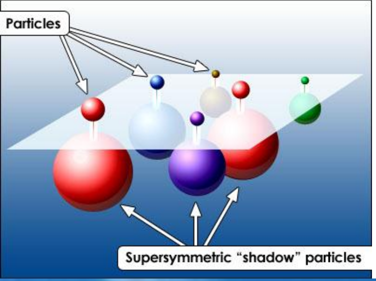
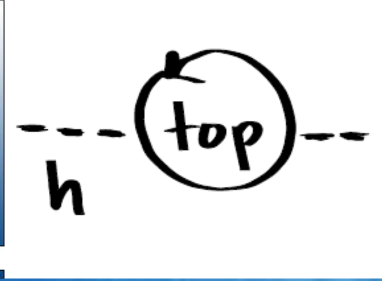
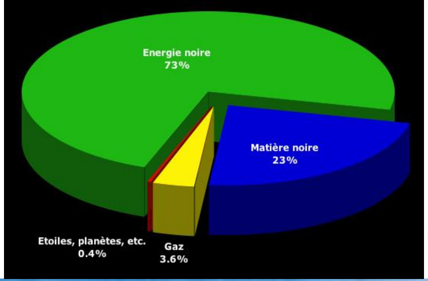
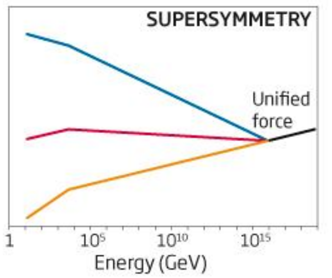
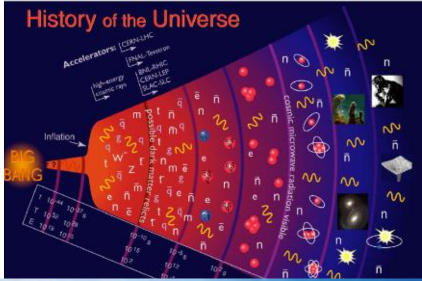










SUSY Searches in ATLAS & CMS

David Côté (UTA)

US ATLAS Physics Workshop

July 15th 2013

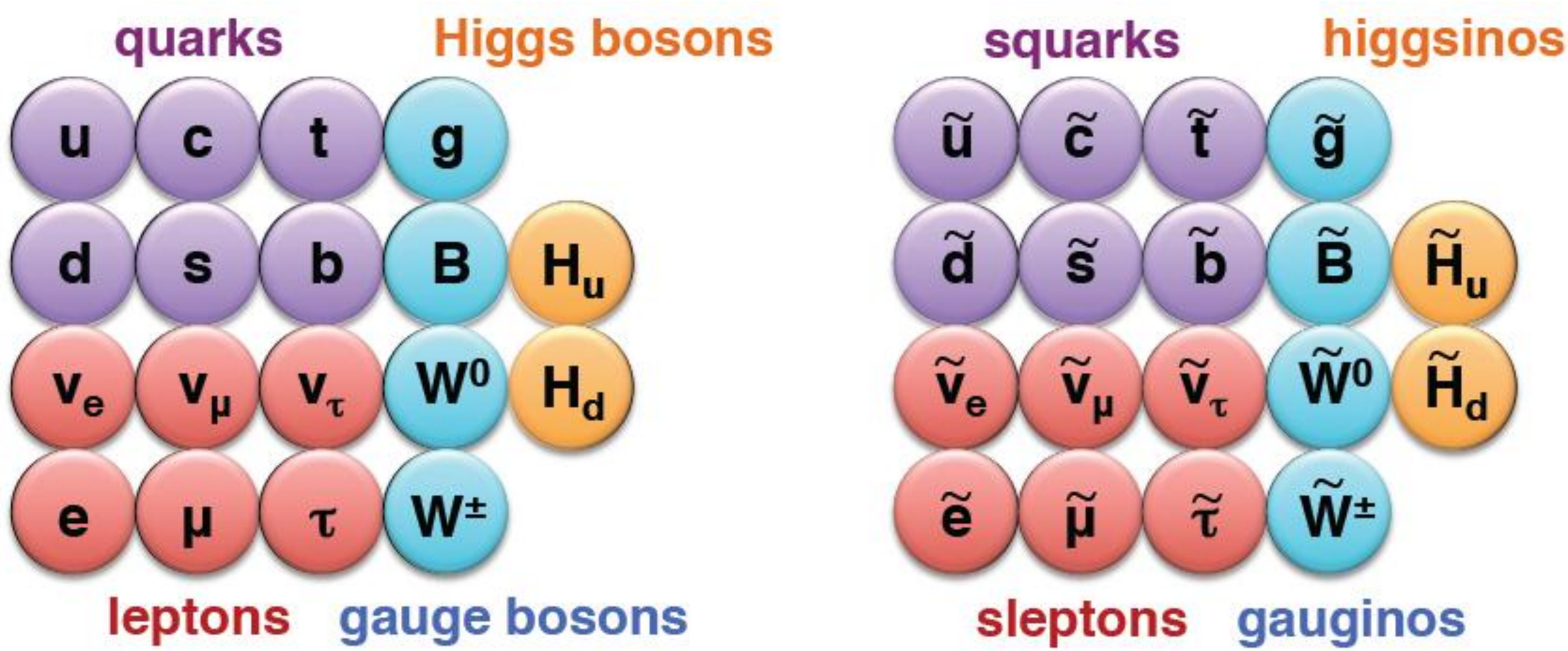
Overview

- Introduction
- Status of 8 TeV data analysis
  - gluino & 1st/2nd generation squarks
  - 3rd generation (top & bottom) squarks
  - electroweak SUSY (chargino, neutralinos, sleptons)
  - R-Parity Violating & Gauge Mediated scenarios
- Outlook
  - other possible searches with 8 TeV data
  - looking forward to ~14 TeV

Talk by Antoine Marzin

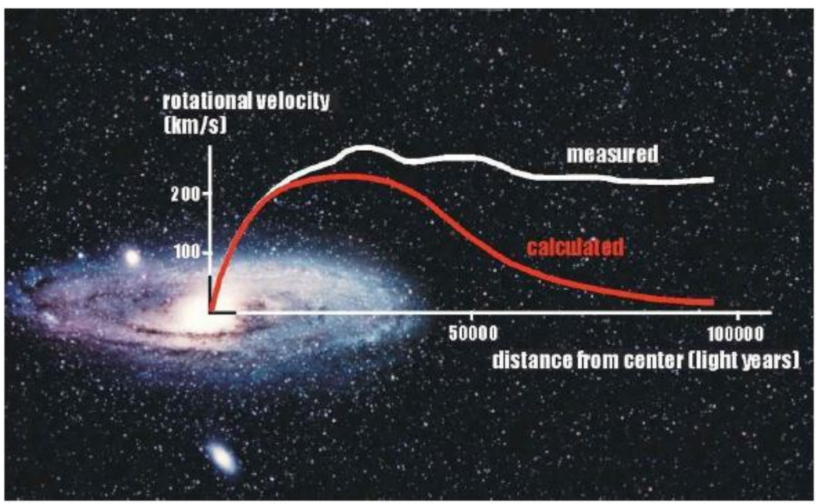
Introduction

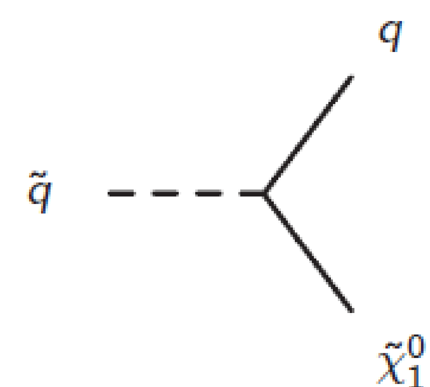
Supersymmetry (SUSY)



Why Searching for SUSY?

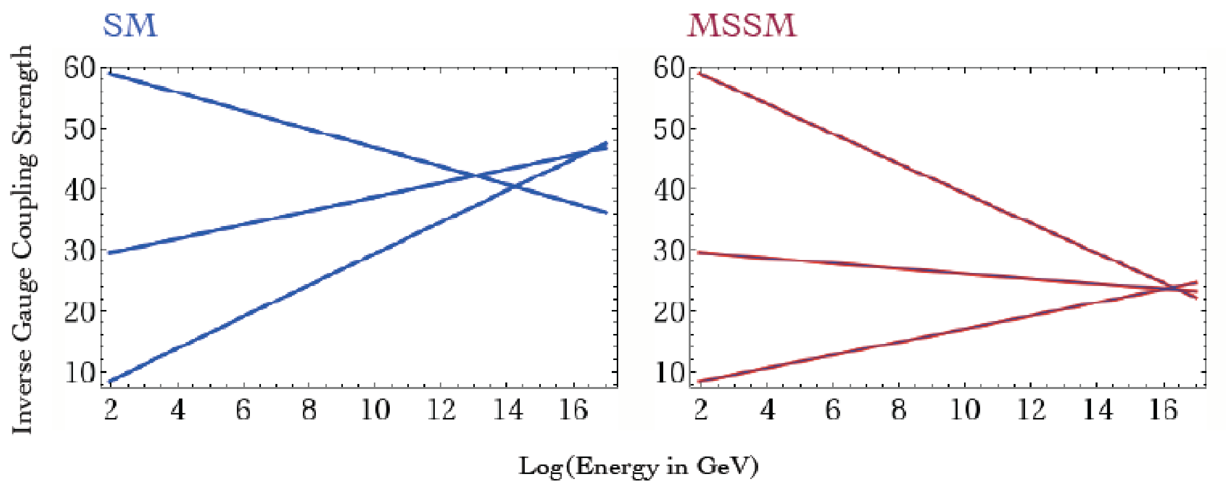
- Can explain WIMP Dark Matter
  - stable neutralino from R-Parity Conservation
    - E_T^{miss} signature at LHC





Why Searching for SUSY?

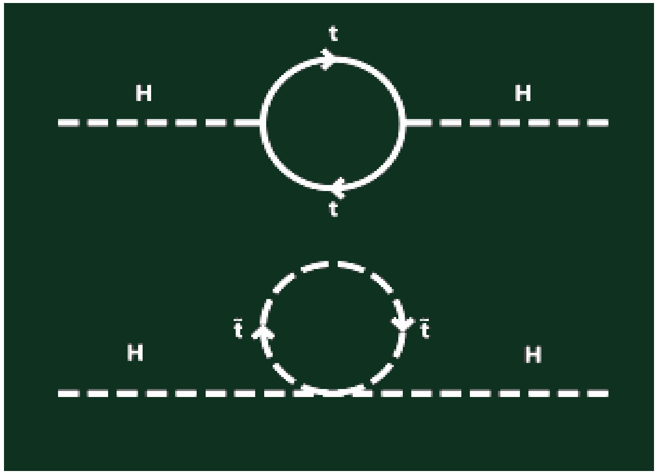
- Fundamental symmetry of space-time
  – super string theories (gravity)
- Gauge-Coupling Unification



Gauge Coupling running at two loops

Why Searching for SUSY?

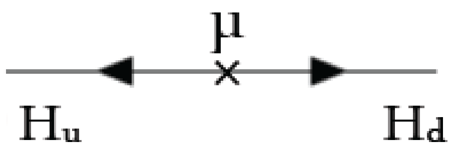
- Naturalness
  - solution to hierarchy problem
  - new physics accessible at LHC



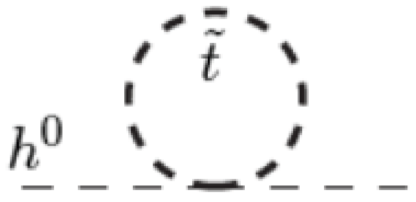
Natural SUSY

For less than 10% fine-tuning…

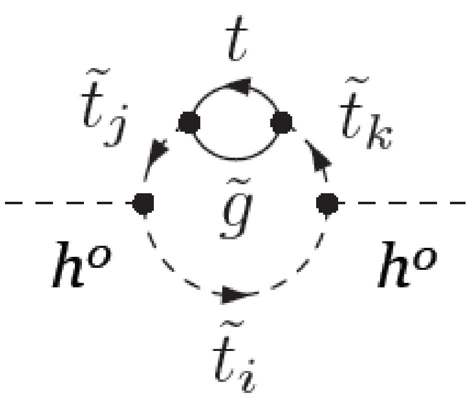
Tree-level: Higgsino < ~250 GeV



One loop: stop < ~600 GeV

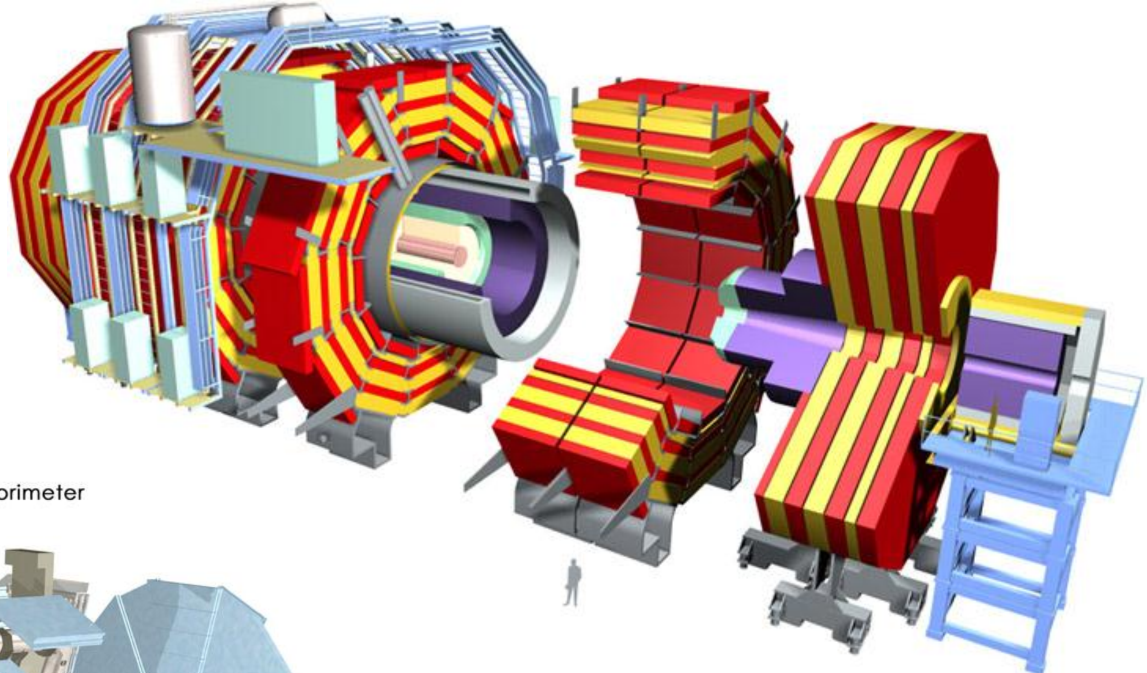


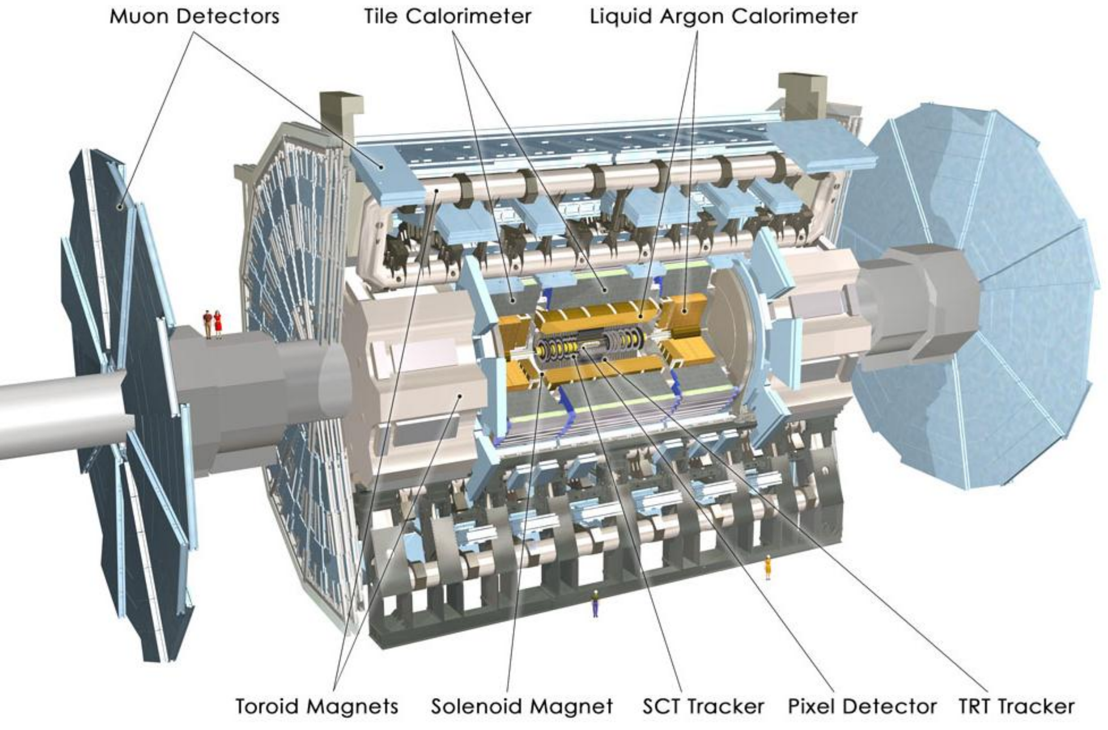
Two loops: gluino < ~1.4 TeV



*Dimopoulos & Giudice (1995)

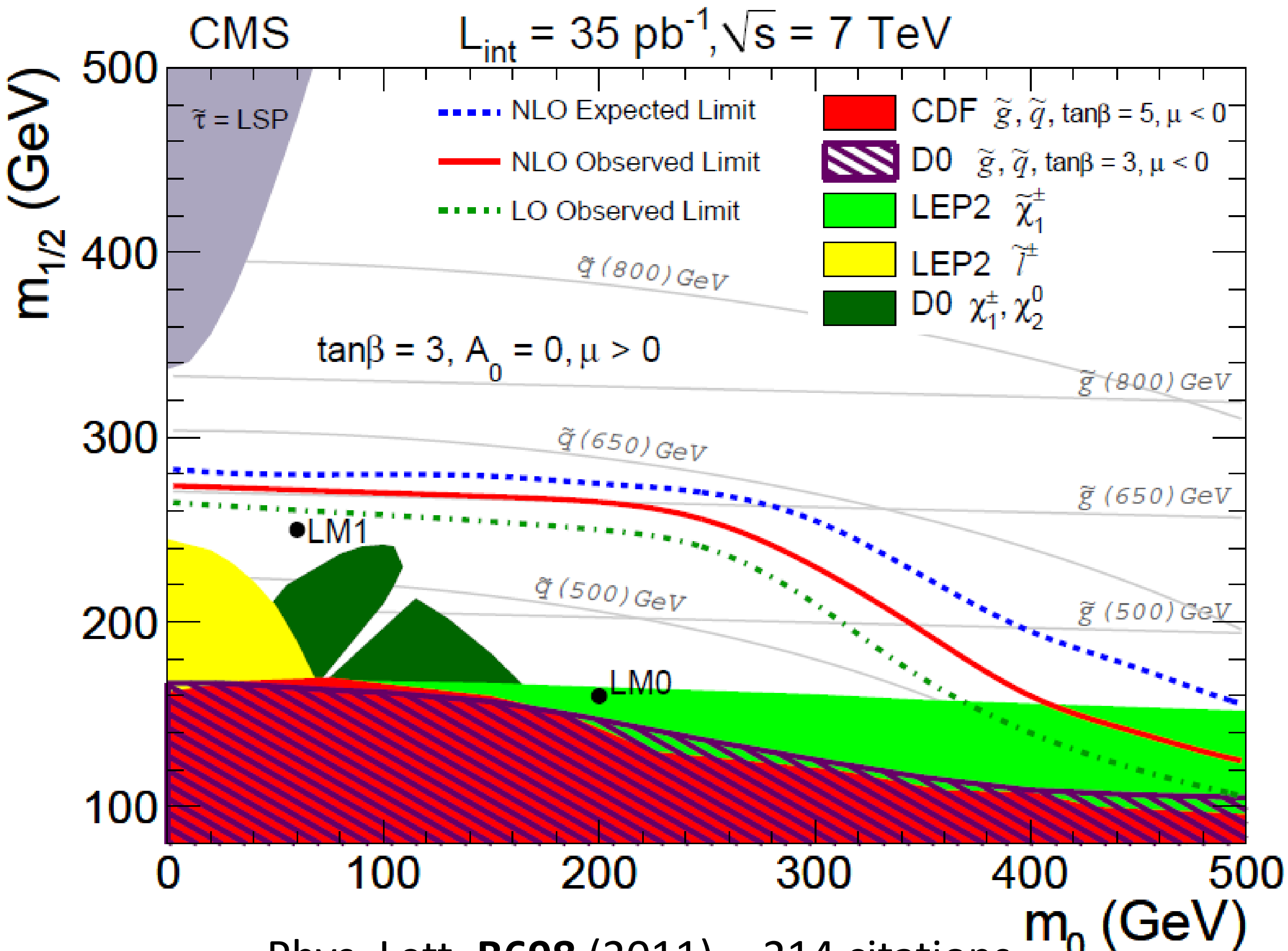
Brief history of SUSY searches in ATLAS & CMS





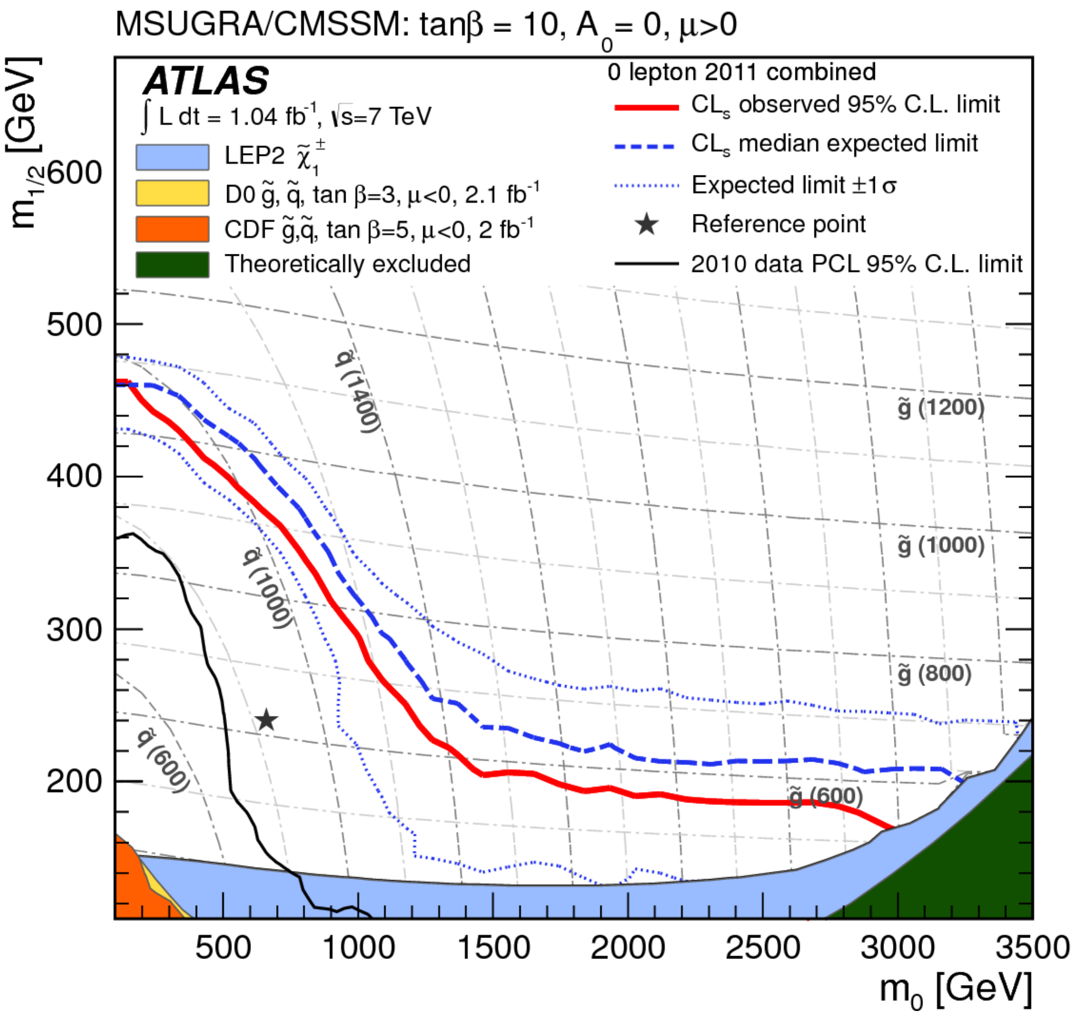
The very first SUSY result! (2010)

alpha$_T$ + jets + E_T^{miss}



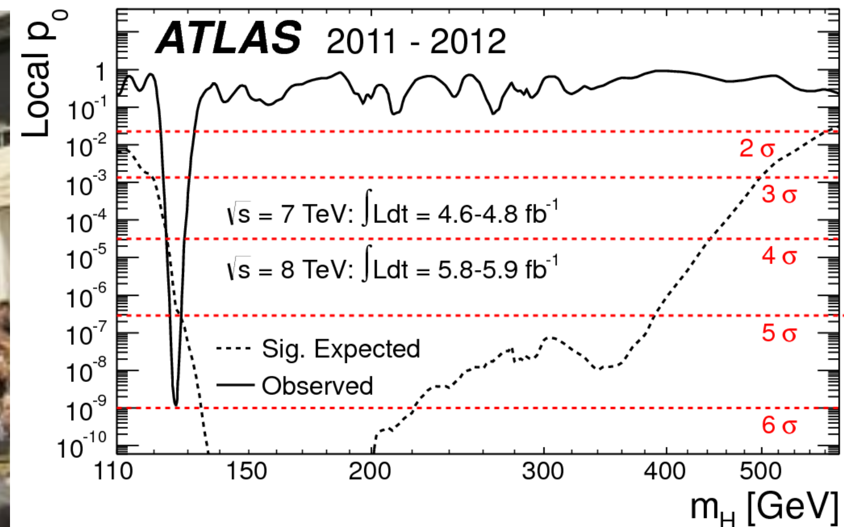
Phys. Lett. **B698** (2011) – 214 citations

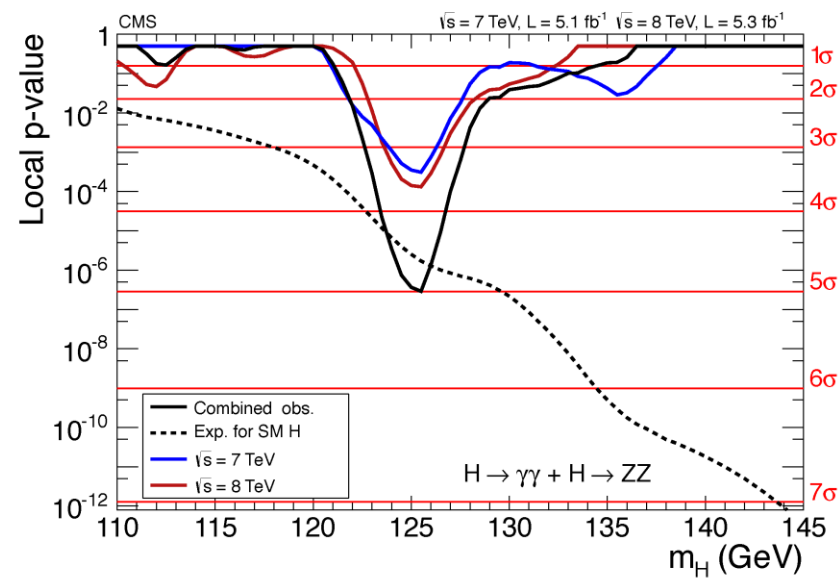
MET + jets + 0 lepton (1 fb^{-1})



Phys. Lett. **B710** (2012) – 263 citations

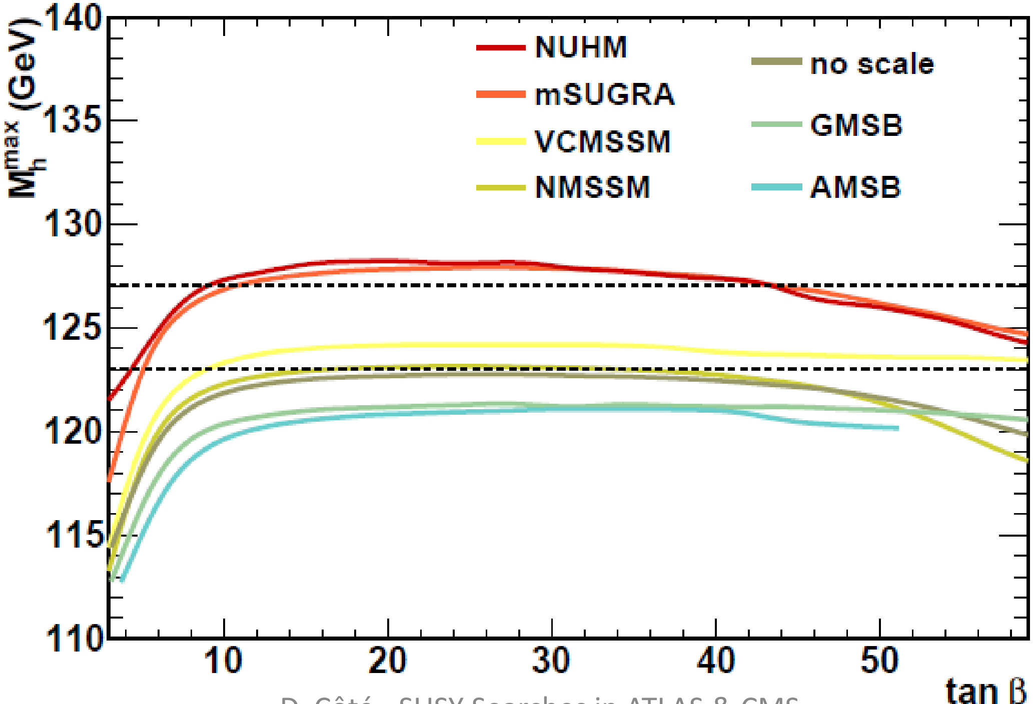
Higgs Discovery: July 4th 2012





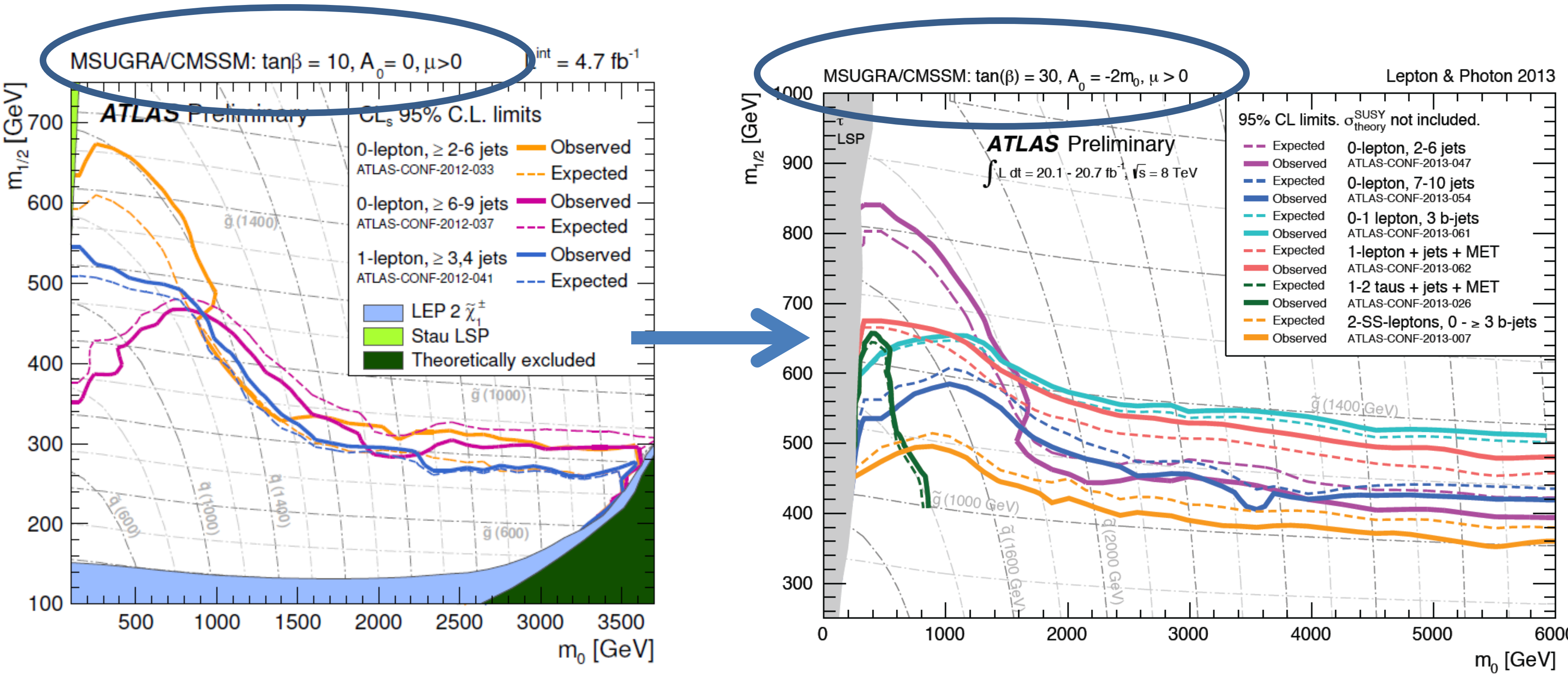
Impact of m_H = 125.5 GeV

- Higgs discovery encourages the SUSY use case
- Measured value $m_H \approx 125.5$ GeV required adjustments of some SUSY models



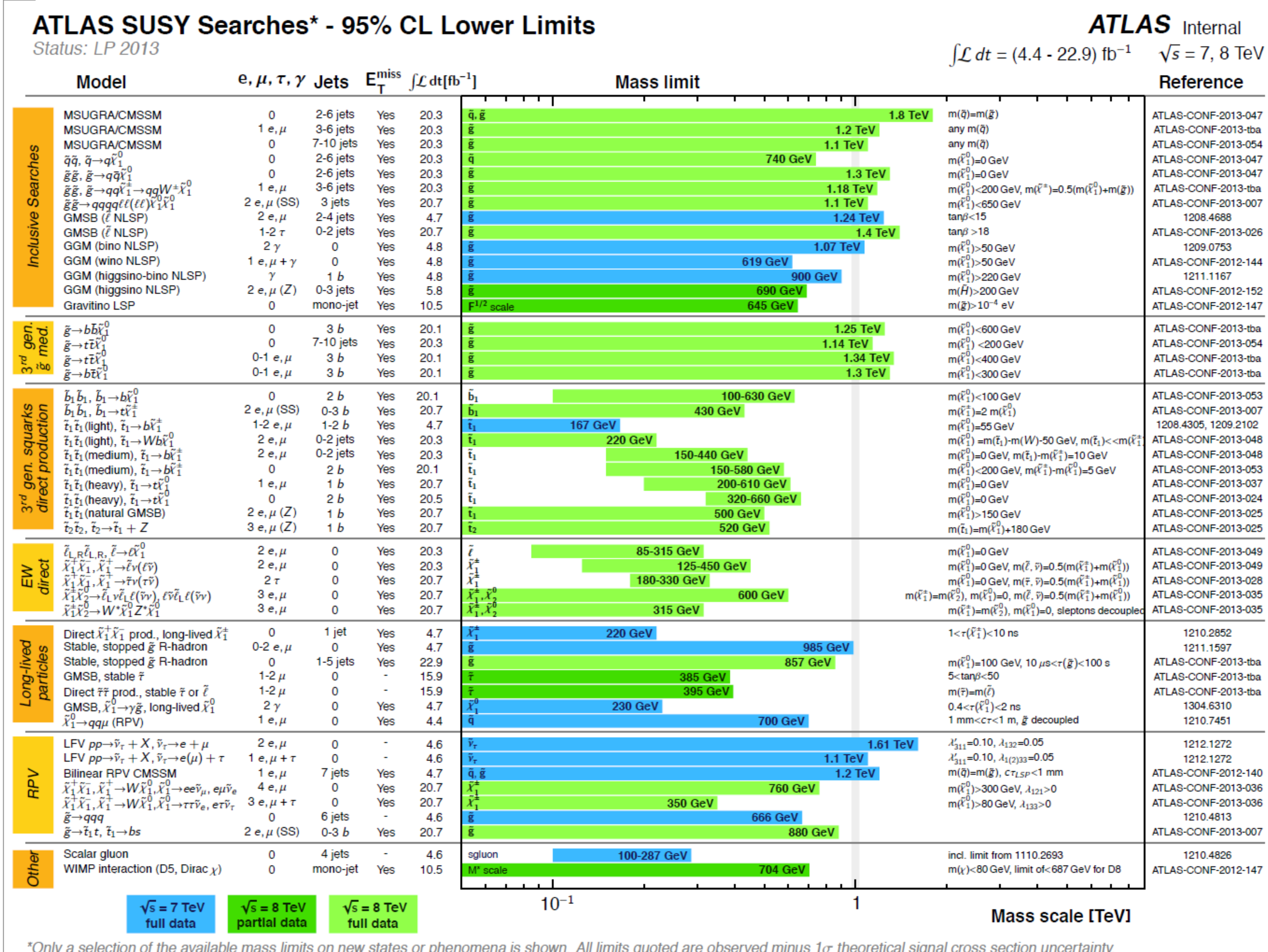
F. Mahmoudi *et al.*
arXiv:1112.3028

Higgs-aware mSUGRA

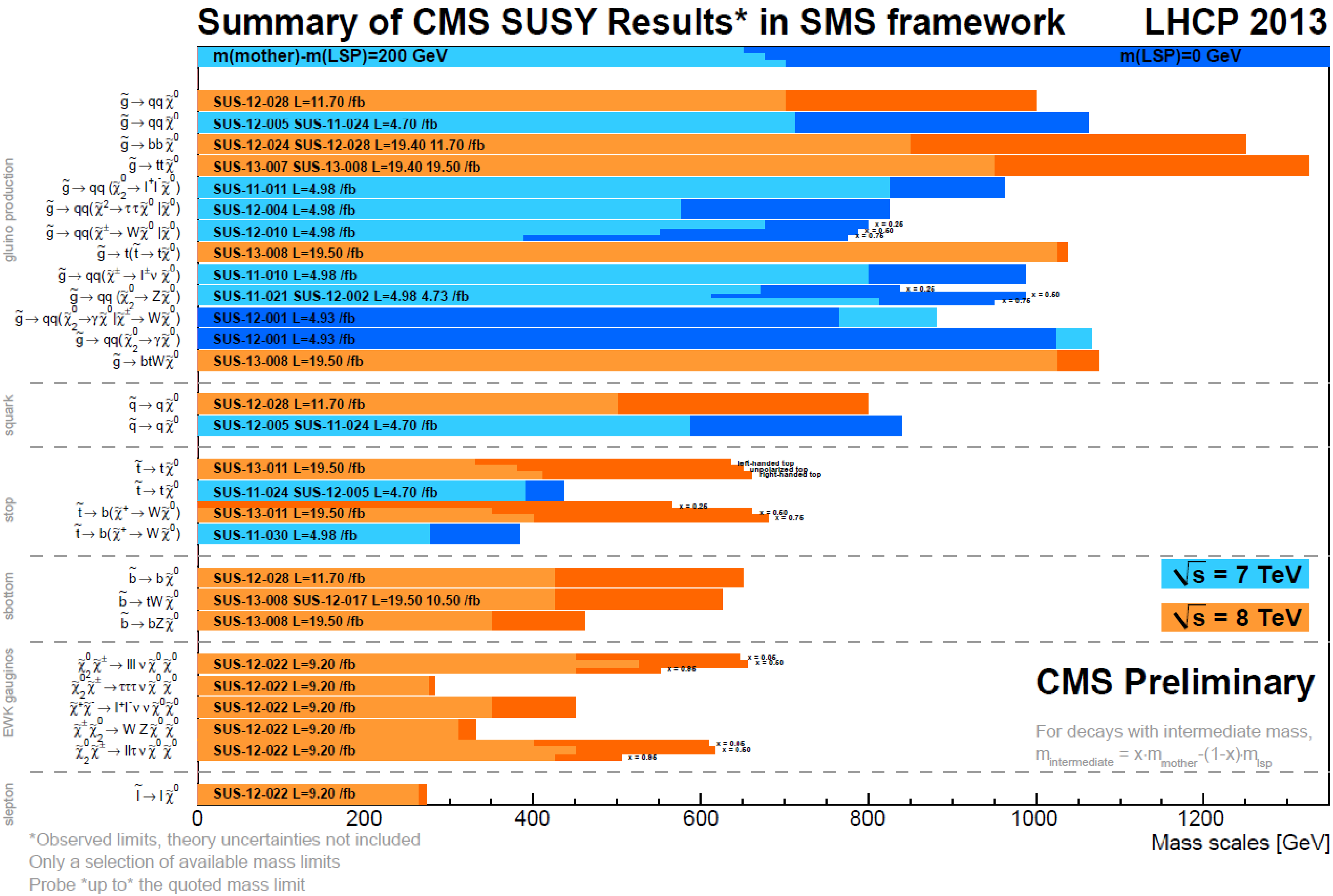


Models like mSUGRA are not statistically excluded, but are no longer the main focus.

Status of 8 TeV data analysis



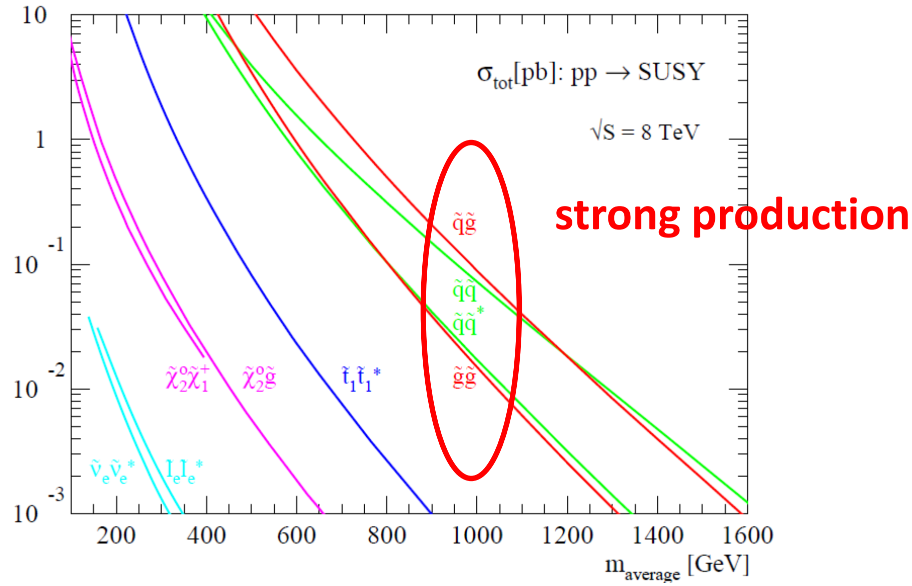
See: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults



See: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

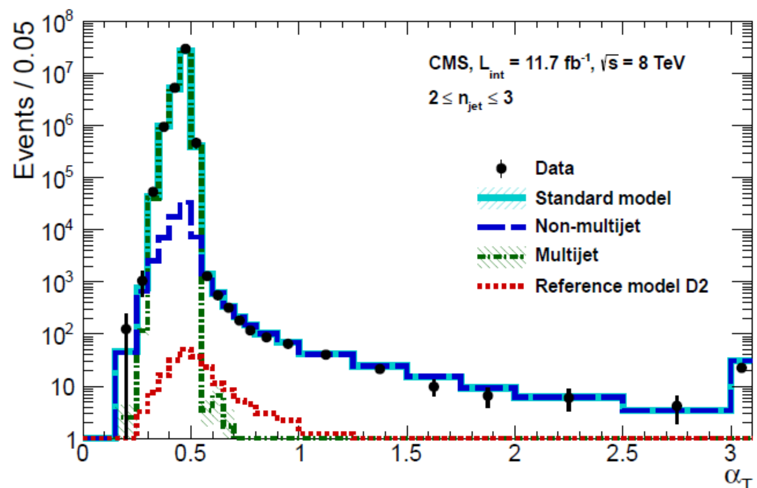
Status of 8 TeV data analysis

- gluino & 1st/2nd generation squarks
- 3rd generation (top & bottom) squarks
- electroweak SUSY (chargino, neutralinos, sleptons)
- R-Parity Violating & Gauge Mediated scenarios

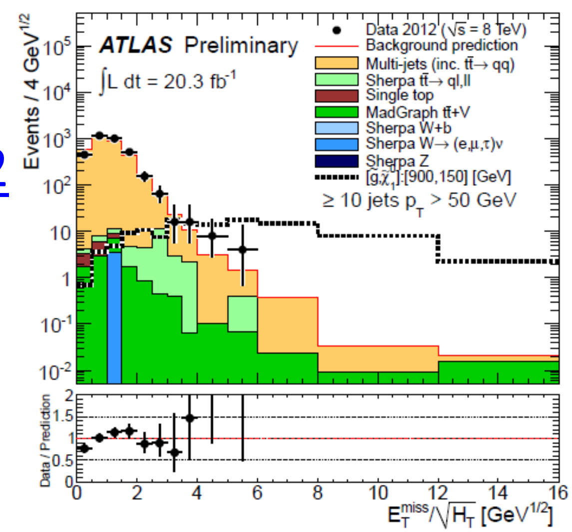


Inclusive searches for gluino & squarks

- Motivations for light gluino:
  - SUSY naturalness
  - gauge coupling unification

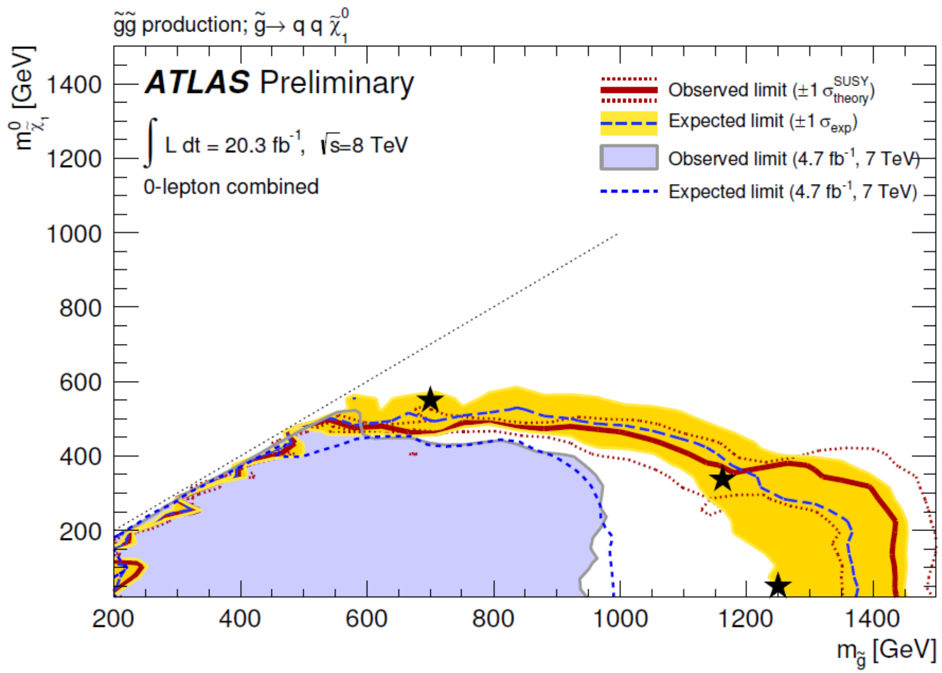


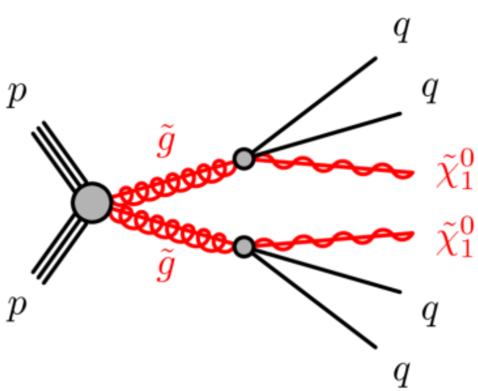
- Recent results:
  - ATLAS (20 fb^{-1})
    - 0 lepton + 2-6 jets + E_T^{miss} 2013-047
    - 0 lepton + 7-10 jets 2013-054
    - 1 lepton (hard/soft) + jets + E_T^{miss} 2013-062
    - 2 same-sign leptons + 0-3 b-jets 2013-007
    - tau + jets + E_T^{miss} (GMSB) 2013-026
  - CMS (11 fb^{-1})
    - alpha$_T$ + 0-4 b-jets SUS12-028



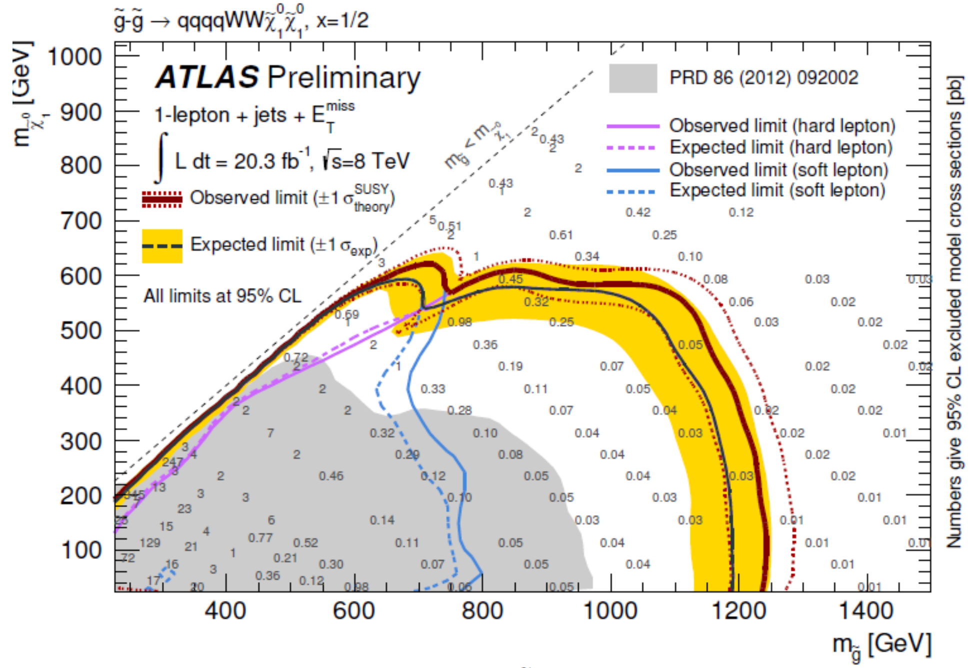
Limits on gluino → squark

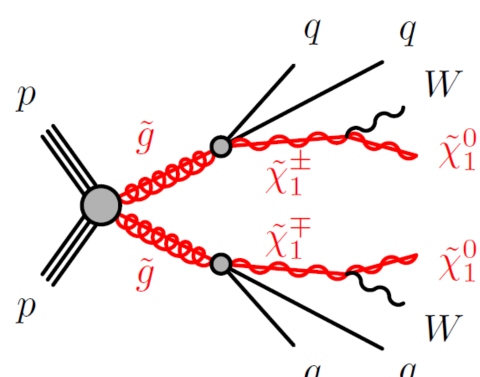
0 lepton + 2-6 jets + E_T^{miss}





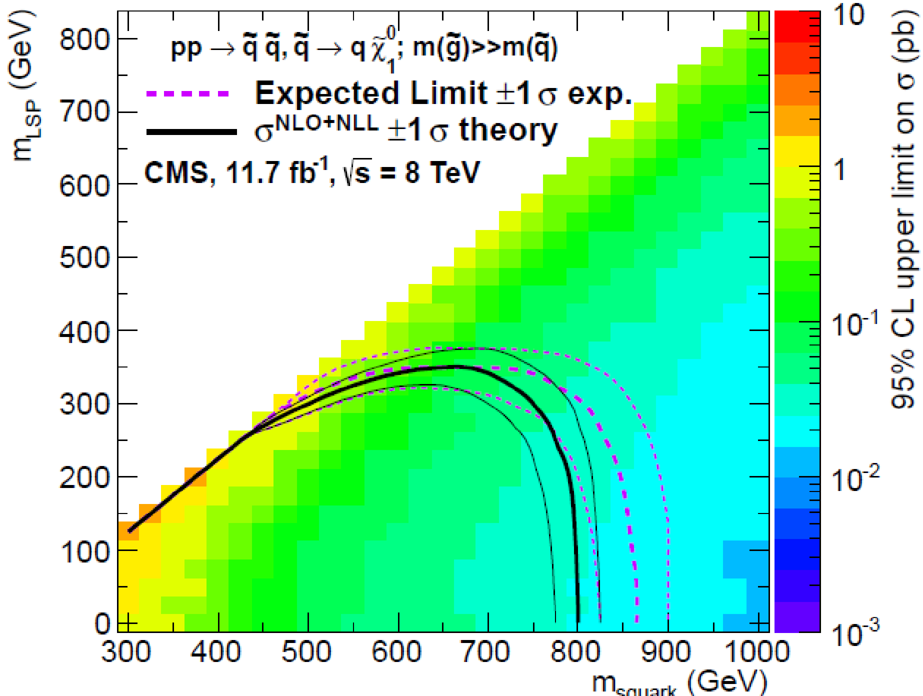
1 lepton (hard/soft) + jets + E_T^{miss}

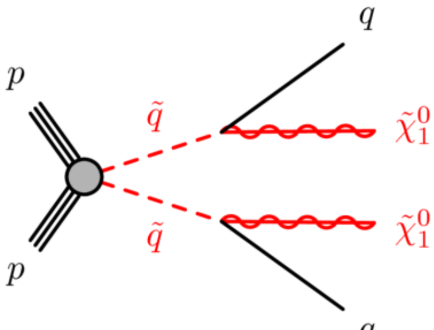




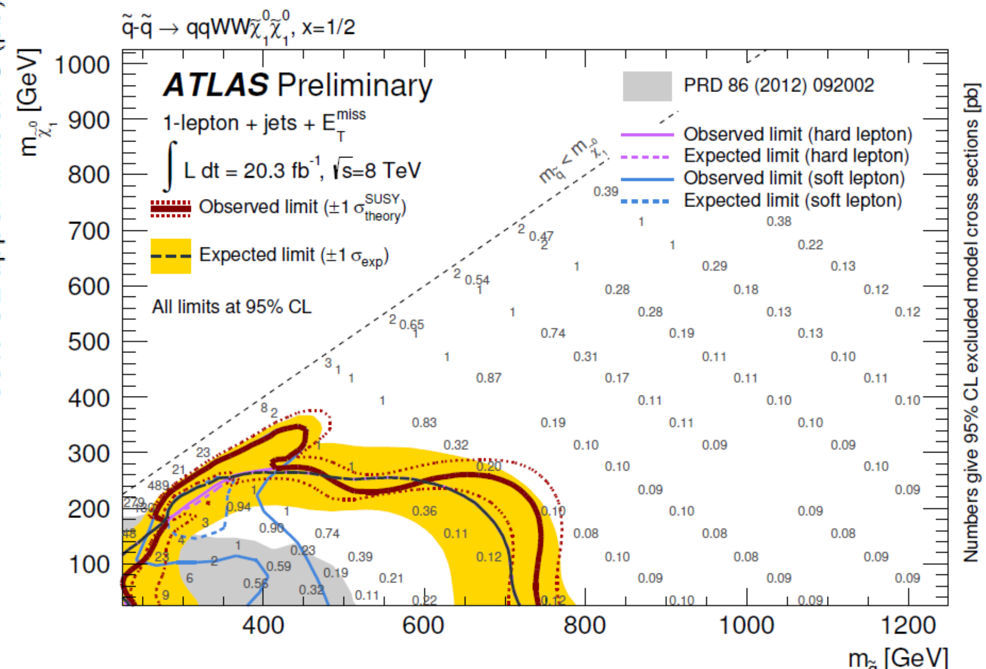
Limits on direct squark

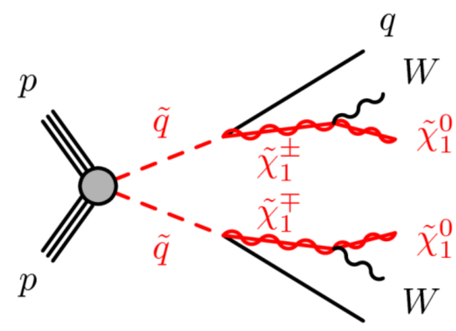
alpha$_T$ + 0-4 b-jets





1 lepton (hard/soft) + jets + E_T^{miss}

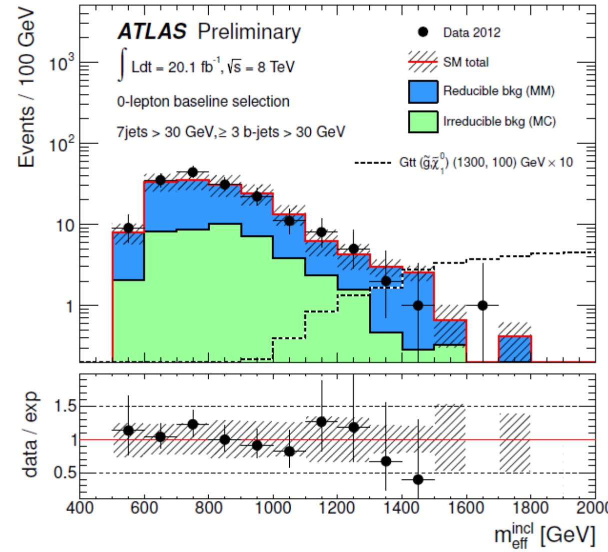


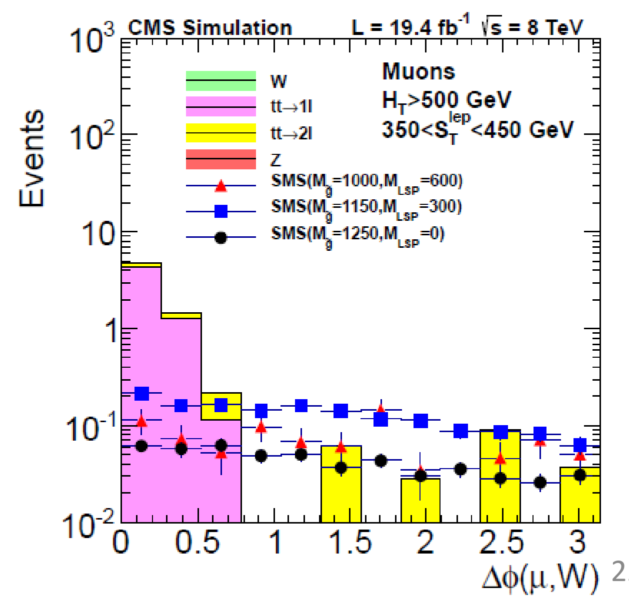


gluino → stop/sbottom

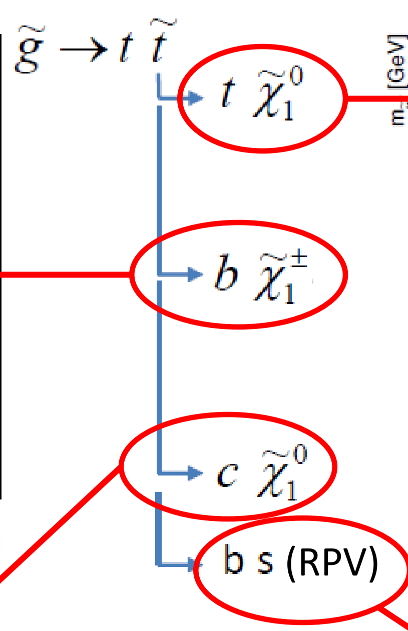
- Motivations:
  - gluino & stop light in Natural SUSY
    - sbottom_L related to stop_L by $SU(2)_L$
    - then BF(gluino→stop/sbottom) ≈ 100%

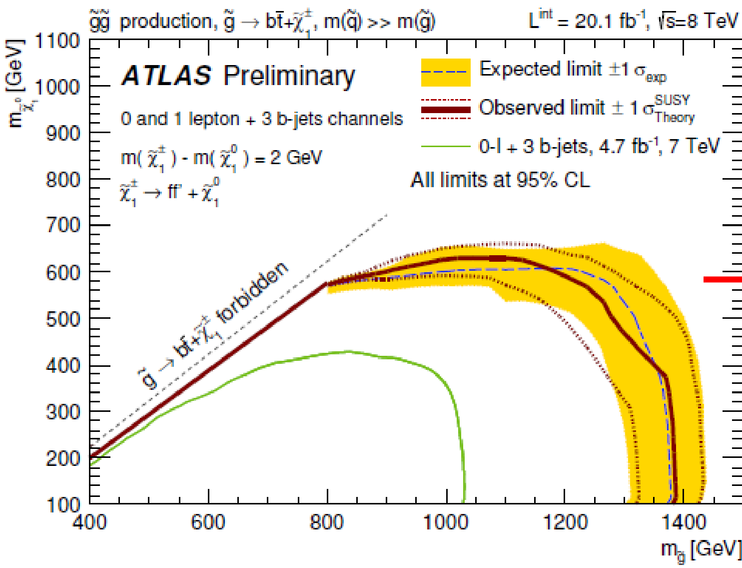
- Recent results:
  - ATLAS (20 fb^{-1})
    - 0/1 lepton + 3 b-jets + E_T^{miss} 2013-061
    - 0 lepton + 2-6 jets + E_T^{miss} 2013-047
    - 0 lepton + 7-10 jets 2013-054
    - 2 same-sign leptons + b-jets 2013-007
  - CMS (19.5 fb^{-1})
    - H_T + 1-3 b-jets + ETmiss SUS12024
    - 1 lepton + b-jets + ETmiss SUS13007
    - 2 leptons same-sign + b-jets SUS12017
    - 3 leptons + b-jets SUS13008

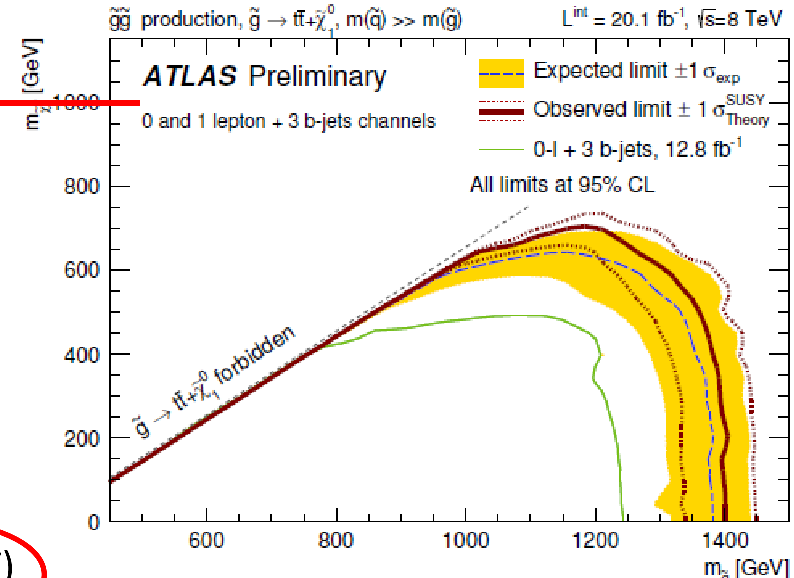


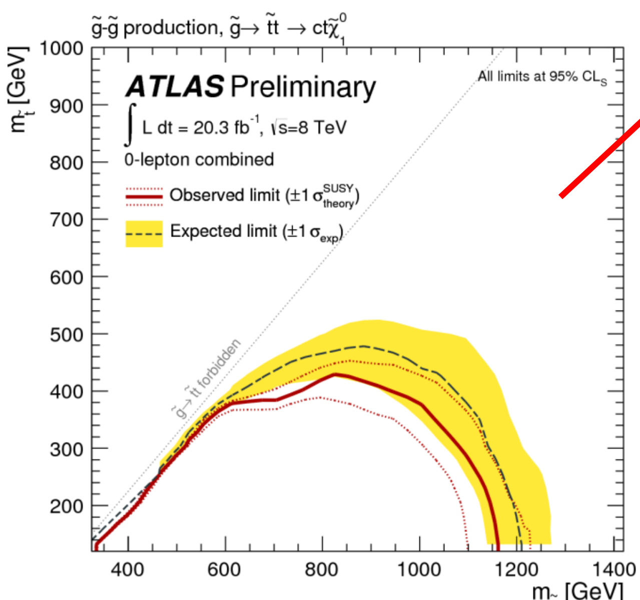


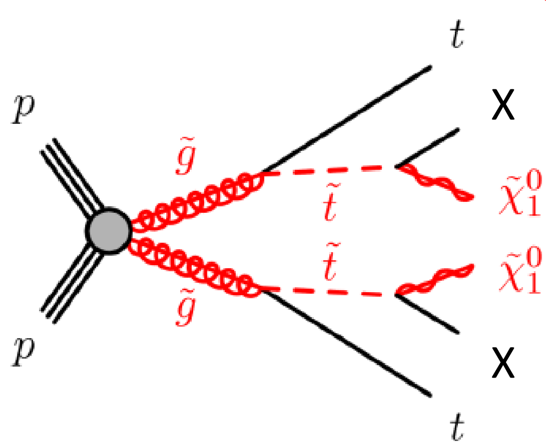
Limits on several gluino→stop decays

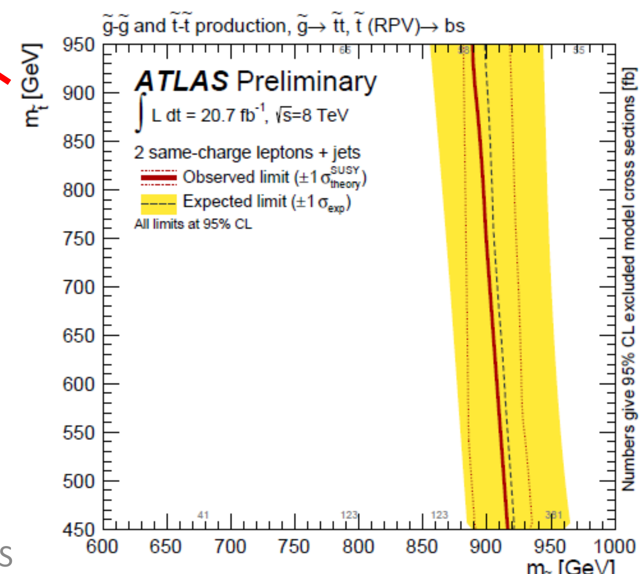




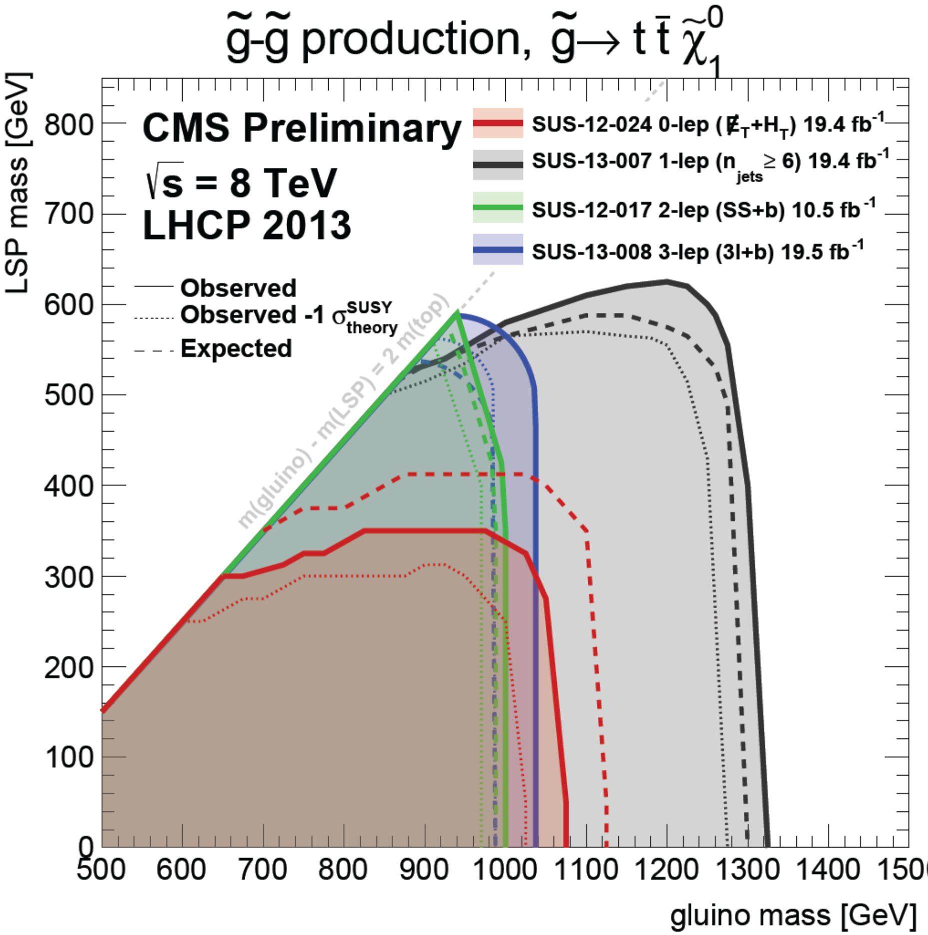


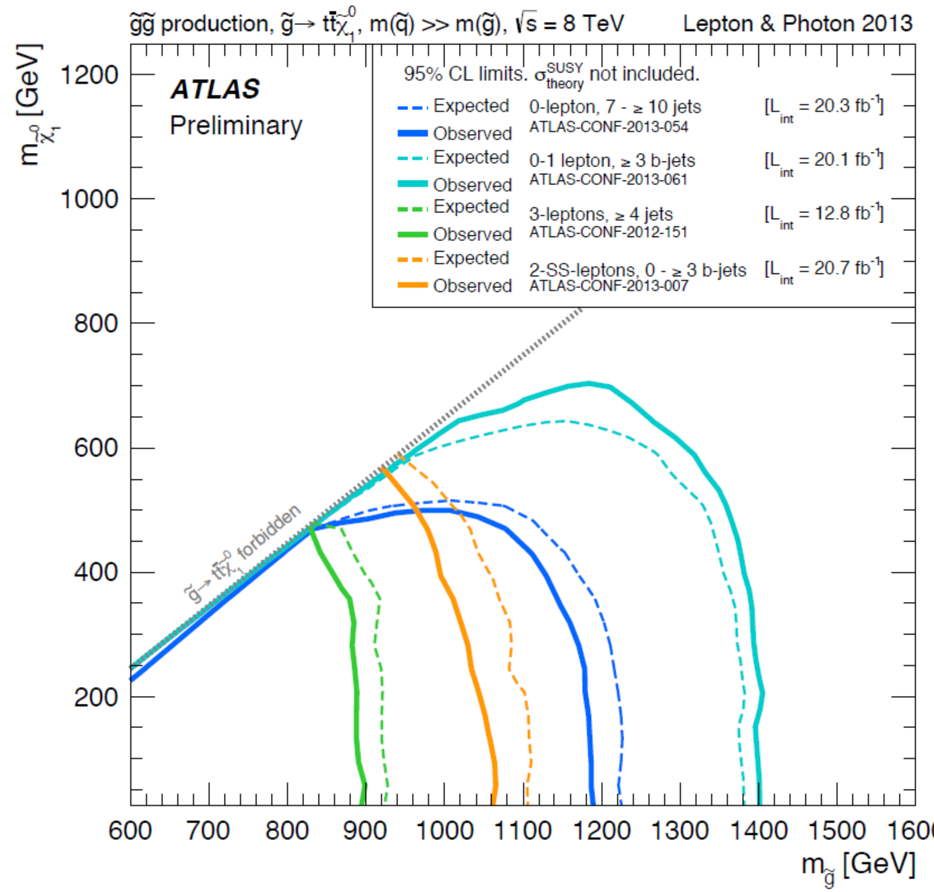






Limits on gluino → $tt\chi^0_1$

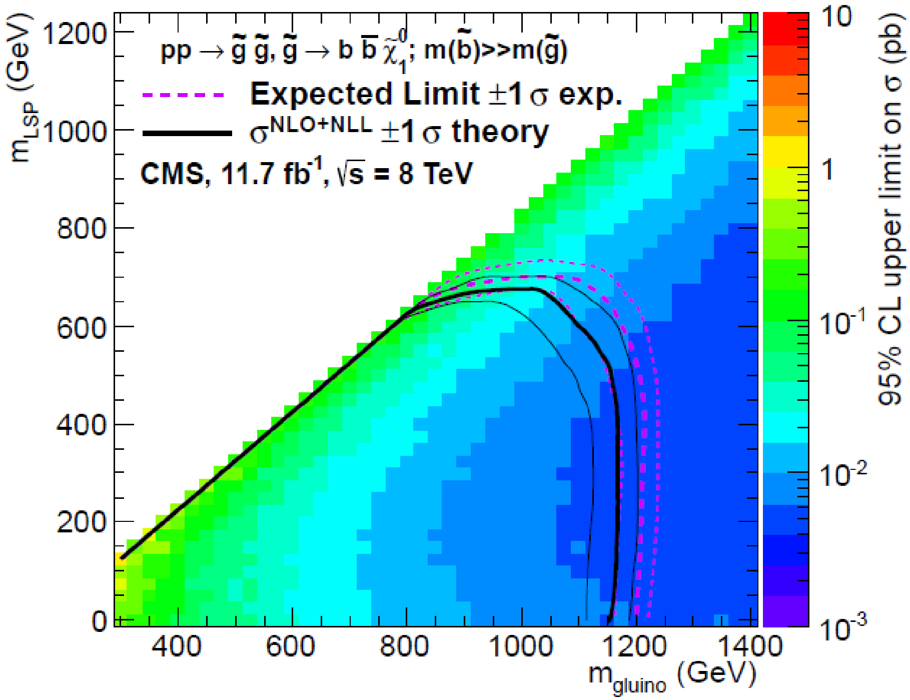


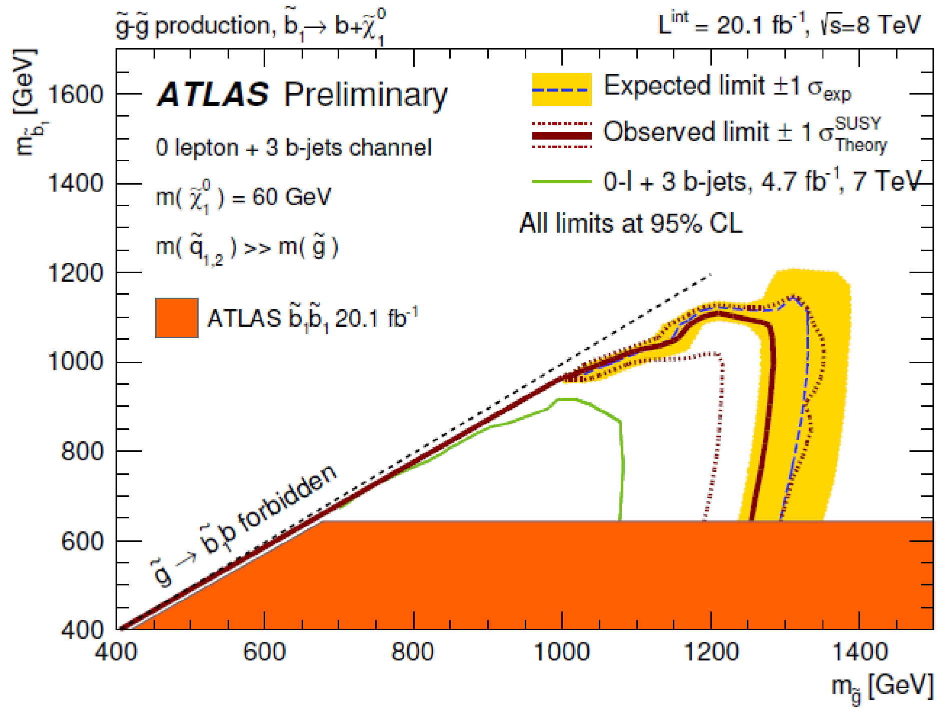


Excluding m_{gluino} < ~1.3 TeV for $m_{\chi^0_1}$ < ~600 GeV

Limits on gluino → bbχ^0_1

$$\tilde{g} \rightarrow b\tilde{b}, \quad \tilde{b} \rightarrow b\tilde{\chi}_1^0$$

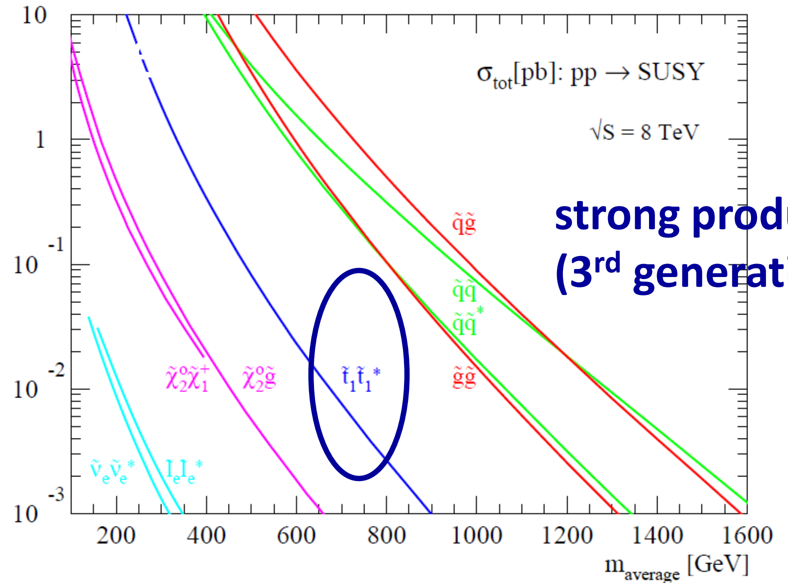




Excluding m_{gluino} < ~1.2 TeV for $m_{\chi^0_1}$ < ~600 GeV,
similarly for on-shell sbottom ($m_{sbottom} < m_{gluino}$) and off-shell sbottom* ($m_{sbottom} > m_{gluino}$).

Recent Results

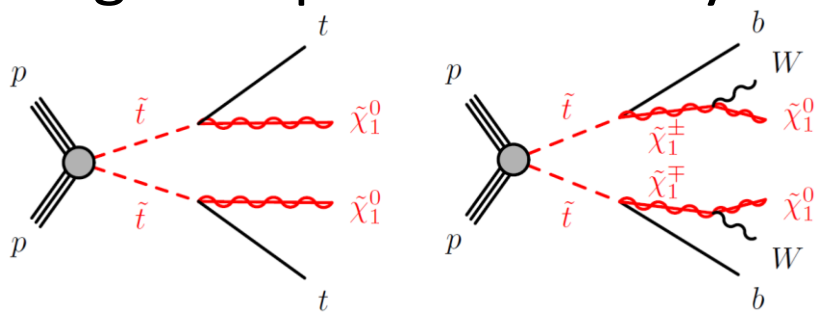
- gluino & 1st/2nd generation squarks
- 3rd generation (top & bottom) squarks
- electroweak SUSY (chargino, neutralinos, sleptons)
- R-Parity Violating & Gauge Mediated scenarios

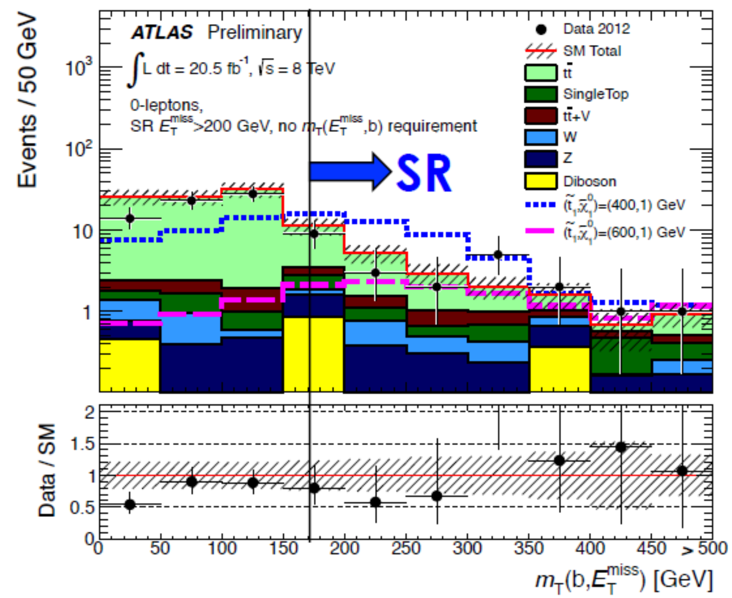


strong production (3rd generation)

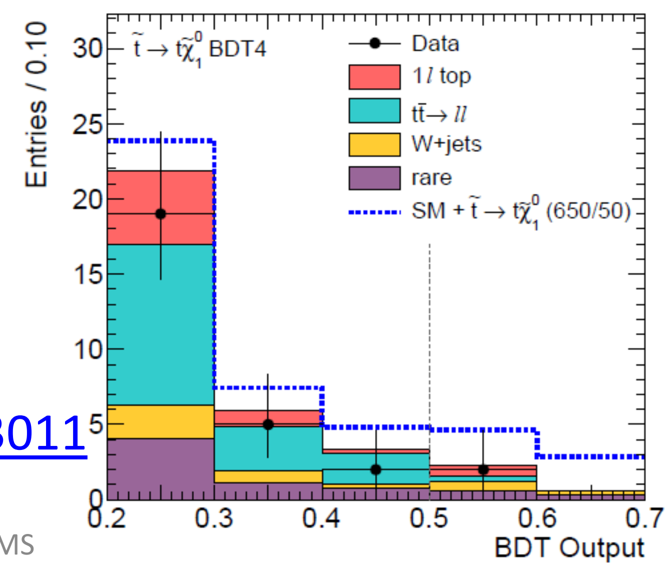
Direct stop production

- Light stop motivated by Naturalness

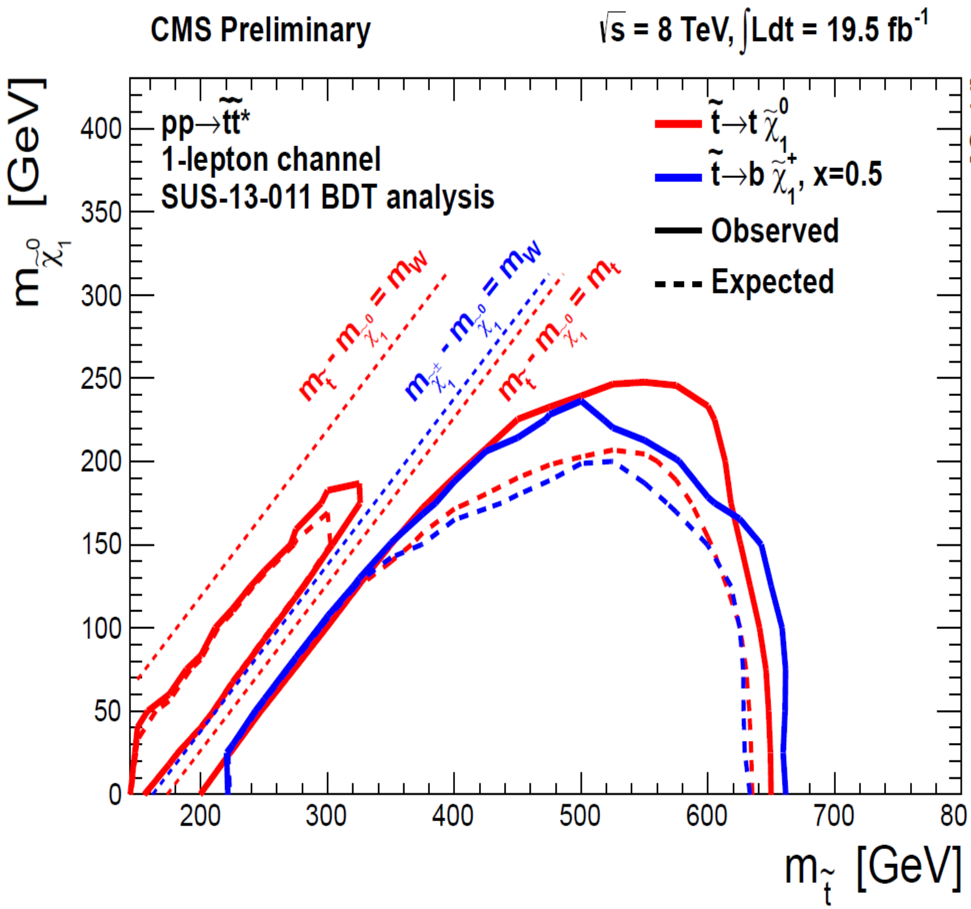


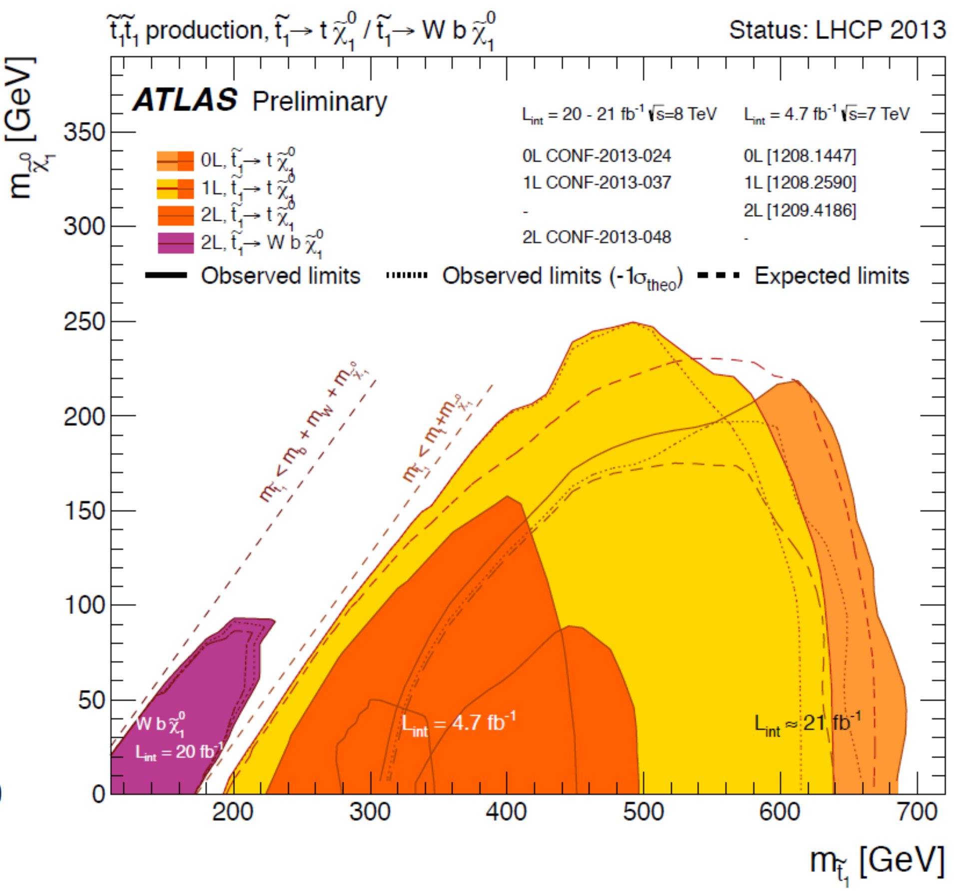


- Recent results :
  - ATLAS (20 fb^{-1})
    - 0 lepton + 6 (2 b-)jets + E_T^{miss} 2013-024
    - 1 lepton + 4 (1 b-)jets + E_T^{miss} 2013-037
    - 2 leptons + jets + E_T^{miss} 2013-048
    - Z + b-jet + jets + E_T^{miss} 2013-025
  - CMS (19.5 fb^{-1})
    - 1 lepton + 4 (1 b-)jets + E_T^{miss} (BDT) SUS13011

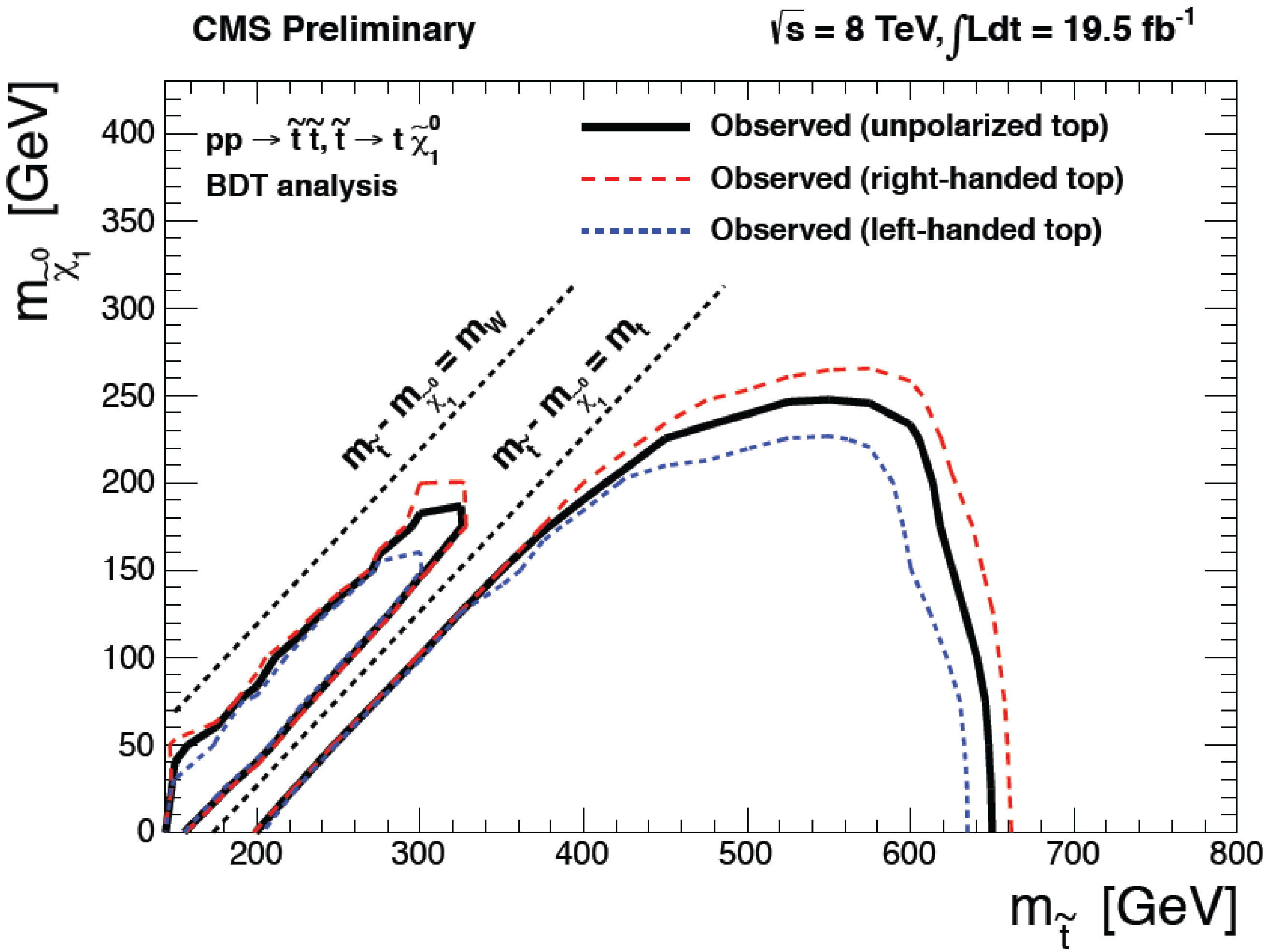


Limits on stop→top/bW $\chi^0{}_1$



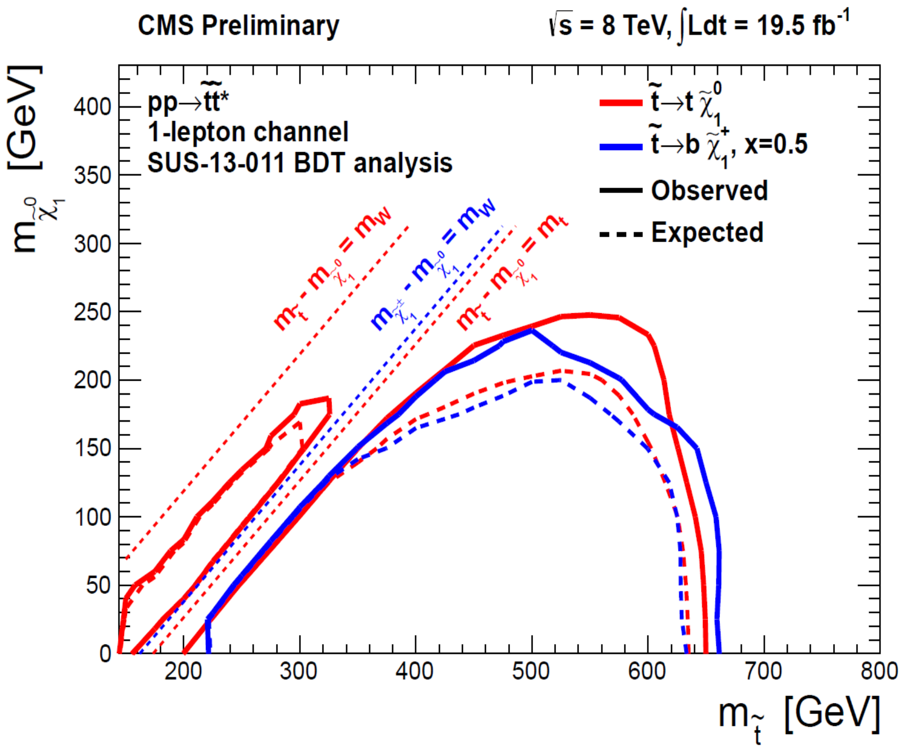


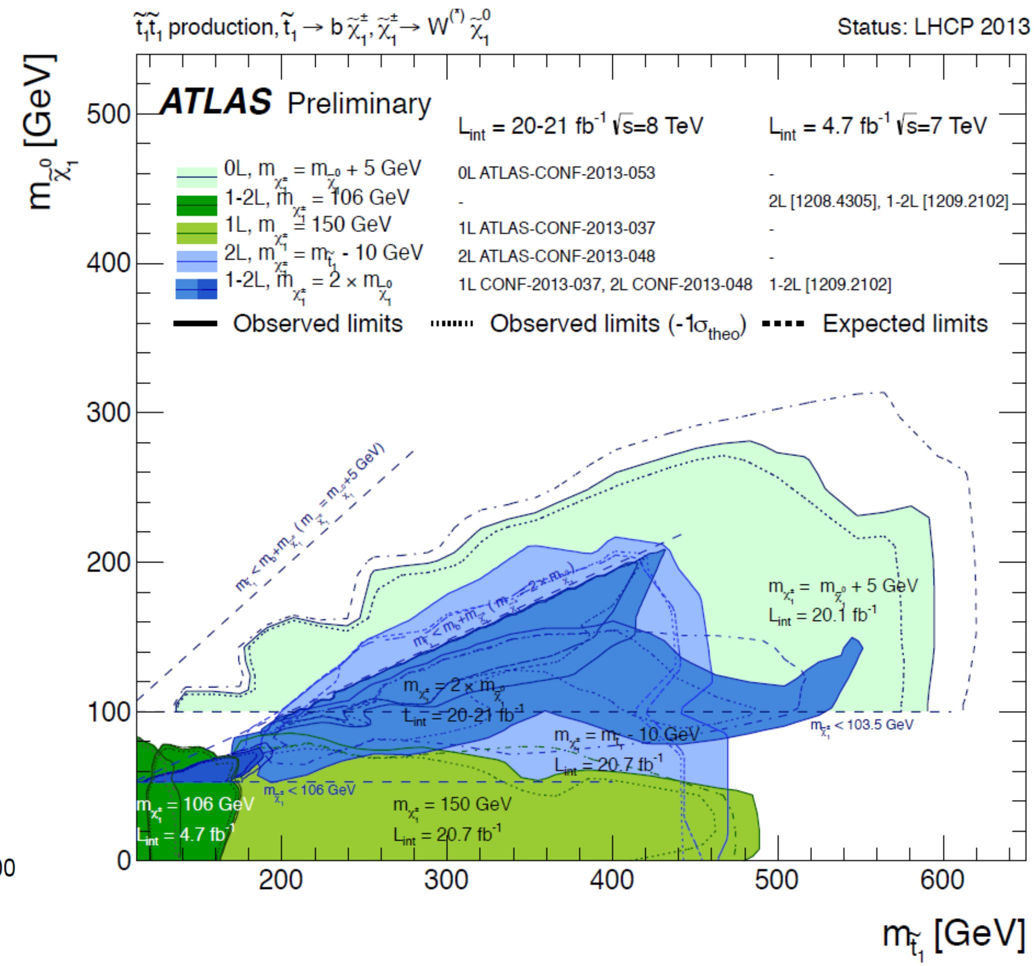
stop polarization



Impact of polarization on limit: ±20 GeV in 1-lepton channel.
No impact in 0-lepton channel.

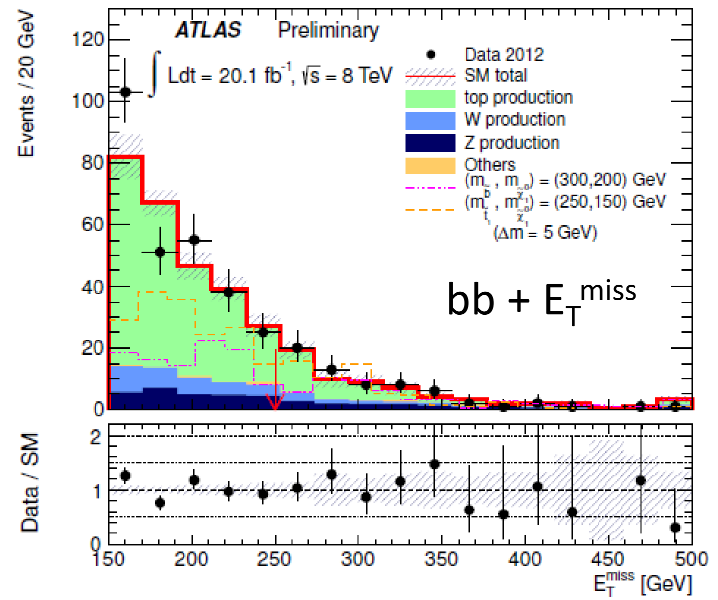
Limits on stop→b $\chi^{\pm}$



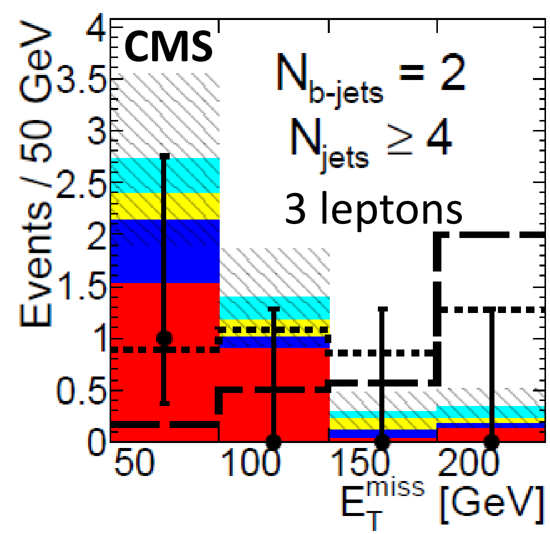


Direct sbottom production

- Light stop motivated by Naturalness
  - sbottom$_L$ related to stop$_L$ by SU(2)$_L$

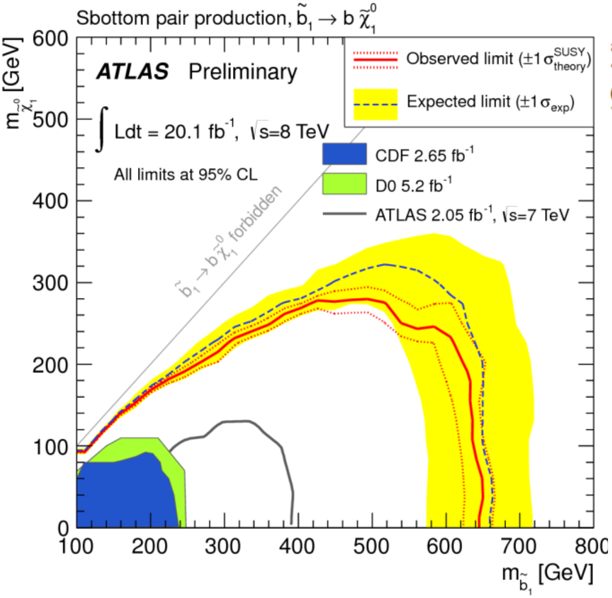


- Recent results:
  - ATLAS
    - 0 lepton + bb + E_T^{miss} 2013-053
    - 0/1 lepton + 3 b-jets + E_T^{miss} 2013-061
    - 2 same-sign leptons + b-jets + E_T^{miss} 2013-007
  - CMS
    - alpha$_T$ + 0-4 b-jets SUS12-028
    - 2 leptons same-sign + b-jets SUS12-017
    - 3 leptons + b-jets SUS13-008

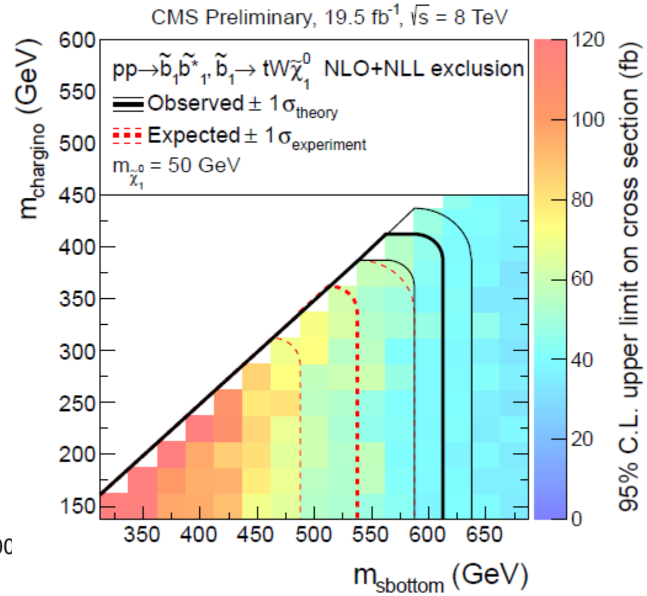


Direct sbottom limits

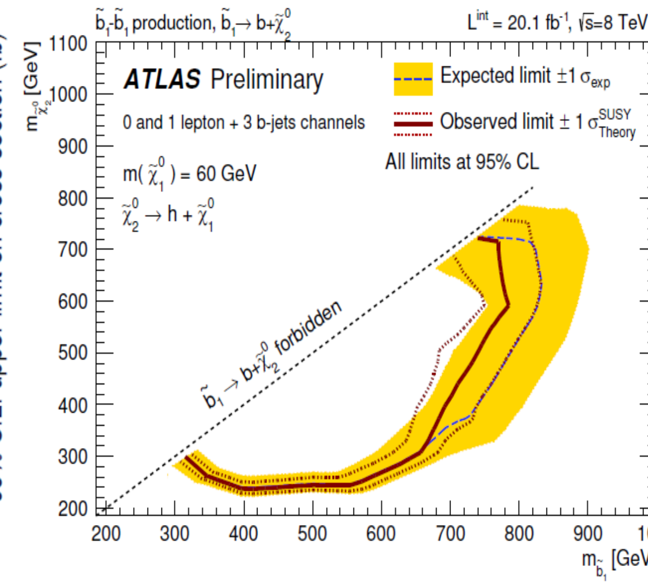
bb + E_T^{miss}



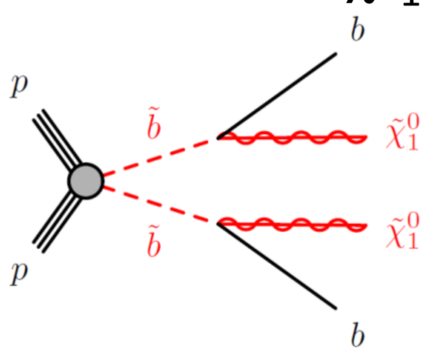
2L SS + b-jet



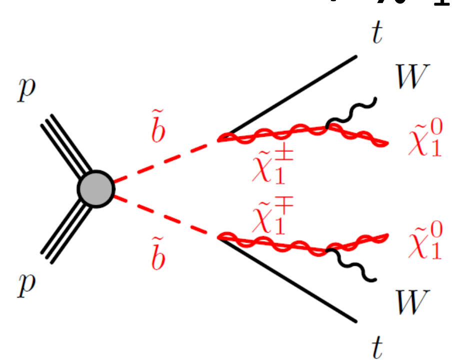
0/1L + 3 b-jets + E_T^{miss}



sbottom → b χ^0_1



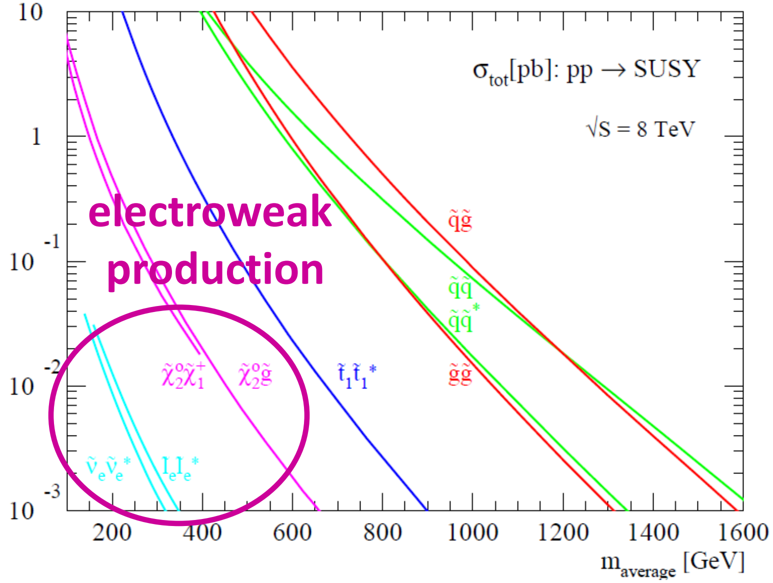
sbottom → top $\chi^\pm_1$



sbottom → b χ^0_2
→ b h(bb) χ^0_1

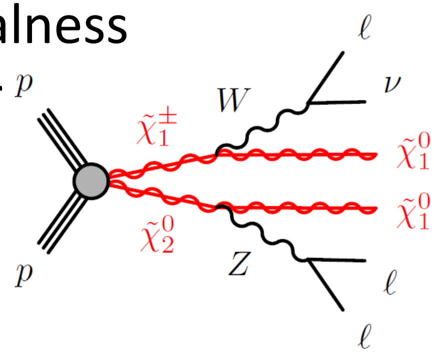
Recent Results

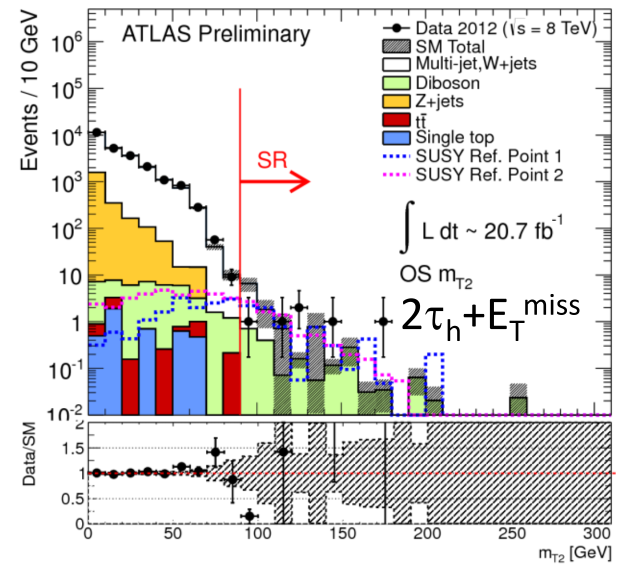
- gluino & 1st/2nd generation squarks
- 3rd generation (top & bottom) squarks
- electroweak SUSY (chargino, neutralinos, sleptons)
- R-Parity Violating & Gauge Mediated scenarios

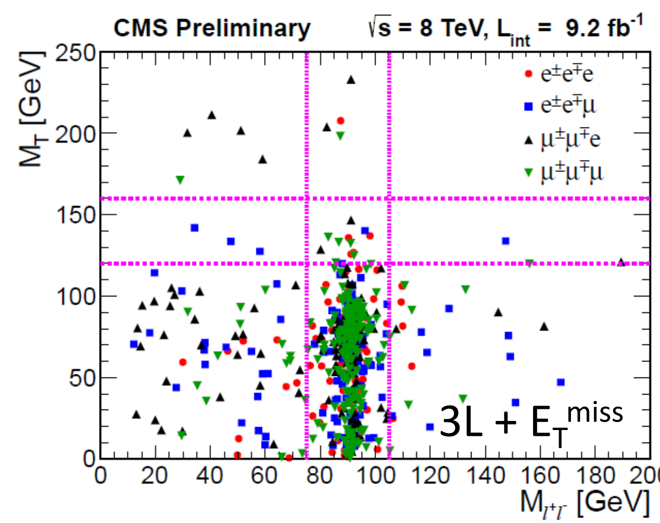


Electroweak SUSY production

- Light neutralino/chargino motivated by:
  - SUSY Naturalness
  - Dark Matter

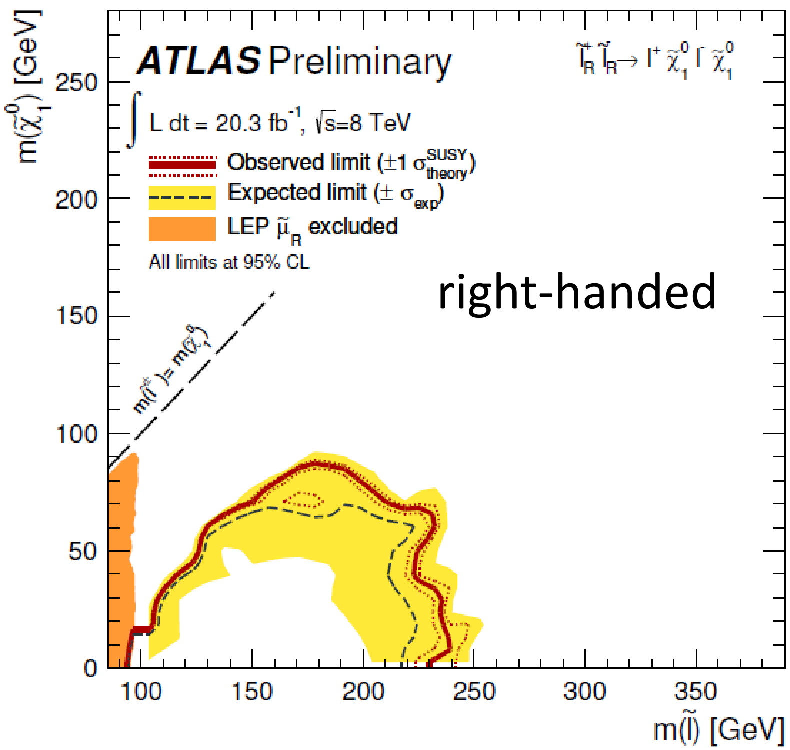


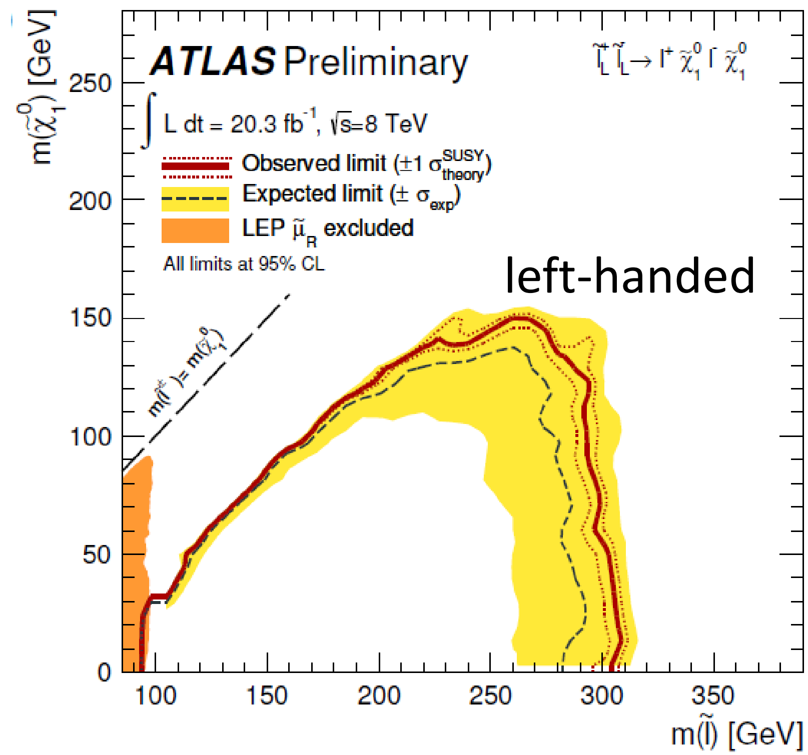


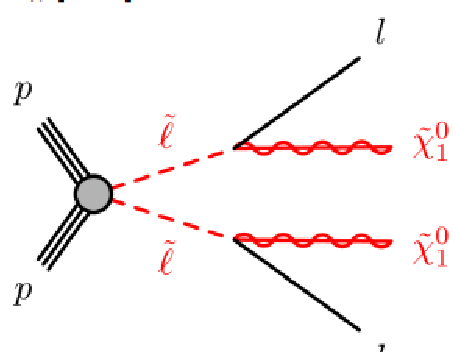


- Recent results:
  - ATLAS
    - 2 leptons (e/μ) + E_T^{miss} 2013-049
    - 2 τ + E_T^{miss} 2013-028
    - 3 leptons (e/μ) + E_T^{miss} 2013-035
    - 4 leptons + E_T^{miss} 2013-036
  - CMS
    - 2,3,4 leptons + E_T^{miss} SUS12022

direct sleptons production

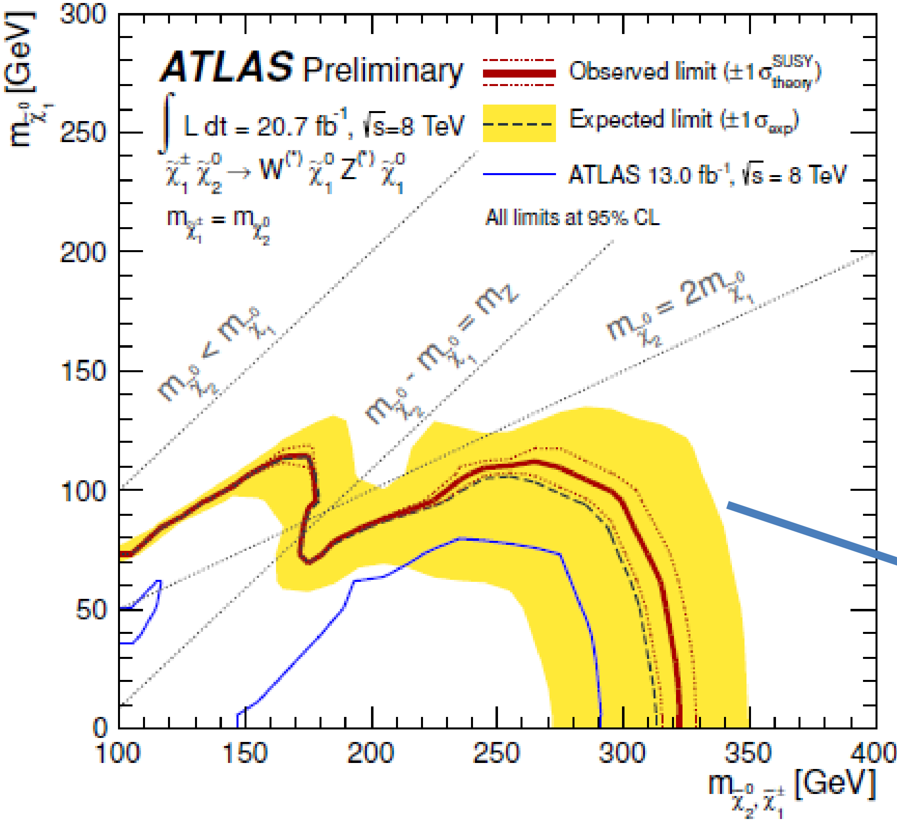


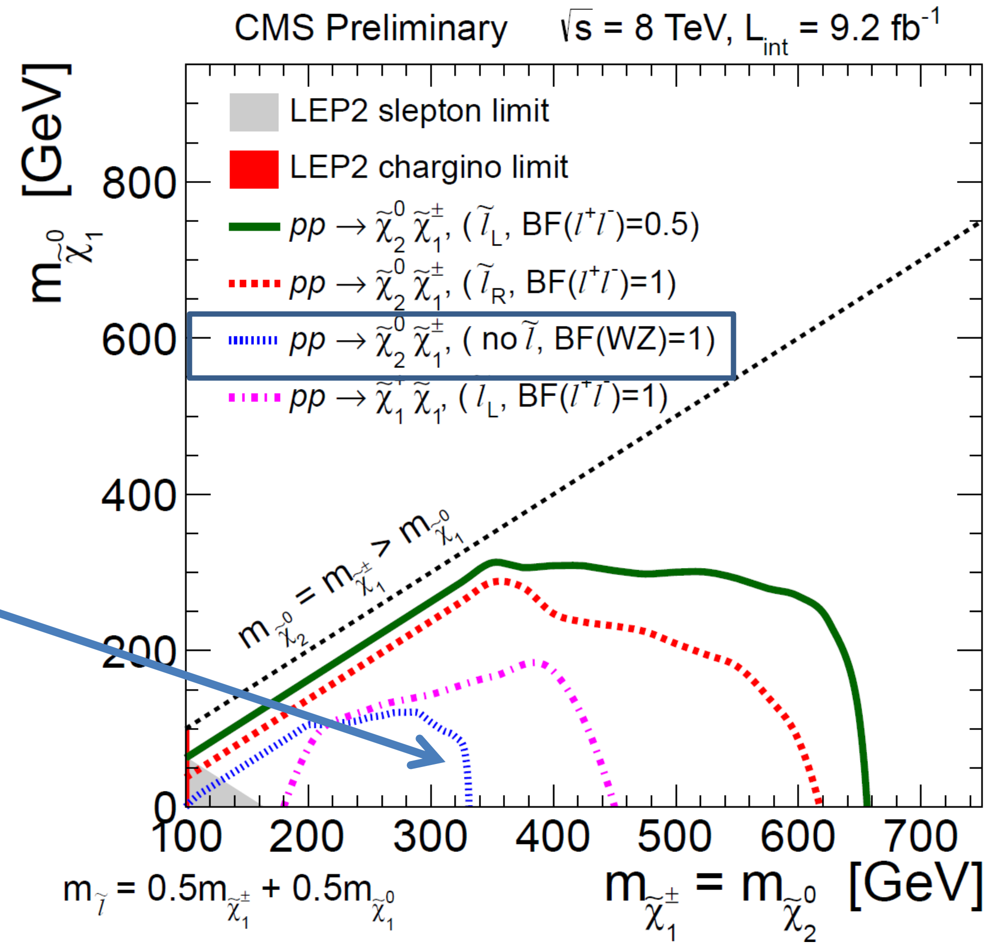




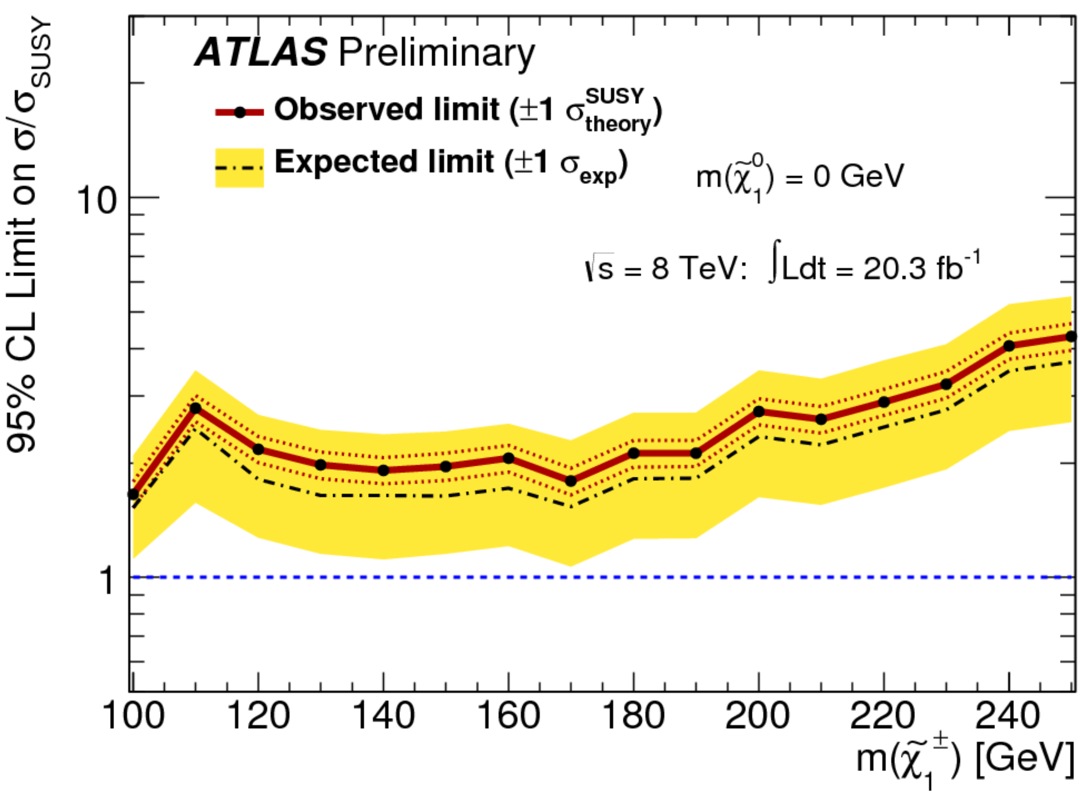
l = e or μ

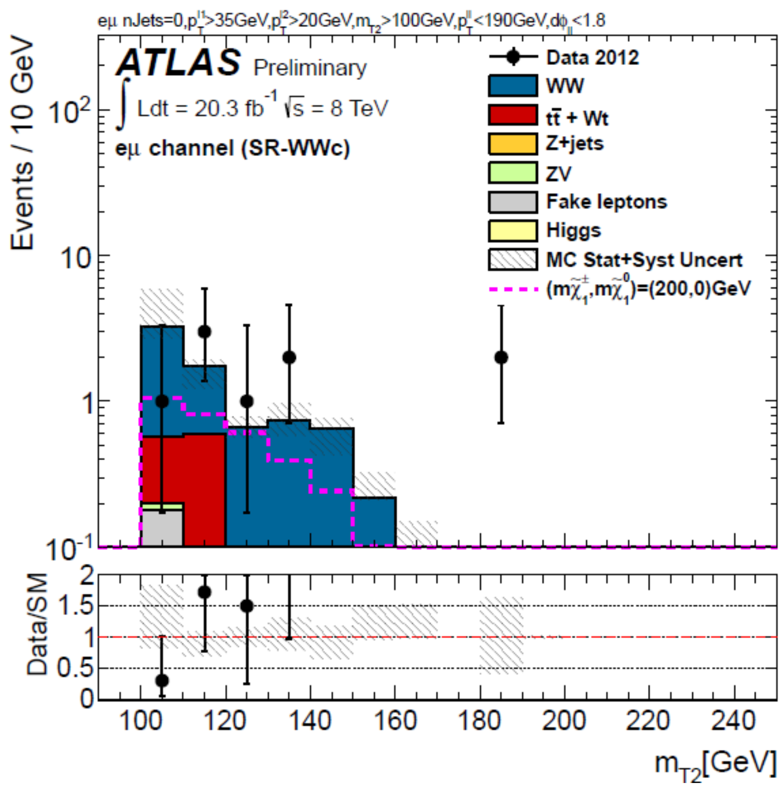
Limits on $\chi^0{}_2\chi^\pm{}_1$





Limited sensitivity to $\chi^{+}_{1}\chi^{-}_{1} \rightarrow W^{+}W^{-} + E_{T}^{miss}$





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- gluino & $1^{st}/2^{nd}$ generation squarks
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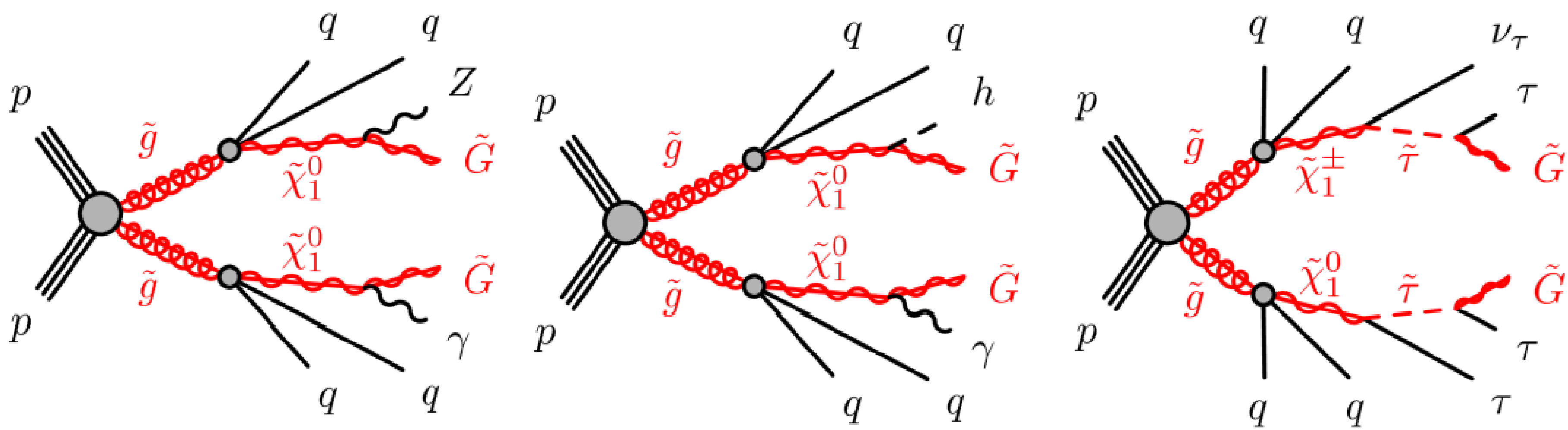
Gauge Mediation

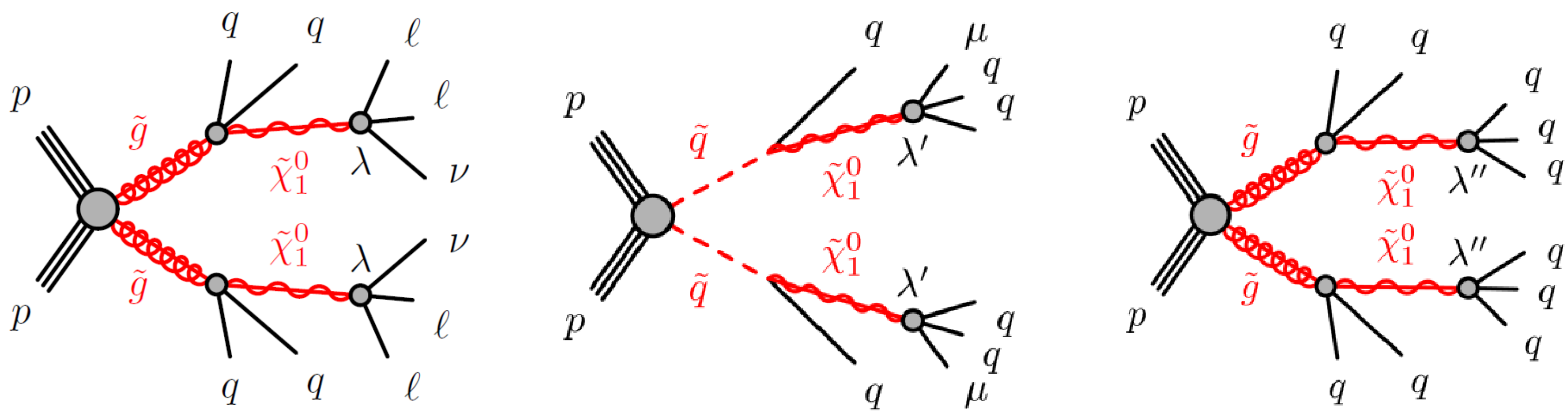
Talk by Andrew Kuhl



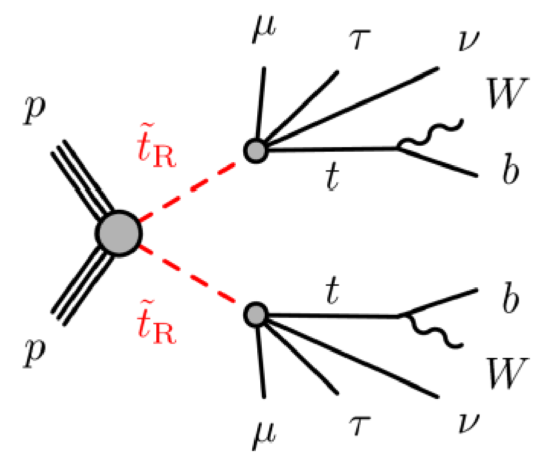
- SUSY production as usual: gluino, squarks, electroweak
- Lightest Supersymmetric Particle is the Gravitino (G)
- Phenomenology driven by NLSP particle & decay
  - $\chi^0{}_1 \rightarrow \gamma$ G
  - $\chi^0{}_1 \rightarrow$ Z/h G
  - stau $\rightarrow \tau$ G
  - etc.

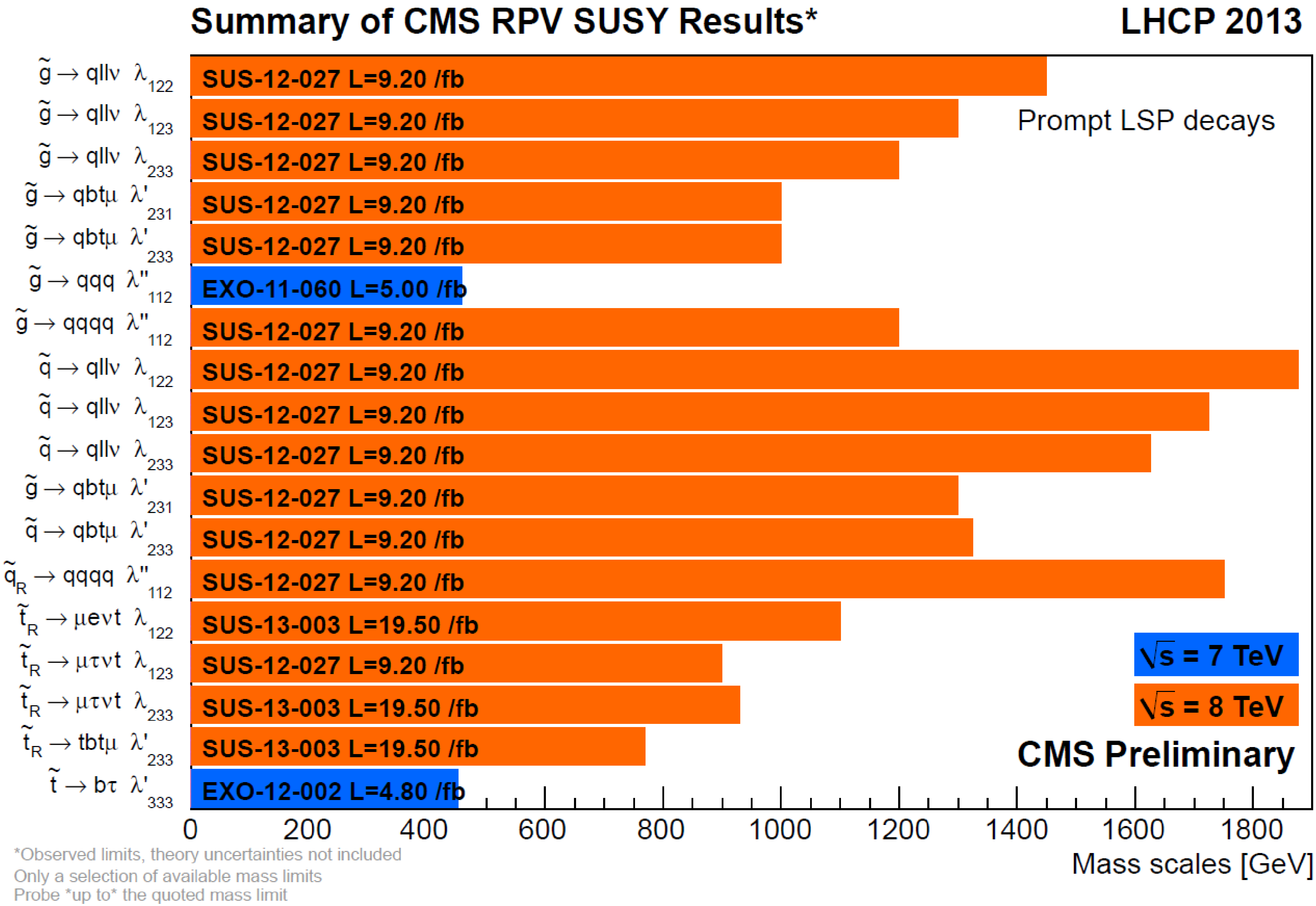
Talk by Antoine Marzin

R-Parity Violation



- R-Parity conservation is not necessary for viable SUSY models
  - SUSY production as usual*: gluino, squarks, electroweak ()
  - Lightest Supersymmetric Particle is not stable:
    - give up on SUSY Dark Matter
- Recent results with 20 fb^{-1} :
  - ATLAS
    - 4 leptons + MET (e/μ/τ, target leptonic λ) 2013-036
    - 0 lepton + 7-10 jets (re-interpretation) 2013-054
    - 2 leptons same-sign + 3 b-jets (re-interpretation) 2013-007
  - CMS
    - 3 leptons + b-jets SUS12027, SUS13003
    - 4 leptons SUS13010



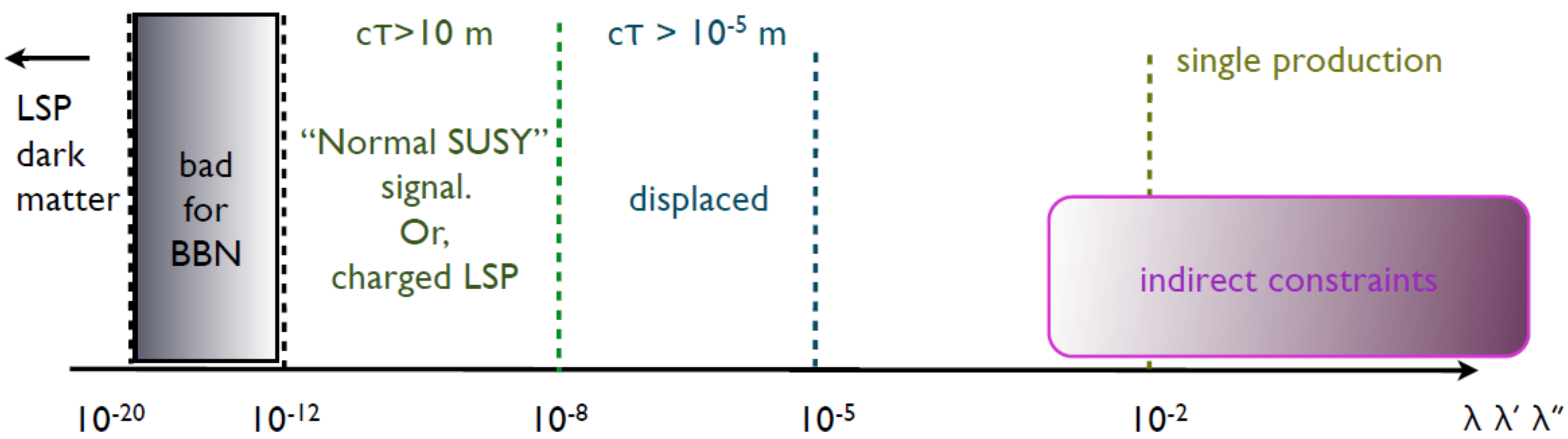


See: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

Long-lived particles

Talk by Antonio Boveia
Talk by Antoine Marzin

- Gauge Mediated and RPV scenarios with weak couplings can produce long-lived particles
  - stau → (like heavy muon) → τ G
  - gluino → (R-hadron) → qqq
  - etc.



Outlook

So we have not found SUSY…

What does it mean? What is coming up?

Impact of LHC on SUSY phenomenology

- In spite of their null results, the ATLAS & CMS searches have transformed the landscape of SUSY phenomenology
  - mSUGRA → Natural SUSY
  - emergence of simplified models
  - generalization of model parameters
    - mSUGRA (4.5 par) → Neutralino pMSSM (19 par)
    - GMSB (4.5 par) → GGM → Gravitino pMSSM (20 par)

see talk by Tom Rizzo

pMSSM interpretations by CMS: SUS-12-024 , SUS-12-030

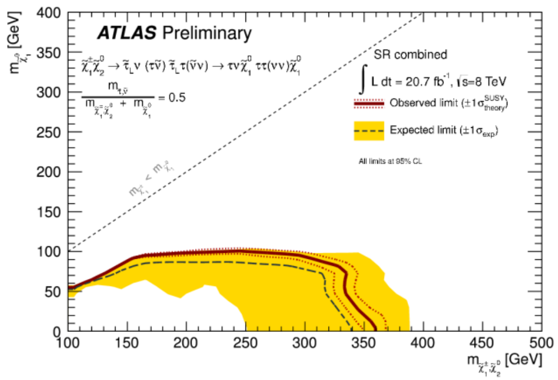
Other searches at 8 TeV

See e.g. H. Baer *et al* arXiv:1201.2949

Gauginos decay via Higgs

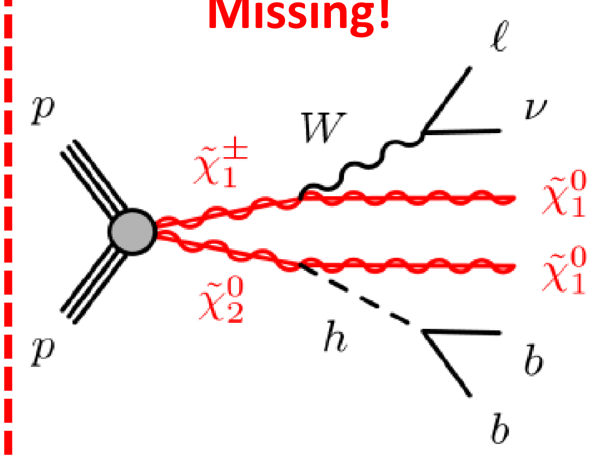
$\chi^{\pm}_1\chi^0_2$

stau

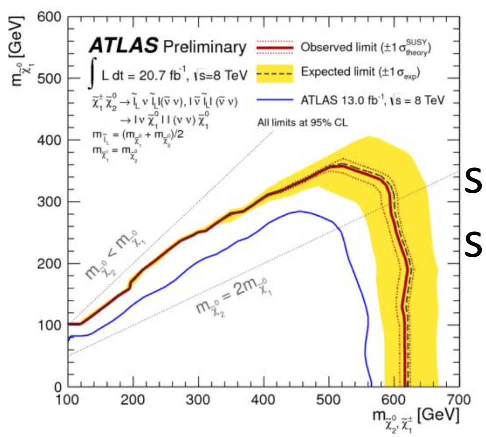


Wh

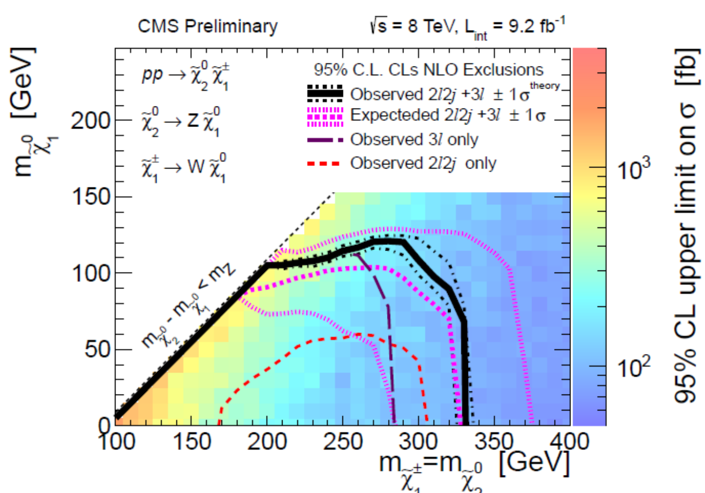
Missing!



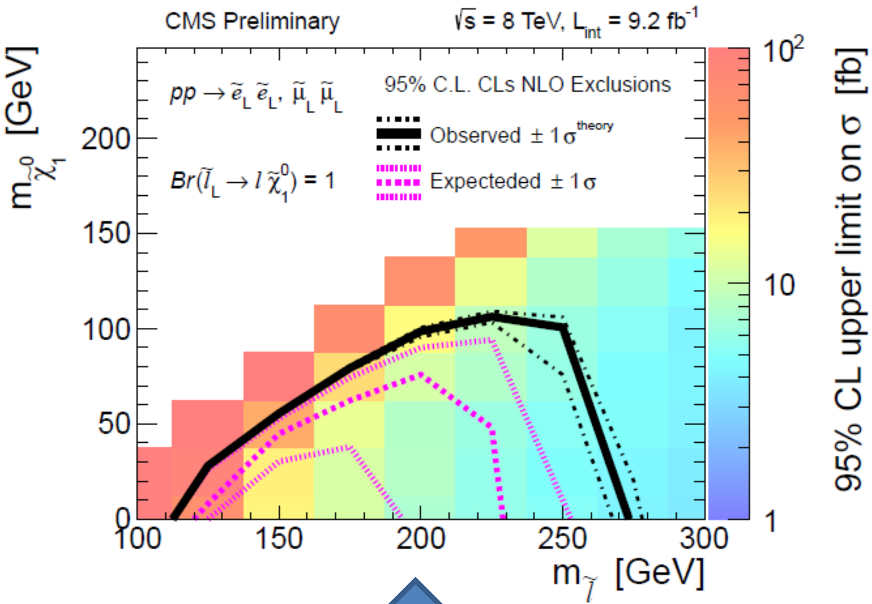
selectron
smuon

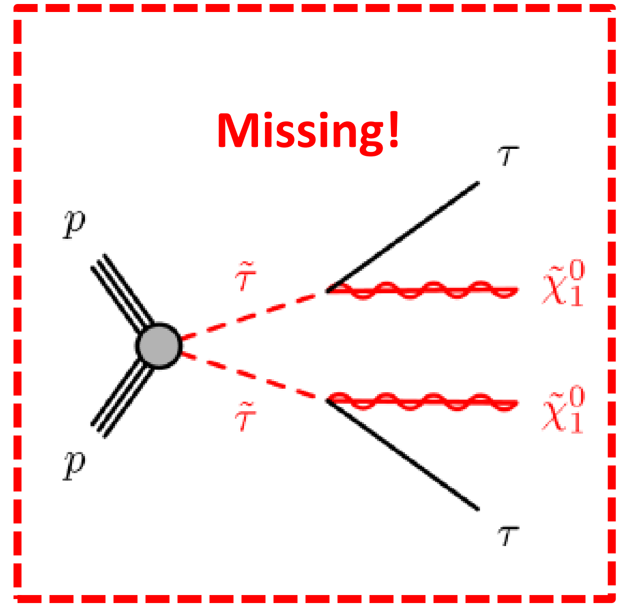


WZ

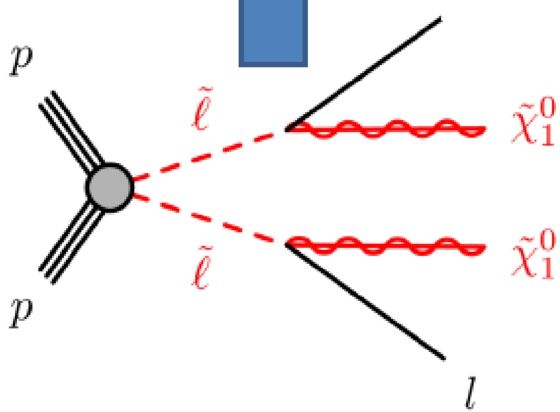


direct stau production

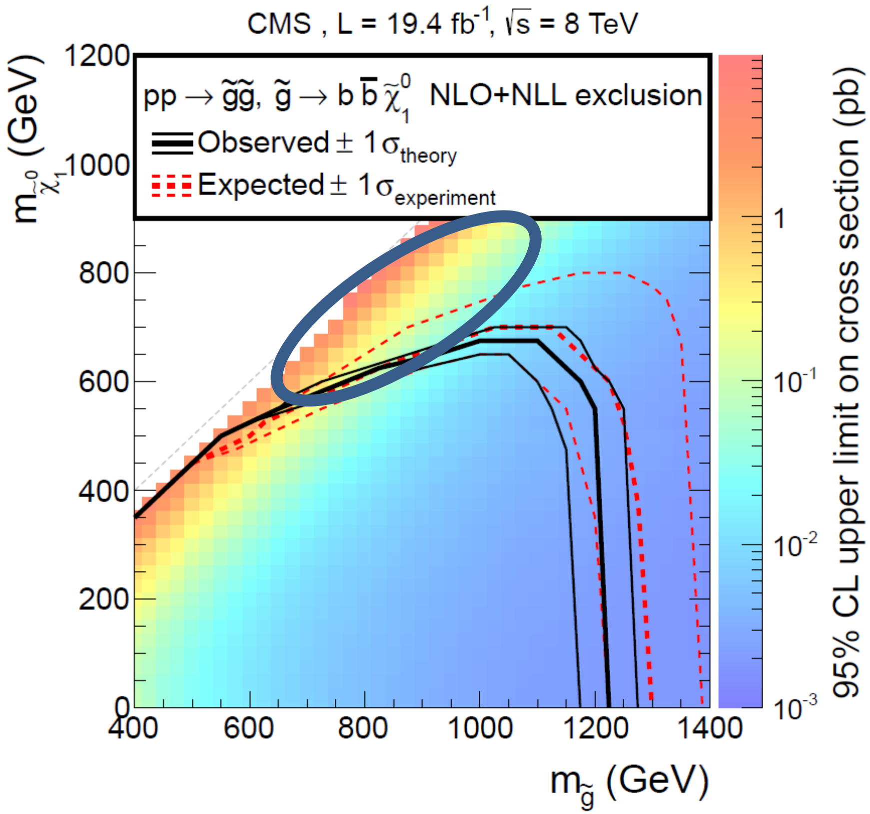


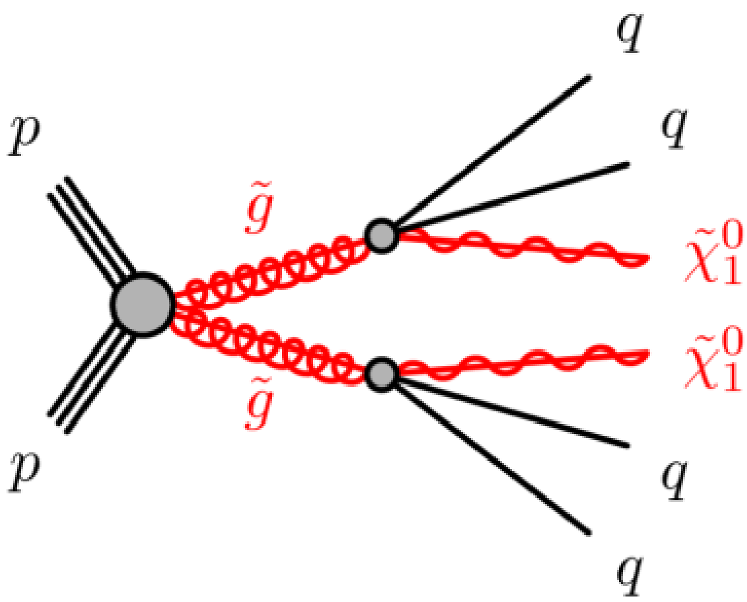


l = e or μ



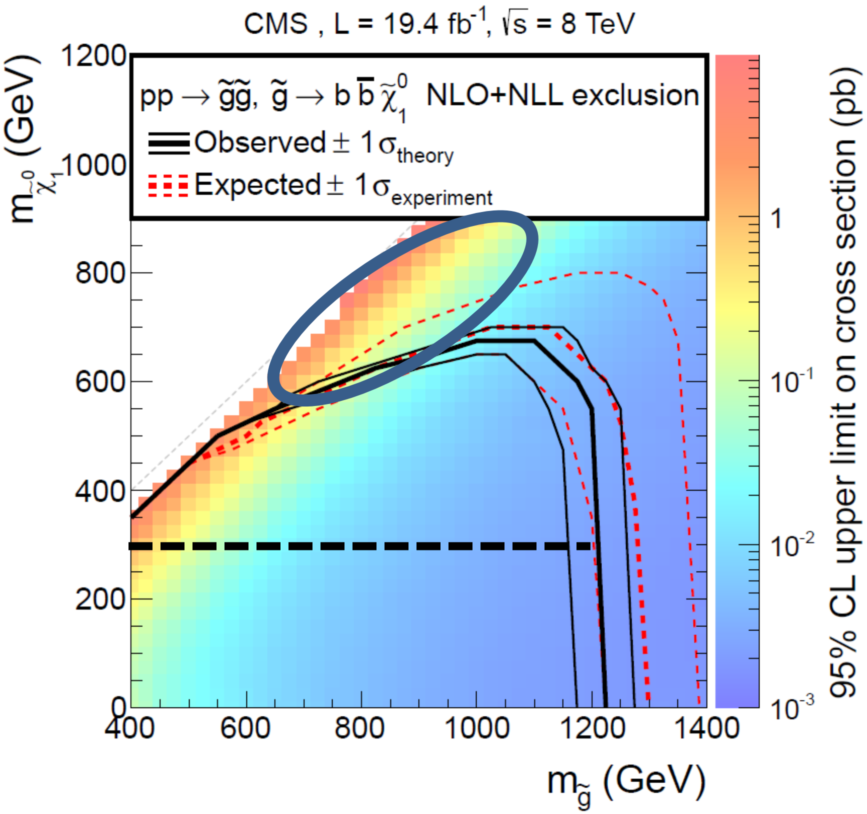
compressed spectra: strong production





Loss of sensitivity with small ΔM(gluino, χ^0_1) or ΔM(squark, χ^0_1) in simplified models.

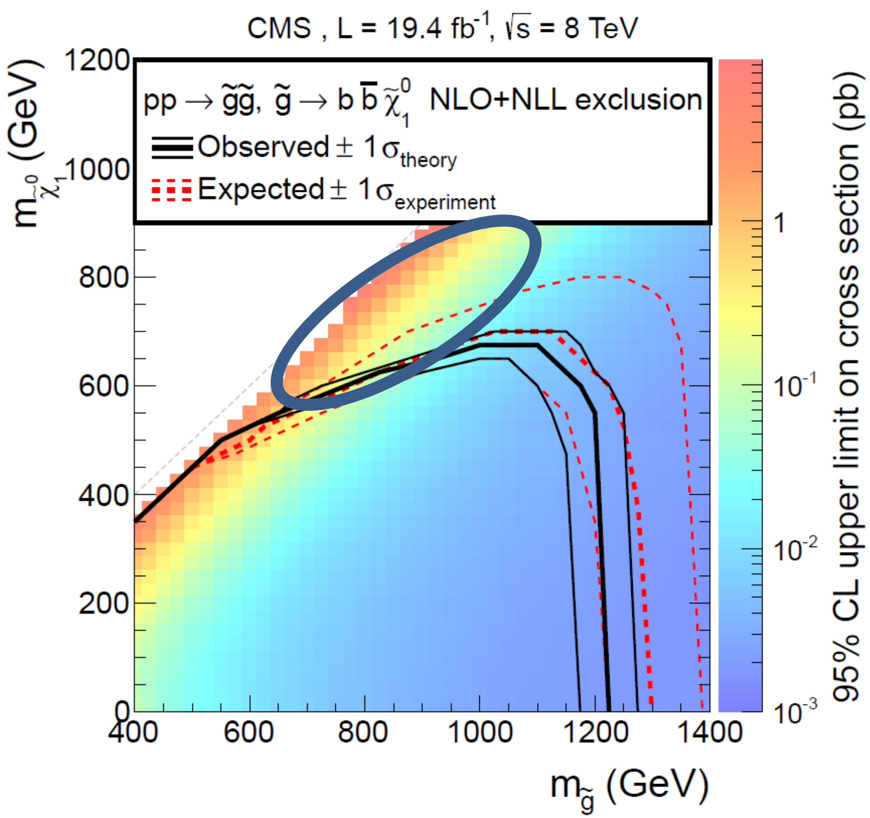
compressed spectra: strong production

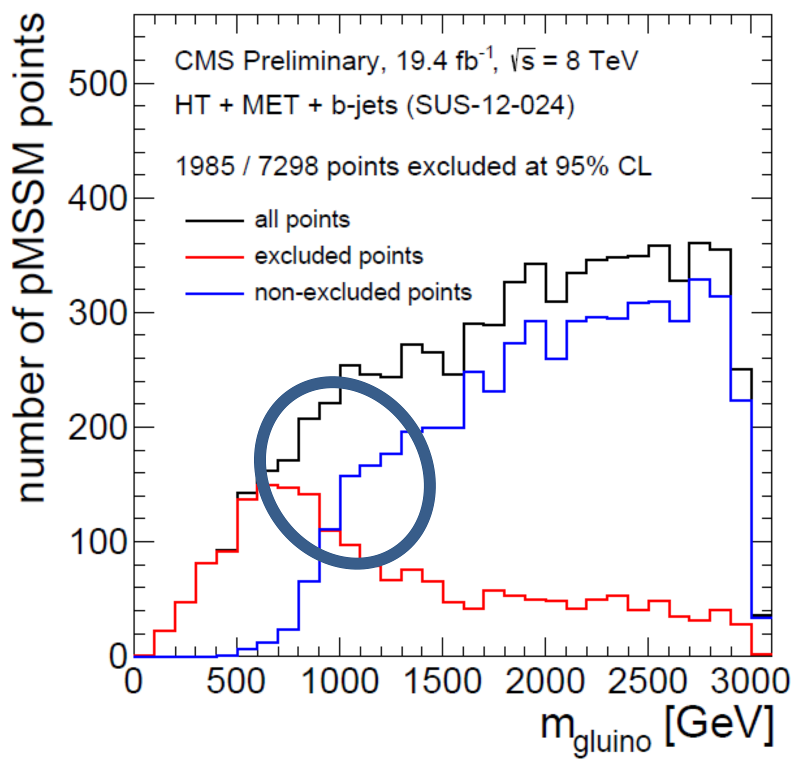


Not really affecting $m\chi^0_1 < \sim 300$ GeV stipulated by light Higgsino in Natural SUSY.

Loss of sensitivity with small ΔM(gluino, χ^0_1) or ΔM(squark, χ^0_1) in simplified models.

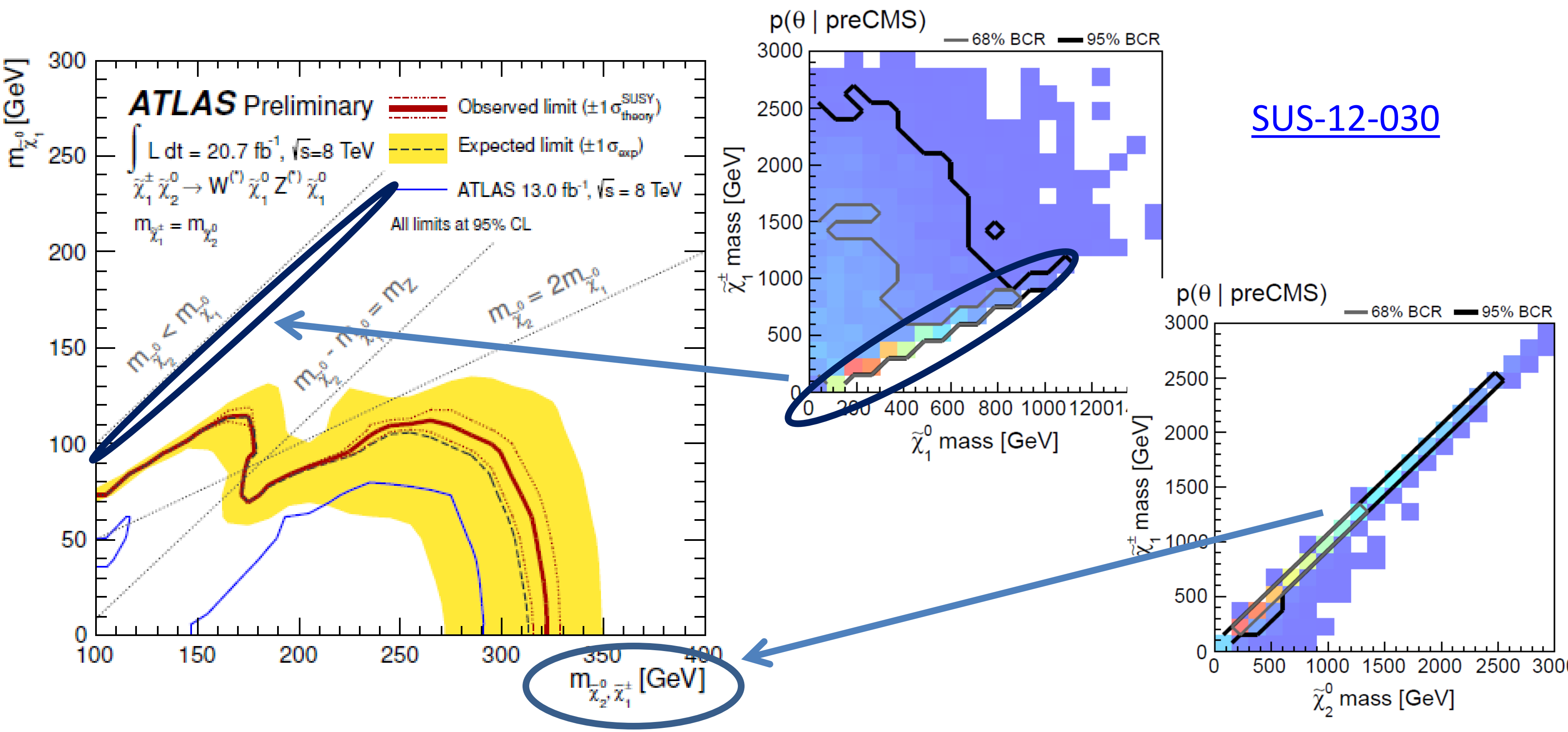
compressed spectra: strong production





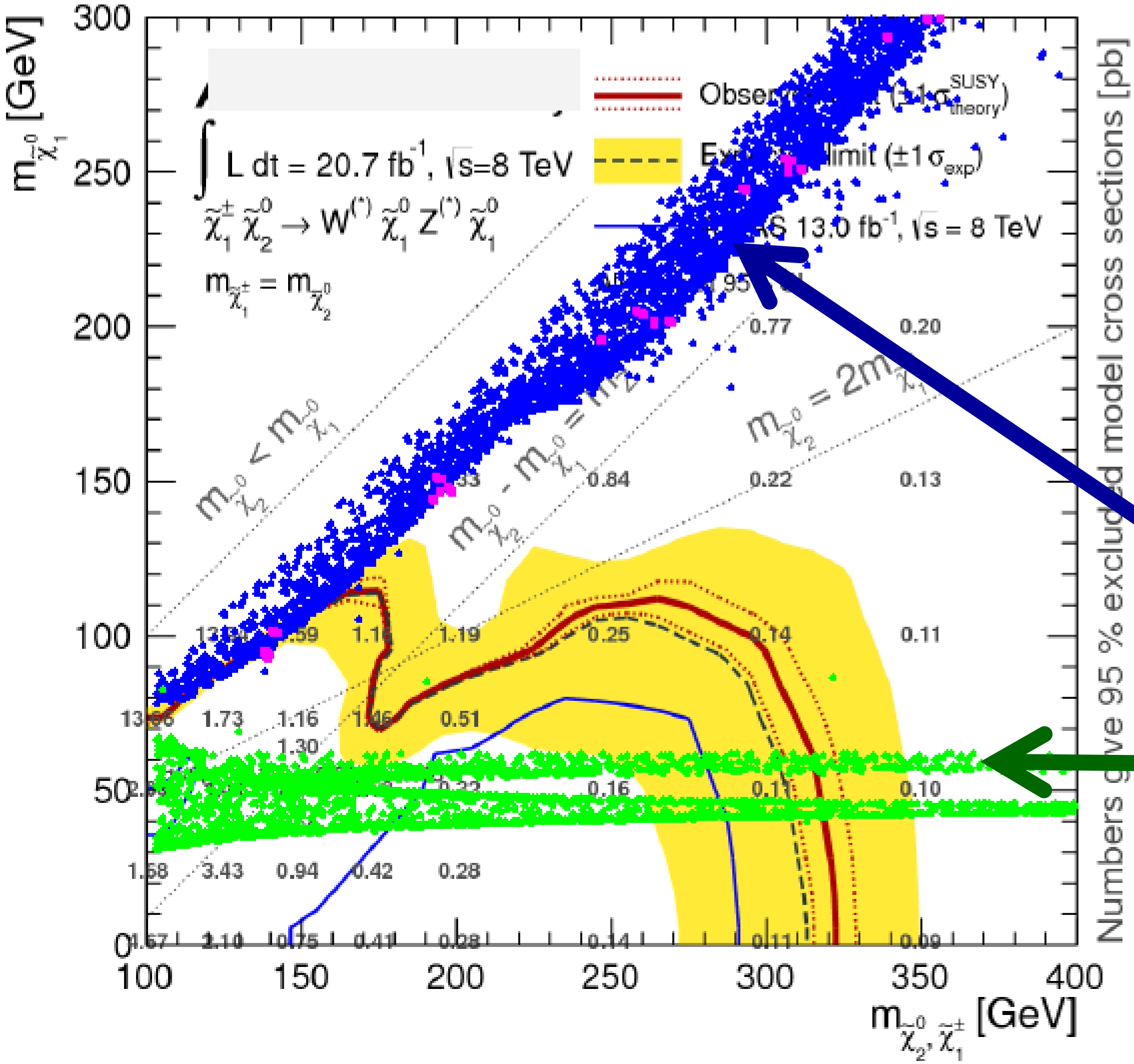
These scenarios are observed in viable pMSSM models, but they don't have a special motivation otherwise.

compressed spectra: gauginos



Very compressed $\Delta m(\chi^{\pm}_1, \chi^0_1)$ from pure Wino or Higgsino state arise naturally in the pMSSM because M1, M2 and μ are un-correlated.

compressed spectra: gauginos



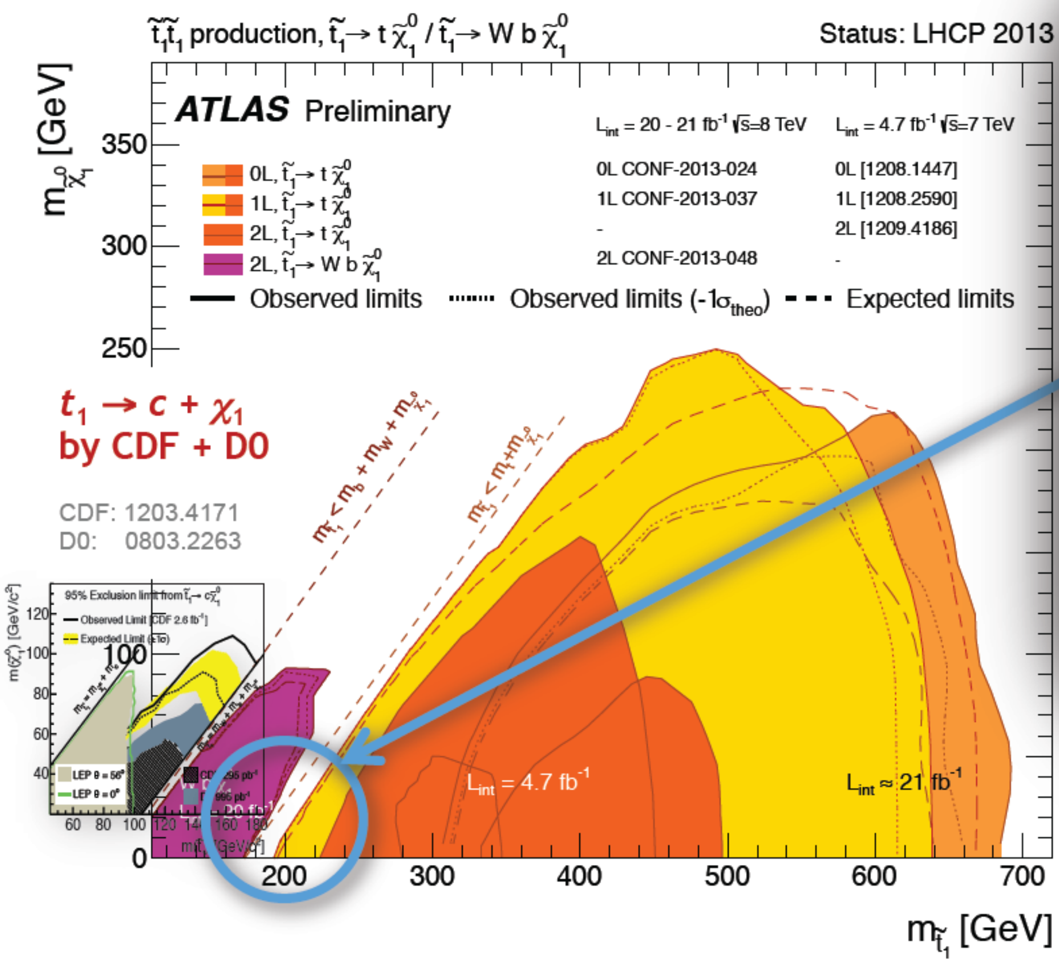
Compressed spectra with small $\Delta m(\chi^{\pm}_1, \chi^0_1)$ or small $\Delta m(\chi^0_2, \chi^0_1)$ are also motivated by dark matter relic density constraints.

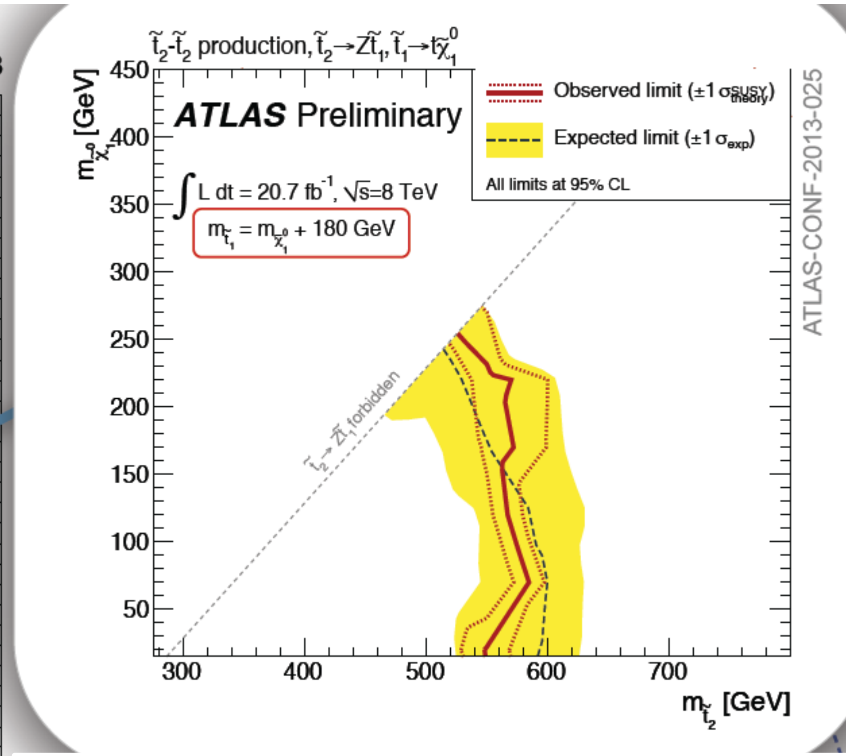
Well-tempered neutralino population in pMSSM scans.

$Z \rightarrow \chi\chi$ and $h \rightarrow \chi\chi$ poles.

credits: A. Hoecker

direct stop near $m_{stop} \approx m_{top}$



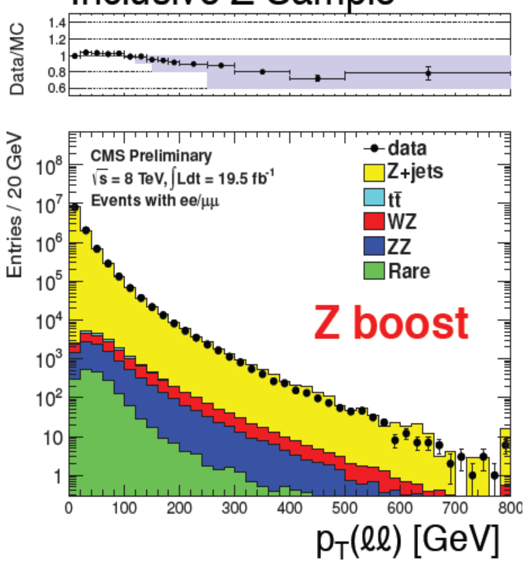


compressed spectra: impact of ISR

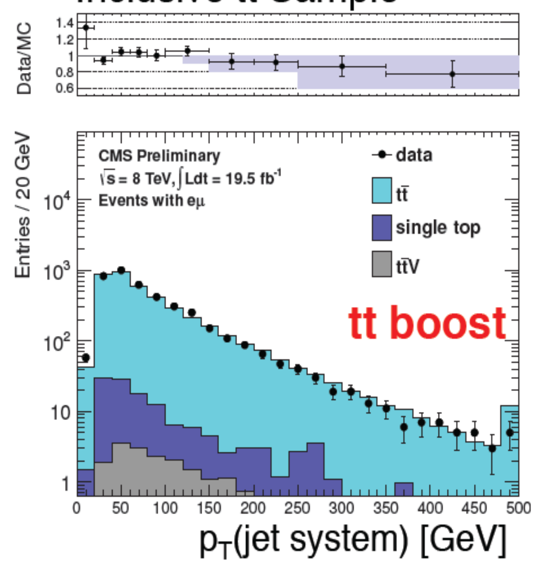
credits: B. Hooberman

- Signal efficiency in the small ΔM region depends on ISR
- Validate with data/MC comparisons in Z+jets and tt samples
  - Different initial state partons → consistent results

Inclusive Z Sample



Inclusive tt Sample

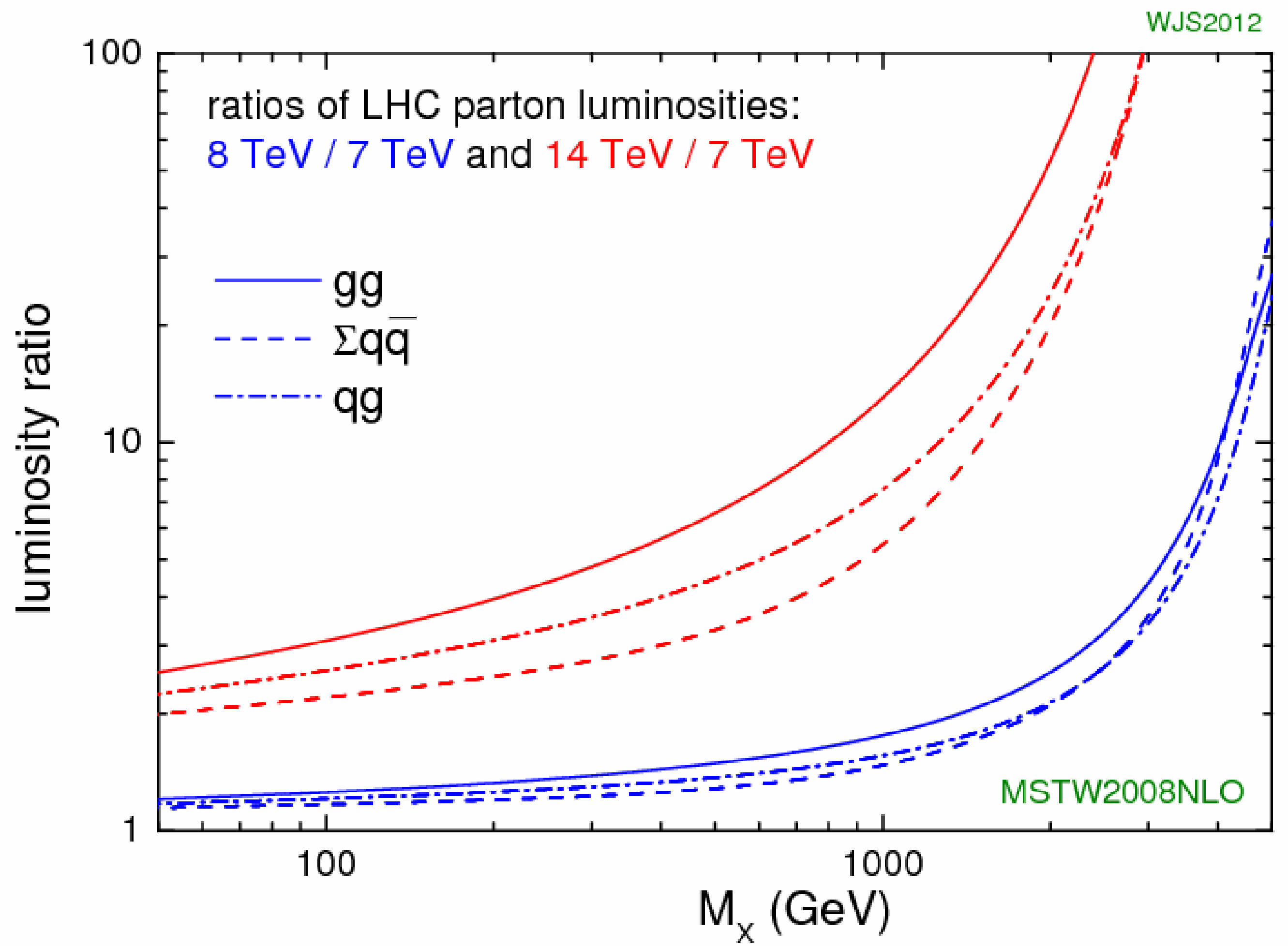


ATLAS also estimates ISR systematic uncertainties by varying normalization and factorization scales with Madgraph+pythia.

- **CMS tuning of madgraph MC tends to <u>overestimate</u> ISR → extract corrections and reweight the signal MC events**

14 TeV

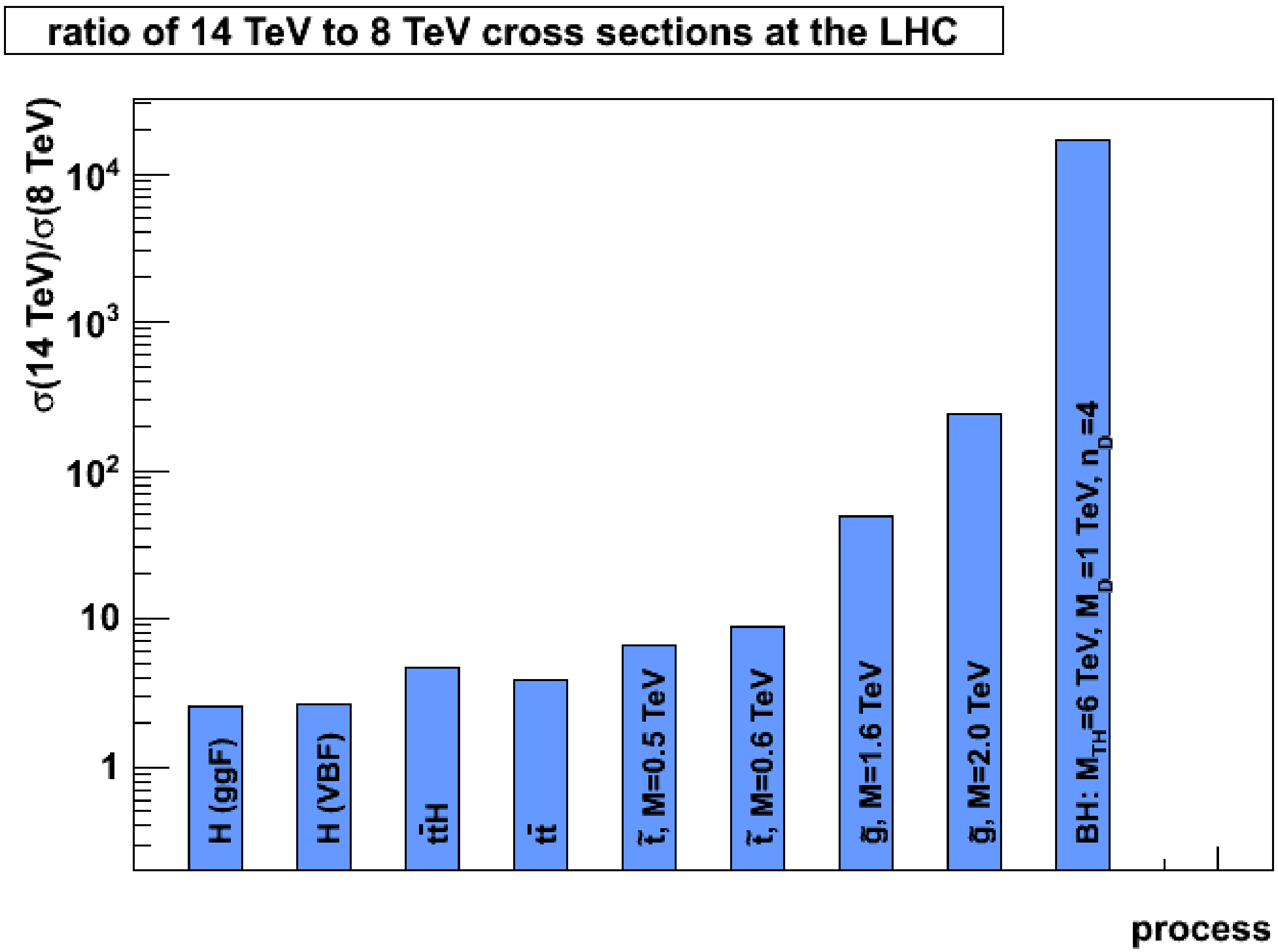
Cross-section increase at 14 TeV



Large sensitivity increase to heavy particles from higher LHC energy!

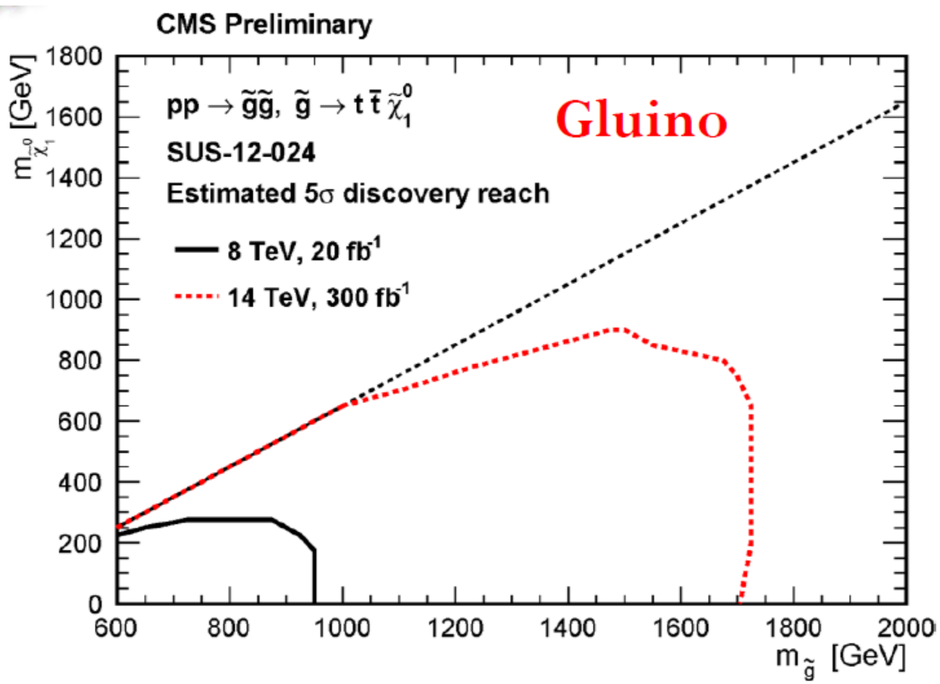
credits: B. Heinemann

SUSY cross-section increase at 14 TeV

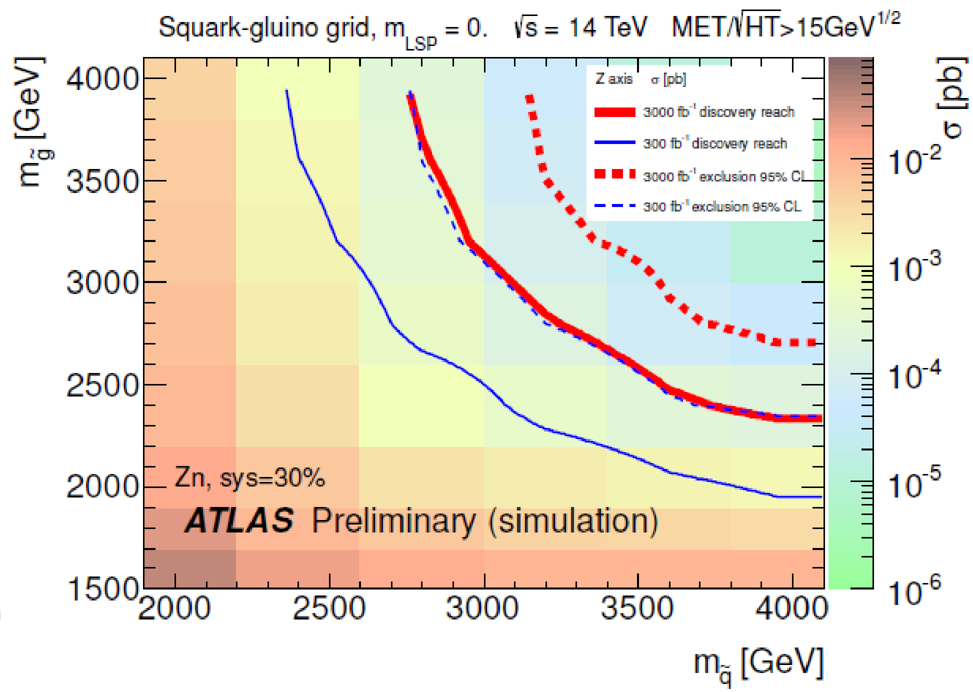


- Expect rapid progress on gluino sensitivity when the LHC re-starts.
- Lower-mass sparticles will also benefit from increased luminosity over time.

gluino reach at 14 TeV



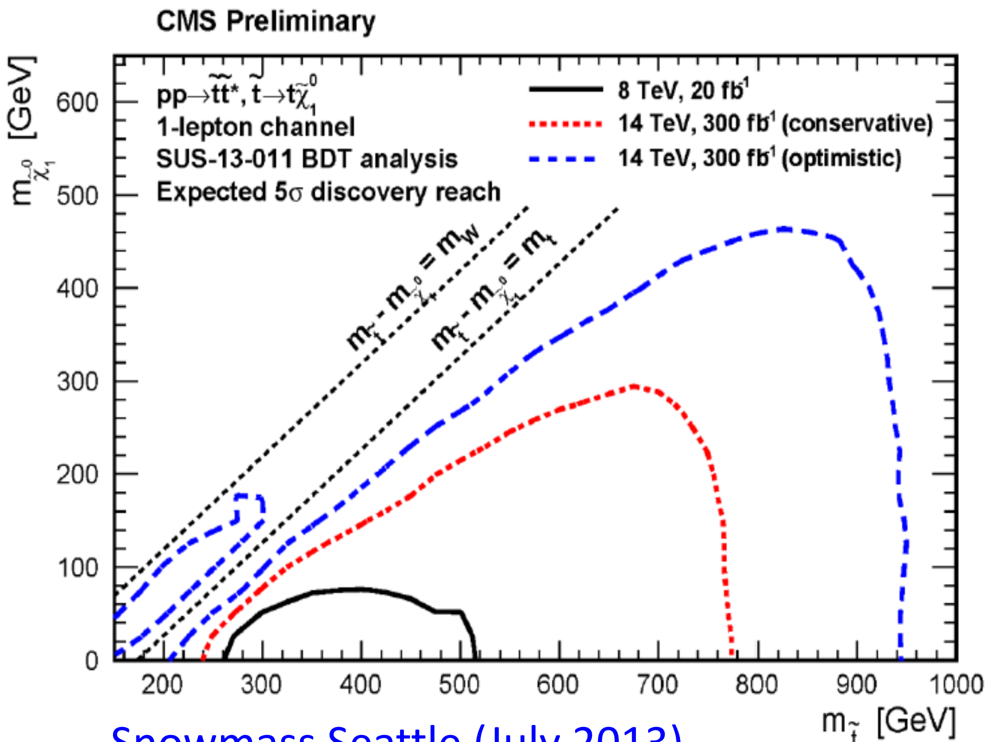
[Snowmass Seattle (July 2013)]



[ATLAS contribution to European Strategy for Particle Physics Open Symposium]
(October 2012)

- Current estimates based on projections of 8 TeV analyses.

direct stop reach at 14 TeV



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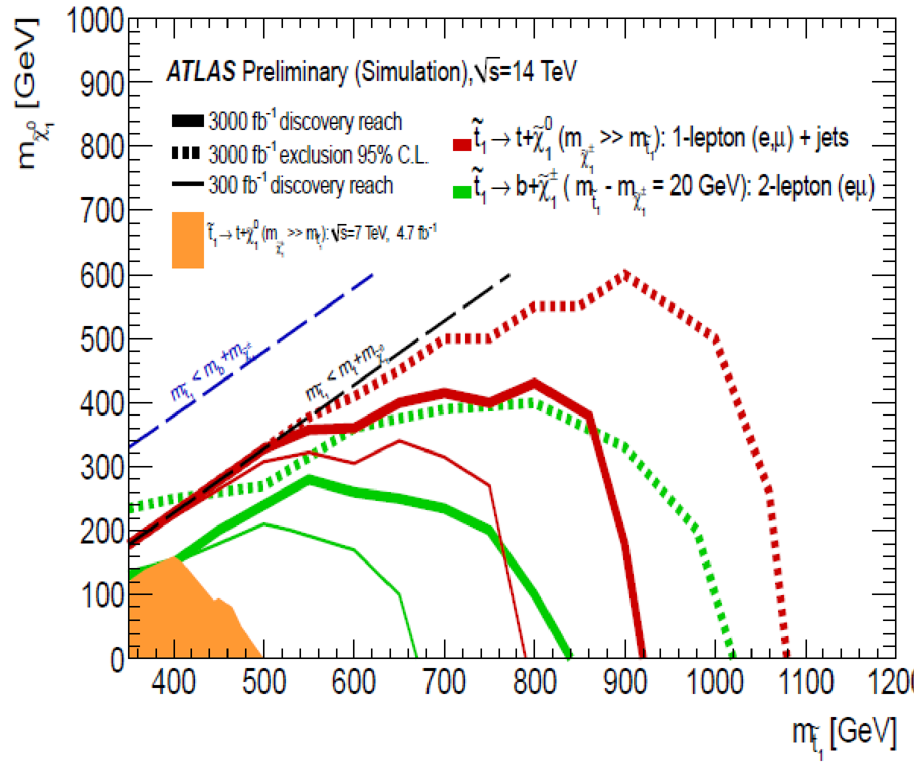

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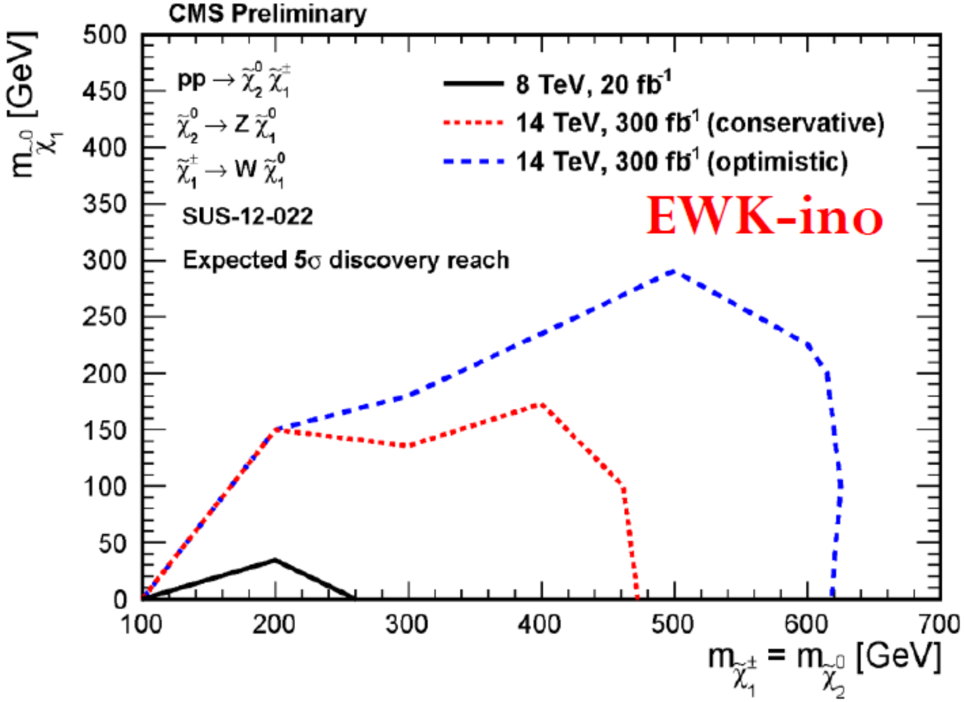
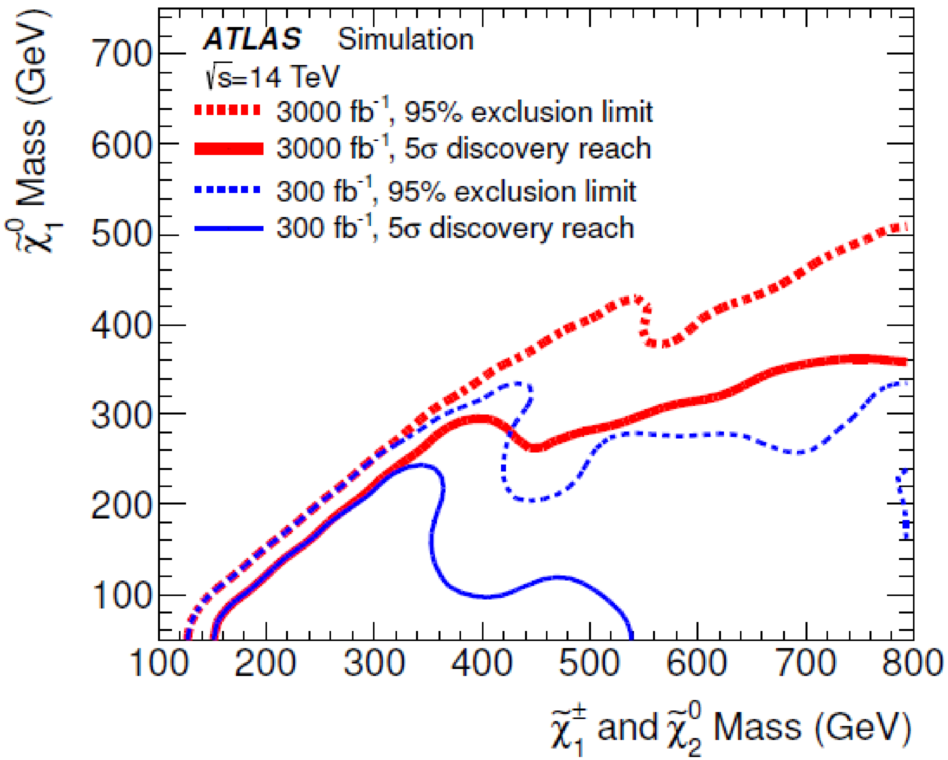
direct gaugino reach at 14 TeV



[Snowmass Seattle (July 2013)](#)

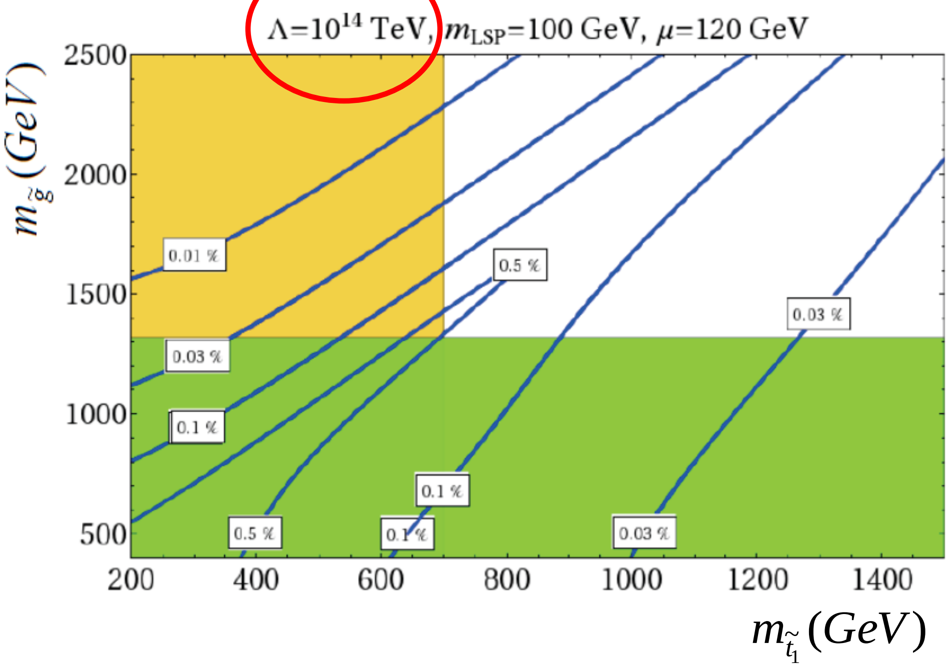


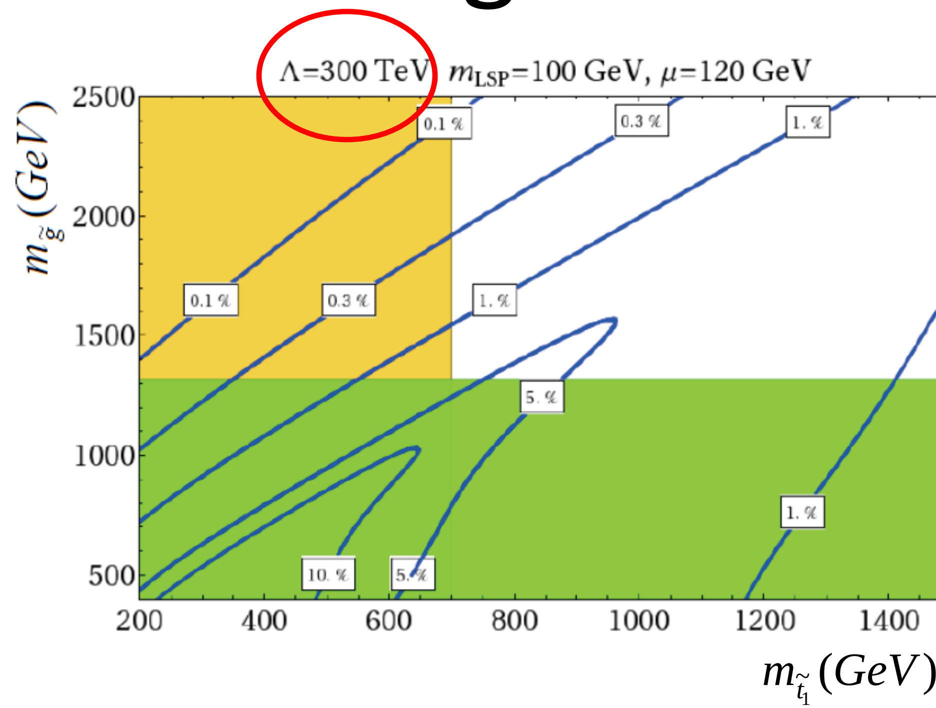
[Letter Of Intent for ATLAS upgrade Phase-II](#)

- Current estimates based on projections of 8 TeV analyses.

A. Arvanitaki *et al.*

How much Fine Tuning?





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

Fine-tuning from stop and gluino depends on the choice of Λ, making it possible to go to higher masses.

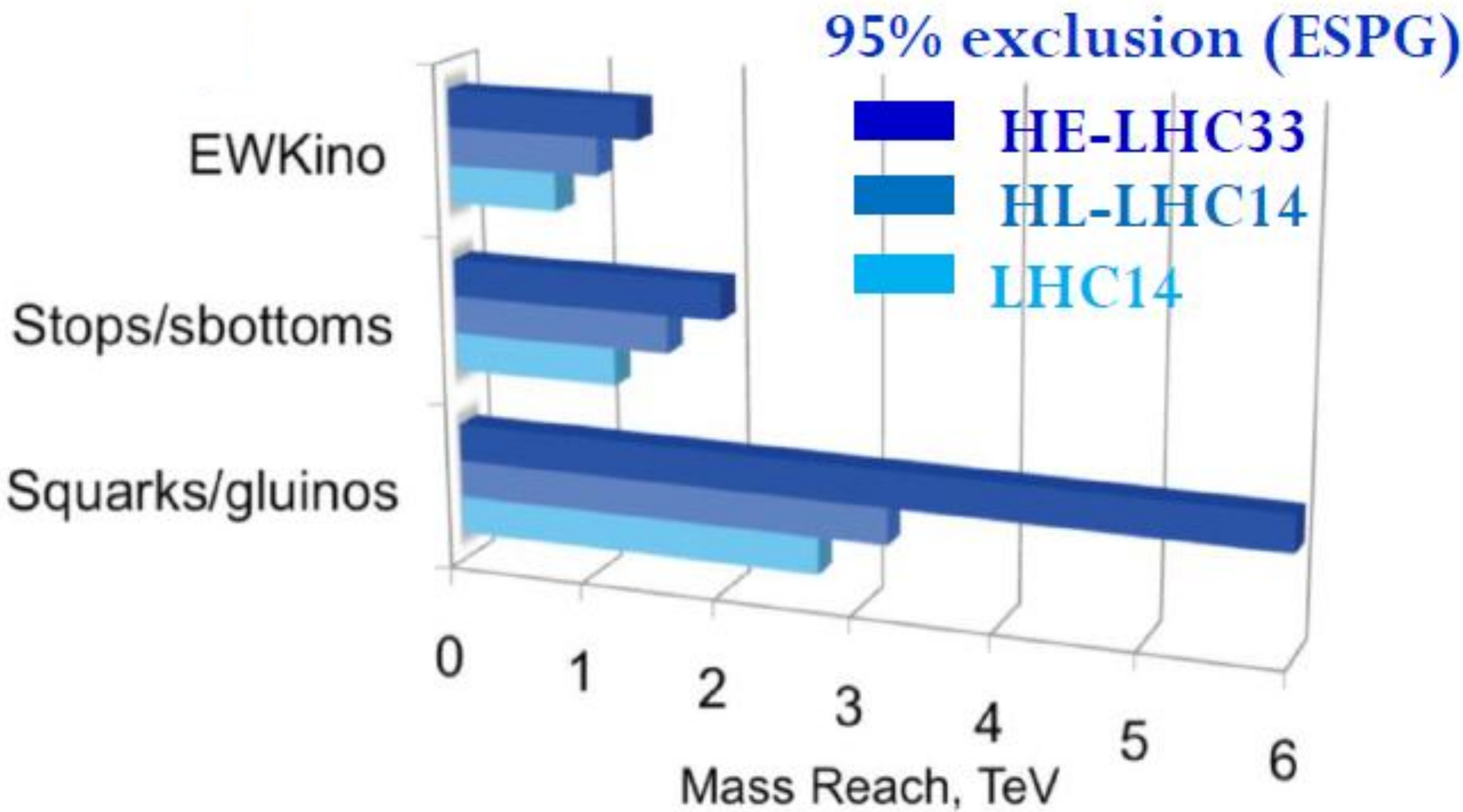
$$\delta m_{h_u}^2 = -\frac{3y_t^2}{4\pi^2} m_{\tilde{t}}^2 (1 + a^2/2) \log \frac{\Lambda}{m_{\tilde{t}}}$$

…but the Higgsino bounds are robust!

$$\delta m_{\tilde{t}}^2 = -\frac{8\alpha_s}{3\pi} M_3^2 \log \frac{\Lambda}{m_3}$$

SUSY reach at future colliders (CMS)

Snowmass Seattle (July 2013)

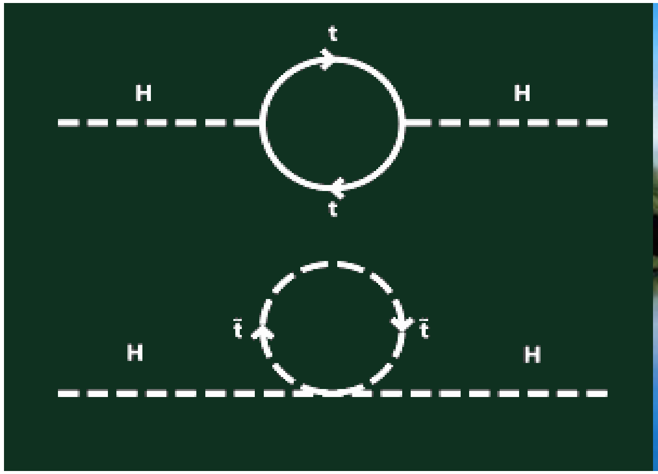


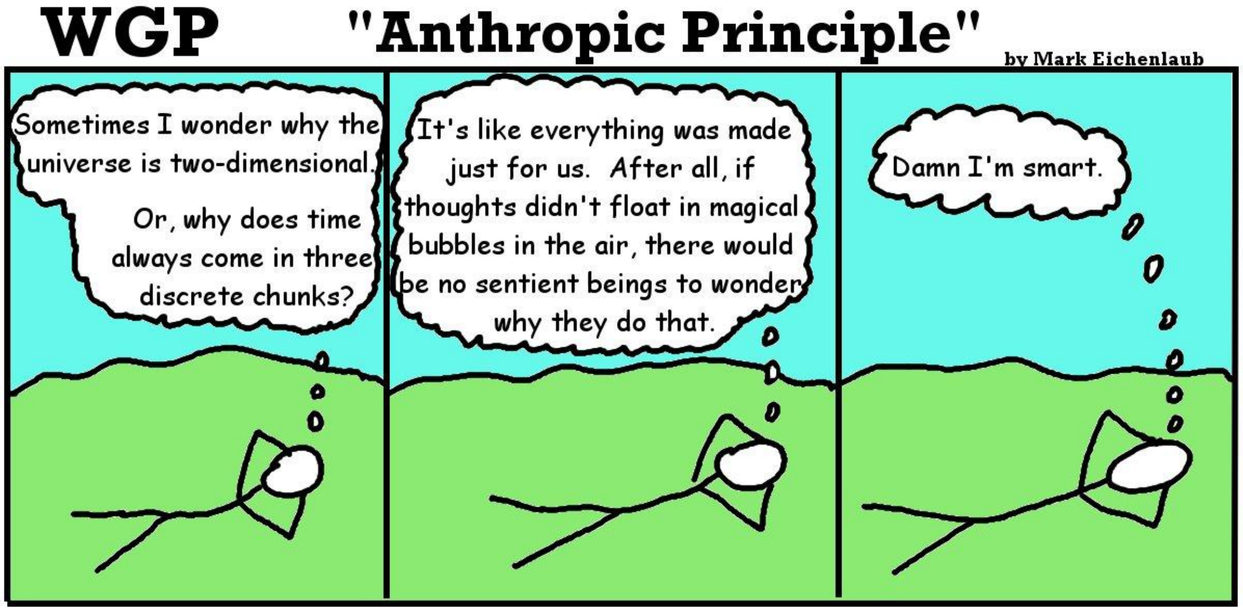
Conclusions

- Fascinating times to search for supersymmetry
  - tremendous effort by ATLAS & CMS
- No evidence for SUSY so far…
  - still possible to hide signals in 7-8 TeV datasets
  - sensitivity boost at 14 TeV and high luminosity
- Emphasis on Natural SUSY
  - but we'll leave no stone unturned…

The absence of evidence may not be evidence of absence!

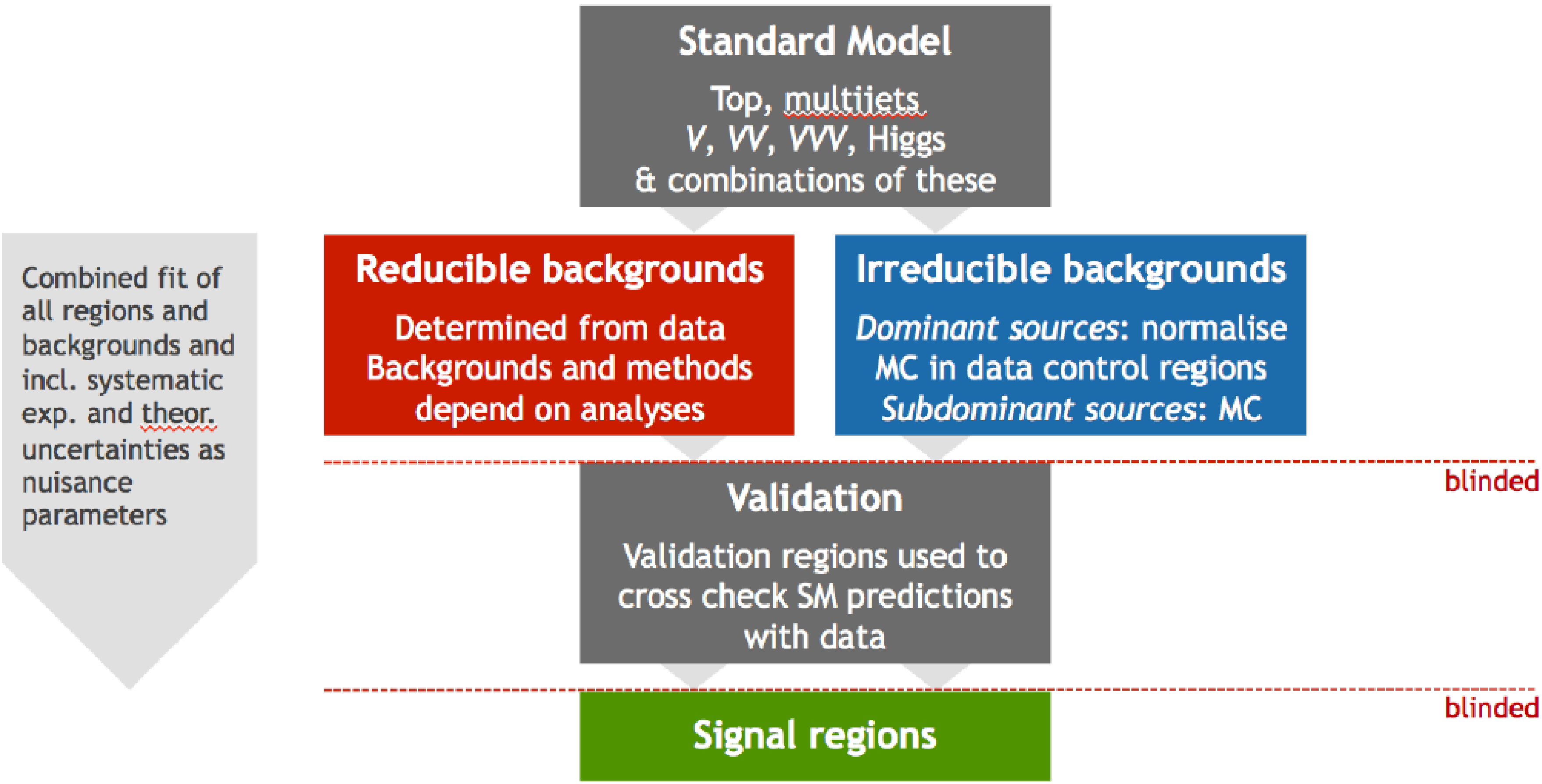
Naturalness



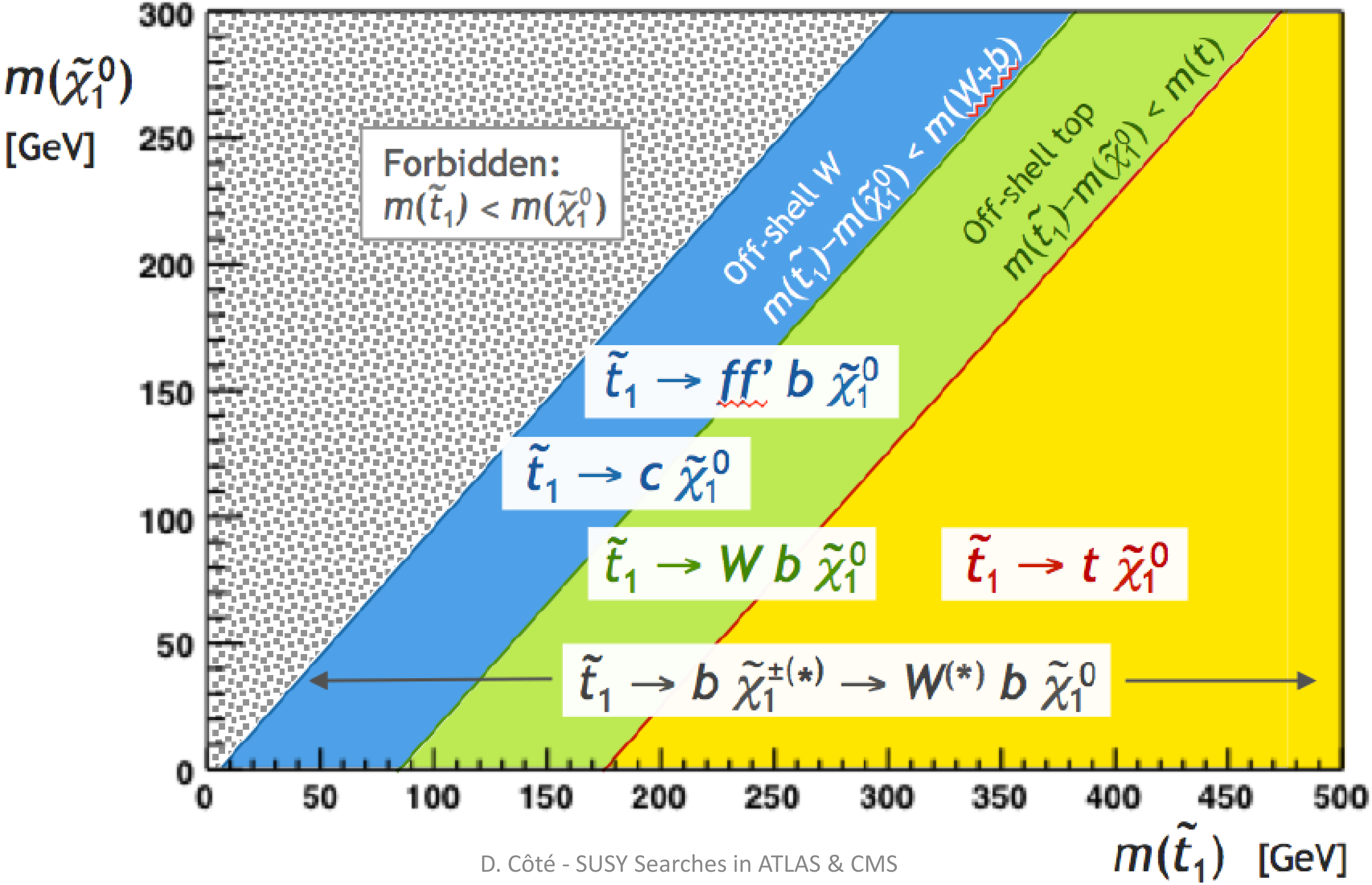


Backup Material

Typical SM Background Estimation



decay modes of the stop to χ^0_1



Definition of SUSY Fine-Tuning

$$M_Z^2 = -2\mu^2 + 2\ \frac{m_{H_d}^2 - t_\beta^2\ m_{H_u}^2}{t_\beta^2 - 1}$$

$$Z_i = \frac{\partial(\log M_Z^2)}{\partial(\log p_i)} = \frac{p_i}{M_Z^2}\ \frac{\partial M_Z^2}{\partial p_i}$$

$$\Delta = max(|Z_i|)$$

One choice: stability of EW scale (identified by M_Z) w.r.t. model parameters.

(Traditional approach from Ellis *et al.*, Barbieri & Giudice.)