Beyond the Standard Model with global fits: then, now and tomorrow

Pat Scott

Imperial College London

Outline

1. The problem
   - Introduction
   - Global fits
   - Including astroparticle observables
2. The current state of the game
   - Present limits
   - Coverage
   - Scanning challenges
3. Future challenges
   - Respectable LHC likelihoods
   - Parameter space $\rightarrow$ Theory space

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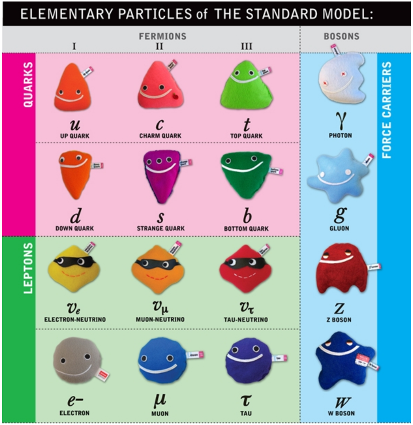

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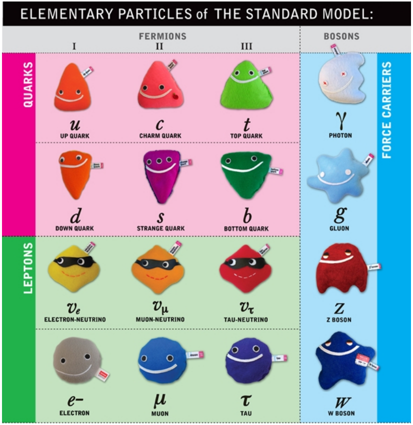

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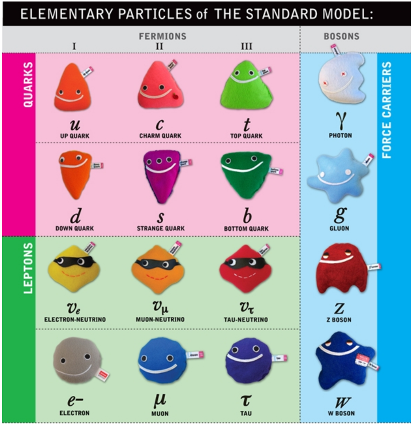

19 free parameters: (10 masses, 3 force strengths, 4 quark mixing parameters, 2 'vacuumy things')

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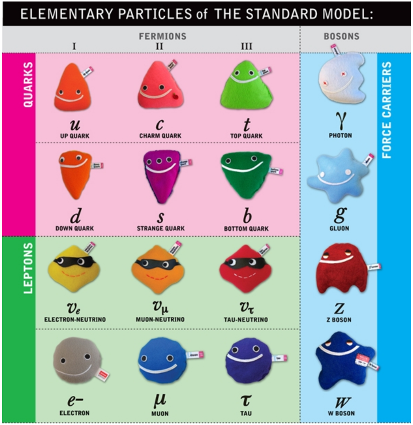

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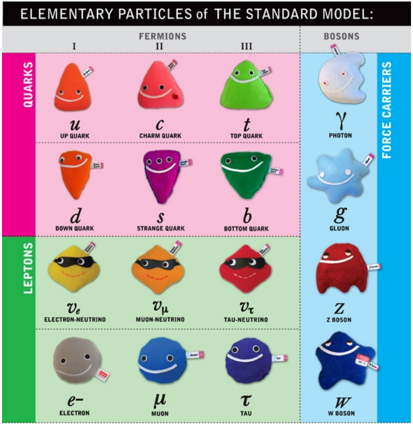

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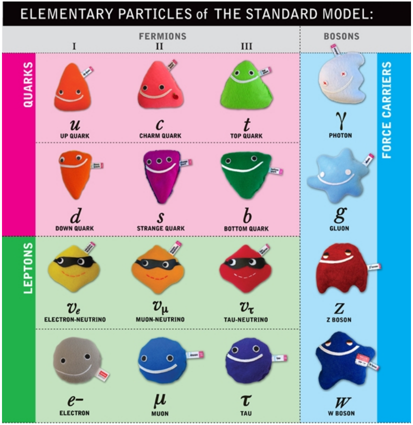

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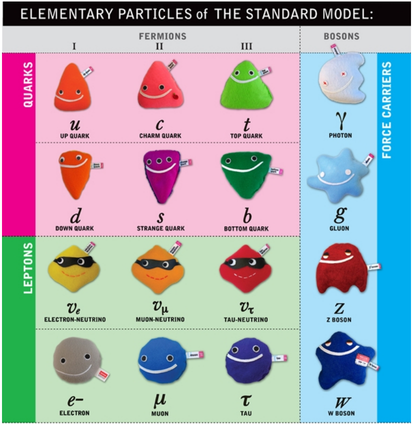

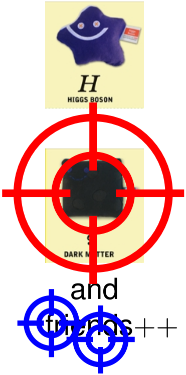

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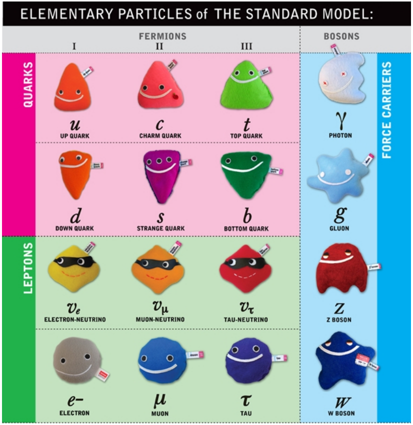

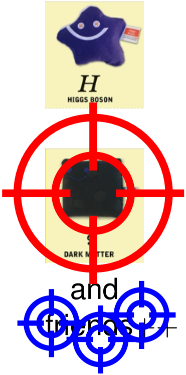

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Searching for new physics

Many reasons to look for physics Beyond the Standard Model (BSM):

- Higgs mass (hierarchy problem + vacuum stability)
- Dark matter exists
- Baryon asymmetry
- Neutrino masses and mixings

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Combining searches I

Question

How do we know which models are in and which are out?

Combining searches I

Question

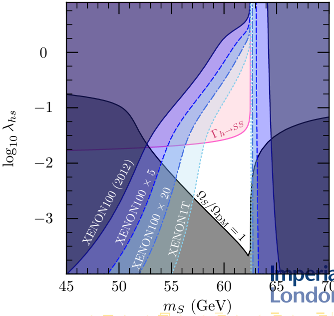
How do we know which models are in and which are out?

Answer

Combine the results from different searches

- Simplest method: take different exclusions, overplot them, conclude things are “allowed” or “excluded”
- Simplest BSM example: the scalar singlet model

(Cline, Kainulainen, PS & Weniger, *PRD*, 1306.4710)



Combining searches II

That's all well and good if there are only 2 parameters and few searches...

Question

What if there are many different constraints?

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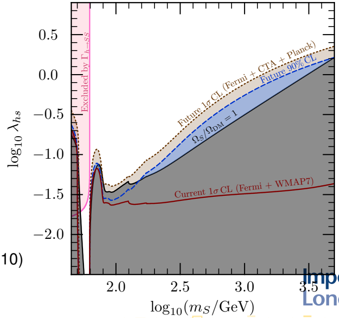
What if there are many different constraints?

Answer

Combine constraints in a statistically valid way
$\longrightarrow$ composite likelihood



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Question

What if there are many parameters?

Combining searches III

That's all well and good if there are only 2 parameters and few searches...

Question

What if there are many parameters?

Answer

Need to

- scan the parameter space (smart numerics)
- interpret the combined results (Bayesian / frequentist)
- project down to parameter planes of interest (marginalise / profile)

$\longrightarrow$ global fits

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Beyond-the-Standard-Model Scanning

Goals:

1. Given a particular theory, determine which parameter combinations fit all experiments, and how well
2. Given multiple theories, determine which fit the data better, and quantify how much better

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Why simple IN/OUT analyses are not enough. . .

- Only partial goodness of fit, no measure of convergence, no idea how to generalise to regions or whole space.
- Frequency/density of models in IN/OUT scans is not proportional to probability $\Longrightarrow$ means nothing.
- $\rightarrow$ attempts to make probabilistic statements with such scans are statistically invalid (sadly, some people still do it. . .)

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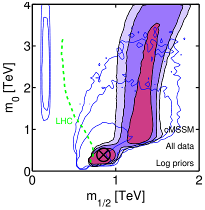
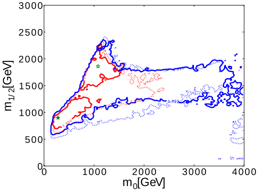
Know your (supersymmetric) parameter scans

Global fits:

Quantitative?
- per-point: always
- overall: always



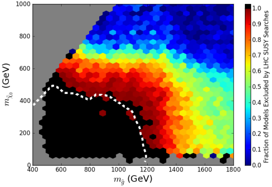
Strege et al *JCAP*, 1212.2636



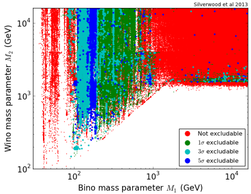
MasterCode, *EPJC*, 1207.7315

Not global fits:

Quantitative?
- per-point: sometimes
- overall: never



Cahill-Rowley et al, 1307.8444



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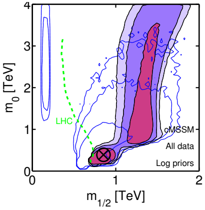

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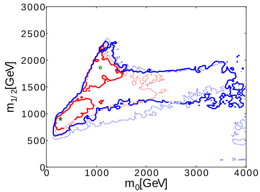

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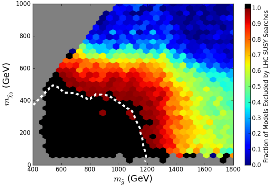

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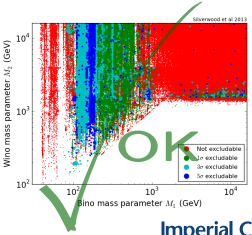

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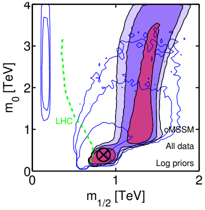

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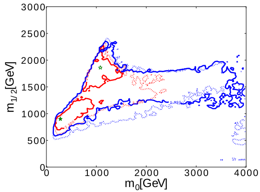

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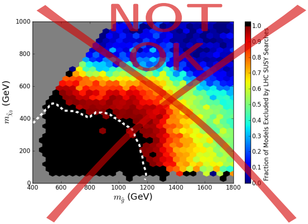

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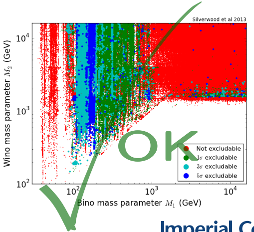

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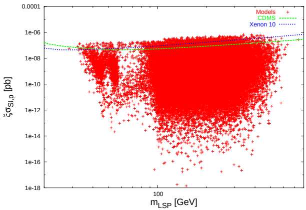
Another example

Berger, Gainer, Hewett & Rizzo, *JHEP* 2009



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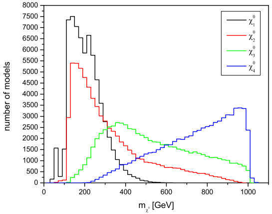

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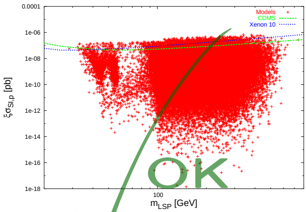

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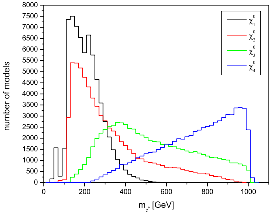

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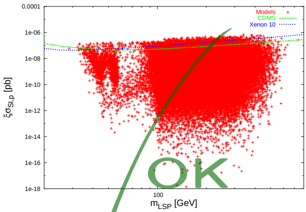

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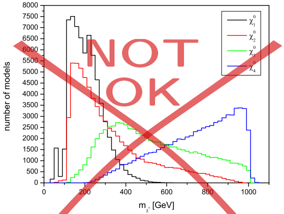

“Values are probable”

Putting it all together

Issue 1: Combining fits to different experiments
Relatively easy – composite likelihood ($\mathcal{L}_1 \times \mathcal{L}_2 \equiv \chi_1^2 + \chi_2^2$ for simplest $\mathcal{L}$)

- dark matter relic density from WMAP/Planck
- precision electroweak tests at LEP
- LEP limits on new particle particle masses
- B-factory data (rare decays, $b \to s\gamma$)
- muon anomalous magnetic moment
- LHC searches, direct detection

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Putting it all together: global fits

Issue 2: Including the effects of uncertainties in input data
Easy – treat them as *nuisance parameters* and profile/marginalise

Issue 3: Finding the points with the best likelihoods
Tough – MCMCs, nested sampling, genetic algorithms, etc

Issue 4: Comparing theories
Depends – Bayesian model comparison, p values
(TS distribution? $\longrightarrow$ coverage???)

Progress including searches for dark matter

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  - secondary impacts on the CMB (yes: WMAP5) Cline & PS *JCAP*, 1301.5908

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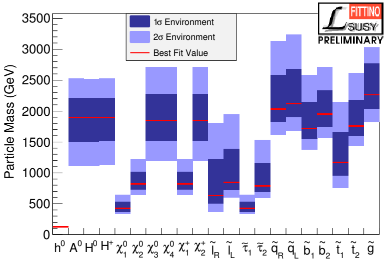
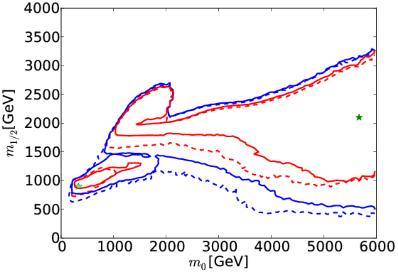
Outline

Current constraints: CMSSM$\pm\epsilon$

- CMSSM, profile likelihoods
- HiggsSignals + resimulation of LHC CMSSM limits
- ATLAS 0-lepton SUSY searches, 20.3 fb^{-1}, 8 TeV





- Fittino (PoS EPS-HEP 2013)
- $\rightarrow$ stau coannihilation + all else decoupled

- MasterCode (EPJC 74:2922)
- $\rightarrow$ stau coannihilation + Higgs funnel

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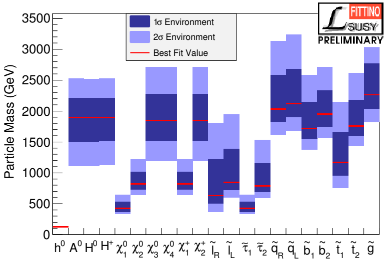

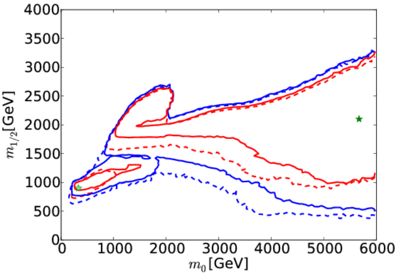

What gives? Probably `FeynHiggs` v2.9 vs 2.10.
Maybe also $g-2$ calculation and DD likelihood.

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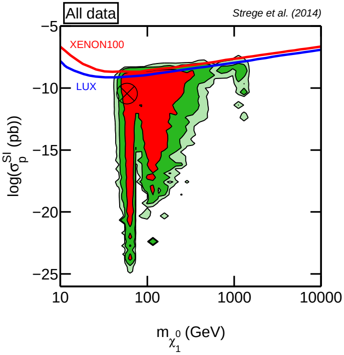
Current constraints: low-scale MSSM

- SuperBayeS (1405.0622)
- 15-parameter weak-scale MSSM
- profile likelihood
- latest *B*/*D* and DM constraints
- 'tall poppy' analysis: post-processed tiny subset of best points with collider limits
- ATLAS 0 and 3-lepton SUSY searches, 4.7 fb^{-1}, 7 TeV



Current issues: Coverage

Test statistic: a measure on data used to construct statistical tests (e.g. χ^2, $\ln\mathcal{L}$, etc.)
Coverage: the percentage of the time that a supposed 'x%' confidence region actually contains the true value

- Distribution of the test statistic and design of the test it's used in determine coverage.
- *p*-value calculation *requires* the test statistic distribution to be well known.

We don't **really** usually know the distribution of our test statistic in BSM global fits, as it is too expensive to Monte Carlo

- coverage is rarely spot-on unless mapping from parameters to data-space is linear

  (Akrami, Savage, PS et al *JCAP*, 1011.4297, Bridges et al *JHEP*, 1011.4306, Strege et al *PRD*, 1201.3631)

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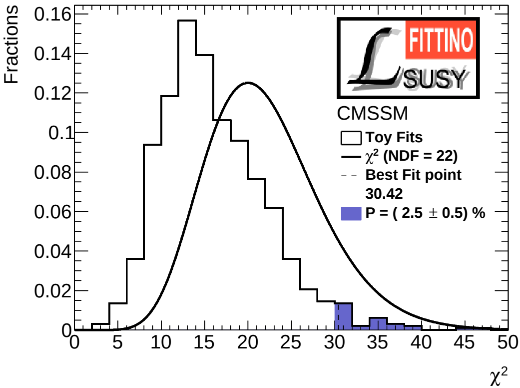
Fittino, arXiv:1410.6035



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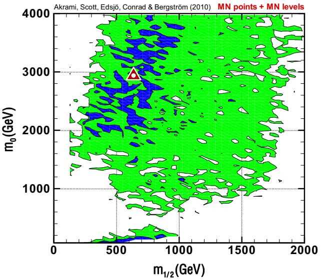
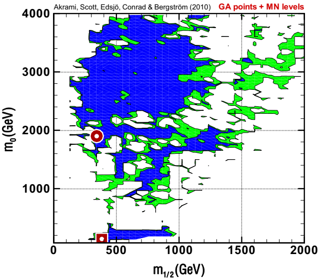
Current issues: Scanning algorithms

Convergence remains an issue, especially for profile likelihood

Messy likelihood $\Longrightarrow$ best-fit point can be (and often is) easily missed (Akrami, PS et al *JHEP*, 0910.3950, Feroz et al *JHEP*, 1101.3296)

- frequentist CLs are off, as isolikelihood levels are chosen incorrectly
- can impact coverage (overcoverage, or masking of undercoverage due to non-χ^2 *TS* distribution)
- need to use multiple priors and scanning algorithms (one optimised for profile likelihoods?)

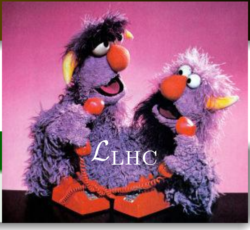




Outline

1. The problem
   - Introduction
   - Global fits
   - Including astroparticle observables
2. The current state of the game
   - Present limits
   - Coverage
   - Scanning challenges
3. Future challenges
   - Respectable LHC likelihoods
   - Parameter space → Theory space

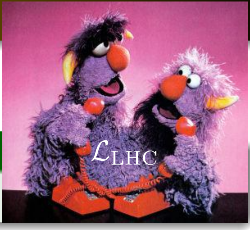
The LHC likelihood monster



Time per point:

$\mathcal{O}$(*minute*) in best cases

The LHC likelihood monster



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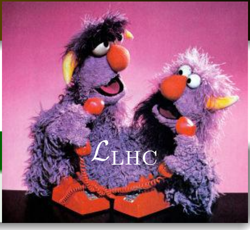

Time per point:

$\mathcal{O}$(*minute*) in best cases

Time per point for global fits to converge:

$\mathcal{O}$(*seconds*) in worst cases

Challenge:

About 2 orders of magnitude too slow to actually include LHC data in global fits properly

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Taming the LHC monster

Zeroth Order Response:

"Just use the published limits and ignore the dependence on other parameters"

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Taming the LHC monster

Zeroth Order Response:

"Just use the published limits and ignore the dependence on other parameters"

Obviously naughty – plotted limits assume CMSSM, and fix two of the parameters

- Don't really know dependence on other parameters
- Don't have a likelihood function, just a line
- Can't use this at all for non-CMSSM global fits – e.g. MSSM-25

(Early) SuperBayeS

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Taming the LHC monster

First Order Response:

"Test if things depend on the other parameters (hope not), re-simulate published exclusion curve"

Taming the LHC monster

First Order Response:

"Test if things depend on the other parameters (hope not), re-simulate published exclusion curve"

Not that great, but OK in some cases

- At least have some sort of likelihood this time
- Still a bit screwed if things do depend a lot on other parameters, but
- allows (potentially shaky) extrapolation, also to non-CMSSM models

Fittino, Mastercode

Taming the LHC monster

Second Order Response:

"That's ridiculous. I've never met a calculation I can't speed up. There must be some way to have my cake and eat it too"

Taming the LHC monster

Second Order Response:

"That's ridiculous. I've never met a calculation I can't speed up. There must be some way to have my cake and eat it too"

Maybe – this is the challenge.

- Interpolated likelihoods (how to choose nodes?)
- Neural network functional approximation (how to train accurately?)
- Some sort of smart reduction based on event topology?
- Something else?

Balázs, Buckley, Farmer, White et al (1106.4613, 1205.1568); GAMBIT

CMSSM, SMS $\neq$ BSM

(SMS = Simplified Model Spectrum)

Want to do model comparison to actually work out which theory is right…

Challenge:

How do I easily adapt a global fit to different BSM theories?

CMSSM, SMS $\neq$ BSM

(SMS = Simplified Model Spectrum)

Want to do model comparison to actually work out which theory is right...

Challenge:

How do I easily adapt a global fit to different BSM theories?

Somehow, we must recast things quickly to a new theory

- data
- likelihood functions
- scanning code 'housekeeping'
- even predictions

$\Longrightarrow$ a new, very abstract global fitting framework

Hitting the wall

Issues with current global fit codes:

- Strongly wedded to a few theories (e.g. constrained MSSM / mSUGRA)
- Strongly wedded to a few theory calculators
- All datasets and observables basically hardcoded
- Rough or non-existent treatment of most experiments (astroparticle + collider especially)
- Sub-optimal statistical methods / search algorithms
- $\Longrightarrow$ *already hitting the wall on theories, data & computational methods*

GAMBIT: a *second-generation* global fit code

GAMBIT: Global And Modular BSM Inference Tool

Overriding principles of GAMBIT: flexibility and modularity

- General enough to allow fast definition of new datasets and theoretical models
- Plug and play scanning, physics and likelihood packages
- Extensive model database – not just small modifications to constrained MSSM (NUHM, etc), and not just SUSY!
- Extensive observable/data libraries (likelihood modules)
- Many statistical options – Bayesian/frequentist, likelihood definitions, scanning algorithms
- A smart and *fast* LHC likelihood calculator
- Massively parallel
- Full open-source code release

The GAMBIT Collaboration

26 Members, 15 institutions, 9 countries
8 Experiments, 4 major theory codes

Fermi-LAT	J. Conrad, J. Edsjö, G. Martinez, P. Scott (leader)
CTA	C. Balázs, T. Bringmann, J. Conrad, M. White (dep. leader)
HESS	J. Conrad
ATLAS	A. Buckley, P. Jackson, C. Rogan, A. Saavedra, M. White
LHCb	M. Chrząszcz, N. Serra
IceCube	J. Edsjö, C. Savage, P. Scott
AMS-02	A. Putze
CDMS, DM-ICE	L. Hsu
DARWIN, XENON	J. Conrad
Theory	P. Athron, C. Balázs, T. Bringmann, J. Cornell, L.-A. Dal, J. Edsjö, B. Farmer, A. Krislock, A. Kvellestad, N. Mahmoudi, M. Pato, A. Raklev, C. Savage, P. Scott, C. Weniger, M. White

So what's so much better about GAMBIT?

Aspect	GAMBIT	MasterCode	SuperBayeS	Fittino	Rizzo et al.
Design	Modular, Adaptive	Monolithic	Monolithic	(∼)Monolithic	Monolithic
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LHC	ATLAS+CMS multi-analysis with neural net and fast detector simulation. Higgs multi-channel with correlations and no SM assumptions. Full flavour inc. complete $B \to X_s ll$ and $B \to K^* ll$ angular set.	ATLAS resim, HiggsSignals, basic flavour.	ATLAS direct sim, Higgs mass only, basic flavour.	ATLAS resim, HiggsSignals, basic flavour.	ATLAS+CMS +Tevatron direct sim, basic flavour.
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Closing remarks

- Robust analysis of dark matter and BSM physics requires multi-messenger global fits
- GAMBIT is coming:
  - $\longrightarrow$ Lots of interesting particle, astronomical, cosmological and astroparticle observables to include in global fits
  - $\longrightarrow$ Serious theoretical, experimental, statistical and computational detail to work though
  - $\longrightarrow$ Oslo is already in the thick of it

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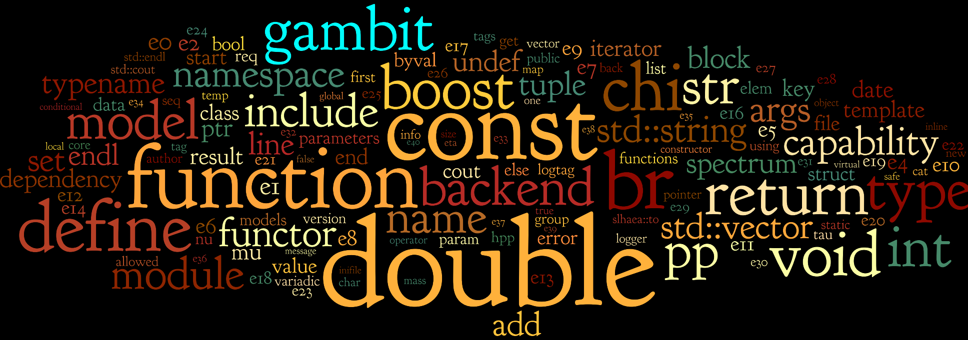
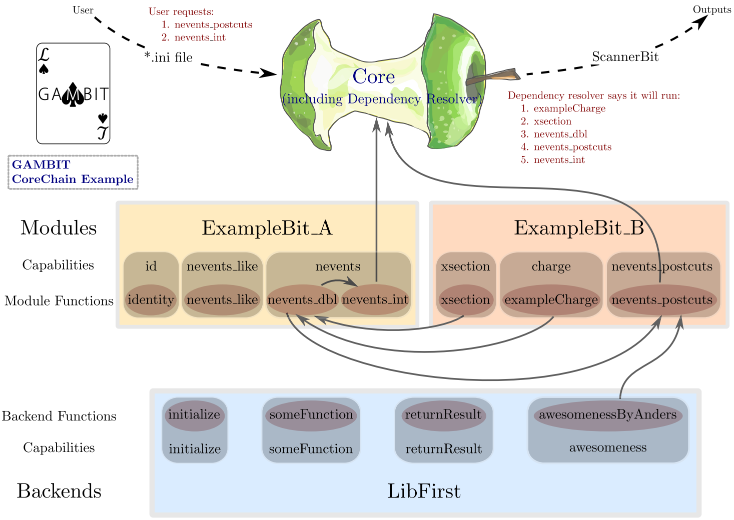

gambit
e24
e0
e2
bool
std::endl
start
req
std::cout
namespace
typename
first
byval
e17
tags
get
vector
e9
iterator
undef
public
map
e26
e7
back
list
block
e27
boost
tuple
chi
str
elem
key
e28
date
conditional
data
e34
seq
temp
class
global
e25
one
include
model
ptr
const
e35
e16
args
object
template
e38
std::string
file
inline
e32
line
parameters
info
e40
size
eta
e33
e5
using
capability
local
core
tag
e22
new
set
endl
author
result
e21
false
end
constructor
functions
spectrum
e31
virtual
e19
e4
e10
cat
dependency
function
e1
cout
else
logtag
struct
safe
backend
br
pointer
e12
return
type
e14
e29
define
e6
models
version
name
true
group
slhaea::to
std::vector
static
e20
nu
functor
e8
e37
e39
tau
operator
param
hpp
error
logger
int
e11
allowed
mu
message
e36
pp
module
value
inifile
void
e30
e18
variadic
char
mass
e13
e23
double
add

Outline

GAMBIT: sneak peek



Imperial College London

Bayesian & Frequentist terminology [Statistical aside]

Likelihood: probability of obtaining observed data D if model parameters Θ are correct

$$\mathcal{L}(D|\Theta) \tag{1}$$

Profiling: maximising the likelihood over a parameter you are not interested in

Posterior probability: probability of parameters Θ being correct given observed data D

$$P(\Theta|D) = \frac{\mathcal{L}(D|\Theta)P(\Theta)}{\mathcal{Z}(D)} \tag{2}$$

Marginalising: integrating the posterior over a parameter you are not interested in