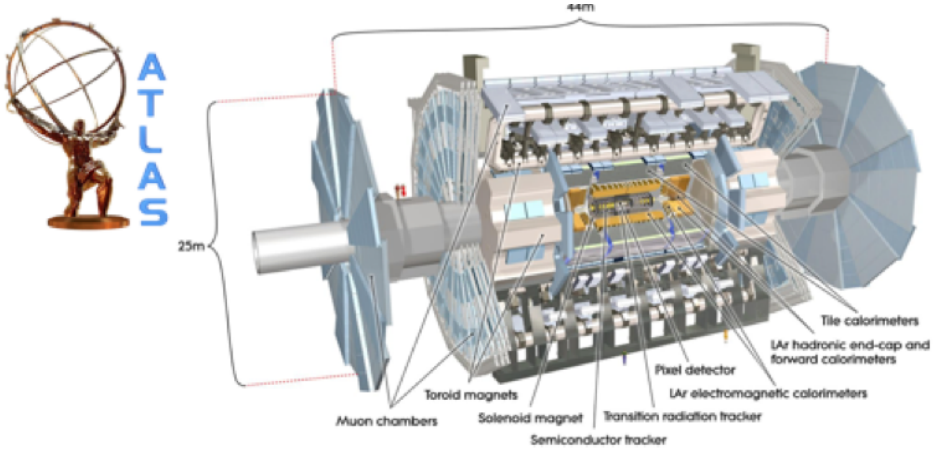
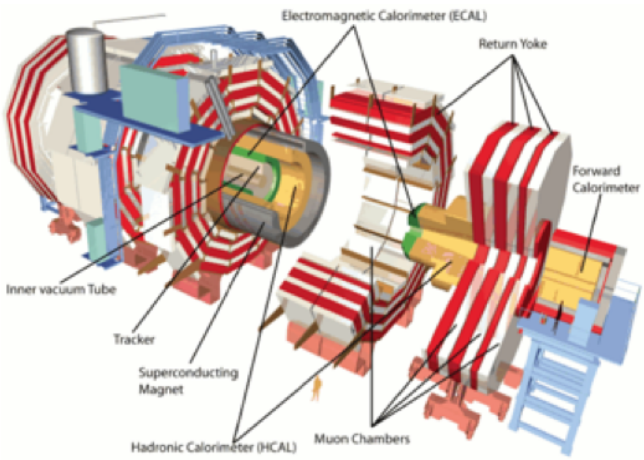
Naturalness 2014

Weizmann Institute of Science,
November 14-17, 2014

Natural SUSY searches in ATLAS and CMS

Margherita Primavera
INFN- Lecce

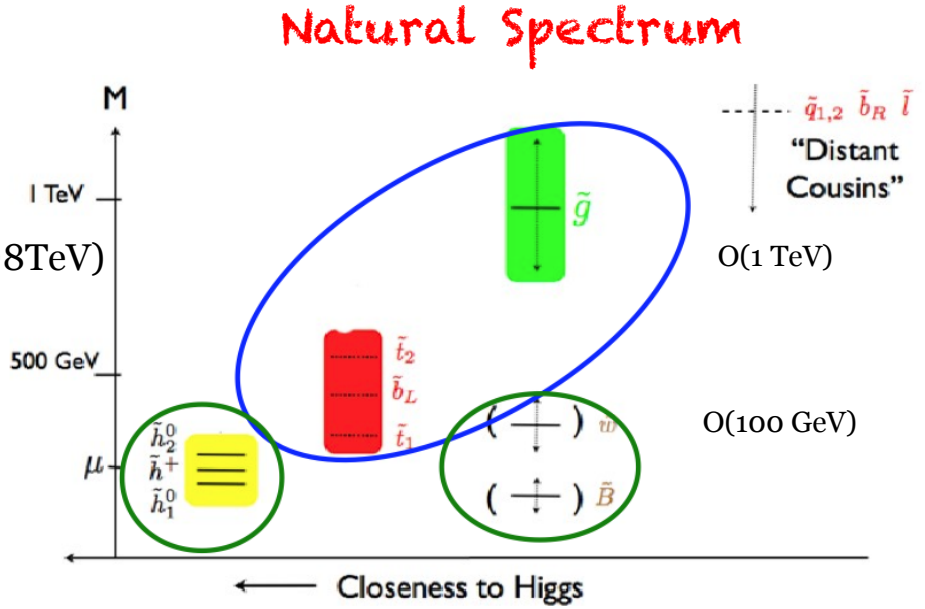




November 14, 2014

"Natural" SUSY

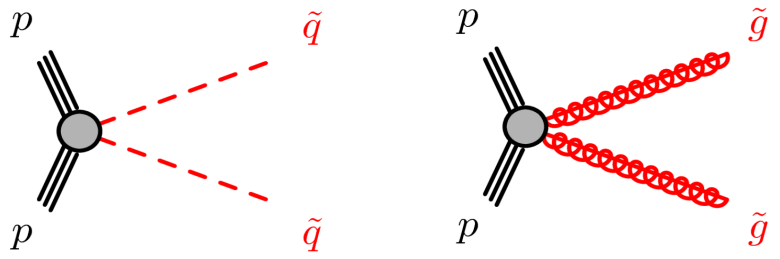
- Provides an elegant solution to the hierarchy problem
  - Put heavy constraints on higher order corrections to H mass
  - Particles which mainly contribute cannot be too heavy ($\tilde{g}$,$\tilde{t}$,$\tilde{b}$,$\tilde{h}$'s accessible at LHC, other particles are heavier, part of the spectrum has to decouple)
  - Natural SUSY searches:



Strong SUSY production

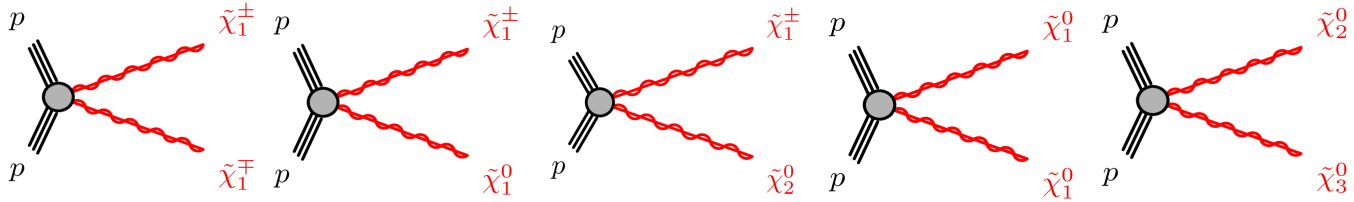
✓ Gluinos (expected sensitivity up to ~1.2TeV@8TeV)

✓ 3rd generation squarks (expected sensitivity ~0.7TeV@8TeV)



EWK SUSY production

✓ Chargino/Neutralino pairs (expected sensitivity ~0.2-0.5TeV@8TeV)



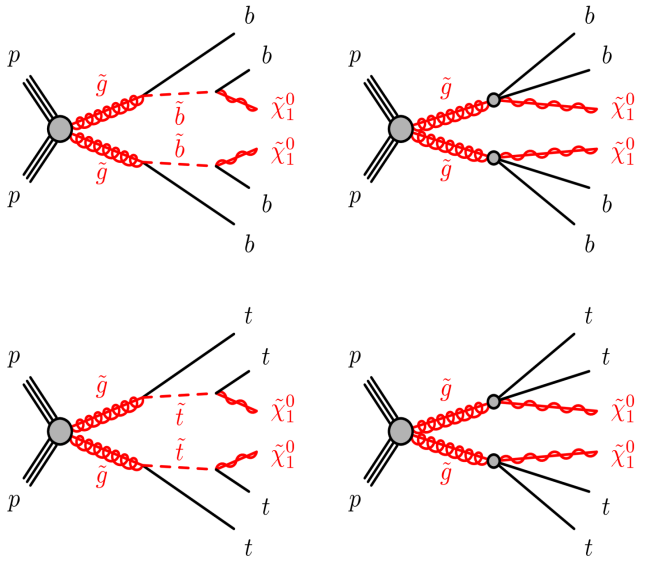
Focus on searches based on ~20. fb^{-1} of data collected at 8 TeV

SUSY analyses in ATLAS and CMS

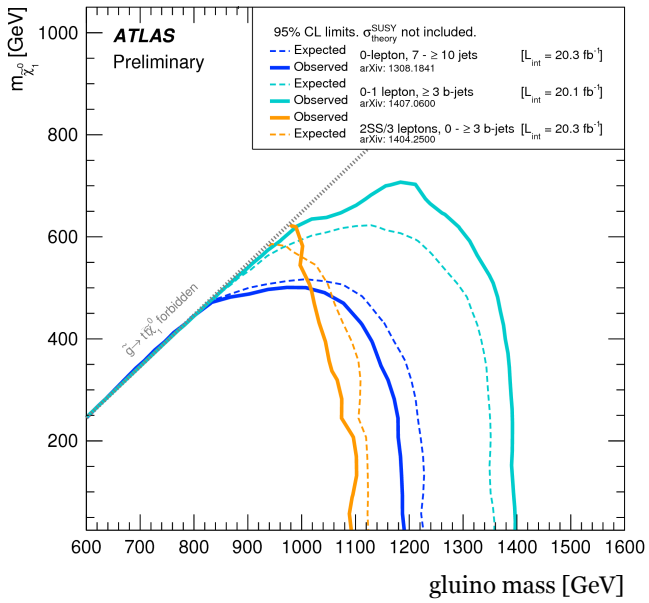
- Strategy:
  - Signal ->look at interesting signatures based on models of interest
  - Signal Region (SR) definition -> apply cuts on discriminating variables (E_t^{miss}, m_{eff}, m_{T2}, Razor, …) to enhance the signal over the background
  - "Cut&Count", multi-variate analyses (MVA), "shape fits"
  - Main irreducible backgrounds -> normalize MC to data in suitable Control Regions (CR): close to SR but no overlap with them, high purity of backgrounds in a given CR
  - Dedicated data-driven methods to estimate fake leptons from QCD or fake E_t^{miss}
  - Data in SR -> blind until background validation, if no excess set limits at given confidence level (CL). Tested many simplified models (BR=100%, parameters are the masses of the SUSY particles)

Gluinos decaying into 3rd generation squarks

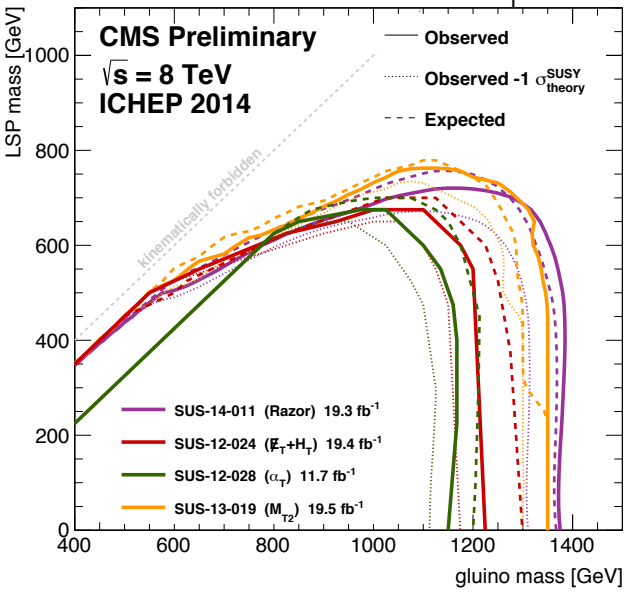
- Events with large E_t^{miss}, # of b-jets (>=3) and 0/1/2 same sign(SS)/3 leptons
- Multiple SRs, depending on jet multiplicity
  - ATLAS -> exploits E_t^{miss}, $m_{eff} = E_t^{miss} + \Sigma_{jet} p_T$ sensitivity
  - CMS -> uses α_T, Razor, m_{T2} and angular selection



$\tilde{g}$-$\tilde{g}$ production, $\tilde{g}$->tt$\tilde{\chi}_1^0$

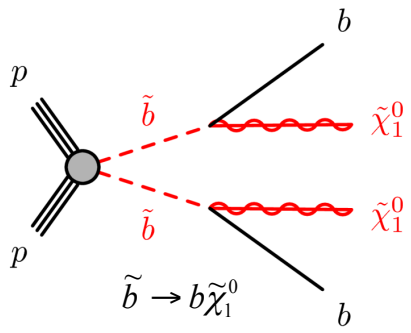


$\tilde{g}$-$\tilde{g}$ production, $\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0$

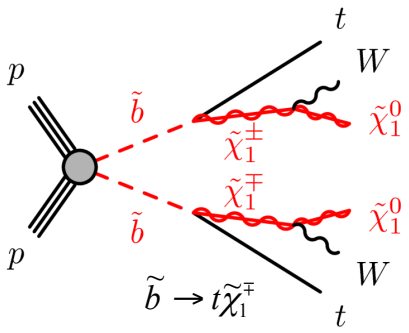


$m_{\tilde{g}}$ > ~1400 GeV independently of decay mode (off-shell stop or sbottom) for massless LSP

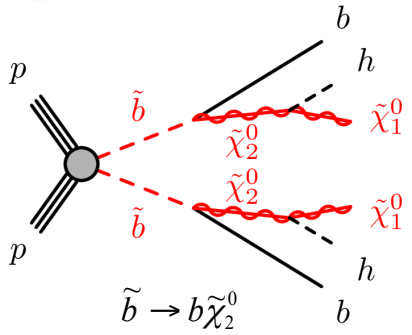
Direct production of sbottom pairs



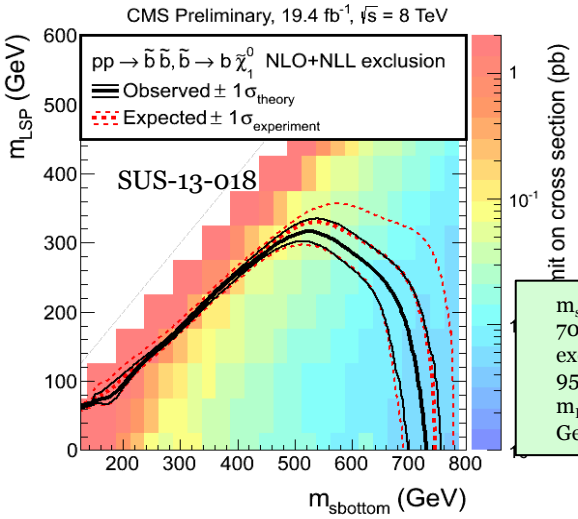
- bjet # =1 or 2, 0 lepton
- Signal discriminant is M_{CT} (8 exclusive SRs)



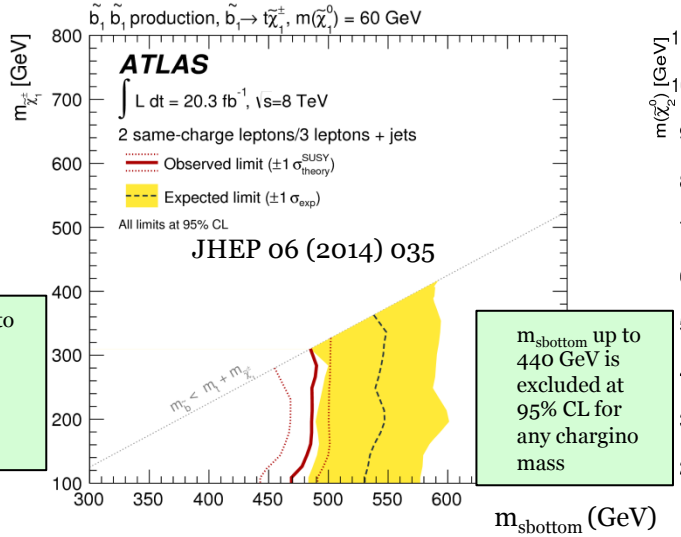
- bjet # =0-2
- 2 same-sign (SS) or 3 leptons
- SRs based on E_T^{miss}, N_{jets}, $M_T(\ell_1\text{-}E_t^{miss})$, $m_{eff}= E_t^{miss} + \Sigma_{jet}p_T + \Sigma_{\ell}p_T$



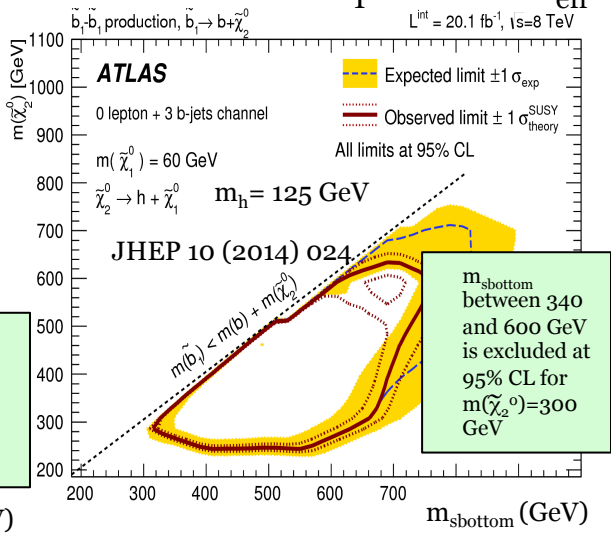
- bjet # >=3, 0 lepton
- $\tilde{\chi}_2^0$ can decay (BR=100%) to the lightest neutral Higgs boson (or Z), h->$b\bar{b}$(same BRs than the SM Higgs)
- SRs based on E_T^{miss} and m_{eff}



$m_{sbottom}$ up to 700 GeV is excluded at 95% CL for m_{LSP} < 50 GeV.



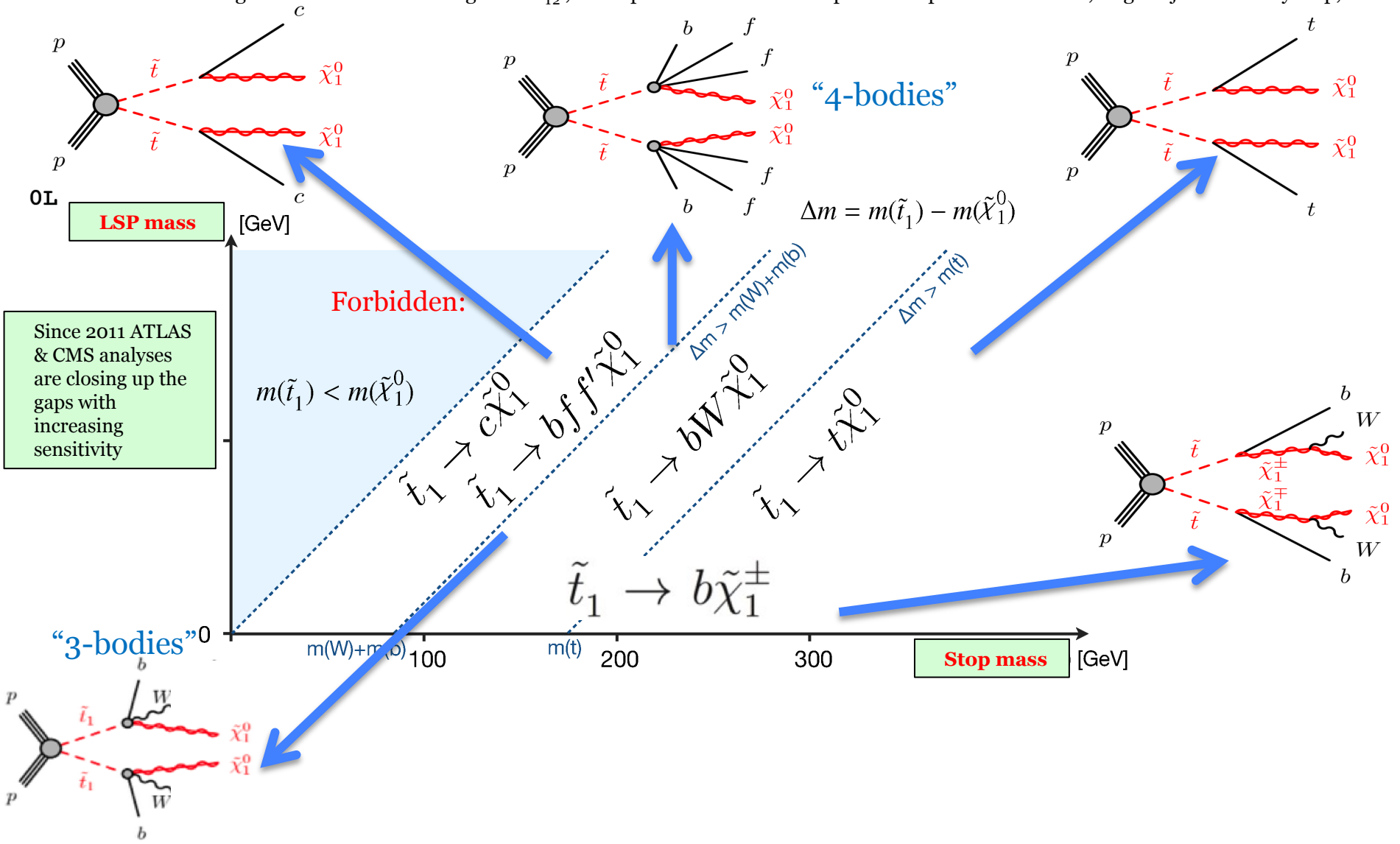
$m_{sbottom}$ up to 440 GeV is excluded at 95% CL for any chargino mass



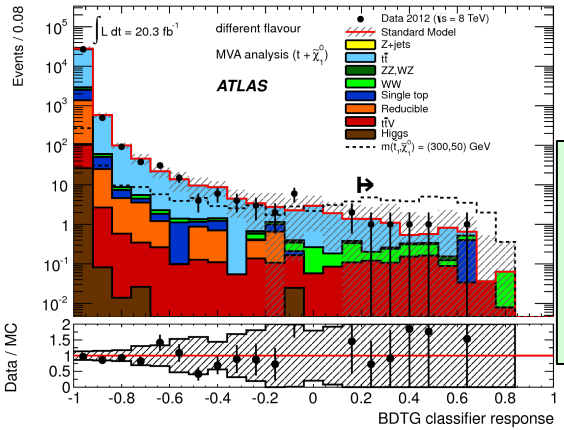
$m_{sbottom}$ between 340 and 600 GeV is excluded at 95% CL for $m(\tilde{\chi}_2^0)$=300 GeV

Direct production of stop pairs

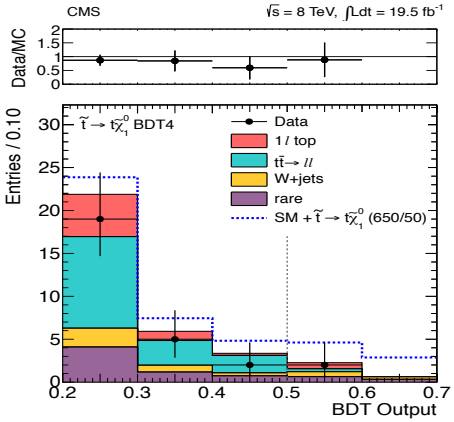
- Large variety of decays, sensitivity highly dependent on the decay mode and the mass hierarchy of the produced (s)particles
- Searches in many final state by both experiments: 0,1,2 leptons (L), (b)-jets, E_t^{miss}
- Several variables target different kinematic regions: m_{T2} , soft leptons for low mass stop and compressed scenarios, large R-jets for heavy stop, ...



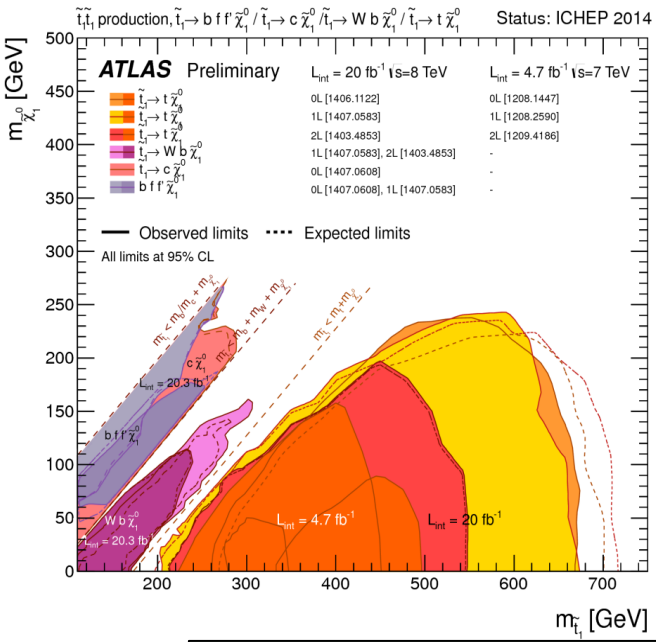
Stops with no chargino in decay: summary plots

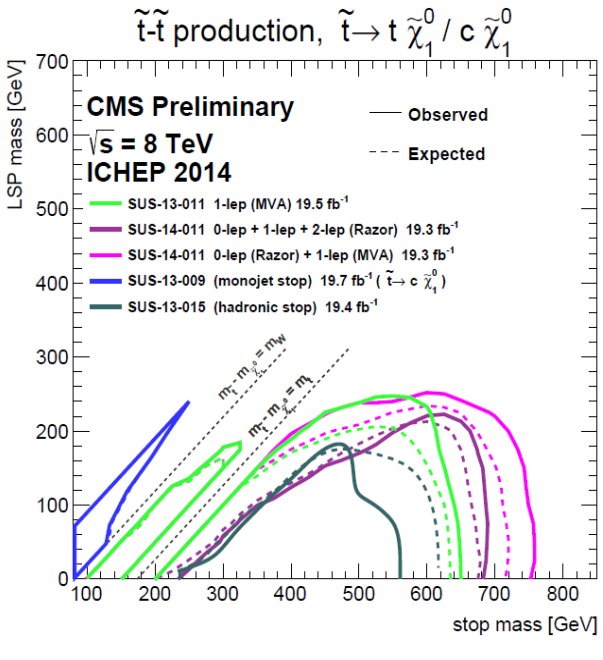


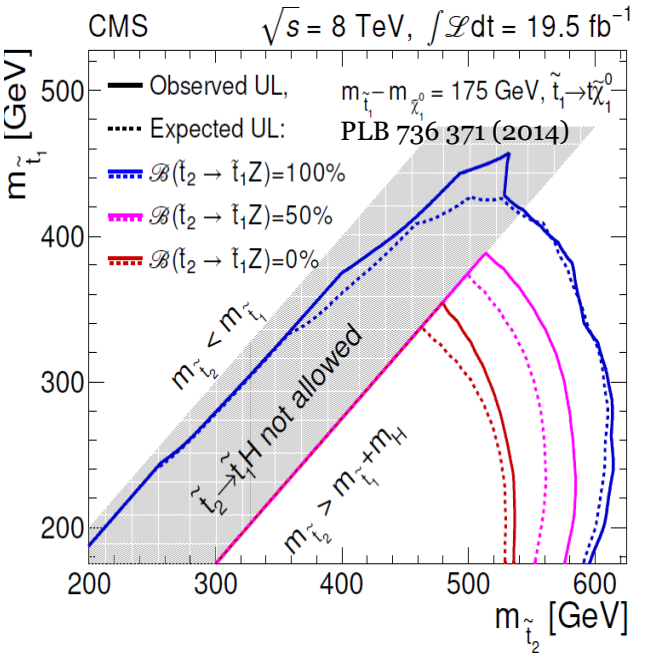
Example of data and expected signal for one SR ($(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0})$ = (300,50) GeV) in $\tilde{t}_1 \to t + \tilde{\chi}_1^0$ analysis with 2 leptons in the final state. MVA with Boosted Decision Trees with Gradient boost (**BDTG**) classifier is used as discriminator.



Example of data and expected signal for the tightest sel. SR in $\tilde{t}_1 \to t + \tilde{\chi}_1^0$ analysis with 1 lepton in the final state. MVA with Boosted Decision Trees (**BDT**) classifier is used as discriminator.



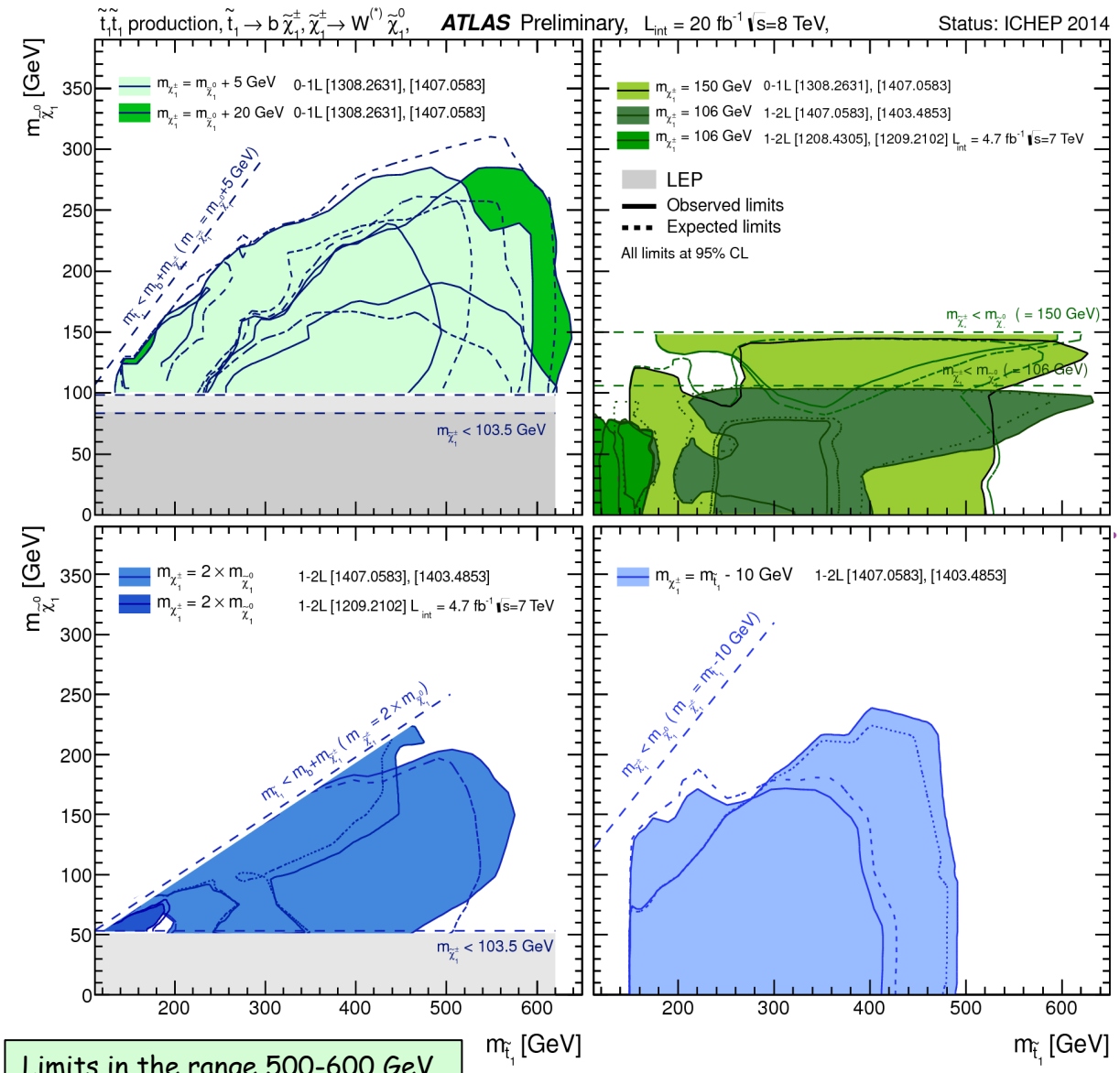




Stop mass > 700 GeV for massless LSP. Gaps in sensitivity: low efficiency on decay products (e.g. p_T of b-tagged jets in 3-body decay) or when neutralinos don't get boost, thus resulting in low E_t^{miss} (compressed areas) -> events are very similar to SM backgrounds

Stop2 mass > ~575 GeV for stop1 mass < ~ 400 GeV

Stops with chargino in decay: summary plots

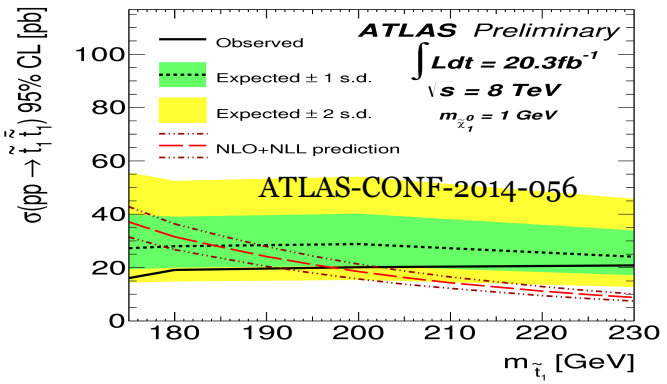


Limits in the range 500-600 GeV

- Several scenarios considered with different sets of $\tilde{t}_1$, $\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_1^0$ masses
- In case of 1L analysis different approaches used for a total of 9 SRs with E_T^{miss} > 140 GeV:
  - based on # of jets and b-tagged jets
  - low-p_T leptons to improve sensitivity for $\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$ decays for small $\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0)$
  - both **cut-and-count** and **shape-fit** methods used to estimate expected and observed exclusion limits

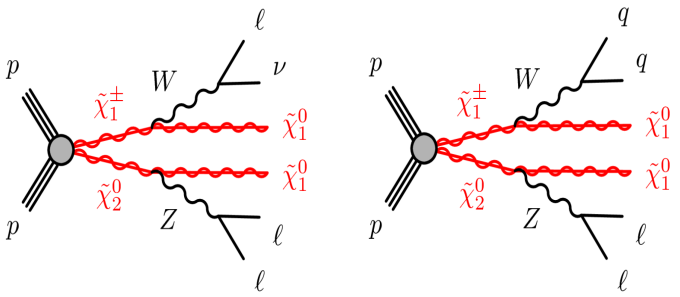
Re-interpretation from $t\bar{t}$ spin correlation measurements

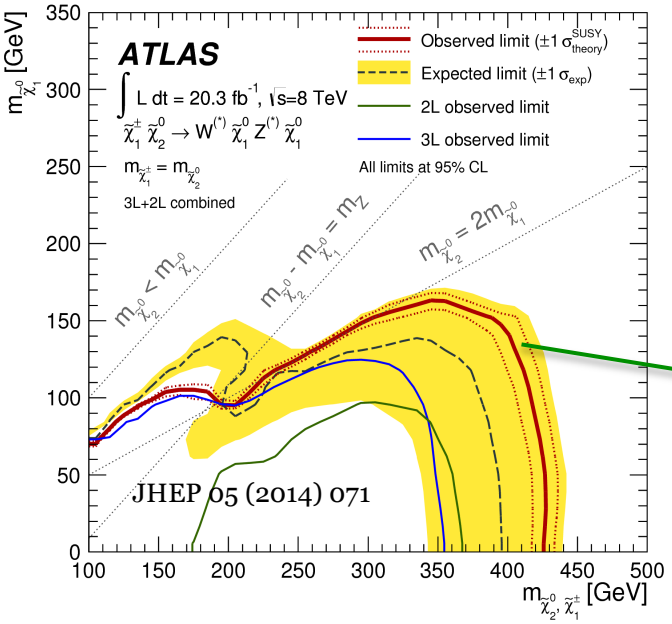
For stop masses close to m_t a small admixture of stop-pair production in addition to the SM $t\bar{t}$ changes the shape of the $\Delta\phi$ distribution between the 2 leptons in dilepton events -> comparing $\Delta\phi$ with SM predictions, a stop decaying (BR = 100%) to mostly right-handed top quarks and neutralino is excluded at 95% CL in [m_t, 191 GeV]

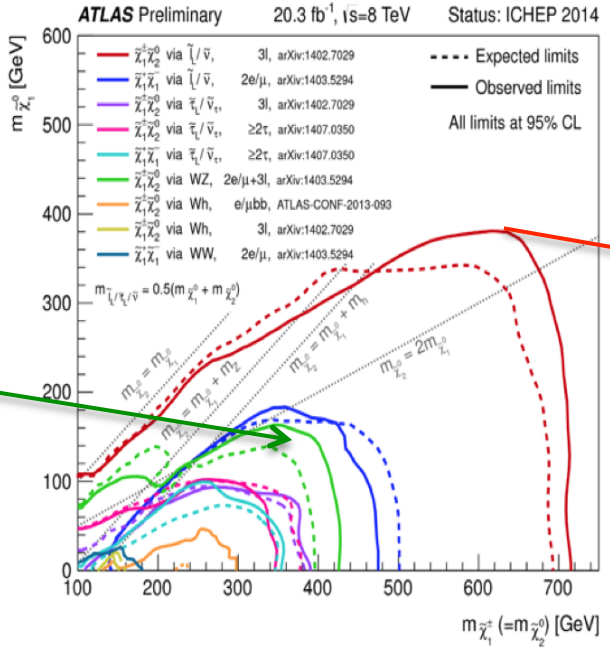


EW direct production of neutralino and chargino pairs

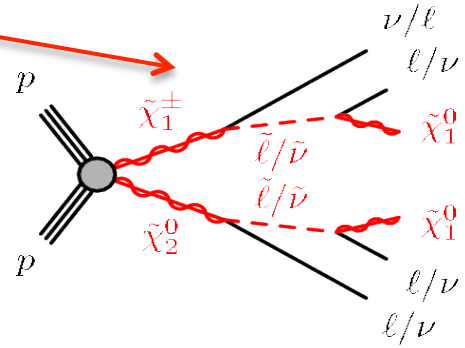
- Challenging searches due to very small production cross sections, but crucial at LHC if the strongly interacting SUSY particles are heavy
- Main background comes from dibosons
- Signatures with leptons: 3L the "golden channel" at LHC
- SRs definition based on lepton flavours, E_t^{miss}, m_T, m_{T2}, N_{jets} , # of b-jets







Best sensitivity reached in 3L analysis, in slepton-mediated scenario (BR=1/6 via $\tilde{e}_L,\tilde{\mu}_L,\tilde{\tau}_L,\tilde{\nu}_e,\tilde{\nu}_m,\tilde{\nu}_\tau$, with masses $m_{\tilde{\nu}} = m_{\tilde{l}} = (m\tilde{\chi}_1^0 + m\,\tilde{\chi}_1^{\pm})/2$

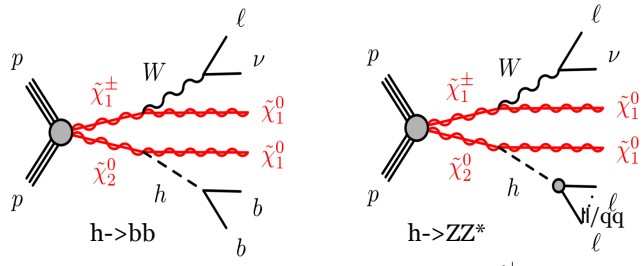


Chargino and heavy neutralino (mass degenerate) > 415 GeV for masseless m_{LSP}

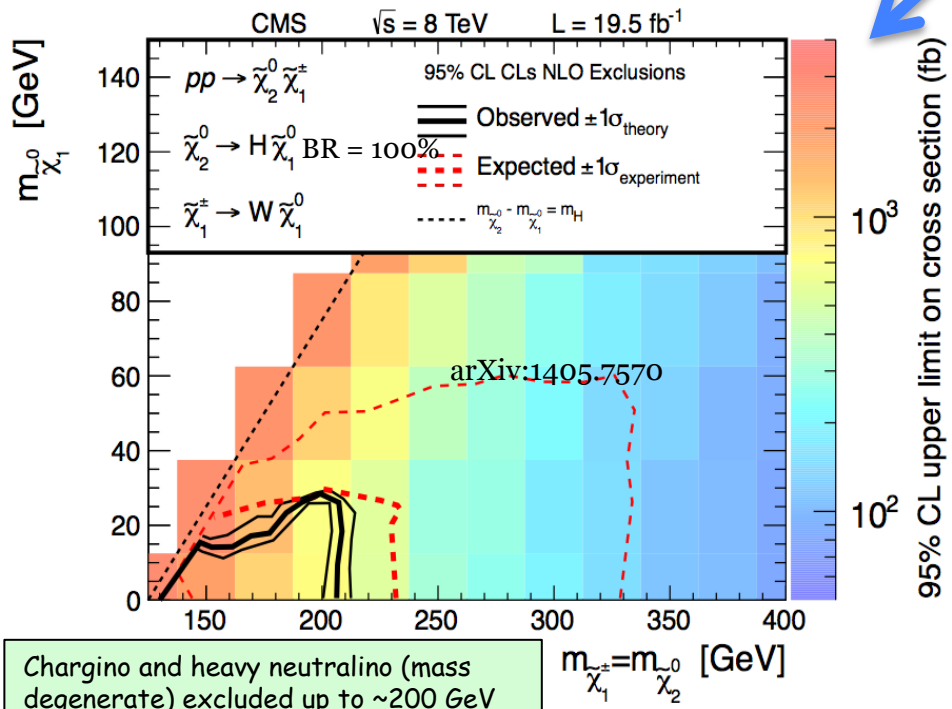
Summary of EW production: chargino and heavy neutralino (mass degenerate) excluded up to ~700 GeV for masseless m_{LSP}

EW direct production of neutralino and chargino pairs

- Higgs boson can probe EW production of SUSY particles
- Very challenging searches, due to low BR of the Higgs into leptonic final states, and high background when Higgs decays into b-quarks
- In all searches W decays leptonically: 1L, 2 SS L, >=3L final states
- Main background comes from ttbar and W+jets
- Selection based on E_t^{miss}, m_{T2}, ...

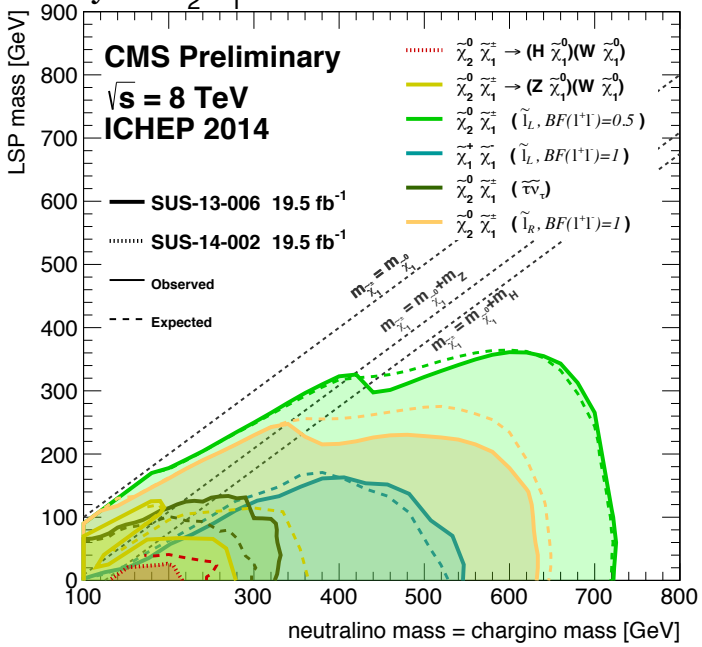


All combined



Chargino and heavy neutralino (mass degenerate) excluded up to ~200 GeV for masseless m_{LSP}

Summary of $\tilde{\chi}_2^0\tilde{\chi}_1^\pm$ production



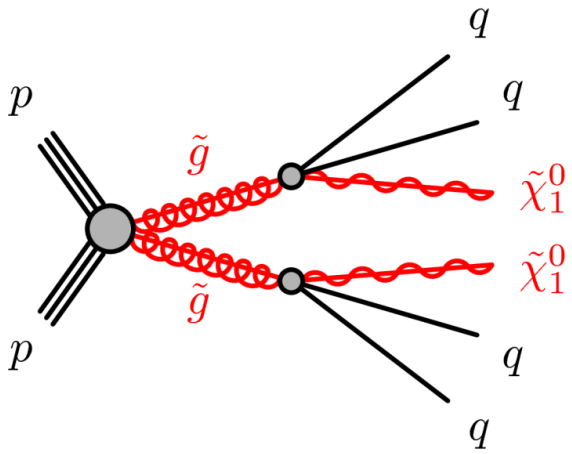
Conclusions

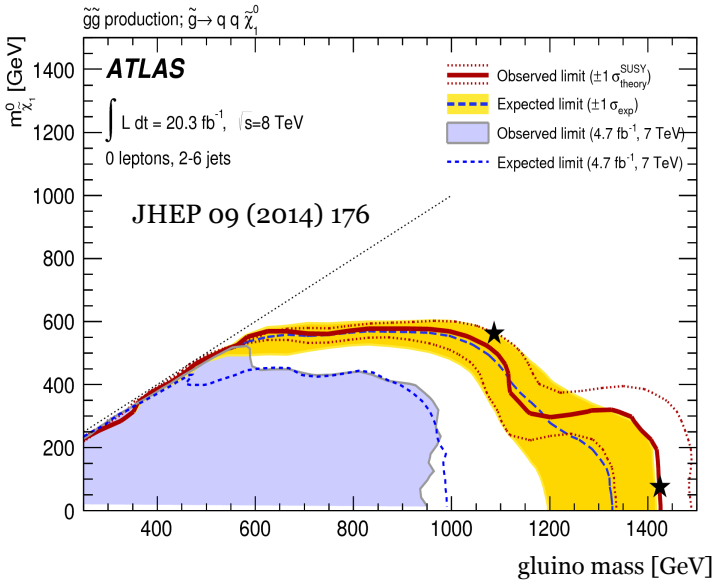
- The present status of Natural SUSY searches at the **LHC** has been presented
- Only some relevant results have been shown here, many more details on **ATLAS** and **CMS** analyses/results in:
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS
  - … and in backup slides: gluinos to virtual light flavour squarks, gluinos to mixed-top-bottom-scenario, gluinos and stops in GMSB scenarios, EW production of $\tilde{\chi}_1^{\pm}\,\tilde{\chi}_1^{\mp}$ and $\tilde{\chi}_1^{0}\,\tilde{\chi}_1^{0}$ in GMSB scenario, etc.….
  - … something missing even in backup: e.g. stop decays to stau (ATLAS-CONF-2014-014)
- No significant excess over the Standard Model background has been observed so far in any analysis
- There is still room for Natural SUSY to be investigated in compressed scenarios, complex decay chains or processes which need higher luminosity
- The next LHC run at $\sqrt{s}$ = 13 TeV will improve knowledge in the uncovered parts of phase space

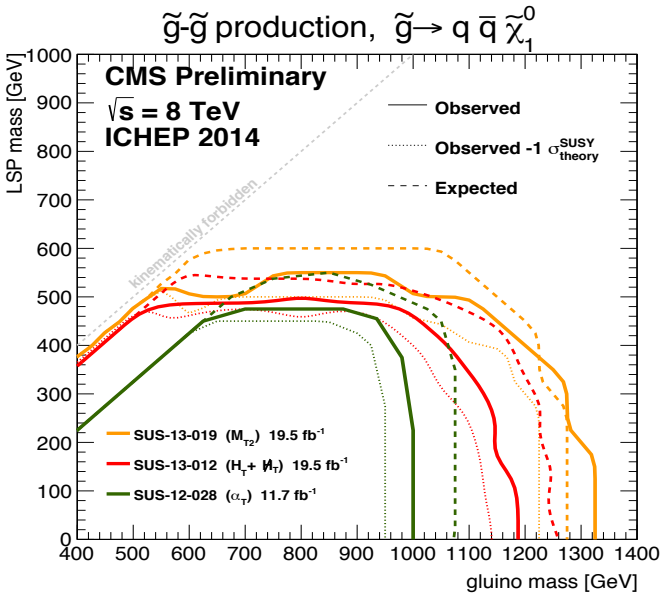
Backup slides

Gluinos decaying into light-flavor squarks

- Direct gluino decays to jets and LSP -> final states with 0 lepton + jets + E_t^{miss}
- Multiple SRs, depending on jet multiplicity (2 to >=6)
  - ATLAS -> exploits E_t^{miss}, $m_{eff} = E_t^{miss} + \Sigma_{jet} p_T$ sensitivity
  - CMS -> reaches the best sensitivity using $H_T = \Sigma_{jet} p_T$ and m_{T2}





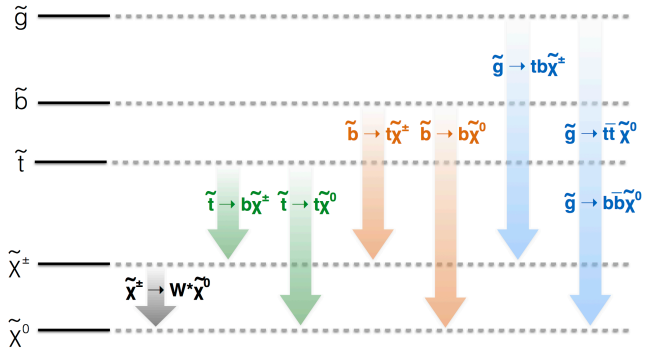


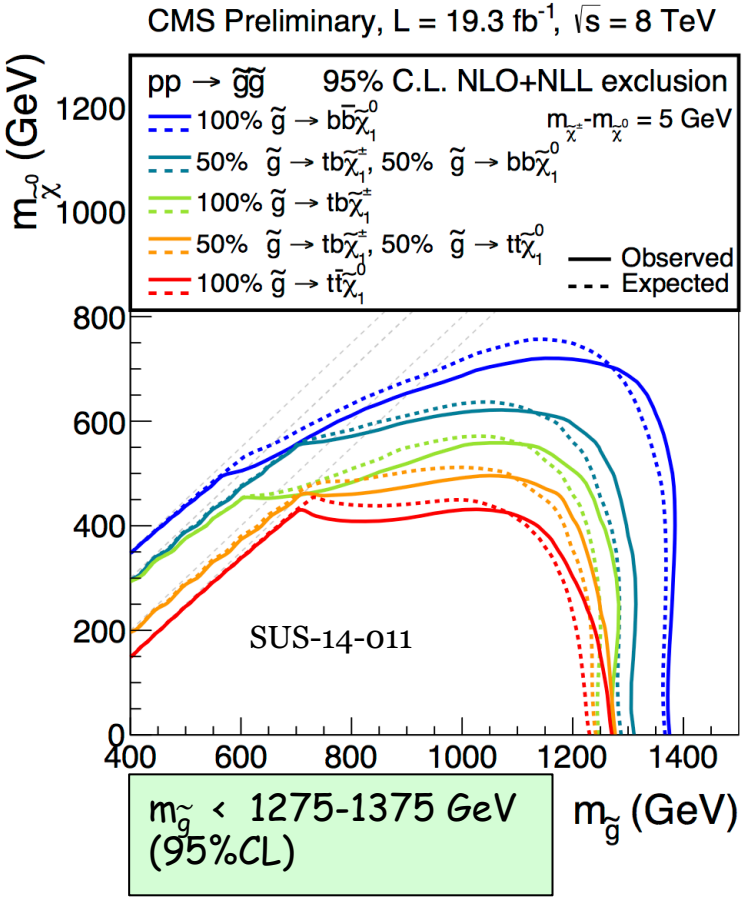
Simplified models with only gluinos and LSP->similar results from both experiments:

$m_{\tilde{g}}$ > 1300 GeV if m_{LSP} < 200 GeV (95%CL)

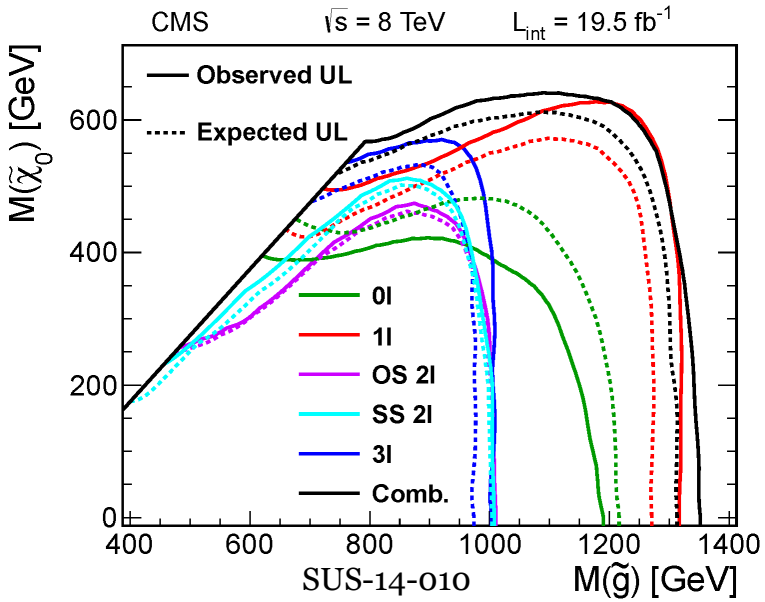
Gluinos decaying into 3rd generation squarks

- Gluino mass limits from the CMS inclusive Razor search for different decay topologies (multi-bottom, multi-top, mixed top-plus-bottom) in the context of the "benchmark" natural SUSY spectrum:





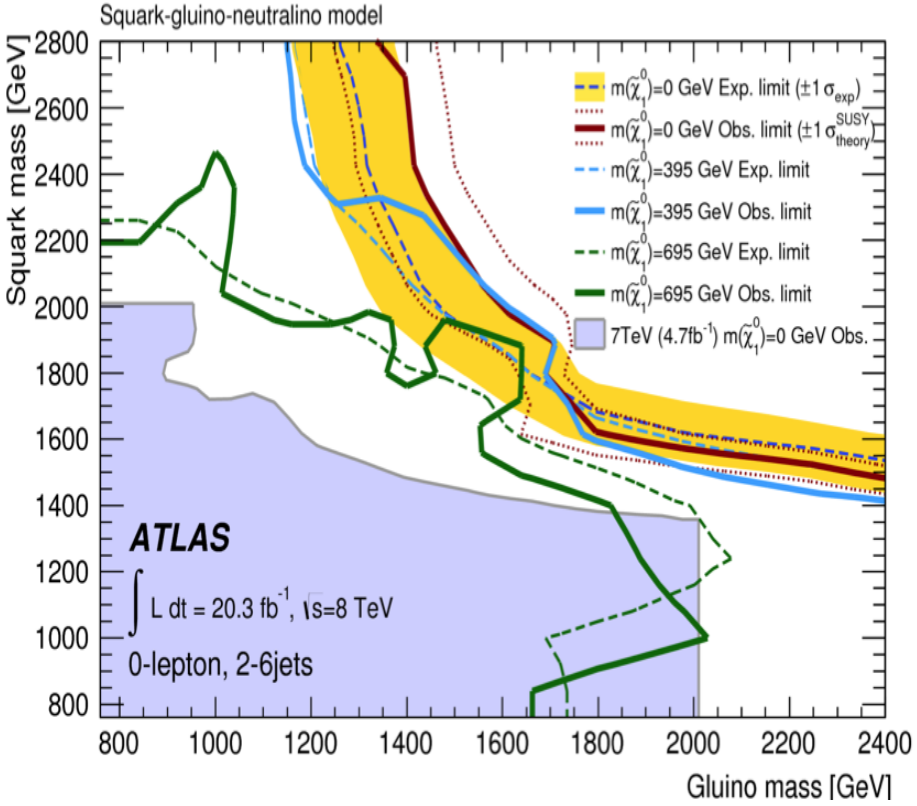
- Gluino mass limits from the CMS 4W+b-jets analyses (0,1,2,2SS,>=3 leptons and all combined) for gluino-mediated stop production with virtual stops

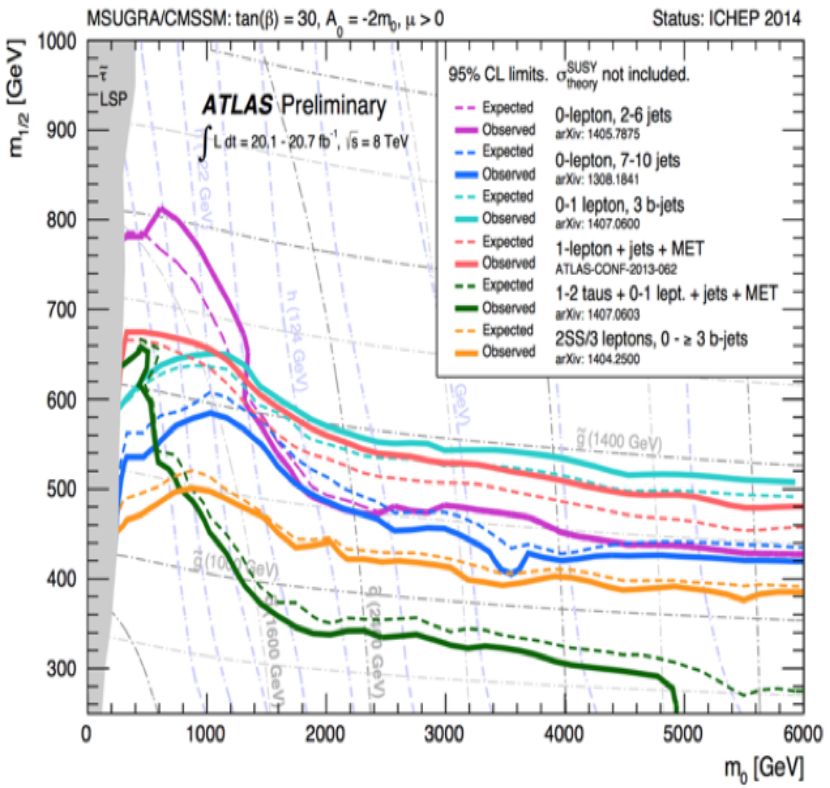


Strong SUSY production: inclusive searches

- Limits on simplified phenomenological MSSM with only strong production of gluinos and 1st and 2nd generation squarks from 0-lepton analysis: excluded Gluino < ~1.2 TeV for massless LSP

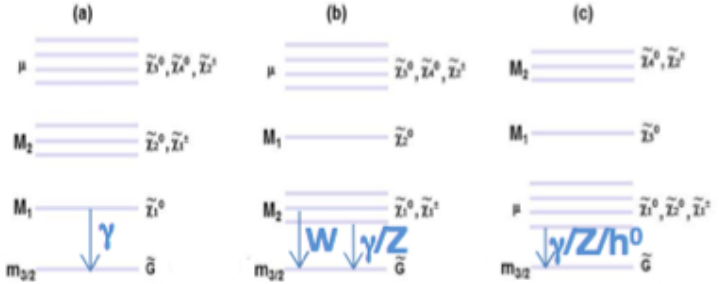
- Limits on mSUGRA/CMSSM models: Gluino < 1.4 TeV, similar to simplified models. Described with 5 parameters, 3 of which fixed in the plot to have Higgs mass close to 125 GeV across the plane



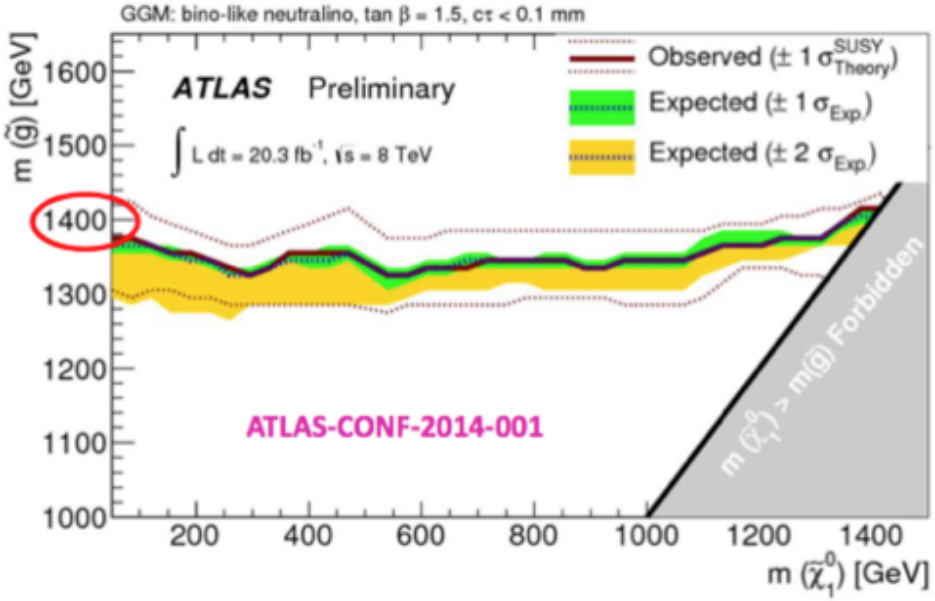


Gluino searches

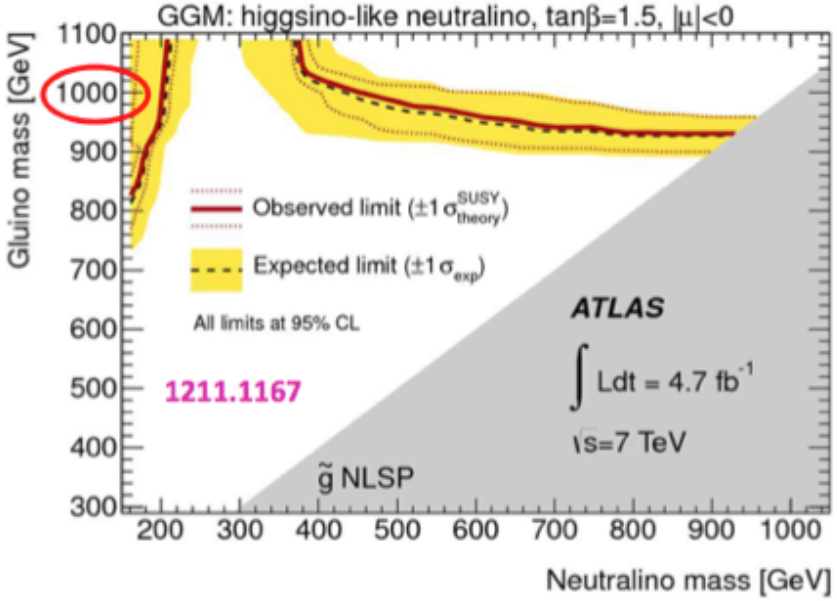
- With $\tilde{G}$ = LSP, searches driven by $\tilde{\chi}_1^0$ decay to $\tilde{G}$:
  - Ask for many energetic jets, E_t^{miss}
  - …or additional photons and leptons/b-jets



$\gamma\gamma + E_t^{miss}$



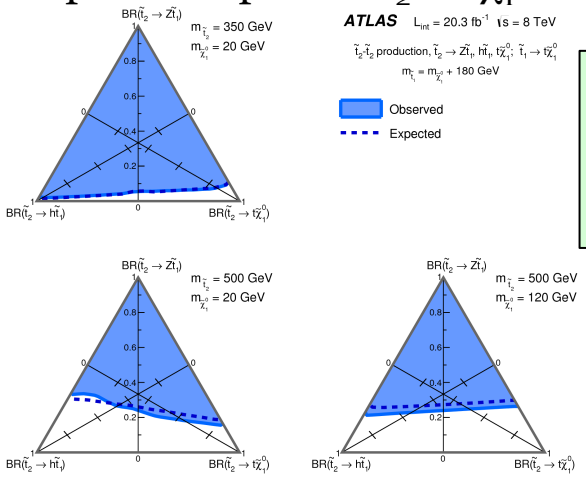
$\gamma h^0(->2b) + E_t^{miss}$



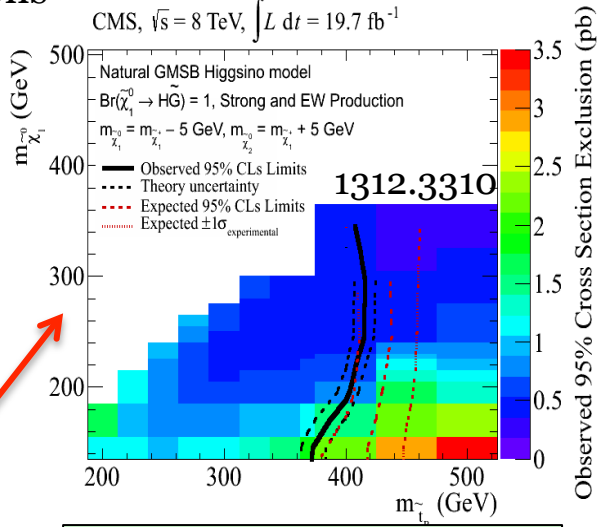
3rd generation squarks: stops

- Vary the branching ratios (100%->50%), polarization assumptions
- Very compressed spectra: $\tilde{t}_2$-> $t\tilde{\chi}_1^0$ or $\tilde{t}_2$-> $Z/H\tilde{t}_1$, $\tilde{t}_1$-> $t\tilde{\chi}_1^0$

1403.5222

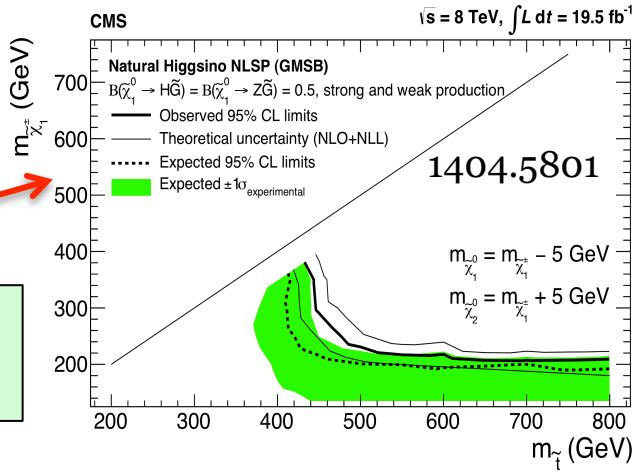


Limits as functions of the BRs for different values of $\tilde{t}_2$ and $\tilde{\chi}_1^0$ masses: BR($\tilde{t}_2$-> $Z/H\tilde{t}_1$) > 10-30% excluded for several mass configurations



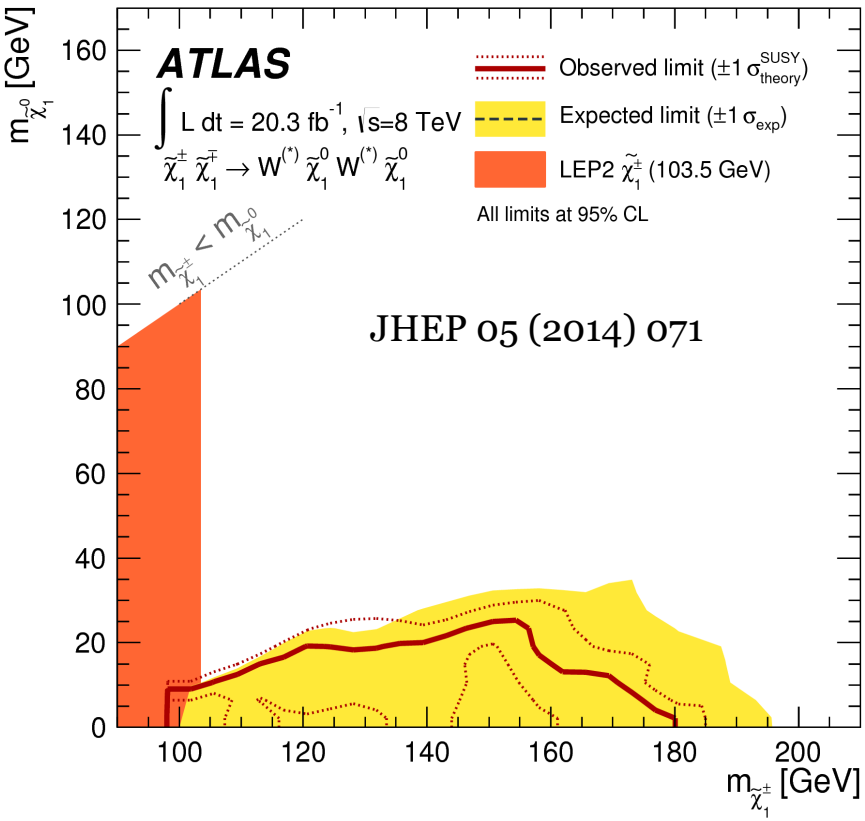
Stop masses below 360 to 410 GeV excluded (95%CL)

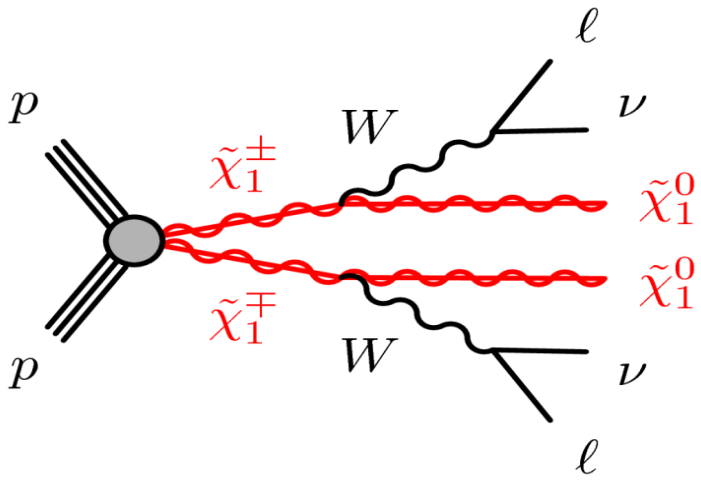
- $\tilde{G}$ = LSP (GMSB scenario) also pursued in:
  - NLSP Higgsino like: $\tilde{t}_1$-> $b\tilde{\chi}_1^{\pm}$-> bff '$\tilde{\chi}_1^0$-> bff 'h^0(->γγ,bb)$\tilde{G}$ 1312.3310 (CMS)
  - NLSP Higgsino like: $\tilde{t}_1$-> $b\tilde{\chi}_1^{\pm}$-> bff '$\tilde{\chi}_1^0$-> bff 'h^0(->ZZ)/ Z(->ll)$\tilde{G}$ 1404.5801 (CMS),1403.5222 (ATLAS)



Region to the left and below the contours is excluded at 95% CL

EW direct production of chargino pairs

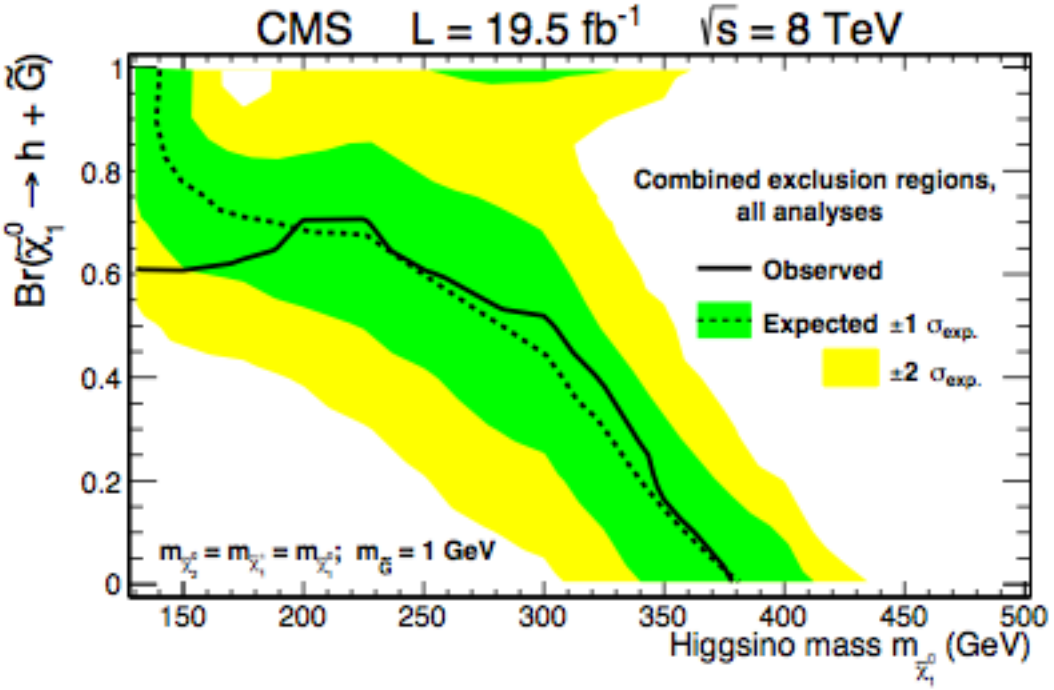




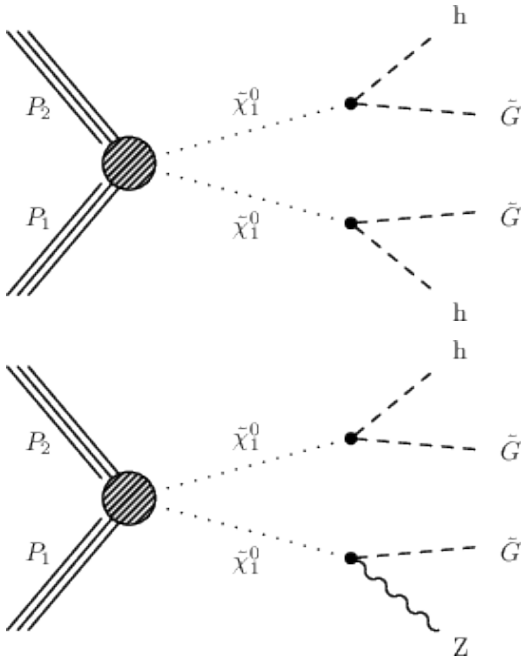
Chargino mass ranges between 100 and 160 GeV excluded for massless m_{LSP}

EW direct production of neutralino pairs

- hh and hZ topologies pursued in R-parity conserving GMSB SUSY scenarios where $\tilde{\chi}_1^0$ is the NLSP and $\tilde{G}$ is the nearly massless LSP. The pair production of any chargino/neutralino combination is allowed, enhancing $\tilde{\chi}_1^0 \tilde{\chi}_1^0$ cross-section
- Searches performed in h->bb/γγ/leptons , Z–> ll/jets channels

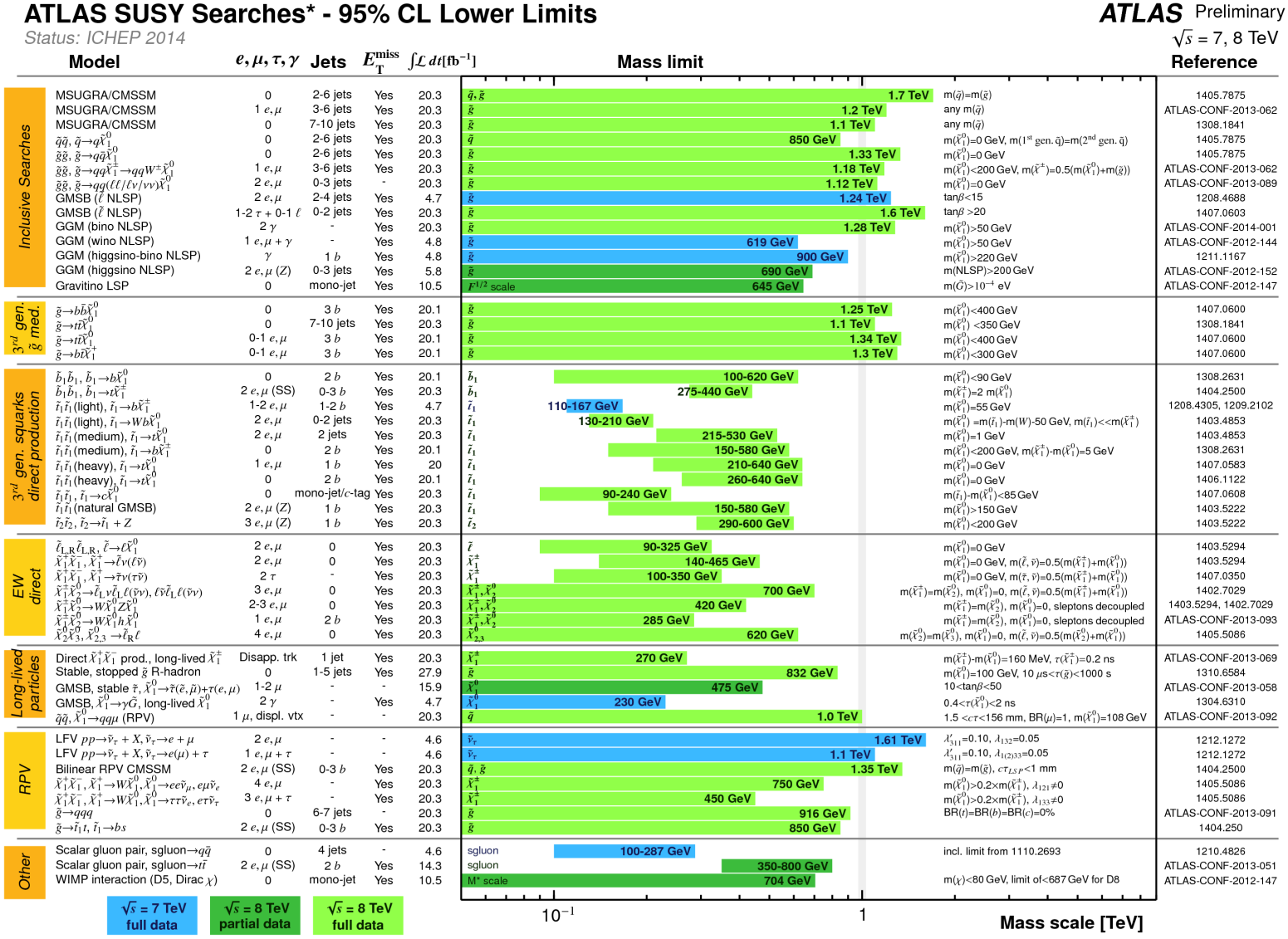


arXiv:1409.3168



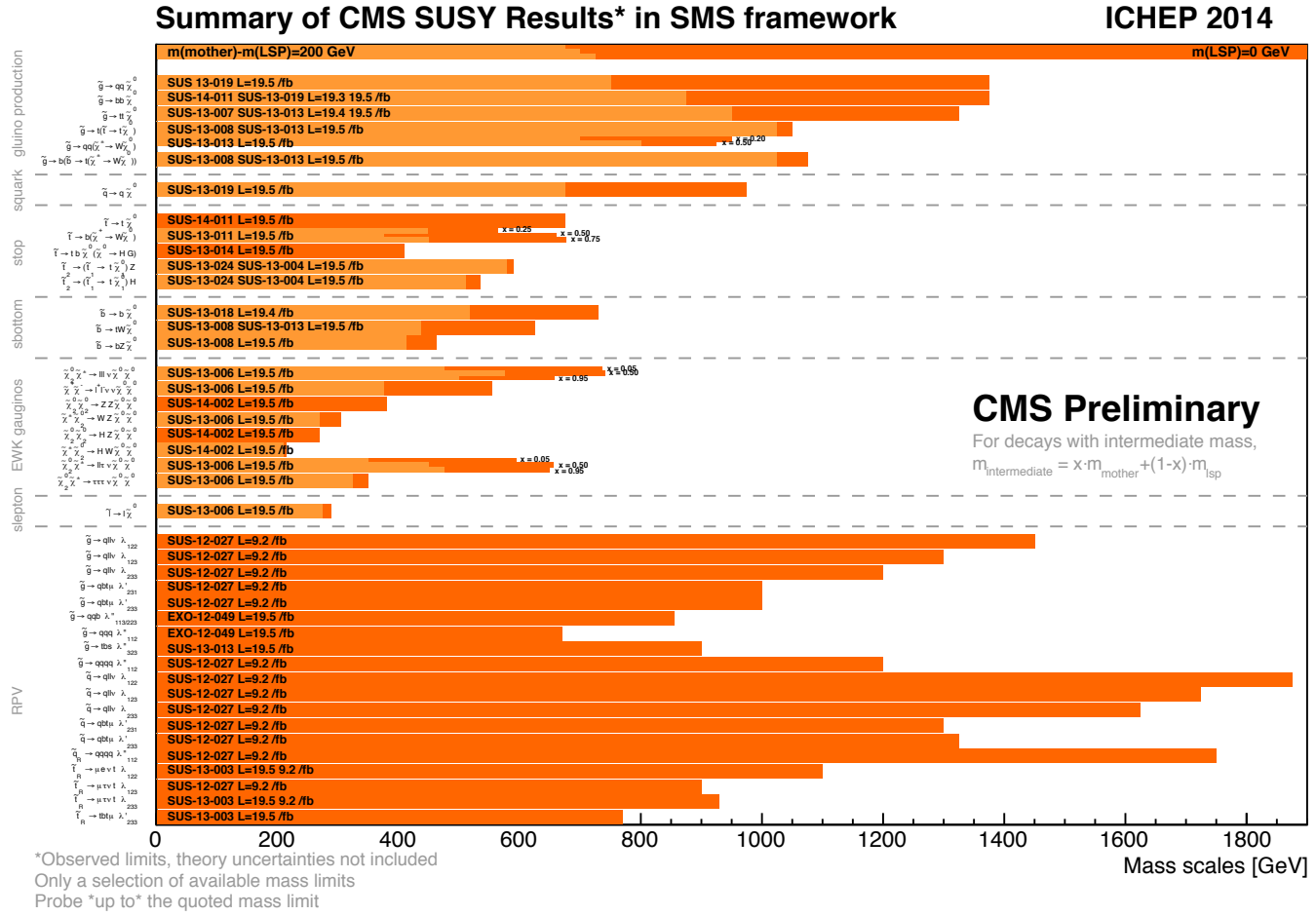
$\tilde{\chi}_1^0$ masses >~ 300 GeV
for BR($\tilde{\chi}_1^0$) -> h+$\tilde{G}$ = 50%

ATLAS SUSY searches: 95% CL exclusion limits



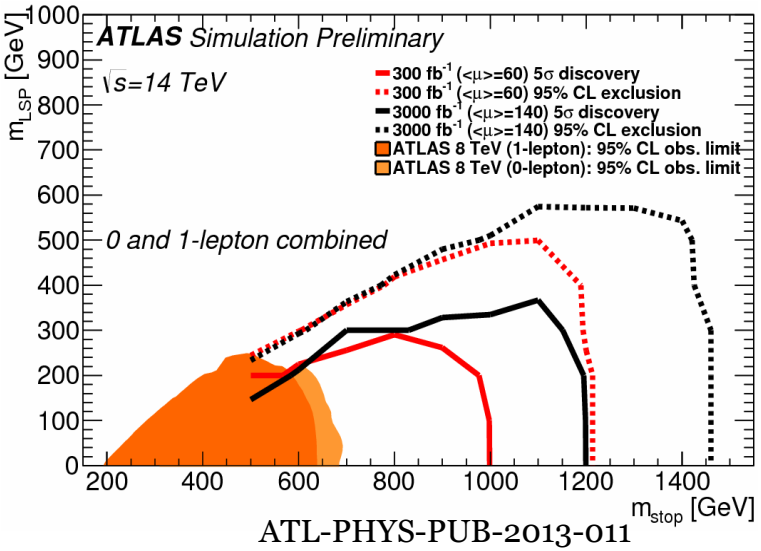
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

CMS SUSY searches: 95% CL exclusion limits

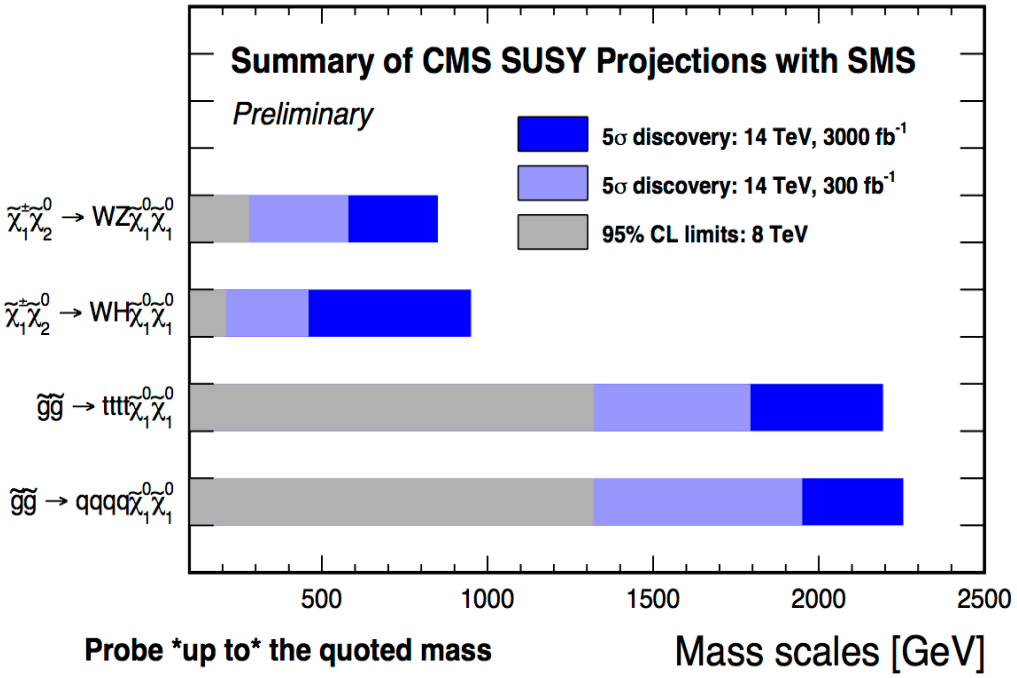


Expected at 14 TeV

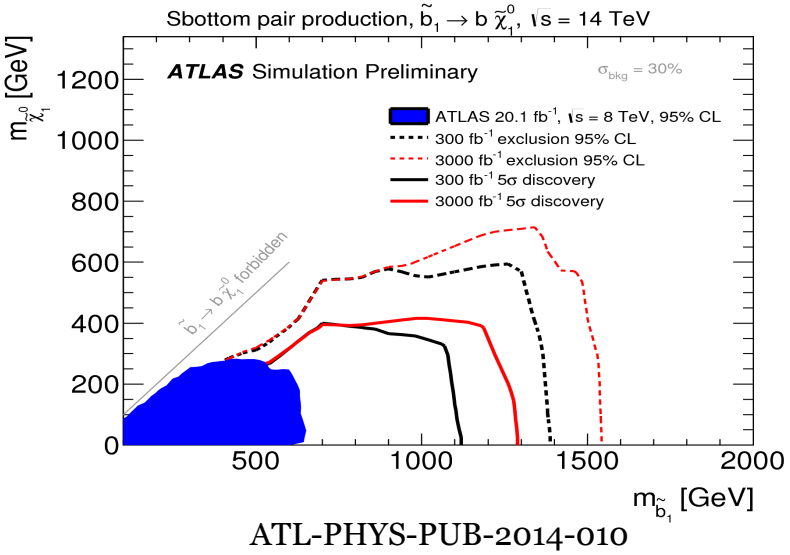
$\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$



ATL-PHYS-PUB-2013-011



SUS-14-012



ATL-PHYS-PUB-2014-010

Mass reach of searches for supersymmetry based on simplified models (SMS)

M_{CT} in CMS hadronic sbottom

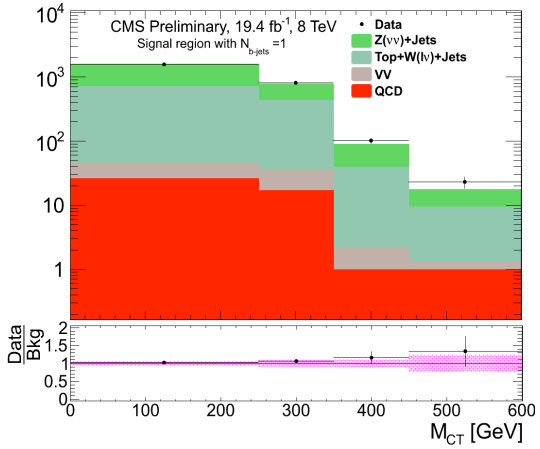
- For processes with two identical decays of heavy particles like $\tilde{b}$-> $J_i\tilde{\chi}_1^0$ the boost-corrected contrasverse mass is defined as:

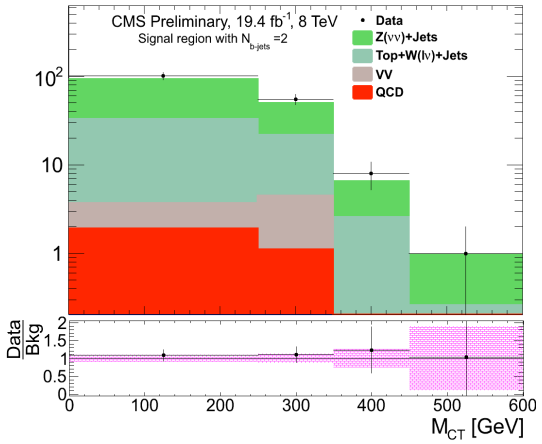
$$M_{CT}^2(J_1, J_2) = [E_T(J_1) + E_T(J_2)]^2 - [\mathbf{p}_T(J_1) - \mathbf{p}_T(J_2)]^2$$
$$= 2p_T(J_1)p_T(J_2)(1 + \cos\Delta\phi(J_1, J_2)),$$

$M_{CT}(J_1,J_2)$ is characterized for signal by an endpoint at $(m(\tilde{b})^2 - m(\tilde{\chi}_1^0)^2)/m(\tilde{b})$.

Table 1: Definition of eight exclusive search regions.

No. of b-jets	M_{CT}	M_{CT}	M_{CT}	M_{CT}
$N_{b-jets} = 1$	< 250 GeV	250 - 350 GeV	350 - 450 GeV	> 450 GeV
$N_{b-jets} = 2$	< 250 GeV	250 - 350 GeV	350 - 450 GeV	> 450 GeV





SUS-13-018

α_T in CMS searches for SUSY

- α_T robust against the presence of jet energy mismeasurements in multijet systems. For events with three or more jets, a pseudo-dijet system is formed and:

$$\alpha_T = \frac{1}{2} \times \frac{H_T - \Delta H_T}{\sqrt{H_T^2 - \not{H}_T^2}} = \frac{1}{2} \times \frac{1 - (\Delta H_T / H_T)}{\sqrt{1 - (\not{H}_T / H_T)^2}}$$

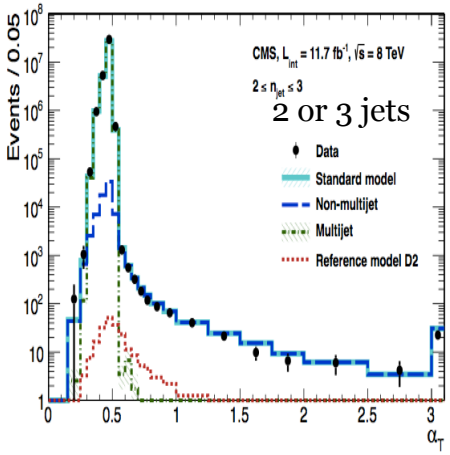
$$H_T = \sum_{i=1}^{n_{jet}} E_T^{j_i}$$

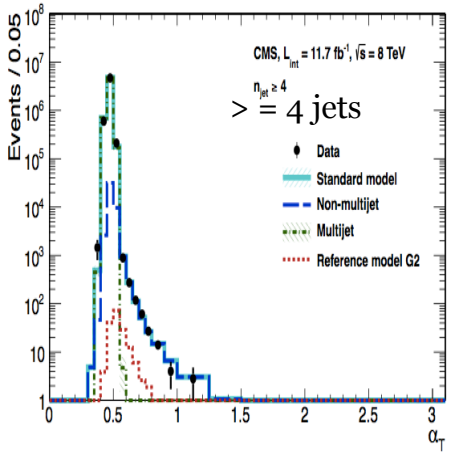
$$\not{H}_T = \left| \sum_{i=1}^{N_{jet}} \vec{p}_T^{\,j_i} \right|$$

Where the combination chosen minimises the absolute difference between the two pseudo-jets ΔH_T

- α_T distribution has a sharp edge at 0.5 beyond which the multijet background falls by several orders of magnitude -> $\alpha_T > 0.5$

Analysis bin H_T [GeV]	Trigger thresholds H_T [GeV]	α_T
275–325	250	0.55
325–375	300	0.53
375–475	350	0.52
≥475	400	0.51





SUS-12-028

m_{T2} in ATLAS and CMS searches for SUSY

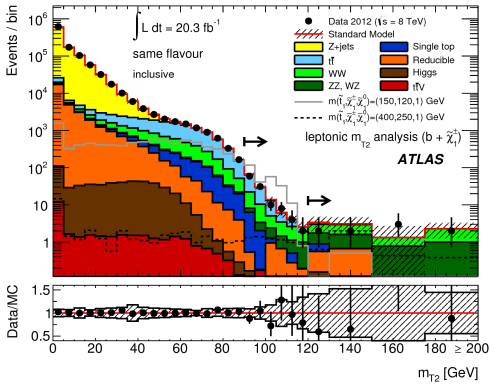
- m_{T_2} or stransverse mass -> to measure the mass of primary pair-produced particles where both decay into visible systems and undetected particles (LSPs). We have:

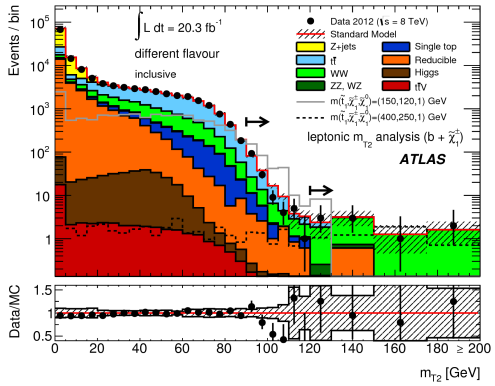
$$(M_{\mathrm{T}}^{(i)})^2 = (m^{\mathrm{vis}(i)})^2 + m_{\tilde{\chi}}^2 + 2\left(E_{\mathrm{T}}^{\mathrm{vis}(i)} E_{\mathrm{T}}^{\tilde{\chi}(i)} - \vec{p}_{\mathrm{T}}^{\,\mathrm{vis}(i)} \cdot \vec{p}_{\mathrm{T}}^{\,\tilde{\chi}(i)}\right)$$

that for the true LSP mass cannot exceed the mass of the parent particle of the decay and have an endpoint at the parent mass value. Only the sum of the invisible particle momenta is known (missing momentum). Then, generalizing the formula above:

$$M_{\mathrm{T2}}(m_{\tilde{\chi}}) = \min_{\vec{p}_{\mathrm{T}}^{\tilde{\chi}(1)} + \vec{p}_{\mathrm{T}}^{\tilde{\chi}(2)} = \vec{p}_{\mathrm{T}}^{\mathrm{miss}}} \left[\max\left(M_{\mathrm{T}}^{(1)}, M_{\mathrm{T}}^{(2)}\right)\right]$$

The minimisation is performed over all the possible decompositions of missing momentum to be sure that the the largest of the two trasverse masses does not exceed the parent particle mass. The m_{T_2} for the correct value of $m_{\tilde{\chi}}$ has an endpoint at the value of the primary particle mass





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Razor frame

- The Razor kinematic variables are designed to be sensitive to processes involving the pair-production of two heavy particles, each decaying to an unseen particle plus jets (e.g. 2 squarks to quark +LSP). Two "megajets" are formed from jets and leptons to minimize the sum of invariant mass of them. Razor approximates the unknown center-of-mass and parent particle rest frames with a frame defined from measured quantities in the laboratory (with assumptions on the boost direction). Defining:

$$M_R \equiv \sqrt{(|\vec{p}_{q_1}| + |\vec{p}_{q_2}|)^2 - (p_z^{q_1} + p_z^{q_2})^2}.$$

$$M_T^R \equiv \sqrt{\frac{E_T^{miss}(p_T^{q_1} + p_T^{q_2}) - \vec{E}_T^{miss}\cdot(\vec{p}_T^{q_1} + \vec{p}_T^{q_2})}{2}},$$

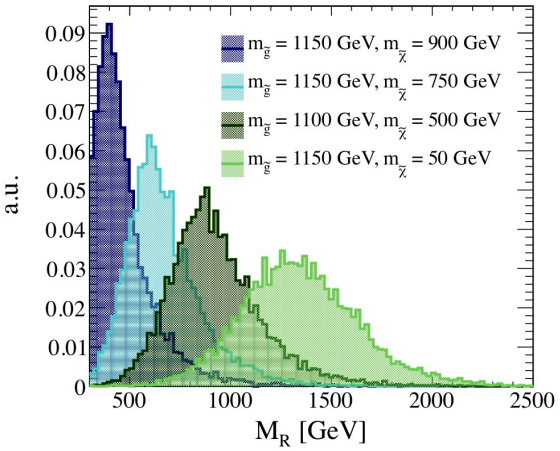
$$R \equiv \frac{M_T^R}{M_R}.$$

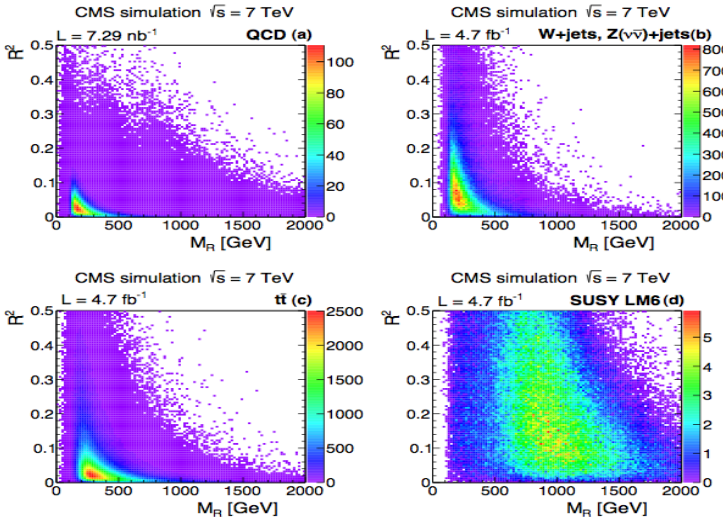
global estimator, the peak provides an estimate of M_Δ

$$M_\Delta = (m_{\tilde{q}}^2 - m_{\tilde{\chi}_1^0}^2)/m_{\tilde{q}}$$

transverse estimator, endpoint at M_Δ

max value at ~ 1





Lepton boxes $M_R > 300$ GeV, $0.11 < R^2 < 0.5$	
ELE-MU (loose-tight)	$p_T > 20$ GeV, $p_T > 15$ GeV
MU-MU (loose-loose)	$p_T > 15$ GeV, $p_T > 10$ GeV
ELE-ELE (loose-tight)	$p_T > 20$ GeV, $p_T > 10$ GeV
MU (tight)	$p_T > 12$ GeV
ELE (loose)	$p_T > 20$ GeV
HAD box $M_R > 400$ GeV, $0.18 < R^2 < 0.5$	

SUSY signals have a peak in R^2-M_R plane while SM background fall smoothly.