SUSY vs Experiments
IMHEP19, IOP

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‘I learned to distrust all physical concepts as the basis for a theory. Instead one should put one’s trust in a mathematical scheme, even if the scheme does not appear at first sight to be connected with physics.’- Paul Dirac

Susy proposed in the early 1970’s purely out of academic interest.

Observable consequences?

To begin with NO CLUE! No Band Wagon Effect!

Contacts with nature: late 1970s/ early 1980’s.Many new avenues opens upSolution of Naturalness Problem, Exciting Missing Energy Signatures, Attractive Dark Matter Candidate, Coupling Constant Unification.....

Band Wagon Effect starts gradually!(Was the hype justified?)

Misleads the physicists as well as fund giving agencies!

The Band Wagon Effect is now rapidly slowing down.

Is it justified ?

Is there any solid exptal evidence against beautiful SUSY ?

Ever increasing lower bounds on sparticle masses at the LHC?

Why bother? Spartcle masses are free parameters unless the SUSY breaking mechanism is known!

The Naturalness Argument!

Naruralness from a new angle

$$m_Z^2 = 2\frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - 2\mu^2 \ ,$$

$$\mathcal{N}_i \equiv \left|\frac{\partial \ln m_Z^2}{\partial \ln a_i^2}\right| = \left|\frac{a_i^2}{m_Z^2}\frac{\partial m_Z^2}{\partial a_i^2}\right| \ .$$

But the allowed values of not fixed by any quantitative argument!

Natural-new angle

$$\mathcal{N}_{M_3} \equiv \left| \frac{\partial \ln m_Z^2}{\partial \ln M_3^2} \right| \approx \frac{M_3^2}{m_Z^2} \left| \frac{\partial[-2m_{H_u}^2(m_{\rm weak}) - 2\mu^2(m_{\rm weak})]}{\partial M_3^2} \right| = 3.84 \frac{M_3^2}{m_Z^2} \ .$$

$$\begin{aligned}
m_{\tilde{H}} &\lesssim 640 \text{ GeV } (\mathcal{N}_{\rm max}/100)^{1/2} \\
m_{\tilde{B}} &\lesssim 3.4 \text{ TeV } (\mathcal{N}_{\rm max}/100)^{1/2} \\
m_{\tilde{W}} &\lesssim 1.2 \text{ TeV } (\mathcal{N}_{\rm max}/100)^{1/2} \\
m_{\tilde{g}} &\lesssim 1.4 \text{ TeV } (\mathcal{N}_{\rm max}/100)^{1/2} \\
m_{\tilde{t}_L,\tilde{b}_L} &\lesssim 1.0 \text{ TeV } (\mathcal{N}_{\rm max}/100)^{1/2} \\
m_{\tilde{t}_R} &\lesssim 1.1 \text{ TeV } (\mathcal{N}_{\rm max}/100)^{1/2} \\
m_{\tilde{b}_R} &\lesssim 4.1 \text{ TeV } (\mathcal{N}_{\rm max}/100)^{1/2} \\
m_{\tilde{\tau}_L,\tilde{\nu}_\tau} &\lesssim 4.0 \text{ TeV } (\mathcal{N}_{\rm max}/100)^{1/2} \\
m_{\tilde{\tau}_R} &\lesssim 4.0 \text{ TeV } (\mathcal{N}_{\rm max}/100)^{1/2} \\
m_{\tilde{c}_L,\tilde{s}_L,\tilde{u}_L,\tilde{d}_L} &\lesssim 4.0 \text{ TeV } (\mathcal{N}_{\rm max}/100)^{1/2} \\
m_{\tilde{c}_R,\tilde{u}_R} &\lesssim 2.7 \text{ TeV } (\mathcal{N}_{\rm max}/100)^{1/2} \\
m_{\tilde{s}_R,\tilde{d}_R} &\lesssim 4.0 \text{ TeV } (\mathcal{N}_{\rm max}/100)^{1/2} \\
m_{\tilde{\mu}_L,\tilde{\nu}_\mu,\tilde{e}_L,\tilde{\nu}_e} &\lesssim 4.0 \text{ TeV } (\mathcal{N}_{\rm max}/100)^{1/2} \\
m_{\tilde{\mu}_R,\tilde{e}_R} &\lesssim 4.0 \text{ TeV } (\mathcal{N}_{\rm max}/100)^{1/2} \ .
\end{aligned}$$

Natural-new angle

Weakness of the naturalness argument

For $N_{max} > 300$ upper limit of $m_{\tilde{g}}$ goes beyond the reach of LHC!

Similar comments hold for other mass bounds

Chasing SUSY at the LHC

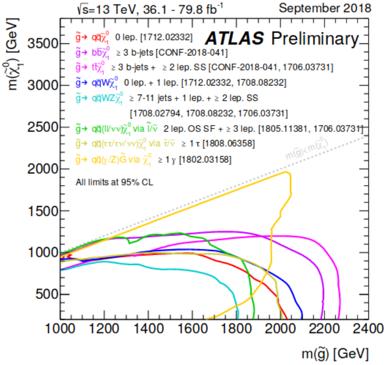
- LHC bounds vs Naturalness
- LHC bounds: Simplified models vs pMSSM
- How to handle difficult SUSY signals: compressed models, longlived sparticles.........
- New Signals: Heavier Electroweakinos

Interplay of LHC and non-accelarator based Constraints.

- Dark matter relic density.
- Direct detection of dark matter.
- Muon g-2 anomally
- Flavour Physics
- ....

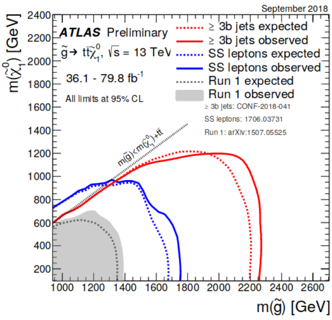
Word of Caution: All indirect constraints have assumptions which are not experimentally verified and have nothing to do with SUSY.

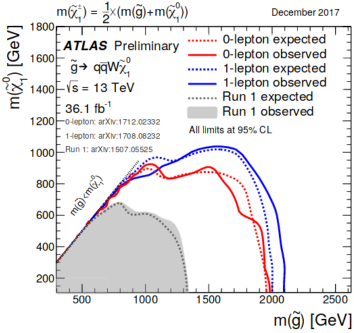
LHC mass bounds(at face value) vs naturalness



Bound at face value consistent with naturalness for $N_{max} \approx 200$

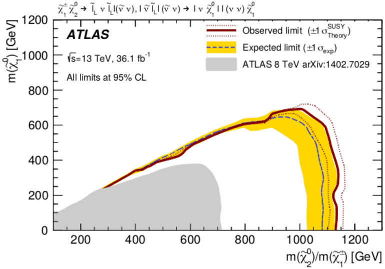
LHC mass bounds(at face value) vs naturalness

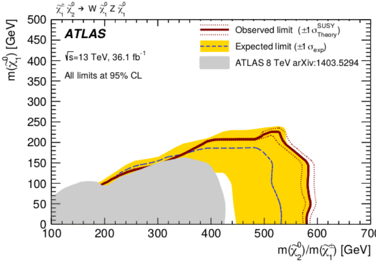




Bound at face value consistent with naturalness for $N_{max} \approx 200$

LHC mass bounds(at face value) vs naturalness





LHC mass bounds(at face value) vs naturalness

Bounds on wino like chargino-2nd neutralino masses at face value consistent with naturalness for $N_{max} \approx 100$

Bounds on Higgsino like chargino-2nd neutralino masses are even weaker and consistent with naturalness

As of now there is no conflict between LHC Bounds(at face value) and Naturalness

Natural-new angle

Weakness of the naturalness argument

For $N_{max} > 300$ upper limit of $m_{\tilde{g}}$ goes beyond the reach of LHC! Similar comments hold for other mass bounds

Physics at Intermediate scale?

Correlations among high scale parameters?

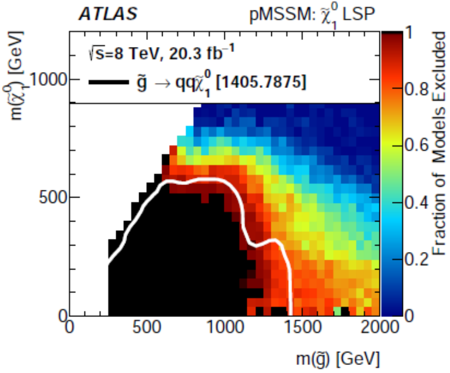
See H. Baer, X. Tata *et al* on Naturalness

A Toy Example of Gluino Mass Limits in pMSSM models

Points	Limit on $m_{\tilde{g}}$ (GeV)		
	$jets + 0l + \not{E}_T$ [4]	$jets + 1l + \not{E}_T$ [5]	$jets + 2l + \not{E}_T$ [6]
BP1	950	1125	885
BP2	860	1140	950
BP3	1015	1110	810
BP4	1150	1175	-
BP5	750	1155	945
BP6	1015	1140	875
BP7	1105	1080	-
BP8	1110	1025	-
BP9	1250	1010	-
BP10	1240	1010	-

M. Chakraborti, U. Chattopadhyay, A. Choudhury, A. Datta and Sujoy Poddar,JHEP 019 (2014) 1407, arXiv 1404.4841.

LHC Bounds: PMSSM vs Simplified Models



(a) Gluino / LSP

Multichannel analyses produces as powerful exclusion which is almost model independent.

pMSSM limits are more conservative!

LHC Bounds: PMSSM vs Simplified Models

To select the points ATLAS also used theoretical constraints and indirect constraints which involve additional constraint.

Parameter	Minimum value	Maximum value
$\Delta\rho$	-0.0005	0.0017
$\Delta(g-2)_\mu$	-17.7×10^{-10}	43.8×10^{-10}
$\mathrm{BR}(b\to s\gamma)$	2.69×10^{-4}	3.87×10^{-4}
$\mathrm{BR}(B_s\to\mu^+\mu^-)$	1.6×10^{-9}	4.2×10^{-9}
$\mathrm{BR}(B^+\to\tau^+\nu_\tau)$	66×10^{-6}	161×10^{-6}
$\Omega_{\tilde{\chi}_1^0}h^2$	—	0.1208
$\Gamma_{\mathrm{invisible(SUSY)}}(Z)$	—	2 MeV
Masses of charged sparticles	100 GeV	—
$m(\tilde{\chi}_1^\pm)$	103 GeV	—
$m(\tilde{u}_{1,2},\tilde{d}_{1,2},\tilde{c}_{1,2},\tilde{s}_{1,2})$	200 GeV	—
$m(h)$	124 GeV	128 GeV

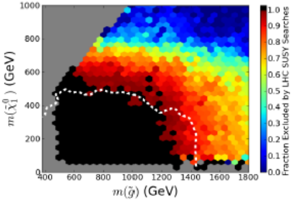
LHC Bounds: PMSSM vs Simplified Models

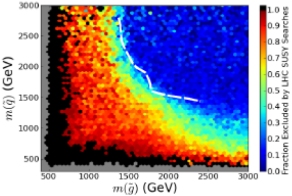
Indirect constraints involve additional assumptions.

5×10^6 pMSSM points reduced to 310 K due to indirect constraints

May Throw baby with bathwater!

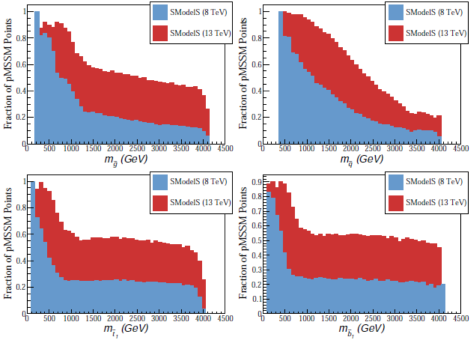
Similar analyses using Run I data by M. Cahill-Rowley, J.L. Hewett, A. Ismail, and T.G. Rizzo , (1407.4130)





LHC Bounds: PMSSM vs Simplified Models

Similar analyses using **Run II data** by Juhi Dutta, Sabine Kraml, Andre Lessa, Wolfgang Waltenberger., (1803.02204). Use SModelS and the ATLAS 310 K points consistent with all indirect constraints.(Agrees with F. Mahmoudi *et al* 1812.08783)




PROCEEDINGS OF THE FIRST MADANALYSIS 5 WORKSHOP ON LHC RECASTING IN KOREA

Benjamin Fuks[1,2] (editor),
Samuel Bein[3], Guillaume Chalons[4], Eric Conte[5], Taejeong Kim[6], Seung J. Lee[7],
Dipan Sengupta[8], Jory Sonneveld[3] (convenors),
Seohyun Ahn[6], Seungwon Baek[9], Jung Chang[10], Soo-Min Choi[11], Sihyun Jeon[12], Sumin Jeong[6], Tae Hyun Jung[13], Dong-Woo Kang[14], Yoojin Kang[11], Gyunggoo Lee[15], Kyeongpil Lee[12], Jinmian Li[16], Jiwon Park[6], Jubin Park[10], Chaehyun Yu[7], Wenxing Zhang[17], Maxime Zumbihl[1]

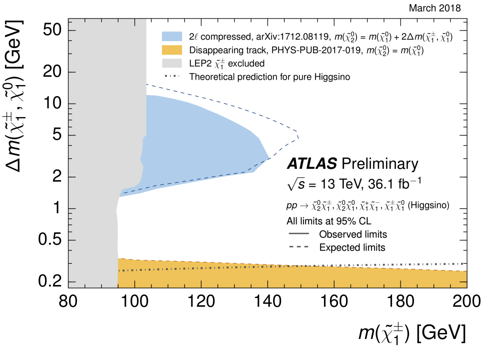
1806.02537

LHC Bounds: PMSSM vs Simplified Models

SUSY is even more safe within the framework of pMSSM!

Difficult Signals: Compressed models

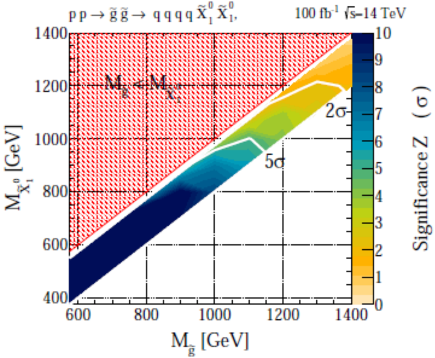
Soft leptons in the final state.



Difficult Signals: Compressed models

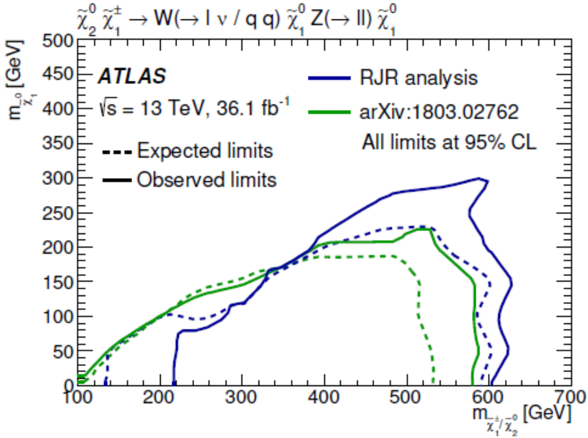
Recursive Jigsaw Reconstruction for Compressed Scenarios

Paul Jackson, Christopher Rogan and Marco Santoni (1607.08307);
Paul Jackson and Christopher Rogan (1705.10733).



Difficult Signals: Compressed models

ATLAS applies Recursive Jigsaw Reconstruction (1806.02293)



Difficult Signals: Other Works Compressed models

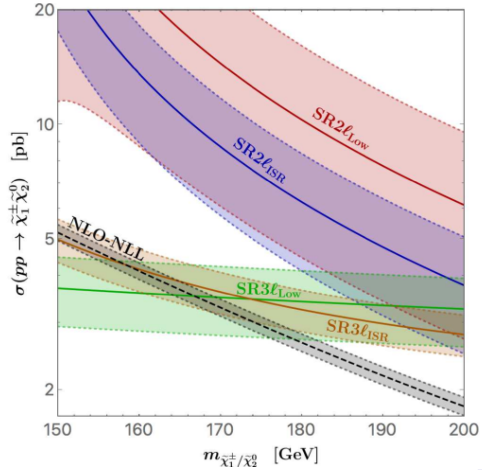
ATLAS data

Signal Region	Observed Events	BG Events	Events above BG	Significance (Z)
$\mathrm{SR}2\ell_{\mathrm{Low}}$	19	8.4 ± 5.8	10.6 ± 5.8	1.39
$\mathrm{SR}2\ell_{\mathrm{ISR}}$	11	$2.7^{+2.8}_{-2.7}$	$8.3^{+2.8}_{-2.7}$	1.99
$\mathrm{SR}3\ell_{\mathrm{Low}}$	20	10 ± 2	10 ± 2	2.13
$\mathrm{SR}3\ell_{\mathrm{ISR}}$	12	3.9 ± 1.0	8.1 ± 1.0	3.02

Table 1. Expected and observed events for the 2ℓ and 3ℓ SRs, as well as the significance of the excess (Z). The number of observed events, background estimates and significance of the excess are taken from Ref. [22]. The errors on the background show statistical plus systematic uncertainties. The third column has been added to show the estimated number of events above expected background.

Difficult Signals: Other Works Compressed models

Comparison of experimental cross sec obtained from the excess and the theoretical cross sec (Marcela Carena, James Osborne, Nausheen R. Shah, Carlos E. M. Wagner 1809.11082



Difficult Signals: Other Works Compressed models

- A. Chakraborty, S. Chakraborty and T. S. Roy, [arXiv:1606.07826 [hep-ph]]
- S. Mukhopadhyay, M. M. Nojiri and T. T. Yanagida,arXiv:1403.6028 [hep-ph]
- B. Bhattacherjee, A. Choudhury, K. Ghosh and S. Poddar, arXiv:1308.1526 [hep-ph]

Why are the Electroweak Sparticles Important?

Best bet for discovering SUSY if strongly interacting sparticles are beyond the kinematic reach of the LHC

Sensitive to Naturalness Condition (small μ)

DM production mechanisms depends mainly on EW sparticles:the electroweakinos and the sleptons.

- neutralino annihilation.
- LSP-NLSP co-annihilation.

Contribution of light electroweak sparticles to anomalous magnetic moment of the muon improves the agreement between theoretical prediction and data.

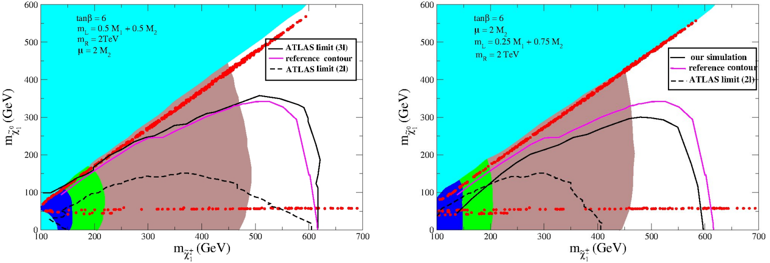
- A. Choudhury, Amitava Datta; "Many faces of low mass neutralino dark matter in the unconstrained MSSM, LHC data and new signals ", JHEP 06 (2012) 006, arXiv:1203.4106.
- A. Choudhury, A. Datta; "Neutralino dark matter confronted by the LHC constraints on Electroweak SUSY signals", JHEP 09(2013)113, arXiv 1305.0928.
- M. Chakraborti, U. Chattopadhyay, A. Choudhury, A. Datta and Sujoy Poddar,JHEP 019 (2014) 1407, arXiv 1404.4841.
- M. Chakraborti, U. Chattopadhyay, A. Choudhury, A. Datta and Sujoy Poddar,JHEP (2015) , arXiv 1507.01395.

Looking beyond simplified model

- Higgsino model : $M_1 < \mu < M_2$
- Mixed model : $M_1 < \mu \sim M_2$
- Compressed model : $M_1 \sim \mu < M_2$

Limits on electroweakinos using ATLAS Run I data

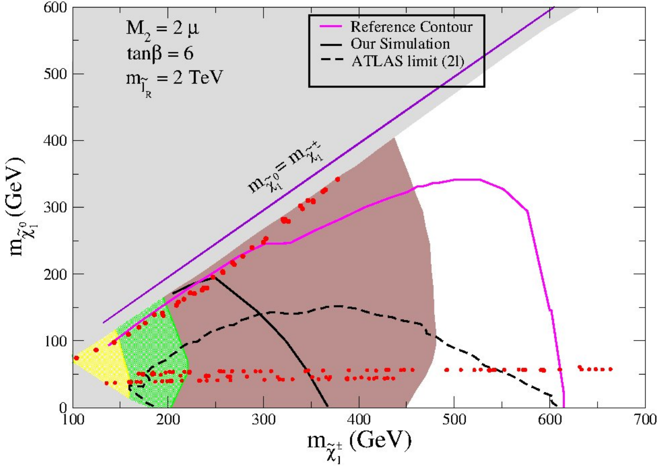
Consider pMSSM models closely related to simplified models used by CMS and ATLAS
$\tilde{\chi}_1^0$ bino, $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ are wino like. Left sleptons are light.
Data: Trileptons from $\tilde{\chi}_1^\pm$ - $\tilde{\chi}_2^0$ pair production and direct slepton search.



The second figure shows the effect of compressed spectrum.

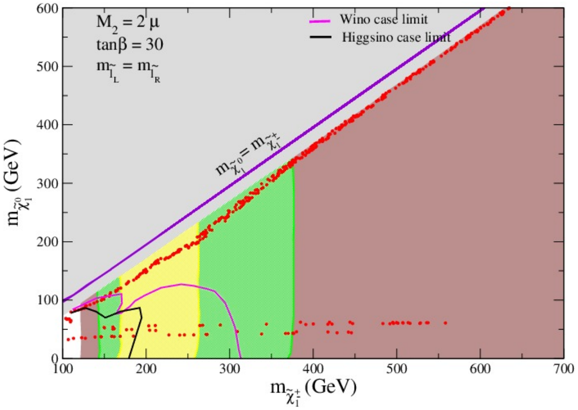
Limits on electroweakinos using ATLAS Run I data

The model same as before except that $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$ are higgsino like. Left sleptons are light.



Limits on electroweakinos using ATLAS Run I data

All sleptons are heavy. Decay modes: $\tilde{\chi}_1^{\pm} \to W\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0$.
Small leptoni BRs of W and Z $\to$ weak limits!



Very weak limits in the Higgsino models.

What about the heavier eweakinos ??

- There is no compelling reason for assuming them to be decoupled
- Can contribute to signal significantly
- Leading to stronger bounds on lighter eweakino masses
- **New bounds on masses of $\widetilde{\chi}_2^{\pm}, \widetilde{\chi}_4^0$**
- Only sourcs of signal if lighter electroweakinos have a compressed spectrum (No trilepton but signals with four and five leptons.)

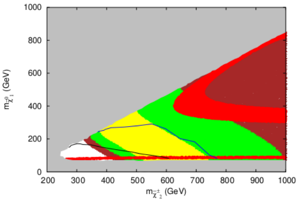
What about the heavier eweakinos ??

- A. Datta, N. Ganguly and Sujoy Poddar, Phys. Lett. B 763, 213-217 (2016), arXiv:1606.04391.
- A. Datta, N. Ganguly and Sujoy Poddar, JHEP 1711 (2017) 117, arXiv:1707.004410.

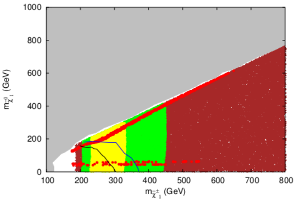
A. Datta and N. Ganguly, to appear in JHEP (2019), arXiv:1809.05129. (Run II)

Interesting pheno if heavier eweakinos are wino like while the lighter eweakinos are made of bino and higgsino.

Heavier Eweakinos at $\sqrt{S} = 13$ TeV



(a) $M_1 \sim \mu < M_{\tilde{l}} < M_2$



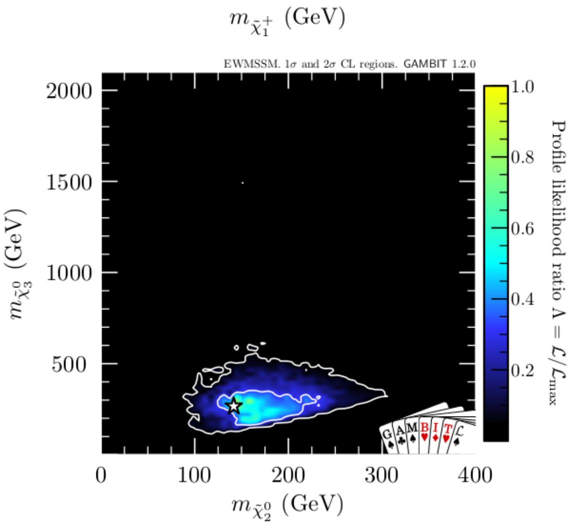
(b) $M_1 < \mu < M_{\tilde{l}} < M_2$

Heavier Eweakinos at $\sqrt{S} = 13$ TeV

Multileptons for sample benchmark points

Parameters/ Masses and Signals	BP1 (COMP)	BP2 (LHHS)	BP3 (LHLS)	Total SM Backgrounds
$m_{\tilde{\chi}_1^0}$	151	100	231	-
$m_{\tilde{\chi}_1^\pm}$	178	260	291	-
$m_{\tilde{\chi}_2^\pm}$	389	447	491	-
$(S/\sqrt{B})_{3l}$	14.3 (3.35)	13.6 (3.12)	26.9 (4.24)	26.71
4 leptons	61.5 (0.69)	16.4 (0.62)	19.6 (2.05)	0.835
SS3OS1 leptons	29.9 (0.69)	7.2 (-)	5.01 (0.17)	0.40
5 leptons	8.46 (-)	6.1 (-)	4.14 (-)	0.60

Results of GAMBIT (All chargino - neutralino data from LHC + much more)



Direct Detection of DM/LSP

At the face value the results look very threatening!

We want to measure LSP mass
There are other quantities in the working formula which are not known precisely.

- ρ_0 DM density at the detector (In practice average density measured over huge volumes of cosmological importance are avaiable.)
- Wimp velocity disdribution (progress).
- Various form factors which are computed theoretically.Calculations involve strong interaction at very low momentum transfer. Results not verified by independent experiments.

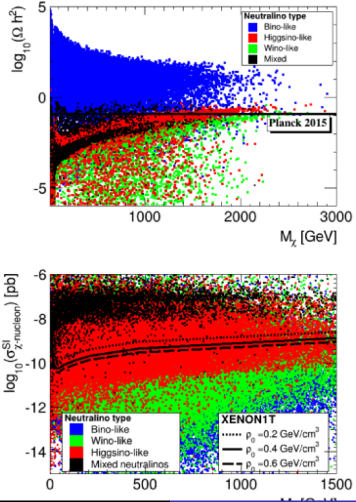
Do the best u can! But don't claim that u have ruled SUSY conclusively. Your results are merely suggestive!

If you want to beat the champion beat him decisively!

DM relic density vs direct detection

At the face value the results look very threatening!

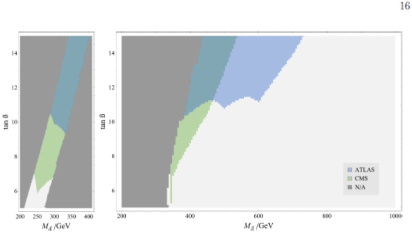
F. Mahmoudi *et al* 1812.08783)



Blind spots and direct detection

Are the blind spots allowed by LHC data?

C.E.M. Wagner et al 1701.02737



To find the locations of the blind spots we must know the cross section more precisely.

Dark Matter Blind Spots at One-Loop
Tao Han, Hongkai Liu, Satyanarayan Mukhopadhyay, Xing Wang (1810.04679)

Work in a simplified model of DM

The one-loop corrections ‘unblind’ the tree level blind spots and lead to detectable blind spots.

New blind spots are found

Conclusion

SUSY is not even hurt let alone be killed!

Thank You