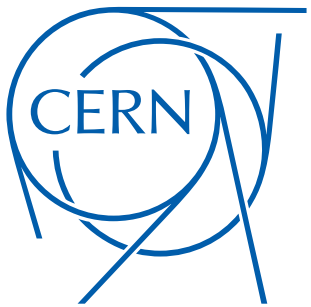
Recent searches for supersymmetry at the LHC

Rencontres du Vietnam
Aug 11-17, 2013
Quy Nhon, Vietnam

Christian Ohm
on behalf of
the ATLAS and CMS collaborations

CERN

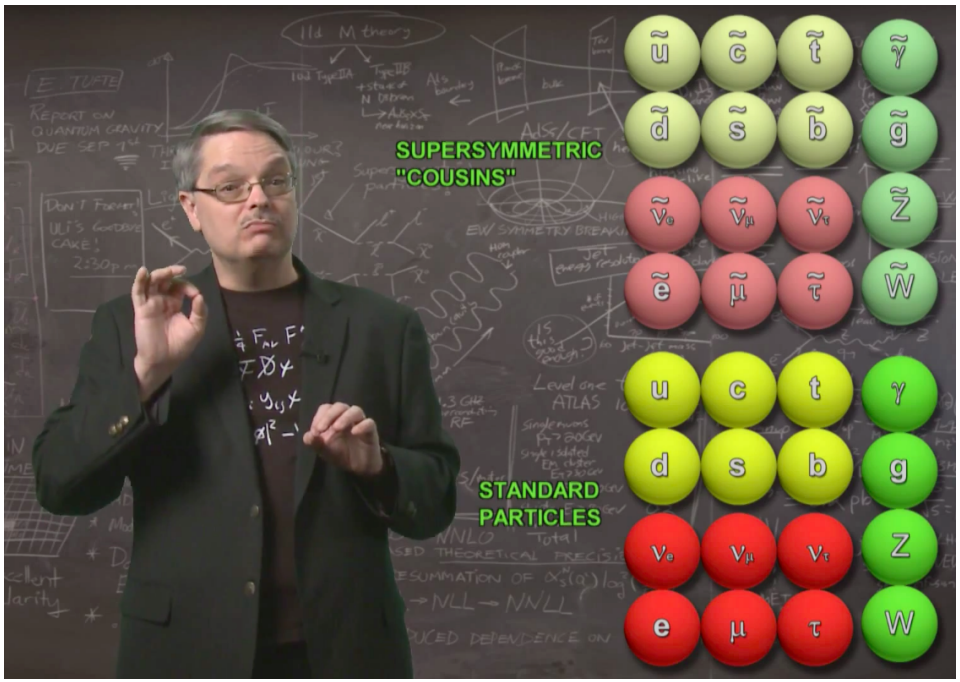
Aug 14, 2013



A brief introduction to supersymmetry

What is it?

- Generalization of the SM where force and matter are described by the same equations!
- Introduces sfermions and gauginos $\Rightarrow$ doubles SM particle content



(picture from Don Lincoln's video describing SUSY for the general public)

SUSY is attractive

- Only possible extension of the Poincaré algebra
- Alleviates hierarchy problem
- Allows for gauge coupling unification
- Can provide Dark Matter particle

but...

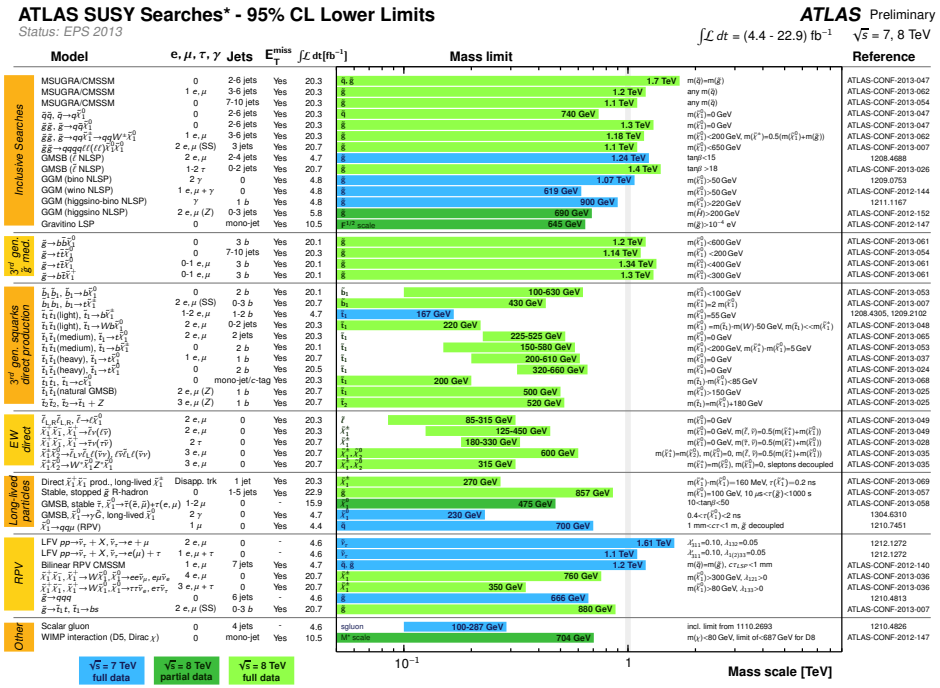
- > 100 free parameters $\Rightarrow$ wide range of possible experimental signatures!

So, SUSY is theoretically appealing, phenomenologically rich, and therefore experimentally challenging (to exclude)

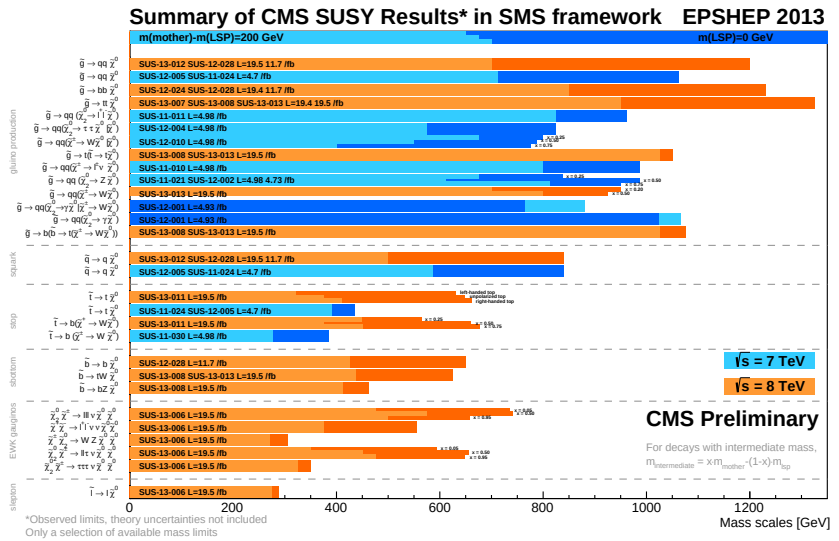
Overview of SUSY searches with ATLAS and CMS

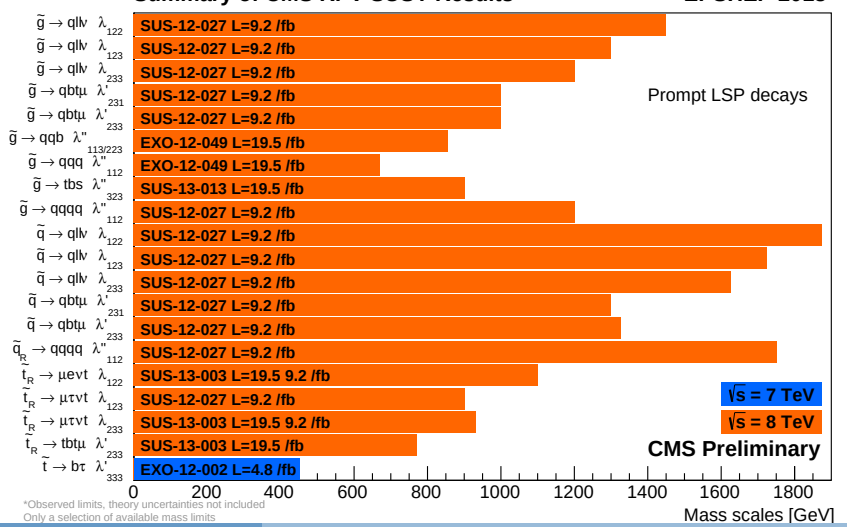
Selected sparticle mass limits from SUSY searches at the LHC

ATLAS (see summary page)



CMS (see summary page)





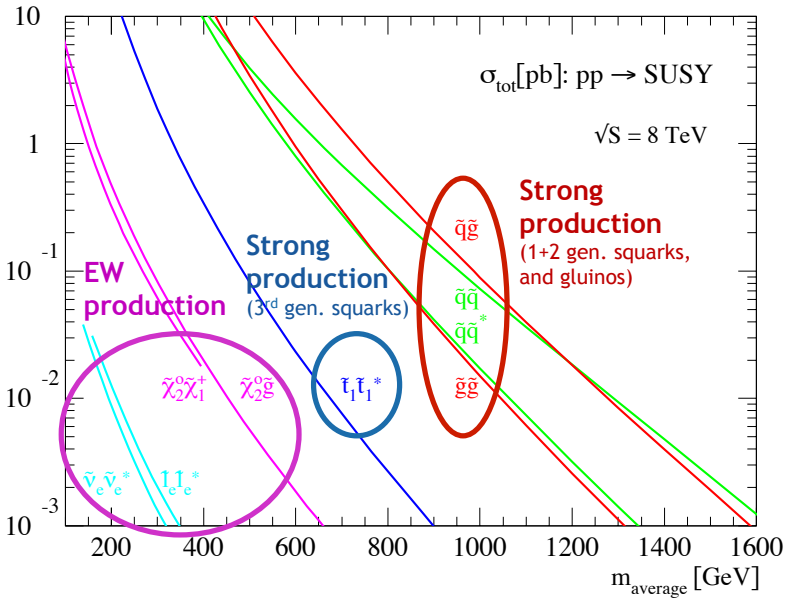
- Large fraction of experimental programs devoted to SUSY searches
- Limits summary: ∼60 papers/notes
- Here four recent and diverse results
- See E. Halkiadakis' summary!

Natural SUSY and direct $\tilde{t}$ pair production at the LHC

Experimental signature & motivation

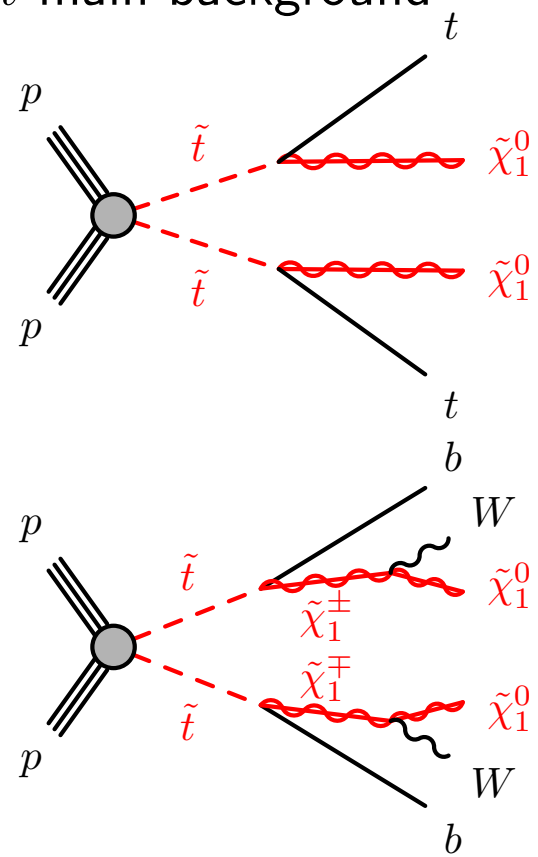
Increasing luminosity $\Rightarrow$ from broad and inclusive searches to dedicated ones targeting specific processes/scenarios, development fueled by "natural" SUSY:

- $\tilde{t}/\tilde{b}$ lightest squarks ($\tilde{g}$ and 1st/2nd gen. $\tilde{q}$ heavier)
- $\tilde{\chi}^0$ and $\tilde{\chi}^\pm$ directly accessible



Experimental signature of direct top-squark pair production:

- Looks like $t\bar{t}$ with higher $E_{\mathrm{T}}^{\mathrm{miss}}$ $\Rightarrow$ $t\bar{t}$ main background



Direct $\tilde{t}$ pair production in 1-lepton channel with CMS

Event selection and example signal region distributions (arXiv:1308.1586, submitted to EPJC)

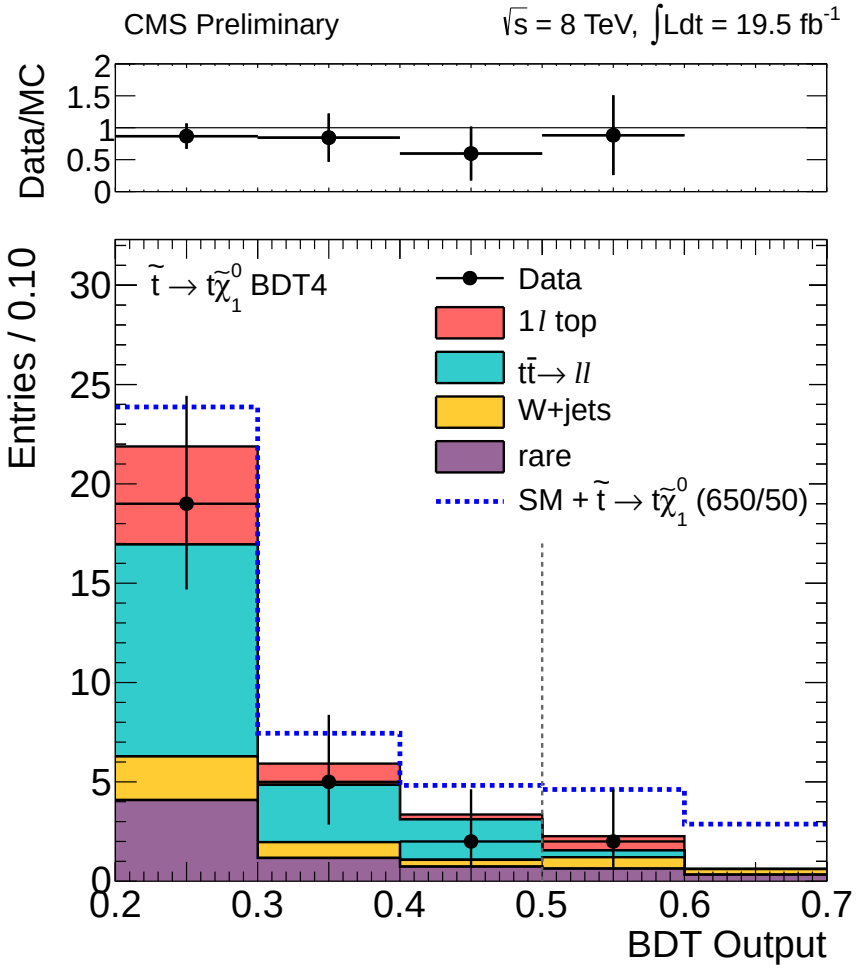
Event selection

Pre-selection

- Single-lepton trigger
- Exactly one isolated lepton
  - $e : p_{\mathrm{T}} > 30\ \mathrm{GeV}, |\eta| < 1.44$
  - $\mu : p_{\mathrm{T}} > 25\ \mathrm{GeV}, |\eta| < 2.1$
- Jets:
  - ≥ 4 jets with $p_{\mathrm{T}} > 30\ \mathrm{GeV}$ and $|\eta| < 2.4$
  - including at least one b-tagged
- $E_{\mathrm{T}}^{\mathrm{miss}} > 100\ \mathrm{GeV}$

Signal regions

- $M_{\mathrm{T}} > 120\ \mathrm{GeV}$
- Several regions defined using cuts on kinematic variables, *or* BDT discriminants

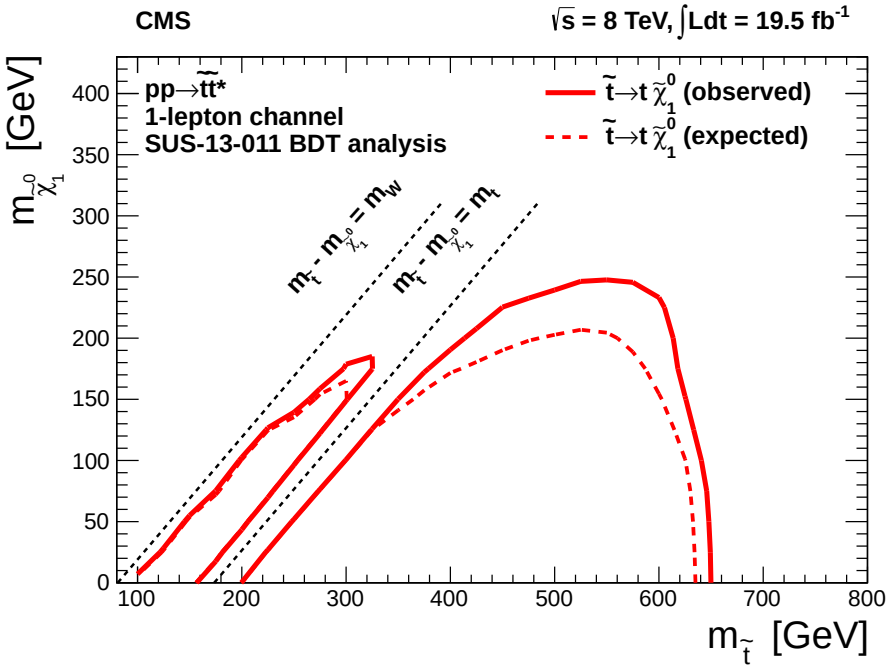


Similar ATLAS results in ATLAS-CONF-2013-037

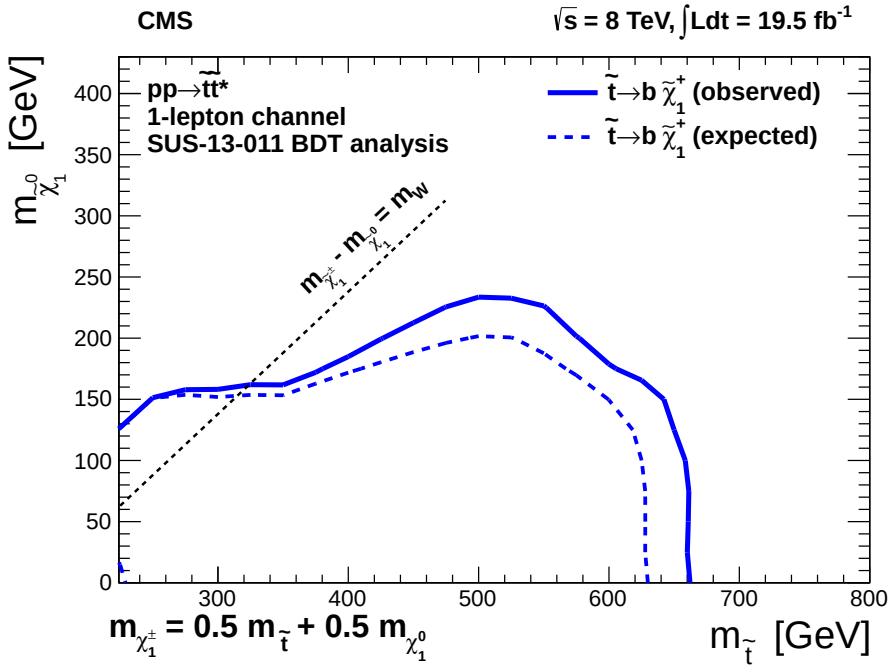
Search for direct $\tilde{t}$ pair production in 1-lepton channel

Exclusion limits (arXiv:1308.1586)

$\tilde{t} \to \tilde{\chi}^0 t$



$\tilde{t} \to b\tilde{\chi}^{\pm} \to bW\tilde{\chi}^0$



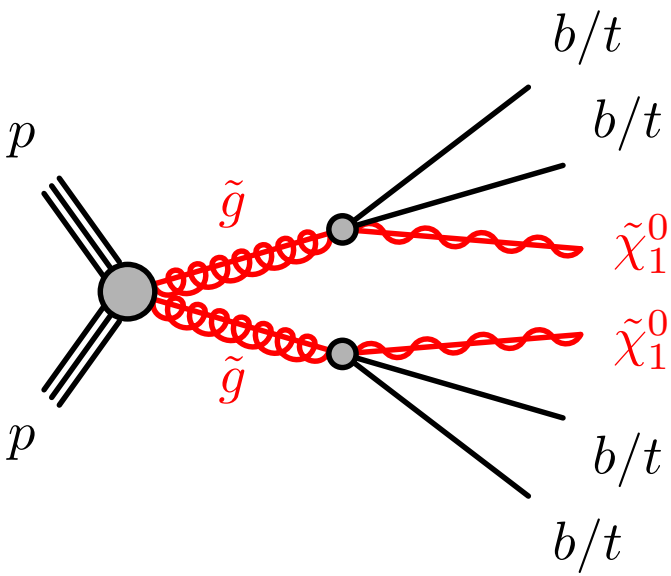
- In both decay scenarios, up to $m_{\tilde{t}} \lesssim 650$ GeV and $m_{\tilde{\chi}^0_1} \lesssim 250$ GeV is excluded
- Main results from BDT analysis, cut-based analysis with similar results also public

Similar ATLAS results in ATLAS-CONF-2013-037

SUSY in final states with at least three b-jets

Experimental signature & motivation

Final states with many third generation quarks can also be $\tilde{g}$-mediated:



$\tilde{g}$-mediated $\tilde{b}$:

- other $\tilde{q}$ heavier than $\tilde{g} \Rightarrow$ BR$(\tilde{g} \to \tilde{b}b) = 100\%$
- BR$(\tilde{b} \to b\tilde{\chi}^0) = 100\%$

$\tilde{g}$-mediated $\tilde{t}$:

- other $\tilde{q}$ heavier than $\tilde{g} \Rightarrow$ BR$(\tilde{g} \to \tilde{t}t) = 100\%$
- BR$(\tilde{t} \to b\tilde{\chi}^{\pm}) = 100\%$ $(m_{\tilde{\chi}^{\pm}} = 2m_{\tilde{\chi}^0})$, *or* BR$(\tilde{t} \to t\tilde{\chi}^0) = 100\%$

"Gbb" ("Gtt"):

- BR$(\tilde{g} \to b\bar{b}\tilde{\chi}^0) = 100\%$, via virtual $\tilde{b}$ (similar for Gtt)
- Yields signature with four b-quarks, two $\tilde{\chi}^0$ (+ leptons, additional jets)

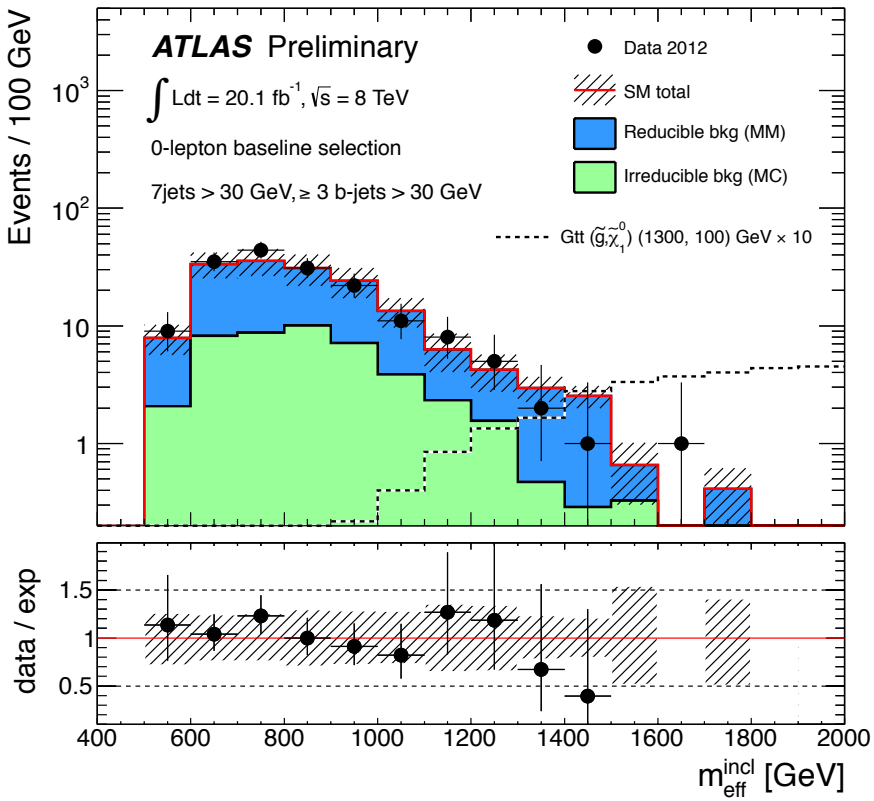
SUSY in final states with at least three b-jets with ATLAS

Event selection and example signal region distributions (ATLAS-CONF-2013-061, June 25)

Event selection

- $E_{\mathrm{T}}^{\mathrm{miss}}$-based trigger, offline $E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV
- ≥ 4 jets with $p_{\mathrm{T}} > 30$ GeV, including ≥ 3 b-tagged, ≥ 1 jet with $p_{\mathrm{T}} > 90$ GeV
- Two classes of signal regions:
  - 0-lepton: defined using $m_{\mathrm{eff}}^{\mathrm{incl}}$, $m_{\mathrm{eff}}^{\mathrm{4j}}$, $\Delta\Phi_{\mathrm{min}}^{\mathrm{4j}}$, $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}^{\mathrm{4j}}}$
  - ≥ 1-lepton: defined using $m_{\mathrm{eff}}^{\mathrm{incl}}$, $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}^{\mathrm{4j}}}$, m_{T}

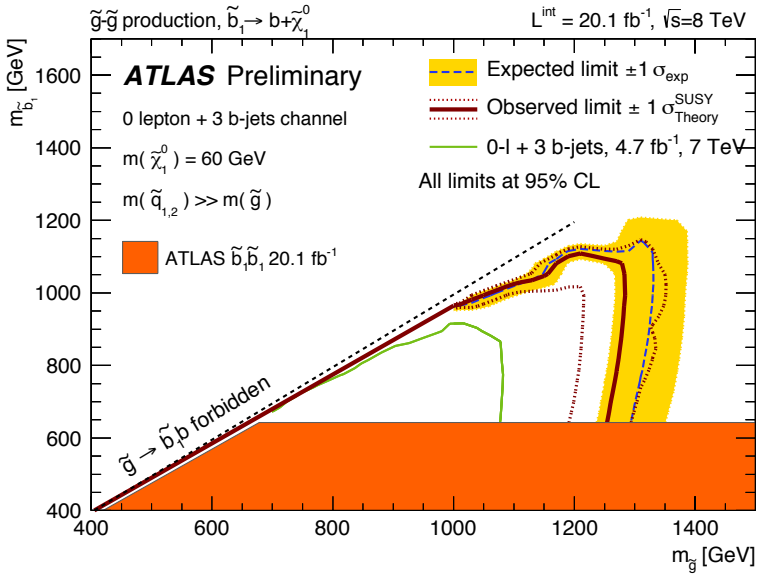
$m_{\mathrm{eff}}^{\mathrm{incl}}$ in 0ℓ

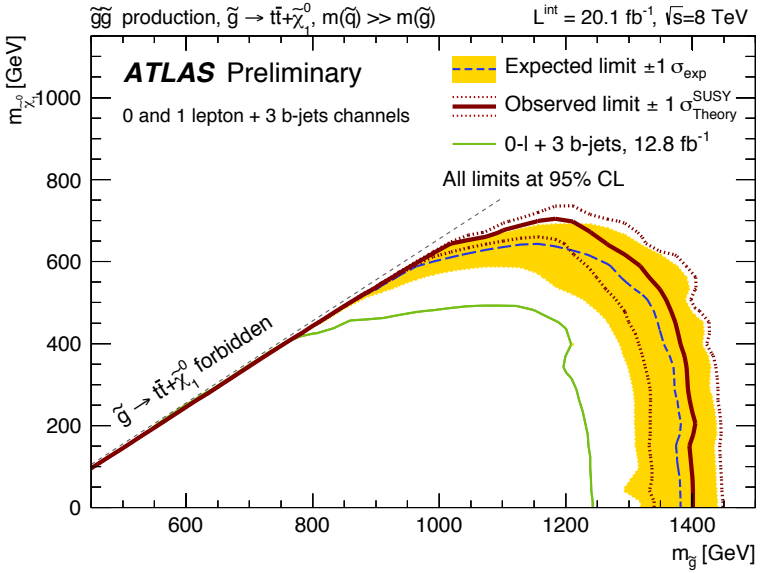


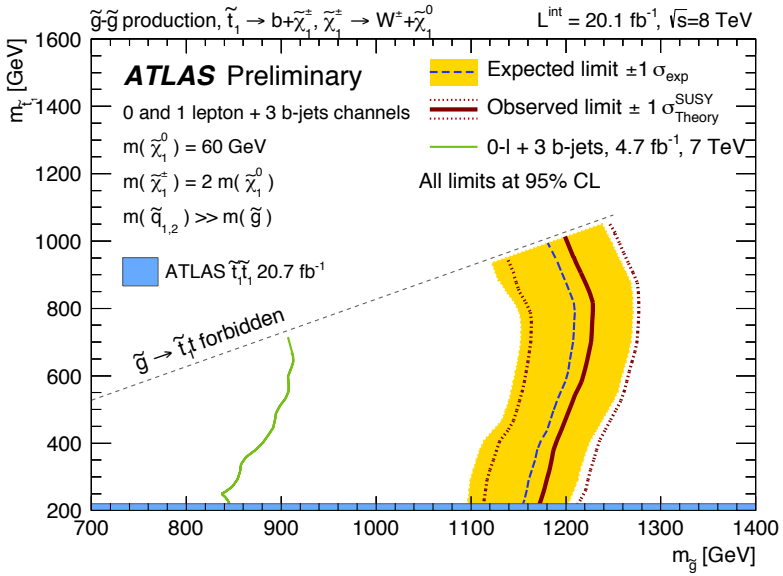
$(m_{\mathrm{eff}}^{\mathrm{incl}} = \sum_j p_{\mathrm{T}} + E_{\mathrm{T}}^{\mathrm{miss}})$

CMS results targeting similar scenarios in 1305.2390, PAS-SUS-13-008, , PAS-SUS-13-007, ...

SUSY in final states with at least three b-jets with ATLAS







Exclusion limits (ATLAS-CONF-2013-061):

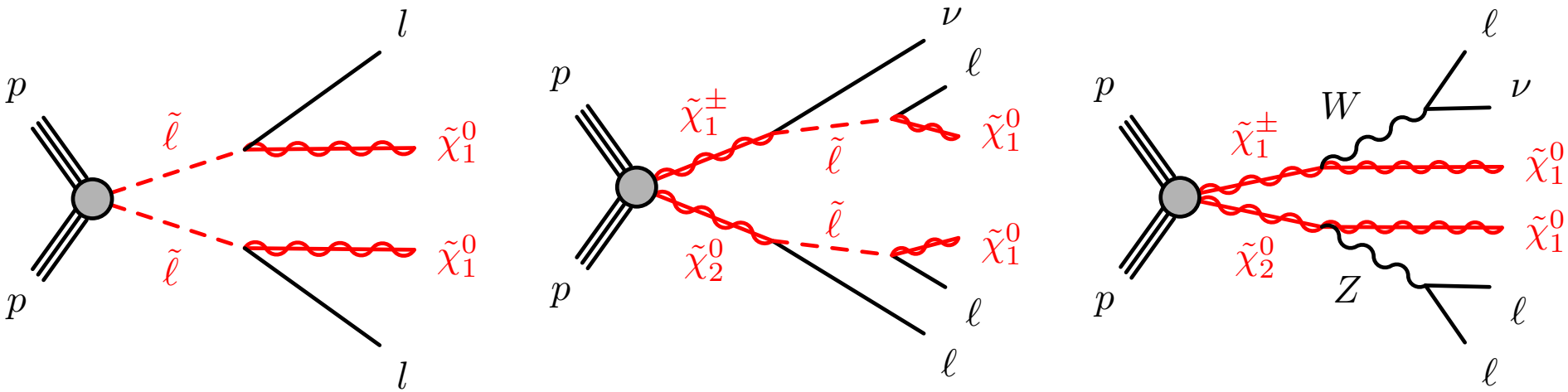
- ↖: $\tilde{g}$-mediated $\tilde{b}$ ($\tilde{g} \to bb\tilde{\chi}^0$)
- ↗: $\tilde{g}$-mediated $\tilde{t}$ ($\tilde{g} \to tbW^*\tilde{\chi}^0$)
- ←: Gtt ($\tilde{g} \to t\bar{t}\tilde{\chi}^0$, $m_{\tilde{q}} \gg m_{\tilde{g}}$)

CMS: 1305.2390, PAS-SUS-13-008, , PAS-SUS-13-007, ...

Electroweak production of $\tilde{\chi}^{\pm}$, $\tilde{\chi}^{0}$ and $\tilde{\ell}$ production

Experimental signature

Direct production of "ewkinos" ($\tilde{\ell}$, $\tilde{\chi}^{\pm}$ and $\tilde{\chi}^{0}$) - does not depend on $m_{\tilde{g}}$ and $m_{\tilde{q}}$



- Many variations in signal models: handedness of leptons (coupling to $\tilde{\nu}$), $m_{\tilde{\ell}}$, lepton flavor assumptions ("democratic", τ-enriched or τ-dominated)
- Final state: $\geq 2\ell + E_{\mathrm{T}}^{\mathrm{miss}}$ (same-sign and opposite-sign configurations)
- Backgrounds: $t\bar{t}$, WZ, fake and non-prompt ℓ ($t\bar{t}$, Z+jets, WW+jets)

Search for electroweak $\tilde{\chi}^{\pm}$, $\tilde{\chi}^{0}$ and $\tilde{\ell}$ production with CMS

Event pre-selection and outline of example signal regions (CMS-PAS-SUS-13-006, July 19)

Common event and object selection

- Di-lepton trigger
- Well-identified and isolated leptons
- Substantial $E_{\mathrm{T}}^{\mathrm{miss}}$
- b-jet veto

3-lepton search:

- 3 leptons: e/μ with $p_{\mathrm{T}} > 10$ GeV, had. τ with $p_{\mathrm{T}} > 20$ GeV

4-lepton search:

- Leptons as above (at most one hadronic τ)
- Require one $e^{+}e^{-}$ or $\mu^{+}\mu^{-}$ pair with $|m_{\ell\ell} - m_{Z}| < 15$ GeV

Two same-sign leptons

- Targets $\tilde{\chi}^{\pm}\tilde{\chi}^{0}$ production where one lepton is missed (compressed spectrum)
- SRs divided by $E_{\mathrm{T}}^{\mathrm{miss}}$, n_{jets}
- Veto OSSF pairs with $|m_{\ell\ell} - m_{Z}| < 15$ GeV ($t\bar{t}Z$ and WZ)

OSSF pair + two jets

- Targets processes with on-shell $Z \to \ell\ell$ another W/Z decaying hadronically

...

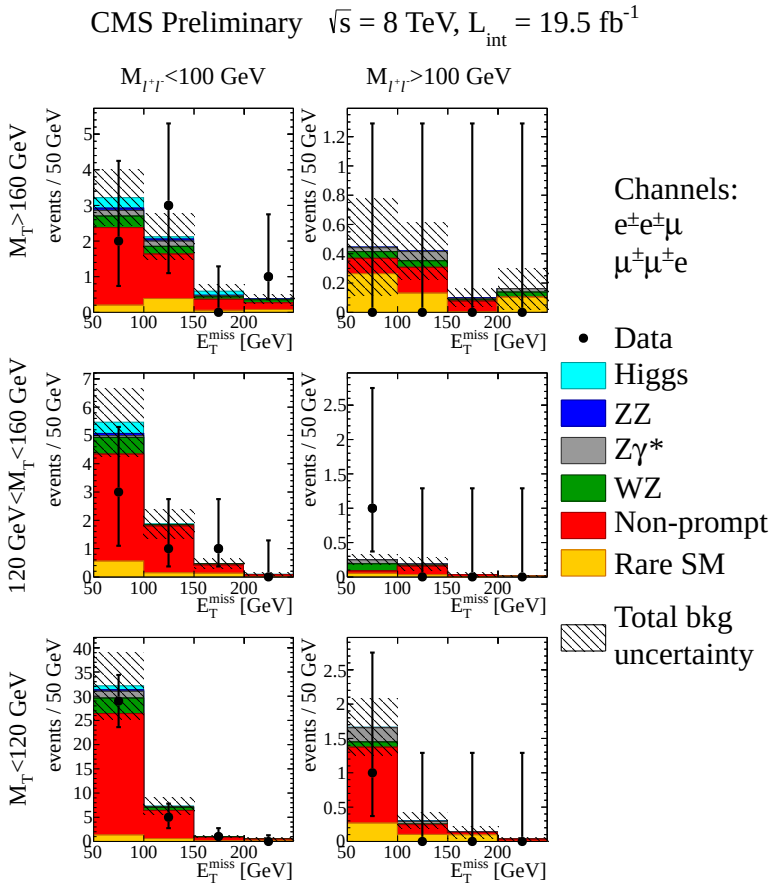
$\Rightarrow$ **>100 mutually exclusive signal regions!**

ATLAS: ATLAS-CONF-2013-049, ATLAS-CONF-2013-028, ATLAS-CONF-2013-035, ATLAS-CONF-2013-036

Search for electroweak $\tilde{\chi}^{\pm}$, $\tilde{\chi}^{0}$ and $\tilde{\ell}$ production with CMS

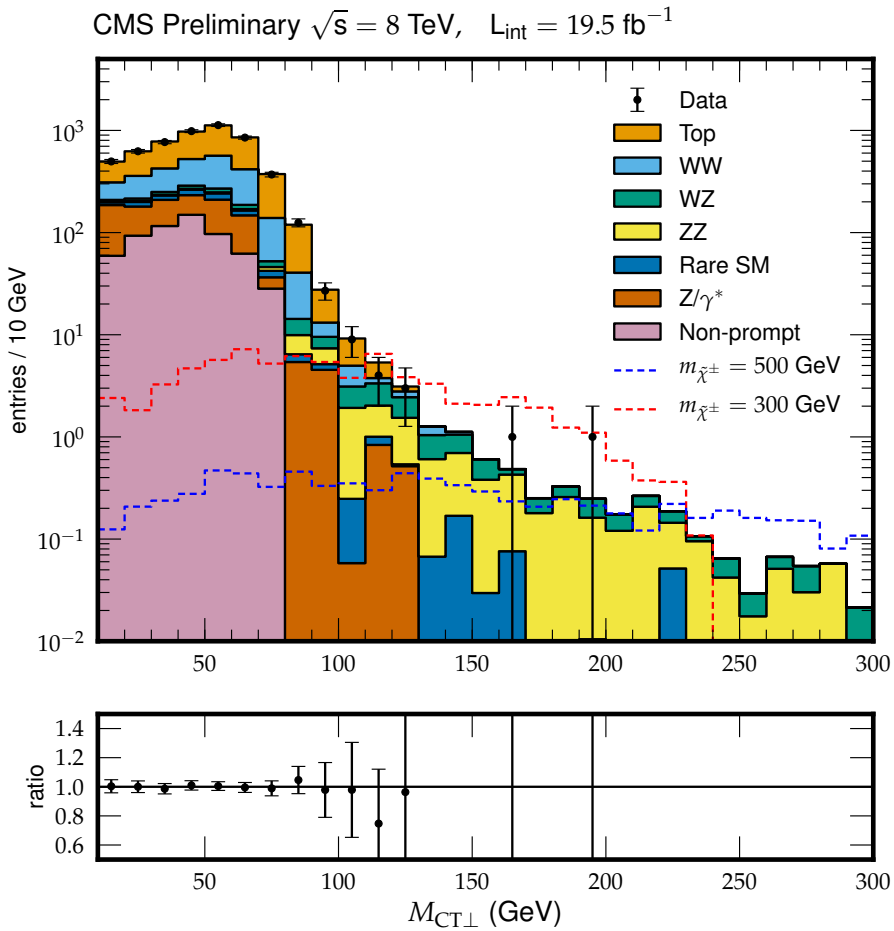
Example distributions in SR (CMS-PAS-SUS-13-006)

$E_{\mathrm{T}}^{\mathrm{miss}}$ in 3ℓ ($e^{\pm}e^{\pm}\mu$ and $e^{\pm}\mu^{\pm}\mu$)



ATLAS: ATLAS-CONF-2013-049, ATLAS-CONF-2013-028, ATLAS-CONF-2013-035, ATLAS-CONF-2013-036

$M_{\mathrm{CT}\perp}$ in non-resonant 2ℓ (OSSF)



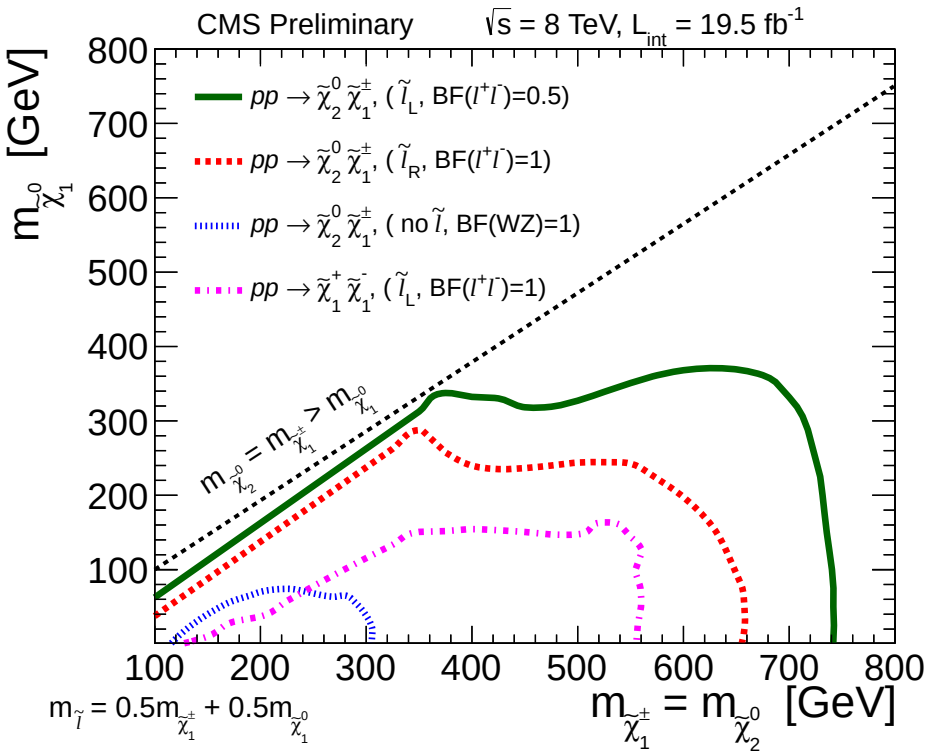
($M_{\mathrm{CT}\perp}$: arXiv:0910.1584)

Search for electroweak $\tilde{\chi}^{\pm}$, $\tilde{\chi}^{0}$ and $\tilde{\ell}$ production with CMS

Example exclusion limits (CMS-PAS-SUS-13-006)

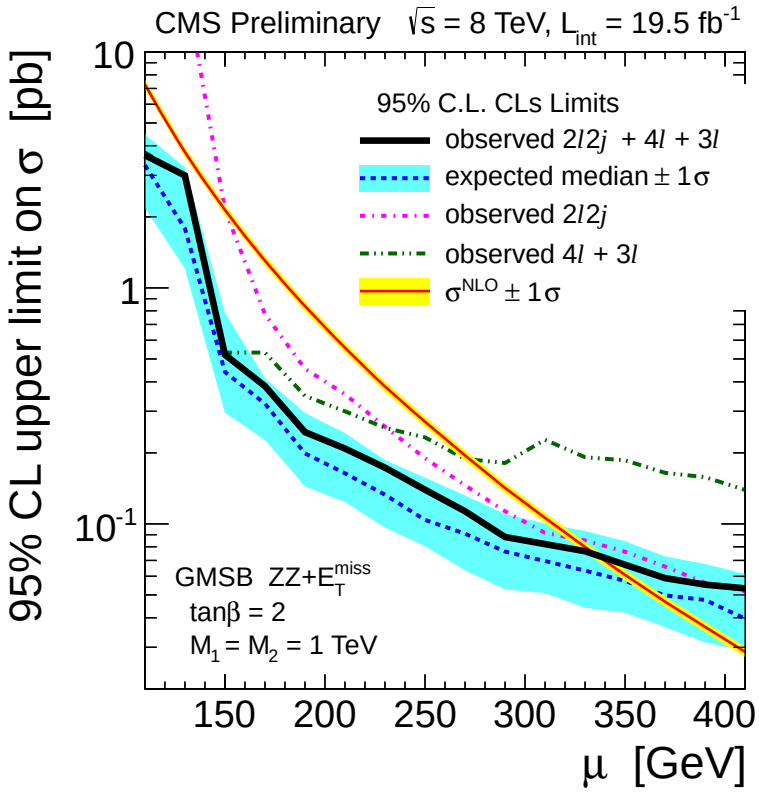
- Results benefit greatly from combining several channels
- Both generic (left) and model-specific (right) limits

$\tilde{\chi}_2^0\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_1^+\tilde{\chi}_1^-$ production



GMSB ($Z + 2j$ & 4ℓ)

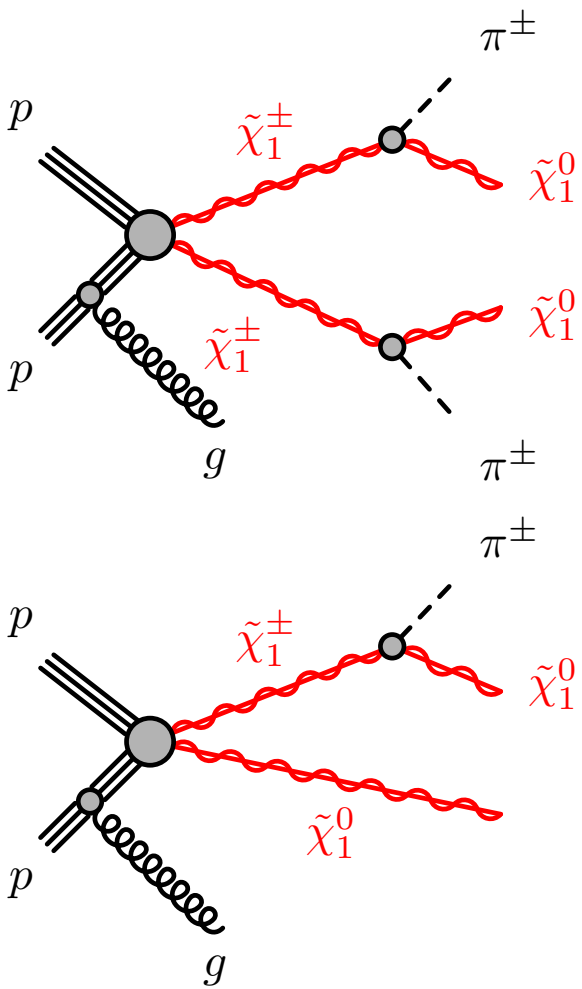
$\mu \approx m_{\tilde{\chi}_1^0} \approx m_{\tilde{\chi}_2^0} \approx m_{\tilde{\chi}_1^{\pm}} < 330$ GeV excl.



ATLAS: ATLAS-CONF-2013-049, ATLAS-CONF-2013-028, ATLAS-CONF-2013-035, ATLAS-CONF-2013-036

Compressed spectrum: nearly mass-degenerate $\tilde{\chi}^{\pm}$ and $\tilde{\chi}^{0}$

Phenomenology



Motivation

- E.g. Anomaly-Mediated Supersymmetry Breaking (AMSB), hep-ph/9810442, hep-th/9810155
- Generally: models with Higgsino- or Wino-like $\tilde{\chi}_1^0/\tilde{\chi}_2^0$

Signature

- Typically: $m_{\tilde{\chi}^{\pm}} - m_{\mathrm{LSP}} \sim 160\ \mathrm{MeV}$ $\Rightarrow c\tau_{\tilde{\chi}^{\pm}} \sim 10\ \mathrm{cm}$, i.e. measurable in collider experiment!
- $\tilde{\chi}^{\pm} \rightarrow \tilde{\chi}^{0} + \pi^{\pm}$, where $p_{\mathrm{T}}^{\pi^{\pm}} \sim 100\ \mathrm{MeV}$
- Disappearing-track signature!
- Exploit QCD ISR jets for triggering

Search for nearly mass-degenerate $\tilde{\chi}^{\pm}$ and $\tilde{\chi}^{0}$ with ATLAS

Event selection & disappearing-track reconstruction (ATLAS-CONF-2013-069, July 16)

Event selection

- Topological jet+$E_{\mathrm{T}}^{\mathrm{miss}}$ trigger
- $E_{\mathrm{T}}^{\mathrm{miss}} > 90$ GeV and ≥ 1 jet with $p_{\mathrm{T}} > 90$ GeV
- Lepton (e/μ) veto (W/Z+jets, $t\bar{t}$)

Backgrounds

- Primarily W+jets with naturally high $E_{\mathrm{T}}^{\mathrm{miss}}$

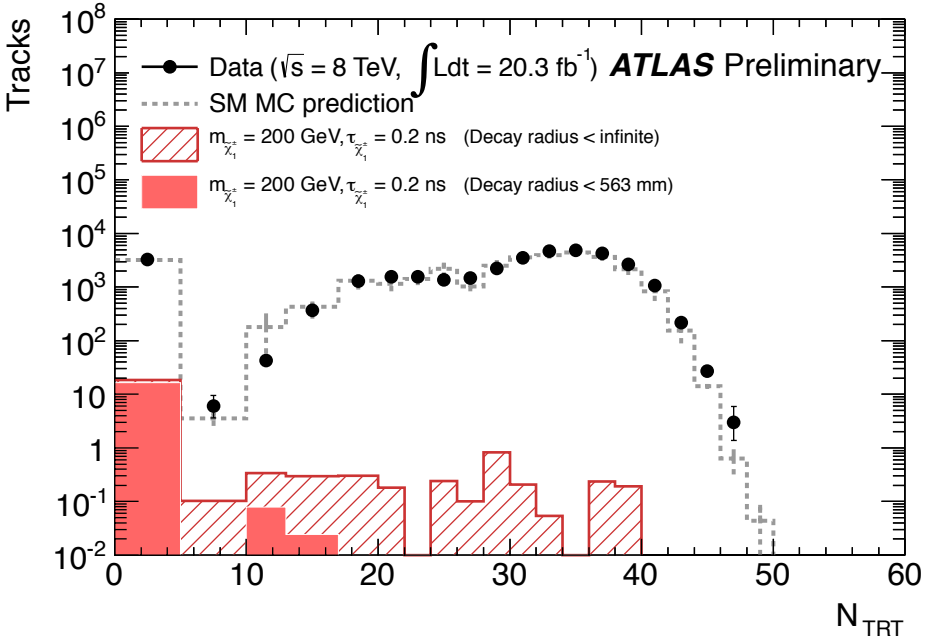
Selection of disappearing-track candidates

- Extended track reconstruction for long-lived $\tilde{\chi}^{\pm}$
- Start from pixel-only tracks
- Good fit quality, no shared or missing hits
- Well-isolated
- $p_{\mathrm{T}} > 15$ GeV

Search for nearly mass-degenerate $\tilde{\chi}^{\pm}$ and $\tilde{\chi}^{0}$ with ATLAS

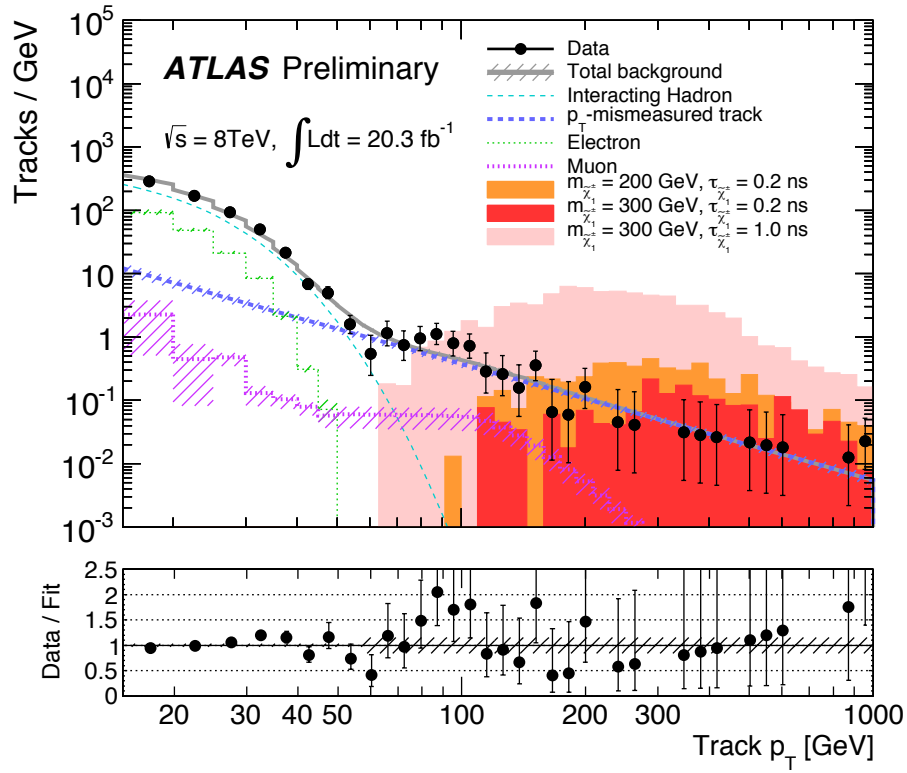
Example distributions (ATLAS-CONF-2013-069)

TRT hits for high-p_{T} isolated tracks



- Hatched: all $\tilde{\chi}^{\pm}$ in signal
  Solid: only those with $c\tau < 563$ mm
- "Disappearing track": $n_{\mathrm{TRT}} < 5$

Disappearing-track candidate p_{T} spectra

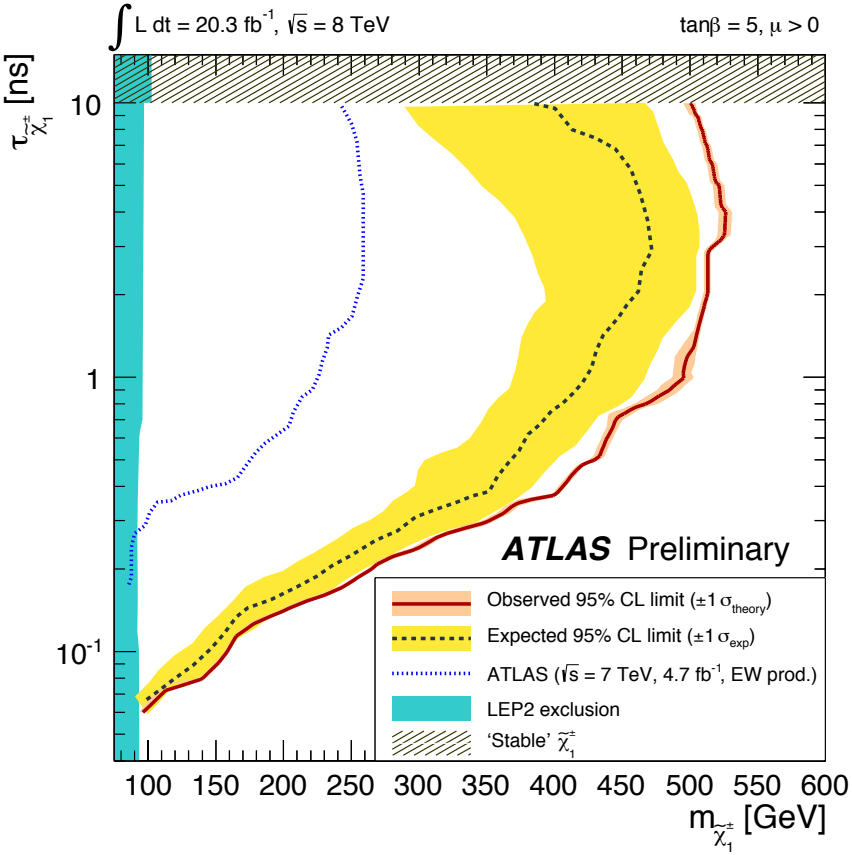


Signal regions: $p_{\mathrm{T}} > 75, 100, 150, 200$ GeV

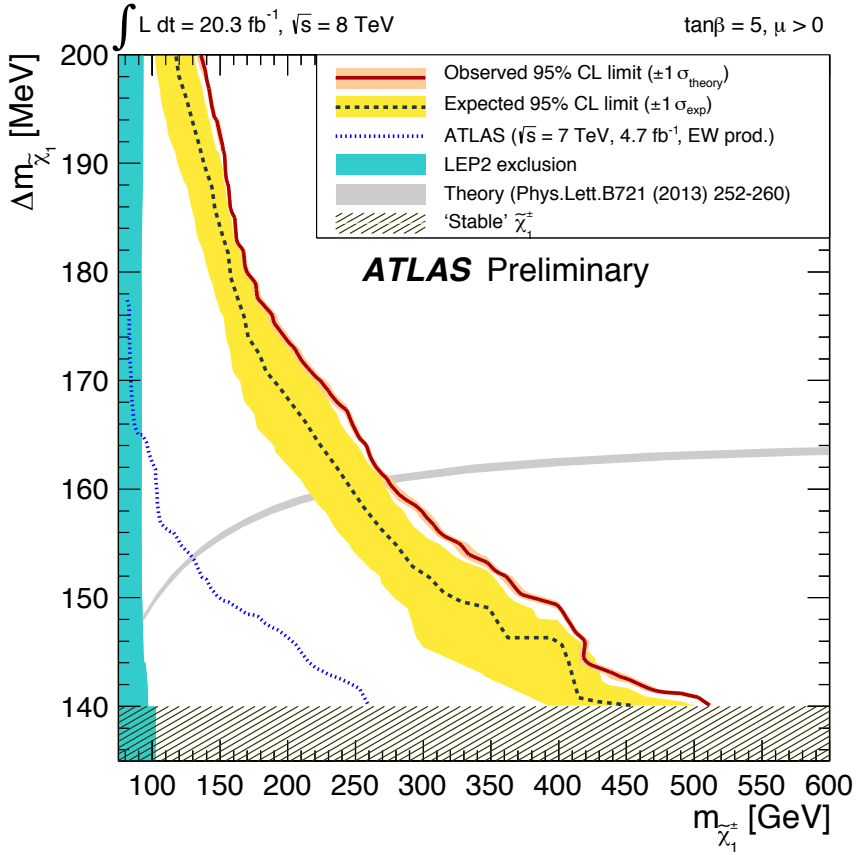
Search for nearly mass-degenerate $\tilde{\chi}^{\pm}$ and $\tilde{\chi}^{0}$ with ATLAS

Exclusion limits (ATLAS-CONF-2013-069)

Exclusions in $m_{\tilde{\chi}^{\pm}}$-$\tau_{\tilde{\chi}^{\pm}}$ space



Exclusions in $m_{\tilde{\chi}^{\pm}}$-$\Delta m_{\tilde{\chi}^{\pm}}$ space



- Excludes up to $m_{\tilde{\chi}^{\pm}} \approx 500$ GeV for 0.1 ns $< \tau_{\tilde{\chi}^{\pm}} <$ 10 ns
- Limits from previous ATLAS analysis (4.7fb^{-1} at 7 TeV) extended considerably

Summary

- Supersymmetry is an attractive extension of the Standard Model
- The LHC and the ATLAS and CMS detectors have been operated very successfully in Run I and have provided around $\sim$20 fb^{-1} of 8 TeV of excellent data per experiment (and ~ 5 fb^{-1} at 7 TeV)
- Four recent signature-driven searches at the LHC were summarized:
  - Direct top squark pair-production in one-lepton channel in CMS: arXiv:1308.1586
  - Searches for strong production of sparticles in final states with at least three b-jets in ATLAS: ATLAS-CONF-2013-061
  - Search for electroweak production of $\tilde{\chi}^{\pm}$, $\tilde{\chi}^{0}$, and $\tilde{\ell}$ using leptonic final states in CMS: CMS-PAS-SUS-13-006
  - Search for $\tilde{\chi}^{\pm}$ nearly mass-degenerate with the lightest $\tilde{\chi}^{0}$ based on a disappearing-track signature in ATLAS: ATLAS-CONF-2013-069

  (far from a complete summary - see ATLAS and CMS public results for more!)

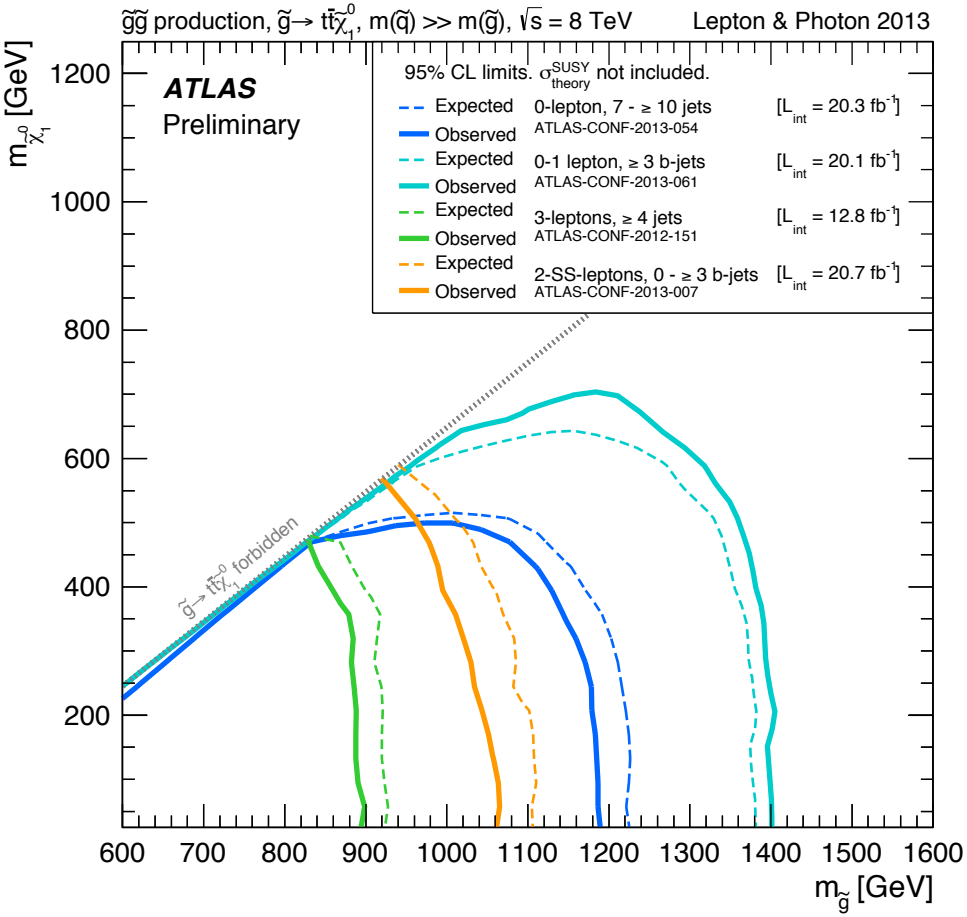
  $\Rightarrow$ no sign of SUSY $\Rightarrow$ exclusion limits!

- . . . but SUSY is hard to kill! Many places left to hide in $\Rightarrow$ hunt will continue at the LHC in Run II at higher $\sqrt{s}$ and luminosities!

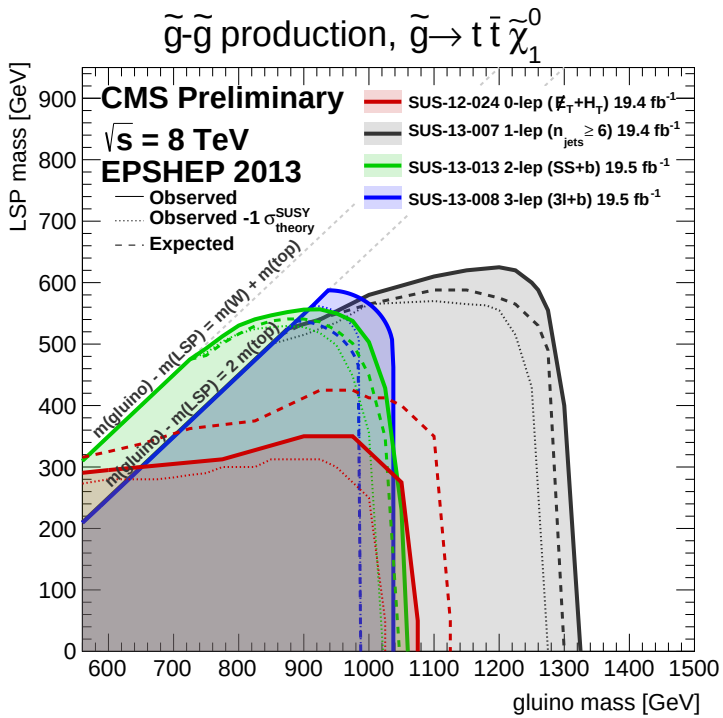
Back-up slides

Summary plots for $\tilde{g}$-mediated $\tilde{t}$ production

ATLAS

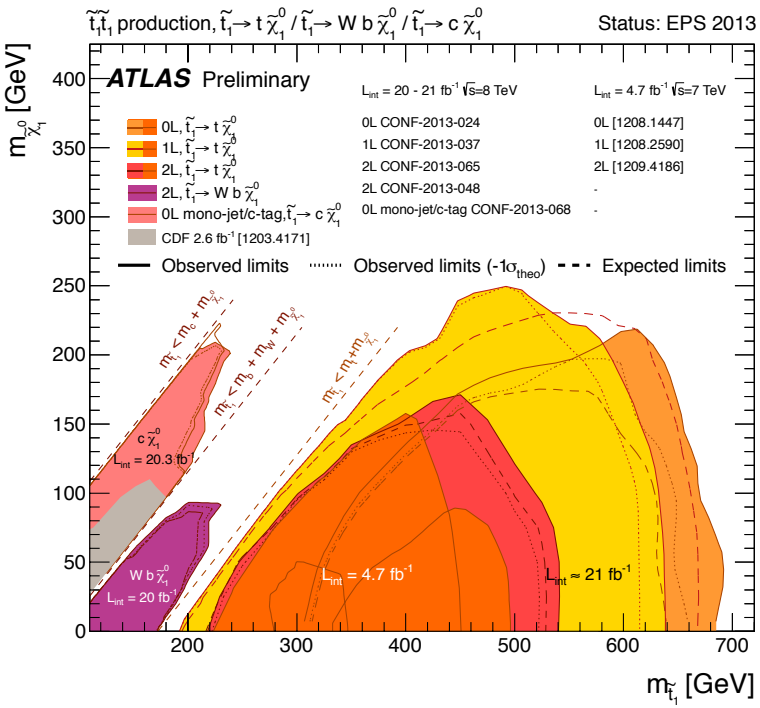


CMS

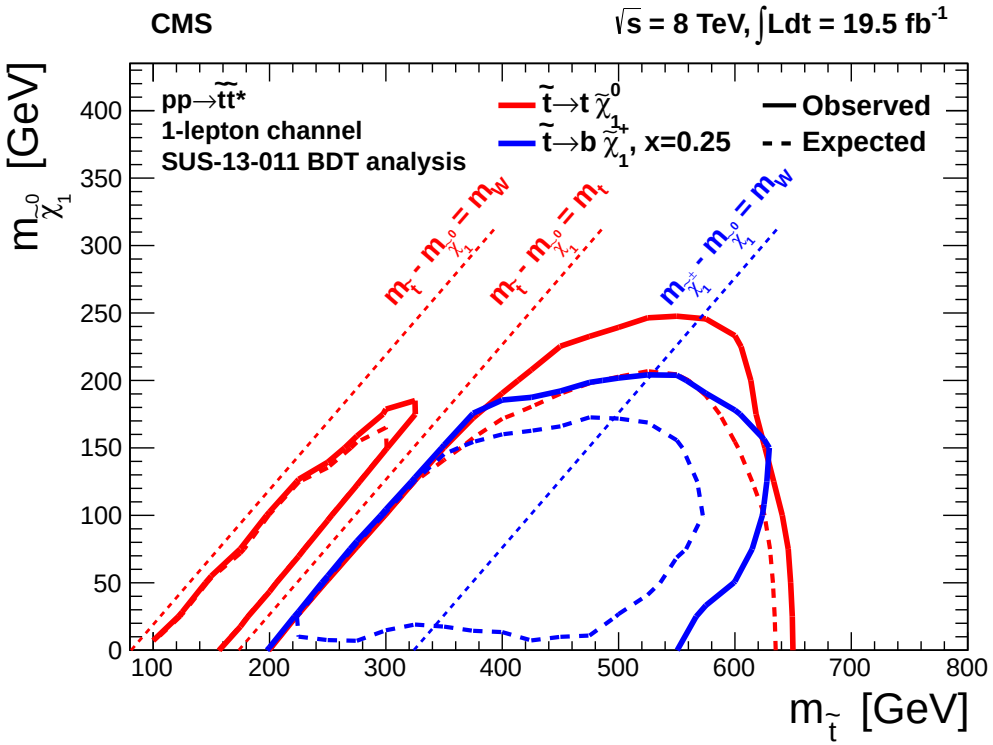


Summary plots for direct $\tilde{t}$ pair-production

ATLAS

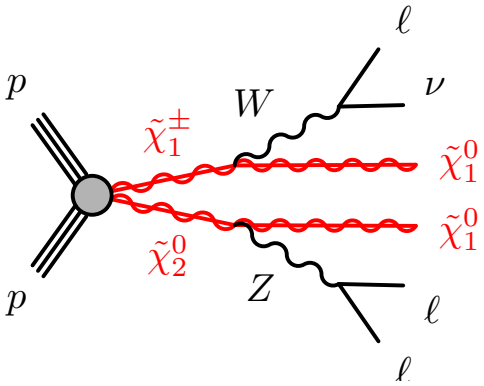


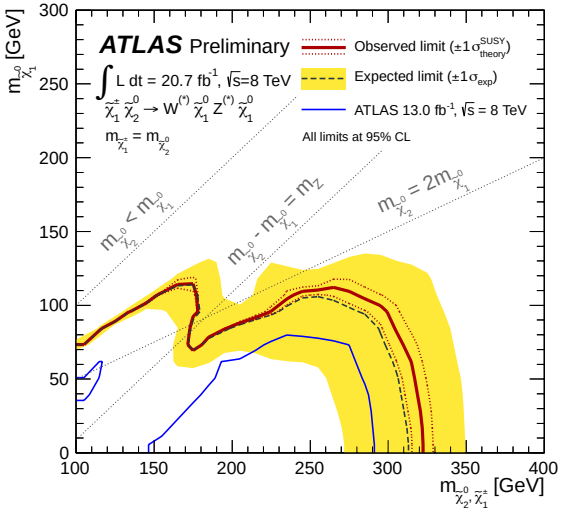
CMS



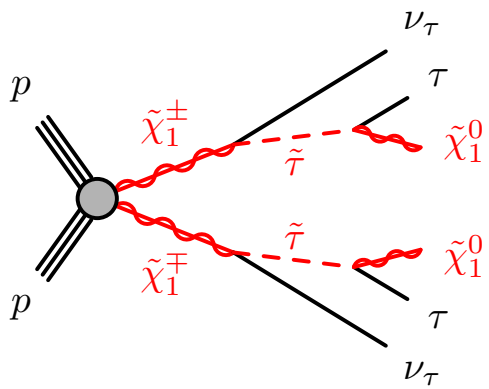
Examples of ATLAS exclusions for direct $\tilde{\chi}^{\pm}/\tilde{\chi}^{0}$ production

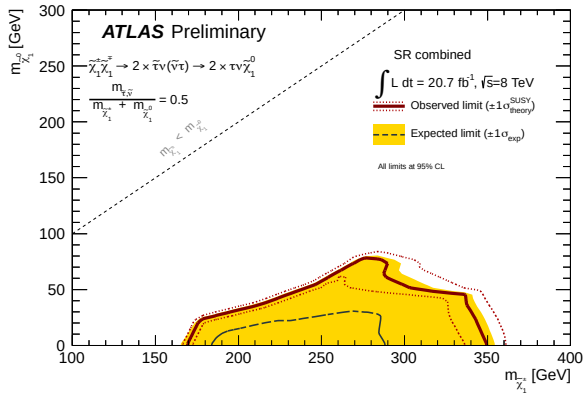
Difficult heavy-$\tilde{\ell}$ scenario



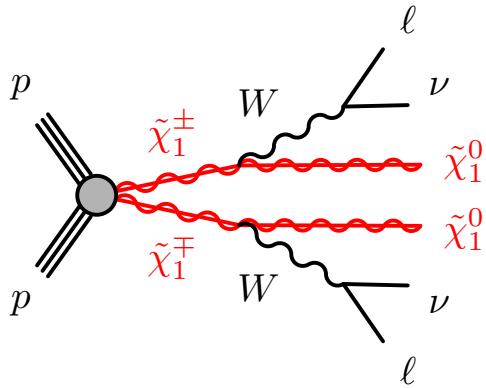


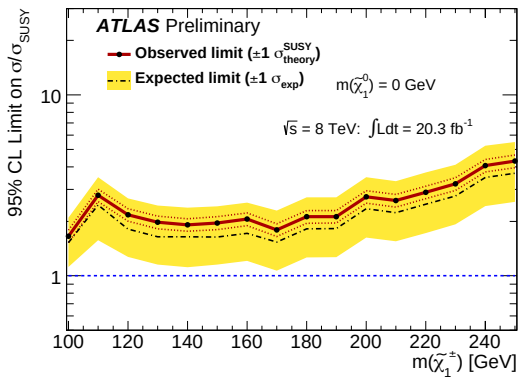
Only $\tilde{\tau}$ is light ($\tilde{e}$, $\tilde{\mu}$ heavy)





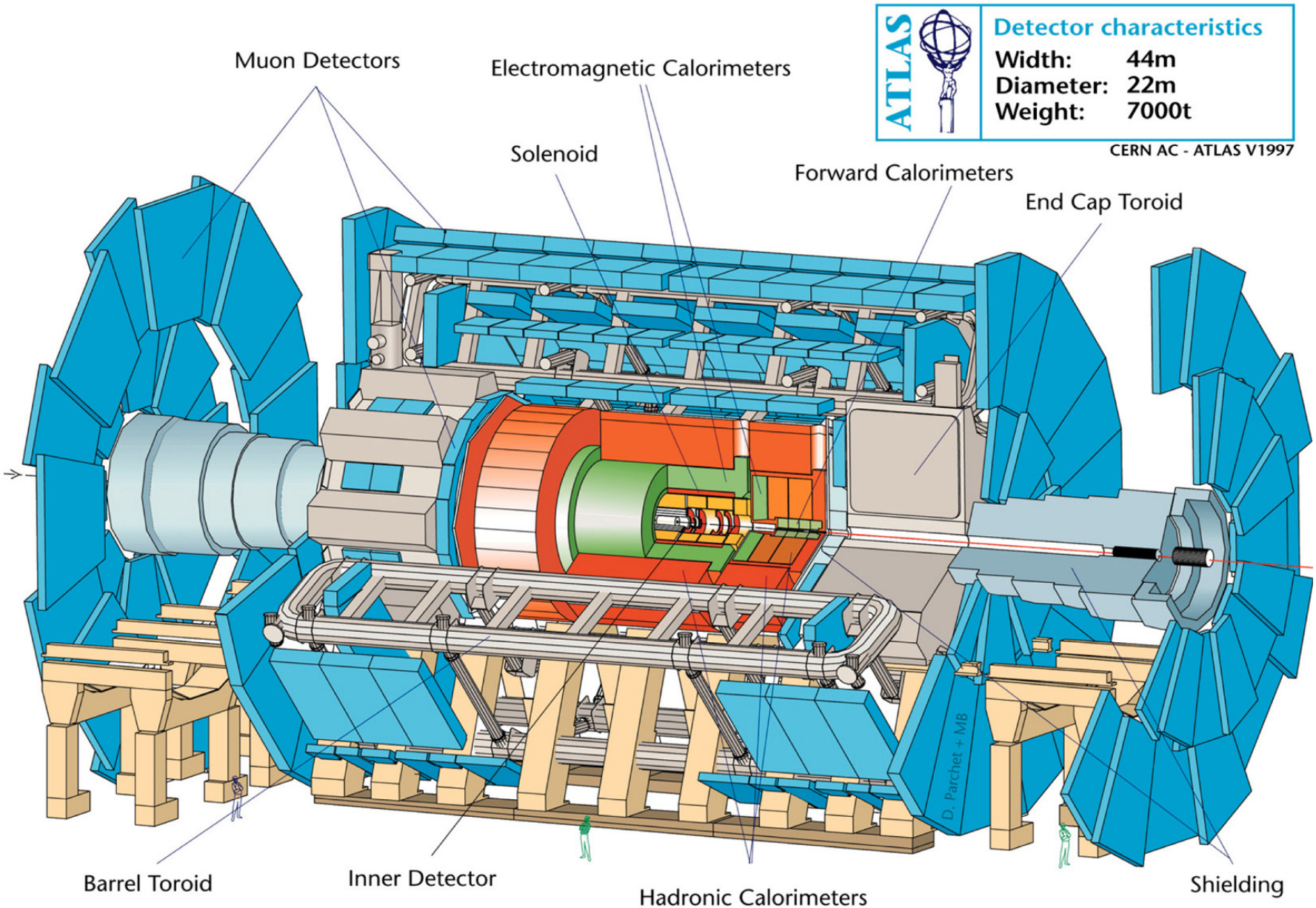
All $\tilde{\ell}$ heavy





(Almost sensitive. . .)

The ATLAS detector



The CMS detector