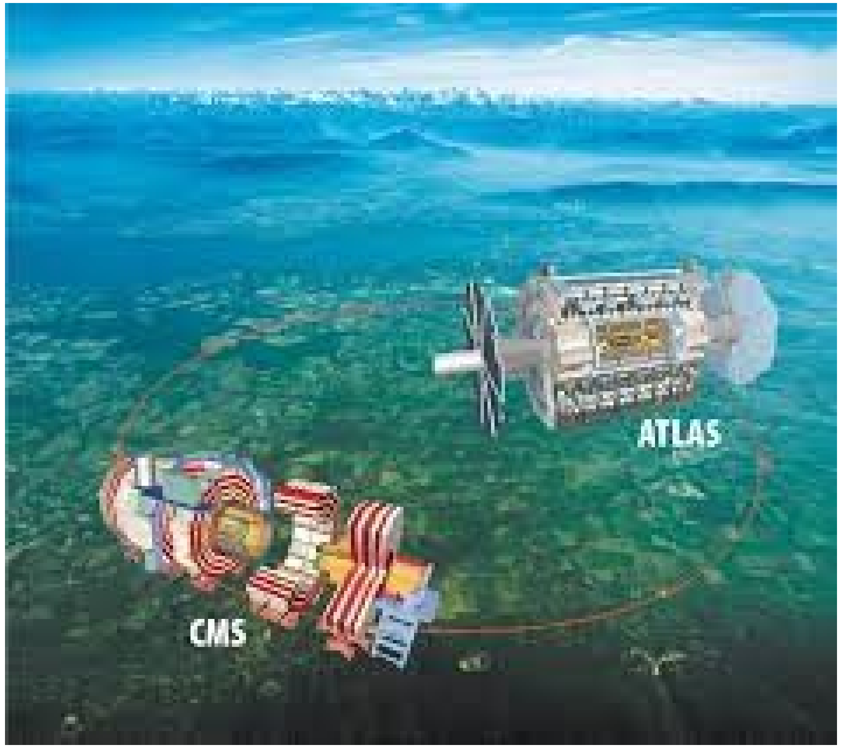
THE UNIVERSITY of ADELAIDE

(Maximising the discovery potential of the Large Hadron Collider)

Prof Martin White

What do I mean by "LHC"?

- I mean ATLAS and CMS for the purposes of this talk
- LHCb is rather interesting, but that's a talk for another day...

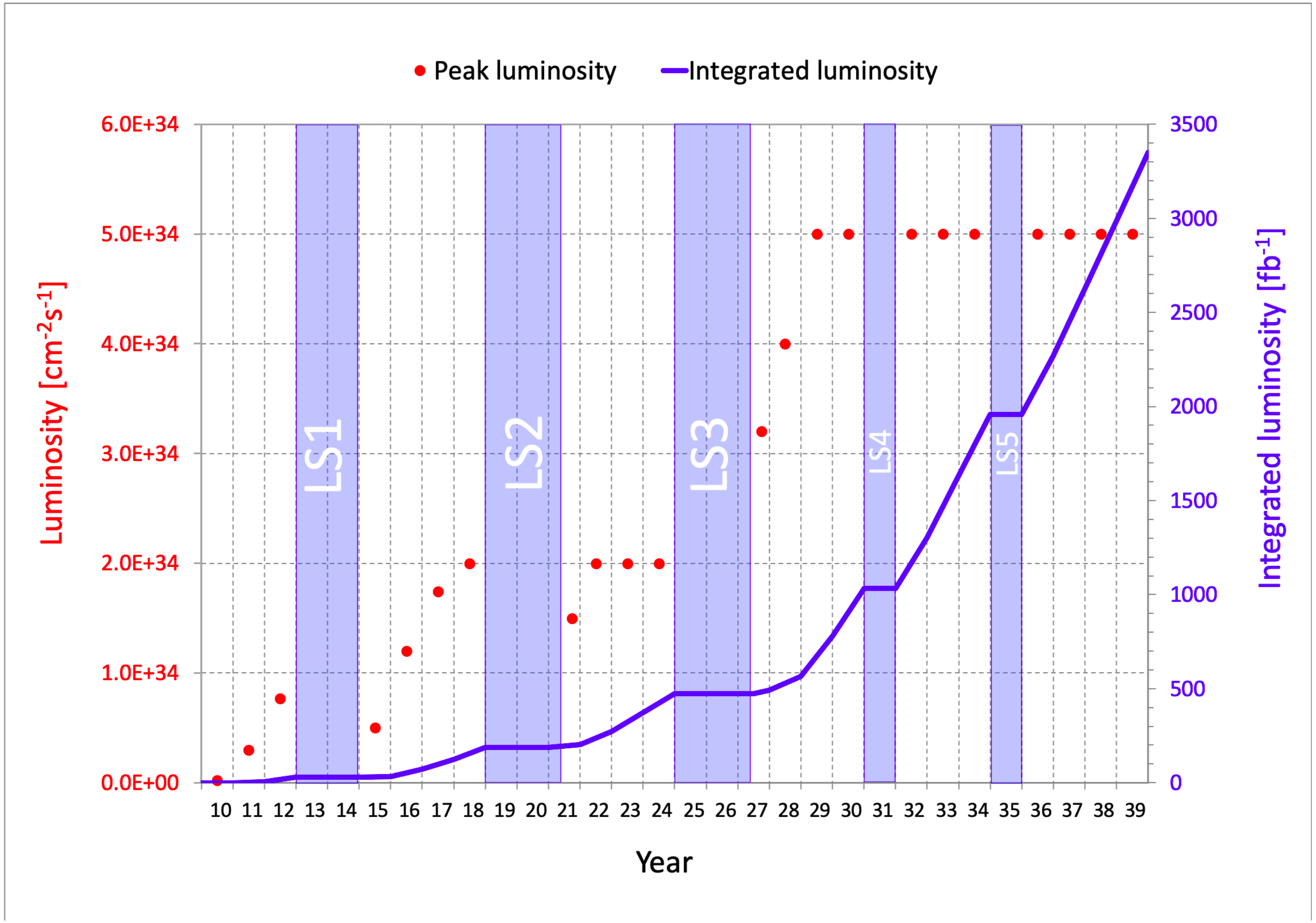


The (abridged) LHC story so far

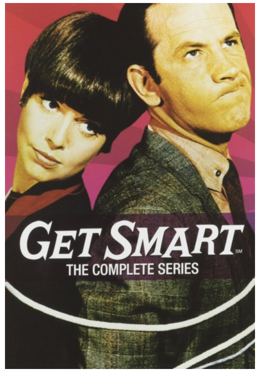
- Lots of ATLAS and CMS precision measurements (e.g. Higgs discovery, masses, cross-sections, differential cross-sections, branching fractions)
- Loads of direct searches for new particles
- **No evidence for beyond-Standard Model physics**

What does this mean?

Solution 1: wait longer!



Solution 2: Get smarter



- LHC detector output (after reconstruction) consists of:

  - four vectors of jets, leptons and photons (plus particle identification)

  - tagging of *b* jets ~ 70% of the time

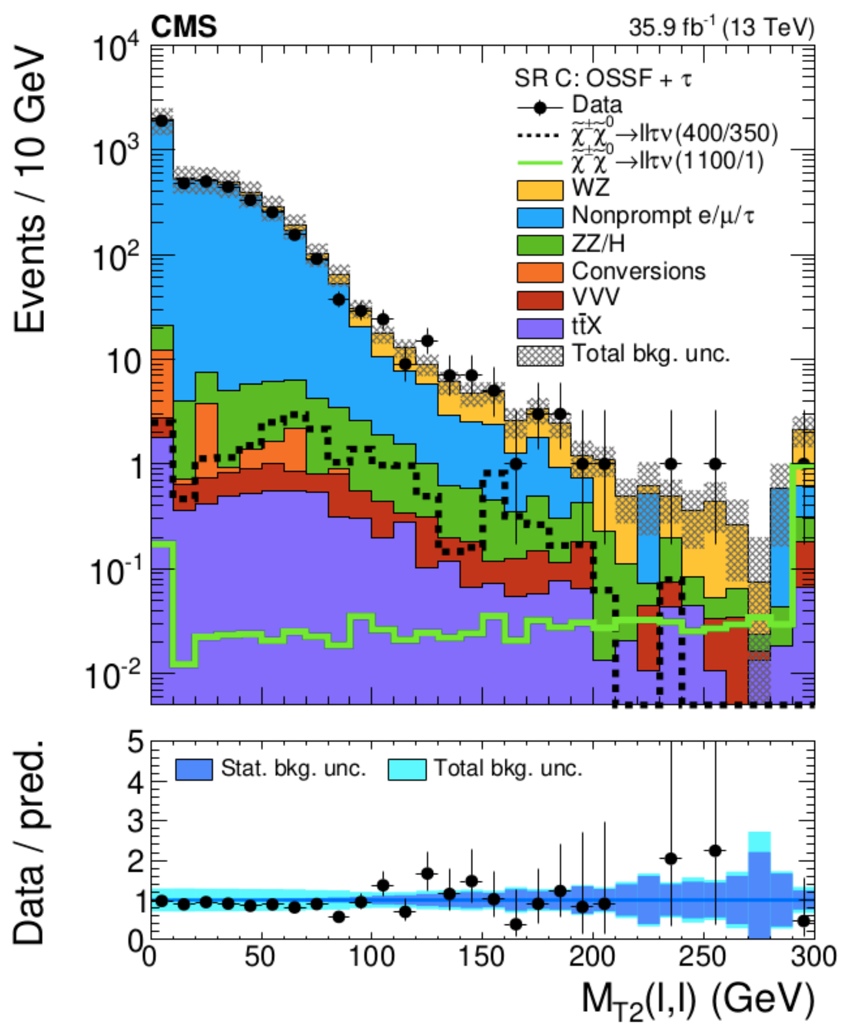
  - tagging of τ leptons ~ 40 % of the time

  - missing transverse energy

  - EXTRA: evidence for exotic objects (long-lived sparticles?)

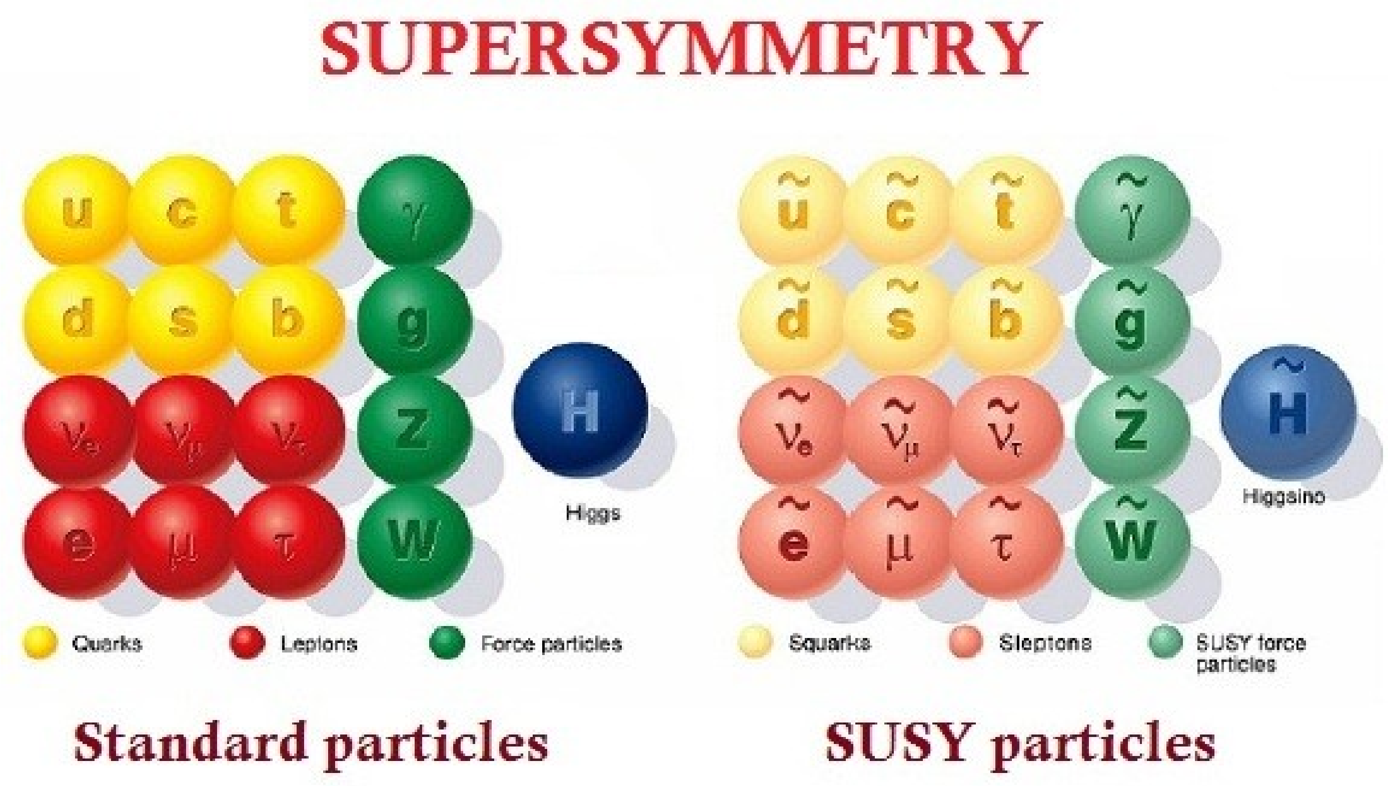
The whole game of experimental searches is to use only this information to discover new particles, then measure the particle properties in case of discovery

How particle searches are typically done



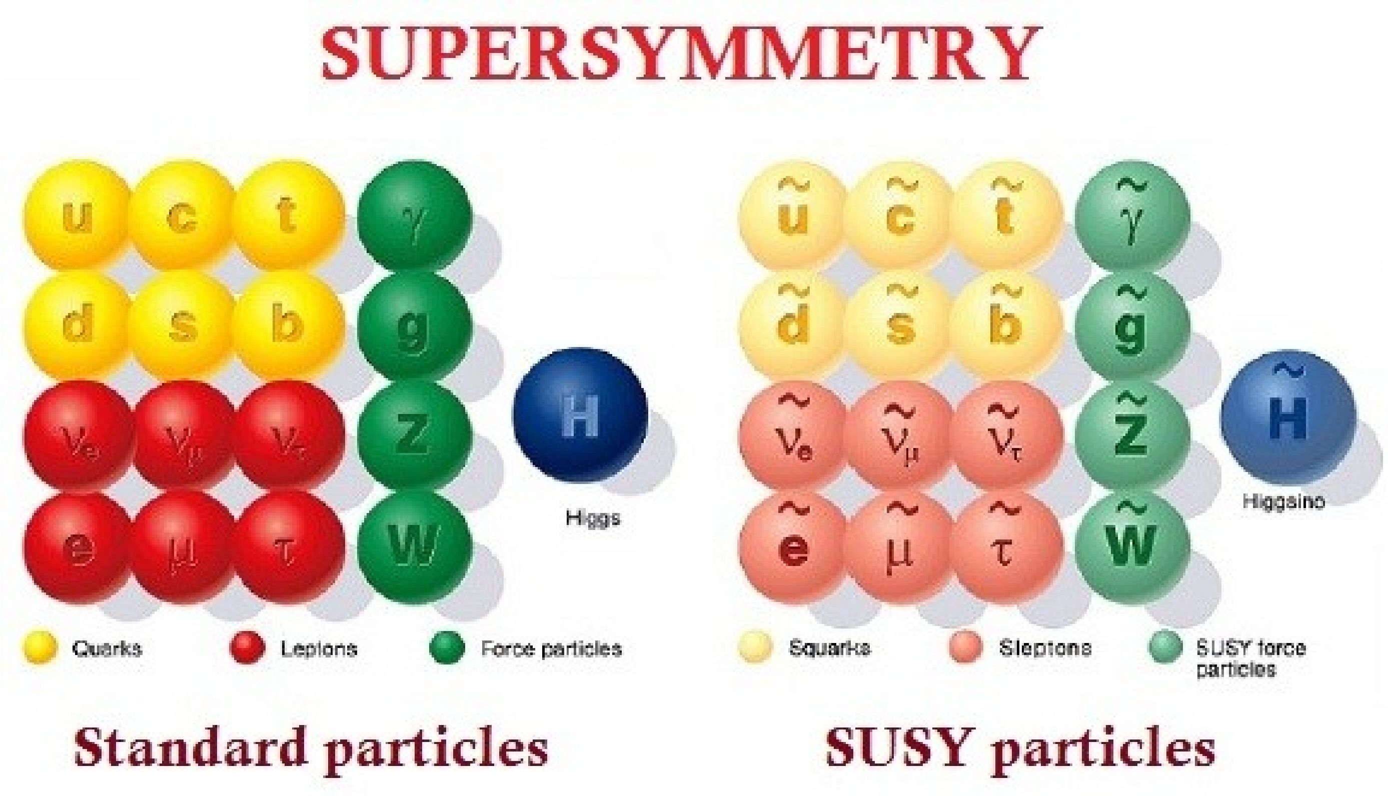
- Pick a particular signal hypothesis
- Find variables (functions of 4 vectors) that look different for the signal and backgrounds
- Look in regions of the data where background is expected to be low

Let’s take an example: SUSY



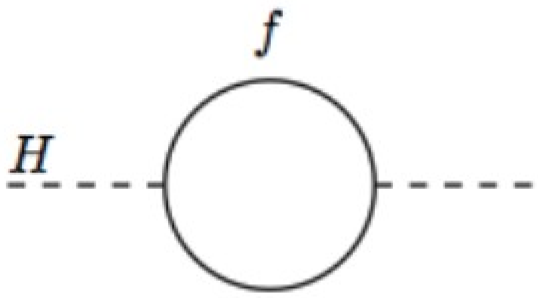
- Solves various theoretical challenges to the Standard Model
- Provides a natural DM candidate
- Has been used to motivate LHC physics analyses for decades now due to complex phenomenology

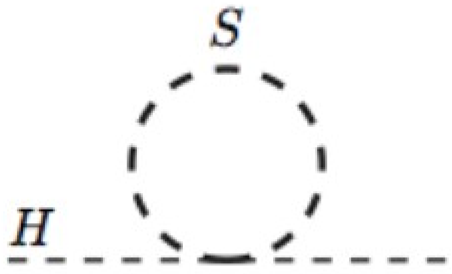
Supersymmetry breaking



- Exact SUSY would require identical SM & SUSY partner masses → SUSY is broken
- Breaking mechanism is *a priori* unknown
- Minimal SUSY breaking Lagrangian has 105 free parameters

Supersymmetry and the hierarchy problem





$$\Delta m_H^2 = \frac{\lambda_f^2}{8\pi^2}\left[-\Lambda^2 + 6 m_f^2 ln\frac{\Lambda}{m_f}\right]$$

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\left[\Lambda^2 - 2 m_S^2 ln\frac{\Lambda}{m_S}\right]$$

- Kindergarten: need SUSY to cancel off radiative corrections
- High school: need rather large radiative corrections to get up to a Higgs mass of 125 GeV in the MSSM → squarks are ***heavy***

Impact of ATLAS and CMS results

Eur. Phys. J. C manuscript No.
(will be inserted by the editor)

CoEPP-MN-18-7

Combined collider constraints on neutralinos and charginos

The GAMBIT Collaboration: Peter Athron[1,2], Csaba Balázs[1,2], Andy Buckley[3], Jonathan M. Cornell[4], Matthias Danninger[5], Ben Farmer[6], Andrew Fowlie[1,2,9], Tomás E. Gonzalo[10], Julia Harz[11], Paul Jackson[2,12], Rose Kudzman-Blais[5], Anders Kvellestad[6,10,a], Gregory D. Martinez[13], Andreas Petridis[2,12], Are Raklev[10], Christopher Rogan[14], Pat Scott[6], Abhishek Sharma[2,12], Martin White[2,12,b], Yang Zhang[1,2]

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Received: date / Accepted: date

Abstract Searches for supersymmetric electroweakinos have entered a crucial phase, as the integrated luminosity of the Large Hadron Collider is now high enough to compensate for their weak production cross-sections. Working in a framework where the neutralinos and charginos are the only light sparticles in the Minimal Supersymmetric Standard Model, we use GAMBIT to perform a

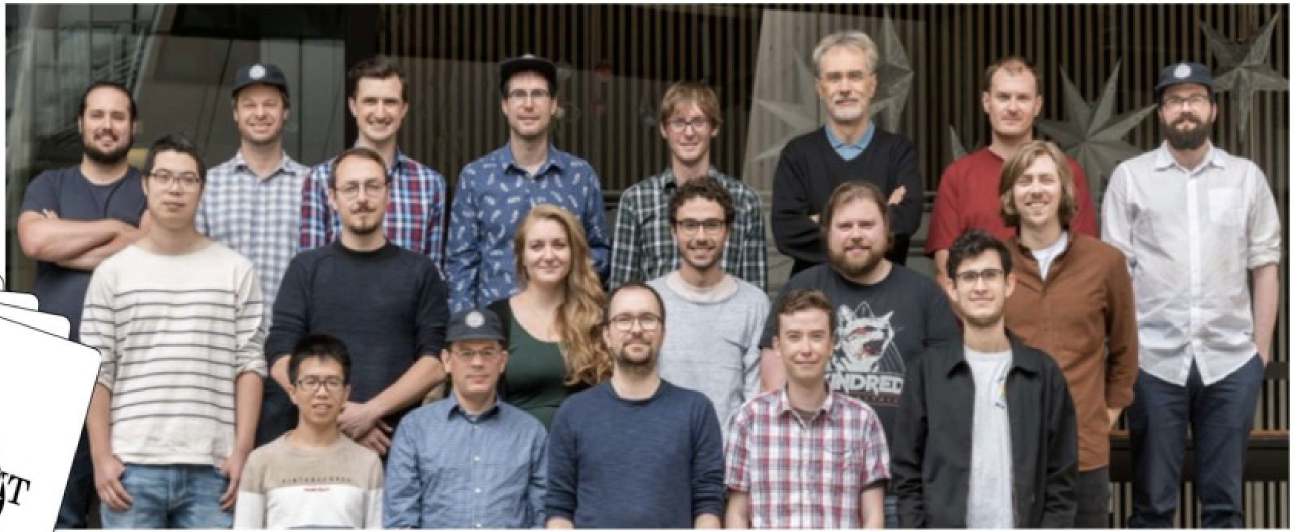
relic density can be obtained through the Higgs-funnel and Z-funnel mechanisms, even assuming that all other sparticles are decoupled. All samples, GAMBIT input files and best-fit models from this study are available on Zenodo.

Contents

GAMBIT: The Global And Modular BSM Inference Tool

gambit.hepforge.org github.com/GambitBSM EPJC 77 (2017) 784 arXiv:1705.07908

- Extensive model database, beyond SUSY
- Fast definition of new datasets, theories
- Extensive observable/data libraries
- Plug&play scanning/physics/likelihood packages
- Various statistical options (frequentist /Bayesian)
- Fast LHC likelihood calculator
- Massively parallel
- Fully open-source



Members of: ATLAS, Belle-II, CLiC, CMS, CTA, Fermi-LAT, DARWIN, IceCube, LHCb, SHiP, XENON

Authors of: BubbleProfiler, Capt'n General, Contur, DarkAges, DarkSUSY, DDCalc, DirectDM, Diver, EasyScanHEP, ExoCLASS, FlexibleSUSY, gamLike, GM2Calc, HEPLike, IsaTools, MARTY, nuLike, PhaseTracer, PolyChord, Rivet, SOFTSUSY, Superlso, SUSY-AI, xsec, Vevacious, WIMPSim

Recent collaborators: P Athron, C Balázs, A Beniwal, S Bloor, T Bringmann, A Buckley, J-E Camargo-Molina, C Chang, M Chrzaszcz, J Conrad, J Cornell, M Danninger, J Edsjö, T Emken, A Fowlie, T Gonzalo, W Handley, J Harz, S Hoof, F Kahlhoefer, A Kvellestad, P Jackson, D Jacob, C Lin, N Mahmoudi, G Martinez, MT Prim, A Raklev, C Rogan, R Ruiz, P Scott, N Serra, P Stöcker , W. Su, A Vincent, C Weniger, M White, Y Zhang, ++

70+ participants in many experiments and numerous major theory codes

Included constraints

- Z and Higgs invisible decays

$$\Gamma(Z \to \text{inv.}) = 499.0 \pm 1.5\,\text{MeV}$$

$$\text{BF}(h \to \text{inv.}) \leq 0.19$$

- LEP cross-section limits

Production	Signature	Experiment
$\tilde{\chi}_i^0 \tilde{\chi}_1^0$	$\tilde{\chi}_i^0 \to q\bar{q}\tilde{\chi}_1^0$	OPAL [53]
$(i = 2, 3, 4)$	$\tilde{\chi}_i^0 \to \ell\bar{\ell}\tilde{\chi}_1^0$	L3 [98]
$\tilde{\chi}_i^+ \tilde{\chi}_i^-$	$\tilde{\chi}_i^+ \tilde{\chi}_i^- \to q\bar{q}' q\bar{q}' \tilde{\chi}_1^0 \tilde{\chi}_1^0$	OPAL [53]
$(i = 1, 2)$	$\tilde{\chi}_i^+ \tilde{\chi}_i^- \to q\bar{q}' \ell\nu \tilde{\chi}_1^0 \tilde{\chi}_1^0$	OPAL [53]
	$\tilde{\chi}_i^+ \tilde{\chi}_i^- \to \ell\nu\ell\nu \tilde{\chi}_1^0 \tilde{\chi}_1^0$	OPAL [53], L3 [98]
	ISR γ + missing energy	OPAL [99]

- LHC searches for EW SUSY

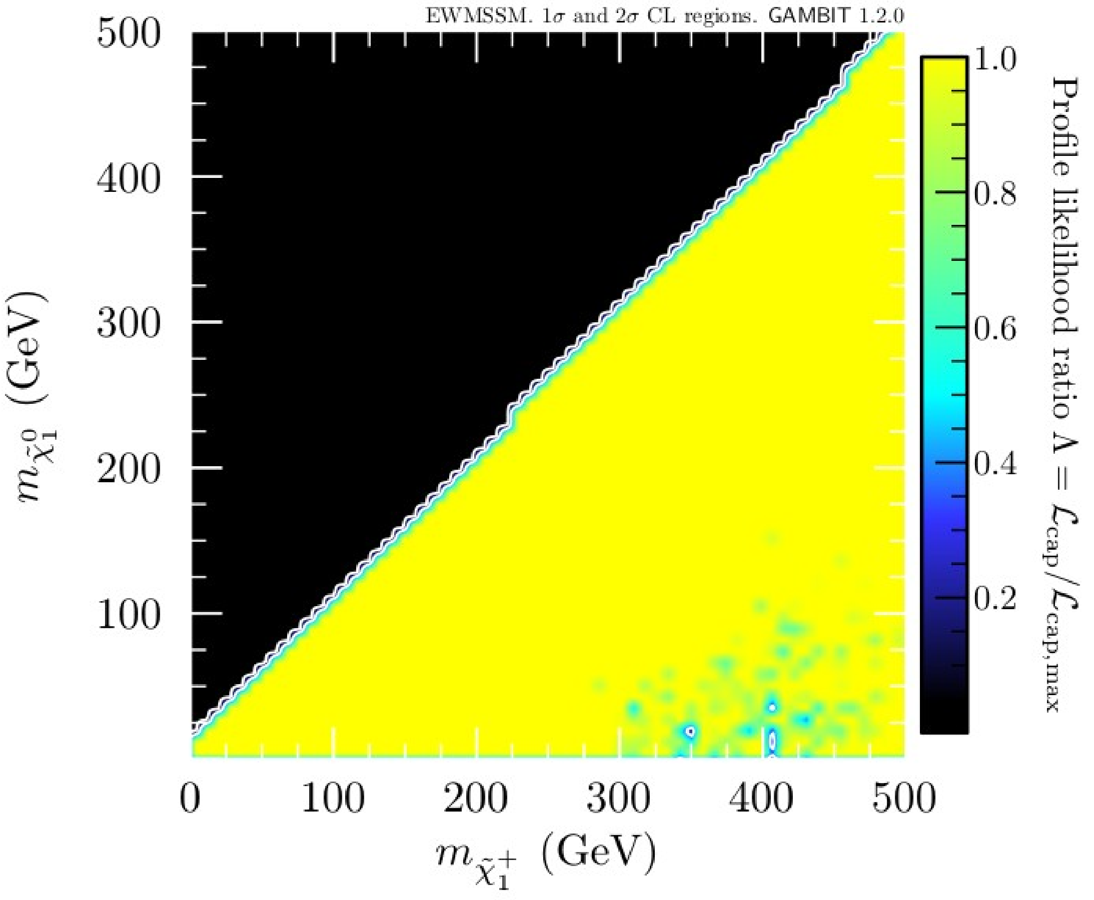
Likelihood label	Source
ATLAS_4b	ATLAS Higgsino search [104]
ATLAS_4lep	ATLAS 4ℓ search [105]
ATLAS_MultiLep_2lep_0jet	ATLAS multilepton EW search [100]
ATLAS_MultiLep_2lep_jet	ATLAS multilepton EW search [100]
ATLAS_MultiLep_3lep	ATLAS multilepton EW search [100]
ATLAS_RJ_2lep_2jet	ATLAS recursive jigsaw EW search [101]
ATLAS_RJ_3lep	ATLAS recursive jigsaw EW search [101]
CMS_1lep_2b	CMS Wh search [106]
CMS_2lep_soft	CMS 2 soft opposite-charge lepton search [109]
CMS_2OSlep	CMS 2 opposite-charge lepton search [110]
CMS_MultiLep_2SSlep	CMS multilepton EW search [111]
CMS_MultiLep_3lep	CMS multilepton EW search [111]

Source: Anders Kvellestad

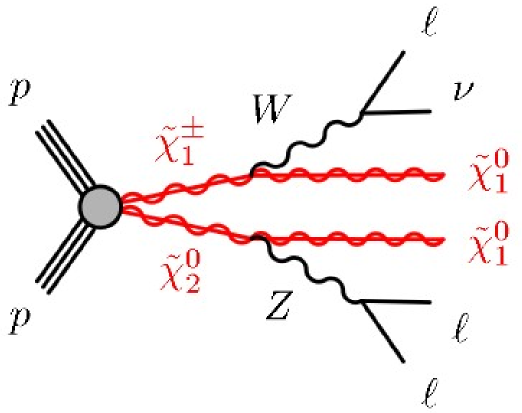
LHC searches for SUSY dark matter

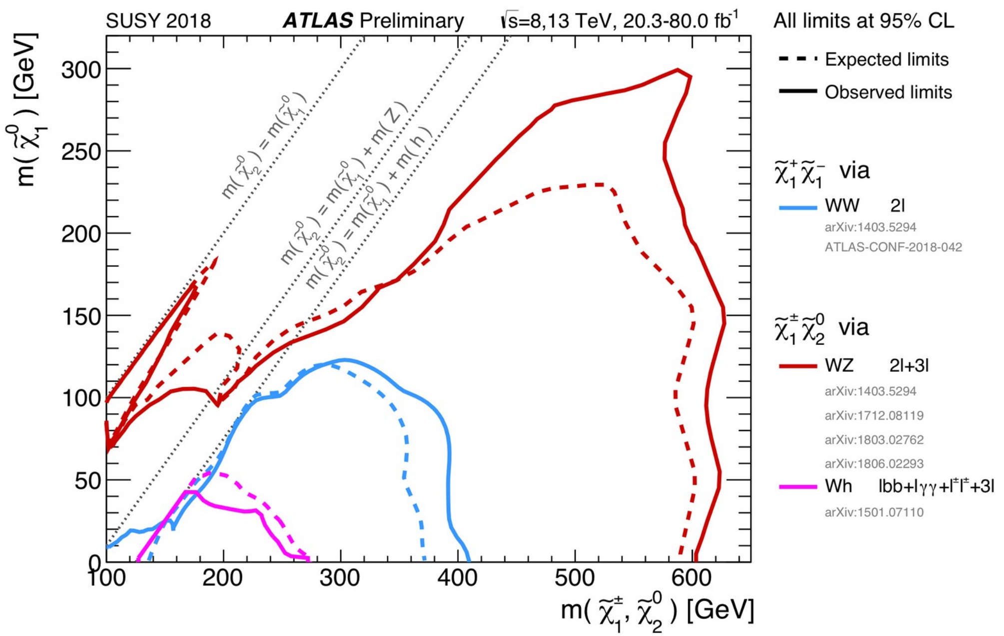
- In a test of exclusion power, we find ***no general constraint*** on the MSSM EW sector from the LHC!

arXiv: 1809.02097



How can SUSY evade LHC searches?





Ideas for improvement

1) Define more inclusive models for optimisation

2) Use unsupervised machine learning

3) Map the topology of LHC events using network analysis

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1) Define more inclusive models for optimisation

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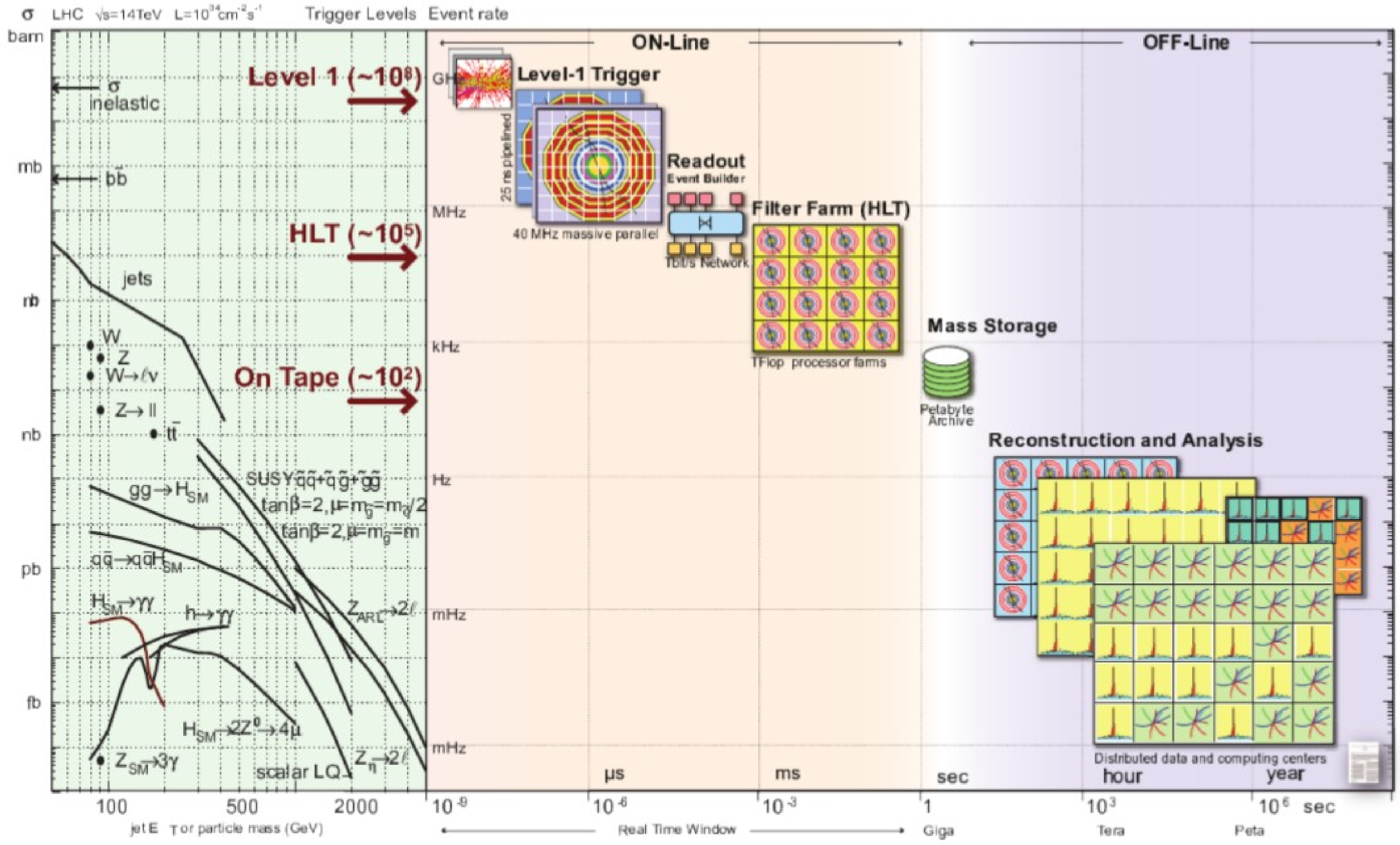
Why is optimisation necessary?



Better models for optimisation

ADP-20-29/T1139

Simple, but not simplified: A new approach for optimising supersymmetry searches at the Large Hadron Collider

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ABSTRACT: Searches for supersymmetry at the Large Hadron Collider are frequently optimised on simplified models. After assuming particular sparticle production and decay processes, analyses are optimised by tuning event selections on benchmark models generated in 2D planes of parameters, with all other parameters held fixed. Motivated by recent evidence that this removes sensitivity to a large volume of viable SUSY models, we propose an alternative approach based on dimensional reduction of global fit results. Starting from the results of a global fit of the 4D electroweak minimimal supersymmetric model performed by the GAMBIT collaboration, we show how to define a 2D plane by using a variational autoencoder to map points in the original 4D parameter space to a 2D latent space. This allows for easy visualisation of the 4D global fit results, which generates insights into what we may be missing at the LHC. Furthermore, the invertible nature of the map to the 2D plane allows experimentalists to choose and simulate benchmark models in a 2D plane (as they could for a simplified model) whilst still accessing the full range of phenomenology of the 4D model. We provide a demonstration of how our visualisation and benchmark model simulation process works, and develop an analysis that is able to exclude four benchmark models not excluded by the ATLAS and CMS collaborations in the set of results used for the global fit.

What is a simplified model?

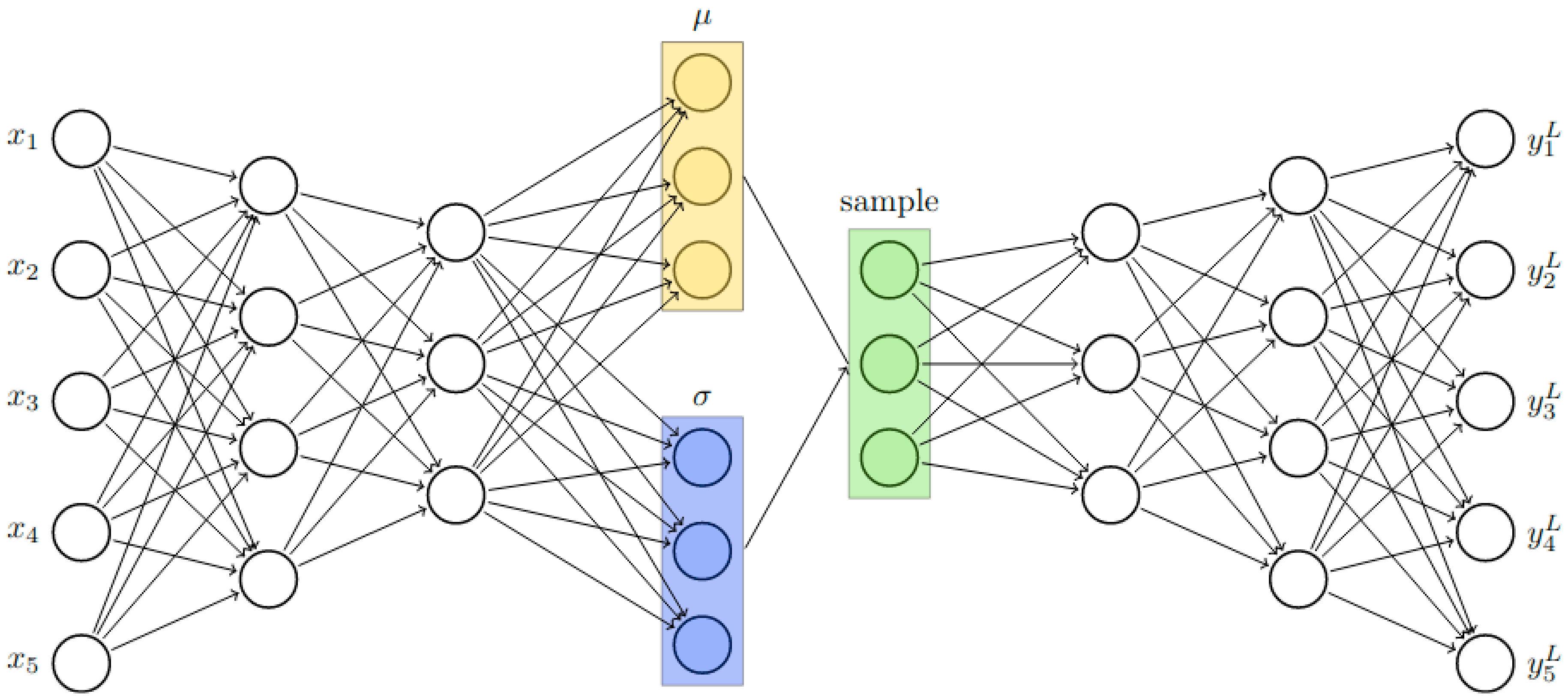
- A SUSY simplified model is typically a 2D parameter set with other relevant SUSY parameters held fixed (most common use: use sparticle masses and branching ratios)
- It is thus related to the original SUSY parameters via dimensional reduction
- In the case of the EWMSSM this is particularly weird:

μ , M_1, M_2, tan β → Large space of electroweakino masses and branching ratios → (Arbitrarily fix masses, fix branching ratios) → 2 mass parameters

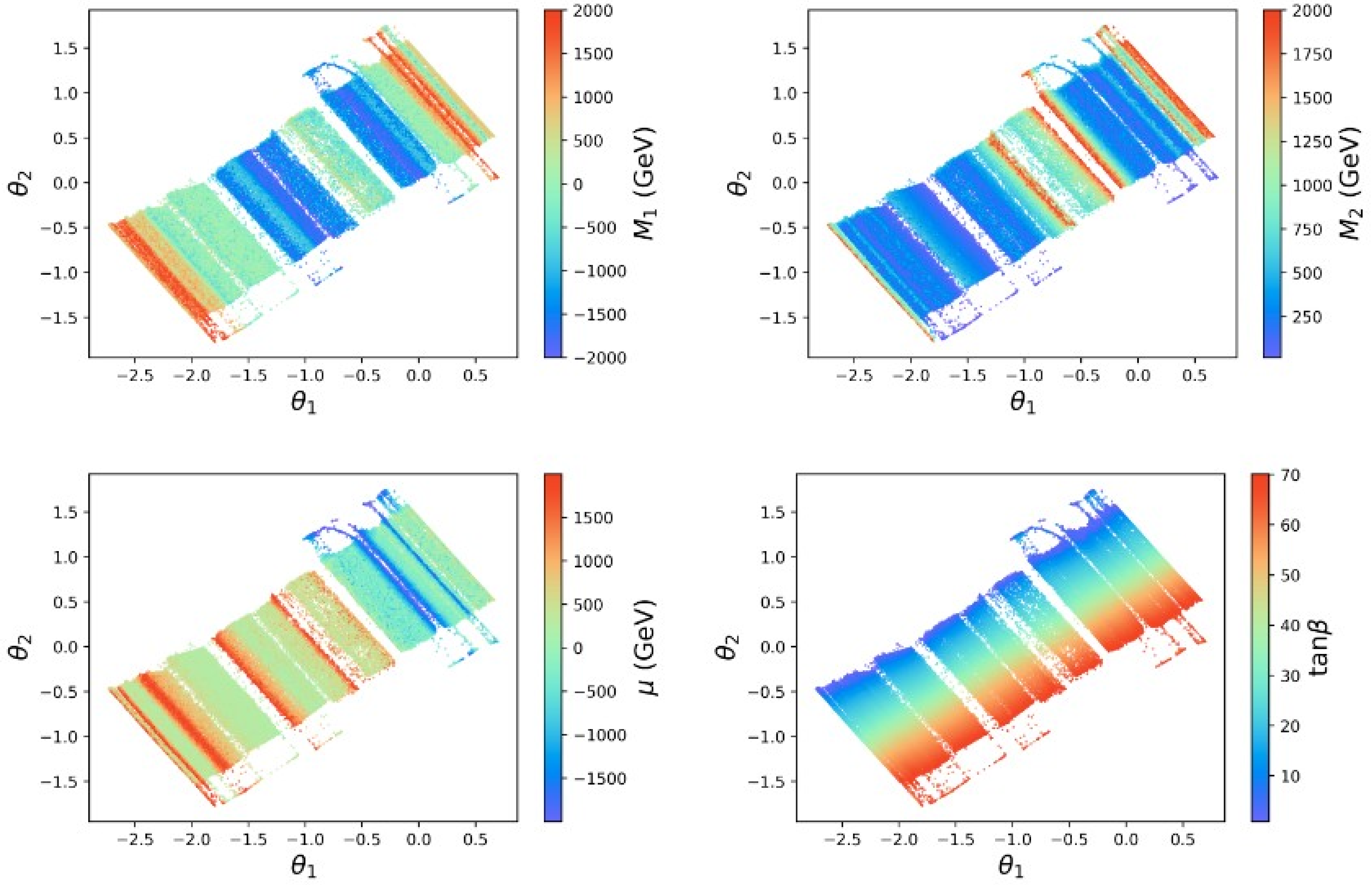
What if we just did the dimensional reduction better?

- We have a set of GAMBIT results that gives us points in the original 4D SUSY space that are not excluded (at some chosen confidence level)
- Can define an invertible, topology-preserving map to a 2D plane *directly* from those results
- We then get a 2D plane which is *simple* but not *simplified*

One possible choice: a variational autoencoder



GAMBIT results in 2D



Visualising phenomenology in 2D

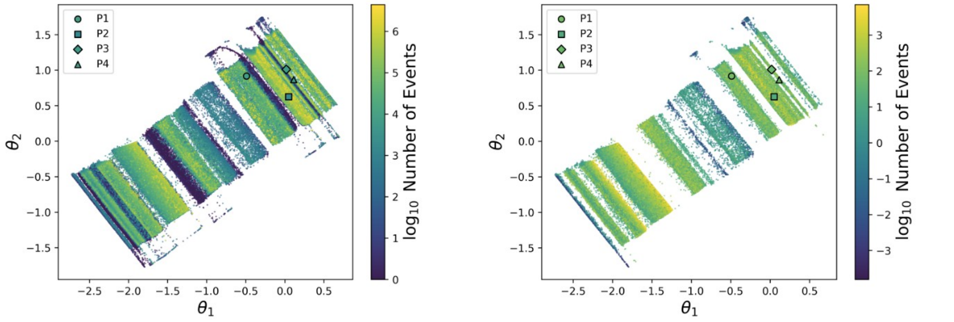


Figure 5: Left: latent-space representations of points with the number of $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ events at 36 fb^{-1} as a colour map. Right: latent-space representations of points with the upper bound on the number of 3-lepton events from $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production at 36 fb^{-1} as a colour map.

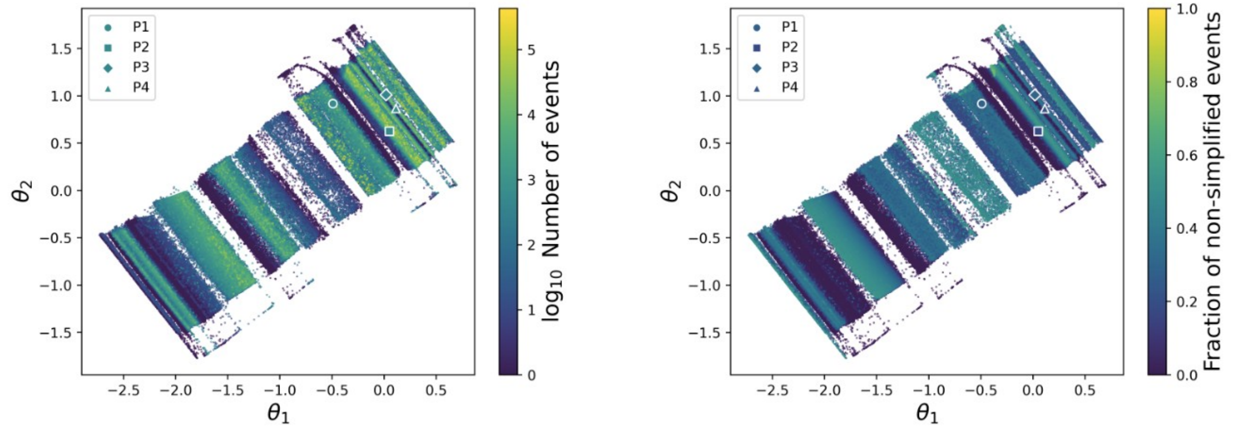


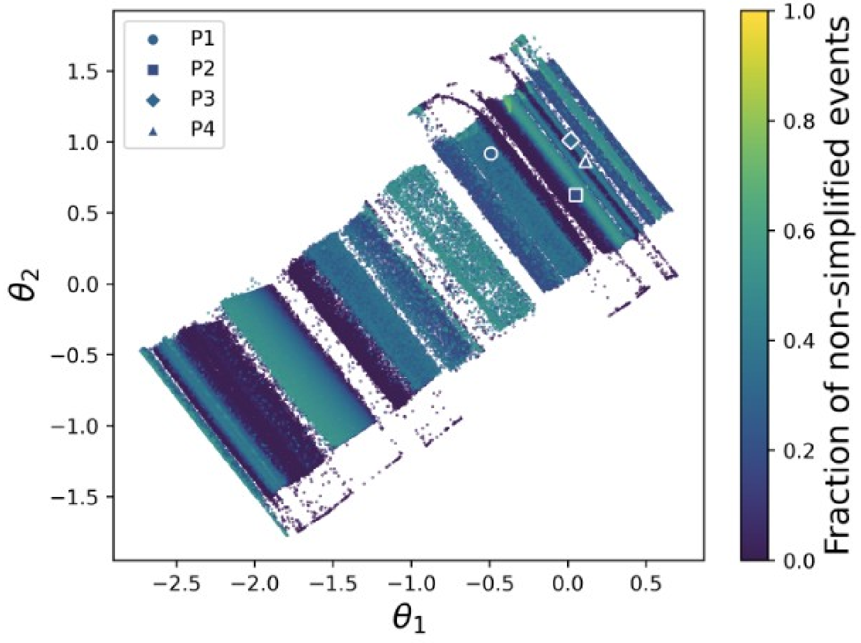
Figure 6: The number (left) and proportion (right) of non-simplified events at 36 fb^{-1} in the $\theta_1 - \theta_2$ plane.

- Have a new way to visualise global fit results
- Can look at number of events in a given final state (e.g. 3 leptons)
- Can also look for points that least resemble the simplified model assumptions used for optimisation
- e.g. put this on the *z* axis:

$$\frac{\sum_i \sigma_i - (\sigma_{\tilde{\chi}_1^0 \tilde{\chi}_1^\pm} + \sigma_{\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp} + \sigma_{\tilde{\chi}_2^0 \tilde{\chi}_1^\pm} + \sigma_{\tilde{\chi}_1^0 \tilde{\chi}_1^0})}{\sum_i \sigma_i}$$

Finding benchmark points

- Can select benchmark points for optimisation
- The invertible nature of the map from 4D→2D means that one can recover the full 4D SUSY parameter set and generate events for LHC studies
- We have chosen 4 benchmark points that are unsimplified-model like



- **P1:** $\sigma_{\chi_1^\pm\chi_1^0}$ =3180 fb, $\sigma_{\chi_1^+\chi_1^-}$ =1660 fb, $\sigma_{\chi_2^\pm\chi_3^0}$ =650 fb, $\sigma_{\chi_1^\pm\chi_2^0}$ =503 fb, and $\sigma_{\chi_2^+\chi_2^-}$ =313 fb.
- **P2:** $\sigma_{\chi_1^\pm\chi_1^0}$ =4047 fb, $\sigma_{\chi_1^+\chi_1^-}$ =2086 fb, $\sigma_{\chi_2^\pm\chi_4^0}$ =450 fb, $\sigma_{\chi_2^+\chi_2^-}$ =226 fb and $\sigma_{\chi_1^\pm\chi_3^0}$ =166 fb.
- **P3:** $\sigma_{\chi_1^\pm\chi_1^0}$ =2130 fb, $\sigma_{\chi_1^+\chi_1^-}$ =1114 fb, $\sigma_{\chi_2^\pm\chi_3^0}$ =625 fb, $\sigma_{\chi_1^\pm\chi_2^0}$ =583 fb and $\sigma_{\chi_2^0\chi_1^0}$ =335 fb.
- **P4:** $\sigma_{\chi_1^\pm\chi_1^0}$ =1382 fb, $\sigma_{\chi_1^+\chi_1^-}$ =720 fb, $\sigma_{\chi_2^\pm\chi_3^0}$ =460 fb, $\sigma_{\chi_1^\pm\chi_2^0}$ =398 fb and $\sigma_{\chi_2^0\chi_1^0}$ =230 fb.

As expected, the simplified model process $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ has a markedly smaller cross section than other processes, including those with more complex decay chains.

Optimising on these points works!

- Have found an analysis that would exclude all four points with a single signal region
- Demonstrates again that optimisation matters at the LHC → generalising the input assumptions leads to better outcomes

Variable	Requirement
n_{lep}	$= 3$
$n_{b-\text{jet}}$	$= 0$
E_T^{miss} [GeV]	> 90
m_T [GeV]	> 20
H_T [Gev]	< 125

Process ID	N_{sig}	N_{bkg}	Z_{bi}
P1	207	187	3.8
P2	140	187	2.7
P3	227	187	4.2
P4	218	188	4.0

Summary

- We are at a crucial stage in the history of the LHC
- Evidence suggests that straightforward discoveries would have flown under the radar of current particle searches
- Have presented a new approach for optimising LHC analyses that shows promising results