

# pMSSM scans in ATLAS

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SUSY2016, Melbourne





# Motivation

**Intermediate approach:** systematic reinterpretations of existing analyses w.r.t low-medium sized parameter sub-spaces of MSSM

- re-use existing measurements, analysis procedures (selections, background estimates, statistical evaluation)
- full SUSY models without high-scale theory assumption

**Challenges to solve:**

- **How to sample parameter space**
- **How to decide which points to run through expensive simulation**
- **How to interpret/combine results of individual analyses**

**This talk: two parameter scans of (a subspace of ) the pMSSM.**



# Theoretical Framework

MSSM fully generic low-scale parametrization. experimentally motivated assumptions can cut number of parameters significantly:

- R-parity conservation
- lightest neutralino as LSP
- degenerate 1st and 2nd generation sparticles
- no new CP violation
- minimal flavor violation
- simplified Yukawa couplings

gives 19-D **phenomenological MSSM (pMSSM)** as a basis for reinterpretation campaigns:

- 3rd gen trilinear couplings:  $A_{e,\mu,\tau}$
- $\tan\beta$
- higgsino mass parameter:  $\mu$
- pseudo-scalar Higgs mass:  $m_A$
- wino/bino/gluino mass:  $M_{1,2,3}$
- squark/slepton soft masses (10)



# pMSSM-19 scan

[arXiv:1508.06608](https://arxiv.org/abs/1508.06608)



# Full pMSSM scan

To study ATLAS Impact on full pMSSM, **comprehensive reinterpretation campaign** was conducted at end of Run-1:

- 22 analyses
- 200 signal regions

## Plan:

1. scan pMSSM space
2. find points that are not excluded by other constraints, yet accessible to ATLAS.
3. generate samples and obtain new exclusion limits for each analysis using original analysis code
4. determine overall status of points based on all analysis results



## Analysis

0-lepton + 2–6 jets + $E_T^{\text{miss}}$	[1405.7875]
0-lepton + 7–10 jets + $E_T^{\text{miss}}$	[1308.1841]
1-lepton + jets + $E_T^{\text{miss}}$	[1501.03555]
$\tau(\tau/\ell)$ + jets + $E_T^{\text{miss}}$	[1407.0603]
SS/3-leptons + jets + $E_T^{\text{miss}}$	[1404.2500]
0/1-lepton + 3b-jets + $E_T^{\text{miss}}$	[1407.0600]
Monojet	[1502.01518]
0-lepton stop	[1406.1122]
1-lepton stop	[1407.0583]
2-leptons stop	[1403.4853]
Monojet stop	[1407.0608]
Stop with Z boson	[1403.5222]
2b-jets + $E_T^{\text{miss}}$	[1308.2631]
$tb + E_T^{\text{miss}}$ , stop	[1506.08616]
$\ell h$	[1501.07110]
2-leptons	[1403.5294]
2- $\tau$	[1407.0350]
3-leptons	[1402.7029]
4-leptons	[1405.5086]
Disappearing Track	[1310.3675]
Long-lived particle	[1211.1597] [1411.6795]
$H/A \rightarrow \tau^+ \tau^-$	[1409.6064]



# Full pMSSM scan — Point Selection

A cartesian grid in 19-D is not possible (*curse of dimensionality*), so we need to **sample the parameter space** statistically.

Sampled from uniform distributions in the 19 parameters with ranges chosen w.r.t existing exclusions and LHC reach

With this initial sampling, points are subjected to existing experimental constraints

## precision electroweak and flavor observables:

- e.g.  $\rho$ -parameter,  $(g-2)_\mu$ ,  $\text{BR}(B_s \rightarrow \mu\mu)$

## dark matter:

- LSP relic abundance (Planck)
- direct detection cross-section limits (LUX, COUPP, XENON100)

## collider results:

- Z inv. width, sparticle mass lower bounds (LEP)
- Higgs mass constraint (ATLAS)

Parameter	Min value	Max value
$m_{\tilde{L}_1} (= m_{\tilde{L}_2})$	90 GeV	4 TeV
$m_{\tilde{e}_1} (= m_{\tilde{e}_2})$	90 GeV	4 TeV
$m_{\tilde{L}_3}$	90 GeV	4 TeV
$m_{\tilde{e}_3}$	90 GeV	4 TeV
$m_{\tilde{Q}_1} (= m_{\tilde{Q}_2})$	200 GeV	4 TeV
$m_{\tilde{u}_1} (= m_{\tilde{u}_2})$	200 GeV	4 TeV
$m_{\tilde{d}_1} (= m_{\tilde{d}_2})$	200 GeV	4 TeV
$m_{\tilde{Q}_3}$	100 GeV	4 TeV
$m_{\tilde{u}_3}$	100 GeV	4 TeV
$m_{\tilde{d}_3}$	100 GeV	4 TeV
$ M_1 $	0 GeV	4 TeV
$ M_2 $	70 GeV	4 TeV
$ \mu $	80 GeV	4 TeV
$M_3$	200 GeV	4 TeV
$ A_t $	0 GeV	8 TeV
$ A_b $	0 GeV	4 TeV
$ A_\tau $	0 GeV	4 TeV
$M_A$	100 GeV	4 TeV
$\tan\beta$	1	60



# Full pMSSM scan — Point Selection

Since full simulation is very CPU intensive, points compatible with constraints go through sequence of processing steps to decide whether simulation is necessary:

1. points with too low cross-section considered not excluded
2. Madgraph+Pythia MC sample generation for remaining points
3. Truth-level analysis of points to categorize into 3 groups based on SR acceptance:
  - a) excluded:  $N_{\text{sig}} \gg$  model-independent  $N_{95}$  limit for at least one SR
  - b) insensitive:  $N_{\text{sig}} \ll N_{95}$  points counted as not excluded
  - c) viable:  $N_{\text{sig}} \sim N_{95}$ . points eligible for further processing using full detector simulation. Total number of viable points: ~45k

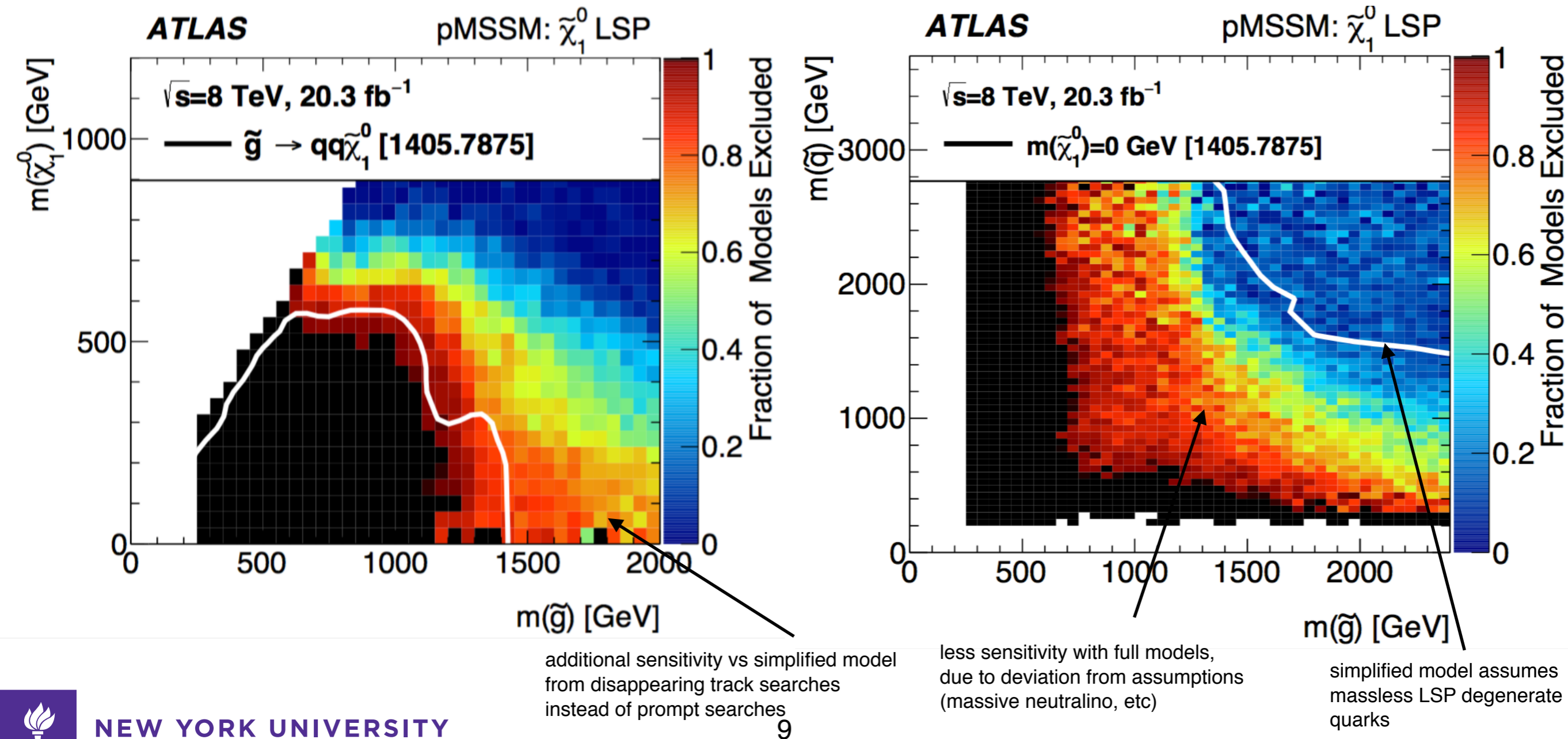
For points in group c), fully simulated and reconstructed samples are passed through original analysis code + statistical evaluation to obtain exclusion status ( $CL_s$  value)



# Full pMSSM scan — Results

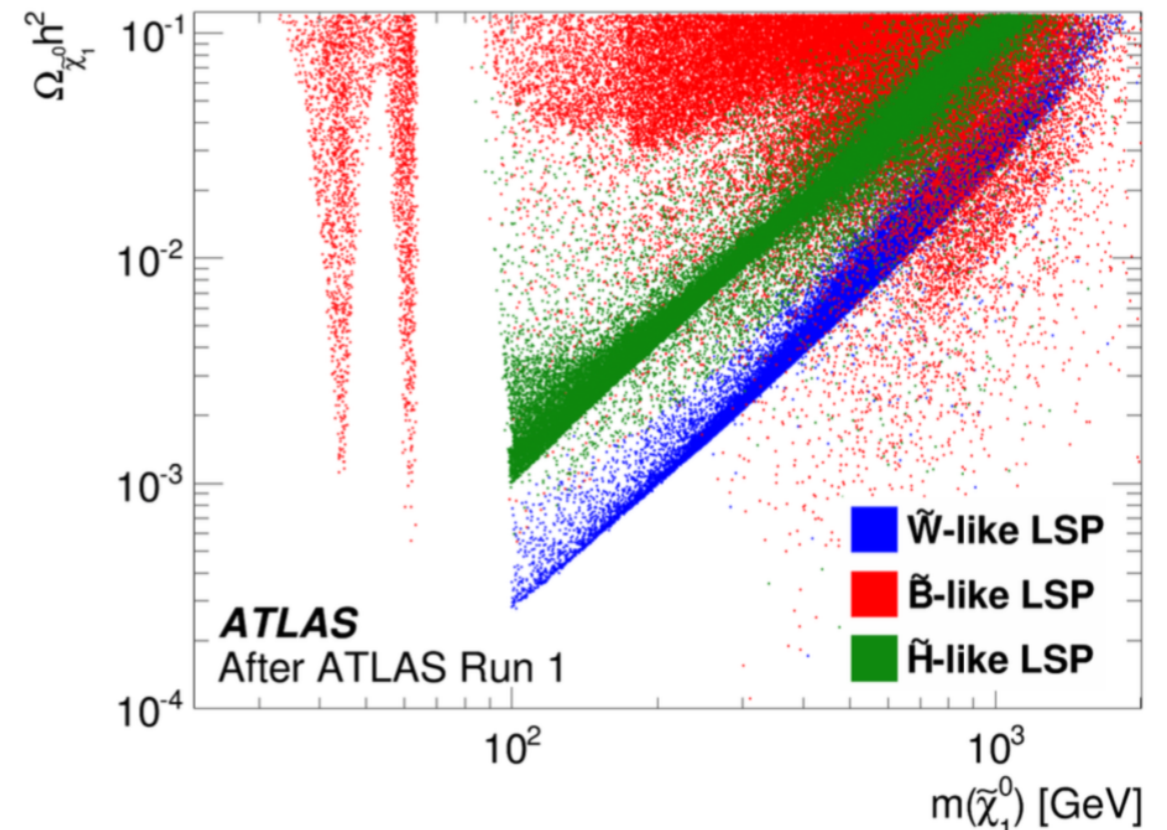
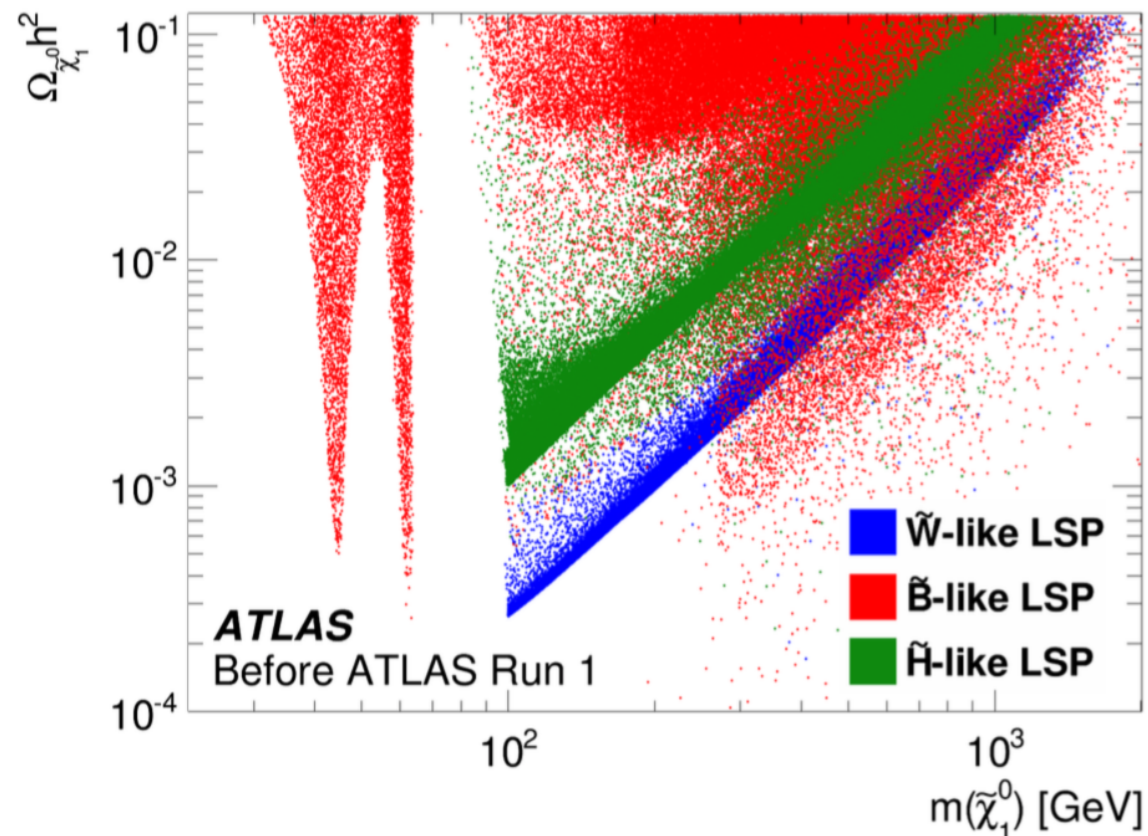
SR with strongest limit defines overall result for parameter point. **no statistical combination of SR.**

Result Presentation as **exclusion fraction maps** in 2-D projections superimposed with relevant simplified model limit contours.



# Full pMSSM scan — Results

Impact on Dark Matter observables:



# EWKH-5 scan

(to appear)



# Model Overview

pMSSM scan investigated full 19D space with strong constraints on colored particle production. Now, a more tailored 5D pMSSM sub-space scan to assess ATLAS impact on electroweak production and DM observables.

## Model parameters

- 1. Bino mass  $M_1$
  - 2. Wino mass  $M_2$
  - 3. Higgs mixing  $\mu$
  - 4.  $\tan\beta$
  - 5. pseudo-scalar Higgs mass
- } fixes electroweakino sector
- } fixes Higgs sector

all other parameters set such as to decouple sfermions, squarks, gluinos.



# Sampling Strategy

## Sampling Strategy:

For initial sampling of viable parameter points, the space sampled using a posterior distribution obtained from a nested bayesian sampling using a joint likelihood that incorporates existing experimental constraints

$$\ln \mathcal{L}_{\text{joint}} = \ln \mathcal{L}_{\text{EW}} + \ln \mathcal{L}_{\text{B}} + \ln \mathcal{L}_{\Omega_\chi h^2} + \ln \mathcal{L}_{\text{DD}} + \ln \mathcal{L}_{\text{Higgs}} + \ln \mathcal{L}_{\text{LEP}-\chi_1^\pm}$$

## Constraints:

Higgs mass constraint from ATLAS measurement

B-physics : combinations on B measurements from HFAG and  $B_s \rightarrow \mu\mu$  BR results from CMS, LHCb

LEP precision measurements of electroweak observables

Observable	Mean value	Standard deviation	
	$\mu$	$\sigma$ (exper.)	$\tau$ (theor.)
$m_h$ [GeV]	125.36	0.41	2.0

Observable	Mean value	Standard deviation	
	$\mu$	$\sigma$ (exper.)	$\tau$ (theor.)
$BR(\bar{B} \rightarrow X_s \gamma) \times 10^4$	3.55	0.26	0.30
$\frac{BR(B_u \rightarrow \tau \nu)}{BR(B_u \rightarrow \tau \nu)_{\text{SM}}}$	1.62	0.57	-
$BR(B_s^0 \rightarrow \mu^+ \mu^-) \times 10^9$	2.9	0.7	0.38

Observable	Mean value	Standard deviation	
	$\mu$	$\sigma$ (exper.)	$\tau$ (theor.)
$m_W$ [GeV]	80.385	0.015	0.01
$\sin^2 \theta_{\text{eff}}^{\text{lept}}$	0.23153	0.00016	0.00010
$\Gamma_Z$ [GeV]	2.4952	0.0023	0.001
$\Gamma_Z^{\text{inv}}$ [GeV]	0.499	0.0015	0.001
$\sigma_{\text{had}}^0$ [nb]	41.540	0.037	-
$R_l^0$	20.767	0.025	-
$R_b^0$	0.21629	0.00066	-
$R_c^0$	0.1721	0.003	-



# Sampling Strategy

DM Relic Density: Neutralino is allowed to be subdominant component of DM  
 Total DM relic density is constrained Planck data.

$$\Omega_{\text{DM}} h^2 = 0.1186 \pm 0.0031(\text{exp.}) \pm 0.012(\text{th.})$$

$$\mathcal{L}_{\Omega_\chi h^2} = \mathcal{L}_0 \int_{\Omega_\chi h^2 / \sigma_{\text{Planck}}}^{\infty} e^{-\frac{1}{2}(x-r_\star)^2} x^{-1} dx$$

DM Direct Detection experiments: limits from XENON100 and LUX in neutralino mass - cross-section plane

	Limit (95% CL)	$\tau$ (theor.)
$m_\chi$ vs. $\sigma_{\chi N}^{\text{SI}}$	XENON100 2012 limits ( $224.6 \times 34$ kg days)	
$m_\chi$ vs. $\sigma_{\tilde{\chi}_1^0 - p}^{\text{SD}}$	XENON100 2012 limits ( $224.6 \times 34$ kg days)	
$m_\chi$ vs. $\sigma_{\chi N}^{\text{SI}}$	LUX 2013 limits ( $118 \times 85.3$ kg days)	

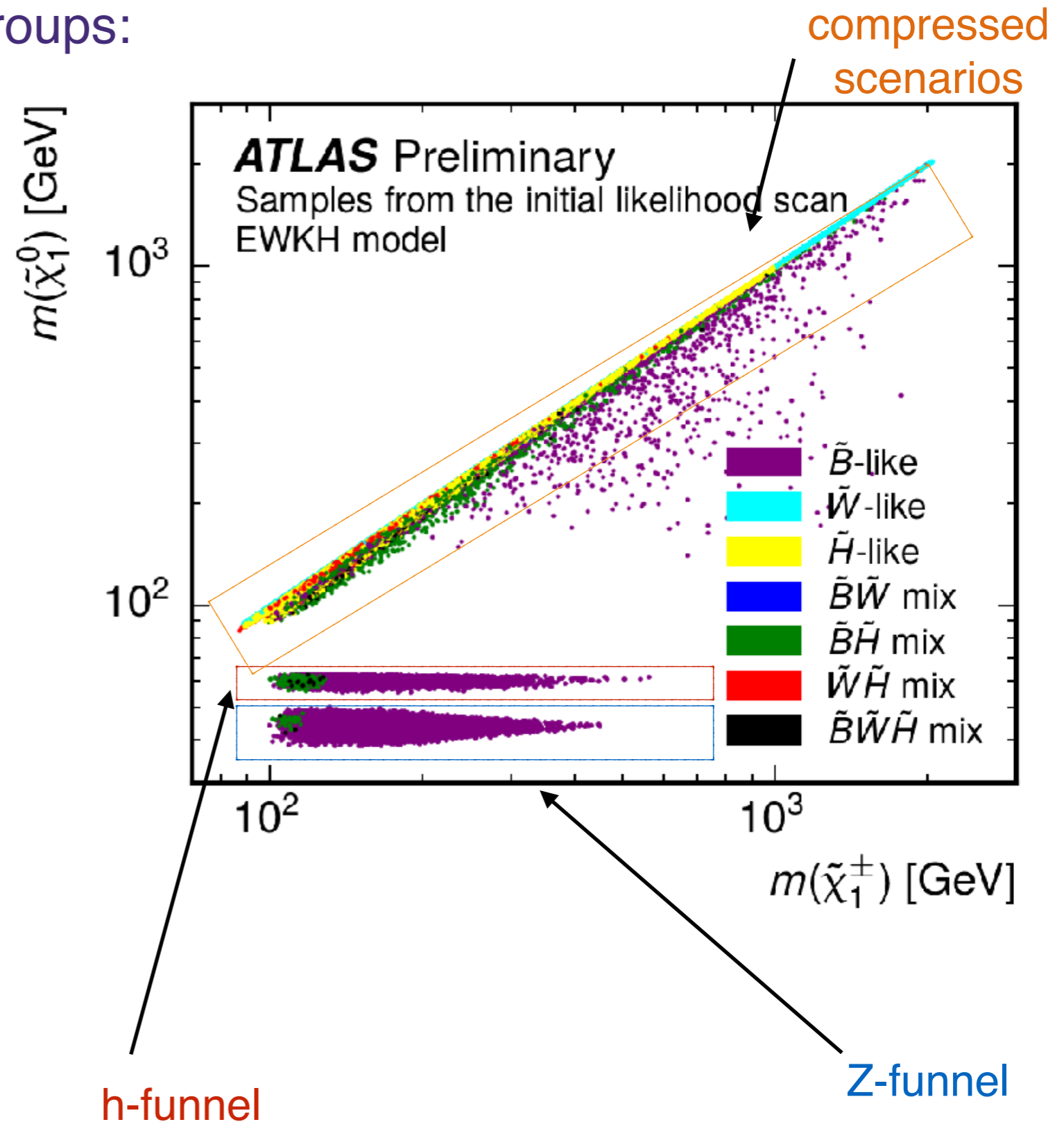
LEP chargino lower bound:  $m_{\chi^\pm} \geq 91.4 \text{ GeV}$



# Sampling Strategy

using initial sampling of  $\sim 570\text{k}$  points, profile likelihood maps are constructed to categorize points into three groups:

1. **Excluded:** outside of 95% confidence region in likelihood scan ( $\sim 98\text{k}$  points)
2. **Unreachable:** no sensitivity due to low cross-section ( $\sigma < 0.25\text{fb}$  from Prospino,  $\sim 146\text{k}$  points)
3. **Viable:** sufficient cross-section to be reachable.  **$\sim 327\text{k}$  points** for which full Madgraph+Pythia samples have been produced to assess ATLAS impact.



# Sampling Strategy

Set of four ATLAS SUSY searches designed for electroweak production are used to assess impact:

## The Analyses:

- **2-lepton:** opposite sign  $2 e/\mu + m_{T2}$  (stransverse mass) in 7 signal regions [\[1403.5294\]](#)
- **2-tau:** opposite sign, hadronically decaying taus +  $m_{T2}$  in four signal regions [\[1407.0350\]](#)
- **3-lepton:**  $2(e/\mu) + \tau_{\text{had}} \parallel 1(e/\mu) + 2\tau_{\text{had}}$  final states in 24 signal regions [\[1402.7029\]](#)
- **4-lepton:**  $(4(e/\mu) \parallel 3(e/\mu) + \tau_{\text{had}} \parallel 2(e/\mu) + 2\tau_{\text{had}}) + \text{MET}$  [\[1405.5086\]](#)

Running all samples for viable parameter points through full detector simulation and analysis to extract CLs values — as in pMSSM-19 — computationally unfeasible.

Instead, a small sample of 500 points is used to **calibrate CLs values to generator yields.**

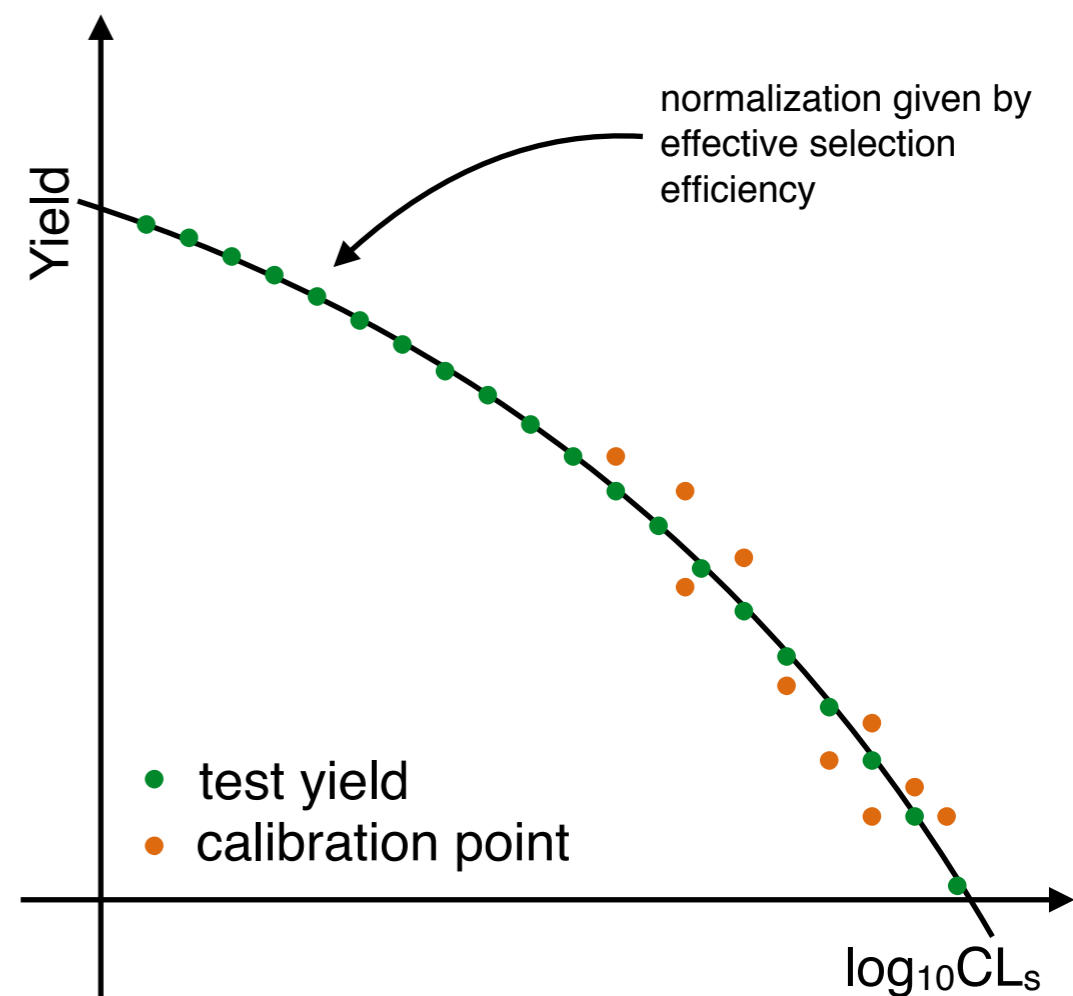


# $CL_s$ Calibration

reconstructed event yields in signal regions — from which we extract  $CL_s$  — related to truth yields by reconstruction efficiency that is assumed to be model-independent.

$$CL_s \leftrightarrow N_{\text{reco}} = \epsilon N_{\text{truth}}$$

- Calibration function shape  $CL_s(N_{\text{reco}}(\epsilon))$  extracted using test yields parametrized by efficiency.
- Fit is performed on 500 fully simulated models for each signal region (bin). SR where efficiency uncertainty  $< 20\%$  retained
- With calibration we can then extract  $CL_s$  values for all  $\sim 327\text{k}$  models and assess ATLAS impact

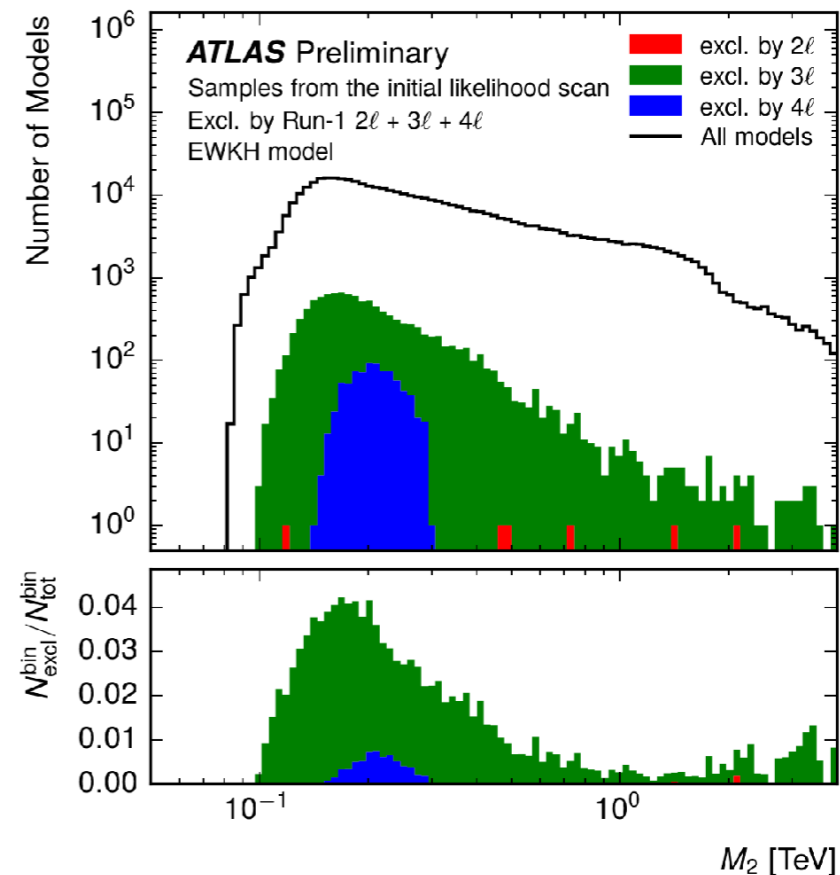
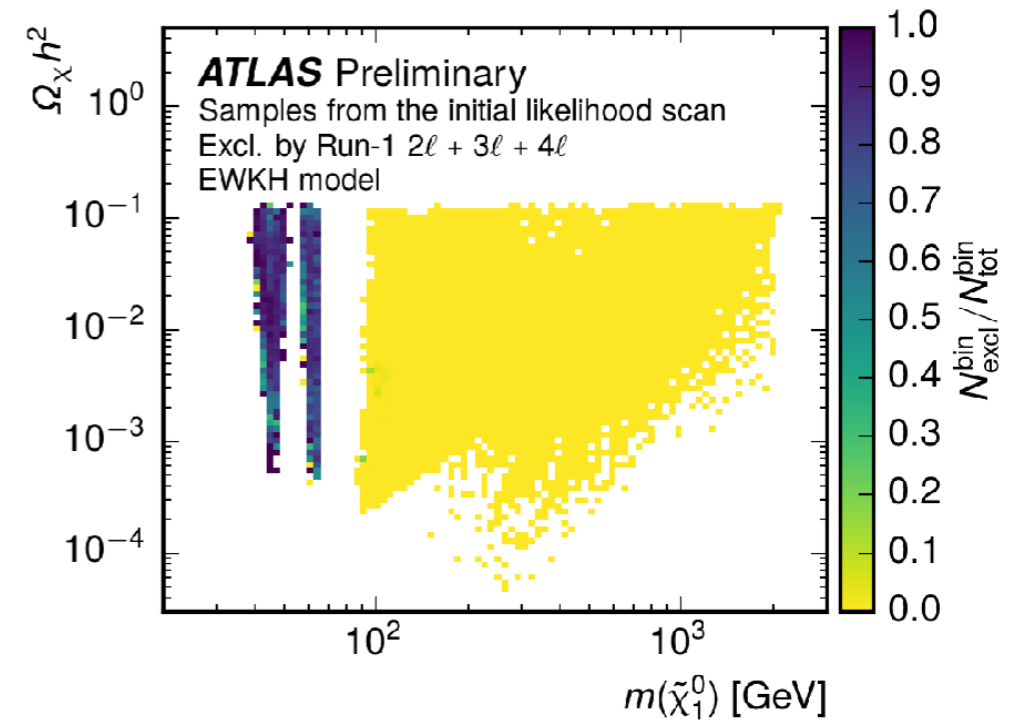
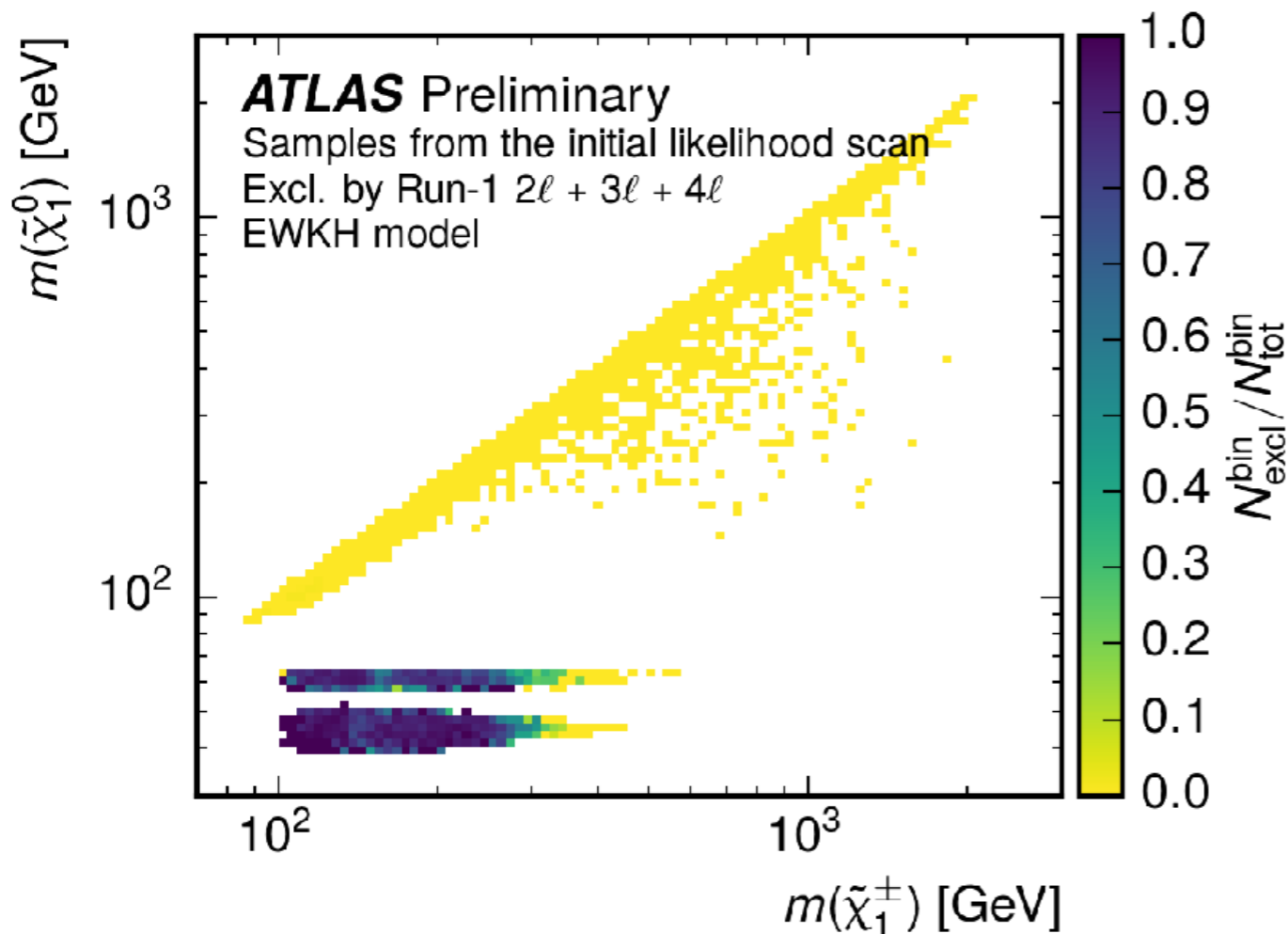


# Results

As in pMSSM-19, no stat. combination of analyses. Most sensitive SR (i.e. smallest  $CL_s$ ) used to either exclude or retain point post-ATLAS.

Presentation as 1-D and 2-D exclusion fraction maps for both model parameters, particle masses and dark matter observables

Z/h-funnels largely excluded. Compressed spectra still viable.



# Conclusions

- medium-dimensional pMSSM scans provide powerful way to reinterpret existing searches in context of full UV-agnostic SUSY models
- Two scans performed using Run-1 analyses: full 19-D pMSSM, 5-D electroweak production subspace (EWKH)
- care needs to be taken in choosing sampling strategy and for which points full detector simulation is worthwhile (e.g. based on expected sensitivity, existing experimental constraints)
- efforts under way to streamline these reinterpretation campaigns for Run-2 within the collaboration

