# Prospects for constrained supersymmetry at $\sqrt{s} = 33\,\text{TeV}$ and $\sqrt{s} = 100\,\text{TeV}$ proton-proton super-colliders

arXiv:1402.5419

Andrew Fowlie

KBFI Tallinn
Andrew.Fowlie@KBFI.ee

DIS, Warsaw, April 2014

# Table of Contents

# Table of Contents

# Supersymmetry...

SUSY motivations you have heard before. Amongst other things:

1. Solves hierarchy problem by canceling divergent loops
2. Dark matter is relic abundance of lightest supersymmetric particle ($R$-parity), usually neutralino, $\chi_1$
3. Unification of couplings at $\sim 10^{16}$ GeV if SUSY particles included in running with $M_{\text{SUSY}} \lesssim 10\,\text{TeV}$

It was expected that SUSY was near the weak-scale.

# No supersymmetry so far...

Numerous experiments could have discovered/found hints for weak-scale supersymmetry:

1. LEP if electroweak sparticles were light
2. LHC if colored sparticles were $\lesssim 1\,\text{TeV}$
3. Direct searches for DM (Xenon, LUX etc.) if LSP is dark matter and has reasonable scattering cross section

None of these experiments found evidence for supersymmetry. The parameter space of supersymmetric models is under pressure.

# Table of Contents

# What shall we do now? Keep going?

A precision Higgs-factory $e^+e^-$ collider:

1. LEP-III in existing LHC tunnel $\sqrt{s} \sim 240\,\text{GeV}$ $(Zh)$
2. TLEP in new CERN tunnel $\sqrt{s} \sim 350\,\text{GeV}$ $(t\bar{t})$
3. ILC linear collider in Japan $\sqrt{s} \sim 250\,\text{GeV}$ initially

Not so good for direct evidence of SUSY. New hadron colliders:

1. LHC keep going at $\sqrt{s} = 13\,\text{TeV}$
2. HE-LHC in existing LHC tunnel $\sqrt{s} = 33\,\text{TeV}$
3. VLHC in huge new tunnel $\sqrt{s} = 100\,\text{TeV}$

# New hadron colliders. . .

The VLHC & HE-LHC are not firm proposals yet (detailed plans/timings/costings?), only preliminary ideas.

- But how "powerful" are these hadron colliders?
- How likely are they find SUSY?

At the moment, we have only qualitative, very subjective answers to these questions.
The experiments are expensive! Can we do any better?

# Table of Contents

# The Bayesian way...

Yes!, we can do better, we can quantify the answer to the following question

> *If nature is described by a particular SUSY model, what is the probability that the LHC/HE-LHC/VLHC will discover SUSY, given that previous experiments found no discrepancies with the Standard Model?*

We use Bayesian statistics. Probability is a numerical measure of our degree of belief in an hypothesis.

# The CMSSM...

*If nature is described by a* **particular SUSY model**...

We pick Constrained Minimal Supersymmetric Standard Model (CMSSM)

- Tractable, only 4 continuous parameters
- Well-known
- Well-studied

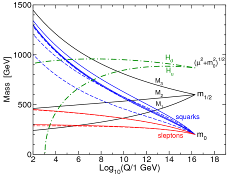
Results would be very different if we picked a model that evaded conventional hadron collider searches with $R$-parity violation or compressed spectra.

# Reminder...

The CMSSM's parameters defined at high-scale

- $m_0$, universal soft-breaking scalar mass
- $m_{1/2}$, universal soft-breaking gaugino mass
- $A_0$, universal soft-breaking trilinear
- $\tan\beta$, ratio of Higgs VEVs (at EW)

Run the parameters to low-scale and calculate sparticle mass spectrum.




MSSM RGE running

# Bayesian statistics...

Quick recap/introduction to Bayesian statistics,

> *...what is the* **probability** *that the LHC/HE-LHC/VLHC will discover SUSY...*

These probabilities are related to the posterior density from Bayes' theorem

$$\underbrace{p\left(m_0, \ldots \middle| \text{data}, \text{CMSSM}\right)}_{\text{Posterior density}} \propto$$

$$\underbrace{p\left(\text{data} \middle| m_0, \ldots, \text{CMSSM}\right)}_{\text{Likelihood}} \times \underbrace{p\left(m_0, \ldots \middle| \text{CMSSM}\right)}_{\text{Prior}}$$

Our posterior density for the CMSSM parameter space is our prior belief updated by the experimental data in the likelihood.

# Experimental data...

We include the experimental data

| Quantity | Experimental data, $\mu \pm \sigma$ |
|---|---|
| $\Omega h^2$ | $0.1199 \pm 0.0027$ |
| $m_h$ | $125.9 \pm 0.4\,\mathrm{GeV}$ |
| $\delta a_\mu$ | $(28.8 \pm 7.9) \times 10^{-10}$ |
| $M_W$ | $80.399 \pm 0.023\,\mathrm{GeV}$ |
| $\sin^2 \theta_{\ell,\mathrm{eff}}$ | $0.23116 \pm 0.00013\,\mathrm{GeV}$ |
| $\Delta M_{B_s}$ | $17.77 \pm 0.12\,\mathrm{GeV}$ |
| $\mathrm{BR}(B_s \to \mu\mu)$ | $(3.2 \pm 1.5) \times 10^{-9}$ |
| $\mathrm{BR}(B_s \to X_s\gamma)$ | $(3.43 \pm 0.22) \times 10^{-4}$ |
| $\mathrm{BR}(B_u \to \tau\nu)/\mathrm{BR}(B_u \to \tau\nu)\vert_{\mathrm{SM}}$ | $1.43 \pm 0.43$ |
| ATLAS 20.1/fb at $\sqrt{s} = 8\,\mathrm{TeV}$ | |
| LUX 85.3 live-days | |

all the most important experiments, including direct detection, mainly from PDG, with appropriate theory errors.

- LHC likelihood is a "hard-cut" on $(m_0, m_{1/2})$ plane; this is a good approximation
- Measurements are Gaussian likelihood functions

# Prior choices...

We must pick priors (probability distributions) for the CMSSM parameters, before seeing experimental data.

- No unique right choice
- But lots of wrong (unfair/dishonest) ones!
- All honest investigators ought to make identical conclusions, if they choose honestly, providing the data is "strong enough"

We investigate logarithmic and linear priors, as is common in the literature, for the $m_0$ and $m_{1/2}$ parameters,

- Logarithmic, $\pi(x) = \text{const.}/x$
- Linear, $\pi(x) = \text{const.}$

and linear priors for $\tan\beta$ and $A_0$. There are other fair/honest choices.

# Bayesian statistics applied to our question...

We say that,

> *CMSSM point would be discovered if, were nature described by that CMSSM point, it is expected that the SM background hypothesis could be rejected at $5\sigma$.*

The regions in which this is expected are found in terms of gluino and squark masses in

> *Timothy Cohen et al. "SUSY Simplified Models at 14, 33, and 100 TeV Proton Colliders". In: (2013). arXiv:*1311.6480 [hep-ph]

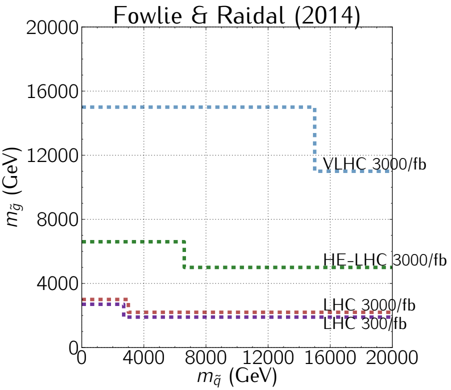
# Discoverable...

For MSSM (without RPV, compressed spectra etc.), we could discover...

1. If gluinos and squarks are light, pair produced and decay to a neutralino and a quark or quark pair
   - $m_{\tilde{g}} \simeq m_{\tilde{q}} \lesssim 2.7\,\text{TeV}$ ($m_{\tilde{g}} \simeq m_{\tilde{q}} \lesssim 3.0\,\text{TeV}$) at the LHC with 300/fb (3000/fb)
   - $m_{\tilde{g}} \simeq m_{\tilde{q}} \lesssim 6.6\,\text{TeV}$ at the HE-LHC
   - $m_{\tilde{g}} \simeq m_{\tilde{q}} \lesssim 15\,\text{TeV}$ at the VLHC with 3000/fb

# Discoverable…

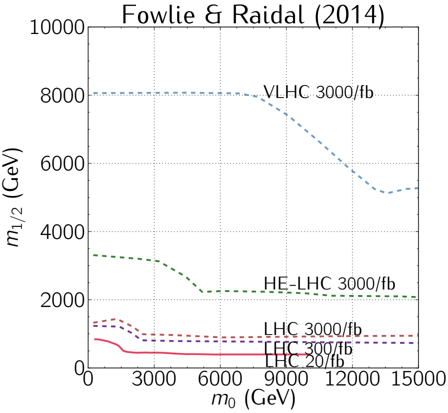
For MSSM (without RPV, compressed spectra etc.), we could discover…




Gluino-squark collider reach

# Discoverable...

For MSSM (without RPV, compressed spectra etc.), we could discover...




$(m_0,\ m_{1/2})$ collider reach

# Bayesian statistics applied to our question...

We assume that

$$p(\text{Would be discovered}) = \begin{cases} 1 & \text{if point } \in \text{Discoverable}, \\ 0 & \text{if point } \notin \text{Discoverable}. \end{cases}$$

- This is an approximation
- E.g. a downwards fluctuation in number of observed events, such that a point that was expected to be discovered is not discovered
- We do not consider this complication

# Table of Contents

# Master formula...

We can now answer our question!,

> *If nature is described by a particular SUSY model, what is the probability that the LHC/HE-LHC/VLHC will discover SUSY, given that previous experiments found no discrepancies with the Standard Model?*

Combining our equations, the answer is

$$\int_{\text{Would be discovered}} p\left(m_0, \ldots \middle| \text{data}, \text{CMSSM}\right) \mathrm{d}X$$

We can perform the integral numerically, by supplying our likelihood functions (experimental data) and priors for the CMSSM parameters to the `(Py)MultiNest` algorithm.

# Master formula in words...

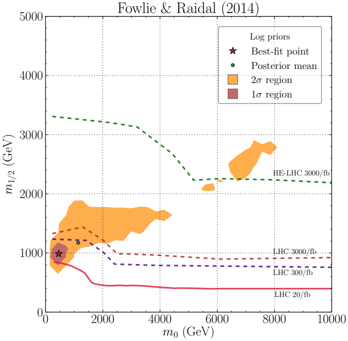
$$\int_{\text{Would be discovered}} p\left(m_0, \ldots \middle| \text{data, CMSSM}\right) \mathrm{d}X$$

1. Find probability density of CMSSM parameter space, given relevant experimental data
2. Normalize it to one
3. Integrate that probability density only over parts expected to be discovered in a particular experiment
4. Result is probability of discovering SUSY at that experiment, given that CMSSM is correct (with a few approximations)

# Table of Contents

# Posterior density. . .

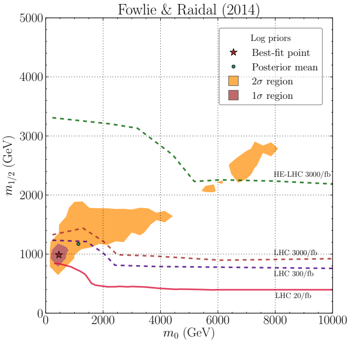
- Posterior density with logarithmic priors, given all the experimental data
- Plot credible regions (Bayesian equivalent of confidence limits)
- DM relic density most important, 3 mechanisms
  1. Stau-coannihilation
  2. *A*-funnel
  3. "1 TeV-higgsino"




$(m_0, m_{1/2})$ plane

# Posterior density...

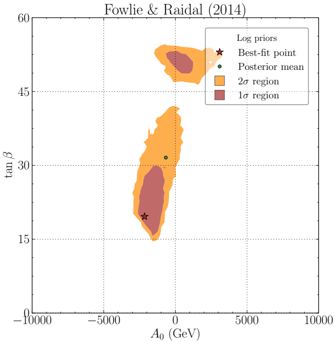
1. Stau-coannihilation accessible at LHC
2. *A*-funnel partially at LHC, fully at HE-LHC
3. "1 TeV-higgsino" only at VLHC




$(m_0, m_{1/2})$ plane

# Posterior density...

- Stau-coannihilation at small $\tan\beta$
- $A$-funnel large $\tan\beta$
- "1 TeV-higgsino" not visible on $(A_0, \tan\beta)$



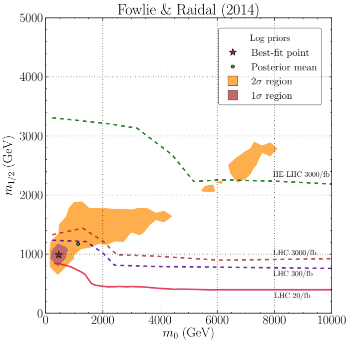

$(A_0, \tan\beta)$ plane

# Table of Contents

# Posterior density...

Calculate the probabilities!

*If nature is described by a particular SUSY model, what is the probability that the LHC/HE-LHC/VLHC will discover SUSY, given that previous experiments found no discrepancies with the Standard Model?*

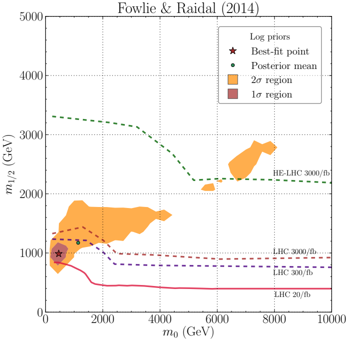



$(m_0, m_{1/2})$ plane

# Posterior density…

Calculate the probabilities!

- Sum the posterior density under each dotted line
- Total posterior density is normalized to one (assume CMSSM is correct model)




$(m_0,\ m_{1/2})$ plane

# Probabilities...

We find that

| Experiment | Probability of discovering SUSY, given data, CMSSM correct model | |
|---|---|---|
| | Log priors | Linear priors |
| LHC 300/fb | 73% | 15% |
| LHC 3000/fb | 76% | 17% |
| HE-LHC 3000/fb | 96% | 45% |
| VLHC 3000/fb | 100% | 100% |

- Dependence on our choice of log or linear prior for $(m_0, m_{1/2})$

# Probabilities...

We find that

| Experiment | Probability of discovering SUSY, given data, CMSSM correct model | |
|---|---|---|
| | Log priors | Linear priors |
| LHC 300/fb | 73% | 15% |
| LHC 3000/fb | 76% | 17% |
| HE-LHC 3000/fb | 96% | 45% |
| VLHC 3000/fb | 100% | 100% |

- Dependence on our choice of log or linear prior for $(m_0, m_{1/2})$
- LHC has 15–75% chance (stau-coannihilation)

# Probabilities...

We find that

| Experiment | Probability of discovering SUSY, given data, CMSSM correct model | |
|---|---|---|
| | Log priors | Linear priors |
| LHC 300/fb | 73% | 15% |
| LHC 3000/fb | 76% | 17% |
| HE-LHC 3000/fb | 96% | 45% |
| VLHC 3000/fb | 100% | 100% |

- Dependence on our choice of log or linear prior for $(m_0,\ m_{1/2})$
- LHC has 15–75% chance (stau-coannihilation)
- HE-LHC has 45–95% chance (stau-coannihilation and $A$-funnel)

# Probabilities...

We find that

| Experiment | Probability of discovering SUSY, given data, CMSSM correct model | |
|---|---|---|
| | Log priors | Linear priors |
| LHC 300/fb | 73% | 15% |
| LHC 3000/fb | 76% | 17% |
| HE-LHC 3000/fb | 96% | 45% |
| VLHC 3000/fb | 100% | 100% |

- Dependence on our choice of log or linear prior for $(m_0, m_{1/2})$
- LHC has 15–75% chance (stau-coannihilation)
- HE-LHC has 45–95% chance (stau-coannihilation and $A$-funnel)
- VLHC has 100% chance! (everything!, independent of log/linear prior)

# Table of Contents

# Conclusions…

- No sign of SUSY so far, but could it be discovered in future experiments?
- Looked at LHC, HE-LHC and VLHC

# Conclusions...

- No sign of SUSY so far, but could it be discovered in future experiments?
- Looked at LHC, HE-LHC and VLHC
- Found probability that they would discover SUSY, assuming CMSSM is the correct model
- Good discovery prospects for future LHC 15–75% and HE-LHC $\gtrsim 45\%$

# Conclusions...

- No sign of SUSY so far, but could it be discovered in future experiments?
- Looked at LHC, HE-LHC and VLHC
- Found probability that they would discover SUSY, assuming CMSSM is the correct model
- Good discovery prospects for future LHC 15–75% and HE-LHC $\gtrsim 45\%$
- But prior dependence in those results...

# Conclusions...

- No sign of SUSY so far, but could it be discovered in future experiments?
- Looked at LHC, HE-LHC and VLHC
- Found probability that they would discover SUSY, assuming CMSSM is the correct model
- Good discovery prospects for future LHC 15–75% and HE-LHC $\gtrsim$ 45%
- But prior dependence in those results...
- VLHC 100%, if CMSSM is correct model, explains DM etc., regardless of log/linear priors

# Priors

| Parameter | Distribution |
|---|---|
| $m_0$ | Log, 0.3–20 TeV |
| $m_{1/2}$ | Log, 0.3–10 TeV |
| $A_0$ | Flat, $\lvert A_0 \rvert < 5 m_0$ |
| $\tan\beta$ | Flat, 3–60 |
| sign $\mu$ | $\pm 1$, with equal probability |
| $m_b(m_b)^{\overline{\text{MS}}}$ | Gaussian, $4.18 \pm 0.03$ GeV[2] |
| $m_t^{\text{Pole}}$ | Gaussian, $173.07 \pm 0.89$ GeV[2] |
| $1/\alpha_{\text{em}}(M_Z)^{\overline{\text{MS}}}$ | Gaussian, $127.944 \pm 0.014$[2] |
| $\alpha_s(M_Z)^{\overline{\text{MS}}}$ | Gaussian, $0.1185 \pm 0.0005$[2] |

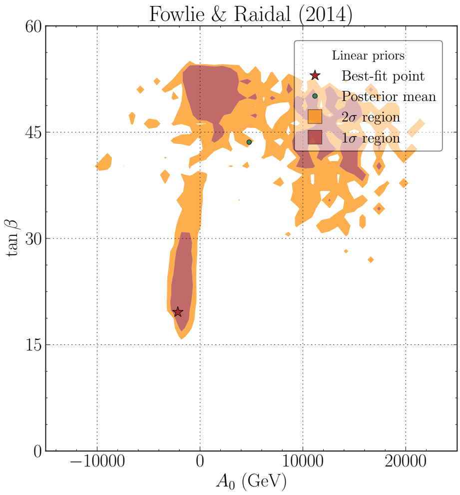
# Likelihoods

| Quantity | Experimental data, $\mu \pm \sigma$ | Theory error, $\tau$ |
|---|---|---|
| $\Omega h^2$ | $0.1199 \pm 0.0027$[3] | 10%[4, 5] |
| $m_h$ | $125.9 \pm 0.4$ GeV[2, 6, 7] | 2.0 GeV[8] |
| $\delta a_\mu$ | $(28.8 \pm 7.9) \times 10^{-10}$[2] | $1.0 \times 10^{-10}$[9] |
| $M_W$ | $80.399 \pm 0.023$ GeV[2] | 0.015 GeV[9] |
| $\sin^2 \theta_{\ell,\text{eff}}$ | $0.23116 \pm 0.00013$ GeV[2] | 0.00015 GeV[9] |
| $\Delta M_{B_s}$ | $17.77 \pm 0.12$ GeV[2] | 2.4 GeV[10] |
| $\text{BR}(B_s \to \mu\mu)$ | $(3.2 \pm 1.5) \times 10^{-9}$[2] | 14%[11] |
| $\text{BR}(B_s \to X_s\gamma)$ | $(3.43 \pm 0.22) \times 10^{-4}$[12] | $0.21 \times 10^{-4}$[13] |
| $\text{BR}(B_u \to \tau\nu)/\text{BR}(B_u \to \tau\nu)\rvert_{\text{SM}}$ | $1.43 \pm 0.43$[14] | |
| ATLAS 20.1/fb at $\sqrt{s} = 8$ TeV[15] | | |
| LUX 85.3 live-days[16] with a factor of 10 uncertainty in $\sigma_p^{\text{SI}}$ [17] | | |

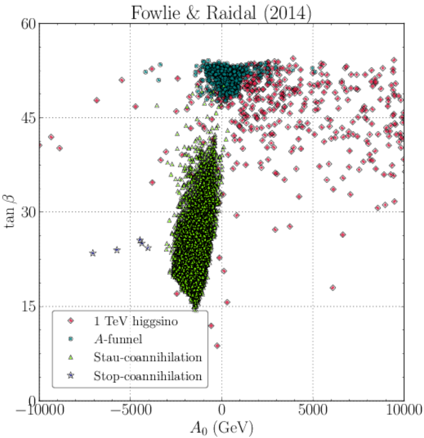
# Probabilities

| Experiment | Probability of discovering SUSY, given data, CMSSM correct model | | . . . and given that previous experiment did not discover the CMSSM | |
|---|---|---|---|---|
| | Log priors | Linear priors | Log priors | Linear priors |
| LHC 300/fb | 73% | 15% | — | — |
| LHC 3000/fb | 76% | 17% | 9% | 2% |
| HE-LHC 3000/fb | 96% | 45% | 83% | 34% |
| VLHC 3000/fb | 100% | 100% | 100% | 100% |

# $(A_0, \tan\beta)$ linear priors

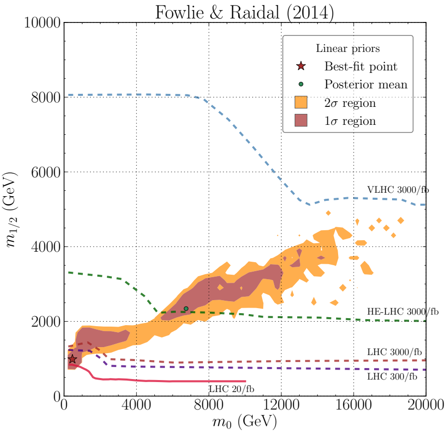



$(A_0, \tan\beta)$ linear priors



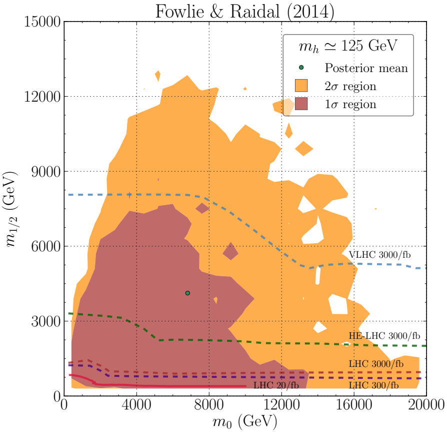

$(A_0, \tan\beta)$ scatter

# $(m_0,\ m_{1/2})$ linear priors



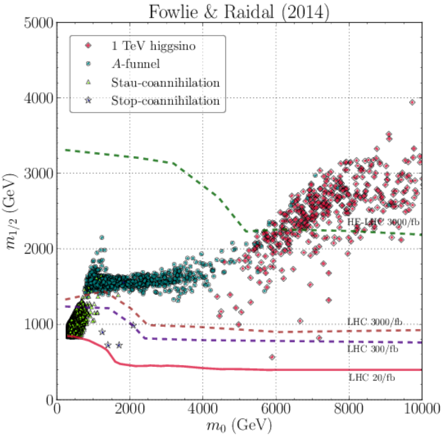

$(m_0,\ m_{1/2})$ linear priors

# ($m_0$, $m_{1/2}$) log priors, Higgs only



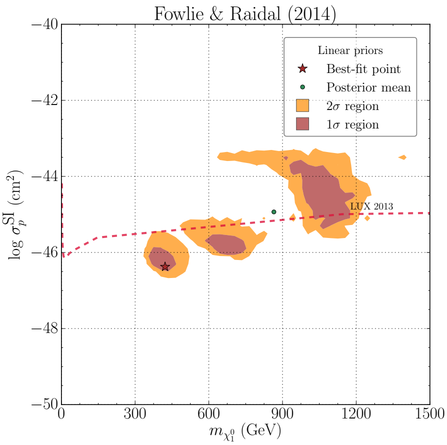

($m_0$, $m_{1/2}$) log priors, Higgs only

# $(m_0,\ m_{1/2})$ scatter



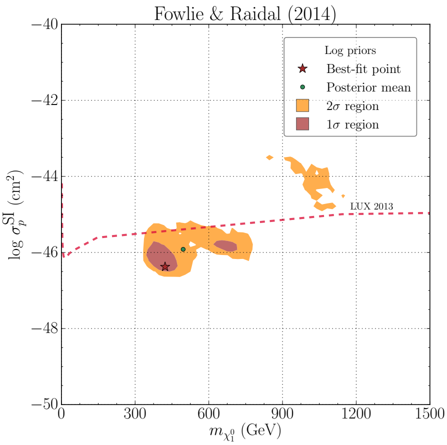

$(m_0,\ m_{1/2})$ scatter

# Direct detection linear priors



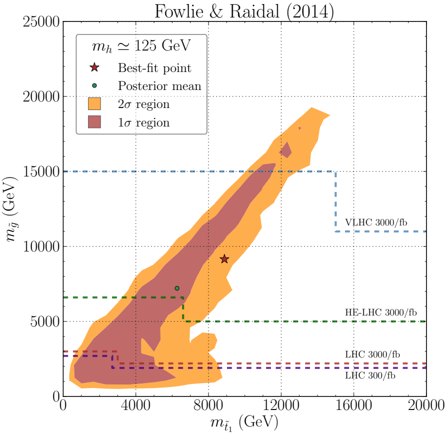

Direct detection linear priors

# Direct detection




Direct detection

# Gluino and squark masses




Gluino and squark masses