Searches for electroweak supersymmetry: *highlights, coverage and limitations*

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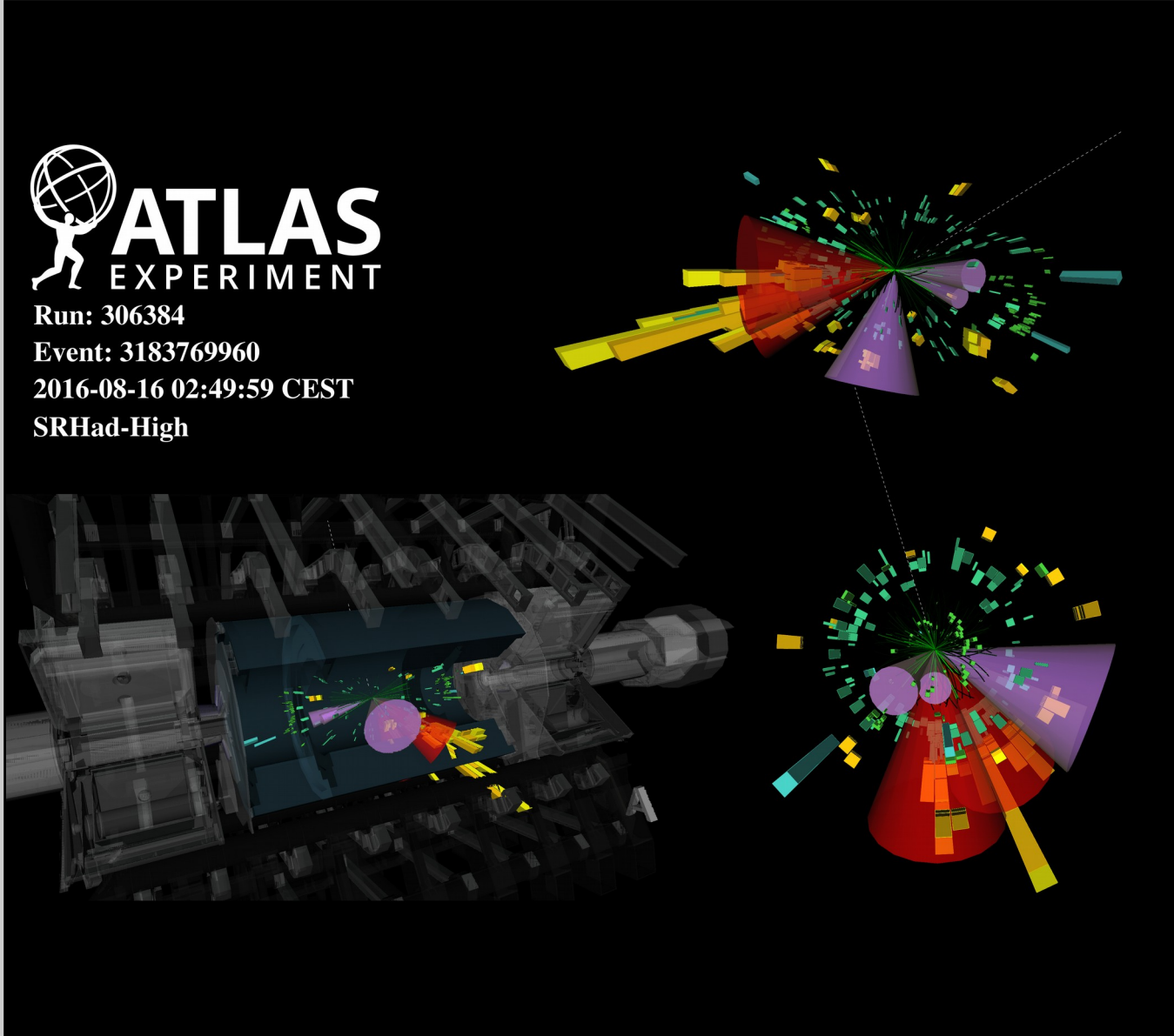
DPG Frühjahrstagung 2021

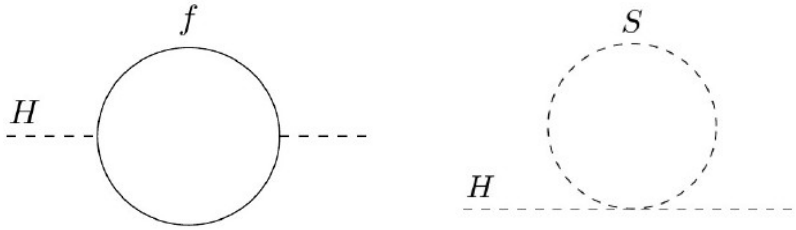


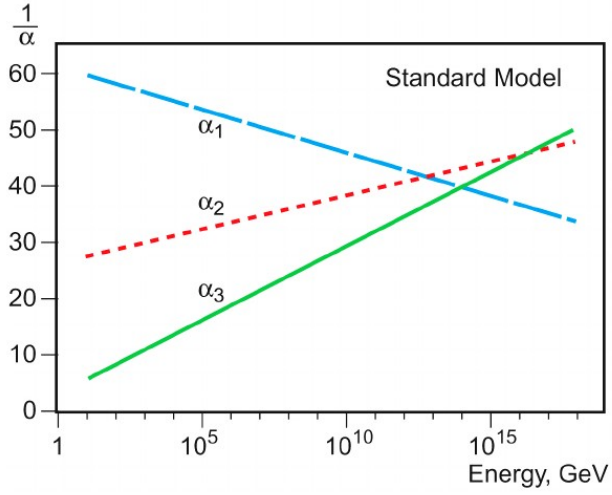
Why to search for physics beyond the Standard Model (SM)?

No cold dark matter candidate.

[https://chandra.harvard.edu/photo/2006/1e0657/more.html]

Higgs mass not stabilized → hierarchy problem.





No unification of inverse gauge couplings.

+ many more…

One solution: Supersymmetry (SUSY)

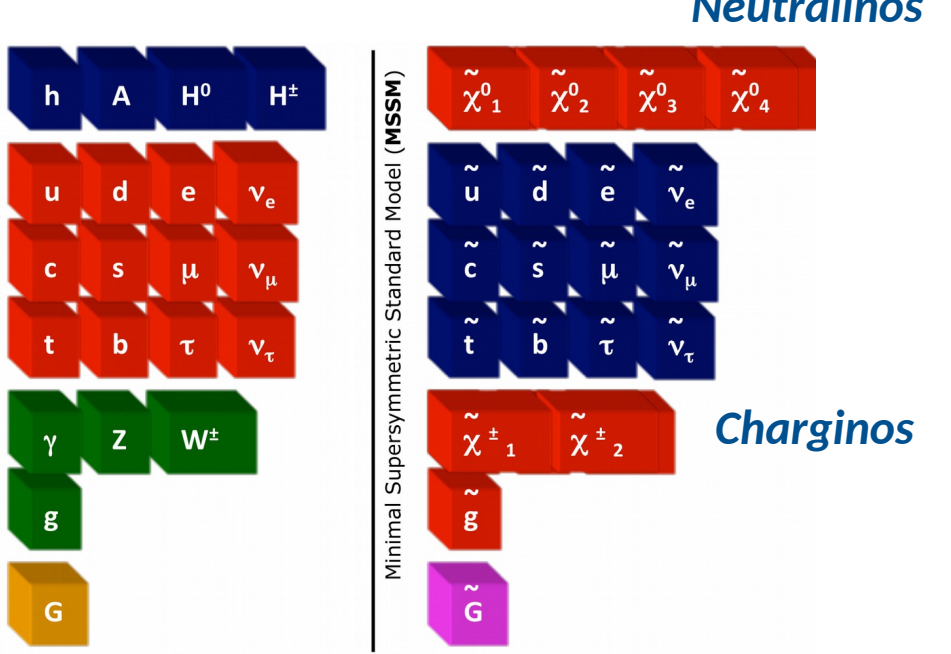
- Symmetry between fermions and bosons
- Supersymmetric partner particles to every Standard Model particle

→ *Roughly doubling of number of particles wrt Standard Model in the **M**inimal **S**upersymmetric **S**tandard **M**odel (MSSM).*

Extended Higgs sector necessary.

Lightest supersymmetric particle (LSP) stable in R-parity conserving SUSY theories.

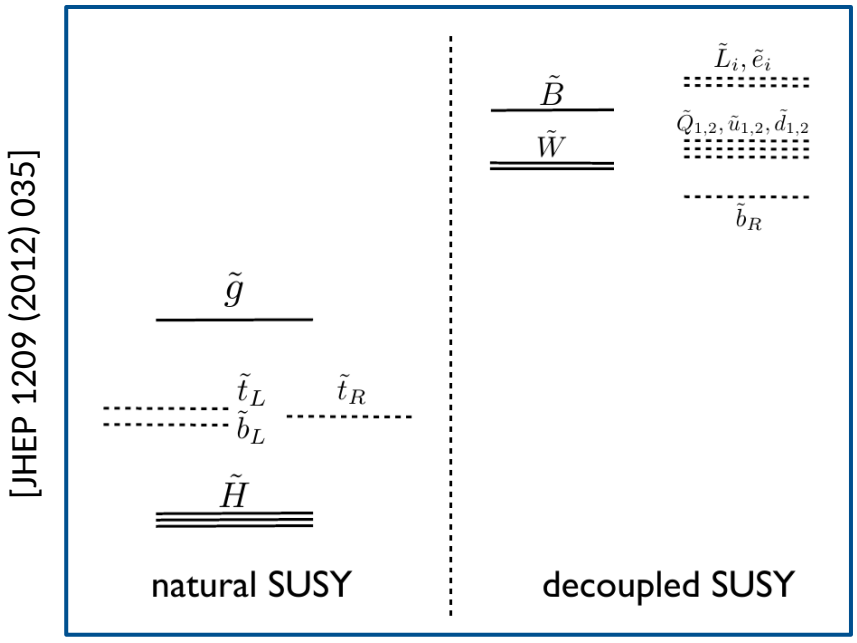
Possible dark matter candidates, Higgs boson mass stabilized, possible unification of inverse gauge couplings,…



Charginos/neutralinos: mixing of supersymmetric partners of Higgs and electroweak bosons → depending on composition **binos, winos, higgsinos**

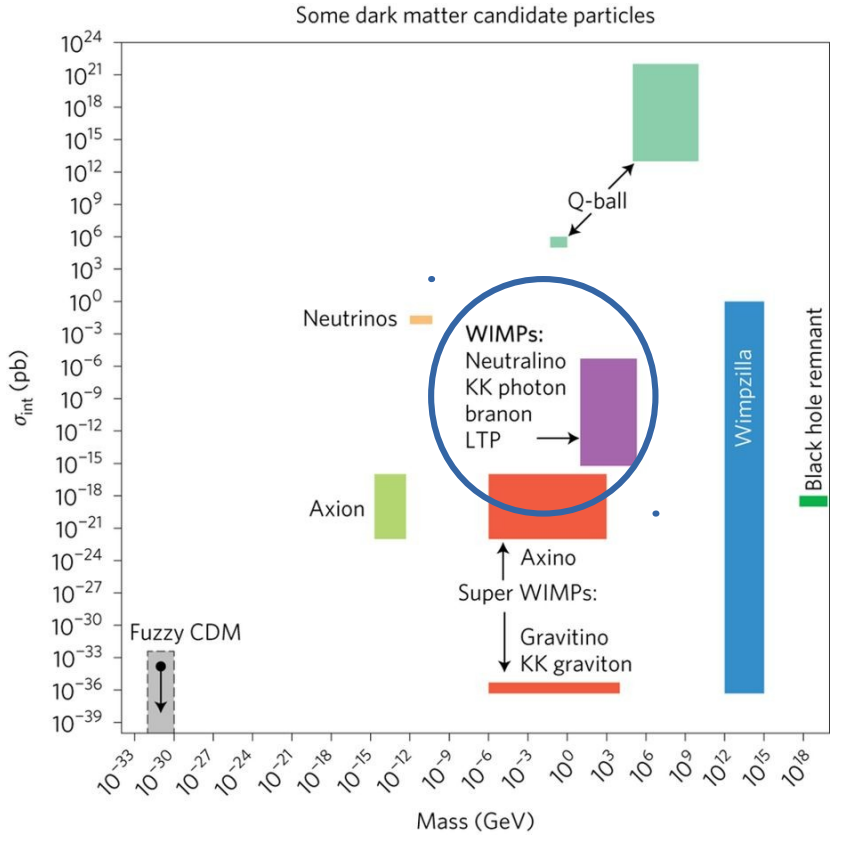
Motivations to search for (light) charginos and neutralinos

Natural SUSY



Light higgsinos motivated by naturalness arguments, as the higgsino mass parameter μ couples to the Higgs mass matrix at **tree level**.

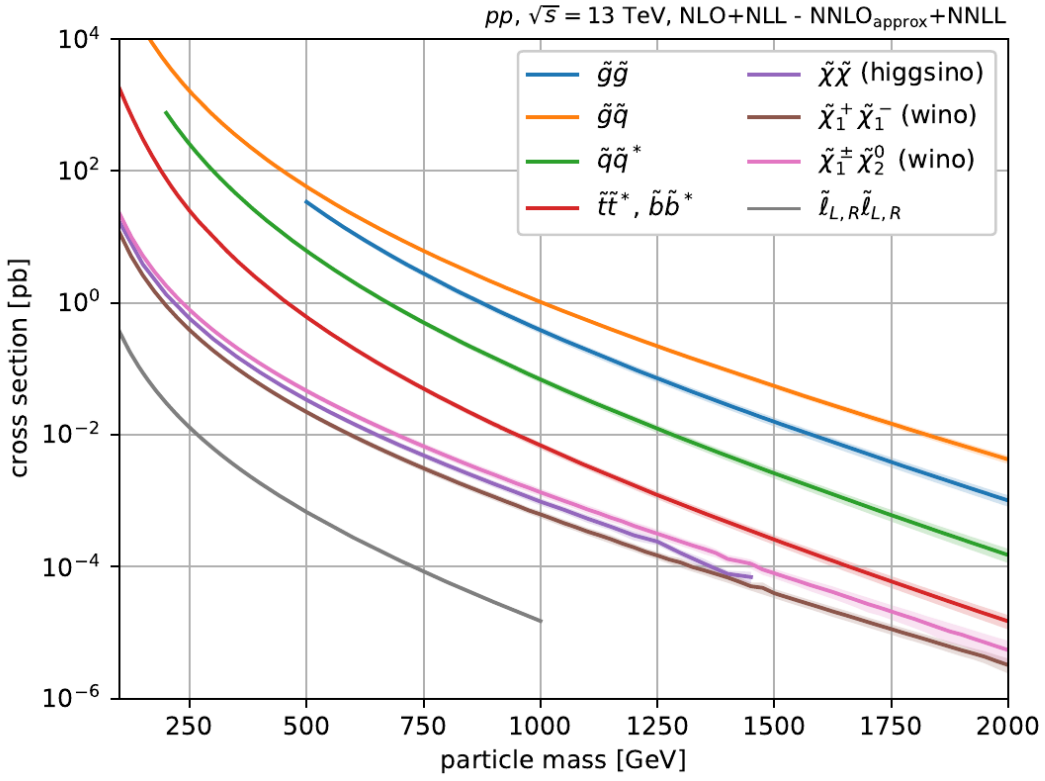
Lightest neutralino good Dark Matter candidate



[https://www.nature.com/articles/nphys4049/figures/1 from Nature Physics volume 13, pages 224–231 (2017)]

Cross sections

[https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections]



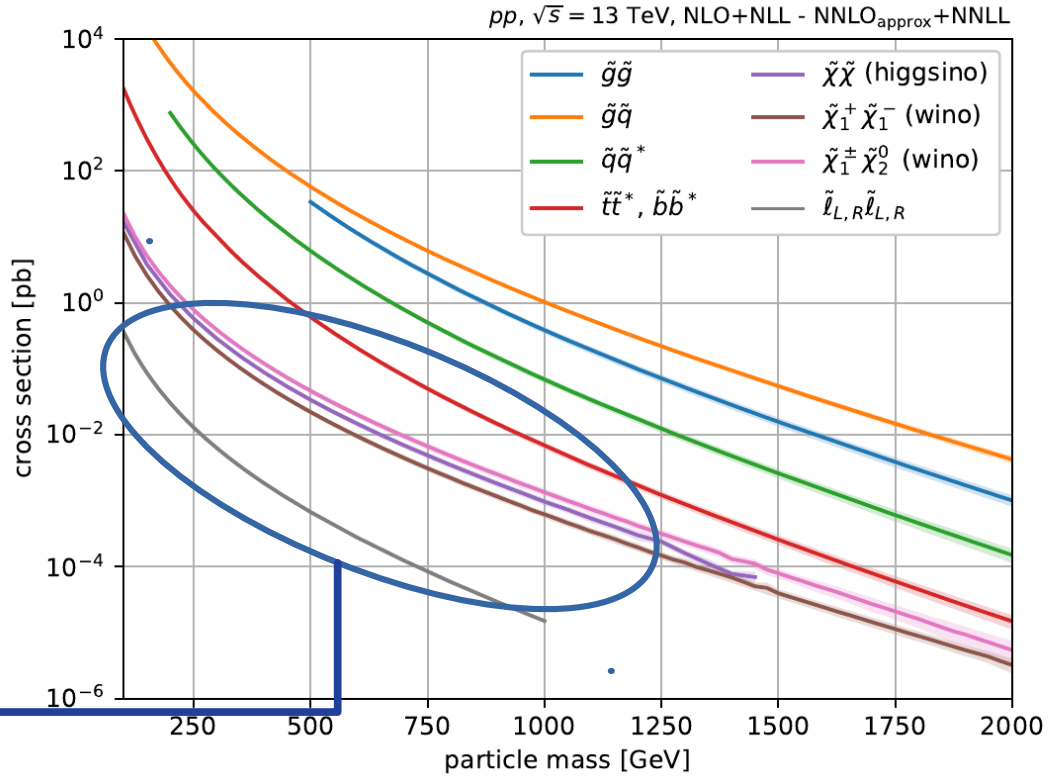
Cross sections

[https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections]

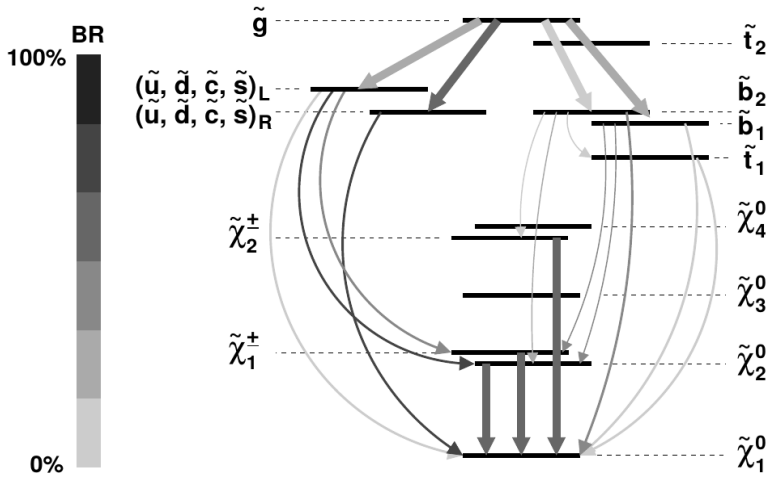
Electroweak SUSY searches

→ **Small cross sections**
– difficult analyses.

Profit from the full data statistics from the second LHC data-taking period.
Some searches are possible for the first time!



Supersymmetric models

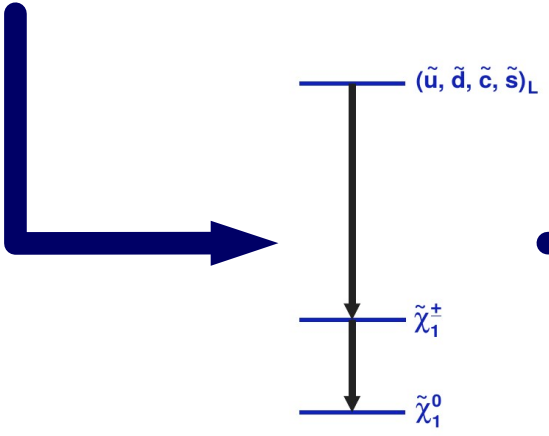


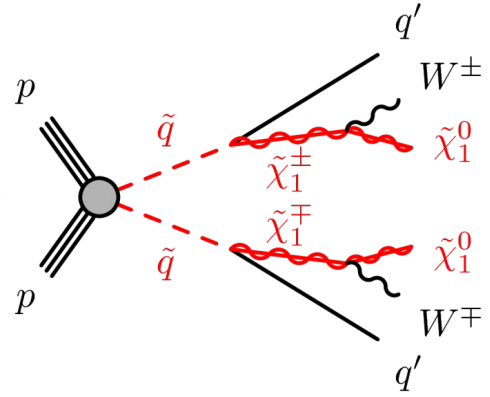
In case of the MSSM 124 free parameters!

We cannot deal with that many free parameters!*

but sometimes we at least look at certain well motivated reductions, like the **phenomenological **MSSM** with 19 parameters*

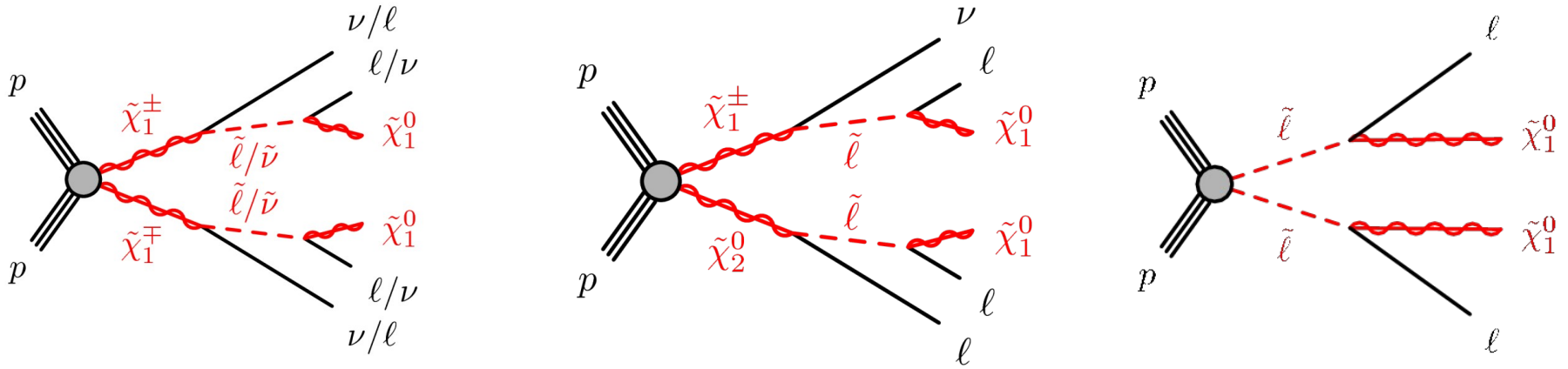
Usually only look at a specific decay chain





Simplified model

Searches for EWK SUSY



Decays of charginos/neutralinos/sleptons **often** studied in multi-lepton signatures + E_T^{miss}:

→ *2,3 or 4 leptons*,

→ *Rather clean signatures, with relatively low SM background.*

Very recently also more and more hadronic signatures studied and proving to be very powerful.

Distinguish signal from background

Use kinematic variables to discriminate signal from background.

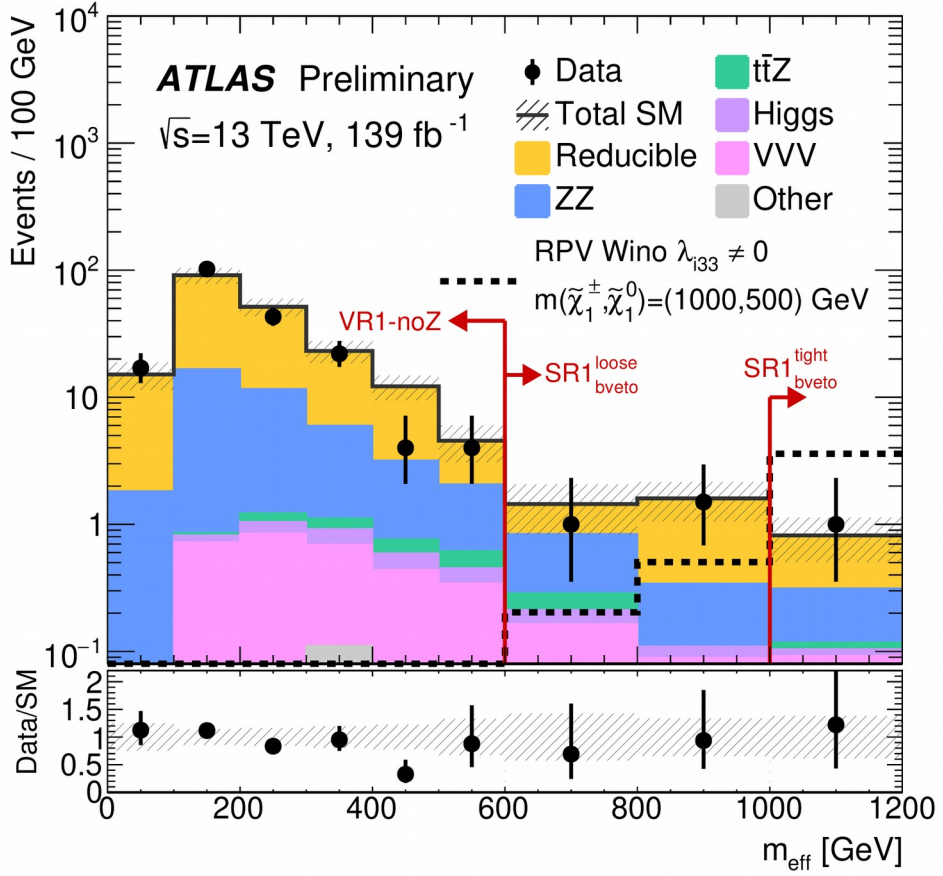
E.g. $m_{eff} = \sum p_T^{jets} + \sum p_T^{leptons} + E_T^{miss}$

→ *Correlated with mass of pair-produced SUSY particles and mass difference between heaviest and lightest SUSY particle in decay cascade.*

Analysis strategy:

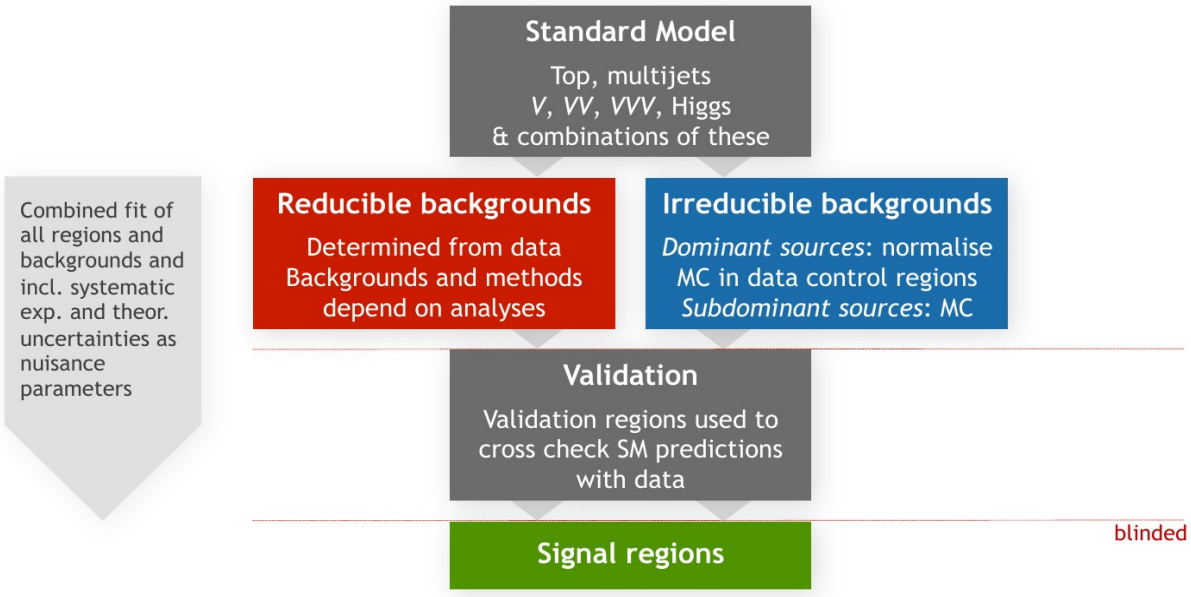
→ *Some analyses use simple combination of cuts on kinematic variables → ' cut-and-count', but most analyses perform a shape analysis (multi-bin fit) or use sophisticated techniques, e.g. machine learning.*

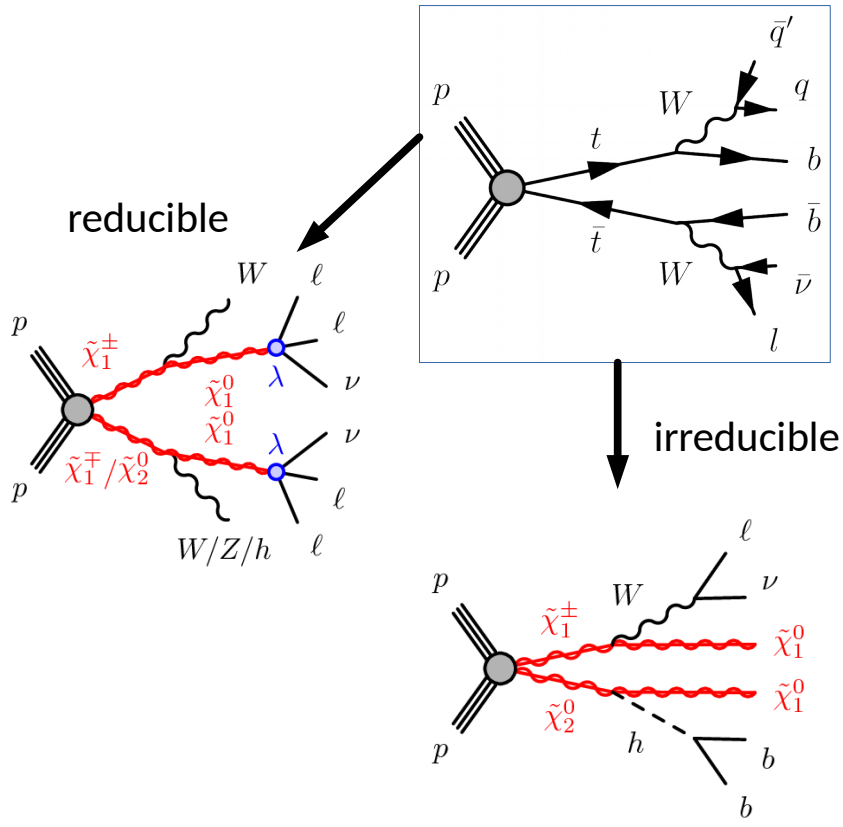
Comparison of methods very interesting!



Analysis flow – background estimation

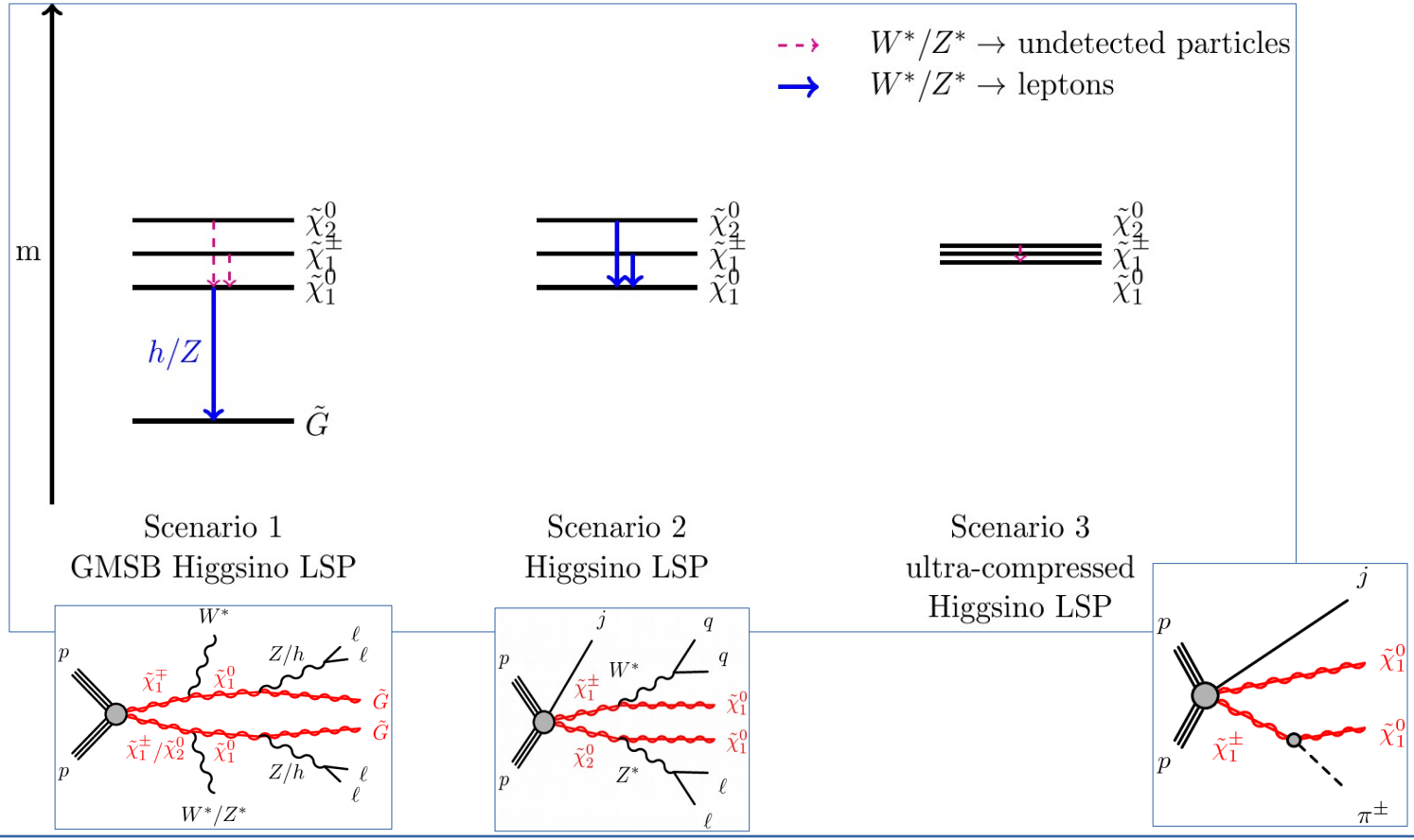
- **Reducible backgrounds:** backgrounds with another final state in comparison to the signal.
- **Irreducible backgrounds:** backgrounds show the same final state as the signal.





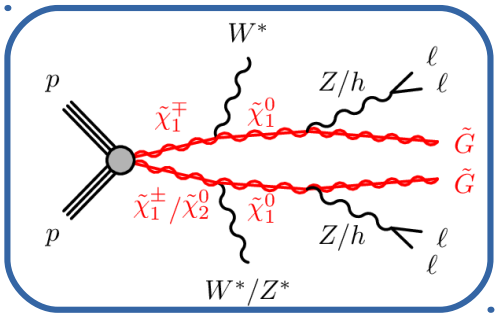
Searches for light higgsinos

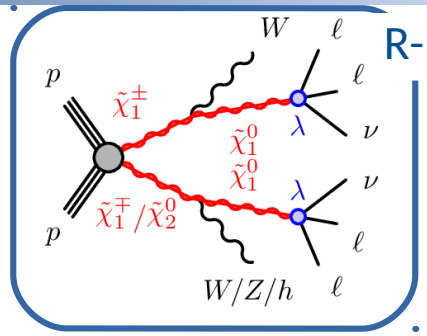
Naturalness arguments require light higgsinos with similar masses.



Search in final states with four or five leptons – e.g. addressing scenario 1

[ATLAS-CONF-2020-040]





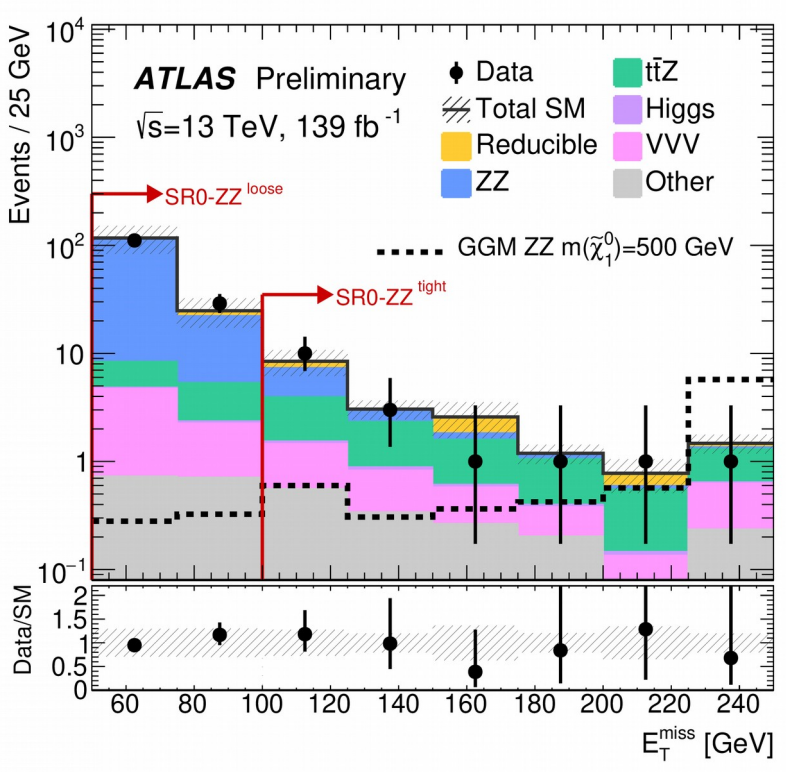
R-parity violation

R-parity conserving and violating SUSY decays may lead to lepton-enriched final states

→ Search for signatures with at least four or five isolated leptons (possibly taus)

→ Only low SM background: pair production of vector bosons, top processes in association with vector bosons …

Very general search: only imposing a few additional criteria: Z boson requirements or vetoes, selection of collision events enriched in E_T^{miss} or m_{eff}.

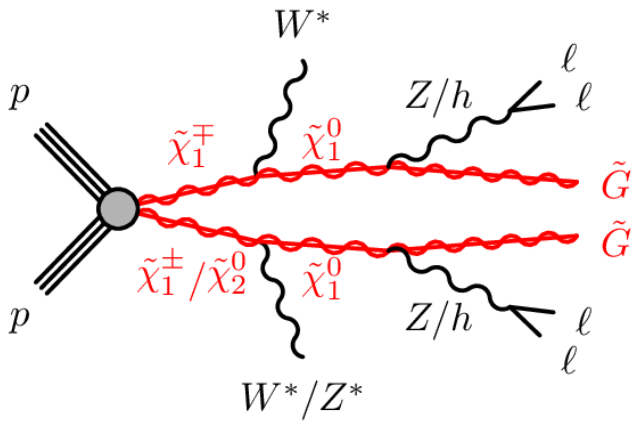


Interpretation in higgsino scenarios

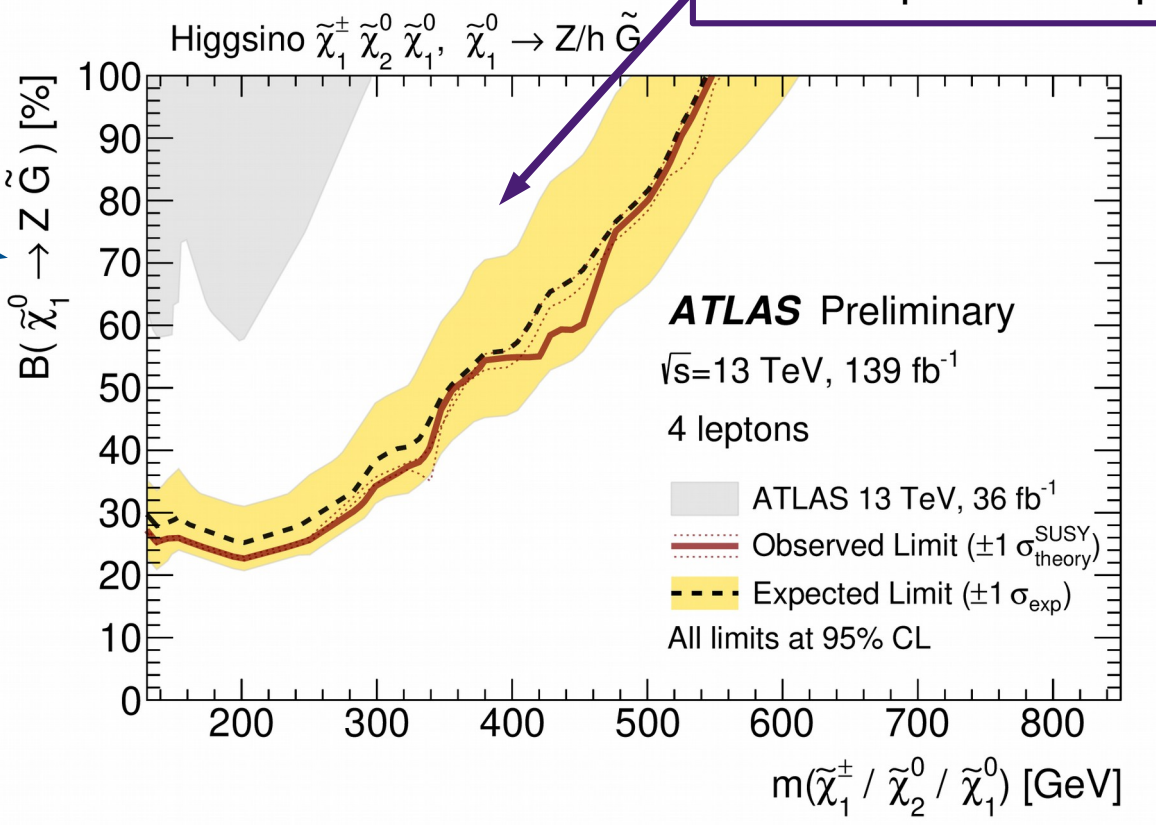
[ATLAS-CONF-2020-040]

No significant data excess wrt SM expectations observed.

Mainly sensitive to decays with Z bosons involved.

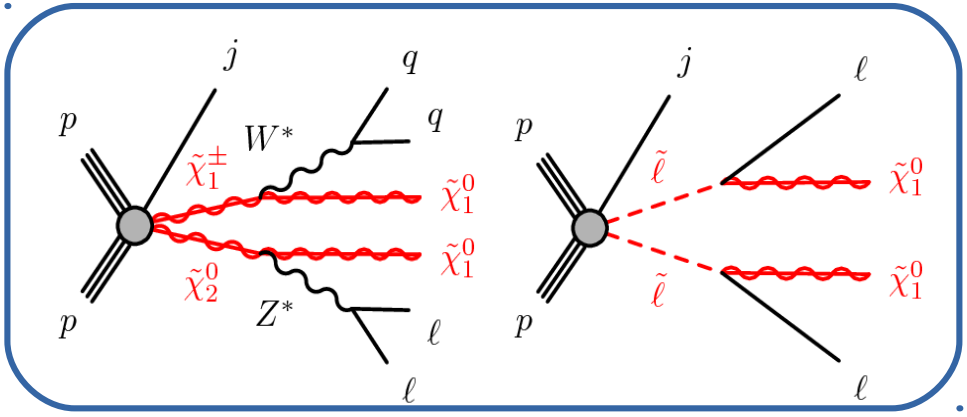


Excluded parameter space



Compressed electroweakinos/sleptons – scenario 2

[Phys. Rev. D 101 (2020) 052005]

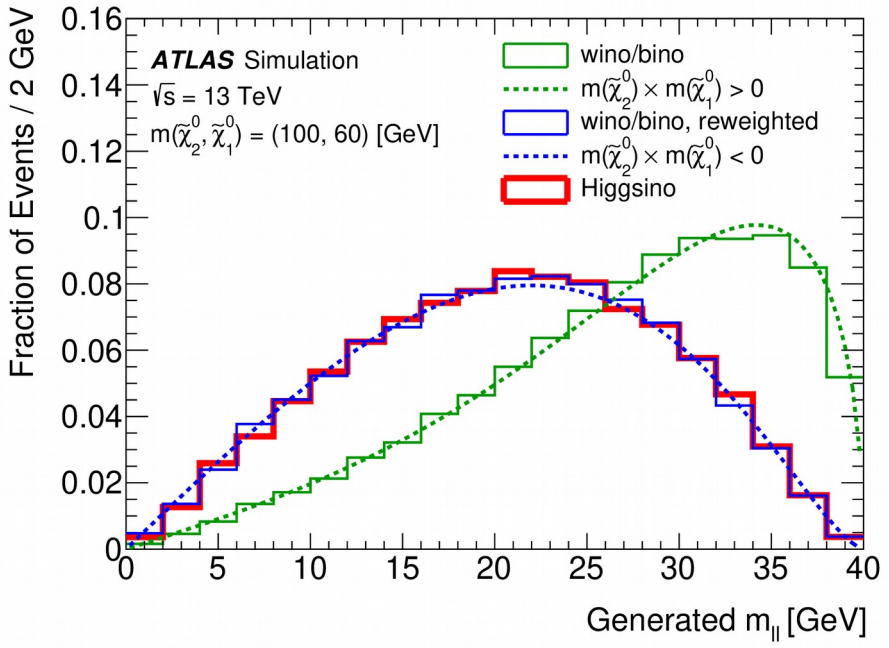


Search for higgsinos and wino/binos with very small mass splittings, or sleptons.

Reconstruction of very low-energetic leptons essential

→ *Electrons p_T > 4.5 GeV, muons p_T > 3 GeV, m_{ll} > 1 GeV*

→ *Possible due to significant progress in lepton reconstruction/identification*



Compressed higgsinos/sleptons

[Phys. Rev. D 101 (2020) 052005]

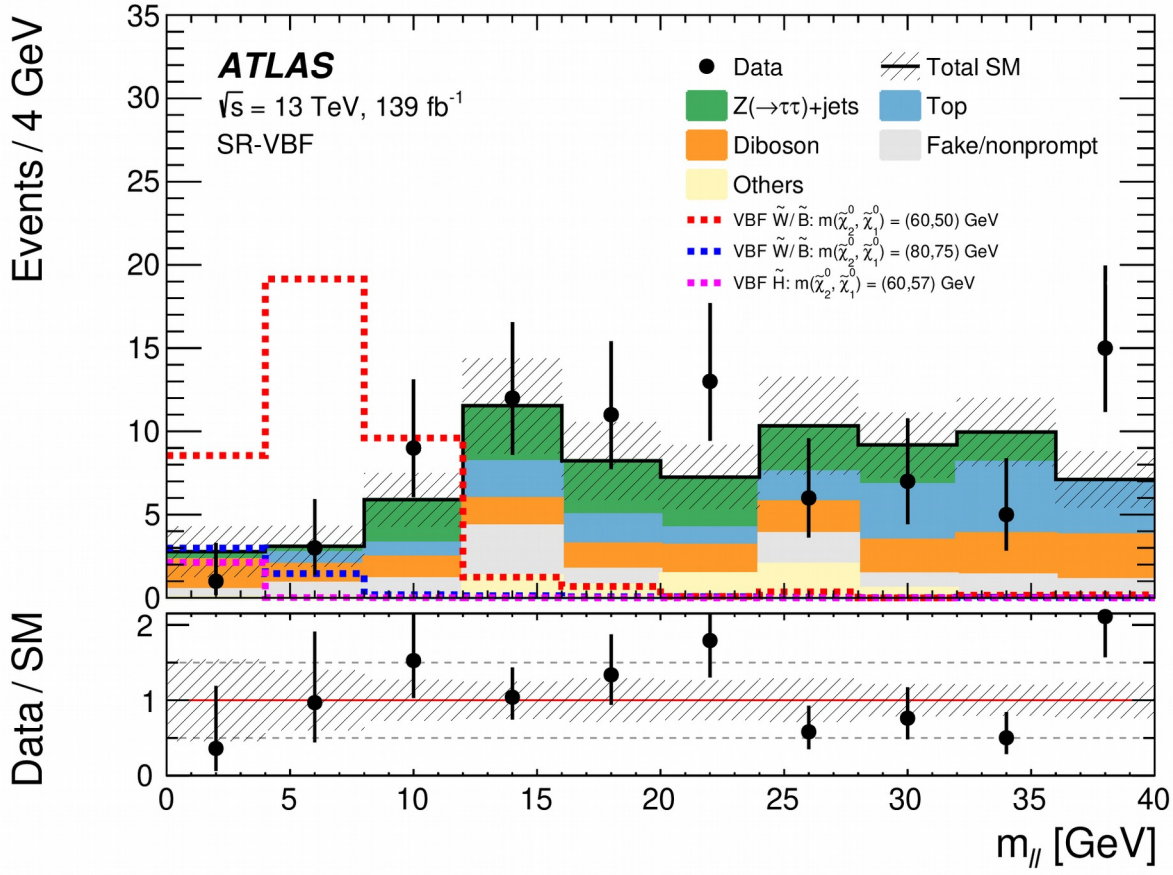
Four searches:

- Direct production of electroweakinos exploiting the presence of an ISR jet

  → *Requiring 2 leptons, or 1 lepton + an isolated track,*
- Production of electroweakinos through vector-boson-fusion with two additional jets.
- Direct production of sleptons using m_{T2}=

$$\min_{\mathbf{q}_T}\left[\max\left(m_T(\mathbf{p}_T^{\ell 1},\mathbf{q}_T), m_T(\mathbf{p}_T^{\ell 2},\mathbf{p}_T^{\text{miss}}-\mathbf{q}_T)\right)\right]$$

→ *Key is estimation of fake backgrounds!*



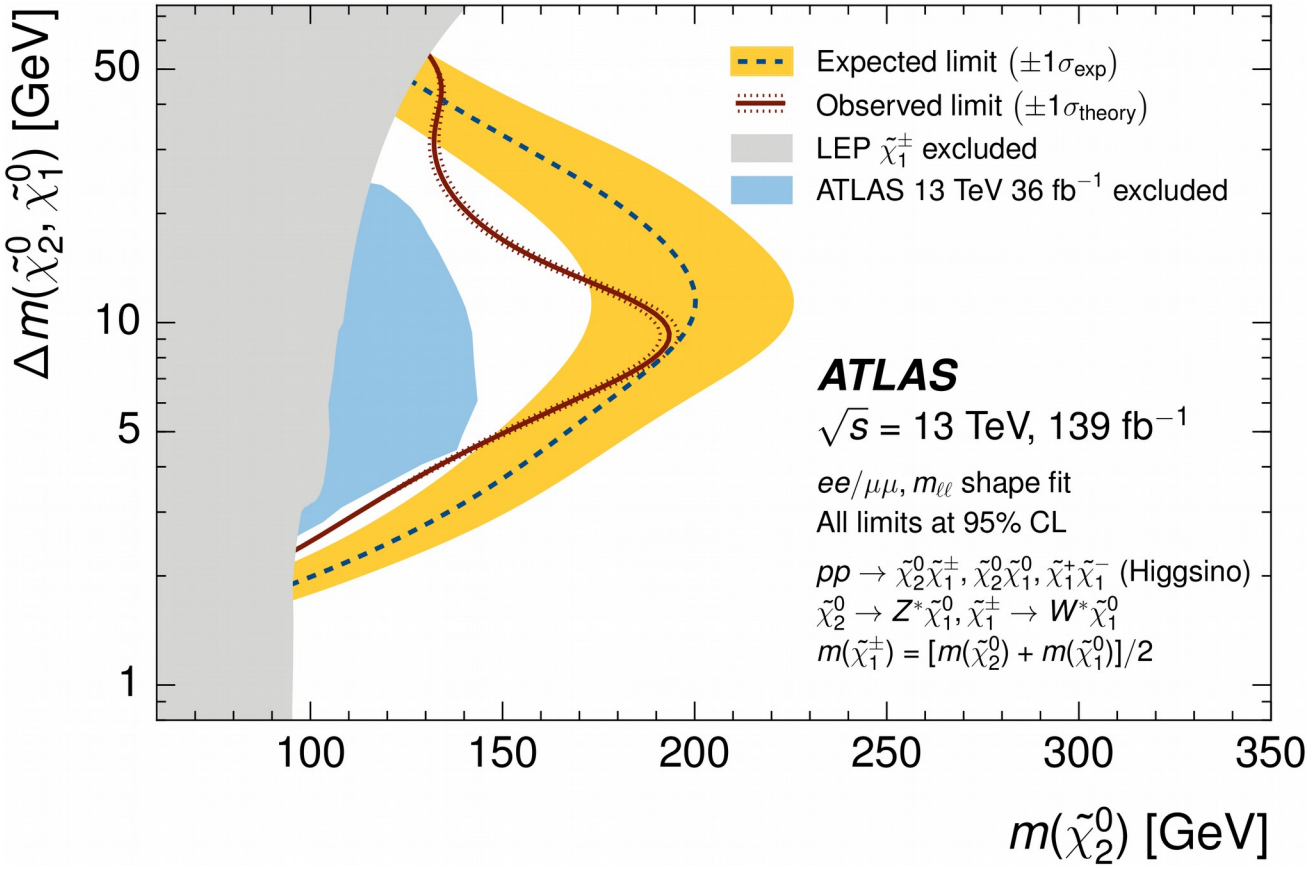
Compressed higgsinos/sleptons

[Phys. Rev. D 101 (2020) 052005]

No significant excess seen.

Exclusion limits e.g. for higgsinos up to 193 GeV for a mass splitting of 9.3 GeV.

Powerful exclusion limits through binning signal regions in m_{ll} and simultaneous fit of regions.



Disappearing tracks – scenario 3

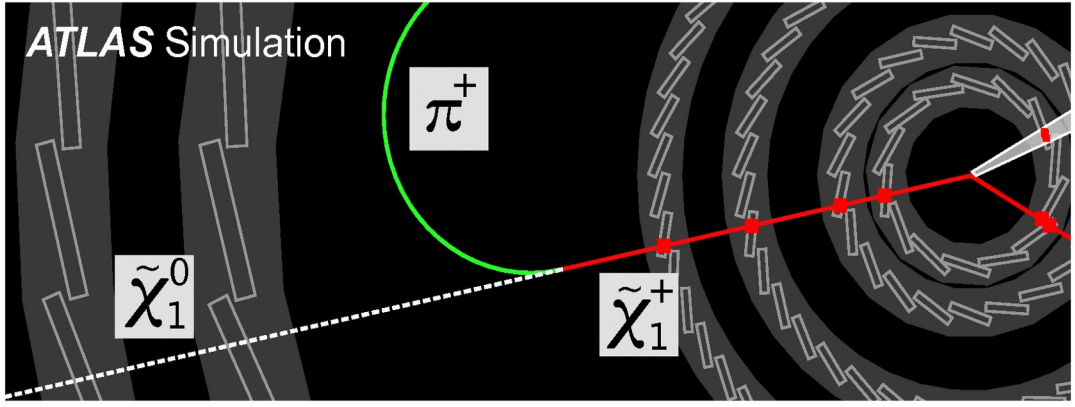
[JHEP 06 (2018) 022, ATL-PHYS-PUB-2017-019]

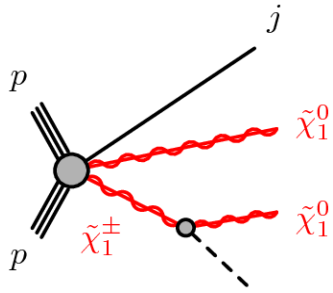
Long-lived chargino decaying to invisible + pion

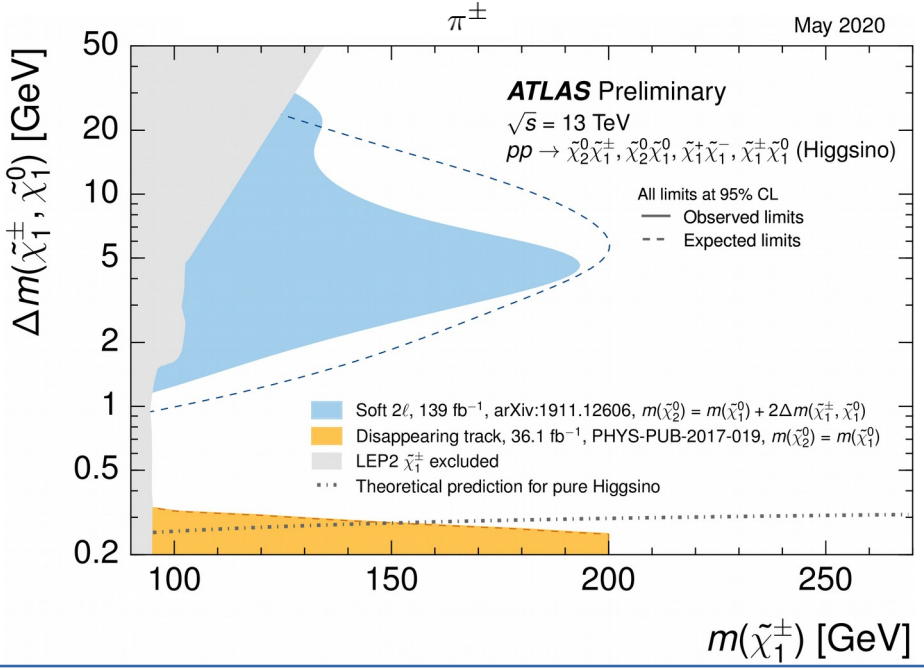
→ *Disappearing track*

Addition of IBL in LS1 allowed reconstruction of smaller minimal track lengths down to 12 cm

→ *Pixel-only tracklets*

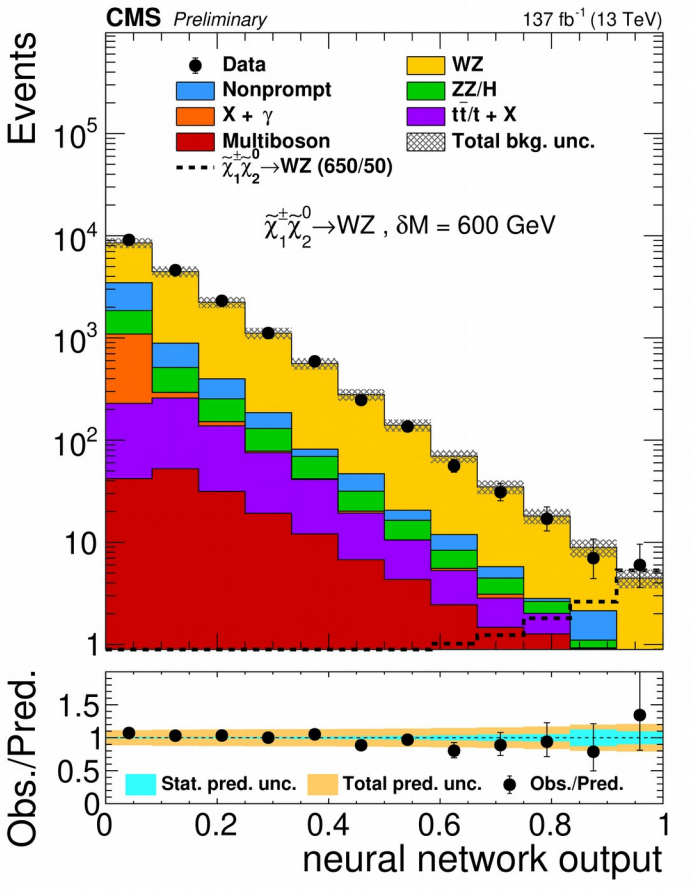


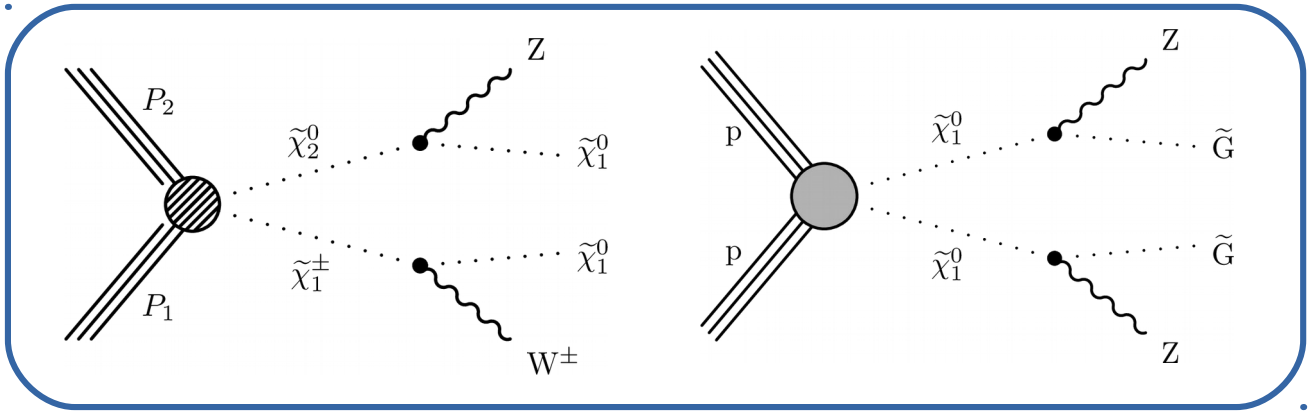




Searches for charginos and neutralinos in multi-lepton final states

[CMS-PAS-SUS-19-012]





Search for chargino/neutralino decays in different scenarios:

- Via **sleptons**, in case that sleptons lighter,
- Via emission of **Higgs, W, Z** boson if sleptons heavier.

Different search strategies, e.g.:

- In signatures with **two same-sign leptons**, if third lepton e.g. too low-energetic. *Good background suppression*
- If **three leptons** present, of which two forming a opposite-sign same-flavour pair: use of multiple parametric neural networks to suppress large SM backgrounds.

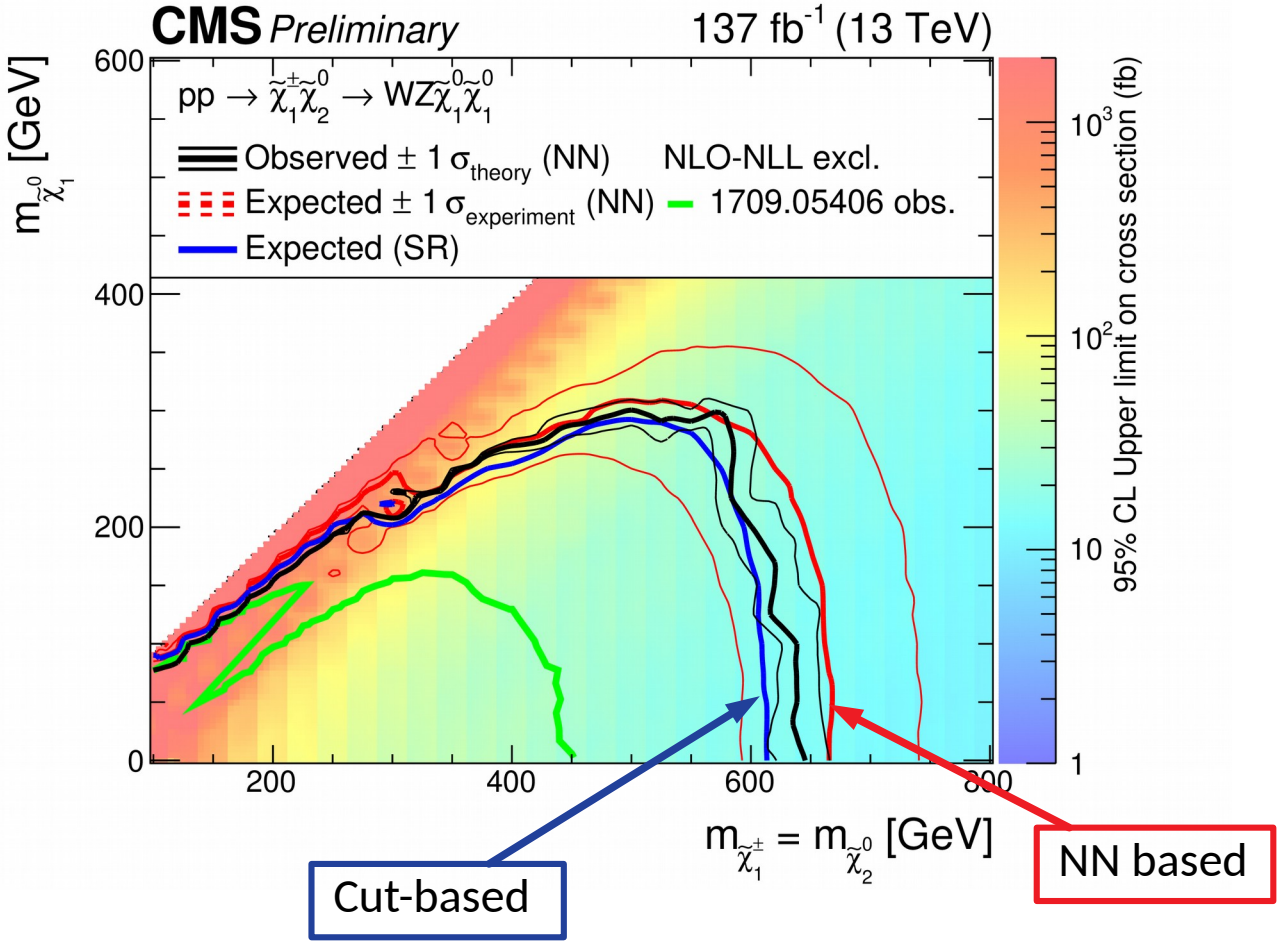
Searches for charginos and neutralinos in multi-lepton final states

[CMS-PAS-SUS-19-012]

No significant excess over SM expectations seen.

Same-sign lepton regions fitted together with 3-lepton regions.

Neural network strategy outperforms an alternative strategy using cut-based regions.



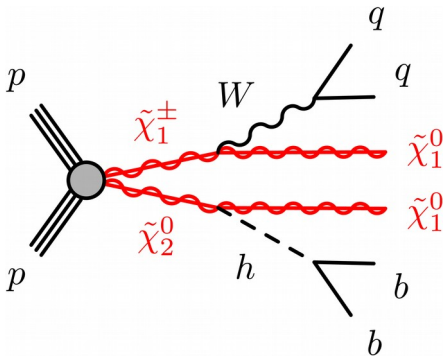
Searches for neutralinos/charginos with decays to a Higgs boson

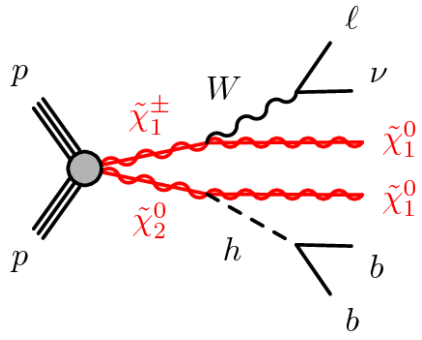
[Phys. Rev. D 100 (2019) 012006]

Often a Higgs boson is created in decays of neutralinos.

Discovering corresponding signatures would explicitly link Higgs bosons with supersymmetric particles.

Necessary for SUSY solving hierarchy problem!

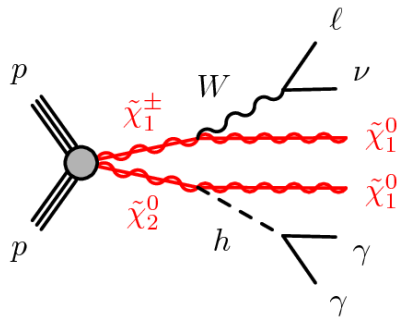


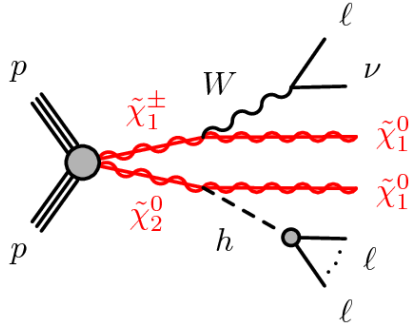


Different signatures depending on decay of Higgs:

- Hadronic (with $b\bar{b}$),
- 1 e/μ + $b\bar{b}$,
- Two same-sign leptons,
- 3 leptons,
- 1 e/μ + γγ

→ *Different searches*

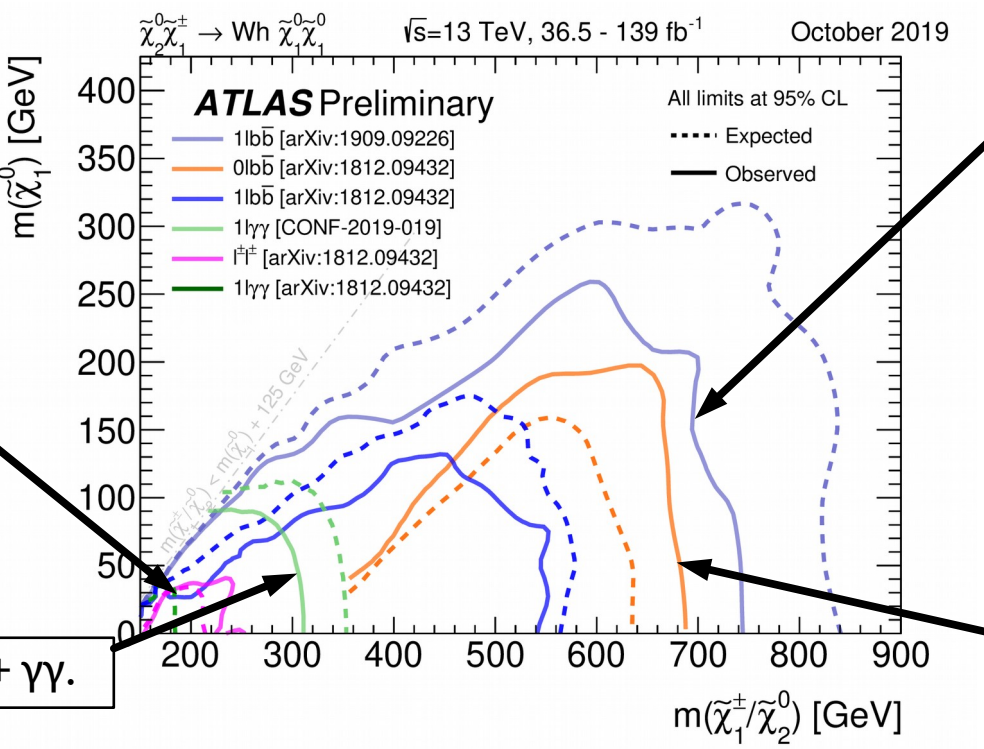




Searches for neutralinos/charginos with decays to a Higgs boson

[ATL-PHYS-PUB-2019-044]

Nice complementarity of the different searches:

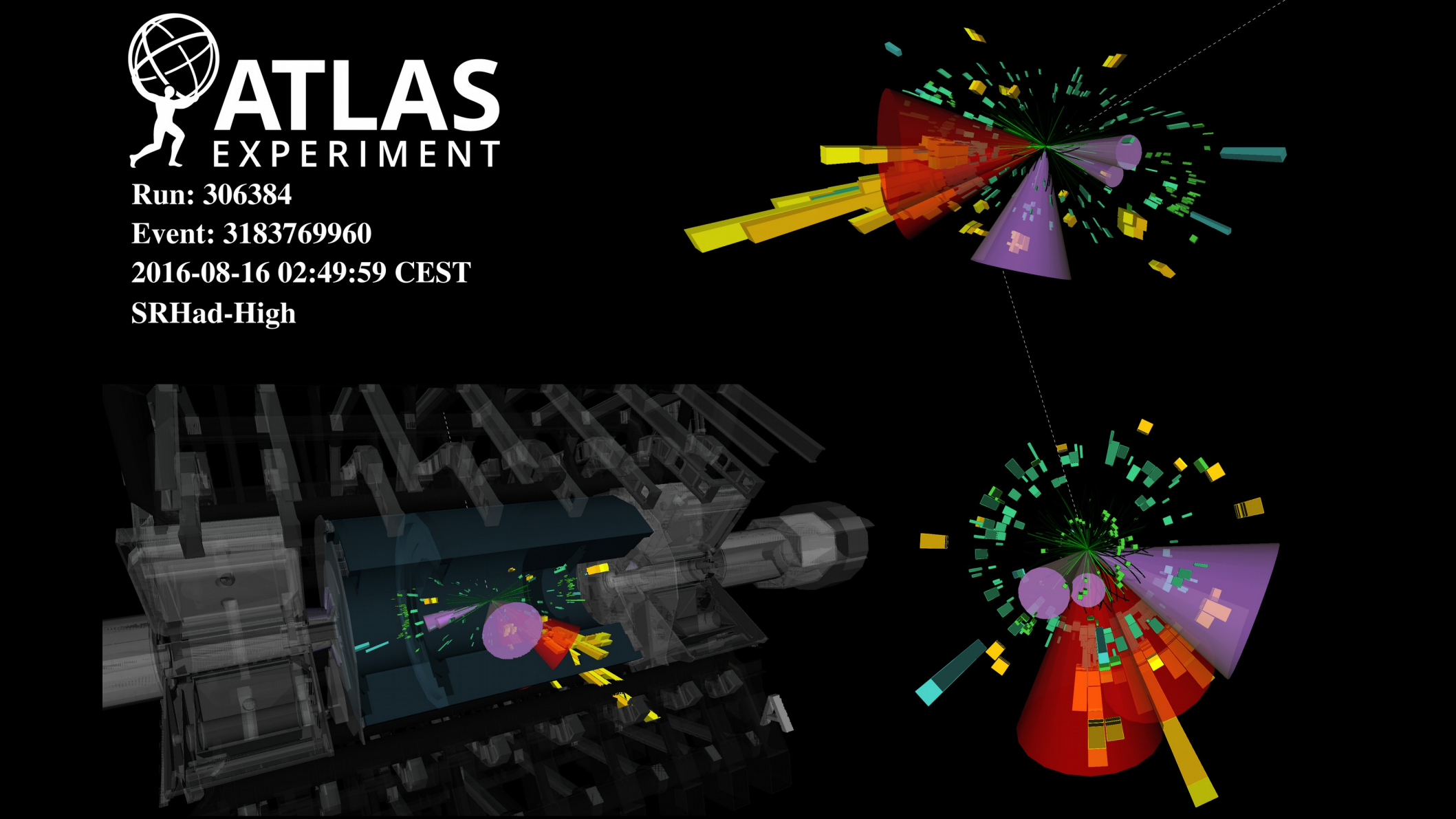


Same-sign analysis sensitive to lower masses and smaller mass splittings.

1 e/μ + bb̄ covers bulk of the plane. Strong limit since small uncertainties.

1 e/μ + γγ.

Hadronic analysis covers high neutralino/ chargino masses.


ATLAS
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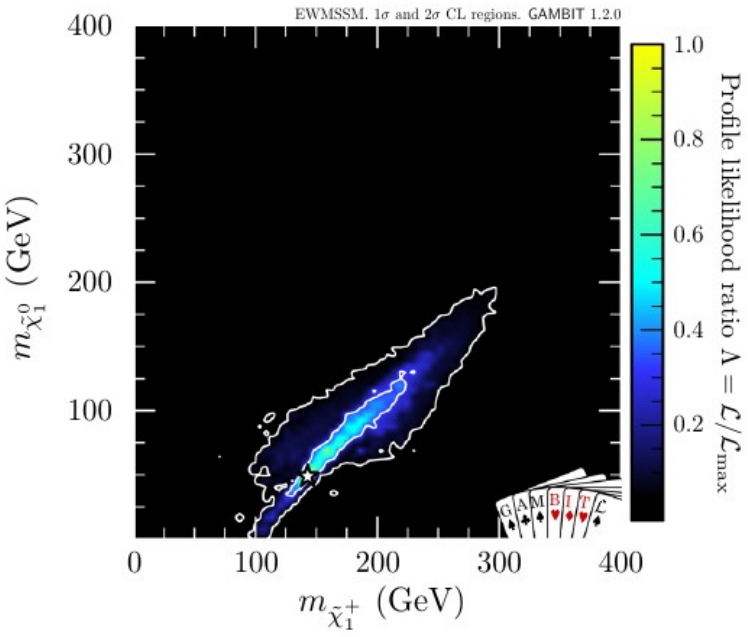
Loopholes? Analysis of electroweak searches by Gambit

[Eur.Phys.J. C79 (2019) no.5, 395]



Likelihood combination of various LEP, ATLAS and CMS searches for electroweakinos:

→ *Using best possible signal region in case of multi-bin signal regions where no information on correlations provided, else approximation of full likelihood of search.*

- $\tilde{\chi}_2^0\tilde{\chi}_3^0$ production, with e.g. $\tilde{\chi}_2^0 \to Z + \tilde{\chi}_1^0$, $\tilde{\chi}_3^0 \to W^- + \tilde{\chi}_1^+ \to W^- + W^+ + \tilde{\chi}_1^0$
- $\tilde{\chi}_2^\pm\tilde{\chi}_2^\mp$ production, with e.g. $\tilde{\chi}_2^\pm \to W^\pm + \tilde{\chi}_2^0 \to W^\pm + Z + \tilde{\chi}_1^0$
- $\tilde{\chi}_2^\pm\tilde{\chi}_3^0$ production, with e.g. $\tilde{\chi}_2^\pm \to W^\pm + \tilde{\chi}_1^0$, $\tilde{\chi}_3^0 \to Z + \tilde{\chi}_2^0 \to Z + Z + \tilde{\chi}_1^0$
- $\tilde{\chi}_2^\pm\tilde{\chi}_3^0$ production, with e.g. $\tilde{\chi}_2^\pm \to W^\pm + \tilde{\chi}_2^0 \to W^\pm + Z + \tilde{\chi}_1^0$, $\tilde{\chi}_3^0 \to W^- + \tilde{\chi}_1^+ \to W^- + W^+ + \tilde{\chi}_1^0$
- $\tilde{\chi}_2^\pm\tilde{\chi}_4^0$ production, with e.g. $\tilde{\chi}_2^\pm \to W^\pm + \tilde{\chi}_2^0 \to W^\pm + Z + \tilde{\chi}_1^0$, $\tilde{\chi}_4^0 \to Z + \tilde{\chi}_1^0$
- $\tilde{\chi}_2^\pm\tilde{\chi}_2^0$ production, with e.g. $\tilde{\chi}_2^\pm \to h + \tilde{\chi}_1^\pm \to h + W^\pm + \tilde{\chi}_1^0$, $\tilde{\chi}_2^0 \to Z + \tilde{\chi}_1^0$
- $\tilde{\chi}_1^\pm\tilde{\chi}_3^0$ production, with e.g. $\tilde{\chi}_1^\pm \to W^\pm + \tilde{\chi}_1^0$, $\tilde{\chi}_3^0 \to W^- + \tilde{\chi}_1^+ \to W^+ + W^- + \tilde{\chi}_1^0$
- $\tilde{\chi}_2^\pm\tilde{\chi}_4^0$ production, with e.g. $\tilde{\chi}_2^\pm \to Z + \tilde{\chi}_1^\pm \to Z + W^\pm + \tilde{\chi}_1^0$, $\tilde{\chi}_4^0 \to h + \tilde{\chi}_2^0 \to h + Z + \tilde{\chi}_1^0$

Identified shortcomings of current searches:
Current searches not sensitive to longer decay chains.

Caveats: not the full complexity of the searches included, no searches of the full Run-2 dataset.

New tools for enabling reinterpretations of complex analyses

Analyses typically focus on a small number of benchmark simplified models, but are typically more general (→ *other DM searches*, *leptoquarks*, *other than the target models)*

New tools/material for re-interpretation of the analyses available!

Preservation of the full analysis software: can rerun the analysis with a different signal assumption at a later point

RECAST for ATLAS

Full likelihood

pyhf
∂ifferentiable
ℒikelihoods

Sometimes simplifications possible and required

Simplified likelihoods

Analysis flow → pseudo-code

SimpleAnalysis

Where to go from here?

- Light electroweakinos motivated by **naturalness** arguments; lightest neutralino is a good candidate for **Dark Matter**.
- Very **comprehensive search program**, using very sophisticated methods, benefiting from improved object reconstruction and identification and large data statistics.

- So far, most interpretations in simplified models.

- We are just beginning to understand the impact of our searches on more complex supersymmetric models, such as the **p**henomenological **MSSM**.
- Reinterpretation tools are being developed to perform these studies.
- In particular starting to release the **full likelihoods of searches**

  → Big step forward to **open science**.

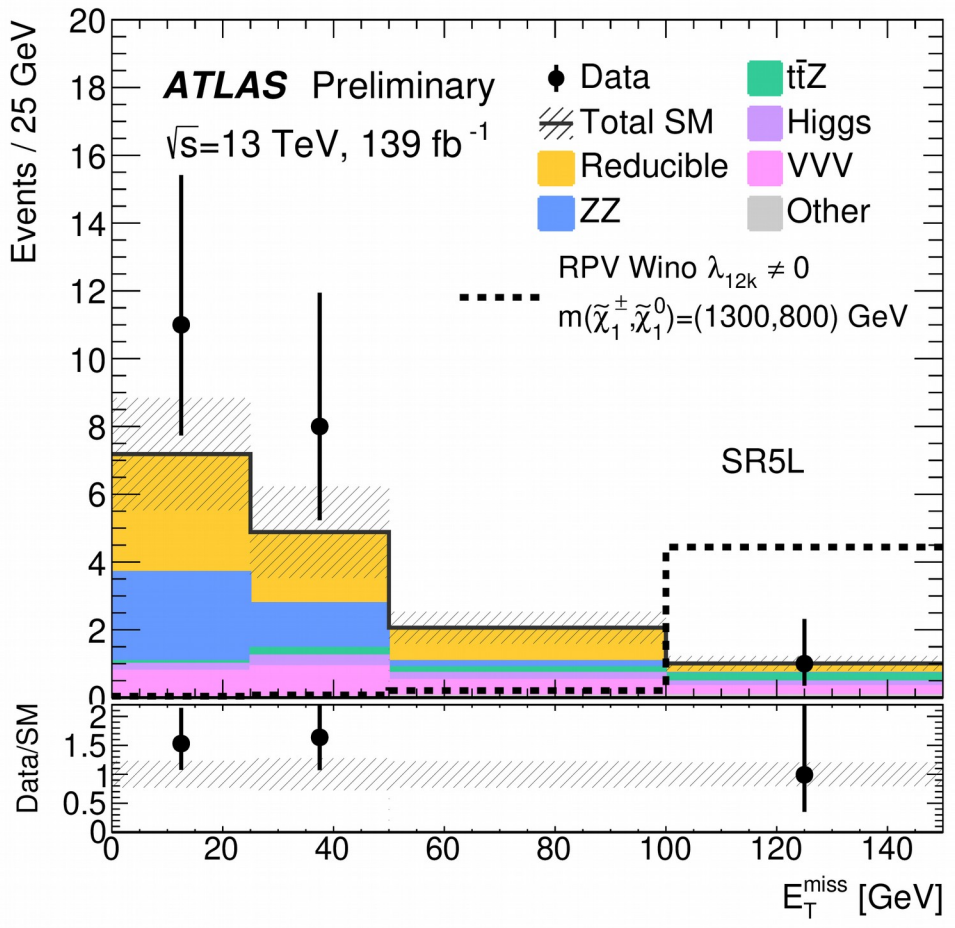
Stay tuned for upcoming summary results!

Backup

Signal region requiring five leptons

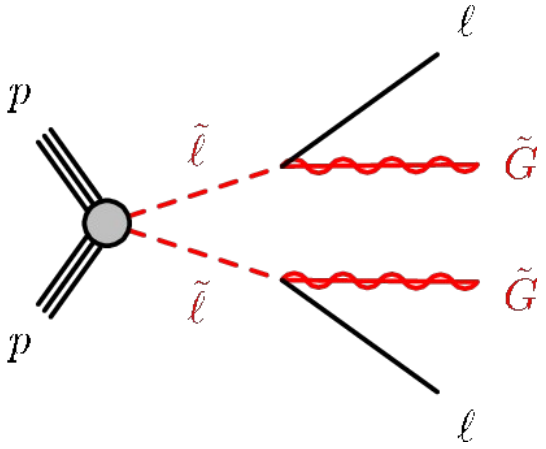
[ATLAS-CONF-2020-040]

Sufficient data statistics available to target final states with five leptons.



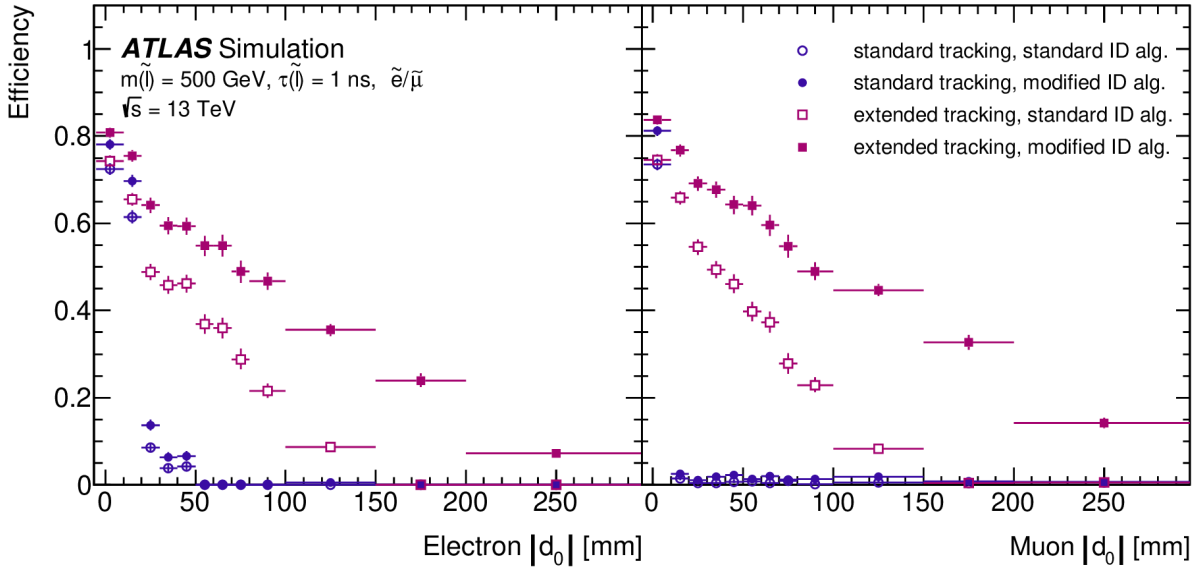
Displaced leptons

arXiv:2011.07812



Most searches target prompt particle decays
→ *Not sensitive to particles decaying delayed because of a long lifetime.*
→ *E.g. predicted in models with a next-to-LSP decaying to a LSP gravitino*
→ *Only couples gravititationally.*

Standard identification/reconstruction algorithms not efficient
→ *Use modified algorithms, in particular lifting requirements on the transverse impact parameter.*



Displaced leptons

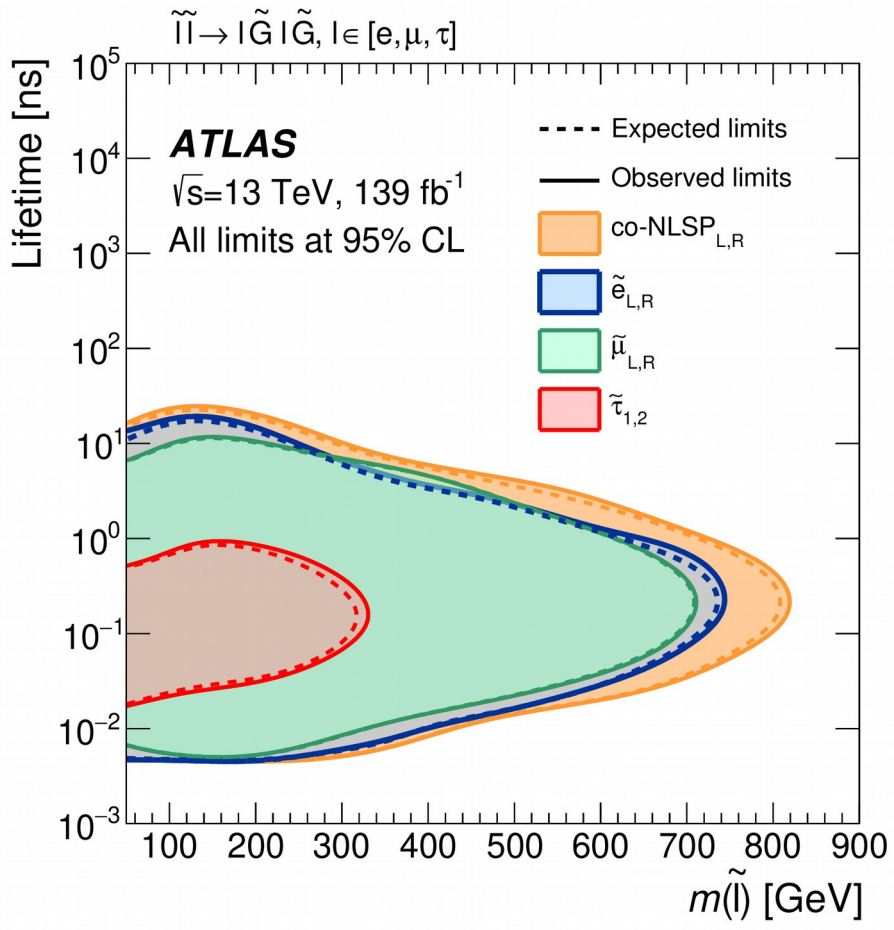
[arXiv:2011.07812]

- Signal regions with two leptons (either electron or muon).
- Rejection of cosmic muons, other backgrounds from misidentified electrons or muons.

No events observed in the signal regions

→ Exclusion limits placed on different next-to-LSP types or considering a mixture.

Surpassing previous LEP limits (~60 - 90 GeV) significantly.



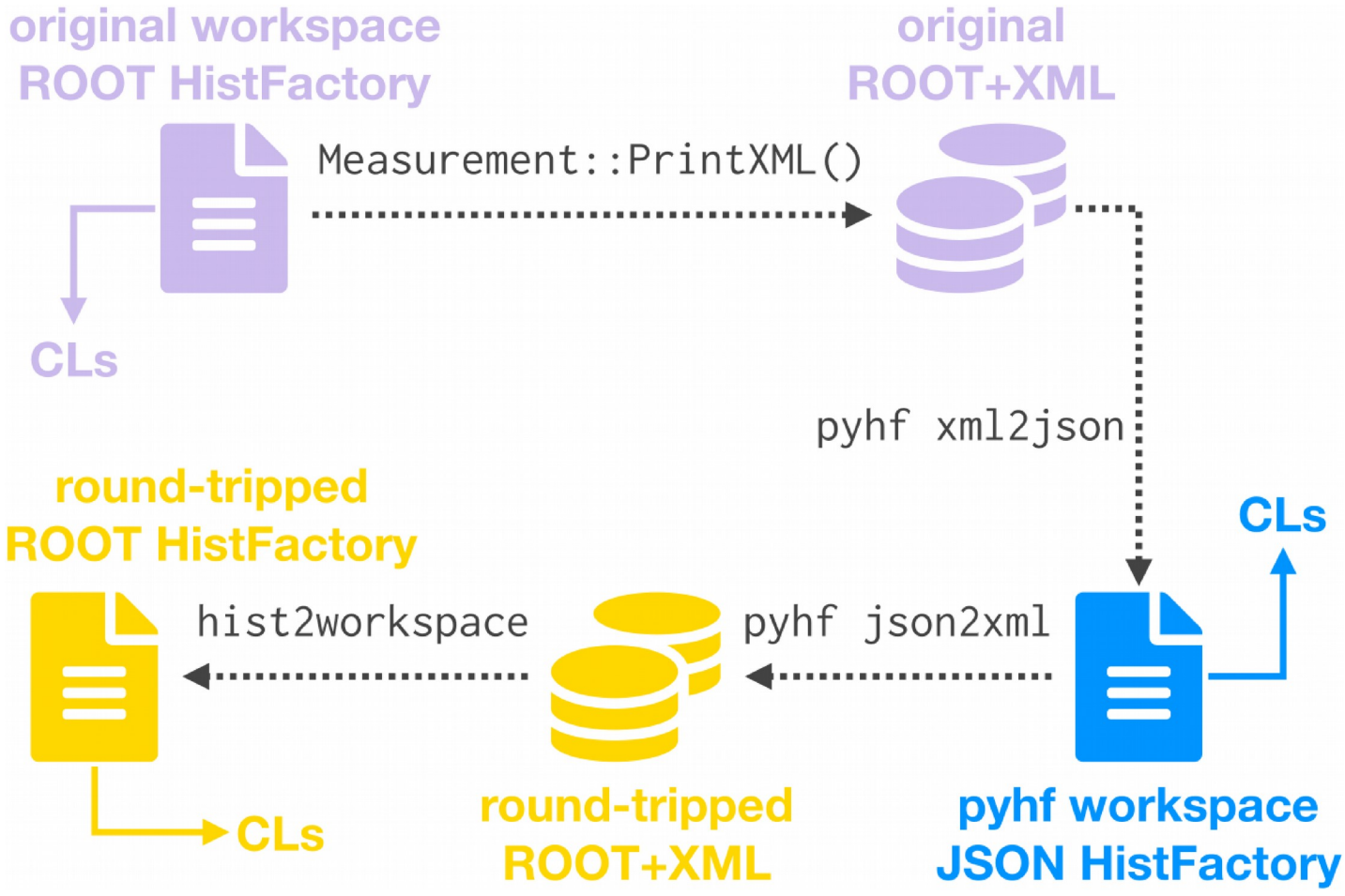
Full likelihood

[ATL-PHYS-PUB-2019-029]

Release of full analysis likelihoods possible via a workspace represented as json file.

Mathematical model of HistFactory re-implemented in pyhf using only standard python packages such as scipy and numpy.

Reproduction of the analysis possible using either pyhf or ROOT.



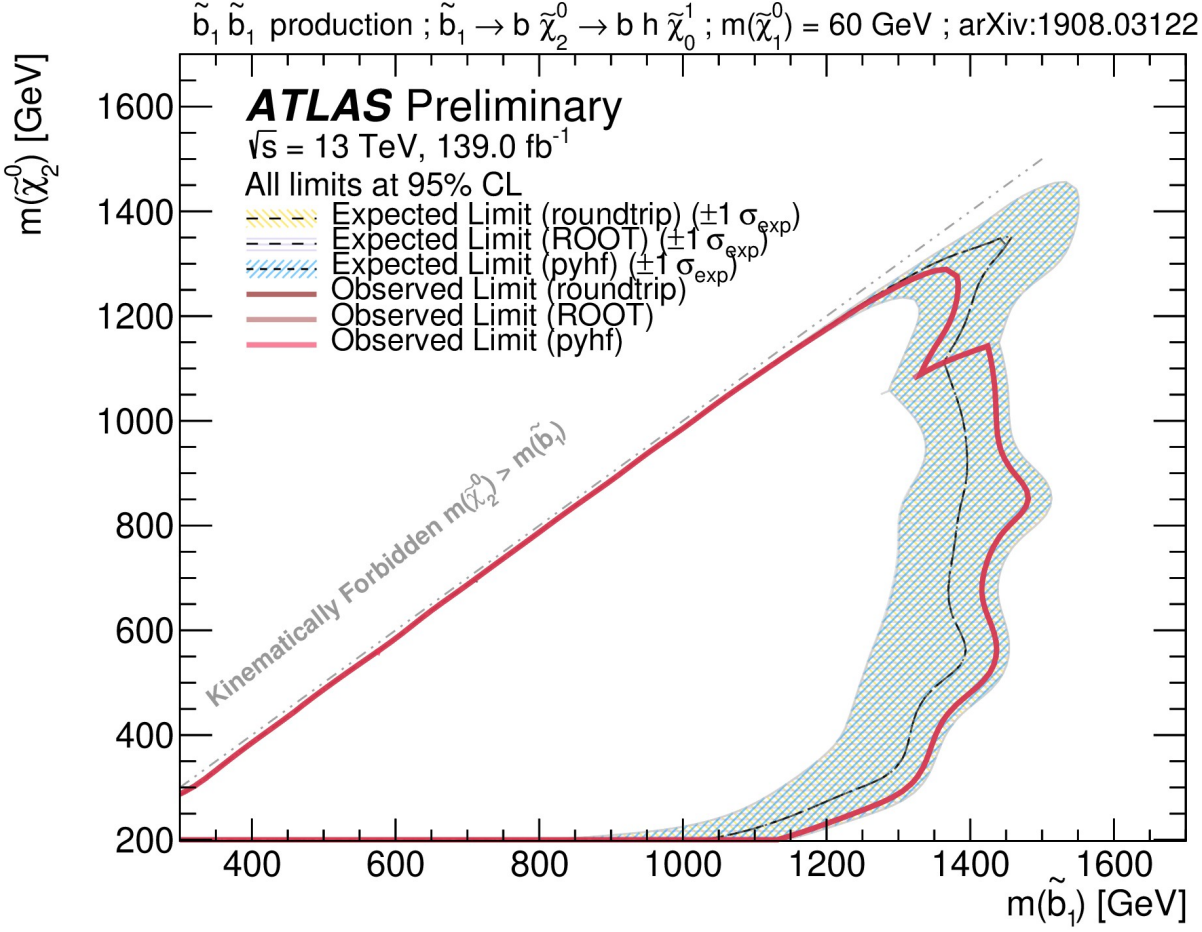
Full likelihood

[ATL-PHYS-PUB-2019-029]

Proof-of-principle: Reimplementation of the likelihood of the sbottom analysis + different tools to calculate limits.

Easily possible to replace original signal in the full likelihood for reinterpretation → *likelihood patch*.

Full likelihood of the sbottom analysis: link



Different likelihoods available

Analysis characteristics: Double parton scattering | BSM search | BSM reinterpretation | LFV | FCNC | Particle flow | MVA / machine learning | EFT interpretation | Differential measurement | Displaced vertex | Lepton-jets | Trigger-level analysis | High luminosity upgrade studies | **Likelihood available**

Min luminosity : 0 fb^{-1} Filter by minimum integrated luminosity

Date : Min. YYYY-MM-DD Max. YYYY-MM-DD Filter by date: ArXiv relase | Publication

Quick links: Papers Confnotes Pubnotes

Papers and publications (7 shown of 167 total)
(Full list of ATLAS papers, List/RSS from CDS)

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Short Title	Journal Reference	Date	√s (TeV)	L	Links
Search for chargino and neutralino pair RPV decays; 3L	Submitted to PRD	20-NOV-20	13	139 fb^{-1}	Documents | 2011.10543 | Inspire HepData | Briefing | Internal
Search for displaced leptons	Submitted to PRL	13-NOV-20	13	139 fb^{-1}	Documents | 2011.07812 | Inspire HepData | Briefing | Internal
Chargino-neutralino pair; 3 leptons, weak-scale mass splittings	Phys. Rev. D 101 (2020) 072001	18-DEC-19	13	139 fb^{-1}	Documents | 1912.08479 | Inspire HepData | Internal
Staus; taus	Phys. Rev. D 101 (2020) 032009	15-NOV-19	13	139 fb^{-1}	Documents | 1911.06660 | Inspire HepData | Briefing | Internal
Chargino-neutralino pair; Higgs boson in final state, 2 b-jets and 1 lepton	Eur. Phys. J. C 80 (2020) 691	19-SEP-19	13	139 fb^{-1}	Documents | 1909.09226 | Inspire HepData | Internal
Stop pair, sbottom pair, gluino pair; two same-sign leptons or three leptons	JHEP 06 (2020) 46	18-SEP-19	13	139 fb^{-1}	Documents | 1909.08457 | Inspire HepData | Internal
Sbottom; b-jets	JHEP 12 (2019) 060	08-AUG-19	13	139 fb^{-1}	Documents | 1908.03122 | Inspire HepData | Briefing | Internal

Simplified likelihoods

[talk at Reinterpretation workshop]

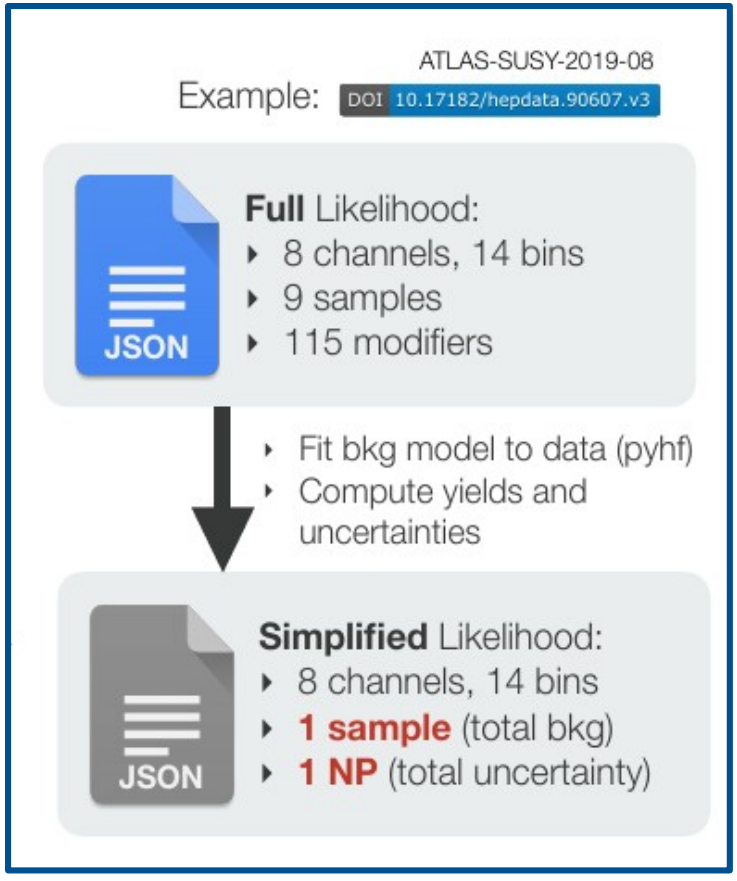
Full likelihoods are sometimes too complex:

→ *Too much CPU time needed, or precision of full likelihood not needed,*

→ *As frequent in reinterpretation efforts considering many new models.*

In certain cases, the full likelihood can be approximated by a simplified background model, with a significantly reduced number of nuisance parameters

→ *Significant reduction of CPU resources.*



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