ATLAS BSM Searches

24th of March

Aaron O'Neill on behalf of the ATLAS Collaboration

ATLAS EXPERIMENT

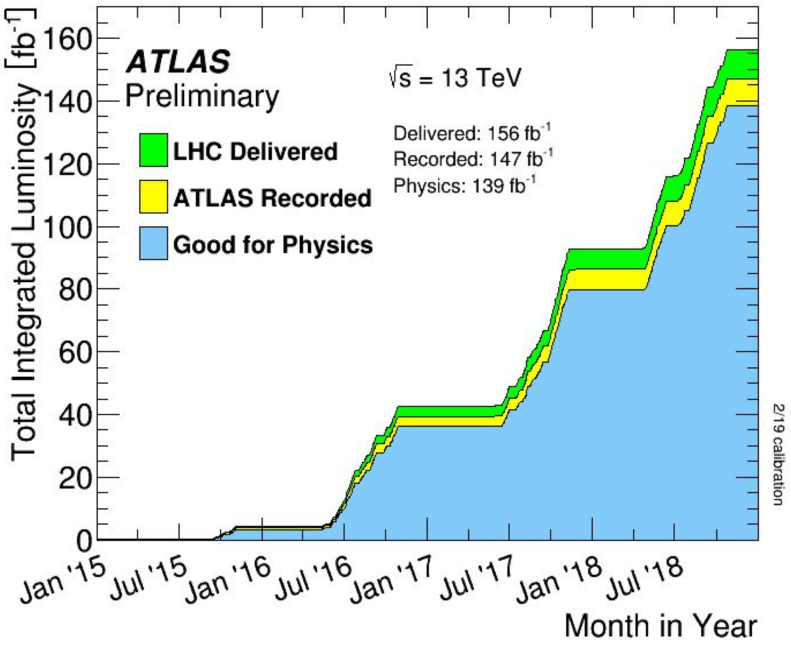
UNIVERSITÄT BERN

Rencontres de Moriond since 1966

Introduction

- Run 2 of the LHC just completed with a record breaking luminosity recorded (revised lumi calculation to 140 ifb).
- Problems with the standard model; no dark matter, the hierarchy problem, etc.
- A solution? There are many extensions possible, including; supersymmetry, leptoquarks, gravitons, axions, to name a few.
- Could BSM physics be hiding in this record breaking dataset?
- This talk will cover a few of the most recent results from ATLAS using Run 2 data.

It must be noted that there are many more excellent efforts that unfortunately could not be covered here (e.g. Strong SS/3L in another talk).



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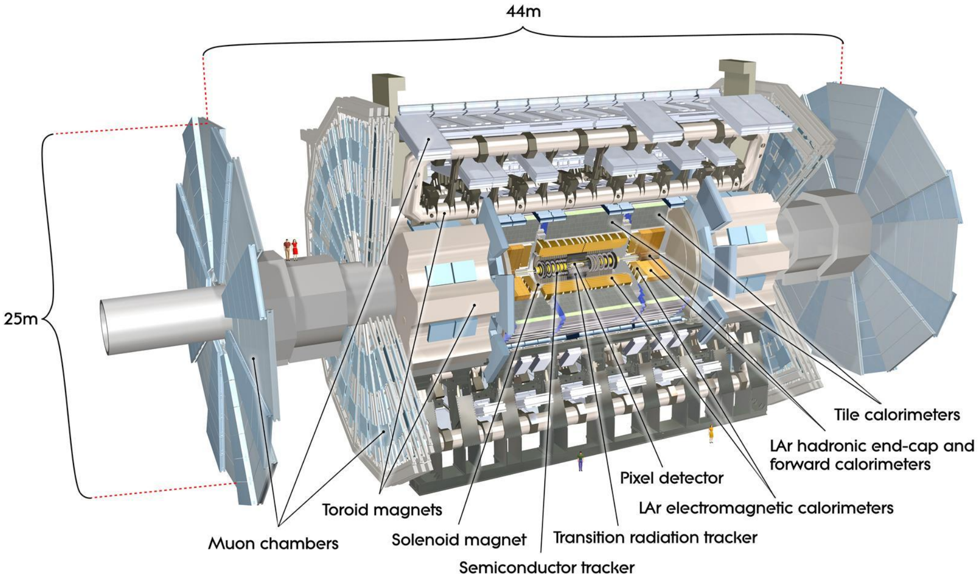

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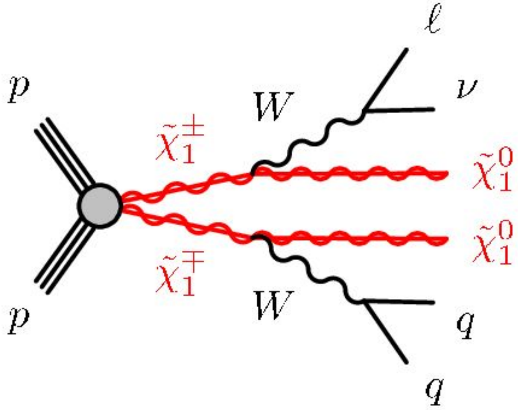
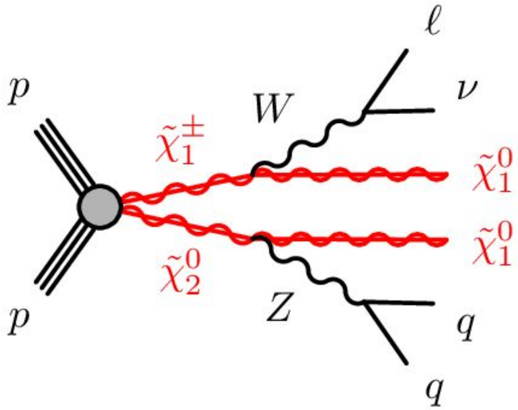
Electroweak 1L: Signal Models

- This search focuses on final states with one lepton, jets and missing transverse momentum.
- This is characteristic of the production and decay of electroweakinos.
- Two models are sought:
  - with one being the production of chargino-chargino pairs.
  - The other with chargino and neutralino production.
- The chargino and neutralinos decay via:

$$\tilde{\chi}_1^{\pm} \rightarrow W^{\pm} \tilde{\chi}_1^0 \qquad \tilde{\chi}_2^0 \rightarrow Z \tilde{\chi}_1^0$$

- Resulting in a signature of exactly one isolated lepton, two jets and missing transverse momentum.

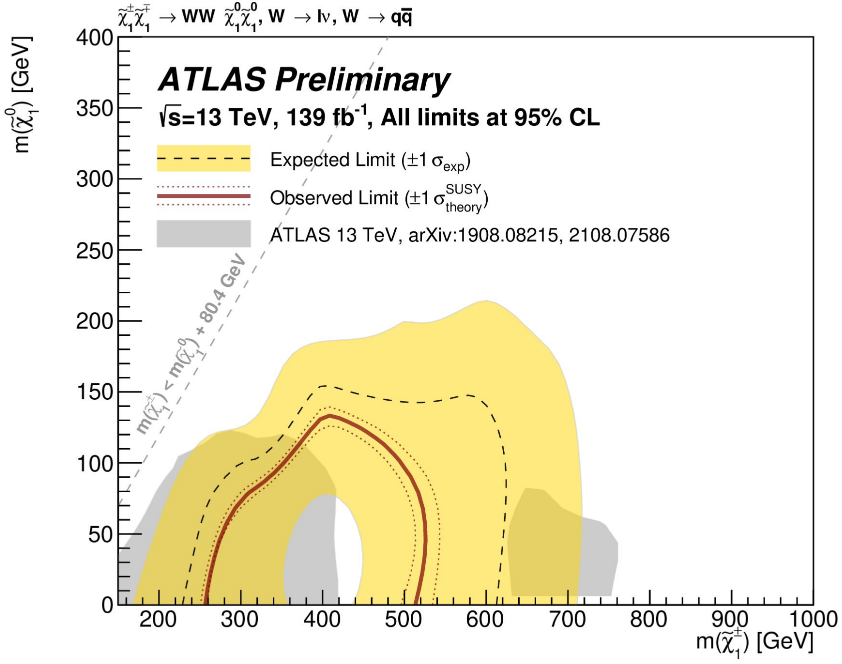




ATLAS-CONF-2022-059

Electroweak 1L: Results

- No significant excess was found and so limits were calculated (**maximum of 2.1 σ** for SRMM of C1N2-WZ).
- Excluding masses between 260 GeV and 420 GeV for a massless LSP.
- For pair produced charginos the limit is set from 260 GeV to 520 GeV at 95% CL.
- A 100 GeV increase on the previous limits.



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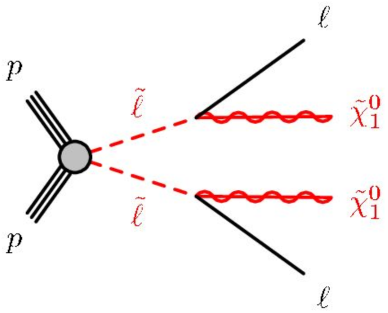
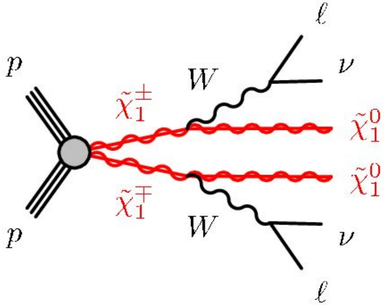
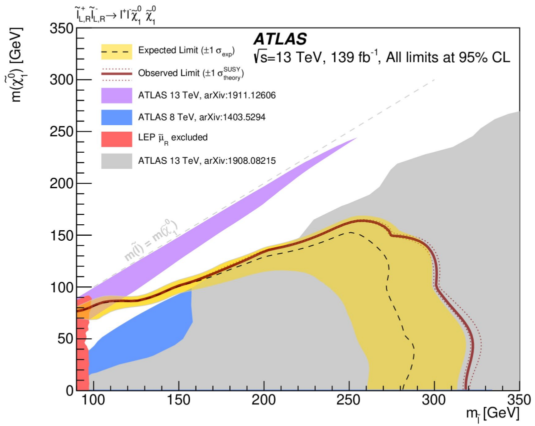
Electroweak 2L 2nd Wave: Results

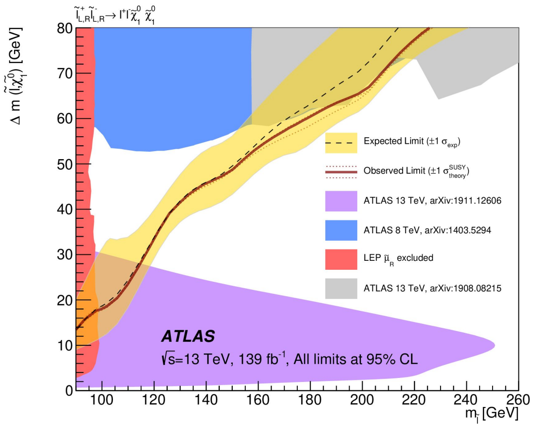
Cut-and-count

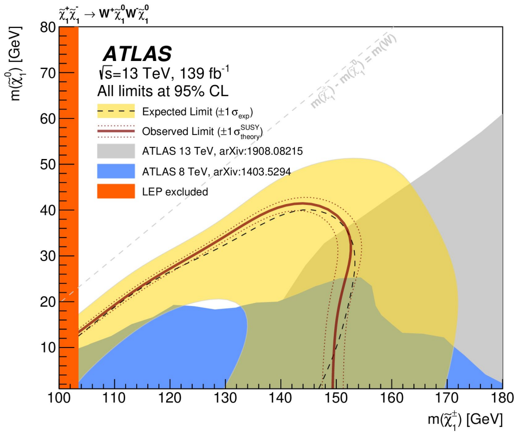


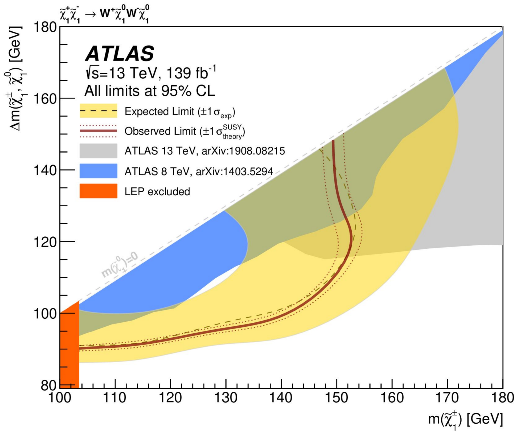
BDT







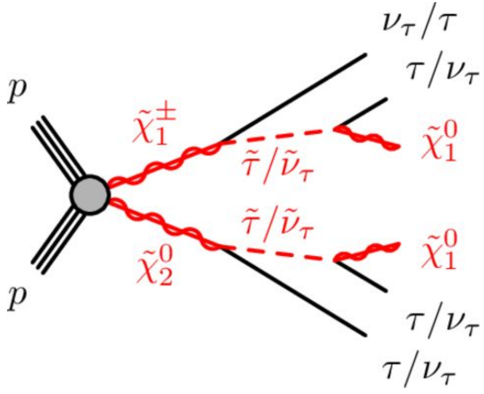


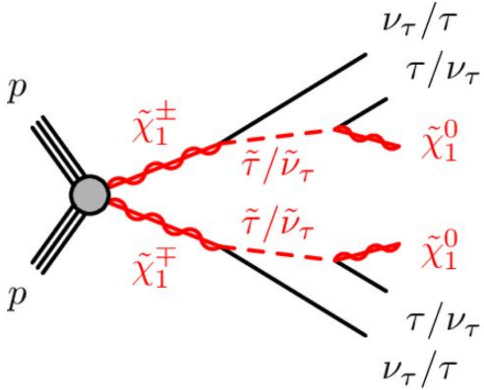


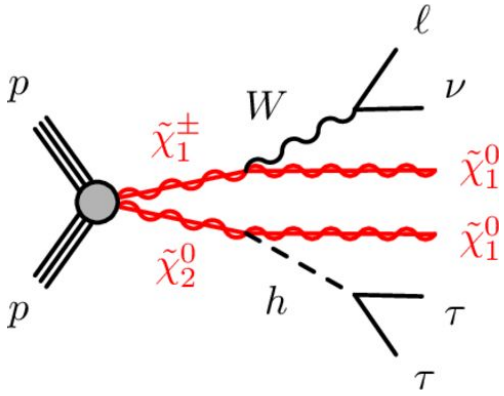
ArXiv:2209.13935

Electroweak 2τ: Signal Models

- Light sleptons could have an important role in the early universe, playing a role in co-annhilation of neutralinos.
- Production of charginos and neutralinos decay via various modes to produce final states with two tau leptons and missing energy.
- Signal regions are classified as being opposite sign (OS) and same sign (SS), based on the charge of the tau.
- The SRs are further divided by low mass and high mass regions.



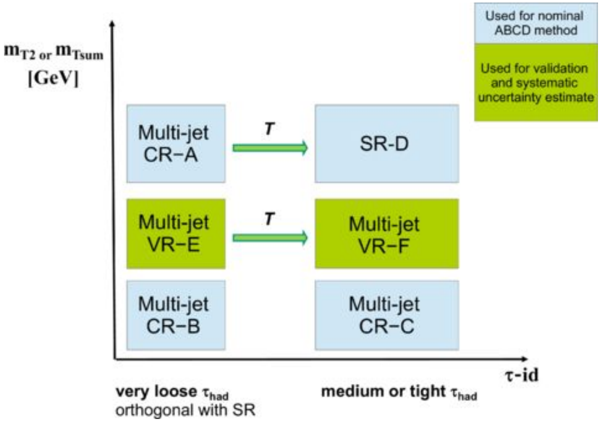


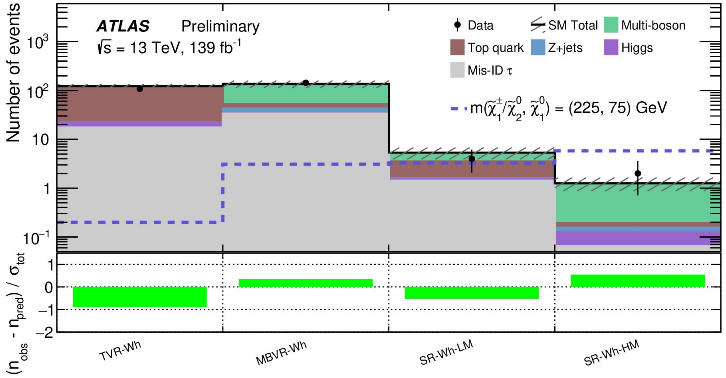


ATLAS-CONF-2022-042

Electroweak 2τ: Analysis

- ABCD method for multijet background determination.
- Difficult to estimate with Monte Carlo and so a data driven method is employed.
- All other backgrounds estimated from Monte Carlo.
- The OS and SS regions are comprised of different background contributions.





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Electroweak 2τ: Results

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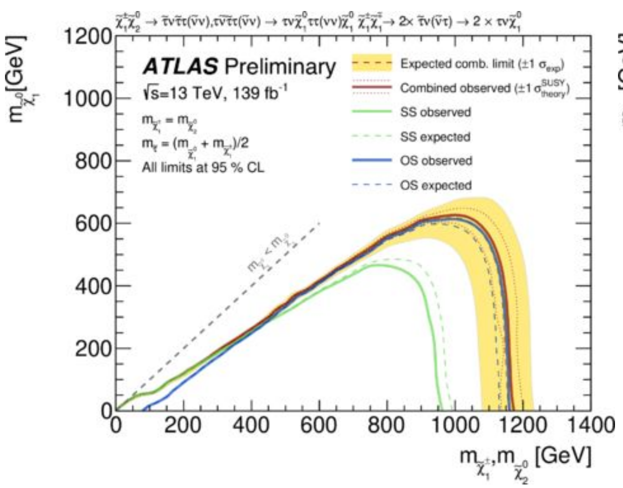
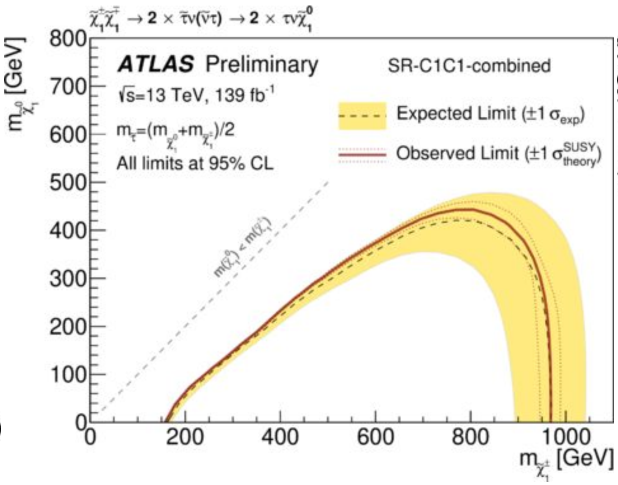
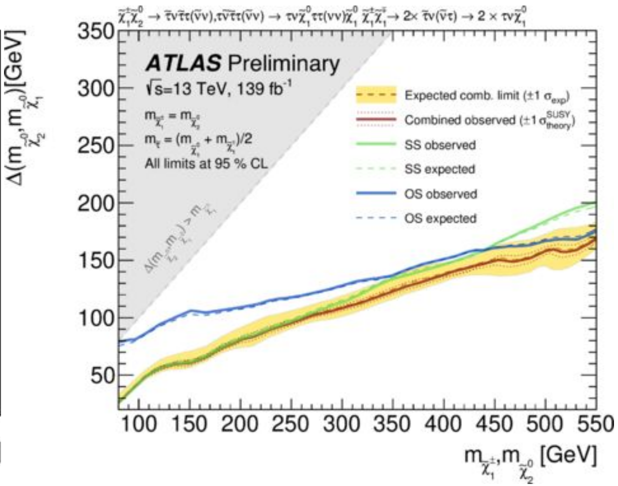
No significant excess was detected and so limits are set through statistical combination. This allow for an impressive exclusion of charginos up to 1160 GeV for a massless neutralino. A large gain on the previous 36ifb effort.





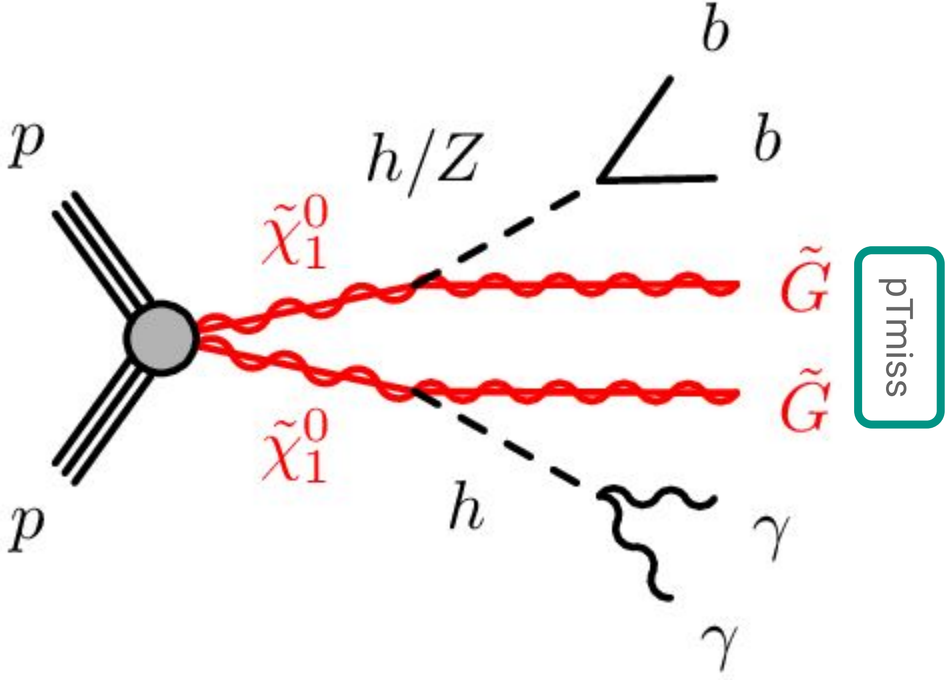


ATLAS-CONF-2022-042

bbγγ: The Model

New!

- A SUSY search for a theory using gauge mediated symmetry breaking (GMSB).
- Pair produced neutralinos decay to SM (photon, Z or Higgs) and gravitino.
- Decay mode depends on the neutralino type;
  - Higgsino: $\tilde{\chi}_1^0 \rightarrow h\tilde{G}$
  - Bino/Wino: $\tilde{\chi}_1^0 \rightarrow Z/\gamma\tilde{G}$



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bbγγ: Regions

New!

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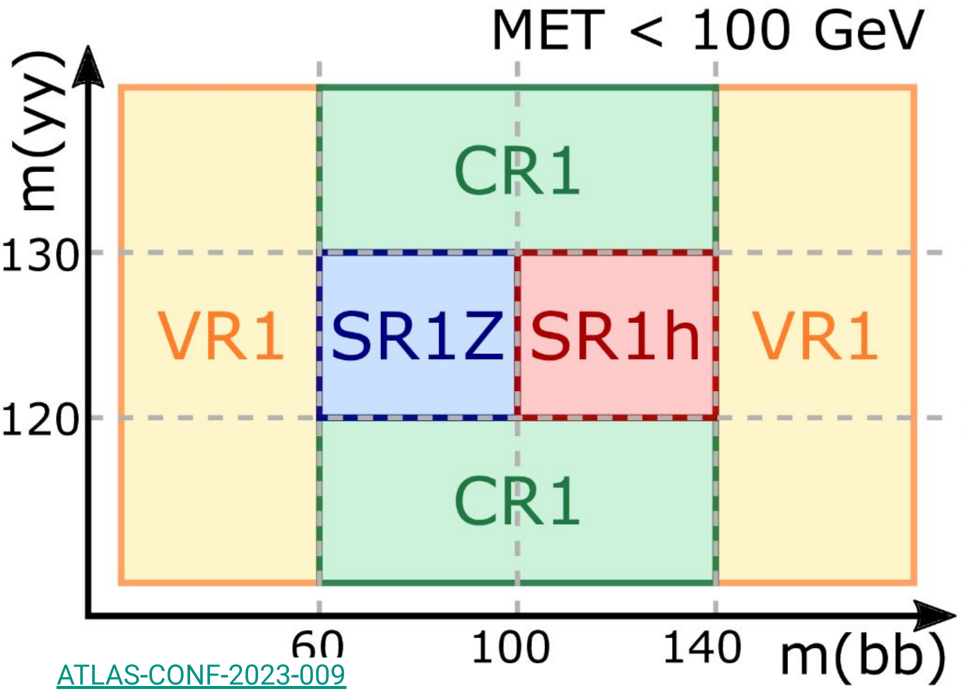
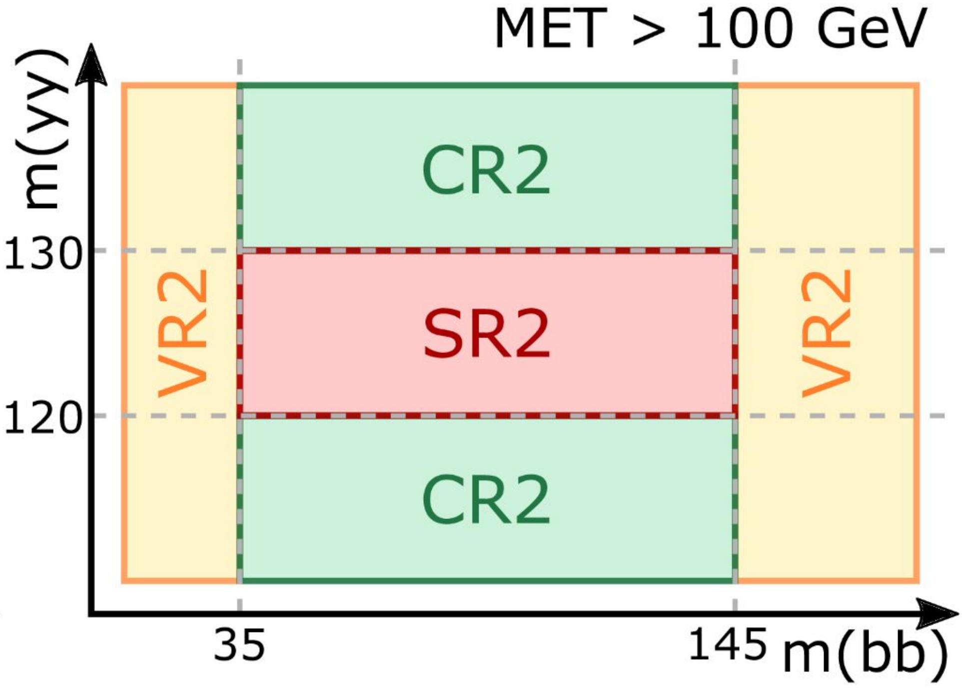
Form SRs with peaks in Higgs and Z mass regions: SR1 and SR1Z respectively.

Repeat for pTmiss > 100 GeV



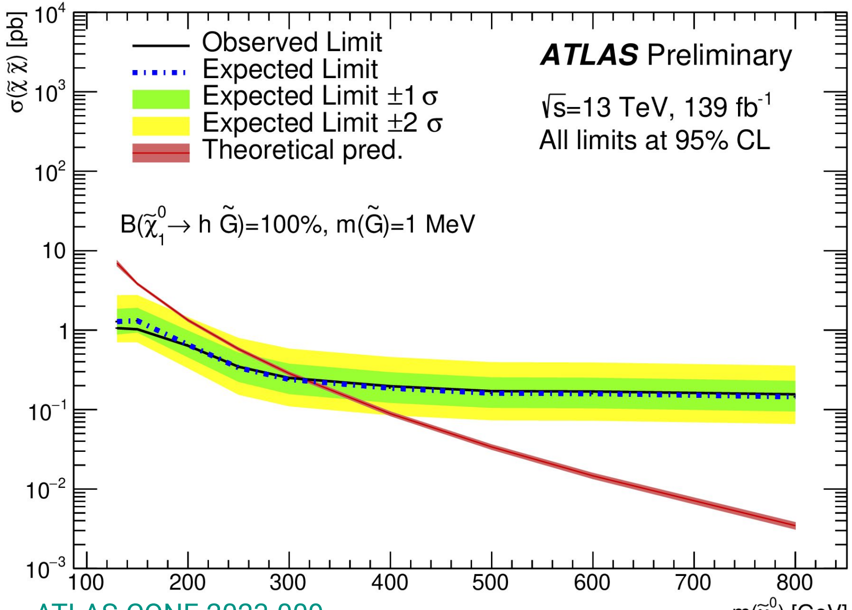


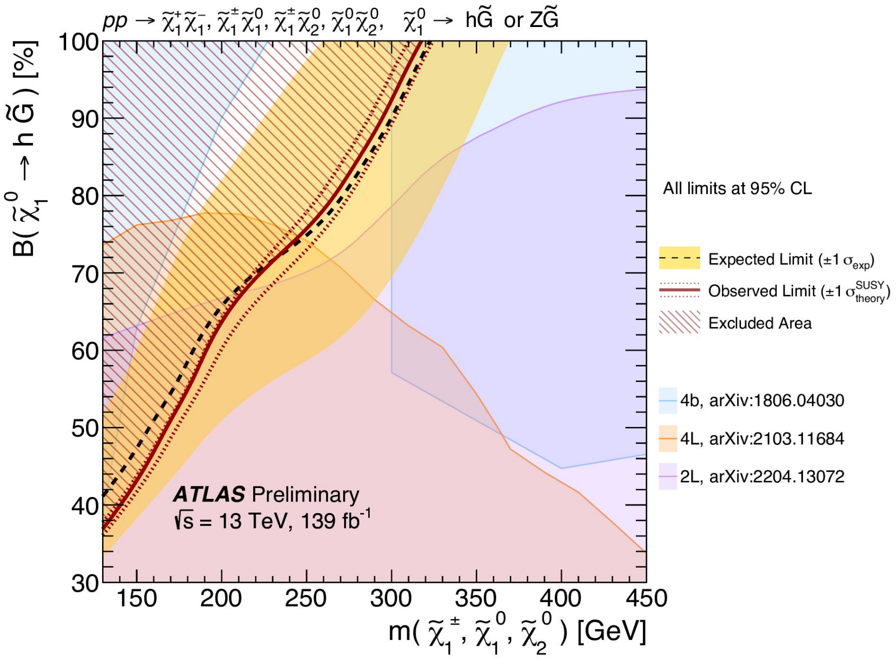
ATLAS-CONF-2023-009

bbγγ: Results

New!

No excess found so limits could be set. Great sensitivity at low neutralino mass (100 GeV - 200 GeV).
Increased coverage in a challenging and previously uncovered region.





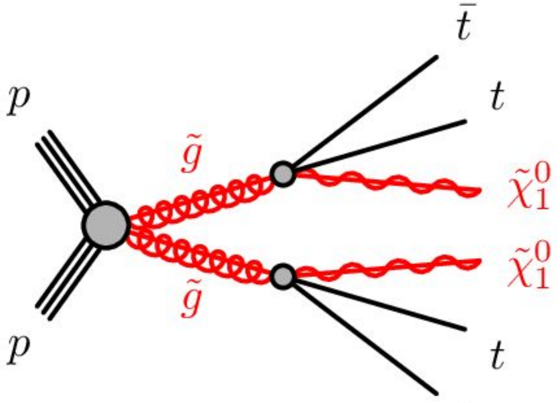
ATLAS-CONF-2023-009

Strong Multi-b: Signal Models

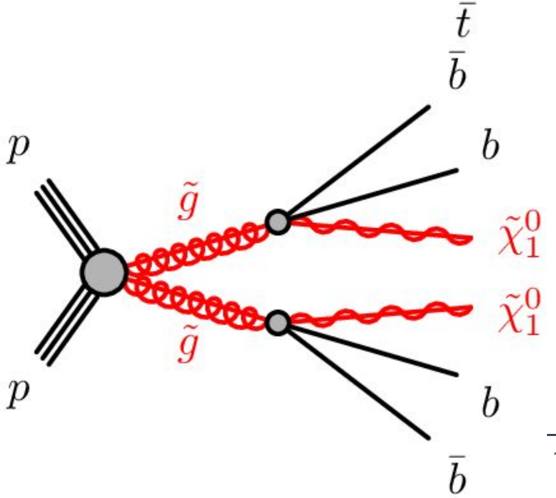
New!

- This analysis focuses on the pair production of gluinos, supersymmetric partner of the gluon.
- These gluinos are allow to decay to two top or bottom quarks and the lightest neutralino (LSP).
- In the detector this results in multiple b-jets and missing transverse momentum (due to the LSP).
- This search employs a cut-and-count (CC) approach as well as some innovative machine learning techniques.
- The cut and count signal regions rely on various jet multiplicities, 0 and 1 lepton regions and other mass variable cuts to target different mass splittings between the gluino and LSP.

Gtt



Gbb



ArXiv:2211.08028

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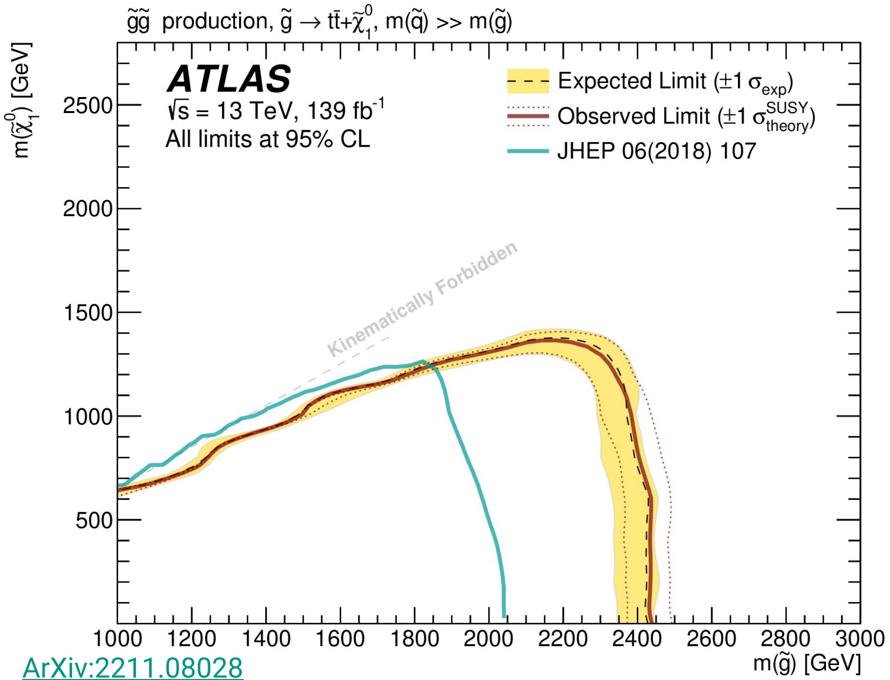
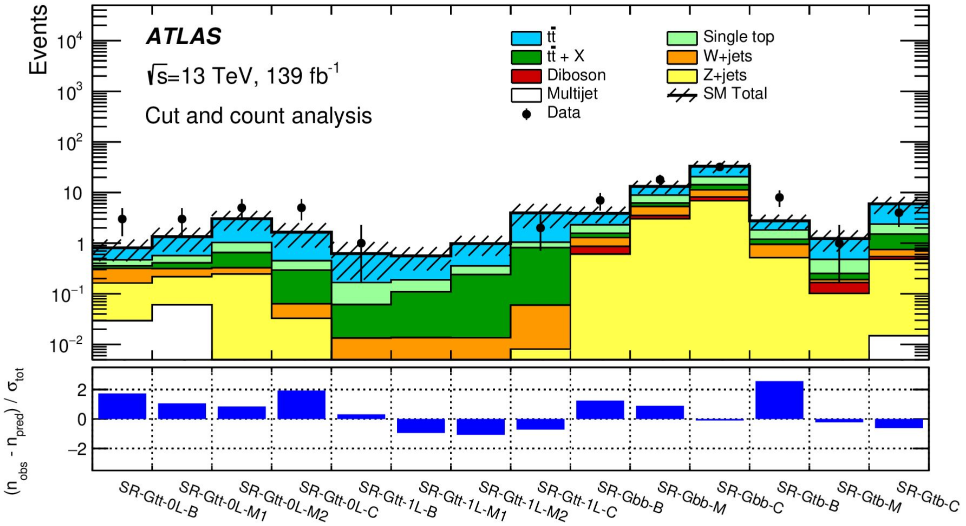
Strong Multi-b: Exclusion and Discovery

New!

Strong increase in exclusion limits. Gluino masses below 2.44 TeV (Gtt) and 2.35 TeV (Gbb) are excluded for a massless neutralino.



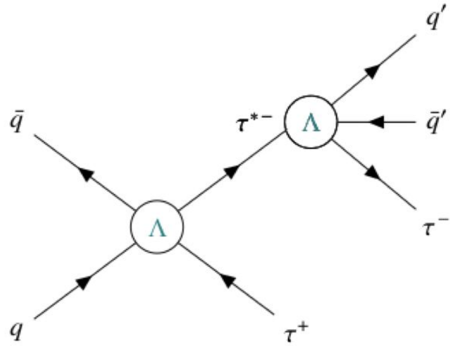


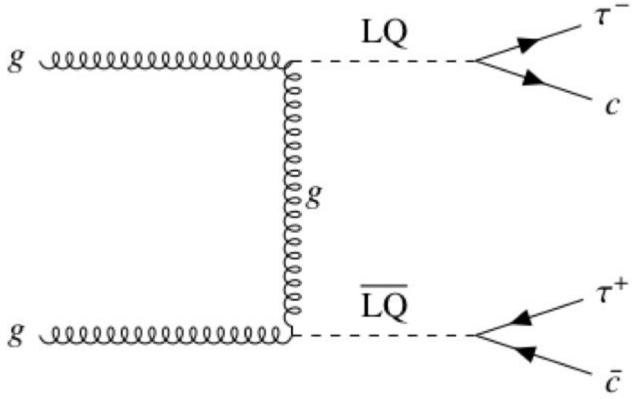
ArXiv:2211.08028

Excited Tau Leptons and Leptoquarks

New!

- Some unexplained observations could be explained if leptons are composite.
- Tests on lepton universality and the anomalous magnetic moment of the muon; for example.
- An explanation could be contact interactions between fermions at large energy scales. This could be observed at the LHC.
- The production of an excited tau and its subsequent decay are targeted here.
- The excited tau mass [300 GeV, 9.75 TeV] define the kinematics at a scale of 10 TeV.
- Not only are excited taus targeted but also leptoquarks.
- These couple to tau leptons and the charm quark.
- Leptoquark masses between 500 GeV and 1.7 TeV are within reach of this search.





arXiv:2303.09444

Excited Tau Leptons and Leptoquarks

New!

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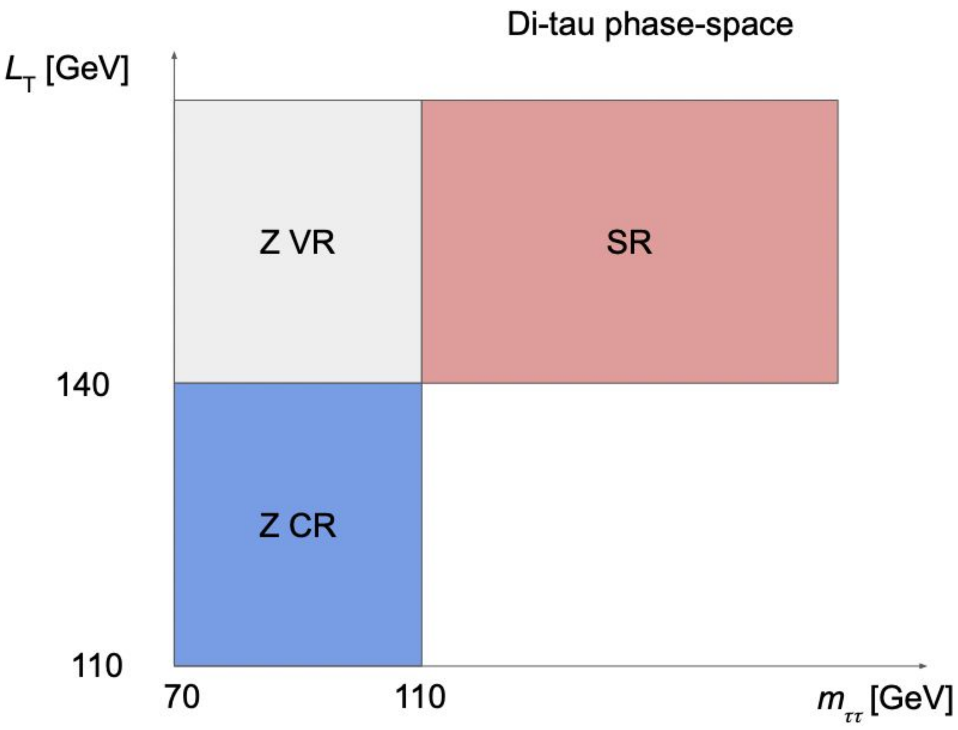
- Not only are excited taus targeted but also leptoquarks.
- These couple to tau leptons and the charm quark.
- Leptoquark masses between 500 GeV and 1.7 TeV are within reach of this search.
- SM backgrounds include Z to ττ, and to leptons, ttbar, single top, W+jets and diboson.
- Regions built using the mass of the di-tau system and the transverse momentum some of the taus (L_T).
- SRs then binned in the pT sum of the two taus and two leading jets (S_T) for the fit.

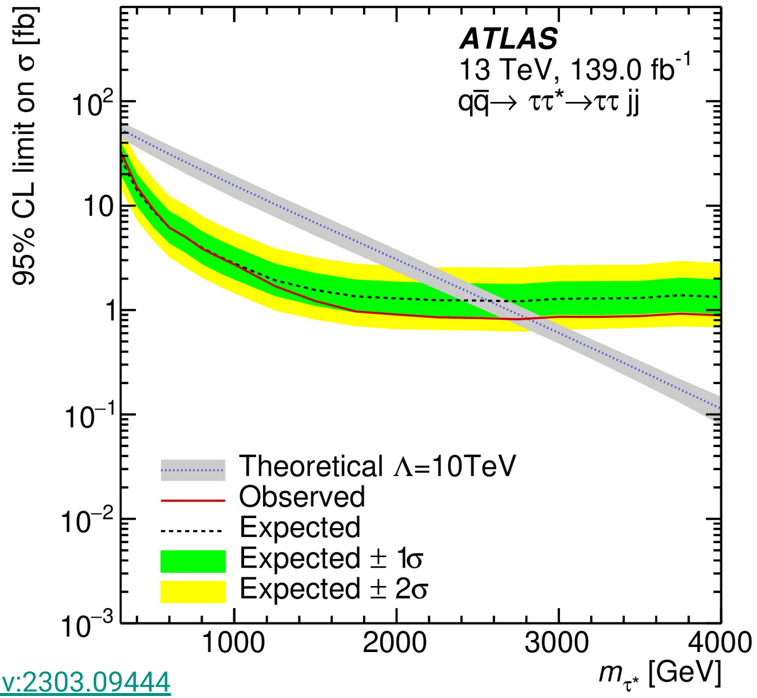


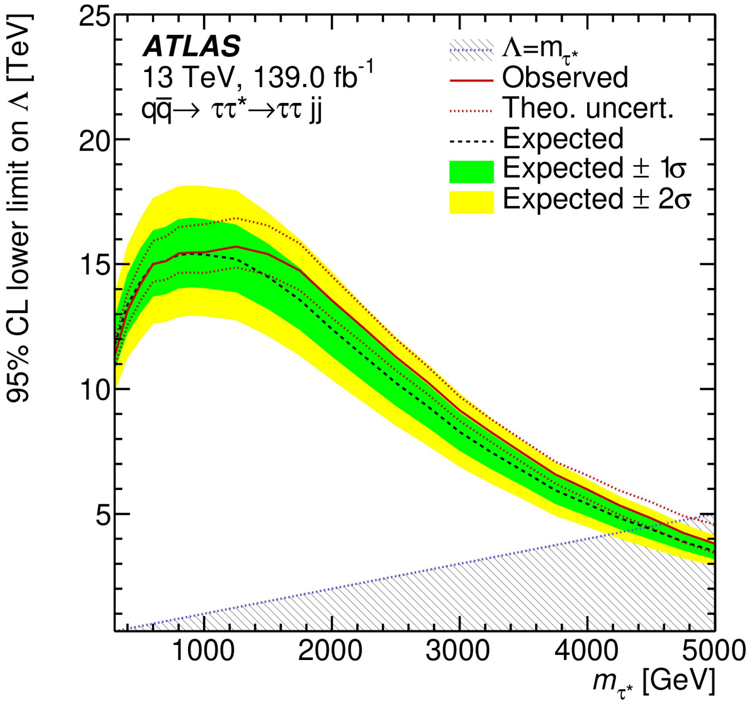
arXiv:2303.09444

Excited Tau Leptons and Leptoquarks

New!

Excited tau leptons below 2.8 TeV are excluded at a scale of 10 TeV. If the scale is equal to the excited tau mass then the exclusion is up to 4.6 TeV.



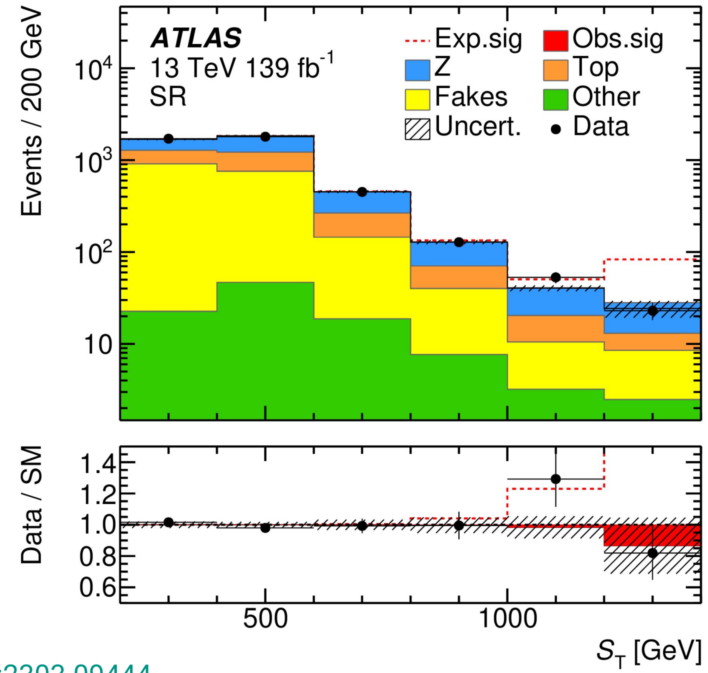


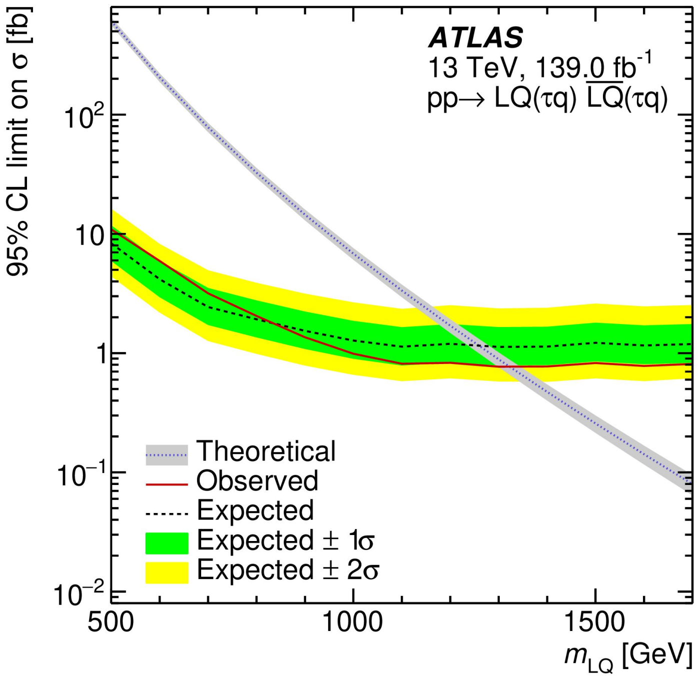
arXiv:2303.09444

Excited Tau Leptons and Leptoquarks

New!

The exclusion of the leptoquarks reaches up to 1.3 TeV if the branching ratio of LQ to tau + charm is assumed to be 1. The same limit holds for LQ to tau + light quarks.





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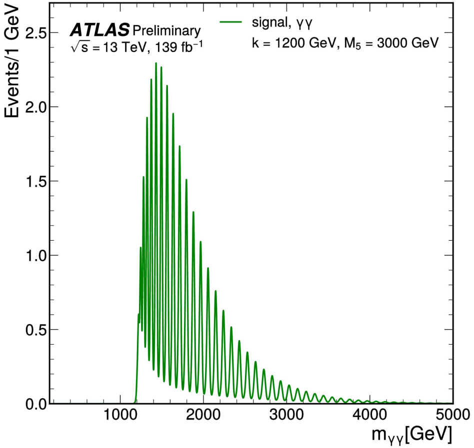
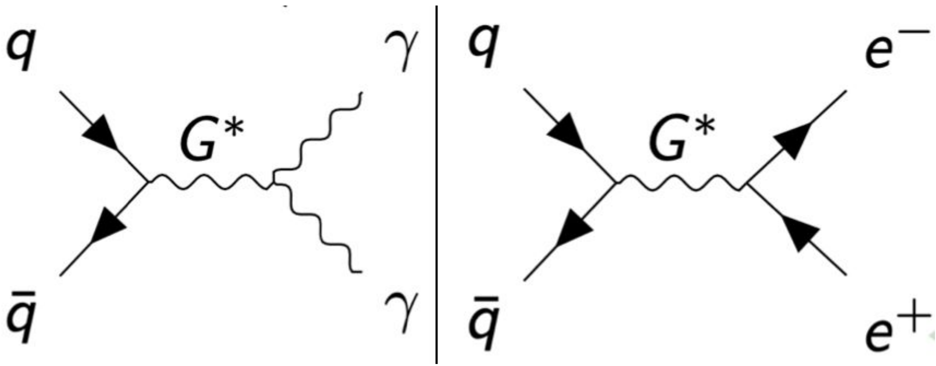
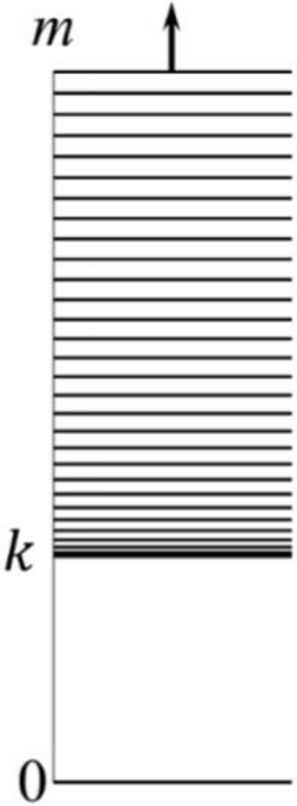
Linear Dilation/Clockwork Analysis

New!







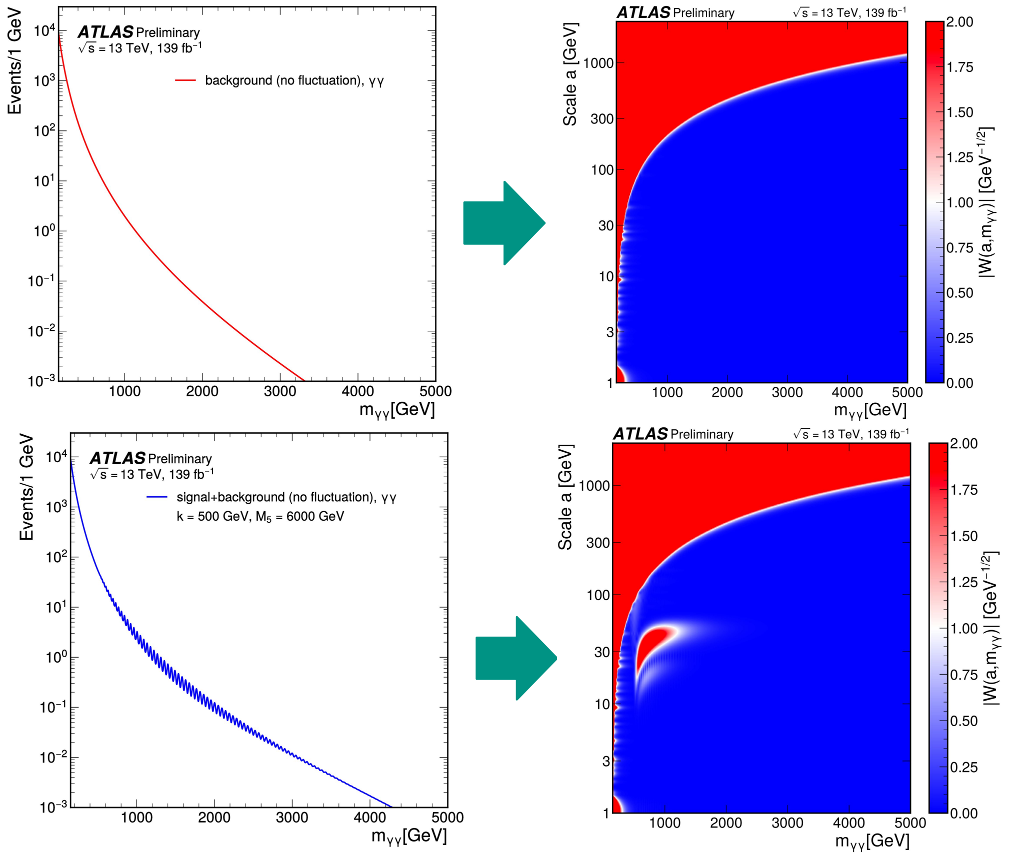
- An interesting quantum gravity theory known as the clockwork mechanism.
- This can be interpreted as Kaluza-Klein (KK) excitations of the 5D graviton, or a continuum version of the clockwork gears.
- This results in a prediction of towers of gravitons with small splitting in mass.
- These splittings would be detectable in as periodic signals in ee/ɣɣ mass spectra (due to the good mass resolution of the detectors).

ATLAS-CONF-2023-010

Linear Dilation/Clockwork Analysis

New!

- Extremely challenging signature as the cross sections are very low.
- Appearing only as tiny periodic resonances.
- A transformation of some kind is required to separate signal from background.
- Continuous wavelet transformation is used.
- These produce “scalograms”.



ATLAS-CONF-2023-010

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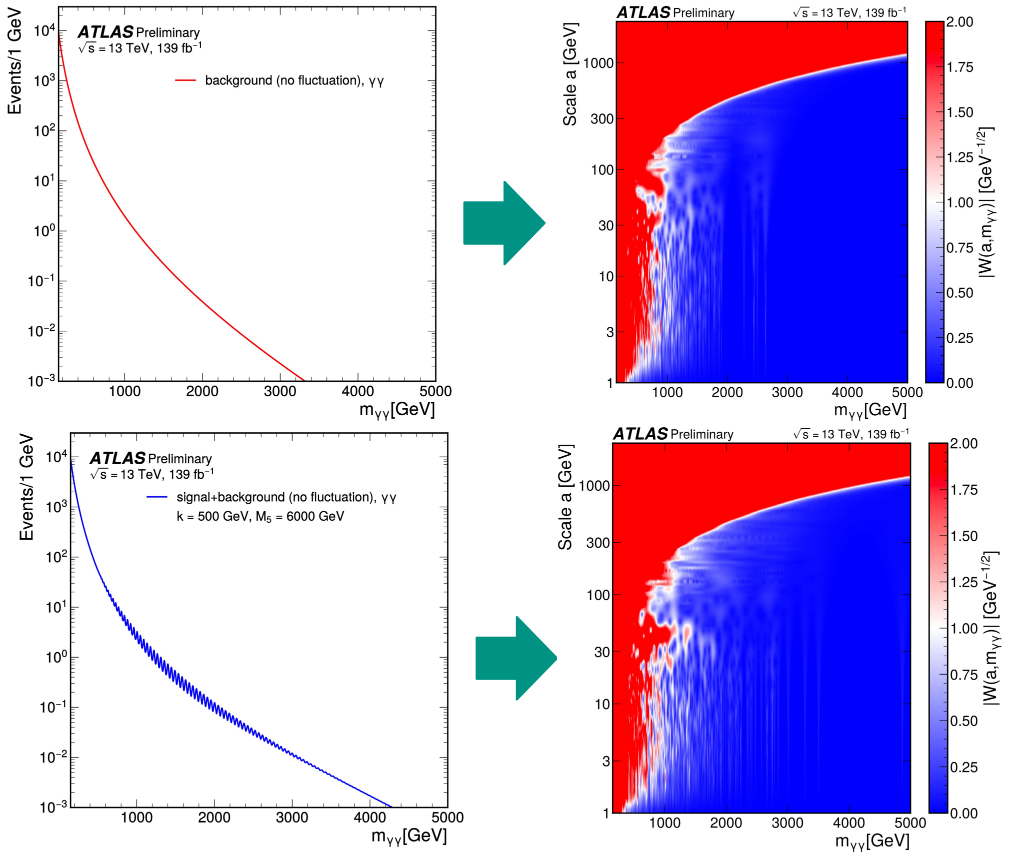
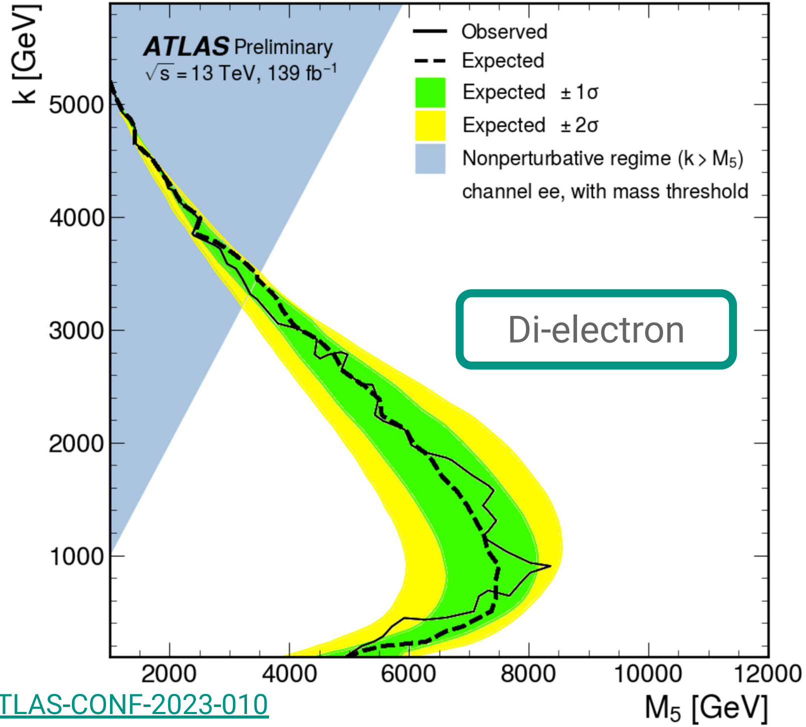


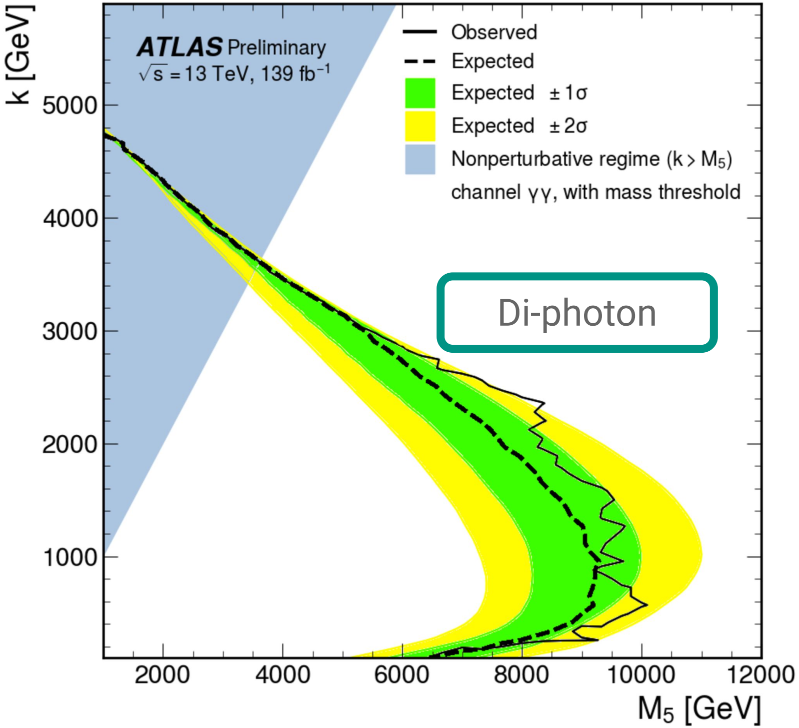
ATLAS-CONF-2023-010

Linear Dilation/Clockwork Analysis

New!

Limits are stronger than expected because the data was smoother than expected.



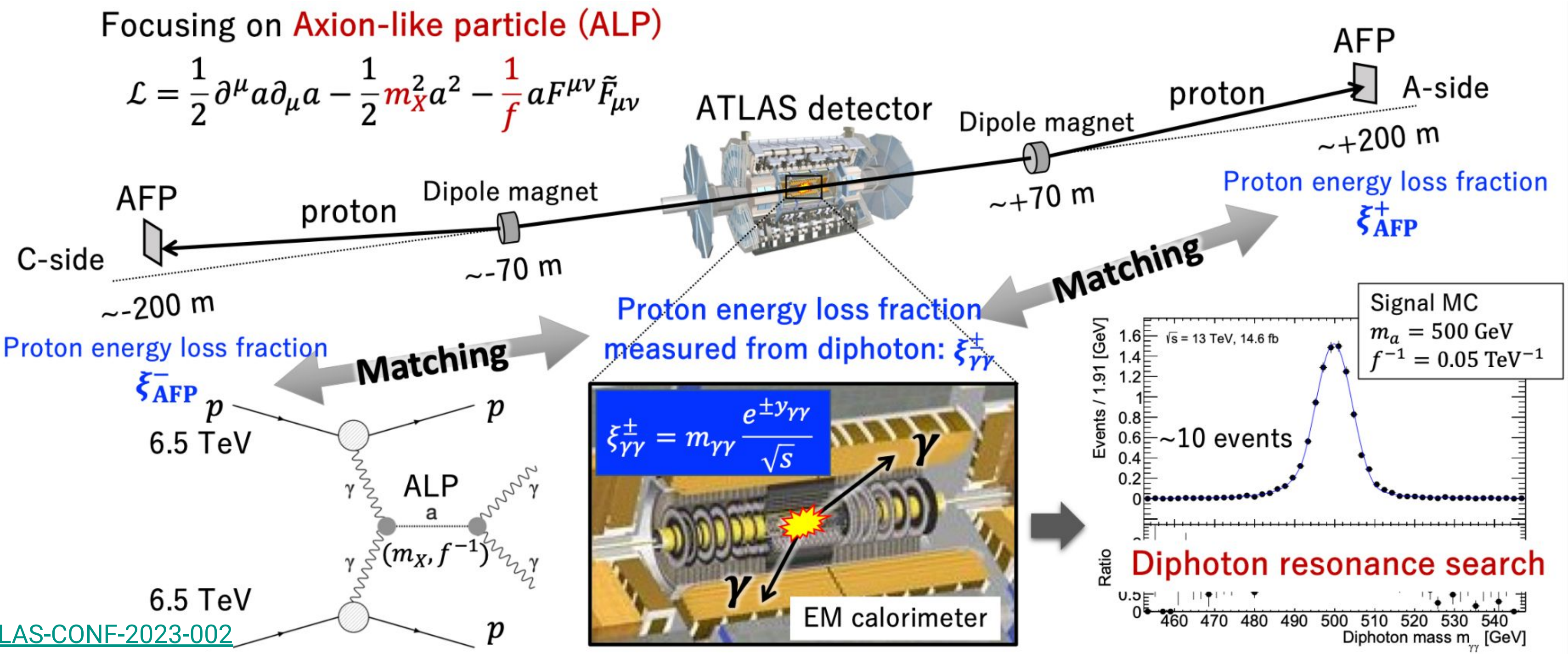


ATLAS-CONF-2023-010

Axion-Like Particle with AFP

New!

- Diphoton resonance search with AFP (14.6 ifb in 2017).
- Targeting masses of 150 GeV to 1600 GeV for a particle intermediating light-by-light scattering.



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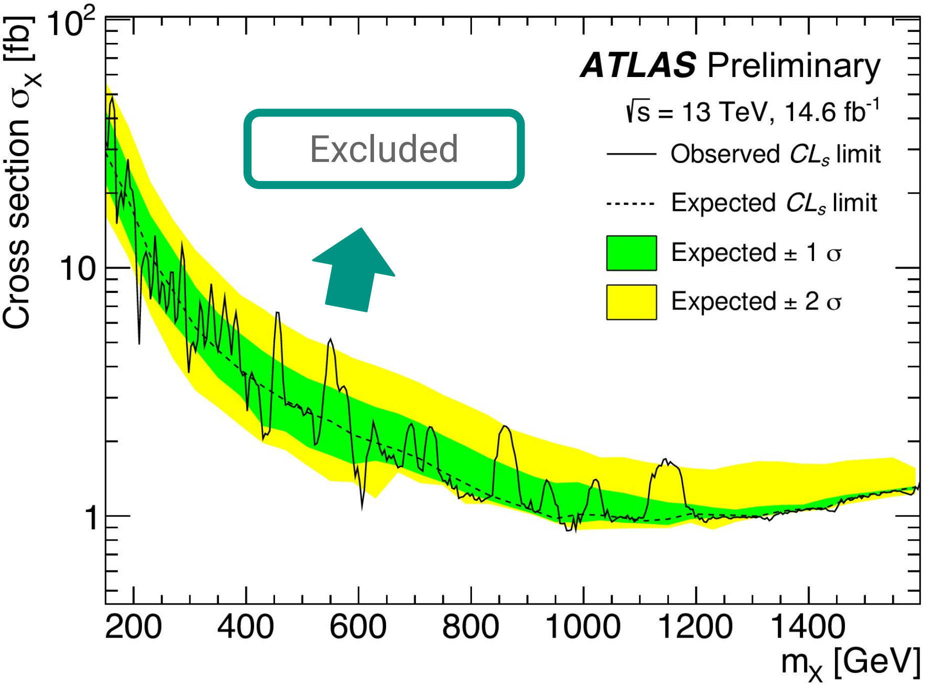
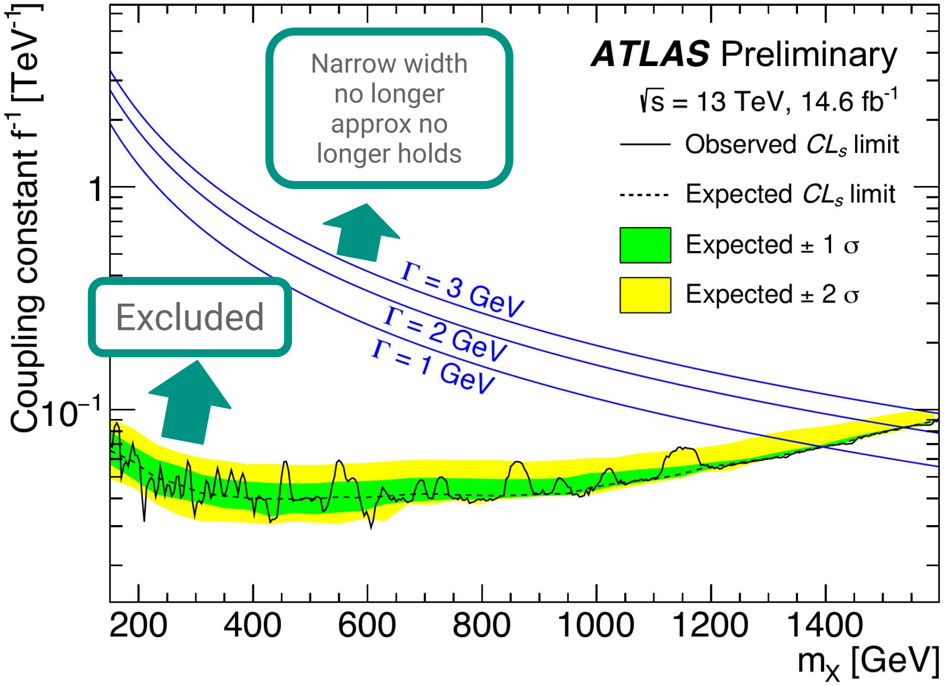
Axion-Like Particle with AFP

New!

Limits assuming 100% BR of ALP to γγ.





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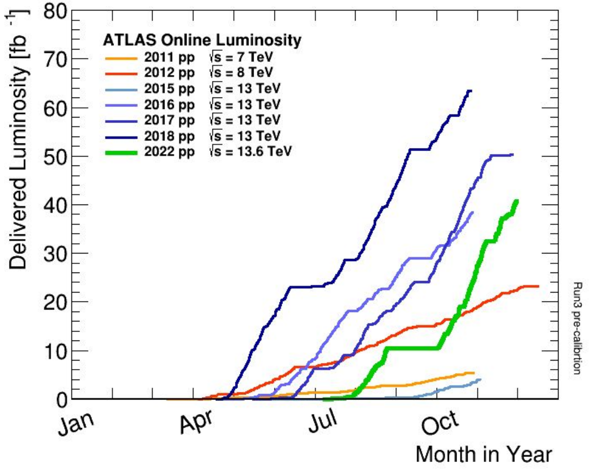
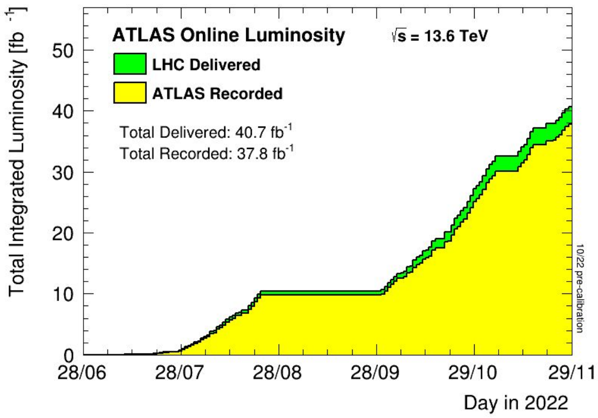
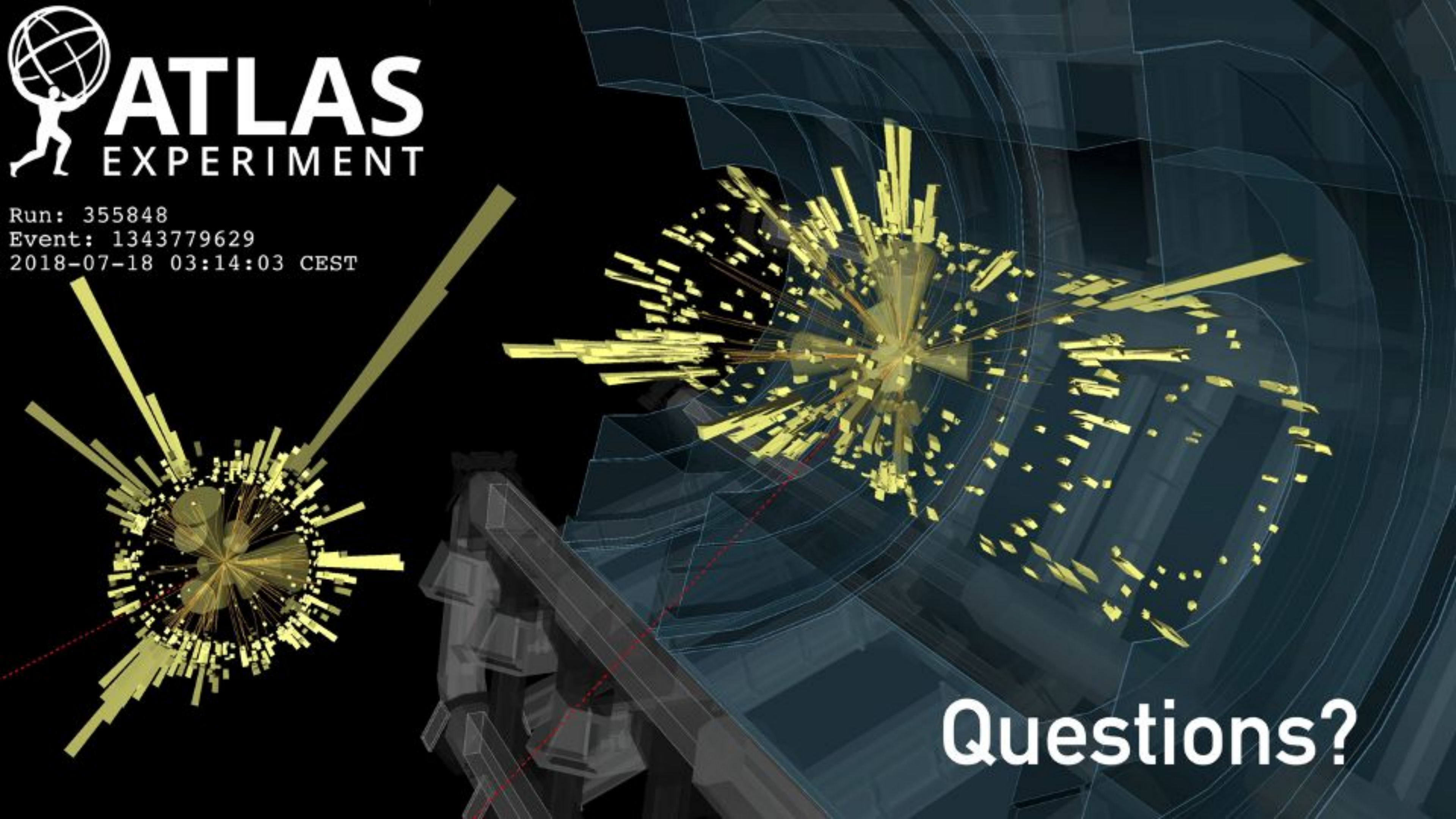
Conclusions

- Unfortunately ATLAS did not manage to detect physics beyond the standard model in Run 2.
- Despite this an impressive amount of work has been completed by the search groups.
- This has allowed large areas of phase space to be excluded.
- This is still an incredibly important achievement to narrow down the places to look.
- Extra power in Run 3 with slightly increased CoM energy and increased total integrated luminosity.
- Keep the faith!






ATLAS
EXPERIMENT
Run: 355848
Event: 1343779629
2018-07-18 03:14:03 CEST
Questions?

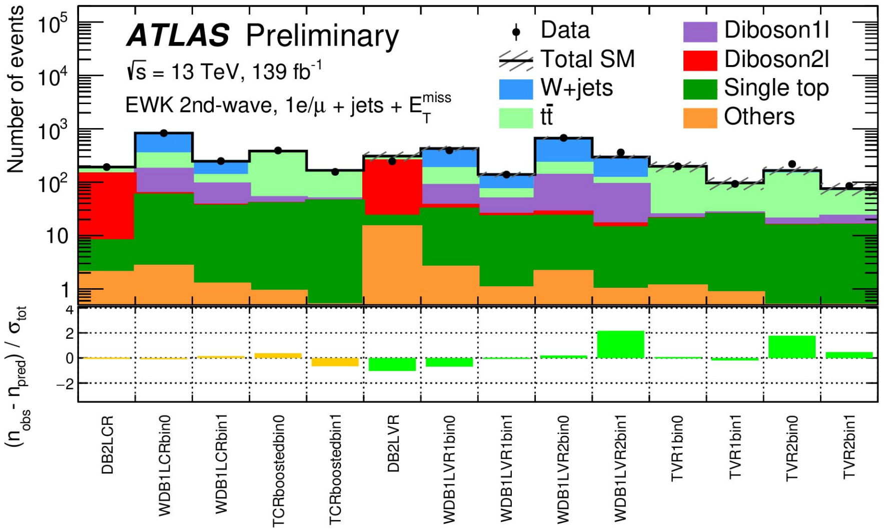
Backup

Electroweak 1L: Background Estimation

- Events are selected from a set satisfying the single lepton triggers.
- Then a set of high level cuts can be applied to identify signal events.
- The main discriminating variable is the effective mass:

$$m_{\text{eff}} = p_{\text{T}}^{\ell} + \sum_{\text{jets}} p_{\text{T}} + E_{\text{T}}^{\text{miss}}$$

- Dominant backgrounds are W+jets (46-73%), diboson (16-39%) and tt (2-17%).

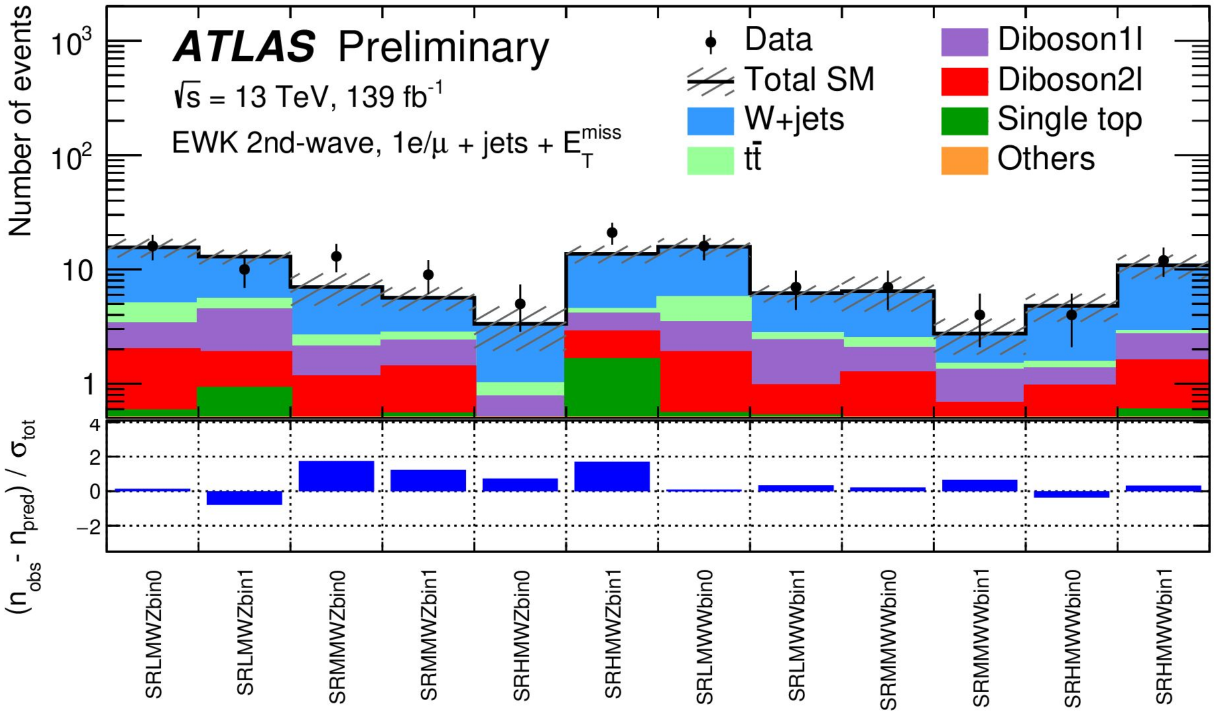


A set of control and validation regions are designed to target each of the major backgrounds.

Electroweak 1L: Signal Regions

Variable	C1C1-WW model			C1N2-WZ model		
	SRLM	**SRMM**	**SRHM**	**SRLM**	**SRMM**	**SRHM**
N_{lep} ($p_{\text{T}} > 25$ GeV)	1					
N_{jet} ($p_{\text{T}} > 30$ GeV)	1 – 3					
$N_{\text{large-Rjet}}$ ($p_{\text{T}} > 250$ GeV)	≥ 1					
$E_{\text{T}}^{\text{miss}}$ [GeV]	> 200					
$\Delta\phi(\ell, \text{E}_{\text{T}}^{\text{miss}})$	< 2.6					
large-R jet type	W-tagged			Z-tagged		
m_{T} [GeV]	120–200	200–300	> 300	120–200	200–300	> 300
	Exclusion SR					
m_{eff} [GeV] (excl.)	[600–850, $>$ 850]			[600–850, $>$ 850]		
m_{jj}[GeV] (excl.)	[70–90, -]			[80–100, -]		
$\sigma_{E_{\text{T}}^{\text{miss}}}$ (excl.)	[$>$ 12, $>$ 15]			[$>$ 12, $>$ 12]		
	Discovery SR					
m_{eff} [GeV] (disc.)	> 600	> 600	> 850	> 600	> 850	> 850
m_{jj}[GeV] (disc.)	-	-	-	80–100	-	-
$\sigma_{E_{\text{T}}^{\text{miss}}}$ (disc.)	> 15	> 15	> 15	> 12	> 12	> 12

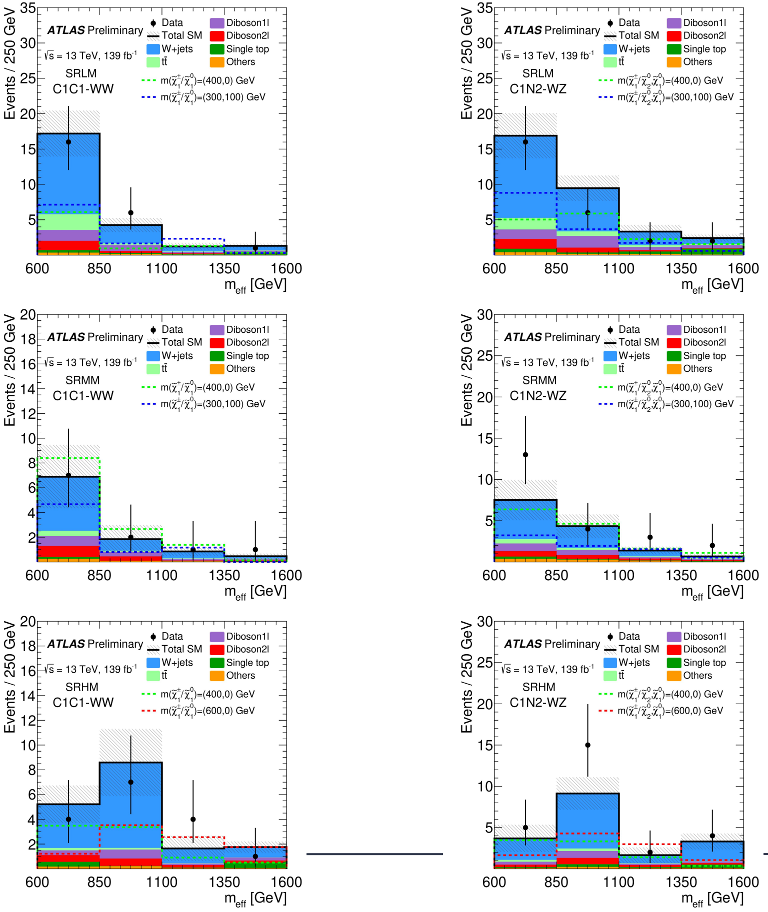
Electroweak 1L: Signal Regions



Electroweak 1L: Signal Regions

- Three classes of signal regions are designed around the transverse mass (mT).
- Target increasing mass differences between the chargino (neutralino 2) and the LSP.

- **SR Low Mass (SRLM)**: 120 GeV < mT < 200 GeV.
- **SR Medium Mass (SRMM)**: 200 GeV < mT < 300 GeV.
- **SR High Mass (SRHM)**: mT > 300 GeV.
- Furthermore, each model can be targeted by requiring a large-R jet tag:
  - C1C1-WW -> W-tagged.
  - C1N1-WZ -> Z-tagged.



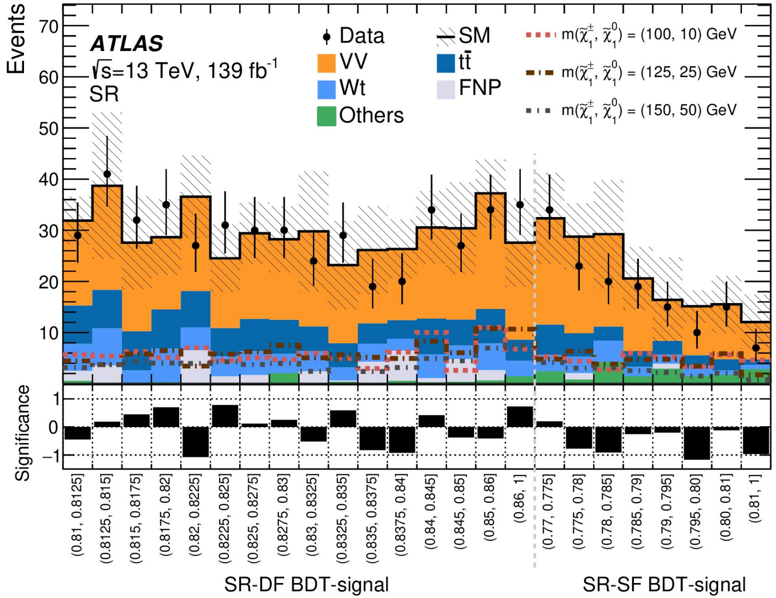
Electroweak 2L: Signal Regions

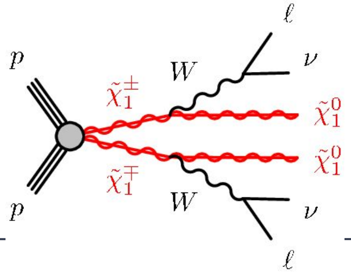
Signal region (SR)	SR-0J	SR-1J
$n_{b\text{-tagged jets}}$	$= 0$	
E_T^{miss} significance	>7	
$n_{\text{non-}b\text{-tagged jets}}$	$= 0$	$= 1$
$p_T^{\ell_1}$ [GeV]	> 140	> 100
$p_T^{\ell_2}$ [GeV]	> 20	> 50
$m_{\ell\ell}$ [GeV]	> 11	> 60
$p_{T,boost}^{\ell\ell}$ [GeV]	< 5	-
$\lvert \cos\theta^*_{\ell\ell}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

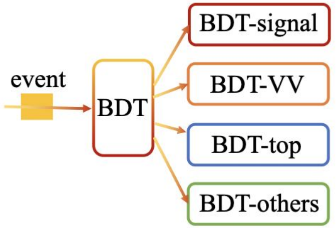
Signal region (SR)	SR-DF	SR-SF
$n_{b\text{-tagged jets}}$	$= 0$	
$n_{\text{non-}b\text{-tagged jets}}$	$= 0$	
E_T^{miss} significance	>8	
m_{T2}^{0} [GeV]	>50	
BDT-other		< 0.01
Binned SRs		
BDT-signal	$\in$(0.81,0.8125]	$\in$(0.77,0.775]
	$\in$(0.8125,0.815]	$\in$(0.775,0.78]
	$\in$(0.815,0.8175]	$\in$(0.78,0.785]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

Electroweak 2L: Signal Regions

- The pair produced charginos are targeted using a detected machine learning approach.
- A BDT was trained with background samples and also signal samples.
- A range of high-level and low level inputs were used to train the BDT.
- pTmiss Significance, lepton pT etc.
- Multiclass approach with four outputs:
  - BDT-signal
  - BDT-VV
  - BDT-top
  - BDT-others







ArXiv:2209.13935

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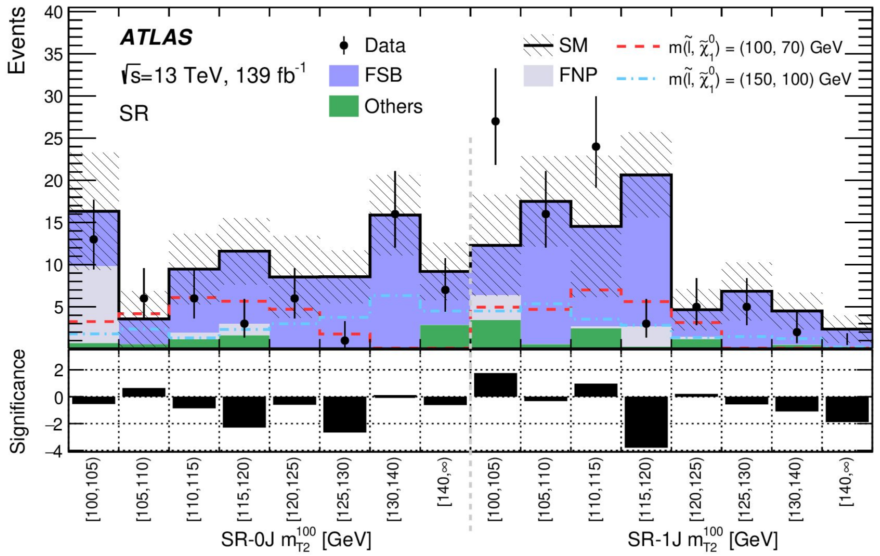
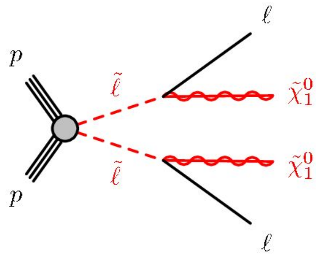
Electroweak 2L: Signal Regions

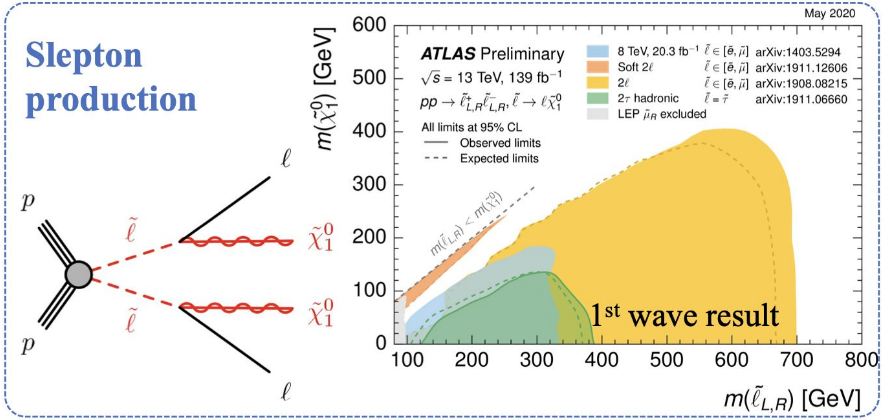
- Once selected, events with SFOS leptons have some preselection applied and also a pTmiss significance > 7 is required.
- The signal regions are split by jet selection and binned in mT2.
- The binning in mT2 defines two classes of SR.
- The first set having an upper and lower limit for a model dependent fit.
- The second "inclusive" set has no upper bound for a model independent fit.
- The large over-prediction in one bin is due to statistical fluctuation in the estimation of the flavour symmetric background (FSB).

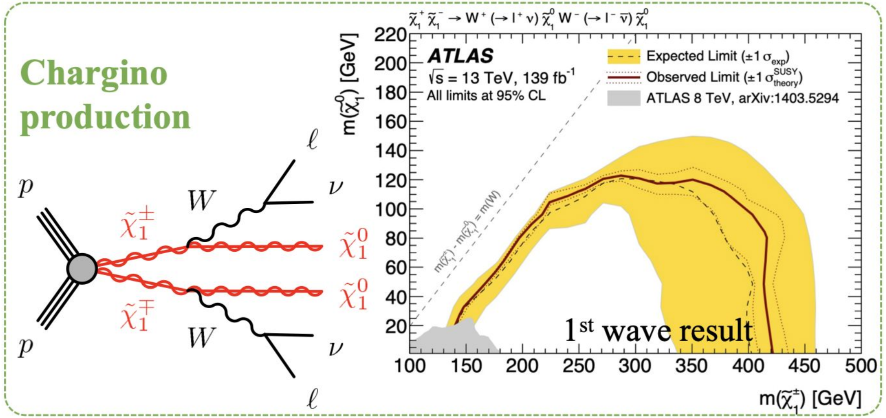




Electroweak 2L: Signal Models

- A second wave analysis targeting challenging small mass splittings in two models.
- The first model being direct production of sleptons.
- Resulting in two opposite sign leptons with 0 or 1 jet channels also considered.
- Data driven background estimation technique and cut-and-count approach.
- Second signal targets chargino production.
- Now there are two opposite sign leptons and there is a zero jet requirement.
- The signal selection in this case is based on machine learning techniques.





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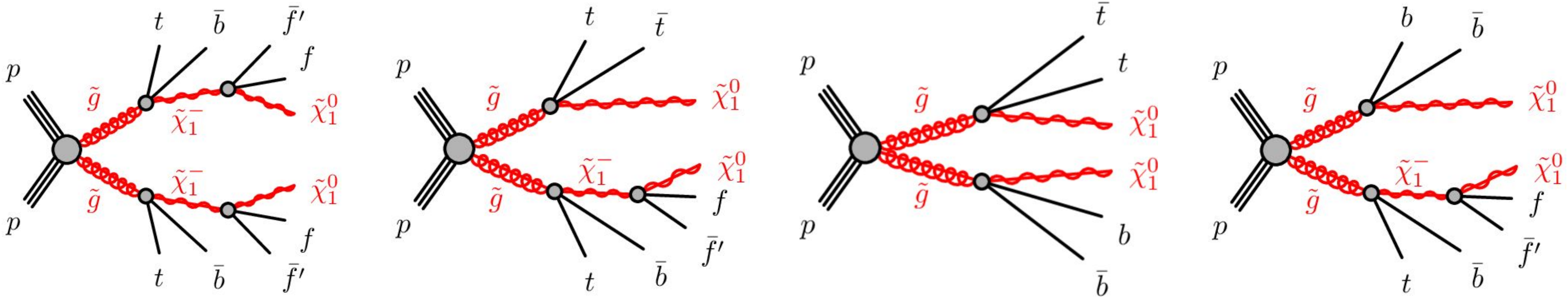
Strong Multi-b: Signal Models



Varying the branching ratios allows for more complex signal models including asymmetric decay chains, the Gtb models.

Strong Multi-b: Neural Network Analysis

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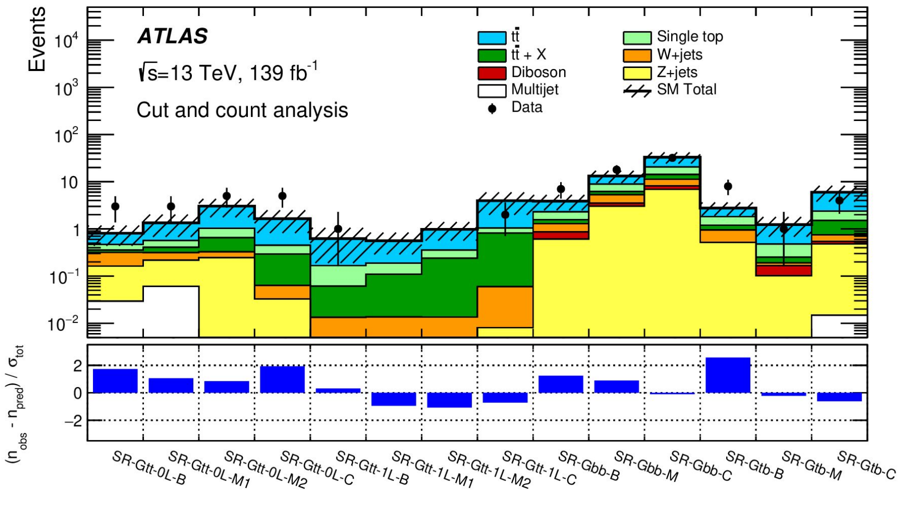
- Low level kinematic variables are used as an input to a dense neural network with three hidden layers.
- This is used to discriminate Gtt/Gbb events from SM background.
- Tained on 9.2E5 signal events and 5.6E5 background events.
- The binary output of the NN analysis is used to classify signal and background processes.
- This method was found to improve sensitivity by 30% over the CC approach.

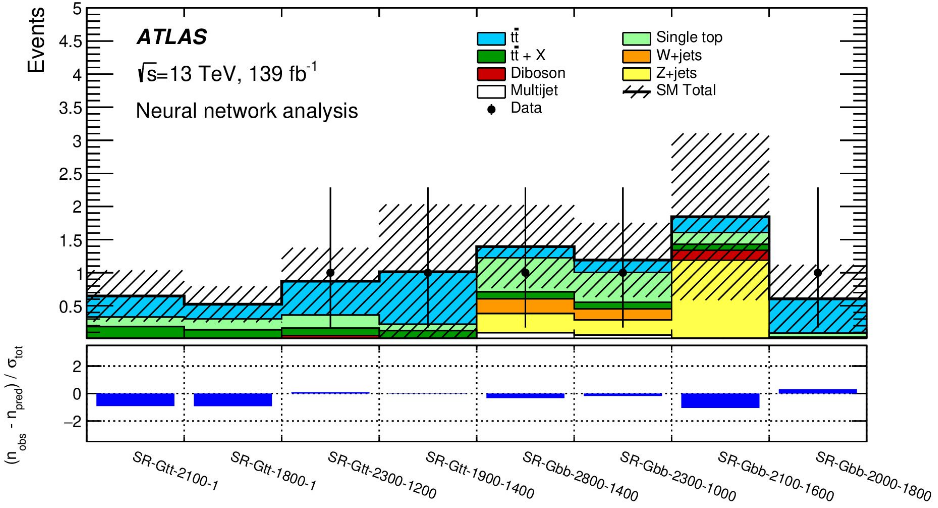
Input variables to the network:

- The four-momenta (pT, η, ϕ, m) of the 10 leading jets, in decreasing order of pT, and a set of binary variables indicating which jets are b-tagged;
- The four-momenta of the four leading large-R jets, in decreasing order of pT;
- The four-momenta of the four leading leptons (e or μ), in decreasing order of pT;
- The two components of the vector pTmiss.

Strong Multi-b: Results

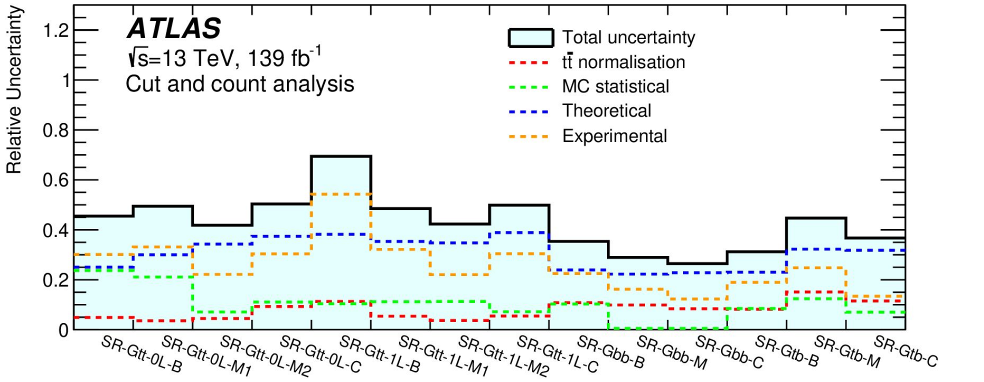
Overall a good agreement with the standard model prediction is observed. The largest excess of the 22 SRs is coming from SR-Gtb-B with 2.3σ, and so not statistically significant.

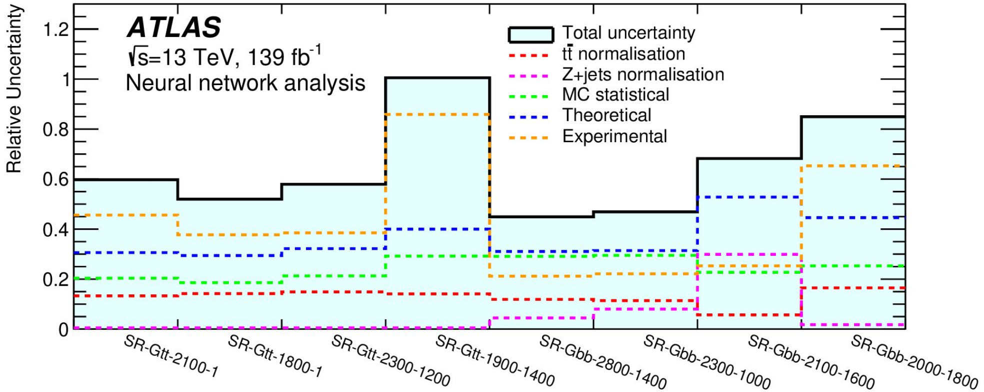




Strong Multi-b: Systematic Uncertainties

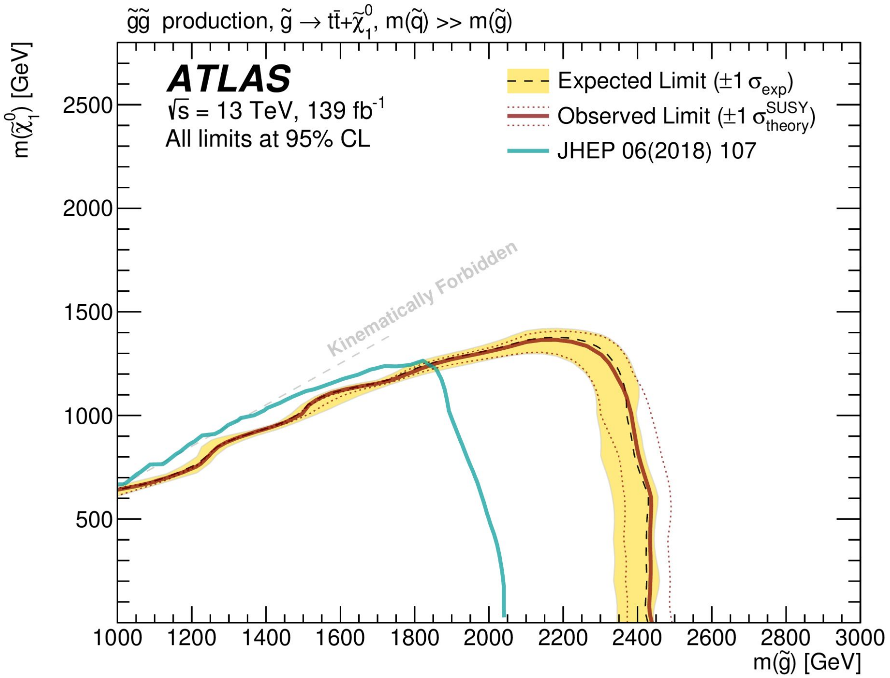
- Systematic uncertainties are evaluated in the standard ATLAS manner for the CC.
- These are primarily driven by theoretical and experimental uncertainties.
- For the NN additional input variables are added that correspond to the sources of systematic uncertainties.
- These are added to the training and validation samples with a weight corresponding to the magnitude of the uncertainty.
- This means events with large uncertainties have less impact on the training.
- Once trained the uncertainties are propagated through using the envelope method.

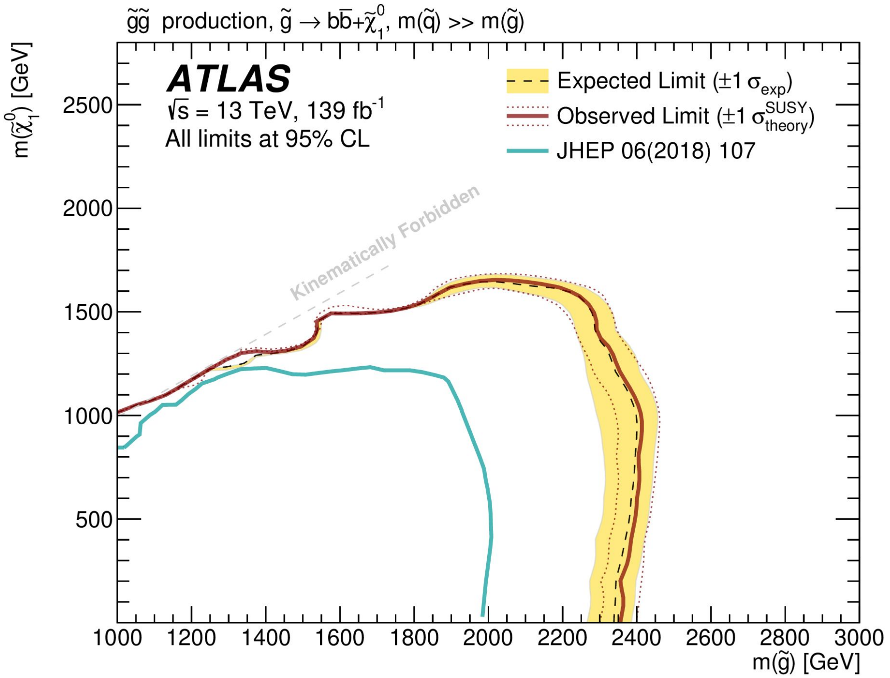




Strong Multi-b: NN Exclusion

Strong increase in exclusion limits. Gluino masses below 2.44 TeV (Gtt) and 2.35 TeV (Gbb) are excluded for a massless neutralino.





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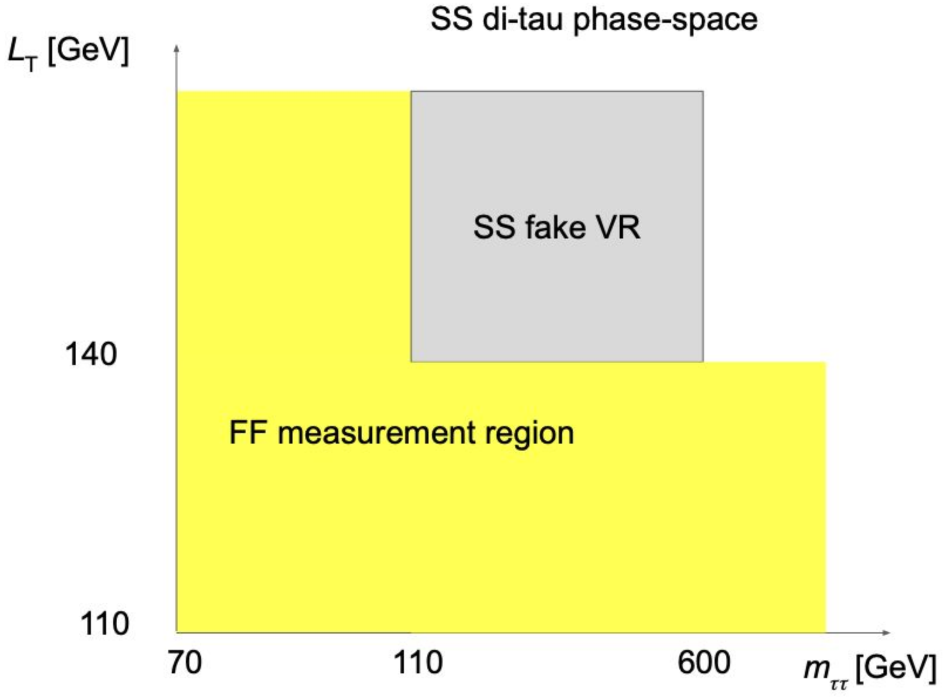
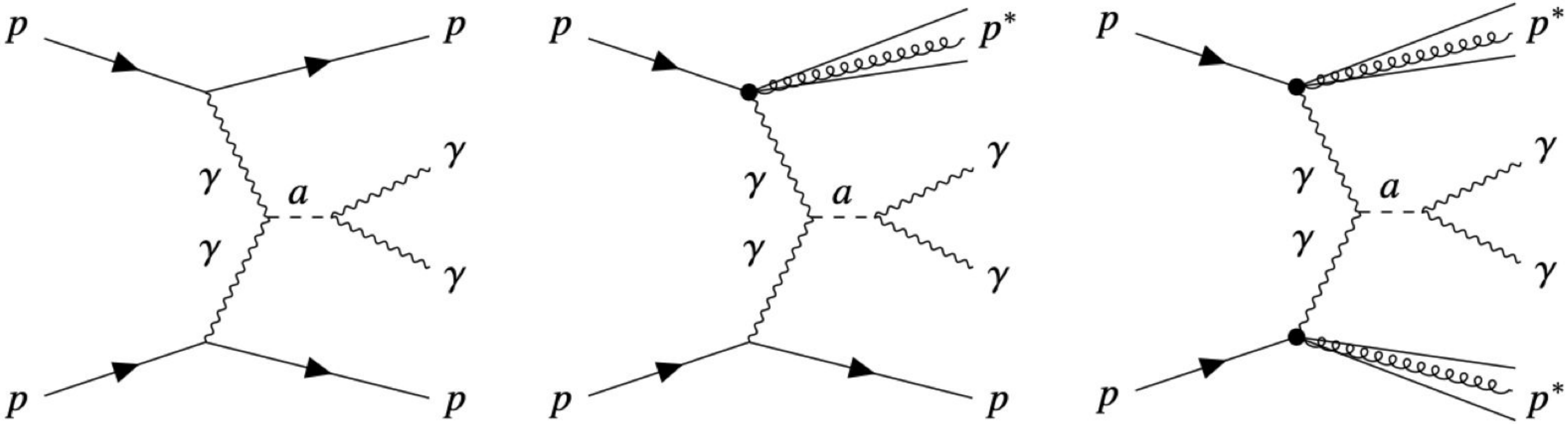
Excited Tau Leptons and Leptoquarks

- Not only are excited taus targeted but also leptoquarks.
- These couple to tau leptons and the charm quark.
- Leptoquark masses between 500 GeV and 1.7 TeV are within reach of this search.
- SM backgrounds include Z to ττ, and to leptons, ttbar, single top, W+jets and diboson.
- Regions built using the mass of the di-tau system and the transverse momentum some of the taus (L_T).
- SRs then binned in the pT sum of the two taus and two leading jets (S_T) for the fit.
- The challenging jet to fake hadronic tau background is estimated with a fake factor method.



Axion-Like Particle with AFP

- Three types of signal according to the proton dissociation pattern.



Elastic (exclusive) **EL**

Single dissociative **SD**

Double dissociative **DD**

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Axion–Like Particle with AFP