### Reinterpretation: How can we maximise the science impact of SUSY searches?

Anders Kvellestad, University of Oslo ATLAS SUSY workshop — Oslo, September 13, 2023





As a community we can **learn far more physics** from an experimental result that is **reinterpretable** compared to one that is not.

Understanding the full implications of [experimental] searches requires the interpretation of the experimental results in the context of many more theoretical models than are currently explored at the time of publication.

See also:

- Publishing statistical models: Getting the most out of particle physics experiments [arxiv:2109.04981]
- [arxiv:2003.07868]
- Simple and statistically sound strategies for analysing physical theories [arxiv:2012.09874]

#### **HEP Software Foundation [arxiv:1712.06982]**

• Reinterpretation of LHC Results for New Physics: Status and Recommendations after Run 2

#### GAMBIT: The Global And Modular BSM Inference Tool EPJC 77 (2017) 784 arXiv:1705.07908

gambit.hepforge.org

github.com/GambitBSM

- 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,

**Recent collaborators**: V Ananyev, P Athron, N Avis-Kozar, C Balázs, A Beniwal, S Bloor, LL Braseth, T Bringmann, A Buckley, J CTA, Fermi-LAT, DARWIN, IceCube, LHCb, SHiP, XENON Butterworth, J-E Camargo-Molina, C Chang, M Chrzaszcz, J Conrad, J Cornell, M Danninger, J Edsjö, T Emken, A Fowlie, T Authors of: BubbleProfiler, Capt'n General, Contur, Gonzalo, W Handley, J Harz, S Hoof, F Kahlhoefer, A Kvellestad, DarkAges, DarkSUSY, DDCalc, DirectDM, Diver, M Lecroq, P Jackson, D Jacob, C Lin, FN Mahmoudi, G Martinez, EasyScanHEP, ExoCLASS, FlexibleSUSY, gamLike, GM2Calc, H Pacey, MT Prim, T Procter, F Rajec, A Raklev, JJ Renk, R Ruiz, A HEPLike, IsaTools, MARTY, nuLike, PhaseTracer, PolyChord, Scaffidi, P Scott, N Serra, P Stöcker, W. Su, J Van den Abeele, A Rivet, SOFTSUSY, Superlso, SUSY-AI, xsec, Vevacious, Vincent, C Weniger, A Woodcock, M White, Y Zhang ++ WIMPSim

80+ participants in many experiments and numerous major theory codes



**Vector and fermion Higgs portal DM:** 1808.10465

EW-MSSM: 1809.02097



More axion-like particles: 2007.05517



Simplified DM, scalar/fermion: 2209.13266





Flavour EFT: 2006.03489



Cosmo ALPs: 2205.13549

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Scalar Higgs portal DM: 1705.07931



Axion-like particles: 1810.07192

GAMBIT::CosmoBit

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Neutrinos and cosmo: 2009.03287



Simplified DM, vector: 2303.08351



Scalar Higgs portal DM w/ vac. stability: 1806.11281



Right-handed neutrinos: 1908.02302



Dark matter EFTs: 2106.02056



EW-MSSM w/ light gravitino: 2303.09082

- **1.** The many interpretations of reinterpretation
- 2. How we can learn more
- **3. A recent SUSY reinterpretation example**
- 4. Some challenges for reinterpretation
- 5. Moving forward: how to best help each other?

# **1.** The many interpretations of reinterpretation

## There are many types of reinterpretation

#### Analysis preservation and reuse internally in an experiment •

- High accuracy (full access to analysis details, full detector simulation, ...) •
- High computational cost per model point ٠



# There are many types of reinterpretation

#### Simulation-based reinterpretation by outside groups •

- Medium accuracy (faster simulations, reimplementing analyses from public info, ...) •
- Medium-to-high computational cost per model point •



- MadAnalysis
- CheckMATE •
- GAMBIT (ColliderBit)
- Contur+Rivet

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## There are many types of reinterpretation

#### Simulation-less reinterpretation by outside groups •

- Medium accuracy •
- Reduced exclusion sensitivity compared to simulation-based methods •
- (Very) low computational cost per model point •



[2306.17676]

- SModelS •
- HiggsTools
- DarkCast



#### Why the need for speed?

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- First, BSM parameter spaces are high-dimensional!
  - And theorists have limited CPU resources :)
- Second, in **global fits** we seek statistically rigorous conclusions about **regions of BSM parameter spaces** 
  - Need properly converged explorations of the likelihood function / posterior distribution
  - Must use adaptive sampling algorithms, that focus on higher-likelihood regions
  - So the problem is not trivially parallelisable (we can't just sample first, simulate later)

#### Four-dimensional Rosenbrock function



# 2. How we can learn more

#### • From Roberto Franceschini's talk on Monday:



it is quite hard to find an experimental signature that can be attained in another model and cannot be attained in SUSY (including

the model also comes with "some" way to judge how likely it is the particular signal at hand (how much do I have to sweat to get this

the model allows to derive the experimental implications of observing such signal (what other signals should I see besides this?)



All the hard-won event counts with background estimates from the LHC SUSY programme hold **a lot** of information about BSM theory space.

What we have learned at time of publication



Impossible to reinterpret





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### What we have learned long after publication





### Learning more #1: We can probe much more of SUSY theory space





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### Reminder: **Theory space is a strange, implausible place**

- «Everyone» would assign negligible prior belief to almost all points in the low-scale MSSM parameter space
- MSSM expresses our ignorance of SUSY breaking
- Any «elegant»/«economic»/«reasonable» high-scale model maps to some tiny subspace of the low-scale MSSM
- And any simplified model plane maps to some strange hypersurface through low-scale MSSM
- A «large» exclusion in simplified model space:
  - Maybe large, maybe small impact on MSSM
- A «large» exclusion in low-scale MSSM
  - Maybe decisive, maybe negligible impact on the space of plausible high-scale models



[hep-ph/9709356]

### Learning more #2: We can probe much more of BSM theory space









### Learning more #3: We can identify best-fit scenarios



Explore MSSM EWino sector [1809.02097]

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Explore space of simplified models [2012.12246]

### Learning more #4: We can learn how to plug «holes» in theory space



• Example:

- Light Higgsinos, heavier winos
- Dominant production mode can be the heavier wino pair (if not too heavy)



### Learning more #4: We can learn how to plug «holes» in theory space



- Studied benchmark points that survived 36 fb<sup>-1</sup> searches. Example:
  - 3 Higgsinos ~200 GeV, Δm ~ 40 GeV
  - 2 winos ~ 300 GeV •
- Compare to wino/bino simplified model with  $\Delta m$ ~ 100 GeV
  - Main signature is similar: on-shell W + Z + MET
  - But gives **less clean final states**, due to not-necessarily-soft products from decays between higgsinos
  - Replace «simplified model cut» **n**<sub>jets</sub> = **0** with a «less simplified» cut  $H_T < X$ ?









#### In short: Given a null-result, the exclusion limits are very interesting and useful...





[ATLAS, 2106.01676]

#### ...but this is the real gold! :)

		Regions	$SR_{SFOS}^{Wh} - 1$	$SR_{SFOS}^{Wh} - 2$	$SR_{SFOS}^{Wh} - 3$	$SR_{SEOS}^{Wh} - 4$	$SR_{SFOS}^{Wh} - 5$	$SR_{SEOS}^{Wh}$ -	6 SR <sup>Wh</sup> <sub>SEOS</sub> -7					
		Observed	152	14	8	47	6	15	19					
		Fitted SM	$136 \pm 13$	$13.5 \pm 1.7$	$4.3 \pm 0.9$	$50 \pm 5$	$4.3 \pm 0.7$	$20.2 \pm 2.$	$.1 16.0 \pm 2.1$					
		WZ	$107 \pm 12$	$10.2 \pm 1.7$	$3.8 \pm 0.8$	$32 \pm 4$	$2.7 \pm 0.6$	$12.3 \pm 1.$	.6 $10.8 \pm 1.7$					
		tī	$10.3\pm2.5$	$1.6 \pm 0.6$	$0.13 \pm 0.12$	$7.7 \pm 1.9$	$0.74 \pm 0.34$	$3.5 \pm 1.$	$.0  2.5 \pm 0.7$					
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		Triboson	$1.9 \pm 0.5$	$0.22 \pm 0.07$	$0.07 \pm 0.02$	$1.4 \pm 0.4$	$0.28 \pm 0.09$	0 Rivet	t analyses refere	nce				
		Others	$8.6 \pm 1.9$	$0.84 \pm 0.11$	$0.08 \pm 0.05$	$4.0 \pm 0.5$	$0.23 \pm 0.24$	<sup>2</sup> ATLAS	S_2020_I1803608					
		Regions	SR <sup>Wh</sup> <sub>SFOS</sub> -8	$SR_{SFOS}^{Wh} - 9$	$SR_{SFOS}^{Wh} - 10$	$SR_{SFOS}^{Wh}$ - 11	SR <sup>Wh</sup> <sub>SFOS</sub> -12	Electro	weak Zjj at 13 TeV					
		Observed	113	184	28	5	82	Inspire	ID: 1803608					
		Fitted SM	$108 \pm 13$	$180 \pm 17$	$31 \pm 4$	$6.6 \pm 0.9$	$90 \pm 11$	1 Authors	s:					
		WZ	54 ± 6	$127 \pm 13$	$19.3 \pm 2.3$	$5.3 \pm 0.8$	47 ± 6	• Ste	ephen Weber					
		tī	$21 \pm 6$	$33 \pm 10$	$8.2 \pm 2.3$	$0.7 \pm 0.5$	$28 \pm 8$	• Da	ag Gillberg					
		Z+jets	$19 \pm 10$	$2.3 \pm 1.9$	$1.0 \pm 1.3$	$0.10\pm0.21$	$2.1 \pm 3.1$	Referen	nces:					
		Higgs	$1.91\pm0.19$	$3.63\pm0.35$	$0.67\pm0.06$	$0.15\pm0.02$	$2.98 \pm 0.25$	0 . ar	Xiv: 2006.15458					
		Triboson	$0.79 \pm 0.24$	$1.4 \pm 0.4$	$0.41 \pm 0.13$	$0.12\pm0.05$	$1.6 \pm 0.5$	0 . Eu	ur. Phys. J. C 81 (2021) 16	3				
		Others	$11.1 \pm 2.2$	$12.2 \pm 2.2$	$1.8 \pm 0.4$	$0.22\pm0.05$	$9.0 \pm 1.1$	Beams:	: p+ p+					
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		Observed	51	5	37	7	4	• pp	> -> Z [-> ee and mumu] + j	ets production at 13 TeV				
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A huge thank you to everyone who works hard to produce some cutflow, a SimpleAnalysis code snippet, an efficiency map, a JSON likelihood file,

# 3. A recent SUSY reinterpretation example

# Collider constraints on electroweakinos in the presence of a light gravitino

The GAMBIT Collaboration: Viktor Ananyev<sup>1</sup>, Csaba Balázs<sup>2</sup>, Ankit Beniwal<sup>3</sup>, Lasse Lorentz Braseth<sup>1</sup>, Andy Buckley<sup>4</sup>, Jonathan Butterworth<sup>5</sup>, Christopher Chang<sup>6</sup>, Matthias Danninger<sup>7</sup>, Andrew Fowlie<sup>8</sup>, Tomás E. Gonzalo<sup>9</sup>, Anders Kvellestad<sup>1</sup>, Farvah Mahmoudi<sup>10,11</sup>, Gregory D. Martinez<sup>12</sup>, Markus T. Prim<sup>13</sup>, Tomasz Procter<sup>4</sup>, Are Raklev<sup>1</sup>, Pat Scott<sup>14</sup>, Patrick Stöcker<sup>15</sup>, Jeriek Van den Abeele<sup>1</sup>, Martin White<sup>16</sup>, Yang Zhang<sup>17,18</sup>



## EW SUSY w/ light gravitino at the LHC















#### Usual ATLAS/CMS simplified model:

- Production of lightest neutralinos/charginos
- 1-2 fixed branching ratios
- Near massless gravitino as LSP



# Our model: all EWinos + light gravitino

- Model: MSSM w/ neutralinos, charginos and gravitino within LHC reach
- 7 SUSY particles below 1 TeV: 4 neutralinos, 2 charginos, light gravitino
- 4D theory parameter space: M1, M2, mu, tan beta
- $\cdot$  Why a gravitino?
  - necessary consequence of supergravity
  - gauge-mediated symmetry breaking (GMSB): gravitino likely the LSP
- Distinct collider pheno: the lightest neutralino/chargino will decay
- Gravitino mass fixed to 1 eV  $\rightarrow$  prompt decay of lightest neutralino/chargino



## Analysis

- Series of parameter scans w/ GAMBIT
- Scanner: **Diver** (differential evolution)
- Per point: simulate 16M SUSY events (Pythia, via ColliderBit)
- CPU cost: tens of millions of CPU hours... •
- Likelihoods: •
  - 15 ATLAS + 12 CMS searches (in ColliderBit)
  - 22 «pools» of 45 ATLAS, CMS and LHCB measurements (Contur+Rivet, via ColliderBit)
  - apply relevant LEP cross-section limits (in ColliderBit) •



## It's a complicated profile likelihood...





## It's a complicated profile likelihood...









## Best fit for light higgsino scenarios



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33

## Several different surviving scenarios



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# Profile likelihood ratio $\mathcal{L}/\mathcal{L}_{ ext{max}}$











# 4. Some challenges for reinterpretation

(Reinterpretation of experiments in other areas of particle physics still often involves scraping data from Figure 73 in Appendix B of an old PhD thesis...)

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The ATLAS and CMS SUSY groups are overall doing a really good job at providing public material for reinterpretation!

## What we do in ColliderBit

- For each parameter point in a scan:
  - Run Pythia simulations of all relevant SUSY processes
  - Pass events through fast detector simulation (four-vector smearing + efficiencies)
  - Pass events through our implementations of ATLAS and CMS searches
    - $\rightarrow$  signal predictions for all SRs
  - Compute a combined likelihood for the parameter point
    - We combine as many analyses and SRs as we reasonably can, given available info
  - Plus an analogous pipeline for measurements, using Rivet + Contur



39



# The information we need to do this

#### **Implementing the analysis:**

- Clear analysis description in the paper •
- SimpleAnalysis code snippets •
- **Reusable NNs?** •

#### Validating our implementation:

- Cutflows for benchmark points •
  - Clear definition of signal model (SLHA file) •
  - Any preselections not mentioned in cutflow?
  - How many MC events generated? •

#### Fully utilising the data (and improving stability):

- Full likelihoods, JSON (ATLAS) •
- Correlation matrices for simplified likelihoods (CMS) •

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	_					
	=		$\mathrm{m}( ilde{\chi}^0_2, ilde{\chi}^0_1)$ [	GeV]		
	S	Selection	(300, 200)	(600, 100)		
	4	$\mathcal{L} \times \sigma$	53784	2799		
	4	$\mathcal{L} \times \sigma \times \mathrm{BF}$	1760		•	$m(\tilde{z}^0, \tilde{z}^0)$ [GeV]
	4	$\mathcal{L} \times \sigma \times BF \times \text{filt. eff.}$	1322	Selection		$\frac{\operatorname{III}(\chi_2,\chi_1)[\operatorname{Oev}]}{(190,60)}$
	3	$\frac{1}{2}$ isolated lepton selection,	227	Selection	I	(190, 00)
		lepton $p_{\rm T}^{1,25} > 25, 20, 10$ GeV,	227	$\mathcal{L} \times \sigma$		303527
		$E_{\rm T}^{\rm max} > 50  {\rm GeV}$	226	$\mathcal{L} \times \sigma \times$	BF	10927
	<i>n</i> 1	$l_{\rm SFOS} \ge 1$	220	$\mathcal{L} \times \sigma \times$	$BF \times filt.$ eff.	1174
	1	h = 0	209	3 isolated	l lepton selection,	102
	/' F	$r_{b-jets} = 0$ Resonance veto $m_{es} > 12$ GeV	209	lepton	$p_{\rm T}^{1,2,5} > 25, 20, 10$ GeV,	192
	1	$m_{3\ell} - m_{Z} > 15 \text{ GeV}$	203	$E_{\rm T}^{\rm mas}$	> 50 GeV	107
	n	$n_{\ell\ell} \in [75, 105] \text{ GeV}$	196	Trigger s	election	186
	v	with MC to data weight	186	$n_{\rm b-jets} = 0$	0	171
	n	$i_{\text{iets}} = 0$	76.4	$= n_{SFOS} \ge$	1	137
	v	with MC to data weight	73.3	Resonance	ce veto $m_{\ell\ell} > 12 \text{ GeV}$	133
	-	$m_{\rm T} \in [100, 160] {\rm GeV}$	26.7	$ m_{3\ell} - m$	Z  > 15  GeV	110
		$SR^{WZ} - 1$	20.9	with MC	to data weight	104
		SR <sup>WZ</sup> -2	4.86	$m_{\ell\ell} < 75$	o GeV	56.2
		$SR^{W2} - 3$	0.78	$n_{\rm jets} =$	$= 0 \left( (SR_{1 \circ W - \mathfrak{m}_{11} \circ \vartheta j}^{m_{11}}) \right)$	22.3
	_	SR" <sup>2</sup> -4	0.14	S	$SR_{SFOS}^{WID} = 1$	8.26
		$m_{\rm T} > 160 \text{ GeV}$	5.80	S	SR <sub>SFOS</sub> -2	1.57
		SR -5	4.64	S	SR <sub>SFOS</sub> -3	0.50
		אר - ט SR <sup>WZ</sup> _ 7	0.10	S	SR <sub>SFOS</sub> -4	5.97
		SR <sup>WZ</sup> -8	0	S	SR <sub>SFOS</sub> -5	0.64
	3	$SR_{ex}^{WZ}$ ( $SR_{ex}^{WZ}$ -1 to 8)	31.4	S	SR <sup>wh</sup> <sub>SFOS</sub> -6	2.67
	=	$h_{0} = 0.0 H_{-} < 200 GeV$	07.5	=S	SR <sup>311</sup> <sub>SFOS</sub> -7	2.75
	<i>n</i>	$r_{jets} > 0, n_T < 200 \text{ GeV}$ with MC to data weight	97.5	$n_{\rm jets}$ >	$> 0, H_{\rm T} < 200 \text{ GeV} (\text{SR}_{low-m_{\rm in}-nj}^{\text{Wn}})$	26.5
	<u>-</u>	$m_{T} \in [100, 160] \text{ GeV}$	29.6	S	SR <sup>win</sup> <sub>SFOS</sub> -8	2.95
		SR <sup>WZ</sup> -9	8.75	S	$R_{SFOS}^{WII} - 9$	5.28
		$SR^{WZ} - 10$	3.46	S	SR <sub>SFOS</sub> -10	1.59
		$SR^{WZ} - 11$	0.54	S	SR <sub>SFOS</sub> -11	0.63
		$SR^{WZ}-12$	0	S	$SR_{SFOS}^{Wn} = 12$	5.55
		$m_{\rm T} > 160 { m ~GeV}$	9.50	S	$SR_{SFOS}^{wn} = 13$	2.91
		SR <sup>WZ</sup> -13	7.19	S	$SR_{SFOS}^{WI} - 14$	0.68
		$SR^{WZ} - 14$	1.53	S	$SR_{SFOS}^{wn} - 15$	5.48
		$SR^{*2}-15$	0.09	S	SR <sup>win</sup> <sub>SFOS</sub> -16	1.39
	=	SR <sup></sup> -16	0	$n_{SFOS} = 0$	)	34
	n	$u_{\text{jets}} > 0, H_{\text{T}} > 200 \text{ GeV}$	22.2	with MC	to data weight	33.5
	1	$H_{\rm T}^{\rm hep} < 350 {\rm GeV}$	20.9	$n_{\rm jets} =$	= 0	14.8
	v	with MC to data weight	19.3	p,	$r_{\rm T}^{\ell_3} > 15  {\rm GeV}$	12.2
		$m_{\rm T} > 100 \text{ GeV}$	10.8	E	$T_{T}^{miss}$ significance > 8	5.36
		SK = 17 $SP^{WZ} = 18$	2.55	Δ	$R_{\rm OS,near} < 1.2$	4.73
		$SR^{WZ} = 19$	1.09	$n_{\rm jets} \in$	∈ [1, 2]	15.6
		$SR^{WZ} - 20$	1.13	p.	$\ell_3 > 20 \text{ GeV}$	9.4
	S	$SR_{\text{ni}}^{\text{WZ}}$ ( $SR^{\text{WZ}}$ -9 to 20)	29.4	E	$_{\rm T}^{\rm miss}$ significance > 8	3.91
Publicatio	n Resou	rces		Δ	$R_{\rm OS,near} < 1.0$	2.84
				SR <sup>Wh</sup> DFOS		7.57
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Fig 8 Offshel /alidation Re

Tab 12 Onsh

**Region Yields** 

Tab 13 Onsh **Region Yields** 

Fig 10 Onshel **Region Yields** 

**Region Yields** 

Fig 11 Onshell Wh Signal

Contents



## The main challenges we encounter

- Limited public information •
  - Limits our ability to validate our implementation
  - Forces us to identify best-expected SR at each point

- **Detector-level variables** •
  - We can't do sophisticated detector simulation when mapping out high-dimensional theory spaces

The big one: **neural networks** ullet



### **Reusing Neural Networks:** Lessons learned and Suggestions for the future

Tomasz Procter Summary from the Les Houches reinterpretable ML working group

Tomasz Procter, RIF, August 2023





- Use an open-source framework (tensorflow, pytorch, etc)
- (e.g. ONNX or lwtnn).
  - Just leaving in a `.h5` file or `.pkl` file is unlikely to be stable Ο
- misstags – or surrogates), but 10 truth-level quantities + pseudo-continuous b-score is frustrating.

Tomasz Procter, RIF, August 2023

Ensure the network can be saved in a useful preservation format for inference

Be considerate with choice of inputs - if a tagger depends entirely on detector level inputs, that's fine (but please provide detailed efficiencies – including



Tomasz Procter, RIF, August 2023

Anders Kvellestad

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> A «Les Houches guide to reusable ML models» document is in preparation!



### Easier and more accurate reinterpretation



Anders Kvellestad



# More complicated selection variables

# 5. Moving forward: how to best help each other?

### Join the discussions in the LHC Reinterpretation Forum!

### (Re)interpretation of the LHC results for new physics

August 29, 2023 to September 1, 2023 Durham University

Europe/London timezone

# What would you like from reinterpretation studies?

- Assuming that we theorists can do reinterpretation in fairly high-dimensional theory spaces at medium accuracy...
- ...what output is most useful for you?
  - Maps of impact of current searches?
  - Benchmark points from surviving scenarios?
  - New low-dimensional planes for analysis optimisation?
  - New simplified models?
  - Suggested event selection strategies?
  - Forecasting for higher luminosity or new colliders?
  - Other things? All of the above?



# What experiments can do to help reinterpretations

- Consider tradeoff between gain from complicated selection ٠ variables and loss of reinterpretability
- Keep in mind that sensitivity in simplified model plane • *≠* sensitivity in BSM theory space
  - Can we e.g. use a «less simplified» SR definition? •
  - Reach out to your friendly neighbourhood theorist! •
- Consider reinterpretation by outside teams when designing ٠ new searches
  - Maybe include alternative, easy-to-reinterpret SRs?
- Support existing ATLAS efforts for reinterpretation ٠
  - SimpleAnalysis code snippets
  - Full likelihoods
  - Reusable NNs

. . .



### So how can we maximise the science impact of SUSY searches?

### So how can we maximise the science impact of SUSY searches?

We can make sure that physicists in our community will be able to compute **reasonably accurate predictions** for **as many of the SRs as possible**, and that this can happen **as efficiently as possible** both in **human hours** and **CPU hours.** 

### So how can we maximise the science impact of SUSY searches?

We can make sure that physicists in our community will be able to compute **reasonably accurate predictions** for **as many of the SRs as possible**, and that this can happen **as efficiently as possible** both in **human hours** and **CPU hours.** 

(And of course, discover SUSY.)

## **Bonus tracks**

### Parameter space

#### Neutralinos

$$\psi^{0} = (\tilde{B}, \tilde{W}^{0}, \tilde{H}_{d}^{0}, \tilde{H}_{u}^{0})$$

$$M_{N} = \begin{pmatrix} M_{1} & 0 & -\frac{1}{2}g'vc_{\beta} & \frac{1}{2}g'vs_{\beta} \\ 0 & M_{2} & \frac{1}{2}gvc_{\beta} & -\frac{1}{2}gvs_{\beta} \\ -\frac{1}{2}g'vc_{\beta} & \frac{1}{2}gvc_{\beta} & 0 & -\mu \\ \frac{1}{2}g'vs_{\beta} & -\frac{1}{2}gvs_{\beta} & -\mu & 0 \end{pmatrix}$$

$$\psi^{\pm} = (\tilde{W}^{+}, \tilde{H}_{u}^{+}, \tilde{W}^{-}, \tilde{H}_{d}^{-})$$
$$M_{C} = \begin{pmatrix} 0 \ X^{T} \\ X \ 0 \end{pmatrix}, \text{ where } X = \begin{pmatrix} M_{2} \ \frac{gvs_{\beta}}{\sqrt{2}} \\ \frac{gvc_{\beta}}{\sqrt{2}} & \mu \end{pmatrix}$$



#### Charginos

(





Search label	Luminosity
ATLAS_2BoostedBosons	$139{\rm fb}^{-1}$
ATLAS_0lep	$139{\rm fb}^{-1}$
ATLAS_0lep_stop	$36{ m fb}^{-1}$
ATLAS_1lep_stop	$36{ m fb}^{-1}$
ATLAS_2lep_stop	$139{ m fb}^{-1}$
ATLAS_20Slep_Z	$139{\rm fb}^{-1}$
ATLAS_20Slep_chargino	$139{ m fb}^{-1}$
ATLAS_2b	$36{ m fb}^{-1}$
ATLAS_3b	$24{ m fb}^{-1}$
ATLAS_3lep	$139{\rm fb}^{-1}$
ATLAS_4lep	$139{\rm fb}^{-1}$
ATLAS_MultiLep_strong	$139{\rm fb}^{-1}$
ATLAS_PhotonGGM_1photon	$139{\rm fb}^{-1}$
ATLAS_PhotonGGM_2photon	$36{ m fb}^{-1}$
ATLAS_Z_photon	$80{ m fb}^{-1}$
CMS_0lep	$137\mathrm{fb}^{-1}$
CMS_1lep_bb	$36{\rm fb}^{-1}$
CMS_1lep_stop	$36{\rm fb}^{-1}$
CMS_2lep_stop	$36{\rm fb}^{-1}$
CMS_2lep_soft	$36{\rm fb}^{-1}$
CMS_20Slep	$137\mathrm{fb}^{-1}$
CMS_20Slep_chargino_stop	$36  {\rm fb}^{-1}$
CMS_2SSlep_stop	$137{\rm fb}^{-1}$
CMS_MultiLep	$137\mathrm{fb}^{-1}$
CMS_photon	$36\mathrm{fb}^{-1}$
CMS_2photon	$36{ m fb}^{-1}$
CMS_1photon_1lepton	$36{\rm fb}^{-1}$

#### Source

ATLAS hadronic chargino/neutralino search [100] ATLAS 0-lepton search [101] ATLAS 0-lepton stop search [102] ATLAS 1-lepton stop search [103] ATLAS 2-lepton stop search [104] ATLAS stop search with Z/H final states [105] ATLAS 2-lepton chargino search [106] ATLAS 2-*b*-jet stop/sbottom search [107] ATLAS 3-b-jet Higgsino search [108] ATLAS 3-lepton chargino/neutralino search [109] ATLAS 4-lepton search [110] ATLAS leptons + jets search [111] ATLAS 1-photon GGM search [112] ATLAS 2-photon GGM search [113] ATLAS Z + photon search [114]CMS 0-lepton search [115] CMS 1-lepton + b-jets chargino/neutralino search [116] CMS 1-lepton stop search [117]CMS 2-lepton stop search [118] CMS 2 soft lepton search [119] CMS 2-lepton search [120] CMS 2-lepton chargino/stop search [121] CMS 2 same-sign lepton stop search [122]CMS multilepton chargino/neutralino search [123] CMS 1-photon GMSB search [124] CMS 2-photon GMSB search [125] CMS 1-photon + 1-lepton GMSB search [126]





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59



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60

- **Explore the model parameter space** ( $\theta_1, \theta_2, \theta_3, ...$ ) •



• (but not necessarily a *good* fit, or the most probable  $\theta$ ...)

#### • At every point $\theta$ : compute all predictions( $\theta$ ) $\rightarrow$ evaluate likelihood L( $\theta$ )

#### Region of highest L( $\theta$ ) or InL( $\theta$ ): model's best simultaneous fit to all data

### Detailed model $\rightarrow$ many parameters $\rightarrow$ high-dimensional parameter space High-dimensional spaces are exponentially tricky to explore...

- For given sample density, the number of required samples increases exponentially •
  - 0.01 resolution for a 1D unit interval: 100 points
  - 0.01 resolution for a 10D unit cube:  $100^{10} = 10^{20}$  points
- The volume of any interesting region decreases exponentially fast with D
- A uniformly sampled point is «always» near at least one of the walls…
- $\cdot$  ...and it's also «always» the surface of a sphere with radius sqrt(D/3)
- Relative differences in distances between points vanish («loss of contrast») •

### Detailed model $\rightarrow$ many parameters $\rightarrow$ high-dimensional parameter space

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### Detailed model → I High-dimensional

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- Relative difference



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# Consequence: Detailed physics models $\rightarrow$ huge computational challenge

[large number of observables]

[long calculation time per observable per parameter point]

[huge number of points required to explore parameter space]











### So we must:

- speed up our physics computations where we can
- pick our parameter samples wisely

maximise the usefulness of the CPU hours we spend

### Parameter space exploration







### Parameter space exploration





# Models $\quad \longleftrightarrow \quad$



### Backends

CaptnGeneral, DarkSUSY, DDCalc, FeynHiggs, FlexibleSUSY, gamLike, gm2calc, HEPLike, HiggsBounds, HiggsSignals, MicrOmegas, nulike, Pythia, SPheno, SUSYHD, SUSYHIT, SuperIso, Vevacious, MontePython, CLASS, AlterBBN, ...

GAM

