SUSY searches with the ATLAS detector

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16th HELLENIC SCHOOL AND WORKSHOPS ON ELEMENTARY PARTICLE PHYSICS AND GRAVITY

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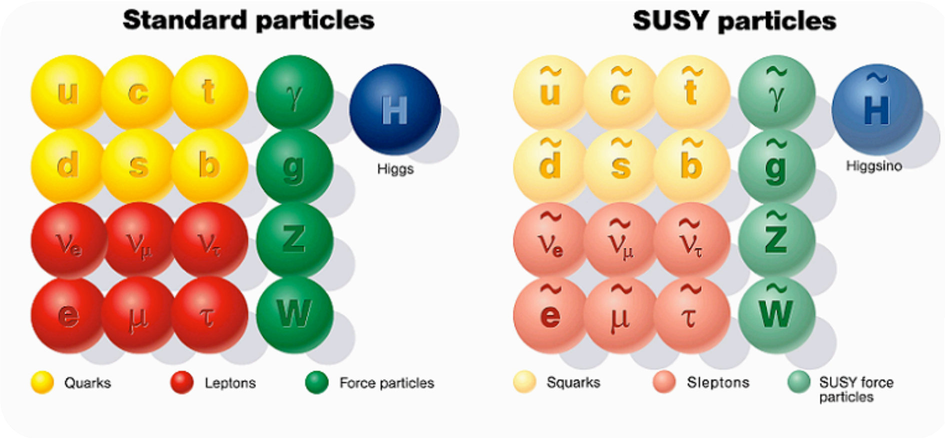
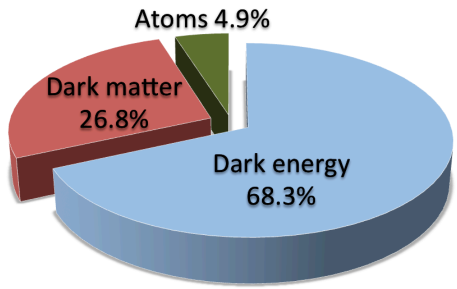
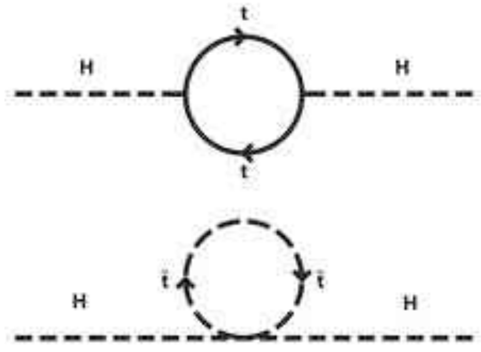
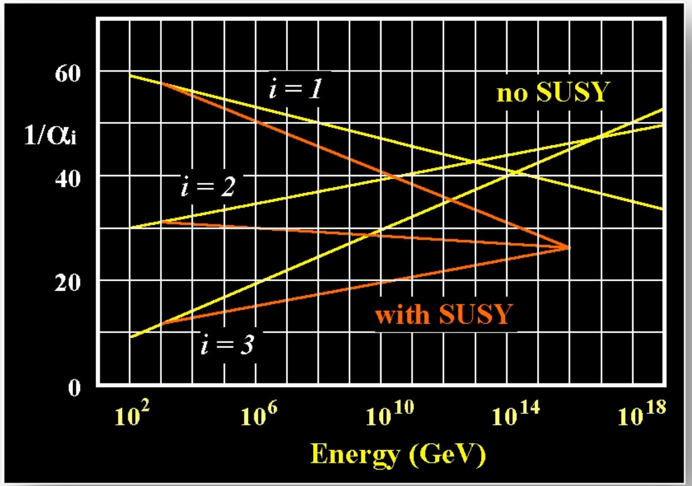
Supersymmetry (SUSY)







- What it is?
  - global symmetry between fermions & bosons
- Why is it attractive?
  - Higgs: predicts a below-135-GeV Higgs scalar
    - may be SM-like
    - completely solves hierarchy problem
  - **unification** of gauge couplings at single scale
  - **dark matter** candidate

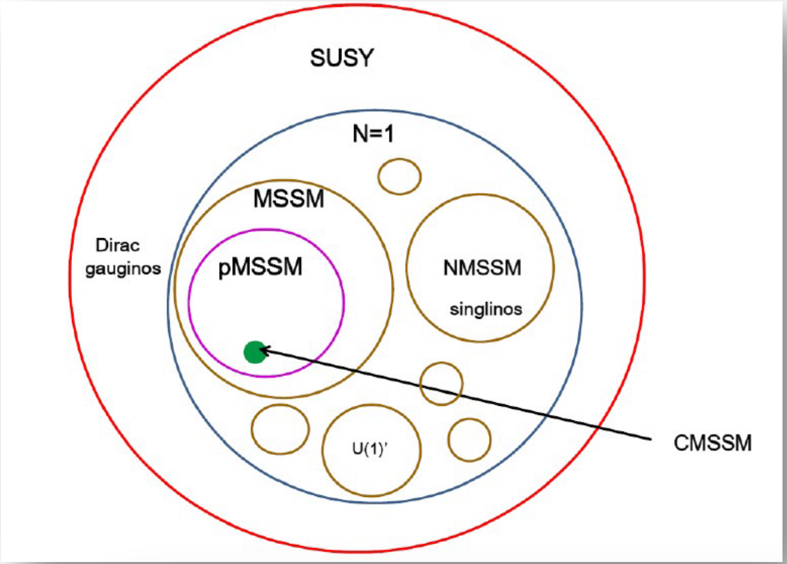


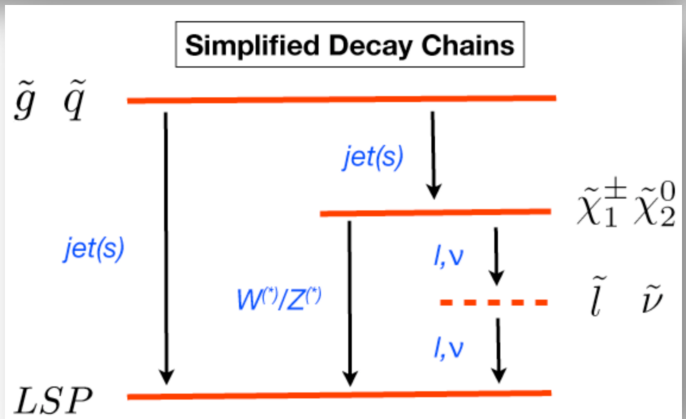
Framework versus model

- Sparticle masses from SUSY breaking not fixed by theory
  ⇒ huge parameter space to explore
  - MSSM: > 100 parameters
  - pMSSM: 19 parameters
  - CMSSM: 5 parameters
- **How to test that at LHC?**

1. Top-down approach
   - SUSY breaking mechanism → different models
   - GUT scale unification → few free parameters
2. Bottom-up approach
   - Phenomenological models
     - fix mass hierarchy and mass scales
     - scan remaining parameters
   - Simplified topologies
     - specific decay chain
     - easy to interpret results in terms of other models

T. Rizzo



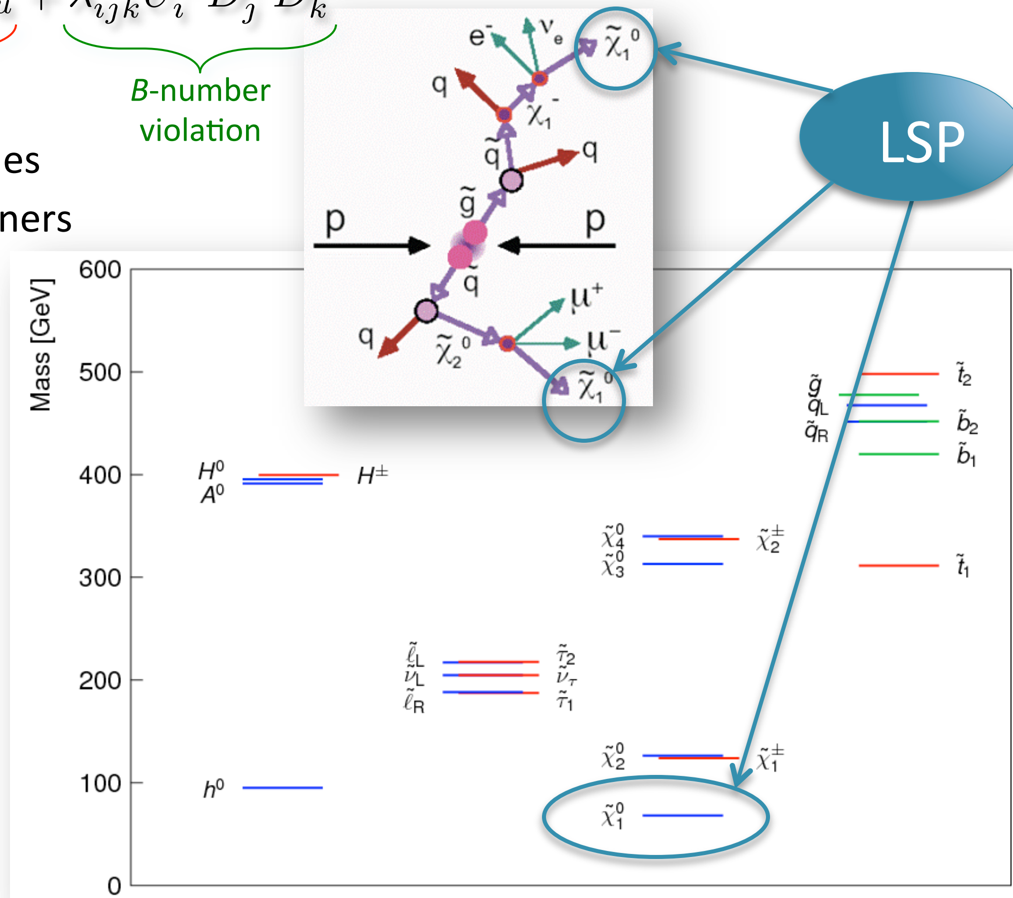


R-parity and the LSP

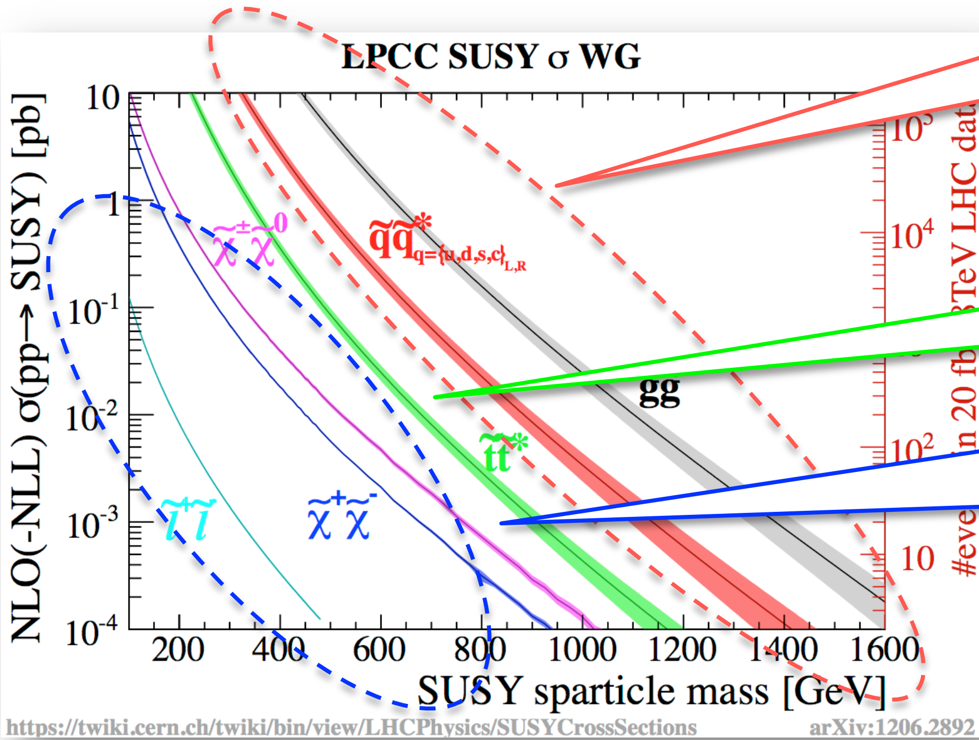
Lightest Supersymmetric Particle (LSP) and R-parity conservation/violation largely define final states of SUSY events

$$W_{\not{R}p} = \underbrace{\lambda_{ijk}\hat{L}_i\hat{L}_j\hat{E}_k^C + \lambda'_{ijk}\hat{L}_i\hat{Q}_j\hat{D}_k^C + \epsilon_i\hat{L}_i\hat{H}_u}_{L\text{-number violation}} + \underbrace{\lambda''_{ijk}\hat{U}_i^C\hat{D}_j^C\hat{D}_k^C}_{B\text{-number violation}}$$

- $R = (-1)^{3(B-L)+2s} \rightarrow R = \begin{cases} +1 \text{ for SM particles} \\ -1 \text{ for superpartners} \end{cases}$
- R-parity conservation hinted but not required by proton stability
- If R-parity conserved
  - stable LSP neutral and colourless
  - in colliders could be detected as "missing energy"(MET)
  - **dark matter candidate**
- In broken R-parity
  - LSP may be charged and/or carry colour
  - **LSP is not stable**



SUSY searches strategy



Strong-production channels
- Copious production at hadron colliders
- MET-based generic channels

Third-generation sparticles
- Naturalness ➜ mass of *O*(<TeV)
- Lighter than other squarks

Leptons/photons

Coloured spartners too heavy

→ direct gaugino/slepton production

→ relevant for **Dark Matter** searches

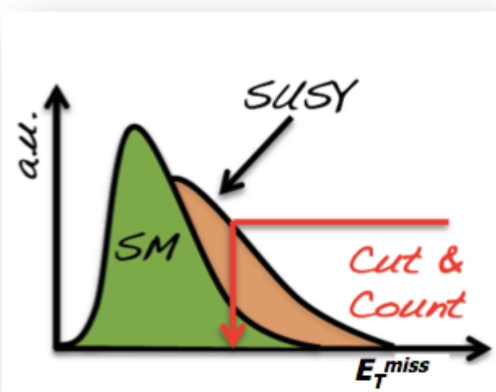
RPC or RPV
- RPV implies more leptons and/or jets and less MET
- RPV prompt or delayed LSP decay

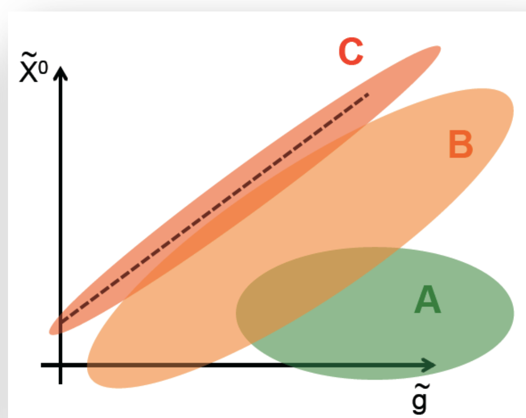
Interpretations on Dark Matter scenarios

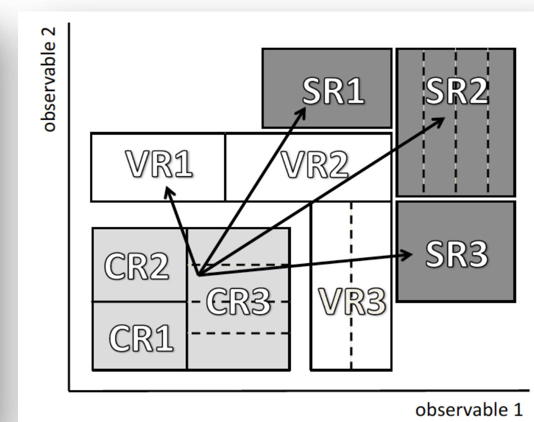
(Meta)stable sparticles
- Suppressed (effective) coupling
- Lack of phase space, e.g. mass degeneracies
- May induce non-trivial signals in detectors

Typical ATLAS SUSY search

- Signal selection targeting specific production/decay mode *(simplified topology)*
- Signal region (**SR**)
    - single-bin optimised for best discovery
    - to cover different mass hierarchies ➔ few SRs for each final state
- Data-driven background estimate
    - irreducible backgrounds estimated using control region (**CR**) data as a constraint and Monte Carlo to extrapolate from CR to SR in likelihood fit
    - reducible background (fake/non isolated leptons, MET from jet mismeasurement) from data
    - only well modelled variable in CR ➔ SR extrapolations
    - validation regions (**VR**) to check assumptions in background estimate and CR ➔ SR variable modelling

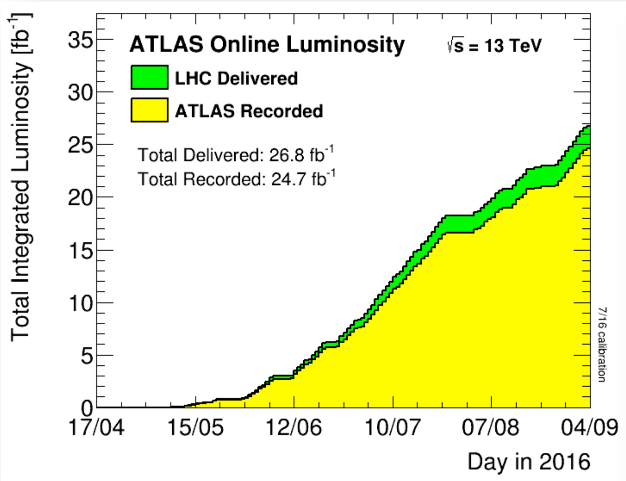


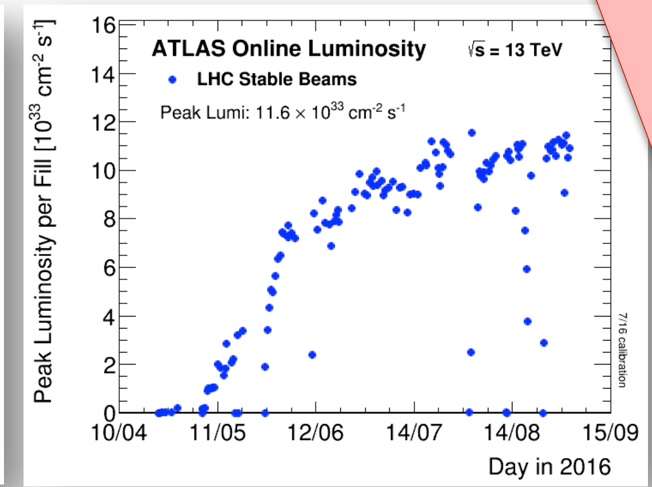




LHC and ATLAS performance

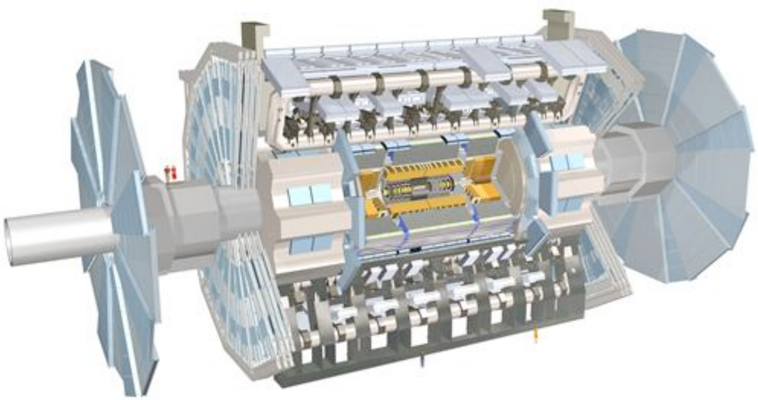
Most results presented here with ~13-18 fb^{-1} at 13 TeV
"NEW" denotes results *not* presented at ICHEP

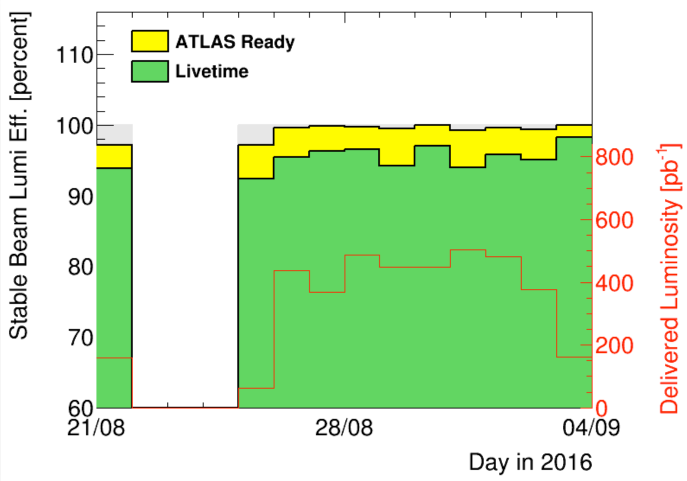




LHC: PHENOMENAL LUMINOSITY

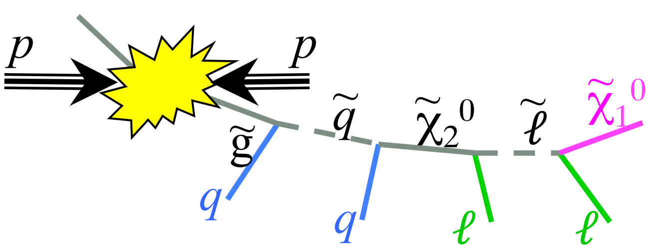
Great performance from ATLAS

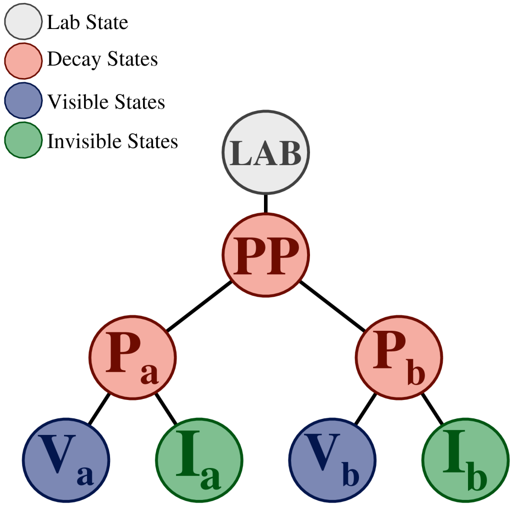




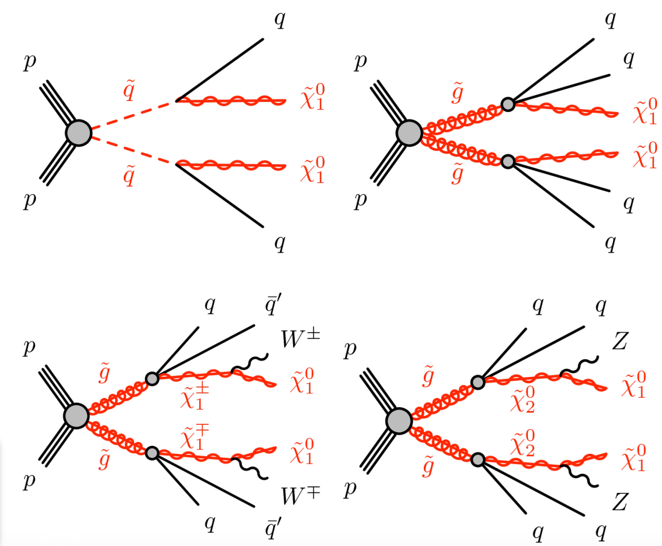
Strong production

Production of 1st and 2nd generation squarks and gluinos with subsequent cascade decay to lighter sparticles





Strong prod: 0L + jets + MET



- Final states with 2-6 jets, MET & no isolated lepton (e/μ)
- Signal enhancement based on: M_{eff}, MET, R_{jigsaw}
- 30 signal regions defined targeting different search scenarios and phase space

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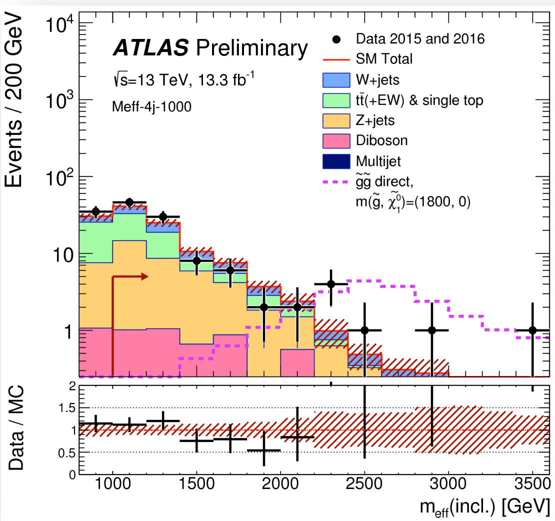
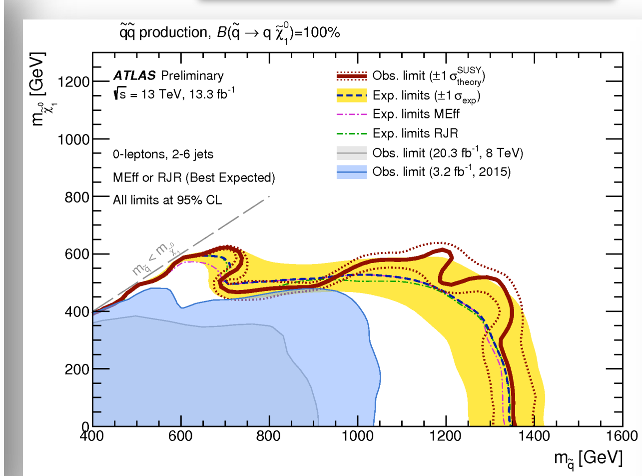
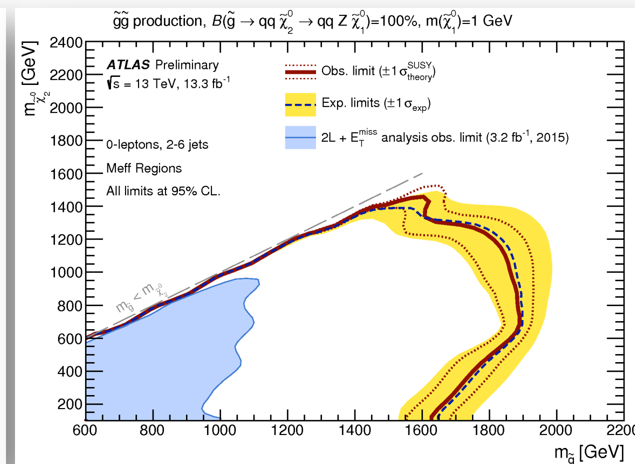
see also EPJC 76 (2016) 392





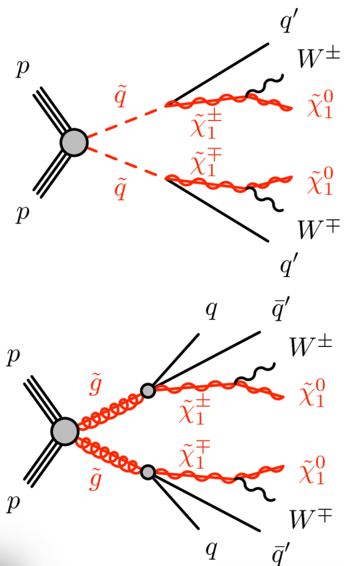


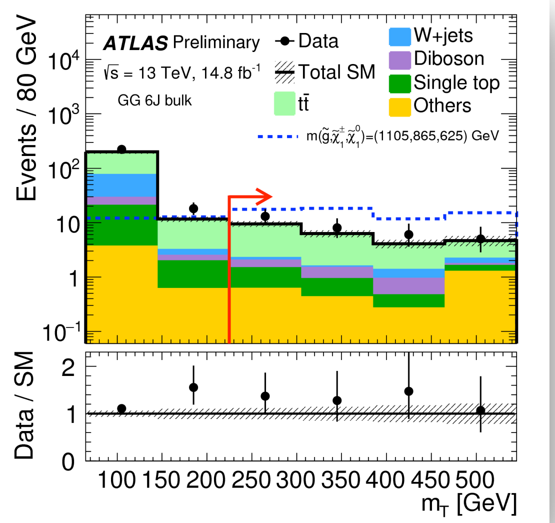
- Excludes gluino (squark) masses up to **1.86 (1.35) TeV** for massless LSP
- For gluino decay via $\tilde{\chi}_2^0$, gluino masses below **1.9 TeV** excluded for $m(\tilde{\chi}_2^0)$ ~ 600 GeV

Strong prod: 1 lepton + 2-6 jets + MET

- Targeting 1-step decays with variety of mass hierarchies
- MET triggered; one soft (6-35 GeV) or hard (> 35 GeV) lepton; 2 to 6 jets
- Dominant background W+jets and ttbar
- Background normalised to CRs with low m_T and aplanarity

$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos[\Delta\phi(\boldsymbol{p}_{\mathrm{T}}^{\ell}, \boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}})])}$$





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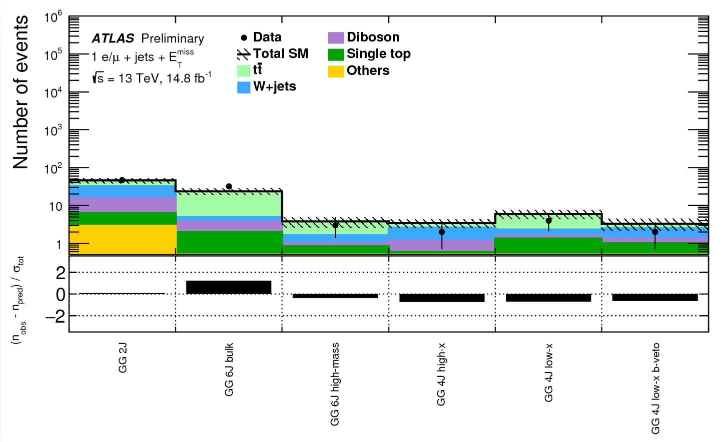
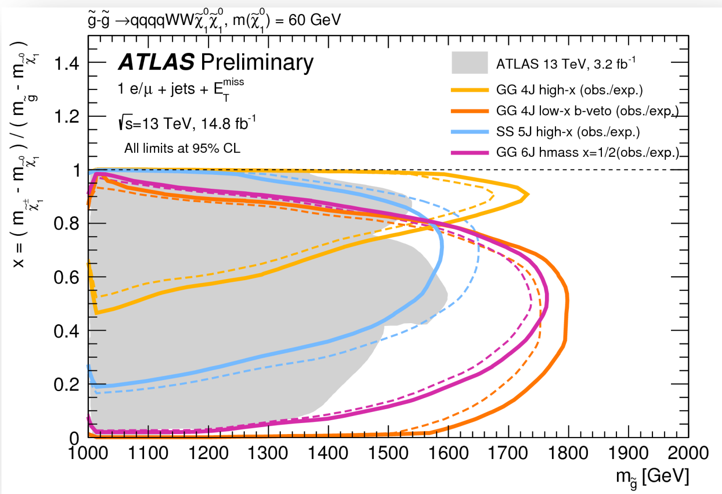




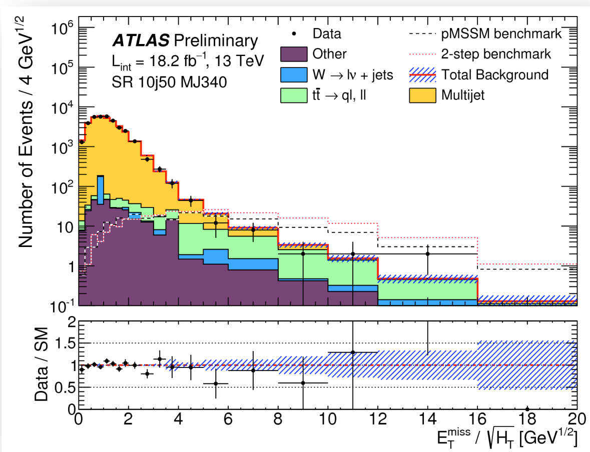
No excess seen, leading to improved limits

Strong prod: 0L + multijets + MET

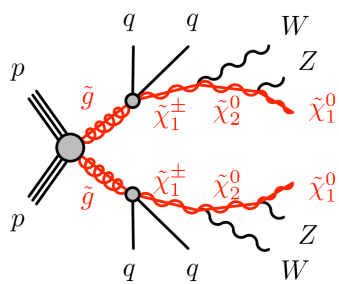
- Veto on isolated leptons (e/μ)
- ≥8 jets up to ≥10 jets, consistent with decays of heavy objects, *reclustered* into smaller number of high-mass jets
- Discrimination also with MET/√H_T

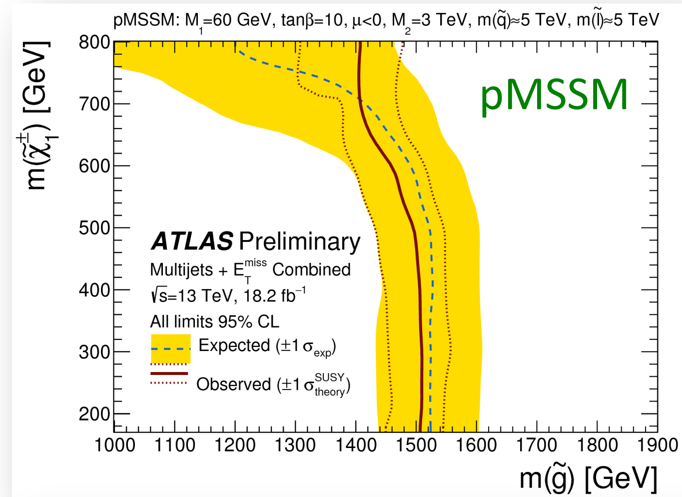
$$M_J^{\Sigma} = \sum_j m_j^{R=1.0}$$

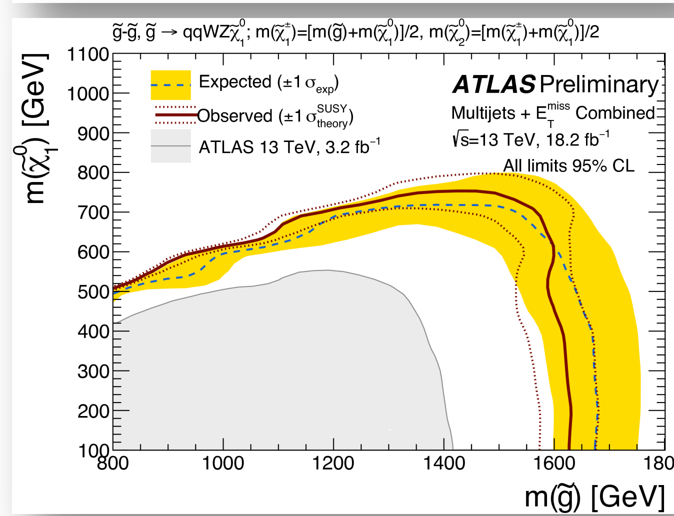
$$H_T = \sum p_T^{\text{jet}}$$



ATLAS-CONF-2016-095
see also PLB 757 (2016) 334





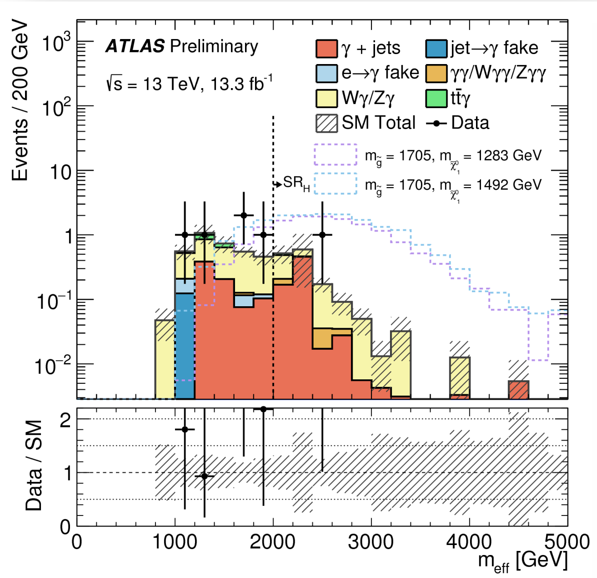


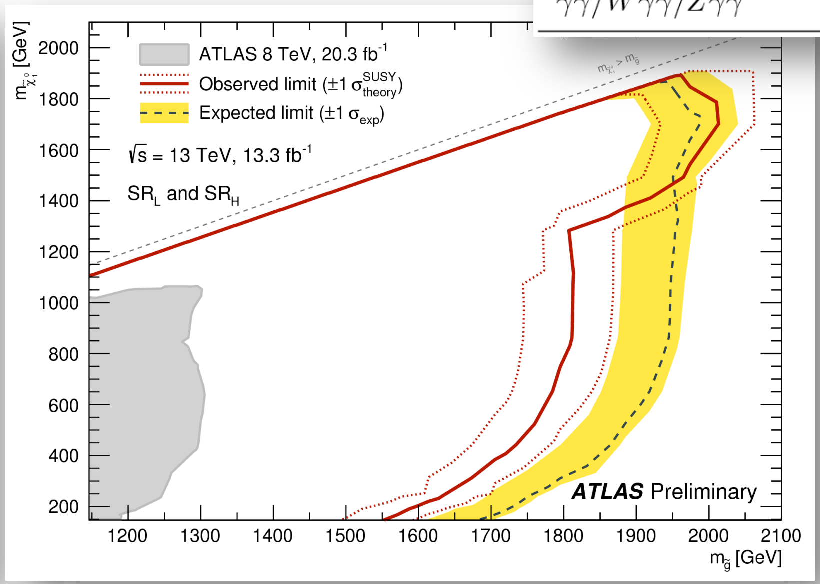
- For a pMSSM slice with bino-like $\tilde{\chi}_1^0$ and higgsino $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$, gluino masses up to **1500 GeV** excluded
- For 2-step simplified model **m($\tilde{g}$) < 1600 GeV** excluded at 95% CL, extending previous limits

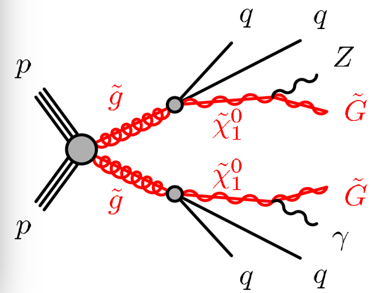
Strong prod: γ + jets + MET

- Targeting neutralino NSLP decaying to gravitino and photon with non-100% branching ratios
- Low-background signature
- Wγ, ttγ, γ+jets normalised in CRs

Signal Region	$\mathrm{SR_L}$	$\mathrm{SR_H}$
Observed events	3	1
Expected SM events	0.78 ± 0.18	1.49 ± 0.45
γ + jets	0.18 ± 0.11	0.70 ± 0.24
$W\gamma$	0.30 ± 0.07	0.37 ± 0.09
$Z\gamma$	0.08 ± 0.08	0.32 ± 0.32
$t\bar{t}\gamma$	0.10 ± 0.04	0.03 ± 0.01
$e \to \gamma$ fakes	0.07 ± 0.03	0.00 ± 0.00
jet $\to \gamma$ fakes	0.04 ± 0.01	0.00 ± 0.00
$\gamma\gamma/W\gamma\gamma/Z\gamma\gamma$	0.01 ± 0.00	0.07 ± 0.01







- No significant excess observed
- Limits set represent **400 GeV** improvement w.r.t. Run-1

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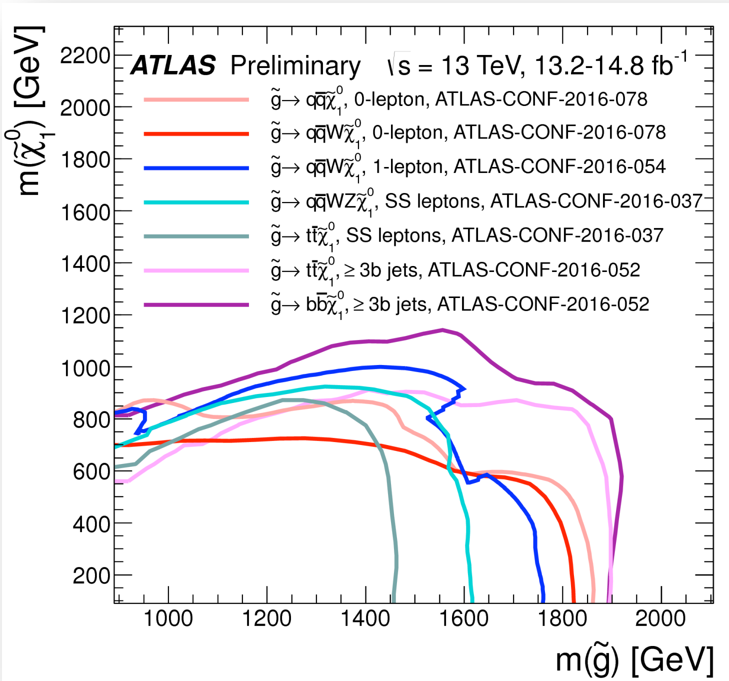
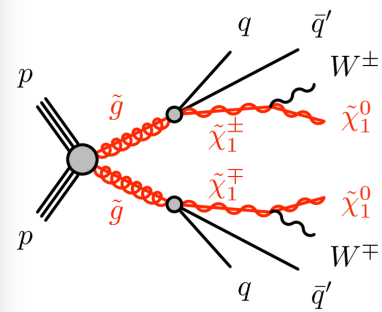
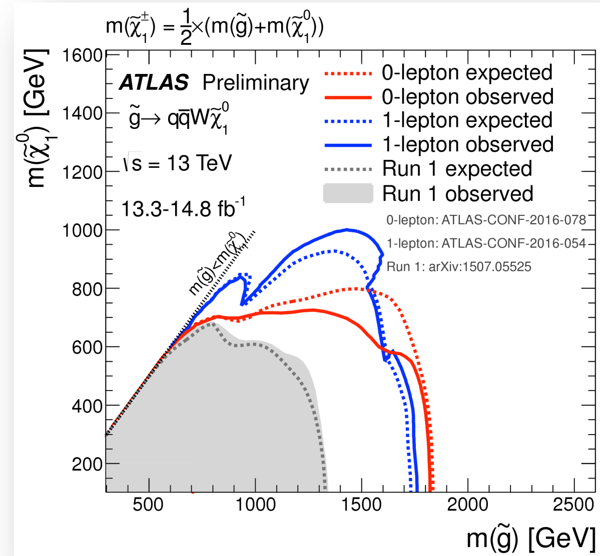
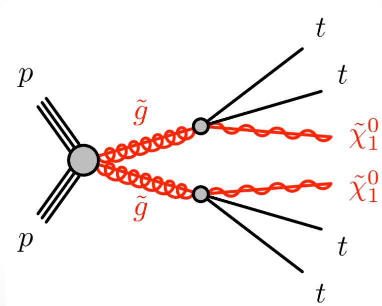
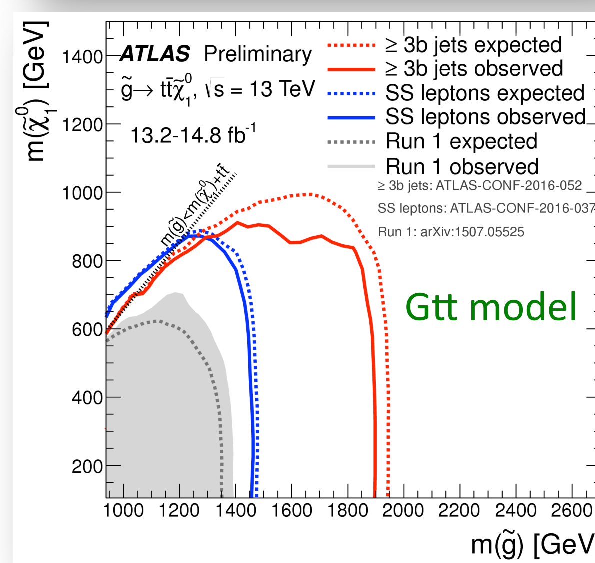
Strong production – summary











Exclusion curves not necessarily directly comparable; different:

- stop decay channels
- sparticle mass hierarchies
- simplified decay scenarios

3rd generation

Only stops are presented here

Emphasis on representative channels

"Natural" SUSY

To cancel large top corrections to Z mass (fine-tuning) …

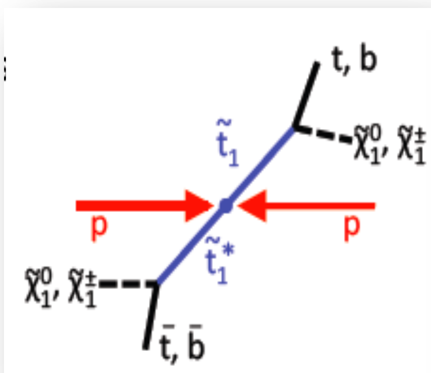
$$m_Z^2 = -2(m_{H_u}^2 + |\mu|^2) + \ldots$$

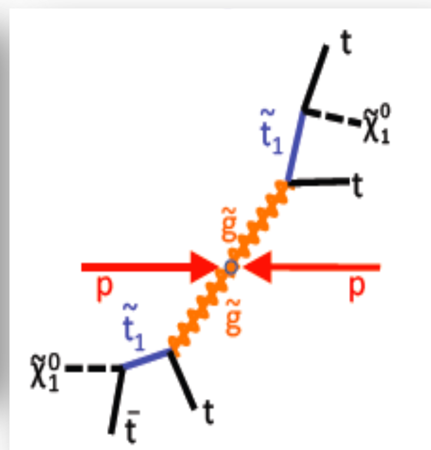
$$\delta m_{H_u}^2 \approx -\frac{3y_t^2 m_{\tilde{t}}^2}{4\pi^2}(1 + a^2/2)\log\frac{\Lambda}{m_{\tilde{t}}}$$

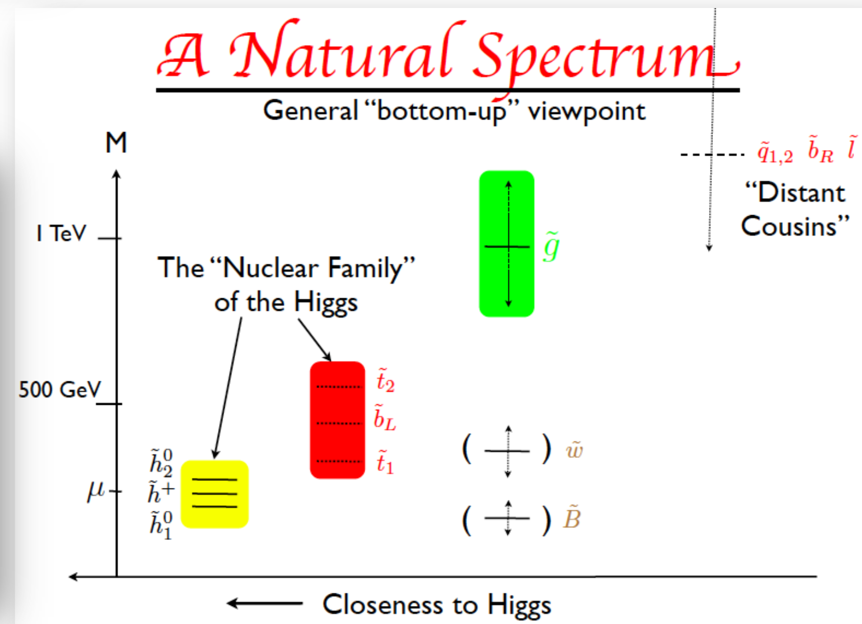
$$\delta m_{\tilde{t}}^2 = \frac{8\alpha_s}{3\pi} M_3^2 \log\frac{\Lambda}{M_3}$$

… only need light higgsinos, stops, gluinos
(and light messenger scale Λ)

Production and decay diagrams at LHC



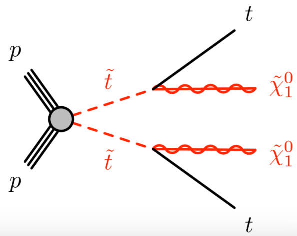
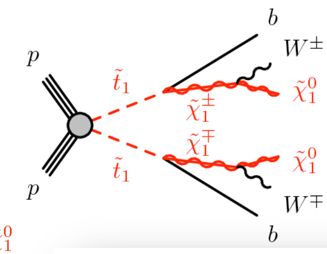
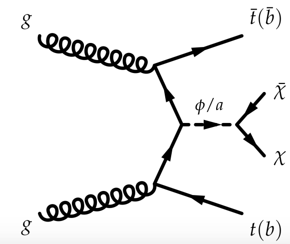


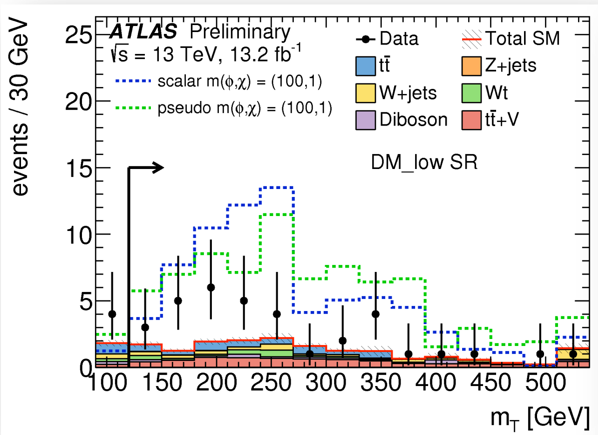


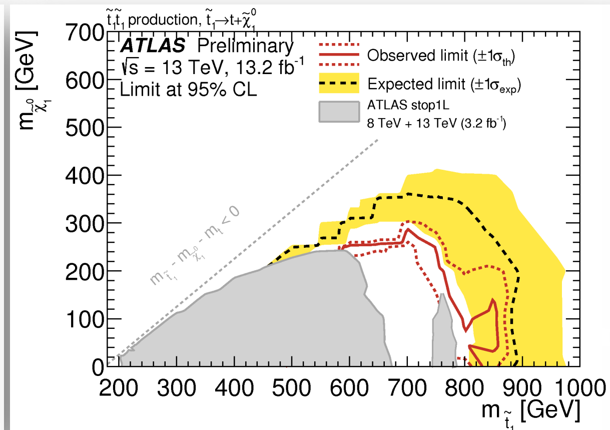
L. Hall, Berkeley 2011

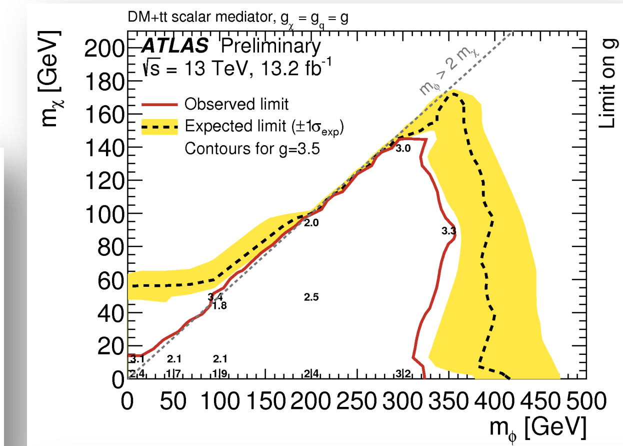
Stop: 1 lepton + (b)jets + MET

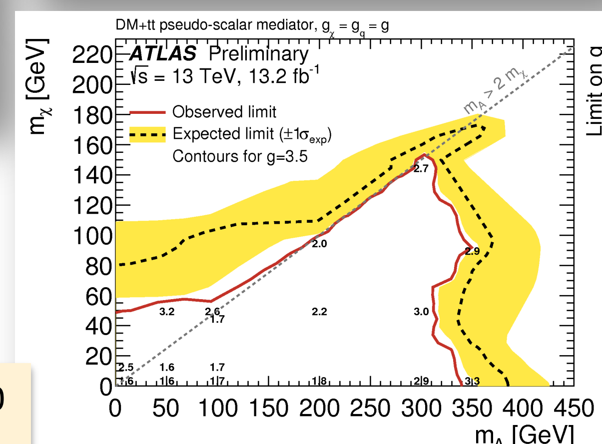
- Search for **stop** and for **dark matter** production in association with two tops
- Selection based on MET, m_T, H_T
- 7 SRs for specific scenarios and phase space
  - 3.3σ excess in DM_low SR







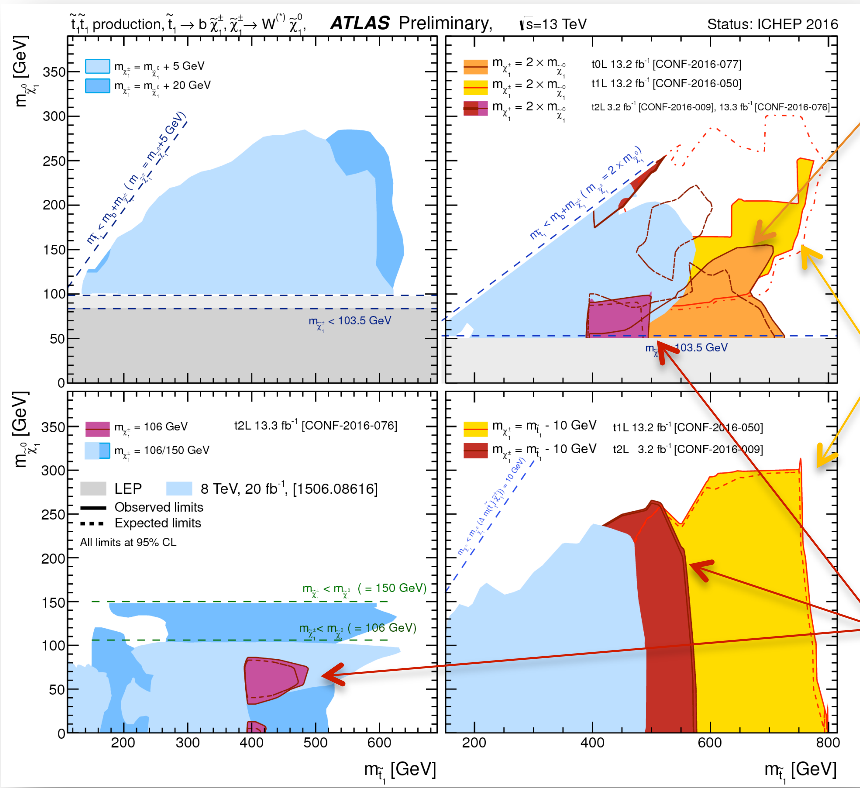


- Exclusion for **$m(\tilde{t}_1)$ < ~830 GeV** for massless LSP
- Maximal coupling of **g = 3.5** is excluded @95% CL for a (pseudo-)scalar mediator mass up to **(350) 320 GeV** assuming a 1 GeV DM mass

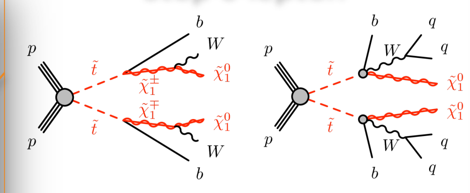
ATLAS-CONF-2016-050
see also 1606.03903

Direct stop production – summary

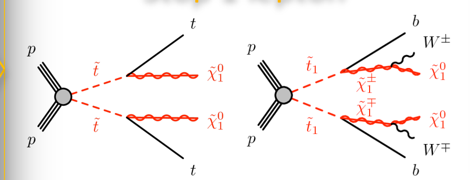
Different assumed chargino masses



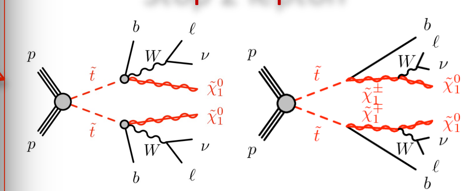
Stop 0 lepton

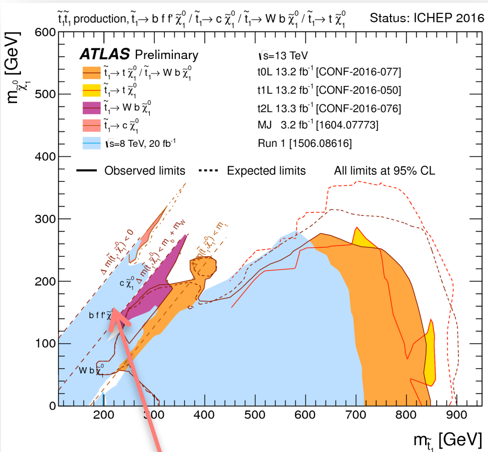


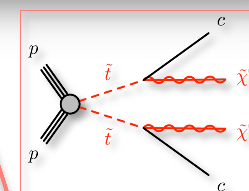
Stop 1 lepton



Stop 2 lepton







Limits depend on chargino-neutralino mass splitting

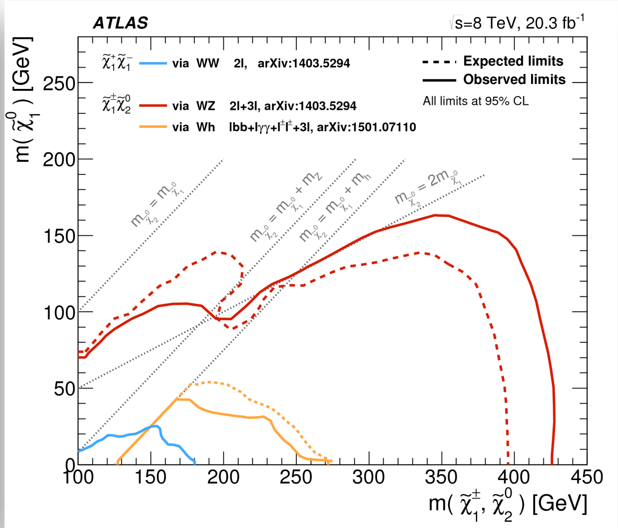
Overlaid contours belong to different
- stop decay channels
- sparticle mass hierarchies
- simplified decay scenarios

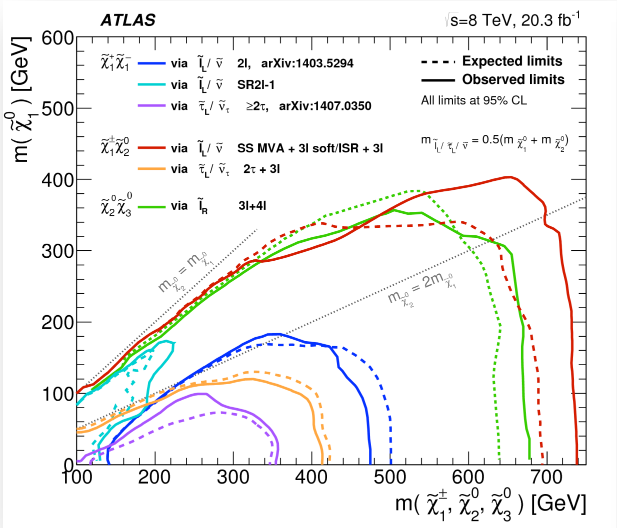
Region **m(stop)** ≲ **m(top) + m(~χ_1^0)** difficult to cover ➔ charm tagging essential

Electroweak production

Summary 8-TeV results

Sensitive to details of scenario considered, e.g. nature of gaugino (bino, wino, higgsino)



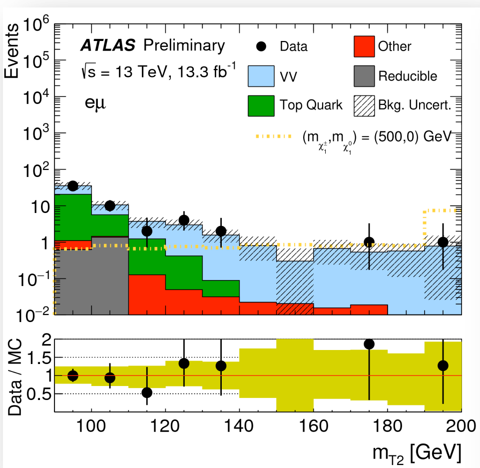


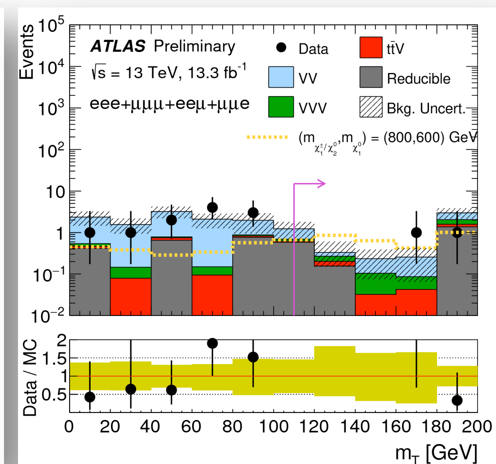
NEW

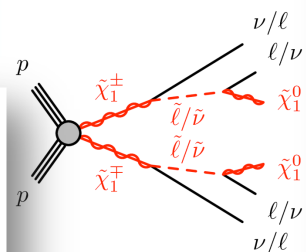
EW prod: 2/3 leptons + MET

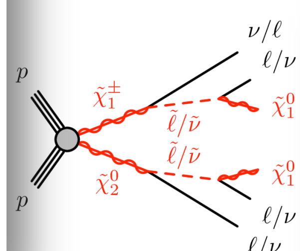
- Two opposite-sign leptons (e/μ) or 3 leptons and large MET
- Jet veto (2L), b-jet veto (3L) and Z veto applied
- Large (s)transverse mass, m_T (m_{T2}), in 3L (2L) SRs

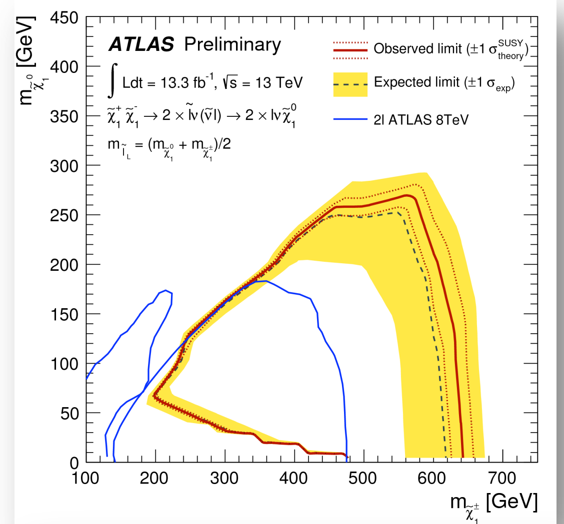
$$m_{T2} = \min_{\mathbf{q}_T}\left[\max\left(m_T(\mathbf{p}_T^{\ell 1}, \mathbf{q}_T), m_T(\mathbf{p}_T^{\ell 2}, \mathbf{p}_T^{\text{miss}} - \mathbf{q}_T)\right)\right]$$

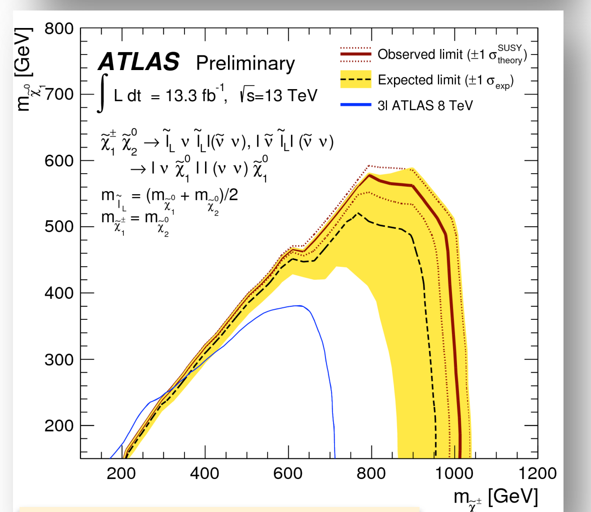












- Results interpreted in *simplified models* of chargino and neutralino production
- Limits set extend previous from Run-1 by **140 GeV** for $\tilde{\chi}_1^+\tilde{\chi}_1^-$ production and by **300 GeV** for $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ production

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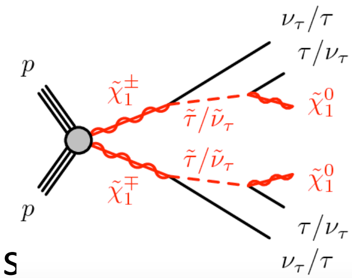
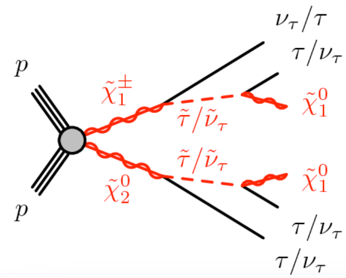
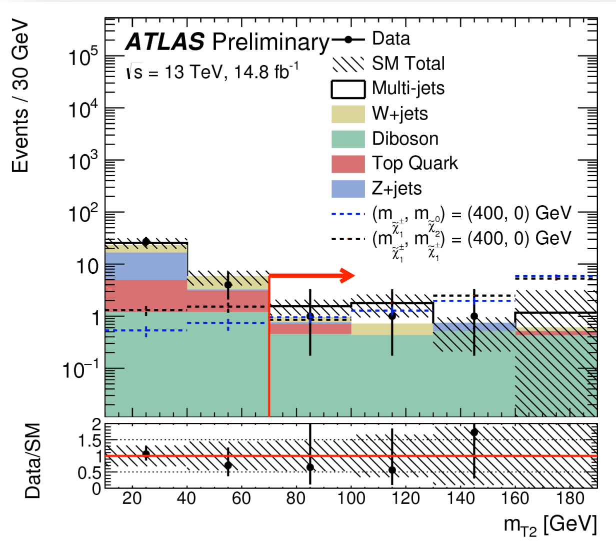
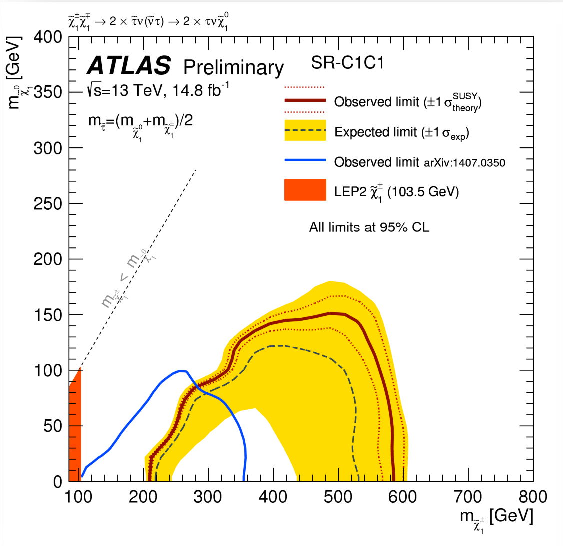
EW prod: di-taus + MET

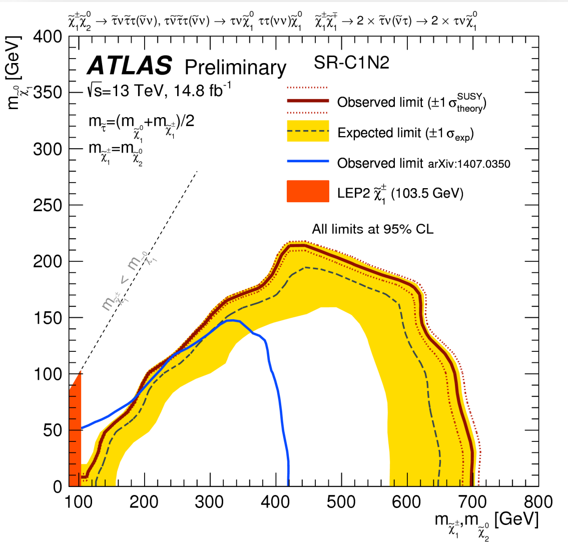
- Analysis similar to 2L (e/μ)
- Motivated by models with light staus leading to dark matter relic density consistent with cosmological observations











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- Limits are derived in scenarios of $\tilde{\chi}_1^+\tilde{\chi}_1^-$ pair production and $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ and $\tilde{\chi}_1^+\tilde{\chi}_1^-$ associated production
- $\tilde{\chi}_1^\pm$ masses and common $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ masses up to **580** and **700 GeV** respectively are excluded at 95% CL assuming a massless $\tilde{\chi}_1^0$

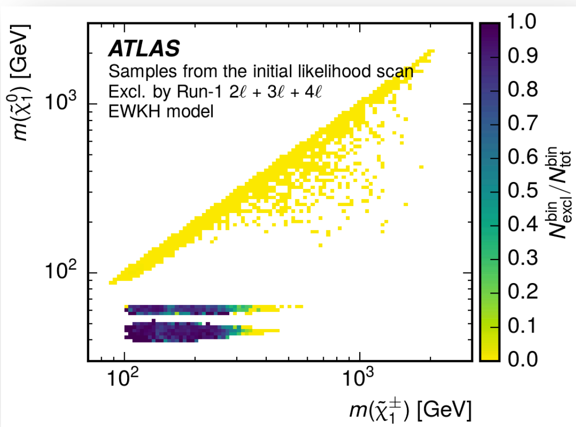
EW prod: dark matter in pMSSM

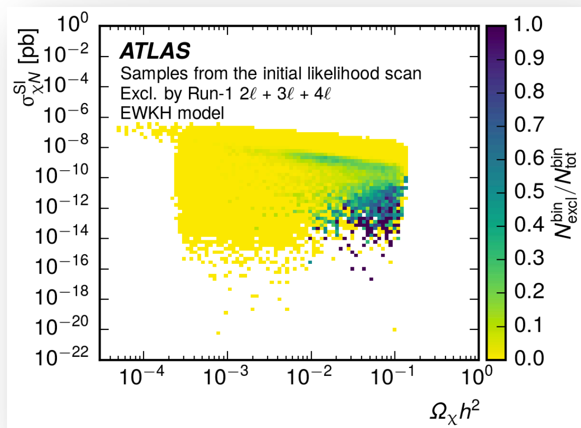
- Aim: study EW SUSY searches impact on dark matter candidates
- Focusing on the gaugino-higgsino and Higgs sector (EWKH) of the phenomenological minimal supersymmetric SM (pMSSM)

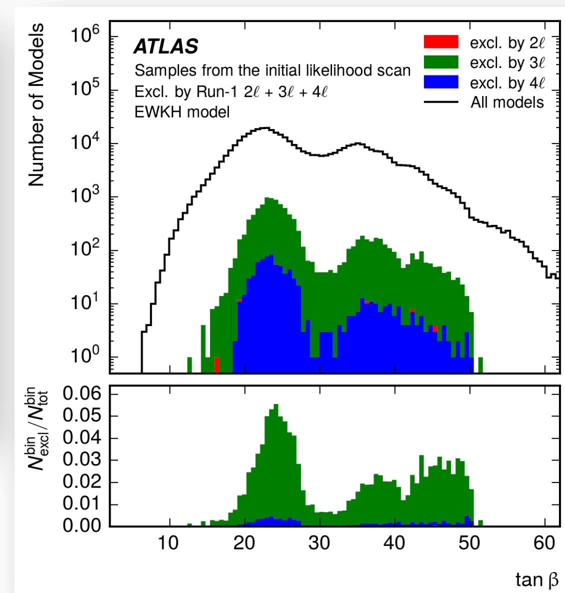
Analysis	Target production processes
2ℓ [30]	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^\pm\tilde{\chi}_2^0, \tilde{\ell}\tilde{\ell}$
2τ [33]	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^\pm\tilde{\chi}_2^0, \tilde{\tau}\tilde{\tau}$
3ℓ [34]	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$
4ℓ [35]	$\tilde{\chi}_2^0\tilde{\chi}_3^0$

20 fb^{-1} @ 8 TeV

Experimental constraints
direct DM detection experiments
relic DM density
precision flavour physics results
ATLAS Higgs mass measurement
SUSY searches at LEP







- **ATLAS searches substantially impact models with $m(\tilde{\chi}_1^0) < 65$ GeV, excluding 86% of such models**
- Searches have limited impact on models with larger $m(\tilde{\chi}_1^0)$ due to either heavy gauginos or compressed mass spectra

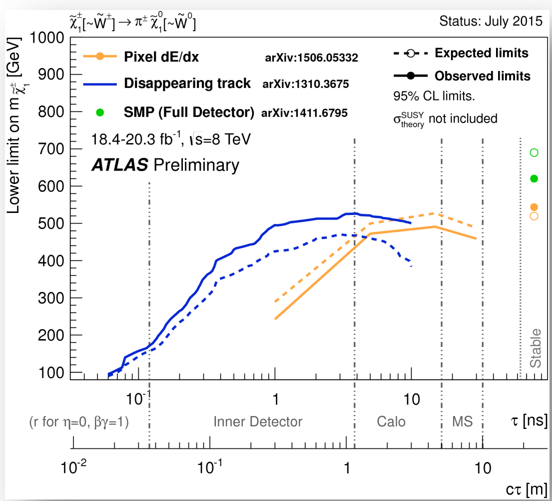
arXiv:1608.00872
see also PRD 93 (2016) 052002

R-parity violation and long-lived particles

- No results with 2016 data on LL particles yet
- Emphasis on RPV analyses with ~14 fb^{-1} presented here

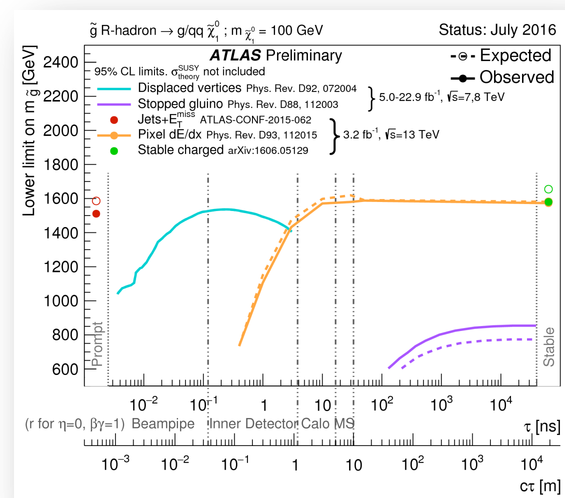
Summary 8-TeV on disappearing track

AMSB model with long lived chargino, $\tilde{\chi}_1^{\pm} \rightarrow \pi^{\pm} \tilde{\chi}_1^0$



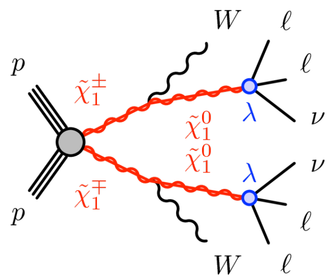
First 13-TeV results on R-hadrons

Split SUSY with metastable $\tilde{g} \rightarrow g/qq\ \tilde{\chi}_1^0$

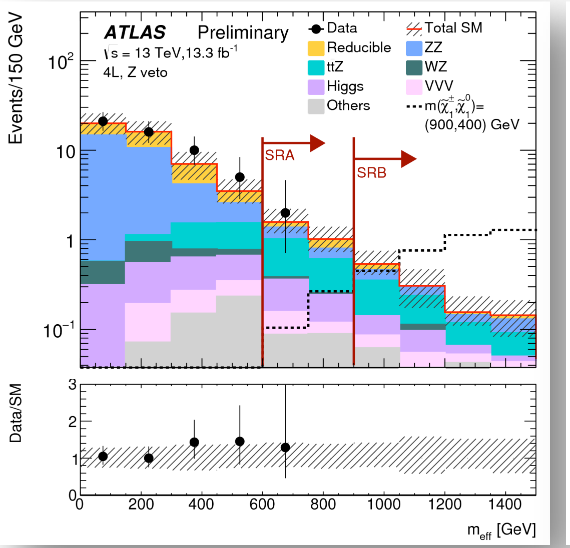


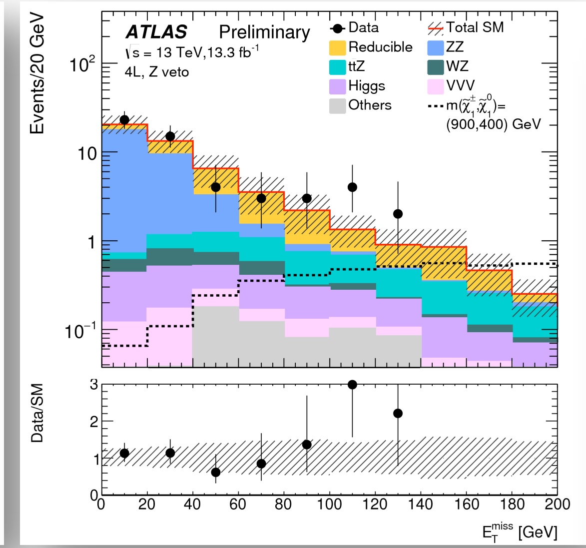
EW prod: 4 leptons + MET with RPV decays

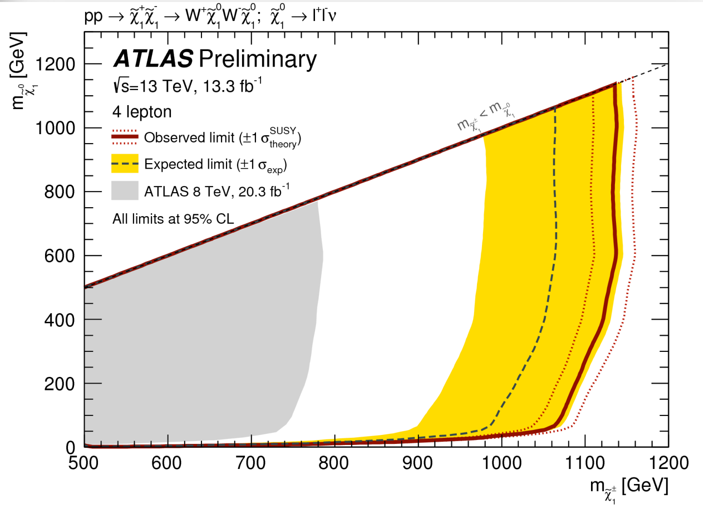
- RPV SUSY scenarios with L-number violation can result in signatures with high lepton multiplicities and substantial MET
- Requiring 4L (e/μ) + MET in chargino production with indirect LSP RPV decay
- Two SRs defined targeting different chargino mass ranges



ATLAS-CONF-2016-075







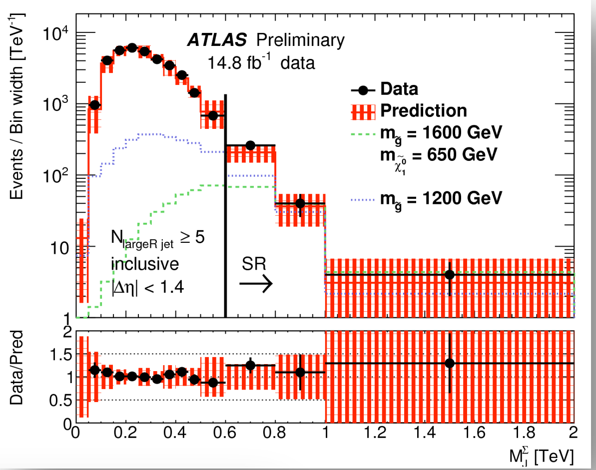
Chargino masses up to **1.14 TeV** are excluded for large LSP masses

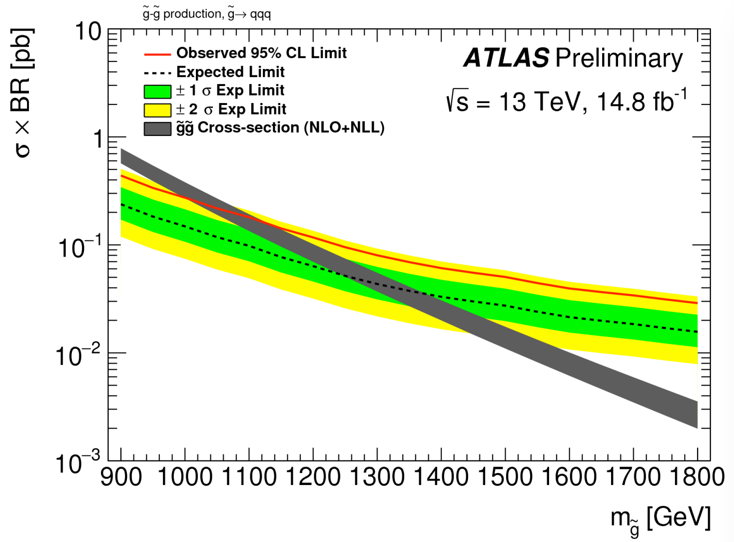
Gluino RPV decays to multijets

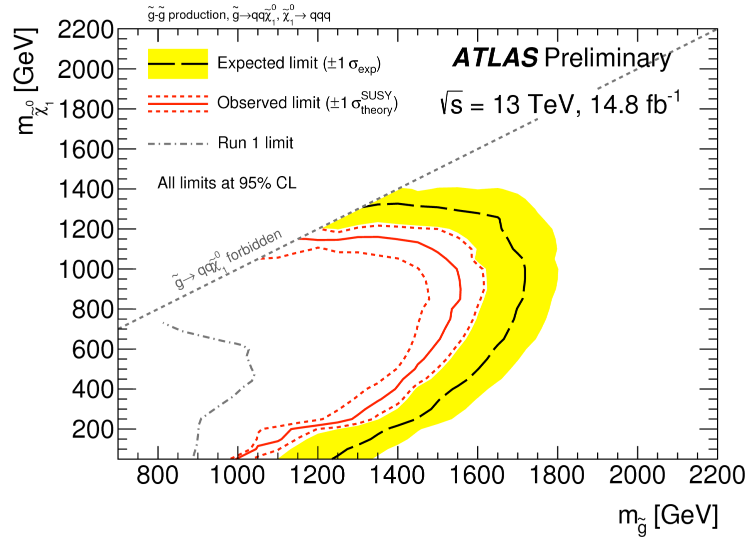
- Search for gluinos with RPV decays to quarks
- Signal to BG discrimination based on M_J^Σ
- 4 SRs defined targeting different search scenarios

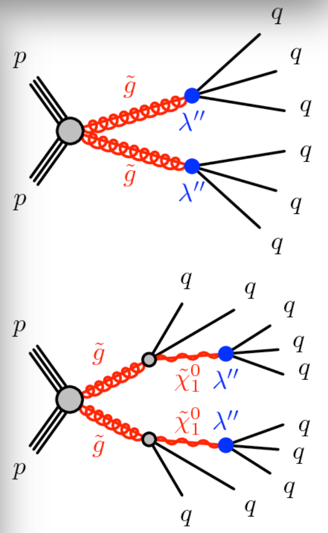
$$M_J^\Sigma = \sum_{\substack{p_T > 200\,\mathrm{GeV} \\ |\eta| \le 2.0}}^{4} m^{\mathrm{jet}}$$

ATLAS-CONF-2016-057





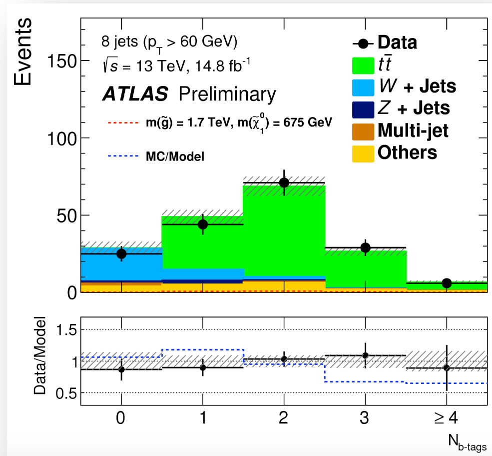




- In the gluino cascade decay model, gluinos with masses up to **1 – 1.55 TeV** are excluded, depending on neutralino mass
- In the gluino direct decay model, gluinos with masses up to **1080 GeV** are excluded

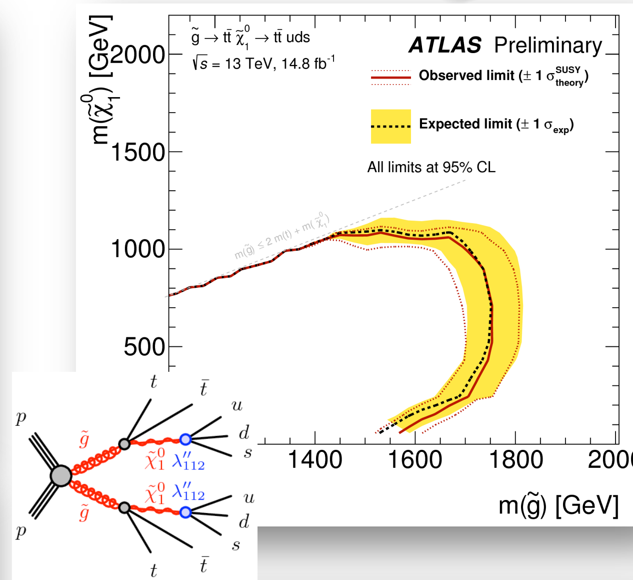
Gluino RPV decays to 1 lepton and jets

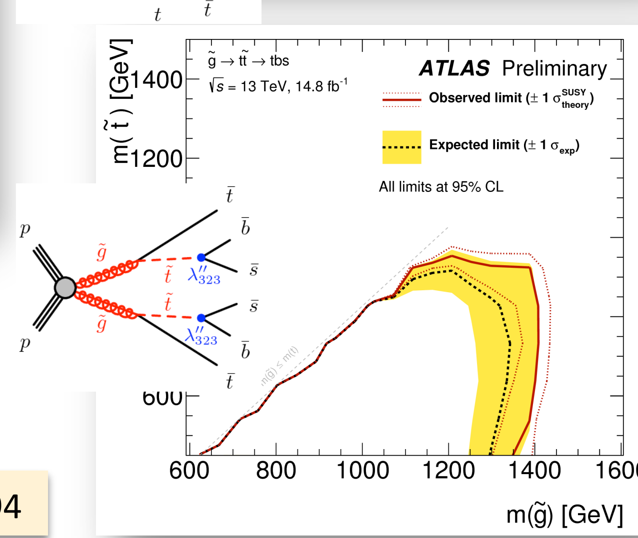
- Requiring one isolated lepton (e/μ) and many jets (>5 in six bins) and b-jets (four bins starting from 0)
- All bins are fitted to SUSY model prediction to obtain model-dependent results



Jet multiplicity	0b obs. [fb]	0b exp. [fb]	≥ 3b obs. [fb]	≥ 3b exp. [fb]
≥ 8 jets (p_T > 40 GeV)	2.2	$3.3^{+1.3}_{-0.9}$	8.4	$4.7^{+2.0}_{-1.3}$
≥ 9 jets (p_T > 40 GeV)	1.1	$1.1^{+0.5}_{-0.3}$	2.8	$2.1^{+0.9}_{-0.6}$
≥ 10 jets (p_T > 40 GeV)	0.43	$0.52^{+0.26}_{-0.14}$	1.19	$1.1^{+0.45}_{-0.31}$
≥ 8 jets (p_T > 60 GeV)	1.2	$1.1^{+0.4}_{-0.3}$	1.5	$1.4^{+0.5}_{-0.4}$
≥ 9 jets (p_T > 60 GeV)	0.97	$0.46^{+0.22}_{-0.13}$	0.5	$0.6^{+0.2}_{-0.2}$
≥ 10 jets (p_T > 60 GeV)	0.2	$0.2^{+0.1}_{-0.1}$	0.26	$0.29^{+0.14}_{-0.08}$

- For $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0 \rightarrow t\bar{t}uds$, gluino masses up to **1.75 TeV** are excluded at 95% CL
- In a model with $\tilde{g} \rightarrow t\tilde{t}_1$ with $\tilde{t}_1 \rightarrow bs$, gluino masses up to **1.4 TeV** are excluded





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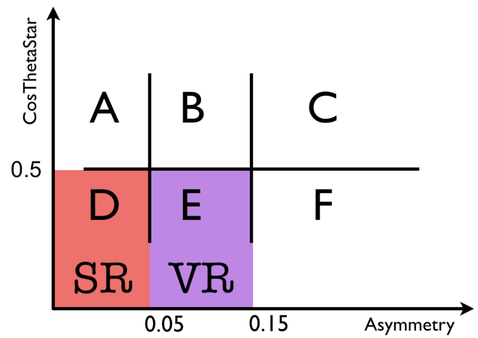
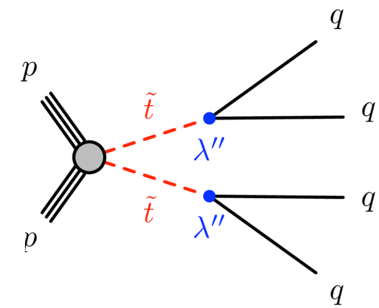
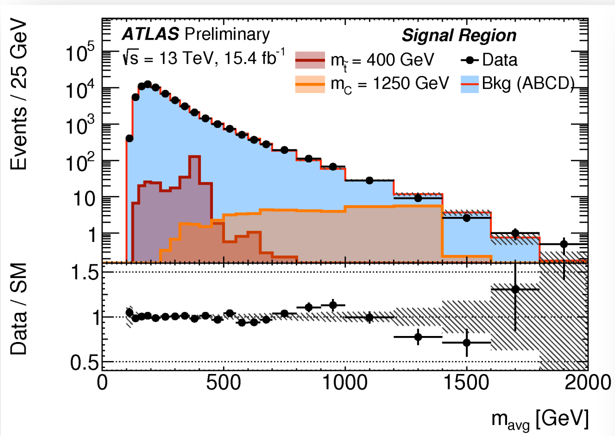
Stop RPV decays to jets

- Requiring at least four jets matched by minimising separation angle
- SR defined w.r.t. asymmetry $\mathcal{A}$ and cosθ* of jets boosted in resonance system

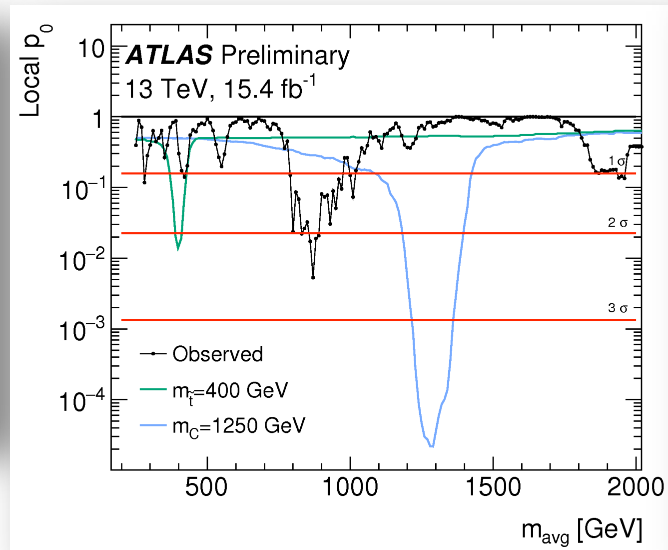


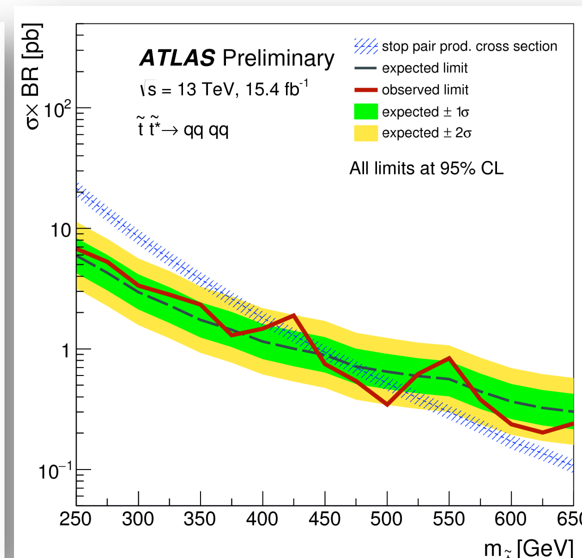


$$\mathcal{A} = \frac{|m_1 - m_2|}{m_1 + m_2}$$



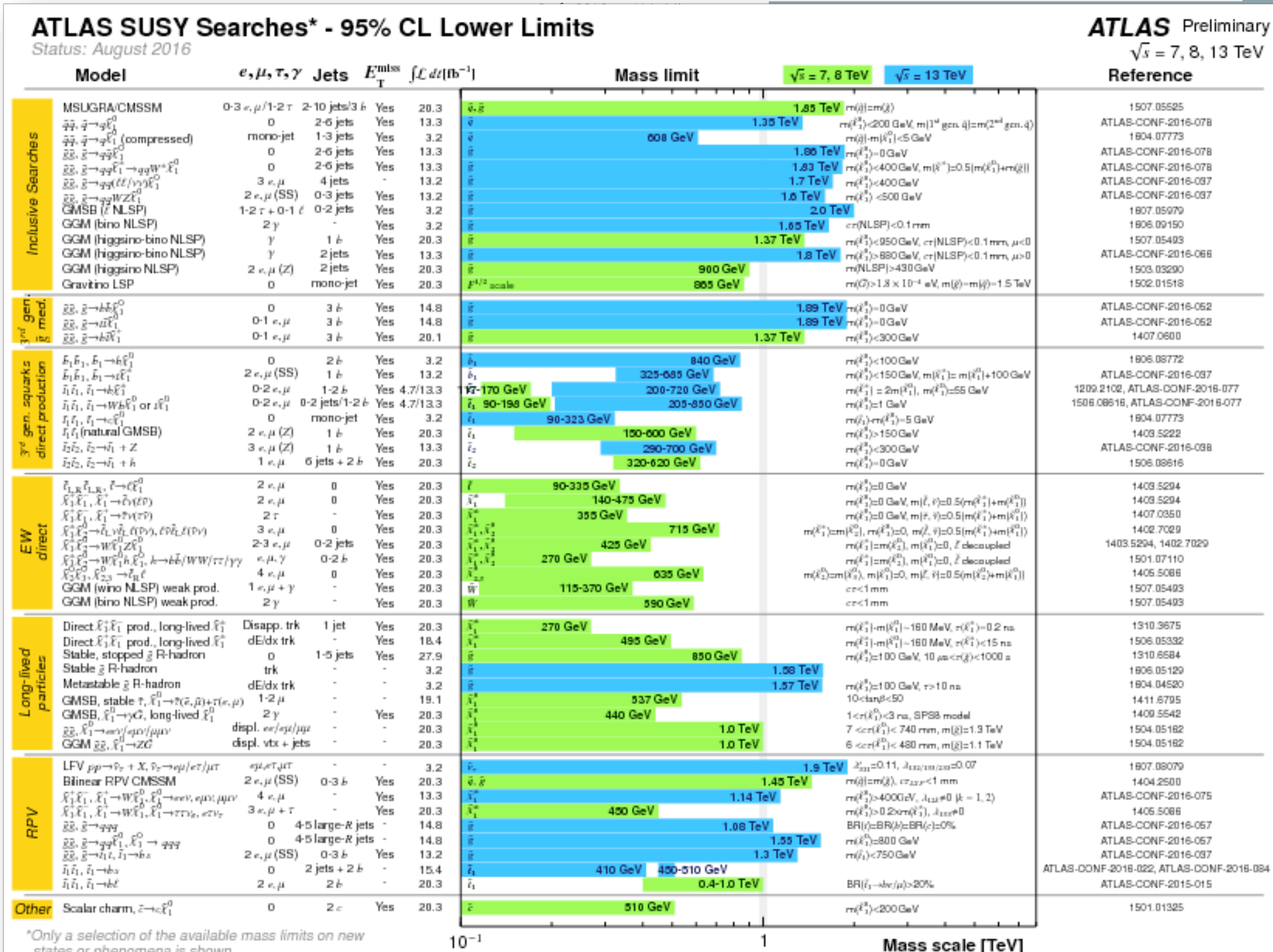
$$m_{\text{avg}} = \frac{1}{2}(m_1 + m_2)$$

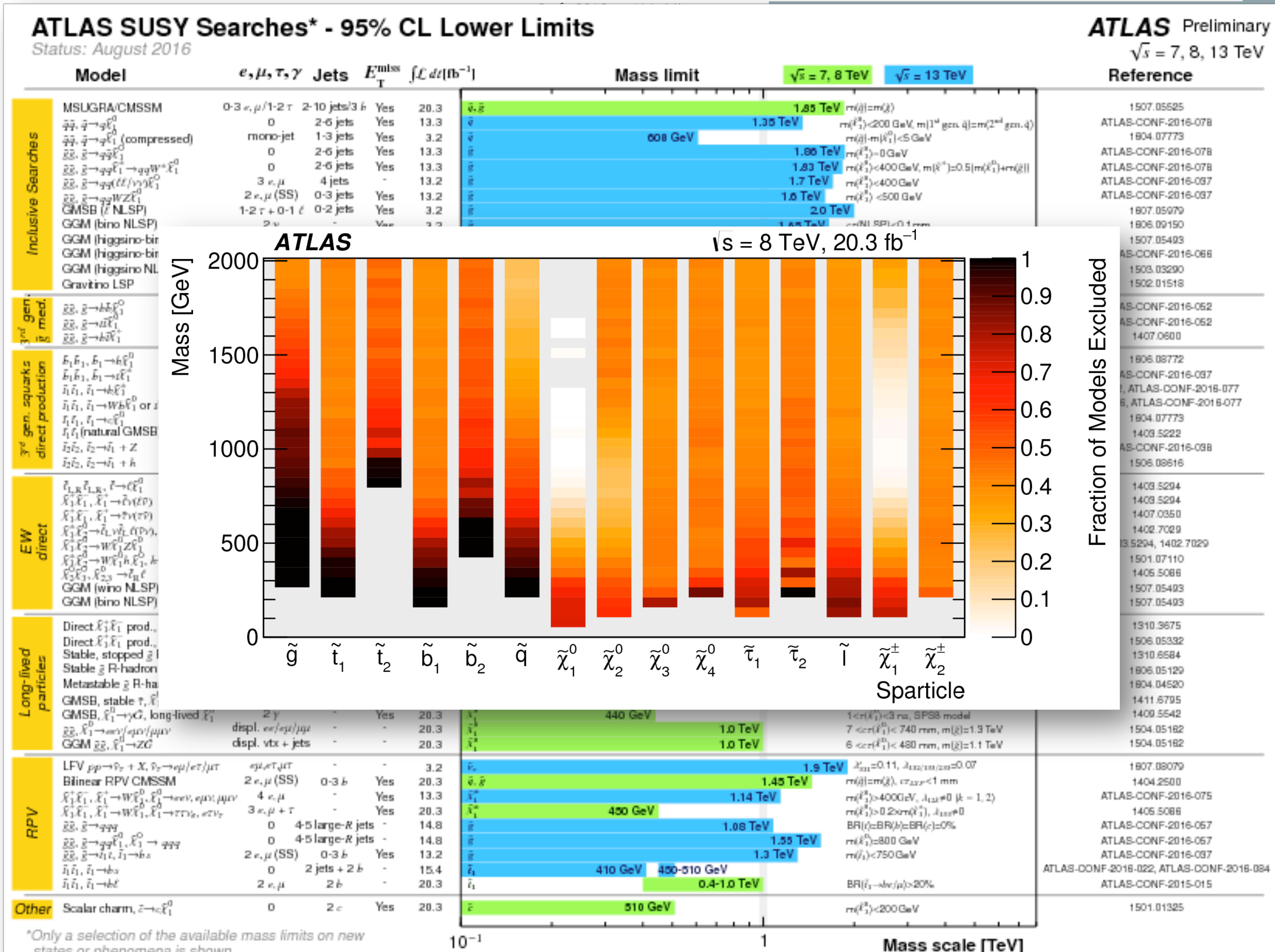




No excess observed ➔ Exclude λ'' **stop-q-q** coupling for
250 GeV < m(stop) < 405 GeV and **445 GeV < m(stop) < 510 GeV**

ATLAS-CONF-2016-084


ATLAS SUSY Searches* - 95% CL Lower Limits
Status: August 2016
ATLAS Preliminary
√s = 7, 8, 13 TeV
Model
Jets
Mass limit
√s = 7, 8 TeV
√s = 13 TeV
Reference
Inclusive Searches
MSUGRA/CMSSM
GMSB
GGM (bino NLSP)
GGM (higgsino-bino NLSP)
GGM (higgsino NLSP)
Gravitino LSP
1.85 TeV
1.35 TeV
608 GeV
1.86 TeV
1.83 TeV
1.7 TeV
1.6 TeV
2.0 TeV
1.65 TeV
1.37 TeV
1.8 TeV
900 GeV
865 GeV
1.89 TeV
1.89 TeV
1.37 TeV
840 GeV
325-685 GeV
200-720 GeV
90-198 GeV
205-850 GeV
90-323 GeV
150-600 GeV
290-700 GeV
320-620 GeV
EW direct
90-335 GeV
140-475 GeV
355 GeV
715 GeV
425 GeV
270 GeV
635 GeV
GGM (wino NLSP) weak prod.
GGM (bino NLSP) weak prod.
115-370 GeV
590 GeV
Long-lived particles
Disapp. trk
dE/dx trk
Stable, stopped g̃ R-hadron
Stable g̃ R-hadron
Metastable g̃ R-hadron
270 GeV
495 GeV
850 GeV
1.58 TeV
1.57 TeV
537 GeV
440 GeV
1.0 TeV
1.0 TeV
RPV
Bilinear RPV CMSSM
1.9 TeV
1.45 TeV
1.14 TeV
450 GeV
1.08 TeV
1.55 TeV
1.3 TeV
410 GeV
450-510 GeV
0.4-1.0 TeV
Other
Scalar charm
510 GeV
*Only a selection of the available mass limits on new states or phenomena is shown.
Mass scale [TeV]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Status: August 2016
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√s = 7, 8, 13 TeV
Model
Mass limit
Reference
Inclusive Searches
EW direct
Long-lived particles
RPV
Other
*Only a selection of the available mass limits on new states or phenomena is shown.
Mass scale [TeV]
ATLAS
√s = 8 TeV, 20.3 fb⁻¹
Mass [GeV]
Fraction of Models Excluded
Sparticle

Summary & outlook

- ATLAS developed a vast program to search for supersymmetry
  - no significant excess seen so far
- In simplified scenarios, exclusion achieved
  - up to ~1.9 TeV for gluinos
  - up to ~900 GeV for top squarks
  - *more results are continuously become available*
- ~30 (100) fb^{-1} data expected by end of 2016 (end of Run-2)
- **Very challenging years for SUSY ahead of us!**

&

More results:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

Spares

- RJigsaw variables
  - decompose an event assuming a decay topology
  - compute invisible momenta by minimizing each hemisphere mass
  - all momenta of decay tree available for selection (mass-sensitive scale variables, angles for compressed topologies)