Physics Beyond the Standard Model: Supersymmetry

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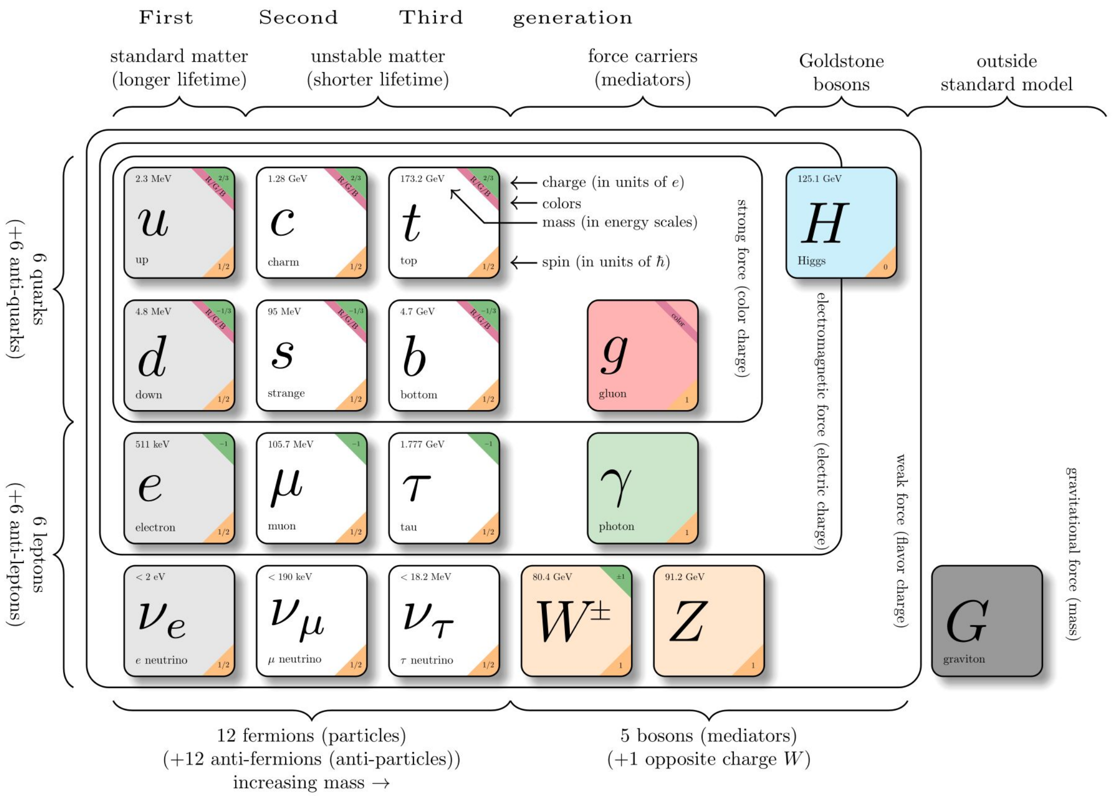
Briefly, about me

- From Antwerp, and did my PhD there on Higgs searches with CMS
- Moved to ATLAS and worked as a postdoc with Nikhef, CERN, and now Edinburgh doing searches for Beyond-the-SM physics
- Focus on electroweak supersymmetry searches
- Work to see how far we can push the detector and software to study hard-to-measure leptons
- Also an operations expert: keep the ATLAS trigger system running, and shift leader

This lecture

- **Why** Supersymmetry?
- **What** is Supersymmetry?
- **How** to Supersymmetry (at the LHC)?

The Standard Model



Particle physics' best model today

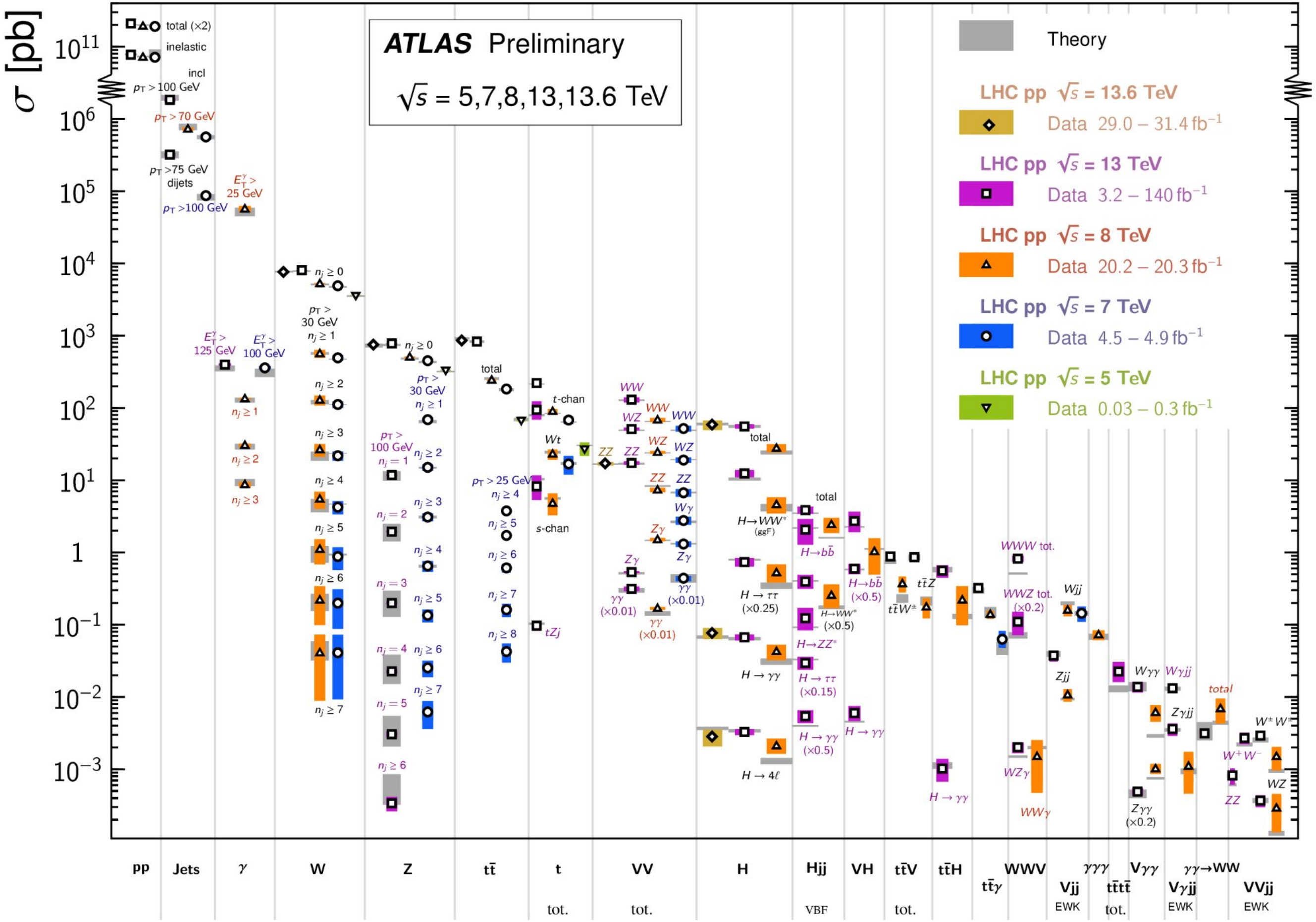
a gauge theory which describes

- elementary particles
  - fermions
  - bosons
- fundamental interactions
  - strong
  - electromagnetic
  - weak

noting particle's

mass, charge, colour, and spin

Success of The Standard Model

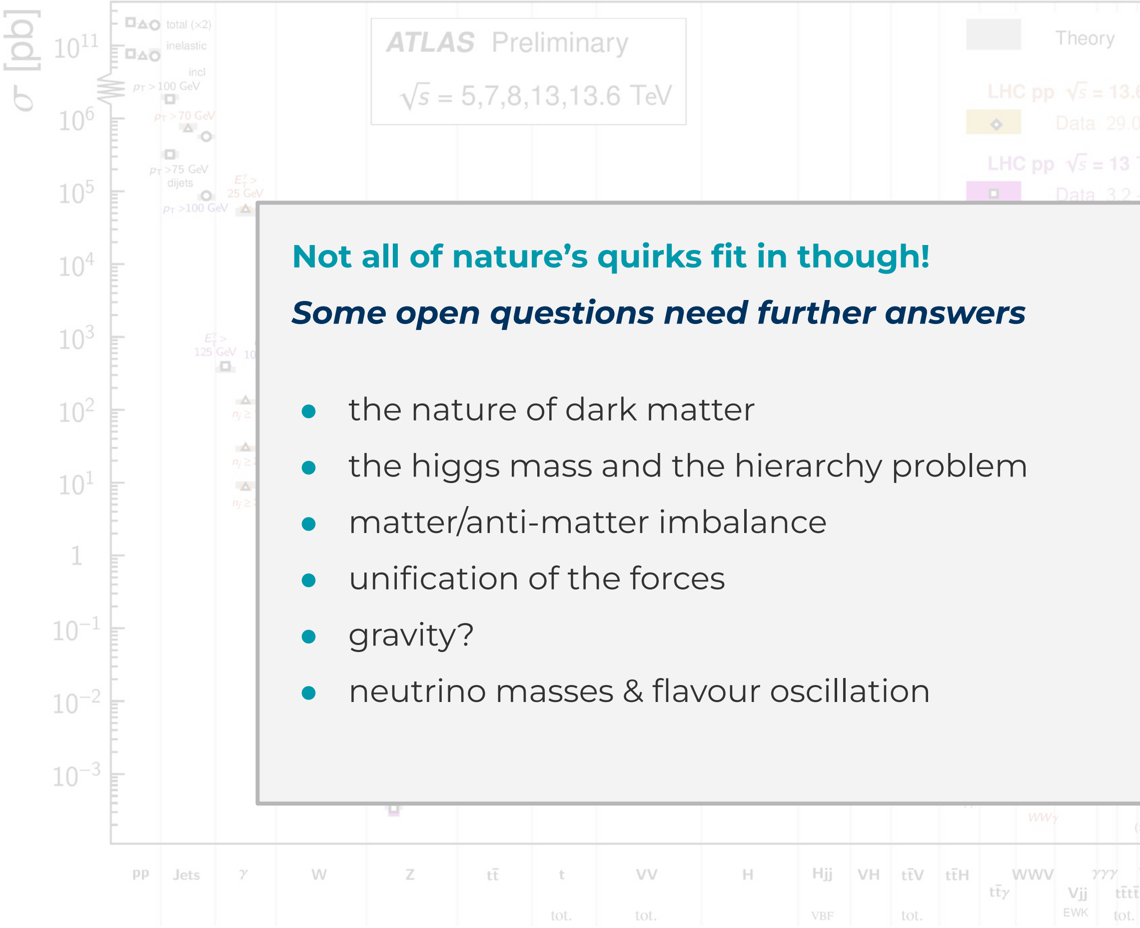


- measurements covering 15 (!) orders of magnitude
- multiple CoM energies

- both precision & agreement with theory predictions are impressive

- despite great success, still occasional tensions seen
    - flavour sector: R_K, R_{K^*}
    - muon g-2
    - W-boson mass
    - …

Success of The Standard Model



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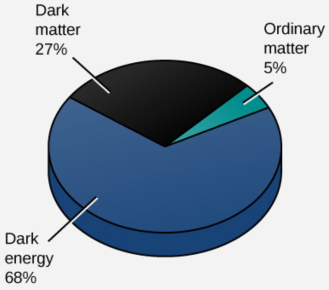
Not all of nature’s quirks fit in though!

Some open questions need further answers

- the nature of dark matter
- the higgs mass and the hierarchy problem
- matter/anti-matter imbalance
- unification of the forces
- gravity?
- neutrino masses & flavour oscillation



Supersymmetry 101

new, broken symmetry between fermions & bosons, including extended higgs sector

→ *SM particle mass ≠ SUSY partner mass*

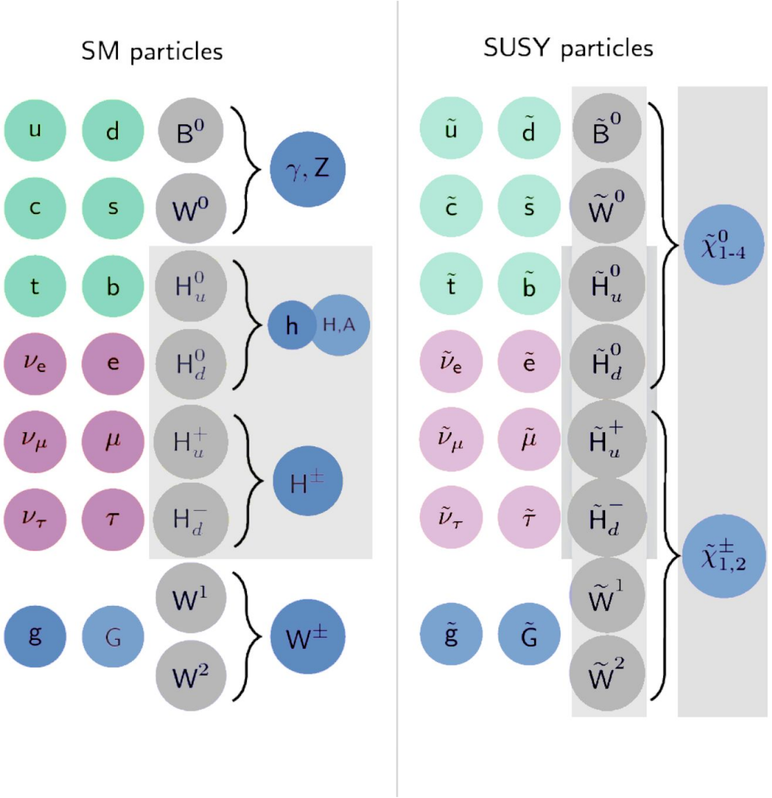
solutions to

- stabilised Higgs boson mass
- unification of the gauge couplings
- (WIMP) Dark Matter candidate with stable lightest supersymmetrical particle (LSP) in R-parity conserving SUSY

beautiful framework to explore extremely broad array of BSM signatures

focus on natural SUSY

- relatively light stops, gluinos and higgsinos
- other particles can be decoupled



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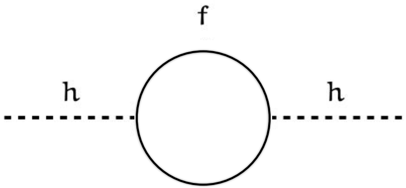
I'm sorry,
say that again?

The Hierarchy Problem

Why is the higgs boson mass so much lighter than the Planck scale?

$$m_H^2 \approx m_{H,0}^2 - \frac{|\lambda_f|^2}{8\pi^2}\Lambda^2 + \ \ldots$$

↳ $\mathcal{O}((10^{19}\mathrm{GeV})^2)$



Naive expectation

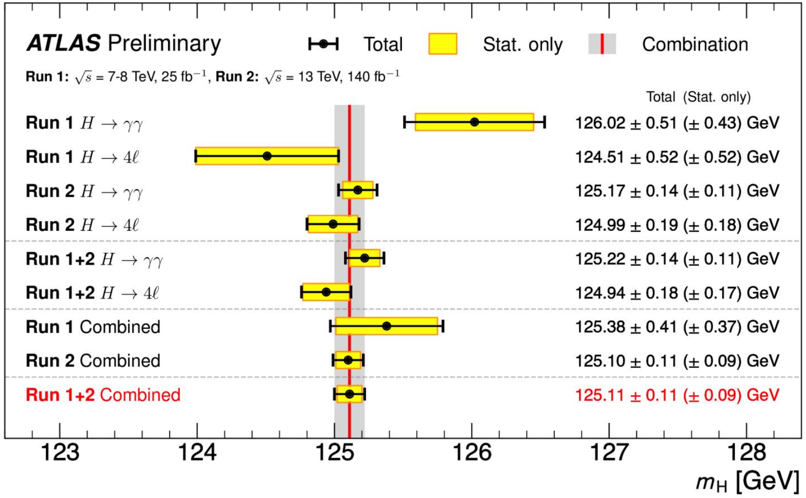
- higgs mass ~ scale at which new physics appears
- unless there is large fine-tuning and terms ~cancel
- fine-tuning is unnatural

Instead

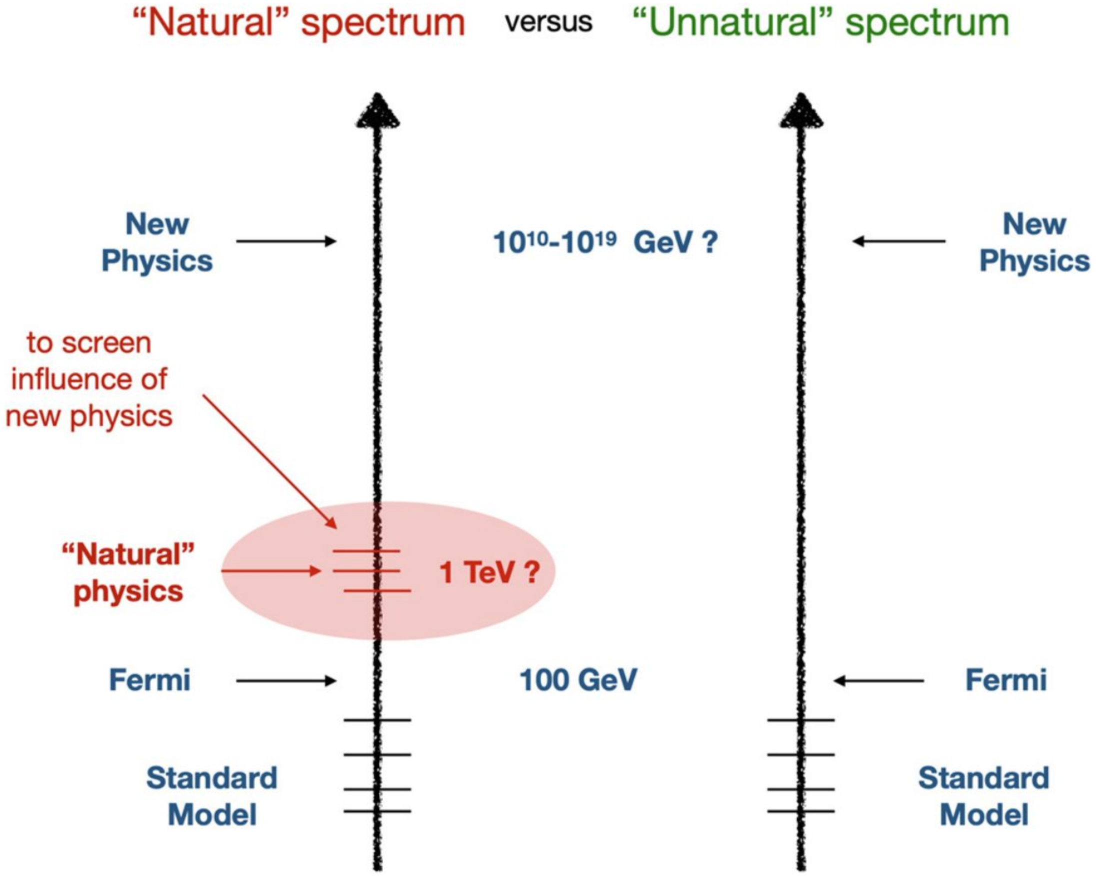
$m_H \approx$ 125.11 GeV

which would be nice to have an explanation for…

arXiv:2308.04775



Naturalness



Symmetries

Global / external: translation, rotation, and inertial frame symmetry (Pointcaré symmetry)

Local / internal: giving rise to the fundamental interactions connected to the gauge fields (Lie groups)

Symmetries described using group theory: group elements connect to transformations,
and groups are described via generators

In field theory, the gauge groups represent the local transformations under which the lagrangian is invariant, ie. under which the system does not change → *symmetries*

For the Standard Model: $\mathbf{U(1)_Y \times SU(2)_L \times SU(3)_C}$
representing electromagnetic force x weak force x strong force

Noether's theorem: each continuous symmetry has to correspond to a conserved quantity

Conserved quantities: lepton number, baryon number, parity, isospin, and strangeness

Unification

Can these global and local aspects be unified in an extension of the previous description?

Skipping a lot of steps...

- → **no**, not with the Lie group description
- → **yes**, using Supersymmetry (as an extension of the Pointcaré symmetry, an extension of space & time in an additional quantum mechanical dimension)

Supersymmetry

Supersymmetry connects **fermions and bosons** using a spinorial generator Q (spin ½)

`Q |fermion> = |boson>`

`Q |boson>   = |fermion>`

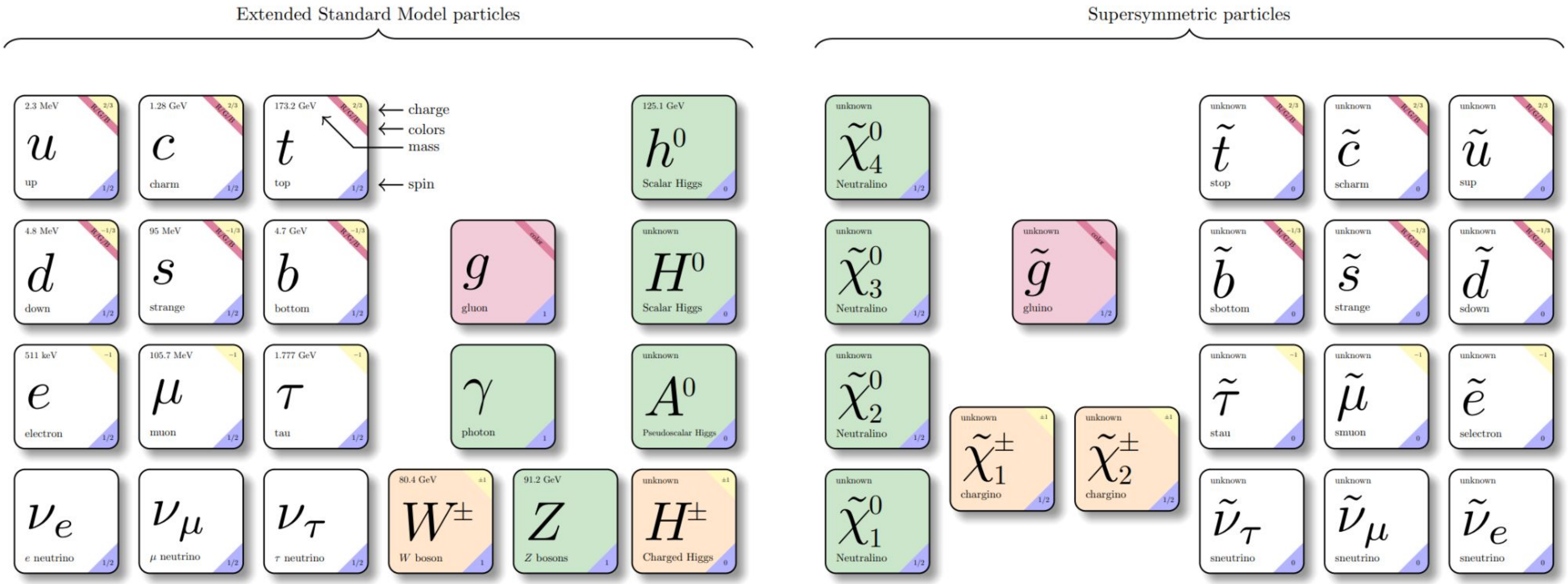
and the representation contains multiplets of particles that have
different spin but *the same mass & quantum numbers*

In order to then set up a Lagrangian that can be invariant under the transformation `|boson> ↔ |fermion>`
one needs double the amount of particles (since we don't already have such particles available in the SM)

In practice: SM fermion ↔ new SUSY scalar boson "s-"
SM boson ↔ new SUSY fermion "-ino"

quarks/leptons/neutrinos (spin ½) ↔ squarks/sleptons/sneutrinos (spin 0)
gauge bosons g, γ/W/Z (spin 1) ↔ gluino, charginos/neutralinos (electroweakinos) (spin ½)
extended Higgs sector ($\mathbf{h^0}$, H^0, A^0, $H^\pm$) (spin 0)

Supersymmetry



Supersymmetry breaking

Remember the statement

SUSY representation contains multiplets of particles that have
different spin but *the same mass & quantum numbers*

→ but we have not observed supersymmetric partners at the same masses, e.g. no selectron at 0.511 MeV

→ **Supersymmetry must be a broken symmetry**

We assume spontaneous symmetry breaking

→ gauge or gravitational interactions couple the SUSY-breaking sector with the Supersymmetric SM (they mediate the supersymmetry breaking)

→ the vacuum is non-Supersymmetric

→ as we don't know the actual mechanism, we manually introduce explicit breaking terms,

→ only soft terms avoiding to re-introduce divergences

The Hierarchy Problem

Coming back to the higgs boson mass

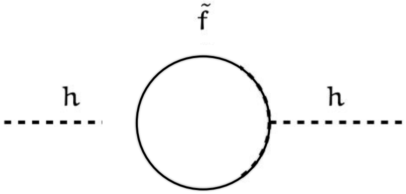
naively: corrections are divergent,
thus the mass has to be large

$$m_H^2 \approx m_{H,0}^2 - \frac{|\lambda_f|^2}{8\pi^2}\Lambda^2 + \dots$$

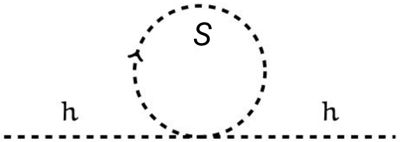
Supersymmetry introduces additional scalars which bring **further corrections that mitigate the problem**

- balances the SM corrections
- reduces the necessary level of fine-tuning
- the observed light higgs boson is possible

$|\lambda_f|^2 = \lambda_s$ connect to two new scalars for each fermion (in the same super-multiplet)



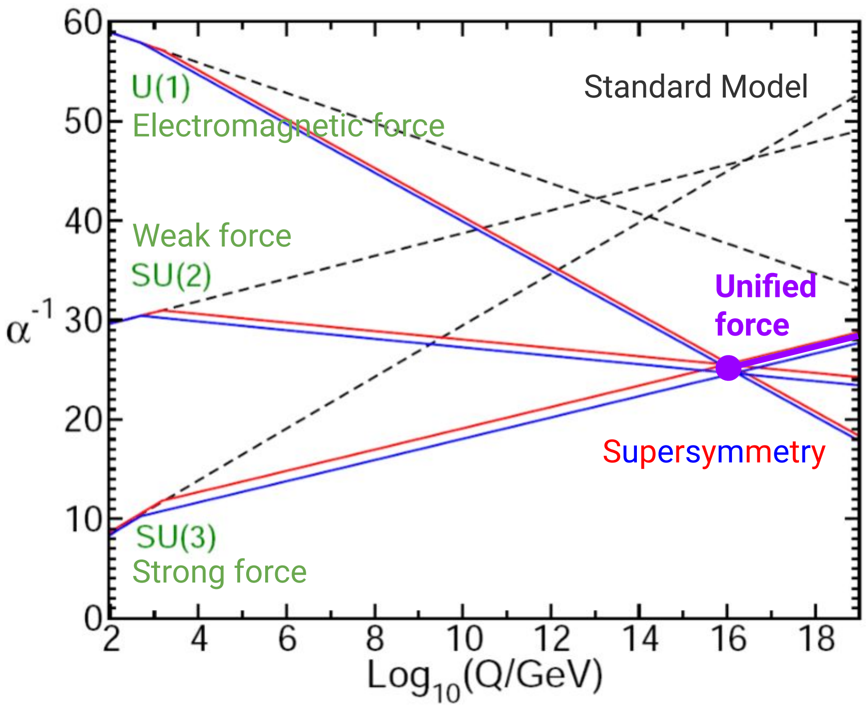
$$\frac{|\lambda_f|^2}{8\pi^2}\Lambda^2$$



$$\frac{\lambda_s}{16\pi^2}\Lambda^2$$

Masses m_s and m_f are not the same,
the cancellation depends on **SUSY breaking**

Unification of SM gauge couplings



When following the Standard Model to predict the running of the couplings,

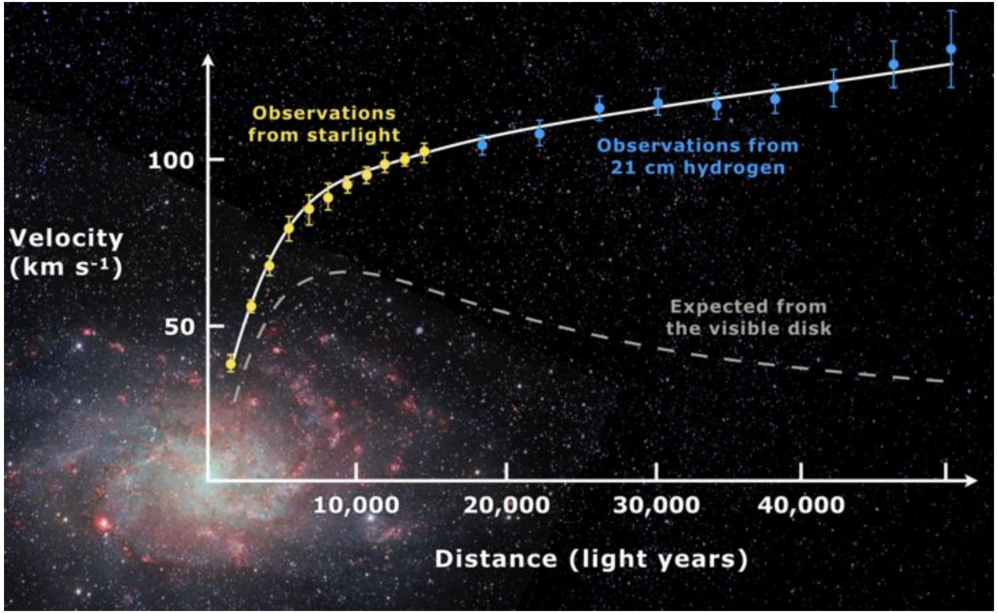
the extrapolation of the experimentally observed gauge couplings does not unify at large scale.

If one instead assumes running according to the Minimal Supersymmetric Standard Model,

they do.

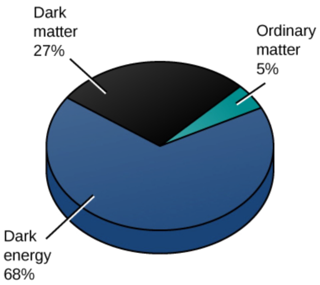
(at energies comparable to those of the early universe)

(WIMP) Dark Matter candidate



Measured rotational velocity for spiral galaxies vs. predictions assuming only visible matter

The Standard Model only accounts for a fraction of the total energy in the universe



- **5% ordinary matter**
- 27% dark matter
- 68% dark energy

Supersymmetry can offer a DM particle candidate that satisfies all the conditions

- stable
- weakly-interacting
- massive

R-parity

Remember Noether's theorem: each continuous symmetry has to correspond to a conserved quantity

However, the most general super-potential we can describe, violates conservation of lepton- and baryon number!

Consequence: the proton would be unstable, and decay much faster than observed in nature

R-parity is a new symmetry, a new conserved quantum number, that restores things

$R = (-1)^{3(B-L)+2S}$ with B,L, and S the baryon number, the lepton number, and the spin

→ R-parity +1 for particles, and -1 for sparticles

Consequence

- supersymmetric particles have to be produced in pairs
- the lightest supersymmetrical particles (LSP) is stable
- if the LSP is neutral, it's a good (WIMP) dark matter particle candidate (e.g. the neutralino)

R-parity violation

All rules need exceptions: one can introduce R-parity violating terms in the Lagrangian

$$W_{RPV} = k_i L_i H_2 \quad + \quad \lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D_k \quad + \quad \lambda''_{ijk} D_i D_j D_k$$

lepton-violating

↓

large lepton multiplicity
& additional leptons from
LSP decays

baryon-violating

↓

multi-jet resonances
(without large additional missing ET)

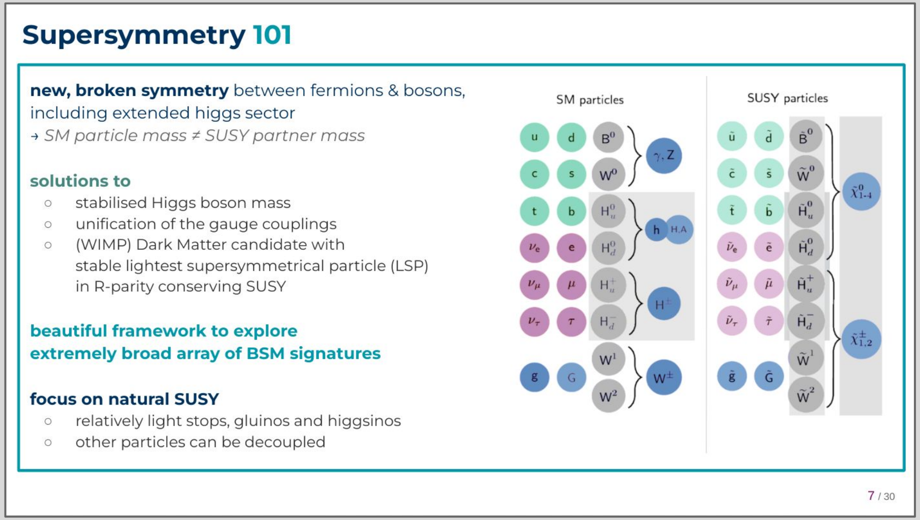
which would result in

- final states with higher particle multiplicities
- final states with less missing transverse momentum
- many different final states possible due to different possible RPV terms

- no stable LSP → no dark matter particle candidate

(but the extra terms also allow flexibility in describing “features”, e.g. fitting in a description of g-2 anomaly, flavour anomalies, …)

REMEMBER



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focus on natural SUSY
- relatively light stops, gluinos and higgsinos
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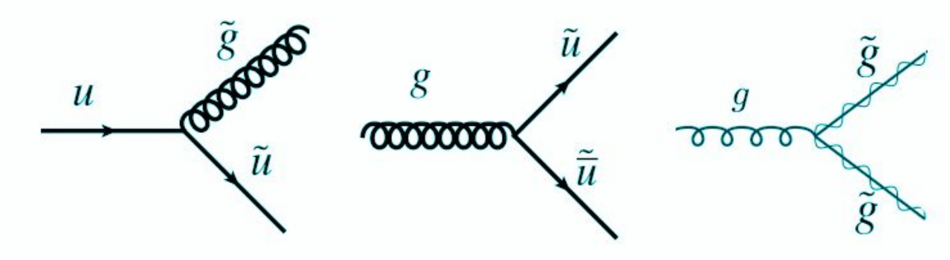
SUSY in a nutshell

- new, broken symmetry
  - R-parity as new quantum number
- solutions to
  - light higgs boson mass
  - unification of gauge couplings
  - dark matter candidate

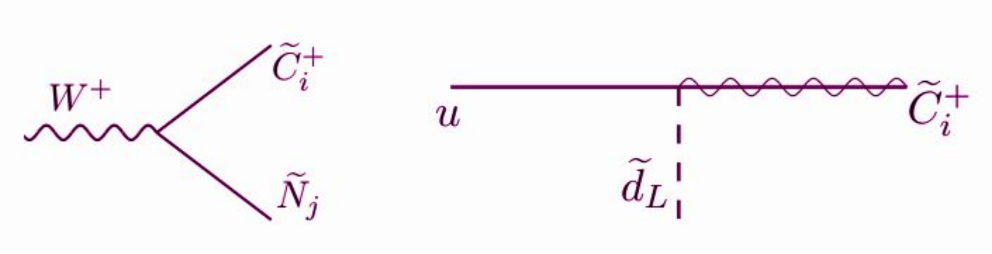
Production of SUSY particles at the LHC

Following the same rules as for the SM, just swapping two(*) particles to be supersymmetrical

(*) sparticles are pair-produced
if R-parity is conserved



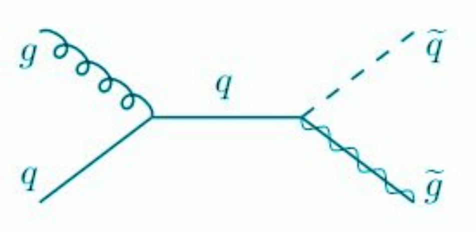
strong production



electroweak production

Production of SUSY particles at the LHC

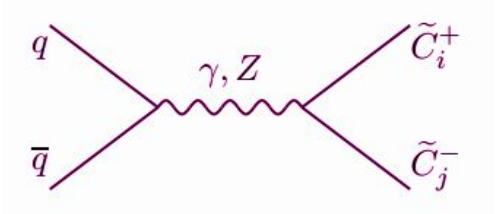
Many possible diagrams!

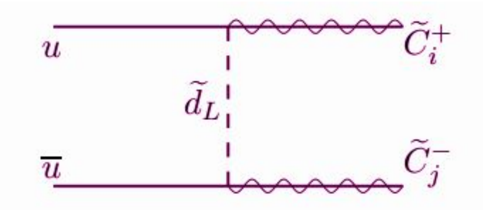


strong production

$gg/gq/\overline{qq}/qq$ initiated → all possible combinations of gluino, squark & anti-squark

- also box-diagrams
- few top and no bottom quarks (given their mass)
- 3rd generation squarks have to come from box-diagrams



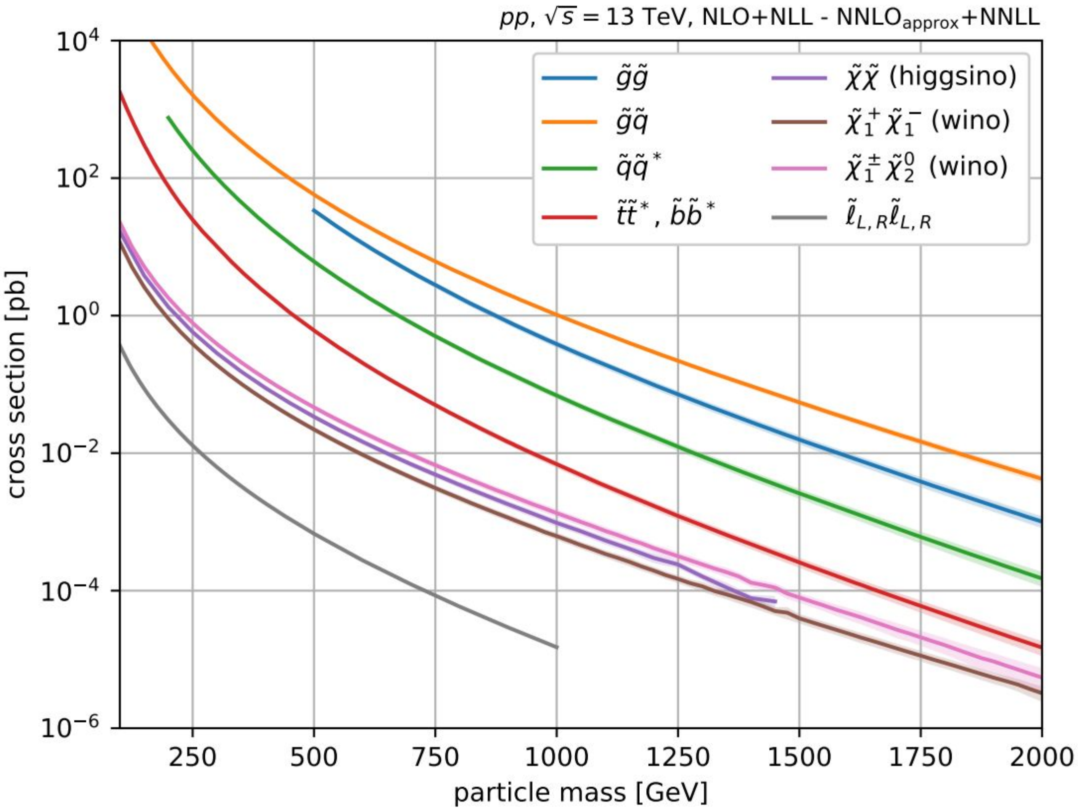


electroweak production

chargino/neutralino pairs or slepton/sneutrino pairs (including c-n and sl-sn)

- LHC collisions involve quarks in the initial state
  → electroweak SUSY diagrams involve at least two EM or weak vertices
- electroweak production is rarer

Cross sections



gluino-squark, gluino-gluino, squark-squark, and even 3rd generation squark production cross sections

(due to strong interaction)

are order(s) of magnitude larger at the LHC than electroweakino pair-production or slepton pair-production

higher cross section for squark and gluino production means

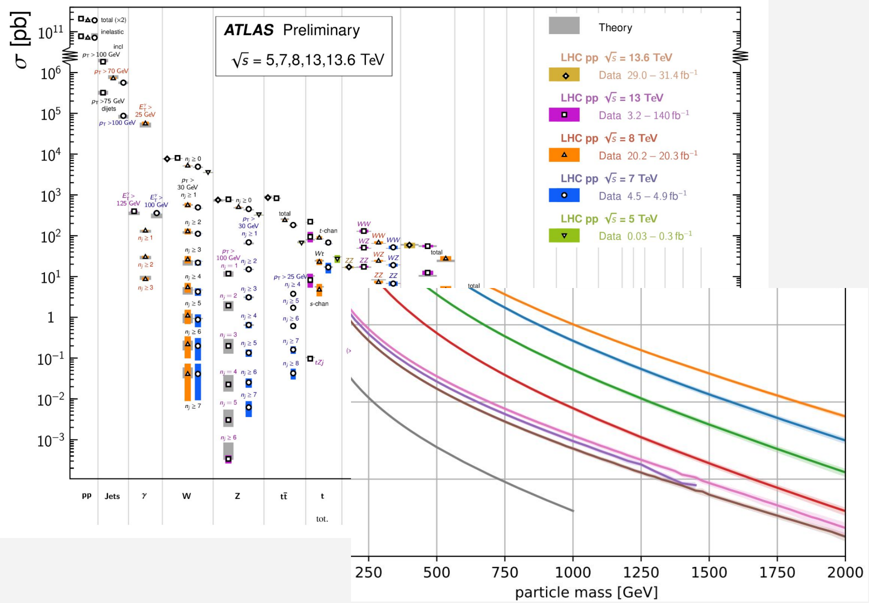
↓

our current **sensitivity reach at the LHC is at higher masses** for squarks and gluinos than for electroweakinos and sleptons

Cross sections

Remember though that SM cross section are orders of magnitude larger!

→ *Out of ~1 billion events per second, expect to produce less than 1 containing SUSY particles*
→ *Plus we can't identify and save everything*



Signatures at the LHC

Supersymmetry is not one model, it’s a family of models, a large framework
→ various scenarios can result in many different signatures we can search for

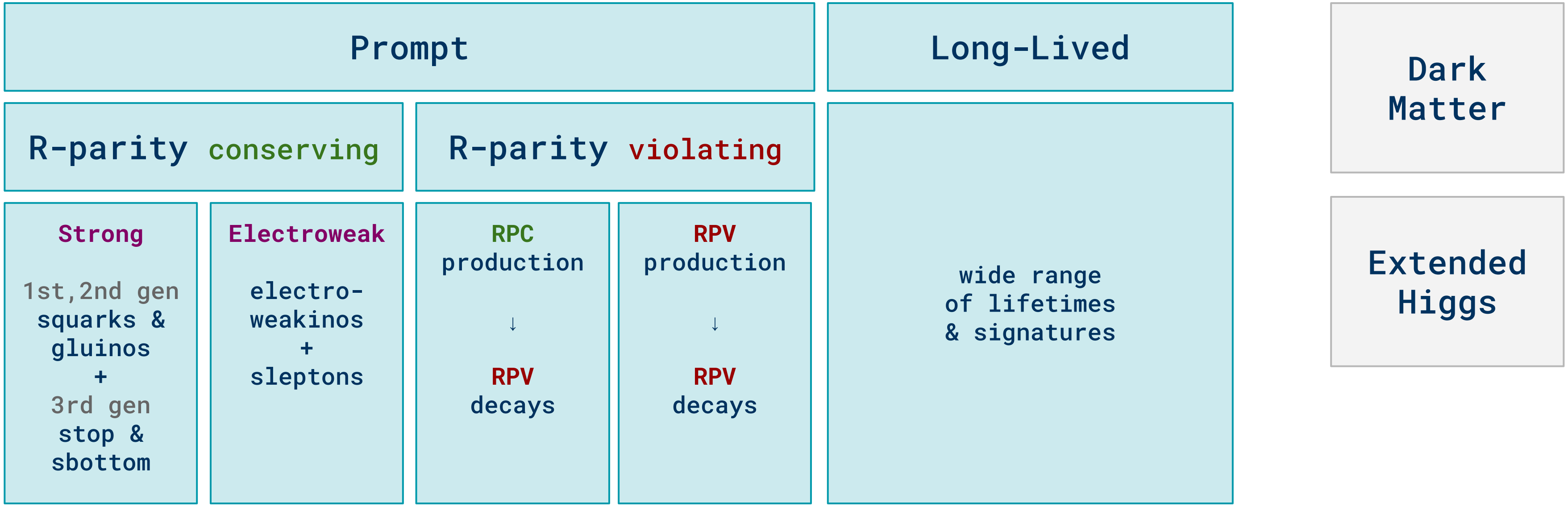
Standard prompt signatures

- SUSY particles (except for LSP) decay to SM particles and other SUSY particles
  → signature is SM+particles + missing ET
- If R-parity violating: no stable LSP, also decays to SM particles, less missing ET & higher multiplicities

Long-lived particles

- Small couplings can lead to long-lived particles
  → e.g. small RPV-coupling, gravitino LSP with small coupling, small mass splittings between LSP/NLSP
- LHC detector reach dictates displacement range we can measure in (for tracks, charge, ...)

The SUSY landscape



Prompt

R-parity conserving

Strong

1st,2nd gen
squarks &
gluinos
+
3rd gen
stop &
sbottom

Electroweak

electro-weakinos
+
sleptons

R-parity violating

RPC production
↓
RPV decays

RPV production
↓
RPV decays

Long-Lived

wide range
of lifetimes
& signatures

Dark Matter

Extended Higgs

Typical SUSY search analysis flow

Identify target signature → define a selection

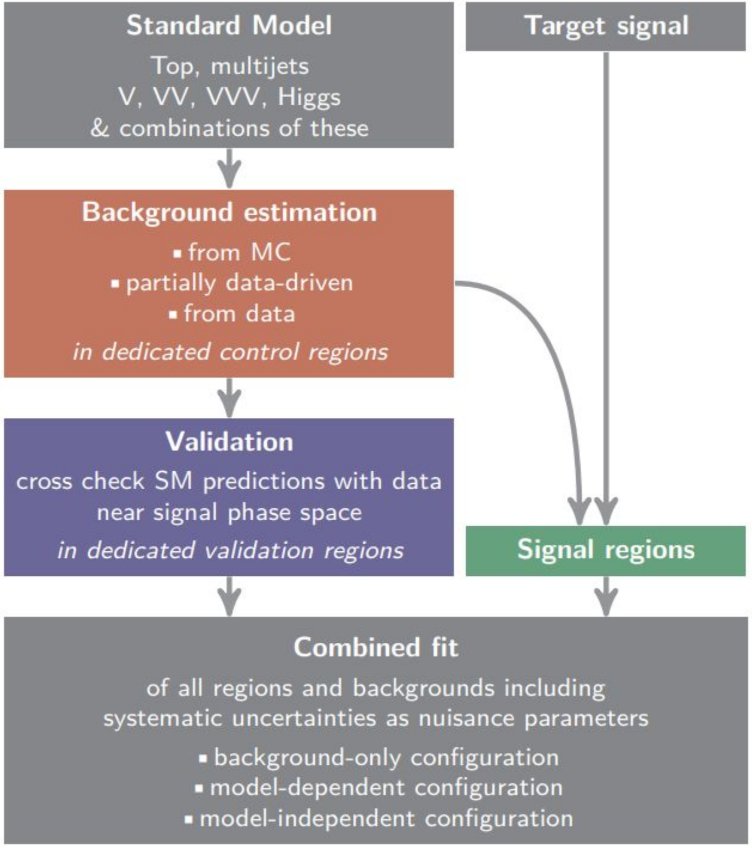
- which particles in final state?
- which SM (or machine) backgrounds look the same?
- which observables allow to distinguish signal & bkg?
- estimate the expected signal event yield in selection

Background estimation

- use Monte Carlo simulation or (semi-) data-driven methods to estimate event yield from background processes
- often estimate in background-rich region (control-region, **CR**) and transfer to signal-rich region (**SR**) after validation in intermediate validation region (**VR**)

Compare results & work out significance

- compare the signal and background expectations
- results for a given model, or for a generic BSM signal



Standard Model

Top, multijets
V, VV, VVV, Higgs
& combinations of these

Target signal

Background estimation

- from MC
- partially data-driven
- from data

in dedicated control regions

Validation

cross check SM predictions with data
near signal phase space

in dedicated validation regions

Signal regions

Combined fit

of all regions and backgrounds including
systematic uncertainties as nuisance parameters

- background-only configuration
- model-dependent configuration
- model-independent configuration

Typical SUSY search analysis flow

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- which particles in final state?
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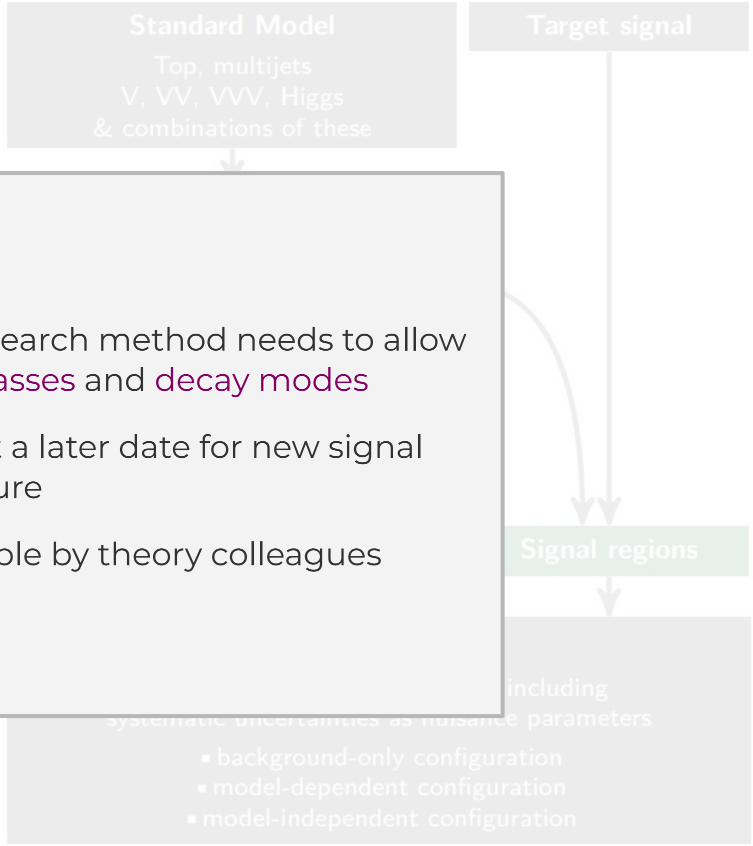


Need to build in flexibility!

→ Since we don’t know what the signal is, the search method needs to allow sensitivity for a range of potential particle masses and decay modes

→ Can be interesting to re-interpret analyses at a later date for new signal models that could produce the same signature

→ Important to provide results in a way digestible by theory colleagues

SUSY models in practice

“Full” models → mSUGRA, GMSB, AMSB, …

- SUSY breaking sector at higher energy scale & no degenerate spectrum at a lower scale (e.g. electroweak scale)
- Impossible to search for if we can’t reach the energy

Generalised models → pMSSM, general gauge mediated model (GGM), …

- Consider only the mass spectrum and parameters relevant at the electroweak scale
- Still complex and impractical to search for

Simplified models

- Consider a minimal set of parameters, usually particle masses and cross sections
- Target specific decays via 100% branching fraction models

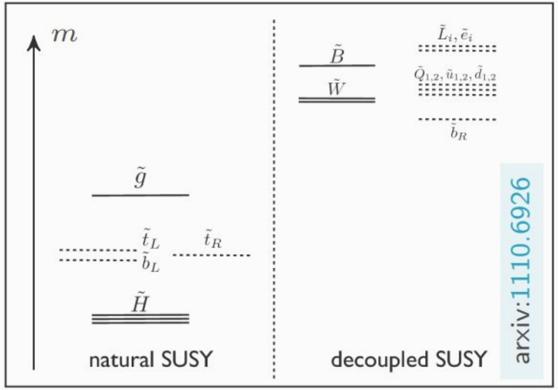
SUSY models in practice

Focus on simplified models

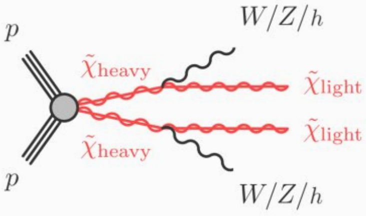
→ target reachable scale

→ systematically cover large phase space

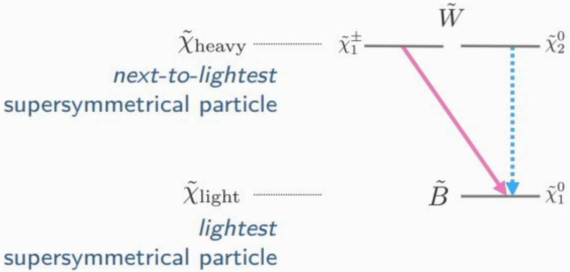
→ can still re-interpret in generalized model later



Example electroweak production scenario



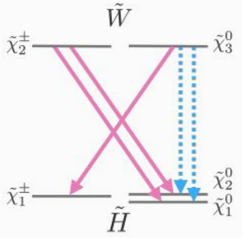
→ **wino** NLSP to **bino** LSP scenarios motivated by DM co-annihilation (and matching observed DM relic density)



next-to-lightest supersymmetrical particle

lightest supersymmetrical particle

→ scenarios with light **higgsinos** motivated by naturalness



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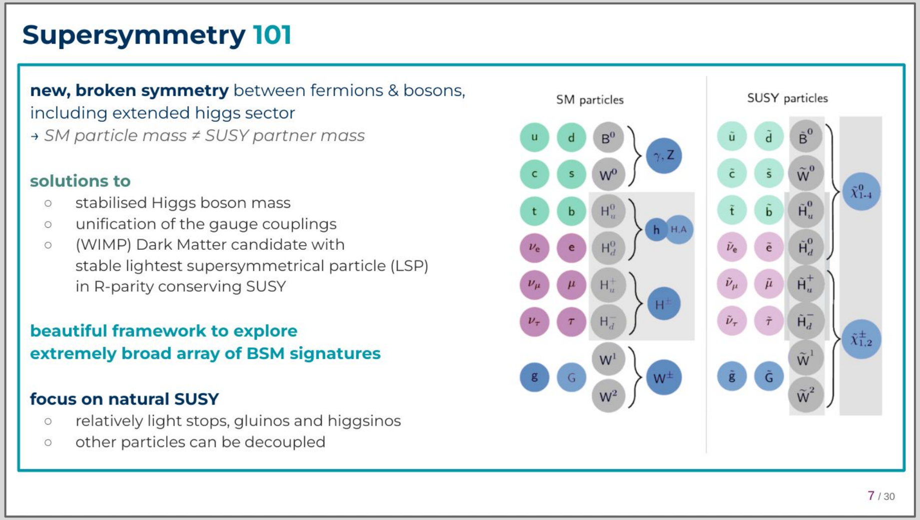

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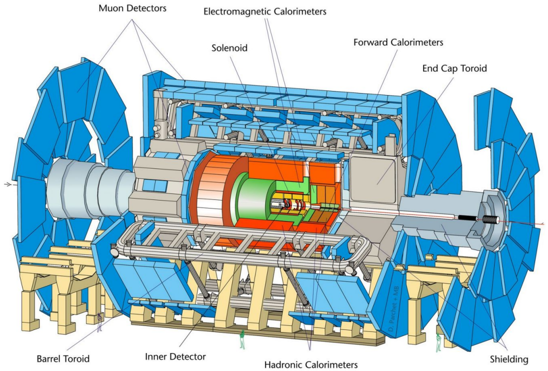
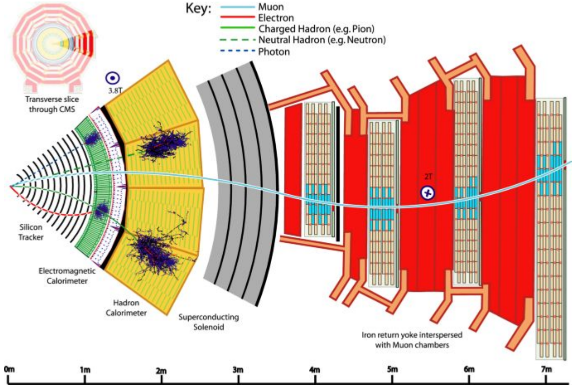
Let’s remind ourselves of our experimental setup

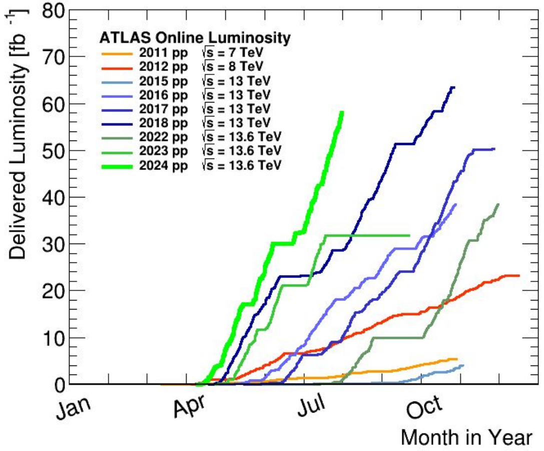
- LHC data set evolution
- particle reconstruction and identification
- selection of interesting events

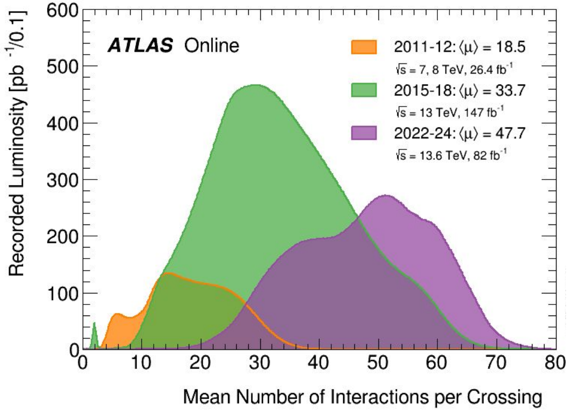
and then look at a step-by-step example of a search

The Large Hadron Collider



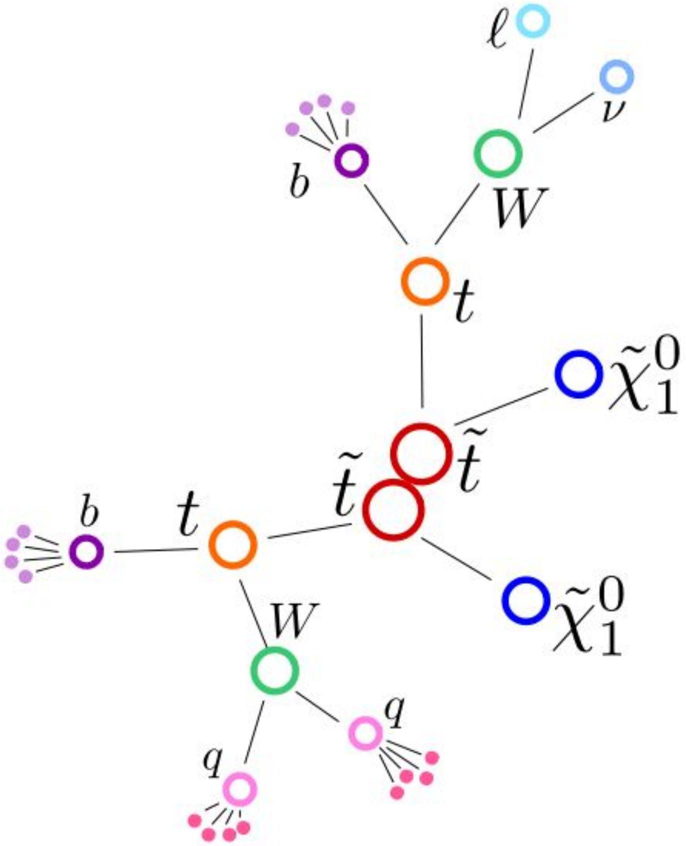






- two general purpose, hermetic, onion-structured detectors
  → *my ATLAS examples have an equivalent CMS counterpart!*
- currently in LHC Run 3, already >10y of data taking
- increasing CoM energy, increasing intensity, and increasing pile-up
- large upgrade scheduled with HL-LHC & detector upgrades for Run 4 and beyond

Particle reconstruction & identification



(diagram borrowed from last year's lecture by C. Merlassino)

Example stop-pair production

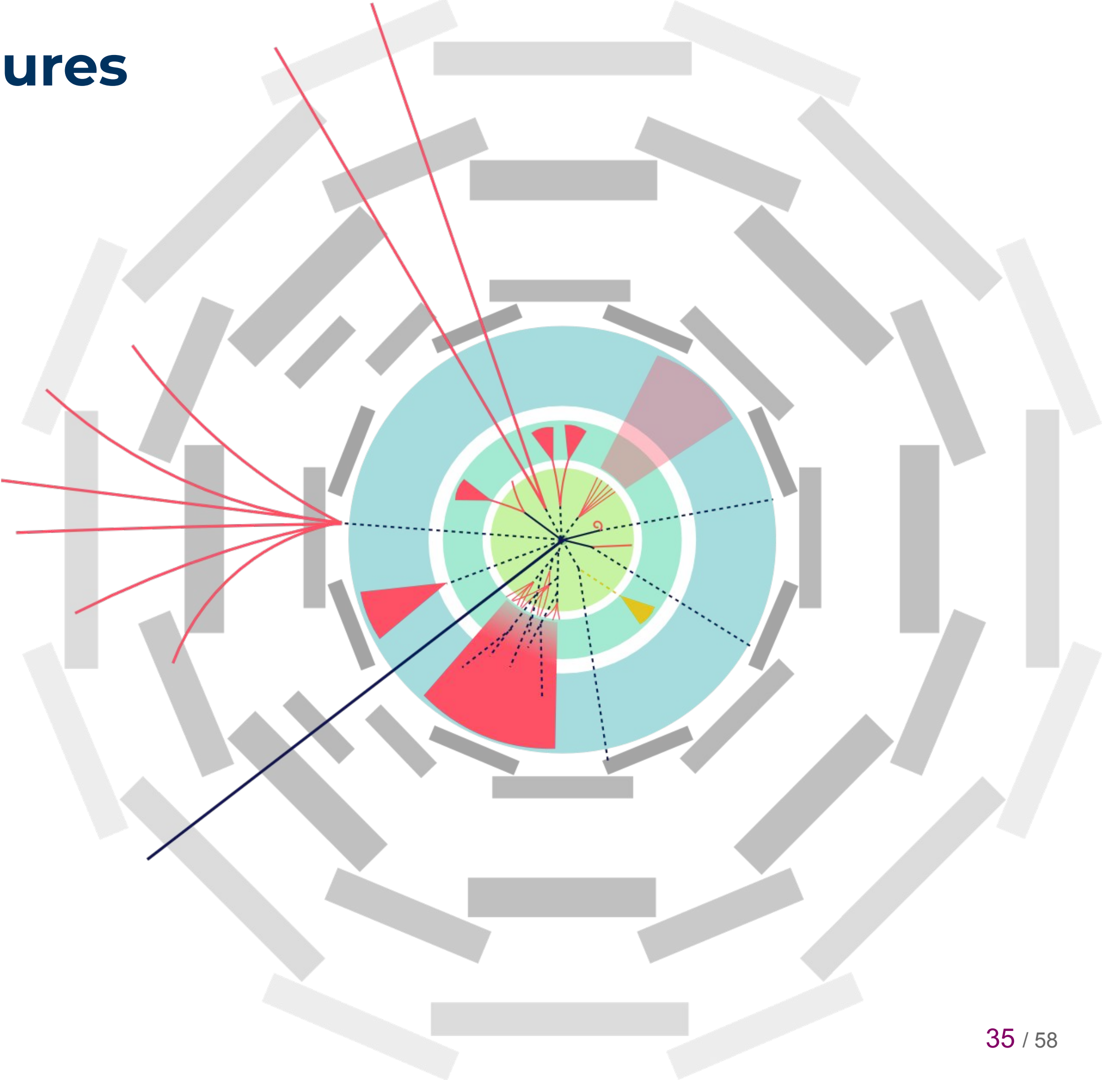
1 lepton + (b)jet + MET final state

- rely on tracking (inner detector), energy measurement (calorimeter), and additional outer muon system
- magnetic field: curved tracks & charge determination

- **neutral/charged particles**
  → electrons/photons
  → muons (to outer system)
- **jets from hadrons**
  → ie. quarks,
  → but also hadronic tau-lepton decays
- **vertex displacement from primary interaction**
  → b-jets
- **missing transverse energy from (weakly-interacting) invisible particles**
  → SM ones, e.g. neutrinos
  → but also SUSY LSP

or less conventional signatures

- disappearing tracks
- displaced leptons/jets
- displaced vertices
- …



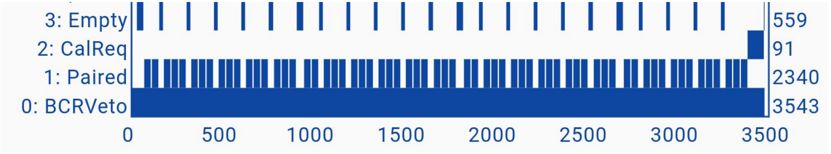
Trigger selection

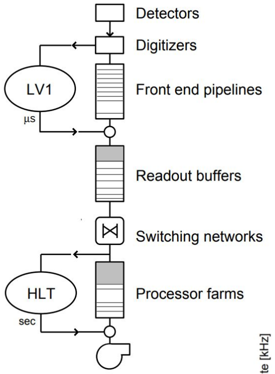
- LHC collisions in bunches of 10^{11} protons, spaced 25ns
- typically ~2400 bunches / beam filled for ~3500 slots

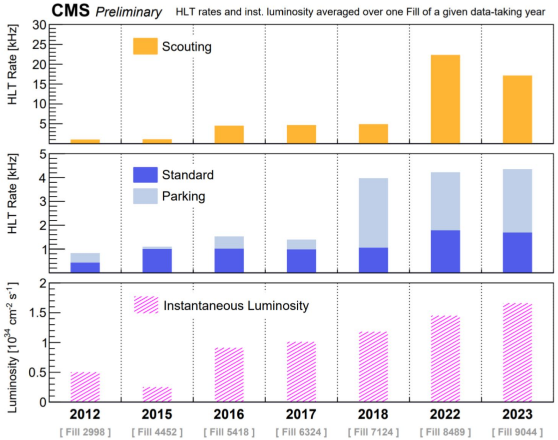
- **Two-level trigger system**
  - hardware-based Level-1 → 4μs decision time
  - software-based High-Level Trigger → 1s decision time
- Reduction from initial **40 MHz** → 100 kHz (L1) → **1 kHz** (HLT) writing out up to 10 Gb/s

- Newer developments target bandwidth optimisation
  - trigger-level analysis / data scouting
    → analysis on online-quality objects
  - delayed stream / data parking
    → general storage for later offline reconstruction
  - partial event building

- ***If an event is not triggered and recorded, it's gone forever!***

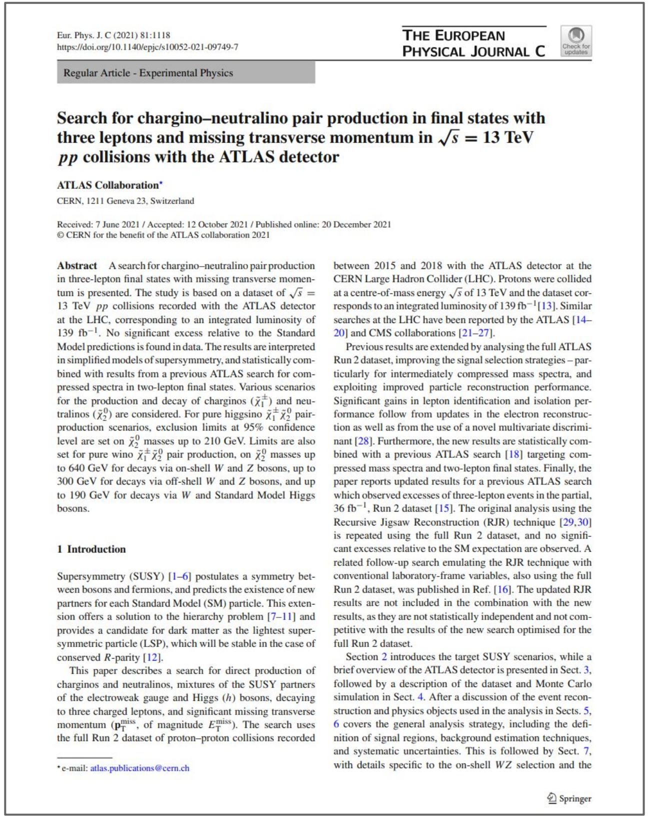



Detectors
Digitizers
LV1
μs
Front end pipelines
Readout buffers
Switching networks
HLT
sec
Processor farms



A step-by-step example: *electroweak, multi-lepton, soft*

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2019-09/



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THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Search for chargino–neutralino pair production in final states with three leptons and missing transverse momentum in $\sqrt{s} = 13$ TeV *pp* collisions with the ATLAS detector

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Abstract A search for chargino–neutralino pair production in three-lepton final states with missing transverse momentum is presented. The study is based on a dataset of $\sqrt{s} =$ 13 TeV *pp* collisions recorded with the ATLAS detector at the LHC, corresponding to an integrated luminosity of 139 fb^{-1}. No significant excess relative to the Standard Model predictions is found in data. The results are interpreted in simplified models of supersymmetry, and statistically combined with results from a previous ATLAS search for compressed spectra in two-lepton final states. Various scenarios for the production and decay of charginos ($\tilde{\chi}_1^{\pm}$) and neutralinos ($\tilde{\chi}_2^0$) are considered. For pure higgsino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ pair-production scenarios, exclusion limits at 95% confidence level are set on $\tilde{\chi}_2^0$ masses up to 210 GeV. Limits are also set for pure wino $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ pair production, on $\tilde{\chi}_2^0$ masses up to 640 GeV for decays via on-shell *W* and *Z* bosons, up to 300 GeV for decays via off-shell *W* and *Z* bosons, and up to 190 GeV for decays via *W* and Standard Model Higgs bosons.

1 Introduction

Supersymmetry (SUSY) [1–6] postulates a symmetry between bosons and fermions, and predicts the existence of new partners for each Standard Model (SM) particle. This extension offers a solution to the hierarchy problem [7–11] and provides a candidate for dark matter as the lightest supersymmetric particle (LSP), which will be stable in the case of conserved *R*-parity [12].

This paper describes a search for direct production of charginos and neutralinos, mixtures of the SUSY partners of the electroweak gauge and Higgs (*h*) bosons, decaying to three charged leptons, and significant missing transverse momentum ($\mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}$, of magnitude $E_{\mathrm{T}}^{\mathrm{miss}}$). The search uses the full Run 2 dataset of proton–proton collisions recorded between 2015 and 2018 with the ATLAS detector at the CERN Large Hadron Collider (LHC). Protons were collided at a centre-of-mass energy $\sqrt{s}$ of 13 TeV and the dataset corresponds to an integrated luminosity of 139 fb^{-1}[13]. Similar searches at the LHC have been reported by the ATLAS [14–20] and CMS collaborations [21–27].

Previous results are extended by analysing the full ATLAS Run 2 dataset, improving the signal selection strategies – particularly for intermediately compressed mass spectra, and exploiting improved particle reconstruction performance. Significant gains in lepton identification and isolation performance follow from updates in the electron reconstruction as well as from the use of a novel multivariate discriminant [28]. Furthermore, the new results are statistically combined with a previous ATLAS search [18] targeting compressed mass spectra and two-lepton final states. Finally, the paper reports updated results for a previous ATLAS search which observed excesses of three-lepton events in the partial, 36 fb^{-1}, Run 2 dataset [15]. The original analysis using the Recursive Jigsaw Reconstruction (RJR) technique [29,30] is repeated using the full Run 2 dataset, and no significant excesses relative to the SM expectation are observed. A related follow-up search emulating the RJR technique with conventional laboratory-frame variables, also using the full Run 2 dataset, was published in Ref. [16]. The updated RJR results are not included in the combination with the new results, as they are not statistically independent and not competitive with the results of the new search optimised for the full Run 2 dataset.

Section 2 introduces the target SUSY scenarios, while a brief overview of the ATLAS detector is presented in Sect. 3, followed by a description of the dataset and Monte Carlo simulation in Sect. 4. After a discussion of the event reconstruction and physics objects used in the analysis in Sects. 5, 6 covers the general analysis strategy, including the definition of signal regions, background estimation techniques, and systematic uncertainties. This is followed by Sect. 7, with details specific to the on-shell *WZ* selection and the

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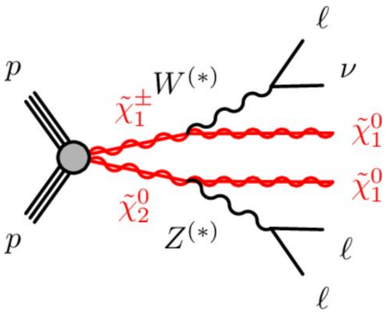
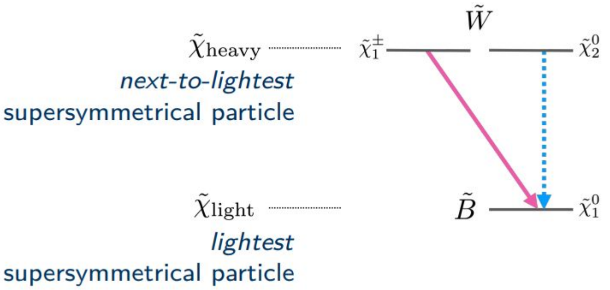




next-to-lightest
supersymmetrical particle

lightest
supersymmetrical particle

Search for SUSY with (intermediately) compressed spectra (Run 2, 2020) → *electroweak production, 3 soft leptons*

- data-driven fake/non-prompt lepton background estimate
- soft-lepton performance is key
- interpretation for different scenarios: wino-bino / higgsino
- combination with soft-2 lepton results
- strong improvement over Run 1 / early Run 2, in some areas LHC limit not yet much beyond LEP results
- slight excess seen in dM = 10-20 GeV range

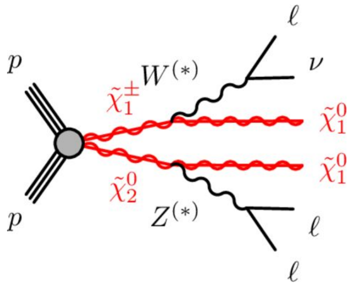
1) Targets

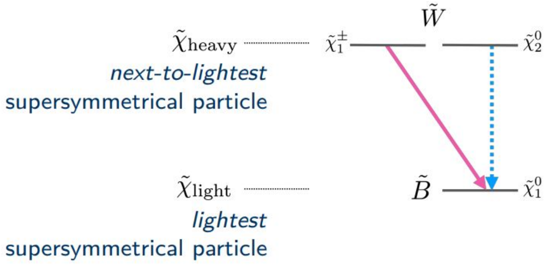
primary signature

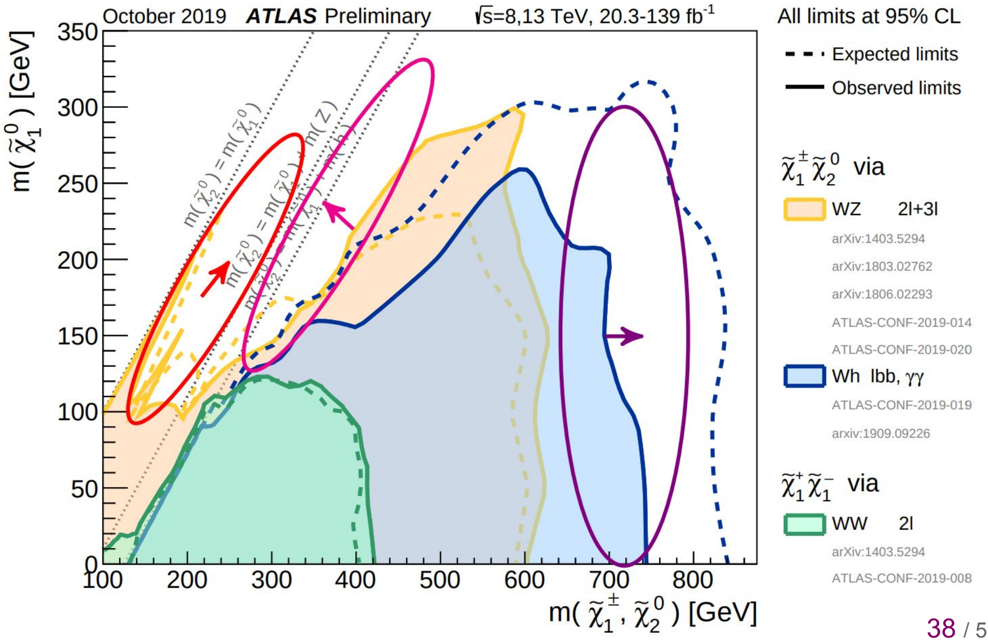
- electroweakino pair-production
- 3 (soft-) lepton + missing ET final state

challenges

- high mass: lower cross section
- near Z-mass: kinematic restrictions
- compressed/soft range: soft-particle reconstruction & identification







2a) signal selection - soft-lepton performance

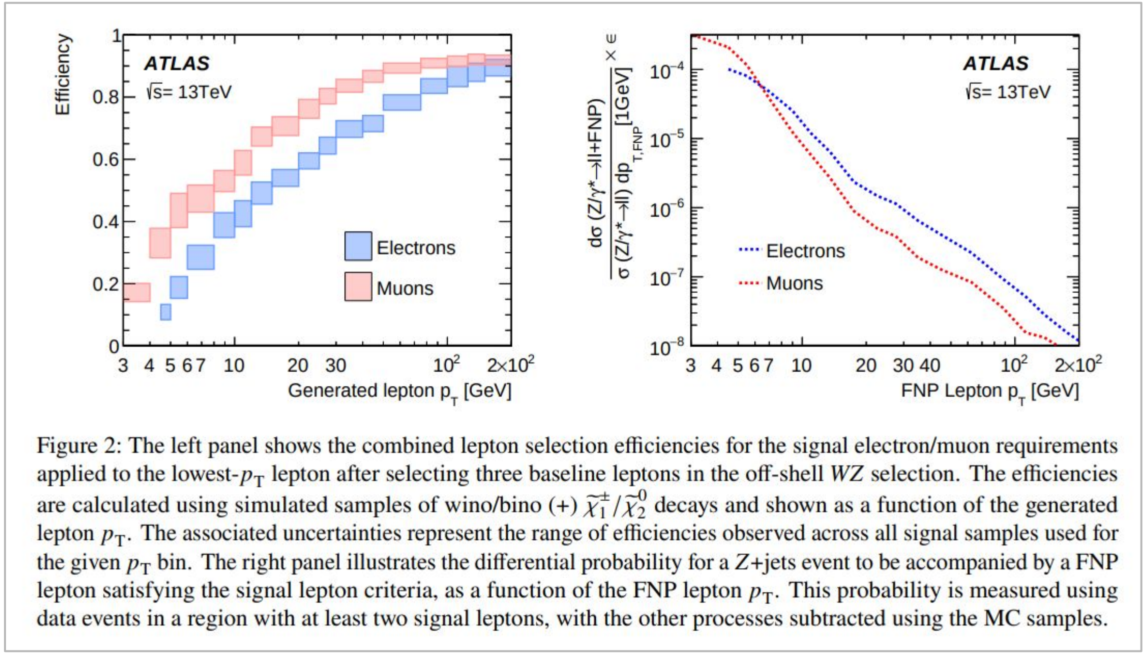
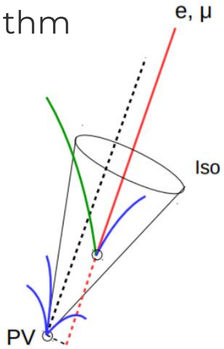


Figure 2: The left panel shows the combined lepton selection efficiencies for the signal electron/muon requirements applied to the lowest-p_T lepton after selecting three baseline leptons in the off-shell WZ selection. The efficiencies are calculated using simulated samples of wino/bino (+) $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ decays and shown as a function of the generated lepton p_T. The associated uncertainties represent the range of efficiencies observed across all signal samples used for the given p_T bin. The right panel illustrates the differential probability for a Z+jets event to be accompanied by a FNP lepton satisfying the signal lepton criteria, as a function of the FNP lepton p_T. This probability is measured using data events in a region with at least two signal leptons, with the other processes subtracted using the MC samples.

challenges

- reconstruction and identification down to pT~4.5/3 GeV for electrons/muons
- a challenge for trigger selection (use di-lepton & missing ET)
- lowest range affected by fake/non-prompt lepton background, mitigated by using
  - additional identification algorithm
  - data-driven fake lepton estimate



2b) signal selection - multiple categories

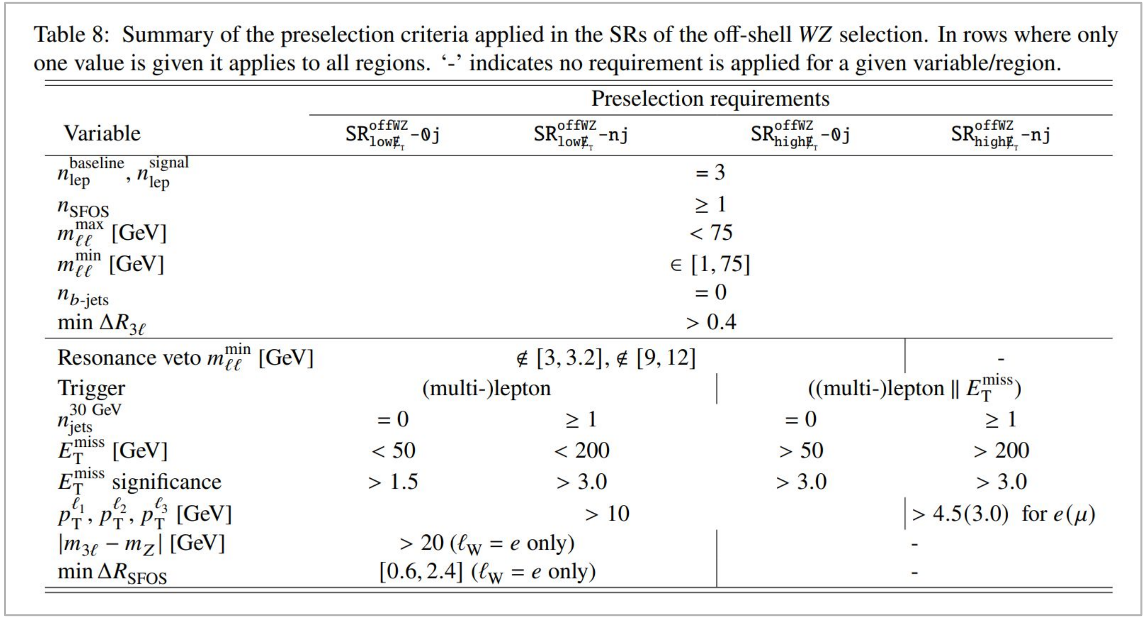


Table 8: Summary of the preselection criteria applied in the SRs of the off-shell *WZ* selection. In rows where only one value is given it applies to all regions. '-' indicates no requirement is applied for a given variable/region.

Variable	Preselection requirements			
	$\mathrm{SR}^{\mathtt{offWZ}}_{\mathtt{low}\not{E}_{T}}\mathtt{-0j}$	$\mathrm{SR}^{\mathtt{offWZ}}_{\mathtt{low}\not{E}_{T}}\mathtt{-nj}$	$\mathrm{SR}^{\mathtt{offWZ}}_{\mathtt{high}\not{E}_{T}}\mathtt{-0j}$	$\mathrm{SR}^{\mathtt{offWZ}}_{\mathtt{high}\not{E}_{T}}\mathtt{-nj}$
$n_{\text{lep}}^{\text{baseline}}, n_{\text{lep}}^{\text{signal}}$	$= 3$			
n_{SFOS}	≥ 1			
$m_{\ell\ell}^{\max}$ [GeV]	< 75			
$m_{\ell\ell}^{\min}$ [GeV]	$\in [1, 75]$			
$n_{b\text{-jets}}$	$= 0$			
min $\Delta R_{3\ell}$	> 0.4			
Resonance veto $m_{\ell\ell}^{\min}$ [GeV]	$\notin [3, 3.2], \notin [9, 12]$			-
Trigger	(multi-)lepton		((multi-)lepton || $E_{\text{T}}^{\text{miss}}$)	
$n_{\text{jets}}^{30\text{ GeV}}$	$= 0$	≥ 1	$= 0$	≥ 1
$E_{\text{T}}^{\text{miss}}$ [GeV]	< 50	< 200	> 50	> 200
$E_{\text{T}}^{\text{miss}}$ significance	> 1.5	> 3.0	> 3.0	> 3.0
$p_{\text{T}}^{\ell_1}, p_{\text{T}}^{\ell_2}, p_{\text{T}}^{\ell_3}$ [GeV]	> 10			$> 4.5(3.0)$ for $e(\mu)$
$\|m_{3\ell} - m_Z\|$ [GeV]	> 20 ($\ell_{\text{W}} = e$ only)		-	
min ΔR_{SFOS}	$[0.6, 2.4]$ ($\ell_{\text{W}} = e$ only)		-	

features

- different expected dominant SM backgrounds
- different trigger handles
- different selection (S/B) handles

\+ each further binned in di-lepton invariant mass mll to target range of SUSY signals (sparticle masses)

2c) signal selection - observables

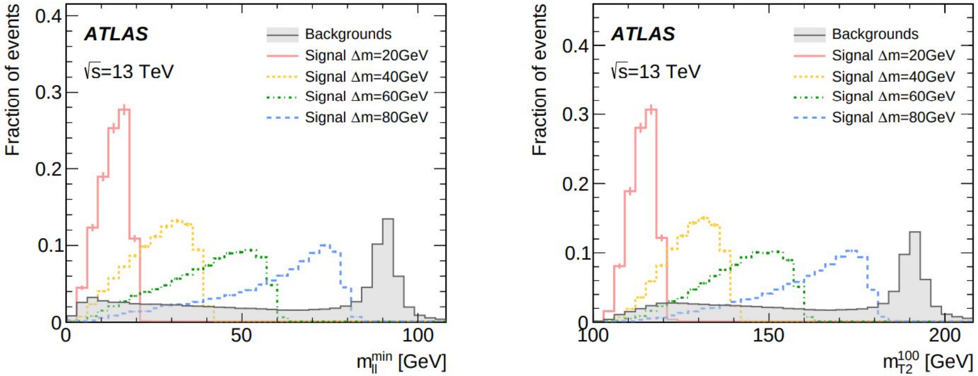


Figure 6: Distributions of (left) $m_{\ell\ell}^{\mathrm{min}}$ and (right) m_{T2}^{100} showing the expected SM background as well as signals with various mass splittings $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ ($m(\tilde{\chi}_1^{\pm}) = m(\tilde{\chi}_2^0) = 200$ GeV), for a selection of exactly three baseline and signal leptons. The distributions are normalised to unity. Signals demonstrate a cut-off in both variables matching the mass splitting, while backgrounds do not. The dominant background in this selection is WZ, with the Z-boson mass peak visible in both distributions.

features

- exploit e.g. invariant mass or transverse mass to distinguish signal and background contributions
- can also distinguish between different signal mass hypothesis

2) Background estimation - Monte Carlo simulation

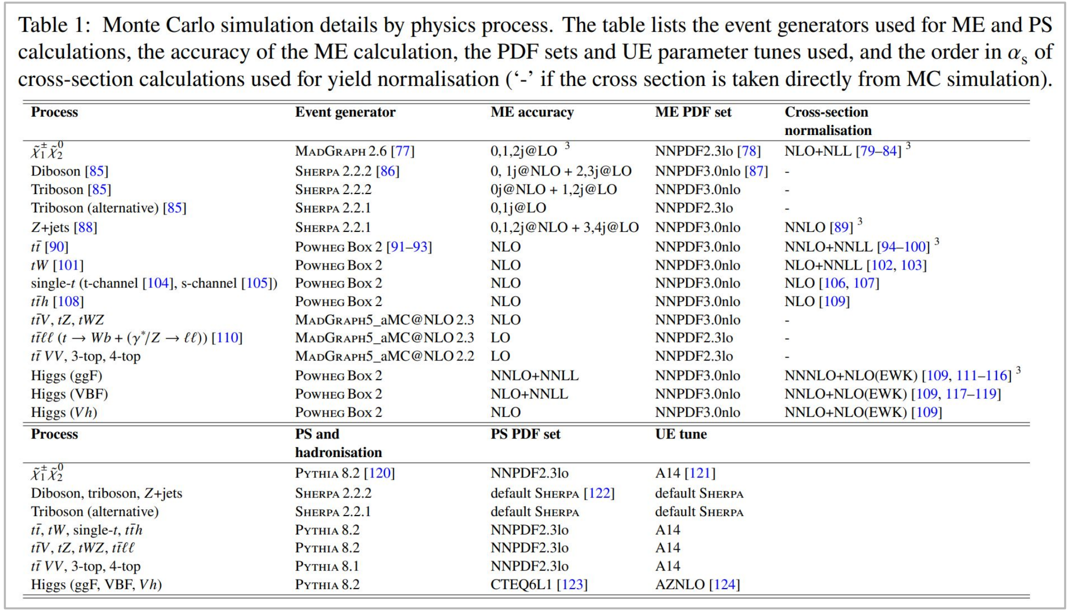


Table 1: Monte Carlo simulation details by physics process. The table lists the event generators used for ME and PS calculations, the accuracy of the ME calculation, the PDF sets and UE parameter tunes used, and the order in α_s of cross-section calculations used for yield normalisation ('-' if the cross section is taken directly from MC simulation).

Process	Event generator	ME accuracy	ME PDF set	Cross-section normalisation
$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$	MadGraph 2.6 [77]	0,1,2j@LO [3]	NNPDF2.3lo [78]	NLO+NLL [79–84] [3]
Diboson [85]	Sherpa 2.2.2 [86]	0, 1j@NLO + 2,3j@LO	NNPDF3.0nlo [87]	-
Triboson [85]	Sherpa 2.2.2	0j@NLO + 1,2j@LO	NNPDF3.0nlo	-
Triboson (alternative) [85]	Sherpa 2.2.1	0,1j@LO	NNPDF2.3lo	-
Z+jets [88]	Sherpa 2.2.1	0,1,2j@NLO + 3,4j@LO	NNPDF3.0nlo	NNLO [89] [3]
$t\bar{t}$ [90]	Powheg Box 2 [91–93]	NLO	NNPDF3.0nlo	NNLO+NNLL [94–100] [3]
tW [101]	Powheg Box 2	NLO	NNPDF3.0nlo	NLO+NNLL [102, 103]
single-t (t-channel [104], s-channel [105])	Powheg Box 2	NLO	NNPDF3.0nlo	NLO [106, 107]
$t\bar{t}h$ [108]	Powheg Box 2	NLO	NNPDF3.0nlo	NLO [109]
$t\bar{t}V$, tZ, tWZ	MadGraph5_aMC@NLO 2.3	NLO	NNPDF3.0nlo	-
$t\bar{t}\ell\ell$ ($t \rightarrow Wb + (\gamma^*/Z \rightarrow \ell\ell)$) [110]	MadGraph5_aMC@NLO 2.3	LO	NNPDF2.3lo	-
$t\bar{t}\,VV$, 3-top, 4-top	MadGraph5_aMC@NLO 2.2	LO	NNPDF2.3lo	-
Higgs (ggF)	Powheg Box 2	NNLO+NNLL	NNPDF3.0nlo	NNNLO+NLO(EWK) [109, 111–116] [3]
Higgs (VBF)	Powheg Box 2	NLO+NNLL	NNPDF3.0nlo	NNLO+NLO(EWK) [109, 117–119]
Higgs (Vh)	Powheg Box 2	NLO	NNPDF3.0nlo	NNLO+NLO(EWK) [109]

Process	PS and hadronisation	PS PDF set	UE tune
$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$	Pythia 8.2 [120]	NNPDF2.3lo	A14 [121]
Diboson, triboson, Z+jets	Sherpa 2.2.2	default Sherpa [122]	default Sherpa
Triboson (alternative)	Sherpa 2.2.1	default Sherpa	default Sherpa
$t\bar{t}$, tW, single-t, $t\bar{t}h$	Pythia 8.2	NNPDF2.3lo	A14
$t\bar{t}V$, tZ, tWZ, $t\bar{t}\ell\ell$	Pythia 8.2	NNPDF2.3lo	A14
$t\bar{t}\,VV$, 3-top, 4-top	Pythia 8.1	NNPDF2.3lo	A14
Higgs (ggF, VBF, Vh)	Pythia 8.2	CTEQ6L1 [123]	AZNLO [124]

Dominant backgrounds

- SM diboson WZ production → CR/VR
- Fake/non-prompt leptons → data-driven
- ttbar, Z+jets, W+jets → MC/VR
- triboson, rare-top, Higgs, … → MC

2a) Background estimation - (semi-)data-driven estimates

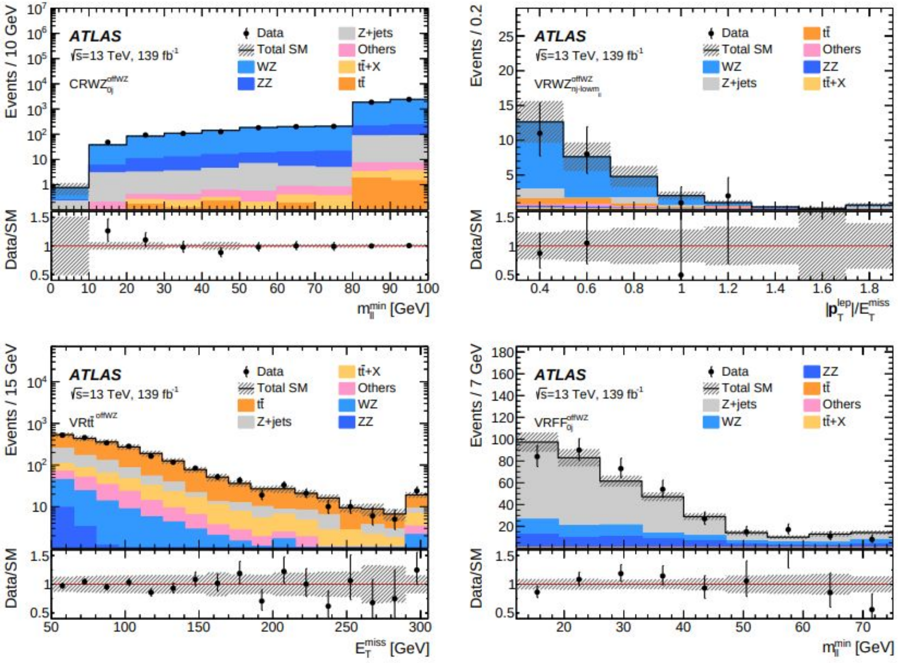


Figure 7: Example kinematic distributions after the background-only fit, showing the data and the post-fit expected background, in regions of the off-shell WZ selection. The figure shows (top left) the $m_{\ell\ell}^{\mathrm{min}}$ distribution in $\mathtt{CRWZ}_{0j}^{\mathtt{offWZ}}$, (top right) the $|\mathbf{p}_{\mathrm{T}}^{\mathrm{lep}}|/E_{\mathrm{T}}^{\mathrm{miss}}$ distribution in $\mathtt{VRWZ}_{\mathtt{nj\text{-}lowm}_{\ell\ell}}^{\mathtt{offWZ}}$, (bottom left) the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution in $\mathtt{VRt\bar{t}}^{\mathtt{offWZ}}$, and (bottom right) the $m_{\ell\ell}^{\mathrm{min}}$ distribution in $\mathtt{VRFF}_{0j}^{\mathtt{offWZ}}$. The last bin includes overflow. The 'Others' category contains backgrounds from single-top, WW, triboson, Higgs and rare top processes. The bottom panel shows the ratio of the observed data to the predicted yields. The hatched bands indicate the combined theoretical, experimental, and MC statistical uncertainties. The slope change in the bottom left $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution illustrates the selection extension with $E_{\mathrm{T}}^{\mathrm{miss}}$ triggered events, which start contributing at $E_{\mathrm{T}}^{\mathrm{miss}} \gtrsim 200$ GeV.

In many cases

use MC & normalise to data

- CR+VR control & validation approach
- normalisation factors can be added in combined statistical interpretation

or e.g. when MC is less reliable / low statistics

fully data-driven estimate

- dedicated measurement selection
- transfer to VR/SR estimate

3) Systematical uncertainties

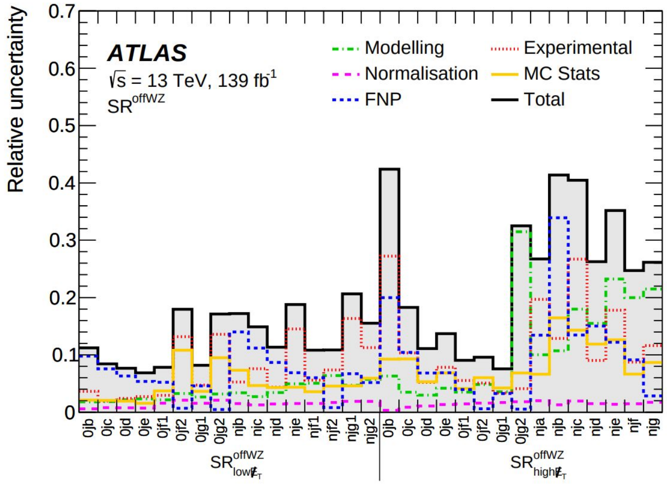


Figure 9: Breakdown of the total systematic uncertainties in the background prediction for the SRs of the off-shell *WZ* selection.

Uncertainties

- statistical uncertainties
- experimental uncertainties
  → object reconstruction, identification, ...
- theoretical uncertainties
  → MC modelling: matrix element, parton shower
- analysis method uncertainties
  → background normalisation
  → data-driven fake lepton estimate

→ uncertainties can be correlated!

→ not all are equally important in all ranges

→ some are inherent, some can be improved using the right analysis techniques

2+3) Before “unblinding”

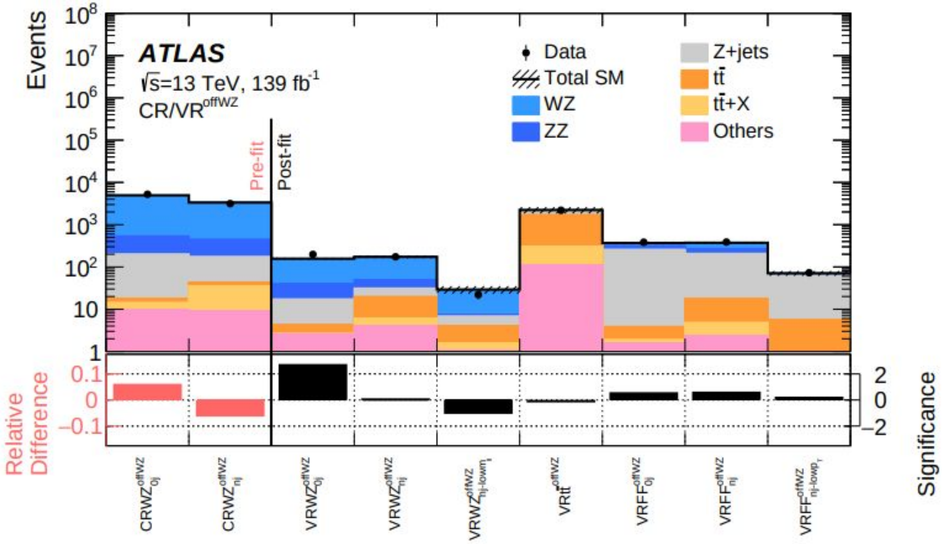


Figure 8: Comparison of the observed data and expected SM background yields in the CRs and VRs of the off-shell *WZ* selection. The SM prediction is taken from the background-only fit. The ‘Others’ category contains the single-top, *WW*, triboson, Higgs and rare top processes. The hatched band indicates the combined theoretical, experimental, and MC statistical uncertainties. The bottom panel shows the significance of the difference between the observed and expected yields, calculated with the profile likelihood method from Ref. [169], adding a minus sign if the yield is below the prediction.

Before opening the box

- all estimates, validation, and uncertainty checks done before looking at the actual data in the target region
- behaviour of statistical interpretation aka. the “fit”, also validated with the background-only hypothesis

4) Results

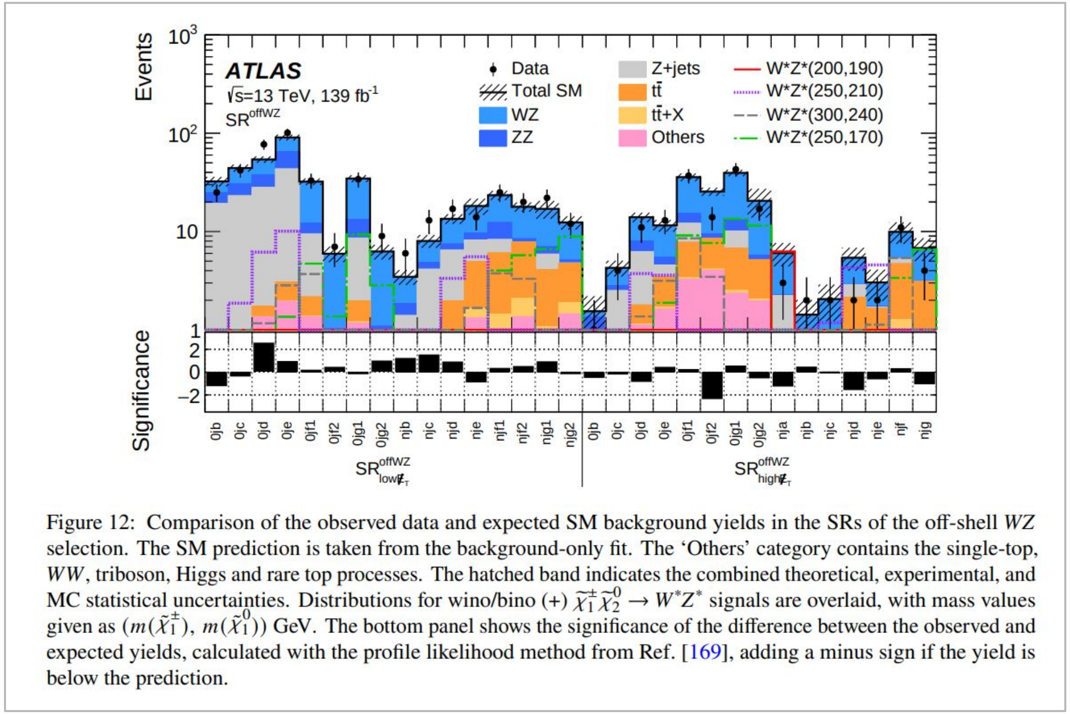
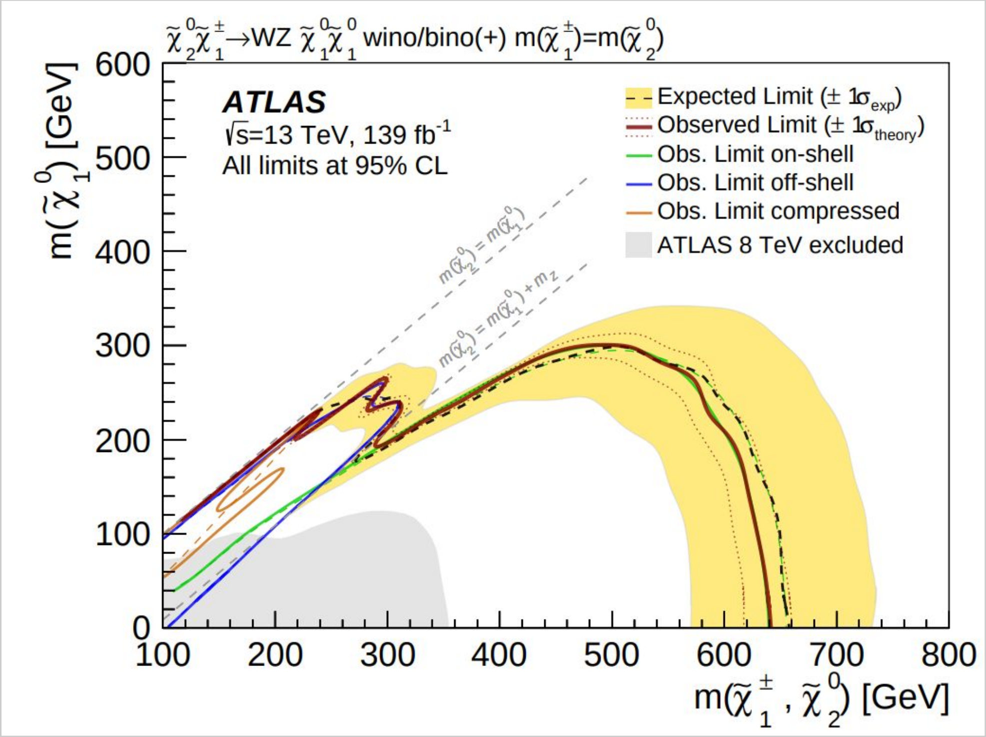


Figure 12: Comparison of the observed data and expected SM background yields in the SRs of the off-shell *WZ* selection. The SM prediction is taken from the background-only fit. The 'Others' category contains the single-top, *WW*, triboson, Higgs and rare top processes. The hatched band indicates the combined theoretical, experimental, and MC statistical uncertainties. Distributions for wino/bino (+) $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to W^*Z^*$ signals are overlaid, with mass values given as $(m(\tilde{\chi}_1^{\pm}), m(\tilde{\chi}_1^0))$ GeV. The bottom panel shows the significance of the difference between the observed and expected yields, calculated with the profile likelihood method from Ref. [169], adding a minus sign if the yield is below the prediction.

"Unblinding" the target signal regions

- look at actual observed data yields in target signal regions
- verify compatibility with background-only hypothesis

4a) Results - model-dependent → limits on SUSY models



Also compare with signal+background hypothesis for specific signal models

- if no excess → set limits on the tested model
- various assumptions included in interpretation:
  cross sections, branching fractions, SUSY particle mass hierarchy, …
- multiple interpretations can be done with the same search data
- including later re-interpretations!
  → provide additional info (e.g. acceptance and efficiency numbers) for theorists

4b) Results - model-independent

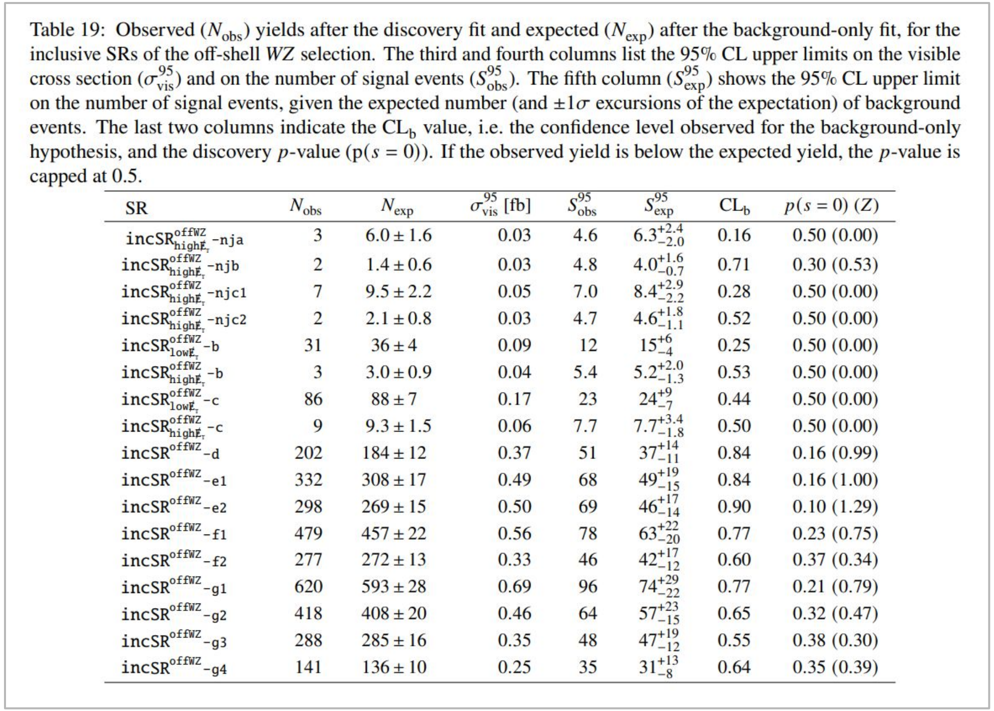


Table 19: Observed (N_{obs}) yields after the discovery fit and expected (N_{exp}) after the background-only fit, for the inclusive SRs of the off-shell *WZ* selection. The third and fourth columns list the 95% CL upper limits on the visible cross section ($\sigma^{95}_{\mathrm{vis}}$) and on the number of signal events (S^{95}_{obs}). The fifth column (S^{95}_{exp}) shows the 95% CL upper limit on the number of signal events, given the expected number (and $\pm 1\sigma$ excursions of the expectation) of background events. The last two columns indicate the $\mathrm{CL_b}$ value, i.e. the confidence level observed for the background-only hypothesis, and the discovery *p*-value ($\mathrm{p}(s = 0)$). If the observed yield is below the expected yield, the *p*-value is capped at 0.5.

SR	N_{obs}	N_{exp}	$\sigma^{95}_{\mathrm{vis}}$ [fb]	S^{95}_{obs}	S^{95}_{exp}	$\mathrm{CL_b}$	$p(s = 0)$ (Z)
$\mathtt{incSR}^{\mathtt{offWZ}}_{\mathtt{high}\not{E}_{T}}\mathtt{-nja}$	3	6.0 ± 1.6	0.03	4.6	$6.3^{+2.4}_{-2.0}$	0.16	0.50 (0.00)
$\mathtt{incSR}^{\mathtt{offWZ}}_{\mathtt{high}\not{E}_{T}}\mathtt{-njb}$	2	1.4 ± 0.6	0.03	4.8	$4.0^{+1.6}_{-0.7}$	0.71	0.30 (0.53)
$\mathtt{incSR}^{\mathtt{offWZ}}_{\mathtt{high}\not{E}_{T}}\mathtt{-njc1}$	7	9.5 ± 2.2	0.05	7.0	$8.4^{+2.9}_{-2.2}$	0.28	0.50 (0.00)
$\mathtt{incSR}^{\mathtt{offWZ}}_{\mathtt{high}\not{E}_{T}}\mathtt{-njc2}$	2	2.1 ± 0.8	0.03	4.7	$4.6^{+1.8}_{-1.1}$	0.52	0.50 (0.00)
$\mathtt{incSR}^{\mathtt{offWZ}}_{\mathtt{low}\not{E}_{T}}\mathtt{-b}$	31	36 ± 4	0.09	12	15^{+6}_{-4}	0.25	0.50 (0.00)
$\mathtt{incSR}^{\mathtt{offWZ}}_{\mathtt{high}\not{E}_{T}}\mathtt{-b}$	3	3.0 ± 0.9	0.04	5.4	$5.2^{+2.0}_{-1.3}$	0.53	0.50 (0.00)
$\mathtt{incSR}^{\mathtt{offWZ}}_{\mathtt{low}\not{E}_{T}}\mathtt{-c}$	86	88 ± 7	0.17	23	24^{+9}_{-7}	0.44	0.50 (0.00)
$\mathtt{incSR}^{\mathtt{offWZ}}_{\mathtt{high}\not{E}_{T}}\mathtt{-c}$	9	9.3 ± 1.5	0.06	7.7	$7.7^{+3.4}_{-1.8}$	0.50	0.50 (0.00)
$\mathtt{incSR}^{\mathtt{offWZ}}\mathtt{-d}$	202	184 ± 12	0.37	51	37^{+14}_{-11}	0.84	0.16 (0.99)
$\mathtt{incSR}^{\mathtt{offWZ}}\mathtt{-e1}$	332	308 ± 17	0.49	68	49^{+19}_{-15}	0.84	0.16 (1.00)
$\mathtt{incSR}^{\mathtt{offWZ}}\mathtt{-e2}$	298	269 ± 15	0.50	69	46^{+17}_{-14}	0.90	0.10 (1.29)
$\mathtt{incSR}^{\mathtt{offWZ}}\mathtt{-f1}$	479	457 ± 22	0.56	78	63^{+22}_{-20}	0.77	0.23 (0.75)
$\mathtt{incSR}^{\mathtt{offWZ}}\mathtt{-f2}$	277	272 ± 13	0.33	46	42^{+17}_{-12}	0.60	0.37 (0.34)
$\mathtt{incSR}^{\mathtt{offWZ}}\mathtt{-g1}$	620	593 ± 28	0.69	96	74^{+29}_{-22}	0.77	0.21 (0.79)
$\mathtt{incSR}^{\mathtt{offWZ}}\mathtt{-g2}$	418	408 ± 20	0.46	64	57^{+23}_{-15}	0.65	0.32 (0.47)
$\mathtt{incSR}^{\mathtt{offWZ}}\mathtt{-g3}$	288	285 ± 16	0.35	48	47^{+19}_{-12}	0.55	0.38 (0.30)
$\mathtt{incSR}^{\mathtt{offWZ}}\mathtt{-g4}$	141	136 ± 10	0.25	35	31^{+13}_{-8}	0.64	0.35 (0.39)

Beyond results for a specific model, we can also test for the presence of any general BSM signal

- limits on the cross section
- often in more generalized (combinations) of signal regions, given optimisation for specific signal features

4b) Results - combination with other results

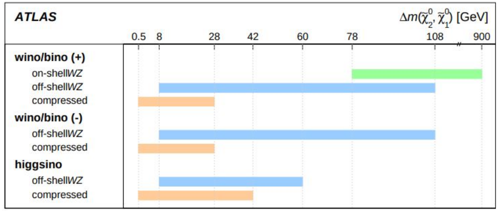
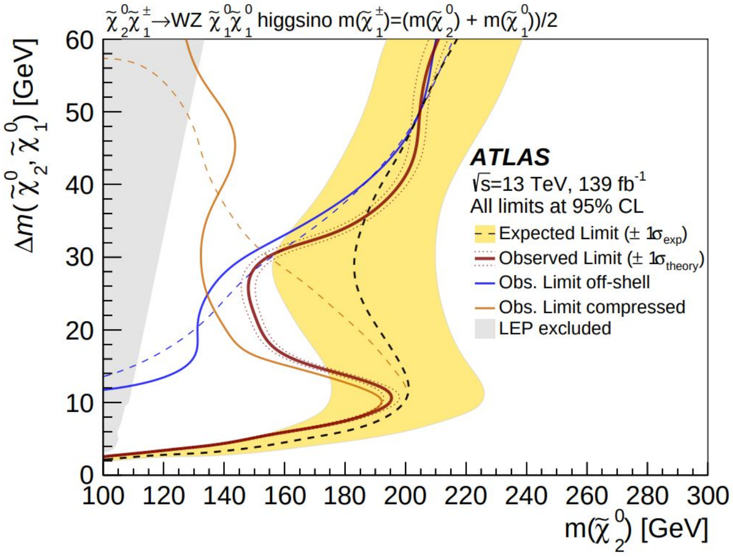
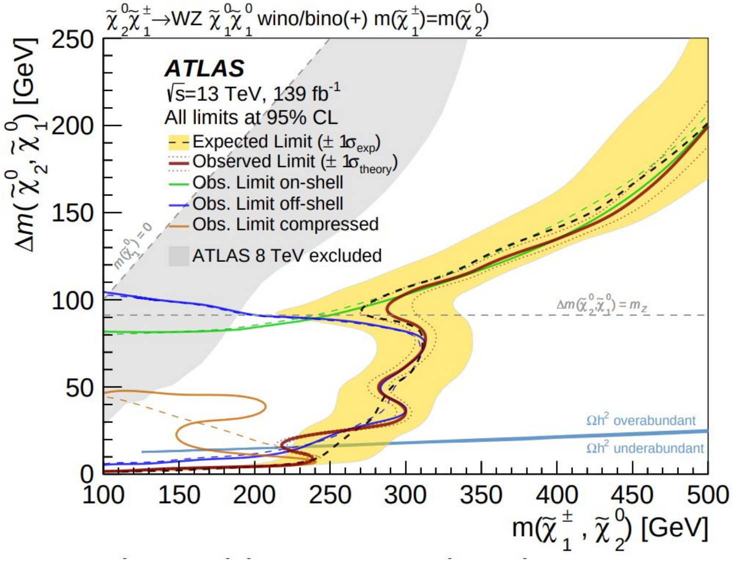


Figure 15: Illustration of the selections considered for the combined result for each scenario, dependent on Δm.

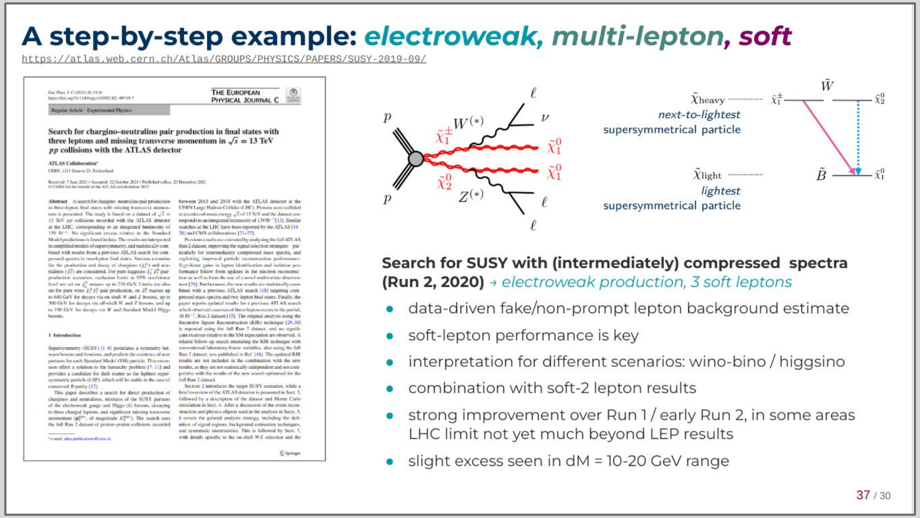
Maximise sensitivity combining results

- soft 3-lepton and even softer 2-lepton results provide sensitivity in compatible range
- (expected) reach for combination has to be stronger than individual results!





REMEMBER



A step-by-step example: *electroweak, multi-lepton, soft*

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2019-09/

The European Physical Journal C

Regular Article - Experimental Physics

Search for chargino–neutralino pair production in final states with three leptons and missing transverse momentum in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector

ATLAS Collaboration

Search for SUSY with (intermediately) compressed spectra (Run 2, 2020) → *electroweak production, 3 soft leptons*

- data-driven fake/non-prompt lepton background estimate
- soft-lepton performance is key
- interpretation for different scenarios: wino-bino / higgsino
- combination with soft-2 lepton results
- strong improvement over Run 1 / early Run 2, in some areas LHC limit not yet much beyond LEP results
- slight excess seen in dM = 10-20 GeV range

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We looked at 1 complete step-by-step example of a search for *electroweak production of supersymmetry with compressed spectra*

For those who are curious, I point to 4 slightly different types of searches/studies

- *example 2:* strong production
- *example 3:* long lived particles
- *example 4:* statistical combination
- *example 5:* global interpretation

Example 2: Strong

Example 3: Long-Lived particles → Displaced Leptons

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2024-011/
https://cms-results.web.cern.ch/cms-results/public-results/publications/EXO-23-014/

ATLAS CONF Note
ATLAS-CONF-2024-011
July 23, 2024

Search for displaced leptons in 13 TeV and 13.6 TeV
***p p* collisions with the ATLAS detector**

The

A search for leptons, displaced from
a center-of-mass energy of 13.6 Te
Hadron Collider is presented. The
$\sqrt{s}$ = 13 TeV proton–proton collis
partial $\sqrt{s}$ = 13.6 TeV Run 3 datase
luminosity of 56.3 fb^{-1}. Final states
novel triggers introduced in Run 3
displaced tracks with low moment
techniques are employed to broade
highly displaced electrons, respecti
background expectations and are u
displaced electrons and muons. T
mediated supersymmetry breaking
include 95% CL exclusions of sele
to 70 ns, and of selectrons, smuons
840 GeV, and 380 GeV, respectively

ATLAS-CONF-2024-011
23 July 2024

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Search for long-lived particles decaying to final states with a pair of muons in proton-proton collisions at $\sqrt{s} = 13.6$ TeV

The CMS collaboration

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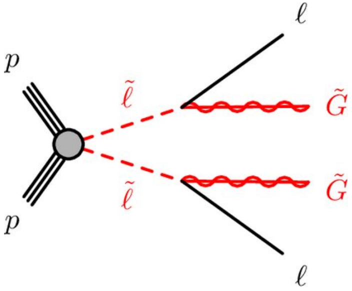
Abstract: An inclusive search for long-lived exotic particles (LLPs) decaying to final states with a pair of muons is presented. The search uses data corresponding to an integrated luminosity of 36.6 fb^{-1} collected by the CMS experiment from the proton-proton collisions at $\sqrt{s}$ = 13.6 TeV in 2022, the first year of Run 3 of the CERN LHC. The experimental signature is a pair of oppositely charged muons originating from a secondary vertex spatially separated from the proton-proton interaction point by distances ranging from several hundred μm to several meters. The sensitivity of the search benefits from new triggers for displaced dimuons developed for Run 3. The results are interpreted in the framework of the hidden Abelian Higgs model, in which the Higgs boson decays to a pair of long-lived dark photons, and of an *R*-parity violating supersymmetry model, in which long-lived neutralinos decay to a pair of muons and a neutrino. The limits set on these models are the most stringent to date in wide regions of lifetimes for LLPs with masses larger than 10 GeV.

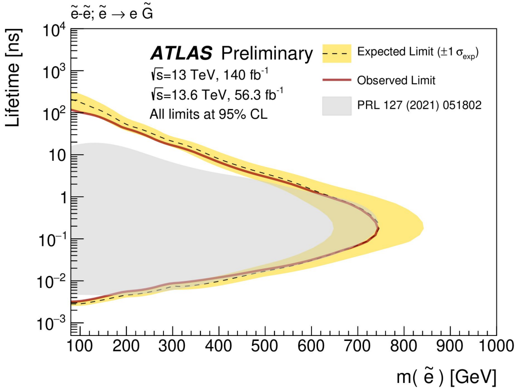
Keywords: Beyond Standard Model, Hadron-Hadron Scattering, Lifetime

ArXiv ePrint: 2402.14491

https://doi.org/10.1007/JHEP05(2024)047

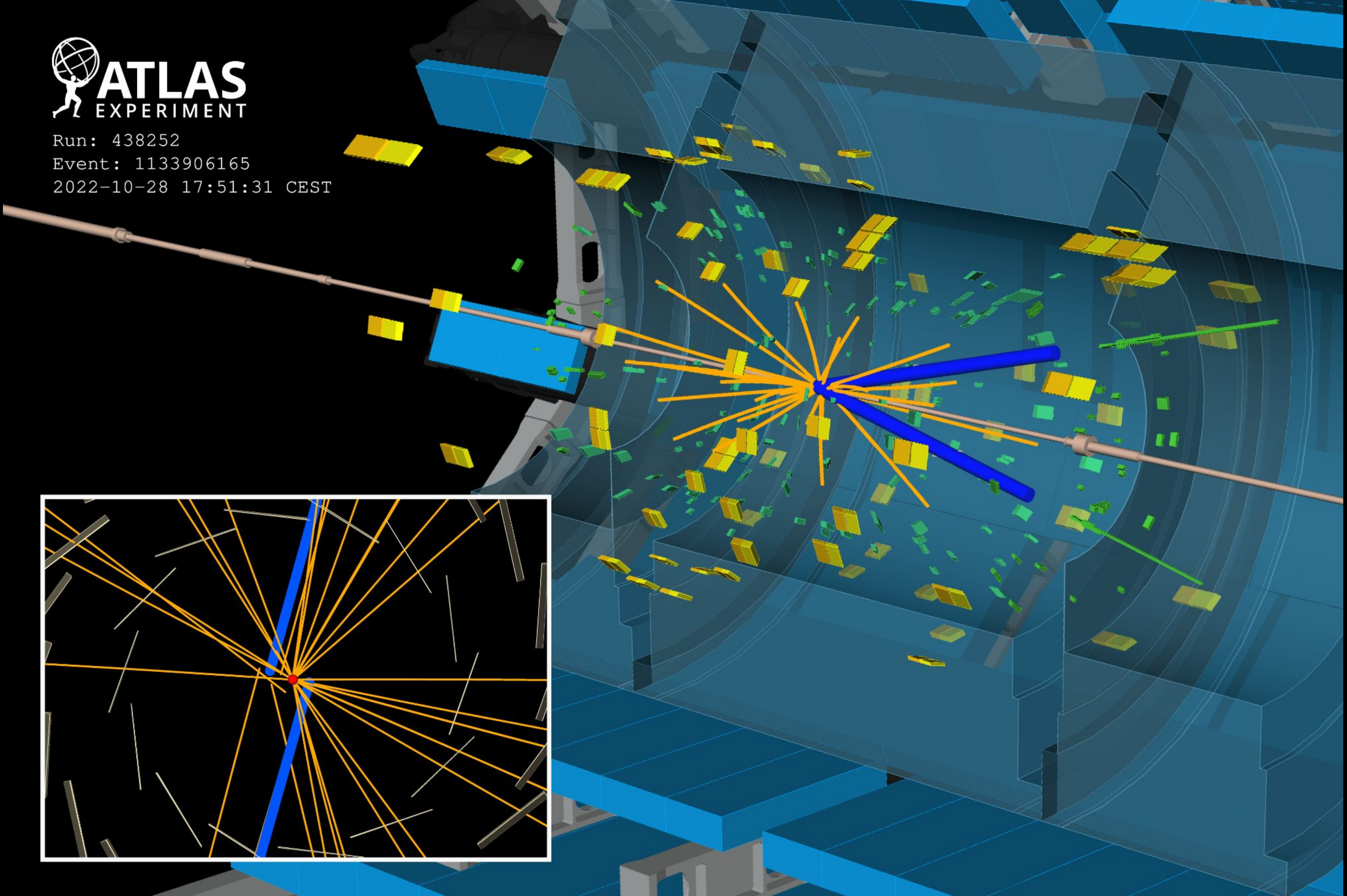
JHEP05(2024)047





Search for displaced leptons

- first ATLAS SUSY result with Run 2 + Run 3 data
- fully data-driven background estimation
  (low background target regions)
- dual approach
  - new large-radius track triggers for Run 3
    → gain from new data also with original analysis method
  - new analysis approach using calorimeter timing information
    → further gain from new methods


ATLAS EXPERIMENT
Run: 438252
Event: 1133906165
2022-10-28 17:51:31 CEST

Example 4: Electroweak Combination

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2020-05/
https://cms-results.web.cern.ch/cms-results/public-results/publications/SUS-21-008/

PHYSICAL REVIEW LETTERS **133,** 031802 (2024)

Statistical Combination of ATLAS Run 2 Searches for Charginos and Neutralinos at the LHC

G. Aad *et al.*[*]
(ATLAS Collaboration)

(Received 14 February 2024; accepted 7 June 2024; published 19 July 2024)

Statistical combinations of searches for charginos and neutralinos using various decay channels are performed using 139 fb^{-1} of pp collision data at $\sqrt{s} = 13$ TeV with the ATLAS detector at the Large Hadron Collider. Searches targeting pure-wino chargino pair production, pure-wino chargino-neutralino production, or Higgsino production decaying via standard model W, Z, or h bosons are combined to extend the mass reach to the produced supersymmetric particles by 30–100 GeV. The depth of the sensitivity of the original searches is also improved by the combinations, lowering the 95% C.L. cross-section upper limits by 15%–40%.

DOI: 10.1103/PhysRevLett.133.031802

Supersymmetry [1–7] (SUSY) proposes a superpartner for every standard model (SM) particle, where the spin differs by one half. It remains one of the more popular beyond the SM theories as it can provide solutions for the hierarchy problem, dark matter, and unification of the fundamental forces [8–11]. Naturalness arguments motivate some SUSY particles to be within reach of the LHC, namely the fermionic superpartners of the gauge and Higgs fields: the charginos $\tilde{\chi}^{\pm}_{1,2}$ and neutralinos $\tilde{\chi}^{0}_{1,2,3,4}$ [12,13]. The lightest neutralino $\tilde{\chi}^{0}_{1}$ (or the gravitino $\tilde{G}$ in general gauge mediated (GGM) SUSY [14–16]) is stable in the R-parity [17] conserving scenarios considered here and is an excellent dark matter candidate [18,19]. In these scenarios, charginos and neutralinos are produced in pairs at the LHC and decay into the $\tilde{\chi}^{0}_{1}$ or $\tilde{G}$ via SM bosons (where the SM boson decays follow SM branching fractions), assuming other SUSY particles are too heavy to play a role. With the limits on strongly produced SUSY particle masses exceeding ~2 TeV [20], electroweakly produced SUSY particles may dominate LHC SUSY production. Small production cross sections and decay modes with similar experimental signatures to SM processes make these some of the more challenging searches at the LHC.

The investigation of electroweakly produced SUSY particles by the ATLAS Collaboration [21–24] comprises searches with multiple final states targeting different production and intermediate decay modes. These searches are harmonized to allow for the statistical combination of the results, increasing the sensitivity to SUSY by broadening the mass reach and improving the cross-section reach. Combining results can be particularly powerful when the searches have different, but complementary, sensitivity to the same SUSY models. This Letter focuses on the pair production of pure-wino or pure-Higgsino next-to-lightest SUSY particles (NLSP) decaying into the lightest SUSY particle (LSP) via a SM boson. The Run 2 electroweak SUSY searches at ATLAS, corresponding to 139 fb^{-1} of pp LHC collision data at a center-of-mass energy of $\sqrt{s} = 13$ TeV, are statistically combined for each SUSY scenario shown in Fig. 1, as reported in Table I. The CMS Collaboration has also performed statistical combinations of their electroweak SUSY searches, found in Ref. [25].

To obtain the best sensitivity to a new physics signal through a statistical combination of the individual results, the searches used should be statistically independent and not overlap in their event selection for signal regions (SR) or control regions (CR). Overlap is avoided for the most part by requiring exclusive lepton multiplicity in any search selection, so that 0ℓ, 1ℓ, 2ℓ, 3ℓ, and 4ℓ searches (where $\ell = e, \mu$) are statistically independent. To achieve this, the searches adopted common loose selection criteria [38] at the very start of each analysis, allowing the free use of any further criteria without overlapping with other lepton multiplicities. The *All Hadronic*, *Multi-b*, and $1L$ searches found the veto of loose and low-p_{T} leptons detrimental to signal acceptance. To avoid this, a less stringent veto was adopted, [41] designed to reject events selected by 2ℓ or 3ℓ searches. The *2L compressed* search used an even looser muon definition; however, the search selection is unique enough to result in orthogonality to the others used in a combination. The harmonization procedure was adopted early in the ATLAS Run 2 search program and proved to be a keystone of this final combination effort.

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[*] Full author list given at the end of the Letter.

0031-9007/24/133(3)/031802(21) 031802-1

PHYSICAL REVIEW D **109,** 112001 (2024)

Combined search for electroweak production of winos, binos, higgsinos, and sleptons in proton-proton collisions at $\sqrt{s} = 13$ TeV

A. Hayrapetyan *et al.*[*]
(CMS Collaboration)

(Received 2 February 2024; accepted 19 March 2024; published 6 June 2024)

A combination of the results of several searches for the electroweak production of the supersymmetric partners of standard model bosons, and of charged leptons, is presented. All searches use proton-proton collision data at $\sqrt{s} = 13$ TeV recorded with the CMS detector at the LHC in 2016–2018. The analyzed data correspond to an integrated luminosity of up to 137 fb^{-1}. The results are interpreted in terms of simplified models of supersymmetry. Two new interpretations are added with this combination: a model spectrum with the bino as the lightest supersymmetric particle together with mass-degenerate Higgsinos decaying to the bino and a standard model boson, and the compressed-spectrum region of a previously studied model of slepton pair production. Improved analysis techniques are employed to optimize sensitivity for the compressed spectra in the wino and slepton pair production models. The results are consistent with expectations from the standard model. The combination provides a more comprehensive coverage of the model parameter space than the individual searches, extending the exclusion by up to 125 GeV, and also targets some of the intermediate gaps in the mass coverage.

DOI: 10.1103/PhysRevD.109.112001

I. INTRODUCTION

The standard model (SM), despite its success in describing the fundamental particles and their interactions, leaves several open questions in particle physics unanswered. Various extensions of the SM, such as supersymmetry (SUSY) [1–5], have been developed to address these questions. Supersymmetry potentially provides a solution to the hierarchy problem [6–8], as well as the unification of the gauge couplings at high energy scales [3,9]. Moreover, if R-parity [10] is conserved, the lightest SUSY particle (LSP) would be stable, and a potential dark matter candidate [11,12].

Supersymmetry introduces a fermionic (bosonic) superpartner for each boson (fermion) of the SM. The superpartners of the leptons are called sleptons; $\tilde{\ell}$ denotes the superpartner of lepton ℓ. Those of the SM $\mathrm{SU}(2)_{\mathrm{L}}$ and U(1) gauge fields before electroweak (EW) symmetry breaking are the winos and binos, respectively, collectively called gauginos. In the minimal SUSY theory, MSSM [2,13,14], a new complex Higgs doublet is added to the SM. The MSSM thus contains five Higgs bosons along with the four Higgsino superpartners of the two Higgs doublets. The bino, winos, and Higgsinos can mix among one another to form in total eight mass eigenstates (collectively, electroweakinos): two chargino pairs ($\tilde{\chi}^{\pm}_{1,2}$) and four neutralinos ($\tilde{\chi}^{0}_{1-4}$). While in some models $\tilde{\chi}^{0}_{1}$ is taken as the LSP, this assumption is not required. For example, models motivated by gauge-mediated SUSY breaking (GMSB) [15,16] introduce a Nambu-Goldstone boson goldstino ($\tilde{G}$) that may be identified with two of the chirality components of the superpartner of a graviton (gravitino), and be considered the LSP.

Interactions among the charginos, neutralinos, and sleptons occur with the same EW couplings as those of their SM partners. At the CERN LHC, the cross sections for production of these particles are correspondingly small compared with those for the SUSY partners of the strongly interacting SM particles (squarks and gluinos). Nevertheless, if the squarks and gluinos are more massive than the EW SUSY particles, the EW superpartners might be the only SUSY particles accessible at the LHC.

The ATLAS [17–44] and CMS [45–77] Collaborations have carried out extensive search programs that target final states that could result from the production and decay of EW interacting SUSY particles. The proton-proton (pp) collision energy $\sqrt{s}$ for Ref. [17] (ATLAS) was 7 TeV; for Refs. [18,19] (ATLAS) and [45–47] (CMS) it was 8 TeV; for all other searches it was 13 TeV. Given that the SUSY particle decays could result in more than one final state, these programs benefit from combining individual searches to maximally exploit the available data, and both collaborations have performed combined searches for EW

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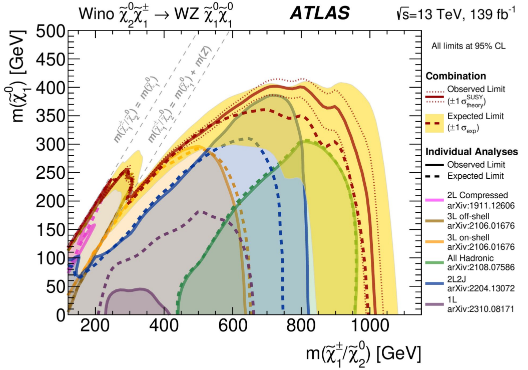
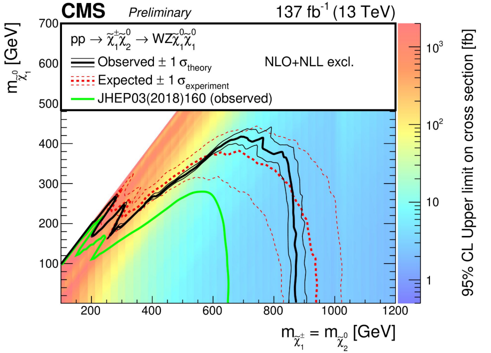
[*] Full author list given at the end of the article.

2470-0010/2024/109(11)/112001(37) 112001-1

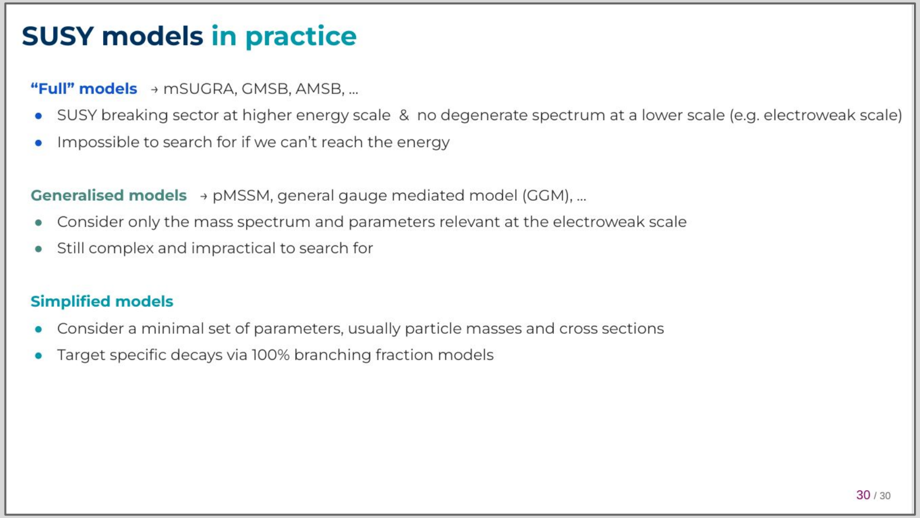




Statistical combination of Run 2 searches for charginos and neutralinos

- joining results from multiple searches for Electroweak SUSY, done by both ATLAS and CMS
- extending the mass reach, and strengthening the depth of exclusion
- reminder to always think carefully about analysis harmonisation and treatment of systematics

REMEMBER



SUSY models in practice

“Full” models → mSUGRA, GMSB, AMSB, ...

- SUSY breaking sector at higher energy scale & no degenerate spectrum at a lower scale (e.g. electroweak scale)
- Impossible to search for if we can’t reach the energy

Generalised models → pMSSM, general gauge mediated model (GGM), ...

- Consider only the mass spectrum and parameters relevant at the electroweak scale
- Still complex and impractical to search for

Simplified models

- Consider a minimal set of parameters, usually particle masses and cross sections
- Target specific decays via 100% branching fraction models

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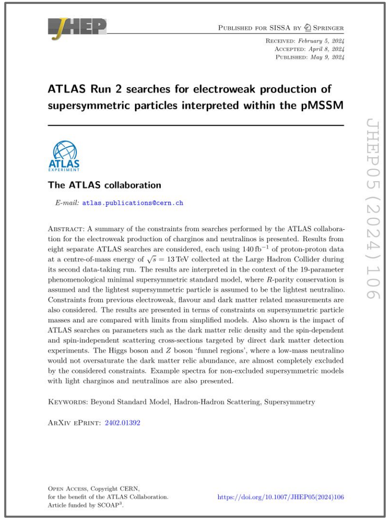
Global interpretation (of Run 2 results)
in the context of the 19-parameter phenomenological minimal supersymmetric standard model,
where R-parity conservation is assumed
and the lightest supersymmetric particle is assumed to be the lightest neutralino

→ *example in next slide*

Example 5: **pMSSM scan**

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2020-15/
https://indico.cern.ch/event/1291157/contributions/5887902/



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Received: February 5, 2024
Accepted: April 8, 2024
Published: May 9, 2024

ATLAS Run 2 searches for electroweak production of supersymmetric particles interpreted within the pMSSM

The ATLAS collaboration

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Abstract: A summary of the constraints from searches performed by the ATLAS collaboration for the electroweak production of charginos and neutralinos is presented. Results from eight separate ATLAS searches are considered, each using 140 fb^{-1} of proton-proton data at a centre-of-mass energy of $\sqrt{s} = 13$ TeV collected at the Large Hadron Collider during its second data-taking run. The results are interpreted in the context of the 19-parameter phenomenological minimal supersymmetric standard model, where R-parity conservation is assumed and the lightest supersymmetric particle is assumed to be the lightest neutralino. Constraints from previous electroweak, flavour and dark matter related measurements are also considered. The results are presented in terms of constraints on supersymmetric particle masses and are compared with limits from simplified models. Also shown is the impact of ATLAS searches on parameters such as the dark matter relic density and the spin-dependent and spin-independent scattering cross-sections targeted by direct dark matter detection experiments. The Higgs boson and Z boson 'funnel regions', where a low-mass neutralino would not oversaturate the dark matter relic abundance, are almost completely excluded by the considered constraints. Example spectra for non-excluded supersymmetric models with light charginos and neutralinos are also presented.

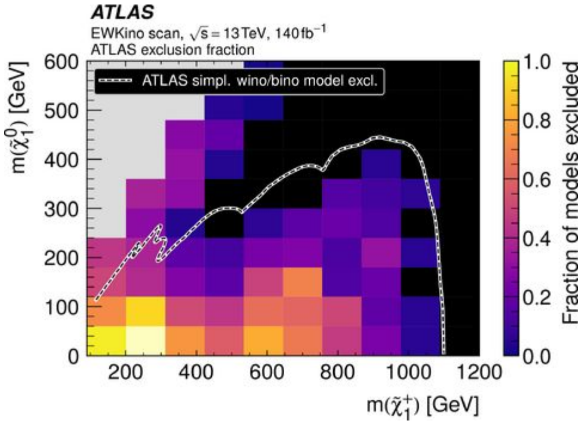
Keywords: Beyond Standard Model, Hadron-Hadron Scattering, Supersymmetry

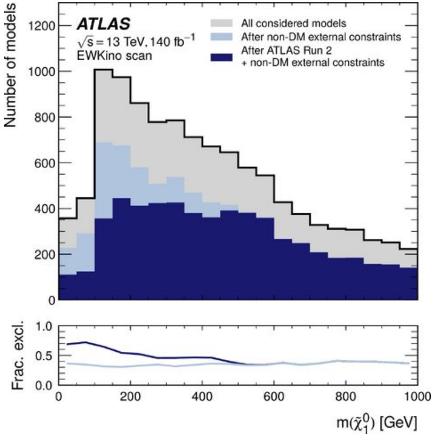
ArXiv ePrint: 2402.01392

https://doi.org/10.1007/JHEP05(2024)106

JHEP05(2024)106

CMS-SUS-24-004





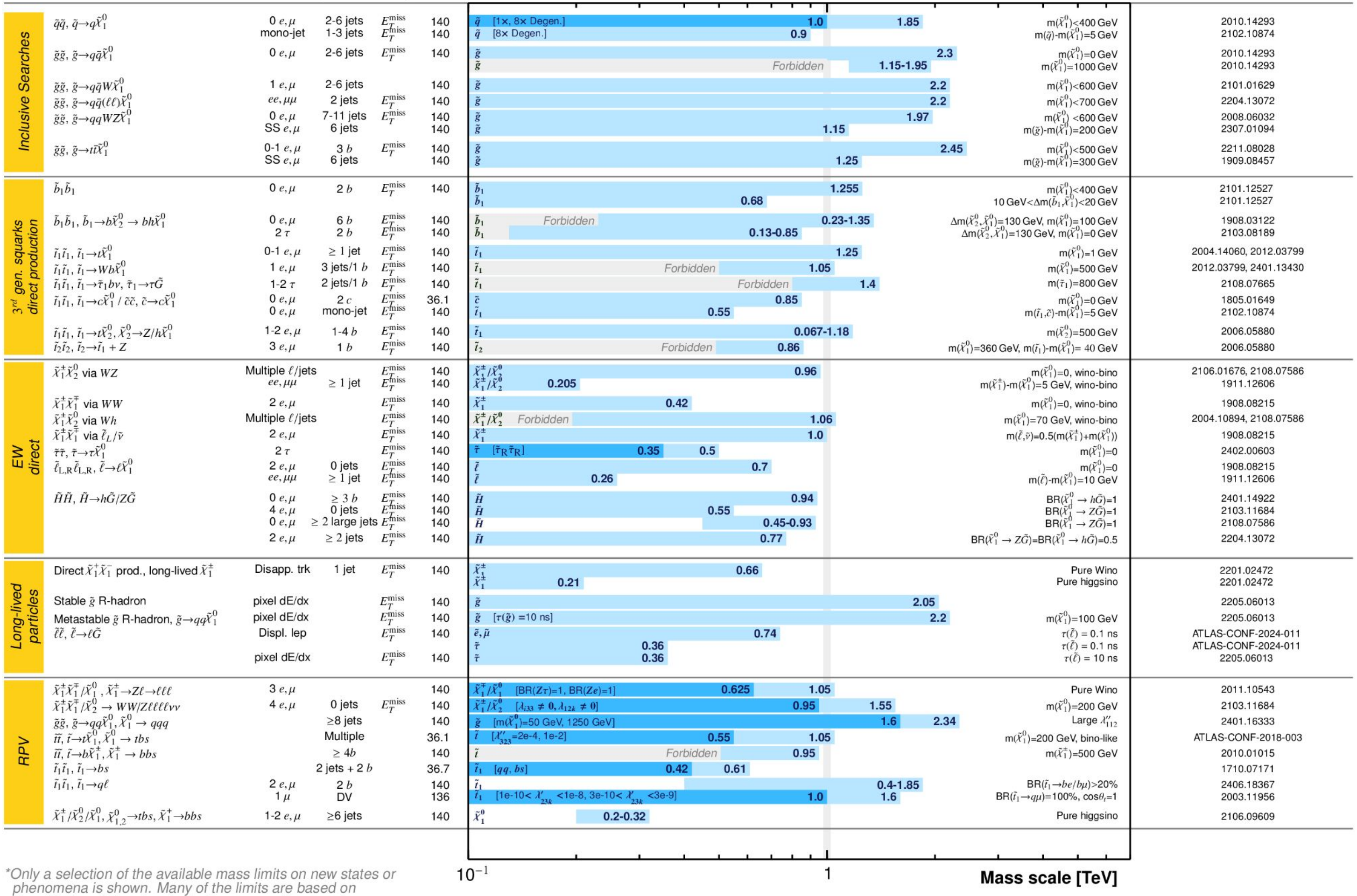
Global interpretation of Run 2 results, in the context of the 19-parameter pMSSM

- joining results from multiple searches for Electroweak SUSY, done by both ATLAS and CMS
- compare ATLAS & CMS impact in addition to external constraints as well

ATLAS SUSY Searches* - 95% CL Lower Limits

July 2024

ATLAS Preliminary
$\sqrt{s}$ = 13 TeV



	Model	Signature			$\int\mathcal{L}\,dt$ [fb^{-1}]	Mass limit		Reference
Inclusive Searches	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	140	$\tilde{q}$ [1×, 8× Degen.] 1.0 1.85	m($\tilde{\chi}_1^0$)<400 GeV	2010.14293
		mono-jet	1-3 jets	$E_T^{\rm miss}$	140	$\tilde{q}$ [8× Degen.] 0.9	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)=5 GeV	2102.10874
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0 e,μ	2-6 jets	$E_T^{\rm miss}$	140	$\tilde{g}$ 2.3	m($\tilde{\chi}_1^0$)=0 GeV	2010.14293
						$\tilde{g}$ Forbidden 1.15-1.95	m($\tilde{\chi}_1^0$)=1000 GeV	2010.14293
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}W\tilde{\chi}_1^0$	1 e,μ	2-6 jets		140	$\tilde{g}$ 2.2	m($\tilde{\chi}_1^0$)<600 GeV	2101.01629
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$	$ee,\mu\mu$	2 jets	$E_T^{\rm miss}$	140	$\tilde{g}$ 2.2	m($\tilde{\chi}_1^0$)<700 GeV	2204.13072
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}_1^0$	0 e,μ	7-11 jets	$E_T^{\rm miss}$	140	$\tilde{g}$ 1.97	m($\tilde{\chi}_1^0$) <600 GeV	2008.06032
		SS e,μ	6 jets		140	$\tilde{g}$ 1.15	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=200 GeV	2307.01094
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	$E_T^{\rm miss}$	140	$\tilde{g}$ 2.45	m($\tilde{\chi}_1^0$)<500 GeV	2211.08028
		SS e,μ	6 jets		140	$\tilde{g}$ 1.25	m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=300 GeV	1909.08457
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$	0 e,μ	2 b	$E_T^{\rm miss}$	140	$\tilde{b}_1$ 1.255	m($\tilde{\chi}_1^0$)<400 GeV	2101.12527
						$\tilde{b}_1$ 0.68	10 GeV<Δm($\tilde{b}_1$,$\tilde{\chi}_1^0$)<20 GeV	2101.12527
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_2^0\to bh\tilde{\chi}_1^0$	0 e,μ	6 b	$E_T^{\rm miss}$	140	$\tilde{b}_1$ Forbidden 0.23-1.35	Δm($\tilde{\chi}_2^0$,$\tilde{\chi}_1^0$)=130 GeV, m($\tilde{\chi}_1^0$)=100 GeV	1908.03122
		2 τ	2 b	$E_T^{\rm miss}$	140	$\tilde{b}_1$ 0.13-0.85	Δm($\tilde{\chi}_2^0$,$\tilde{\chi}_1^0$)=130 GeV, m($\tilde{\chi}_1^0$)=0 GeV	2103.08189
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}_1^0$	0-1 e,μ	≥ 1 jet	$E_T^{\rm miss}$	140	$\tilde{t}_1$ 1.25	m($\tilde{\chi}_1^0$)=1 GeV	2004.14060, 2012.03799
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	1 e,μ	3 jets/1 b	$E_T^{\rm miss}$	140	$\tilde{t}_1$ Forbidden 1.05	m($\tilde{\chi}_1^0$)=500 GeV	2012.03799, 2401.13430
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to\tilde{\tau}_1 b\nu$, $\tilde{\tau}_1\to\tau\tilde{G}$	1-2 τ	2 jets/1 b	$E_T^{\rm miss}$	140	$\tilde{t}_1$ Forbidden 1.4	m($\tilde{\tau}_1$)=800 GeV	2108.07665
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$ / $\tilde{c}\tilde{c}$, $\tilde{c}\to c\tilde{\chi}_1^0$	0 e,μ	2 c	$E_T^{\rm miss}$	36.1	$\tilde{c}$ 0.85	m($\tilde{\chi}_1^0$)=0 GeV	1805.01649
		0 e,μ	mono-jet	$E_T^{\rm miss}$	140	$\tilde{t}_1$ 0.55	m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}_1^0$)=5 GeV	2102.10874
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}_2^0$, $\tilde{\chi}_2^0\to Z/h\tilde{\chi}_1^0$	1-2 e,μ	1-4 b	$E_T^{\rm miss}$	140	$\tilde{t}_1$ 0.067-1.18	m($\tilde{\chi}_2^0$)=500 GeV	2006.05880
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ	1 b	$E_T^{\rm miss}$	140	$\tilde{t}_2$ Forbidden 0.86	m($\tilde{\chi}_1^0$)=360 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)= 40 GeV	2006.05880
EW direct	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via WZ	Multiple ℓ/jets		$E_T^{\rm miss}$	140	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.96	m($\tilde{\chi}_1^0$)=0, wino-bino	2106.01676, 2108.07586
		$ee,\mu\mu$	≥ 1 jet	$E_T^{\rm miss}$	140	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.205	m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV, wino-bino	1911.12606
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via WW	2 e,μ		$E_T^{\rm miss}$	140	$\tilde{\chi}_1^\pm$ 0.42	m($\tilde{\chi}_1^0$)=0, wino-bino	1908.08215
	$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via Wh	Multiple ℓ/jets		$E_T^{\rm miss}$	140	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ Forbidden 1.06	m($\tilde{\chi}_1^0$)=70 GeV, wino-bino	2004.10894, 2108.07586
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp$ via $\tilde{\ell}_L/\tilde{\nu}$	2 e,μ		$E_T^{\rm miss}$	140	$\tilde{\chi}_1^\pm$ 1.0	m($\tilde{\ell}$,$\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$))	1908.08215
	$\tilde{\tau}\tilde{\tau}$, $\tilde{\tau}\to\tau\tilde{\chi}_1^0$	2 τ		$E_T^{\rm miss}$	140	$\tilde{\tau}$ [$\tilde{\tau}_{\rm R}\tilde{\tau}_{\rm R}$] 0.35 0.5	m($\tilde{\chi}_1^0$)=0	2402.00603
	$\tilde{\ell}_{\rm L,R}\tilde{\ell}_{\rm L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0 jets	$E_T^{\rm miss}$	140	$\tilde{\ell}$ 0.7	m($\tilde{\chi}_1^0$)=0	1908.08215
		$ee,\mu\mu$	≥ 1 jet	$E_T^{\rm miss}$	140	$\tilde{\ell}$ 0.26	m($\tilde{\ell}$)-m($\tilde{\chi}_1^0$)=10 GeV	1911.12606
	$\tilde{H}\tilde{H}$, $\tilde{H}\to h\tilde{G}/Z\tilde{G}$	0 e,μ	≥ 3 b	$E_T^{\rm miss}$	140	$\tilde{H}$ 0.94	BR($\tilde{\chi}_1^0\to h\tilde{G}$)=1	2401.14922
		4 e,μ	0 jets	$E_T^{\rm miss}$	140	$\tilde{H}$ 0.55	BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=1	2103.11684
		0 e,μ	≥ 2 large jets	$E_T^{\rm miss}$	140	$\tilde{H}$ 0.45-0.93	BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=1	2108.07586
		2 e,μ	≥ 2 jets	$E_T^{\rm miss}$	140	$\tilde{H}$ 0.77	BR($\tilde{\chi}_1^0\to Z\tilde{G}$)=BR($\tilde{\chi}_1^0\to h\tilde{G}$)=0.5	2204.13072
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	$E_T^{\rm miss}$	140	$\tilde{\chi}_1^\pm$ 0.66	Pure Wino	2201.02472
						$\tilde{\chi}_1^\pm$ 0.21	Pure higgsino	2201.02472
	Stable $\tilde{g}$ R-hadron	pixel dE/dx		$E_T^{\rm miss}$	140	$\tilde{g}$ 2.05		2205.06013
	Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$	pixel dE/dx		$E_T^{\rm miss}$	140	$\tilde{g}$ [$\tau(\tilde{g})$ =10 ns] 2.2	m($\tilde{\chi}_1^0$)=100 GeV	2205.06013
	$\tilde{\ell}\tilde{\ell}$, $\tilde{\ell}\to\ell\tilde{G}$	Displ. lep		$E_T^{\rm miss}$	140	$\tilde{e},\tilde{\mu}$ 0.74	$\tau(\tilde{\ell})$ = 0.1 ns	ATLAS-CONF-2024-011
						$\tilde{\tau}$ 0.36	$\tau(\tilde{\ell})$ = 0.1 ns	ATLAS-CONF-2024-011
		pixel dE/dx		$E_T^{\rm miss}$	140	$\tilde{\tau}$ 0.36	$\tau(\tilde{\ell})$ = 10 ns	2205.06013
RPV	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_1^0$, $\tilde{\chi}_1^\pm\to Z\ell\to\ell\ell\ell$	3 e,μ			140	$\tilde{\chi}_1^\mp/\tilde{\chi}_1^0$ [BR($Z\tau$)=1, BR(Ze)=1] 0.625 1.05	Pure Wino	2011.10543
	$\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0\to WW/Z\ell\ell\ell\ell\nu\nu$	4 e,μ	0 jets	$E_T^{\rm miss}$	140	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ [$\lambda_{i33}\neq 0, \lambda_{12k}\neq 0$] 0.95 1.55	m($\tilde{\chi}_1^0$)=200 GeV	2103.11684
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$		≥8 jets		140	$\tilde{g}$ [m($\tilde{\chi}_1^0$)=50 GeV, 1250 GeV] 1.6 2.34	Large λ''_{112}	2401.16333
	$\tilde{t}\tilde{t}$, $\tilde{t}\to t\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to tbs$		Multiple		36.1	$\tilde{t}$ [λ''_{323}=2e-4, 1e-2] 0.55 1.05	m($\tilde{\chi}_1^0$)=200 GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{t}\tilde{t}$, $\tilde{t}\to b\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^\pm\to bbs$		≥ 4b		140	$\tilde{t}$ Forbidden 0.95	m($\tilde{\chi}_1^\pm$)=500 GeV	2010.01015
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$		2 jets + 2 b		36.7	$\tilde{t}_1$ [qq, bs] 0.42 0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to q\ell$	2 e,μ	2 b		140	$\tilde{t}_1$ 0.4-1.85	BR($\tilde{t}_1\to be/b\mu$)>20%	2406.18367
		1 μ	DV		136	$\tilde{t}_1$ [1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k} <3e-9] 1.0 1.6	BR($\tilde{t}_1\to q\mu$)=100%, cosθ_t=1	2003.11956
	$\tilde{\chi}_1^\pm/\tilde{\chi}_2^0/\tilde{\chi}_1^0$, $\tilde{\chi}_{1,2}^0\to tbs$, $\tilde{\chi}_1^+\to bbs$	1-2 e,μ	≥6 jets		140	$\tilde{\chi}_1^0$ 0.2-0.32	Pure higgsino	2106.09609

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

In summary

We’ve studied

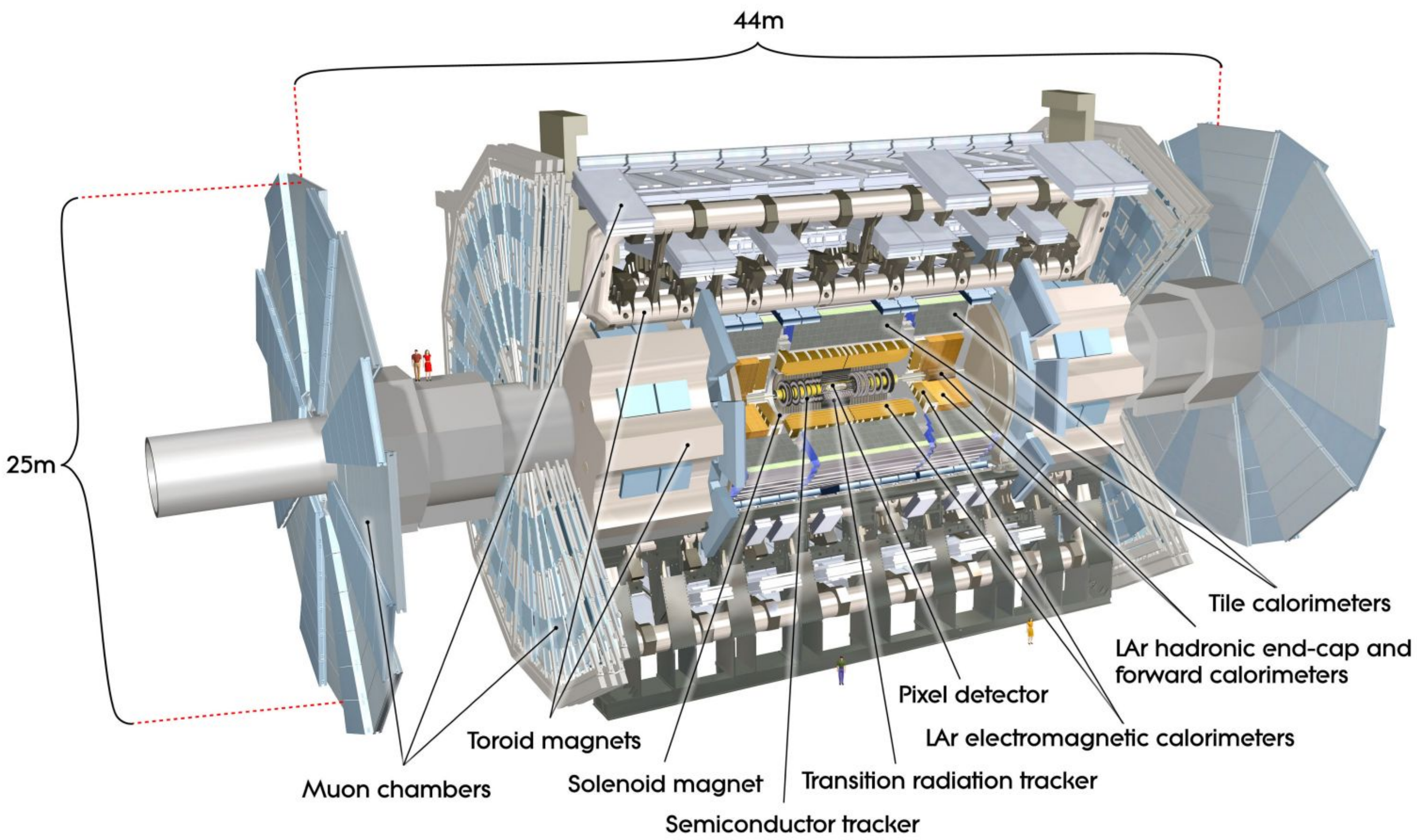
- the main problems in nature for which supersymmetry can provide answers
- the main features the we could search for in experiments
- the challenges in constructing a model and searching for it, and exceptions to some rules

and we’ve looked at a specific example of how to execute such search at the LHC

This illustrates the continuing motivation to keep searching for BSM physics at collider experiments

- supersymmetry is a beautiful theory, but als a beautiful framework to organise searches in general
- BSM physics is out there find, we won’t find it without looking, and even if we find hints of it, it’ll be a long road ahead to characterise the details

Go forth and have fun searching!


44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker