Searches for Supersymmetry at the LHC

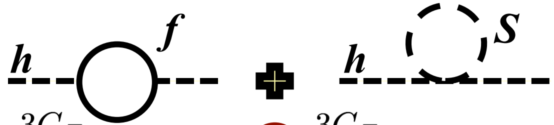
Isabell-Alissandra Melzer-Pellmann
DESY Hamburg

Outline

- Introduction
- Searches for strong SUSY production
- Searches for electroweak production
- *R*-Parity violating scenarios
- Searches for long-lived particles
- Indirect searches

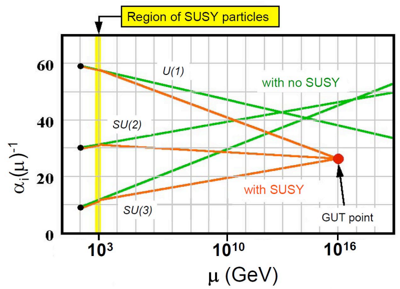
Introduction

- SUSY: each SM particle gets assigned at least one partner with spin differing by ½
- SUSY can provide solutions to many open questions:
  - **Large radiative corrections** to the Higgs mass? Fermion loops largely cancelled by add. boson loops

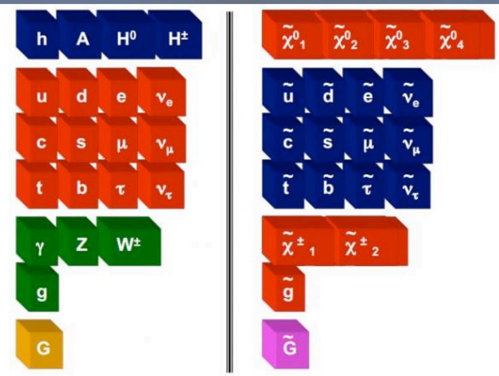


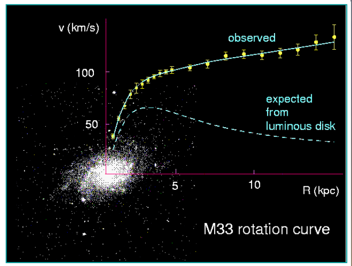
$$m_h^2 = (m_h^2)_0 - \frac{3G_F}{4\sqrt{2}\pi^2}(4m_t^2)\Lambda_{NP}^2 + \frac{3G_F}{4\sqrt{2}\pi^2}(4m_t^2)\Lambda_{NP}^2 + \mathcal{O}(ln[\Lambda_{NP}/m_h])$$

  - **Unification of forces**? Possible due to contribution of SUSY particles at higher energies



  - Dark matter? If lightest SUSY particle is stable (*R*-parity conserved), it is a viable **dark matter candidate**

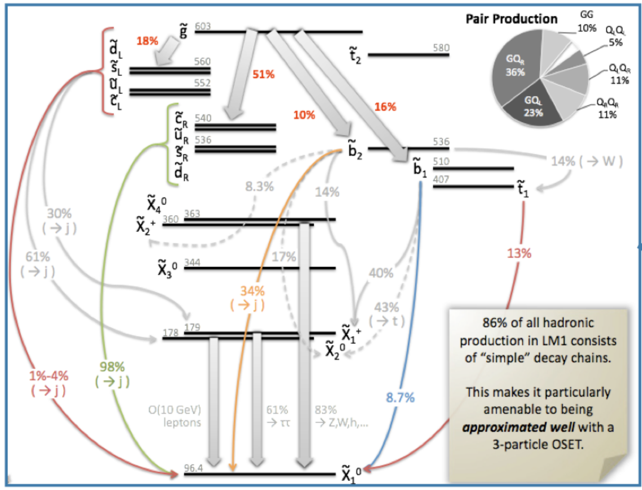




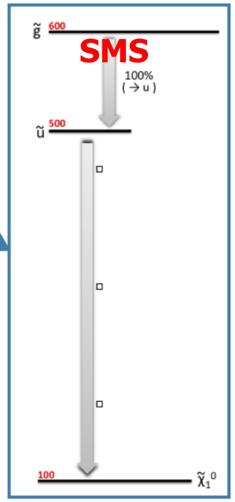
SUSY models

- MSSM → 105 free parameters (masses, couplings, phases)
- CMSSM → 4 free parameters + 1 phase (used until ~2011)
- Since then: interpretation in simplified models

CMSSM



Simplified Model Spectrum (SMS) with 3 particles, 2 decay modes

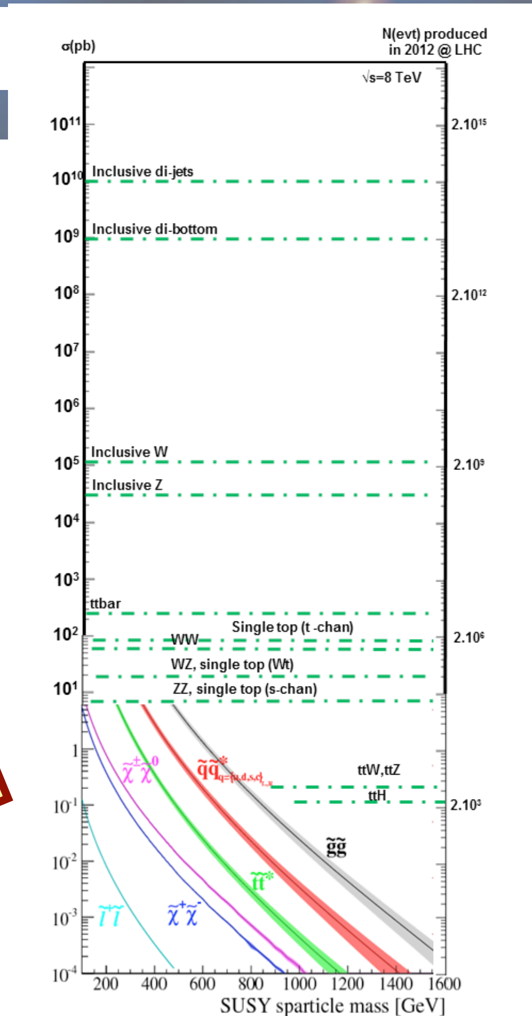


- SMS can later be combined, e.g. by programs like SmodelS in order to test full models
- Careful interpretation of SMS results needed, since branching ratios of 100% are assumed

SUSY cross sections

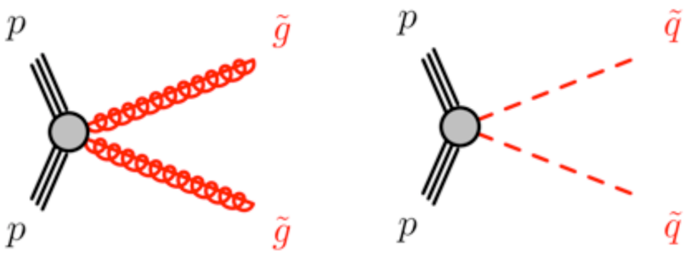
SUSY particle production **very rare** compared to Standard Model particle production

→ need large amount of data
→ expect large SM backgrounds



Strong production

- Searches tuned on **final states**:
  - Full hadronic final states
  - Single-lepton
  - Di-lepton (opposite- and same-sign)
  - Multi-lepton
  - B-tagged jets
  - Explore jet substructure



- SM background mostly in the tails of distributions
  - Difficult to determine from simulation
  - Estimated from control regions in data and transfer factors

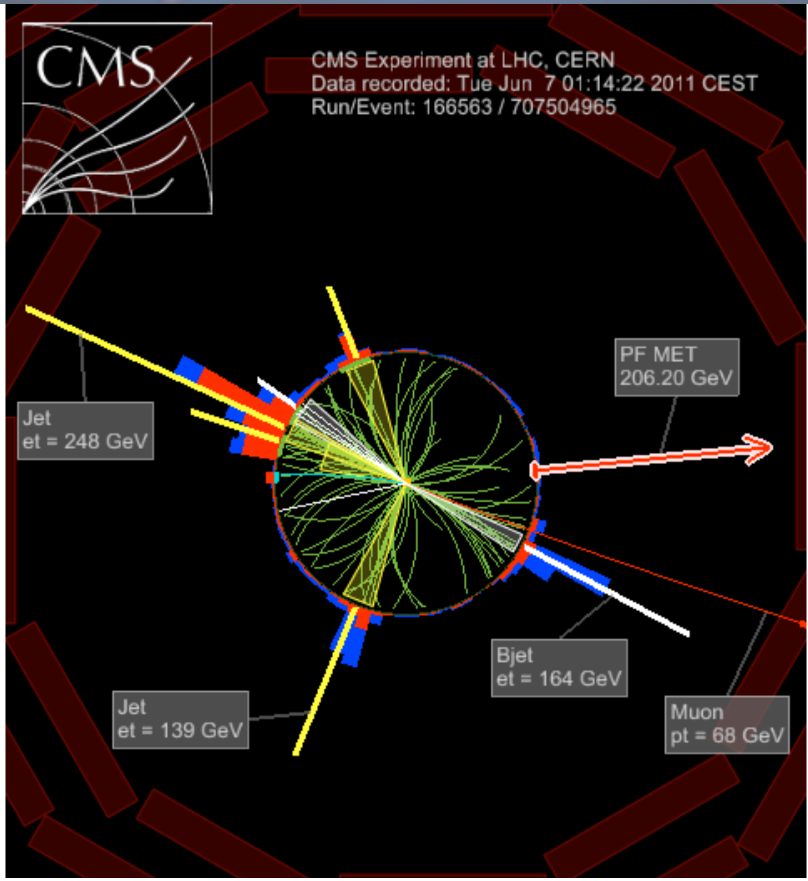
Searches for gluinos and squarks

- Characteristic for strong production: (large) number of high-energetic jets and missing transverse energy

- typical variables:

$$H_{\mathrm{T}} = \sum p_{\mathrm{T}}^{\mathrm{jet}}$$

$$H_{\mathrm{T}}^{\mathrm{miss}} = \left| -\sum \vec{p}_{\mathrm{T}}^{\mathrm{jet}} \right|$$



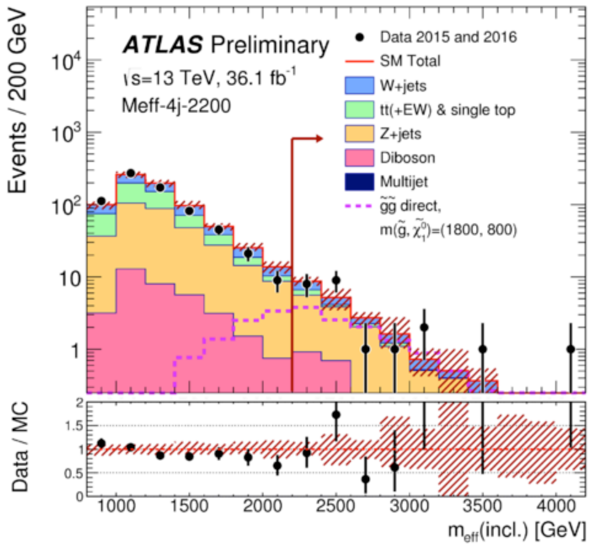
Hadronic searches for gluinos and squarks

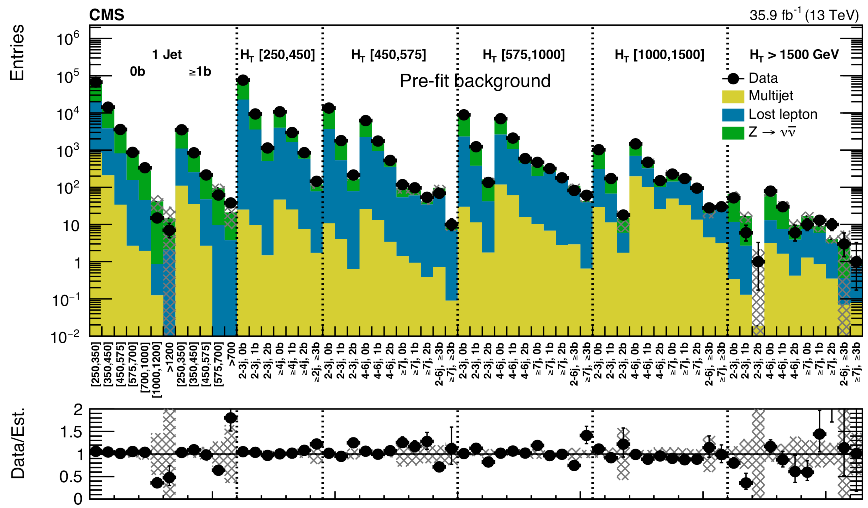
- Most all-hadronic searches cover a large model range; typical variables:

$$m_{\text{eff}} = \sum p_{\text{T}}^{\text{jet}>50\text{ GeV}} + p_{\text{T}}^{\text{miss}}$$

$$M_{\text{T2}} = \min_{\vec{p}_{\text{T}}^{\text{miss}X(1)} + \vec{p}_{\text{T}}^{\text{miss}X(2)} = \vec{p}_{\text{T}}^{\text{miss}}} \left[\max\left(M_{\text{T}}^{(1)}, M_{\text{T}}^{(2)}\right)\right]$$

ATLAS-CONF-2017-022



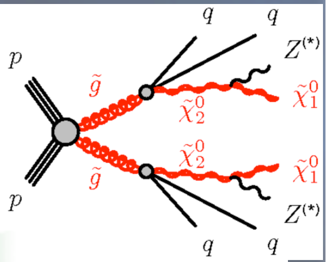


CMS-PAS-SUS-16-036

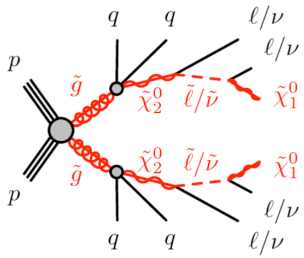
No excess observed

Opposite-sign dileptons

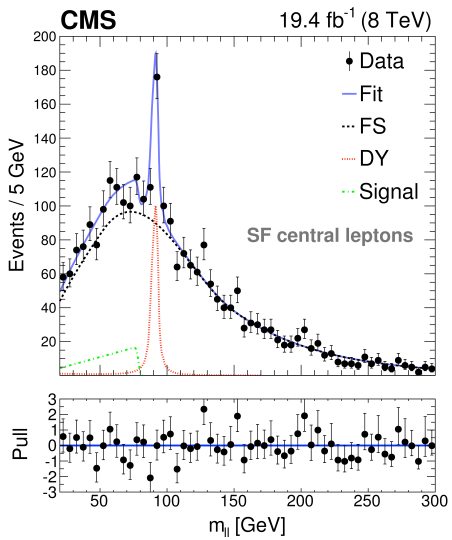
- The **hottest topic in Run 1** – excesses observed by CMS and ATLAS:



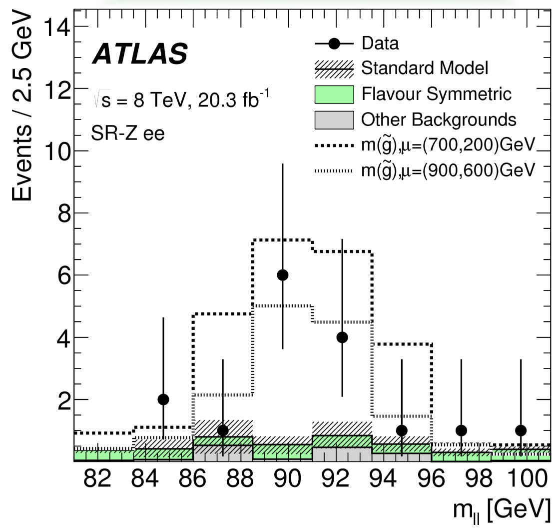
m_{ll}



CMS: Excess off-Z



ATLAS: Excess on-Z



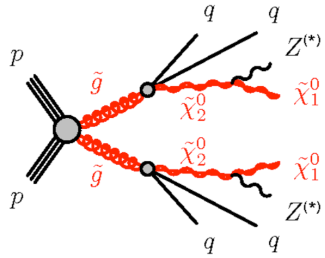
JHEP 04 (2015) 124

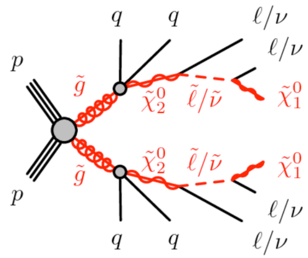
Eur. Phys. J. C75 (2015) 318

Opposite-sign dileptons

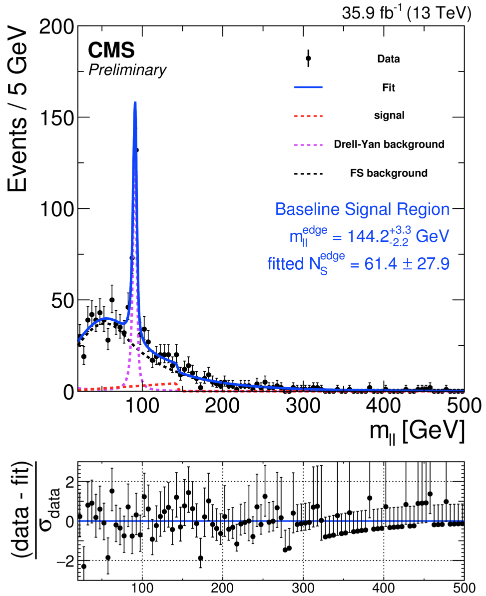
- But with Run 2:

m_{ll}



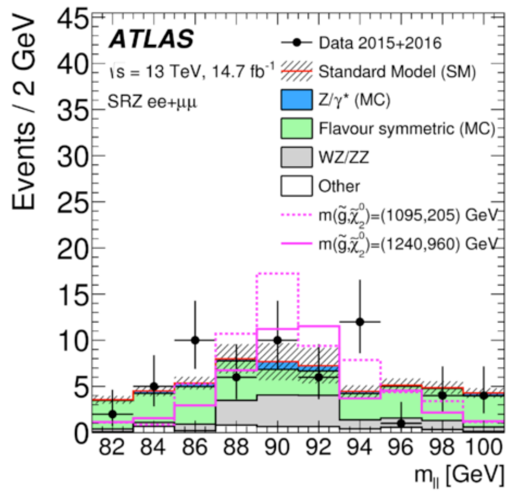


CMS: No excess



CMS-PAS-SUS-16-034

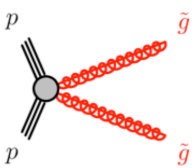
ATLAS: No excess

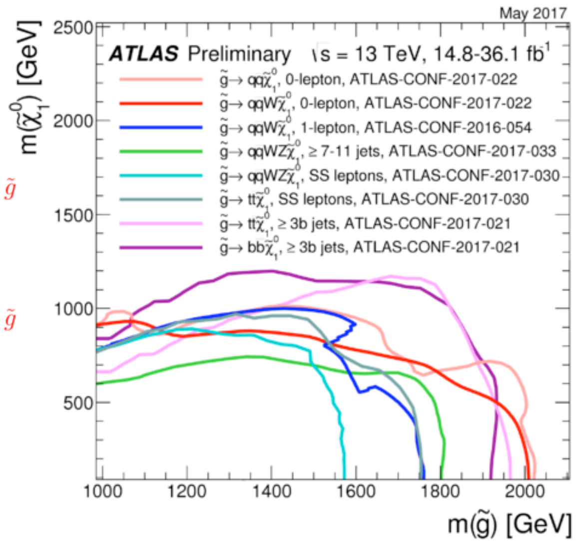


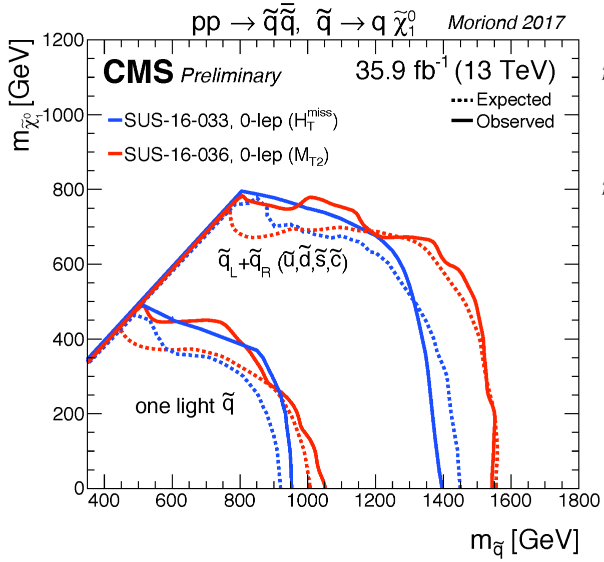
Eur. Phys. J C 77 (2017) 144

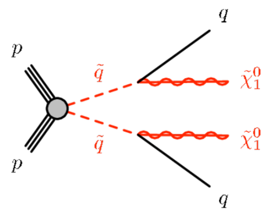
Limits on squark and gluino production

- Set limits in models with decay to all or only one generation







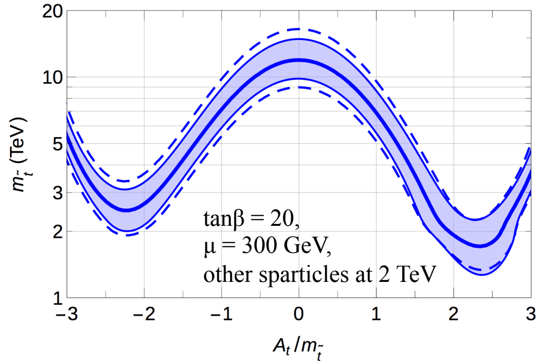


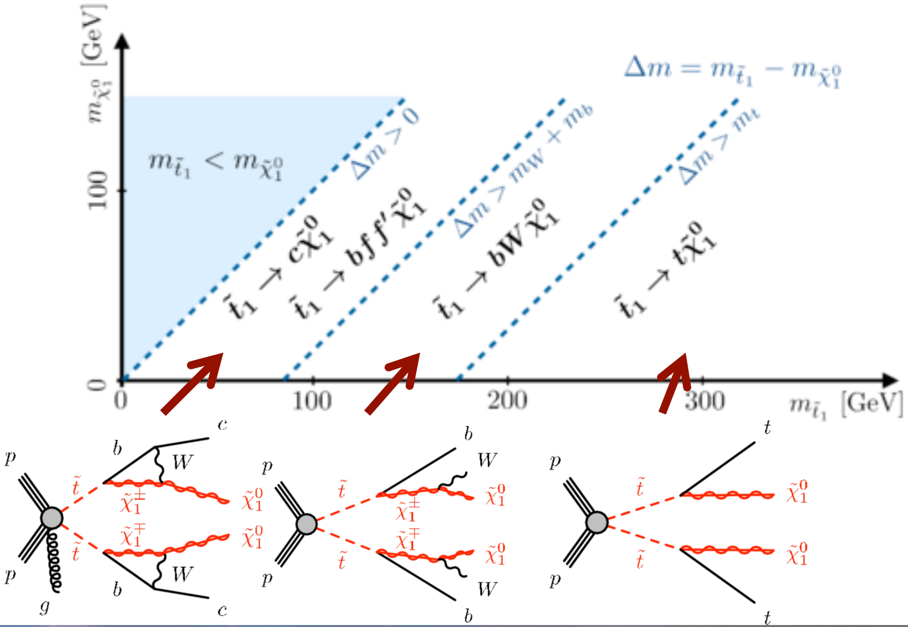
Gluinos (squarks) excluded <2 TeV (1.6 TeV), LSP <1 TeV (800 GeV)

But: squarks excluded <1TeV if only one squark is light

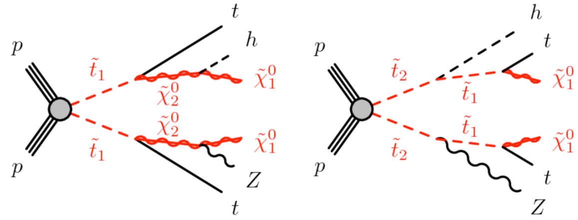
Searches for top squarks

- Top squarks are expected to be lighter (by naturalness predictions), but recent calculations allow for several TeV
- Search strategy depends on expected final state



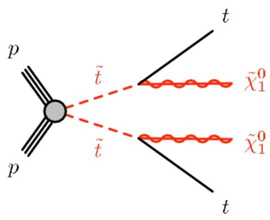


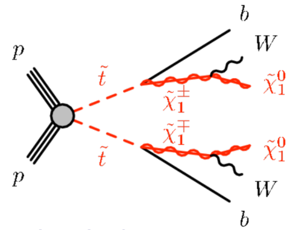
- Search also for more complex scenarios like $\tilde{t}_2$ production and decays to $\tilde{\chi}^0_2$



Example: 1- and 2-lepton top squark searches

- Require
  - isolated electron or muon
  - several energetic jets
  - missing transverse momentum
- Define several signal regions based on targeted parameter space, e.g.



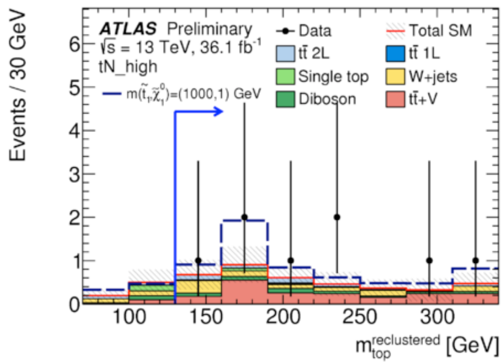


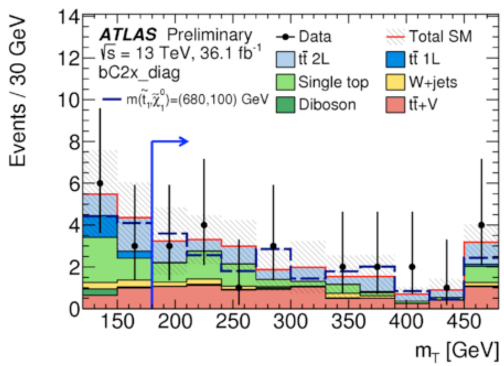
$m_{top}^{reclustered}$ from large-radius jets

$$m_T = \sqrt{2 p_T^{\ell} E_T^{miss}(1 - \cos[\Delta\phi(\boldsymbol{p}_T^{\ell}, \boldsymbol{p}_T^{miss})])}$$

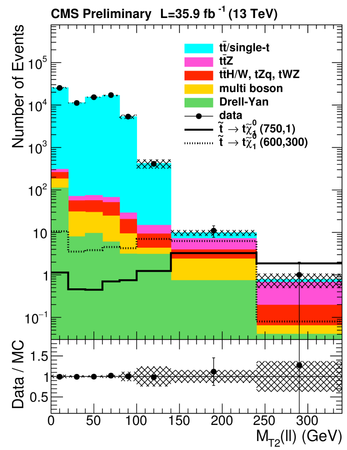
$m_{T2\ (ll)}$

ATLAS-CONF-2017-037





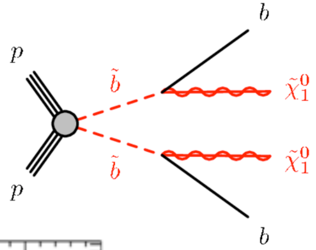
No excess observed



CMS-PAS-SUS-17-001

Search for bottom squarks

- Search for two b-jets, no leptons, and missing transverse energy
- Example for discriminating variable: contransverse mass m_{CT}

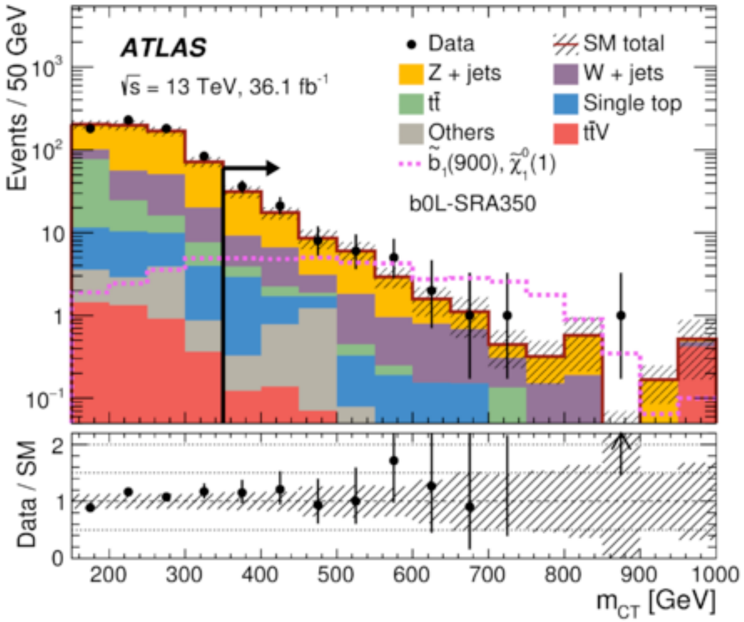


$$m_{\mathrm{CT}}^2(v_1,\ v_2) = [E_{\mathrm{T}}(v_1) + E_{\mathrm{T}}(v_2)]^2 - [\mathbf{p}_{\mathrm{T}}(v_1) - \mathbf{p}_{\mathrm{T}}(v_2)]^2$$

with endpoint at

$$m_{\mathrm{CT}}^{\max} = (m_i^2 - m_X^2)/m_i$$

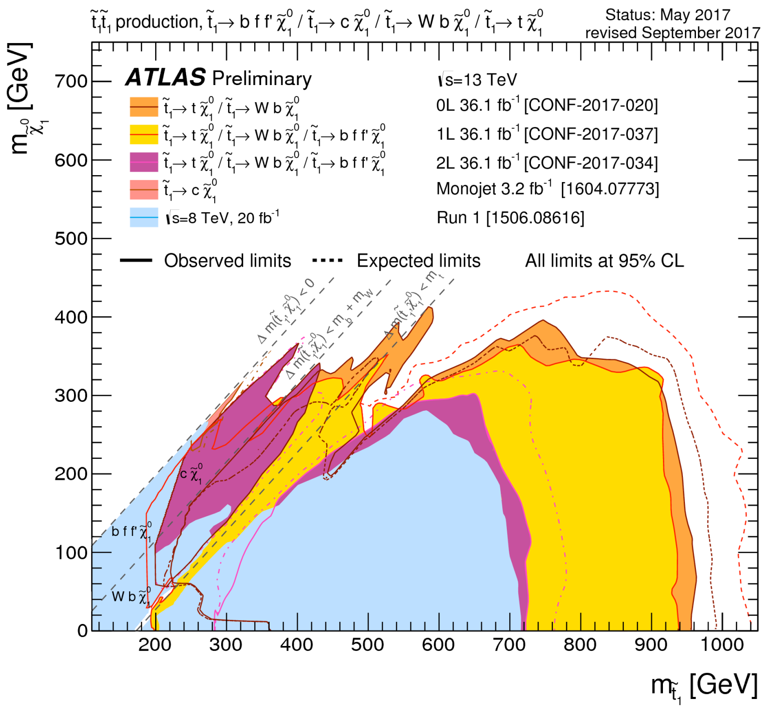
(=135 GeV for $t\bar{t}$)

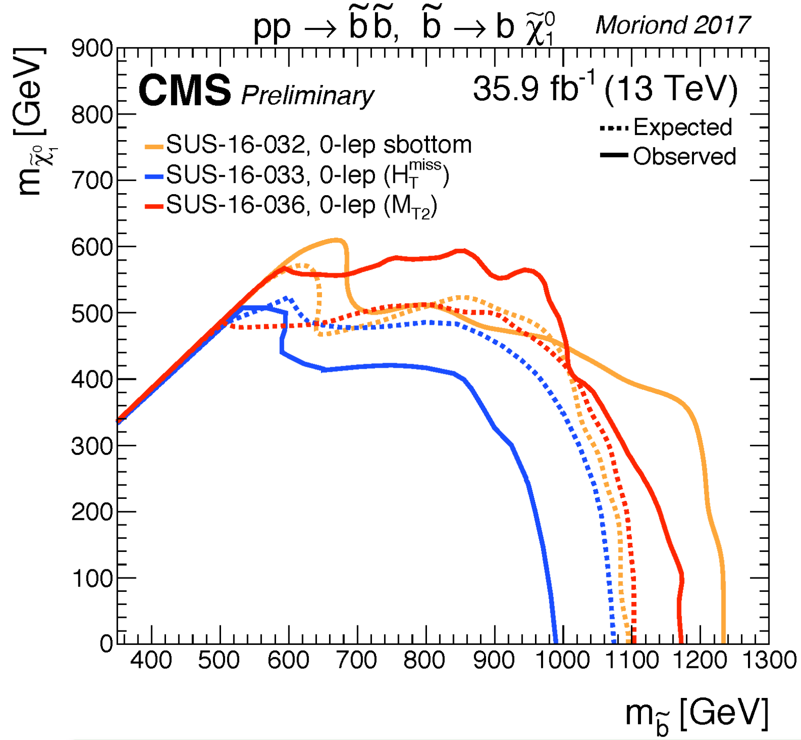


arXiv:1708.09266

No excess observed

Results of third-generation searches



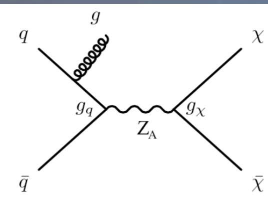


Top squarks excluded < 950 GeV

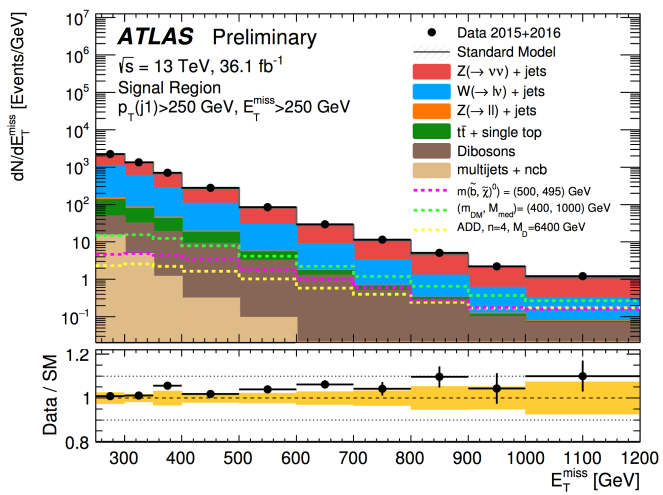
Bottom squarks excluded <1.2 TeV

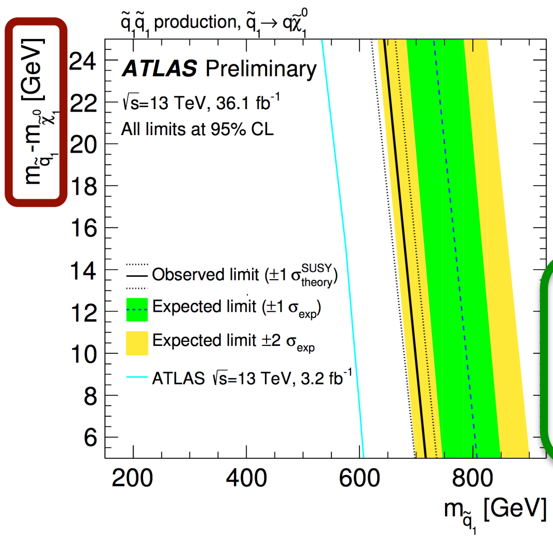
Monojet searches

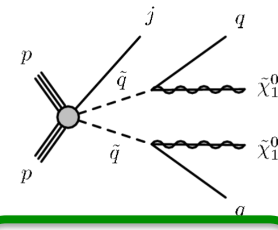
- Targeting all models where final state particles are soft or invisible
  - Dark matter production
  - Squark searches with small mass difference between squark and LSP
- Event selection: require at least one jet with p_T > 250 GeV and 0 leptons
- Main discriminating variable: E_T^{miss}



ATLAS-CONF-2017-060



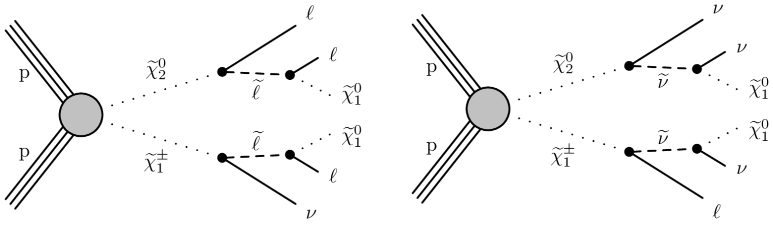




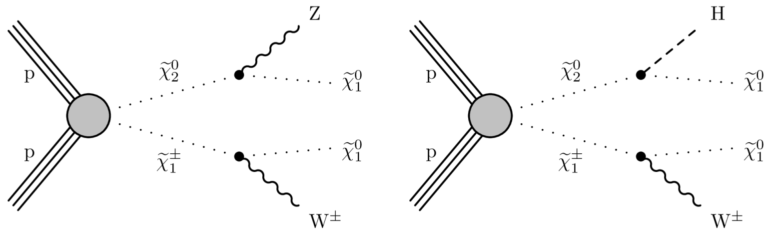
Exclude squarks < 700 GeV for small mass diff. to LSP

Searches for electroweak production

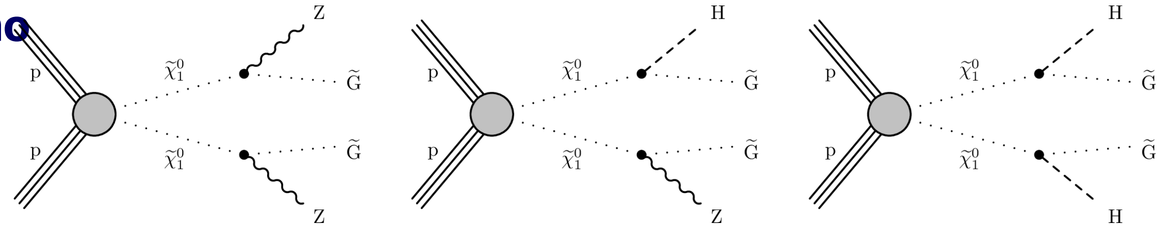
- **Chargino-neutralino** production assuming decay through **sleptons**



- **Chargino-neutralino** production assuming mass-degenerate Winos, decay includes **W, Z or H**

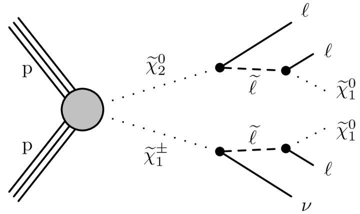


- **Neutralino-neutralino** (assuming Higgsino-like neutralinos) production in GMSB (higher cross section than Winos)

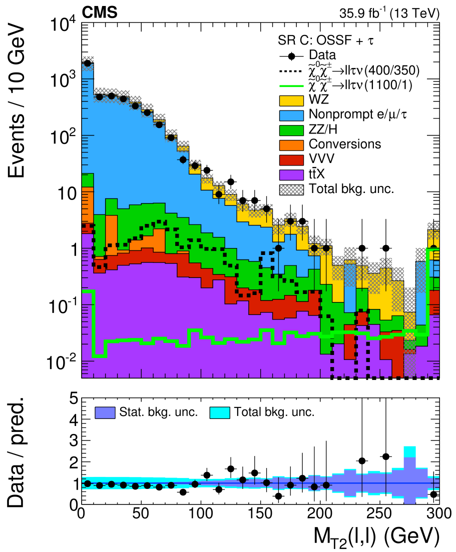


Electroweak production including sleptons

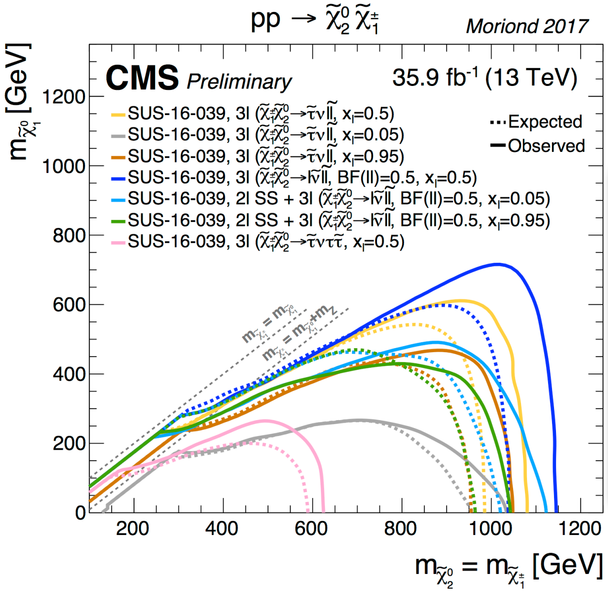
- Assume light slepton masses and require either
  - 2 same-sign leptons
  - 3 leptons (with or without hadronic tau)
  - ≥4 leptons (with or without hadronic tau)



arXiv:1709.05406



No excess observed

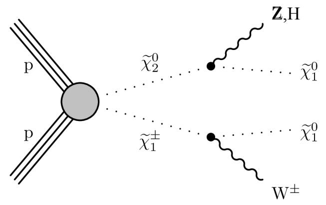


Exclude $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0$ below 600 GeV (decay through τ) and 1150 GeV (flavor symm. decay and large mass splitting)

Electroweak production with decay to bosons

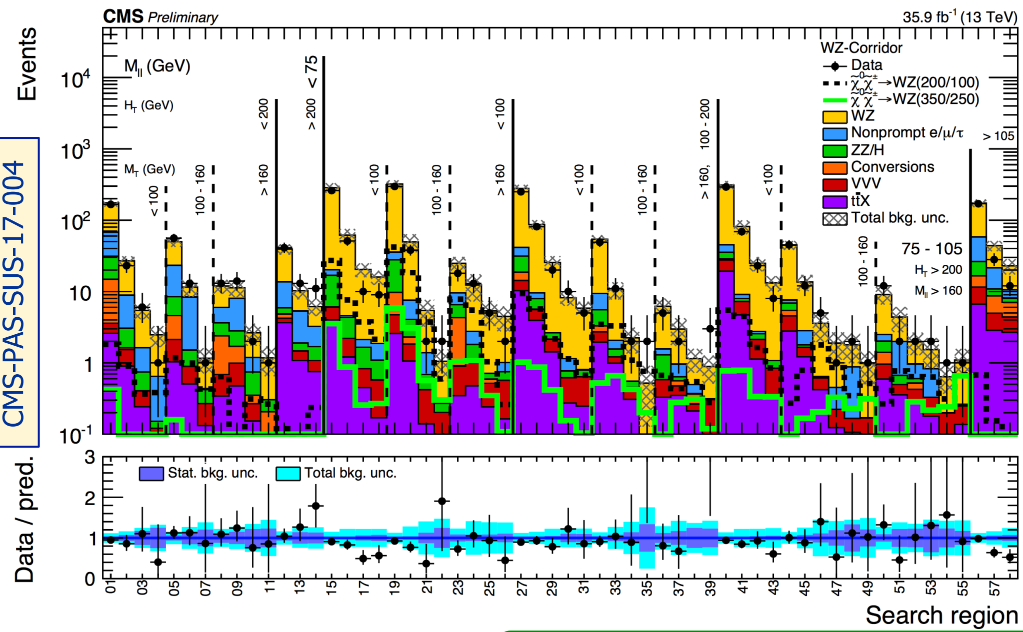
- Several analyses targeting the **different signatures (for decays including Z or H)**
- Signal regions in bins of M_{ll}, H_T, M_T

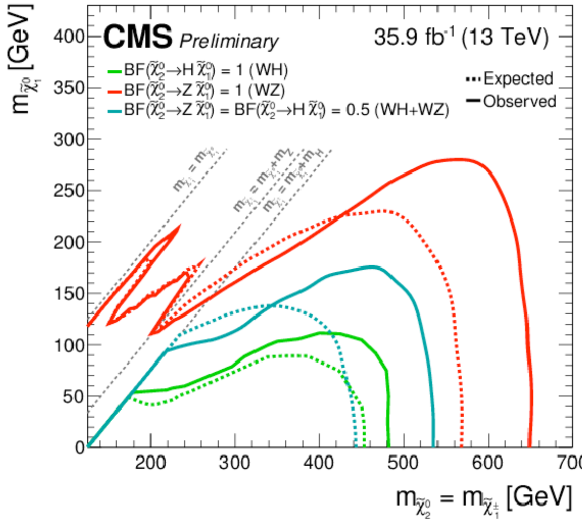
Search	Signal topology WZ	WH	ZZ	ZH	HH
1ℓ 2b		✓			
4b					✓
2ℓ on-Z	✓		✓	✓	
2ℓ soft	✓				
2ℓ SS, $\geq 3\ell$	✓	✓	✓	✓	✓
$H(\gamma\gamma)$		✓		✓	✓



$pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^\pm$

CMS-PAS-SUS-17-004



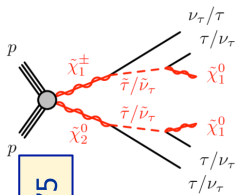


No excess observed

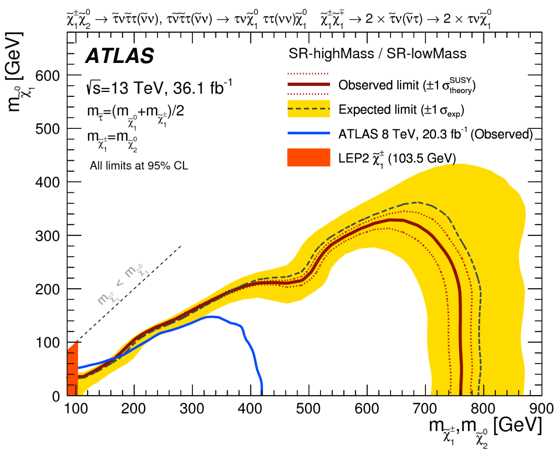
Exclude $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0$ below 480/540/650 GeV

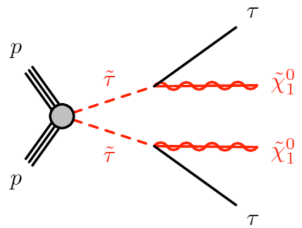
Slepton production

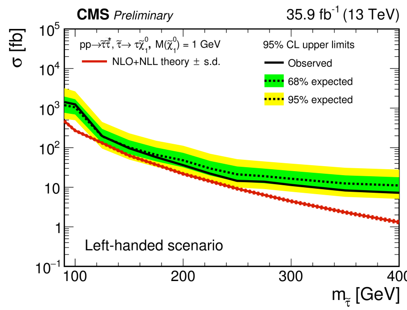
- Searches for direct $\tilde{\tau}$ production suffer from low cross section
- Search for $\tilde{\tau}$ also in decays of neutralinos and charginos

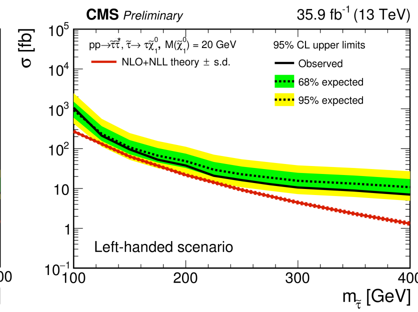


arXiv:1708.07875









CMS-PAS-SUS-17-003

Exclude $\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_2^{0}$ below 750 GeV

Need more data for direct $\tilde{\tau}$ production

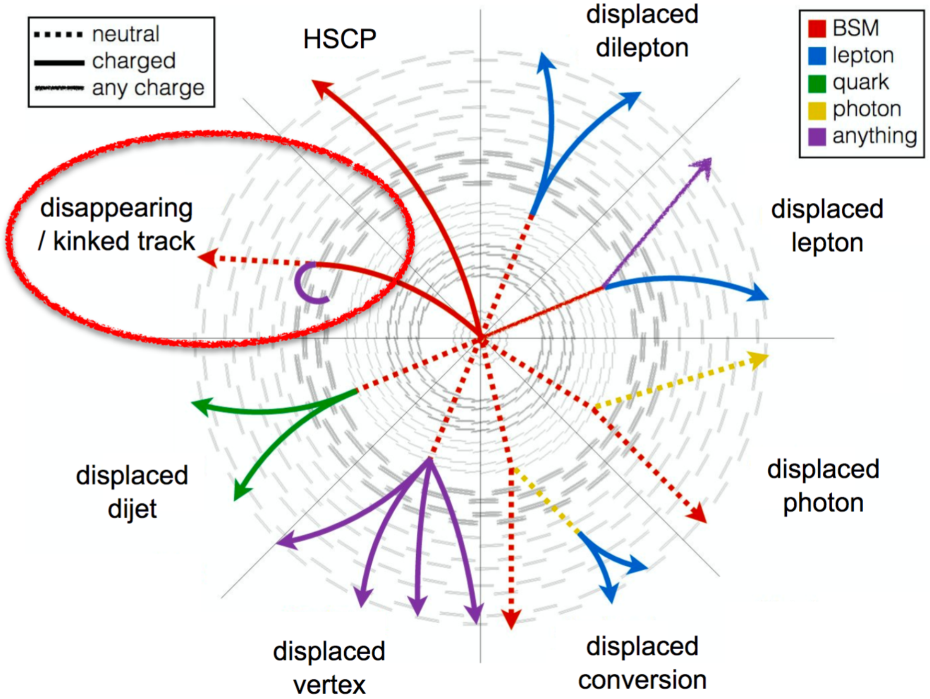
SUSY not yet discovered, but...

SUSY might be hiding somewhere else, so we check also other scenarios:

- decays to long-lived particles
- *R*-parity violating scenarios

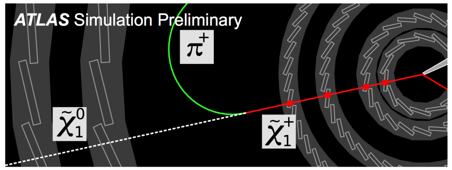
Searches for long-lived particles

- Many BSM models suggest long-lived particles, leading to different topologies

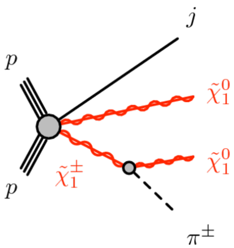


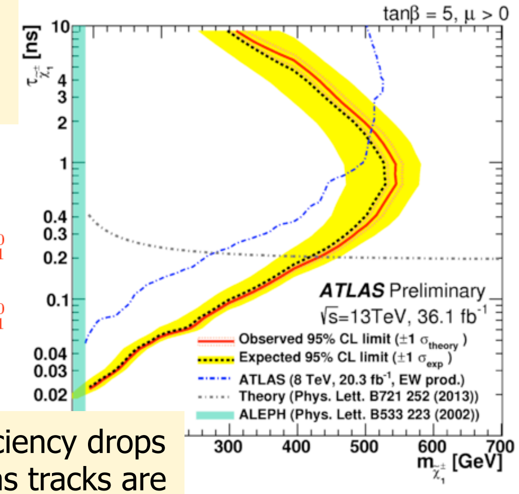
Search for disappearing tracks

- MSSM scenarios with **Wino LSP:** $\chi_1^\pm$ and χ_1^0 are mass-degenerate if Higgsino is decoupled
  → $\chi_1^\pm$ has longer lifetimes leading to disappearing track when decaying to χ_1^0 and $\pi^\pm$

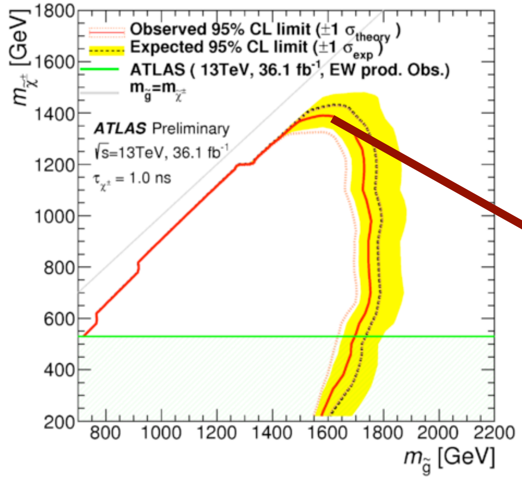


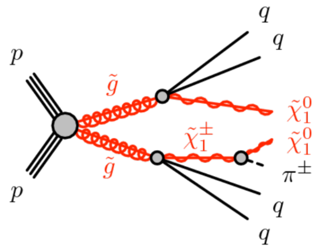
Eff. drops as tracks are too long

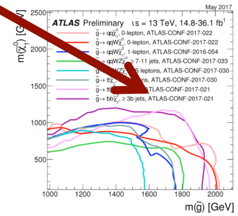




Efficiency drops as tracks are too short



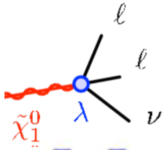


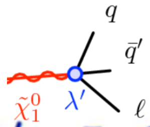


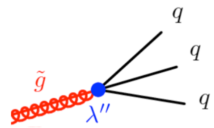
Gluino search more sensitive in compressed region than prompt searches

R-Parity violating models

- Proton decay only forbids simultaneous violation of lepton and baryon number… but not one or the other:







$$W = W_{MSSM} + \underbrace{\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k}_{\text{Lepton Number Violation (LFV)}} + \kappa_i L_i H_u + \underbrace{\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k}_{\text{Baryon Number Violation (BNV)}}$$

- Add 48 new Yukawa couplings and 96 complex parameters
- LSP can decay

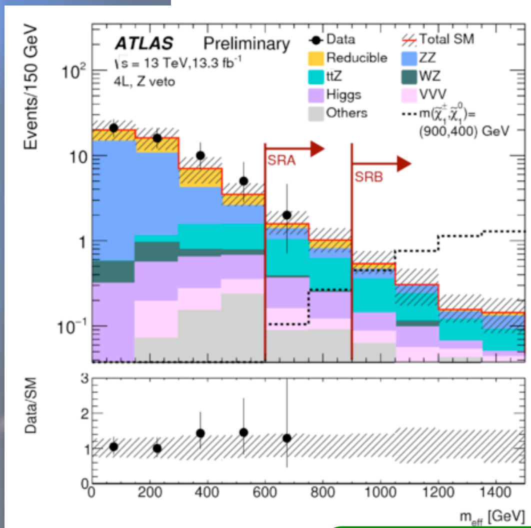
→ **Considerable change in the final states!**

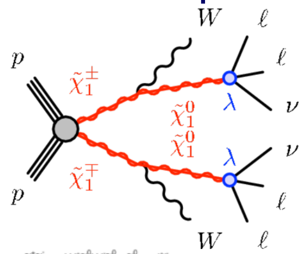
→ **Background generally lower (no LFV nor BNV in SM, despite having no E_T^{miss}) than in RPC**

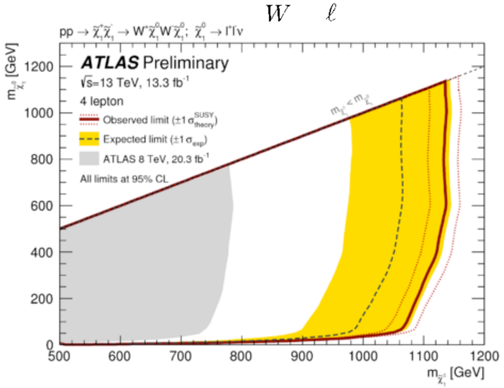
Lepton number violation (λ≠0 or λ’ ≠0)

- Search for model with lepton number violation in events with four leptons

ATLAS-CONF-2016-075

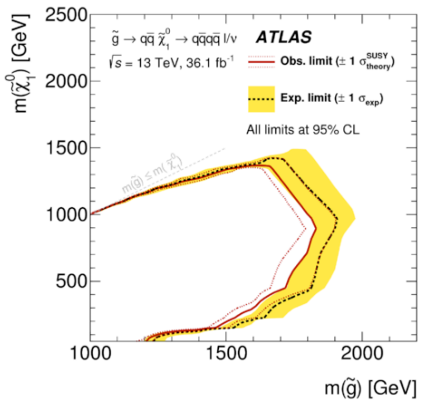




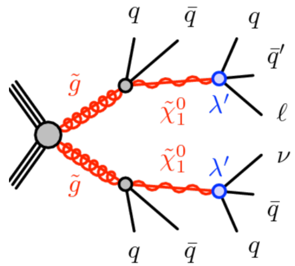


Exclude chargino and neutralino masses <1.1 TeV

- Search for lepton number violation in LSP decays to quarks and leptons in gluino-gluino production
- Require 1 lepton and multiple jets



JHEP 09 (2017) 88

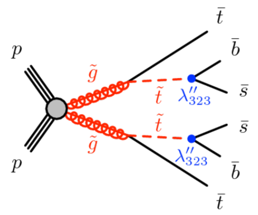


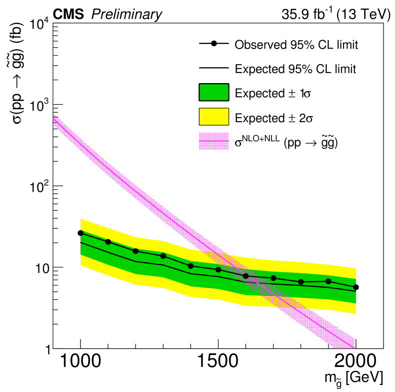
Exclude gluino masses <1.8 TeV

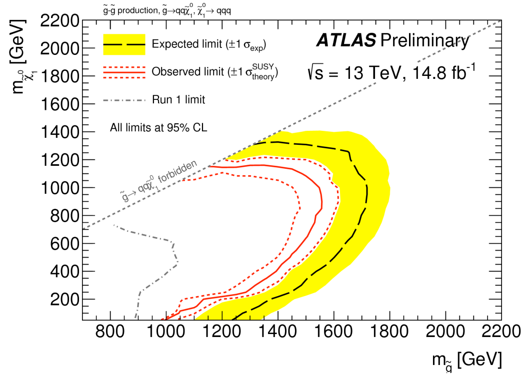
Baryon number violation ($\lambda''\neq 0$)

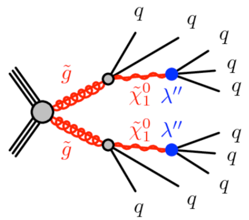
- Several scenarios of baryon number violation tackled with final state containing multiple jets (+1 lepton in case of decays to top quarks)

CMS-PAS-SUS-16-040



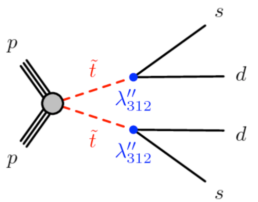


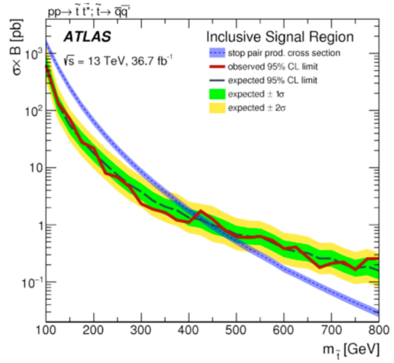


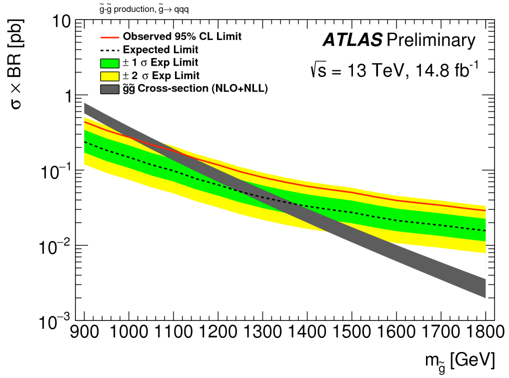


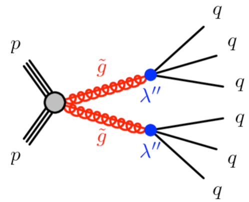
ATLAS−CONF−2016−057

arXiv:1710.07171



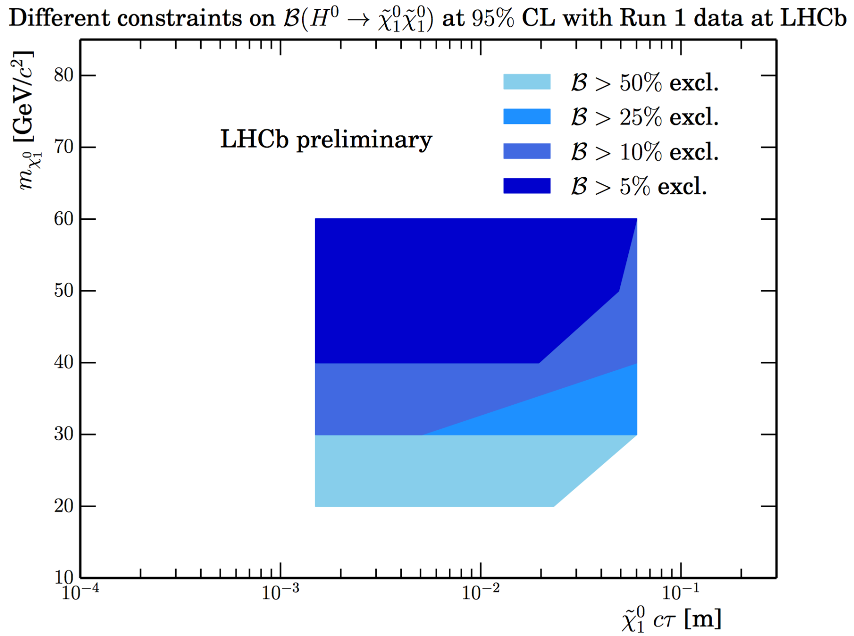


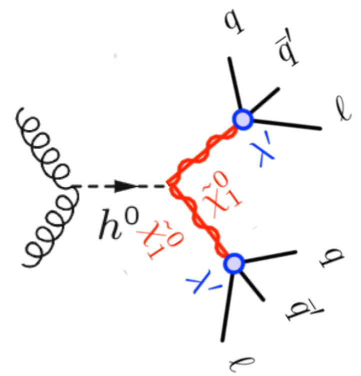




Long-lived particles with P_R violating decay

- Search for neutralinos decaying to muon + jets (λ' ≠0) with different production models with RPV decay
  - Example: Interpretation with Higgs as mediator





Eur. Phys. J. C (2017) 77

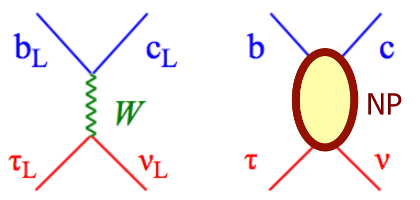
Exclude
Br (H→$\tilde{\chi}\tilde{\chi}$)>5% for
$\tilde{\chi}$ masses of 40-60 GeV
for decay lenghts from
mm up to ½ m

SUSY not yet discovered

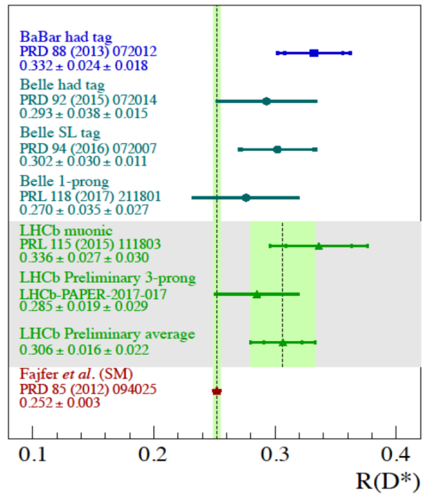
- SUSY might be hiding somewhere else, so we check also other scenarios:
  - indirect hints

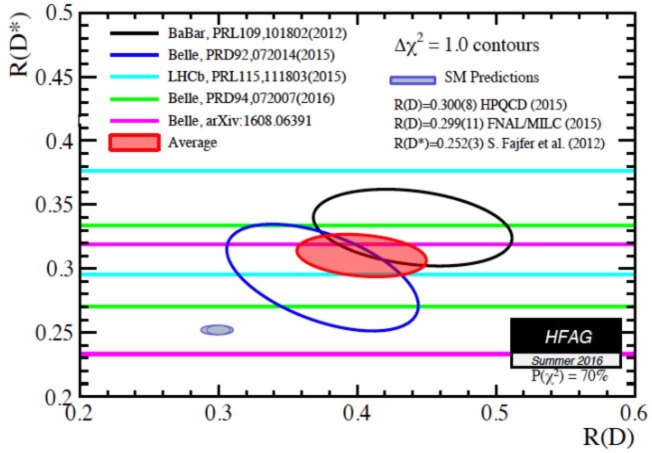
Indirect searches: lepton flavor universality (cc)

- Flavor asymmetry in charged currents: B meson decays into tau + neutrino
- Measure ratio of decays to taus compared to decay to electron and muon:



$$R(X) = \frac{\Gamma(B \to X\tau\bar{\nu})}{\Gamma(B \to X\ell\bar{\nu})}$$





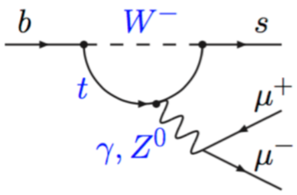
- Consistent result from 3 different experiments (+small theor. uncertainty)
- Combination of D and D* results reach 3.9σ excess over SM

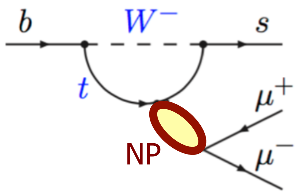
Hint for charged Higgs boson??

Indirect searches: lepton flavor universality (NC)

- Example: $B \rightarrow K\ (K^*) + ll$: mediated by the "clean" Z-penguin diagrams and by the "less clean" photon-penguin diagrams
- In both cases rate for decays to electrons expected to be the same as for decays to muons (with slight difference at low q^2 due to phase-space effects)

arXiv:1705.05802

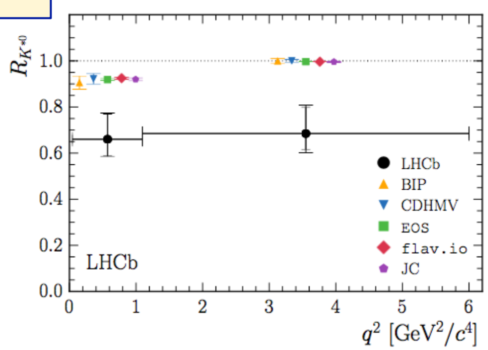


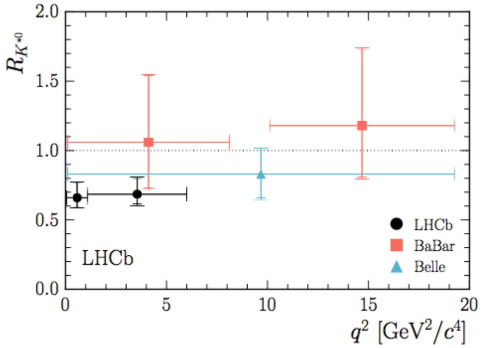


$$\left.\frac{\int d\Gamma(B \rightarrow K\ \mu\mu)}{\int d\Gamma(B \rightarrow K\ ee)}\right|_{SM} = \left.\frac{\int d\Gamma(B \rightarrow K^*\ \mu\mu)}{\int d\Gamma(B \rightarrow K^*\ ee)}\right|_{SM} = 1$$

In practice, measure double ratio:

$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi\,(\to \mu^+\mu^-))} \bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi\,(\to e^+e^-))}$$



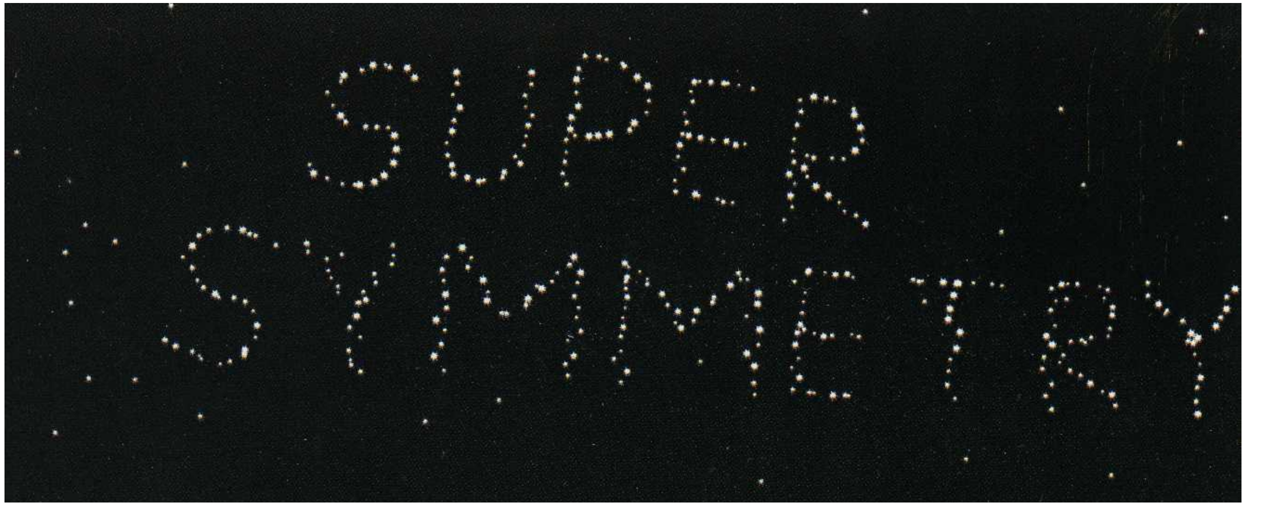


Less decays to muons (2.4–2.5σ) than expected!

Hint for lepton flavor violating SUSY (or Z′, leptoquarks,...)?

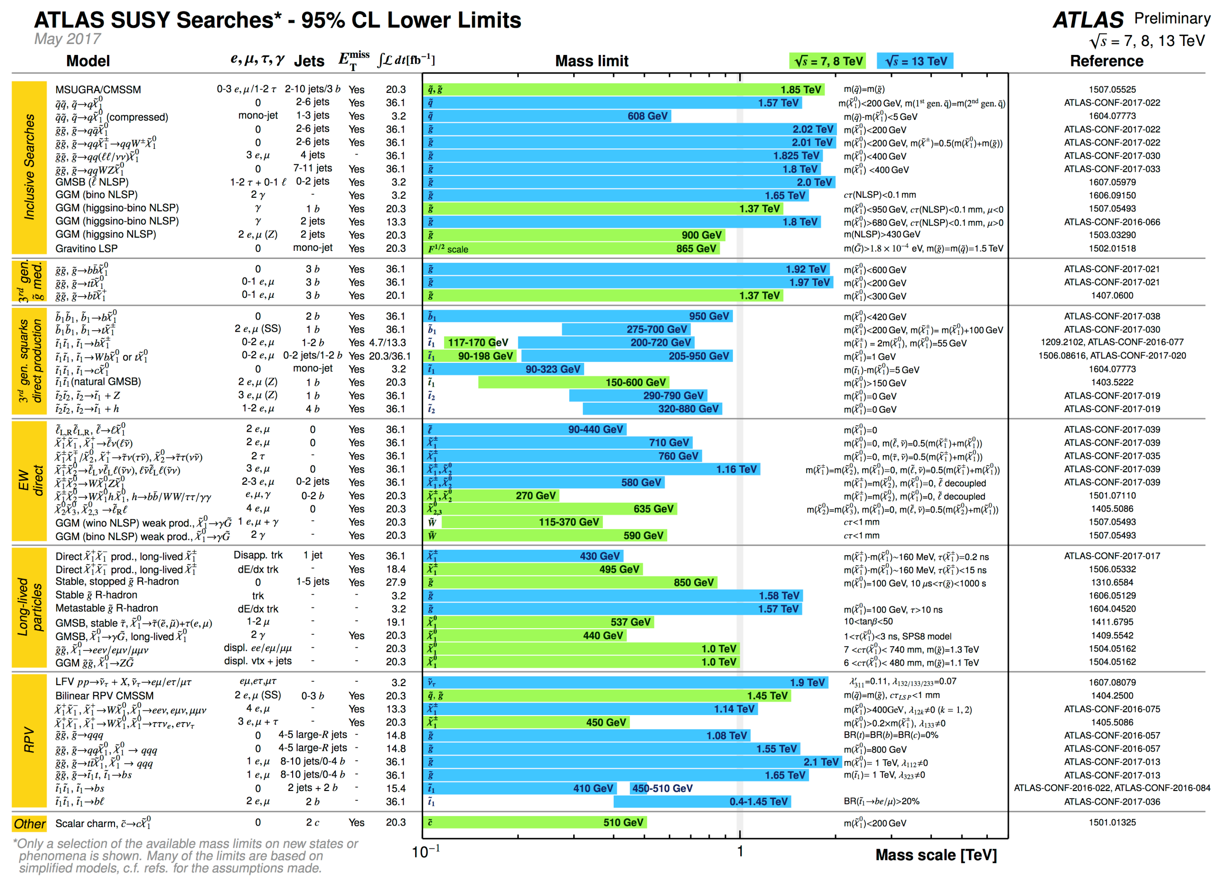
Conclusion and outlook

- Many direct searches for SUSY performed – no smoking gun so far
- Models with low cross section profit from increasing luminosity
- Standard plain-vanilla searches would profit more from accelerators with higher energy
- Indirect searches show consistently disagreement to SM prediction – looking forward to results with higher statistics!

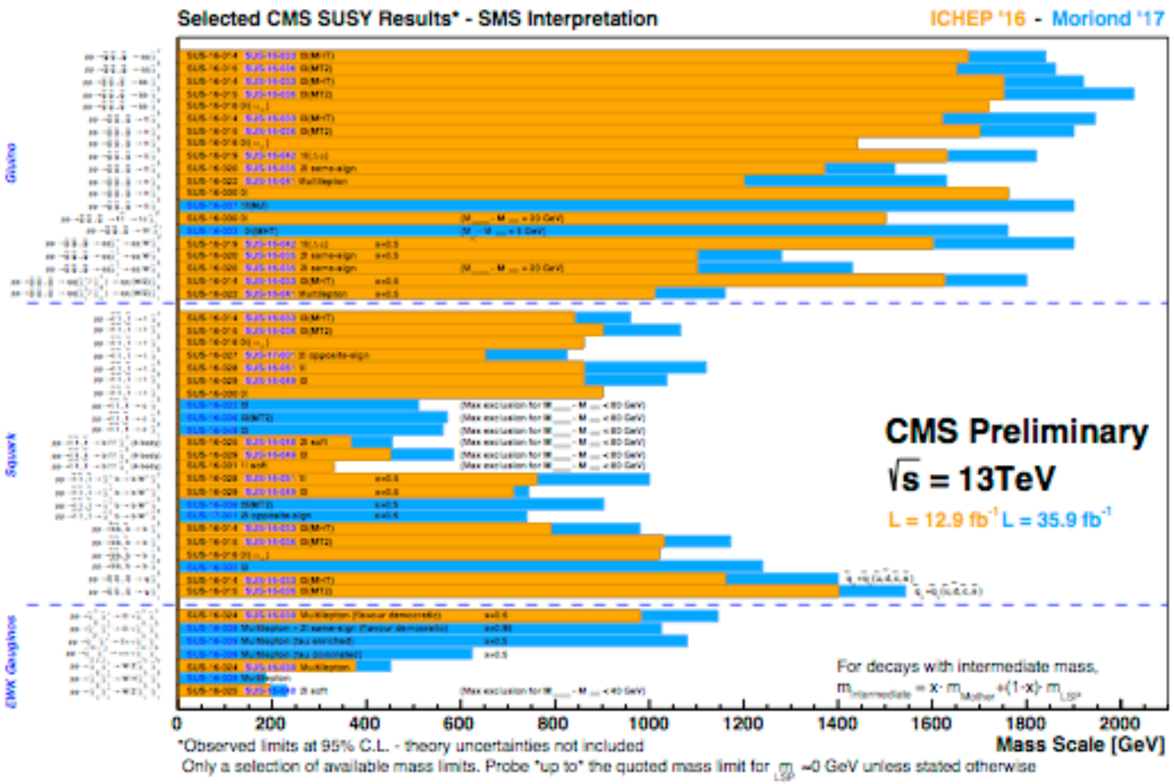


BACKUP – leaving no stone unturned...

Summary ATLAS



Summary CMS



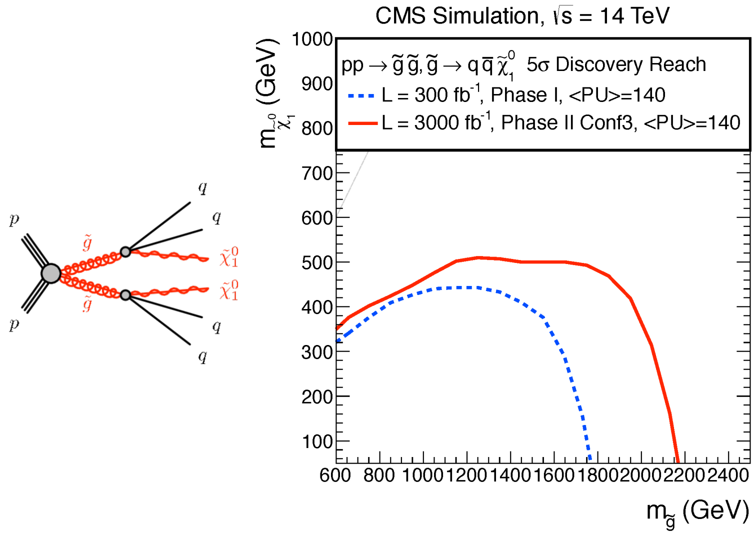
Selected CMS SUSY Results* - SMS Interpretation
ICHEP '16 - Moriond '17
Gluino
Squark
EWK Gauginos
CMS Preliminary
√s = 13TeV
L = 12.9 fb⁻¹ L = 35.9 fb⁻¹
For decays with intermediate mass,
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Mass Scale [GeV]
*Observed limits at 95% C.L. - theory uncertainties not included
Only a selection of available mass limits. Probe *up to* the quoted mass limit for m_LSP ~0 GeV unless stated otherwise

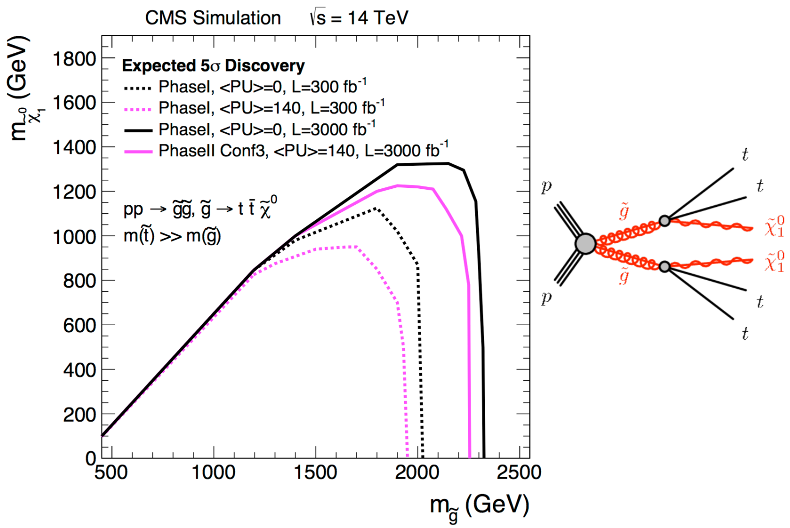
SUSY models and signatures

- The SUSY parameters determines the signature in **simplified models**
  - **R-parity conserving (RPC) + large mass difference** between SUSY particles
    → Large missing transverse energy, high activity in the detector (at least if produced in strong production)
  - **RPC + small mass difference** ('compressed spectra')
    → Events often difficult to distinguish from SM background
  - **R-parity violating (RPV)**, lightest SUSY particle (LSP) decays to SM particles
    → No missing transverse energy, but possibly several leptons

  - **Nature of LSP** can drive final state as well:
    - Gravity mediated SUSY breaking: Mostly neutralino LSP
    - Gauge mediated SUSY breaking: Gravitino LSP – photons, Z or W in final state

HL-LHC Projections for gluinos

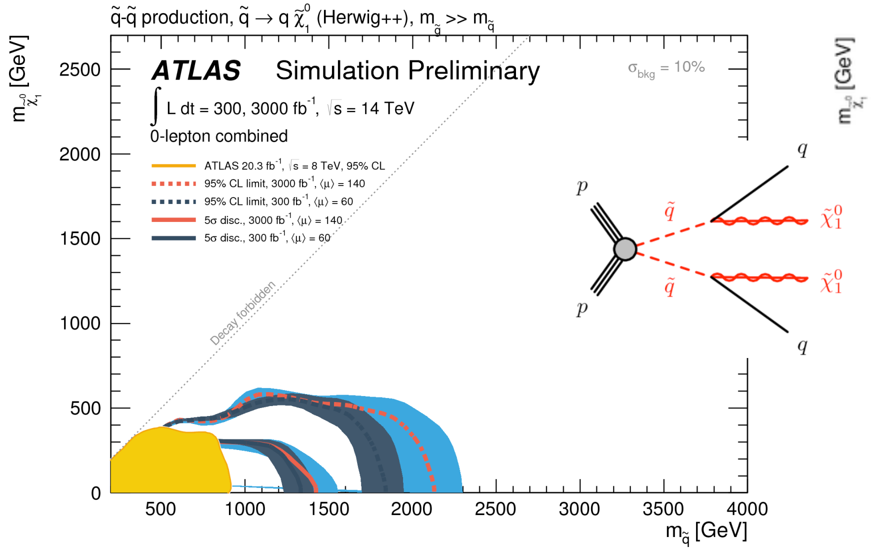


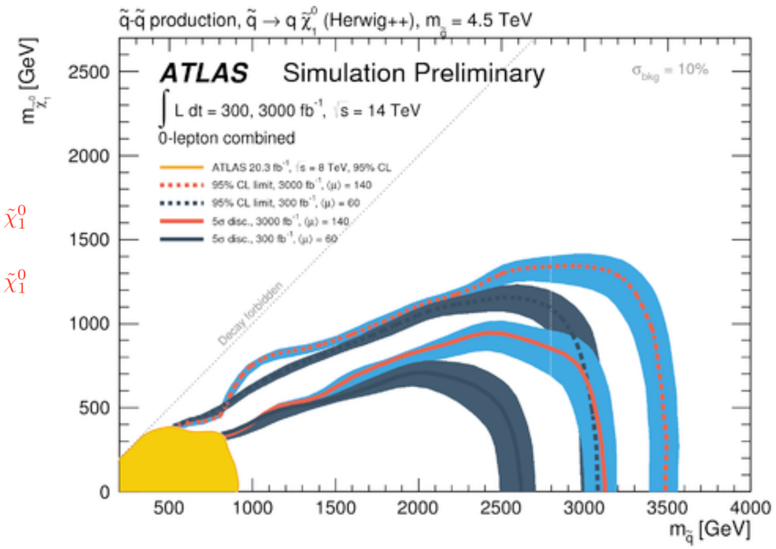


CMS-PAS-FTR-13-014

5σ discovery reach extended up to 2.2 TeV,
up to 2.3 TeV for decays through top quarks

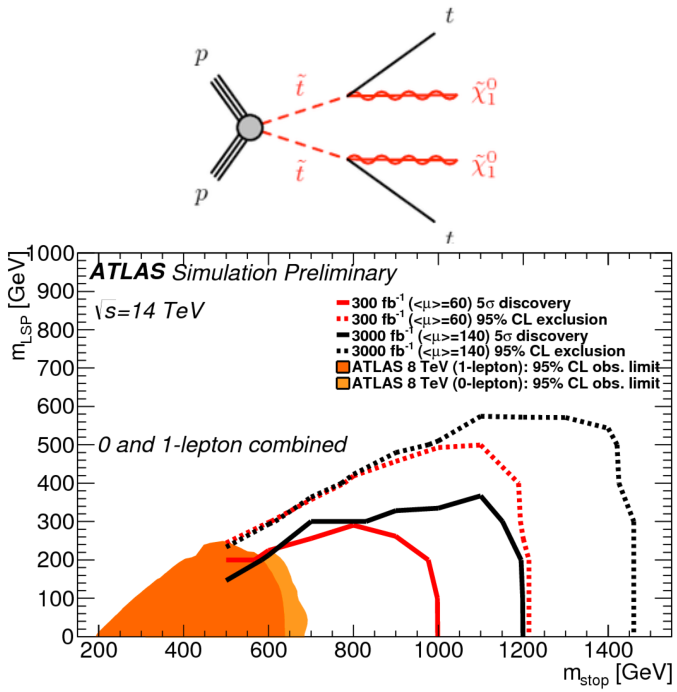
HL-LHC Projections for squarks

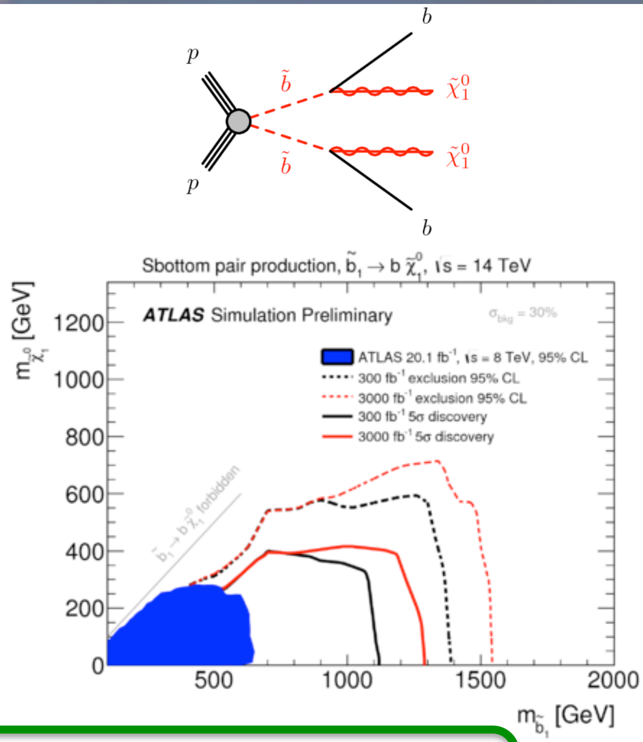




5σ (2σ) discovery reach extended up to 1.4 (1.9) TeV, up to 2.6 (3) TeV for decays if m_{gluino}=4.5 TeV

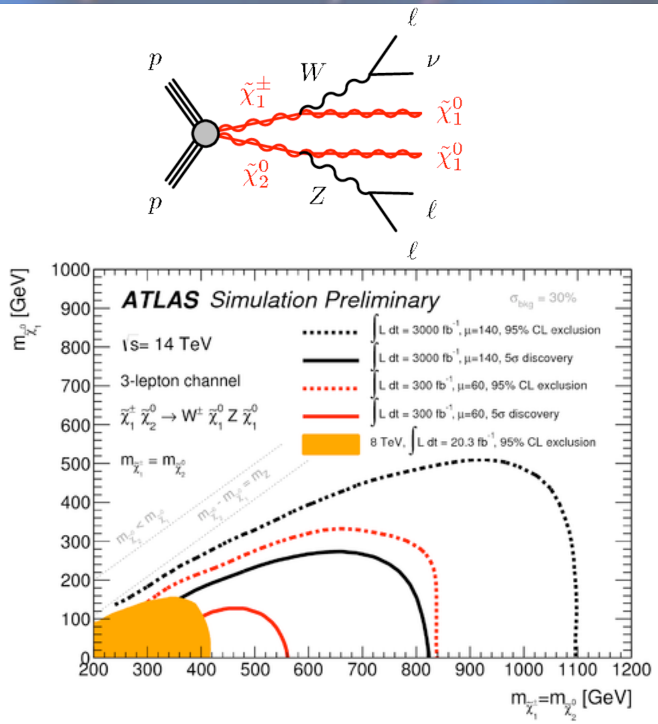
HL-LHC projections for 3rd gen. squarks

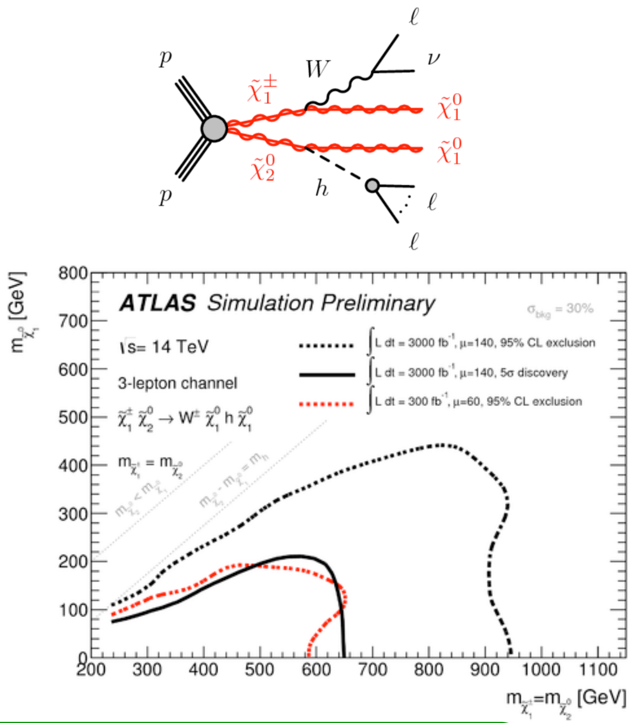




5σ (2σ) discovery reach up to 1.2 (1.5) TeV for $\tilde{t}$, up to 1.3 (1.5) TeV for $\tilde{b}$ production

Projections for electroweak searches

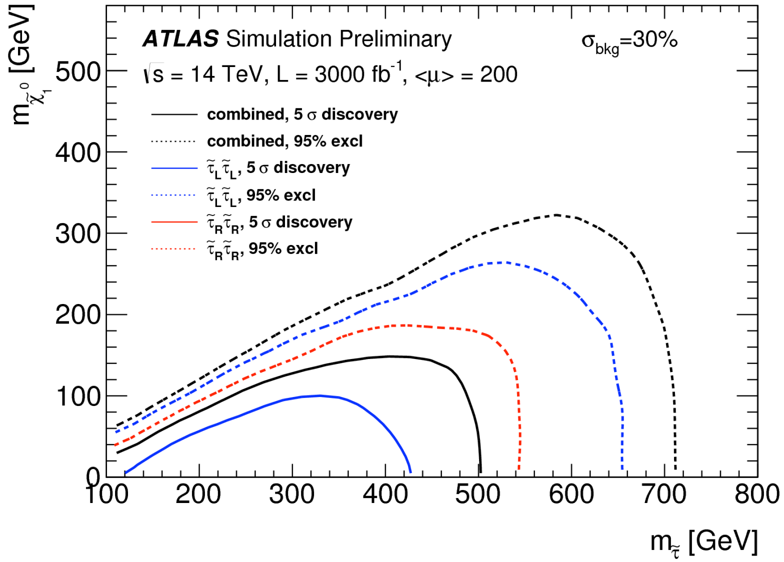




5σ discovery reach extended to 800 GeV in WZ channel, 650 GeV for WH decays

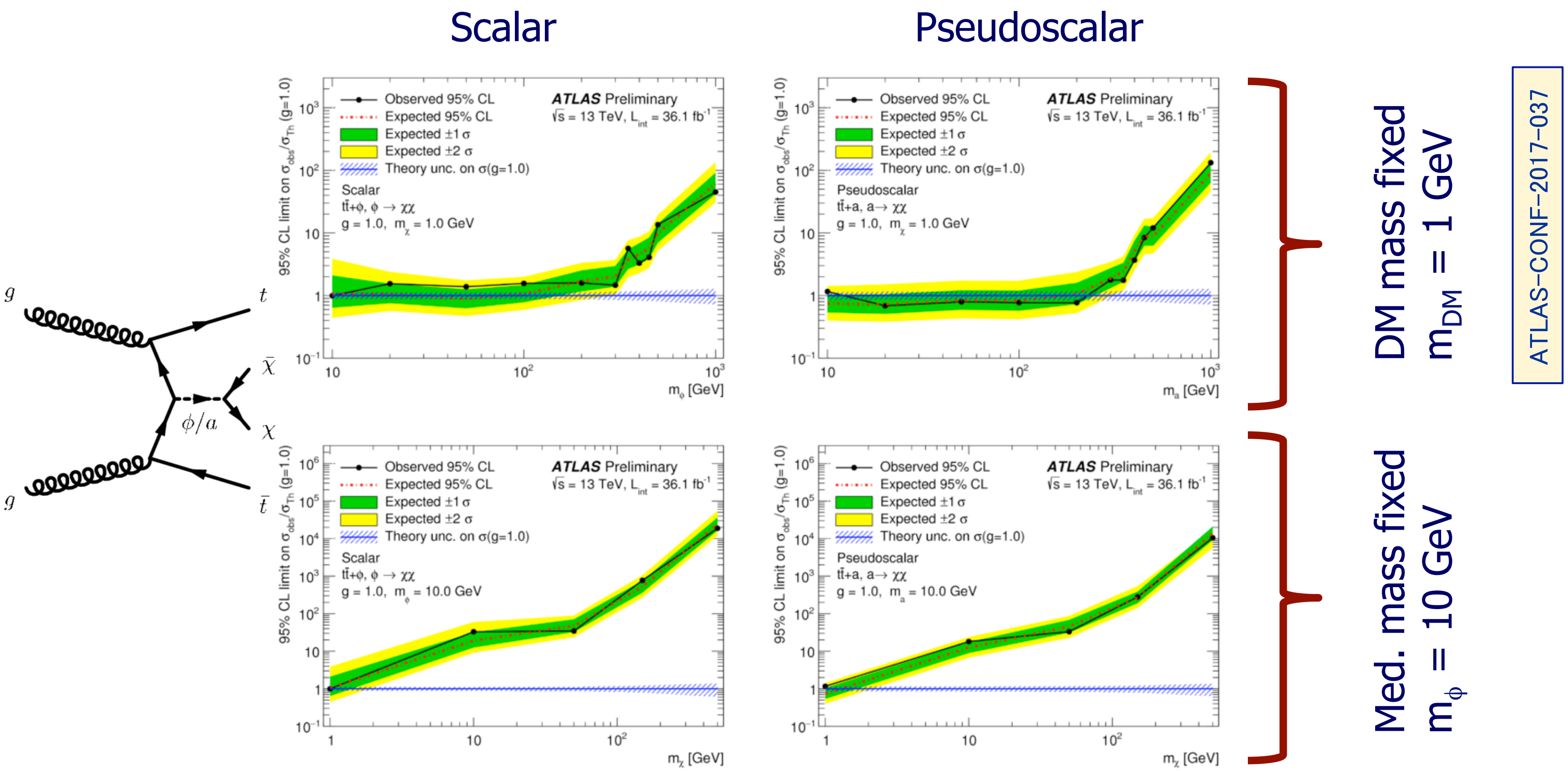
HL-LHC projections for $\tilde{\tau}$ search

Sensitivity depends on model assumption (right-handed $\tilde{\tau}$ are challenging)



5σ (2σ) discovery reach up to 700 (500) GeV for combined scenario, for right-handed $\tilde{\tau}$ only 2σ exclusion possible <400 GeV

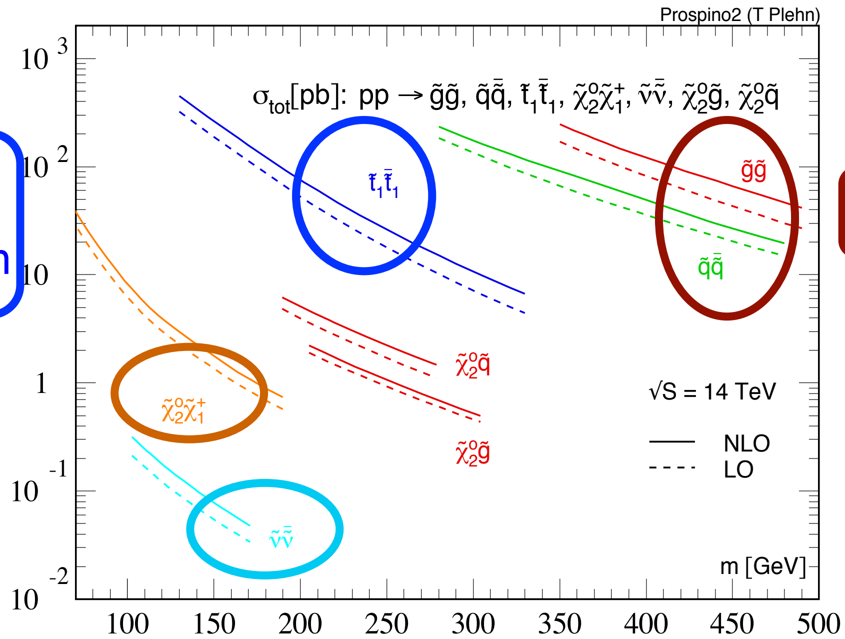
Dark Matter interpretation of stop search



SUSY Cross sections

third generation interesting due to loop cancellation

electroweak production decoupled from possibly high-mass g̃ and s̃



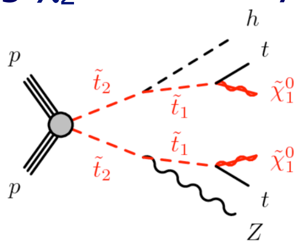
plain vanilla searches

High interest in higgsinos due to tree-level connection to Higgs mass

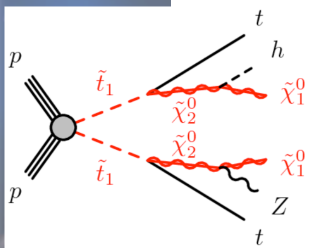
slepton production with lowest cross section

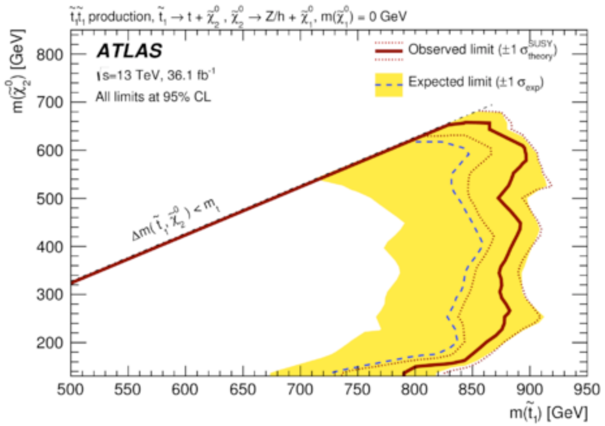
Other stop searches

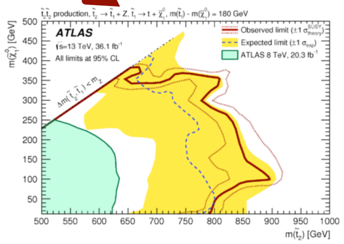
- Searches reach out to more complex final states including $\tilde{\chi}_2^0$ and decays to Z or Higgs
- $\tilde{t}_2$ interesting if $m(\tilde{t}_1) = m(t)$
- Two signal selections:
  - 1 lepton + 4 b-jets (assuming h→bb)
  - 3 leptons + 1 b-jet (assuming Z→ll)

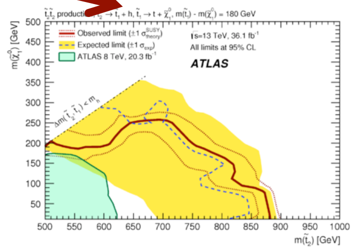


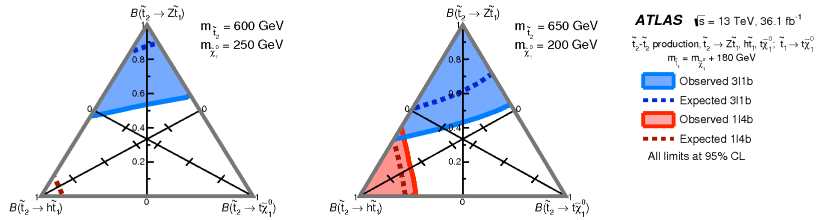
JHEP08(2017)006





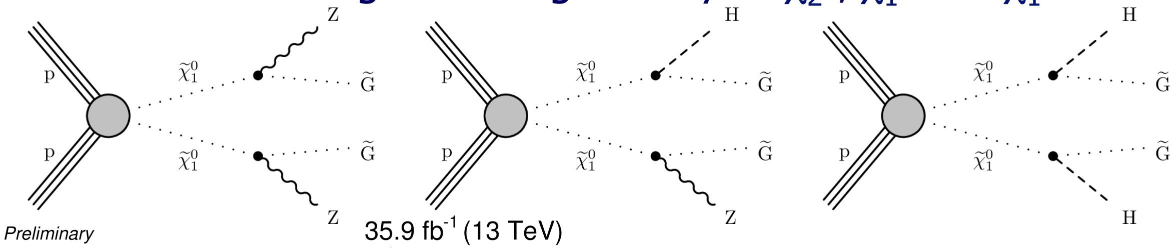


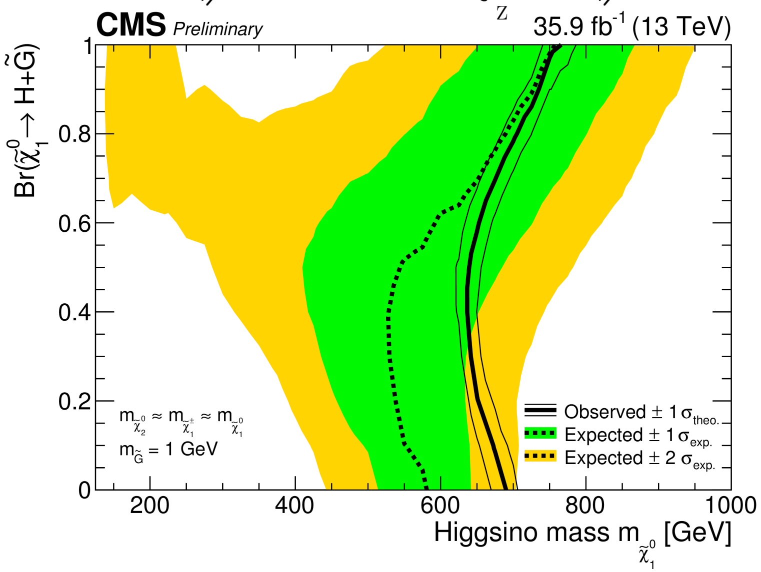




GMSB with Higgsinos

- Neutralino-neutralino production assuming **higgsino-like neutralinos** in GMSB: decays to Z or H assuming mass degeneracy of $\tilde{\chi}_2^0$, $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_1^0$

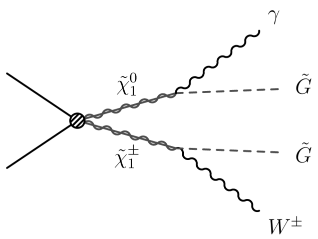


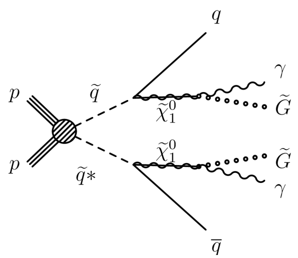


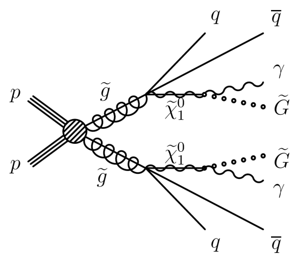
Exclude higgsinos below 600 GeV in GMSB model

GMSB with Bino/Wino-like charginos

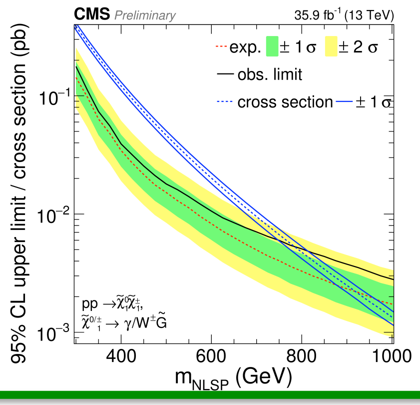
- If lightest charginos and neutralinos are **Bino- or Wino-like**: decays to photons or W bosons and gravitinos

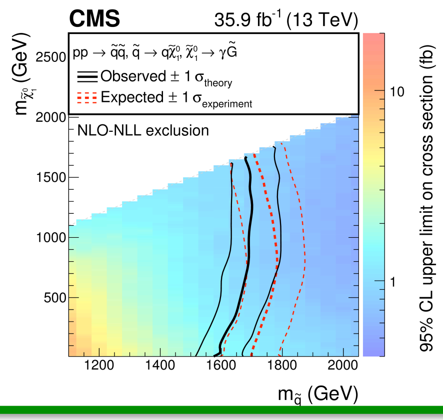


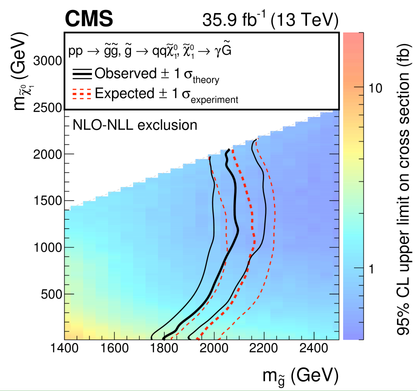




CMS-PAS-SUS-16-046







CMS-PAS-SUS-16-047

Exclude $\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_1^0$ <800 GeV, squarks <1.6 TeV, gluinos < 2 TeV