SUSY searches at LHC and HL-LHC perspectives

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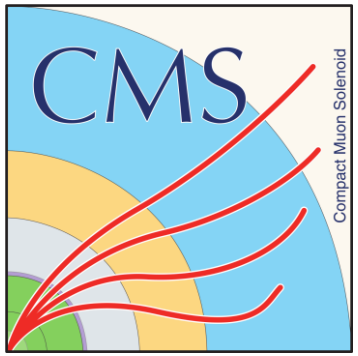
26.10.2017, LCWS 2017, Strasbourg

Brandeis University

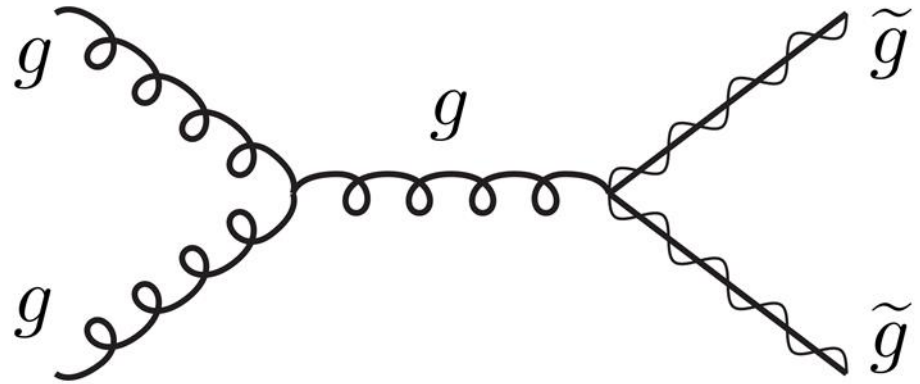


SUSY particle production in p-p collisions

Two main directions for searches

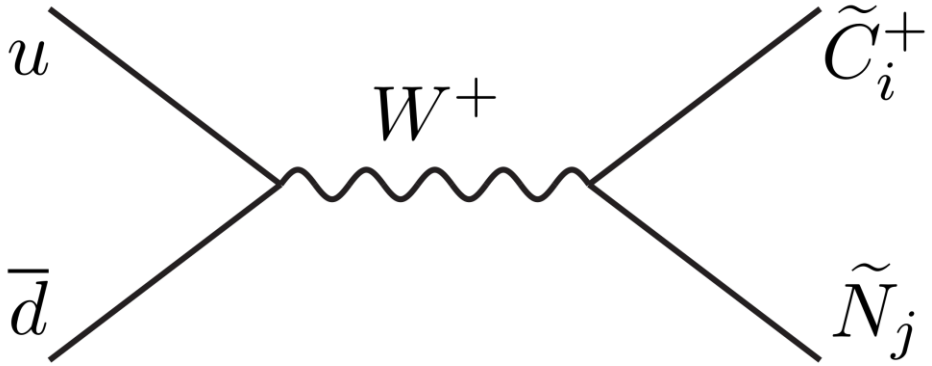
Strong production of squarks and gluinos

- QCD production – high cross-sections
- ➢ High expected production rates even for massive particles (several TeV)
- May lead to jet-rich final states



Electroweak production

- Electroweak cross-sections – smaller rates than for strong production
- Can be dominant if squarks / gluinos decoupled
- May lead to final states with leptons and/or gauge/Higgs bosons



SUSY decay phenomenology

some exceptions!

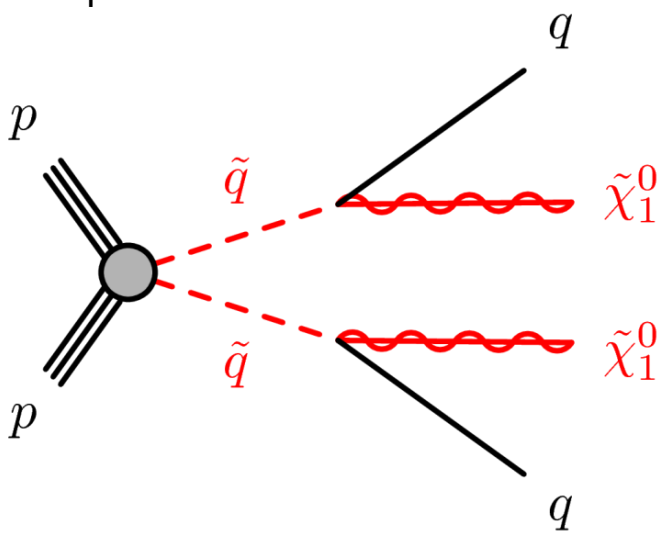
LHC searches detect SUSY production via **decay signatures**

- Cascade decays to standard model particles and lighter sparticles
- Nature of cascades: Determined by initial sparticles, mass spectrum, couplings/mixing

Two distinct scenarios, based on **R-Parity** $R_P = \begin{cases} -1 \text{ for Superpartners} \\ 1 \text{ for SM particles} \end{cases}$

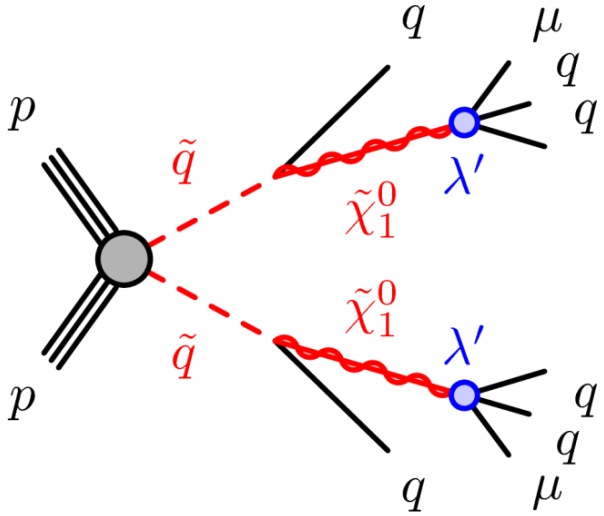
R-Parity conservation (RPC)

- Lightest SUSY particle (LSP) **stable**
  - typically assumed to be χ_1^0
  - ➢ escapes detector



R-Parity violation (RPV)

- Only SM particles in final state



LHC SUSY searches – common tools

Challenge: Separate a potential signal from vast standard model background ($\sigma_{inel}^{pp}(13TeV) \sim O(10^2)$ mb)

- **RPC** SUSY: Escaping Neutralino LSP – **missing momentum**
  - p-p collisions: Total z momentum unknown - use transverse component, E_T^{Miss}
  - complex observable: Rely on precise and efficient reconstruction of all physics objects
    - particularly challenging: Assure robustness against pileup...

- Cascade decays and high SUSY mass scales: Object **multiplicity** and high **momenta**
  - Often drives **trigger strategy** – (multi)leptons, high-pT multijets, jets+E_T^{Miss}
  - But not always the case – compressed scenarios more challenging (triggers may rely on ISR jets)

- If top/bottom squarks accessible: **Flavour tagging**

Today

- Try to showcase **selection** of recent results – representing the main areas
  - small subset of the full range – much more to see/read!
  - Mostly stick to **simplified model** interpretations

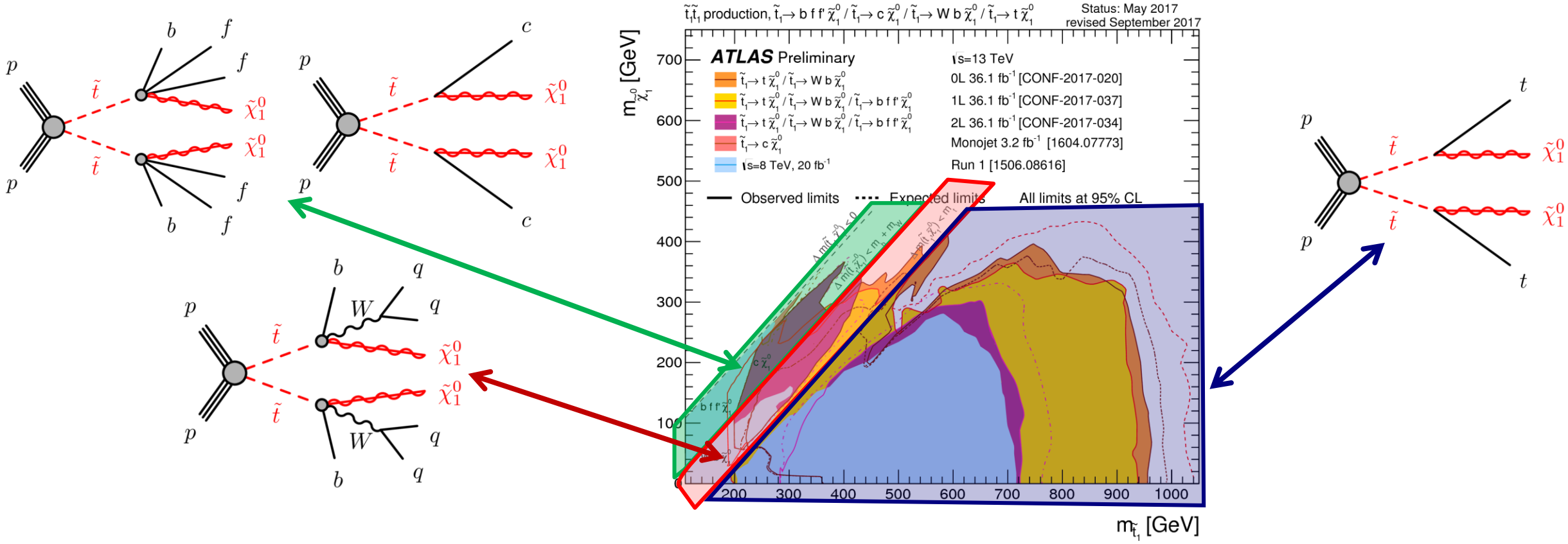
- **Topics covered today**
  - Top squark searches – all-hadronic, leptons, RPV-specific searches
  - Inclusive strong production searches – fully hadronic and with leptons
  - Searches for electroweak gaugino production – leptonic final states
  - Long-lived particle searches – displaced vertices
  - Prospects studies with HL-LHC

One main LHC search target: 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 "acceptable" fine-tuning)
- In reach for **direct production** at LHC?

Simplified RPC SUSY model: **Mass hierarchy** between top squark and LSP defines final state



- **Dedicated searches** and search regions targeting different parameter-space regions

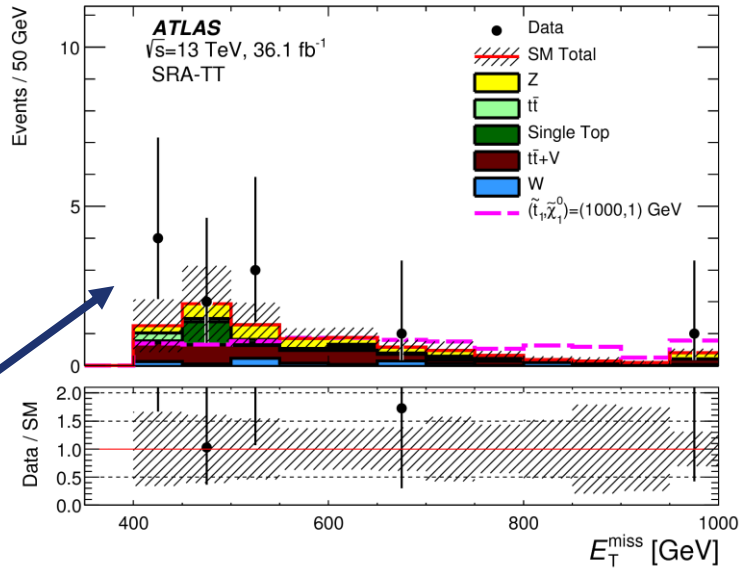
All-hadronic final states

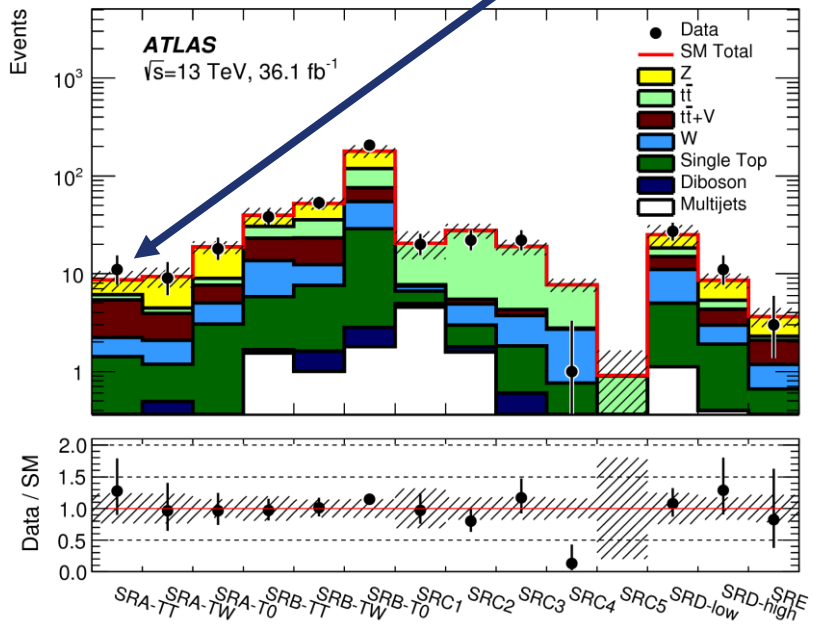
arXiv:1709.04183 / submitted to JHEP
see also:
JHEP 10 (2017) 005
CMS-PAS-SUS-16-050

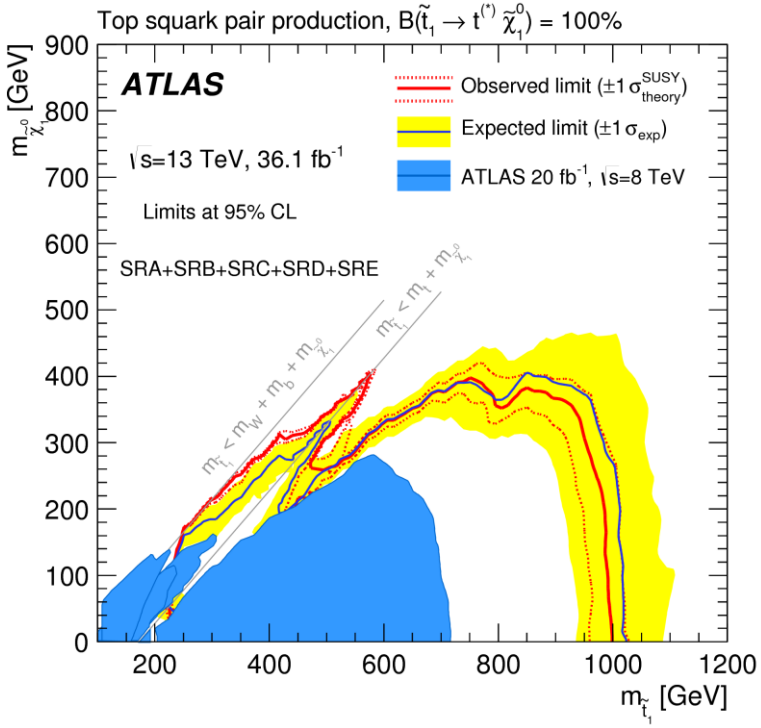
- Background suppression through combination of
  - **Lepton veto**
  - **requirement of b-tagged jets**
  - Large **E_T^{Miss}** and **jet kinematics** (b-b separation, transverse mass)
- High mass splittings: Use of **large-R-jets** to form top candidates
- For m($\tilde{t}$)~m(t)+m(χ_1^0): Rely on **ISR activity** to boost system
  - Ensures presence of **E_T^{Miss}** for background suppression

- Important backgrounds:
  Z+jets and top

- Observations in agreement with SM prediction

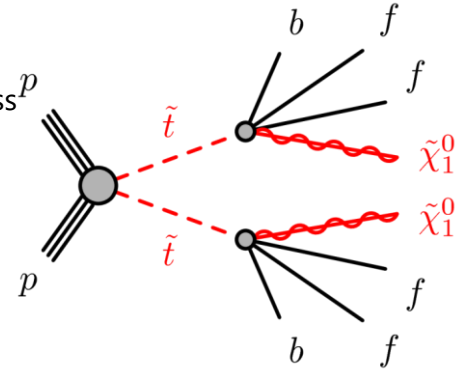






Compressed scenarios – working with soft leptons

- Challenging: $m(\tilde{t}) \sim m(\chi_1^0)$ – soft final state objects, no E_T^{Miss}
  - Again rely on ISR jet to boost top squark system – restores E_T^{Miss}
  - SM decay particles still very soft – but **within acceptance for leptons**

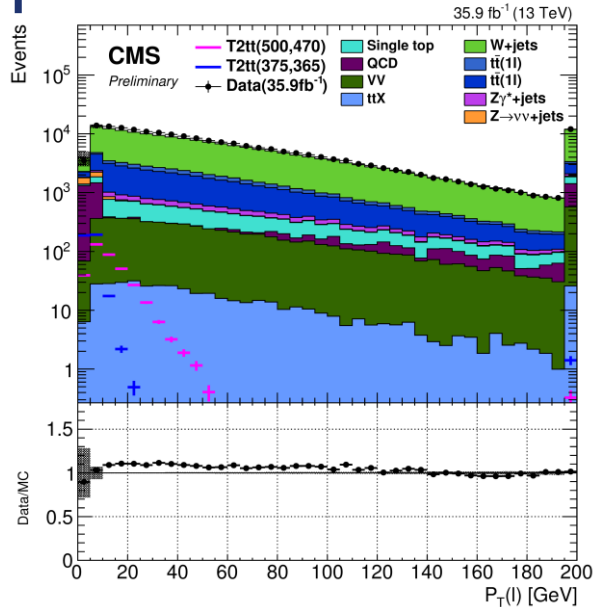


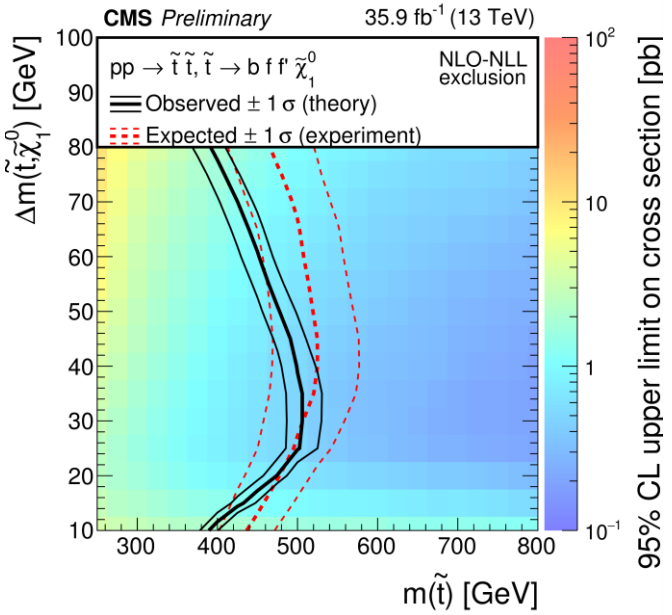
- Select events with one **ISR jet candidate**, at least one **soft lepton** and **E_T^{Miss}**
  - Veto presence of hard (>20 GeV) leptons or more than one additional hard (>60GeV) jet

- Main backgrounds: p_T tails in W+jets and top, non-prompt leptons

- Observation in agreement with SM prediction

- Note: Several additional searches in this phase-space region



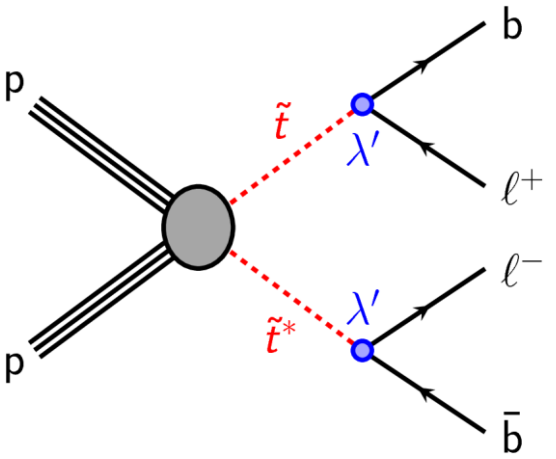


Top squark decays with R-Parity violation

If R-Parity is violated, **new decay signatures** need to be considered

One interesting case: **resonant top squark** decays

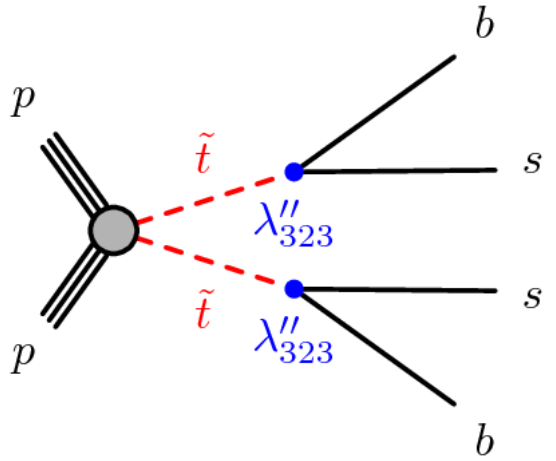
- Final state depends on type of R-Parity violation
  - Lepton+Quark, Quark+Quark possible
  - B or L violated



- No E_T^{Miss} - elude searches discussed so far

- Strategy: pair jets with leptons/jets to reconstruct resonance candidates

- Main observables for searching a signal: **Mass asymmetry** between candidates, **candidate masses**

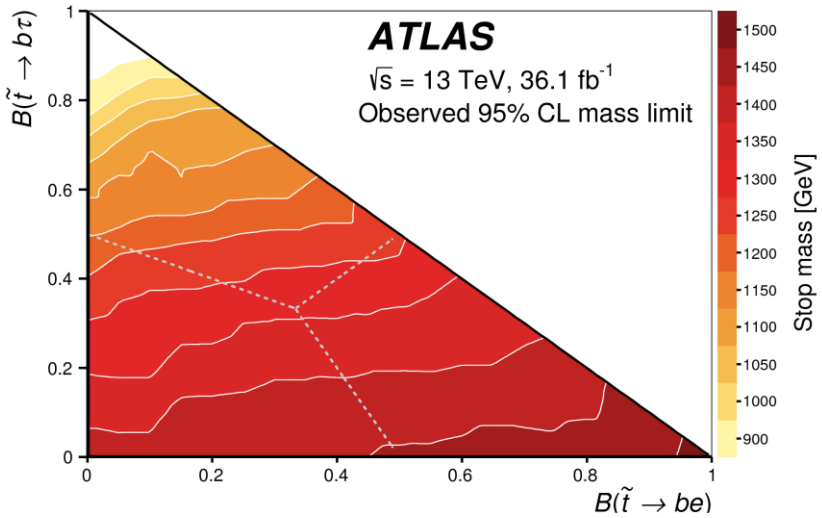


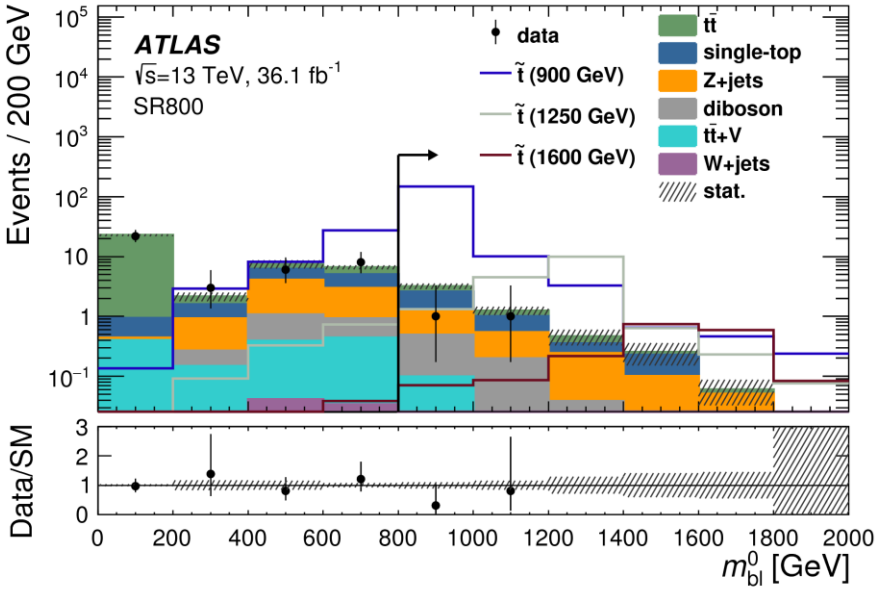
R-Parity violation

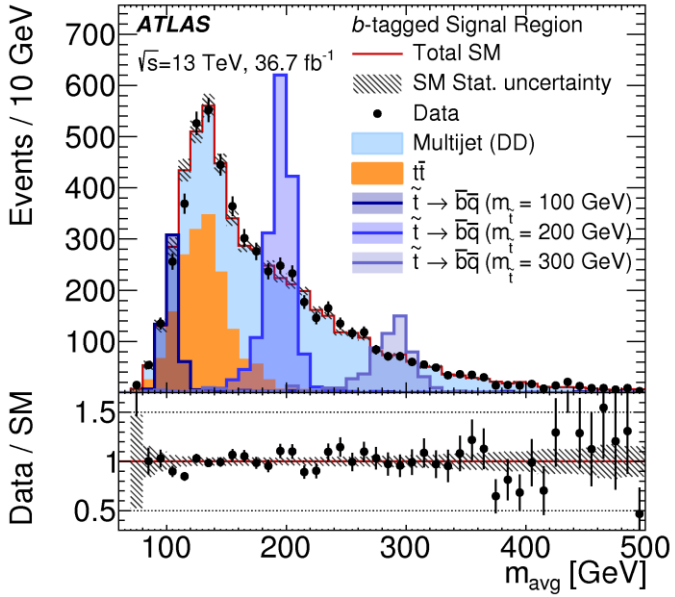
arXiv:1710.05544 (submitted to PRD)
arXiv:1710.07171 (submitted to EPJC)

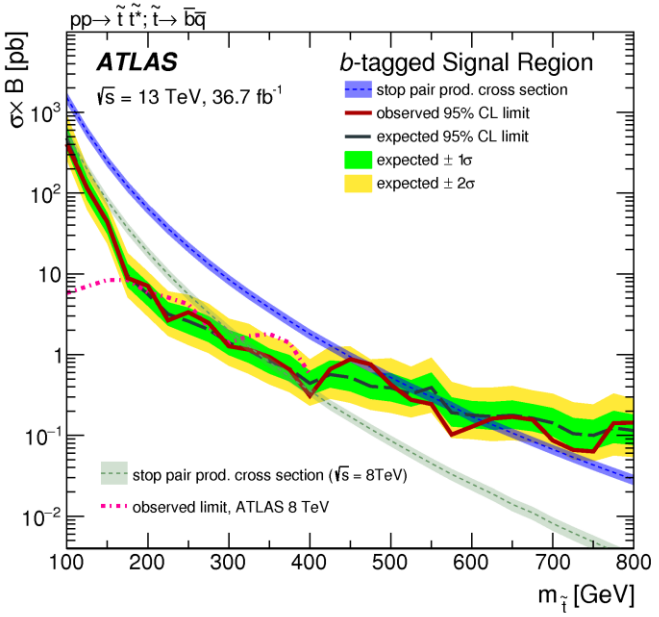
Main **backgrounds**:

- single top, tt, Z+jets for $\tilde{t}\rightarrow lq$
  - Estimated by scaling MC in control regions
- QCD multijets and tt for $\tilde{t}\rightarrow qq$
  - Fully data-driven QCD, MC-based tt
- SUSY signal expected to appear as resonance in mass distributions
- Observations consistent with absence of a signal





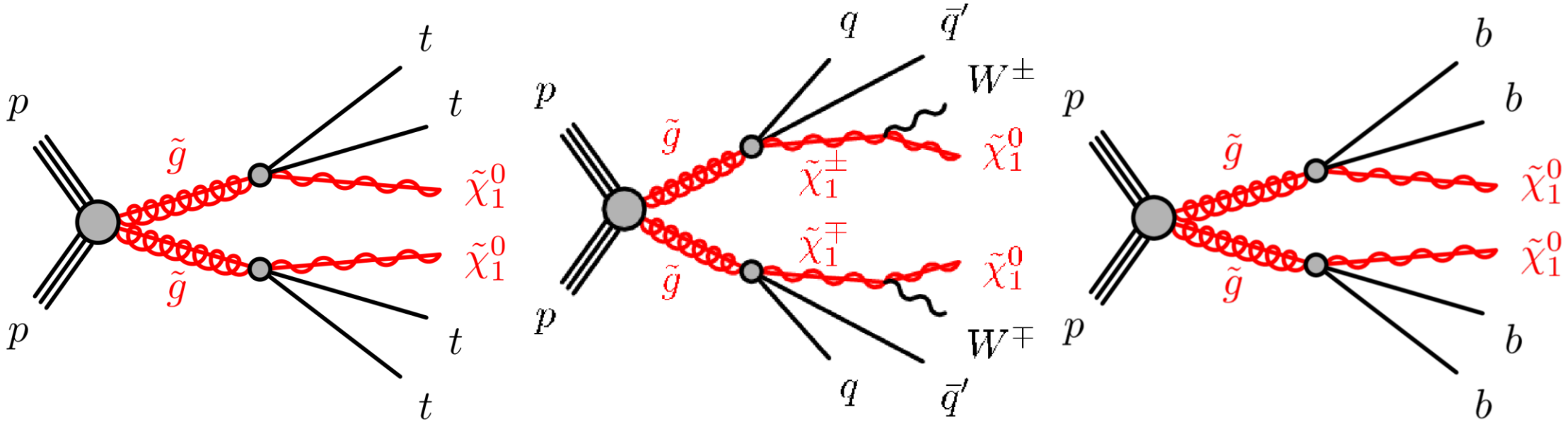




General strong production searches

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

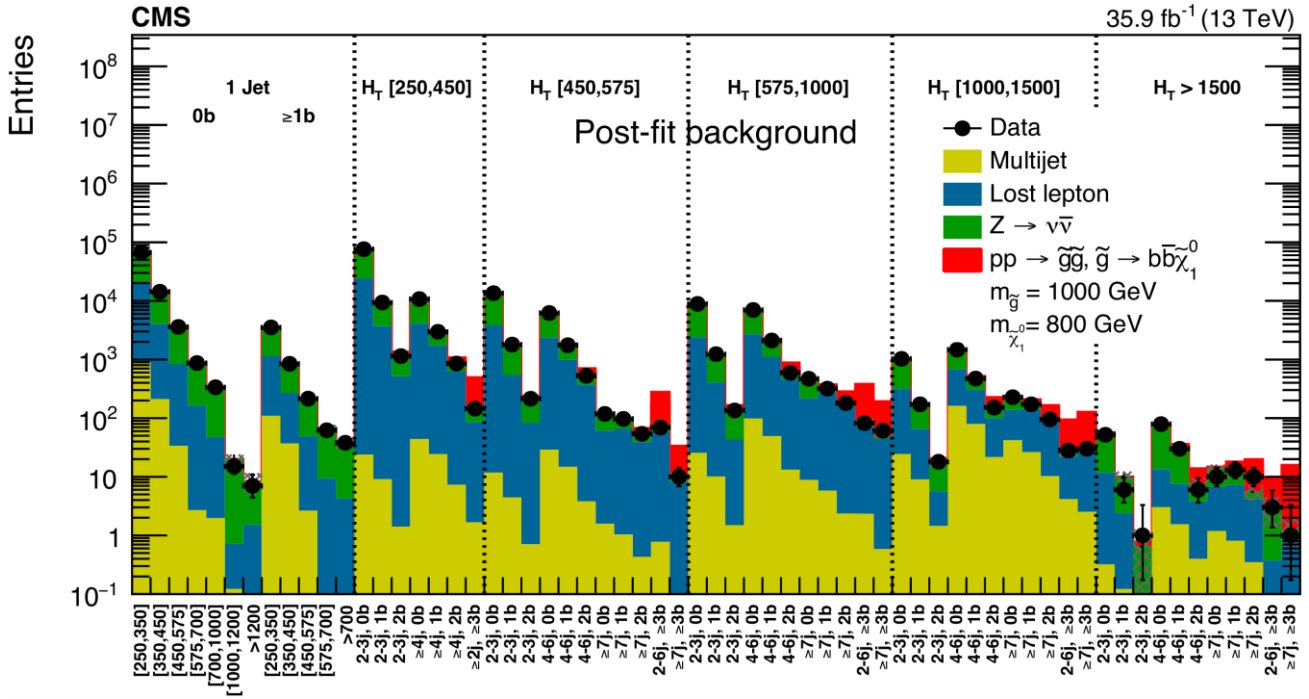
- One main interest: Gluino pair production
  - ➢Large cross-section if mass accessible
- Main feature: multijet signatures
  - Missing transverse momentum for RPC SUSY
  - Additional activity possible through cascade

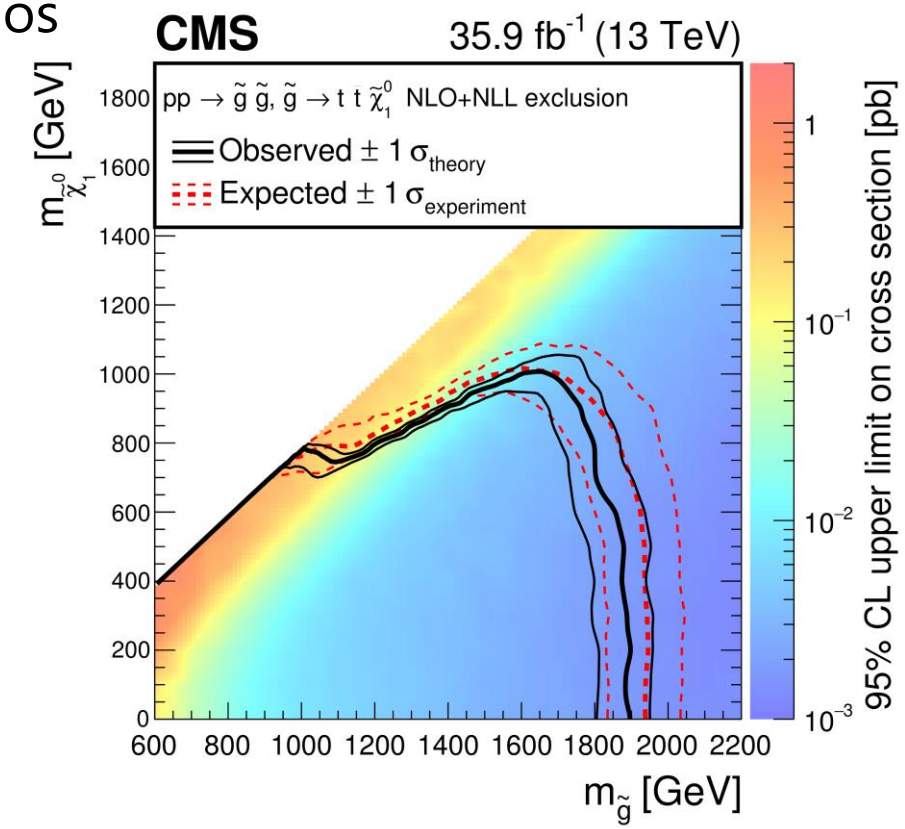


Classical RPC strong production searches

arXiv:1705.04650 (accepted by EPJC)
See also:
Phys. Rev. D 96 (2017) 032003
ATLAS-CONF-2017-025
arXiv:1708.02794 (submitted to JHEP)

- Searches for events with jets, E_T^{Miss} and no leptons
- Decay chains can include intermediate, virtual top/bottom squarks
  - ➢ Exploit via b-tagging
- High number of signal regions binned in jet, b-tag multiplicity, H_T
  - ➢ sensitive to wide range of strong production SUSY scenarios
- Example: ***Stransverse mass*** based search



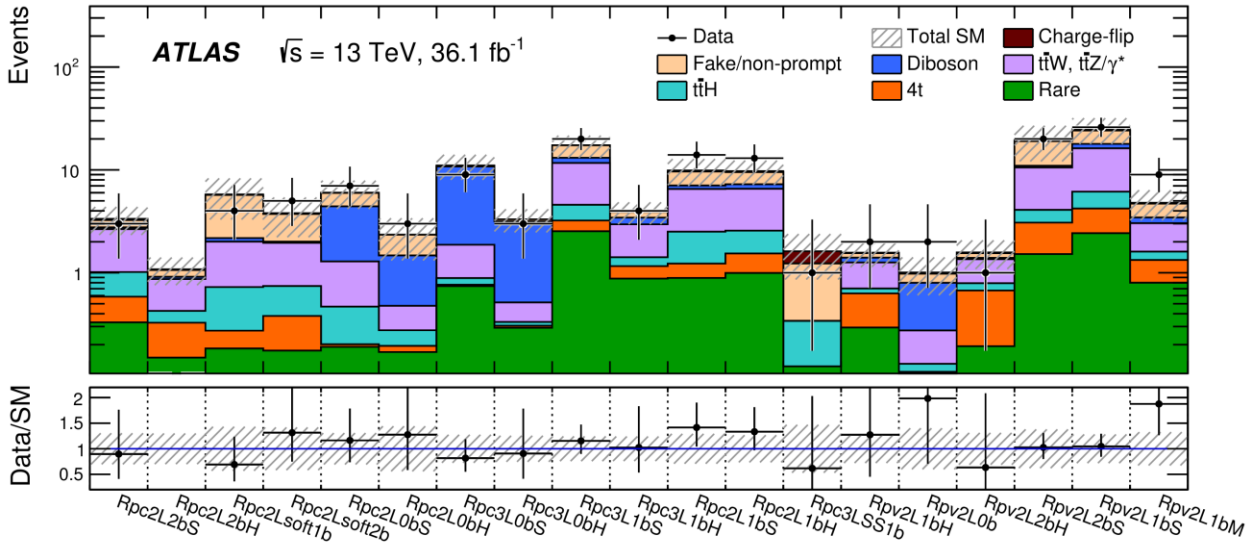


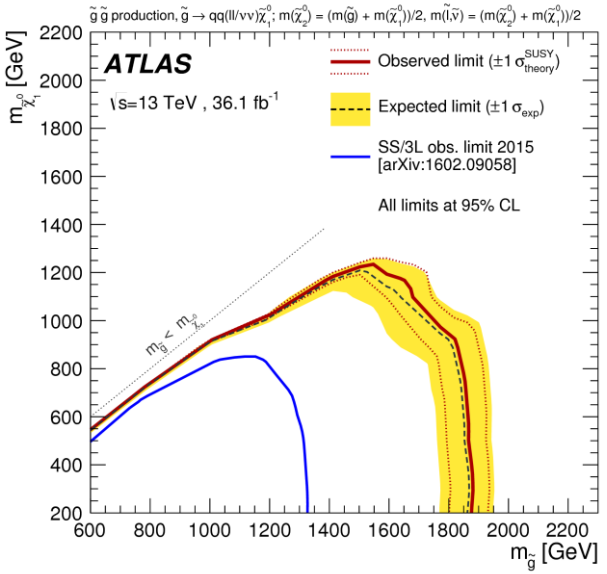
Leptonic signatures in strong production

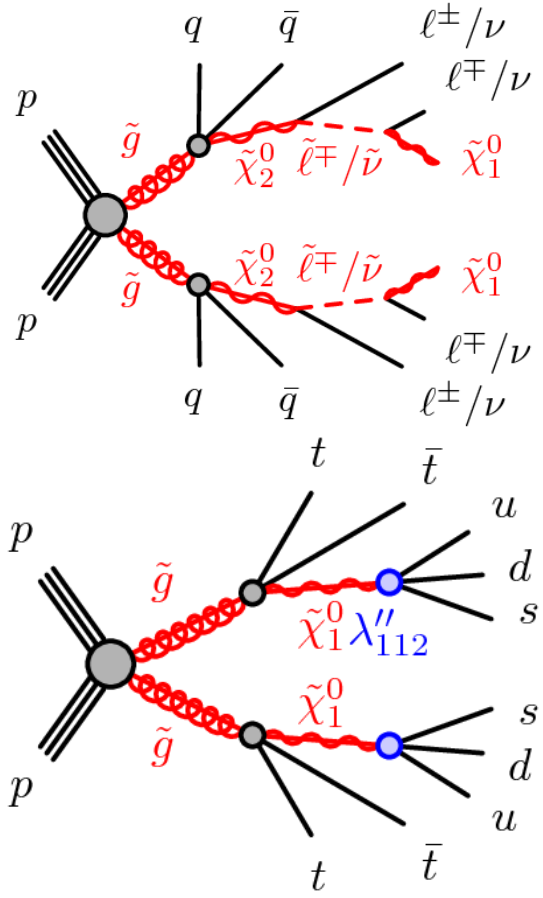
We can also use **leptons** to probe for strong production signals

- Intermediate top squarks, sleptons or gauginos can lead to **lepton-rich** final states
- Example: Search for events with at least 2 same-sign leptons and jets
  - When targeting RPC SUSY: Require E_T^{Miss}
  - Additional tool: ***Effective mass*** – universal between RPC and RPV
- Main backgrounds: non-prompt leptons, ttV, dibosons

JHEP 09 (2017) 084
See also:
EPJC 77 (2017) 144
arXiv: 1708.08232 (Submitted to PRD)
Eur. Phys. J. C 76 (2016) 683
PRL 119 (2017) 151802
arXiv:1709.09814 (submitted to PLB)
Eur. Phys. J. C 77 (2017) 578
CMS-PAS-SUS-16-041







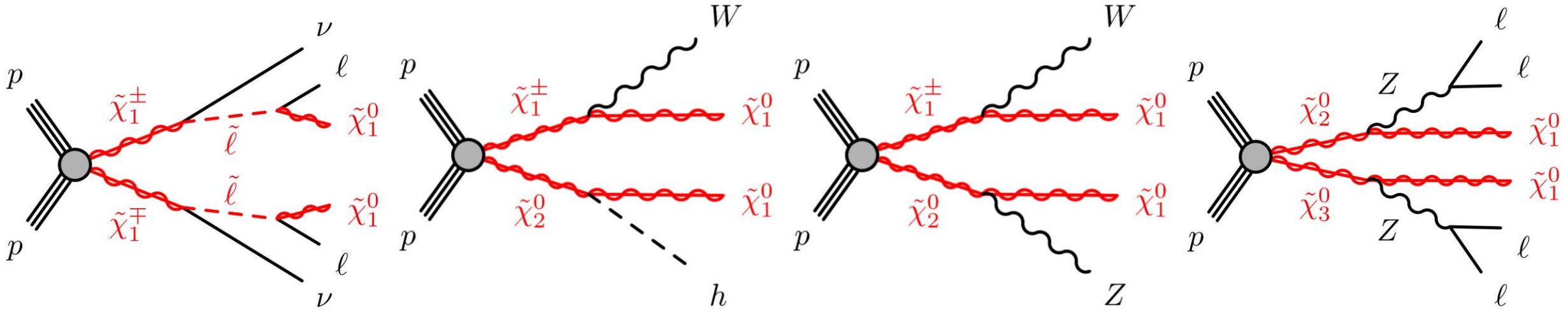
Multilepton search for charginos/neutralinos

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

➢ Intermediate gauge bosons: More challenging - SM leptonic W/Z BR

- Of particular importance: Hadronic τ decays - H→ττ and higgsinos

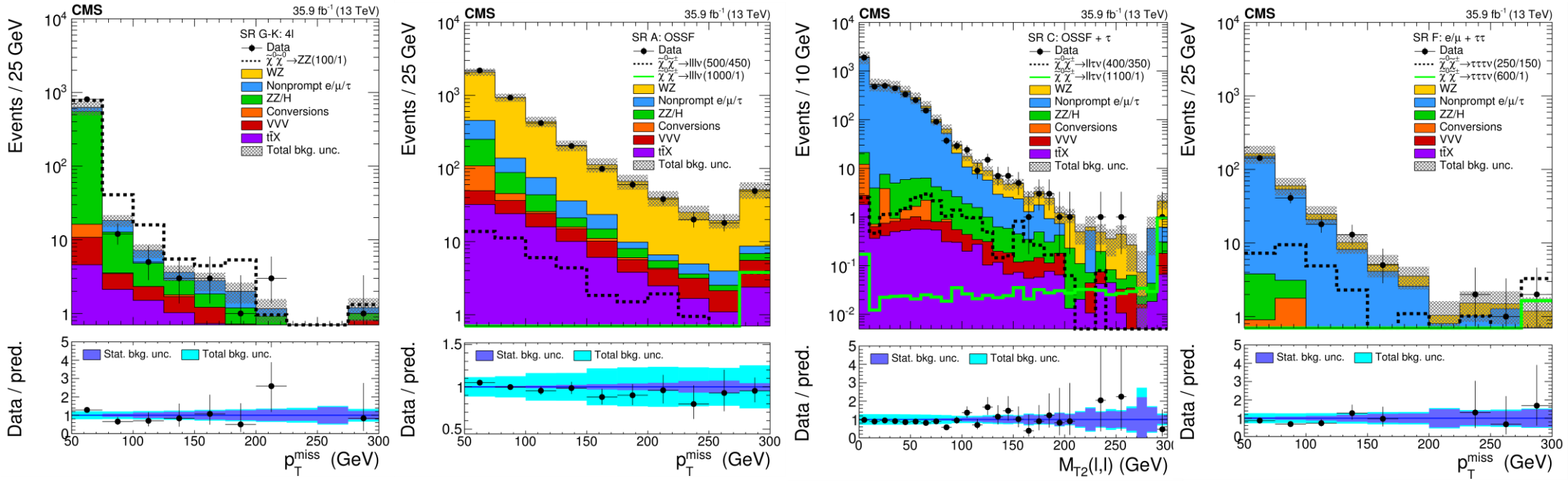


General multilepton search for charginos/neutralinos

- Select events with at least 3 leptons (e/μ/τ)

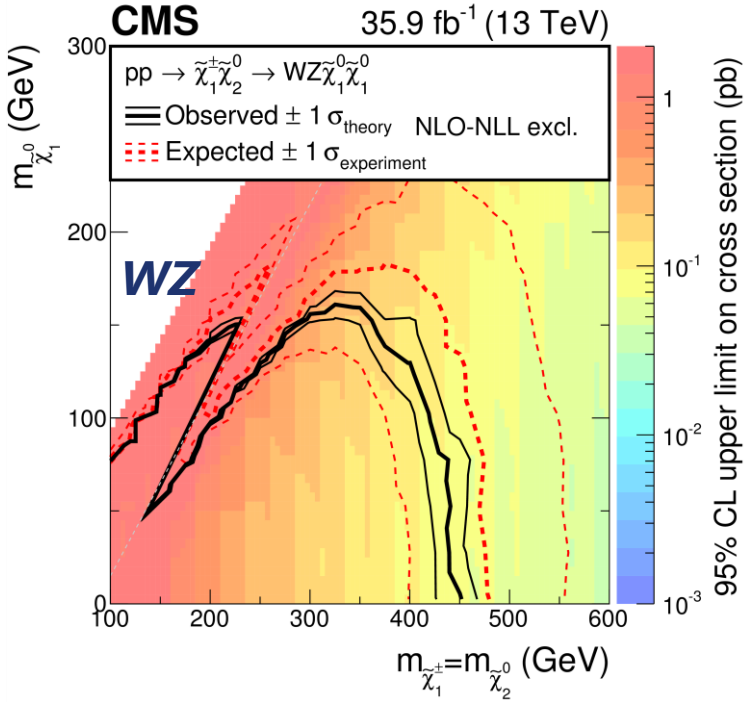
- Background contributions depend on lepton multiplicity
  - More pronounced fake component for τ-rich regions
  - Diboson and triboson relevant for light-lepton final states

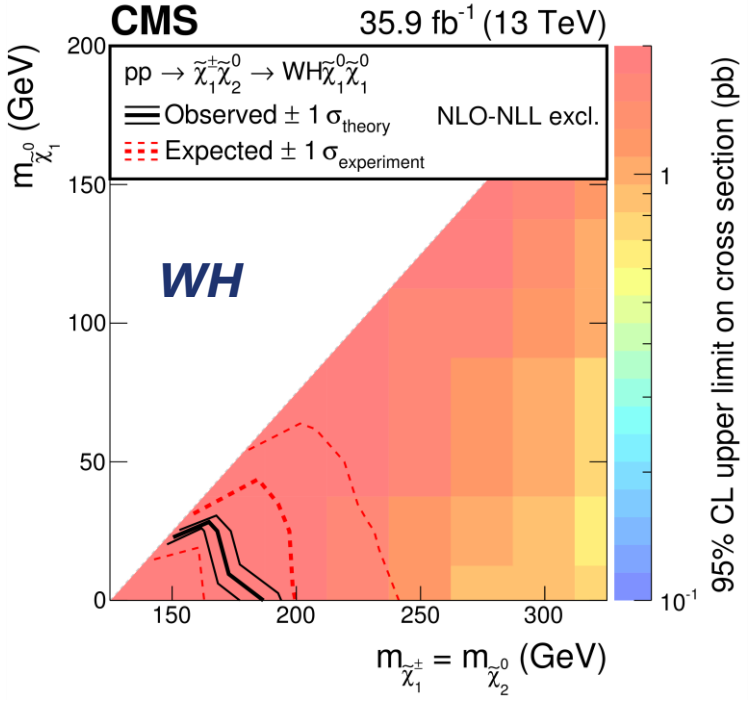
arXiv:1709.05406 (submitted to JHEP)
see also:
ATLAS-CONF-2017-039
CMS-PAS-SUS-17-004
arXiv:1709.08908 (submitted to JHEP)
CMS-PAS-SUS-16-048
arXiv:1708.07875 (submitted to EPJC)
ATLAS-CONF-2016-075

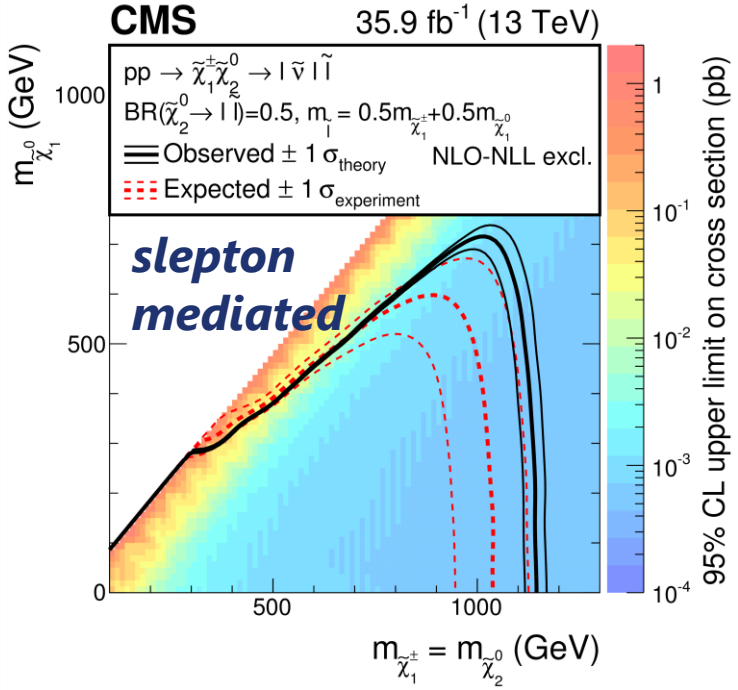


General multilepton search for charginos/neutralinos

- Large set of signal regions covering the phase-space
- Set limits for several decay chains and branching ratio assumptions
- Important role of τ-rich regions for Higgsino production
  - Challenging nature of τ-reconstruction

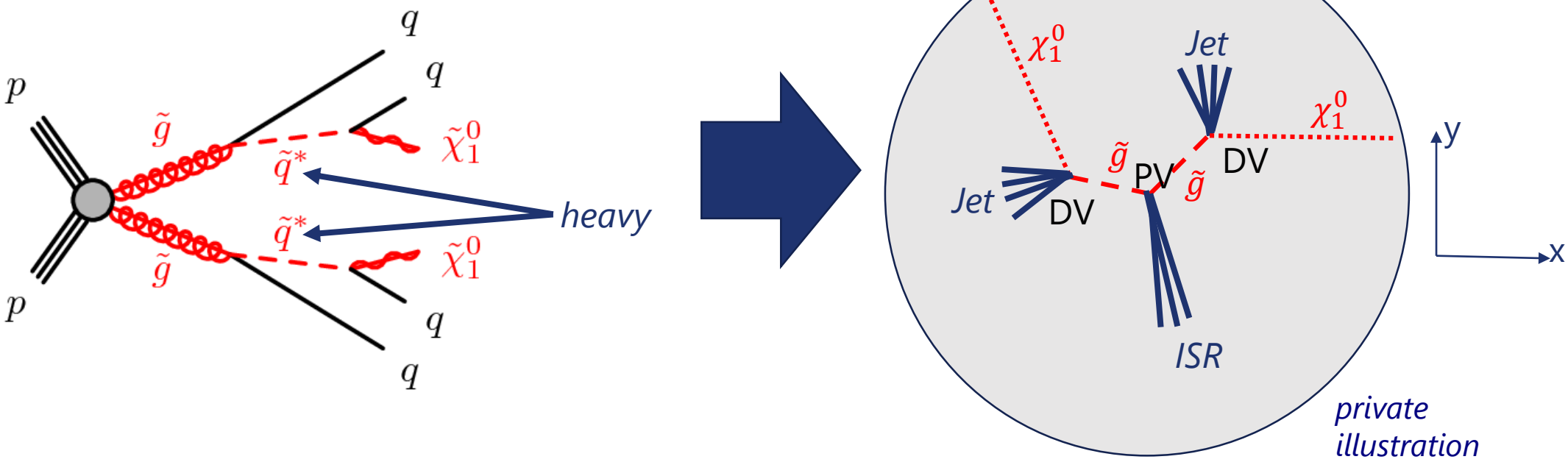






Long-lived particle signatures

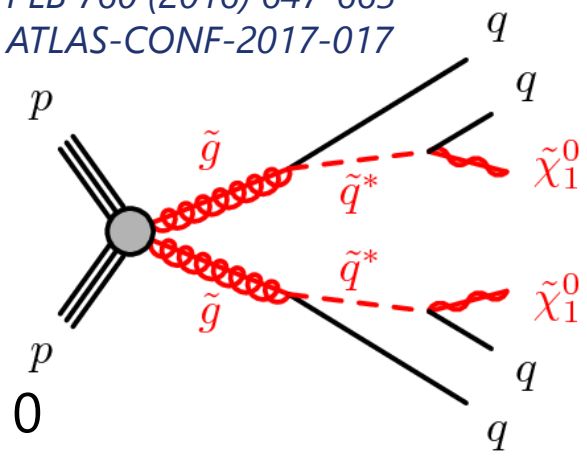
- Highly degenerate gaugino mass eigenstates or special mass hierarchies (e.g. split SUSY, weak RPV couplings) can lead to **long-lived sparticles**
- Signatures include disappearing tracks, **displaced vertices** and others
- Require **dedicated techniques** for candidate reconstruction and background estimation

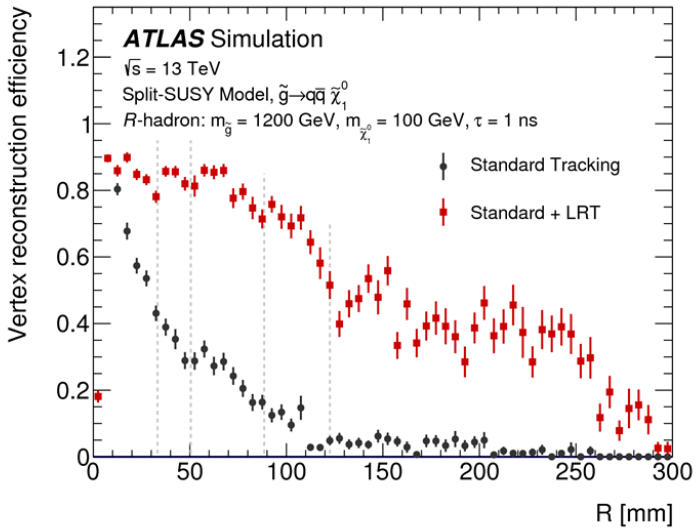


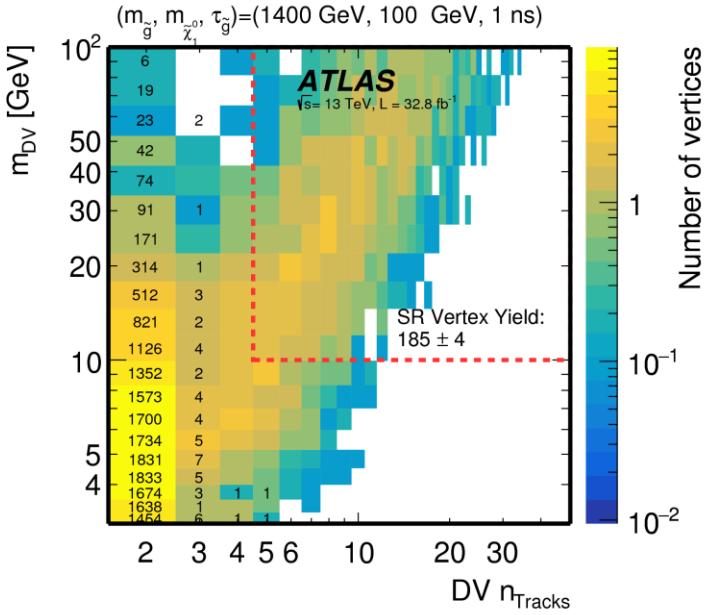
Example: Displaced vertices in the ATLAS Inner Detector

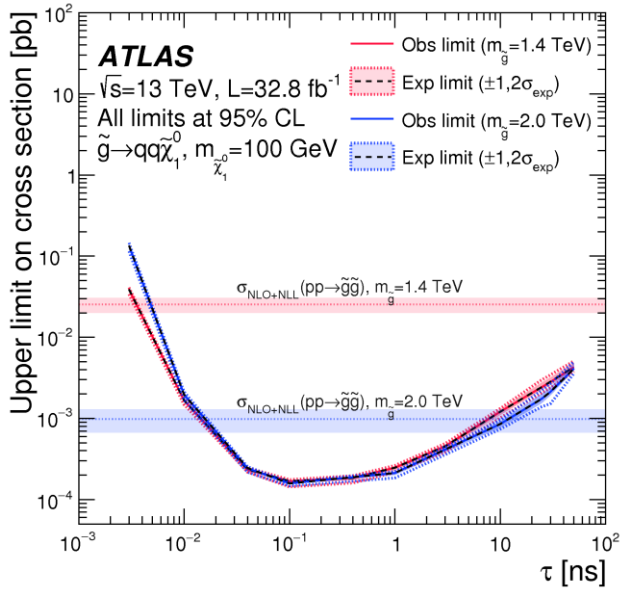
- Assume RPC scenario: Trigger using jet+E_T^{Miss} (requires ISR jet)
- Reconstruct tracks up to high transverse impact parameters
- Search for high-mass **displaced vertices** consisting of at least 5 tracks
- Backgrounds: Instrumental
  - Material interactions
  - multiple close-by hadron decays
  - hadron decay vertices crossed by unrelated tracks
- After selection "Zero-background" (0.02 expected) – data observation of 0

ATLAS-CONF-2017-026
see also:
PRD 93 (2016) 112015
PLB 760 (2016) 647-665
ATLAS-CONF-2017-017





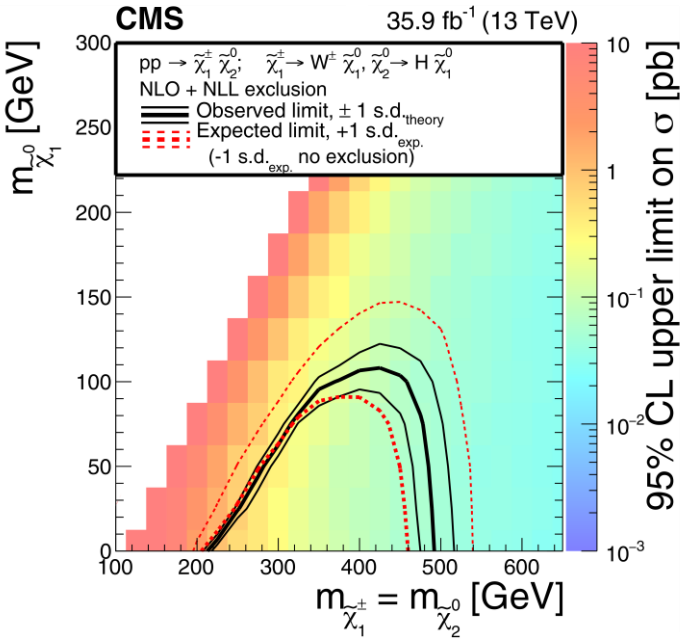


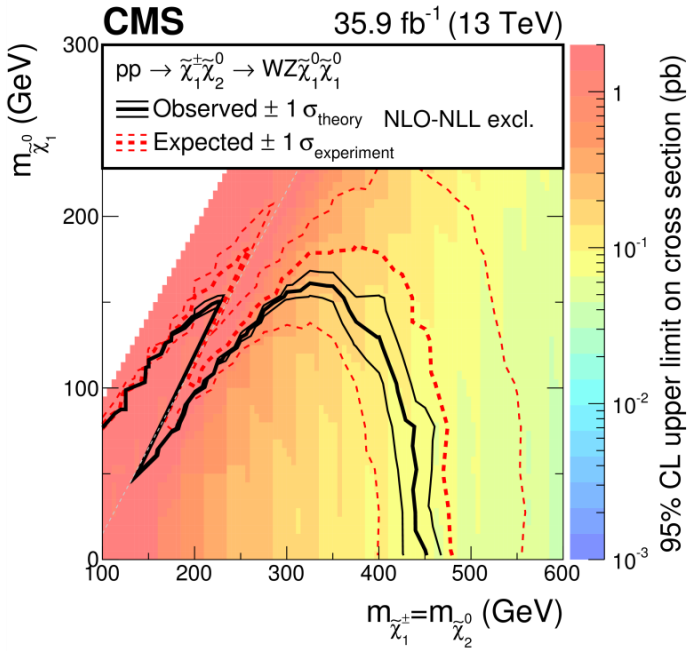


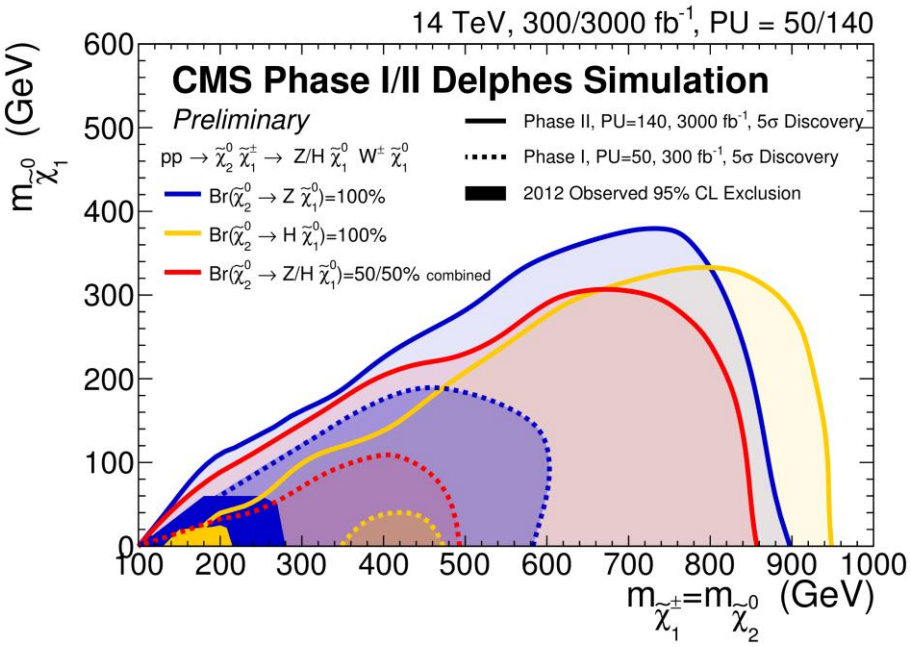
Towards the future – HL-LHC

CMS-PAS-SUS-14-012
ATL-PHYS-PUB-2016-021
see also:
CMS-PAS-FTR-13-014
ATL-PHYS-PUB-2016-022
ATL-PHYS-PUB-2015-032

- Prospects for SUSY searches with the HL-LHC under study in both experiments
- Reminder: Expect to gain **factor ~10 in statistics**, but **no large energy increase** (13→14 TeV)
  - Main gain expected for statistically limited searches – low masses, challenging topologies
  - One main goal: Extend reach to **still-uncovered corners** of the parameter space
- Example: Gaugino discovery potential – ***factor 2 beyond Phase-1 in mass reach for light LSP***







Towards the future – HL-LHC

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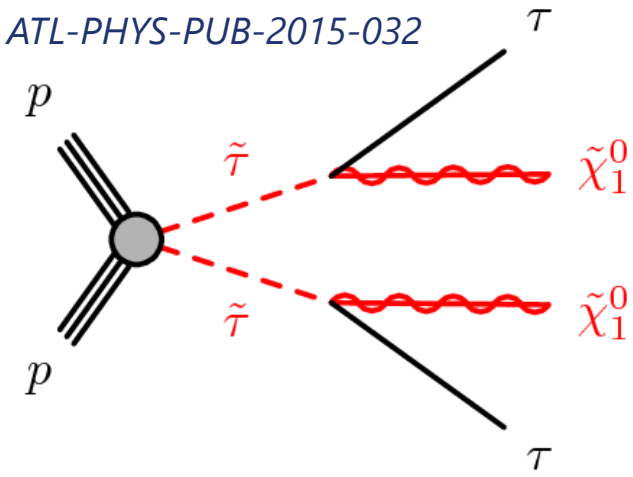
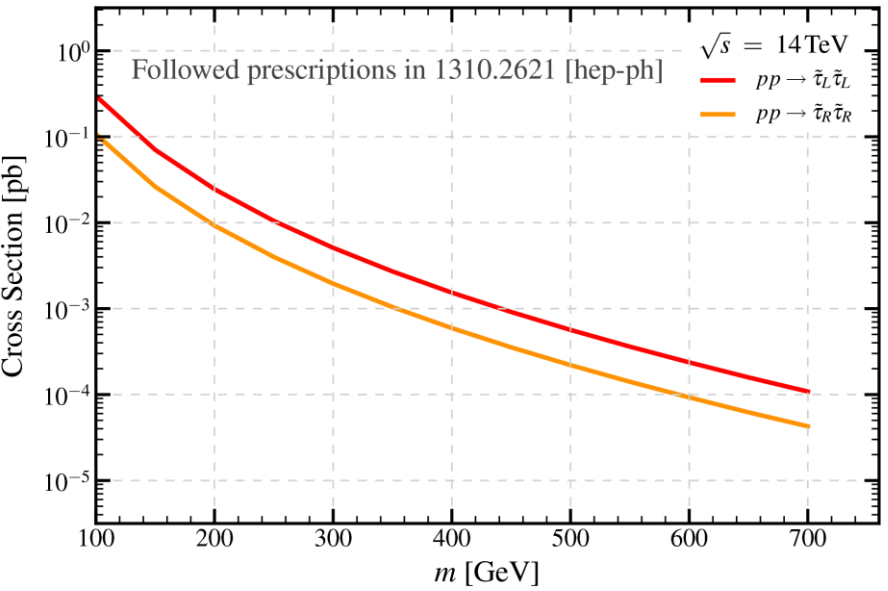
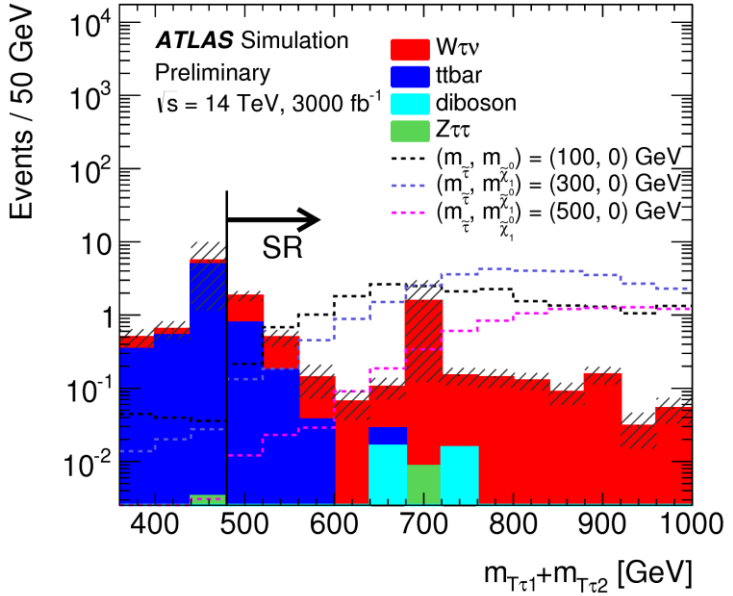
ATL-PHYS-PUB-2016-021
see also:
CMS-PAS-FTR-13-014
ATL-PHYS-PUB-2016-022
ATL-PHYS-PUB-2015-032

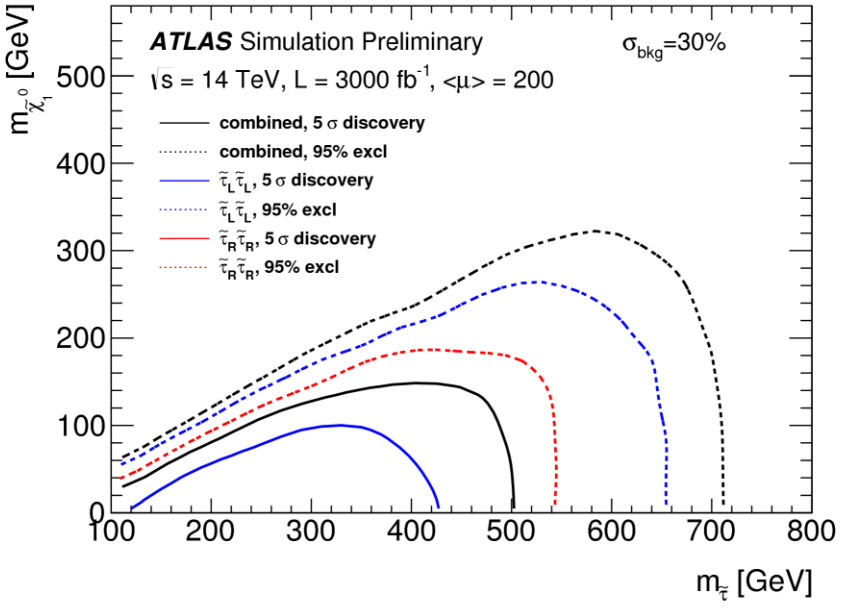
- Example: Direct tau slepton pair production
  - 2τ + MET signature
  - Challenging: τ reconstruction and background (fake) suppression
    - Comparably small slepton production cross-section doesn't help!
  - ➢ current sensitivity very limited (exclusion at $m_{\tilde{\tau}} \sim 100\text{GeV}, m_{\chi_1^0} = 0$)



- With 3000 fb-1, expect ***5σ discovery sensitivity*** *to* $\tilde{\tau}_L$-pair or mixed production up to ***450-500 GeV*** for light LSP!
- Complement possible linear collider searches for compressed scenarios







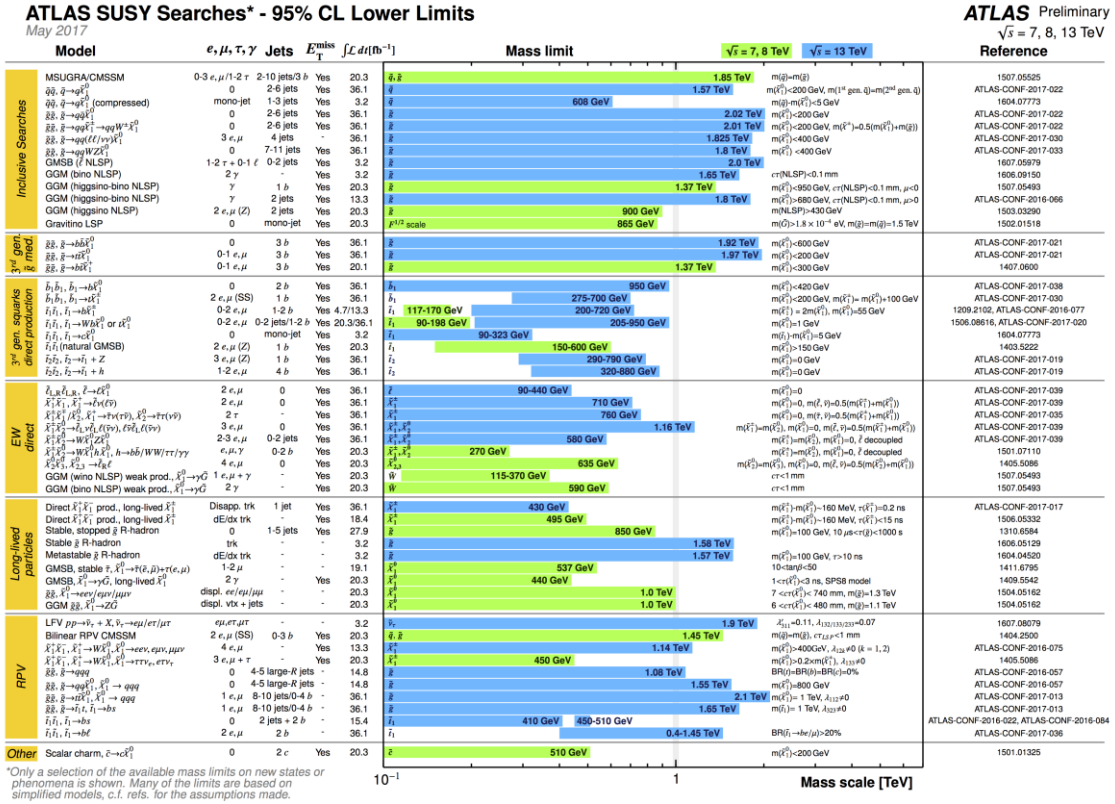
Summary and Outlook

- Search for BSM physics is one main goal of the LHC
  - **Supersymmetry** used as framework for developing and interpreting searches

- Extensive search program already completed, sensitivity far beyond reach of previous colliders
  - Profit from centre-of-mass energy
  - Showed only small subset of results

- **HL-LHC** will further extend sensitivity
  - Become sensitive to new signatures (e.g direct stau)
  - Double mass reach in some scenarios
  - Some scenarios only with small gains

- Complementarity between HL-LHC (direct production reach, most sensitive to large mass splittings) and linear colliders (compressed scenarios, indirect constraints through precision measurements)



Backup

Reminder: Supersymmetry in a nutshell

Supersymmetry (SUSY): A symmetry between fermions and bosons

Q |Fermion> = |Boson> Q |Boson> = |Fermion>

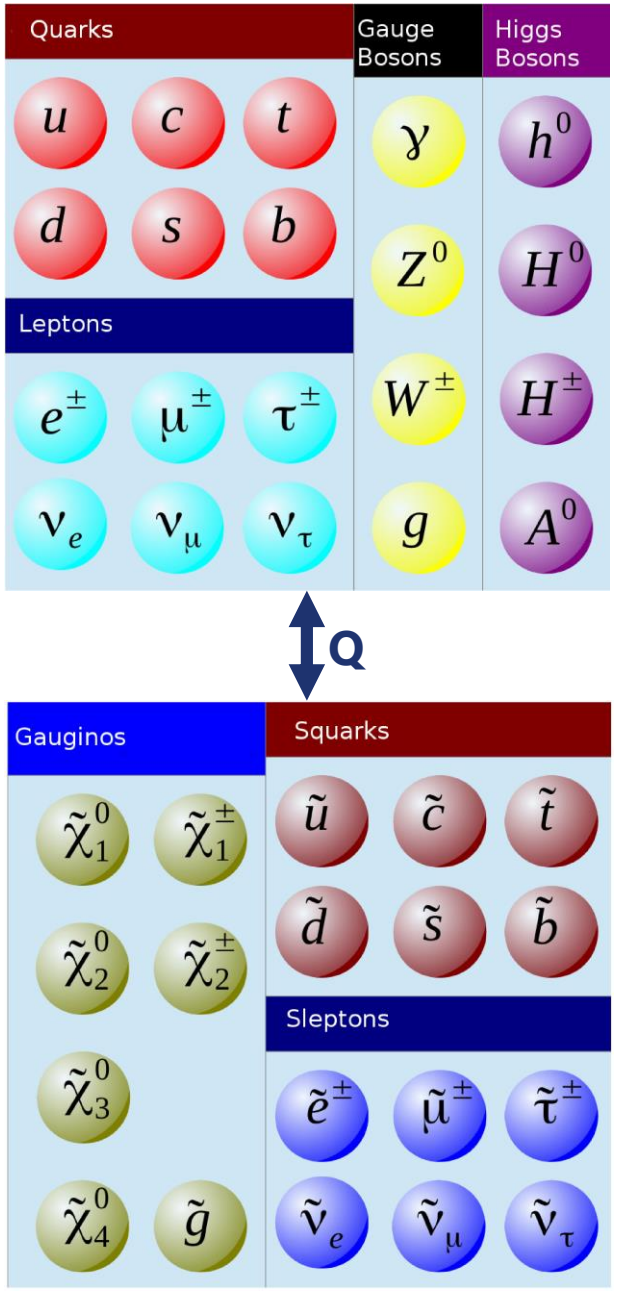
Most obvious consequence: **Double the SM particle content**

- 'Superpartners' for every SM degree of freedom ('sparticles')

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

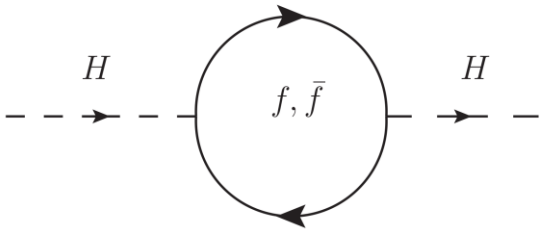
- SUSY breaking allows masses of sparticles to differ from SM partners
  - Also introduces wide parameter space: > 100 free parameters!

SUSY models used as benchmark for guiding development and interpretation of BSM collider searches



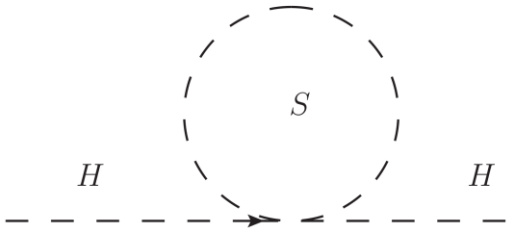
Motivation for SUSY searches

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



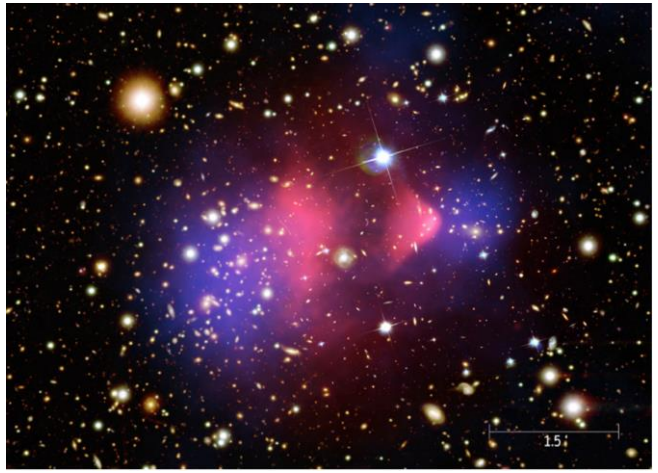
$$\Delta m_h^2 \sim -\frac{\lambda^2}{8\pi^2}\Lambda_{UV}^2 + m_f^2 O(ln\Lambda_{UV}) + ...$$

- 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!
  - Feature of string theories



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

- Most important: **Rich and varied spectrum of predicted signatures**
  - Use to drive a systematic search for BSM physics
  - SUSY models as benchmark for guiding development and interpretation of collider searches



LHC SUSY searches – interpretation framework

Frequently 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 driving collider 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!