + bb̄
Z + b
Z+udscg
W + bb̄
W + b
W+udscg
tt̄
Single top
VH (125 GeV)
VZ(bb̄)
MC uncert. (stat.)
(a)
Entries / 15 GeV
χ2/dof = 0.44
MC uncert. (stat.)
Data/MC
m_bb̄ [GeV]
CMS
√s = 8TeV, L = 18.9 fb-1
pp → VZ; Z → bb̄
Data
VZ(bb̄)
VV+udscg
VH (125 GeV)
MC uncert. (tot.)
Uncert. on VZ + VH
(b)
Entries / 15 GeV
m_bb̄ [GeV]


ATLAS
VZ, Z→ bb̄/cc̄, √s=13 TeV, 140 fb⁻¹
Total unc
Stat. unc
Tot. (Stat., Syst.)
WZ, Z→ bb̄
1.00 +0.24 −0.20 (+0.09 −0.09 , +0.22 −0.18)
ZZ, Z→ bb̄
0.81 +0.16 −0.14 (+0.06 −0.06 , +0.15 −0.12)
Comb. VZ, Z→ bb̄
0.92 +0.13 −0.11 (+0.05 −0.05 , +0.12 −0.10)
0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2
μ VZ bb


ATLAS
VZ, Z→ bb̄/cc̄, √s=13 TeV, 140 fb⁻¹
Total unc
Stat. unc
Tot. (Stat., Syst.)
WZ, Z→ cc̄
1.46 +0.48 −0.41 (+0.24 −0.24 , +0.42 −0.34)
ZZ, Z→ cc̄
0.71 +0.28 −0.24 (+0.17 −0.17 , +0.22 −0.18)
Comb. VZ, Z→ cc̄
0.98 +0.25 −0.22 (+0.13 −0.13 , +0.22 −0.18)
0.5 1 1.5 2 2.5 3 3.5 4
μ VZ cc


VBS WW/
WZ/ZZ
fully-leptonic
semi-leptonic
fully-hadronic
WW/
WZ/ZZ
fully-leptonic
semi-leptonic
fully-hadronic
W/Z
W(lν)+jets
Z(ll)+jets
Z(qq)+jets
W(qq)+jets
Run-1
Run-2
Run-3
HL