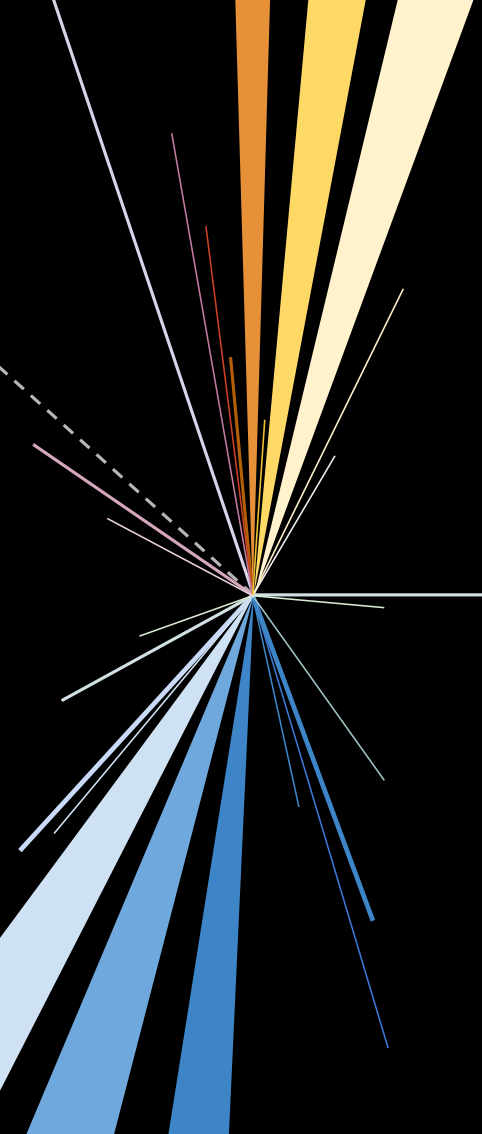


SUSY:

SOFT PHYSICS & INTERPRETATION CHALLENGES

Young Theorists Forum @ Durham

Jesse Liu
University of Oxford
12 January 2017

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

FOCUS OF TALK

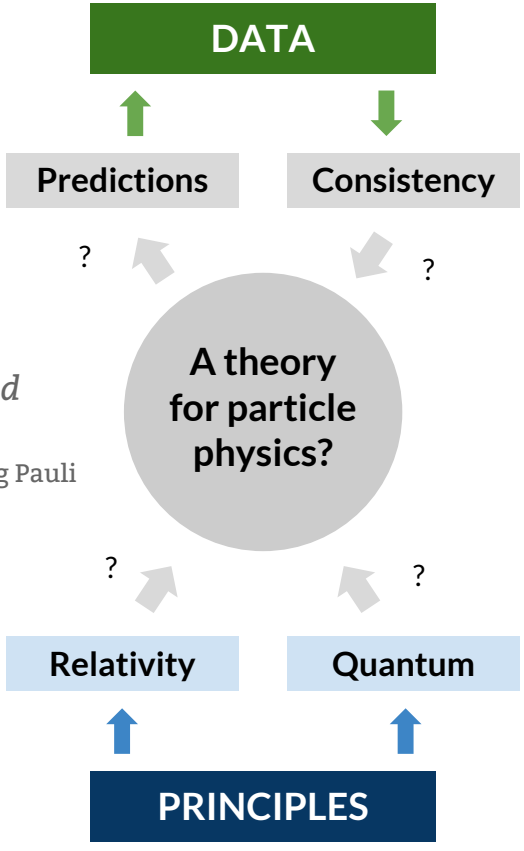
LHC: testing relativity + quantum theory

Interpretation: what do the searches mean?

Soft physics: experimental challenges

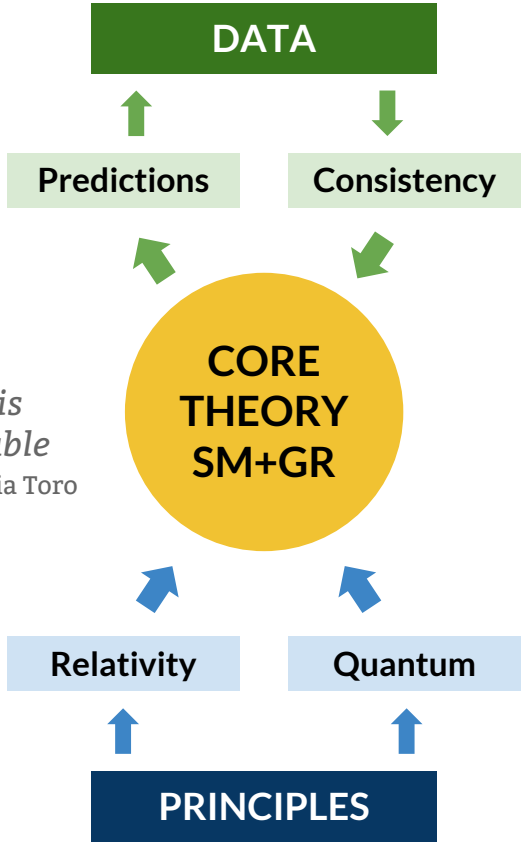
Particle Zoo era: is there a theory for particles?

> *Had I foreseen this, I would have gone into botany*
>
> - Enrico Fermi or Wolfgang Pauli

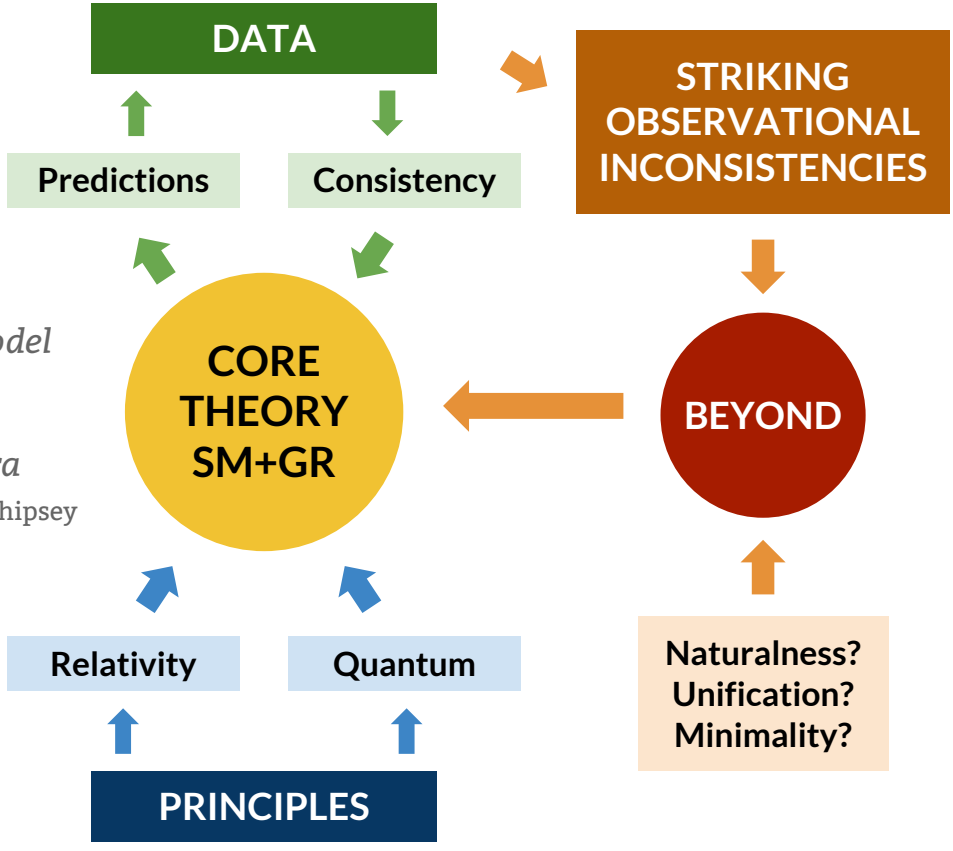


Golden age: experiment & theory triumph

> *The most dramatic lasting impact is realising that this structure is almost inevitable*
>
> - Natalia Toro



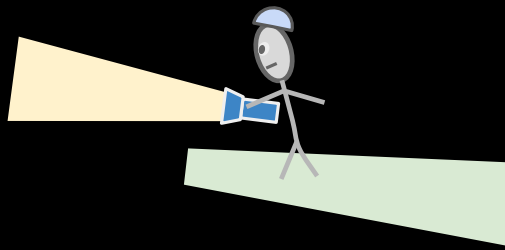
In search of the new particle zoo



> *Now that the Standard Model is complete, there are no further no-lose theorems... We are in a data driven era*
>
> - Ian Shipsey

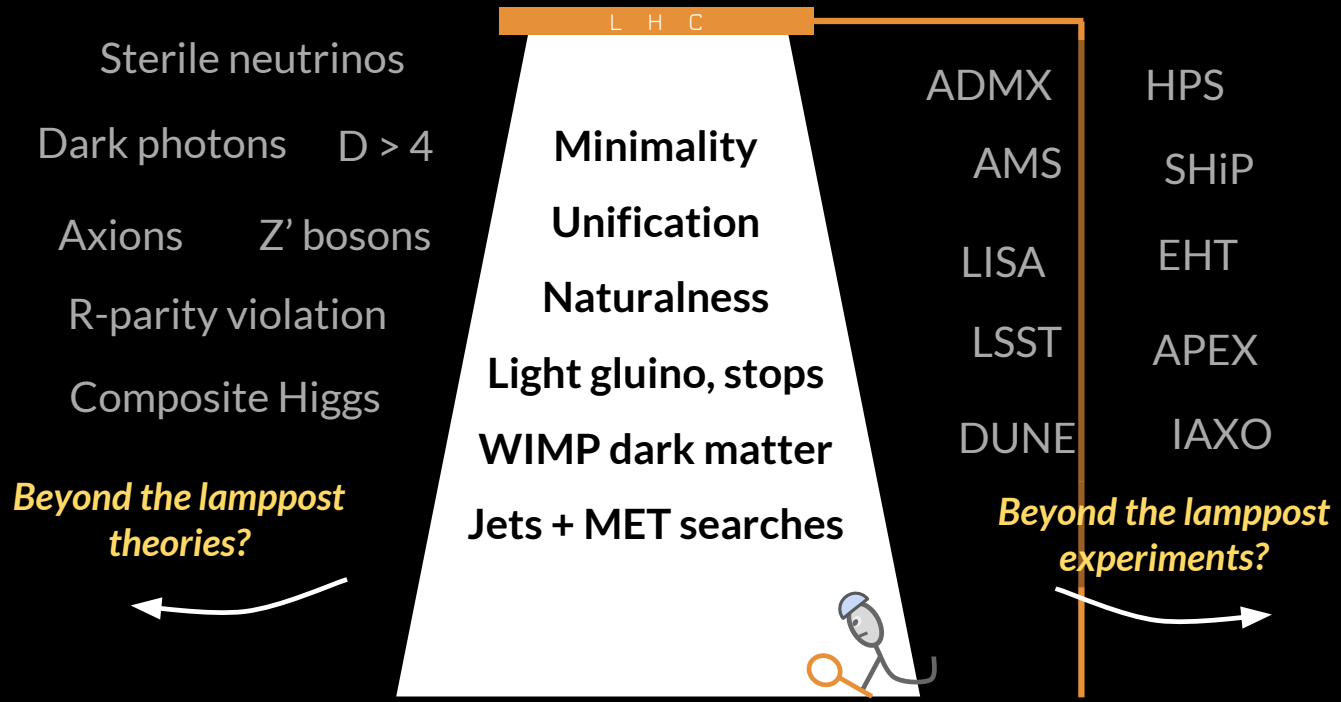
DARKNESS OF UNKNOWN

Where do we start searching?



LAMPPOSTS EXIST: SEARCH THERE FIRST

Relativity + quantum underpins supersymmetry

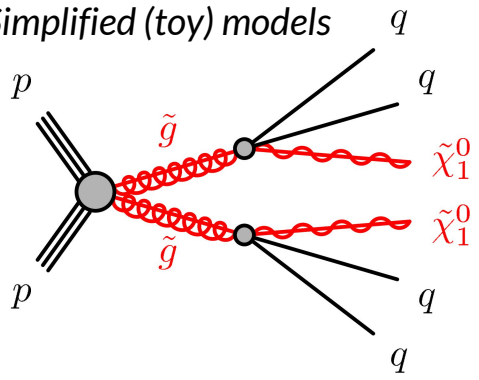


NEW PHYSICS AT WEAK SCALE IS

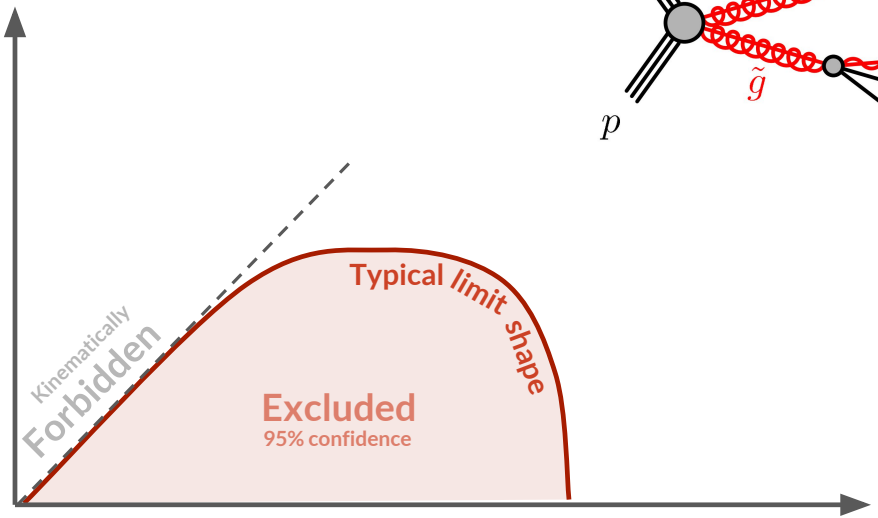
theoretically motivated + experimentally observable

Easy: how do we read SUSY limits?

Simplified (toy) models

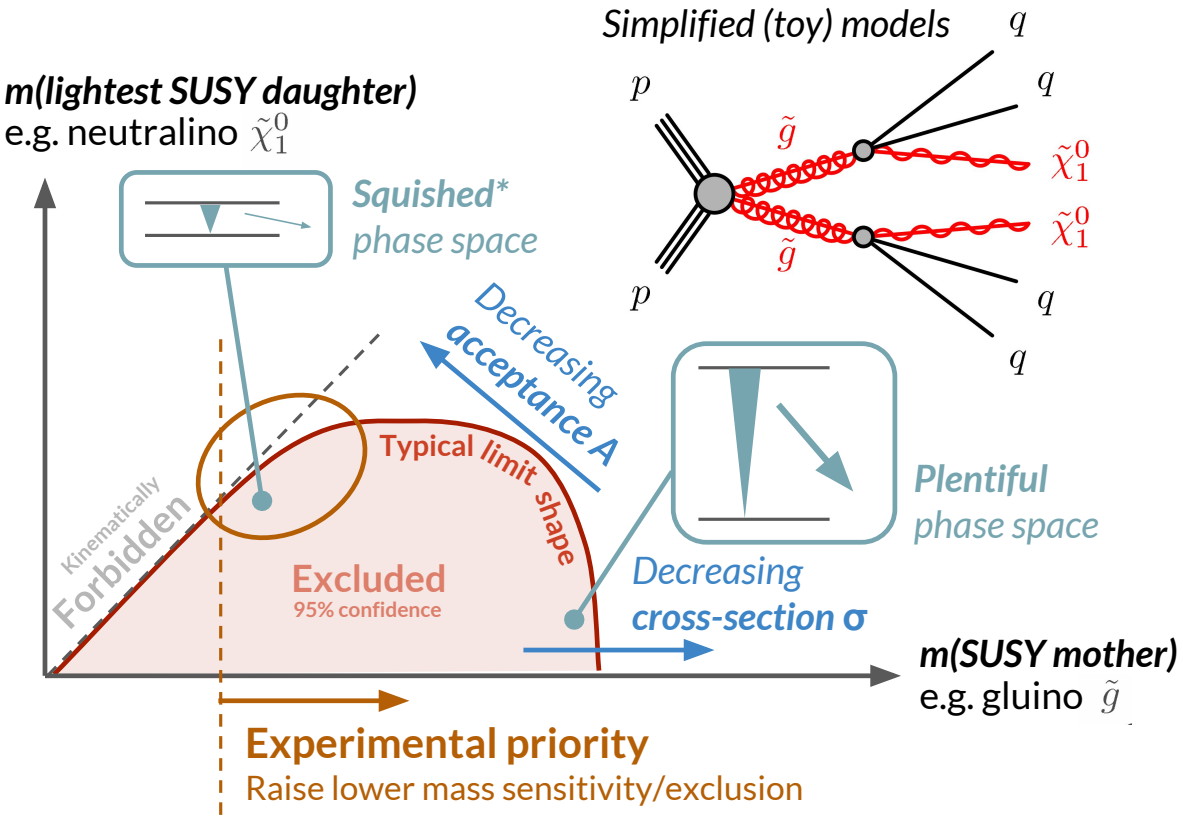


m(lightest SUSY daughter)
e.g. neutralino $\tilde{\chi}_1^0$



m(SUSY mother)
e.g. gluino $\tilde{g}$

Easy: how do we read SUSY limits?



* Aka 'compressed', 'squashed', 'squeezed', small mass-splittings

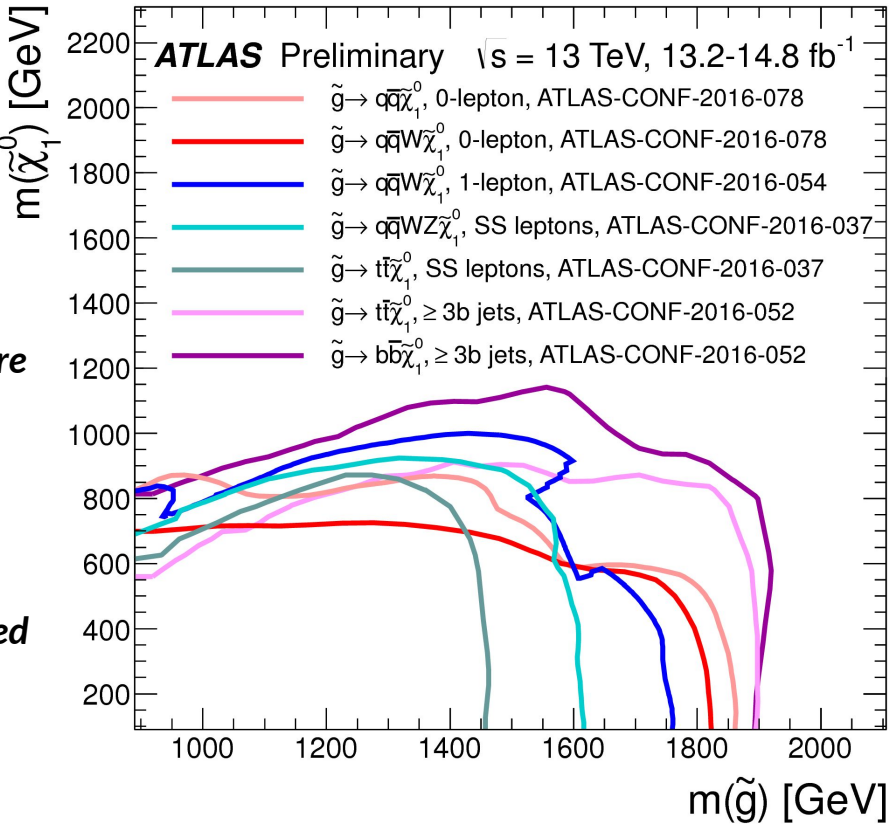
Tricky: how do we interpret SUSY limits?

> ***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 probe realistic MSSM scenarios?***
>
> - natural MSSM advocate friend

ATLAS SUSY Public @ ICHEP 2016

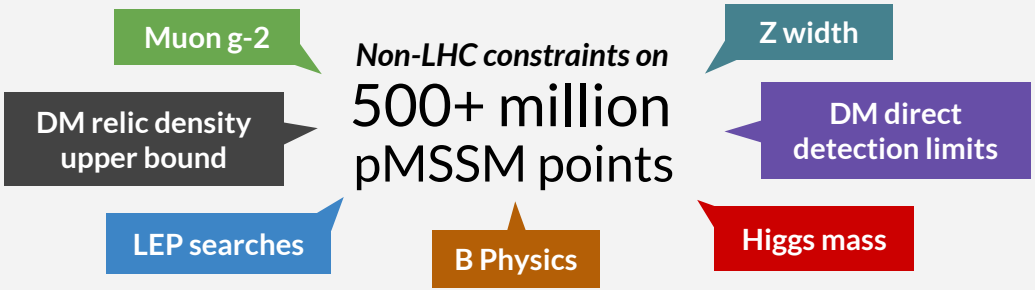


The ATLAS p(henomenological)MSSM

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

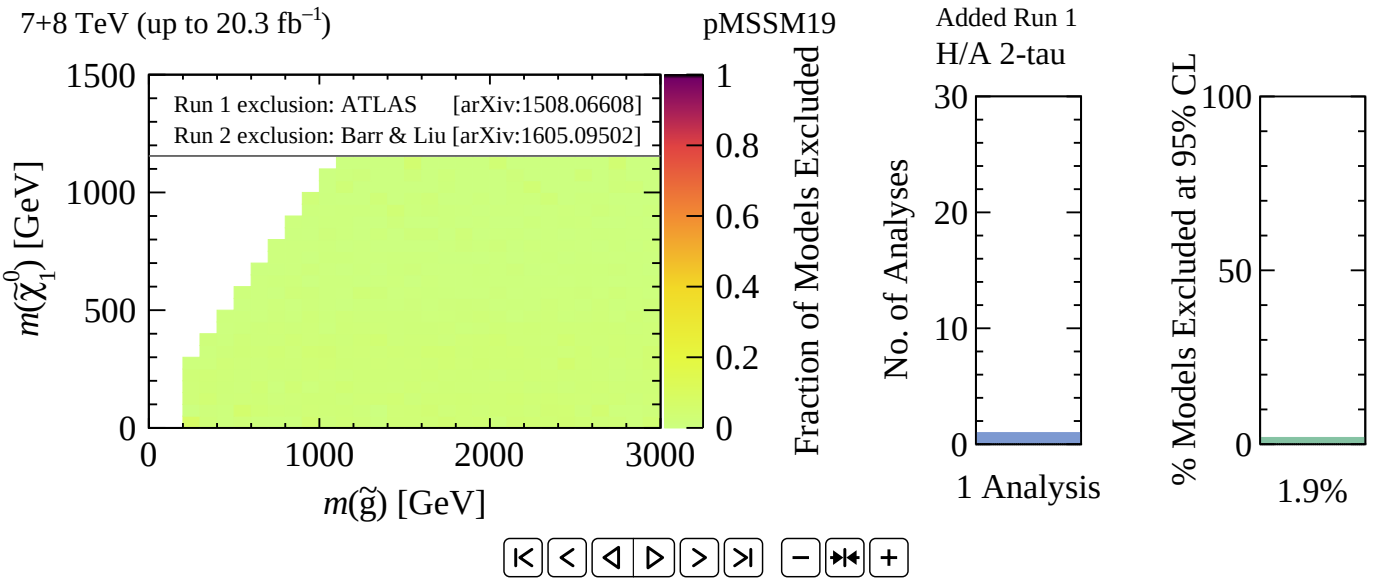
ATLAS Collaboration [arXiv:1508.06608]

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

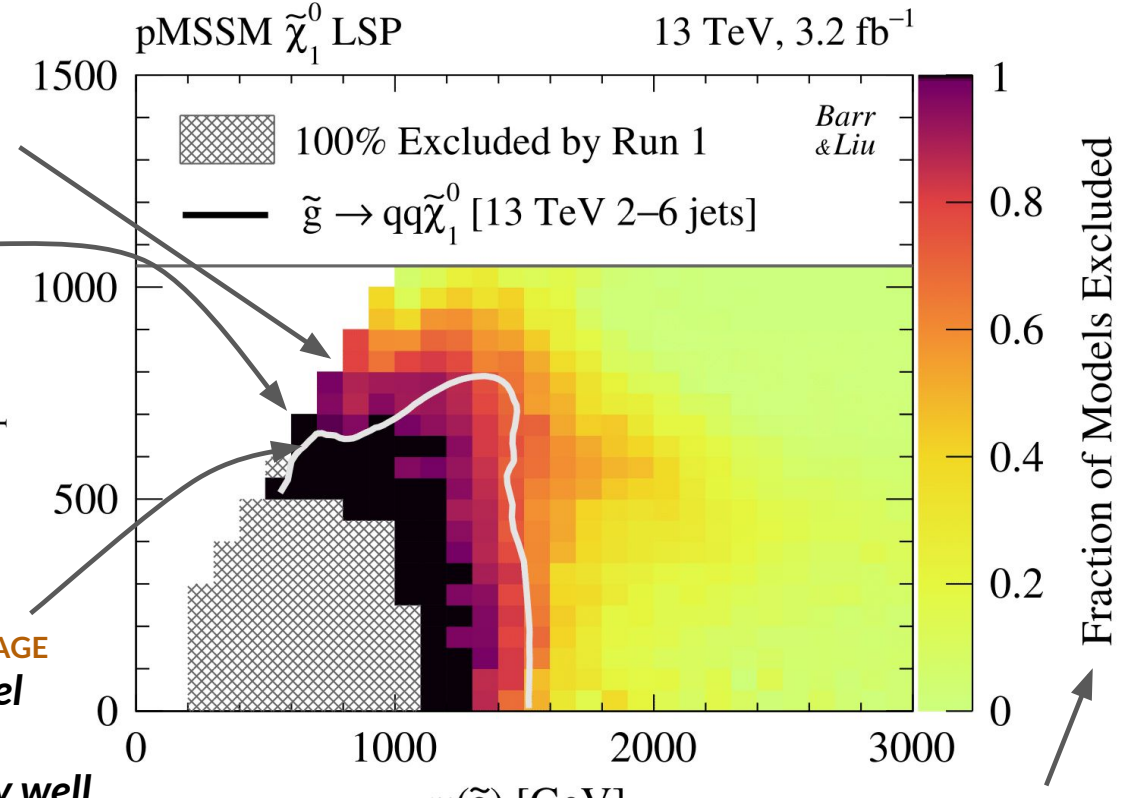


Impact of 28 SUSY searches on pMSSM19

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.

Gluino-LSP plane



Sub-TeV gluinos generally close to with LSP mass

Black = 100% exclusion

Lightest supersymmetric particle (LSP DM)

Normalised to Run 1 survivors, without long-lived

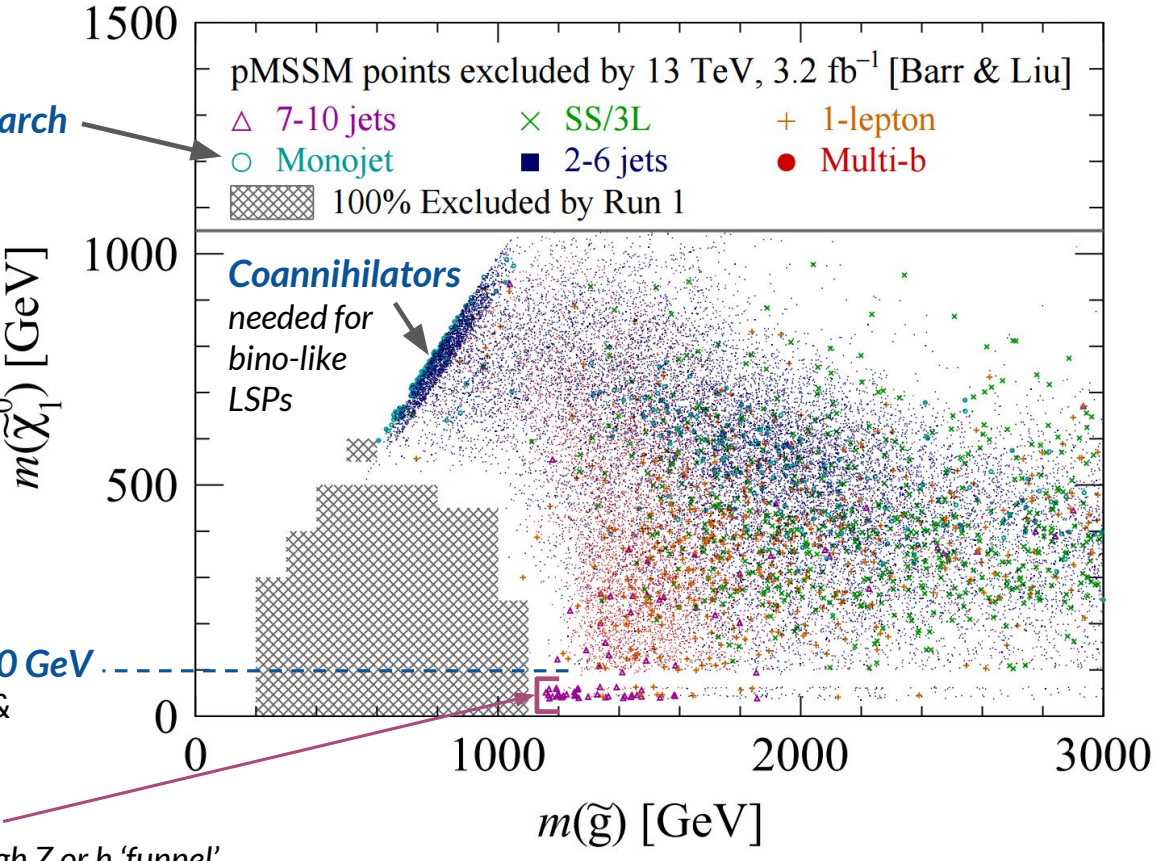
TAKE-HOME MESSAGE

Simplified model captures gluino sensitivity fairly well

A Barr & JL [arXiv:1605.09502]

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

Scatter 28k points excluded by six 13 TeV searches



Most sensitive search
= lowest CLs value used for exclusion

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]

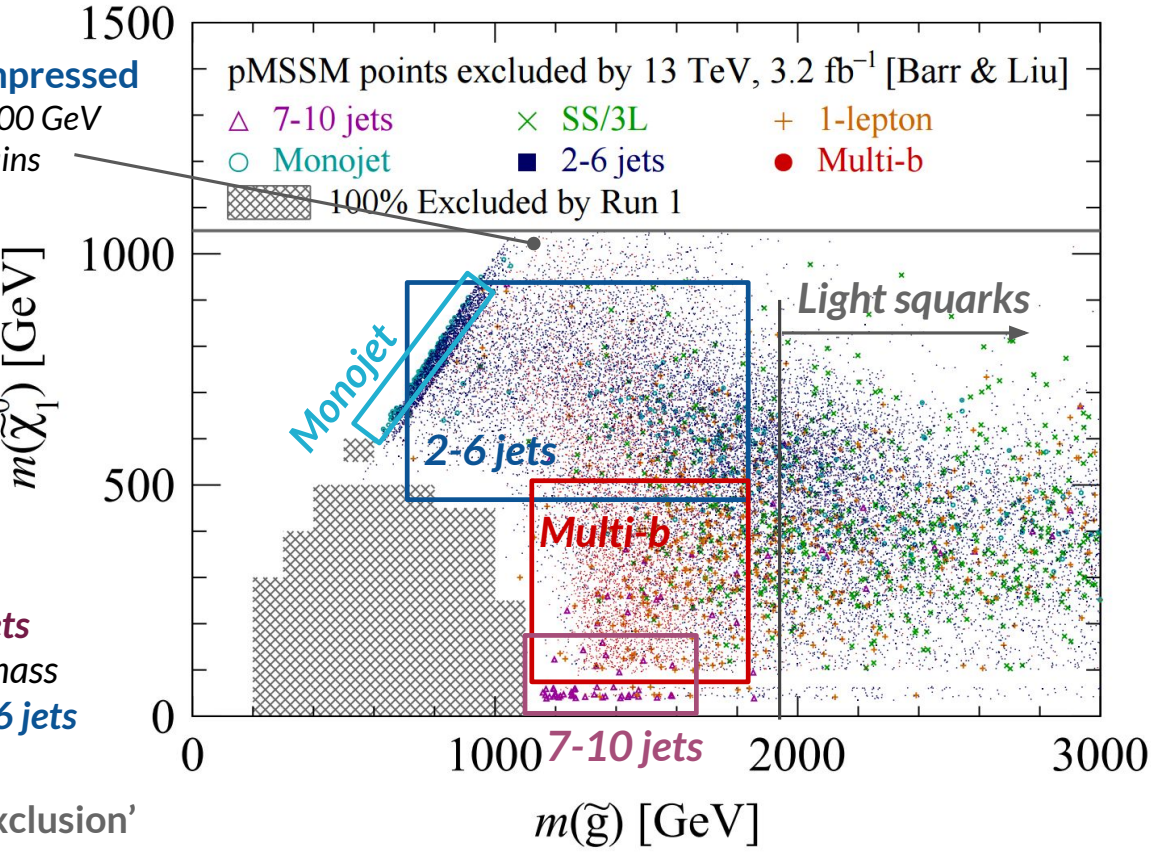
Distinct regions of sensitivity identified

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

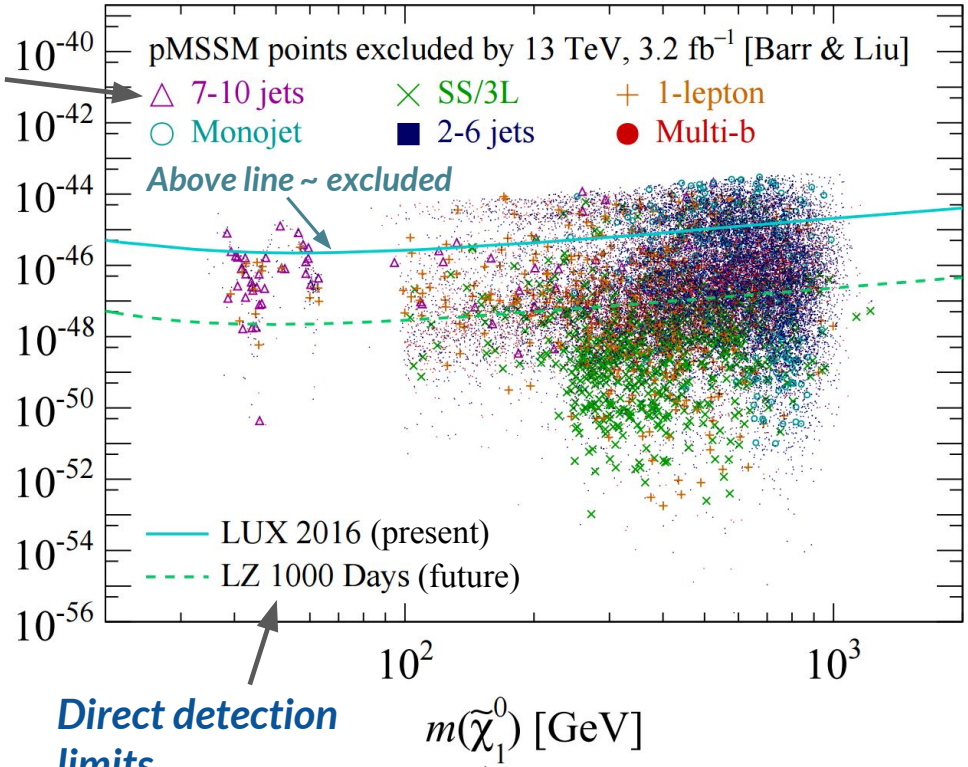
***Monojet** still needed for ultra compressed*

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

'Heavy gluino exclusion'
correlated with light squark sensitivity



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

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

Direct detection limits

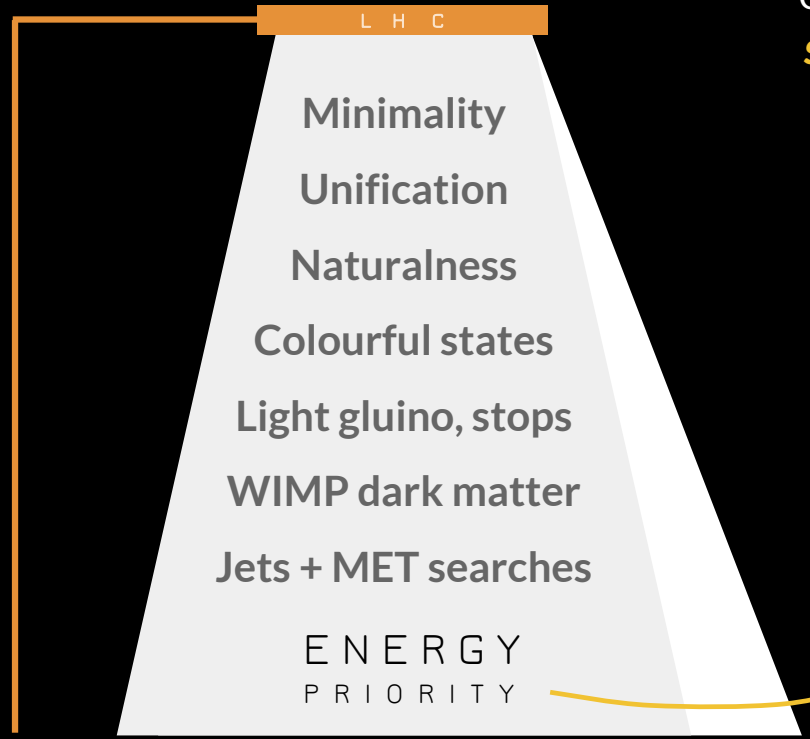
Recent + future
Xenon-target experiments

WIMP dark matter mass

Neutralino LSP

THE SEARCHLIGHT IS SHIFTING

from spectacular to subtle discoveries



Opportunities & challenges for

soft, rare, quirky signals

Soft stuff

Particle identification
Trigger thresholds

Rare SUSY

Colourless sparticles
Dark sector

Quirky creatures

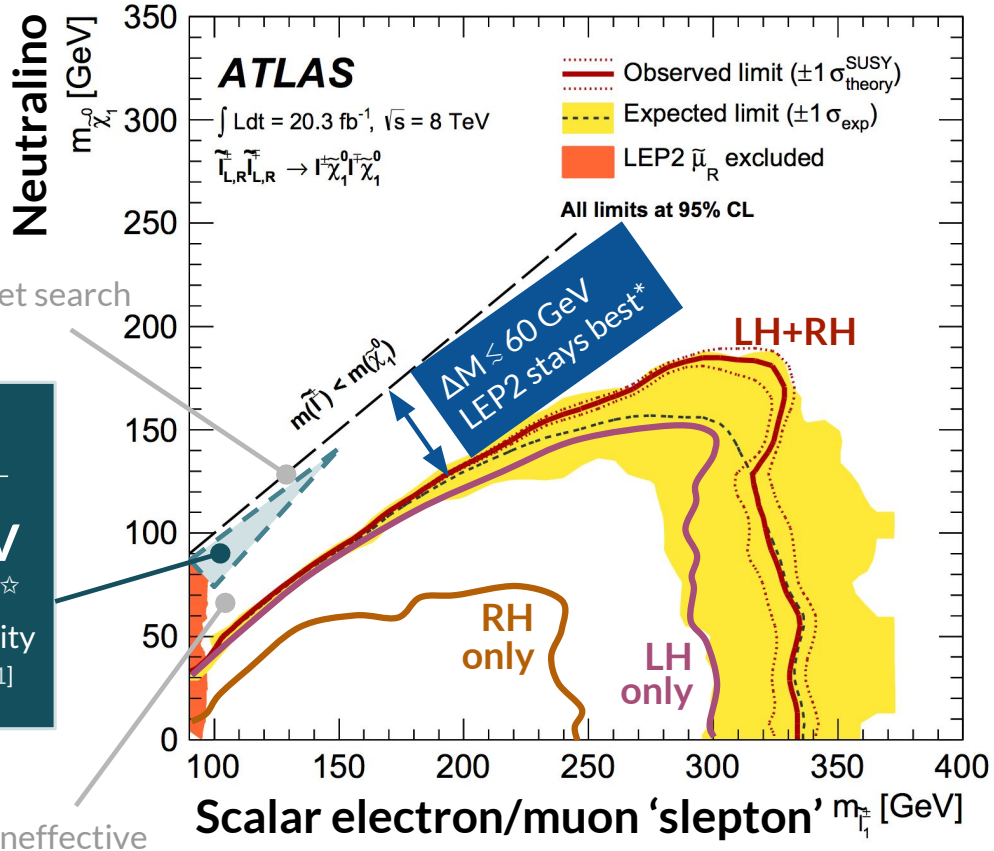
Displaced difficulties
Long-lived exotica

Scalar leptons

*Also phenomenologically motivated DM 'coannihilation' region

☆ See backup 28-29 for slepton selection

arXiv:1403.5294



ΔM ≲ 3 GeV

Need low-MET 0/1L Monojet search

A new hope

ΔM ~ 3 → 24 GeV

Monojet + 2L + MET mT2 ☆

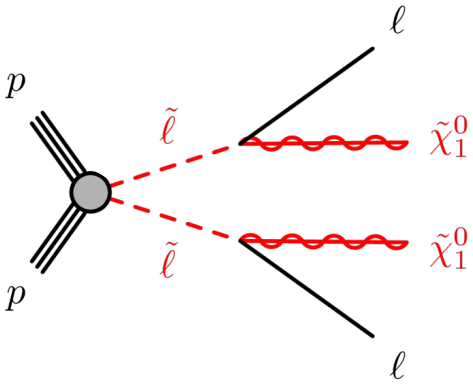
projected LH 100/fb sensitivity

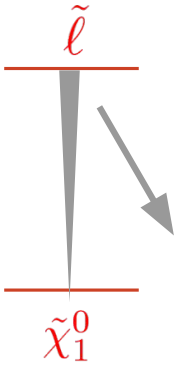
[arXiv:1412.0618, arXiv:1501.02511]

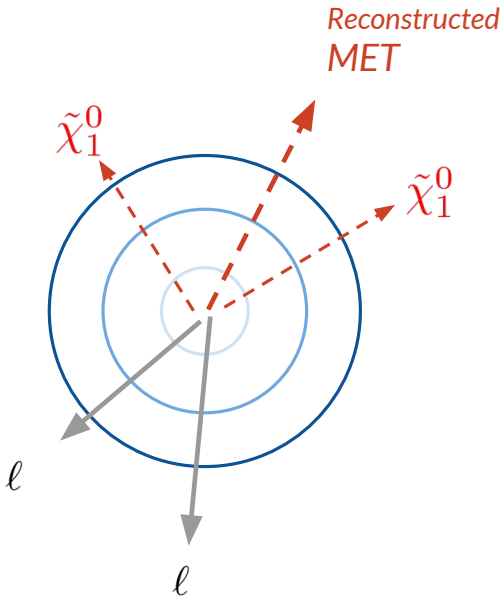
ΔM ~ 24 → 60 GeV

Usual mT2 kinematic edge ineffective against formidable WW & di-top background

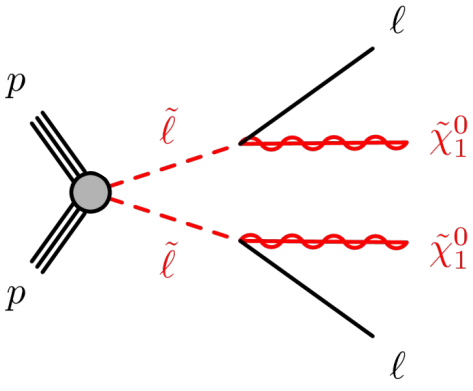
Scenario: scalar leptons with plentiful phase space

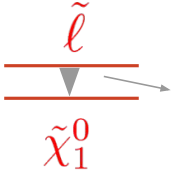


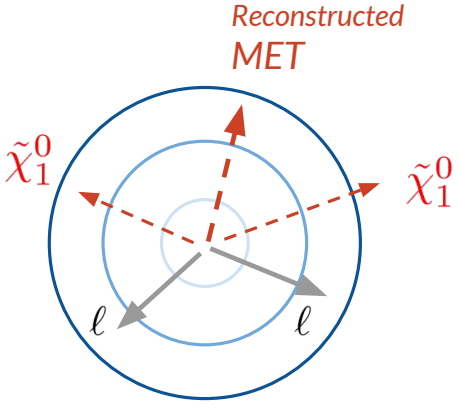




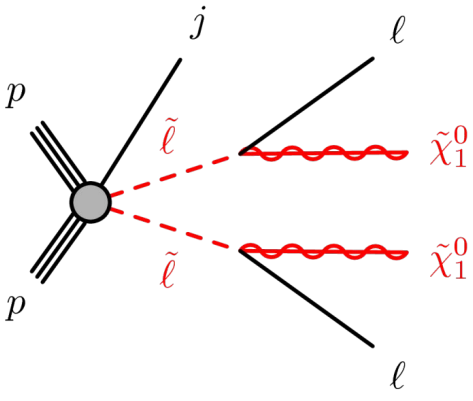
Problem: squished phase space hampers detectability

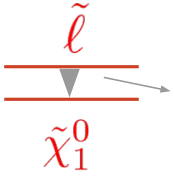


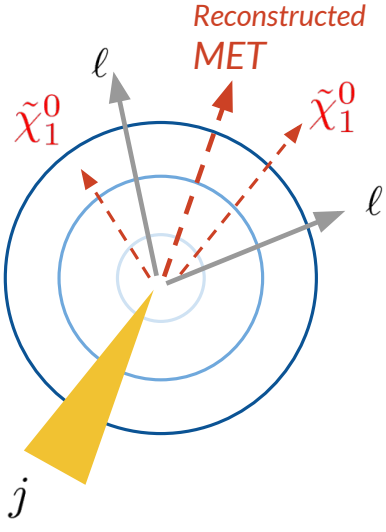




Solution: boost SUSY system off jet







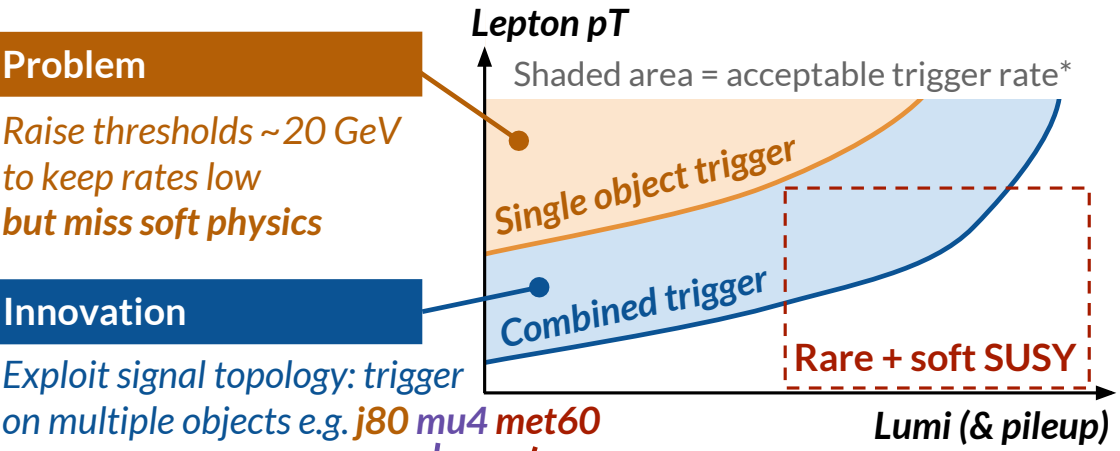
New triggers enable new searches

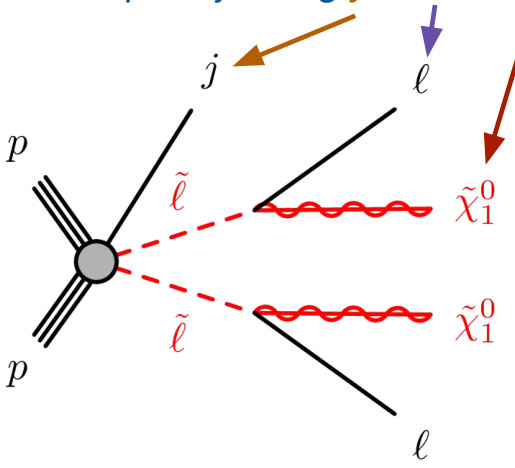
Problem

Raise thresholds ~20 GeV to keep rates low
but miss soft physics

Innovation

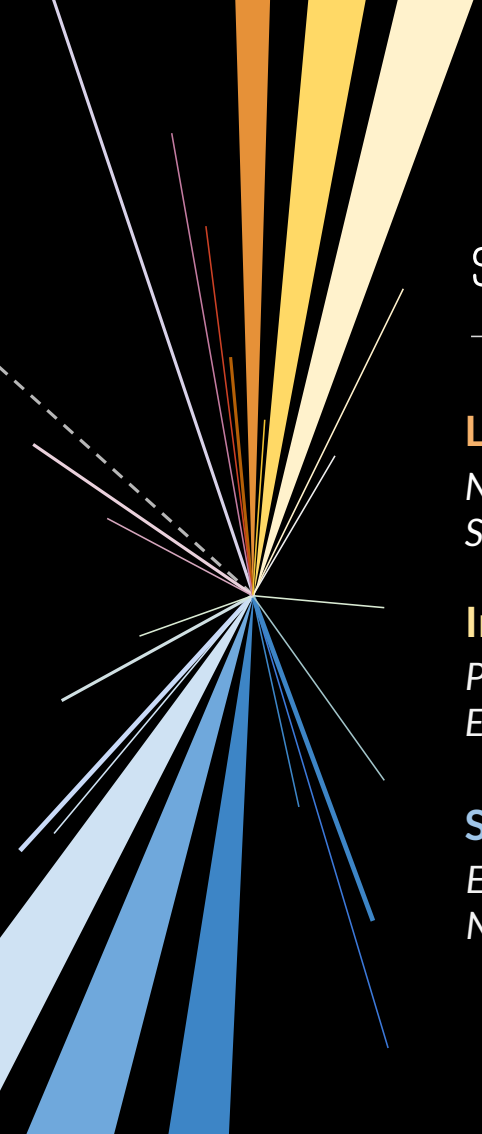
Exploit signal topology: trigger on multiple objects e.g. ***j80 mu4 met60***





CMS introduced such triggers for 2016 data-taking
[PAS-SUS-16-025]

* Experimental bottleneck: limited by e.g. data transfer bandwidth



SUMMARY

LHC: testing relativity + quantum theory

Need for new data era
SUSY remains key search lamppost

Interpretation: what do the searches mean?

Phenomenological (realistic) 19-parameter MSSM
Explore distinct regions of sensitivity

Soft physics: experimental challenges

Exploit luminosity for tough rare+soft SUSY
New detector triggers needed

EXTRAS

Spins of massless particles allowed by*

RELATIVITY & QUANTUM THEORY

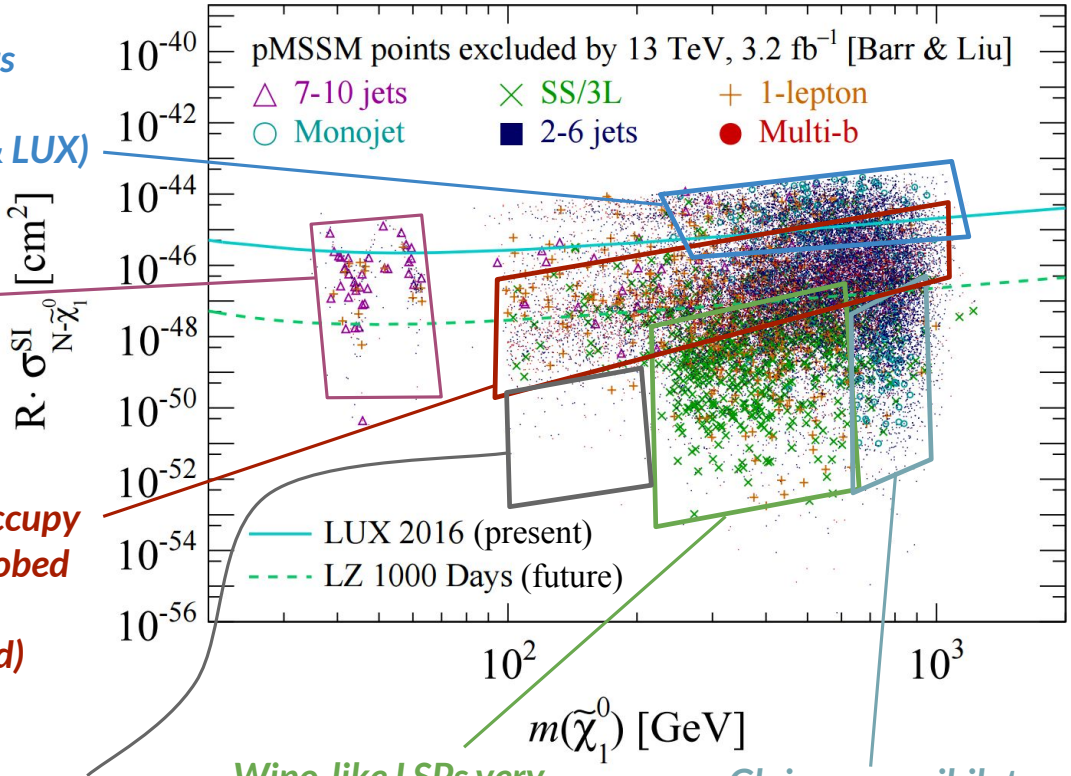
Weinberg 1964, Grisaru & Pendleton 1977

Higgs et al. **Matter** **Gauge bosons** **[Unseen]** **Gravity**

Spacetime symmetries & unitarity
fix sub-Planckian interactions to be those of the Standard Model & General Relativity

* Wigner's 'continuous-spin particles' also allowed Schuster & Toro arXiv:1302.1198

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)

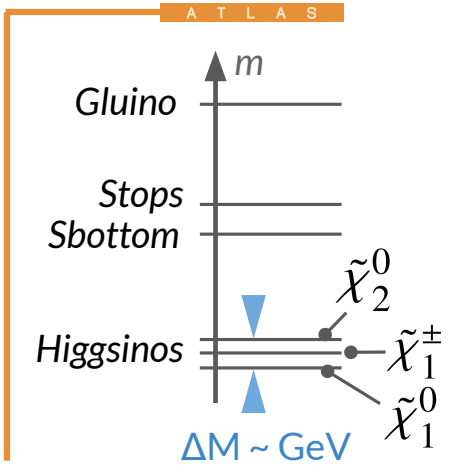
Higgsino-like LSPs occupy region marginally probed by direct detection (e.g. Multi-b favoured)

Region depleted by Run 1 disappearing track wino search

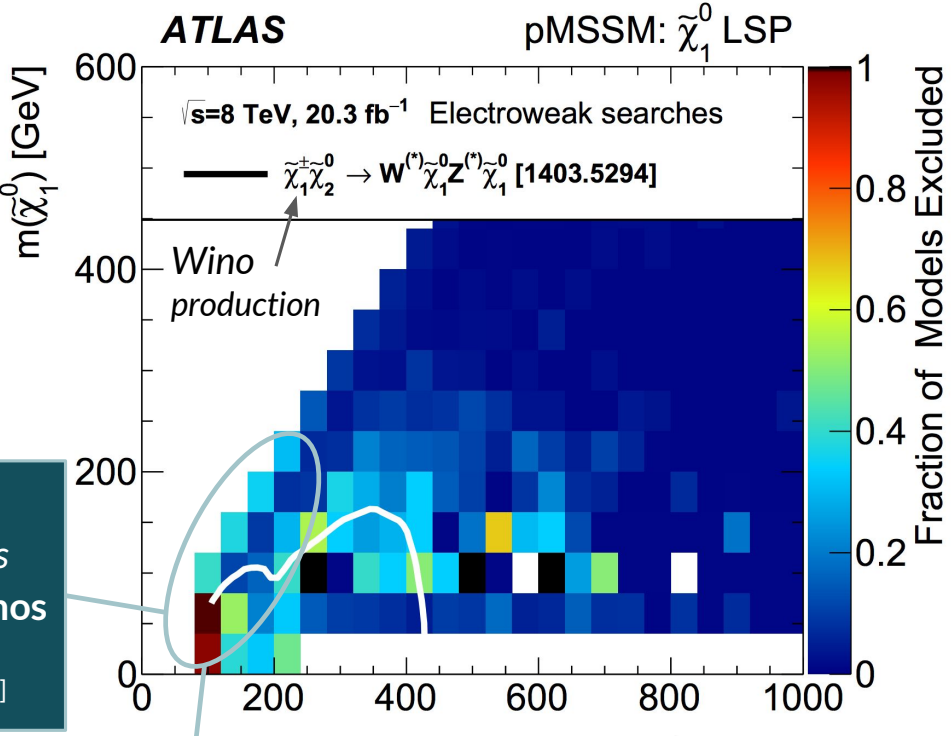
Wino-like LSPs very challenging for direct detection (SS/3L)

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

Signature can also illuminate Higgsinos



arXiv:1508.06608



Naturalness lamppost turning to tough Higgsinos

Rare: ~4x smaller σ vs Winos

Soft: ΔM ~ 5 → 50 GeV

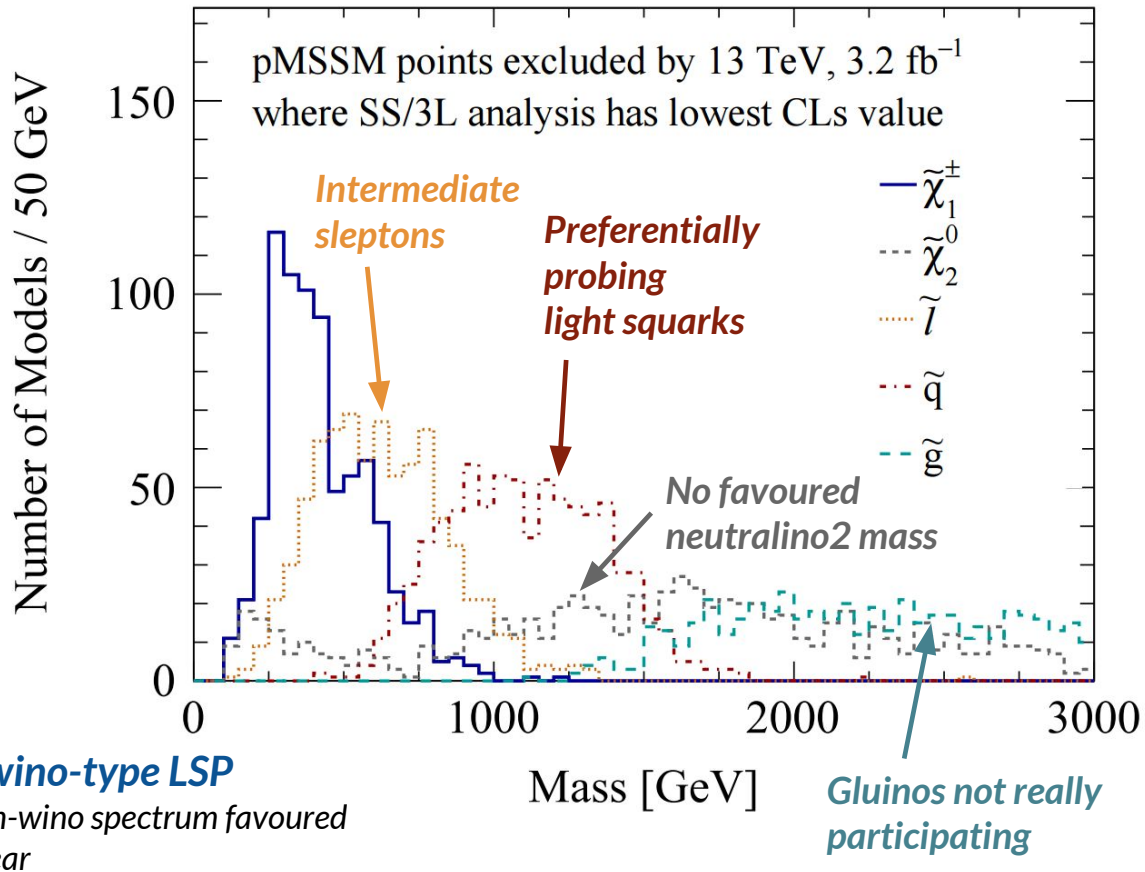
[arXiv:1110.6926, arXiv:1401.1235]

LEP2 *m*(chargino) ~ 103 GeV remains best Higgsino lower limit

40% exclusion along diagonal in pMSSM plane due to excluded wino-LSP

See backup 18 for Higgsino cross-sections, 30-31 for hep-ph studies

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



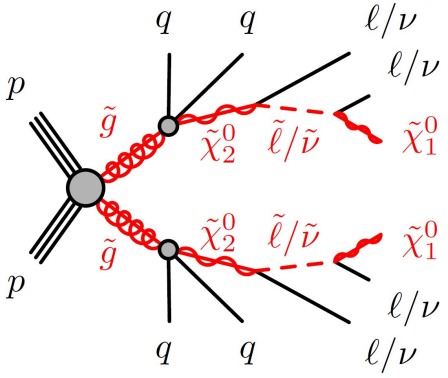
Almost all wino-type LSP

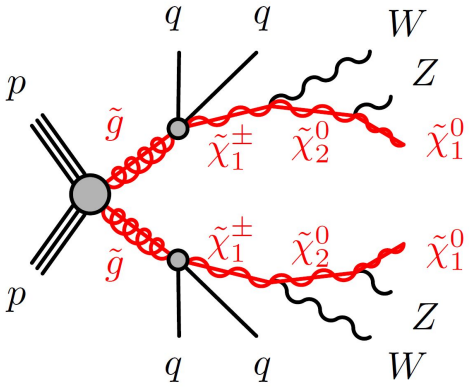
Squark-slepton-wino spectrum favoured (winos have near mass-degenerate chargino-LSP)

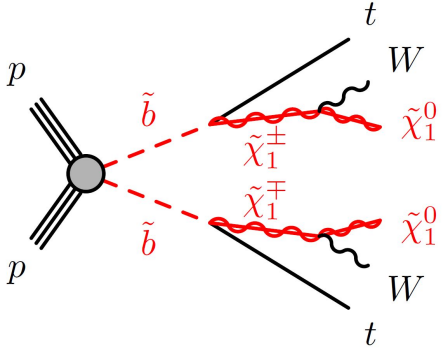
Simplified models considered by ATLAS SS/3L

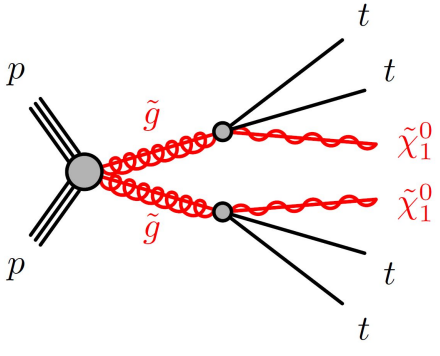
One signal region per simplified model

ATLAS SS/3L Paper [arXiv:1602.09058]



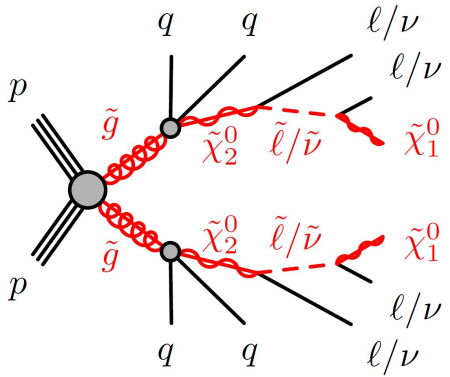




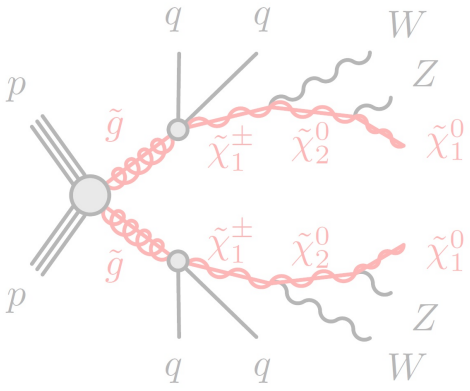


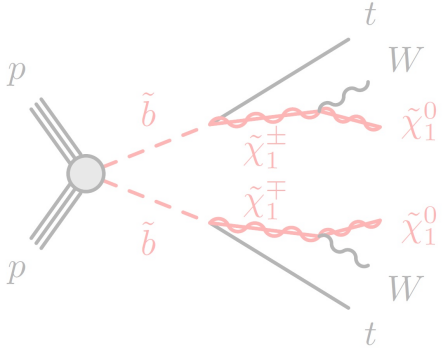
pMSSM points where SS/3L is most sensitive

Almost all probed by signal region targeting this model

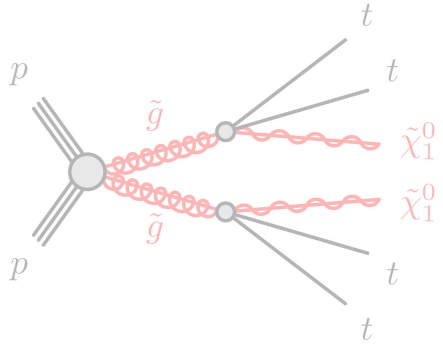


'2-step' also used by 0L 7-10 jets analysis

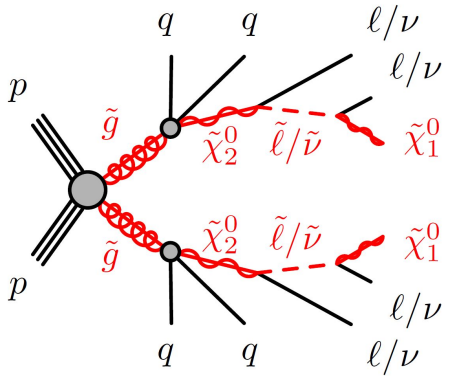


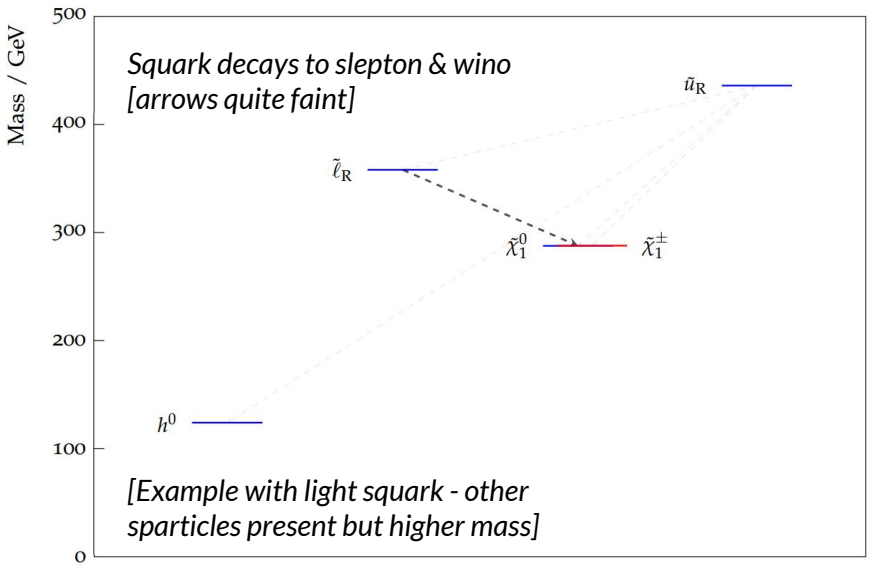


'Gtt' also used by Multi-b analysis



Interesting simplified models → pMSSM mapping





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

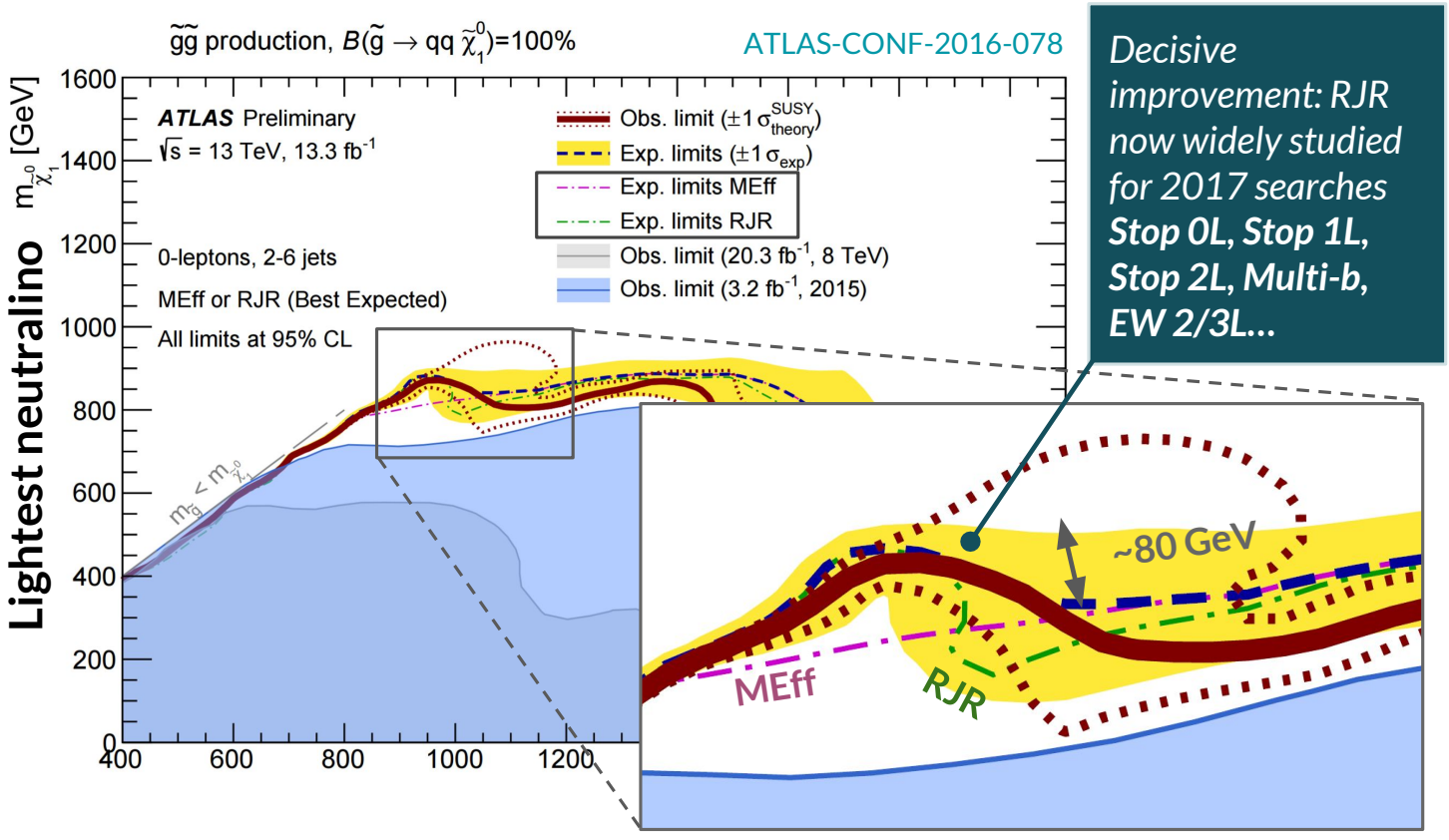
- ***pMSSM scenario different but not far off***

  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

Result: RJR improves squished sensitivity by ~80 GeV

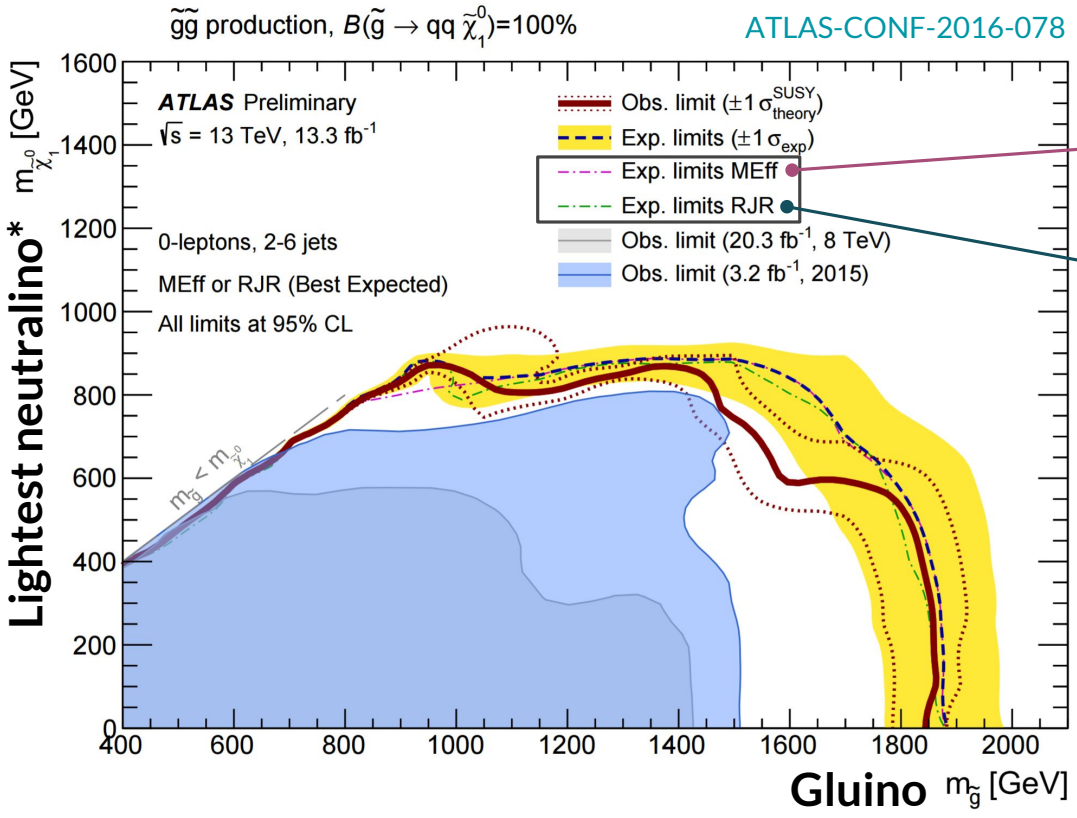


Decisive improvement: RJR now widely studied for 2017 searches ***Stop 0L, Stop 1L, Stop 2L, Multi-b, EW 2/3L…***

RJR used for 1st time in ICHEP 0L 2-6 jets search

See backup 22 for ICHEP 2016 stop limits

Innovation: recursive jigsaw reconstruction (RJR)



Classic analysis using m(effective) = proxy for SUSY mass scale

New standalone proof-of-concept analysis using RJR

See backup 19 for other gluino scenarios

See backup 20-21 for squark limits

RJR used for 1st time in ICHEP 0L 2-6 jets search

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*