# Experimental results on SUSY searches with top from the LHC

**TOP2014**:
7th International Workshop on Top-Quark Physics, Sep-Oct 2014, Cannes, France.

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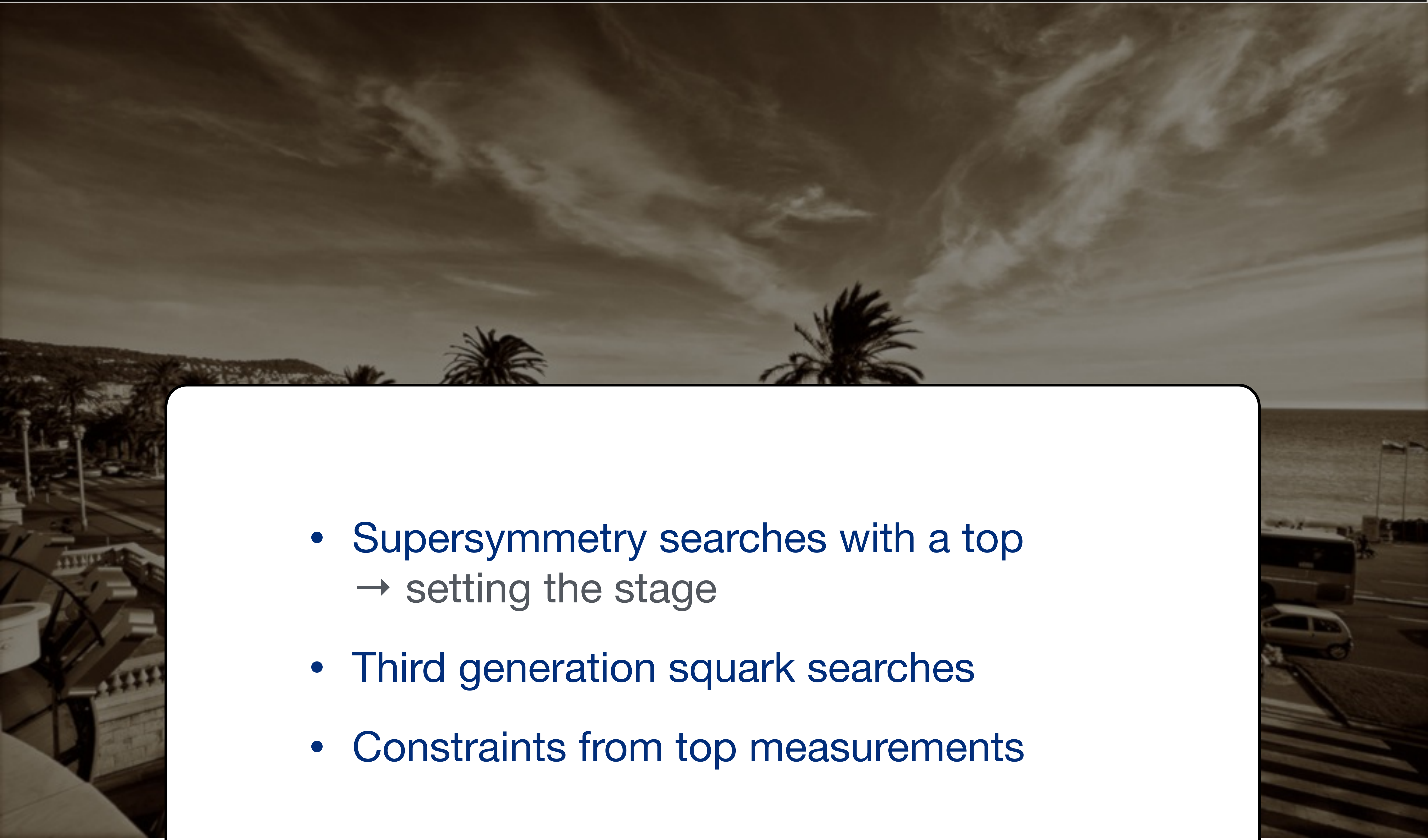
on behalf of the ATLAS and CMS Collaborations

Prepared with the help from Henning Flacher.

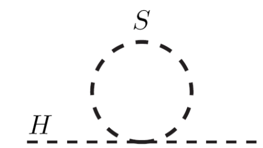
# Outline



- Supersymmetry searches with a top
  → setting the stage
- Third generation squark searches
- Constraints from top measurements

# Supersymmetry

Supersymmetry (SUSY) adds a new fundamental symmetry relating fermions and bosons → more than doubles the particle spectrum w.r.t. the Standard Model.

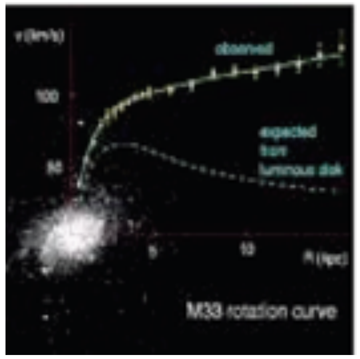



quantumdiaries.org

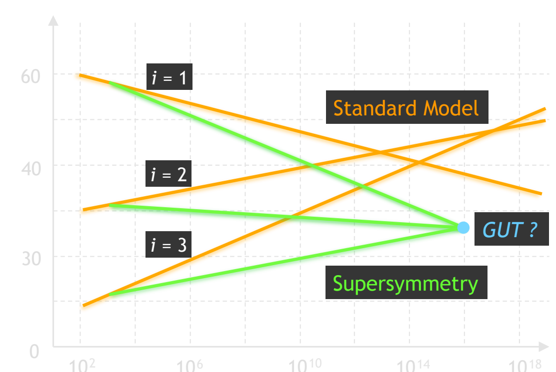
## Solves the gauge hierarchy problem

Fermion and boson loops contribute with different signs to the Higgs radiative corrections.

## SUSY with R-parity conservation predicts a suitable dark matter candidate



## Grand unification of forces




## Predicts an elementary Higgs scalar …

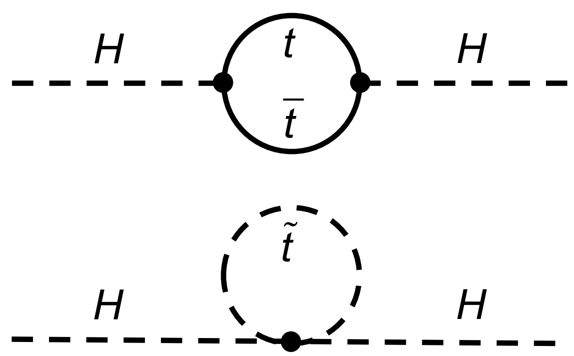
- with a beautiful SM-like limit,
- with a mass below 135 GeV (in the MSSM)

SUSY widely considered to remain the chief amongst beyond-SM proposals.
However, most simplistic versions under stress.

# Natural SUSY

What are the minimal requirements for `natural' (low level of fine-tuning) SUSY?

Recall: **Top loop** is the most important contribution in Higgs virtual corrections:




While inclusive LHC searches set O(TeV) limits mostly on 1st and 2nd generation squarks and gluinos, which are less relevant in Higgs corrections.

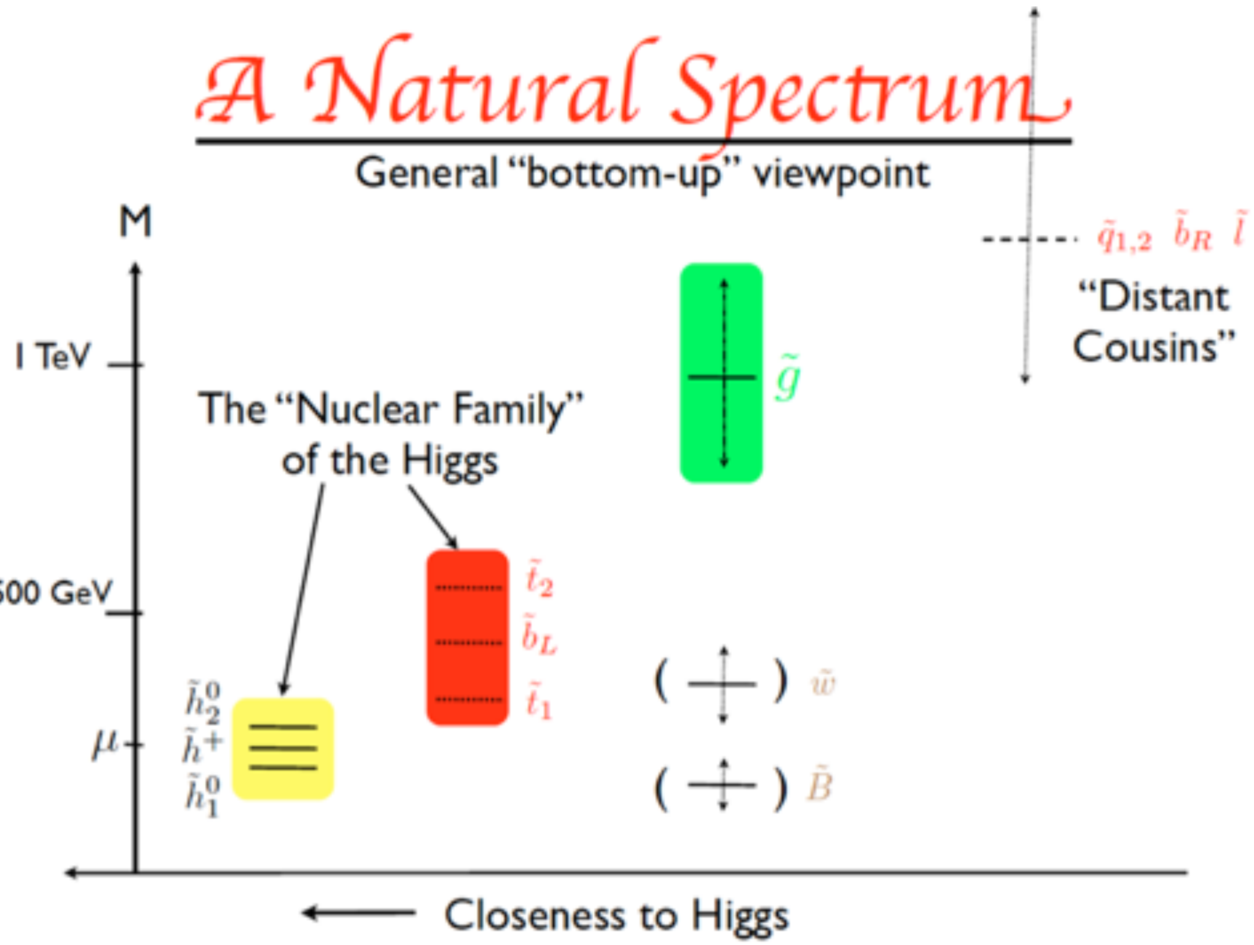



Illustration taken from: L. Hall, LBNL workshop, Oct-2011

For **natural SUSY** need:

- light higgsinos
- light top and bottom squarks (stop, sbottom, respectively)
- not-too-heavy gluinos

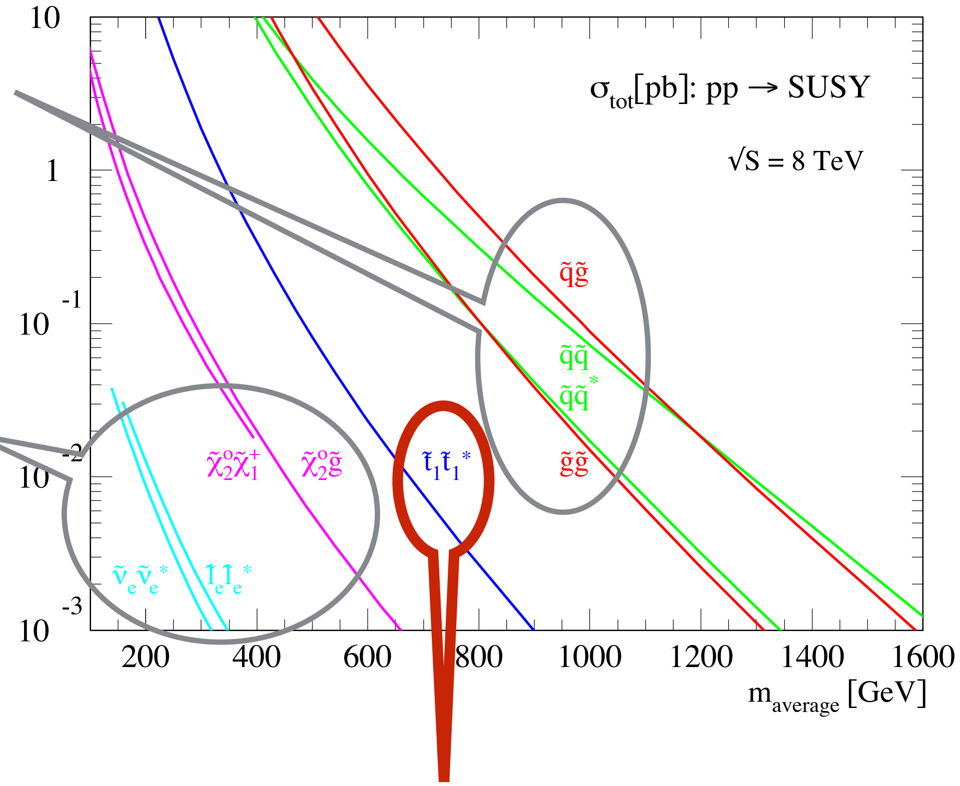
➡ strong physics case for **third generation squarks**

# 3rd generation searches at the LHC

Inclusive searches for strong prod. of gluinos & first two gen. squarks

EW searches

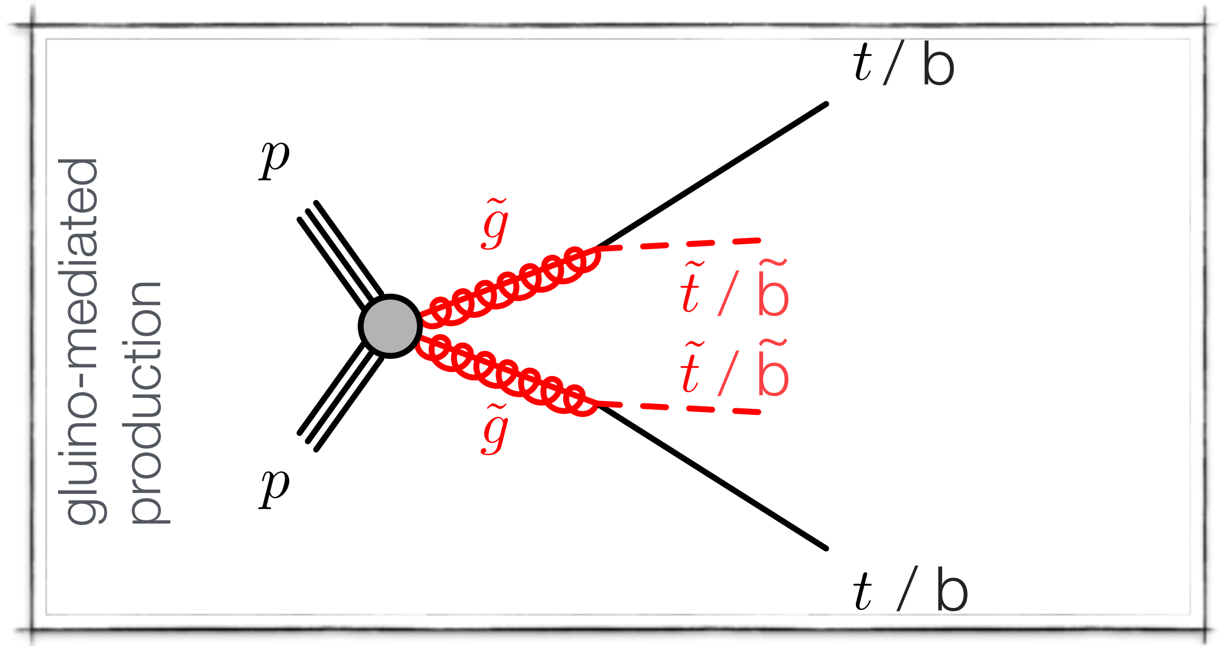
SUSY pair production cross-section

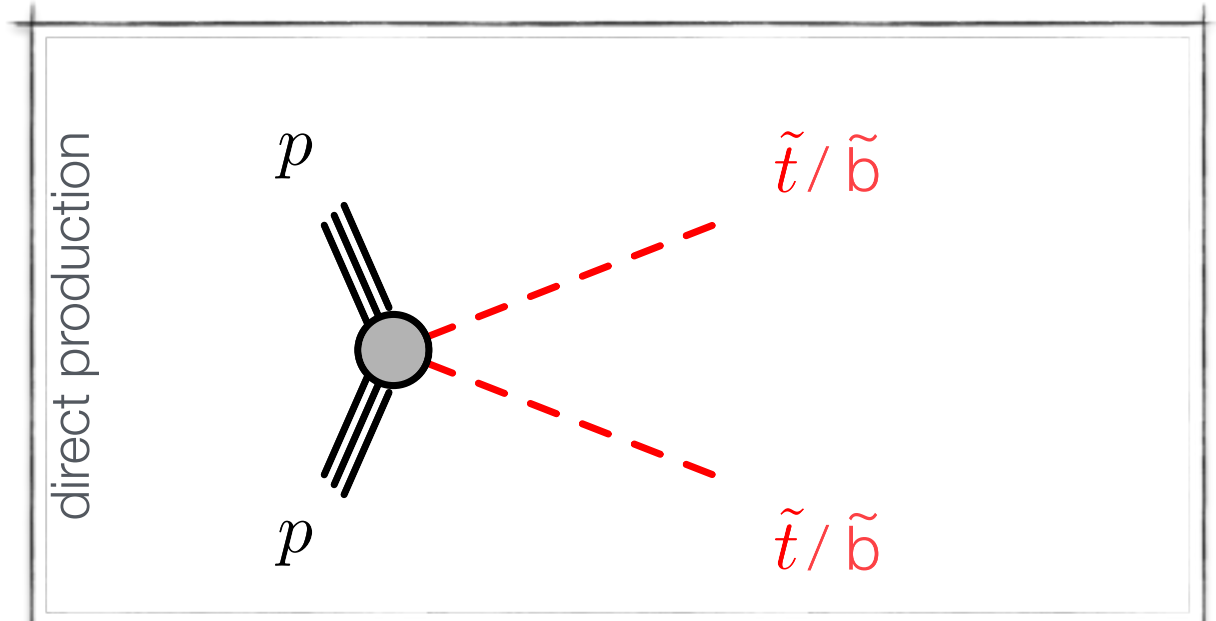



Third generation squarks.

Search for stop and sbottom via:

- **gluino-mediated** production,
- **direct pair** production.



# 3rd generation searches at the LHC

LHC search program relies on the complementarity of many analyses.

**CMS** direct stop:
- 0L, PAS-SUS-13-015
- ▶ 1L, EPJC 73 (2013) 2677
- combination 0L razor, 1L, PAS-SUS-14-011
- stop in charm, PAS-SUS-13-009
- ▶ stop2 in Z/h, PLB 736 371 (2014)

**CMS** direct sbottom:
- 0L, PAS-SUS-13-018

**CMS** gluino-mediated stop/sbottom:
- (0,1,2)L razor, PAS-SUS-14-011
- 0L, CMS-SUS-13-012
- 1L, PLB 733 328 (2014)
- 2OS L, PAS-SUS-13-016
- 2SS L,JHEP 01 (2014) 163
- 3L, PAS-SUS-13-008
- ▶ combination of above 5 searches, PAS-SUS-14-010 (coming out soon)

**ATLAS** direct stop:
- 0L, JHEP 09 (2014 ) 015
- ▶ 1L, Submitted to JHEP [1407.0583]
- 2L, JHEP 06 (2014) 124
- stop in charm, Accepted by PRD [1407.0608]
- ▶ stop2 in Z/GMSB stop, Eur. Phys. J. C (2014) 74:2883
- stop in stau, ATLAS-CONF-2014-037

**ATLAS** direct sbottom/stop:
- 0L, JHEP 10 (2013) 189

**ATLAS** gluino-mediated stop/sbottom:
- ▶ 0-1L + ≥3 b-jets, Accepted by JHEP [1407.0600]
- 2SS/3L, JHEP 06 (2014) 035 (also direct sbottom)
- 0L + ≥(7-10) jets, JHEP 10 (2013) 130

**ATLAS** constraints from tT measurements:
- ▶ 2L cross section, Submitted to EPJC [1406.5375]
- ▶ 2L spin correlation, ATLAS-CONF-2014-056

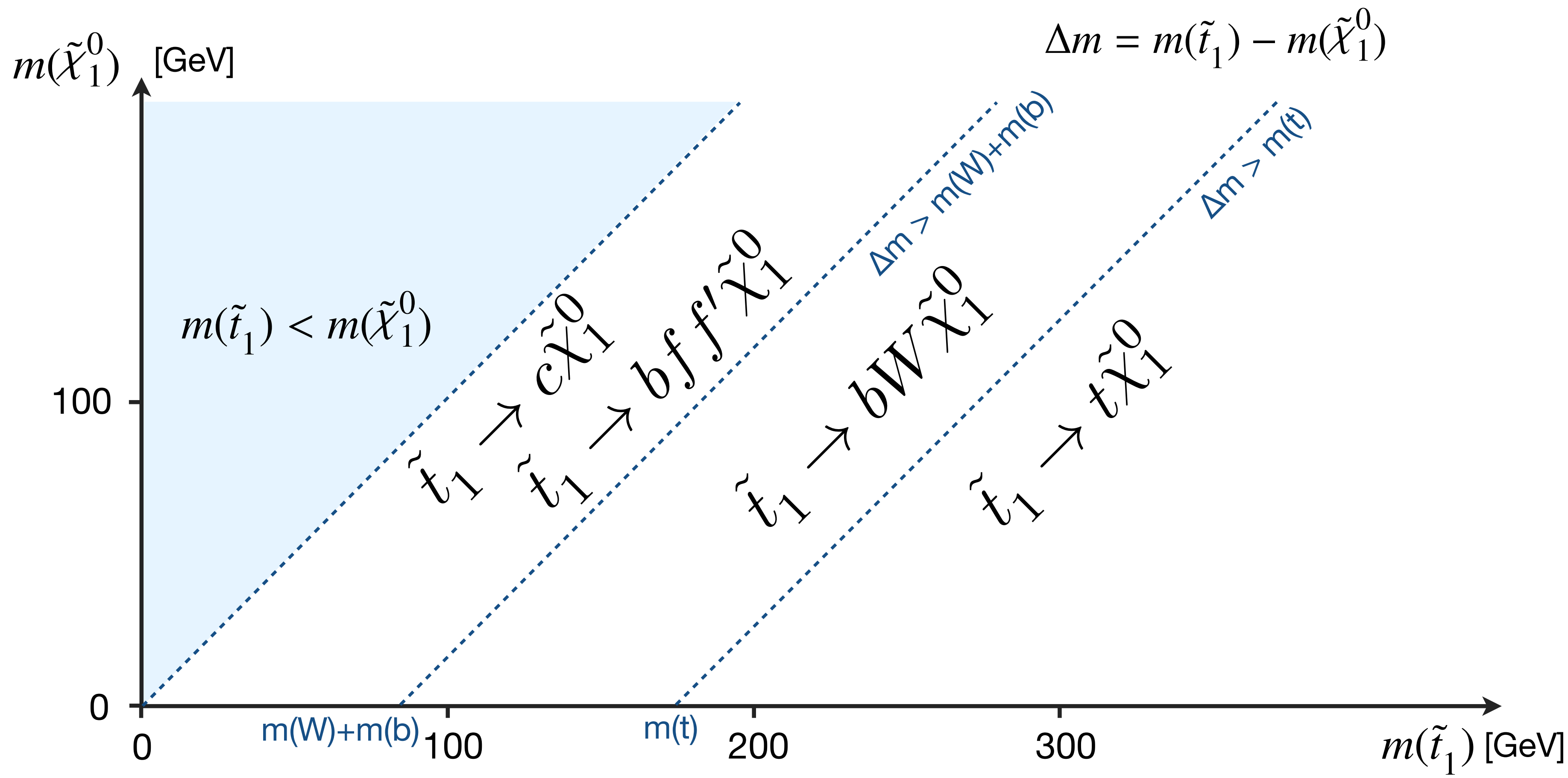
▶ Results presented in this talk, focus on a light stop and processes with a top quark in the decay.

Comprehensive list of all public ATLAS and CMS SUSY search results.

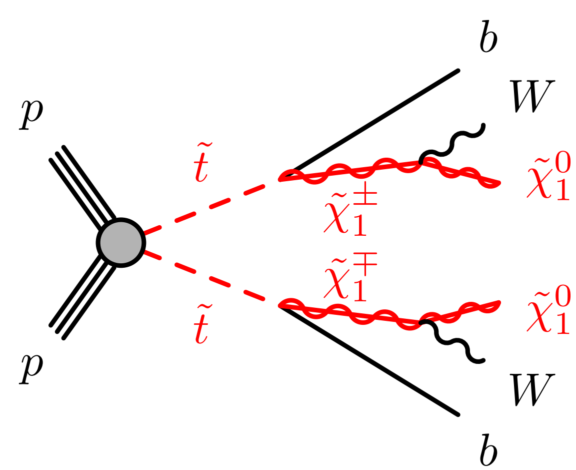
# Overview: direct stop searches

Most searches target lightest eigenstate (stop1).
Several decay modes possible.

$$\begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_t & \sin\theta_t \\ -\sin\theta_t & \cos\theta_t \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}$$




stop decays directly to the lightest neutralino



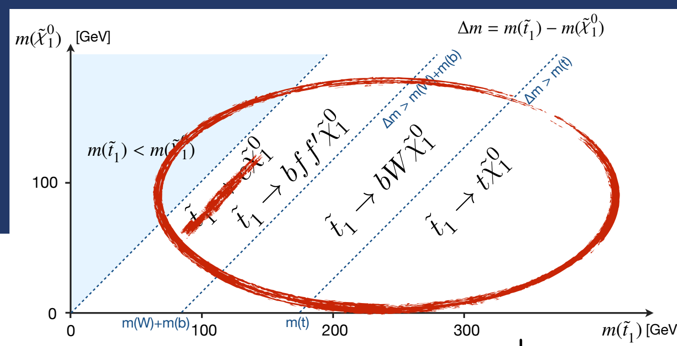

$$\tilde{t}_1 \to b\tilde{\chi}_1^\pm$$

stop decays via the lightest chargino

other (complex) decays possible …

# ATLAS searches 1L channel

submitted to JHEP [1407.0583]



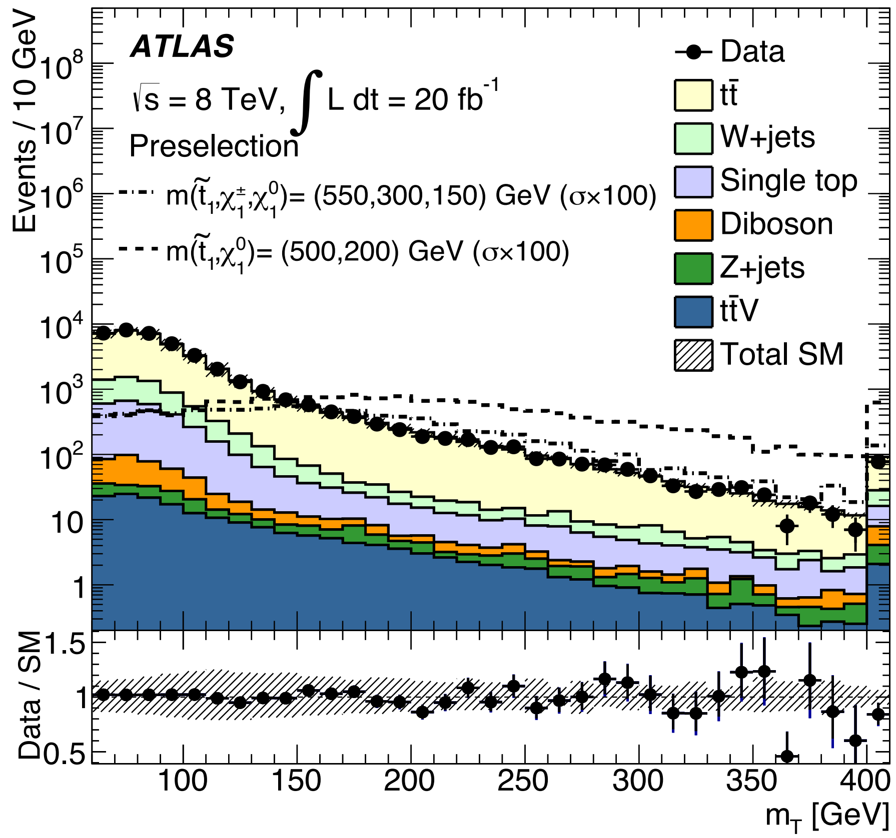

$$\tilde{t}_1 \to b\tilde{\chi}_1^\pm$$

Search targets light to heavy stops in various decay modes: 4-body, 3-body, tN1, and bC1.

**1-leptons, ≥2-4 jets, MET, MT(lep, pTmiss)**

15 signal regions (SRs).

- soft-lepton: pT > 7(6) GeV for electrons (muons), employed for 4-body, and bC1 decays with small mC1-mN1 values.
- large-R (1.0) jets: collect decay products of boosted top in heavy stop search.
- 1D and 2D shape-fits: enhance search sensitivity in challenging scenarios (with difficult S-vs-B separation).
- b-tagged jets: utilised in event selection (ranging from a veto to ≥2) and for constructing kinematic variables.
  - MT2-like variables, hadronic top mass, topness




- Dominant background: **semi (di)-leptonic ttbar** for the stop 0L (1L) search, where the (2nd) lepton is
  1. not identified (failed PID) / outside acceptance,
  2. hadronically decaying tau-lepton.

} missed particle / extra neutrino(s) → more $E_T^{miss}$, mT > m(W)

# ATLAS searches 1L channel

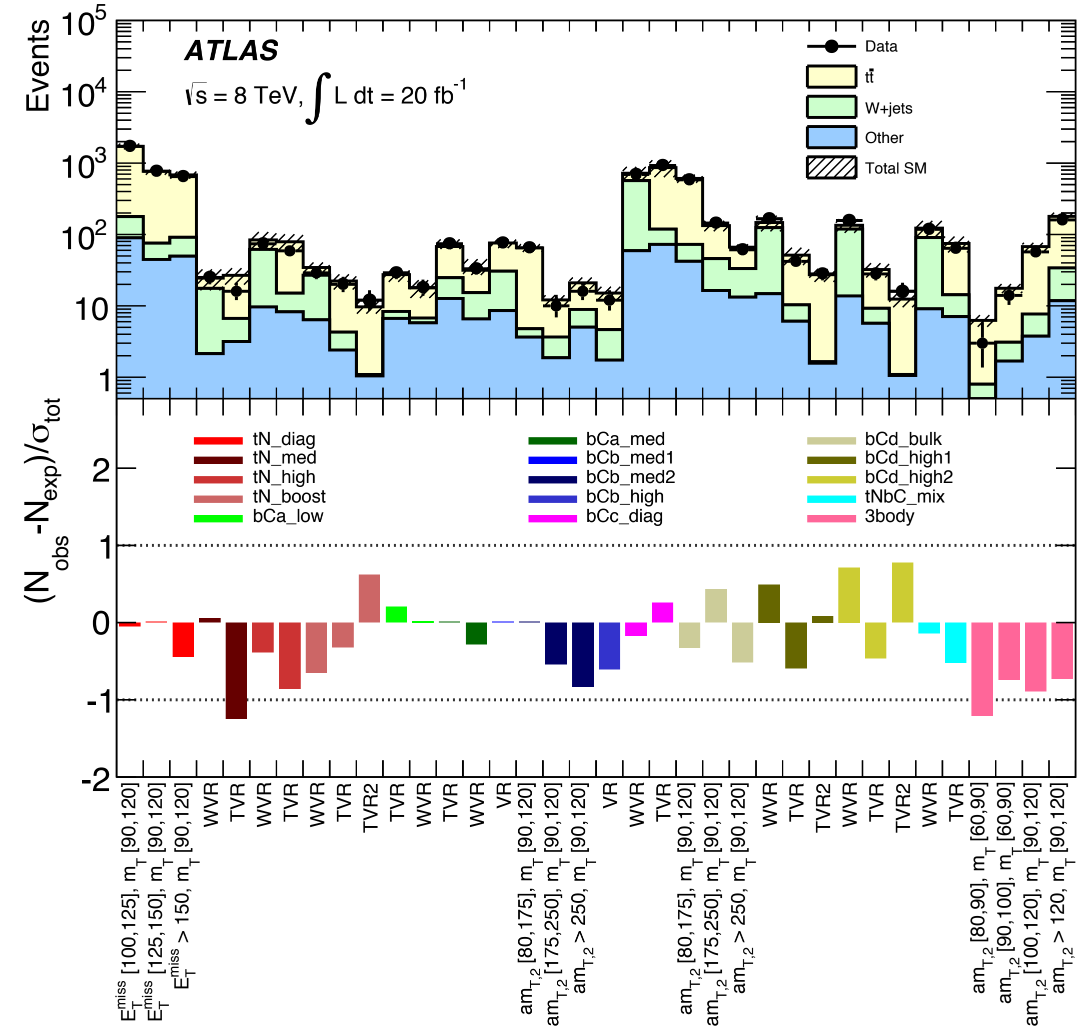
submitted to JHEP [1407.0583]

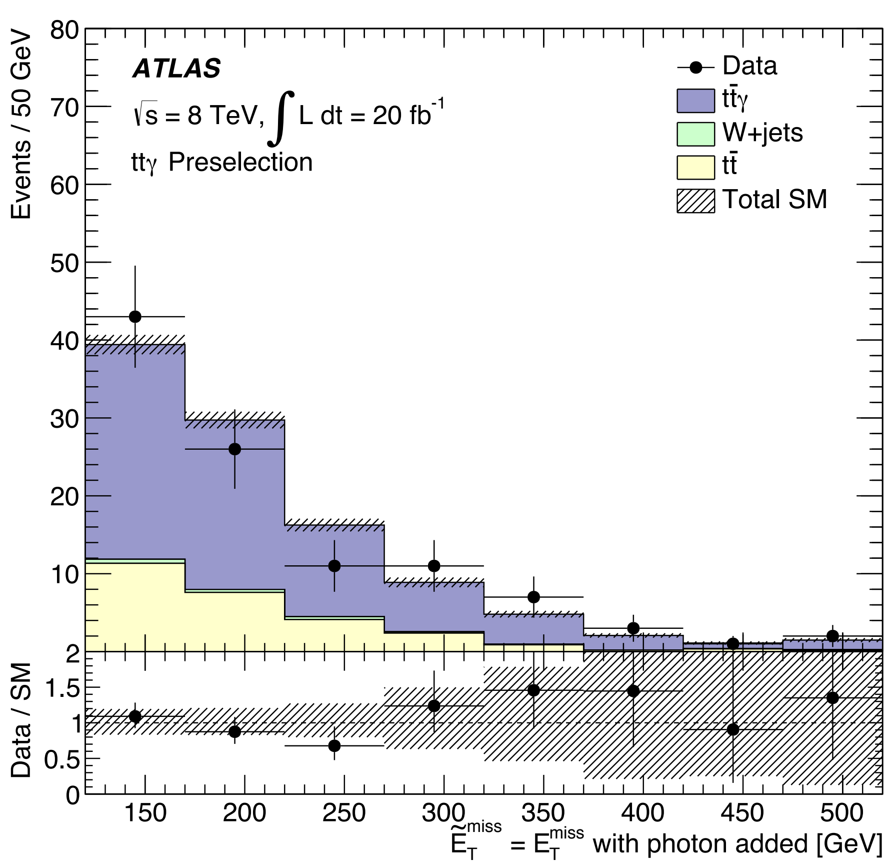
## Backgrounds

- dileptonic tT (with one lep. out of acceptance, not identified, or is a had tau) — 1L lower-MT CR
- W+jets + HF — 1L lower-MT, b-veto CR
- tT+Z(nunu), and other (small) backgrounds — MC

**Validation:** compare data with prediction in dedicated samples

- kinematically close to SR (see plot),
- 2L, Z-veto — tT additional jets,
- W+HF validation selection,
- tT+Z(nunu) validation via tT+gamma (see plot), and more.



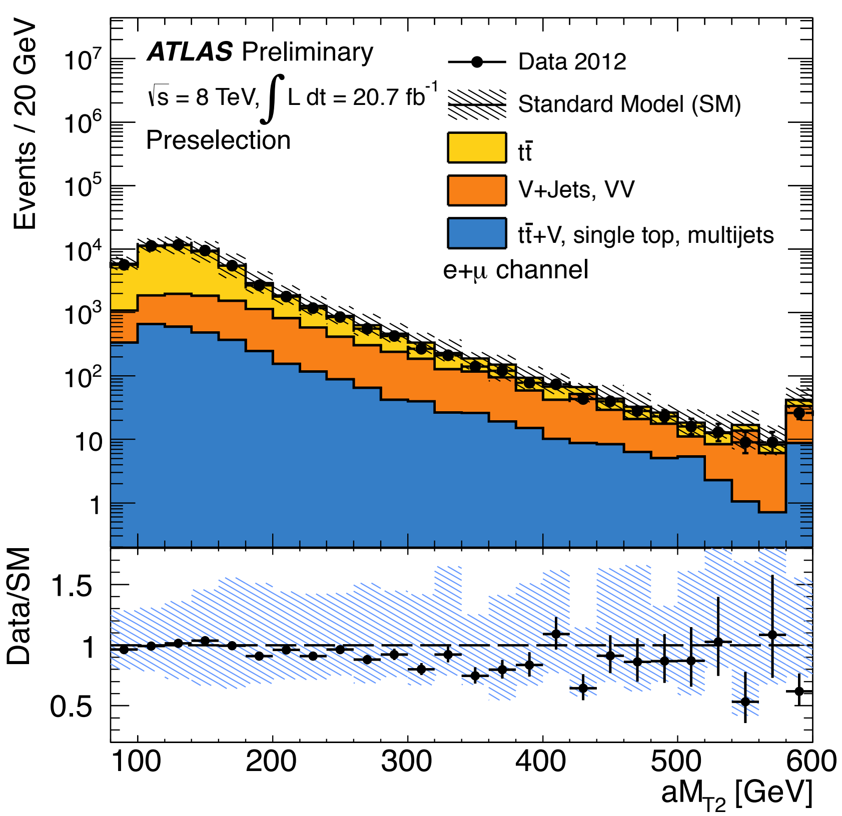



## Tools to suppress dominant tT bkg

Similar variables also employed by CMS search.

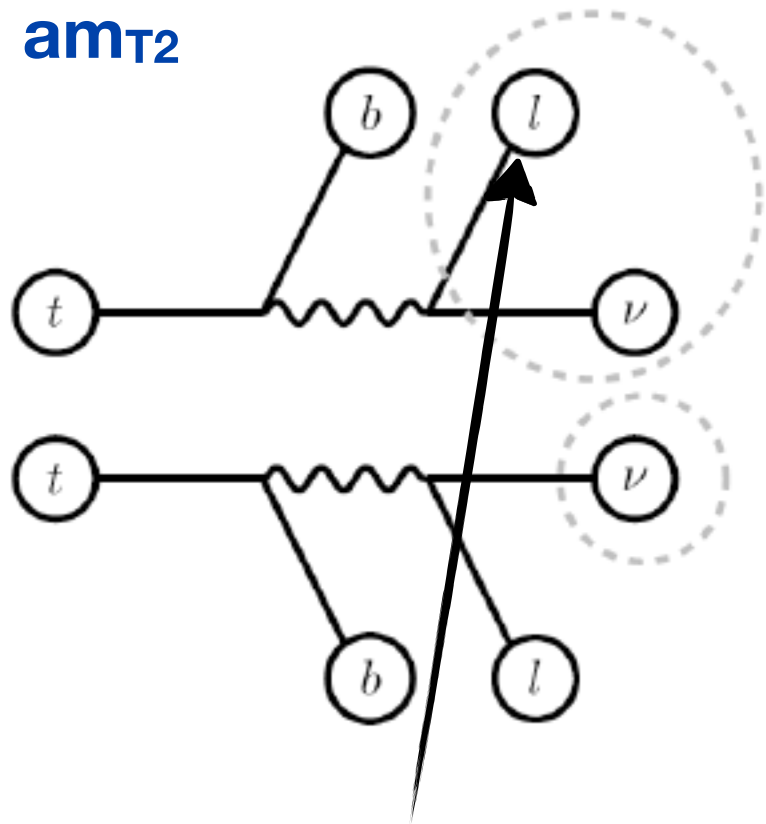
### Kinematic variables: $M_{T2}$

$$m_{T2} \equiv \min_{\vec{p}_{Ta}^{\,C}+\vec{p}_{Tb}^{\,C}=\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}} \{\max(m_{Ta}, m_{Tb})\}$$



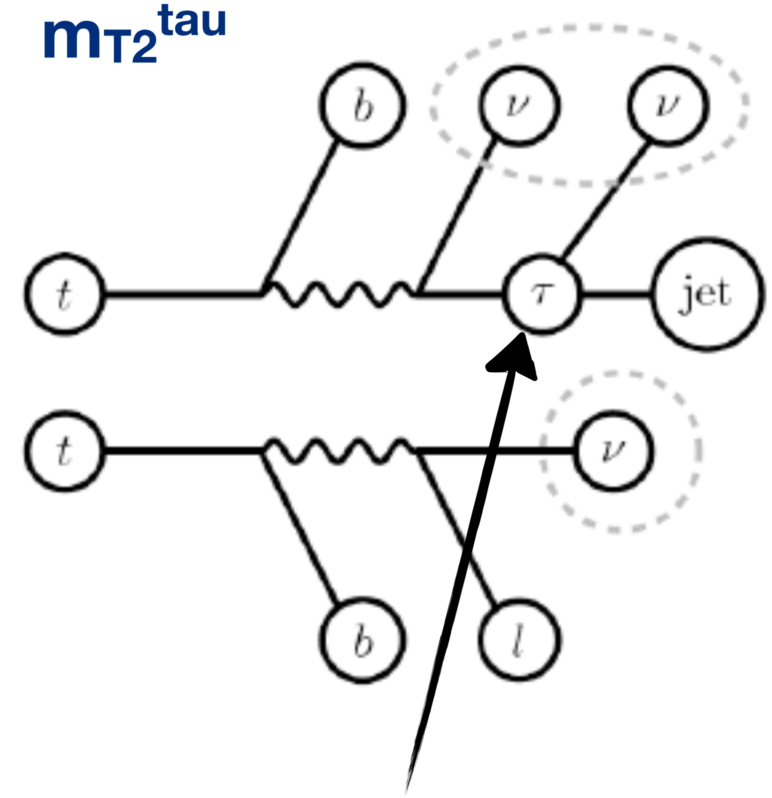

Dedicated variants of $M_{T2}$:

**$am_{T2}$**



"lost" lepton (category 1), $leg_a$=bjet1+lep, $leg_b$=bjet2, or vice versa (take min.)

**$m_{T2}^{tau}$**

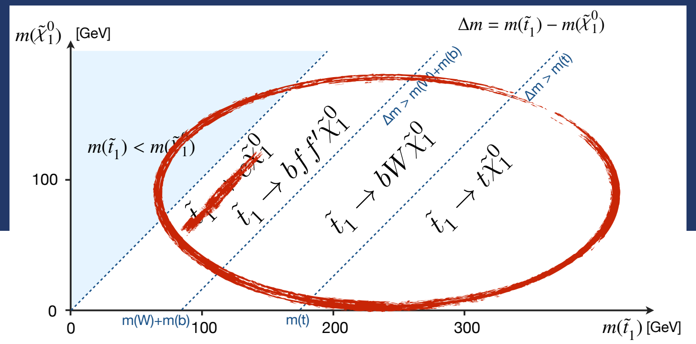


Had-tau (category 2), $leg_a$=jet3, $leg_b$=lep, where jet3 is hardest non b-tagged jet

di-leptonic ttbar has kinematic end-points: around top mass ($am_{T2}$), and the W mass ($m_{T2}^{tau}$); while signal can exceed these.

# ATLAS searches 1L channel

submitted to JHEP [1407.0583]




**4-body:**

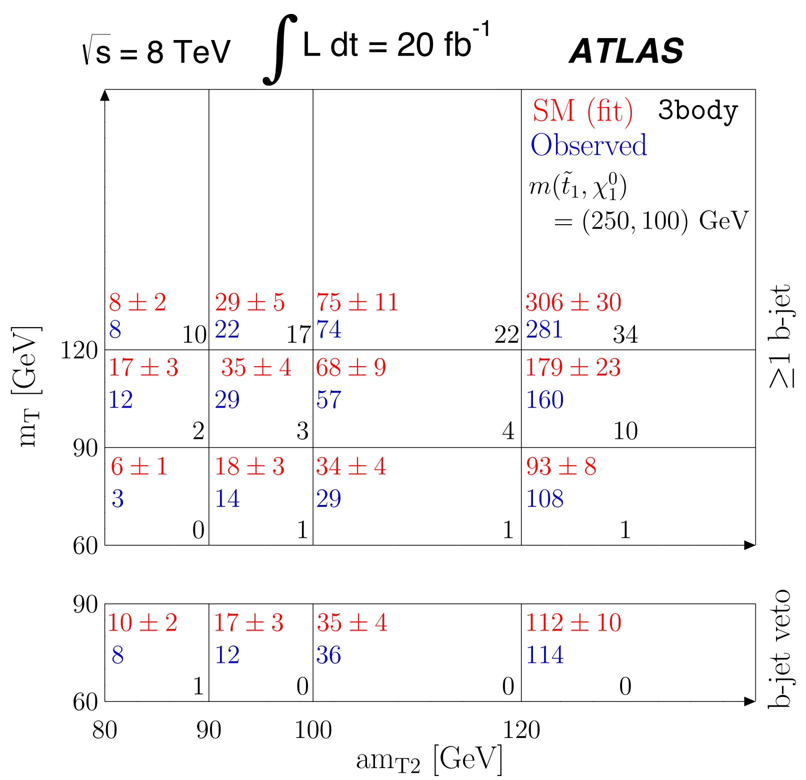
- 1 soft-lepton
- 1 hard non-b-tagged jet (ISR)
- ≥1 b-tag in sub-leading jets
- high MET, MT>mW,

**3-body:**

- 1 lepton
- ≥4 jets, at least one of which is b-tagged
- high MET, 2D shape-fit in MT and amT2

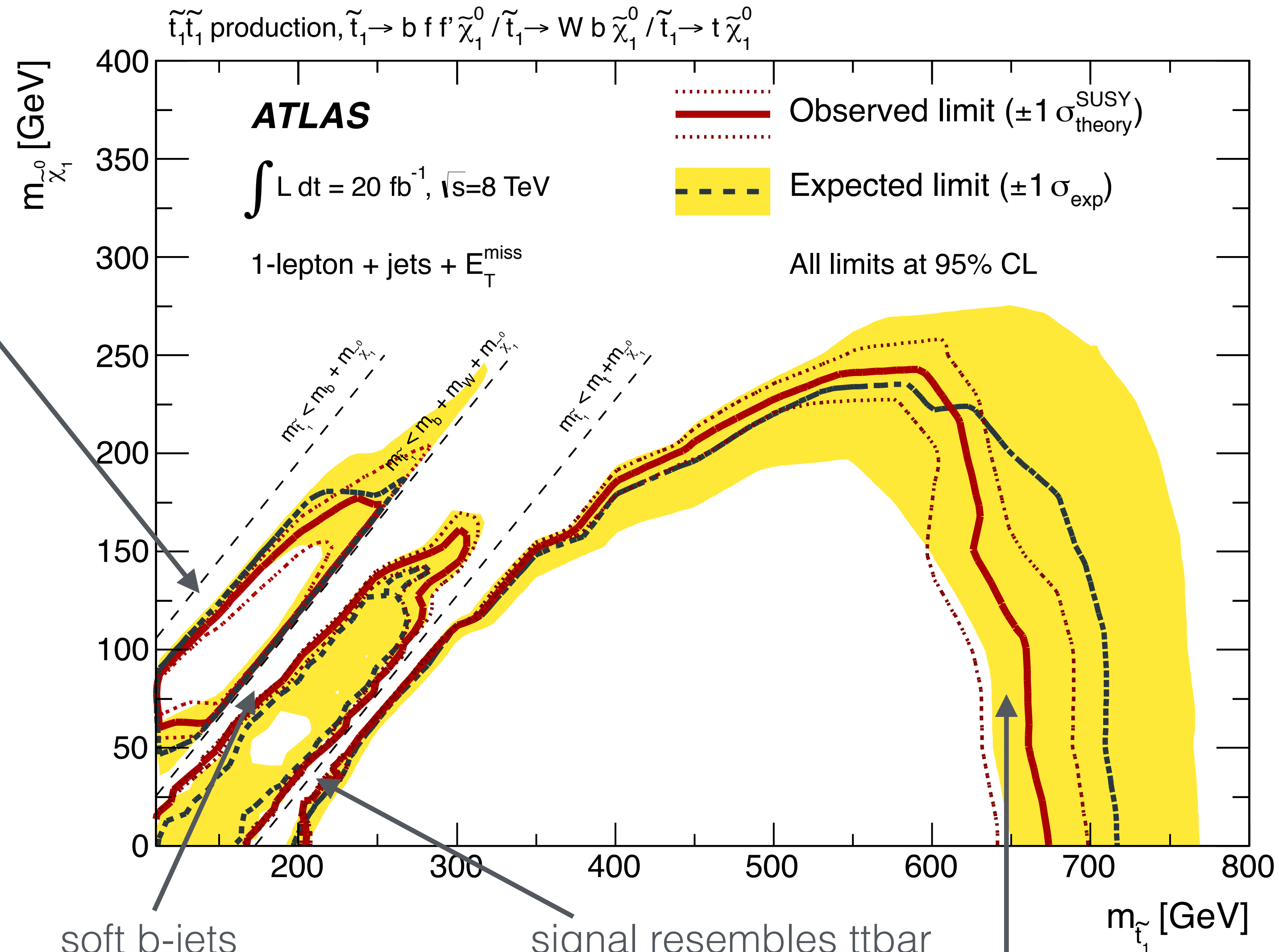
**mStop ≳ mTop+mN1:**

- 2D shape fit but with looser selection, MT-MET




| $m_T$ [GeV] \ $am_{T2}$ [GeV] | 80–90 | 90–100 | 100–120 | >120 |
|---|---|---|---|---|
| ≥1 b-jet, >120 | 8 ± 2 / 8 / 10 | 29 ± 5 / 22 / 17 | 75 ± 11 / 74 / 22 | 306 ± 30 / 281 / 34 |
| ≥1 b-jet, 90–120 | 17 ± 3 / 12 / 2 | 35 ± 4 / 29 / 3 | 68 ± 9 / 57 / 4 | 179 ± 23 / 160 / 10 |
| ≥1 b-jet, 60–90 | 6 ± 1 / 3 / 0 | 18 ± 3 / 14 / 1 | 34 ± 4 / 29 / 1 | 93 ± 8 / 108 / 1 |
| b-jet veto, 60–90 | 10 ± 2 / 8 / 1 | 17 ± 3 / 12 / 0 | 35 ± 4 / 36 / 0 | 112 ± 10 / 114 / 0 |

too small Δm, but monojet




soft b-jets

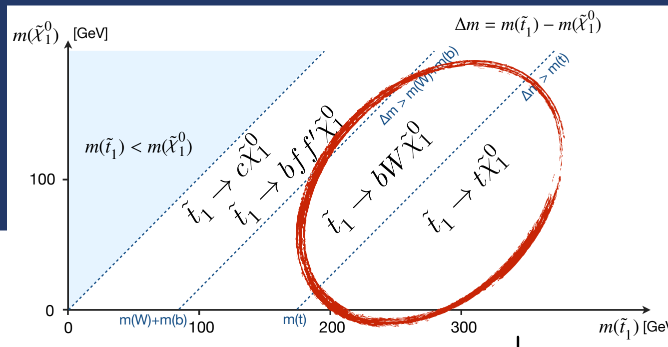
signal resembles ttbar

boosted top, large-R jet

“boosted tops” covered in talk by Johannes Erdmann (Wednesday)

# CMS searches 1L channel

EPJC 73 (2013) 2677




$\tilde{t}_1 \rightarrow b\tilde{\chi}_1^{\pm}$

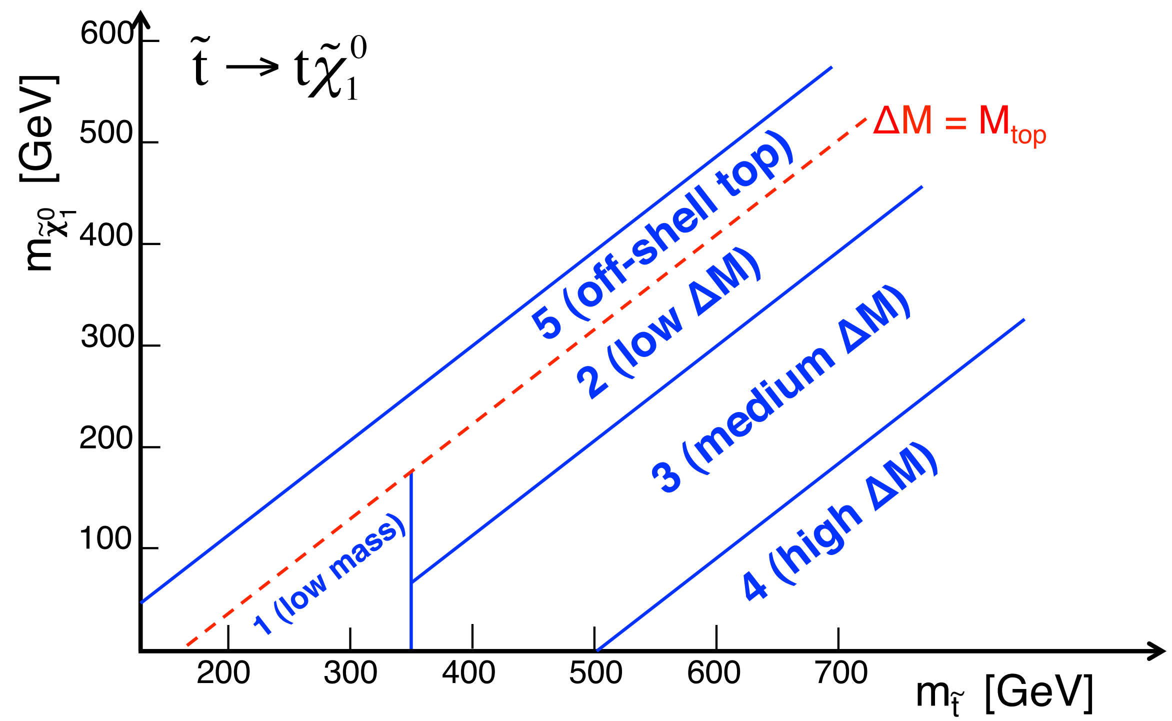
Search targets medium to heavy stops in various decay modes: 3-body, tN1, and bC1.

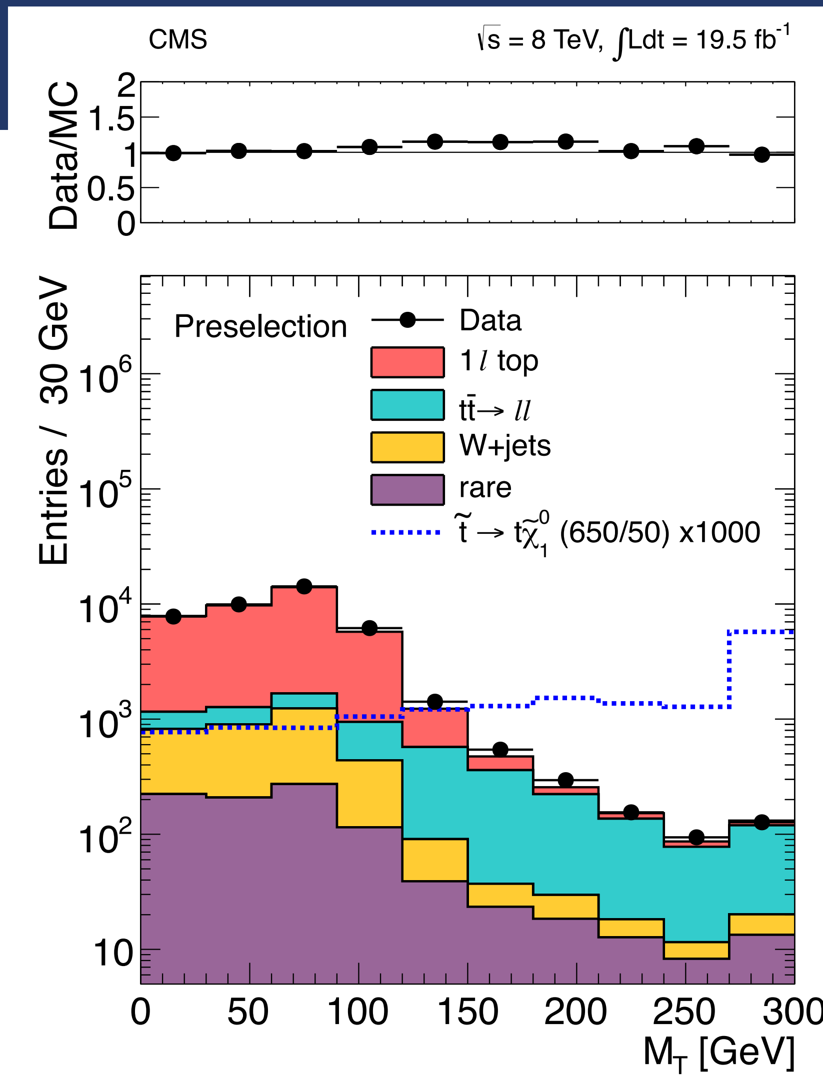
**Baseline selection**

- 1 isolated lepton (e/mu, veto extra e,mu,tau)
- ≥4 jets, at least one b-tagged
- MET >100 GeV
- MT(lep,pTmiss) > 120 GeV

**18 BDT analyses**

- trained on different regions of signal models (tN1 example shown in plot)
- MET, MT2W, relative HT btw. event hemispheres,
- hadronic top compatibility (chi2)
- lep, b-jet pT
- distance btw. lep and b-jet
- cut-based analyses for cross check.






## Backgrounds

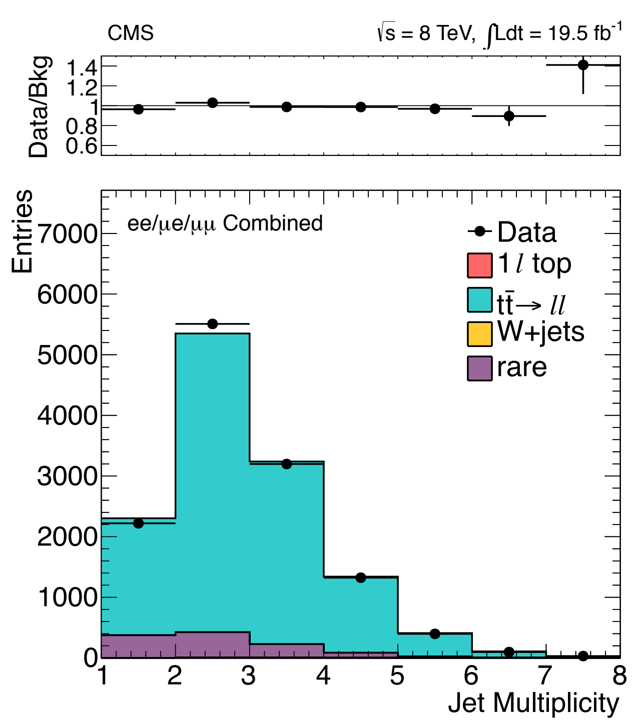
- dileptonic tT (one lepton missed) →ll
- semi-lepton tT + t →1l top
- W+jets
- other (small) backgrounds →rare

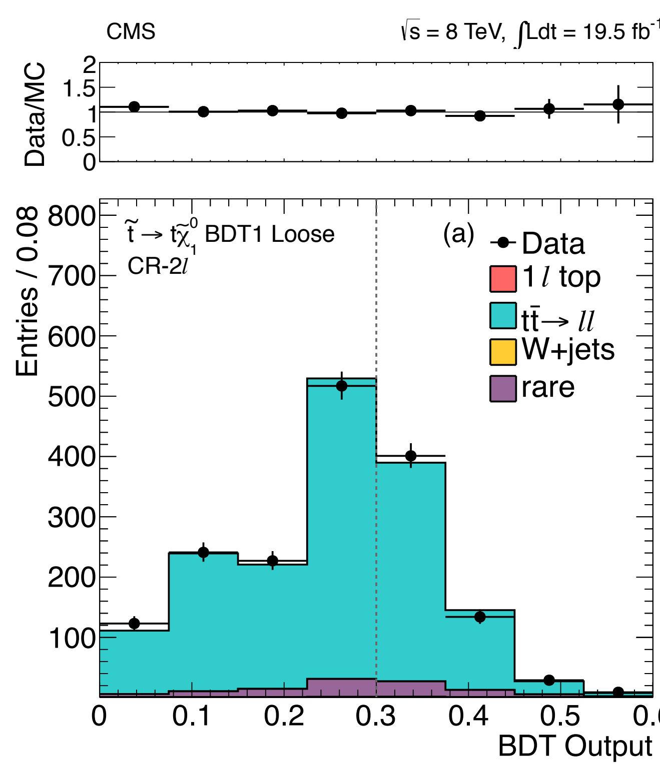
**Estimation:**

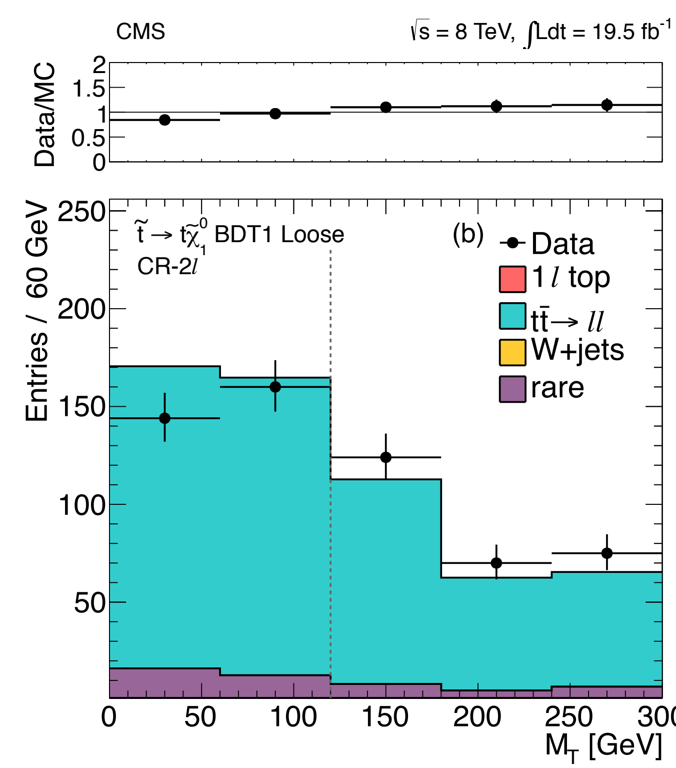
- normalise backgrounds in low MT window

**Validation:** compare data with prediction in dedicated samples

- 2L, 1L+isolated track, b-veto
- uncertainties derived from these studies



# CMS searches 1L channel

EPJC 73 (2013) 2677

## Tools to suppress dominant tT bkg

Similar variables also employed by ATLAS search.

**Tight 2nd lepton veto**:

Signal has no `edge' in mT hence dominated by single lepton.

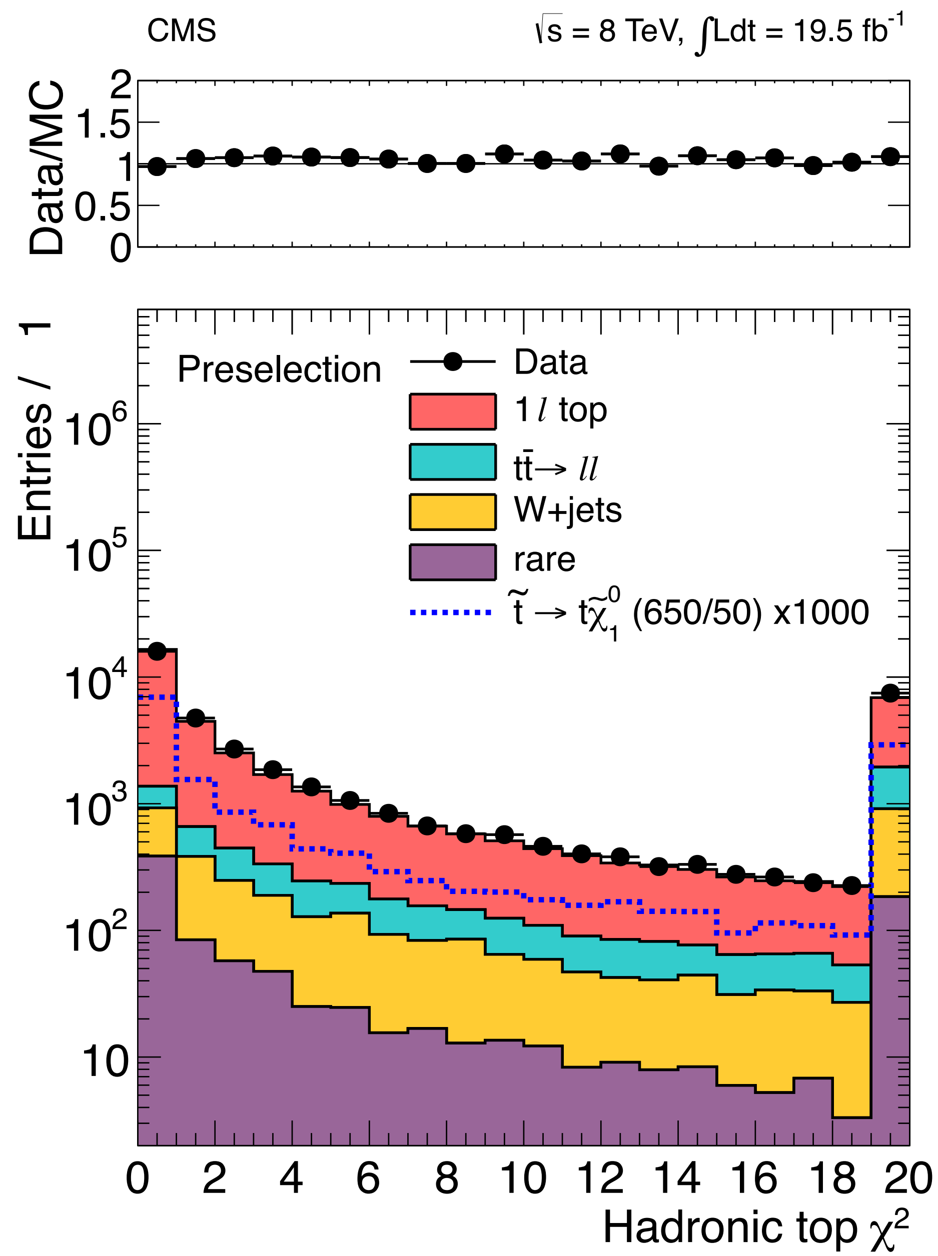
- lepton pT, PID
- veto on isolated tracks
- veto on had-taus

**Hadronic top mass**:

While for decay via top quark, three jets stem from a hadronic top decay, this is not true for di-lep ttbar.

- reconstruct hadronic top mass from three jets m(jjj),
- consider b-tagging & jet energy resolution

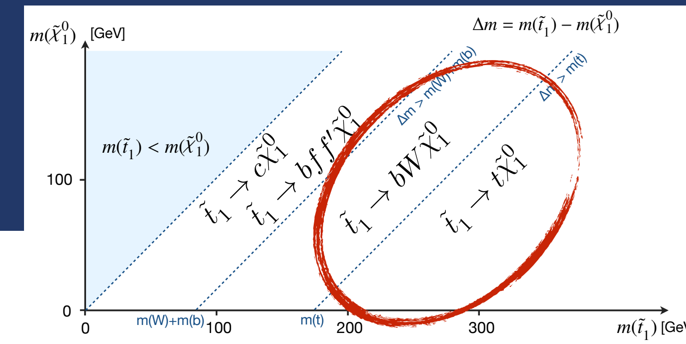
$$\chi^2 = \frac{(M_{j_1 j_2 j_3} - M_{\text{top}})^2}{\sigma^2_{j_1 j_2 j_3}} + \frac{(M_{j_1 j_2} - M_{\text{W}})^2}{\sigma^2_{j_1 j_2}}$$



# CMS searches

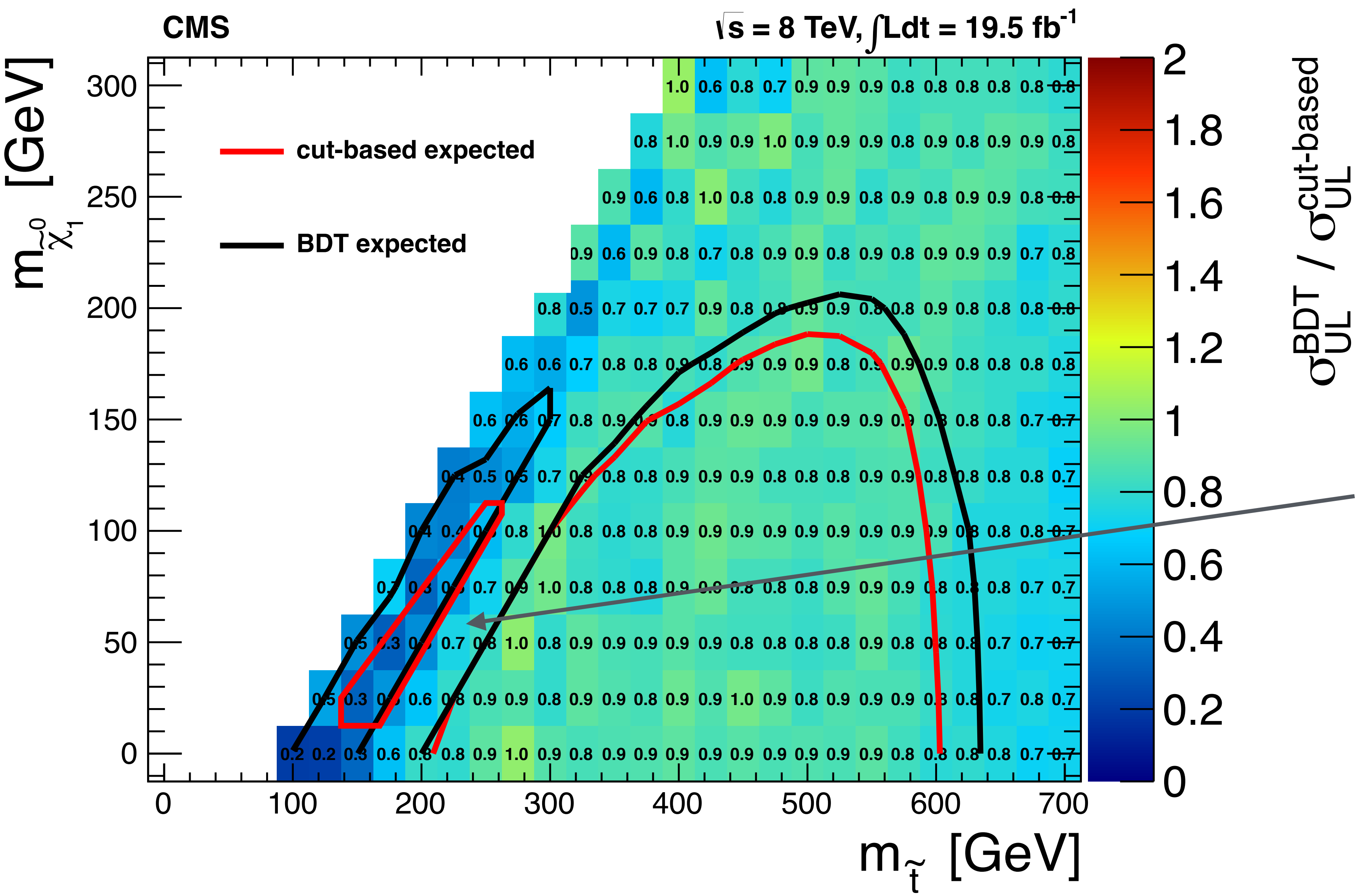
## 1L channel

EPJC 73 (2013) 2677




Exclusion limits

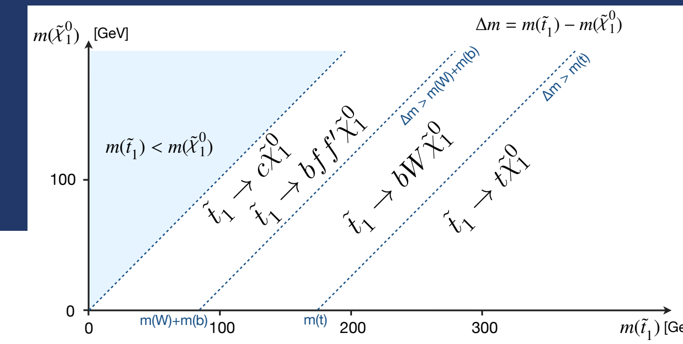
- BDT analyses
- cross section limits from BDT improve over cut-based analysis by up to ~40%



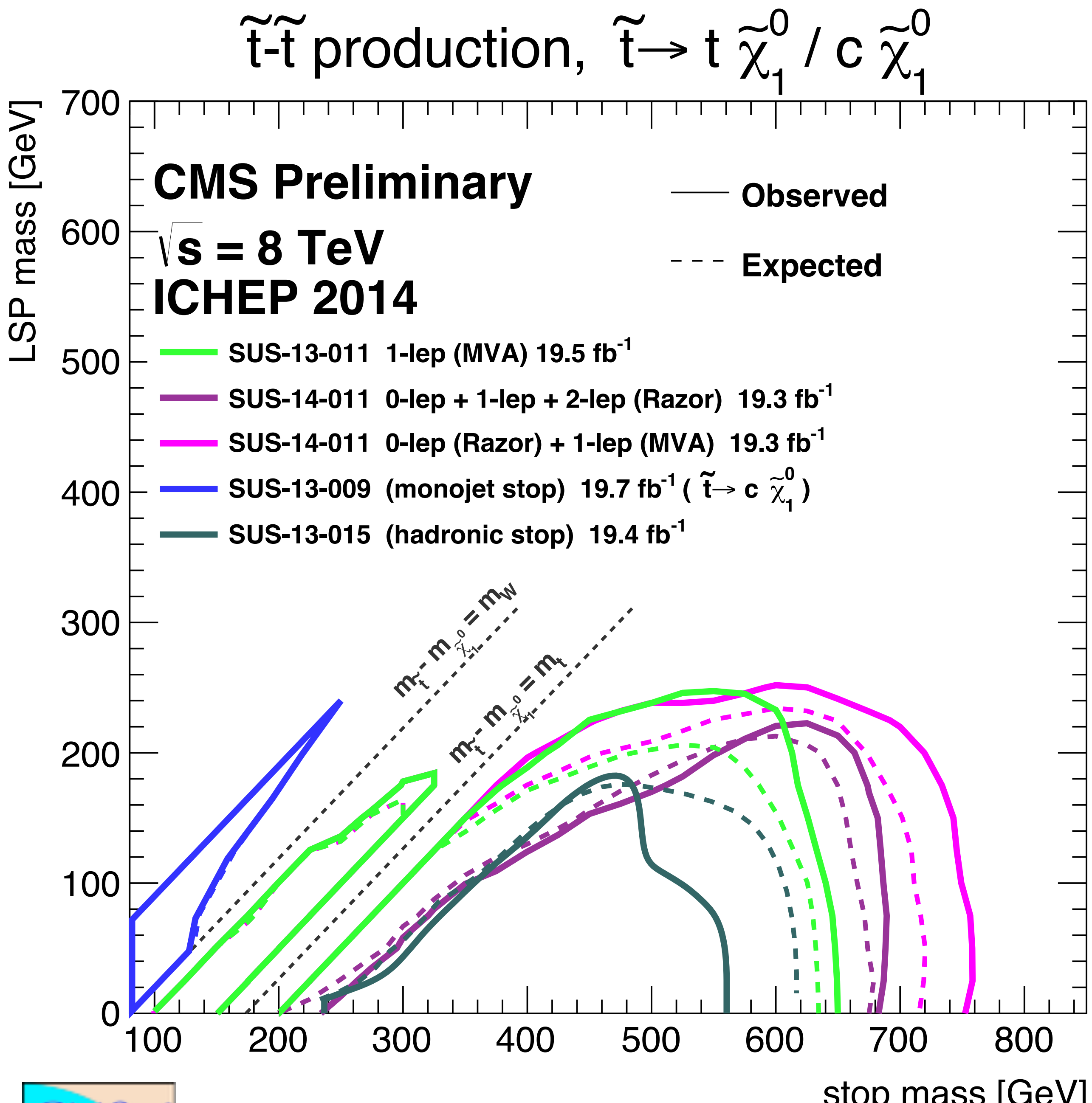

largest improvement from BDT approach

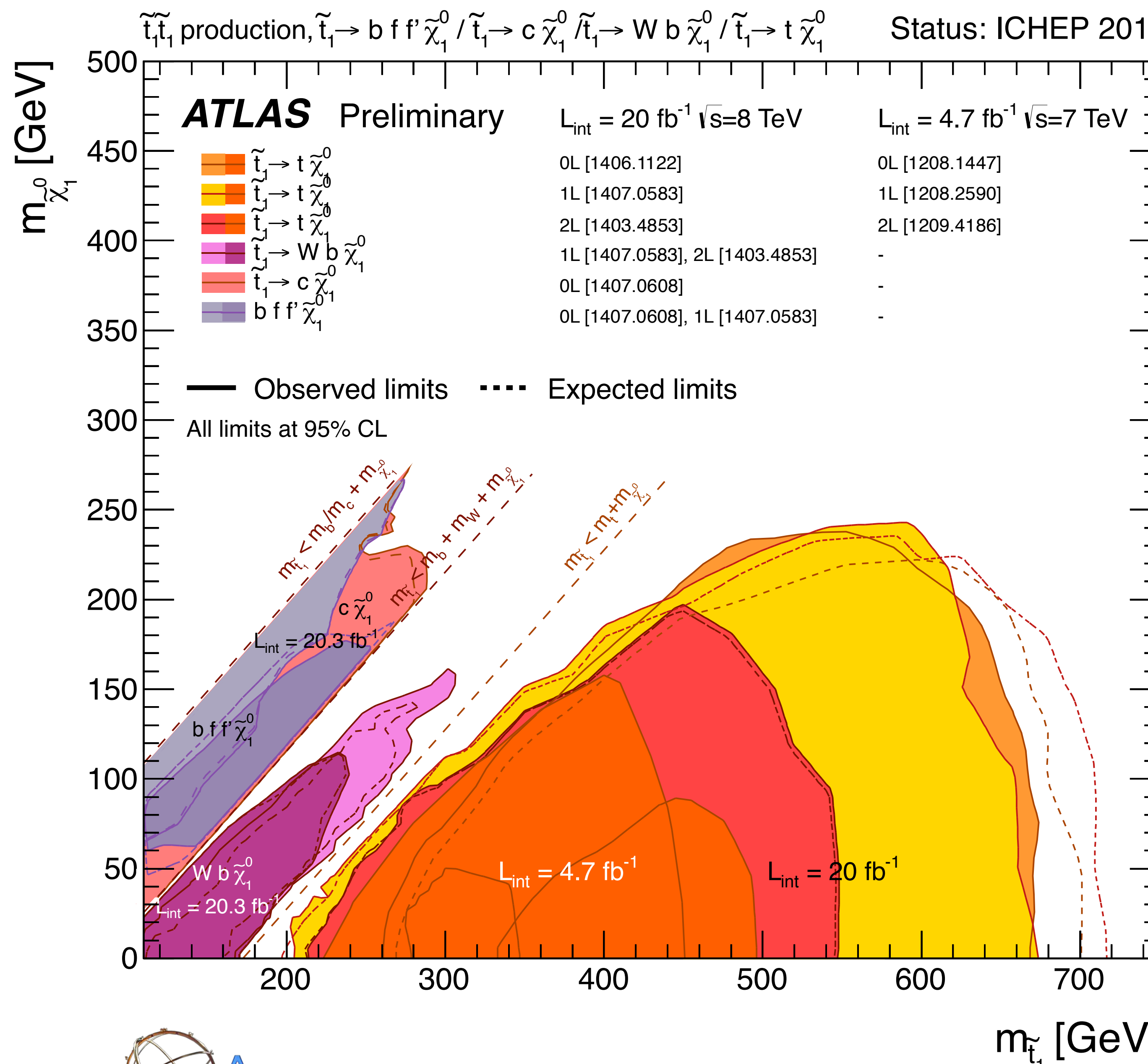
Acceptance also depends on the polarization of the the top quarks in the stop decay. Effect from left/right mixing of the stops and on the mixing matrices of the neutralino and charginos, impact shown in backup (CMS & ATLAS).

# Complementarity of searches

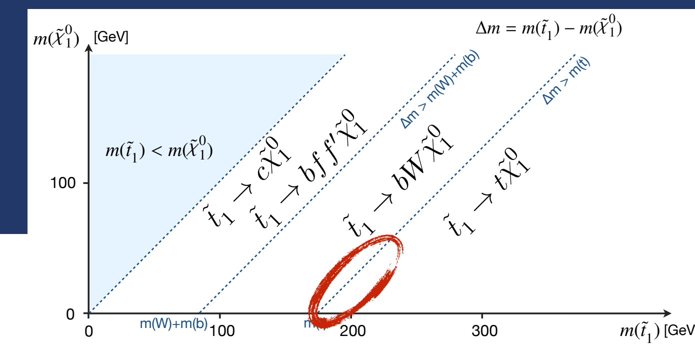



Many analyses to cover the various decays and mass regions.
Furthermore, other decays such as via a chargino are considered & largely covered. However, holes remain!



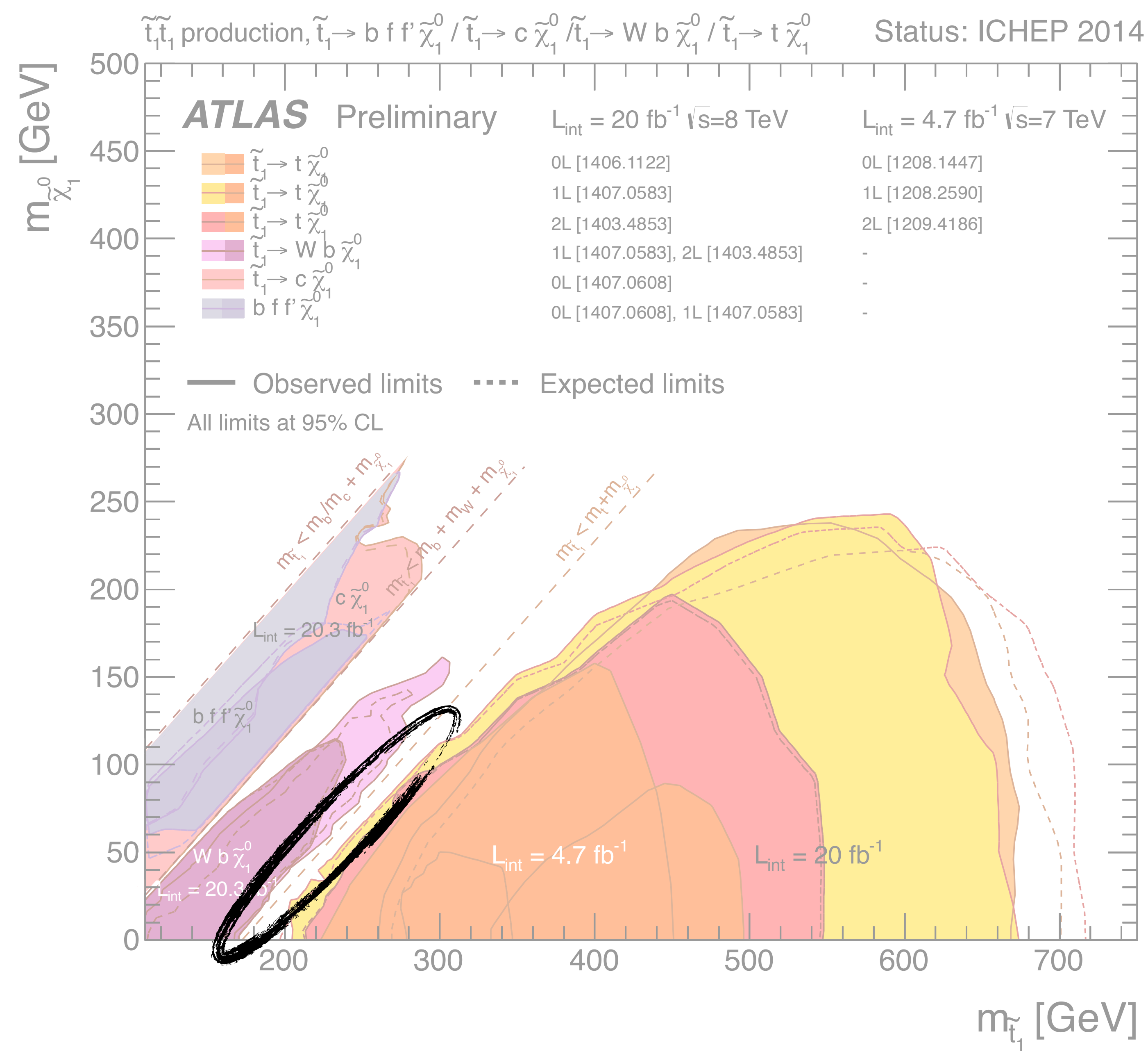
# ‘Stealth’ stop




**Close the gap where m(stop1) - m(N1) ≈ m(top)**

**challenge**: kinematic variables ($E_T^{miss}$, $M_T$, etc.) resemble those of ttbar background.

- But smaller signal cross-section, ~15% of SM tT for same mass.

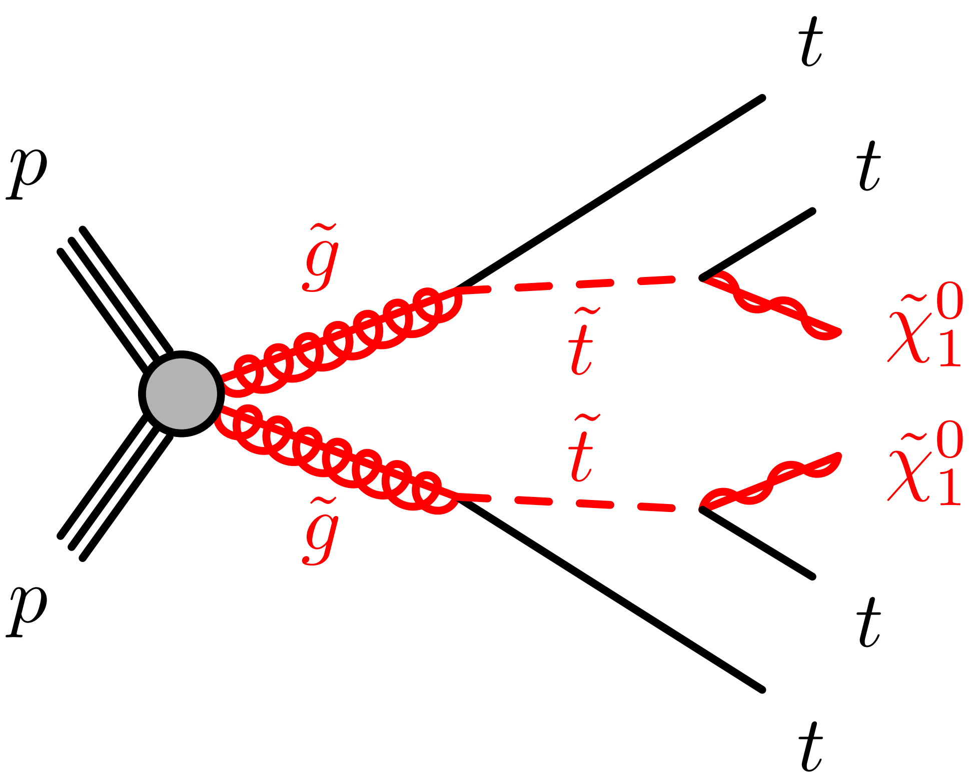



1. **Direct approaches:**
   - shape-fit
   - Multivariate analysis
   - Top measurements (later)

2. **Indirect approach:**
   - search for heavier SUSY production with subsequent decay via stop1.
     - gluino to stop1 + t
     - stop2 to stop1 + Z/H

# Searches for gluino-mediated stop production

Gluino pairs decaying via on- or off-shell stop lead to a spectacular signature of four top quarks + extra MET.




- Up to 4 (el,mu), 4 b-jets, ..
- Various searches in 0L — 3L channels,

SUSY: mGluino < (3-5) x mStop,

and gluino pair production cross section much larger (x50)

Gluino-mediated searches give handle to search for a stealthy stop (mass degenerate with top).

**Backgrounds**:

- **reducible**: for example, fake b-jets (mainly tT) estimated from data (matrix method)
- **irreducible**: for example, processes with ≥3 bjets:
  - tT + b bbar, (using 2L control region),
  - tT + Z/h(→bbbar) from MC

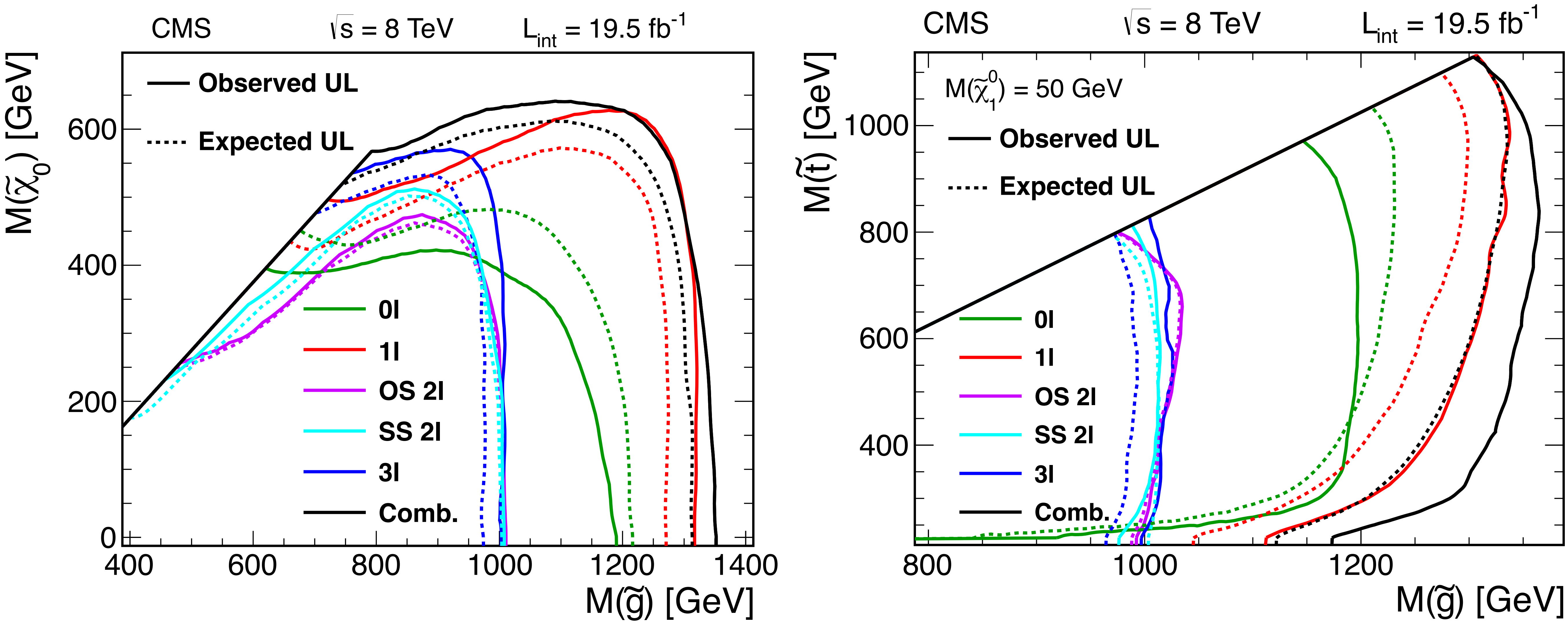
# CMS searches 0-3L combination

SUS-14-010

NEW

Combination of five orthogonal searches:

- 0L + multijets (3-8j) [CMS-SUS-13-012]
- 1L + ≥6 jets with ≥3 b-tagged [PLB 733 328 (2014)]
- 2OS L + ≥5 jets with ≥3 b-tagged + MET>180 GeV [PAS-SUS-13-016]
- 2SS L + ≥(2-4) jets with (0, 1, ≥2) b-tagged + MET cut [JHEP 01 (2014) 163]
- 3L + ≥(2-4) jets with (1,2, ≥3) b-tagged [PAS-SUS-13-008]

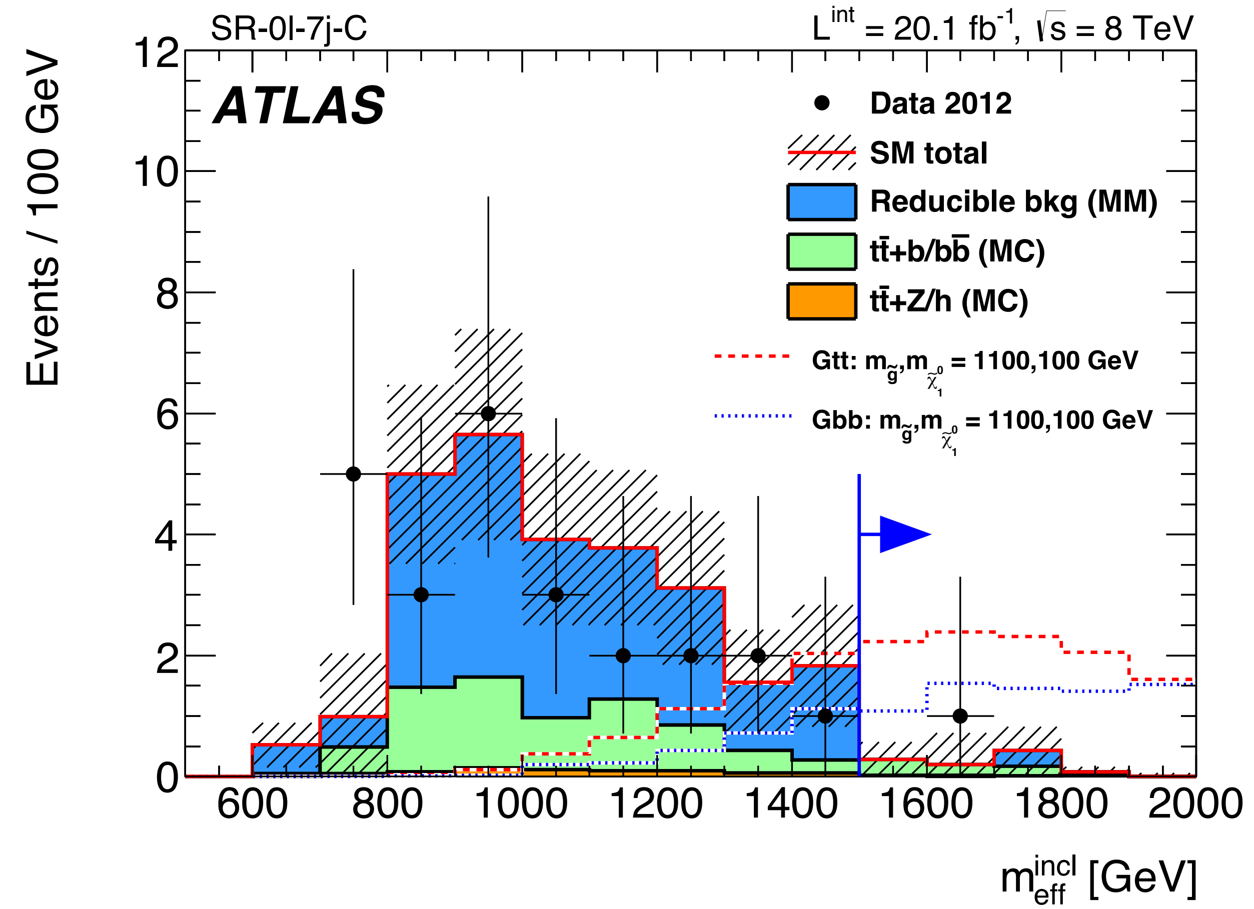


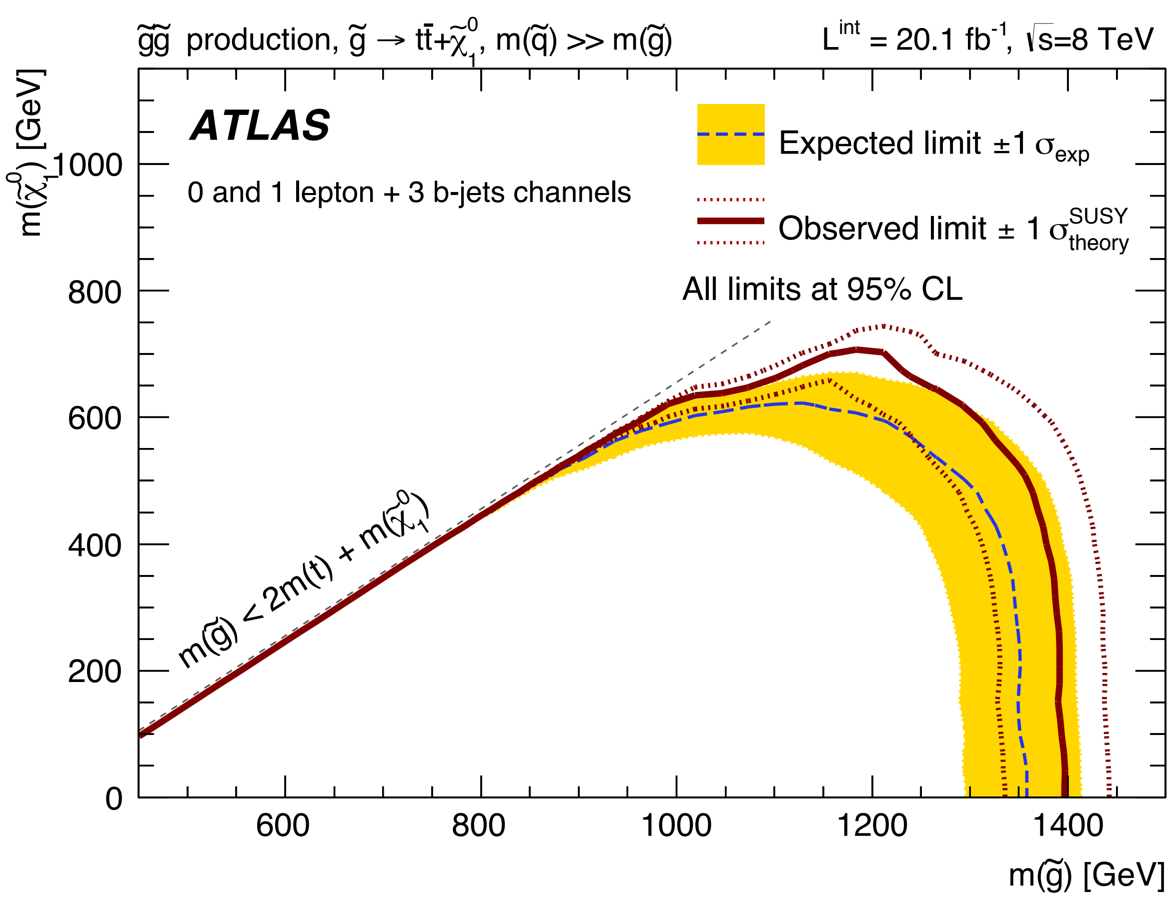
# ATLAS searches 0-1L + 3 bjets

Accepted by JHEP [1407.0600]

0L and 1L channels, optimized for various decays (sbottom, stop,..)

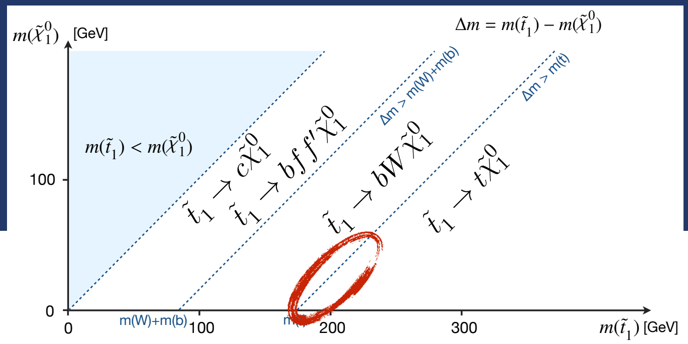
- 0L + ≥4 jets or ≥7 jets (≥3 b-tagged), with Meff (scalar sum over jets, MET) cuts btw. 1 and 1.5 TeV and high MET
- 1L + ≥6 jets (≥3 b-tagged), with Meff>700—900 GeV and high MET and high mT.



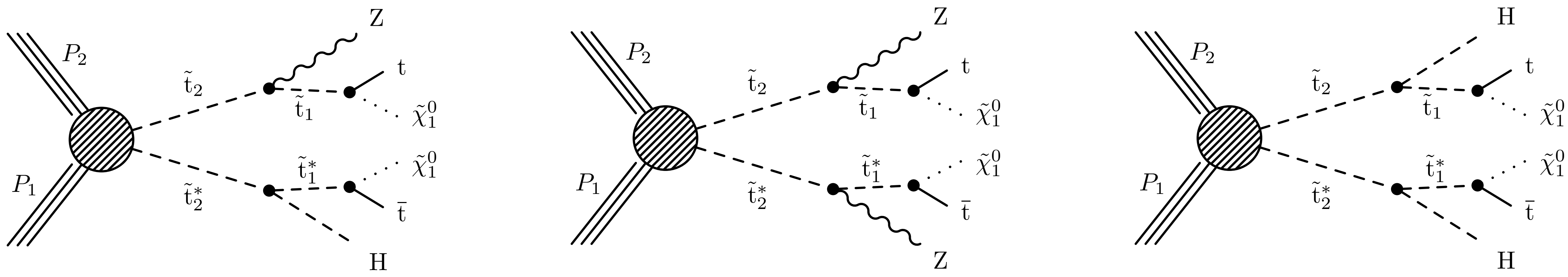



# CMS searches stop2 to Z/H

PLB 736 371 (2014)




Target stop2 pair production, decay via (stealth) stop1 and Z or H.

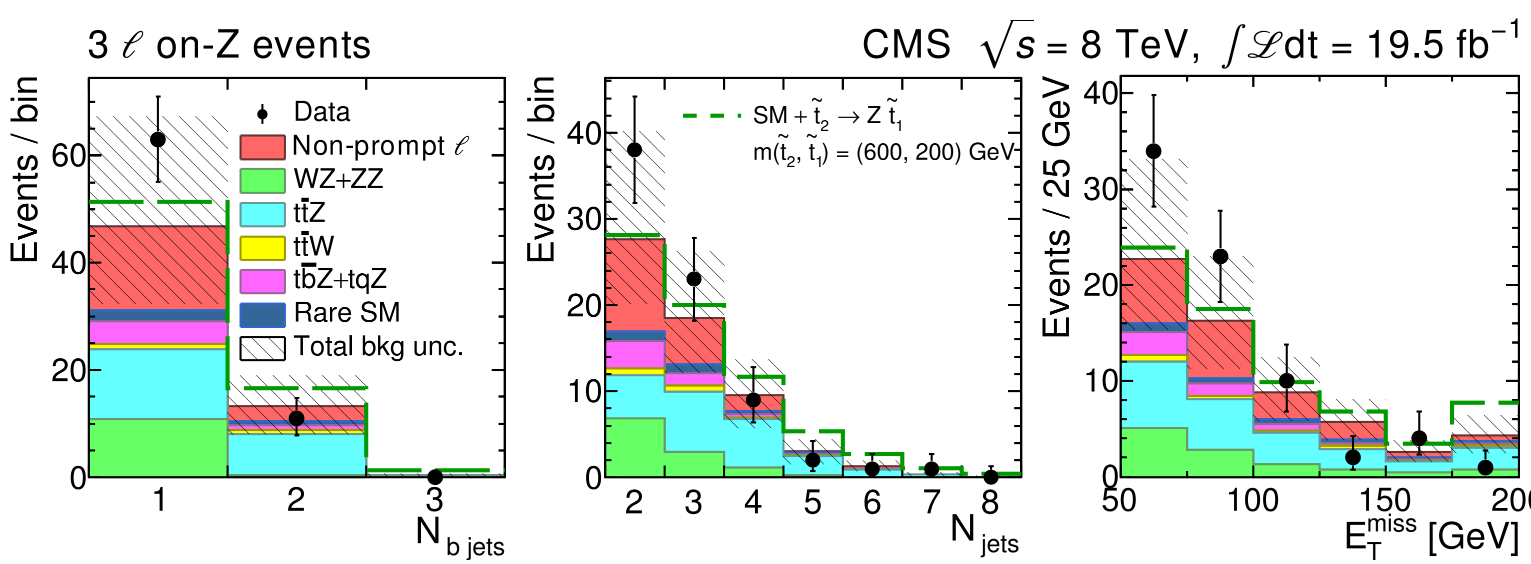



Sensitive to H to bb, H to ZZ, H to WW decays

- search with 1L, 2L (SS, OS), and ≥3L
- b-tags (up to 4),
- split by on- and off-shell Z

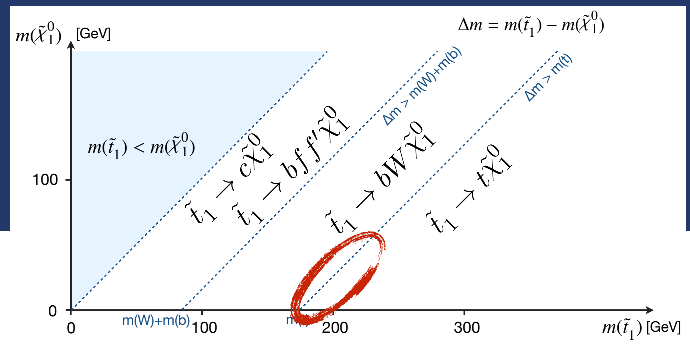
**3L analysis**:

- sensitive to all scenarios
- background from WZ+jets is suppressed by b-tag requirements,
- remaining background from rare processes or non-prompt leptons
  - WZ/ZZ from MC
  - non-prompt lepton from data

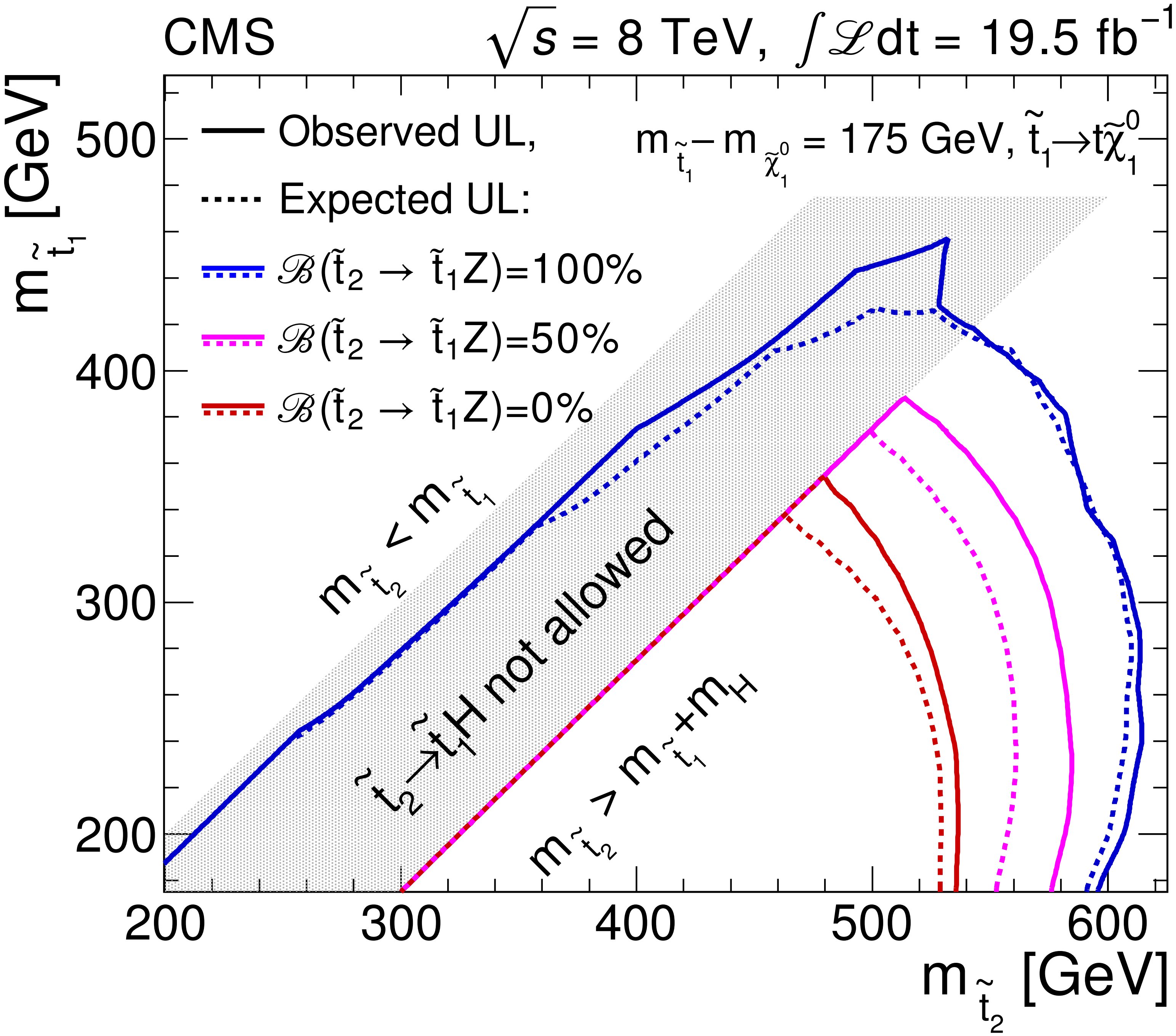


# CMS searches stop2 to Z/H

PLB 736 371 (2014)



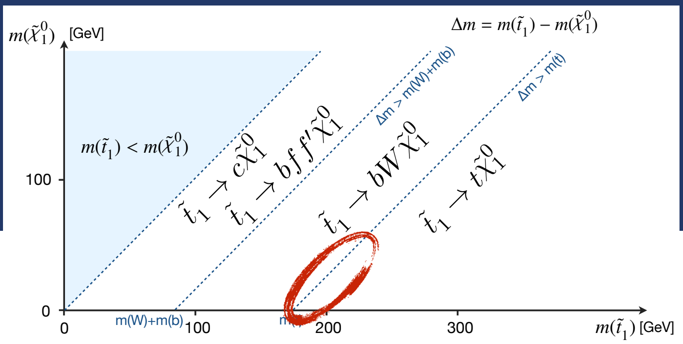
stop2 to stop1 Z/H




- **m(stop1) - m(N1) ≃ m(t)**
- 3L analysis most sensitive

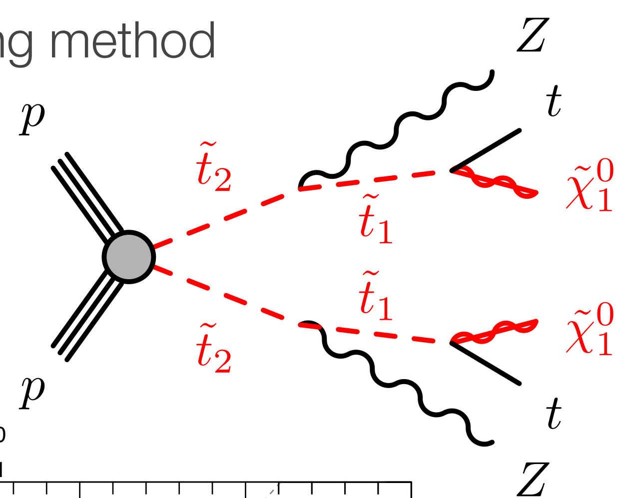
# ATLAS searches **stop2 to Z**

Eur. Phys. J. C (2014) 74:2883

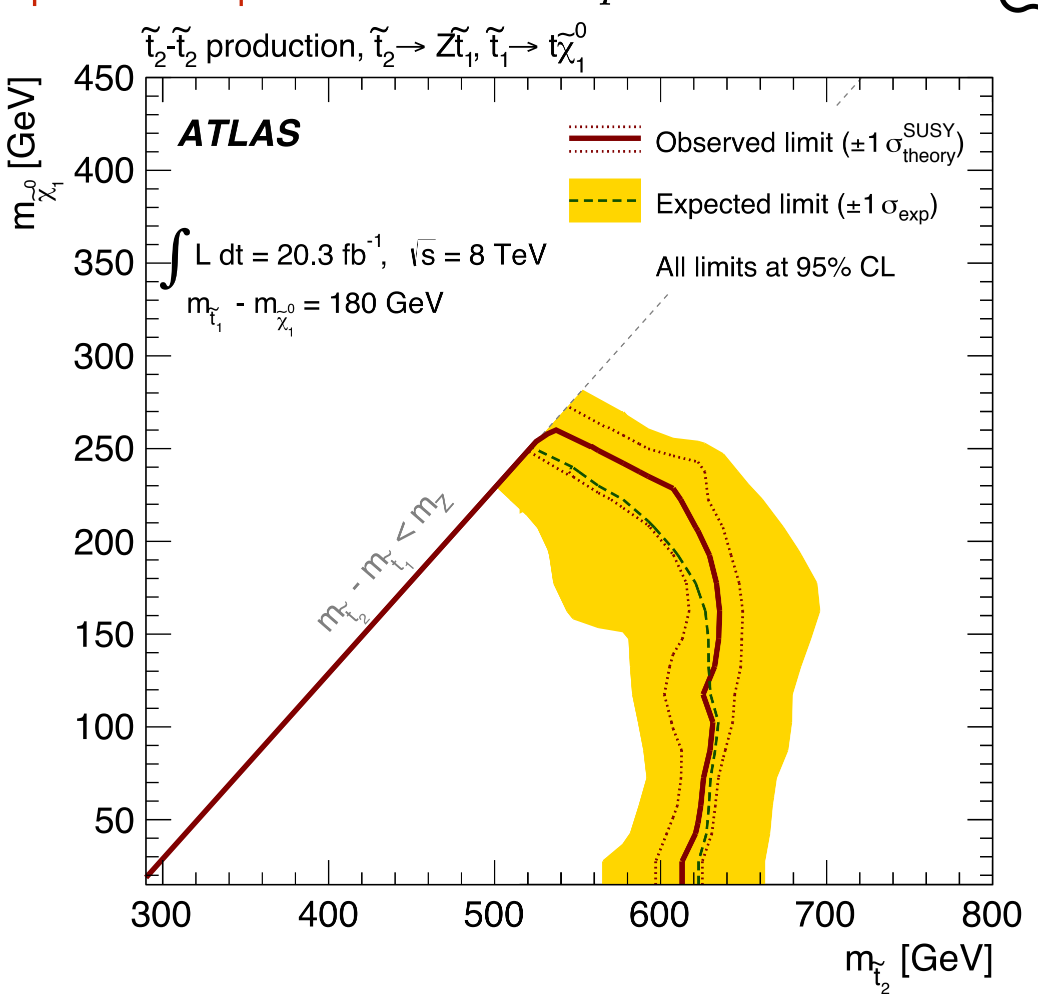



## 2L + 3L with Z(ll) + jets + b-jet + $E_T^{miss}$

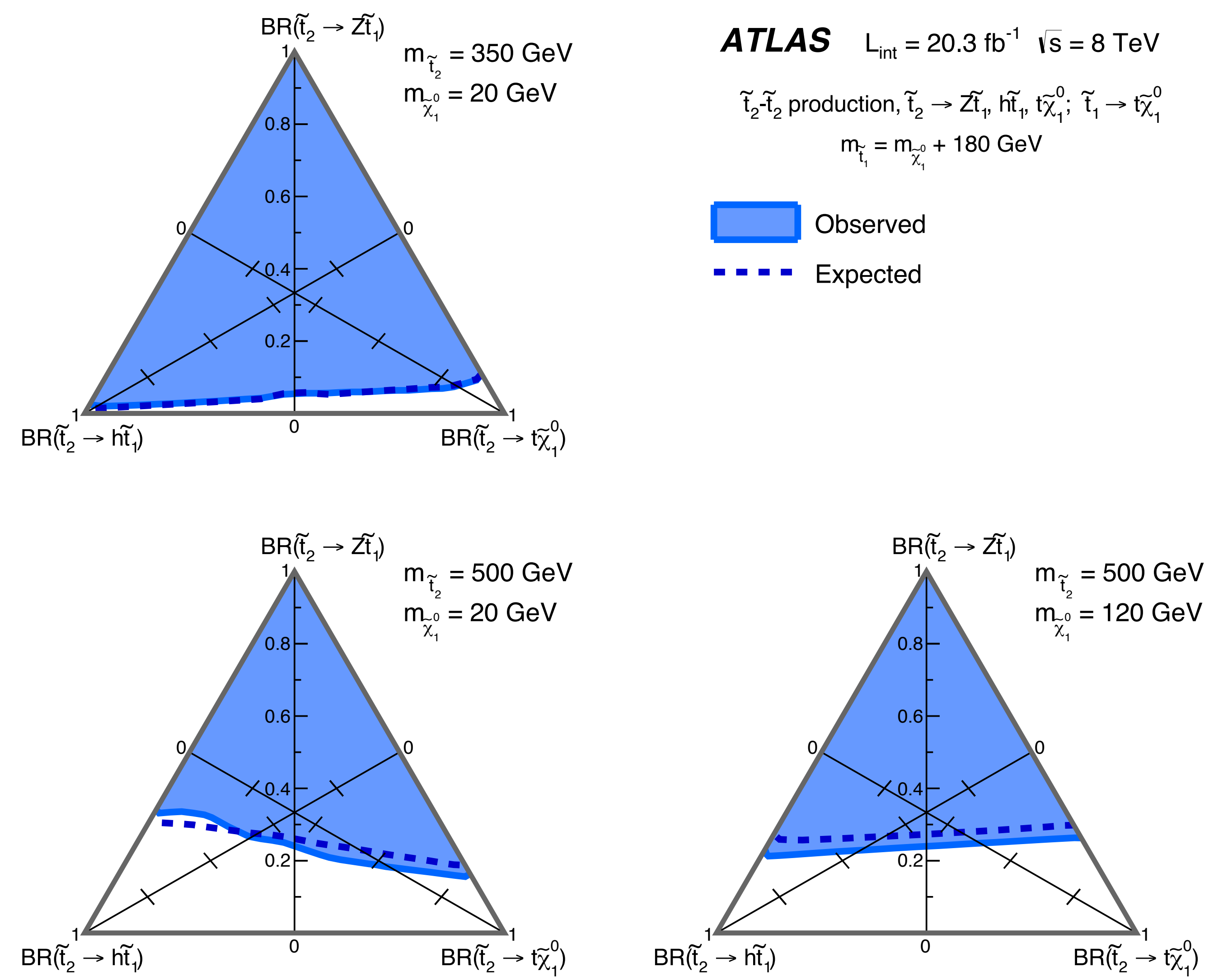
- Background estimates:
  - Fake leptons using "matrix method"
  - Z+jets using jet smearing method




## stop2 to stop1 Z




## stop2 to (stop1 Z, stop1 H, t N1)



# Constraints from top measurements

- In the context of tT measurements,
  - Stop-pair production with stop→top+neutralino (invisible) could be an annoying background
  - or perhaps an interesting signal.

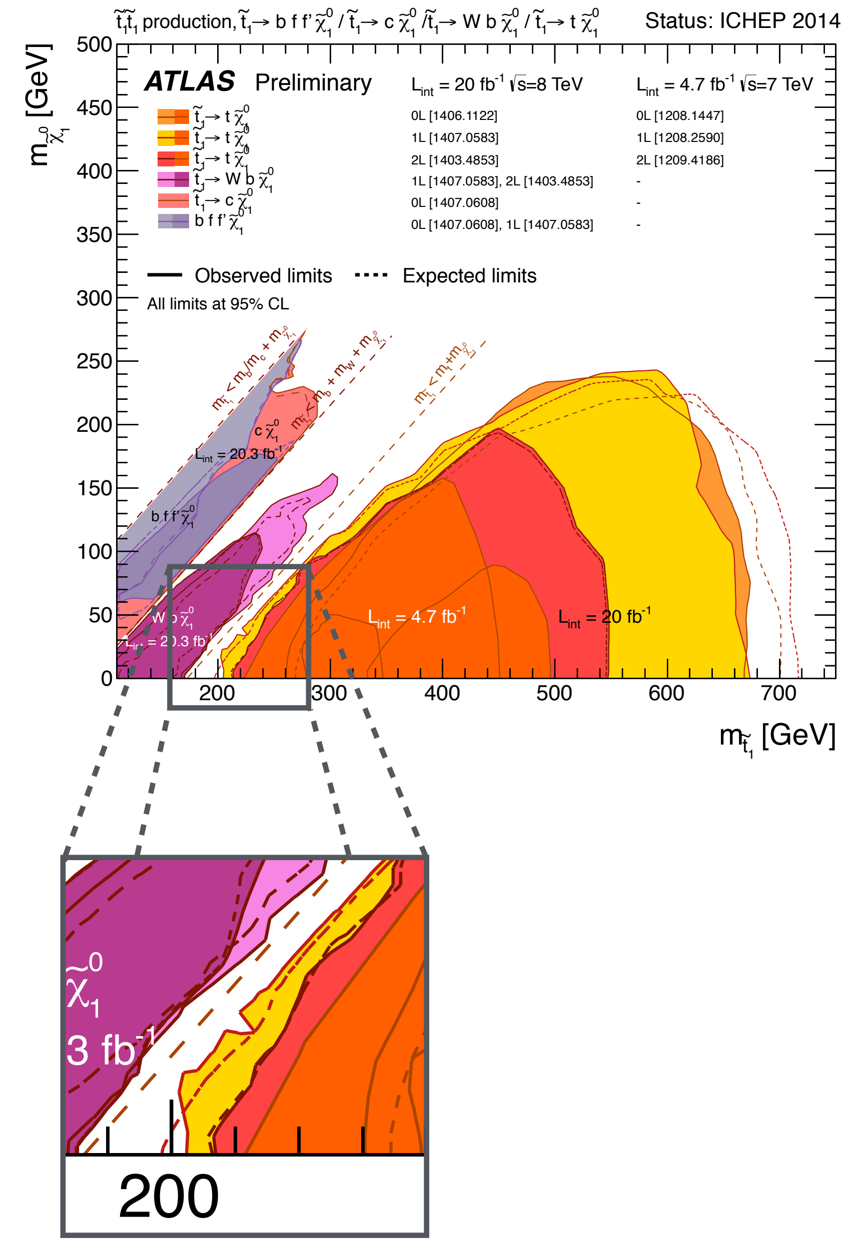
(1) What is the effect of stop pair production with m(stop)≈m(top) on **cross-section** analysis?

➡ Extra contribution to tT production with soft missing energy – otherwise similar kinematics.

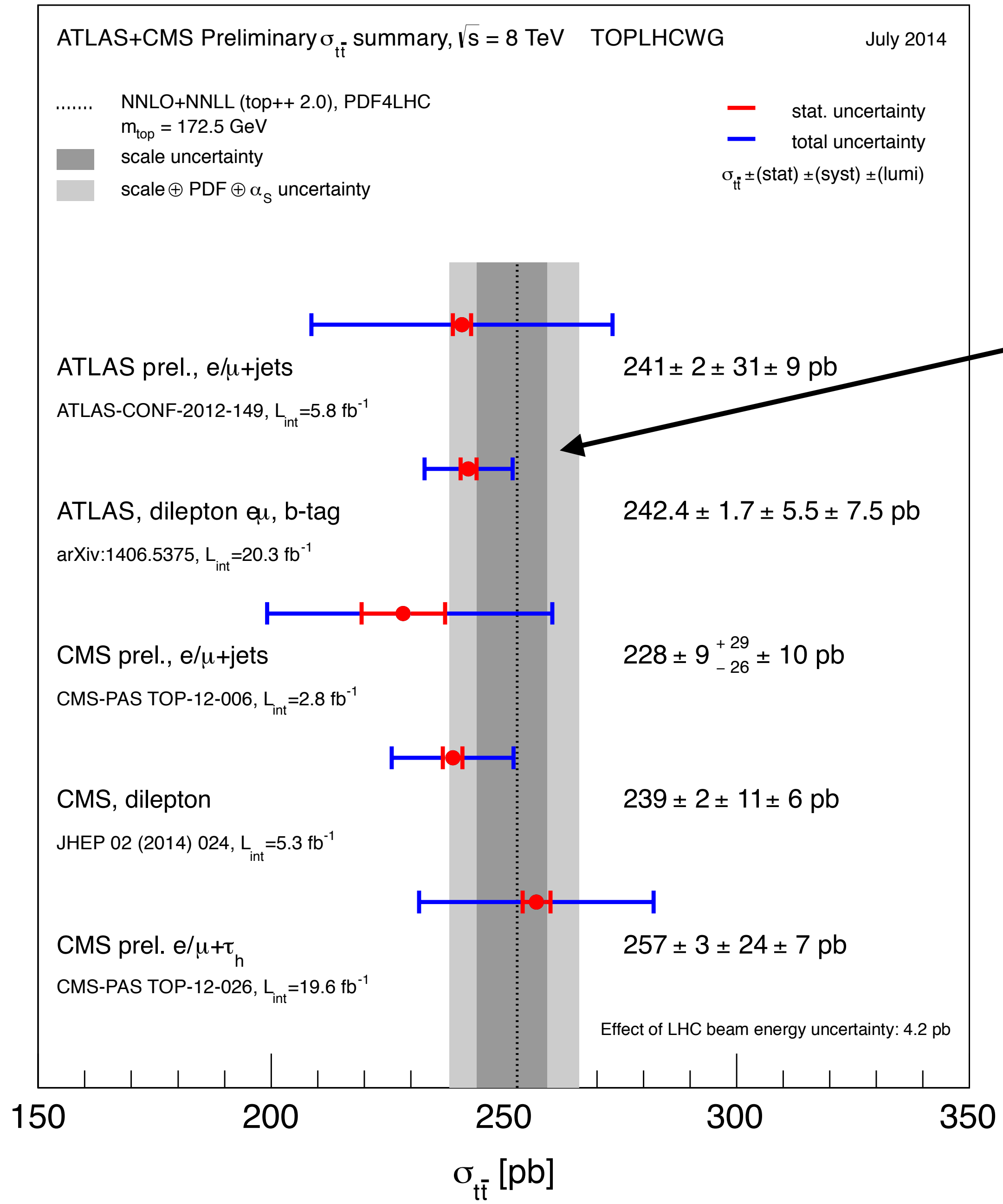
(2) What is the effect of stop pair production with m(stop)≈m(top) on **spin correlation** analysis?

➡ Extra contribution without spin correlation (stop is scalar).

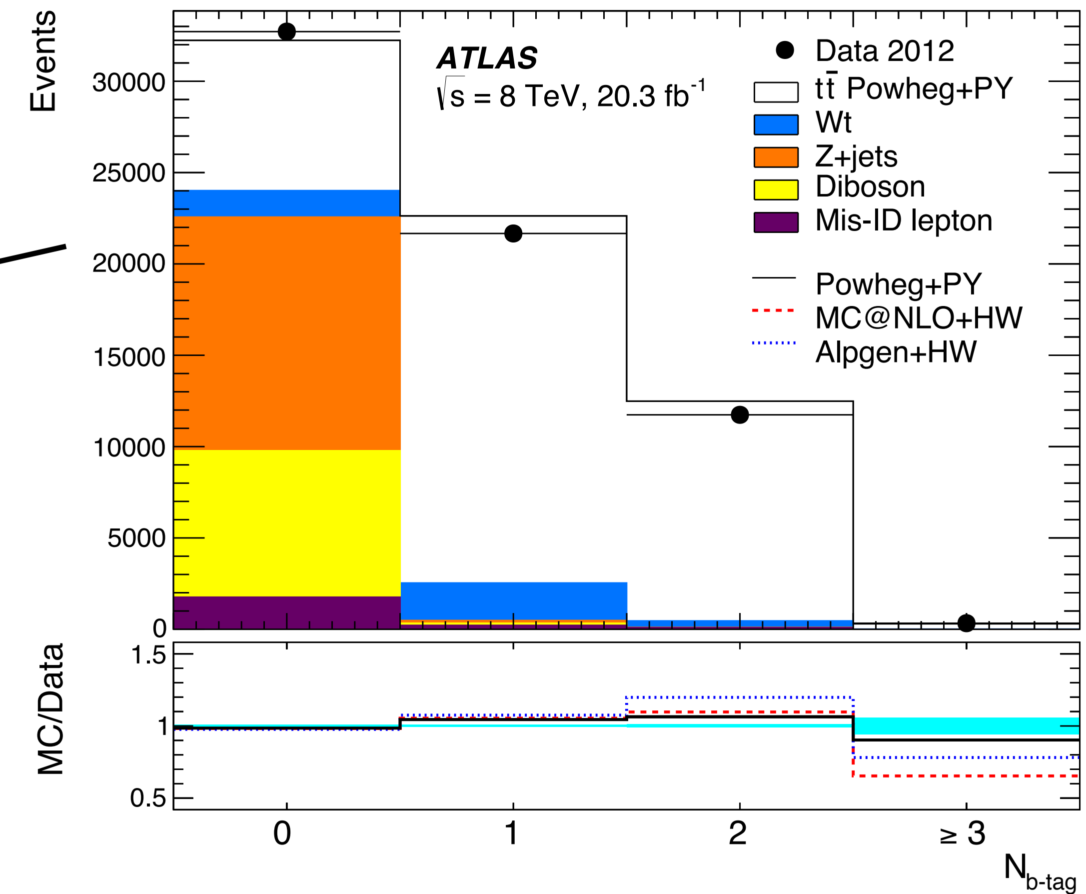
- Could we see or exclude this contribution with stop mass < ~200 GeV
  - E.g. 180 GeV stop-pair contribution is 32 pb at 8 TeV c.f. QCD tT of ~250 pb



# Limit from ttbar cross section




Submitted to EPJC (1406.5375)



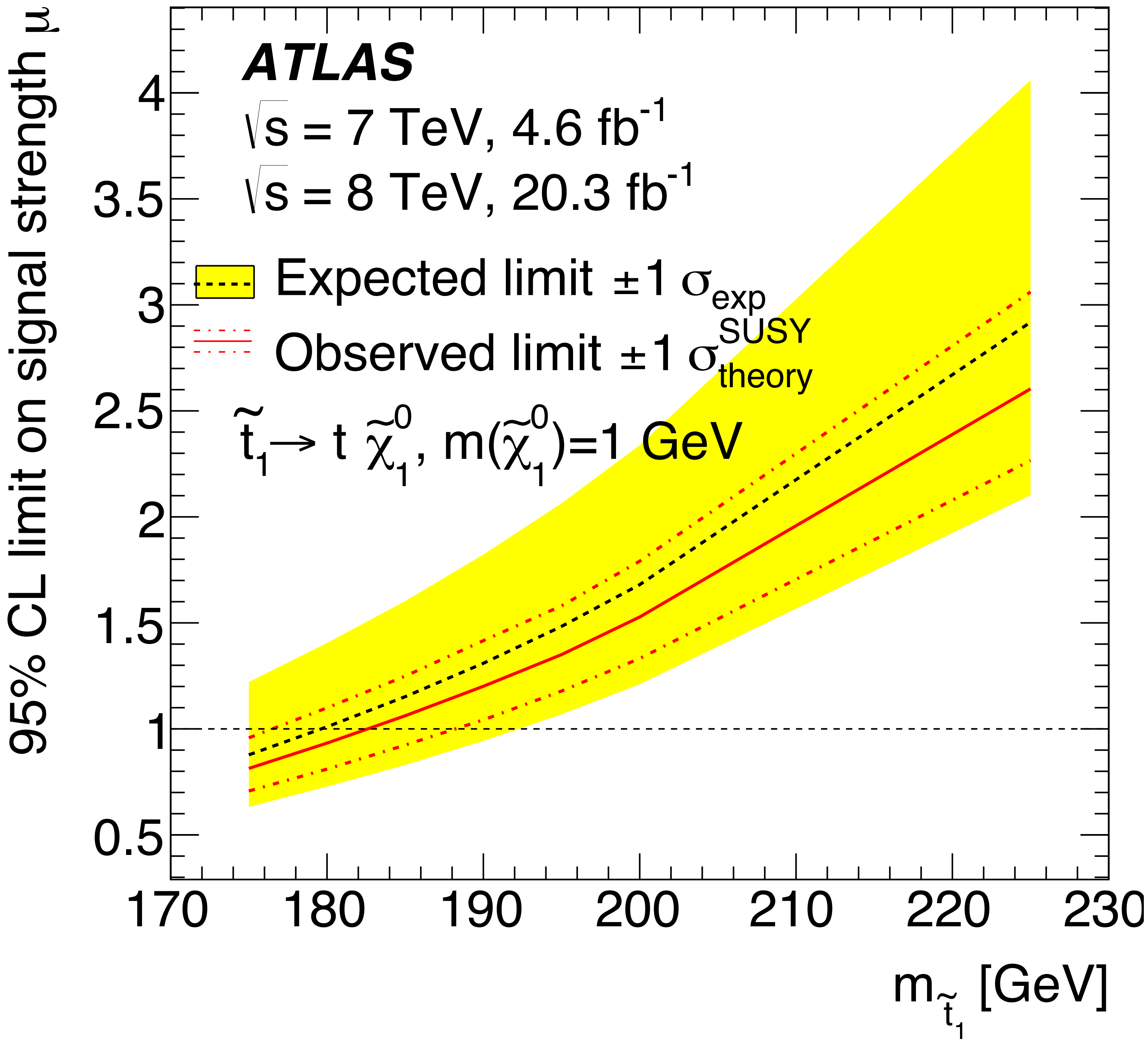

Measurement described in talk by Javier Brochero Cifuentes (Monday)

$$\sigma_{t\bar{t}} = 182.9 \pm 3.1 \pm 4.2 \pm 3.6 \pm 3.3\,\mathrm{pb}\ (\sqrt{s} = 7\,\mathrm{TeV})\ \text{and}$$
$$\sigma_{t\bar{t}} = 242.4 \pm 1.7 \pm 5.5 \pm 7.5 \pm 4.2\,\mathrm{pb}\ (\sqrt{s} = 8\,\mathrm{TeV}),$$

- Precise measurement of tT production cross-section at 7 and 8 TeV
  - events with eμ (opp-sign) and exactly 1 or 2 b-tagged jets, ratio reduces systematics.
  - Theory (including Δmtop) $177.3^{+11.5}_{-12.0}$ pb (7 TeV), $252.9^{+15.3}_{-16.3}$ pb (8 TeV)

# Limit from ttbar cross section

Submitted to EPJC (1406.5375)




- Exclude a small region between top threshold and ~180 GeV
  - Expected limit 179 GeV
  - Observed limit 183 GeV
  - Observed limit -1σ (sig-theo) 177 GeV
    - Signal theoretical uncertainty of 15% (PDFs, scales)
  - Sensitivity driven by stop-pair production cross-section
  - Always assuming 100% BR to stop+χ
- Limits shown for m(χ)=1 GeV
  - Only slightly weaker with increasing neutralino mass
    - E.g. 3% less for 20 GeV neutralino at 200 GeV stop
  - top quark polarision (stop mixing)
    - full left-handed polarisation 4% weaker than plot which is for mostly right-handed case

CMS tT cross section measurement (see previous slide) is not yet interpreted in terms of stop limits.

# Limit from ttbar spin correlation

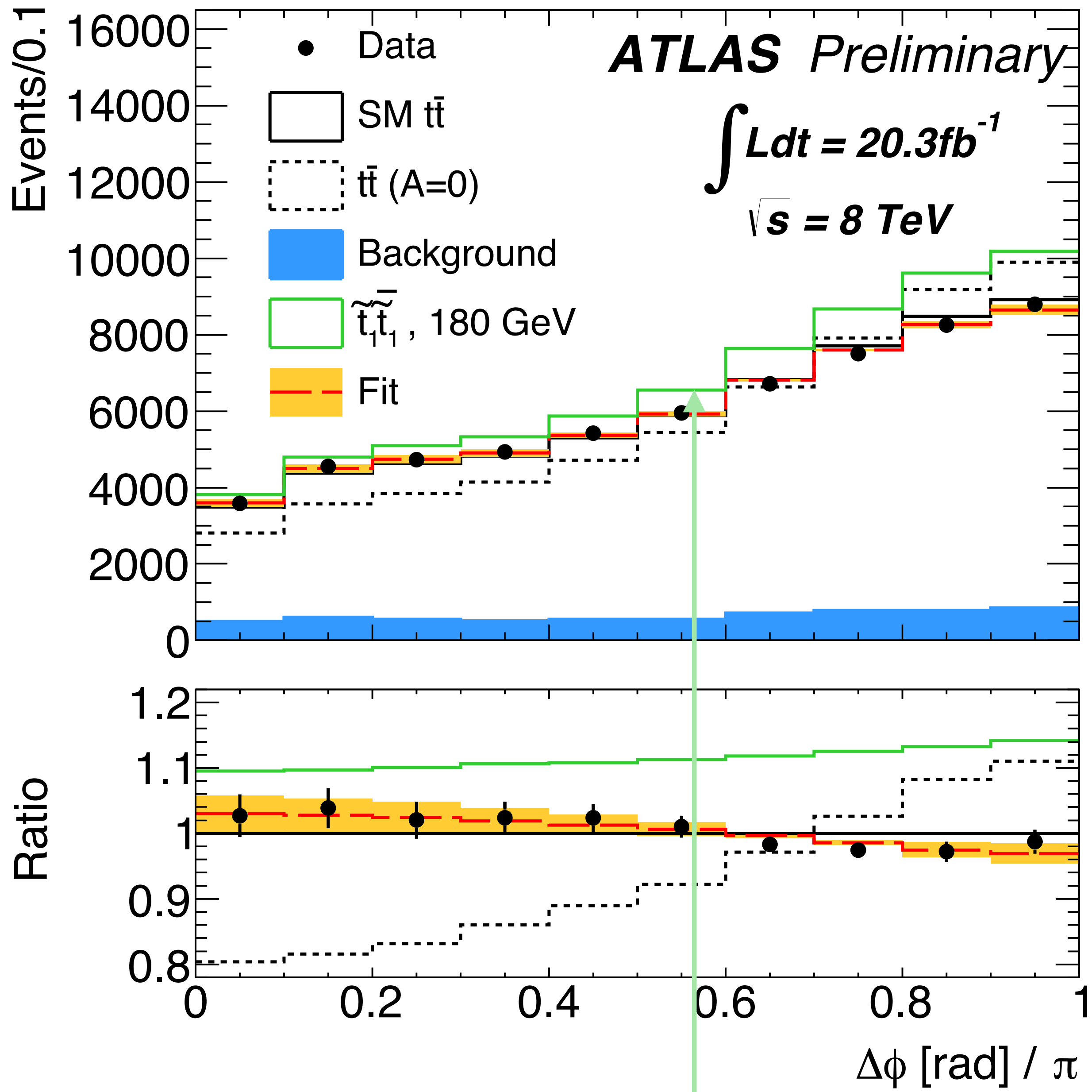
NEW

ATLAS-CONF-2014-056

- Precise measurement of tT spin correlation at 8 TeV
  - events with ee, eμ, μμ (opp-sign)
  - at least 2 jets, of which at least one is b-tagged
  - in ee, μμ channels: MET, m(ll) cuts
  - in eμ channel: HT(jets, lep) cut
- Investigate Δϕ(l,l) distribution
- Results

$$A = \frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\uparrow\downarrow} - N_{\downarrow\uparrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} + N_{\uparrow\downarrow} + N_{\downarrow\uparrow}}$$

$$A_{\text{helicity}} = 0.38 \pm 0.04 \qquad A^{\text{SM}}_{\text{helicity}} = 0.318 \pm 0.005$$



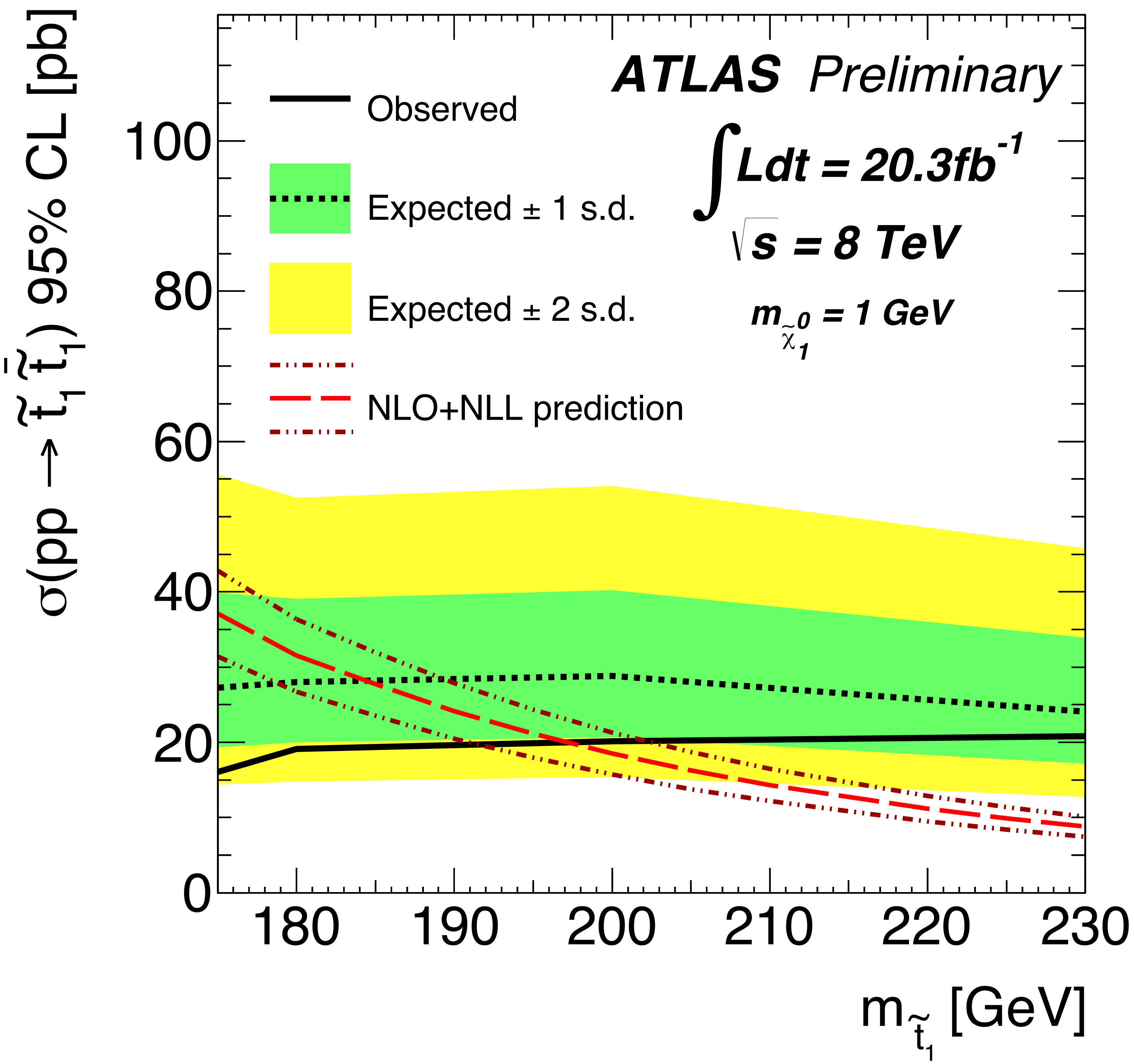

Measurement described in talk by Richard Hawkings (Tuesday)

SM+ SUSY (180 GeV mStop)

# Limit from ttbar spin correlation

NEW

ATLAS-CONF-2014-056



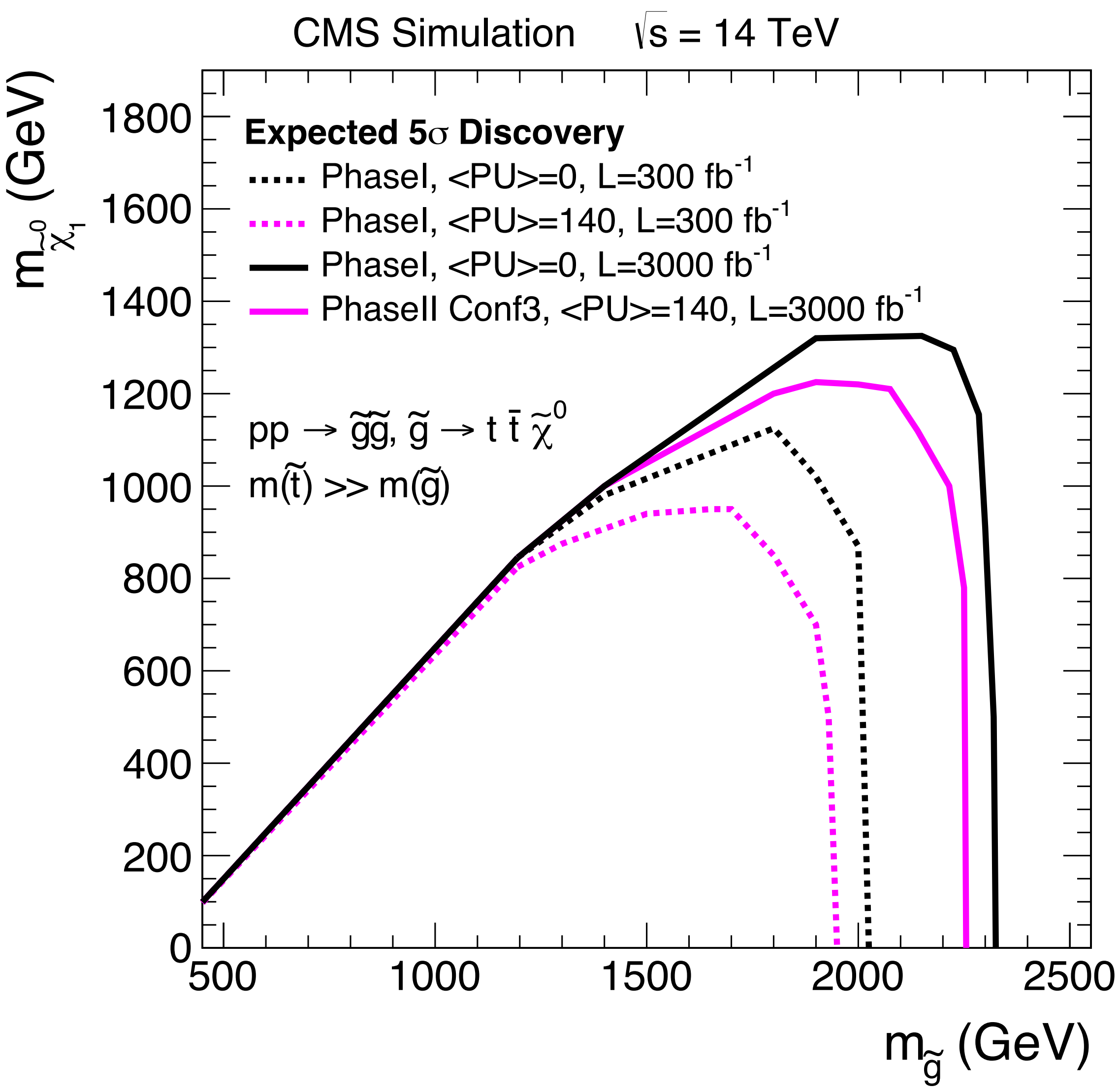

- Exclude a small region between top threshold and ~190 GeV
  - Expected limit 185 GeV
  - Observed limit 197 GeV
  - Observed limit -1σ (sig-theo) 191 GeV
    - Signal theoretical uncertainty of 15% (PDFs, scales)
  - Sensitivity driven by stop-pair production cross-section
  - Always assuming 100% BR to stop+χ
- Limits shown for m(χ)=1 GeV
  - Only slightly weaker with increasing neutralino mass
- Without the shape-information Δϕ the limit would deteriorate by 30-40%.
  - constraint from cross section only

# Long-term prospects

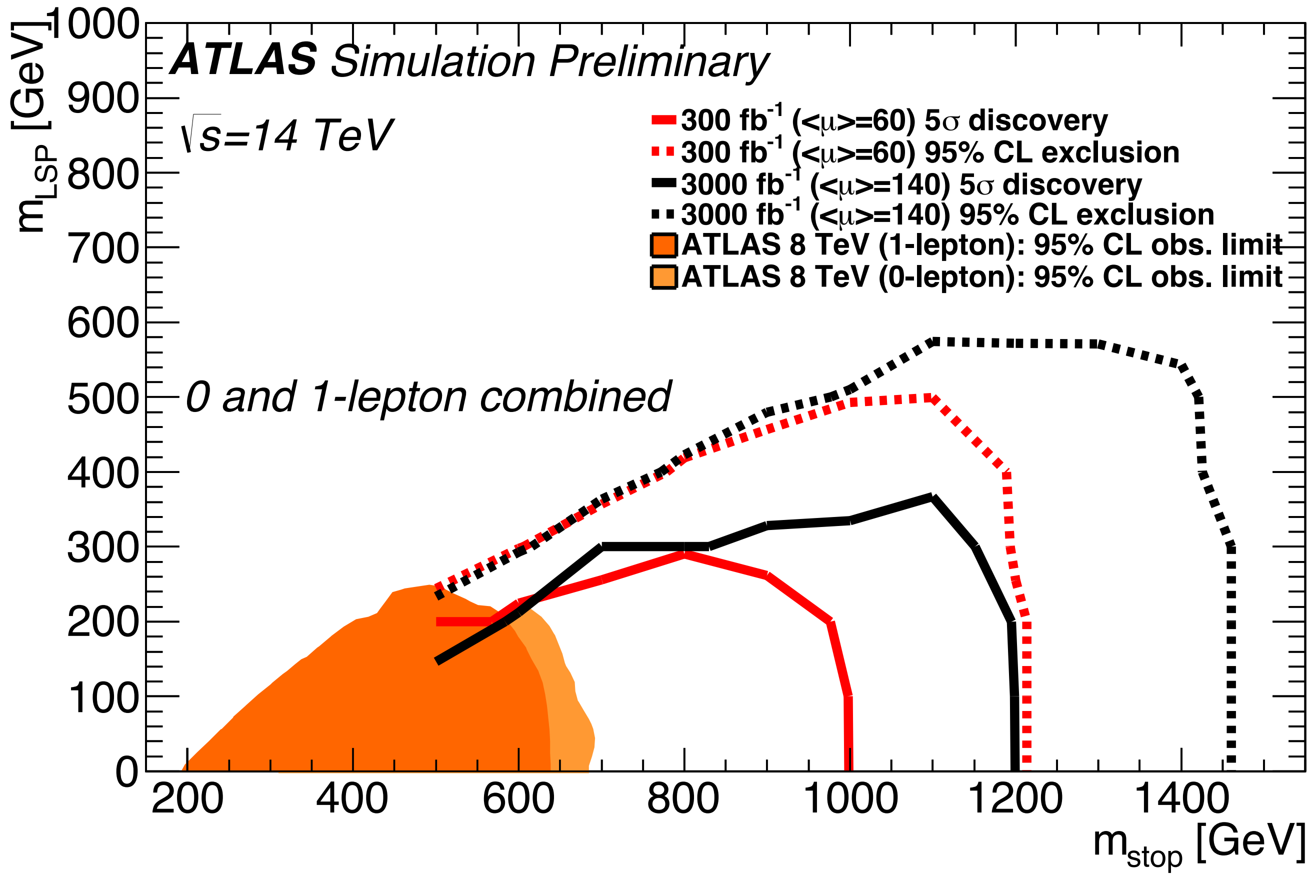
CMS and ATLAS studied long-term prospects for the (HL) LHC.

- with 300 and 3000 /fb at 14 TeV
- searches for gluino-mediated stop production reach beyond 2 TeV
- searches for direct stop production reach well beyond 1 TeV

CMS PAS FTR-13-014

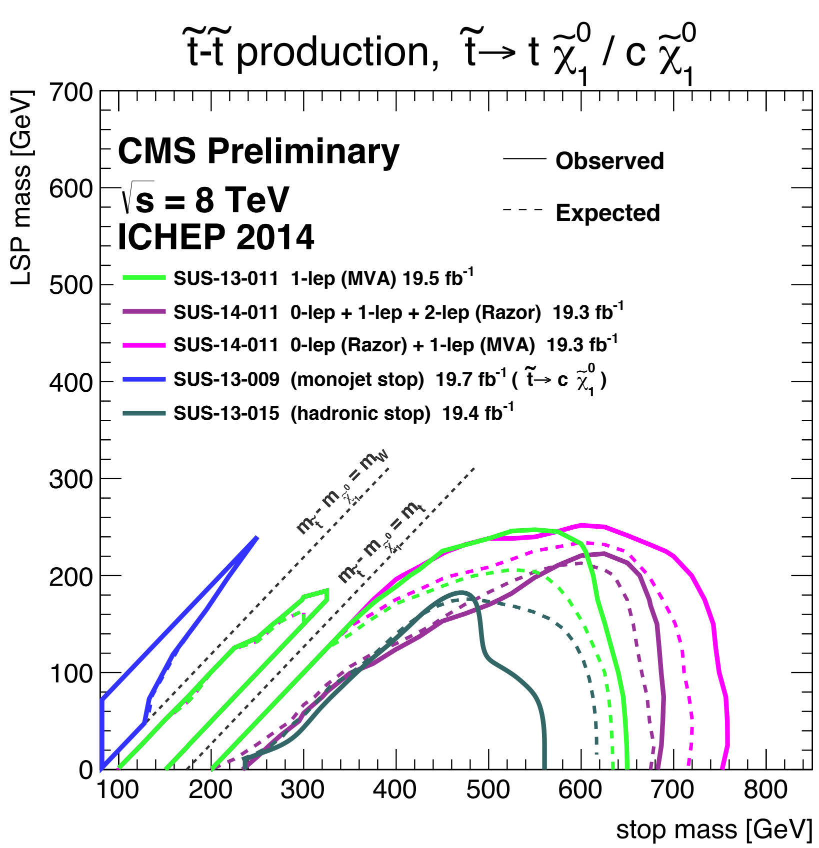


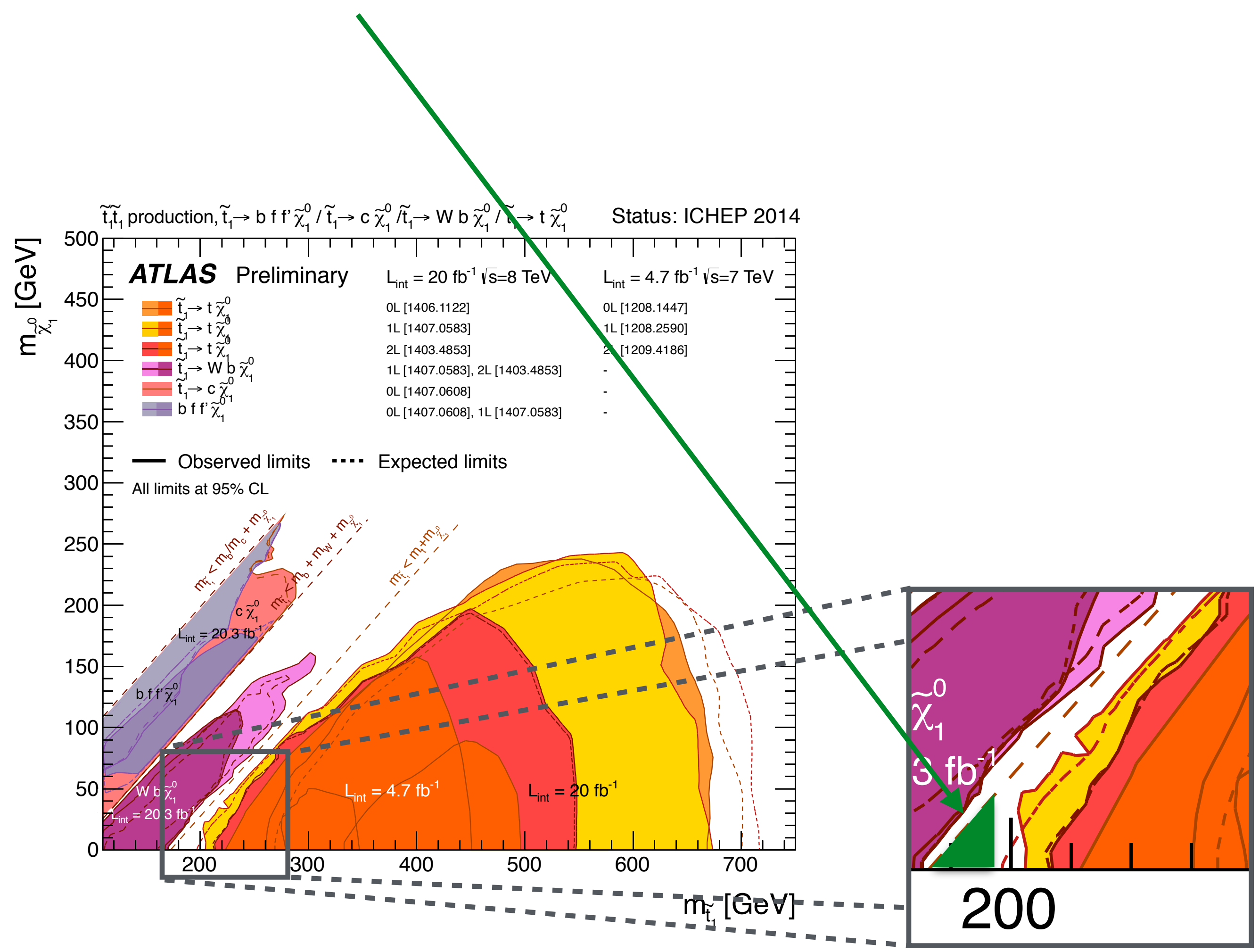

ATL-PHYS-PUB-2013-011



# Summary

- Strong search programs for a top quark partner (stop) at the ATLAS and CMS experiments.
  - direct searches for stop covering range from low to heavy masses, various decay modes
  - new indirect constraints from SM tT measurements begin to fill gap in mStop ~ mTop scenario



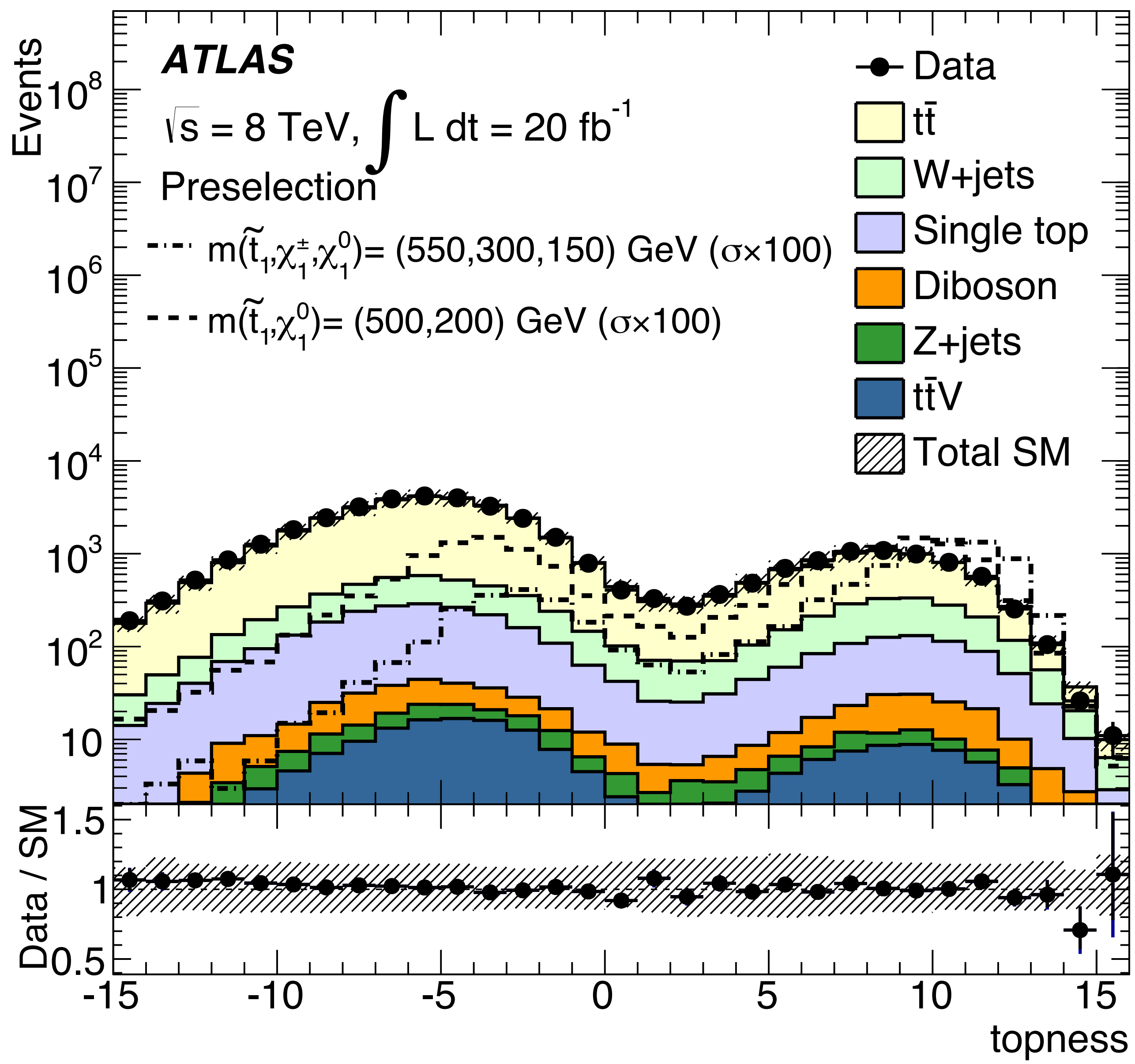



# Extra slides

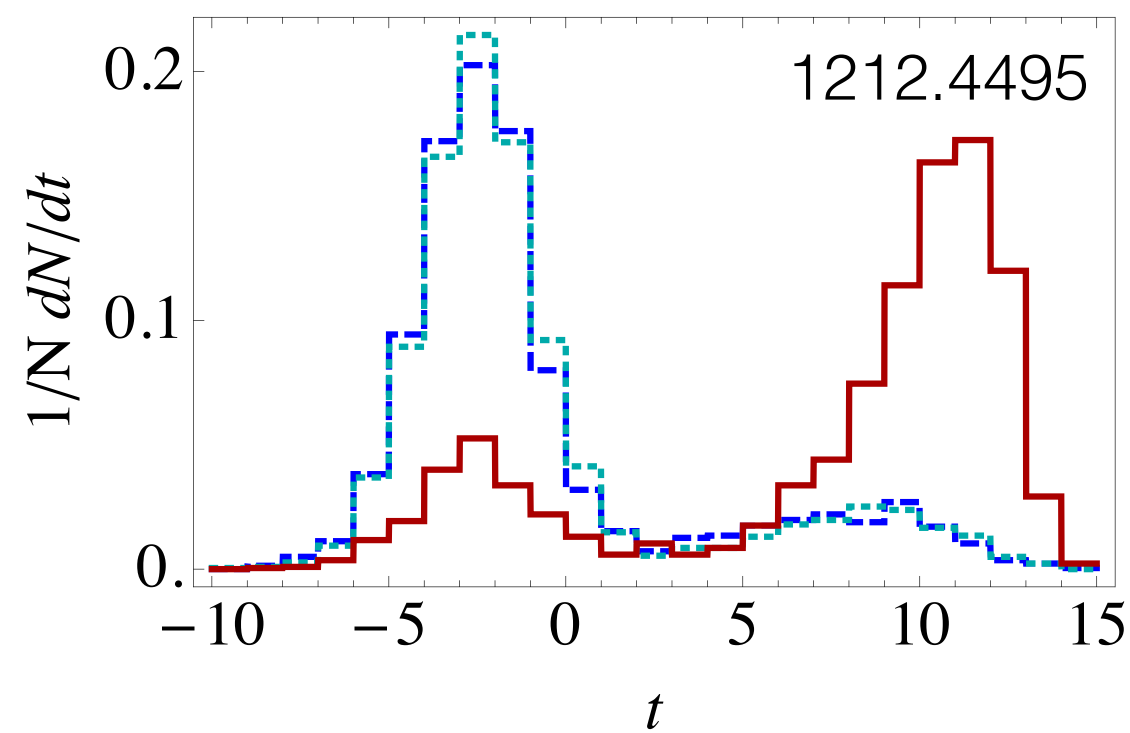
# Topness

Topness is a variable designed to identify and suppress partially reconstructed dileptonic tT events, as proposed in ref. [1212.4495]. The topness variable is based on minimising a chi2-type function indicating the similarity of the event to dileptonic tT events. One lepton is assumed to be lost.

=1L, >=4j, MET>100 GeV, MT>60 GeV




=1L, >=4j, MET>100 GeV, MT>150 GeV




- signal, red, solid
- dileptonic top, blue, dashed
- dileptonic top, one (el,mu), one tau, cyan, dotted

# Topness

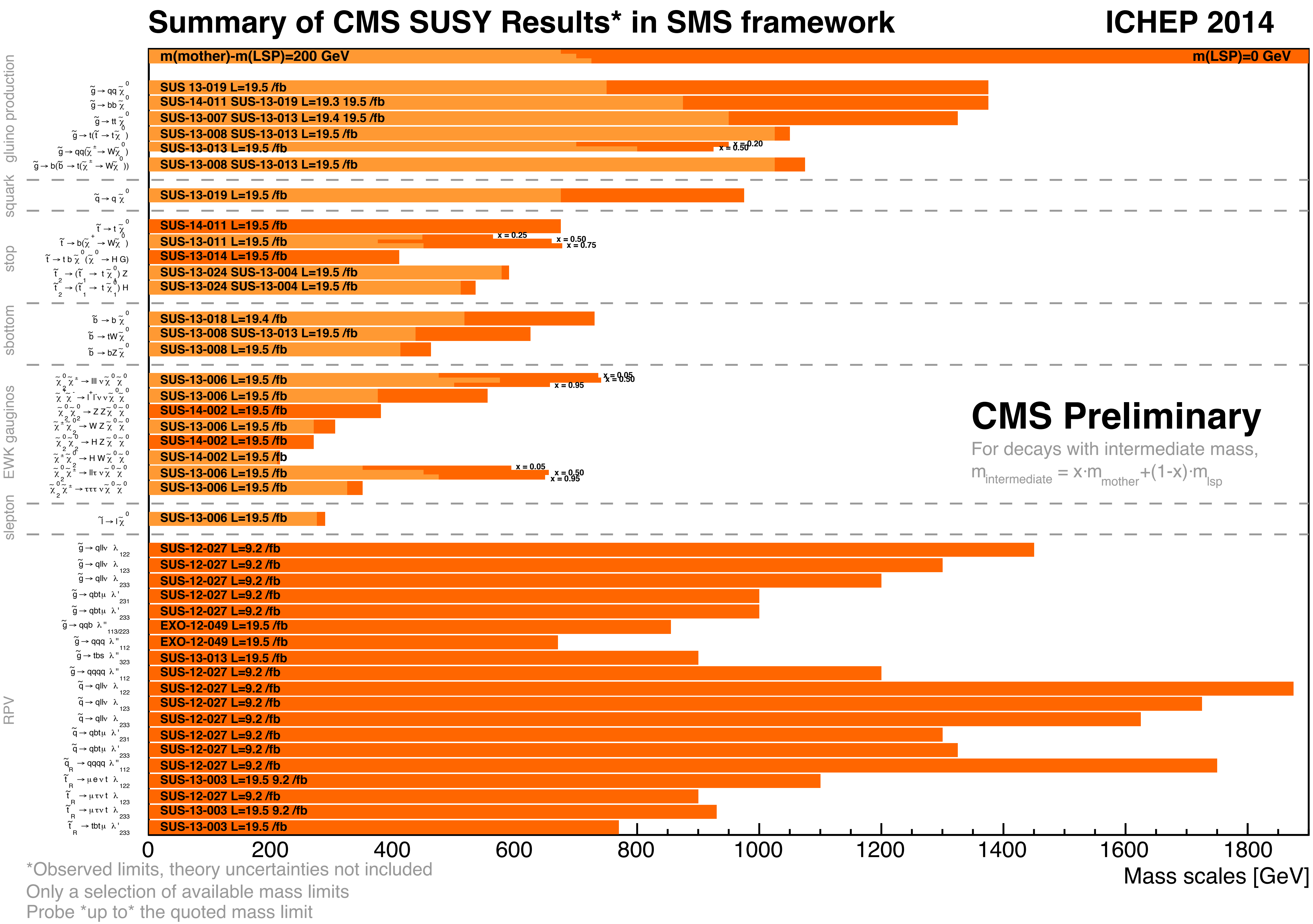
The *topness* event value is defined as $\ln(\min \hat{S})$, where $\hat{S}$ is the minimum of the $\chi^2$-type function $S$:

$$S(p_{W,x}, p_{W,y}, p_{W,z}, p_{\nu,z}) = \frac{\left(m_W^2 - (p_\ell + p_\nu)^2\right)^2}{a_W^4} + \frac{\left(m_t^2 - (p_{b_1} + p_\ell + p_\nu)^2\right)^2}{a_t^4} + \frac{\left(m_t^2 - (p_{b_2} + p_W)^2\right)^2}{a_t^4} + \frac{\left(4\,m_t^2 - (\Sigma p)^2\right)^2}{a_{\rm CM}^4}.$$

The first three arguments of $S$ are the components of the non-reconstructed $W$ boson 3-momentum ($p_{W,x}$, $p_{W,y}$, $p_{W,z}$). This $W$ is assumed to decay leptonically, but the lepton is not reconstructed and is thus only noticeable in the missing transverse momentum. The variable $p_{\nu,z}$ is the longitudinal momentum of the neutrino from the other $W$ boson decay, for which the lepton was successfully reconstructed. These four numbers are varied to find the minimum of $S$.

The momenta appearing on the right-hand side of the equation above are either 4-momenta of the reconstructed objects (one lepton, $p_\ell$, and two $b$-jets, $p_{b_1}$ and $p_{b_2}$) or 4-momenta assigned by the minimisation procedure ($p_W$ and $p_\nu$). To find all four components, the neutrinos and the $W$ boson without reconstructed decay products are assumed to be on-shell. Both combinations for $b_1$ and $b_2$ are evaluated during the minimisation; if only one $b$-tagged jet is present, it is used together with the leading or subleading jet (that means, a total of four possible jet assignments is evaluated in this case).

# LHC Run-1 SUSY Searches: CMS summary table



# LHC Run-1 SUSY Searches: ATLAS summary table

## ATLAS SUSY Searches* - 95% CL Lower Limits

Status: ICHEP 2014

**ATLAS** Preliminary

$\sqrt{s}$ = 7, 8 TeV

| | Model | $e,\mu,\tau,\gamma$ | Jets | $E_T^{miss}$ | $\int\mathcal{L}\,dt[fb^{-1}]$ | Mass limit | | | Reference |
|---|---|---|---|---|---|---|---|---|---|
| Inclusive Searches | MSUGRA/CMSSM | 0 | 2-6 jets | Yes | 20.3 | $\tilde{q},\tilde{g}$ | 1.7 TeV | $m(\tilde{q})=m(\tilde{g})$ | 1405.7875 |
| | MSUGRA/CMSSM | 1 $e,\mu$ | 3-6 jets | Yes | 20.3 | $\tilde{g}$ | 1.2 TeV | any $m(\tilde{q})$ | ATLAS-CONF-2013-062 |
| | MSUGRA/CMSSM | 0 | 7-10 jets | Yes | 20.3 | $\tilde{g}$ | 1.1 TeV | any $m(\tilde{q})$ | 1308.1841 |
| | $\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 20.3 | $\tilde{q}$ | 850 GeV | $m(\tilde{\chi}_1^0)$=0 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$) | 1405.7875 |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 20.3 | $\tilde{g}$ | 1.33 TeV | $m(\tilde{\chi}_1^0)$=0 GeV | 1405.7875 |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$ | 1 $e,\mu$ | 3-6 jets | Yes | 20.3 | $\tilde{g}$ | 1.18 TeV | $m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^{\pm})=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$ | ATLAS-CONF-2013-062 |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$ | 2 $e,\mu$ | 0-3 jets | - | 20.3 | $\tilde{g}$ | 1.12 TeV | $m(\tilde{\chi}_1^0)$=0 GeV | ATLAS-CONF-2013-089 |
| | GMSB ($\tilde{\ell}$ NLSP) | 2 $e,\mu$ | 2-4 jets | Yes | 4.7 | $\tilde{g}$ | 1.24 TeV | $\tan\beta$<15 | 1208.4688 |
| | GMSB ($\tilde{\ell}$ NLSP) | 1-2 $\tau$ + 0-1 $\ell$ | 0-2 jets | Yes | 20.3 | $\tilde{g}$ | 1.6 TeV | $\tan\beta$ >20 | 1407.0603 |
| | GGM (bino NLSP) | 2 $\gamma$ | - | Yes | 20.3 | $\tilde{g}$ | 1.28 TeV | $m(\tilde{\chi}_1^0)$>50 GeV | ATLAS-CONF-2014-001 |
| | GGM (wino NLSP) | 1 $e,\mu$ + $\gamma$ | - | Yes | 4.8 | $\tilde{g}$ | 619 GeV | $m(\tilde{\chi}_1^0)$>50 GeV | ATLAS-CONF-2012-144 |
| | GGM (higgsino-bino NLSP) | $\gamma$ | 1 $b$ | Yes | 4.8 | $\tilde{g}$ | 900 GeV | $m(\tilde{\chi}_1^0)$>220 GeV | 1211.1167 |
| | GGM (higgsino NLSP) | 2 $e,\mu$ (Z) | 0-3 jets | Yes | 5.8 | $\tilde{g}$ | 690 GeV | m(NLSP)>200 GeV | ATLAS-CONF-2012-152 |
| | Gravitino LSP | 0 | mono-jet | Yes | 10.5 | $F^{1/2}$ scale | 645 GeV | $m(\tilde{G})>10^{-4}$ eV | ATLAS-CONF-2012-147 |
| 3rd gen. $\tilde{g}$ med. | $\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$ | 0 | 3 $b$ | Yes | 20.1 | $\tilde{g}$ | 1.25 TeV | $m(\tilde{\chi}_1^0)$<400 GeV | 1407.0600 |
| | $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$ | 0 | 7-10 jets | Yes | 20.3 | $\tilde{g}$ | 1.1 TeV | $m(\tilde{\chi}_1^0)$ <350 GeV | 1308.1841 |
| | $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$ | 0-1 $e,\mu$ | 3 $b$ | Yes | 20.1 | $\tilde{g}$ | 1.34 TeV | $m(\tilde{\chi}_1^0)$<400 GeV | 1407.0600 |
| | $\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$ | 0-1 $e,\mu$ | 3 $b$ | Yes | 20.1 | $\tilde{g}$ | 1.3 TeV | $m(\tilde{\chi}_1^0)$<300 GeV | 1407.0600 |
| 3rd gen. squarks direct production | $\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$ | 0 | 2 $b$ | Yes | 20.1 | $\tilde{b}_1$ | 100-620 GeV | $m(\tilde{\chi}_1^0)$<90 GeV | 1308.2631 |
| | $\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^{\pm}$ | 2 $e,\mu$ (SS) | 0-3 $b$ | Yes | 20.3 | $\tilde{b}_1$ | 275-440 GeV | $m(\tilde{\chi}_1^{\pm})=2\,m(\tilde{\chi}_1^0)$ | 1404.2500 |
| | $\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$ | 1-2 $e,\mu$ | 1-2 $b$ | Yes | 4.7 | $\tilde{t}_1$ | 110-167 GeV | $m(\tilde{\chi}_1^0)$=55 GeV | 1208.4305, 1209.2102 |
| | $\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ | 2 $e,\mu$ | 0-2 jets | Yes | 20.3 | $\tilde{t}_1$ | 130-210 GeV | $m(\tilde{\chi}_1^0)=m(\tilde{t}_1)-m(W)$-50 GeV, $m(\tilde{t}_1)<<m(\tilde{\chi}_1^{\pm})$ | 1403.4853 |
| | $\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$ | 2 $e,\mu$ | 2 jets | Yes | 20.3 | $\tilde{t}_1$ | 215-530 GeV | $m(\tilde{\chi}_1^0)$=1 GeV | 1403.4853 |
| | $\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$ | 0 | 2 $b$ | Yes | 20.1 | $\tilde{t}_1$ | 150-580 GeV | $m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)$=5 GeV | 1308.2631 |
| | $\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$ | 1 $e,\mu$ | 1 $b$ | Yes | 20 | $\tilde{t}_1$ | 210-640 GeV | $m(\tilde{\chi}_1^0)$=0 GeV | 1407.0583 |
| | $\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$ | 0 | 2 $b$ | Yes | 20.1 | $\tilde{t}_1$ | 260-640 GeV | $m(\tilde{\chi}_1^0)$=0 GeV | 1406.1122 |
| | $\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$ | 0 | mono-jet/$c$-tag | Yes | 20.3 | $\tilde{t}_1$ | 90-240 GeV | $m(\tilde{t}_1)-m(\tilde{\chi}_1^0)$<85 GeV | 1407.0608 |
| | $\tilde{t}_1\tilde{t}_1$(natural GMSB) | 2 $e,\mu$ (Z) | 1 $b$ | Yes | 20.3 | $\tilde{t}_1$ | 150-580 GeV | $m(\tilde{\chi}_1^0)$>150 GeV | 1403.5222 |
| | $\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$ | 3 $e,\mu$ (Z) | 1 $b$ | Yes | 20.3 | $\tilde{t}_2$ | 290-600 GeV | $m(\tilde{\chi}_1^0)$<200 GeV | 1403.5222 |
| EW direct | $\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$ | 2 $e,\mu$ | 0 | Yes | 20.3 | $\tilde{\ell}$ | 90-325 GeV | $m(\tilde{\chi}_1^0)$=0 GeV | 1403.5294 |
| | $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$ | 2 $e,\mu$ | 0 | Yes | 20.3 | $\tilde{\chi}_1^{\pm}$ | 140-465 GeV | $m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$ | 1403.5294 |
| | $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$ | 2 $\tau$ | - | Yes | 20.3 | $\tilde{\chi}_1^{\pm}$ | 100-350 GeV | $m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$ | 1407.0350 |
| | $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$ | 3 $e,\mu$ | 0 | Yes | 20.3 | $\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ | 700 GeV | $m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$ | 1402.7029 |
| | $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0Z\tilde{\chi}_1^0$ | 2-3 $e,\mu$ | 0 | Yes | 20.3 | $\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ | 420 GeV | $m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled | 1403.5294, 1402.7029 |
| | $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0h\tilde{\chi}_1^0$ | 1 $e,\mu$ | 2 $b$ | Yes | 20.3 | $\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ | 285 GeV | $m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled | ATLAS-CONF-2013-093 |
| | $\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$ | 4 $e,\mu$ | 0 | Yes | 20.3 | $\tilde{\chi}_{2,3}^0$ | 620 GeV | $m(\tilde{\chi}_2^0)=m(\tilde{\chi}_3^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_2^0)+m(\tilde{\chi}_1^0))$ | 1405.5086 |
| Long-lived particles | Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$ | Disapp. trk | 1 jet | Yes | 20.3 | $\tilde{\chi}_1^{\pm}$ | 270 GeV | $m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)$=160 MeV, $\tau(\tilde{\chi}_1^{\pm})$=0.2 ns | ATLAS-CONF-2013-069 |
| | Stable, stopped $\tilde{g}$ R-hadron | 0 | 1-5 jets | Yes | 27.9 | $\tilde{g}$ | 832 GeV | $m(\tilde{\chi}_1^0)$=100 GeV, 10 $\mu$s<$\tau(\tilde{g})$<1000 s | 1310.6584 |
| | GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$ | 1-2 $\mu$ | - | - | 15.9 | $\tilde{\chi}_1^0$ | 475 GeV | 10<$\tan\beta$<50 | ATLAS-CONF-2013-058 |
| | GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$ | 2 $\gamma$ | - | Yes | 4.7 | $\tilde{\chi}_1^0$ | 230 GeV | 0.4<$\tau(\tilde{\chi}_1^0)$<2 ns | 1304.6310 |
| | $\tilde{q}\tilde{q}$, $\tilde{\chi}_1^0\to qq\mu$ (RPV) | 1 $\mu$, displ. vtx | - | - | 20.3 | $\tilde{q}$ | 1.0 TeV | 1.5 <$c\tau$<156 mm, BR($\mu$)=1, $m(\tilde{\chi}_1^0)$=108 GeV | ATLAS-CONF-2013-092 |
| RPV | LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e+\mu$ | 2 $e,\mu$ | - | - | 4.6 | $\tilde{\nu}_\tau$ | 1.61 TeV | $\lambda'_{311}$=0.10, $\lambda_{132}$=0.05 | 1212.1272 |
| | LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e(\mu)+\tau$ | 1 $e,\mu$ + $\tau$ | - | - | 4.6 | $\tilde{\nu}_\tau$ | 1.1 TeV | $\lambda'_{311}$=0.10, $\lambda_{1(2)33}$=0.05 | 1212.1272 |
| | Bilinear RPV CMSSM | 2 $e,\mu$ (SS) | 0-3 $b$ | Yes | 20.3 | $\tilde{q},\tilde{g}$ | 1.35 TeV | $m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm | 1404.2500 |
| | $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$ | 4 $e,\mu$ | - | Yes | 20.3 | $\tilde{\chi}_1^{\pm}$ | 750 GeV | $m(\tilde{\chi}_1^0)>0.2\times m(\tilde{\chi}_1^{\pm})$, $\lambda_{121}\neq0$ | 1405.5086 |
| | $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$ | 3 $e,\mu$ + $\tau$ | - | Yes | 20.3 | $\tilde{\chi}_1^{\pm}$ | 450 GeV | $m(\tilde{\chi}_1^0)>0.2\times m(\tilde{\chi}_1^{\pm})$, $\lambda_{133}\neq0$ | 1405.5086 |
| | $\tilde{g}\to qqq$ | 0 | 6-7 jets | - | 20.3 | $\tilde{g}$ | 916 GeV | BR($t$)=BR($b$)=BR($c$)=0% | ATLAS-CONF-2013-091 |
| | $\tilde{g}\to\tilde{t}_1t$, $\tilde{t}_1\to bs$ | 2 $e,\mu$ (SS) | 0-3 $b$ | Yes | 20.3 | $\tilde{g}$ | 850 GeV | | 1404.250 |
| Other | Scalar gluon pair, sgluon$\to q\bar{q}$ | 0 | 4 jets | - | 4.6 | sgluon | 100-287 GeV | incl. limit from 1110.2693 | 1210.4826 |
| | Scalar gluon pair, sgluon$\to t\bar{t}$ | 2 $e,\mu$ (SS) | 2 $b$ | Yes | 14.3 | sgluon | 350-800 GeV | | ATLAS-CONF-2013-051 |
| | WIMP interaction (D5, Dirac $\chi$) | 0 | mono-jet | Yes | 10.5 | M* scale | 704 GeV | $m(\chi)$<80 GeV, limit of<687 GeV for D8 | ATLAS-CONF-2012-147 |

$\sqrt{s}$ = 7 TeV full data | $\sqrt{s}$ = 8 TeV partial data | $\sqrt{s}$ = 8 TeV full data

$10^{-1}$ 1 Mass scale [TeV]

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1$\sigma$ theoretical signal cross section uncertainty.

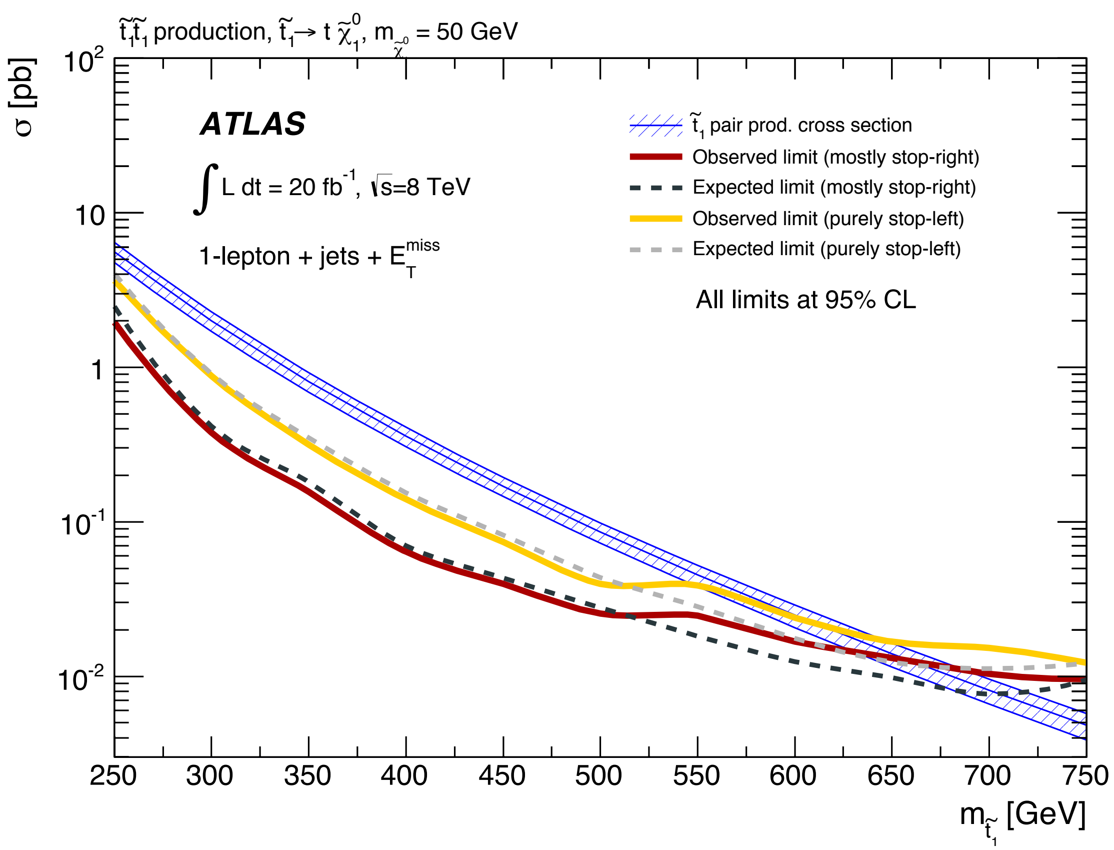
# Polarization effects

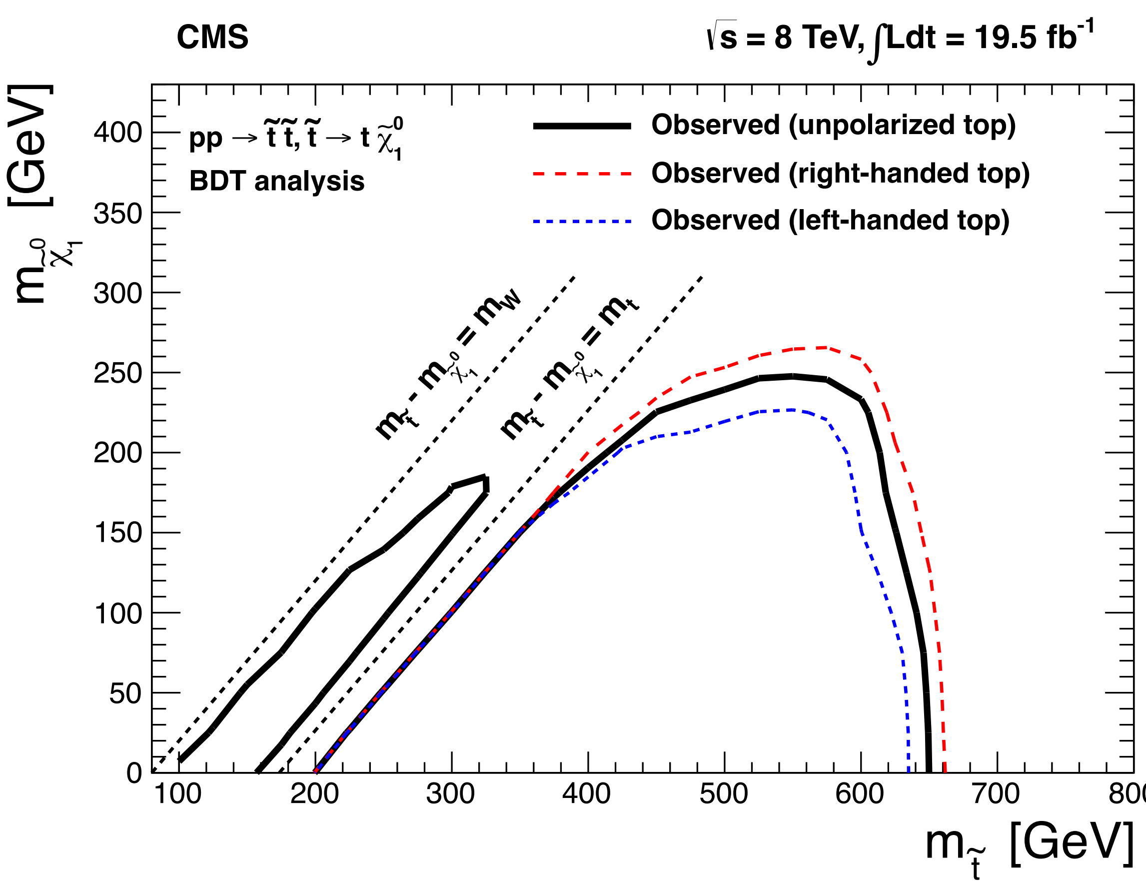
## 1L channels

submitted to JHEP [1407.0583] EPJC 73 (2013) 2677

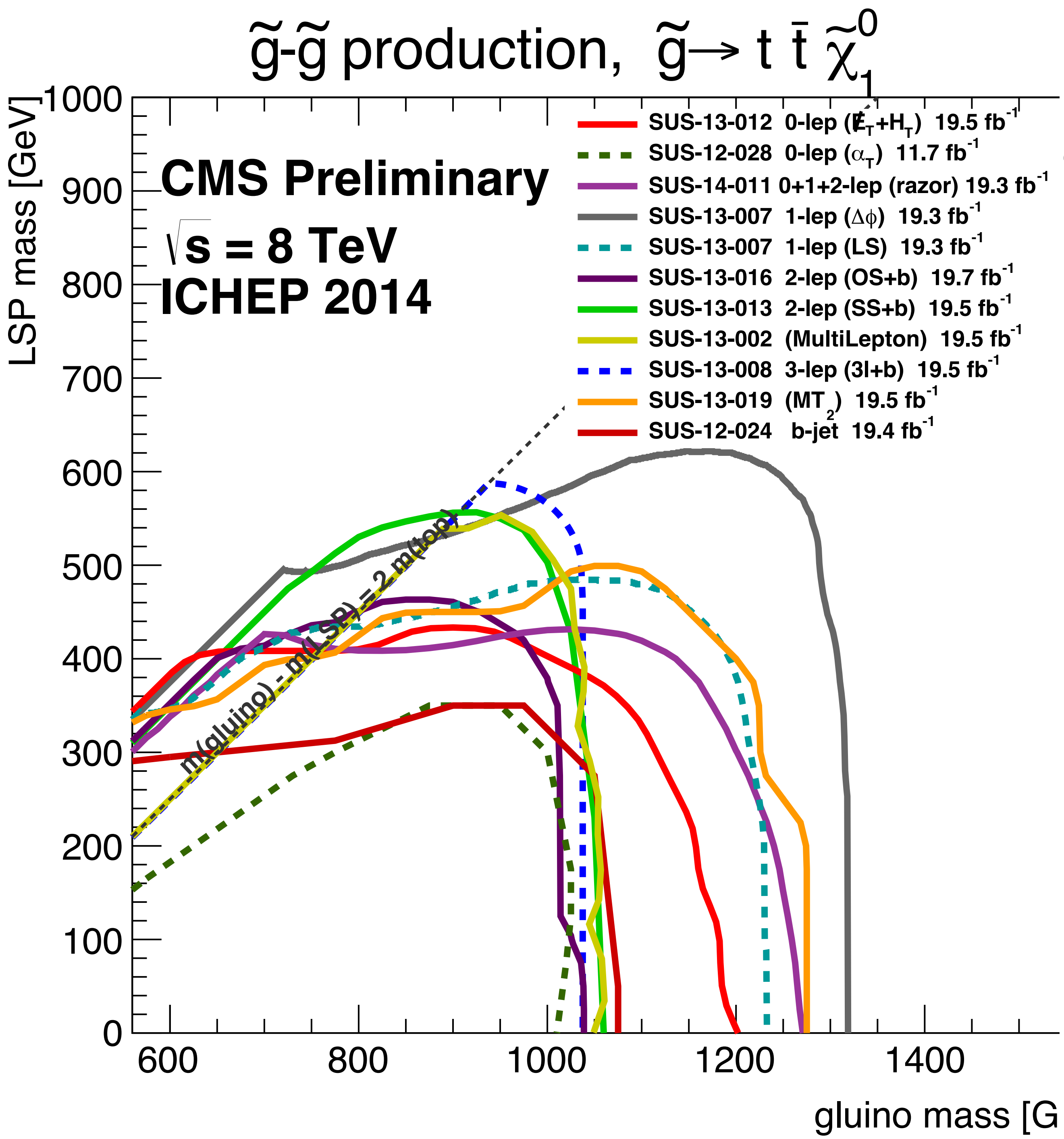
The acceptance depends on the polarization of the the top quarks in the stop1 to tN1 scenario. These polarizations depend on the left/right mixing of the stops and on the mixing matrices of the neutralino and charginos.

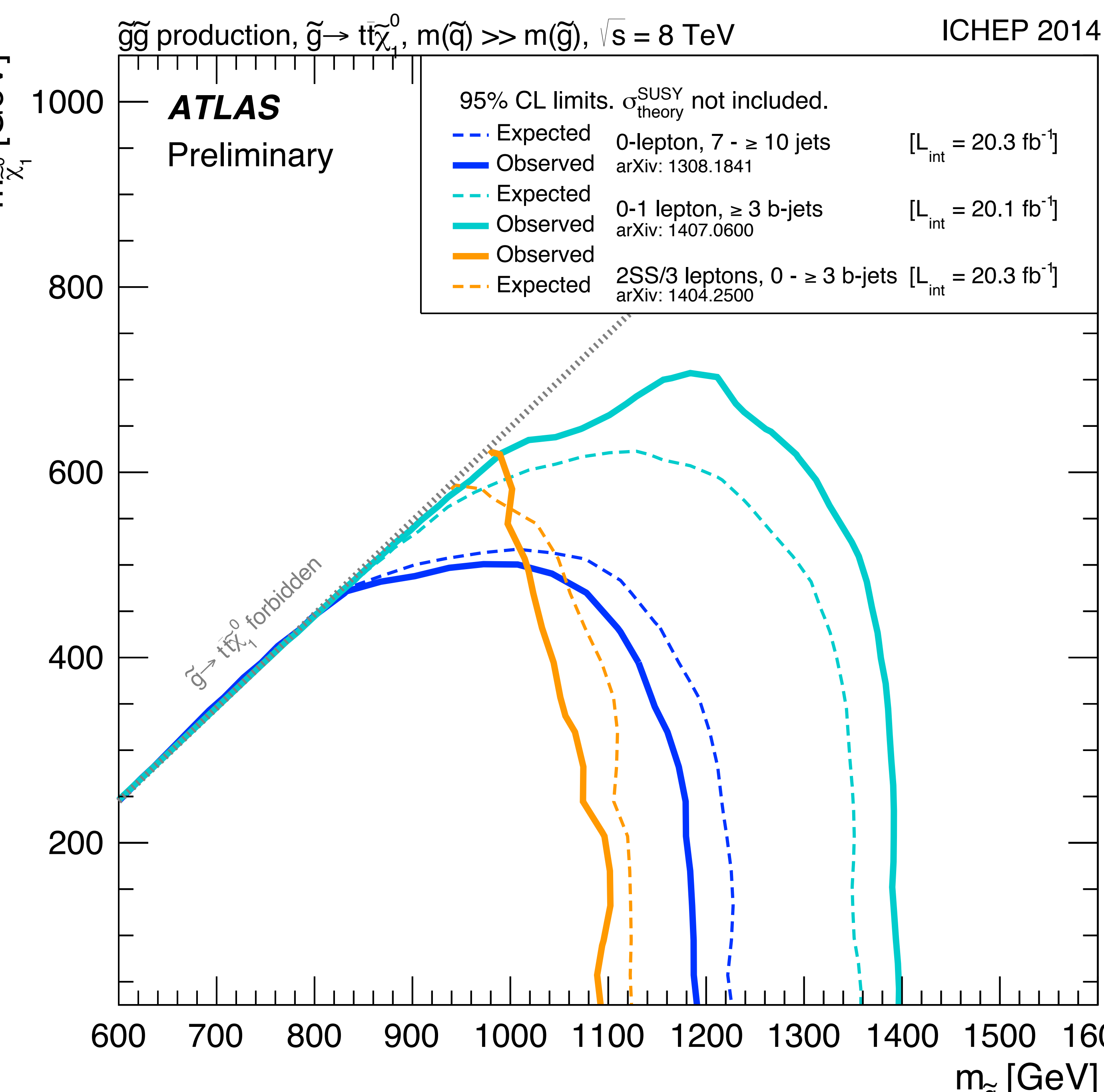
- Nominal ATLAS stop 1L result obtained using stop1 ~70% stopR. Comparison with fully left-handed top quarks: exp. limit reduced by ~50 GeV.
- Nominal CMS stop 1L result obtained using unpolarized particles. Comparison with right- and left-handed top quarks: limits vary by ±(10-20) GeV.



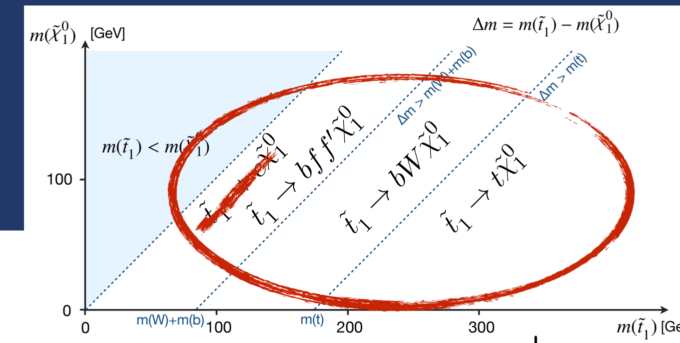
# Overview: gluino-mediated stop searches



# ATLAS searches 1L channel

submitted to JHEP [1407.0583]



$\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$

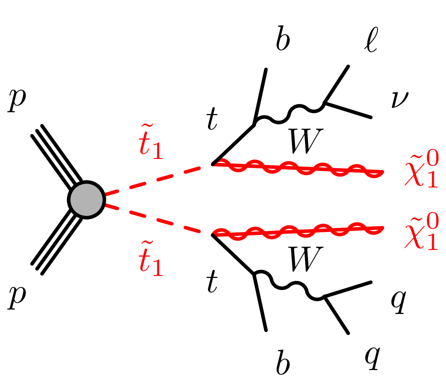
Search targets light to heavy stops in various decay modes: 4-body, 3-body, tN1, and bC1.

**1-leptons, ≥2-4 jets, MET, MT(lep, pTmiss)**

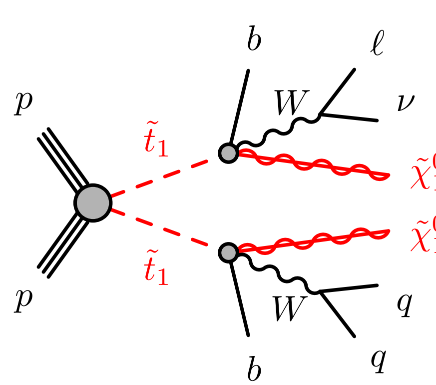
15 signal regions (SRs).

- soft-lepton: pT > 7(6) GeV for electrons (muons), employed for 4-body, and bC1 decays with small mC1-mN1 values.
- large-R (1.0) jets: collect decay products of boosted top in heavy stop search.
- 1D and 2D shape-fits: enhance search sensitivity in challenging scenarios (with difficult S-vs-B separation).
- b-tagged jets: utilised in event selection (ranging from a veto to ≥2) and for constructing kinematic variables.
  - MT2-like variables, hadronic top mass, topness

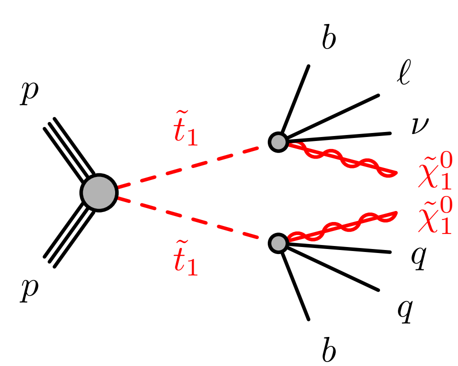
stop1 to tN1



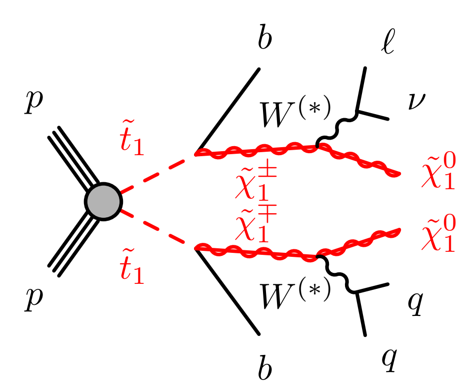
stop1 3-body decay



stop1 4-body decay



stop1 to bC1



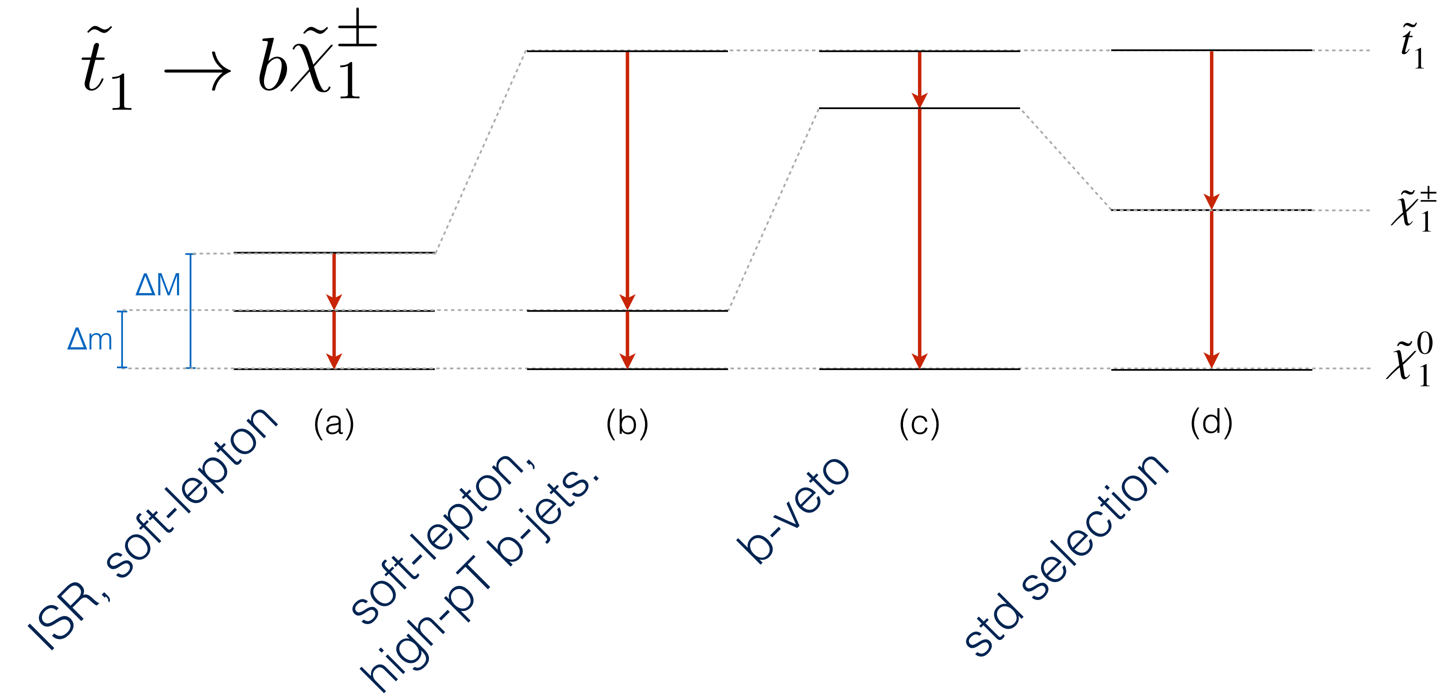
As well as mixed tN1, bC1 decays

# ATLAS searches 1L channel

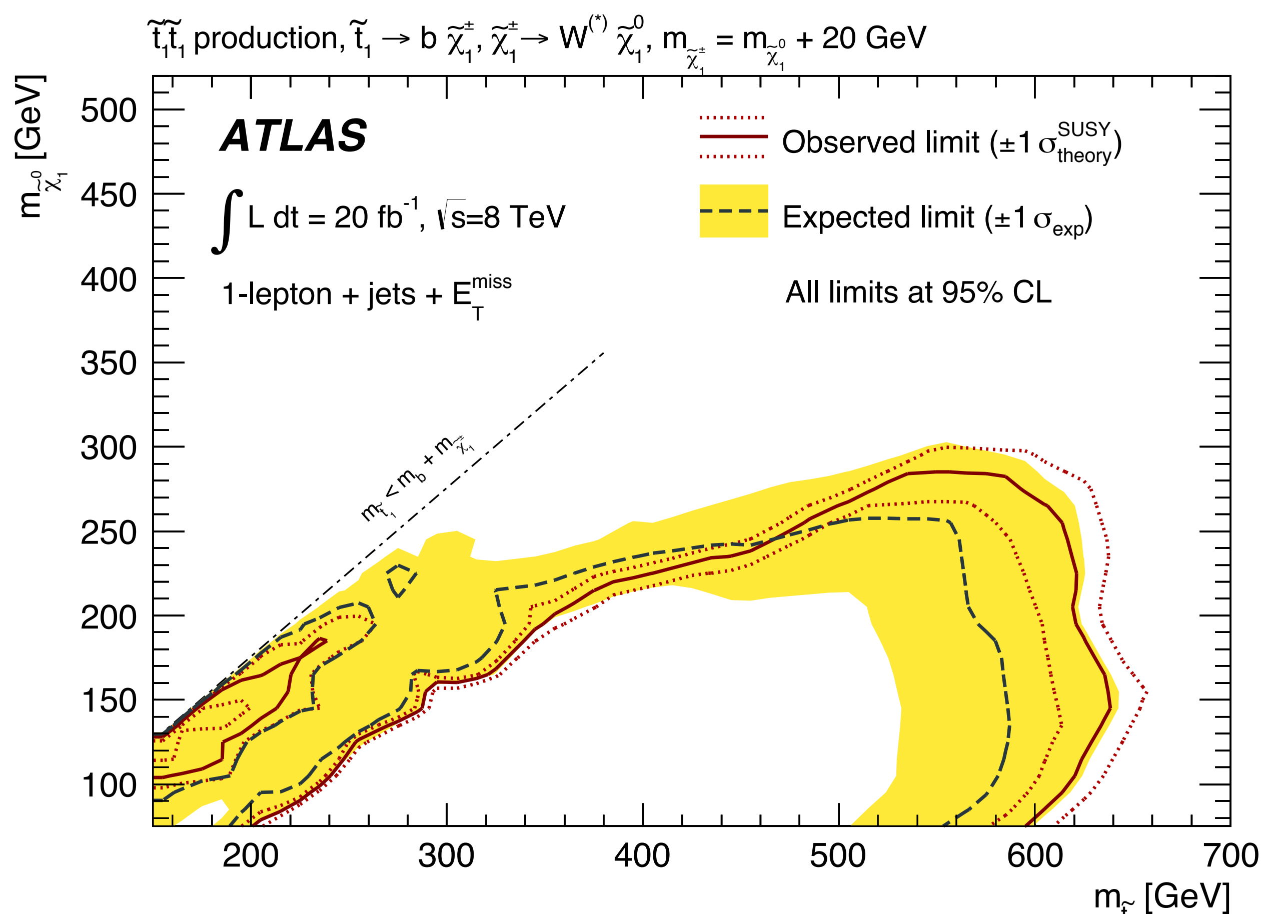
submitted to JHEP [1407.0583]

Signature driven by mass hierarchy of stop, C1, and N1. Dedicated selections to cover all scenarios.

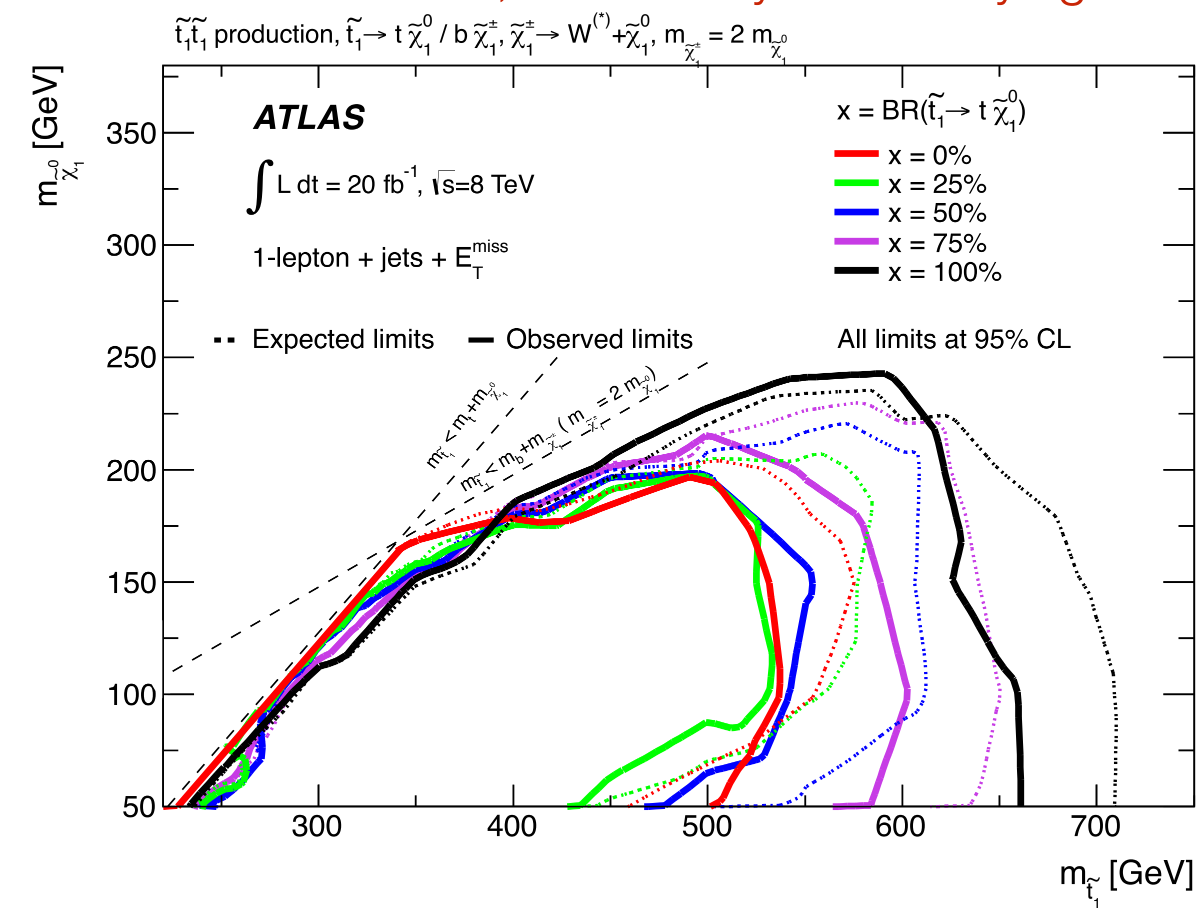
Showing example interpretations.




mass hierarchies (a), (b)




mixed tN1, bC1 decays with varying BR




Three SUSY mass parameters to consider (LEP limit $m_{\tilde{\chi}_1^{\pm}} > 103.5\,\mathrm{GeV}$)

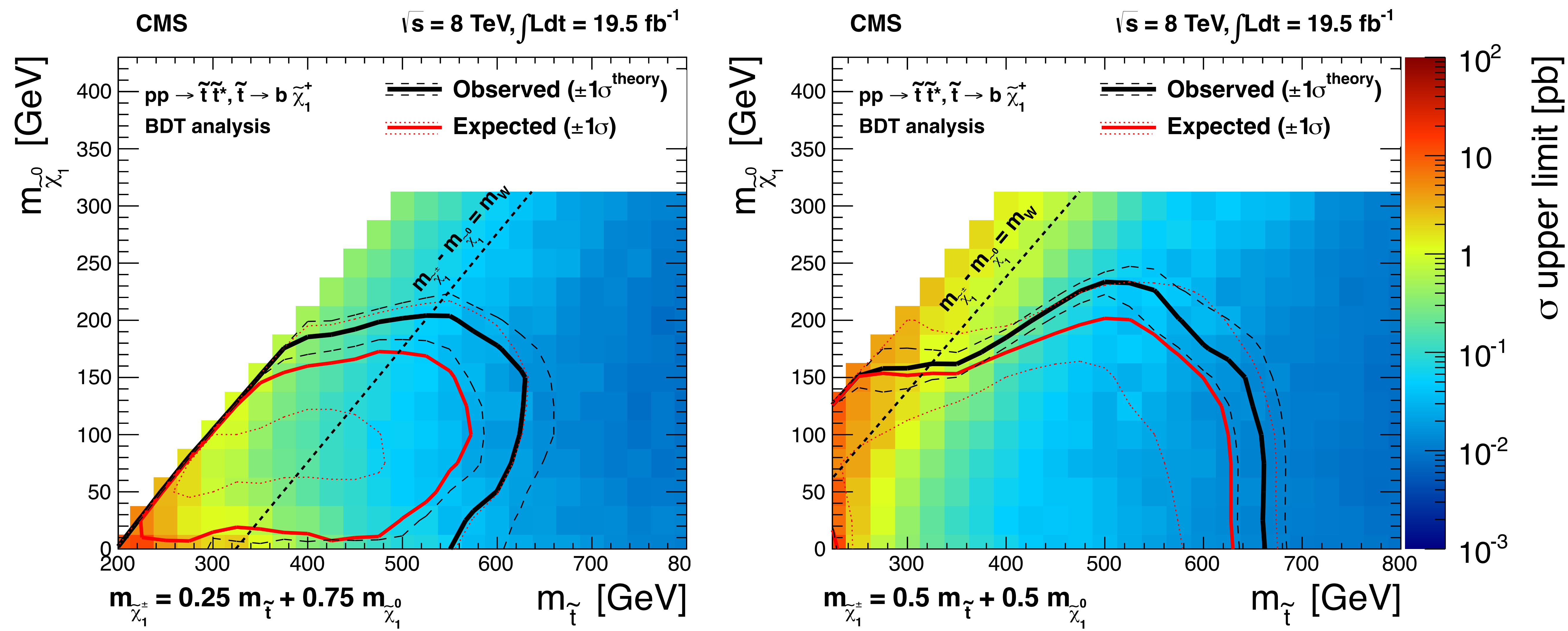
# CMS searches 1L channel

EPJC 73 (2013) 2677

$\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$

BDT Exclusion limits

- stop1 to bC1 scenario
- mC1 = 0.25 mTop + 0.75 mN1 (left)
- mC1 = 0.5 mTop + 0.5 mN1 (left)

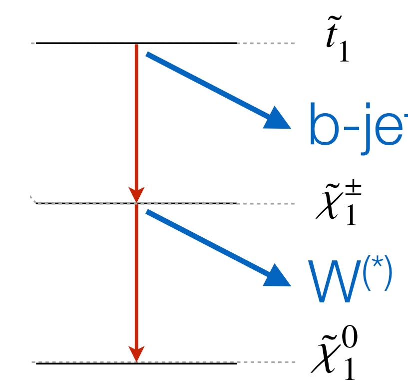


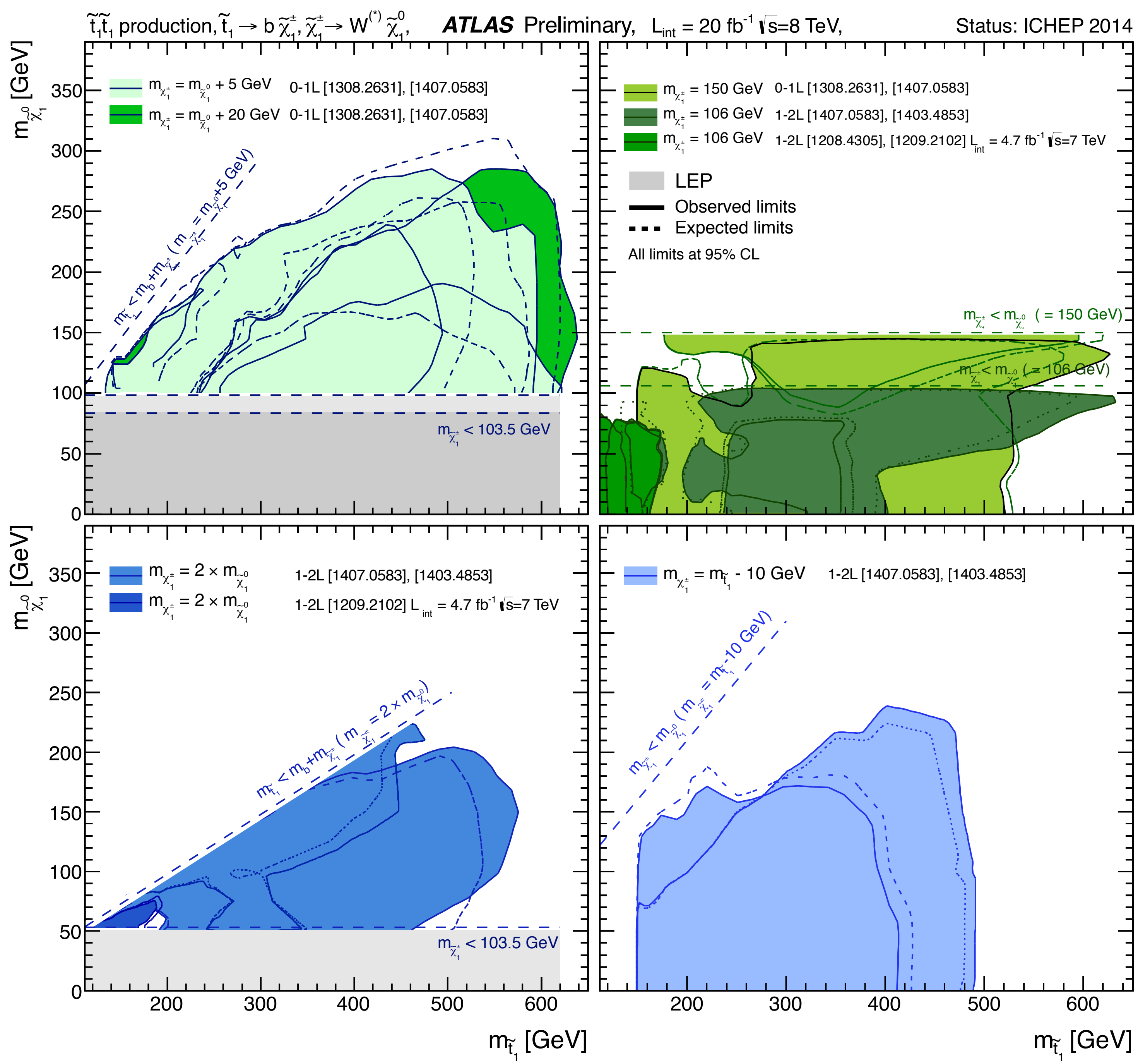

Small acceptance for models with small mC1-mN1 values (due to soft decay products, incl. lepton)

# Complementarity of searches

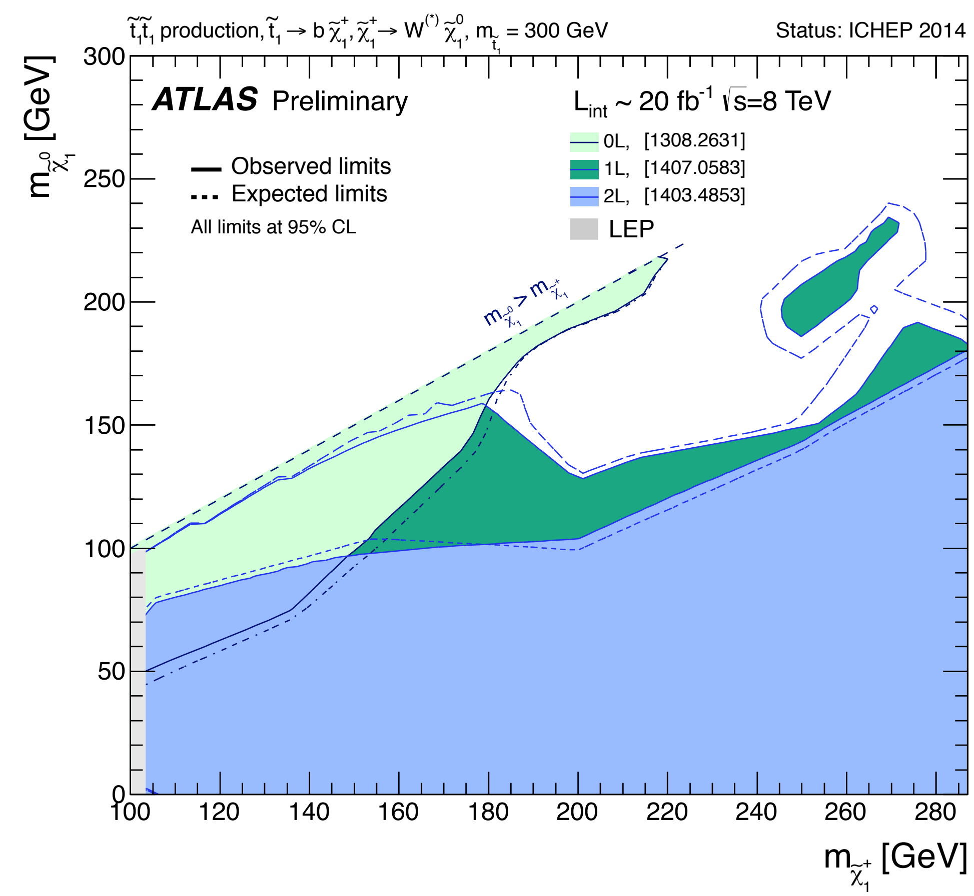
Various assumptions on stop, C1, N1 mass hierarchies.

$$\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$$




Fixed stop mass, limit in the mC1-mN1 plane.

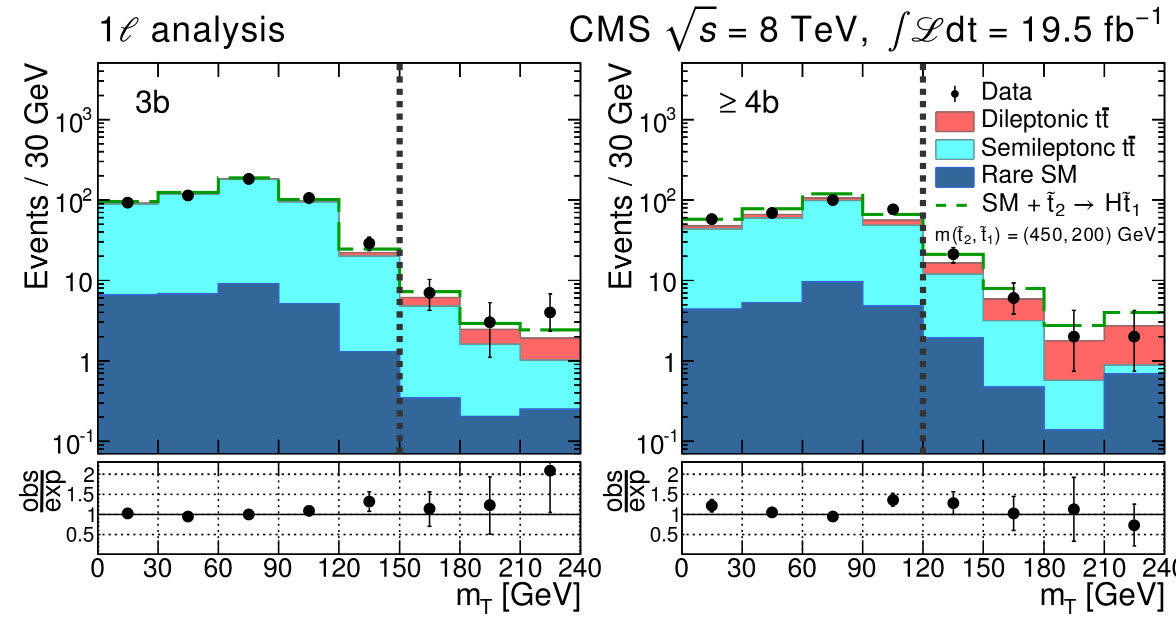


# CMS searches stop2 to Z/H

PLB 736 371 (2014)

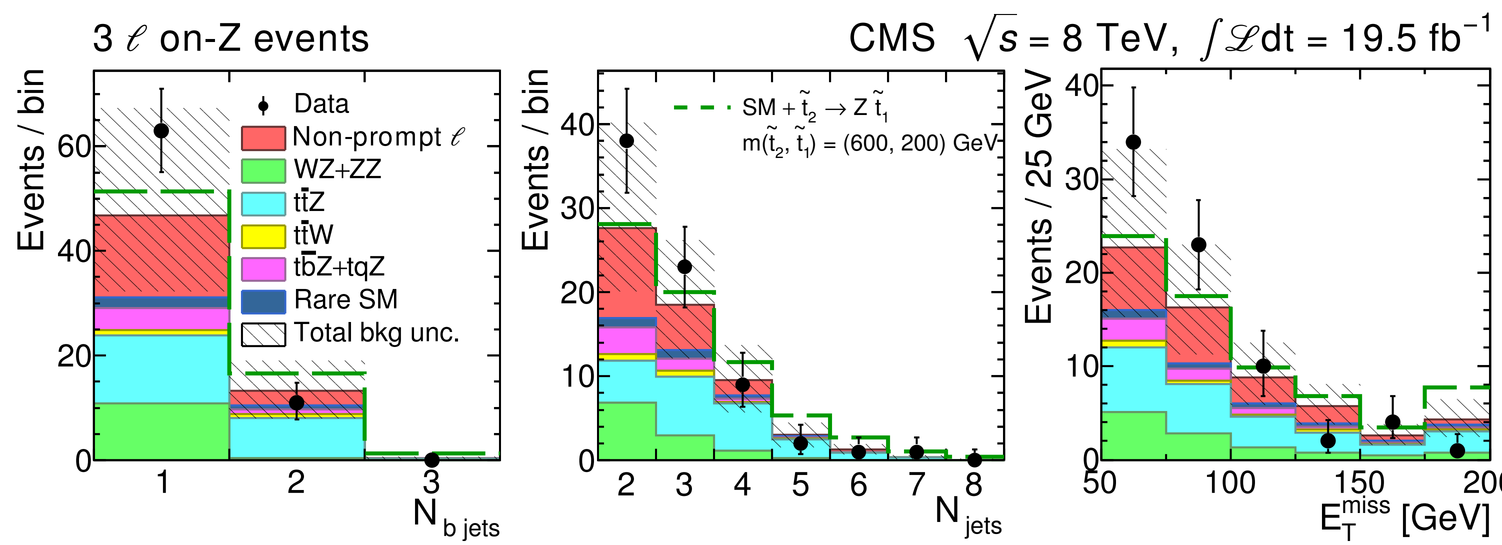
**1L analysis**:

- targets H to bb signature
- main background is tT + extra b-jet (for instance from mis-tag, or gluon splitting)
- use low MT to estimate background.



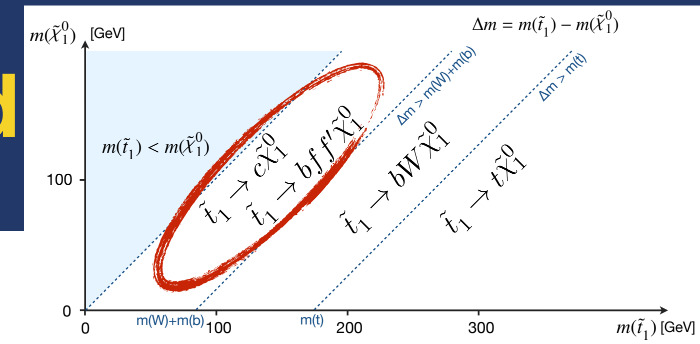

**3L analysis**:

- sensitive to all scenarios
- background from WZ+jets is suppressed by b-tag requirements,
- remaining background from rare processes or non-prompt leptons
  - WZ/ZZ from MC
  - non-prompt lepton from data

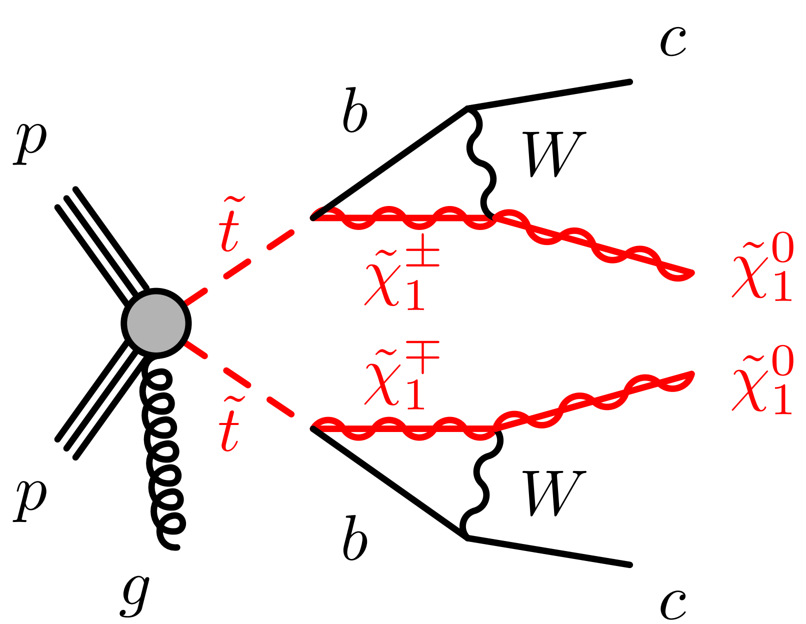


# ATLAS searches monojet/c-tagged

accepted by PRD [1407.0608]




Signature: two charm-jets with little momentum, some MET




→ require ISR to boost the system

**Two approaches**

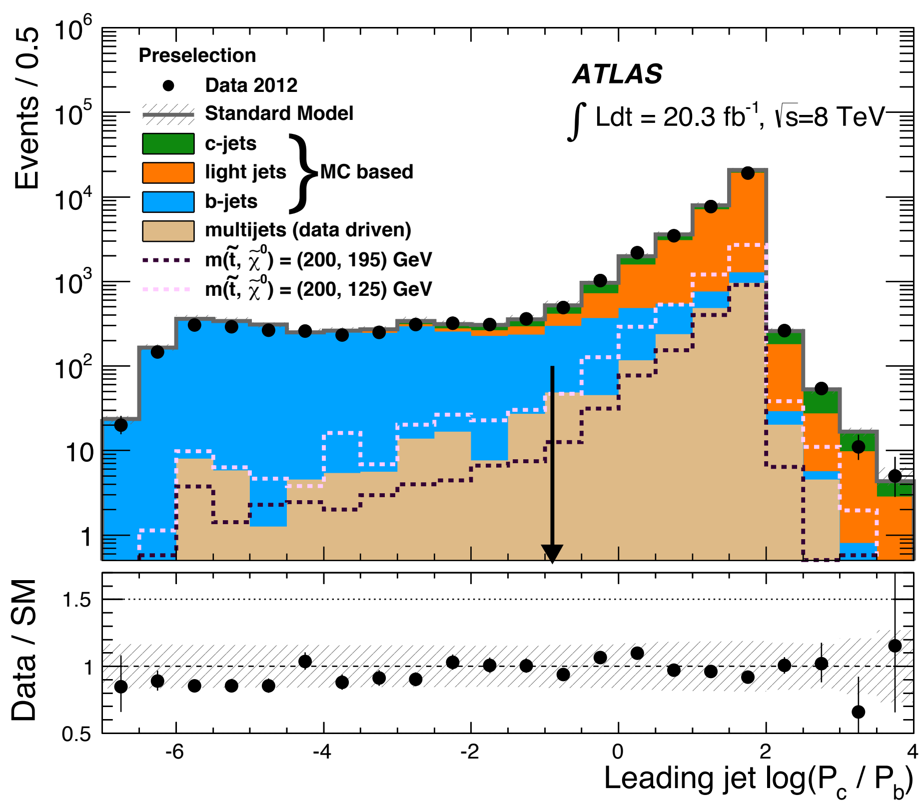
(1) small Δm=stop-N1 < 20 GeV: c-jets with too low pT

➡ monojet analysis: high-pT leading jet, large MET, jet veto (≤3 jets),

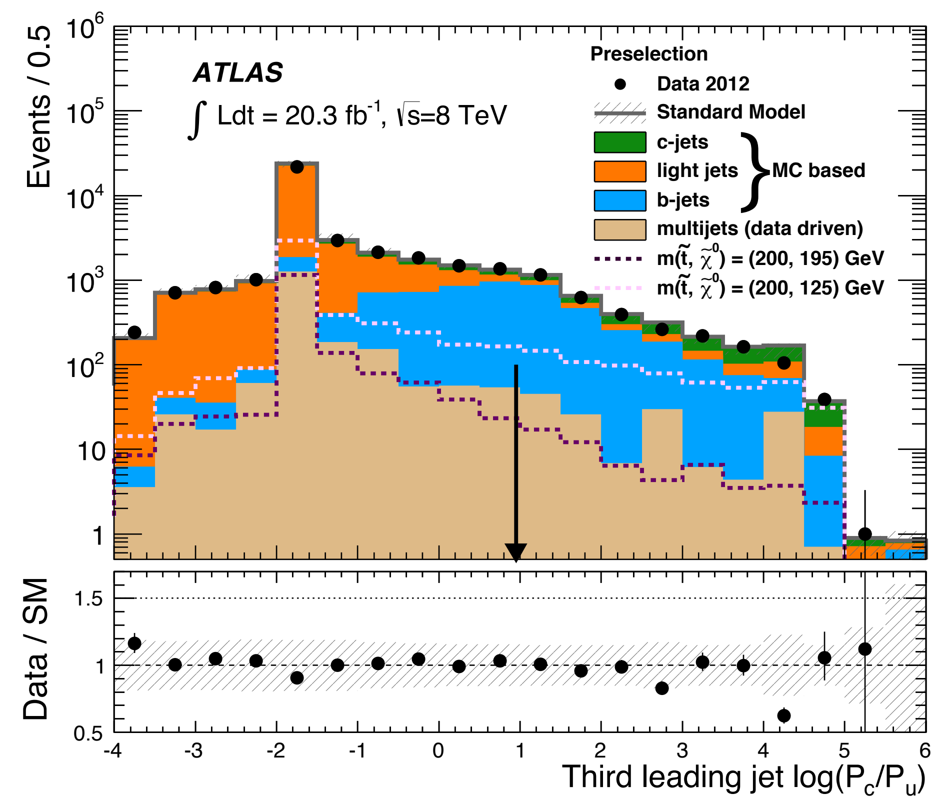
(2) large Δm>20 GeV: c-jets can be reconstructed

➡ c-tagged analysis: ≥4 jets, ≥1 c-tag, high-pT untagged leading jet (ISR), large MET

Loose anti b-tag on the leading jet

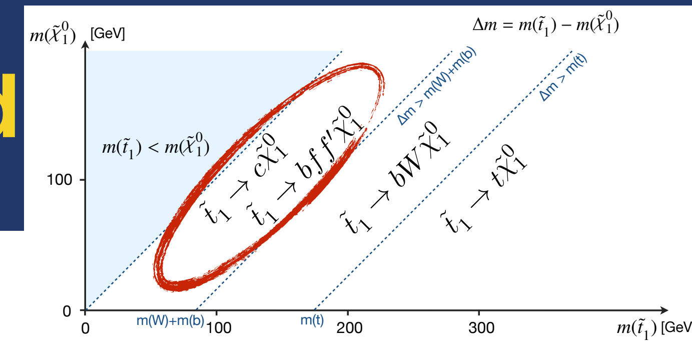


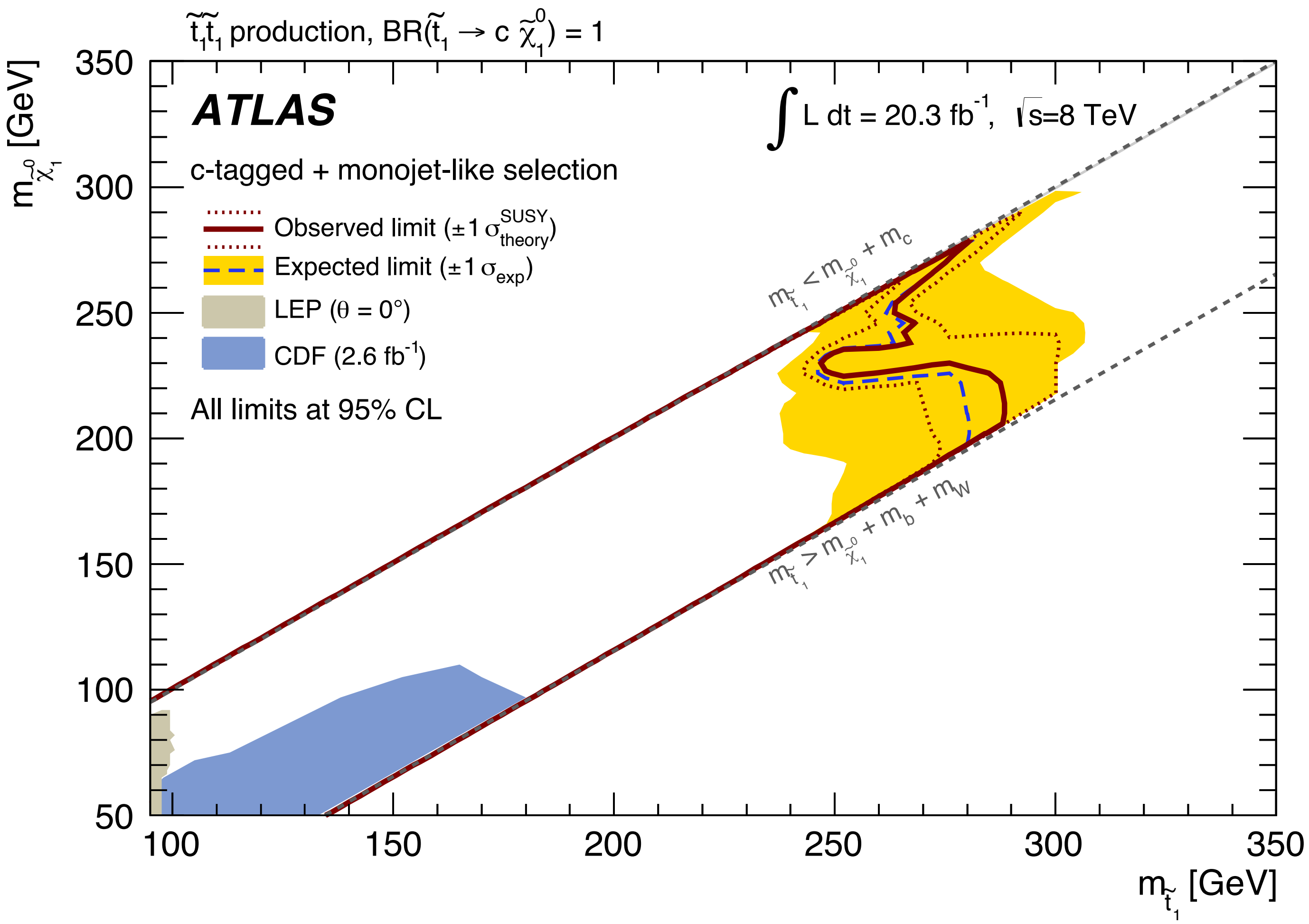

Medium c-tag on the 3 sub-leading jets



# ATLAS searches monojet/c-tagged

accepted by PRD [1407.0608]

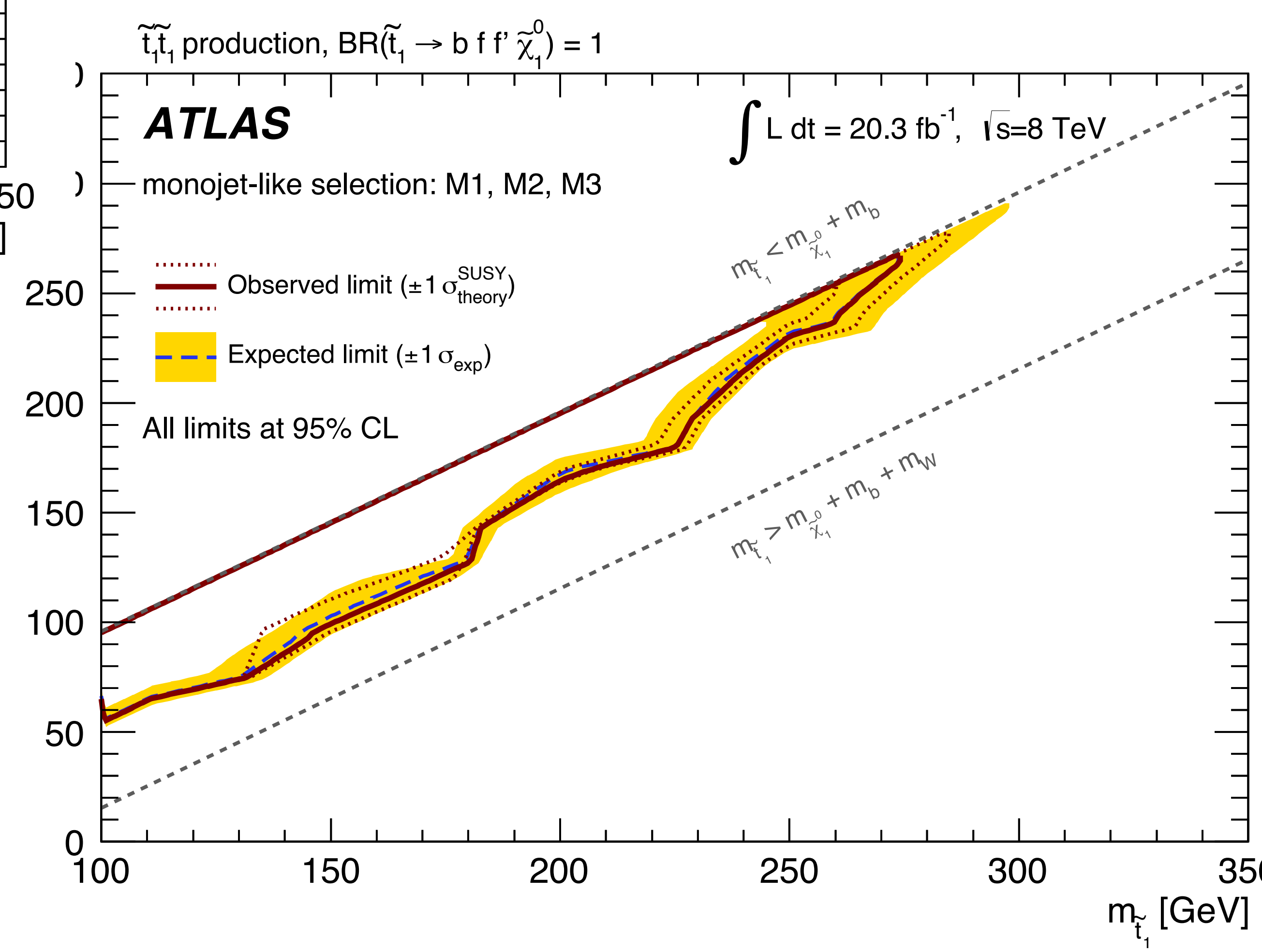



Limits in stop to cN1.

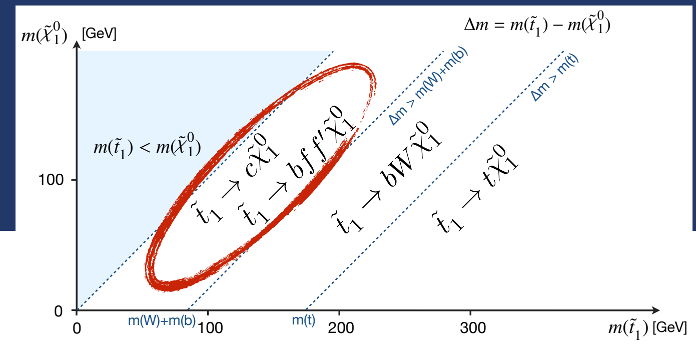
Limits in 4-body scenario

sensitivity of monojet search independent of stop decay (soft b-, c-jets, leptons, etc.). Similar reach for compressed scenarios in case of sbottom pair production.

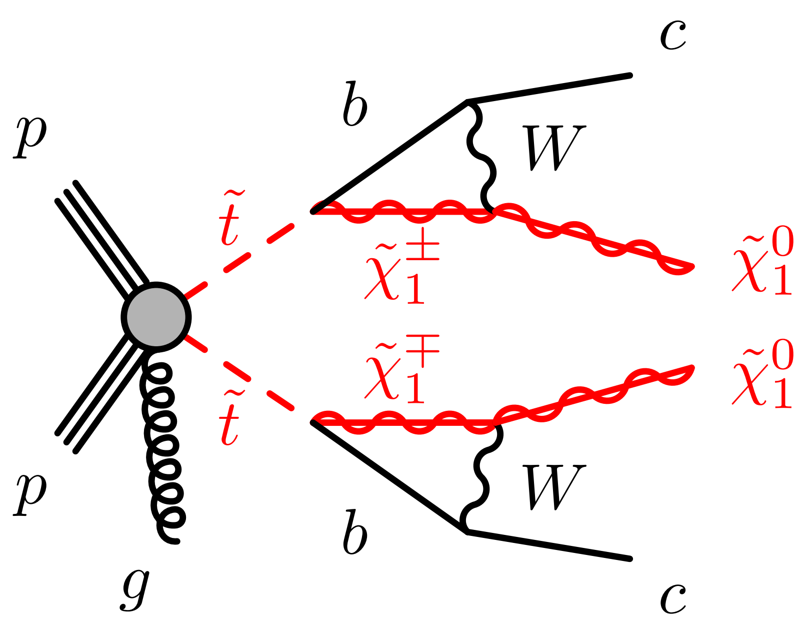


# CMS searches monojet

PAS-SUS-13-009




Signature: two charm-jets with little momentum, some MET



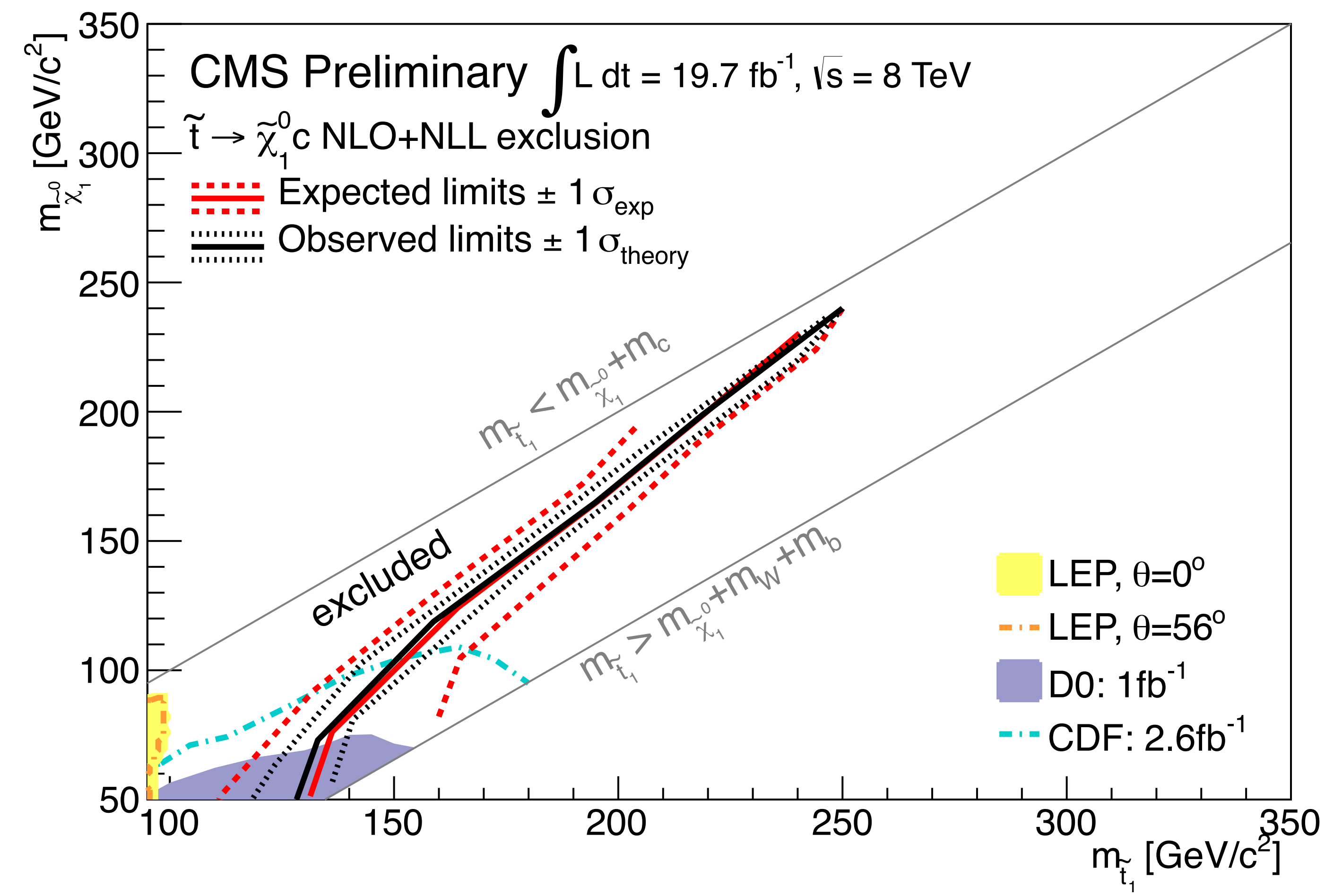

→ require ISR to boost the system

Monojet analysis:

- high-pT leading jet, allow for 2nd jet with pT>60 GeV, veto 3rd jet, veto leptons.

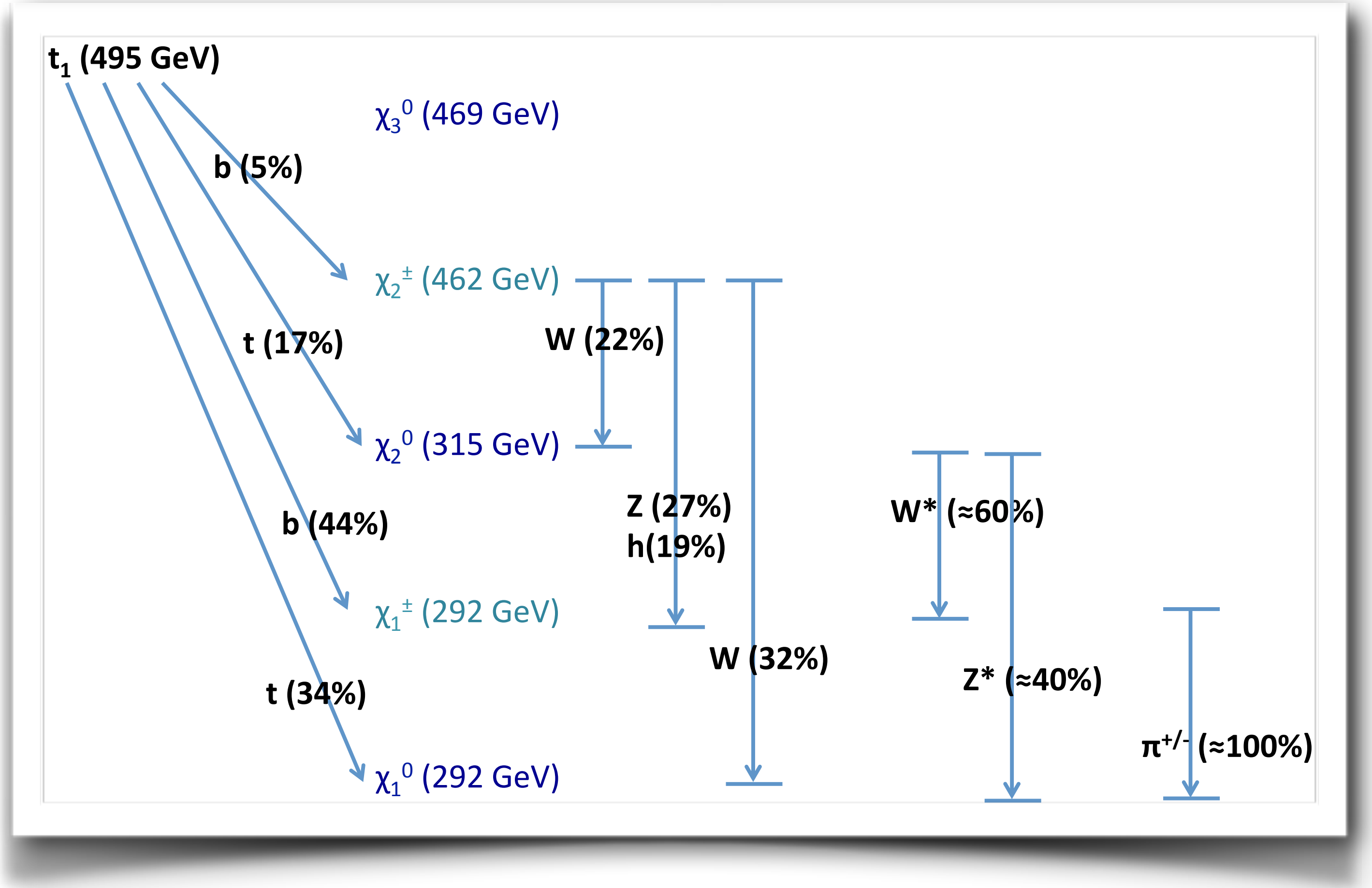
**Backgrounds**:

- Z(nunu)+jets, W(lnu)+jets
- estimated from data in CRs,
- total SM uncertainty as low as ~4%

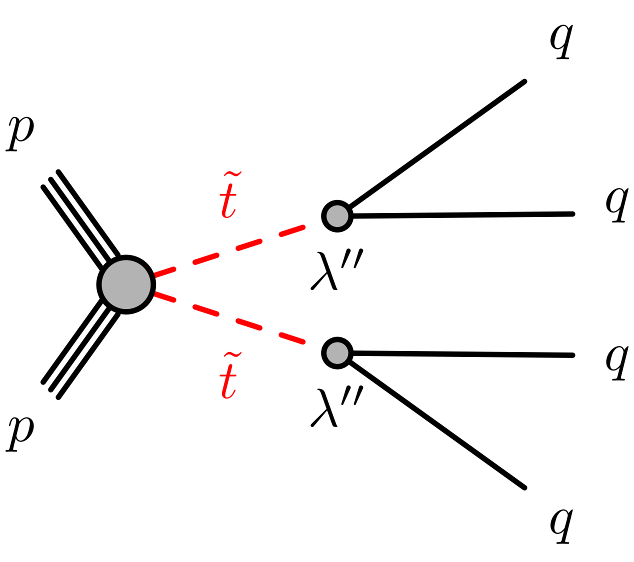


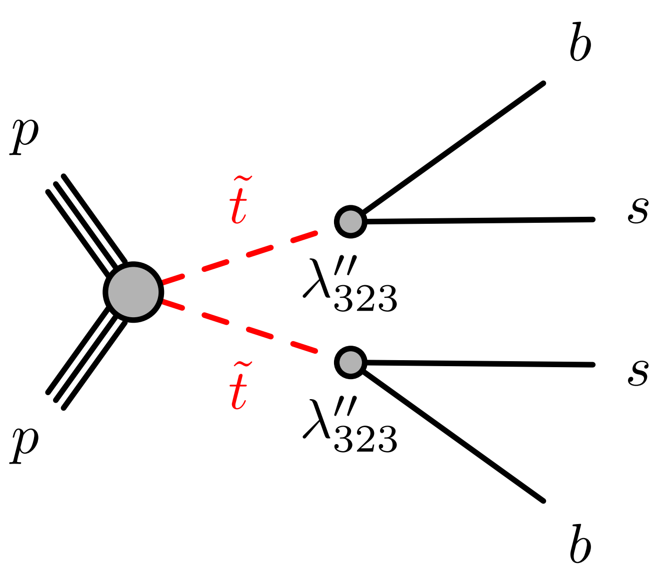
# Other (complex) decay possibilities

1. Longer decay chains
   - with heavier neutralinos and/or charginos
2. Asymmetric decays
3. N1 is not the LSP, but e.g. the gravitino ($\tilde{G}$),
   for example:
   $$\tilde{t}_1 \rightarrow b + \tilde{\chi}_1^{\pm} \rightarrow bff'\tilde{\chi}_1^0 \rightarrow bff'Z\tilde{G}$$




4. (some) R-parity violation, opens many more possible final states, for example:



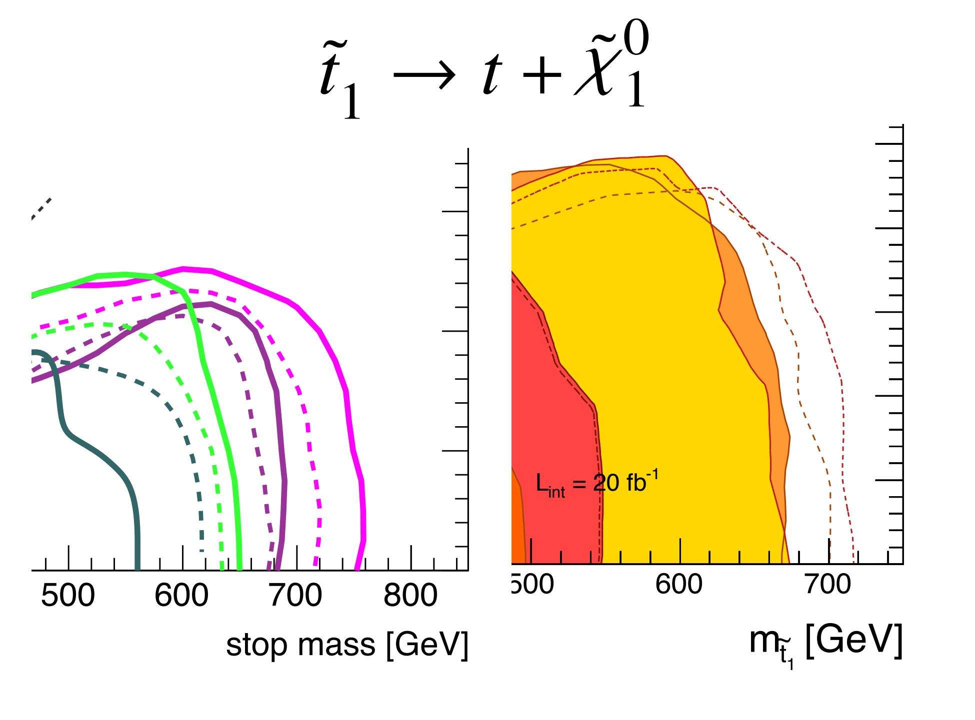




6. but also long-lived (R-hadron, stoponium)

# Heavy stop search

- **stop to t N1,**
- **stop to b C1 (to b W N1)**

$$\tilde{t}_1 \rightarrow b\tilde{\chi}_1^{\pm}$$




challenge: tiny cross section

- ~8 fb for m(stop) at 700 GeV
- compared to ~250 pb for ttbar production
  - and ~0.2 pb for ttbar+ Z

Best sensitivity from 0L and 1L channels.

- Dominant background: **semi (di)-leptonic ttbar** for the stop 0L (1L) search, where the (2nd) lepton is
  1. not identified (failed PID) / outside acceptance,
  2. hadronically decaying tau-lepton.

} missed particle / extra neutrino(s) → more $E_T^{miss}$, mT > m(W)

- Remove background (while retaining high signal acceptance) using:
  - lepton veto, tau-veto, hadronic top reconstruction, kinematic variables (next slide).

# Top pair background suppression

## Tools to suppress dominant bkg

**Tight 2nd lepton veto**:

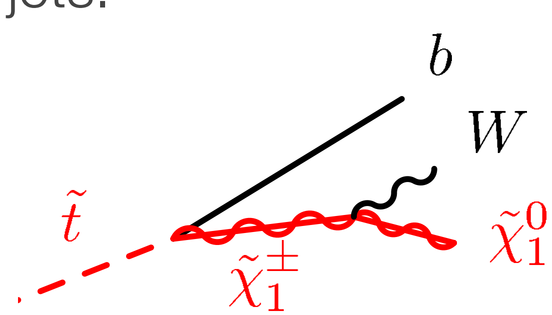
Signal has no `edge' in mT hence dominated by single lepton.

- lepton pT, PID
- veto on isolated tracks
- veto on had-taus

**B-tagged jets**:

For chargino decays, *b*-jet pT can be significantly larger than in SM ttbar.

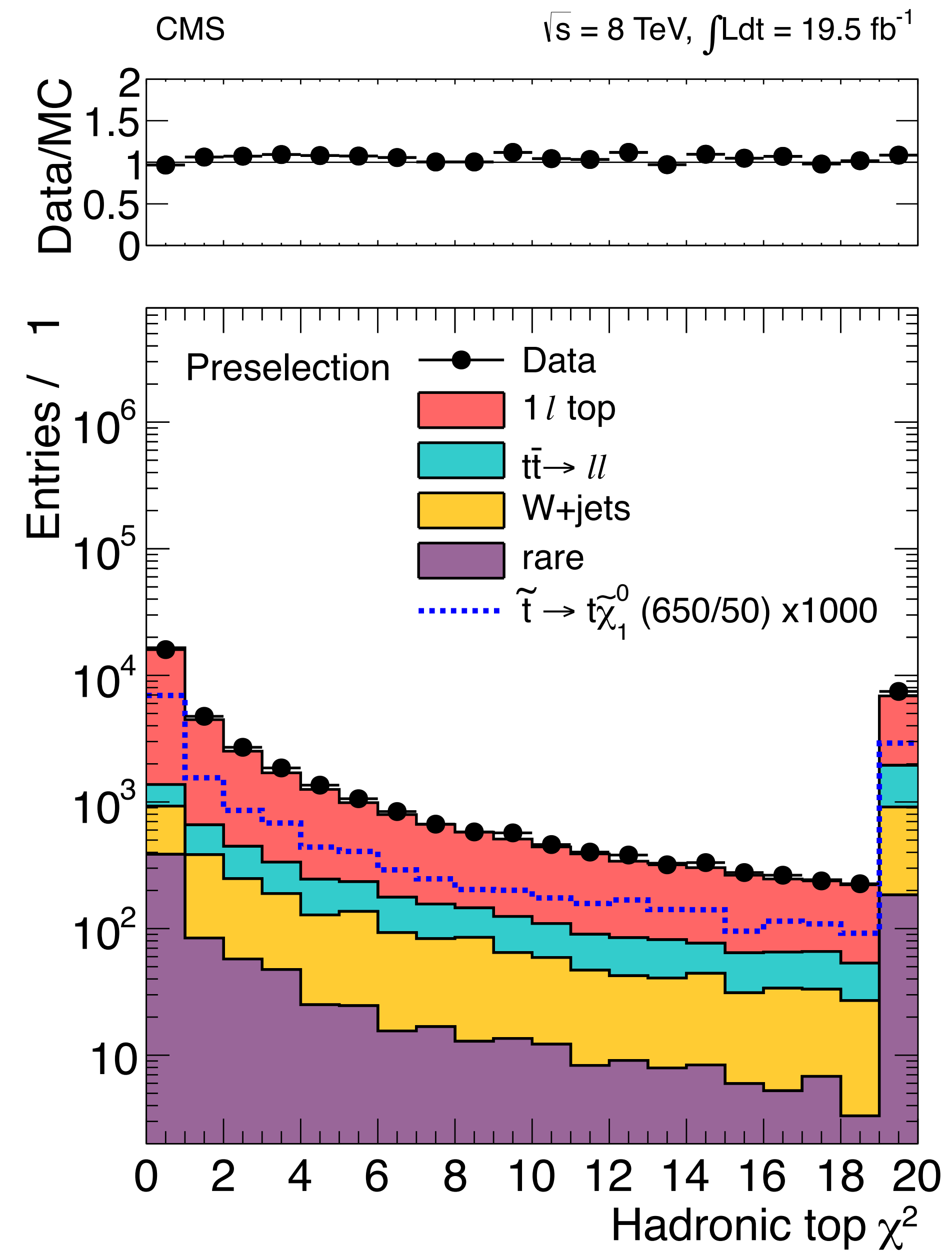
- require high pT b-jet(s),
- require two b-tagged jets.




**Hadronic top mass**:

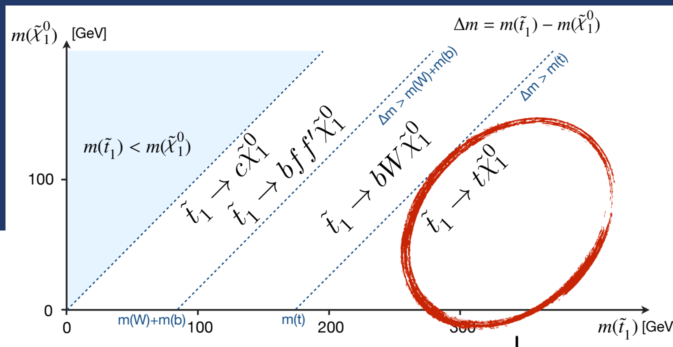
While for decay via top quark, three jets stem from a hadronic top decay, this is not true for di-lep ttbar.

- reconstruct hadronic top mass from three jets m(jjj),
- require loose compatibility with m(t)



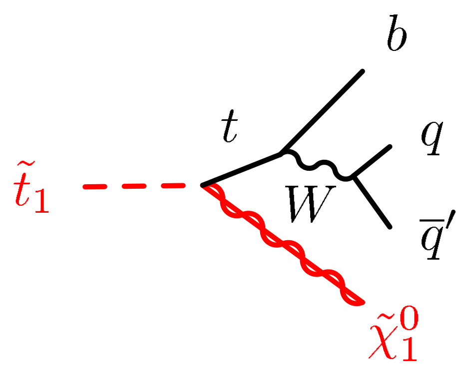
# ATLAS searches **0L channel**

JHEP 09 (2014 ) 015 [1406.1122]

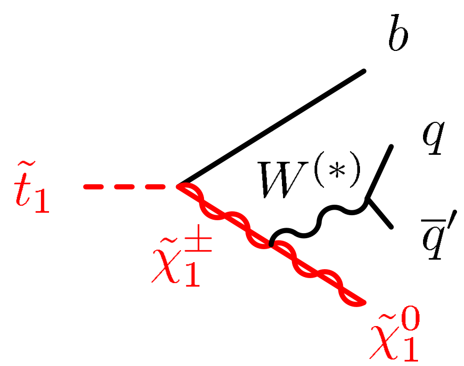



$$\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$$

Target stop1 pair production with 2 possible decays (BR=100%, or mixed)




mode A




mode B

**0-leptons, ≥2 b-tagged jets, MET**

Three sets of signal regions (SRs):

- SR-A `fully resolved': 6 distinct jets (akt0.4) [A or B].
- SR-B `partially resolved': 4 or 5 jets (akt0.4) and 2 re-clustered akt1.2 jets compatible with mTop [boosted tops in A].
- SR-C: 5 jets (akt0.4) for scenarios with at least one B decay, and small mC1-mN1 values.

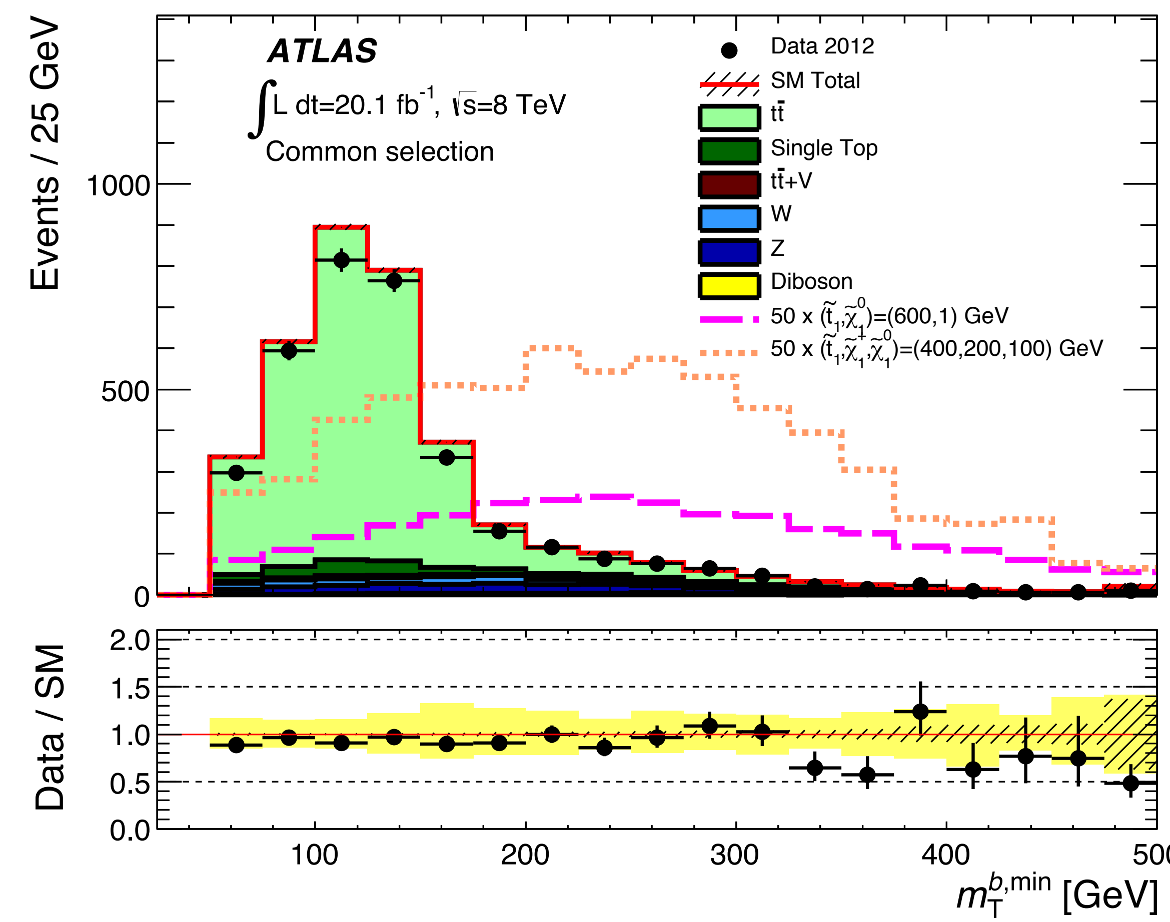
**Analysis idea**: reconstruct two hadronic top quarks, investigate $E_T^{miss}$ distribution.

**Backgrounds**:

- semi-leptonic ttbar (with had tau) — 1L CR, treat lepton as jet,
- Znunu +HF — 2L CR, add lepton pT to MET
- residual multijet — jet smearing method.

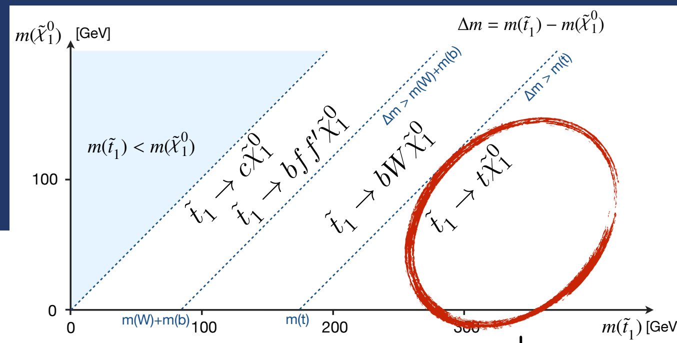
**Discriminating** variables:

- min Δϕ(pTmiss, jet): reject fake MET
- mT(pTmiss, b-jet closest in ϕ to pTmiss): reject tT
- MET, and more.

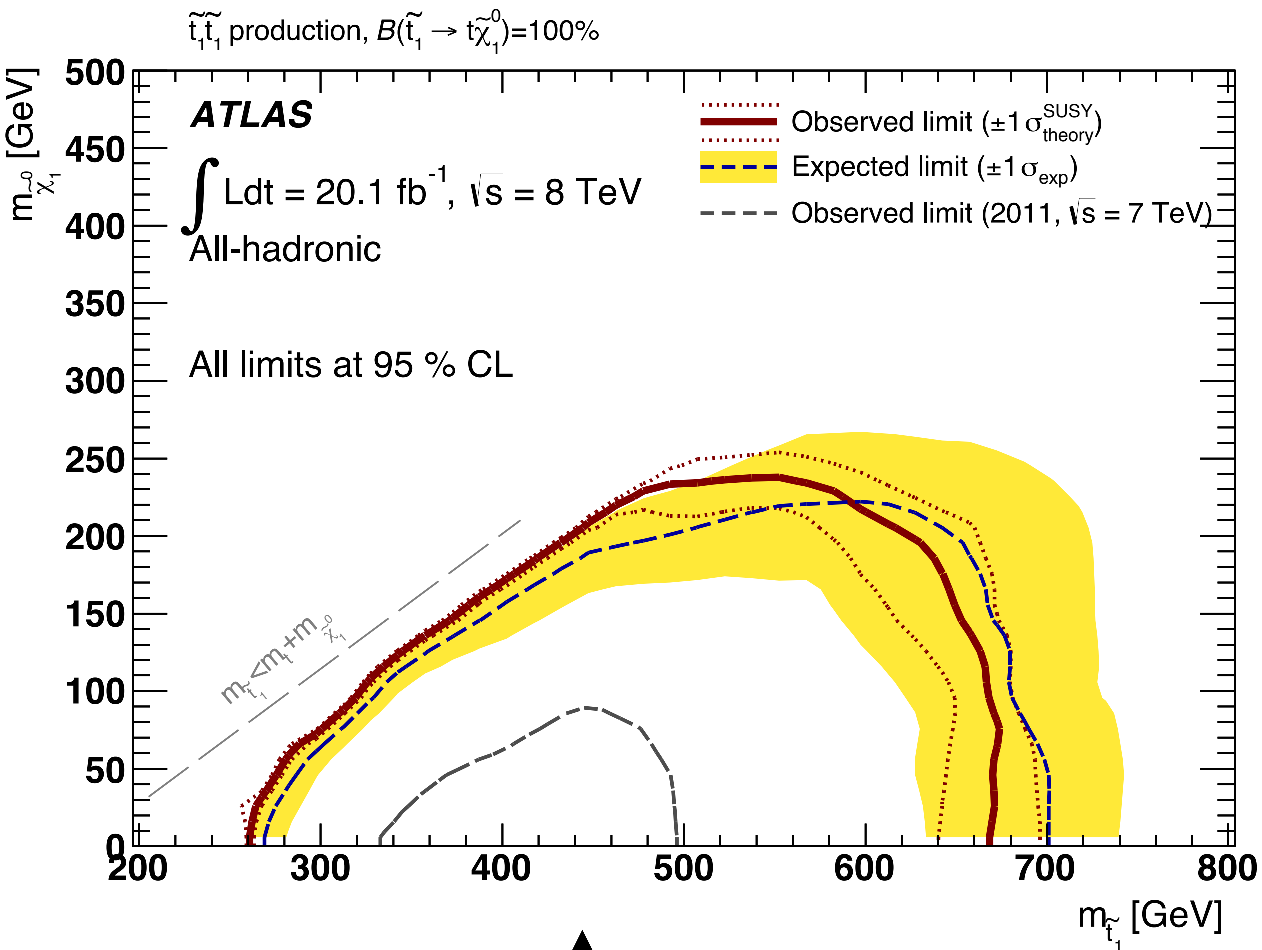


# ATLAS searches **0L channel**

JHEP 09 (2014 ) 015 [1406.1122]

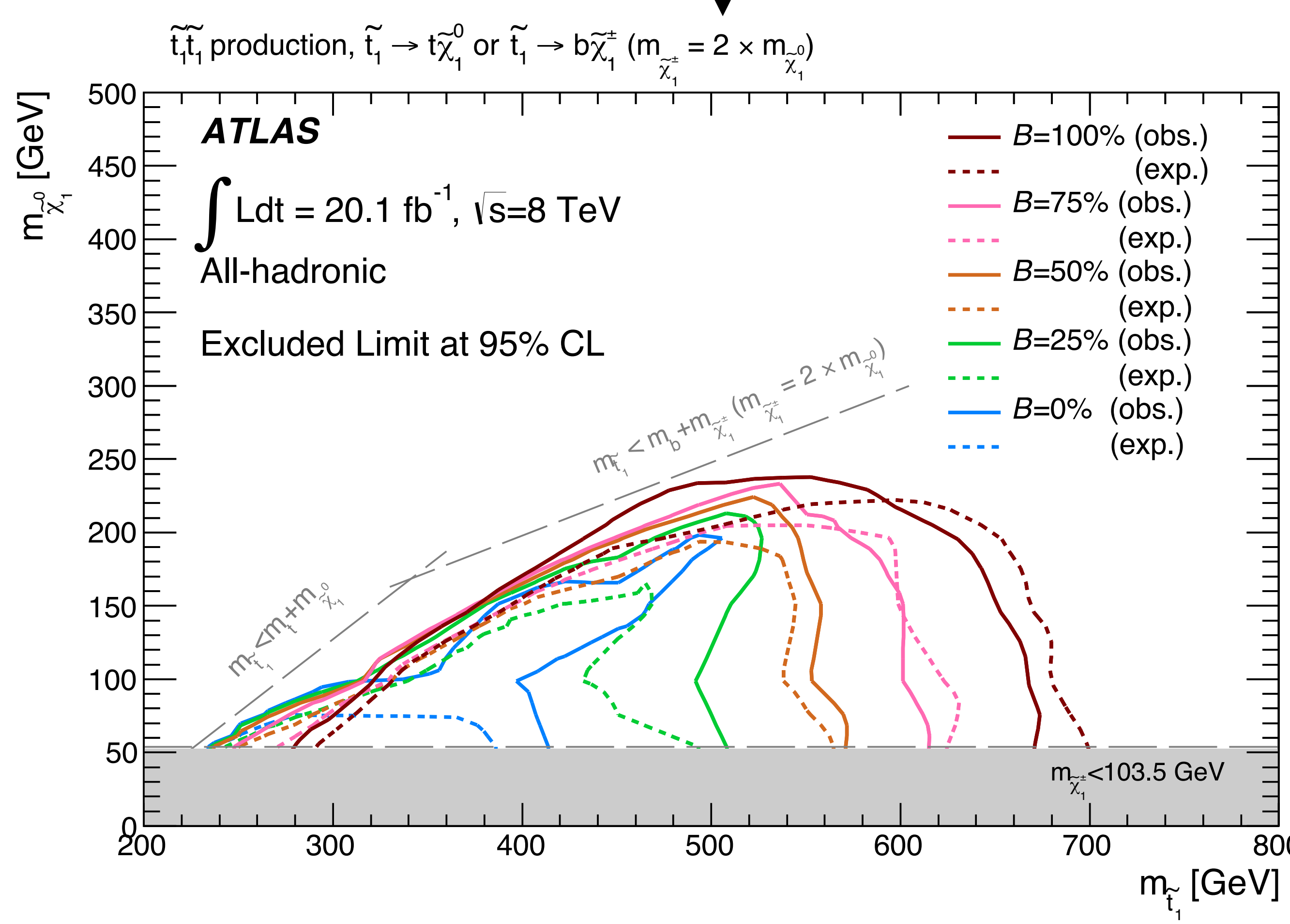



$\tilde{t}_1 \to b\tilde{\chi}_1^\pm$



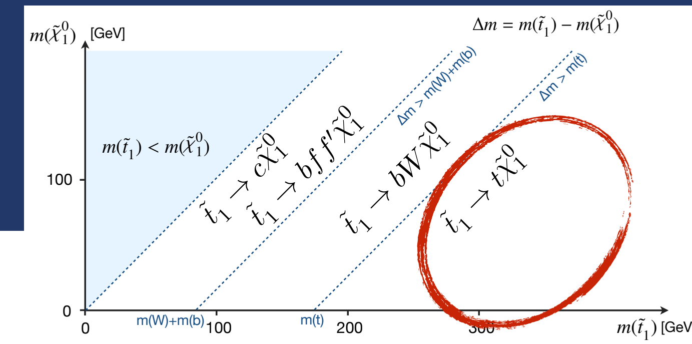

Decay A with BR=100%, combination of SR A+B most sensitive for models with large Δm(stop,N1).

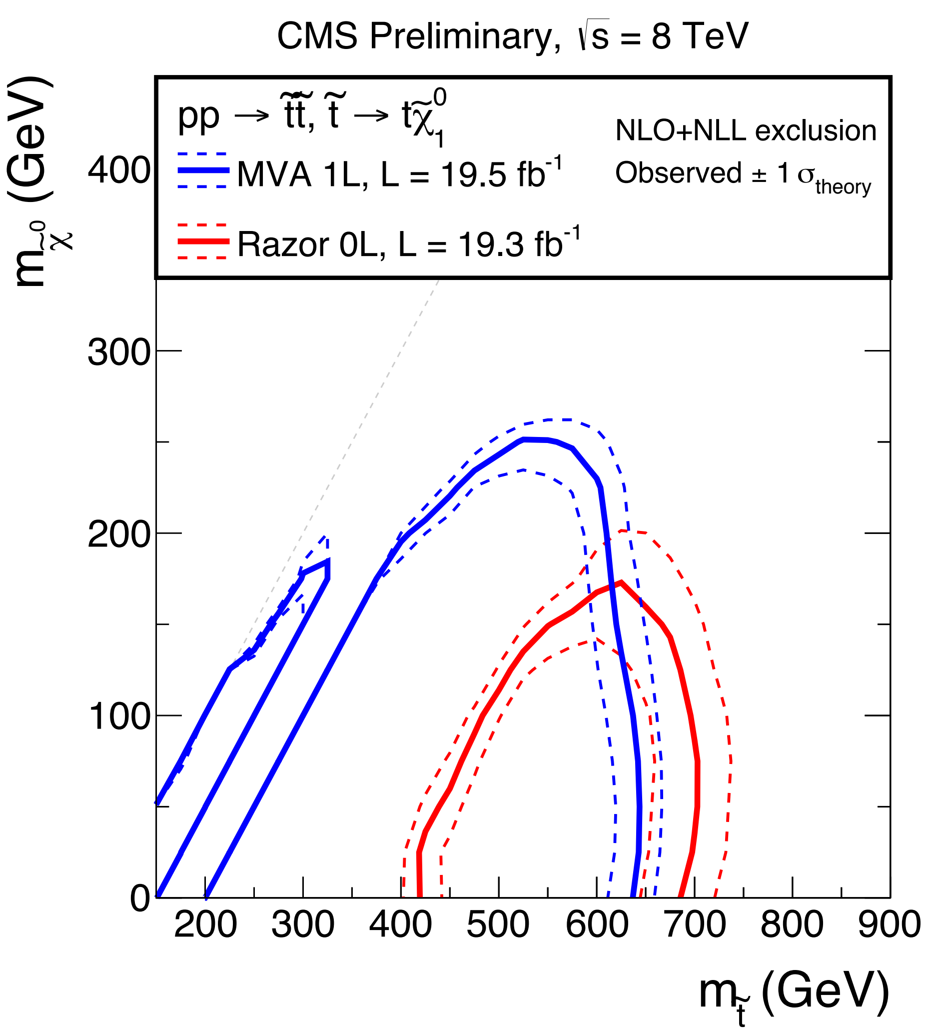
Mixed decay A, B with varying BRs

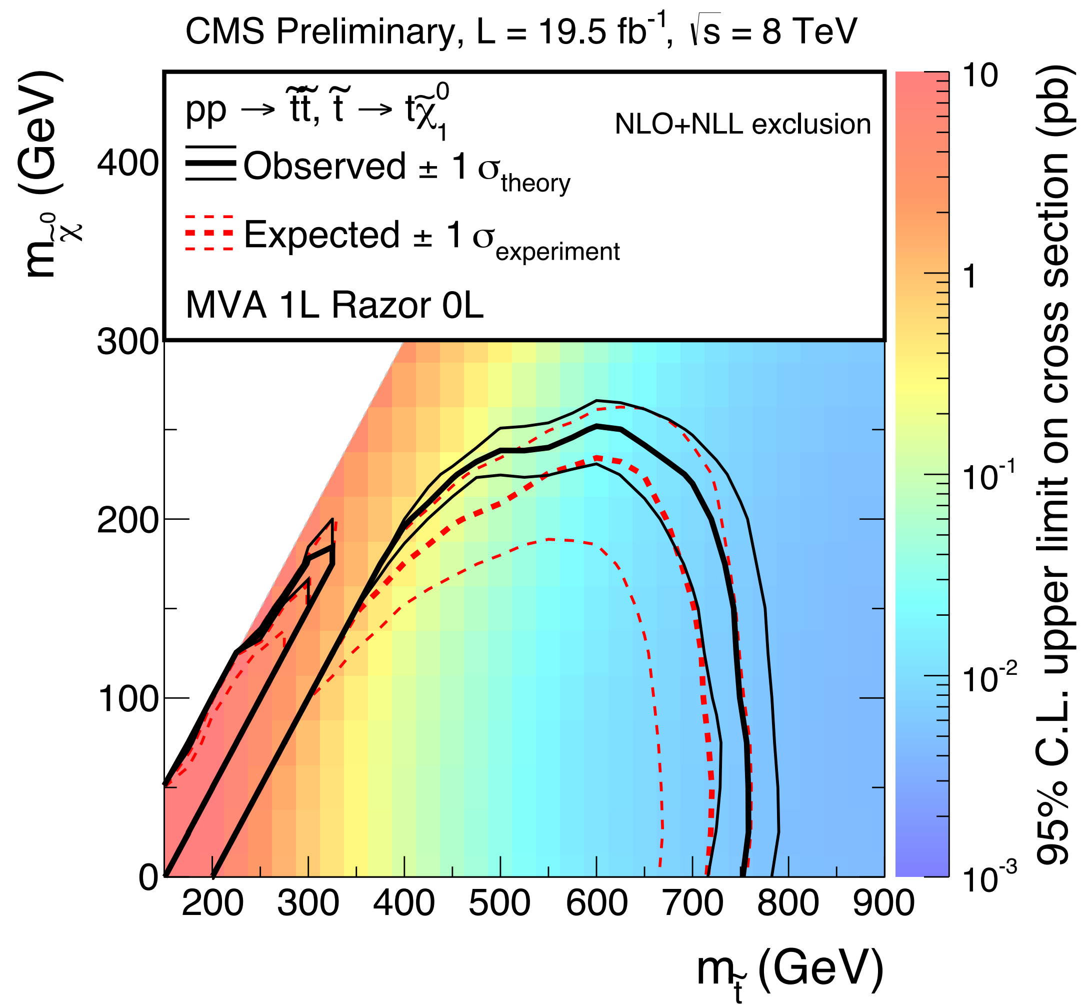


# CMS searches 1L + razor 0L

PAS-SUS-14-011




Statistical combination of

- Razor hadronic box, SUS-13-004
- stop 1L BDT, SUS-13-011

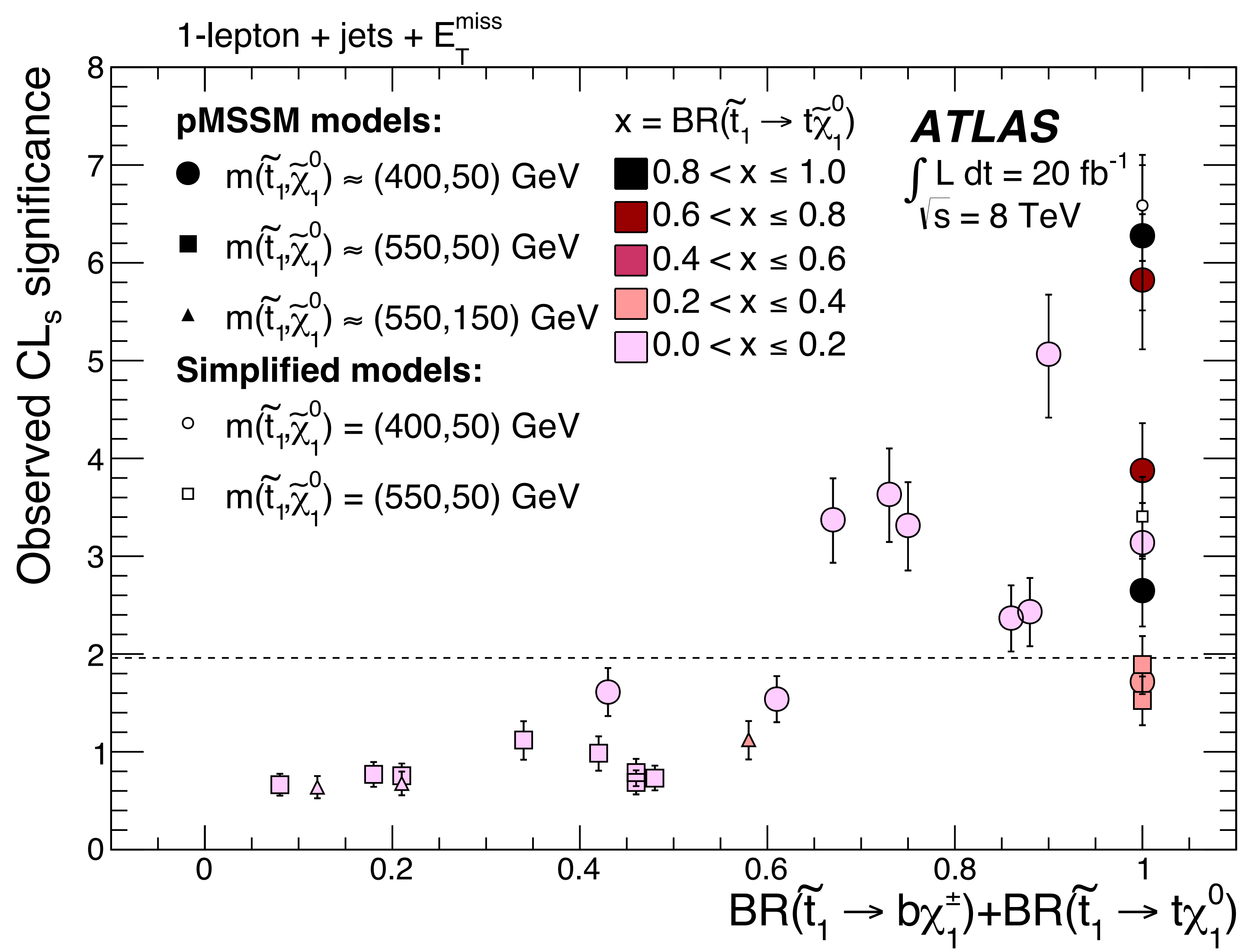
# Dependence on other parameters

**1L channels**

submitted to JHEP [1407.0583]

The change in sensitivity when varying parameters other than the stop and N1 masses is studied using pMSSM samples, classified into three groups of similar stop and N1 masses.

- strongest impact on the CLs significance from the sum of the branching ratios for stop1 → tN1 and stop1 → bC1.
  - signal selections being optimised using only simplified models.
- sensitivity also depends on the kinematic properties of the events, which are affected, e.g., by the stop mixing matrix and by the masses and field content of other SUSY particles.
  - explains the large spread in CLs significance

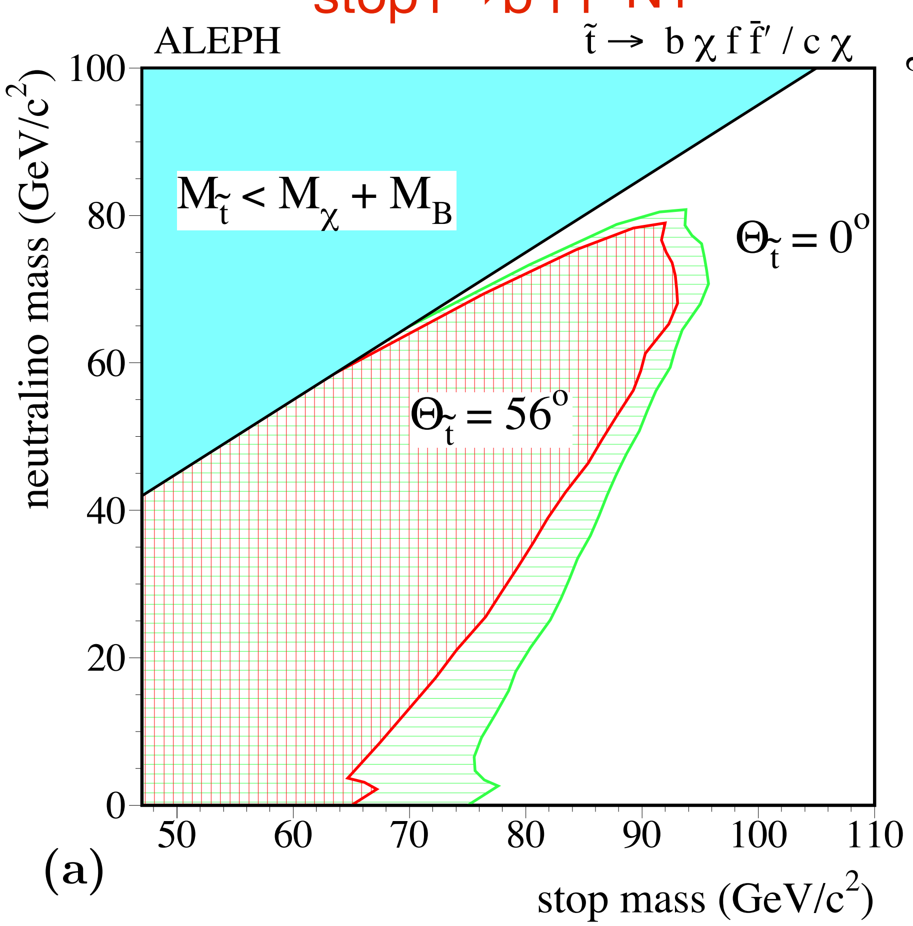


# LEP

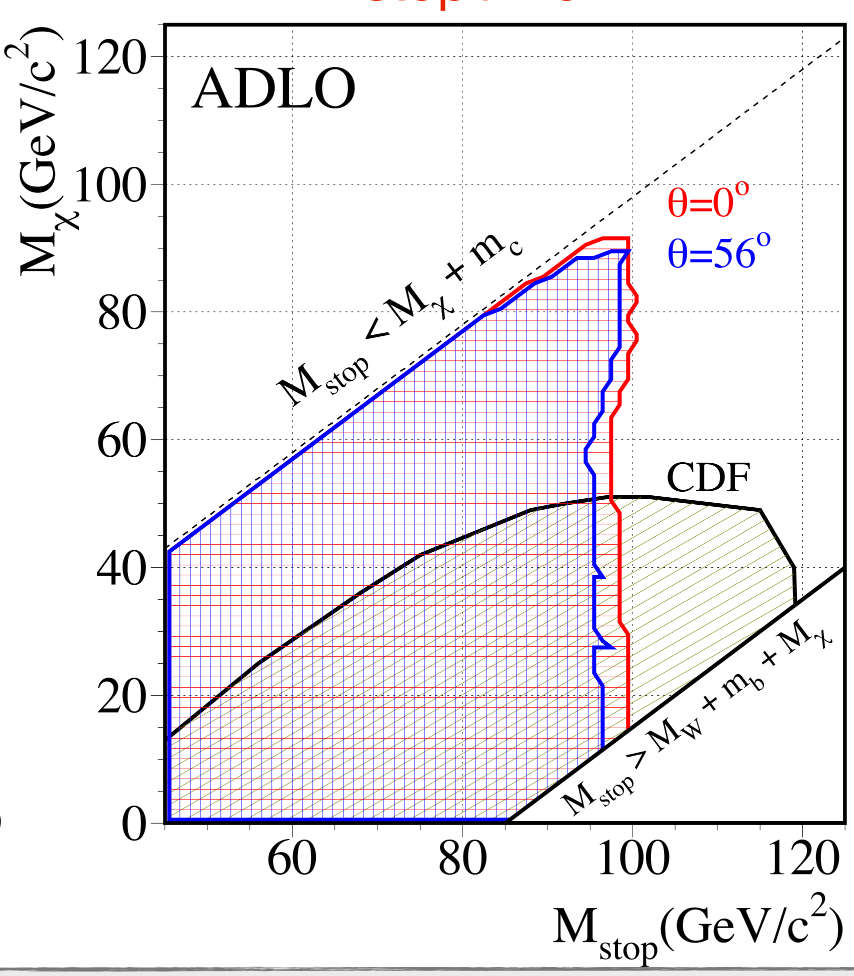
http://lepsusy.web.cern.ch/lepsusy/

- ALEPH, DELPHI, L3, and OPAL at LEP performed searches for the top squark considering the decays stop1→c N1 and stop1→b l sneu.
  - In the latter, the sneutrino is assumed to be the LSP. (The sneutrino LSP is mostly considered to be ruled out because of direct detection experiments since it couples directly to the Z boson.)
- 2 different squark mixing angles: theta = 0 (squark_Left), and in case of "max mixing" where the mixing angle is choosen such that the cross section is minimal.
- Furthermore, ALEPH published limits on the four-body decay, stop1→b f f’ N1 [Phys. Lett. B537 (2002) 5–20]

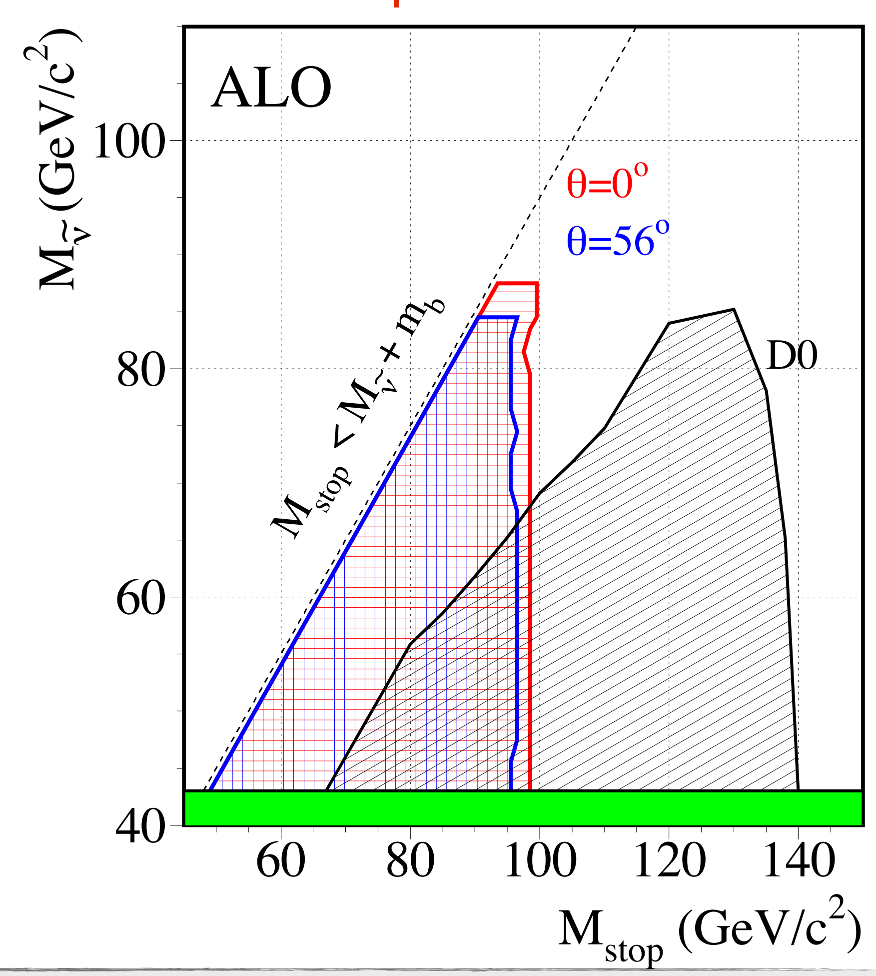
stop1→b f f’ N1




stop1→c N1




stop1→b l sneu

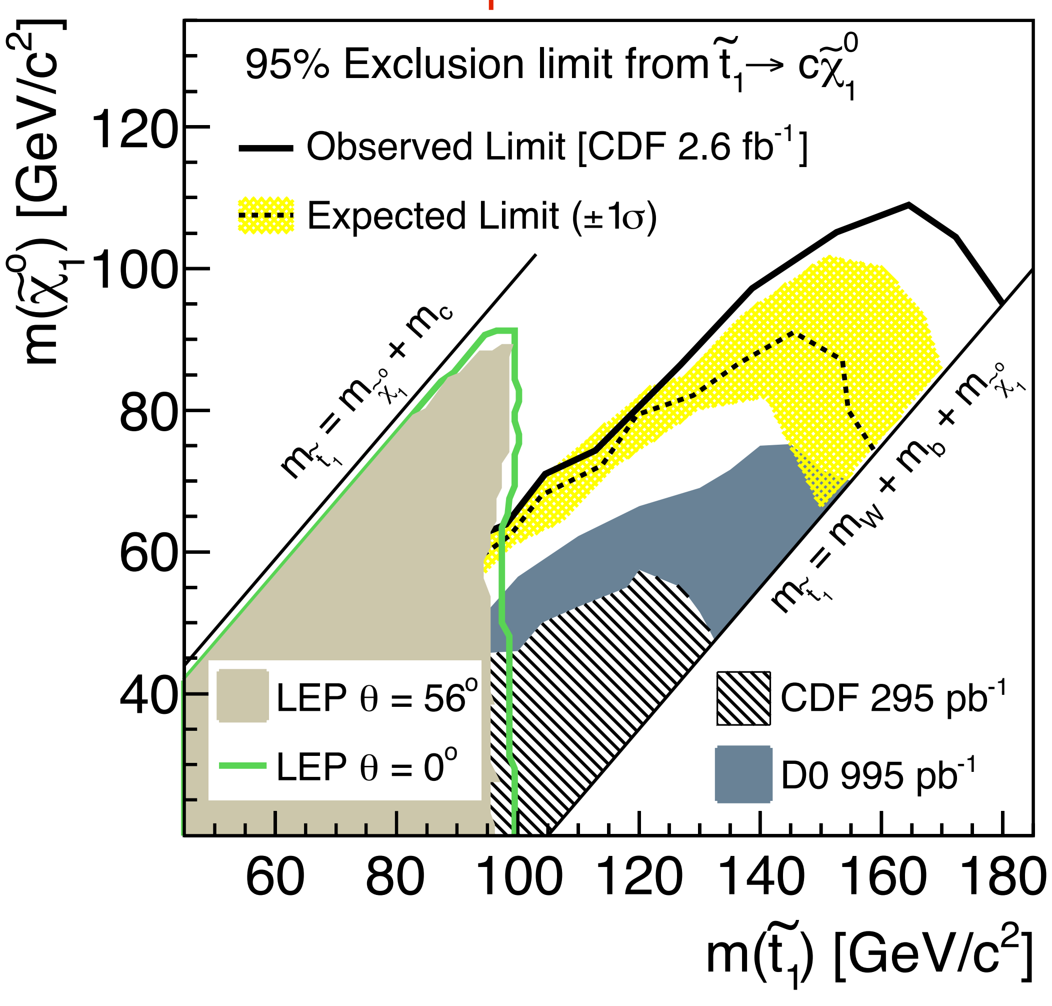


# Tevatron

- The CDF and DØ detectors (at the Tevatron collider) performed searches for the top squark in several analyses considering the decays: stop1→c N1 (Ref.[19,20]), stop1→b l sneutr (Ref.[21]), and stop1→b C1 (Ref.[22]).

- Plot shows summary of Tevatron (and LEP) exclusion limits for the stop1→c N1 decay scenario. Limits for the stop1→b l sneutr decay are comparable, while the sensitivity for the stop1→b C1 decay is considerably weaker: only a small window in top squark mass (125 GeV < m(stop1 ) < 138 GeV) is excluded under the assumption that the decay proceeds via a W boson (C1→W+N1).

stop1→c + N1





[19] CDF Collaboration, *Search for Scalar Top Quark Production in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV*, JHEP **1210** (2012) 158.

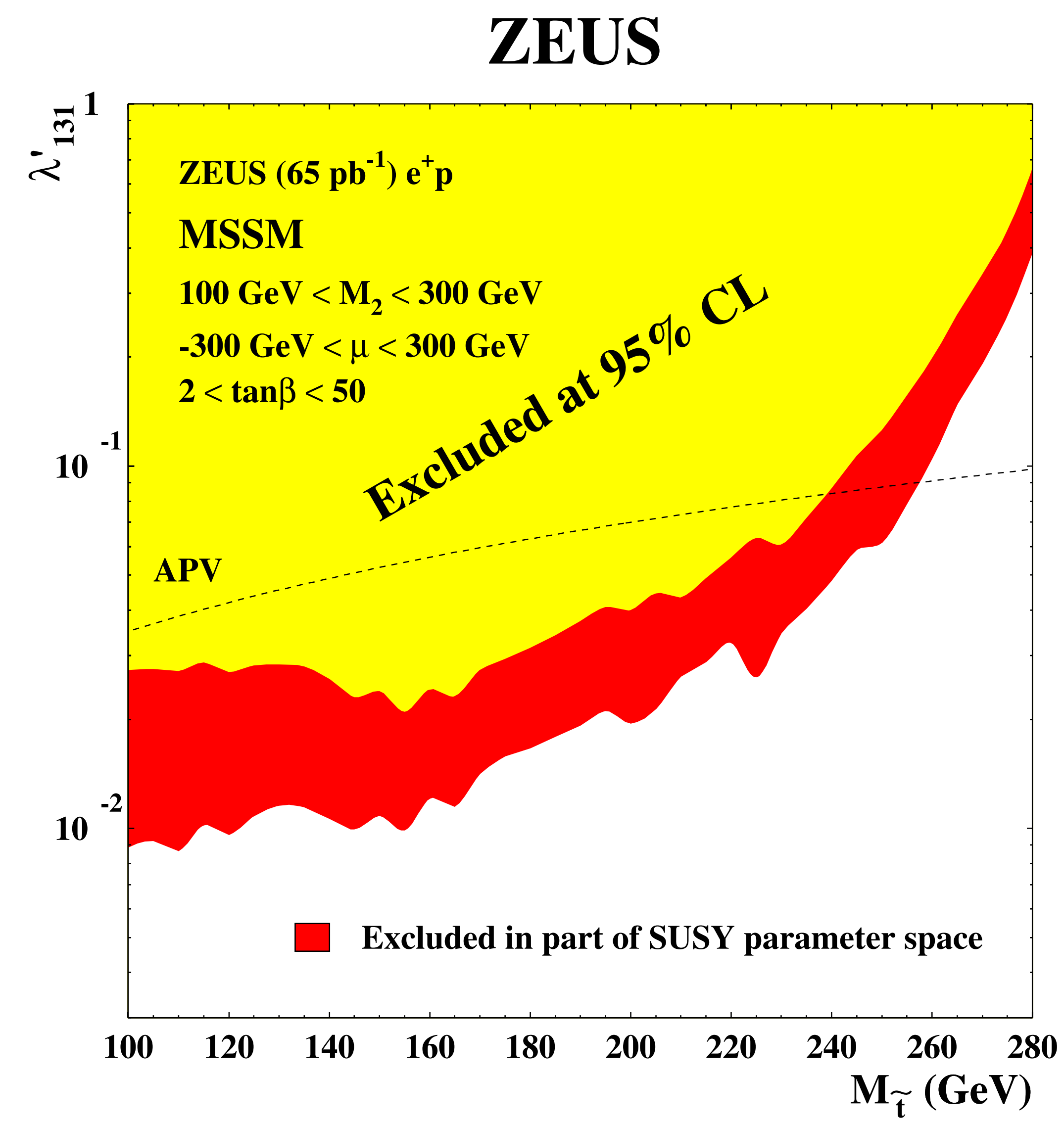
[20] D0 Collaboration, *Search for scalar top quarks in the acoplanar charm jets and missing transverse energy final state in $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96-TeV*, Phys.Lett. **B665** (2008) 1–8.

[21] D0 Collaboration, *Search for the lightest scalar top quark in events with two leptons in ppbar collisions at* $\sqrt{s} = 1.96$ *TeV*, Phys. Lett. **B675** (2009) 289.

[22] CDF Collaboration, *Search for Pair Production of Supersymmetric Top Quarks in Dilepton Events from $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV*, Phys. Rev. Lett. **104** (2010) 251801.

# DESY

- A search for R-parity violating production of top squarks was performed by the ZEUS experiment at HERA (electron–proton collider at DESY).
- The top squark production depends on the strength of R-parity violation (λ′), and the decay was assumed to be either to b+C1 or R-parity violating to a lepton and a jet. A top squark lighter than 260 GeV was excluded for λ′ = 0.3 and under specific model assumptions [1].




[1] ZEUS Collaboration, *Search for stop production in R-parity-violating supersymmetry at HERA*, Eur.Phys.J. **C50** (2007) 269–281.

# Limit from ttbar cross section

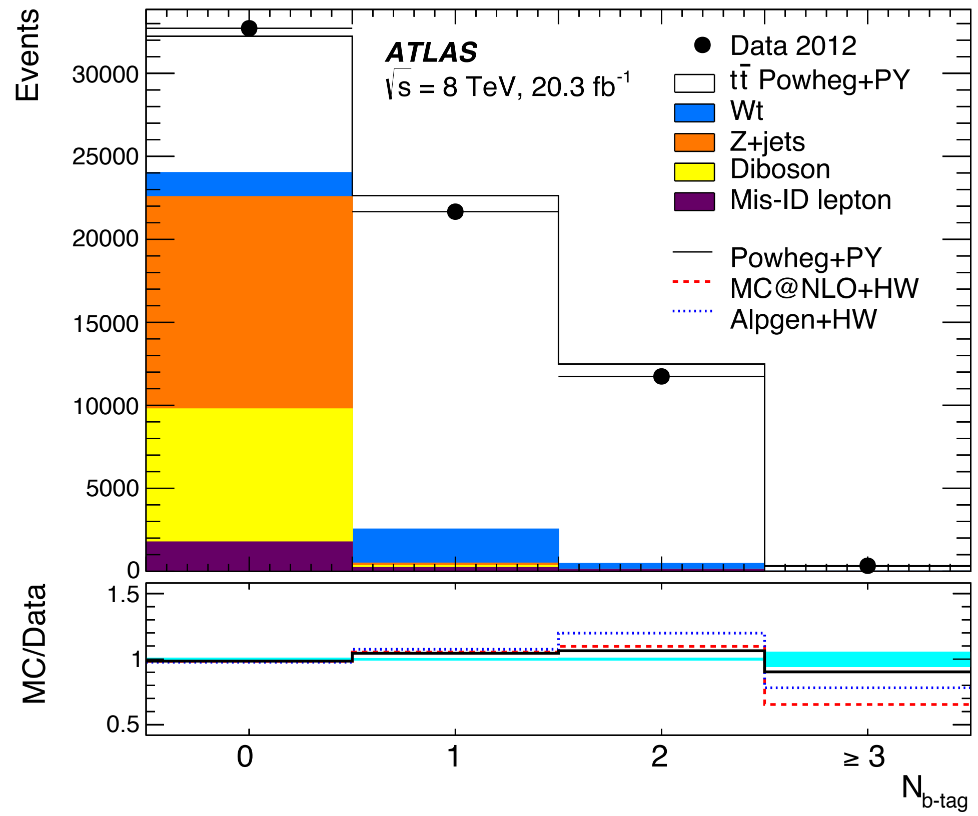
Submitted to EPJC (1406.5375)

- Exclusion set in terms of measured vs. theory cross-section difference Δ.
- The two datasets were fitted simultaneously, including the uncertainty due to a ±1 GeV variation in the top quark mass.
- The limits were determined using a profile likelihood ratio, using nuisance parameters to account for correlated theoretical and experimental uncertainties.
- observed and expected limits on $\mu_{SIG}$ (signal strength) at the 95 % CL were extracted using the CLs prescription.

- Checking 8 / 7TeV exclusions separately:
  - 8 TeV limits better than 'expected', 7 TeV slightly worse.
  - Not much difference in sensitivity, not much gained in combining (large correlations in theor. and exp. uncertainties).

# Limit from ttbar cross section

Submitted to EPJC (1406.5375)




Measurement described in talk by Javier Brochero Cifuentes (Monday)

- Precise measurement of tT production cross-section at 7 and 8 TeV
  - events with eμ (opp-sign) and exactly 1 or 2 b-tagged jets.
  - Use ratio of 1 to 2 b-jet events to estimate probability of reconstructing and tagging a b-jet from the data – reduce JES, b-tagging, ISR/FSR, b-jet modelling uncertainties
- Results

$$\sigma_{t\bar{t}} = 182.9 \pm 3.1 \pm 4.2 \pm 3.6 \pm 3.3\,\text{pb}\ (\sqrt{s} = 7\,\text{TeV})\ \text{and}$$
$$\sigma_{t\bar{t}} = 242.4 \pm 1.7 \pm 5.5 \pm 7.5 \pm 4.2\,\text{pb}\ (\sqrt{s} = 8\,\text{TeV}),$$

  - Uncertainties from data statistics, systematics, luminosity, beam energy
  - Theory (including Δmtop) $177.3^{+11.5}_{-12.0}$ pb (7 TeV), $252.9^{+15.3}_{-16.3}$ pb (8 TeV)