# SUSY searches at the LHC

**V. A. Mitsou**

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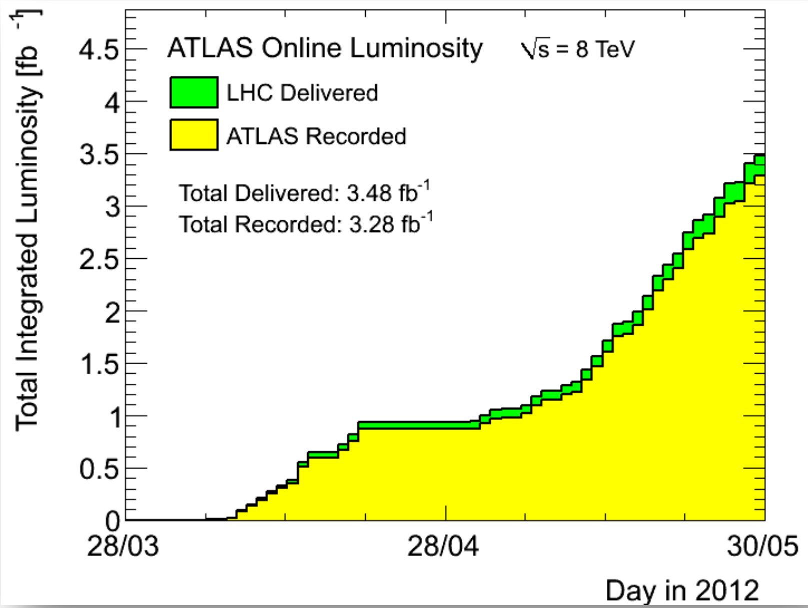
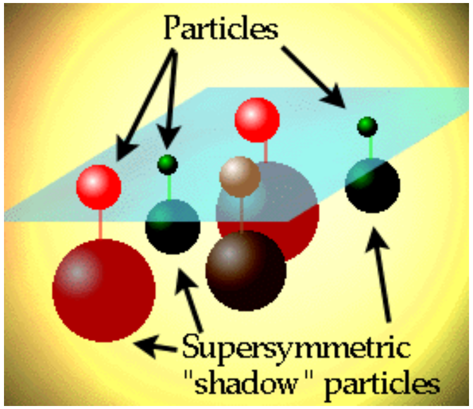
# Outline

- Strategy for SUSY searches at LHC
- R-parity conserving supersymmetry
  - strong-production channels
  - 3rd-generation sparticle searches
  - direct gaugino production
- R-parity violation (RPV)
  - multi-lepton signatures
  - eμ final states
  - bilinear RPV
- Long-lived particles
  - displaced vertices
- Summary – outlook

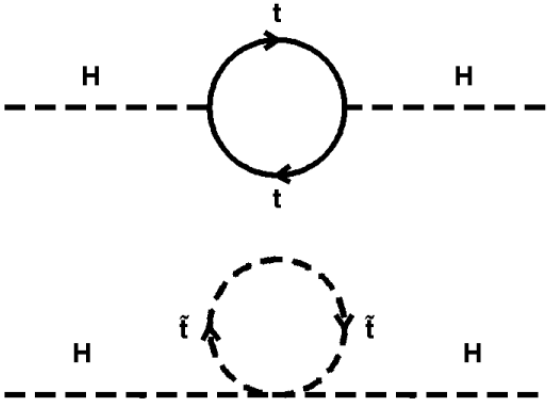


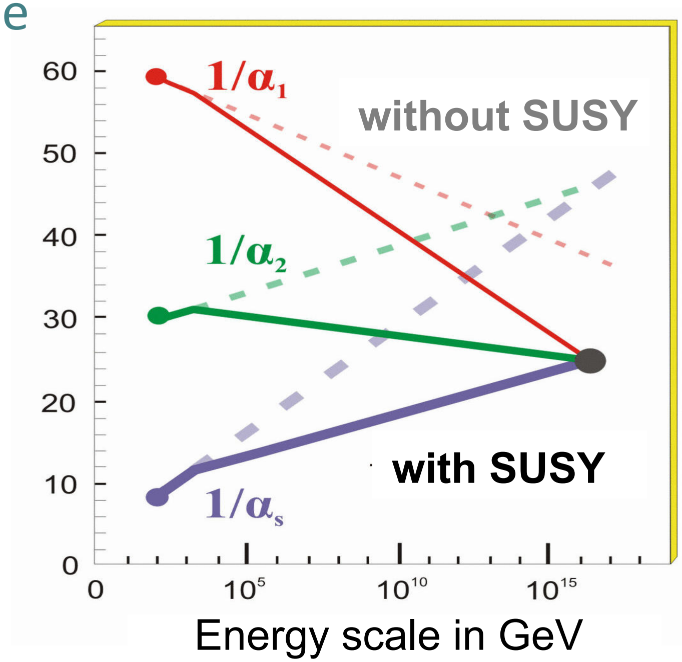

Results for up to 5 fb$^{-1}$ pp collisions at $\sqrt{s}$ = 7 TeV are presented here

# Supersymmetry (SUSY)

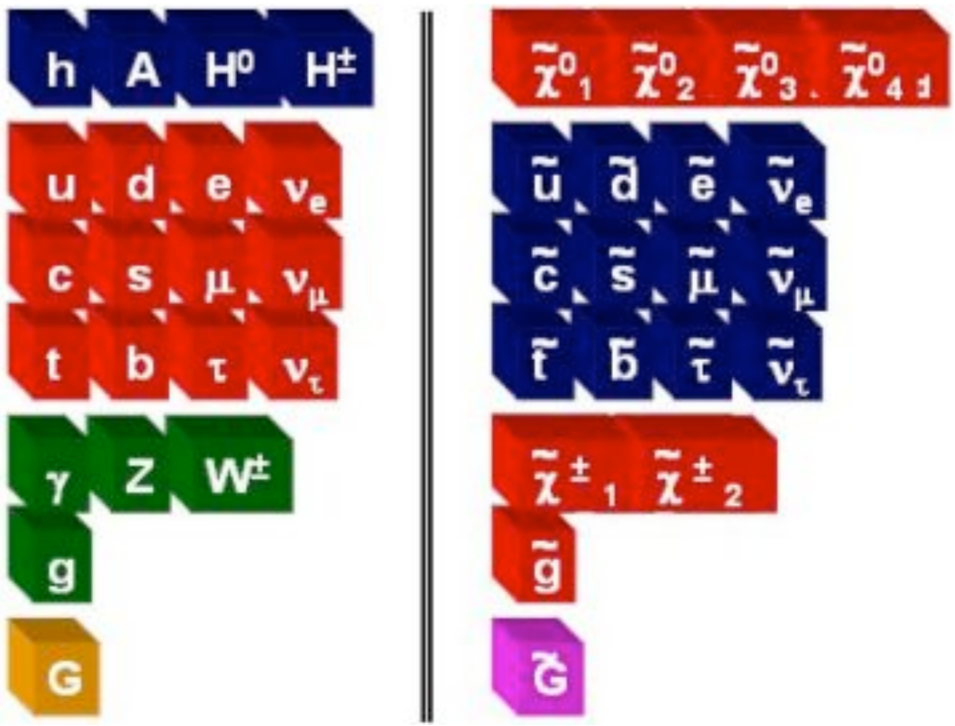



- Supersymmetry := fundamental global symmetry between fermions-bosons
- Theoretical motivation
  - Higgs mass stabilisation against loop corrections (fine-tuning problem)
  - unification of gauge couplings at single scale
  - dark matter candidate: Lightest supersymmetric particle (LSP)

# SUSY particle spectrum



SM particles have supersymmetric partners that differ by ½ unit in spin

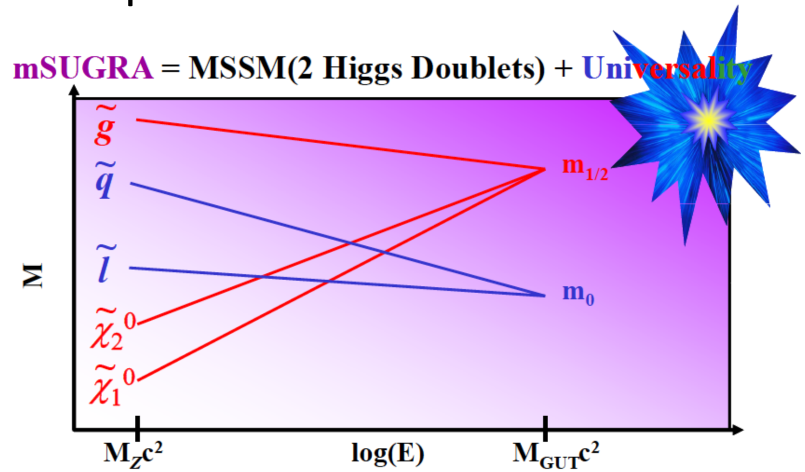
- sfermions: spin 0
  - squarks
  - sleptons
  - sneutrinos
- gauginos: spin ½
  - charginos / neutralinos
  - gluino
  - gravitino

- No SUSY particles found yet → SUSY must be broken
- Breaking mechanism affects phenomenology
  - more than 100 parameters even in "minimal" models like the Minimal Supersymmetric Standard Model (MSSM)

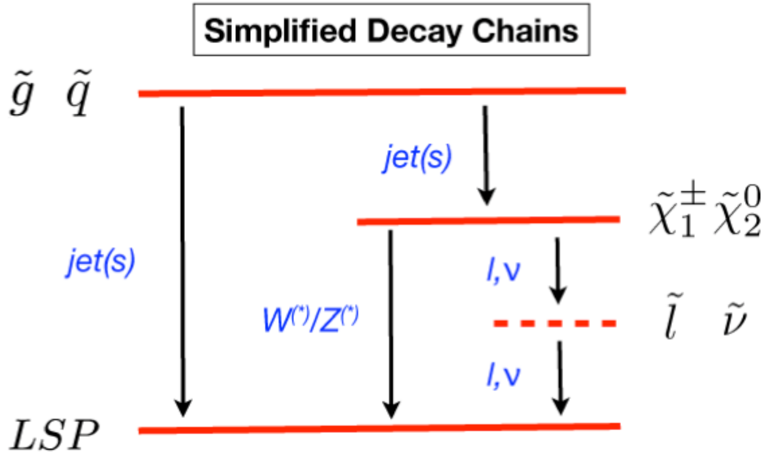
# Theoretical models

- Simplest extension of SM (MSSM) has > 100 new parameters
- How to test that at LHC?

1. Top-down approach
   - SUSY breaking mechanism ➞ different models
     - Gravity mediated (SUGRA)
     - Gauge mediated (GSMB)
     - …
   - GUT scale unification ➞ few free parameters

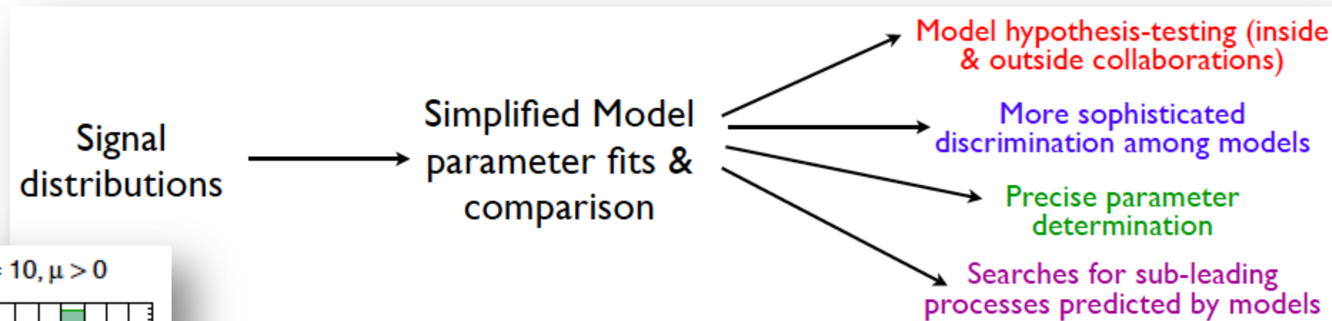


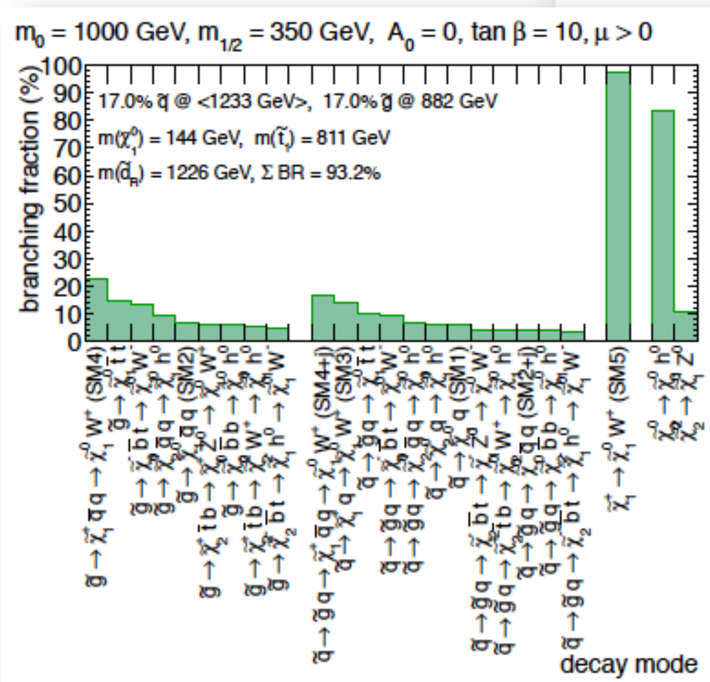

2. Bottom-up approach
   - Phenomenological models
     - assume masses and hierarchy
     - scan remaining parameters
   - Simplified models
     - specific decay chain



# Simplified ~~models~~ topologies

- Identifying the boundaries of search sensitivity
  - e.g., dependence of reconstruction and selection efficiencies on sparticle mass differences
- Characterising new physics signals



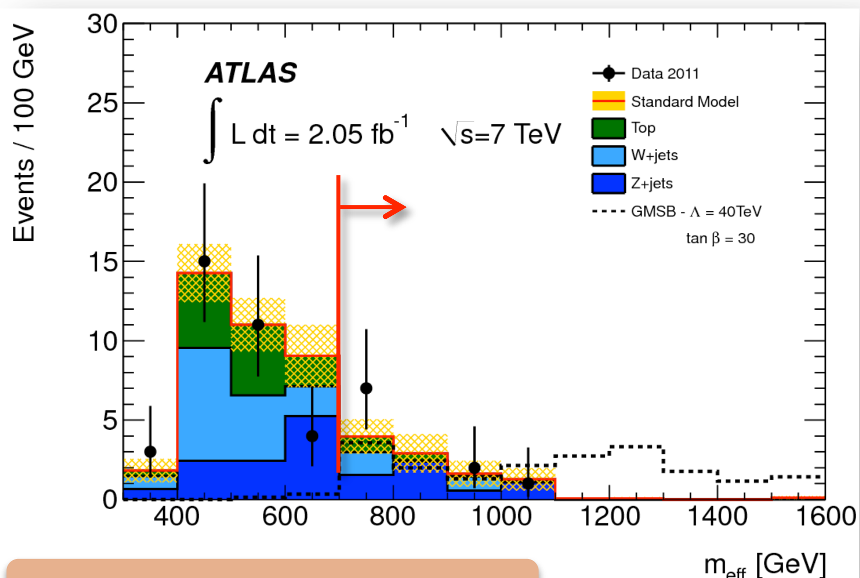

- Deriving limits on more general models
  - "project" model on set of topologies and use their σ×BR experimental limits to constrain model

Gütschow, Marshall, arXiv:1202.2662 [hep-ex]

# Typical $E_T^{miss}$-based analysis

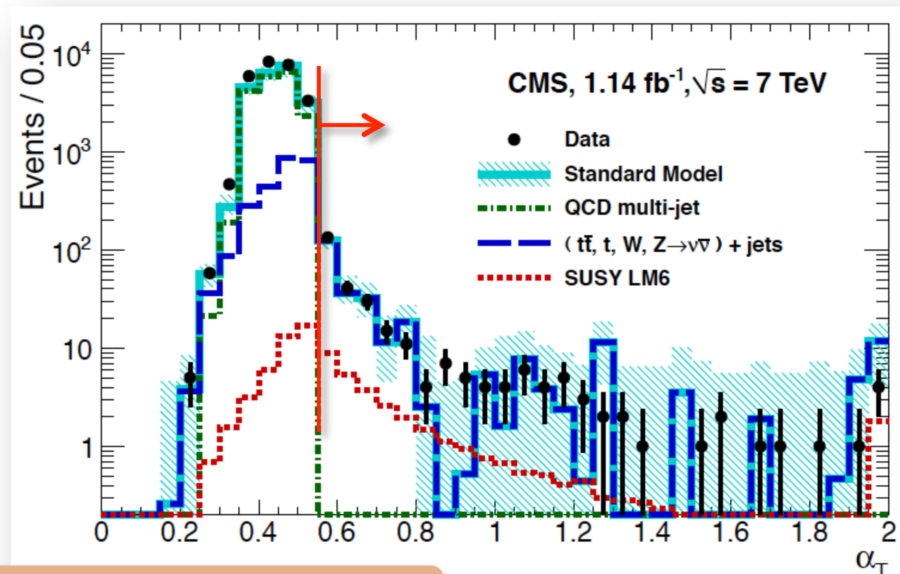
- Many jets + large $E_T^{miss}$ + leptons(incl. taus)/photons/bjets
- Cut sufficiently hard to reduce largely unknown background processes (fake MET, fake-leptons from QCD)
- Apply discriminating cuts to enhance signal/background ratio

**2τ + $E_T^{miss}$ analysis**




arXiv:1203.6580 [hep-ex]

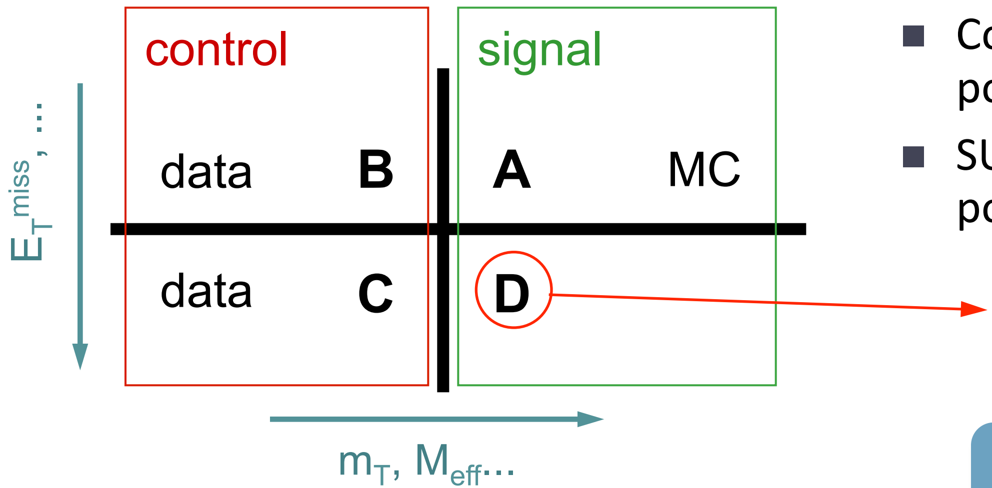
**all-hadronic analysis**




PRL 107, 221804 (2011)

# More on analysis techniques

- Background estimation from data: measure bkg in a 'control' sample and propagate this measurement to the 'signal' sample



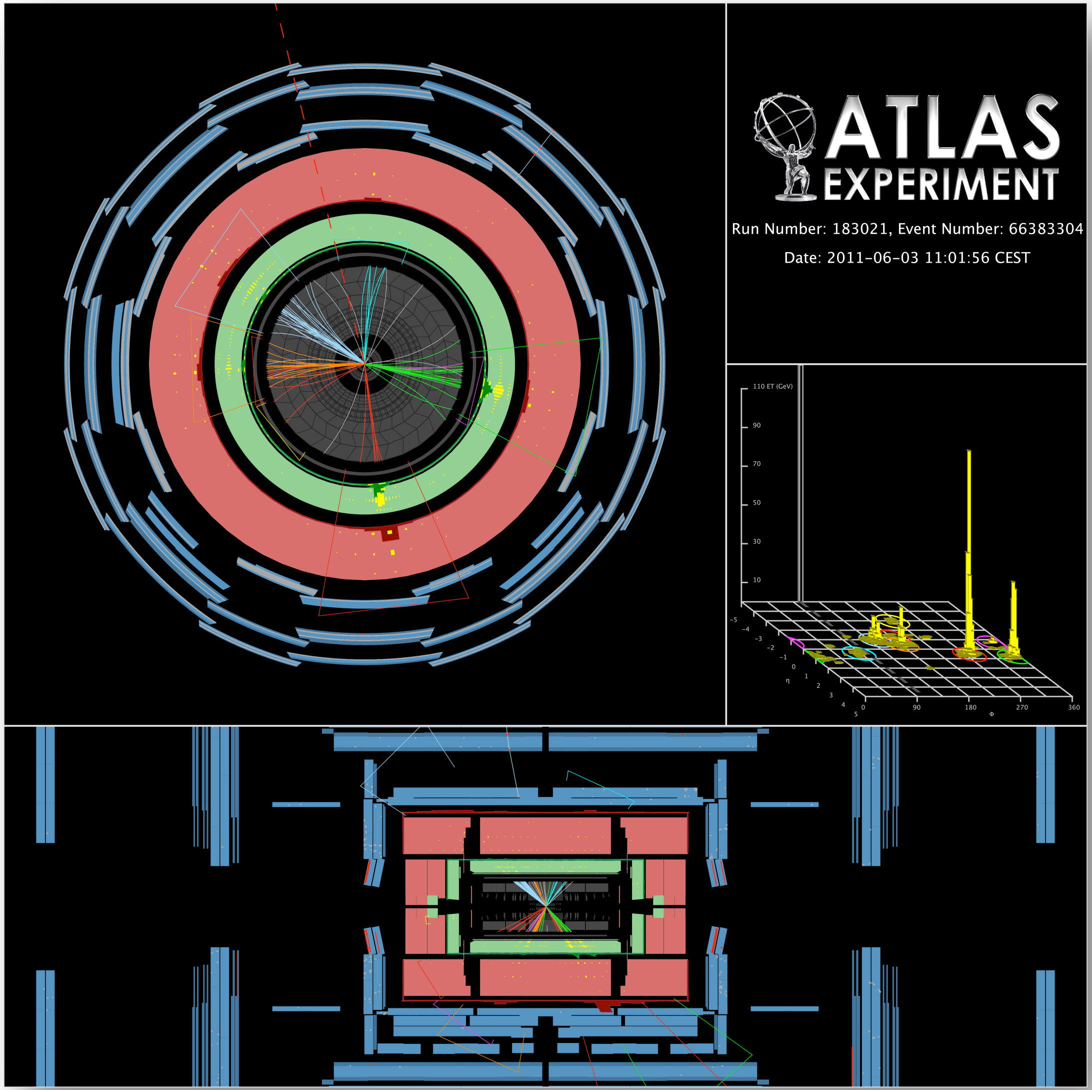

- Control region should be as close as possible to signal region
- SUSY contamination should be as low as possible

**D = A × C/B**

see also Cabrera, Casas, VAM, Ruiz de Austri, Terron, JHEP1204 (2012) 133

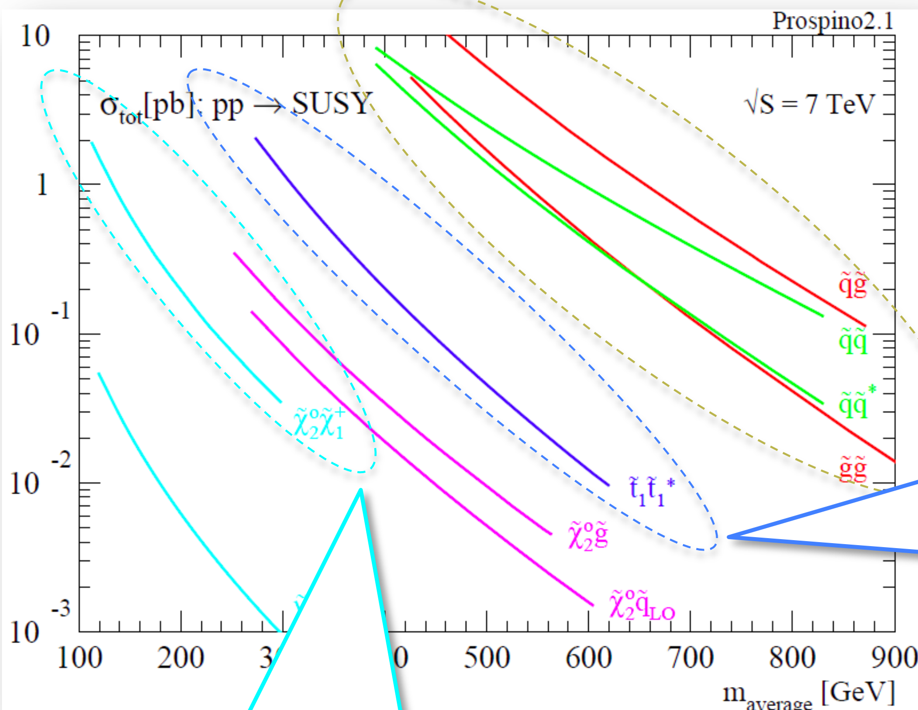
- Using distribution shape (ATLAS)
  - fit to jet multiplicity distribution in background control regions
  - likelihood is extended to include bin-by-bin $M_{eff}$ information
- Neural networks (CMS)
  - artificial neural network (ANN) to suppress SM backgrounds
- Templates method (CMS)

# A high-missing-$E_T$ high-$M_{eff}$ event




- $M_{eff}$ = 1810 GeV
- MET = 460 GeV
- 5 jets with $p_T$ > 40 GeV (528, 418, 233, 171 and 42 GeV)

# SUSY searches strategy




**Strong-production channels**
- Copious production at hadron colliders
- $E_T^{miss}$-based generic search channels
- Plus more exotic channels

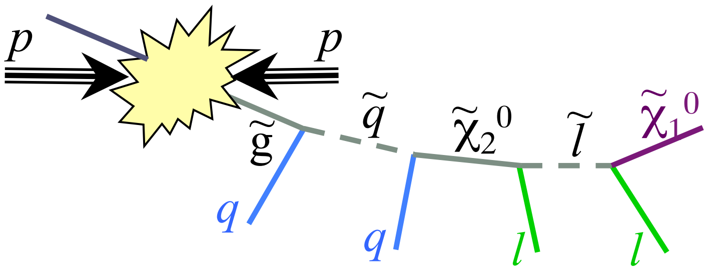
**Third-generation sparticle searches**
- Expected from naturalness to be *O*(<TeV)
- Expected lighter than other squarks due to mixing
- Can search for specific final states involving b-jets and maybe leptons

**Leptons/photons searches**
- colored spartners too heavy
  → direct gaugino production
- RPV decays
- gauge-mediated models

- Complementarity of channels without/ with leptons
- Small mass splittings (compressed spectra) require specific channels

# Strong production – top-down approach

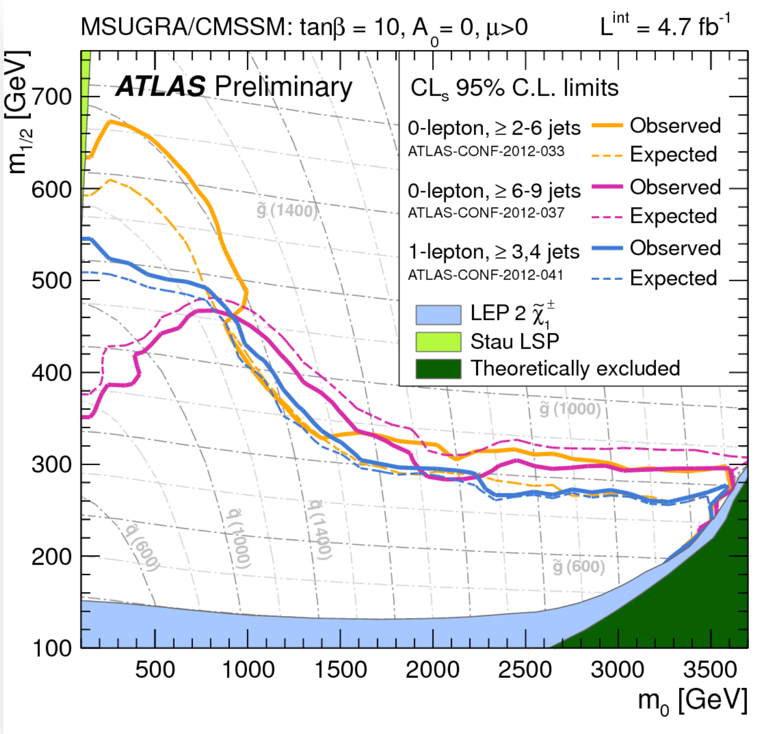
- SUSY particles mainly produced via strong interaction (gluino, squarks) at hadron colliders
- If R-parity is conserved:
  - sparticles produced by pair
  - cascade decay to invisible LSP
- ⇒ Search for jets + $E_T^{miss}$ + 0,1,2-leptons




## Benchmark interpretation in CMSSM

- Exclude m ~ 1400 GeV for m(~q) = m(~g)
- 3 very different analysis confirm exclusion limit at high $m_0$

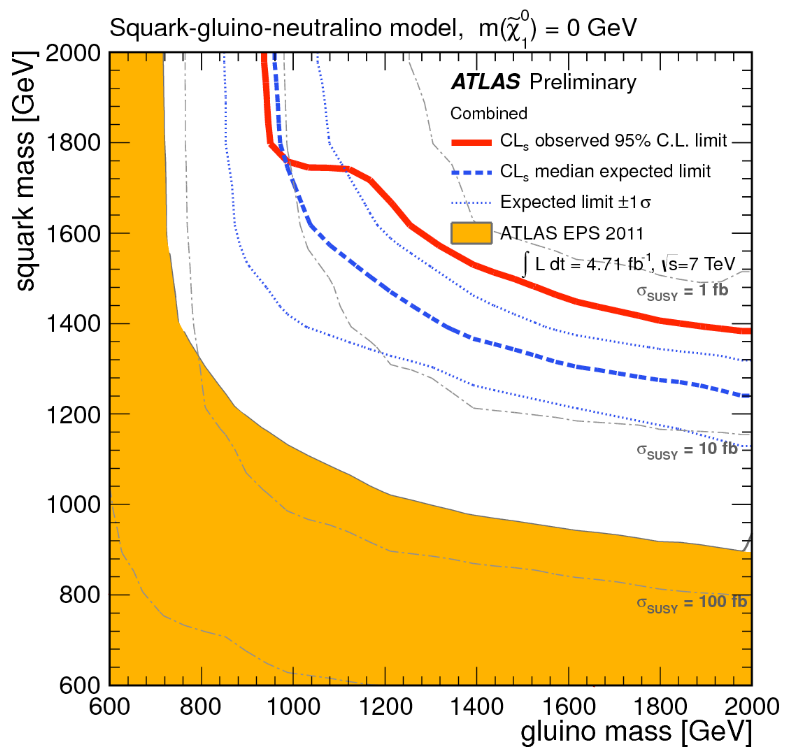
ATLAS-CONF-2012-041



# Strong production – bottom-up interpretations

## Pheno MSSM model

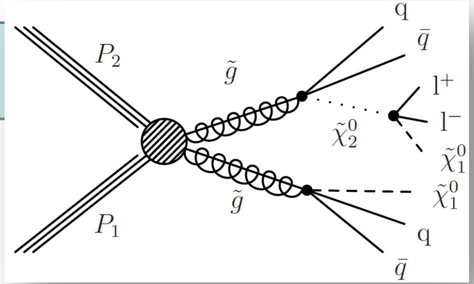
- Only gluino + squark + (light) LSP
- 0-lepton + jets + MET

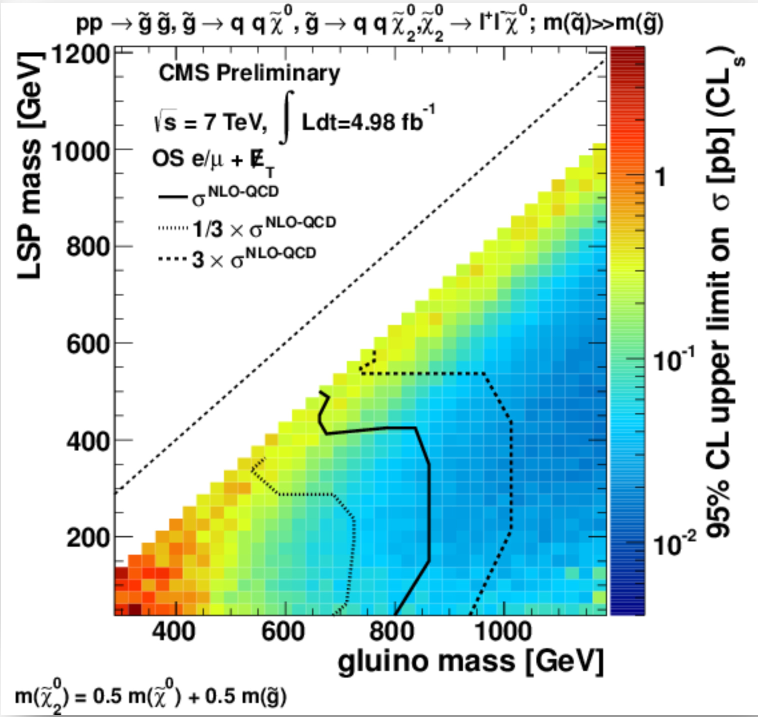



ATLAS-CONF-2012-033

## Simplified model

- Only gluino + ~$\chi_2^0$ + LSP are accessible
- OS dilepton + MET + HT

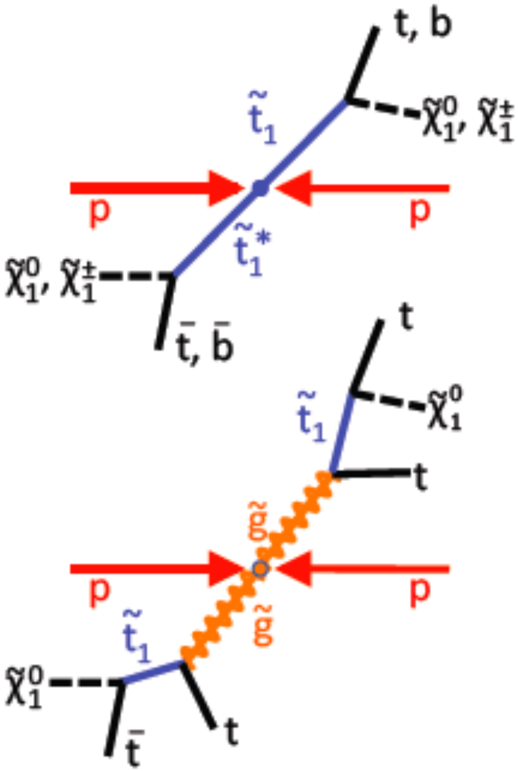





CMS-PAS-SUS-11-016

# Third-generation squarks

- Main motivation for TeV-scale SUSY is solving hierarchy problem
- If SUSY solves the hierarchy problem **naturally**, then 3rd gen. squarks must be light (few hundred GeV)

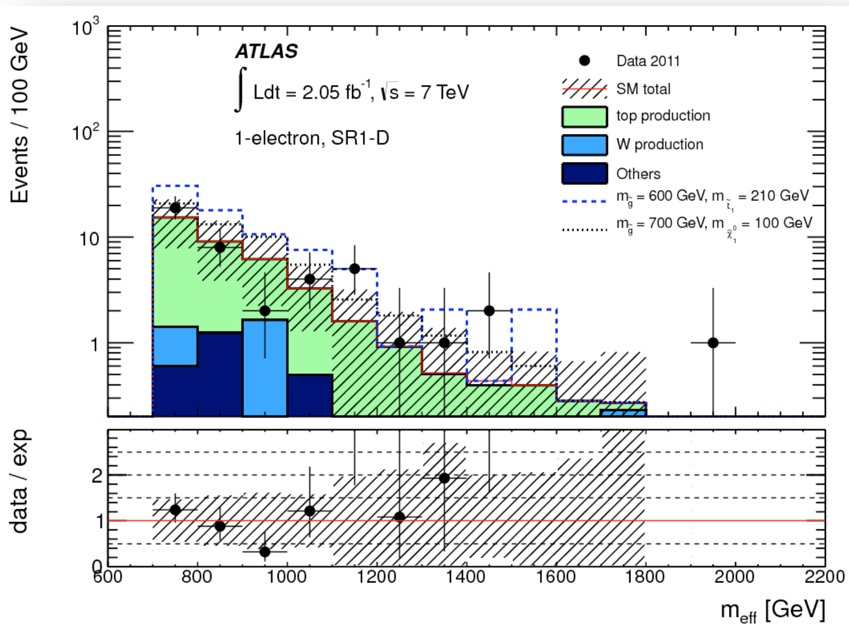



**Possible search strategies**

- If gluino is light enough ➞ dominant process
  - gluino pair production
  - $\tilde{g} \to b\tilde{b}_1, \tilde{g} \to t\tilde{t}_1$
  - search for b-jets + MET + jets
- If only 3rd gen. squarks are light
  - sbottom pair production ➞ 2 b-jets + MET
  - stop pair production ➞ 2 opposite-sign leptons + MET + jets

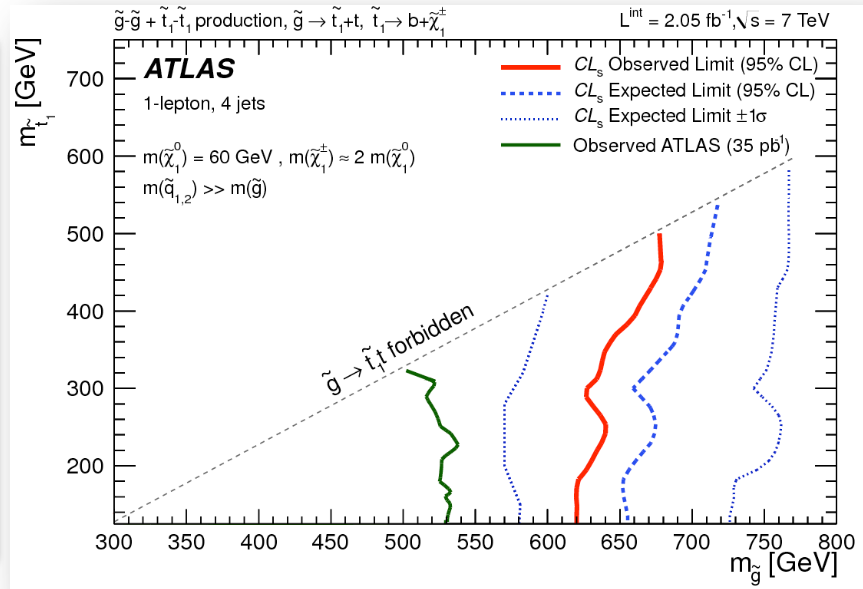
# Gluino-mediated stop production: 1ℓ + b-jets

- Event selection
  - exactly 1e(μ) with $p_T >$ 25 (20) GeV
  - at least 4 jets with $p_T >$ 50 GeV, 1 b-jet
  - $m_T > 100$ GeV; $m_{eff} > 700$ GeV
  - $E_T^{miss} > 80$ GeV or 200 GeV




arXiv:1203.6193 [hep-ex]

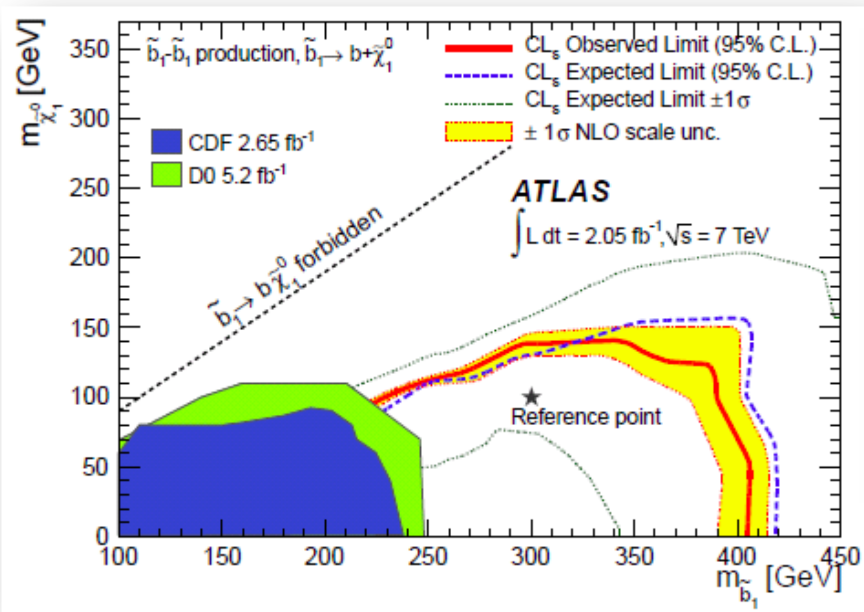
- MSSM scenario considering both gluino-mediated and direct stop production

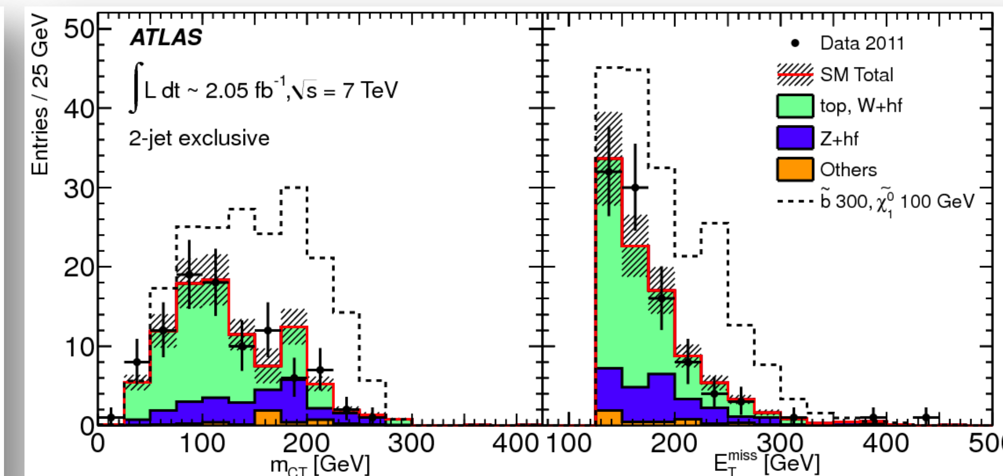



- No significant excess is observed wrt SM bkg
- m(gluino) < 620 GeV excluded for m(stop) < 440 GeV

# Direct sbottom pair production

- Signature: exactly 2 b-jets + $E_T^{miss}$ → use flavour tagging
- Interpretations: pheno model with $Br(\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0) = 1$




$$m_{CT}^2(v_1, v_2) \equiv [E_T(v_1) + E_T(v_1)]^2 - [\mathbf{p_T}(v_1) - \mathbf{p_T}(v_1)]^2$$

$$m_{CT} \propto (m_{\tilde{b}_1} - m_{\tilde{\chi}_1^0})^2 / m_{\tilde{b}_1}$$

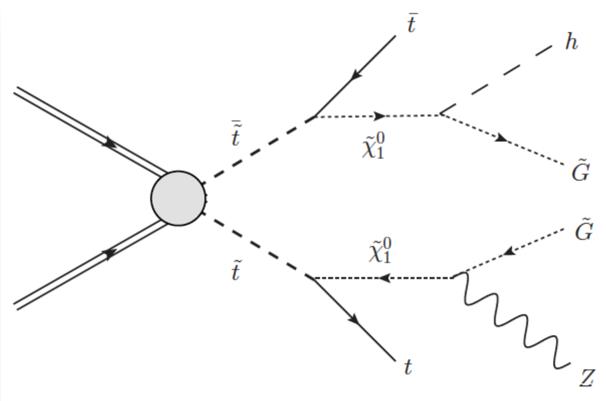
PRL 108 (2012) 181802

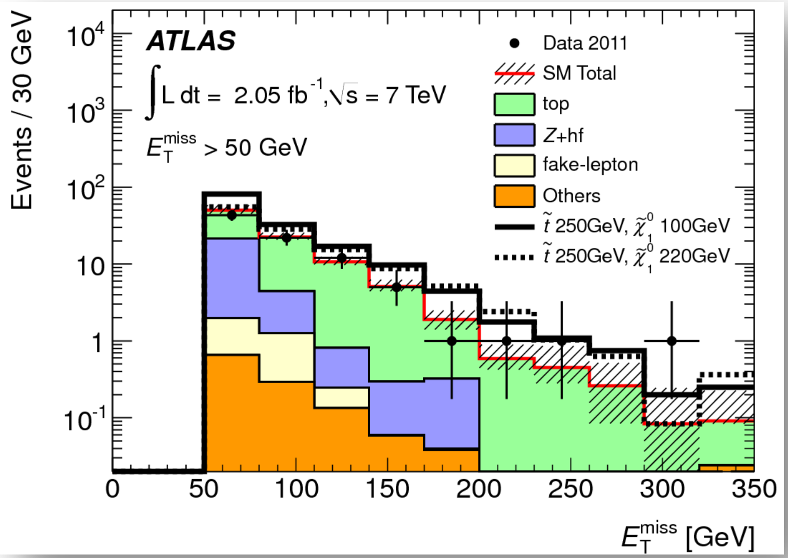
- Excluding sbottom mass < 380 GeV for neutralino masses up to ~ 100 GeV

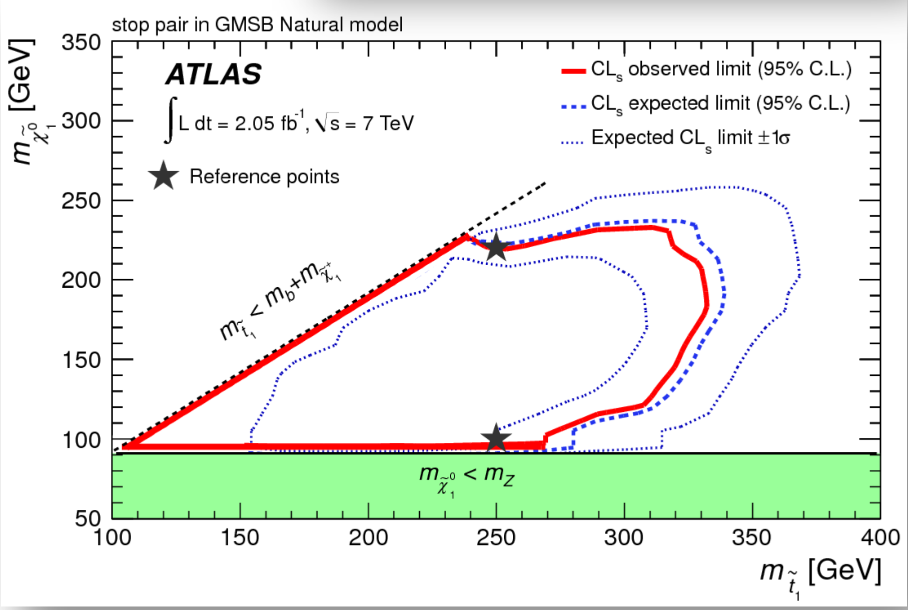
# Direct stop production

arXiv:1204.6736 [hep-ex]

- Event selection: 1 b-jet, 2 OSSF leptons consistent with $m_Z$, MET and jets
- Exclusion
  - neutralino masses below 220 GeV for stop masses below 270 GeV
  - stop masses below 310 GeV for 125 GeV < m(~$\chi_1^0$) < 220 GeV



# Direct weak gaugino production

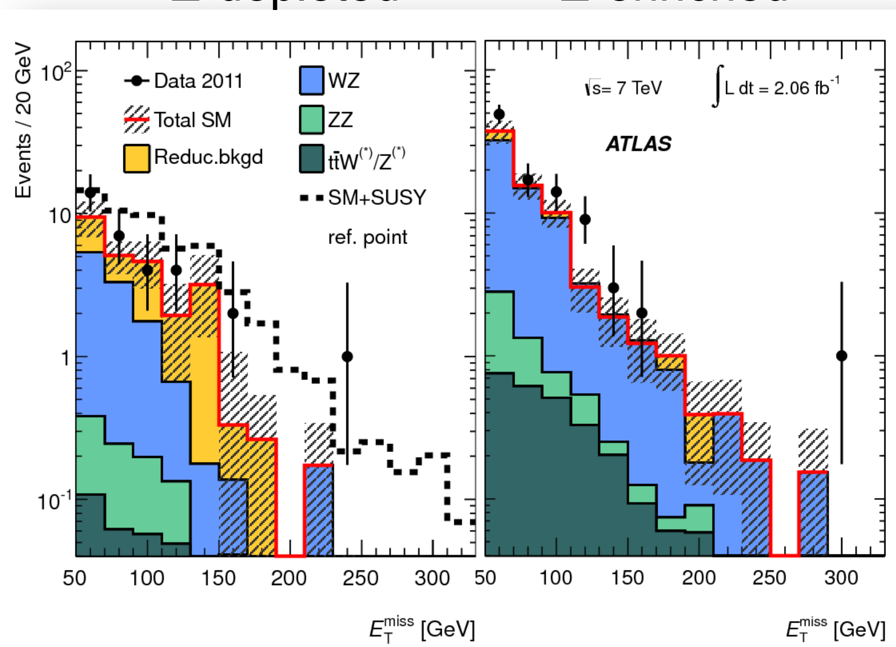
arXiv:1204.5638 [hep-ex]

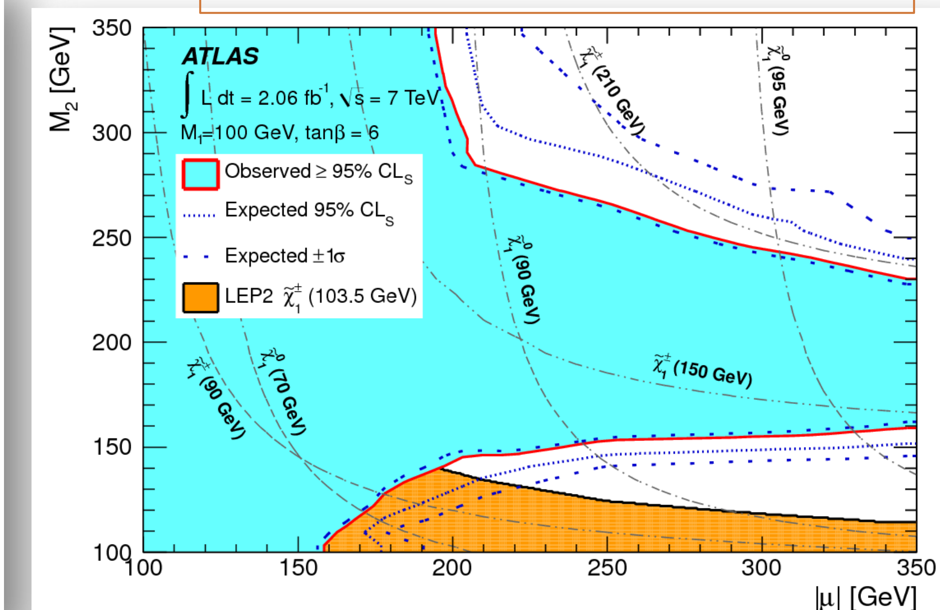
- If both gauginos decay leptonically ➞ 3 leptons + high MET
- Selection
  - exactly 3 leptons; $E_T^e > 25$ GeV, $p_T^\mu > 20$ GeV ; one SFOS pair
  - MET > 20 GeV

pMSSM $m_{\tilde{q}}, m_{\tilde{g}}, m_{\tilde{\ell}_R} > 1\ \mathrm{TeV}$

$$m_{\tilde{\ell}_L} = (m_{\tilde{\chi}_2^\pm} + m_{\tilde{\chi}_1^0})/2$$

Z-depleted Z-enriched



# Searches for R-parity violating SUSY

- eμ final states
- multi-lepton signatures
- bilinear RPV

# R-parity violation (RPV)

- R-parity: R = $(-1)^{3(B-L)+2s}$ → R = $\begin{cases} +1, \text{ for SM particles} \\ -1, \text{ for superpartners} \end{cases}$

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

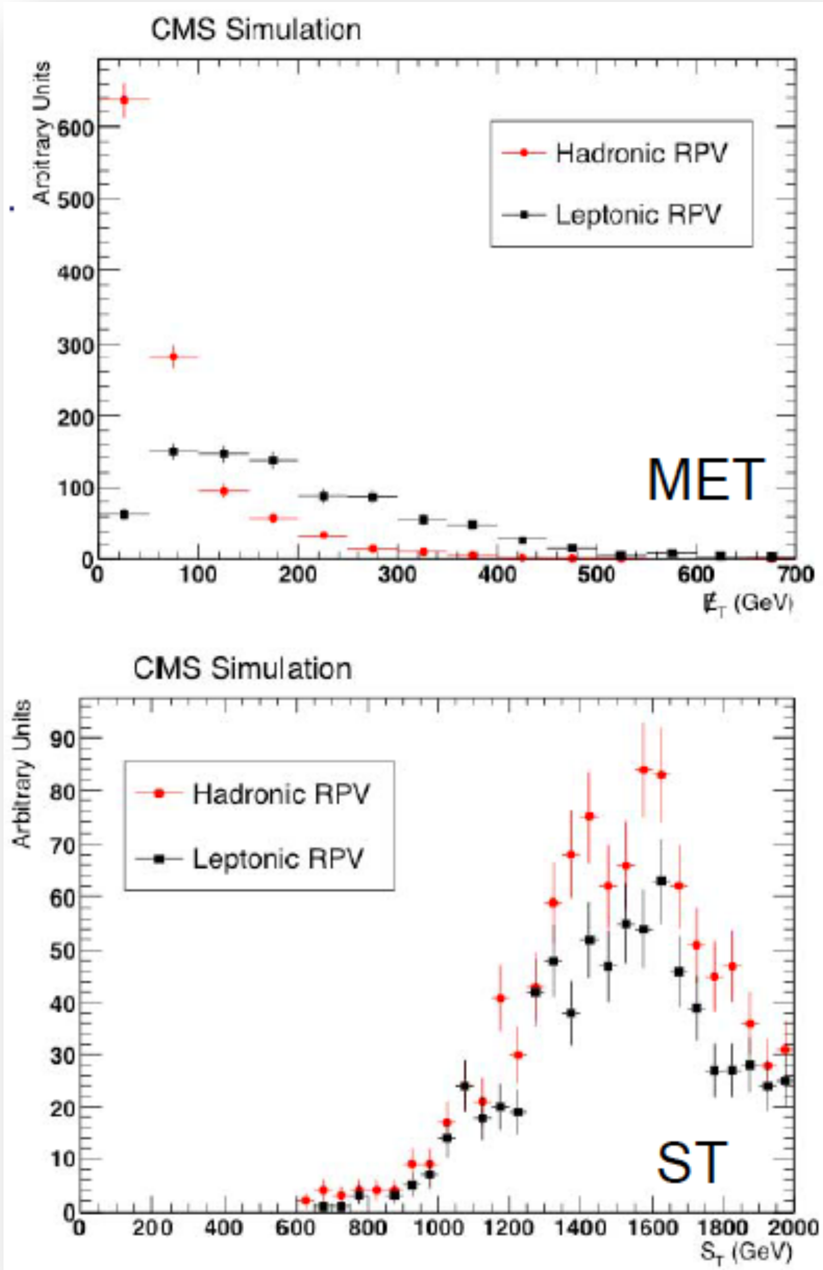
bilinear terms: $\epsilon_i\hat{L}_i\hat{H}_u$

- R-parity conservation hinted but not required by proton stability

| Rp conservation | Rp violation |
|---|---|
| Sparticles produced in pairs | Single sparticle production possible |
| Neutral and colorless LSP | LSP may be charged and/or carry color |
| Stable LSP ➞ gives rise to high missing momentum | LSP decays ➞ possibility for new signals<br>• potentially long LSP lifetime<br>• MET may or may not be high<br>• exploit LSP invariant mass |

# RPV SUSY at LHC

- LSP decays to SM particles
  → no MET in trilinear RPV
- Examine $S_T$ instead
  - $S_T$ = sum of jet+lepton $p_T$'s and MET
  - a.k.a. "inclusive effective mass"
- $S_T$ recovers the low-MET signal
- Many signal regions explored by CMS
  - MET and $H_T$ selection
  - ST selection
  - electrons, muons and taus




- Leptonic RPV: lepton number violation, λ, λ'
- Hadronic RPV: baryon number violation, λ'''

# Multilepton signals

| Selection | N(τ)=0 obs | N(τ)=0 expect | N(τ)=1 obs | N(τ)=1 expect | N(τ)=2 obs | N(τ)=2 expect |
|---|---|---|---|---|---|---|
| **4ℓ Lepton Results** | | | | | | |
| 4ℓ (DY0) $S_T$(High) | 0 | 0.0010 ± 0.0009 | 0 | 0.01 ± 0.09 | 0 | 0.18 ± 0.07 |
| 4ℓ (DY0) $S_T$(Mid) | 0 | 0.004 ± 0.002 | 0 | 0.28 ± 0.10 | 2 | 2.5 ± 1.2 |
| 4ℓ (DY0) $S_T$(Low) | 0 | 0.04 ± 0.02 | 0 | 2.98 ± 0.48 | 4 | 3.5 ± 1.1 |
| 4ℓ (DY1, no Z) $S_T$(High) | 1 | 0.009 ± 0.004 | 0 | 0.10 ± 0.07 | 0 | 0.12 ± 0.05 |
| 4ℓ (DY1, Z) $S_T$(High) | 1 | 0.09 ± 0.01 | 0 | 0.51 ± 0.15 | 0 | 0.43 ± 0.15 |
| 4ℓ (DY1, no Z) $S_T$(Mid) | 0 | 0.07 ± 0.02 | 1 | 0.88 ± 0.26 | 1 | 0.94 ± 0.29 |
| 4ℓ (DY1, Z) $S_T$(Mid) | 0 | 0.45 ± 0.11 | 5 | 4.1 ± 1.2 | 3 | 3.4 ± 0.9 |
| 4ℓ (DY1, no Z) $S_T$(Low) | 0 | 0.09 ± 0.04 | 7 | 5.5 ± 2.2 | 19 | 13.7 ± 6.4 |
| 4ℓ (DY1, Z) $S_T$(Low) | 2 | 0.80 ± 0.34 | 19 | 17.7 ± 4.9 | 95 | 60 ± 31 |
| 4ℓ (DY2, no Z) $S_T$(High) | 0 | 0.02 ± 0.01 | – | – | – | – |
| 4ℓ (DY2, Z) $S_T$(High) | 0 | 0.89 ± 0.34 | – | – | – | – |
| 4ℓ (DY2, no Z) $S_T$(Mid) | 0 | 0.20 ± 0.09 | – | – | – | – |
| 4ℓ (DY2, Z) $S_T$(Mid) | 3 | 7.9 ± 3.2 | – | – | – | – |
| 4ℓ (DY2, no Z) $S_T$(Low) | 1 | 2.4 ± 1.1 | – | – | – | – |
| 4ℓ (DY2, Z) $S_T$(Low) | 29 | 29 ± 12 | – | – | – | – |
| **3ℓ Lepton Results** | | | | | | |
| 3ℓ (DY0) $S_T$(High) | 2 | 1.14 ± 0.43 | 17 | 11.2 ± 3.2 | 20 | 22.5 ± 6.1 |
| 3ℓ (DY0) $S_T$(Mid) | 5 | 7.4 ± 3.0 | 113 | 97 ± 31 | 157 | 181 ± 24 |
| 3ℓ (DY0) $S_T$(Low) | 17 | 13.5 ± 4.1 | 522 | 419 ± 63 | 1631 | 2018 ± 253 |
| 3ℓ (DY1, no Z) $S_T$(High) | 6 | 3.5 ± 0.9 | 10 | 13.1 ± 2.3 | – | – |
| 3ℓ (DY1, Z) $S_T$(High) | 17 | 18.7 ± 6.0 | 35 | 39.2 ± 4.8 | – | – |
| 3ℓ (DY1, no Z) $S_T$(Mid) | 32 | 25.5 ± 6.6 | 159 | 141 ± 27 | – | – |
| 3ℓ (DY1, Z) $S_T$(Mid) | 89 | 102 ± 31 | 441 | 463 ± 41 | – | – |
| 3ℓ (DY1, no Z) $S_T$(Low) | 126 | 150 ± 36 | 3721 | 2983 ± 418 | – | – |
| 3ℓ (DY1, Z) $S_T$(Low) | 727 | 815 ± 192 | 17631 | 15758 ± 2452 | – | – |
| Total 4ℓ | 37 | 42 ± 13 | 32.0 | 32.1 ± 5.5 | 124 | 85 ± 32 |
| Total 3ℓ | 1021 | 1137 ± 198 | 22649 | 19925 ± 2489 | 1808 | 2222 ± 255 |
| Total | 1058 | 1179 ± 198 | 22681 | 19957 ± 2489 | 1932 | 2307 ± 257 |

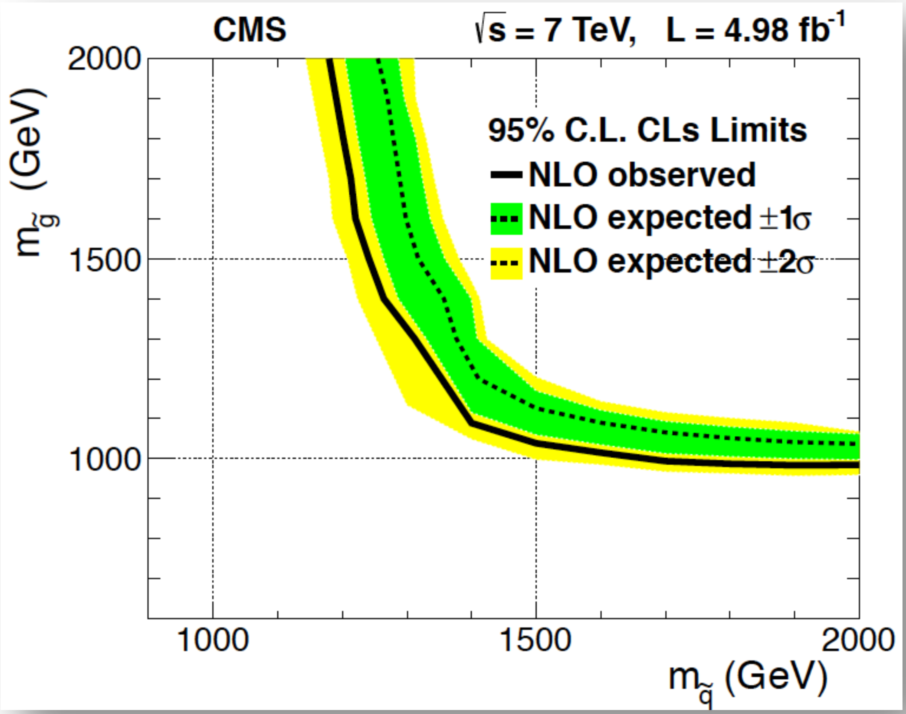
No significant excess of events observed so far

ℓ: e, μ, τ

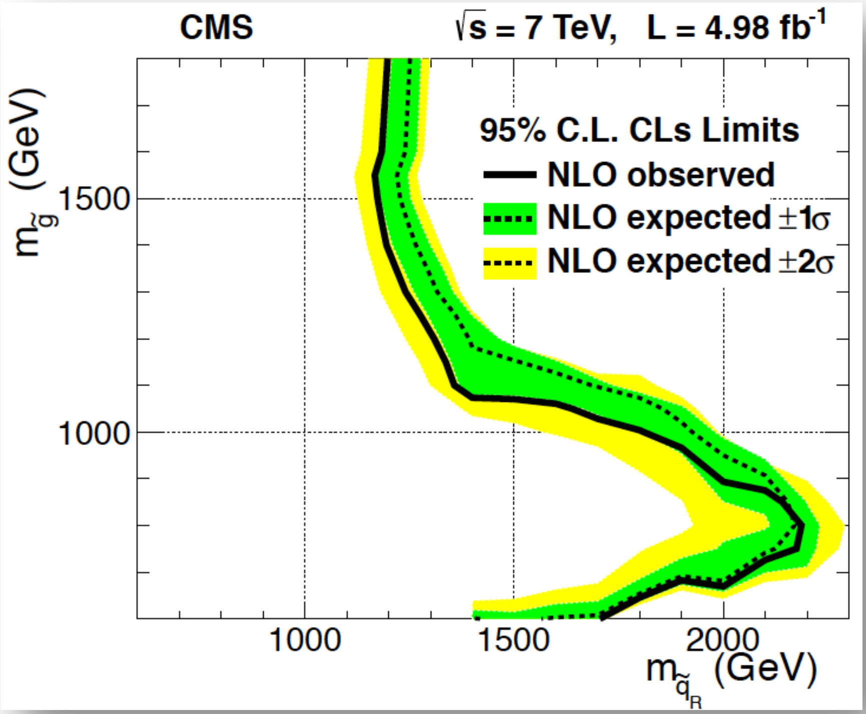
CMS, arXiv:1204.5341 [hep-ex]

# Multileptons: constraints on RPV models

- Gluino vs. squark masses in GMSB RPV



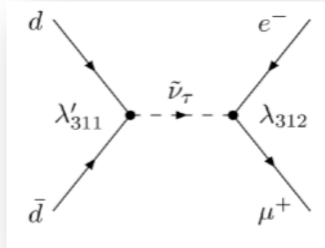

$\lambda_{e\mu\tau}$ – L-RPV




$\lambda''_{uds}$ – H-RPV

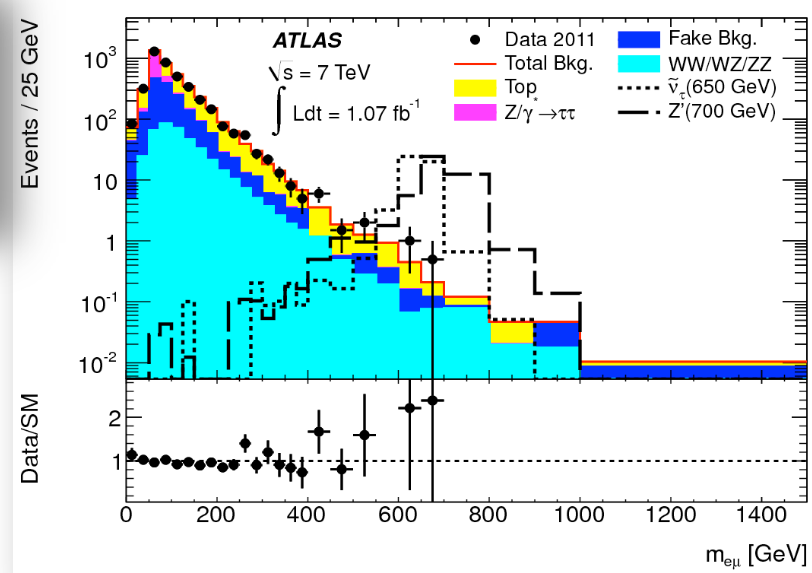
arXiv:1204.5341 [hep-ex]

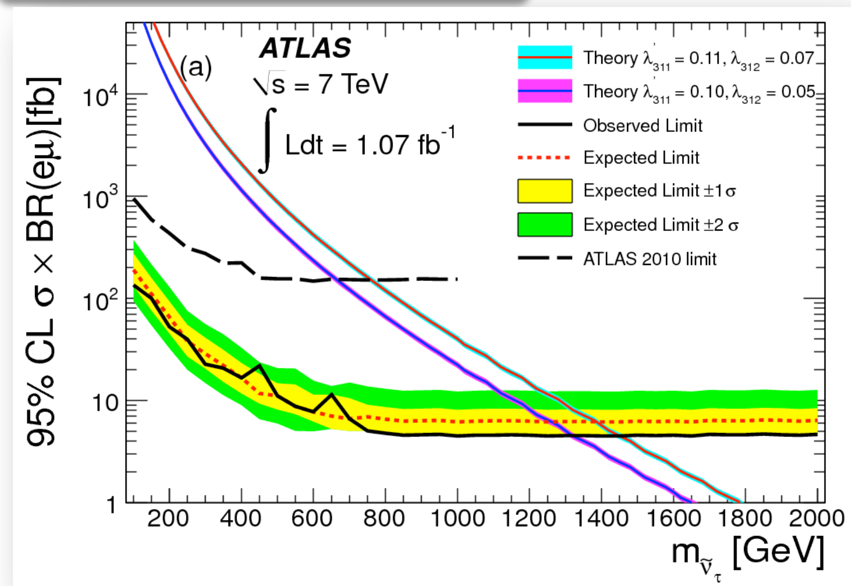
# eμ resonance

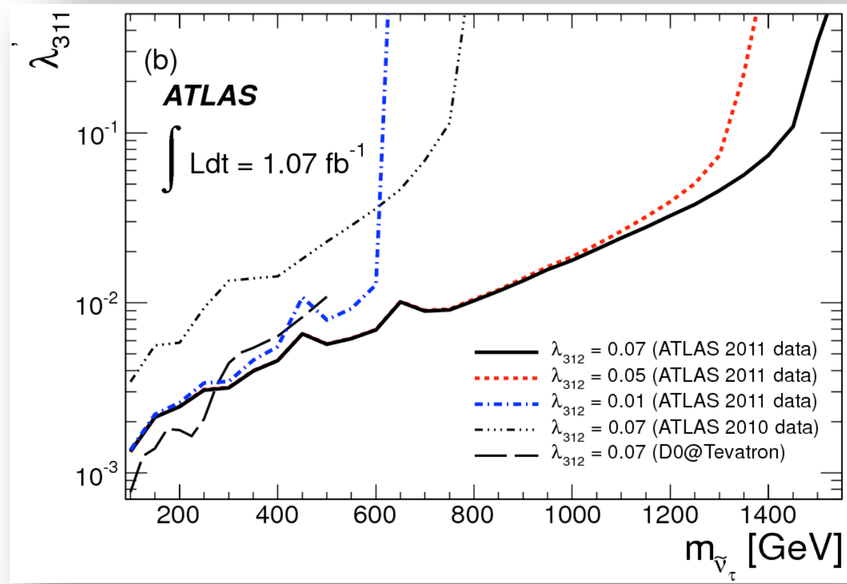



- Search for an excess in high eμ invariant mass
- Clean signal: look for exactly one isolated **electron** and exactly one isolated **muon** with opposite charge and $p_T$ > 25 GeV

EPJC 71 (2011) 1809



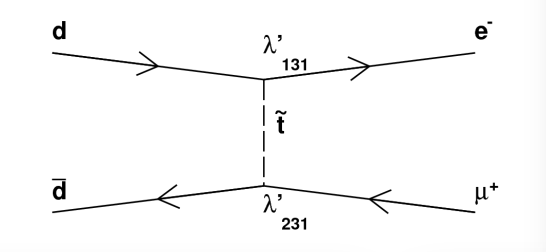



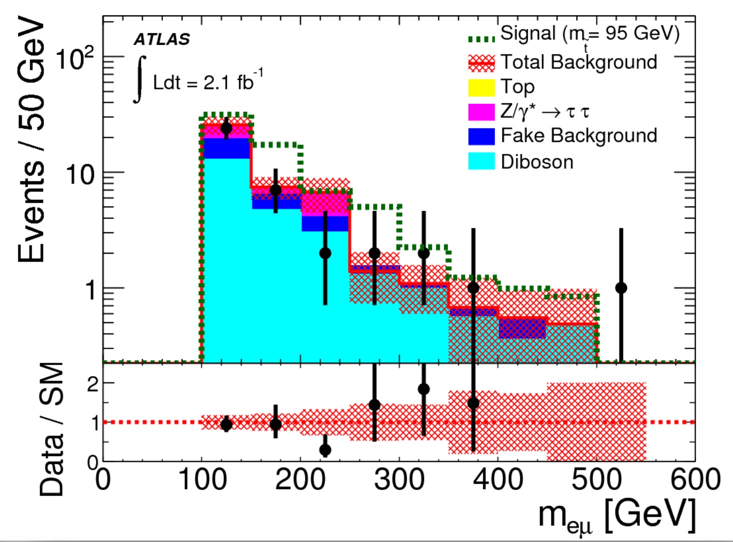



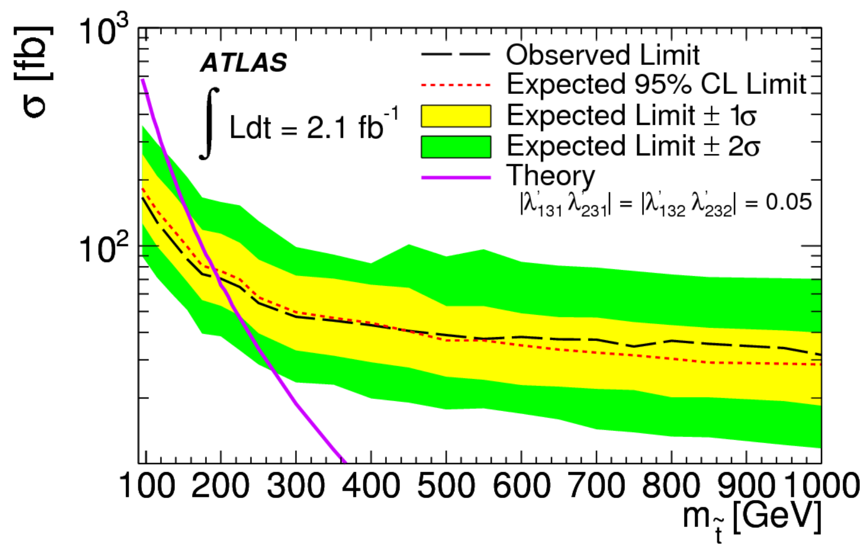
# eμ continuum

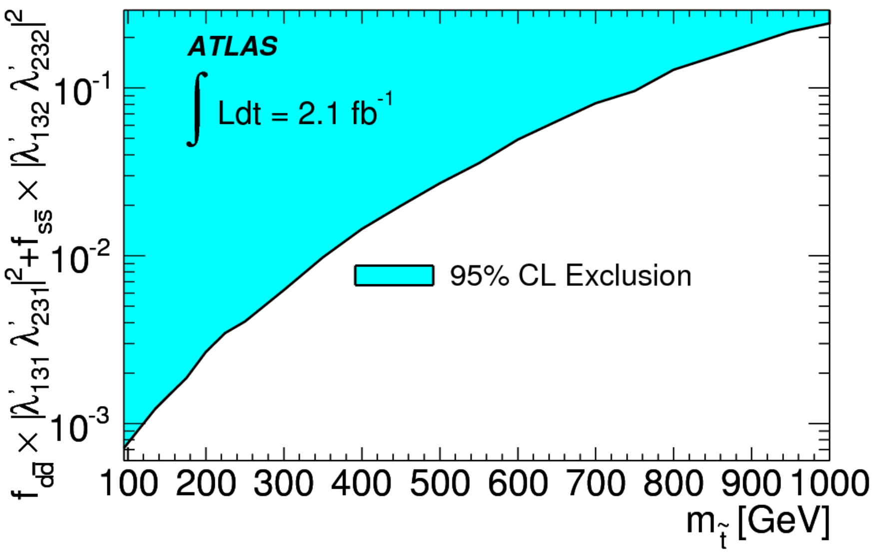
arXiv:1205.0725 [hep-ex]

- Similar lepton selection criteria as for eμ resonance
  - $m_{e\mu} > 100$ GeV
  - $\Delta\phi_{e\mu} > 3$
  - MET < 25 GeV



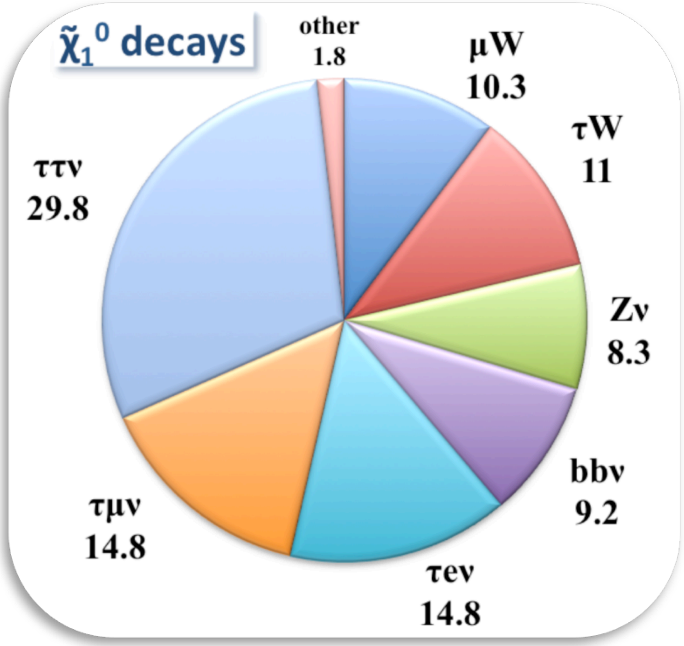



# Bilinear RPV

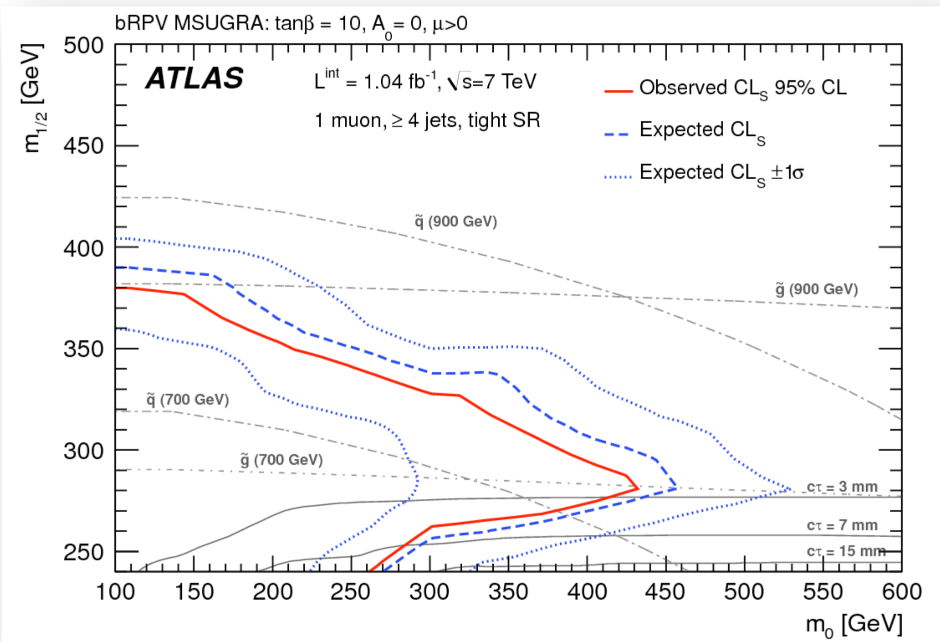
Valle, Hirsch, Porod, Romao, et al

- Bilinear R-parity violating (bRPV) terms in superpotential introduce **neutrino masses and mixings** in an natural way
  - RPV parameters constrained by neutrino measurements: $\Delta m_{atm}^2$, $\Delta m_{sol}^2$, $\tan^2\theta_{atm}$, $\tan^2\theta_{sol}$
- bRPV couplings embedded in mSUGRA
  - same cascade decay
  - LSP decays at the end
- Large variety of final states
  - most involve leptons and taus
- Features high MET originating mainly from various LSP decays to neutrinos



# Bilinear RPV & 1-lepton analysis

- Event selection:
  - exactly one isolated muon with $p_T > 20$ GeV
  - veto for events with at least one electron with $p_T > 20$ GeV
  - requiring 3 or 4 jets with loose or tight cuts




PRD 85 (2012) 012006

| Muon channel | | |
|---|---|---|
| Signal region | Observed | Fitted background |
| 3JL | 58 | 64 ± 19 |
| 3JT | 11 | 13.9 ± 4.3 |
| 4JL | 50 | 53 ± 16 |
| 4JT | 7 | 6.0 ± 2.7 |

- 95% CL exclusion limits for mSUGRA bRPV

# Searches for long-lived particles

- displaced vertices

# Long-lived particles in SUSY

- GMSB: NLSP decays to LSP ($\tilde{G}$) only via the (small) gravitational coupling
  - N$_{mes}$=1: **non-pointing photons**

$$\tilde{\chi}_1^0 \rightarrow \tilde{G} + \gamma$$

  - N$_{mes}$>1: **penetrating sleptons**

$$\tilde{\ell} \xrightarrow{\text{long}} \tilde{G} + \ell$$

- Split SUSY: squarks are heavy, suppressing **gluino** decays
  - colored heavy particles (**R-hadrons**)

$$R = \tilde{g}q\bar{q},\ \tilde{g}qqq,\ \tilde{g}g$$

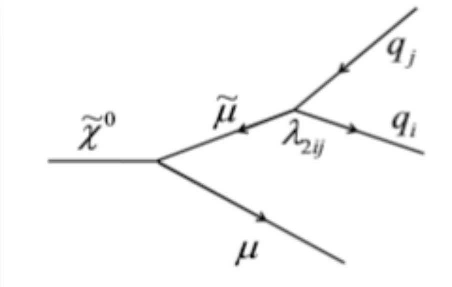
- AMSB (or in fine-tuned MSSM): $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ are mass degenerate
  - long-lived **chargino** (decay on flight → kink track)

$$\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 + \pi^\pm$$

| SMP | LSP | Scenario | Conditions |
|---|---|---|---|
| $\tilde{\tau}_1$ | $\tilde{\chi}_1^0$ | MSSM | $\tilde{\tau}_1$ mass (determined by $m^2_{\tilde{\tau}_{L,R}}$, $\mu$, $\tan\beta$, and $A_\tau$) close to $\tilde{\chi}_1^0$ mass. |
| | $\tilde{G}$ | GMSB | Large $N$, small $M$, and/or large $\tan\beta$. |
| | | $\tilde{g}$MSB | No detailed phenomenology studies, see [20]. |
| | | SUGRA | Supergravity with a gravitino LSP, see [21]. |
| | $\tilde{\tau}_1$ | MSSM | Small $m_{\tilde{\tau}_{L,R}}$ and/or large $\tan\beta$ and/or very large $A_\tau$. |
| | | AMSB | Small $m_0$, large $\tan\beta$. |
| | | $\tilde{g}$MSB | Generic in minimal models. |
| $\tilde{\ell}_{i1}$ | $\tilde{G}$ | GMSB | $\tilde{\tau}_1$ NLSP (see above). $\tilde{e}_1$ and $\tilde{\mu}_1$ co-NLSP and also SMP for small $\tan\beta$ and $\mu$. |
| | $\tilde{\tau}_1$ | $\tilde{g}$MSB | $\tilde{e}_1$ and $\tilde{\mu}_1$ co-LSP and also SMP when stau mixing small. |
| $\tilde{\chi}_1^+$ | $\tilde{\chi}_1^0$ | MSSM | $m_{\tilde{\chi}_1^+} - m_{\tilde{\chi}_1^0} \lesssim m_{\pi^+}$. Very large $M_{1,2} \gtrsim 2$ TeV $\gg |\mu|$ (Higgsino region) or non-universal gaugino masses $M_1 \gtrsim 4M_2$, with the latter condition relaxed to $M_1 \gtrsim M_2$ for $M_2 \ll |\mu|$. Natural in O-II models, where simultaneously also the $\tilde{g}$ can be long-lived near $\delta_{GS} = -3$. |
| | | AMSB | $M_1 > M_2$ natural. $m_0$ not too small. See MSSM above. |
| $\tilde{g}$ | $\tilde{\chi}_1^0$ | MSSM | Very large $m^2_{\tilde{q}} \gg M_3$, e.g. split SUSY. |
| | $\tilde{G}$ | GMSB | SUSY GUT extensions [22–24]. |
| | $\tilde{g}$ | MSSM | Very small $M_3 \ll M_{1,2}$, O-II models near $\delta_{GS} = -3$. |
| | | GMSB | SUSY GUT extensions [22–26]. |
| $\tilde{t}_1$ | $\tilde{\chi}_1^0$ | MSSM | Non-universal squark and gaugino masses. Small $m^2_{\tilde{q}}$ and $M_3$, small $\tan\beta$, large $A_t$. |
| $\tilde{b}_1$ | | | Small $m^2_{\tilde{q}}$ and $M_3$, large $\tan\beta$ and/or large $A_b \gg A_t$. |

Fairbairn et al, Phys Rept 438 (2007) 1

# Displaced vertices: analysis




- RPV: LSP decays 4 – 180 mm from the interaction point for couplings $\lambda'_{2ij} \neq 0$
- Search for high-impact-parameter vertices: **$|d_0| > 2$ mm**
  - trigger: high-$p_T$ muon
  - SM-particle late decays ➞ require high mass & high track multiplicity
  - overlap of high-$p_T$ track with hadronic interaction vertex ➞ veto to vertices reconstructed within regions of high-density material

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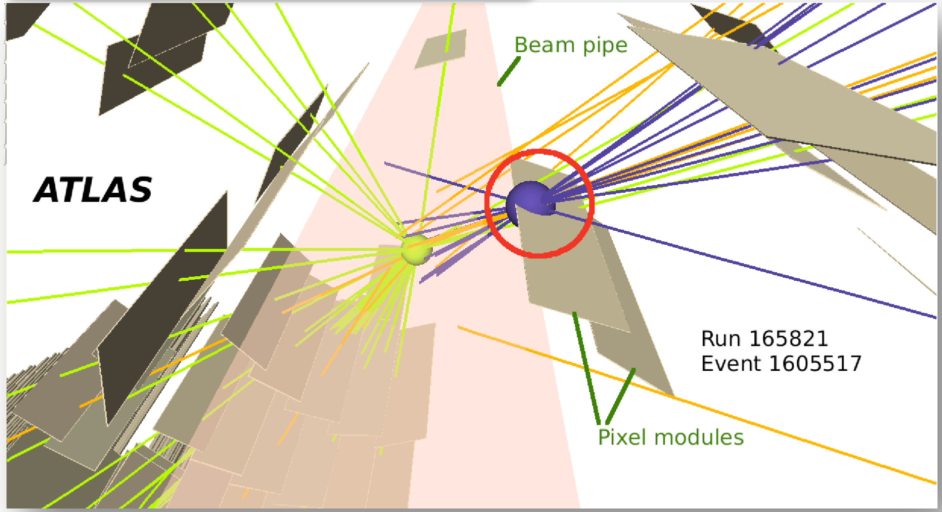


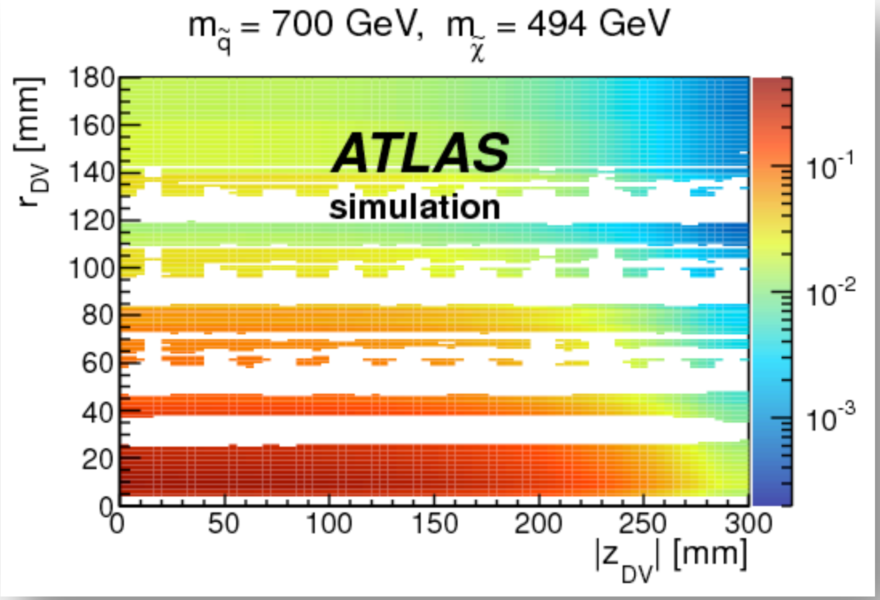

# Displaced vertices: results

- Number of events passing the selected requirements except for the $m_{DV}$ and $N_{DVtracks}$
- No data events observed in the signal region

- Upper exclusion limits at 95% CL for different squark and neutralino masses

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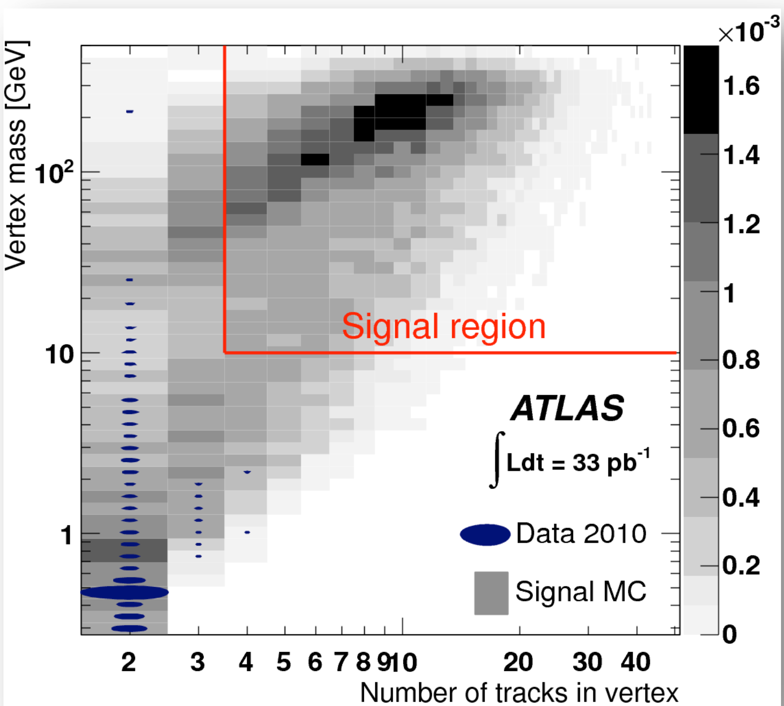
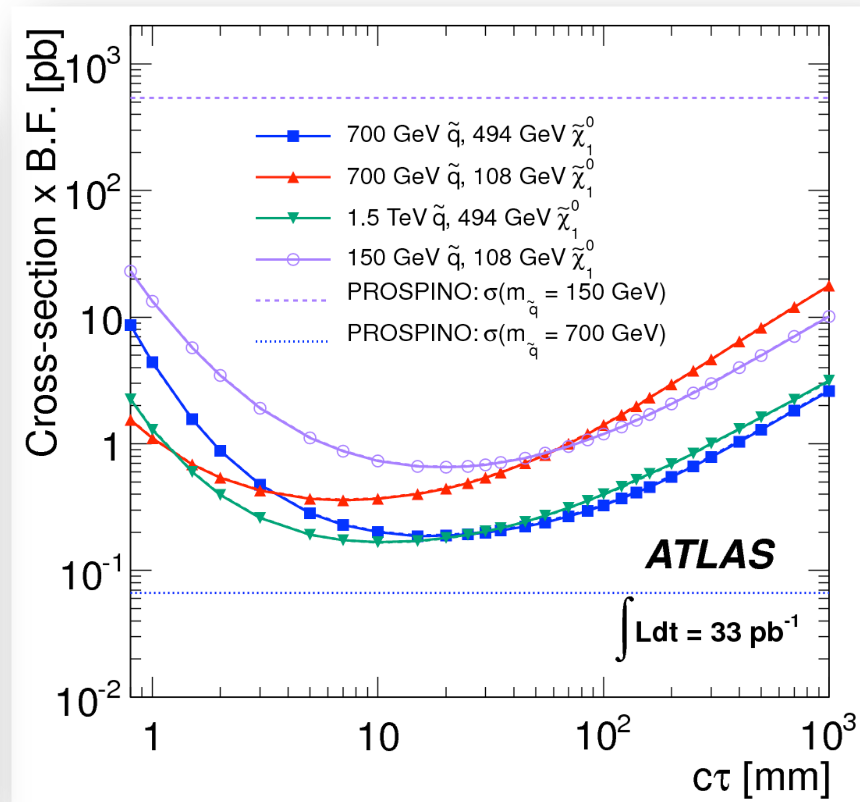
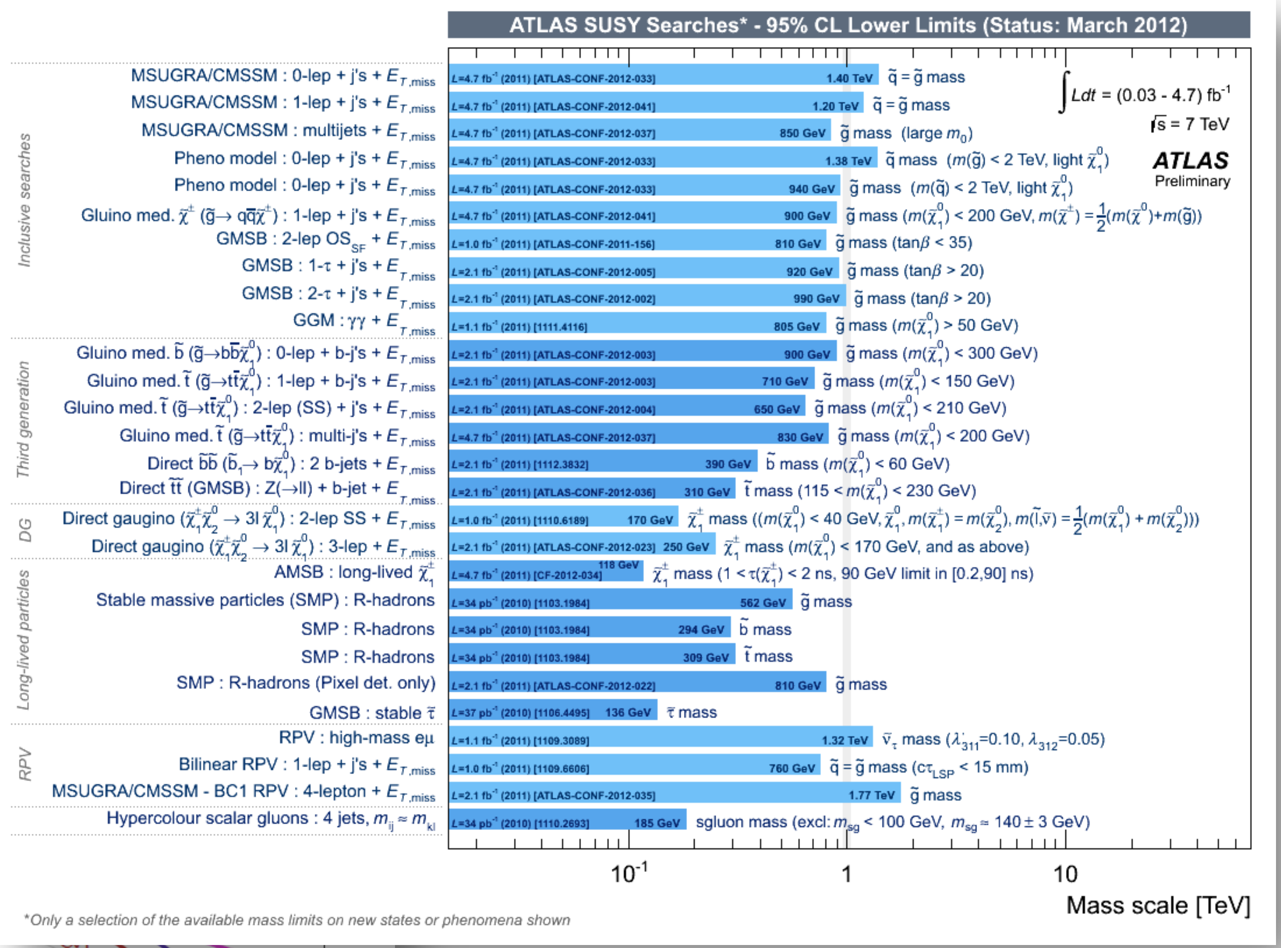
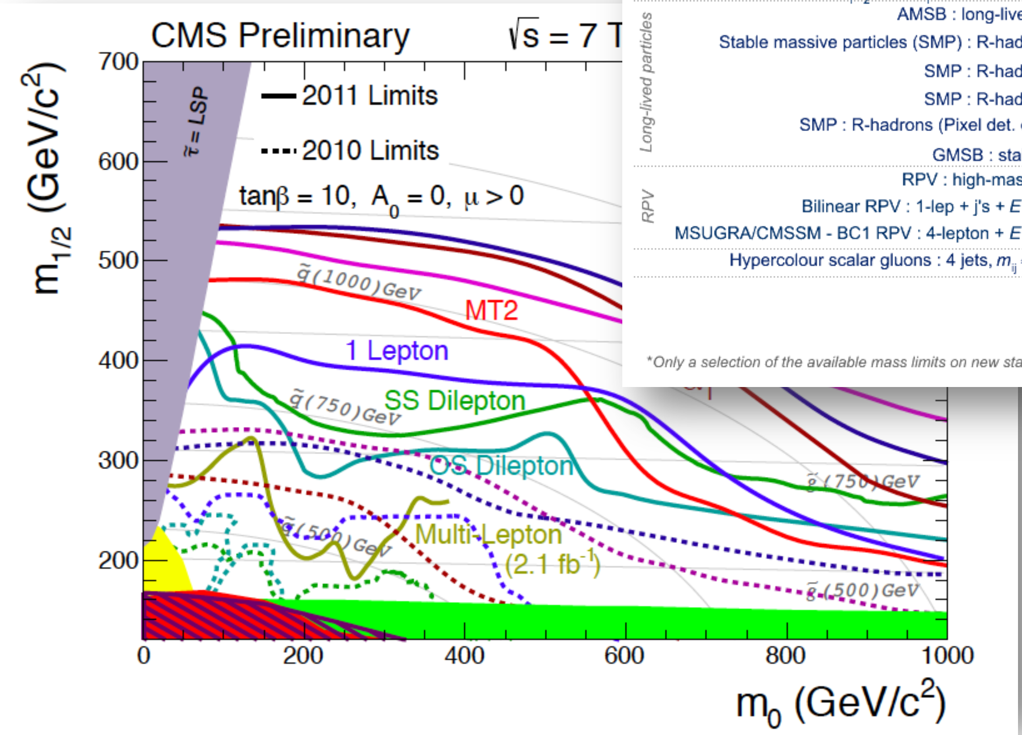


# SUSY searches limits



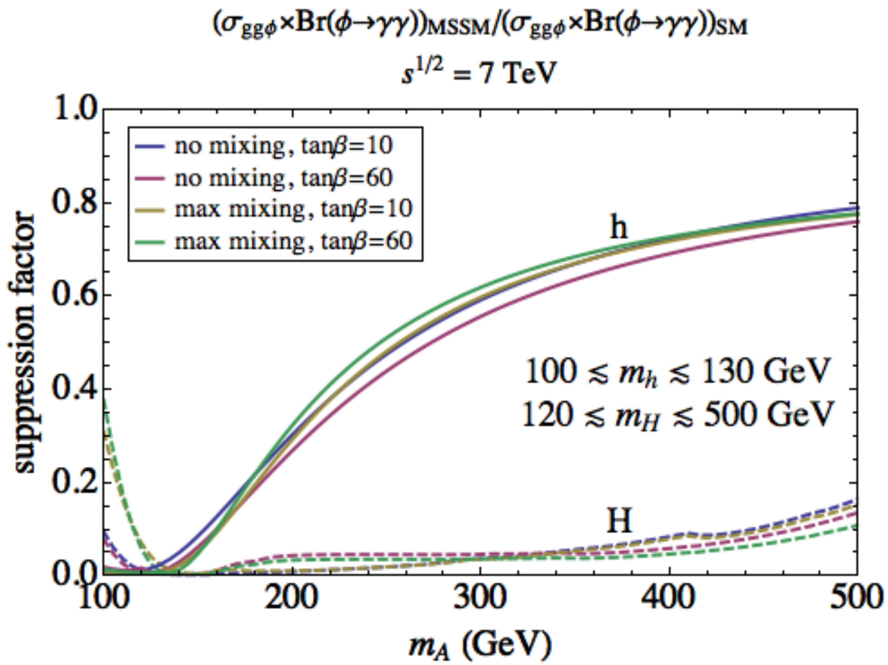
# Summary & outlook

- Supersymmetry (-like) signals have been sought after by the ATLAS and CMS experiments
  - motivated by various models/topologies: strong production, 3$^{rd}$ generation fermions, degeneracies, R-parity violation ….
  - … leading to a wide spectrum of signatures: MET + jets + leptons/ photons/b-jets/taus, displaced vertices, resonant peaks, …
  - both techniques and strategy keep evolving
- No deviation from known SM processes observed so far (5 $fb^{-1}$ at $\sqrt{s}$ = 7 TeV)
  ➞ approaching/reaching the 1-TeV scale
- Future: SUSY may be “hidden” in:
  - light stops / sbottoms / staus
  - R-parity violation
  - long-lived (s)particles

# Backup…

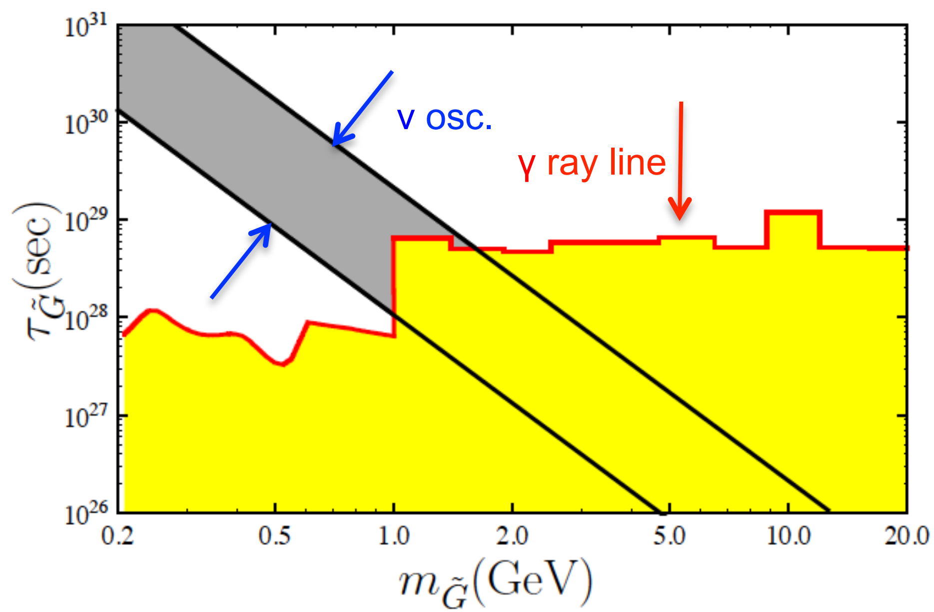
# SUSY in view of Higgs (non-)discovery

- If a light SM-like Higgs ~ 125 GeV is discovered → fully compatible with SUSY
  - however for BSM to be established, we need to observe
    - deviations of Higgs couplings from their SM values
    - additional heavier non-SM-like Higgs boson(s)
- If not → departure from decoupling limit
  - light stop suppresses $h \to \gamma\gamma$, WW
  - light neutralino leading to invisible Higgs decays $h \to \chi\chi$ (also favoured by DM fits)



# R-parity violation and dark matter

- Gravitivo LSP with cosmologically-long lifetime
- Bilinear RPV: neutrino masses are generated in an intrinsically supersymmetric way
- Signal: monochromatic gamma-rays $\tilde{G} \rightarrow \gamma\nu$
- Constrained by
  - ν-oscillations
  - DM relic density $\Omega_\chi h^2$
  - γ-ray line searches (Fermi, EGRET)

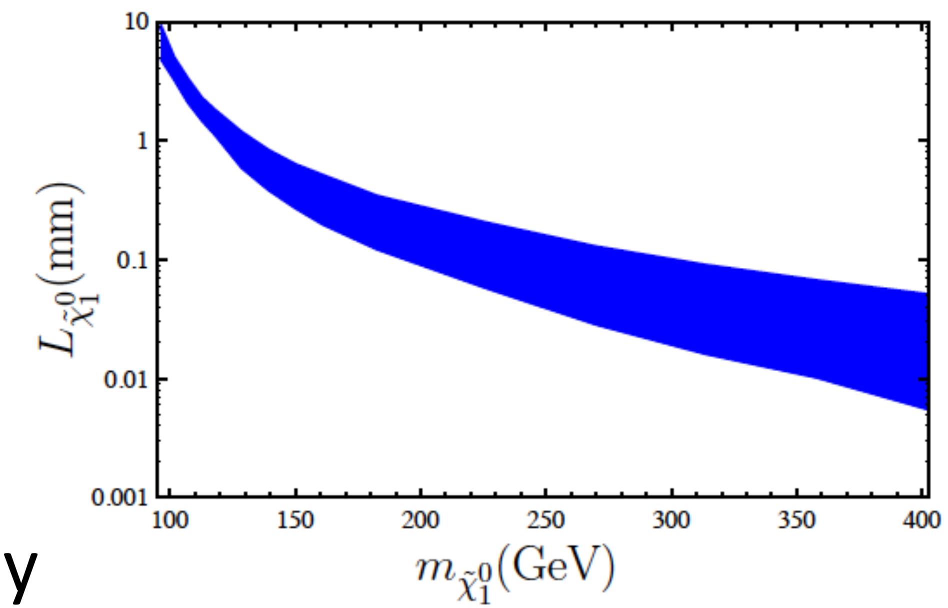



Restrepo et al, arXiv:1109.0512

# bRPV with gravitino LSP and LHC signatures

- If lightest neutralino is the NLSP, a variety of signatures are predicted

$$\tilde{\chi}_1^0 \to h^0 \nu_i,$$
$$\tilde{\chi}_1^0 \to \gamma \nu_i,$$
$$\tilde{\chi}_1^0 \to W^{\pm} l_i^{\mp},$$
$$\tilde{\chi}_1^0 \to Z^0 \nu_i.$$



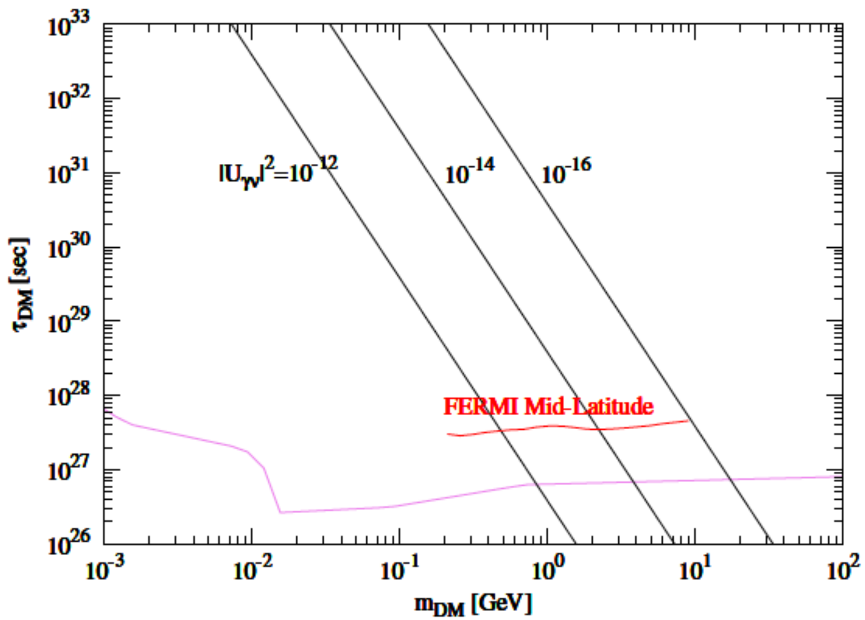

Restrepo et al, arXiv:1109.0512

- Neutralino can also decay to three fermions
- Neutralino is also long lived
  - displaced vertices
- → Many final states to be explored

# Beyond bRPV: μνSSM

Muñoz, Lopez-Fogliani, Ruiz de Austri *et al.*

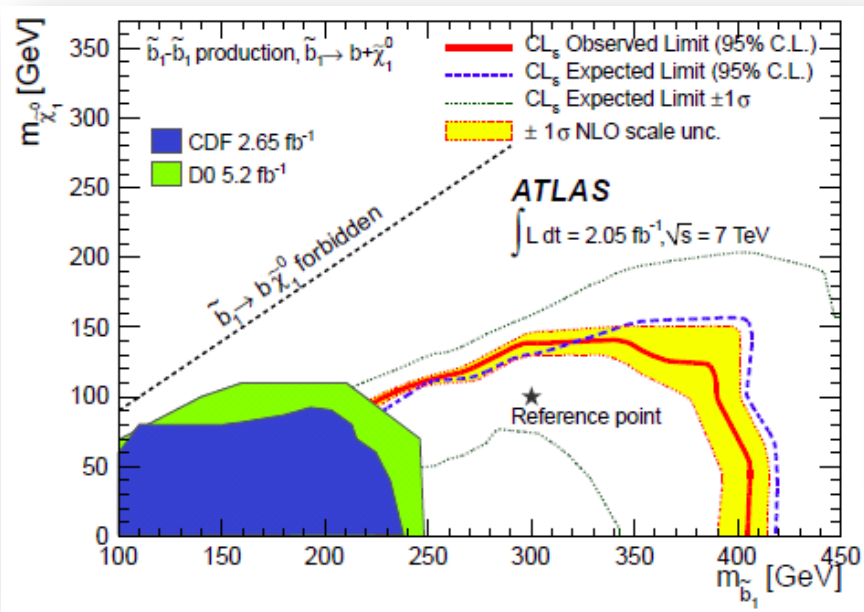
- μ-from-ν Supersymmetric Standard Model has been introduced to solve the μ-problem of MSSM while keeping the bilinear RPV couplings, and the associated connection with neutrino masses
- Very rich phenomenology
  - many Higgs and neutalinos
  - lifetimes longer than in bRPV
  - gravitino dark matter also possible

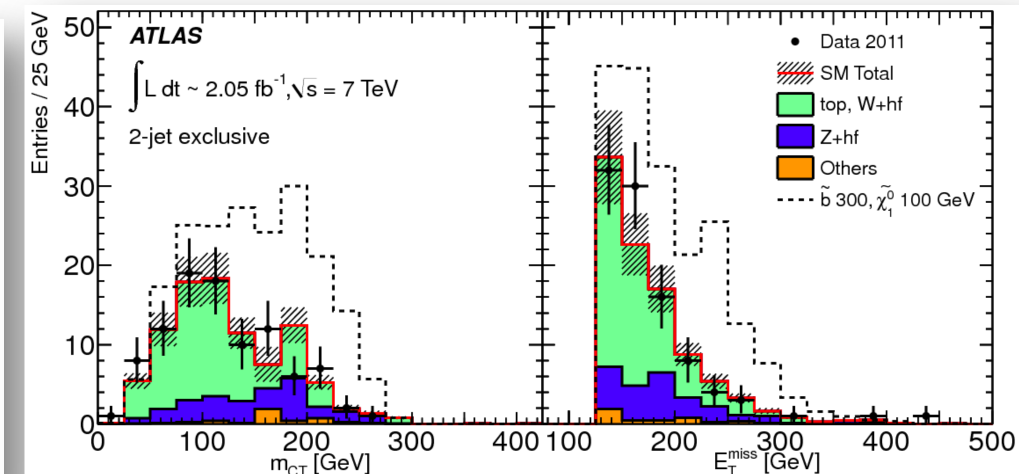



Choi, Lopez-Fogliani, Muñoz, Ruiz de Austri, arXiv:0906.3681 [hep-ph]

# Direct sbottom pair production

- Signature: exactly 2 b-jets + $E_T^{miss}$ ➞ use flavour tagging
- Interpretations: pheno. model with $Br(\tilde{b}_1 \to b\tilde{\chi}_1^0) = 1$




$$m_{CT}^2(v_1, v_2) \equiv [E_T(v_1) + E_T(v_1)]^2 - [\mathbf{p_T}(v_1) - \mathbf{p_T}(v_1)]^2$$

$$m_{CT} \propto (m_{\tilde{b}_1} - m_{\tilde{\chi}_1^0})^2 / m_{\tilde{b}_1}$$

- Excluding sbottom mass < 380 GeV for neutralino masses up to ~ 100 GeV

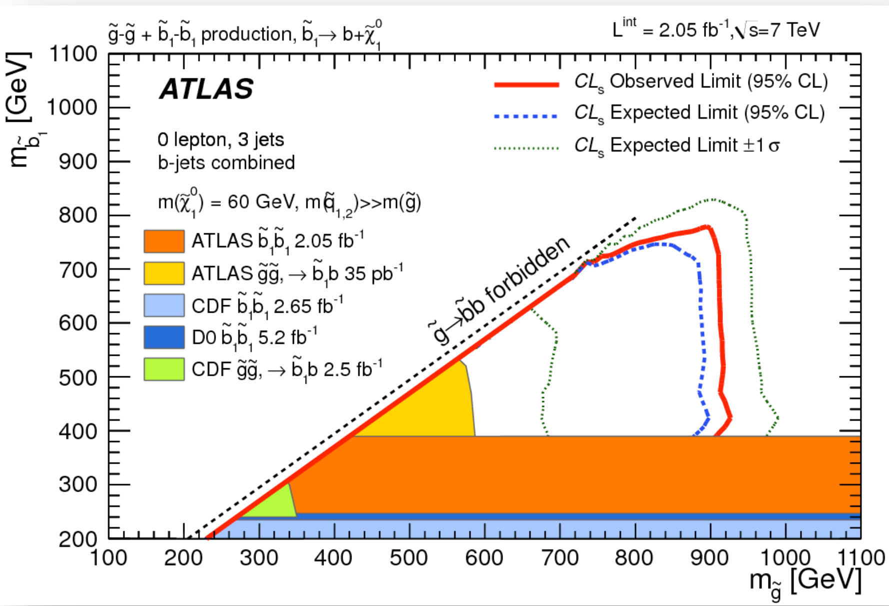
# Gluino-mediated sbottom production

Signature: 0-lepton + 1 or 2 b-jets + $E_T^{miss}$

arXiv:1203.6193 [hep-ex]

## Pheno MSSM model $\tilde{g} \to \tilde{b}_1 \bar{b} \to b\bar{b}\tilde{\chi}_1^0$

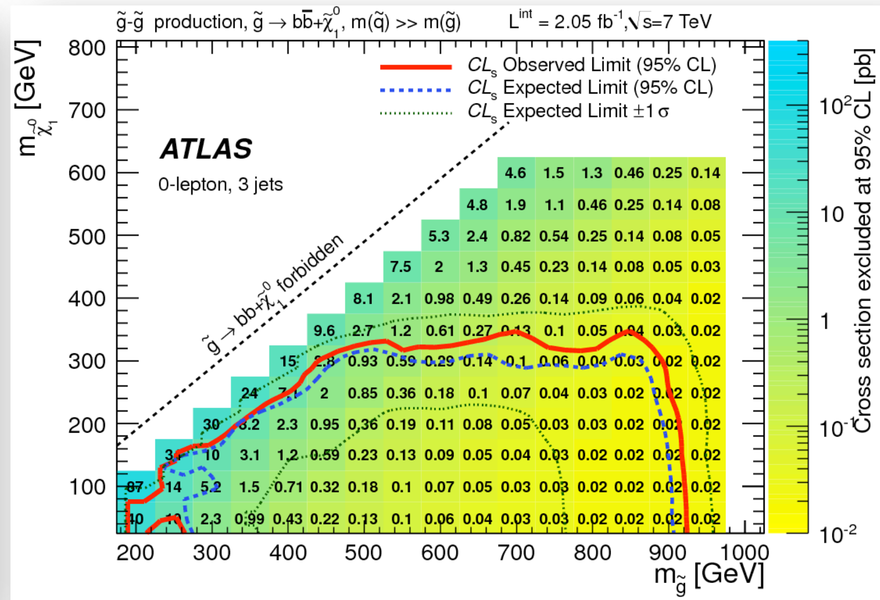
- Only gluino + sbottom + LSP
- Mass spectrum: $m(\tilde{g}) > m(\tilde{b}_1) > m(\tilde{\chi}_1^0)$




- Exclude m(gluino) < 920 GeV for m(sbottom) up to ~ 800 GeV

## Simplified model $\tilde{g} \to b\bar{b}\tilde{\chi}_1^0$

- Only gluino + sbottom + LSP
- Mass spectrum: $m(\tilde{b}_1) > m(\tilde{g}) > m(\tilde{\chi}_1^0)$




- Exclude m(gluino) < 900 GeV for m(neutralino) up to ~ 300 GeV