pMSSM:

PARAMETER SPACE CORRELATIONS OF GLUINO & SQUARK SEARCHES

LHC Reinterpretation Workshop @ CERN

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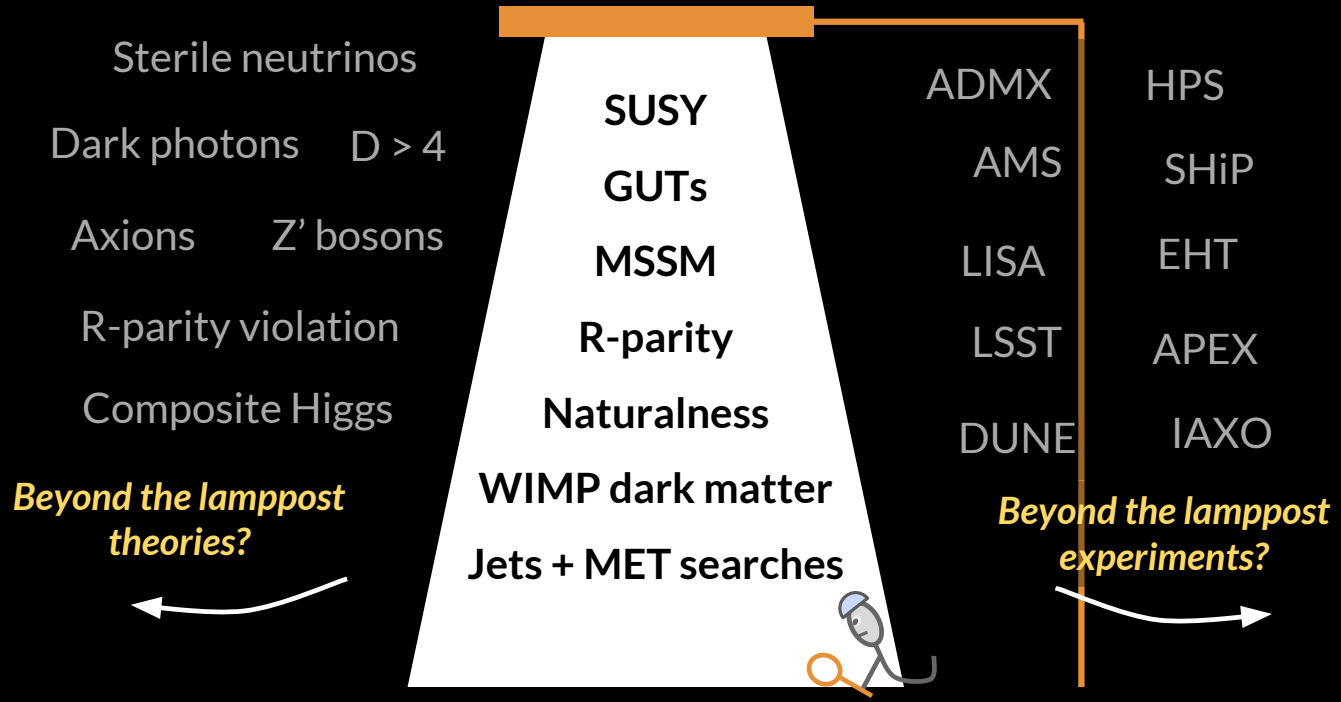
14 December 2016

Based on
Alan Barr & JL | arXiv:1605.09502 | arXiv:1608.05379

Searching under the BSM lamppost



How well are simplified models covering realistic MSSM scenarios?

What dark sectors can strong SUSY searches probe?

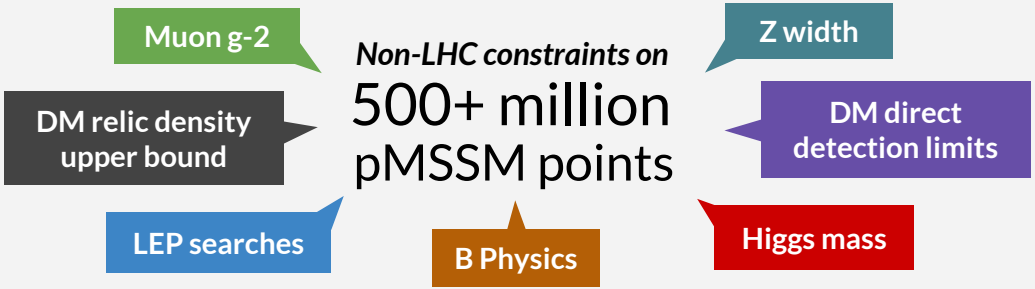
pMSSM helps us answer these questions

The ATLAS p(henomenological)MSSM

ATLAS [arXiv:1508.06608], Berger et al [arXiv:0812.0980],
Cahill-Rowley et al [arXiv:1206.4321, arXiv:1211.1981, arXiv:1407.4130]

Scan 19-parameter MSSM

Vanilla assumptions: R-parity conserved, neutralino LSP, flavour & CP violation only in CKM,…



22 ATLAS 7+8 TeV (up to 20/fb) searches constrain ~310k points

ATLAS Collaboration [arXiv:1508.06608]

6 ATLAS 13 TeV (3.2/fb) searches constrain ~183k points

A Barr & JL [arXiv:1605.09502]

MadGraph5 + Pythia6 + Delphes3 + MadAnalysis5

~3 billion events generated | ~250k CPU hours

13 TeV simulation & interpretation

58.1%
181.8k POINTS SURVIVE RUN 1 CONSTRAINTS**

40.9%
EXCLUDED BY 22 ATLAS RUN 1 SEARCHES**

1% long lived***

Particle & fast detector simulation*
MadGraph 5 + Pythia 6 + Delphes 3

Event selection
MadAnalysis 5

All object isolation done in Delphes
(main difference from standard MadAnalysis)

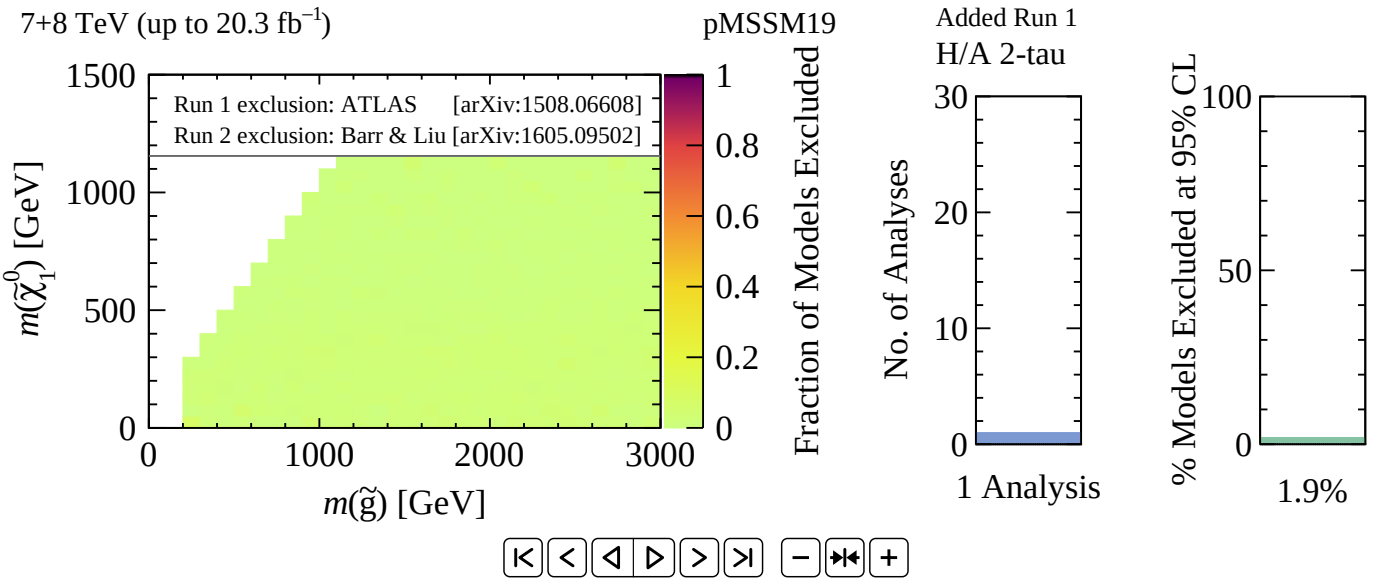
ATLAS search [13 TeV, 3.2/fb]	Reference	Signal regions
2-6 jets	1605.03814	7
7-10 jets	1602.06194	15
Monojet	1604.07773	13
Multi-b	1605.09318	8
1-lepton	1605.04285	6
SS/3L	1602.09058	4
All	-	40

Further details in
A Barr & JL arXiv:1605.09502

**We simulated the 71.4% of the 181.8k with σ(tot) > 5 fb, else model deemed viable*

***Run 1 exclusion & points publically available [ATLAS arXiv:1508.06608]*

****Long-lived gluinos, squarks, sleptons ($c\tau > 1mm$) omitted from our study*

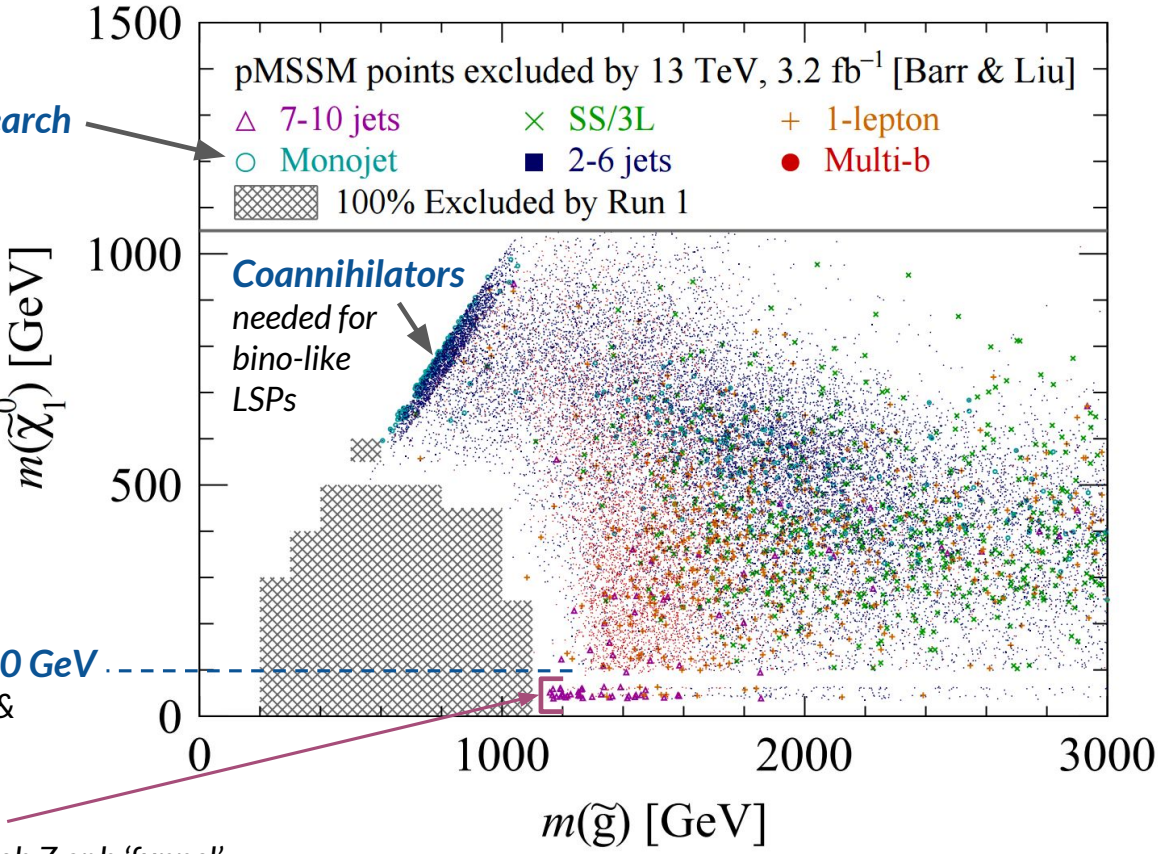


Impact of 28 SUSY searches on pMSSM19

28 ATLAS SUSY searches applied in following order:
Run 1 | electroweak, stops & sbottoms, squarks & gluinos
Run 2 | squarks & gluinos.

Fractions normalised to 310.3k pre-selected points with long-lived gluinos, squarks & sleptons removed.
Raw exclusion info for this is publicly available at Run 1 HEPData [ATLAS] and Run 2 up to 3.2/fb [Barr & Liu].
Please download and use Adobe Reader to view animation.

Scatter 28k points excluded by six 13 TeV searches



Most sensitive search
= lowest CLs value used for exclusion

Coannihilators
needed for bino-like LSPs

LEP chargino lower limit ~ 100 GeV
(bounds Higgsino & wino-like LSPs)

Bino-like LSPs
annihilating through Z or h 'funnel'

A Barr & JL [arXiv:1608.05379]

Exclusion info available at www-pnp.physics.ox.ac.uk/~jesseliu/pmssm

Successfully used by SUSY-AI collaboration http://susy-ai.com/

Distinct regions of sensitivity identified

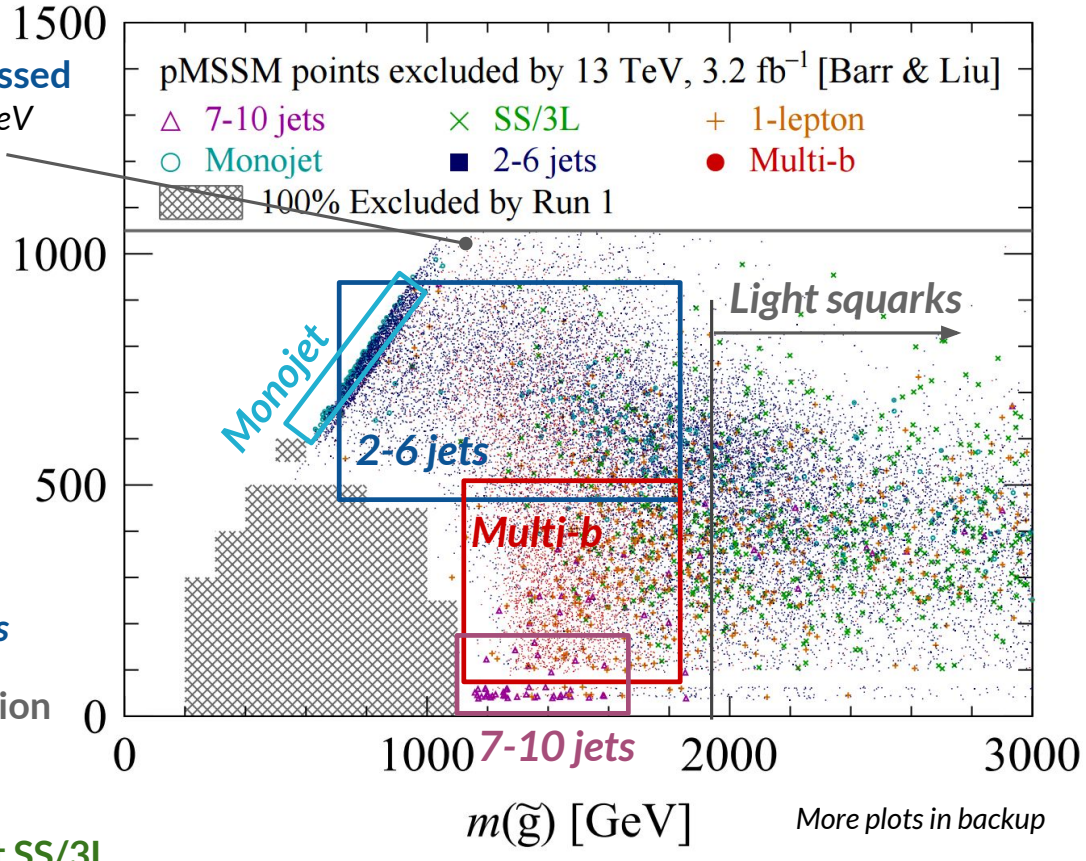
Moderately compressed
30 ≲ m(g̃) - m(χ̃) ≲ 200 GeV
low sensitivity remains

***Monojet** still needed for ultra compressed*

Multi-b** & **7-10 jets** better for larger mass splittings than **2-6 jets

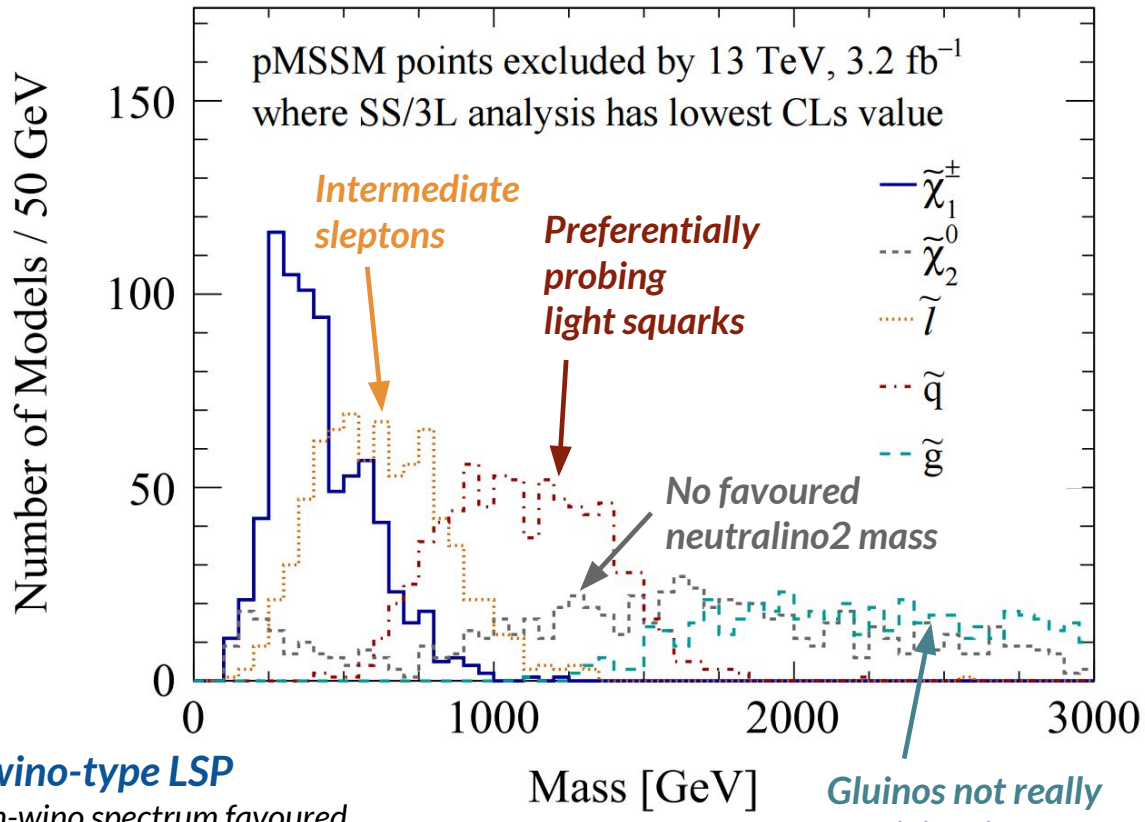
Heavy gluino exclusion
correlated with light squark sensitivity

Take a closer look at SS/3L
as case study…



More plots in backup

Case study: take points where SS/3L is most sensitive



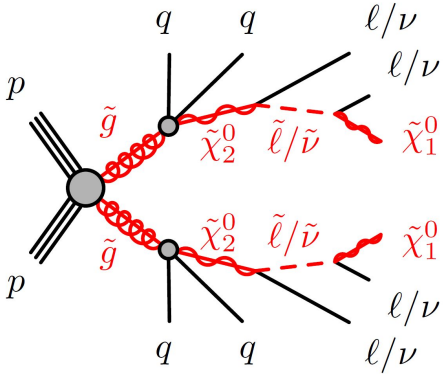
Almost all wino-type LSP

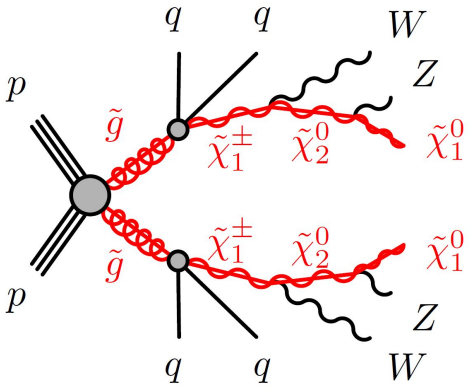
Squark-slepton-wino spectrum favoured (winos have near mass-degenerate chargino-LSP)

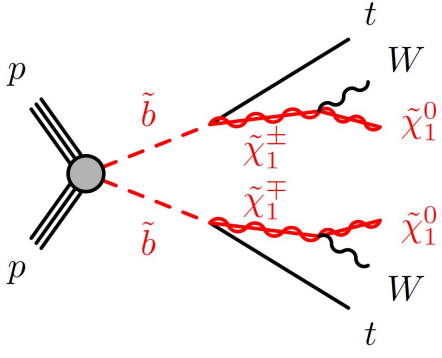
Simplified models considered by ATLAS SS/3L

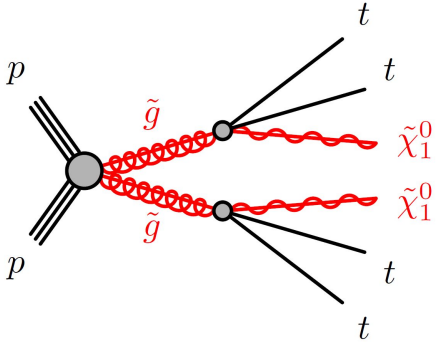
One signal region per simplified model

ATLAS SS/3L Paper [arXiv:1602.09058]



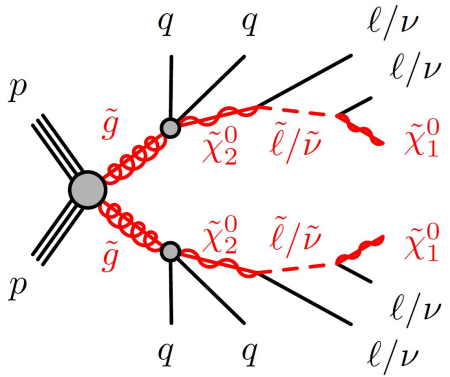




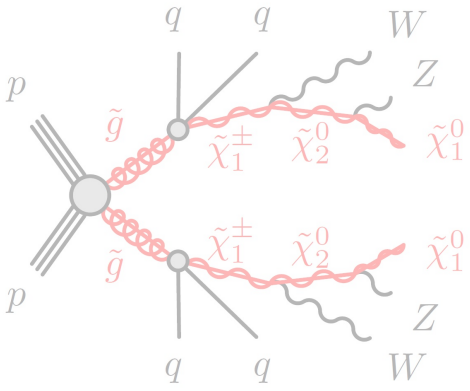


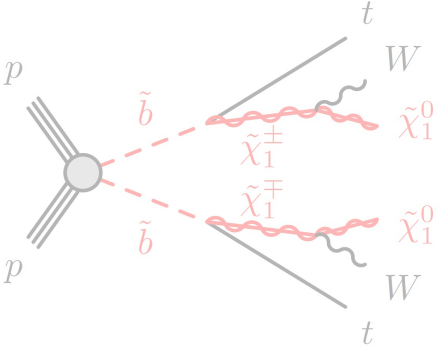
pMSSM points where SS/3L is most sensitive

Almost all probed by signal region targeting this model

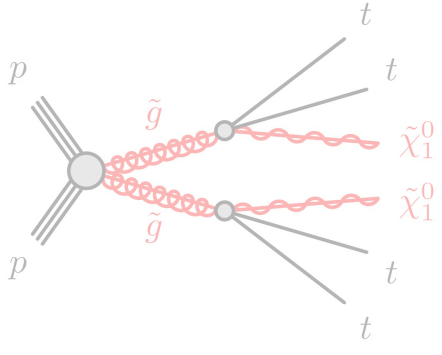


'2-step' also used by 0L 7-10 jets analysis

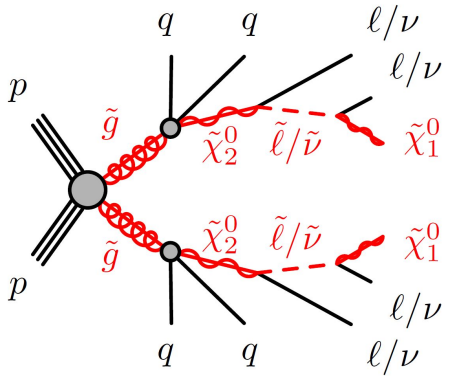


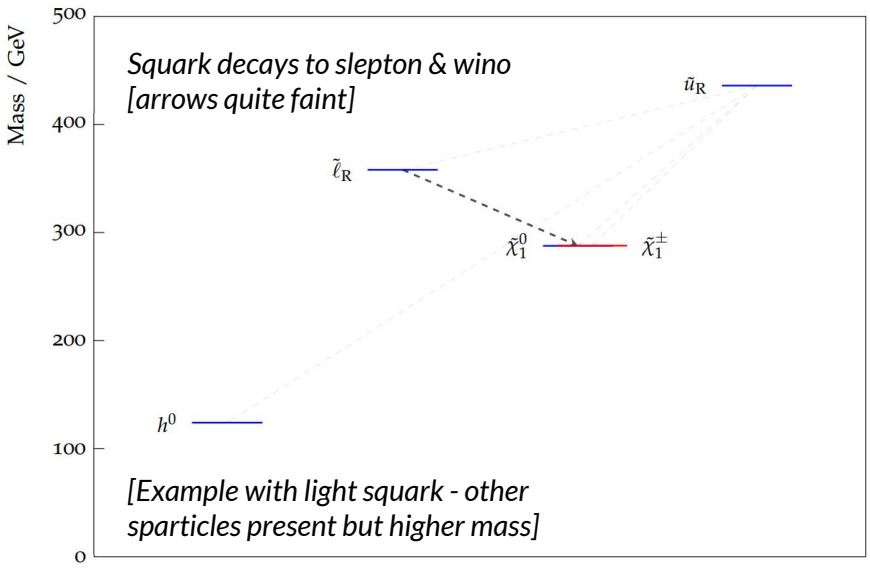


'Gtt' also used by Multi-b analysis



Interesting simplified models → pMSSM mapping





(d) Model 11733067 (SS/3L).

- ***pMSSM scenario different but not far off***

  pMSSM points prefer
  - *less correlated to neutralino2*
  - *light squark production*
  - *wino LSP: (other analyses target larger chargino-LSP gap)*

- ***Squark-slepton-wino spectrum***

  Common to points where SS/3L is most sensitive

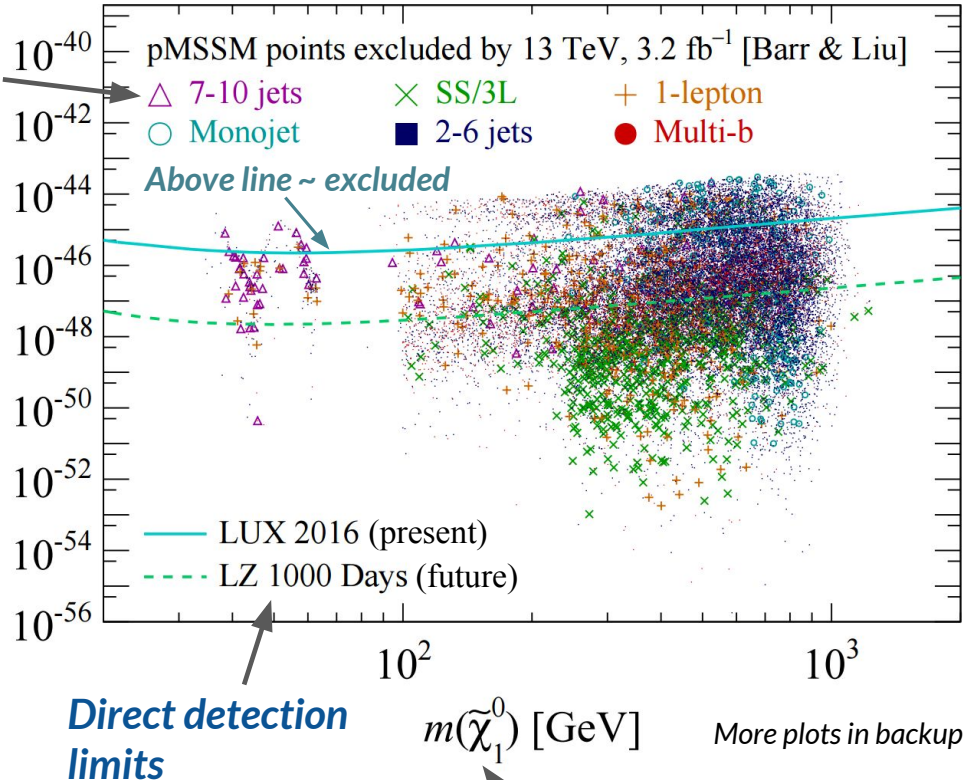
Project into direct detection cross-section vs DM mass

Points excluded by LHC
Most sensitive ATLAS search

WIMP-nucleus cross-section
spin-independent normalised by nucleon

Relic density saturation factor
Reduced by WIMP relic density under-saturation

$$R \equiv \Omega_{\tilde{\chi}_1^0} h^2 / \Omega_{\mathrm{CDM}}^{\mathrm{Planck}} h^2$$

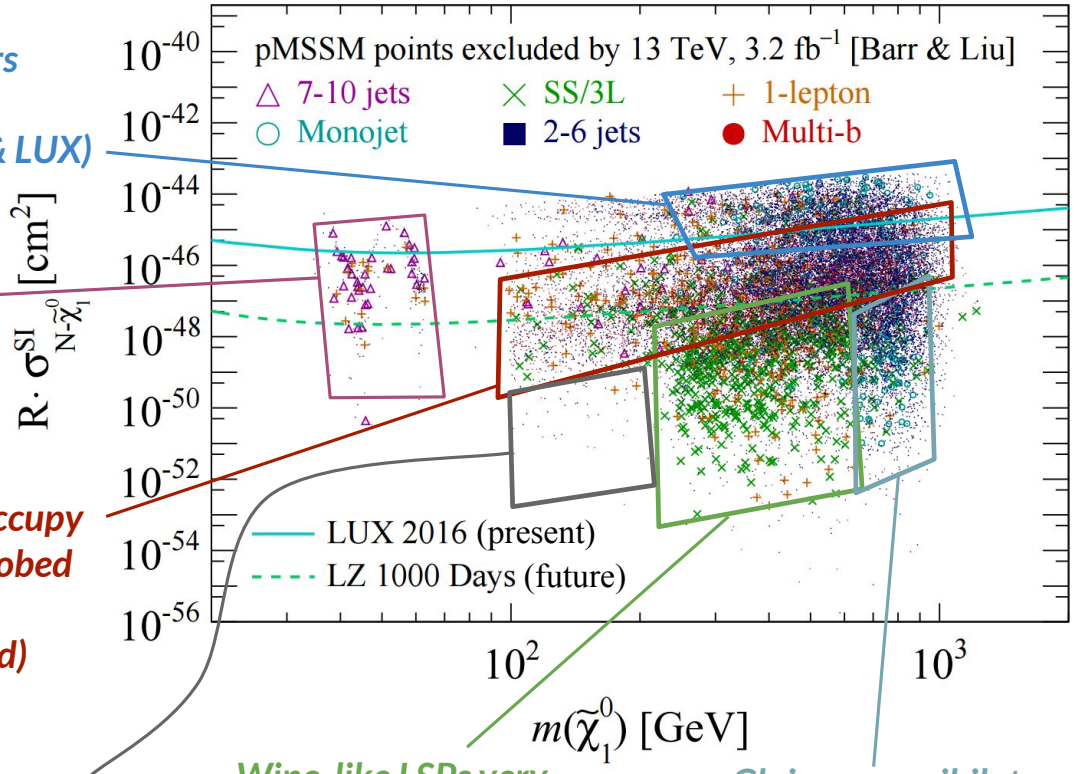


Direct detection limits
Recent Xenon-target experiments

WIMP dark matter mass
Neutralino LSP

More plots in backup

Strong SUSY searches probe rich pMSSM dark sector



Squark coannihilators & bino-like LSP (Monojet & 2-6 jets & LUX)

Bino-like LSP with Higgsino mixing (7-10 jets)

Higgsino-like LSPs occupy region marginally probed by direct detection (e.g. Multi-b favoured)

Region depleted by Run 1 disappearing track wino search

Wino-like LSPs very challenging for direct detection (SS/3L)

Gluino coannihilators & bino-like LSP (Monojet & 2-6 jets)

SUMMARY OF pMSSM19 INTERPRETATION

*Based on **Alan Barr & JL** | arXiv:1605.09502 | arXiv:1608.05379*
Exclusion info available at www-pnp.physics.ox.ac.uk/~jesseliu/pmssm

RECASTING THOUGHTS

Fast, robust, lightweight public tools enabled large study
Delphes-only object isolation made .root file ~20MB per pMSSM point

Public cutflows very helpful for validation
Currently available for published (on arXiv) searches (restricted us to 3.2/fb)

Impact of 2016 dataset (~35/fb) searches will be important
Many non-compressed gluino & squark limits will be the legacy constraints

PHYSICS LESSONS

Revealed distinct regions of sensitivity in pMSSM19
2-6 jets & Multi-b show striking separation in mass planes

Identified different class of pMSSM model (squark-slepton-wino)
Beyond simplified models considered for SS/3L search

Strong SUSY searches probe rich pMSSM dark sector
Could motivate simplified DM models beyond Monojet-like

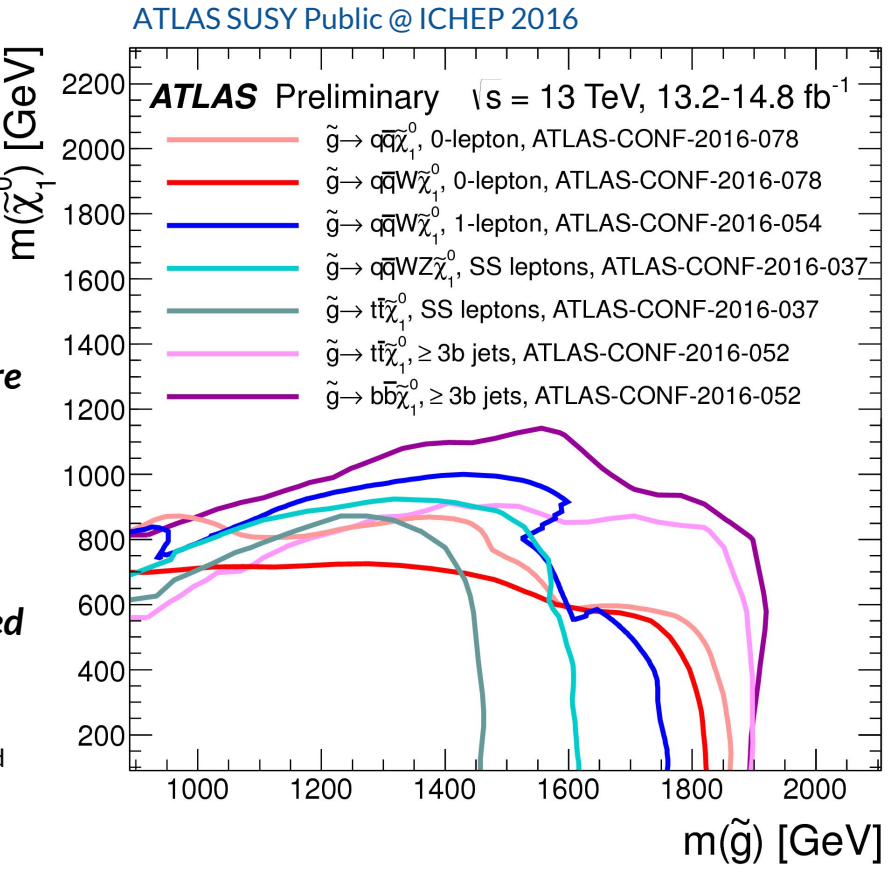
EXTRAS

The need to (re)interpret searches

> ***What do these constraints mean for my favourite BSM model?***
>
> - anxious model builder friend

> ***Surely it's unfair to compare analyses using different simplified models?***
>
> - wise collider physics friend

> ***How well do these simplified models capture realistic MSSM scenarios?***
>
> - natural MSSM advocate friend



Interpret using pMSSM

Scan range

Parameter	Min value	Max value	Note
$m_{\tilde{L}_1}(= m_{\tilde{L}_2})$	90 GeV	4 TeV	Left-handed slepton (first two gens.) mass
$m_{\tilde{e}_1}(= m_{\tilde{e}_2})$	90 GeV	4 TeV	Right-handed slepton (first two gens.) mass
$m_{\tilde{L}_3}$	90 GeV	4 TeV	Left-handed stau doublet mass
$m_{\tilde{e}_3}$	90 GeV	4 TeV	Right-handed stau mass
$m_{\tilde{Q}_1}(= m_{\tilde{Q}_2})$	200 GeV	4 TeV	Left-handed squark (first two gens.) mass
$m_{\tilde{u}_1}(= m_{\tilde{u}_2})$	200 GeV	4 TeV	Right-handed up-type squark (first two gens.) mass
$m_{\tilde{d}_1}(= m_{\tilde{d}_2})$	200 GeV	4 TeV	Right-handed down-type squark (first two gens.) mass
$m_{\tilde{Q}_3}$	100 GeV	4 TeV	Left-handed squark (third gen.) mass
$m_{\tilde{u}_3}$	100 GeV	4 TeV	Right-handed top squark mass
$m_{\tilde{d}_3}$	100 GeV	4 TeV	Right-handed bottom squark mass
$\lvert M_1\rvert$	0 GeV	4 TeV	Bino mass parameter
$\lvert M_2\rvert$	70 GeV	4 TeV	Wino mass parameter
$\lvert\mu\rvert$	80 GeV	4 TeV	Bilinear Higgs mass parameter
M_3	200 GeV	4 TeV	Gluino mass parameter
$\lvert A_t\rvert$	0 GeV	8 TeV	Trilinear top coupling
$\lvert A_b\rvert$	0 GeV	4 TeV	Trilinear bottom coupling
$\lvert A_\tau\rvert$	0 GeV	4 TeV	Trilinear τ lepton coupling
M_A	100 GeV	4 TeV	Pseudoscalar Higgs boson mass
$\tan\beta$	1	60	Ratio of the Higgs vacuum expectation values

Table 2: Scan ranges used for each of the 19 pMSSM parameters. Where the parameter is written with a modulus sign both the positive and negative values are permitted. In the above, "gen(s)" refers to generation(s).

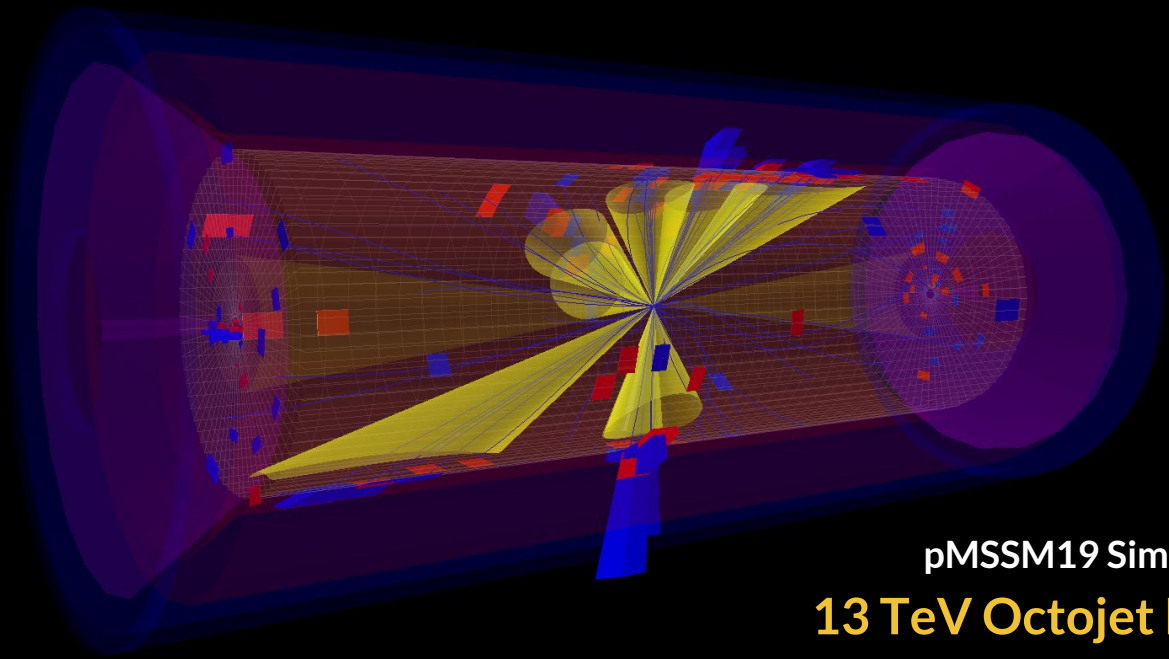
ATLAS [arXiv:1508.06608]

Non-LHC constraints

Parameter	Minimum value	Maximum value
$\Delta\rho$	-0.0005	0.0017
$\Delta(g-2)_\mu$	-17.7×10^{-10}	43.8×10^{-10}
BR($b \to s\gamma$)	2.69×10^{-4}	3.87×10^{-4}
BR($B_s \to \mu^+\mu^-$)	1.6×10^{-9}	4.2×10^{-9}
BR($B^+ \to \tau^+\nu_\tau$)	66×10^{-6}	161×10^{-6}
$\Omega_{\tilde{\chi}_1^0}h^2$	—	0.1208
$\Gamma_{\text{invisible(SUSY)}}(Z)$	—	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

Table 3: Constraints on acceptable pMSSM points from considerations of precision electroweak and flavour results, dark matter relic density, and other collider measurements. A long dash (—) indicates that no requirement is made. Further details may be found in the text.

ATLAS [arXiv:1508.06608]



pMSSM19 Simulation

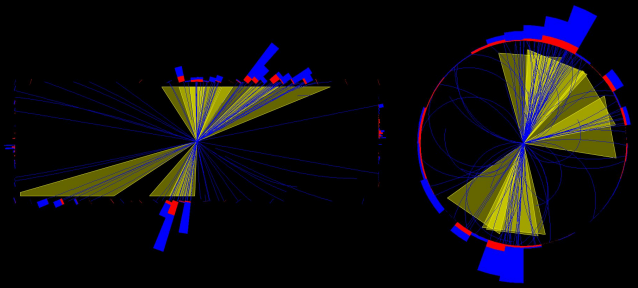
13 TeV Octojet Event

DELPHES 3 DETECTOR

Model no. 13471230 | Event 22602

1 b-tag, MET 248 GeV, MET/sqrt(HT) 5.7 $GeV^{1/2}$

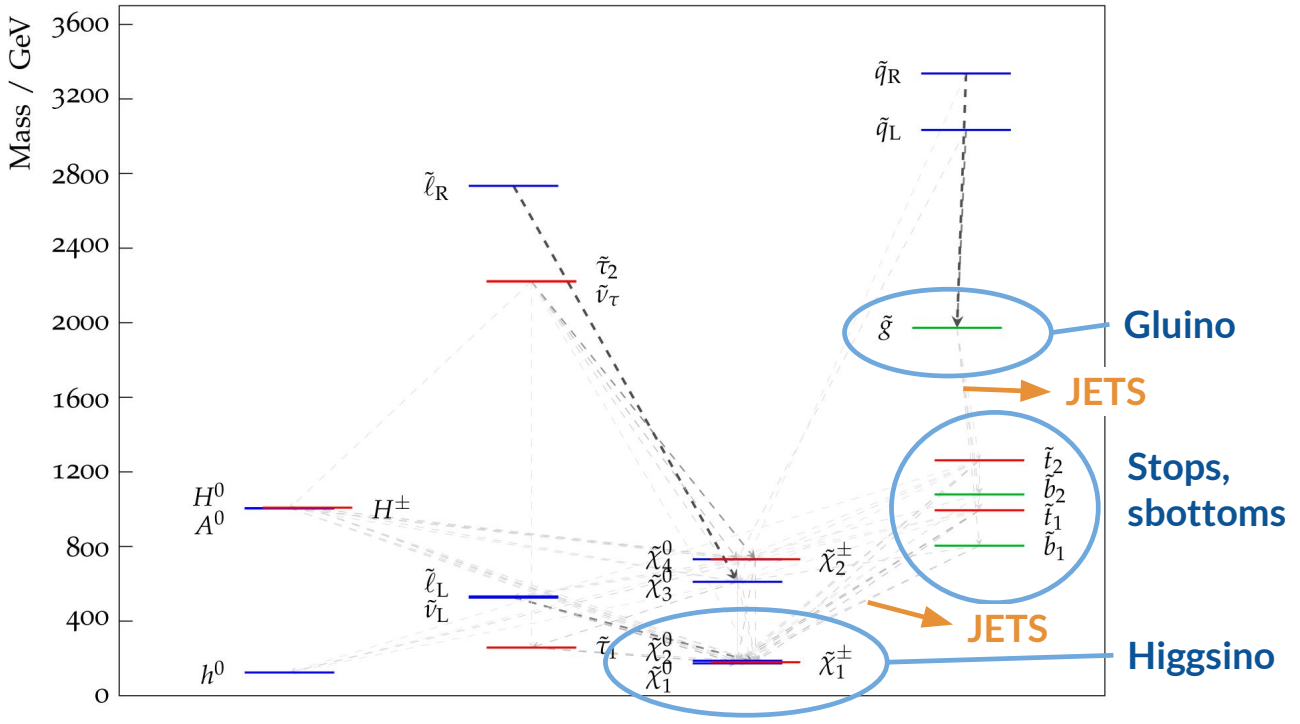
Accepted by 8j50-1b (7-10 jets analysis)



Model survives 13 TeV (3.2 fb^{-1}) constraints

A Barr & JL arXiv:1605.09502

Model 13471230 from arXiv:1508.06608 | fine-tuning 1/87



13 TeV Recasting with MadAnalysis5

CODES Adapted Run 1 2-6 jets & 7-10 jets codes from MadAnalysis Public Analysis Database into 13 TeV incarnations

DELPHES Object reconstruction efficiencies and isolation & overalp removal definitions at Delphes level (not implemented in analyses) to save disk space

APLANARITY 13 TeV 2-6 jets & 1-lepton searches introduced aplanarity variable - implemented ourselves

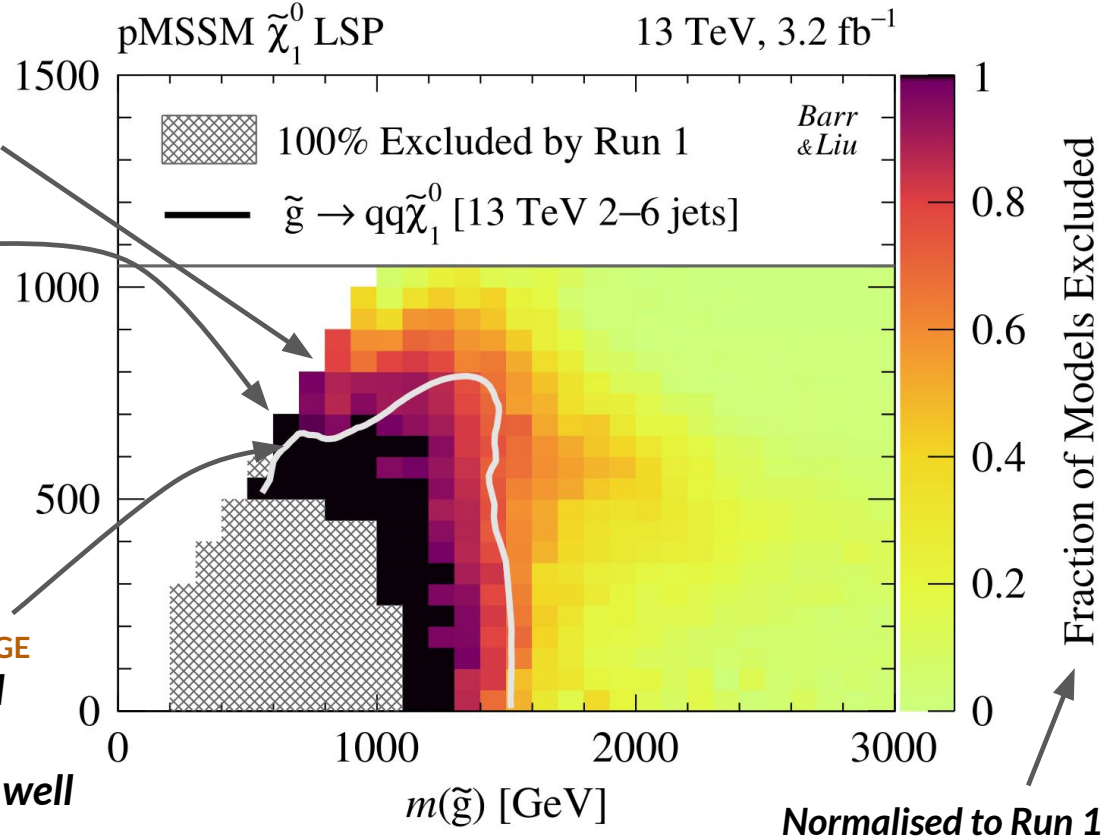
TOP TAG Added jet reclustering of R=0.4 to R=1.0 using Fastjet to emulate top candidates in Multi-b analysis

VALIDATION Validated cutflows for at least 1 benchmark point to better than 30% and reproduced published limits to within 100 GeV

LIMIT SETTING Used RecastingTools included in MadAnalysis5 for limit setting

A Barr & JL arXiv:1605.09502

Gluino-LSP plane



Sub-TeV gluinos generally close to with LSP mass

Black = 100% exclusion

Lightest supersymmetric particle (LSP DM)

TAKE-HOME MESSAGE

Simplified model captures gluino sensitivity fairly well

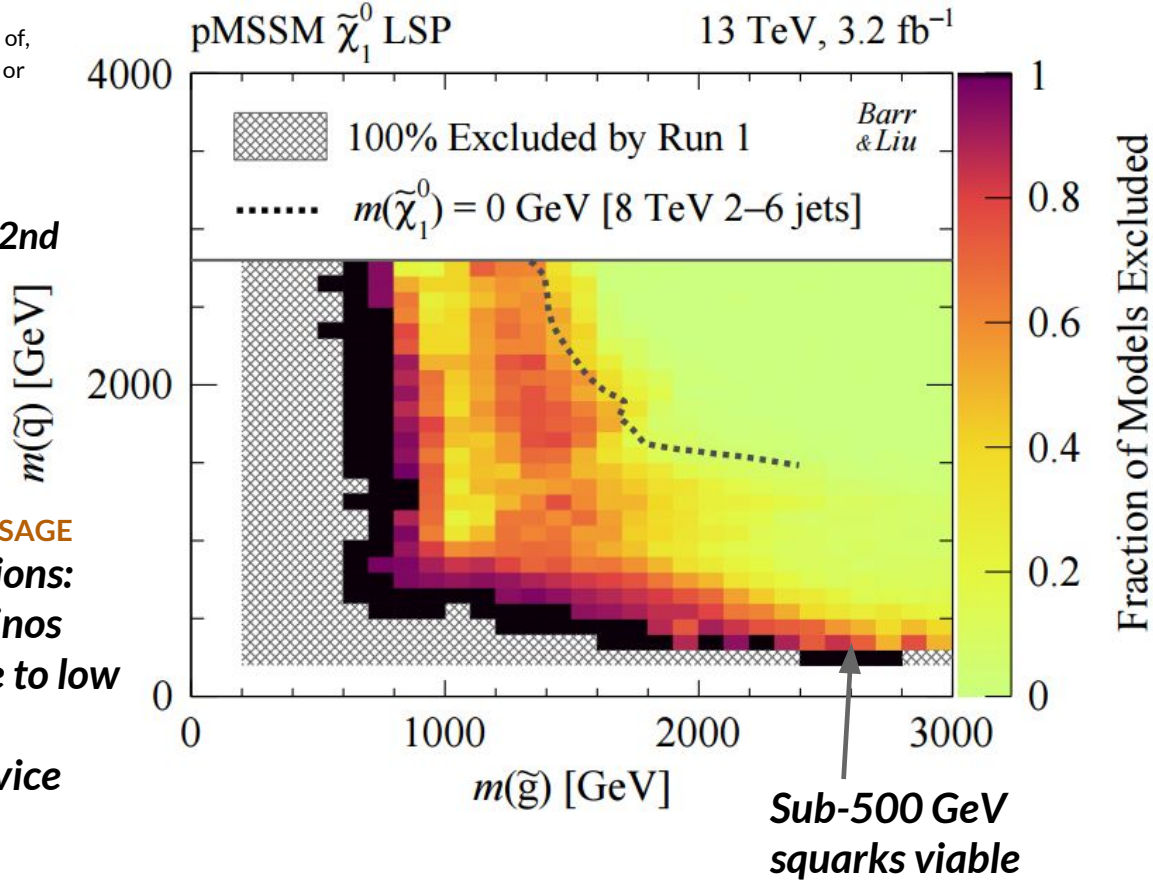
Normalised to Run 1 survivors, without long-lived

A Barr & JL [arXiv:1605.09502]
Exclusion info: www-pnp.physics.ox.ac.uk/~jesseliu/pmssm

Gluino-lightest squark plane

Disclaimer: not the work of, nor endorsed by ATLAS or CMS collaborations

Lightest of 1st/2nd generation



Sub-500 GeV squarks viable

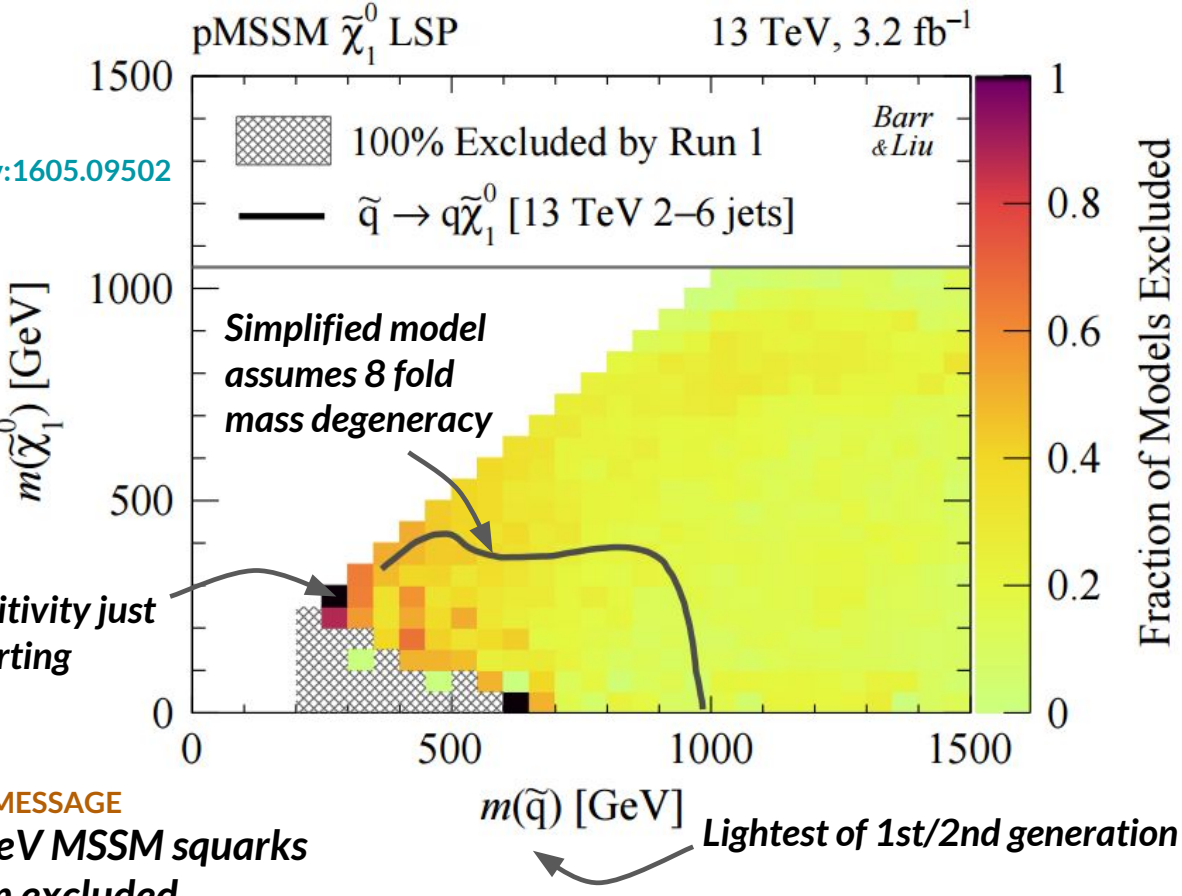
TAKE-HOME MESSAGE

Mass correlations: high mass gluinos 'excluded' due to low mass squark sensitivity (& vice versa)

A Barr & JL arXiv:1605.09502

Lightest squark-LSP plane

A Barr & JL arXiv:1605.09502

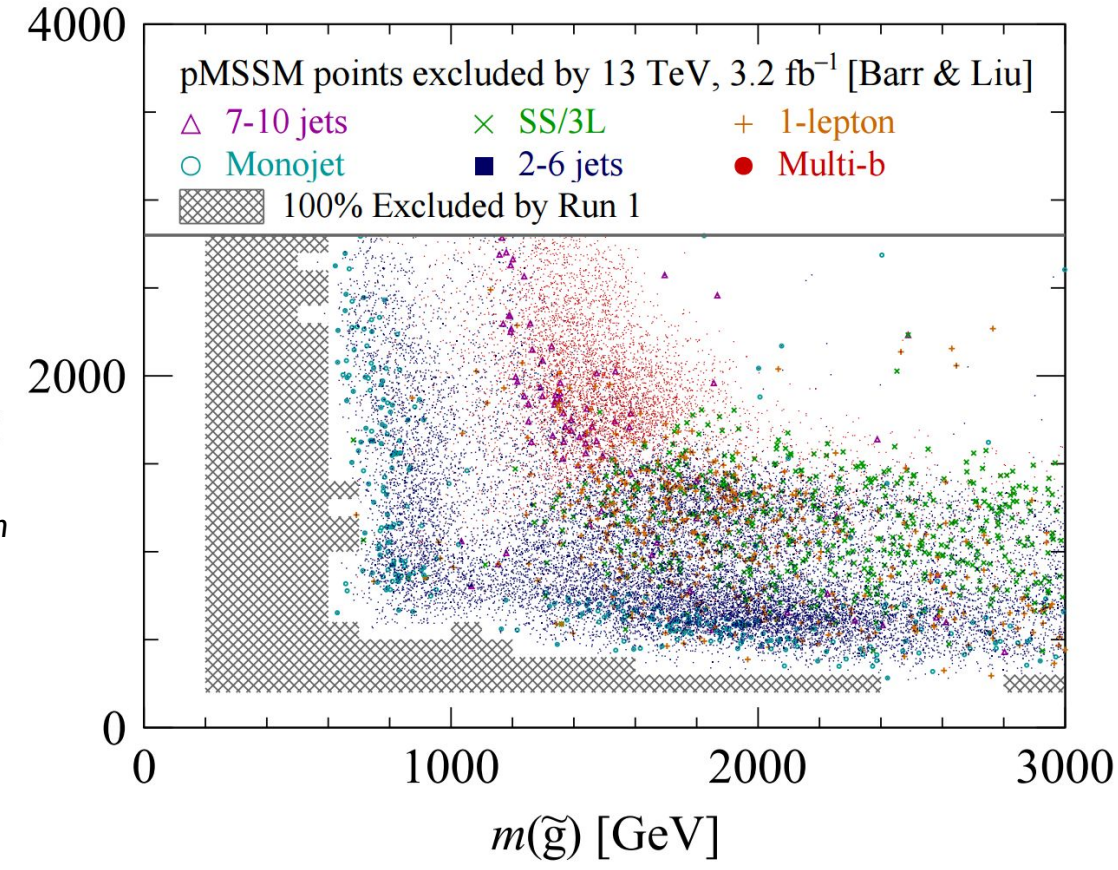


Lightest of 1st/2nd generation

TAKE-HOME MESSAGE

Sub-500 GeV MSSM squarks are far from excluded

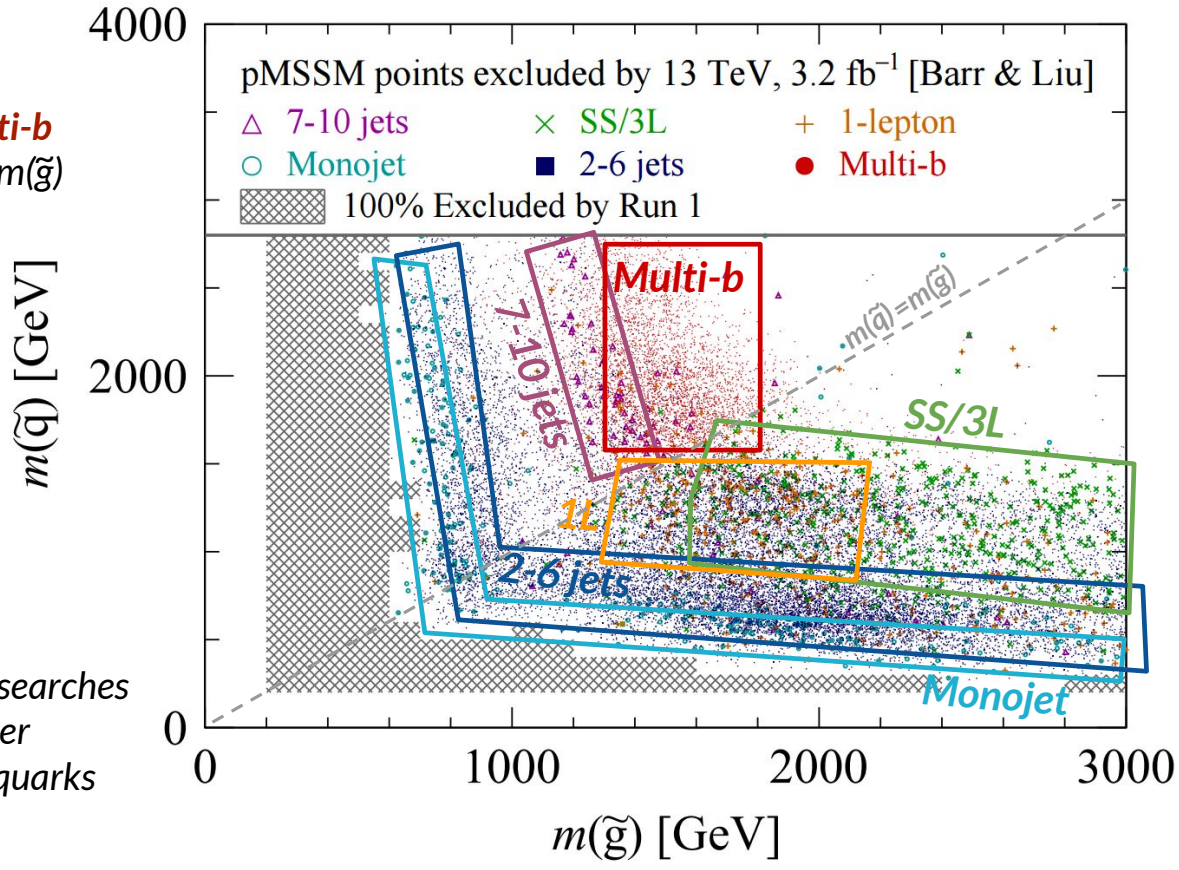
Squark-gluino correlations



Lightest squark
of 1st or 2nd generation

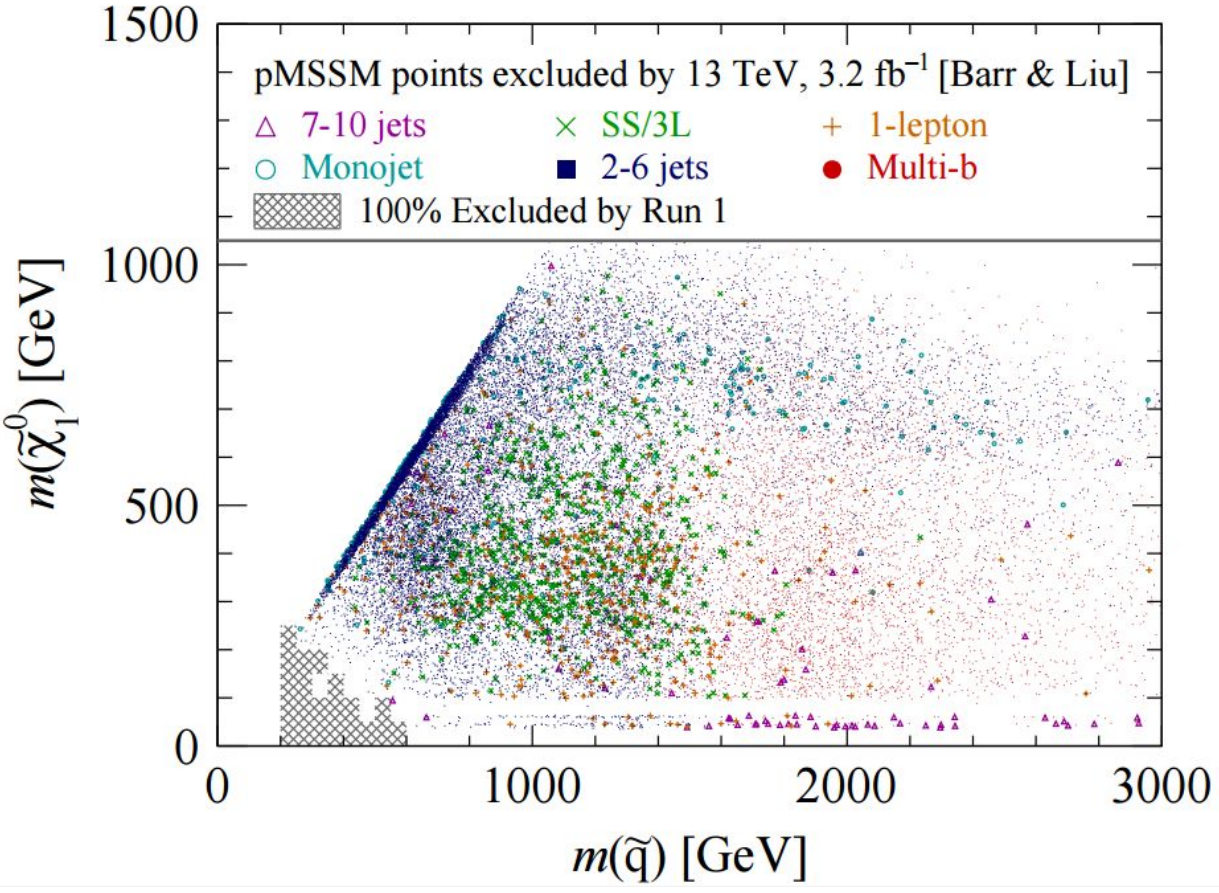
Squark-gluino correlations

7-10 jet *&* ***Multi-b*** *favours m(q̃) > m(g̃)*



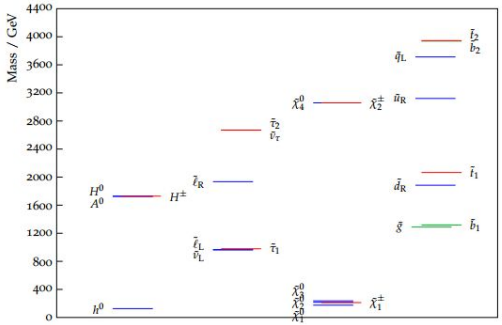
*Leptonic strong searches (**1L**, **SS/3L**) cluster around lighter squarks*

By most sensitive analysis

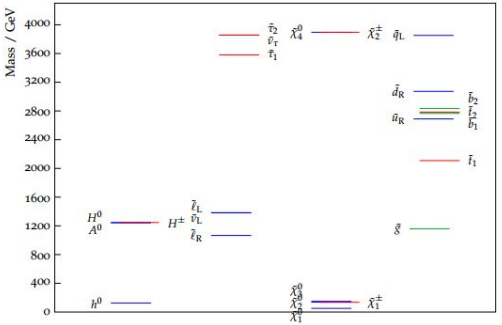


A Barr & JL arXiv:1608.05379

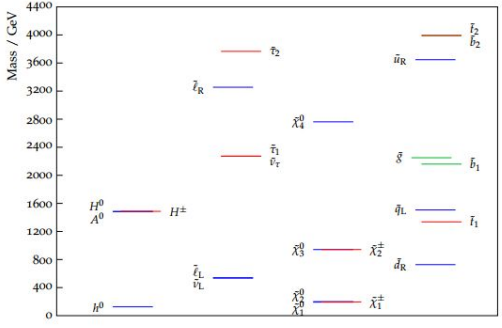
Representative sensitivity for analyses



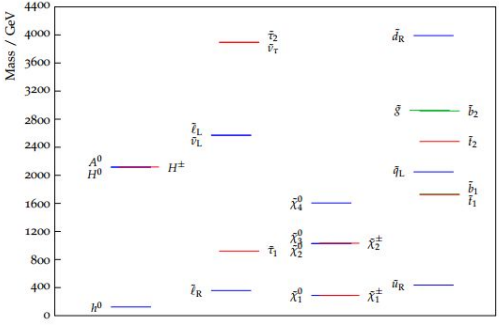
(a) Model 148229034 (Multi-b).



(b) Model 227558023 (7–10 jets).



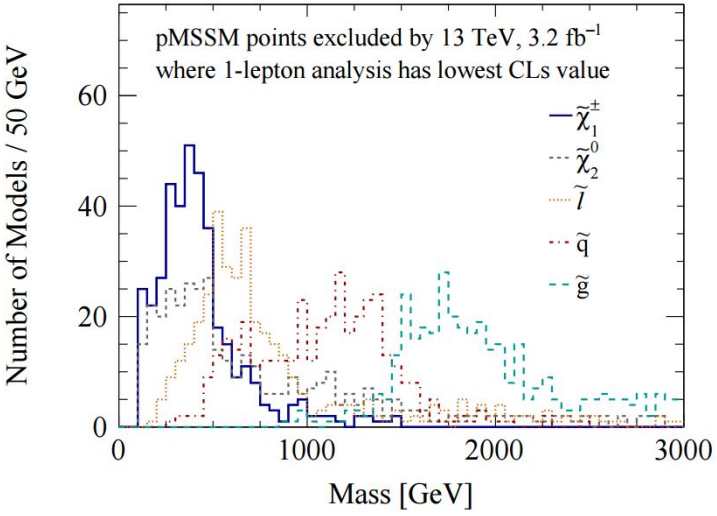
(c) Model 13382371 (1-lepton).

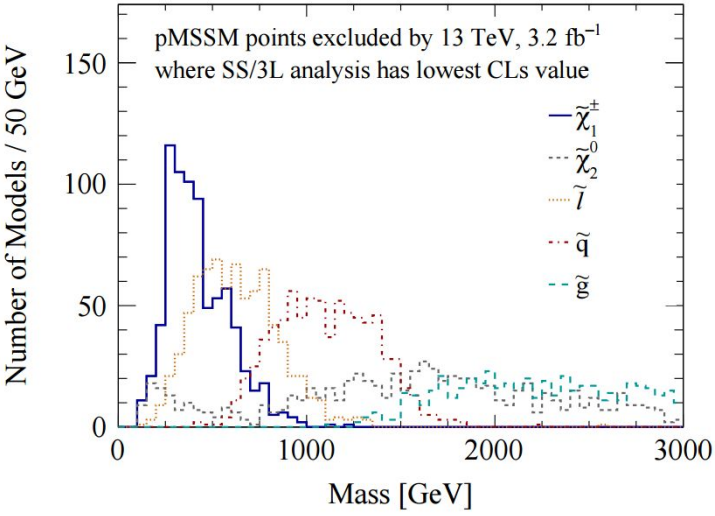


(d) Model 11733067 (SS/3L).

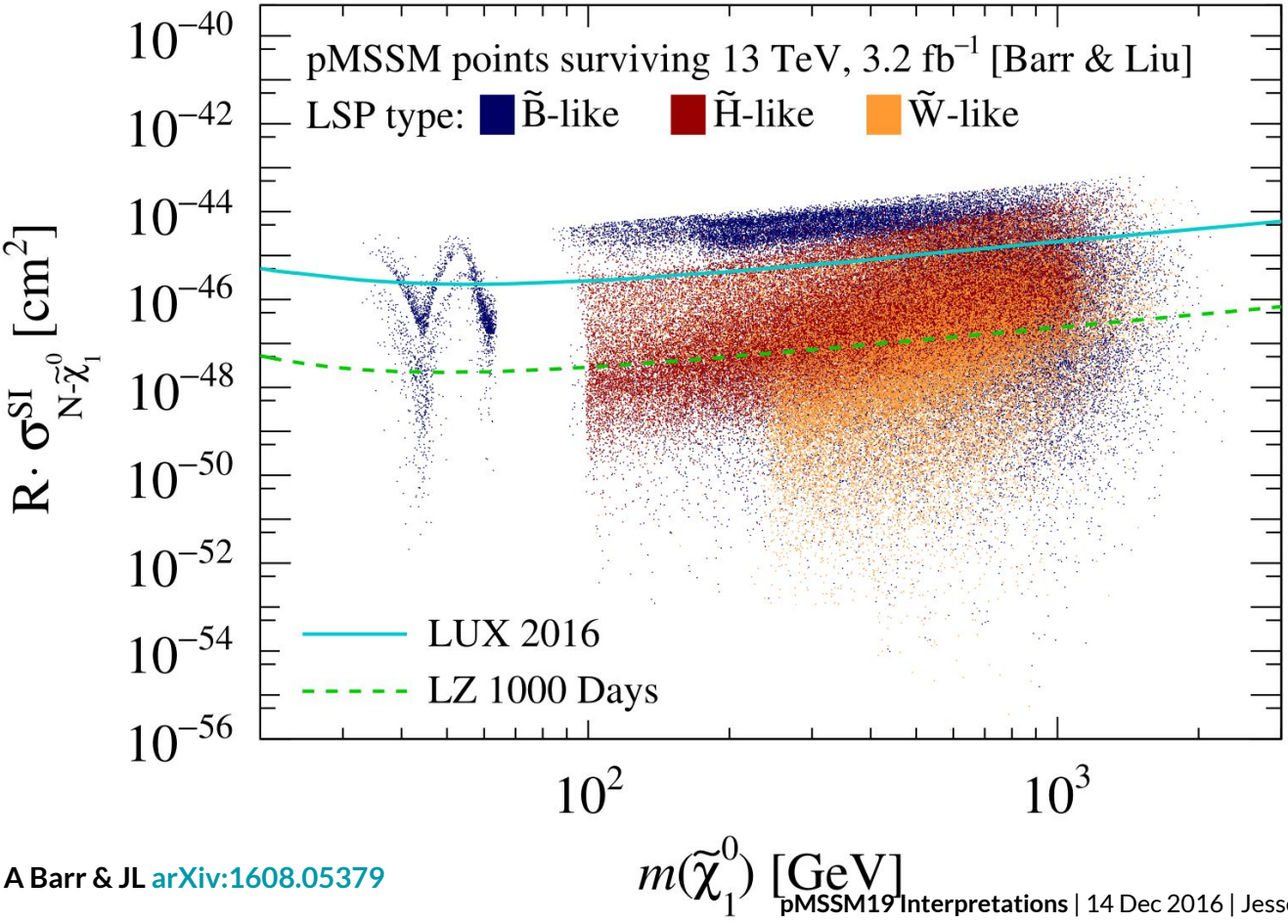
A Barr & JL arXiv:1608.05379

Leptonic strong analyses





Surviving pMSSM19 points



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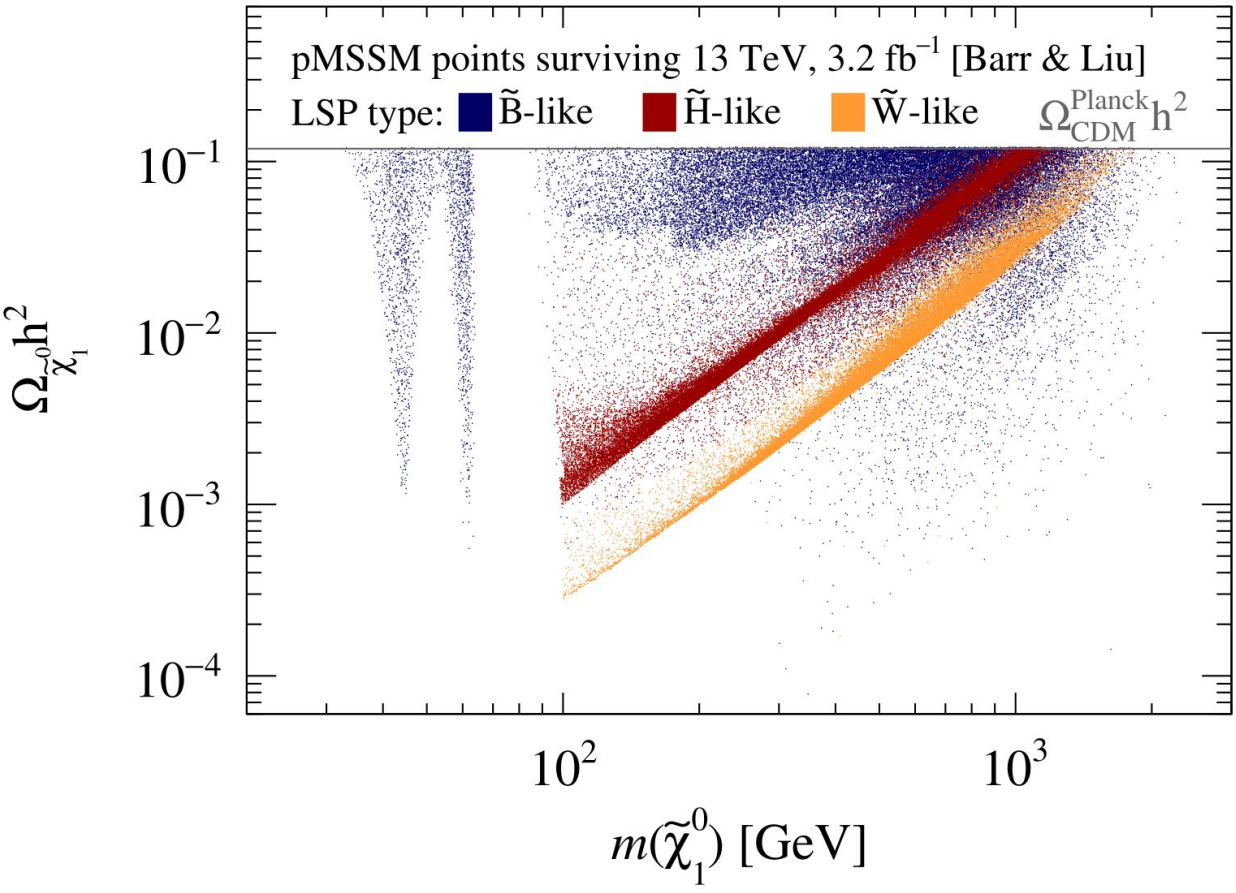
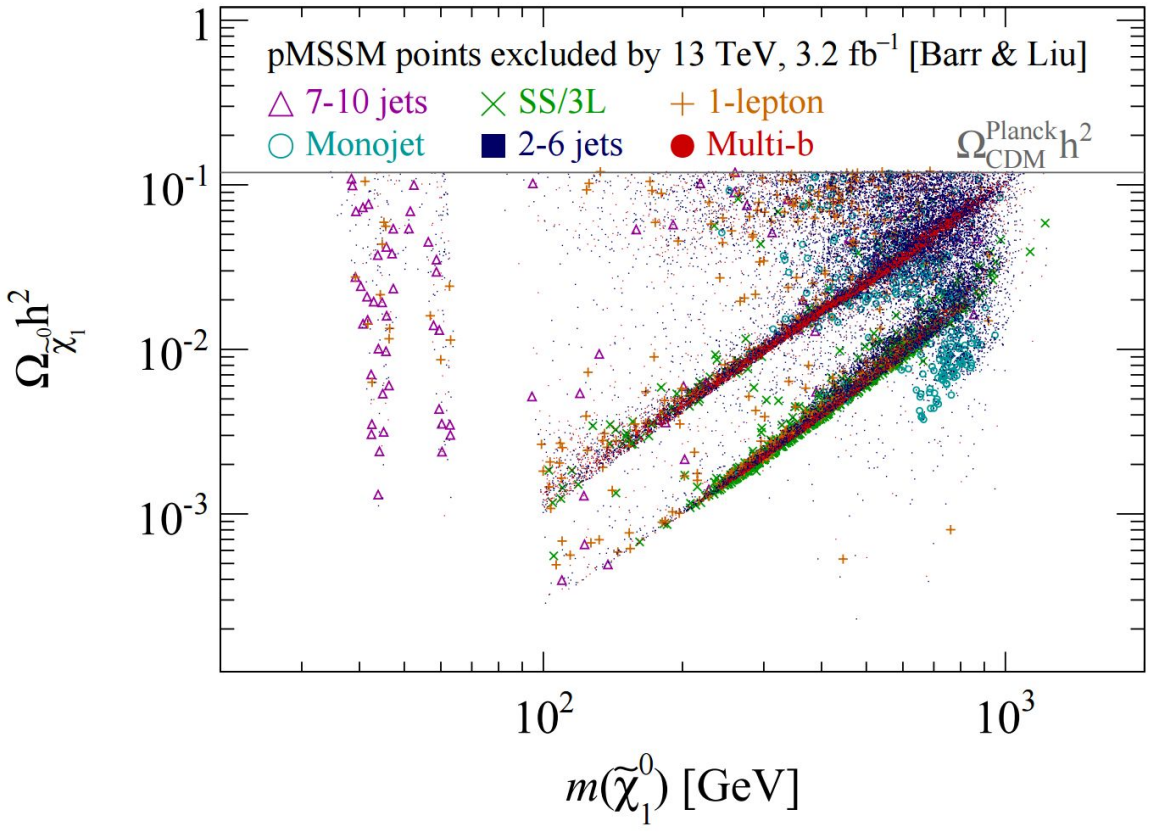
Surviving pMSSM19 points: relic density



A Barr & JL arXiv:1608.05379

pMSSM19 points excluded by 13 TeV 3.2/fb: relic density



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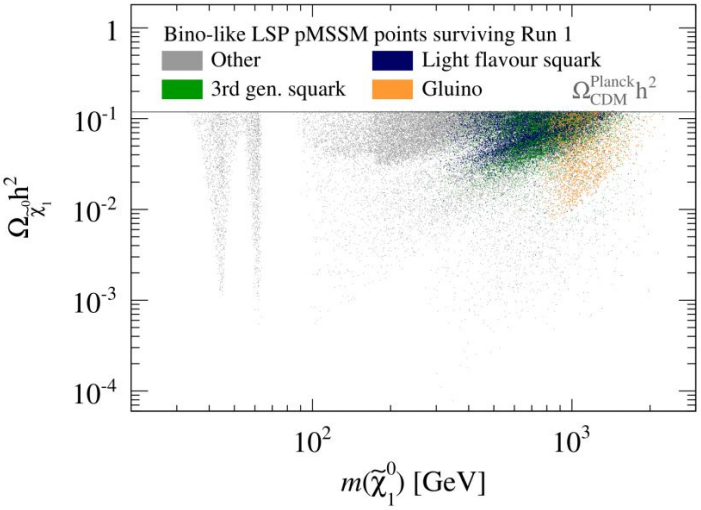
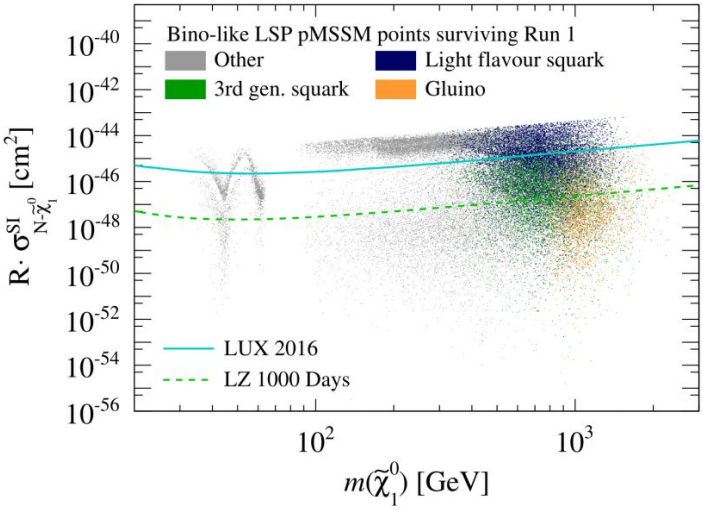
By strong coannihilator





Exclusion by LUX 2016

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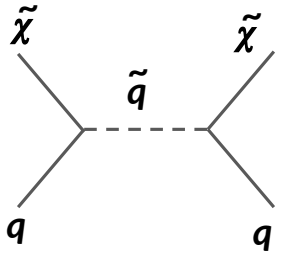
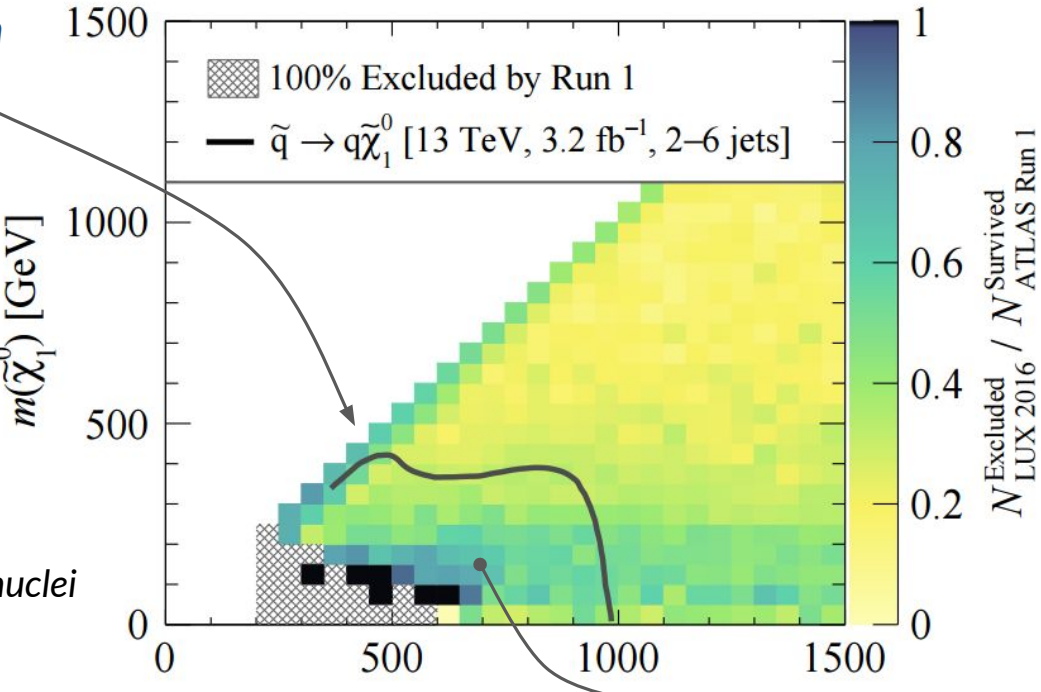
Squark coannihilation scenarios enhance direct detection

due to s-channel resonance enhancement



Light flavour quarks in nuclei



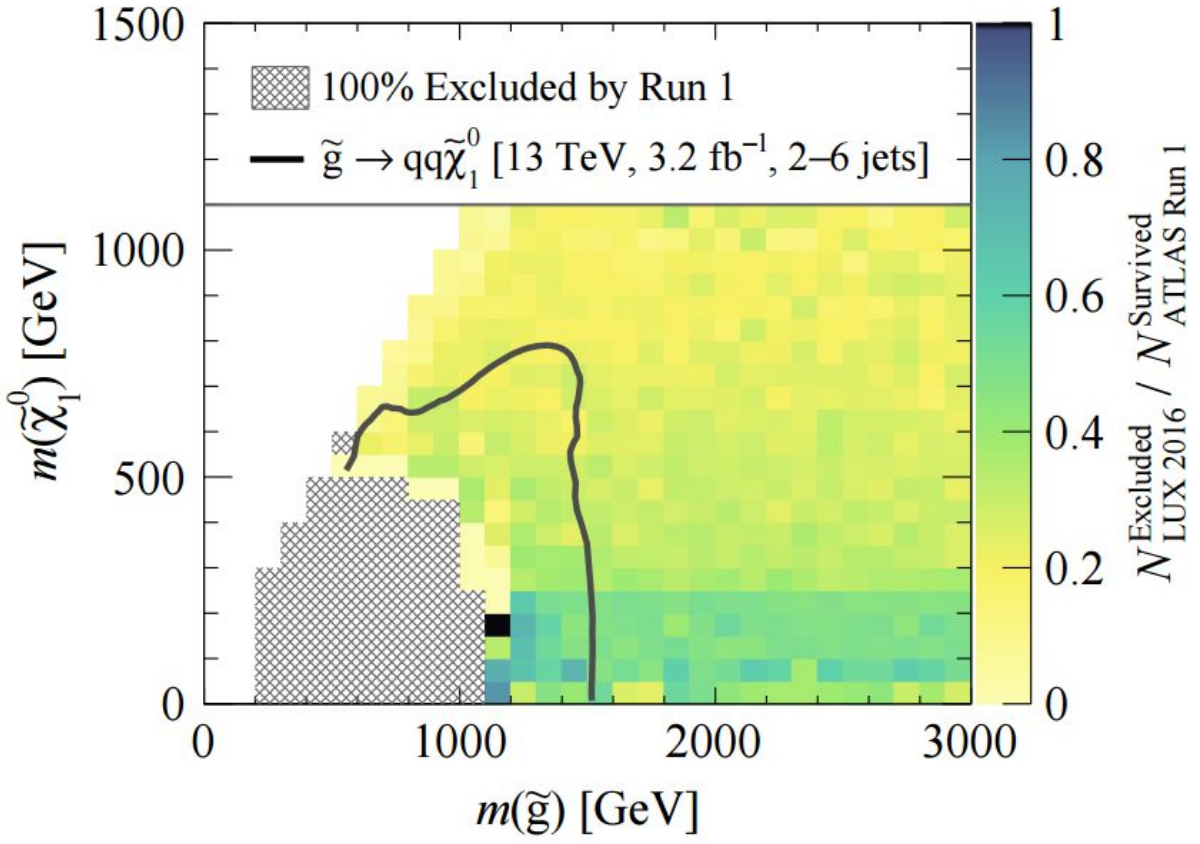
Gaugino coannihilators mostly

Squarks of 1st/2nd gen.

Coloured supersymmetry sector can play prominent DM role

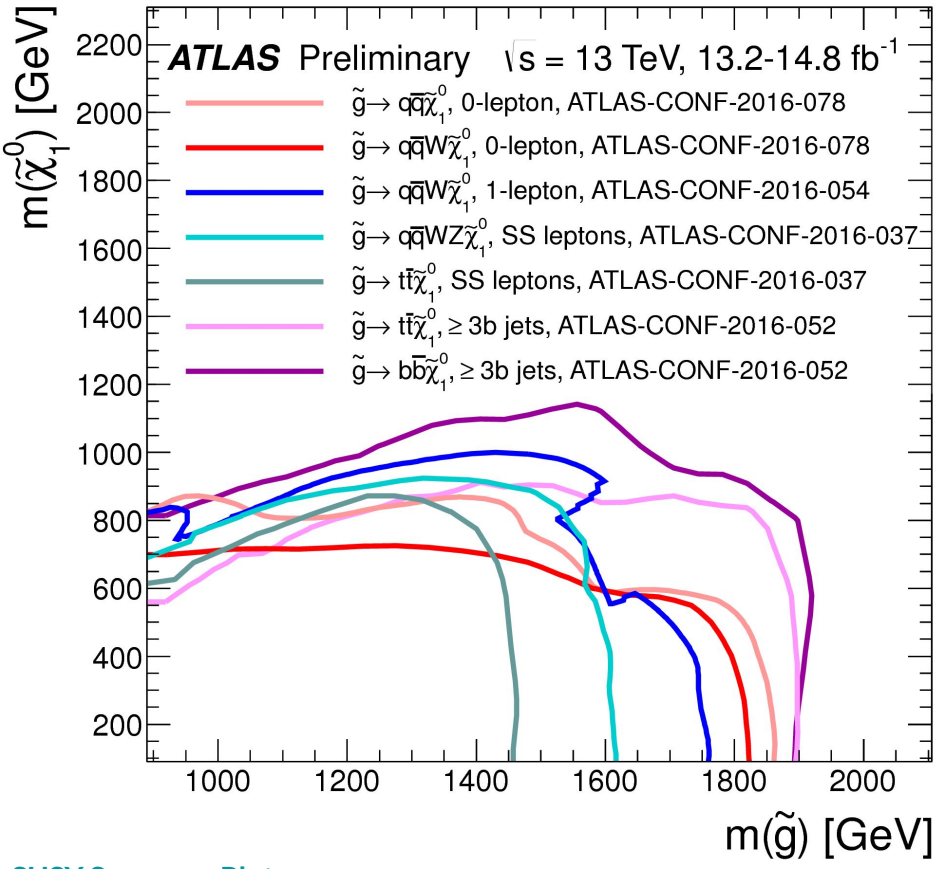
ATLAS 8 TeV EW DM pMSSM paper
Only looks at electroweakino sector

Exclusion by LUX 2016



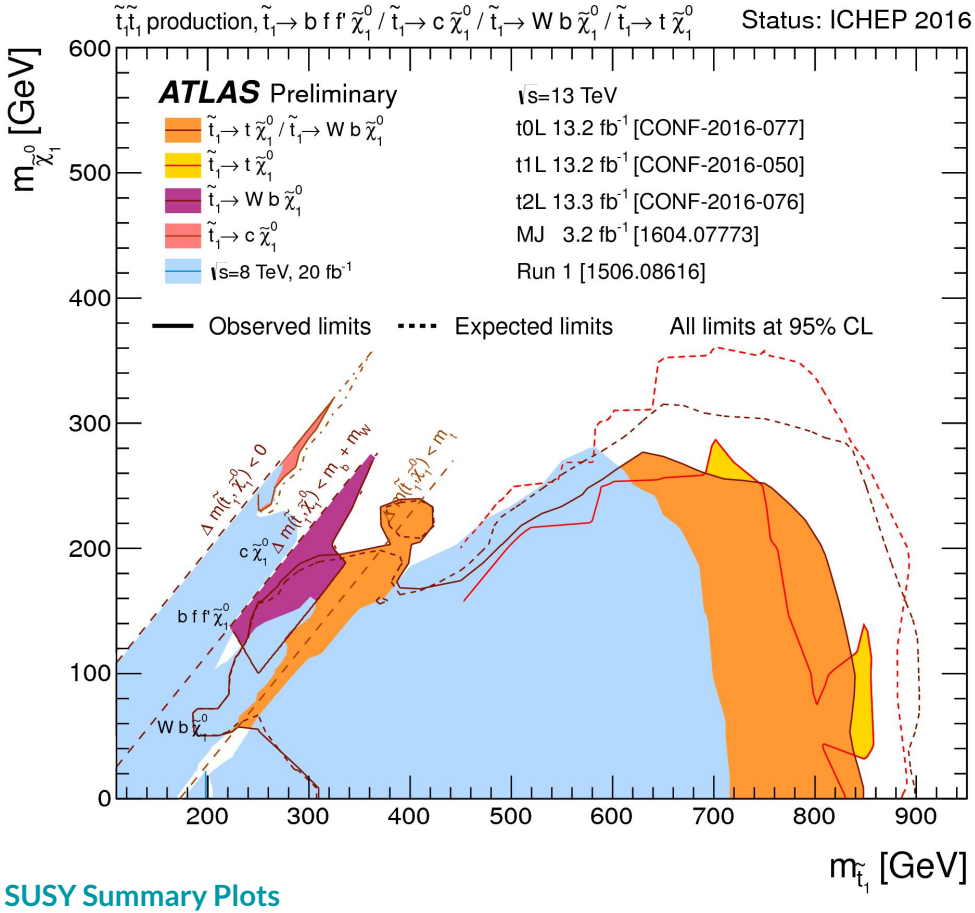
A Barr & JL arXiv:1608.05379

ICHEP 2016 gluinos



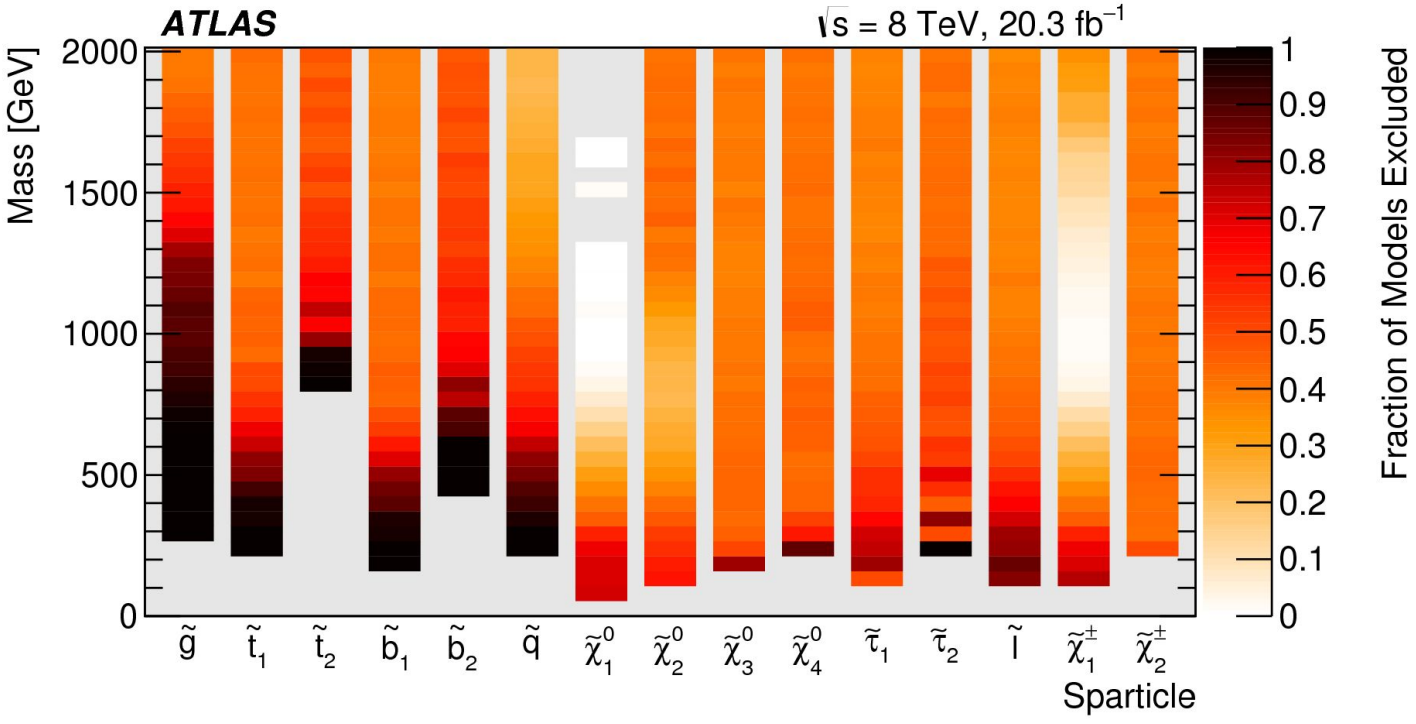
ATLAS Public SUSY Summary Plots

Stop searches



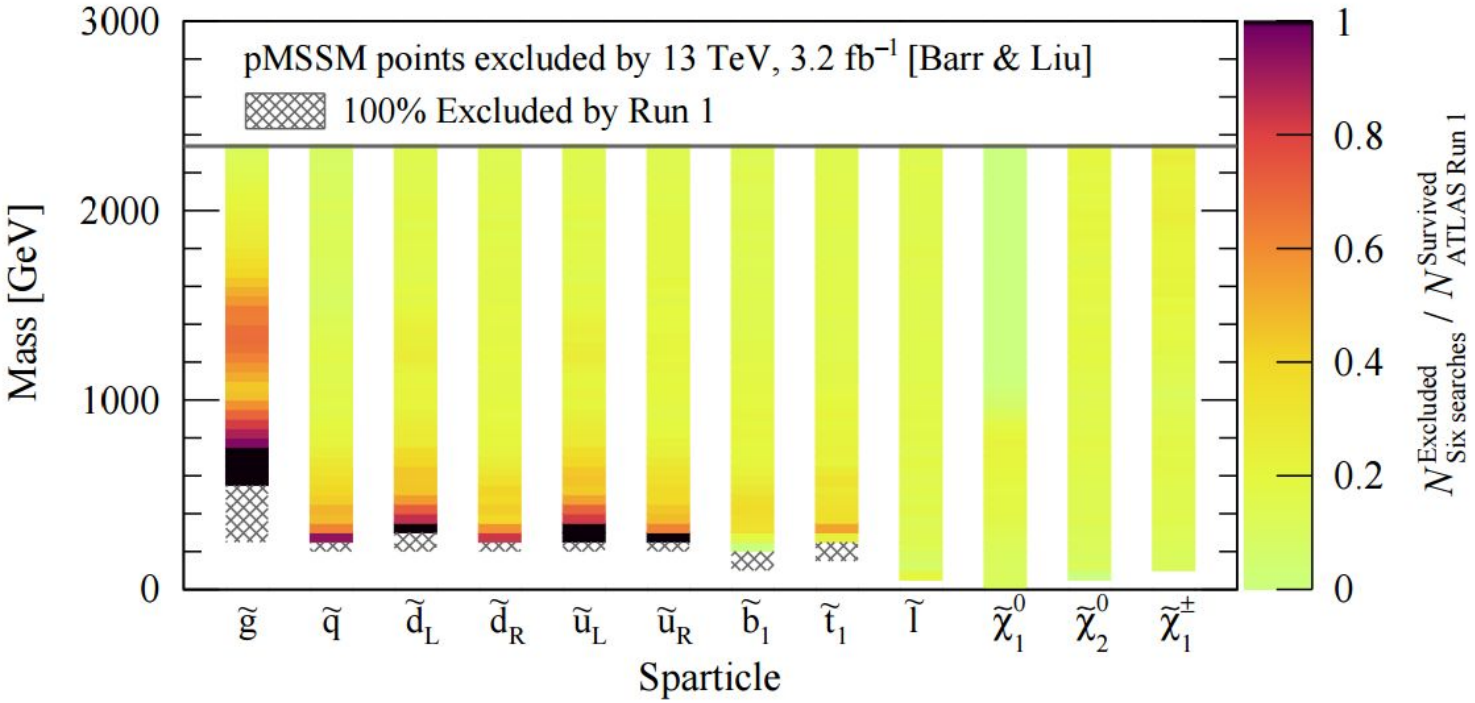
ATLAS Public SUSY Summary Plots

pMSSM19 after ATLAS Run 1



ATLAS Public SUSY Results

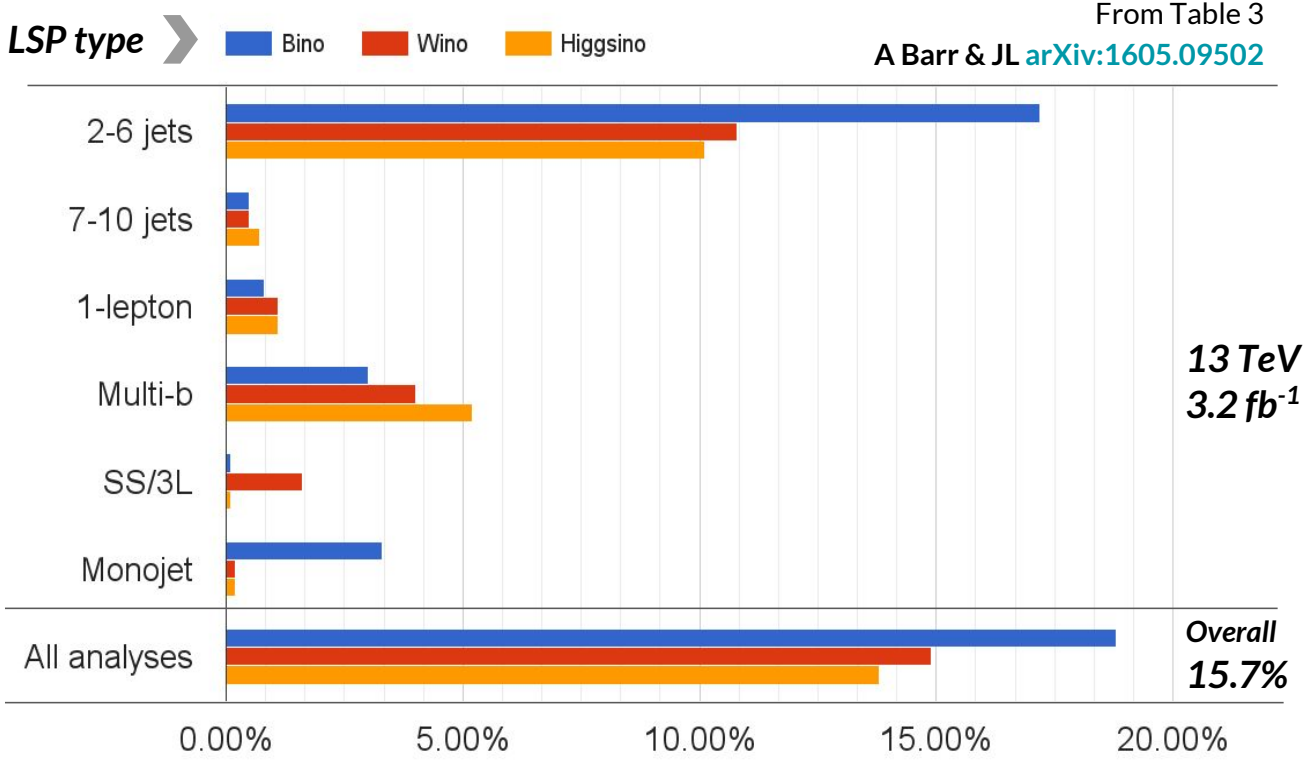
Selection of strong & electroweak sparticles



A Barr & JL arXiv:1608.05379

13 TeV (3.2 fb^{-1}) sensitivity extends beyond 8 TeV (20.3 fb^{-1})

From Table 3
A Barr & JL arXiv:1605.09502



Out of Run 1 survivors, without long-lived