# pMSSM scan for future colliders (& more)

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# Intro to pMSSM

- Most SUSY searches are optimized in terms of simplified models (2-3 free parameters)
- However, the full MSSM contains 120 free parameters
- The pMSSM goes **beyond simplified models**, but uses motivated assumptions to reduce the total number of parameters to a more tenable **19 parameters**:

$\tan\beta$: the ratio of the vev of the two–Higgs doublet fields.
$M_A$: the mass of the pseudoscalar Higgs boson
$\mu$: the Higgs–higgsino mass parameter
$M_1, M_2, M_3$: the bino, wino and gluino mass parameters.
$m_{\tilde{q}}, m_{\tilde{u}_R}, m_{\tilde{d}_R}, m_{\tilde{l}}, m_{\tilde{e}_R}$: first/second generation sfermion masses
$m_{\tilde{Q}}, m_{\tilde{t}_R}, m_{\tilde{b}_R}, m_{\tilde{L}}, m_{\tilde{\tau}_R}$: third generation sfermion masses
$A_t, A_b, A_\tau$: third generation trilinear couplings.

arXiv 9901246

# Goal of Snowmass pMSSM scan

- Explore future sensitivity in a framework that goes beyond simplified SUSY models
- Understand the physics potential of different future experiments in the context of the pMSSM
  - How will SUSY sensitivity from various collider scenarios overlap/complement each other?
  - What interesting pMSSM models have limited coverage, and how can we expand this coverage?
- Complementarity across Snowmass Frontiers: input from dark matter, rare frontier, etc.

# Overview of pMSSM scan strategy

- **Sample points** in the 19D pMSSM space
  - Build in well-established physics knowledge
- **Focus in** on interesting regions of phase space
  - Accessible to different experiments
  - Well-motivated by existing measurements
  - Well-motivated by theoretical considerations
- **Generate** signal events
  - Will be made available to all interested groups
  - SM backgrounds can mostly be generated centrally
- **Get event counts** for various signal regions
  - Based on selections chosen by different collider groups
- **Compare performance** across different future experiments

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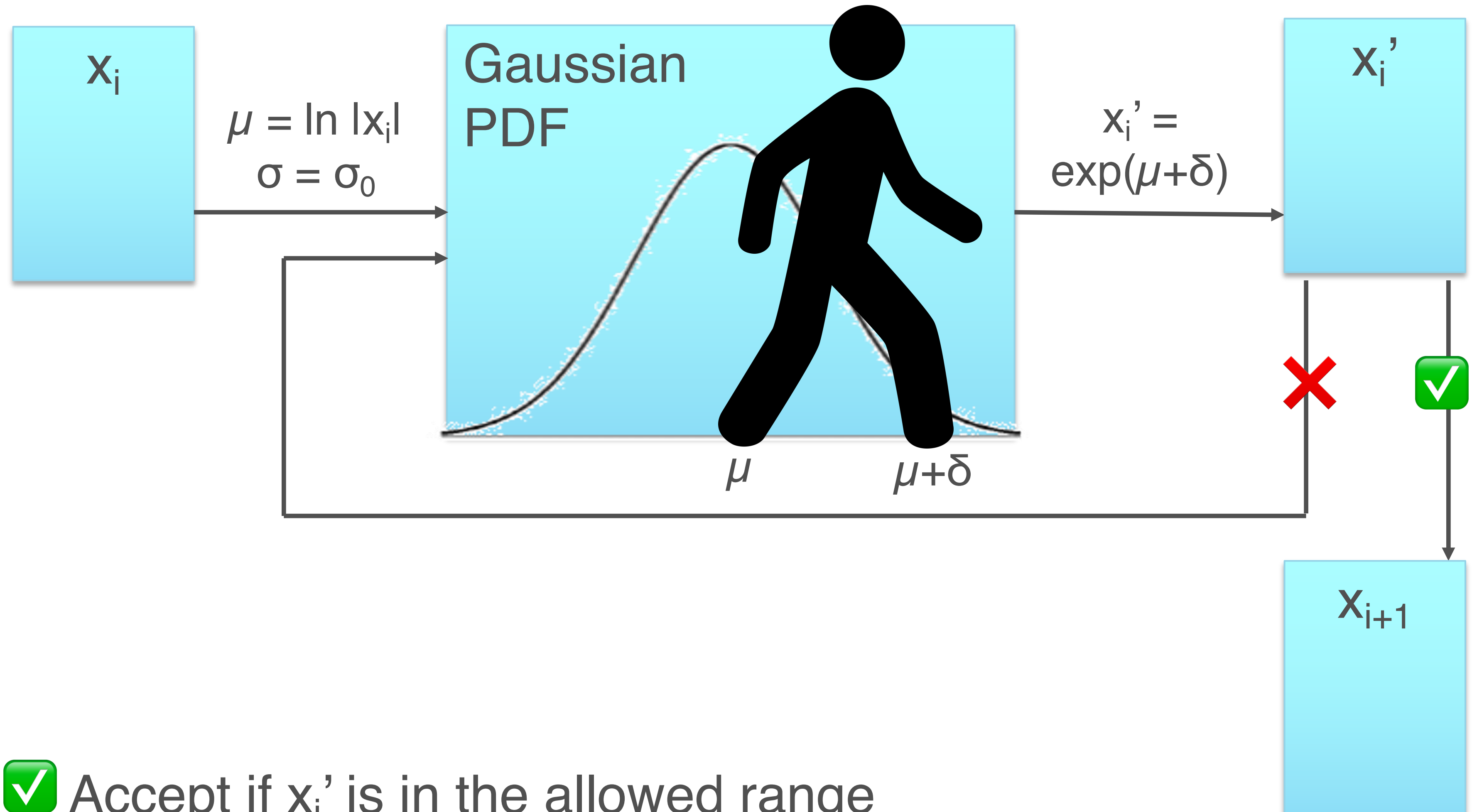
# Sampling 19D pMSSM space

- We will perform a **grand scan** that aims to cover the OR of accessible ranges of many collider scenarios, up to 100 TeV pp collider
- This is a HUGE parameter space. Use a **Markov chain Monte Carlo** to step through the space in a smart way
  - Use **logarithmic stepping** to populate low values of mass parameters more densely than high values
  - **Likelihood** for accepting/rejecting a point is based on existing experimental results

# Parameter ranges

| Parameter | Minimum | Maximum | Stepping |
|---|---|---|---|
| tan β | 1 | 60 | Log |
| $M_A$ | 100 GeV | 25 TeV | Log |
| $\|\mu\|$ | 80 GeV | 25 TeV | Log |
| $\|M_1\|$ | 1 GeV | 25 TeV | Log |
| $\|M_2\|$ | 70 GeV | 25 TeV | Log |
| $M_3$ | 200 GeV | 50 TeV | Log |
| $m_L$123~, $m_e$123~ | 90 GeV | 25 TeV | Log |
| $m_Q$12~, $m_u$12~, $m_d$12~ | 200 GeV | 50 TeV | Log |
| $m_Q$3~, $m_u$3~, $m_d$3~ | 100 GeV | 50 TeV | Log |
| $\|A_b\|$, $\|A_\tau\|$ | 1 GeV | 7 TeV | Log |
| $\|A_t\|$ | 1 GeV | $3\sqrt{(m_Q3\sim m_u3\sim)}$ | Log |

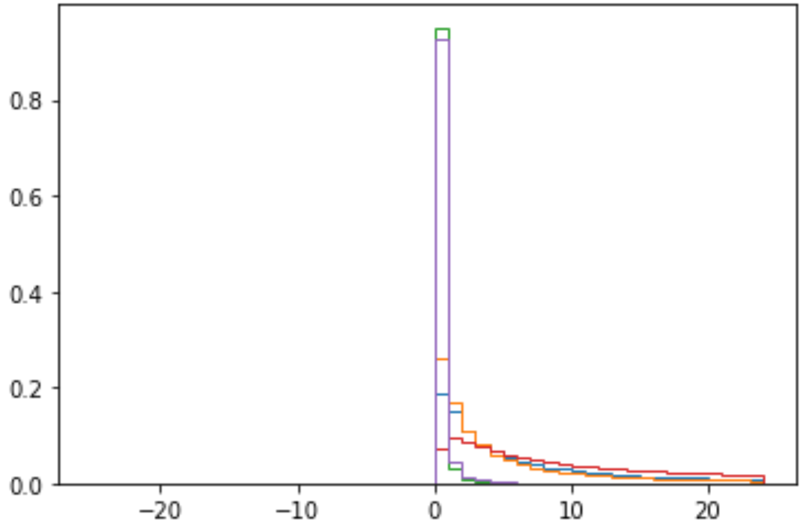
# McMC: logarithmic stepping




✅ Accept if $x_i'$ is in the allowed range and $L(x_i')$ satisfies criteria

# Logarithmic stepping: a simple McMC test

- Use a 1D parameter space with 0 < x < 25
- Use a flat likelihood for simplicity
- Run McMC with 1,000,000 iterations
- Do this 5 times with random starting points
  - **5.1**, **3.2**, **14.1**, **15.7**, **0.1**




Log stepping, fixed width gaussian

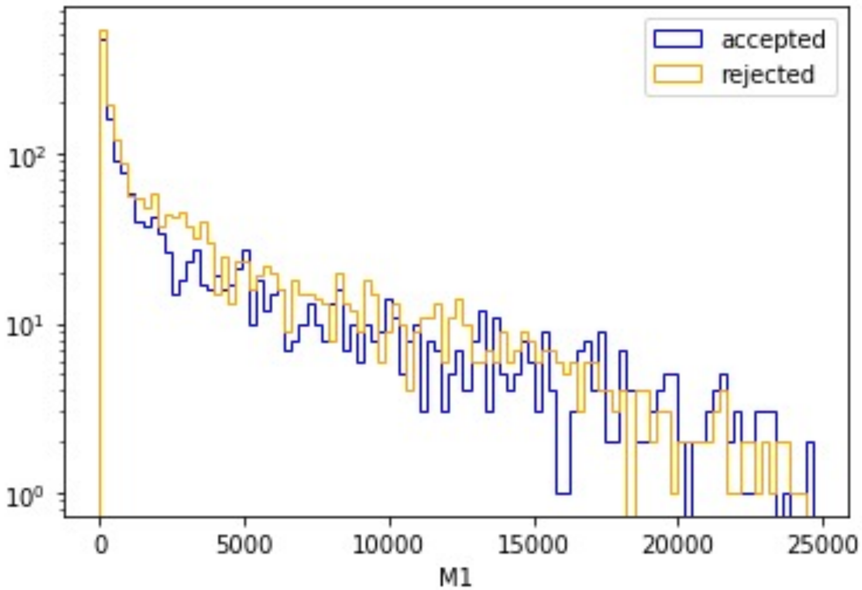
Gives the qualitative behavior we want

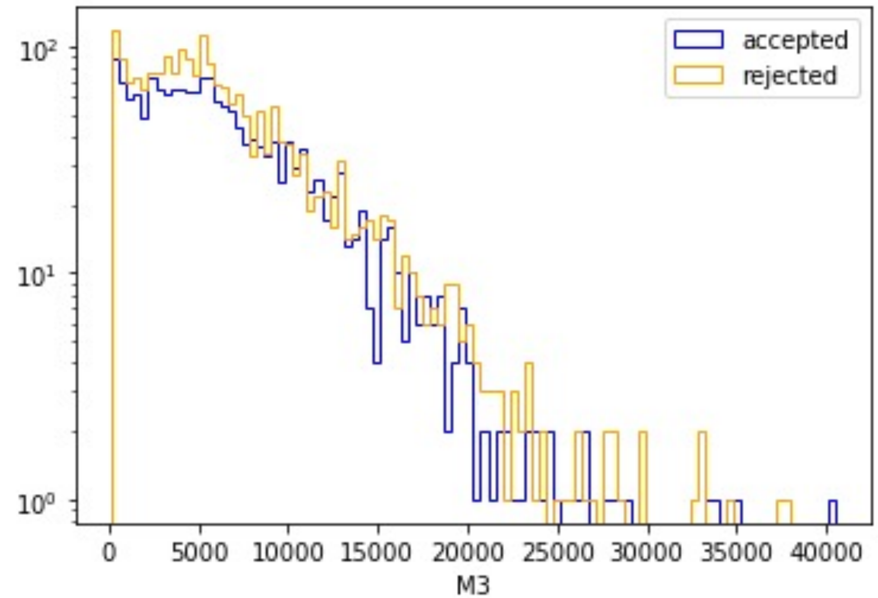
# McMC: logarithmic stepping


- Log stepping achieves the desired effect: lower masses are explored with finer granularity than higher masses
- Width $\sigma_0$ determines the fraction of high mass points
  - Currently $\sigma_0$ = 1-10% of the allowed parameter range
- Optimization study of $\sigma_0$ ongoing
  - e.g. are there enough points where strong SUSY is decoupled

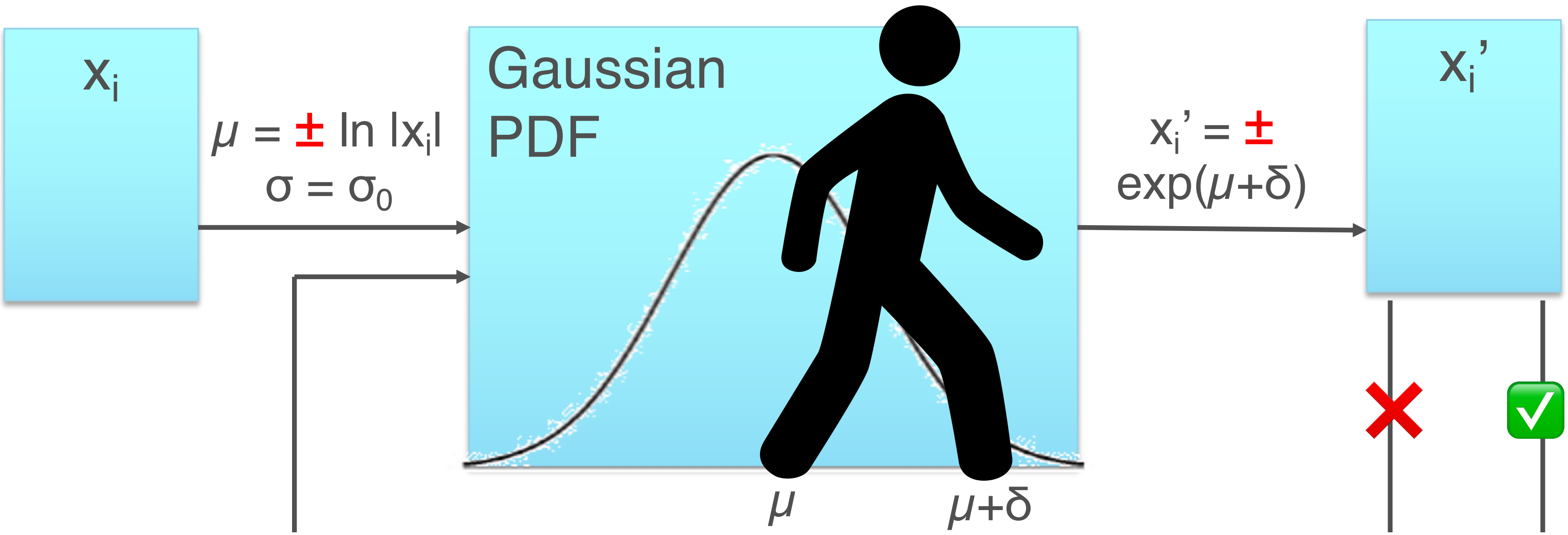
# McMC: impact of Gaussian's width

- In a 4000 point scan with $\sigma_0$ = 5% of the parameter range:
  - Mass parameters are explored up to 25 TeV (see M1), but not well up to 50 TeV (see M3)
  - Tanß, Al, Ab, At are explored out to their limits



# McMC: logarithmic stepping

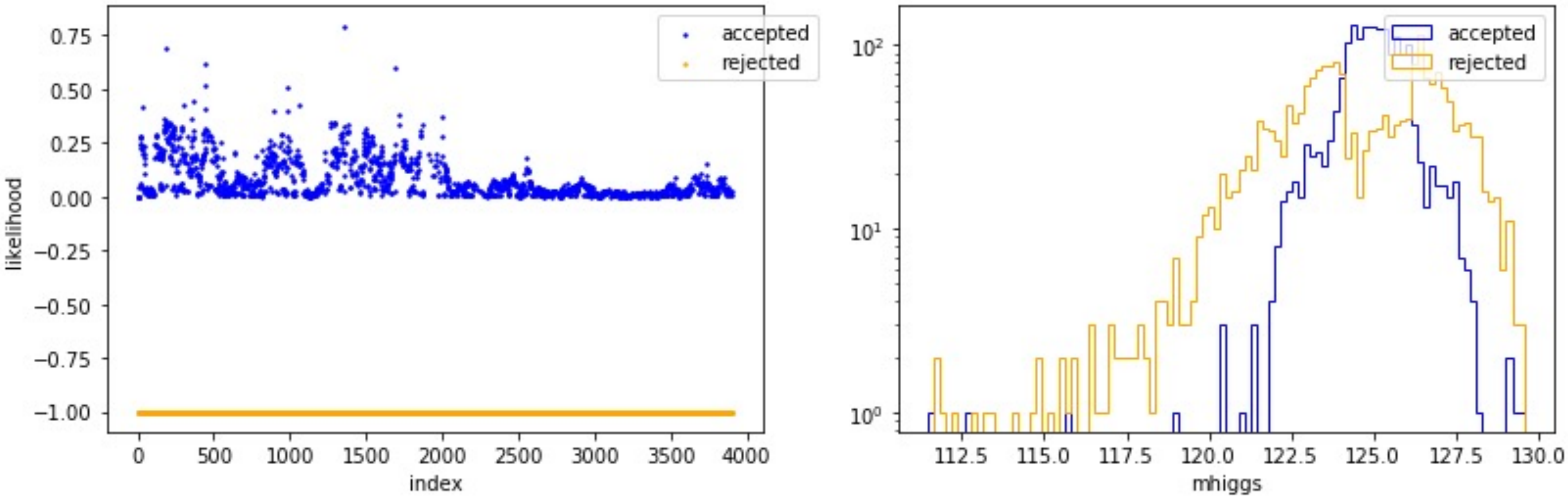



- Drawback: log stepping cannot cross zero
  - Some pMSSM parameters can have ± values
- Solution: keep sign convention of initial point
  - When multiple scans are launched in parallel, different initial conditions will be chosen at random, including signs

# McMC likelihood

- Construct a likelihood for the pMSSM point based on its agreement with existing measurements
  - The McMC prefers to take steps to new points with higher likelihood (better agreement with measurements)

Example 4000 point scan:



# McMC likelihood

- Contributions from **SPheno** and $m_W$ (**FeynHiggs**): Gaussian with mean/width = experimental value/uncertainty
- Contributions from **Superiso**, **HiggsSignals**, and **HiggsBounds**: $\chi^2$ is calculated directly by the program

| Superiso 4.0 | SPheno 4.0.4 | FeynHiggs 2.18.0 | Higgs Signals 2.6.0 | Higgs Bounds 5.9.1 |
|---|---|---|---|---|
| $\Delta_0(B\to K\gamma)$ | $BR(B^+ \to \tau\nu)$ | $m_W$ | LHC Higgs meas. | LHC Heavy $H(\tau\tau)$ |
| $BR(b\to s\gamma)$ | $BR(D_s\to \tau\nu)$ | | | |
| $BR(B_s\to \mu\mu)$ | $BR(D_s\to \mu\nu)$ | $m_H$, H properties | | |
| $BR(B_d\to \mu\mu)$ | $\Delta(\rho)$ | | | |
| $BR(b\to s\mu\mu)$ | $\alpha_S$ | | | |
| $BR(b\to see)$ | $m_{top}$ | | | |
| $BR(B0\to K^{*0}\gamma)$ | $m_{bottom}$ | | | |

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# Narrowing the focus

- We can't simulate events for every pMSSM point. Will need to decide what regions to focus on
- Could decide to **not simulate inaccessible points**
  - With small cross sections / low yield at fixed luminosity
  - Based on truth-based likelihood, as ATLAS does
- Could **focus the scan by over-sampling**, i.e. simulating a high density of points in interesting regions:
  - Near the measured value of g-2
  - With DM relic density consistent with observations
  - Satisfying naturalness criteria

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# Sample generation

- Signal samples can be generated by feeding SLHA files into Pythia, then Pythia events through Delphes
  - Workflow is being developed
- SM backgrounds to be provided for the colliders and center of mass energies listed below (link to slides)

| Machine | Energy | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| CEPC | $m_Z$ | $2m_W$ | 240 | | | | | GeV |
| FCC-ee | $m_Z$ | $2m_W$ | 240 | $2m_t$ | | | | |
| ILC | 250 | 350 | | 500 | 1000 | | | |
| CLIC | | | 380 | | | 1500 | 3000 | |
| HL-LHC/FCC-hh | 14 | 75 | 100 | 150 | | | | TeV |
| LHeC/FCC-eh | 1.3 | 3.5 | | | | | | |
| μμ | 3 | 10 | 14 | 30 | | | | |

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# Conclusions

- The technical implementation of a pMSSM grand scan using Markov chain Monte Carlo is in place
  - Likelihood based on existing measurements steers the scan away from excluded regions
  - Logarithmic stepping ensures the whole phase space is explored, while populating low parameter values with high density
- What subset of signal points to generate? Brainstorm is ongoing, already have a few possibilities
- Workflow for signal MC generation is under development

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# Welcoming input

- We hope this pMSSM scan can be very widely useful for Snowmass studies
  - pMSSM points and generated signal events will be made available to everyone
- More groups using the scan points for studies = more complete comparison as the final product
  - Let us know if you want a particular collider setup for generated events, etc.
  - Want to extend beyond just EF (dark matter, rare, etc.)
- Feel free to exercise the scan code. Details and instructions can be found on this twiki