SUSY-Collider and Dark Matter searches

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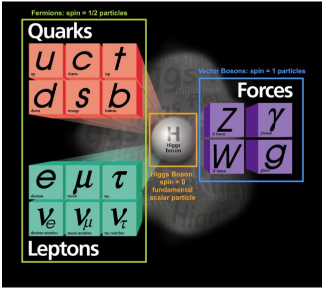
Standard Model versus New Physics

The Standard Model fails to explain:

- Number of fermion families
- *Dark matter and dark energy
- *Mass of the Higgs boson
- *Inclusion of gravity
- *Unification of forces
- *Matter-antimatter imbalance
- Neutrino masses

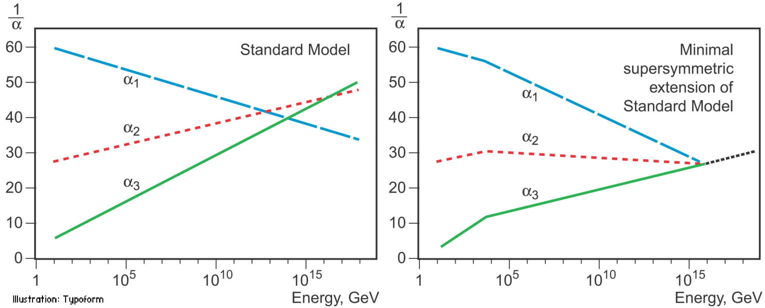


Different models are proposed in order to *solve* these problems

→ **Supersymmetry** could address points indicated with *

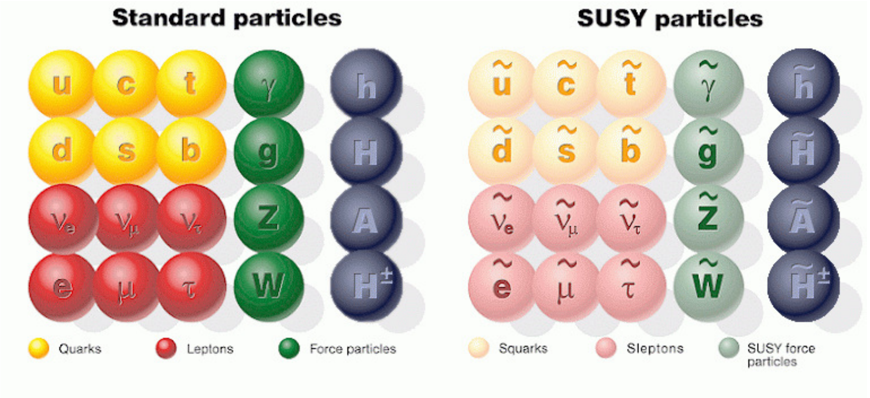
Quick reminder of SUSY

- Invariance under the transformations of fermions to bosons.
  $\Rightarrow$ number of fermions = number of bosons
- R-parity conservation, $R = (-1)^{3B+L+2S}$.
  - B: baryonic number; L: leptonic number; S: spin



Minimal Supersymmetric Standard Model (MSSM)

- Minimal SUSY extension of the SM
- Supersymmetric partners of SM particles + 2 Higgs doublets
- R-parity conserved
- Lightest Supersymmetric Particle stable → good candidate for DM
- Dark matter and unification



Minimal Supersymmetric Standard Model (MSSM)

SUSY provides several Dark-Matter candidates:

- Sneutrino
  - Ruled out in the MSSM because of the current limits on the interaction cross section of dark matter particles with ordinary matter as measured by direct detection experiments
- Lightest neutralino:
  - Bino
  - Higgsino
  - Wino
  - Mixed states of the above
- Gravitino

Problem: MSSM has more than 100 free parameters.

The MSSM

Alternatives:

pMSSM11 (11 parameters)

Pure phenomenological approach (*)

Reasonable assumptions based on current measurements

- squark mass parameters: $m_{\tilde{q}_1} = m_{\tilde{q}_2}, m_{\tilde{q}_3}$
- slepton mass parameters: $m_{\tilde{l}_{1,2}}$, $m_{\tilde{\tau}}$
- gaugino masses: M_1, M_2, M_3
- trilinear coupling: A
- Higgs sector parameters: M_A, $\tan\beta$
- Higgs mixing parameter: μ

subGUT-CMSSM (5 parameters)

Universality at an input scale:

$M_{in} < M_{\rm GUT}$

- input scale: M_{in}
- gaugino mass: $m_{1/2}$
- soft SUSY-breaking scalar mass: m_0
- trilinear mixing parameter: A
- ratio of MSSM Higgs vevs: $\tan\beta$
- Higgs mixing parameter: $\mu > 0$

(*) pMSSM11 is only one of many possible selections. Results will depend on the choice of free parameters.

MasterCode framework

- Frequentist approach to BSM global fits
- Collaborative effort of theorists and experimentalists
- Codes interfaced through SUSY Les Houches Accord (SLHA)

Tools:

- `SoftSusy` : spectrum generator
- `FeynWZ` : electroweak precision observables
- `FeynHiggs` : Higgs sector and $(g-2)_\mu$
- `SuFla` ,`SusyFlavor` and `SuperIso` : B-physics observables
- `Micromegas` and `SSARD`: dark matter relic density
- `SSARD` : spin-independent cross section, σ_p^{SI}
- `SDECAY` : sparticle branching ratios
- `HiggsSignals` and `HiggsBounds`: constraints on the Higgs sector
- + own LHC SUSY search implementation

http://mastercode.web.cern.ch/

Sampling ranges

pMSSM11

Parameter	Range
M_1	(-4 , 4) TeV
M_2	(0 , 4) TeV
M_3	(-4 , 4) TeV
$m_{\tilde{q}}$	(0 , 4) TeV
$m_{\tilde{q}_3}$	(0 , 4) TeV
$m_{\tilde{l}}$	(0 , 2) TeV
$m_{\tilde{\tau}}$	(0 , 2) TeV
M_A	(0 , 4) TeV
A	(-5 , 5) TeV
μ	(-5 , 5) TeV
$\tan\beta$	(1 , 60)

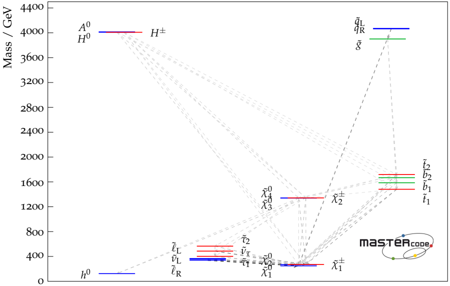
subGUT-CMSSM

Parameter	Range
M_{in}	$(10^3, 10^{16})$ GeV
$m_{1/2}$	(0,6) TeV
m_0	(0,6) TeV
A_0	(-15,10) TeV
$\tan\beta$	(1,60)

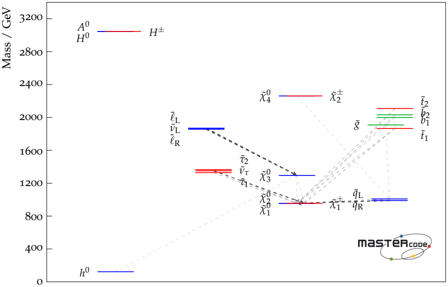
- With and without LHC13; with and without $(g-2)_\mu$
- Sampled a total of 2×10^9 points (pMSSM11) & 112×10^6 points (subGUT-CMSSM)

Best fit points

With $(g-2)_\mu$



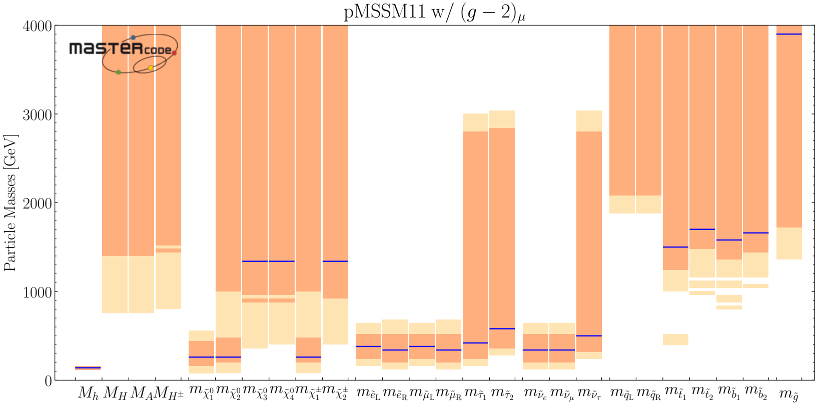
Without $(g-2)_\mu$



- First and second generation sleptons much lighter than third generation
- Heavy Higgses, squarks and gluinos relatively unconstrained
- Sleptons are at less than 1 TeV

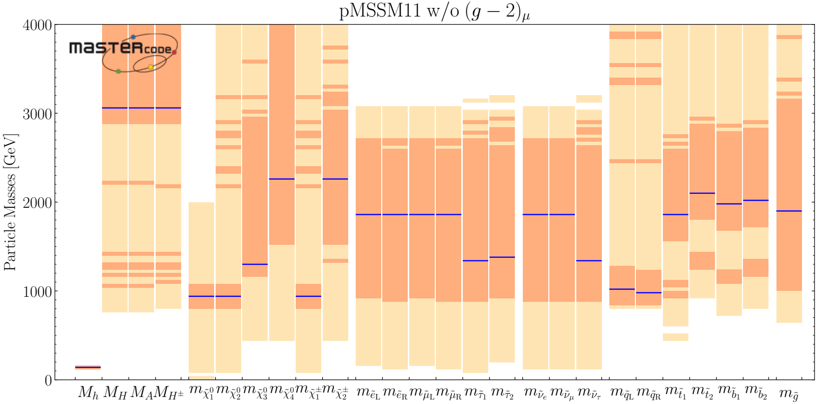
- Heavier spectrum, with two generation squarks around 1 TeV
- Higgs bosons mainly decay to SM particles

Mass spectrum



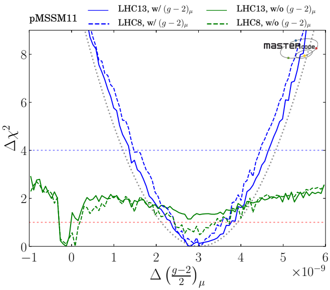
- CL ranges for most particles overlap with ranges accessible for future LHC runs
- Larger freedom allows to fulfill the $(g-2)_\mu$ constraint without being in tension with the LHC searches
- Improved fit with respect to the GUT models (better p-value)
- Best prospects for future colliders: $\tilde\chi^0_1, \tilde\chi^0_2, \tilde\chi^\pm_1$ + 1st and 2nd generation sleptons

Mass spectrum without $(\mathbf{g}-\mathbf{2})_\mu$



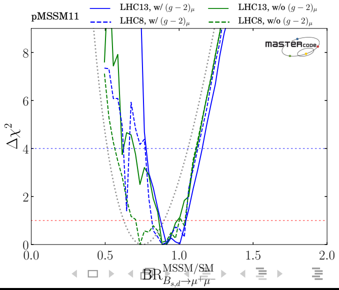
- Heavier neutralino, lighter squarks.
- Reduced parameter range at 68% CL because of slightly improved fit of flavor observables.

pMSSM11 EPJ C78 3 256 (2018)

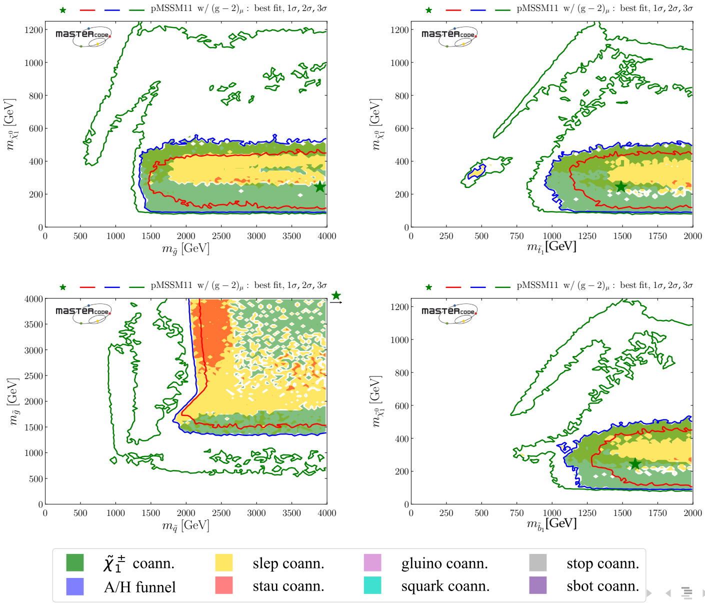


- Experimental value of $(g-2)_\mu$ can be accommodated at 1.5σ level
- Little difference between (not) using LHC13

- Value of $BR(B_{s,d} \to \mu^+\mu^-)^{\text{MSSM}}$ close to the SM value is preferred if both constraints are applied
- $(g-2)_\mu$ dropped: larger range allowed
- Smaller value possible



pMSSM11 EPJ C78 3 256 (2018)



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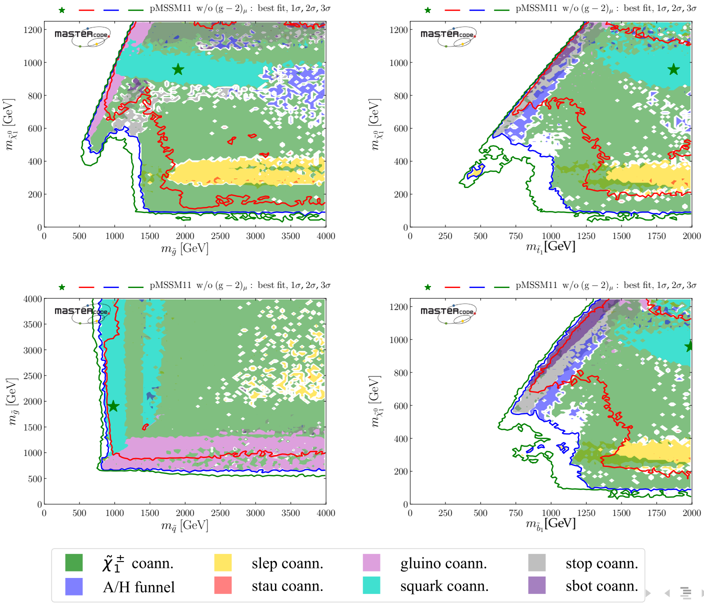
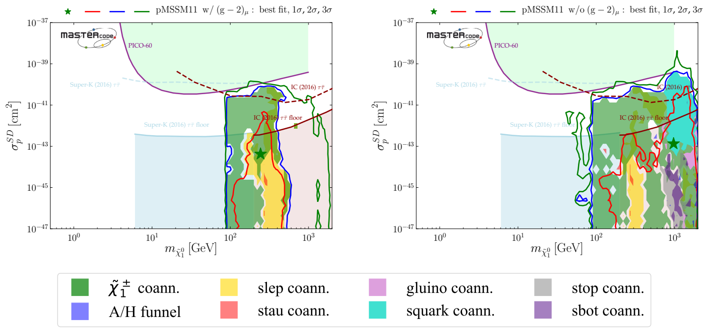


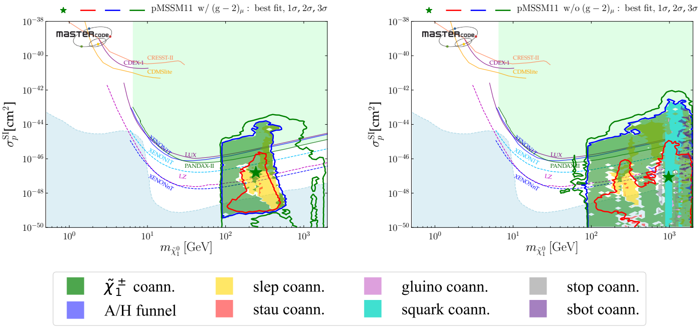
Spin-dependent scattering cross-section



- 95% and 68% CL below the upper limit from PICO
- IceCube constraints relevant only for a minority of points in the sample

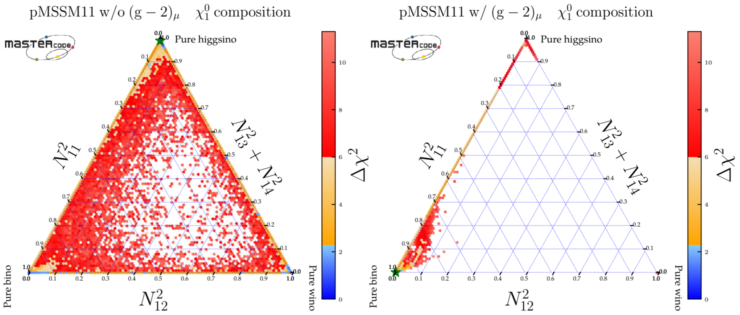
pMSSM11 EPJ C78 3 256 (2018)

Spin-independent scattering cross-section

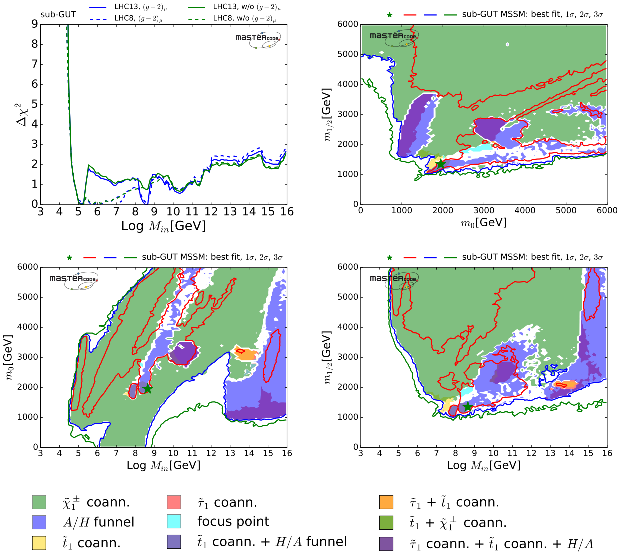


- bfp at the level of the projected sensitivities without $(g-2)_\mu$, higher with $(g-2)_\mu$
- No $(g-2)_\mu$: light higgs funnel/Z funnel/t-channel-stau regions appear at the 2σ and 3σ level

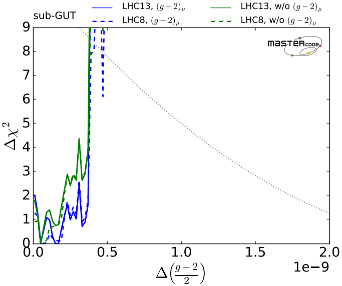
LSP composition



- Without $(g-2)_\mu$: all binary combinations allowed
- With $(g-2)_\mu$: small Wino fraction + unconstrained Bino and Higgsino
- Three-way mixtures disfavoured

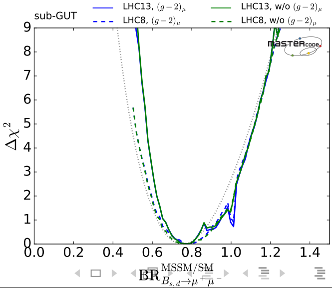


- $M_{in} \simeq 4.2 \times 10^8$ GeV **with** LHC13 and $(g-2)_\mu$; $M_{in} \simeq 5.9 \times 10^5$ GeV **without** LHC13



- Only a small contribution to $(g-2)_\mu$ possible with subGUT models
  - $\tilde{\mu}$ mass more constrained that in GUT-scale CMSSM
- With and without LHC13 and $(g-2)_\mu$ similar

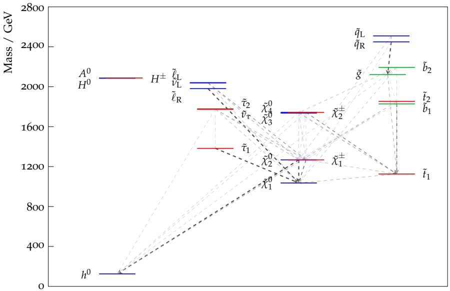
- Values of $BR(B_{s,d} \to \mu^+\mu^-)^{\mathrm{MSSM}}$ smaller than the SM favoured



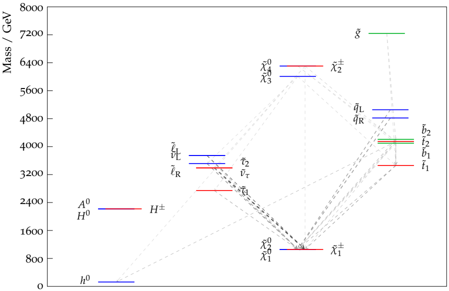
subGUT-CMSSM EPJ C77 2 104 (2017)

Best fit points

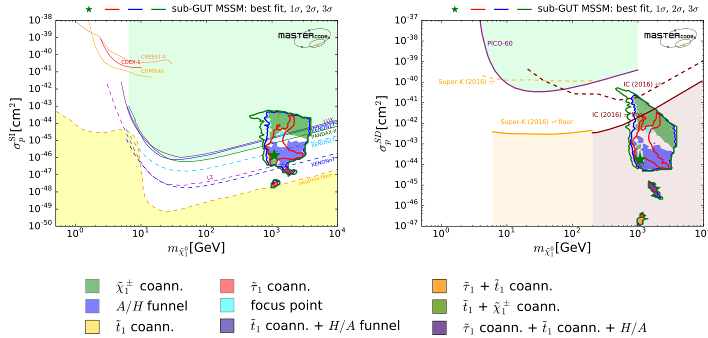
With $(\mathbf{g}-\mathbf{2})_\mu$



Without $(\mathbf{g}-\mathbf{2})_\mu$



- Heavy Higgs bosons decay predominantly to SM final states
- Squarks and gluino beyond the LHC reach
- Sleptons beyond the e^+e^- collider reach
- Best prospects for $\tilde{\chi}_1^\pm, \tilde{\chi}_2^0$ @ CLIC



- Range of $\sigma_p^{\rm SI}$ close to the present limit
- 95% CL contour within the projected reaches
- Range of $\sigma_p^{\rm SD}$ below the present upper limit from PICO

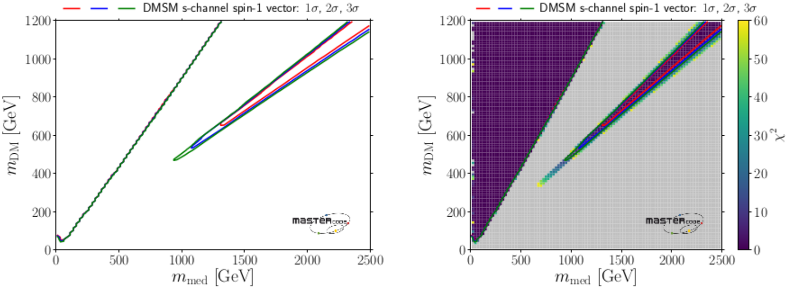
LSP composition:

- Small Wino admixtures ; Bino and Higgsino fractions relatively unconstrained
- With $(g-2)_\mu$: $\sim$ pure Bino; without $(g-2)_\mu$: $\sim$ pure Higgsino

Dark Matter Simplified Models (work in progress)

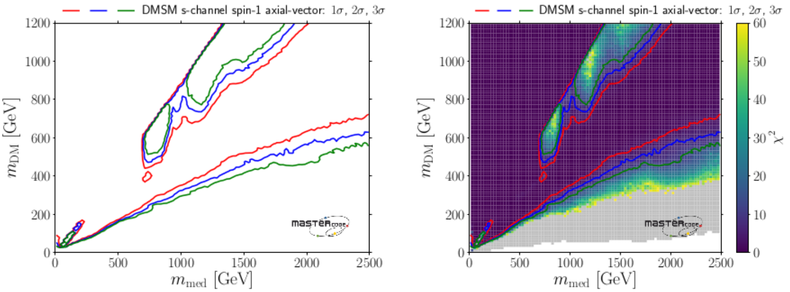
- Growing attention in simplified frameworks motivated by more generic experimental signatures
- **DMSM:** Mediator particle (Y) and its interactions with DM (χ) and SM particles explicitly in the lagrangian
- Bottom-up approach: mediator particle in the LHC mass range
  - Only s-channel mediators, spin-1
  - Dirac fermion
  - Leptophobic interactions
  - **Parameters:** $m_Y, m_\chi, g_{\rm SM}, g_{\rm DM}$
- `MasterCode` framework to study correlations between parameters
  - `MG5_aMC(N)LO`: mediator properties and collider constraints (`DMSIMP` models)
  - `micrOMEGAs`: DM density and scattering calculations
  - **Constraints:** relic density (Planck) + monojet + dijet (CMS)

Vector mediator



- Two regions where the DM constraint can be accommodated
- Low-masses allowed for very small couplings

Axial-vector mediator



- Likelihood function varies less rapidly than before
- Low-masses allowed for very small couplings

Conclusions

- Supersymmetry is a good framework for explaining the origin of Dark Matter & other SM defficiencies
- Studied pMSSM11 and subGUT-CMSSM using $36\mathrm{fb}^{-1}$ + DM constraints
  - Both pMSSM11 and subGUT-CMSSM have shown to provide good candidates for DM
- Studied the interplay between $(g-2)_\mu$ and flavor constraints
- Shown preliminary studies for DMSM from a global perspective
  - Plan to look at more complex models in the future

Stay tuned for more results!