UNIVERSITÉ DE GENÈVE

ATLAS EXPERIMENT

Searches for electroweak production of supersymmetric particles with the ATLAS detector

Pantelis Kontaxakis
on behalf of the ATLAS Collaboration

EPS-HEP Workshop
Marseille, France

July 7, 2025

EW-SUSY Production at the LHC

◉ EW interactions → Small production cross-sections

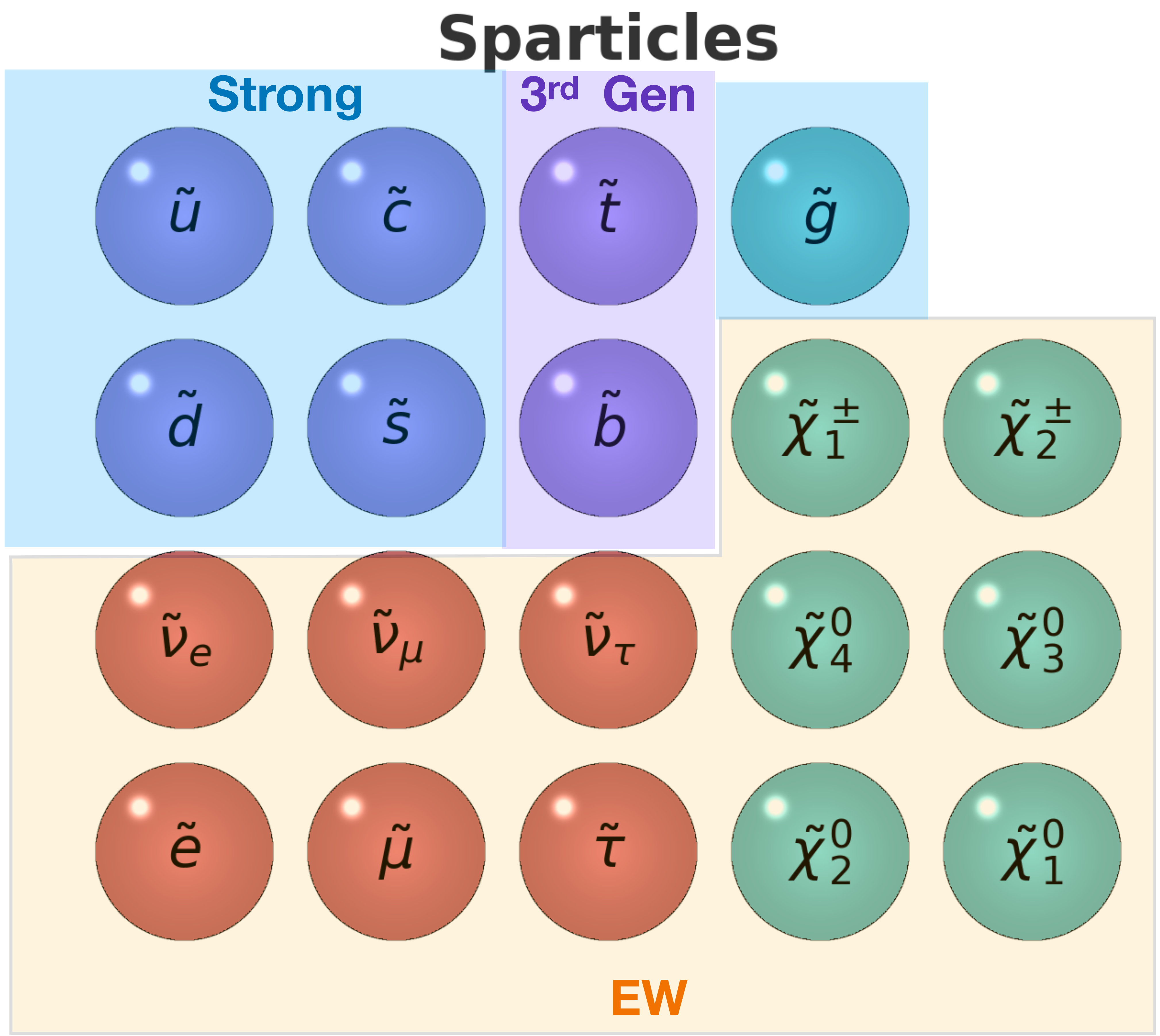
- Direct production of charginos, neutralinos and sleptons are created only through W/Z/γ exchange, thus cross-sections ~100x smaller w.r.t. to strong SUSY*

◉ SM-like, but often soft signatures

- Decays produce leptons + W/Z/h + MET from invisible neutralino.
- In compressed spectra (Δm≤40 GeV) visible objects are soft and hover at trigger thresholds, challenging detection

◉ Search strategies in ATLAS experiment aim to:

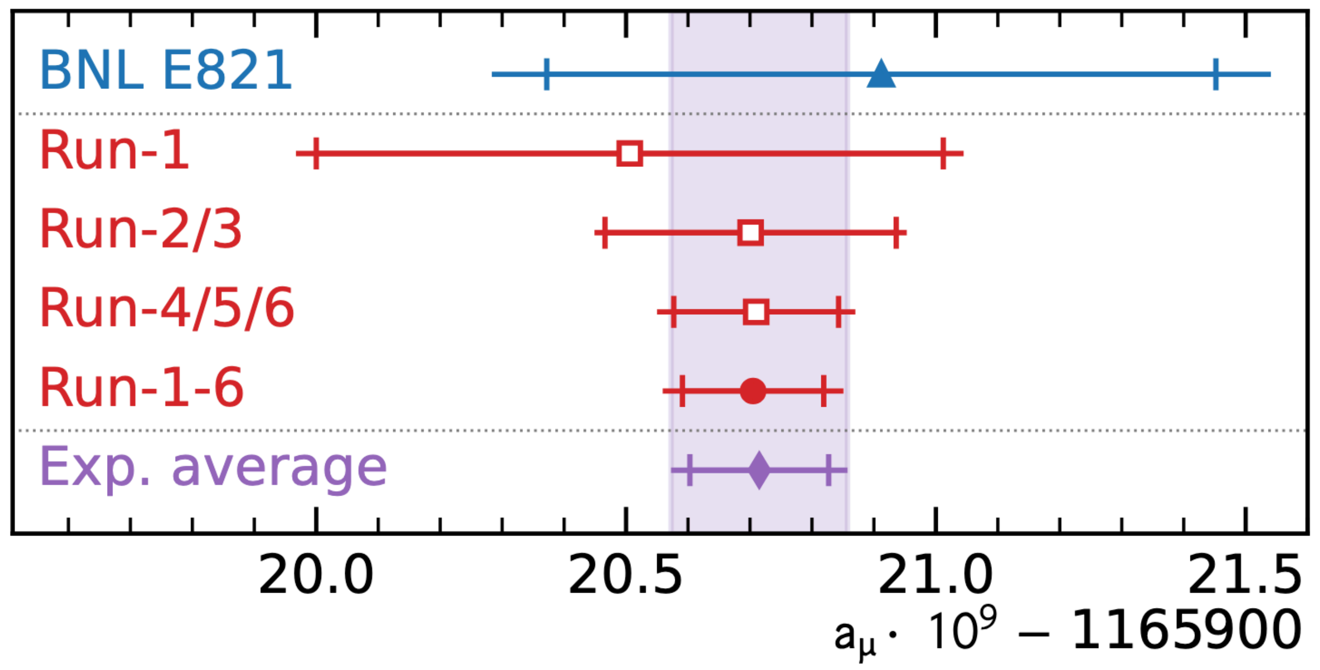
- Increase sensitivity in compressed SUSY scenarios
  - Soft final states, ISR, ML algorithms,…
- Increase sensitivity to higher (neutralino) masses
  - Boosted decays, tight kinematic selections,…



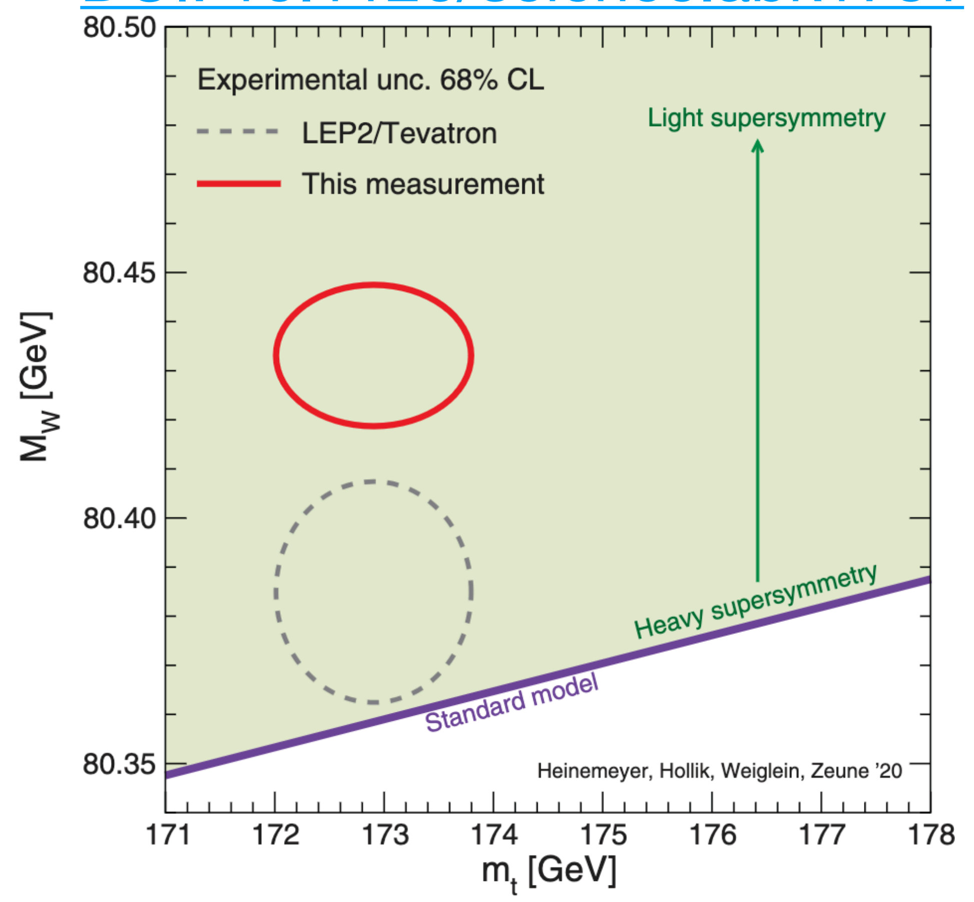
*See Jiarong's talk for SUSY Strong production results

Why in particular EW-SUSY?

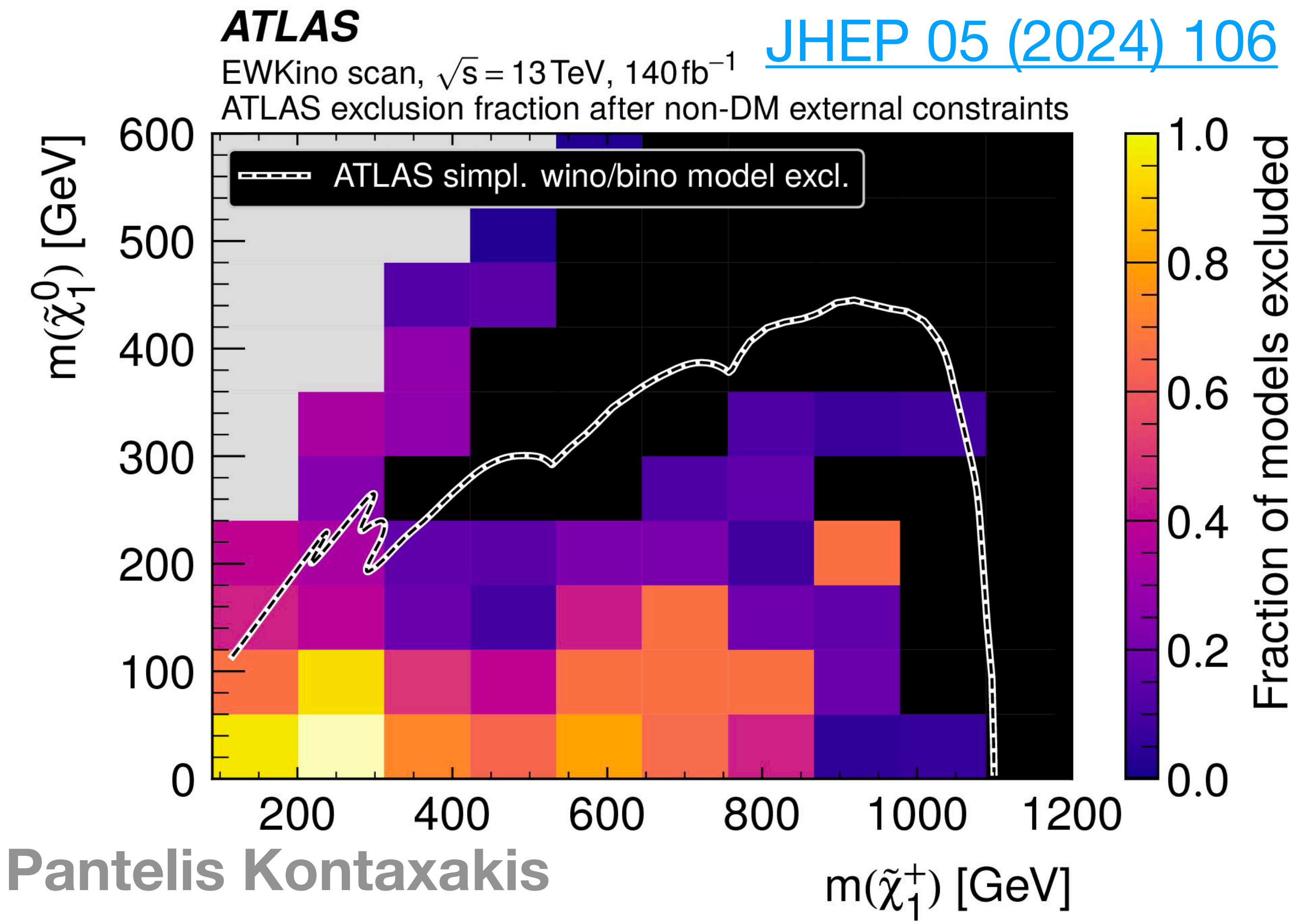
arXiv:submit/6490134



DOI: 10.1126/science.abk1781



JHEP 05 (2024) 106



◉ Naturalness

- μ ≦ 1 TeV light higgsinos soften Higgs mass corrections

◉ Dark matter

- Neutralino is a textbook WIMP, MSSM parameter scans allow points cluster below 1 TeV

◉ Anomalies in precision measurements

- O(100 GeV) sleptons/inos can explain the muon g-2 excess and the CDF W-mass shift

◉ Unprobed phase space

- Even with full Run-2 data, >30% of models below 600 GeV of the produced electroweakinos mass survive, dominated by compressed spectra that evade current limits.
- Plenty of uncovered space and data to analyse

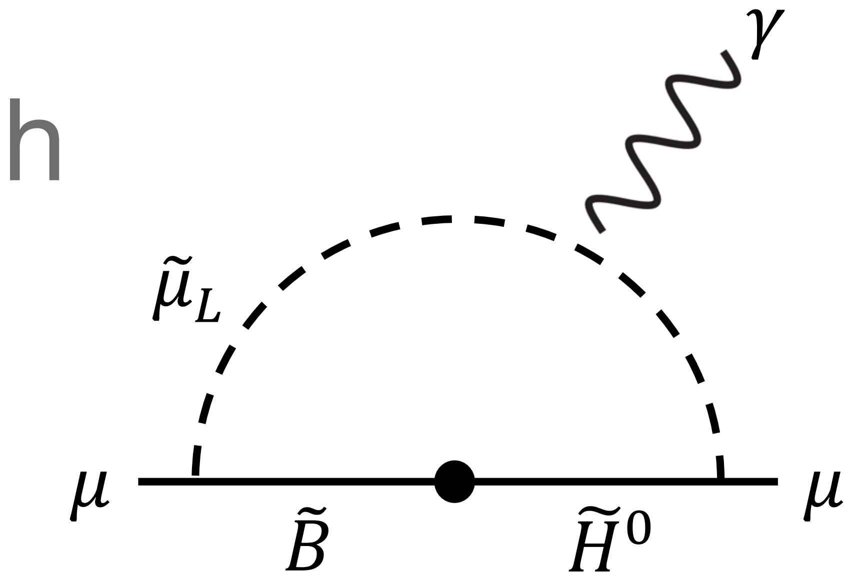
Disclaimer: Due to the wide scope of ongoing EW-SUSY researches in ATLAS experiment, only a selection of recent results and developments will be highlighted in this presentation

EW Slepton-Bino-Higgsino (SBH) analysis

◉ Analysis motivation

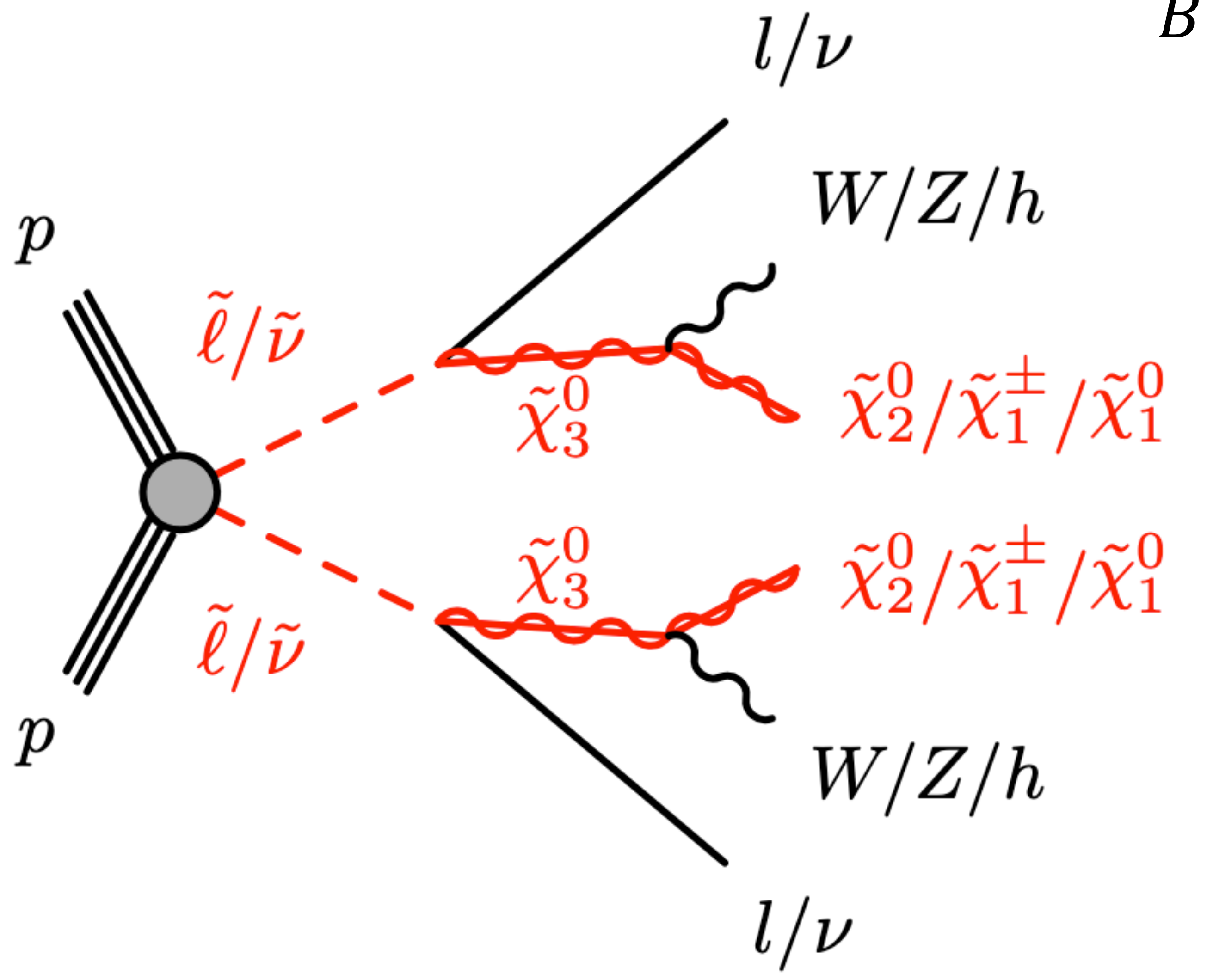
arXiv:2503.13135

- Muon anomalous magnetic momentun: $\alpha_\mu = (g-2)_\mu/2$ accurate calculated with significant discrepancy from SM
- SUSY can explain the muon g-2 anomaly (all SUSY particles must be light)



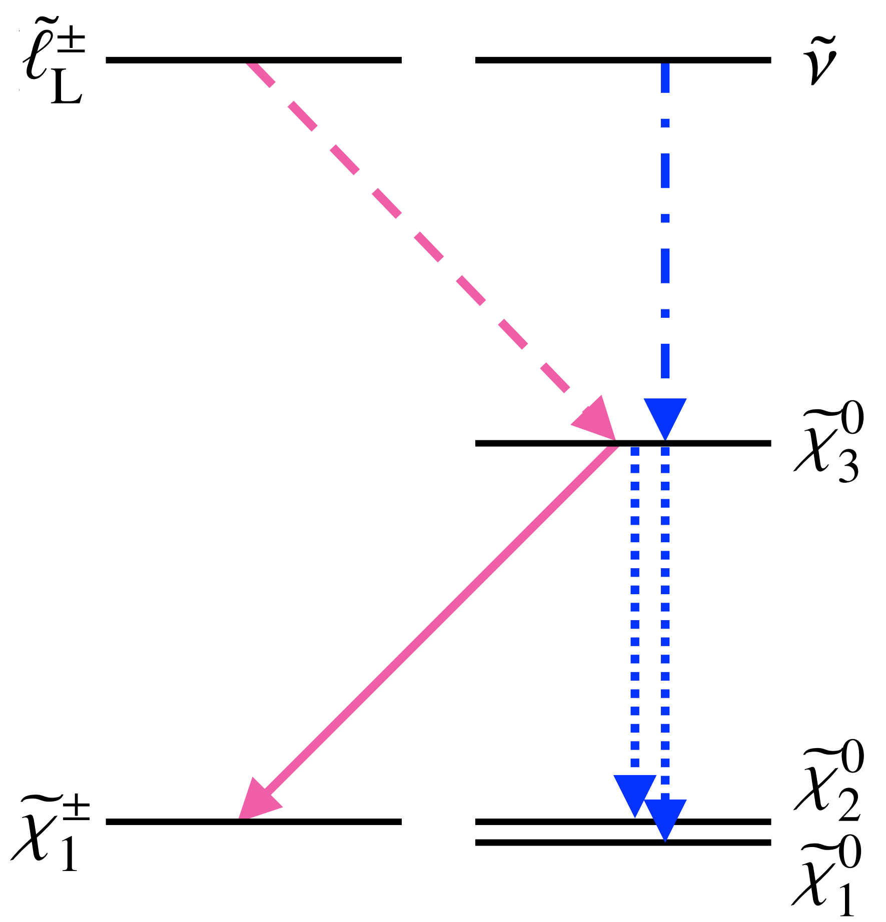
◉ Target signal

- Scenario with light **left-handed slepton, bino, higgsino**
- SUSY **production processes** considered:
  - $\tilde{e}_L^+\tilde{e}_L^-, \tilde{e}_L^\pm\tilde{\nu}_e, \tilde{\nu}_e\tilde{\nu}_e, \tilde{\mu}_L^+\tilde{\mu}_L^-, \tilde{\nu}_\mu\tilde{\nu}_\mu$
- **Focus on the three lepton final state**



◉ Event preselection

- Single lepton trigger (e or μ)
- Exactly 3 leptons
- Veto on b-jets (suppress tt and single-t bkg)



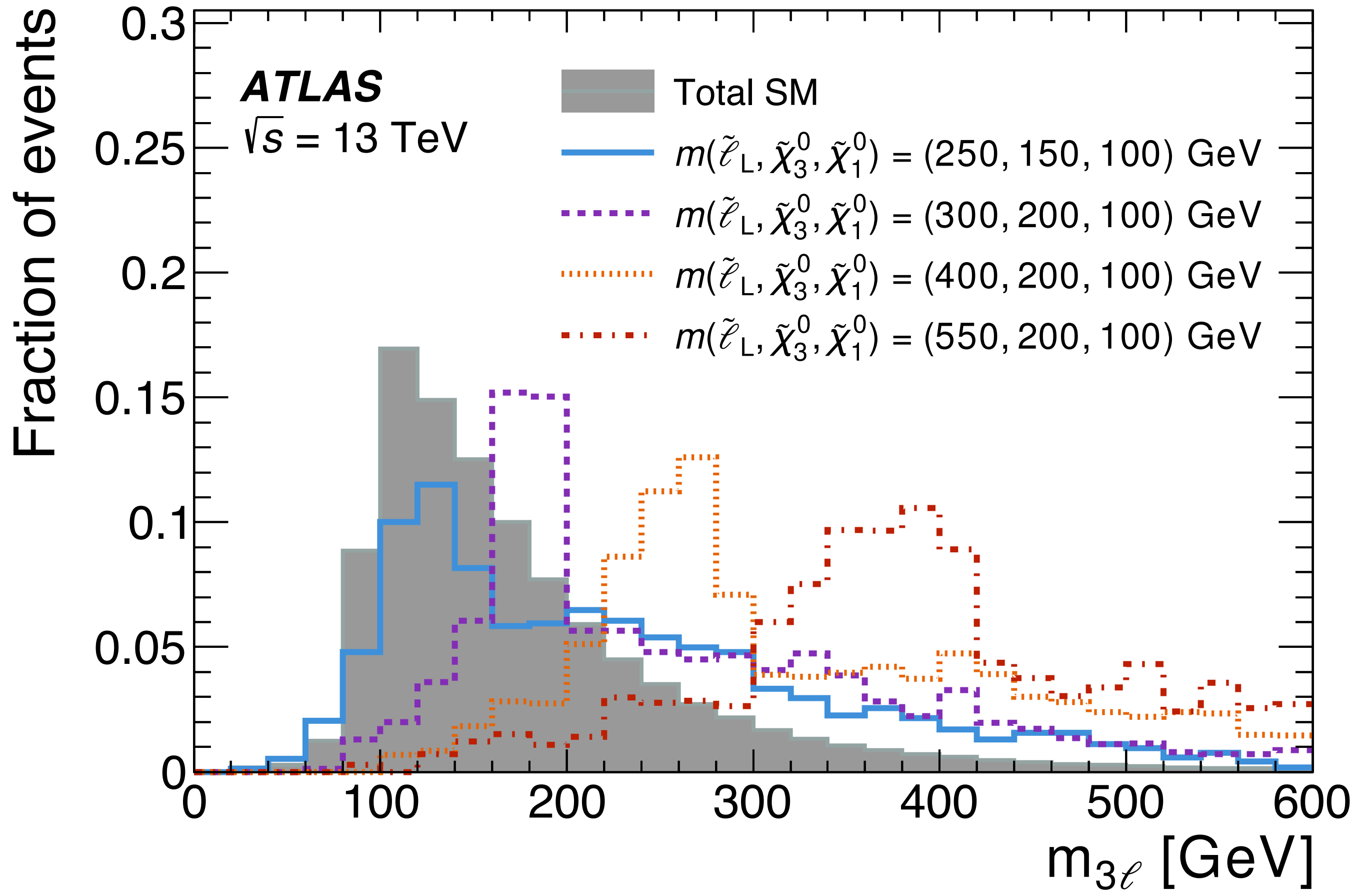
Mass spectrum and the decay pattern of the considered simplified SBH model

SBH - Signal Regions (SRs) & Background Estimation

1. SROS (3 Lepton Same-Flavor Opposite-Sign)

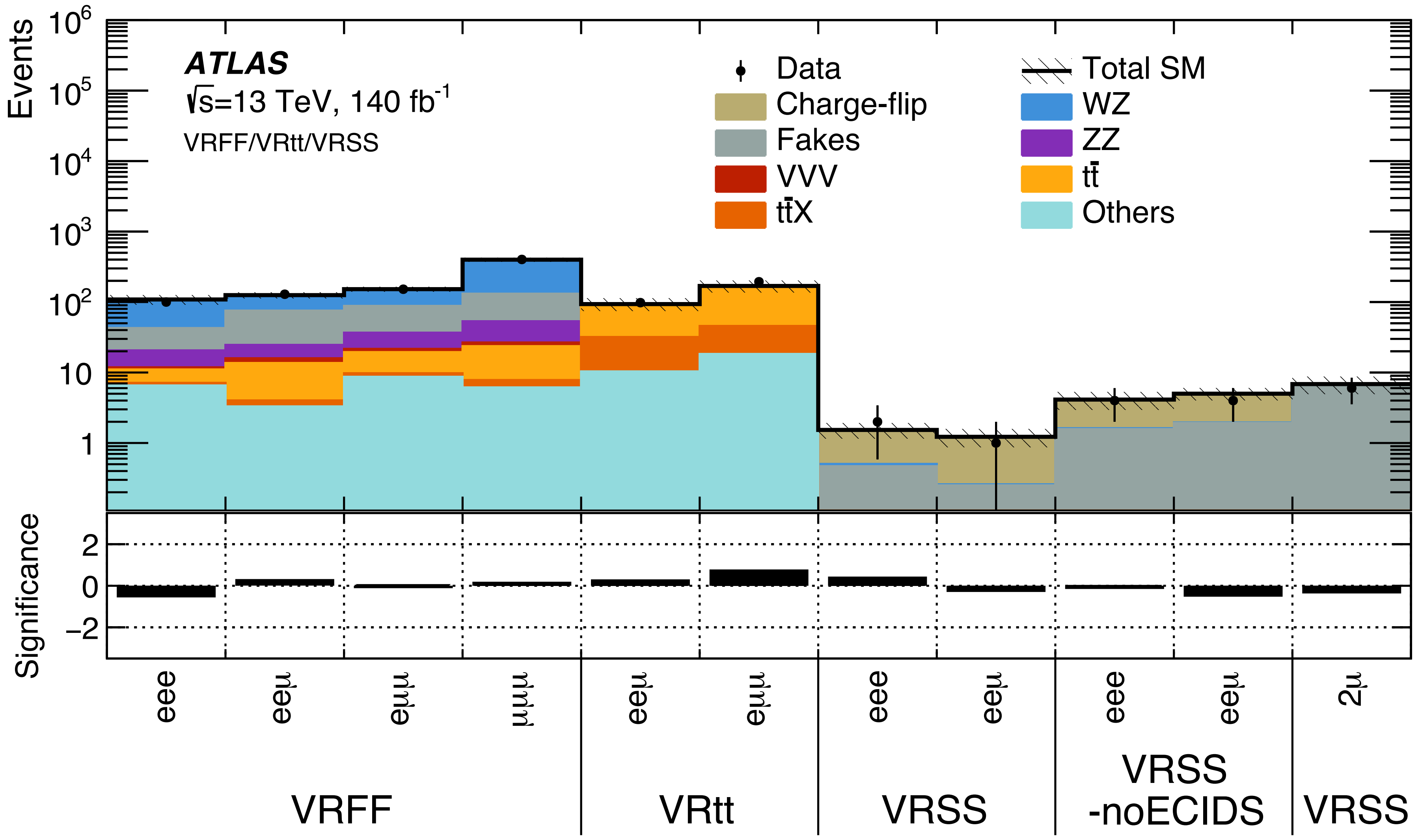
- Require SFOS pair & classify by the presence of SFOS pair with $|m_{ll}-m_Z|<10$ GeV (Z on or off-shell)
- **Additional cuts** on the preselection: $E_T^{miss} > 150GeV, m_T^{min} > 125GeV$ *
- Further **divided into m_{3l} bins**
- **Main Background: WZ→lνll**

Variables	SROS-on				SROS-off			
	eee	$ee\mu$	$e\mu\mu$	$\mu\mu\mu$	eee	$ee\mu$	$e\mu\mu$	$\mu\mu\mu$
$m_{\ell\ell}$ [GeV]	$\in [81.2, 101.2]$				$\notin [81.2, 101.2]$			
$m_{3\ell}$ binning [GeV][a]	a : $\in [30, 200)$ b : $\in [200, 400)$ c : $\in [400, +\infty)$							



2. SRSS (3 Lepton Same-Sign)

- All 3 leptons with same charge
- **Additional cut** on the preselection: $E_T^{miss} > 50GeV$
- **Main Backgrounds: WZ→lνll+Charge flip, Fakes**



◉ Background estimation

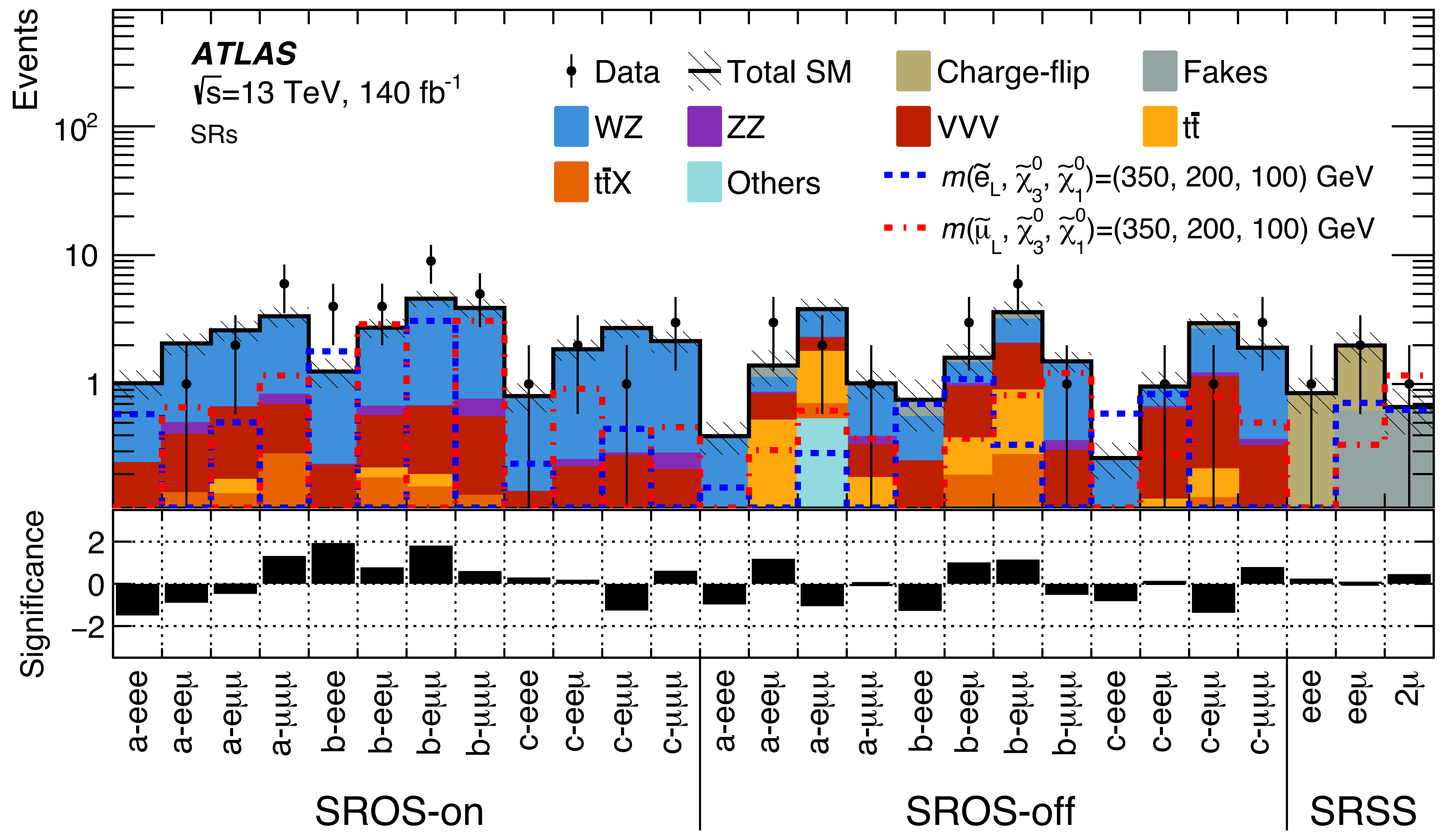
- **WZ→lνll :** Dedicated CR with MC-to-data normalization
- **Charge flip :** SF measurement using Z→ee MC
- **Fakes :** Fake Factor method
- **Other**: directly taken from MC

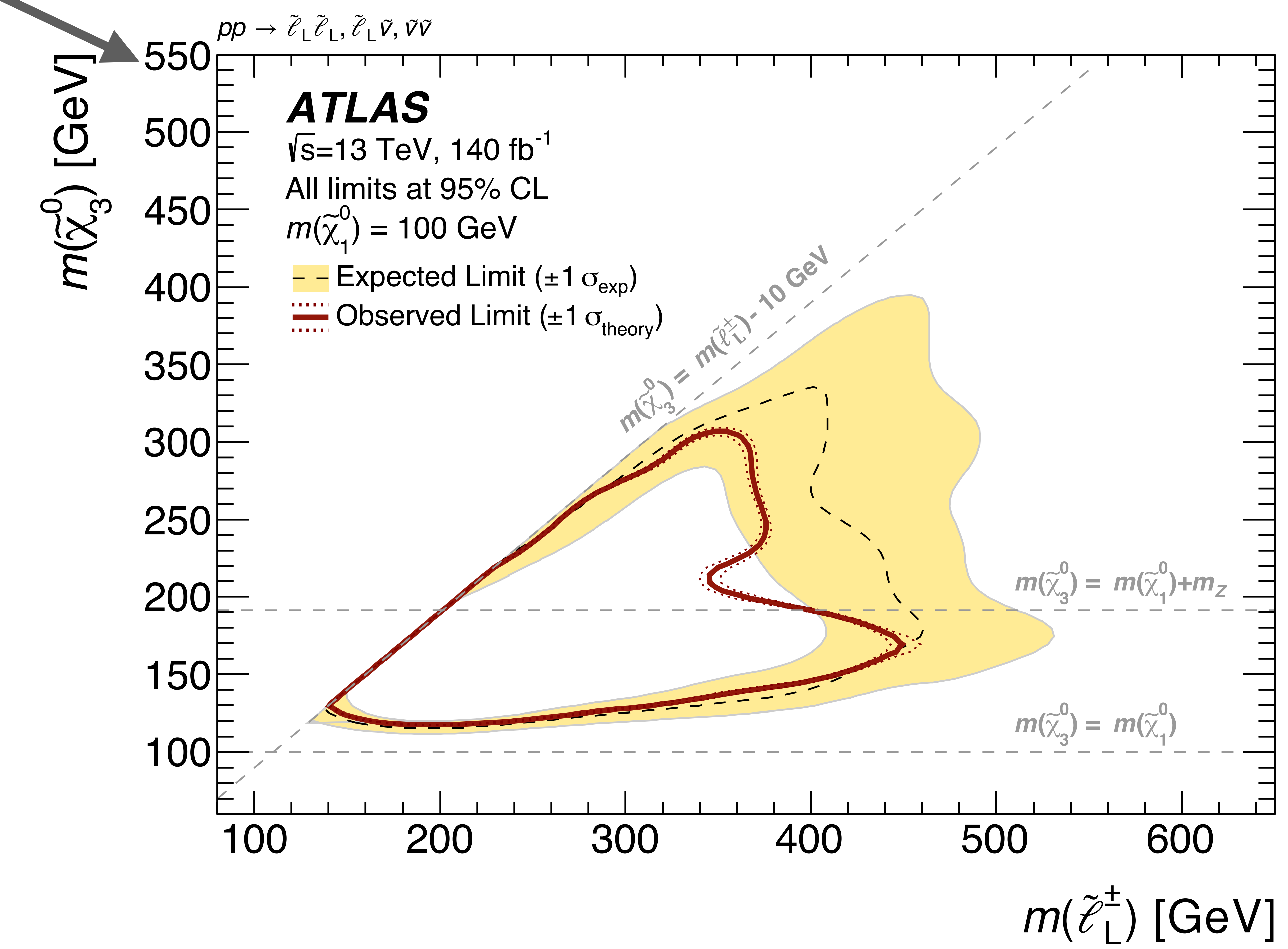
Bkg estimation successfully tested on Validation Regions (VRs)

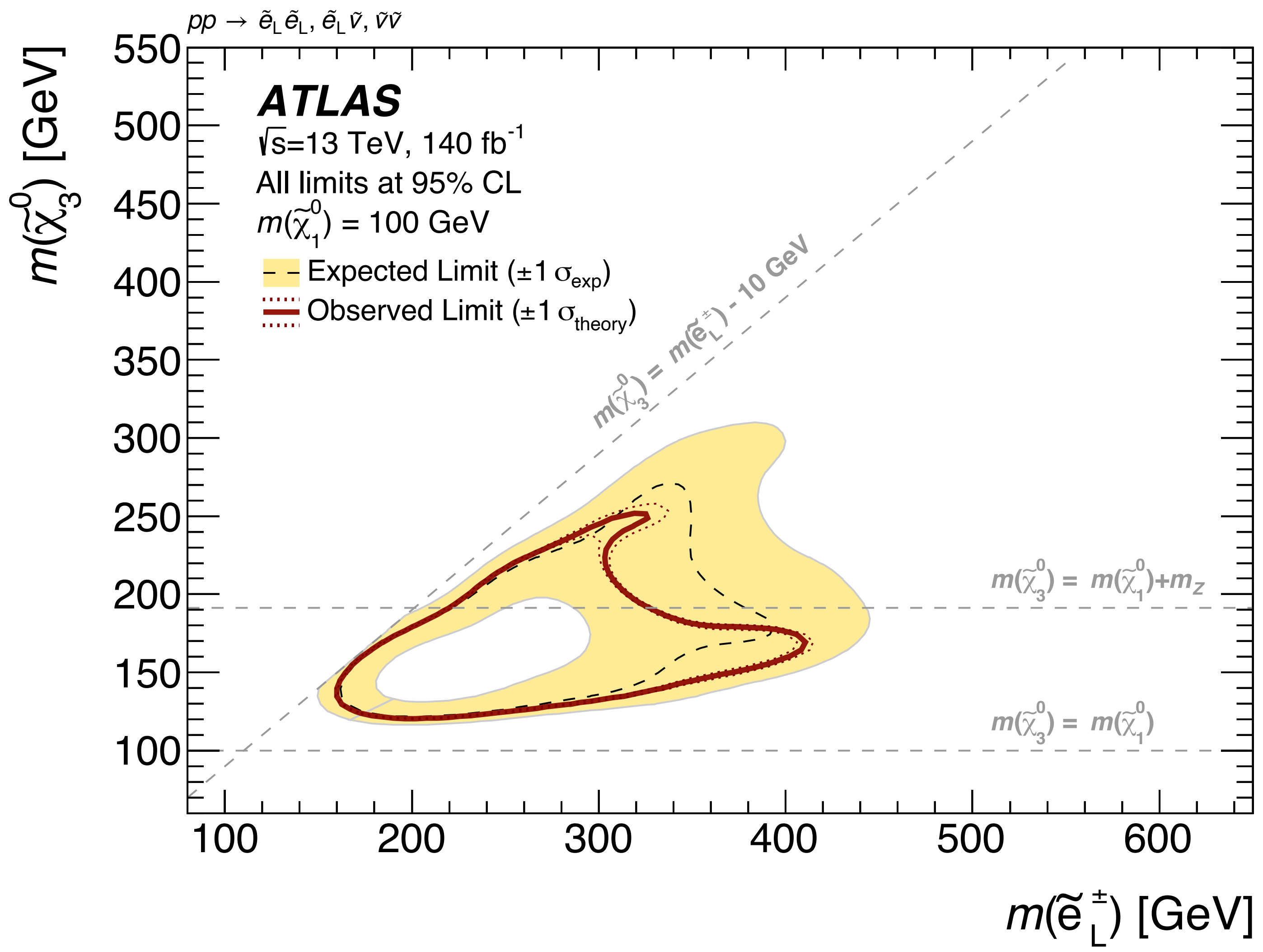
*calculates m_T for all available leptons and selects the minimum

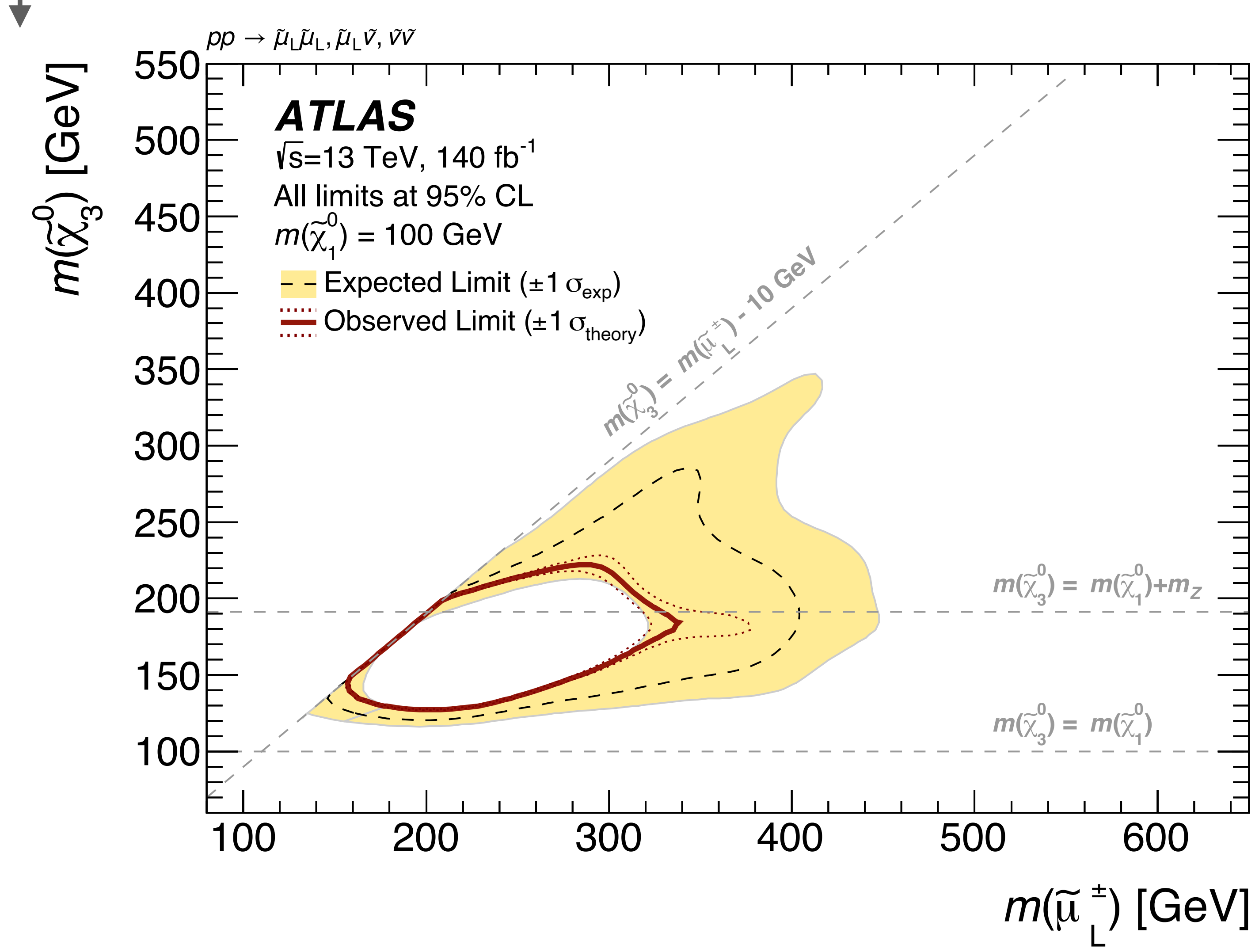
SBH - Exclusion Limits

- **No significant excess observed after unblinding SRs**
- **Constrains on the SBH models derived by combining all the SR channels**
  - Exclusion limits calculated for the mass-degenerate selectrons, smuons and sneutrinos
  - **Masses up to 450 GeV are excluded for neutralino mass = 100 GeV**
  - Limits also set for selectrons, smuons separately assuming they are decoupled



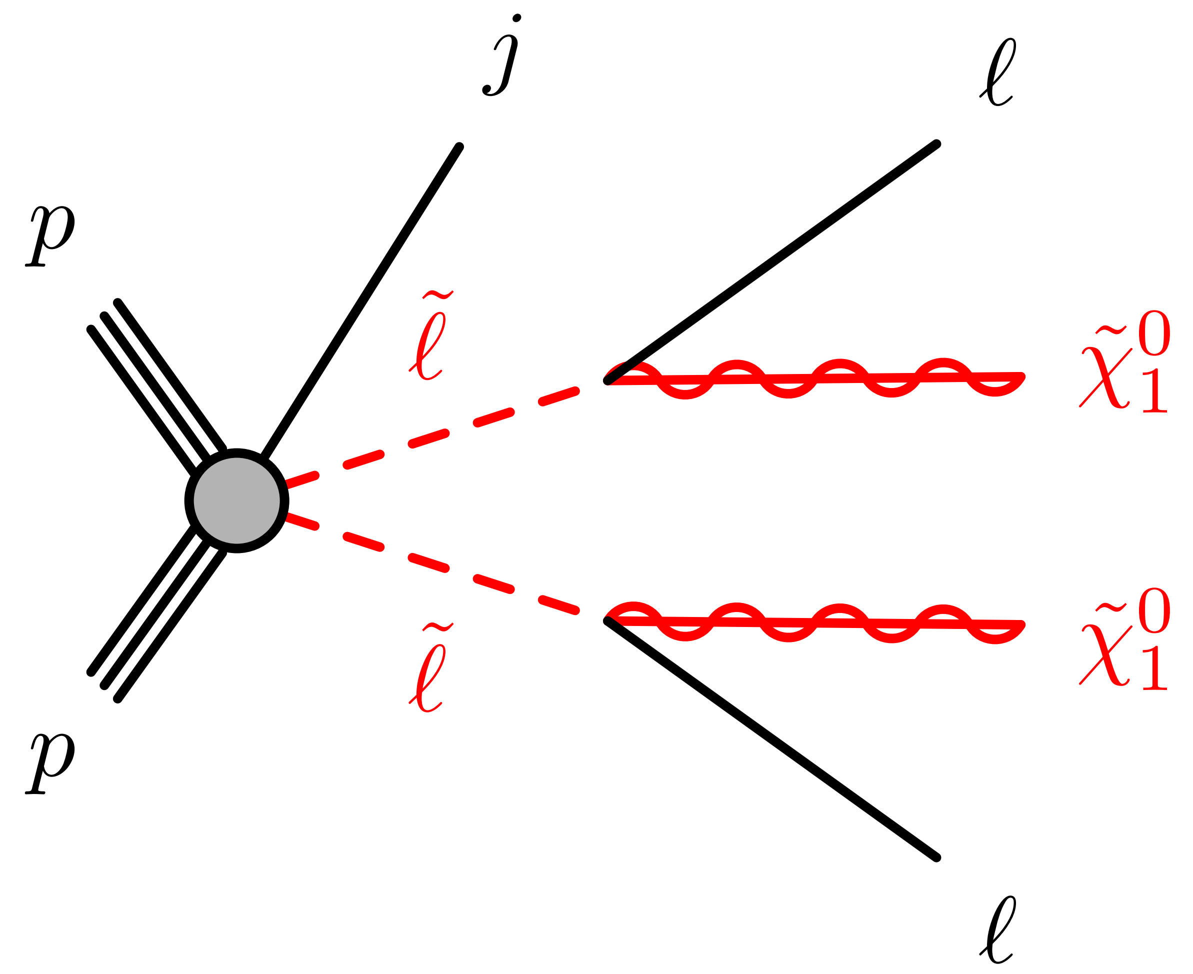






ISR Compressed Slepton Analysis

arXiv:2503.17186



◉ Analysis dedicated to compressed mass spectra

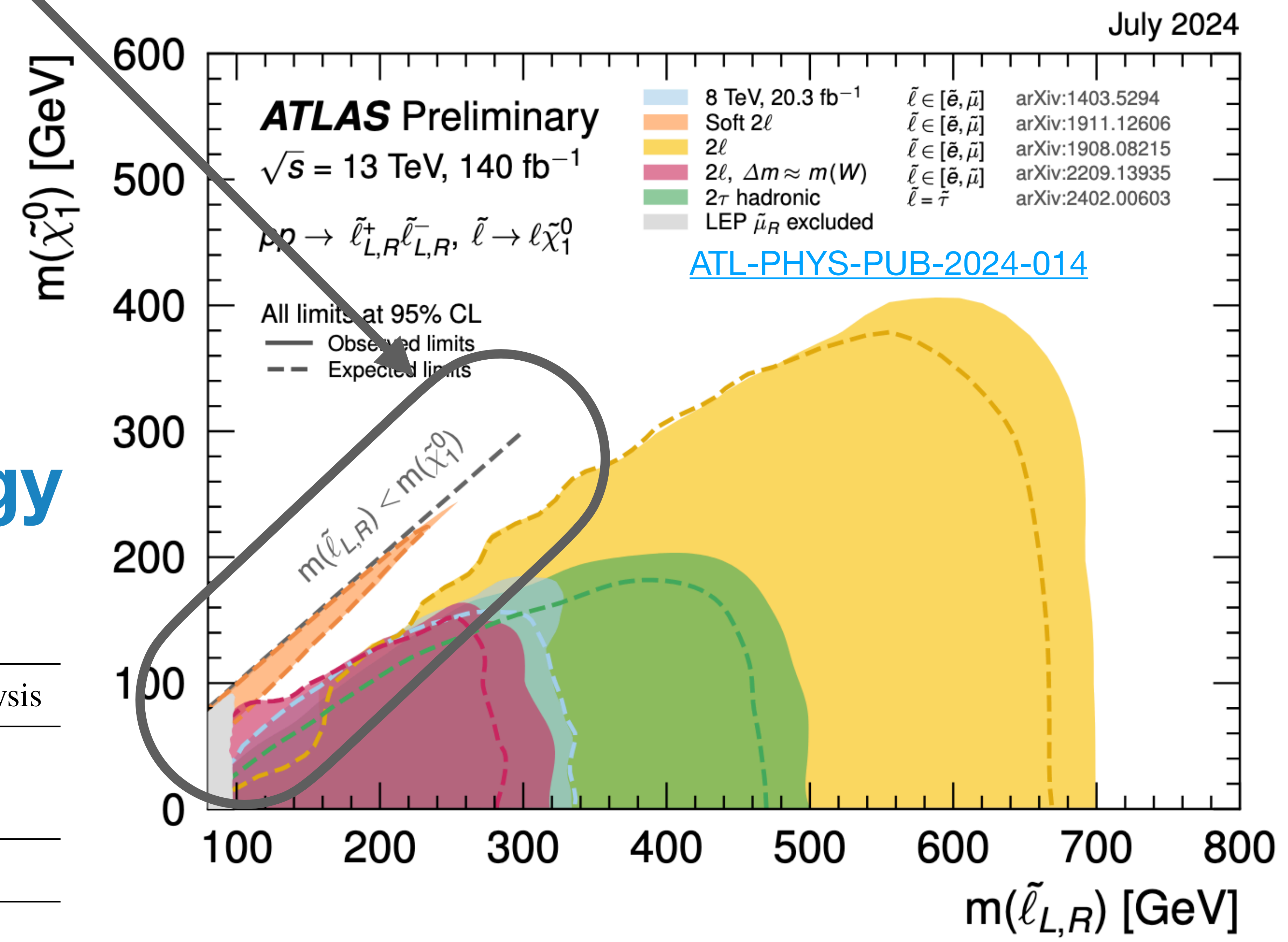
- Search for **EWK slepton** production decaying to **lepton + LSP**
- Focus on the compressed-mass region (**Δm**$^{\text{(slepton, LSP)}}$ ≃ **30-70 GeV**) that remains unconstrained by earlier searches

◉ Final State

- ISR jet, 2 leptons, large missing transverse momentum

◉ Two complementary approaches followed

- Employ BDT selection to maximize sensitivity to the benchmark scenario and a cut-and-count (CC) strategy for model-independent results



◉ Common preselection used to capture the ISR topology

Common preselection requirements	
E_T^{miss}	> 200 GeV
N_{lep}^{base}	= 2
N_{lep}^{sig}	= 2
$\min(\Delta\phi(\text{jets}, \mathbf{p}_T^{miss}))$	> 0.4
$\Delta\phi(\mathbf{j_1}, \mathbf{p}_T^{miss})$	> 2.0
$\Delta R_{\ell\ell}$	> 0.75
N_{jet}^{30}	> 0
$p_T^{j_1}$	> 100 GeV

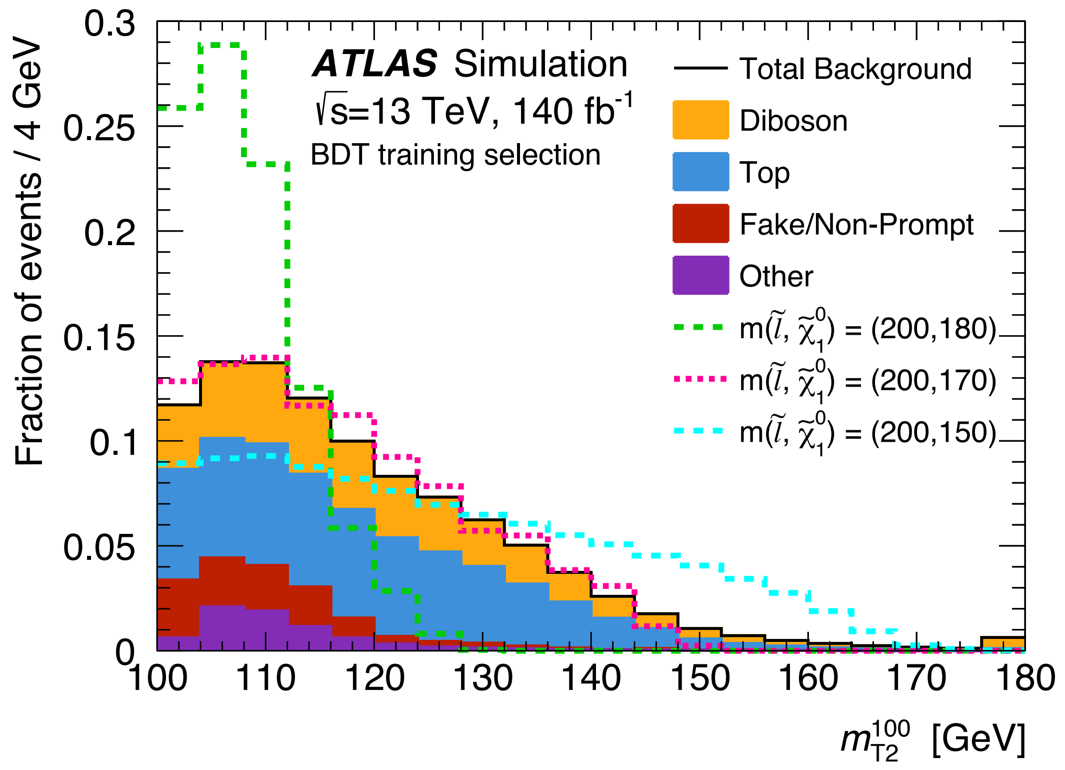
Additional requirements for cut-and-count-based analysis	
$p_T^{\ell_1}$ and $p_T^{\ell_2}$	> 10 GeV
N_{jet}^{30}	< 3
Additional requirements for BDT-based analysis	
$p_T^{\ell_1}$ and $p_T^{\ell_2}$	> 6 GeV

Compressed Slepton - Analysis Strategy

◉ CC Analysis

- Selections designed to **reflect** the signal topology, suppress key bkgs and boost S/B
- **2 orthogonal SRs** (“high” and “low) based on leading lepton m_T + **binned in m_{T2}^{100} variable**

Variable	SR-CC$_{High}$	SR-CC$_{Low}$
Lepton charge and flavour	SFOS	
$N_{b\text{-jet}}^{20}$	= 0	
E_T^{miss}	> 300 GeV	
$\lvert m_{\ell\ell} - m_Z \rvert$	> 10 GeV	
$m_T^{\ell_1}$	> 100 GeV	< 100 GeV
$m_T^{\ell_2}$	> 100 GeV	



◉ BDT Analysis

- Utilizing XGBoost **Binary Classification**
- Events splitted into **5 BDT’s** to capture the changing signal kinematics across different mass splittings
- For each BDT, **3 SRs** defined + Further split into e/μ channels

General requirements		
SFOS leptons	$N_{b\text{-jet}}^{20} = 0$	$\lvert m_{\ell\ell} - m_Z \rvert > 10$ GeV

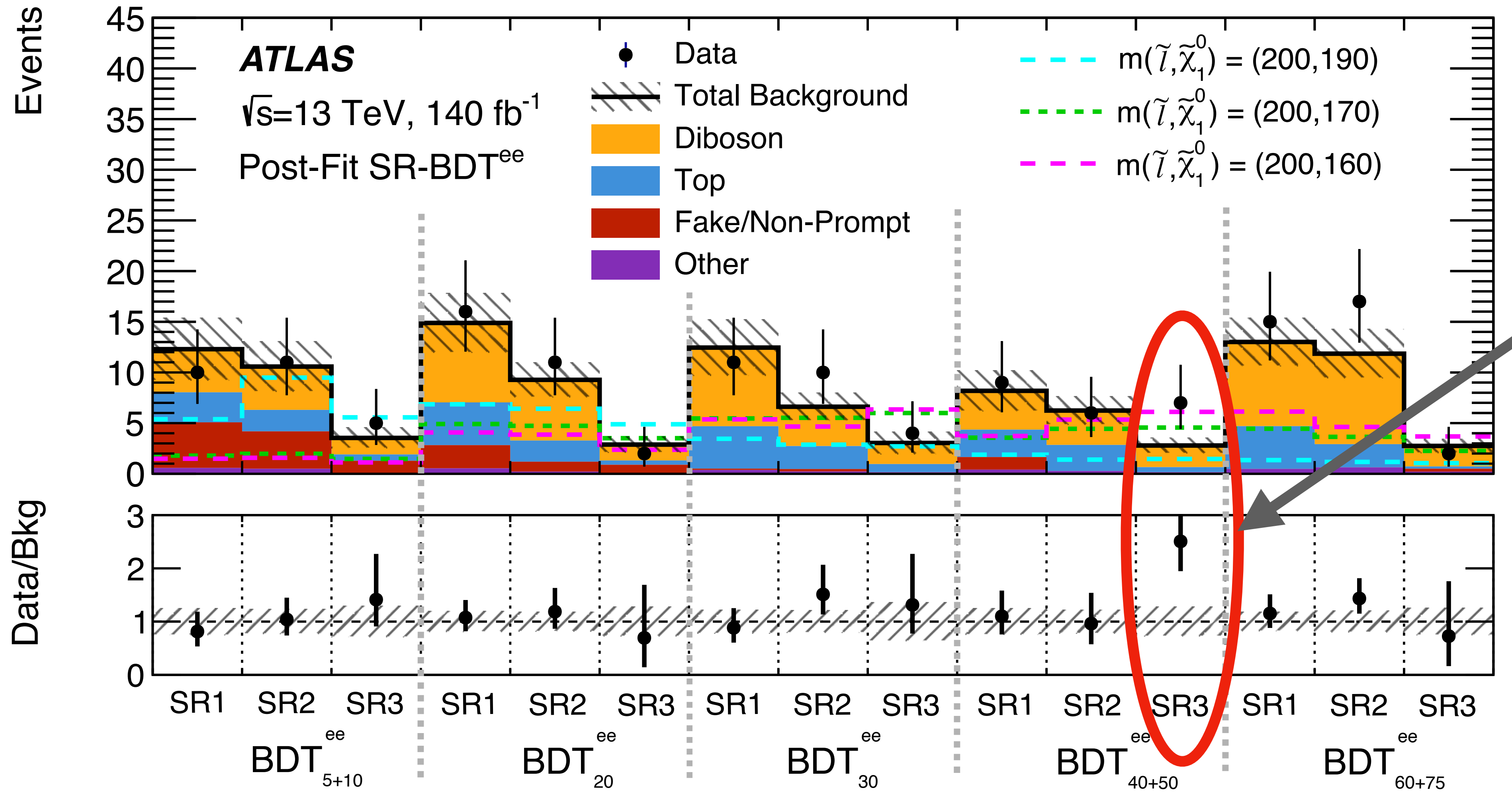
BDT set	BDT Score requirements: SR1$^{ee/\mu\mu}$	SR2$^{ee/\mu\mu}$	SR3$^{ee/\mu\mu}$
BDT$_{5+10}$	[0.93, 0.953]	(0.953, 0.976]	(0.976, 1.0]
BDT$_{20}$	[0.90, 0.928]	(0.928, 0.956]	(0.956, 1.0]
BDT$_{30}$	[0.88, 0.915]	(0.915, 0.95]	(0.95, 1.0]
BDT$_{40+50}$	[0.90, 0.928]	(0.928, 0.956]	(0.956, 1.0]
BDT$_{60+75}$	[0.90, 0.935]	(0.935, 0.97]	(0.97, 1.0]

◉ Primary Backgrounds

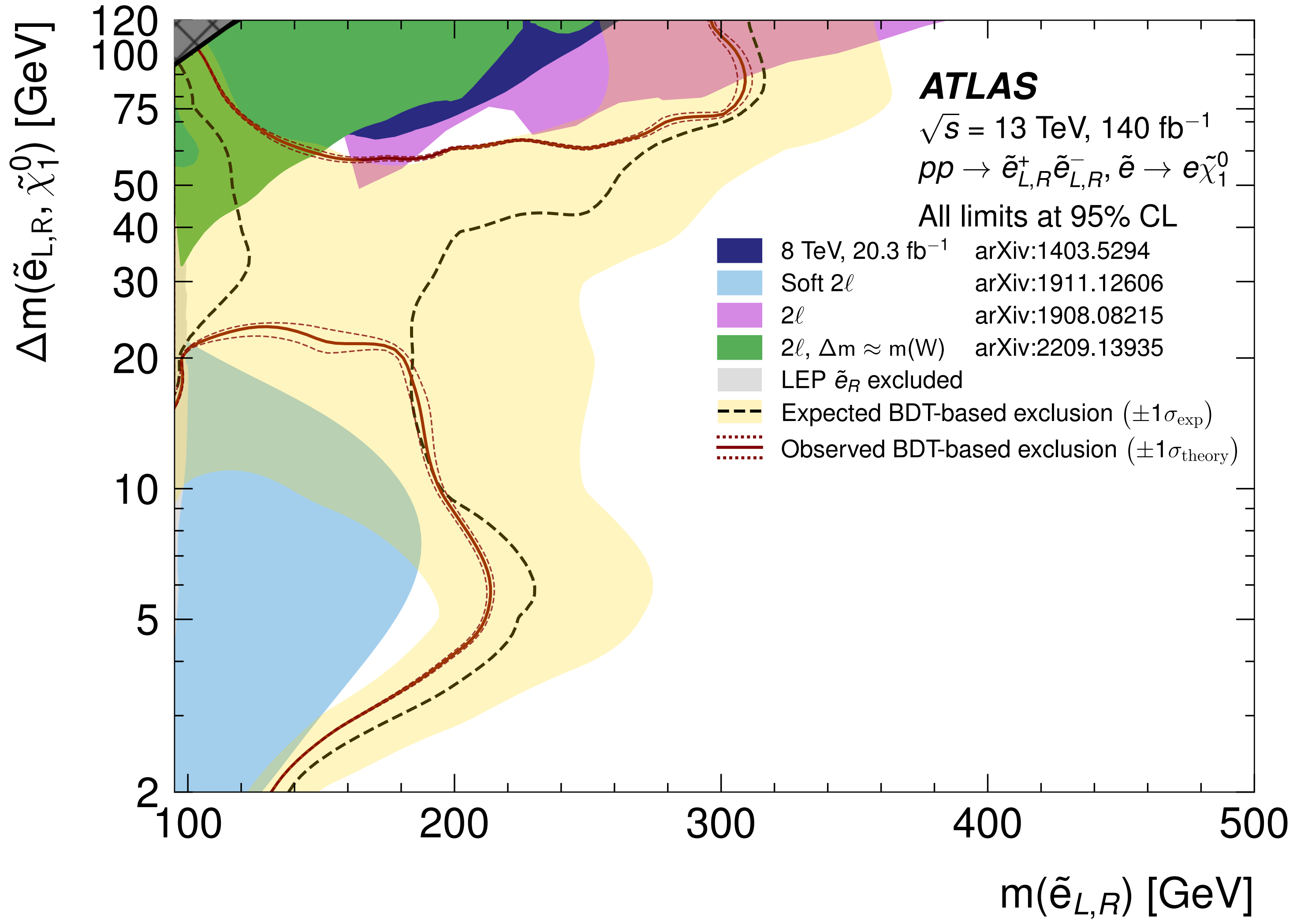
- Backgrounds dominated by diboson and top contributions
- Fake/non-prompt (NP) bkg estimated using data-driven **Fake Factor method**

Compressed Slepton - Results & Exclusion Limits

- Here, results only for the BDT approach (Cut & Count results on Backup)
- BDT has two excesses in separate channels

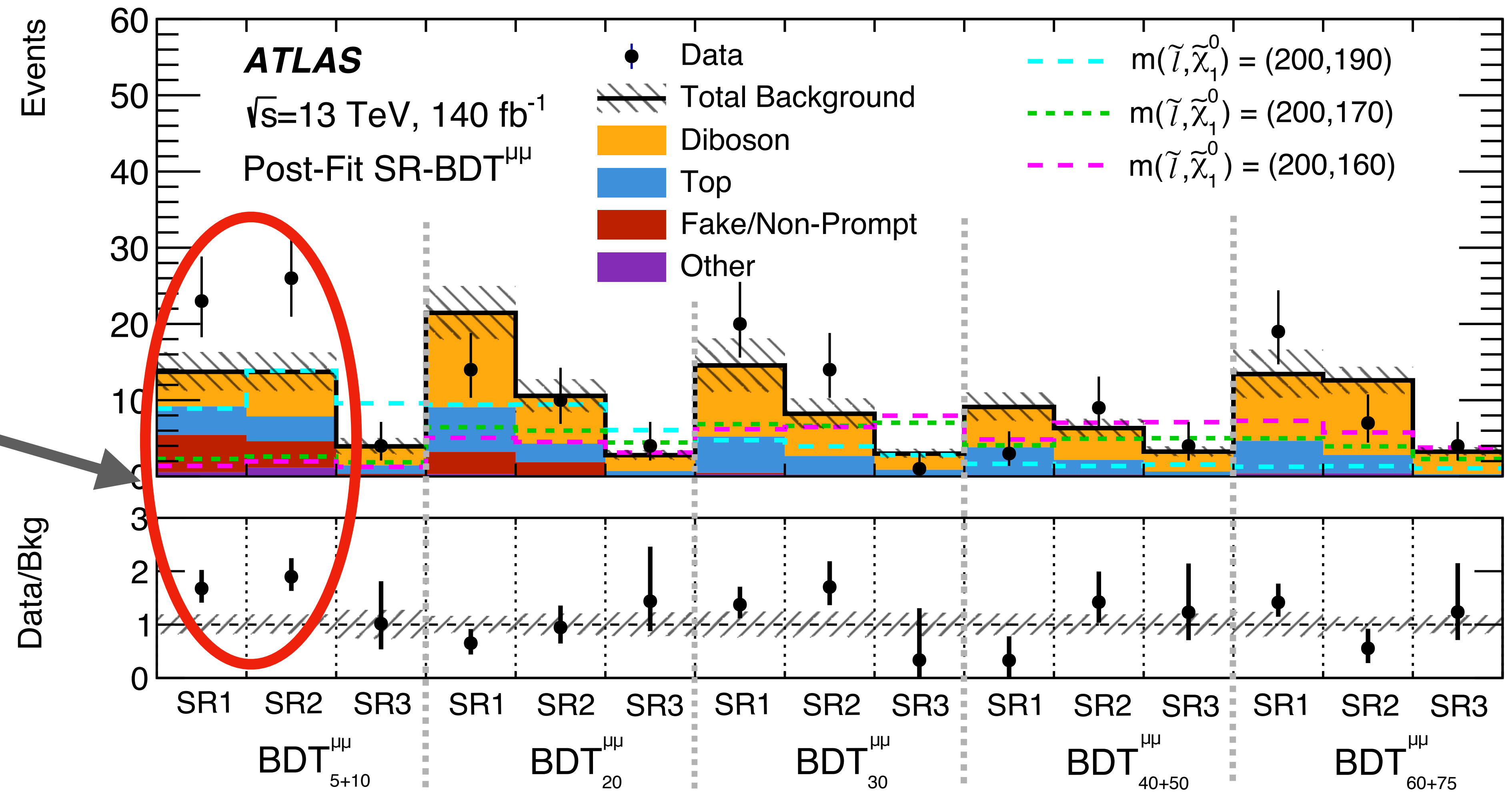


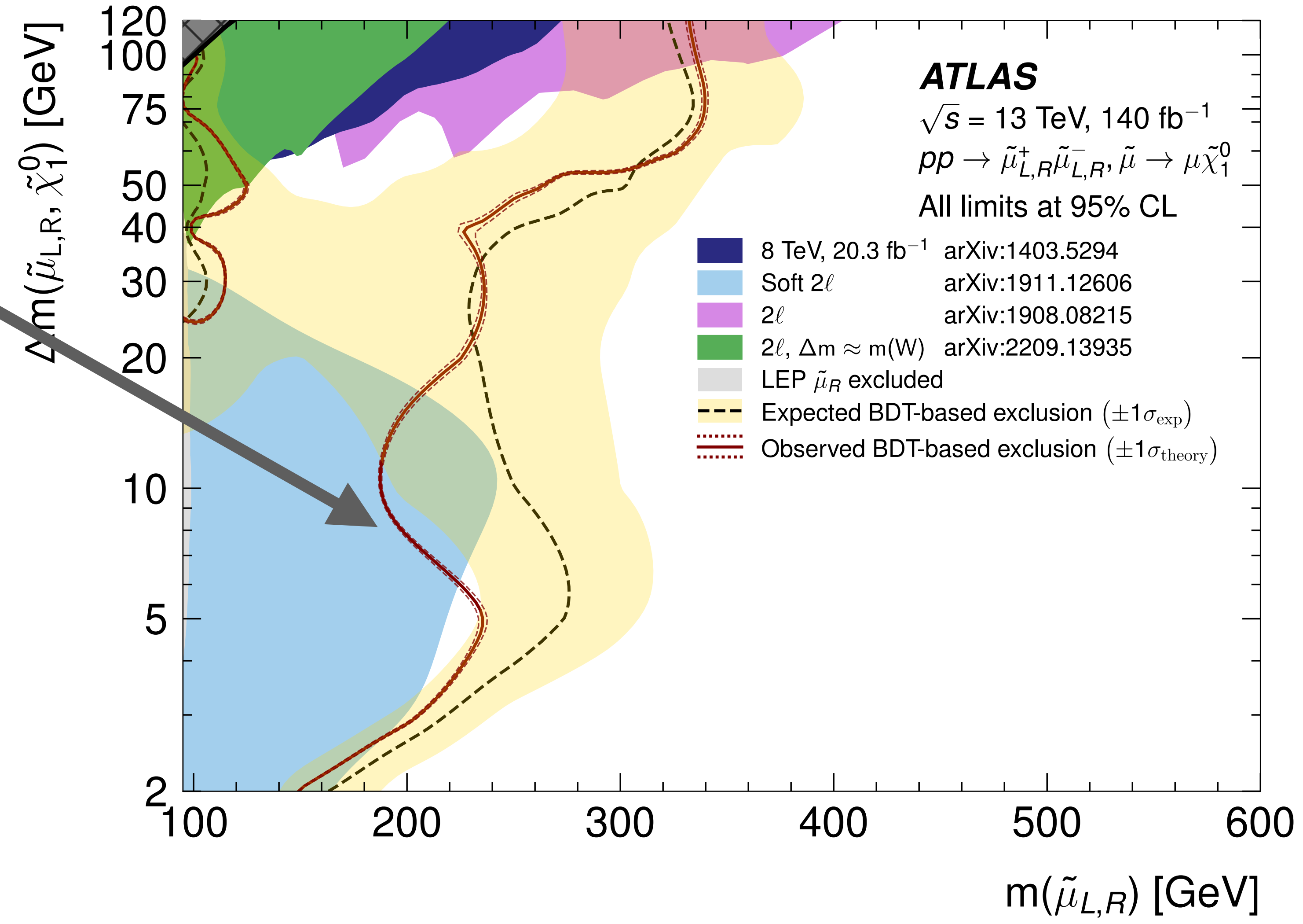
2σ SR significance



Large drop in exclusion for small mass splitting Δm= 10 GeV

1.8σ and 2.4σ SR significance (3.2σ combined)



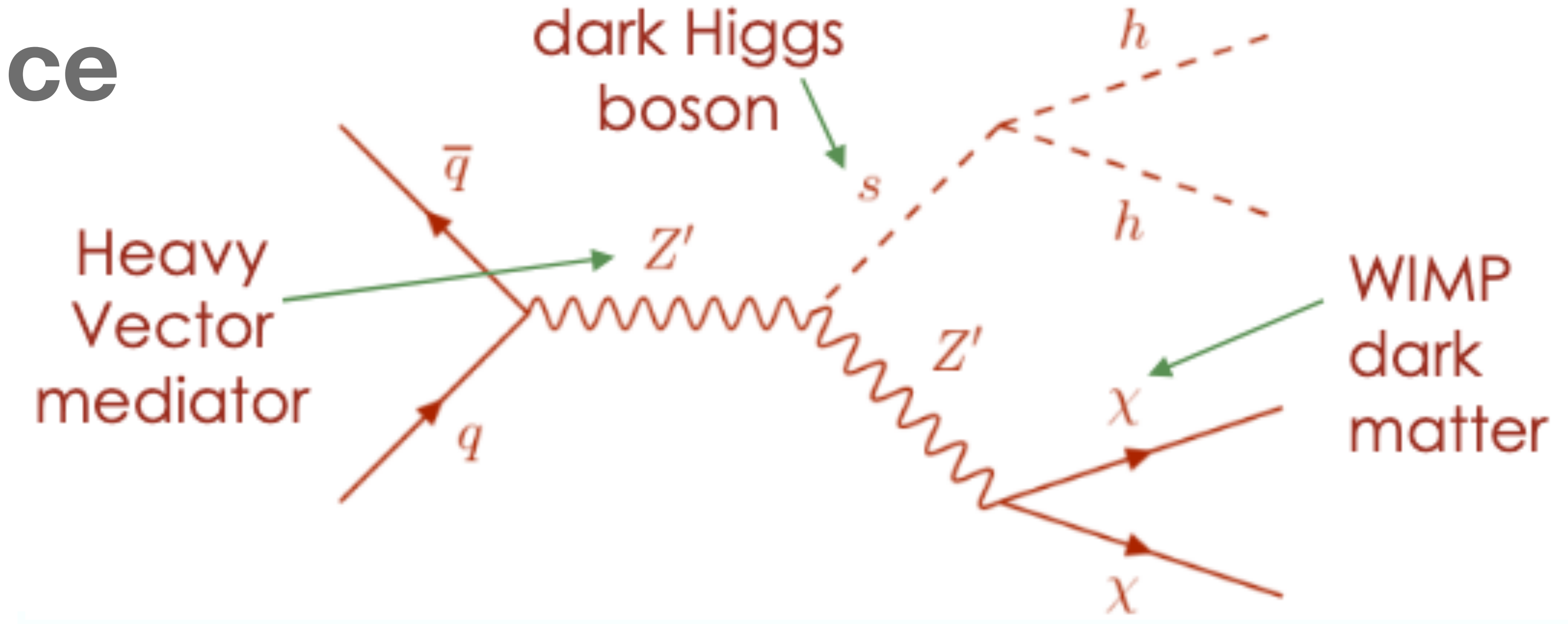


EWK multi-b Dark Higgs Analysis

◉ Analysis Motivation

arXiv:2507.02175

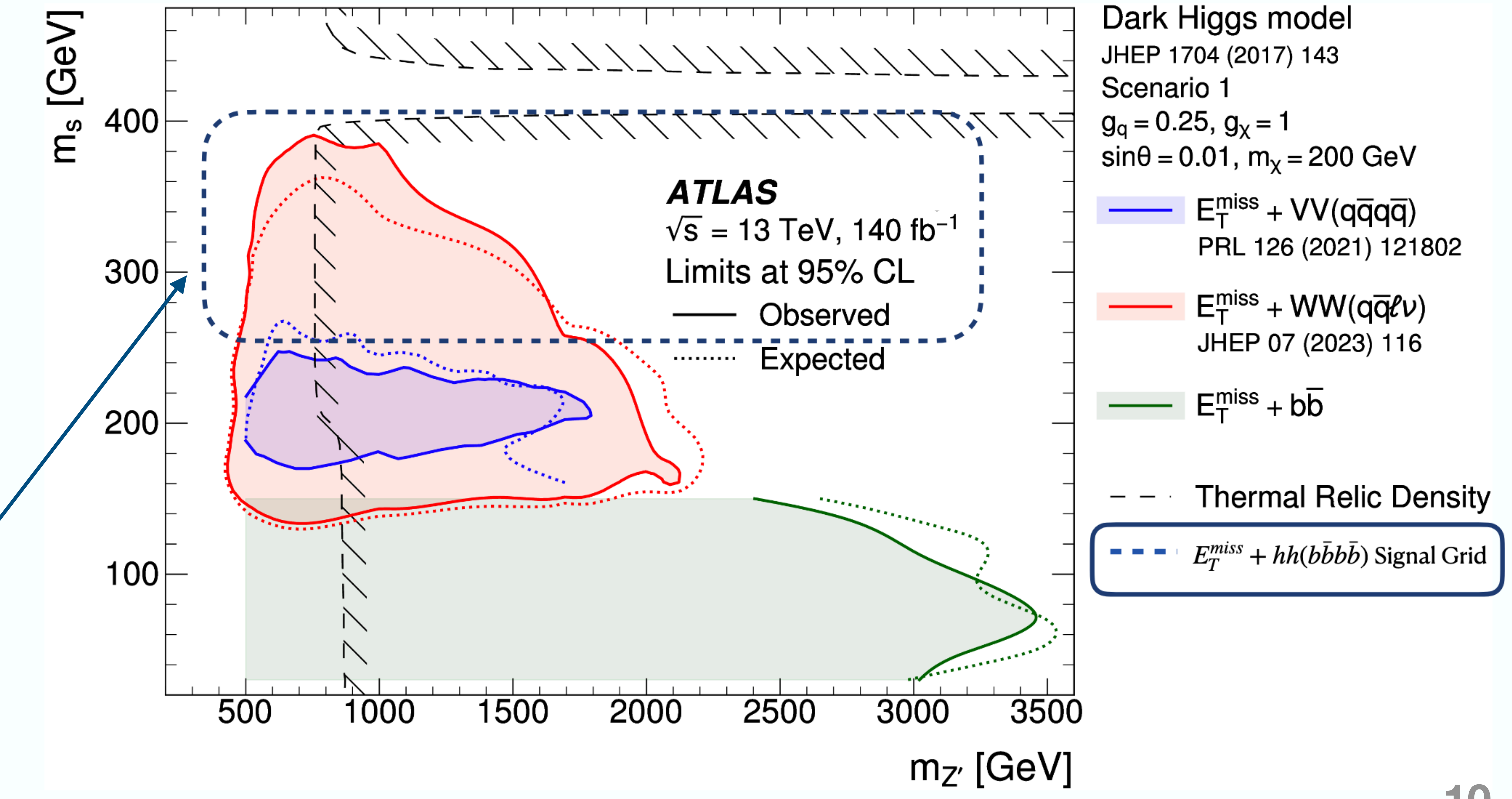
- Investigate models connecting **Dark Matter (DM)** to the **Higgs boson**
- Dark Higgs model posits a spontaneously broken U′(1) gauge group
  - Resulting a **dark-Higgs** giving mass to the DM candidate and the Z′ gauge boson
  - Naturally satisfies the observed **relic abundance**



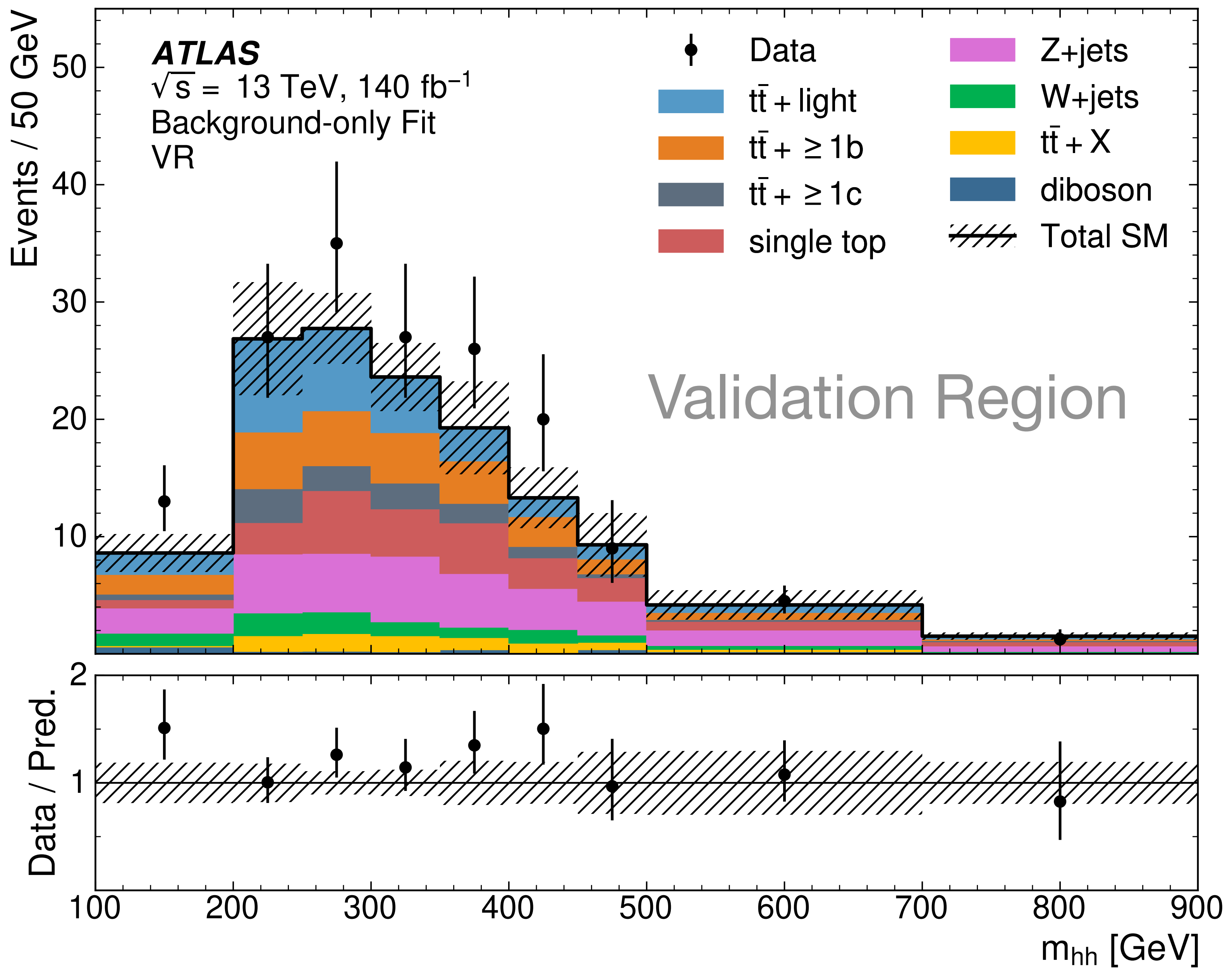
◉ Dark-Higgs-Strahlung with s→hh decay

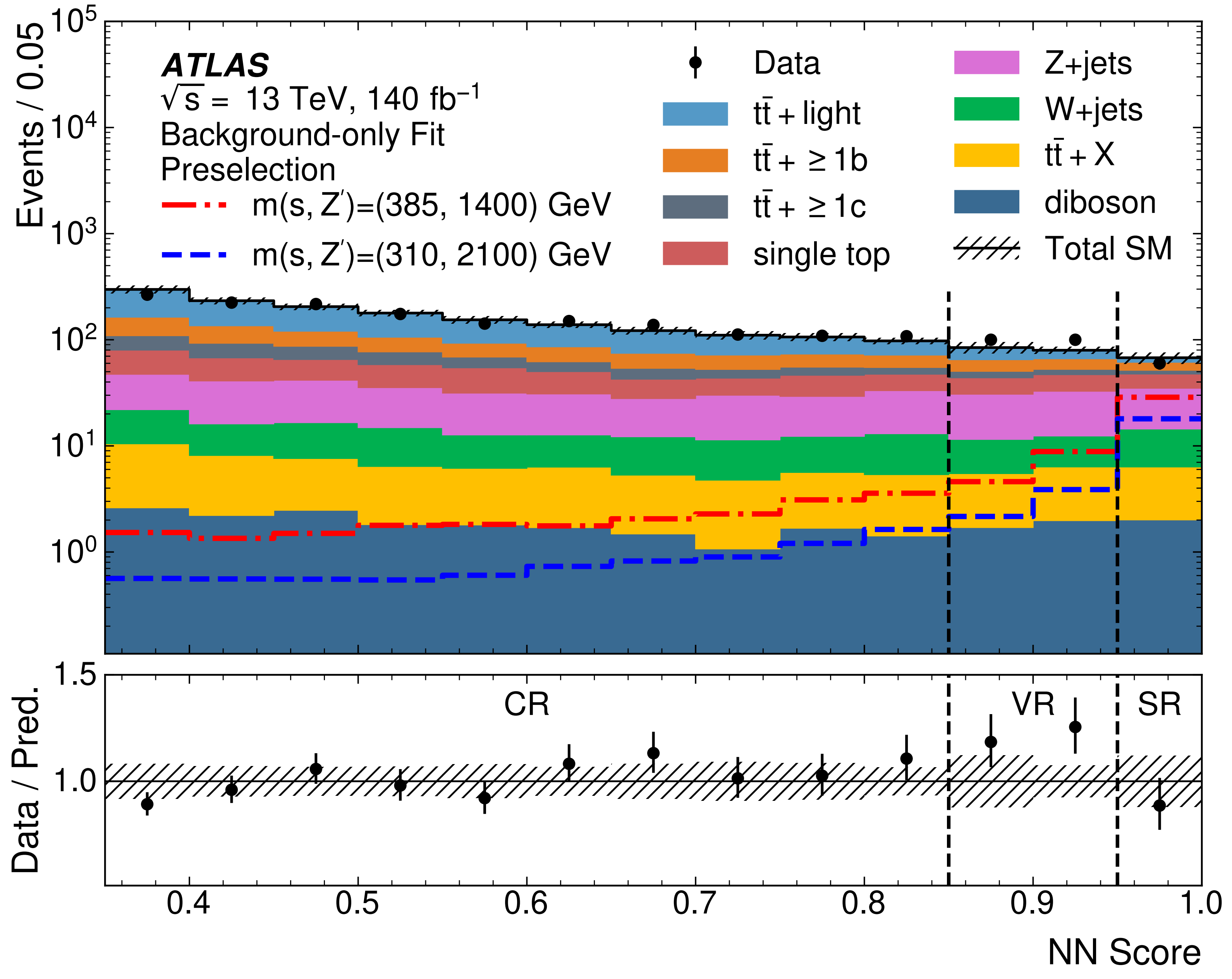
- Target **hh→4b** to maximize signal yields
- **First ATLAS search of the resonant topology in this final state!**
  - Common signature in many extended Higgs DM models
- Offers **unique sensitivity** across the **($m_{Z'}$, m_s)** phase space

Targeted parameter space



EWK multi-b Dark Higgs - Analysis Strategy

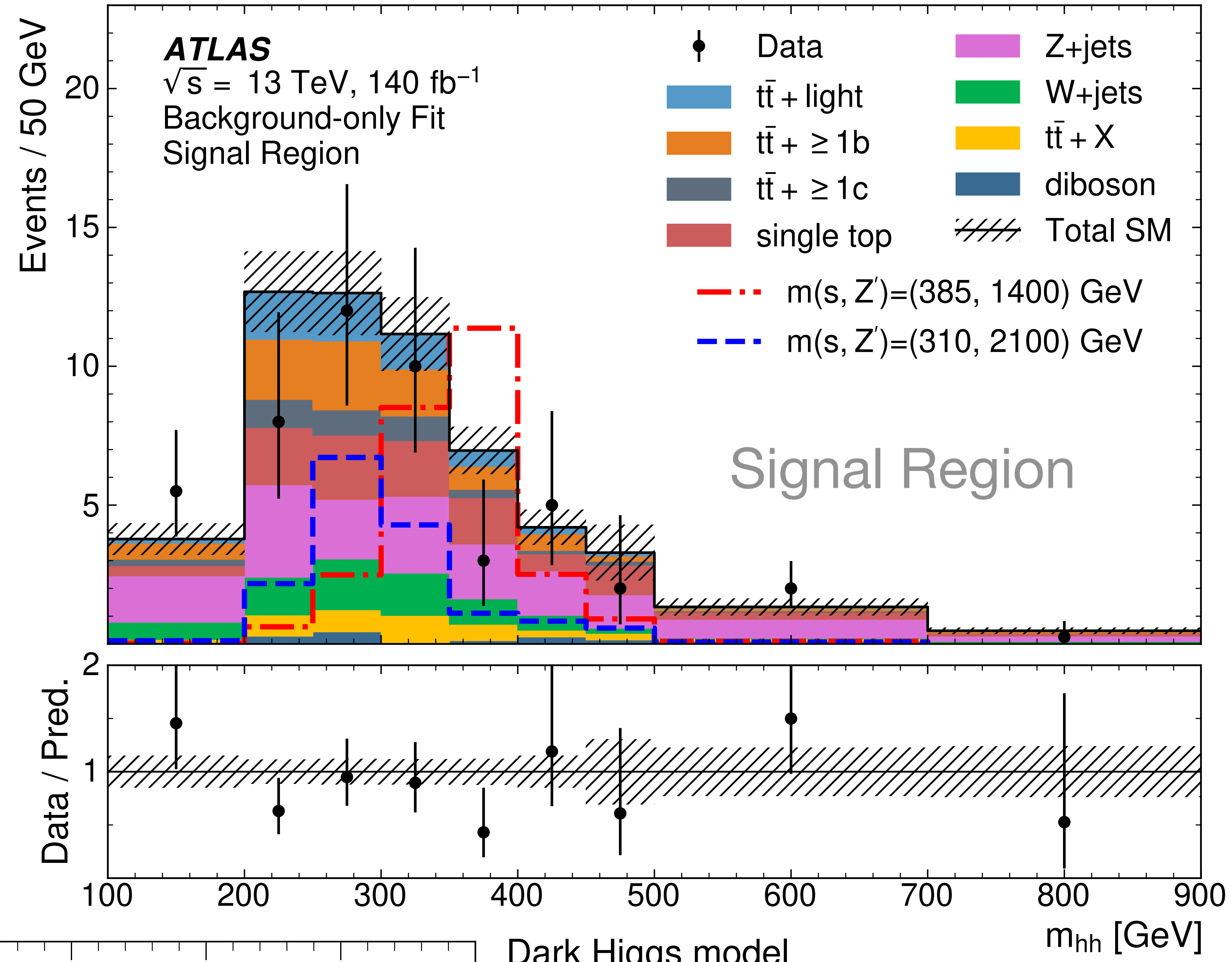


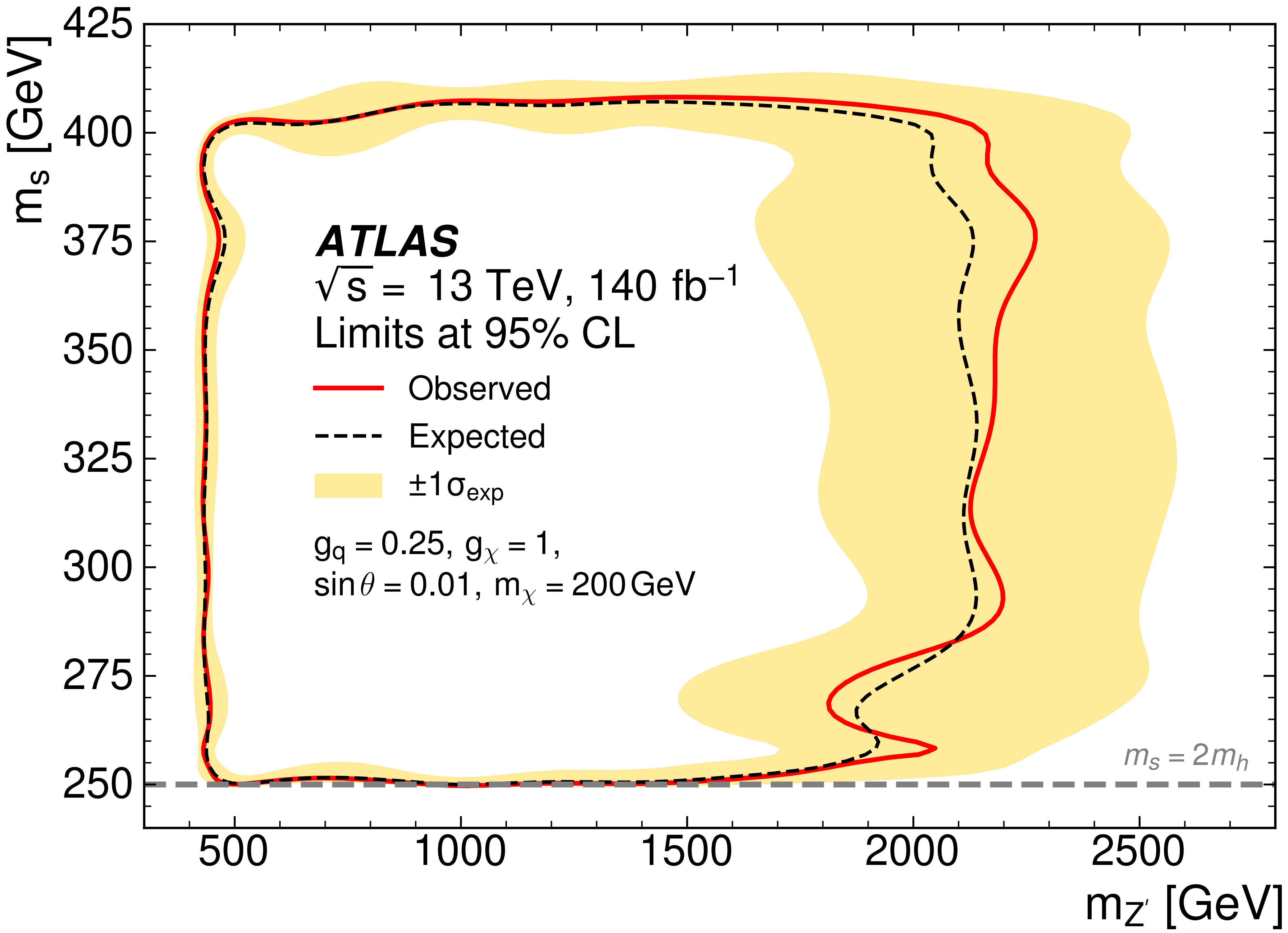


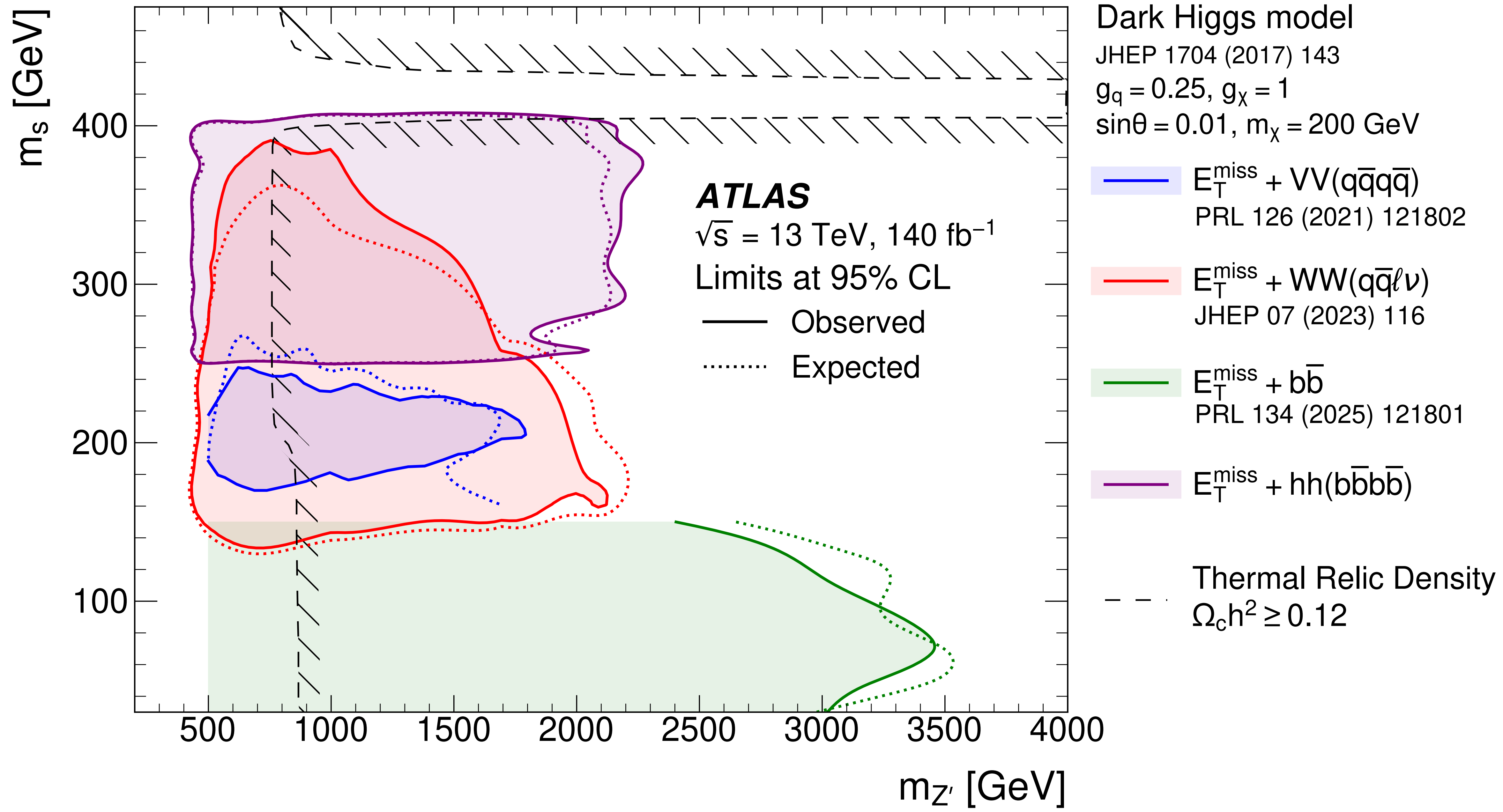
- **MET triggers used for the event selection**
- **Form Higgs candidates by pairing b-jets according to their angular separation**
  - Shape main discrimination variable $\mathbf{m_{hh}}$ **(~$\mathbf{m_s}$)**
- **Train NN classifier for signal vs background**
  - Decorrelate m_{hh} to preserve shape independence using a distance correlation term in Loss function ([arXiv:2001.05310v2])
  - Cut on NN score for SR (lower score used in bkg estimate)
  - Good Data-MC agreement seen for NN output score (after unblinding)
- **Main backgrounds:**
  - $t\bar{t}+\geq 1b-jet$, $t\bar{t}+\geq 1light-jet$, $Z+jets$
  - Specific Control Regions (CRs) defined to normalize MC
  - Background estimation successfully tested in Validation Regions (VRs)

EWK multi-b Dark Higgs - Results

- **No significant excess observed above the SM expectation**
- **Exclusion Limits**
  - Within 1-sigma expectation for whole region
  - Sharp cut-offs for dark-Higgs masses via: $2m_h < m_s < 2m_\chi$
  - **Significant exclusion of previously unexplored dark-Higgs model phase space, extending limits up to m_s = 400 GeV**







Summary & Outlook

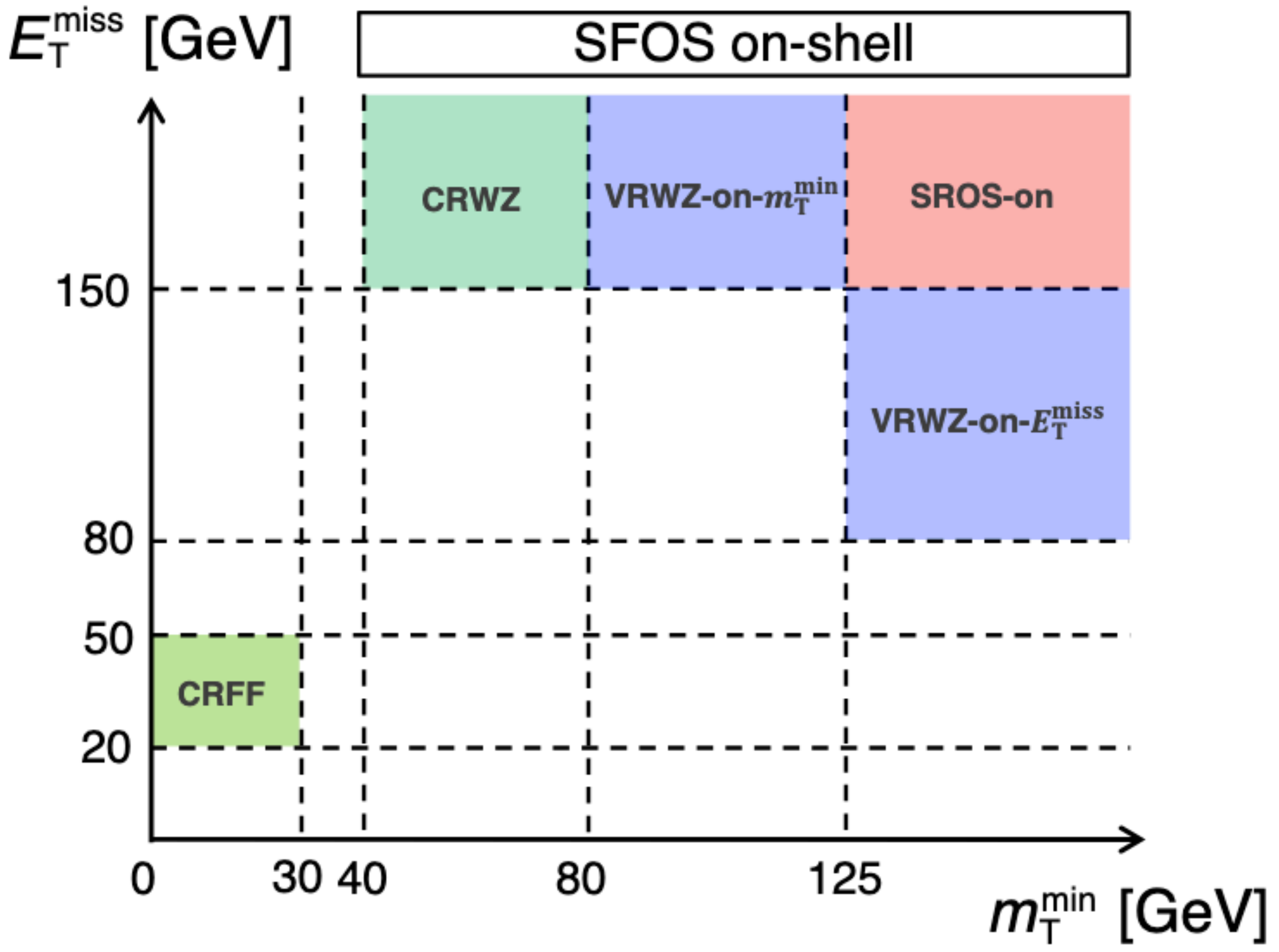
- **Presented some of the latest ATLAS results on electroweak SUSY searches**
  - Highlighted challenging signatures like compressed mass spectra and Dark Higgs
  - Established new exclusion limits, substantially constraining previously unexplored parameter spaces
  - Successfully employed advanced ML techniques to enhance sensitivity in challenging scenarios

- **Covered only a small fraction of the ongoing efforts and newly published results within ATLAS**
  - Many other interesting analyses can be found on ATLAS web page
  - Continued development and refinement of analysis methods remain crucial
  - Push for Run3 searches

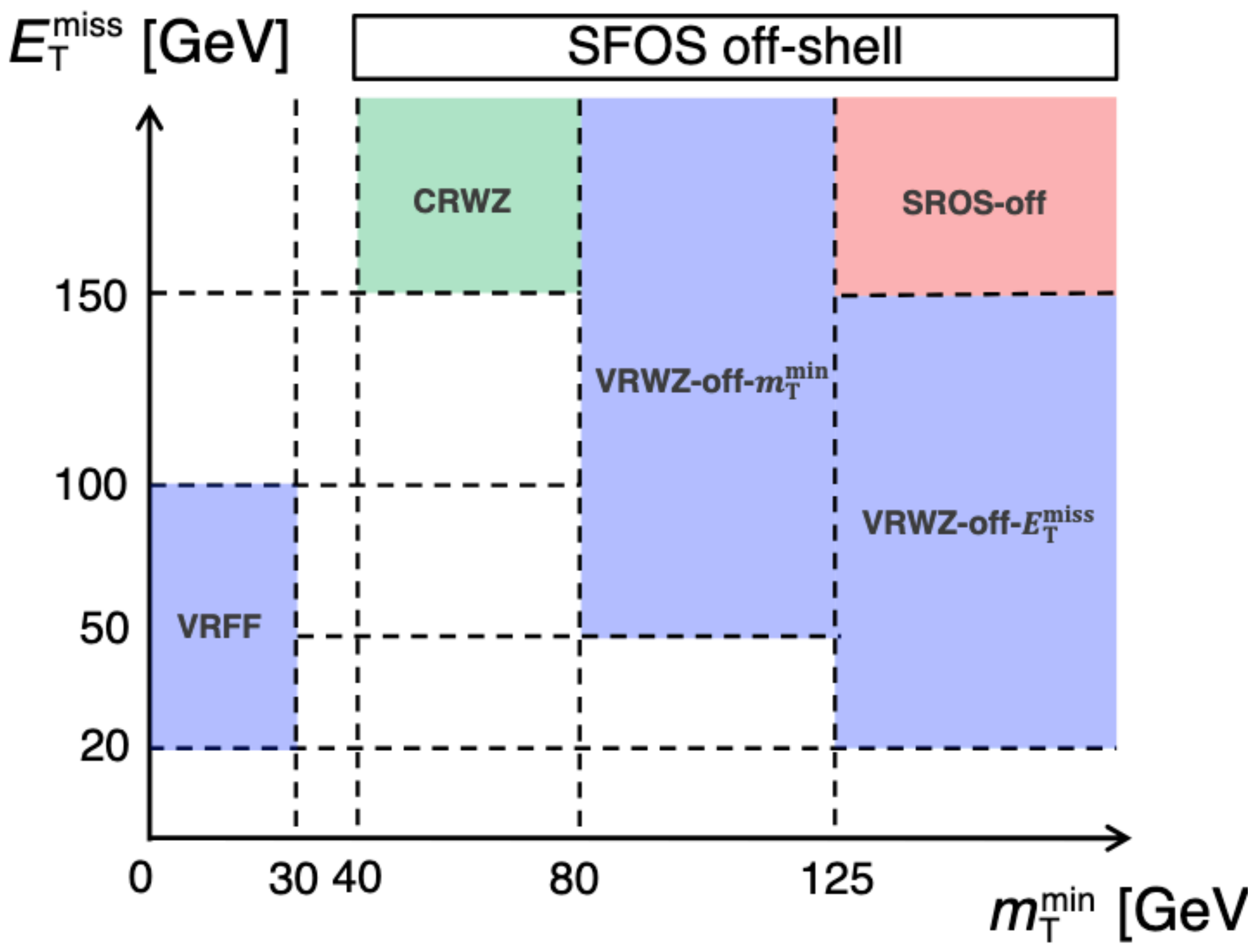
- **Additional results from ATLAS electroweak SUSY searches are anticipated soon!**

Backup Slides

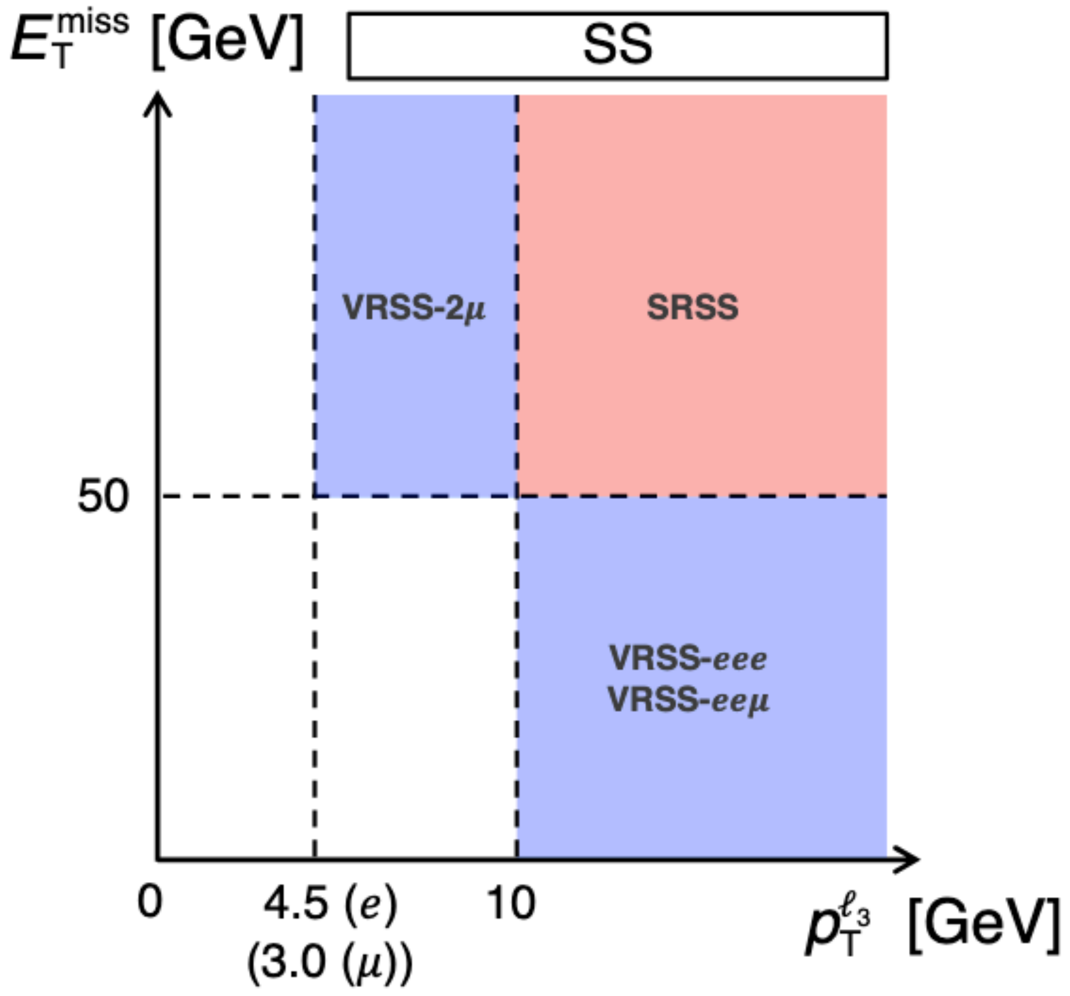
SBH - Regions Summary



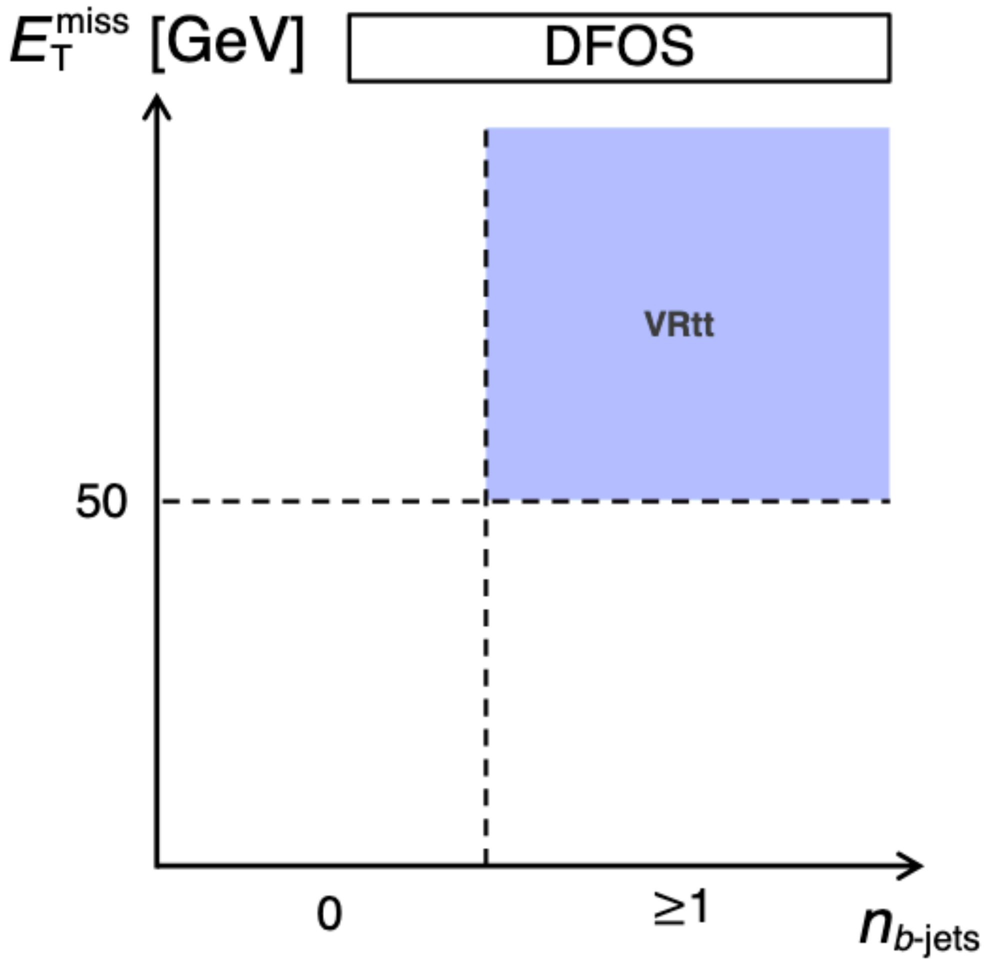
(a)



(b)

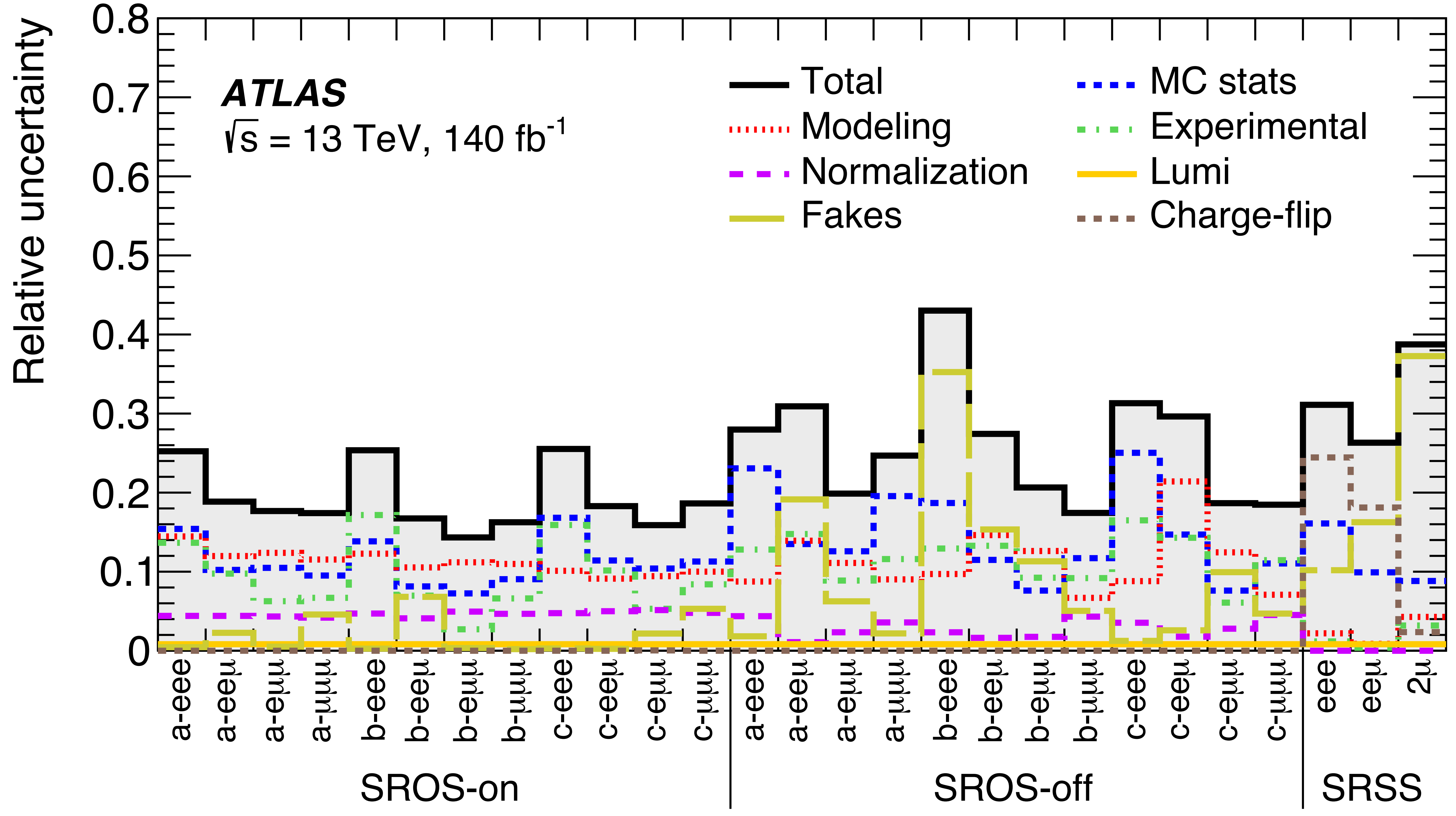


(c)



(d)

SBH - Systematics Uncertainties in SRs



- **SROS** mainly dominated by MC stats. and WZ, triboson theory uncertainties
- **SRSS** dominated by charge-flip and fake systematics

SBH - Observed & Expected yields in SRs

Region	SROS-on-a-eee	SROS-on-a-$ee\mu$	SROS-on-a-$e\mu\mu$	SROS-on-a-$\mu\mu\mu$
Observed data	0	1	2	6
Fitted SM	1.0 ± 0.3	2.1 ± 0.4	2.6 ± 0.5	3.4 ± 0.6
WZ	0.77 ± 0.20	1.6 ± 0.3	2.0 ± 0.4	2.4 ± 0.5
ZZ	< 0.005	0.090 ± 0.034	< 0.005	0.14 ± 0.05
VVV	0.17 ± 0.13	0.26 ± 0.19	0.47 ± 0.28	0.40 ± 0.31
$t\bar{t}$	< 0.05	< 0.05	$0.04 \pm^{0.04}_{0.04}$	< 0.05
$t\bar{t}X$	0.059 ± 0.029	0.14 ± 0.06	0.13 ± 0.05	0.28 ± 0.09
Fakes	< 0.005	$0.00 \pm^{0.05}_{0.00}$	$0.000 \pm^{0.014}_{0.000}$	$0.11 \pm^{0.15}_{0.11}$
Others	$0.019 \pm^{0.021}_{0.019}$	< 0.007	0.011 ± 0.005	< 0.006

Region	SROS-on-b-eee	SROS-on-b-$ee\mu$	SROS-on-b-$e\mu\mu$	SROS-on-b-$\mu\mu\mu$
Observed data	4	4	9	5
Fitted SM	1.3 ± 0.3	2.7 ± 0.5	4.6 ± 0.7	3.9 ± 0.6
WZ	1.0 ± 0.3	1.9 ± 0.3	3.9 ± 0.6	3.1 ± 0.6
ZZ	< 0.005	0.11 ± 0.04	0.012 ± 0.009	0.21 ± 0.06
VVV	0.18 ± 0.13	0.34 ± 0.23	0.46 ± 0.28	0.42 ± 0.30
$t\bar{t}$	< 0.05	$0.04 \pm^{0.04}_{0.04}$	$0.04 \pm^{0.05}_{0.04}$	< 0.05
$t\bar{t}X$	0.05 ± 0.04	0.18 ± 0.05	0.15 ± 0.07	0.13 ± 0.06
Fakes	< 0.003	$0.14 \pm^{0.19}_{0.14}$	$0.000 \pm^{0.016}_{0.000}$	< 0.008
Others	< 0.002	< 0.005	< 0.006	< 0.004

Region	SROS-on-c-eee	SROS-on-c-$ee\mu$	SROS-on-c-$e\mu\mu$	SROS-on-c-$\mu\mu\mu$
Observed data	1	2	1	3
Fitted SM	0.81 ± 0.21	1.9 ± 0.3	2.7 ± 0.4	2.2 ± 0.4
WZ	0.66 ± 0.19	1.6 ± 0.3	2.4 ± 0.4	1.8 ± 0.4
ZZ	< 0.005	0.031 ± 0.028	0.013 ± 0.007	0.073 ± 0.028
VVV	0.09 ± 0.06	0.19 ± 0.10	0.18 ± 0.11	0.20 ± 0.13
$t\bar{t}$	< 0.05	< 0.05	$0.06 \pm^{0.08}_{0.06}$	< 0.05
$t\bar{t}X$	0.052 ± 0.026	0.036 ± 0.024	0.031 ± 0.022	$0.011 \pm^{0.023}_{0.011}$
Fakes	< 0.002	< 0.004	$0.02 \pm^{0.06}_{0.02}$	$0.09 \pm^{0.11}_{0.09}$
Others	< 0.002	< 0.002	< 0.001	< 0.001

Region	SROS-off-a-eee	SROS-off-a-$ee\mu$	SROS-off-a-$e\mu\mu$	SROS-off-a-$\mu\mu\mu$
Observed data	0	3	2	1
Fitted SM	0.39 ± 0.11	1.4 ± 0.4	3.8 ± 0.8	1.0 ± 0.3
WZ	0.30 ± 0.10	0.26 ± 0.12	1.5 ± 0.2	0.62 ± 0.21
ZZ	< 0.005	0.027 ± 0.019	0.027 ± 0.016	0.053 ± 0.034
VVV	0.06 ± 0.04	0.31 ± 0.16	0.48 ± 0.20	0.15 ± 0.08
$t\bar{t}$	< 0.05	0.41 ± 0.24	1.1 ± 0.4	0.13 ± 0.10
$t\bar{t}X$	0.028 ± 0.017	0.08 ± 0.04	0.16 ± 0.06	0.046 ± 0.020
Fakes	< 0.007	0.28 ± 0.27	$0.00 \pm^{0.24}_{0.00}$	$0.000 \pm^{0.022}_{0.000}$
Others	< 0.01	0.032 ± 0.012	0.5 ± 0.5	0.0101 ± 0.0034

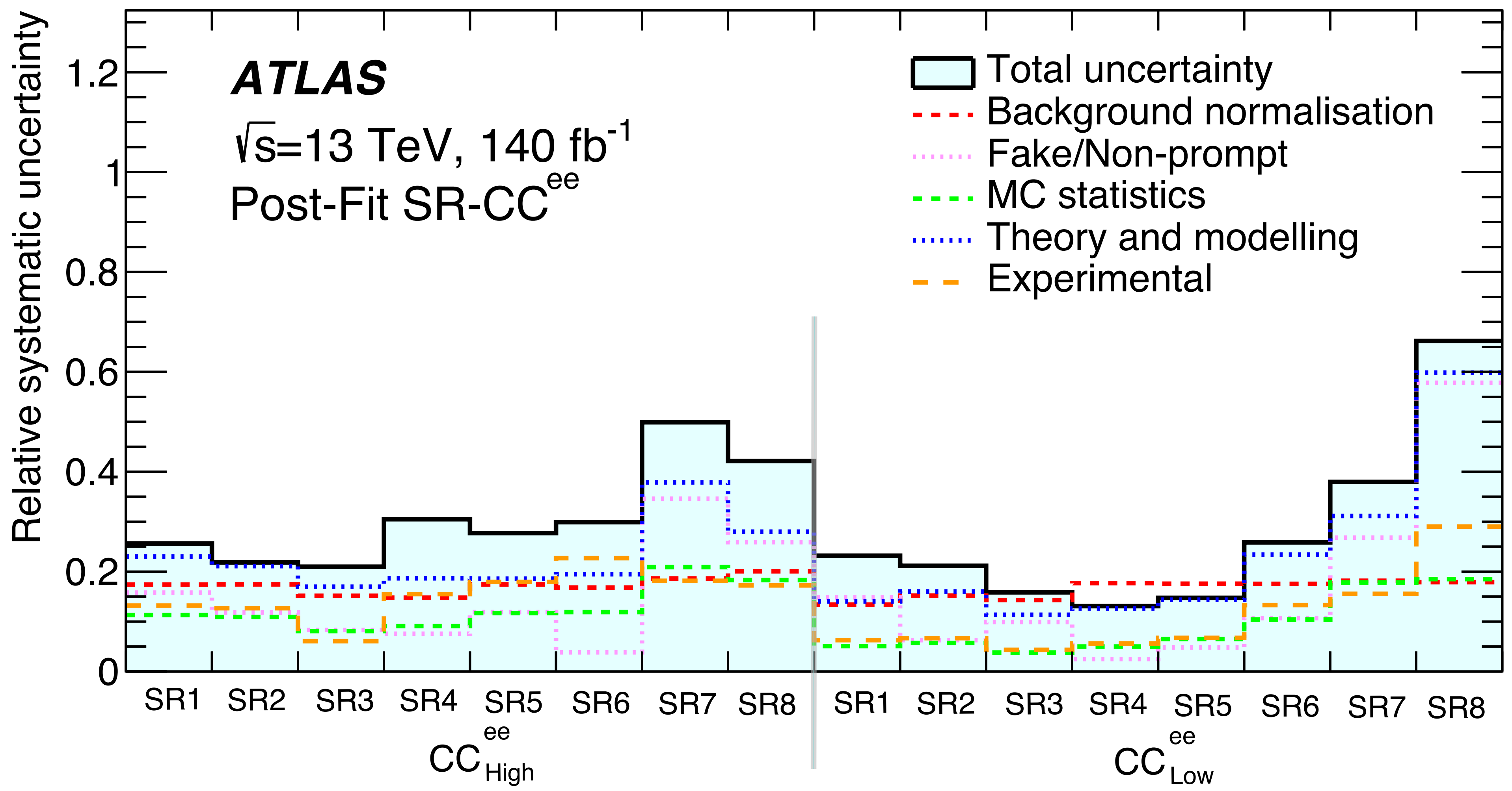
Region	SROS-off-b-eee	SROS-off-b-$ee\mu$	SROS-off-b-$e\mu\mu$	SROS-off-b-$\mu\mu\mu$
Observed data	0	3	6	1
Fitted SM	0.75 ± 0.33	1.6 ± 0.4	3.6 ± 0.7	1.5 ± 0.3
WZ	0.30 ± 0.10	0.45 ± 0.14	1.1 ± 0.2	1.1 ± 0.2
ZZ	< 0.005	0.049 ± 0.029	0.034 ± 0.023	0.058 ± 0.029
VVV	0.17 ± 0.11	0.57 ± 0.28	1.1 ± 0.5	0.23 ± 0.11
$t\bar{t}$	< 0.05	0.18 ± 0.11	0.61 ± 0.25	< 0.05
$t\bar{t}X$	< 0.01	0.15 ± 0.05	0.24 ± 0.07	0.064 ± 0.031
Fakes	$0.20 \pm^{0.27}_{0.20}$	$0.15 \pm^{0.25}_{0.15}$	0.5 ± 0.4	$0.02 \pm^{0.08}_{0.02}$
Others	$0.07 \pm^{0.11}_{0.07}$	0.040 ± 0.016	0.039 ± 0.011	< 0.01

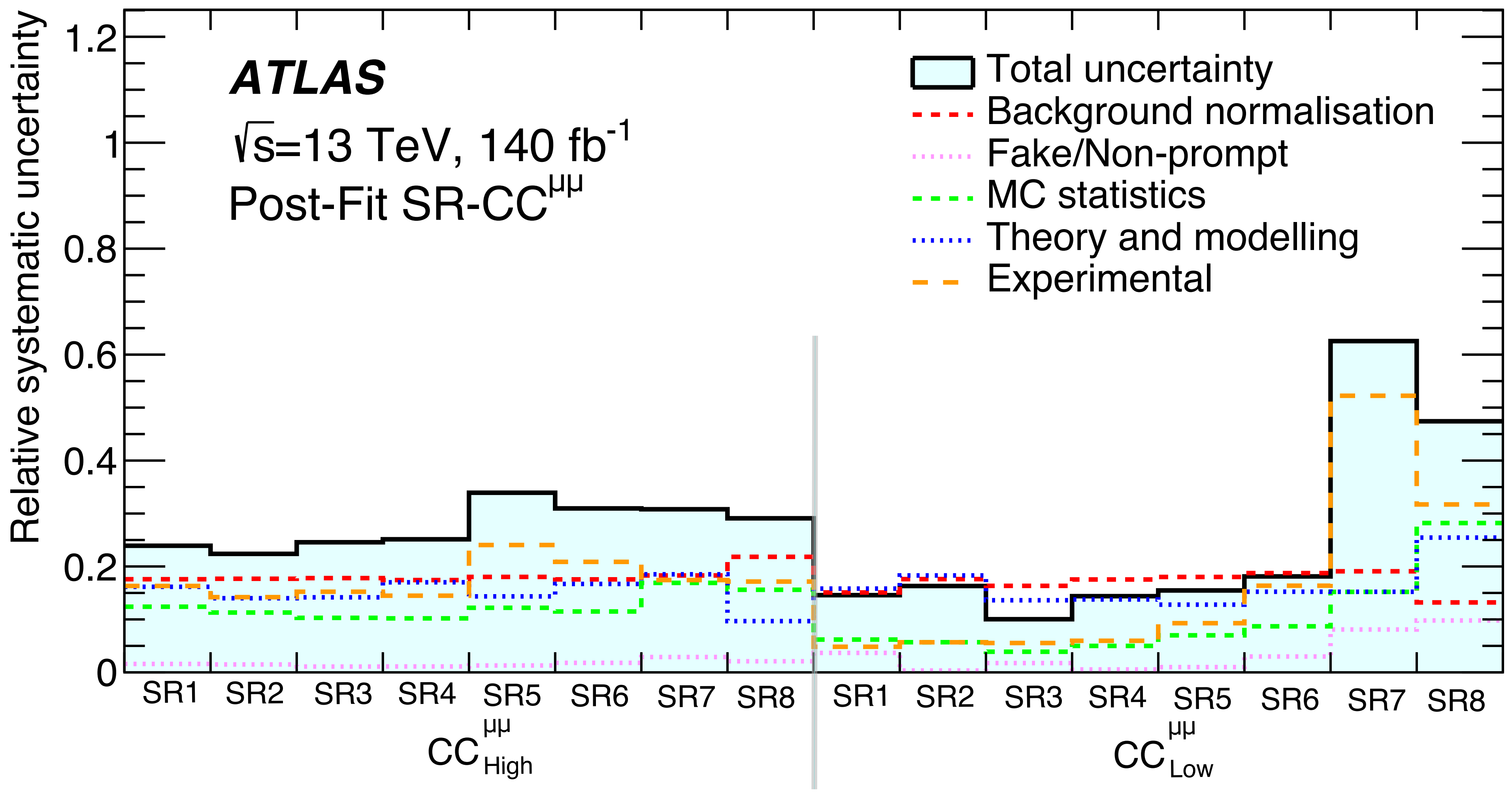
Region	SROS-off-c-eee	SROS-off-c-$ee\mu$	SROS-off-c-$e\mu\mu$	SROS-off-c-$\mu\mu\mu$
Observed data	0	1	1	3
Fitted SM	0.27 ± 0.08	0.96 ± 0.28	3.0 ± 0.6	1.9 ± 0.4
WZ	0.16 ± 0.07	0.29 ± 0.09	1.4 ± 0.2	1.5 ± 0.3
ZZ	< 0.005	0.020 ± 0.013	0.09 ± 0.04	0.04 ± 0.04
VVV	0.063 ± 0.026	0.52 ± 0.25	0.9 ± 0.4	0.31 ± 0.15
$t\bar{t}$	< 0.05	$0.04 \pm^{0.05}_{0.04}$	0.09 ± 0.07	< 0.05
$t\bar{t}X$	0.039 ± 0.029	0.08 ± 0.04	0.12 ± 0.05	$0.02 \pm^{0.05}_{0.02}$
Fakes	< 0.003	$0.000 \pm^{0.025}_{0.000}$	0.33 ± 0.30	$0.05 \pm^{0.09}_{0.05}$
Others	< 0.002	< 0.005	< 0.01	< 0.004

Region	SRSS-eee	SRSS-$e\mu\mu$	SRSS-2μ
Observed data	1	2	1
Fitted SM	0.85 ± 0.26	2.0 ± 0.5	0.66 ± 0.26
Charge-flip	0.74 ± 0.25	1.4 ± 0.4	0.015 ± 0.006
Fakes	$0.06 \pm^{0.09}_{0.06}$	0.57 ± 0.33	0.55 ± 0.25
WZ	< 0.01	0.032 ± 0.027	< 0.005
VVV	< 0.01	$0.012 \pm^{0.018}_{0.012}$	$0.016 \pm^{0.022}_{0.016}$
$t\bar{t}$	$0.04 \pm^{0.04}_{0.04}$	< 0.05	0.08 ± 0.06

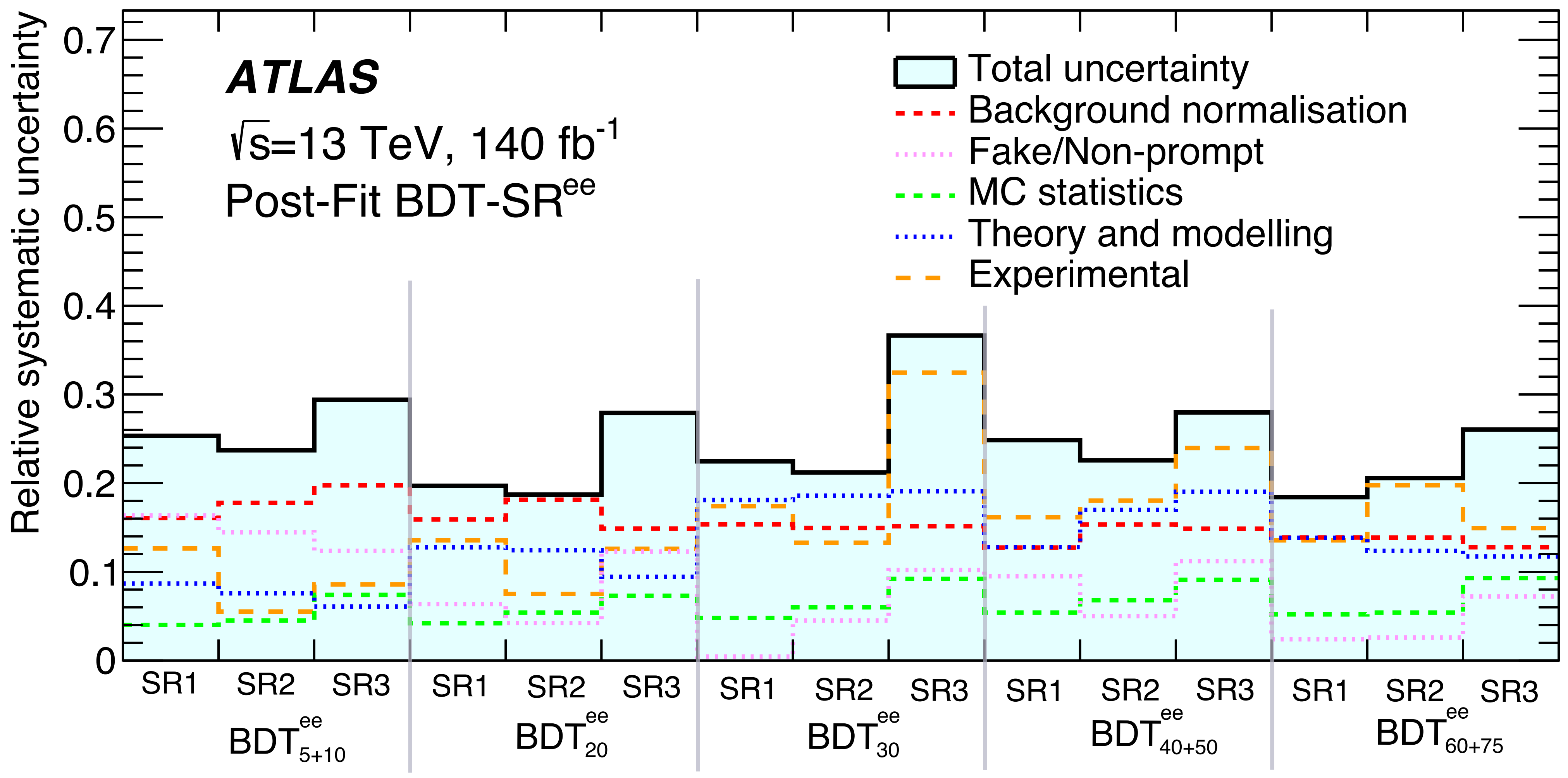
Compressed Slepton Analysis - Systematic Uncertainties

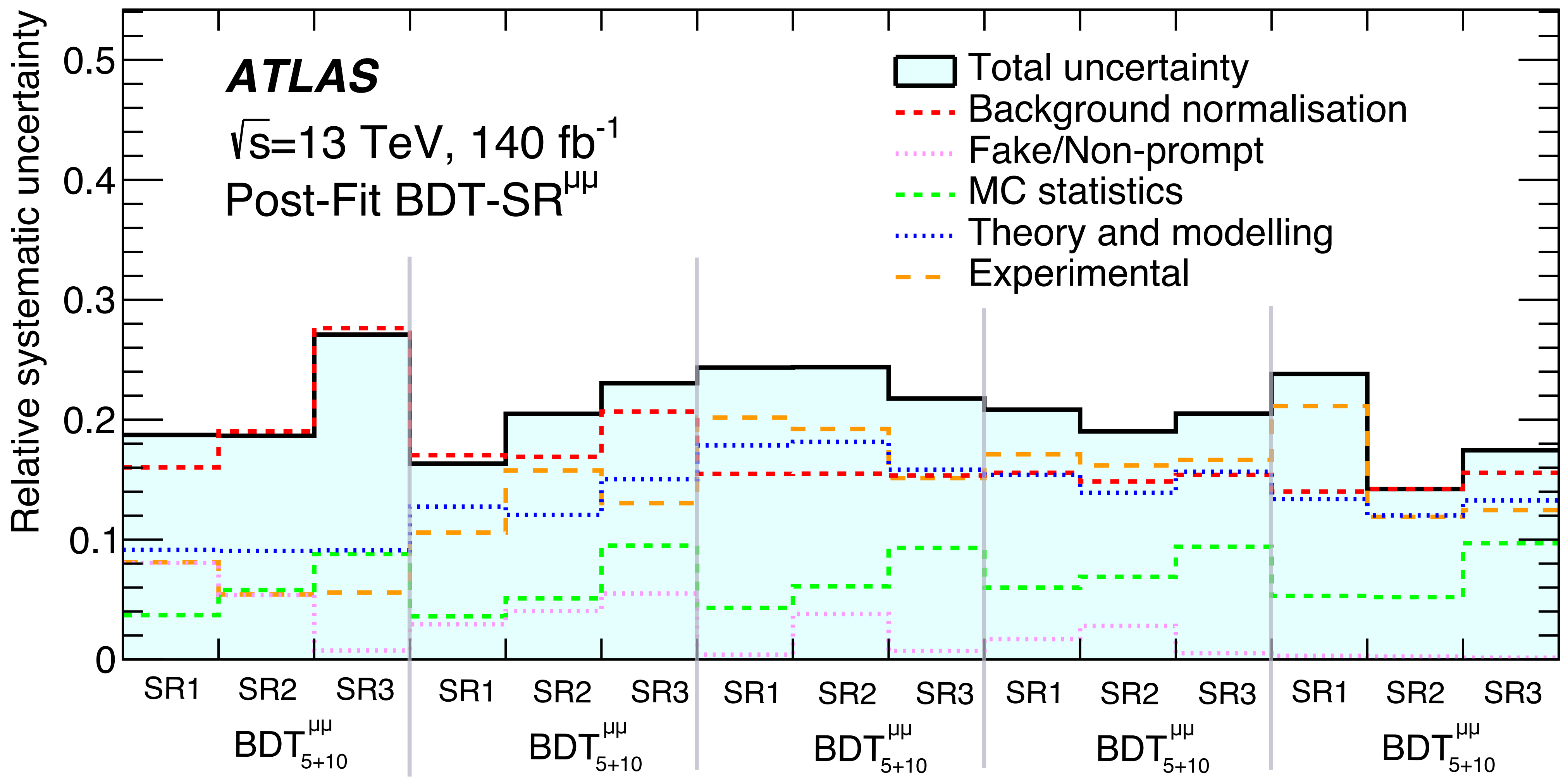
◉ CC Analysis



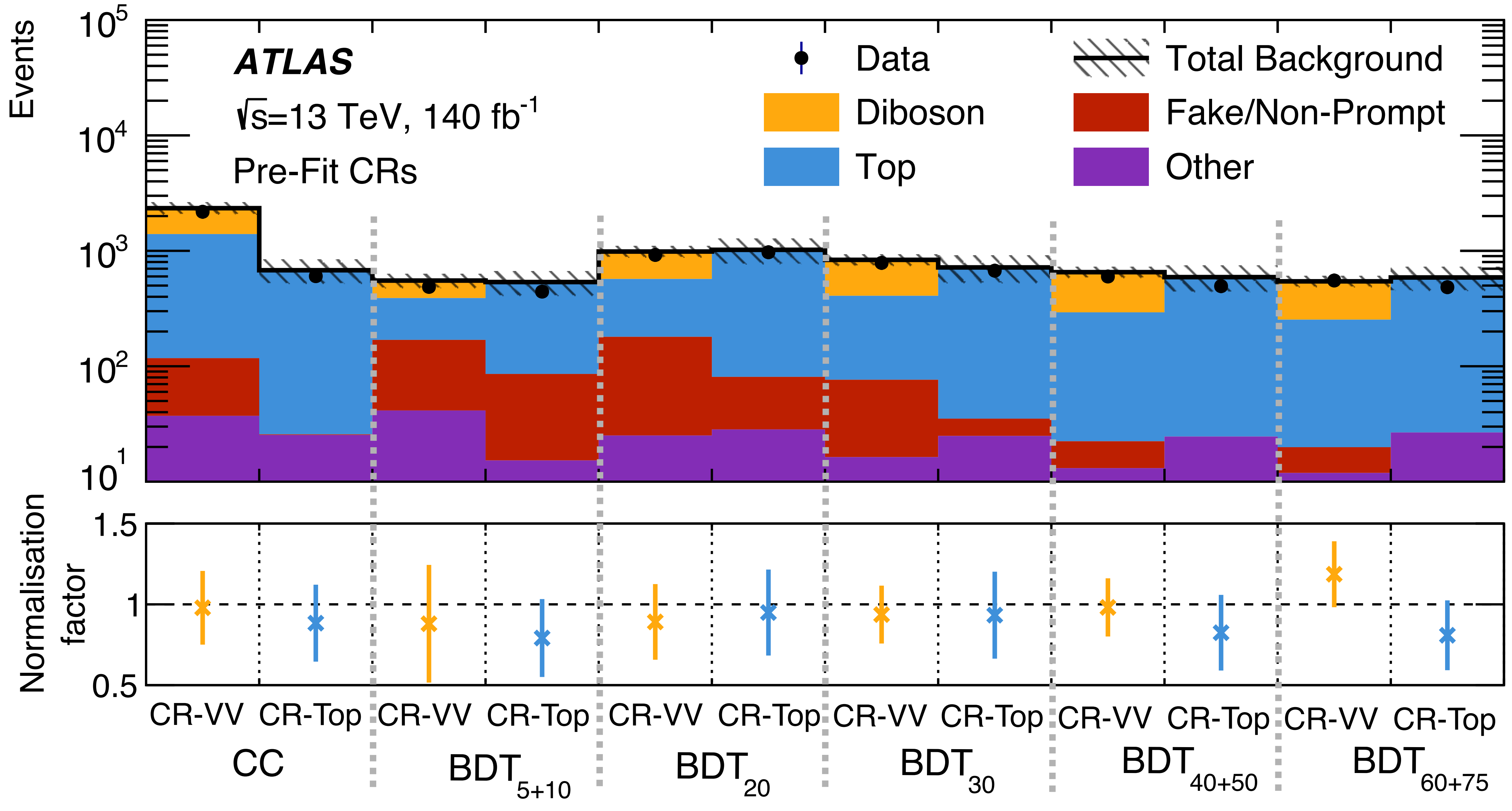


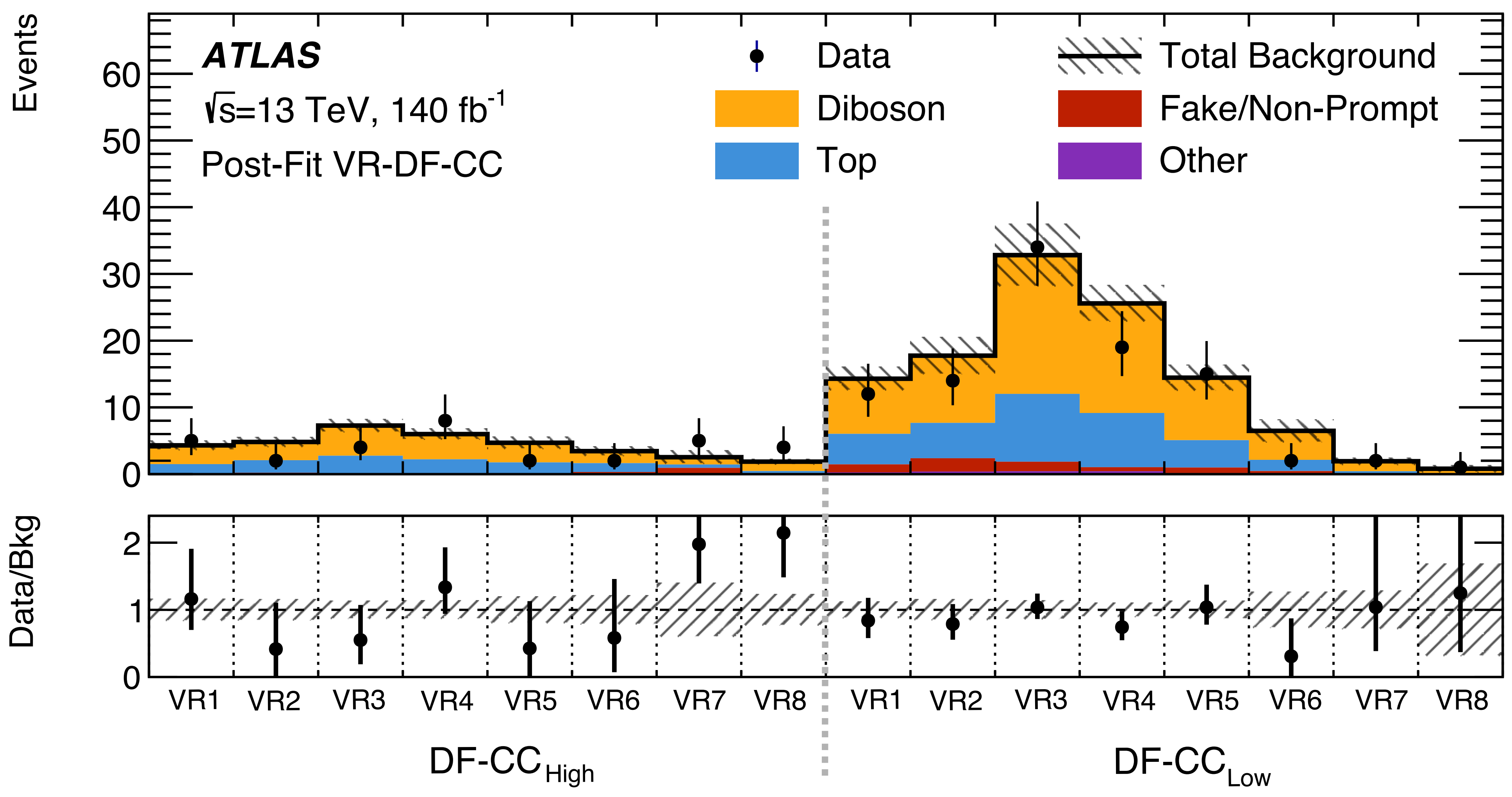
◉ BDT Analysis

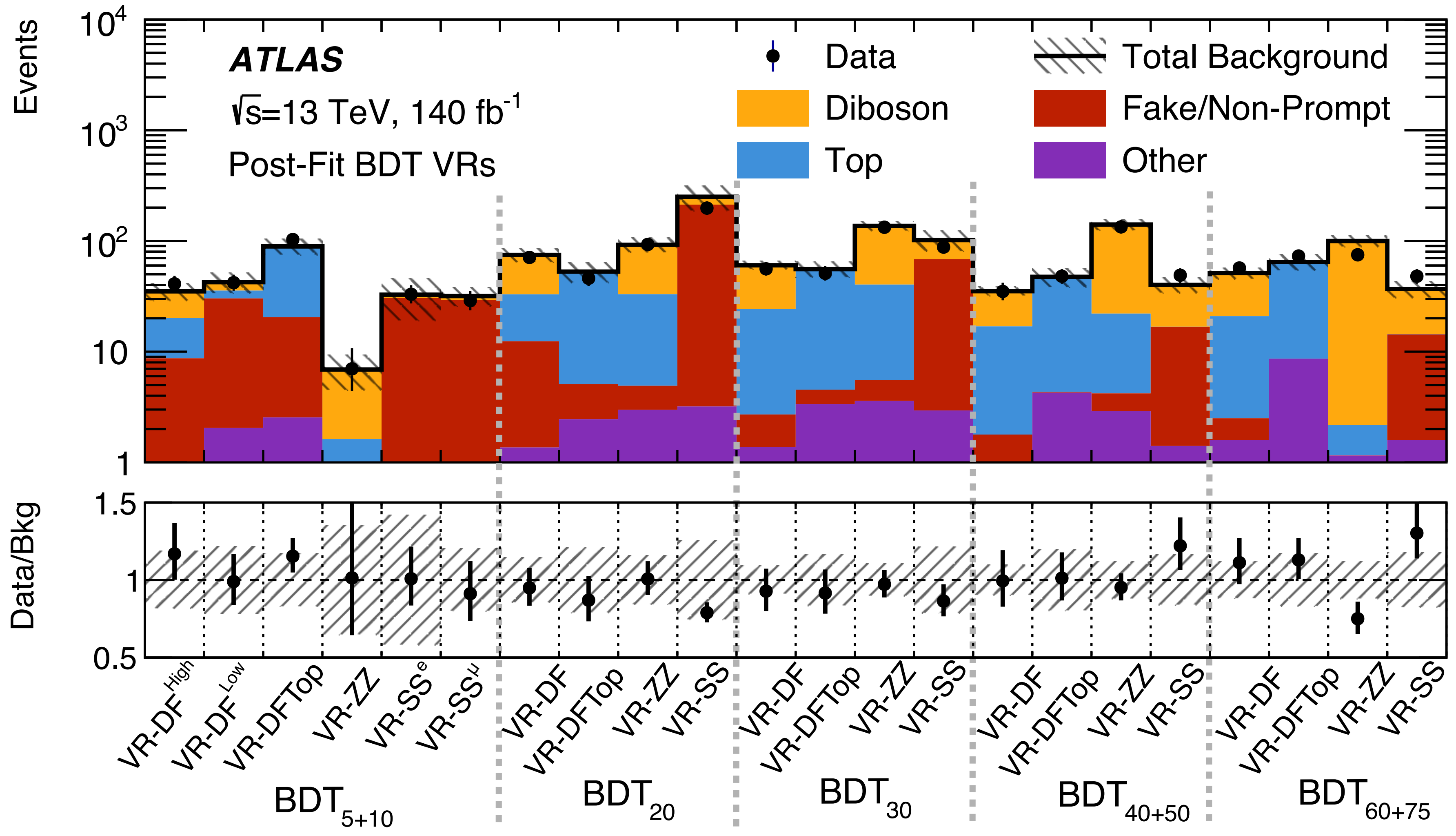




Compressed Slepton Analysis - CR & VR Data MC Comparison

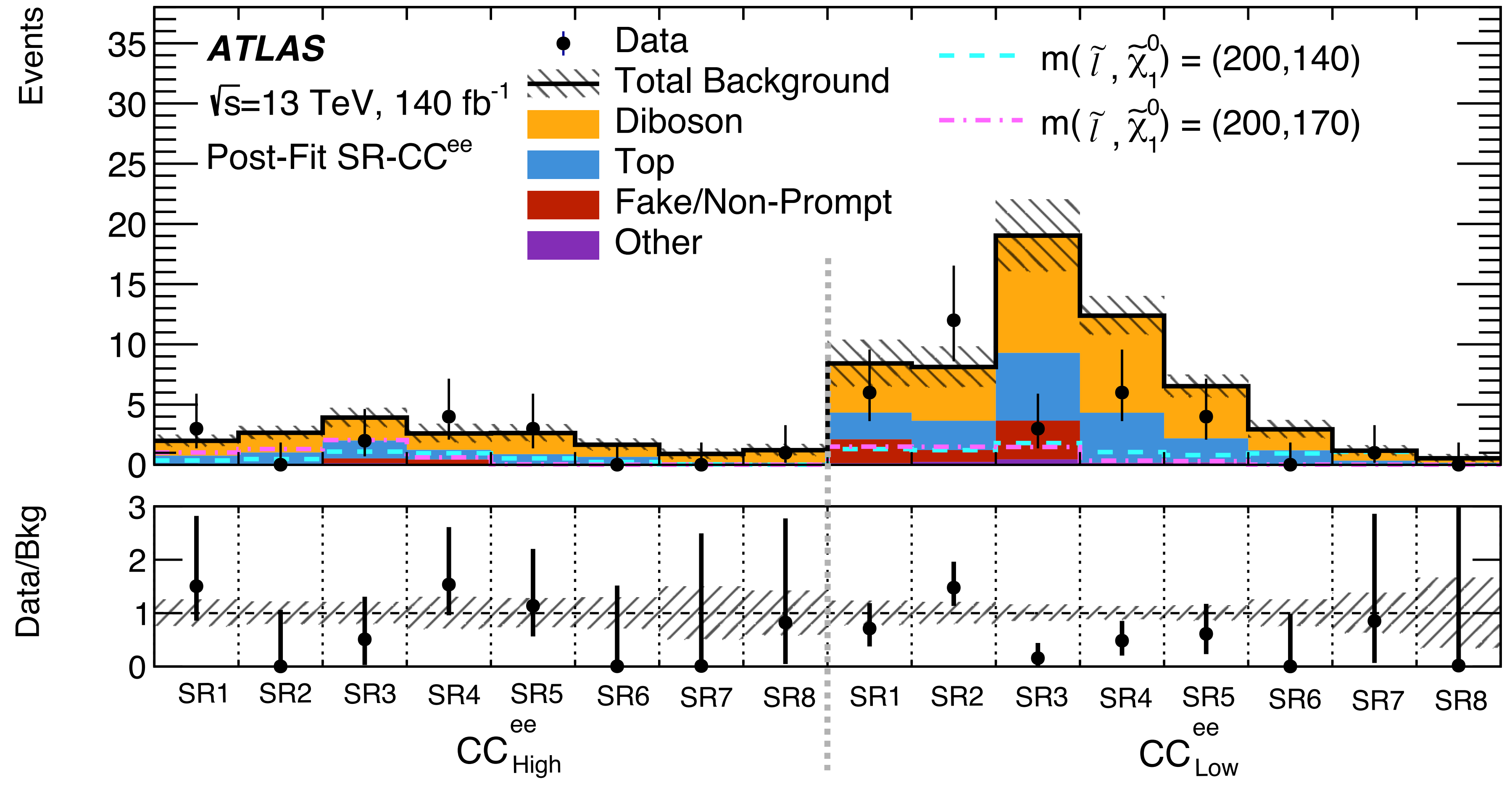


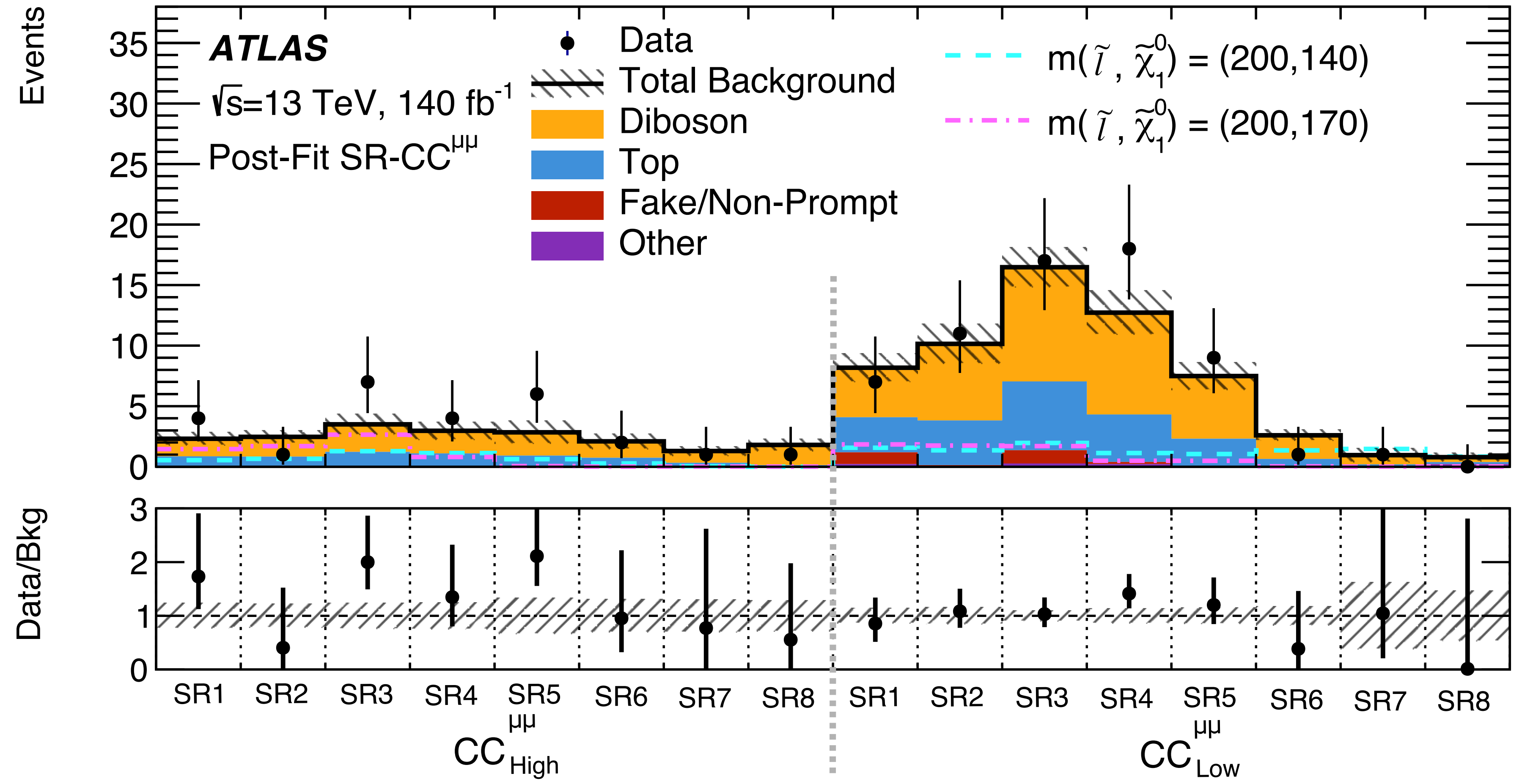


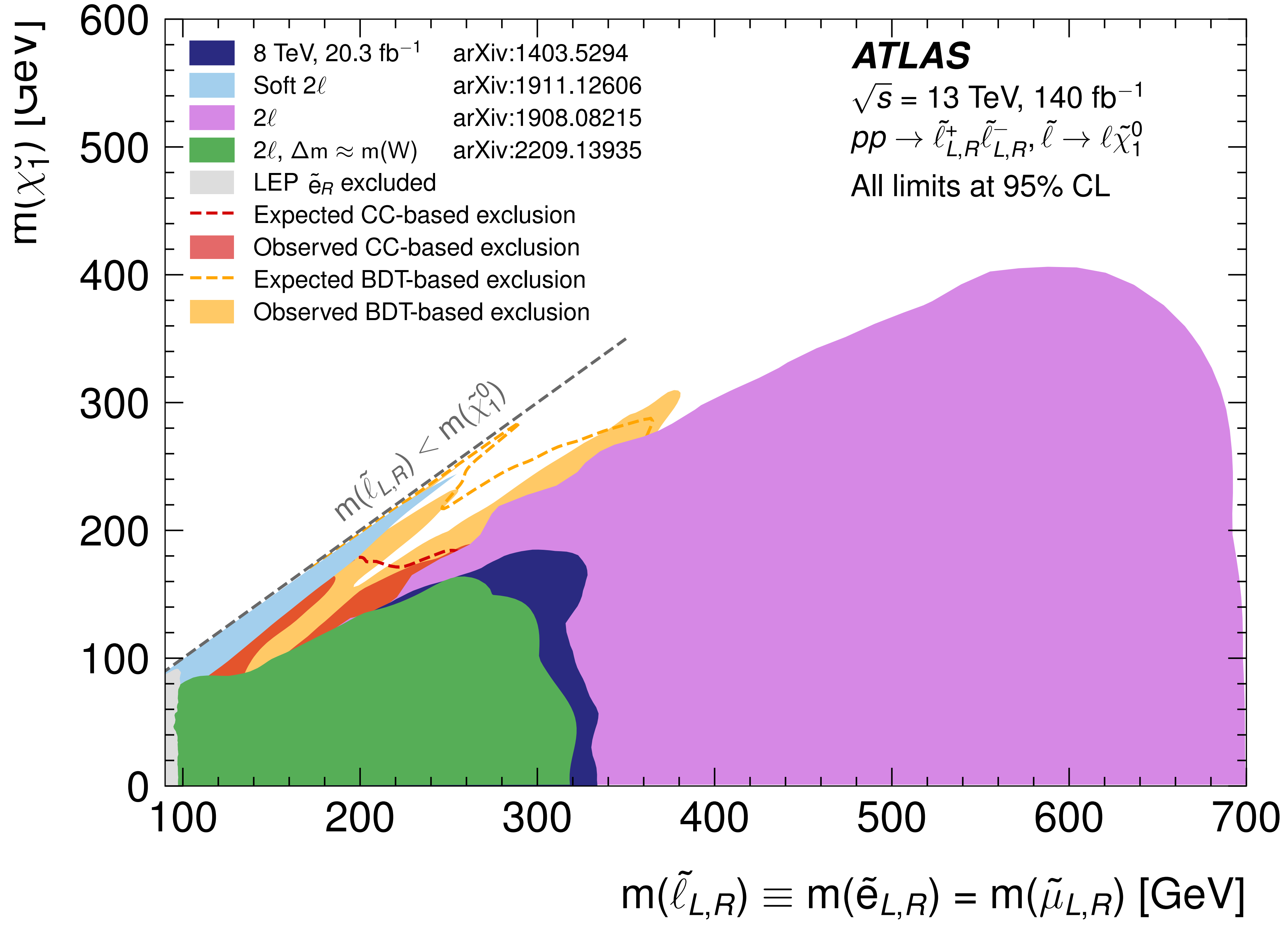


Compressed Slepton - Results & Exclusion Limits (Cut & Count)

- No significant excess found for Cut & Count approach

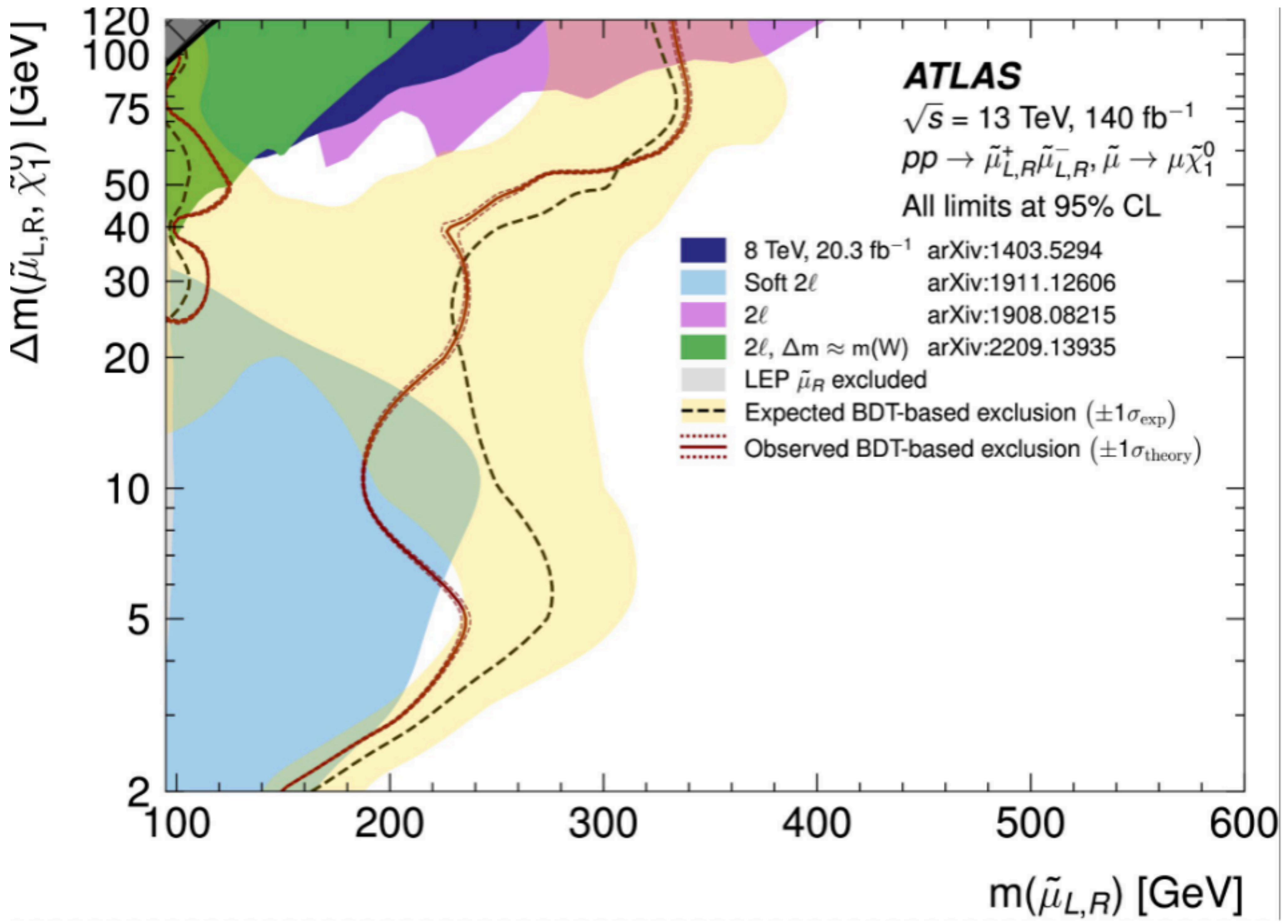






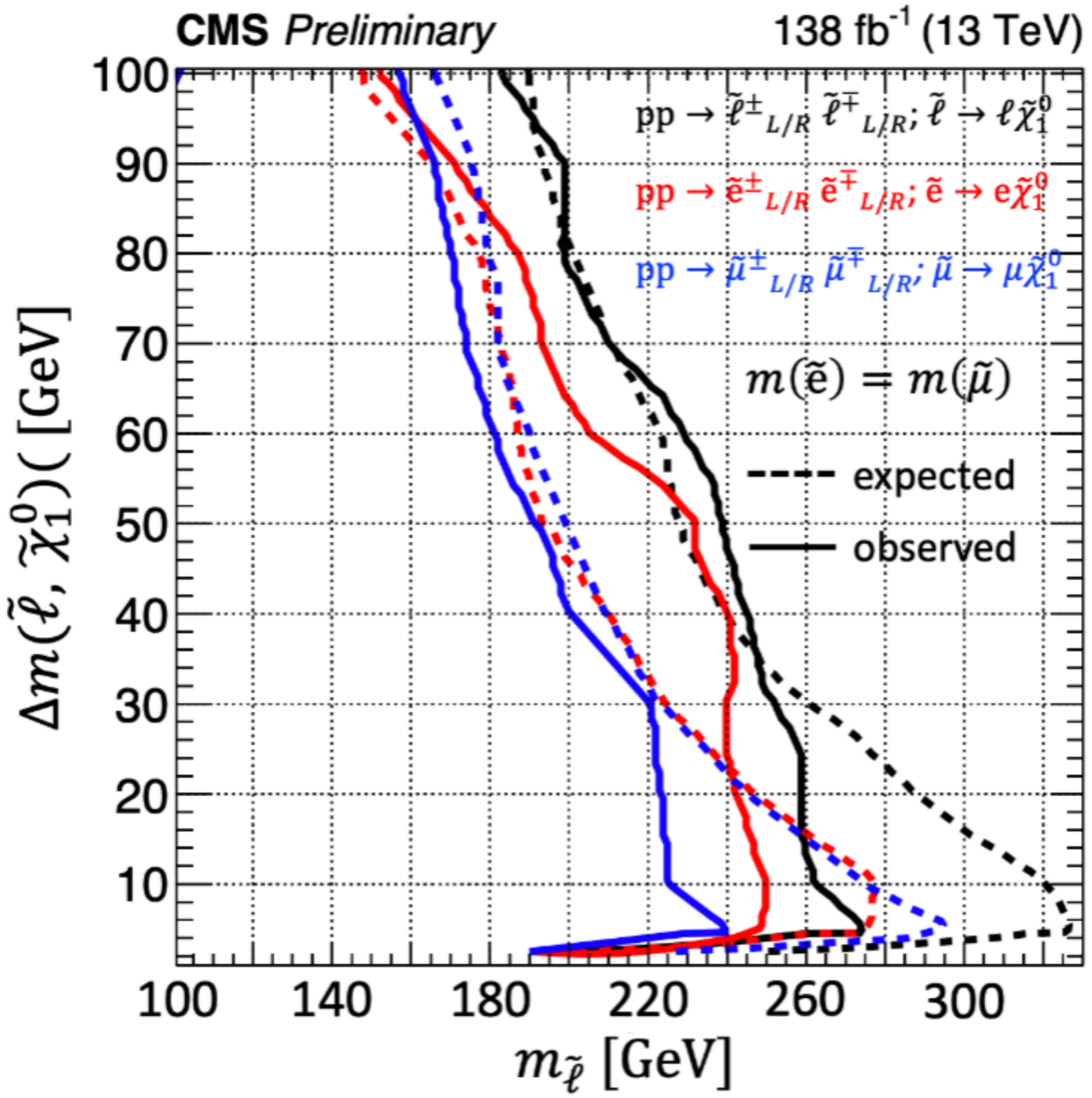
Compressed Slepton - Comparison with CMS (BDT approach)

Large drop in exclusion for small mass splitting $\Delta m(\tilde{\mu}, \chi_1^0) = 10\ \mathrm{GeV}$



Preliminary CMS result shows a similar drop in observed exclusion

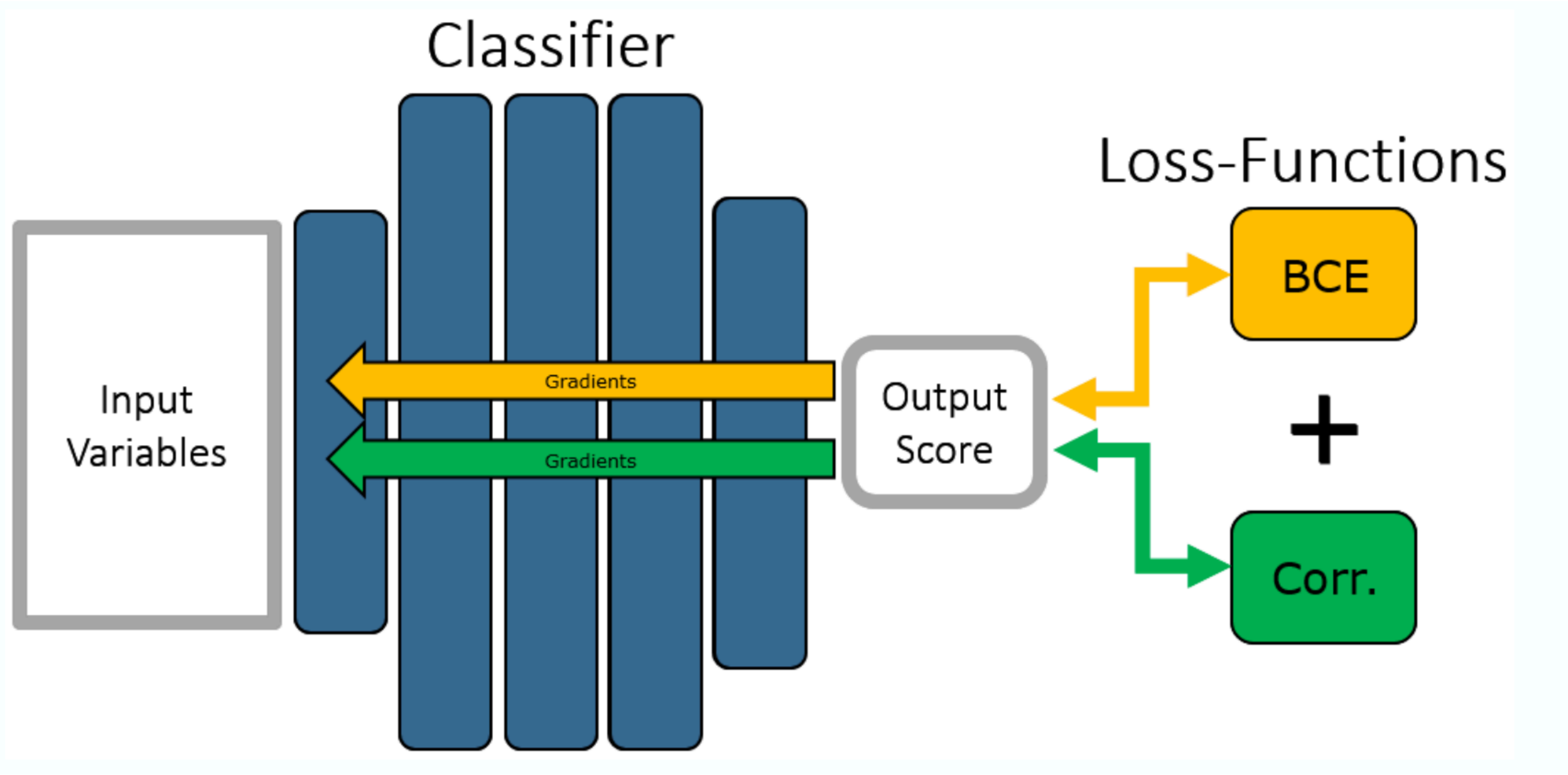
Limited info on SR kinematics…

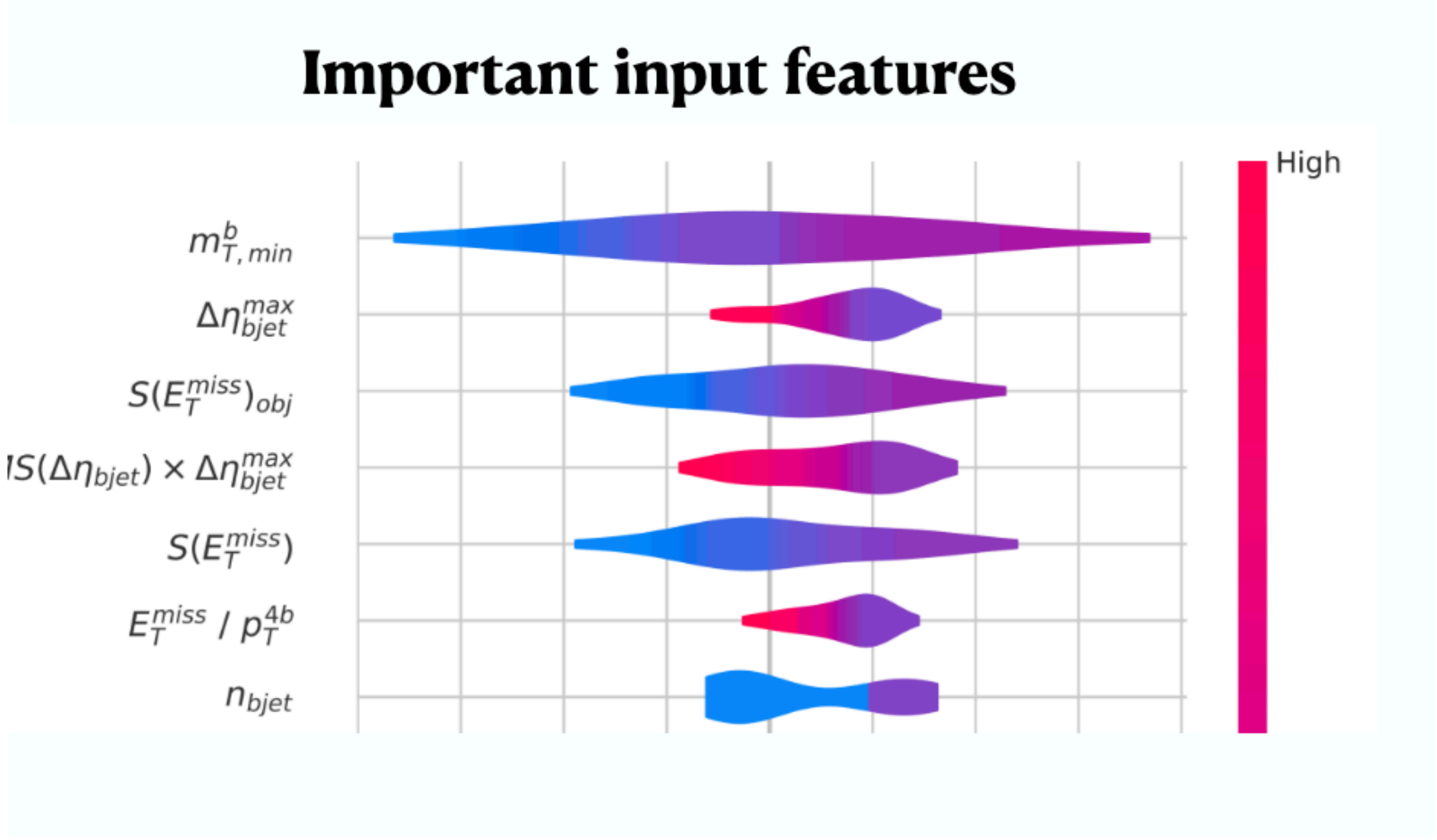


SUS-23-003-pas

EWK multi-b Dark Higgs - ML

- Train NN classifier on equal set of signal and bkg events
- Decorrelate m_{hh} to avoid mass sculpting using modified loss-function
- MET-based features most relevant



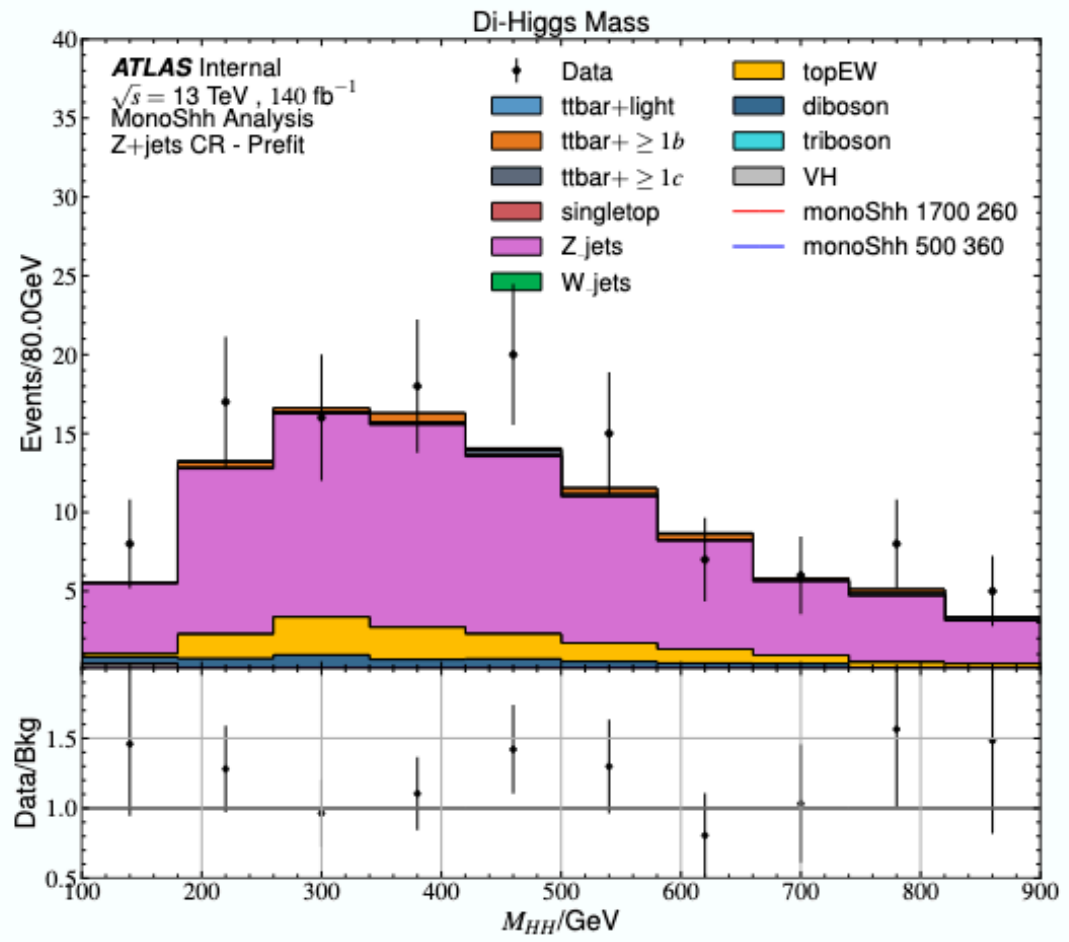


EWK multi-b Dark Higgs - Bkg estimation

- MC samples used to estimate bkg processes, fits to data are performed in analysis regions
- Normalization factors for dominant processes are allowed to float

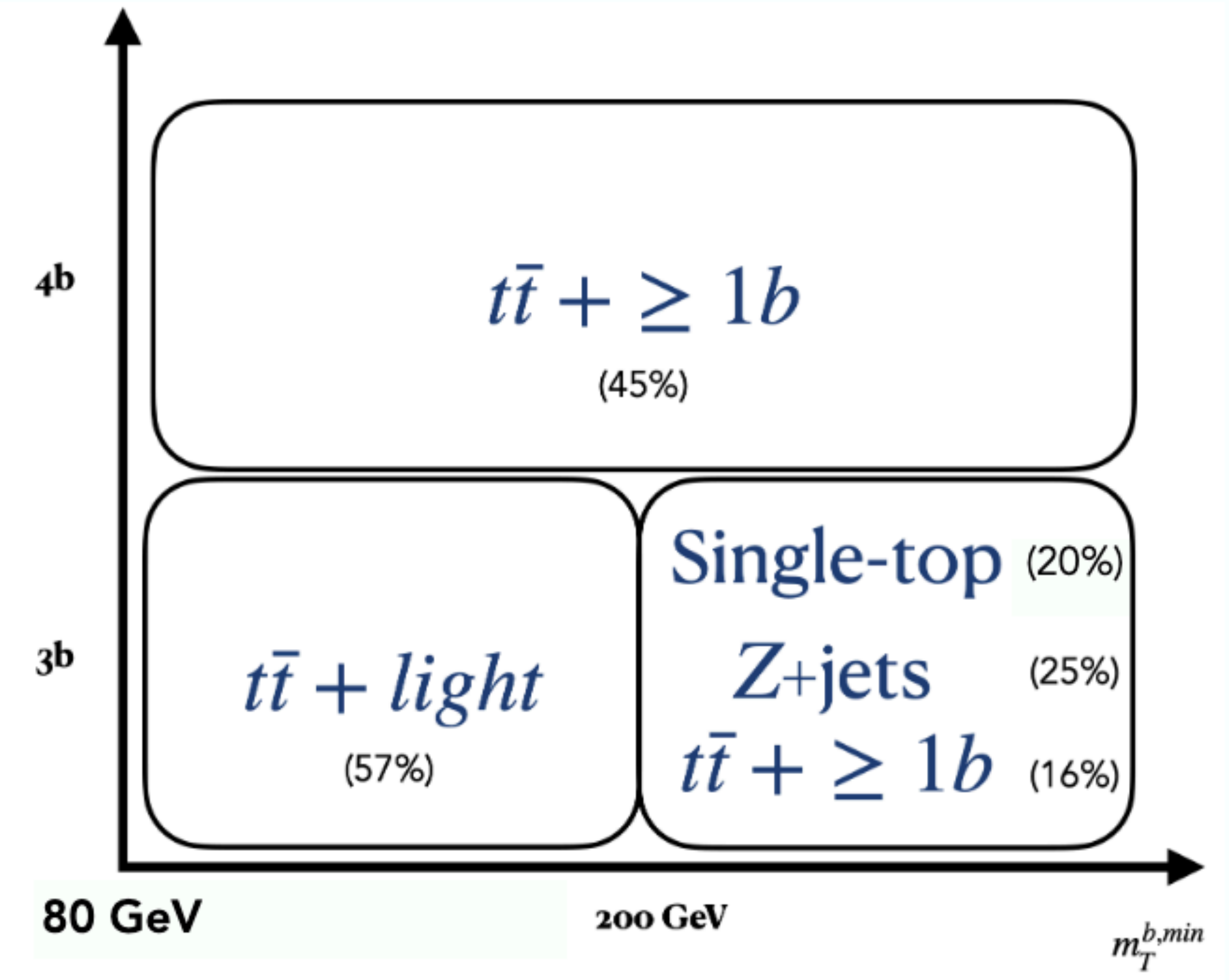
Z+jets:

➡Replace $Z \to \nu\bar{\nu}$ with $Z \to \mu\bar{\mu}$ events by lifting muon veto and require $n_{\mu} = 2$



Top Processes:

➡Require $0.35 < NN < 0.85$ for greater kinematic similarity events whilst maintaining orthogonality to VR/SR



Fake Factor Method

- Fake/NP backgrounds poorly modeled by MC ➔ *data-driven method*
- Measure *fake factors* in region enriched with fake leptons

$$F(i) = \frac{N_{\mathrm{ID}}(i) - N_{\mathrm{ID}}^{\mathrm{PromptMC}}(i)}{N_{\mathrm{anti-ID}}(i) - N_{\mathrm{anti-ID}}^{\mathrm{PromptMC}}(i)}$$

  - ID leptons: pass signal criteria; antiID leptons: fail some but not all

- Apply *F* to antiID leptons in the *signal* region to get bkg estimate

$$N_{\mathrm{SR}} = \sum_i [N_{\mathrm{anti-ID\ CR}}(i) - N_{\mathrm{anti-ID\ CR}}^{\mathrm{PromptMC}}(i)] * F(i)$$