Conciliating SUSY with the Z-peaked excess

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Based on: G. Barenboim, J. Bernabeu, VAM, E. Romero, E. Torro, O. Vives, "METing SUSY on the Z peak", arXiv:1503.04184 [hep-ph]

ICNFP 2015
4th International Conference on New Frontiers in Physics
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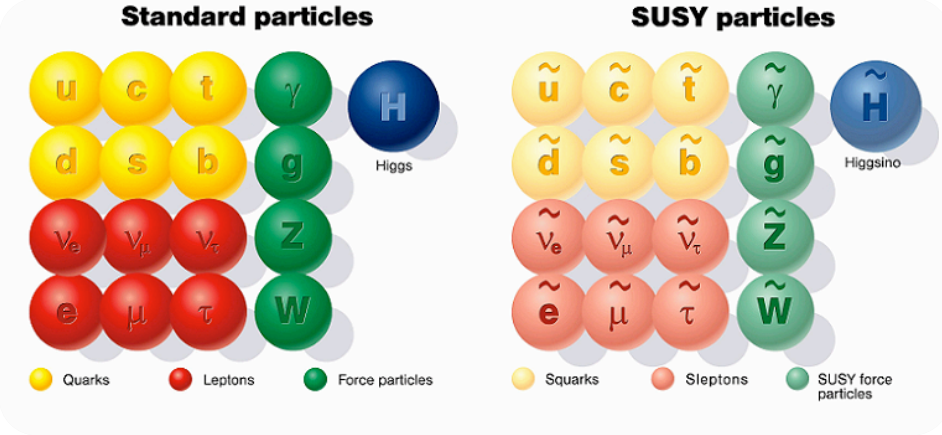
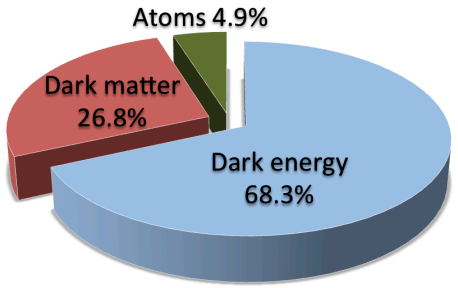
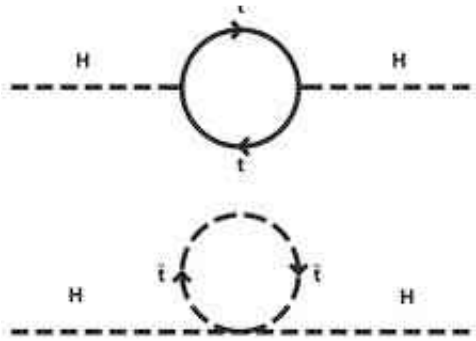
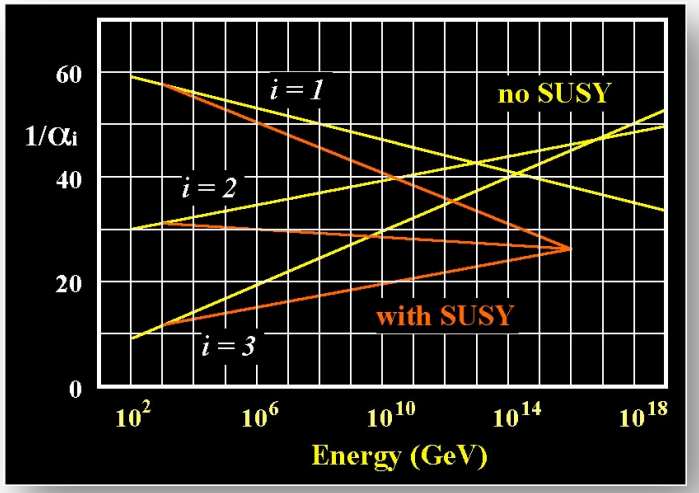
Supersymmetry (SUSY)





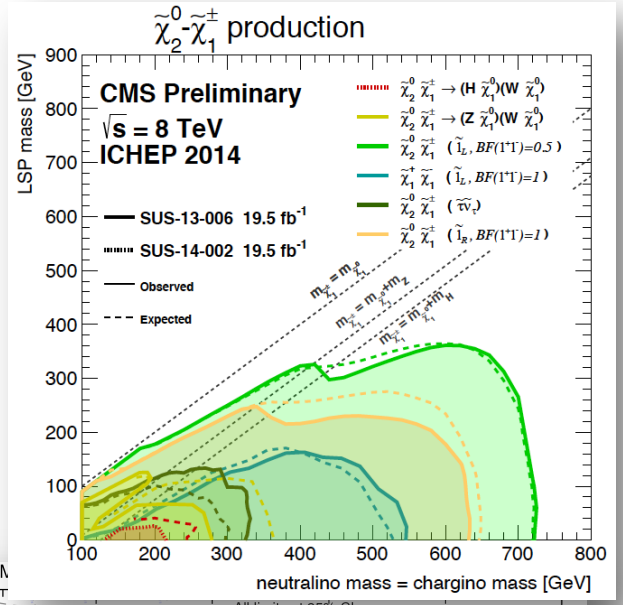


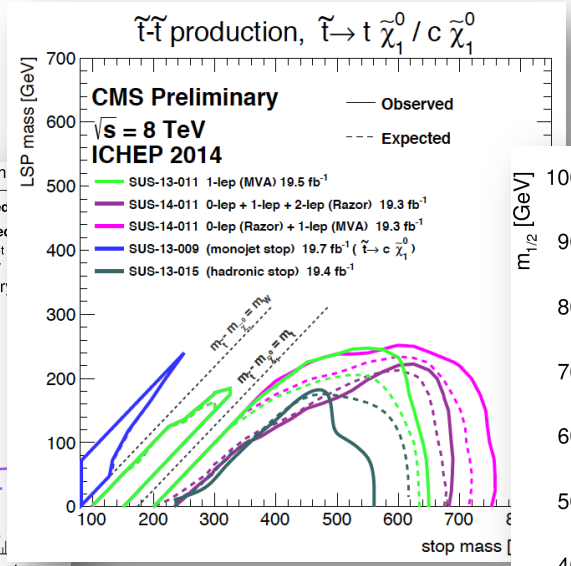
- Global symmetry between fermions & bosons
- Why is it attractive?
  - Higgs: predicts a below-135-GeV Higgs scalar
    - may be SM-like
    - completely solves hierarchy problem
  - **unification** of gauge couplings at single scale
  - **dark matter** candidate

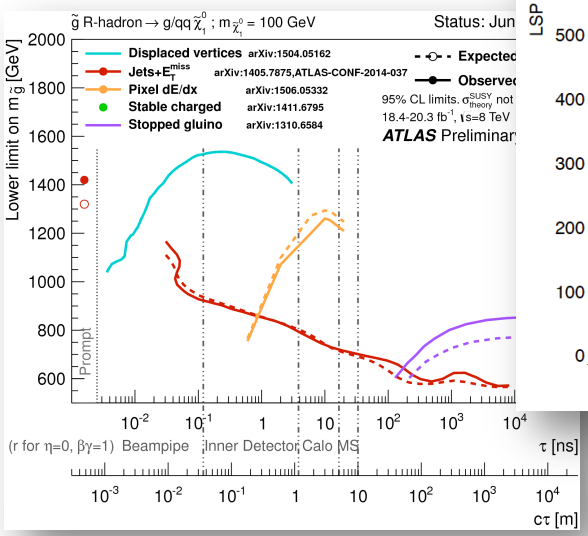


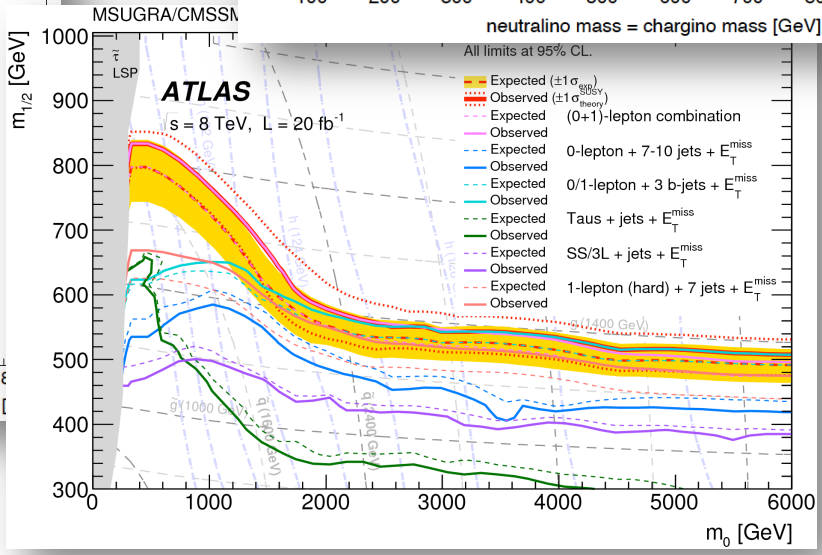
Hunting SUSY at the LHC

- Immense number of searches for various production and decay processes in many signatures
- No significant deviations from SM observed so far…
  - exclusion limits set on many SUSY models









- … however some small excesses of events have drawn attention …

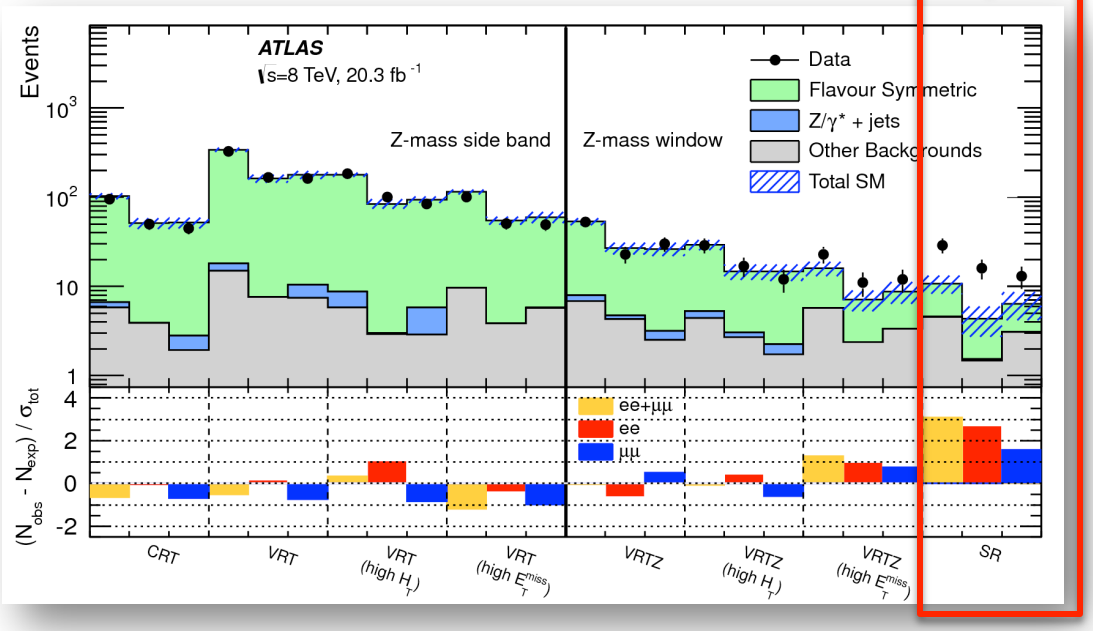
Z (→ℓℓ) + jets + MET analysis

- ATLAS search inspired by higgsino-like $\tilde{\chi}_1^0$ NLSP decaying to a Z boson & gravitino ($\tilde{G}$) LSP
  - peak at $m_{\ell\ell} \approx m_Z$
- Event selection ("Signal region")
  - two opposite-sign leptons (e, μ) with $p_{T,1} > 25$ GeV and $p_{T,2} > 10$ GeV; $M_{\ell\ell} > 15$ GeV
  - ≥ 2 jets with $p_T > 35$ GeV
  - $\ell^{\pm}\ell^{\mp}$ pair consistent with m_Z : $81 < m_{\ell\ell} < 101$ GeV
  - $H_T > 600$ GeV; MET > 225 GeV
- Backgrounds
  - ttbar (dominant)
  - Z/γ* + jets; fake leptons
  - dibosons: WW, WZ, ZZ
  - single top (tZ, tW), ttbar+V, Z → ττ

√s = 8 TeV
L = 20.3 fb^{-1}

$$H_T \equiv \sum_i p_T^{\text{jet},i} + \sum_{i=1,2} p_T^{\text{lepton},i}$$

Signal region



Data-driven methods for all major backgrounds
- thoroughly cross-checked with other methods

Eur.Phys.J. C75 (2015) 318 [arXiv:1503.03290]

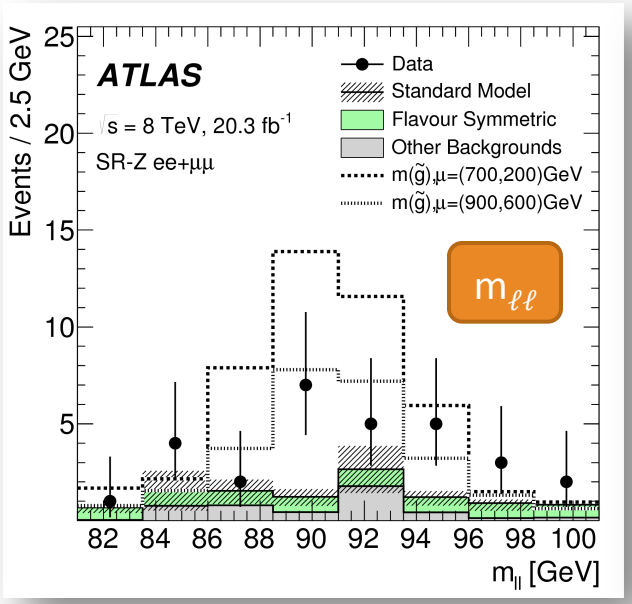
Z ($\to \ell\ell$) + jets + MET results

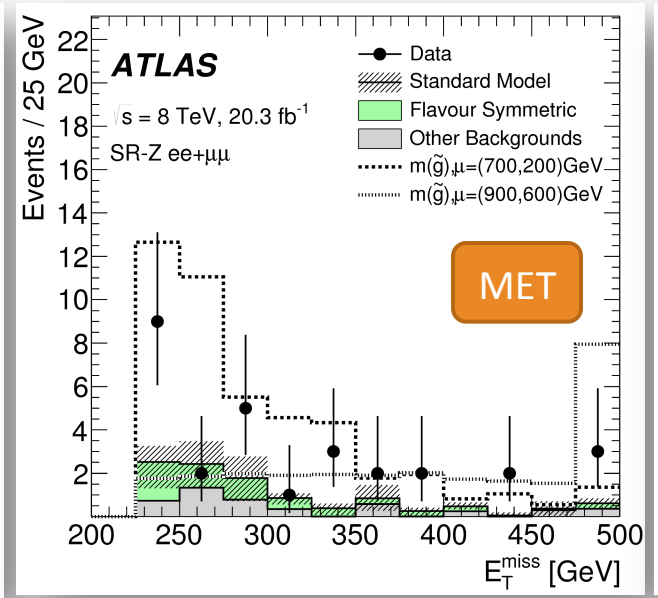
- Excess of events over expected background observed with **3σ significance**
- No such excess observed in similar CMS analysis [arXiv:1502.06031], but without H_T cut (in addition to other differences)

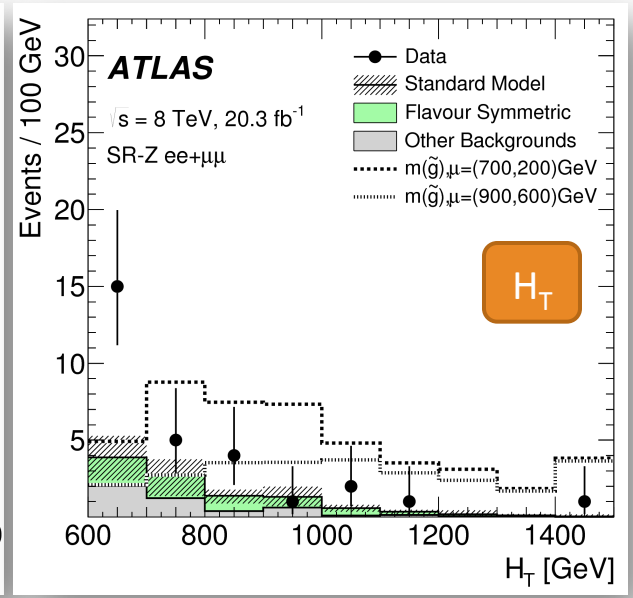
$\sqrt{s}$ = 8 TeV
L = 20.3 fb^{-1}

Channel	Z → e⁺e⁻	Z → μ⁺μ⁻	Combined
Observed	16	13	29
Expected bkg.	4.2 ± 1.6	6.4 ± 2.2	10.6 ± 3.2
Significance	3σ	1.7σ	3σ

Eur.Phys.J. C75 (2015) 318
[arXiv:1503.03290]



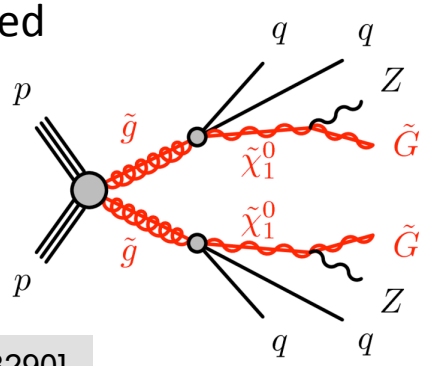




Z (→ℓℓ) + jets + MET interpretation

- 95% CL exclusion limits set for target model GGM
- Limits weaker than expected due to observed excess

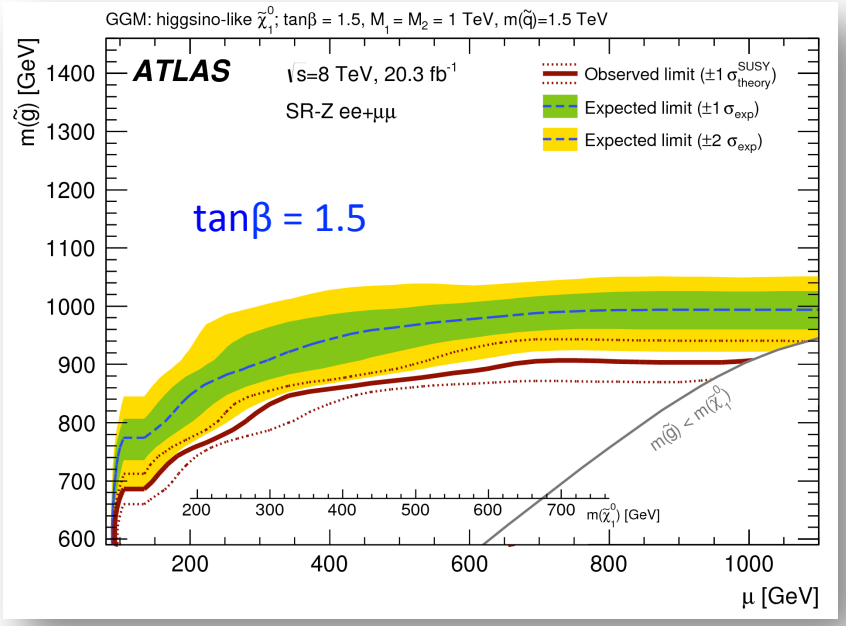
√s = 8 TeV
L = 20.3 fb^{-1}

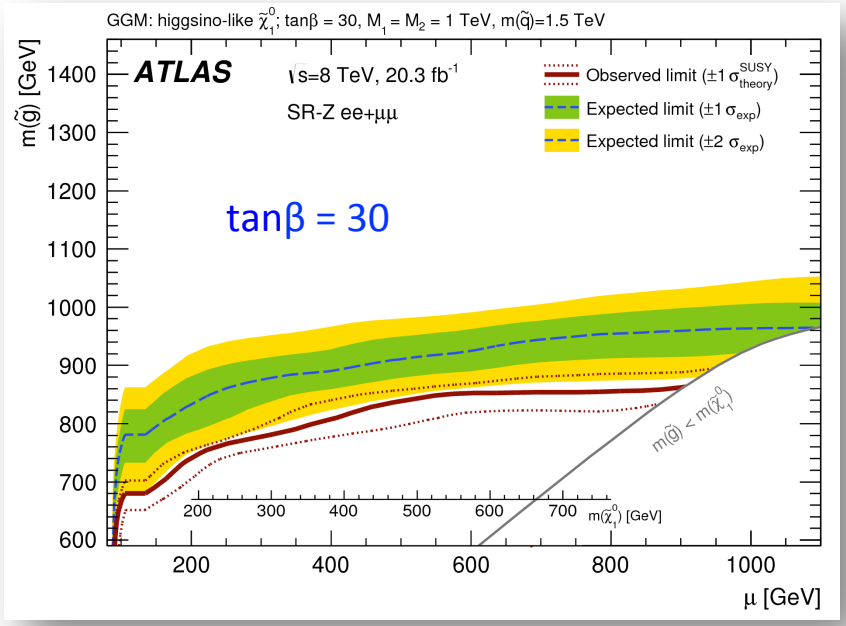


Model independent limits

Channel	Z → e⁺e⁻	Z → μ⁺μ⁻	Combined
$\langle\varepsilon\sigma\rangle^{95}_{obs}$ [fb]	1.00	0.72	1.46
S^{95}_{obs}	20.2	14.7	29.6
S^{95}_{exp}	8^{+4}_{-2}	9^{+4}_{-2}	12^{+5}_{-2}
p_0-value	0.0013	0.0430	0.0013

Eur.Phys.J. C75 (2015) 318 [arXiv:1503.03290]





If this excess is indeed evidence of beyond-SM physics…

- 29 observed $\ell^+\ell^-$ pairs when 10.6 ± 3.2 are expected
  ⇒ 273 ± 48 (for 20.3 fb^{-1}) additional Z-bosons (*)

$$\sigma(pp \to Y\overline{Y}) \simeq \frac{N_{\rm ev}/(2\mathcal{N}(Y \to Z))}{\mathcal{L}} = \frac{6.7(5.6)\text{fb}}{\mathcal{N}(Y \to Z)}$$

- Are there theoretical models (supersymmetric or not) compatible with observed excess?
- Which ones?
- How to identify them?

(*) Assuming A = ε = 1, where A acceptance of cuts to model and ε the detector efficiency

Candidate model requirements

1. Higgs mass: 125 GeV
2. Current LHC constraints on SUSY (beware of model assumptions)
3. Many Z bosons
   - many Z in SUSY cascade, e.g. $\tilde{g} \rightarrow \ldots\ldots \rightarrow \tilde{\chi}_2^0 \rightarrow Z\,\tilde{\chi}_1^0$
   - gravitino LSP with large BR($\tilde{\chi}_1^0 \rightarrow Z\tilde{G}$)
4. Hadronic activity [≥2 jets with $p_T > 35$ GeV]
5. Large MET [> 225 GeV]
   - guaranteed in RPC SUSY
6. Large $H_T \equiv \sum p_T^{jet}$ + "Z p_T" [> 600 GeV]
   - production of heavy particles, pp $\rightarrow \tilde{X}\tilde{Y}$
   - many high-E_T jets, e.g. cascade decay from gluino
   - absence of other high-p_T leptons and/or taus
7. Signal strength compatible with observed signal ⇒ high cross section
8. Cosmological considerations (dark matter relic density)

Bottom-up approach

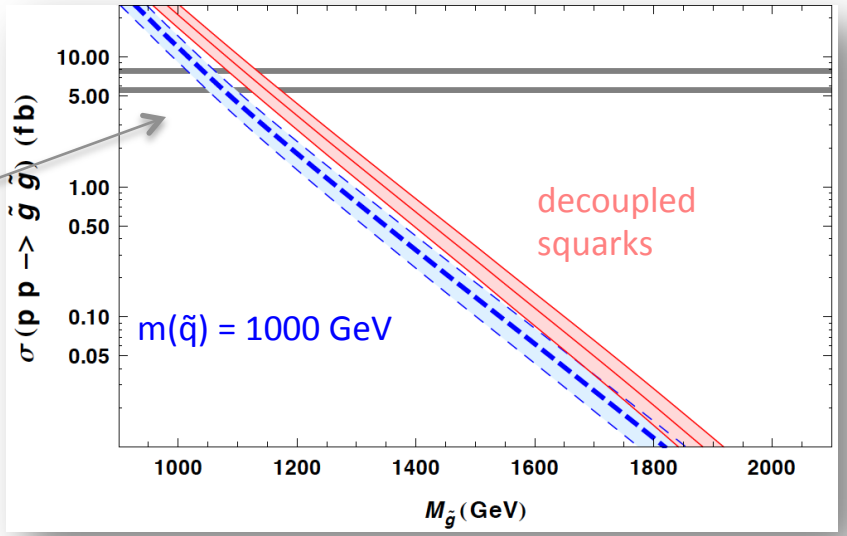
Identify models/parameter-regions that satisfy all/partly these requirements

Starting with MSSM production…

Strong production I

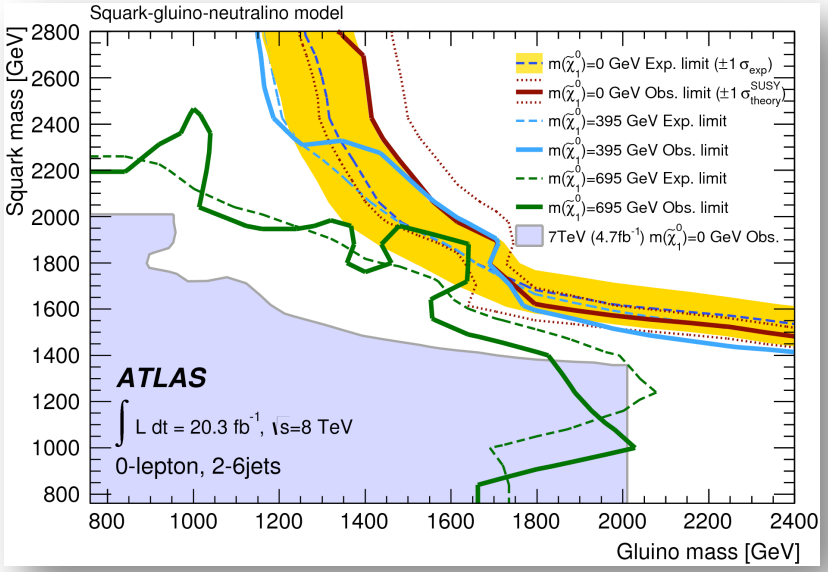
$$N_{\text{obs}} = A\varepsilon\sigma BR\int L\,\mathrm{d}t$$

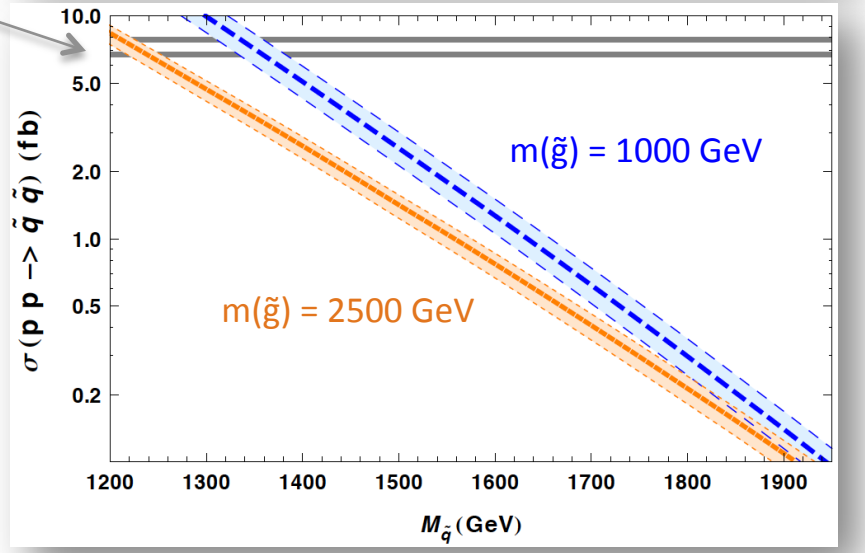
arXiv:1503.04184



Cross section needed to reproduce observed excess for **Aε = 1** and **one Z per g̃/q̃**

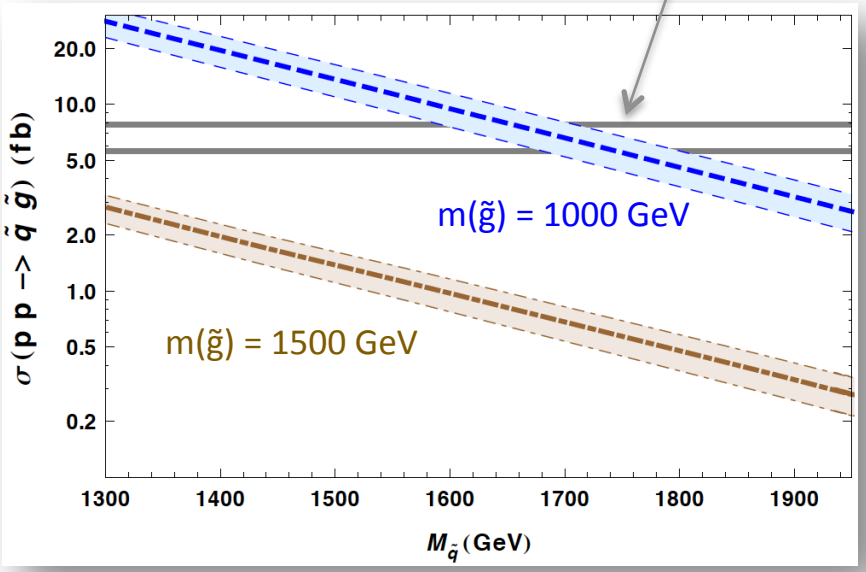
arXiv:1507.05525

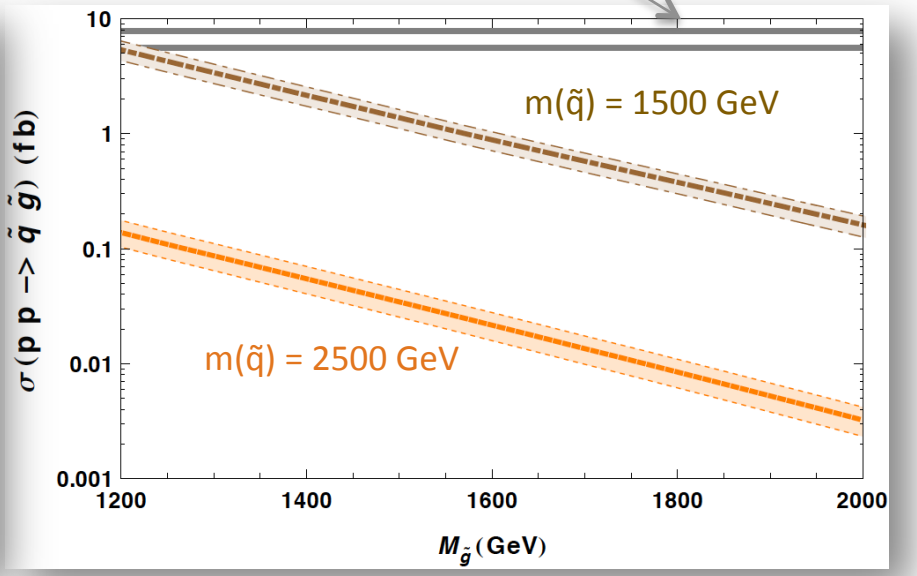




Strong production II

Cross section needed to reproduce observed excess for **Aε = 1** and **one Z per g̃/q̃**





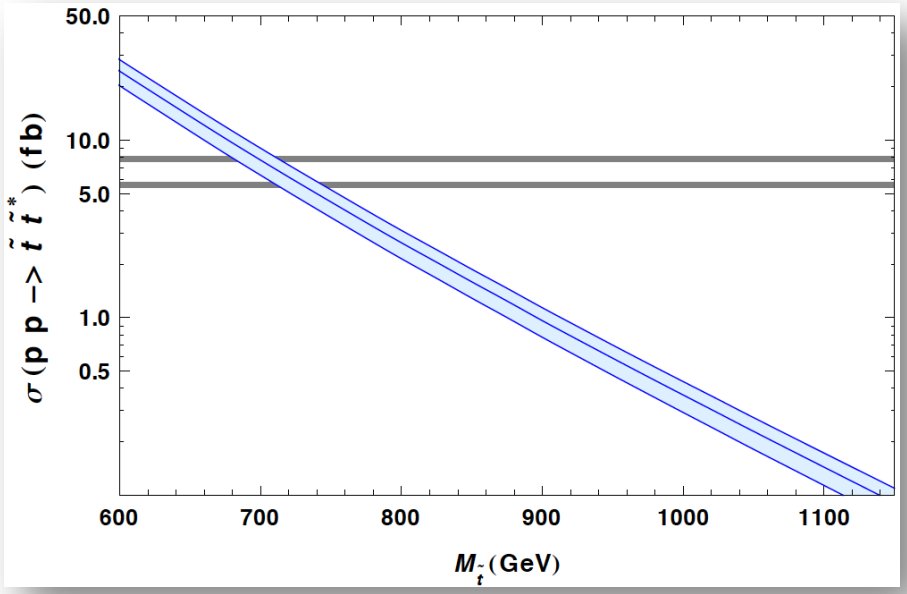
- High H_T implies heavy particles in production
  - current set limits also require heavier states
- Excess "strength" implies high cross section

→ Many Z bosons in decay chain
  - to maintain high acceptance *A*

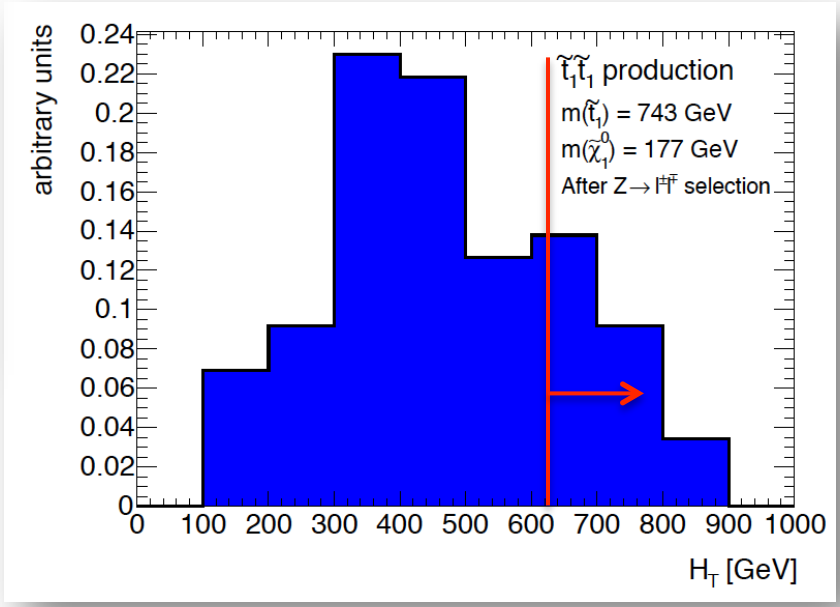
arXiv:1503.04184

Stop-pair production

- Weaker bounds on stop masses: $m(\tilde{t}_1) \gtrsim 650$ GeV



- But... for $m(\tilde{t}_1) \approx 750$ GeV
  H_T distribution "soft"
  ⇒ **heavier stops needed**
  (yet not enough cross section then)



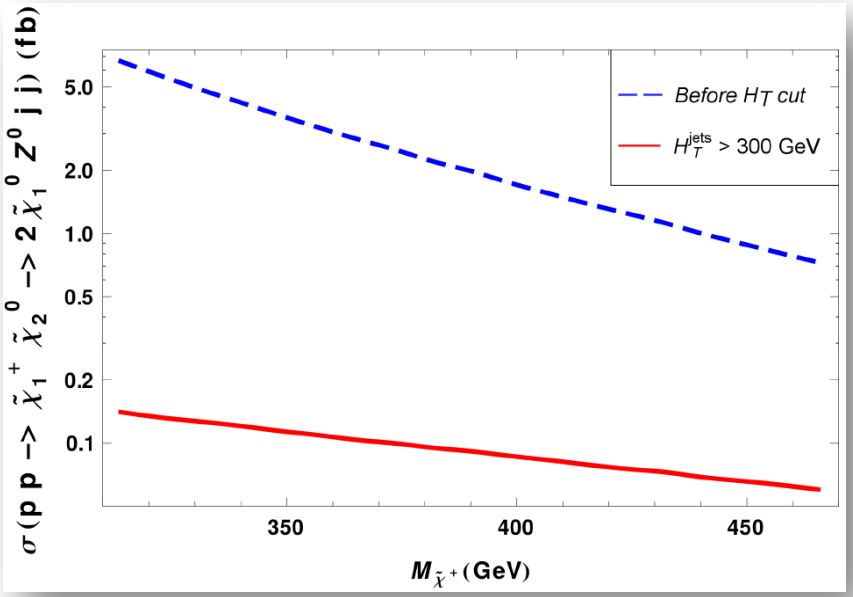
arXiv:1503.04184

Electroweak production

- Z-bosons expected in decays of higgsino-like charginos/neutralinos
- EW gauginos can be light with present bounds
- Large cross section for light $\tilde{\chi}_2^0 \tilde{\chi}_1^{\pm}$
- Could they contribute to Z production?

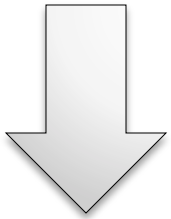
$$H_{\mathrm{T}}^{\mathrm{jets}} \equiv \sum_i p_{\mathrm{T}}^{\mathrm{jet},i}$$

- Large production cross section for light charginos
- But even after a mild cut on hadronic H_T, **great loss of acceptance**



arXiv:1503.04184

Gluino production is the best option, but difficult to get required cross section within LHC bounds



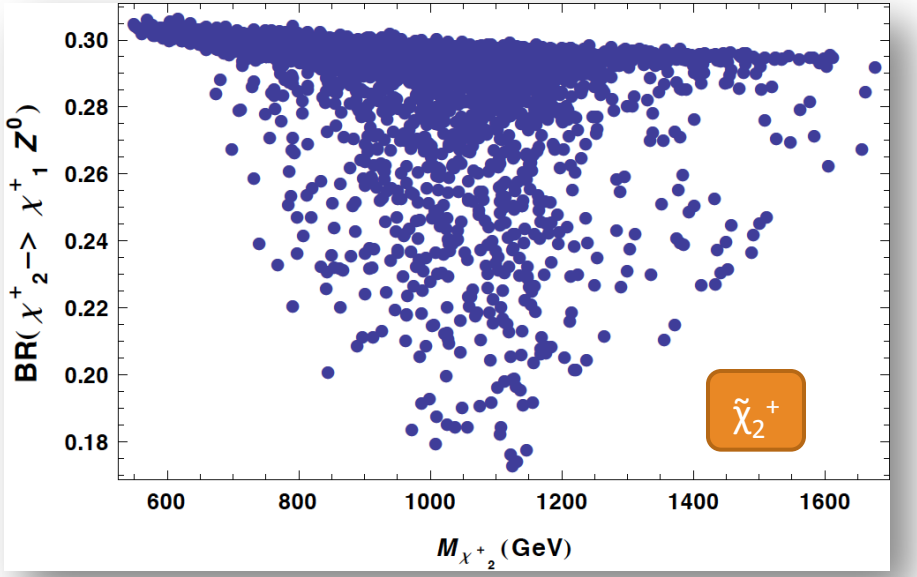
Large fraction of Z-bosons from every produced SUSY particle needed.
Is this possible within MSSM?

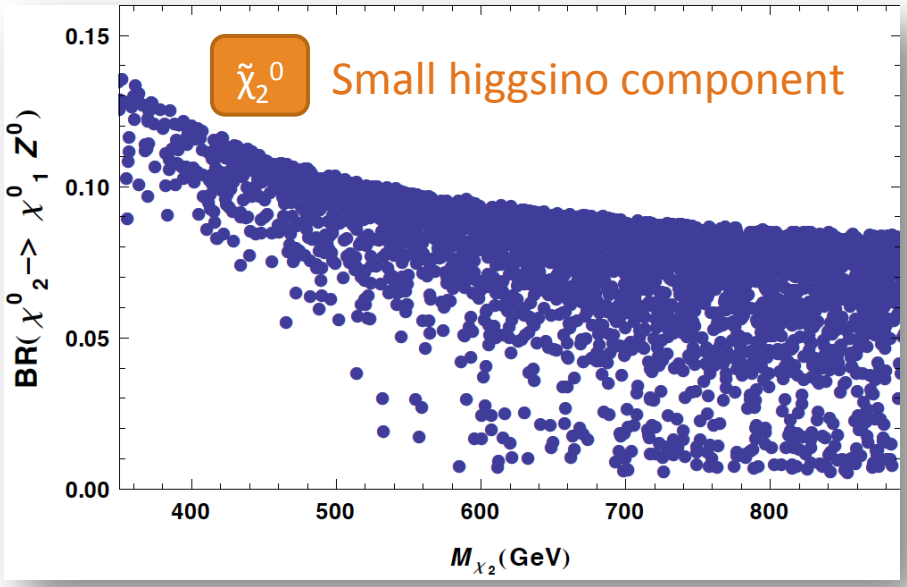
Adding Z production…

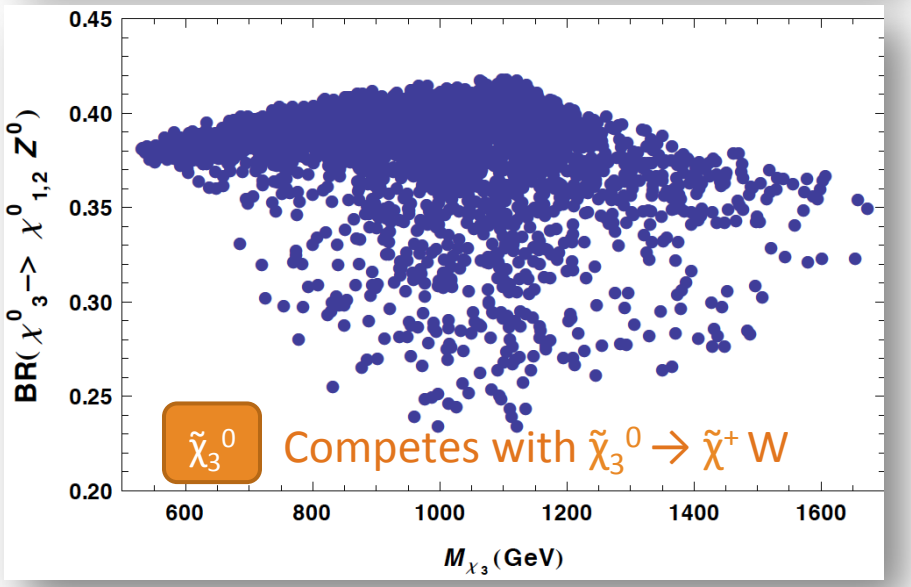
EWKino decay to Z

- mSUGRA parameter scan
- Z-bosons produced in decays of heavy charginos and higgsino-like neutralinos

arXiv:1503.04184



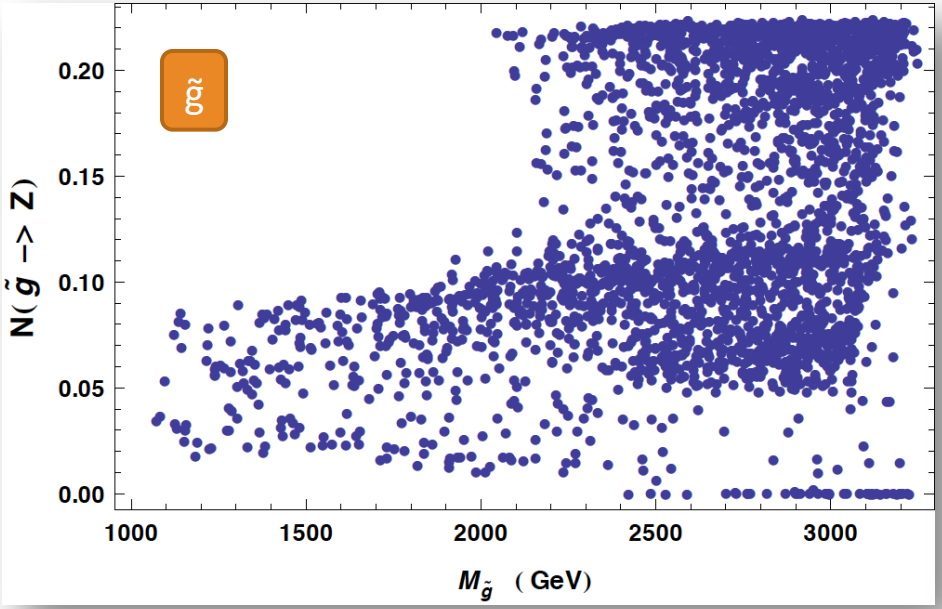


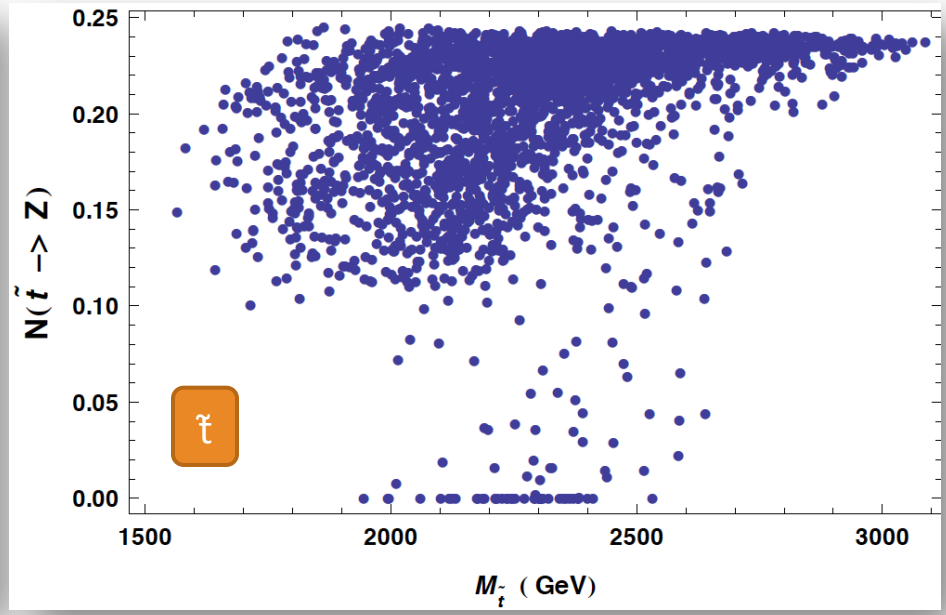


Gluino/stop decay to Z

- Gluino or squark decay chains may produce several Z-bosons:

$$\tilde{g} \to \tilde{t}_2 t \to (\tilde{t}_1 Z)t \to (\tilde{\chi}_2^+ bZ)t \to (\tilde{\chi}_1^+ ZbZ)t$$





- ➜ at most 0.1 Z-bosons per gluino/squark for light sparticles

arXiv:1503.04184

Z-boson production insufficient to account for observed excess in mSUGRA under present constraints

Alternatives

Compressed spectrum: large production of "light" gluinos (~800 GeV) decaying to heavy neutralinos (> 600 GeV)?

- Lightest neutralino is the NLSP decaying to Z-boson plus gravitino → **possible in Gauge Mediation**
- However large BR($\tilde{\chi}_1^0 \to \tilde{G}Z$) necessitates $\tilde{\chi}_1^0$ higgsino- or wino-like while in Minimal Gauge Mediation $\tilde{\chi}_1^0$ mostly bino-like
- Solution → **General Gauge Mediation**

Trying General Mediation…

Generalised Gauge Mediation

- Dependence of soft-masses on hidden sector obtained from hidden sector current-current correlators
  → 6 independent parameters
- Gravitino always LSP: $m_{3/2} = F/\sqrt{3}M_P$ ($\sqrt{F}$: SUSY-breaking scale)
- The NLSP has a universal two-body decay to SM partner + gravitino:

$$\Gamma(\tilde{x} \to x\tilde{G}) = \frac{m_x^5}{16\pi(\sqrt{3}M_P m_{3/2})^2} \quad \text{(prompt or delayed)}$$

- Large $M_S=\sqrt{(\tilde{t}_1\tilde{t}_2)}$ is the simplest solution to achieve a 125 GeV Higgs
- More freedom in GGM: $\frac{M_1}{g_1^2} \neq \frac{M_2}{g_2^2} \neq \frac{M_3}{g_3^2}$
- Most of the GGM collider phenomenology is determined by the nature of the NLSP and the production mechanism

P. Meade, N. Seiberg and D. Shih, Prog. Theor. Phys. Suppl. 177 (2009) 143 [arXiv:0801.3278]

GGM simulation study

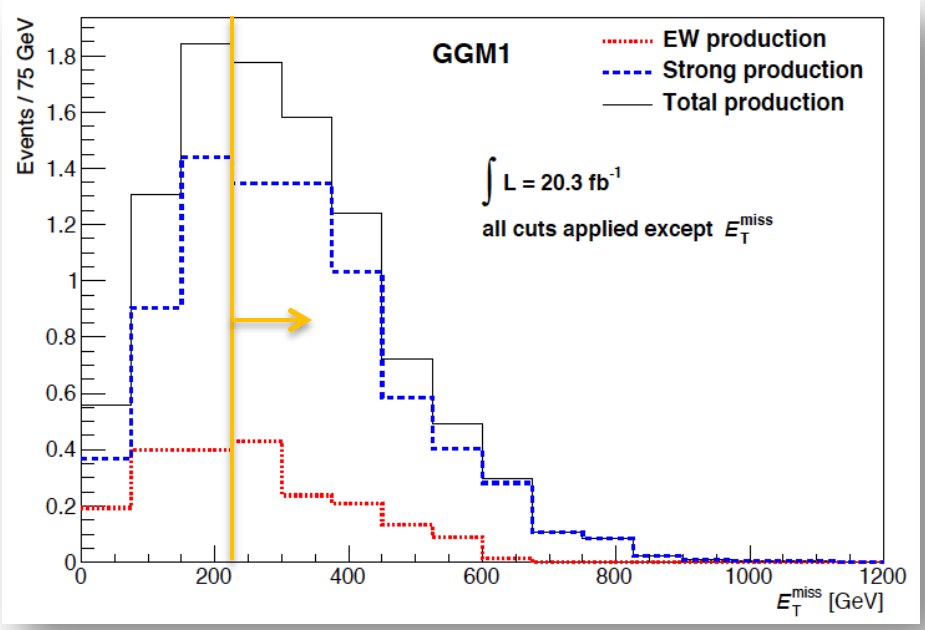
- Two benchmark points considered
  - relatively light gluinos allow abundant $\tilde{g}\tilde{g}$ production
  - squarks heavy enough to be outside set bounds by LHC
  - Z produced in NLSP decay to gravitino: $\tilde{\chi}_1^0 \rightarrow Z\tilde{G}$
  - higgsino-like $\tilde{\chi}_1^0$ assures high (>90%) branching ratio $\tilde{\chi}_1^0 \rightarrow Z\tilde{G}$
  - large mixing between semi-degenerate in mass lightest neutralinos
  - too light Higgs (~120 GeV) may be solved by new operators or heavier squarks without affecting the phenomenology on the Z-peak
- "Quasi-realistic" simulation with Pythia8 and Delphes (tuned to ATLAS detector performance)
- NLO + NLL cross sections from Prospino2

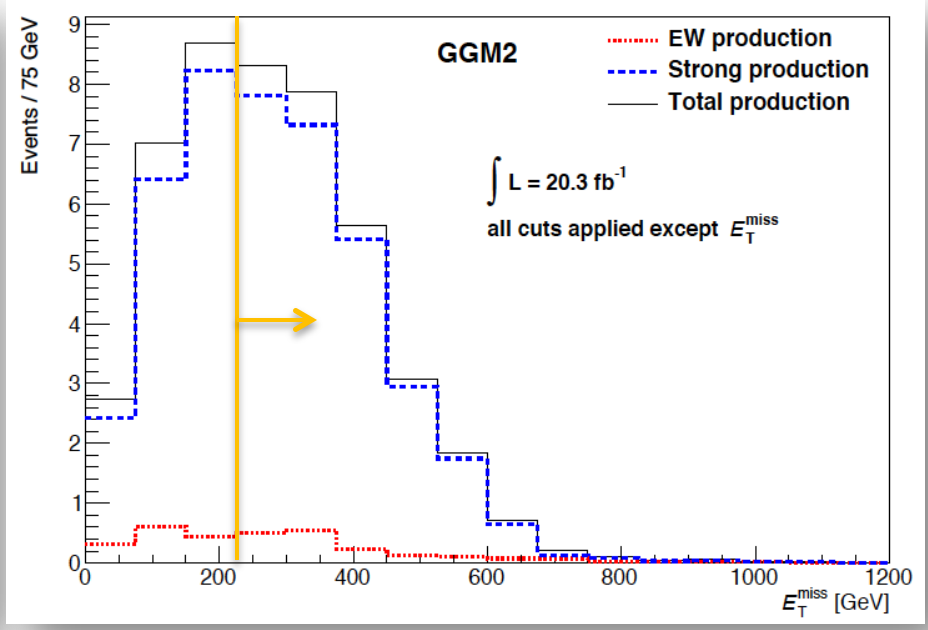
	GGM1	GGM2
$m(\tilde{g})$ [GeV]	1088	911
$m(\tilde{q}_L)$ [GeV]	3006	2510
$m(\tilde{q}_R)$ [GeV]	2957	2470
$m(\tilde{t}_1)$ [GeV]	2750	2350
$m(\tilde{b}_1)$ [GeV]	2876	2400
$m(\tilde{\chi}_1^0)$ [GeV]	428	425
$m(\tilde{\chi}_2^0)$ [GeV]	431	433
$m(\tilde{\ell}_R)$ [GeV]	5328	5360
$m(\tilde{G})$ [eV]	4.8	4.8
m(h) [GeV]	119	118
$BR(\tilde{\chi}_1^0 \rightarrow Z\tilde{G})$	99%	94%
$\sigma(pp \rightarrow \tilde{g}\tilde{g})$ [fb]	**8.4**	**41.6**

GGM & Z + MET selection (I)

- **Strong production** represents approximately 20% of the total production for GGM1 while in GGM2 the corresponding fraction is ~70%
  - it reflects the difference in gluino mass: 1088 GeV versus 911 GeV

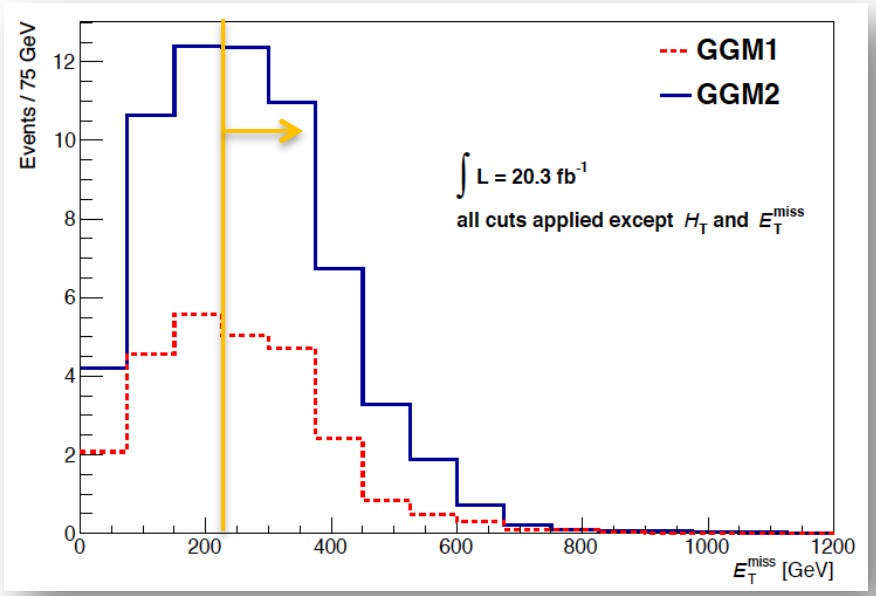
arXiv:1503.04184

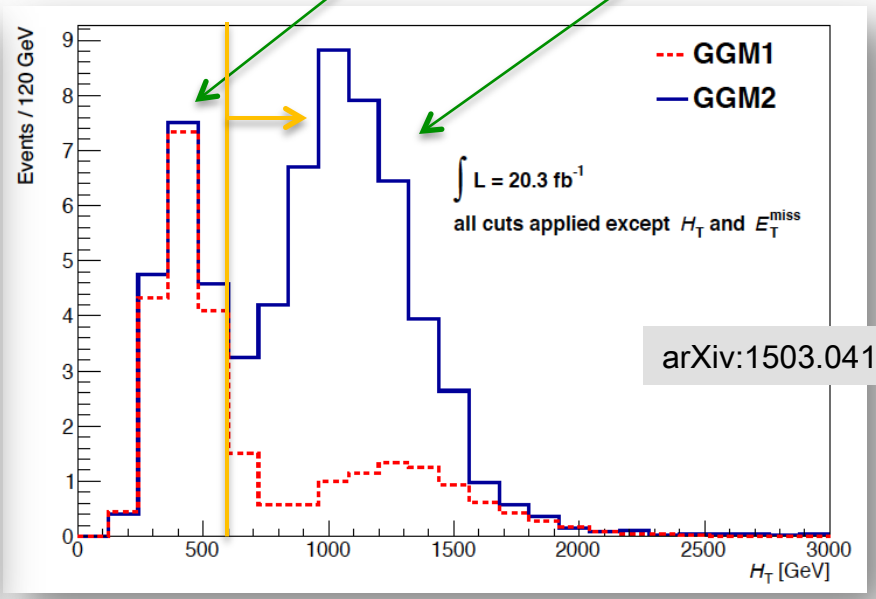




- Similar MET distributions after all but MET-cut between GGM1 and GGM2
  - strong production yields slightly harder MET

GGM & Z + MET selection (II)





- The electroweak component is significantly reduced by the H_T cut while mainly only events coming from strong production survive the cut
- After experimental cuts for GGM1 (GGM2), 6.34 ± 1.02 (28.0 ± 4.7) leptonic pairs survive, compared with observed excess of 19.4 ± 3.2

☞ Possible solution somewhere between GGM1 and GGM2

Prospects for LHC Run II at 13 TeV

- "Light" gluinos (or other strongly produced particles) required
  ➜ production cross section increased by factor ~20 for GGM1 or ~15 for GGM2 at 13 TeV
- Squarks required to be heavier: > 2.5 TeV
  ➜ production cross section ~1 fb
  ➜ detection based on jets + MET searches very challenging
- Neutralinos and charginos degenerate and light
  ➜ sizeble cross sections in some cases, e.g.:

$$\sigma(pp \to \tilde{\chi}_1^+ \tilde{\chi}_1^0)^{\mathrm{NLO}}_{13\mathrm{TeV}} = 154 \pm 5\,\mathrm{fb}, \text{ for } m_{\tilde{\chi}_1^+} = 315\ \mathrm{GeV}$$

- Note: In GGM, dark matter particle is the gravitino
  ➜ neutralino mass has no relation with the dark matter abundance of the universe

Conclusions & outlook

- Searches for SUSY have been performed with LHC Run I data
- No significant deviation from SM predictions, yet…
- …an intriguing 3σ excess observed by ATLAS in the Z+MET channel
- Large MET and H_T require production of heavy particles and large-mass stable neutral particle
- Possible in GGM with light gluino and wino-like neutralino
- Other models may be suitable, but always with strongly produced ~1 TeV particles decaying to Z-bosons *[in progress]*
- ***Waiting for results from Run II data to confirm or disprove excess and, if confirmed, to provide more hints on the New Physics involved***

&

Backup

Run I overview