https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2017-22/

Evidence for triboson production at ATLAS

Alex Tuna

(Harvard University)

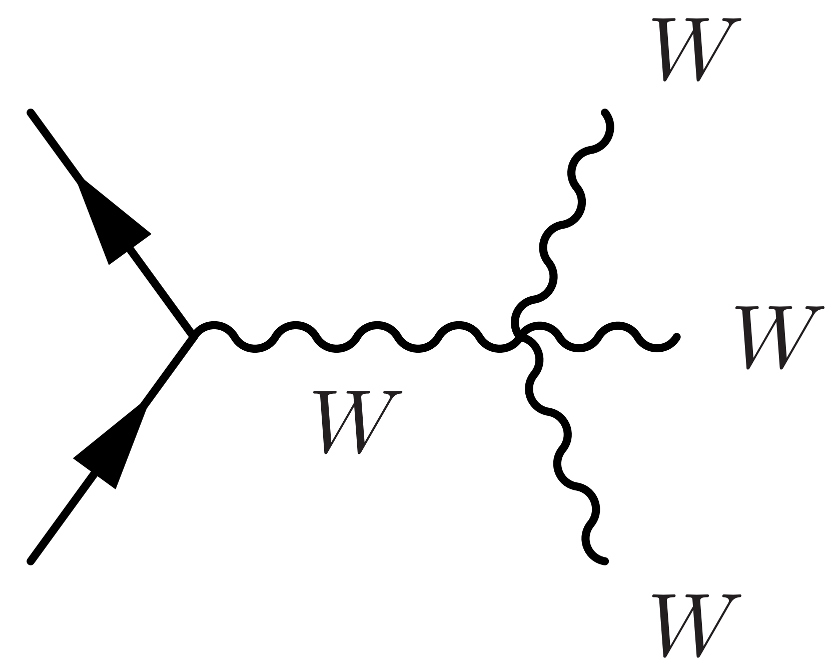
on behalf of the ATLAS collaboration

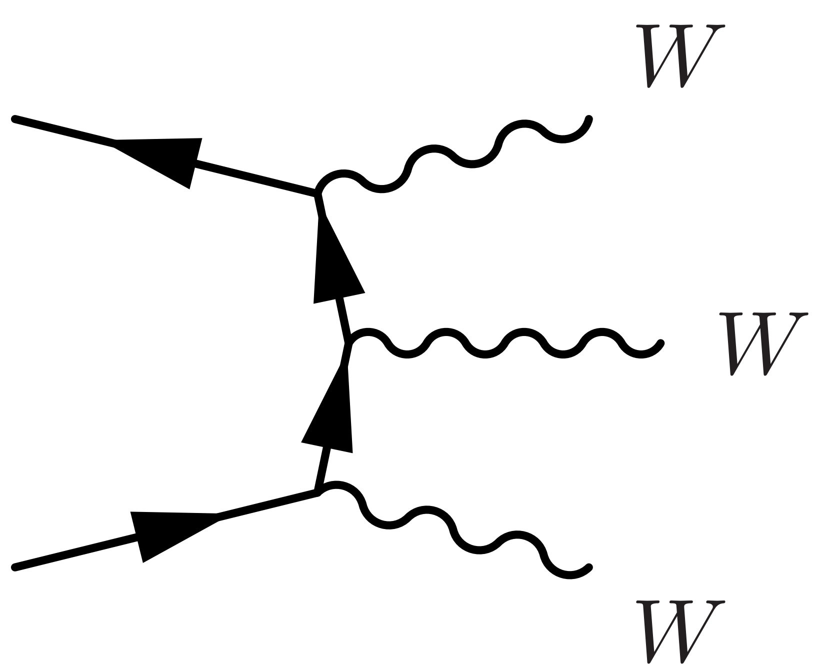
EPS-HEP2019
13 July

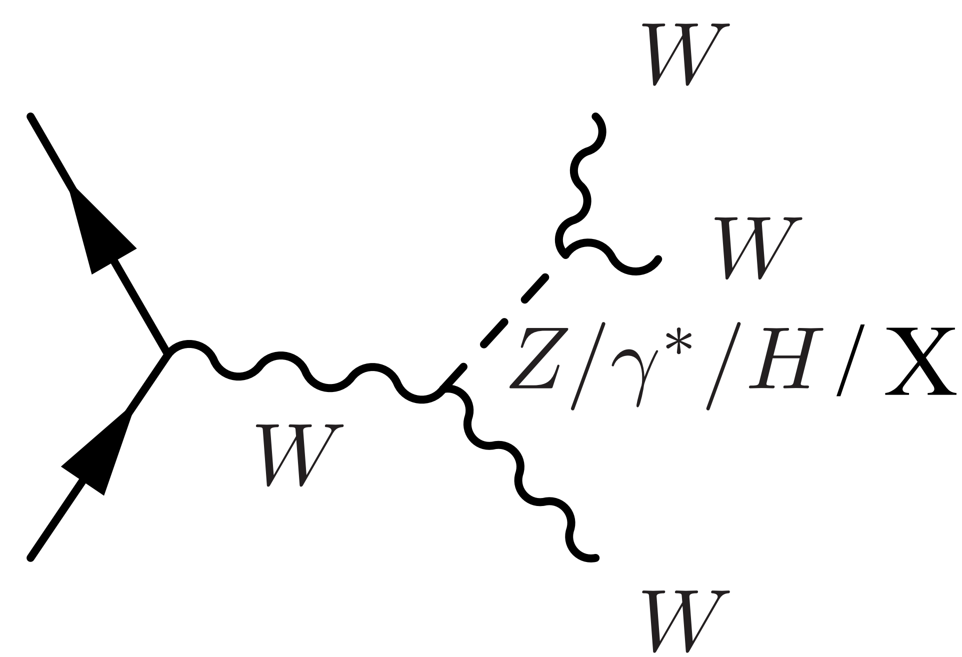
Context

Massive tribosons *VVV* not yet observed

Sensitive to anomalous triple/quartic gauge couplings, and also new heavy particles decaying to bosons







Triboson at the LHC

Recently, both ATLAS and CMS released new triboson results using *pp* collision data with $\sqrt{s}$ = 13 TeV

80 fb^{-1}

ATLAS finds evidence of three massive vector boson production

By ATLAS Collaboration, 17th March 2019

https://atlas.cern/updates/physics-briefing/evidence-three-massive-vector-boson-production

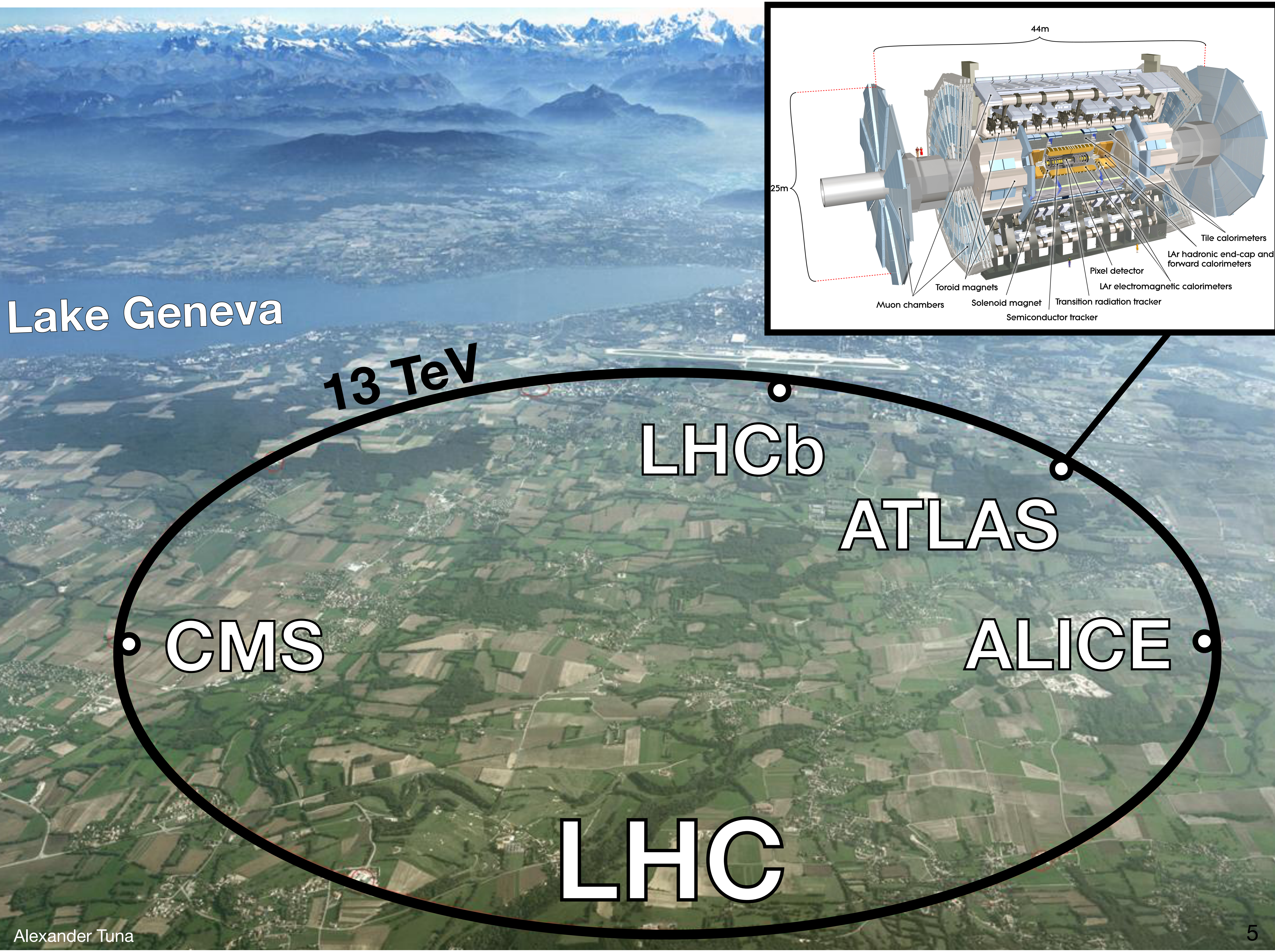
Submitted to PLB

36 fb^{-1}

CMS Physics Analysis Summaries

Report number	CMS-PAS-SMP-17-013
Title	**Search for the production of WWW events with two equally charged or three leptons at sqrt(s) = 13 TeV**
Corporate author(s)	CMS Collaboration
Collaboration	CMS Collaboration
Subject category	Particle Physics - Experiment

Analysis


Lake Geneva
13 TeV
LHCb
ATLAS
CMS
ALICE
LHC
44m
25m
Tile calorimeters
LAr hadronic end-cap and
forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker
Alexander Tuna

Analysis approach

Categorize based on VVV

WWW   WVZ

Analysis approach

Categorize based on VVV

WWW

WVZ

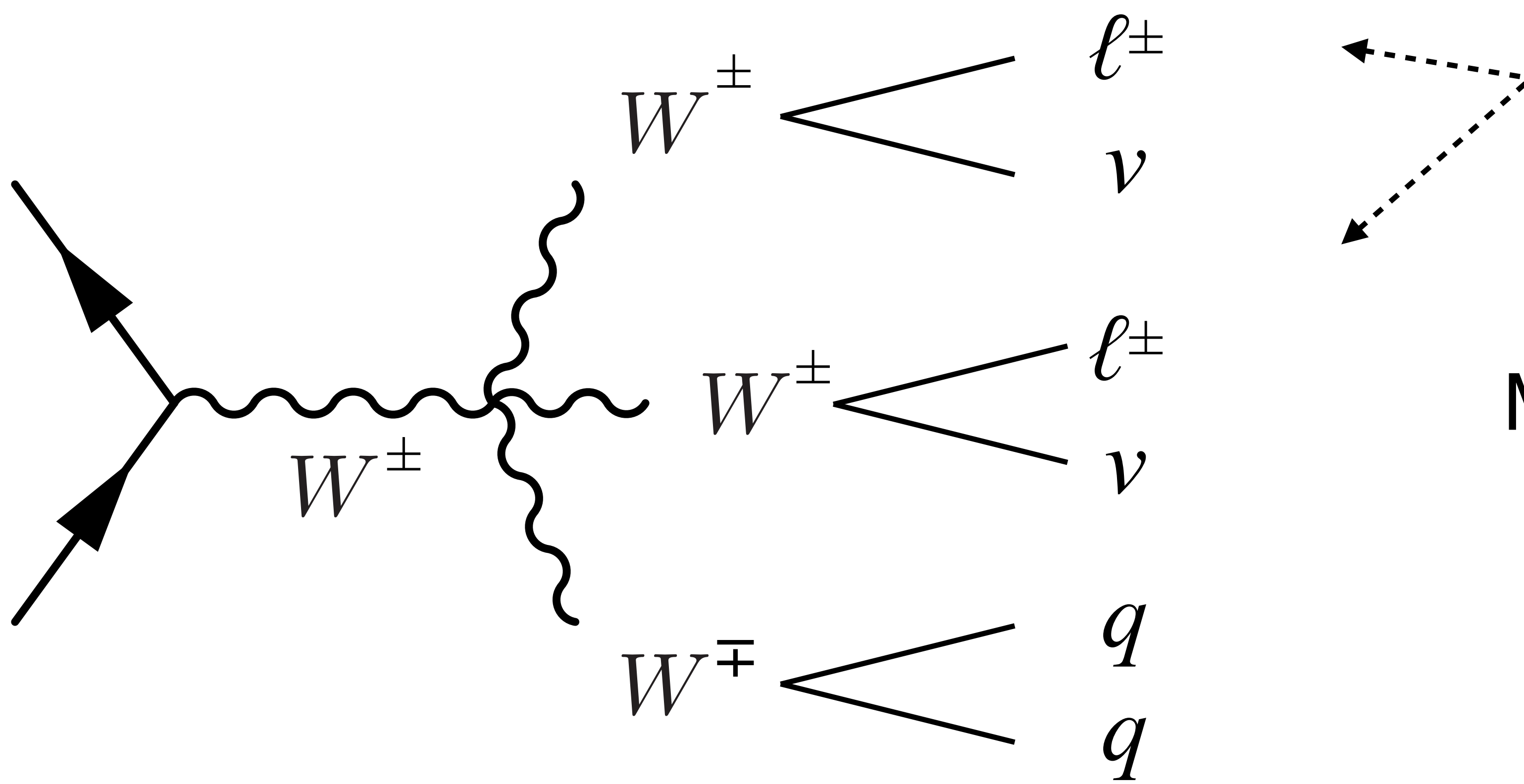
Categorize further based on boson decays

WWW	WVZ (WWZ/WZZ)	WVZ (WZZ/WWZ)
$WWW \rightarrow \ell\nu\ell\nu qq$	$WWZ \rightarrow \ell\nu qq\ell\ell$	$WZZ \rightarrow qq\ell\ell\ell\ell$
$WWW \rightarrow \ell\nu\ell\nu\ell\nu$	$WZZ \rightarrow \ell\nu qq\ell\ell$	$WWZ \rightarrow \ell\nu\ell\nu\ell\ell$

Let's go through two categories in detail

WWW → ℓνℓνqq

WWW categories target decays with good S/B (emphasis on B)



Two same-sign leptons

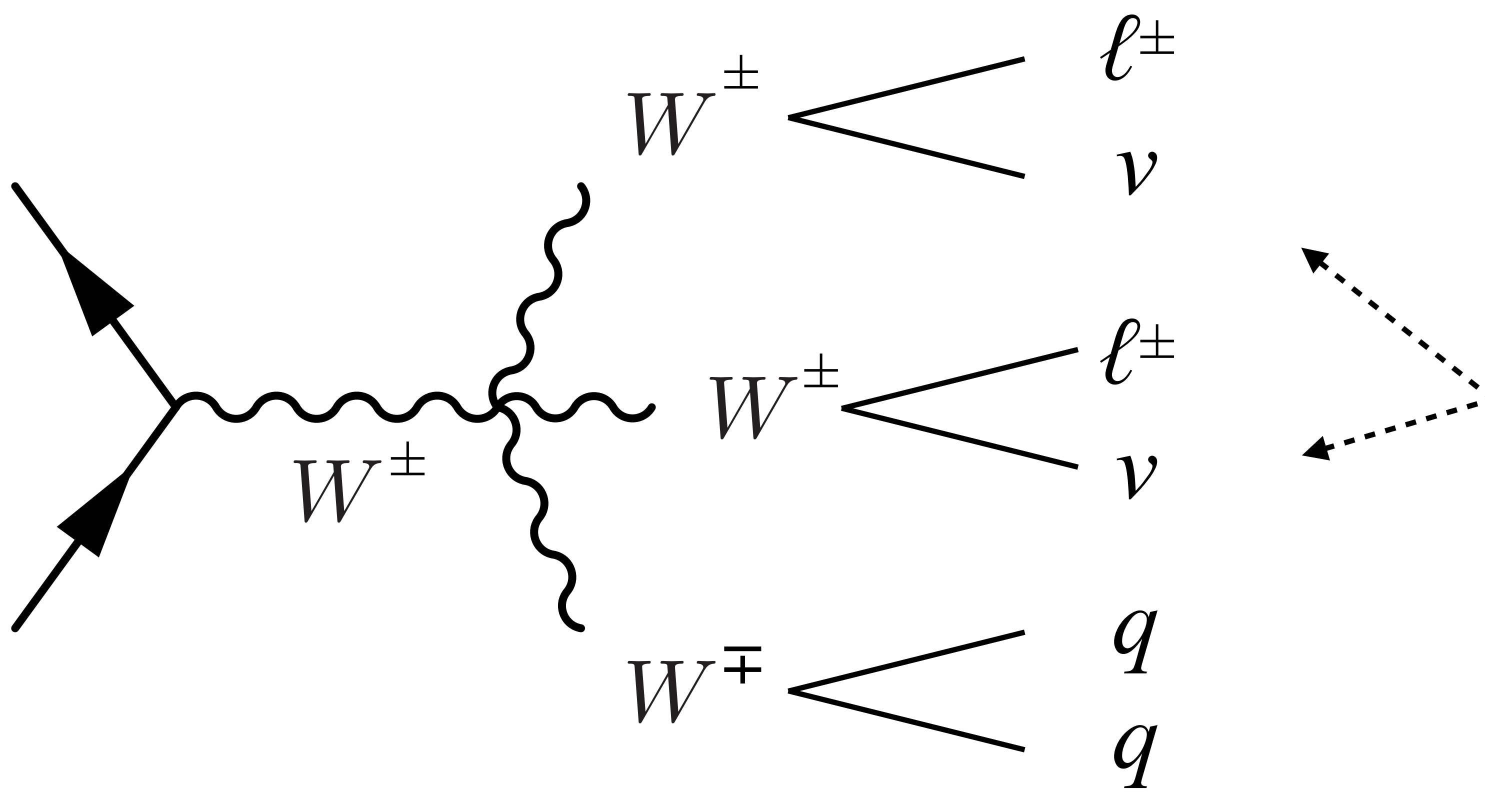
Missing energy via two ν's

Two jets from W decay

Two same-sign leptons is an otherwise rare occurrence in SM

WWW → ℓvℓvqq

WWW categories target decays with good S/B (emphasis on B)



Two same-sign leptons

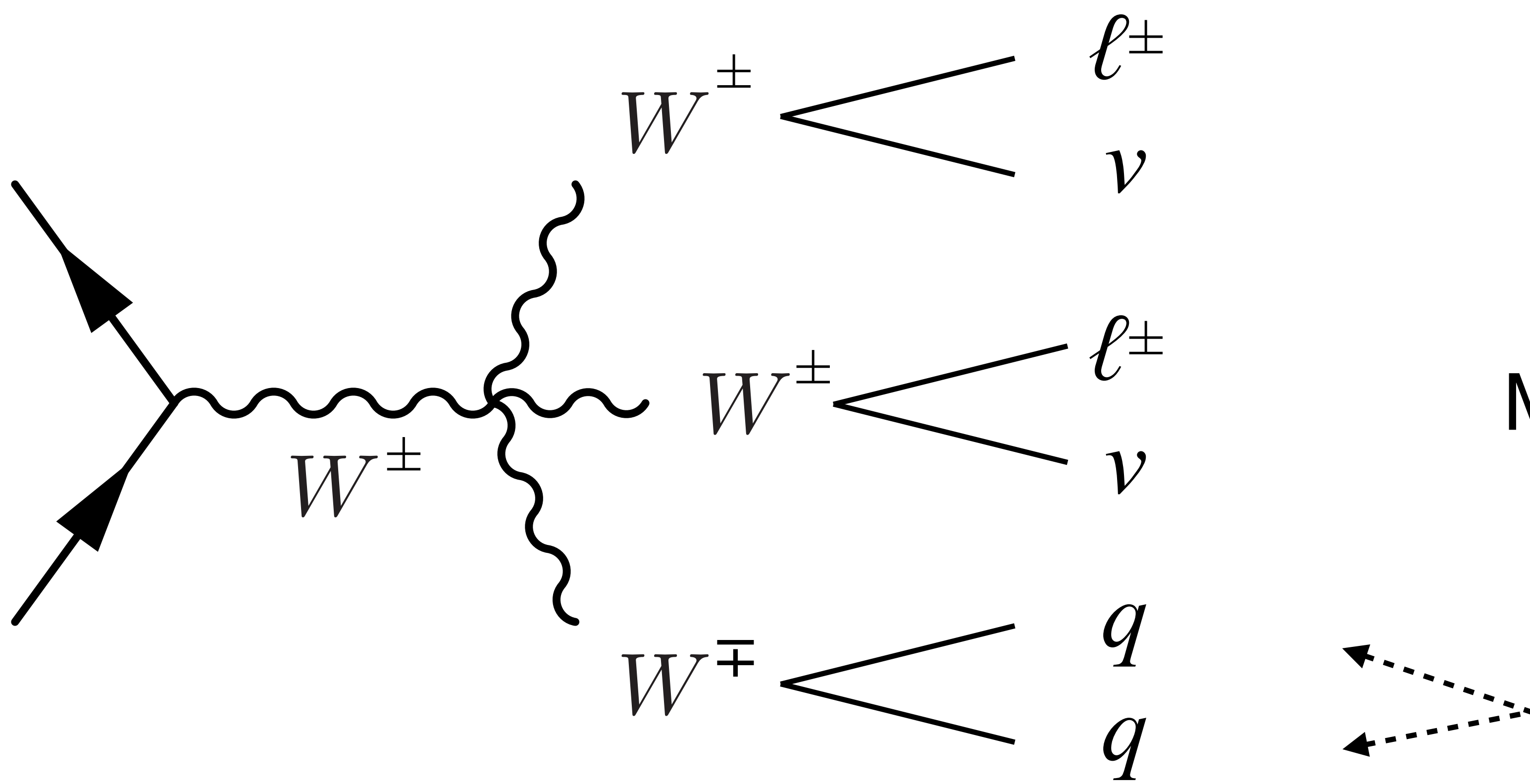
Missing energy via two ν's

Two jets from W decay

Two same-sign leptons is an otherwise rare occurrence in SM

WWW → ℓνℓνqq

WWW categories target decays with good S/B (emphasis on B)



Two same-sign leptons

Missing energy via two ν's

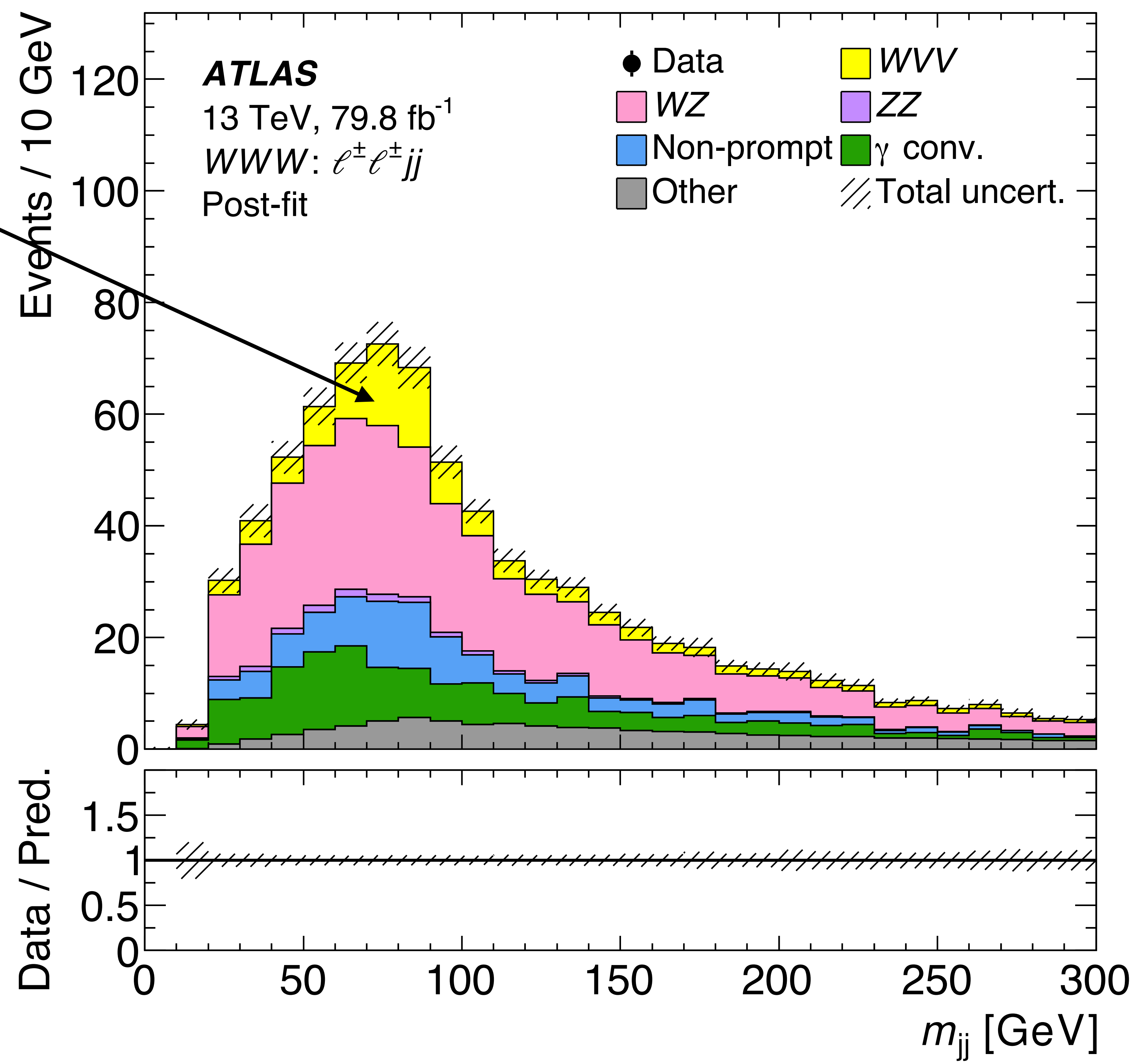
Two jets from W decay

Two same-sign leptons is an otherwise rare occurrence in SM

WWW → ℓνℓνqq

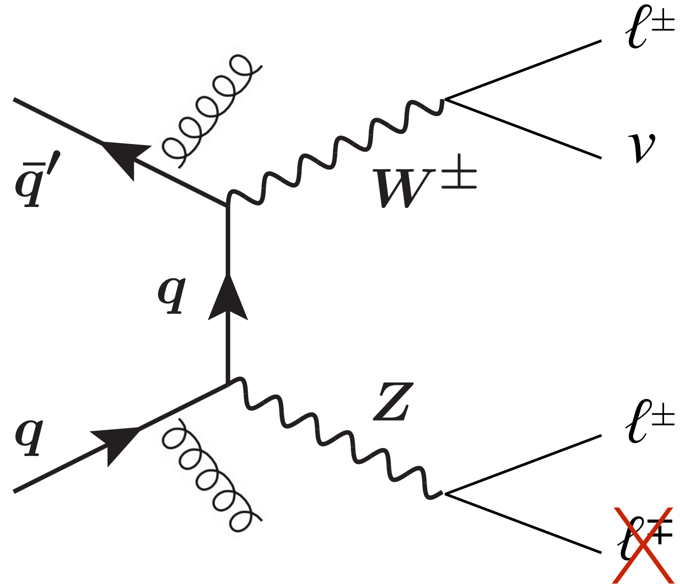
WWW: expect a bump at m(jj) ~ m(W)

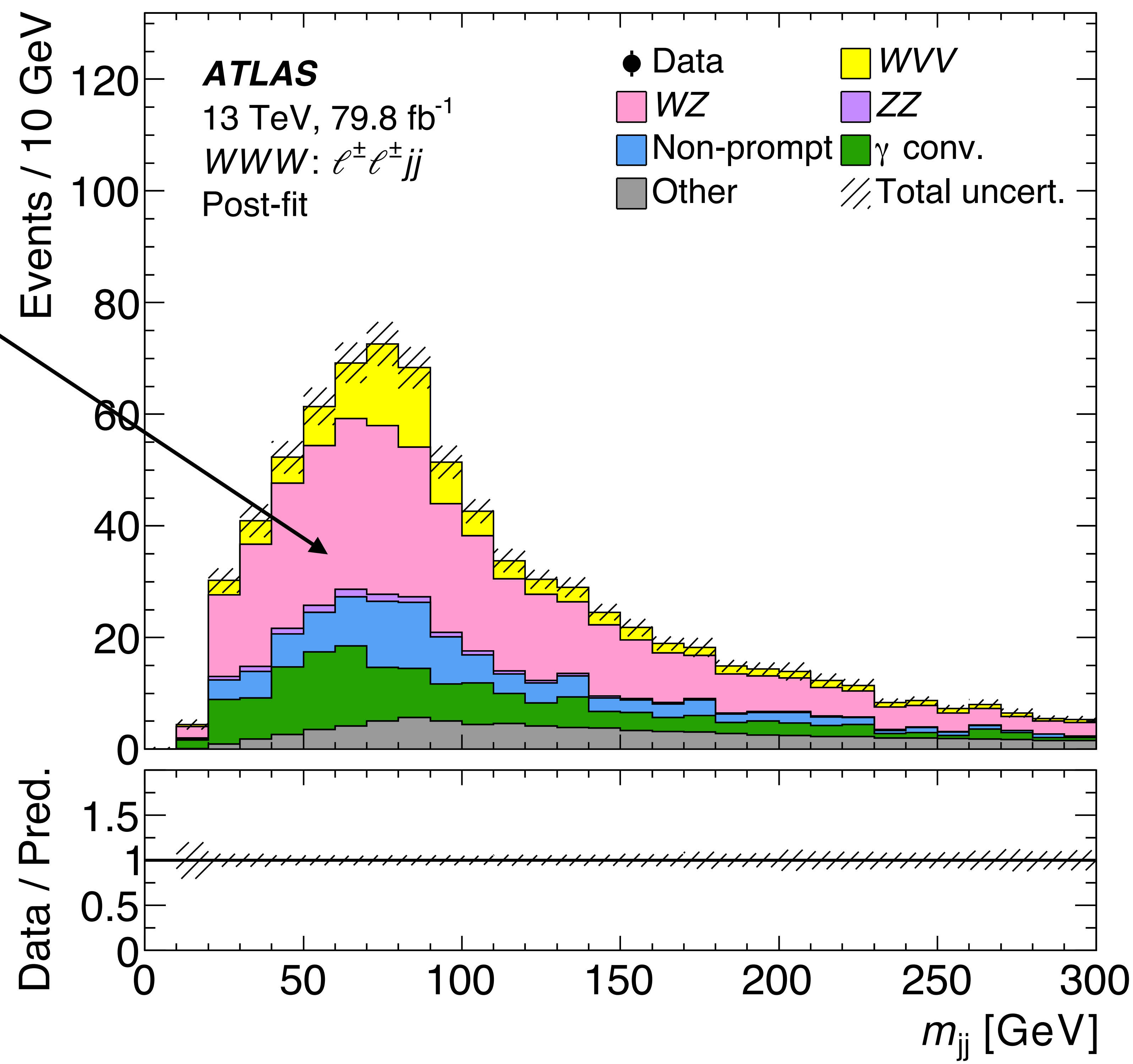
No such m(jj) resonance for backgrounds



WWW → ℓνℓνqq

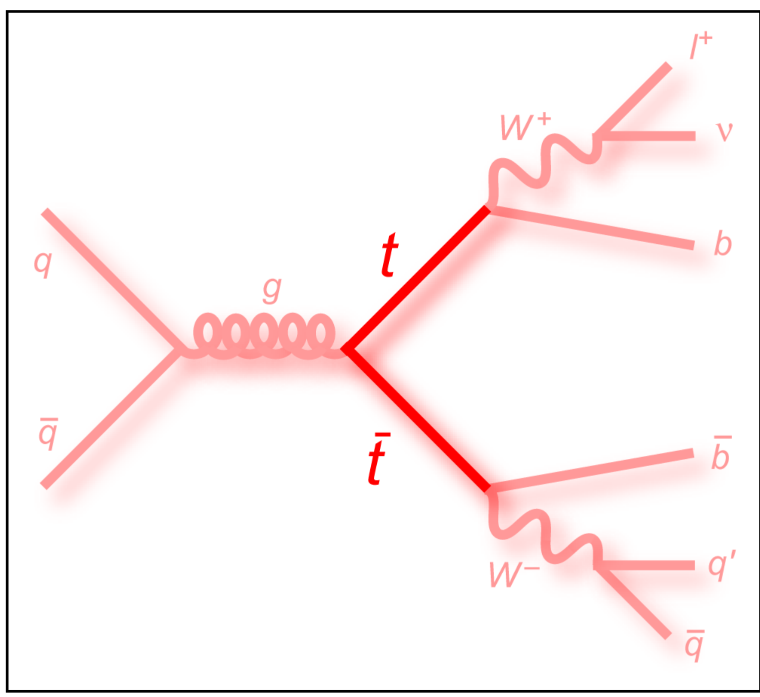
WZ: leptonic decays and a lost lepton

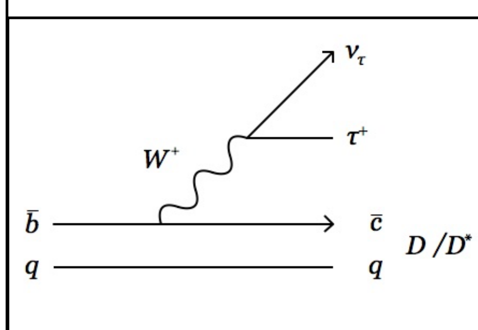


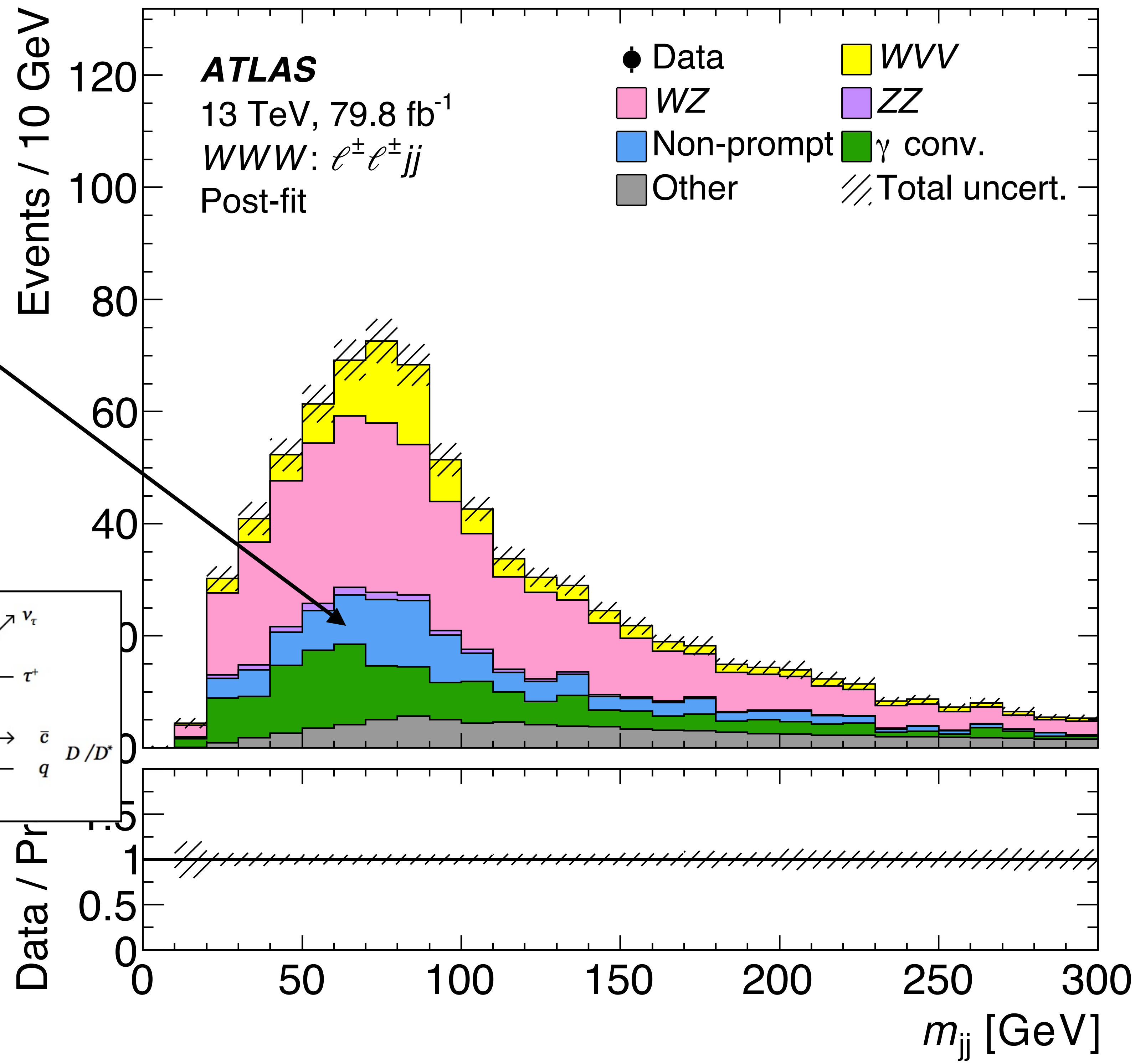


WWW → ℓνℓνqq

“Non-prompt” leptons:
Mostly via ttbar

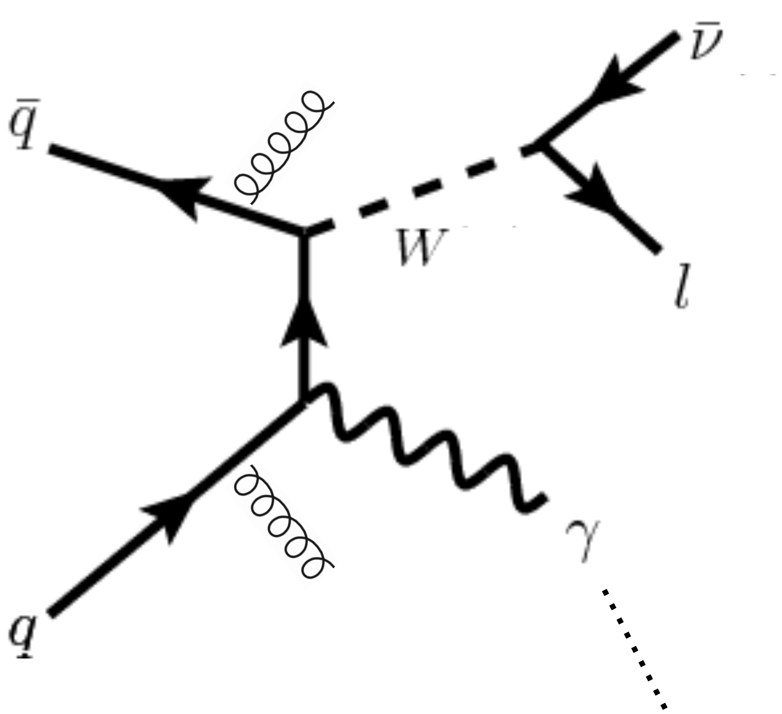




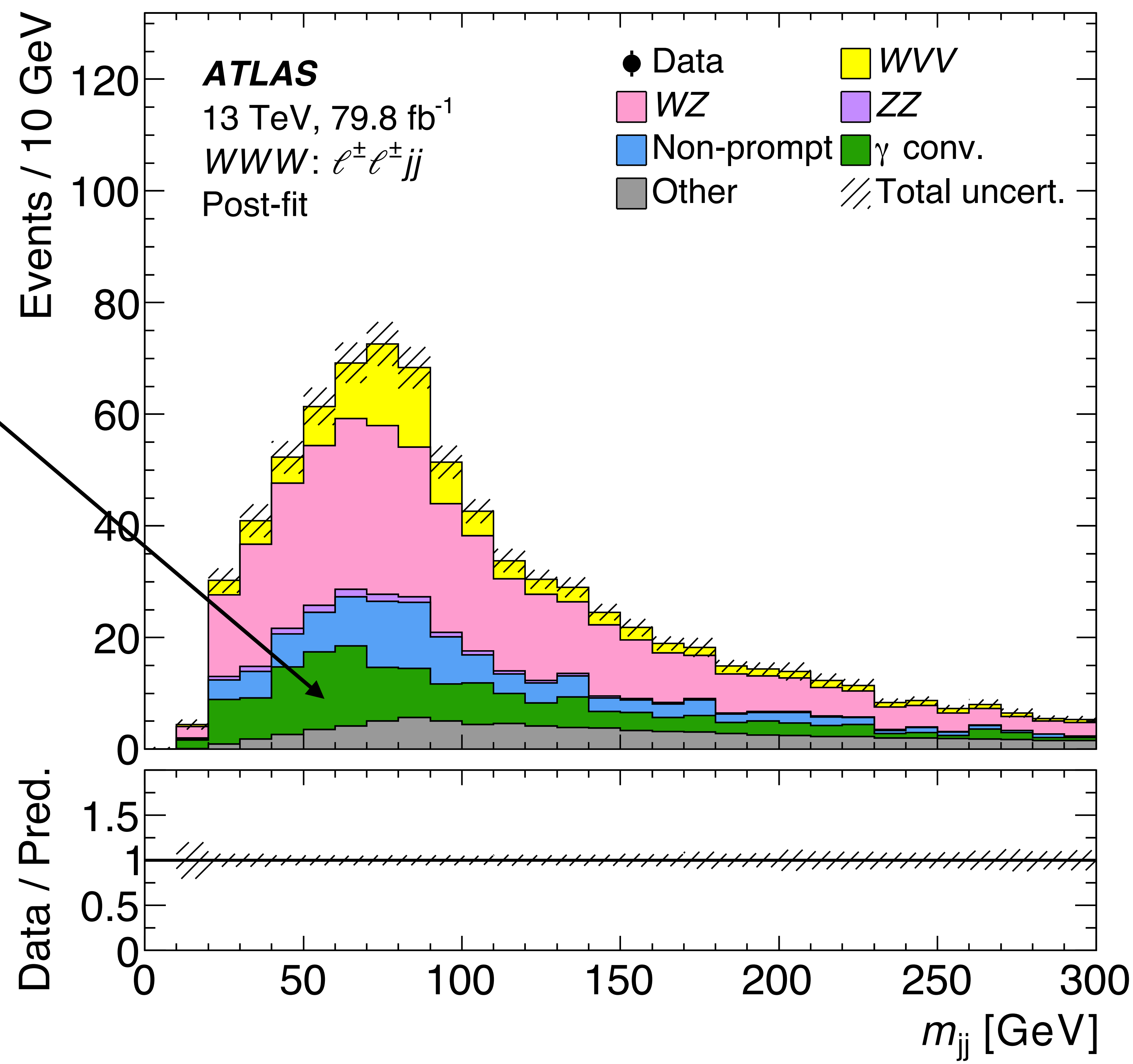


WWW → ℓνℓνqq

γ conversions:
Mostly via Wγ



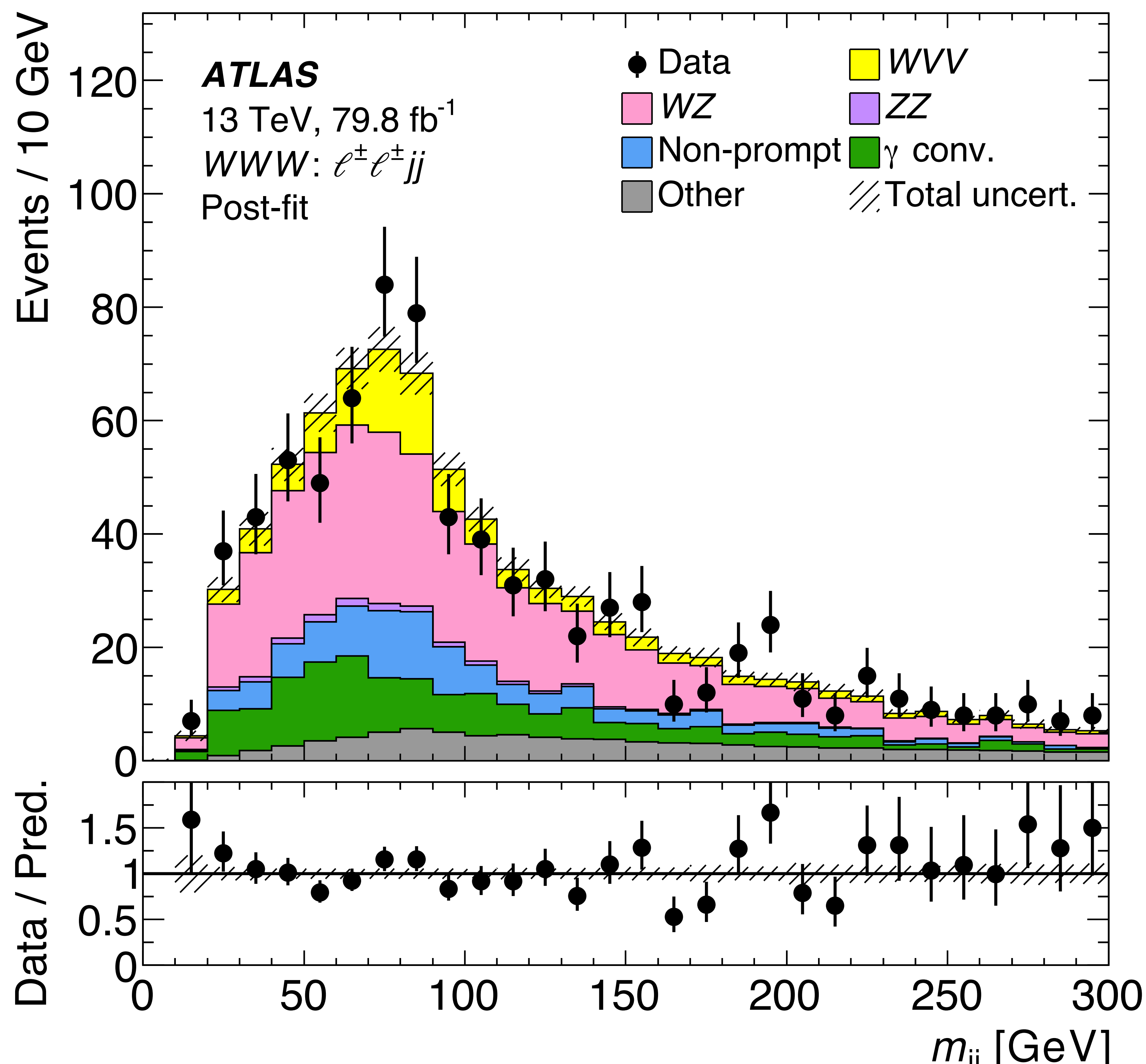
mis-ID'd
as *e*



WWW → ℓνℓνqq

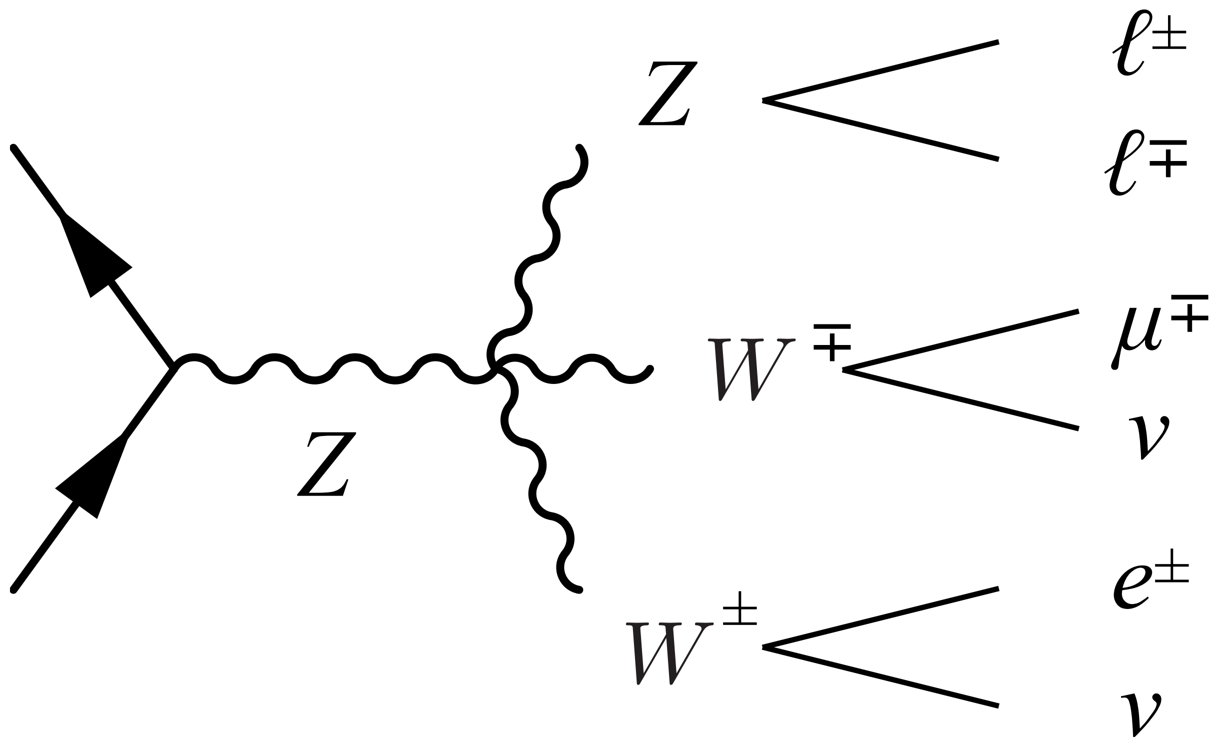
Good agreement between data and prediction

Signal hypothesis is favored given the data near m(jj) ~ 80 GeV



WWZ → eνμνℓℓ

WVZ categories target final states with Z→ℓℓ



Two leptons from Z decay

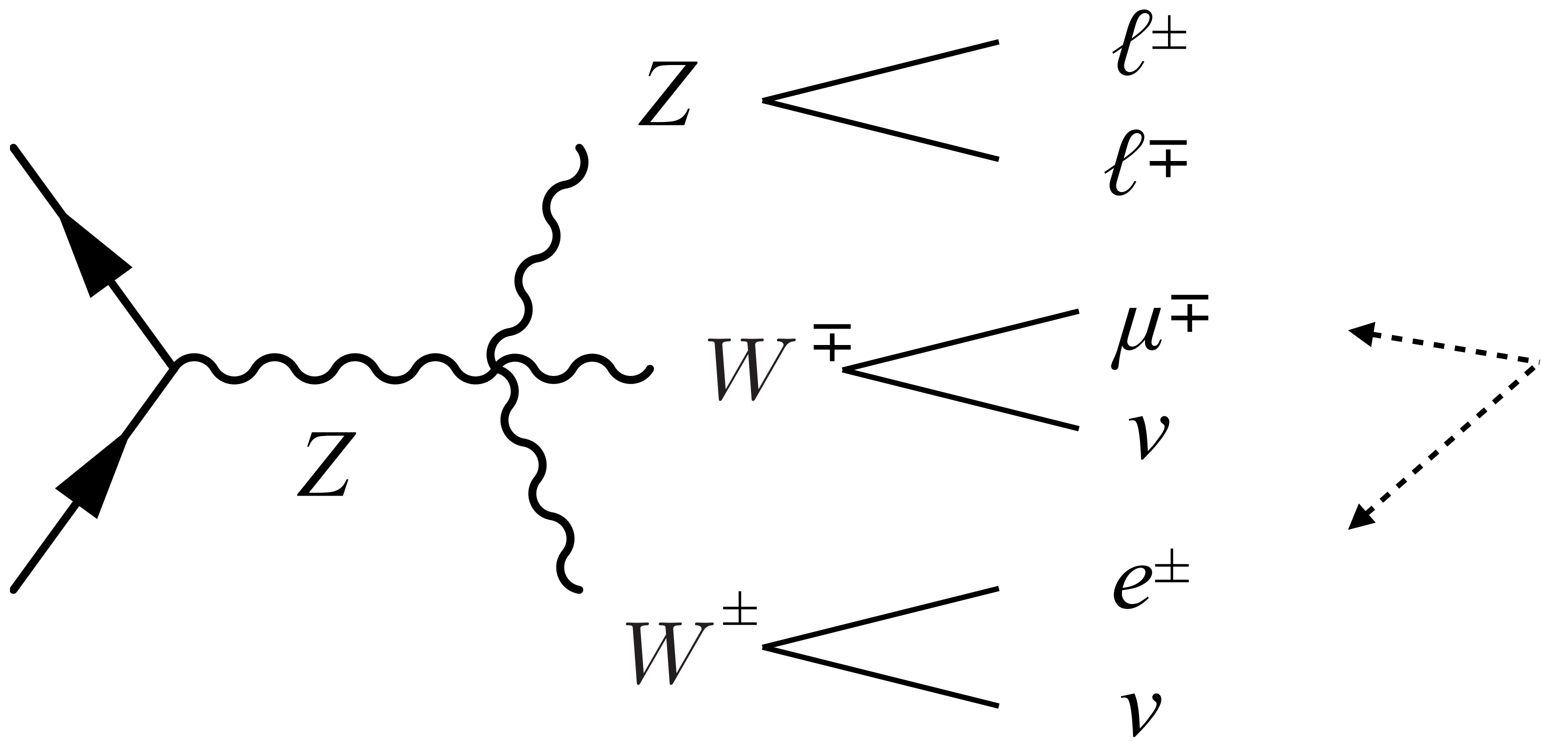
Two different-flavor leptons

Missing energy via two ν's

Dominant backgrounds: SM processes which also contain Z→ℓℓ, e.g. WZ→ℓνℓℓ and ZZ→ℓℓℓℓ

WWZ → eνμνℓℓ

WVZ categories target final states with Z→ℓℓ



Two leptons from Z decay

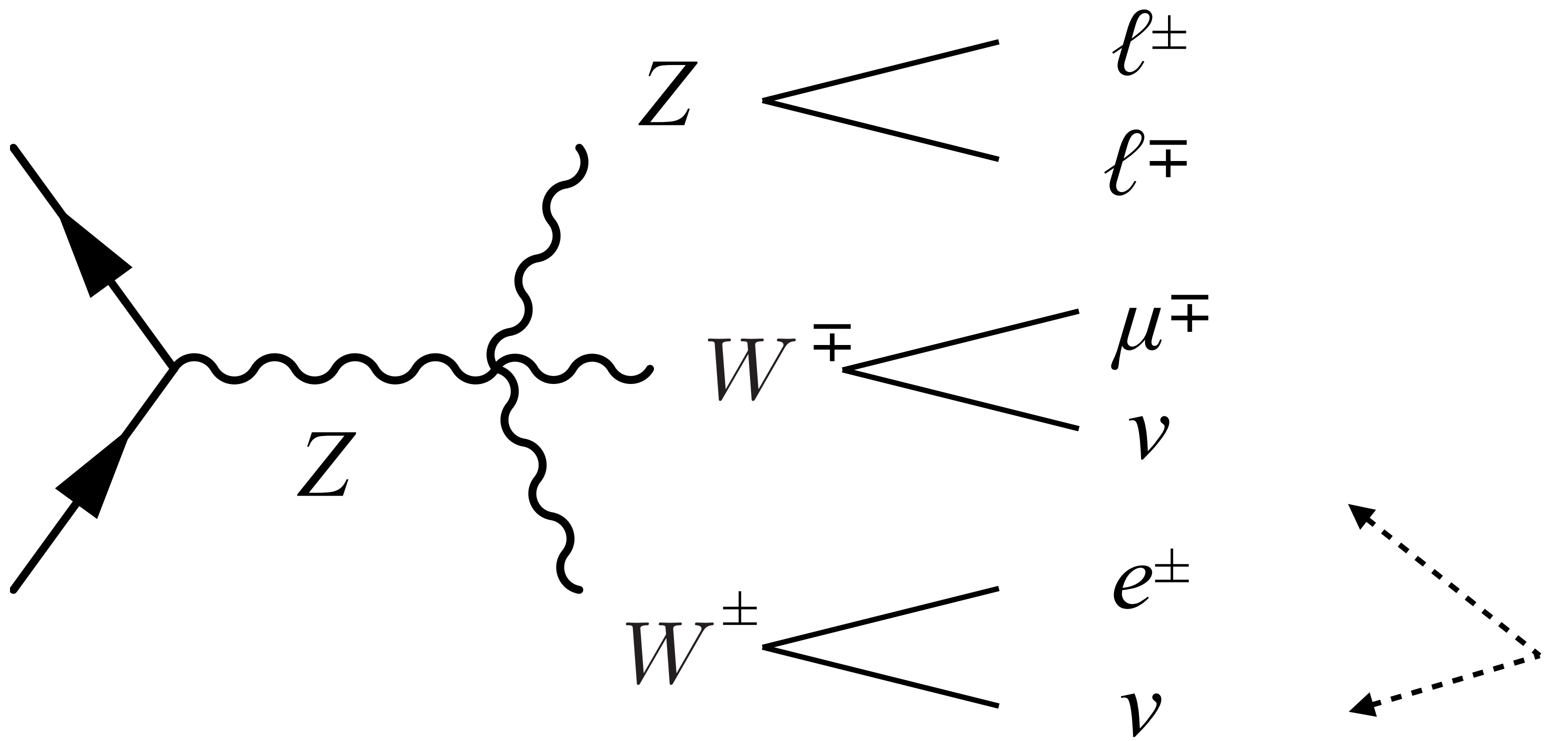
Two different-flavor leptons

Missing energy via two ν's

Dominant backgrounds: SM processes which also contain Z→ℓℓ, e.g. WZ→ℓνℓℓ and ZZ→ℓℓℓℓ

WWZ → eνμνℓℓ

WVZ categories target final states with Z→ℓℓ



Two leptons from Z decay

Two different-flavor leptons

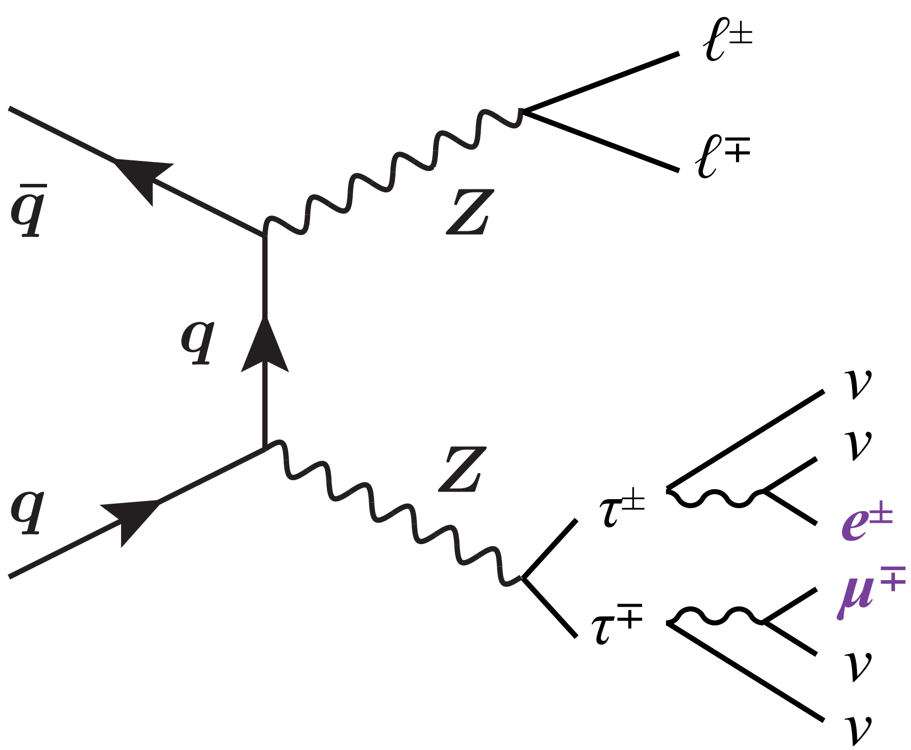
Missing energy via two ν's

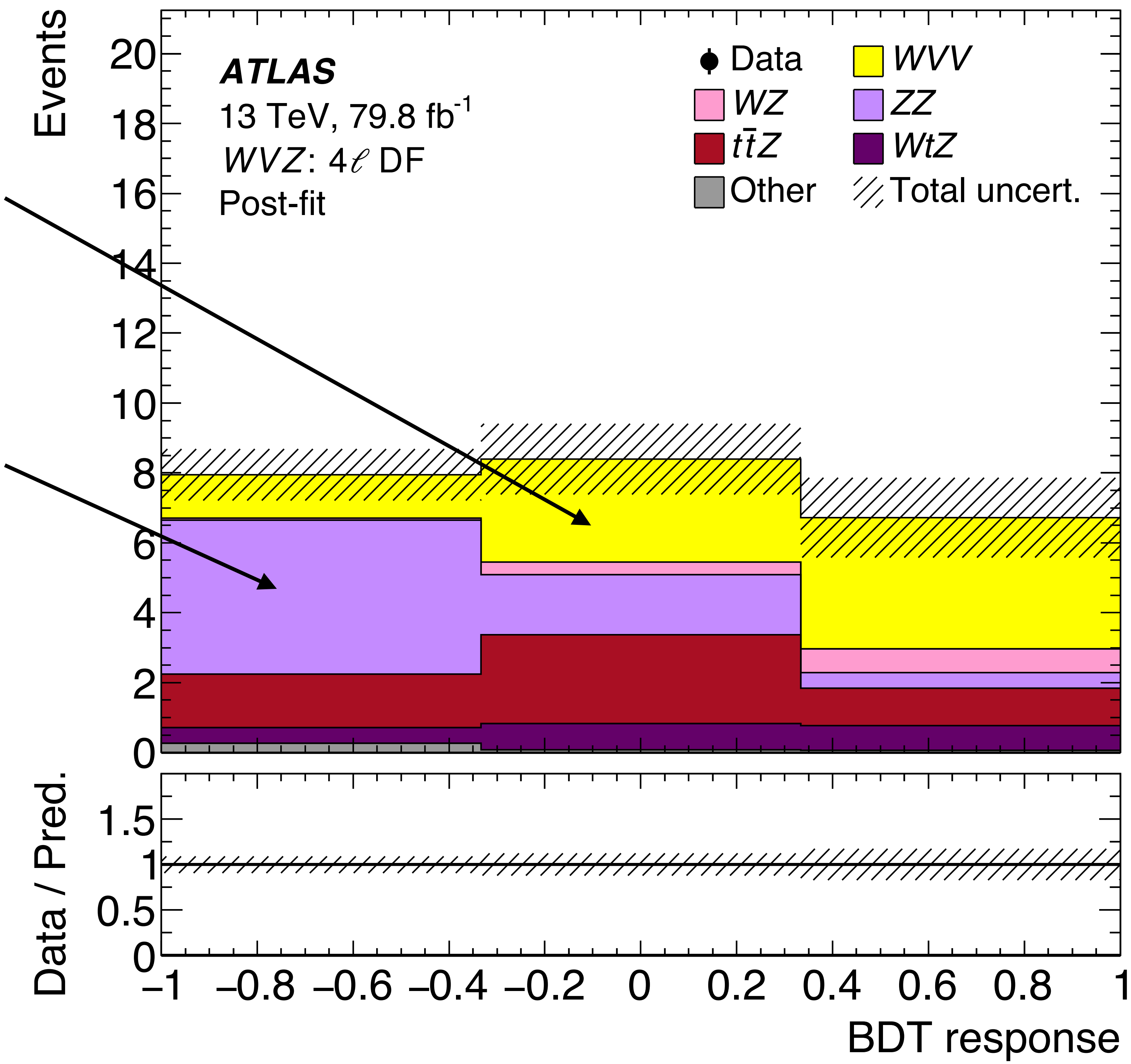
Dominant backgrounds: SM processes which also contain Z→ℓℓ, e.g. WZ→ℓνℓℓ and ZZ→ℓℓℓℓ

WWZ → eνμνℓℓ

WWZ→eνμνℓℓ:
Weak correlation between leptons from W decays

Z(ℓℓ)Z(ττ):
Stronger correlation between leptons from τ decays

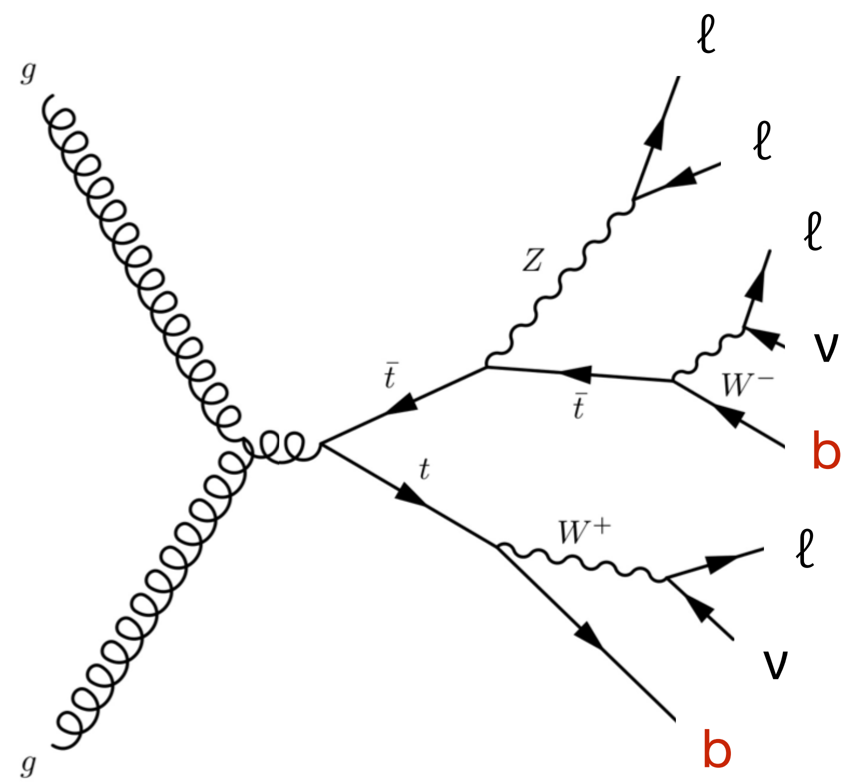


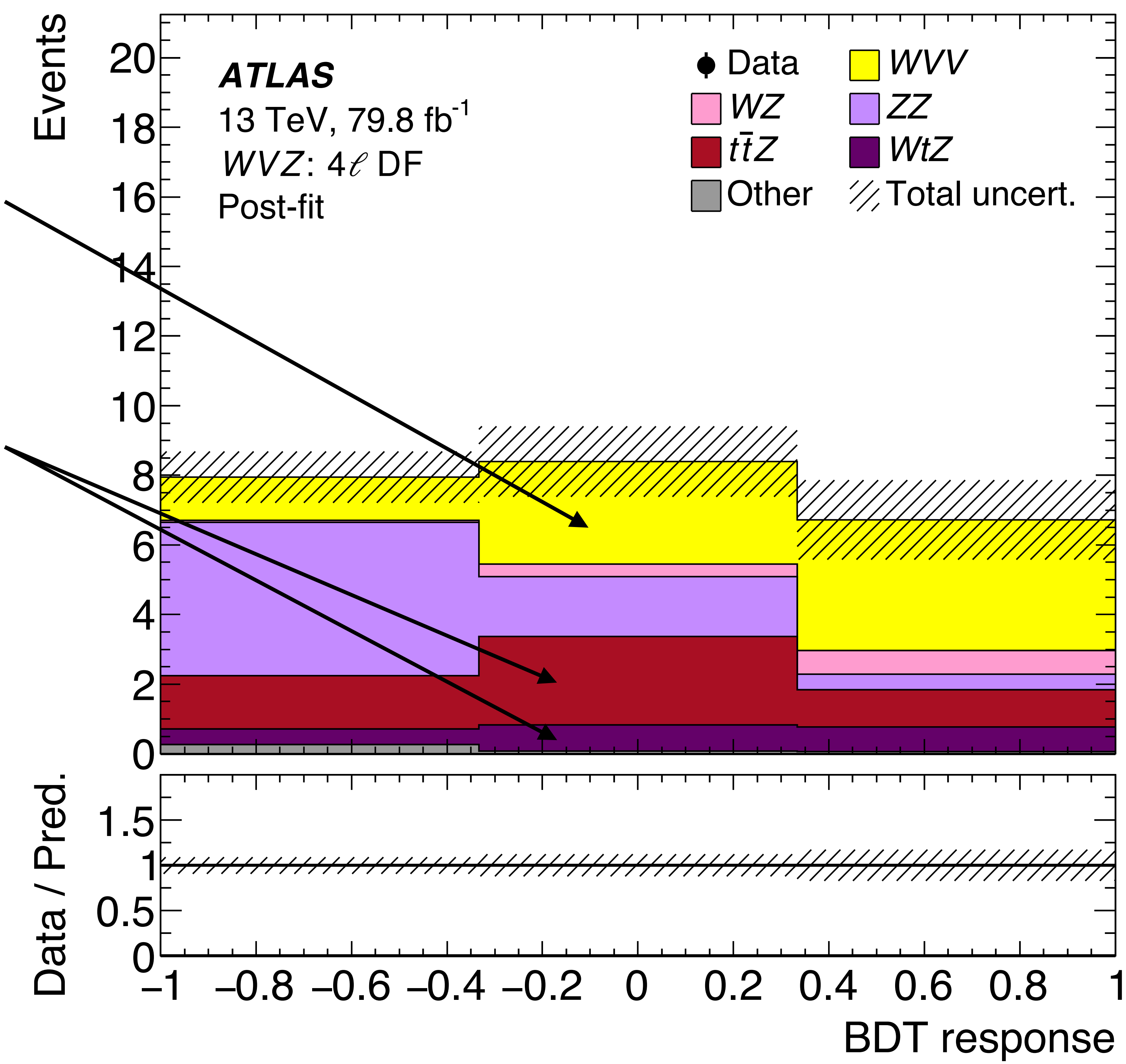


WWZ → eνμνℓℓ

WWZ→eνμνℓℓ:
Tends to not have additional jet activity

ttZ and tWZ: Tend to have additional jets in the event

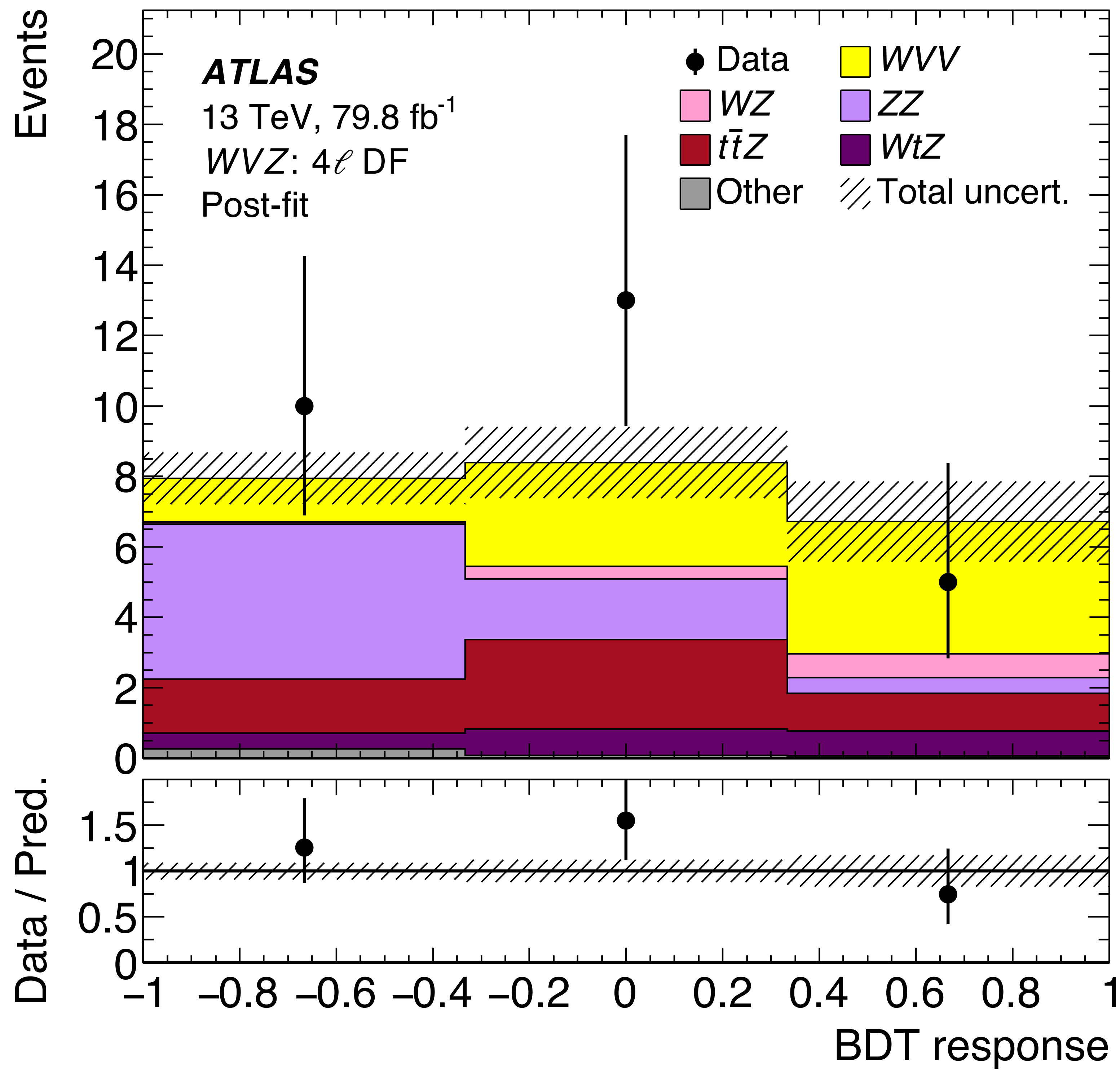




Analysis approach

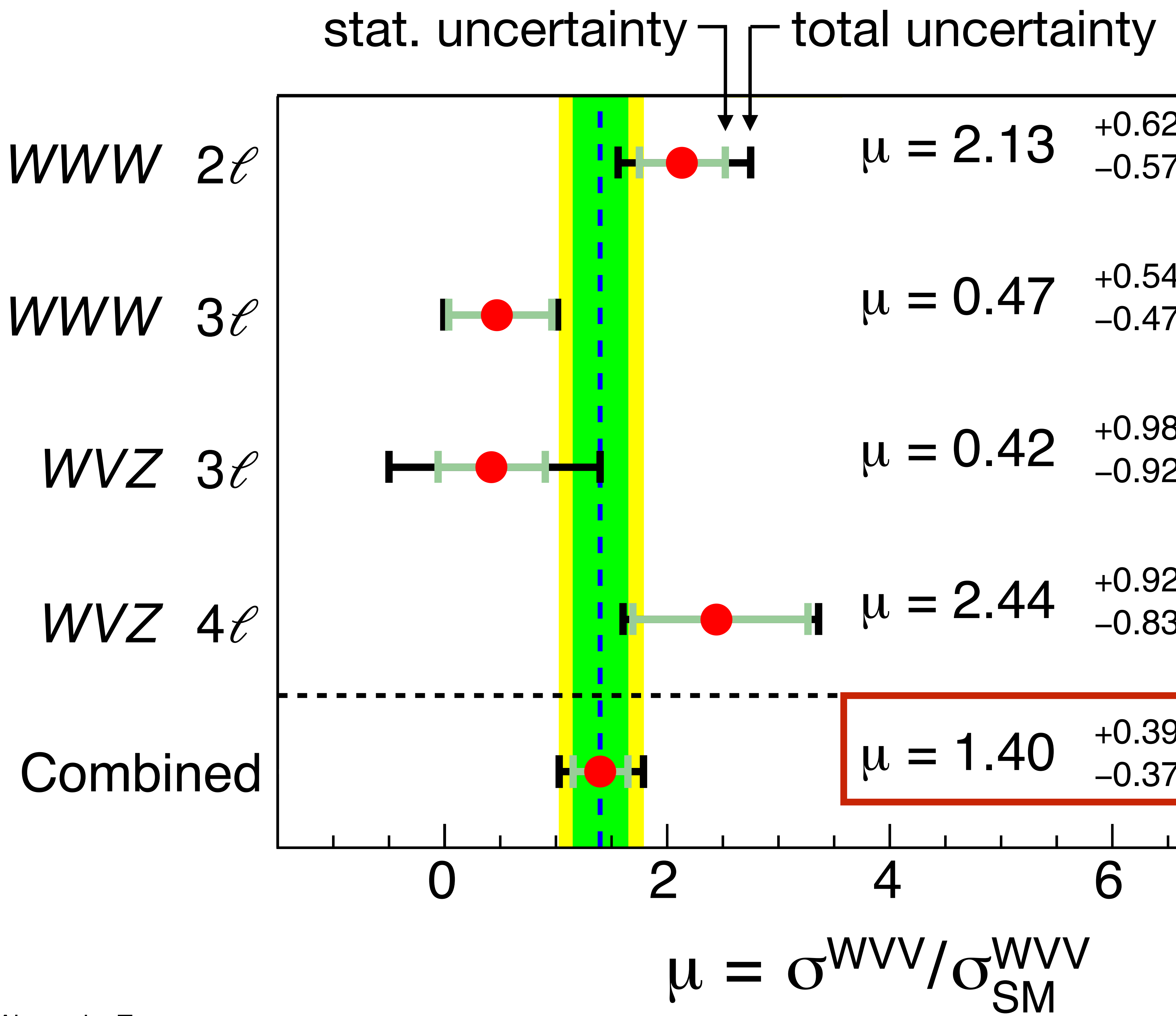
Good agreement between data and prediction

Signal hypothesis is favored given the data with BDT response ~ 1



Combination

Measured cross-section



Incompatibility with the "no-triboson" hypothesis: 3.3σ (WWW), 2.9σ (WVZ), 4.0σ (VVV)

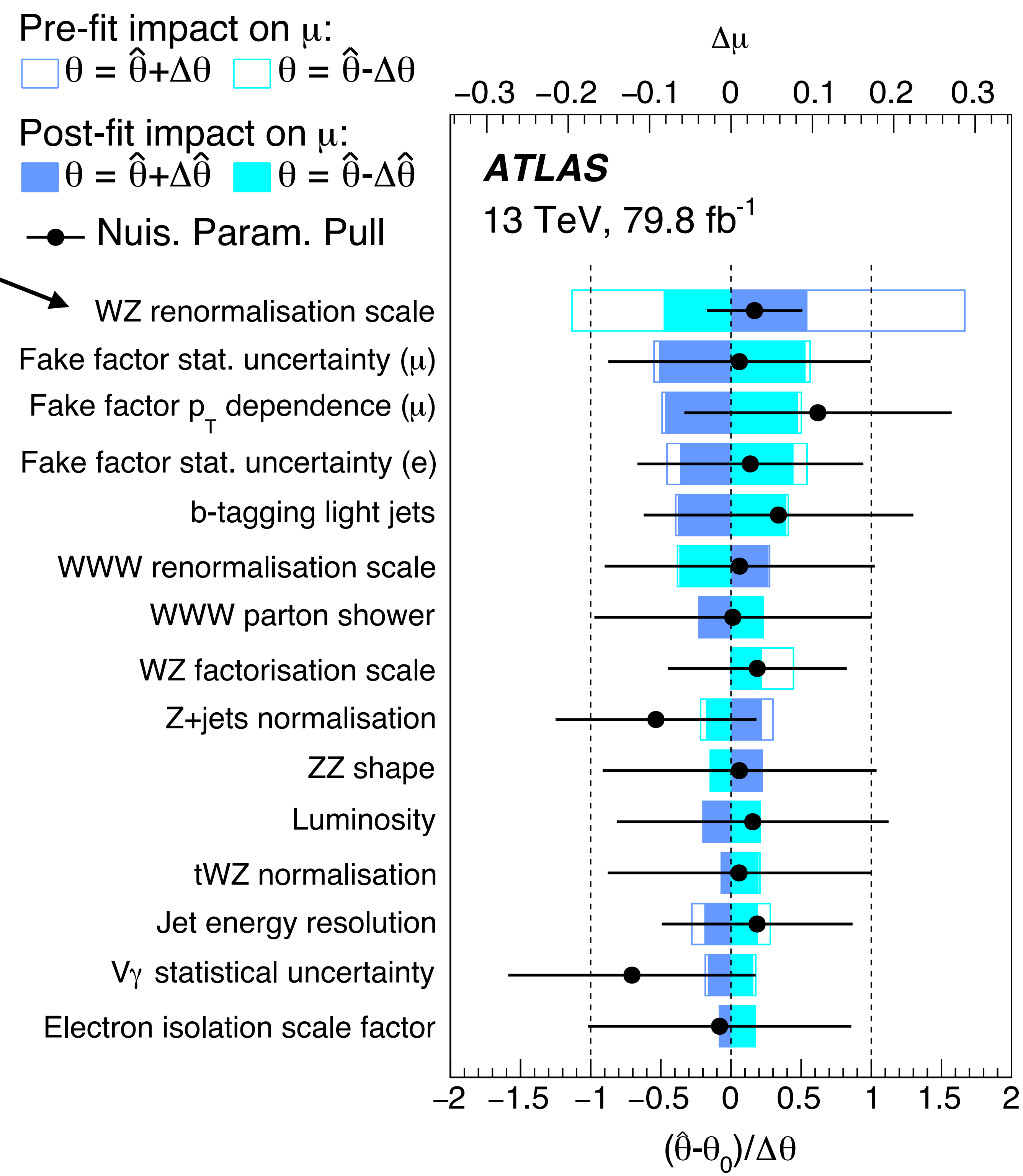
Uncertainties

ranked by importance

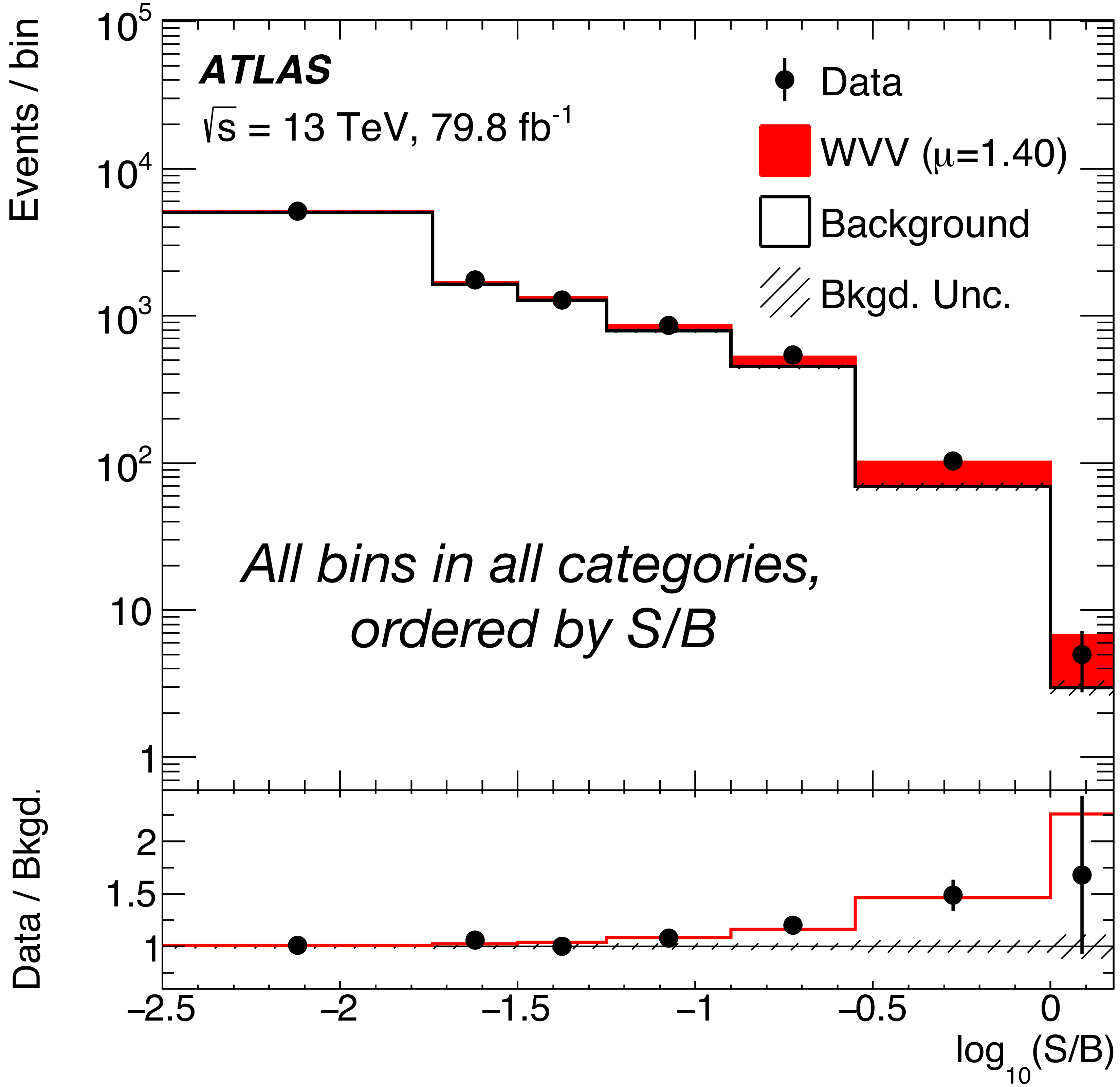
Sherpa: large uncertainty of WZ renormalisation scale (WWW and WVZ)

Significant uncertainties from data-driven prediction of non-prompt (WWW)

Remaining uncertainties: a mix of exp. and theory



Triboson in 1 plot

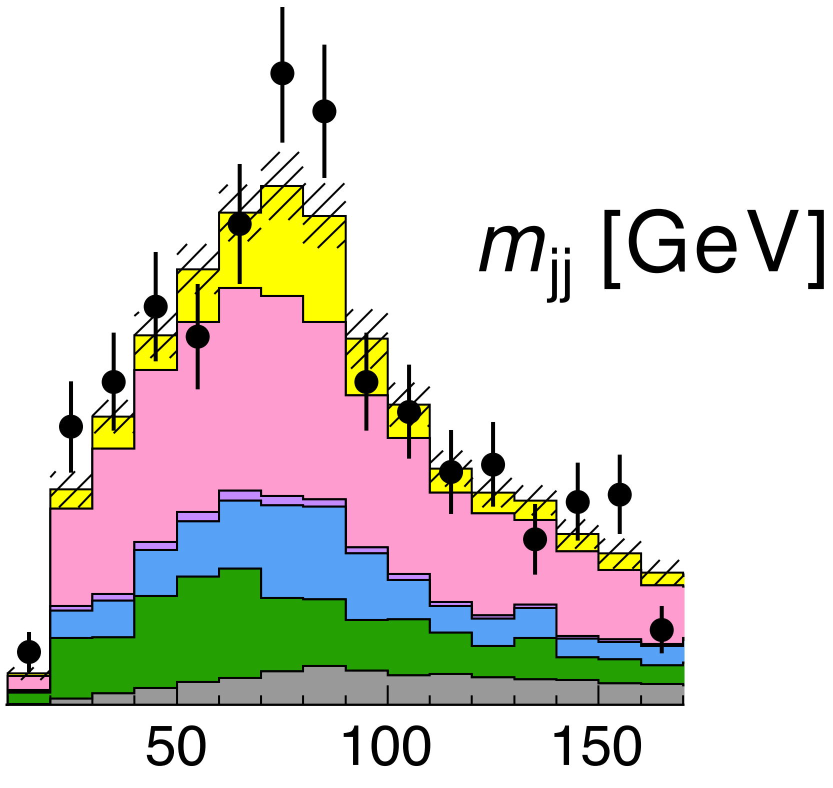


Summary

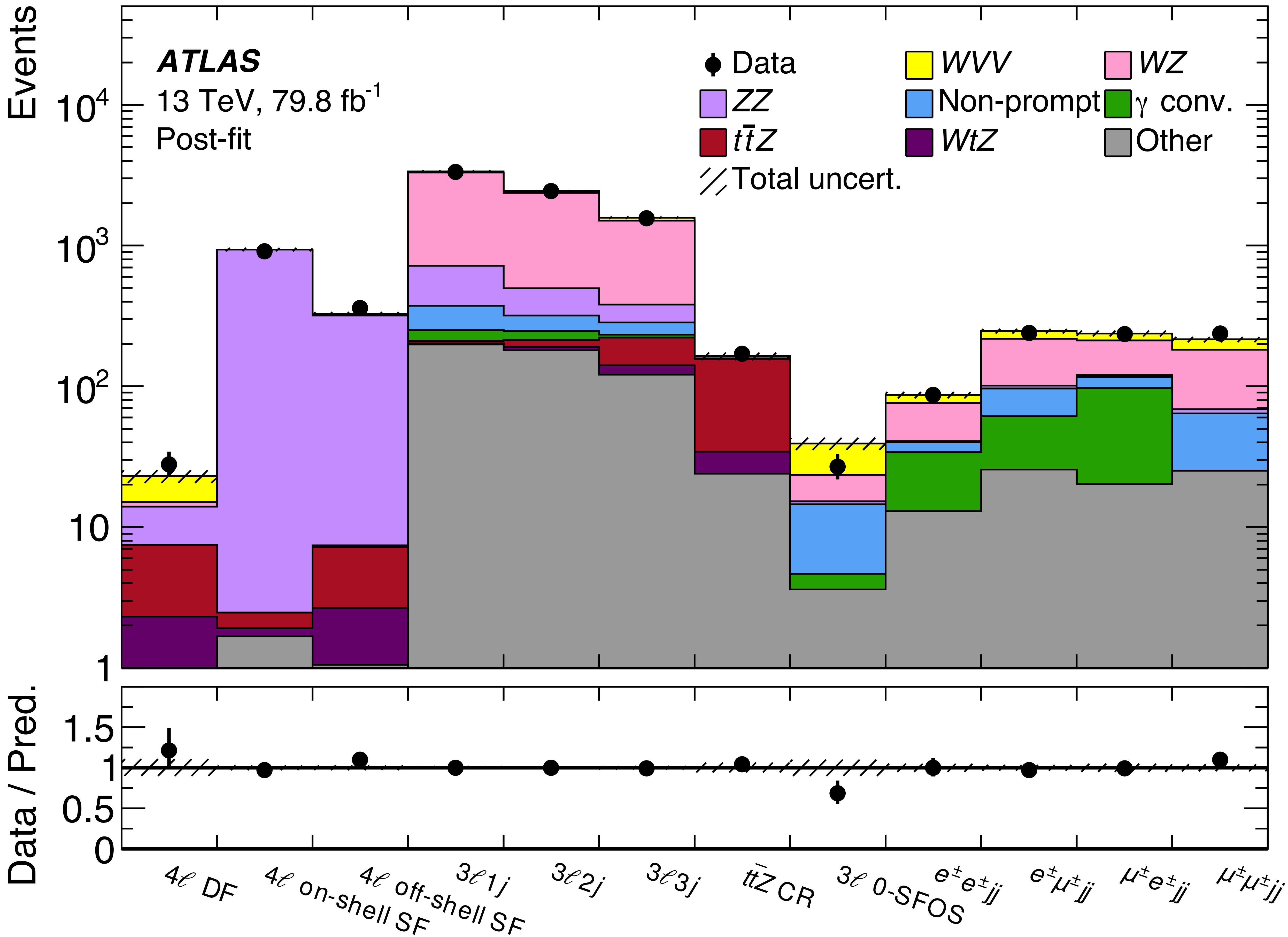
ATLAS measured triboson *VVV* for the first time at $\sqrt{s}$ = 13 TeV

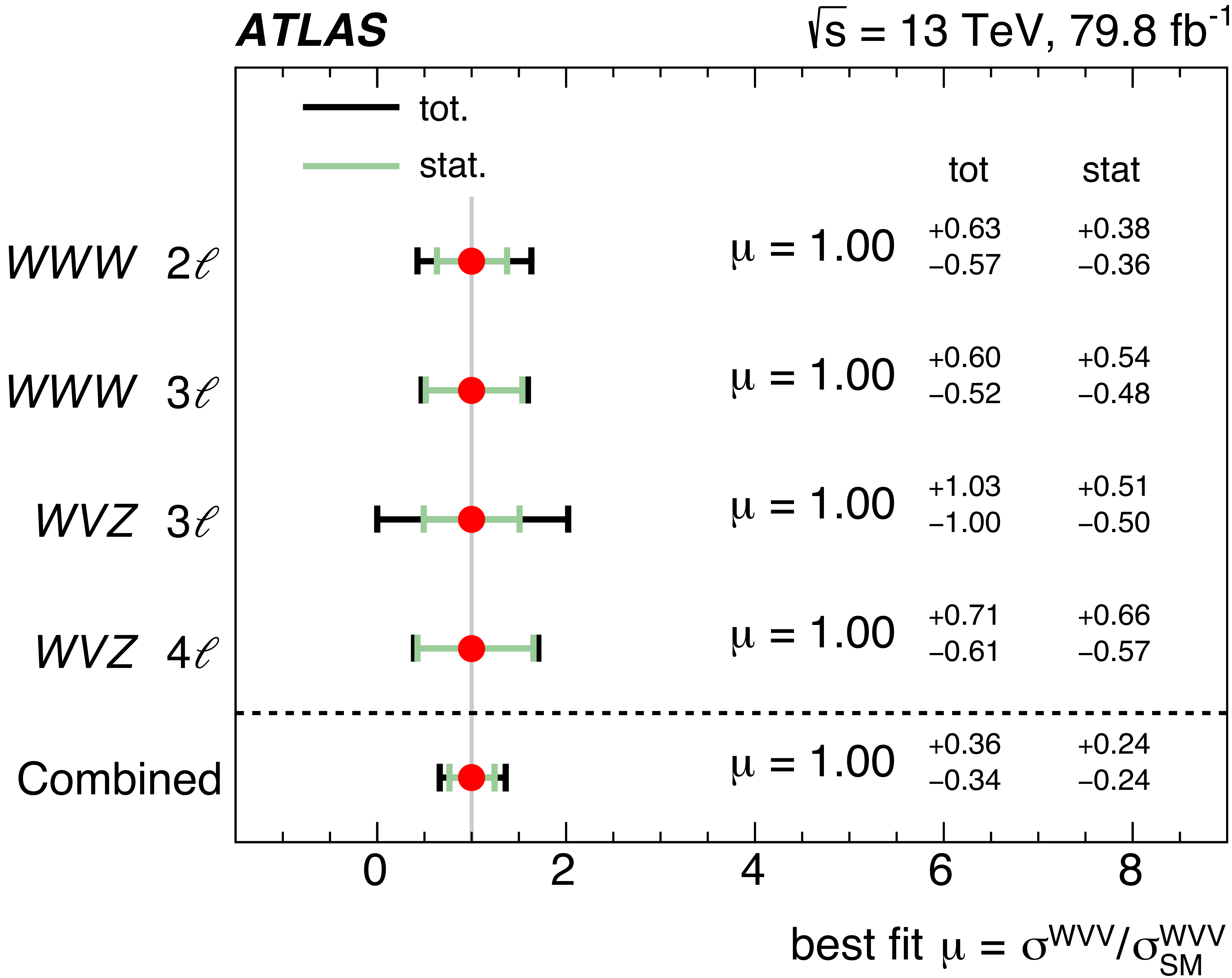
The measured cross-section is consistent with Standard Model expectation

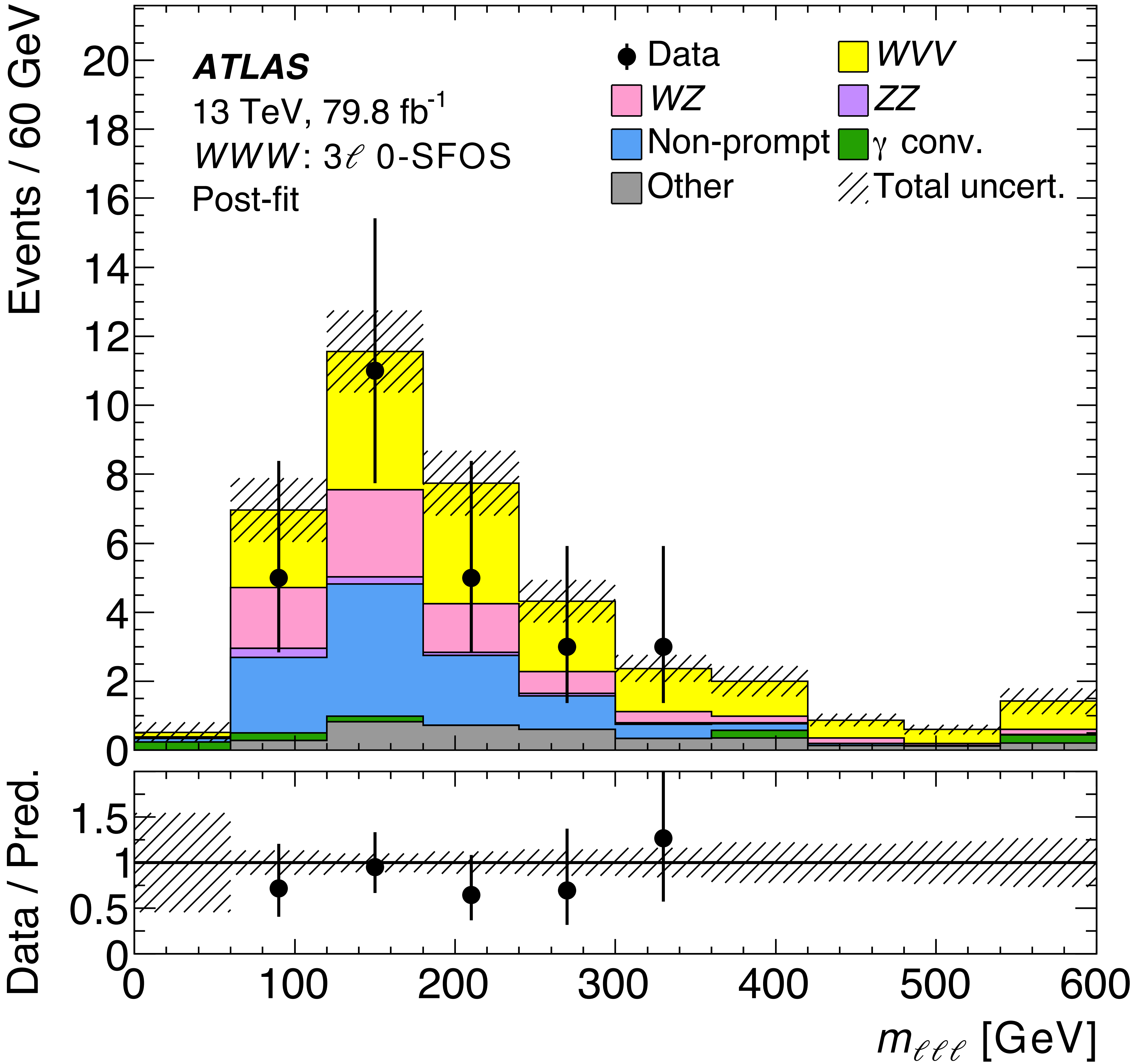
This analysis includes roughly half of the Run 2 ATLAS dataset — stay tuned for a new result with the entire dataset



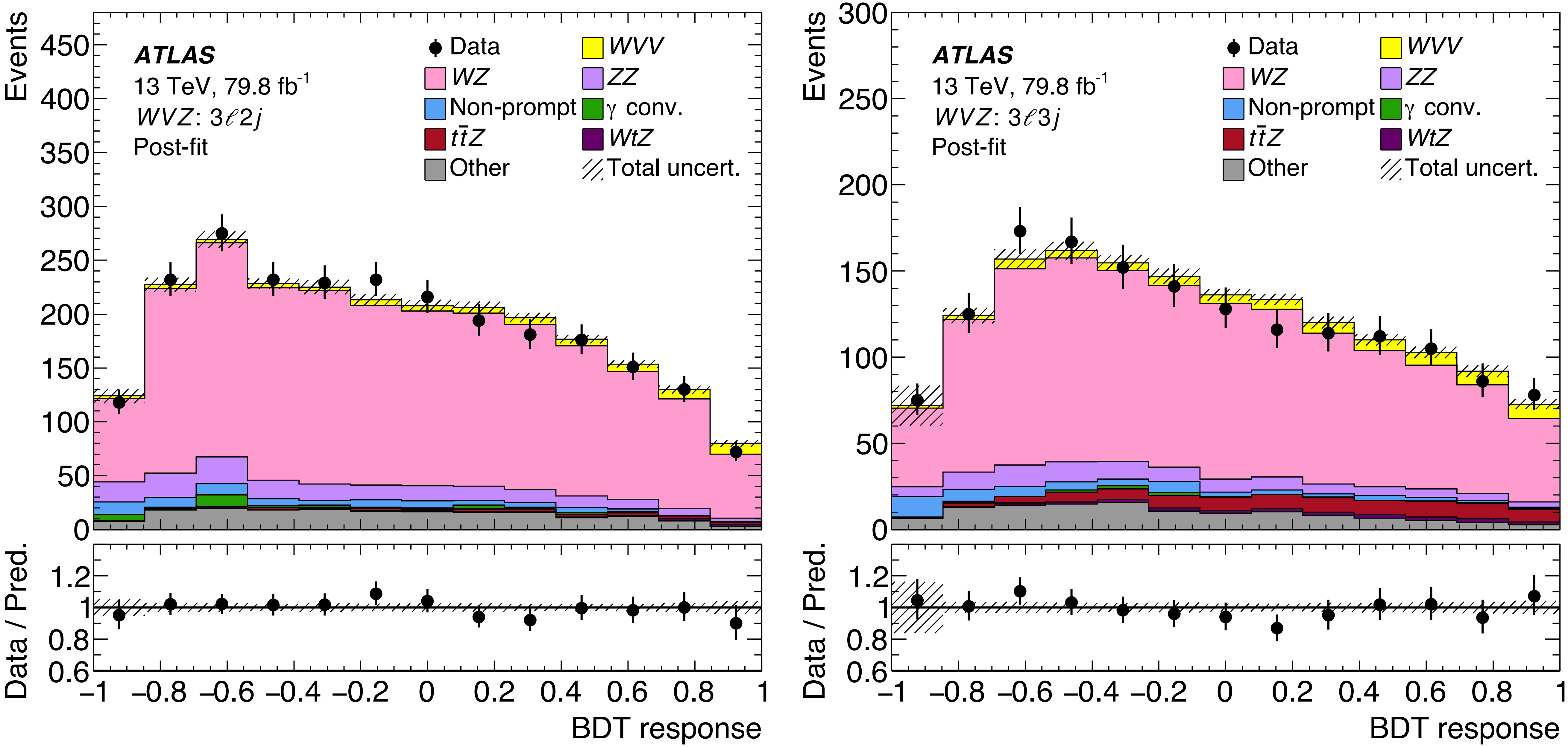
Bonus

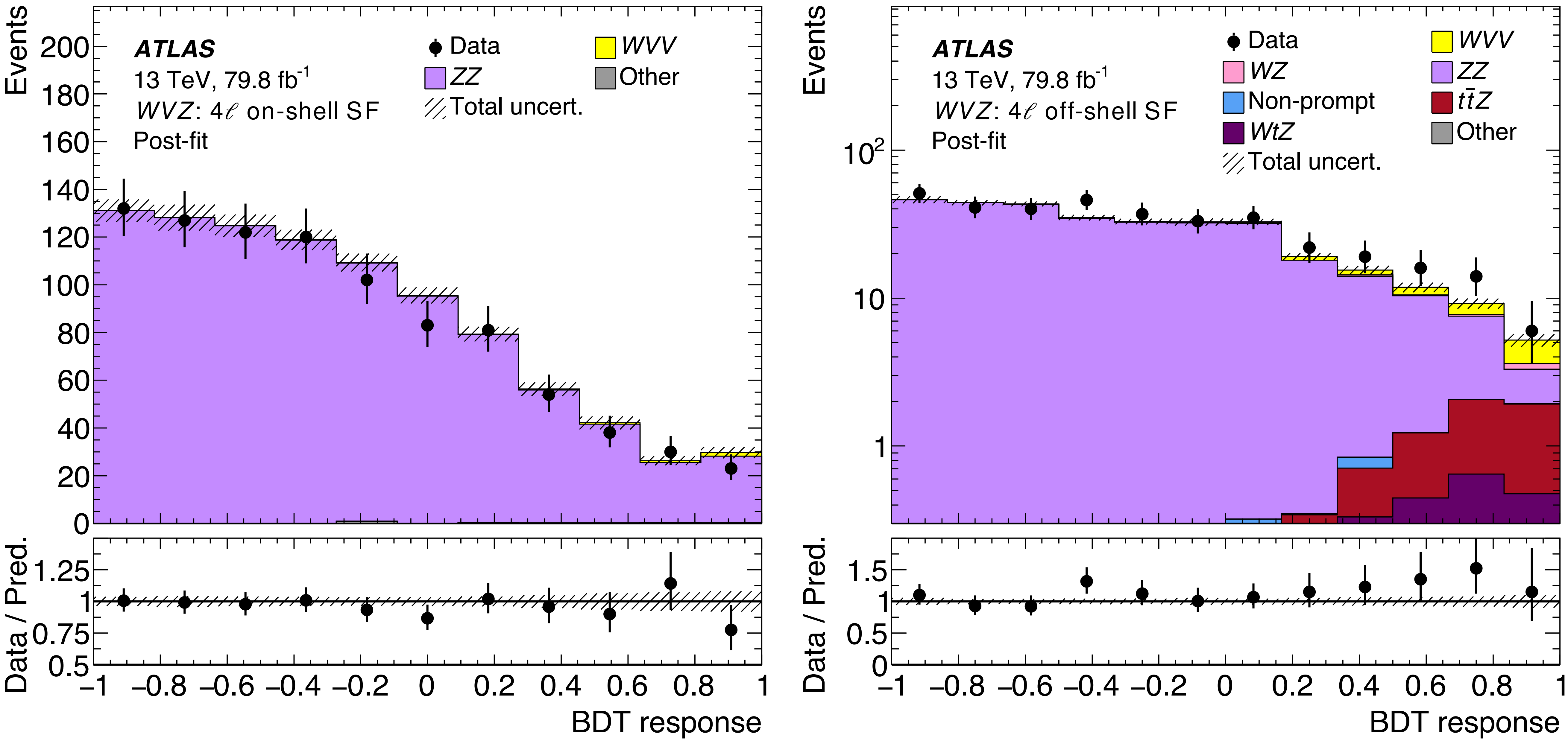

ATLAS
13 TeV, 79.8 fb^{-1}
Post-fit
Data
WVV
WZ
ZZ
Non-prompt
γ conv.
$t\bar{t}Z$
WtZ
Other
Total uncert.
Events
Data / Pred.
4ℓ DF
4ℓ on-shell SF
4ℓ off-shell SF
3ℓ1j
3ℓ2j
3ℓ3j
$t\bar{t}Z$ CR
3ℓ 0-SFOS
$e^{\pm}e^{\pm}jj$
$e^{\pm}\mu^{\pm}jj$
$\mu^{\pm}e^{\pm}jj$
$\mu^{\pm}\mu^{\pm}jj$


ATLAS
$\sqrt{s}$ = 13 TeV, 79.8 fb^{-1}
tot.
stat.
tot
stat
WWW 2ℓ
μ = 1.00 $^{+0.63}_{-0.57}$ $^{+0.38}_{-0.36}$
WWW 3ℓ
μ = 1.00 $^{+0.60}_{-0.52}$ $^{+0.54}_{-0.48}$
WVZ 3ℓ
μ = 1.00 $^{+1.03}_{-1.00}$ $^{+0.51}_{-0.50}$
WVZ 4ℓ
μ = 1.00 $^{+0.71}_{-0.61}$ $^{+0.66}_{-0.57}$
Combined
μ = 1.00 $^{+0.36}_{-0.34}$ $^{+0.24}_{-0.24}$
0
2
4
6
8
best fit $\mu = \sigma^{WVV}/\sigma^{WVV}_{SM}$



ATLAS
13 TeV, 79.8 fb^{-1}
WWW: 3ℓ 0-SFOS
Post-fit
Data
WVV
WZ
ZZ
Non-prompt
γ conv.
Other
Total uncert.
Events / 60 GeV
Data / Pred.
$m_{\ell\ell\ell}$ [GeV]


Events
ATLAS
13 TeV, 79.8 fb^{-1}
WVZ: $3\ell 2j$
Post-fit
Data
WVV
WZ
ZZ
Non-prompt
γ conv.
$t\bar{t}Z$
WtZ
Other
Total uncert.
Data / Pred.
BDT response
Events
ATLAS
13 TeV, 79.8 fb^{-1}
WVZ: $3\ell 3j$
Post-fit
Data
WVV
WZ
ZZ
Non-prompt
γ conv.
$t\bar{t}Z$
WtZ
Other
Total uncert.
Data / Pred.
BDT response


ATLAS
13 TeV, 79.8 fb^{-1}
WVZ: 4ℓ on-shell SF
Post-fit
Data
ZZ
Total uncert.
WVV
Other
Events
Data / Pred.
BDT response
ATLAS
13 TeV, 79.8 fb^{-1}
WVZ: 4ℓ off-shell SF
Post-fit
Data
WZ
Non-prompt
WtZ
Total uncert.
WVV
ZZ
$t\bar{t}Z$
Other
Events
Data / Pred.
BDT response

Uncertainty source	$\Delta\mu_{WVV}$	
Data-driven	+0.14	–0.14
Theory	+0.15	–0.13
Instrumental	+0.12	–0.09
MC stat. uncertainty	+0.06	–0.04
Generators	+0.04	–0.03
Total systematic uncertainty	+0.30	–0.27

Decay channel	Significance	
	Observed	Expected
WWW combined	3.2σ	2.4σ
$WWW \to \ell\nu\ell\nu qq$	4.0σ	1.7σ
$WWW \to \ell\nu\ell\nu\ell\nu$	1.0σ	2.0σ
WVZ combined	3.2σ	2.0σ
$WVZ \to \ell\nu qq\ell\ell$	0.5σ	1.0σ
$WVZ \to \ell\nu\ell\nu\ell\ell/qq\ell\ell\ell\ell$	3.5σ	1.8σ
WVV combined	4.1σ	3.1σ

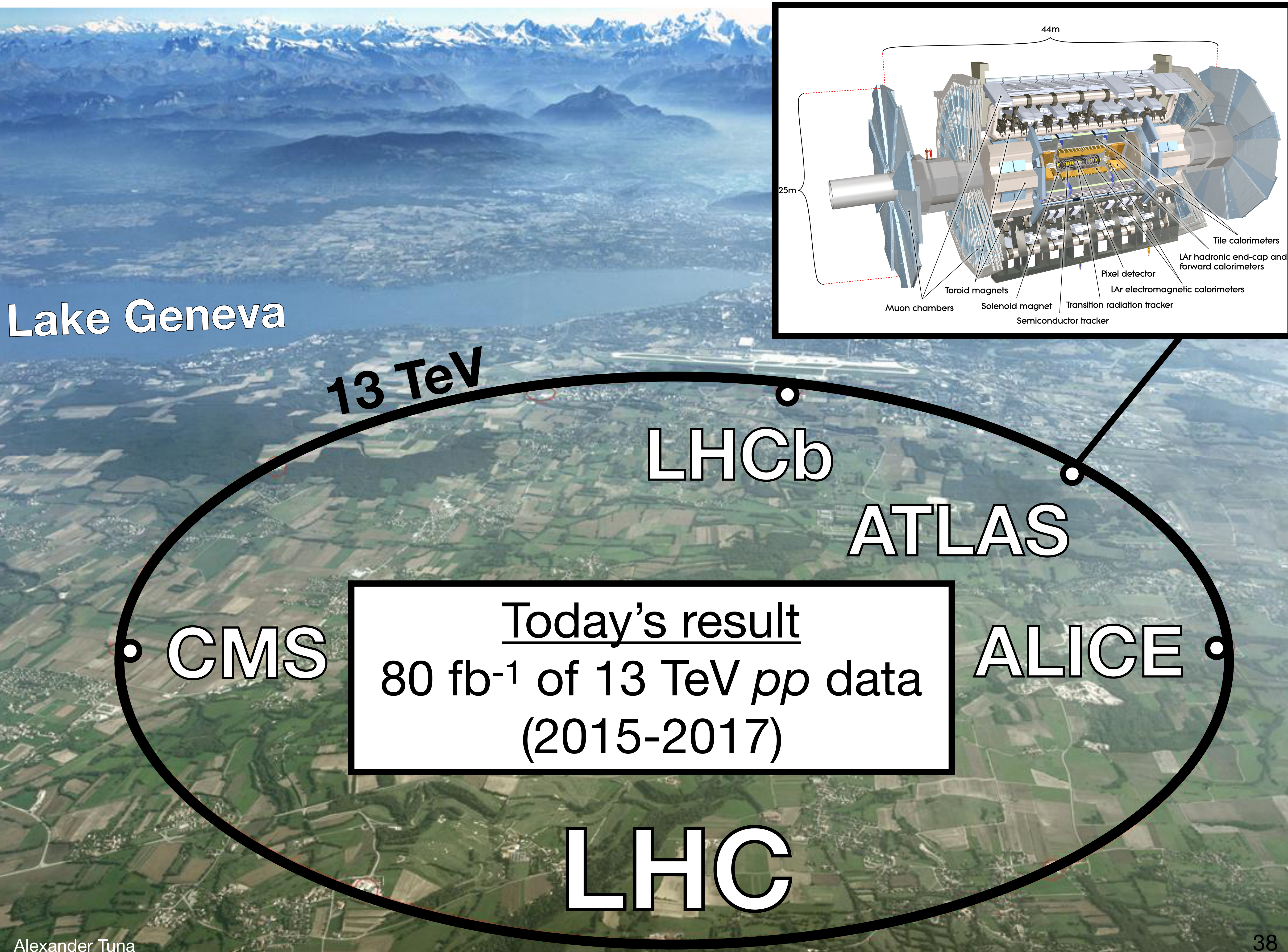
	$WWW \to \ell\nu\ell\nu qq$	$WWW \to \ell\nu\ell\nu\ell\nu$
Lepton	Two leptons with $p_{\mathrm{T}} > 27(20)\,GeV$ and one same-sign lepton pair	Three leptons with $p_{\mathrm{T}} > 27(20,20)\,GeV$ and no same-flavour opposite-sign lepton pairs
$m_{\ell\ell}$	$40 < m_{\ell\ell} < 400\,\mathrm{GeV}$	–
Jets	At least two jets with $p_{\mathrm{T}} > 30(20)\,GeV$ and $\|\eta\| < 2.5$	–
m_{jj}	$m_{jj} < 300\,\mathrm{GeV}$	–
$\Delta\eta_{jj}$	$\|\Delta\eta_{jj}\| < 1.5$	–
$E_{\mathrm{T}}^{\mathrm{miss}}$	$E_{\mathrm{T}}^{\mathrm{miss}} > 55\,\mathrm{GeV}$ (only for ee)	–
Z boson veto	$m_{ee} < 80\,\mathrm{GeV}$ or $m_{ee} > 100\,\mathrm{GeV}$ (only for ee and μee)	
Lepton veto	No additional lepton with $p_{\mathrm{T}} > 7\,\mathrm{GeV}$ and $\|\eta\| < 2.5$	
b-jet veto	No b-jets with $p_{\mathrm{T}} > 25\,\mathrm{GeV}$ and $\|\eta\| < 2.5$	

	$WWW \to \ell\nu\ell\nu qq$	$WWW \to \ell\nu\ell\nu\ell\nu$
Lepton	Two leptons with $p_{\mathrm{T}} > 27(20)\,GeV$ and one same-sign lepton pair	Three leptons with $p_{\mathrm{T}} > 27(20,20)\,GeV$ and no same-flavour opposite-sign lepton pairs
$m_{\ell\ell}$	$40 < m_{\ell\ell} < 400\,\mathrm{GeV}$	–
Jets	At least two jets with $p_{\mathrm{T}} > 30(20)\,GeV$ and $\lvert\eta\rvert < 2.5$	–
m_{jj}	$m_{jj} < 300\,\mathrm{GeV}$	–
$\Delta\eta_{jj}$	$\lvert\Delta\eta_{jj}\rvert < 1.5$	–
$E_{\mathrm{T}}^{\mathrm{miss}}$	$E_{\mathrm{T}}^{\mathrm{miss}} > 55\,\mathrm{GeV}$ (only for ee)	–
Z boson veto	$m_{ee} < 80\,\mathrm{GeV}$ or $m_{ee} > 100\,\mathrm{GeV}$ (only for ee and μee)	
Lepton veto	No additional lepton with $p_{\mathrm{T}} > 7\,\mathrm{GeV}$ and $\lvert\eta\rvert < 2.5$	
b-jet veto	No b-jets with $p_{\mathrm{T}} > 25\,\mathrm{GeV}$ and $\lvert\eta\rvert < 2.5$	

	$WVZ \to \ell\nu qq\ell\ell$	$WVZ \to \ell\nu\ell\nu\ell\ell/qq\ell\ell\ell\ell$
Z boson	At least one OS lepton pair with $\lvert m_{\ell\ell} - 91.2\,\mathrm{GeV}\rvert < 10\,\mathrm{GeV}$	
Low mass veto	$m_{\ell\ell} > 12\,\mathrm{GeV}$ for any OS lepton pair	
b-jet veto	No b-jets with $p_{\mathrm{T}} > 25\,\mathrm{GeV}$ and $\lvert\eta\rvert < 2.5$	
Leptons	One additional nominal lepton	One additional OS lepton pair; third and fourth lepton nominal
H_{T}	$H_{\mathrm{T}} > 200\,\mathrm{GeV}$	–

WZ control region	Three nominal leptons with one SFOS pair No b-tagged jets $E_{\mathrm{T}}^{\mathrm{miss}} > 55$ GeV $m_{\ell\ell\ell} > 110$ GeV
W sideband validation region	Same as the $WWW \to \ell\nu\ell\nu qq$ SR, with $m_{jj} < 50$ GeV or $m_{jj} > 120$ GeV
$t\bar{t}Z$ control region	Same as the 3ℓ-3j SR region, except: no requirement on H_{T}, at least four jets, at least two b-tagged jets.
WZ+jets and Z+jets validation regions	Same as the 3ℓ-1j SR region, except: no requirement on H_{T}; third-highest-p_{T} lepton has 10 GeV $< p_T <$ 15 GeV; $m_{\ell\ell\ell} < 150$ GeV.

Variable	3ℓ-1j	3ℓ-2j	3ℓ-3j	4ℓ DF	4ℓ SF on-shell	4ℓ SF off-shell
$p_{\mathrm{T}}(\ell_1)$	×	×				
$p_{\mathrm{T}}(\ell_2)$	×	×	×			
$p_{\mathrm{T}}(\ell_3)$	×	×	×			
Sum of $p_{\mathrm{T}}(\ell)$	×	×	×			
$m_{\ell_1\ell_2}$	×	×				
$m_{\ell_1\ell_3}$	×	×				
$m_{\ell_2\ell_3}$	×	×				
$m_{\ell\ell}$ of best Z					×	×
$m_{\ell\ell}$ of other leptons				×	×	×
$m_{3\ell}$	×	×	×			
$m_{4\ell}$				×	×	×
Sum of lepton charges	×	×	×			
$p_{\mathrm{T}}(j_1)$	×	×				
$p_{\mathrm{T}}(j_2)$		×	×			
Sum of $p_{\mathrm{T}}(j)$			×			
Number of jets			×	×	×	×
$m_{j_1j_2}$		×				
$m_{\mathrm{T}}(W_\ell)$		×				
m_{jj} of best W			×			
Smallest m_{jj}			×			
$E_{\mathrm{T}}^{\mathrm{miss}}$		×	×	×	×	×
H_{T}	×	×			×	×
Leptonic H_{T}				×		
Hadronic H_{T}				×		
Invariant mass of all leptons, jets and $E_{\mathrm{T}}^{\mathrm{miss}}$	×		×			
Invariant mass of the best Z leptons and j_1	×					


44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker
Lake Geneva
13 TeV
LHCb
ATLAS
CMS
ALICE
Today's result
80 fb^{-1} of 13 TeV *pp* data
(2015-2017)
LHC

The ATLAS Detector