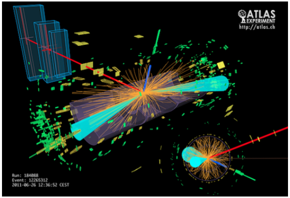
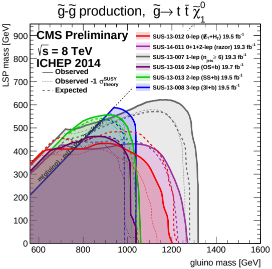
CLOSING IN ON COMPRESSED GLUINO-NEUTRALINO SPECTRA AT THE LHC

Guillaume CHALONS

LPSC Grenoble



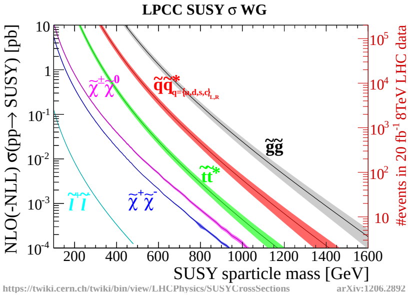


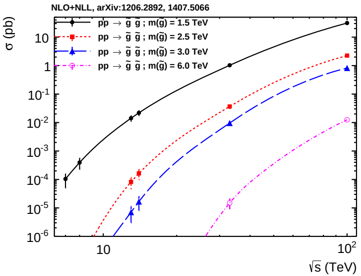
based on G. C, D. Sengupta, ArXiv: 1508.06735 [hep-ph]
accepted for publication in JHEP

MOTIVATIONS

Gluinos ($\tilde{g}$) are

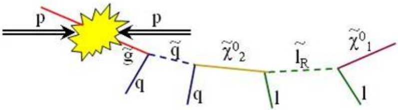
- SUSY partners of the *gluon*
- Majorana fermions
- coupled flavour-blindly only to quarks and gluinos with strength g_s





- Gluinos have the largest production cross section at the LHC (if sufficiently "light")
- Maybe most sensitive (with $\tilde{q}\tilde{q}$) if 1^{st} and 2^{nd} gen. are heavy due to $M_h = 125$ GeV.

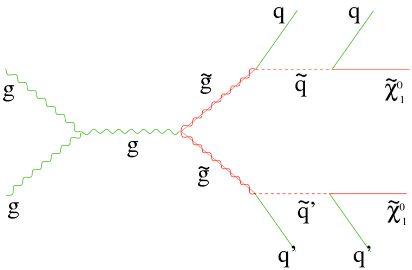
- If R-parity conserved then gluinos are pair-produced
- If $m_{\tilde{g}} \gg m_{\tilde{\chi}_1^0}$ → and "short-lived" Cascade decays

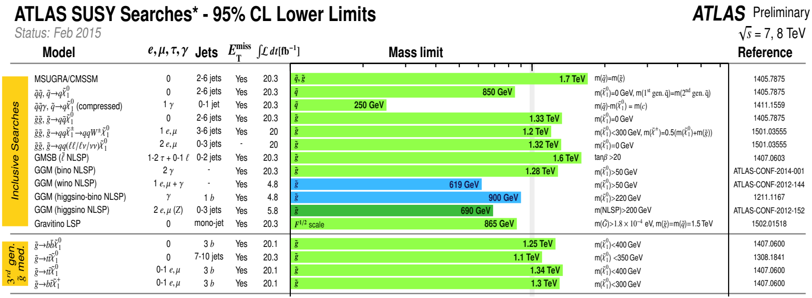


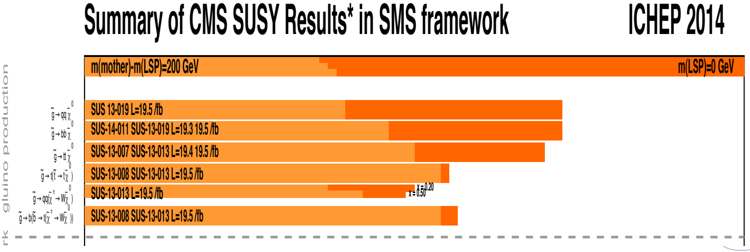
Signatures : Jets + $\not{E}_T$, Jets + b-jets + $\not{E}_T$, Jets + b-jets + ℓ + $\not{E}_T$

Results intepreted in terms of

- Constrained models : MSUGRA/CMSSM, GMSB, GGM
- Simplified Models

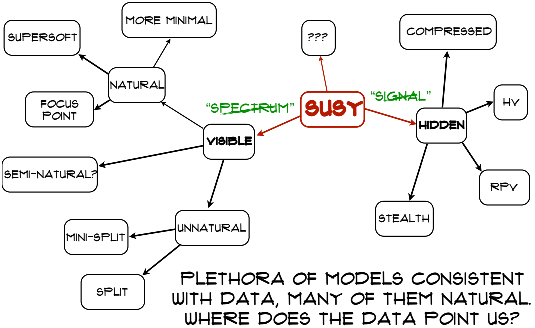



ATLAS SUSY Searches* - 95% CL Lower Limits
Status: Feb 2015
ATLAS Preliminary
√s = 7, 8 TeV
Model | e, μ, τ, γ | Jets | E_T^miss | ∫L dt[fb⁻¹] | Mass limit | Reference
Inclusive Searches
MSUGRA/CMSSM | 0 | 2-6 jets | Yes | 20.3 | q̃, g̃ 1.7 TeV | m(q̃)=m(g̃) | 1405.7875
q̃q̃, q̃→qχ̃⁰₁ | 0 | 2-6 jets | Yes | 20.3 | q̃ 850 GeV | m(χ̃⁰₁)=0 GeV, m(1st gen. q̃)=m(2nd gen. q̃) | 1405.7875
q̃q̃γ, q̃→qχ̃⁰₁ (compressed) | 1 γ | 0-1 jet | Yes | 20.3 | q̃ 250 GeV | m(q̃)-m(χ̃⁰₁) = m(c) | 1411.1559
g̃g̃, g̃→qq̄χ̃⁰₁ | 0 | 2-6 jets | Yes | 20.3 | g̃ 1.33 TeV | m(χ̃⁰₁)=0 GeV | 1405.7875
g̃g̃, g̃→qqχ̃±₁→qqW±χ̃⁰₁ | 1 e, μ | 3-6 jets | Yes | 20 | g̃ 1.2 TeV | m(χ̃⁰₁)<300 GeV, m(χ̃±)=0.5(m(χ̃⁰₁)+m(g̃)) | 1501.03555
g̃g̃, g̃→qq(ℓℓ/ℓν/νν)χ̃⁰₁ | 2 e, μ | 0-3 jets | - | 20 | g̃ 1.32 TeV | m(χ̃⁰₁)=0 GeV | 1501.03555
GMSB (ℓ̃ NLSP) | 1-2 τ + 0-1 ℓ | 0-2 jets | Yes | 20.3 | g̃ 1.6 TeV | tanβ >20 | 1407.0603
GGM (bino NLSP) | 2 γ | - | Yes | 20.3 | g̃ 1.28 TeV | m(χ̃⁰₁)>50 GeV | ATLAS-CONF-2014-001
GGM (wino NLSP) | 1 e, μ + γ | - | Yes | 4.8 | g̃ 619 GeV | m(χ̃⁰₁)>50 GeV | ATLAS-CONF-2012-144
GGM (higgsino-bino NLSP) | γ | 1 b | Yes | 4.8 | g̃ 900 GeV | m(χ̃⁰₁)>220 GeV | 1211.1167
GGM (higgsino NLSP) | 2 e, μ (Z) | 0-3 jets | Yes | 5.8 | g̃ 690 GeV | m(NLSP)>200 GeV | ATLAS-CONF-2012-152
Gravitino LSP | 0 | mono-jet | Yes | 20.3 | F^1/2 scale 865 GeV | m(G̃)>1.8 × 10⁻⁴ eV, m(g̃)=m(q̃)=1.5 TeV | 1502.01518
3rd gen. g̃ med.
g̃→bb̄χ̃⁰₁ | 0 | 3 b | Yes | 20.1 | g̃ 1.25 TeV | m(χ̃⁰₁)<400 GeV | 1407.0600
g̃→tt̄χ̃⁰₁ | 0 | 7-10 jets | Yes | 20.3 | g̃ 1.1 TeV | m(χ̃⁰₁) <350 GeV | 1308.1841
g̃→tt̄χ̃⁰₁ | 0-1 e, μ | 3 b | Yes | 20.1 | g̃ 1.34 TeV | m(χ̃⁰₁)<400 GeV | 1407.0600
g̃→bt̄χ̃⁺₁ | 0-1 e, μ | 3 b | Yes | 20.1 | g̃ 1.3 TeV | m(χ̃⁰₁)<300 GeV | 1407.0600


Summary of CMS SUSY Results* in SMS framework
ICHEP 2014
m(mother)-m(LSP)=200 GeV
m(LSP)=0 GeV
gluino production
g̃→qqχ̃⁰
g̃→bbχ̃⁰
g̃→ttχ̃⁰
g̃→t(t̃→tχ̃⁰)
g̃→qq(χ̃±→Wχ̃⁰)
g̃→b(b̃→t(χ̃±→Wχ̃⁰))
SUS 13-019 L=19.5 /fb
SUS-14-011 SUS-13-019 L=19.3 19.5 /fb
SUS-13-007 SUS-13-013 L=19.4 19.5 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-13-013 L=19.5 /fb
x=0.20
x=0.50
SUS-13-008 SUS-13-013 L=19.5 /fb

Two solutions

- SUSY is at the EW scale but signal hidden
- SUSY spectrum is somehow decoupled



From Craig, SUSY 14

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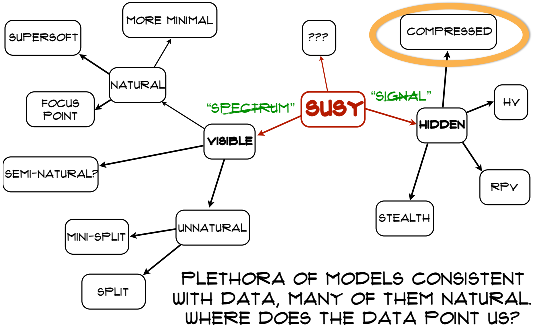
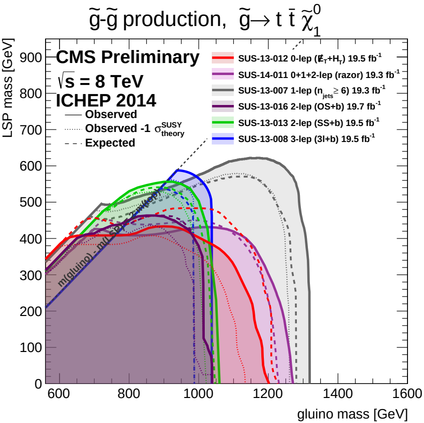


From Craig, SUSY 14

RADIATIVE GLUINO DECAY

If $1^{\text{st.}}$ and $2^{\text{nd.}}$ generation squarks are decoupled $m_{\tilde{q}} \gg m_{\tilde{g}}$

- SMS Exp. limits on $m_{\tilde{g}}$ use $\tilde{g} \to t\bar{t}\tilde{\chi}^0_1, b\bar{b}\tilde{\chi}^0_1, t\bar{b}\tilde{\chi}^\pm_1$
- Loss of **sensitivity** when threshold is **closed**



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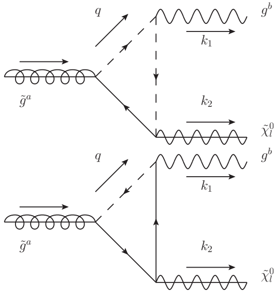
- Loss of **sensitivity** when threshold is **closed**

- Not (fully) considered : $\tilde{g} \to g\tilde{\chi}_i^0$
- Would give an indication of effective SUSY breaking scale $\widetilde{M}$
- For $m_h \simeq 125$ GeV, non-negligible BR when $t_\beta \simeq \mathcal{O}(1)$
  Sato,Shirai,Tobioka JHEP 11 (2012) 041
- Sensitive probe to compressed spectra



Haber, Kane (1984);Ma, Wong (1988); Sato,Shirai,Tobioka (2012);Barbieri *et al.* (1988); Baer, Tata, Woodside (1990);Gambino, Giudice, Slavich (2005); Toharia, Wells (2006)

$$\tilde{\chi}_1^0 = N_{11}\widetilde{B} + N_{12}\widetilde{W}^0 + N_{13}\widetilde{H}_d + N_{14}\widetilde{H}_u$$

- Branching fraction into a wino $\widetilde{W}^0$ is induced by dim 7. operator

$$\mathcal{L}_{\text{eff.}} \simeq \frac{m_{\widetilde{W}}}{m^4_{\tilde{q}_L}}(H^\dagger \tau^a H)\widetilde{W}^a \sigma^{\mu\nu}\widetilde{g}G_{\mu\nu} \Longrightarrow \text{suppressed}$$

For $\widetilde{B}$ and $\widetilde{H}$ loop dominated by stops/tops,

$$\Gamma(\tilde{g} \to g\tilde{B}) \simeq \frac{g'^2 g_s^4}{32786\pi^5}\frac{(m^2_{\tilde{g}} - m^2_{\tilde{B}})^3}{m^3_{\tilde{g}}}\left(\sum_q \frac{Y_{q_L}}{m^2_{\tilde{q}_L}} - \frac{Y_{q_R}}{m^2_{\tilde{q}_R}}\right)^2 (m_{\tilde{g}} - m_{\tilde{B}})^2,$$

$$\Gamma(\tilde{g} \to g\tilde{h}) \simeq \frac{\hat{y}_t^2 g_s^4}{4096\pi^5}\frac{(m^2_{\tilde{g}} - m^2_{\tilde{h}})^3}{m^3_{\tilde{g}}}\left[\frac{m_t}{m^2_{\tilde{t}_L}}\left(\log\frac{m^2_{\tilde{t}_L}}{m_t^2} - 1\right) + \frac{m_t}{m^2_{\tilde{t}_R}}\left(\log\frac{m^2_{\tilde{t}_R}}{m_t^2} - 1\right)\right]^2.$$

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$\Gamma(\tilde{g}\to g\tilde{h})$ has an enhancement factor $m_t^2/m_{\tilde{g}}^2(\ln(m_{\tilde{t}}^2/m_t^2))^2$

$\Gamma(\tilde{g}\to g\tilde{B})$ damps as $m_{\tilde{q}}^{-4}$.

The most important 3-body decay is $\tilde{g} \to q\bar{q}\widetilde{B}$ mediated by a $\tilde{q}_R$

In the massless quark limit we have

$$\Gamma(\tilde{g} \to q\bar{q}\widetilde{B}) = \frac{\alpha_s g'^2 Y_q^2}{384\pi} \frac{m_{\tilde{g}}^5}{\boxed{m_{\tilde{q}}^4}} \left[f\left(\frac{m_{\widetilde{B}}^2}{m_{\tilde{g}}^2}\right) + 2\frac{m_{\widetilde{B}}}{m_{\tilde{g}}} g\left(\frac{m_{\widetilde{B}}^2}{m_{\tilde{g}}^2}\right)\right]$$

Then we have roughly in the limit $m_{\tilde{g}} \ll \tilde{m}$

$$R_{2/3} = \frac{\Gamma(\tilde{g} \to g\tilde{h})}{\Gamma(\tilde{g} \to q\bar{q}\widetilde{B})} \propto \frac{m_t^2}{m_{\tilde{g}}^2}\left(\ln \frac{m_{\tilde{t}}^2}{m_t^2}\right)^2 \Rightarrow \text{Resum LL (Gambino,Giudice,Slavich 05)}$$

For massive quarks, in the limit $m_{\tilde{g}} \ll \tilde{m}$, for higgsinos,

$$R_{2/3} = \frac{24\alpha_s}{\pi}\left(\frac{\tilde{m}_b}{\tilde{m}_t}\right)^4 \left(\frac{m_t^2}{m_{\tilde{g}} m_b \tan\beta}\right)^2 \left[\frac{1}{1-x_t} + \frac{\ln x_t}{(1-x_t)^2}\right]^2$$

COMPETITION WITH 3-BODY DECAY $\widetilde{g} \to q\bar{q}\tilde{\chi}_1^0$

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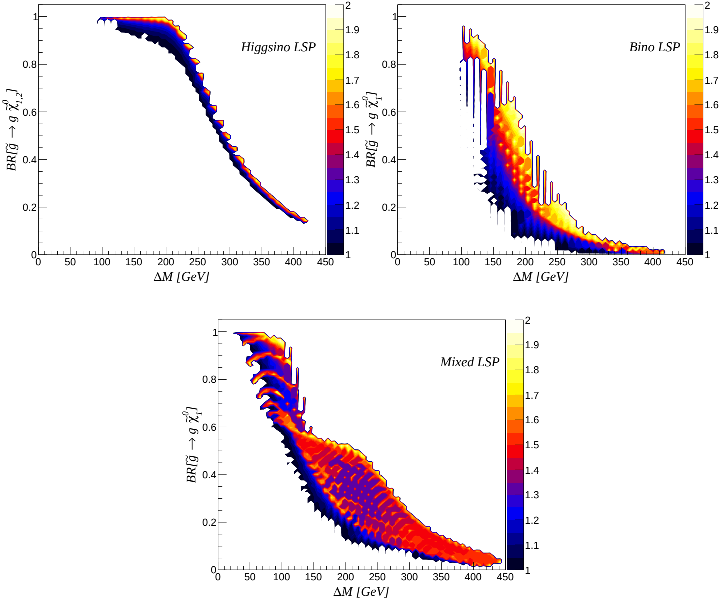
Two-body decay is favoured for relatively lighter stops and decoupled sbottoms

We performed a parameter scan within the pMSSM using SUSY-HIT,

- Sfermion sector, sleptons and 1^{st} two $\tilde{q}$ gen. decoupled
  - $M_{\tilde{t}_R} = 1$ TeV, $M_{\tilde{Q}_3} = 2$ TeV, $A_b = 0$
  - 1 TeV $< M_{\tilde{b}_R} < 2$ TeV
  - -2 TeV $< A_t < 2$ TeV
- Gaugino sector
  - 400 GeV $< M_1, \mu < 800$ GeV
  - $M_2 = 2$ TeV, $M_3 = 600$ GeV, $\tan\beta = 10$

Competing three-body decays

- Higgsino: $\tilde{g} \to g\widetilde{H}^0_{1,2}$ vs. $\tilde{g} \to t\bar{b}/\bar{t}b\widetilde{H}^{\pm}_1$
- Bino: $\tilde{g} \to g\widetilde{B}$ vs. $\tilde{g} \to b\bar{b}\widetilde{B}$
- Mixed-LSP: 3-body decays from both the Higgsino and Bino case contribute.


Higgsino LSP
Bino LSP
Mixed LSP
$BR[\tilde{g} \to g\,\tilde{\chi}^0_{1,2}]$
$BR[\tilde{g} \to g\,\tilde{\chi}^0_1]$
ΔM [GeV]

REINTERPRETATION OF ATLAS AND CMS ANALYSIS

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- In principle can be reinterpreted using monojet or multijet analyses

Analyses of interest

- ATLAS-SUSY-2013-21, PRD 90, 052008 (2014), 0ℓ + monojets/c-jets + $\not{E}_T$
- ATLAS-SUSY-2013-02, JHEP 09, 176 (2014), 0ℓ + 2-6 jets + $\not{E}_T$
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RECASTING OF THE ANALYSIS MANDATORY

PERFORMED WITHIN THE MADANALYSIS 5 FRAMEWORK
(see Daniele Barducci's talk)

We reimplemented the ATLAS mono- and multijet analyses and validated it against

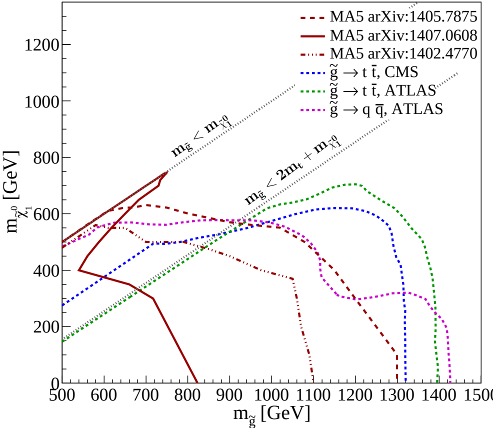
- Official cutflows
- Official distributions
- Reproduce the official exclusion plot

To generate the signal sample

- We used `MadGraph5.0.7` + `PYTHIA 6.24`
- Defined a simplified topology to target

$$\mathrm{BR}(\widetilde{g} \rightarrow g + \chi) = 100\%$$

- Existing Run I analyses can provide sensitivity to $\tilde{g} \to g + \tilde{\chi}_1^0$
- Can probe small $\Delta m = m_{\tilde{g}} - m_{\tilde{\chi}_1^0}$
- Less sensitive at high $m_{\tilde{g}}$ compared to published analyses
- Recasted analyses available on MA5 PAD
- Quantitative agreement with Arbey,Battaglia, Mahmoudi '15, ATLAS JHEP 10 (2015) 054



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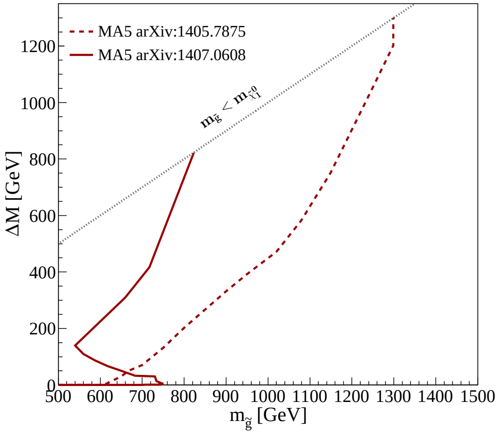

Ideally one would like

- To fully take into account the systematics (only experimentalists can do that)
- Combine the ≠ searches (probably very tedious, only exp.)
- Perform a dedicated analysis at Run II

DESIGNING AN ANALYSIS FOR 13 TEV

- For illustration, concentrated on a low mass gap ($\Delta M \simeq 10$) GeV
- Expect a lot of Hard ISR jets at 13 TeV from the gluino
- Instead of monojet search, we designed a di-jet + MET (from ISR/FSR) analysis to uncover the radiative $\tilde{g}$ decay
- Expected backgrounds:
  - reducible: QCD, $t\bar{t}$+ jets, W + jets,
  - irreducible: Z + jets, ZZ, WZ

- Signal & Bckgd generated with `MG5`+ 3 j + `Delphes3`
- $m_{\tilde{g}} \simeq 1.2$ TeV, $m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} \simeq 6$ GeV, $\mathrm{BR}(\tilde{g} \to g + \tilde{\chi}_{1,2}^0) \simeq 100\%$

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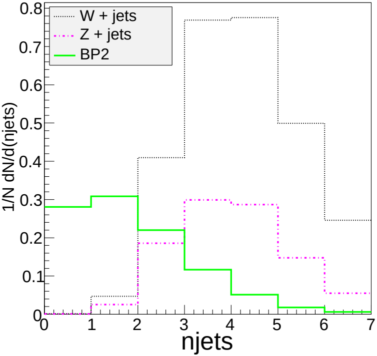
- Simple Cut-based analysis: 2 hard jets



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- Signal & Bckgd generated with `MG5`+ 3 j + `Delphes3`
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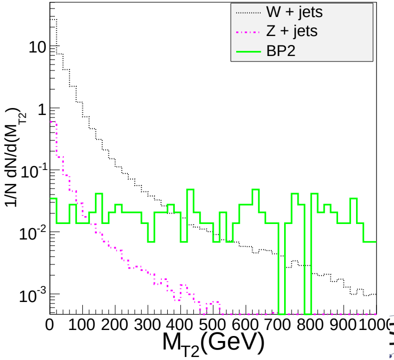
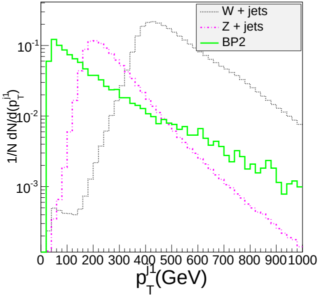
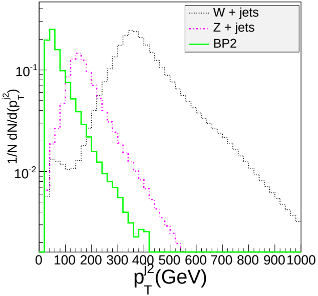
- Simple Cut-based analysis: 2 hard jets
- MT_2 cut



- Lepton veto to suppress weak bckgd
- b-jet veto to suppress $t\bar{t}+$ jets
- $p_T^{j1} > 600$ GeV, $p_T^{j2} > 200$ GeV
- $M_{T2} > 800$ GeV





- Lepton veto to suppress weak bckgd
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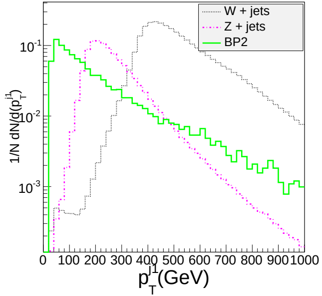
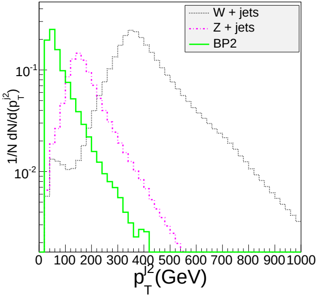
- After M_{T2} cut, only W/Z + jets remain

	P1	P2	P3
$m_{\tilde{g}}$, $m_{\tilde{\chi}_1^0}$ (GeV)	1005,999	1205,1195	1405,1395
$S/\sqrt{B}(30\ \mathrm{fb}^{-1})$	5.3	2.0	0.7
$S/\sqrt{B}(100\ \mathrm{fb}^{-1})$	9.7	3.7	1.27
$S/\sqrt{B}(3000\ \mathrm{fb}^{-1})$	53	20	7





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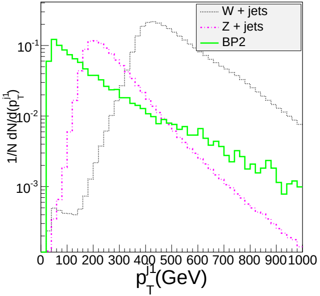
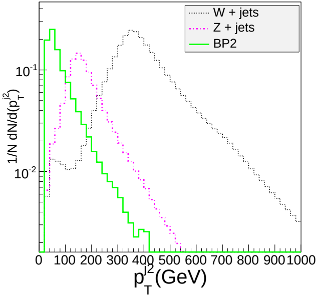
Expected Discovery reach :

- 1 TeV with 30 fb^{-1} luminosity
- 1.4 TeV with 3000 fb^{-1} luminosity





SUMMARY

- If all squarks are decoupled except the stops + $(t\bar{t}, t\bar{b})$ thresholds closed $\widetilde{g} \rightarrow g + \tilde{\chi}_1^0$ can dominate

- The radiative gluino decay can be used as a probe of compressed spectra scenarios
- ATLAS and CMS Run I analyses can test this scenario,maybe Run II ?

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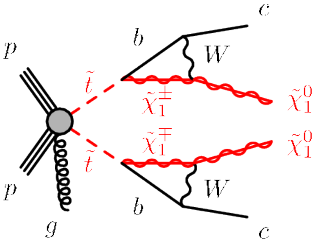
- This search can have an impact on gluino NLSP scenarios
- Can be realised in realistic class of $t - b - \tau$ Yukawa unified models (Ananthanarayan, Laazarides, Shafi 91...)
- Non-universal gaugino masses at $M_{\rm GUT}$ (Ellis, Enqvist, Nanopoulos, Tamvakis 85...)

BACKUP

- This analysis targets direct $\tilde{t}_1$ pair production in compressed spectra scenarios
- In particular it is optimised for $\tilde{t}_1 \rightarrow c + \tilde{\chi}_1^0$ using a monojet and c-tagged search strategies



- We only implemented the monojet search since
  - It can be reinterpreted in DM or other compressed spectra scenarios
  - We do not have access to the needed charm-tagging information

cut	$\tilde{t} \rightarrow c\tilde{\chi}_1^0$ (200/125) cutflow # events (scaled to σ and $\mathcal{L}$)	# events (official)	$\tilde{t} \rightarrow c\tilde{\chi}_1^0$ (200/195) cutflow # events (scaled to σ and $\mathcal{L}$)	# events (official)
Initial # of events	376047.3		376047.3	
ALL		181902.0		103191.0

cut	$\tilde{t} \to c\tilde{\chi}_1^0$ (200/125) cutflow # events (scaled to σ and $\mathcal{L}$)	# events (official)	$\tilde{t} \to c\tilde{\chi}_1^0$ (200/195) cutflow # events (scaled to σ and $\mathcal{L}$)	# events (official)
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$\not{E}_T > 100$ GeV	136257.1 (−29.3%)	97217.0	82619.0 (−21.0%)	64652.0 (−37.3%)

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$N_{\text{jets}} \leq 3$	101653.7 (−24.6%)	59315.0 (−27.5%)	75391.5 (−8.6%)	52491.0 (−8.6%)
$\Delta\phi(\not{E}_T, \text{jets}) > 0.4$	95568.8 (−2.1%)	54295.0 (−8.5%)	70888.1 (−1.2%)	49216.0 (−6.2%)
$p_T(j_1)$ > 150 GeV	17282.8 (−81.9%)	14220.0 (−73.8%)	25552.0 (−64.0%)	20910.0 (−57.5%)
$\not{E}_T$ > 150 GeV	10987.8 (−36.4%)	9468.0 (−33.4%)	21569.1 (−15.6%)	18297.0(−12.5%)
M1 Signal Region				

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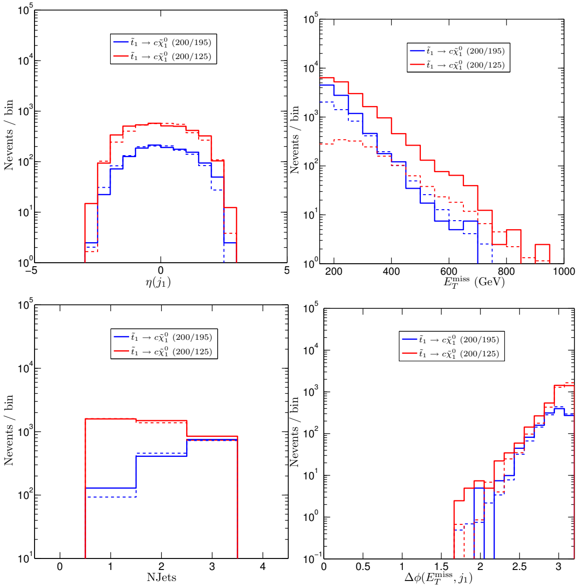
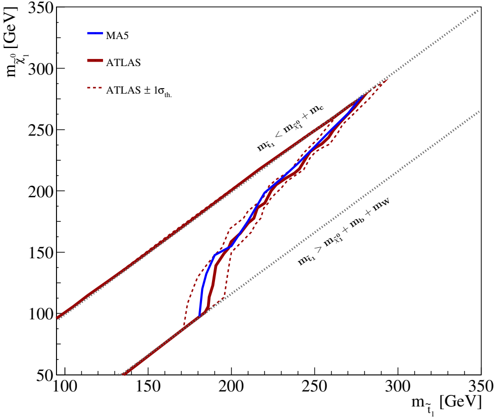
$p_T(j_1) > 280$ GeV	2031.2 (-81.5%)	1627.0 (-82.8%)	4922.0 (-77.2%)	3854.0 (-78.9%)
$\not{E}_T > 220$ GeV	1517.6 (-25.3%)	1276.0 (-21.6%)	4628.4 (-6.0%)	3722.0 (-3.4%)
M2 Signal Region				
$p_T(j_1) > 340$ GeV	858.0 (-92.2%)	721.0 (-92.4%)	2509.0 (-88.4%)	1897.0 (-89.6%)
$\not{E}_T > 340$ GeV	344.4 (-59.9%)	282.0 (-60.9%)	1758.9 (-29.9%)	1518.0 (-20.0%)
M3 Signal Region				
$p_T(j_1) > 450$ GeV	204.3 (-98.1%)	169.0 (-98.2%)	773.3 (-96.4%)	527.0 (-97.1%)
$\not{E}_T > 450$ GeV	61.3 (-70.0%)	64.0 (-62.1%)	476.8 (-38.3%)	415.0 (-21.3%)


$\tilde{t}_1 \to c\tilde{\chi}_1^0$ (200/195)
$\tilde{t}_1 \to c\tilde{\chi}_1^0$ (200/125)
Nevents / bin
$\eta(j_1)$
E_T^{miss} (GeV)
NJets
$\Delta\phi(E_T^{\mathrm{miss}}, j_1)$

REPRODUCTION OF THE EXCLUSION PLOT

To derive limits we use a lightweight exclusion code picking the most sensitive SR via

$$\mathcal{L} = \text{poiss}(n_i^{obs.}|n_i^s + n_i^b) \cdot \text{gauss}(n_i^b|n_i^{b,exp}, \Delta n_i^b)$$



- We aim at a precision of order 20-30% on the limit setting