Search for particles predicted by Supersymmetry

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Reminder: Supersymmetry in a nutshell

Supersymmetry (SUSY): A symmetry between fermions and bosons

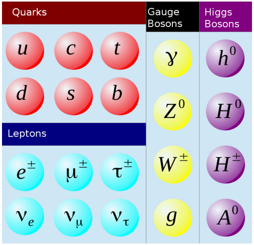
$$Q|Fermion\rangle = |Boson\rangle; \qquad Q|Boson\rangle = |Fermion\rangle$$

Most obvious consequence: Double the SM particle content

- 'Superpartners' for every SM degree of freedom ('sparticles')
- SM fermions: Scalar **squarks**, **sleptons** and **sneutrinos**
- Gauge and Higgs bosons: Fermionic **gauginos** and **higgsinos**

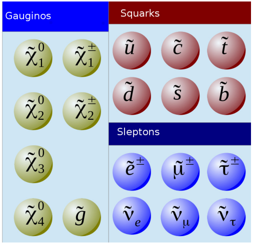
→ Note: SUSY requires extended Higgs sector - 2 doublets, 5 massive higgs bosons (h,H,A,$H^{\pm}$)

- Partners of EW gauge and Higgs bosons mix into 4 **neutralinos** and 2 **charginos**



Experimental data: SUSY must be a **broken symmetry**

- Apart from spin, unbroken SUSY predicts identical quantum numbers for SM particles and their superpartners
- SUSY breaking allows masses of sparticles to differ from SM partners
- Also introduces **wide parameter space**: $>$ 100 free parameters!



Why is this interesting for LHC searches?

Why search for SUSY?

Why is SUSY one main branch of LHC new physics searches?

SUSY has compelling theoretical aspects ...

- Solution to *Hierarchy Problem*
- Potential for *DM Candidate*
- Potential for *B/L violation*
- Mechanism for generating *neutrino masses*

Note: Some of these mutually exclusive!

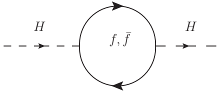
Most important: **Rich spectrum of predicted signatures**

- Drive a wide range of searches

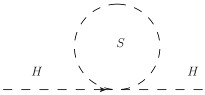
$\rightarrow$ Guideline to full exploitation of the LHC dataset

Early LHC run 2: The most interesting time for SUSY searches!

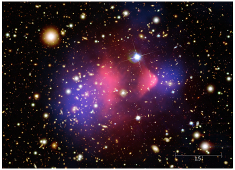
- Expect massive improvement of search sensitivity when increasing collider $\sqrt{s}$!



$$\Delta m_h^2 \sim -\frac{\lambda^2}{8\pi^2}\Lambda_{UV}^2 + m_f^2 O(ln\Lambda_{UV}) + ...$$



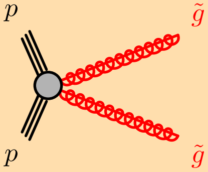
$$\Delta m_h^2 \sim \frac{\lambda}{16\pi^2}\Lambda_{UV}^2 - m_S^2 O(ln\Lambda_{UV}) + ...$$



This talk: Attempt at coarse overview of direct searches, highly biased selection!

Two main production mechanisms of interest

Strong production of squarks and gluinos



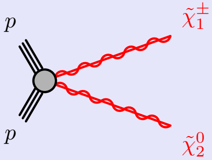
- QCD production - high cross-sections

→ Sensitivity up to high sparticle masses

→ Greatest gain from $\sqrt{s}$ increase

- Jet-rich final states

Electroweak production production of gauginos



- Electroweak cross-sections - lower than for QCD production
- Can be dominant in case of decoupled squarks/gluinos
- Final states with leptons and gauge bosons

LHC run 2 (focus of this talk):

First batch of 13 TeV searches targeted **strong production**, electroweak searches catching up with 2015 + 2016 dataset

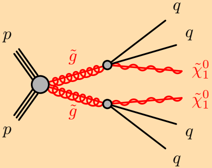
SUSY decay phenomenology

LHC search strategies depend on assumed **decay chains** of produced sparticles

- Cascade decays to SM particles and lighter sparticles
- Nature of cascade determined by initial sparticles, mass spectrum, couplings

Two distinct scenarios, based on **R-Parity** ($R_p = 1$ for SM, -1 for superpartners):

R-Parity conservation (RPC)

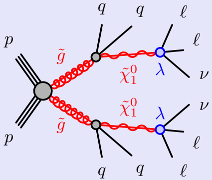


- B, L conserved
- Lightest supersymmetric particle (LSP) **stable**, typically neutralino χ_1^0

→ Escapes detection

- Searches based on **Missing transverse energy**

R-Parity violation (RPV)



- B or L violated

→ Strong constraints through proton lifetime and flavour sector

- Only SM particles in final state
- Requires **dedicated search strategies**

This Talk: Assume **zero sparticle lifetime** - however, many interesting scenarios with long-lived sparticles

Searching for Supersymmetric Particles - the framework

Use **simplified models** to guide development and interpretation of searches

Bottom-up approach:

- Consider a single production process, typically producing one given pair of sparticles.
- Also fix decay of the sparticles, typically assume 100% BR (manually assigned)

→ Sparticle lifetimes also manually assigned (most common: 'prompt', $\tau = 0$)

- Sparticle masses are usually free and independent parameters to scan over

Useful for searches . . .

- One clearly defined physics signature to look for
- Low-dimensional phase-space for exploration

→ Often just two sparticle masses

. . . but keep in mind when looking at results:

- **Not** a full-fledged physics model!

→ Limits within simplified models give measure of the search sensitivity

→ But are valid only within a strong set of assumptions

Think of an approximate limit on $\sigma \cdot BR$ for one signature occuring within a full-scale model!

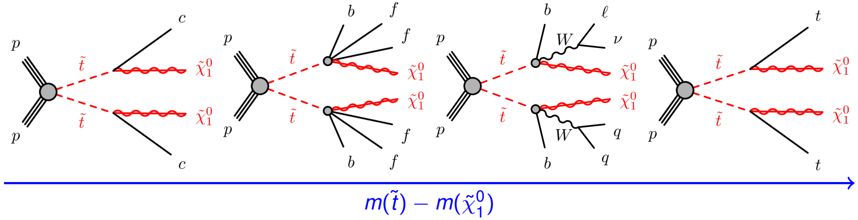
Of particular interest: The top squark

Natural supersymmetry (solution to hierarchy problem): Top squark expected to be **light**

- Mass expected not far above TeV scale (depending on amount of fine-tuning accepted)

$\rightarrow$ In range of LHC experiments?

Simplified RPC SUSY models: Investigate several final states based on **mass hierarchy** between top squark and LSP



- Dedicated searches for the different decay modes.
- As for SM top physics: Consider both leptonic and hadronic final states

$\rightarrow$ Leptons: Lower trigger thresholds, rarity in SM pocesses

$\rightarrow$ But: Yield limited by SM leptonic BR ($W \rightarrow \ell\nu$) - tradeoff against statistics

Top squark searches - high mass splittings (zero leptons)

ATLAS-CONF-2016-077

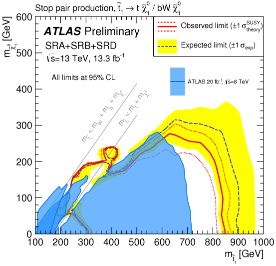
see also CMS-PAS-SUS-16-029, CMS-PAS-SUS-16-030

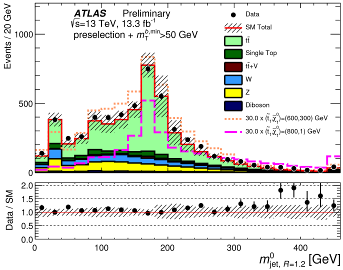
Search for $\tilde{t} \to t\tilde{\chi}_1^0$ using boosted topologies:

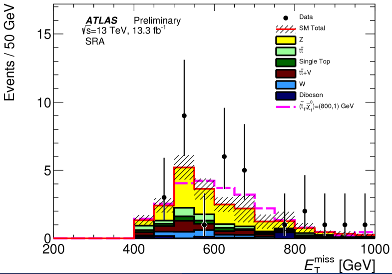
- Events with at least 4 jets (2 b-tags), E_T^{Miss} and no leptons
- Recluster AntiKt4 jets into large-R (1.2) jets to reconstruct t and W candidates

→ See talk on boosted techniques (Monday afternoon session)

- Main backgrounds include $Z \to \nu\nu$+jets, $t\bar{t}$, $W \to \ell\nu$+jets
- Note: Other signal regions based on resolved AntiKt4 jets (not shown here) cover smaller mass splittings





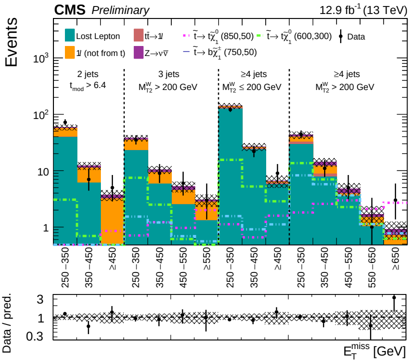


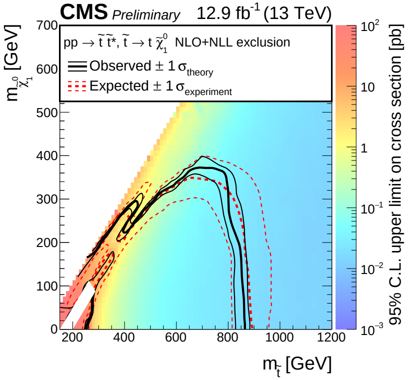
Complementary channel: one lepton

CMS-PAS-SUS-16-028, see also: ATLAS-CONF-2016-050

- Events with at least 2 jets ($\geq$ 1 b), H_T^{Miss} and exactly one lepton
- Separate optimisation for low and high mass splittings
- Main backgrounds: Dileptons with one missed lepton and W+jets /$t\bar{t}$ with one lepton (MET tails)

$\rightarrow$ Missed leptons: Data driven using dilepton region





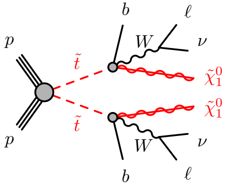
ATLAS-CONF-2016-076

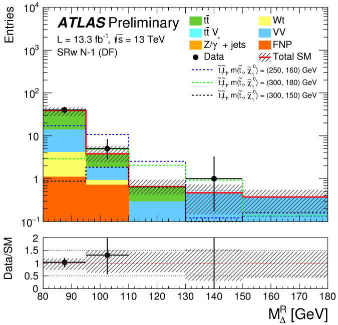
- Target 3-body stop decay ($\tilde{t} \rightarrow Wb\tilde{\chi}_1^0$) with dedicated SR

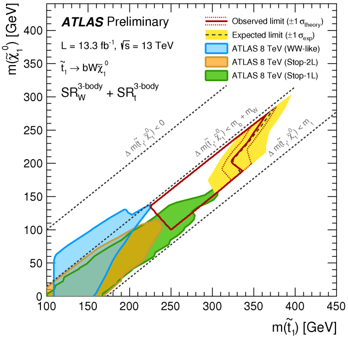
$\rightarrow$ Leptons: Can use lower p_T thresholds than for jets

- Background suppression via kinematic 'super-razor' variables
- Main backgrounds for 3-body SR: Dibosons, $t\bar{t}$

$\rightarrow$ Estimation using MC simulation, scaled to data in control regions







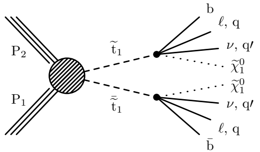
CMS-PAS-SUS-16-025 , see also: CMS-PAS-SUS-16-029

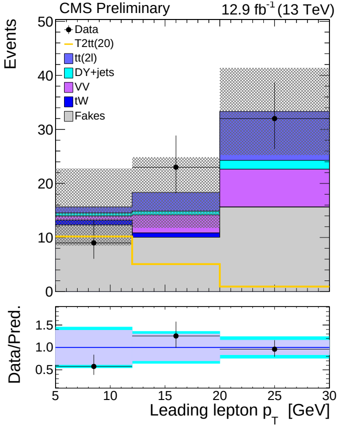
- $m(\tilde{t}) \approx m(\tilde{\chi}^0_1)$: Target 4-body stop decay ($\tilde{t} \to \ell \nu b \tilde{\chi}^0_1$)

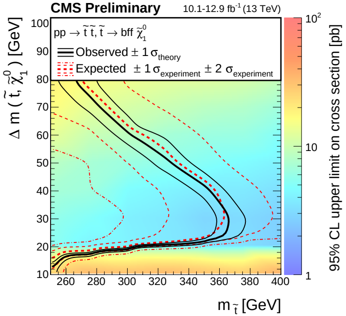
→ Leptons can reach very low momenta

- Challenging: Very low lepton p_T thresholds (3.5-5 GeV)
- Trigger using E_T^{miss} and dedicated dimuon+E_T^{miss} triggers
- Main backgrounds: DY $Z^*/\gamma^* \to \tau\tau$, $t\bar{t}$, W+jets (fake leptons)

→ Estimation using MC simulation normalised in control regions, fake leptons data driven





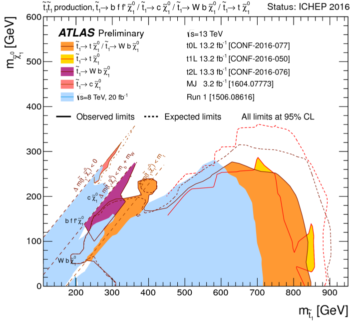


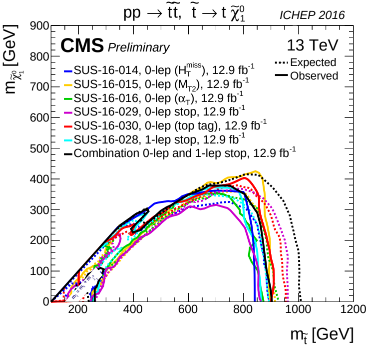
Top squark searches - summary

- RPC: Searches target the most likely decay scenarios
- Disclaimer: Summary plots combine different stop decay channels, mass hierarchies and decay scenarios
- Most challenging region: $m(\tilde{t}) \sim m(\tilde{\chi}_1^0)$ - reduced $E_{\mathrm{T}}^{\mathrm{miss}}$, soft cascade particles

$\rightarrow$ Reminder: Simplified models

- Also note: Only showed a subset of all the searches - much more to see!





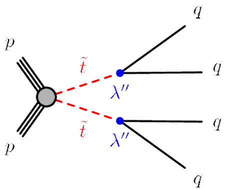
We covered a lot of RPC scenarios - but could we still miss a stop signal?

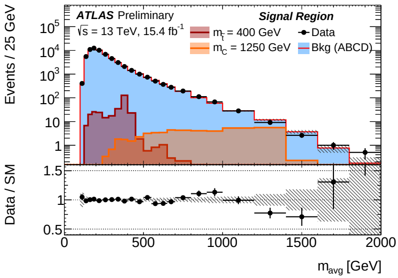
ATLAS-CONF-2016-084

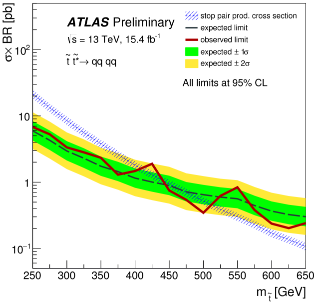
- R-Parity violation (RPV): Stop can decay into two SM quarks

→ no E_T^{miss}, no leptons, low jet multiplicity: Eludes RPC searches

- Dedicated search for 'double dijet resonance'
- Main background: SM multijets - data-driven ABCD estimation
- High level of background: Challenging, mass reach reduced compared to RPC scenarios







Inclusive strong production searches

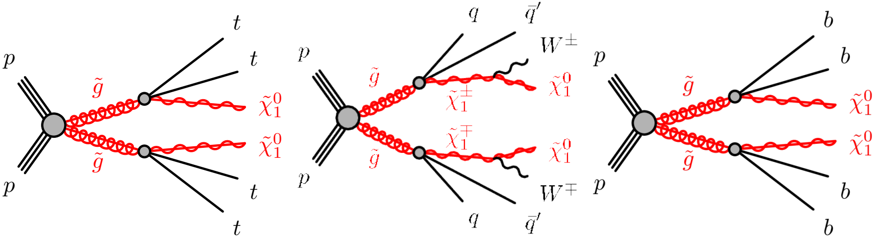
In addition to direct stop production: Wide set of **inclusive searches for strong production**

- Main interest: Gluino pair production

$\rightarrow$ Large cross-section if mass accessible

- Decay cascades can provide sensitivity to sparticles not accessible to direct production
- Especially interesting: virtual top/bottom squarks

$\rightarrow$ heavy-flavour-rich final states



Showing only few examples here - much more available!

All-hadronic final states - classical RPC strong production searches

CMS-PAS-SUS-16-014, -015, -016, -030, ATLAS-CONF-2016-078, -052,

- Searches for events with jets, H_T^{Miss} and no leptons
- Decay chains can include intermediate, virtual top/bottom squarks

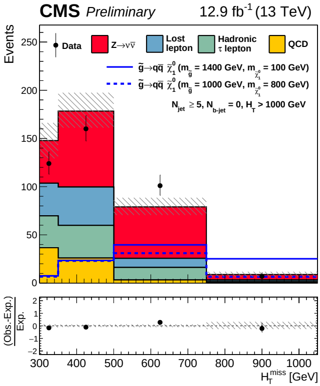
$\rightarrow$ Exploit via b-tagging

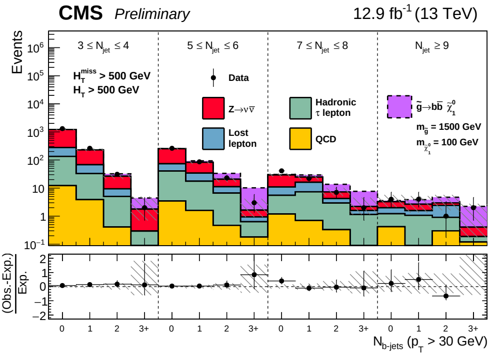
- High number of signal regions binned in jet, b-tag multiplicity, H_T

$\rightarrow$ sensitive to wide range of strong production SUSY scenarios

- Several search variants using various techniques

Example: CMS, H_T^{miss} based discrimination





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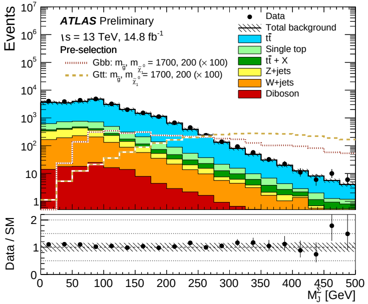
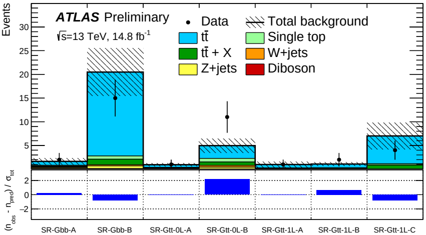
Example: ATLAS, multiple b-jets + E_T^{miss} - using large-R jets for stop-mediated decays





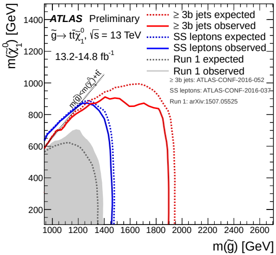
All-hadronic final states - classical RPC strong production searches

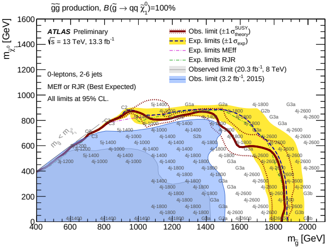
CMS-PAS-SUS-16-014, -015, -016, -030,
ATLAS-CONF-2016-078, -052,

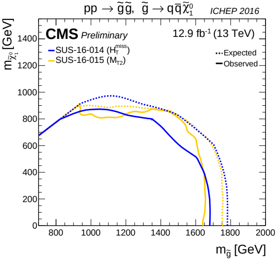
- Limits demonstrate large mass reach of run-2 strong production searches
- Reduced sensitivity close to diagonal: Typical feature of $E_{\mathrm{T}}^{\mathrm{miss}}$ based RPC Searches

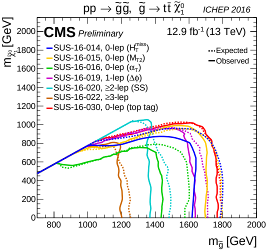
$\rightarrow$ $E_{\mathrm{T}}^{\mathrm{miss}}$ reduced due to high LSP mass, softer jets

- Again: Keep in mind simplified models!









All-hadronic final states - also relevant for RPV SUSY

ATLAS-CONF-2016-057

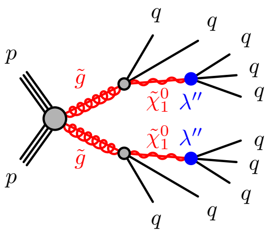
- RPV SUSY: Gluino and neutralino can decay to 3 SM quarks

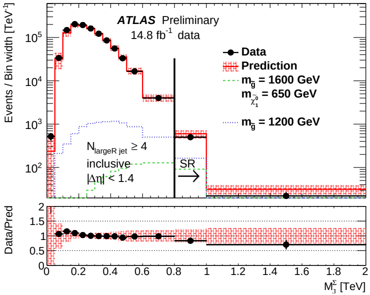
→ Gluino pair production: 6- or 10-quark final state, no $E_{\mathrm{T}}^{\mathrm{miss}}$!

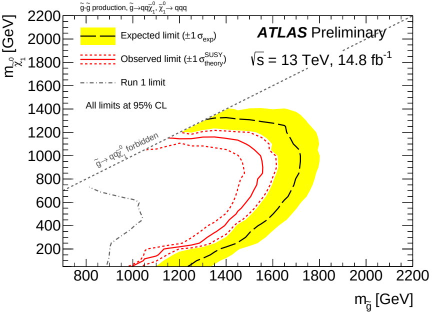
- Dedicated search using large-radius jets

→ Discrimination against SM multijets using centrality and masses of four most energetic large-R jets

→ Fully data driven, jet mass template based background estimation





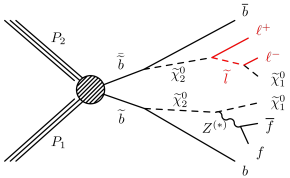


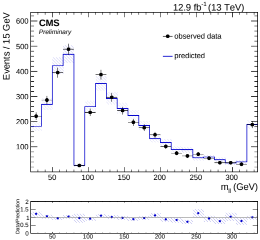
We can also use **leptons** to probe for strong production signals

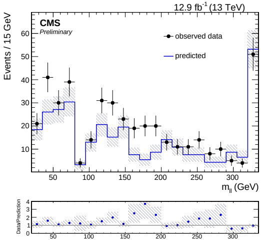
CMS-PAS-SUS-16-021, see also ATLAS-CONF-2015-082

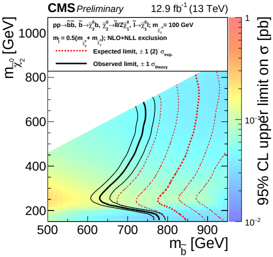
- Virtual sleptons in the decay chain can lead to same-flavour, opposite sign (SFOS) lepton pairs in the final state
- Interesting: **Kinematic edge** in dilepton invariant mass corresponds to mass splitting in the decay chain
- Look for SFOS lepton pairs in association with jets and $E_{\mathrm{T}}^{\mathrm{miss}}$
- Dominant backgrounds: $Z^*/\gamma^* \to \ell\ell$ + jets, $t\bar{t}$

$\to$ Estimation via different-flavour dileptons and γ+jets events









Leptonic signatures: Same-sign leptons

ATLAS-CONF-2016-037

- Strong production scenarios can also lead to final states with same-sign leptons

→ Intermediate sleptons or gauginos, or R-parity violation

→ Rare in SM!

ATLAS RPV signal region (shown here):

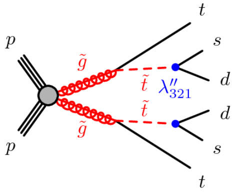
- Require $\geq$ 6 jets and 2 same-sign / 3 leptons

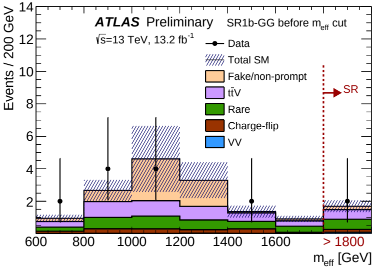
→ Main backgrounds: $t\bar{t}V$, Fake leptons

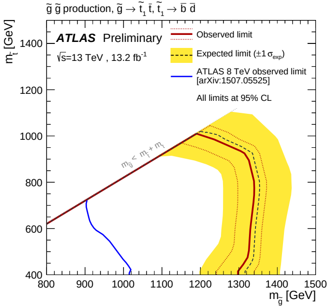
- No $E_{\mathrm{T}}^{\mathrm{miss}}$ for RPV signal: Final discrimination using effective mass

Many other signal regions, also targeting RPC ($E_{\mathrm{T}}^{\mathrm{miss}}$-based)

See also: CMS-PAS-SUS-16-020







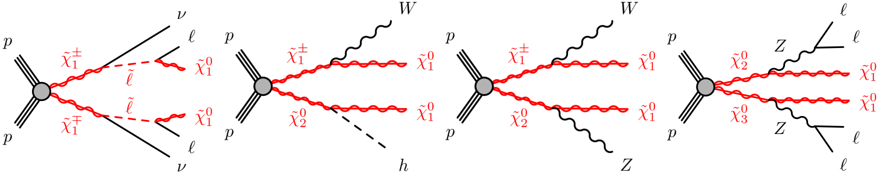
Lepton-based electroweak searches

Final state leptons are an essential tool when searching for **gaugino pair production**

- EW cross-sections lower than for strong production
- But: SM background in lepton-rich topologies also much lower
- Leptons can come from intermediate gauge / Higgs bosons or virtual sleptons/sneutrinos

$\rightarrow$ Intermediate gauge bosons: More challenging - SM leptonic W/Z BR

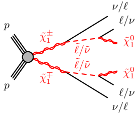
- Of particular importance: Hadronic τ decays - $H \rightarrow \tau\tau$ and higgsinos



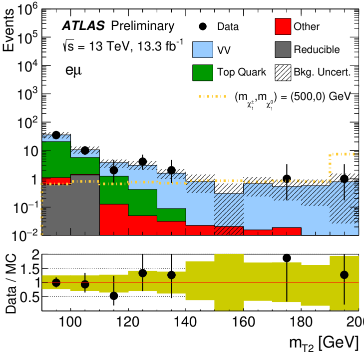
Chargino pairs - two-lepton final states

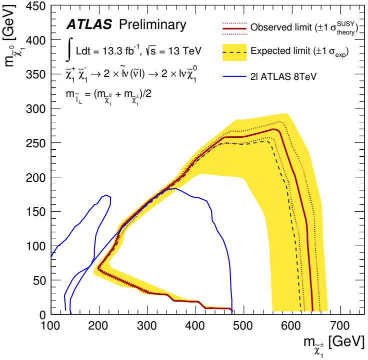
ATLAS-CONF-2016-093, ATLAS-CONF-2016-096

Virtual sleptons and sneutrinos enhance the leptonic BR in chargino production



- Does not rely on leptonic W/Z BR
- Search for events with 2 leptons and $E_{\mathrm{T}}^{\mathrm{miss}}$
- Jet veto to suppress backgrounds

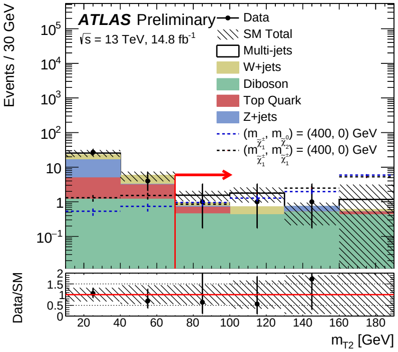


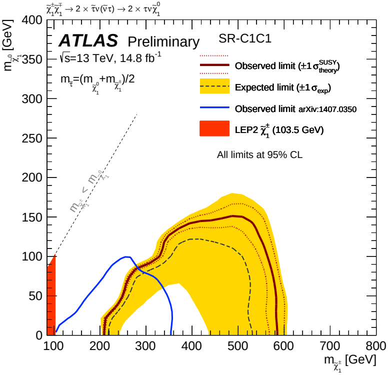


ATLAS-CONF-2016-093, ATLAS-CONF-2016-096

Light staus: Tau-rich final states of particular interest

- Lower purity than light leptons: particularly challenging
- Search for events with 2 τ_{had} and $E_{\text{T}}^{\text{miss}}$
- b-jet veto to suppress backgrounds



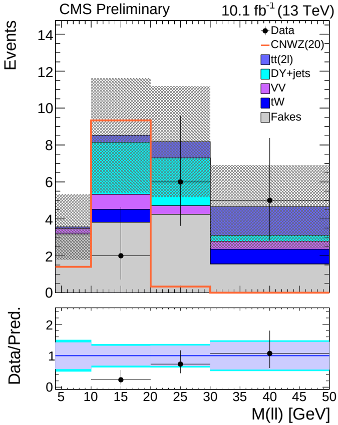


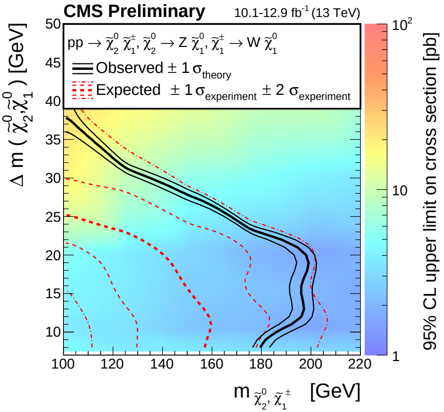
CMS-PAS-SUS-16-025

Very small gaugino mass splittings: Leptons become very soft

- CMS soft lepton pair + E_T^{miss} search (see earlier): Also target $\tilde{\chi}_2^0\tilde{\chi}_1^\pm \rightarrow Z^*(\rightarrow \ell\ell)W^*\tilde{\chi}_1^0\tilde{\chi}_1^0$

$\rightarrow$ First search at such low splittings since LEP



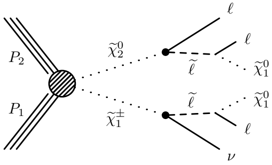


Chargino-neutralino final states - three-lepton searches

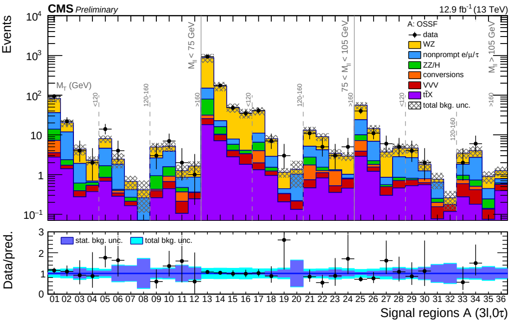
CMS-PAS-SUS-16-024

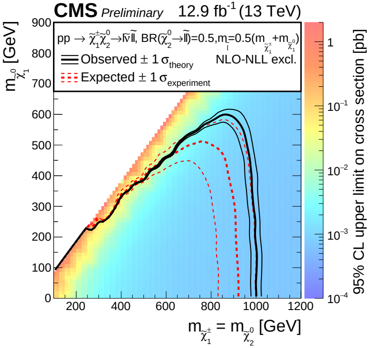
See also: CMS-PAS-SUS-16-025, ATLAS-CONF-2016-096

$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production: Final states with 3 leptons (W+Z / W+H / slepton-mediated) accessible



- Either require or veto same-flavour, opposite sign lepton pairs
- Include hadronic tau decays - interesting for final states with $H \rightarrow \tau\tau$
- Main backgrounds: Dibosons, fakes (esp. τ regions)
- Highest sensitivity: Slepton-mediated decays

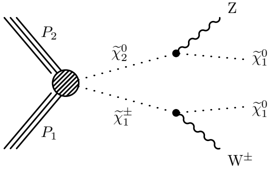




CMS-PAS-SUS-16-024

See also: CMS-PAS-SUS-16-025, ATLAS-CONF-2016-096

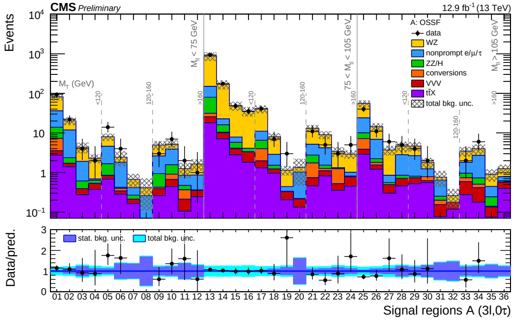
$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production: Final states with 3 leptons (W+Z / W+H / slepton-mediated) accessible

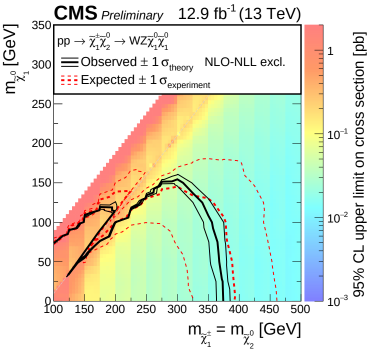


- More challenging: Decoupled sleptons
- Decays via gauge or Higgs bosons
- Easier case: WZ final state

→ suppression via $\mathcal{BR}(Z \to \ell\ell) \times \mathcal{BR}(W \to \ell\nu)$

- Note: Realistic model would include both *WZ* and *WH* modes

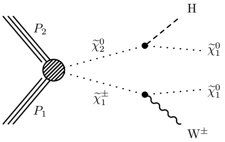


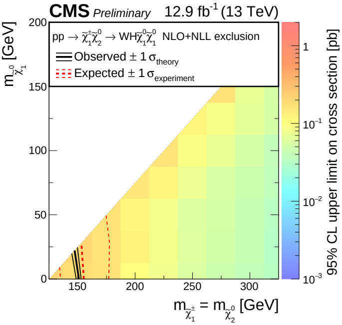


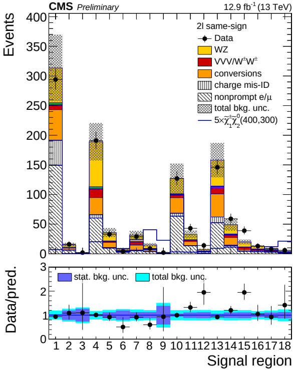
CMS-PAS-SUS-16-024

$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production: Final states with 3 leptons (W+Z / W+H / slepton-mediated) accessible

- Hardest case: WH final state
- $\rightarrow$ suppression via $\mathcal{BR}(H \rightarrow \tau\tau) \times \mathcal{BR}(W \rightarrow \ell\nu)$
- $\rightarrow$ Added complication: Reduced purity for τ leptons
- Note: Realistic model would include both *WZ* and *WH* modes



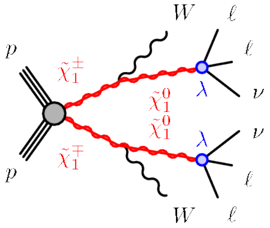




Lepton-based signatures - increasing the multiplicity even more

ATLAS-CONF-2016-075

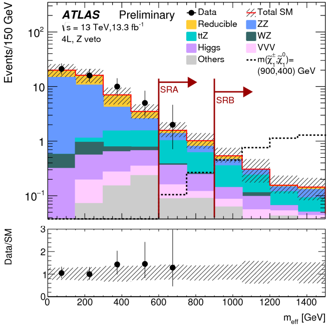
'LLE' RPV couplings can lead to final states with **at least** 4 charged leptons

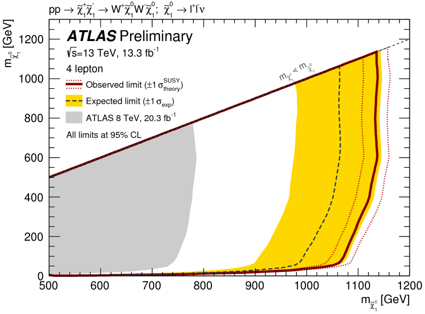


- Look for events with at least 4 charged leptons
- Non-resonant signal: strong background suppression via Z-veto
- Dominant backgrounds: $t\bar{t}Z$, $t\bar{t}$ (fakes), ZZ

→ Estimation via MC (Data-driven for fakes)

- Final discriminant: **Effective mass**





Summary

Supersymmetry is a key provider of new physics scenarios for the LHC

- Predicts wide range of physics signatures

$\rightarrow$ Guideline to an exhaustive search program

- Framework of **simplified models** used for experimental exploration

Searches often limited by production cross-sections - strong gain from E_{cm} increase

- LHC run 2: Largest leap in sensitivity for decades to come!

Analysis of 13 TeV LHC data ramping up

- Strong production searches mostly updated to early $\sqrt{s} = 13$ TeV dataset
- Electroweak and RPV searches catching up, first results arriving
- Reminder: This talk is only an overview, several interesting aspects not covered, including ...

$\rightarrow$ Long-lived particle signatures

$\rightarrow$ Gauge-mediated SUSY breaking

Interesting times ahead! Stay tuned!