Putting it all together: what we can learn from BSM global fits

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LNF, September 19, 2024





Outline

- 1. BSM global fits
- 2. What we can learn (example: LHC global fits)
- 3. Why it's difficult
- 4. GAMBIT

1. BSM global fits

How can we extract the most physics from our data?

repeat as needed...

- But what is **a model**?
- And how to test it against data?

Easy! Construct a physics model, test it against data,

But what is a model? A joint probability distribution for the data

$f(x) = ax + b + \epsilon, \quad \epsilon \sim N(0, \sigma)$

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$p(y_1, y_2, \dots | x_1, x_2, \dots, a, b, \sigma) = N(f(x_1; a, b), \sigma) N(f(x_2; a, b), \sigma) \dots$





- Lagrangian parameters
- Experiment parameters
- Expected background rates

$$p(n_1, n_2, \dots | \boldsymbol{\theta}) = \operatorname{Pois}(\lambda_1(\boldsymbol{\theta})) \operatorname{Pois}(\lambda_2(\boldsymbol{\theta}))$$
$$\operatorname{Pois}(\lambda(\boldsymbol{\theta})) = \frac{\lambda(\boldsymbol{\theta})^n e^{-\lambda(\boldsymbol{\theta})}}{n!}$$

Differential cross-sections, decay rates, ...

• Simulate events

•

•

- Simulate detector effects
- Mimic the experiment's data selection procedure

• • •

How to compare your model against data? The likelihood is key

Bayesian

$$p(\boldsymbol{\theta}|\boldsymbol{D}_{\text{obs}}) = \frac{p(\boldsymbol{D}_{\text{obs}}|\boldsymbol{\theta}) p(\boldsymbol{\theta})}{p(\boldsymbol{D}_{\text{obs}})}$$
$$p(\boldsymbol{\theta}|\boldsymbol{D}_{\text{obs}}) = \frac{L(\boldsymbol{\theta}) \pi(\boldsymbol{\theta})}{Z}$$

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$p(\boldsymbol{D}_{obs}|\boldsymbol{\theta}) \equiv L(\boldsymbol{\theta})$

frequentist

$p(\boldsymbol{D}_{\mathrm{obs}}|\boldsymbol{\theta})$

+ assumptions/simulations of hypothetical data

Global fits



The basic steps of a BSM global fit

- Choose your **BSM theory and parameterisation** •
- collider physics, dark matter, flavor physics, +++

$$\mathcal{L} = \mathcal{L}_{collider} \mathcal{L}$$

- function across the parameter space of the theory
- (parameter estimation, model comparison, ...)

Construct the joint likelihood function including observables from

 $\mathcal{L}_{\mathrm{DM}}\mathcal{L}_{\mathrm{flavor}}\mathcal{L}_{\mathrm{EWPO}}\dots$

Use sophisticated scanning techniques to explore the likelihood

From likelihood samples, carry out frequentist or Bayesian inference

- **Explore the model parameter space** (θ_1 , θ_2 , θ_3 , ...) •

Region of highest $L(\theta)$: ٠ the model's highest predicted joint probability for the observed data (but not necessarily a *good* fit to the data, or the most *probable* θ ...)

• At every point θ : compute all predictions(θ) \rightarrow evaluate likelihood L(θ)

2. What we can learn

Example: LHC global fits

Understanding the full implications of [experimental] searches 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]

requires the interpretation of the experimental results in the context of many more theoretical models than are currently explored at the

HEP Software Foundation [arxiv:1712.06982]

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

The many interpretations 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 •
- Simulation-based reinterpretation by outside groups
 - Medium accuracy •
 - Medium-to-high computational cost per model point •

Simulation-less reinterpretation by outside groups

- Medium accuracy •
- Often reduced exclusion sensitivity for a given model point •
- Low computational cost per model point •

Wildly optimistic / very incomplete reinterpretations

E.g. just checking model points from some many-parameter theory against a couple of 2D exclusion contours

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experiments hold a lot of information about BSM theory space.

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All the hard-won event counts with background estimates from the LHC

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 BSM theory space

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

Learning more #2: 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 #3: We can learn how to plug «holes» in theory space

- Studied benchmark points that survived 36 fb⁻¹ searches. Example:
 - 3 Higgsinos ~200 GeV, Δm ~ 40 GeV
 - 2 winos ~ 300 GeV •
- Compare to wino/bino simplified model with Δm ~ 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**_{jets} = **0** with a «less simplified» cut $H_T < X$?

Learning more #3: W 400 When optimising searches on simplified 300models, at what point do we start losing $m_{{ ilde\chi}_1^0}~({ m GeV})$ rather than gaining sensitivity to volumes 200

of «similar» theory space?

100

In short: Results like these 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_{SFOS}^{Wh} - 4	$SR_{SEOS}^{Wh} - 5$	SR ^{Wh}	6 SR ^{Wh} _{SFOS} -7							
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			136 ± 13	13.5 ± 1.7 4.3 ± 0.9		50 ± 5	4.3 ± 0.7	20.2 ± 2	$.1 16.0 \pm 2.1$							
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				1.6 ± 0.6	0.13 ± 0.12	7.7 ± 1.9	0.74 ± 0.34	3.5 ± 1	$.0 2.5 \pm 0.7$							
				$0.00 \pm 0.02_{0.00}$	$0.00\pm_{0.00}^{0.02}$	2.0 ± 1.6	$0.00 \pm 0.04_{0.00}$	$0.00\pm_{0.0}^{0.0}$	$^{0.04}_{0.00} = 0.00 \pm ^{0.02}_{0.00}$							
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				0.84 ± 0.11	0.08 ± 0.05	4.0 ± 0.5	0.23 ± 0.24		ATLAS_2020_11803608							
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		WZ	54 ± 6	127 ± 13	19.3 ± 2.3	5.3 ± 0.8	47 ± 6	• St	tephen Weber							
		tī	21 ± 6	33 ± 10	8.2 ± 2.3	0.7 ± 0.5	28 ± 8	• Da	ag Gillberg							
		Z+jets	19 ± 10	2.3 ± 1.9	1.0 ± 1.3	0.10 ± 0.21	2.1 ± 3.1	Referen	nces:							
		Higgs	1.91 ± 0.19	3.63 ± 0.35	0.67 ± 0.06	0.15 ± 0.02 0.12 ± 0.05	2.98 ± 0.25	0 • ar	• arXiv: 2006.15458							
		Triboson	0.79 ± 0.24	1.4 ± 0.4	0.41 ± 0.13		1.6 ± 0.5	0 • Ei	ur. Phys. J. C 81 (2021) 163	3						
		Others	11.1 ± 2.2	12.2 ± 2.2	1.8 ± 0.4	0.22 ± 0.05	9.0 ± 1.1	Beams	: p+ p+	Gal						
		Regions SR ^{Wh} _{SFC}		SR_{SFOS}^{Wh} - 16	SR_{SFOS}^{Wh} - 17	SR_{SFOS}^{Wh} - 18	SR_{SFOS}^{Wh} - 19	Run de	Run details:							
	Observed		51	5	37	7	4	• pp	o -> Z [-> ee and mumu] + j	ets production at 13 TeV						
		Fitted SM	46 ± 7	9.8 ± 1.6	43 ± 7	12.6 ± 1.7	1.8 ± 0.4	Differen	ifferential cross-section measurements are prese							
		WZ	18.9 ± 2.2	3.9 ± 0.8	35 ± 6	9.8 ± 1.6	1.44 ± 0.32	0 provide	a fundamental test of the g	auge structure of the Star						
		tt	18 ± 6	3.2 ± 1.3	1.00 ± 0.34	0.33 ± 0.17	0.00 ± 0.00	The diff	proton collision data collect	ed by ATLAS at $\sqrt{s}=13$ measured in the $Z o\ell^+$						
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As a community we can **learn far more physics** from an experimental result that is **reinterpretable** compared to one that is not.

3. Why it's difficult

Is enough information public?

Digitise a graph in Figure 73 c) in Appendix B of some PhD thesis from 10 years ago...

VS

Is enough information public?

And can the information be used?

Les Houches guide to reusable ML models in LHC analyses

Jack Y. Araz¹, Andy Buckley², Gregor Kasieczka³, Jan Kieseler⁴, Sabine Kraml⁵, Anders Kvellestad⁶, Andre Lessa⁷, Tomasz Procter², Are Raklev⁶, Humberto Reyes-Gonzalez^{8,9,10}, Krzysztof Rolbiecki¹¹, Sezen Sekmen¹², Gokhan Unel¹³

VS

Digitise a graph in Figure 73 c) in Appendix B of some PhD thesis from 10 years ago...

[2312.14575]

Will the scan take forever?

- 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

Computational challenges:

- Need **smart exploration** of parameter space
- Need fast theory calculations
- Need fast simulations of experiments (e.g. LHC)
- Need sufficiently detailed likelihoods or full statistical models

- Some code infrastructure challenges:
 - Need different parameter scanning algorithms
 - Need model-agnostic core framework
 - Need to interface *many* external physics codes
 - Need massive parallelisation...
 - ...which implies a need for **diskless interfacing**
 - ...which implies a need to stop external codes from calling STOP and kill your 10,000-CPU scan... :)

4. GAMBIT

Anders Kvellestad

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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

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

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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, ...

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Technical features

- Collection of state-of-the-art sampling algorithms as **plug-ins** (e.g. evolutionary algorithms, nested sampling, ...)
- Model-agnostic core framework
- Run configuration through YAML input file
- Many highly detailed experiment likelihoods

Anders Kvellestad

 Fast parallel Monte Carlo simulations of experiments (e.g. LHC)

• **Dynamic dependency resolution**: order of computations not hard-coded, decided at run time

Technical features

- Two-level parallelisation:
 - **MPI** for parameter sampling algorithm
 - **OpenMP** for per-point model computations
- **Diskless interface** to external (physics) codes. C, C++, Fortran, • Python and Mathematica codes as runtime plug-ins
- **Printer system** to store results in different formats, with buffering and resume ability for aborted scans
- Logging system for information and debugging
- GAMBIT Universal Model machine (GUM): code auto-generation for new physics models

[2107.00030]

Dependency resolution

- Basic building blocks: module functions
- A physics module: **a collection of module** functions related to the same physics topic
- Each module function has a single **capability** (what it calculates)
- A module function can have **dependencies** on the results of other module functions
- A module function can declare which **models** it can work with
- GAMBIT determines which module functions should be run in which order for a given scan (dependency resolution)

```
void function_name(double &result)
  • •
 result = ... // something useful
```

```
// Observable: BR(B \rightarrow tau nu)
#define CAPABILITY Btaunu
START_CAPABILITY
  #define FUNCTION SI_Btaunu
  START_FUNCTION(double)
  DEPENDENCY(SuperIso_modelinfo, parameters)
  BACKEND_REQ(Btaunu, (libsuperiso), double, (const parameters*))
  BACKEND_OPTION( (SuperIso, 3.6), (libsuperiso) )
  #undef FUNCTION
#undef CAPABILITY
```

```
/// Br B->tau nu_tau decays
void SI_Btaunu(double &result)
  using namespace Pipes::SI_Btaunu;
  parameters const& param = *Dep::SuperIso_modelinfo;
  result = BEreq::Btaunu(&param);
```


Dependency resolution

Dependency resolution

EW-MSSM: 1809.02097

More axion-like particles: 2007.05517

Simplified DM, scalar/fermion: 2209.13266

Flavour EFT: 2006.03489

Cosmo ALPs: 2205.13549

Scalar Higgs portal DM: 1705.07931

Axion-like particles: 1810.07192

AMBIT::CosmoBi

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

Plus new results on sub-GeV DM! [2405.17548]

Vector and fermion Higgs portal DM: 1808.10465

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Anders Kvellestad

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Plus new results on sub-GeV DM! [2405.17548]

Simulation-based EWino fits with GAMBIT

Question: What are the 13 TeV collider constraints on the chargino/neutralino sector of the MSSM? $(MSSM \neq simplified model)$

- At every point: Run MC simulations of 13 TeV searches
 - Calculate joint likelihood function for all searches
- Produce profile likelihood plots

Method:

Scan 4D EWino parameter space w/ adaptive sampler

Main challenges:

Computational cost

Reproduce ATLAS/CMS searches w/ sufficient accuracy

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

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Two models: EWMSSM and G-EWMSSM

EWMSSM

- MSSM w/ neutralinos and charginos within LHC reach
- 6 SUSY particles below 1.5 TeV:
 4 neutralinos, 2 charginos
- **4D theory parameter space**: M1, M2, mu, tan beta

G-EWMSSM

- EWMSSM + near-massless gravitino (1eV gravitino, for prompt decays)
- 7 SUSY particles below 1.5 TeV:
 4 neutralinos, 2 charginos, 1 gravitino
- Same 4D parameter space, quite different collider pheno

Back in 2019: EWMSSM

Identified a possible explanation for a pattern of (at the time interesting) excesses across multiple ATLAS searches

[1809.02097] - 12 ATLAS/CMS searches - LEP cross-section limits

Comparing to SM rather than to the best-fit point: Found that no point in the chargino-neutralino mass plane was conclusively ruled out at that time

2023: G-EWMSSM

Scenario with light higgsinos \rightarrow Z/H + gravitino could partly fit small excesses in searches for leptons + MET and b-jets + MET

[2303.09082]- 27 ATLAS/CMS searches - Many «SM measurements» - LEP cross-section limits

Comparing to SM rather than to the best-fit point: Strong constraints, but several scenarios survive

2023: G-EWMSSM

Profile likelihoods can be complicated: Neighbouring points in e.g. a mass plane can belong to very different theoretical scenarios

[2303.09082] - 27 ATLAS/CMS searches

- Many «SM measurements»
- LEP cross-section limits

 $\mathbf{A} \mathbf{M} \mathbf{B} \mathbf{I} \mathbf{T} \mathbf{\mathcal{L}}$

Ongoing work: EWMSSM and G-EWMSSM after Run 2

G-EWMSSM: Preliminary

Compared to 2023 G-EWMSSM study:

Summary

- How can we maximise the scientific impact of experimental results?
 - Reinterpret experimental results in terms of many (realistic) theories

 - $\cdot \rightarrow Do global fits!$
- GAMBIT is an open-source tool for large-scale BSM global fits
- Most recent GAMBIT results:
 - Here: LHC impact on SUSY w/ light gravitino [2303.09082]
 - Sub-GeV dark matter [2405.17548]
- More results in the pipeline
 - Neutrinos, DM, SUSY after LHC Run 2, THDMs, ...
- theory prediction or likelihood? Do get in touch :)
- · gambitbsm.org

• Combine constraints from many experiments in a statistically sound way

• Got a neat idea for a global fit study? Got a new, shiny code for computing some

Soon public: GAMBIT-light

G-EWMSSM: Preliminary

Lowest-mass non-excluded higgsino scenarios violate the common simplified model assumption that N2/C1 always decay to N1 + soft stuff

- 34 ATLAS/CMS searches - LEP cross-section limits - TODO: SM measurements

G-EWMSSM: Preliminary

...and these scenarions are higgino-bino mixture scenarios (M1 ~ mu)

- 34 ATLAS/CMS searches - LEP cross-section limits - TODO: SM measurements

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]

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

(

Typical result: Parameter estimation, presented as **profile likelihood** and/or **posterior density** plots

[arxiv:1808.10465]

