VLL@ATLAS

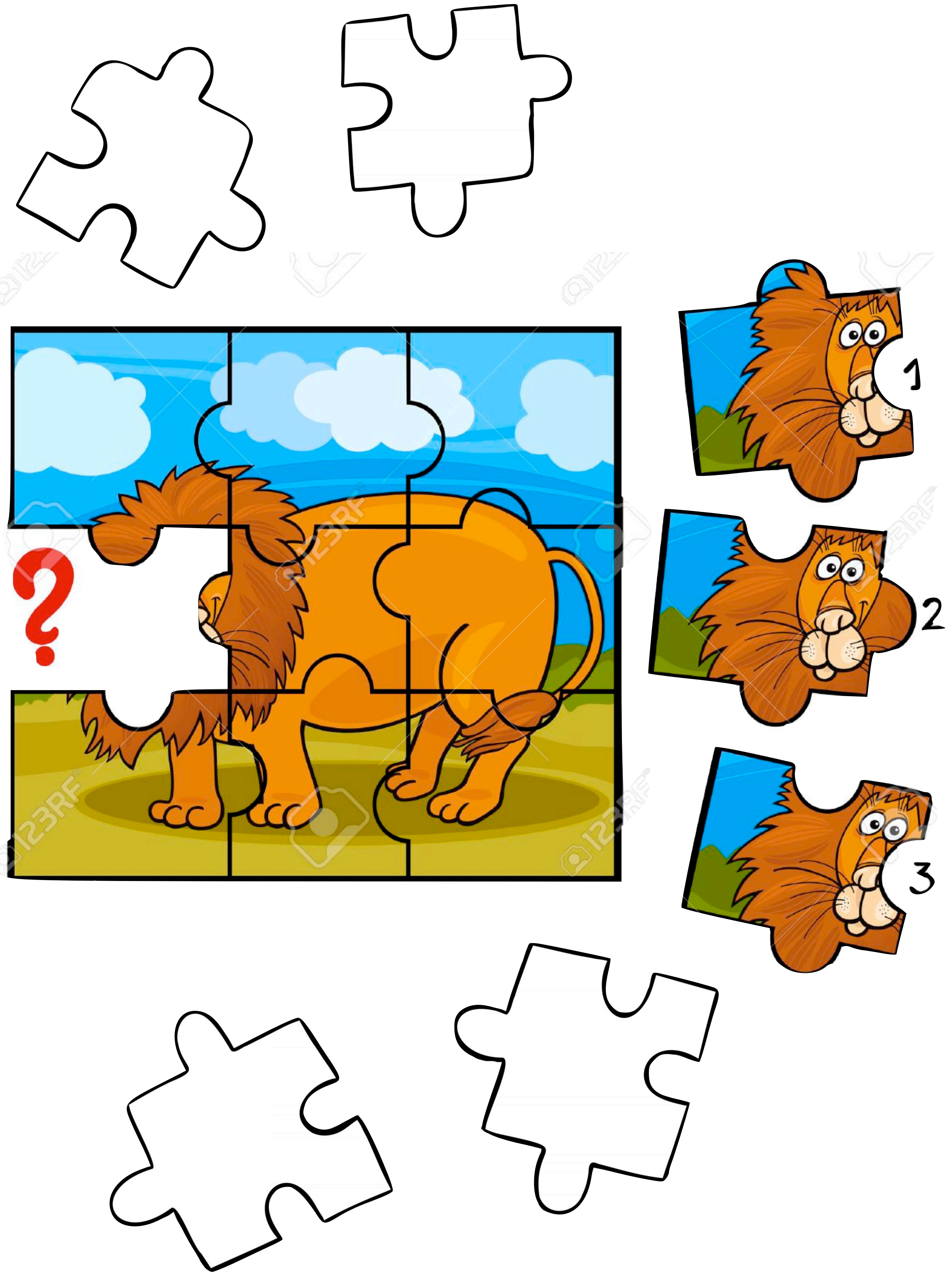
Shalini Epari

On behalf of the ATLAS collaboration

12th Edition of the Large Hardon Collider Physics Conference

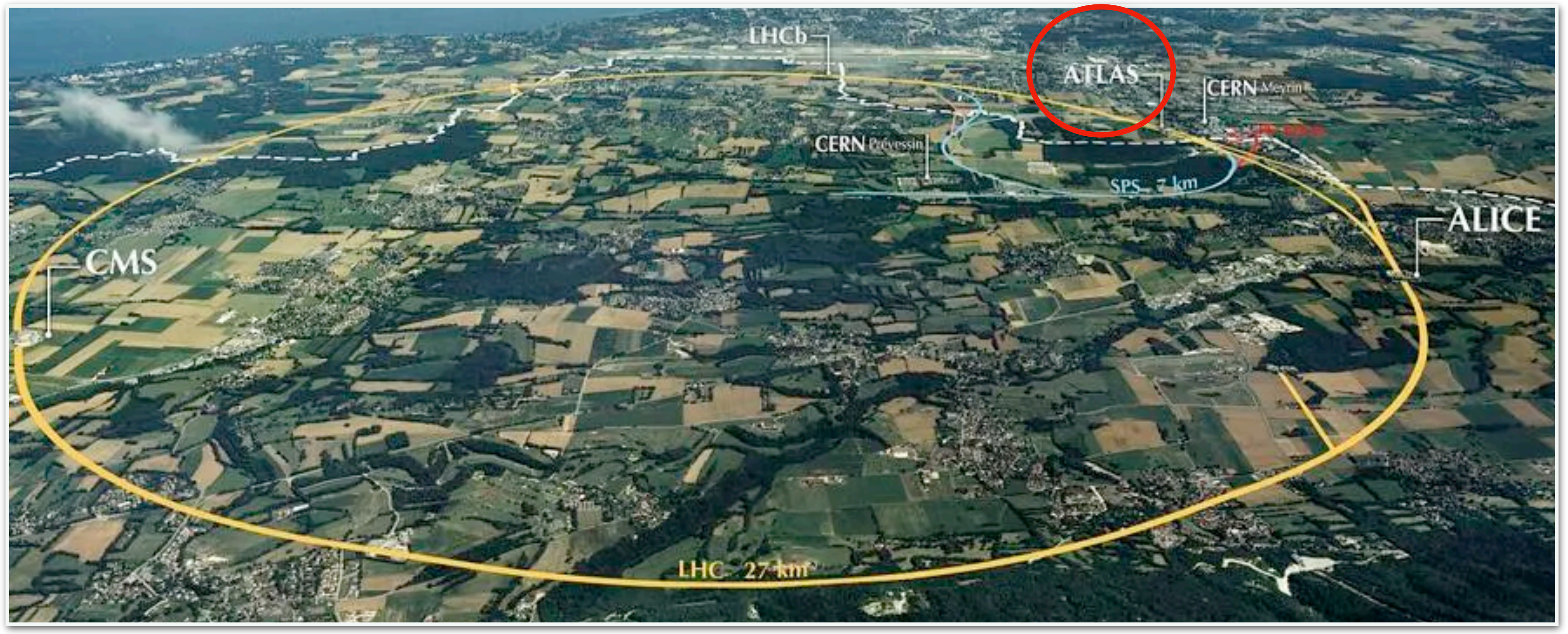
Introduction

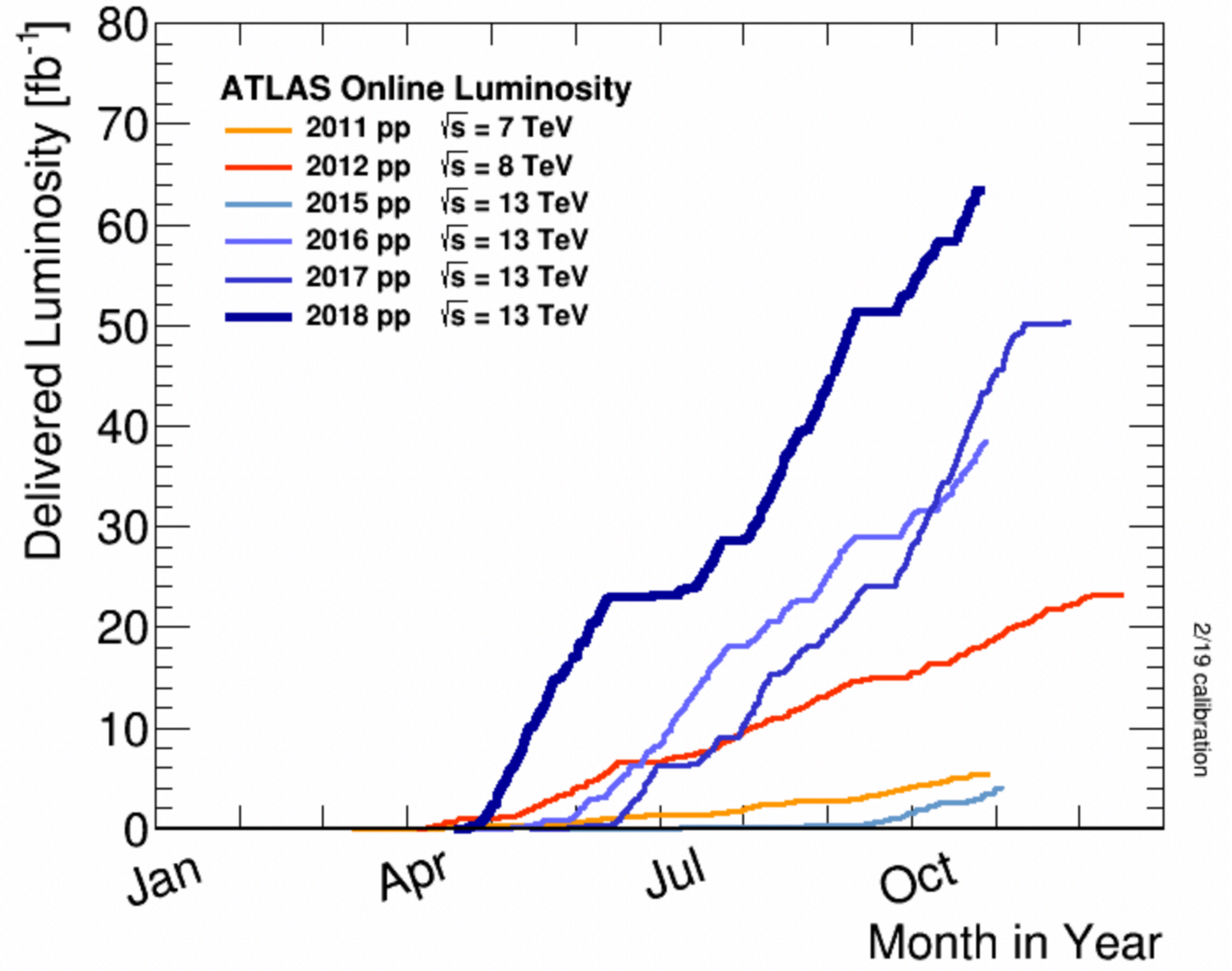
- Multiple hints of physics beyond the Standard Model with no clear answer.
- ‘Vector-like’ fermions are some of the simplest extensions of the SM at the electroweak scale.
- Several searches for Vector-like Quarks (VLQ) at the LEP and LHC with exclusion up to ~TeV scale.
- Vector-like Leptons (VLL) searches are relatively new:
  - Appear in many UV complete models: composite Higgs, ‘4321’, warped extra dimensions.
  - May explain the persistent $(g-2)_\mu$, Cabibbo angle anomaly, neutrino masses, flavor anomalies.



The ATLAS experiment

ATLAS (A Toroidal LHC Apparatus): general purpose experiment for precision tests of the SM and searches for exotic particles.

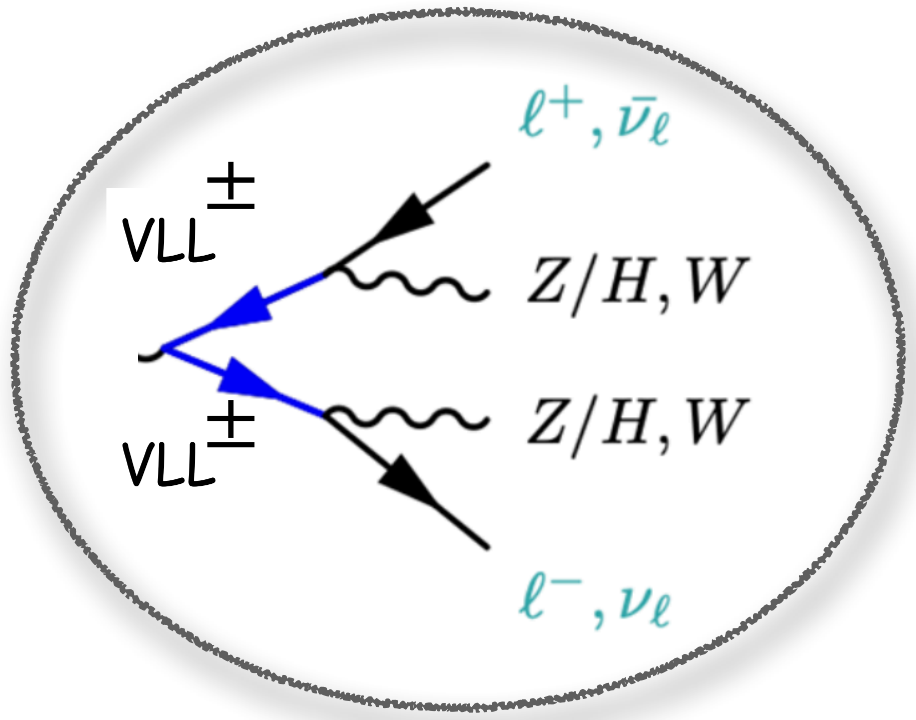




- Run 1 (2010-2012) recorded ~5 fb^{-1} at $\sqrt{s}$ = 7 TeV and ~20 fb^{-1} at $\sqrt{s}$ = 8 TeV.
- Run 2 (2015 - 2018) recorded ~140 fb^{-1} at $\sqrt{s}$ = 13 TeV.
- Significant upgrades to the detector sub-systems between Runs improved particle reconstruction and identification.
- Broad program for VLLs searches in both LHC Runs.

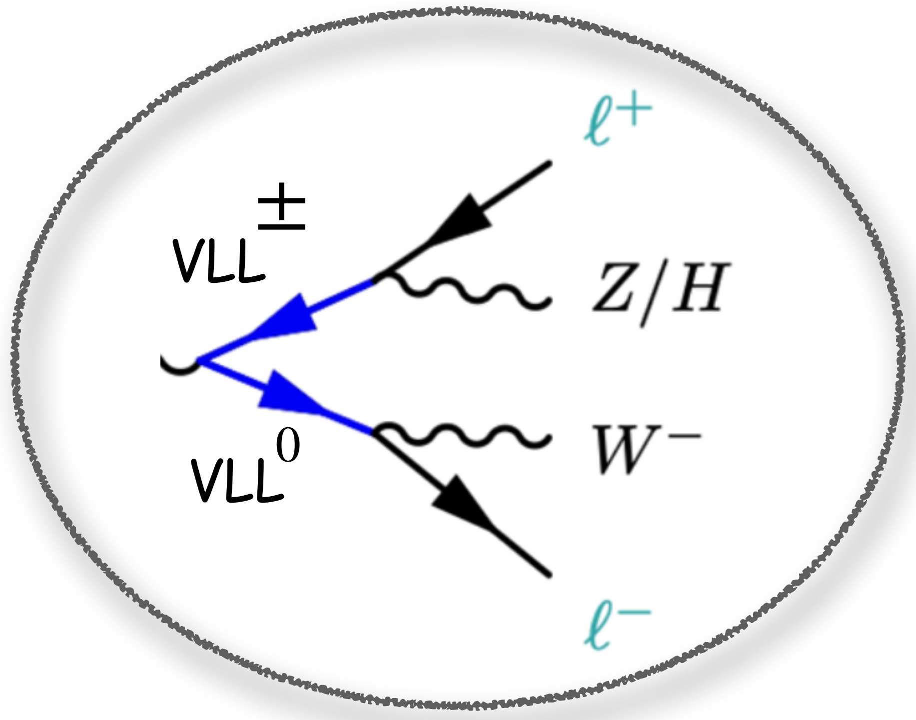
Phenomenology of VLLs

VLLs from an SU(2) singlet



PhysRevD.92.115018

VLLs from an SU(2) doublet



- Simplest VLLs may occur as an SU(2) singlet or SU(2) doublet:
  - SU(2) singlet models allow only charged VLLs coupling to SM charged leptons and neutrinos.
  - SU(2) doublet models allow an additional neutral VLL; provide substantial enchancement to production cross-sections.
- Rich phenomenology with multiple light leptons, jets and missing transverse energy.
- Today's talk:
  - (Run 1) Search for heavy lepton resonances decaying to a Z boson and leptons, with sensitivity to light VLLs from an SU(2) singlet model, available at JHEP 09 (2015) 108.
  - (Run 2) Search for third generation VLLs from an SU(2) doublet model, available at JHEP 07 (2023) 118.

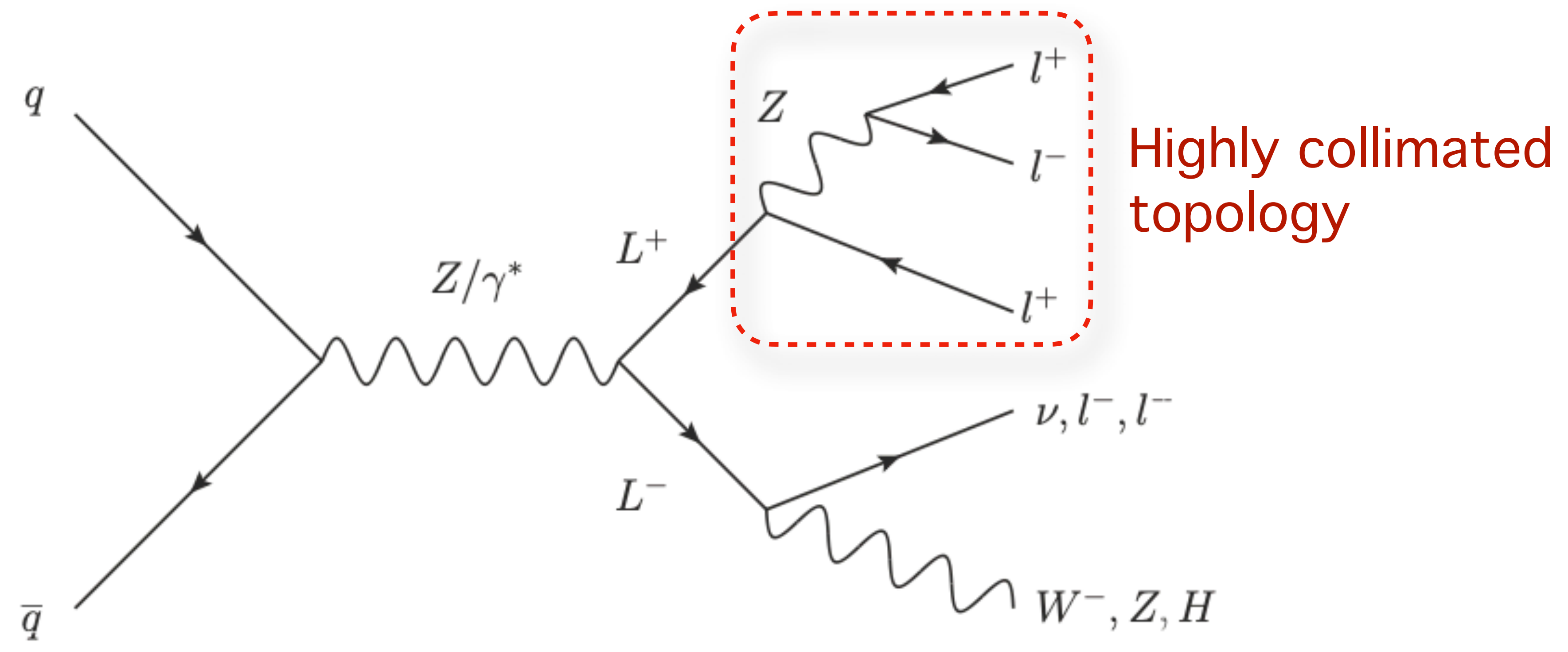
Search for heavy lepton resonances decaying to a Z boson and a lepton in pp collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector

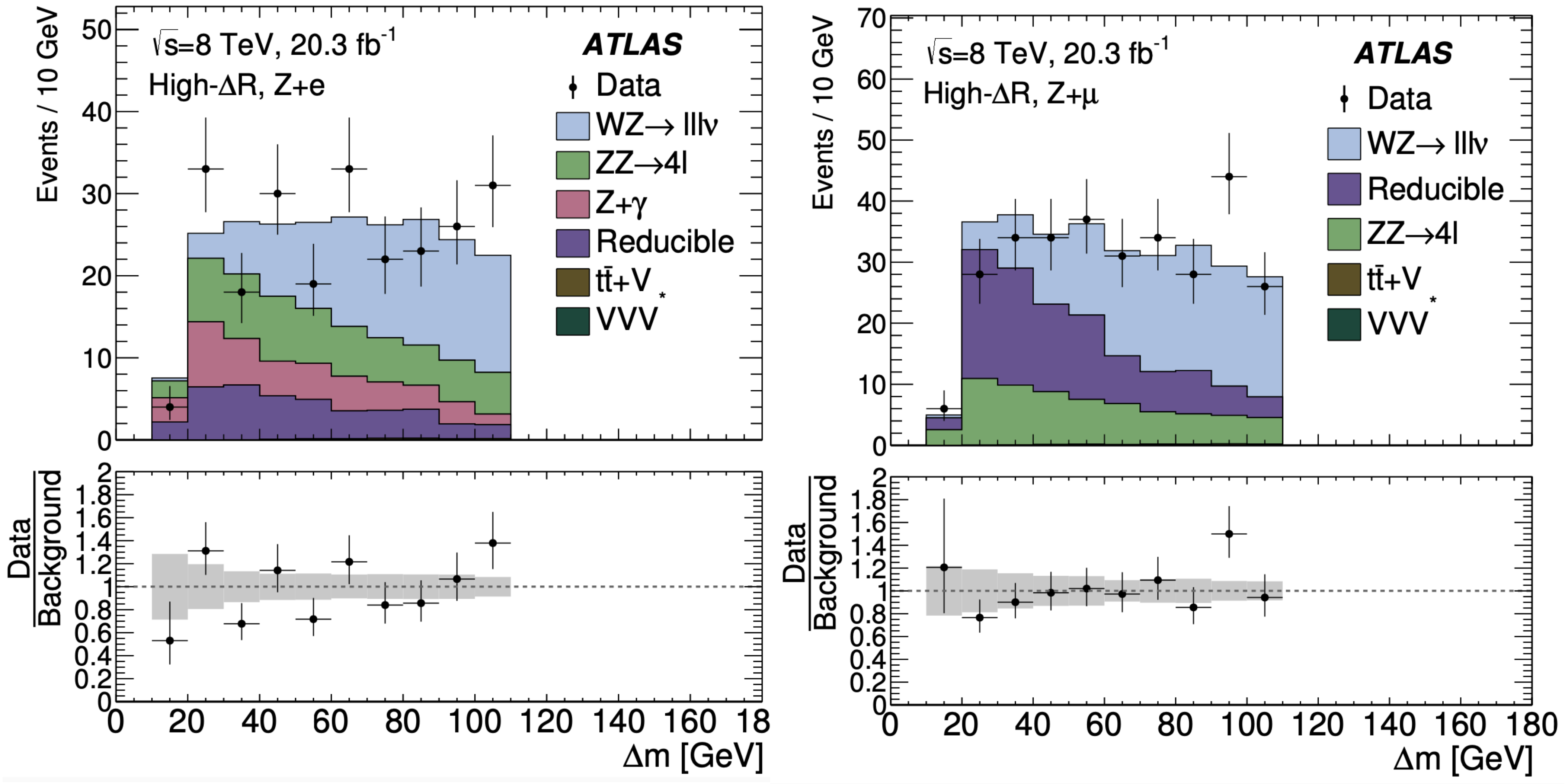
JHEP 09 (2015) 108

Analysis Strategy

- Model-(in)dependant search for heavy lepton resonances with a leptonically decaying Z boson and additional light lepton.
  - Sensitivity to pair-produced VLLs from an SU(2) singlet.
- Select events with atleast 3 charged leptons with exactly one pair compatible with a Z boson and third lepton collimated with Z ($\Delta R_{Z,l} < 3$).
- Signal regions split according to flavor of additional lepton to maximise sensitivity:
  - '$Z+e$': $3l(W \to qq)$, '$3l$-only'$(!W \to qq)$, $4l$.
  - '$Z+\mu$': $3l(W \to qq)$, '$3l$-only'$(!W \to qq)$, $4l$.
- Hunt for a narrowly peaked excess in $\boxed{\Delta m \equiv m_{3l} - m_{Z \to ll}}$
- Major backgrounds (diboson) validated in dedicated regions (WZ, ZZ, off-Z, high $\Delta R_{Z,l}$)

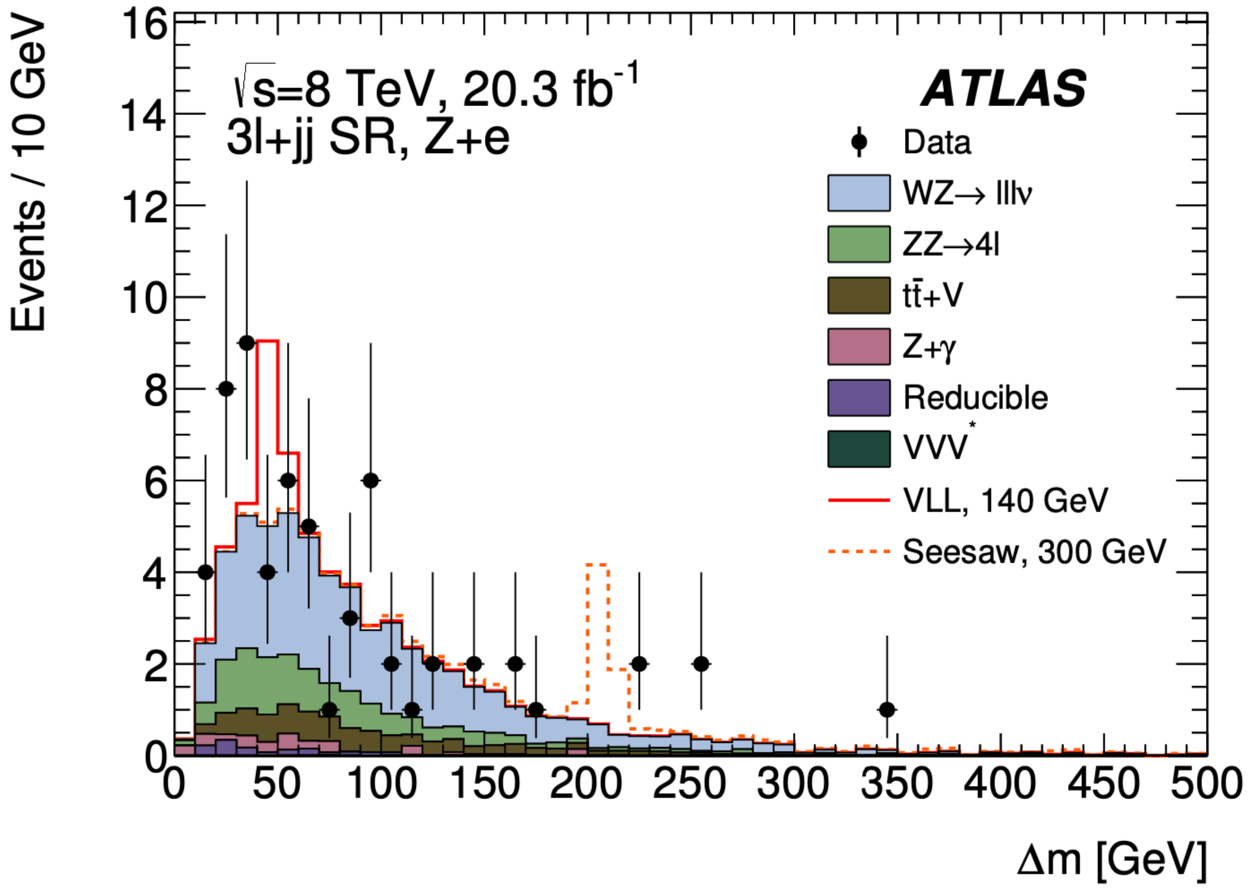
VLLs from an SU(2) singlet

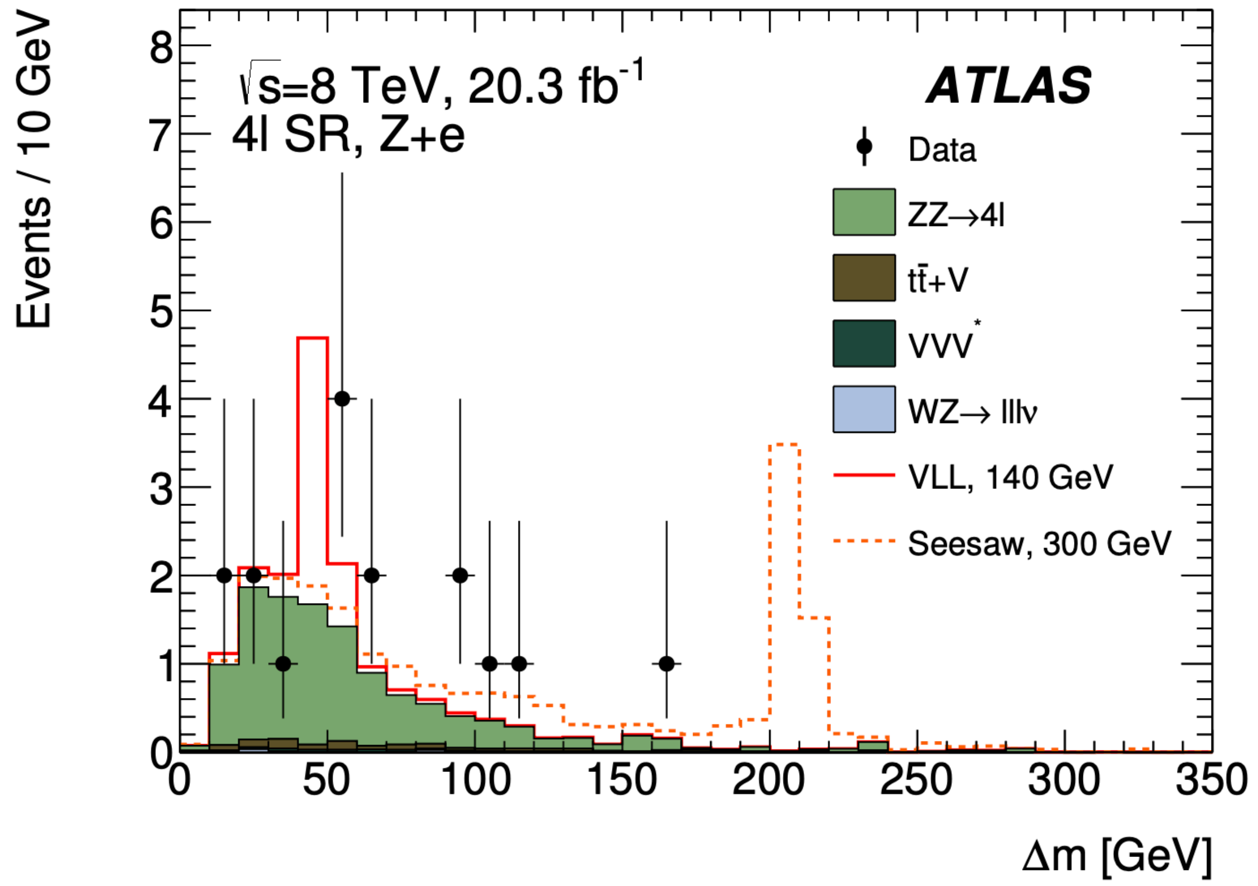


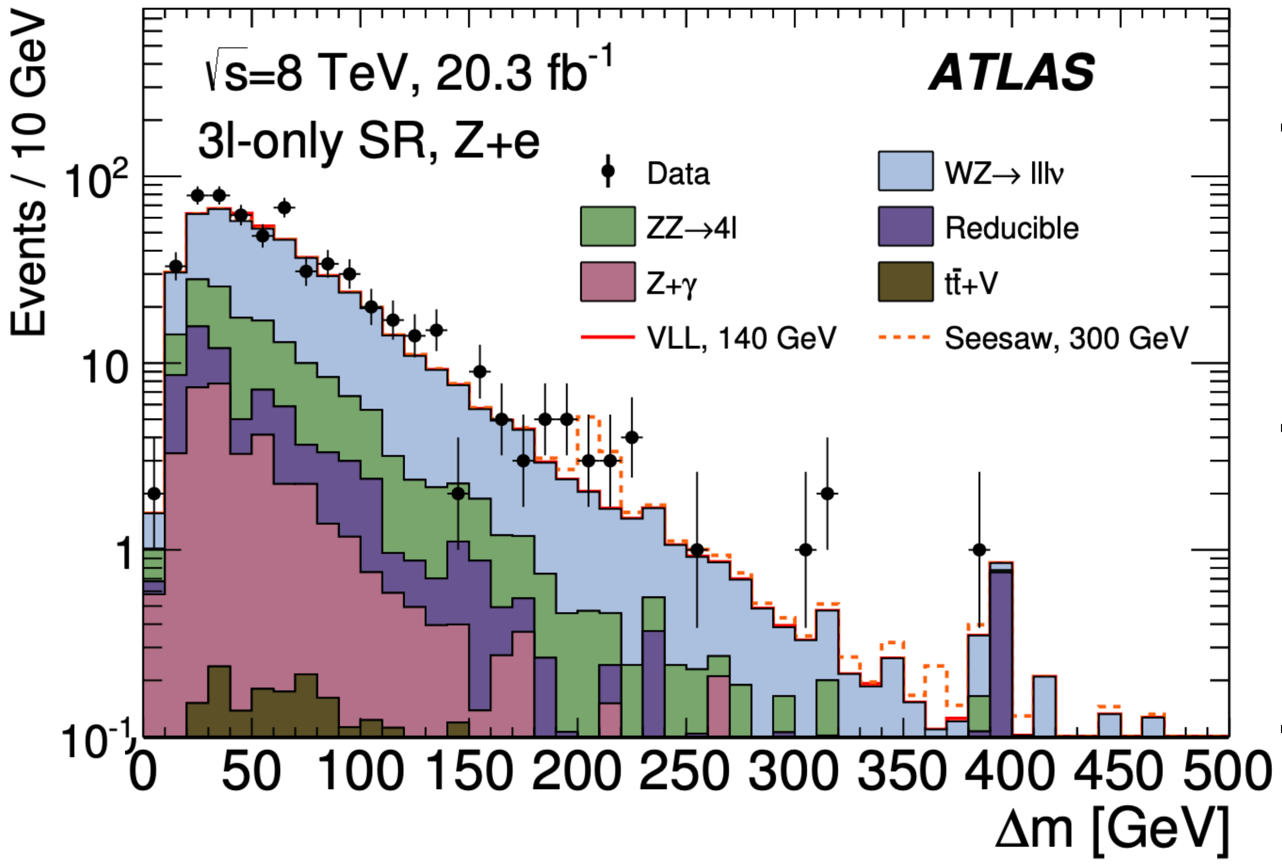


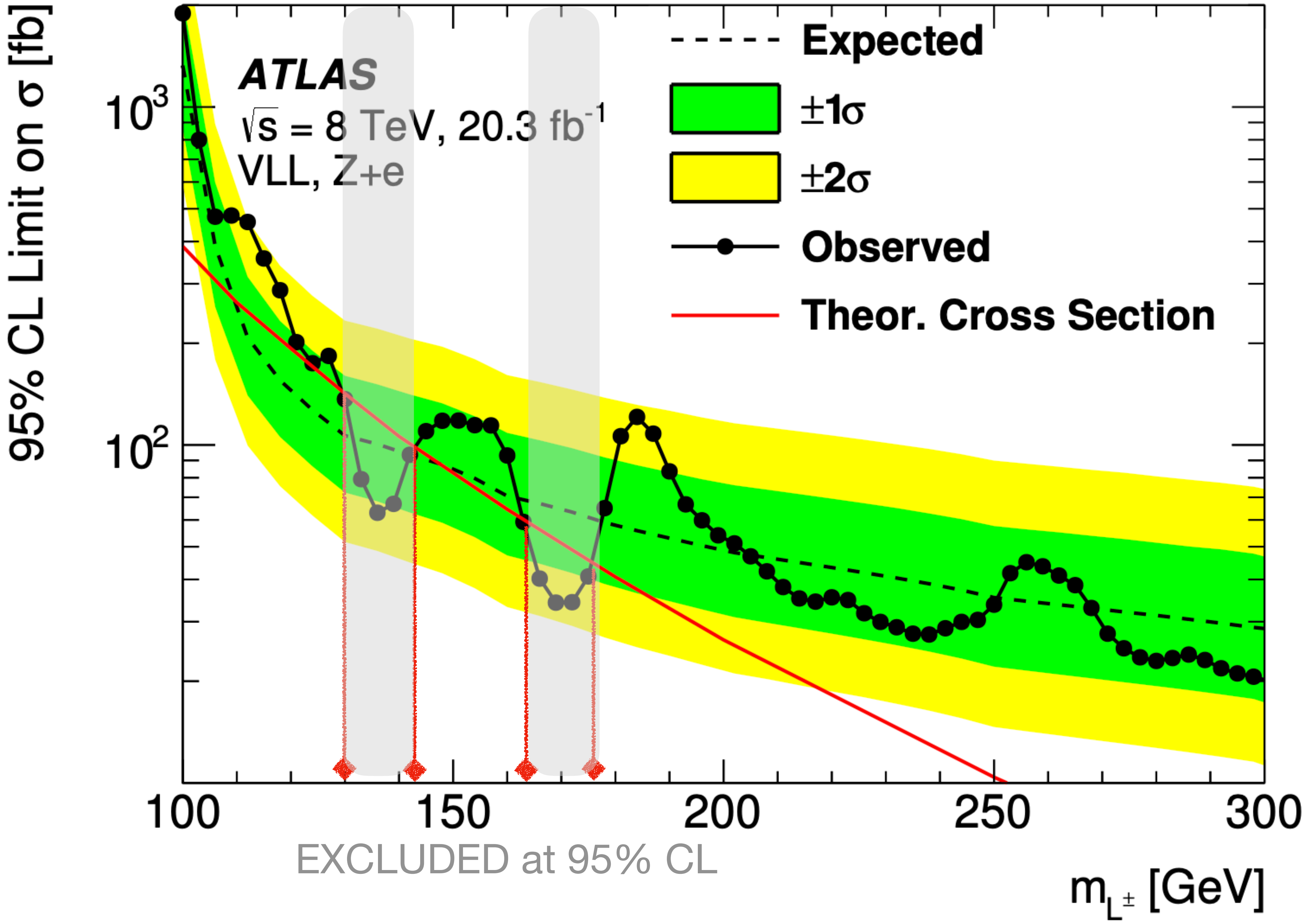
Validation of backgrounds in high $\Delta R_{Z,l}$ (>3) regions

Result: Vector-like electrons



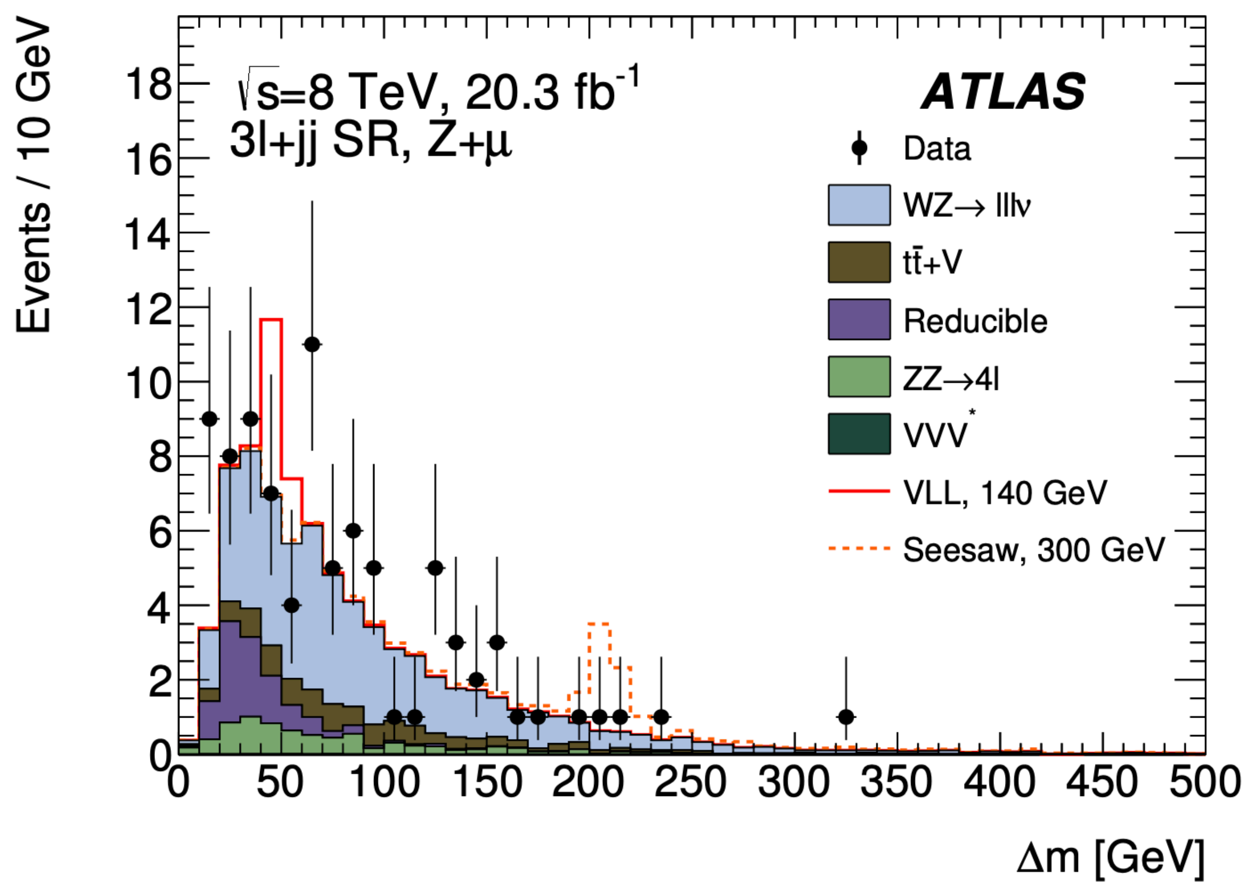


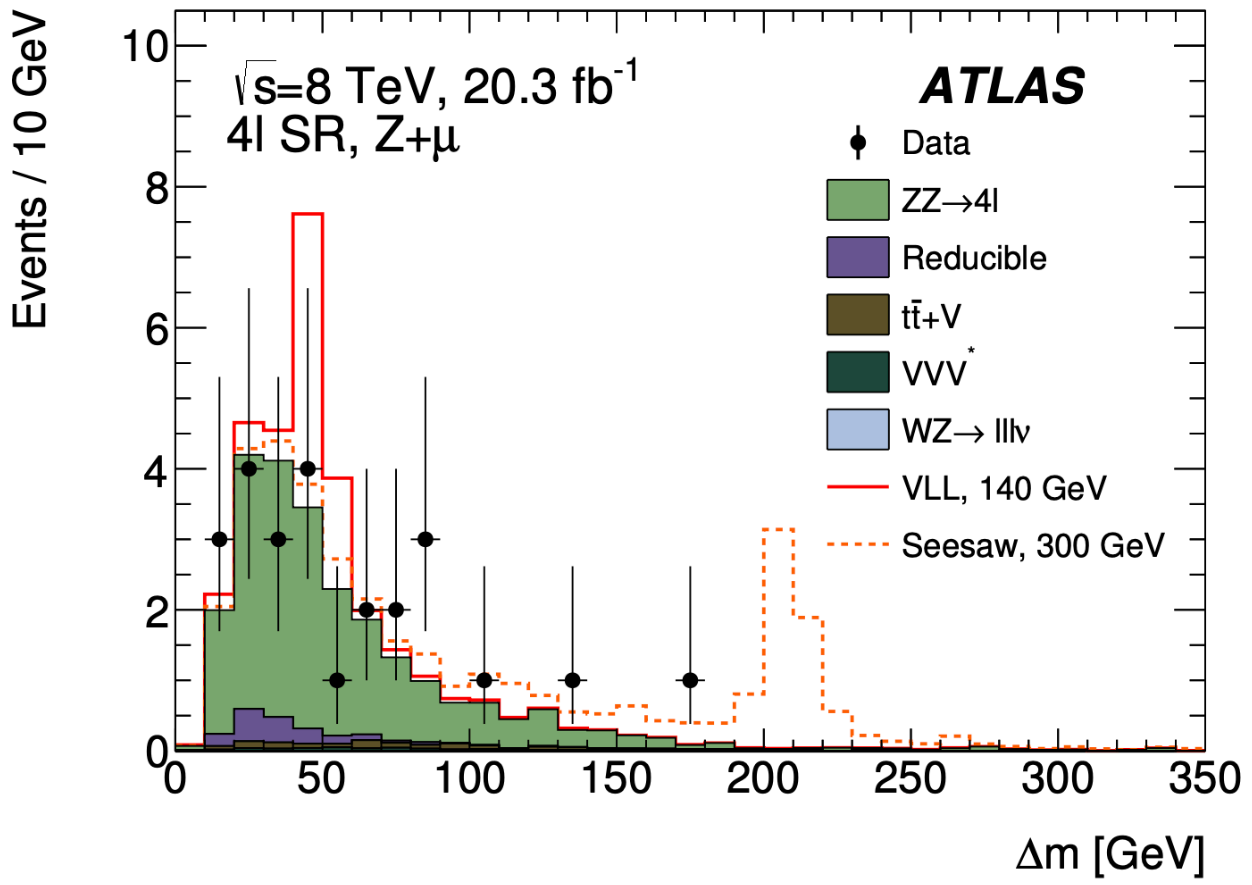


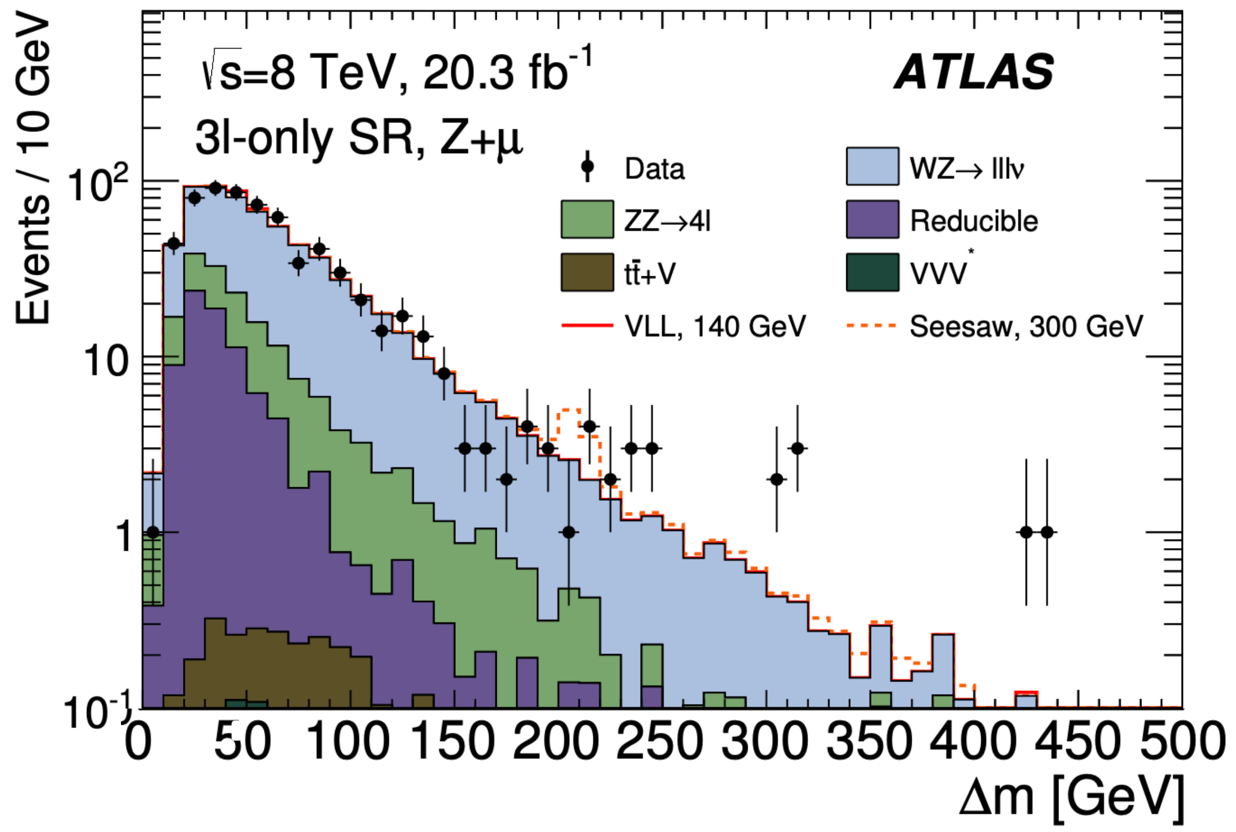


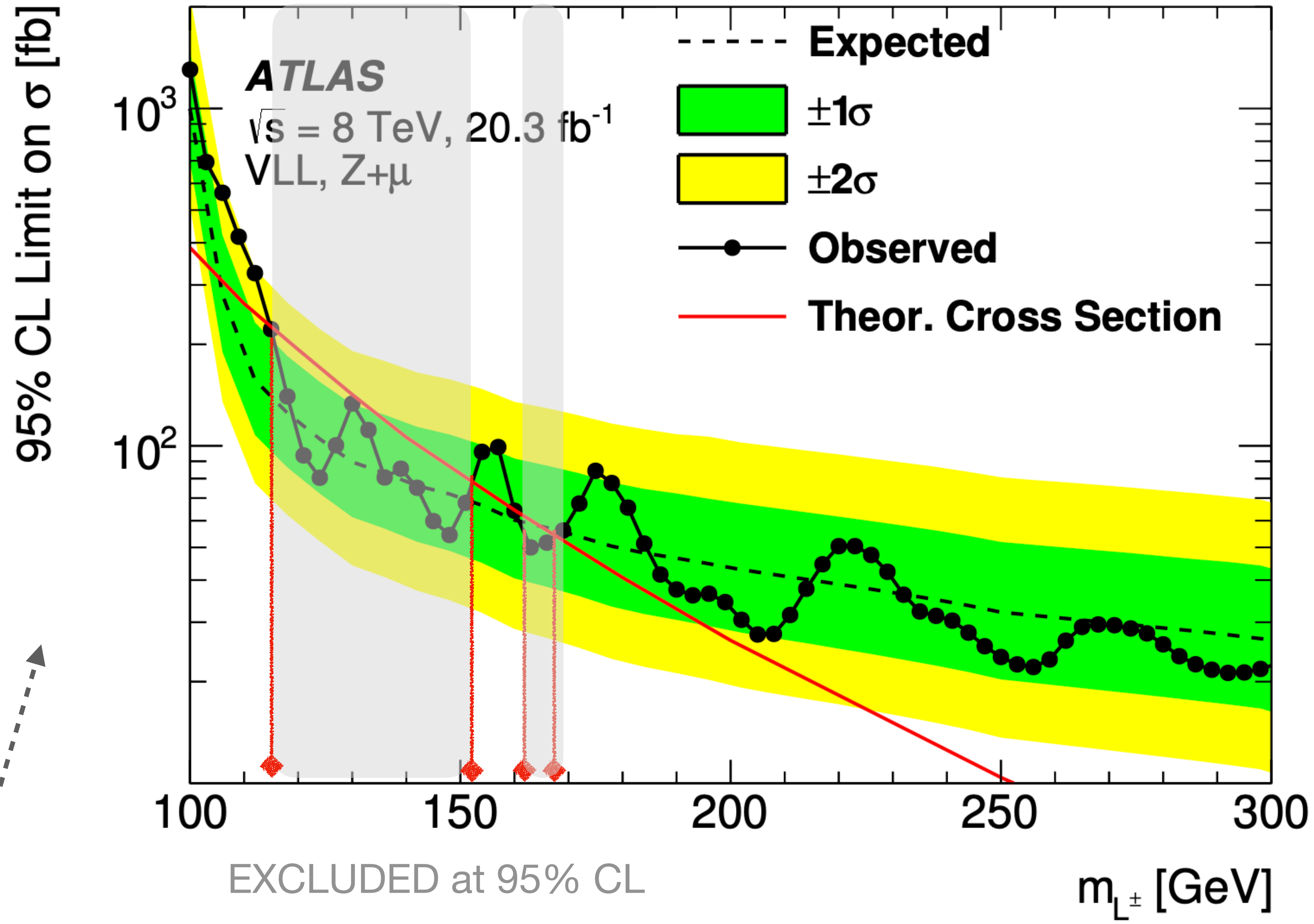
- Maximum likelihood fit to data including all signal regions and major backgrounds (WZ, ZZ).
- Excluded VLLe in mass range 129-176 GeV (except 144-163 GeV).
- Statistically limited search; strictest limits to-date

Result: Vector-like muons



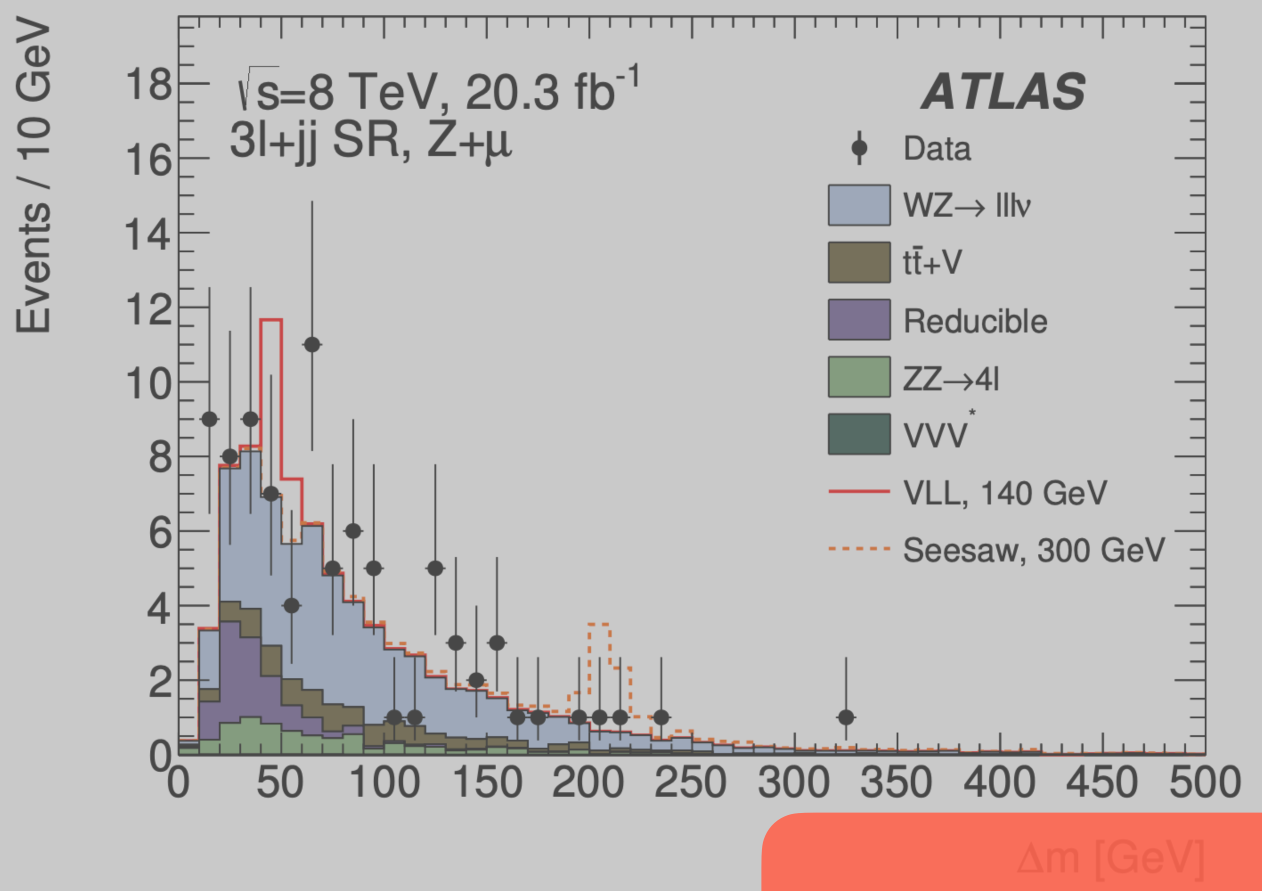


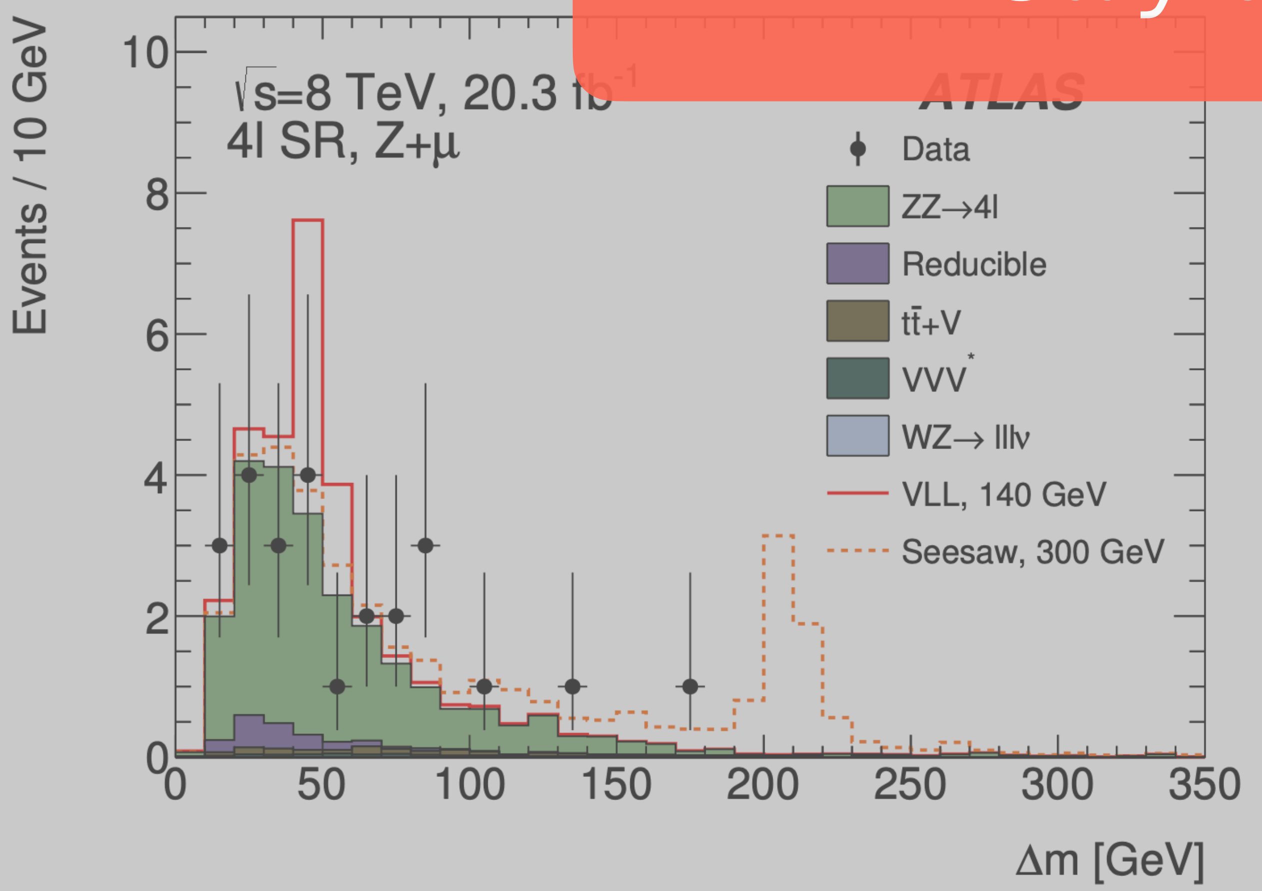


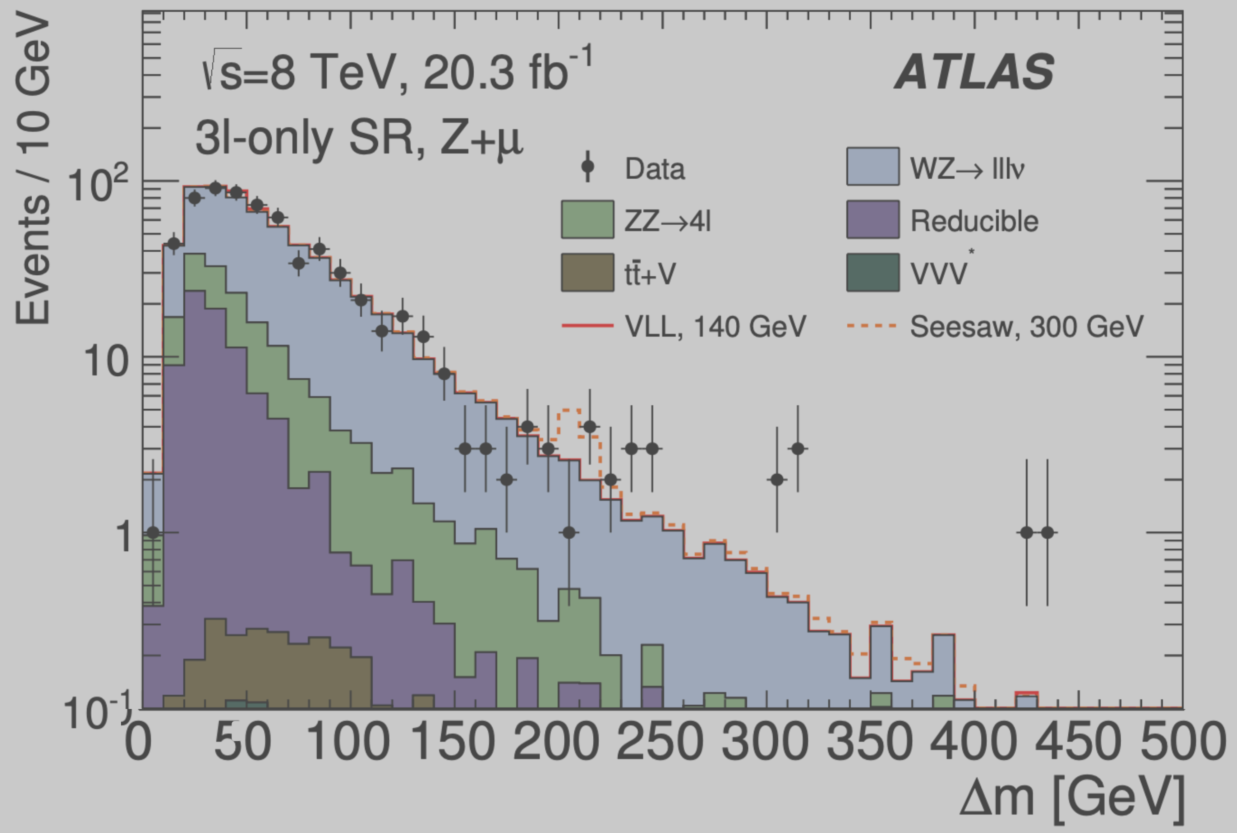


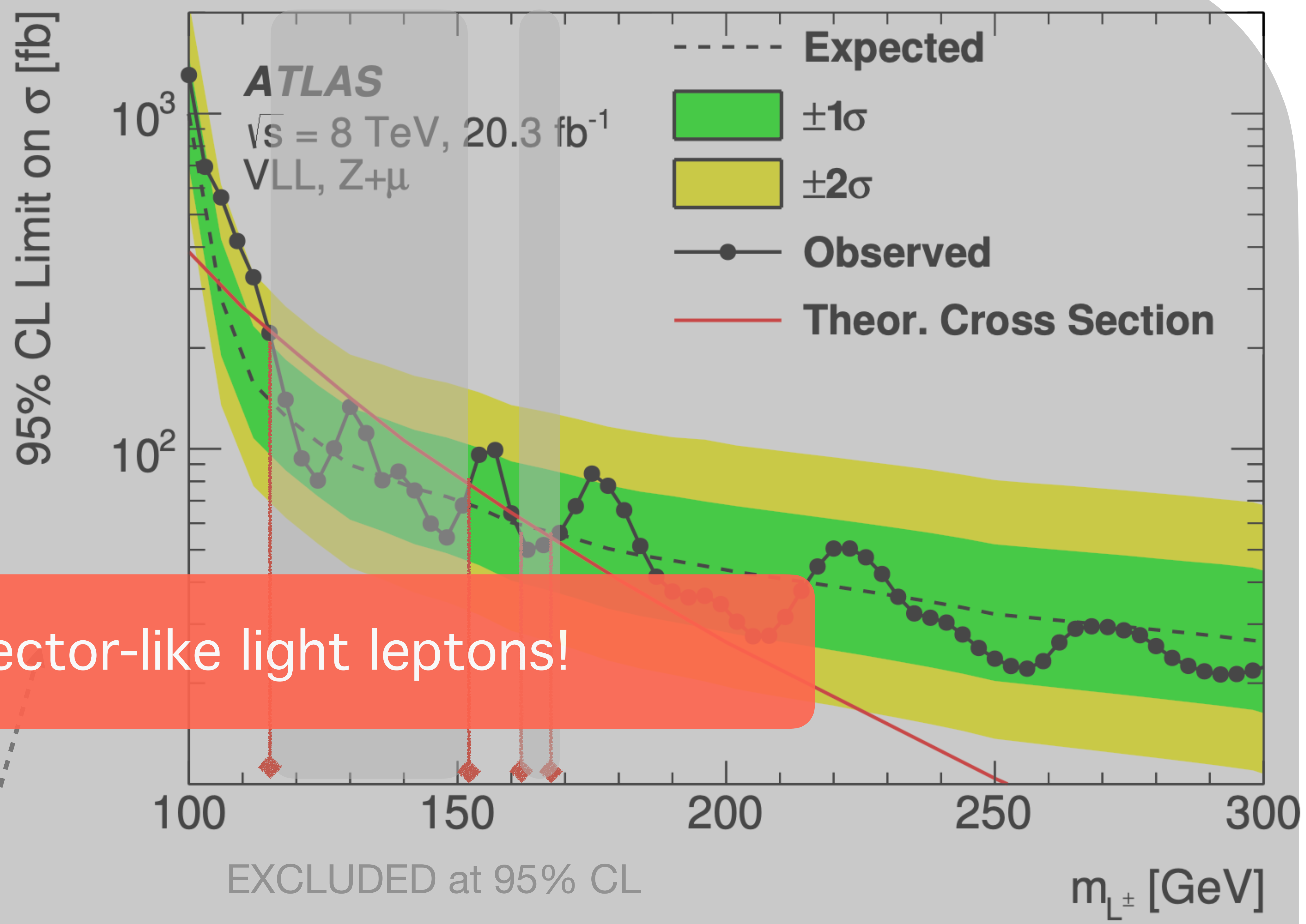
- Maximum likelihood fit to data including all signal regions and major backgrounds (WZ, ZZ).
- Excluded VLLμ in mass range 114-168 GeV (except 153-160 GeV).
- Statistically limited search; strictest limits to-date

Result: Vector-like muons









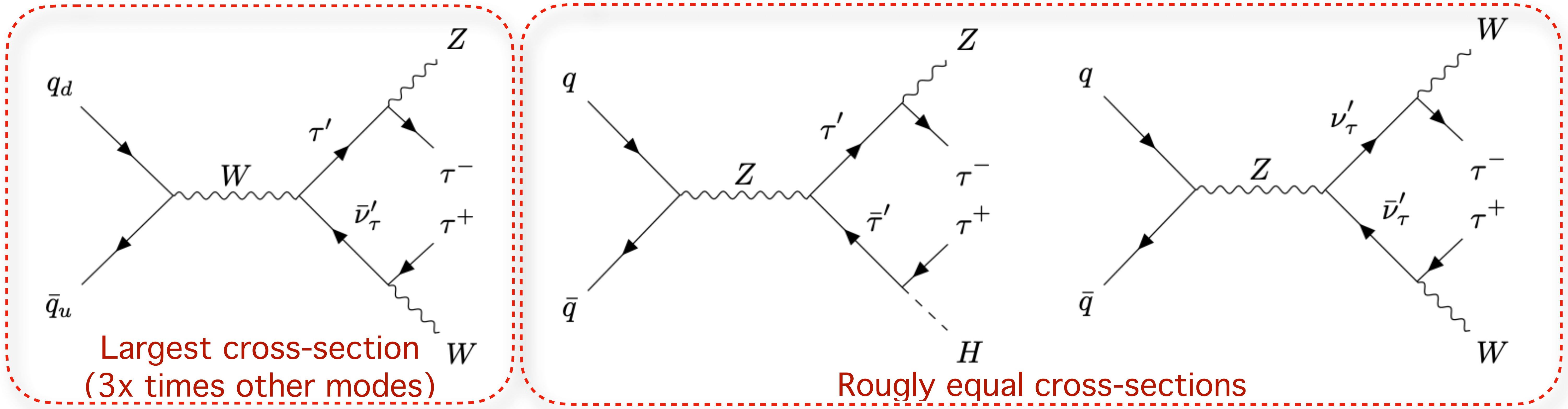
Stay tuned for updates on vector-like light leptons!

- Maximum likelihood fit to data including all signal regions and major backgrounds (WZ, ZZ).
- Excluded VLLμ in mass range 114-168 GeV (except 153-160 GeV).
- Statistically limited search; strictest limits to-date

Search for third generation vector-like leptons in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

JHEP 07 (2023) 118

Analysis Strategy



- Mass-degenerate vector-like leptons (τ' and ν'_τ) from an SU(2) doublet coupling to SM τ-leptons.
- Multilepton final states ($2l$, $3l$ and $4l$) with 0 or more hadronic taus (τ_{had}) and atleast one jet.
- State-of-art RNN for distinguish τ_{had} from quark or gluon-initiated jets.
- BDT used to maximise signal efficiency vs background rejection and control major backgrounds (backup).

$2l$ SRs | $3l$ SRs | $4l$ SRs

Variables	BDT Training Regions						
BDT	2ℓ SSSF, 1τ	2ℓ SSOF, 1τ	2ℓ OSSF, 1τ	2ℓ OSOF, 1τ	2ℓ, $\geq 2\tau$	3ℓ, $\geq 1\tau$	4ℓ, $\geq 0\tau$
N_ℓ	2	2	2	2	2	3	≥ 4
Charge/flavour	SSSF	SSOF	OSSF	OSOF	-	-	-
N_τ	1	1	1	1	≥ 2	≥ 1	≥ 0
E_T^{miss} [GeV]	≥ 120	≥ 90	≥ 60	≥ 100	≥ 60	≥ 90	≥ 60
BDT Score	≥ 0.15	≥ 0.1	≥ 0.1	≥ 0.1	≥ -0.11	≥ 0.08	≥ 0.08

High Missing transverse energy from τ_{had}

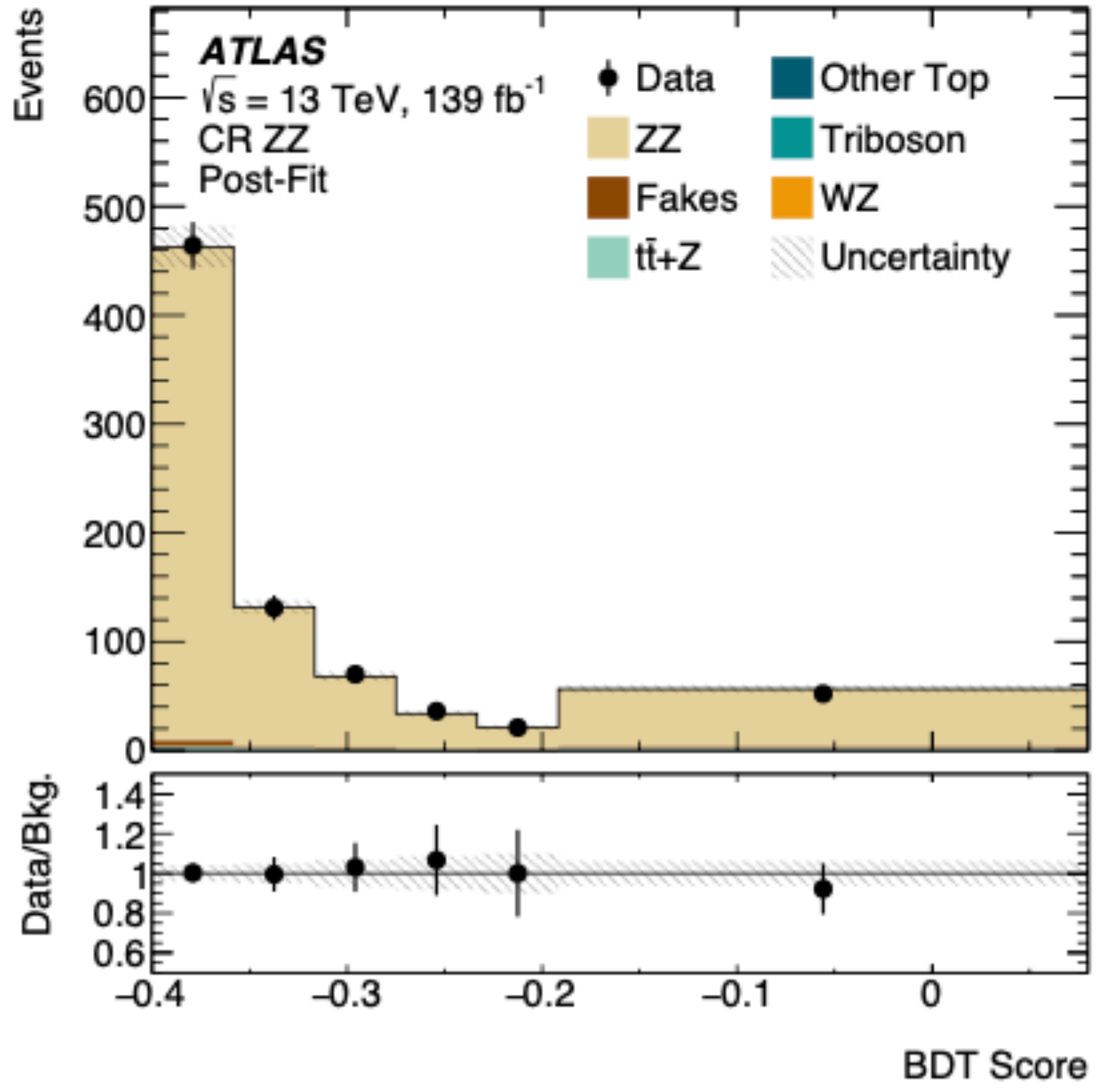
ATLAS EXPERIMENT

Analysis Strategy

- Control regions defined by modifying signal region requirements for orthogonality:

Variables	BDT Training Regions						
BDT	2ℓ SSSF, 1τ	2ℓ SSOF, 1τ	2ℓ OSSF, 1τ	2ℓ OSOF, 1τ	2ℓ, $\geq 2\tau$	3ℓ, $\geq 1\tau$	4ℓ, $\geq 0\tau$
N_ℓ	2	2	2	2	2	3	≥ 4
Charge/flavour	SSSF	SSOF	OSSF	OSOF	-	-	-
N_τ	1	1	1	1	≥ 2	≥ 1	≥ 0
E_T^{miss} [GeV]	≥ 120	≥ 90	≥ 60	≥ 100	≥ 60	≥ 90	≥ 60
BDT Score	≥ 0.15	≥ 0.1	≥ 0.1	≥ 0.1	≥ -0.11	≥ 0.08	≥ 0.08

Flip for ZZ CR

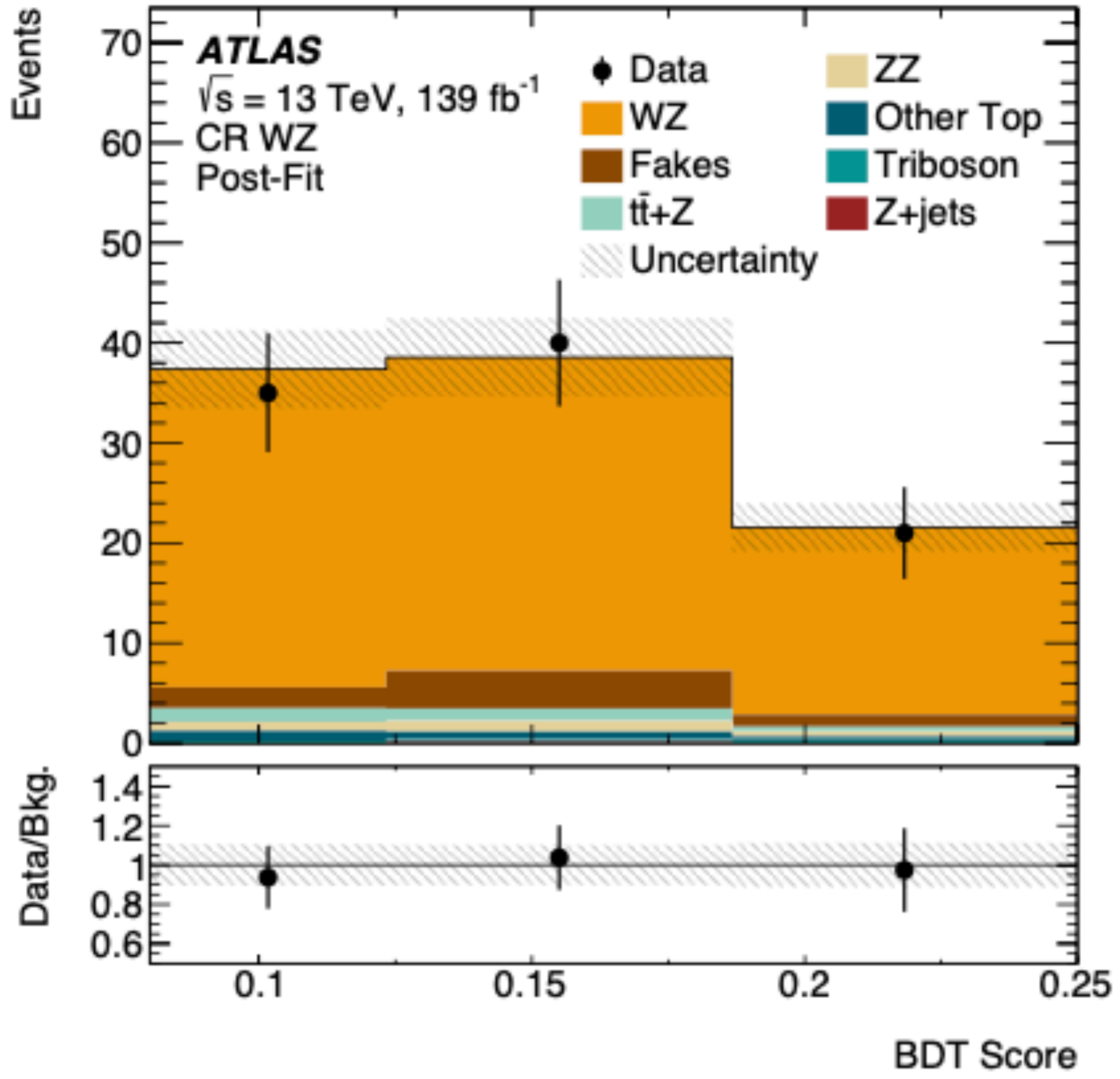


Analysis Strategy

- Control regions defined by modifying signal region requirements for orthogonality:

Variables	BDT Training Regions						
BDT	2ℓ SSSF, 1τ	2ℓ SSOF, 1τ	2ℓ OSSF, 1τ	2ℓ OSOF, 1τ	2ℓ, $\geq 2\tau$	3ℓ, $\geq 1\tau$	4ℓ, $\geq 0\tau$
N_ℓ	2	2	2	2	2	3	≥ 4
Charge/flavour	SSSF	SSOF	OSSF	OSOF	-	-	-
N_τ	1	1	1	1	≥ 2	≥ 1	≥ 0
E_T^{miss} [GeV]	≥ 120	≥ 90	≥ 60	≥ 100	≥ 60	≥ 90	≥ 60
BDT Score	≥ 0.15	≥ 0.1	≥ 0.1	≥ 0.1	≥ -0.11	≥ 0.08	≥ 0.08

$=0\tau_{had}$ for WZ CR

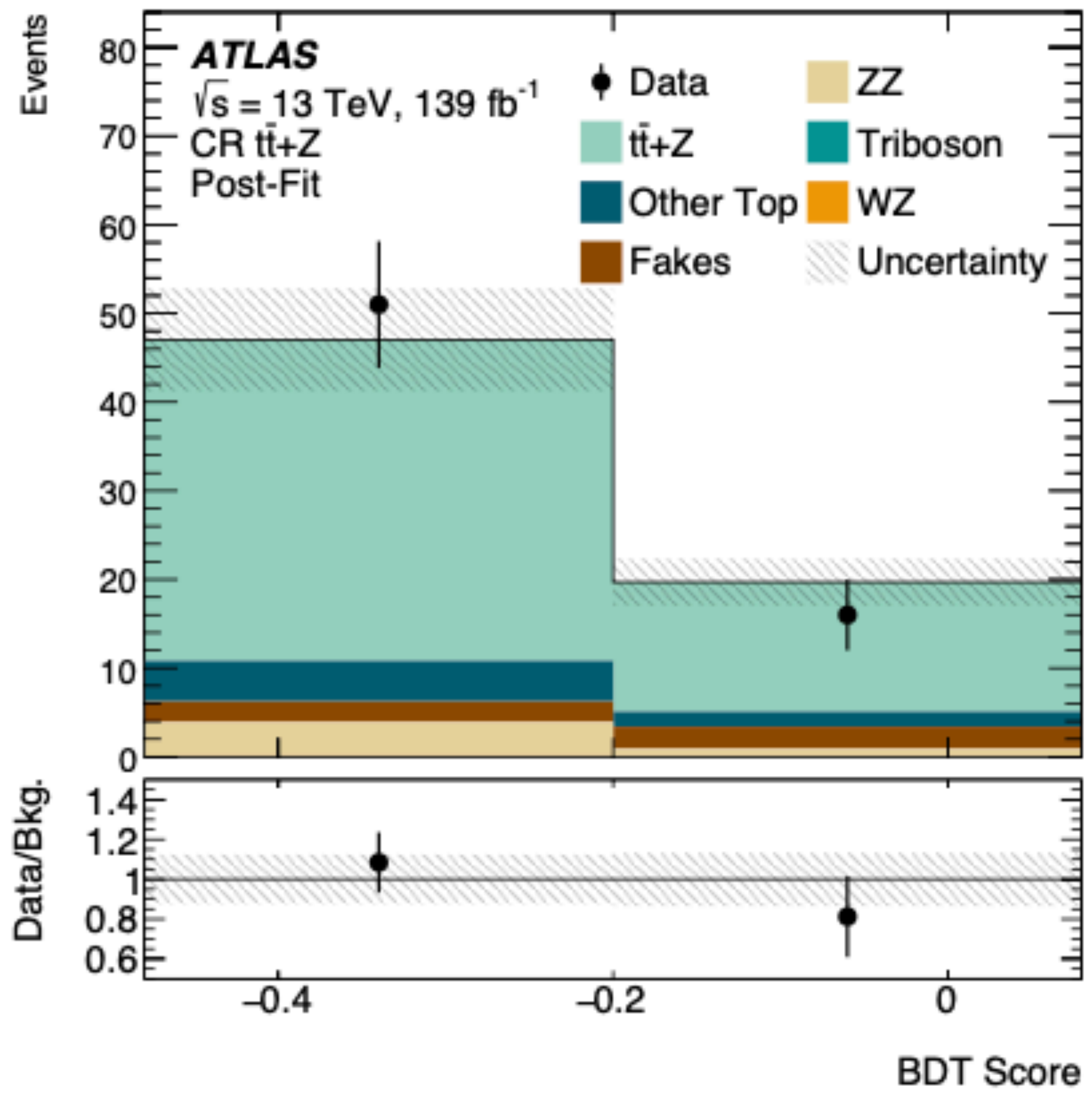


Analysis Strategy

- Control regions defined by modifying signal region requirements for orthogonality:

Variables	BDT Training Regions						
BDT	2ℓ SSSF, 1τ	2ℓ SSOF, 1τ	2ℓ OSSF, 1τ	2ℓ OSOF, 1τ	2ℓ, $\geq 2\tau$	3ℓ, $\geq 1\tau$	4ℓ, $\geq 0\tau$
N_ℓ	2	2	2	2	2	3	≥ 4
Charge/flavour	SSSF	SSOF	OSSF	OSOF	-	-	-
N_τ	1	1	1	1	≥ 2	≥ 1	≥ 0
E_T^{miss} [GeV]	≥ 120	≥ 90	≥ 60	≥ 100	≥ 60	≥ 90	≥ 60
BDT Score	≥ 0.15	≥ 0.1	≥ 0.1	≥ 0.1	≥ -0.11	≥ 0.08	≥ 0.08

$=0\tau_{had}$ for ttZ CR

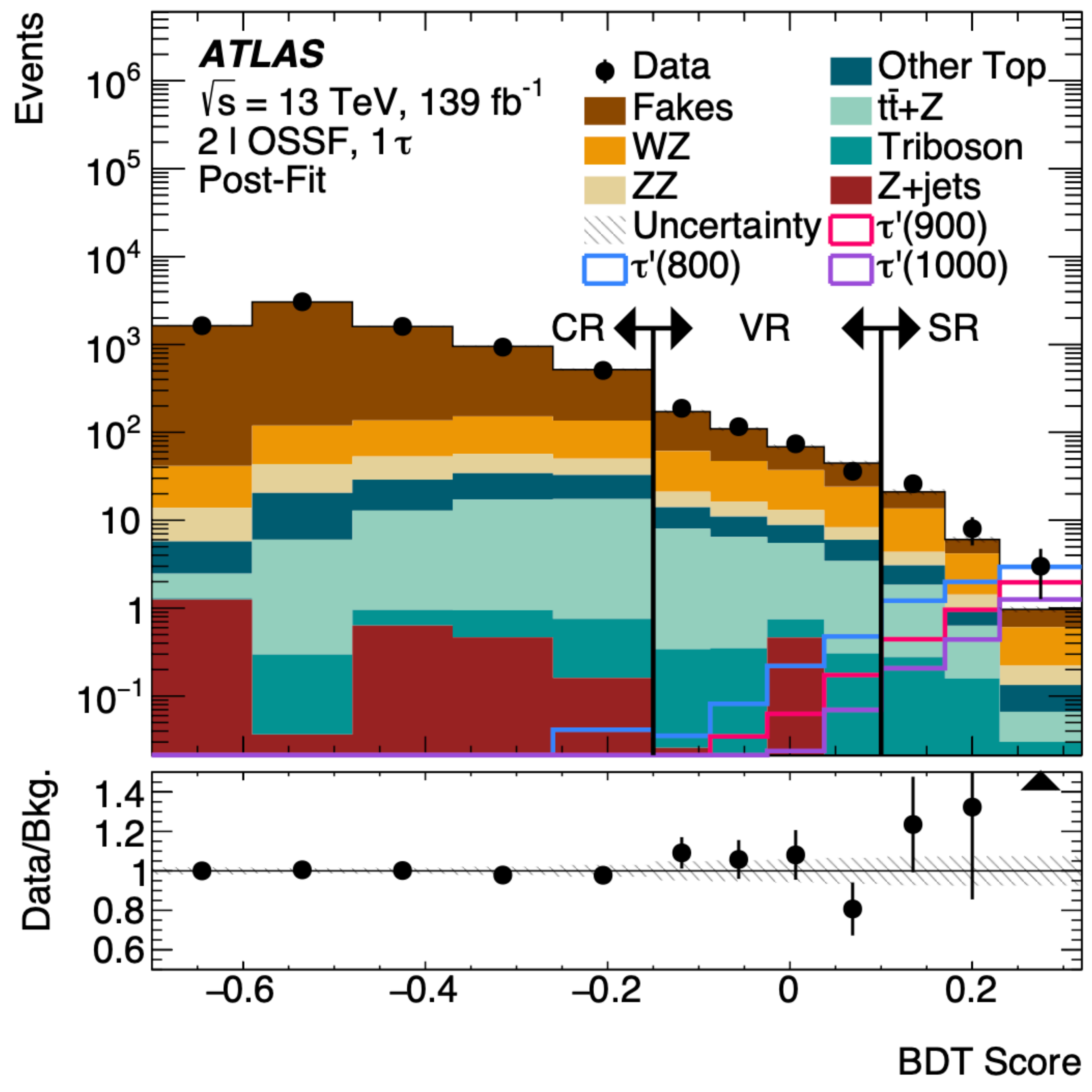


Analysis Strategy

- Control regions defined by modifying signal region requirements for orthogonality:

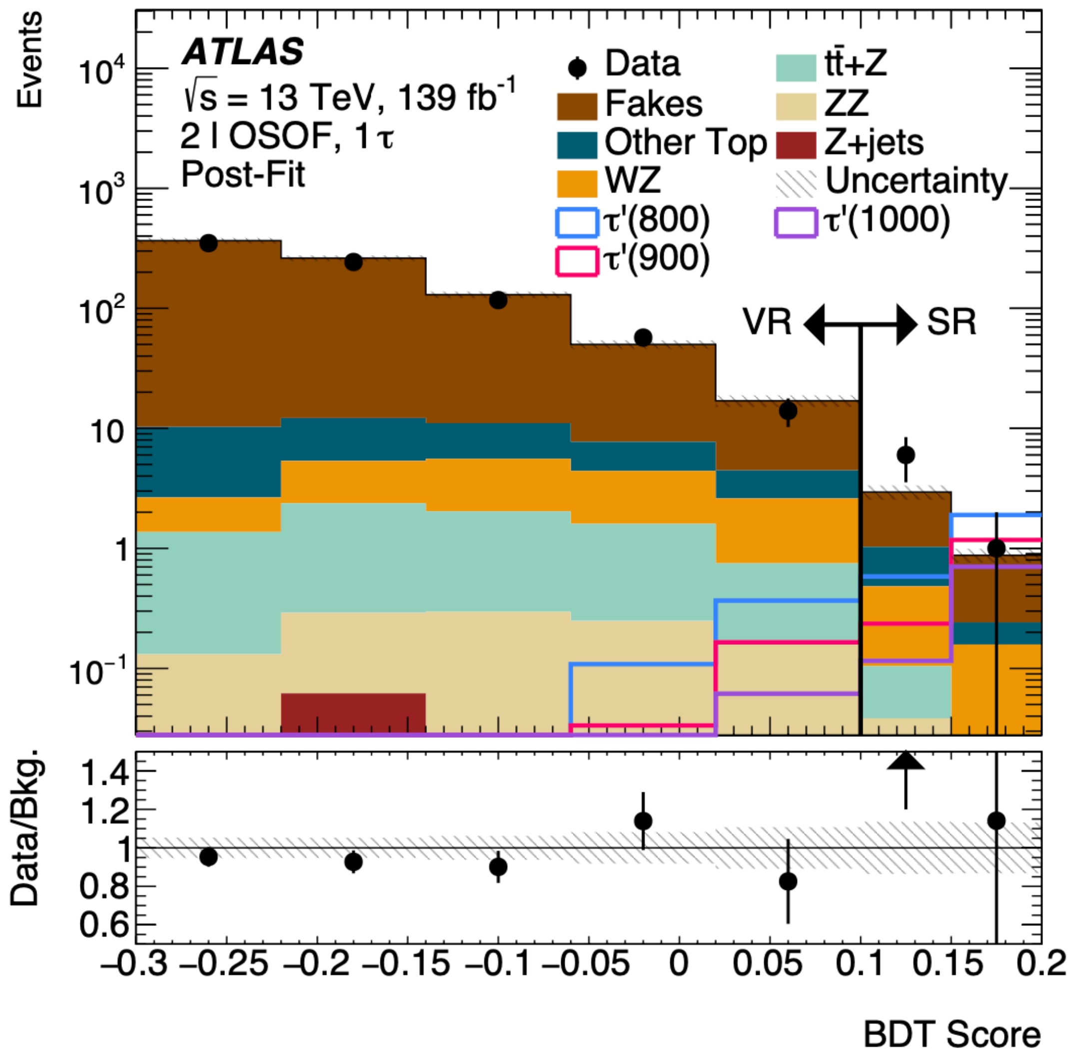
Variables	BDT Training Regions						
BDT	2ℓ SSSF, 1τ	2ℓ SSOF, 1τ	2ℓ OSSF, 1τ	2ℓ OSOF, 1τ	2ℓ, $\geq 2\tau$	3ℓ, $\geq 1\tau$	4ℓ, $\geq 0\tau$
N_ℓ	2	2	2	2	2	3	≥ 4
Charge/flavour	SSSF	SSOF	OSSF	OSOF	-	-	-
N_τ	1	1	1	1	≥ 2	≥ 1	≥ 0
E_T^{miss} [GeV]	≥ 120	≥ 90	≥ 60	≥ 100	≥ 60	≥ 90	≥ 60
BDT Score	≥ 0.15	≥ 0.1	≥ 0.1	≥ 0.1	≥ -0.11	≥ 0.08	≥ 0.08

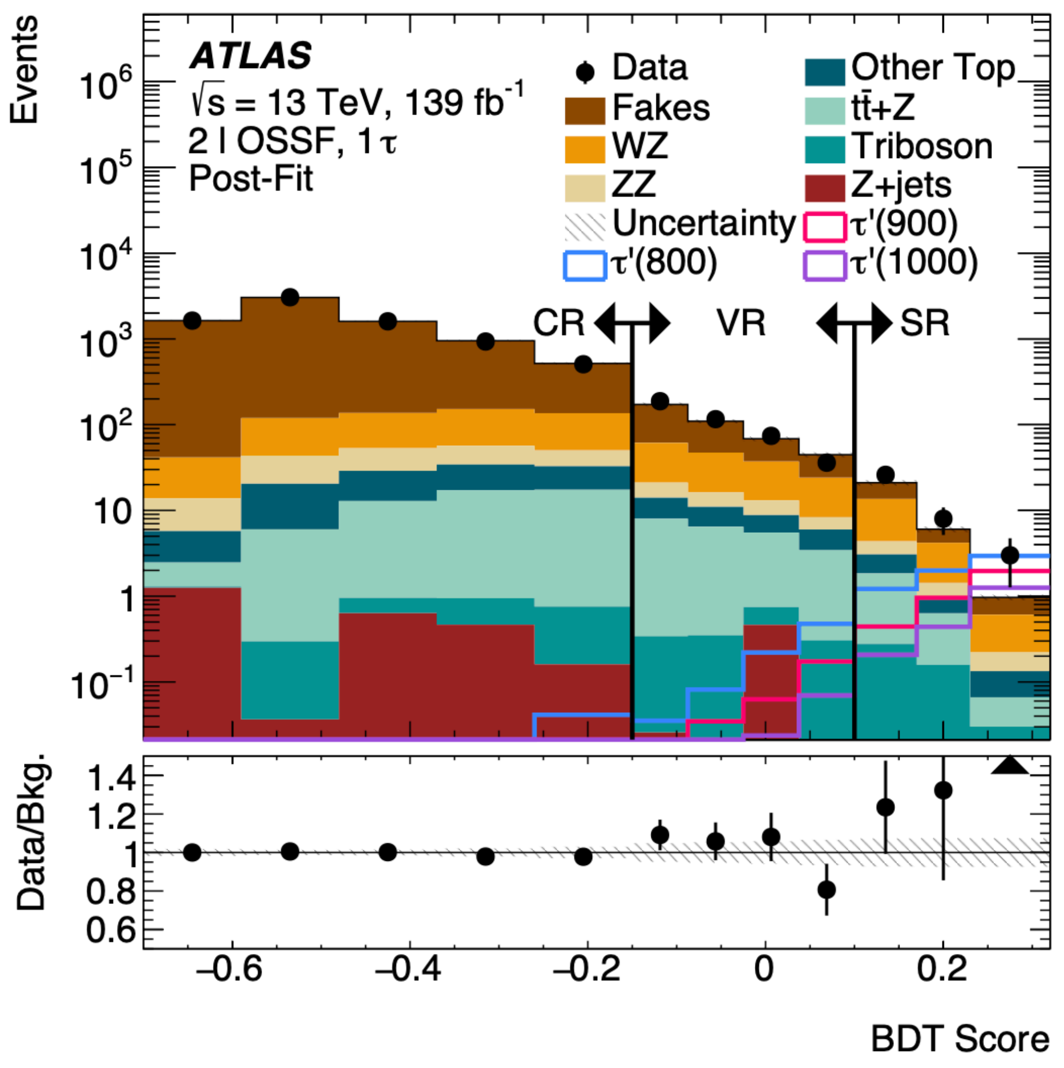
Flip for fake τ_{had} CR

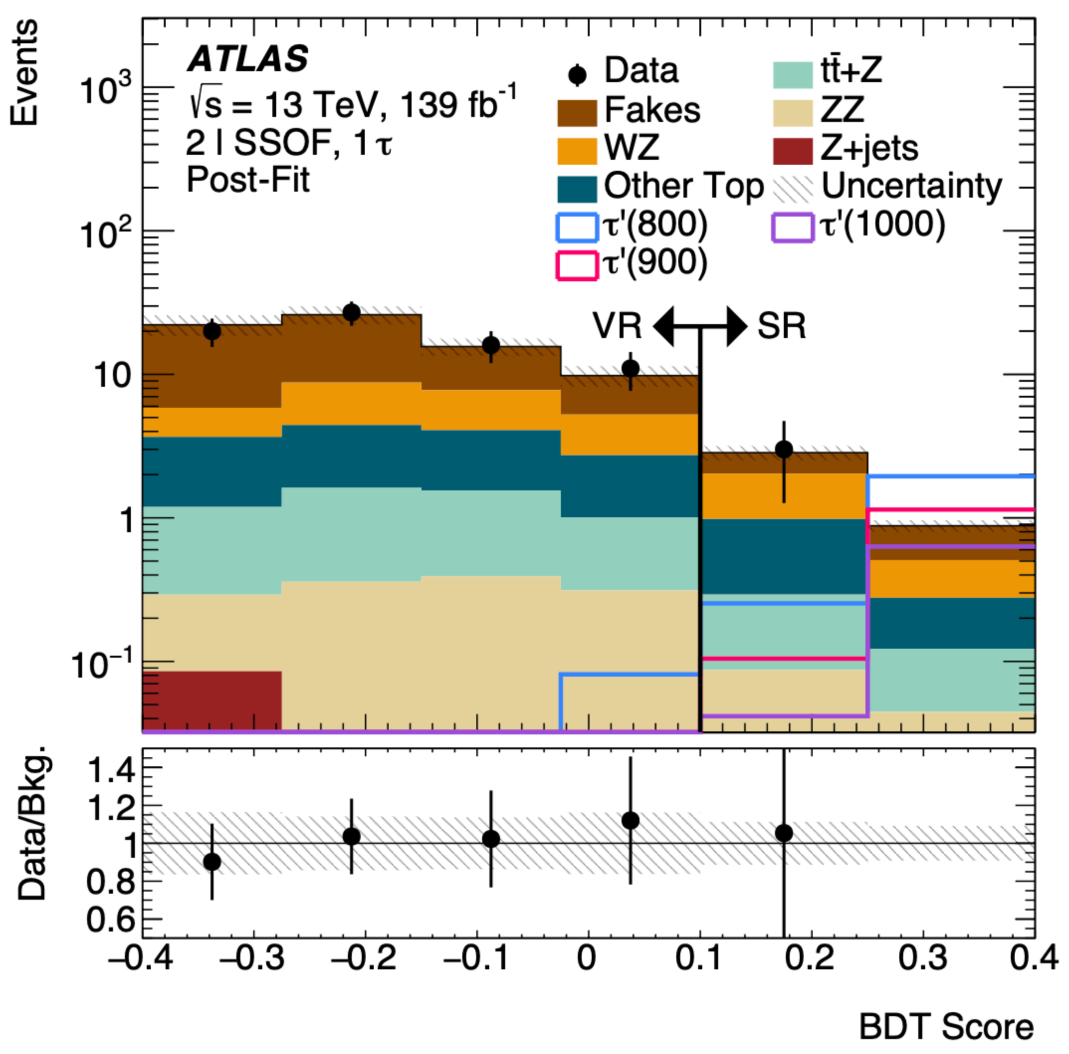


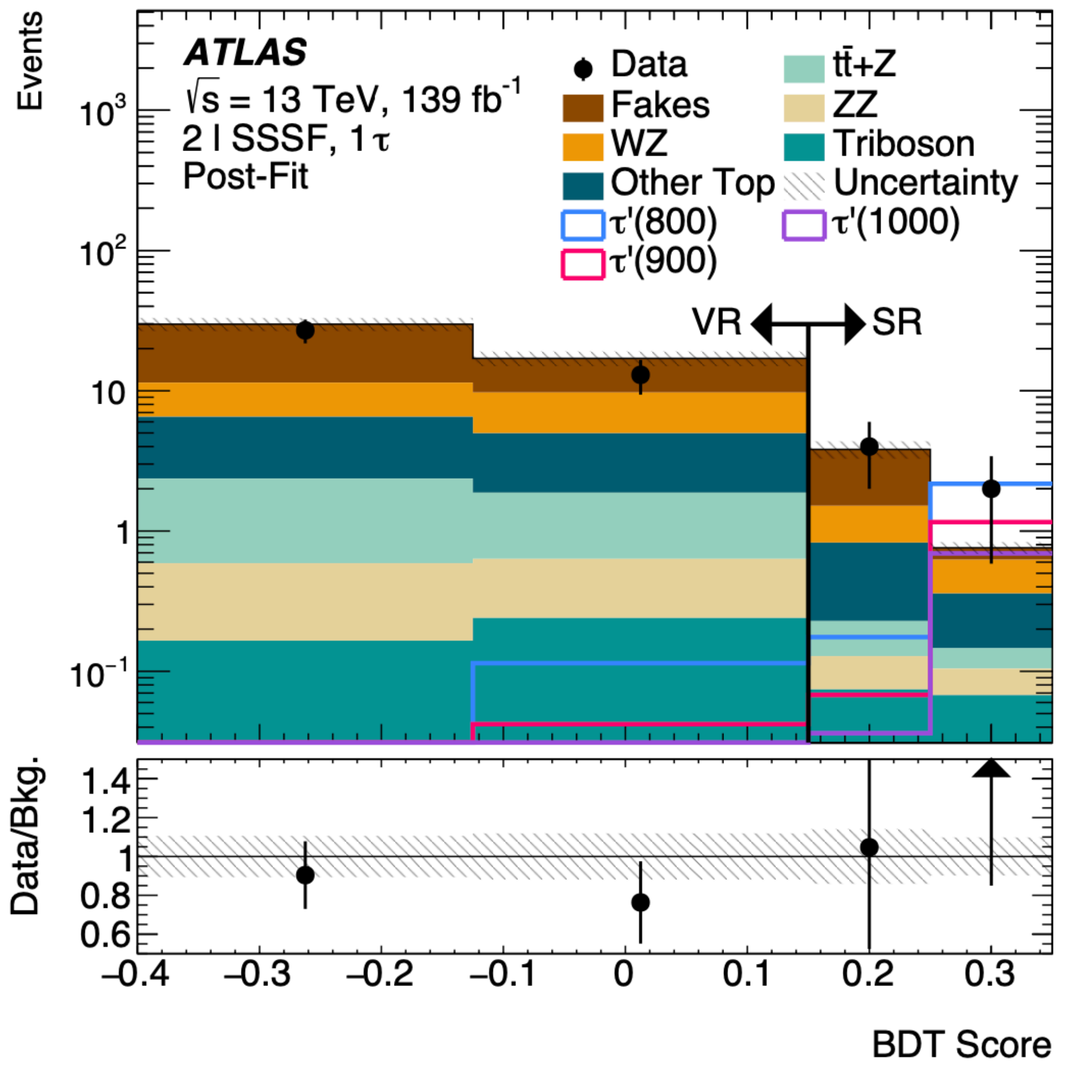
Analysis regions

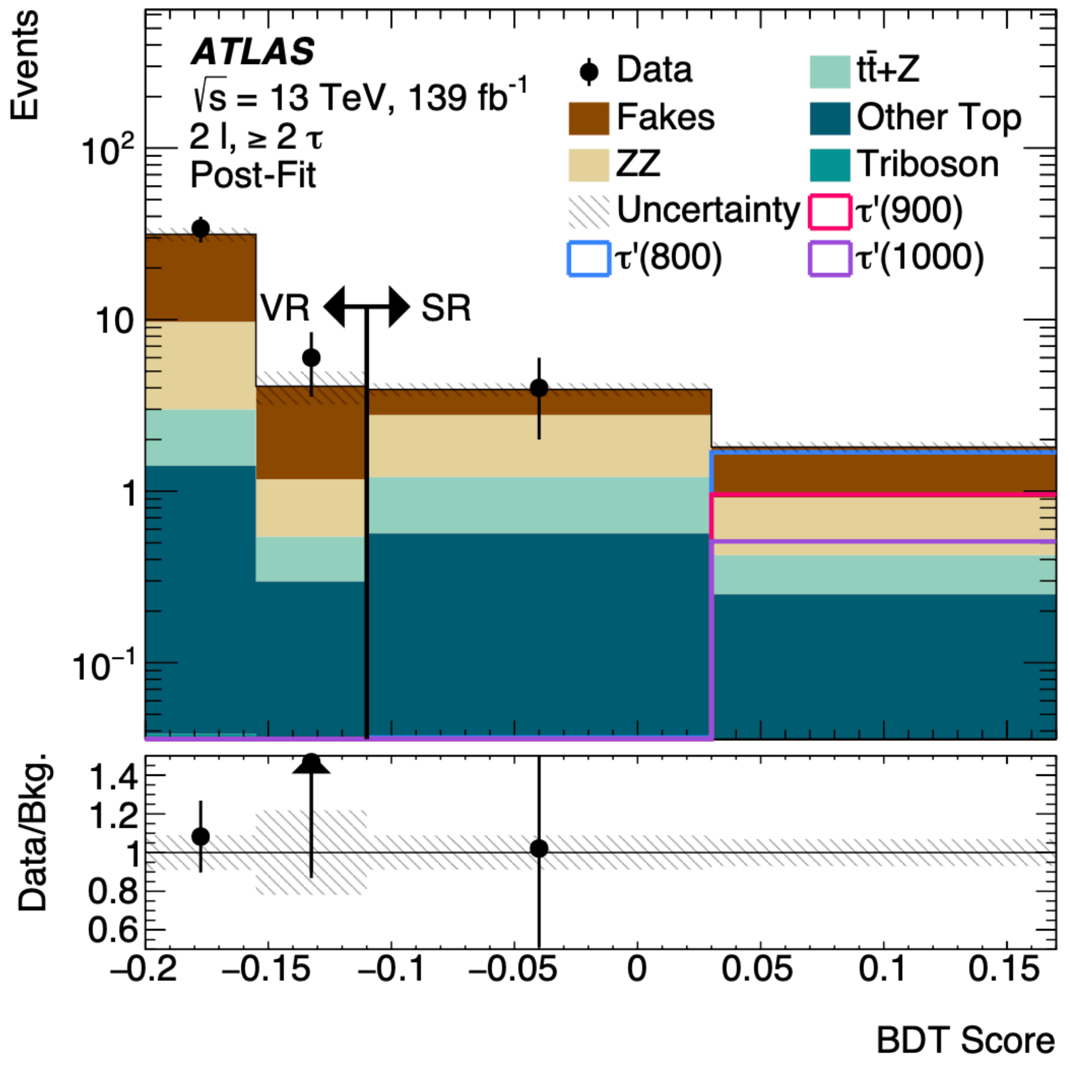
- ‘High’ BDT score regions serve as signal regions; inverting the BDT cut serves as validation.

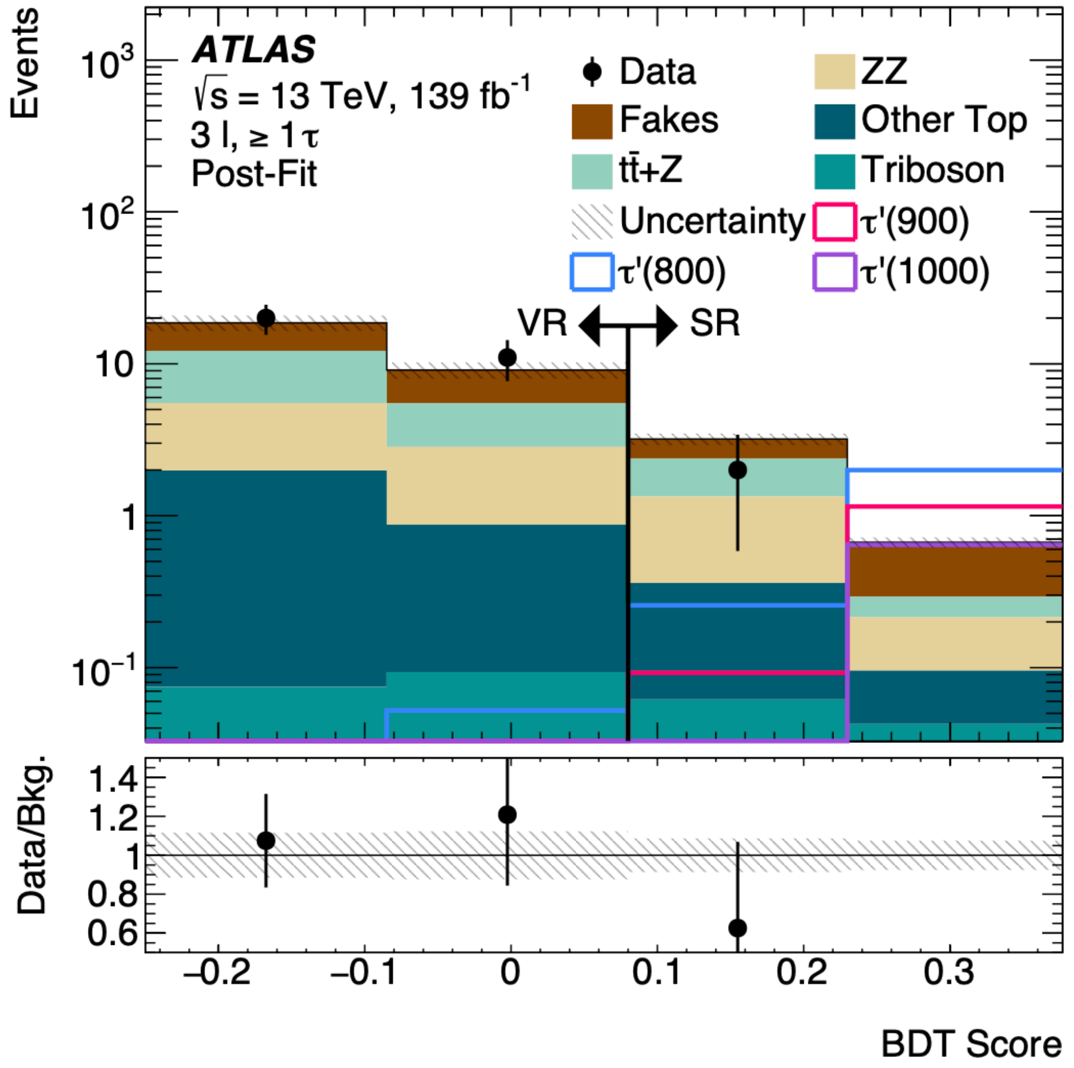


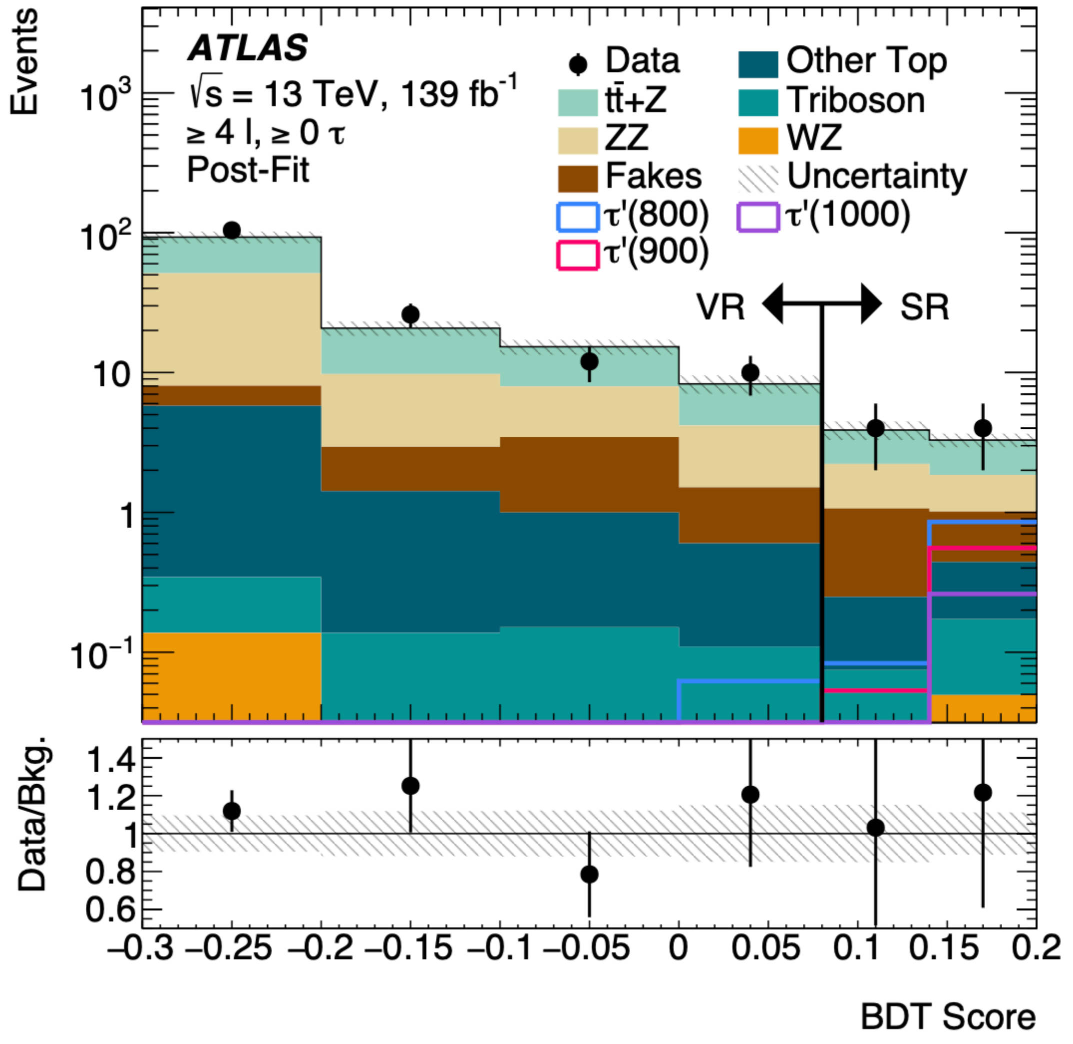






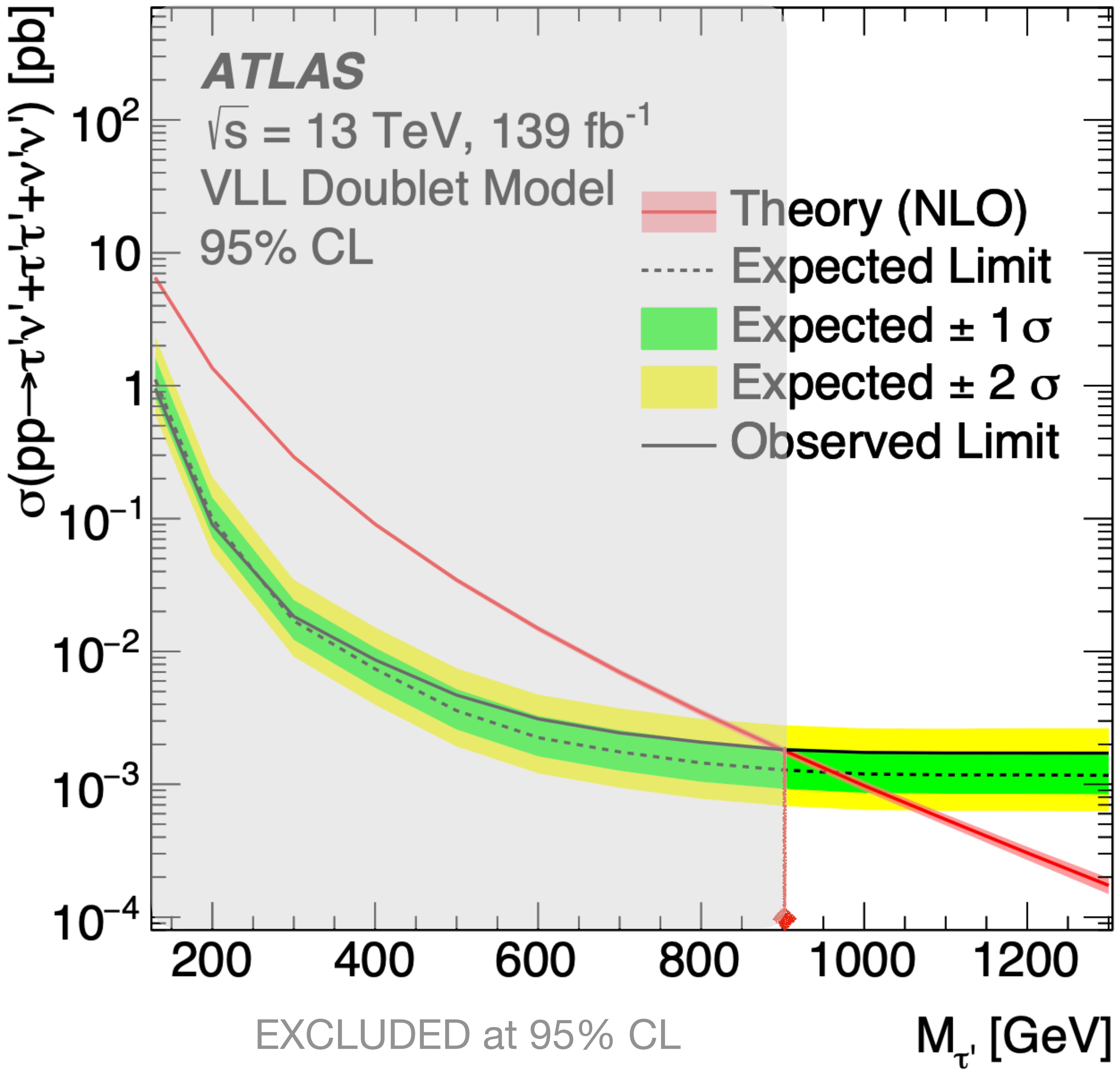






Result: Vector-like taus

- Maximum likelihood fit to data including all signal regions and major backgrounds (WZ, ZZ, ttZ, fake τ_{had}).
- No mass-senstivity in BDT.
- Excluded VLLτ in mass range 130-900 GeV.
- Statistically limited search.



Summary

- Vector-like Leptons (VLL) searches are relatively new:
  - Appear in many UV complete models: composite Higgs, '4321', warped extra dimensions.
  - May explain the persistent $(g-2)_{\mu}$, Cabibbo angle anomaly, neutrino masses, flavor anomalies.
- Broad program for searches for vector-like leptons in ATLAS:
  - (Run 1) Search for heavy lepton resonances decaying to a Z boson and leptons, with sensitivity to light VLLs from an SU(2) singlet model, available at JHEP 09 (2015) 108.
  - (Run 2) Search for third generation VLLs from an SU(2) doublet model, available at JHEP 07 (2023) 118.
- Both searches place 95% CL on different VLL models and are statistically-limited!
- Stay tuned for fresh results on VLLs from the ATLAS experiment!

ATLAS EXPERIMENT

Backup

BDT

Variable	Description
E_T^{miss}	The missing transverse momentum in the event
$\mathcal{S}(E_T^{miss})$	The missing transverse momentum's significance in the event
L_T	The scalar sum of light lepton p_T in the event
$L_T + E_T^{miss}$	The scalar sum of light lepton p_T and the missing transverse momentum in the event
$L_T + p_T(\tau)$	The scalar sum of light lepton p_T and τ-lepton p_T in the event
$p_T(\ell_1)$	The leading light lepton's p_T in the event
$p_T(\ell_2)$	The sub-leading light lepton's p_T in the event
$p_T(j_1)$	The leading jet's p_T in the event
$p_T(\tau_1)$	The leading τ-lepton's p_T in the event
N_j	The number of jets in the event
N_b	The number of b-jets in the event
H_T	The scalar sum of jet p_T in the event
$L_T + H_T$	The scalar sum of light lepton p_T and jet p_T in the event
$M_{\ell\ell}$	The invariant mass of all light leptons in the event
$M_{\ell\tau}$	The invariant mass of all light leptons and τ-leptons in the event
$M_{\ell j}$	The invariant mass of all light leptons and jets in the event
M_{jj}	The invariant mass of all jets in the event
$M_{j\tau}$	The invariant mass of all jets and τ-leptons in the event
M_T	The transverse mass of the leading light lepton and E_T^{miss} in the event
M_{OSSF}	The invariant mass of the opposite-sign same-flavour light-lepton pair closest to the Z mass in the event
$\Delta\phi(j_1 E_T^{miss})$	$\Delta\phi$ between the leading p_T jet in the event and E_T^{miss}
$\Delta\phi(\ell_1 E_T^{miss})$	$\Delta\phi$ between the leading p_T light lepton in the event and E_T^{miss}
$\Delta\phi(\ell_1\ell_2)$	$\Delta\phi$ between the leading and sub-leading p_T light leptons in the event
$\Delta\phi(\ell_1 j_1)$	$\Delta\phi$ between the leading p_T light lepton and jet in the event
$\Delta\phi(\tau_1 E_T^{miss})$	$\Delta\phi$ between the leading p_T τ-lepton in the event and E_T^{miss}
$\Delta\phi(\ell_1\tau_1)$	$\Delta\phi$ between the leading p_T light lepton and τ-lepton in the event
$\Delta\phi(j_1\tau_1)$	$\Delta\phi$ between the leading p_T jet and τ-lepton in the event
$\Delta R(j_1 E_T^{miss})$	ΔR between the leading p_T jet in the event and E_T^{miss}
$\Delta R(\ell_1 E_T^{miss})$	ΔR between the leading p_T light lepton in the event and E_T^{miss}
$\Delta R(\ell_1\ell_2)$	ΔR between the leading and sub-leading p_T light leptons in the event
$\Delta R(\ell_1 j_1)$	ΔR between the leading p_T light lepton and jet in the event
$\Delta R(\tau_1 E_T^{miss})$	ΔR between the leading p_T τ-lepton in the event and E_T^{miss}
$\Delta R(\ell_1\tau_1)$	ΔR between the leading p_T light lepton and τ-lepton in the event
$\Delta R(j_1\tau_1)$	ΔR between the leading p_T jet and τ-lepton in the event

[JHEP 07 (2023) 118]

List of the input variables used to train the BDT. The final set is reduced by assessing the impact of removing the lowest-ranked variables on the ROC score for each training region independently.

Analysis Strategy

JHEP 07 (2023) 118

Variables	BDT Training Regions						
BDT	2ℓ SSSF, 1τ	2ℓ SSOF, 1τ	2ℓ OSSF, 1τ	2ℓ OSOF, 1τ	2ℓ, $\geq 2\tau$	3ℓ, $\geq 1\tau$	4ℓ, $\geq 0\tau$
N_ℓ	2	2	2	2	2	3	≥ 4
Charge/flavour	SSSF	SSOF	OSSF	OSOF	-		-
N_τ	1	1	1	1	≥ 2	≥ 1	≥ 0
E_T^{miss} [GeV]	≥ 120	≥ 90	≥ 60	≥ 100	≥ 60	≥ 90	≥ 60

0T for WZ CR

Flip for ZZ VR

Flip for ZZ CR

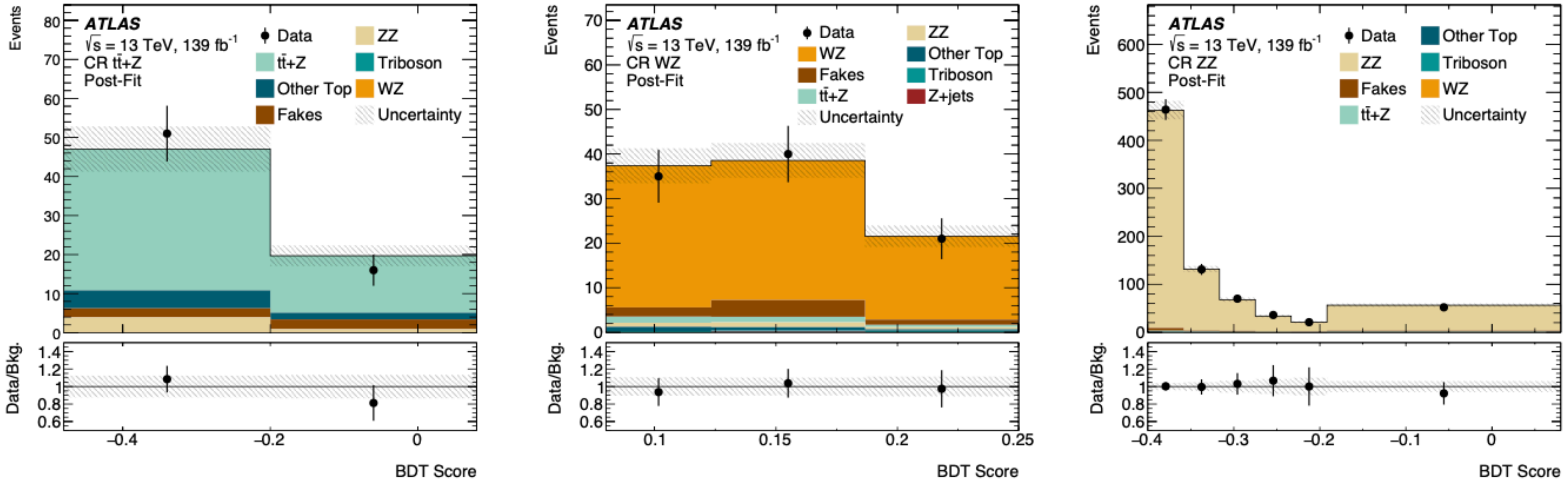
Variables	Signal Regions						
BDT	2ℓ SSSF, 1τ	2ℓ SSOF, 1τ	2ℓ OSSF, 1τ	2ℓ OSOF, 1τ	2ℓ, $\geq 2\tau$	3ℓ, $\geq 1\tau$	4ℓ, $\geq 0\tau$
BDT Score	≥ 0.15	≥ 0.1	≥ 0.1	≥ 0.1	≥ -0.11	≥ 0.08	≥ 0.08

Flip for ttZ VR

Flip for ttZ CR

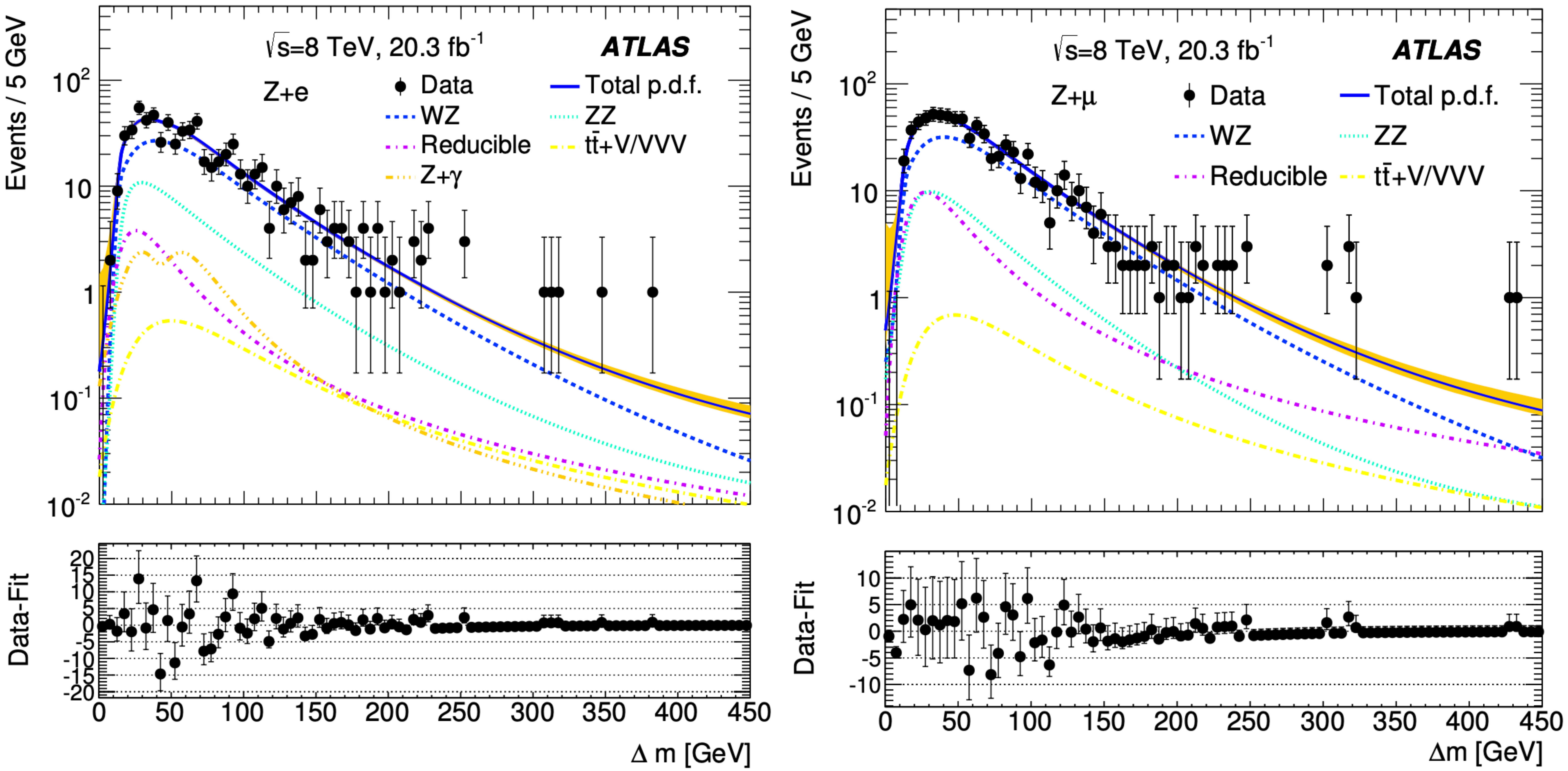
Flip for WZ VR

<-0.15 for tauhad CR



Results

JHEP 09 (2015) 108



- Projections on to the Δm variable of the background-only unbinned maximum likelihood fits for all three channels