Searches for supersymmetry using two same-sign leptons or three leptons with ATLAS detector

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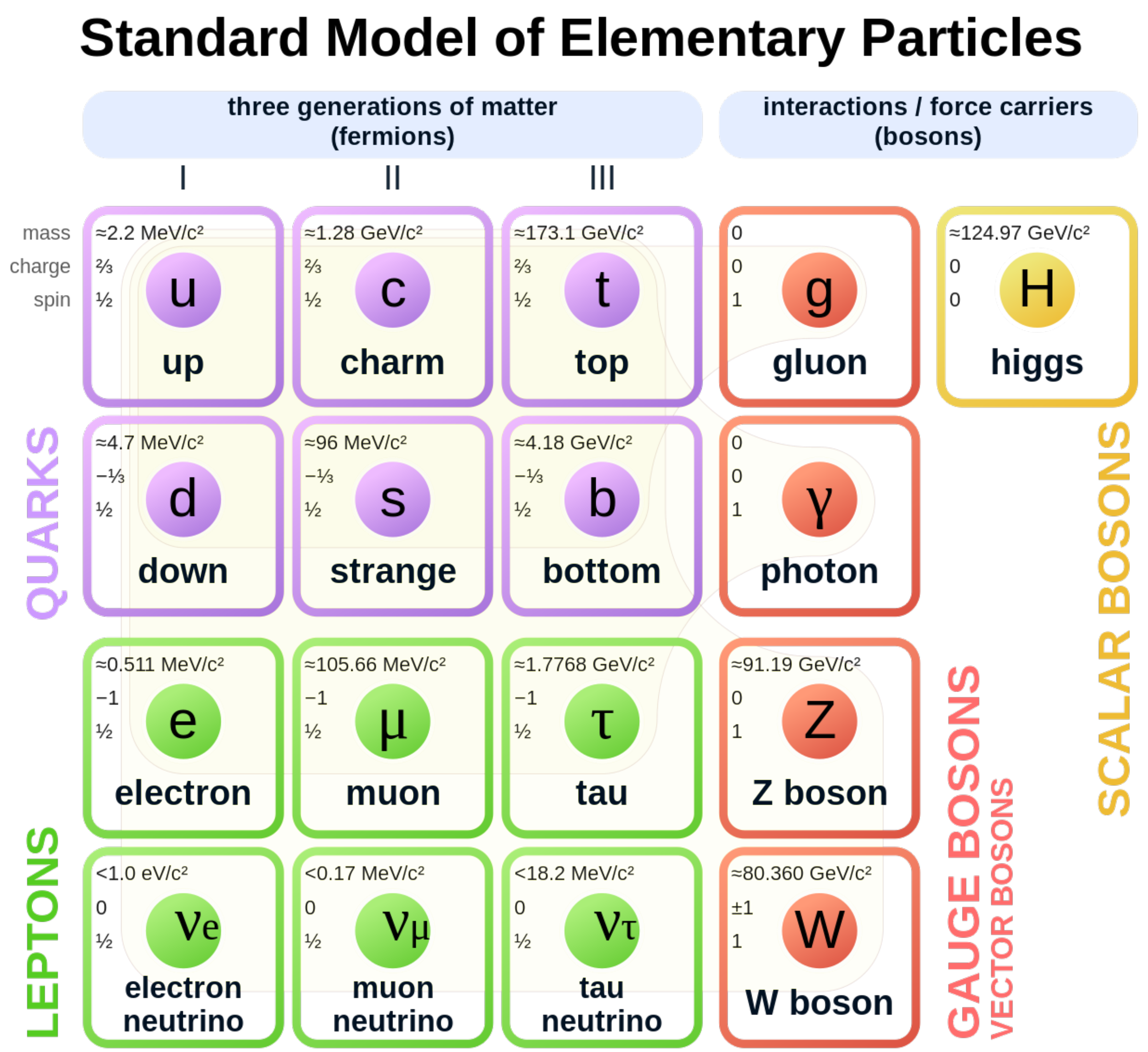
Introduction

- The Standard Model (SM) provides the most precise description for most of experimental phenomenon in particle physics. However, it is not flawless.

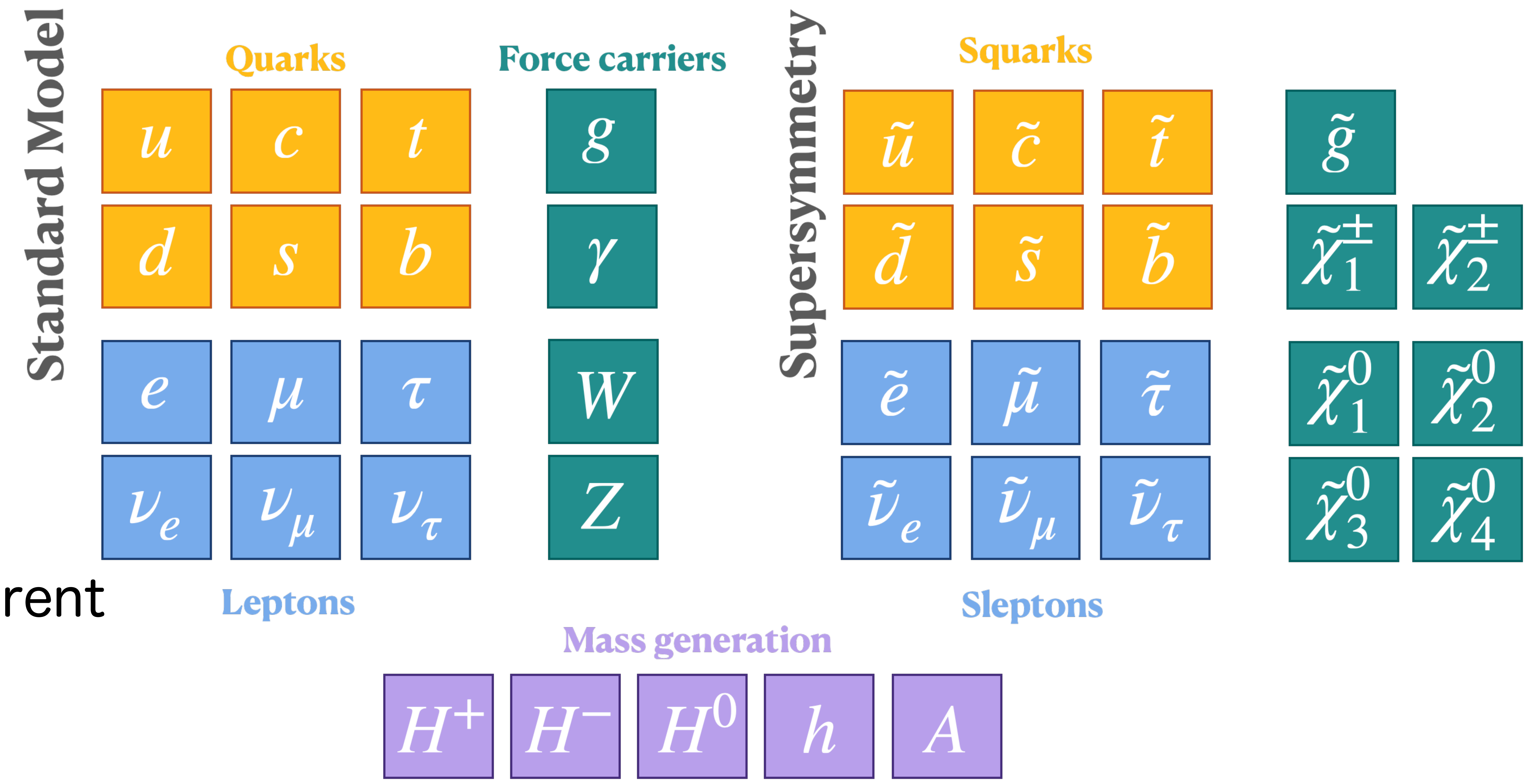
- Many open questions in SM
  - the hierarchy problem
  - unification of fundamental forces
  - dark matter
  - matter-antimatter asymmetry
  - neutrinos masses
  - . . .



- Beyond SM (BSM) searches can shed the light on these open questions of SM

Introducing Supersymmetry

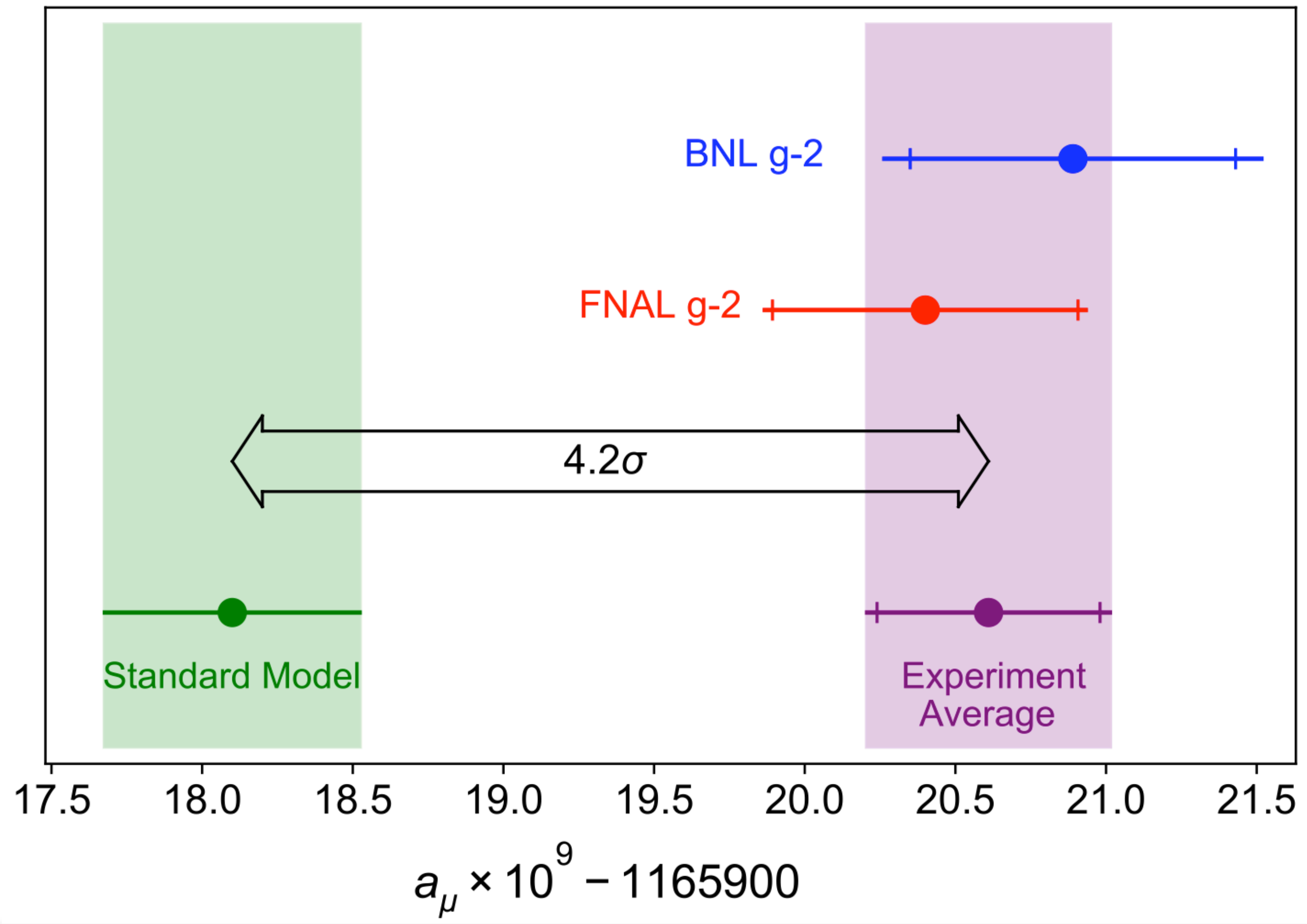
- Supersymmetry (SUSY) is one of the promising extensions of SM by assuming a new symmetry relates bosons and fermions.
- The Minimal Supersymmetric Standard Model (MSSM) introduces supersymmetric partners to SM particles
  - Quarks <-> Squarks
  - Leptons <-> Sleptons
  - SM gauge bosons <-> Gauginos
  - Higgs sector <-> Higgsinos
  - Electroweak (EW) gauginos and Higgsinos are mixed to form different mass eigenstates
    - Neutralinos: $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$
    - Charginos: $\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$



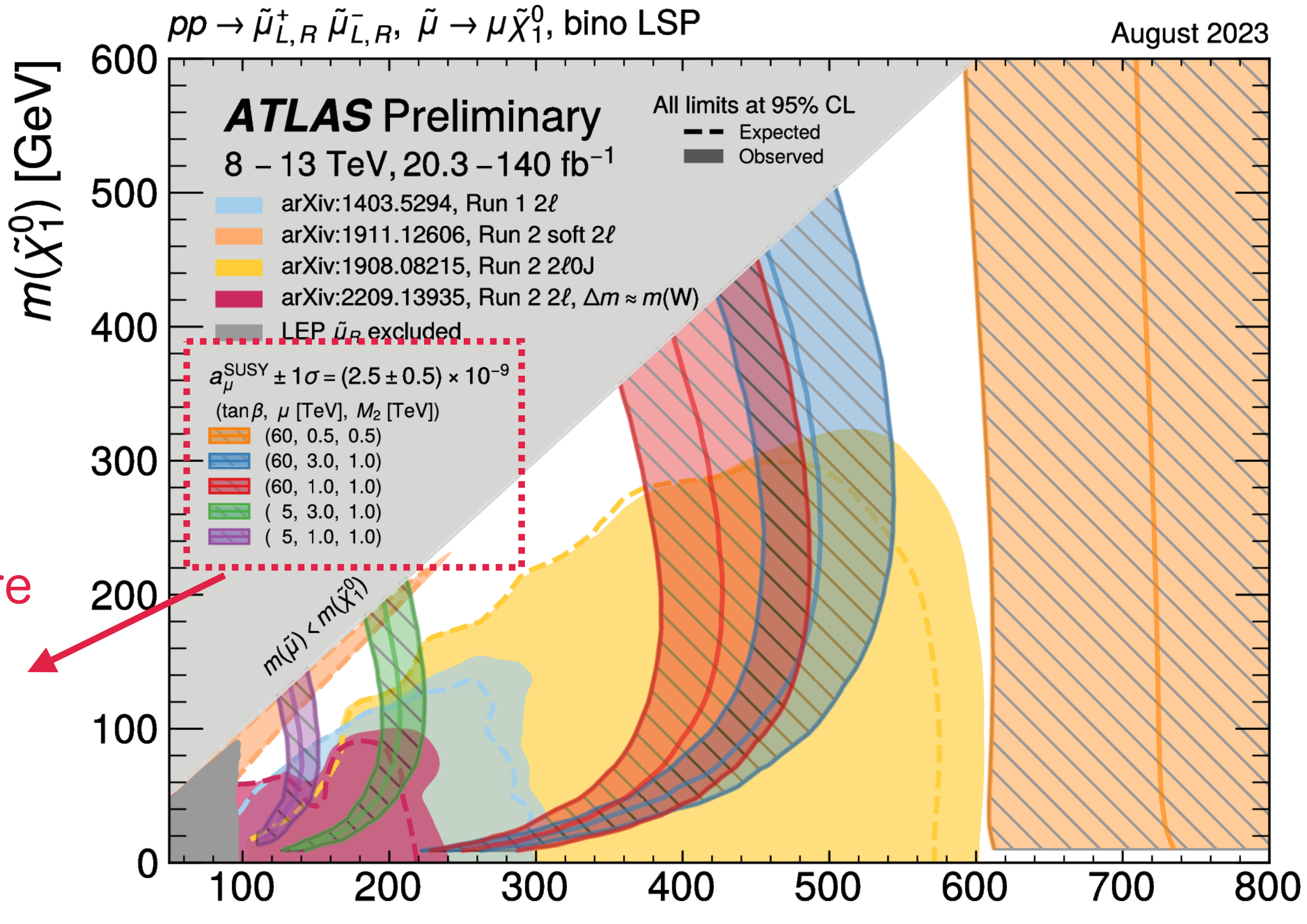
Some references:
[1] I. J. R. Aitchison. "Supersymmetry and the MSSM: An Elementary introduction".arXiv: hep-ph/0505105
[2] S. P. Matrin. "A Supersymmetry Primer" arXiv:hep-ph/9709356

Motivation for SUSY

- Provide a natural solution to the hierarchy problem
- By assuming an ad hoc symmetry called R-parity, $R = (-1)^{3(B-L)+2S}$, the lightest stable SUSY particle (LSP) can be a suitable dark matter candidate
- In R-parity broken SUSY scenarios, baryon number violation (BNV) or lepton number violation (LNV) is allowed
  - BNV: abundant source for baryon asymmetry
  - LNV: possible explanation for neutrino physics
- Light sleptons and neutralinos can provide possible explanation to $(g-2)_\mu$ anomaly



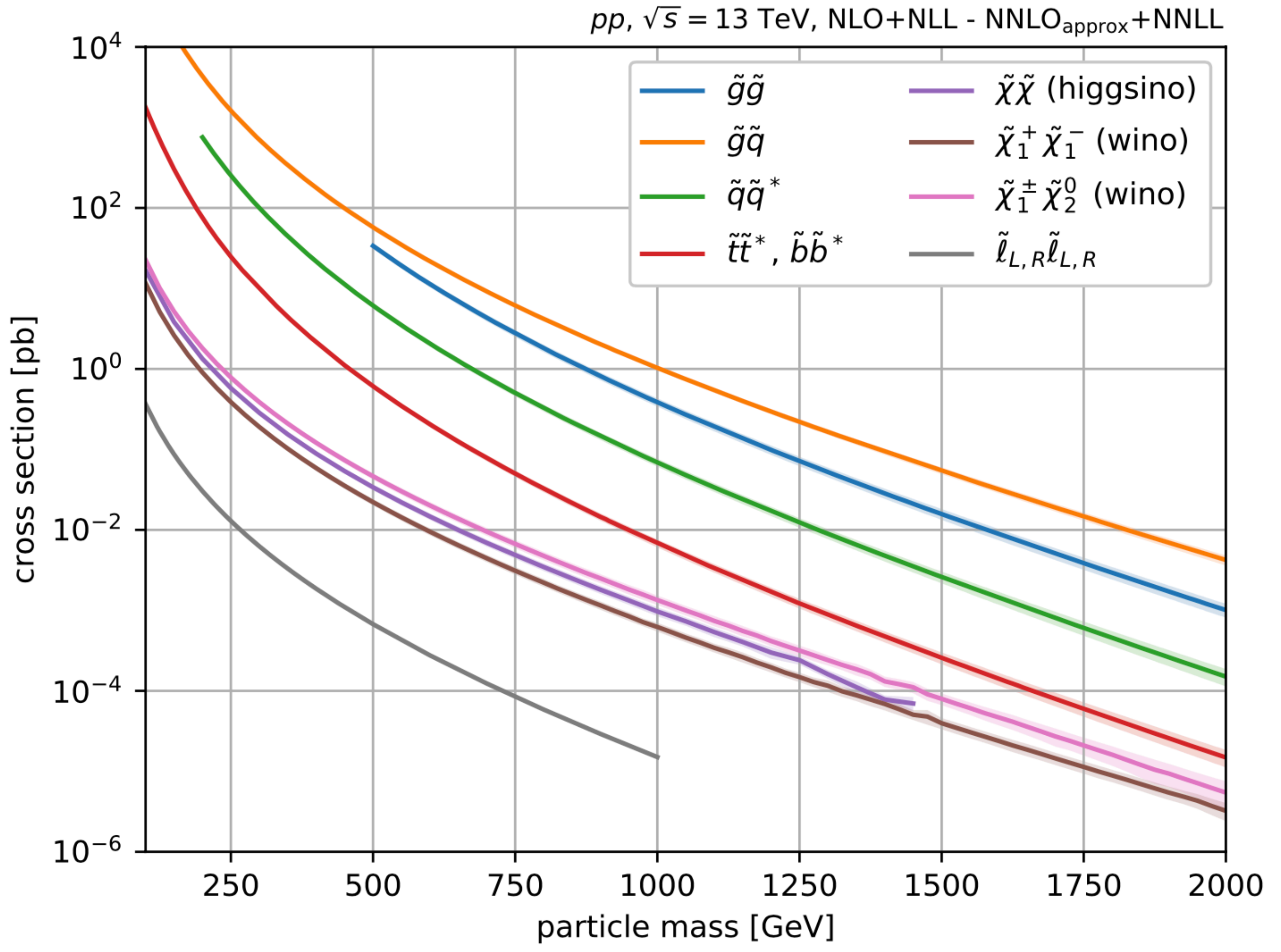
Shaded regions that are compatible with the muon g-2 anomaly



ATL-PHYS-PUB-2023-025

Search for SUSY with two same-sign and three leptons

- SUSY production at LHC under $\sqrt{s} = 13$ TeV proton-proton collisions
  - Strong processes have relatively larger cross-section than others
  - EW processes are motivated by naturalness arguments and expected to dominate if squarks and gluinos are heavy
- In this talk: two analyses searching for SUSY with ATLAS detector
  - Dataset: 139 fb^{-1} (full Run 2 data)
  - Channel: two same-sign (SS) leptons or at least three leptons (3L)
  - SS signature is rarely predicted by SM but exists widely in many BSM extensions like SUSY
  - EW SS/3L: arXiv:2305.09322
  - Strong SS/3L: arXiv:2307.01094



Signal models

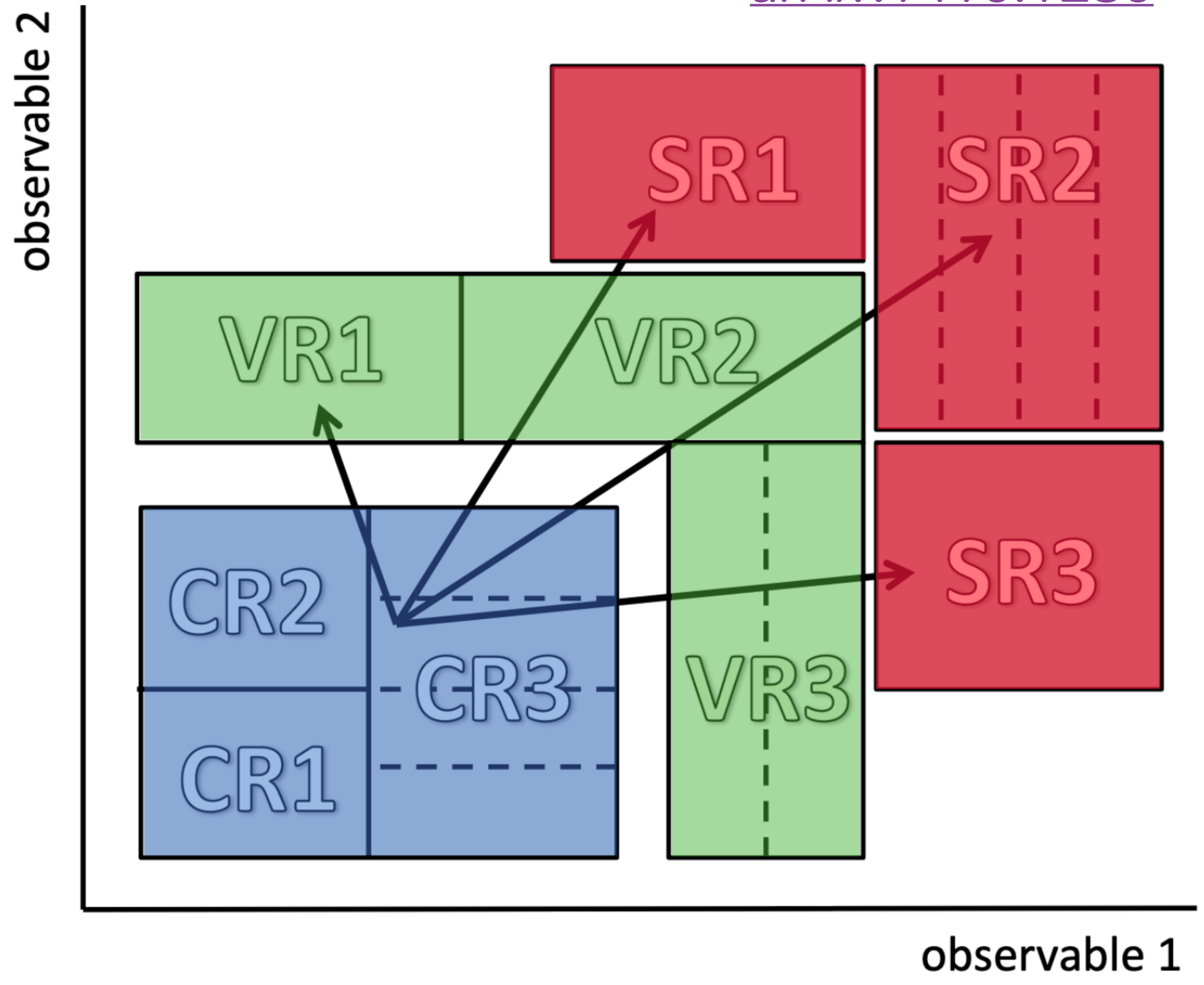
- Consider both EW and strong production of SUSY simplified models yielding SS/3L + jets + E_T^{miss}
- Covering both R-parity conserving (RPC) and violating (RPV) scenarios
  - RPC: decay via weak bosons or sleptons($\tilde{l}$) in the intermediate states, with the lightest neutralino $\tilde{\chi}_1^0$ (LSP) remaining in final state
  - RPV: decay via LNV or BNV terms

Large E_T^{miss}

General analysis strategy

- Maximize BSM signal significance
  - Signal Region (SR): enrich in SUSY signal events, minimal background contamination
- SM background modelling
  - Control Region (CR): free from signal contamination, designed to normalise major backgrounds to data
  - Validation Region (VR): in the middle between SR and CR, used to check background predictions before extrapolation from CR to SR

arXiv:1410.1280



- Statistical interpretation
  - If no significance excess in SR(s) is observed on data, statistical interpretation will be performed by a combined fit over CR(s)+SR(s) to set exclusion limits at 95% Confidence Level (CL) in context of targeted SUSY signal model.

Signal regions

- Optimised event selections for each simplified model to maximise the sensitivity

Number of signal leptons
- SS $2l$
- $3l$
- $\geq 3l$

→

Veto on b-jets
- 0 b
- 1b, 2b, $\geq$ 2b, $\geq$ 3b

↓ benefit search of UDD RPV models

→

Kinematic selections
- p_T requirement on final state leptons
- Jet multiplicity and p_T threshold
- Invisible objects constraints E_T^{miss}, m_{T2}, $\mathcal{S}(E_T^{miss})$

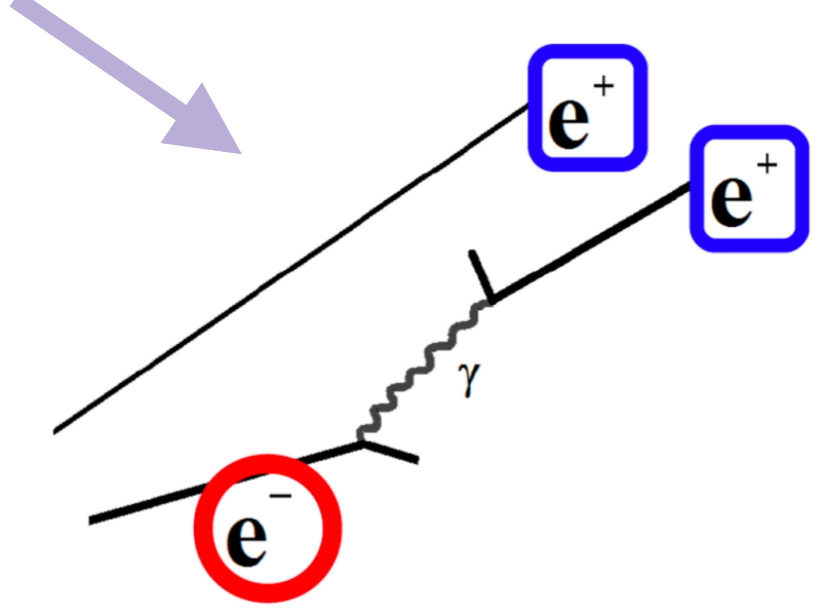
→

Geometric selections
- Angular difference between 2 leptons or lepton and jet
- Azimuthal difference between 2 leptons and missing p_T

- Multi-bin SRs defined on top of the distribution of discriminant variables
- Feasible statistical combination of orthogonal SRs

Background estimation

- Reducible background
  - Electrons with incorrect charge (Charge-Flip) and fake/non-prompt leptons
  - Measured by data-driven techniques



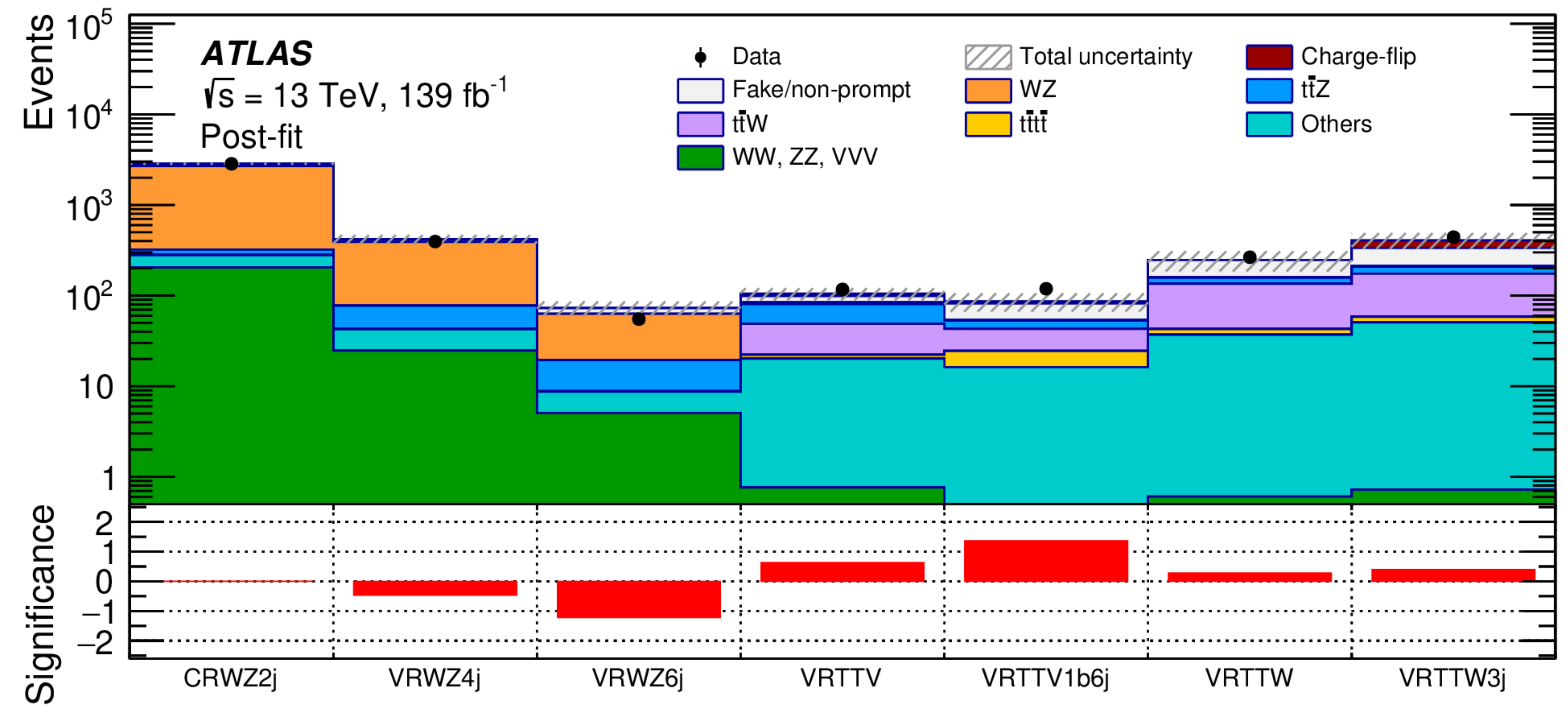
From heavy or light hadron decays, photon conversion or misidentified jets

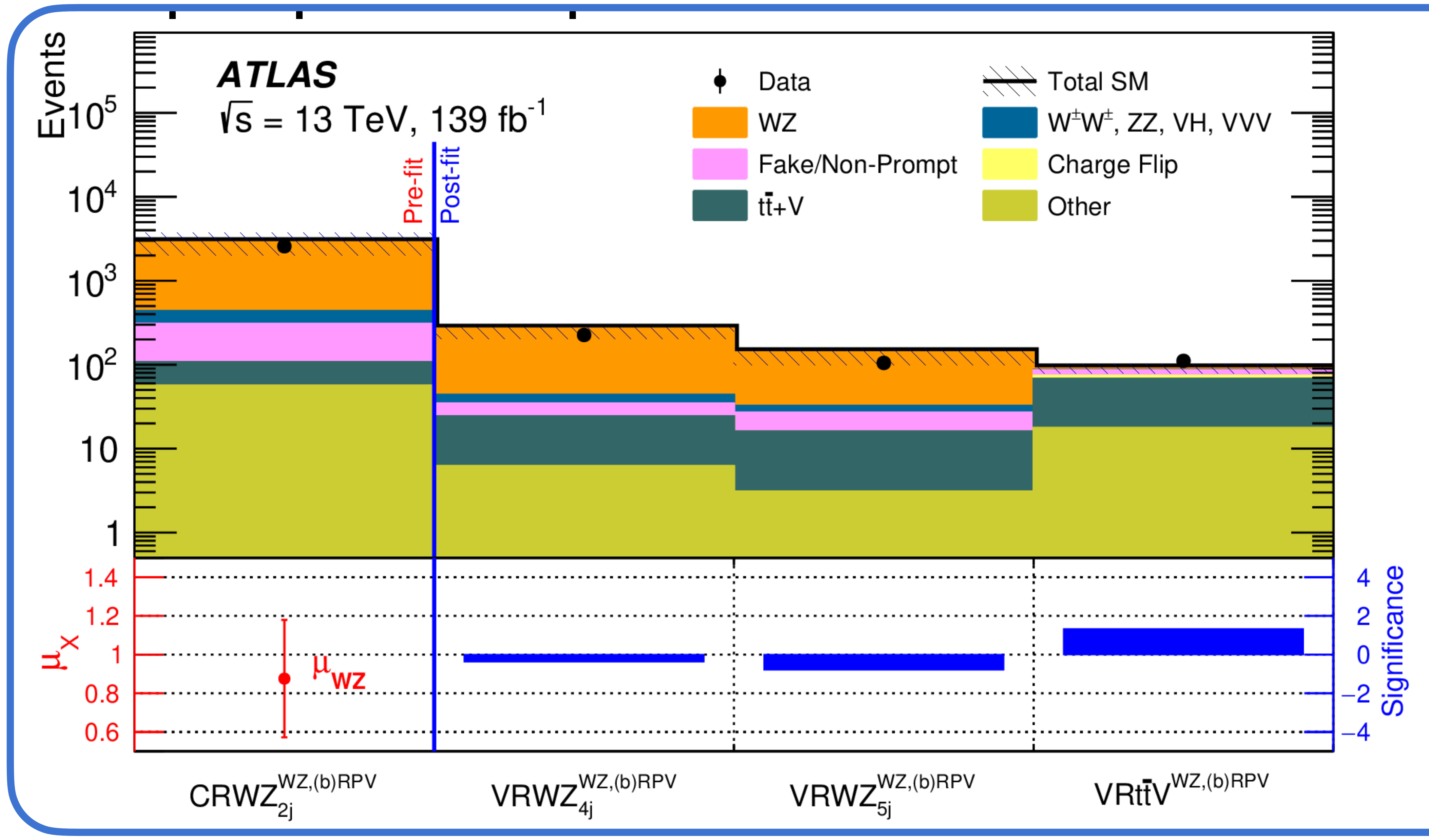
- Irreducible background
  - SM prompt processes that yield SS/3L in final states
    - Diboson, triboson processes, $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}H$, $t\bar{t}t$, $t\bar{t}t\bar{t}$ and other rare processes
  - Most of them are estimated by MC simulation
    - A dedicated CR defined for WZ+jets where this process is normalised to data
    - A dedicated CR defined for $W^{\pm}W^{\pm}$ for Wino Wh model, since this process is dominant in Wh SRs

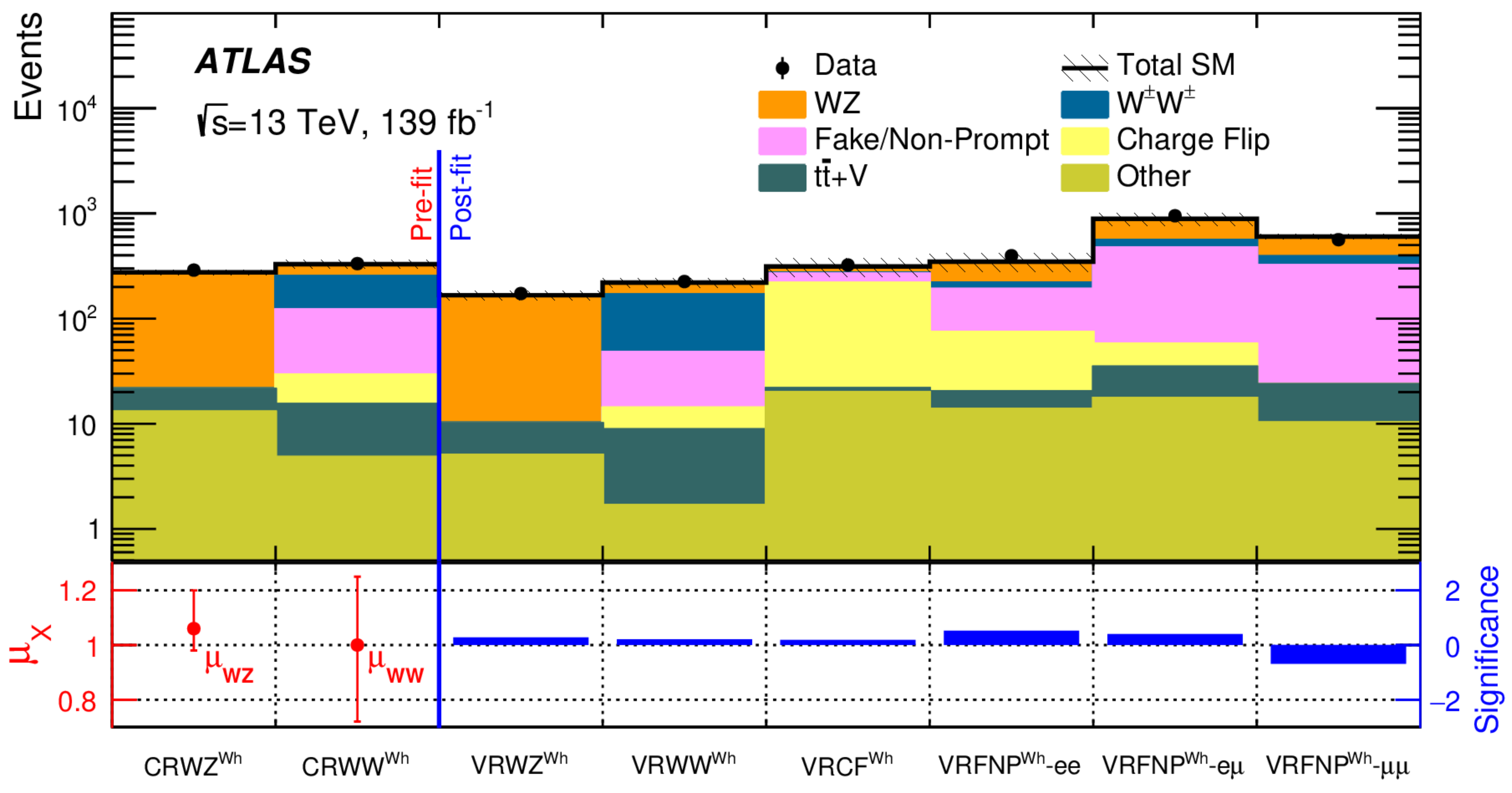
Validation on background estimation

Strong

- Excellent agreement between SM prediction and data in CRs and VRs
  - In EW SS/3L, different WZ CRs defined for Wh and non-Wh models based on different event topologies
  - In strong SS/3L, a universal WZ CR proposed to constraint WZ+jets



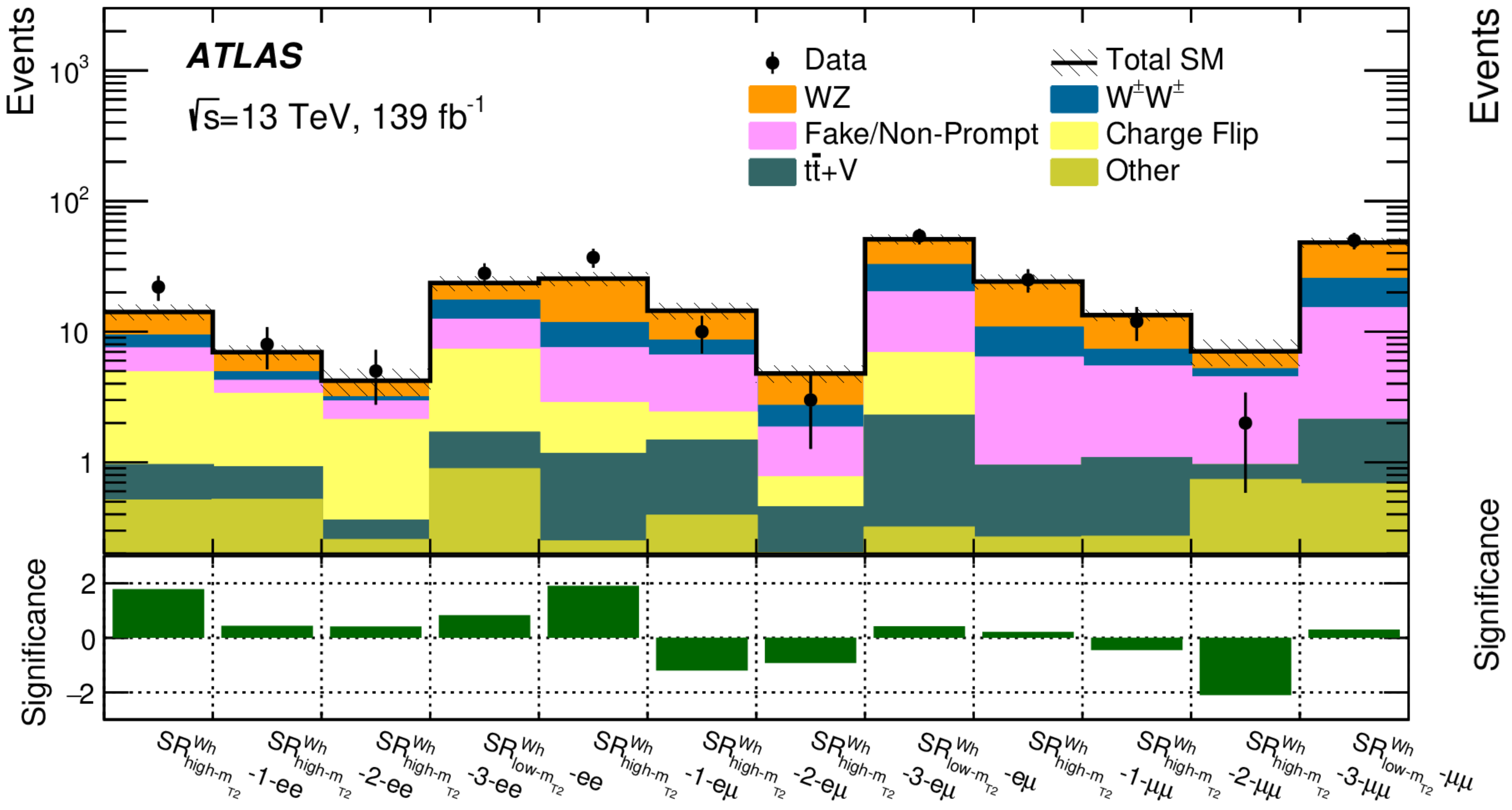


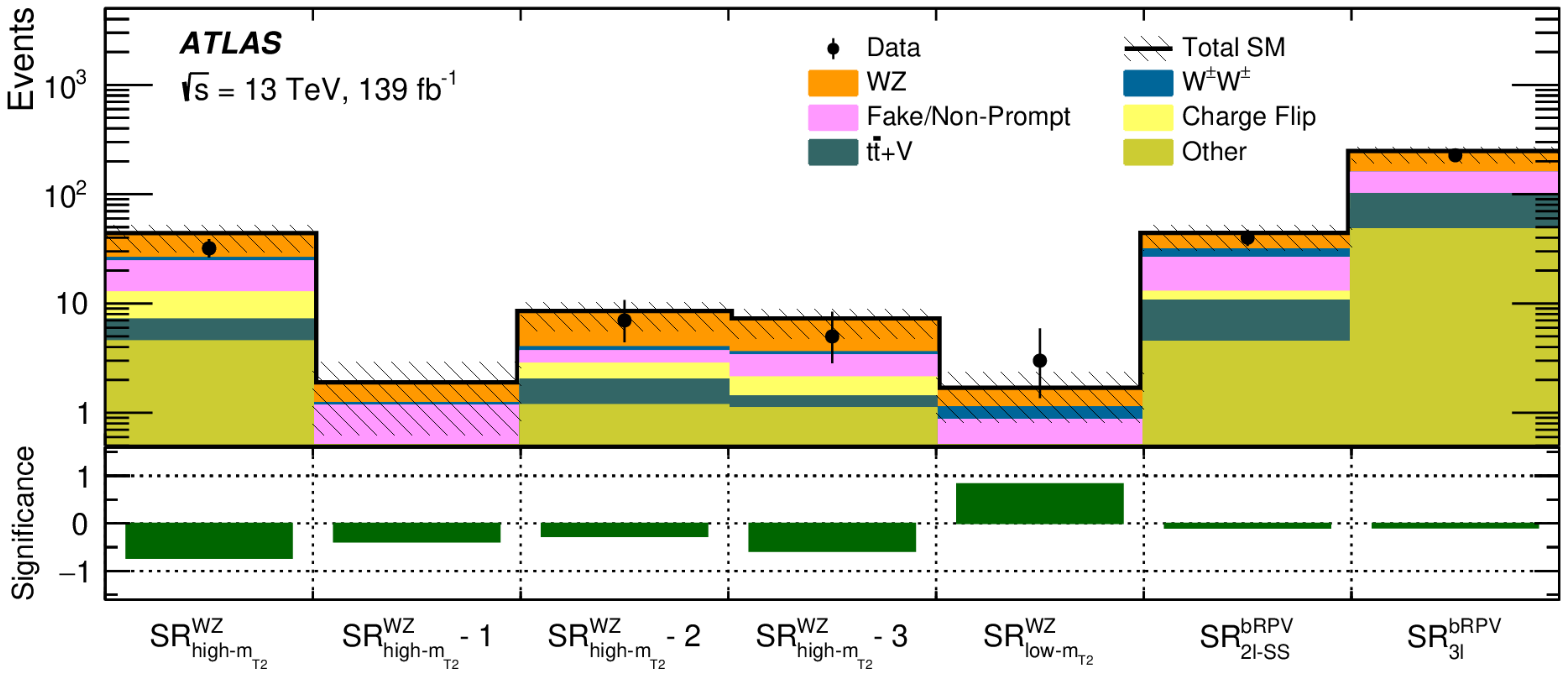


EW

Results in signal regions: EW SS/3L

- No significant excess over the SM predictions
  - The largest excess less than 2σ in Wh SRs is compatible with statistical fluctuation
  - The 2.1σ deficit in one Wh SR is due to large statistical fluctuation
  - Observed data are compatible with SM predictions in non-Wh SRs

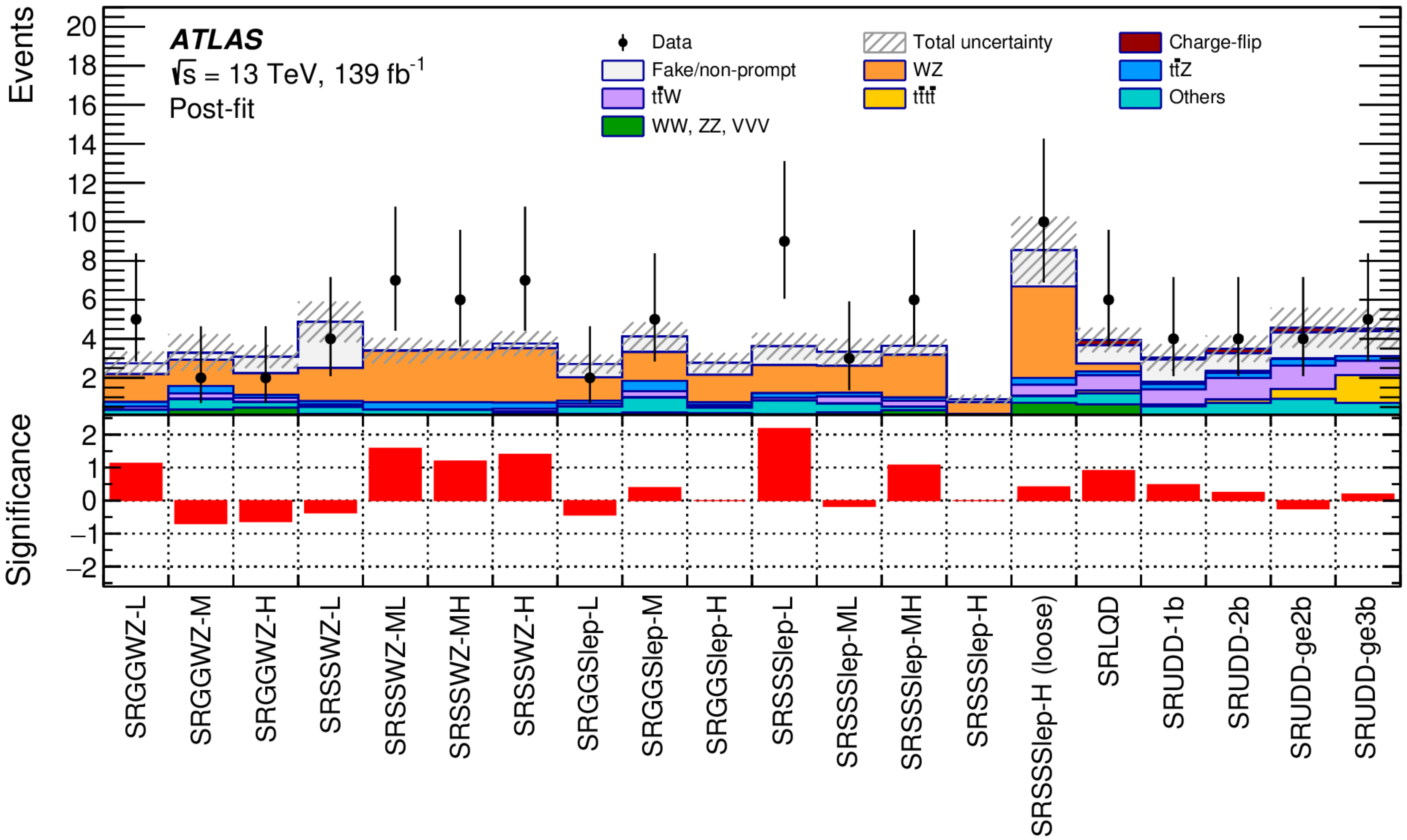




Results in signal regions: strong SS/3L

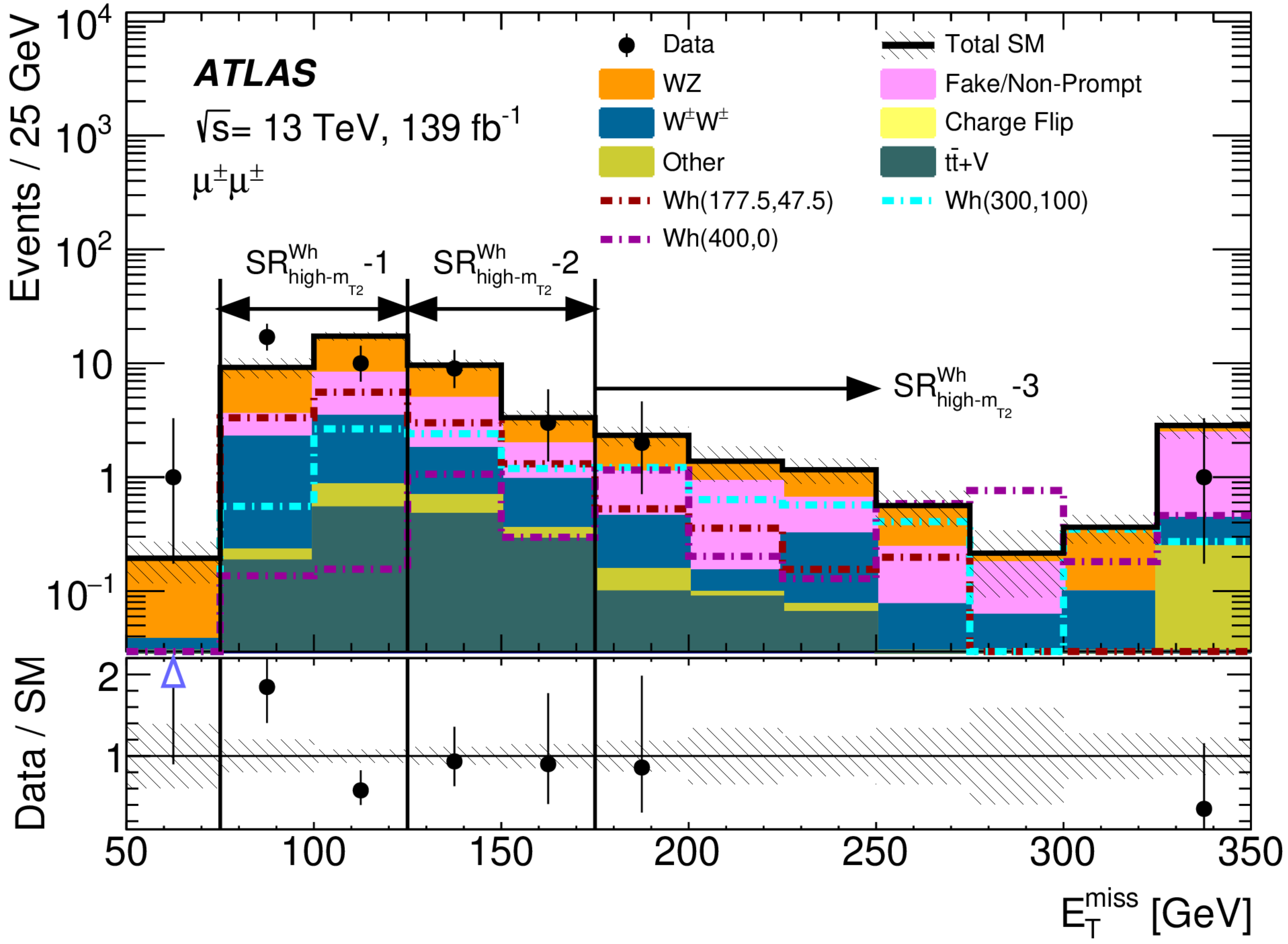
- No significant excess over the SM expectation
  - An overall excess with less than 2σ in SRSSWZ-ML, SRSSWZ- MH, and SRSSWZ-H, due to the overlap among these regions with 3 data events in common.

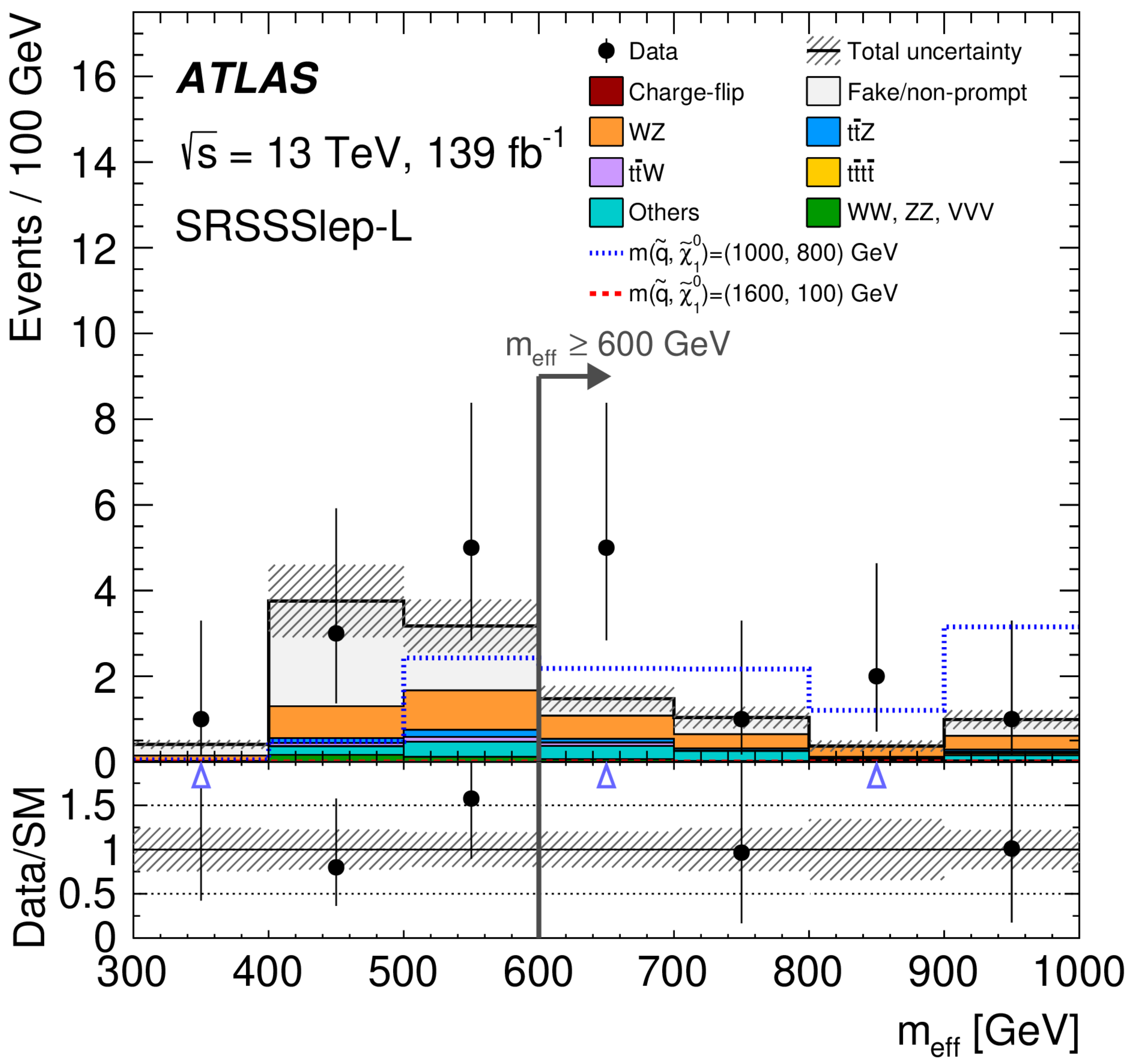
- 2.3σ deviation found in SRSSSlep-L due to large statistical fluctuation
- Observed data and background expectation are in agreement in remaining SRs



Distributions in signal regions with mild deviation

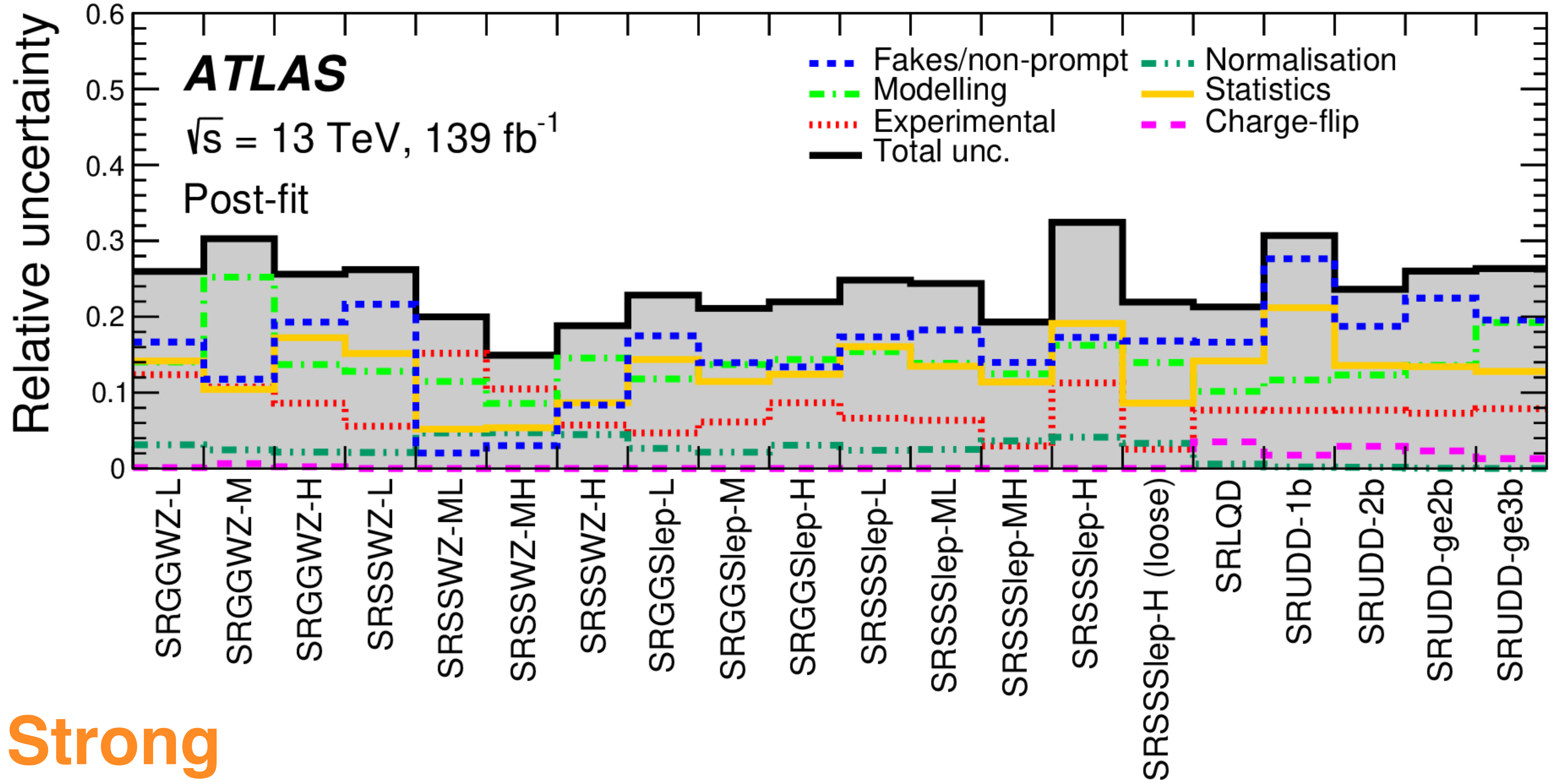
- 2.1σ deficit in Wh SR and 2.3σ excess in SSSlep SR
- Dominate by statistical fluctuations in most of bins





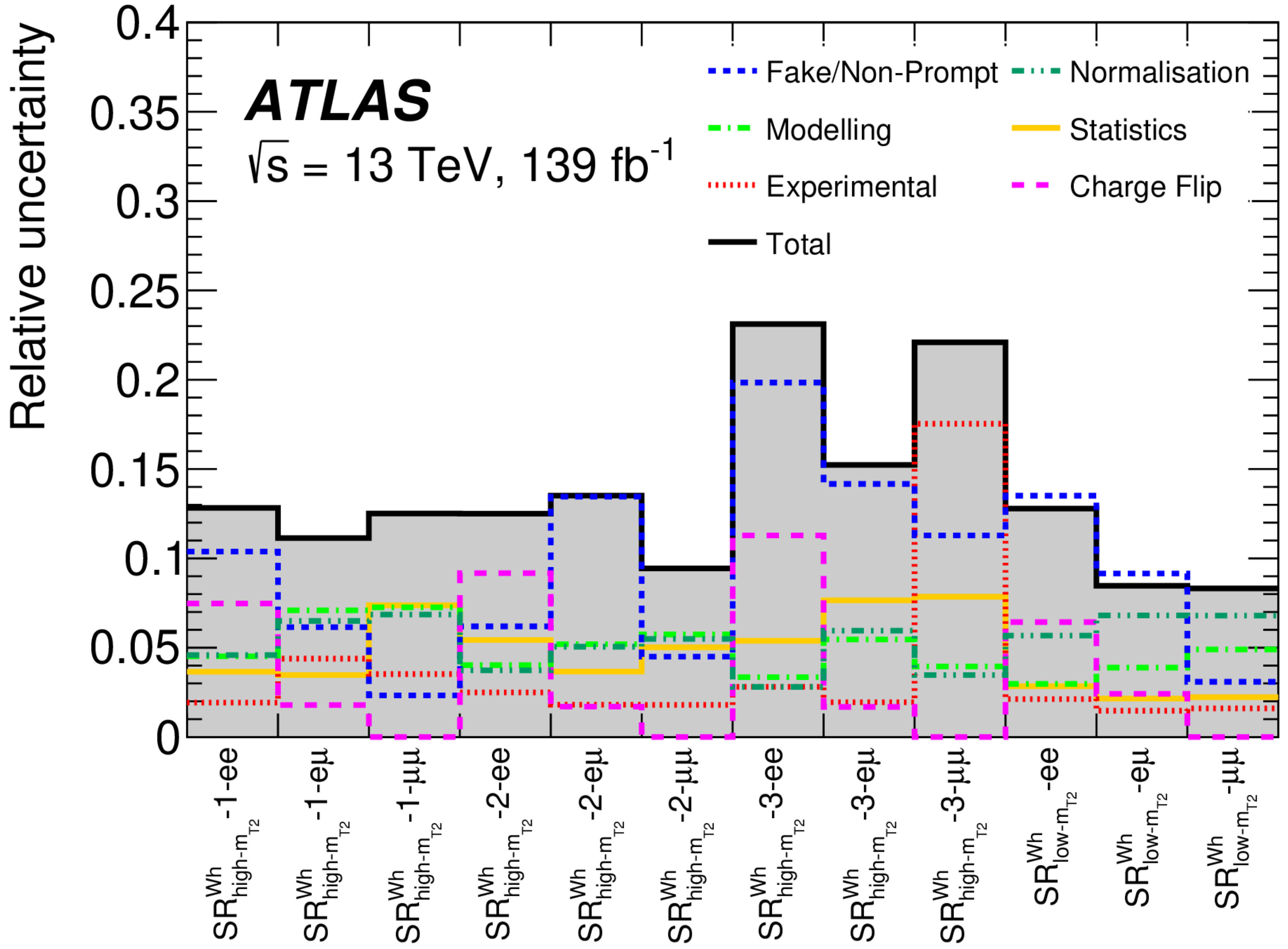
Uncertainties in signal regions

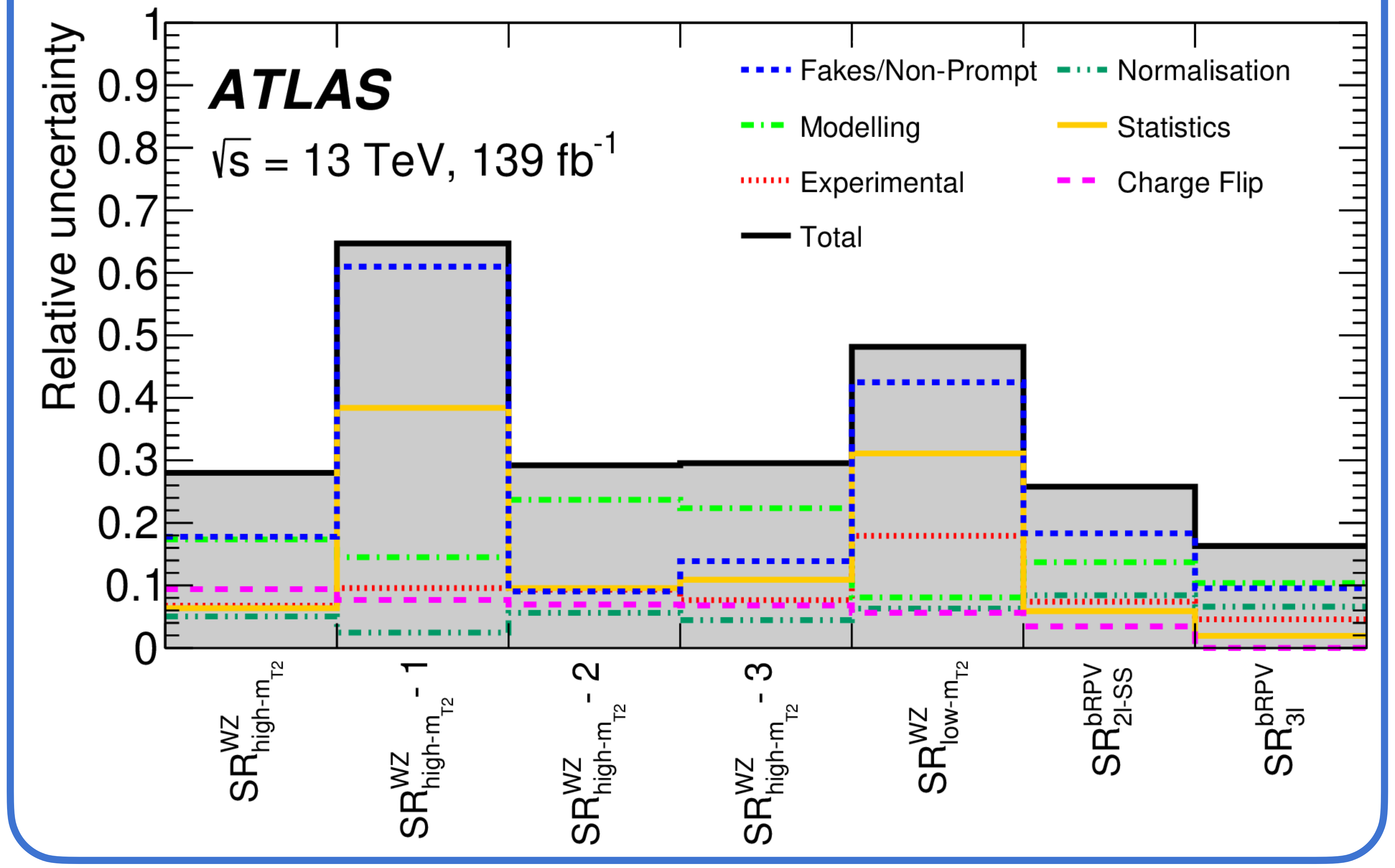
- Major source of systematic uncertainty is measurement on fake/non-prompt leptons
- Theoretical modelling uncertainty has a significant contribution
- Statistical uncertainty is also an important factor



Strong

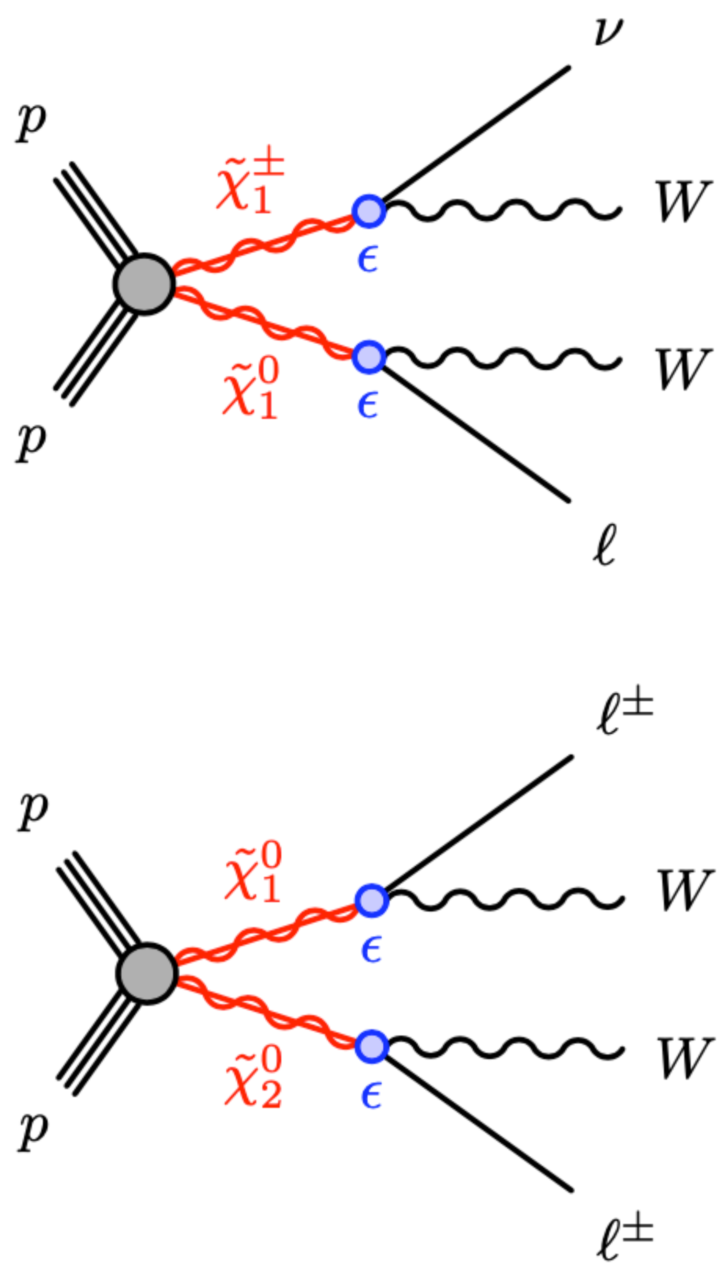
EW

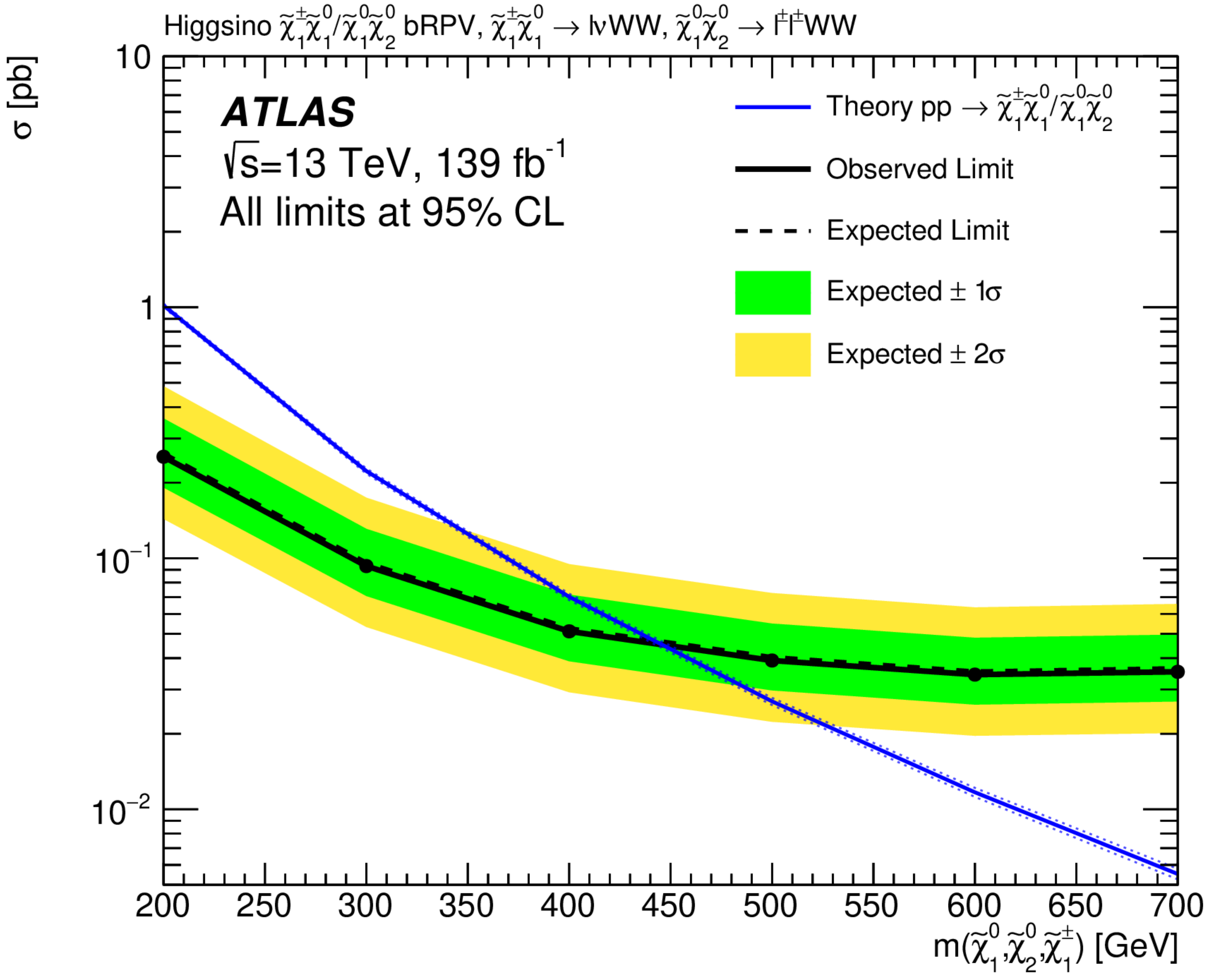


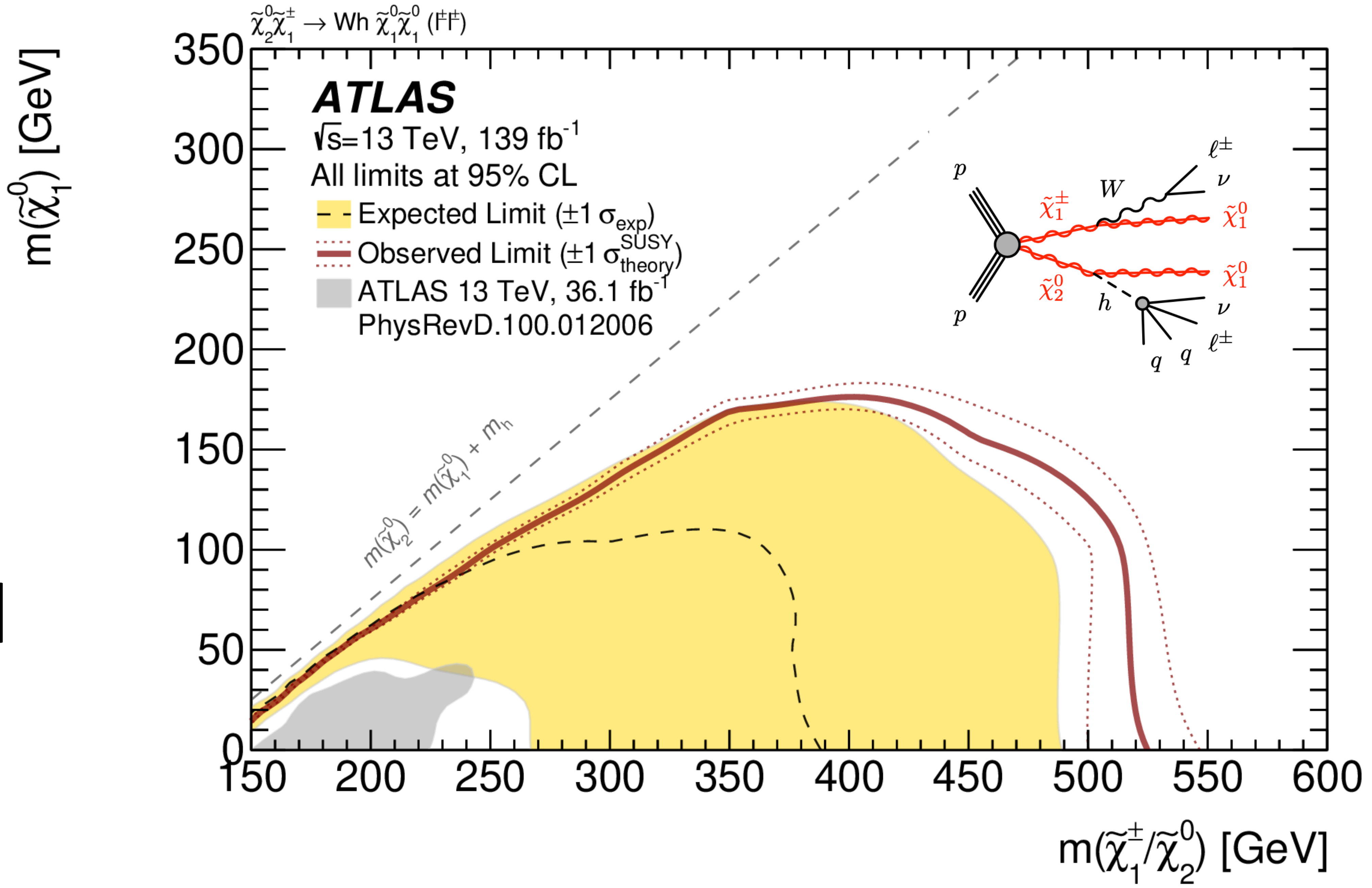


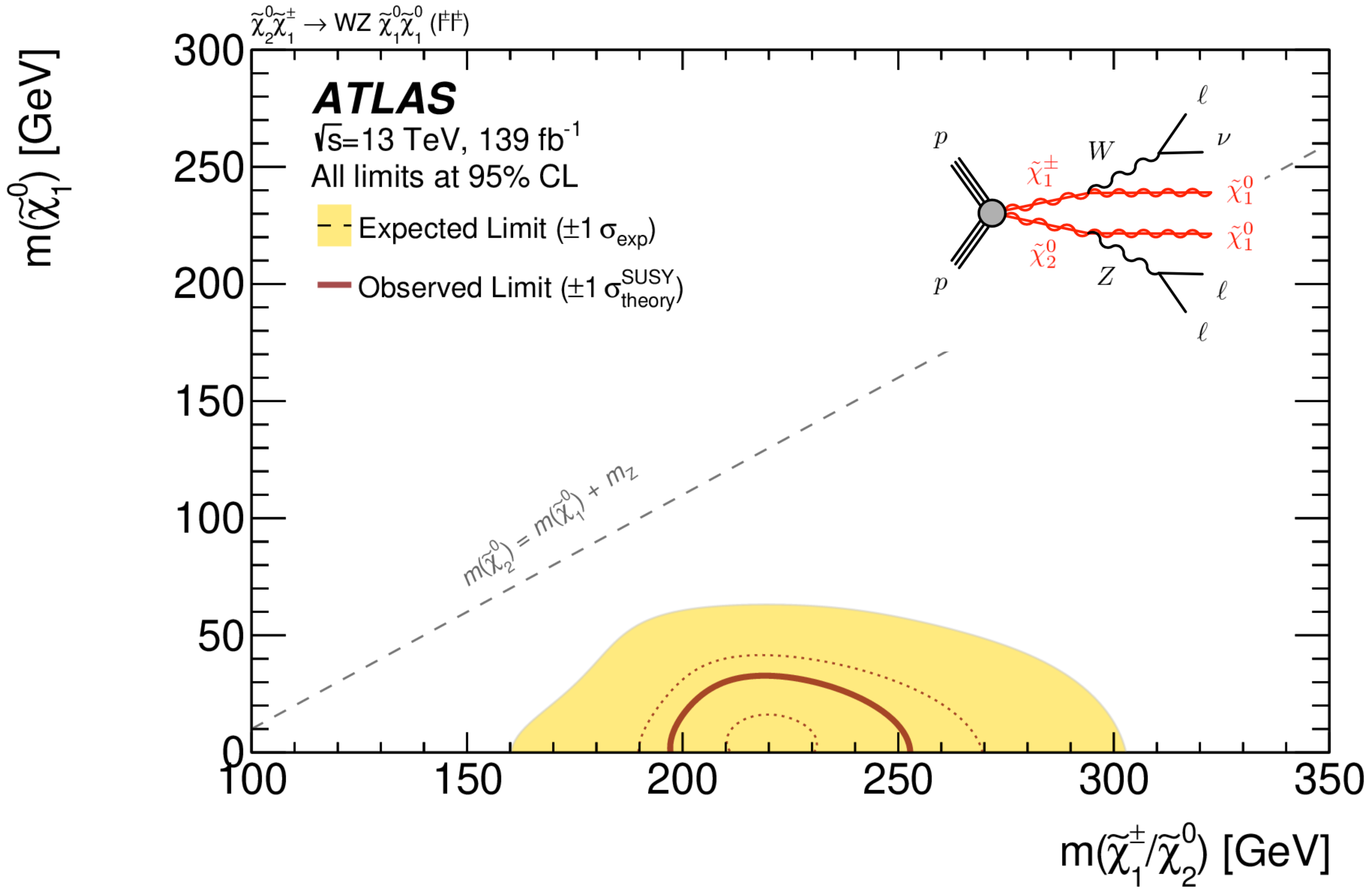
Interpretation: EW SS/3L

- Next-to-LSP masses of up to 525 GeV have been excluded for a massless LSP in wino Wh model
- In the natural bRPV model, mass-degenerate Higgsinos lighter than 440 GeV have been excluded









Interpretation: strong SS/3L

- Gluinos (squarks) masses excluded up to 2.3 (1.7) TeV with a massless LSP

Model independent upper limits

- 95% CL upper limits on the visible cross section σ_{vis} and on the number of signal events observed S^{95}_{obs} in defined SRs

EW

Signal region	$\langle\epsilon\sigma\rangle^{95}_{\text{obs}}$ [fb]	S^{95}_{obs}	S^{95}_{exp}	CL_b	p_0 (Z)
$\text{SR}^{Wh}_{\text{high-}m_{T2}}$	0.28	39.3	$33.9^{+14.3}_{-10.0}$	0.66	0.34 (0.41)
$\text{SR}^{Wh}_{\text{high-}m_{T2}}\text{-1-}ee$	0.13	17.4	$9.9^{+4.4}_{-2.8}$	0.94	0.04 (1.72)
$\text{SR}^{Wh}_{\text{high-}m_{T2}}\text{-1-}e\mu$	0.17	23.6	$12.9^{+5.6}_{-3.6}$	0.96	0.03 (1.85)
$\text{SR}^{Wh}_{\text{high-}m_{T2}}\text{-1-}\mu\mu$	0.09	13.0	$12.6^{+5.4}_{-3.6}$	0.55	0.45 (0.14)
$\text{SR}^{Wh}_{\text{high-}m_{T2}}\text{-2-}ee$	0.06	7.8	$7.2^{+3.1}_{-2.2}$	0.63	0.36 (0.36)
$\text{SR}^{Wh}_{\text{high-}m_{T2}}\text{-2-}e\mu$	0.05	6.8	$9.5^{+4.0}_{-2.7}$	0.16	0.50 (0.00)
$\text{SR}^{Wh}_{\text{high-}m_{T2}}\text{-2-}\mu\mu$	0.07	9.6	$7.7^{+0.6}_{-0.2}$	0.64	0.50 (0.00)
$\text{SR}^{Wh}_{\text{high-}m_{T2}}\text{-3-}ee$	0.05	6.9	$6.1^{+3.0}_{-1.6}$	0.61	0.37 (0.33)
$\text{SR}^{Wh}_{\text{high-}m_{T2}}\text{-3-}e\mu$	0.03	4.8	$6.1^{+3.0}_{-1.6}$	0.24	0.50 (0.00)
$\text{SR}^{Wh}_{\text{high-}m_{T2}}\text{-3-}\mu\mu$	0.03	4.3	$6.9^{+3.0}_{-2.0}$	0.06	0.50 (0.00)
$\text{SR}^{Wh}_{\text{low-}m_{T2}}$	0.24	33.0	$29.5^{+11.7}_{-8.8}$	0.63	0.33 (0.43)
$\text{SR}^{Wh}_{\text{low-}m_{T2}}\text{-}ee$	0.12	16.2	$12.6^{+5.4}_{-3.6}$	0.76	0.23 (0.76)
$\text{SR}^{Wh}_{\text{low-}m_{T2}}\text{-}e\mu$	0.14	19.9	$17.6^{+7.4}_{-5.1}$	0.63	0.36 (0.35)
$\text{SR}^{Wh}_{\text{low-}m_{T2}}\text{-}\mu\mu$	0.13	18.2	$17.0^{+7.0}_{-4.9}$	0.59	0.41 (0.22)
$\text{SR}^{WZ}_{\text{high-}m_{T2}}$	0.13	18.7	$24.4^{+6.8}_{-5.0}$	0.12	0.50 (0.00)
$\text{SR}^{WZ}_{\text{high-}m_{T2}}\text{-1}$	0.01	1.7	$3.6^{+1.3}_{-0.6}$	0.02	0.45 (0.12)
$\text{SR}^{WZ}_{\text{high-}m_{T2}}\text{-2}$	0.05	7.4	$8.3^{+3.2}_{-2.2}$	0.34	0.50 (0.00)
$\text{SR}^{WZ}_{\text{high-}m_{T2}}\text{-3}$	0.04	5.2	$7.3^{+2.7}_{-1.8}$	0.11	0.50 (0.00)
$\text{SR}^{WZ}_{\text{low-}m_{T2}}$	0.04	5.9	$4.4^{+1.8}_{-0.8}$	0.81	0.22 (0.76)
$\text{SR}^{\text{bRPV}}_{2\ell\text{-SS}}$	0.16	22.6	$25.8^{+7.9}_{-5.8}$	0.29	0.50 (0.00)
$\text{SR}^{\text{bRPV}}_{3\ell}$	0.44	61.4	$93.0^{+56.0}_{-20.3}$	0.02	0.50 (0.00)

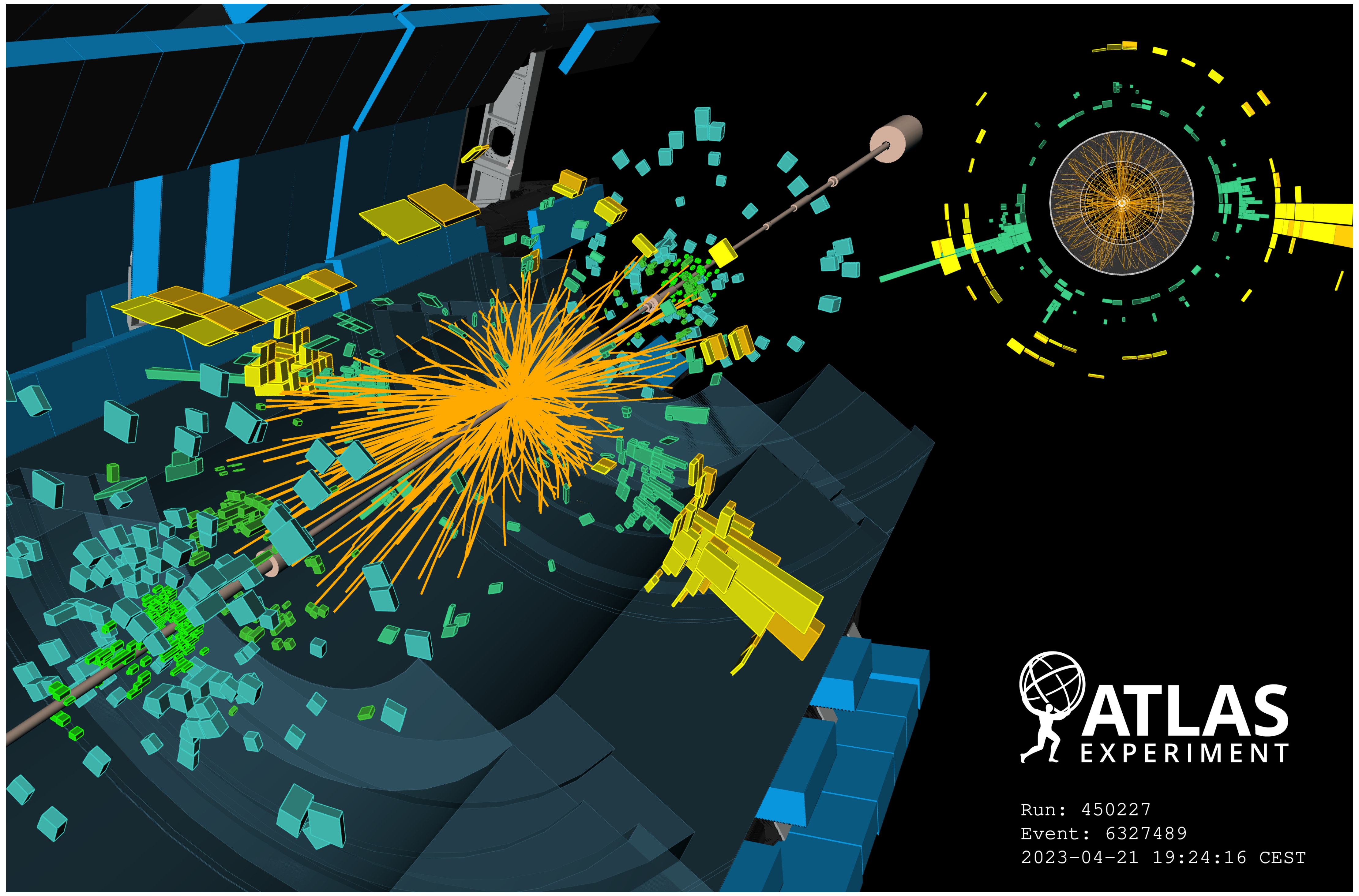
Strong

SR	σ_{vis} [fb]	S^{95}_{obs}	S^{95}_{exp}	CL_b	$p(s=0)$ (Z)
SRGGWZ-L	0.06	8.1	$5.2^{+2.2}_{-1.1}$	0.91	0.05 (1.64)
SRGGWZ-M	0.03	4.5	$5.2^{+2.1}_{-1.3}$	0.32	0.50 (0.00)
SRGGWZ-H	0.03	3.9	$5.0^{+2.0}_{-1.4}$	0.23	0.50 (0.00)
SRSSWZ-L	0.04	5.7	$6.1^{+2.3}_{-1.6}$	0.41	0.50 (0.00)
SRSSWZ-ML	0.07	10.4	$6.5^{+2.3}_{-1.5}$	0.94	0.02 (2.04)
SRSSWZ-MH	0.06	8.6	$5.3^{+2.0}_{-1.4}$	0.93	0.04 (1.74)
SRSSWZ-H	0.06	8.6	$5.4^{+2.5}_{-1.1}$	0.91	0.09 (1.32)
SRGGSlep-L	0.03	4.0	$4.7^{+2.0}_{-1.2}$	0.33	0.50 (0.00)
SRGGSlep-M	0.04	6.2	$5.8^{+2.2}_{-1.7}$	0.60	0.43 (0.17)
SRGGSlep-H	0.02	3.0	$4.7^{+2.0}_{-1.1}$	0.00	0.35 (0.39)
SRSSSlep-L	0.08	11.7	$5.6^{+2.4}_{-1.3}$	0.99	0.01 (2.33)
SRSSSlep-ML	0.03	4.8	$5.1^{+2.2}_{-1.3}$	0.43	0.50 (0.00)
SRSSSlep-MH	0.06	7.9	$5.4^{+2.3}_{-1.4}$	0.85	0.15 (1.06)
SRSSSlep-H	0.02	3.0	$3.5^{+1.3}_{-0.5}$	0.04	0.36 (0.35)
SRSSSlep-H (loose)	0.07	9.9	$8.1^{+3.3}_{-2.0}$	0.70	0.32 (0.46)
SRLQD	0.05	7.3	$5.3^{+2.3}_{-1.2}$	0.82	0.21 (0.81)
SRUDD-1b	0.05	6.6	$5.1^{+2.3}_{-1.1}$	0.77	0.21 (0.80)
SRUDD-2b	0.05	6.4	$5.2^{+2.4}_{-1.1}$	0.69	0.26 (0.66)
SRUDD-ge2b	0.04	5.8	$6.1^{+2.4}_{-1.4}$	0.44	0.50 (0.00)
SRUDD-ge3b	0.05	6.8	$6.1^{+2.4}_{-1.7}$	0.62	0.40 (0.24)

Summary

- Search for TeV-scale direction production of $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ and $\tilde{g}/\tilde{q}$ with two same-sign leptons or at least three leptons signature using full Run 2 data collected by ATLAS
  - EW SS/3L: arXiv:2305.09322
  - Strong SS/3L: arXiv:2307.01094
- No significant excess observed over the SM prediction
- Significant improvement on the constraints of $m(\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0)$ and $m(\tilde{g}/\tilde{q})$ in context of different R-parity conserving and R-parity violating SUSY scenarios
- Look forward to Run 3 results! Stay tuned!

Thank you!



Backup

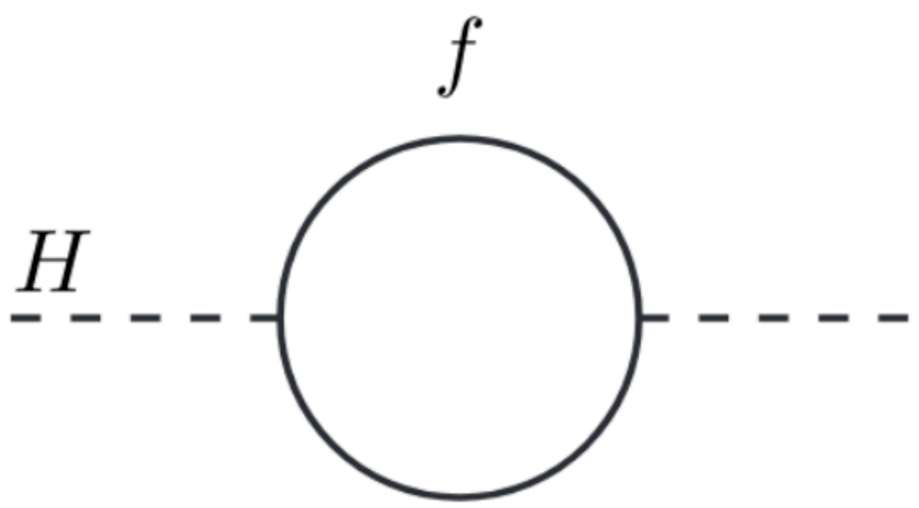
The hierarchy problem

- The Higgs squared masses calculation in SM includes the coupling terms of other massive SM particles as loop corrections
- If assume the validity of SM at Planck scale, the Higgs boson, observed with a mass of 125 GeV, has to receive an unnatural fine-tuning on the bare mass term, in order to keep its mass at 125 GeV.
- The huge hierarchy between Higgs mass scale (10^2 GeV) and Planck scale (10^{19} GeV), is known as the hierarchy problem.
- SUSY can provide a natural solution to the hierarchy problem by introducing extra scalar fields which give opposite-sign contributions to the loop correction.

$$m_{\mathrm{H}}^2 = m_{\mathrm{H(bare)}}^2 + \Delta m_{\mathrm{H}}^2$$

Loop correction from a SM fermion

$$\Delta m_{\mathrm{H}}^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda^2 + \ldots$$



(a)

Loop correction from a scalar field

$$\Delta m_H^2 = +\frac{|\lambda_S|}{16\pi^2}\Lambda^2 + \ldots$$

(b)

If $|\lambda_S| = |\lambda_f|^2$
natural cancellation on the quadratic terms!

MSSM

- The minimal realization of supersymmetry with the same gauge group SU(3)$_C$× SU(2)$_L$× U(1)$_Y$ as in SM

	Names	Spin	Interaction eigenstates	Mass eigenstates	Names	Spin	Interaction eigenstates	Mass eigenstates
Quark Sector: $Q, \bar{u}, \bar{d}$	Quarks (× 3 generations)	$\frac{1}{2}$	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, u_R, d_R$		Squarks (× 3 generations)	0	$\begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix}, \tilde{u}_R, \tilde{d}_R$	
Lepton Sector: $L, \bar{e}$	Leptons (× 3 generations)	$\frac{1}{2}$	$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, e_R$		Sleptons (× 3 generations)	0	$\begin{pmatrix} \tilde{\nu}_L \\ \tilde{e}_L \end{pmatrix}, \tilde{e}_R$	
Higgs Sector: H_u, H_d	Higgs bosons	0	$\begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$	$h^0, H^0, A^0, H^\pm$	Higgsinos	$\frac{1}{2}$	$\begin{pmatrix} \tilde{H}_u^+ \\ \tilde{H}_u^0 \end{pmatrix}, \begin{pmatrix} \tilde{H}_d^0 \\ \tilde{H}_d^- \end{pmatrix}$	Neutralinos: $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$
Gauge Sector	Gauge bosons	1	$W^\pm, W^0, B$	$W^\pm, Z^0, \gamma$	Gauginos	$\frac{1}{2}$	$\tilde{W}^\pm, \tilde{W}^0, \tilde{B}$	Charginos: $\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$
			Gluon g				Gluinos $\tilde{g}$	

- The superpotential of MSSM (analogue to SM Lagrangian)

$$W_{MSSM} = \bar{u} y_u Q H_u - \bar{d} y_d Q H_d - \bar{e} y_e L H_d + \mu H_u H_d$$

$$R = (-1)^{3(B-L)+2S}$$

$$W_{\Delta L=1} = \frac{1}{2} \lambda^{ijk} L_i L_j \bar{e}_k + \lambda'^{ijk} L_i Q_j \bar{d}_k + \mu'^i L_i H_u$$

$$W_{\Delta B=1} = \frac{1}{2} \lambda''^{ijk} \bar{u}_i \bar{d}_j \bar{d}_k$$

Some references:

[1] I. J. R. Aitchison. “Supersymmetry and the MSSM: An Elementary introduction”.arXiv: hep-ph/0505105

[2] S. P. Matrin. “A Supersymmetry Primer” arXiv:hep-ph/9709356

Special variables used in SUSY search

- Significance of $E_{\mathrm{T}}^{\mathrm{miss}}$
  - To quantify the robustness of the $E_{\mathrm{T}}^{\mathrm{miss}}$ values against object mis-measurement in events lacking a genuine source of $E_{\mathrm{T}}^{\mathrm{miss}}$

$$\mathcal{S}(E_{\mathrm{T}}^{\mathrm{miss}}) = \frac{|E_{\mathrm{T}}^{\mathrm{miss}}|^2}{\sigma_L^2(1-\rho_{LT}^2)}$$

σ_L: total longitudinal resolution relative to the direction of $\vec{p}_{\mathrm{T}}^{\,miss}$.
σ_{LT}^2: correlation factor between total longitudinal and transverse relative resolution.

  - Large $\mathcal{S}(E_{\mathrm{T}}^{\mathrm{miss}})$ value indicates a real source of $E_{\mathrm{T}}^{\mathrm{miss}}$, e.g. the (invisible) LSP in RPC scenarios

- m_{T2} ‘stransverse mass’
  - An event variable used to bound the masses of an unseen pair of particle

$$m_{\mathrm{T2}} = \min_{\mathbf{q}_{\mathrm{T}}}\left[\max\left(m_{\mathrm{T},\ell_1}(\mathbf{p}_{\mathrm{T},\ell_1},\mathbf{q}_{\mathrm{T}}), m_{\mathrm{T},\ell_2}(\mathbf{p}_{\mathrm{T},\ell_2},\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}-\mathbf{q}_{\mathrm{T}})\right)\right],$$

SRs definitions in EW SS/3L

	$\mathrm{SR}^{Wh}_{\text{high-}m_{T2}}$			$\mathrm{SR}^{Wh}_{\text{low-}m_{T2}}$		
	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$
$N_{\mathrm{BL}}(\ell)$	= 2					
$N_{\mathrm{Sig}}(\ell)$	= 2					
$\mathrm{Charge}(\ell)$	same-sign					
$p_{\mathrm{T}}(\ell)$	$\geq$ 25 GeV					
n_{jets} ($p_{\mathrm{T}} > 25$ GeV)	$\geq$ 1					
$n_{b\text{-jets}}$	= 0					
m_{jj}	< 350 GeV					
m_{T2}	$\geq$ 80 GeV			< 80 GeV		
$m_{\mathrm{T}}^{\mathrm{min}}$	–			$\geq$ 100 GeV		
$\mathcal{S}(E_{\mathrm{T}}^{\mathrm{miss}})$	$\geq$ 7			$\geq$ 6		
$E_{\mathrm{T}}^{\mathrm{miss}}$	$\geq$ 75 GeV			$\geq$ 50 GeV		
$E_{\mathrm{T}}^{\mathrm{miss}}$ binning [GeV][a]	$\mathrm{SR}^{Wh}_{\text{high-}m_{T2}}$-1: $\in [75, 125)$ $\mathrm{SR}^{Wh}_{\text{high-}m_{T2}}$-2: $\in [125, 175)$ $\mathrm{SR}^{Wh}_{\text{high-}m_{T2}}$-3: $\in [175, +\infty)$			–		

[a] The $E_{\mathrm{T}}^{\mathrm{miss}}$ binning applies separately to each flavour channel of $\mathrm{SR}^{Wh}_{\text{high-}m_{T2}}$.

	$\mathrm{SR}^{WZ}_{\text{high-}m_{T2}}$	$\mathrm{SR}^{WZ}_{\text{low-}m_{T2}}$
$N_{\mathrm{BL}}(\ell)$	= 2	
$N_{\mathrm{Sig}}(\ell)$	= 2	
$\mathrm{Charge}(\ell)$	same-sign	
$p_{\mathrm{T}}(\ell)$	$\geq$ 25 GeV	
n_{jets} ($p_{\mathrm{T}} > 25$ GeV)	$\geq$ 1	
$n_{b\text{-jets}}$	= 0	
m_{jj}	$\leq$ 350 GeV	
m_{T2}	$\geq$ 100 GeV	$\leq$ 100 GeV
$m_{\mathrm{T}}^{\mathrm{min}}$	$\geq$ 100 GeV	$\geq$ 130 GeV
$E_{\mathrm{T}}^{\mathrm{miss}}$	$\geq$ 100 GeV	$\geq$ 140 GeV
m_{eff}	–	$\leq$ 600 GeV
$\Delta R(\ell^\pm, \ell^\pm)$	–	$\leq$ 3
Bins	$\mathcal{S}(E_{\mathrm{T}}^{\mathrm{miss}})$: $\in [0, 10)$, Spread(Φ) $\geq$ 2.2 $\mathcal{S}(E_{\mathrm{T}}^{\mathrm{miss}})$: $\in [10, 13)$ $\mathcal{S}(E_{\mathrm{T}}^{\mathrm{miss}})$: $\in [13, +\infty]$, $\Delta R(\ell^\pm, \ell^\pm) \geq 1$	–

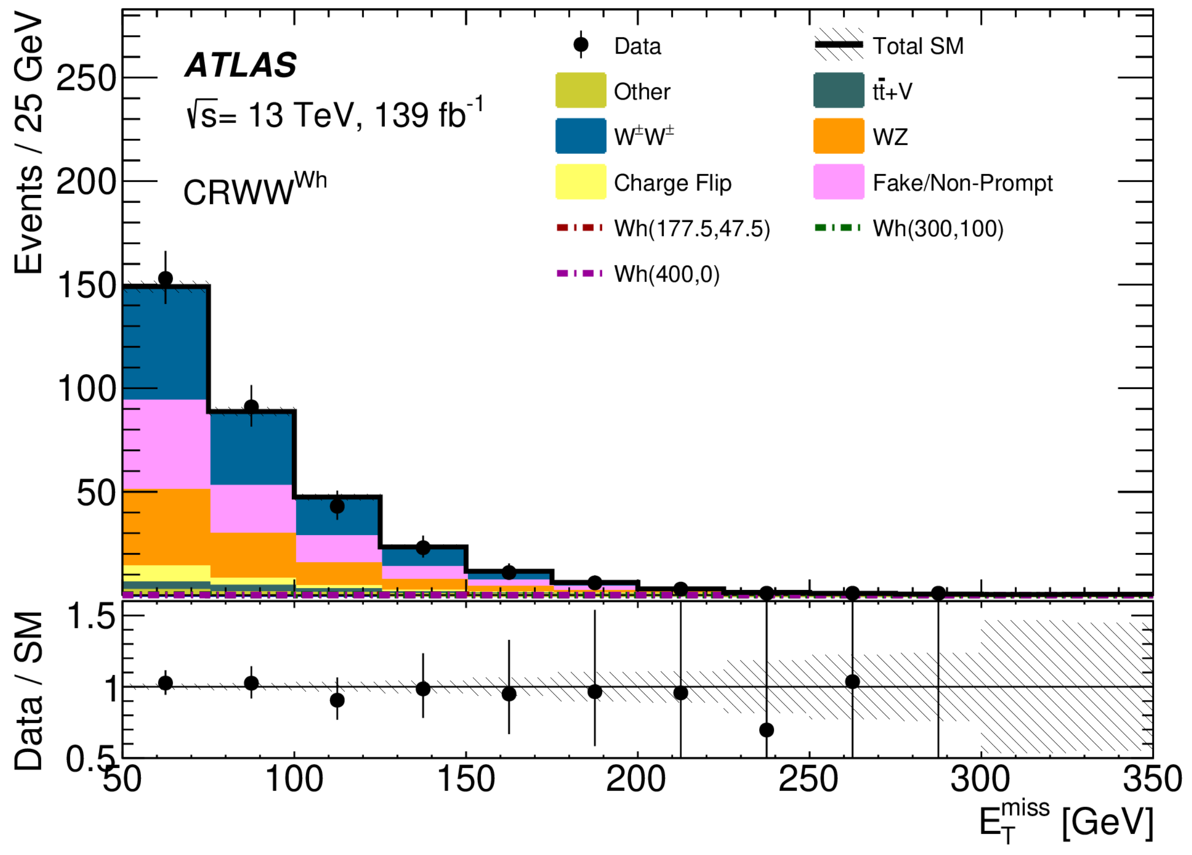
	$\mathrm{SR}^{\mathrm{bRPV}}_{2\ell\text{-SS}}$	$\mathrm{SR}^{\mathrm{bRPV}}_{3\ell}$
$N_{\mathrm{BL}}(\ell)$	–	
$p_{\mathrm{T}}(\ell)$	$\geq$ 20 GeV for (sub)leading leptons	
n_{jets} ($p_{\mathrm{T}} > 25$ GeV)	$\geq$ 1	
$N_{\mathrm{Sig}}(\ell)$	= 2	= 3
$\mathrm{Charge}(\ell)$	same-sign	–
m_{T2}	$\geq$ 60 GeV	$\geq$ 80 GeV
$E_{\mathrm{T}}^{\mathrm{miss}}$	$\geq$ 100 GeV	$\geq$ 120 GeV
m_{eff}	–	$\geq$ 350 GeV
$n_{b\text{-jets}}$	= 0	–
n_{jets} ($p_{\mathrm{T}} > 40$ GeV)	$\geq$ 4	–
$m_{e^\pm e^\mp}$, $m_{\mu^\pm \mu^\mp}$	–	$\notin$ [81, 101] GeV

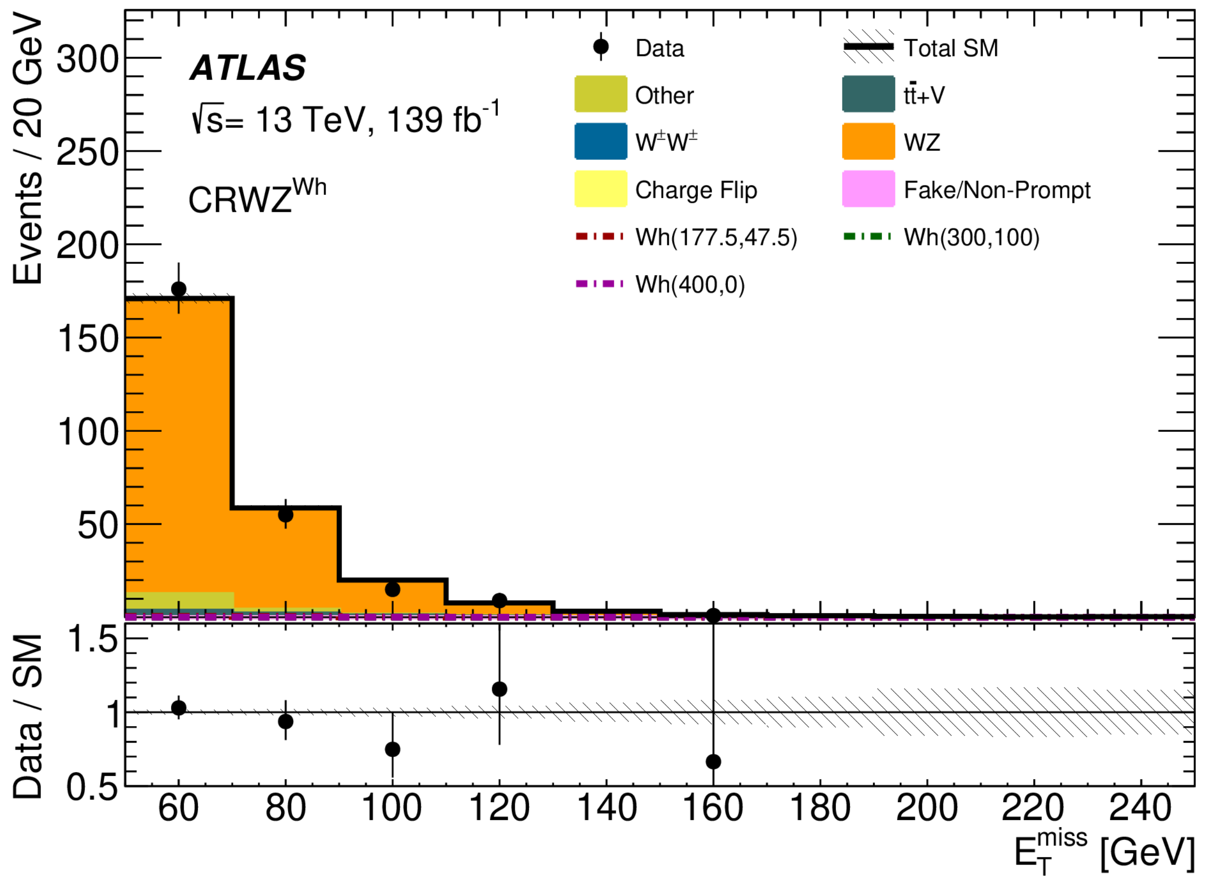
CRs/VRs definitions in EW SS/3L

	$\mathrm{CR}WZ^{Wh}$	$\mathrm{VR}WZ^{Wh}$	$\mathrm{CR}WW^{Wh}$	$\mathrm{VR}WW^{Wh}$
$N_{\mathrm{BL}}(\ell)$	$= 3$		$= 2$	
$N_{\mathrm{Sig}}(\ell)$	$= 2$			
$\mathrm{Charge}(\ell)$	same-sign			
$p_{\mathrm{T}}(\ell)$	≥ 25 GeV			
$n_{b\text{-jets}}$	$= 0$			
$E_{\mathrm{T}}^{\mathrm{miss}}$	≥ 50 GeV			
n_{jets}	≥ 1		≥ 2	
$\mathcal{S}(E_{\mathrm{T}}^{\mathrm{miss}})$	$< \mathbf{6}$	≥ 6	$< \mathbf{6}$	≥ 6
Other cuts	$75 < m_{\mathrm{SFOS}} < 105$ GeV		–	
	$m_{\ell\ell\ell} \notin [80, 100]$ GeV		–	
	–		$\boldsymbol{m_{jj} \geq 350}$ **GeV**	
	–		$p_{\mathrm{T}}(\mathrm{jets}) \geq 75$ GeV for (sub)leading jets	
	–		$\lvert m_{e^\pm e^\pm} - m_Z \rvert \geq 15$ GeV	
Purity	90%	90%	45%	55%

	$\mathrm{CR}WZ_{2j}^{WZ,\mathrm{(b)RPV}}$	$\mathrm{VR}WZ_{4j}^{WZ,\mathrm{(b)RPV}}$	$\mathrm{VR}WZ_{5j}^{WZ,\mathrm{(b)RPV}}$	$\mathrm{VR}t\bar{t}V^{WZ,\mathrm{(b)RPV}}$
$N_{\mathrm{BL}}(\ell)$	$= 3$			≥ 2
$N_{\mathrm{Sig}}(\ell)$	$= 3$			≥ 2
$\mathrm{Charge}(\ell)$	–			same-sign
$p_{\mathrm{T}}(\ell)$	$p_{\mathrm{T}} > 20$ GeV for (sub)leading leptons			$p_{\mathrm{T}} > 30$ GeV for SS pair leptons
$n_{b\text{-jets}}$	$= 0$			≥ 1
n_{jets} ($p_{\mathrm{T}} \geq 25$ GeV)	≥ 2	≥ 4	≥ 5	≥ 3 with $p_{\mathrm{T}} > 40$ GeV
Other selections	$50 < E_{\mathrm{T}}^{\mathrm{miss}} < 150$ GeV	$50 < E_{\mathrm{T}}^{\mathrm{miss}} < 250$ GeV		–
	$m_{\mathrm{eff}} < 1$ TeV	$m_{\mathrm{eff}} < 1.5$ TeV		–
	$81 < m_{\mathrm{SFOS}} < 101$ GeV	$81 < m_{\mathrm{SFOS}} < 101$ GeV		–
	–			$\Delta R(\ell_1, \mathrm{jet})_{\mathrm{min}} > 1.1$
	–			$\sum p_{\mathrm{T}}^{b\text{-jet}} / \sum p_{\mathrm{T}}^{\mathrm{jet}} > 0.4$
	–			$E_{\mathrm{T}}^{\mathrm{miss}} / m_{\mathrm{eff}} > 0.1$
	explicit veto on $\mathbf{SR}_{\mathbf{high}\text{-}m_{\mathbf{T2}}}^{WZ}$ **&** $\mathbf{SR}_{\mathbf{low}\text{-}m_{\mathbf{T2}}}^{WZ}$ **&** $\mathbf{SR}_{\mathbf{2\ell\text{-}SS}}^{\mathbf{bRPV}}$ **&** $\mathbf{SR}_{\mathbf{3\ell}}^{\mathbf{bRPV}}$ **events**			
Vetoing other possible BSM events	$n_{b\text{-jets}} \geq 3$			
	$n_{b\text{-jets}} \geq 1$, $n_{\mathrm{jets}} \geq 4$ ($p_{\mathrm{T}} > 50$ GeV), $E_{\mathrm{T}}^{\mathrm{miss}} > 130$ GeV			
	$n_{b\text{-jets}} = 0$, $n_{\mathrm{jets}} \geq 3$ ($p_{\mathrm{T}} > 50$ GeV), $E_{\mathrm{T}}^{\mathrm{miss}} > 130$ GeV			
	$n_{b\text{-jets}} = 0$, $n_{\mathrm{jets}} \geq 5$ ($p_{\mathrm{T}} > 50$ GeV)			
Purity	85%	84%	77%	62%

	$\mathrm{CR}FF_e$	$\mathrm{CR}FF_\mu$	$\mathrm{VR}FNP^{Wh}$			$\mathrm{VR}CF^{Wh}$
	$e^\pm e^\pm$	$\mu^\pm \mu^\pm$	$e^\pm e^\pm$	$e^\pm \mu^\pm$	$\mu^\pm \mu^\pm$	$e^\pm e^\pm$
$N_{\mathrm{BL}}(\ell)$	$= 2$					
$\mathrm{Charge}(\ell)$	same-sign					
$N_{\mathrm{Sig}}(\ell)$	$= 1$		$= 2$			
$p_{\mathrm{T}}(\ell)$	≥ 25 GeV					
n_{jets}	≥ 1					
$n_{b\text{-jets}}$	–	$= 1$	$= 0$			
$E_{\mathrm{T}}^{\mathrm{miss}}$	$\in$ **[30, 50) GeV**	$<$ **50 GeV**	≥ 50 GeV			
$\lvert m_{\ell^\pm \ell^\pm} - m_Z \rvert$	≥ 15 GeV	–	≥ 15 GeV	–	–	< 15 GeV
m_{jj}	–		< 350 GeV			
m_{T2}	–		< 80 GeV			
$m_{\mathrm{T}}^{\mathrm{min}}$	–		< 100 GeV			
$\mathcal{S}(E_{\mathrm{T}}^{\mathrm{miss}})$	–		$< \mathbf{5}$			





SRs definitions in strong SS/3L

SR name	$n_{\mathrm{Sig}}(\ell)$ ($n_{\mathrm{BL}}(\ell)$)	$n_{b\text{-jets}}$	n_{jets}	$p_{\mathrm{T}}^{\mathrm{jet}}$ [GeV]	$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	m_{eff} [GeV]	$\Delta\phi(\ell 1\ell 2, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}})$	$\mathcal{S}(E_{\mathrm{T}}^{\mathrm{miss}})$
SRGGWZ-L	≥ 2 (≥ 3)	$= 0$	≥ 6	> 25	> 200	$> 8 \times \sum p_{\mathrm{T}}^{\ell}$	> 0.2	> 6
SRGGWZ-M	≥ 2 (–)		≥ 6	> 40	> 190	> 1300	> 0.8	–
SRGGWZ-H	≥ 2 (–)		≥ 6	> 40	> 150	> 2100	–	–

SR name	$n_{\mathrm{Sig}}(\ell)$	$n_{b\text{-jets}}$	n_{jets}	$p_{\mathrm{T}}^{\mathrm{jet}}$ [GeV]	$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	m_{eff} [GeV]	$E_{\mathrm{T}}^{\mathrm{miss}}/\sum p_{\mathrm{T}}^{\ell}$	$\sum p_{\mathrm{T}}^{\ell}/\sum p_{\mathrm{T}}^{\mathrm{jet}}$	$n_{Z\to\ell^+\ell^-}$
SRSSWZ-L	≥ 3	$= 0$	≥ 4	> 25	$> 0.2 \times m_{\mathrm{eff}}$	–	–	< 0.2	$= 0^{\dagger}$
SRSSWZ-ML			≥ 6	> 25	> 150	> 800	> 1.2	< 0.3	$\geq 1^{\dagger}$
SRSSWZ-MH			≥ 5	> 40	> 200	> 900	> 1.1	< 0.4	$\geq 1^{\dagger}$
SRSSWZ-H			≥ 5	> 40	> 250	> 1500	> 0.3	< 0.7	–

†: based on number of SFOS pairs with $81 < m_{\mathrm{SFOS}} < 101$ GeV

SR name	$n_{\mathrm{Sig}}(\ell)$	$n_{b\text{-jets}}$	n_{jets}	$p_{\mathrm{T}}^{\mathrm{jet}}$ [GeV]	$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	$E_{\mathrm{T}}^{\mathrm{miss}}/\sum p_{\mathrm{T}}^{\mathrm{jet}}$	$p_{\mathrm{T}}^{\ell 2}$ [GeV]	Other
SRGGSlep-L	$\geq 3^{\dagger}$	$= 0$	≥ 4	≥ 40	–	> 0.4	> 30	$E_{\mathrm{T}}^{\mathrm{miss}}/\sum p_{\mathrm{T}}^{\ell} > 1.4$
SRGGSlep-M					> 150	> 0.3	> 70	$\Delta\phi(\ell 1\ell 2, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}) > 0.7$
SRGGSlep-H					> 100	–	–	$\sum p_{\mathrm{T}}^{\mathrm{jet}} > 1200$ GeV

†: SFOS pairs with $81 < m_{\mathrm{SFOS}} < 101$ GeV are not allowed

SR name	$n_{\mathrm{Sig}}(\ell)$	p_{T}^{ℓ} [GeV]	$n_{b\text{-jets}}$	n_{jets}	$p_{\mathrm{T}}^{\mathrm{jet}}$ [GeV]	$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	m_{eff} [GeV]	$\Delta\phi(\ell 1\ell 2, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}})$
	other requirements							
SRSSSlep-L	$= 3^{*}$	< 60	$= 0$	≥ 3	$> 60, 60, 25$	> 100	> 600	> 1.4
	$\sum p_{\mathrm{T}}^{\ell}/\sum p_{\mathrm{T}}^{\mathrm{jet}} < 0.6$							
SRSSSlep-ML	$= 3^{*}$	> 30	$= 0$	≥ 3	$> 60, 60, 25$	> 100	> 700	> 1.4
	$E_{\mathrm{T}}^{\mathrm{miss}}/\sum p_{\mathrm{T}}^{\ell} > 0.7$, $\sum p_{\mathrm{T}}^{\ell}/\sum p_{\mathrm{T}}^{\mathrm{jet}} < 0.6$							
SRSSSlep-MH	$= 3^{*}$	> 40	$= 0$	≥ 2	> 60	> 200	> 1000	> 0.5
	$E_{\mathrm{T}}^{\mathrm{miss}}/\sum p_{\mathrm{T}}^{\ell} > 0.7$, $\Delta R(\ell 1, \ell 2) > 0.2$							
SRSSSlep-H	$= 3^{*}$	> 40	$= 0$	≥ 2	> 60	> 200	> 2000	> 0.3
	$\Delta R(\ell 1, \ell 2) > 0.5$							
SRSSSlep-H (loose)	$= 3^{*}$	> 40	$= 0$	≥ 2	> 60	> 200	> 1000	> 0.3
	$\Delta R(\ell 1, \ell 2) > 0.5$							

*: additional baseline leptons are not allowed, nor SFOS pairs with $81 < m_{\mathrm{SFOS}} < 101$ GeV

SR name	$n_{\mathrm{Sig}}(\ell)$	$n_{b\text{-jets}}$	n_{jets}	$p_{\mathrm{T}}^{\mathrm{jet}}$ [GeV]	m_{eff} [GeV]
SRLQD	$= 2$	–	≥ 5	> 50	> 2600

SR name	$n_{\mathrm{Sig}}(\ell)$	$n_{b\text{-jets}}$	n_{jets}	$p_{\mathrm{T}}^{\mathrm{jet}}$ [GeV]	m_{eff} [GeV]	$\sum p_{\mathrm{T}}^{\mathrm{jet}}$ [GeV]
SRUDD-1b	$= 2$	$= 1$	≥ 6	> 50	–	> 1600
SRUDD-2b		$= 2$	≥ 2	> 25	–	> 1700
SRUDD-ge2b		≥ 2	≥ 5	> 50	–	> 1600
SRUDD-ge3b		≥ 3	≥ 4	> 50	> 1600	–

CR/VRs definitions in strong SS/3L

	$N_{\text{lept}}^{\text{signal}}$	$N_{\text{b-jets}}^{\text{20GeV}}$	$N_{\text{jets}}^{\text{25GeV}}$	$E_{\text{T}}^{\text{miss}}$ [GeV]	m_{eff} [GeV]	$\sum p_T^{\text{lep}}$ [GeV]	Purity
CRWZ2j	3	0	2 or 3	$[30, 150]$	< 1500	> 130	$> 85\%$
	Other cuts: $81 < m_{\text{SFOS}} < 101$ GeV , $p_{\text{T}} > 15$ GeV for two same-sign leptons						

	$n_{\text{Sig}}(\ell)$	$n_{b\text{-jets}}$	n_{jets}	$p_{\text{T}}^{\text{jet}}$ [GeV]	m_{eff} [GeV]	$E_{\text{T}}^{\text{miss}}$ [GeV]
	other requirements					
VRWZ4j	$= 3^*$	$= 0$	≥ 4	> 25	$[600, 1500]$	$[30, 250]$
	$E_{\text{T}}^{\text{miss}}/m_{\text{eff}} < 0.2$, $81 < m_{\text{SFOS}} < 101$ GeV					
VRWZ6j	$= 3^*$	$= 0$	≥ 6	> 25	$[400, 1500]$	$[30, 250]$
	$E_{\text{T}}^{\text{miss}}/m_{\text{eff}} < 0.15$, $81 < m_{\text{SFOS}} < 101$ GeV					
VRTTV	≥ 2	≥ 1	≥ 3	> 40	$[600, 1500]$	$[30, 250]$
	$p_{\text{T}} > 30$ GeV for the two leading-p_{T} same-sign leptons, $\Delta R > 1.1$ between the leading-p_{T} lepton and any jet, $\sum p_{\text{T}}^{b\text{-jet}}/\sum p_{\text{T}}^{\text{jet}} > 0.4$, $E_{\text{T}}^{\text{miss}}/m_{\text{eff}} > 0.1$					
VRTTV1b6j	≥ 2	≥ 1	≥ 6	> 40	< 1500	$[30, 250]$
	$p_{\text{T}} > 30$ GeV for the two leading-p_{T} same-sign leptons, $E_{\text{T}}^{\text{miss}}/m_{\text{eff}} < 0.15$					
VRTTW	$= 2^*$ $(\mu^{\pm}\mu^{\pm})$	≥ 2	≥ 2	> 25	< 1500	$[30, 250]$
	both leptons with $p_{\text{T}} > 25$ GeV, one with $p_{\text{T}} > 40$ GeV					
VRTTW3j	$= 2^*$ $(e^{\pm}\mu^{\pm})$	≥ 2	≥ 3	> 25	< 1500	$[30, 250]$
	both leptons with $p_{\text{T}} > 25$ GeV					

*: additional baseline leptons are not allowed