Inclusive searches for squarks and gluinos with the ATLAS detector

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The University Of Sheffield.

ATLAS EXPERIMENT

Outlook:

(I) Introduction

(II) Search for supersymmetry in events with multiple *b*-jets

(III) SUSY searches in invariant mass distributions of OSSF leptons

(IV) Search for SUSY in final states with τ-leptons

(V) Summary

ATLAS EXPERIMENT

ATLAS CONF Note

ATLAS-CONF-2018-041

24th July 2018

CERN

Search for supersymmetry in final states with missing transverse momentum and multiple b-jets in proton–proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

The ATLAS Collaboration

A search for supersymmetry involving the pair production of gluinos decaying via third-generation squarks into the lightest neutralino ($\tilde{\chi}_1^0$) is reported. It uses LHC proton–proton collision data at a centre-of-mass energy $\sqrt{s}$ = 13 TeV with an integrated luminosity of 79.8 fb^{-1} collected with the ATLAS detector from 2015 to 2017. The search is performed in events containing large missing transverse momentum and several energetic jets, at least three of which must be identified as containing b-quarks. No excess is found above the predicted background. For $\tilde{\chi}_1^0$ masses below approximately 800 GeV, gluino masses of less than 2.2 TeV are excluded at 95% confidence level in simplified models involving the pair production of gluinos that decay via top or bottom squarks. An interpretation of the limits in terms of the branching ratios of the gluinos into third-generation squarks is also provided.

(I) ATLAS-CONF-2018-041

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

CERN

Eur. Phys. J. C 78 (2018) 625
DOI: 10.1140/epjc/s10052-018-6081-9

CERN-EP-2018-053
25th September 2018

Search for new phenomena using the invariant mass distribution of same-flavour opposite-sign dilepton pairs in events with missing transverse momentum in $\sqrt{s}$ = 13 TeV pp collisions with the ATLAS detector

The ATLAS Collaboration

A search for new phenomena in final states containing an e^+e^- or $\mu^+\mu^-$ pair, jets, and large missing transverse momentum is presented. This analysis makes use of proton–proton collision data with an integrated luminosity of 36.1 fb^{-1}, collected during 2015 and 2016 at a centre-of-mass energy $\sqrt{s}$ = 13 TeV with the ATLAS detector at the Large Hadron Collider. The search targets the pair production of supersymmetric coloured particles (squarks or gluinos) and their decays into final states containing an e^+e^- or $\mu^+\mu^-$ pair and the lightest neutralino ($\tilde{\chi}_1^0$) via one of two next-to-lightest neutralino ($\tilde{\chi}_2^0$) decay mechanisms: $\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0$, where the Z boson decays leptonically leading to a peak in the dilepton invariant mass distribution around the Z boson mass; and $\tilde{\chi}_2^0 \to \ell^+\ell^-\tilde{\chi}_1^0$ with no intermediate $\ell^+\ell^-$ resonance, yielding a kinematic endpoint in the dilepton invariant mass spectrum. The data are found to be consistent with the Standard Model expectation. Results are interpreted using simplified models, and exclude gluinos and squarks with masses as large as 1.85 TeV and 1.3 TeV at 95% confidence level, respectively.

(II) Eur. Phys. J. C 78 (2018) 625

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

CERN

Phys. Rev. D 99 (2019) 012009
DOI: 10.1103/PhysRevD.99.012009

CERN-EP-2018-185
January 31, 2019

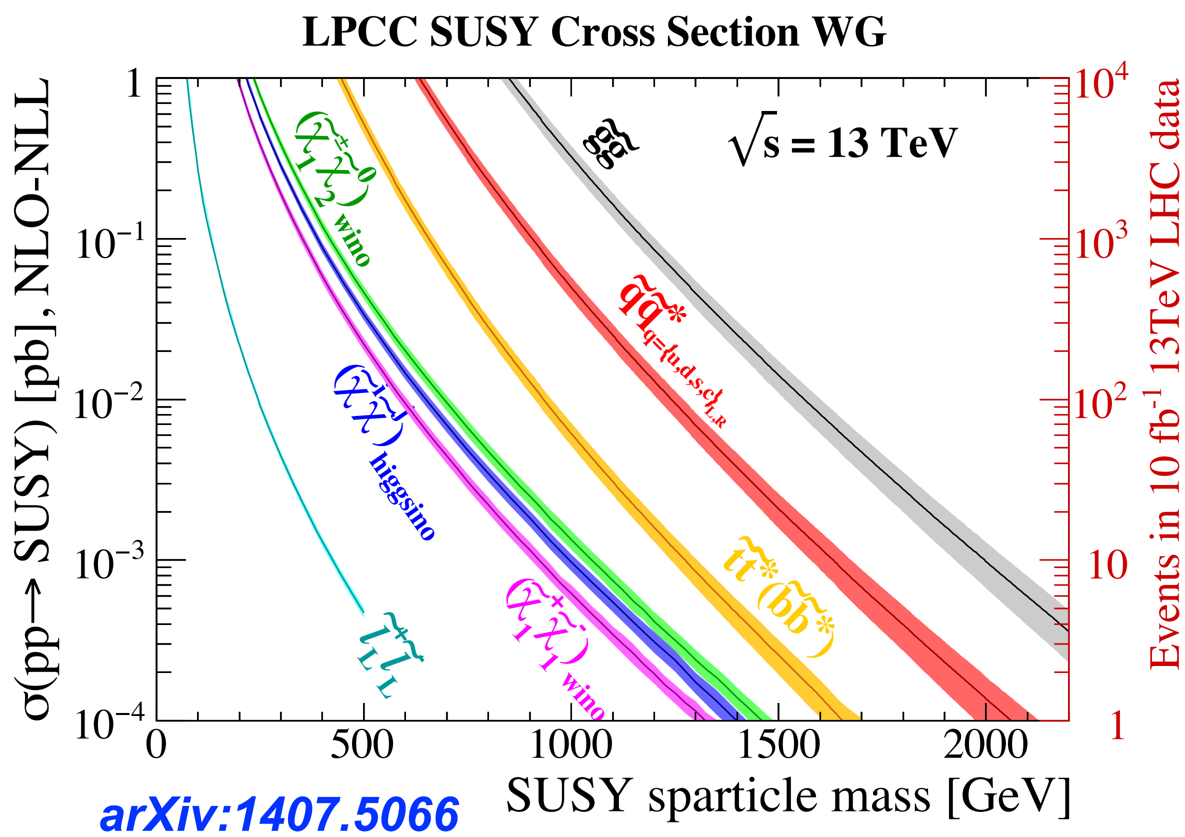
Search for squarks and gluinos in final states with hadronically decaying τ-leptons, jets, and missing transverse momentum using pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

The ATLAS Collaboration

A search for supersymmetry in events with large missing transverse momentum, jets, and at least one hadronically decaying τ-lepton is presented. Two exclusive final states with either exactly one or at least two τ-leptons are considered. The analysis is based on proton–proton collisions at $\sqrt{s}$ = 13 TeV corresponding to an integrated luminosity of 36.1 fb^{-1} delivered by the Large Hadron Collider and recorded by the ATLAS detector in 2015 and 2016. No significant excess is observed over the Standard Model expectation. At 95% confidence level, model-independent upper limits on the cross section are set and exclusion limits are provided for two signal scenarios: a simplified model of gluino pair production with τ-rich cascade decays, and a model with gauge-mediated supersymmetry breaking (GMSB). In the simplified model, gluino masses up to 2000 GeV are excluded for low values of the mass of the lightest supersymmetric particle (LSP), while LSP masses up to 1000 GeV are excluded for gluino masses around 1400 GeV. In the GMSB model, values of the supersymmetry-breaking scale are excluded below 110 TeV for all values of $\tan\beta$ in the range $2 \leq \tan\beta \leq 60$, and below 120 TeV for $\tan\beta > 30$.

(III) Phys. Rev. D 99 (2019) 12009

- Supersymmetry (SUSY): spacetime symmetry that relates bosons (integer-valued spin) with fermions (half-integer spin).
- Each fermion/boson is associated with a boson/fermion known as its *superpartner*.
- Conservation of R-parity $P_R = (-1)^{3B+L+2s}$:
  - SUSY particles are produced in pairs.
  - The lightest supersymmetric particle (LSP) is stable, neutral and only weakly interacting ⇒ Escapes the detector without signature.
- Cross section for production of 1st or 2nd gen. squarks or gluinos expected to be larger than for 3rd gen. squarks or electroweak SUSY.
- Experimental signatures:
  - Large E_T^{miss} (from LSP).
  - Multiple high p_T light-flavor jets or b-jets.
  - Other objects (e.g. leptons, Z bosons).



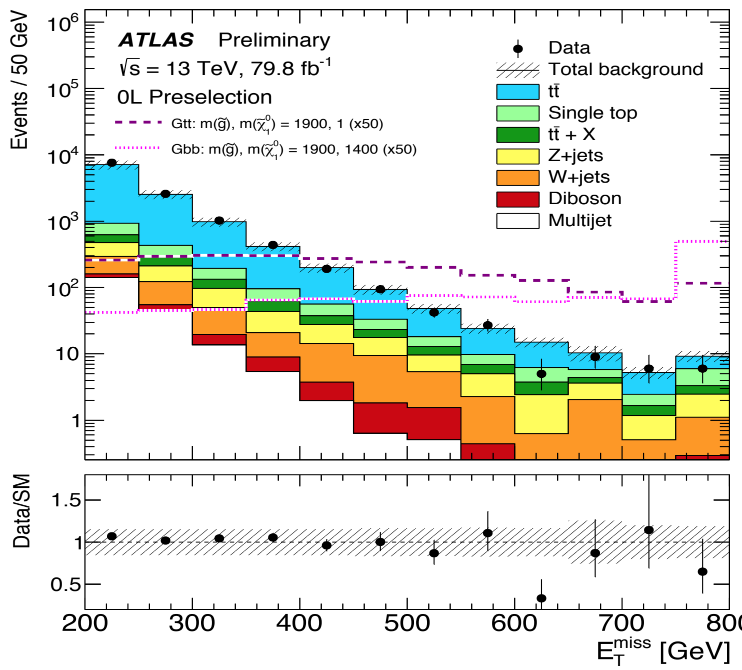
Expected production cross section for several types of SUSY particles at 13 TeV

- Only direct squark/gluino production with conserved R-parity shown here ⇒ other models are addressed in the talks from **L. Schaefer/M. Ayoub/T. Yamazaki**.

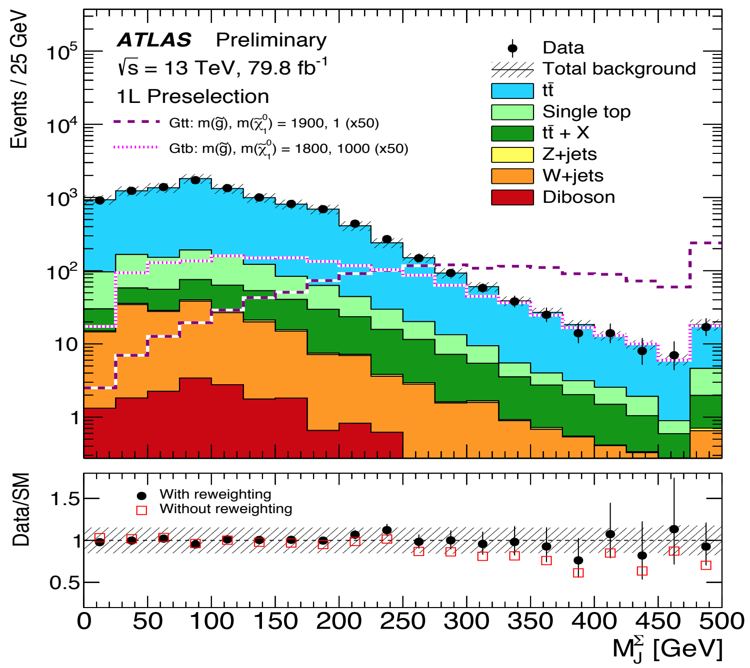
Search for supersymmetry in events with multiple *b*-jets

Multi-b analysis: Motivation

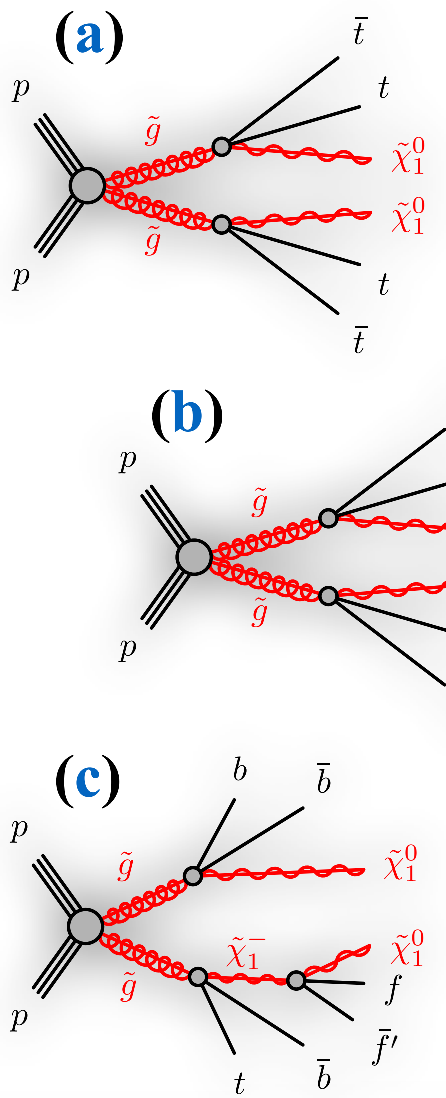
- Many SUSY scenarios featuring direct gluino production are expected to produce events with multiple b-jets and large E_T^{miss}.
  - Signal regions with $N_{b\text{-jets}} \geq 3$, $E_T^{miss} > 200$ GeV and separation into **0-lepton** and **1-lepton** events to be sensitive to top/bottom quark **(a,b)** production and different gluino branching ratios **(c)**.
- Other discriminating variables: m_{eff}, m_T, m_T^b (transverse mass of b-jets), M_j^{Σ} (sum of invariant jet masses).
- Cut on $\Delta\varphi^{4j}_{min} = \min_{i\leq4}(|\varphi^i_{jet} - \varphi^{miss}|) > 0.4$ to suppress mutijet background in 0-lepton channels.



0-lepton preselection



1-lepton preselection



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- Dominant SM background in all SRs: $t\bar{t}$ production ⇒ one $t\bar{t}$ CR for each SR. Typically lower E_T^{miss}, m_{eff}, M_j^{Σ} requirements (or inverting m_T cut).
  - Signal contamination in CRs typically below 6% ($t\bar{t}$ normalization checked in VRs).
- Subdominant background processes (single-top, W+jets, Z+jets, $t\bar{t}+Z/W/H$ and diboson) are estimated purely from MC.
- Remaining multijet background is estimated in multijet enriched region (reverting $\Delta\varphi^{4j}_{min}$ cut to < 0.1) and extrapolating to SR.

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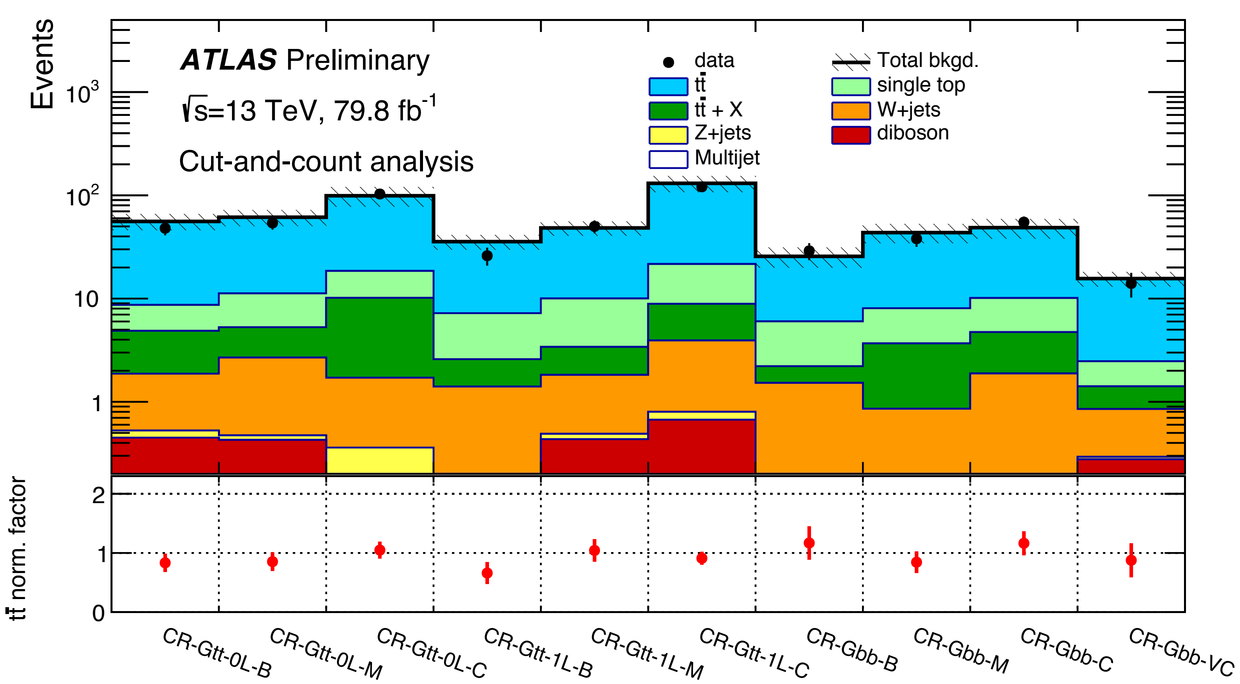

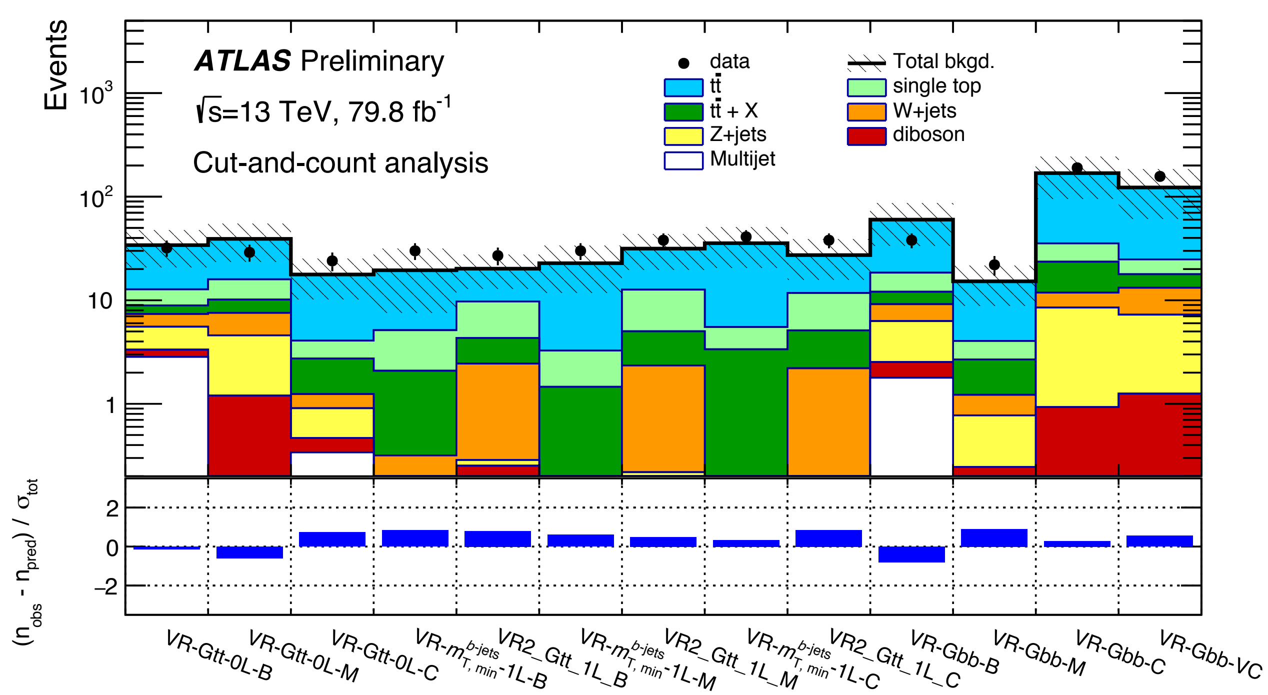

Pre-fit event yields in CRs (left) and results of the background-only fit in VRs (right): normalization factors are obtained only for the $t\bar{t}$ background

- SRs designed for kinematically different scenarios ⇒ increasing E_T^{miss}, m_{eff} or M_j^{Σ} cuts:
  - Boosted (B) → large Δm between SUSY particles.
  - Compressed (C) → low Δm.
  - Moderate (M) → intermediate regions.
- Model-independent interpretations done with inclusive SRs (simple **cut-and-count** approach).
- Model-dependent exclusion limits obtained with **multi-bin** SRs: statistical combination of non-overlapping N_{jet}, m_{eff} bins.
- Analysed data from 2015-2017, corresponding to 79.8 fb^{-1} ⇒ no significant deviation from SM observed in any of the SRs.

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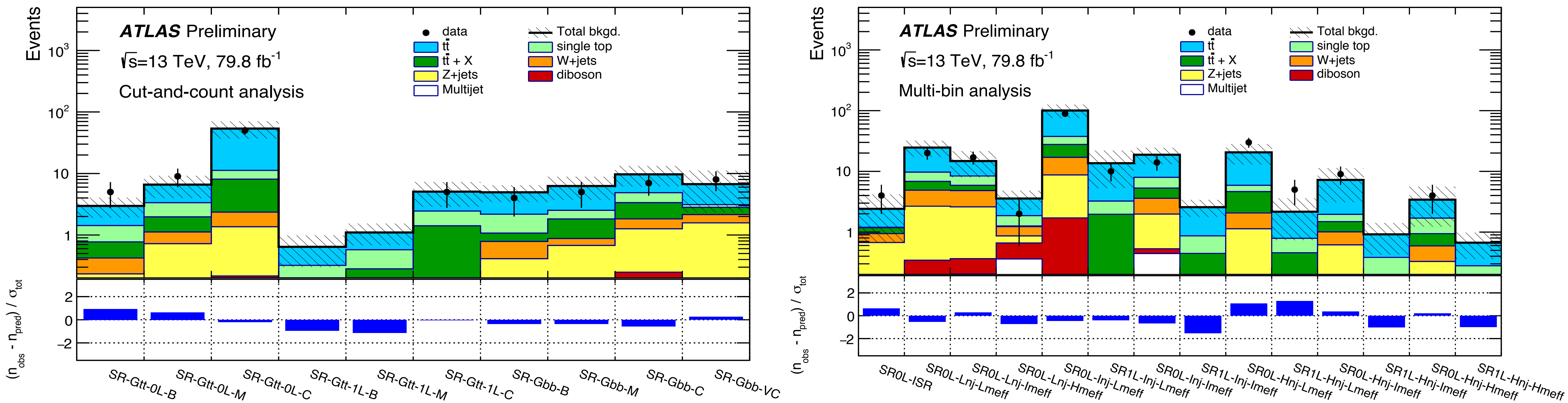

Results in SRs for inclusive (cut-and-count) approach (left) and multi-bin SRs (right)

- No significant excess observed ⇒ can derive exclusion limits for most relevant SUSY benchmark models.
  - Two simplified models featuring gluino production with decay into bottom/top quarks pairs and neutralinos: $\tilde{g}\rightarrow tt\tilde{\chi}_1^0$ and $\tilde{g}\rightarrow bb\tilde{\chi}_1^0$ model.
  - Can exclude neutralino masses up to 1.2 TeV and gluino masses below 2.3 TeV (at 95% CL_s) for $\tilde{g}\rightarrow tt\tilde{\chi}_1^0$ scenario **(a)**. Slightly lower for $\tilde{g}\rightarrow bb\tilde{\chi}_1^0$ **(b)**.
  - Limits can be also set depending on the branching ratio of the gluino decay to top/bottom quark pairs **(c)**.

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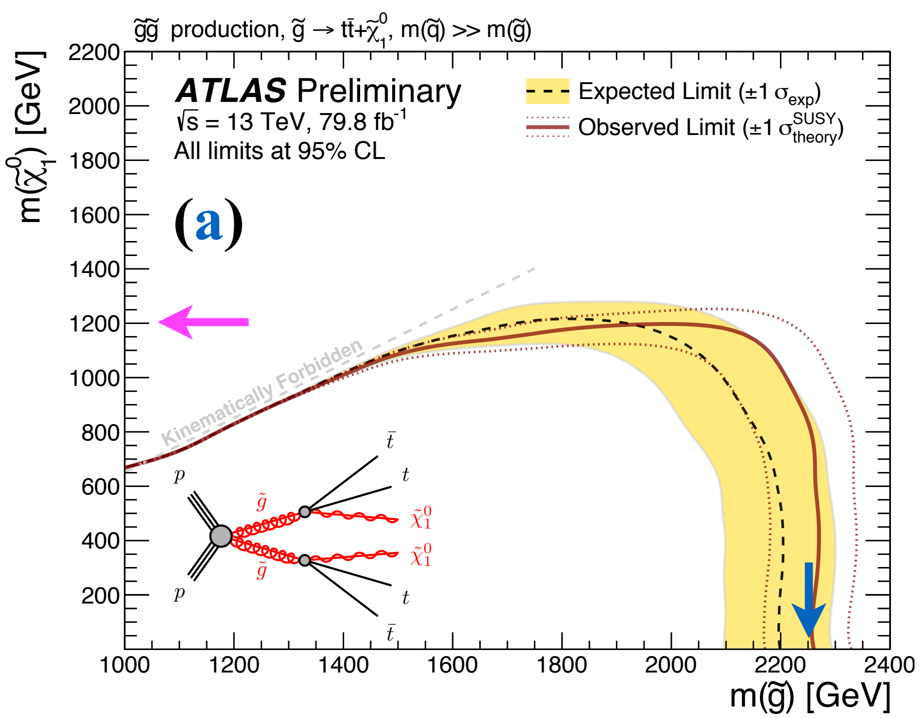
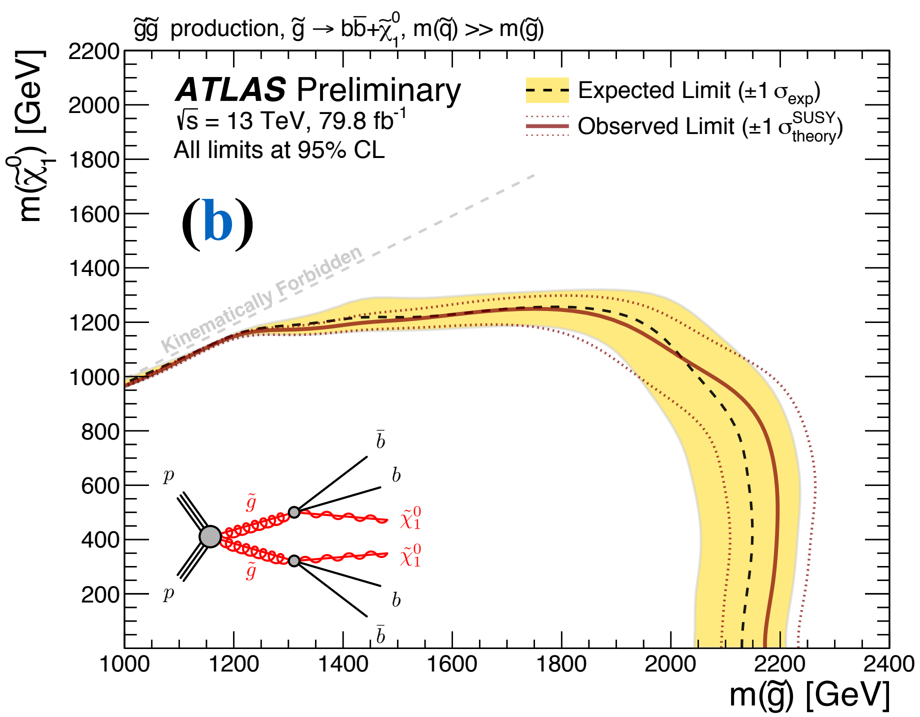
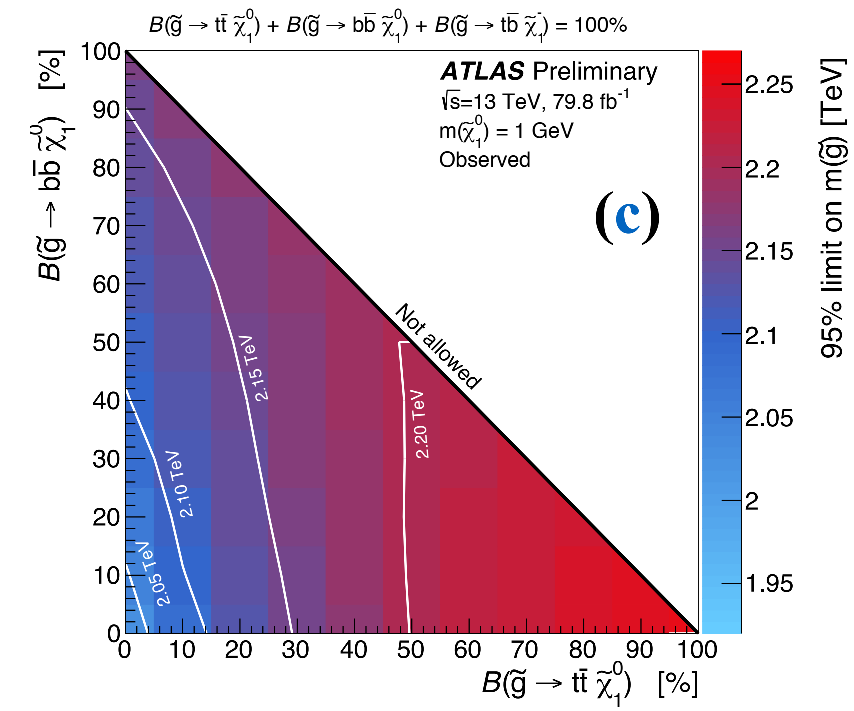






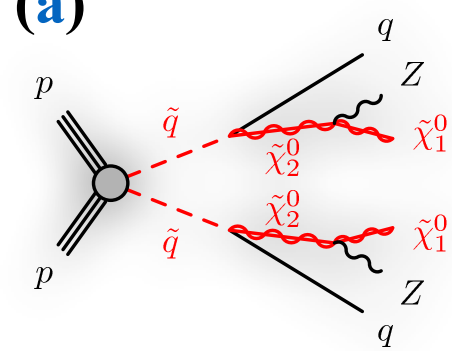
Observed (red solid) and expected (grey dashed) exclusion limits for the simplified $\tilde{g}\rightarrow tt\tilde{\chi}_1^0$ (left) and $\tilde{g}\rightarrow bb\tilde{\chi}_1^0$ (right) scenario

Observed limit on the branching ratio of the gluino to $tt\tilde{\chi}_1^0$ (x) or $bb\tilde{\chi}_1^0$ (y)

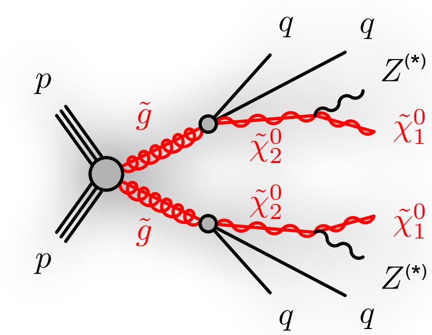
Search for SUSY in invariant mass distributions of OSSF leptons

- Sensitive to scenarios featuring squark or gluino production with Z bosons **(a,b)** or multiple leptons **(c)** in the final state.
- All signal regions require **≥ 2 leptons** (e or μ) and an *opposite-sign-same-flavor* (OSSF) lepton pair: e^+e^- or $\mu^+\mu^-$
  - m_{ll} inside (**on-Z**) or outside the Z mass window (**high/low-p_T edge**).
  - On- and off-shell Z production, depending on $\Delta m = m(\tilde{\chi}_2^0) - m(\tilde{\chi}_1^0)$.
- SRs are divided into several m_{ll} windows to be sensitive a broad range of different lepton/Z kinematics.
  - Partially overlapping m_{ll} bins for model-independent interpretations.
  - Orthogonal bin ranges (m_{ll} shape fit) for model-dependent limits.

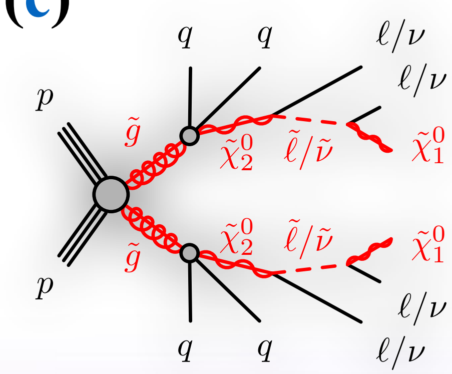
(a)

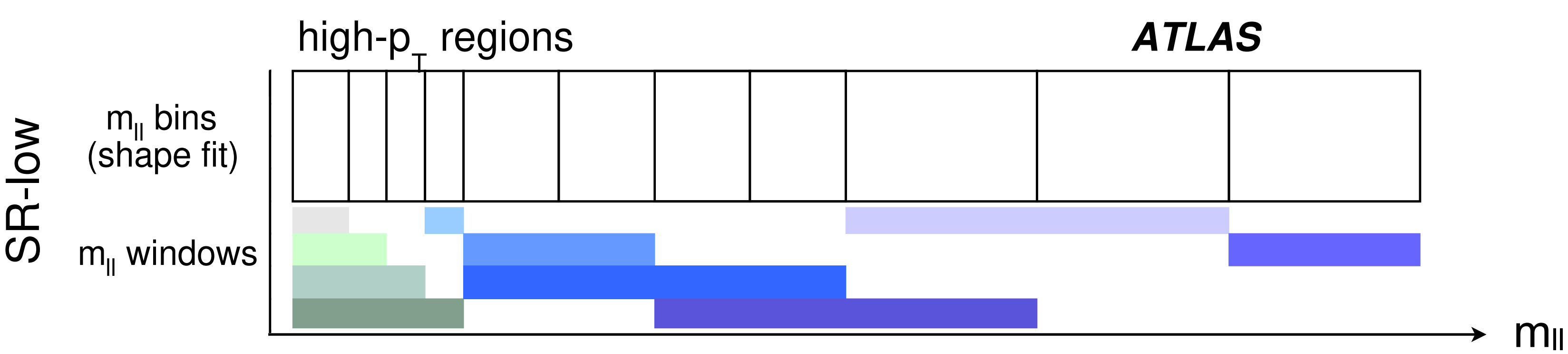


(b)



(c)





m_{ll} binning for one of the SRs (for model-independent interpretations and for the m_{ll} shape fit)

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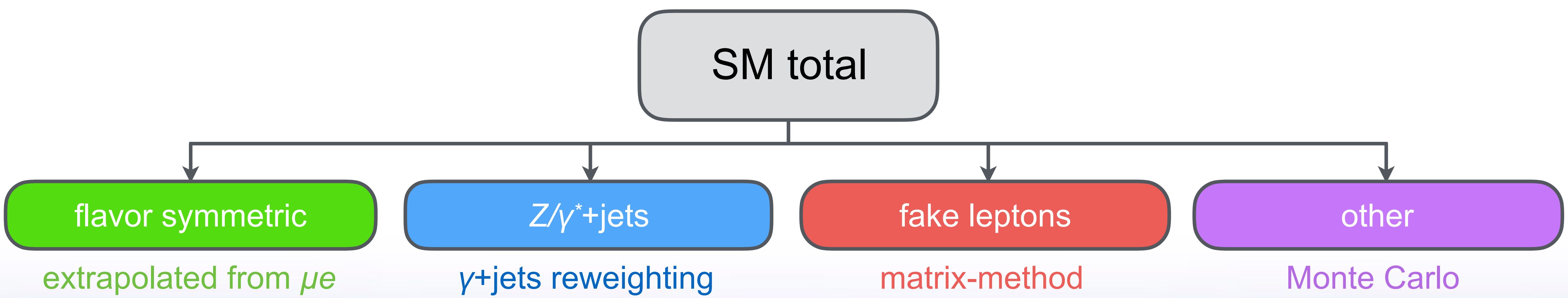
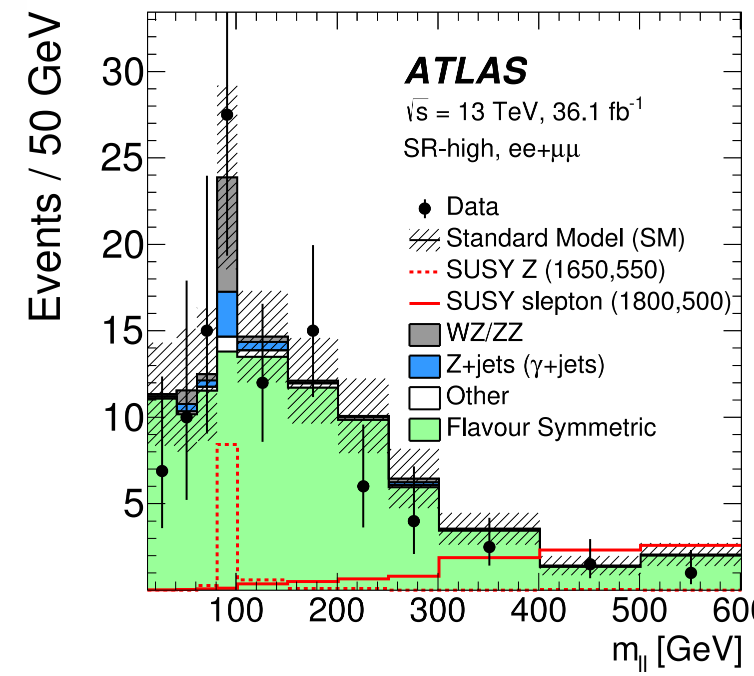
2L OSSF analysis: Background estimation

- Flavor-symmetric processes (e.g. WW, $t\bar{t}$, $Z\rightarrow\tau\tau$) with $ee : \mu\mu : e\mu = 1 : 1 : 2$ in SRs can be estimated from different-flavor (DF) control regions and extrapolated to SRs: *flavor-symmetry-method.*
  - p_{T} and $|\eta|$ dependent corrections applied to DF-CRs to account for different trigger/selection efficiencies for electrons/muons.
- Z/γ^{*}+jets background is evaluated from γ+jets enriched control regions with a photon instead of a OSSF lepton pair.
  - Reweighing/smearing to match $p_{\mathrm{T}}(\gamma)$ to $p_{\mathrm{T}}(Z)$ and to correct for differences in resolution between photon and electrons/muons.
- Fake leptons are estimated with *matrix-method.*
  - Measuring efficiencies for prompt/fake leptons $\varepsilon_{\mathrm{real,fake}}$ in dedicated CRs and inverting efficiency matrix to obtain number of fake leptons passing SRs.
- Other backgrounds ($t\bar{t}+Z$, $t\bar{t}+H$, WZ, ZZ) estimated purely from MC.



- Analysed 36.1 fb^{-1} of data (2015/16).
  - Looking at m_{ll} distributions in inclusive SRs and agreement in each m_{ll} window: **12** in low-p_T SRs **(a)**, **29** in on-Z SRs **(b)**.
  - No significant deviation from SM. Neither in inclusive SRs, nor in m_{ll}-binned.
- Largest excess observed in SR with 101 GeV < m_{ll} < 201 GeV $\Rightarrow$ around 2σ.



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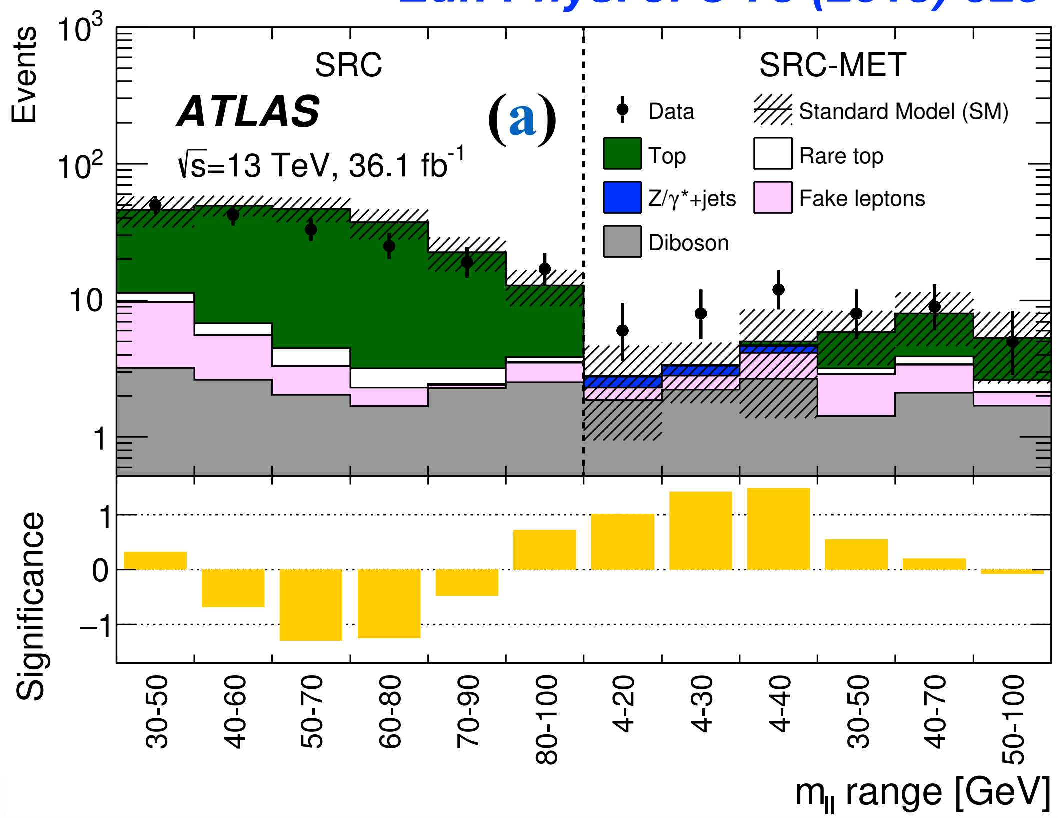
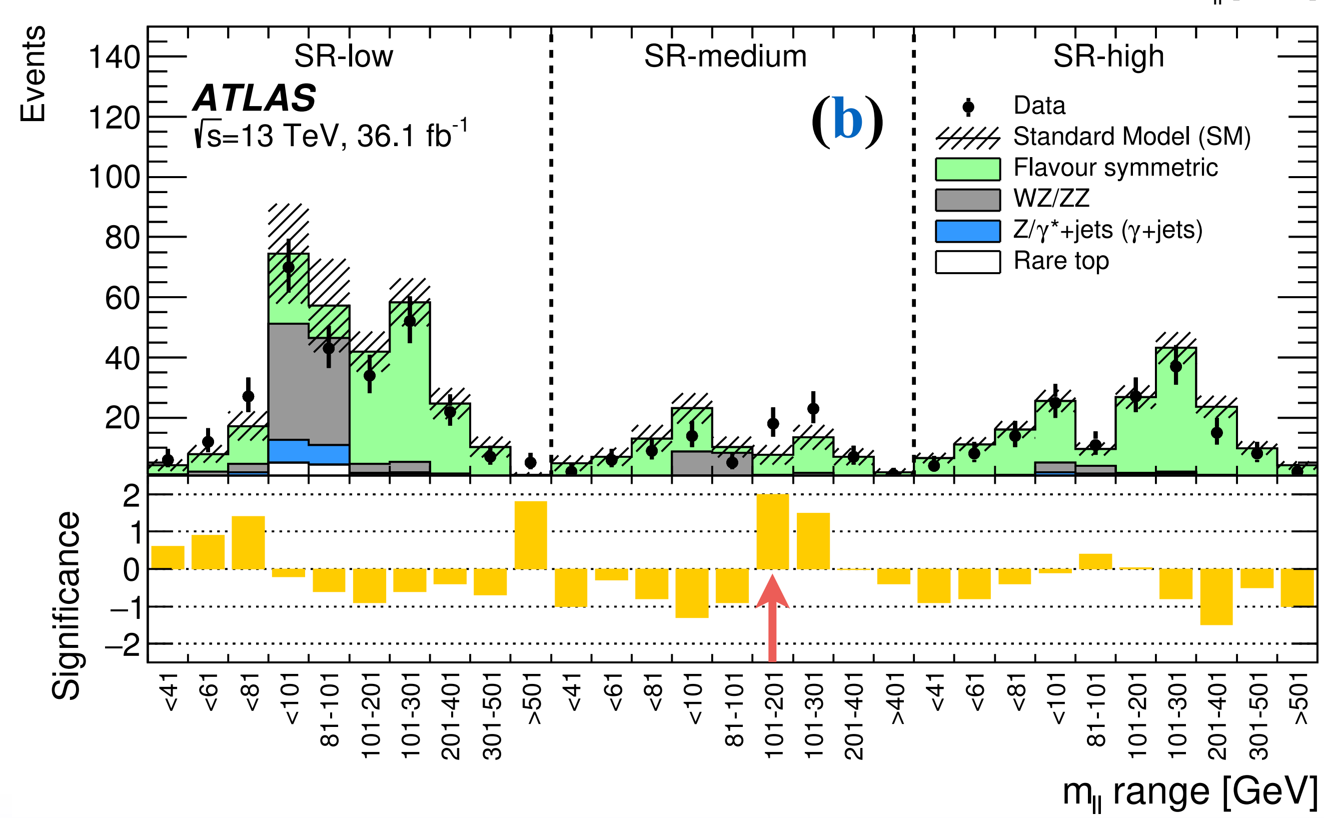
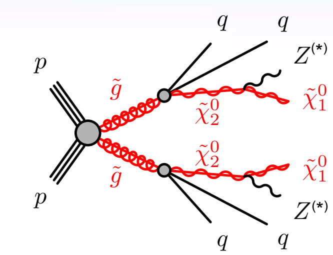
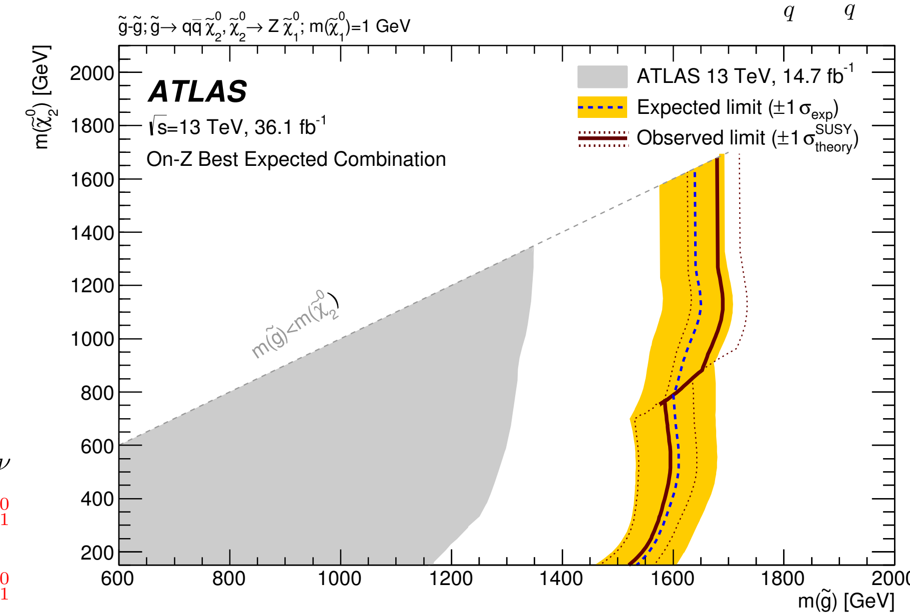




Data vs. expected SM background for each m_{ll} window of the low-p_T edge SRs (left) and on-Z SRs (right)

- Exclusion limits on several models featuring direct squark or gluino production with Z bosons (on/off-shell) or multiple leptons in the final states.
  - Using m_{ll} shape fit for limit setting ⇒ statistical combination of orthogonal m_{ll} bins.
  - Limits derived for different $m(\tilde{g})$, $m(\tilde{\chi}_1^0)$, but also depending on $m(\tilde{\chi}_2^0)$ (with a fixed $\tilde{\chi}_1^0$ mass of 1 GeV).
  - Excluding gluino masses up to 1.85 TeV and squark masses up to 1.35 TeV.





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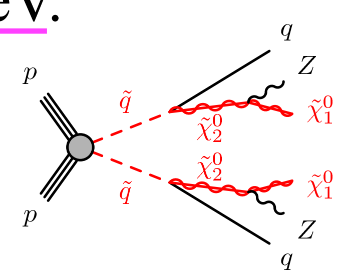
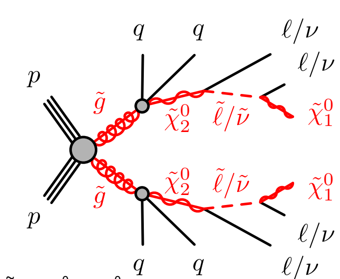
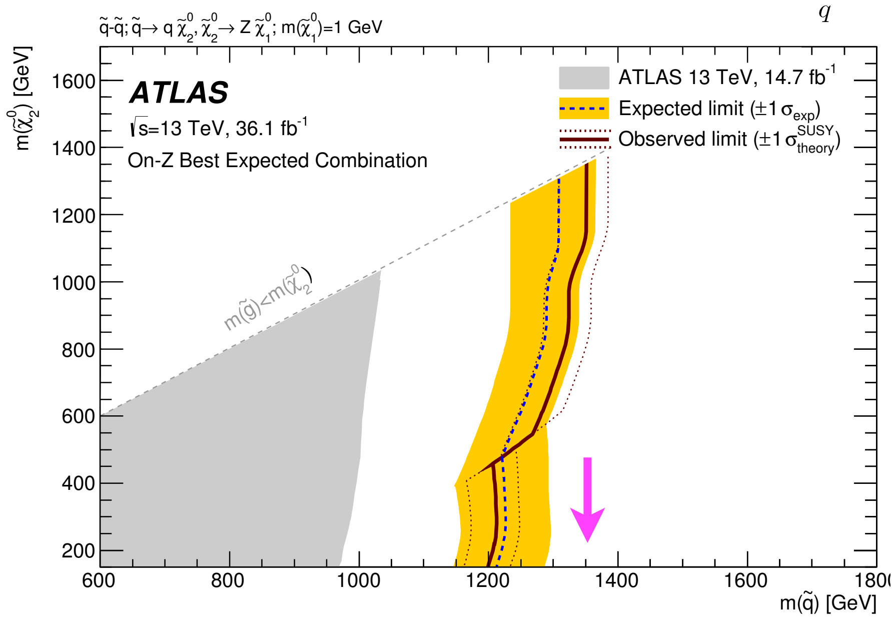
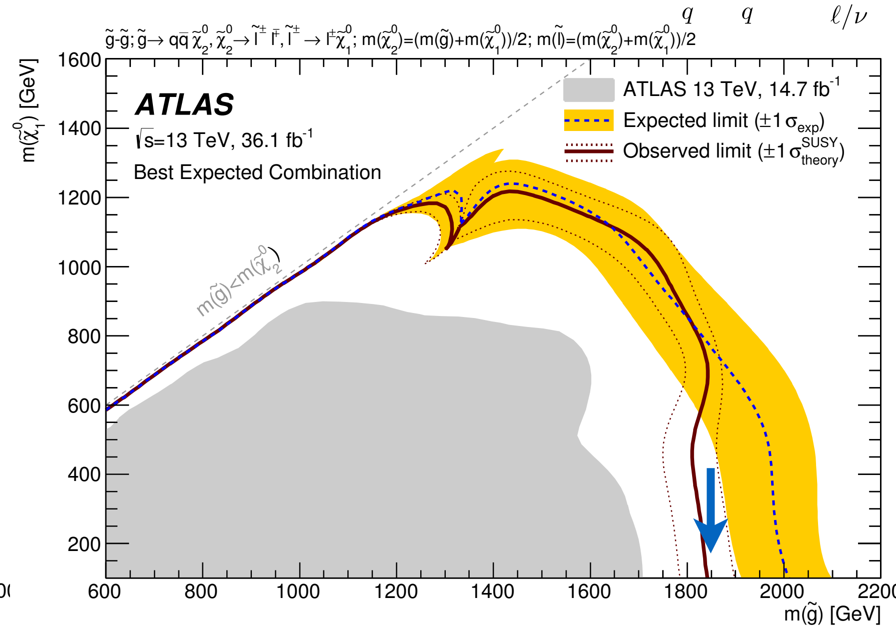
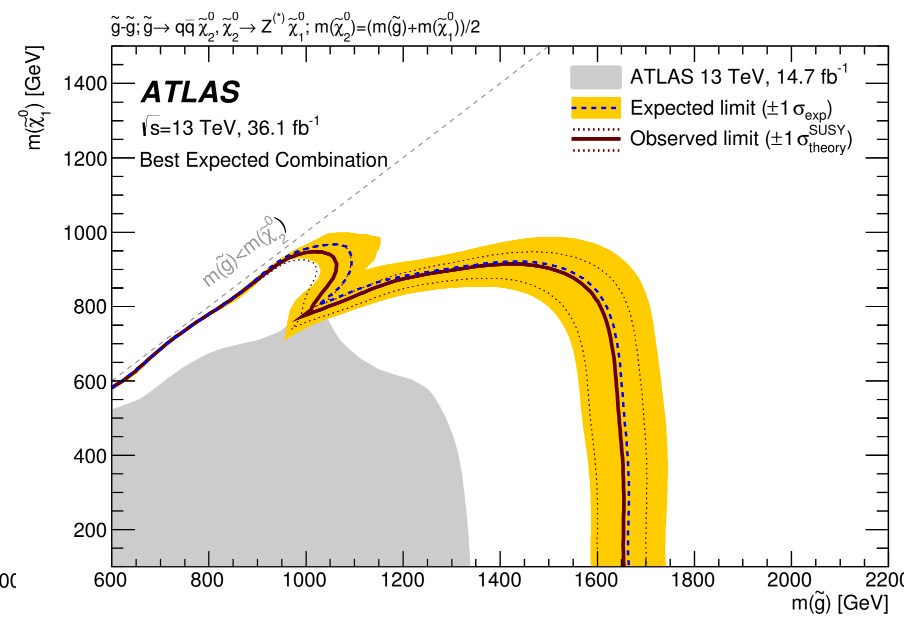










Observed (red solid) and expected (grey dashed) exclusion limits for different SUSY scenarios producing Z bosons or multiple leptons

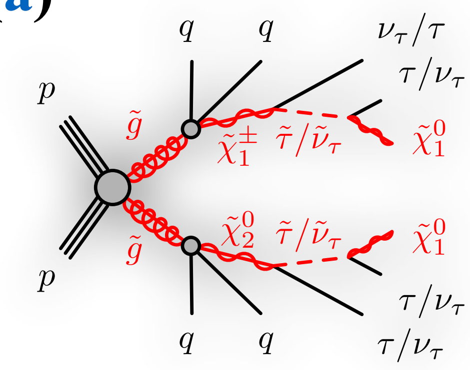
Search for supersymmetry in final states with τ-leptons and E_T^{miss}

- Different SUSY scenarios expect τ-leptons, jets and $E_{\mathrm{T}}^{\mathrm{miss}}$ in their final states.
  - Direct gluino production (simplified model) with two-step decay via $\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_2^0$ and $\tilde{\tau}$ (superpartner of τ-lepton) to τ-leptons and $\tilde{\chi}_1^0$ (**a**).
  - GMSB (gauge-mediated SUSY breaking) model: SUSY breaking is translated to visible sector via massive gauge field $\tilde{G}$ (**b**).
- Selecting events with **exactly one** or **at least two** hadronically decaying τ-leptons, $E_{\mathrm{T}}^{\mathrm{miss}} > 180$ GeV and two jets ($p_{\mathrm{T}}^{\mathrm{1st/2nd}} > 120/25$ GeV).
- Discriminant variables: H_{T}, $E_{\mathrm{T}}^{\mathrm{miss}}$, transverse mass of τ-lepton $m_{\mathrm{T}}(\tau)$ or *stransverse mass* of the di-tau system:

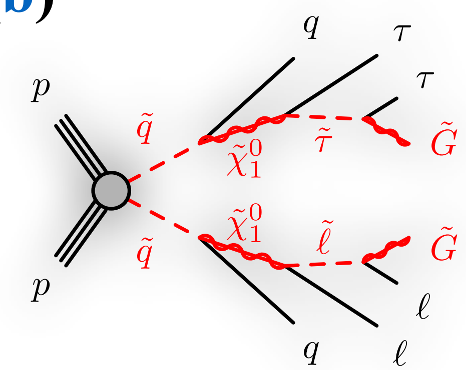
$$m_{\mathrm{T2}}^{\tau\tau} = \min_{\boldsymbol{p}_{\mathrm{T}}^{a}+\boldsymbol{p}_{\mathrm{T}}^{b}=\boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}}} \left(\max \left[m_{\mathrm{T}}(\boldsymbol{p}^{\tau_1}, \boldsymbol{p}_{\mathrm{T}}^{a}), m_{\mathrm{T}}(\boldsymbol{p}^{\tau_2}, \boldsymbol{p}_{\mathrm{T}}^{b}) \right] \right)$$

- SRs in 1τ and 2τ-channel optimized for compressed scenarios and larger mass-splittings.
- **Multi-bin** approach in 2τ-channel for model-dependent interpretations.
  - Binned in sum of transverse tau-masses: $m_{\mathrm{T}}(\tau_1) + m_{\mathrm{T}}(\tau_2)$.

(**a**)



(**b**)



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- Dominant background processes: $W\rightarrow\tau\nu$, $t\bar{t}$, diboson, $Z\rightarrow\nu\nu$ (only in 1τ-channels), $Z\rightarrow\tau\tau$ (only in 2τ-channels).
- Control regions for W/Top, $Z\rightarrow\nu\nu$, $Z\rightarrow\tau\tau$.
  - Top and W CRs separated into regions targeting real or fake-τ (from light/heavy-flavor jets).
- Multijet background estimated with *jet-smearing-method.*
  - Estimation for large E_T^{miss} events (from jet mis-measurements) by "smearing" low E_T^{miss} events with a jet-response function (E_T^{truth} - E_T^{reco}).
- VRs for different background sources (different kinematic cuts).

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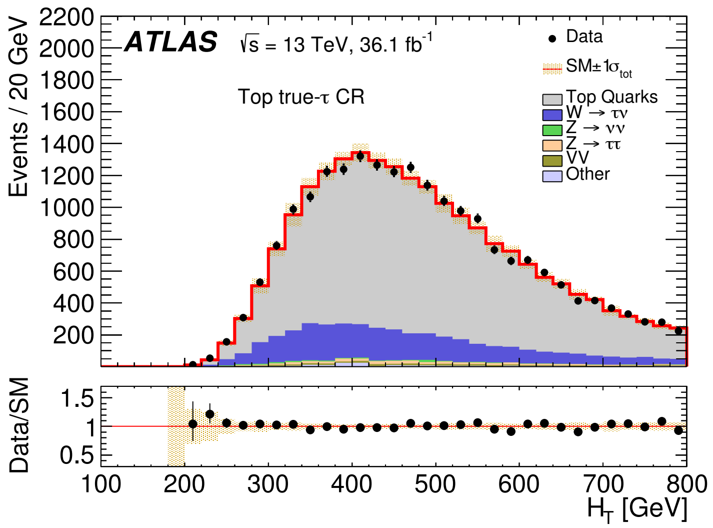
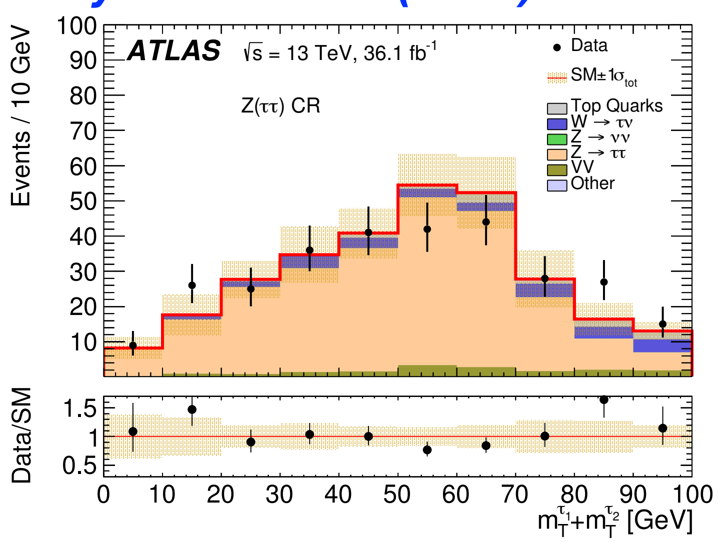
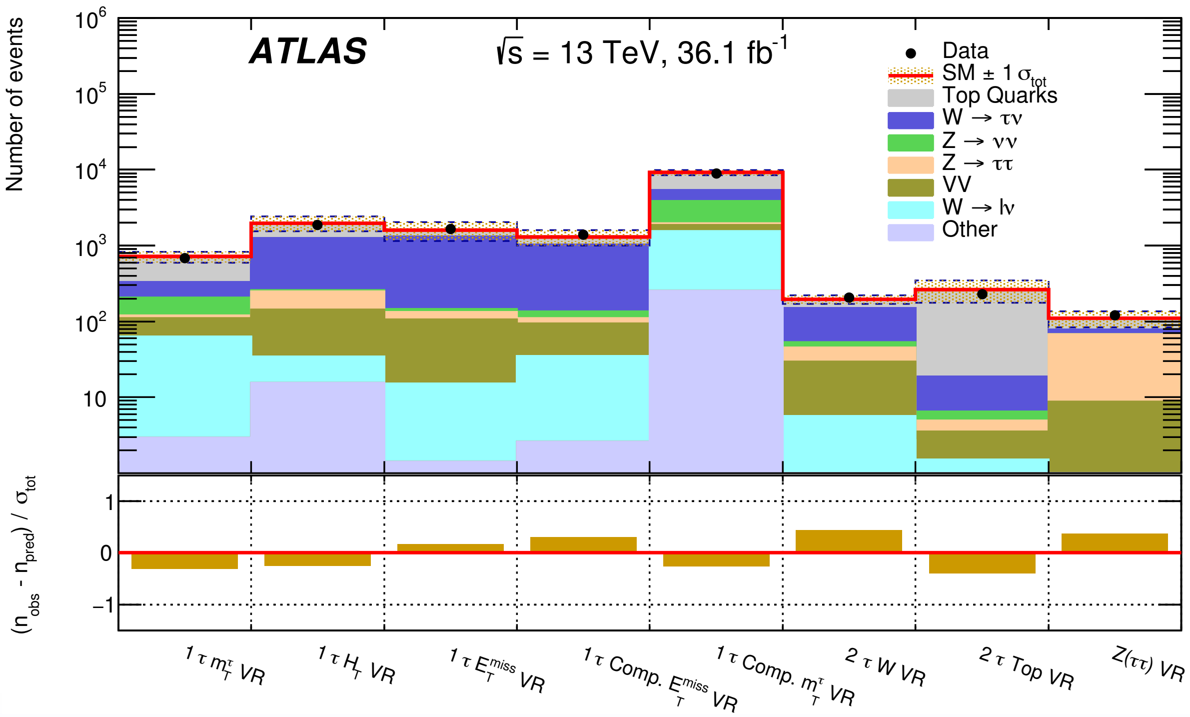




H_T in top true-τ CR (left). Sum of transverse tau-masses $m_T(\tau_1) + m_T(\tau_2)$ in $Z\rightarrow\nu\nu$ CR (right)



Summary of event yields in all VRs

- Analysed 36.1 fb^{-1} of data (2015/16).
  ⇒ Good agreement between data and SM prediction in all 1τ and 2τ-SRs.
- Limits for gluino two-step decay **(a)** and GMSB model **(b)**:
  - Gluino two-step: Excluding gluino masses up to 2 TeV and neutralinos below 1 TeV.
  - GMSB: Limits depending on SUSY breaking scale Λ and ratio of Higgs doublets tan(β).
    ⇒ Excluding the region below Λ = 110 TeV.

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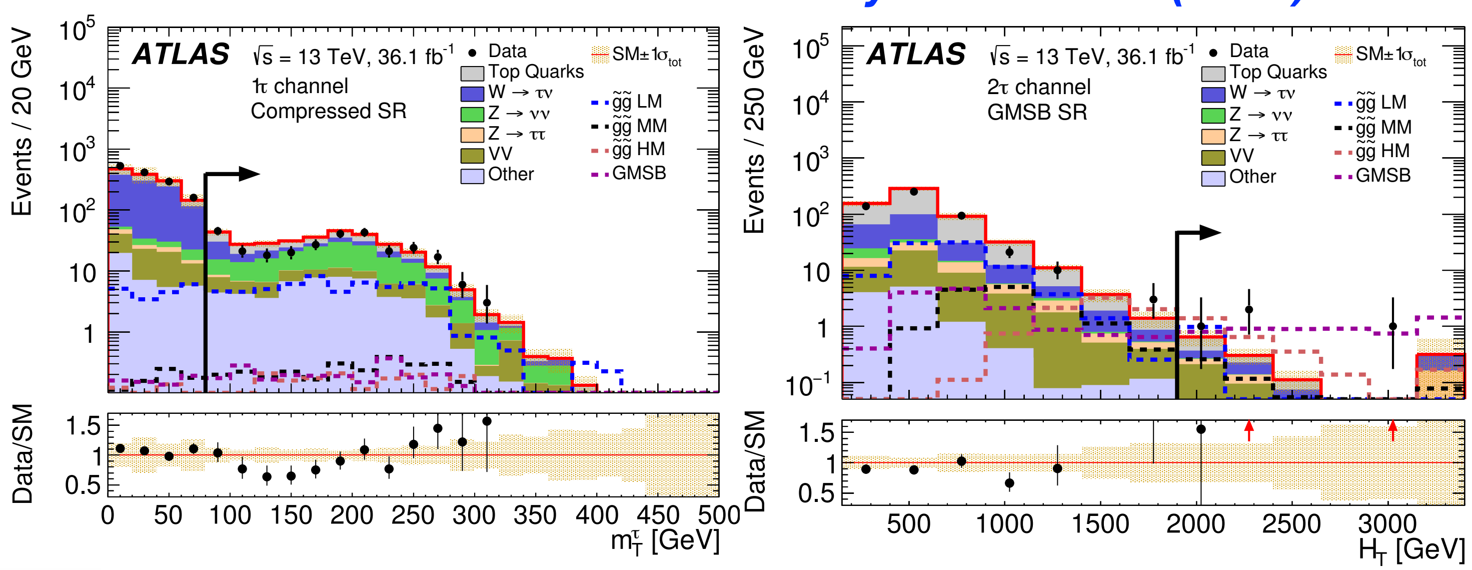
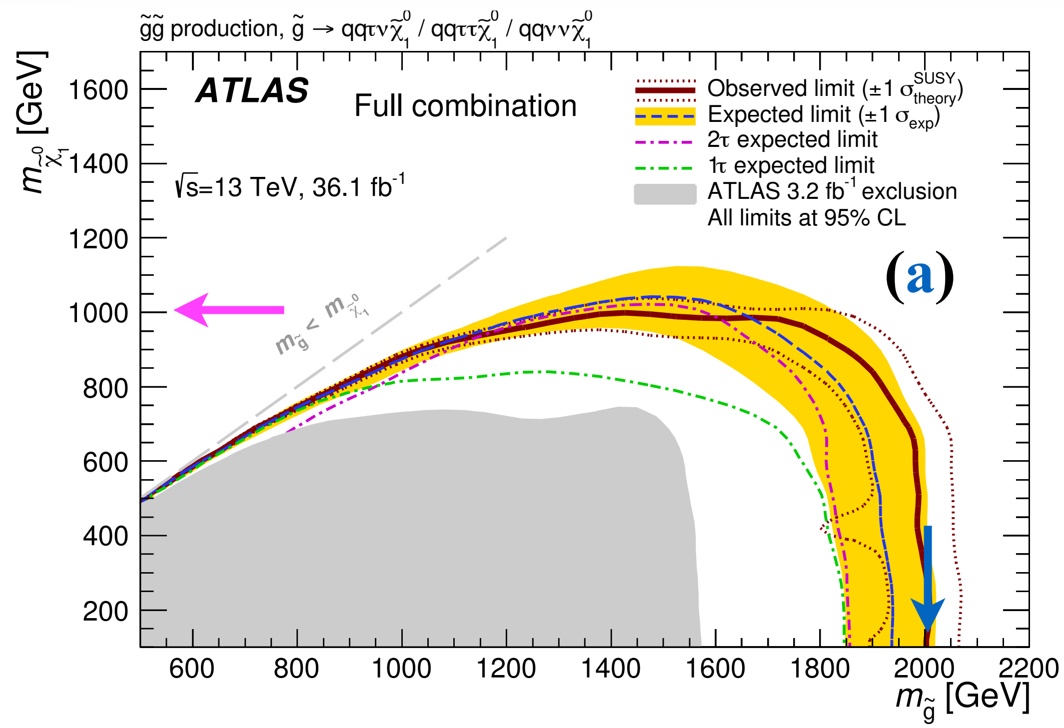
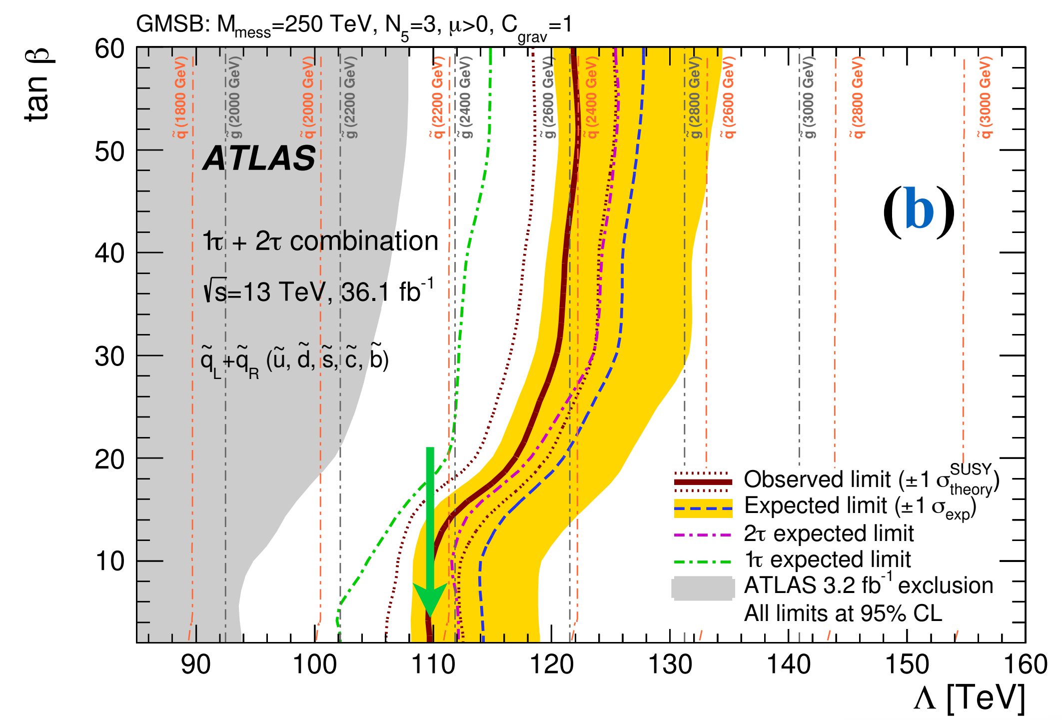


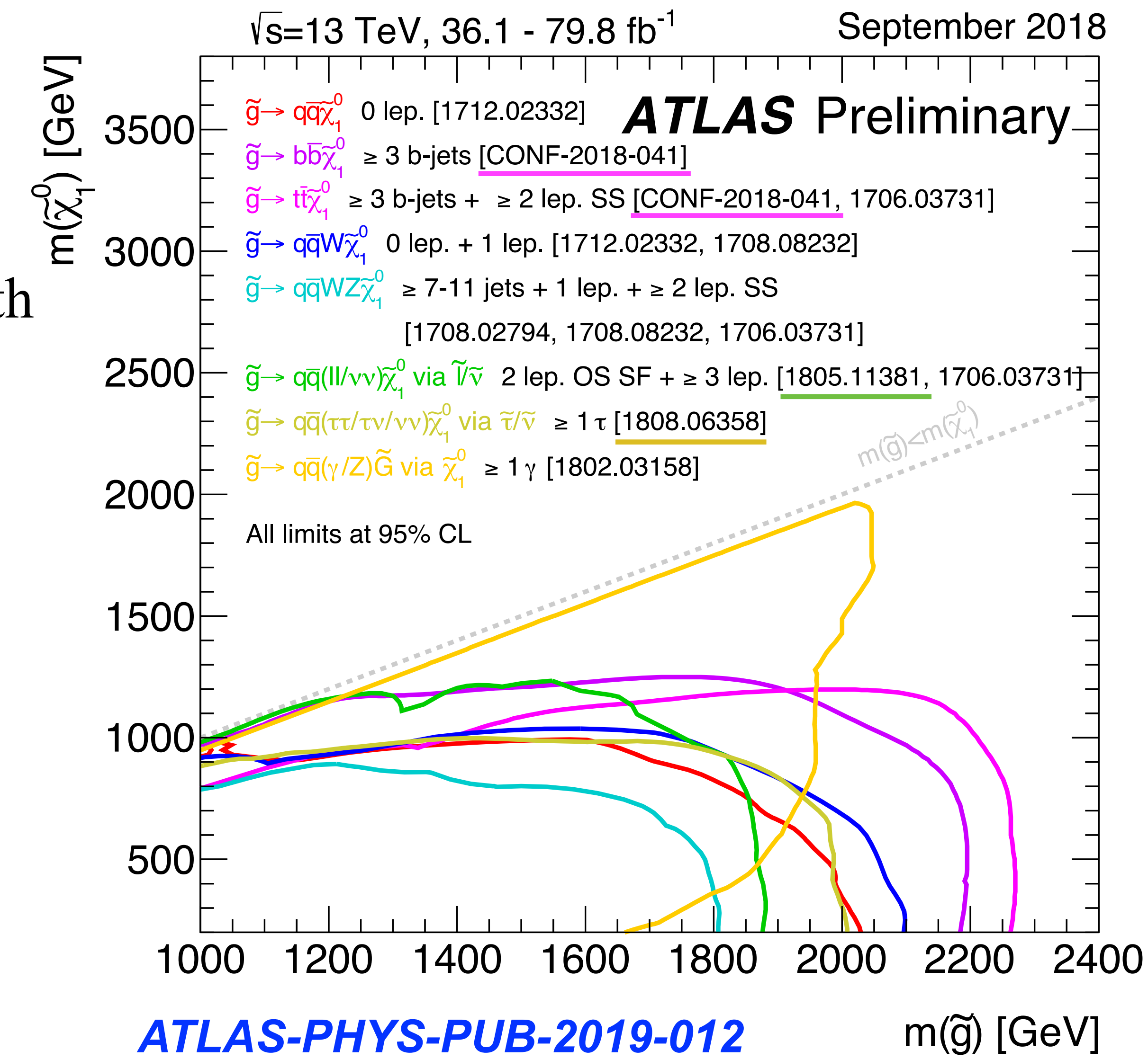
$m_T(\tau)$ in a 1τ-SR (left) and H_T in the GMSB SR (right): SRs are indicated by the back arrows





Observed/expected limits for gluino two-step decay (top) and GMSB (bottom)

- Inclusive searches for squarks and gluinos can set strong constrains on a wide range of supersymmetric models.
- Distinct signatures (0-lepton, 1-lepton, 2L OSSF, etc.) can be investigated and have sensitivities to different SUSY scenarios.
- Multi-*b* analysis: searching in events with ≥ 3 *b*-jets and light-flavor jets.
  $\Rightarrow$ Can exclude gluino masses up to 2.3 TeV.
- 2L OSSF analysis: sensitive to SUSY models with *Z* prod. by investigating m_{ll} shapes.
  $\Rightarrow$ Excluding gluino (squark) masses up to 1.85 TeV (1.3 TeV).
- $\tau + E_T^{miss}$ analysis: final states with large E_T^{miss} and hadronically decaying τ-leptons.
  $\Rightarrow$ Can obtain limits on simplified and GMSB models.
- Unfortunately no public result with full Run 2 data (139 fb^{-1}) yet.
  Looking forward to interesting new results in the coming months… hopefully to be presented at Pheno 2020!



Summary plot showing exclusion limits from several inclusive squark and gluino searches

Backup

How do we search for SUSY?

- Define signal regions (SRs) ⇒ using variables which discriminate SUSY signals from SM background.
- Transverse momentum p_T, missing transverse energy E_T^{miss}, effective mass m_{eff}, transverse mass m_T

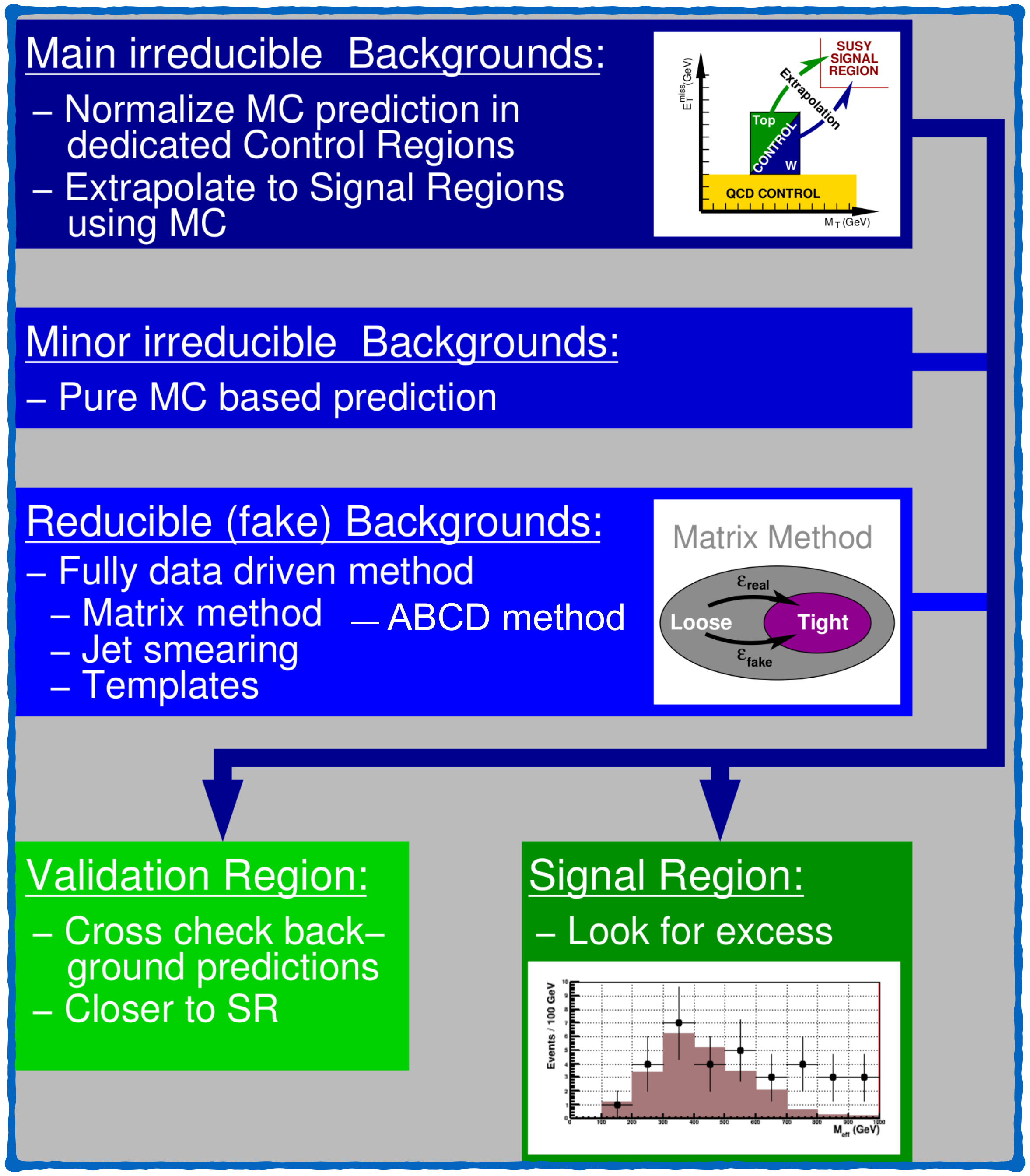
$$p_T = \sqrt{(p_x)^2 + (p_y)^2}$$

$$H_T = \sum_i |p_T|^i$$

$$m_{eff} = H_T + E_T^{miss}$$

$$m_T = \sqrt{2 p_T^{\ell} E_T^{miss} \cdot (1 - \cos(\Delta\phi(p_T^{\ell}, p_T^{miss})))}$$

- Irreducible backgrounds: Monte Carlo normalized in control region (CR) or pure MC.
- Reducible backgrounds: data-driven or semi data-driven approaches.
- Validation regions (VRs) to verify the background estimation.



from M. Hohlfelds talk at SUSY13 (link)

- Definition of the 0-lepton and 1-lepton signal/control regions of the multi-*b* analysis (for the simple cut-and-count approach).

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Gtt 1-lepton

Criteria common to all regions: ≥ 1 signal lepton, $N_{b\text{-jets}} \geq 3$

Targeted kinematics	Type	N_{jet}	m_{T}	$m_{\text{T,min}}^{b\text{-jets}}$	$E_{\text{T}}^{\text{miss}}$	$m_{\text{eff}}^{\text{incl}}$	M_J^{Σ}
Region B (Boosted, Large Δm)	SR	≥ 5	> 150	> 120	> 500	> 2200	> 200
	CR	$= 5$	< 150	–	> 300	> 1700	> 150
Region M (Moderate Δm)	SR	≥ 6	> 150	> 160	> 450	> 1800	> 200
	CR	$= 6$	< 150	–	> 400	> 1500	> 100
Region C (Compressed, small Δm)	SR	≥ 7	> 150	> 160	> 350	> 1000	–
	CR	$= 7$	< 150	–	> 350	> 1000	–

Gtt 0-lepton

Targeted kinematics	Type	N_{lepton}	$N_{b\text{-jets}}$	N_{jet}	$\Delta\phi_{\text{min}}^{4\text{j}}$	m_{T}	$m_{\text{T,min}}^{b\text{-jets}}$	$E_{\text{T}}^{\text{miss}}$	$m_{\text{eff}}^{\text{incl}}$	M_J^{Σ}
Region B (Boosted, Large Δm)	SR	$= 0$	≥ 3	≥ 7	> 0.4	–	> 60	> 350	> 2600	> 300
	CR	$= 1$	≥ 3	≥ 6	–	< 150	–	> 275	> 1800	> 300
Region M (Moderate Δm)	SR	$= 0$	≥ 3	≥ 7	> 0.4	–	> 120	> 500	> 1800	> 200
	CR	$= 1$	≥ 3	≥ 6	–	< 150	–	> 400	> 1700	> 200
Region C (Compressed, moderate Δm)	SR	$= 0$	≥ 4	≥ 8	> 0.4	–	> 120	> 250	> 1000	> 100
	CR	$= 1$	≥ 4	≥ 7	–	< 150	–	> 250	> 1000	> 100

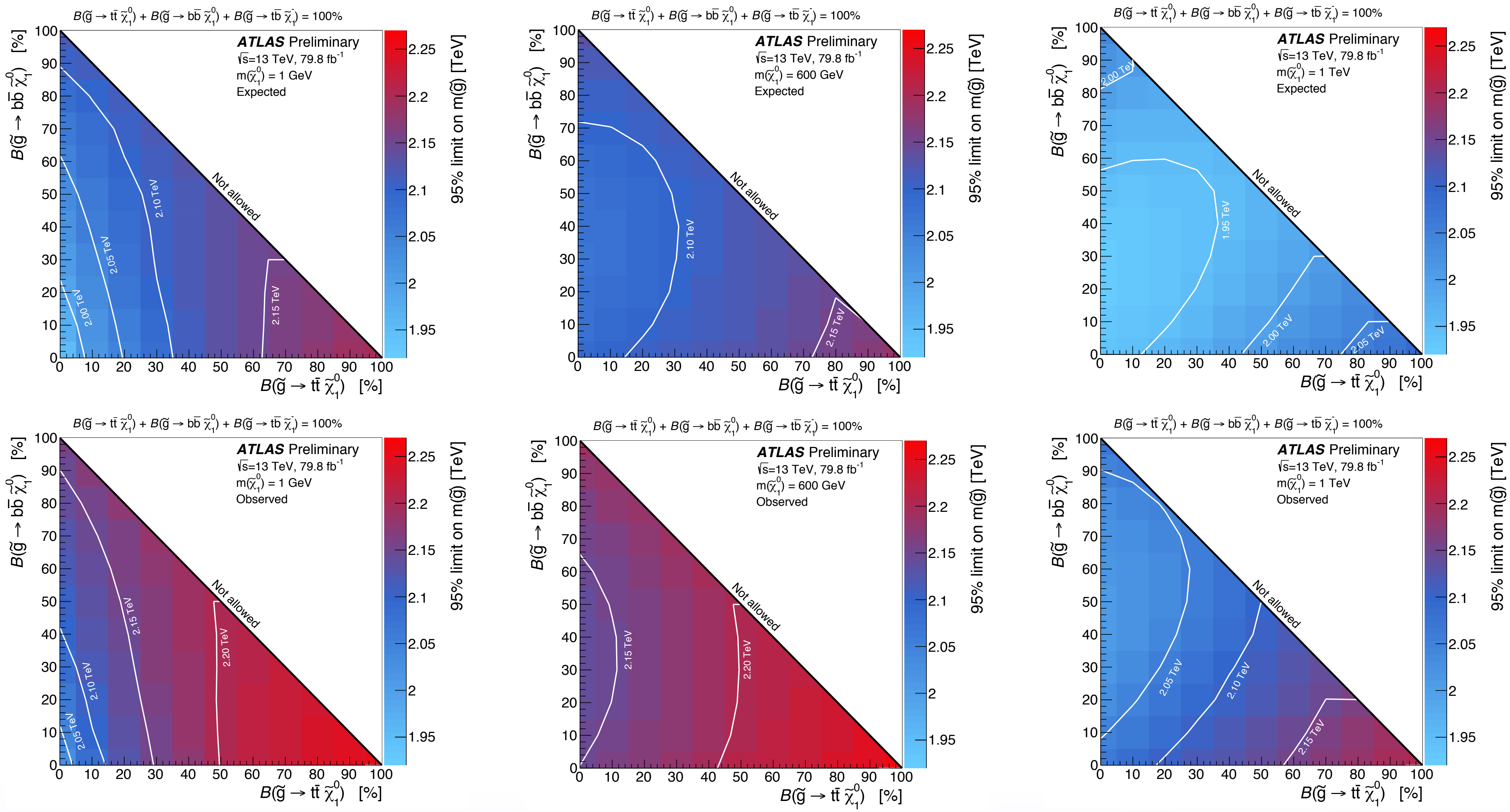
Gbb

Criteria common to all regions: $N_{\text{jet}} \geq 4$

Targeted kinematics	Type	N_{lepton}	$N_{b\text{-jets}}$	$\Delta\phi_{\text{min}}^{4\text{j}}$	m_{T}	$m_{\text{T,min}}^{b\text{-jets}}$	$E_{\text{T}}^{\text{miss}}$	m_{eff}	Others
Region B (Boosted, Large Δm)	SR	$= 0$	≥ 3	> 0.4	–	–	> 400	> 2800	–
	CR	$= 1$	≥ 3	–	< 150	–	> 400	> 2500	–
Region M (Moderate Δm)	SR	$= 0$	≥ 4	> 0.4	–	> 90	> 450	> 1600	–
	CR	$= 1$	≥ 4	–	< 150	–	> 300	> 1600	–
Region C (Compressed, small Δm)	SR	$= 0$	≥ 4	> 0.4	–	> 155	> 450	–	–
	CR	$= 1$	≥ 4	–	< 150	–	> 375	–	–
Region VC (Very Compressed, very small Δm)	SR	$= 0$	≥ 3	> 0.4	–	> 100	> 600	–	$p_{\text{T}}^{\text{j}_1} > 400$, $\text{j}_1 \neq b$, $\Delta\phi^{\text{j}_1} > 2.5$
	CR	$= 1$	≥ 3	–	< 150	–	> 600	–	

Multi-b analysis: Limits on gluino branching ratios

- Observed (top) and expected (bottom) exclusion limits as a function of the gluino branching ratio to top quarks (*x*-axis) and bottom quarks (*y*-axis).
  - The neutralino mass is fixed to either 1 GeV (left), 600 GeV (middle) or 1 TeV (right).



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- Definition of the 2L OSSF signal, validation and control regions: on-Z, high-p_{T} (left) and low-p_{T} edge (right).
  - All SRs need to have at least two leptons (e or μ) and a OSSF pair.
  - Besides the cuts listed here, SRs are further subdivided into several m_{ll} bins (overlapping or orthogonal for m_{ll} for shape fit).

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High-p_{T} regions	$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	H_{T} [GeV]	n_{jets}	$m_{\ell\ell}$ [GeV]	m_{T2} [GeV]	SF/DF	$n_{b\text{-jets}}$	$\Delta\phi(\mathrm{jet}_{12}, p_{\mathrm{T}}^{\mathrm{miss}})$	$m_{\ell\ell}$ windows
Signal regions									
SR-low	> 250	> 200	≥ 2	> 12	> 70	SF	–	> 0.4	10
SR-medium	> 400	> 400	≥ 2	> 12	> 25	SF	–	> 0.4	9
SR-high	> 200	> 1200	≥ 2	> 12	–	SF	–	> 0.4	10
Control regions									
CR-FS-low	> 250	> 200	≥ 2	> 12	> 70	**DF**	–	> 0.4	–
CR-FS-medium	> 400	> 400	≥ 2	> 12	> 25	**DF**	–	> 0.4	–
CR-FS-high	> 100	> 1100	≥ 2	> 12	–	**DF**	–	> 0.4	–
CRγ-low	–	> 200	≥ 2	–	–	**0ℓ, 1γ**	–	–	–
CRγ-medium	–	> 400	≥ 2	–	–	**0ℓ, 1γ**	–	–	–
CRγ-high	–	> 1200	≥ 2	–	–	**0ℓ, 1γ**	–	–	–
CRZ-low	< 100	> 200	≥ 2	> 12	> 70	SF	–	–	–
CRZ-medium	< 100	> 400	≥ 2	> 12	> 25	SF	–	–	–
CRZ-high	< 100	> 1200	≥ 2	> 12	–	SF	–	–	–
Validation regions									
VR-low	**100–200**	> 200	≥ 2	> 12	> 70	SF	–	> 0.4	–
VR-medium	**100–200**	> 400	≥ 2	> 12	> 25	SF	–	> 0.4	–
VR-high	**100–200**	> 1200	≥ 2	> 12	–	SF	–	> 0.4	–
VR-$\Delta\phi$-low	> 250	> 200	≥ 2	> 12	> 70	SF	–	**< 0.4**	–
VR-$\Delta\phi$-medium	> 400	> 400	≥ 2	> 12	> 25	SF	–	**< 0.4**	–
VR-$\Delta\phi$-high	> 200	> 1200	≥ 2	> 12	–	SF	–	**< 0.4**	–
VR-WZ	**100–200**	**> 200**	≥ 2	> 12	–	**3ℓ**	**0**	> 0.4	–
VR-ZZ	**< 50**	**> 100**	**≥ 1**	> 12	–	**4ℓ**	**0**	> 0.4	–

Low-p_{T} regions	$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	$p_{\mathrm{T}}^{\ell\ell}$ [GeV]	n_{jets}	$n_{b\text{-jets}}$	$m_{\ell\ell}$ [GeV]	SF/DF	OS/SS	$\Delta\phi(\mathrm{jet}_{12}, p_{\mathrm{T}}^{\mathrm{miss}})$	m_{T} [GeV]	$m_{\ell\ell}$ windows
Signal regions										
SRC	> 250	< 20	≥ 2	–	> 30	SF	OS	> 0.4	–	6
SRC-MET	> 500	< 75	≥ 2	–	> 4, ∉ [8.4, 11]	SF	OS	> 0.4	–	6
Control regions										
CRC	> 250	< 20	≥ 2	–	> 30	**DF**	OS	> 0.4	–	–
CRC-MET	> 500	< 75	≥ 2	–	> 4, ∉ [8.4, 11]	**DF**	OS	> 0.4	–	–
CR-real	–	–	≥ 2	–	**81–101**	2ℓ SF	OS	–	–	–
CR-fake {	**< 125**	–	–	–	> 4, ∉ [8.4, 11] > 4, ∉ [8.4, 11], **∉ [81, 101]**	**2ℓ μe** **2ℓ $\mu\mu$**	**SS**	–	–	–
Validation regions										
VRA	**200–250**	**< 20**	≥ 2	–	> 30	SF	OS	> 0.4	–	–
VRA2	**200–250**	**> 20**	≥ 2	–	> 4, ∉ [8.4, 11]	SF	OS	> 0.4	–	–
VRB	**250–500**	**20–75**	≥ 2	–	> 4, ∉ [8.4, 11]	SF	OS	> 0.4	–	–
VRC	**250–500**	**> 75**	≥ 2	–	> 4, ∉ [8.4, 11]	SF	OS	> 0.4	–	–
VR-WZ-low-p_{T}	**> 200**	–	**≥ 1**	**0**	> 4, ∉ [8.4, 11]	**3ℓ**	–	> 0.4	–	–
VR-ZZ-low-p_{T}	**> 200**	–	–	**0**	> 4, ∉ [8.4, 11]	**4ℓ**	–	> 0.4	–	–
VR-$\Delta\phi$	**> 250**	–	≥ 2	–	> 4, ∉ [8.4, 11]	SF	OS	**< 0.4**	–	–
VR-fakes	**> 225**	–	≥ 2	–	> 4, ∉ [8.4, 11]	**DF**	OS	> 0.4	**ℓ_1, ℓ_2 < 100**	–
VR-SS	**> 225**	–	≥ 2	–	> 4, ∉ [8.4, 11]	SF	SS	> 0.4	**ℓ_1, ℓ_2 < 100**	–

- Left: Results in inclusive on-Z (top) and low-p_T edge (bottom) SRs (without m_{ll} binning applied).
- Right: Results in WZ and ZZ validation regions (separate WZ, ZZ VRs for low-p_T validation).

	SR-low	SR-medium	SR-high
Observed events	134	40	72
Total expected background events	144 ± 22	40 ± 10	83 ± 9
Flavour-symmetric ($t\bar{t}$, Wt, WW and $Z \to \tau\tau$) events	86 ± 12	29 ± 9	75 ± 8
$Z/\gamma^* +$ jets events	9^{+13}_{-9}	$0.2^{+0.8}_{-0.2}$	2.0 ± 1.2
WZ/ZZ events	43 ± 12	9.8 ± 3.2	4.1 ± 1.2
Rare top events	6.7 ± 1.8	1.20 ± 0.35	1.8 ± 0.5

	SRC	CRC	SRC-MET	CRC-MET
Observed events	93	98	17	10
Total expected background events	104 ± 17	98 ± 10	10 ± 4	10.0 ± 2.6
Top-quark events	85 ± 17	81 ± 14	3^{+4}_{-3}	$2.5^{+3.0}_{-2.5}$
Fake-lepton events	8.3 ± 1.5	10 ± 10	2.00 ± 0.35	3.6 ± 1.2
Diboson events	7.6 ± 1.3	5.7 ± 1.6	4.4 ± 1.3	3.1 ± 1.2
Rare top events	3.26 ± 0.95	1.8 ± 0.7	0.53 ± 0.15	0.59 ± 0.18
$Z/\gamma^* +$ jets events	0.050 ± 0.010	0.0 ± 0.0	0.52 ± 0.12	0.18 ± 0.05

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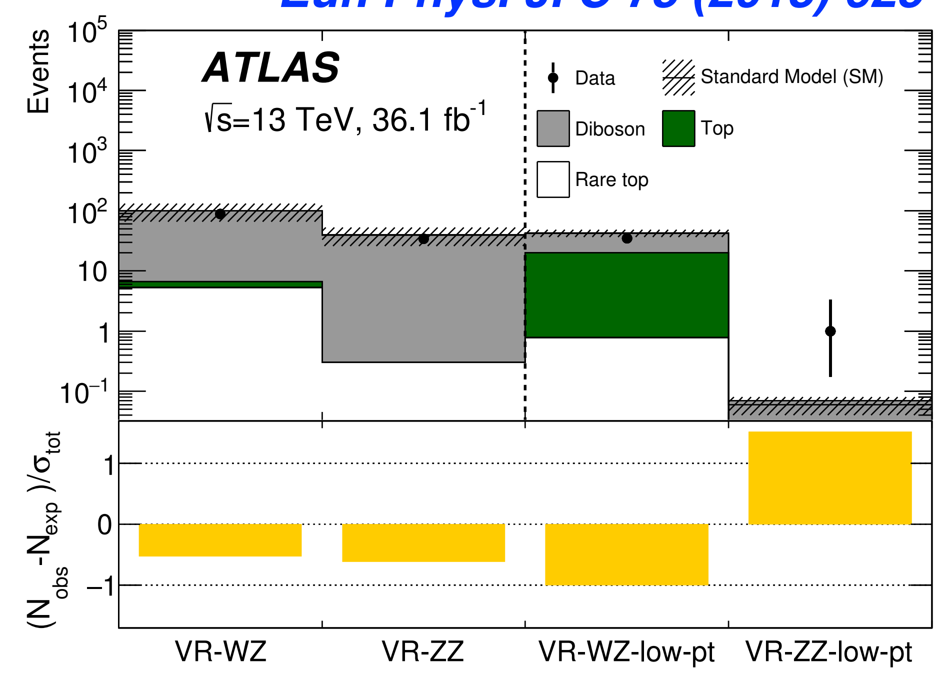

- Definition of the 1τ and 2τ-SRs, targeting different models and different kinematic scenarios:

Subject of selection	1τ SRs Compressed	 Medium-mass
τ-leptons	$20 < p_T^\tau < 45$ GeV	$p_T^\tau > 45$ GeV
Event kinematics	$E_T^{miss} > 400$ GeV $m_T^\tau > 80$ GeV —	 $m_T^\tau > 250$ GeV $H_T > 1000$ GeV

Subject of selection	2τ SRs Compressed	 High-mass	 Multibin	 GMSB
Event kinematics	$m_{T2}^{\tau\tau} > 70$ GeV $H_T < 1100$ GeV $m_T^{sum} > 1600$ GeV	$m_T^{\tau_1}+m_T^{\tau_2} > 350$ GeV $H_T > 1100$ GeV —	$m_T^{\tau_1}+m_T^{\tau_2} > 150$ GeV $H_T > 800$ GeV $N_{jet} \geq 3$ 7 bins in $m_T^{\tau_1}+m_T^{\tau_2}$	$m_T^{\tau_1}+m_T^{\tau_2} > 150$ GeV $H_T > 1900$ GeV —

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- Definition of the W/Top CRs, as well as the CRs for $Z\rightarrow\nu\nu$, $Z\rightarrow\tau\tau$ and mutijet:

Subject of selection	W/ Top kinematic CR	W/ Top true-τ CR	W/ Top fake-τ CR
τ-leptons	$N_\tau = 0$	$N_\tau = 1$	
Jets	$N_{jet} \geq 3$		—
Muons	$N_\mu = 1$	$N_\mu = 0$	$N_\mu = 1$
W/top separation	$N_{b\text{-jet}} = 0/\geq 1$		
Event kinematics	$H_T < 800$ GeV $E_T^{miss} < 300$ GeV $m_T^\mu < 100$ GeV —	 $m_T^\tau < 80$ GeV —	 $m_T^\mu < 100$ GeV $m_{\tau\mu} > 60$ GeV (W CR)

Subject of selection	$Z(\nu\nu)$ CR	$Z(\tau\tau)$ CR	Multijet CR
τ-leptons	$N_\tau = 1$	$N_\tau \geq 2$, $q_{\tau_1} = -q_{\tau_2}$	$N_\tau = 1$
Multijet events	$\Delta\phi(p_T^{jet_{1,2}}, p_T^{miss}) > 0.4$		$\Delta\phi(p_T^{jet_{1,2}}, p_T^{miss}) < 0.3$
Muons	$N_\mu = 0$	—	—
Top suppression	$N_{b\text{-jet}} = 0$		—
Event kinematics	$H_T < 800$ GeV $E_T^{miss} < 300$ GeV $100 \leq m_T^\tau < 200$ GeV $E_T^{miss}/m_{eff} > 0.3$ $\Delta\phi(p_T^{jet_1}, p_T^{miss}) > 2.0$ $\Delta\phi(p_T^{\tau_1}, p_T^{miss}) > 1.0$	 — $m_T^{\tau_1} + m_T^{\tau_2} < 100$ GeV $m_{T2} < 70$ GeV — —	— — $100 < m_T^\tau < 200$ GeV $E_T^{miss}/m_{eff} < 0.2$ — —

- Results in 1τ-SRs (left) and in 2τ-SRs (right):
  - Two SRs in 1τ-channel (for compressed and medium-mass scenarios) and three SRs in 2τ-channel (compressed, high-mass and GMSB).

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1τ channel	Compressed SR		Medium-mass SR	
Data	286		12	
Total background	[290]	320±32	[15.2]	15.9±3.0
Top quarks	[66]	77±21	[5.2]	5.8±1.6
$W(\tau\nu)$+jets	[57]	51±18	[2.4]	2.2±1.7
$Z(\nu\nu)$+jets	[77]	110±24	[1.5]	2.2±0.5
Other V+jets	[52]	45±10	[1.9]	1.7±0.4
Diboson	[28]	28±5	[3.0]	3.0±0.6
Multijet	[10.0]	9.2±1.2	[1.24]	1.14±0.14
S^{95}_{obs} (S^{95}_{exp})	49.5 ($64.3^{+24.1}_{-14.9}$)		7.7 ($10.0^{+4.3}_{-2.7}$)	
$\langle\sigma_{vis}\rangle^{95}_{obs}$[fb]	1.37		0.21	
CL_b	0.18		0.24	
p_0 (Z)	0.5 (0.0)		0.5 (0.0)	

2τ channel	Compressed SR		High-mass SR		GMSB SR	
Data	5		6		4	
Total background	[4.7]	5.4±1.9	[2.3]	2.3±0.7	[1.5]	1.4±0.5
Top quarks	[2.3]	2.9±1.7	[0.9]	1.0±0.5	[0.34]	0.39±0.23
$W(\tau\nu)$+jets	[0.5]	$0.4^{+0.5}_{-0.4}$	[0.4]	0.4±0.4	[0.4]	0.4±0.4
$Z(\tau\tau)$+jets	[0.035]	0.030±0.011	[0.37]	0.32±0.11	[0.33]	0.28±0.10
$Z(\nu\nu)$+jets	[0.47]	0.67±0.35	[0.065]	0.093±0.028	[0.008]	0.011±0.007
Other V+jets	[0.32]	0.30±0.08	[0.019]	0.015±0.012	[< 0.01]	< 0.01
Diboson	[1.06]	1.05±0.25	[0.56]	0.56±0.15	[0.29]	0.29±0.08
Multijet	[0.0261]	0.0241±0.0031	[0.0131]	0.0121±0.0015	[0.065]	0.060±0.008
S^{95}_{obs} (S^{95}_{exp})	6.7 ($6.7^{+2.8}_{-1.5}$)		9.0 ($5.0^{+1.9}_{-1.3}$)		7.3 ($4.4^{+1.5}_{-0.9}$)	
$\langle\sigma_{vis}\rangle^{95}_{obs}$[fb]	0.18		0.25		0.20	
CL_b	0.50		0.96		0.95	
p_0 (Z)	0.5 (0.0)		0.03 (1.83)		0.05 (1.68)	