Goldstini and the Z-peaked ATLAS excess

Alberto Mariotti

Vrije Universiteit Brussel

iihe BRUXELLES BRUSSEL

fwo

Based on arXiv:1506.08803 with S. Liew, K. Mawatari, K. Sakurai, M. Vereecken,
and on arXiv:1102.2386 with R. Argurio,Z. Komargodski,
and on arXiv:1112.5058 with also G. Ferretti, K. De Causmaecker

03 - 09 - 2015
GGI - Gearing up for LHC13

SUSY after LHC8

- SUSY under pressure by negative LHC8 results
- However still main candidate for BSM physics
- Bet: ***SUSY beyond Minimality***
- Investigate un-explored SUSY scenarios !!!
- ***Keep eyes open on possible ahead indications from LHC8***

ATLAS
Z-peaked excess

Non-minimal
SUSY

ATLAS Z-peaked excess (1503.03290)

- 2 SF leptons + at least 2-jets + MET
- Minimal cuts (object selection, isolation, etc …)
- MET> 225 GeV, H_T > 600 GeV
- Different categories based on m_ll
- ***Excess over SM bkg in Z-mass region (81 — 101 GeV)***

Channel	SR-Z ee	SR-Z $\mu\mu$	SR-Z same-flavour combined
Observed events	16	13	29
Expected background events	4.2 ± 1.6	6.4 ± 2.2	10.6 ± 3.2
Flavour-symmetric backgrounds	2.8 ± 1.4	3.3 ± 1.6	6.0 ± 2.6
Z/γ+jets (jet-smearing)	0.05 ± 0.04	$0.02^{+0.03}_{-0.02}$	0.07 ± 0.05
Rare top	0.18 ± 0.06	0.17 ± 0.06	0.35 ± 0.12
WZ/ZZ diboson	1.2 ± 0.5	1.7 ± 0.6	2.9 ± 1.0
Fake leptons	$0.1^{+0.7}_{-0.1}$	$1.2^{+1.3}_{-1.2}$	$1.3^{+1.7}_{-1.3}$

ATLAS Z-peaked excess (1503.03290)

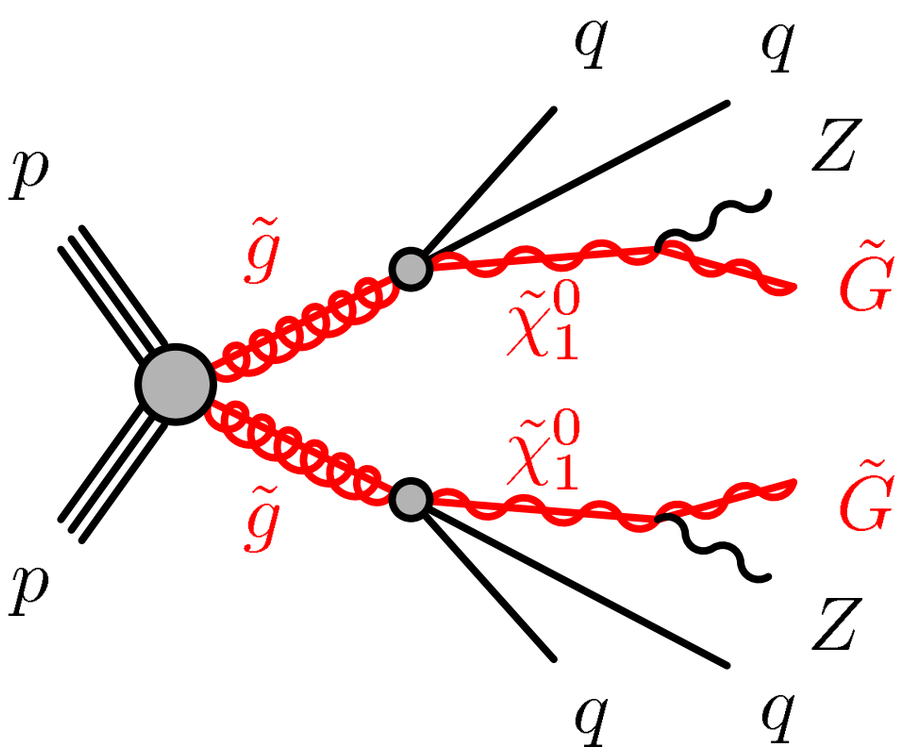
- 2 SF leptons + at least 2-jets + MET
- Minimal cuts (object selection, isolation, etc …)
- MET> 225 GeV, H_T > 600 GeV
- Different categories based on m_ll
- ***Excess over SM bkg in Z-mass region (81 — 101 GeV)***

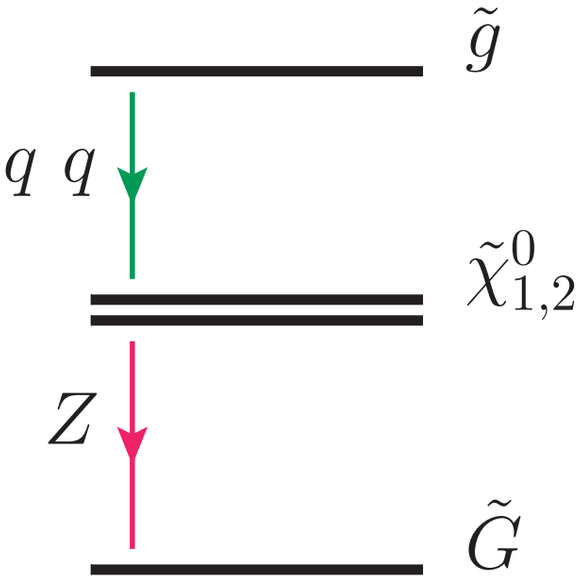
Channel	SR-Z ee	SR-Z $\mu\mu$	SR-Z same-flavour combined
Observed events	16	13	29
Expected background events	4.2 ± 1.6	6.4 ± 2.2	10.6 ± 3.2
Flavour-symmetric backgrounds	2.8 ± 1.4	3.3 ± 1.6	6.0 ± 2.6
Z/γ+jets (jet-smearing)	0.05 ± 0.04	$0.02^{+0.03}_{-0.02}$	0.07 ± 0.05
Rare top	0.18 ± 0.06	0.17 ± 0.06	0.35 ± 0.12
WZ/ZZ diboson	1.2 ± 0.5	1.7 ± 0.6	2.9 ± 1.0
Fake leptons	$0.1^{+0.7}_{-0.1}$	$1.2^{+1.3}_{-1.2}$	$1.3^{+1.7}_{-1.3}$

!!! Significance 3.0 sigma !!!

ATLAS Z-peaked excess (1503.03290)

- ***ATLAS interpretation in GMSB scenario***
- Gluino pair production
- Higgsino decaying to Goldstino + Z-boson



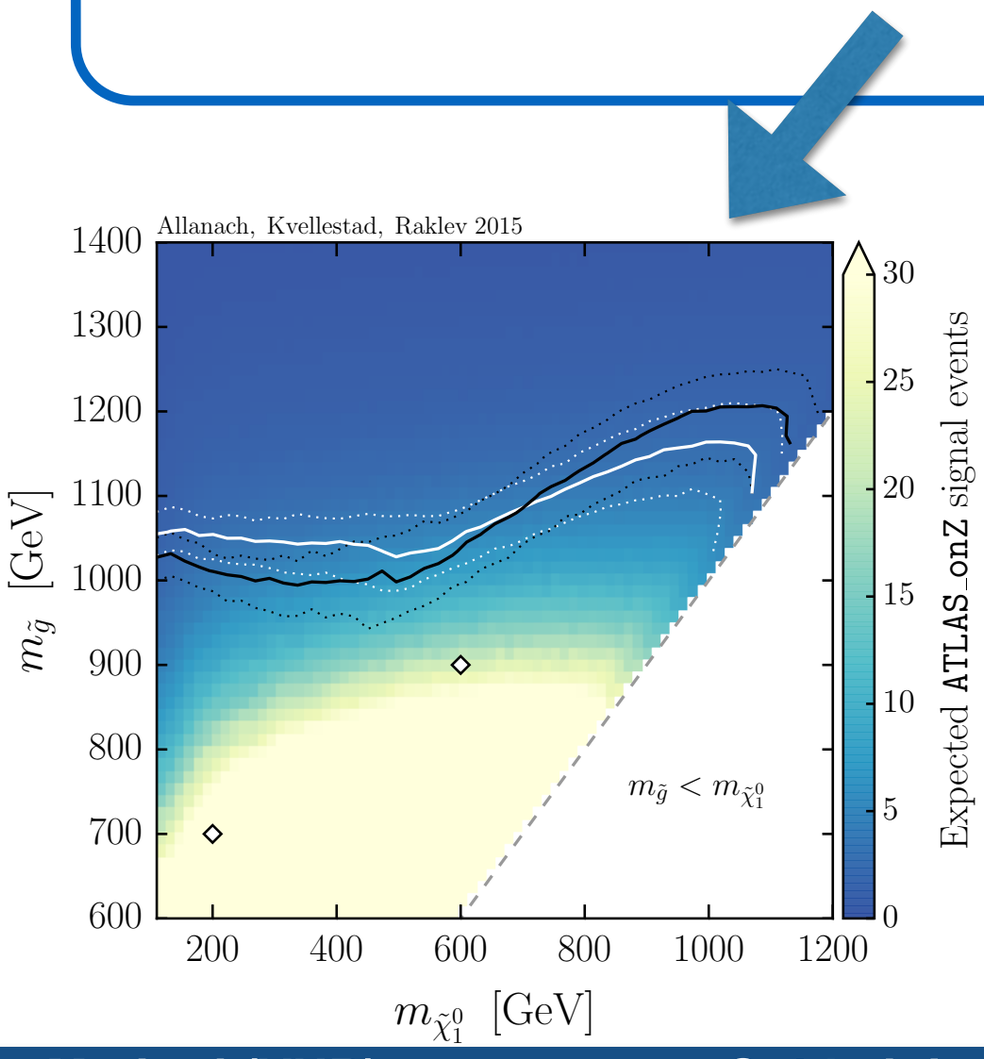


BP1	BP2	
900 GeV	700 GeV	$m_{\tilde{g}}$
600 GeV	200 GeV	$m_{\tilde{\chi}^0}$
~ 0 GeV	~ 0 GeV	$m_{\tilde{G}}$

B. Allanach, A. Raklev, A. Kvellastad

GMSB interpretation

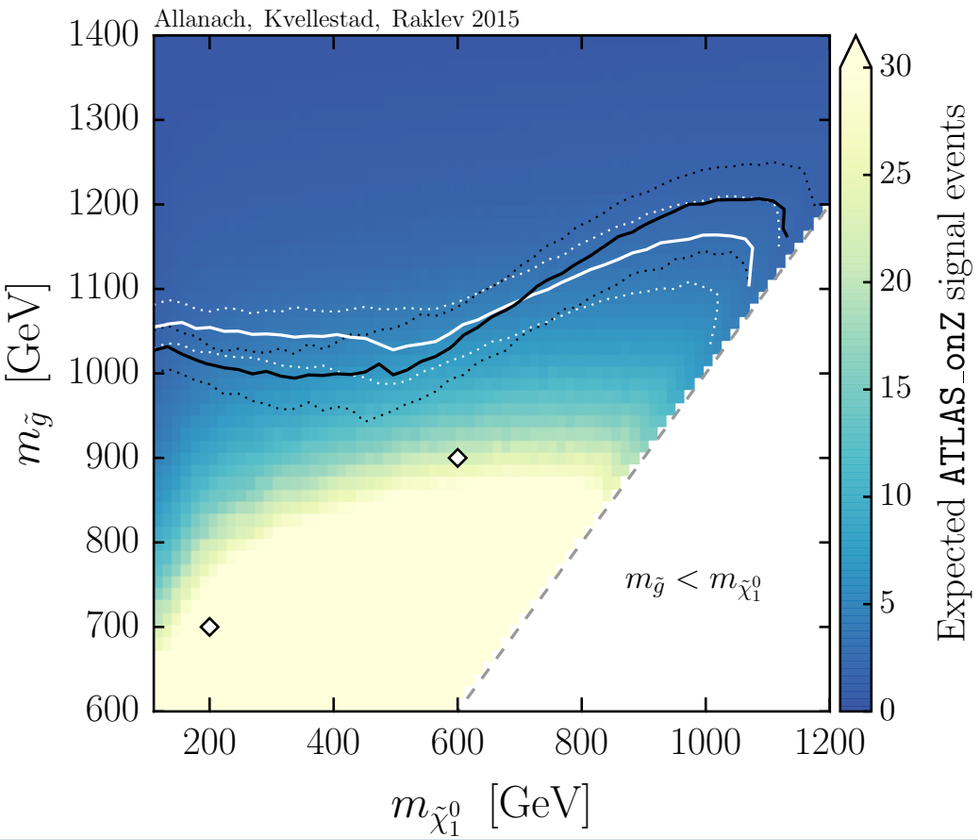
- GMSB interpretation conflict with JETS+MET searches
- Hadronic decay of Z-boson contribute significantly
- Also analogous CMS search impose stringent constraints
- ***ATLAS benchmark points are already excluded***

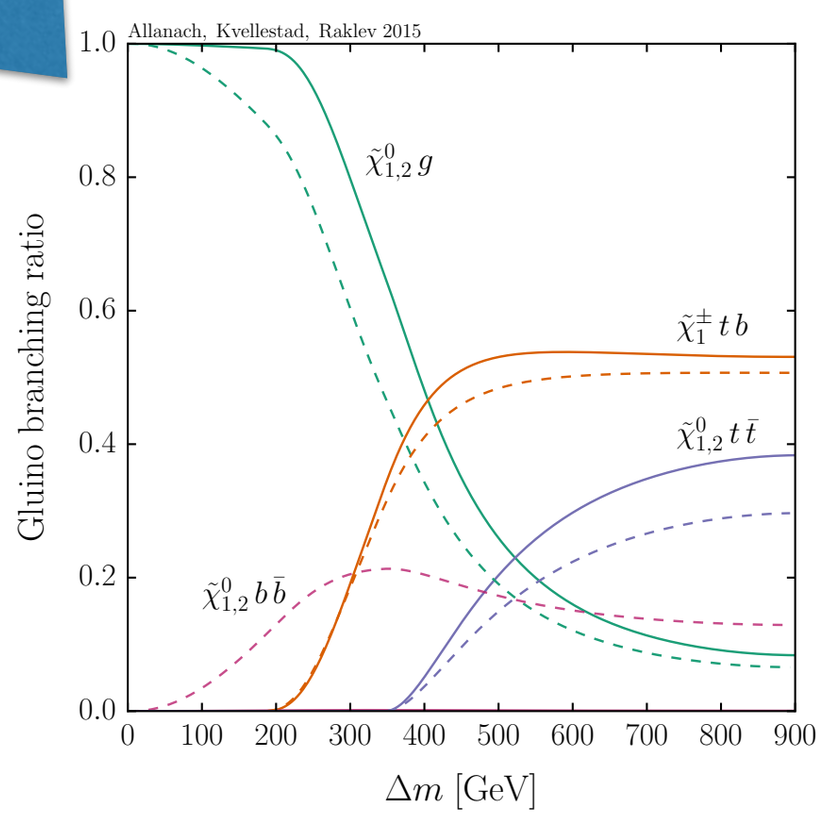


B. Allanach, A. Raklev, A. Kvellastad

GMSB interpretation

- GMSB interpretation conflict with JETS+MET searches
- Hadronic decay of Z-boson contribute significantly
- Also analogous CMS search impose stringent constraints
- ***ATLAS benchmark points are already excluded***
- ***Also decay chain not viable in the MSSM***





Recap: ATLAS Z-peaked excess

Alternative Proposed Explanations

- NMSSM
- Split SUSY
- Composite models
- MSSM with light squarks, bino, higgsino

G. Barenboim, J. Bernabeu, et al.
B. Allanach, A. Raklev, A. Kvellastad
U. Ellwanger
N. Vignaroli
A. Kobakhidze, A. Saavedra, L. Wu , J. Min Yang
J. Cao, L. Shang, J. Min Yang, Y. Zhang
M. Cahill-Rowley, J.L. Hewett, A. Ismail, T.G. Rizzo
X. Lu, S.Shirai, T. Terada
J.H. Collins, J. Asaf Dror, M. Farina

Recap: ATLAS Z-peaked excess

Alternative Proposed Explanations

- NMSSM
- Split SUSY
- Composite models
- MSSM with light squarks, bino, higgsino

Main LHC8 Constraints

- ***JETS+MET*** *arXiv:1405.7875*
- ***Analogous CMS search*** *arXiv:1502.06031*
  - Two Jets + 2 leptons + MET
  - No H_T cut

Recap: ATLAS Z-peaked excess

Alternative Proposed Explanations

- NMSSM
- Split SUSY
- Composite models
- MSSM with light squarks, bino, higgsino

Main LHC8 Constraints

- ***JETS+MET*** ⟷ ***Spectrum compression***
- ***Analogous CMS search***
  - Two Jets + 2 leptons + MET
  - No H_T cut ⟷ ***Different selection cuts***

Gauge Mediation interpretation

S. Liew, A. M., K. Mawatari, K. Sakurai, M. Vereecken

Gauge Mediation with multiple susy br sectors

- Extra fermionic light modes (**Goldstini**) in the spectrum
- Mass computable perturbatively
- Coupling structure dictated by supersymmetry
- Exotic phenomenology at collider
- Accommodate the ATLAS excess!!!

SUSY breaking paradigm

F

- Hidden sector with spontaneous SUSY breaking
- Mediation transmits SUSY breaking to MSSM
- ***Two main scenarios: Gravity or Gauge Mediation***

Gauge Mediation

- Susy breaking mediated by SM gauge interactions
- Soft terms are loop suppressed $m_{soft} = \frac{\alpha}{4\pi}\frac{F}{M}$
- M typical supersymmetric hidden sector scale
- Low supersymmetry breaking scale F
- ***Calculability, address susy flavour problem …***

Goldstino

- What do we know about hidden sector?
- Spontaneous susy breaking → ***Massless Goldstino*** G
- Eaten via superHiggs mechanism: $m_{3/2} \simeq \frac{F}{M_{Pl}}$

Gauge Mediation	**Gravity mediation**
$m_{3/2} \ll m_{soft}$	$m_{3/2} \sim m_{soft}$

Goldstino

- What do we know about hidden sector?
- Spontaneous susy breaking → ***Massless Goldstino*** G
- Eaten via superHiggs mechanism: $m_{3/2} \simeq \frac{F}{M_{Pl}}$

Gauge Mediation

$$m_{3/2} \ll m_{soft}$$

- Tipically gravitino mass of order eV
- Light Gravitino equivalent to Goldstino in HE processes
- Goldstino interaction with MSSM fixed by supersymmetry

Goldstino Interactions

Z.Komargodski and N.Seiberg '09

Goldstino can be described as constrained superfield

$$X_{NL}^2 = 0 \qquad \Rightarrow \qquad X_{NL} = \frac{G^2}{2F} + \sqrt{2}\theta G + \theta^2 F$$

Reproduce Volkov-Akulov lagrangian

Goldstino Lagrangian

$$\mathcal{L} \supset \int d^2\theta \frac{m_\lambda}{2F} X_{NL} \mathcal{W}^2 = \frac{1}{2} m_\lambda \lambda\lambda + \frac{i m_\lambda}{\sqrt{2}F}\left(G\lambda D - \frac{i}{2}\lambda\sigma^\mu\bar{\sigma}^\nu G F_{\mu\nu}\right) + \dots$$

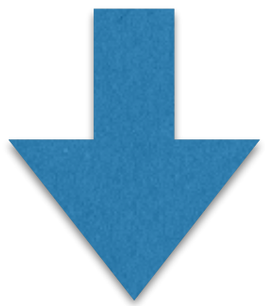
$$\mathcal{L} \supset \int d^4\theta \frac{m_Q^2}{F^2} X_{NL}^\dagger X_{NL} Q^\dagger Q = m_Q^2 q^\dagger q + \frac{m_Q^2}{F}\left(GG\psi q^\dagger + \bar{G}\bar{\psi} q\right) + \dots$$

Reproduce both soft terms and Goldstino couplings

Multiple SUSY br sectors

What changes if there are multiple susy breaking sectors?

- Suppose having two decoupled susy breaking sector
- What are the pheno consequences?



- ***Every sector has its own goldstino field***
- ***One combination is the true goldstino eaten by the superHiggs***
- ***The others are extra fermionic particles (Pseudo-Goldstini)***

K.Benakli and C.Moura '07
C.Cheung, Y.Nomura and J.Thaler '10

Goldstino and Pseudo-Goldstino

True-Goldstino $G = \frac{1}{F}\left(F_1 G_1 + F_2 G_2\right) \qquad m_G = m_{3/2}$

Pseudo-Goldstino $G' = \frac{1}{F}\left(-F_2 G_1 + F_1 G_2\right) \qquad m_{G'} = ???$

- Total susy breaking scale $F = \sqrt{F_1^2 + F_2^2}$
- Total soft terms are sum of two sector contributes $m_\lambda = m_\lambda^{(1)} + m_\lambda^{(2)}$

Pseudo-Goldstino mass

Gravity Mediation

- PseudoGoldstino get mass $m_{G'} = 2m_{3/2}$

Cheung, Nomura, Thaler '10

Gauge Mediation

- Contribution from gravity is negligible
- Pseudogoldstino can get mass via radiative corrections
- ***What is the typical size of*** $m_{G'}$ ***?***

R. Argurio, A.M., Z. Komargodski '11

PGId mass computation

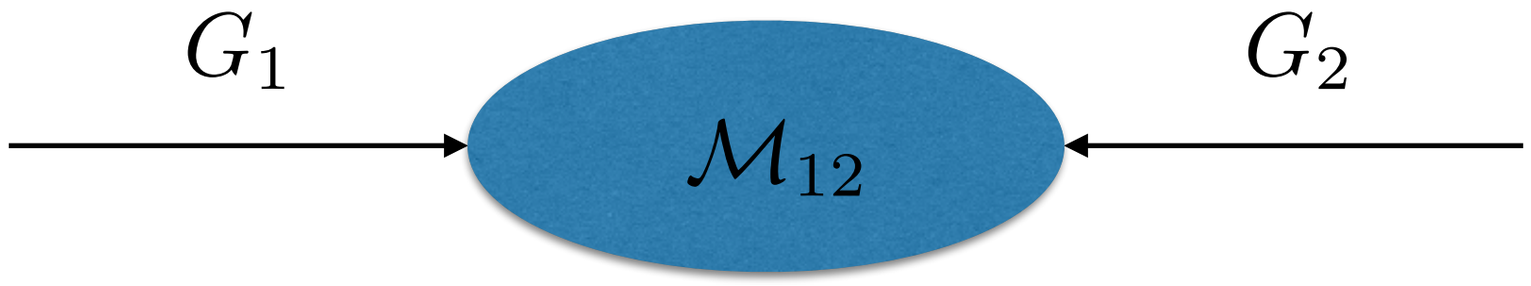
- Mass matrix for the Goldstini (one zero eigenvalue)

$$\mathcal{L} \supset \begin{pmatrix} G_1 & G_2 \end{pmatrix} \begin{pmatrix} -F_2/F_1\ \mathcal{M}_{12} & \mathcal{M}_{12} \\ \mathcal{M}_{12} & -F_1/F_2\ \mathcal{M}_{12} \end{pmatrix} \begin{pmatrix} G_1 \\ G_2 \end{pmatrix}$$

- Physical PGId mass

$$m_{G'} = \left(\frac{F_1}{F_2} + \frac{F_2}{F_1} \right) \mathcal{M}_{12}$$

- One has to compute radiative corrections to



Pseudo-Goldstino couplings

General Gauge Mediation (GGM) Lagrangian *P.Meade, N.Seiberg and D.Shih '08*

$$\frac{1}{g^2}\mathcal{L}_{GGM} = \frac{1}{2}C_0 D^2 - iC_{1/2}\lambda\sigma^\mu\partial_\mu\bar{\lambda} - \frac{1}{4}C_1 F_{\mu\nu}^2 - \frac{1}{2}\left(B_{1/2}\lambda^2 + h.c.\right)$$

- B and C are GGM functions encoding susy breaking sector
- Goldstino coupling reads

$$\begin{aligned}\frac{1}{g^2}\mathcal{L}_{Gold} &= \frac{iB_{1/2}}{\sqrt{2}f}\left(G\lambda D - \frac{i}{2}\lambda\sigma^\mu\bar{\sigma}^\nu G F_{\mu\nu}\right) + \\ &\frac{1}{\sqrt{2}f}(C_0 - C_{1/2})G\sigma^\mu\partial_\mu\bar{\lambda}D + \frac{i}{\sqrt{2}f}(C_1 - C_{1/2})G\sigma_\nu\partial_\mu\bar{\lambda}F^{\mu\nu} + \ldots\end{aligned}$$

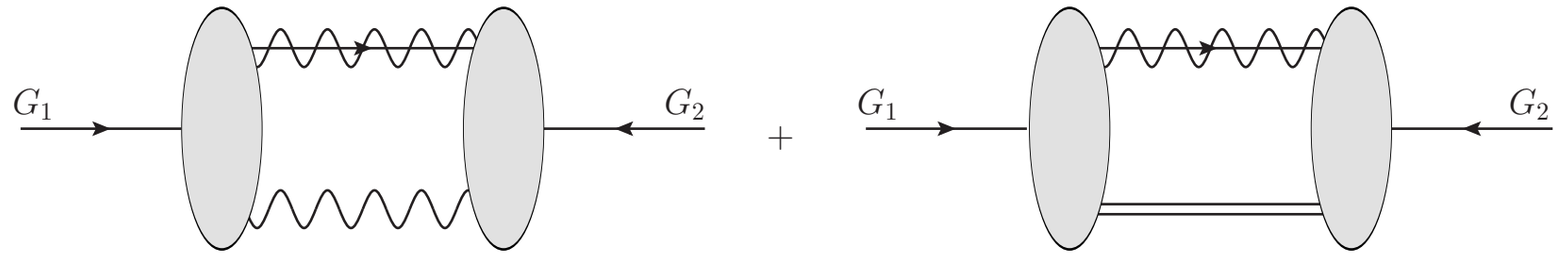
- Goldstino coupling in model independent formalism

Pseudo-Goldstino mass

Lagrangian for two goldstini coupled only via MSSM gauge fields

$$\mathcal{L} = \mathcal{L}^{(1)}_{GGM} + \mathcal{L}^{(2)}_{GGM} + \mathcal{L}^{(1)}_{G_1} + \mathcal{L}^{(2)}_{G_2}$$

- GGM parameterization of SUSY breaking sectors
- Leading contribution at order g^4



- PseudoGoldstino mass

$$m_{\tilde{G}'} = \frac{g^4}{2}\left(\frac{1}{F_1^2}+\frac{1}{F_2^2}\right)\int \frac{d^4p}{(2\pi)^4} B^{(1)}_{1/2}\left(C^{(2)}_0 - 4C^{(2)}_{1/2} + 3C^{(2)}_1\right) + 1 \leftrightarrow 2$$

- B and C are GGM functions encoding susy breaking sectors
- Expressions checked in toy models (MGM)

Pseudo-Goldstino mass

- Typical value of PGLD mass is around weak scale
- For instance in Minimal Gauge Mediation with same scales

$$F_1 \sim F_2 \sim F \quad \Rightarrow \quad m_{\tilde{G}'} \simeq \frac{g^4}{(16\pi^2)^3}\frac{F}{M} \simeq \frac{g^2}{(16\pi^2)^2} m_{soft}$$

- Can be enhanced if susy breaking scales are different

$$F_1 \gg F_2 \sim F \quad \Rightarrow \quad m_{\tilde{G}'} \simeq \frac{g^2}{(16\pi^2)^2}\left(\frac{F_1}{F_2}\right) m_{soft}$$

- For heavy soft terms we can reach hundreds of GeV
- Validity limit set by backreaction of sector 1 on sector 2

PGLD in Gauge Mediation

More SUSY breaking sectors + ***Gauge Mediation of SUSY breaking***

Pseudo-Goldstini

- Extra light fermionic degrees of freedom w.r.t. to MSSM
- PGLD get mass radiatively
- Their couplings is fixed by soft terms of the different sectors
- Can lead to distinctive phenomenology

PGLD Lagrangian for two sectors

Simplified model for Goldstino and PseudoGoldstino and the MSSM

$$\mathcal{L} = \mathcal{L}_{MSSM} + \mathcal{L}_{kin}(G) + \mathcal{L}_{kin}(G') + m_{G'} G' G' + \\ + \frac{m_\chi}{2\sqrt{2}F} G \sigma^\mu \bar{\sigma}^\nu \chi F_{\mu\nu} + K_\chi \frac{m_\chi}{2\sqrt{2}F} G' \sigma^\mu \bar{\sigma}^\nu \chi F_{\mu\nu} + \dots$$

- $m_\chi = m_\chi^{(1)} + m_\chi^{(2)}$ is the total neutralino mass
- K_χ determines PGLD coupling with neutralino
- It depends on contributions from the two sectors

$$K_\chi = -\frac{m_\chi^{(1)}}{m_\chi}\frac{F_2}{F_1} + \frac{m_\chi^{(2)}}{m_\chi}\frac{F_1}{F_2}$$

- If $K_\chi \gg 1$ susy decay chains will end into massive PGLD

PGLD phenomenology at LHC

- If PGLD coupling are enhanced susy decays end into PGLD
- Phenomenology determined by
  - LOSP: lightest observable supersymmetry particle
  - NLSP: Pseudo-Goldstino
- True Goldstino is the LSP but does not play a role at LHC
- At LHC the MET is carried by PGLD (massive particle)
- ***New signatures can be realized***

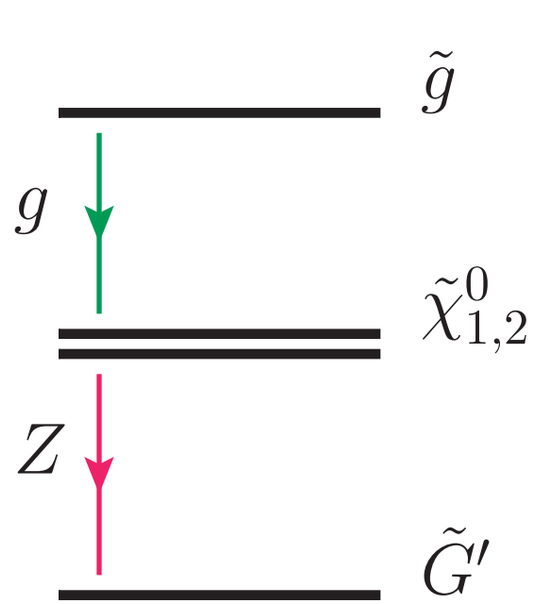
  N.Craig, J.March-Russell and M.McCullough '10
  J.Thaler and Z.Thomas '11;
  G.Ferretti, A.M., K.Mawatari and C.Petersson '13
- ***Possibility of hiding signals of Gauge Mediated SUSY***

  R.Argurio, K.De Causmaecker, G.Ferretti, A.M., K.Mawatari and Y.Takaesu '12
  K.i.Hikasa, T.Liu, L.Wang and J.M.Yang '14

Back to ATLAS excess

Can it be the Pseudo-Goldstino of gauge mediation?

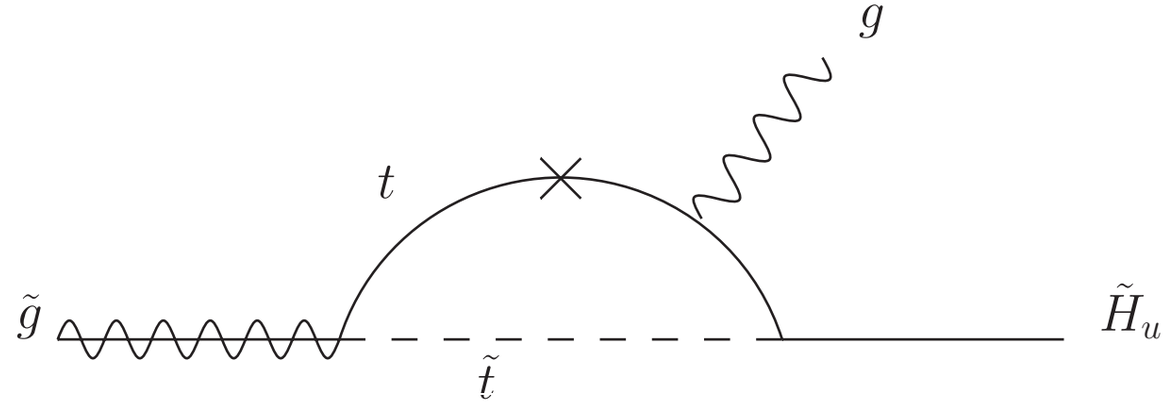
- Simplified model with Gluino, Higgsino and Pseudo-Goldstino
- Other sparticles decoupled
- Pseudo-Goldstino carries missing energy
- Different phenomenology varying PGLD mass



Susy decay channels: gluino

- We fix the Neutralino (Higgsino) mass such that one loop gluino decay process dominates

$$m_{\tilde{g}} - m_{\tilde{\chi}^0_{1,2}} = 200 \text{ GeV} \quad \Rightarrow \quad BR[\tilde{g} \to g\tilde{\chi}^0_{1,2}] \geq 85\%$$



- Squarks at O(TeV) scale
- Robust result as soon as Neutralino is mostly Higgsino

Susy decay channels: Higgsino

- Higgsino decay determined by effective Lagrangian

$$\mathcal{L}_{\tilde{G}'} = i\frac{\tilde{y}^i_\gamma}{2\sqrt{2}F}\,\tilde{G}'\sigma^\mu\bar{\sigma}^\nu\tilde{\chi}^0_i A_{\mu\nu} + i\frac{\tilde{y}^i_{Z_T}}{2\sqrt{2}F}\,\tilde{G}'\sigma^\mu\bar{\sigma}^\nu\tilde{\chi}^0_i Z_{\mu\nu}$$
$$+\frac{\tilde{y}^i_{Z_L} m_Z}{\sqrt{2}F}\,\bar{\tilde{\chi}}^0_i\bar{\sigma}^\mu\tilde{G}' Z_\mu + \frac{\tilde{y}^i_h}{\sqrt{2}F}\,\tilde{\chi}^0_i\tilde{G}' h$$

- Couplings $\tilde{y}$ depends on susy breaking soft terms
- We can find configurations such that the decay into PGLD and Z is dominant

Susy decay channels: Higgsino

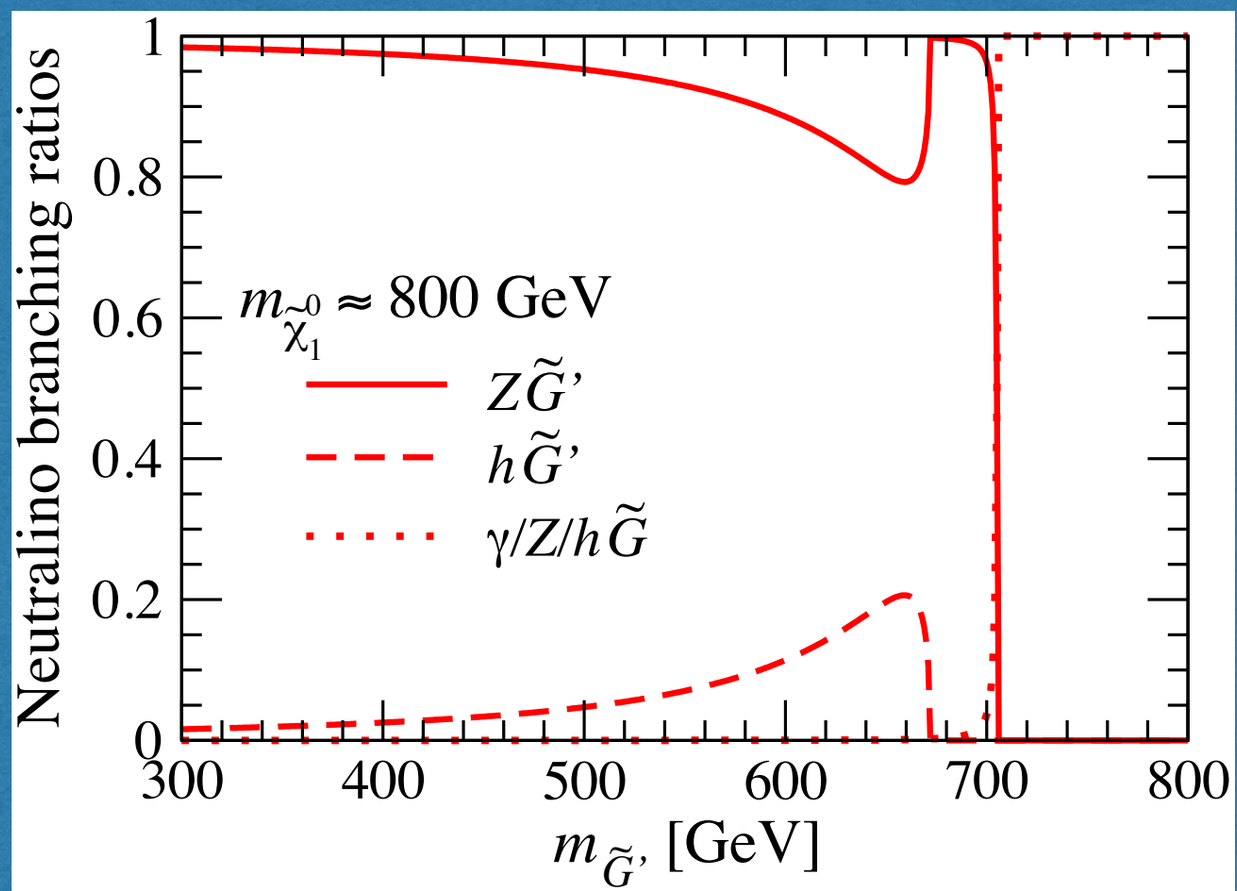
- Higgsino decay determined by effective Lagrangian

$$\mathcal{L}_{\tilde{G}'} = i\frac{\tilde{y}^i_\gamma}{2\sqrt{2}F}\tilde{G}'\sigma^\mu\bar{\sigma}^\nu\tilde{\chi}^0_i A_{\mu\nu} + i\frac{\tilde{y}^i_{Z_T}}{2\sqrt{2}F}\tilde{G}'\sigma^\mu\bar{\sigma}^\nu\tilde{\chi}^0_i Z_{\mu\nu}$$

$$+ \frac{\tilde{y}^i_{Z_L} m_Z}{\sqrt{2}F}$$

- Couplings $\tilde{y}$ depen
- We can find configu and Z is dominant

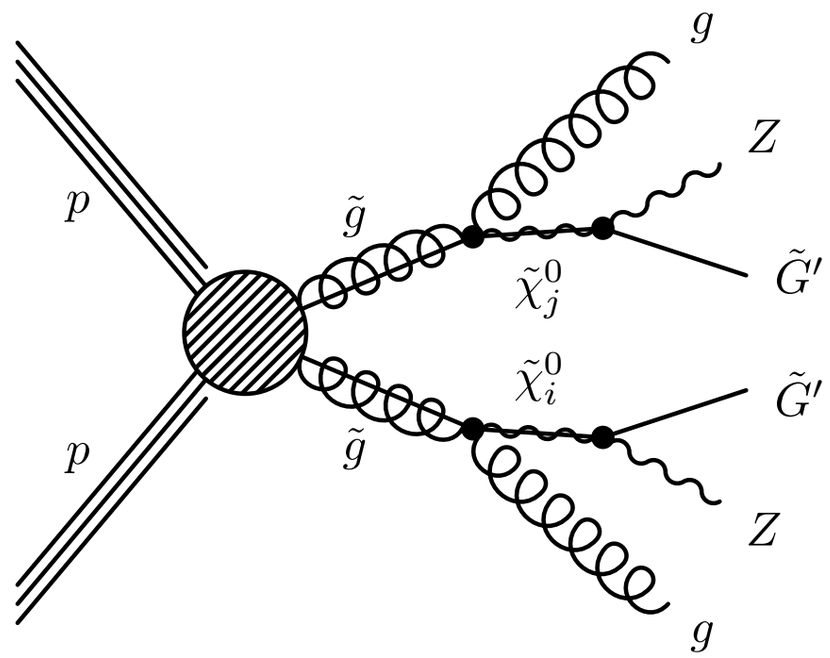
Example with $BR[\tilde{\chi}^0 \to Z\tilde{G}'] \geq 80\%$



Susy production and decay chain

Main SUSY channel is gluino pair production

- Decay chain leads to two Z plus jets plus MET

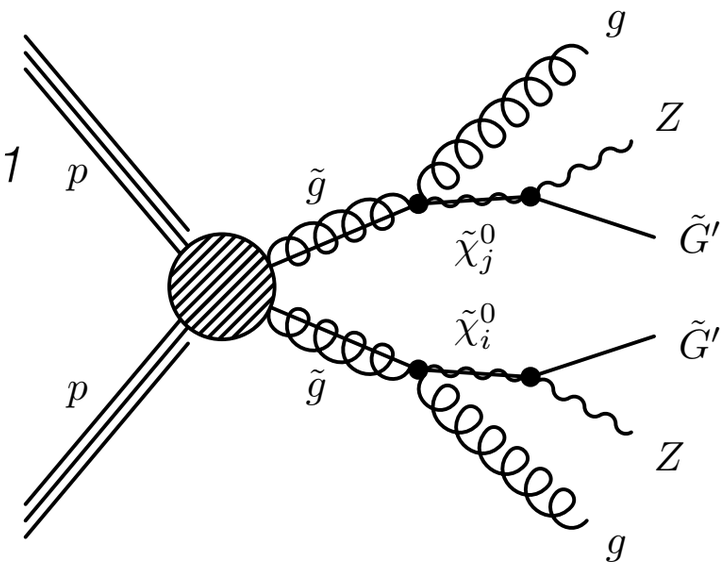


Differences with ATLAS model

- First step of decay only one jet (gluon)
- Missing energy carried by PGLD (massive particle)

Simulation and main constraints

- Model simulated in MadGraph5+Pythia
  J.Alwall, M.Herquet, F.Maltoni, O.Mattelaer and T.Stelzer '11
- FastLim/Atom for detector simulator
  M.Papucci, K.Sakurai, A.Weiler and L.Zeune '14
- LHC constraints from
  - ATLAS multi-jet *arXiv:1405.7875*
  - CMS 2-leptons plus Jets + MET *arXiv:1502.06031*



Fit and exclusion parameterized by R factor

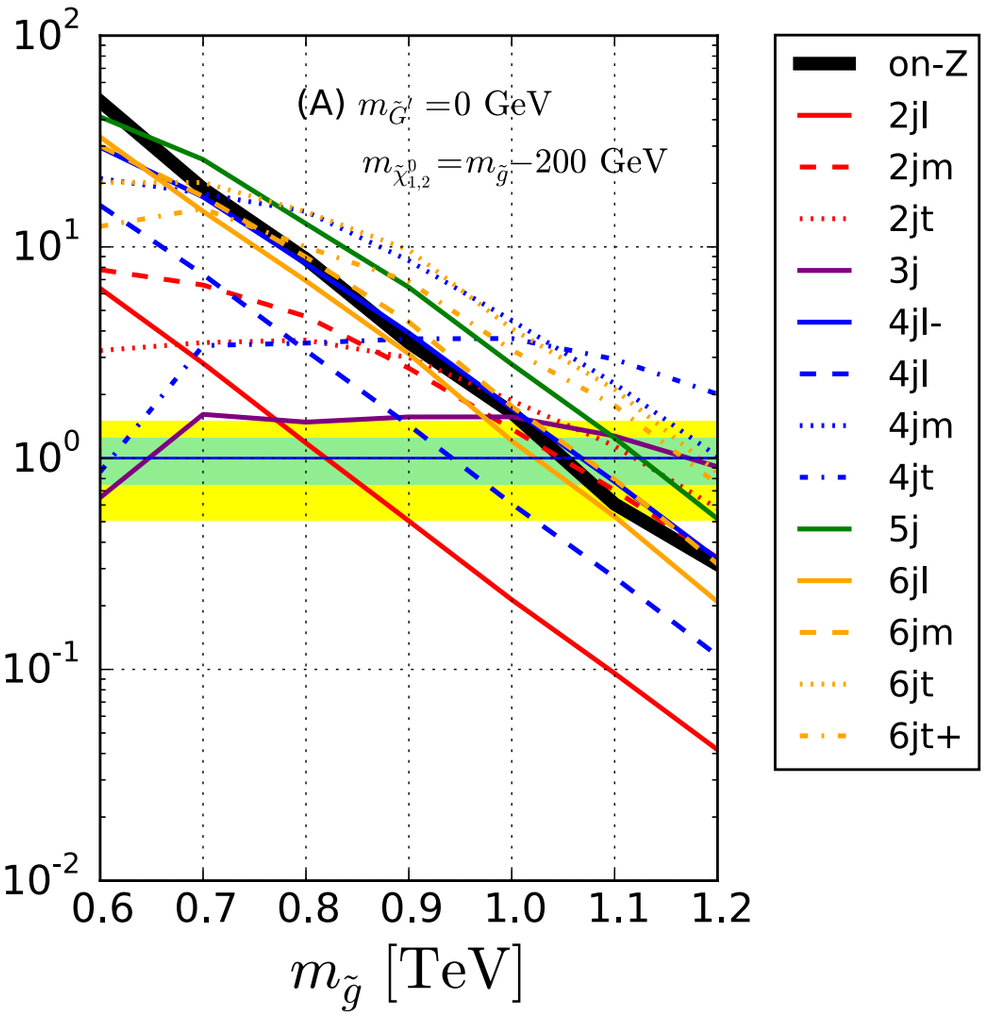
- For FIT: $R \equiv N_{\rm SUSY}/(N_{\rm obs} - N_{\rm SM})$
- For EXCLUSION at 95%CL: $R^i \equiv N^i_{\rm SUSY}/N^{{\rm UL},i}_{\rm BSM}$

Results for benchmark scenarios

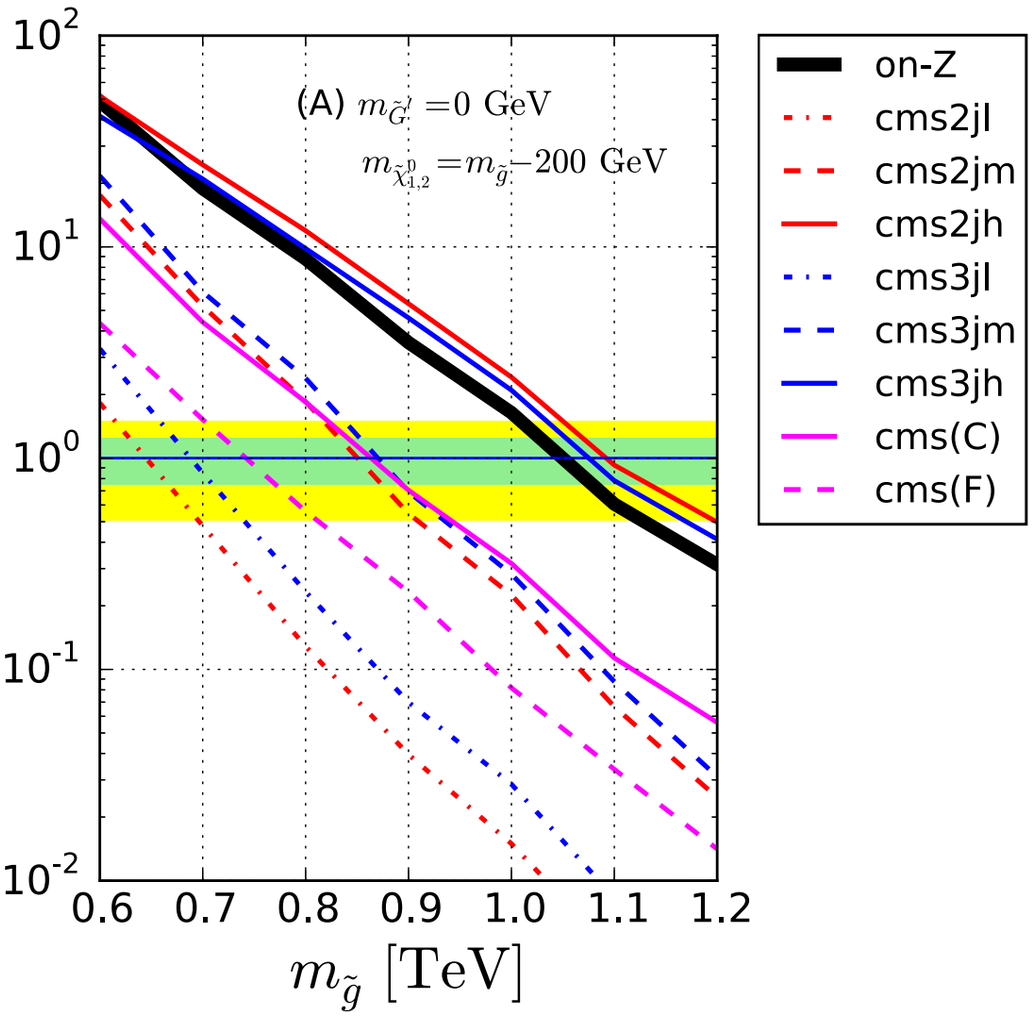
As GMSB with one $m_{\tilde{\chi}^0_{1,2}} = m_{\tilde{g}} - 200\ \mathrm{GeV}$

SUSY br sector $m'_{\tilde{G}} = 0$

ATLAS fit and ATLAS constraints



ATLAS fit and CMS constraints



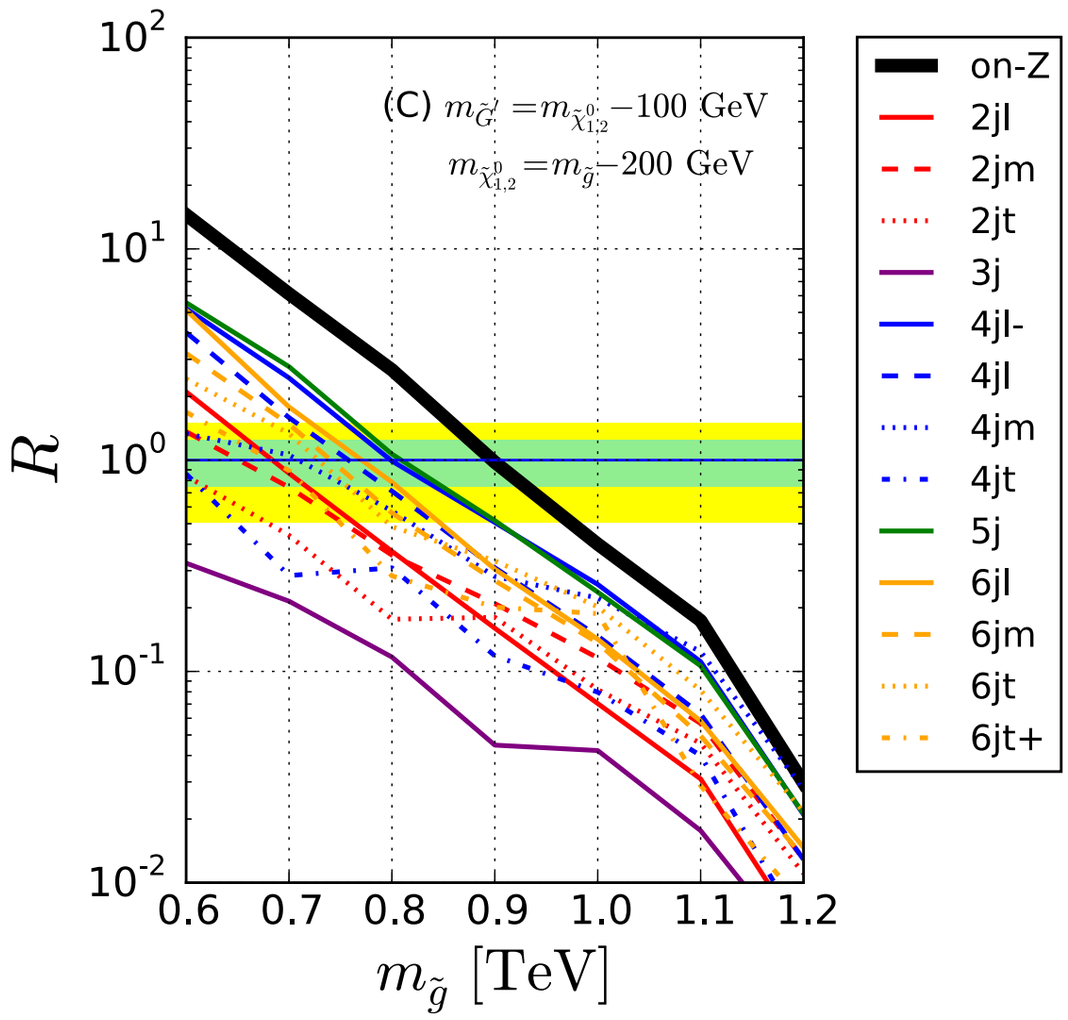
Results for benchmark scenarios

Very compressed scenario

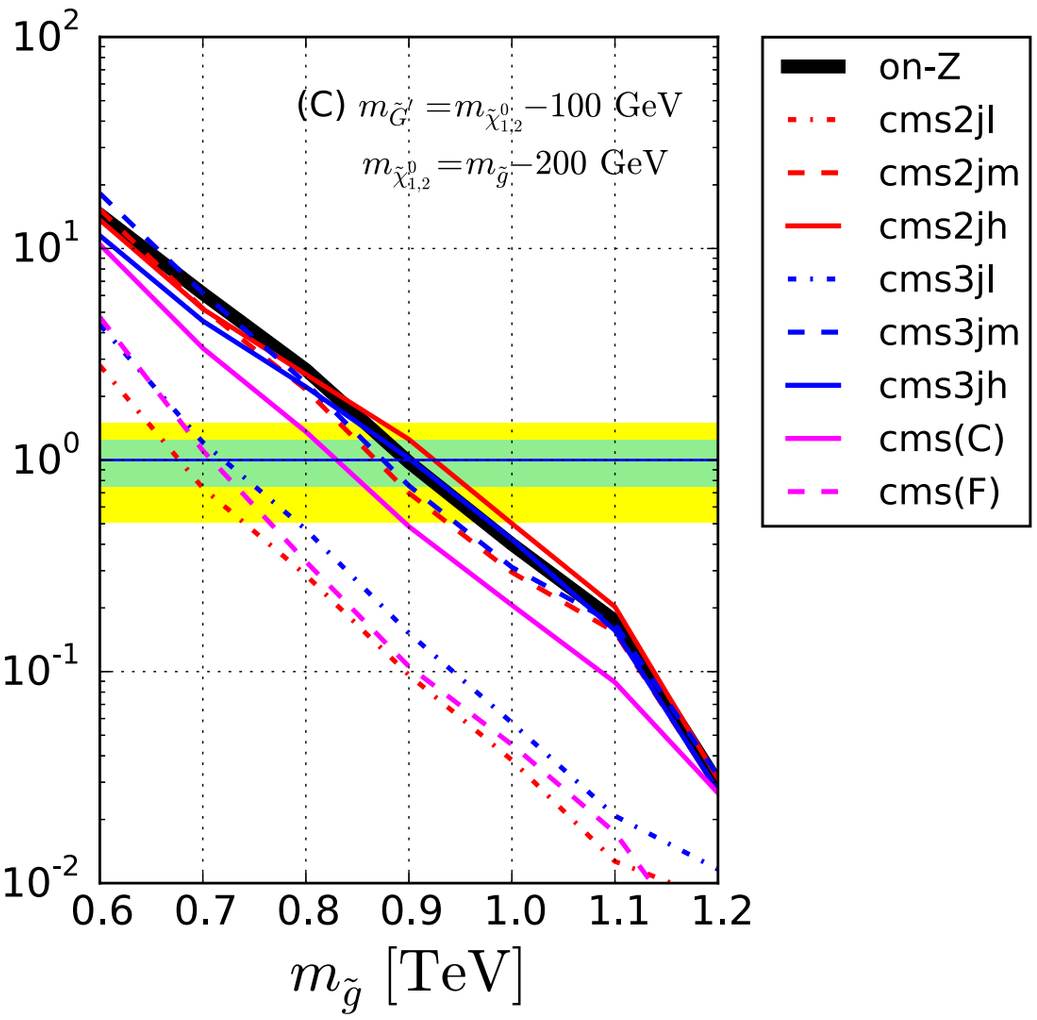
$$m_{\tilde{\chi}^0_{1,2}} = m_{\tilde{g}} - 200 \text{ GeV}$$

$$m_{\tilde{G}'} = m_{\tilde{\chi}_0} - 100 \text{ GeV}$$

ATLAS fit and ATLAS constraints



ATLAS fit and CMS constraints

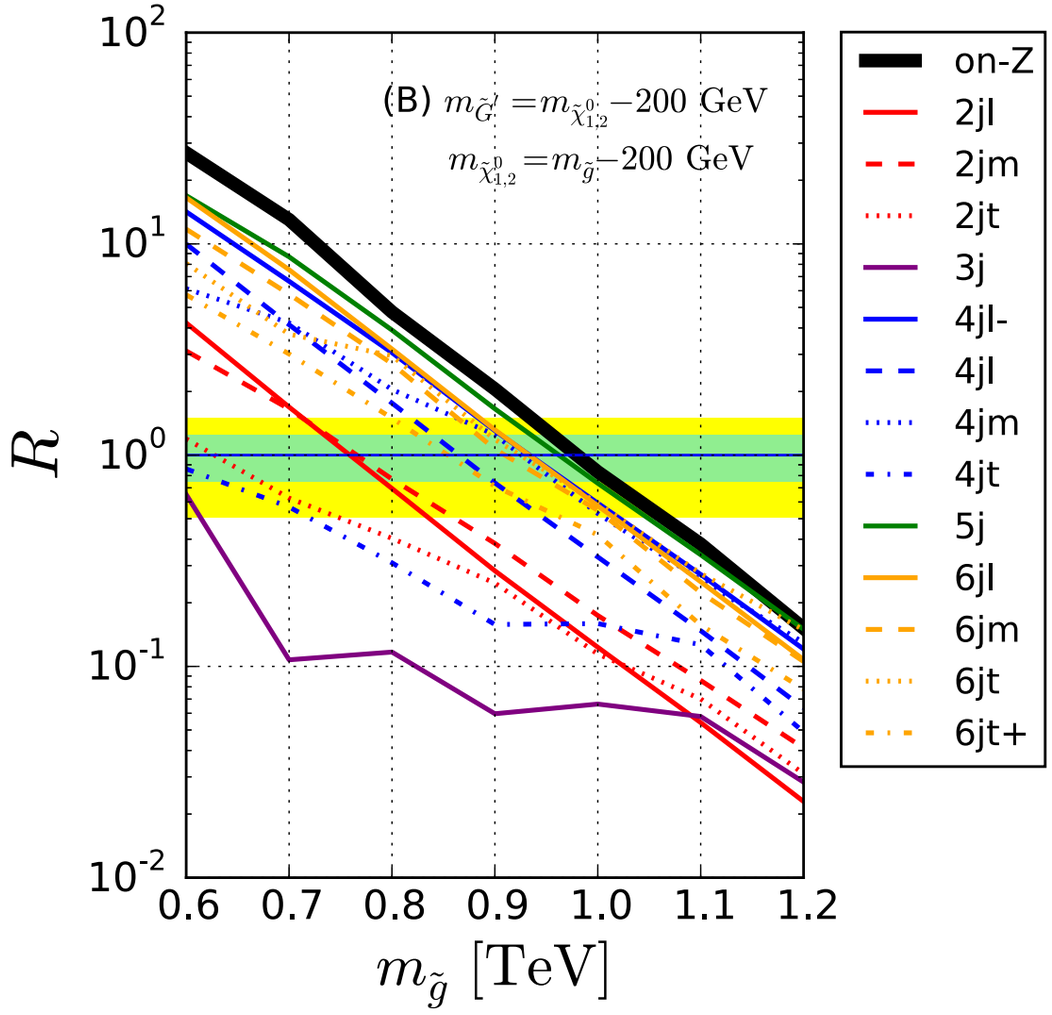


Results for benchmark scenarios

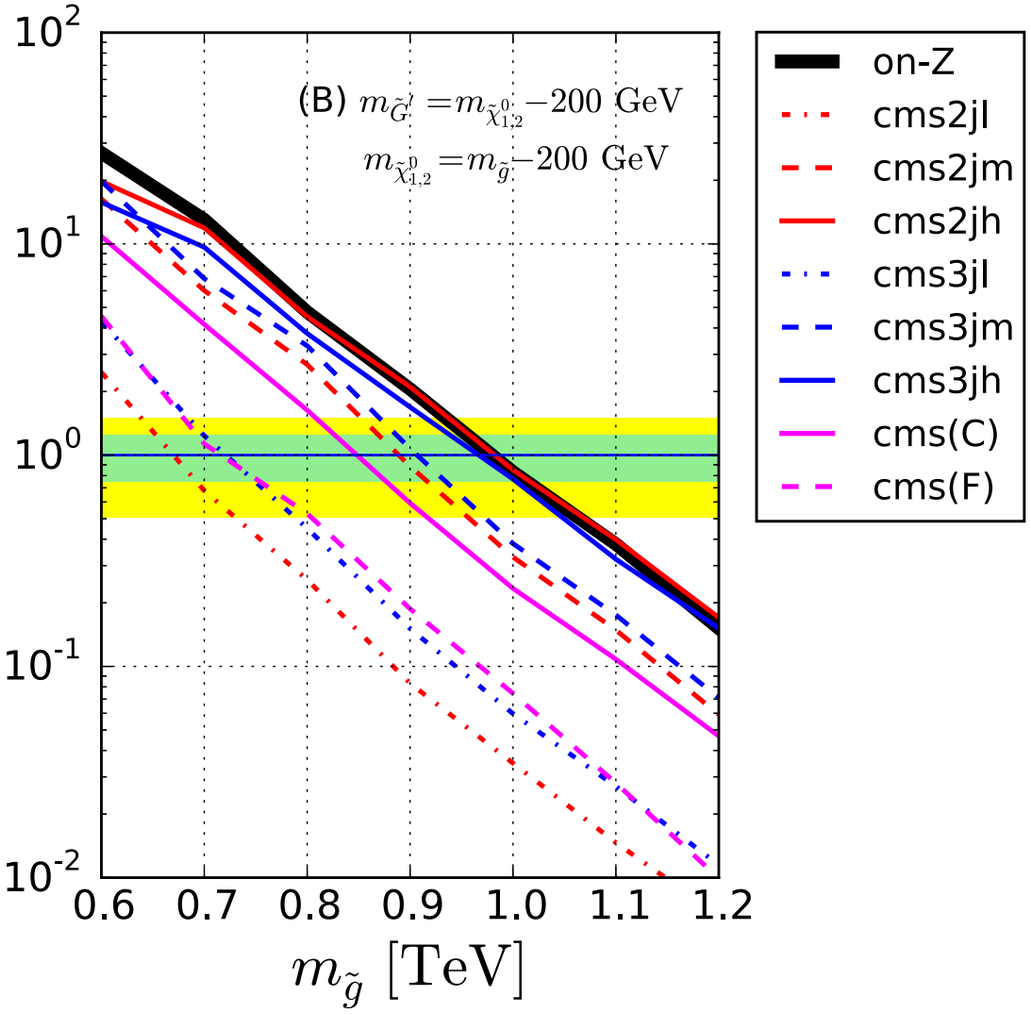
OPTIMAL CASE

$$m_{\tilde{\chi}^0_{1,2}} = m_{\tilde{g}} - 200 \text{ GeV}$$
$$m_{\tilde{G}'} = m_{\tilde{\chi}0} - 200 \text{ GeV}$$

ATLAS fit and ATLAS constraints



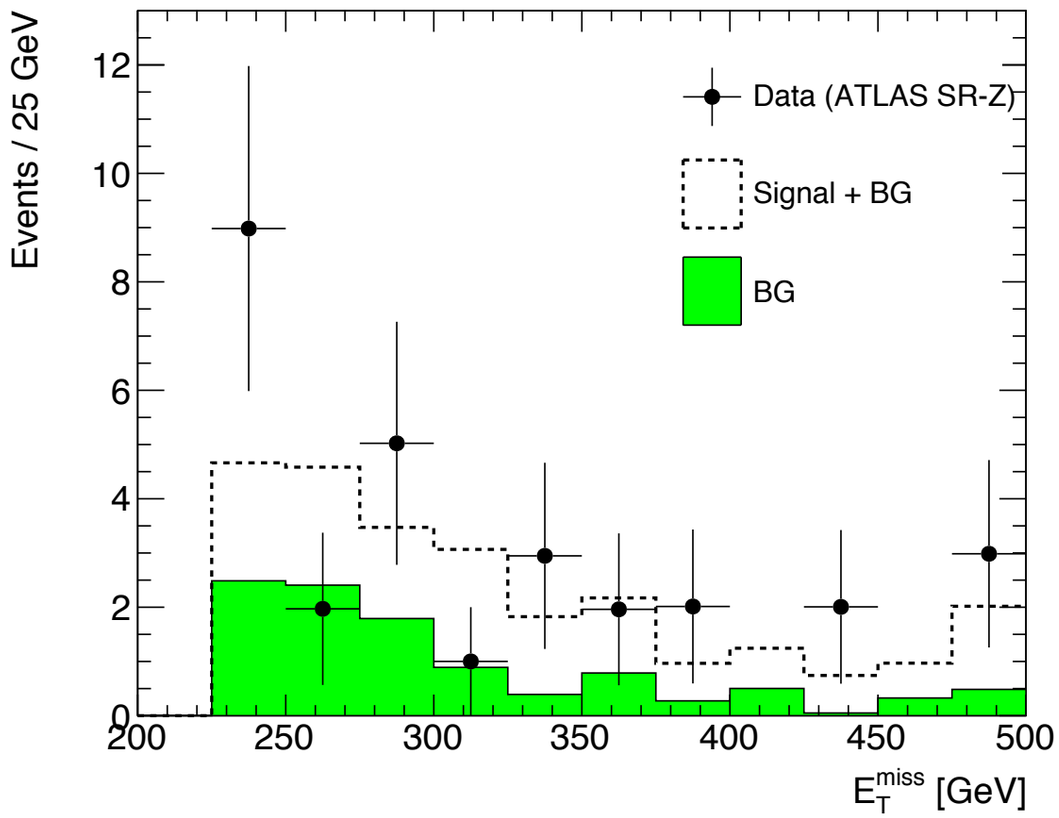
ATLAS fit and CMS constraints

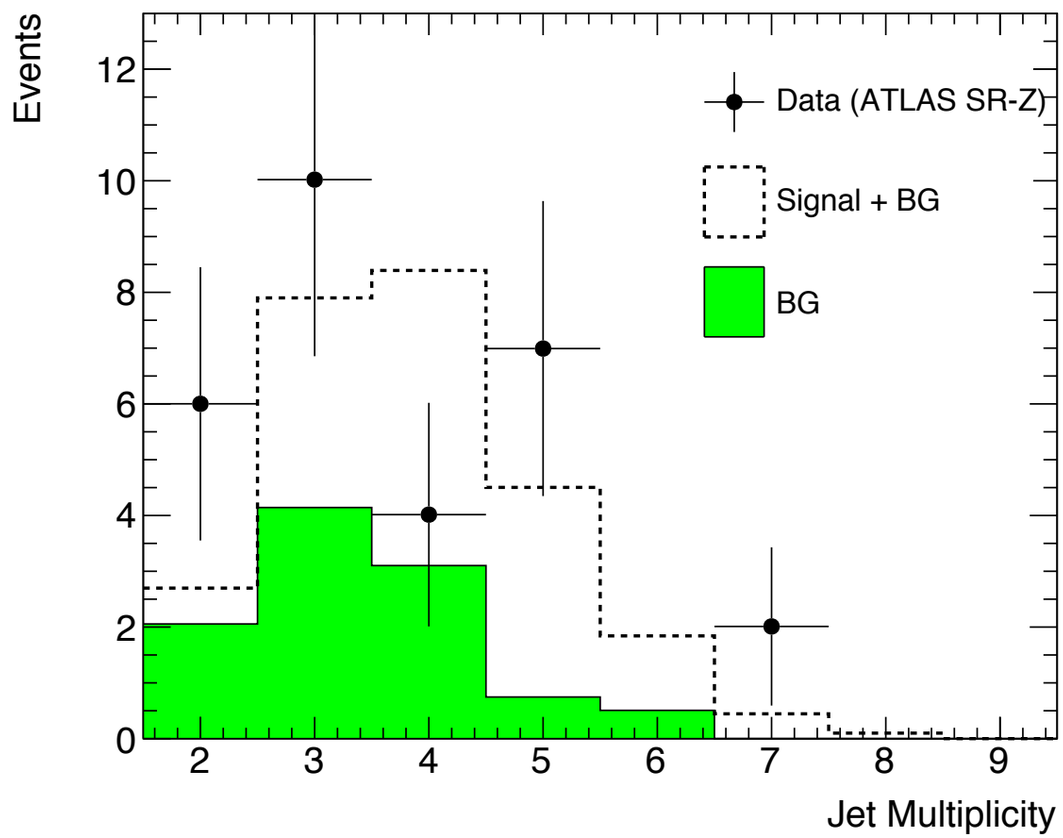


Diff distributions for best fit point

$$m_{\tilde{g}} = 1 \text{ TeV} \qquad m_{\tilde{\chi}^0} = 800 \text{ GeV} \qquad m_{\tilde{G}'} = 600 \text{ GeV}$$

Statistics is poor but shape is consistent





Jet multiplicity differs from scenario with

3-body gluino decay $\tilde{g} \to qq\tilde{\chi}^0$

and fit better the ATLAS excess data

Comments

- ATLAS Jets + MET search evaded thanks to compression
- CMS constraint evaded because of different H_T cut
- Statistics is low so it is premature to draw strong conclusions

Comparison with other SUSY explanations

- Jet distribution hints at one-loop 2-bd gluino decay
- SUSY decay chain is robust in PGLD model
- More parameters to fit the excess

Conclusions

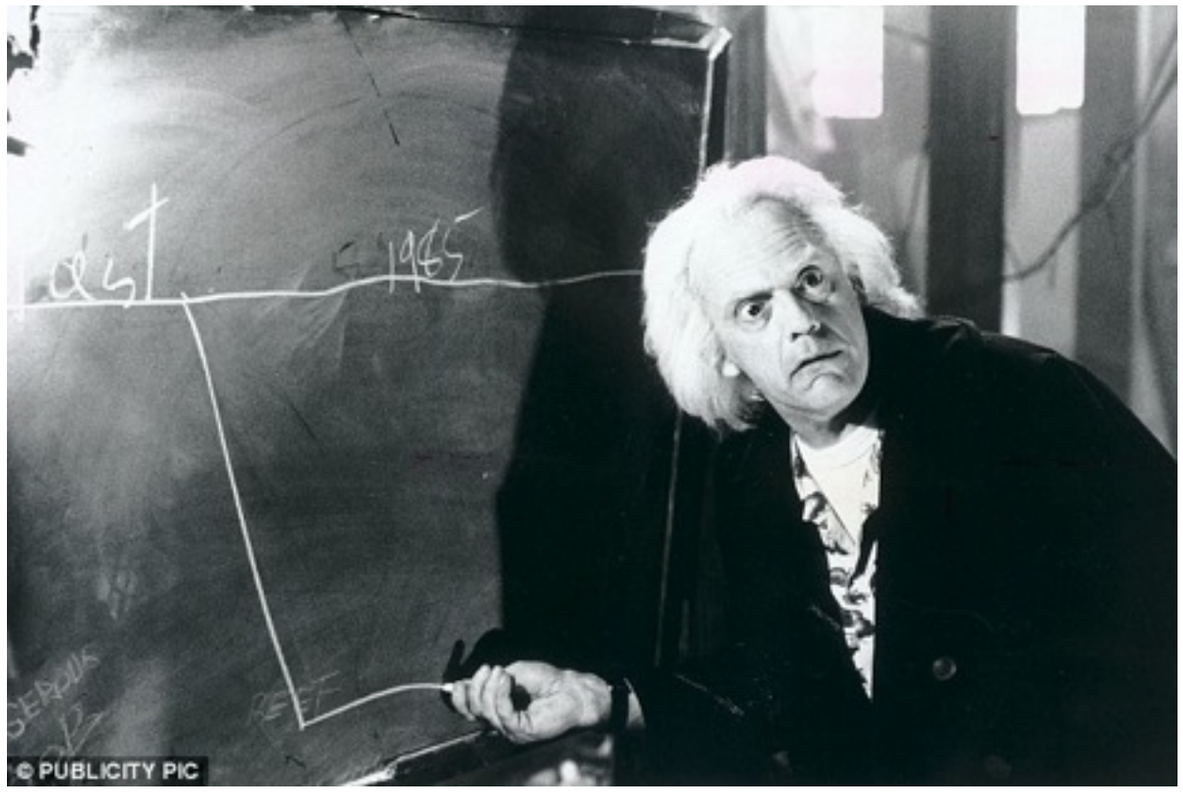
- SUSY is under pressure after LHC8
- However:
  - SUSY can be realized in non-minimal way
  - SUSY can be already hidden in the existing LHC8 data

Goldstini

- Scenarios with multiple susy breaking sectors present rich phenomenology
- Goldstini: extra light fermionic degrees of freedom with computable couplings
- A simplified goldstini model can fit the Z-peaked ATLAS excess without conflicting with other LHC constrains

Conclusions

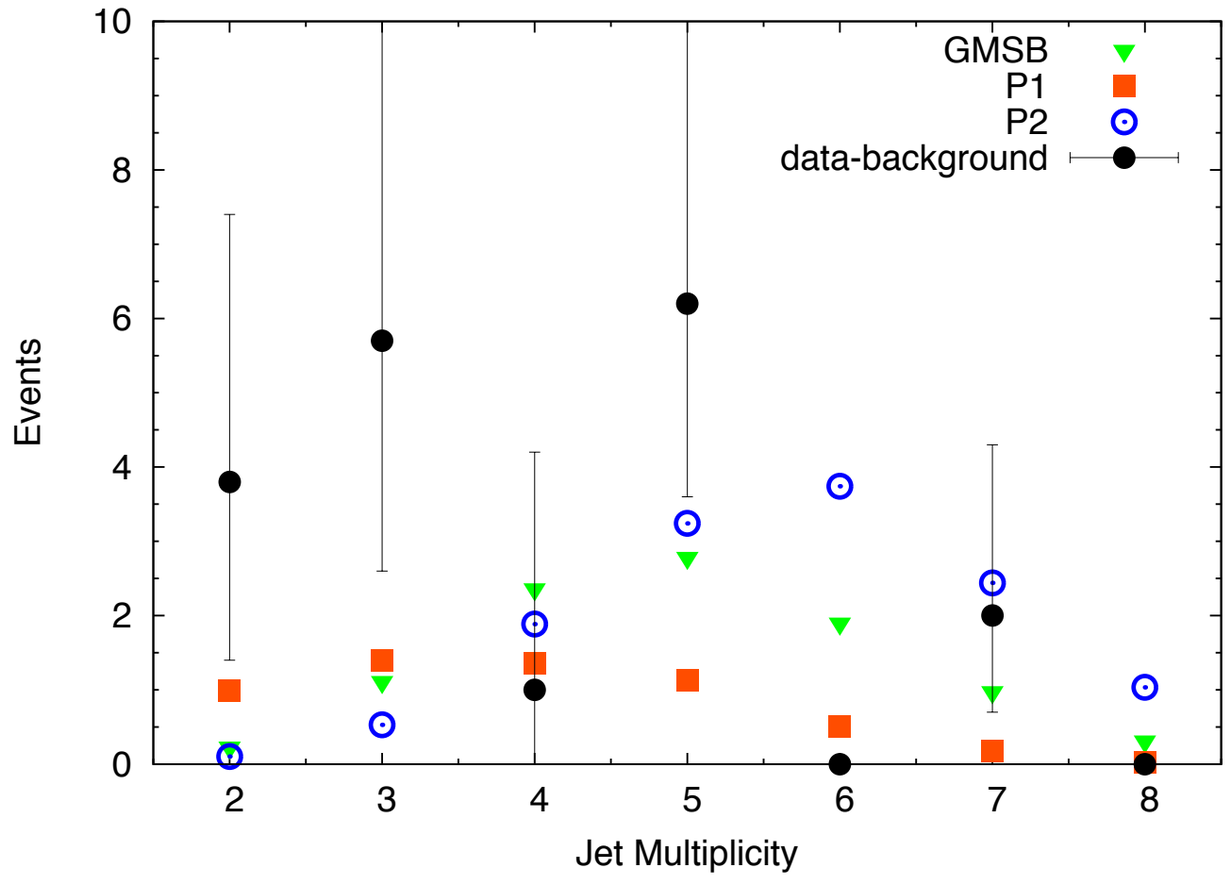
LHC13 will soon give some new excitement !!!



Thank you very much for your attention!

Backup slides

- Jet Multiplicity distribution for GMSB ATLAS model and for NMSSM compressed possibility



Ellwanger arXiv:1504.02244

Backup slides

ATLAS

- pt_lep1 > 25, pt_lep2 > 10
- eta_lep < 2.4
- d_0 differs from electron to muon (more stringent to avoid cosmic)
- N_lep > 1
- pt_jet > 35, eta_j < 2.5
- N_jet > 1
- MET > 225
- H_T = p_T(j)+p_T(lep) > 600
- 81 < m_ll < 101
- also delta_phi (jet_1,2 , MET) < 0.4 to suppress DY

- main background is ttbar
- DY Z contributes with mismisured jet as MET

Backup slides

CMS

- pt_lep1,2 > 20
- eta_lep < 2.4
- N_lep > 1
- pt_jet > 40, eta_j < 3.0
- N_jet > 1
- 81 < m_ll < 101
- bin on
  - MET (100-200,200-300,>300)
  - N_jet > 1, N_jet > 2