Missing energy signature for low scale supersymmetry breaking

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June 28, 2017

QFTHEP, Yaroslavl

Outline

- Introduction: spontaneous SUSY breaking
- Goldstino supermultiplet: minimal model and interactions
- Processes contributing to gravitino pair production and contribution of sgoldstinos
- Bounds from missing E_T analysis and comparison with di-jet searches
- Conclusions

- SUSY - attractive extension of SM, extensively studied at the LHC experiments
- SUSY breaking: hidden sector $\to$ visible sector
  No direct interactions between visible and hidden sectors
- Transmission of SUSY breaking at a scale M: messengers (gravity, gauge interactions, etc.)
- Spontaneous SUSY breaking: goldstino and its superpartners

(Chiral) Goldstino supermultiplet

- $\Phi = \phi + \sqrt{2}\theta\psi + F_\phi\theta^2$, F_ϕ – auxiliary field
- SUSY — broken $\rightarrow$ $F \equiv \langle F_\phi \rangle \neq 0$
- $\sqrt{F}$ — supersymmetry breaking scale
- $\sqrt{F} \gg M_{EW}$ — goldstino supermultiplet decouples – usual MSSM
- $\sqrt{F} \gtrsim M_{EW}$ — we should include S, P and ψ in low energy theory — low scale supersymmetry breaking
- ψ – Goldstone fermion,
- goldstino $\rightarrow$ longitudinal gravitino component : $m_{3/2} = \sqrt{8\pi/3}F/M_{Pl}$
- for $\sqrt{F} = 1$ TeV, $m_{3/2} \approx 2.4 \cdot 10^{-13}$ GeV – superlight gravitino
- $\phi = (S + iP)/2$, where $S(P)$ — scalar(pseudoscalar) sgoldstino

Spontaneous SUSY breaking

Effective lagrangian ($\Phi = \phi + \sqrt{2}\theta\psi + F_\phi\theta^2$):

$$\mathcal{L}_\Phi = \int d^2\theta\, d^2\bar{\theta} \left(\Phi^\dagger\Phi + \tilde{K}(\Phi^\dagger, \Phi) \right) + \left(\int d^2\theta F\Phi + \text{h.c.} \right),$$

$$\tilde{K}(\Phi^\dagger, \Phi) = -\frac{m_s^2 + m_p^2}{8F^2} \left(\Phi^\dagger\Phi \right)^2 - \frac{m_s^2 - m_p^2}{12F^2} \Phi^\dagger\Phi \left(\Phi^2 + (\Phi^\dagger)^2 \right)$$

Expanding in $1/F$:

$$\mathcal{L}_\Phi = -\frac{m_s^2}{2} S^2 - \frac{m_p^2}{2} P^2 + \frac{m_s^2}{2\sqrt{2}F} S\bar{\psi}\psi + i\frac{m_p^2}{2\sqrt{2}F} P\bar{\psi}\gamma_5\psi$$

Interactions of goldstino supermultiplet with SM

- MSSM + goldstino supermultiplet
  $\Phi = \phi + \sqrt{2}\theta\psi + F_\phi\theta^2, \ \langle F_\phi \rangle = F,$

$$\mathcal{L} = \mathcal{L}_{MSSM} + \mathcal{L}_{\Phi-K\ddot{a}hler} + \mathcal{L}_{\Phi-gauge} + \mathcal{L}_{\Phi-superpotential}$$

$$\mathcal{L}_{\Phi-K\ddot{a}hler} = -\int d^2\theta \ d^2\bar{\theta} \ \Phi^\dagger\Phi \cdot \sum_k \frac{m_k^2}{F^2} \Phi_k^\dagger \, e^{g_1 V_1 + g_2 V_2 + g_3 V_3} \, \Phi_k$$

$$\mathcal{L}_{\Phi-gauge} = \frac{1}{2}\int d^2\theta \ \Phi \cdot \sum_\alpha \frac{M_\alpha}{F} \, TrW^\alpha W^\alpha + h.c. \, ,$$

$$\mathcal{L}_{\Phi-superpotential} = \int d^2\theta \ \Phi \cdot \epsilon_{ij}\left(-\frac{B}{F} H_D^i H_U^j + \frac{A_{ab}^D}{F} Q_a^j D_b^c H_D^i + \ldots \right) +$$

- Nonrenormalizable, low energy effective theory $E \lesssim \sqrt{F}$
- Weak coupling regime: hierarchy $m_{soft} \lesssim \sqrt{F}$
- Higher order interactions are suppressed by higher powers of F

Goldstino interactions

Single goldstino interactions with strong sector:

$$\mathcal{L}_{\psi-\text{vis}} \supset \frac{M_3}{4\sqrt{2}F}\bar{\psi}\left[\gamma^\mu,\gamma^\nu\right]\lambda^a F^a_{\mu\nu} - \frac{iM^2_{\tilde{d}_R,ij}}{F}\left(\tilde{d}^\dagger_{R,i}\bar{\psi}P_R d_j - \bar{d}_j P_L \psi \tilde{d}_{R,i}\right) -$$

$$-\frac{iM^2_{\tilde{u}_R,ij}}{F}\left(\tilde{u}^\dagger_{R,i}\bar{\psi}P_R u_j - \bar{u}_j P_L \psi \tilde{u}_{R,i}\right) + \frac{iM^2_{\tilde{q}_L,ij}}{F}\left(\tilde{q}^\dagger_{L,i}\bar{\psi}P_L q_j - \bar{q}_j P_R \psi \tilde{q}_{L,i}\right)$$

for $E \gg m_{3/2}$, goldstino-gravitino equivalence $\mathcal{L}_\psi = \frac{1}{F}J^\mu_{SUSY}\partial_\mu\psi$

Double goldstino interactions with strong sector:

$$\mathcal{L}_{\psi-\text{vis}} \supset -\frac{M^2_{\tilde{d}_R,ij}}{F^2}(\bar{\psi}P_R d_i)(\bar{d}_j P_L \psi) - \frac{M^2_{\tilde{u}_R,ij}}{F^2}(\bar{\psi}P_R u_i)(\bar{u}_j P_L \psi)$$

$$-\frac{M^2_{\tilde{q}_L,ij}}{F^2}(\bar{\psi}P_L q_j)(\bar{q}_i P_R \psi)$$

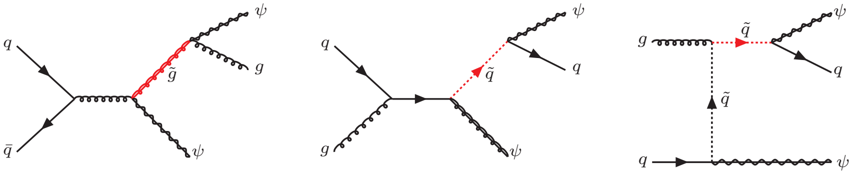
Gravitino ψ – LSP, very light

Goldstino production with jet (or γ, W, Z) – missing energy signature $R=-1$: production in pairs

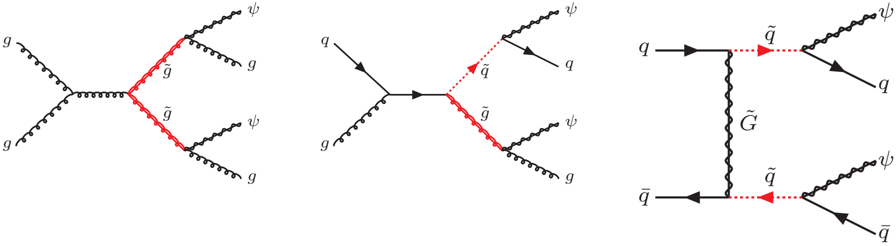
Goldstino at colliders: jet + missing energy signature

F.Maltoni et al, 1502.01637, ATLAS, 8 TeV, 10.5 fb^{-1}, $m_{s,p} = 20$ TeV

Associated gravitino production $pp \to \tilde{g}\psi, \tilde{q}\psi \to \psi\psi + jet$, $\sigma \sim \frac{1}{F^2}$

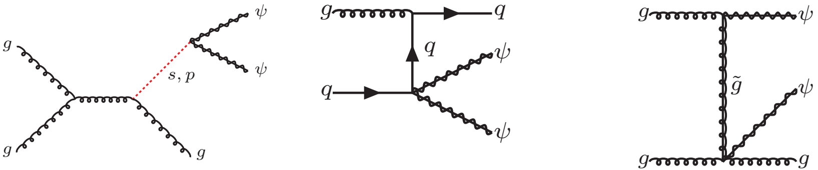


SUSY QCD pair production $pp \to \tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g} \to \psi\psi + 2jets$, $\sigma \sim \frac{1}{F^0}$



Goldstino at colliders: jet + missing energy signature

Direct gravitino pair production: $pp \to \psi\psi + jet$, $\sigma \sim \frac{1}{F^4}$



What about light sgoldstino contribution???

Sgoldstino interaction lagrangian with gauge fields and fermions

$$\mathcal{L}_\phi = -\sum_\alpha \frac{M_\alpha}{4\sqrt{2}F} S F^\alpha_{a\,\mu\nu} F^{\alpha\,\mu\nu}_a - \epsilon_{ij}\left(\frac{A^D_{ab}}{\sqrt{2}F} q^j_a d^c_b \cdot h^i_D S + \ldots\right)$$

$$-\sum_\alpha \frac{M_\alpha}{8\sqrt{2}F} P F^\alpha_{a\,\mu\nu}\epsilon^{\mu\nu\lambda\rho} F^\alpha_{a\lambda\rho} - \epsilon_{ij}\left(i\frac{A^D_{ab}}{\sqrt{2}F} q^j_a d^c_b \cdot h^i_D P + \ldots\right)$$

... and with gravitino

$$+\frac{m_s^2}{2\sqrt{2}F} S\bar{\psi}\psi + i\frac{m_p^2}{2\sqrt{2}F} P\bar{\psi}\gamma_5\psi$$

Sgoldstino phenomenology

Main decay channels for sgoldstinos:

$\sqrt{F} = 2$ TeV, $M_1 = 0.5$ TeV, $M_2 = 1$ TeV, $M_3 = 1.5$ TeV, $A = 0.7$ TeV

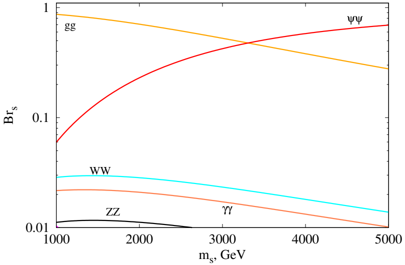
$X = S$ or P

$X \to \psi\psi$: $\Gamma \sim \frac{m_X^5}{F^2}$

$X \to \gamma\gamma, gg, ZZ, WW, Z\gamma$: $\Gamma \sim \frac{M_\lambda^2 m_X^3}{F^2}$

$X \to f_{SM} f_{SM}$: $\Gamma \sim \frac{A_f^2 m_f^2 m_X}{F^2}$

$X \to$ Higgs bosons, superpartners are typically suppressed



Sgoldstino production in *pp* collisions

- strongly dominant channel: $pp \to gg \to X$: governed by $\frac{M_3}{F}$, i.e. mass of gluino!

Analysis

Apply CMS monojet results, $\sqrt{s} = 8$ TeV, 19.6 fb^{-1} (Eur.Phys.J. C75 (2015) no.5, 235)

Assumptions and methods:

- $m_{\tilde{q}} = m_{\tilde{g}}$, $1 - 2.5$ TeV, no mixing $A = 0$
- $\tilde{q} \to q + \psi$, $\tilde{g} \to g + \psi$ – dominant decay modes

$$\Gamma(\tilde{q}(\tilde{g}) \to q(g) + \psi) = \frac{m^5_{\tilde{q}(\tilde{g})}}{16\pi F^2}$$

- $m_s = m_p$, $1 - 5$ TeV
- $s, p \to gg$ or $s, p \to \psi\psi$

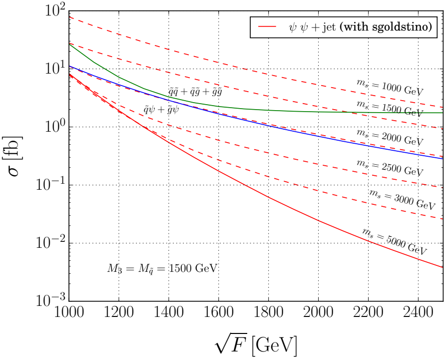
$$\Gamma(s(p) \to \psi\psi) = \frac{m^5_{s(p)}}{32\pi F^2}, \quad \Gamma(s(p) \to gg) = \frac{M_3^2 m^3_{s(p)}}{4\pi F^2}$$

- MadGraph, parton level at LO, $p_T(j_1) > 110$ GeV, $|\eta(j_1)| < 2.4$, $p_T(j_2) > 30$ GeV, $|\eta(j_2)| < 4.5$, $|\Delta\phi(j_1, j_2)| < 2.5$
- missing energy $E_T^{miss} > 450$ GeV, $\sigma^{CMS\ limit}_{jet+E_T^{miss}} \lesssim 7.8$ fb

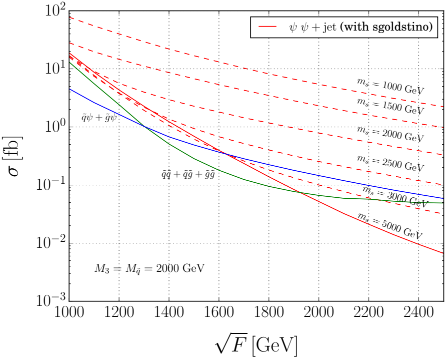
Subprocesses

Cross sections as functions of $\sqrt{F}$

$m_{\tilde{q}} = m_{\tilde{g}} = 1.5$ TeV



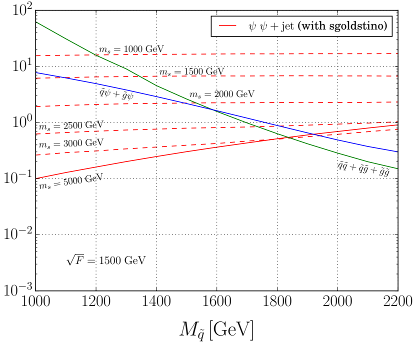
$m_{\tilde{q}} = m_{\tilde{g}} = 2.0$ TeV



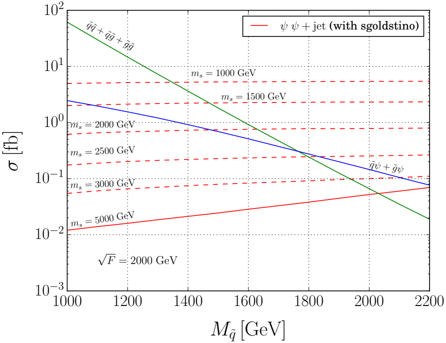
Subprocesses

Cross sections as functions of $m_{\tilde{q}} = m_{\tilde{g}}$

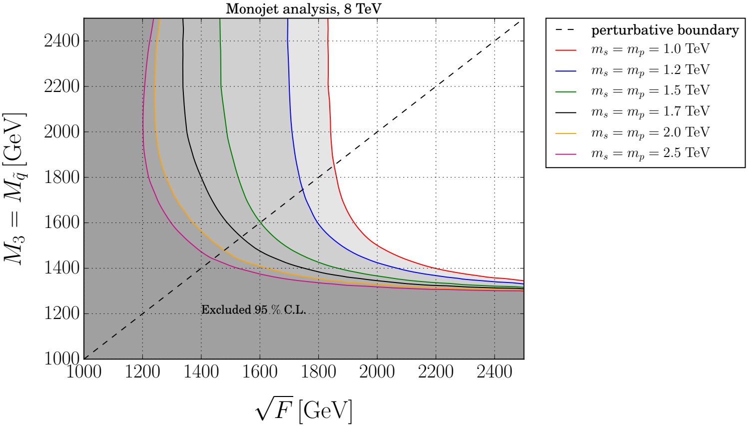
$\sqrt{F} = 1.5$ TeV



$\sqrt{F} = 2.0$ TeV

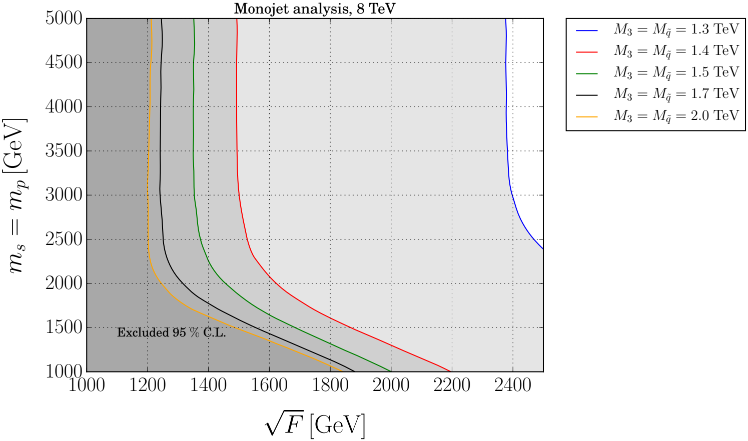


Results



Light sgoldstinos can change the bounds considerably!

Results

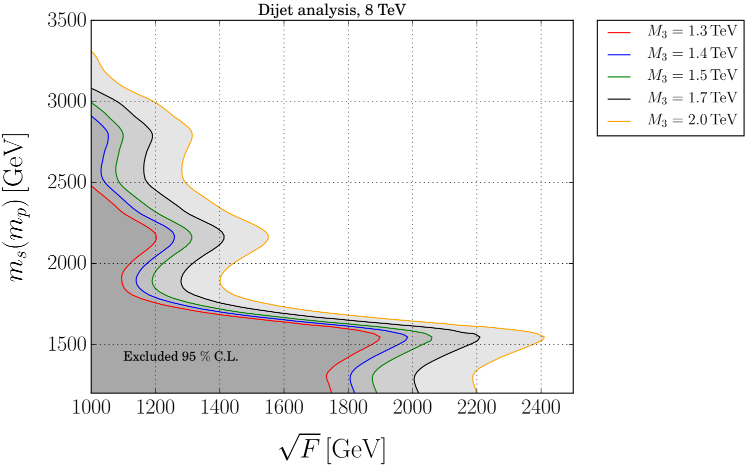


Monojet analysis, 8 TeV
$m_s = m_p$ [GeV]
5000
4500
4000
3500
3000
2500
2000
1500
1000
1000
1200
1400
1600
1800
2000
2200
2400
$\sqrt{F}$ [GeV]
Excluded 95 % C.L.
$M_3 = M_{\tilde{q}} = 1.3$ TeV
$M_3 = M_{\tilde{q}} = 1.4$ TeV
$M_3 = M_{\tilde{q}} = 1.5$ TeV
$M_3 = M_{\tilde{q}} = 1.7$ TeV
$M_3 = M_{\tilde{q}} = 2.0$ TeV

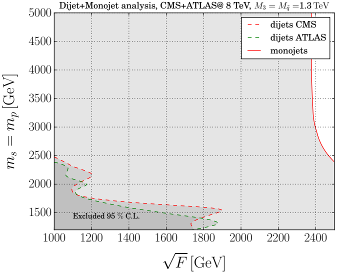
Di-jet resonances

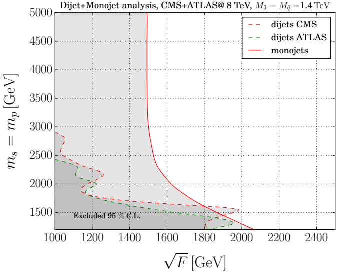
Sgoldstino decays into gg pair – di-jet resonance signature!

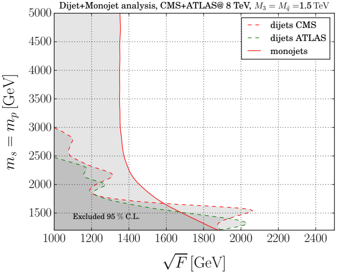
Use results by CMS (8 TeV, 19.7 fb^{-1})

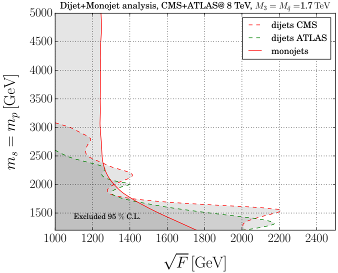


ATLAS (arXiv:1407.1376), CMS (arXiv:1501.04198)

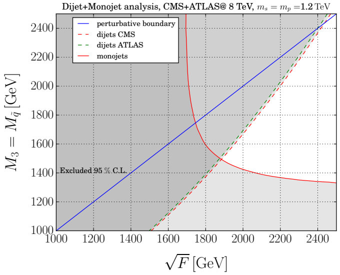


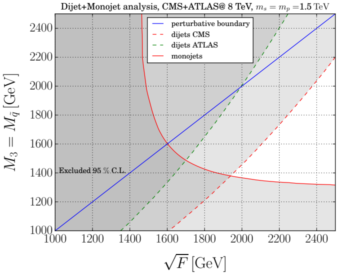


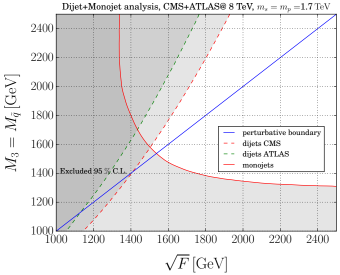


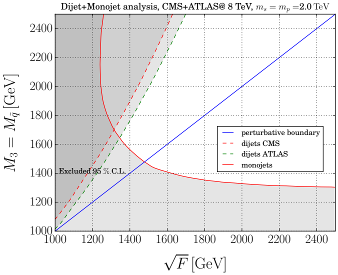


Di-jet resonances and missing energy comparison









Conclusions

- Superpartners of goldstino - sgoldstinos - can contribute considerably to gravitino pair production
- We obtain bounds on parameter space of the model from monojets
- Bounds from monojets and di-jets are complimentary
- It would be interesting to probe this scenario with new LHC data at $\sqrt{s} = 13$ TeV!