ATLAS EXPERIMENT

Search for supersymmetric sleptons and charginos with the ATLAS detector

INFN BOLOGNA

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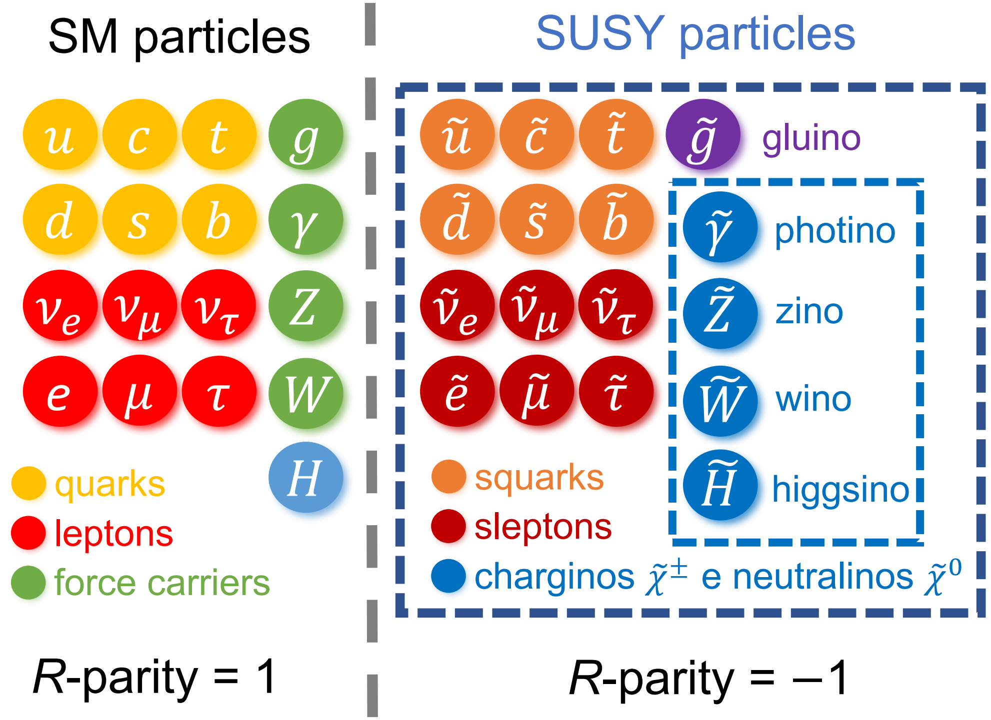
Supersymmetry

Supersymmetry (SUSY) is an extension of the Standard Model (SM).

For each boson/fermion in the SM, a new fermionic/bosonic supersymmetric partner with spin differing by 1⁄2 unit is introduced.



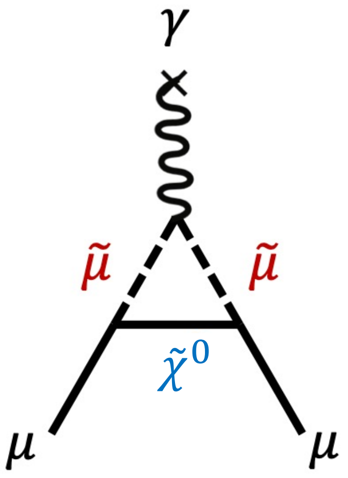
The superpartners of the SM Higgs and the electroweak gauge bosons, known as **electroweakinos**, mix to form chargino $\tilde{\chi}^{\pm}$ and neutralino $\tilde{\chi}^0$ mass eigenstates.

If *R*-parity is conserved, $\tilde{\chi}^0$ is the lightest SUSY particle and a potential candidate as **dark matter constituent**.

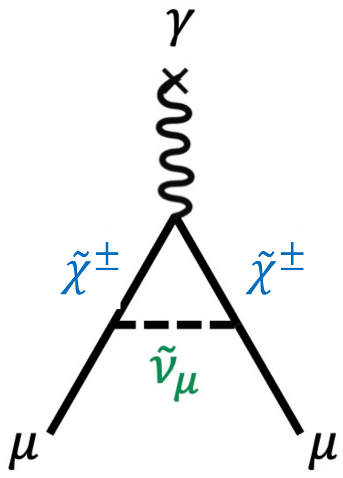
New searches target the **direct production of sleptons or chargino pairs** at $\sqrt{s}$ = 13 TeV in proton-proton collisions collected by the ATLAS experiment during Run 2 (2015-2018) [1].

Supersymmetry and the g-2 anomaly

Smuons, sneutrinos, neutralinos and charginos couple to μ and γ and cause deviations to the anomalous magnetic moment of the muon, $a_\mu = (g-2)/2$.

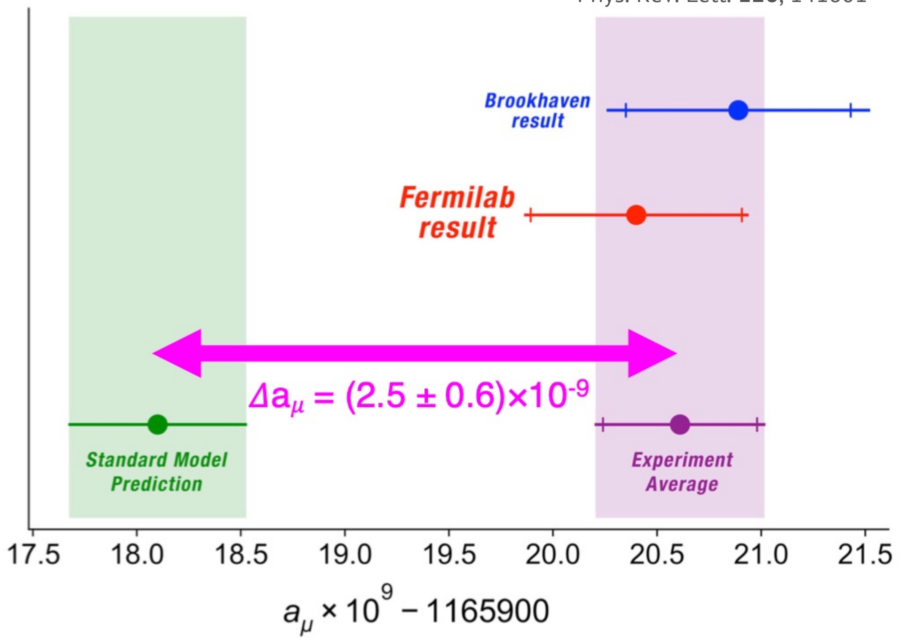


smuon / neutralino loop



sneutrino / chargino loop

Phys. Rev. Lett. **126**, 141801

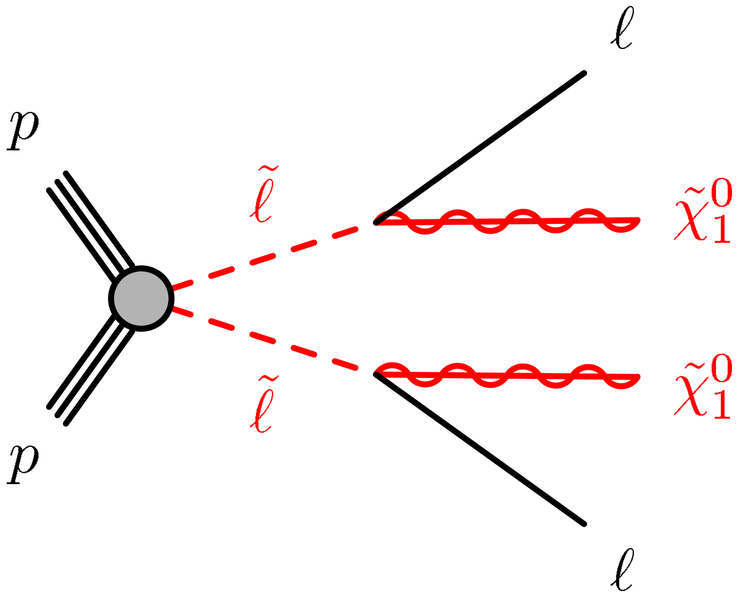


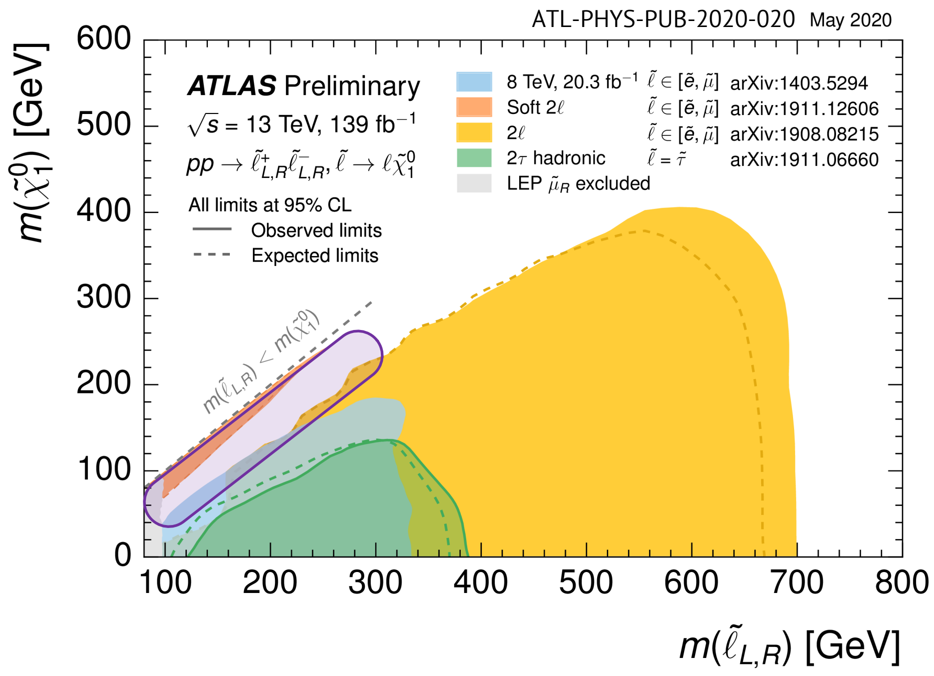
The discrepancy Δa_μ is as large as the SM electroweak contribution to the muon g−2 [2]

→ physics beyond the SM around the electroweak scale may be responsible for Δa_μ [3].

The slepton search

- Production of **sleptons** (a pair of selectrons or smuons) decaying into neutralinos through SM leptons [1].
- **Signature**: 2 Same Flavour (SF) leptons, 0/1 jets and $E_{\mathrm{T}}^{\mathrm{miss}}$.
- Targeting **compressed mass splittings** where $\Delta m(\tilde{\ell}, \tilde{\chi}_1^0) \lesssim m_W$: existing gap between previous searches.
- **Data-driven method** for background estimation and **cut-and-count** approach to optimise the significance of the slepton signal.

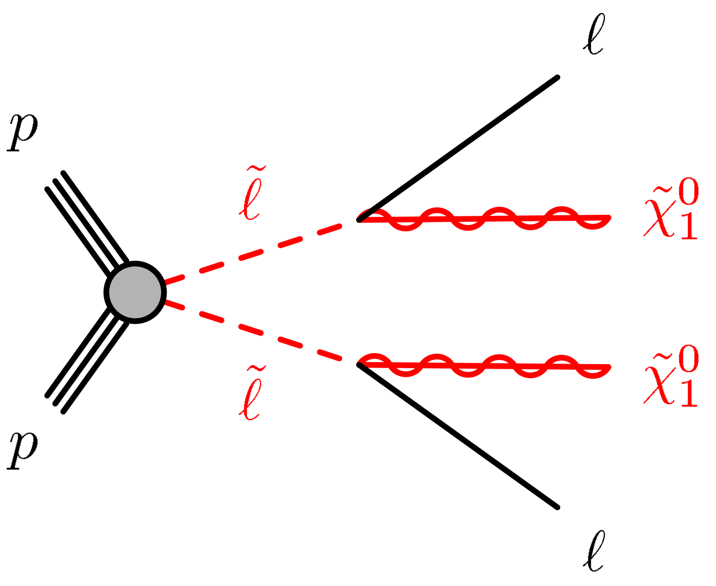




Background estimation for sleptons

- Decays of SM particles in events from background processes such as $t\bar{t}$, single-top, WW and $Z(\rightarrow \tau\tau)$+jets produce opposite-sign SF or DF leptons with the same probability (**Flavour-Symmetric Backgrounds**, FSB).

  → Data events with DF leptons passing the SR selection (N_{DF}) are used to predict the FSB contribution in the SF channel.



- Differences in trigger, reconstruction, isolation and identification efficiencies between electrons and muons are accounted for by the efficiency correction method

  → The number of expected FSB events in the SF channel, $N_{\mathrm{SF}}^{\mathrm{expected}}$, is computed as:

$$N_{ee}^{\mathrm{expected}} = 0.5 \times \frac{1}{\kappa} \times \alpha \times N_{\mathrm{DF}},$$

$$N_{\mu\mu}^{\mathrm{expected}} = 0.5 \times \kappa \times \alpha \times N_{\mathrm{DF}}$$

$$\Rightarrow N_{\mathrm{SF}}^{\mathrm{expected}} = 0.5 \times \left(\kappa + \frac{1}{\kappa}\right) \times \alpha \times N_{\mathrm{DF}}$$

- κ and α take into account the different acceptances and efficiencies for muons and electrons:

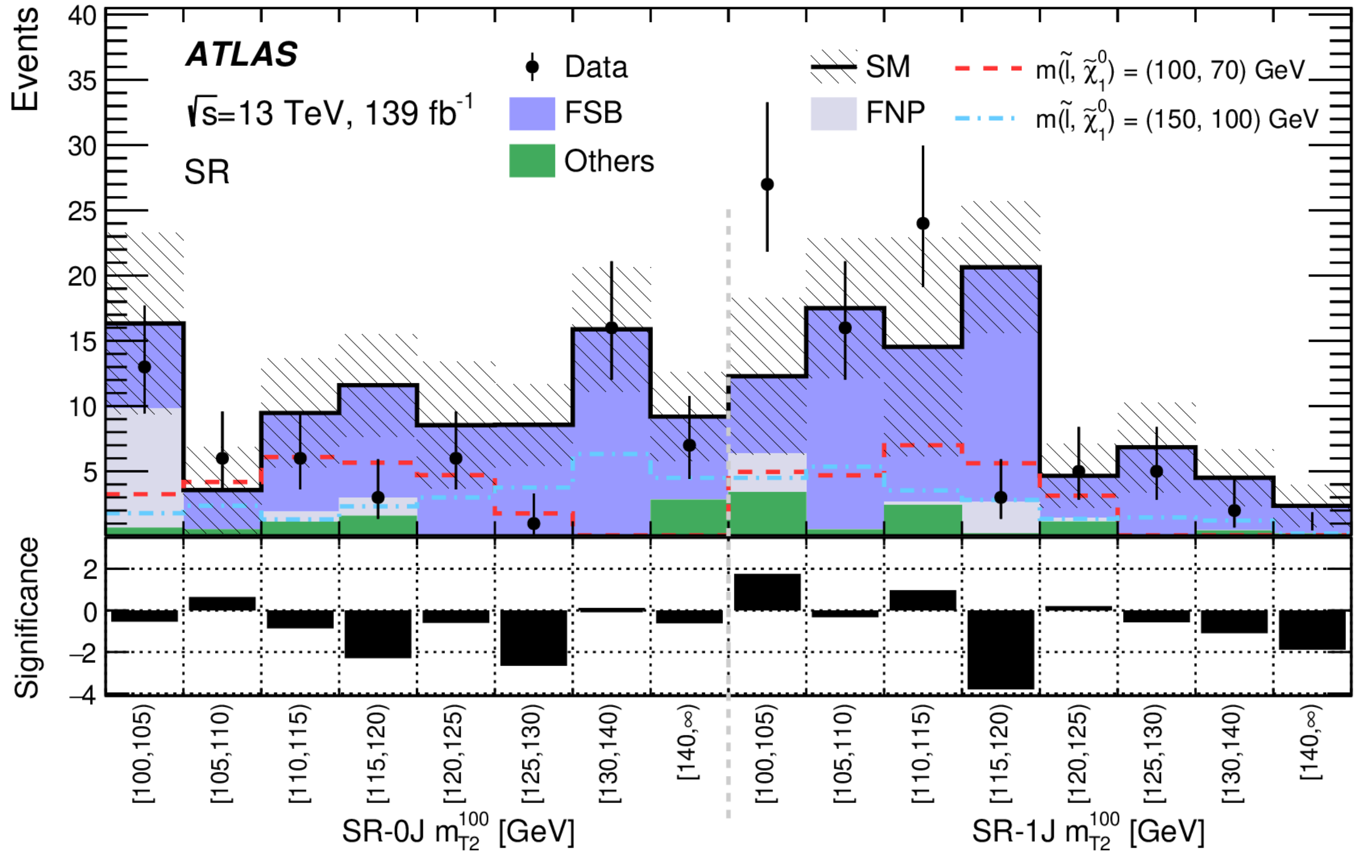
$$\kappa = \sqrt{\frac{N_{\mu^+\mu^-}}{N_{e^+e^-}}} \qquad \alpha = \sqrt{\frac{\epsilon_{\mu\mu}^{\mathrm{trig}}\epsilon_{ee}^{\mathrm{trig}}}{\epsilon_{e\mu}^{\mathrm{trig}}}}$$

Signal region for the slepton search

- Signal Region (SR) defined maximizing the signal significance with selections on a set of variables:

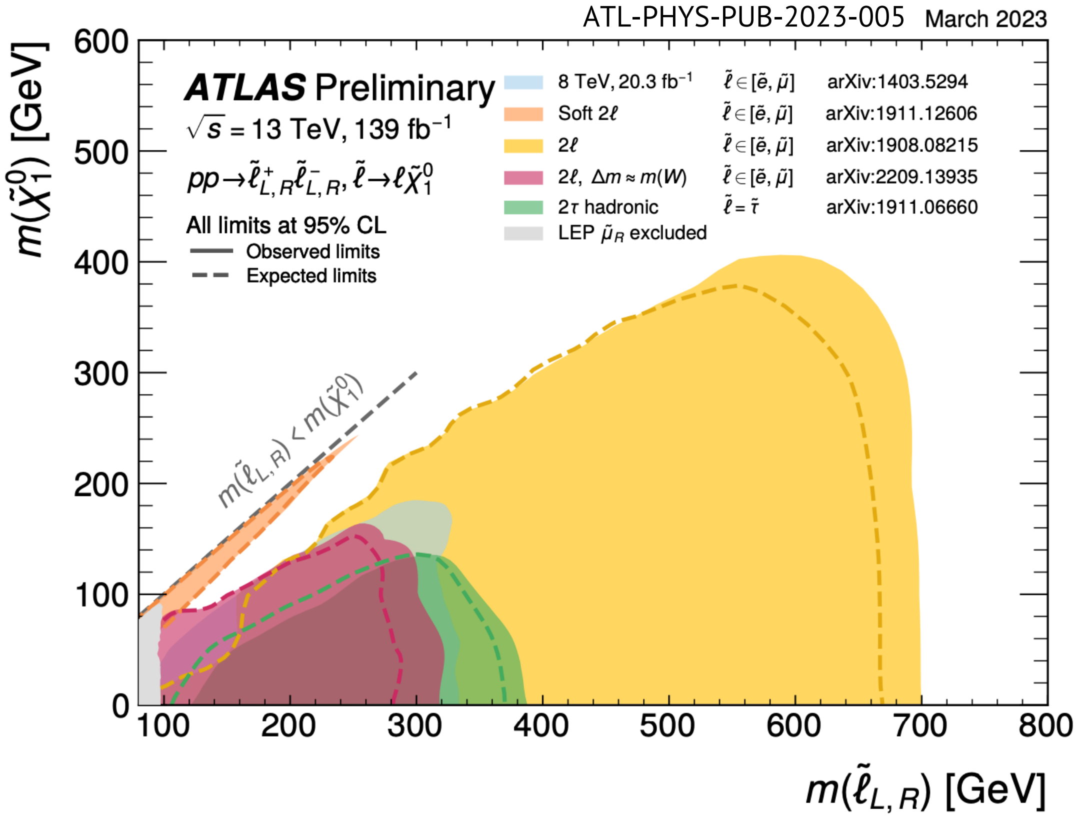
  $p_{\mathrm{T}}^{\ell_1},\ p_{\mathrm{T}}^{\ell_2},\ m_{\ell\ell},\ p_{\mathrm{T,boost}}^{\ell\ell},$
  $\Delta\phi_{p_{\mathrm{T}}^{\mathrm{miss}},\ell_1},\ \Delta\phi_{\ell,\ell},\ |\cos\theta_{\ell\ell}^{*}|$

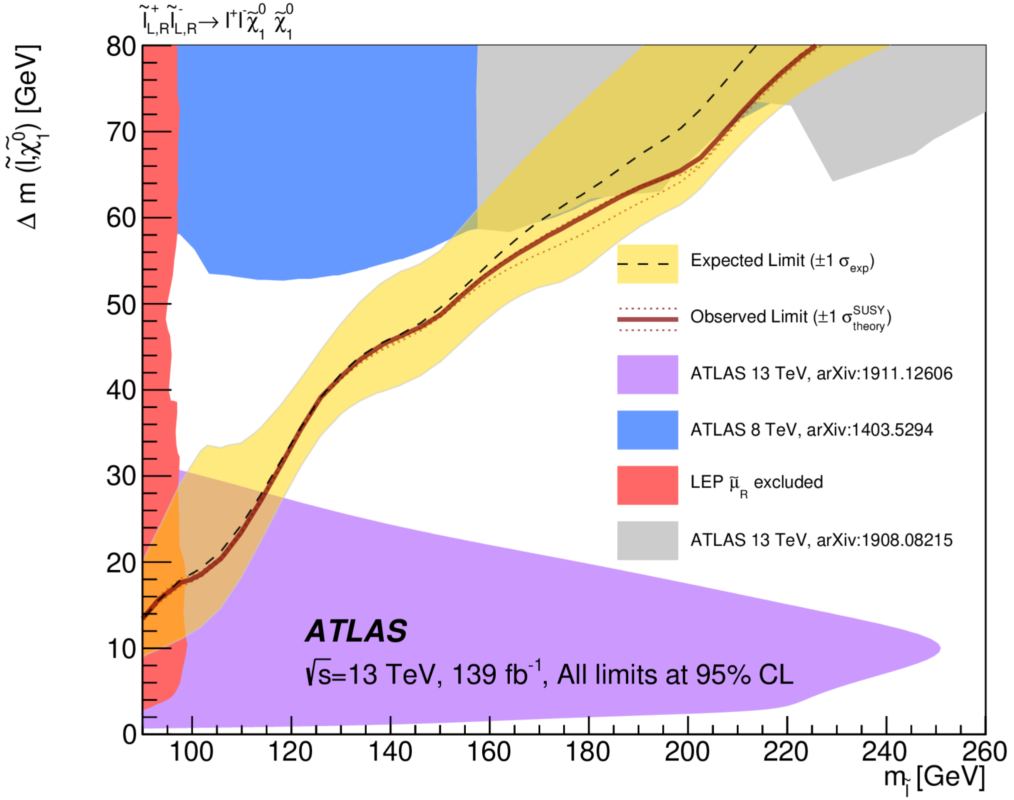
- SRs for 0 or 1 jets with a shape-fit in m_{T2}^{100} (binning is chosen to maximise the search sensitivity to the slepton model).



Exclusion limits for the slepton search

- Exclusion limits at 95% Confidence Level (CL) are set on the slepton pair production model.

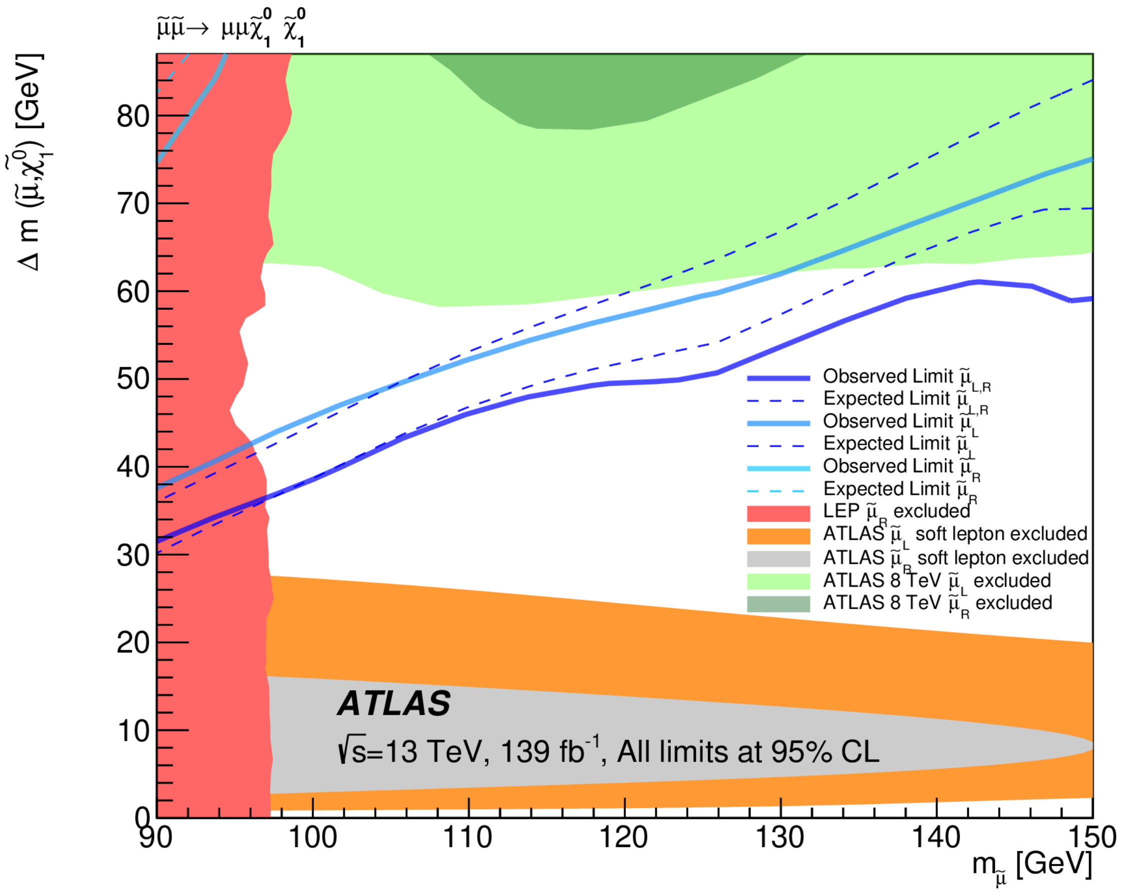


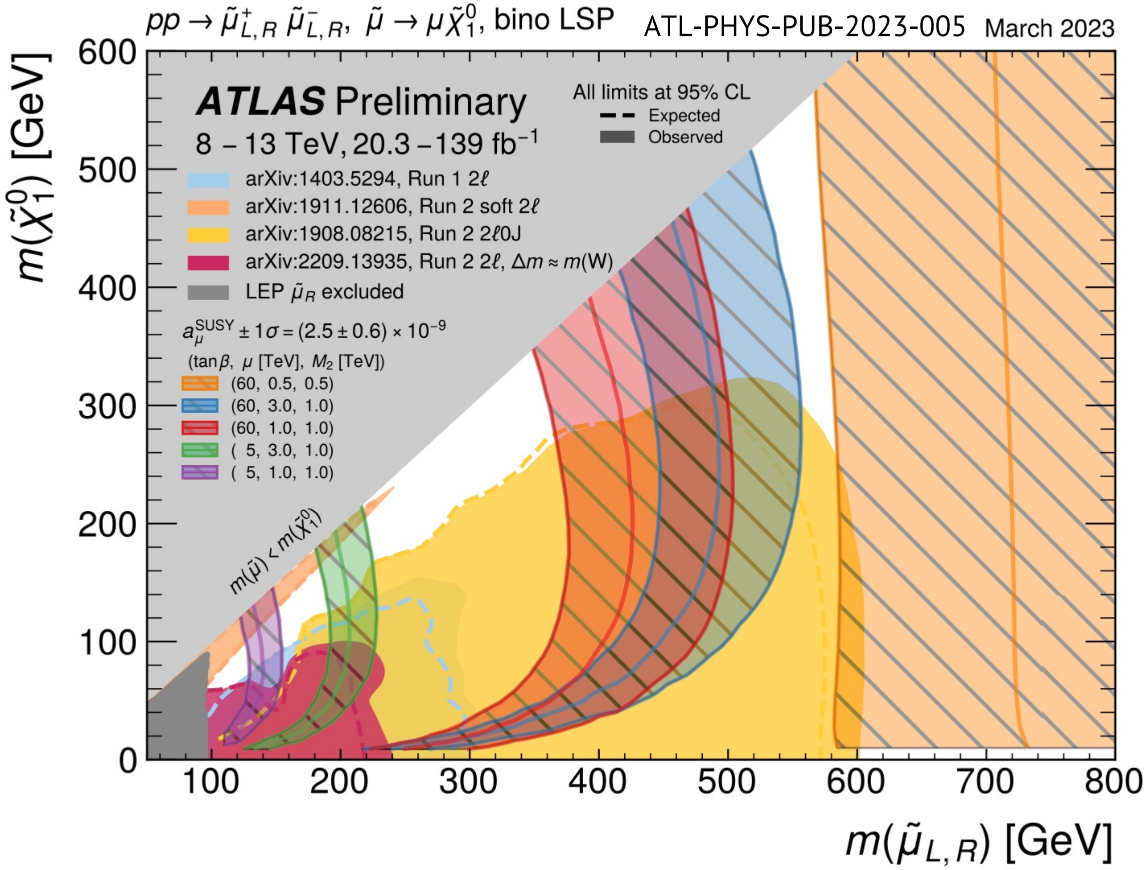


- Slepton masses up to 150 GeV are excluded at 95% CL for the case of a mass-splitting between the slepton and the neutralino down to about 50 GeV.

Exclusion limits for the slepton search

- Sleptons exclusion limits are also set for the smuon pair production alone.
  → Smuons excluded in regions compatible with the *g-2* anomaly.





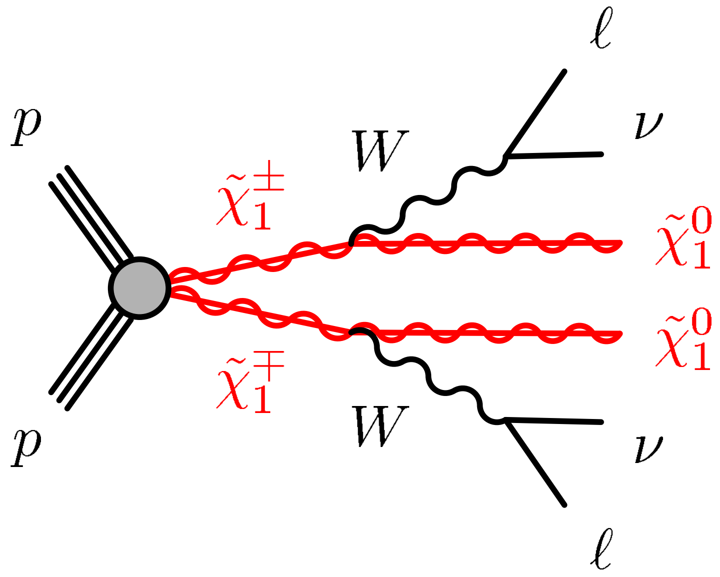
The chargino search

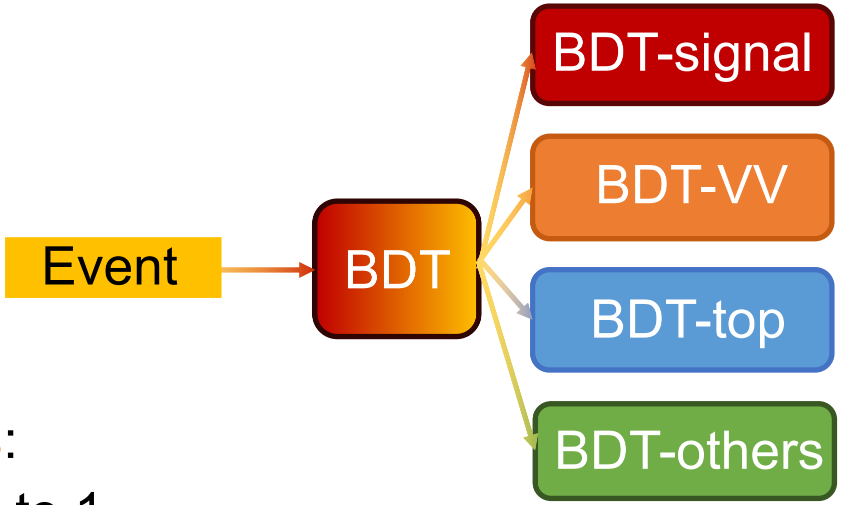
- Production of **charginos** decaying into neutralinos through SM *W* bosons [1].

- **Signature**: 2 leptons of Same Flavor (SF) or Different Flavor (DF), no jets and $E_{\mathrm{T}}^{\mathrm{miss}}$.

- Very **challenging signature**
  - low signal production cross section
  - leptonic decays of the *W* bosons
  - targeting **compressed mass splittings** where $\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0) \lesssim m_W$
    → signal similar to the *WW* background.

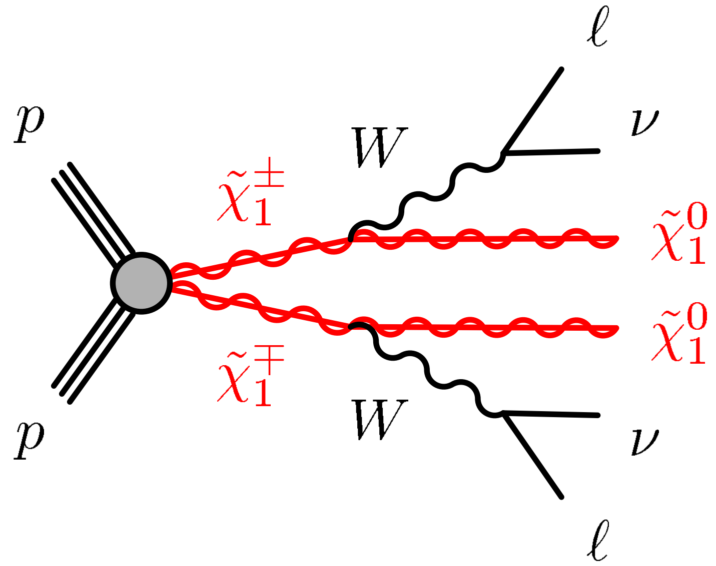
- Analysis strategy based on **machine learning techniques**:
  → Multi-class classification with 4 output scores that sum to 1.

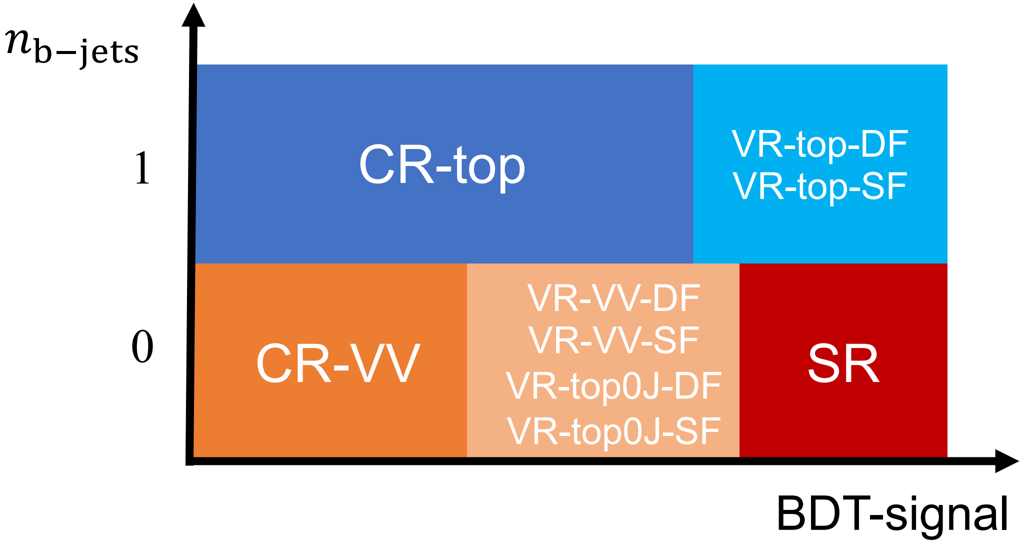




Background estimation for charginos

- **Main backgrounds:** Diboson (*VV* with *V=W/Z)* and top-quark processes ($t\bar{t}$ and *Wt*).
- **Background estimation**: main backgrounds normalized to data in dedicated Control Regions (CRs).
  → 2 CRs: CR-VV and CR-Top.

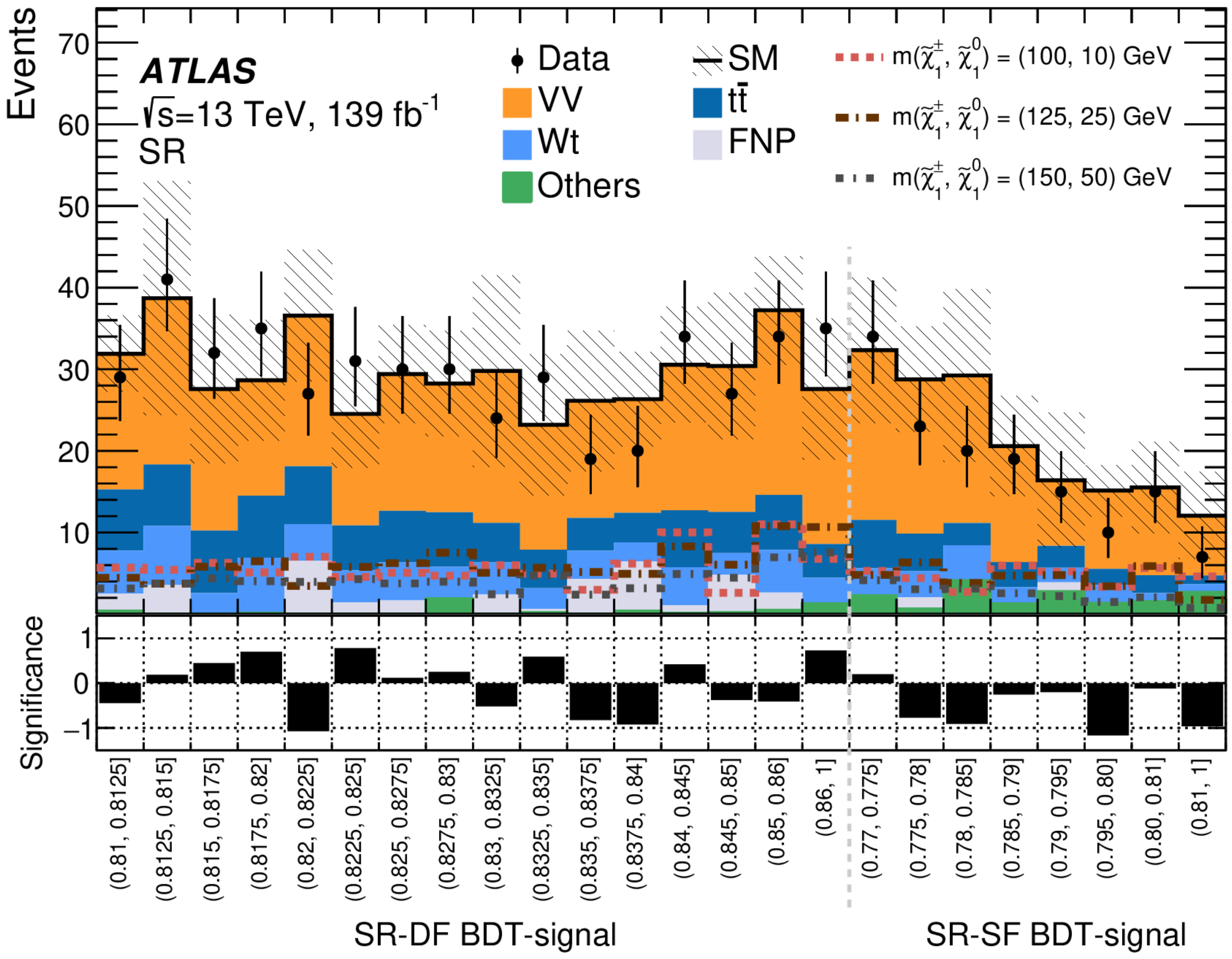




- CR-VV in $n_{\mathrm{b-jets}}$ = 0 phase space close to the Signal Region (SR).
- CR-top in $n_{\mathrm{b-jets}}$ = 1 phase space to reach high purity of top backgrounds.

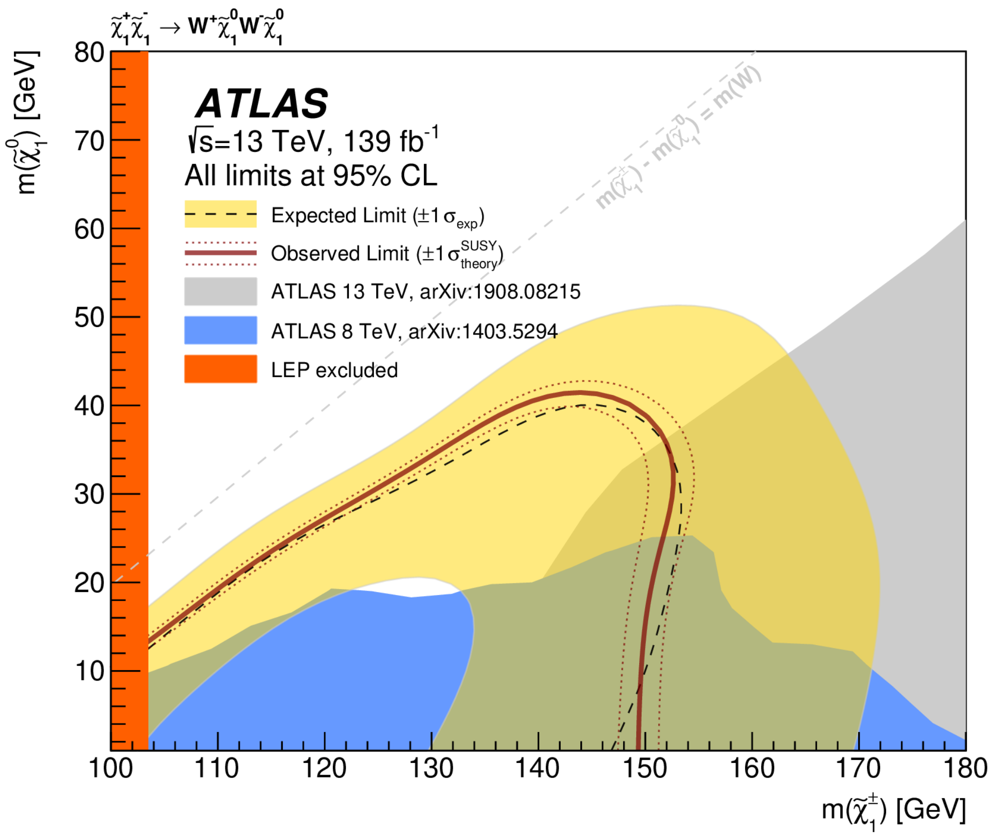
Signal region for the chargino search

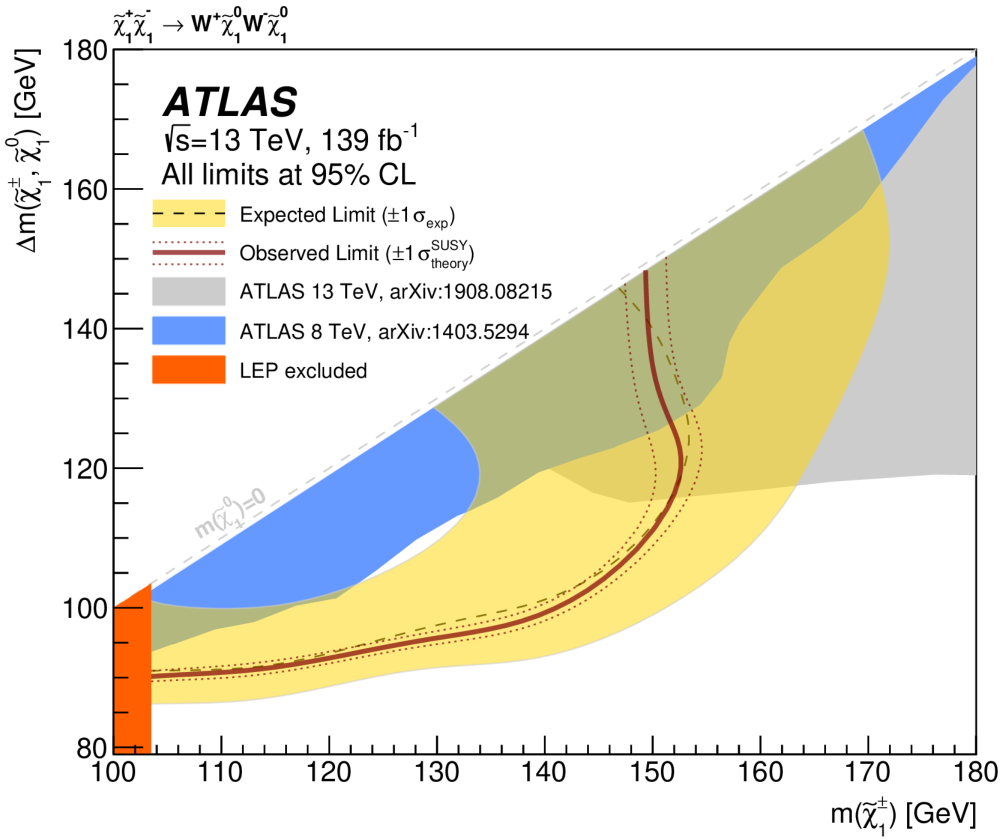
- SR defined for high values of BDT-signal to maximise chargino signal significance:
  - SF and DF channels combined together in a likelihood fit.
  - Shape-fit in BDT-signal bins performed to increase sensitivity.
- No significant deviations from the SM observed in SR bins.



Exclusion limits for the chargino search

- Exclusion limits at 95% CL are set on the chargino pair production model.



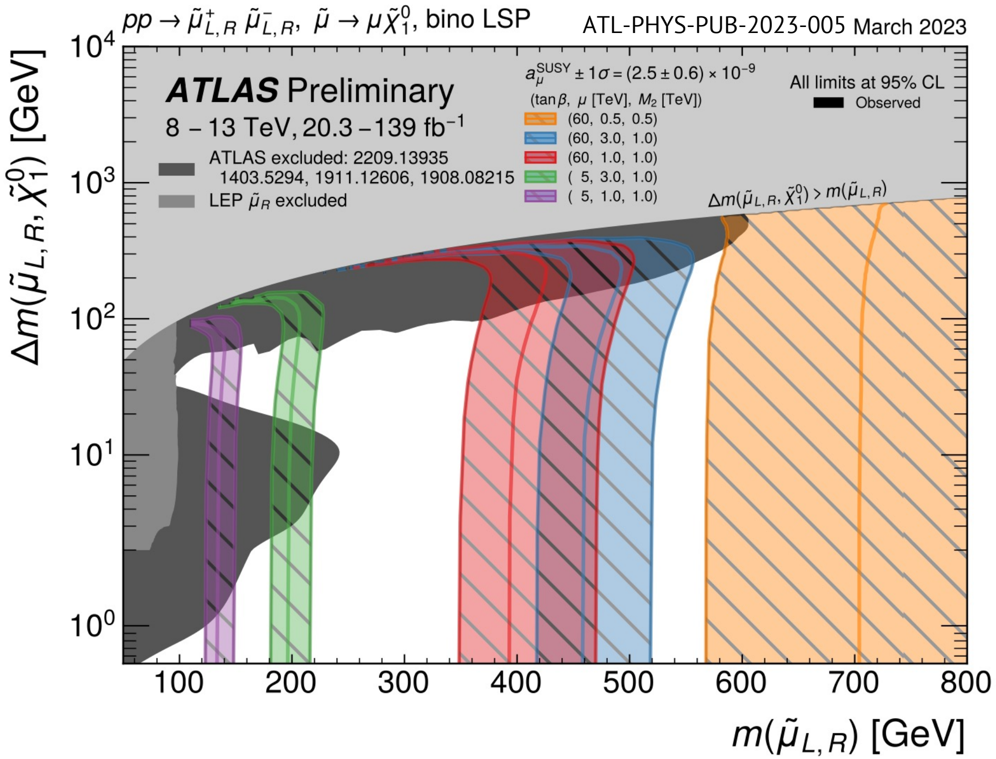


- Chargino masses up to 140 GeV are excluded at 95% CL for the case of a mass-splitting between the chargino and the neutralino down to about 100 GeV.

Conclusions

Improved analysis strategies for the **slepton** and **chargino** searches allowed to reach **unprecedented sensitivities:**

- Slepton masses excluded in the gap region from previous searches, the new limits supersede the LEP ones and exclude regions compatible with the *g-2* anomaly.
- Charginos excluded in regions with mass splittings close to the mass of the *W* boson where they could have hidden behind the looking alike *VV* background.



The SM is surviving our new ATLAS searches. However, **challenging regions** compatible with the *g-2* anomaly remain uncovered.

- Exploring these gaps requires larger datasets, improved data analysis techniques or even dedicated new searches.
- **Compressed searches** will continue to be a key target of these efforts in Run 3. Stay tuned to see if they lead to future discoveries!

Backup

References

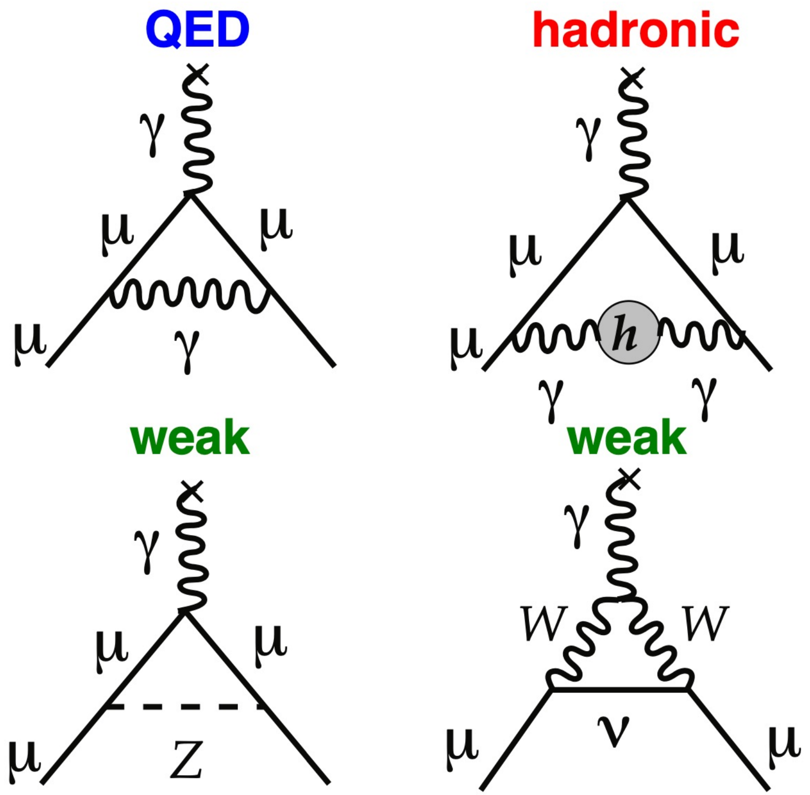
1. ATLAS Collaboration, *Search for direct pair production of sleptons and charginos decaying to two leptons and neutralinos with mass splittings near the W-boson mass in* $\sqrt{s}$*=13TeV pp collisions with the ATLAS detector*, arXiv:2209.13935.
2. T. Aoyama et al., *The anomalous magnetic moment of the muon in the Standard Model*, Phys. Rept. 887 (2020) 1–166, arXiv:2006.04822.
3. M. Endo, K. Hamaguchi, S. Iwamoto, T. Kitahara, *Supersymmetric Interpretation of the Muon g-2 Anomaly*, JHEP 07 (2021) 075, arXiv:2104.03217.

Analysis variables

- $p_{\mathrm{T}}^{\ell_1}$: the magnitude of the transverse momentum of the leading lepton;
- $p_{\mathrm{T}}^{\ell_2}$: the magnitude of the transverse momentum of the subleading lepton;
- $E_{\mathrm{T}}^{\mathrm{miss}}$: the magnitude of the missing transverse momentum;
- $E_{\mathrm{T}}^{\mathrm{miss}}$ significance: the significance of the $E_{\mathrm{T}}^{\mathrm{miss}}$ as defined in ATLAS-CONF-2018-038;
- $m_{\ell\ell}$: the invariant mass of the two leptons;
- m_{T2}: the stransverse mass as defined in Phys. Lett. B 463, Eur. Phys. J. C 80 (2020) 123;
- $\Delta\phi_{\mathrm{boost}}$: the azimuthal angular separation between $E_{\mathrm{T}}^{\mathrm{miss}}$ and the vectorial sum of the two leptons p_{T} and the $E_{\mathrm{T}}^{\mathrm{miss}}$;
- $\Delta\phi_{E_{\mathrm{T}}^{\mathrm{miss}},\ell_1}$: the azimuthal angular separation between $E_{\mathrm{T}}^{\mathrm{miss}}$ and the leading lepton;
- $\Delta\phi_{E_{\mathrm{T}}^{\mathrm{miss}},\ell_2}$: the azimuthal angular separation between $E_{\mathrm{T}}^{\mathrm{miss}}$ and the sub−leading lepton;
- $p_{\mathrm{T,boost}}^{\ell\ell}$: the module of the vectorial sum of the p_{T} of the two leptons and the $E_{\mathrm{T}}^{\mathrm{miss}}$;
- $|\cos\theta_{\ell\ell}^{*}| = |\cos(2\tan^{-1}e^{\frac{\Delta\eta_{\ell\ell}}{2}})| = |\tanh e^{\frac{\Delta\eta_{\ell\ell}}{2}}|$, sensitive to the spin of the particles JHEP 0602.

The g-2 anomaly

- Charged particles with spin have magnetic moment $\vec{\mu}_s = g \frac{q}{2m} \vec{S}$.
- Magnetic moment determines how strongly a particle couples to the electromagnetic field.
- SM prediction: at "tree-level" (no loops) ⟶ g = 2 identically.
- Loops cause "anomalous magnetic moment" $a_\mu = (g-2)/2$.

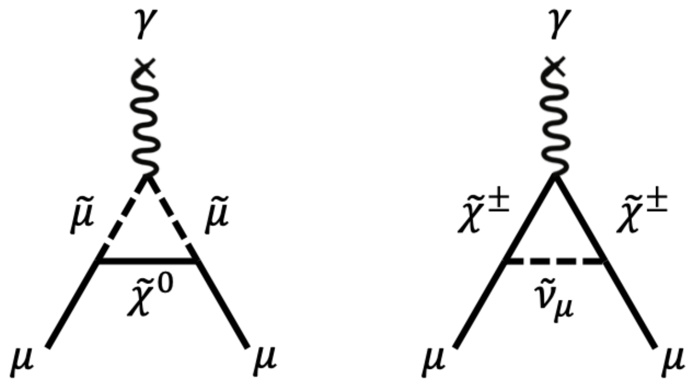


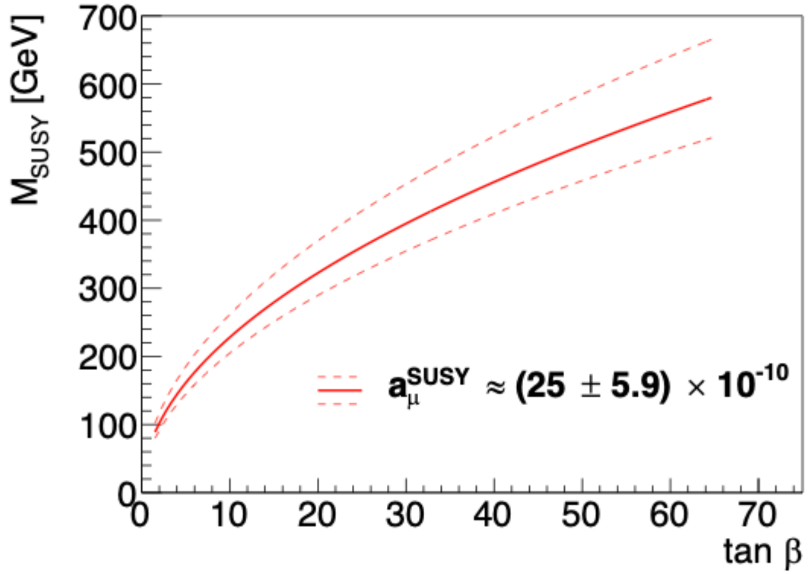
SUSY contribution to g-2 (1/3)

- Assuming common mass scale M_{SUSY} for $\tilde{\mu}$, $\tilde{\nu}_\mu$, $\tilde{\chi}^{\pm}$, $\tilde{\chi}^{0}$, the SUSY one loop (1L) contributions to $a_\mu = (g-2)/2$ are [3]:

$$a_\mu^{\mathrm{SUSY,1L}} = 13 \times 10^{-10} \left(\frac{100\ \mathrm{GeV}}{M_{\mathrm{SUSY}}}\right)^2 \tan\beta\ \mathrm{sign}(\mu)$$

- **SUSY at electroweak scale can explain the observed g-2 deviation!**
- **Preferred mass range is well-matched to our direct SUSY searches.**





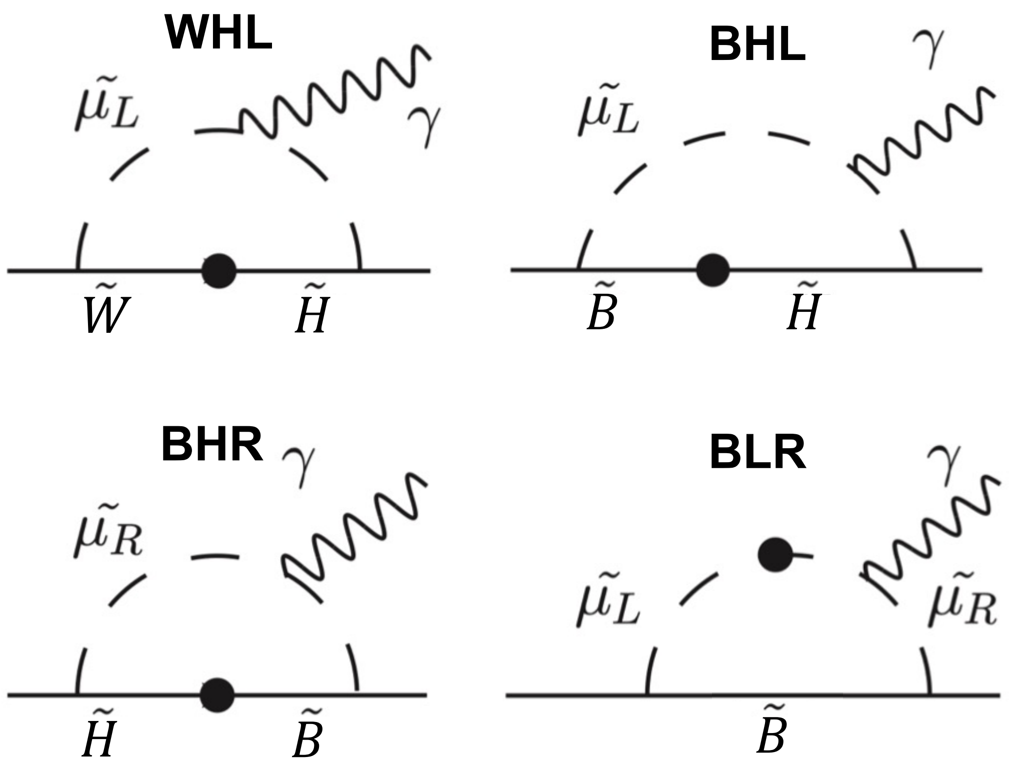
SUSY contribution to g-2 (2/3)

- The SUSY contributions to the muon $g-2$ can be sizable when at least three SUSY multiplets are as light as O(100) GeV.

- They are classified into four types:

Type	$\widetilde{W}$	$\widetilde{B}$	$\widetilde{H}$	$\widetilde{\mu}_L/\widetilde{\nu}_L$	$\widetilde{R}$
WHL	X		X	X	
BHL		X	X	X	
BHR		X	X		X
BLR		X		X	X

W = wino, B = bino, H = higgsino,
L/R = left-handed/ right-handed smuon



SUSY contribution to g-2 (3/3)

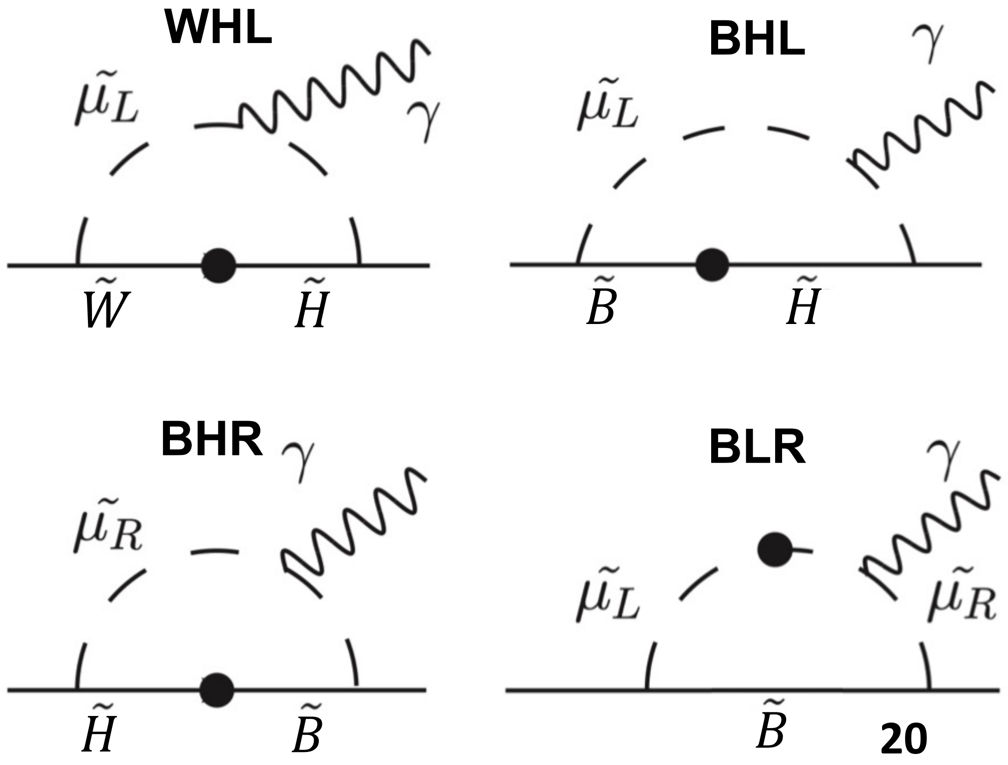
- The four sizeable contributions are:

$$a_\mu^{\mathrm{WHL}} = \frac{\alpha_2}{4\pi}\frac{m_\mu^2}{M_2\mu}\tan\beta\cdot f_C\left(\frac{M_2^2}{m_{\tilde{\nu}_\mu}^2},\frac{\mu^2}{m_{\tilde{\nu}_\mu}^2}\right) - \frac{\alpha_2}{8\pi}\frac{m_\mu^2}{M_2\mu}\tan\beta\cdot f_N\left(\frac{M_2^2}{m_{\tilde{\mu}_\mathrm{L}}^2},\frac{\mu^2}{m_{\tilde{\mu}_\mathrm{L}}^2}\right),$$

$$a_\mu^{\mathrm{BHL}} = \frac{\alpha_Y}{8\pi}\frac{m_\mu^2}{M_1\mu}\tan\beta\cdot f_N\left(\frac{M_1^2}{m_{\tilde{\mu}_\mathrm{L}}^2},\frac{\mu^2}{m_{\tilde{\mu}_\mathrm{L}}^2}\right),$$

$$a_\mu^{\mathrm{BHR}} = -\frac{\alpha_Y}{4\pi}\frac{m_\mu^2}{M_1\mu}\tan\beta\cdot f_N\left(\frac{M_1^2}{m_{\tilde{\mu}_\mathrm{R}}^2},\frac{\mu^2}{m_{\tilde{\mu}_\mathrm{R}}^2}\right),$$

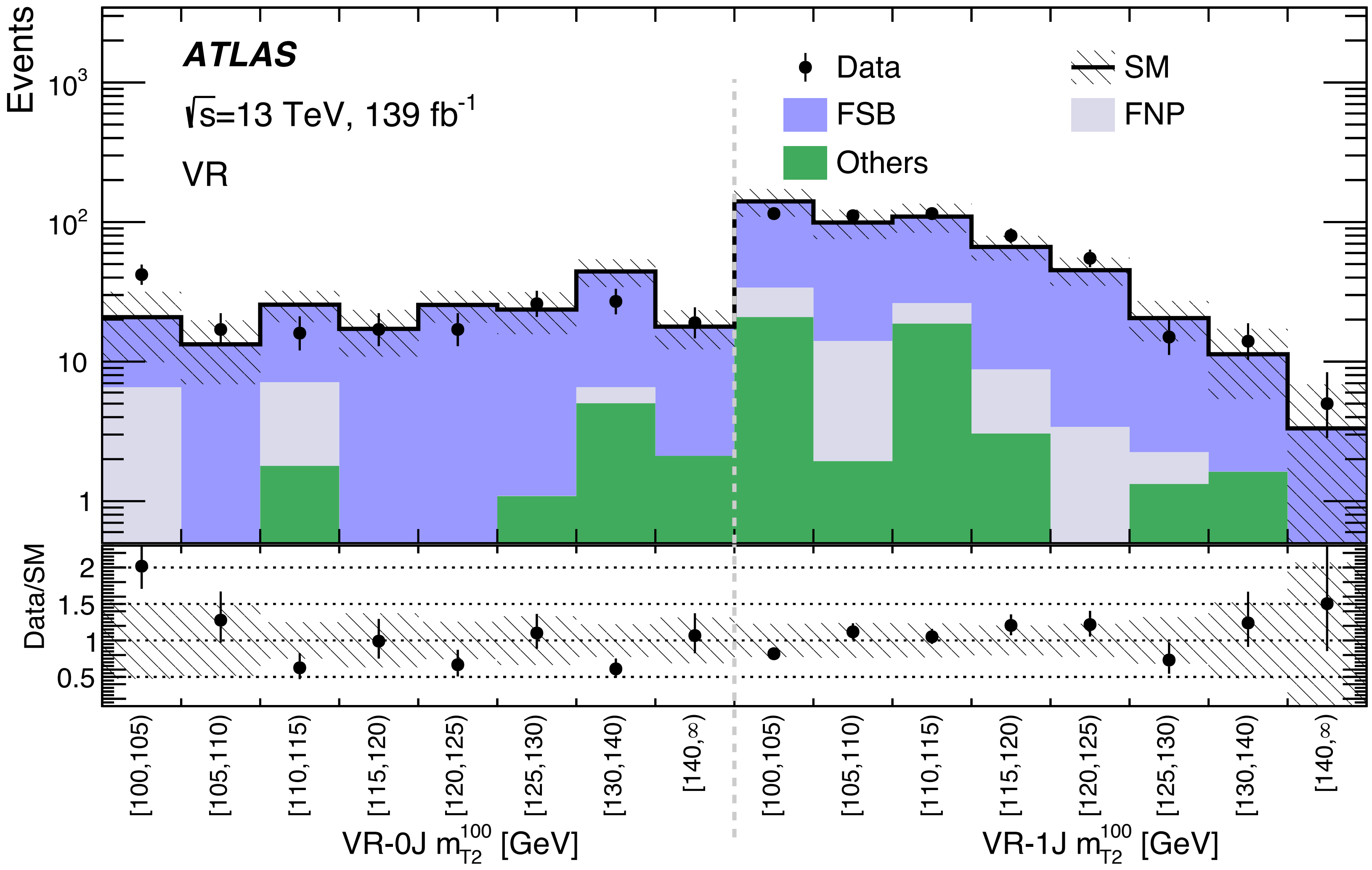
$$a_\mu^{\mathrm{BLR}} = \frac{\alpha_Y}{4\pi}\frac{m_\mu^2 M_1\mu}{m_{\tilde{\mu}_\mathrm{L}}^2 m_{\tilde{\mu}_\mathrm{R}}^2}\tan\beta\cdot f_N\left(\frac{m_{\tilde{\mu}_\mathrm{L}}^2}{M_1^2},\frac{m_{\tilde{\mu}_\mathrm{R}}^2}{M_1^2}\right),$$



M_1 = bino soft mass, M_2 = wino soft mass
μ = higgsino mass parameter

Refs: Phys. Rev. D **53**, 6565 (1996), Phys. Rev. D **56**, 4424 (1997)

Background validation for sleptons



Signal region for sleptons

Signal region (SR)	SR-0J	SR-1J
$n_{b\text{-tagged jets}}$	$= 0$	
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance	>7	
$n_{\text{non-}b\text{-tagged jets}}$	$= 0$	$= 1$
$p_{\mathrm{T}}^{\ell_1}$ [GeV]	> 140	> 100
$p_{\mathrm{T}}^{\ell_2}$ [GeV]	> 20	> 50
$m_{\ell\ell}$ [GeV]	> 11	> 60
$p_{\mathrm{T,boost}}^{\ell\ell}$ [GeV]	< 5	-
$\lvert\cos\theta^*_{\ell\ell}\rvert$	< 0.2	< 0.1
$\Delta\phi_{\ell,\ell}$	> 2.2	> 2.8
$\Delta\phi_{p_{\mathrm{T}}^{\mathrm{miss}},\ell_1}$	> 2.2	-
Binned SRs		
m_{T2}^{100} [GeV]	$\in[100,105)$ $\in[105,110)$ $\in[110,115)$ $\in[115,120)$ $\in[120,125)$ $\in[125,130)$ $\in[130,140)$ $\in[140,\infty)$	

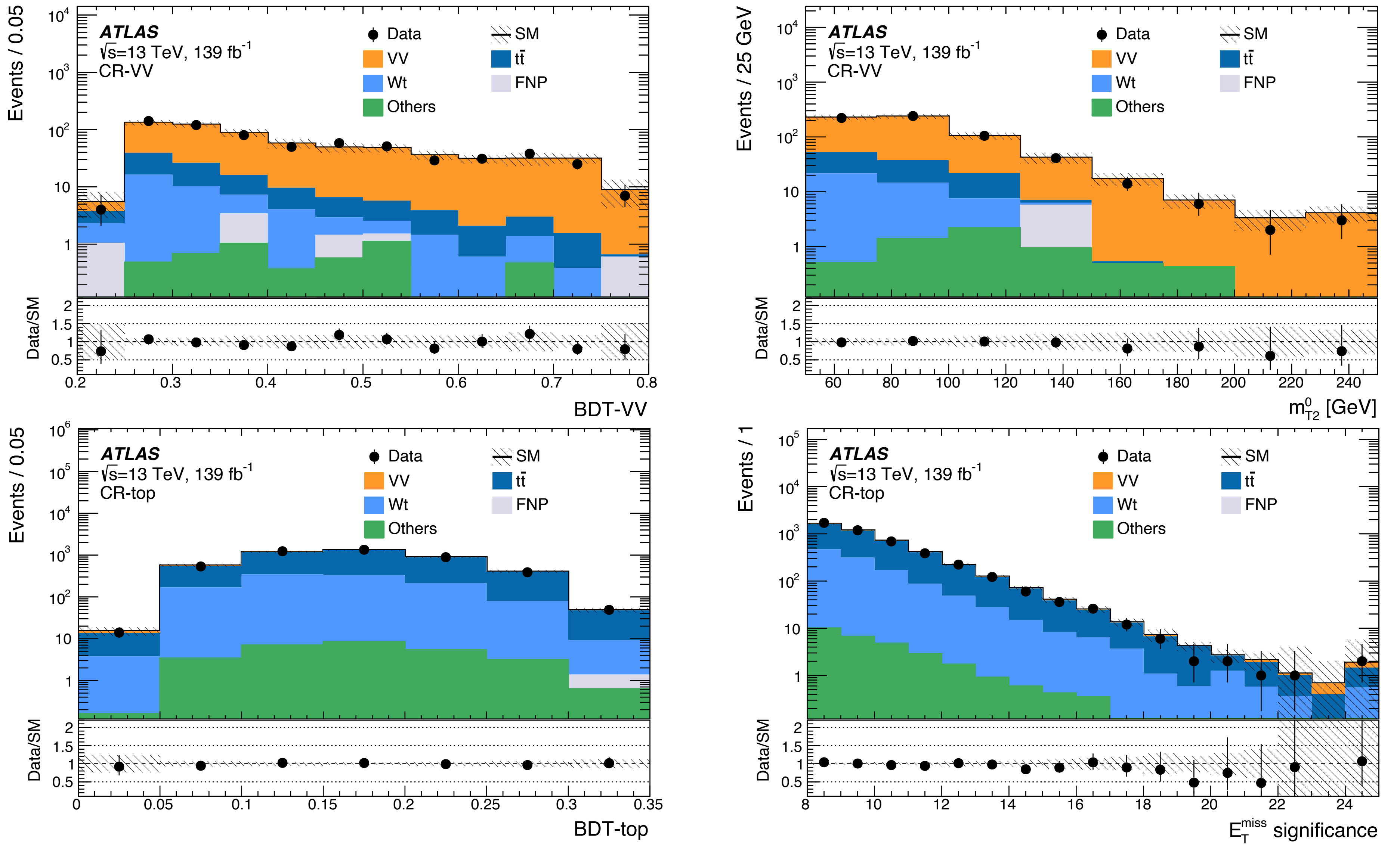
Background estimation for charginos (1/3)

Control region (CR)	CR-VV		CR-top	
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance	> 8			
m_{T2} [GeV]	> 50			
$n_{\text{non-}b\text{-tagged jets}}$	$= 0$			
Leptons flavour	DF	SF	DF	SF
$n_{b\text{-tagged jets}}$	$= 0$	$= 0$	$= 1$	$= 1$
BDT-other	-	< 0.01	-	< 0.01
BDT-signal	$\in (0.2, 0.65]$	$\in (0.2, 0.65]$	$\in (0.5, 0.7]$	$\in (0.7, 0.75]$
BDT-VV	> 0.2	> 0.2	-	-
BDT-top	< 0.1	< 0.1	-	-

Background estimation for charginos (2/3)

Region	CR-VV	CR-top
Observed events	634	4468
Fitted backgrounds	634 ± 25	4470 ± 70
Fitted VV	520 ± 27	68 ± 12
Fitted $t\bar{t}$	69 ± 7	3240 ± 100
Fitted single-top	40 ± 6	1130 ± 90
Other backgrounds	$4.8^{+5.1}_{-4.8}$	29 ± 5
FNP leptons	$0.02^{+1.4}_{-0.02}$	$0.06^{+12}_{-0.06}$
Simulated VV	376	49
Simulated $t\bar{t}$	63	2974
Simulated single-top	37	1040

Background estimation for charginos (3/3)



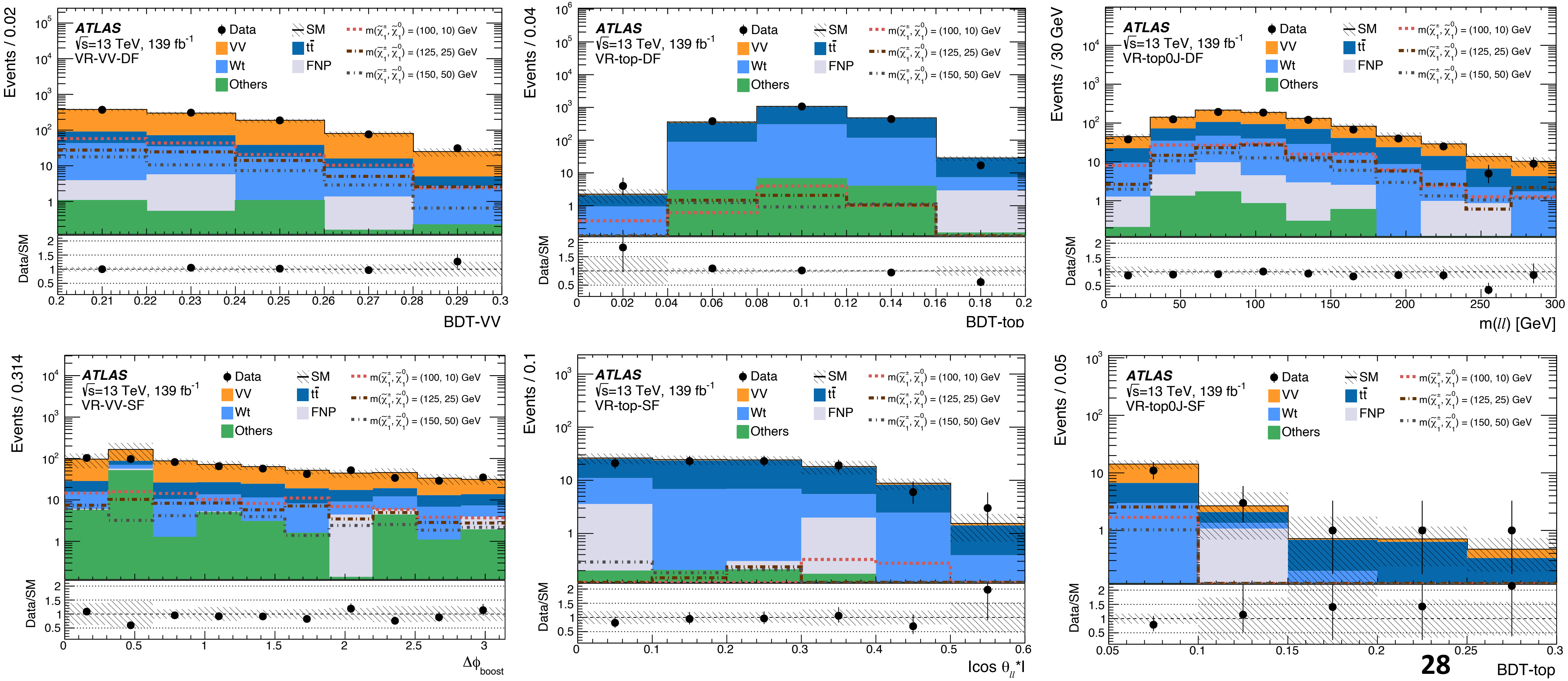
Background validation for charginos (1/3)

Validation region (VR)	VR-VV-DF	VR-VV-SF	VR-top-DF	VR-top-SF	VR-top0J-DF	VR-top0J-SF
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance			> 8			
m_{T2} [GeV]			> 50			
$n_{\text{non-}b\text{-tagged jets}}$			$= 0$			
$n_{b\text{-tagged jets}}$	$= 0$	$= 0$	$= 1$	$= 1$	$= 0$	$= 0$
BDT-other	-	< 0.01	-	< 0.01	-	< 0.01
BDT-signal	$\in (0.65, 0.81]$	$\in (0.65, 0.77]$	$\in (0.7, 1]$	$\in (0.75, 1]$	$\in (0.5, 0.81]$	$\in (0.5, 0.77]$
BDT-VV	> 0.2	> 0.2	-	-	< 0.15	< 0.15
BDT-top	< 0.1	< 0.1	-	-	-	-

Background validation for charginos (2/3)

Regions	VR-VV-DF	VR-VV-SF	VR-top-DF	VR-top-SF	VR-top0J-DF	VR-top0J-SF
Observed events	972	596	1910	95	810	17
Fitted backgrounds	940 ± 60	670 ± 90	1900 ± 90	101 ± 10	880 ± 40	18 ± 4
Fitted VV	730 ± 50	400 ± 50	32 ± 13	2.2 ± 2.1	427 ± 30	8.1 ± 2.6
Fitted $t\bar{t}$	116 ± 12	111 ± 11	1350 ± 50	67 ± 7	260 ± 21	5.8 ± 1.8
Fitted single-top	94 ± 19	75 ± 11	500 ± 60	27 ± 7	168 ± 18	4 ± 1
Other backgrounds	3.1 ± 1.5	70 ± 70	13.6 ± 2.5	0.8 ± 0.4	5.2 ± 1.9	0.05 ± 0.05
FNP leptons	$0.02^{+2.3}_{-0.02}$	7 ± 4	$0.03^{+5}_{-0.03}$	4.2 ± 1.3	21 ± 8	$0.05^{+0.15}_{-0.05}$
Simulated VV	527	291	23	1.6	309	5.9
Simulated $t\bar{t}$	106	102	1240	61	239	5.3
Simulated single-top	87	69	460	25	154	3.2

Background validation for charginos (3/3)



Signal region for charginos

Signal region (SR)	SR-DF	SR-SF
$n_{b\text{-tagged jets}}$	= 0	
$n_{\text{non-}b\text{-tagged jets}}$	= 0	
E_T^{miss} significance	>8	
m_{T2} [GeV]	>50	
BDT-other	< 0.01	
Binned SRs		
BDT-signal	∈(0.81,0.8125]	∈(0.77,0.775]
	∈(0.8125,0.815]	∈(0.775,0.78]
	∈(0.815,0.8175]	∈(0.78,0.785]
	∈(0.8175,0.82]	∈(0.785,0.79]
	∈(0.82,0.8225]	∈(0.79,0.795]
	∈(0.8225,0.825]	∈(0.795,0.80]
	∈(0.825,0.8275]	∈(0.80,0.81]
	∈(0.8275,0.83]	∈(0.81,1]
	∈(0.83,0.8325]	
	∈(0.8325,0.835]	
	∈(0.835,0.8375]	
	∈(0.8375,0.84]	
	∈(0.84,0.845]	
	∈(0.845,0.85]	
	∈(0.85,0.86]	
	∈(0.86,1]	

Summary of ATLAS SUSY searches