

# Falsifying the pMSSM with Genetic Algorithms

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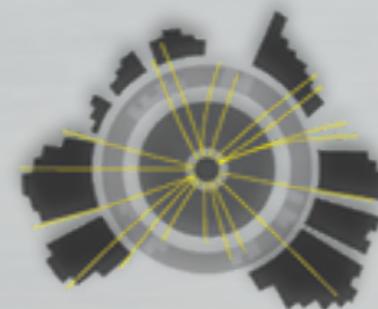
*arXiv:1805.03615*



SUSY 2018, Barcelona



THE UNIVERSITY OF  
MELBOURNE



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# Outline

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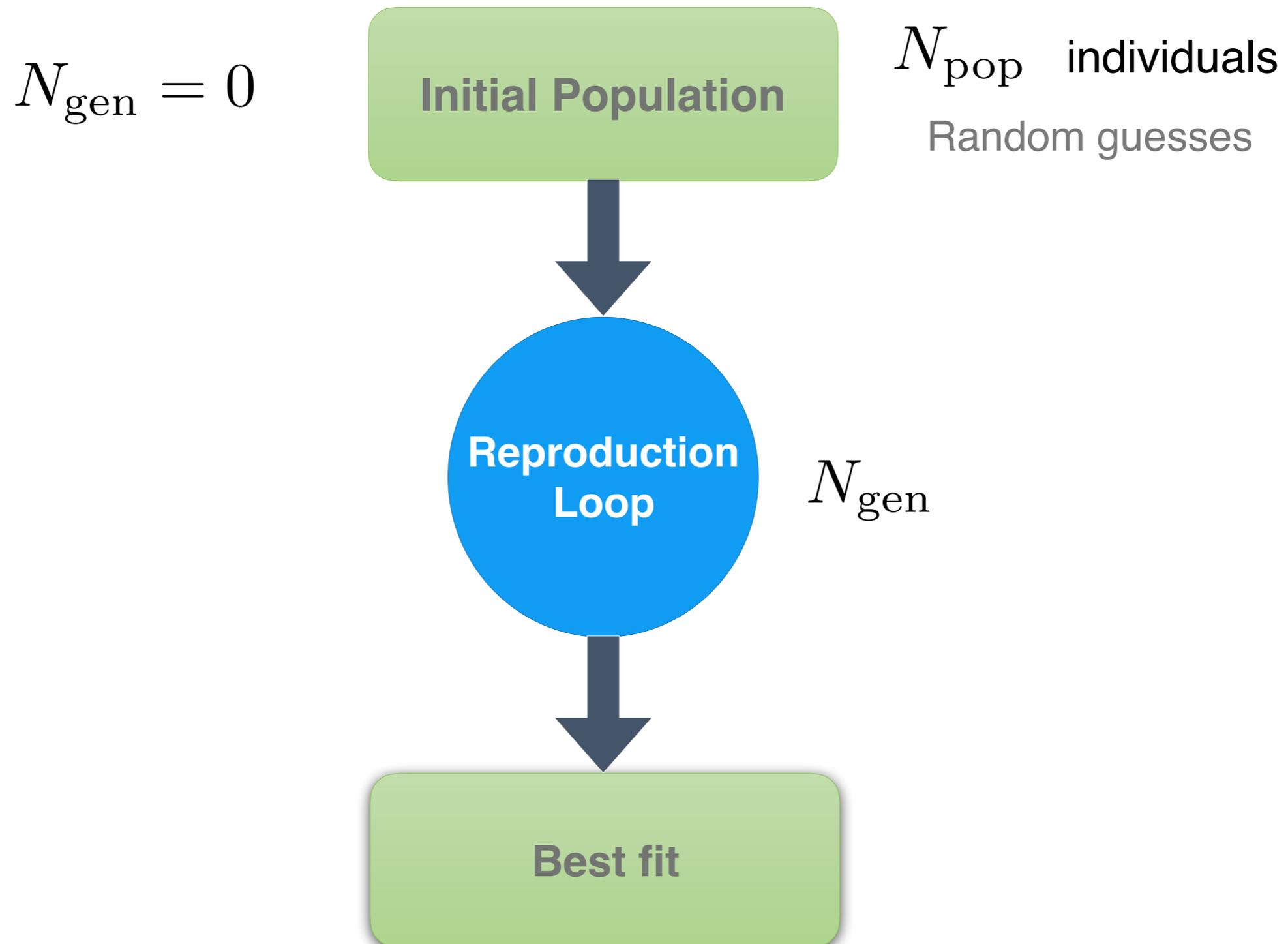
- 1** Introduction
- 2** Genetic Algorithms in a nutshell
- 3** Application to the pMSSM
- 4** Results
- 5** Summary and conclusions

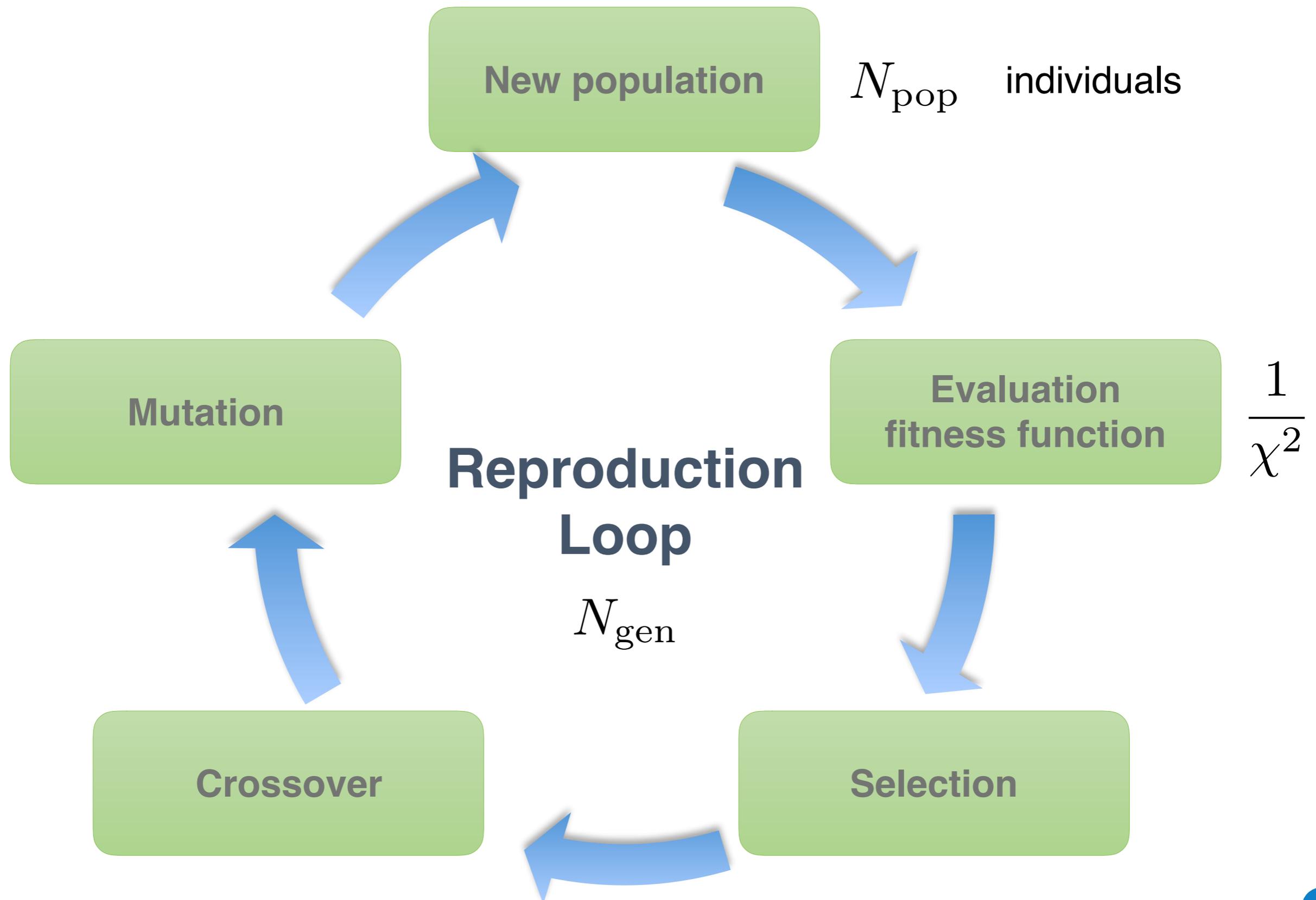
# Introduction

- ⊗ Experimental results force us to consider **less constrained SUSY scenarios**.
- ⊗ Analysis of high dimensionality models is a **computationally intensive task**.
- ⊗ **Can we attempt to falsify a model such as the pMSSM?**
- ⊗ More sophisticated methods than traditional scanning
  - ✓ Bayesian inference techniques: Multinest  
F. Feroz & M. P. Hobson, 2007
  - ✓ Genetic Algorithms in the CMSSM  
Y. Akrami, P. Scott, J. Edsjö, J. Conrad & L. Bergström, 2010

- ⊗ **Genetic Algorithms (GAs), heuristic search technique.**  
J. Holland, 1975
- ⊗ **Inspired by biological evolution through natural selection to solve precisely complex optimisation problems in computer science.**
- ⊗ **Well suited to probe high-dimensional spaces.**  
Designed to search for the region of parameter space that contains the **global minimum**.
- ⊗ **GAs can find a best fit point orders of magnitude more quickly.**

# Genetic Algorithms in a nutshell





## Aim

Maximise the fitness function:  $\frac{1}{\chi^2}$

## Mpikaia

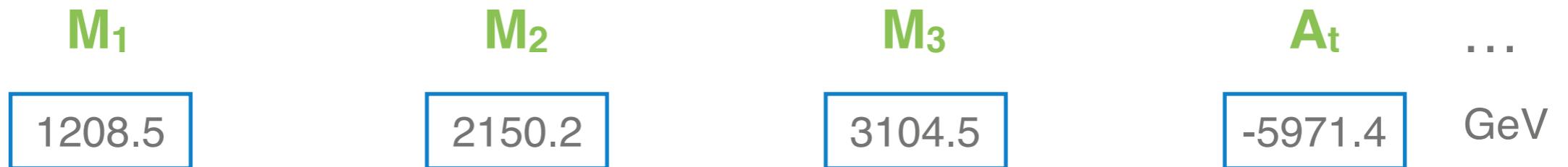
P. Charbonneau, 1995

T. S. Metcalfe & P. Charbonneau, 2003

Individual

Initial parameters  $\Theta_i$ 

Phenotype



Observables

$$\chi^2(\Theta_i)$$

Fitness function

$$\frac{1}{\chi^2(\Theta_i)}$$

## Selection

- ⊗  $N_{\text{pop}}$  breeding pairs
- ⊗ Select individuals based on their fitness

**Fitter individuals selected more often**

**Parent 1**

6	5	8	1	9	8	1	2	5	6	0	7	9	6	4	1	2	3	4	0
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

**Parent 2**

9	5	4	7	2	8	0	1	3	1	9	0	5	4	2	7	0	3	4	6
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

### Phenotype

### Initial parameters $\Theta_i$

### Individual

$M_1$

3908.5



$M_2$

2150.2



$M_3$

1104.0



$A_t$

-9987.0



...

GeV

Encode phenotype

$M_1$

1 2 3 4 0

$M_2$

4 6 9 3 1

$M_3$

7 0 3 4 6

$A_t$

7 0 3 4 6

...

gene

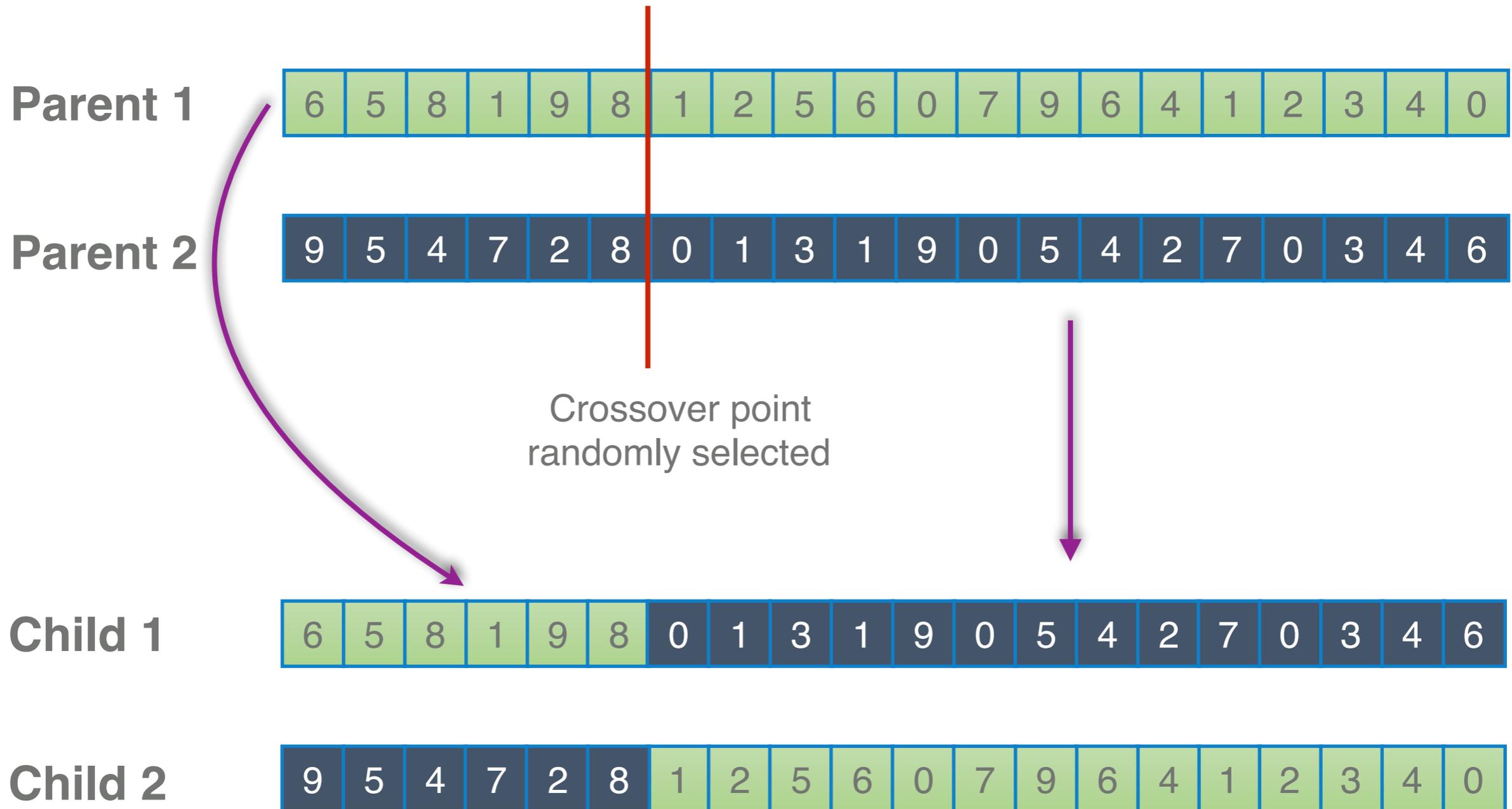
### Genotype/Chromosome

1 2 3 4 0 4 6 9 3 1 7 0 3 4 6 7 0 3 4 6 ...



L

## Breeding/Crossover



## Mutation

Child 1



Child 1



Child 1

 $M_1$  $M_2$  $M_3$  $A_t$ 

...



Decode genotype

 $M_1$  $M_2$  $M_3$  $A_t$ 

...

1208.5

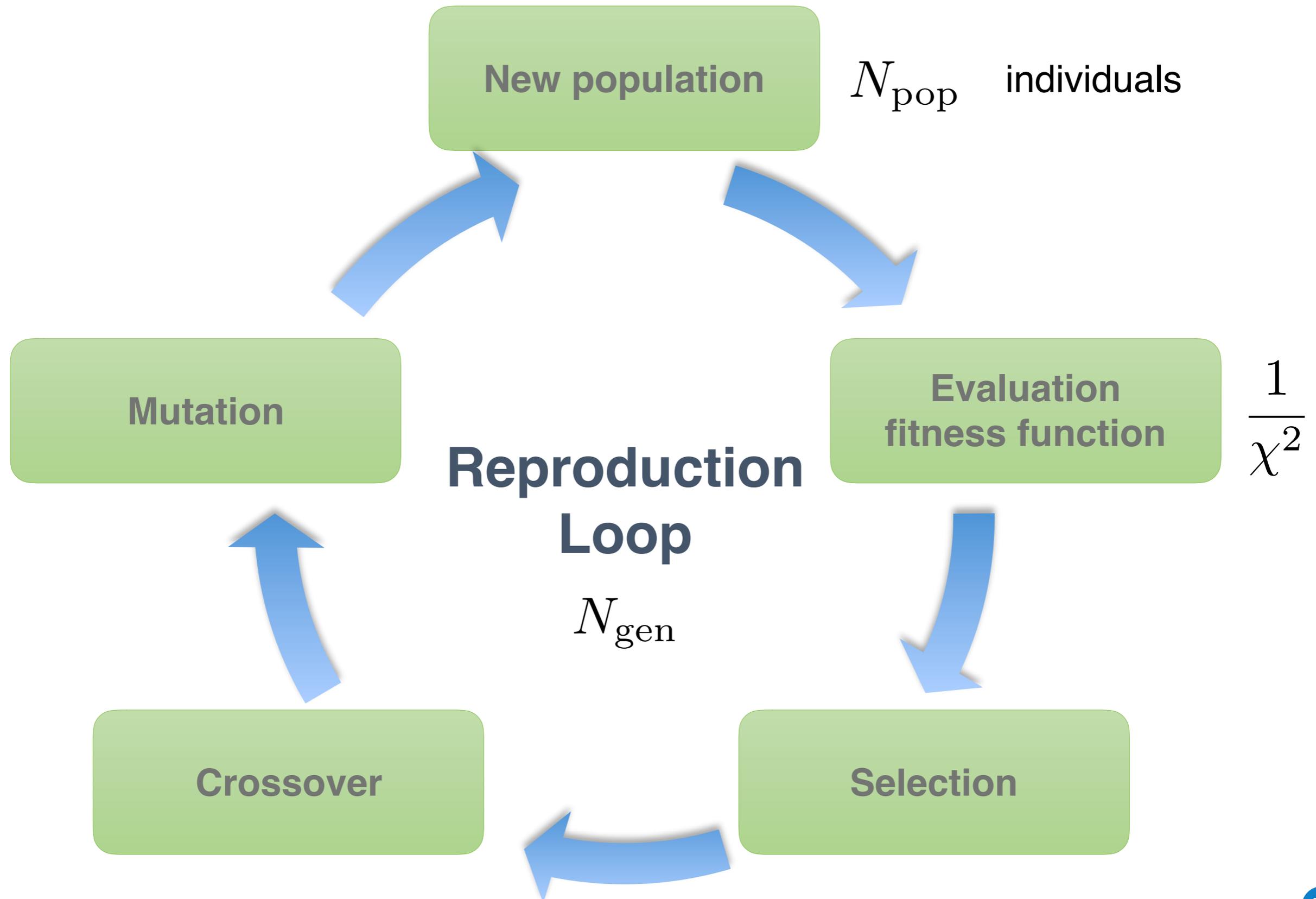
2150.2

3104.5

-5971.4

GeV

Phenotype



# Application to the pMSSM

4 SM nuisance parameters + 19 pMSSM (GUT scale) parameters

Parameter	Range
$[\alpha_{\text{EM}}(m_Z)^{\overline{MS}}]^{-1}$	[127.882, 128.018]
$\alpha_S(m_Z)^{\overline{MS}}$	[0.1161, 0.1209]
$m_b(\text{GeV})$	[4.54, 5.02]
$m_t(\text{GeV})$	[170.1, 175.5]

Parameter	Range
$M_1, M_2, M_3(\text{GeV})$	[50, 10000]
$m_{H_u}, m_{H_d}(\text{GeV})$	[50, 10000]
$m_{\tilde{Q}_{1,2}}, m_{\tilde{Q}_3}(\text{GeV})$	[50, 10000]
$m_{\tilde{U}_{1,2}}, m_{\tilde{U}_3}(\text{GeV})$	[50, 10000]
$m_{\tilde{D}_{1,2}}, m_{\tilde{D}_3}(\text{GeV})$	[50, 10000]
$m_{\tilde{L}_{1,2}}, m_{\tilde{L}_3}(\text{GeV})$	[50, 10000]
$m_{\tilde{E}_{1,2}}, m_{\tilde{E}_3}(\text{GeV})$	[50, 10000]
$A_t, A_b, A_\tau(\text{TeV})$	[-10, 10]
$\tan \beta$	[2, 62]

## Joint likelihood

### → Electroweak Precision Observables (EWPOs)

$$\ln \mathcal{L}_{\text{EWPO}} = \ln \mathcal{L}_{M_W} + \ln \mathcal{L}_{\sin^2 \theta_{\text{eff}}^{\text{lept}}} + \ln \mathcal{L}_{\Gamma_Z} + \ln \mathcal{L}_{\Gamma_Z^{\text{inv}}}$$

### → Flavour observables from B physics

$$\ln \mathcal{L}_B = \ln \mathcal{L}_{BR(B \rightarrow X_s \gamma)} + \ln \mathcal{L}_{BR(B_s^0 \rightarrow \mu^+ \mu^-)} + \ln \mathcal{L}_{\frac{BR(B_u \rightarrow \tau \nu)}{BR(B_u \rightarrow \tau \nu)_{\text{SM}}}}$$

### → Constraints from Higgs physics

$$\ln \mathcal{L}_{\text{Higgs}} = \ln \mathcal{L}_{m_{h^0}} + \ln \mathcal{L}_{\text{Higgs sector}}$$

FeynHiggs  
HiggsBounds  
HiggsSignals

## Joint likelihood

→ **LEP bounds on chargino and slepton masses** 95% CL

$$\ln \mathcal{L}_{\text{LEP}} = \ln \mathcal{L}_{m_{\tilde{\chi}_1^\pm}} + \ln \mathcal{L}_{m_{\tilde{e}_R}} + \ln \mathcal{L}_{m_{\tilde{\mu}_R}} + \ln \mathcal{L}_{m_{\tilde{\tau}_1}} + \ln \mathcal{L}_{m_{\tilde{\nu}}}$$

→ **LHC results on SUSY searches**  $\ln \mathcal{L}_{\text{LHC}}$

SModelS

→ **Dark matter relic abundance**  $\ln \mathcal{L}_{\Omega_{\text{DM}} h^2}$

micrOMEGAs

## GA control parameters

⊗  $N_{\text{pop}} = 100$

⊗  $N_{\text{gen}} = 300$



$3 \times 10^4$  evaluations of the  
fitness function

⊗ **Full generational replacement**

⊗ **Elitism, keep the best individual**

⊗ **Mutation rate adjustable, based on fitness**

**Mpikaia**

P. Charbonneau, 1995

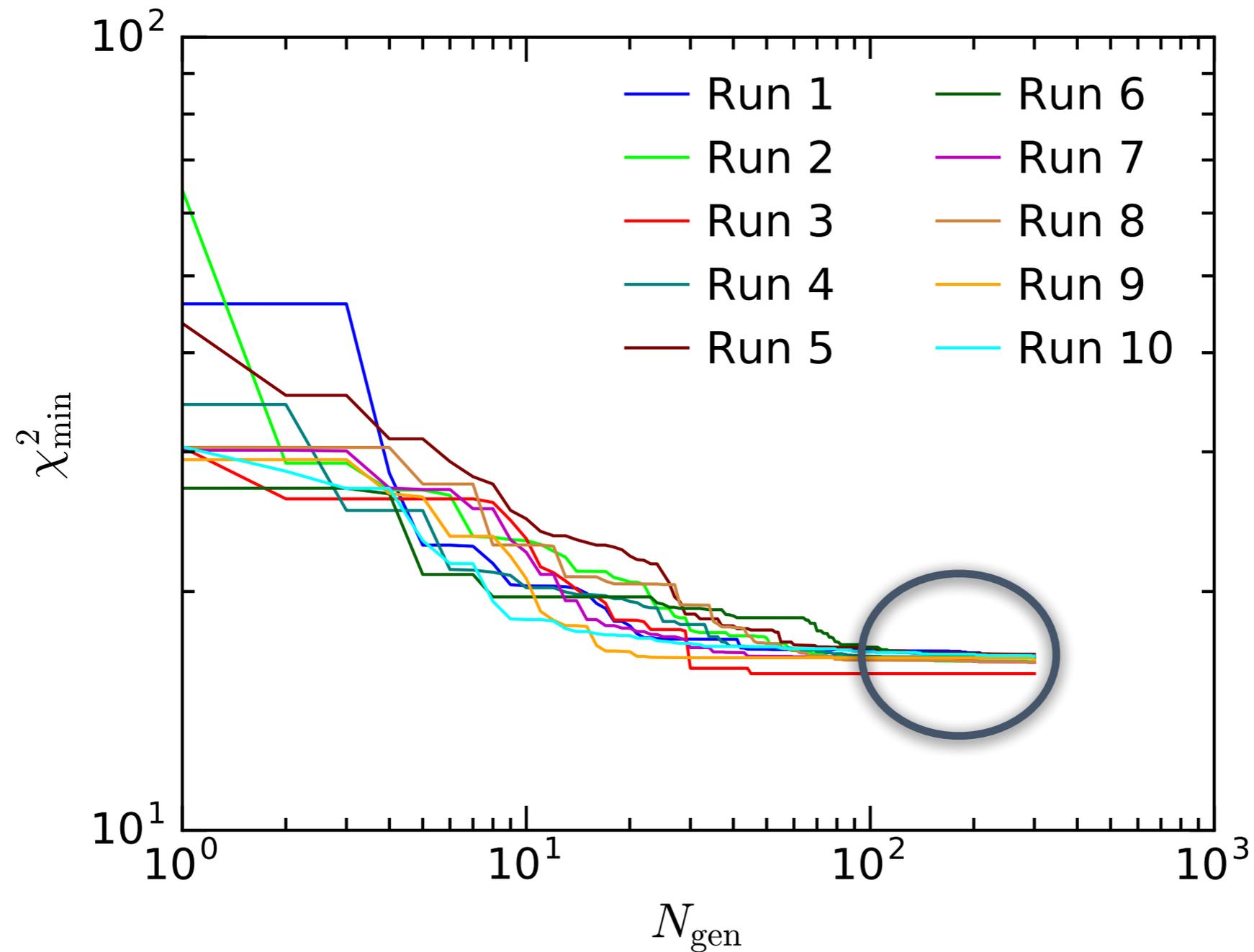
T. S. Metcalfe & P. Charbonneau, 2003

# Results

## Muon anomalous magnetic moment

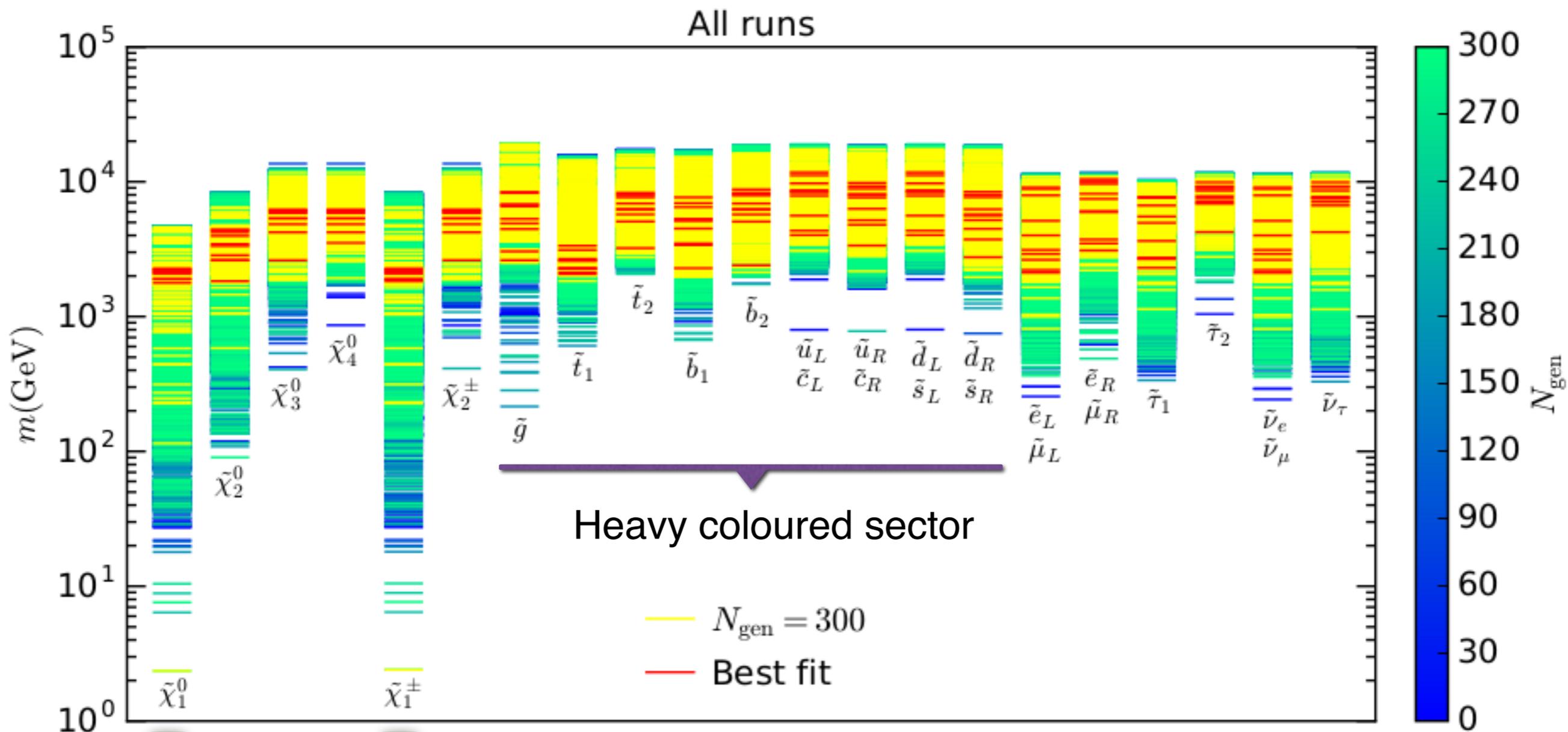
$$\ln \mathcal{L}_{\text{Joint}} = \ln \mathcal{L}_{\text{EWPO}} + \ln \mathcal{L}_B + \ln \mathcal{L}_{\text{Higgs}} + \ln \mathcal{L}_{\text{LEP}} + \ln \mathcal{L}_{\text{LHC}} + \ln \mathcal{L}_{\Omega_{\text{DM}} h^2} + \ln \mathcal{L}_{\delta a_{\mu}^{\text{SUSY}}}$$

## Muon anomalous magnetic moment



$$\chi^2 \approx 16$$

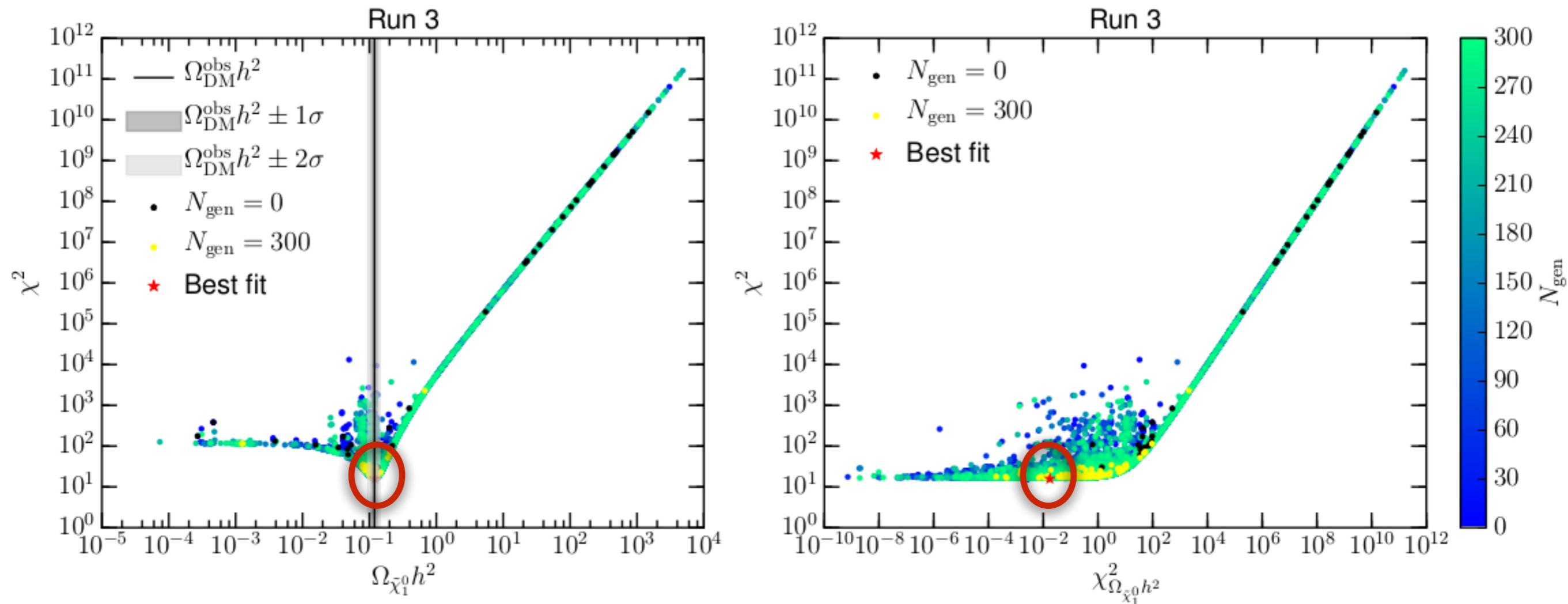
# Mass spectrum



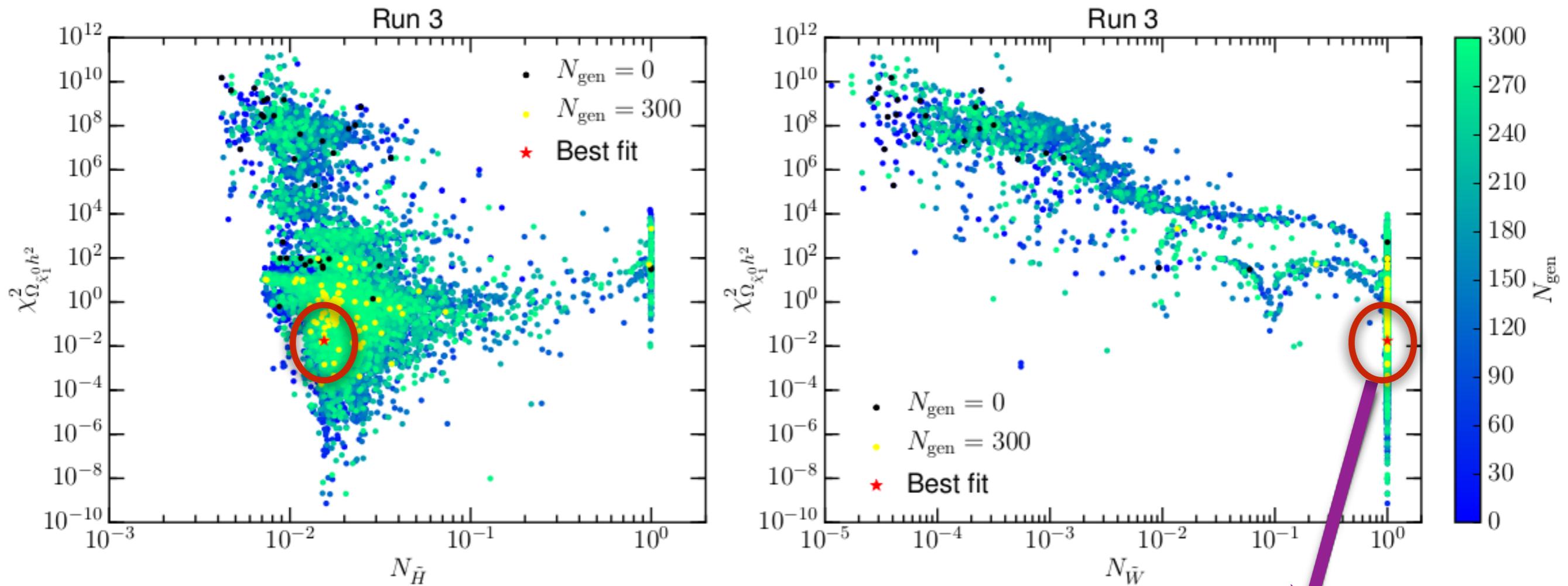
$$m_{\tilde{\chi}_1^0} \simeq m_{\tilde{\chi}_1^\pm} \simeq 2 \text{ TeV}$$

$$m_{\tilde{t}_1} \simeq 2 - 3 \text{ TeV}$$

## DM relic abundance



## Lightest neutralino composition

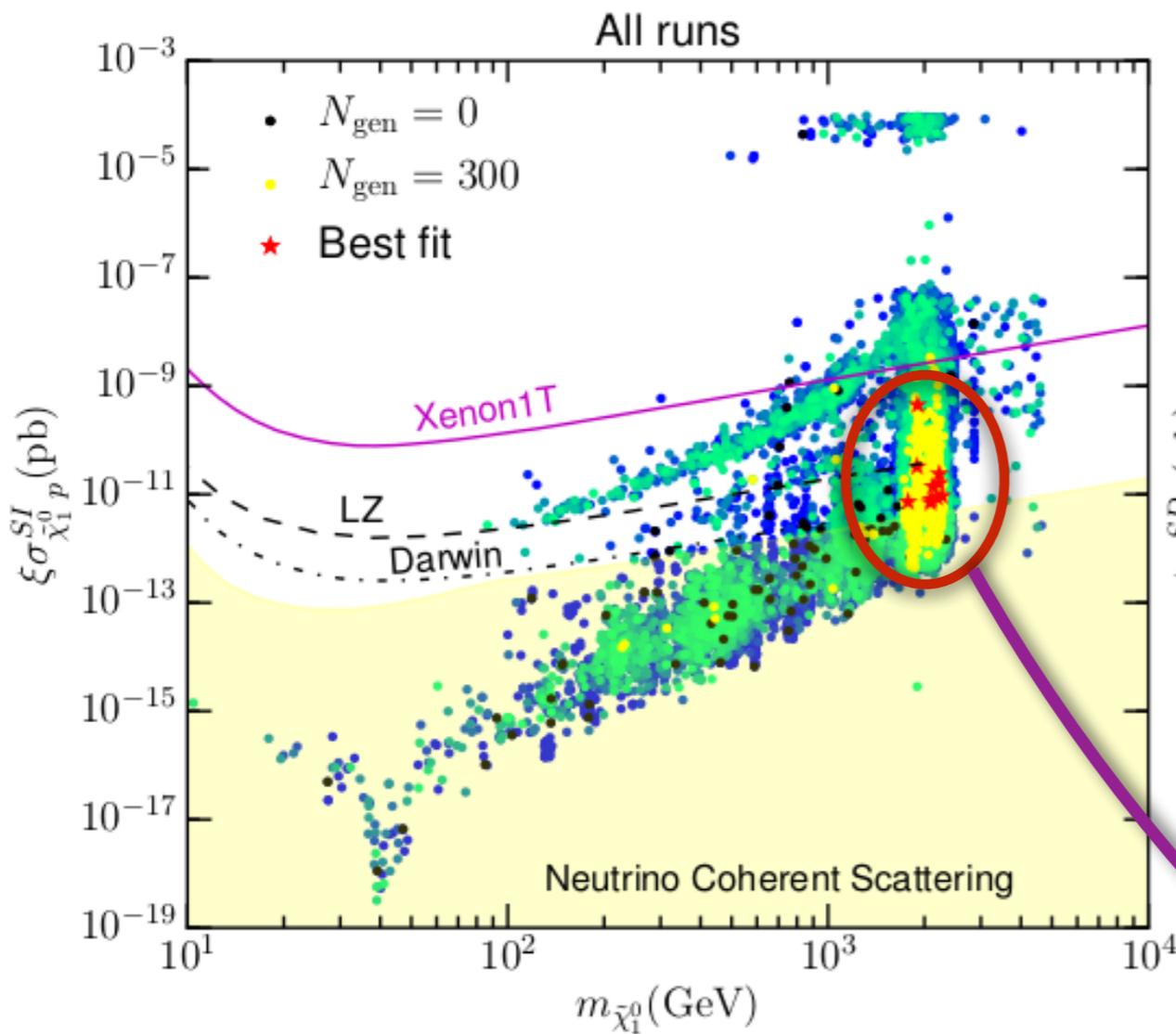


Subleading Higgsino component

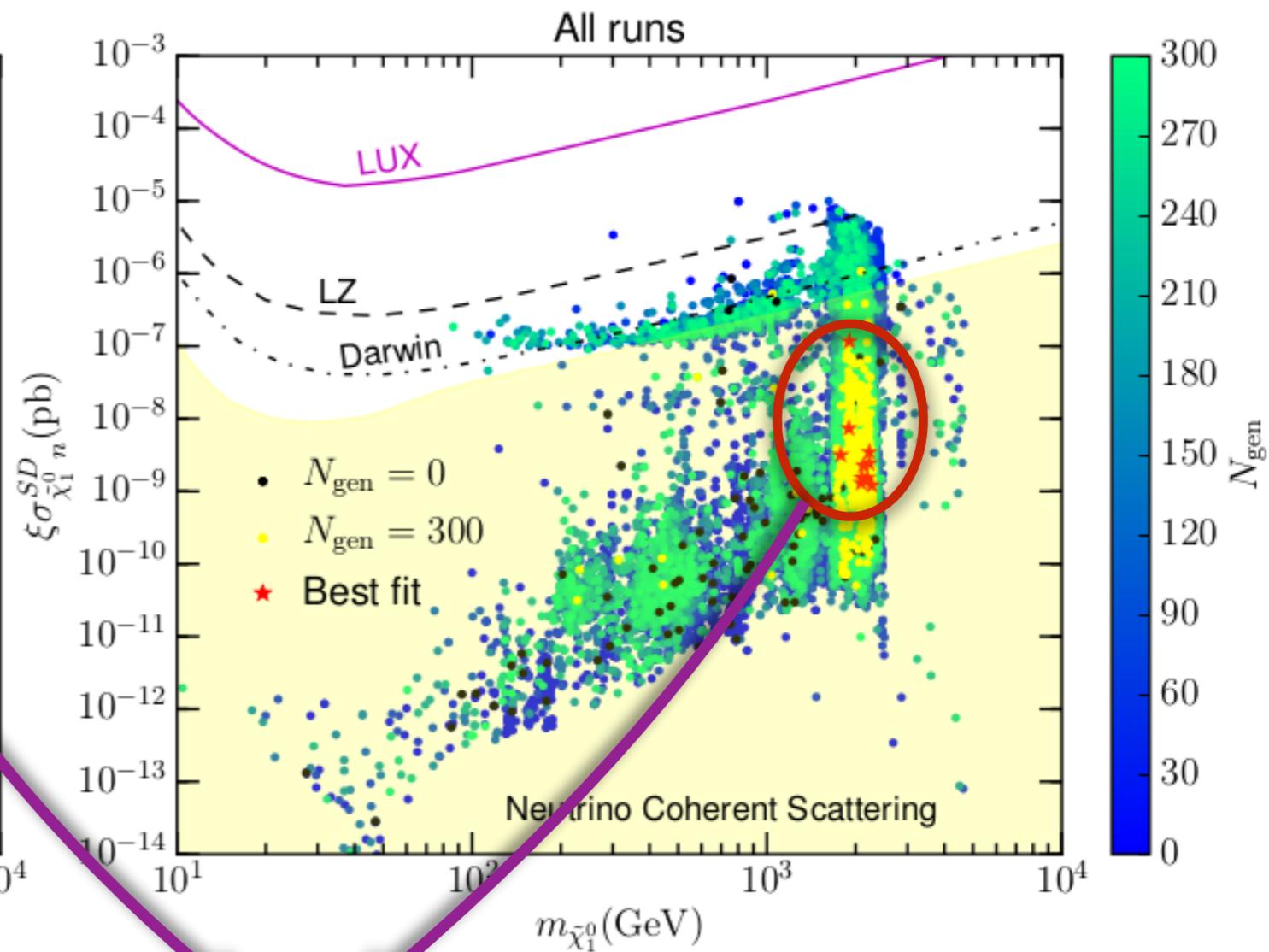
wino-like

# Direct Detection

## Spin Independent

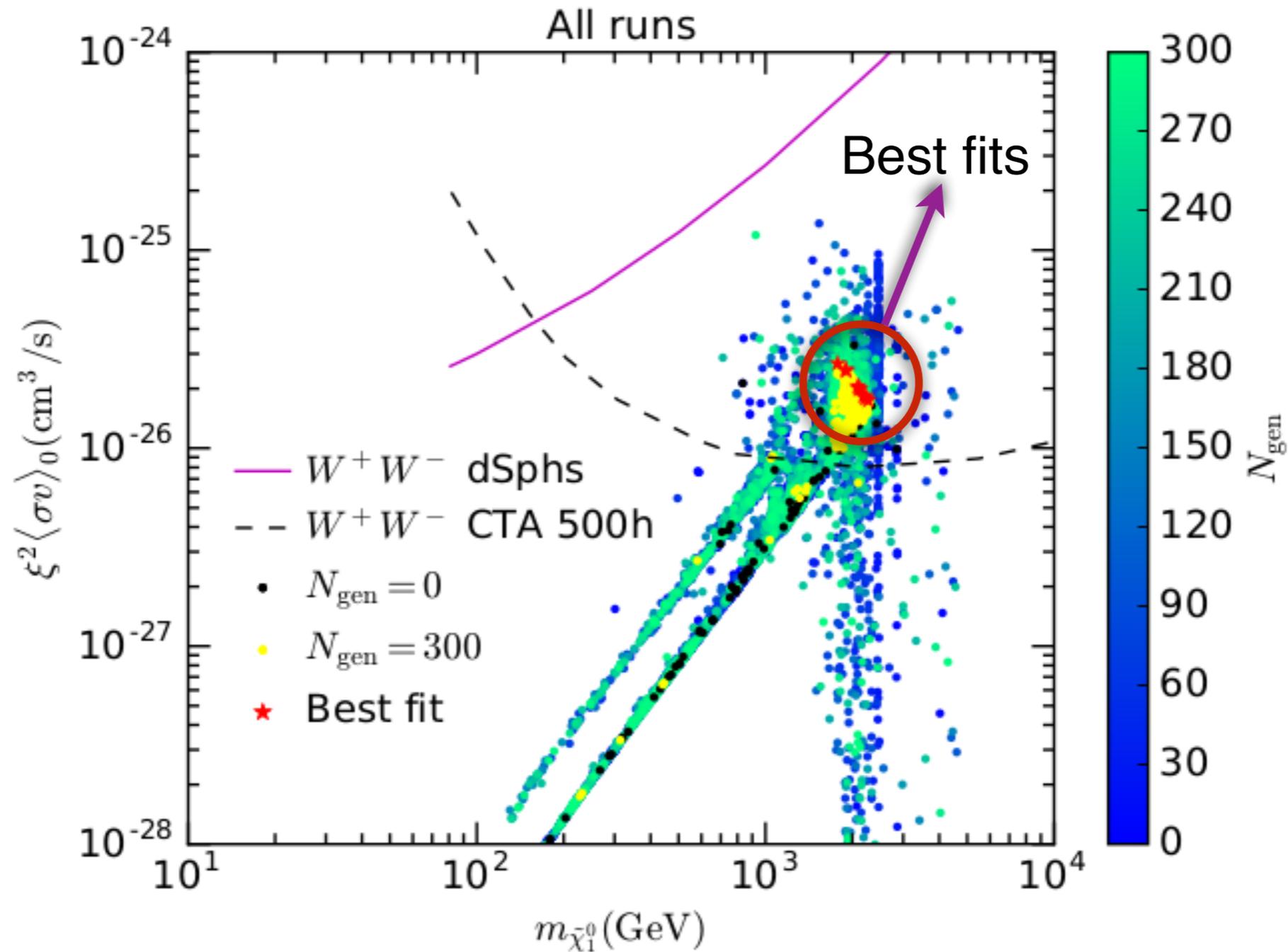


## Spin Dependent

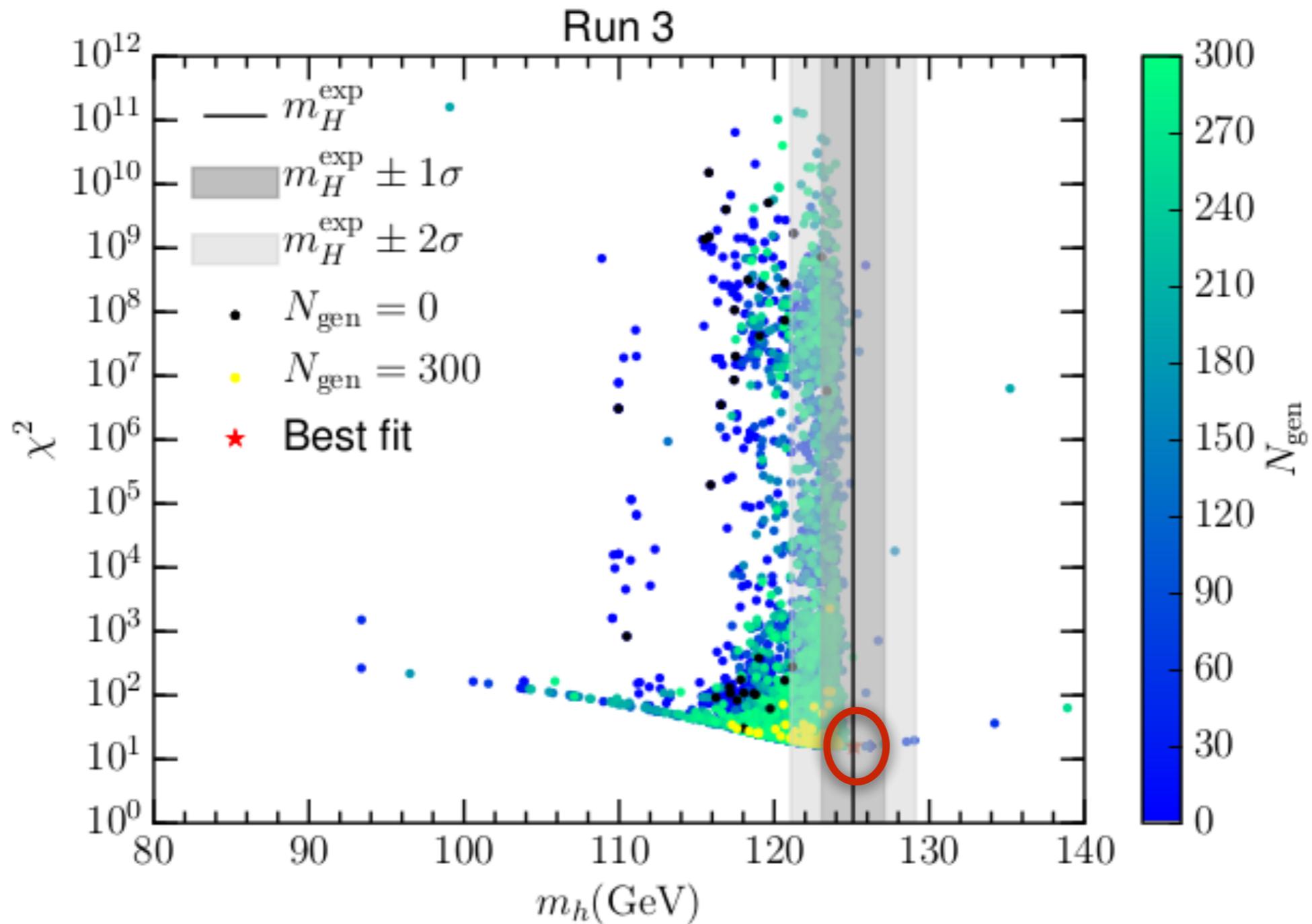


Best fits

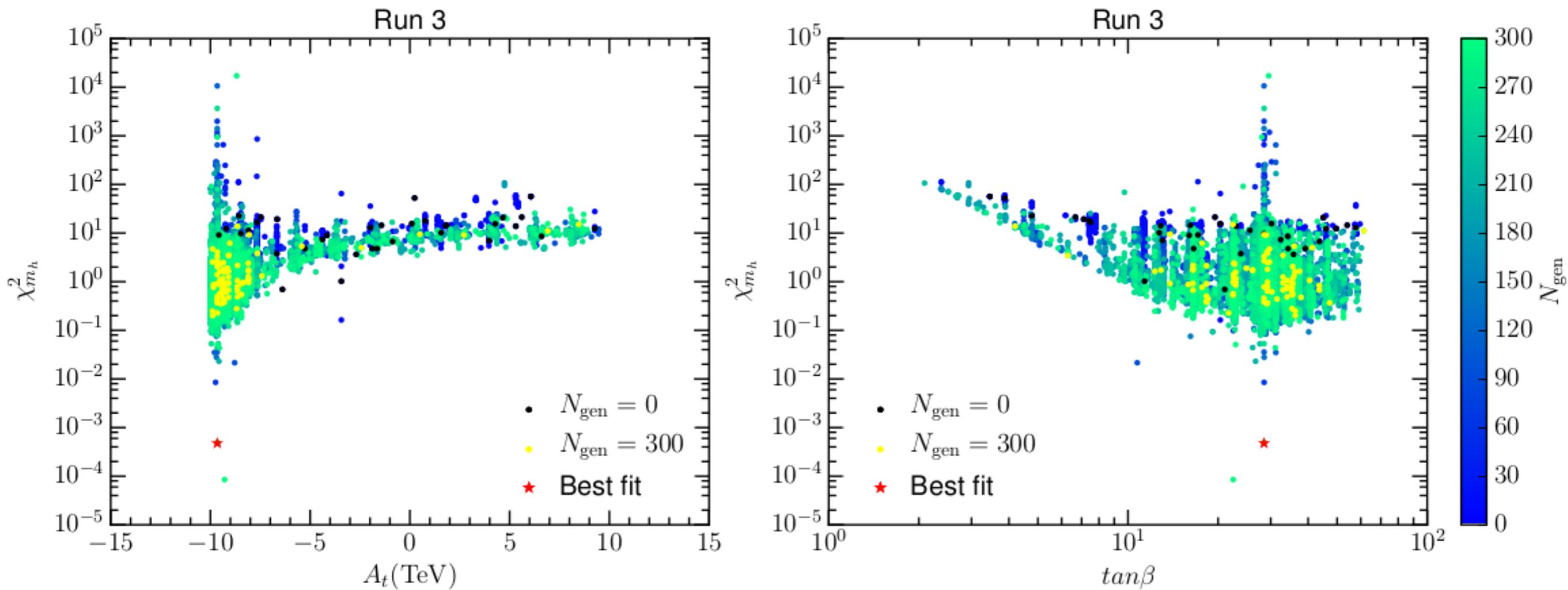
## Indirect Detection



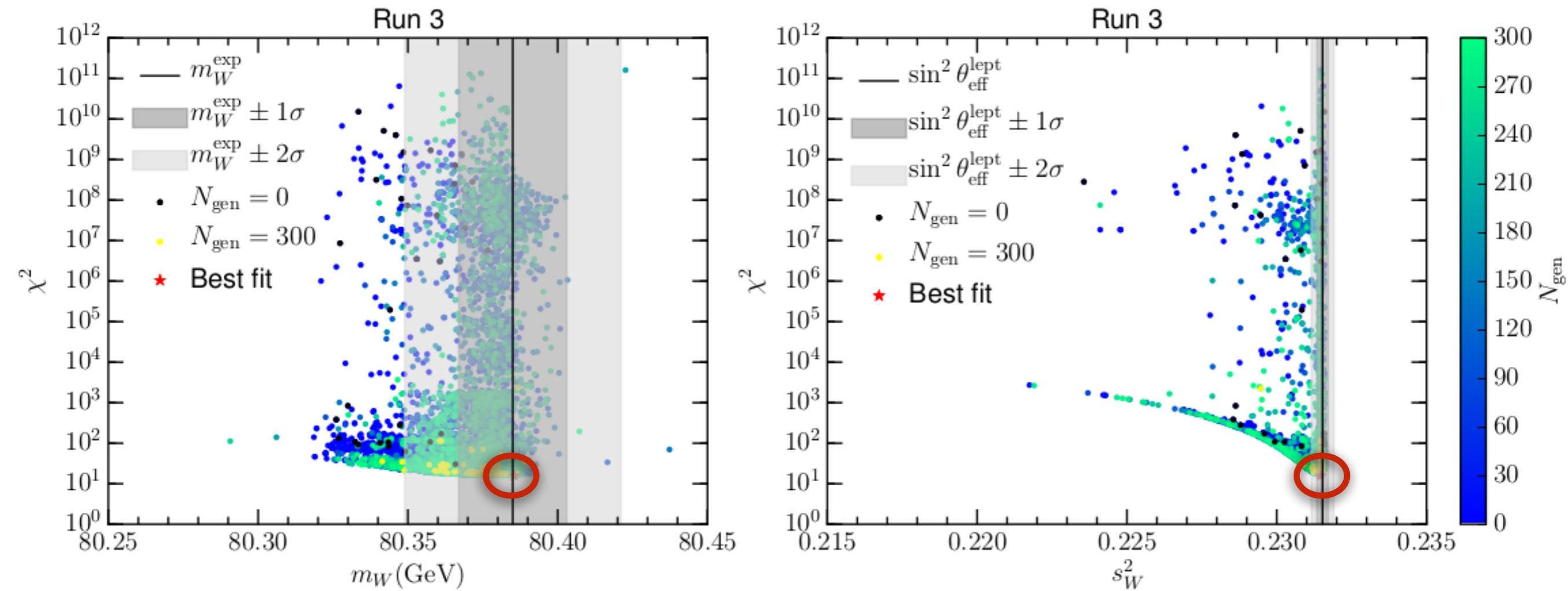
# Higgs mass



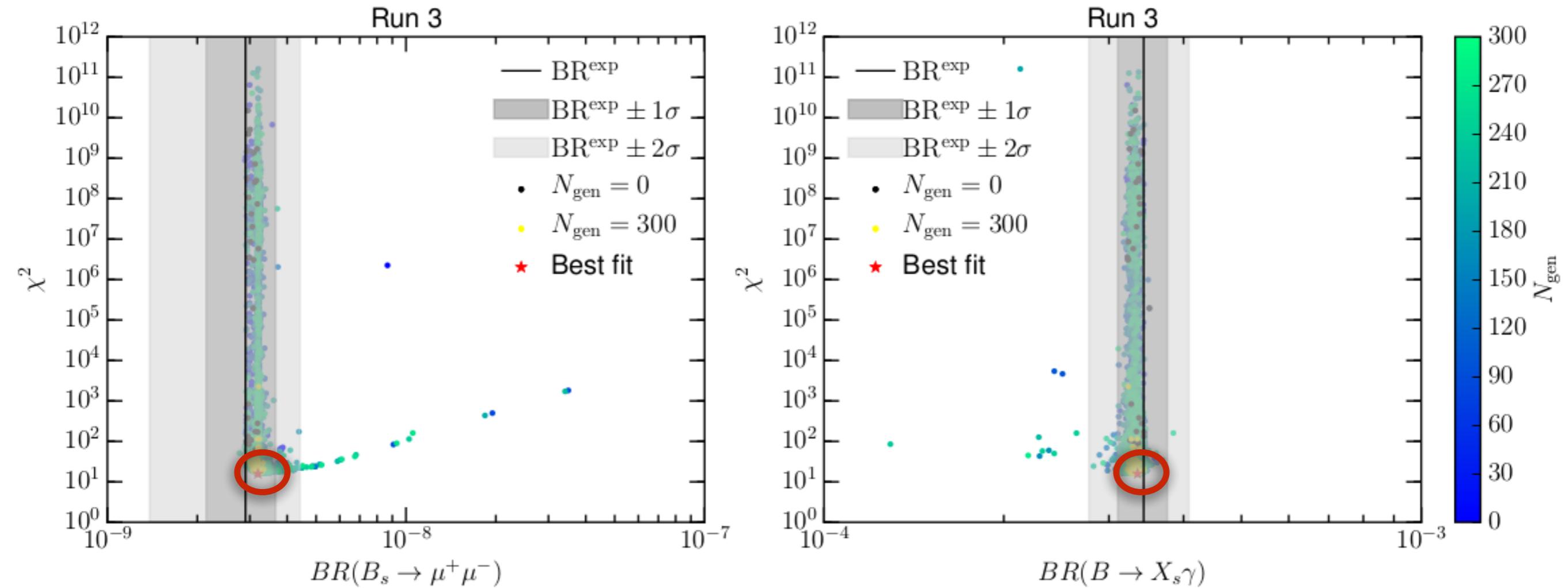
# Higgs mass



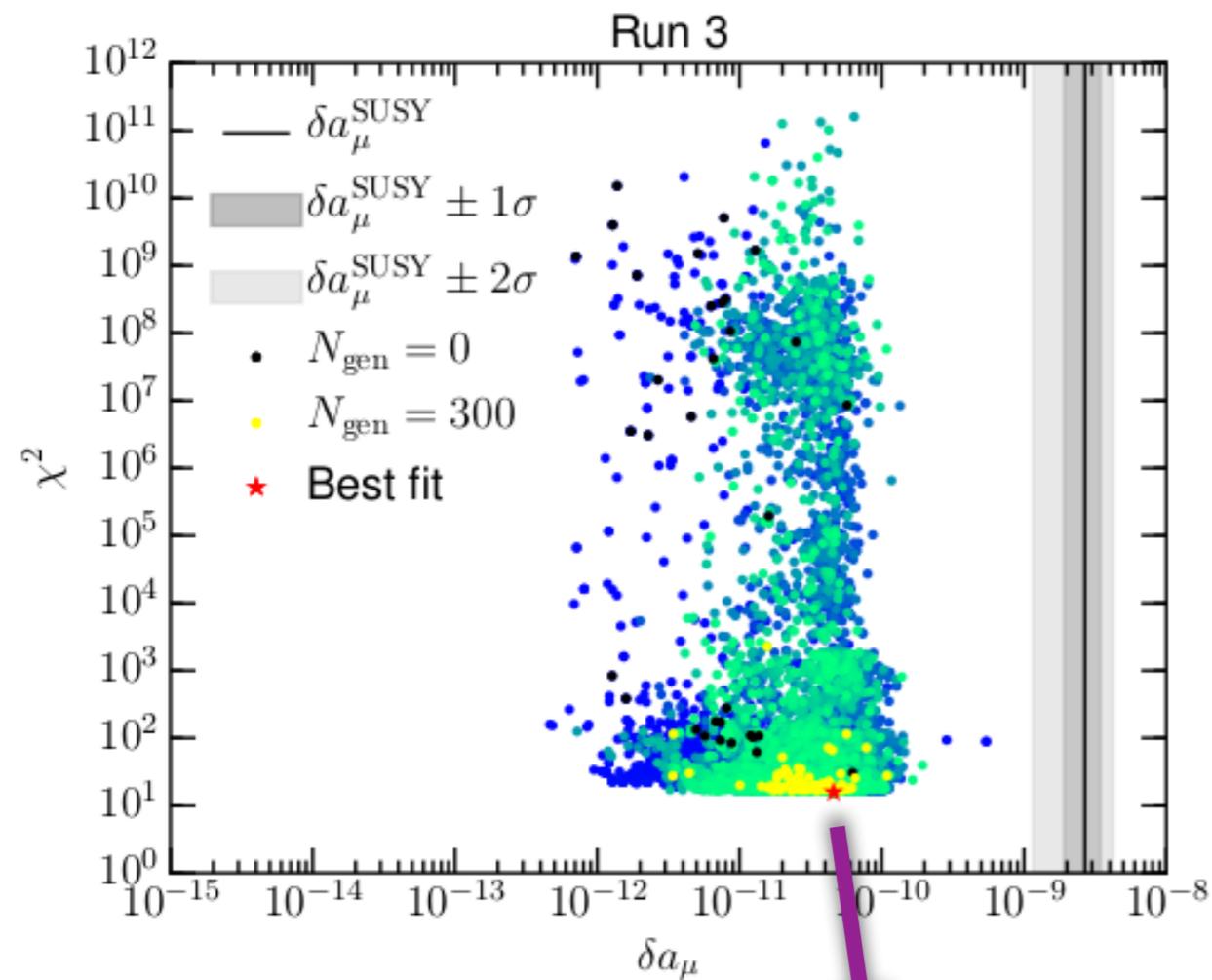
## EWPOs



## B physics

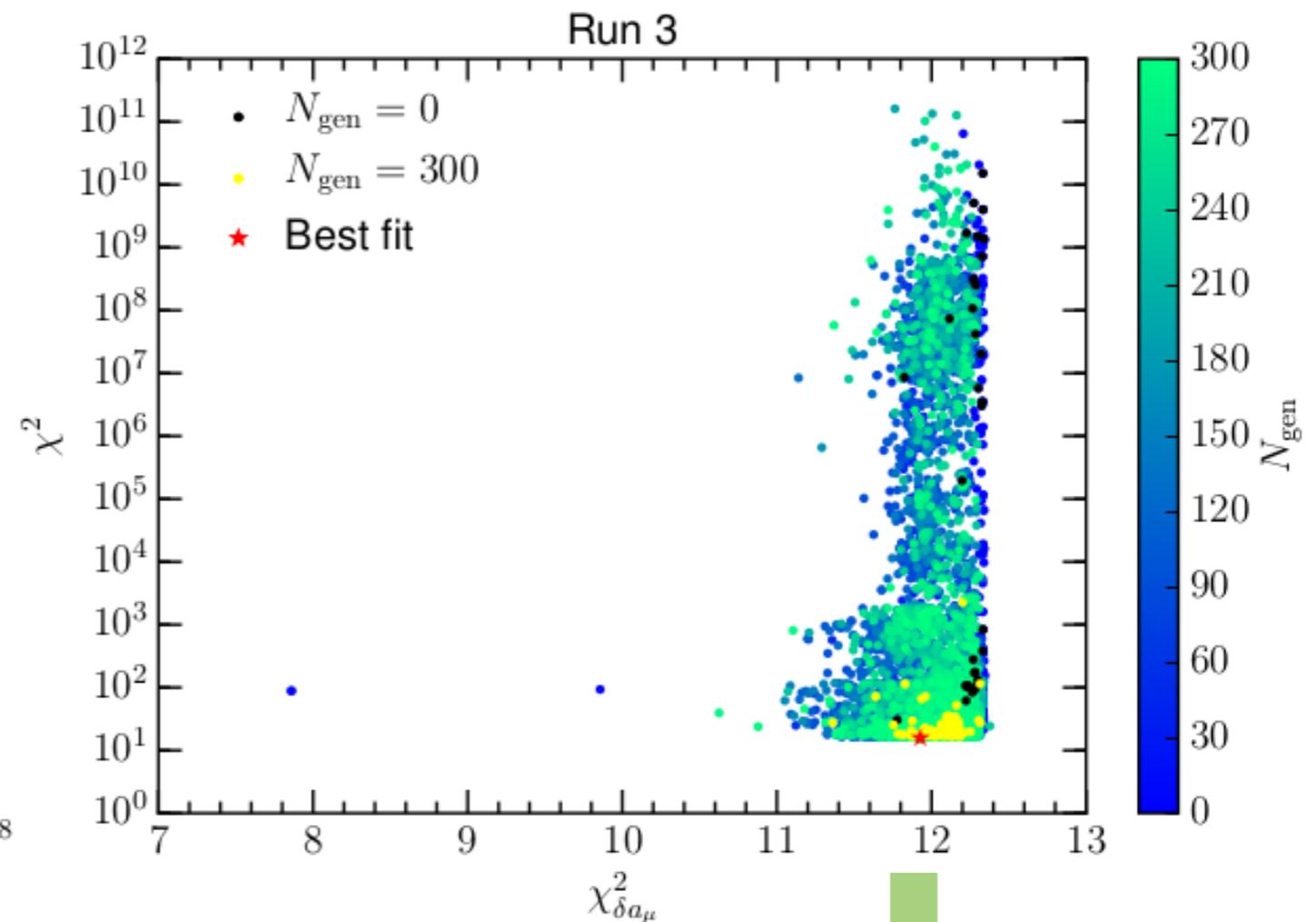


# Muon anomalous magnetic moment



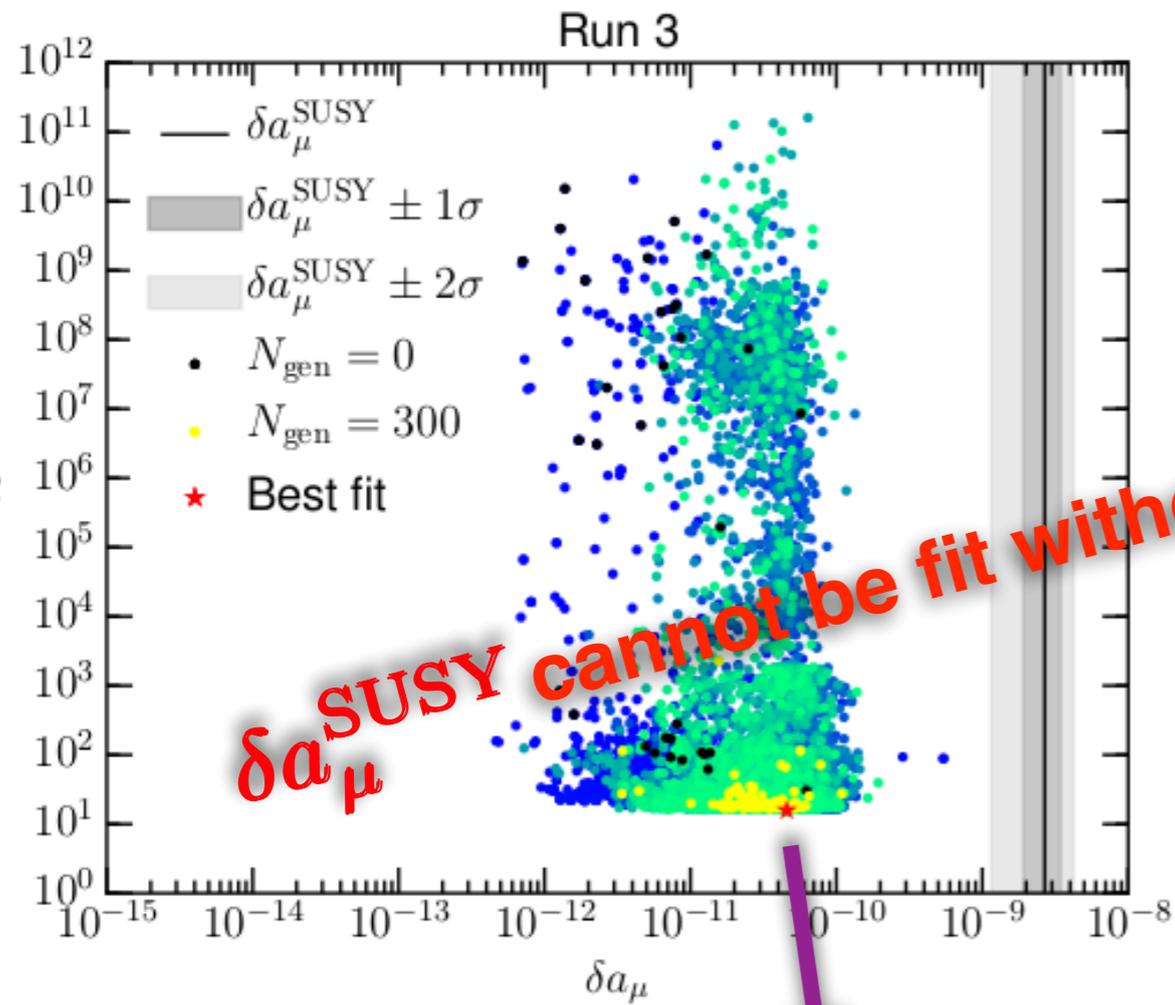
3 $\sigma$  away

$$\delta a_\mu^{\text{SUSY}} \lesssim 10^{-10}$$



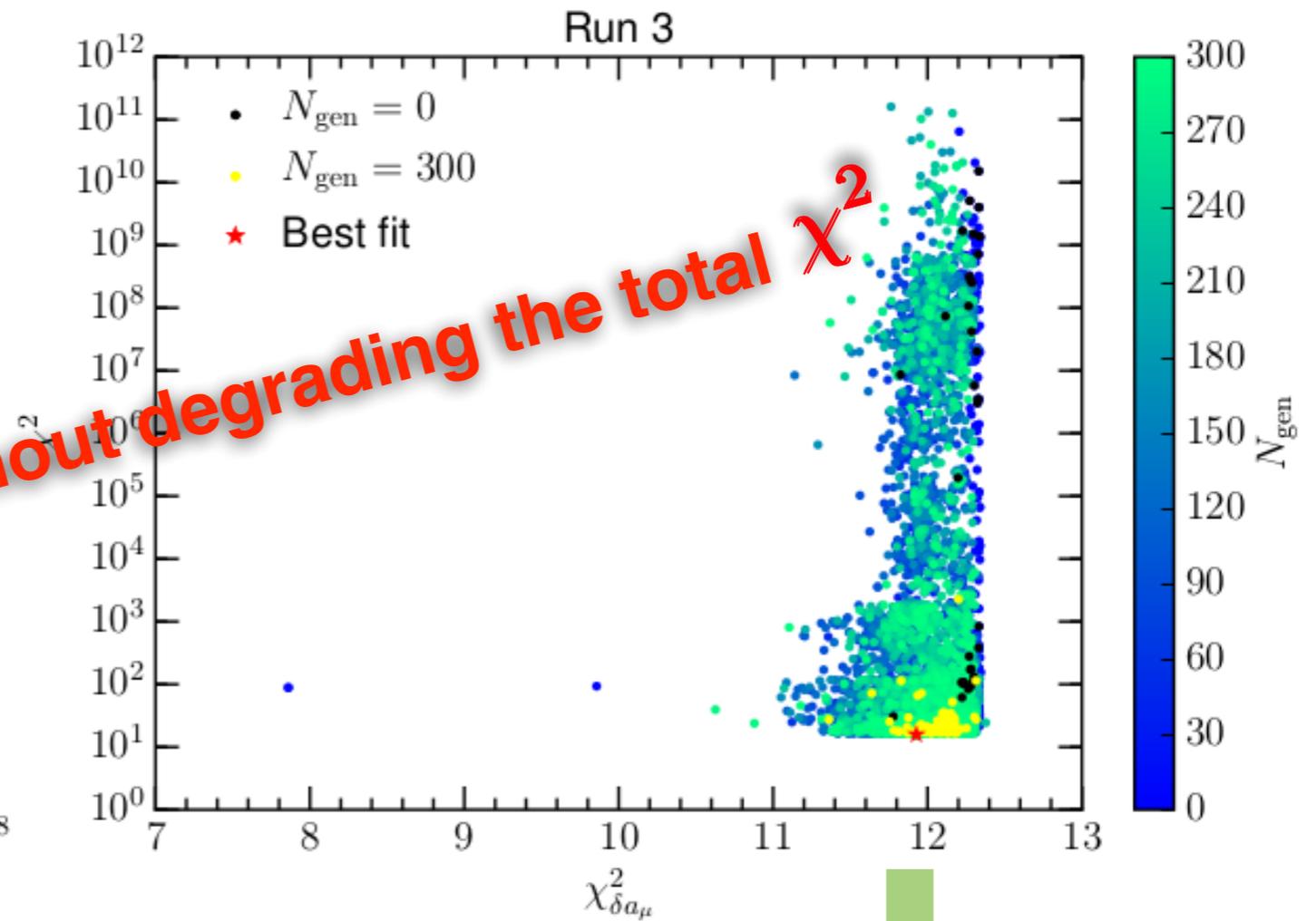
$$\chi_{\delta a_\mu}^2 \approx 12$$

# Muon anomalous magnetic moment



3 $\sigma$  away

$$\delta a_\mu^{\text{SUSY}} \lesssim 10^{-10}$$



$$\chi_{\delta a_\mu}^2 \approx 12$$

## The Galactic Center Excess

$$\ln \mathcal{L}_{\text{Joint}} = \ln \mathcal{L}_{\text{EWPO}} + \ln \mathcal{L}_B + \ln \mathcal{L}_{\text{Higgs}} + \ln \mathcal{L}_{\text{LEP}} + \ln \mathcal{L}_{\text{LHC}} + \ln \mathcal{L}_{\Omega_{\text{DM}} h^2} + \ln \mathcal{L}_{\text{GCE}}$$

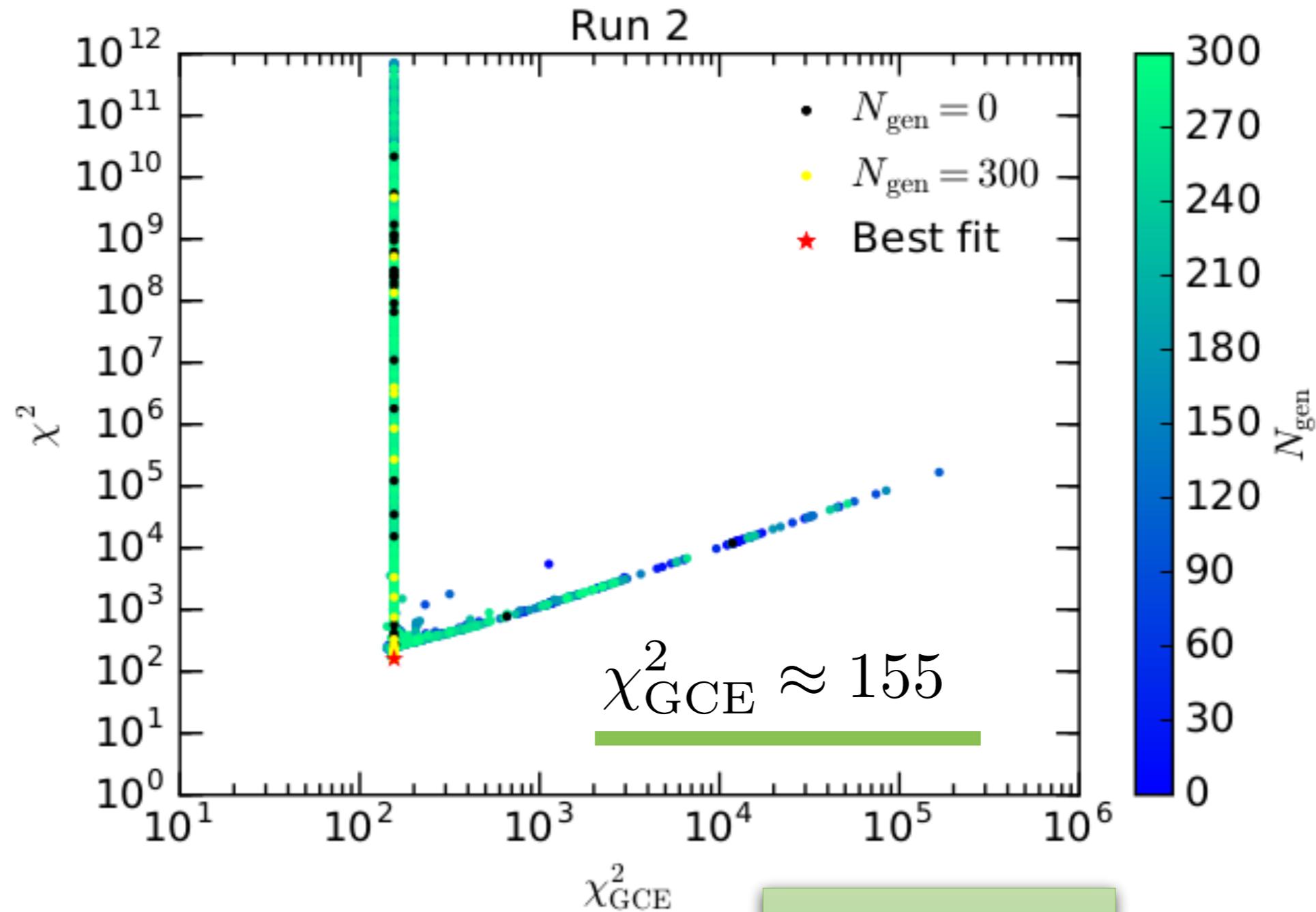
$$\chi_{\text{GCE}}^2 = \sum_{ij} \left( \frac{d\bar{N}}{dE_i}(\boldsymbol{\theta}) - \frac{dN}{dE_i} \right) \Sigma_{ij}^{-1} \left( \frac{d\bar{N}}{dE_j}(\boldsymbol{\theta}) - \frac{dN}{dE_j} \right)$$

F. Calore et al., 2014

A. Achterberg et al., 2017

M. Ackermann et al., Fermi-LAT collaboration, 2017

# The Galactic Center Excess



$$\chi^2 \approx 160$$

# Summary and conclusions

- ⊗ We have used GAs to study the compatibility of the pMSSM, featuring **parameters defined at the GUT scale** with experimental constraints
- ⊗ GAs require only **~10000 likelihood evaluations** to find a **best fit solution**
- ⊗ Main drivers of the GA evolution: **DM relic abundance and the Higgs mass**
- ⊗ **Best fits:**

$$m_{\chi_1^0} \simeq 2 \text{ TeV} \quad \text{wino-like}$$

⊗ **Heavy coloured sector**

$$m_{\tilde{t}_1} \approx 2 - 3 \text{ TeV}$$

$$m_{\tilde{g}} \gtrsim 5 \text{ TeV}$$

⊗ **Not clear prediction for the slepton sector**

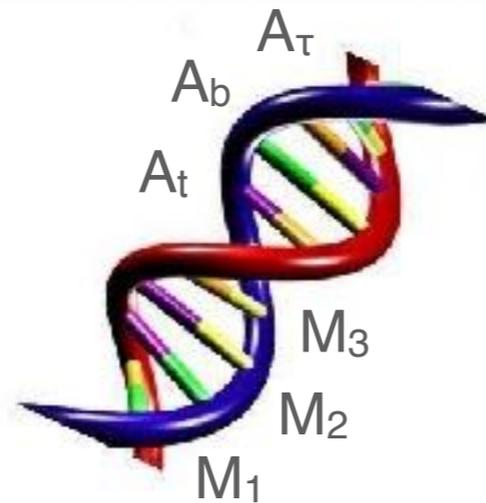
$$m_{\tilde{\tau}_1} \sim 2.3 - 8 \text{ TeV}$$

⊗ **GAs can deal with potential signals of new physics, e.g. g-2 and the GC excess**

$$\chi_{\delta a_\mu}^2 \text{SUSY} \approx 12$$

$$\chi_{\text{GCE}}^2 \approx 155$$

**GAs** are able to **divine patterns** of interesting models, and assess their consistency **exceedingly quickly**.



**Thanks!**

**¡Gracias!**

**Backup**

# Experimental constraints implemented as Gaussian PDFs

Observable	Mean value	Standard deviation	
		experimental	theoretical
$M_W$ (GeV)	80.385	0.015	0.01
$\sin^2 \theta_{\text{eff}}^{\text{lept}}$	0.231 53	0.000 16	0.0001
$\Gamma_Z$ (GeV)	2.4952	0.0023	0.001
$\Gamma_Z^{\text{inv}}$ (GeV)	0.499	0.0015	0.001
$m_{h^0}$ (GeV)	125.09	0.24	2.0
$BR(B \rightarrow X_s \gamma) \times 10^4$	3.43	0.22	0.24
$BR(B_s^0 \rightarrow \mu^+ \mu^-) \times 10^9$	2.9	0.7	0.29
$\frac{BR(B_u \rightarrow \tau \nu)}{BR(B_u \rightarrow \tau \nu)_{\text{SM}}}$	1.04	0.34	-
$\delta a_\mu^{\text{SUSY}} \times 10^{10}$	26.8	6.3	4.3
$\Omega_{\text{DM}} h^2$	0.1186	0.0010	0.012

## Codes used to calculate observables

Observable	Code
$m_W$	SOFTSUSY 4.1.0
$\sin^2 \theta_{\text{eff}}^{\text{lept}}$	FeynHiggs 2.13.0
$\Gamma_Z$	Zfitter 6.42, micrOMEGAs 4.3.2
$\Gamma_Z^{\text{inv}}$	Zfitter 6.42, micrOMEGAs 4.3.2
$\delta a_{\mu}^{\text{SUSY}}$	micrOMEGAs 4.3.2
B physics	micrOMEGAs 4.3.2
Higgs sector	FeynHiggs 2.13.0
SUSY spectrum	SOFTSUSY 4.1.0
Sparticle decays	SOFTSUSY 4.1.0
DM observables	micrOMEGAs 4.3.2
Cross sections	micrOMEGAs 4.3.2 (LO), PYTHIA 8.2 & NLL-fast (NLO+NLL)

# Muon anomalous magnetic moment

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
$\chi_{\Omega_{\tilde{\chi}_1^0} h^2}^2$	0.0067	0.0044	0.0174	0.0002	0.0045	0.0035	0.0096	0.0021	0.0000	0.0020
$\chi_{\text{HiggsSignals}}^2$	1.2950	1.2983	1.1452	1.2899	1.2902	1.2914	1.1579	1.2811	1.2804	1.2995
$\chi_{m_{h^0}}^2$	0.1125	0.2174	0.0005	0.0921	0.0879	0.0782	0.3911	0.0656	0.1475	0.1331
$\chi_{M_W}^2$	0.1190	0.0350	0.0008	0.1006	0.2500	0.0223	0.0004	0.1642	0.1205	0.2239
$\chi_{\sin^2 \theta_{\text{eff}}^{\text{lept}}}^2$	0.1538	0.1463	0.1569	0.1575	0.1552	0.1665	0.1639	0.1601	0.1567	0.1470
$\chi_{\Gamma_Z}^2$	0.0332	0.0121	0.0001	0.0602	0.0388	0.1175	0.0102	0.0451	0.0362	0.0561
$\chi_{\Gamma_Z^{\text{inv}}}^2$	2.3054	2.3027	2.2842	2.3056	2.3045	2.3089	2.2998	2.3028	2.3003	2.3024
$\chi_{BR(B \rightarrow X_s \gamma)}^2$	0.0664	0.0741	0.0596	0.0911	0.0689	0.1050	0.1664	0.0929	0.0717	0.0761
$\chi_{BR(B_s^0 \rightarrow \mu^+ \mu^-)}^2$	0.1647	0.1818	0.1498	0.1707	0.1617	0.1623	0.1733	0.1888	0.1715	0.1593
$\chi_{\frac{BR(B_u \rightarrow \tau \nu)}{BR(B_u \rightarrow \tau \nu)_{\text{SM}}}}^2$	0.0140	0.0143	0.0142	0.0143	0.0141	0.0140	0.0142	0.0154	0.0143	0.0140
$\chi_{\text{LEP}}^2$	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
$\chi_{\text{LHC}}^2$	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
$\chi_{\delta a_\mu^{\text{susy}}}^2$	<b>12.2691</b>	<b>12.0273</b>	<b>11.9275</b>	<b>12.2113</b>	<b>12.2873</b>	<b>12.2926</b>	<b>11.8926</b>	<b>11.9721</b>	<b>12.1162</b>	<b>12.1683</b>
$\chi_{\text{tot}}^2$	16.5398	16.3138	15.7562	16.4935	16.6631	16.5621	16.2793	16.2904	16.4152	16.5816

## Muon anomalous magnetic moment

Observable	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
$m_{h^0}$ (GeV)	124.42	124.15	125.13	124.48	124.49	124.53	123.83	124.57	124.32	124.36
$M_W$ (GeV)	80.379	80.382	80.386	80.379	80.376	80.382	80.385	80.378	80.379	80.377
$\sin^2 \theta_{\text{eff}}^{\text{lept}}$	0.23146	0.23146	0.23146	0.23146	0.23146	0.23145	0.23145	0.23146	0.23146	0.23146
$\Gamma_Z$ (GeV)	2.4947	2.4949	2.4952	2.4946	2.4947	2.4943	2.4950	2.4947	2.4947	2.4946
$\Gamma_Z^{\text{inv}}$ (GeV)	0.5017	0.5017	0.5017	0.5017	0.5017	0.5017	0.5017	0.5017	0.5017	0.5017
$BR(B \rightarrow X_s \gamma) \times 10^4$	3.35	3.34	3.35	3.33	3.34	3.32	3.30	3.33	3.34	3.34
$BR(B_s^0 \rightarrow \mu^+ \mu^-) \times 10^9$	3.21	3.22	3.19	3.21	3.20	3.21	3.22	3.23	3.21	3.20
$\frac{BR(B_u \rightarrow \tau \nu)}{BR(B_u \rightarrow \tau \nu)_{\text{SM}}}$	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
$\Omega_{\tilde{\chi}_1^0} h^2$	0.1178	0.1180	0.1204	0.1190	0.1180	0.1195	0.1200	0.1194	0.1188	0.1193
$\delta a_\mu^{\text{SUSY}} \times 10^{10}$	<b>0.0827</b>	<b>0.3472</b>	<b>0.4572</b>	<b>0.1457</b>	<b>0.0063</b>	<b>0.0057</b>	<b>0.4958</b>	<b>0.4081</b>	<b>0.2497</b>	<b>0.1927</b>

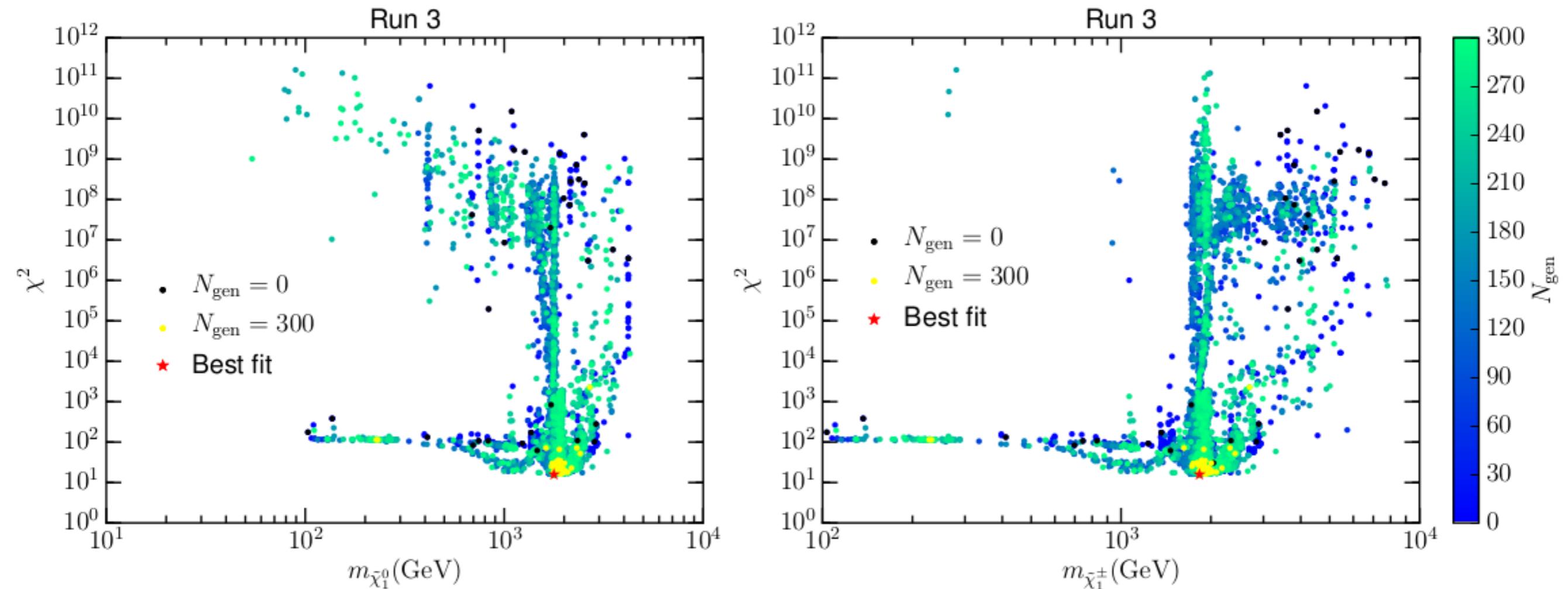
# SUSY spectrum

m(TeV)	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
$m_{\tilde{\chi}_1^0}$	2.1899	2.1016	1.7779	2.1262	2.2249	2.2701	1.8967	1.9043	2.0891	2.2252
$m_{\tilde{\chi}_2^0}$	4.3778	4.4140	1.8323	3.4508	2.6267	3.9700	3.3381	2.6099	4.2132	2.8475
$m_{\tilde{\chi}_1^\pm}$	2.1901	2.1017	1.8308	2.1264	2.2250	2.2702	1.8968	1.9045	2.0893	2.2254
$m_{\tilde{g}}$	6.7304	4.9071	2.6147	6.8046	8.2574	6.5645	3.0447	4.4649	5.3003	8.3863
$m_{\tilde{t}_1}$	3.1168	3.3535	2.1280	2.2745	2.5939	2.6113	2.2757	2.0702	2.2747	2.6774
$m_{\tilde{t}_2}$	6.2486	5.0756	8.1006	7.6622	7.9175	6.8952	3.2181	5.7306	6.2510	8.2790
$m_{\tilde{b}_1}$	5.2788	3.4830	5.2605	7.6589	6.9380	5.1184	2.2860	3.3888	4.4942	6.4800
$m_{\tilde{b}_2}$	6.2432	5.0657	8.0991	8.7702	7.9142	6.8912	2.4021	5.7259	6.2467	8.2761
$m_{\tilde{\tau}_1}$	2.6846	4.9582	3.6410	2.3003	2.6804	5.5212	7.5905	6.6731	7.7304	2.7379
$m_{\tilde{\tau}_2}$	7.0855	9.1210	4.2356	9.2520	7.4738	9.9211	8.8642	6.8868	7.8166	8.5809
$m_{\tilde{e}_L}$	7.9354	2.6358	2.2153	5.1338	9.0696	8.8432	2.1177	3.1214	2.9146	4.0030
$m_{\tilde{e}_R}$	9.9813	3.4901	3.7335	8.1401	9.6424	10.4569	3.0946	5.9648	7.4653	6.0597

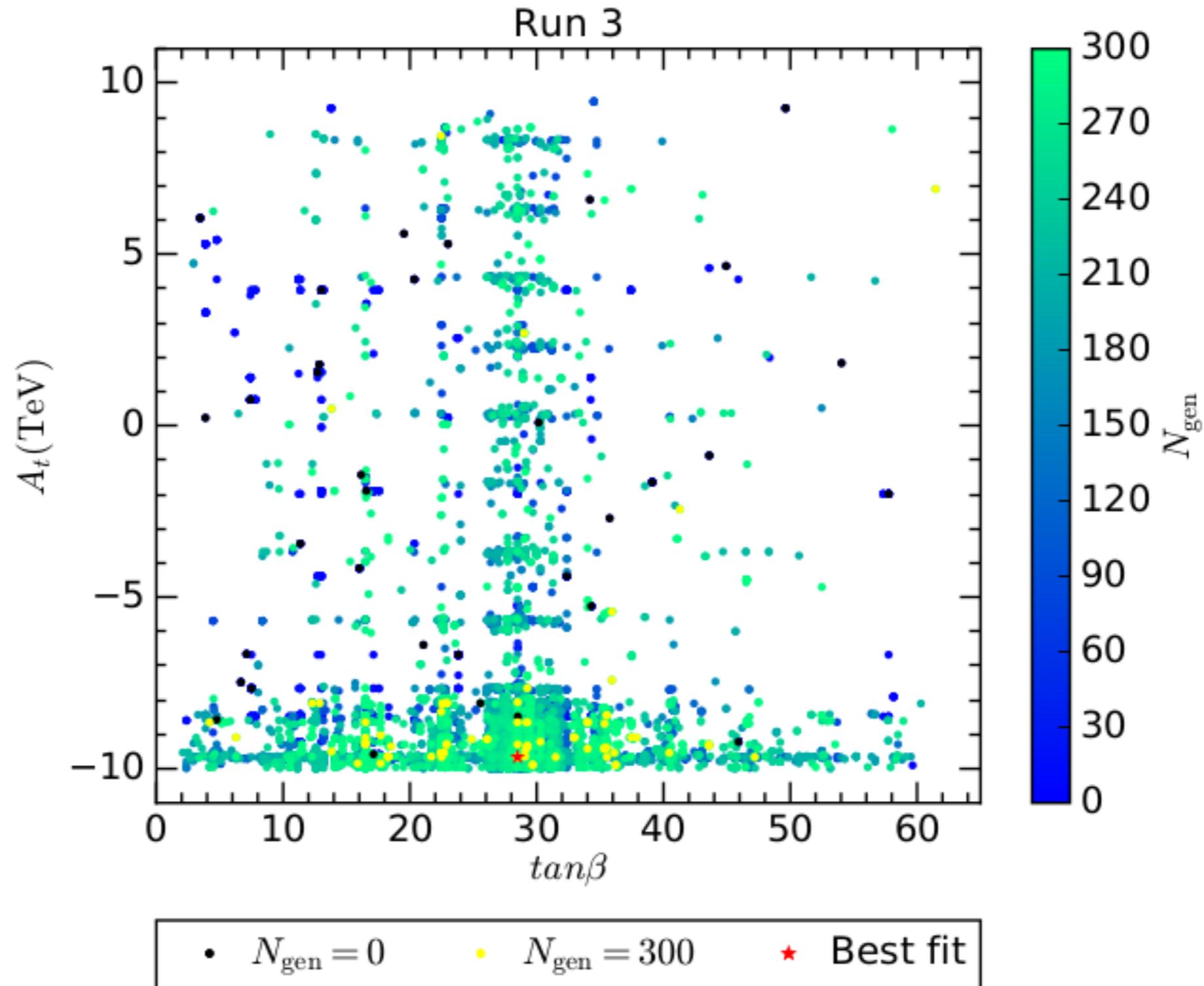
## pMSSM GUT scale input parameters for the best fit points

Parameter	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
$M_1$ (TeV)	9.5703	9.7113	3.9085	7.5518	5.7486	8.6224	7.4272	7.8098	9.2195	6.2369
$M_2$ (TeV)	2.5890	2.4750	2.1502	2.5057	2.6390	2.6583	2.2613	2.2840	2.4634	2.6338
$M_3$ (TeV)	3.2780	2.2800	1.1040	3.2561	4.0505	3.1197	1.3771	2.1184	2.4783	4.0718
$m_{H_u}$ (TeV)	1.6667	1.3993	4.1690	5.8189	5.0971	2.2366	0.3387	6.8716	0.9580	6.3635
$m_{H_d}$ (TeV)	7.1708	5.2775	8.2714	1.1057	6.3784	8.0392	6.9334	1.6798	3.1264	7.2671
$m_{\tilde{Q}_3}$ (TeV)	4.7038	4.9000	9.0737	7.0818	5.8858	5.9333	2.2149	6.0595	5.8636	6.6930
$m_{\tilde{Q}_{1,2}}$ (TeV)	5.3936	7.6163	3.6165	8.0554	4.6423	9.7422	4.8321	1.0849	7.1282	9.5621
$m_{\tilde{U}_3}$ (TeV)	0.1784	3.9889	6.6280	2.1355	1.9408	3.0753	4.0231	4.4181	3.1066	0.6947
$m_{\tilde{U}_{1,2}}$ (TeV)	1.4621	2.2405	8.0701	4.2783	6.5618	7.0730	1.6677	1.5040	6.5059	6.8387
$m_{\tilde{D}_3}$ (TeV)	0.7708	0.4281	5.4714	7.2873	1.4363	0.3643	0.1945	0.0882	1.8254	0.7754
$m_{\tilde{D}_{1,2}}$ (TeV)	0.1395	4.1474	7.2591	0.4960	3.9536	3.1839	0.7612	0.9395	1.3482	5.1211
$m_{\tilde{L}_3}$ (TeV)	6.7797	8.9868	4.8607	8.7979	7.6243	9.8535	7.6822	6.3356	7.6277	8.3796
$m_{\tilde{L}_{1,2}}$ (TeV)	7.5105	0.8366	2.6651	4.1286	9.0621	8.6661	1.0870	1.7923	1.6668	3.3159
$m_{\tilde{E}_3}$ (TeV)	1.3255	4.6784	3.1272	3.3281	0.7113	4.5917	8.9473	6.9846	7.7331	3.0309
$m_{\tilde{E}_{1,2}}$ (TeV)	9.4672	1.2755	1.8426	8.3371	9.0375	9.8130	1.1521	5.6990	6.7869	5.9095
$A_t$ (TeV)	-9.4740	-9.8184	-9.6588	-9.9870	-9.9878	-9.7382	-7.3392	-9.3542	-9.8716	-9.6492
$A_b$ (TeV)	-7.7118	-6.1908	8.5946	0.3908	9.4784	-6.1000	-1.2494	-2.1864	2.3702	-1.1100
$A_\tau$ (TeV)	8.6880	6.2710	-6.5096	-0.0063	-9.9068	-0.9948	8.6904	8.9710	-9.2448	-1.9952
$\tan \beta$	22.6238	29.3282	28.4906	21.5324	19.4162	18.4574	26.7140	22.5170	24.8102	20.9054

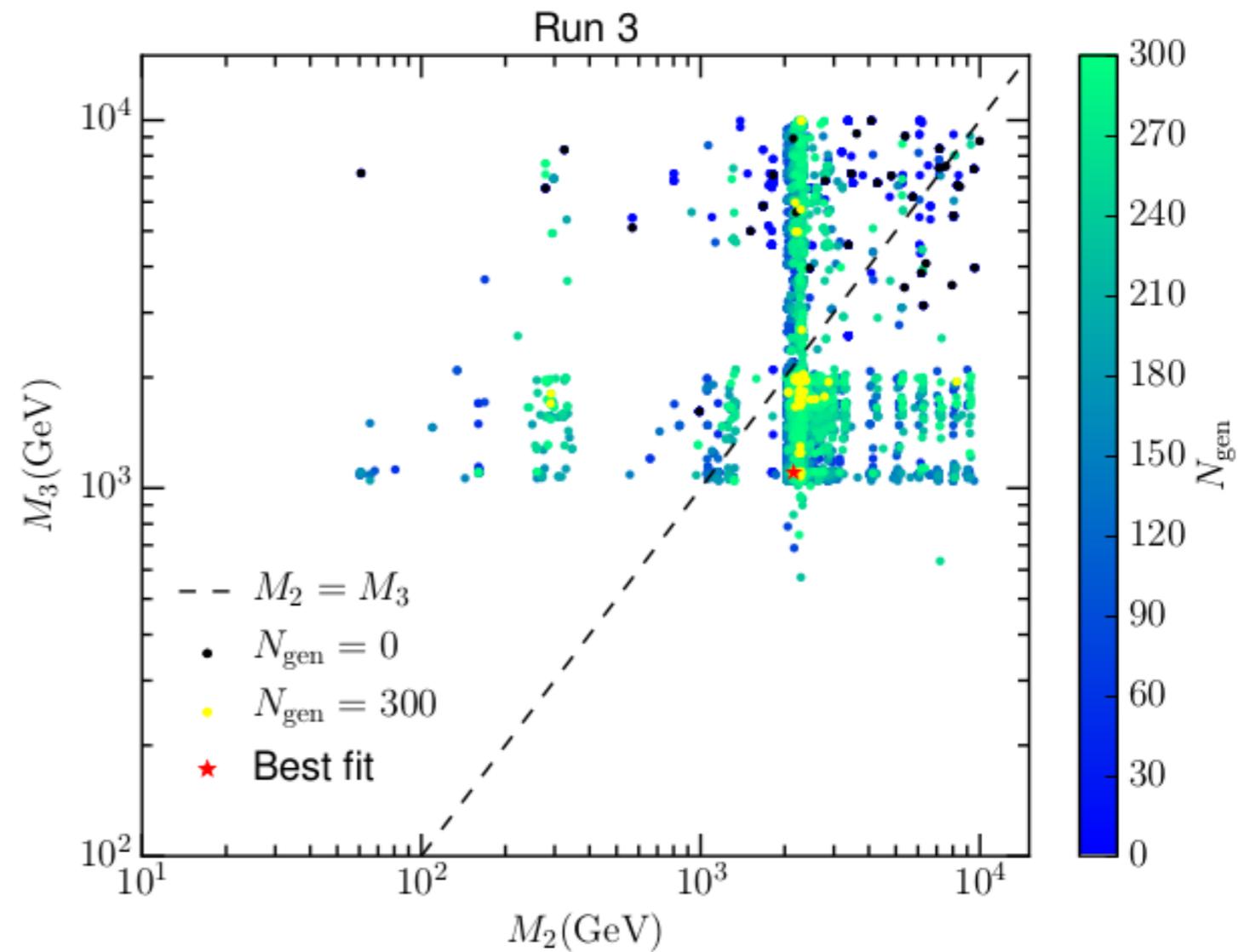
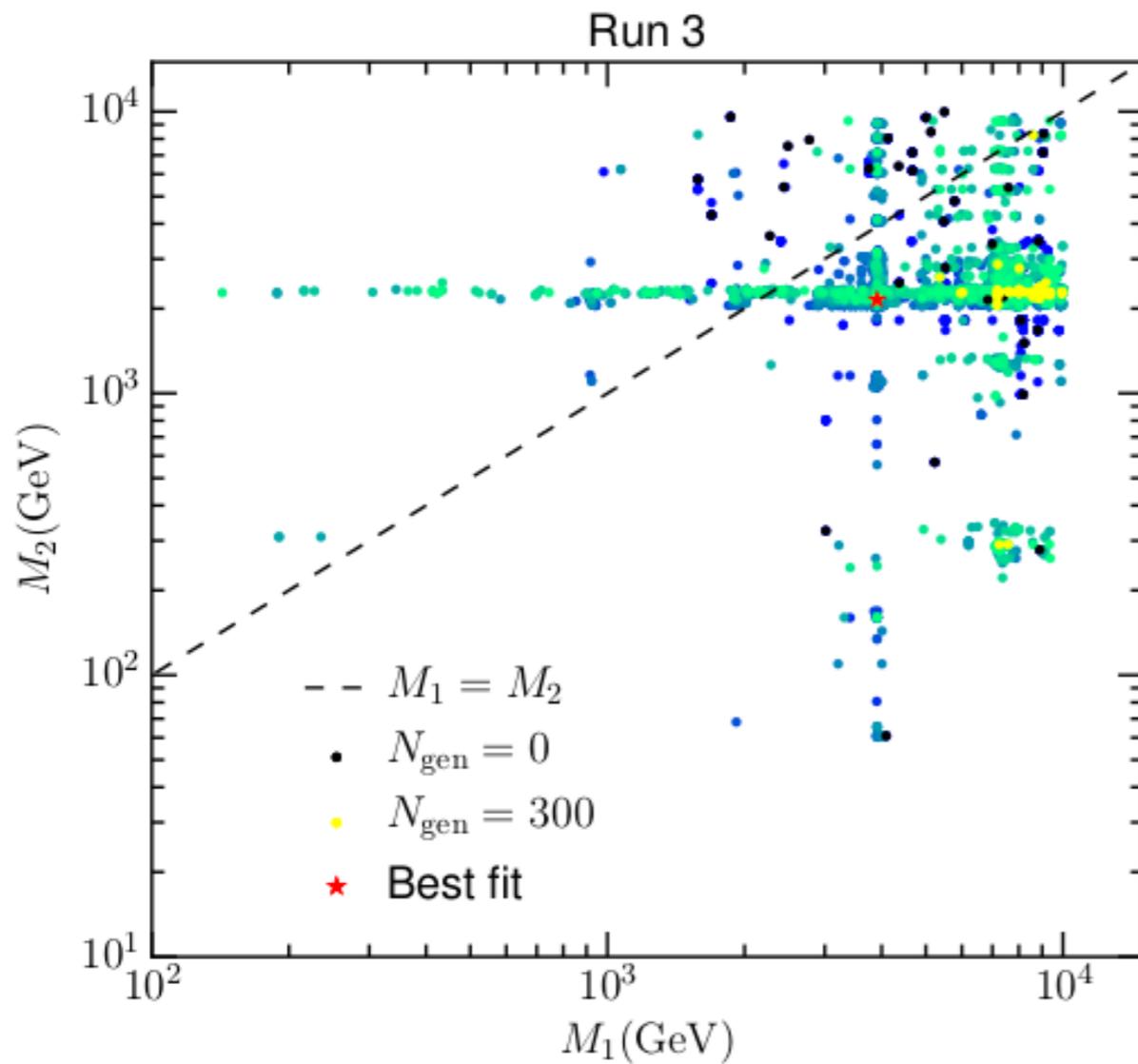
# Lightest neutralino and chargino



# Input parameters (GUT scale)



## Gaugino masses (GUT scale)



## The Galactic Center Excess

	Run 1	Run 2	Run 3	Run 4	Run 5
$\chi_{\Omega_{\tilde{\chi}_1^0} h^2}^2$	0.0040	0.0165	0.0015	0.0003	0.0472
$\chi_{\text{HiggsSignals}}^2$	1.2913	1.2812	1.2896	1.2938	1.2879
$\chi_{m_{h^0}}^2$	0.1411	0.1630	0.2316	0.5483	0.2214
$\chi_{M_W}^2$	0.2283	0.1652	0.3996	0.0999	0.2341
$\chi_{\sin^2 \theta_{\text{eff}}^{\text{lept}}}^2$	0.1509	0.1459	0.1266	0.1527	0.1416
$\chi_{\Gamma_Z}^2$	0.1208	0.0668	0.1584	0.0076	0.0425
$\chi_{\Gamma_Z^{\text{inv}}}^2$	2.3020	2.2954	2.2874	2.2985	2.2955
$\chi_{BR(B \rightarrow X_s \gamma)}^2$	0.1087	0.1283	0.1563	0.1016	0.0951
$\chi_{BR(B_s^0 \rightarrow \mu^+ \mu^-)}^2$	0.1575	0.1534	0.1508	0.1577	0.1547
$\chi_{\frac{BR(B_u \rightarrow \tau \nu)}{BR(B_u \rightarrow \tau \nu)_{\text{SM}}}}^2$	0.0140	0.0140	0.0142	0.0141	0.0140
$\chi_{\text{LEP}}^2$	0.0000	0.0000	0.0000	0.0000	0.0000
$\chi_{\text{LHC}}^2$	0.0000	0.0000	0.0000	0.0000	0.0000
<b><math>\chi_{\text{GCE}}^2</math></b>	<b>155.3494</b>	<b>155.3459</b>	<b>155.3588</b>	<b>155.3656</b>	<b>155.3490</b>
$\chi_{\text{tot}}^2$	159.8680	159.7755	160.1747	160.0401	159.8832