Associated single top-quark production in leptonic channels at 13 TeV (t + V)

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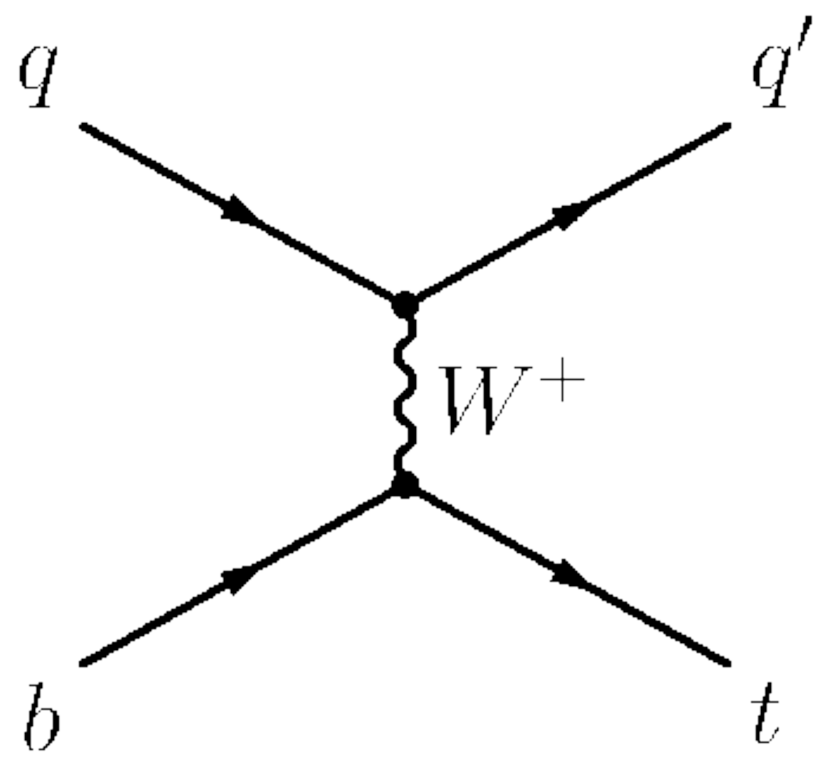
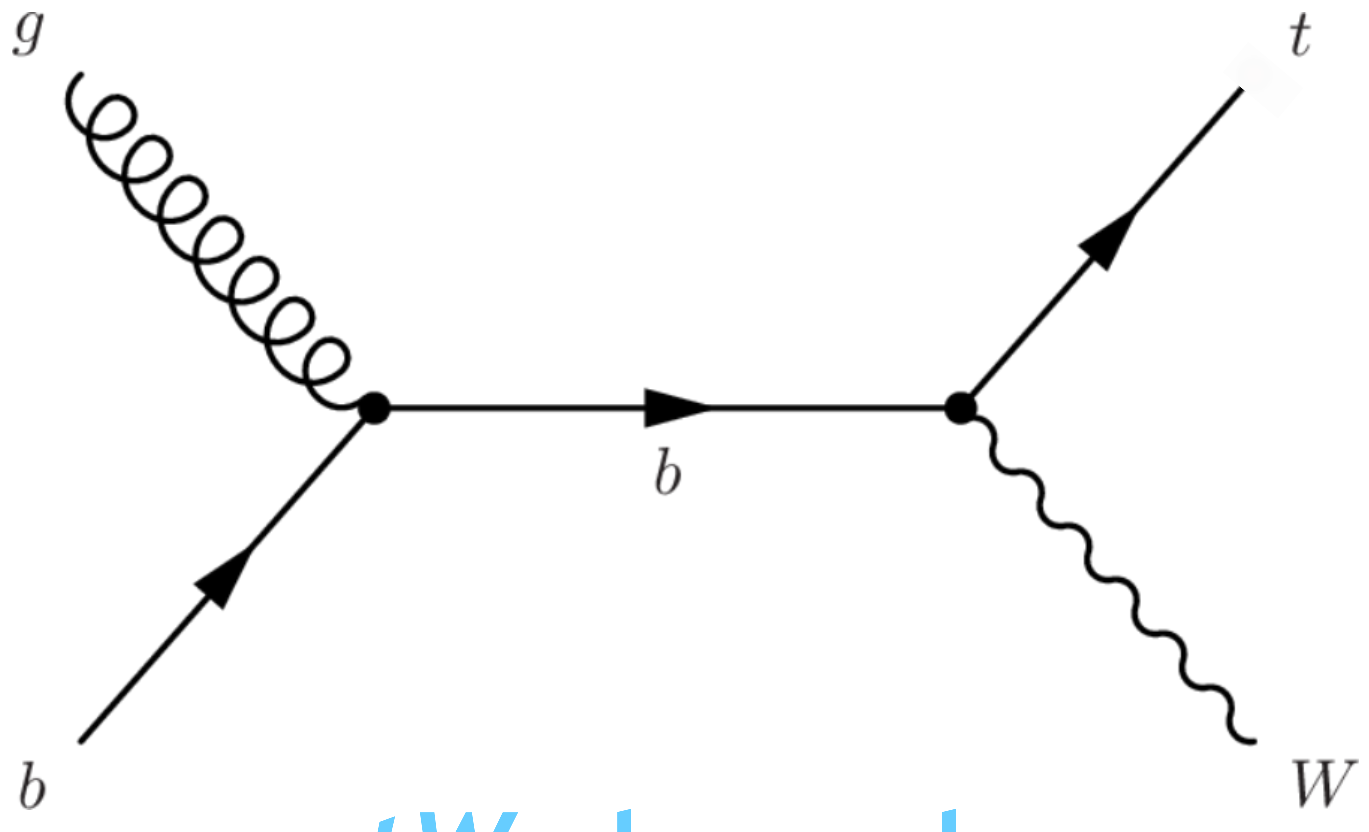
(in collaboration with
University of Oklahoma, Boston University and the University of Sydney)

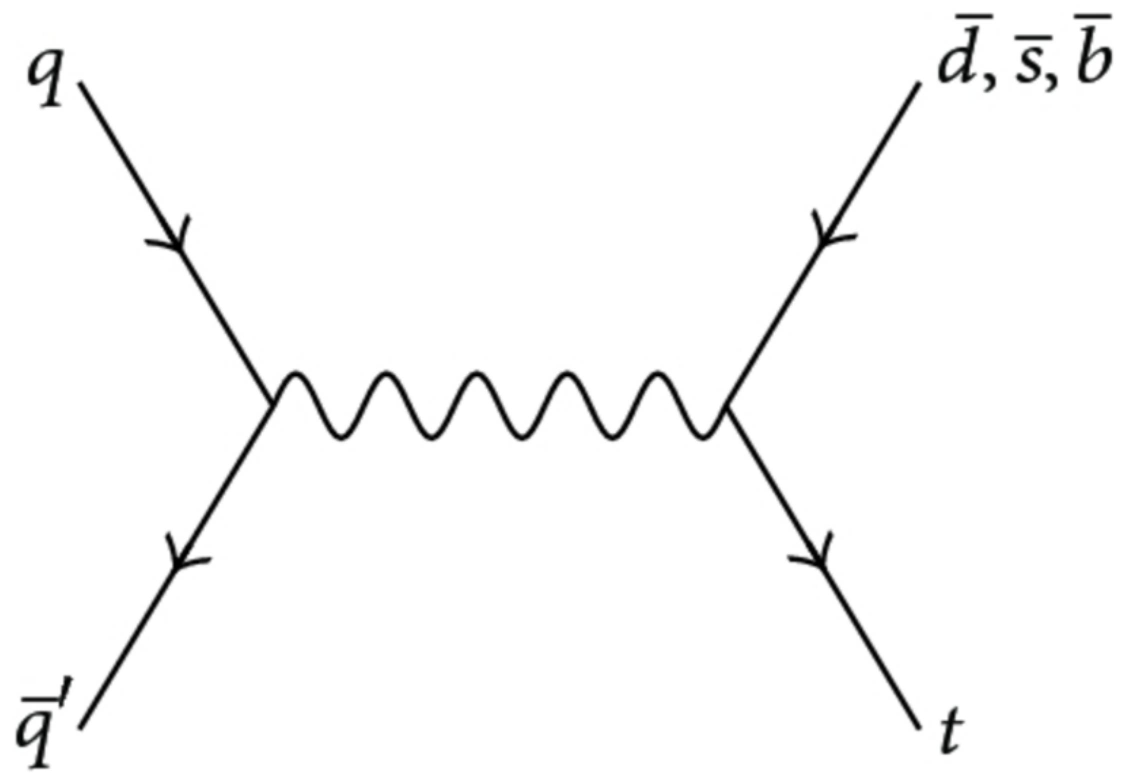
Introduction on single top-quark production



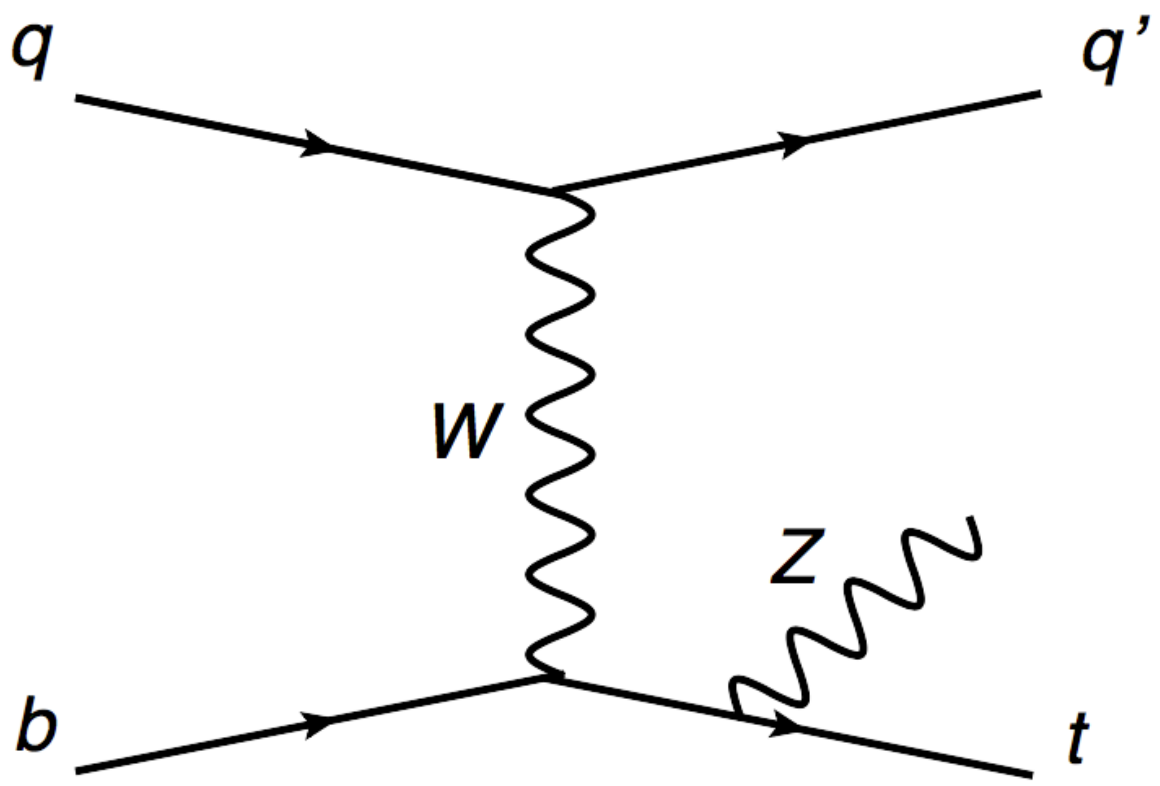
t-channel
σ(13 TeV) ~ 217 pb



tW-channel
σ(13 TeV) ~ 72 pb



s-channel
σ(13 TeV) ~ 10 pb

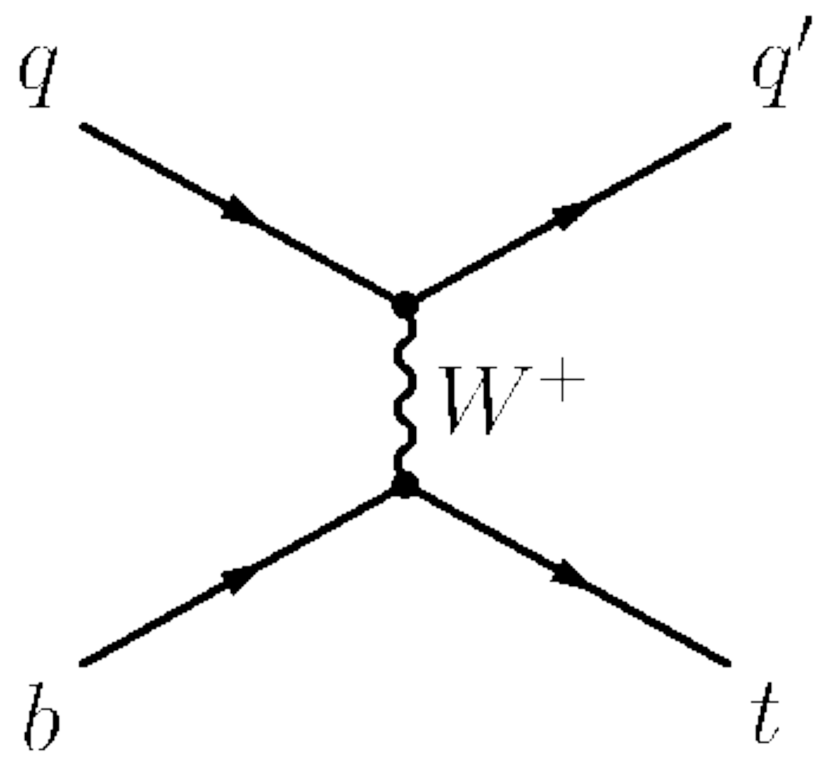


tZq
σ(13 TeV) ~ 0.6 pb

- Electroweak processes
- Tests of SM predictions
  - Sensitive to V_{tb}
  - Constrain PDFs
- Probing new physics
- Help tuning MC generators (unfolded distributions)

- *t*/*tW*/*s*-channels observed at LHC
- *t*-channel differential measured at LHC

Introduction on single top-quark production



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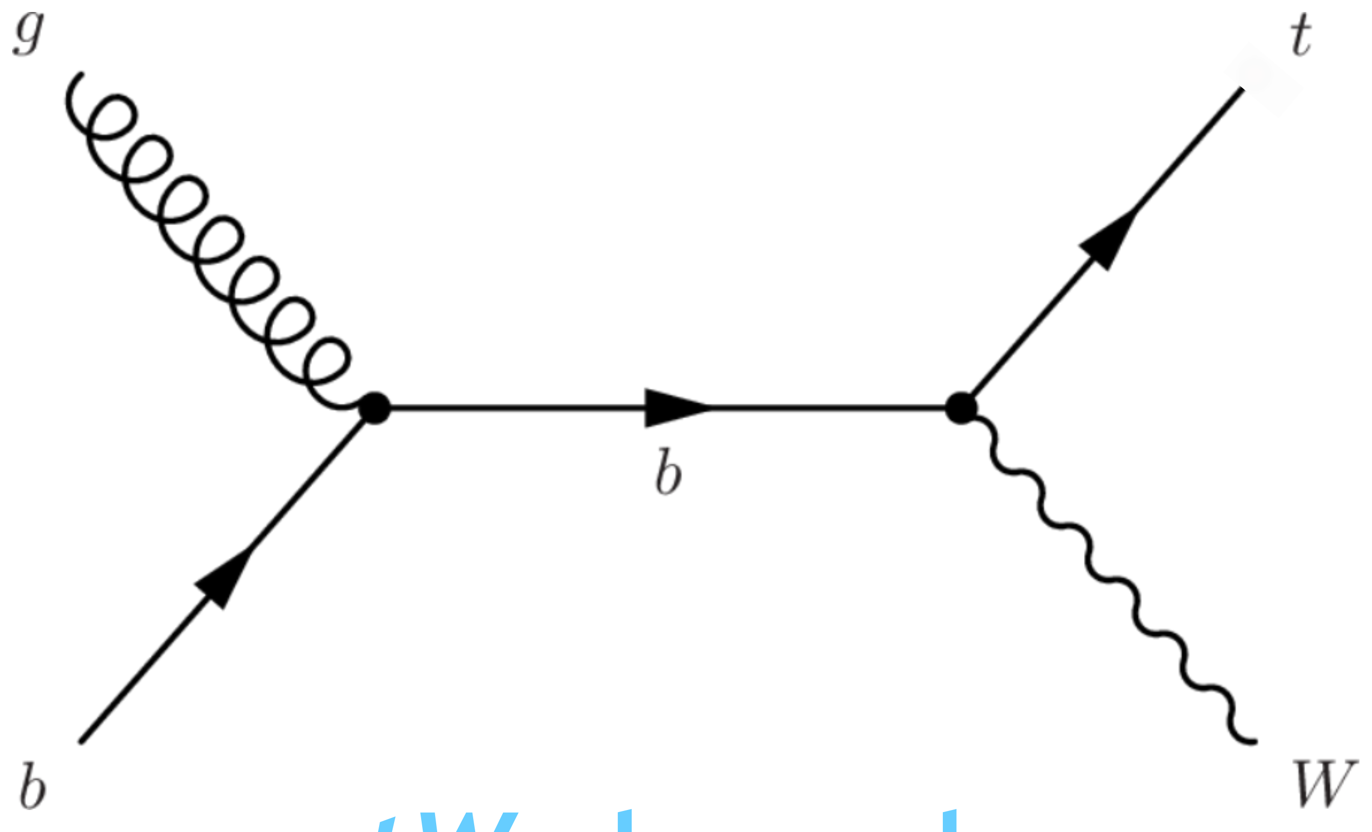
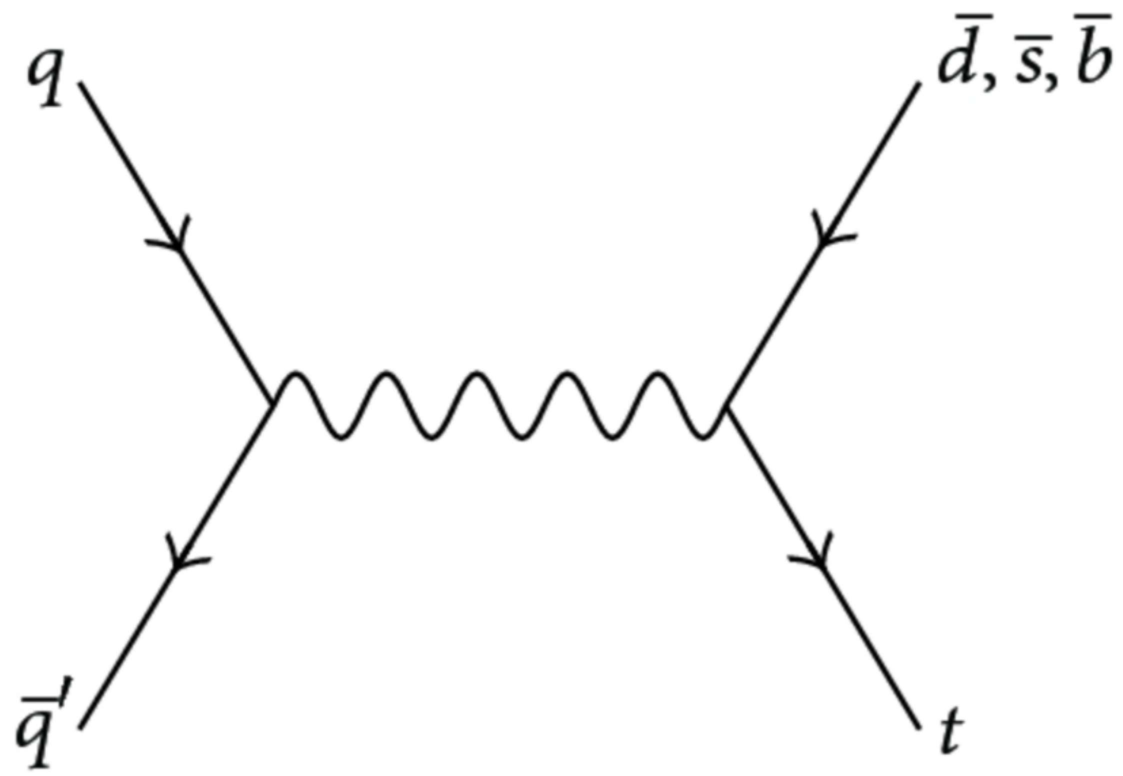


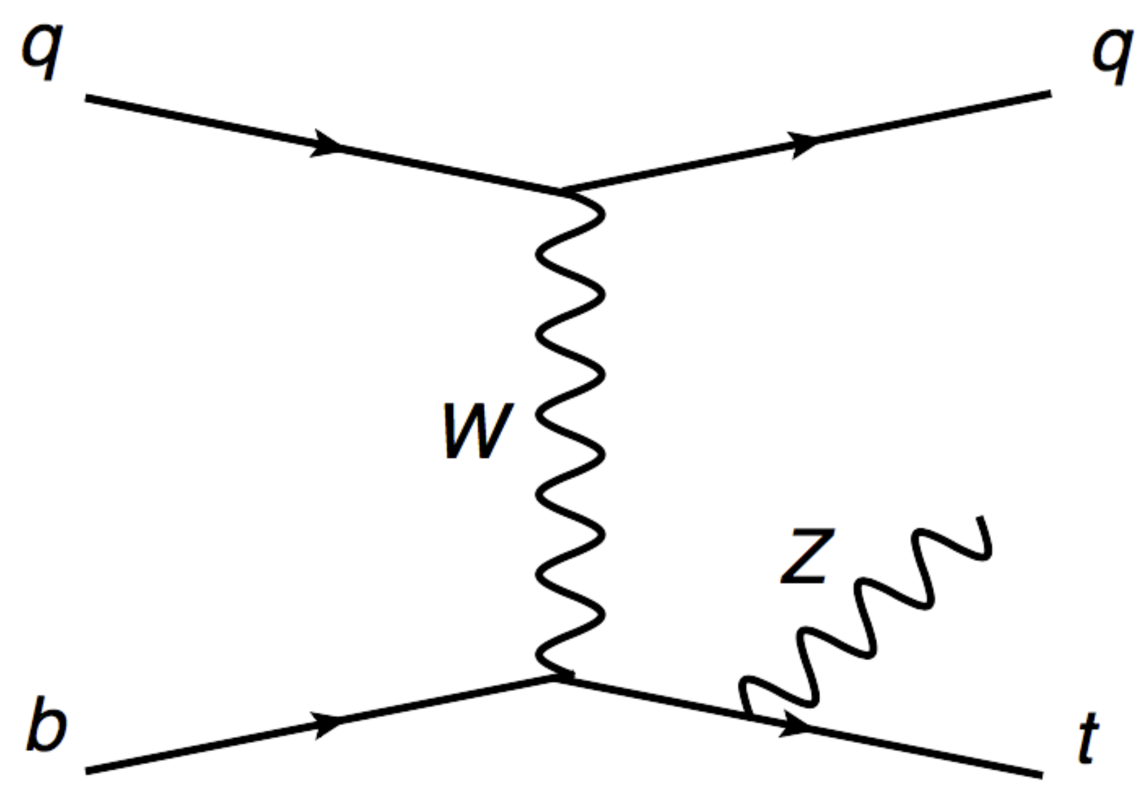
tW-channel

σ(13 TeV) ~ 72 pb



s-channel

σ(13 TeV) ~ 10 pb



tZq

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- Electroweak processes
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- Help tuning MC generators (unfolded distributions)

- t/tW/s-channels observed at LHC
- t-channel differential measured at LHC

This talk:
tZq
tW differential

Data and simulated sample

Data: 2015+2016 25ns dataset corresponding to 36.1 fb^{-1}

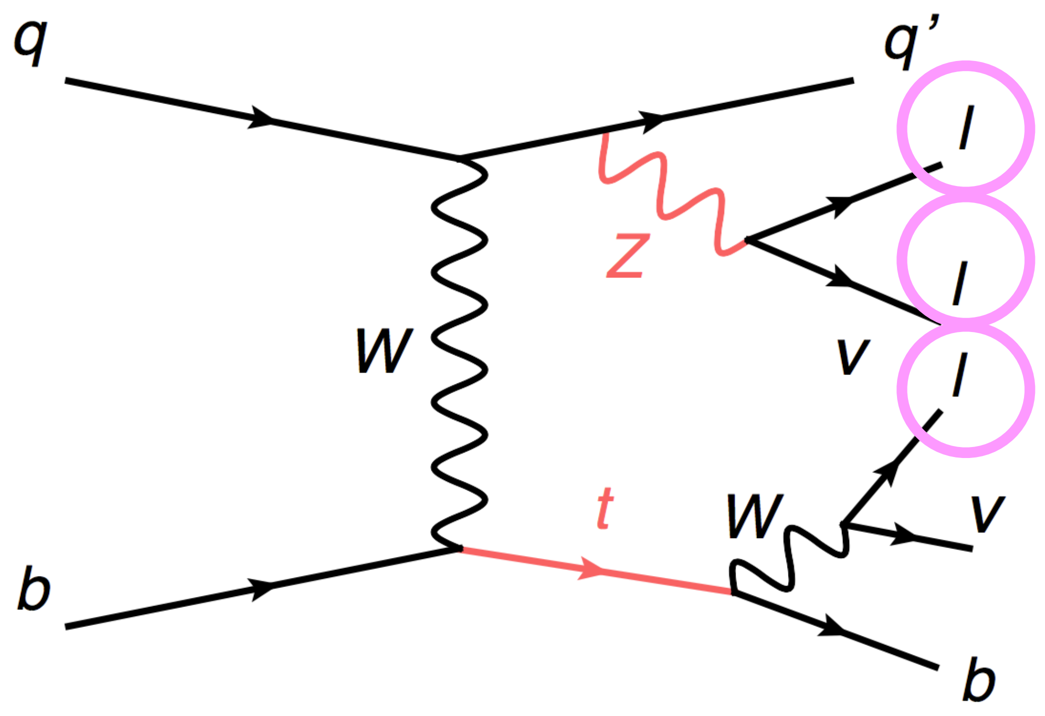
Simulated samples: signal, backgrounds

tW • Nominal (DR): Powheg + Pythia 6 • AFII: aMC@NLO + Herwig++ • AFII: Powheg + Herwig++ • DS: Powheg + Pythia 6	**$t\bar{t}$** • Nominal: Powheg + Pythia 6 • AFII: aMC@NLO + Herwig++ • AFII: Powheg + Herwig++ • radHi/Lo: Powheg + Pythia 6
tZq @LO • MadGraph (5.2.2) in the four-flavour scheme + Pythia6	**Z+jets, diboson** • Sherpa **$t\bar{t}$+ $W/Z/H$** • MadGraph + Pythia8

tZq cross-section measurement

- Important test of SM predictions
  - SM tZq involves both tZ and WWZ couplings, unlikely that $t\bar{t}Z$ only probes tZ
- SM single-top production in association with a Z boson (t-channel) yet unmeasured
  - CMS search on 8 TeV data [JHEP], observed (expected) significance 2.4σ (1.8σ)
- Important background for:
  - FCNC tZ production
  - tH final state
  - Vector-like quarks

- Trilepton final state
  - low branching fraction (2.2%)
  - High s/b ratio

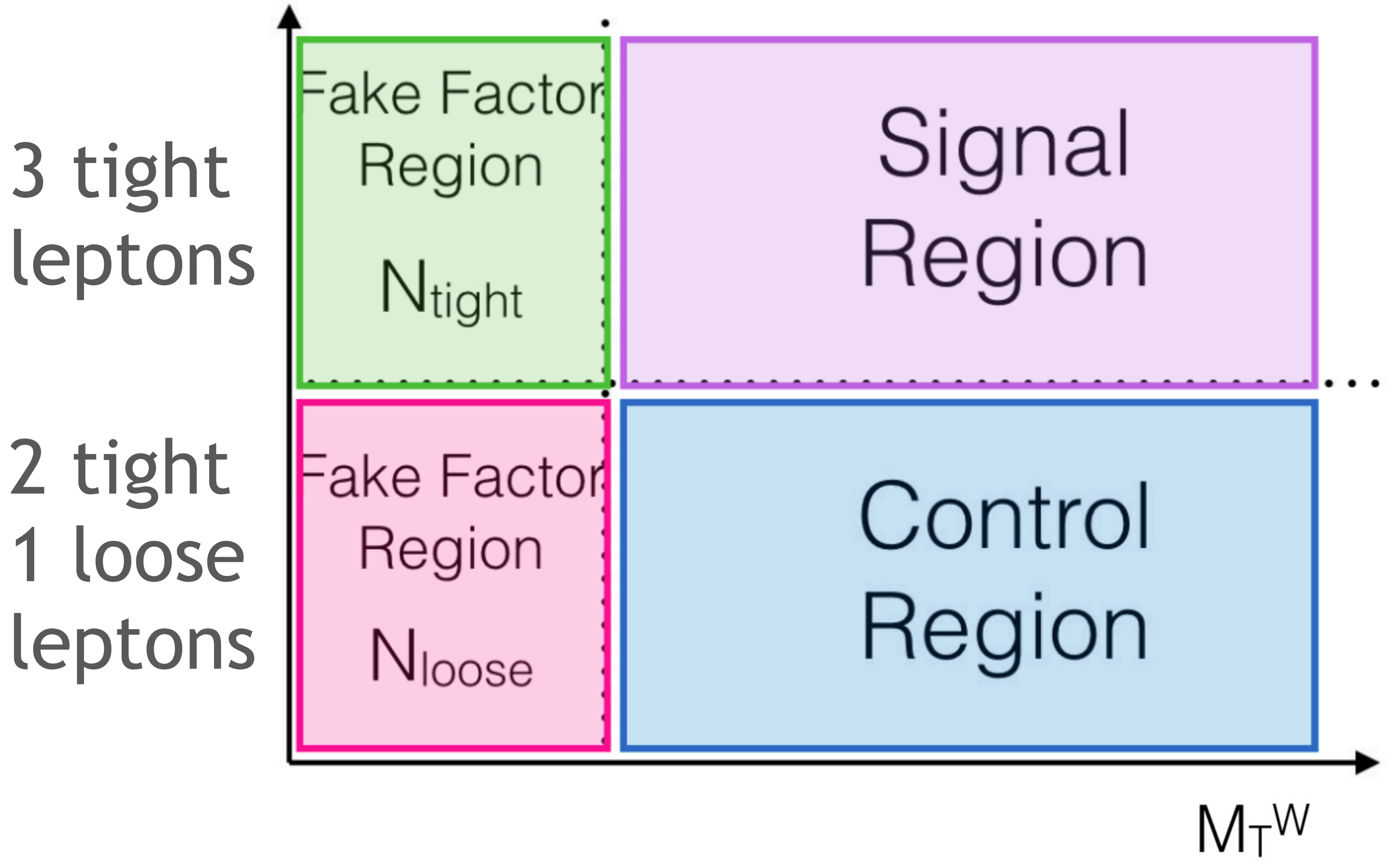


Event selection table

Common selections			
exactly 3 leptons with $\lvert\eta\rvert < 2.5$ and $p_T > 15$ GeV $p_T(\ell_1) > 28$ GeV, $p_T(\ell_2) > 25$ GeV, $p_T(\ell_3) > 15$ GeV $p_T(\text{jet}) > 30$ GeV $m_T(\ell_W, \nu) > 20$ GeV			
SR	**Diboson VR / CR**	**$t\bar{t}$ VR**	**$t\bar{t}$ CR**
≥ 1 OSSF Pair	≥ 1 OSSF Pair	≥ 1 OSSF Pair	≥ 1 OSOF Pair
$\lvert m_{\ell\ell} - m_Z\rvert < 10$ GeV	$\lvert m_{\ell\ell} - m_Z\rvert < 10$ GeV	$\lvert m_{\ell\ell} - m_Z\rvert > 10$ GeV	—
$= 2$ jets, $\lvert\eta\rvert < 4.5$	$= 1$ jet, $\lvert\eta\rvert < 4.5$	$= 2$ jets, $\lvert\eta\rvert < 4.5$	$= 2$ jets, $\lvert\eta\rvert < 4.5$
$= 1$ b-jet, $\lvert\eta\rvert < 2.5$	—	$= 1$ b-jet, $\lvert\eta\rvert < 2.5$	$= 1$ b-jet, $\lvert\eta\rvert < 2.5$
—	VR/CR: $m_T(\ell_W, \nu) > 20/60$ GeV	—	—

Backgrounds estimation

- Diboson (dominant)
  - Scale factor of normalisation derived from diboson CR
  - Systematics taken by varying the $m_T(W)$ cut in diboson CR, and compare SHERPA and POWEG
  - Scale factor = 1.47 ± 0.44
- $t\bar{t}$ (non-prompt or fake leptons)
  - Scale factor of normalisation derived from $t\bar{t}$ CR
  - Systematics taken by varying the m_{ll} cut in $t\bar{t}$ CR, as well as statistical uncertainty in CR
  - Scale factor = 1.21 ± 0.51
- Z+jets (non-prompt or fake leptons)
  - Data-driven method
  - w.r.t. $p_T(l_W)$ of the lepton not associated to the Z boson and lepton flavour
- Others are small



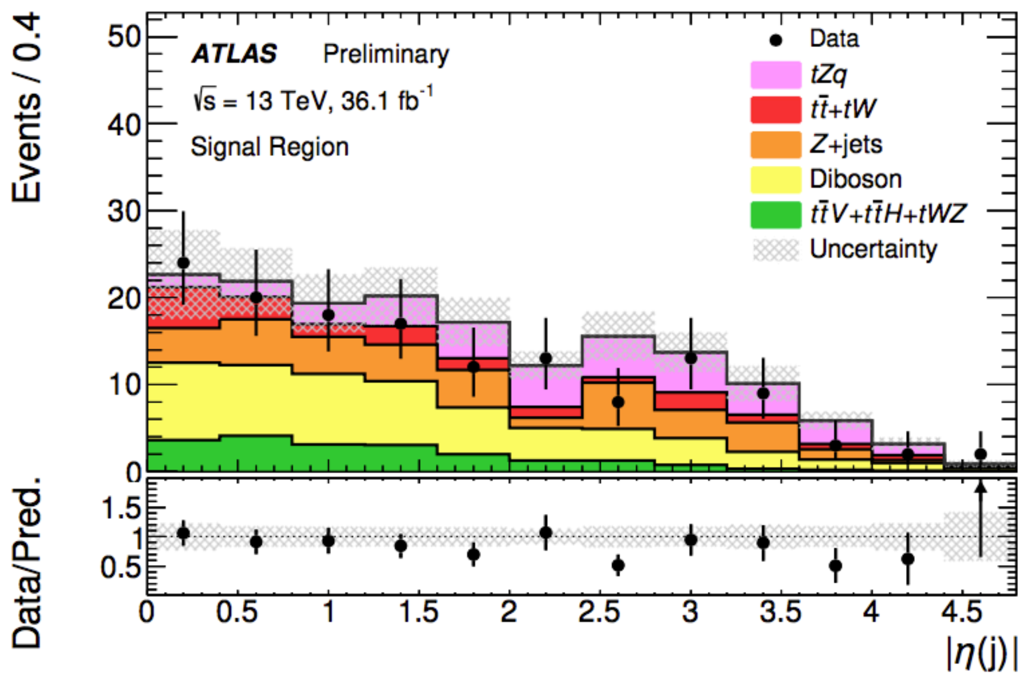
$$F = \frac{N^{FF}_{tight}}{N^{FF}_{loose}}$$

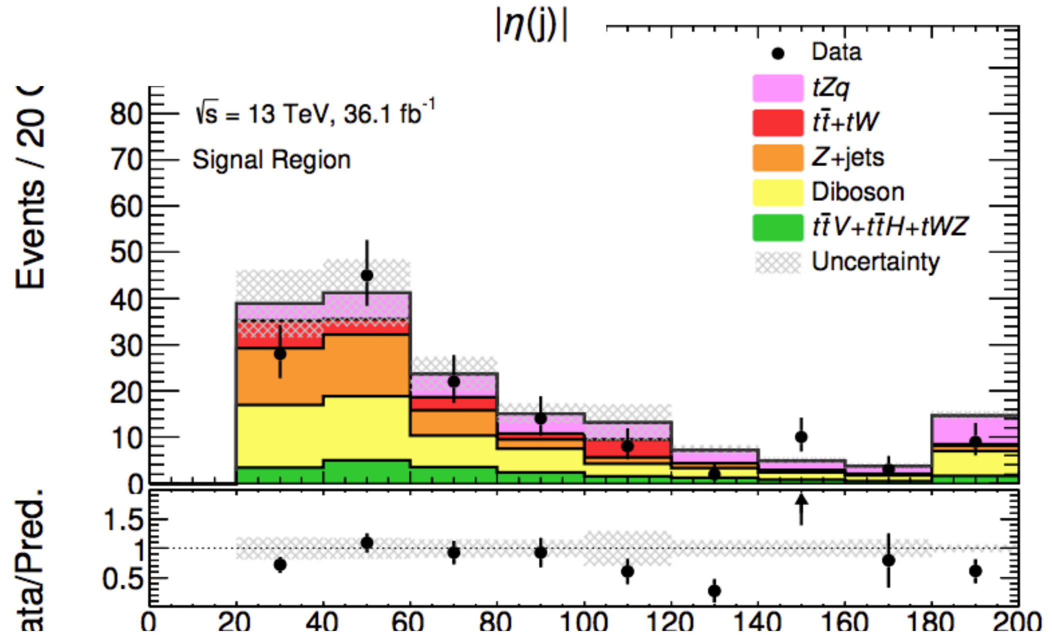
$$F \times N^{CR}_{loose} = N^{SR}$$

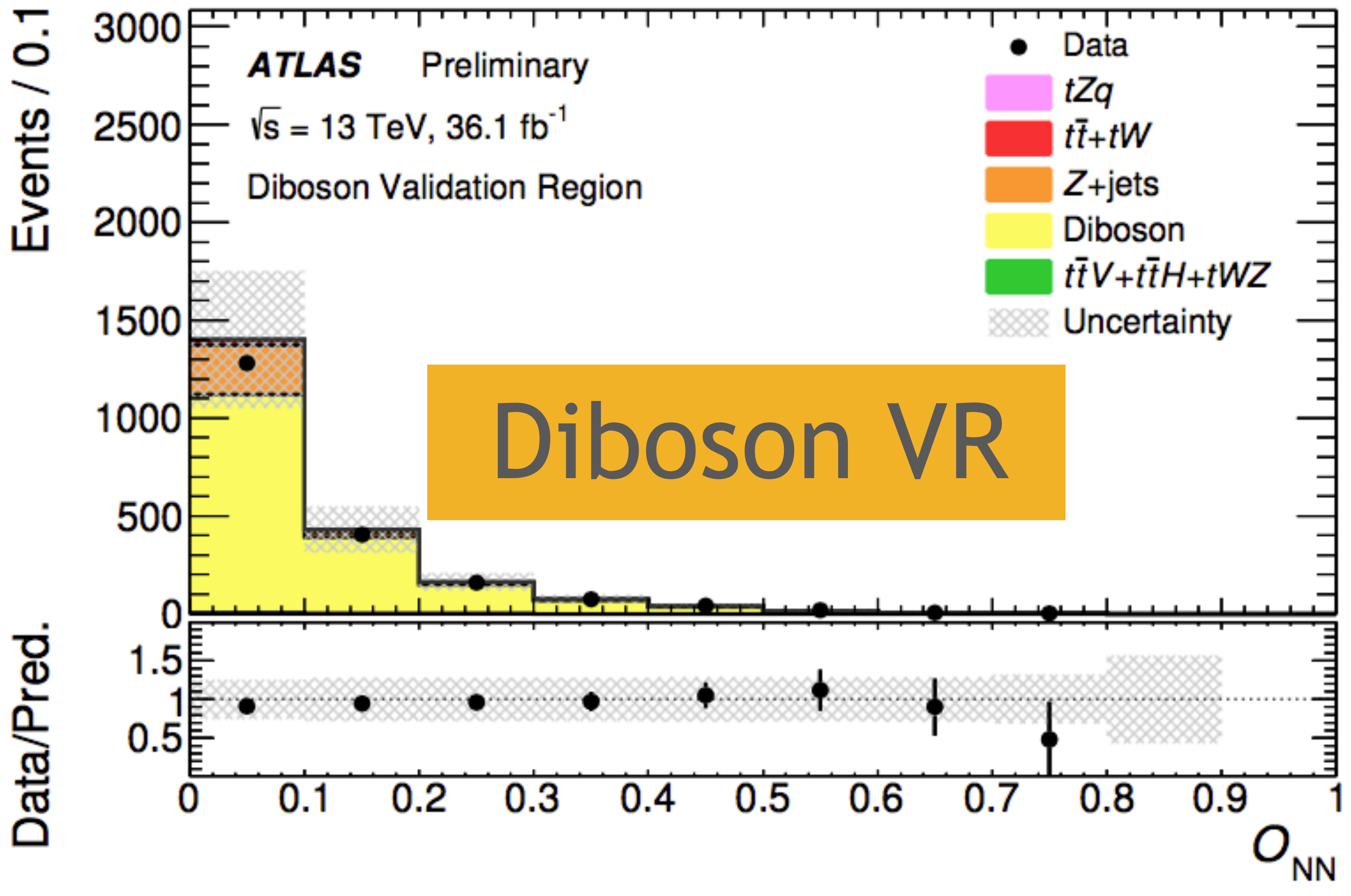
Multivariate analysis

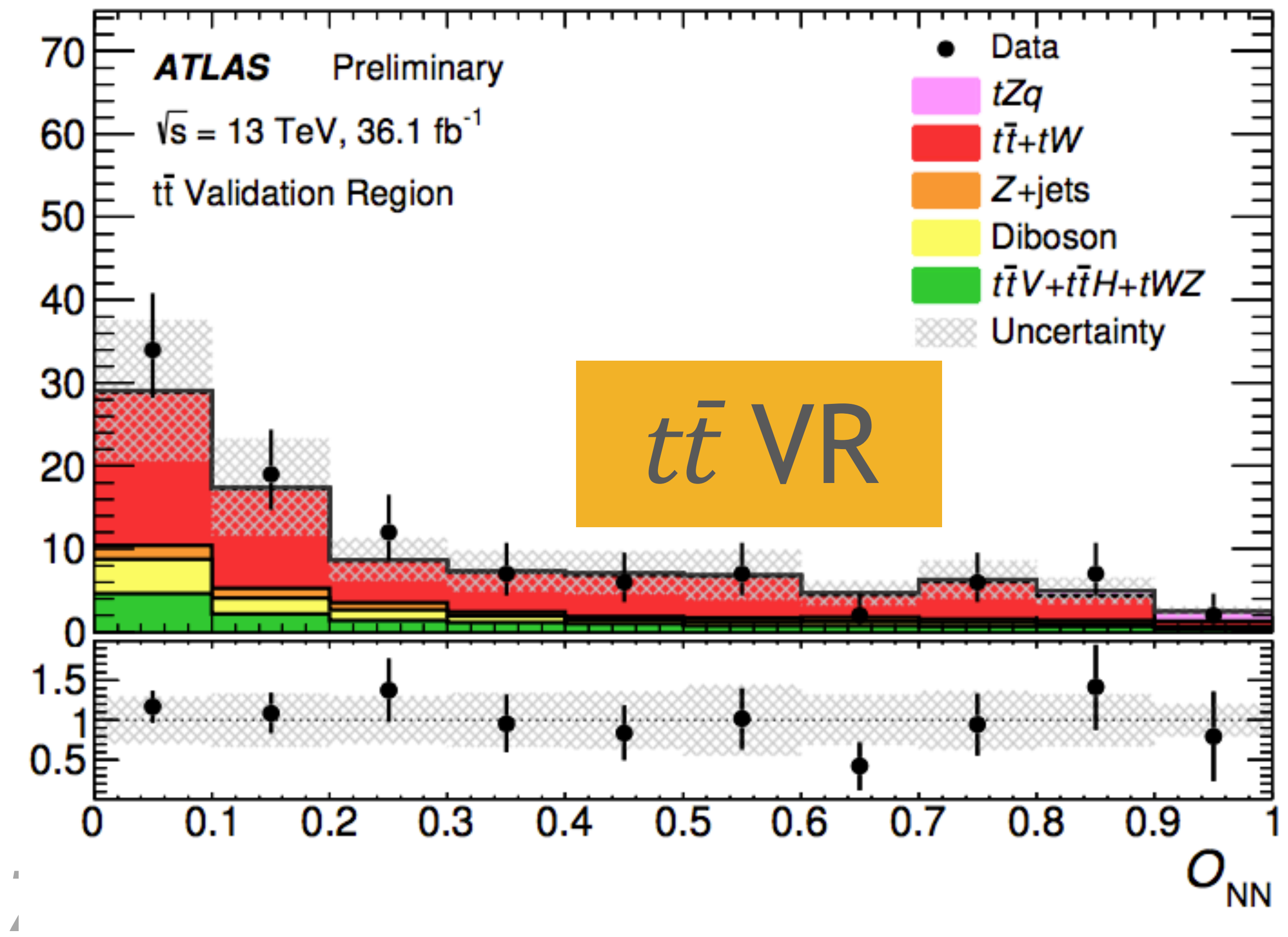
- Neural network (NN) used to separate signal from background
- Signal trained against all backgrounds (except $t\bar{t}$, tW and tWZ)
- 10 variables kept for training
- The separation worked very well and the NN description was checked in VRs and in the SR for NN<0.5 before unblinding.

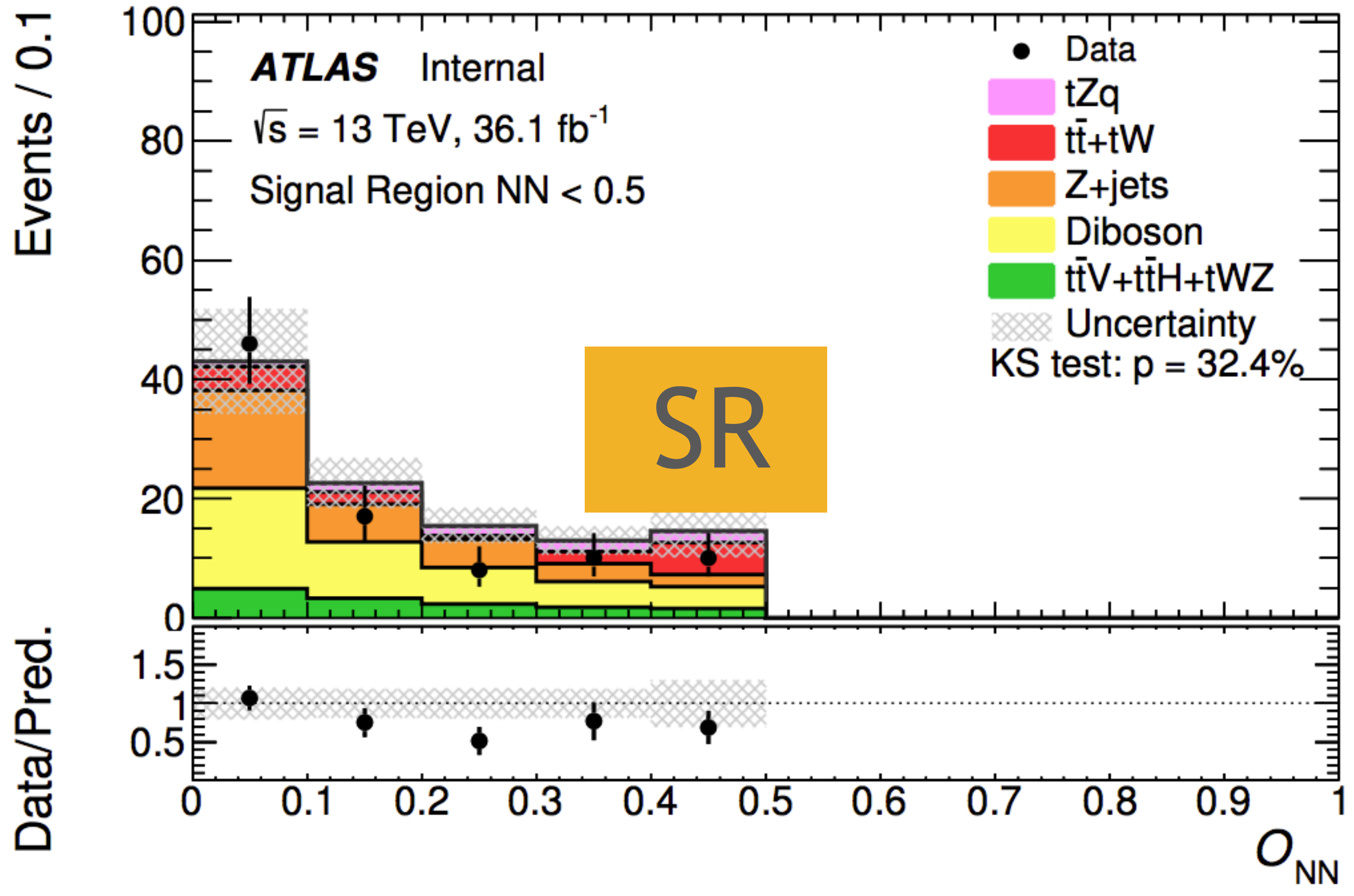
Variable
$\lvert\eta(\mathrm{j})\rvert$
$p_{\mathrm{T}}(\mathrm{j})$
m_t
$p_{\mathrm{T}}(\ell^W)$
$\Delta R(\mathrm{j}, Z)$
$m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}})$
$p_{\mathrm{T}}(t)$
$p_{\mathrm{T}}(b)$
$p_{\mathrm{T}}(Z)$
$\lvert\eta(\ell^W)\rvert$









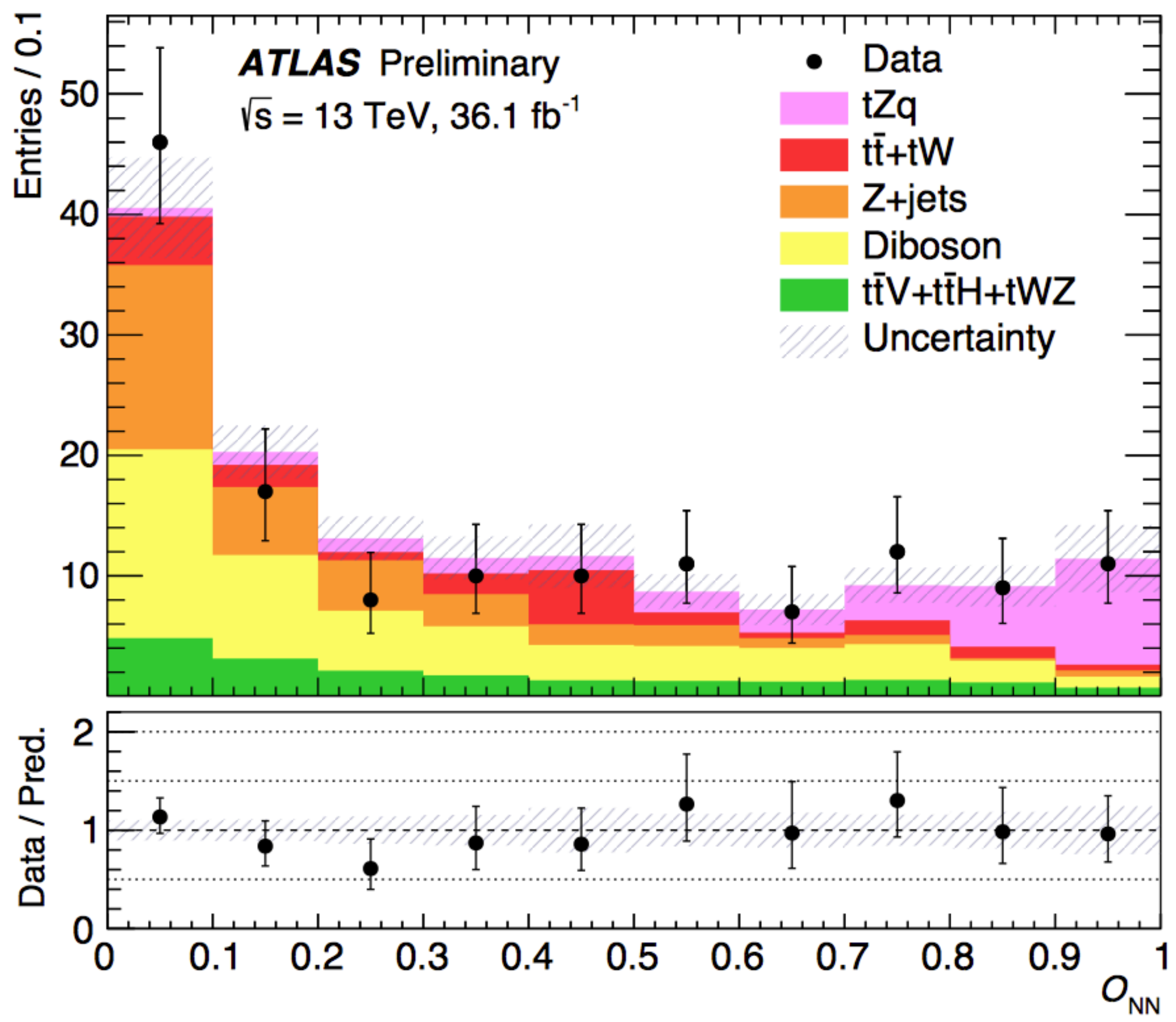


Systematics and results

- Systematics sources
  - Object reconstruction and calibration uncertainties
  - Signal PDF and radiation
  - Backgrounds
  - Luminosity 2.1%
- A likelihood fit performed
  - Clear evidence of single-top production in association with a *Z* boson
  - Signal cross-section extracted to be

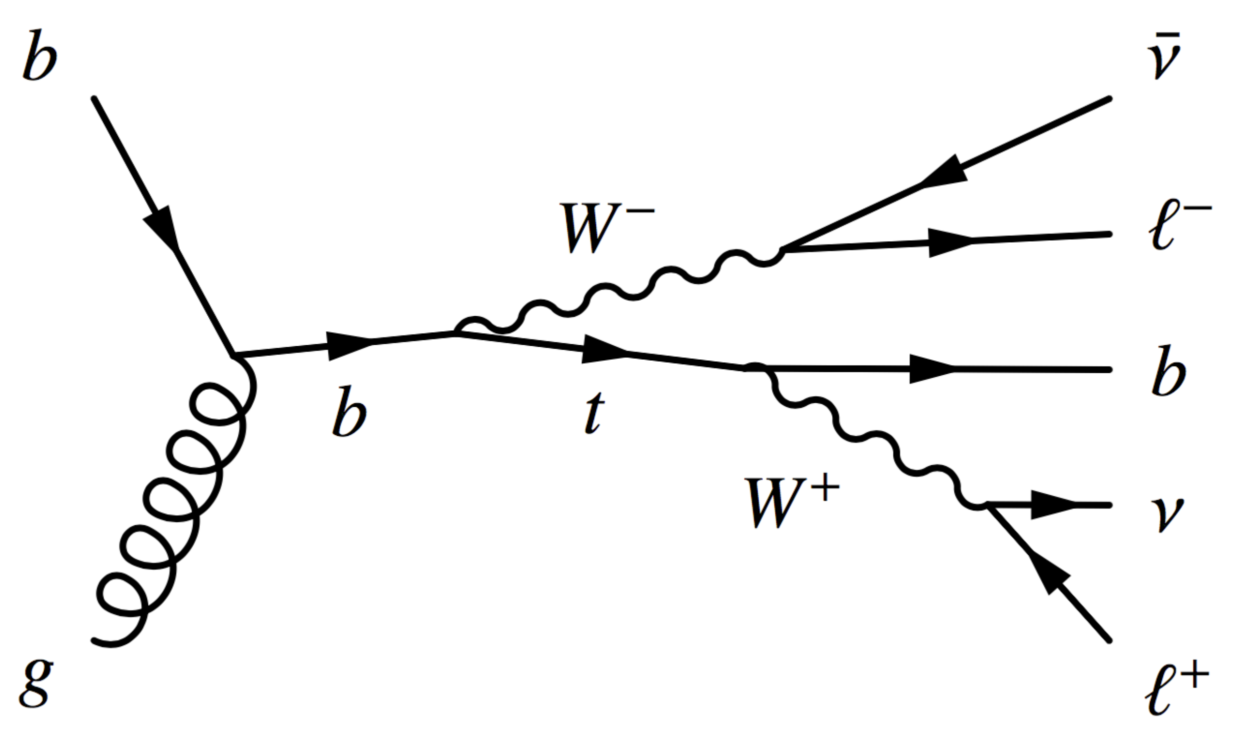
    $600 \pm 170\ (\text{stat.}) \pm 140\ (\text{syst.})\ \text{fb}$
  - corresponding to observed (expected) significance 4.2σ (5.4σ)
- CONF note and the paper is at the PubCom sign-off stage
- FSP Newsflash and Physics Briefing available

Source	Uncertainty [%]
tZq radiation	±10.8
Jets	±4.6
b-tagging	±2.9
MC statistics	±2.8
Luminosity	±2.1
Leptons	±2.1
tZq PDF	±1.2
E_T^{miss}	±0.3



tW differential cross-sections

- First tW differential cross-section measurement
  - Can be done with 36.1fb^{-1} 13 TeV data
  - Di-lepton final state to reduce backgrounds
- Variables to unfold
  - E(llb), mT($ll\nu\nu b$), m(llb): tW system
  - E(b): top-quark production
  - m(l_1b), m(l_2b): top-quark decay



Event selection table

At least one jet with $p_T > 25$ GeV, $\|\eta\| < 2.5$		
Exactly two leptons of opposite charge with $p_T > 20$ GeV,		
$\|\eta\| < 2.5$ for muons and $\|\eta\| < 2.47$ excluding $1.37 < \|\eta\| < 1.52$ for electrons		
At least one lepton with $p_T > 25$ GeV, veto if third lepton with $p_T > 20$ GeV		
At least one lepton matched to the trigger object		
Different flavour	$E_T^{miss} > 50$ GeV,	if $m_{\ell\ell} < 80$ GeV
	$E_T^{miss} > 20$ GeV,	if $m_{\ell\ell} > 80$ GeV
Same flavour	$E_T^{miss} > 40$ GeV,	always
	veto,	if $m_{\ell\ell} < 40$ GeV
	$4E_T^{miss} > 5m_{\ell\ell}$,	if 40 GeV $< m_{\ell\ell} <$ 81 GeV
	veto,	if 81 GeV $< m_{\ell\ell} <$ 101 GeV
	$2m_{\ell\ell} + E_T^{miss} > 300$ GeV,	if $m_{\ell\ell} > 101$ GeV

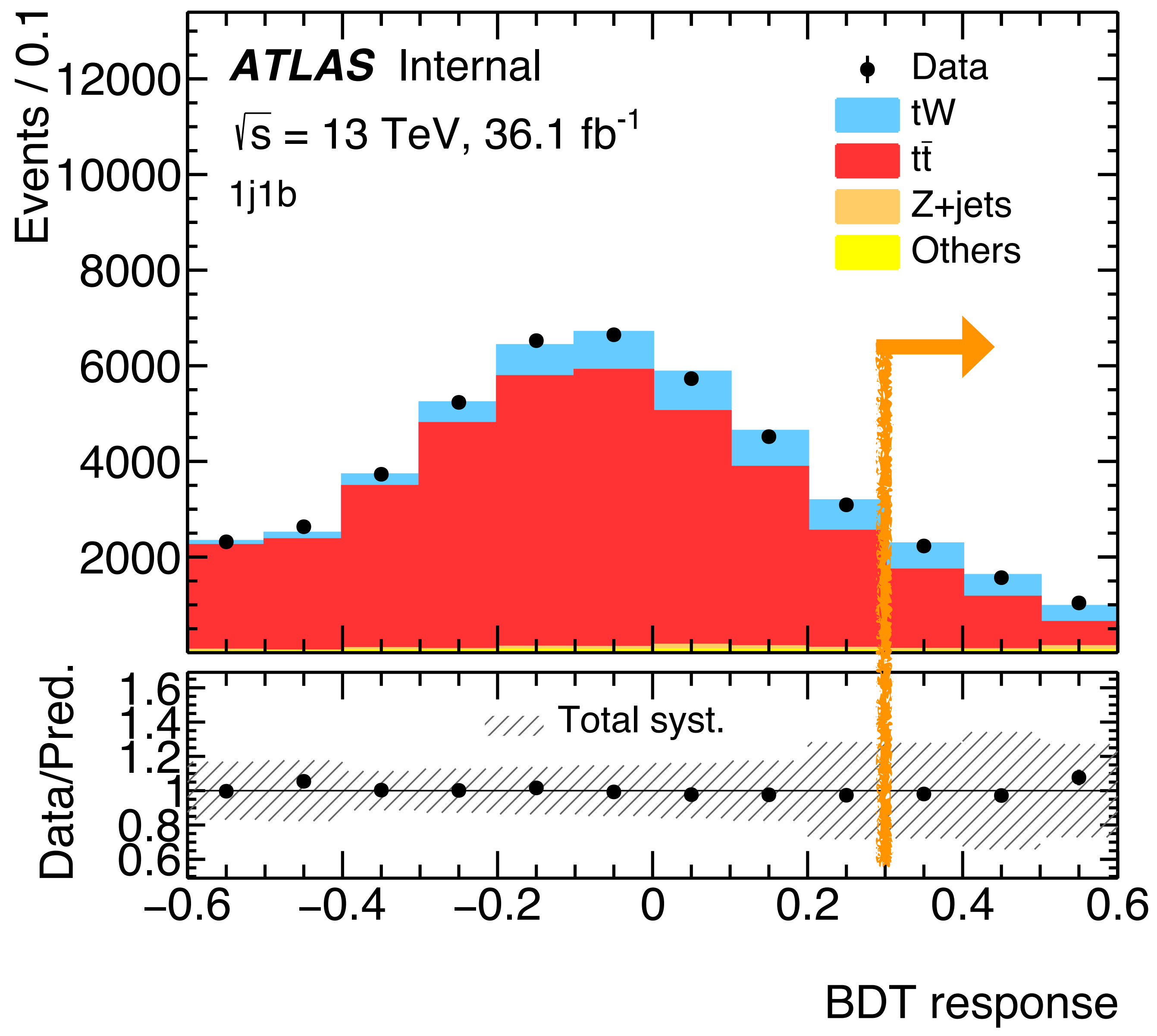
Multivariate analysis

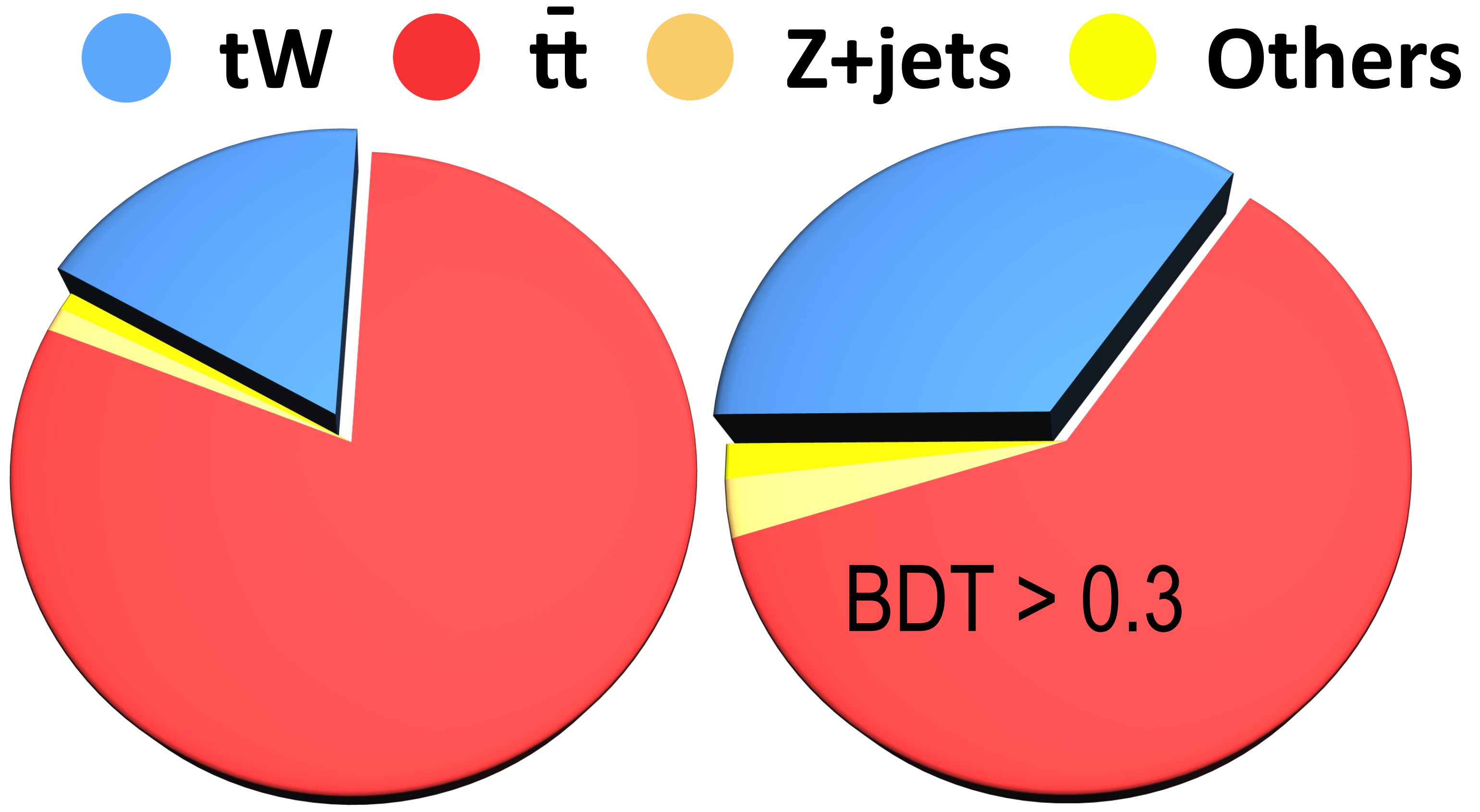
- Gradient BDT provided by TMVA
- Selection of variables
  - Rank variables by separation power:

$$< S^2 >= \frac{1}{2} \int \frac{(Y_S(y) - Y_B(y))^2}{(Y_S(y) + Y_B(y))} dy$$

  - Keep only one variable if several are correlated (>0.8)
  - Find combinations that give highest $<S^2>$
  - Use the set of fewer variables that give similar $<S^2>$
- Enrich signal by requiring BDT > 0.3

Variable	$S\ [10^{-2}]$
$p_T^{sys}(\ell_1\ell_2E_T^{miss}b)$	4.1
$\Delta p_T(\ell_1\ell_2b, E_T^{miss})$	2.5
$\sum E_T$	2.3
$\eta(\ell_1\ell_2E_T^{miss}b)$	1.3
$\Delta p_T(\ell_1\ell_2, E_T^{miss})$	1.1
$p_T^{sys}(\ell_1\ell_2b)$	1.0
$C(\ell_1\ell_2)$	0.9
$m(\ell_2, b)$	0.2
$m(\ell_1, b)$	0.1
BDT response	8.1





Unfolding and cross-section determination

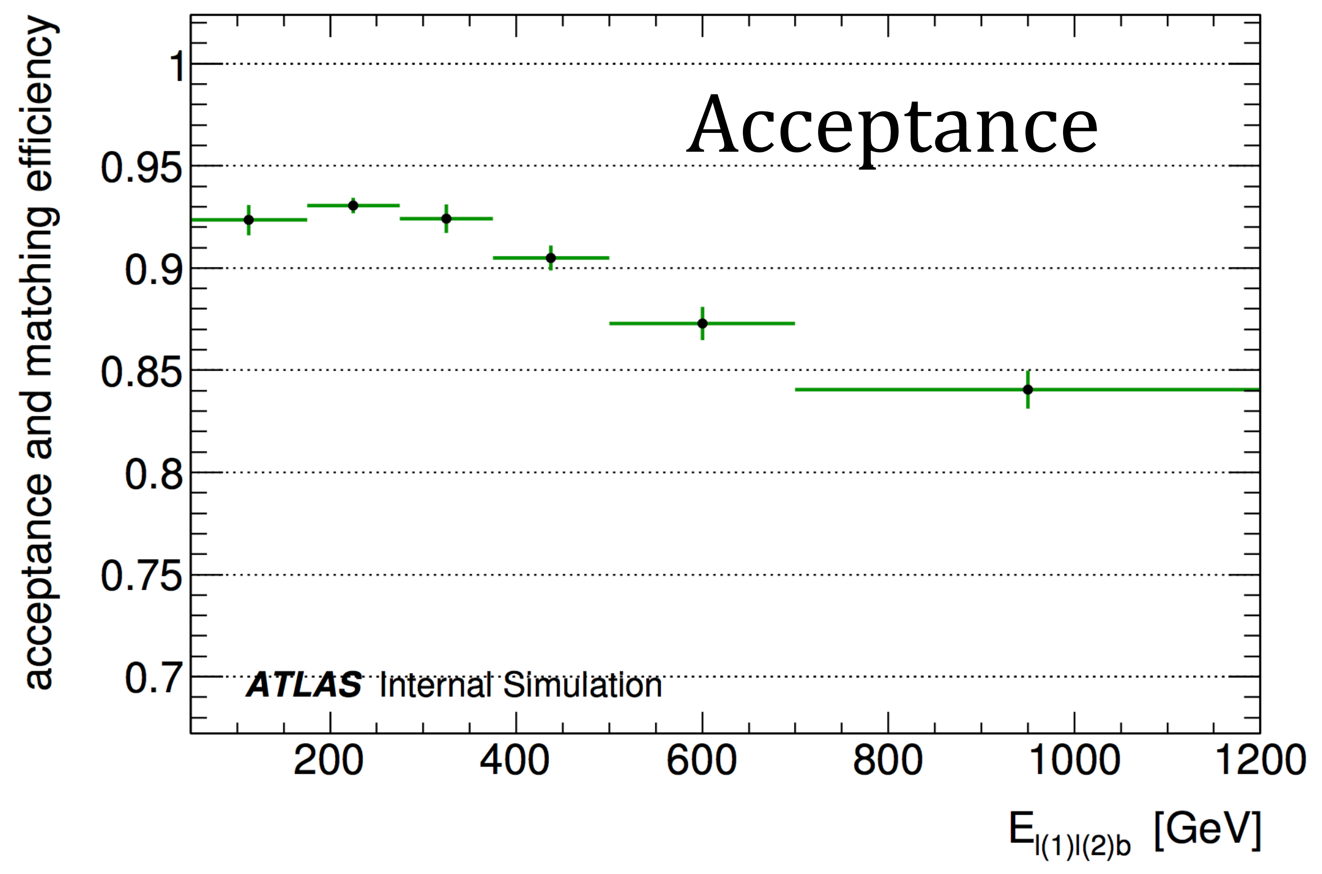
- Iterative Bayesian unfolding technique of D'Agostini implemented in RooUnfold

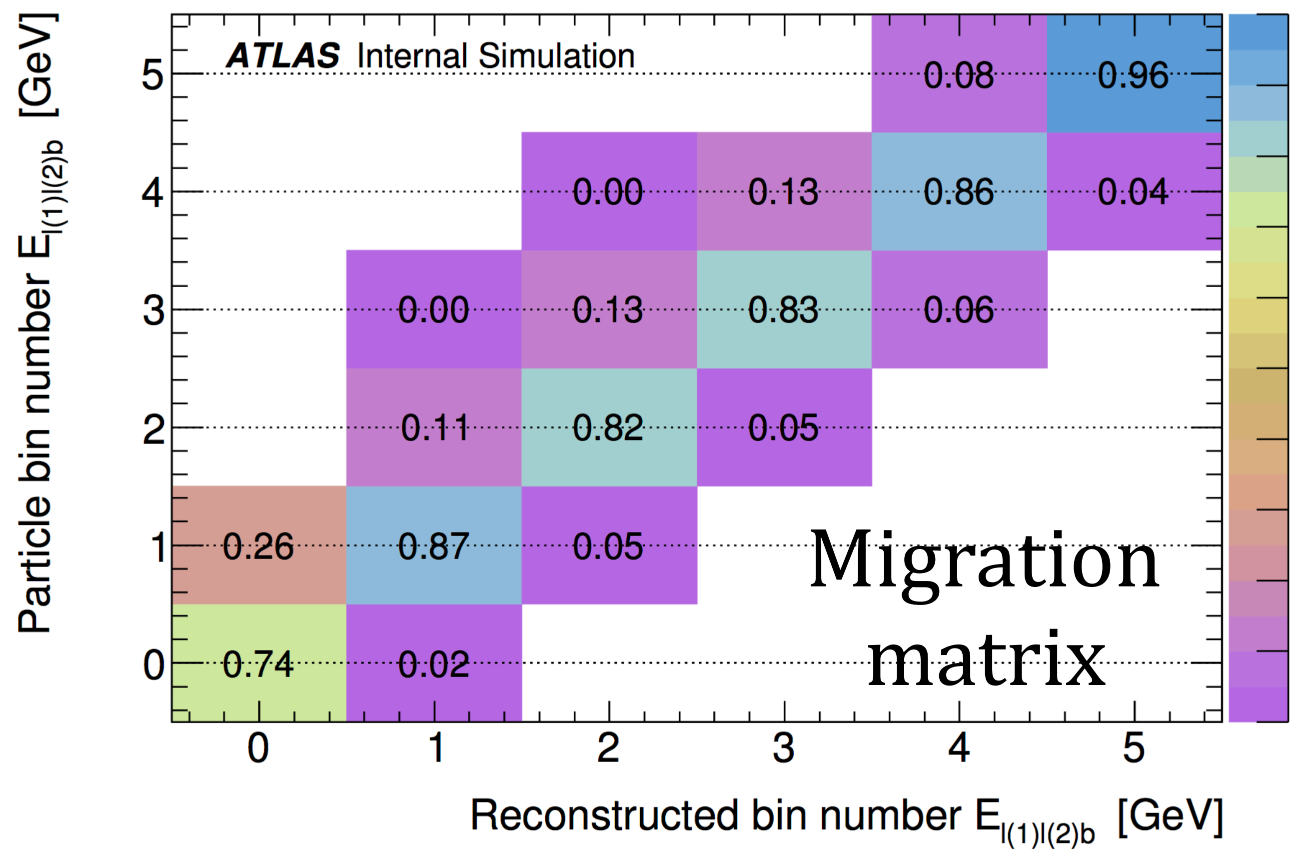
$$N_i^{\mathrm{ufd}} = \frac{1}{C_i^{\mathrm{eff}}} \sum_j M_{ij}^{-1} C_j^{\mathrm{oof}} (N_j^{\mathrm{data}} - B_j)$$

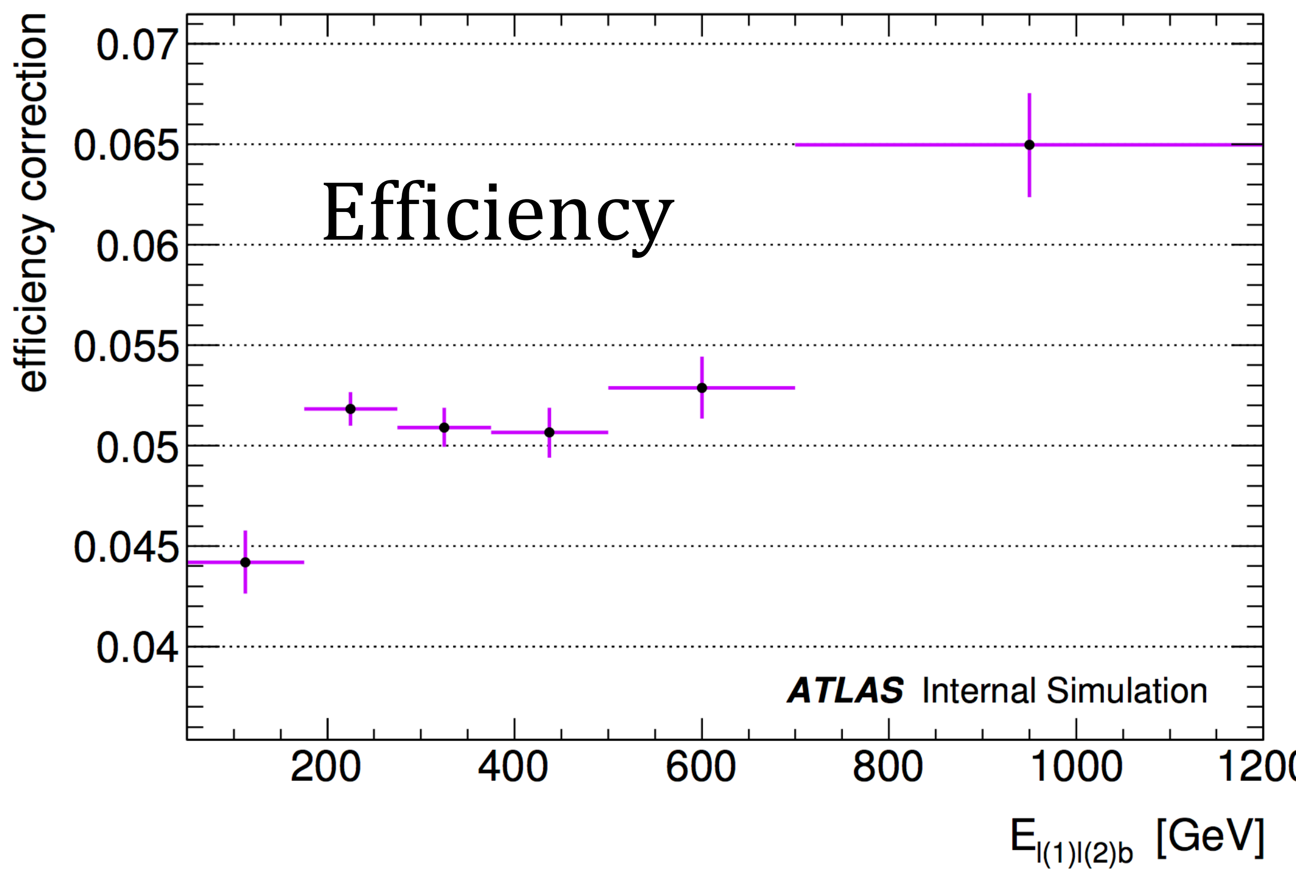
  - Corrections for detector acceptance (out-of-fiducial), resolution (migration matrix) and efficiency
- Binning is determined so that more than ~60% events in diagonal and ~20% stat. unc. in each bin
- Cross-section calculation

$$\frac{\mathrm{d}\sigma_i}{\mathrm{d}X} = \frac{N_i^{\mathrm{ufd}}}{L\Delta_i}$$

$$\sigma^{\mathrm{fid}} = \sum_i \left(\frac{\mathrm{d}\sigma_i}{\mathrm{d}X} \cdot \Delta_i\right) = \sum_i \frac{N_i^{\mathrm{ufd}}}{L}$$

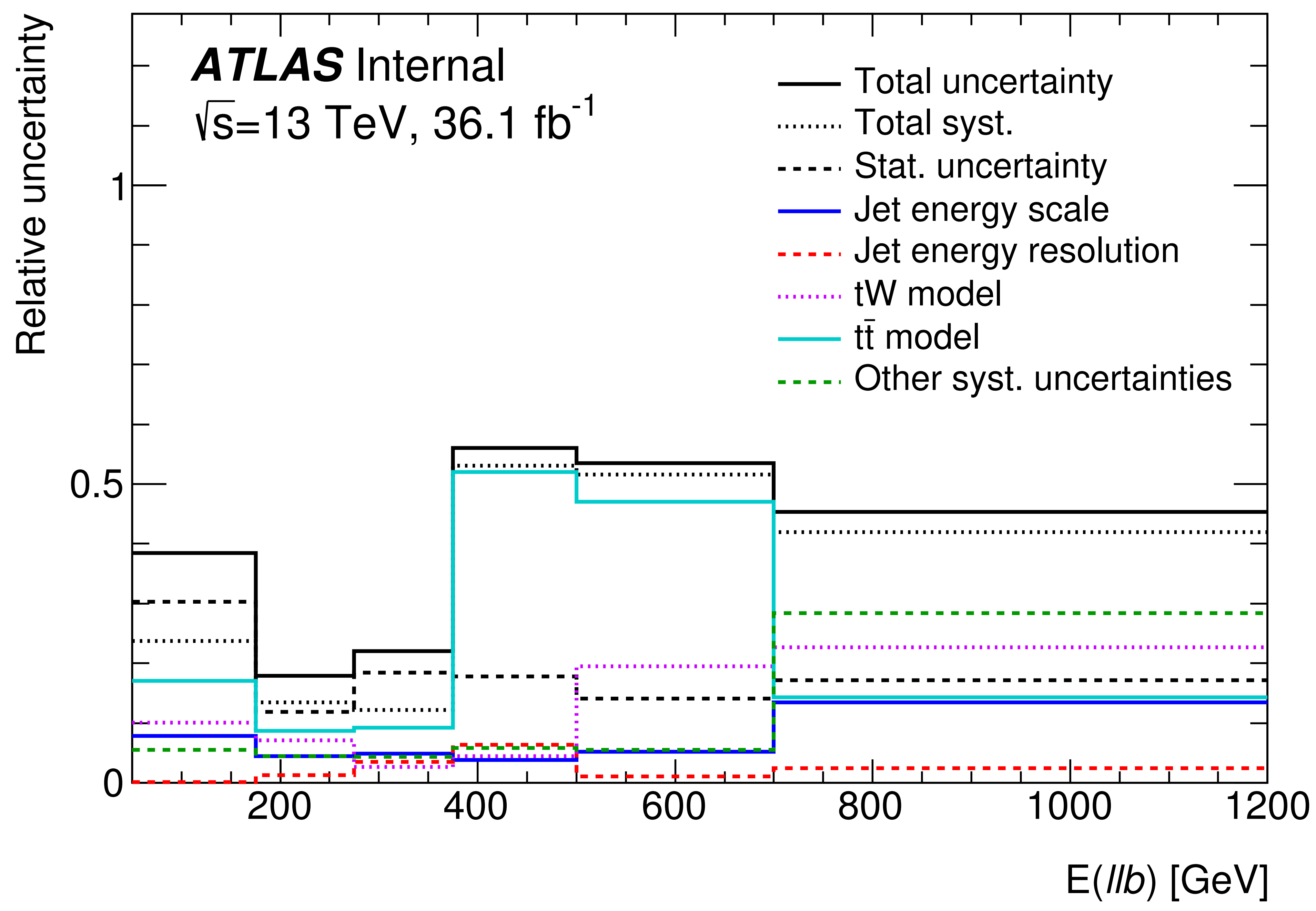


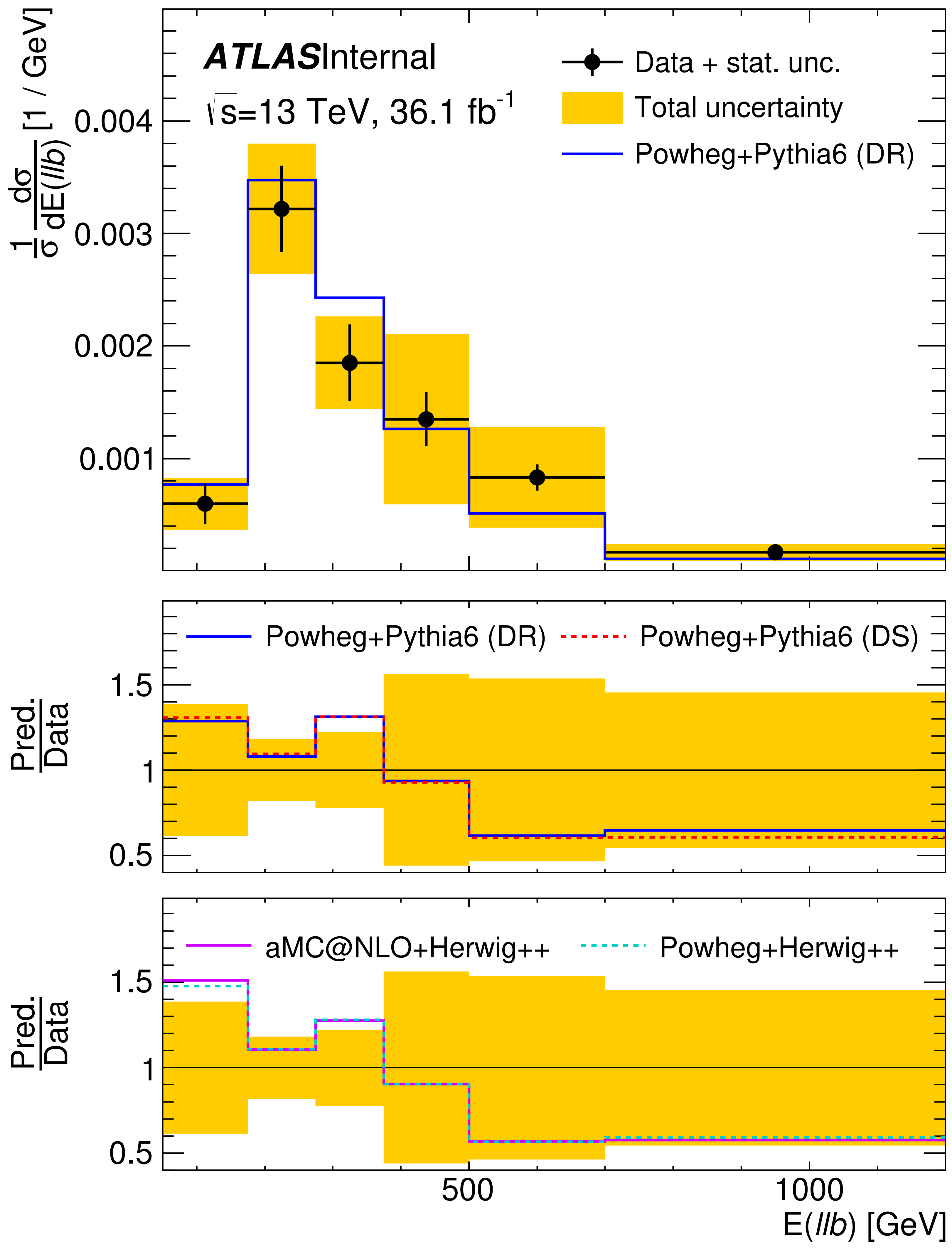




Systematics and results

- Systematics sources
  - Object reconstruction and calibration uncertainties
  - Signal and $t\bar{t}$ modelling
  - Background normalisations
  - Non-closure on stress test
  - Luminosity 2.1%





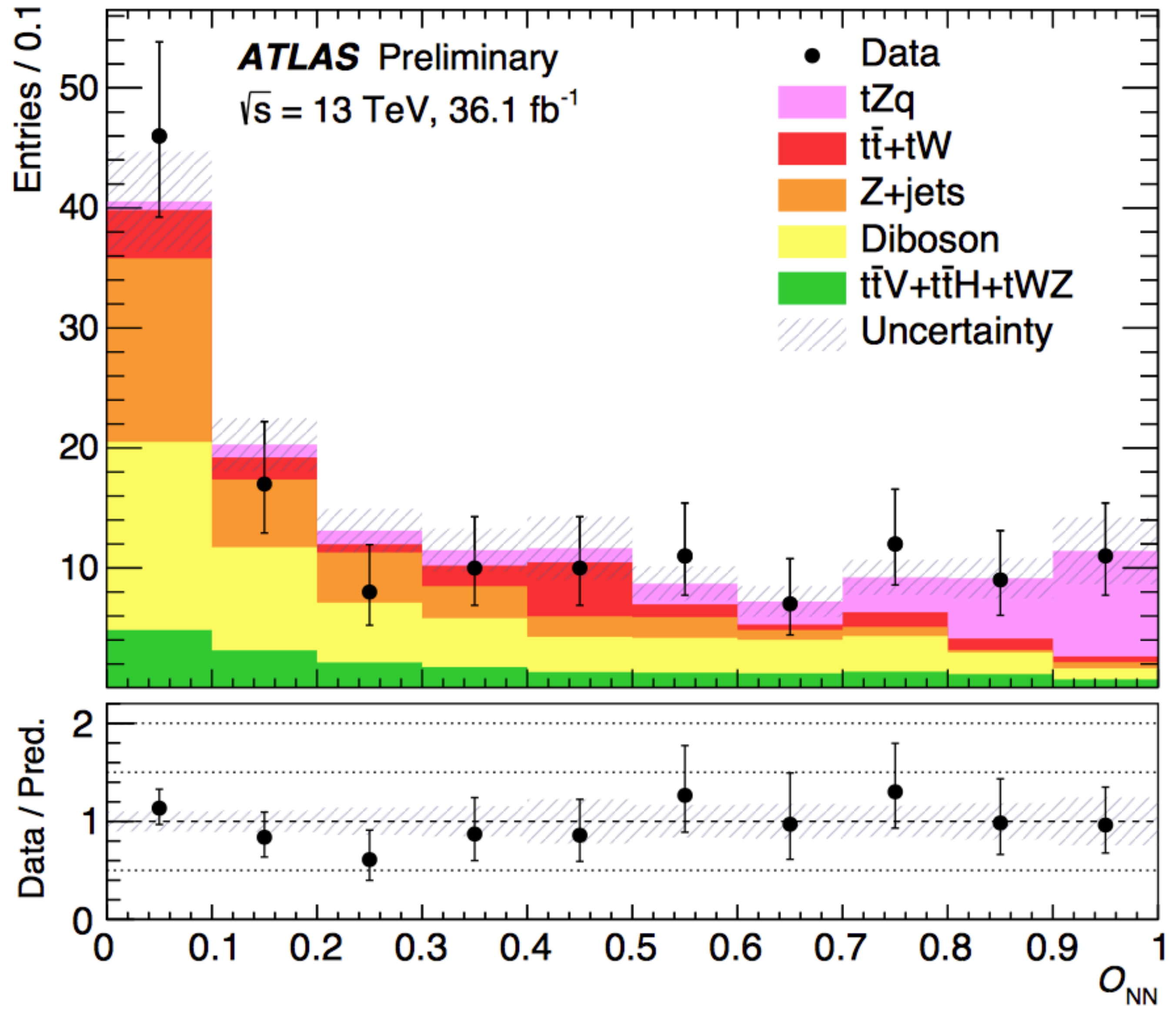
Discussions

- In general most MC models show fair agreement with data
  - Many variables show a negative slope in Pred./Data, indicating softer final objects in MC
  - Powheg-Box +Herwig++ deviates more from the data and from the other predictions in certain bins of the E(llb), m(l_1b) and m(llb) distributions
  - DR is systematically closer to the data than DS for several variables
  - No significant difference between ISR/FSR is seen
- Public Reading today (Wednesday) and release plots for Top 2017.

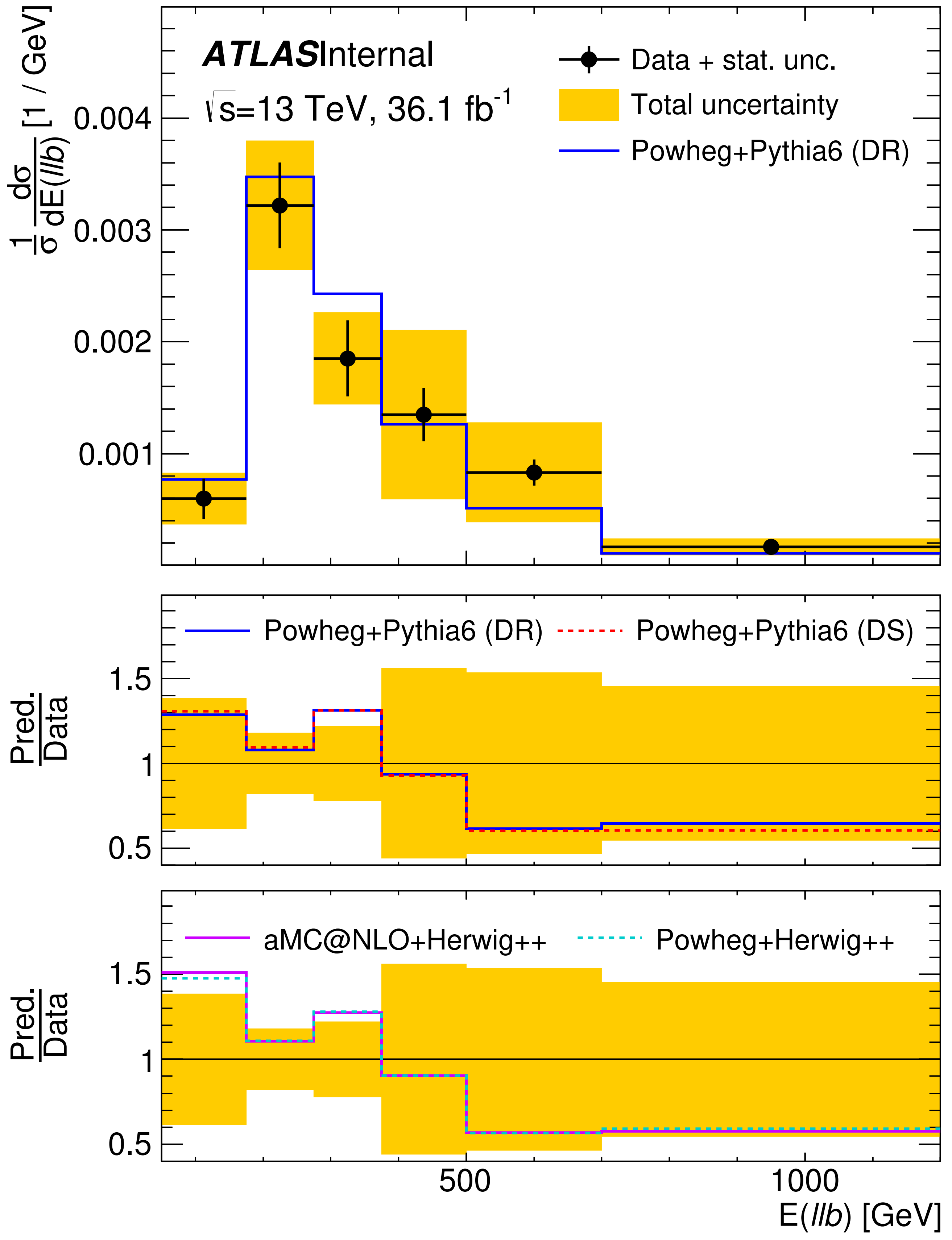
Observable	$E(b)$		$E(\ell\ell b)$		$m_T(\ell\ell\nu\nu b)$		$m(\ell_1 b)$		$m(\ell\ell b)$		$m(\ell_2 b)$	
Prediction	χ^2	p	χ^2	p	χ^2	p	χ^2	p	χ^2	p	χ^2	p
Powheg+Pythia6 (DR)	4.8	0.31	8.1	0.15	2.0	0.56	5.7	0.34	4.0	0.55	2.6	0.45
Powheg+Pythia6 (DS)	5.0	0.29	9.1	0.11	2.4	0.49	6.1	0.30	4.4	0.50	2.6	0.46
aMC@NLO+Herwig++	5.6	0.23	8.7	0.12	1.8	0.61	5.4	0.37	3.6	0.61	2.4	0.49
Powheg+Herwig++	6.2	0.18	11.0	0.05	2.0	0.57	8.1	0.15	5.2	0.40	2.3	0.52
Powheg+Pythia6 radHi	4.8	0.30	7.9	0.16	1.9	0.60	5.3	0.38	3.7	0.60	2.5	0.48
Powheg+Pythia6 radLo	5.0	0.29	8.4	0.14	2.1	0.56	5.8	0.33	4.0	0.55	2.6	0.45

Conclusion

- A clear evidence of single-top production in association with a *Z* boson



- Normalised differential cross-sections for the tW channel are measured for several variables



Thank you!

Backup

tZq cross-section measurement

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  - CMS search on 8 TeV data [JHEP], observed (expected) significance 2.4σ (1.8σ)
- Important test of SM predictions
  - SM tZq involves both tZ and WWZ couplings
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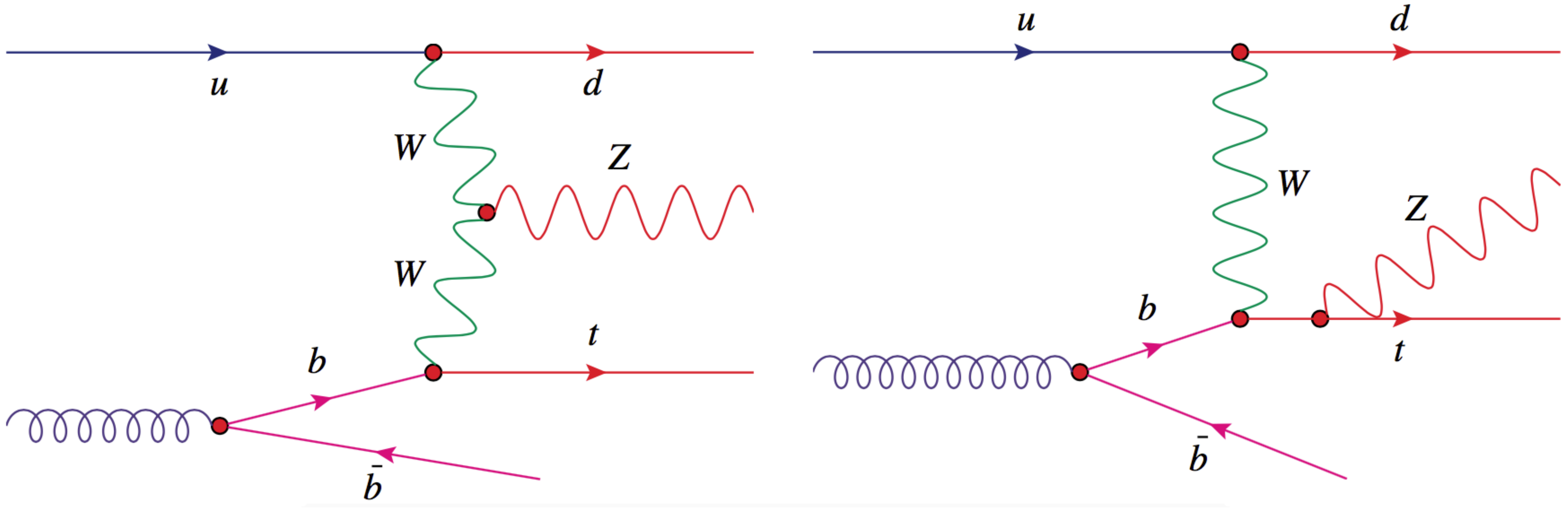

Event selection

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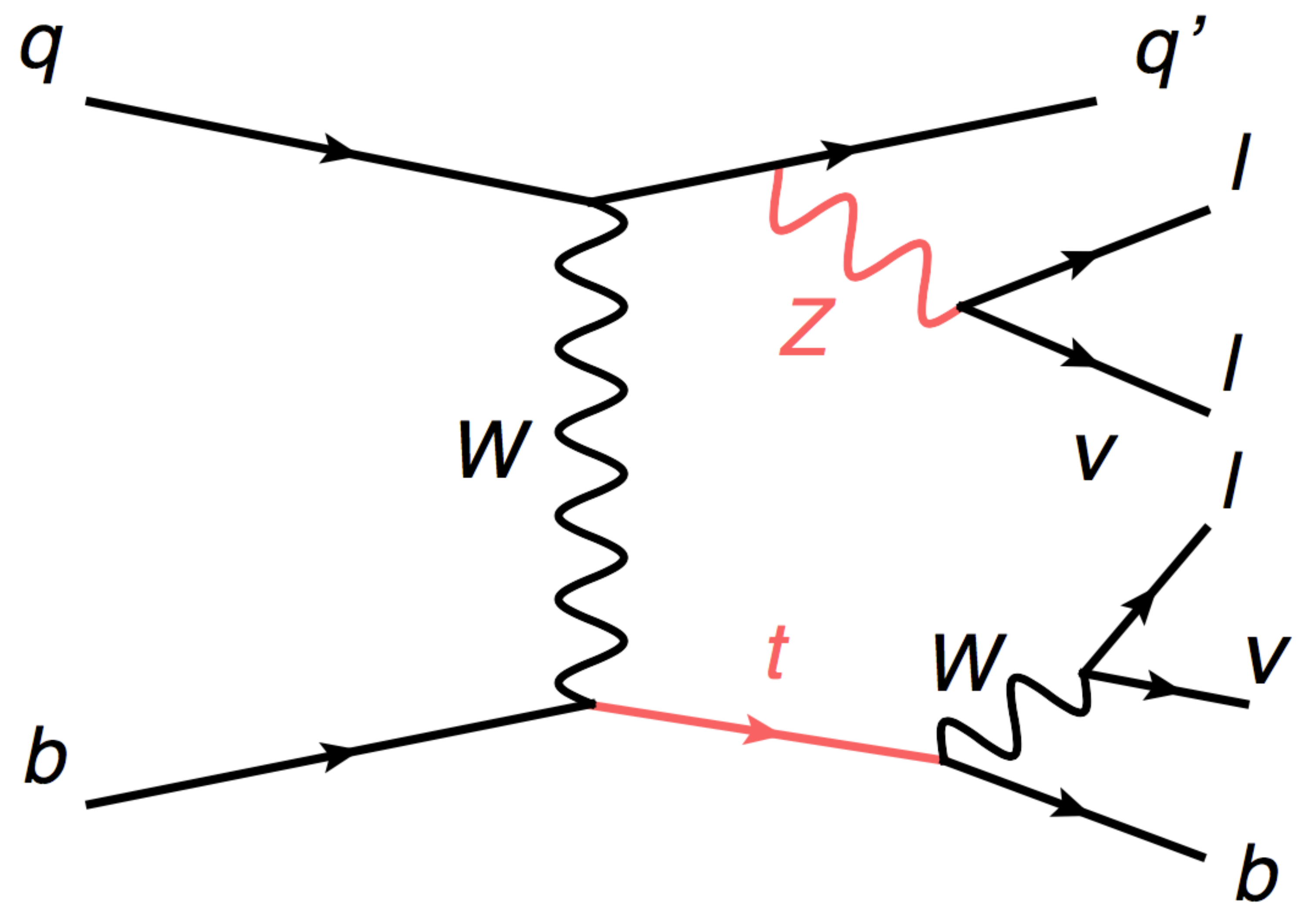
SR	Diboson VR / CR	$t\bar{t}$ VR	$t\bar{t}$ CR
≥ 1 OSSF Pair	≥ 1 OSSF Pair	≥ 1 OSSF Pair	≥ 1 OSOF Pair
$\|m_{\ell\ell} - m_Z\| < 10$ GeV	$\|m_{\ell\ell} - m_Z\| < 10$ GeV	$\|m_{\ell\ell} - m_Z\| > 10$ GeV	—
= 2 jets, $\|\eta\| < 4.5$	= 1 jet, $\|\eta\| < 4.5$	= 2 jets, $\|\eta\| < 4.5$	= 2 jets, $\|\eta\| < 4.5$
= 1 b-jet, $\|\eta\| < 2.5$	—	= 1 b-jet, $\|\eta\| < 2.5$	= 1 b-jet, $\|\eta\| < 2.5$
—	VR/CR: $m_T(\ell_W, \nu) > 20/60$ GeV	—	—



Process	Raw events	Scaled events
$t\bar{t}V + t\bar{t}H + tWZ$	9 311	19.9 ± 0.4
Diboson	2 456	52.7 ± 15.9
Z + jets	275	36.9 ± 15.1
$t\bar{t} + tW$	44	18.1 ± 8.6
tZq	3 438	35.2 ± 0.7
Total expected	15 524	162.7 ± 23.5
Data	141	141

Process	Raw events	Scaled events
$t\bar{t}V + t\bar{t}H + tWZ$	4 448	9.9 ± 0.3
Diboson	64 082	1 778.9 ± 533.8
Z + jets	1 792	290.8 ± 116.6
$t\bar{t} + tW$	119	36.5 ± 15.8
tZq	1 760	17.7 ± 0.5
Total expected	72 201	2 133.7 ± 546.6
Data	1 984	1 984

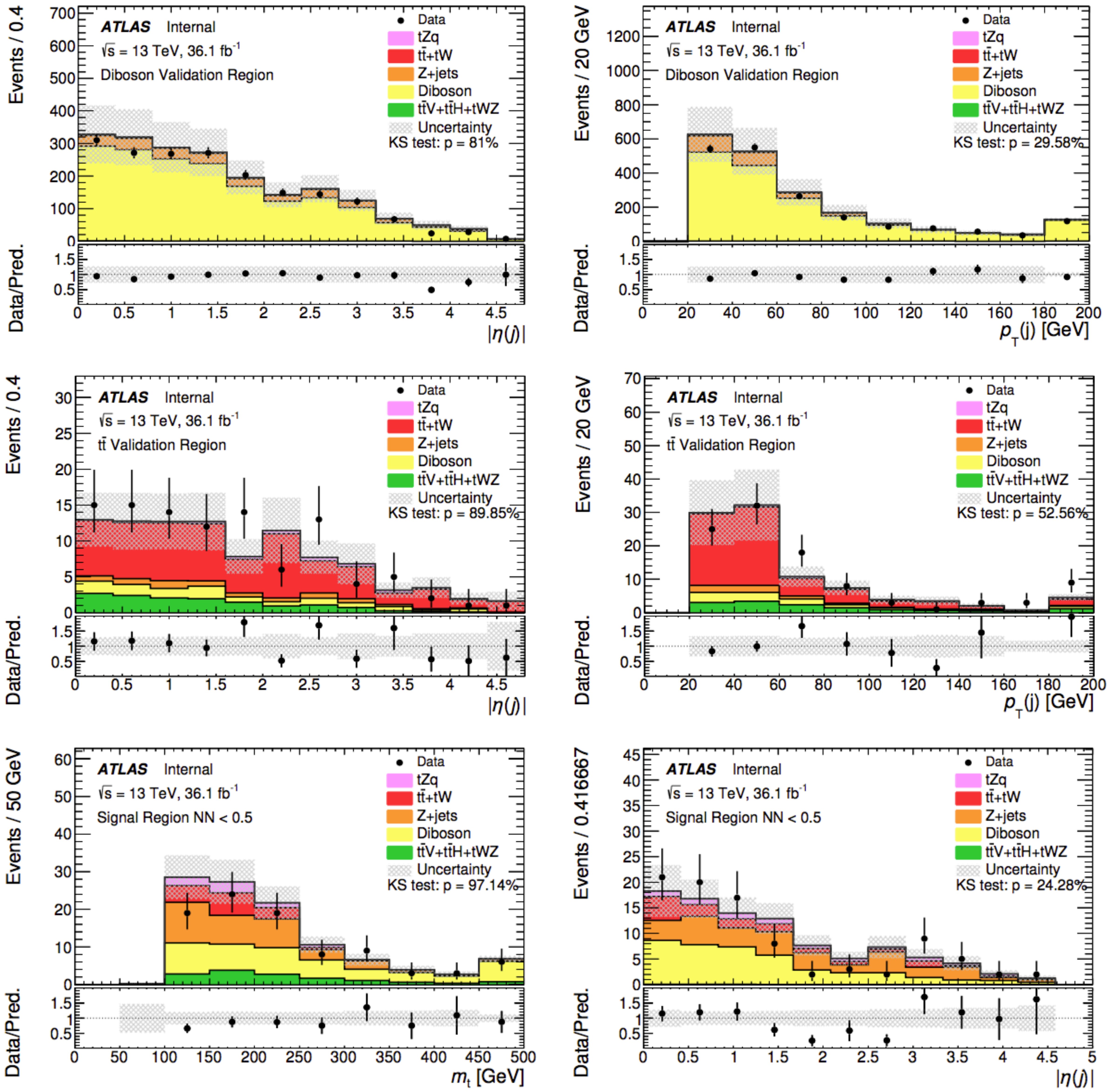
Process	Scaled events	Raw events
$t\bar{t}V + t\bar{t}H + tWZ$	13.7 ± 0.3	7 979
Diboson	10.4 ± 3.2	571
Z + jets	6.7 ± 2.7	531
$t\bar{t}$	61.2 ± 26.3	178
tZq	3.3 ± 0.2	320
Total expected	95.4 ± 26.6	9 579
Data	102	102

NN output

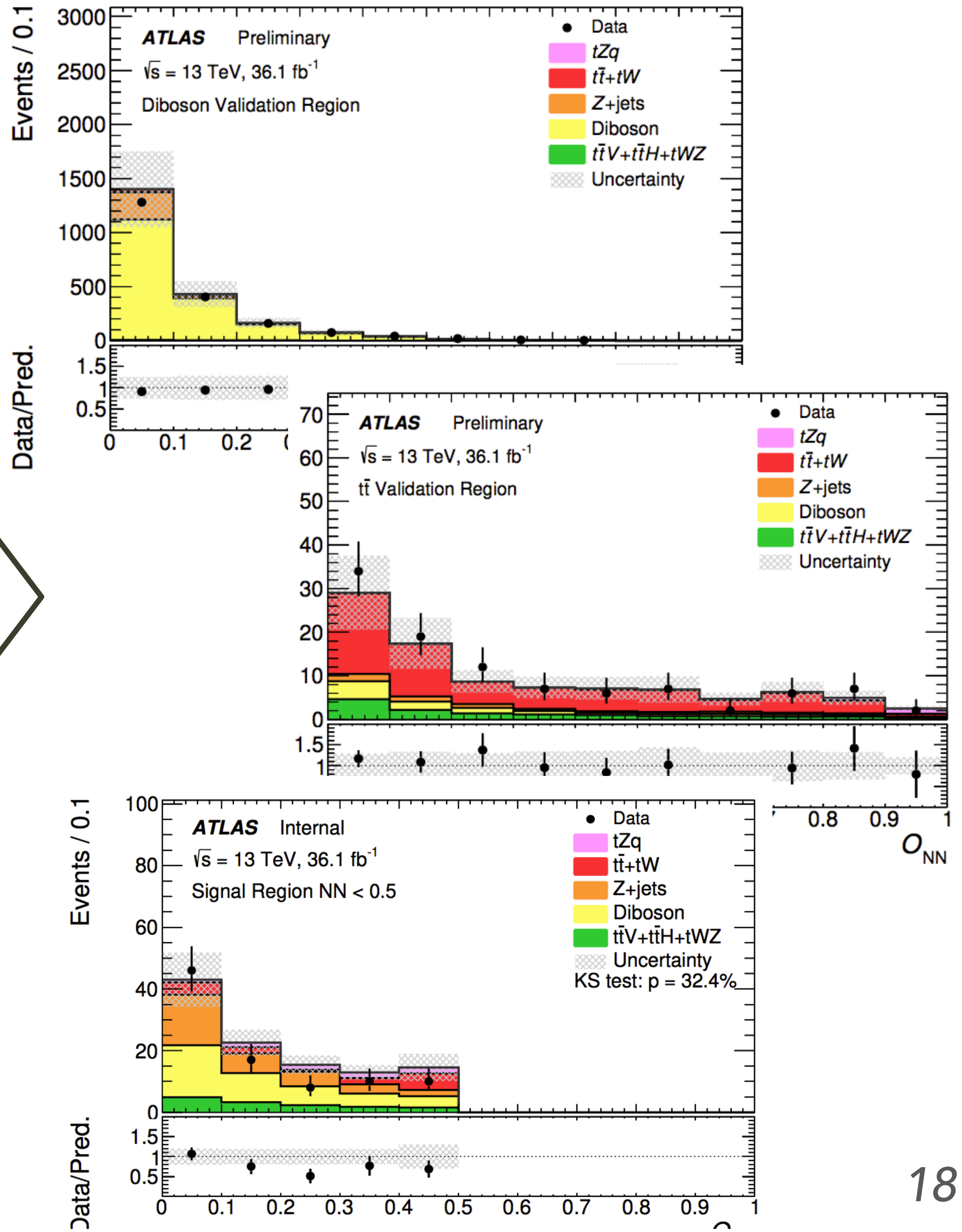
Diboson VR

$t\bar{t}$ VR

SR NN<0.5



NN



R. Zhang

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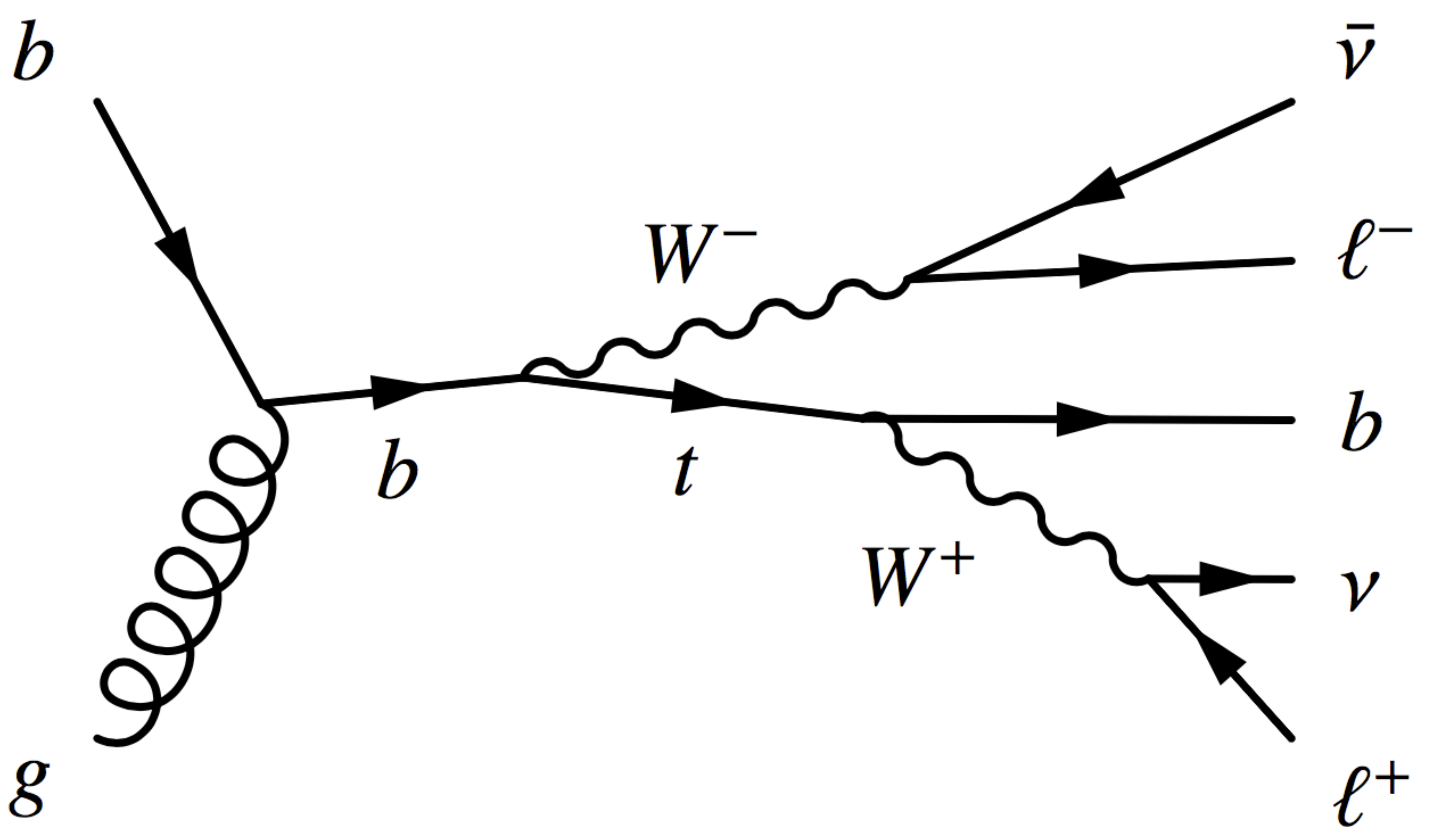
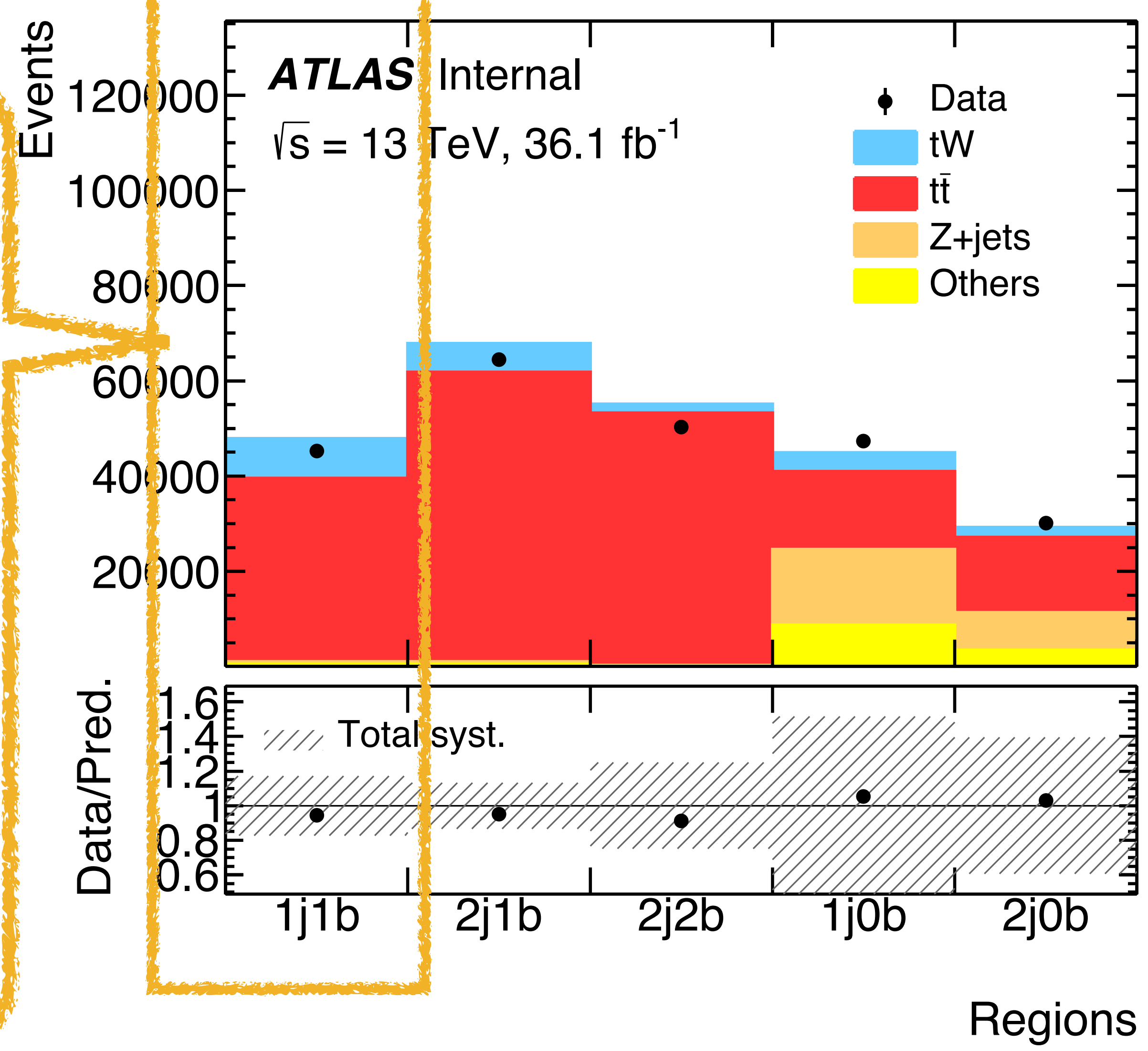
	$4E_T^{miss} > 5m_{\ell\ell}$,	if 40 GeV $< m_{\ell\ell} <$ 81 GeV
	veto,	if 81 GeV $< m_{\ell\ell} <$ 101 GeV
	$2m_{\ell\ell} + E_T^{miss} > 300$ GeV,	if $m_{\ell\ell} > 101$ GeV



Process	Events
tW	8400 ± 1400
$t\bar{t}$	38000 ± 13000
Z + jets	590 ± 300
Diboson	230 ± 58
Fakes	220 ± 220
Predicted	48000 ± 14000
Observed	45706



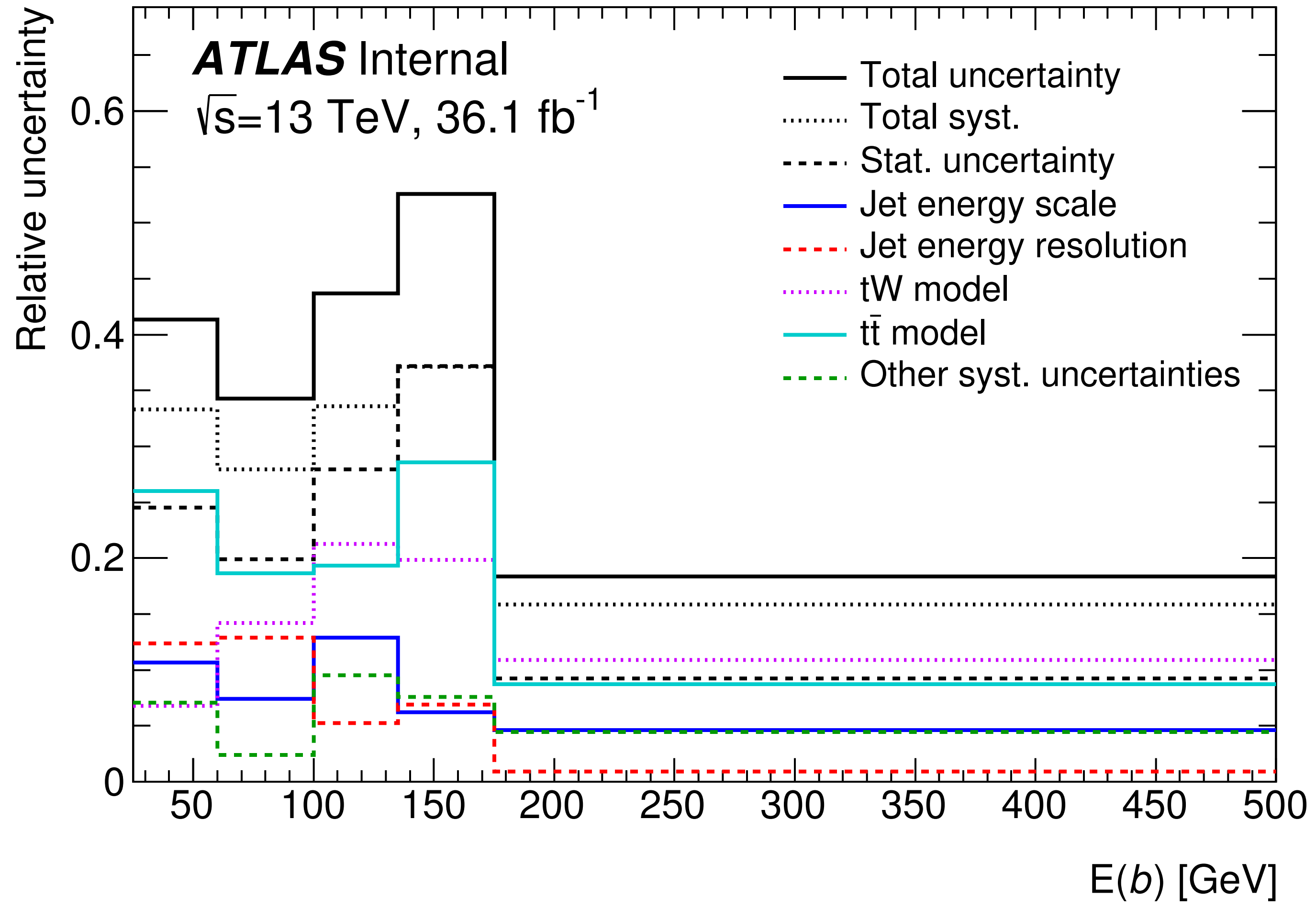
- **Particle-level fiducial region selection**
  - 2 lepton with p_T>20GeV, |η|<2.5, of which >=1 lepton p_T>27GeV
  - *b*-jet p_T>25GeV, |η|<2.5
  - No particular E_T^{miss} cut

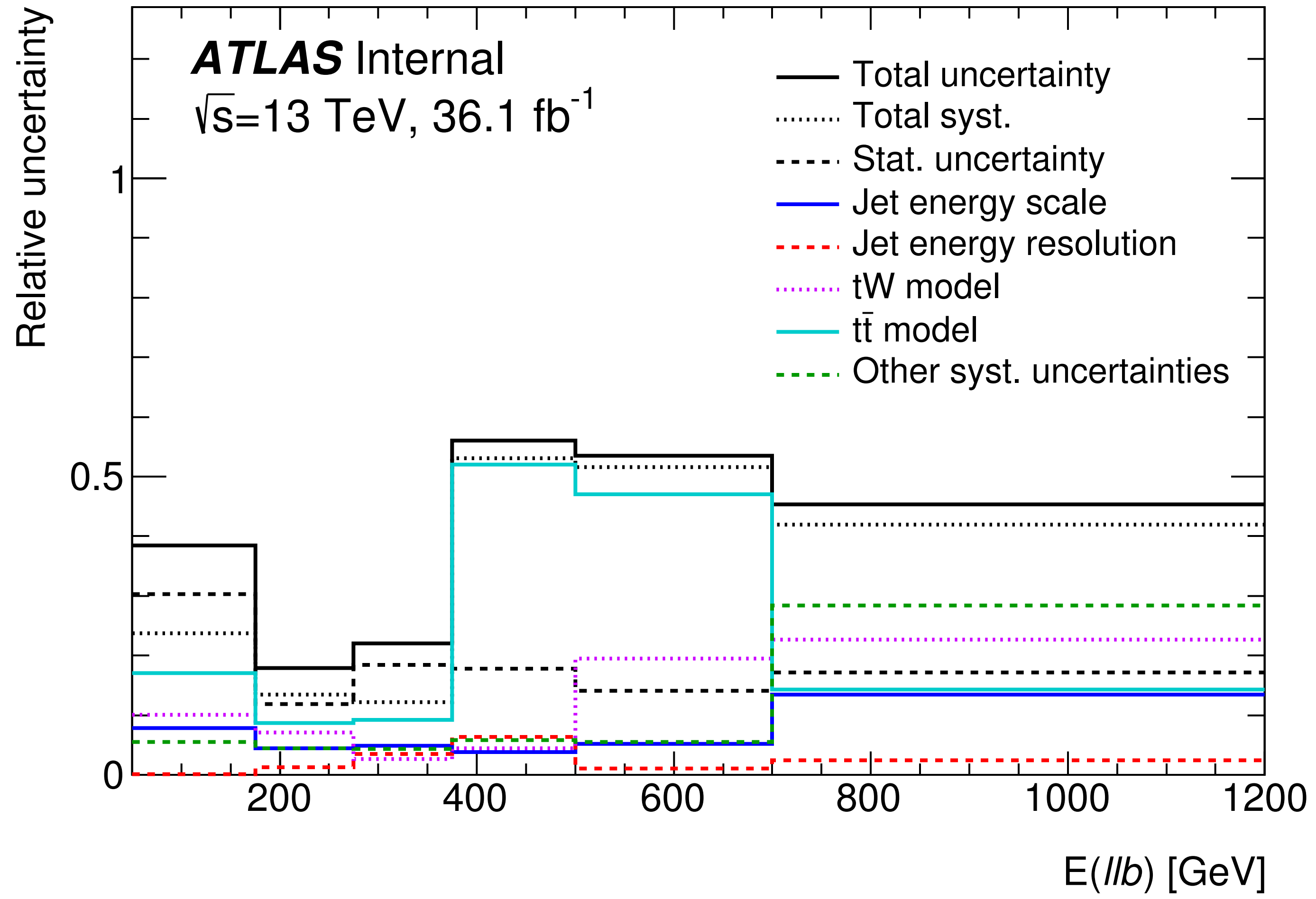
Results - normalised unfolded cross-section I

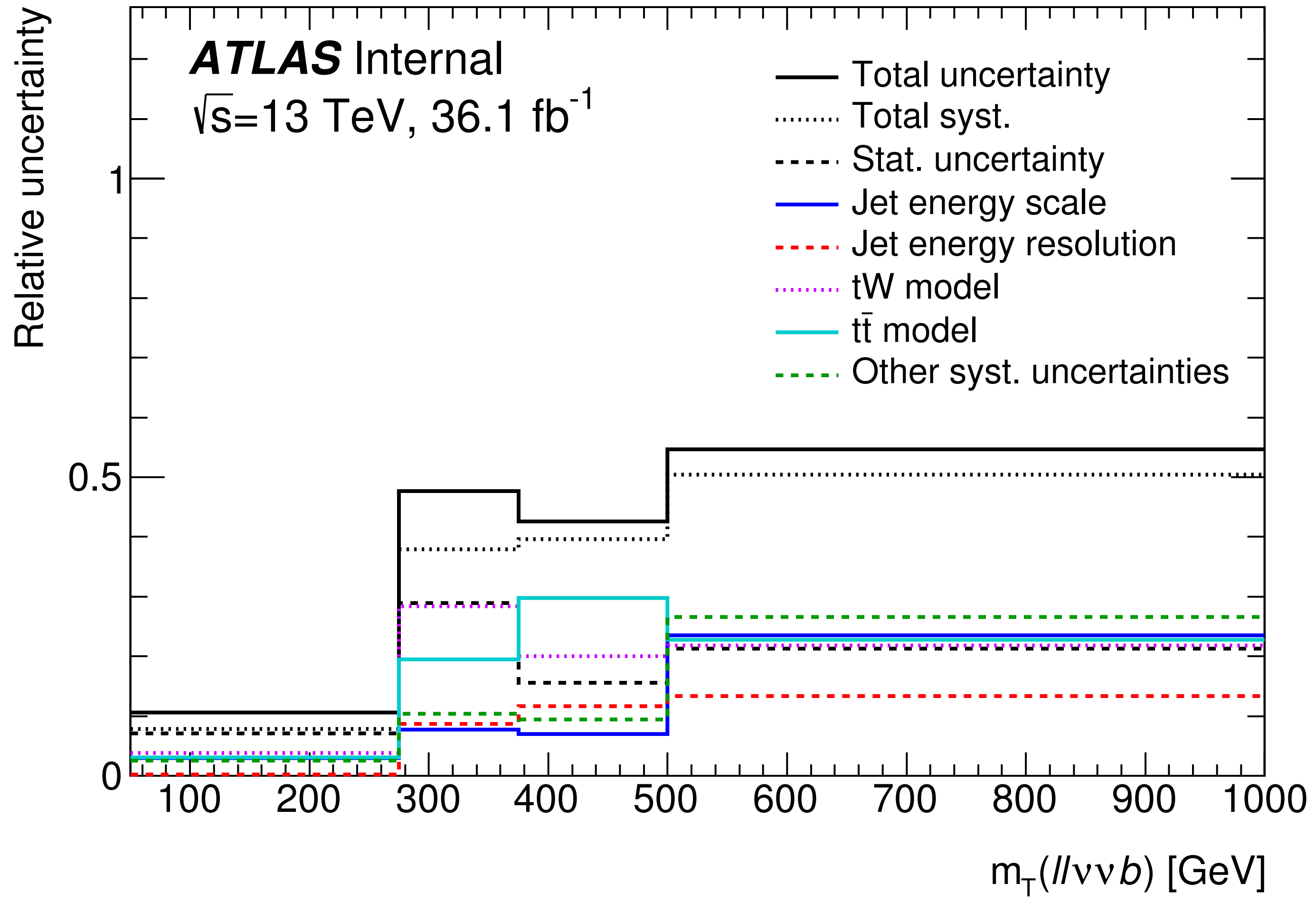
Results - normalised unfolded cross-section II

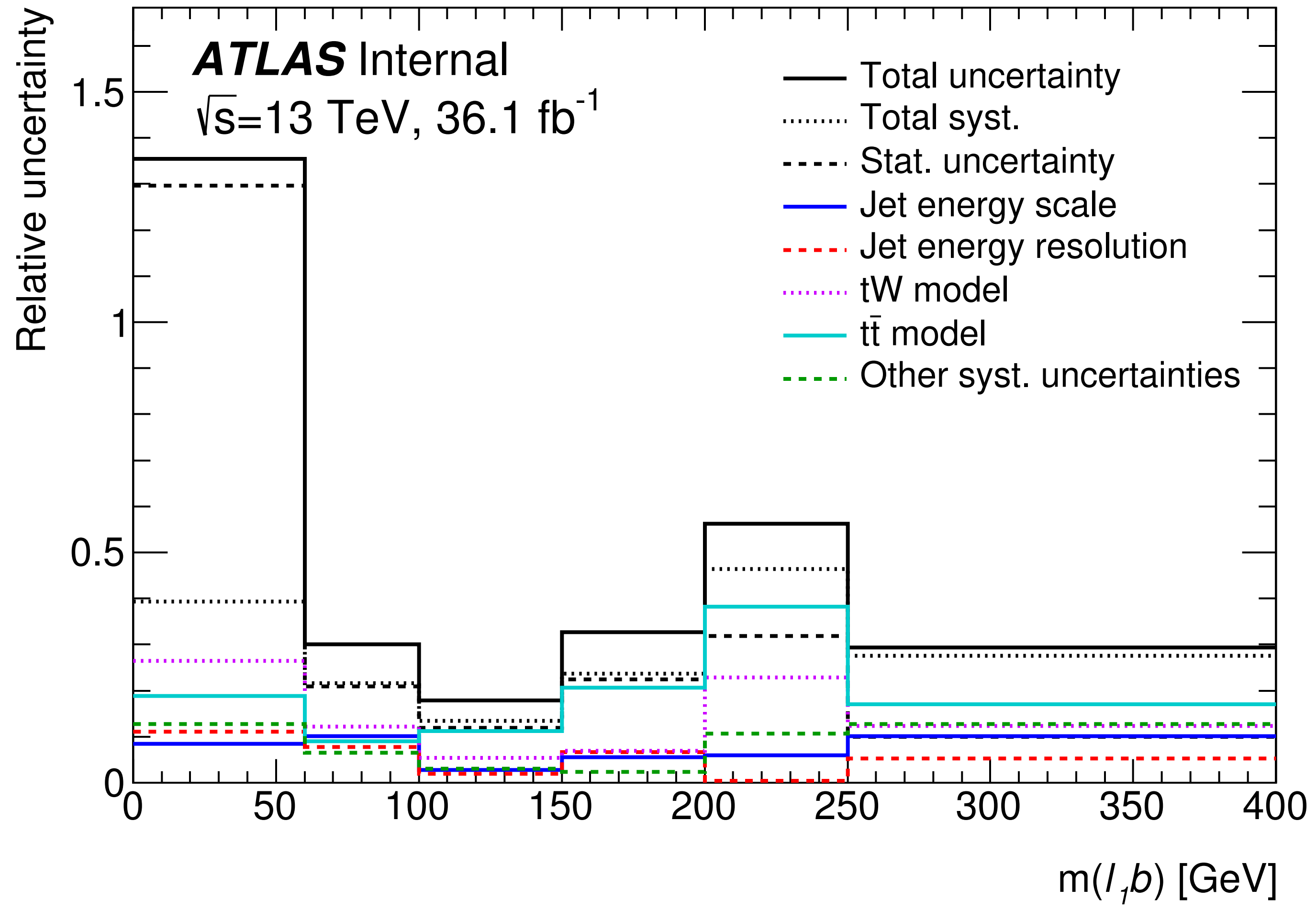
Results and discussions

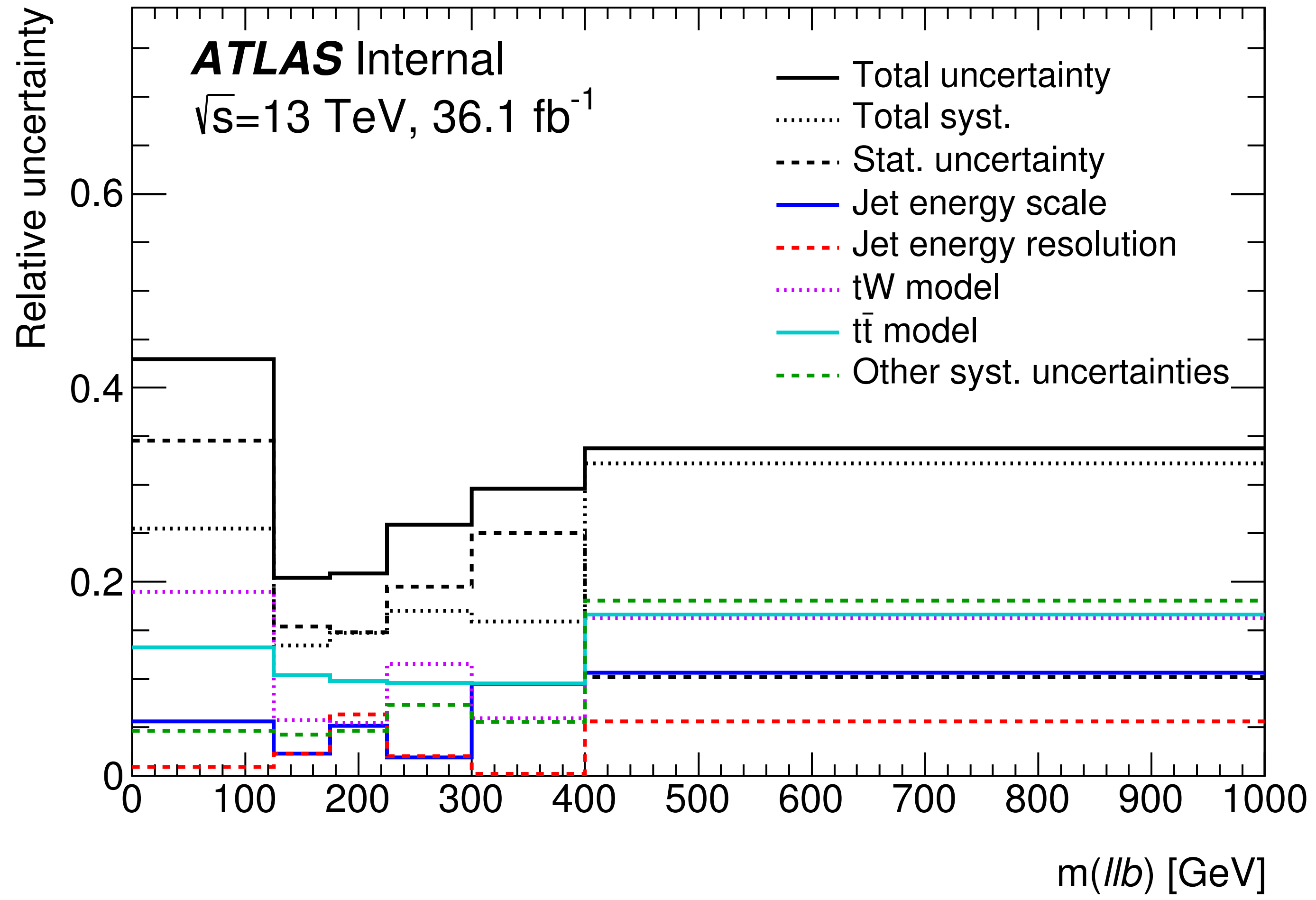
- Both stat. and syst. uncertainties have a significant impact on the results

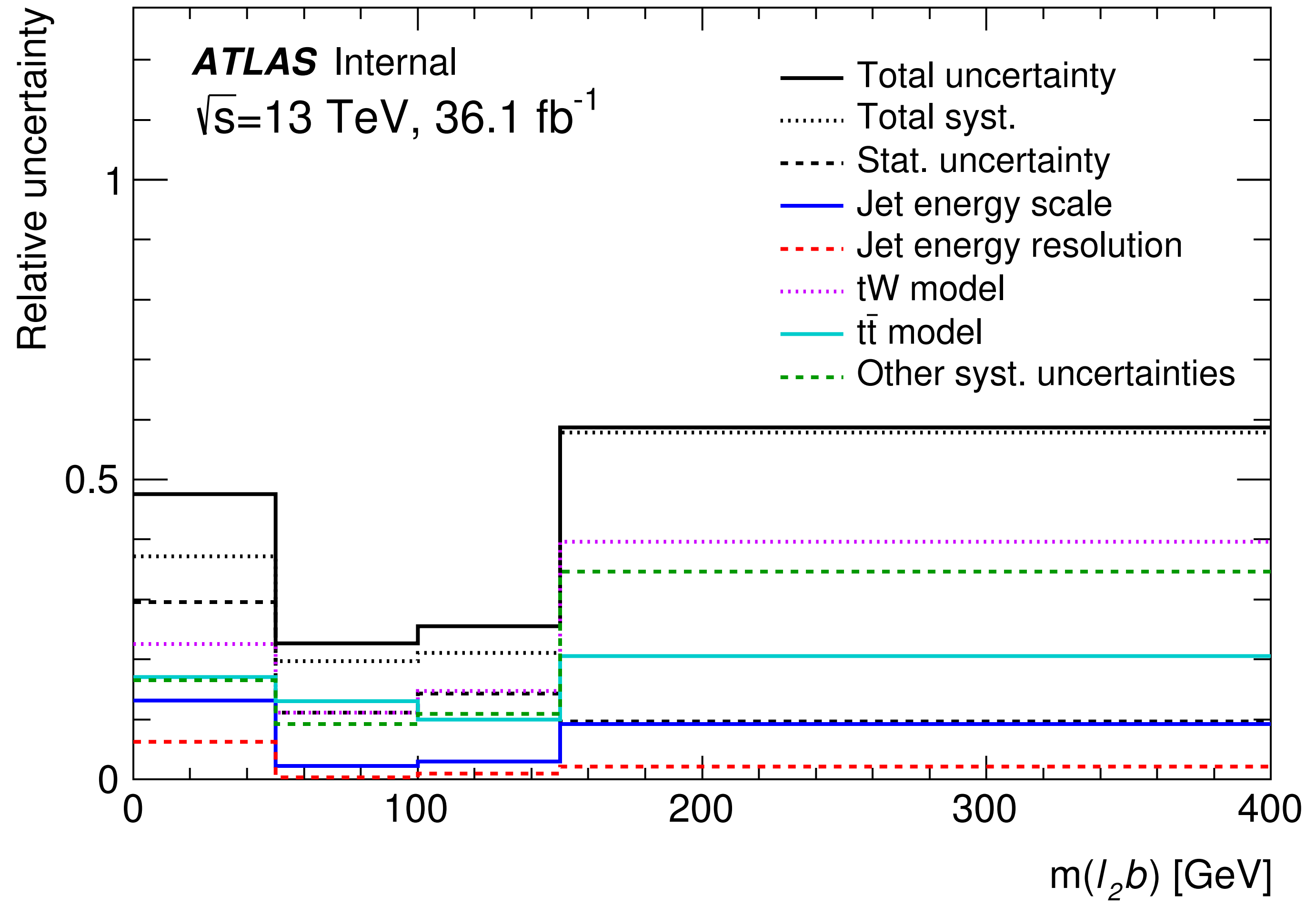












Results and discussions

- In general most MC models show fair agreement with data
  - Many variables show a negative slope in Pred./Data, indicating softer final objects in MC
  - Powheg-Box +Herwig++ deviates more from the data and from the other predictions in certain bins of the E(*llb*), m(l_1*b*) and m(*llb*) distributions
  - DR is systematically closer to the data than DS for several variables
  - No significantly difference is seen in ISR/FSR

Observable	$E(b)$		$E(\ell\ell b)$		$m_{\mathrm{T}}(\ell\ell\nu\nu b)$		$m(\ell_1 b)$		$m(\ell\ell b)$		$m(\ell_2 b)$	
Prediction	χ^2	p	χ^2	p	χ^2	p	χ^2	p	χ^2	p	χ^2	p
Powheg+Pythia6 (DR)	4.8	0.31	8.1	0.15	2.0	0.56	5.7	0.34	4.0	0.55	2.6	0.45
Powheg+Pythia6 (DS)	5.0	0.29	9.1	0.11	2.4	0.49	6.1	0.30	4.4	0.50	2.6	0.46
aMC@NLO+Herwig++	5.6	0.23	8.7	0.12	1.8	0.61	5.4	0.37	3.6	0.61	2.4	0.49
Powheg+Herwig++	6.2	0.18	11.0	0.05	2.0	0.57	8.1	0.15	5.2	0.40	2.3	0.52
Powheg+Pythia6 radHi	4.8	0.30	7.9	0.16	1.9	0.60	5.3	0.38	3.7	0.60	2.5	0.48
Powheg+Pythia6 radLo	5.0	0.29	8.4	0.14	2.1	0.56	5.8	0.33	4.0	0.55	2.6	0.45

Conclusion

- Differential cross-section for the tW channel is measured for several variables using 2015+2016 dataset
- Fiducial phase-space is 1j1b region
- Normalised differential cross-section are shown to cancel some systematics

$E(b)$ Bin [GeV]	[25, 60]	[60, 100]	[100, 135]	[135, 175]	[175, 500]
$(1/\sigma)d\sigma/dx$ [1/x]	0.00438	0.00613	0.00474	0.00252	0.00103
Statistical uncertainty	25	20	28	37	9.3
Total systematic uncertainty	33	28	34	37	16
Total uncertainty	41	34	44	53	18

$E(\ell\ell b)$ Bin [GeV]	[50, 175]	[175, 275]	[275, 375]	[375, 500]	[500, 700]	[700, 1200]
$(1/\sigma)d\sigma/dx$ [1/x]	0.000597	0.00322	0.00185	0.00135	0.000832	0.000167
Statistical uncertainty	30	12	18	18	14	17
Total systematic uncertainty	24	13	12	53	52	42
Total uncertainty	38	18	22	56	53	45

$m_T(\ell\ell\nu\nu b)$ Bin [GeV]	[50, 275]	[275, 375]	[375, 500]	[500, 1000]
$(1/\sigma)d\sigma/dx$ [1/x]	0.0033	0.00123	0.000856	5.51e-05
Statistical uncertainty	7.1	29	16	21
Total systematic uncertainty	7.8	38	40	50
Total uncertainty	11	48	43	55

$m(\ell_1 b)$ Bin [GeV]	[0, 60]	[60, 100]	[100, 150]	[150, 200]	[200, 250]	[250, 400]
$(1/\sigma)d\sigma/dx$ [1/x]	0.000191	0.00428	0.00806	0.00333	0.00153	0.00114
Statistical uncertainty	130	21	12	22	32	10
Total systematic uncertainty	39	22	13	24	46	28
Total uncertainty	140	30	18	33	56	29

$m(\ell\ell b)$ Bin [GeV]	[0, 125]	[125, 175]	[175, 225]	[225, 300]	[300, 400]	[400, 1000]
$(1/\sigma)d\sigma/dx$ [1/x]	0.00051	0.00533	0.00538	0.00242	0.000949	0.000208
Statistical uncertainty	35	15	15	19	25	10
Total systematic uncertainty	25	13	15	17	16	32
Total uncertainty	43	20	21	26	30	34

$m(\ell_2 b)$ Bin [GeV]	[0, 50]	[50, 100]	[100, 150]	[150, 400]
$(1/\sigma)d\sigma/dx$ [1/x]	0.00184	0.00845	0.00531	0.000879
Statistical uncertainty	30	11	14	9.6
Total systematic uncertainty	37	20	21	58
Total uncertainty	48	23	25	59

Thank you for your attention!