Searches for sleptons with the ATLAS detector

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DESY

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

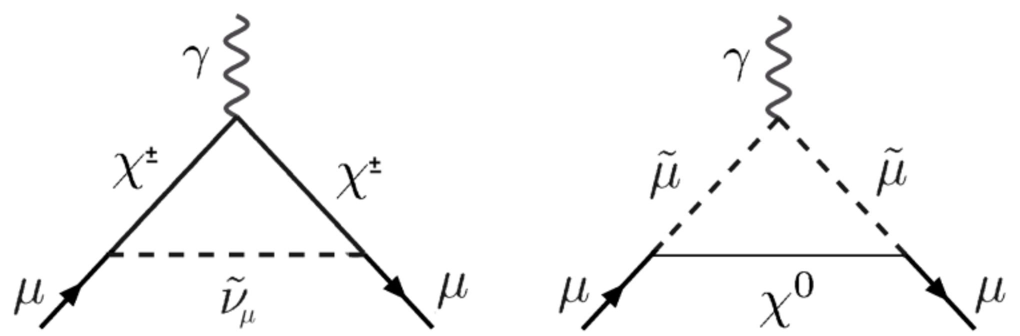
ATLAS EXPERIMENT

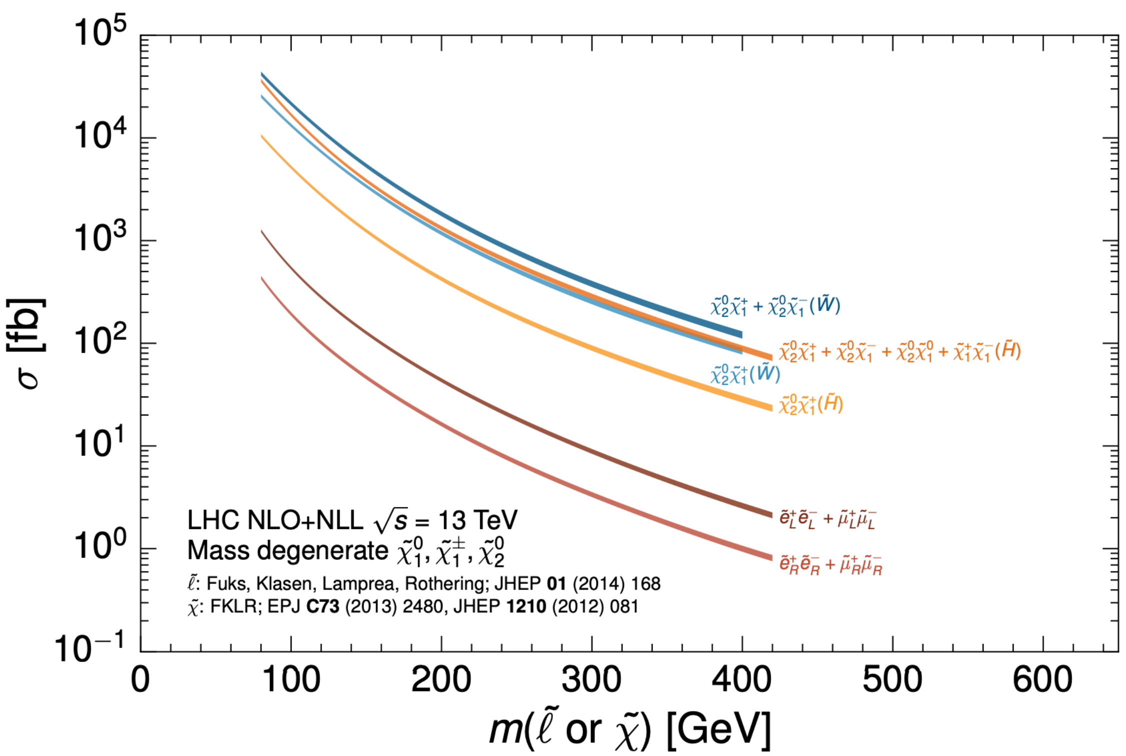
DESY.

Supersymmetry: sleptons

Sleptons play a key role in several models:

- **Smuons** ($\tilde{\mu}$) and **sneutrinos** ($\tilde{\nu}$) can play a key role in $(g-2)_\mu$
- **Staus** ($\tilde{\tau}$) could play a role in co-annihilation of neutralinos ($\tilde{\chi}^0$) and give correct Dark Matter relic density consistent with cosmological observations
- **Naturalness** reasons suggest that sleptons might have masses close to the EWK scale
- **Rare processes** but with very clean signatures

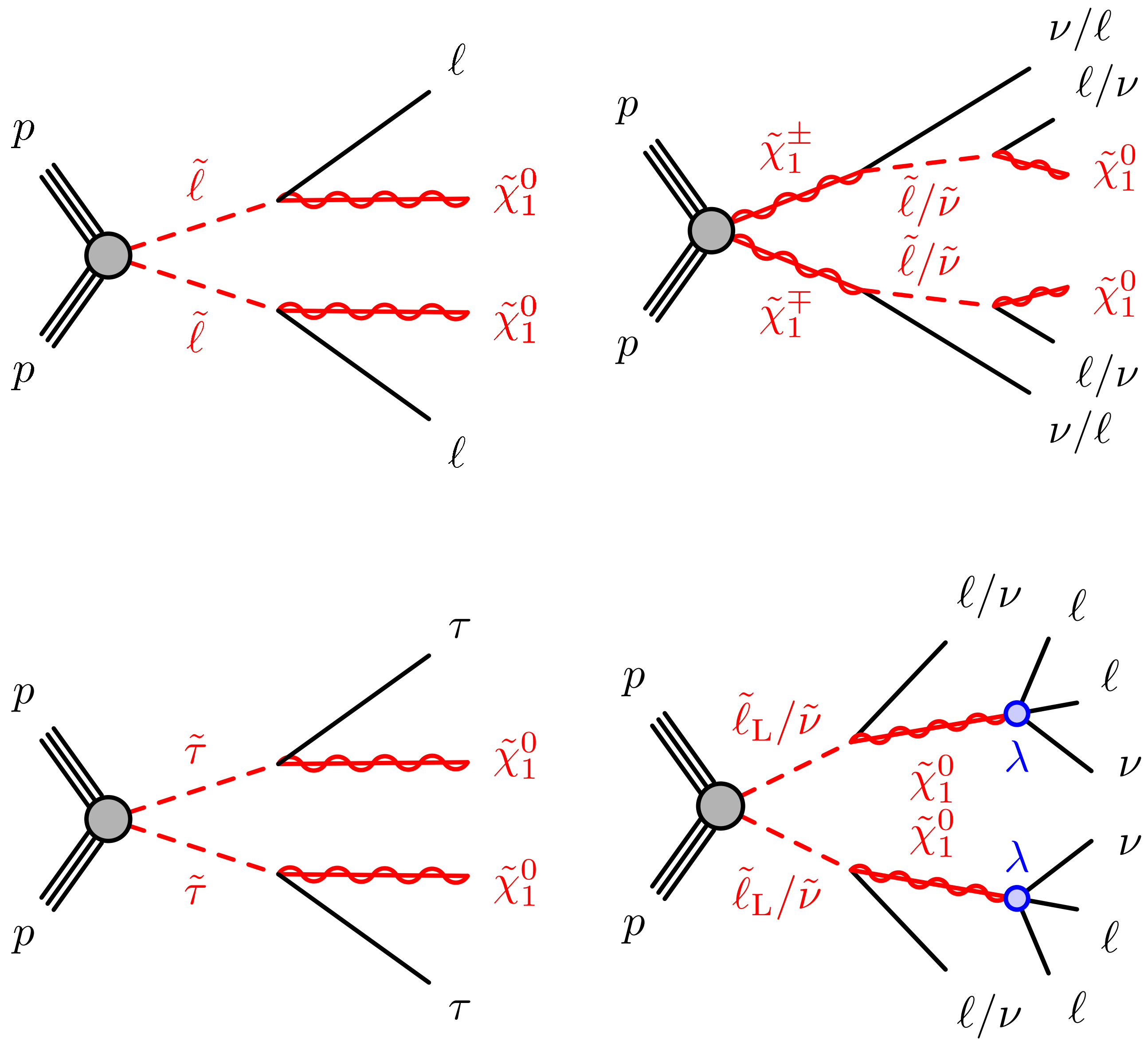




ATLAS and the Sleptons

Several searches at ATLAS target direct sleptons production

- Different experimental final states
- Sleptons ($\tilde{e}/\tilde{\mu}$) → Soft leptons (e/μ) + E_T^{miss} (compressed mass splitting between $\tilde{\ell}$ and $\tilde{\chi}_1^0$)
- Sleptons ($\tilde{e}/\tilde{\mu}$) → high p_T leptons (e/μ) + E_T^{miss}
- Direct stau → hadronic taus + E_T^{miss}
- R-parity violating models
- Both direct production and cascade from heavier particles



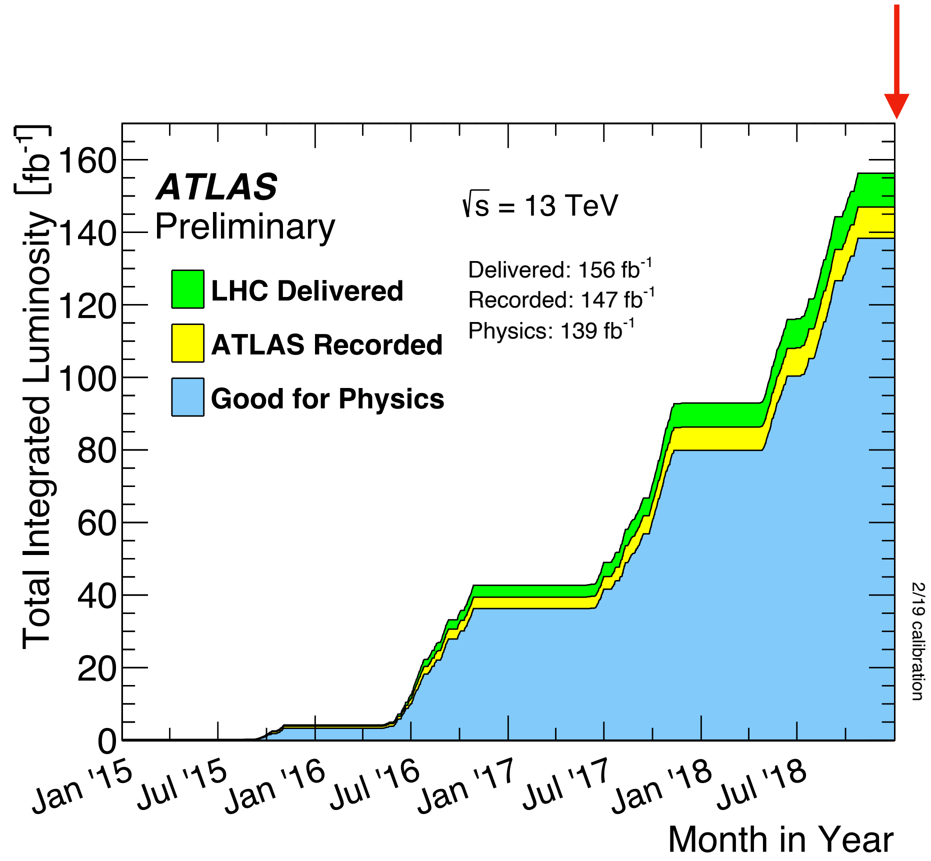
ATLAS and the Sleptons

Analysis references:

(looking at two of these decays in the event)

Signature	Signal	More info
$2\ell + E_T^{miss}$ (**compressed**)	$\tilde{\ell}_{L,R} \rightarrow \ell \tilde{\chi}_1^0$	Phys. Rev. D 101 (2020) 052005
$2\tau + E_T^{miss}$	$\tilde{\tau}_{L,R} \rightarrow \tau \tilde{\chi}_1^0$	Phys. Rev. D 101 (2020) 032009
$2\ell + E_T^{miss}$ + **0 jet**	$\tilde{\chi}_1^{\pm} \rightarrow \tilde{\ell}_{L,R} \nu \rightarrow \ell \nu \tilde{\chi}_1^0$ $\tilde{\ell}_{L,R} \rightarrow \ell \tilde{\chi}_1^0$	Eur. Phys. J. C 80 (2020) 123
$4\ell + E_T^{miss}$	$\tilde{\ell}_{L,R}/\tilde{\nu} \rightarrow \tilde{\chi}_1^0 \ell \rightarrow 3\ell\, \nu$	JHEP 167 (2021)
2 **displaced** ℓ	$\tilde{\ell}_{L,R} \rightarrow \ell \tilde{G}$	Phys. Rev. Lett. 127 (2021) 051802 (*)

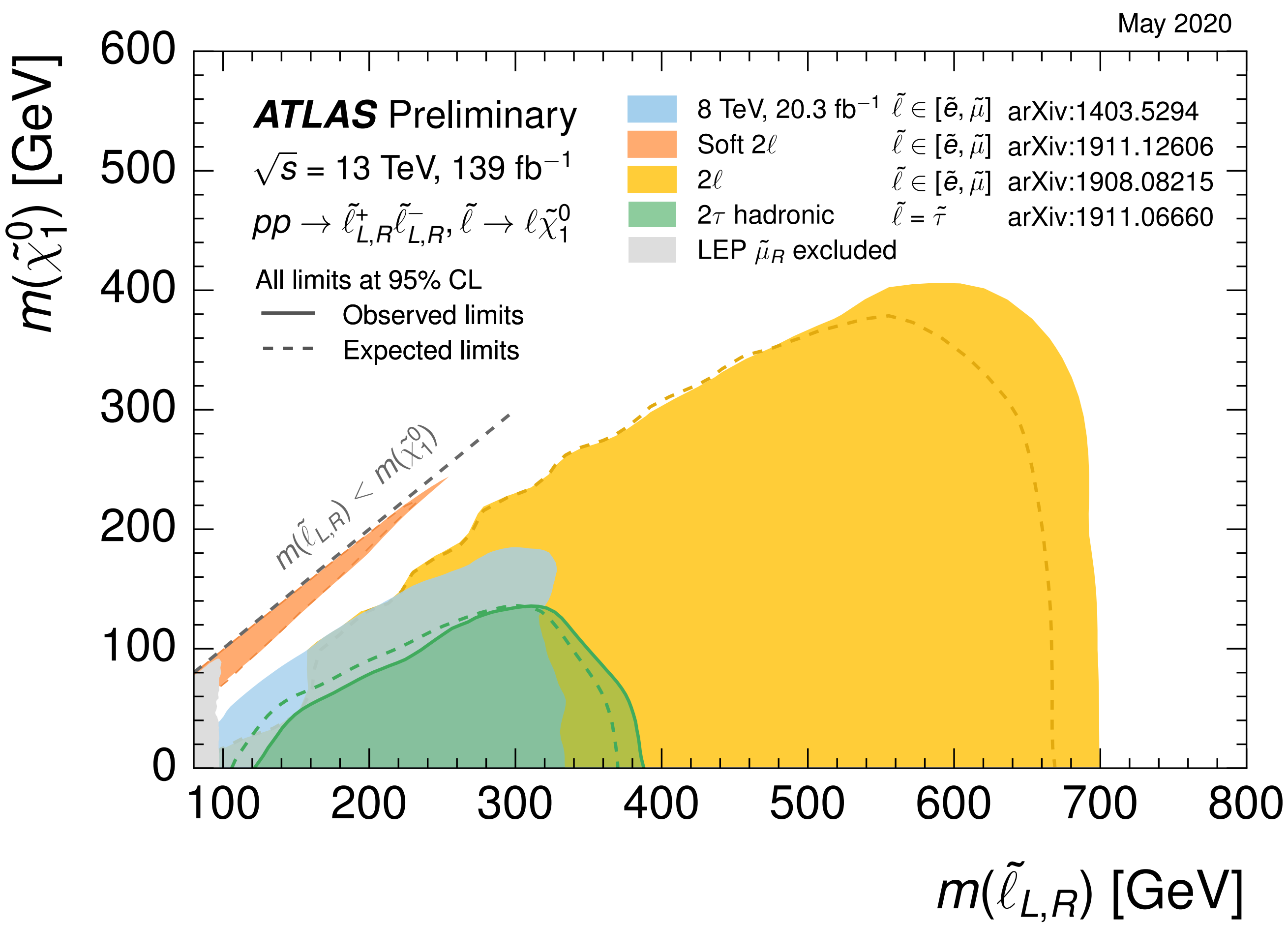
All analysis using full Run 2 dataset

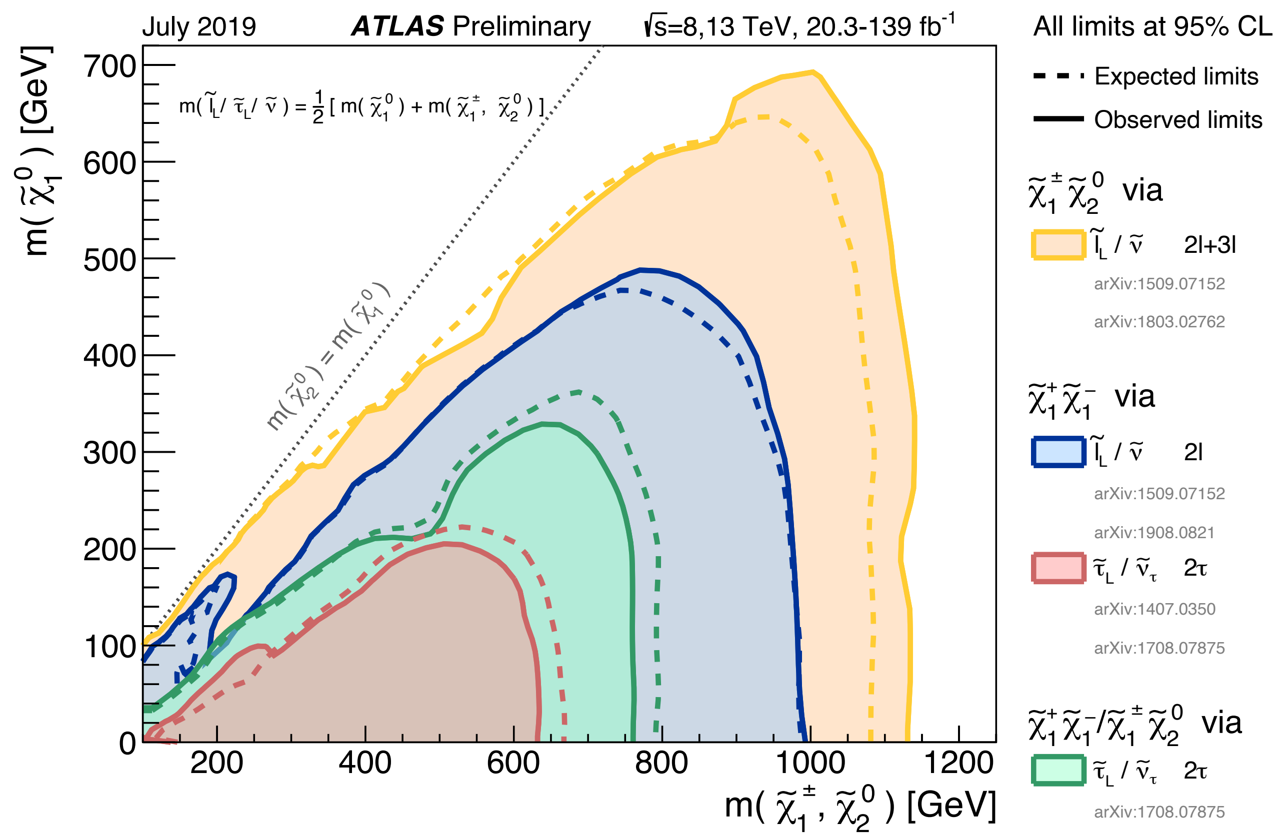


(*) displaced leptons will be presented by Emily Thompson!

ATLAS current limits

Current limits on direct sleptons and chargino/neutralino via sleptons



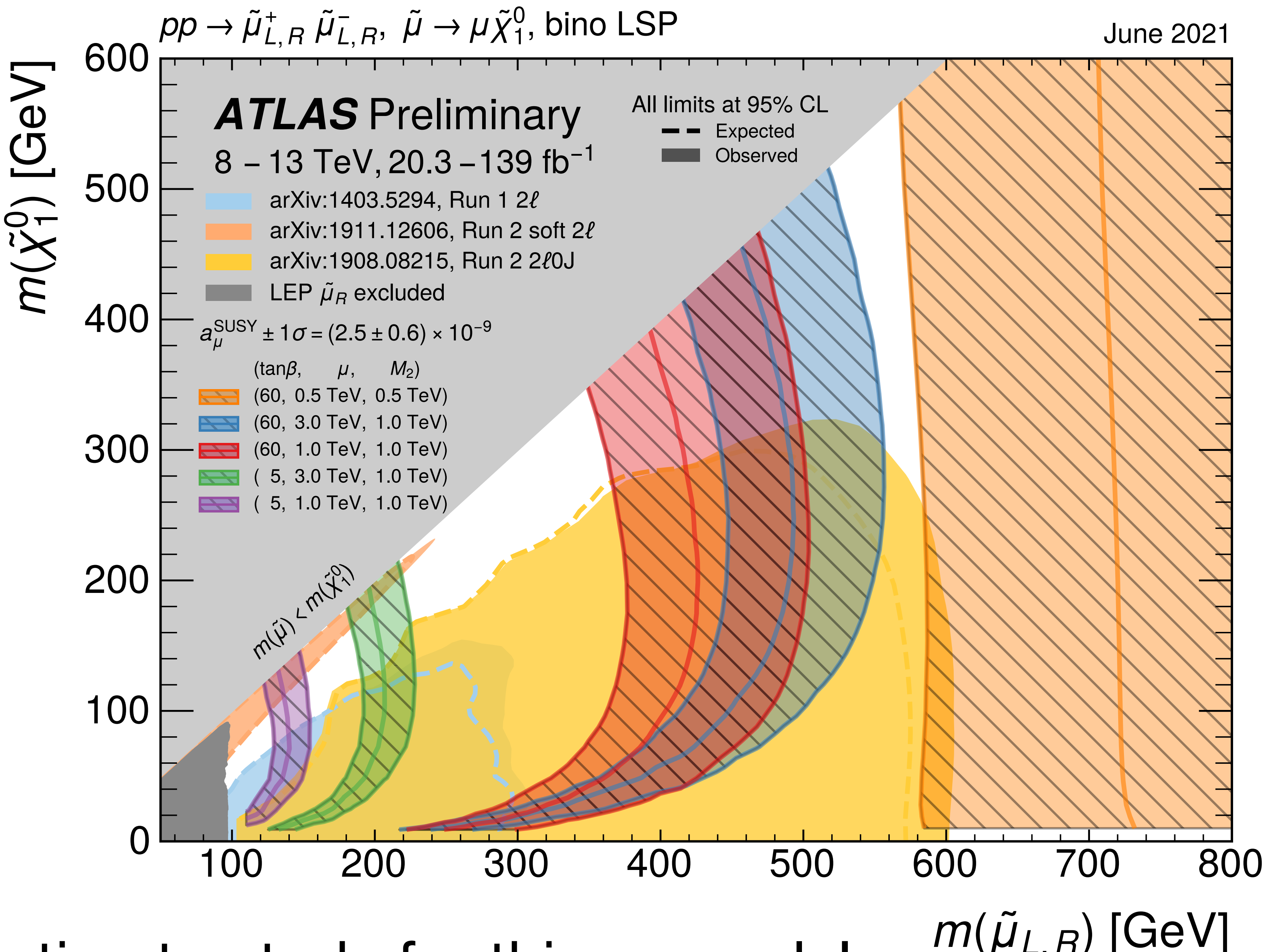


Strong constraint on mass degenerate sleptons

ATLAS current limits and $(g-2)_\mu$

Current limits on (only) **direct smuons** production

- The bands indicate regions that are **compatible** with the observed **muon** $(g-2)_\mu$ anomaly (arXiv:2104.03281)
- Calculated using the **GM2Calc** and **SPheno** packages for $m(\tilde{\chi}_1^0) \geq 10$ GeV

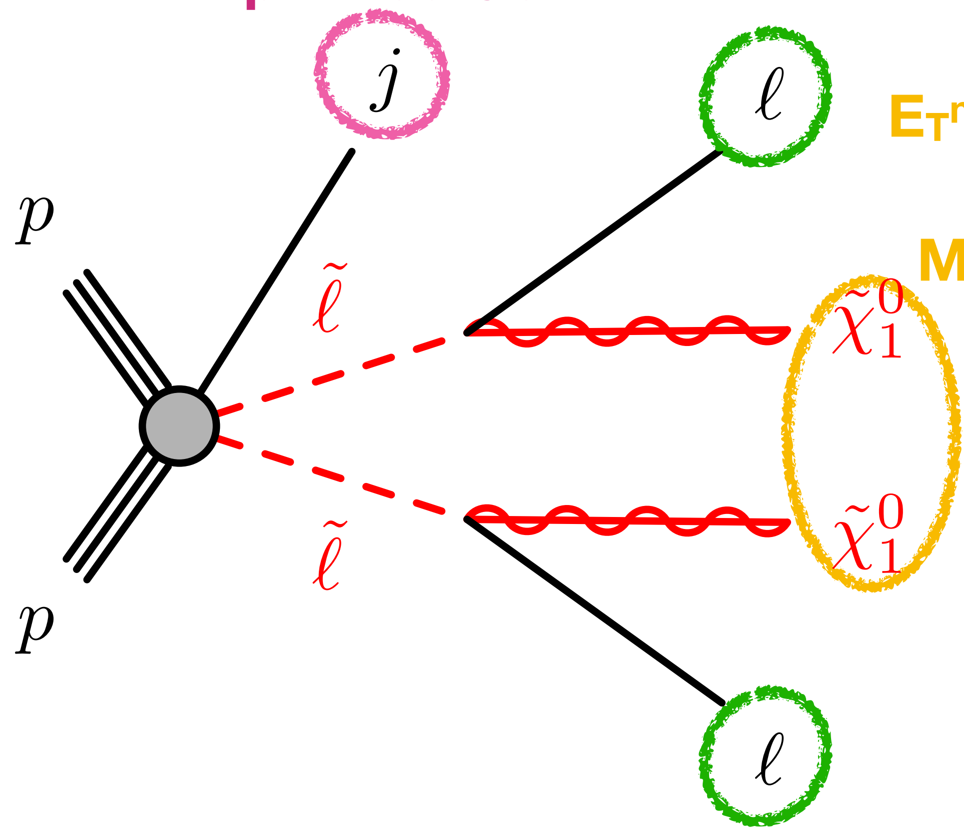


Sleptons are very interesting to study for this anomaly!

Compressed EKW: analysis overview

[Phys. Rev. D 101 (2020) 052005](#) analysis targeting very compressed spectra:

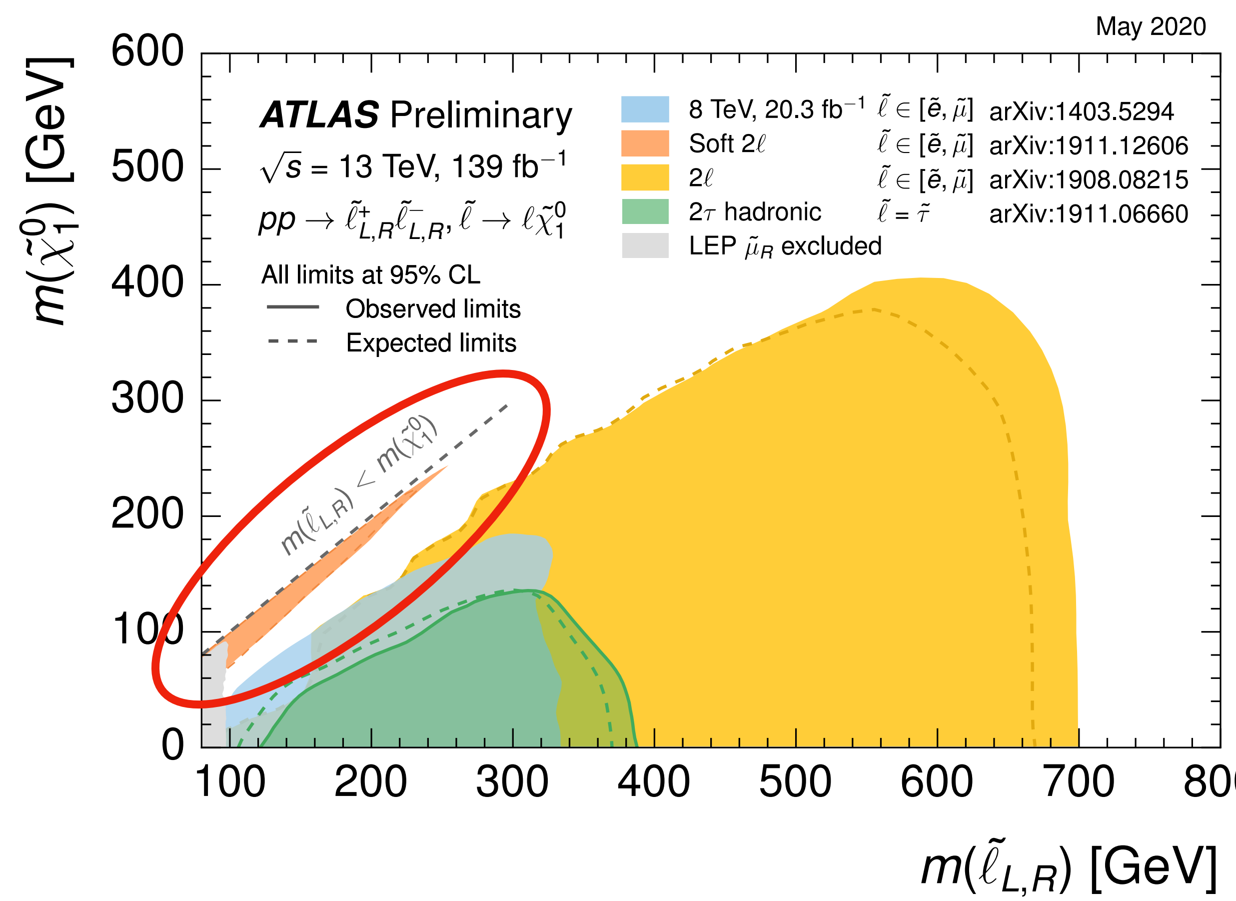
Boost to MET from ISR jet
pT>100 GeV



E_T^{miss}> 200 GeV
+
MET Triggers

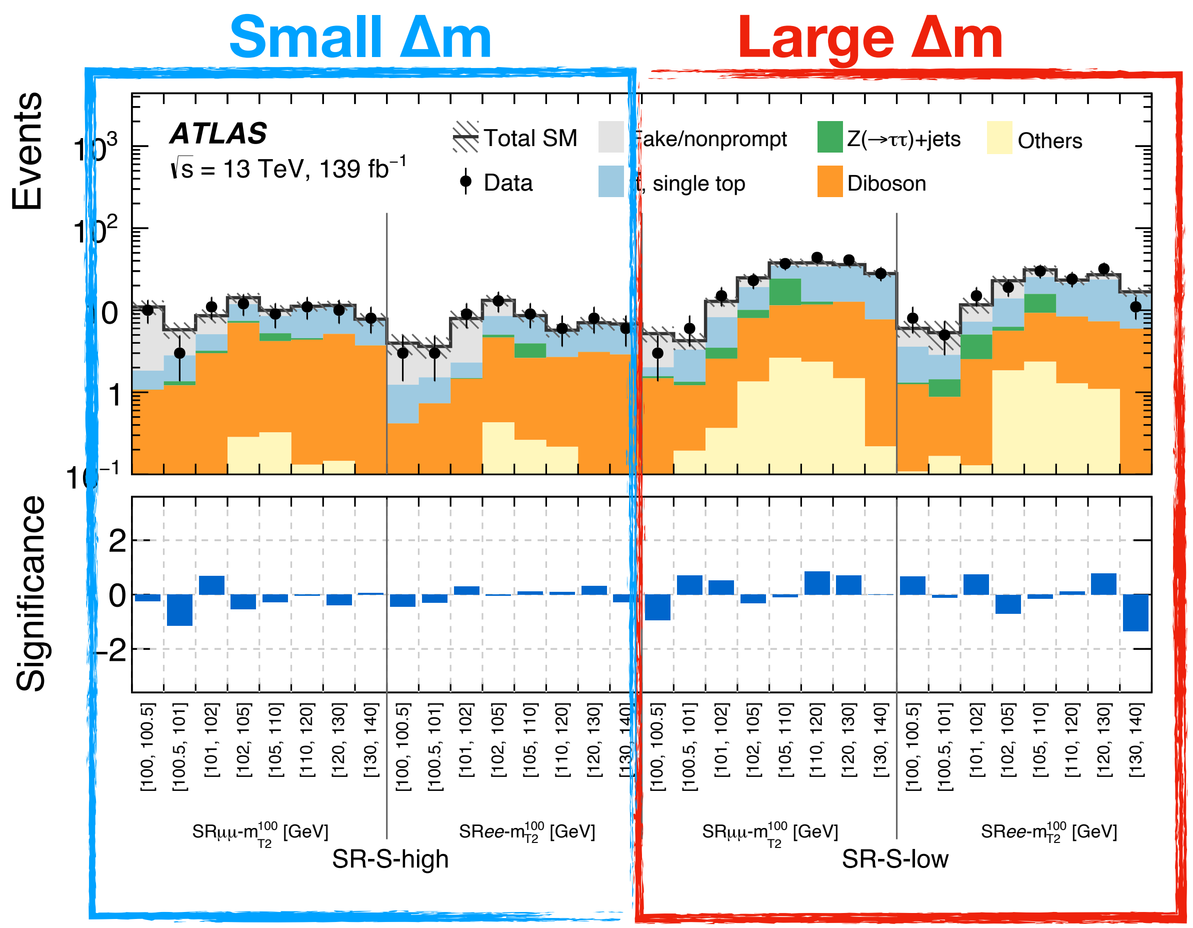
Very soft leptons!
p_T>4(4.5) GeV for muons (electrons)

Pure bino $\tilde{\chi}^0$



Targeting region with
$\Delta m(\tilde{\ell}, \tilde{\chi}^0)$ ~ 2 - 50 GeV

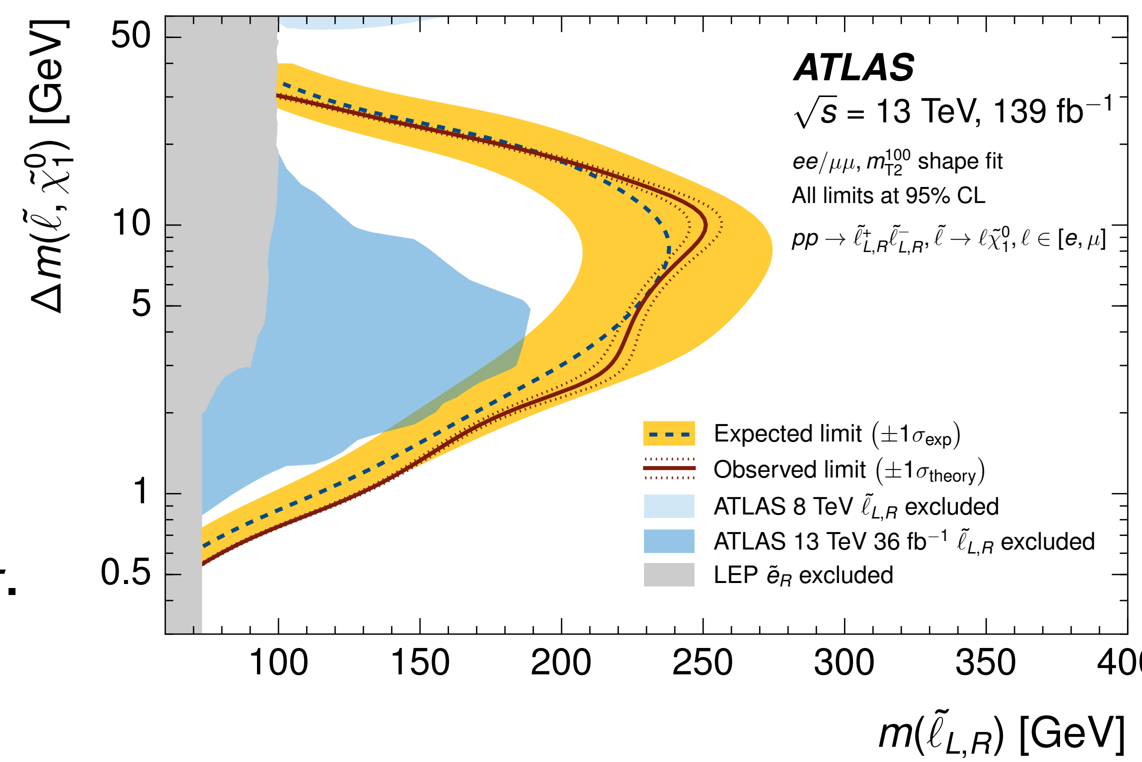
Compressed EKW: analysis Strategy



- Shape fit stransverse mass (m_{T2}) to exploit kinematic edge in signal
- SR divided in High E_T^{miss} (SR-S-high) and low E_T^{miss} (SR-S-low) to target different Δm regions
- Limits set on both mass degenerate sleptons (below) and divided by flavour (backup)

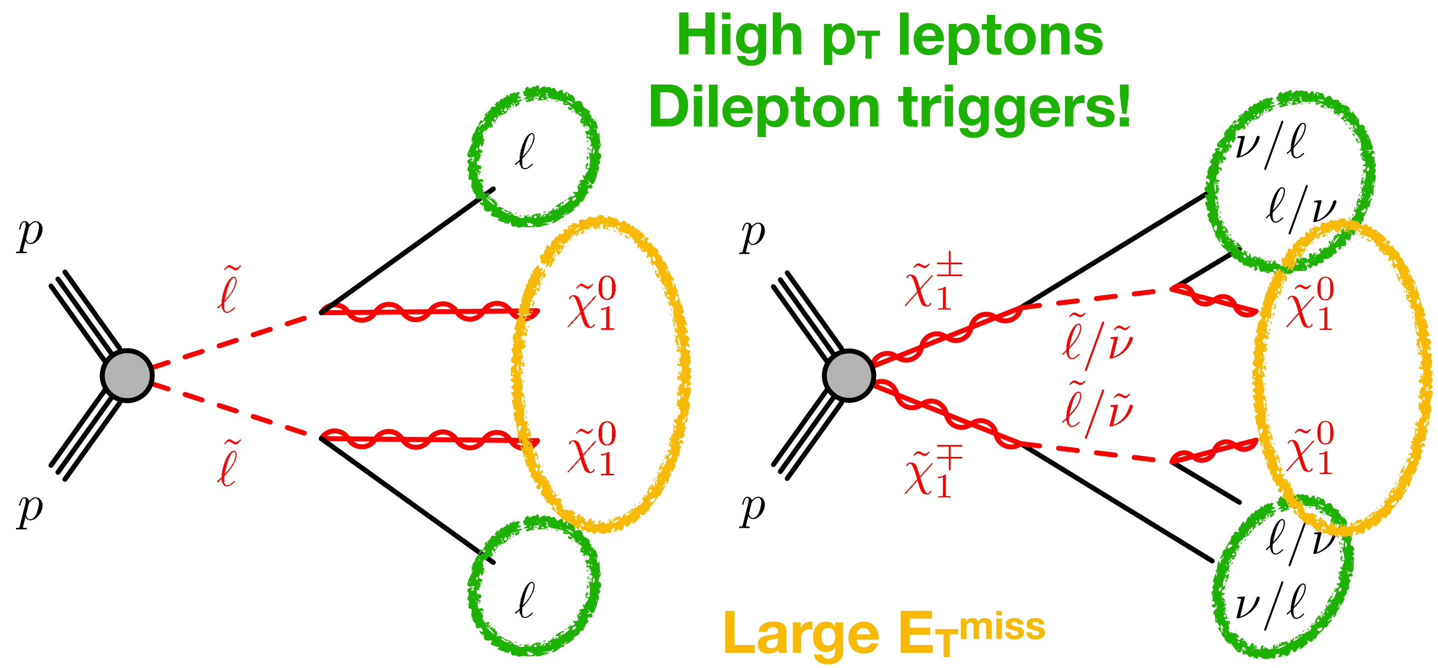
Main Backgrounds:

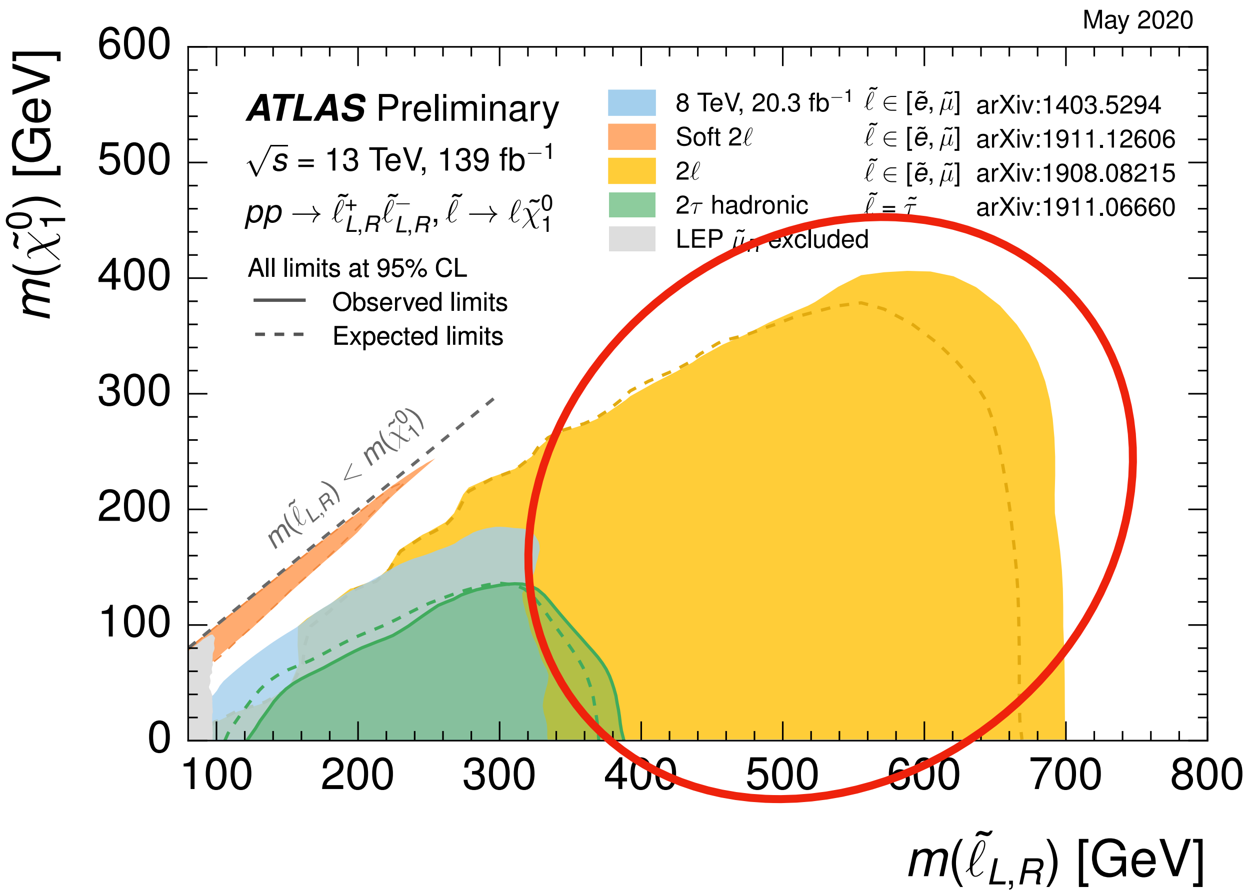
- **Non prompt leptons**: Main source of background → Data Driven method
- **Irreducible backgrounds**: VV, top (tt, Wt), and Z→$\tau\tau$. Taken from MC, normalised in dedicated CR



2ℓ0J: analysis overview

Phys. Rev. D 101 (2020) 032009 Analysis targeting both direct production of sleptons and direct chargino production with intermediated sleptons

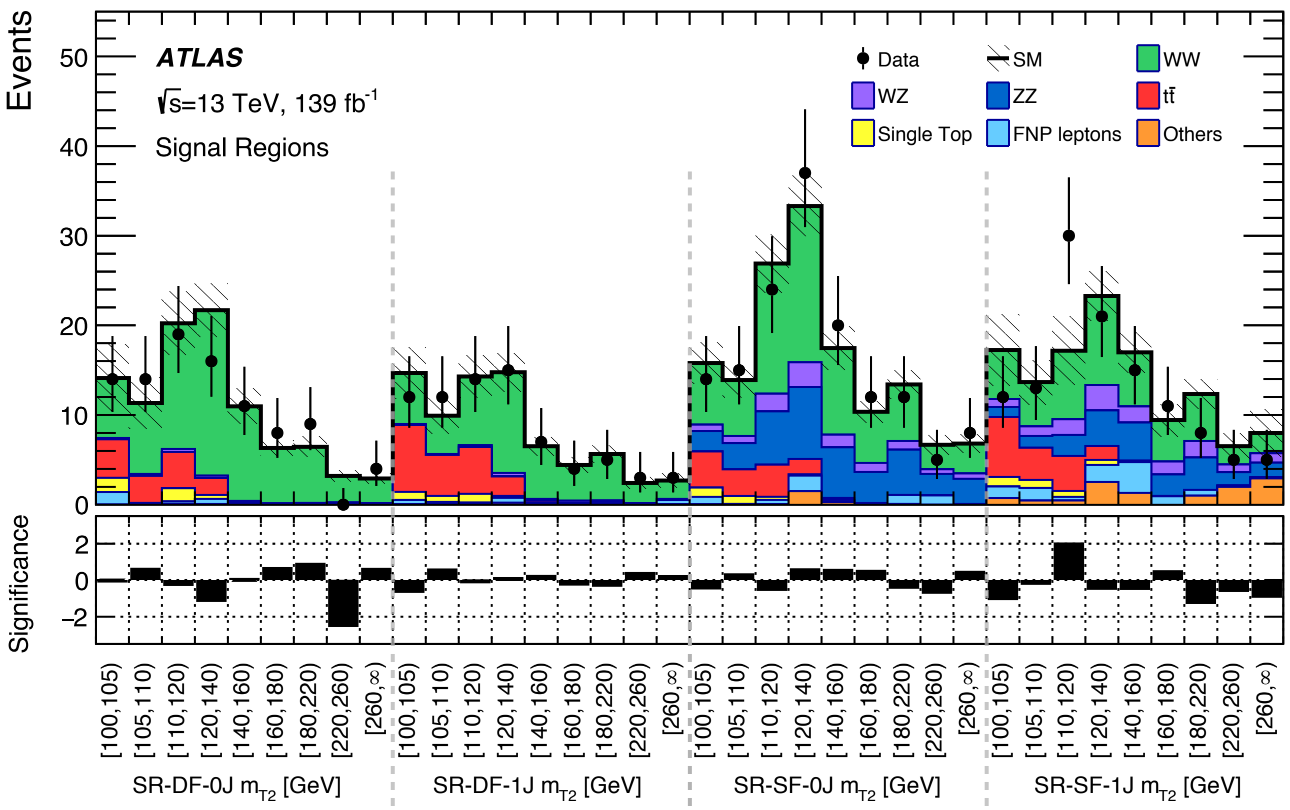




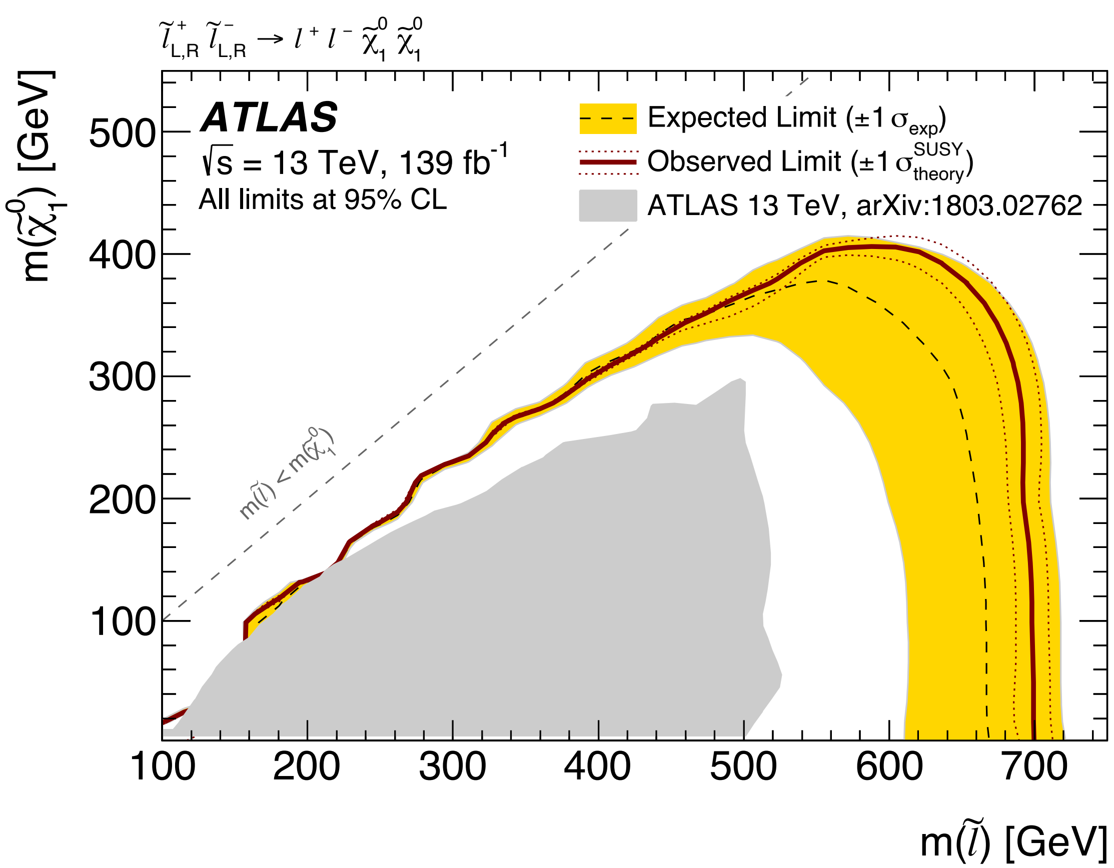
- Shape fit stransverse mass (m_{T2})
- Left model assumes other SUSY particles highly decoupled
- Right model assumes **Wino** $\tilde{\chi}_1^{\pm}$

Targeting region with large $\Delta m(\tilde{\ell}, \tilde{\chi}^0)$

2ℓ0J: analysis strategy



- Binned SR in stransverse mass (m_{T2})
- SR divided by number of jets and lepton flavour (SF/DF)
- Relying on high E_T^{miss} significance to suppress background from fake E_T^{miss}



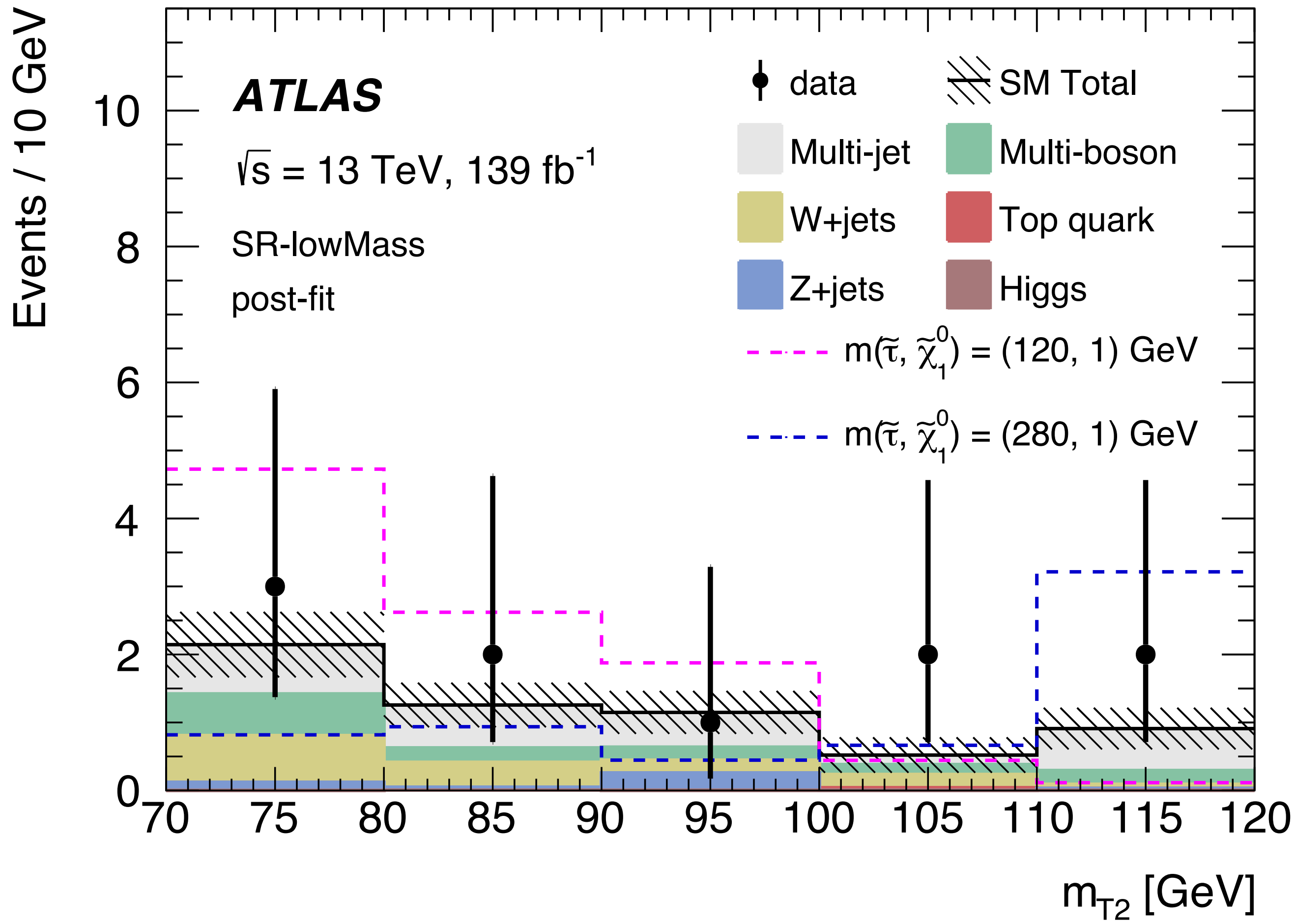
Main Backgrounds:

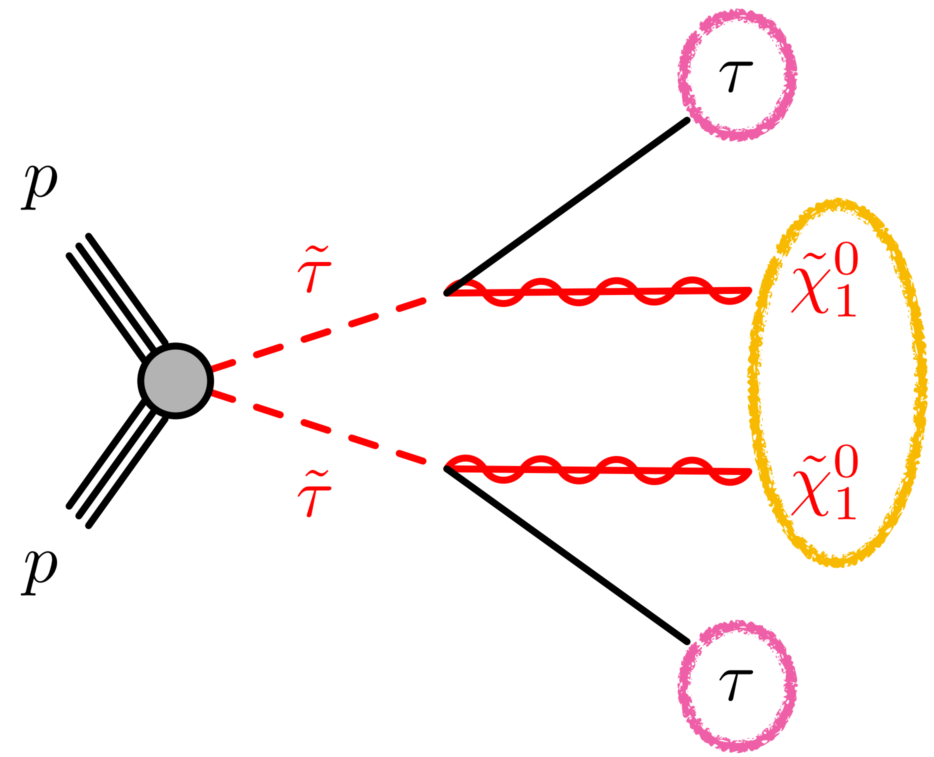
- **Irreducible backgrounds**: top (tt, Wt) and VV. Main source is WW: exactly same signature, especially when Δm ~ mW
- **Non prompt leptons** → Data Driven method

Direct τ: analysis overview

Phys. Rev. D 101 (2020) 032009 Analysis targeting direct production of staus decaying to fully hadronic tau

- First LHC results for direct status
- Analysis based on BDT to identify hadronically decaying taus
- Di-tau trigger + MET trigger
- **High** mass and **low** mass signal region (orthogonal)



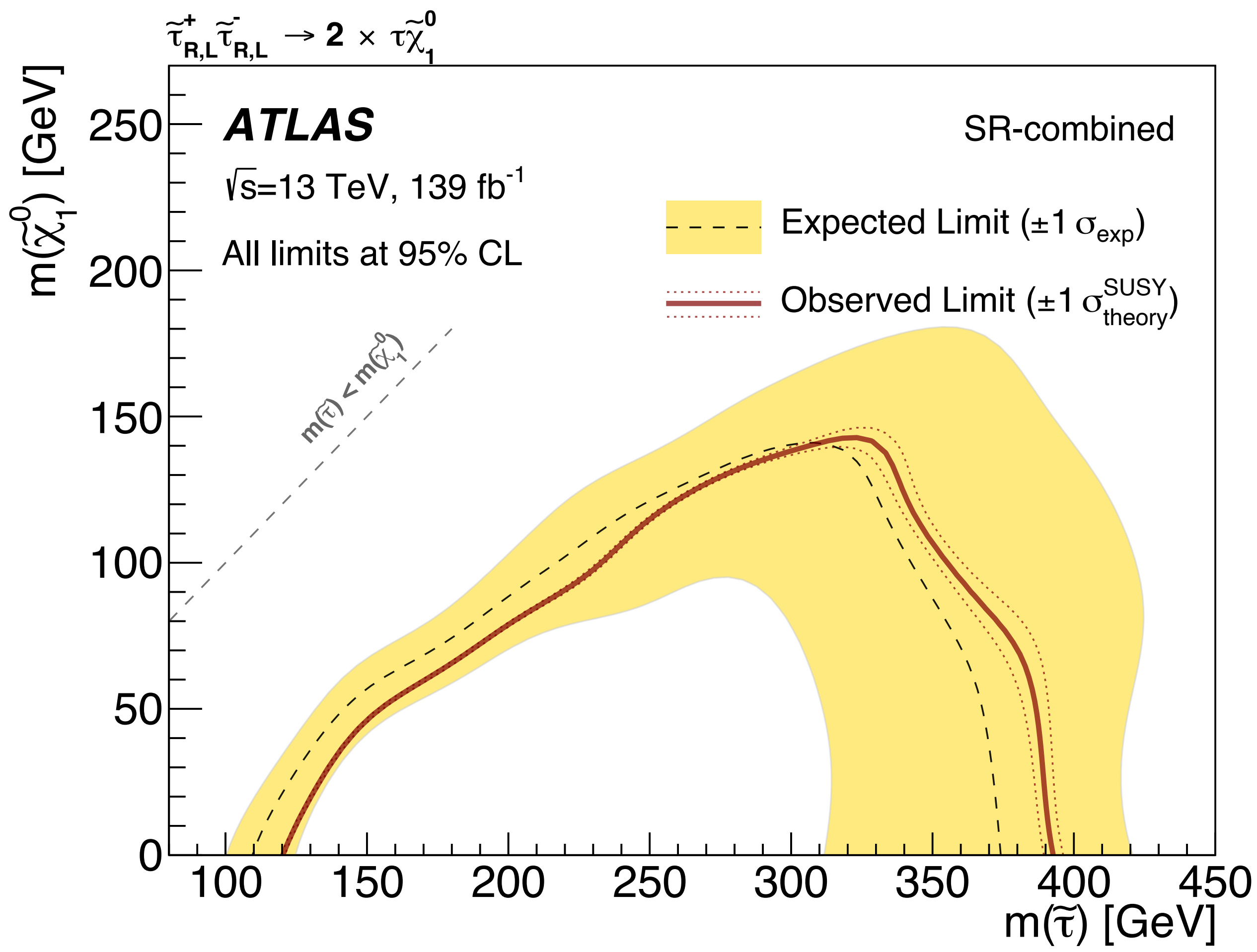


Main Backgrounds:

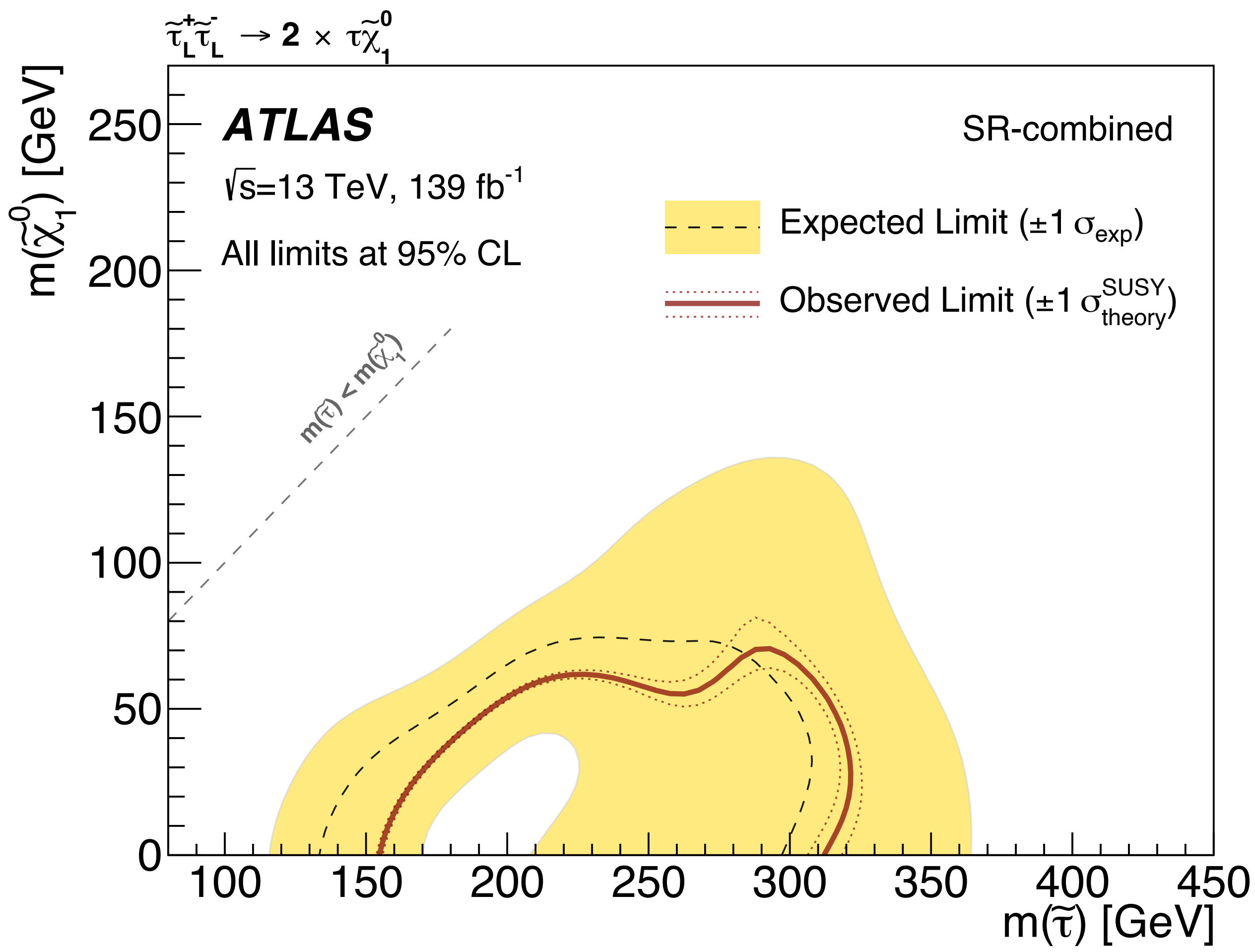
- **Multijet backgrond (2 fakes τ)**: main background, estimated with ABCD method
- **W+jets background (1 fake 1 real τ)**→ Control Region

Direct τ: results

No excess observed. Limits set on sleptons masses (two SR combined)



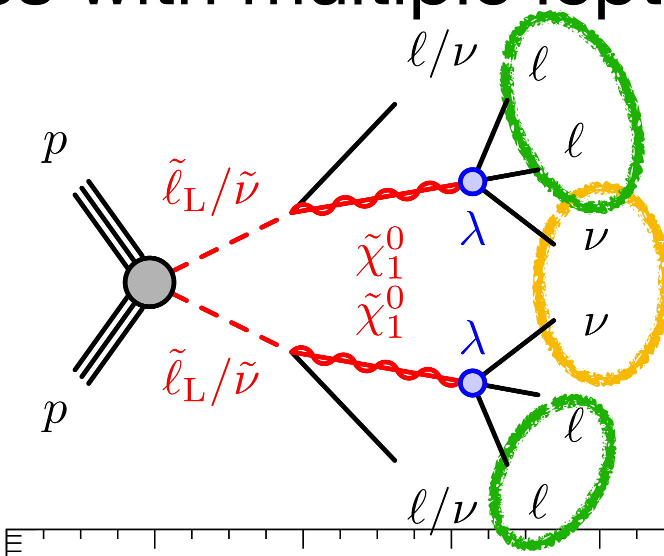
Combined production of $\tilde{\tau}_L/\tilde{\tau}_R$



Only $\tilde{\tau}_L$ production

Multi lepton: analysis overview

JHEP 167 (2021) Analysis targeting final states with multiple leptons (4+)



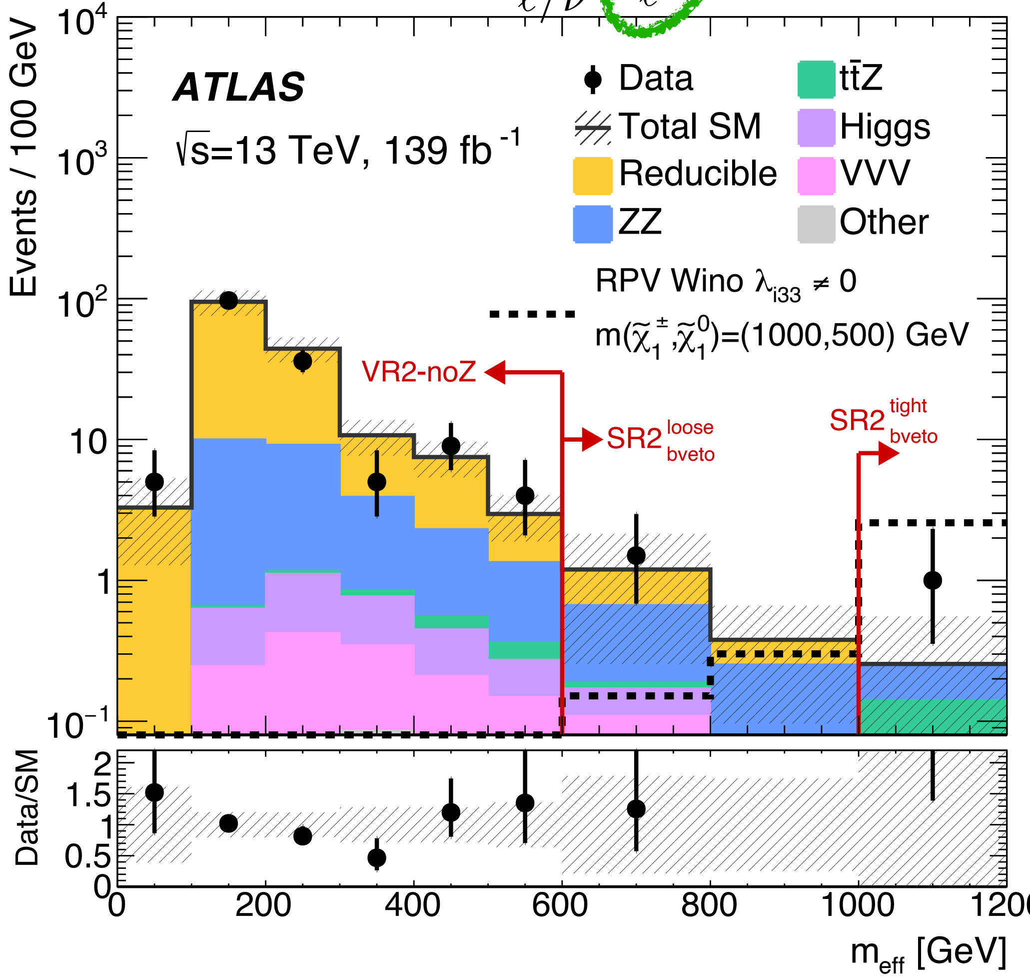
- Assuming R-Parity violating (RPV) term (λ): neutralino (LSP) to leptons ($\tilde{\chi}_1^0 \to \ell^{\pm}\ell^{\mp}\nu$).
- Sleptons (NLSP) mass degenerate
- Two assumptions on λ:
  - Only decay to e/μ allowed (λ_{12k})
  - Only decay to τ and e/μ allowed (λ_{k33})

Scenario	$\tilde{\chi}_1^0$ branching ratios					
	$e^+e^-\nu$	$e^{\pm}\mu^{\mp}\nu$	$\mu^+\mu^-\nu$	$e^{\pm}\tau^{\mp}\nu$	$\tau^+\tau^-\nu$	$\mu^{\pm}\tau^{\mp}\nu$
$LL\bar{E}12k$	1/4	1/2	1/4	0	0	0
$LL\bar{E}i33$	0	0	0	1/4	1/2	1/4

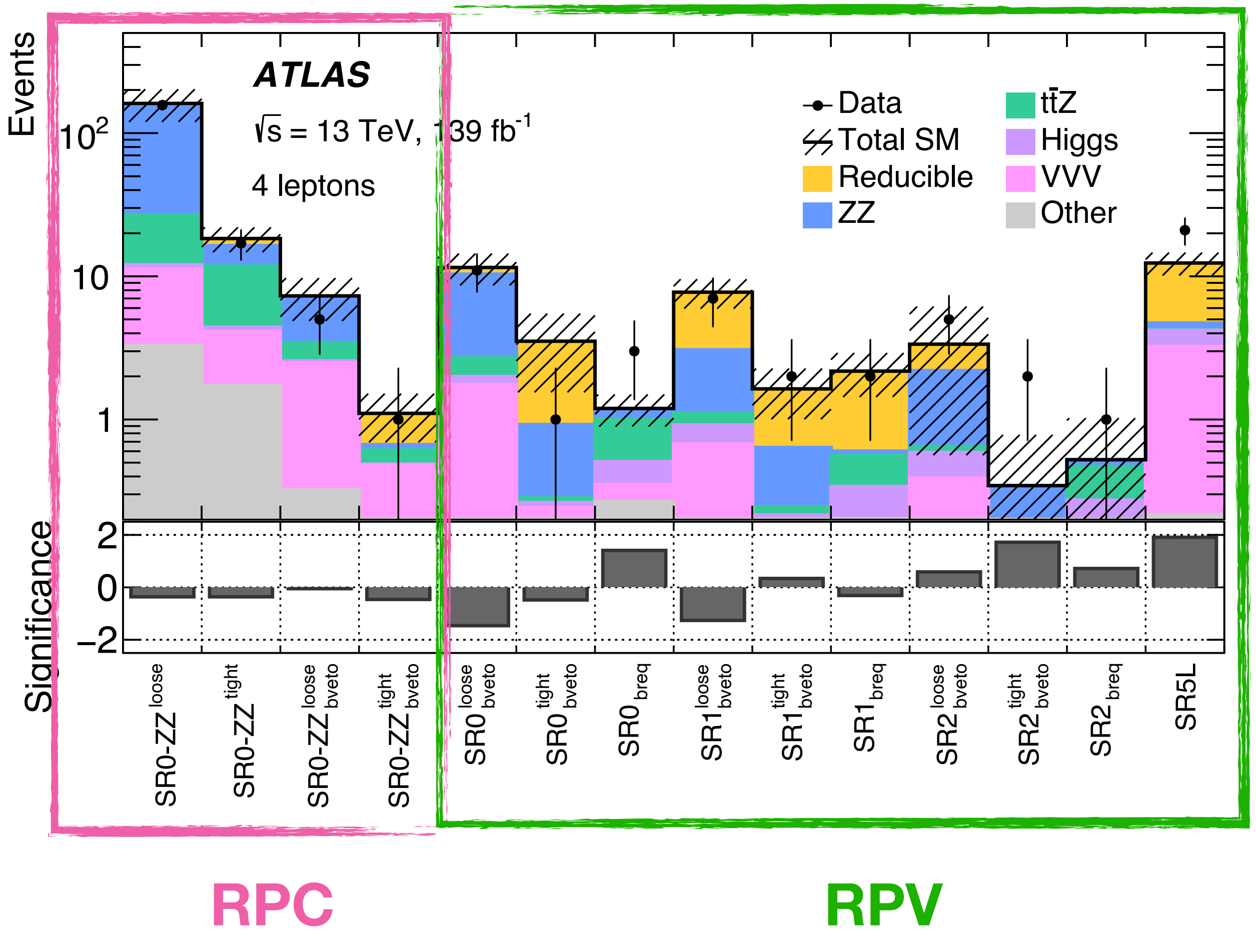
- Signal regions based on m_{eff}

$$m_{eff} = E_T^{miss} + \sum p_T^{lep} + \sum p_T^{jet}$$

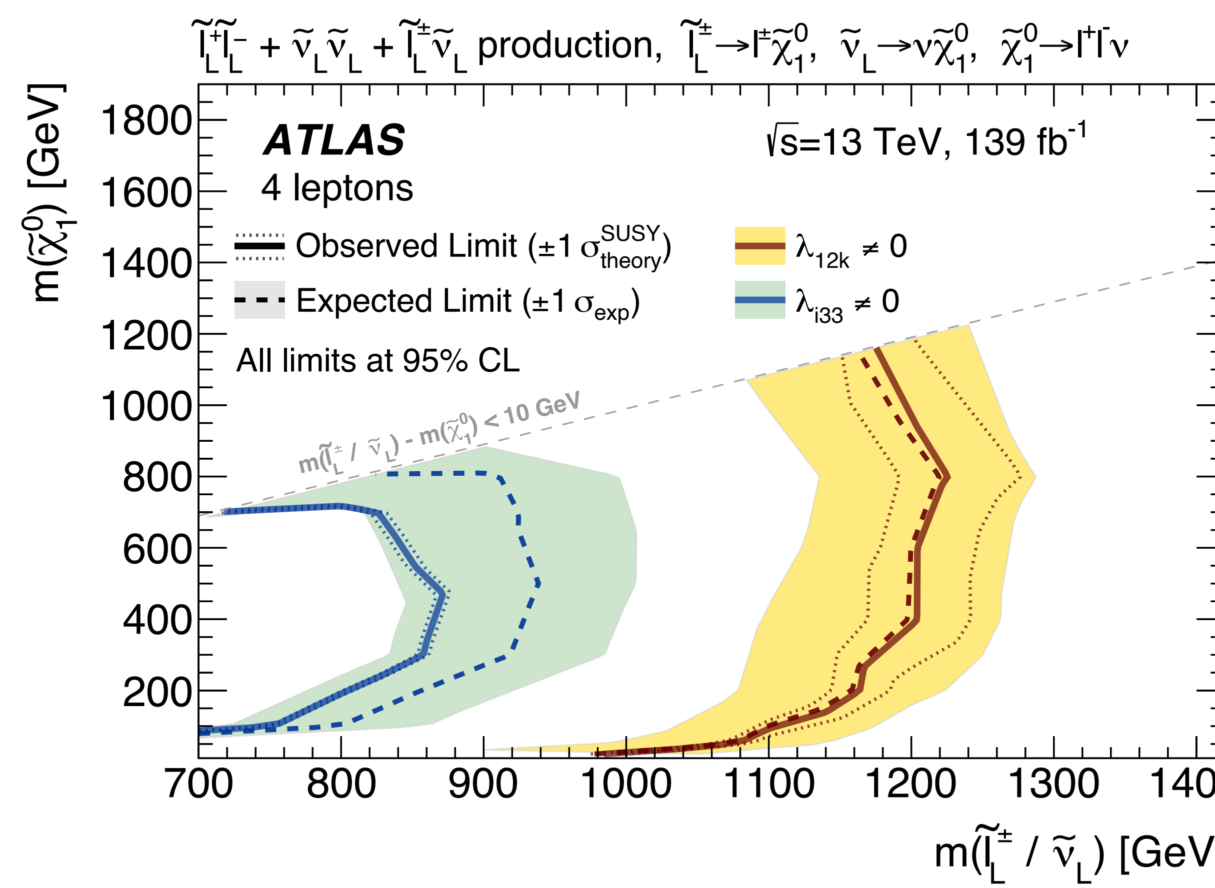
- Analysis has also R-Parity Conserving (RPC) signals



Multi lepton: analysis strategy



- Binned SR to target different scenarios (**RPV** and **RPC**)
- SR divided in b-jets veto and b-jet "agnostic"
- SR split by number of taus and electrons/muons:
  - 4Leptons 0Taus, 3Leptons 1Tau, 2Leptons 2Tau



Main Backgrounds:

- **Irreducible background** → From ZZ and ttZ. MC normalised in data (main bkg in 4L0T)
- **Reducible backgrounds**: estimated in data with Fake Factor method (main bkg in 3L1T/2L2T)

Conclusions

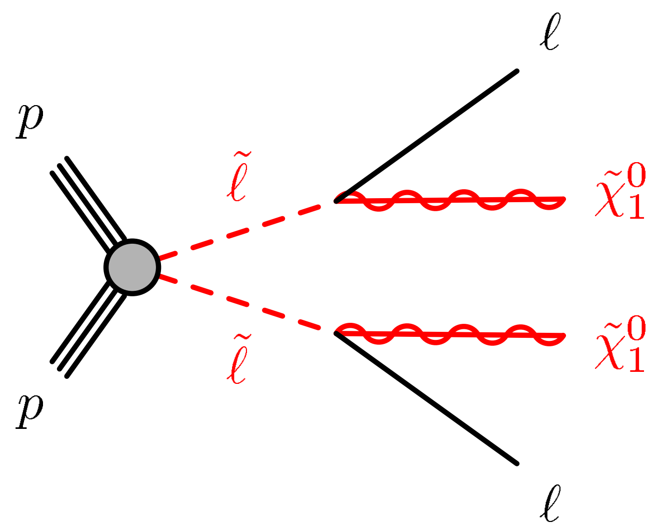
- Sleptons are a well motivated scenario to investigate
- ATLAS has a large variety of searches targeting sleptons in different final states and with different models
- No significant excess has been observed
- Improved reconstruction techniques and new strategies allowed us to reach new phase space and set new strong limits
- Stay tuned for even more results from ATLAS!

Backup

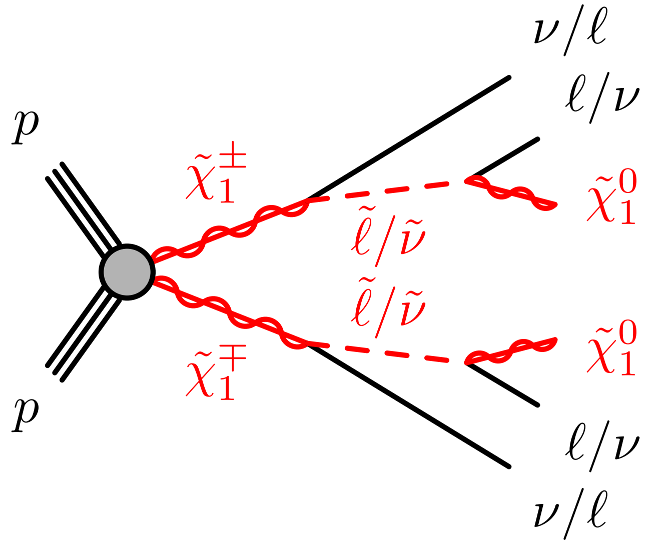
ATLAS and the Sleptons

Several searches at ATLAS target direct sleptons production

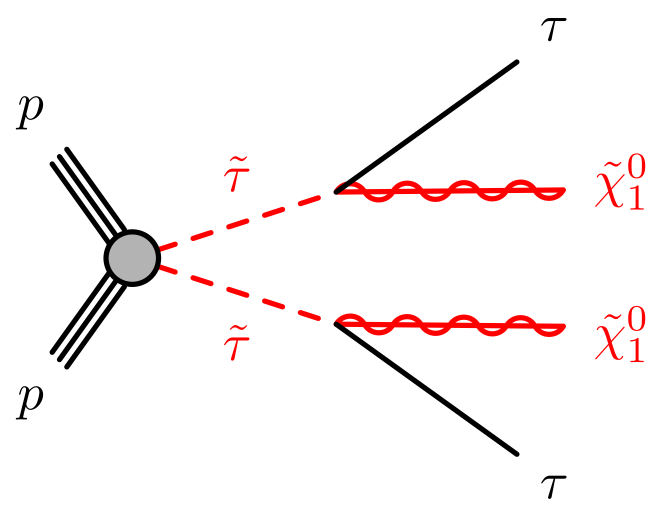
Sleptons ($\tilde{e}/\tilde{\mu}$) →
Soft/hard leptons (e/μ) + E_T^{miss} (+ ISR jet)



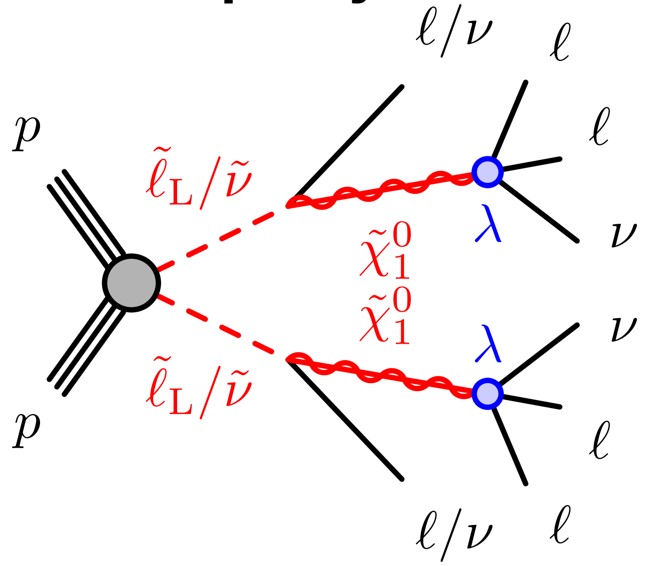
Chargino to neutralino via sleptons



Direct stau in tau



R-parity violation



Compressed EKW: analysis Strategy

Compressed analysis SR definition

Variable	Preselection requirements 2ℓ	$1\ell 1T$
Number of leptons (tracks)	= 2 leptons	= 1 lepton and ≥ 1 track
Lepton p_{T} [GeV]	$p_{\mathrm{T}}^{\ell_1} > 5$	$p_{\mathrm{T}}^{\ell} < 10$
$\Delta R_{\ell\ell}$	$\Delta R_{ee} > 0.30$, $\Delta R_{\mu\mu} > 0.05$, $\Delta R_{e\mu} > 0.2$	$0.05 < \Delta R_{\ell\mathrm{track}} < 1.5$
Lepton (track) charge and flavor	$e^{\pm}e^{\mp}$ or $\mu^{\pm}\mu^{\mp}$	$e^{\pm}e^{\mp}$ or $\mu^{\pm}\mu^{\mp}$
Lepton (track) invariant mass [GeV]	$3 < m_{ee} < 60$, $1 < m_{\mu\mu} < 60$	$0.5 < m_{\ell\mathrm{track}} < 5$
J/ψ invariant mass [GeV]	veto $3 < m_{\ell\ell} < 3.2$	veto $3 < m_{\ell\mathrm{track}} < 3.2$
$m_{\tau\tau}$ [GeV]	< 0 or > 160	no requirement
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 120	> 120
Number of jets	≥ 1	≥ 1
Number of b-tagged jets	= 0	no requirement
Leading jet p_{T} [GeV]	≥ 100	≥ 100
$\min(\Delta\phi(\text{any jet}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}))$	> 0.4	> 0.4
$\Delta\phi(j_1, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}})$ †	≥ 2.0	≥ 2.0

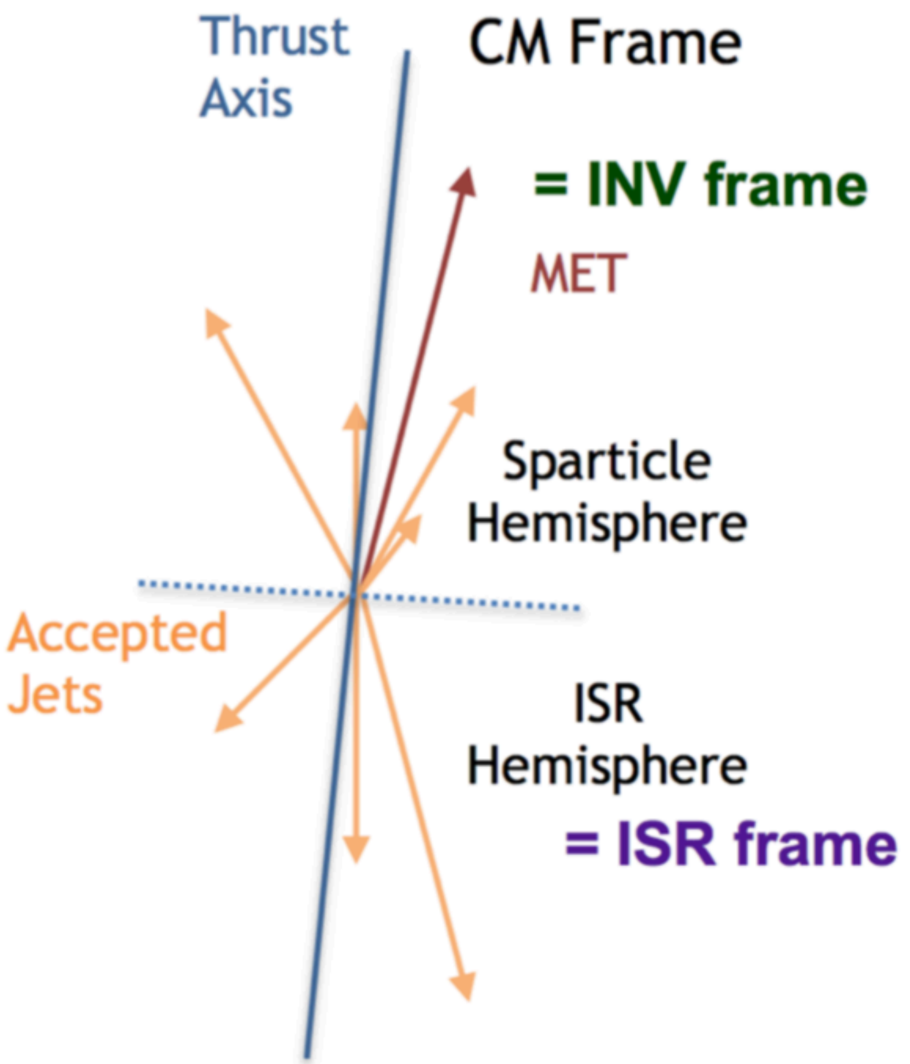
Variable	Slepton SR Requirements SR–S–low	SR–S–high
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	[150, 200]	> 200
m_{T2}^{100} [GeV]	< 140	< 140
$p_{\mathrm{T}}^{\ell_2}$ [GeV]	$> \min(15, 7.5 + 0.75 \times (m_{\mathrm{T2}} - 100))$	$> \min(20, 2.5 + 2.5 \times (m_{\mathrm{T2}} - 100))$
R_{ISR}	[0.8, 1.0]	$[\max(0.85, 0.98 - 0.02 \times (m_{\mathrm{T2}} - 100)), 1.0]$

Compressed EKW: analysis Strategy

Stansverse mass defined by:

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

Compressed EKW: analysis Strategy



$$R_{\mathrm{ISR}} \equiv \frac{\left|\vec{p}^{\,\mathbf{CM}}_{\mathbf{I},T} \cdot \hat{p}^{\,\mathbf{CM}}_{\mathbf{ISR},T}\right|}{\left|\vec{p}^{\,\mathbf{CM}}_{\mathbf{ISR},T}\right|}$$

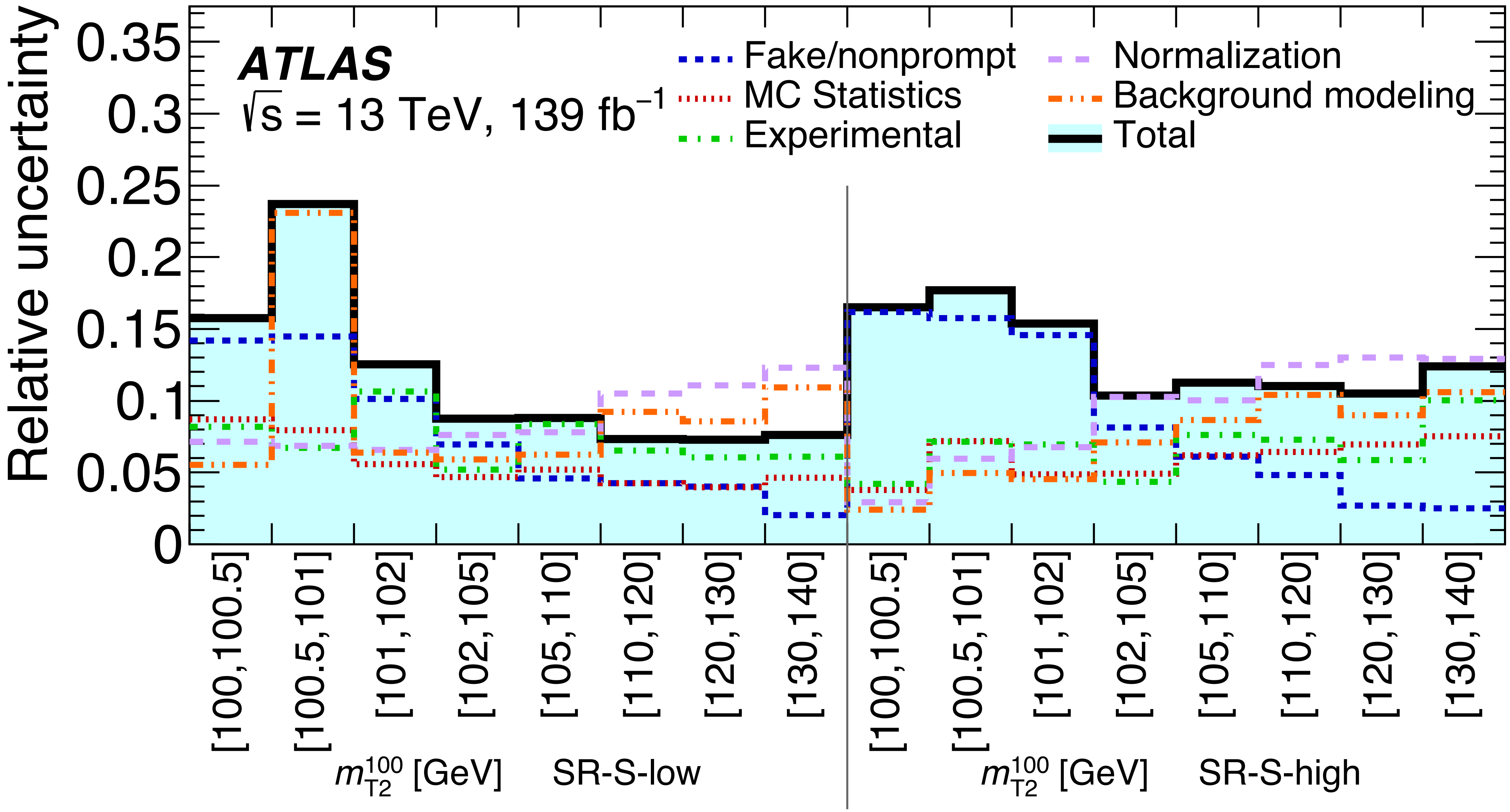
$$\sim \frac{m_{daughter}}{m_{parent}}$$

(for very small mass splittings)

$m_{T,S}$ = transverse mass of the sparticle system

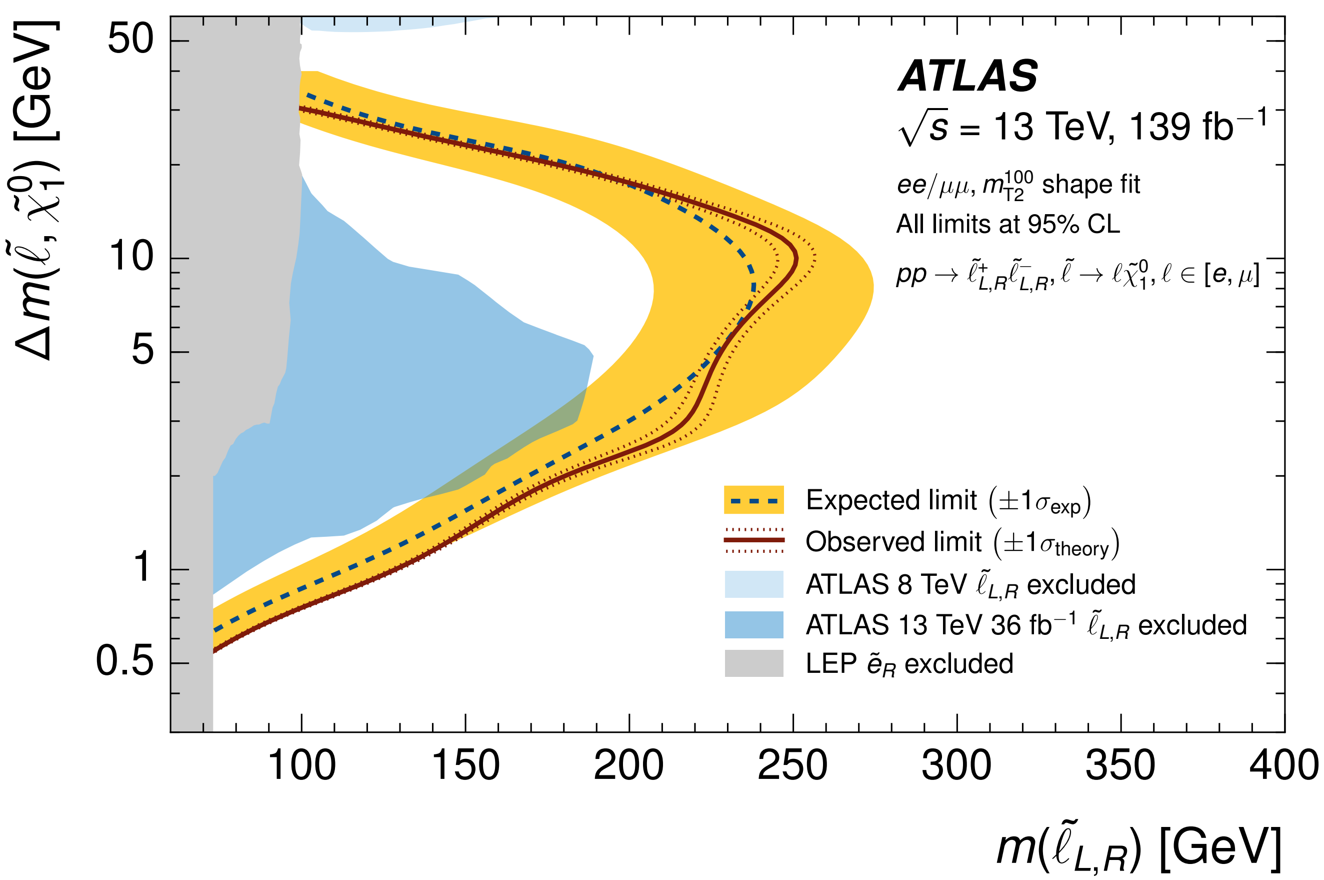
Compressed EKW: analysis Strategy

Compressed analysis SR systematics

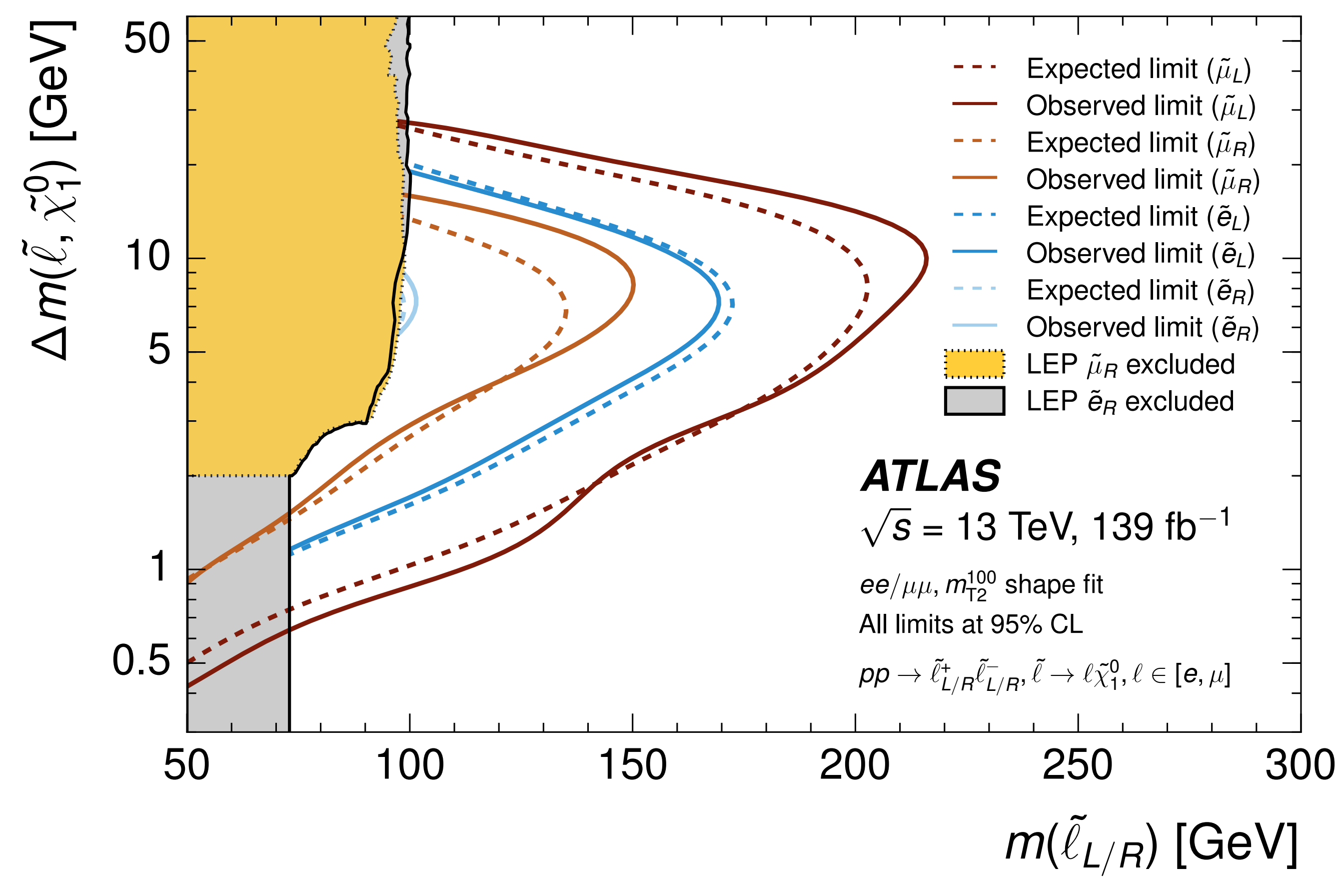


Compressed EKW: results

No excess observed. Limits set on sleptons masses



Considering mass degenerate sleptons



Limits divided by flavour

Direct τ: analysis Strategy

Direct τ analysis SR definition

SR-lowMass	SR-highMass
2 tight τ (OS)	2 medium τ (OS) , $\geq$ 1 tight τ
asymmetric di-τ trigger	di-τ+$E_{\mathrm{T}}^{\mathrm{miss}}$ trigger
$75 < E_{\mathrm{T}}^{\mathrm{miss}} < 150$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV
τ p_{T} cut described in Section 5	
light lepton veto and 3rd medium τ veto	
b-jet veto	
Z/H veto ($m(\tau_1, \tau_2) > 120$ GeV)	
$\lvert\Delta\phi(\tau_1, \tau_2)\rvert > 0.8$	
$\Delta R(\tau_1, \tau_2) < 3.2$	
$m_{\mathrm{T2}} > 70$ GeV	

2ℓ0J: analysis Strategy

2ℓ0J analysis SR definition

Signal region (SR)	SR-DF-0J	SR-DF-1J	SR-SF-0J	SR-SF-1J
$n_{\text{non-}b\text{-tagged jets}}$	$= 0$	$= 1$	$= 0$	$= 1$
$m_{\ell_1\ell_2}$ [GeV]	>100		>121.2	
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	>110			
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance	>10			
$n_{b\text{-tagged jets}}$	$= 0$			
Binned SRs				
m_{T2} [GeV]	$\in[100,105)$ $\in[105,110)$ $\in[110,120)$ $\in[120,140)$ $\in[140,160)$ $\in[160,180)$ $\in[180,220)$ $\in[220,260)$ $\in[260,\infty)$			
Inclusive SRs				
m_{T2} [GeV]	$\in[100,\infty)$ $\in[160,\infty)$ $\in[100,120)$ $\in[120,160)$			

2ℓ0J: analysis Strategy

2ℓ0J analysis SR Systematics

Region m_{T2} [GeV]	SR-DF-0J ∈[100,∞)	SR-DF-1J ∈[100,∞)	SR-SF-0J ∈[100,∞)	SR-SF-1J ∈[100,∞)
Total background expectation	96	75	144	124
MC statistical uncertainties	3%	3%	2%	3%
WW normalisation	7%	6%	4%	3%
VZ normalisation	$< 1\%$	$< 1\%$	1%	1%
$t\bar{t}$ normalisation	1%	2%	$< 1\%$	1%
Diboson theoretical uncertainties	7%	7%	4%	3%
Top theoretical uncertainties	7%	8%	3%	6%
E_T^{miss} modelling	1%	1%	$< 1\%$	2%
Jet energy scale	2%	3%	2%	2%
Jet energy resolution	1%	2%	1%	2%
Pile-up reweighting	$< 1\%$	1%	$< 1\%$	$< 1\%$
b-tagging	$< 1\%$	2%	$< 1\%$	1%
Lepton modelling	1%	1%	1%	3%
FNP leptons	1%	1%	1%	1%
Total systematic uncertainties	15%	12%	8%	10%

Direct τ: analysis Strategy

Direct τ analysis SR systematics

Source of systematic uncertainty on background prediction	SR-lowMass [%]	SR-highMass [%]
Statistical uncertainty of MC samples	11	21
τ-lepton identification and energy scale	19	10
Normalization uncertainties of the multi-jet background	12	8
Multi-jet estimation	4	10
Jet energy scale and resolution	5	8
Diboson theory uncertainty	5	6
W+jets theory uncertainty	2	3
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft-term resolution and scale	2	2
Total	28	32

Source of systematic uncertainty on signal prediction	SR-lowMass [%]	SR-highMass [%]
m $(\tilde{\tau},\tilde{\chi}_1^0)$ [GeV]	(120, 1)	(280, 1)
τ-lepton identification and energy scale	29	14
Statistical uncertainty of MC samples	6	10
Jet energy scale and resolution	3	2
Signal cross-section uncertainty	2	2
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft-term resolution and scale	3	< 1
Total	31	17

Multi Lepton: analysis Strategy

Multi Lepton analysis SR definition

Name	Signal Region	$N(e,\mu)$	$N(\tau_{had})$	$N(b\text{-tagged jets})$	Z boson	Selection	Target
$4L0T$	$\mathtt{SR0\text{-}ZZ}^{\text{loose}}_{\text{bveto}}$	≥ 4	≥ 0	$= 0$	require 1st & 2nd	$E_T^{\text{miss}} > 100$ GeV	higgsino GGM
	$\mathtt{SR0\text{-}ZZ}^{\text{tight}}_{\text{bveto}}$	≥ 4	≥ 0	$= 0$	require 1st & 2nd	$E_T^{\text{miss}} > 200$ GeV	higgsino GGM
	$\mathtt{SR0\text{-}ZZ}^{\text{loose}}$	≥ 4	≥ 0	≥ 0	require 1st & 2nd	$E_T^{\text{miss}} > 50$ GeV	Excess from Ref. [18]
	$\mathtt{SR0\text{-}ZZ}^{\text{tight}}$	≥ 4	≥ 0	≥ 0	require 1st & 2nd	$E_T^{\text{miss}} > 100$ GeV	Excess from Ref. [18]
	$\mathtt{SR0}^{\text{loose}}_{\text{bveto}}$	≥ 4	≥ 0	$= 0$	veto	$m_{\text{eff}} > 600$ GeV	General
	$\mathtt{SR0}^{\text{tight}}_{\text{bveto}}$	≥ 4	≥ 0	$= 0$	veto	$m_{\text{eff}} > 1250$ GeV	RPV $LL\bar{E}12k$
	$\mathtt{SR0}_{\text{breq}}$	≥ 4	≥ 0	≥ 1	veto	$m_{\text{eff}} > 1300$ GeV	RPV $LL\bar{E}12k$
$3L1T$	$\mathtt{SR1}^{\text{loose}}_{\text{bveto}}$	$= 3$	≥ 1	$= 0$	veto	$m_{\text{eff}} > 600$ GeV	General
	$\mathtt{SR1}^{\text{tight}}_{\text{bveto}}$	$= 3$	≥ 1	$= 0$	veto	$m_{\text{eff}} > 1000$ GeV	RPV $LL\bar{E}i33$
	$\mathtt{SR1}_{\text{breq}}$	$= 3$	≥ 1	≥ 1	veto	$m_{\text{eff}} > 1300$ GeV	RPV $LL\bar{E}i33$
$2L2T$	$\mathtt{SR2}^{\text{loose}}_{\text{bveto}}$	$= 2$	≥ 2	$= 0$	veto	$m_{\text{eff}} > 600$ GeV	General
	$\mathtt{SR2}^{\text{tight}}_{\text{bveto}}$	$= 2$	≥ 2	$= 0$	veto	$m_{\text{eff}} > 1000$ GeV	RPV $LL\bar{E}i33$
	$\mathtt{SR2}_{\text{breq}}$	$= 2$	≥ 2	≥ 1	veto	$m_{\text{eff}} > 1100$ GeV	RPV $LL\bar{E}i33$
$5L0T$	SR5L	≥ 5	≥ 0	≥ 0	–	–	General

Multi Leptons: analysis Strategy

Multi Leptons analysis SR Systematics