The Phenomenological MSSM for Run 2 CMS

Snowmass Meeting (June 2020)

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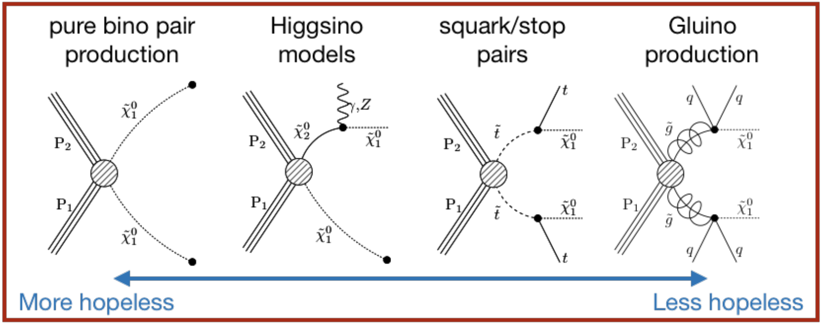
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Supersymmetry and the MSSM

SUSY is used widely for interpretations and designing searches at the LHC; why?

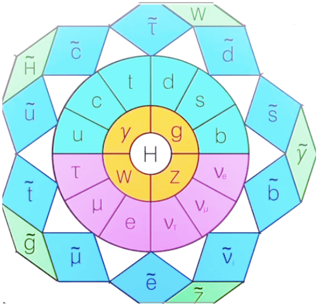
1. naturalness arguments for SUSY at the terascale
2. many SUSY scenarios could explain DM
3. broad set of models to test the reach of analyses, identify gaps in coverage



The MSSM

Minimal supersymmetric standard model

Supermultiplets	spin 0	spin 1/2	spin 1	number of fields/2
Higgs, Higgsino	H_u	$\tilde{H}_u$		2
	H_d	$\tilde{H}_d$		2
quark, squark	$\tilde{Q}_L$	Q_L		6
	$\tilde{u}_R^*$	$u_R^\dagger$		3
	$\tilde{d}_R^*$	$d_R^\dagger$		3
lepton, slepton	$\tilde{L}_L$	L_L		6
	$\tilde{e}_R^*$	$e_R^\dagger$		3
B boson, bino		$\tilde{B}$	B	1
W boson, wino		$\tilde{W}$	W	3
gluon, gluino		$\tilde{g}$	g	8



1. 107 unknown SUSY parameters
2. 19 original, 4 new SM-sector params

LSP
$\tilde{\chi}_1^0 = N11 \cdot \tilde{B}^0 + N12 \cdot \tilde{W}^0 + N13 \cdot \tilde{H}_u^0 + N14 \cdot \tilde{H}_d^0$

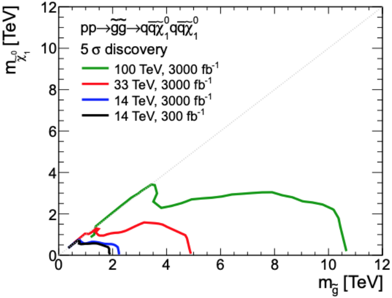
total: 130 free parameters

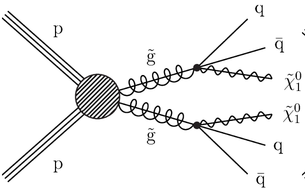
Simplified models

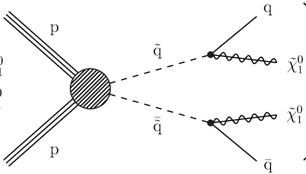
SNOWMASS 2013: A Comparison of Future Proton Colliders Using SUSY Simplified Models: A Snowmass Whitepaper
https://arxiv.org/pdf/1310.0077.pdf

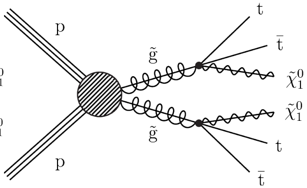
1. previous meetings established a set of simplified models (SMS's) to standardize the sensitivity evolves over time
2. T1qqqq: $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$
3. T2qq: $\tilde{q} \rightarrow q\tilde{\chi}_1^0$
4. T1tttt: $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$

SNOWMASS 2013 Whitepaper









The phenomenological MSSM

C.F. Berger, et.al: **arXiv:0812.0980**

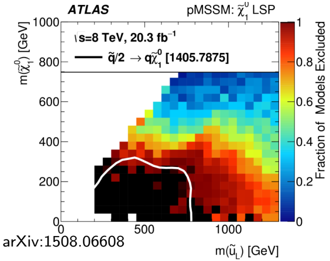
Idea: reduce the MSSM dimensionality but preserve phenomenology
4 assumptions:

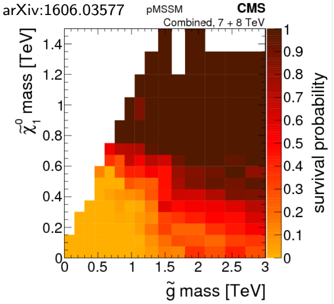
1. no flavor changing neutral currents;
2. no new CP-violating terms, no tachyons;
3. first and second generation sfermions masses degenerate;
4. the lightest superpartner is a neutralino.

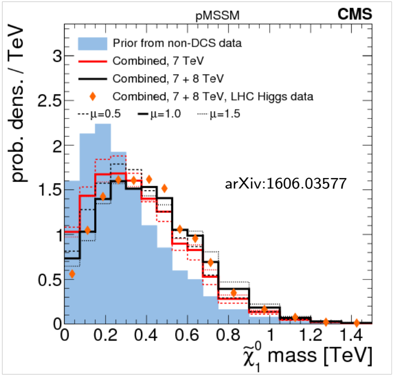
leaves 130→19 unknown free parameters, 19 SM parameters in pMSSM:

- **3** gaugino mass parameters M_1, M_2, and M_3;
- **1** Higgsino mass parameter μ and **1** pseudo-scalar Higgs mass m_A;
- **10** sfermion mass parameters $m_{\tilde{f}}$, $\tilde{f} = \tilde{Q}_1, \tilde{U}_1, \tilde{D}_1, \tilde{L}_1, \tilde{Q}_3, \tilde{U}_3, \tilde{D}_3, \tilde{L}_1, \tilde{E}_3$;
- **3** trilinear couplings A_t, A_b, and A_τ; and
- **1** VEV ratio $\tan(\beta) = \mathrm{VEV}_A/\mathrm{VEV}_h$.

Run 1 results by CMS and ATLAS







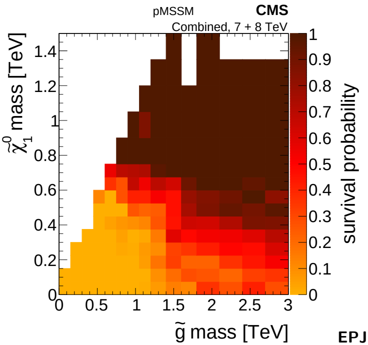
- survival probability based on frequentist exclusion
- marginalized prior/posterior probability densities

- Run 2 results of all-hadronic jets+E_T^{miss} search interpreted

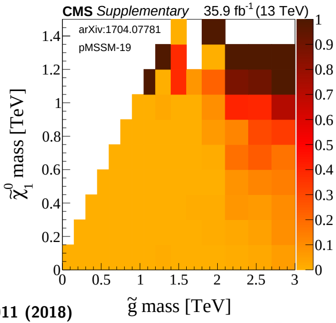
  →**arXiv:1704.07781**

- results based on 2016 data, scan of 7200 pMSSM points

Run 1 combination



Run 2 multi-jet+E_T^{miss}



EPJ Web 182, 02011 (2018)

Run 2 plans

- perform a new scan over the pMSSM parameter space
- sample a large number of points for usably high density
- extend the reach in terms of mass (for a long-lasting scan)
- cover and emphasize interesting regions and pheno
- incorporate inclusive and targeted analyses
- make Bayesian and frequentist interpretations
- provide useful feedback for theorists

New scan over the parameter space

Run 1

$$
\begin{aligned}
-3 \leq & \; M_1, M_2, \mu \; \leq 3\,TeV, \\
0 \leq & \; \tilde{L} \; \leq 3\,TeV, \\
0 \leq & \; m_{\mathrm{A}} \; \leq 3\,TeV, \\
0 \leq & \; M_3, \tilde{q} \; \leq 3\,TeV, \\
2 \leq & \; \tan\beta \; \leq 60, \\
-7 \leq & \; A_{\mathrm{t,b},\tau} \; \leq 7\,TeV,
\end{aligned}
$$

Run 2

$$
\begin{aligned}
-4 \leq & \; M_1, M_2, \mu \; \leq 4\,TeV, \\
0 \leq & \; \tilde{L} \; \leq 4\,TeV, \\
0 \leq & \; m_{\mathrm{A}} \; \leq 4\,TeV, \\
0 \leq & \; M_3, \tilde{q} \; \leq 10\,TeV, \\
2 \leq & \; \tan\beta \; \leq 60, \\
-7 \leq & \; A_{\mathrm{t,b},\tau} \; \leq 7\,TeV,
\end{aligned}
$$

- throw millions of random points in this subspace
- compute the spectrum with Spheno (arXiv:hep-ph/0301101)
- accept points according to likelihood based on pre-Run2 results (MCMC)

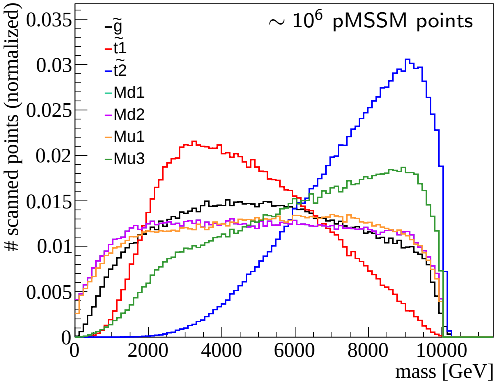
  → DM observables not used in likelihood to allow more generic studies
  → density of points approximates a posterior density

Scan the parameter space

Run 2

$$-4 \leq M_1, M_2 \leq 4\,TeV,$$
$$-4 \leq \mu, \tilde{L} \leq 4\,TeV,$$
$$0 \leq m_{\mathrm{A}} \leq 4\,TeV,$$
$$0 \leq M_3, \tilde{q} \leq 10\,TeV,$$
$$2 \leq \tan\beta \leq 60,$$
$$-7 \leq A_{t,b,\tau} \leq 7\,TeV,$$

SU(3) masses



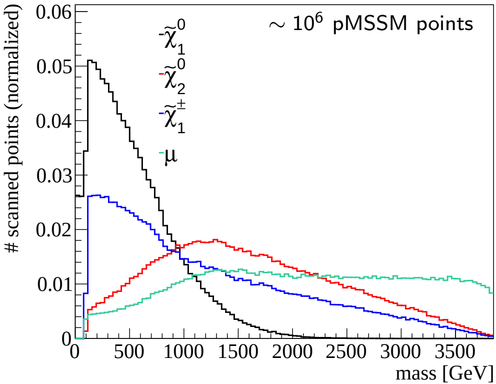
Malte Mrowietz

Scan the parameter space

Run 2

$$-4 \leq M_1, M_2 \leq 4\,TeV,$$
$$-4 \leq \mu, \tilde{L} \leq 4\,TeV,$$
$$0 \leq m_A \leq 4\,TeV,$$
$$0 \leq M_3, \tilde{q} \leq 10\,TeV,$$
$$2 \leq \tan\beta \leq 60,$$
$$-7 \leq A_{t,b,\tau} \leq 7\,TeV,$$

electroweak parameters



Malte Mrowietz

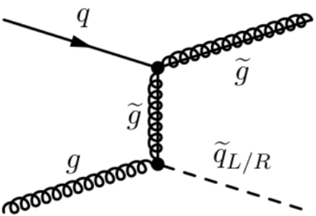
Perks of new range choices

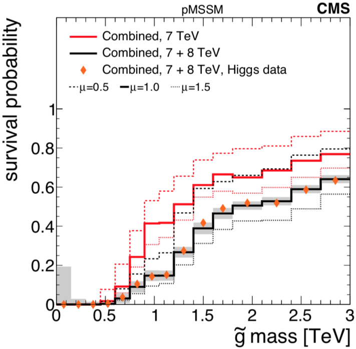
- squark/gluino decoupling limit better covered
- often correct Higgs boson mass
- 1 TeV higgsinos abundant
- more emphasis on electroweak production
- long-lived electroweakinos, staus, stops

Perk: squark/gluino decoupling limit

- in Run 1, the gluino was not heavy enough to have no impact

  →almost not necessary due to the natural range of values





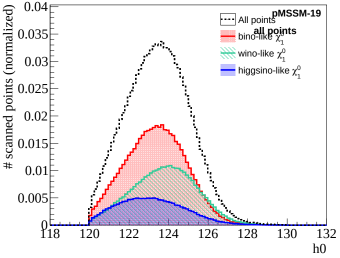
- extending $m(\tilde{g}), m(\tilde{q})$ from 3→10 TeV for better coverage
- this will also emphasize EWK production modes over squark/gluino

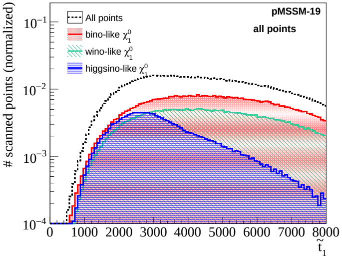
Perk: Higgs mass

- m_h not a free parameter in the MSSM (or pMSSM)
- window cut placed on the Higgs mass: $m_h \in [120, 130]$ GeV

  $\rightarrow$almost not necessary due to the natural range of values
- heaviness of Higgs boson (∼125 GeV) associated largely with heavier stops

$$m_{h^0}^2 \sim m_Z^2 \cos^2 2\beta + \frac{3}{\pi^2} \frac{m_{\tilde{t}}^4 \sin^4\beta}{v} log\left(\frac{m_{\tilde{t}}}{m_t}\right)$$





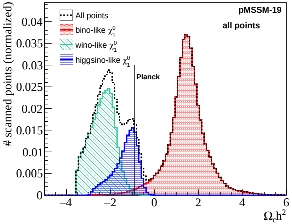
Perk: 1 TeV higgsinos

- 1 TeV higgsinos are known to accomodate DM relic density measured by Planck

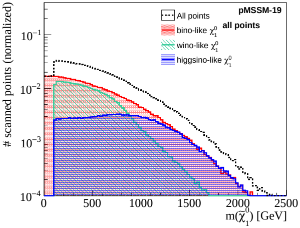
  →**arXiv:1807.06209** (Planck 2018)
  $\Omega_c h^2 = 0.120 \pm 0.001$

  →**arXiv:1507.07446** (K. Kowalska, et. al)

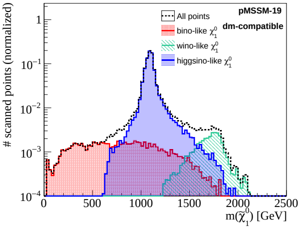
- complimentarity with 1t direct detection experiments



all points



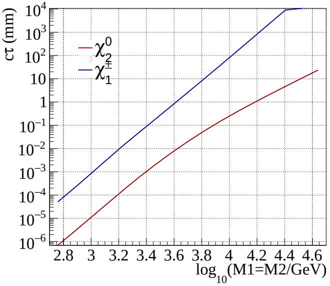
$$\Omega_c h^2 = 0.120 \pm 0.002$$



Perk: long-lived (LL) charginos

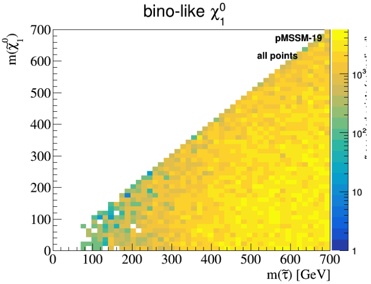
- pure winos give rise to charginos with $c\tau \sim 1$m
  - $c\tau > 10$ cm not covered in Run 1
- pure higgsinos can have micro-displacements

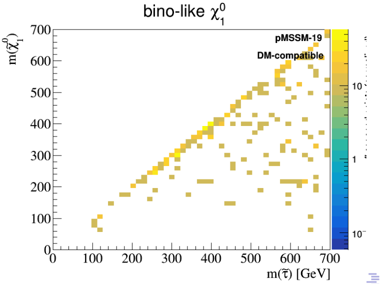
  $\rightarrow$ only for large M1, M2 (right)
- extending $|M_1|, |M_2|$ from 3$\rightarrow$10 TeV for better coverage

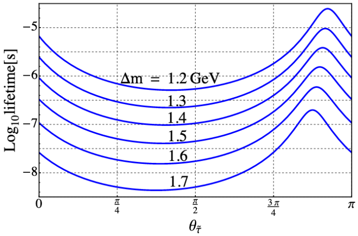


Perk: other long-lived particles

- pure bino scenarios tend to over-predict $\Omega_c h^2$ (low annihilation rates)
- bino-gluino co-annihilation **arXiv:1504.00504**
- stau-, stop-bino co-annihilation **arXiv:1809.10061**
- long-lived $\tilde{g}$s, $\tilde{q}$s, $\tilde{\tau}$s in DM-compatible bino models







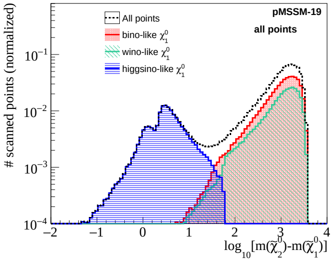
J.Ellis, et.all **arXiv:1404.5061.pdf**

Pick probability for oversampling

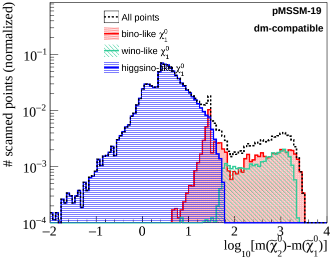
Over-sample regions with

- low fine-tuning
  - ΔEW based on *H. Baer, et.al:* **arXiv:0812.0980**
- relic density-consistency $\Omega_c h^2 = 0.120 \pm 0.002$
- light stops, ...

all points



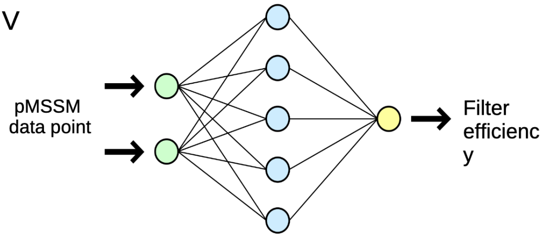
DM-compatible ($\pm 2\sigma$)

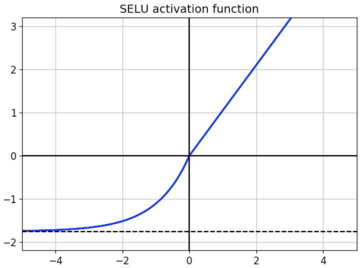


- this over-sampling tends to emphasize compressed regions

Machine learning and the pMSSM

- it is convenient to have fast tools to estimate the likelihood of a model point based on a given search
- a proof of principle with mock signal region typical of an LHC SUSY analysis
- feed forward network used to regress on the model parameters and output the efficiency*acceptance



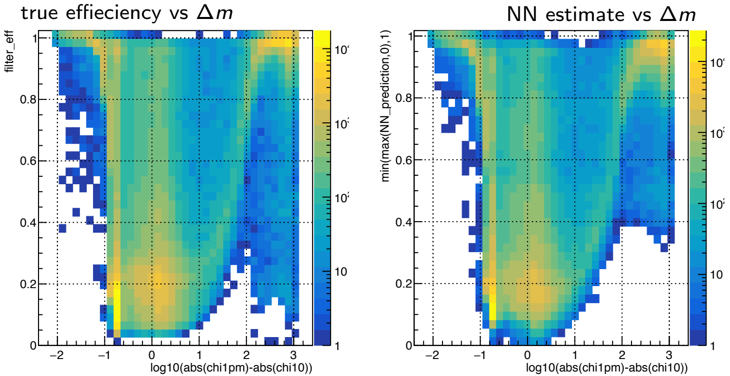


NN trained/developed by Bogdan Wiederspan

Machine learning and the pMSSM

Mock signal region with simulated events for each pMSSM point

- sum of jet transverse mometum $H_T > 140$ GeV; or
- at least one lepton with transverse momentum $p_T > 15, 30$ GeV for el$/\mu$,τ



Bogdan Wiederspan

Larger picture

- we are planning to have a similar but expanded analysis as in Run 1
- more plots dedicated to particular phenomenological features
- smarter sampling which preserves Bayesian interpretation
- hope to incorporate more final states and targeted analyses

Information to provide

- survival probabilities for 1-D and 2-D projections
- prior and posterior probabilities
- SLHA files and likelihoods
- hopefully: estimates of acceptance

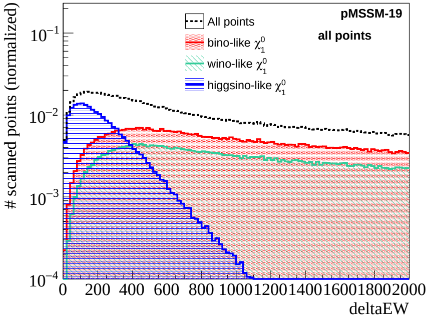
Backup

Impact of DM-compatibility: fine tuning

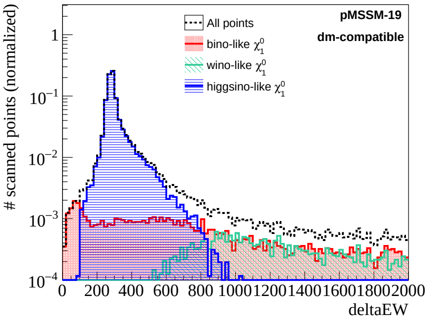
H. Baer, et.al: **arXiv:0812.0980**

Howie Baer's ΔEW

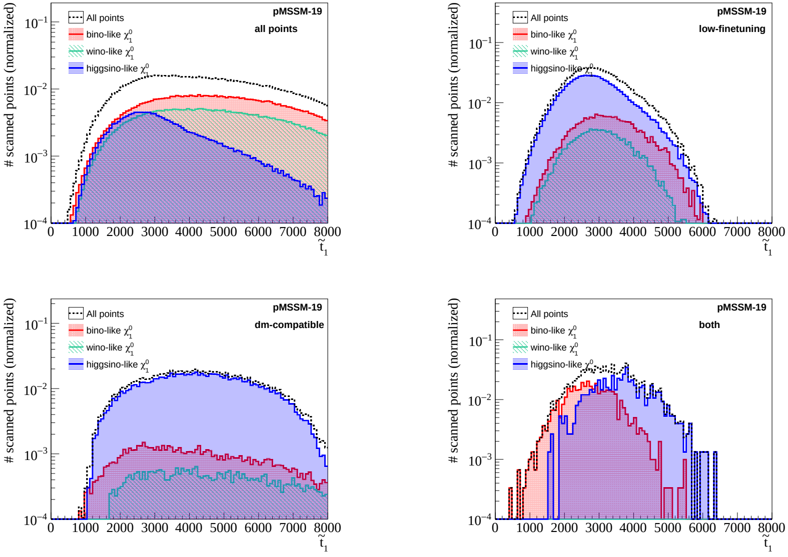
all points



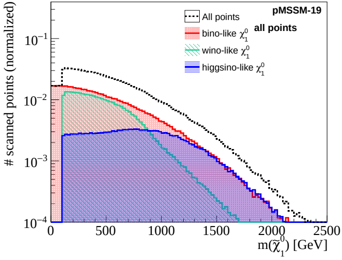
DM-compatible ($\pm 2\sigma$)

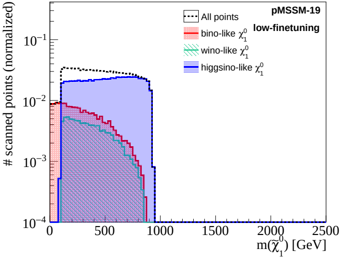


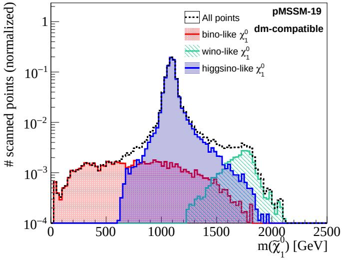
Impact of DM-compatibility and fine-tuning: stop

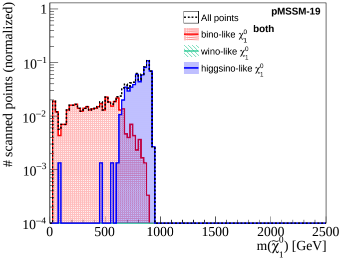


Impact of DM-compatibility and fine-tuning: LSP mass

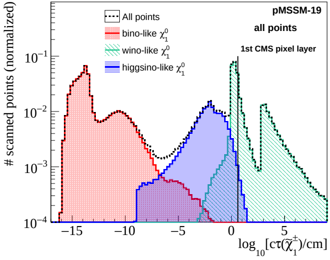


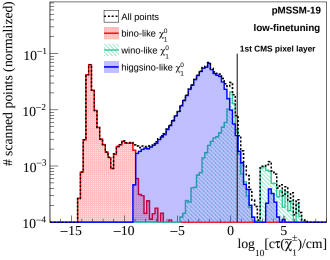


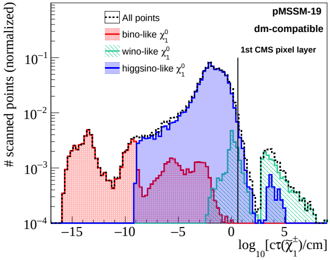


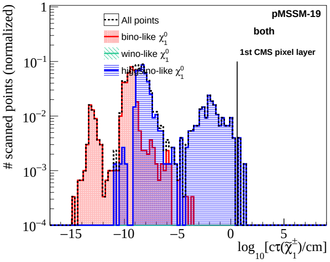


Impact of DM-compatibility and fine-tuning: $\tilde{\chi}^{\pm}$ lifetime

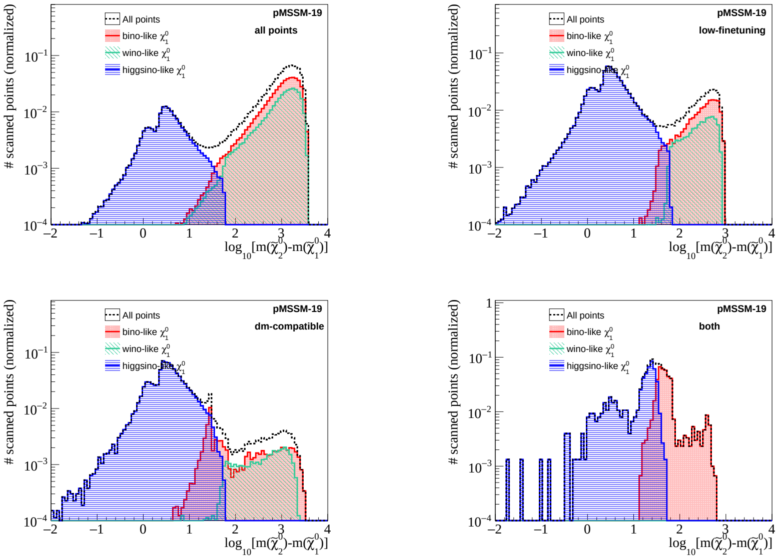




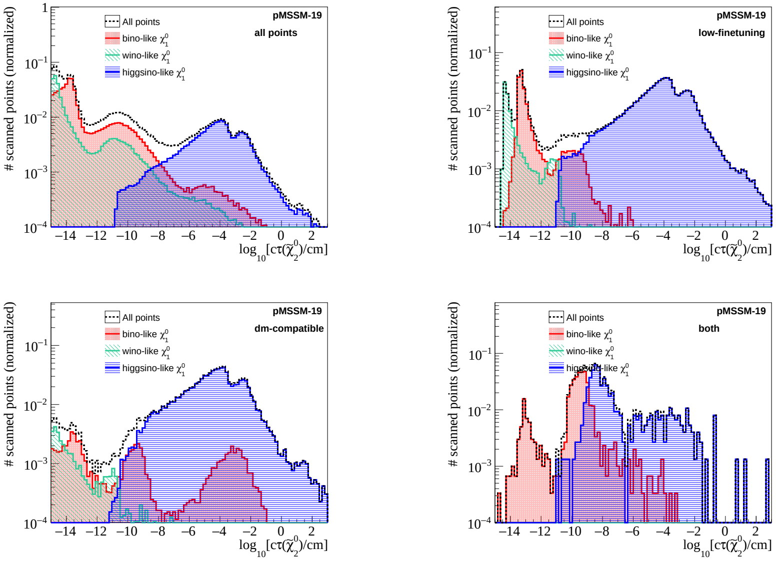




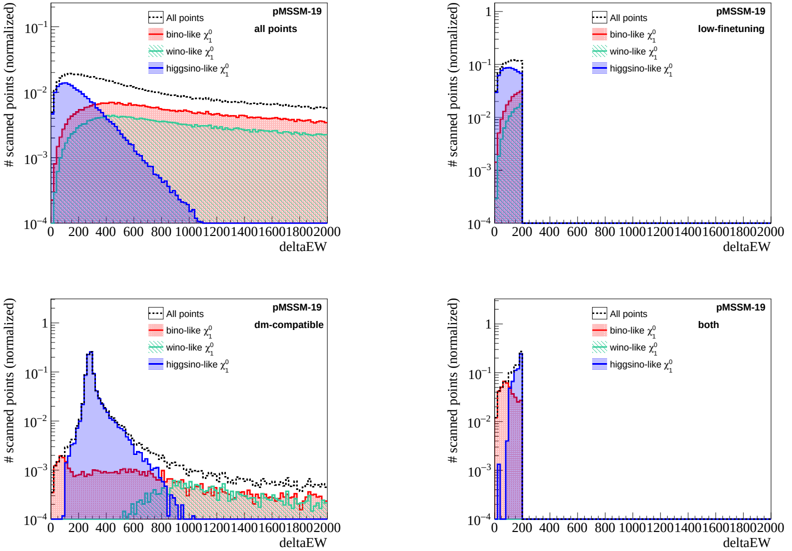
Impact of DM-compatibility and fine-tuning: mass splitting



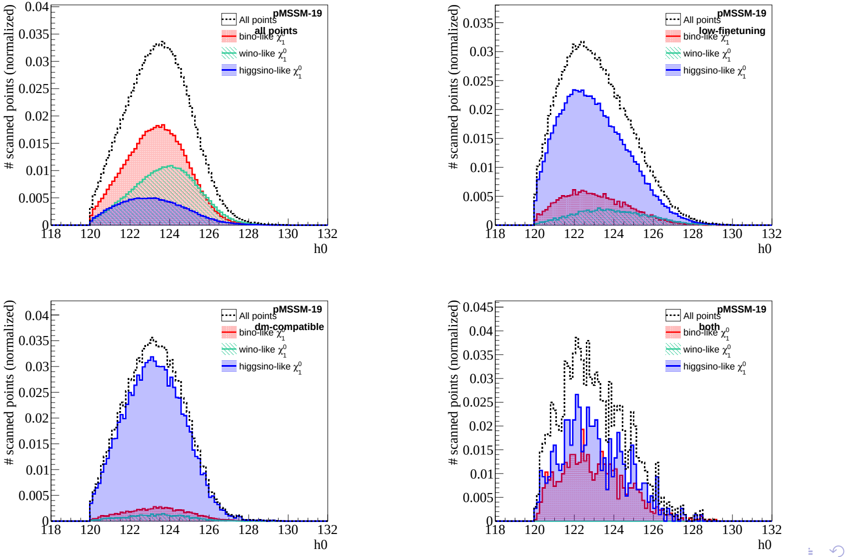
Impact of DM-compatibility and fine-tuning: $\tilde{\chi}_2^0$ lifetime



Impact of DM-compatibility and fine-tuning: deltaEW

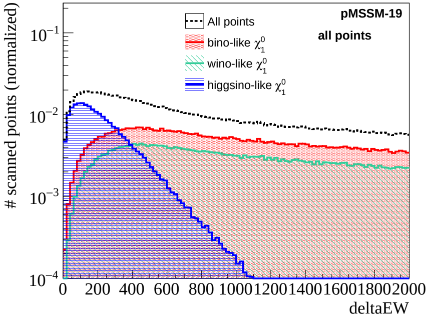


Impact of DM-compatibility and fine-tuning

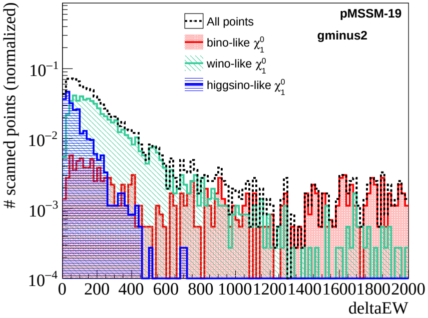


Impact of DM-compatibility: deltaEW

all points

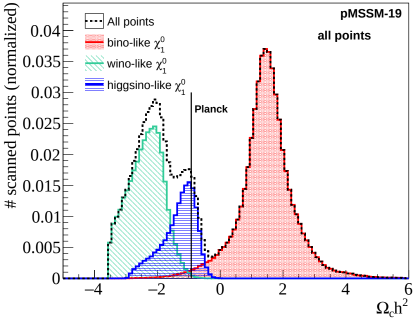


g-2 compatible

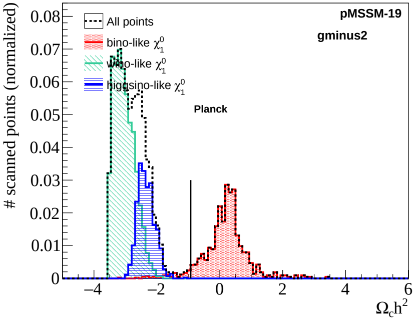


Impact of DM-compatibility: omega

all points

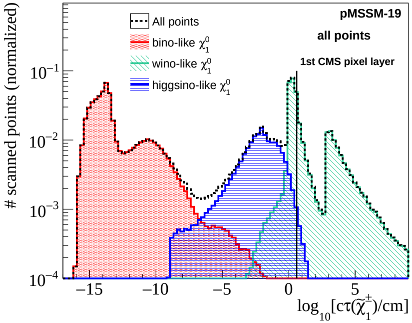


g-2 compatible

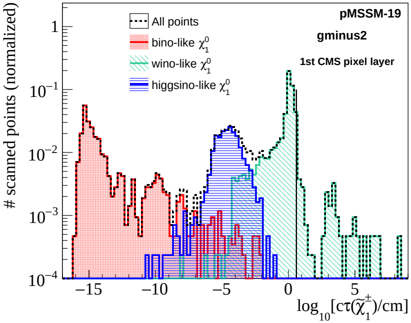


Impact of DM-compatibility: lifetime

all points



g-2 compatible



Supersymmetry and the MSSM

SUSY is used widely for interpretations and designing searches at the LHC; why?

1. naturalness arguments for SUSY at the terascale
2. many SUSY scenarios could explain DM
3. broad set of models to test the reach of analyses, identify gaps in coverage