Recent searches for new phenomena with the ATLAS detector

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on behalf of the ATLAS collaboration

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The Standard Model and Searches for New Phenomena

- The SM while successful is incomplete for a multitude of reasons
  - Hierarchy problem
  - CP violation
  - Neutrino masses
  - Dark matter

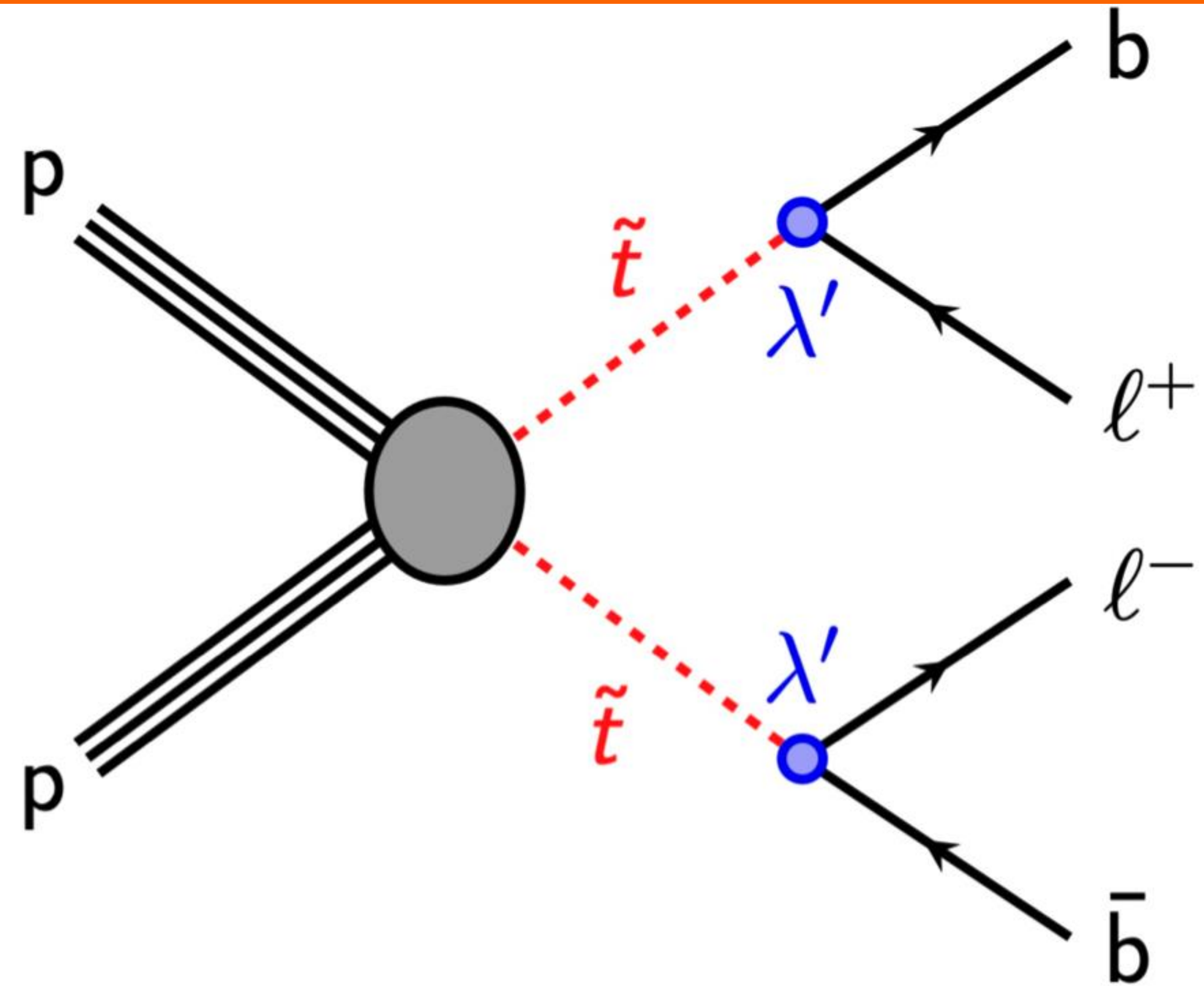
The Standard Model and Searches for New Phenomena

- The SM while successful is incomplete for a multitude of reasons
  - Hierarchy problem
  - CP violation
  - Neutrino masses
  - Dark matter
- Various BSM theories available to ”shield” us from the issues of the SM
- ATLAS physics program actively investigates many of these extensions for new phenomena
  - Unfortunately, I can’t cover every ATLAS analysis so I will present my (biased) selection of interesting results

SUSY searches

- An extension predicting bosonic(fermionic) super-partners of SM fermions(bosons)
- Would allow for processes that violate both baryon number (B) and lepton number (L) => proton decay
  - The typical solution is to impose R-parity conservation (RPC) defined as
$$R = (-1)^{3(B-L)+2s}$$
  - Alternatively, allow for L violation within currents bounds and entirely avoid B violation to ensure proton stability => R-parity violating (RPV) SUSY
- RPC SUSY leads to stable lightest SUSY partner (LSP) => dark matter candidate?
  - RPV SUSY leads to LSP decaying to SM particles

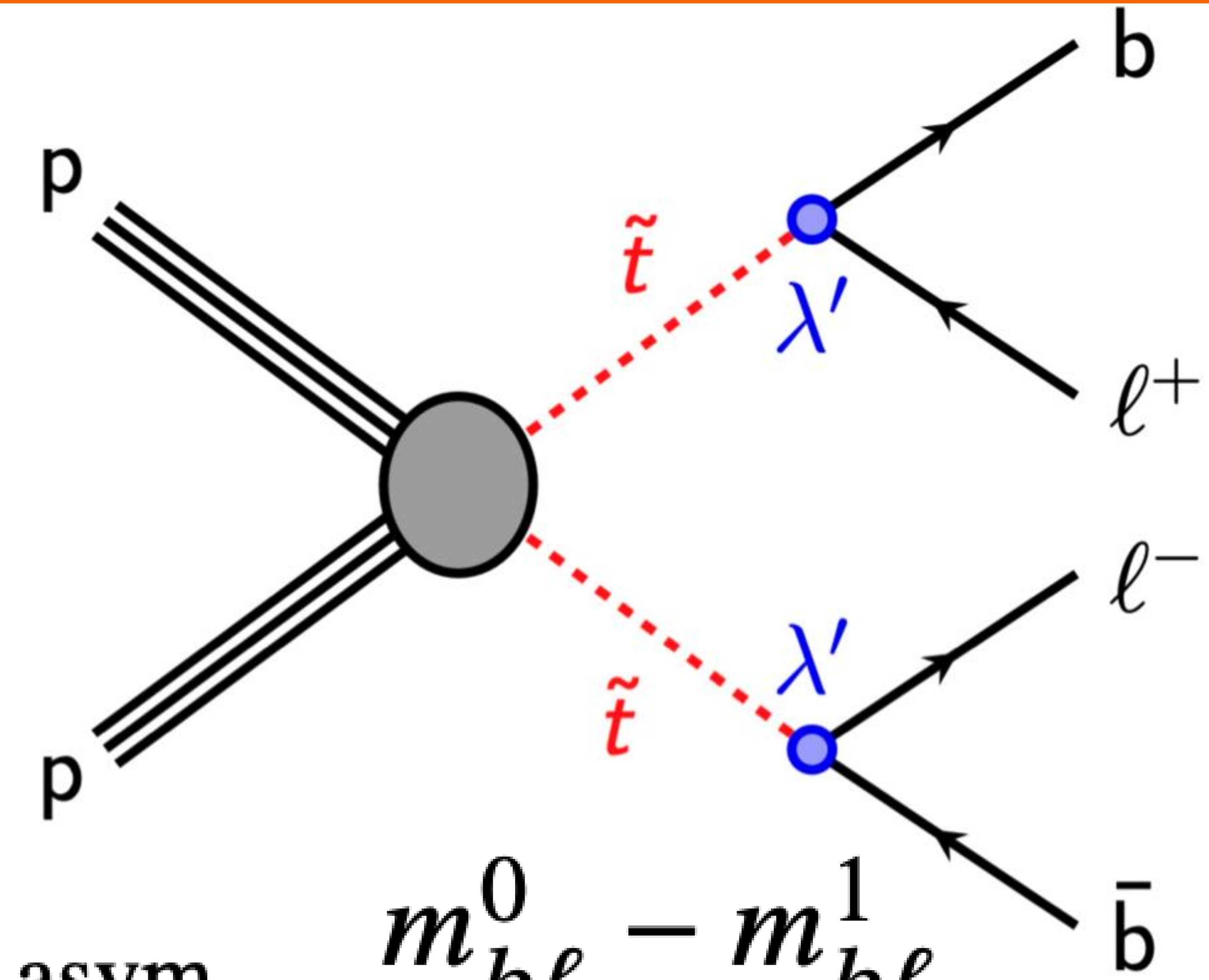
- R-parity violation but conserve $B - L$
- Rate of PP stop via strong interaction > PP electroweak gauginos => stop is LSP candidate
- Final state composed of two OS leptons and two b-jets



$\tilde{t} \rightarrow b\ell$ in RPV SUSY

Phys. Rev. D 110 (2024) 092004

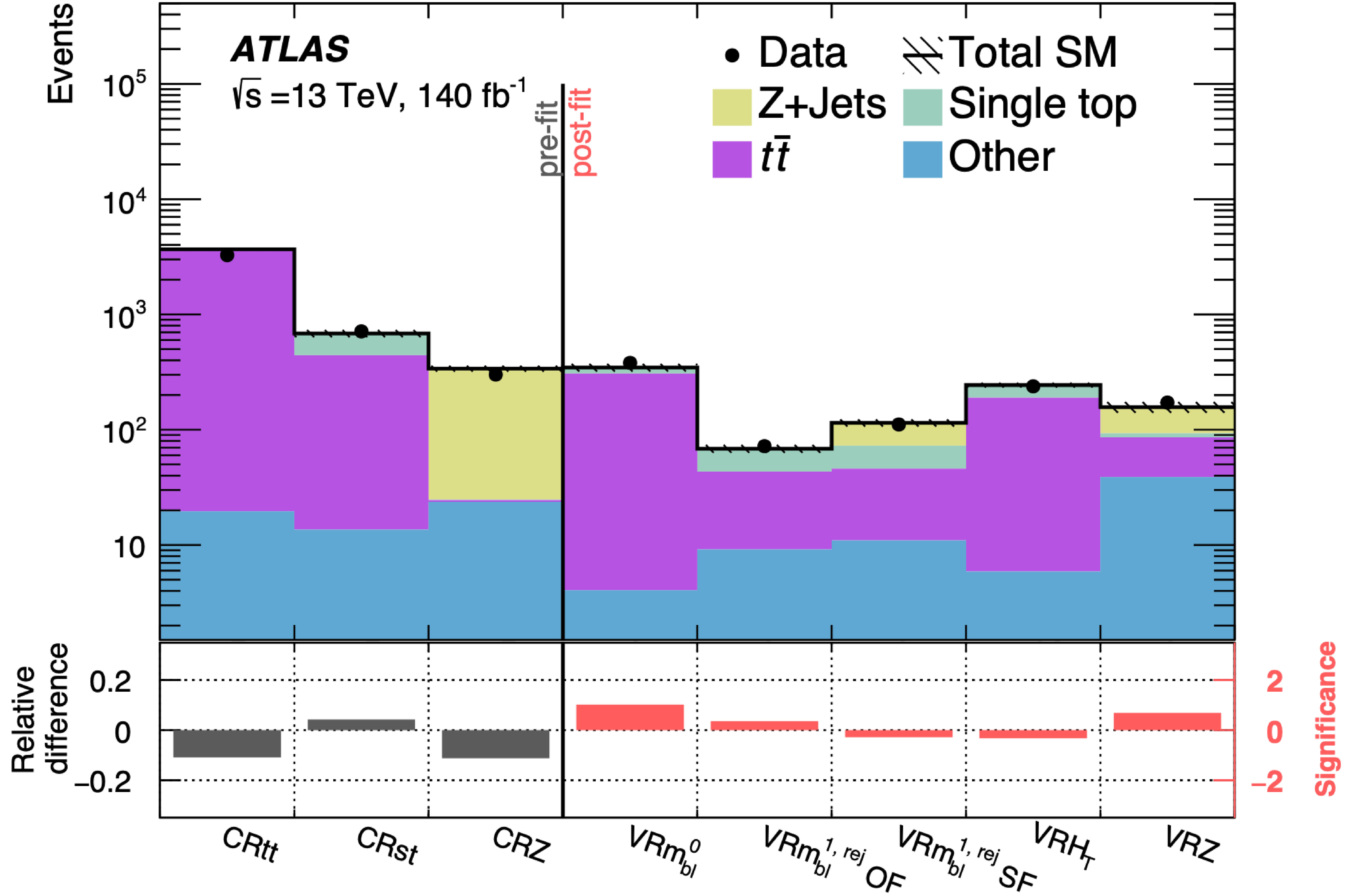
- R-parity violation but conserve $B - L$
- Rate of PP stop via strong interaction > PP electroweak gauginos => stop is LSP candidate
- Final state composed of two OS leptons and two b-jets
- Reconstruct the stops from the lepton-jet pairs
    - Pair such that the mass asymmetry is minimized
- Large stop mass => large H_T value

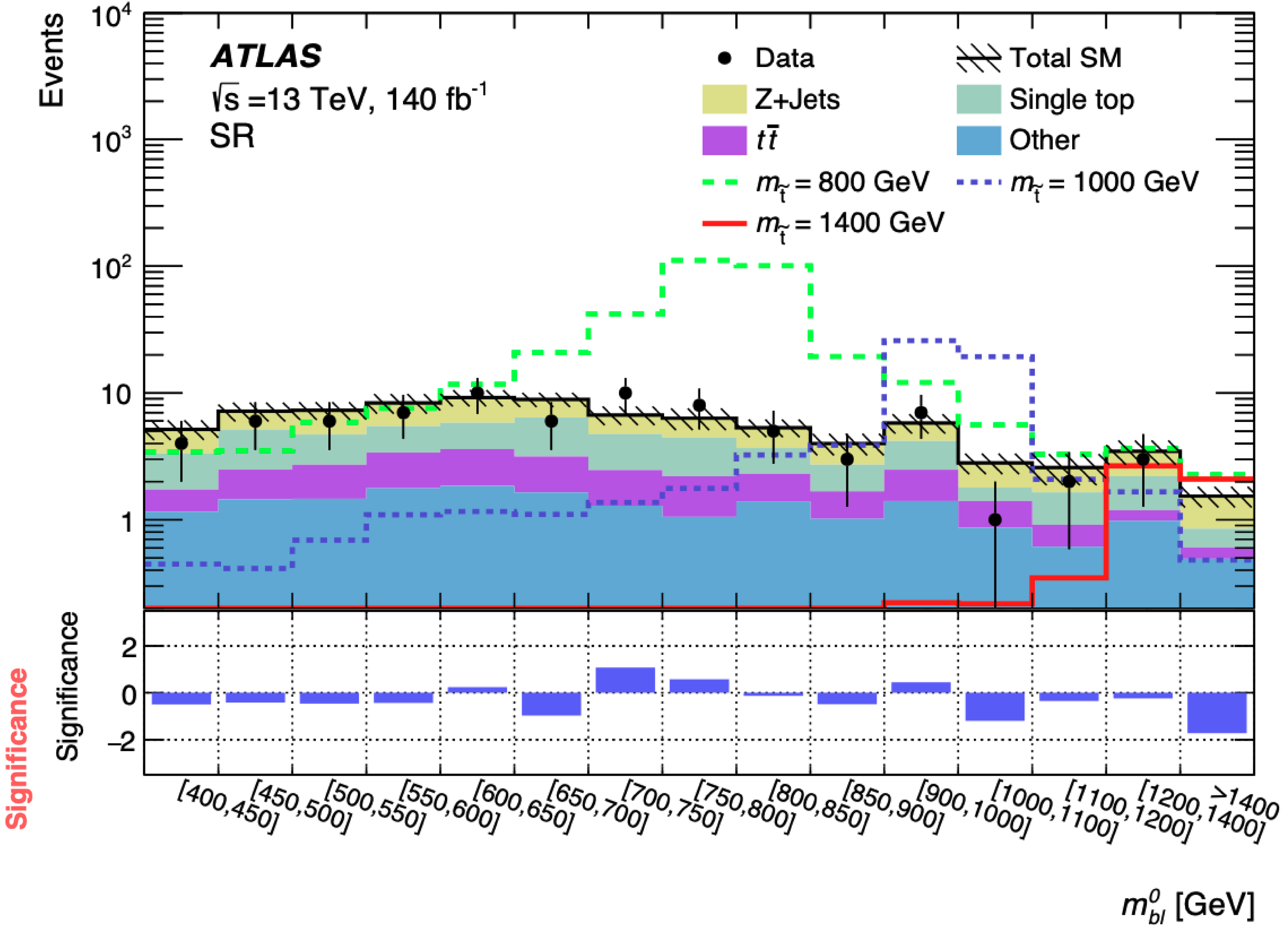


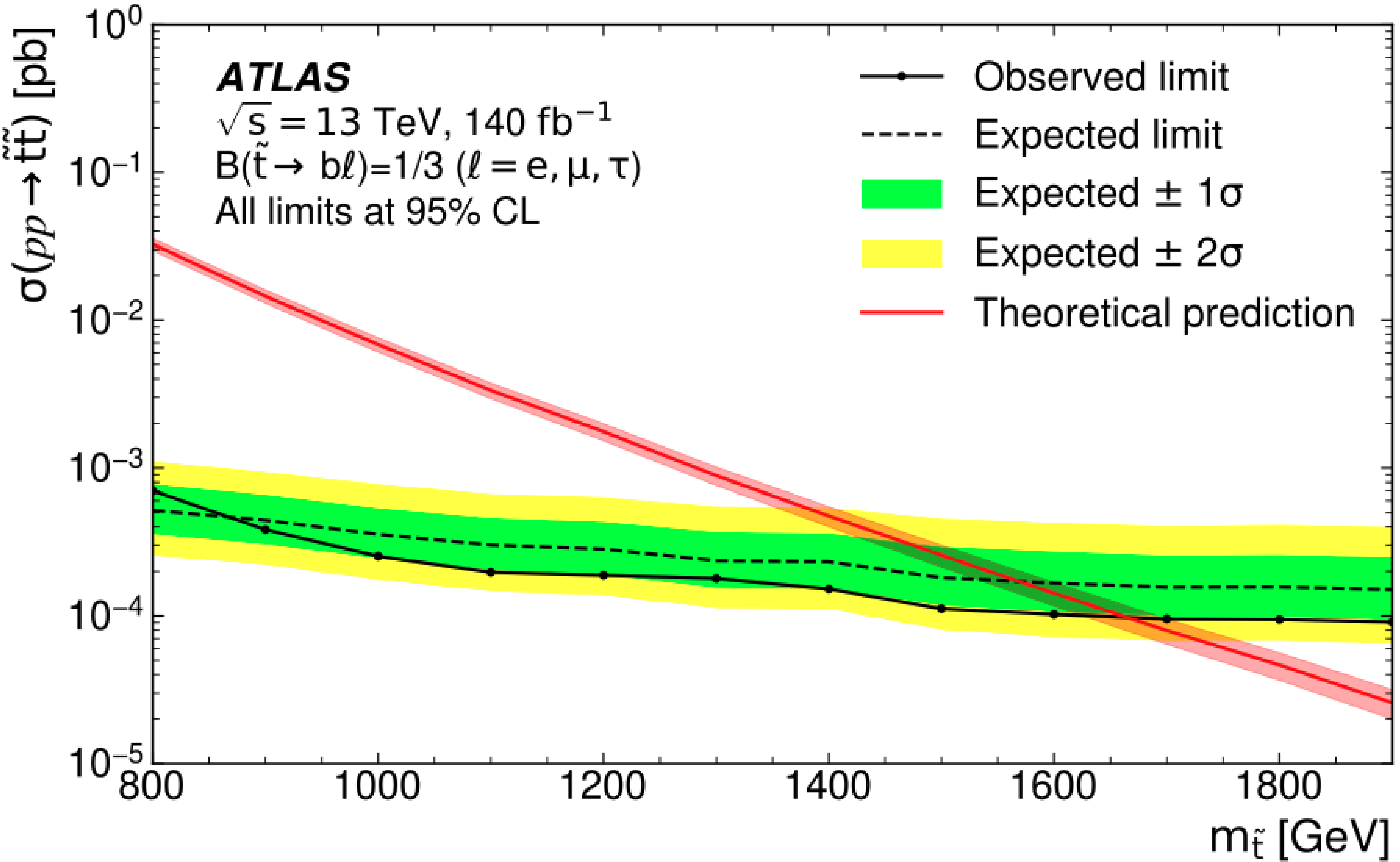
$$m_{b\ell}^{\text{asym}} = \frac{m_{b\ell}^{0} - m_{b\ell}^{1}}{m_{b\ell}^{0} + m_{b\ell}^{1}}$$

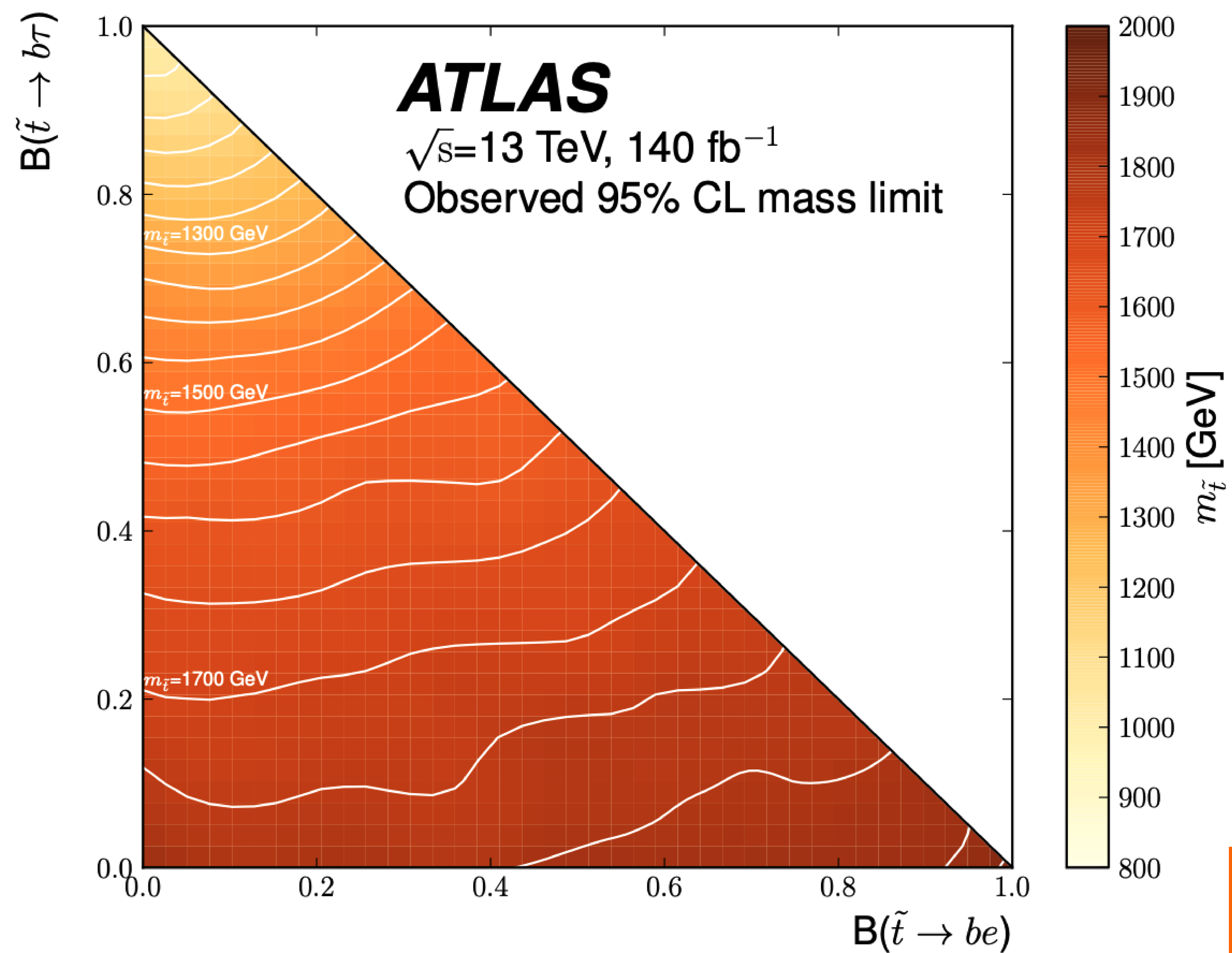
$$H_{\text{T}} = \sum_{i=1}^{2} p_{\text{T}}^{\ell_i} + \sum_{j=1}^{2} p_{\text{T}}^{\text{b-jet}_j}$$

Region	N_b	$m_{b\ell}^0$ [GeV]	$m_{b\ell}^{1,\text{rej}}$ [GeV]	H_T [GeV]	$m_{b\ell}^{\text{asym}}$	m_{ll} [GeV]	$m_{b\ell}^{0,\text{rej}}$ [GeV]
SR	≥ 1	> 400	> 150	> 1000	< 0.2	>300 GeV	–
CRtt	≥ 1	[180, 500]	< 150	[500, 800]	< 0.2	>200 GeV	< 180
CRst	$= 2$	[180, 500]	< 150	[400, 800]	< 0.2	>200 GeV	> 180
CRZ	≥ 1	> 700	–	> 1000	< 0.2	[76.2, 106.2]	–
VR $m_{b\ell}^0$	≥ 1	> 500	< 150	[600, 800]	< 0.2	>300 GeV	–
VR $m_{b\ell}^{1,\text{rej}}$	≥ 1	[200, 500]	> 150	[600, 800]	< 0.2	>300 GeV	–
VR H_{T}	≥ 1	[200, 500]	< 150	> 800	< 0.2	>300 GeV	–
VRZ	$= 0$	[500, 800]	> 150	> 1000	< 0.2	>300 GeV	–


ATLAS
√s =13 TeV, 140 fb⁻¹
Data
Total SM
Z+Jets
Single top
tt̄
Other
pre-fit
post-fit
Events
Relative difference
Significance
CRtt
CRst
CRZ
VRm0bl
VRm1, rej bl OF
VRm1, rej bl SF
VRHT
VRZ


ATLAS
√s =13 TeV, 140 fb⁻¹
SR
Data
Total SM
Z+Jets
Single top
tt̄
Other
m_t̃ = 800 GeV
m_t̃ = 1000 GeV
m_t̃ = 1400 GeV
Events
Significance
[400,450]
[450,500]
[500,550]
[550,600]
[600,650]
[650,700]
[700,750]
[750,800]
[800,850]
[850,900]
[900,1000]
[1000,1100]
[1100,1200]
[1200,1400]
>1400
m0bl [GeV]

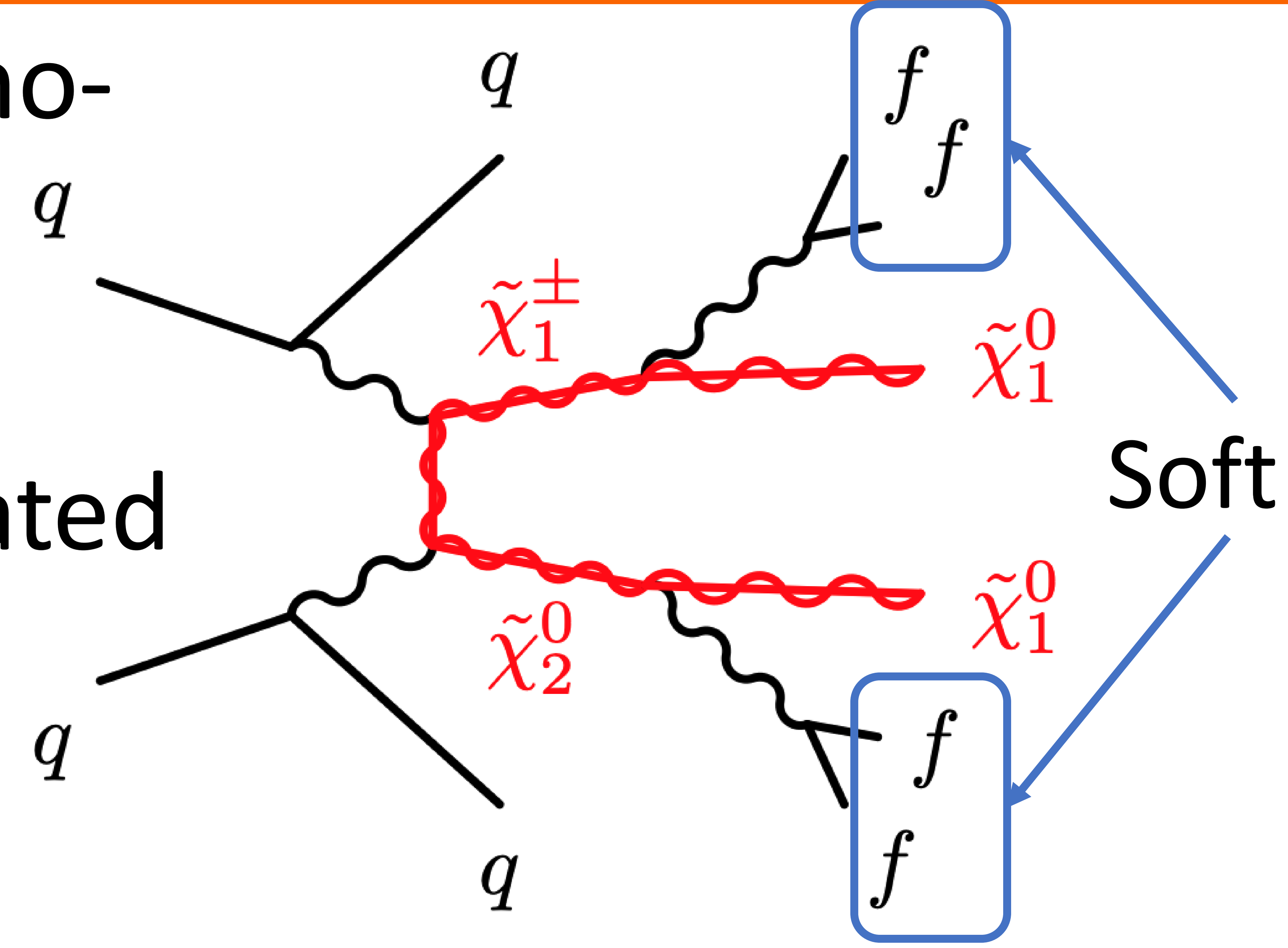

ATLAS
√s = 13 TeV, 140 fb⁻¹
B(t̃→ bℓ)=1/3 (ℓ = e, μ, τ)
All limits at 95% CL
Observed limit
Expected limit
Expected ± 1σ
Expected ± 2σ
Theoretical prediction
σ(pp→t̃t̃) [pb]
m_t̃ [GeV]


ATLAS
√s=13 TeV, 140 fb⁻¹
Observed 95% CL mass limit
m_t̃=1300 GeV
m_t̃=1500 GeV
m_t̃=1700 GeV
B(t̃ → bτ)
B(t̃ → be)
m_t̃ [GeV]

Compressed VBF SUSY

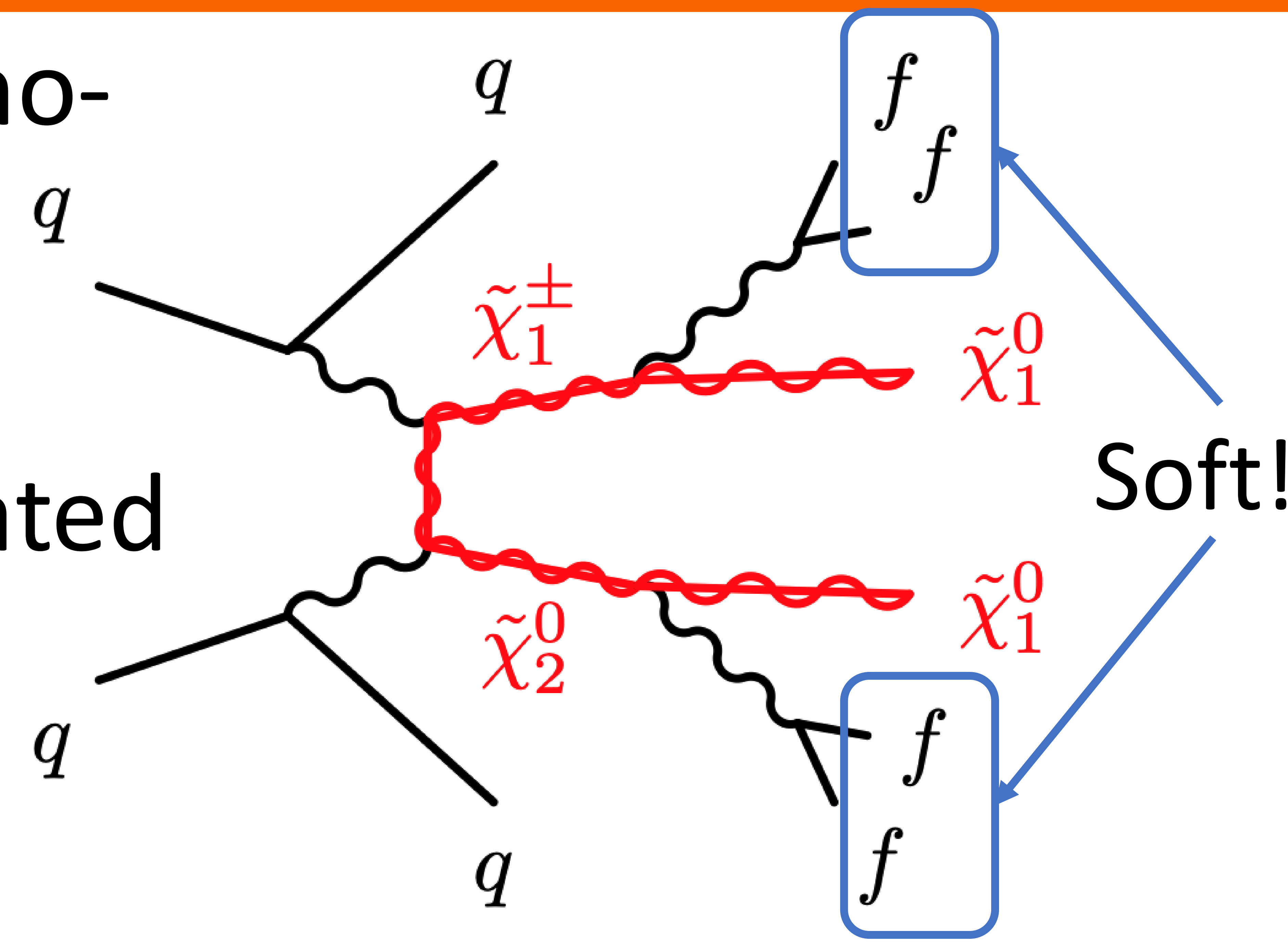
2409.18762

- Search for VBF production of a degenerate chargino-neutralino pair decaying to a neutralino LSP and soft fermions
- Final state is composed of E_T^{miss} and 2 well-separated jets



Compressed VBF SUSY [2409.18762](2409.18762)

- Search for VBF production of a degenerate chargino-neutralino pair decaying to a neutralino LSP and soft fermions
- Final state is composed of E_T^{miss} and 2 well-separated jets
- Split Regions based on $N_{\mathrm{jets}} = 2\mathrm{j}$ and $\geq 3\mathrm{j}$
- Use BDT score as a discriminating variable
  - Final and single bin of BDT displays the greatest sensitivity!



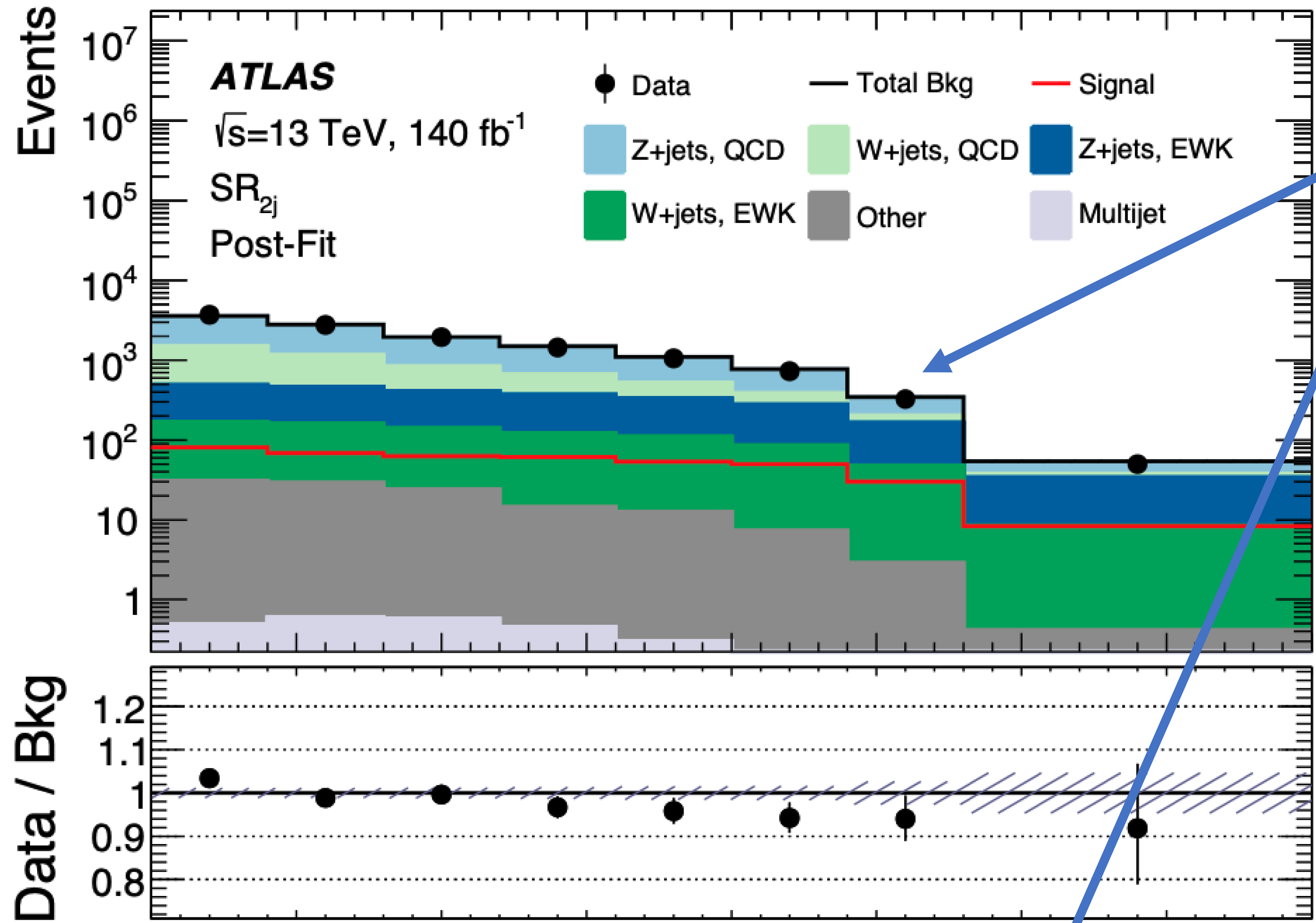
Feature	CR−Z	VR−Z	CR−W	VR−W	VR−0L	Multi-bin SR	Single-bin SR
N_{leptons}	2		1		0		
$m_{\ell\ell}$	$\lvert m_{\ell\ell} - m_Z \rvert < 30$ GeV		–		–		
$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{\Sigma E_{\mathrm{T}}}$	–		$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{\Sigma E_{\mathrm{T}}} > 5\sqrt{\mathrm{GeV}}$		–		
BDT score	[0.50, 0.84)	[0.84, 1.0]	[0.50, 0.84)	[0.84, 1.0]	[0.4, 0.6)	[0.6, 1.0]	[0.88, 1.0]
BDT score bins	1	2	1	2	5	8	1

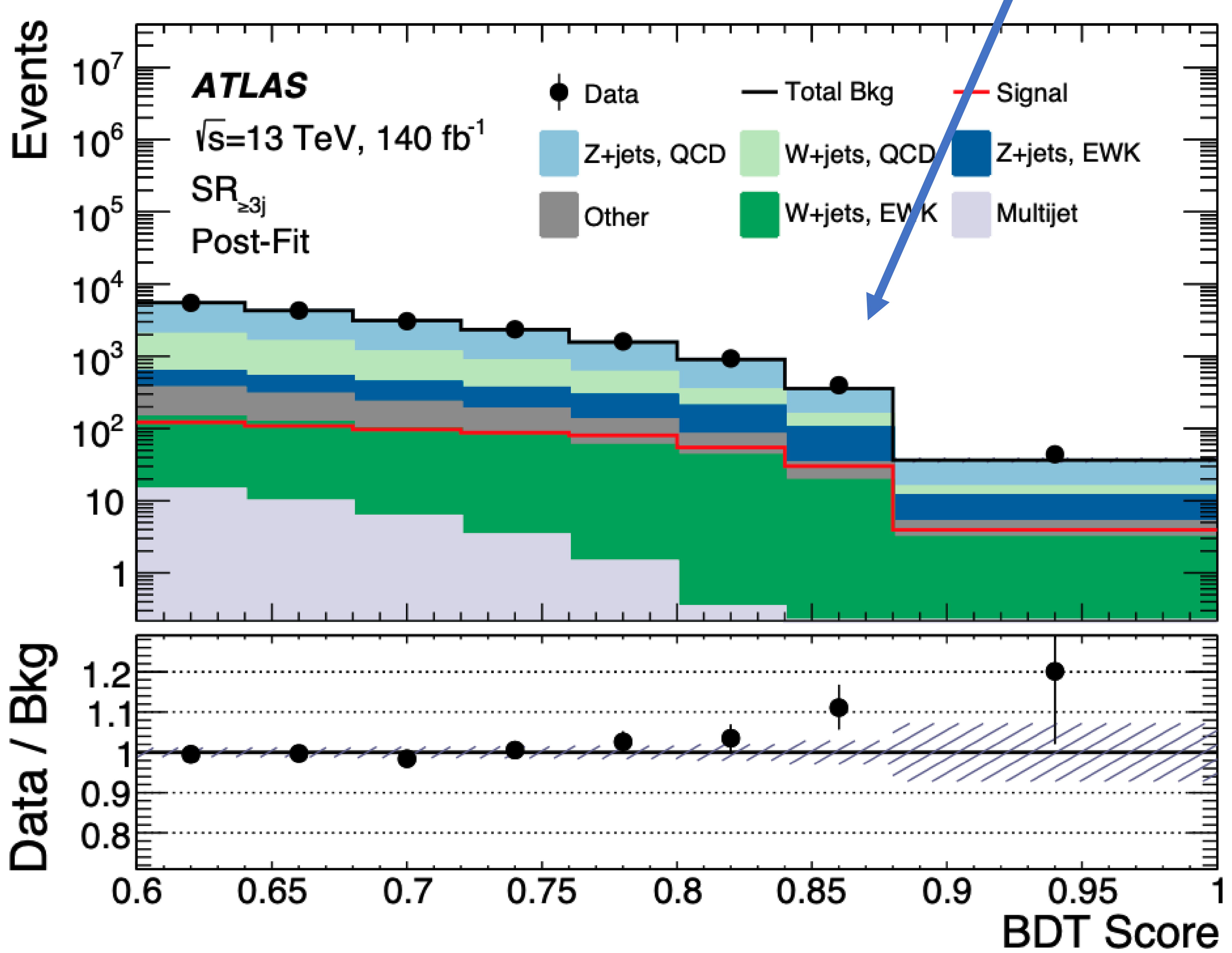
Single-Bin Region	N_{obs}	N_{exp}	$\langle\epsilon\sigma\rangle_{\mathrm{obs}}^{95}$ [fb]	S_{obs}^{95}	S_{exp}^{95}	$p(s=0)$
$\mathrm{SR}_{2\mathrm{j}}$	50	55.9 ± 3.7	0.09	13	18^{+7}_{-5}	0.50
$\mathrm{SR}_{\geq 3\mathrm{j}}$	44	39.8 ± 4.3	0.18	25	19^{+9}_{-6}	0.19

Compressed VBF SUSY

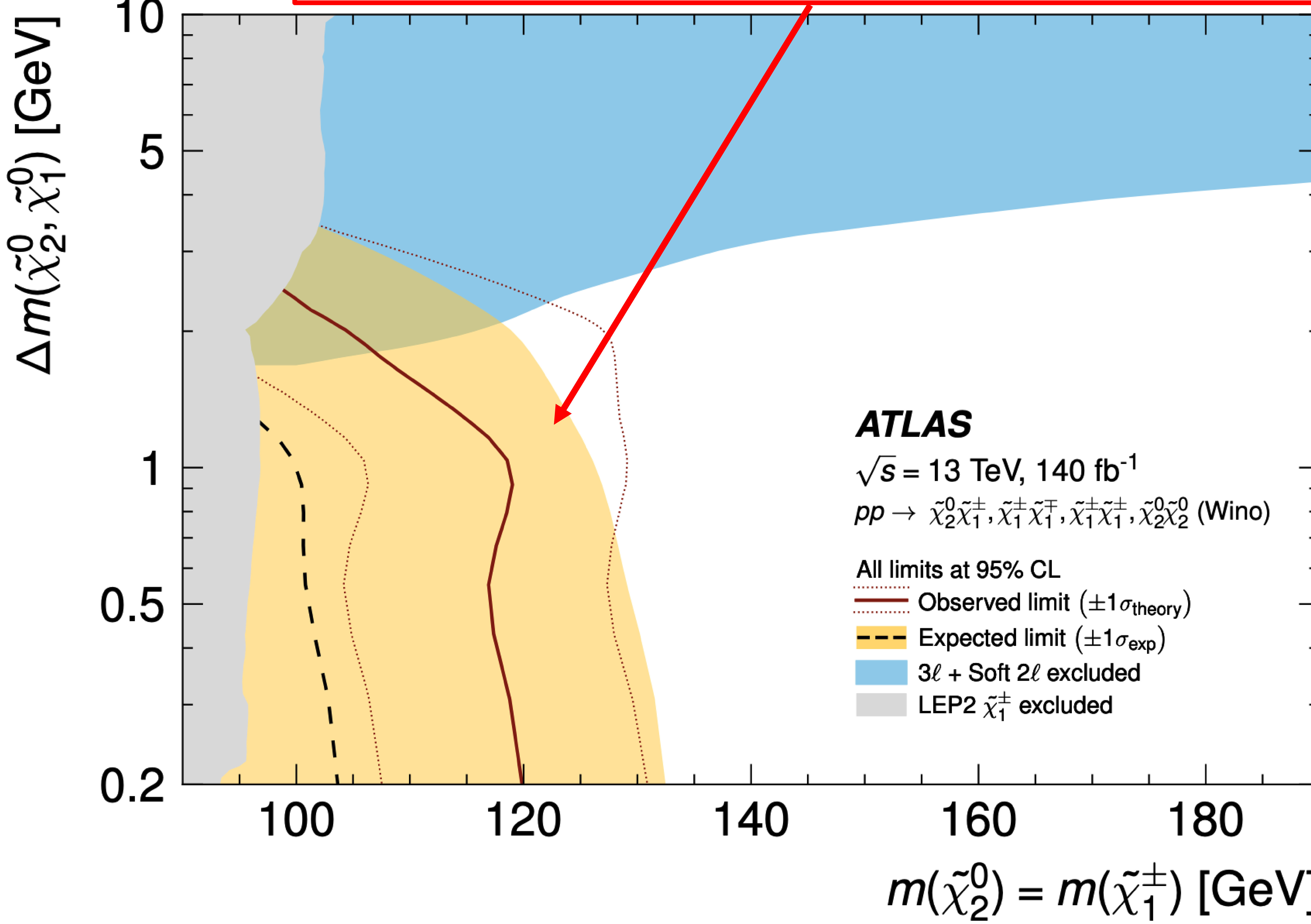
2409.18762

Data consistent with no new physics!





Significant improvement in limit for low mass difference region



Vector-like fermion searches

- SM fermion weak current is V-A

$$\bar{f}\gamma^{\mu}(1-\gamma^{5})f'$$

- Vector-like fermion weak current is purely V

$$\bar{F}\gamma^{\mu}F'$$

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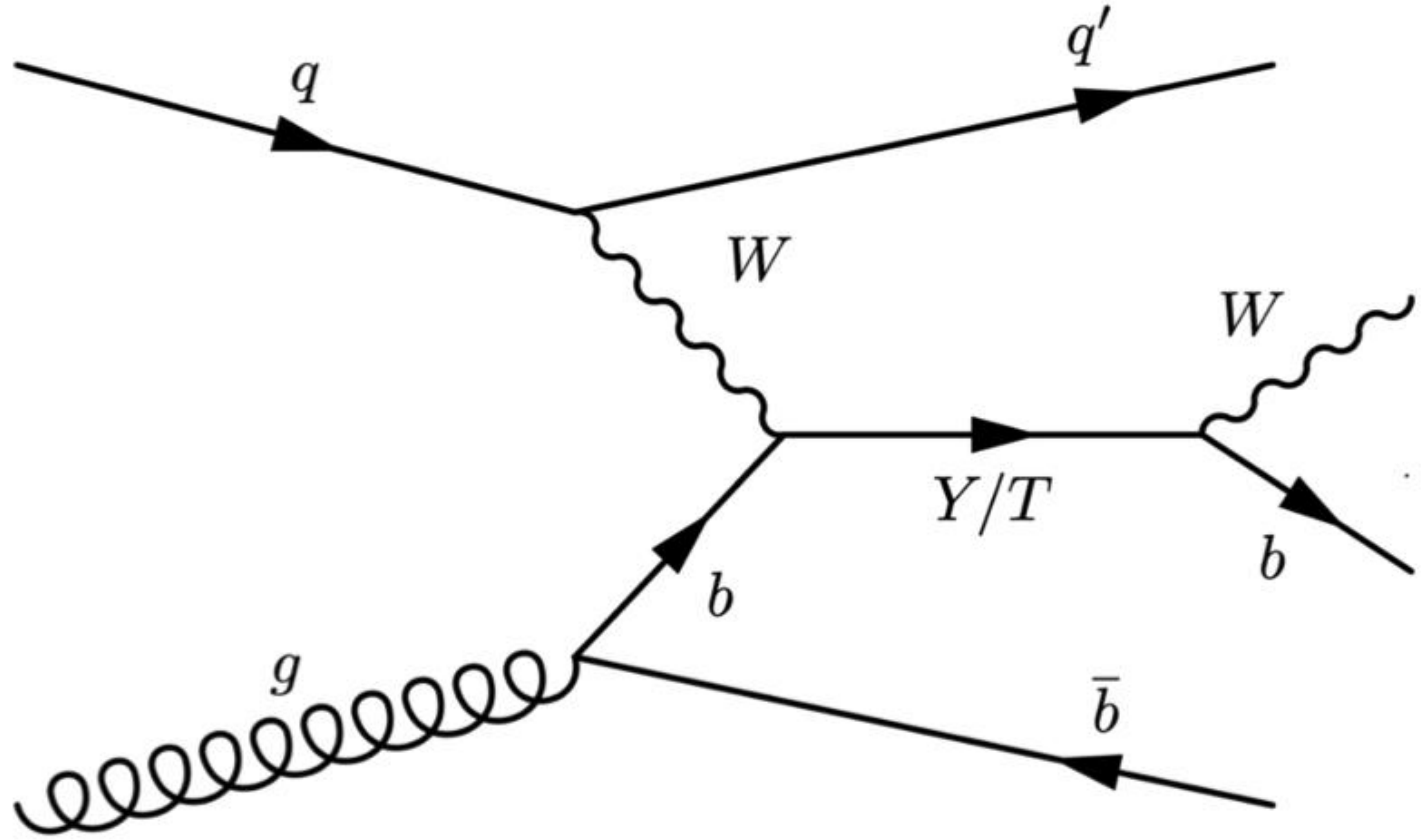
$$\bar{F}\gamma^{\mu}F'$$

- VLF Lagrangian possesses a bare mass term => avoids Higgs measurement constraints
- Couple to SM particles via interactions with the Higgs and weak bosons and SM fermions
- Capable of resolving different shortcomings in the SM
  - VLQs coupling to 3rd generation SM quarks are capable of resolving the hierarchy problem
  - VLLs are capable of resolving the muon g-2 anomaly

$T/Y \to Wb\ (0\ell)$ [2409.20273](2409.20273)

- Search for single-production of a T/Y VLQ
  - Occur in a variety of representations

Q[e]	singlets		doublets			triplets	
				VLQs			
5/3			X			X	
2/3	(T)		T	T		T	T
−1/3		(B)		B	B	B	B
−4/3					Y		Y



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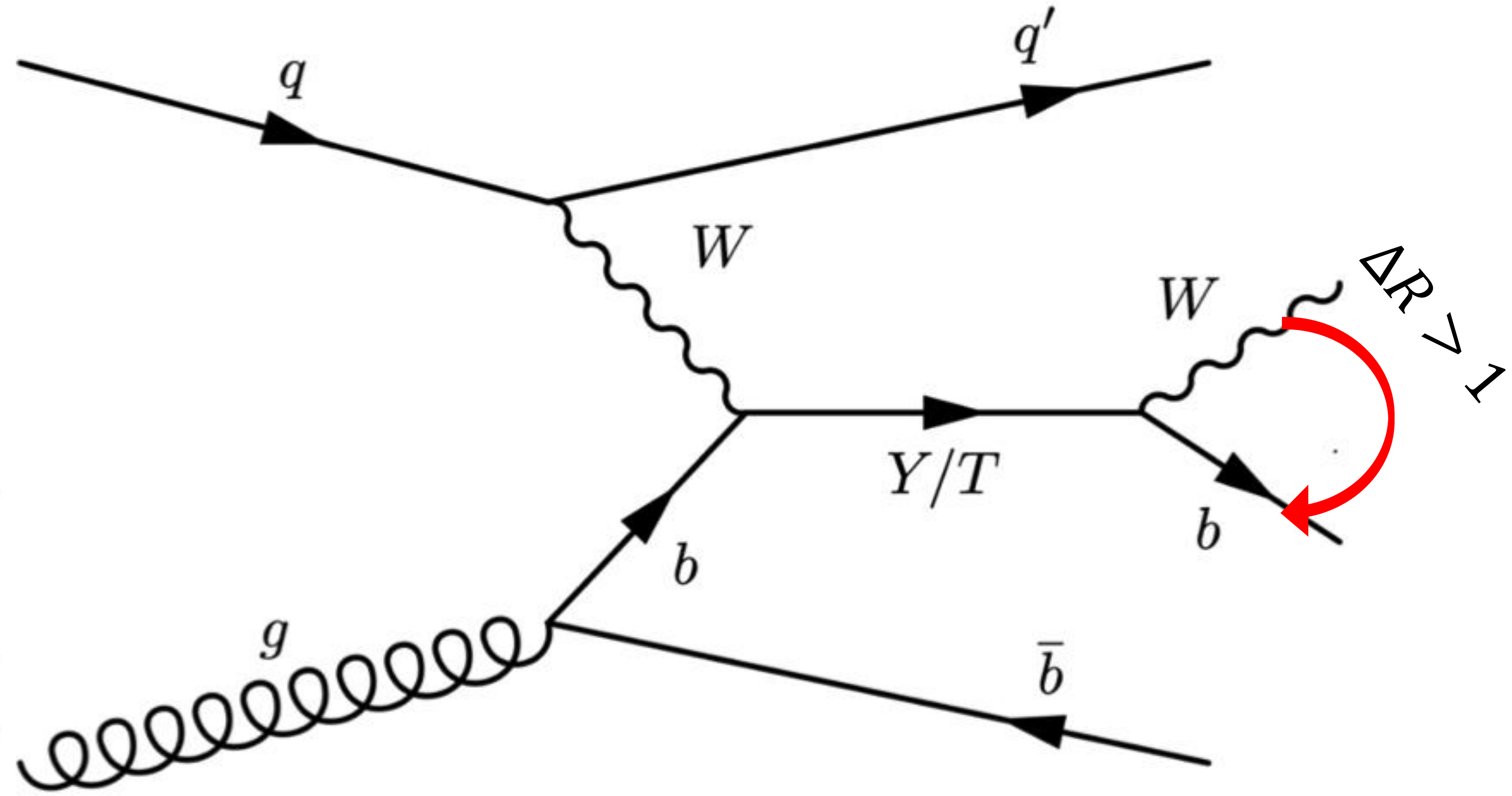
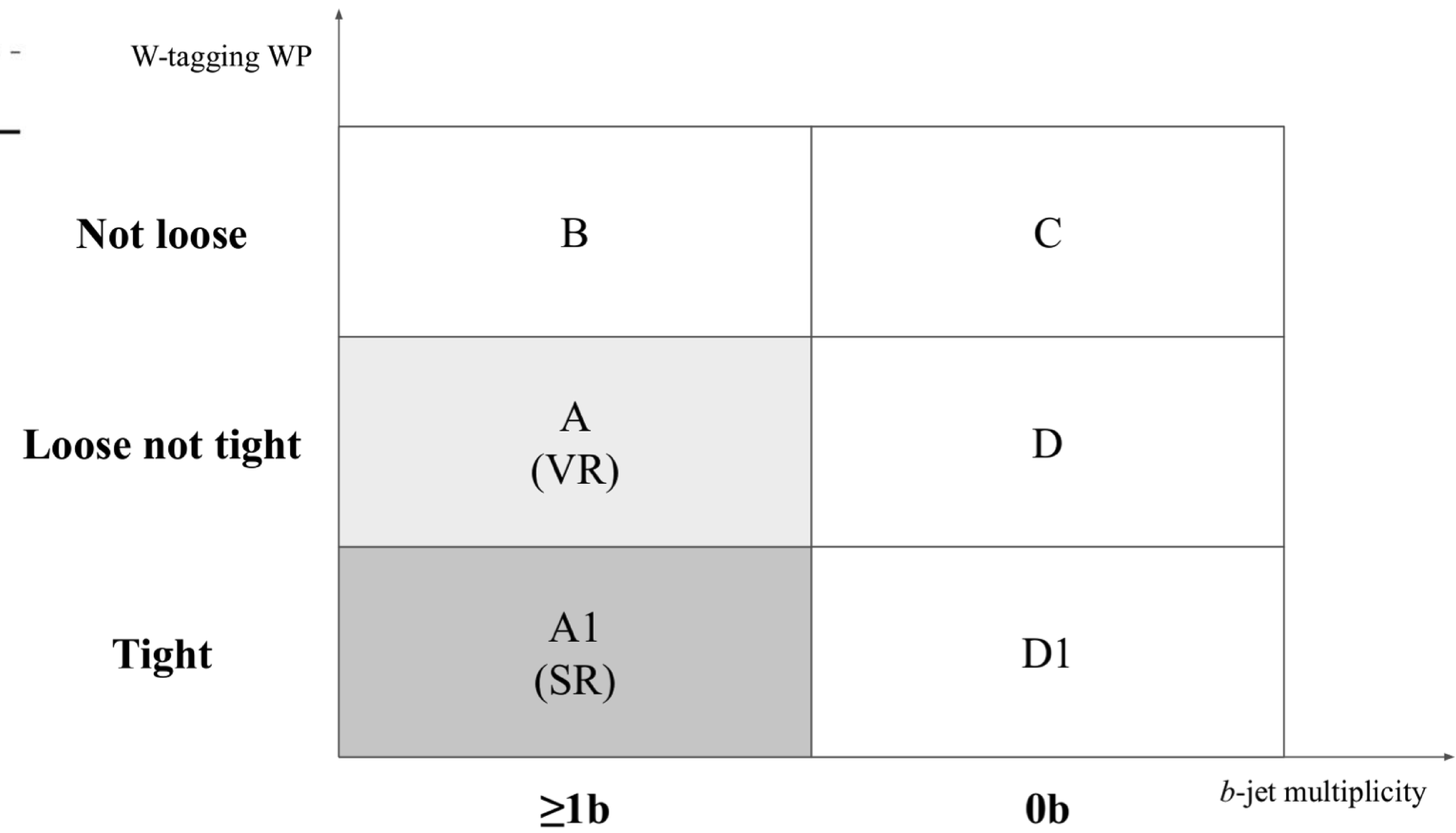
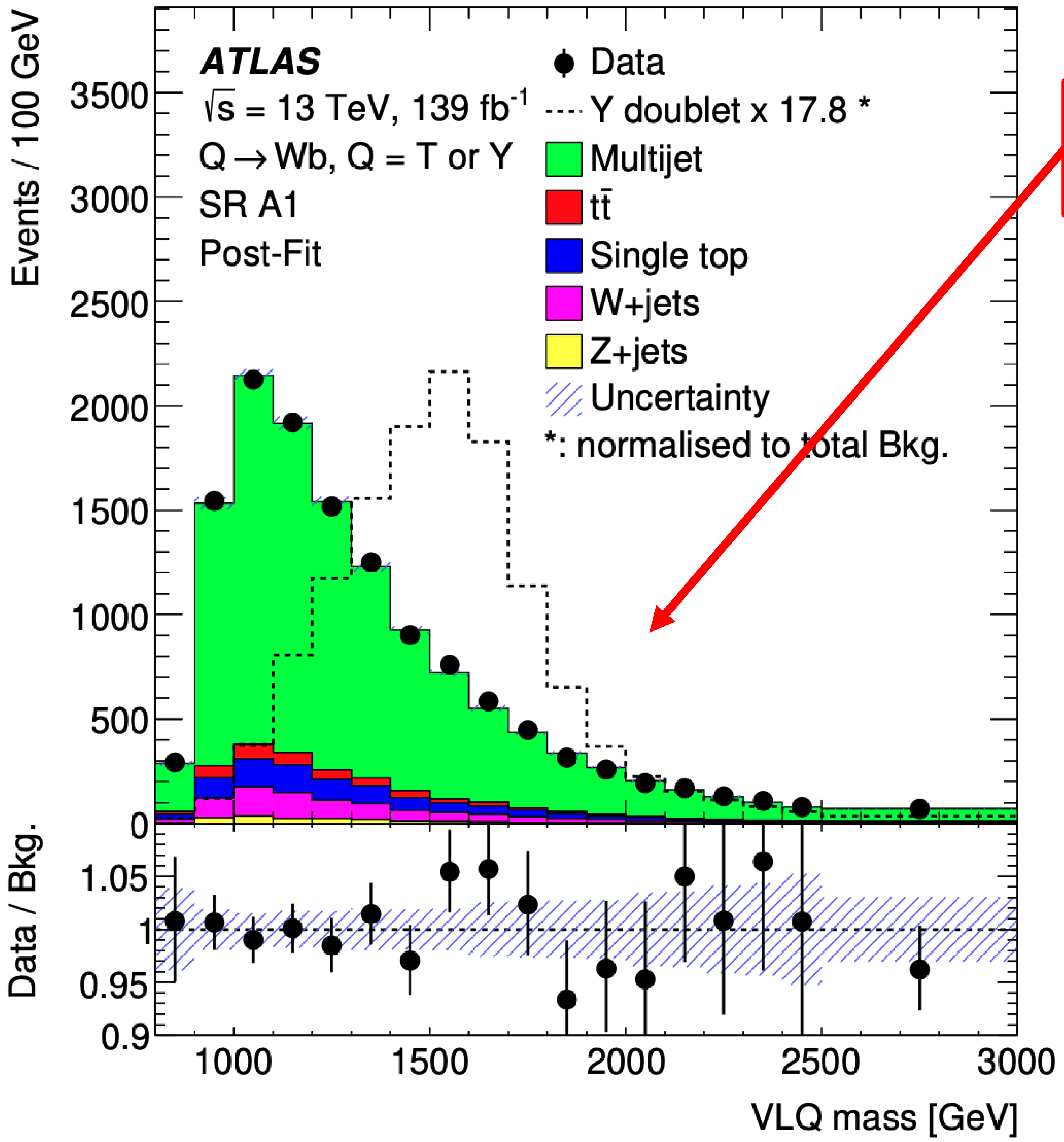


Q[e]	VLQs singlets		doublets			triplets	
5/3			X			X	
2/3	(T)		T	T		T	T
−1/3		(B)		B	B	B	B
−4/3					Y		Y

- Analysis regions split based on W-tagging WP and b-jet multiplicity
  - Fit m_{VLQ}
    - Reconstructed from leading large- and small-R jet

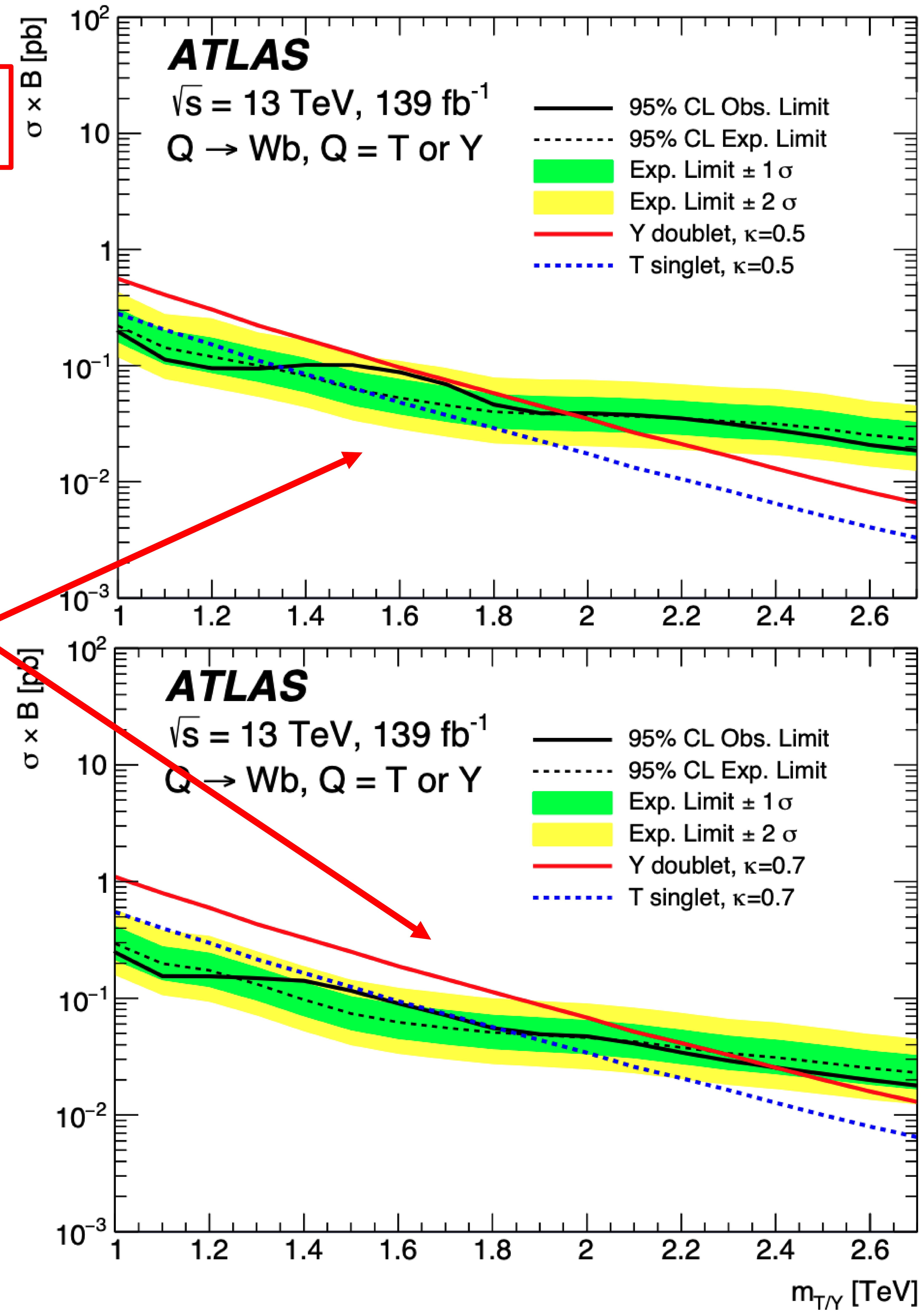


$T/Y \to Wb\ (0\ell)$ 2409.20273



No new physics…

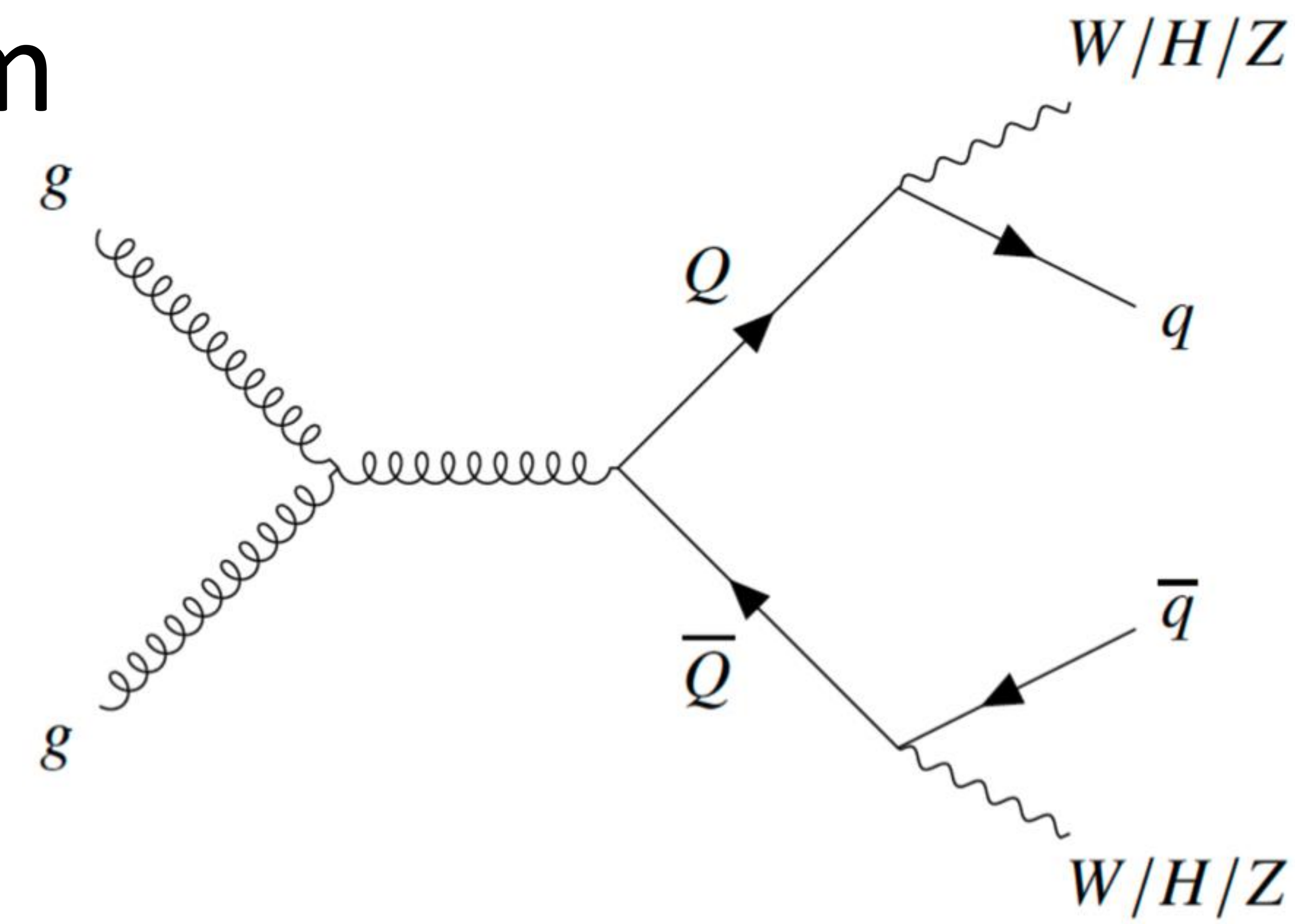
But best limits to date!



$$m_Y = 1.6\ \text{TeV}, \kappa = 0.5$$

$QQ \to Wq + X$ Phys. Rev. D 110 (2024) 052009

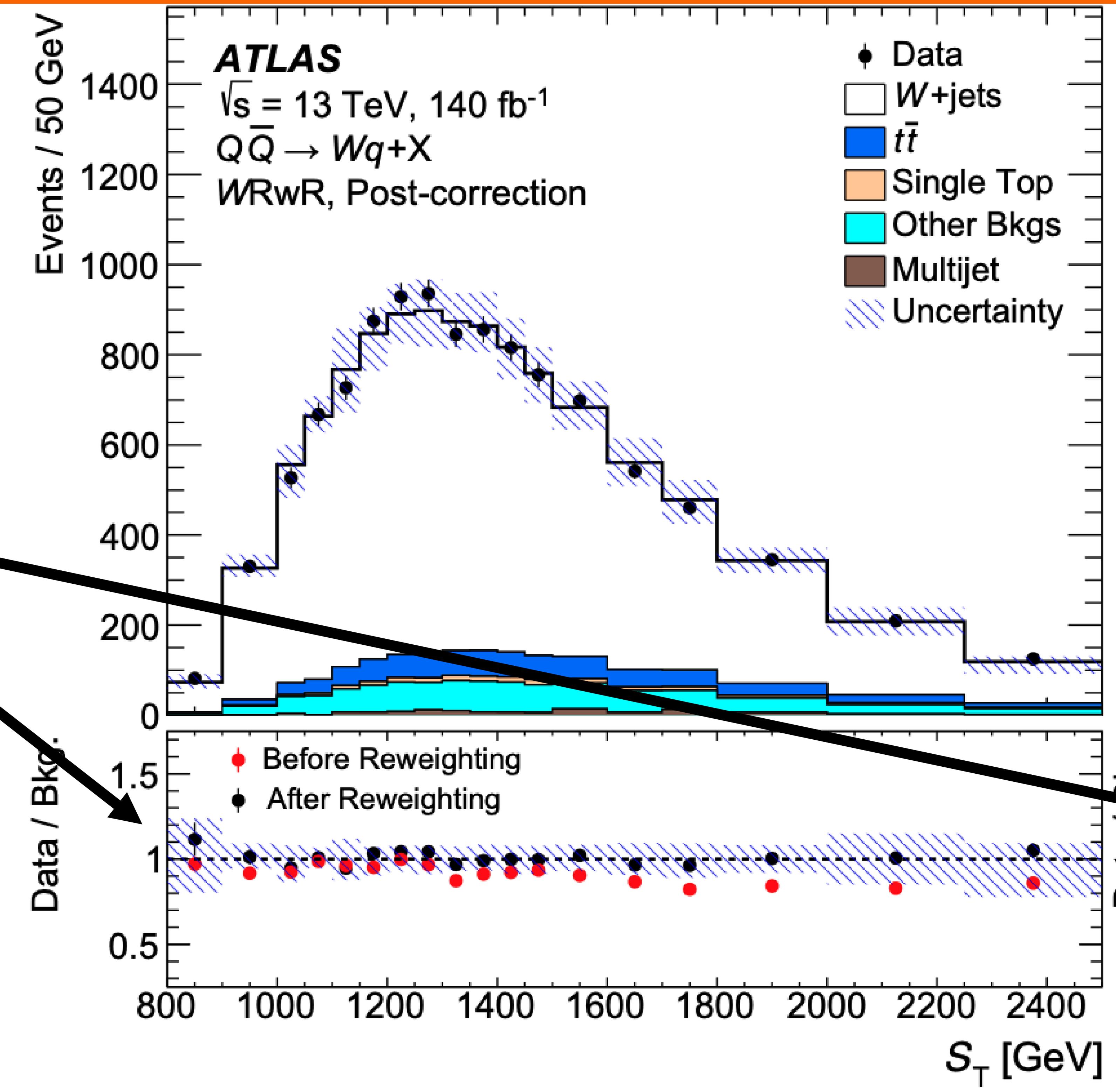
- Models that resolve the hierarchy problem favor VLQs with large couplings to 3rd generation SM particles
  - Couplings to lighter particles are not expressly forbidden
- Define a series of regions to derive data-driven corrections on backgrounds
  - S_T correction for $t\bar{t}$ and W+jets
  - Fit only 2 SRs exploiting mass peak of $m_{\mathrm{VLQ}}^{\mathrm{lep}}$!

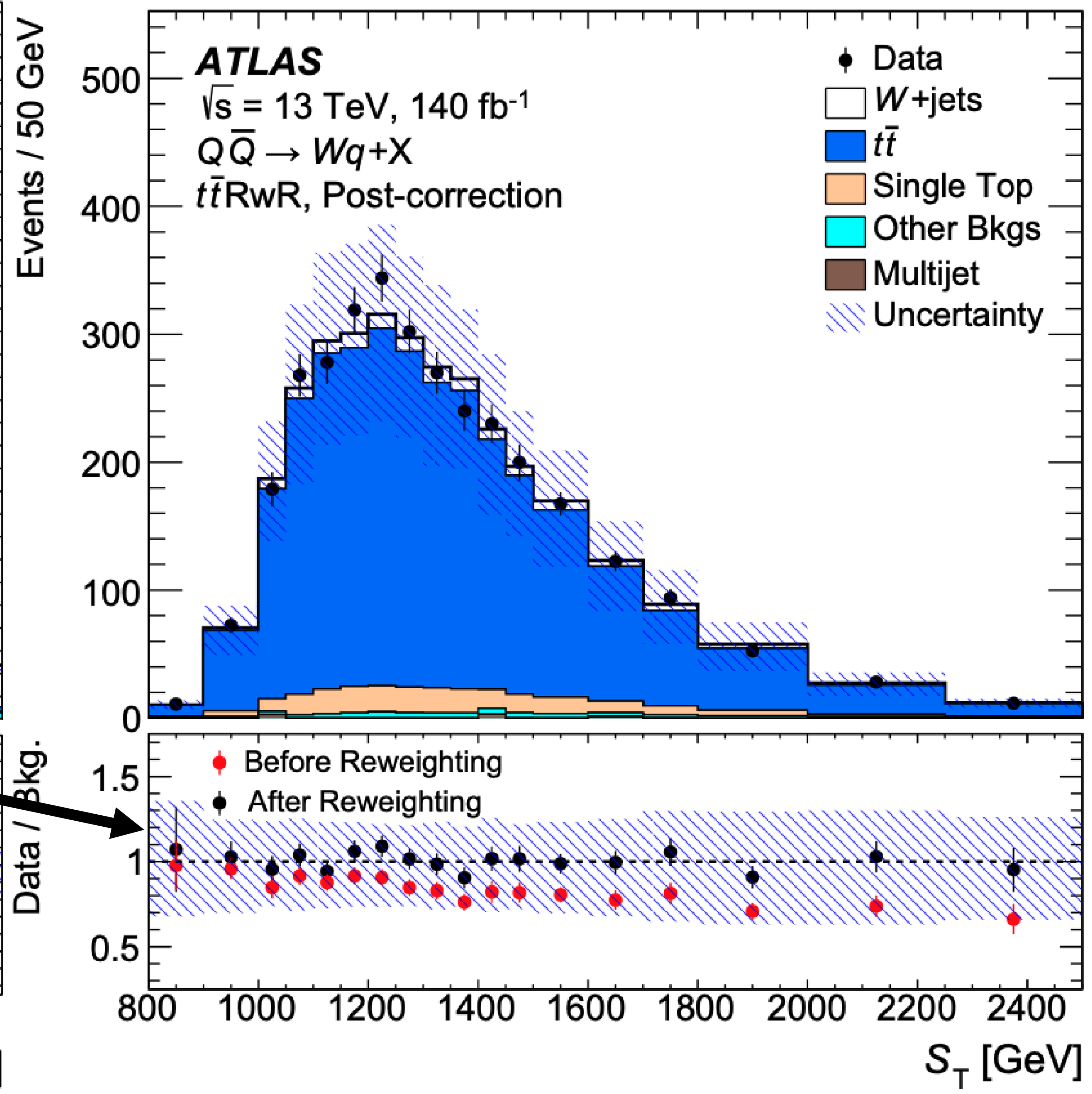


Variable	SR1 (SR2)	multijetRwR	multijetVR	WRwR	WVR	$t\bar{t}$RwR	$t\bar{t}$VR
$N_{b\text{-tags}}$	$= 0$	$= 0$	$= 0$	$= 0$	$= 0$	≥ 1	≥ 1
$N_{W\text{-tags}}$	≥ 1	$= 0$	≥ 1	$= 0$	> 0	≥ 1	$= 0$
$\Delta R(W_{\mathrm{lep}}, W_{\mathrm{had}})$	≥ 0.8	< 0.8	< 0.8	≥ 0.8	< 0.8	< 0.8	≥ 0.8
$\Delta\phi(\mathrm{lepton}, E_{\mathrm{T}}^{\mathrm{miss}})$	≤ 0.5	≤ 0.1	≤ 0.1		> 0.1		
S_{T}	≥ 2000 GeV						
$\Delta\phi(\mathrm{leading\ jet}, E_{\mathrm{T}}^{\mathrm{miss}})$	< 2.75 (≥ 2.75)						
Included in Fit	Yes	No	No	No	No	No	No

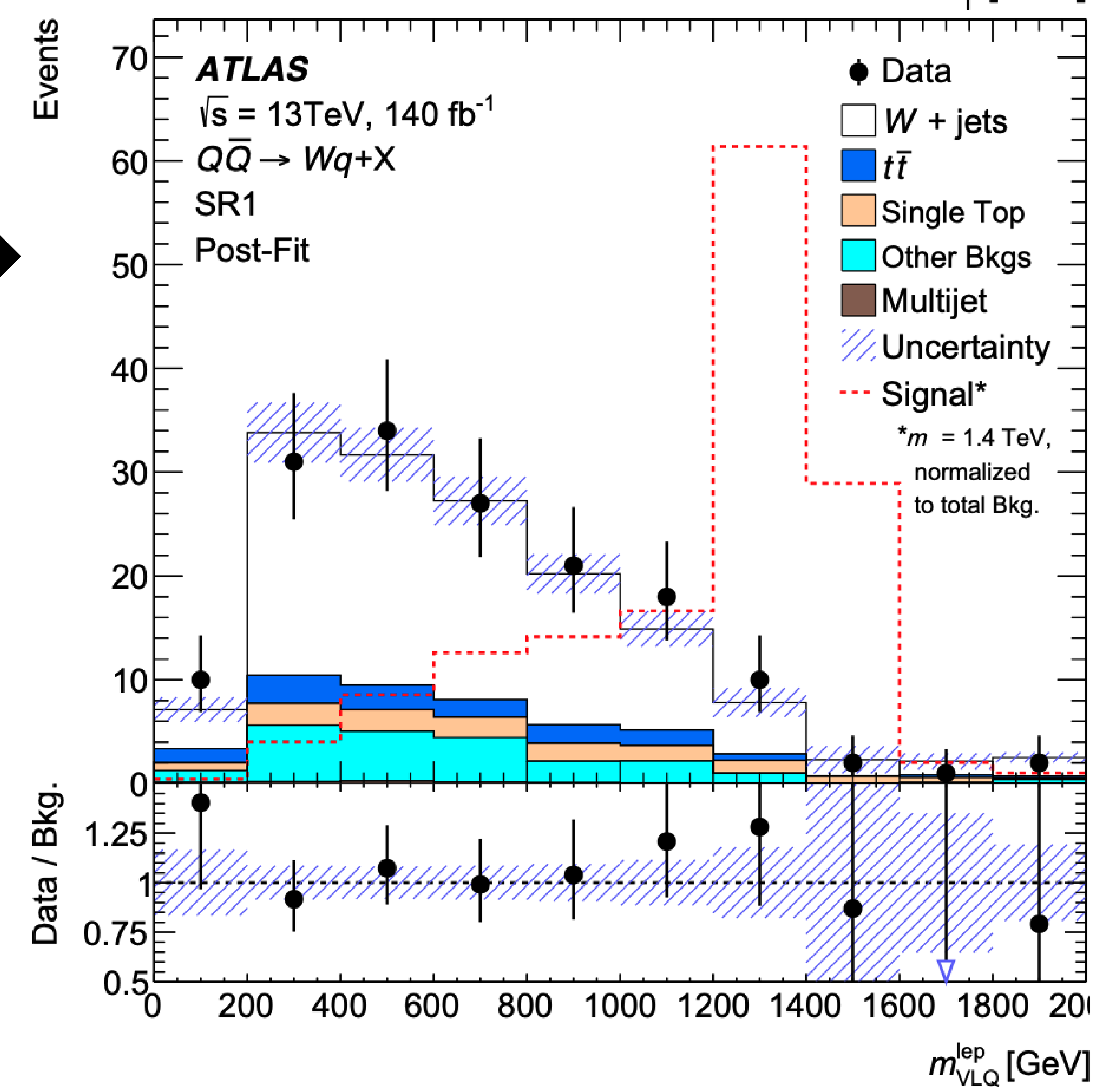
$QQ \to Wq + X$ Phys. Rev. D 110 (2024) 052009

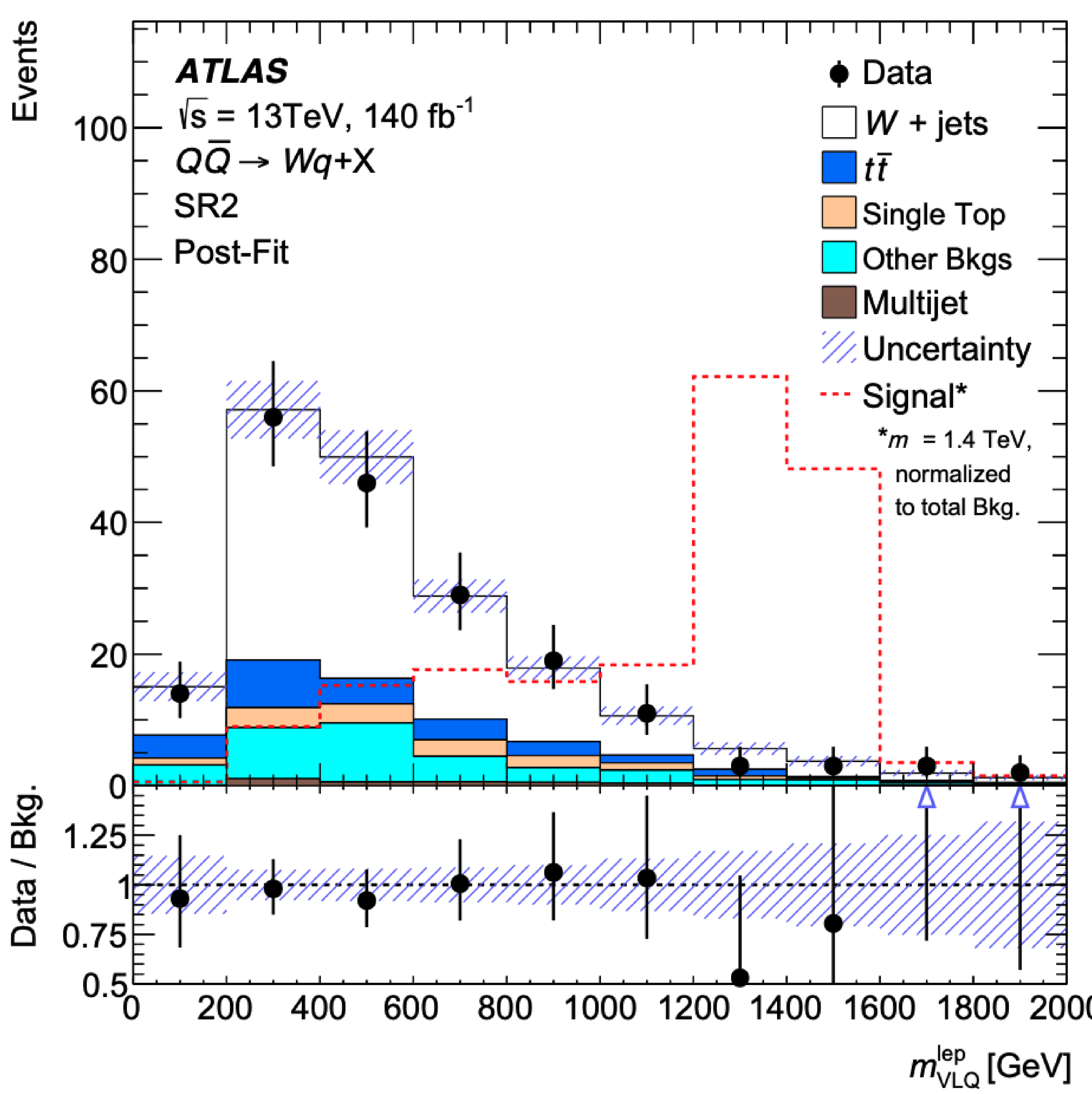
Improved agreement post-correction in RwRs!

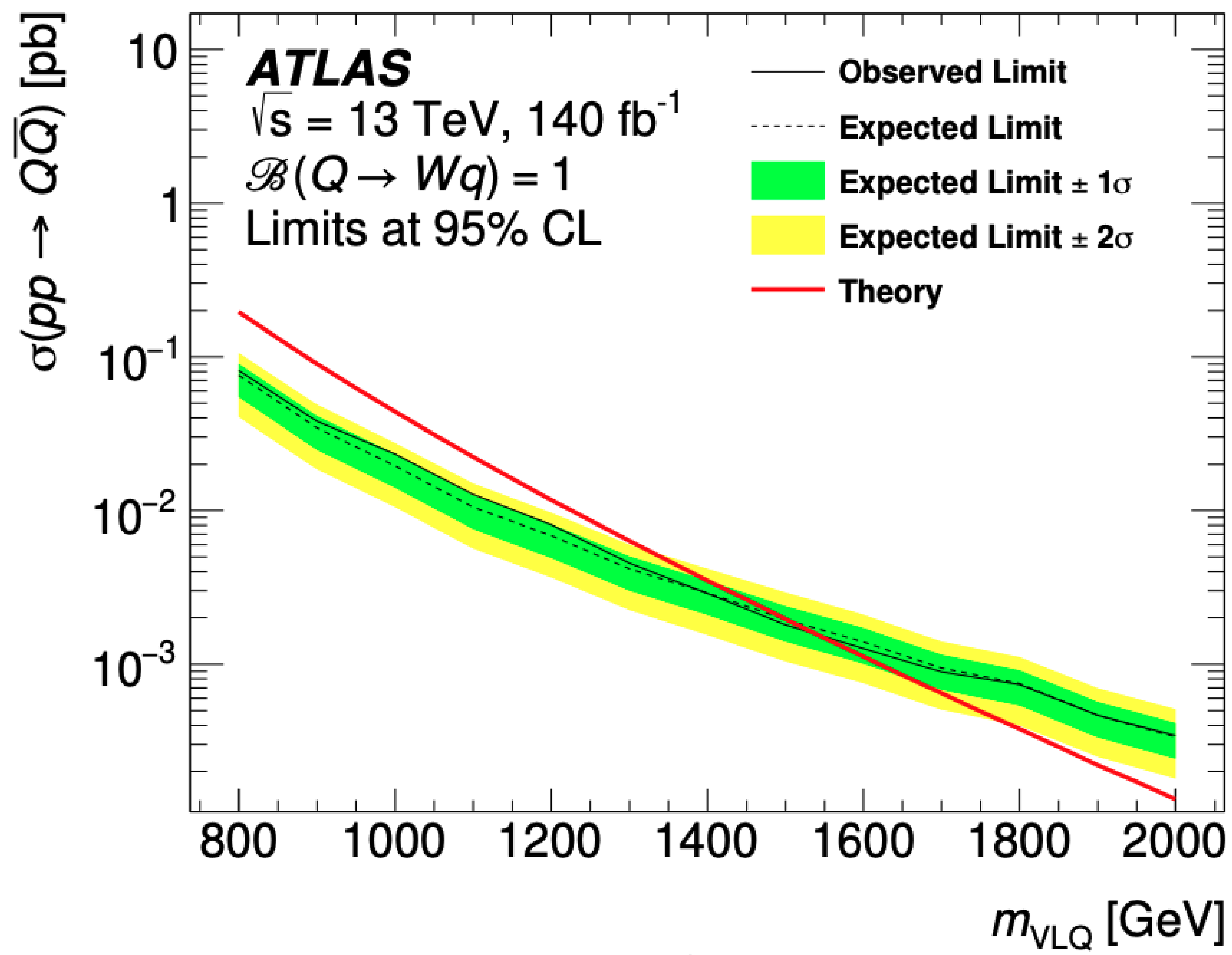


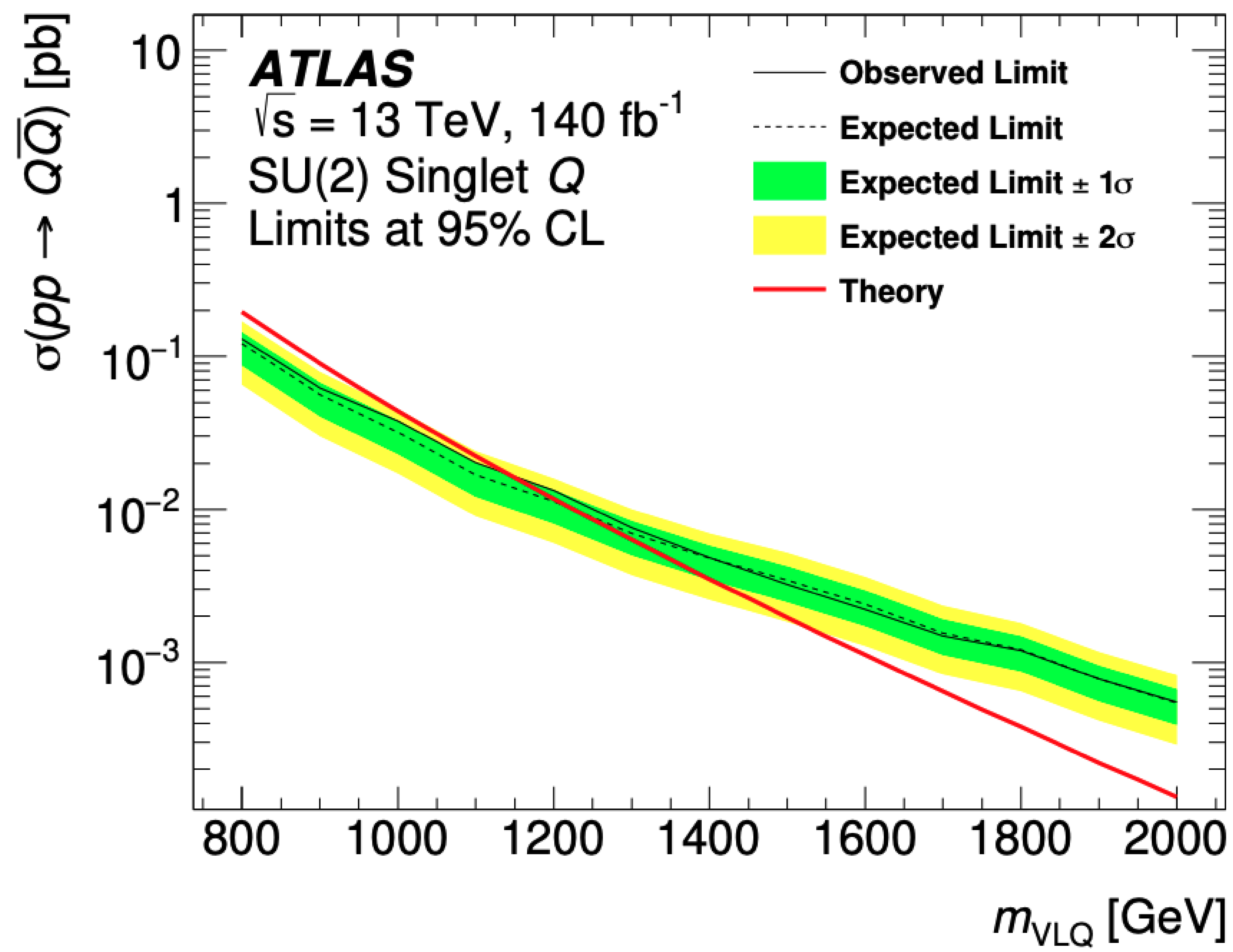


Results consistent with the SM!

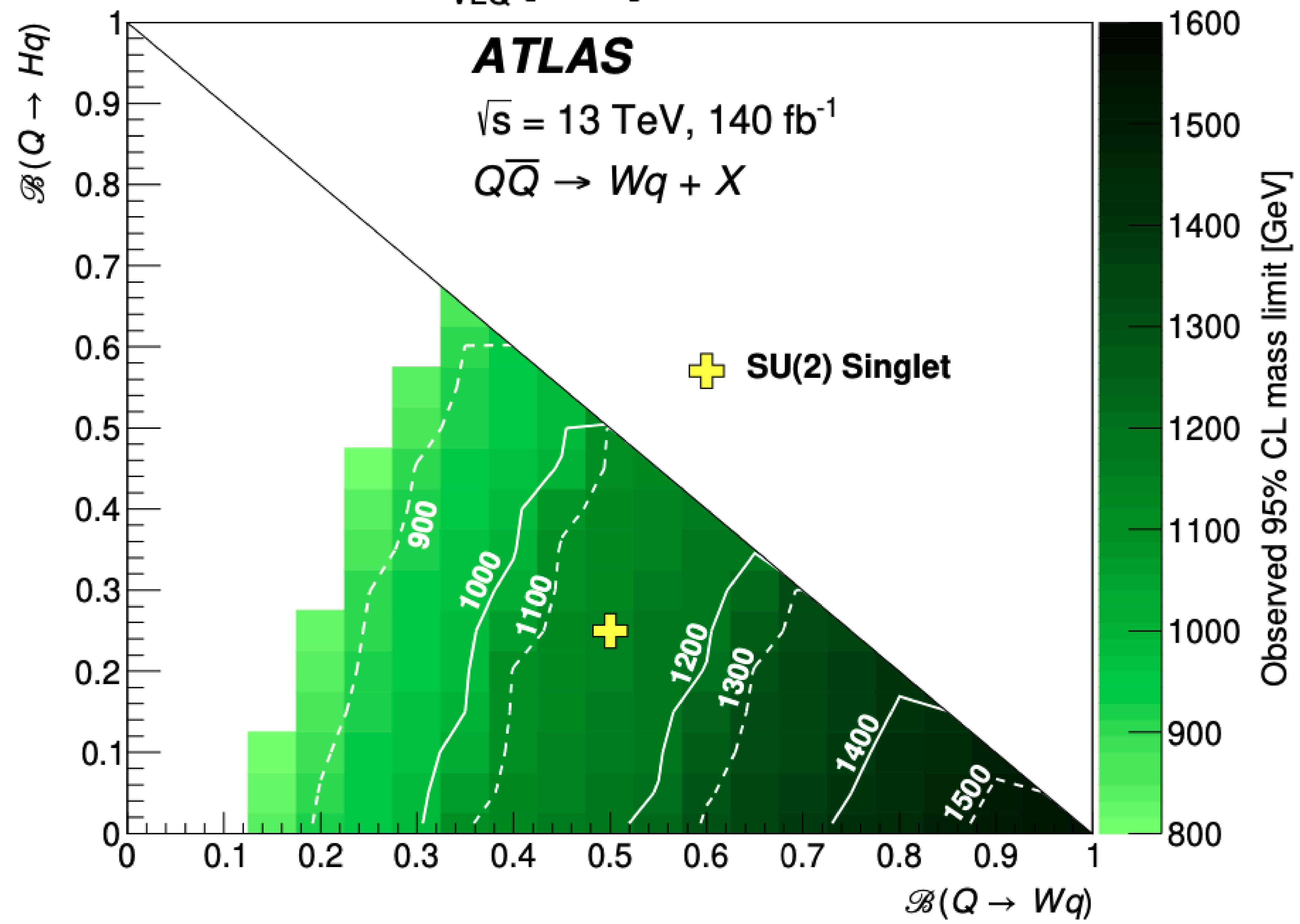






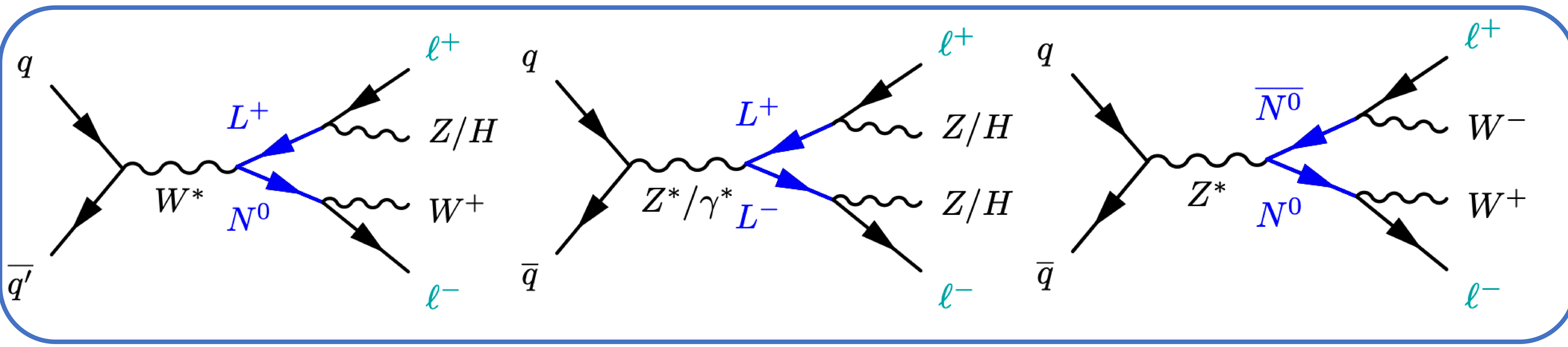


Best limits to date!

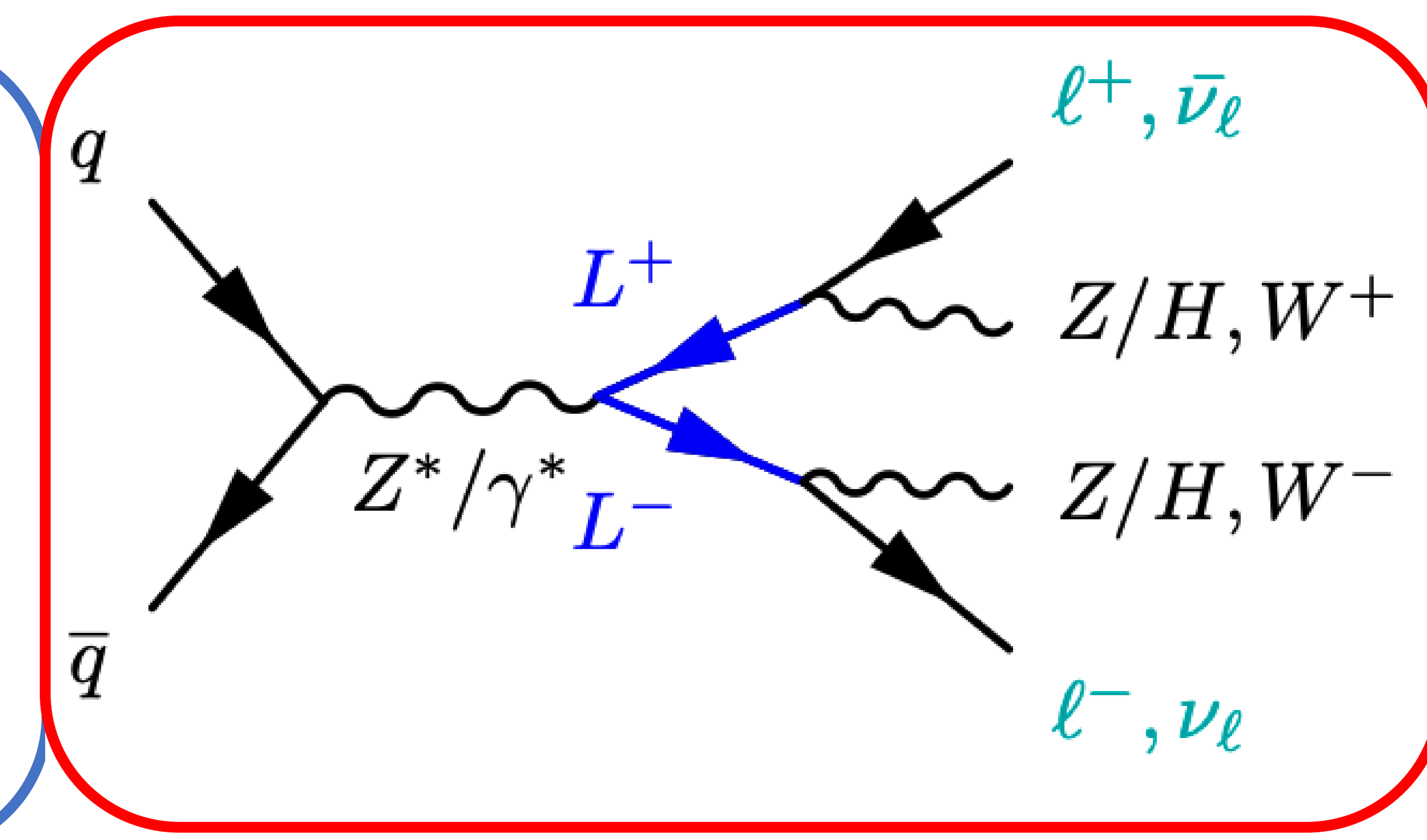


- First ATLAS search for VLL coupling to first and second-generation SM leptons using the full Run 2 dataset
  - Doublet contains an electrically charged $L^{\pm}$ and neutral N^0 VLL forming the SU(2) doublet => characterized by mostly low E_T^{miss}
  - Singlet only contains the charged VLL => characterized by larger E_T^{miss} due to neutrino from VLL in final state

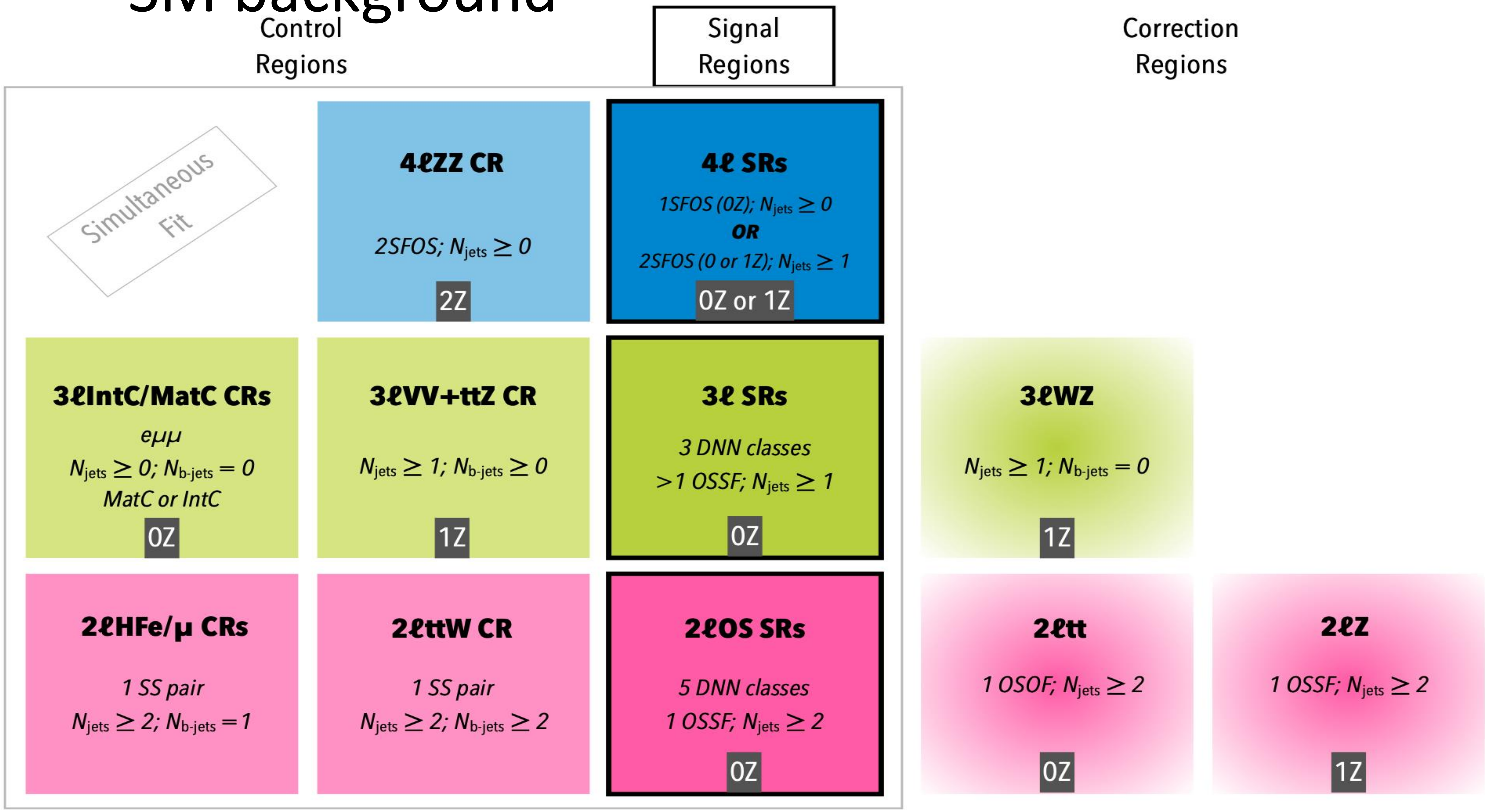
Doublet diagrams



Singlet diagram



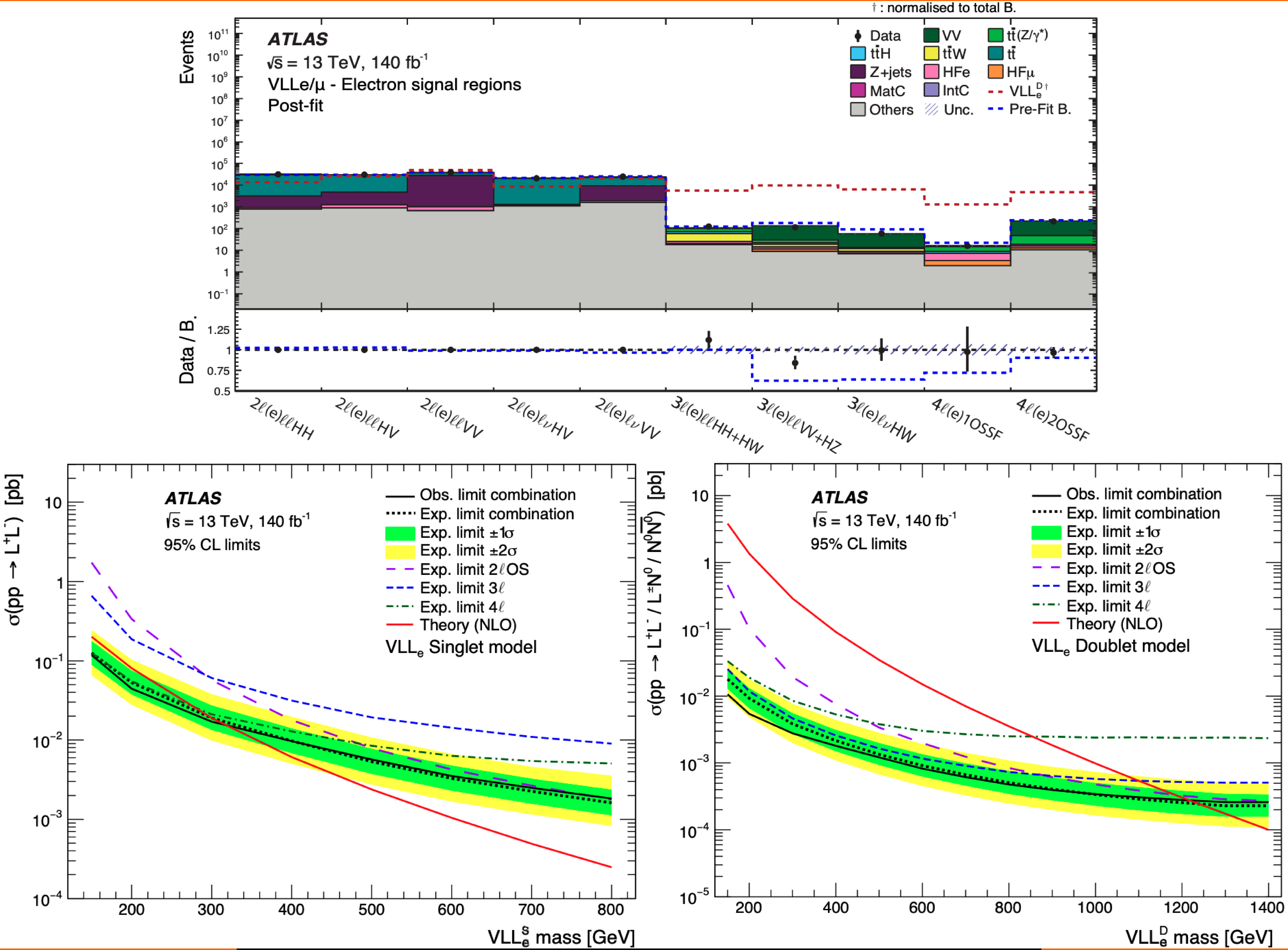
- 10 SRs and 9 CRs simultaneously fit for each lepton flavor
  - DNN classifier for $2\ell OS$ and 3ℓ SRs => reduce migrations & reject SM background



  - A kinematic variable is fit to improve sensitivity in SRs while modelling of background is improved by fitting CRs

Vector-like Electrons and Muons

2411.07143



Vector-like Electrons and Muons

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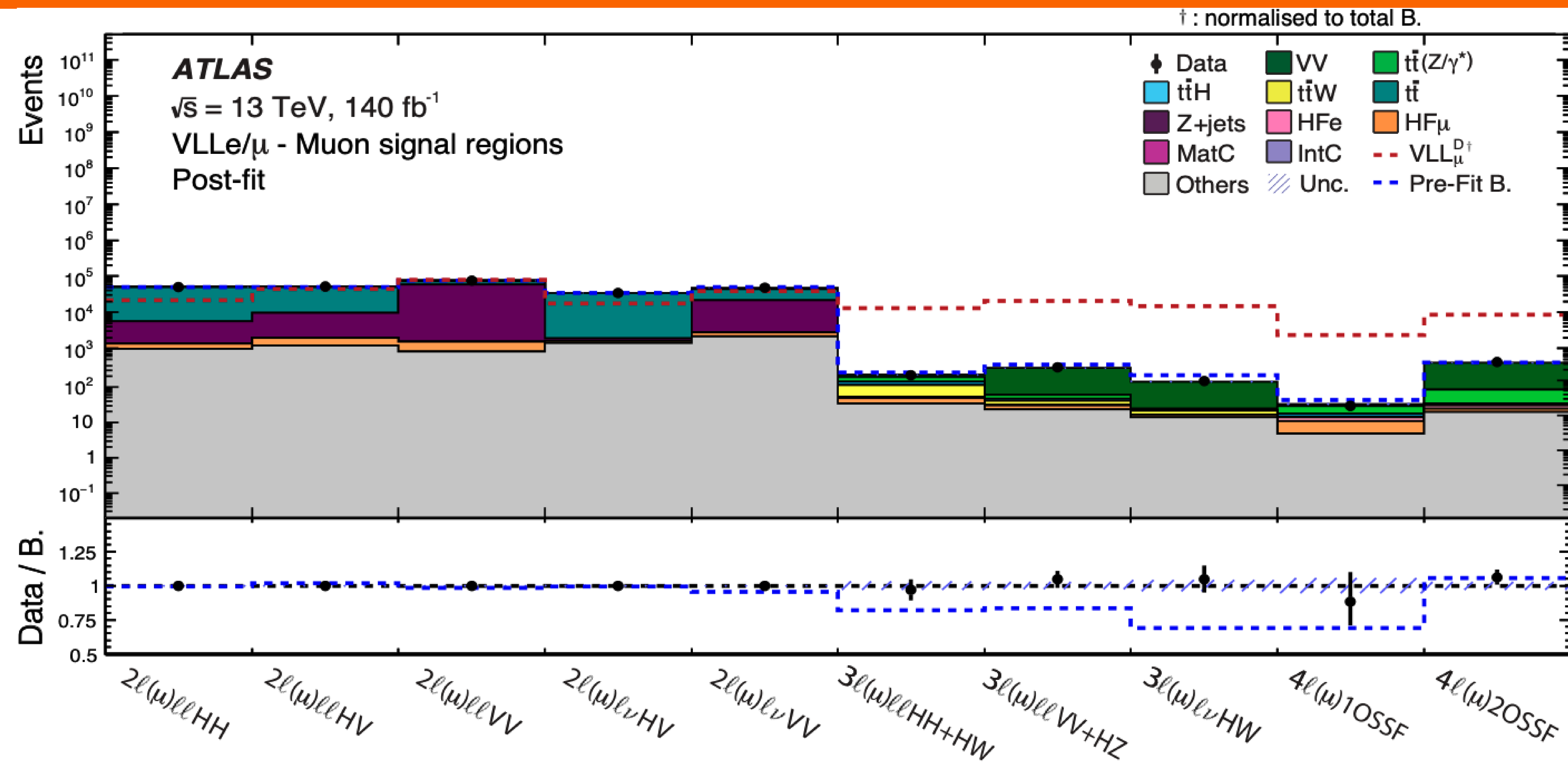
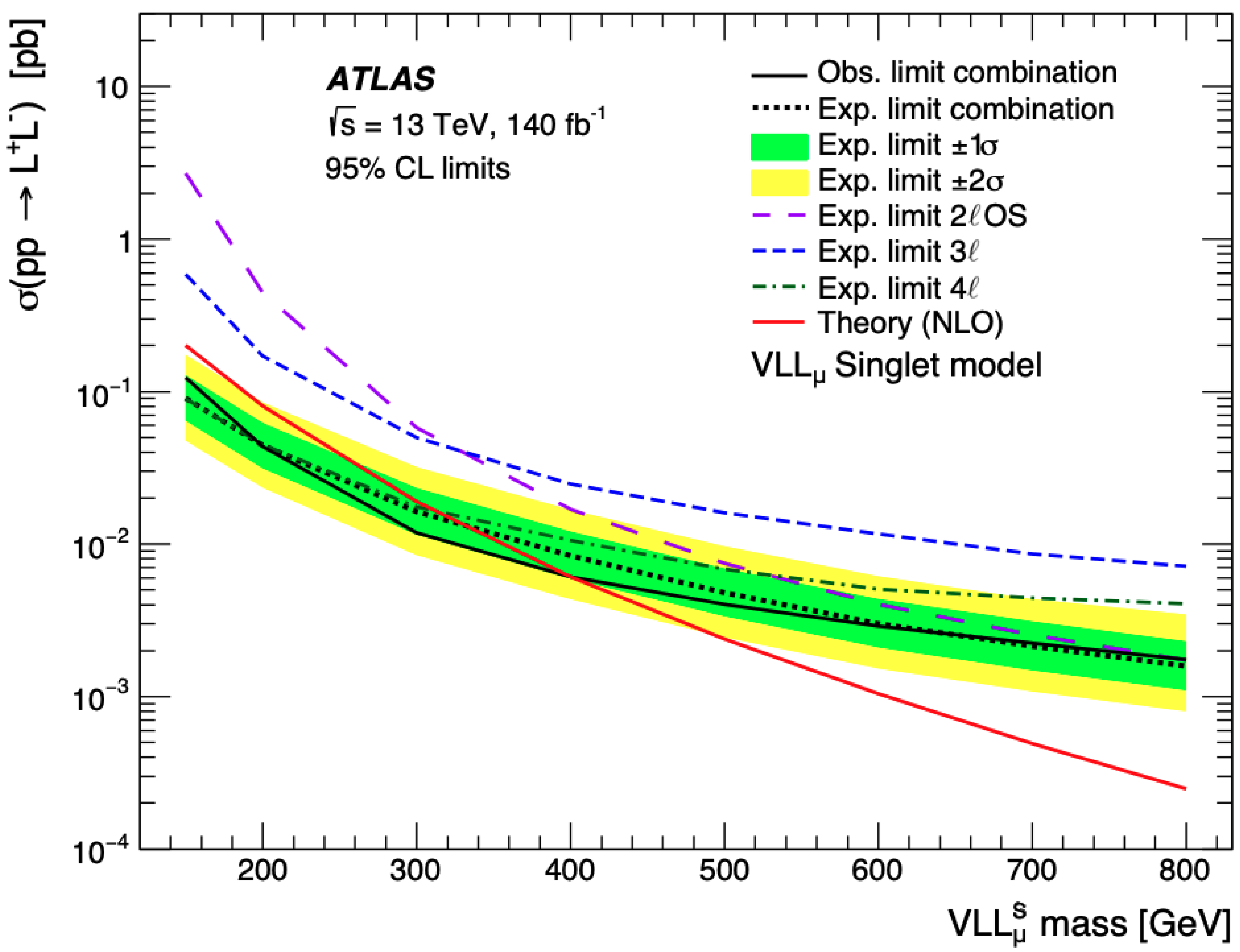
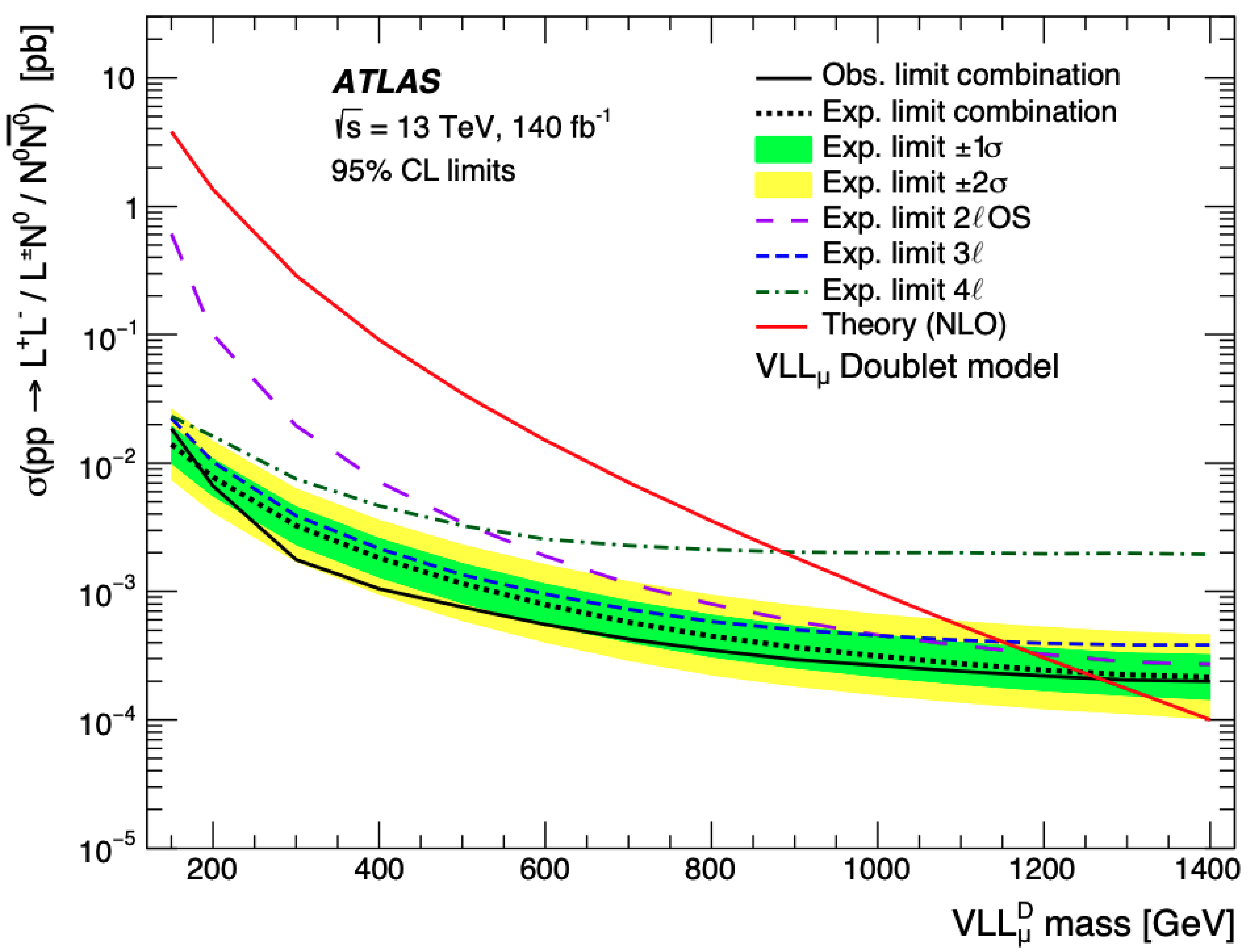






Higgs extension searches

- Various models postulate additional Higgs particles
  - Adding a second Higgs doublet leads to the presence of several Higgs-like particles with differing characteristics in addition to the CP even SM-like Higgs (h)
    - two charged ($H^{\pm}$) particles
    - A heavier CP even scalar (H) particle
    - A CP odd pseudo-scalar (A) particle

Higgs extension searches

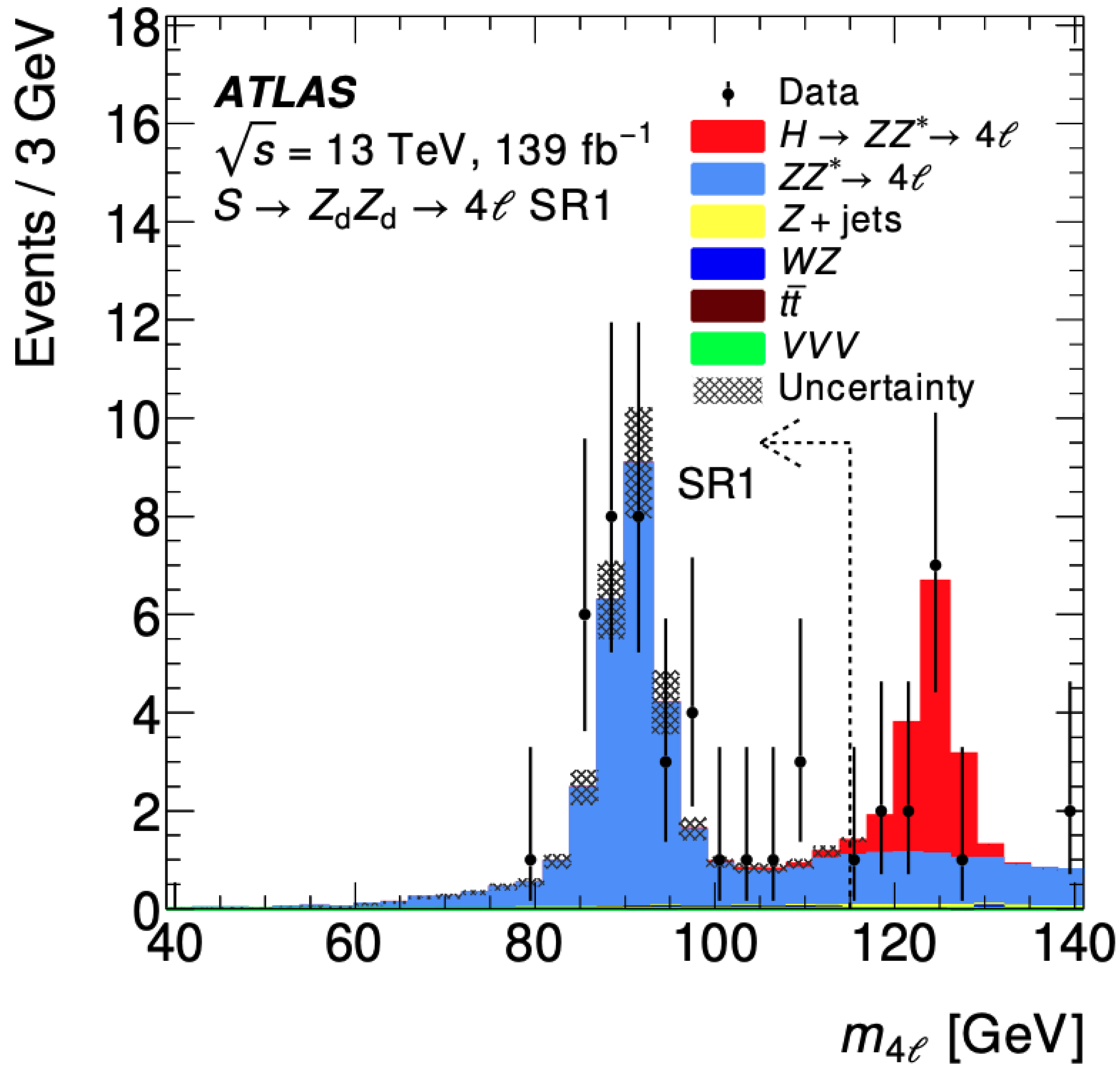
- Various models postulate additional Higgs particles
  - Adding a second Higgs doublet leads to the presence of several Higgs-like particles with differing characteristics in addition to the CP even SM-like Higgs (h)
    - two charged ($H^{\pm}$) particles
    - A heavier CP even scalar (H) particle
    - A CP odd pseudo-scalar (A) particle
- Possible to consider additional scalar particles
  - Additional scalars could even have couplings to dark matter candidate particles!
- These would resolve various inconsistencies in the SM i.e. CP violation, baryon asymmetry, etc.

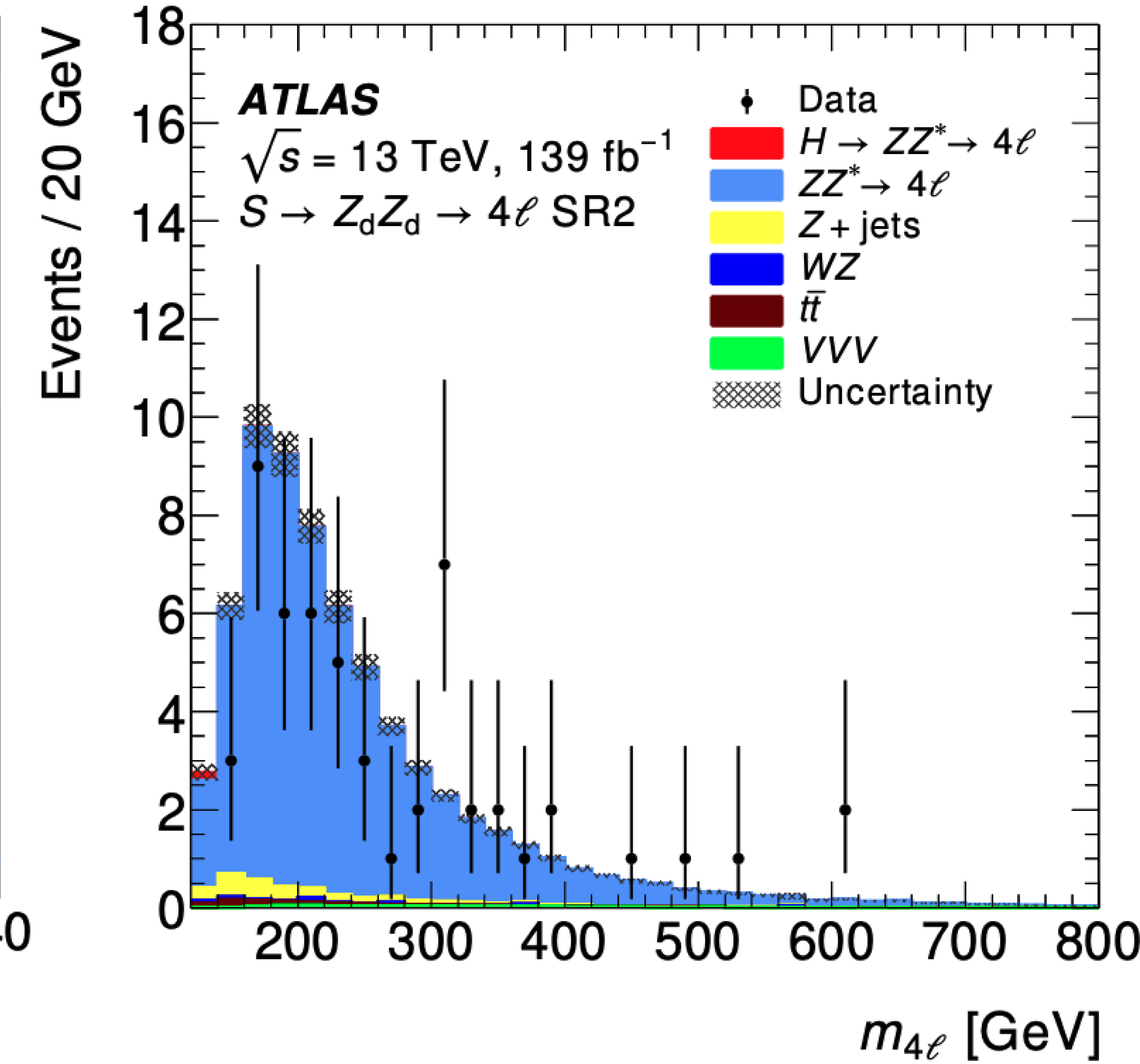
$S \to XX \to 4\ell$ 2410.16781

- Consider a Hidden Abelian Higgs Model (HAHM) which posits the existence of a scalar (S) and a dark gauge (Z_d) boson
  - Extends on previous analysis of $H \to Z_d Z_d \to 4\ell$
  - Only considering ggF
- Require all pairs of $m_{\ell^-\ell^+} > 11.105$ GeV => rejects J/ψ and Υ decays
  - Construct pairs such that $m_{ab} > m_{cd}$
- 2 SRs
  - SR1 requirements
    - $m_{4\ell} < 115$ GeV
    - $m_{ab} \notin (50,106)$ GeV => Orthogonal to $H \to ZZ_d$
  - SR2 requirements
    - $m_{4\ell} > 130$ GeV
    - $|m_{ab,cd} - m_Z| > 8$ GeV unless all 4ℓ are SF then $|m_{ad,bc} - m_Z| > 4$ GeV
- Reduce ZZ^* by requiring $|E'_{ab}/\mathrm{m}_{4\ell} - 0.5| < 0.008$

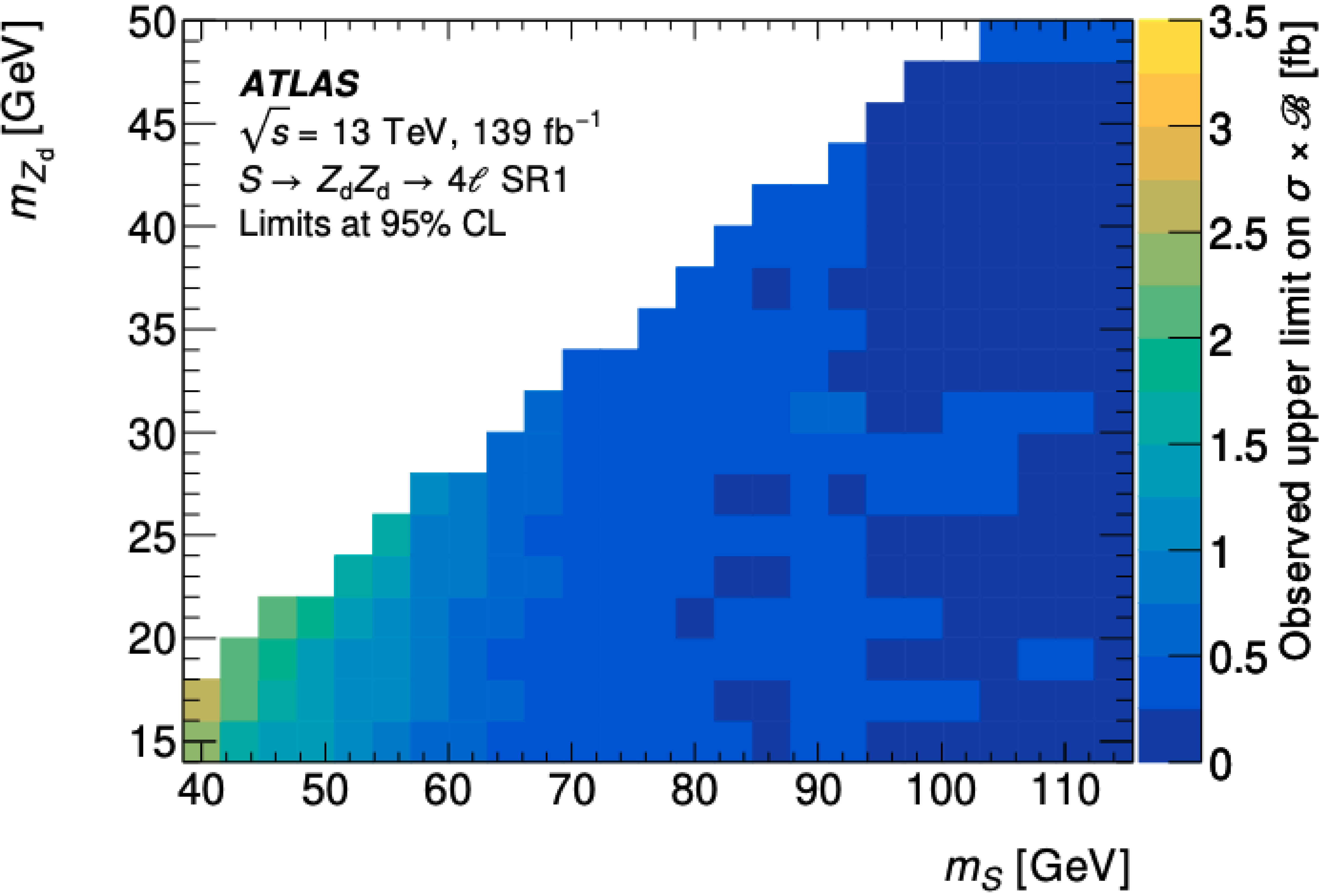
$$\frac{E'_{ab}}{m_{4\ell}} = \frac{1}{2}\left(1 + \frac{m^2_{ab} - m^2_{cd}}{m^2_{4\ell}}\right)$$

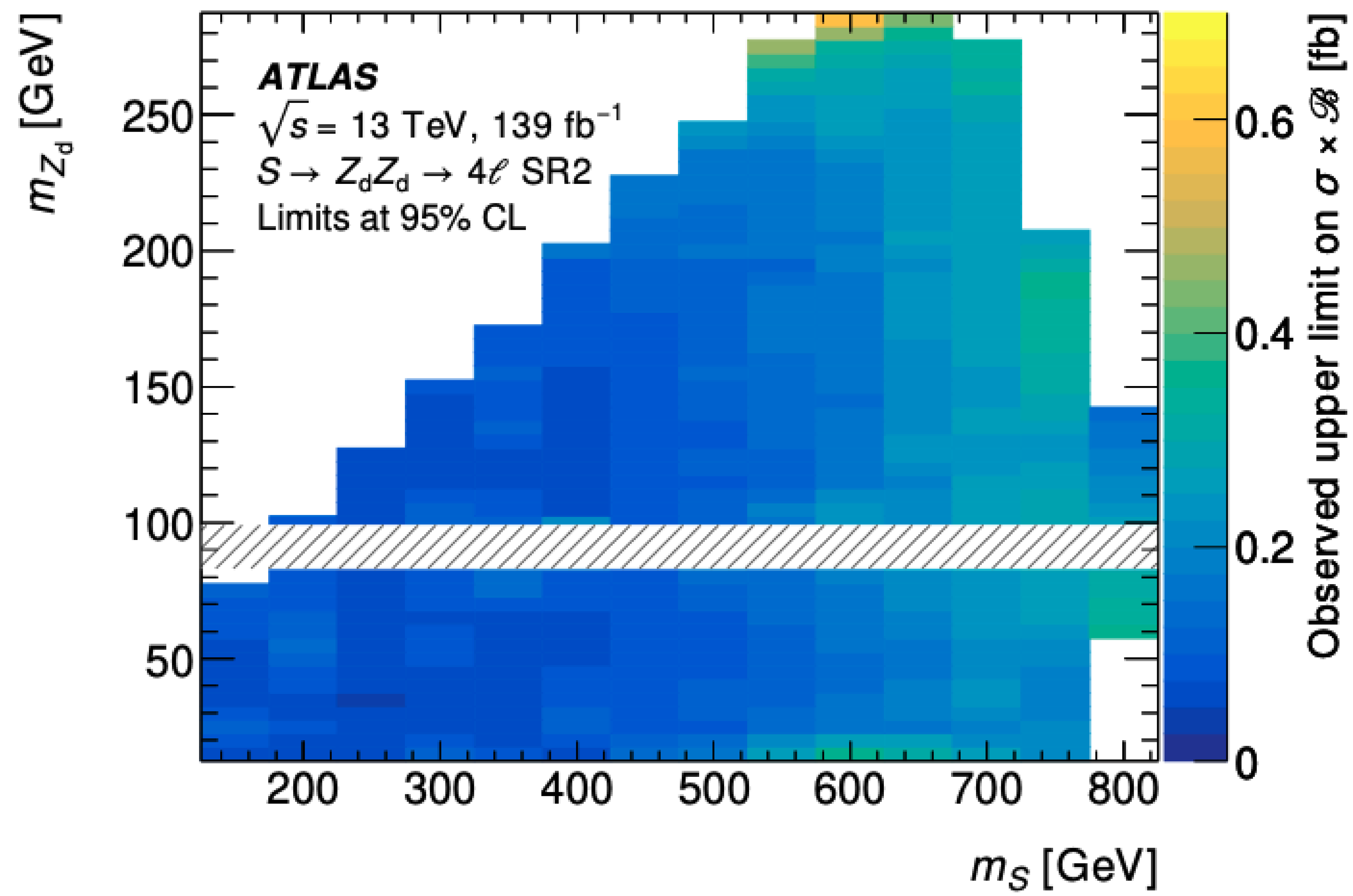
$< 3\sigma$ excess!





Set limits on $\sigma \times \mathcal{B}$!





$H \to Za \to \ell\ell j$ 2411.16361

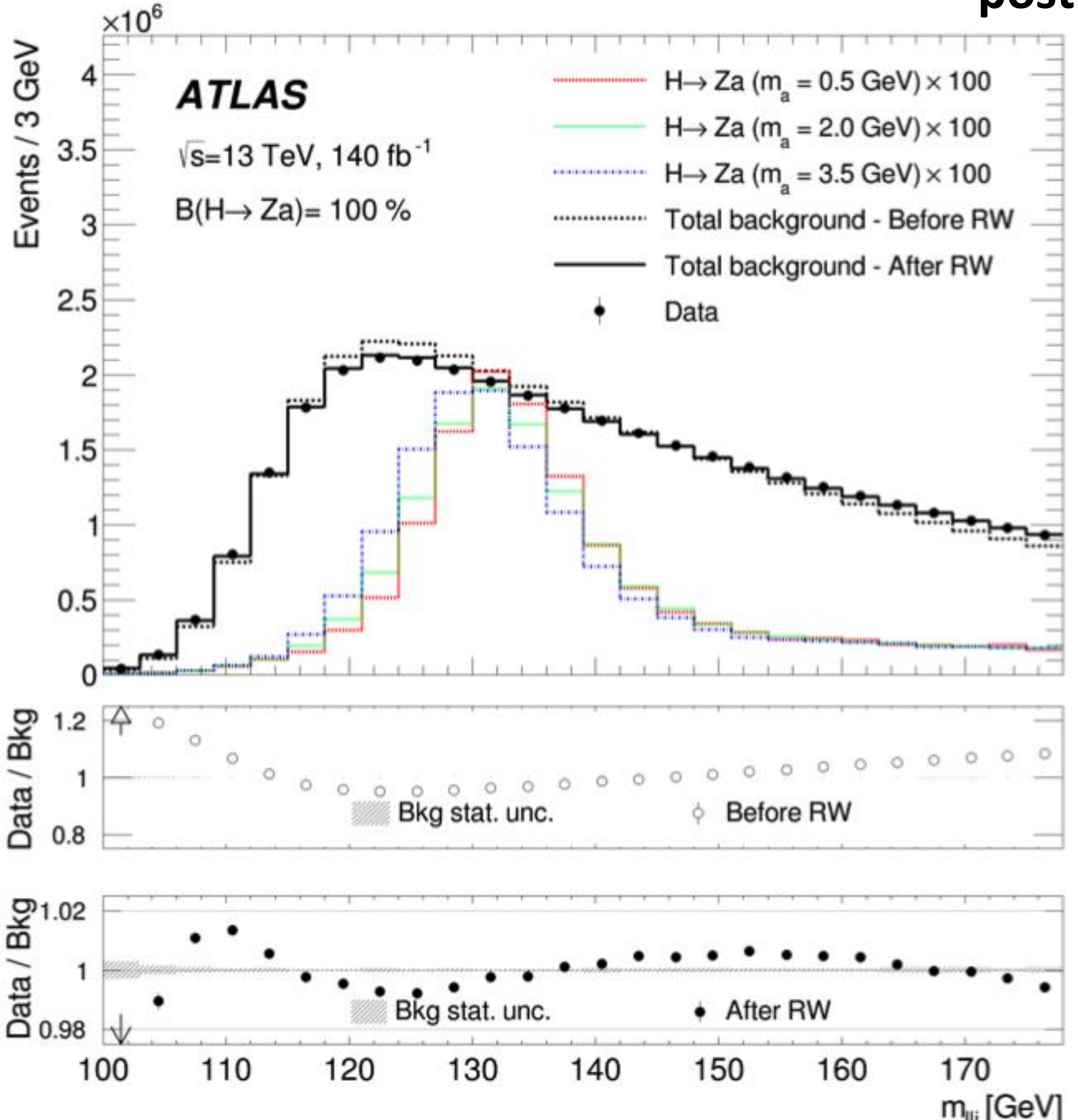
- Increased interest in light resonance (a) decays of the Higgs
  - Prior analyses have focused on leptonic and photonic decays with m_a $\mathcal{O}(1-10\ \mathrm{GeV})$
- Consider light resonances such that $m_a \leq 4\ \mathrm{GeV}$, decaying hadronically
  - Follow up on analysis published in 2020 that was limited by the background modelling uncertainty => poor Z+jets modelling
- Train a NN to estimate density ratio of total background to data => additional MC event weight equalizing density functions

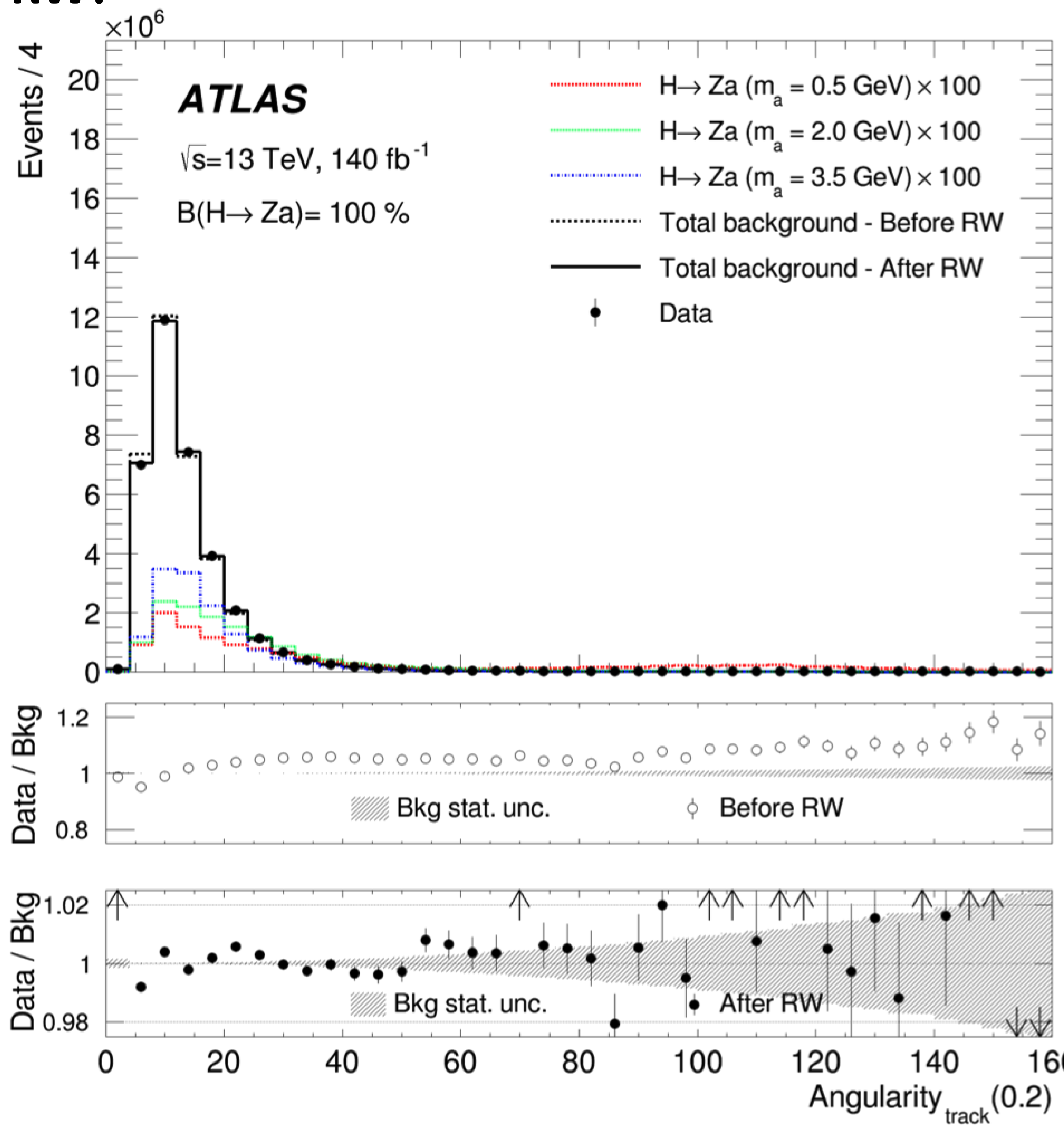
$$p_1(x)/p_2(x) \approx C(x)/(1 - C(x))$$

  - Simultaneously improves modelling of jet substructure and event kinematic variables

$H \to Za \to \ell\ell j$ 2411.16361

Great improvement in ratio of data to background post-RW!

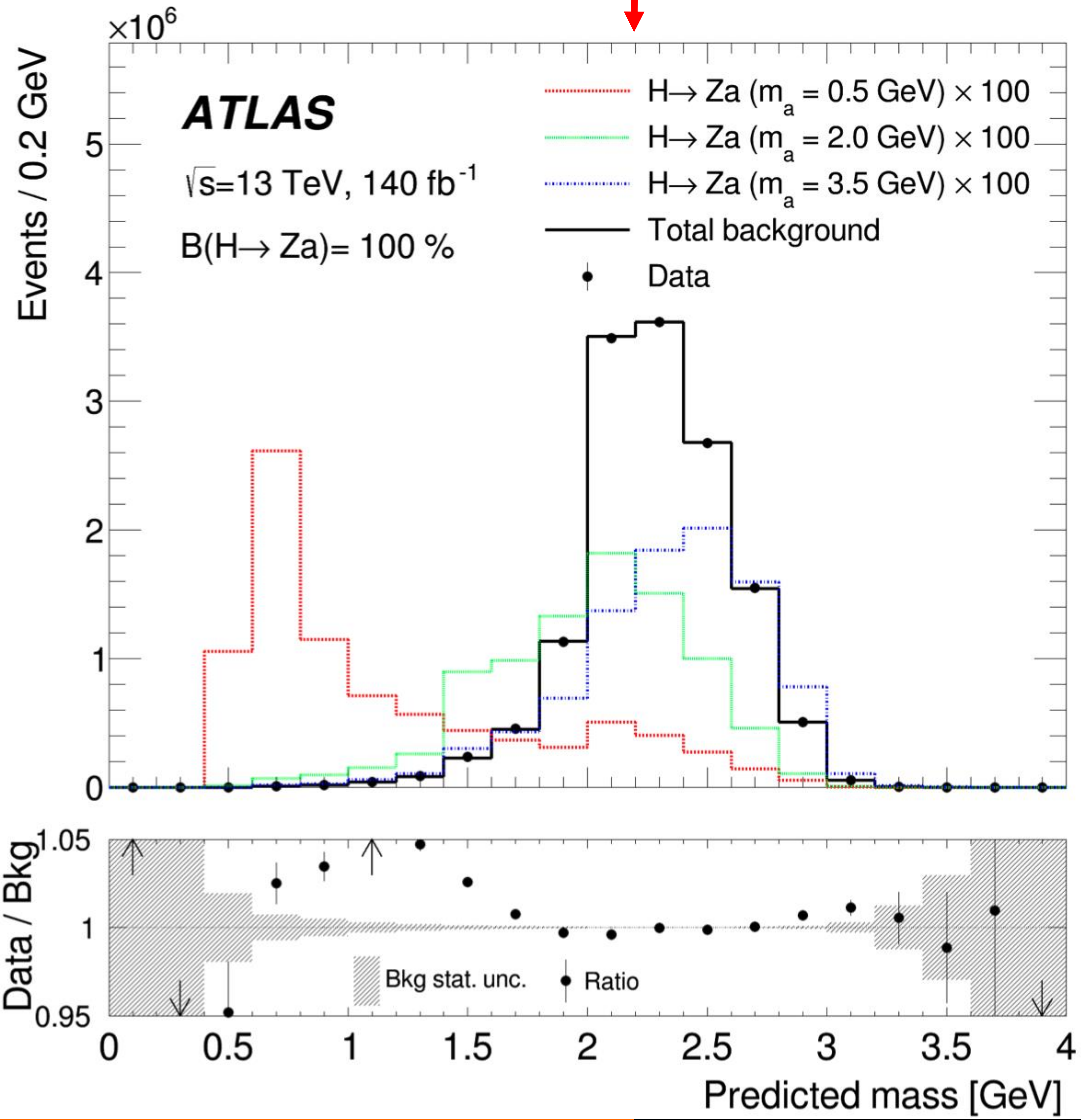


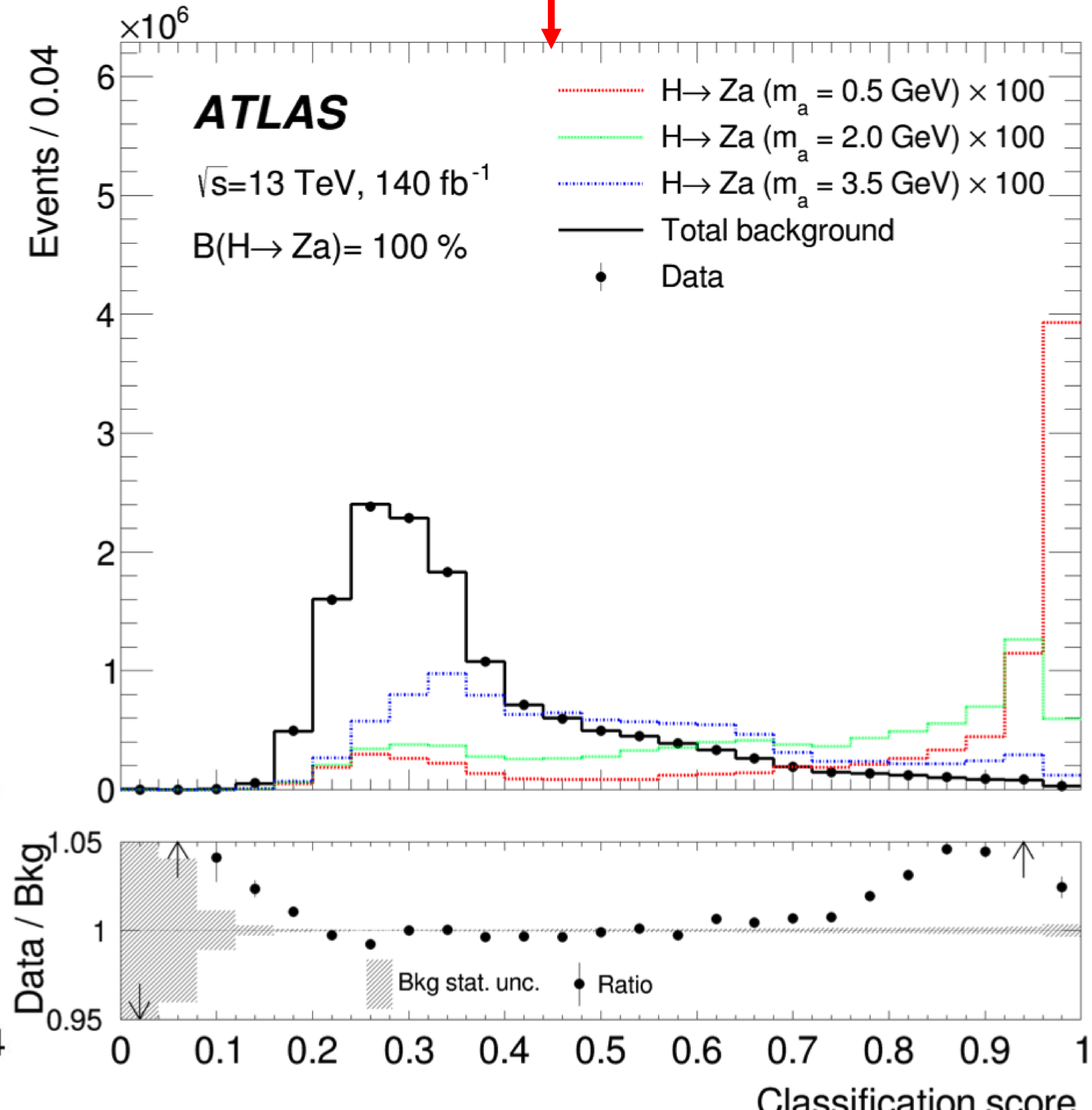


- Train two additional NNs

Regression NN estimates m_a

Classification NN to perform signal-background discrimination



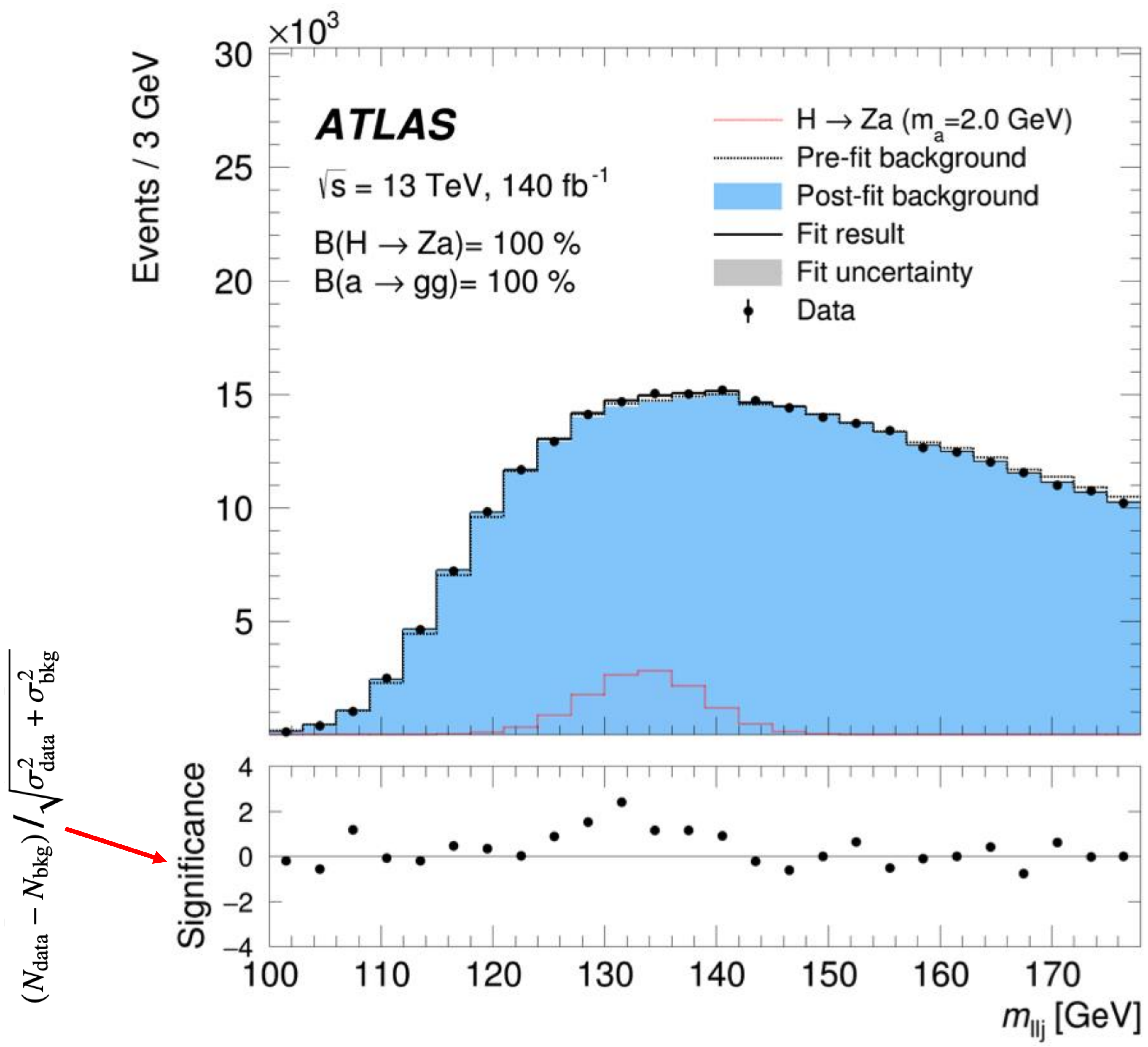


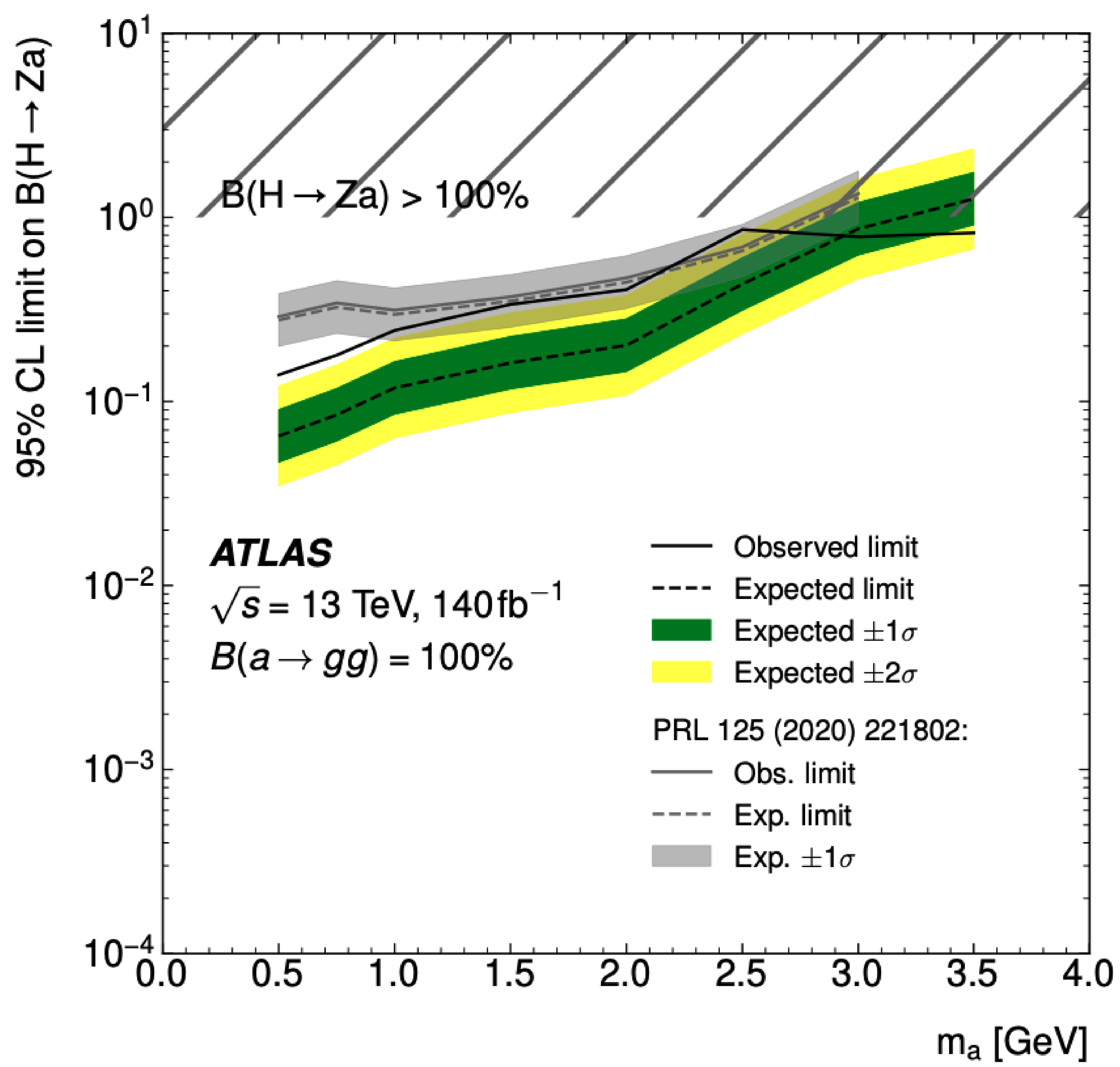
Cut @ 0.93 removes 99.3% of Background!

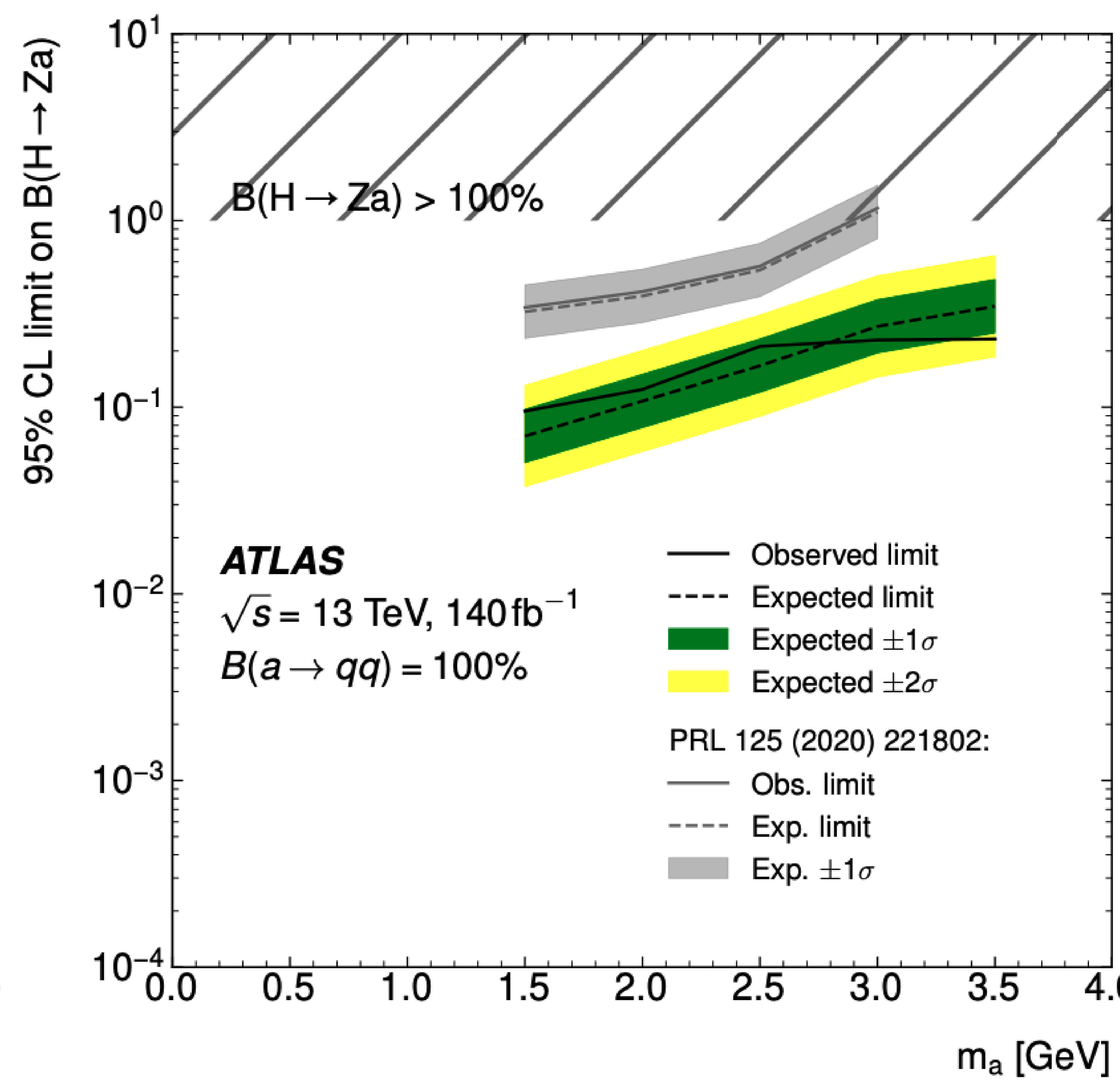
Score > 0.93 defines SR

$H \to Za \to \ell\ell j$ 2411.16361

- Signal model is fit with Gaussian
  - μ shifts from 125 to 131.5 GeV as m_a shifts from 4 to 0.5 GeV
    - μ < ~130 GeV => consistent with $H_{\mathrm{b-only}}$
    - μ > ~130 GeV ($m_a = 0.5 - 2.5$ GeV with $a \to gg$) accommodates slight excess @ $m_{\ell\ell j} \sim 135$ GeV
      - Largest local significance $\sim 1.5\sigma$ for $m_a = 0.5$ GeV with $a \to gg$

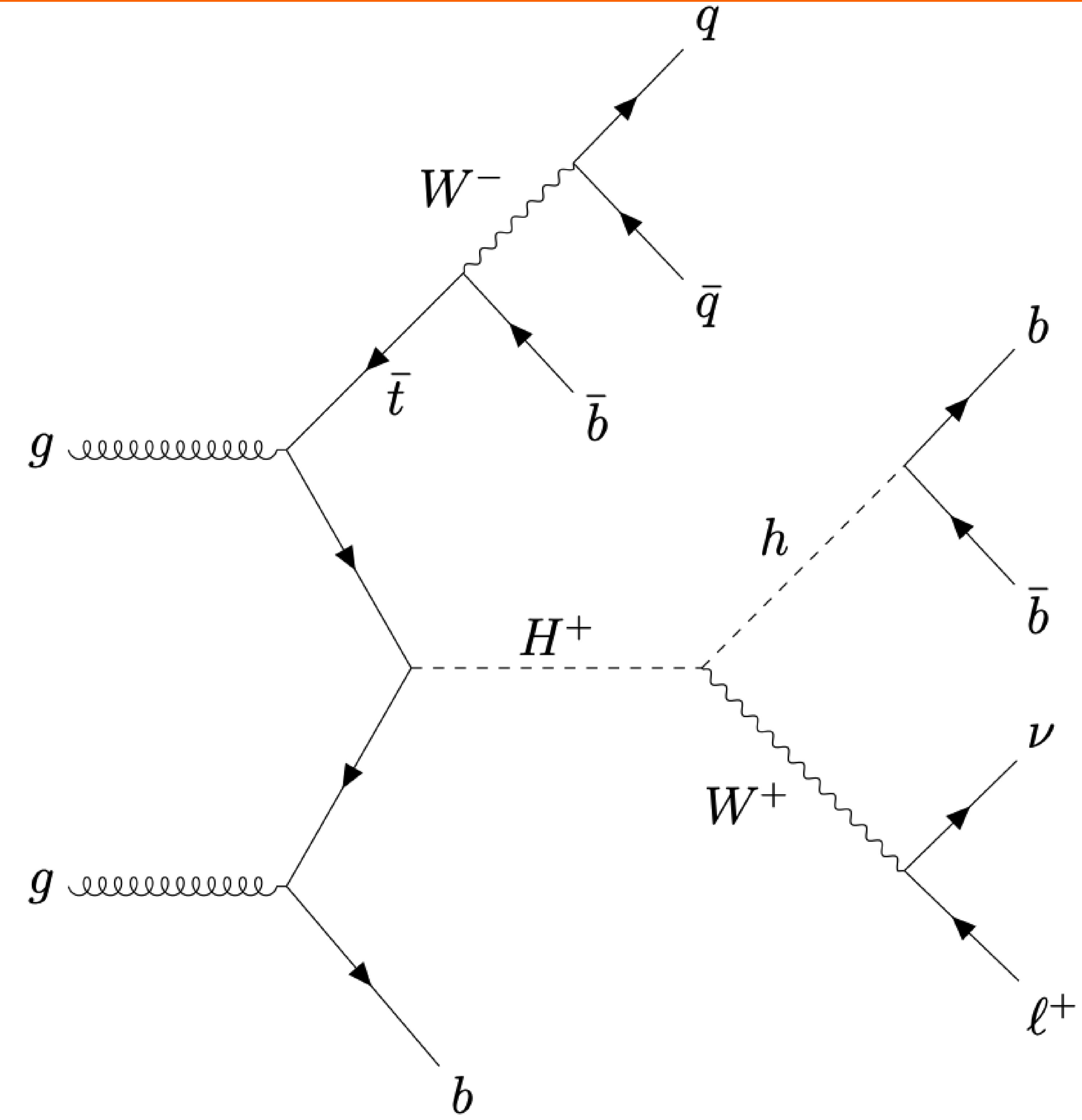


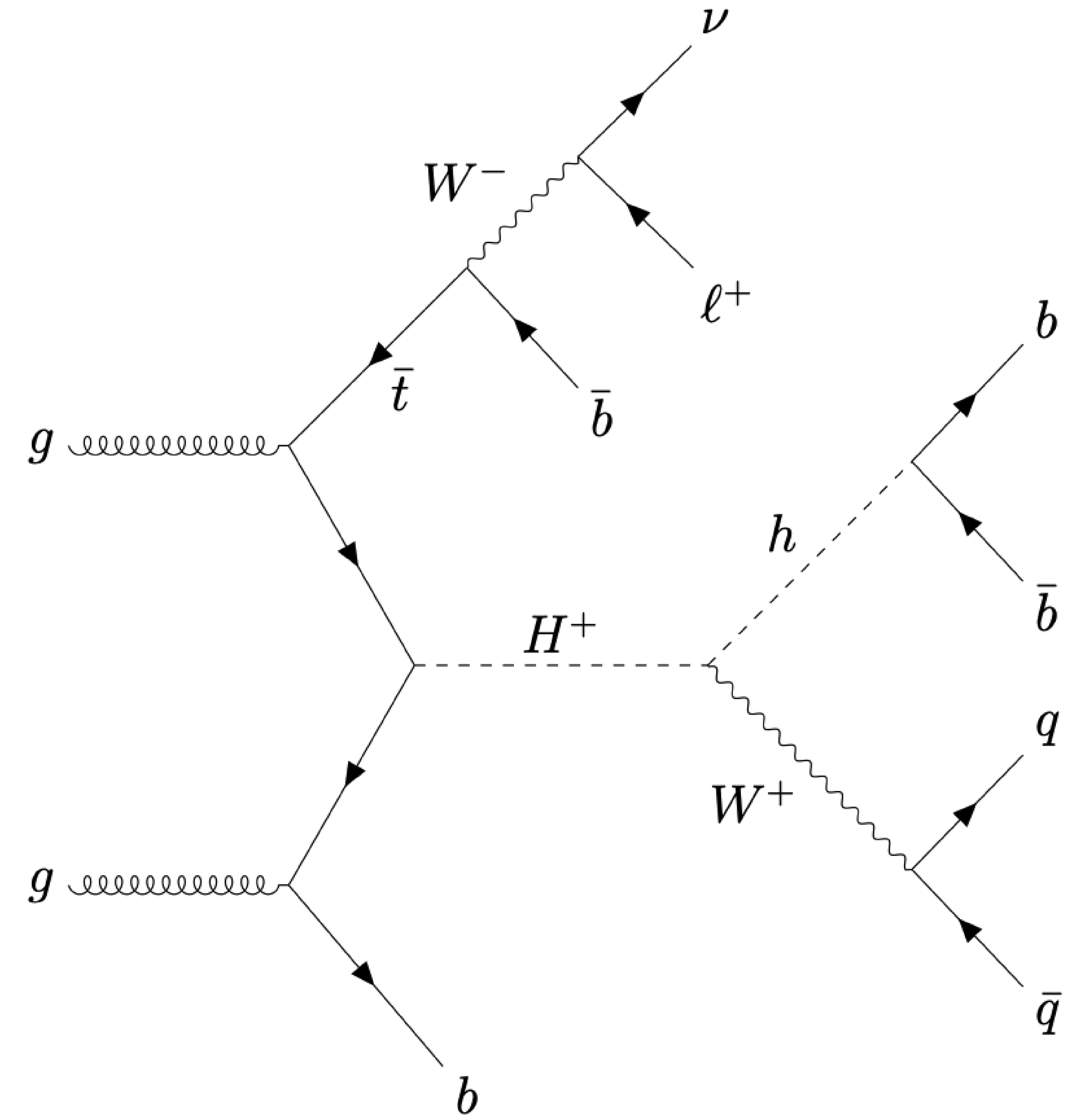




$H^{\pm} \rightarrow W^{\pm}h$ 2411.03969

- Search for charged Higgs boson produced in conjunction with a top and b-quark
  - First time the channel is measured in ATLAS!
  - Probe the $\mathrm{H}^{\pm} \rightarrow \mathrm{W}^{\pm}\mathrm{h} \rightarrow \ell^{\pm}\nu bb$ and $qq'bb$ final state
  - Low and high mass charged Higgs considered leading to two classes of decays
    - Resolved: final state objects are well separated => small-R jets
    - Merged: final state objects are strongly boosted => large-R jet(s)



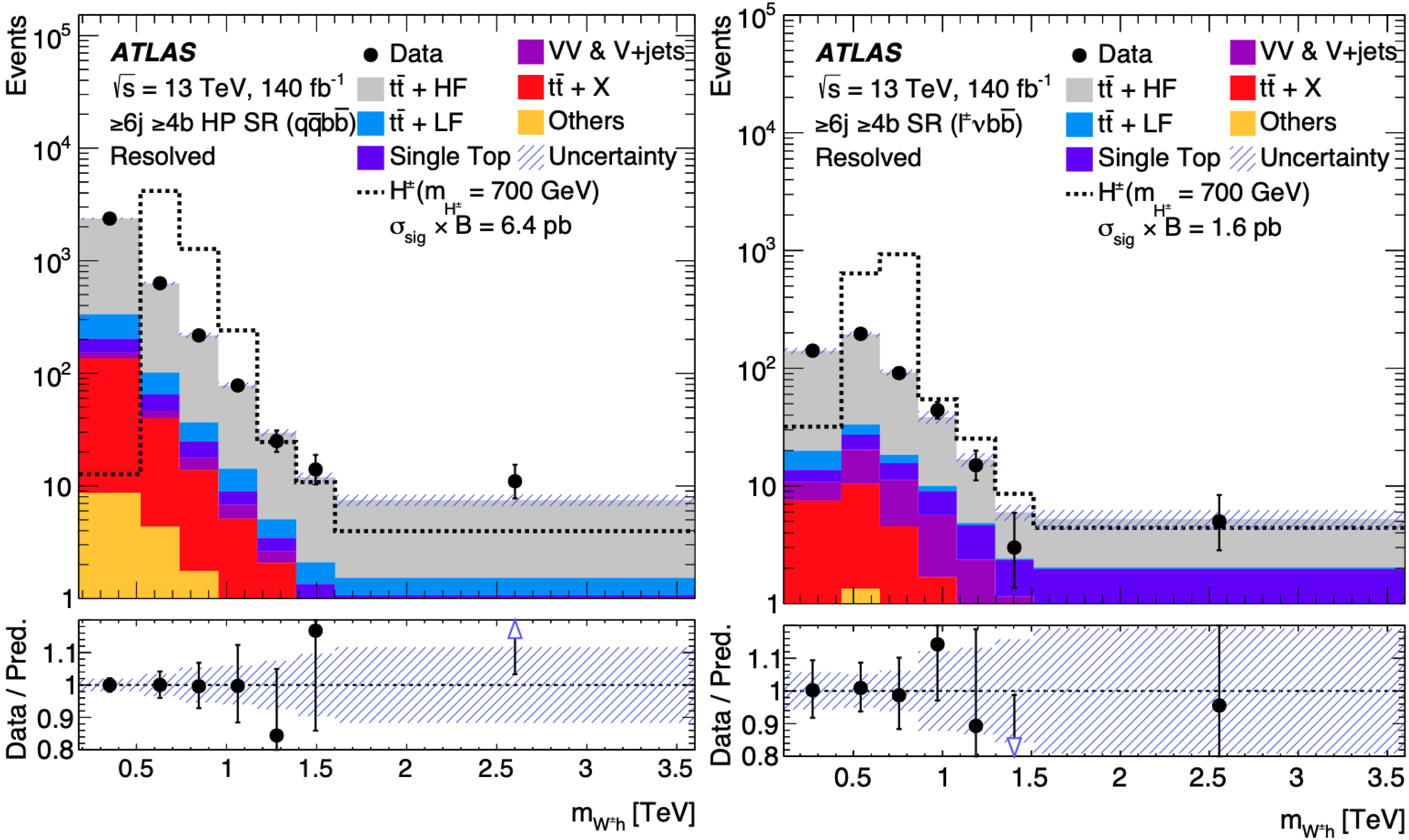


$H^{\pm} \to W^{\pm}h$ 2411.03969

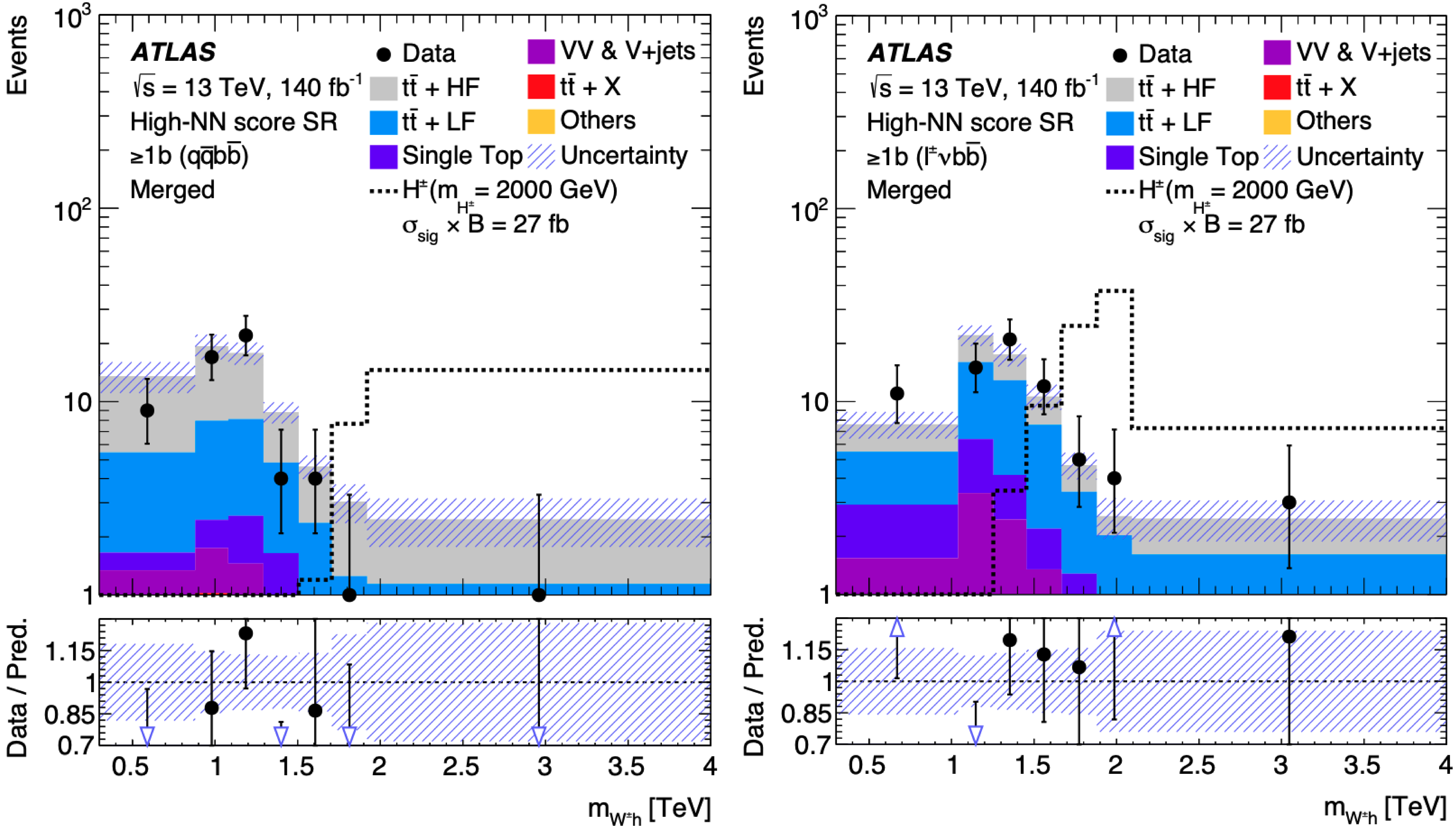
- Construct a BDT and NN to reconstruct the signal by finding the correct object pairings for the resolved and merged cases, respectively
  - Score along with kinematic requirements leads to various region definitions
- Use $m_{W^{\pm}h}$ as final fit variable

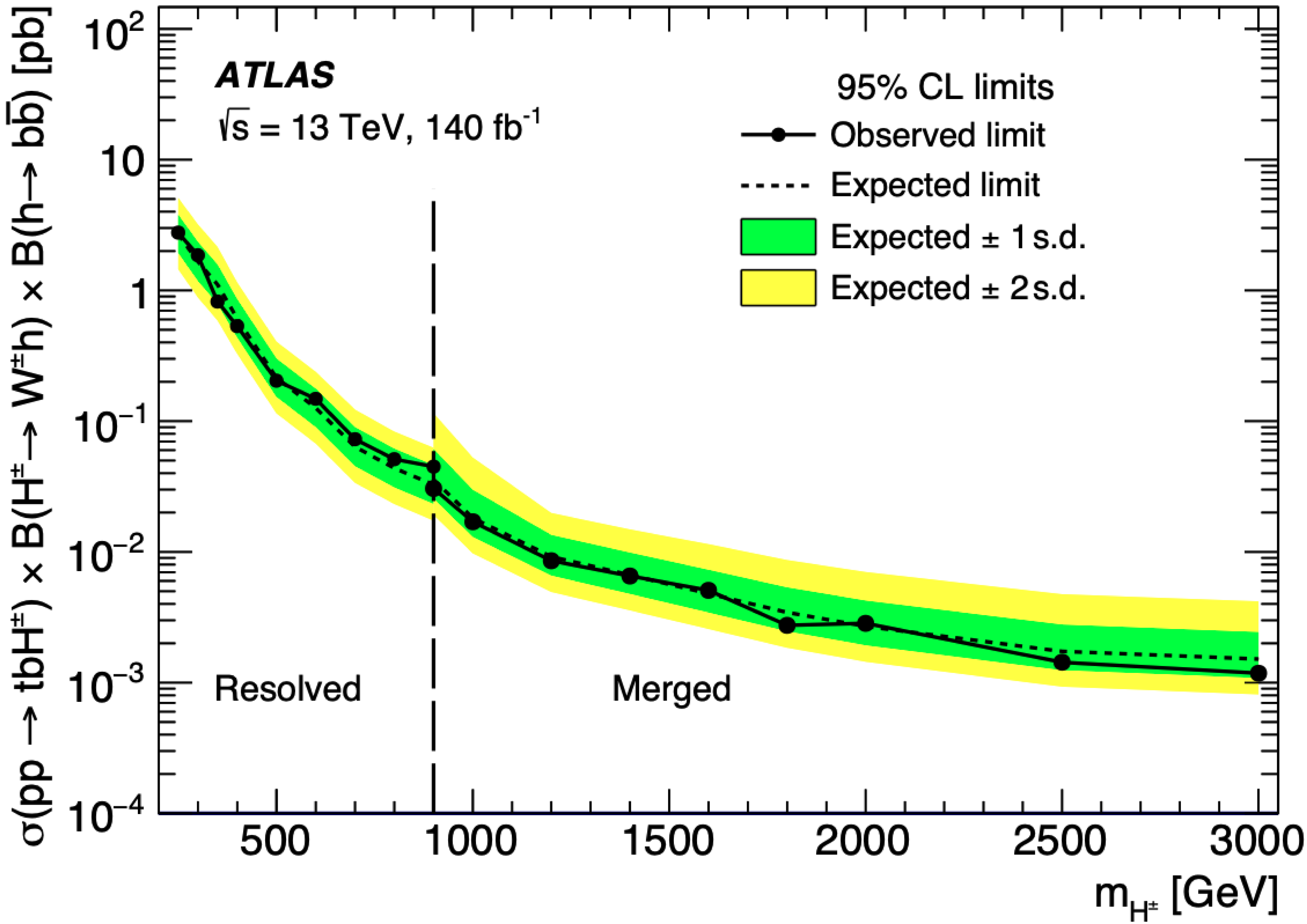
Region	Requirement	$\ell^{\pm}\nu b\bar{b}$ channel	$q\bar{q}b\bar{b}$ channel
Resolved			
Signal regions	Jet & b-tag multiplicity		$5j3b$, $5j \geq 4b$, $\geq 6j3b$, $\geq 6j \geq 4b$
	BDT score	$w_{\mathrm{BDT}}^{\max} \geq 0.7$	$w_{\mathrm{BDT}}^{\max} \geq 0.9$
Low-purity signal regions	Jet & b-tag multiplicity		$5j3b$, $5j \geq 4b$, $\geq 6j3b$, $\geq 6j \geq 4b$
	BDT score	–	$0.0 \leq w_{\mathrm{BDT}}^{\max} < 0.9$ (for events with $5j3b$ or $\geq 6j3b$) $0.6 \leq w_{\mathrm{BDT}}^{\max} < 0.9$ (for events with $5j \geq 4b$ or $\geq 6j \geq 4b$)
Control regions	Jet & b-tag multiplicity		$5j3b$, $5j \geq 4b$, $\geq 6j3b$, $\geq 6j \geq 4b$
	BDT score	$-0.5 \leq w_{\mathrm{BDT}}^{\max} < 0.5$	$-0.5 \leq w_{\mathrm{BDT}}^{\max} < 0.0$ (for events with $5j3b$ or $\geq 6j3b$) $-0.5 \leq w_{\mathrm{BDT}}^{\max} < 0.6$ (for events with $5j \geq 4b$ or $\geq 6j \geq 4b$)
Merged			
High-NN score signal region	b-tag multiplicity	$0b$, $\geq 1b$	
	Mass window	$95\,\mathrm{GeV} \leq m_J < 140\,\mathrm{GeV}$	
	NN score	$w_{\mathrm{NN}} \geq 0.83$	$w_{\mathrm{NN}} \geq 0.2$ (for events with $0b$) $w_{\mathrm{NN}} \geq 0.1$ (for events with $\geq 1b$)
Medium-NN score signal region	b-tag multiplicity	$0b$, $\geq 1b$	
	Mass window	$95\,\mathrm{GeV} \leq m_J < 140\,\mathrm{GeV}$	
	NN score	$0.4 \leq w_{\mathrm{NN}} < 0.83$	–
Low-NN score signal region	b-tag multiplicity	$0b$, $\geq 1b$	
	Mass window	$95\,\mathrm{GeV} \leq m_J < 140\,\mathrm{GeV}$	
	NN score	$w_{\mathrm{NN}} < 0.4$	$w_{\mathrm{NN}} < 0.2$ (for events with $0b$) $w_{\mathrm{NN}} < 0.1$ (for events with $\geq 1b$)
Low-mass control region	b-tag multiplicity	$0b$, $\geq 1b$	
	Mass window	$m_J < 95\,\mathrm{GeV}$	
	NN score	–	
High-mass control region	b-tag multiplicity	$0b$, $\geq 1b$	
	Mass window	$m_J \geq 140\,\mathrm{GeV}$	
	NN score	–	

$\geq 6j \geq 4b$ HP Resolved Results!



$\geq 1b$ High NN Score Merged Results!




ATLAS
√s = 13 TeV, 140 fb-1
95% CL limits
Observed limit
Expected limit
Expected ± 1 s.d.
Expected ± 2 s.d.
Resolved
Merged
σ(pp → tbH±) × B(H± → W±h) × B(h→ bb̄) [pb]
m_H± [GeV]
10^2
10
1
10^-1
10^-2
10^-3
10^-4
500
1000
1500
2000
2500
3000

Closing remarks

- The ATLAS physics program probes a wide range of new phenomena beyond the SM
  - Some results are the best ones to date!
  - Improvements in analysis techniques, especially in the application of ML methods, aid in the collaboration's ability to set such powerful limits
- Currently, there are no signs of new physics, but the data collected during Run 3 of the LHC will provide even more opportunity to improve/refine our searches!
- While I (unfortunately) couldn't cover everything there are other talks covering interesting work
  - Recent Results from the ATLAS experiment at the LHC – Sergei Chekanov
  - Higgs boson Property Measurements at the ATLAS experiment – Michela Biglietti
  - Highlights of SM measurements including Top with the ATLAS experiment at the LHC – John Patrick Mc Gowan

Last but not least…

Thank you for your time and special thanks to:

The US Department of Energy for funding this research

The ATLAS collaboration for a fruitful physics program

The organizers of Miami 2024