More MasterCode?

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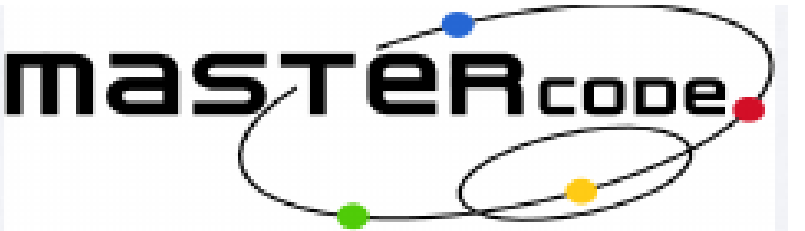
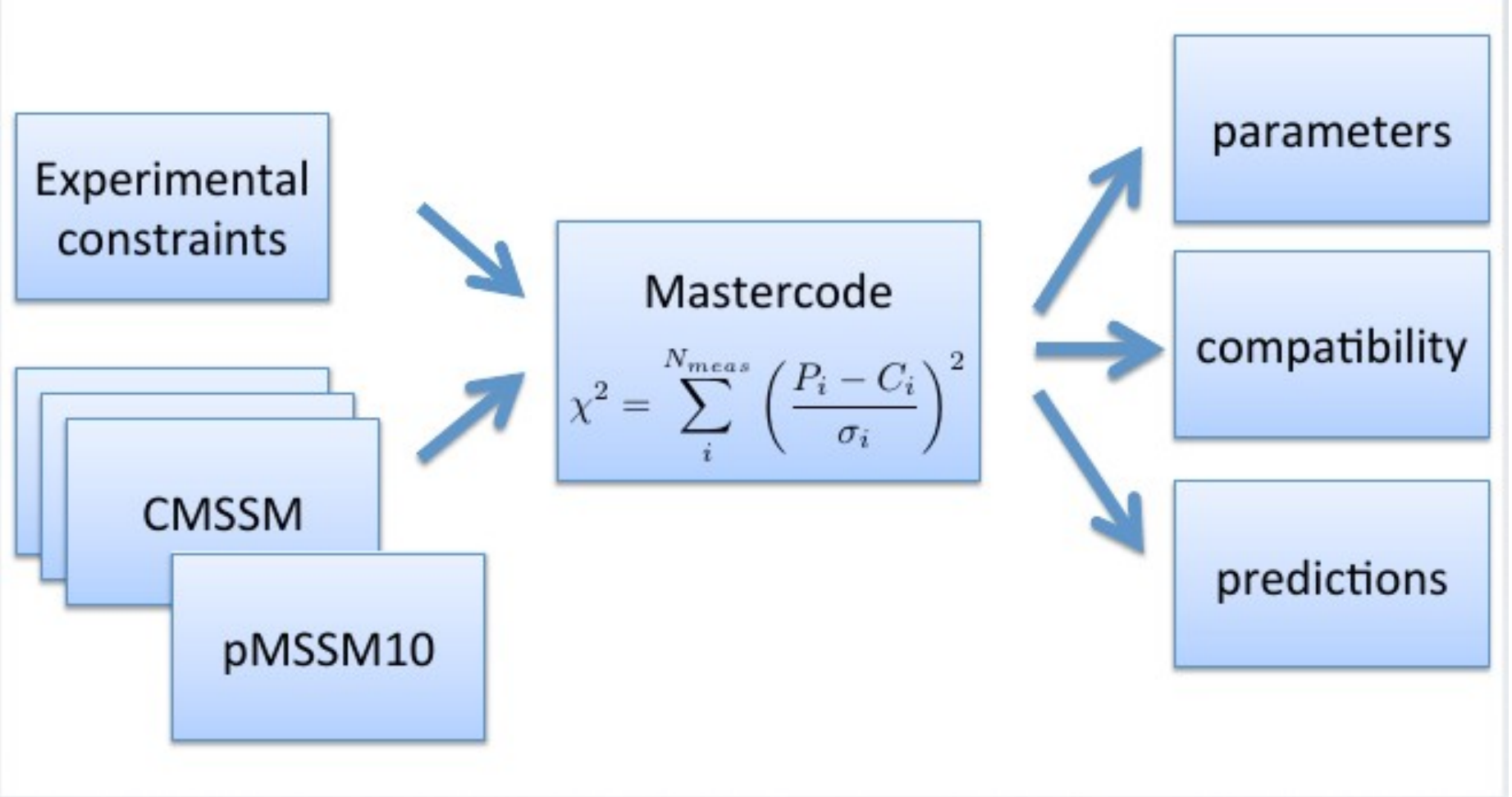
Based on 1504.03260, 1508.01173 and work in progress



Australia: Natural Home of SUSY Fits

The Global Fit Game



Experimental Constraints

We use a suite of constraints from

- Higgs Physics
- Precision Electroweak
- Direct Detection and Cosmology
- Flavour Physics
- LHC SUSY Searches

Softsusy, FEWZ, FeynHiggs, SuFla, SuperIso, MicroMegas, SSARD, HiggsSignals, HiggsBounds, ATOM, Scorpion, Fastlim

Parametrising the PMSSM

- A 10 dimensional avatar of the pMSSM

$$
\begin{aligned}
\text{3 gaugino masses} &: M_{1,2,3}\,, \\
\text{2 squark masses} &: m_{\tilde{q}_1} = m_{\tilde{q}_2} \neq m_{\tilde{q}_3}, \\
\text{1 slepton mass} &: m_{\tilde{\ell}}\,, \\
\text{1 trilinear coupling} &: A\,, \\
\text{Higgs mixing parameter} &: \mu\,, \\
\text{Pseudoscalar Higgs mass} &: M_A\,, \\
\text{Ratio of vevs} &: \tan\beta\,.
\end{aligned}
\tag{1}
$$

- Currently (WIP) looking at an 11D pMSSM
- As above but split slepton masses $m_{\tilde{l}_1} = m_{\tilde{l}_2} \neq m_{\tilde{l}_3}$

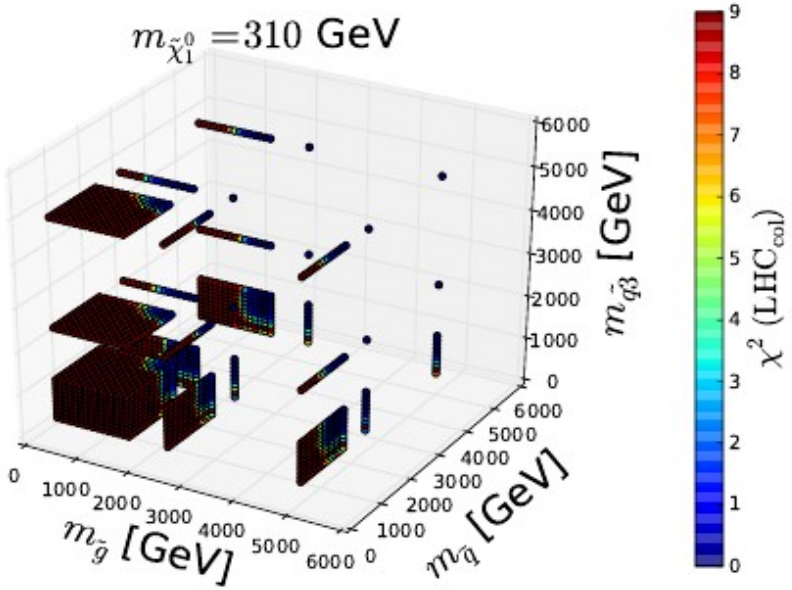
Implementing LHC Searches

O(10^9) points: Point-by-point event generation unfeasible

Interpolation and lookup tables with simplified models

- Coloured searches: 4D grid in $m_{\chi_1^0}, m_{\tilde{g}}, m_{\tilde{q}}, m_{\tilde{q}_3}$
- Stop searches: $\tilde{t} \to b\chi^{\pm}, \quad \tilde{t} \to bW\chi_1^0, \quad \tilde{t} \to b\nu\tilde{\tau}_1, \quad \tilde{t} \to \tilde{c}\chi_1^0$
- Electroweak: $\chi_1^{\pm}\chi_2^0 \,\mathrm{via}\, \tilde{\mathrm{l}}, \quad \chi_1^{\pm}\chi_2^0 \,\mathrm{via}\, \mathrm{W}, \mathrm{Z}, \quad \tilde{\mathrm{l}} \to \mathrm{l}\chi_{1,2}^0\chi_1^{\pm}$

- Greater density of points at low masses for greater accuracy/sensitivity
- 25,564 points used for coloured search grid
- Chi-squared calculated and interpolation used over rest of grid



Implementing LHC Searches

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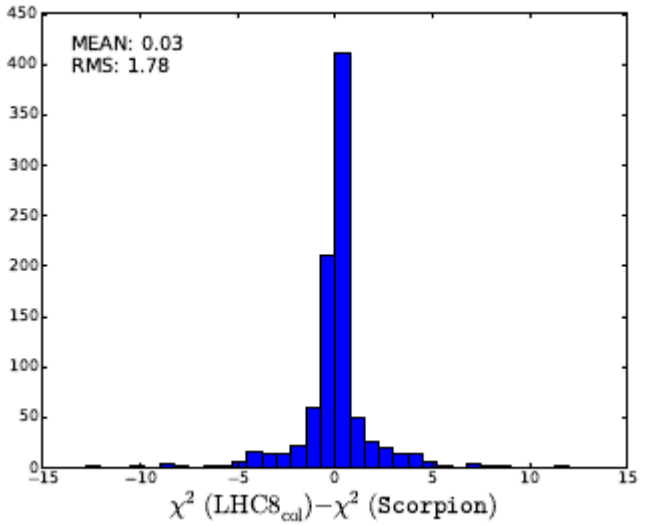
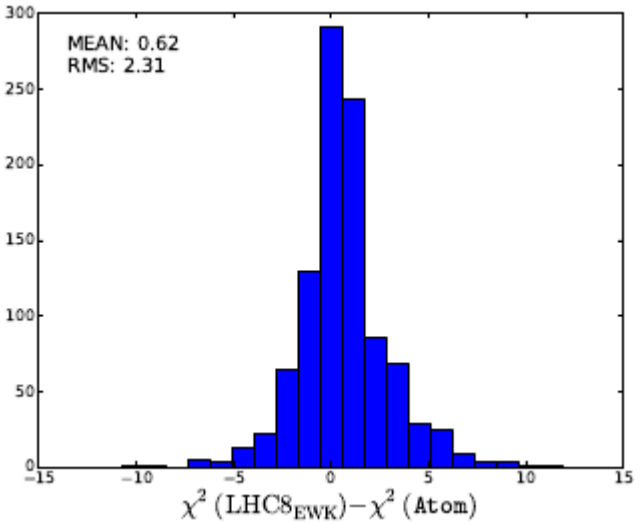
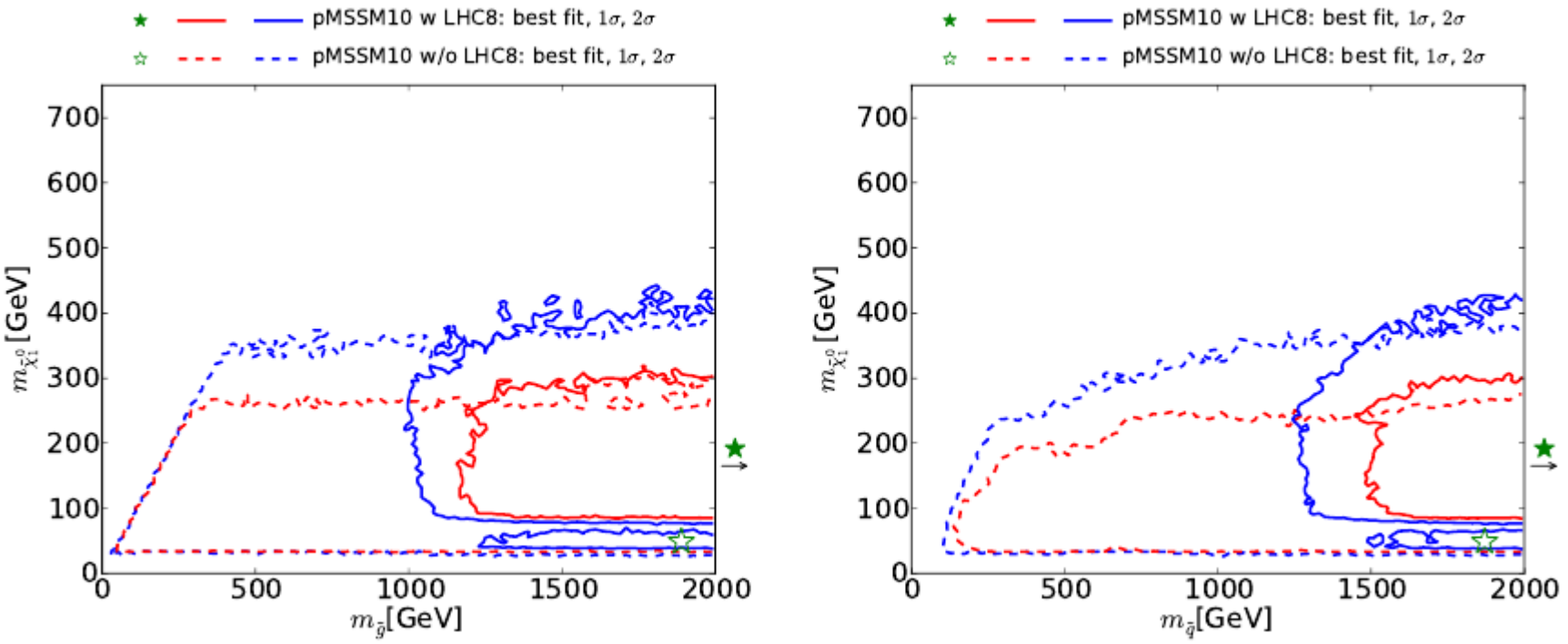




Comparison of chi-squared from interpolation vs ATOM/Scorpion

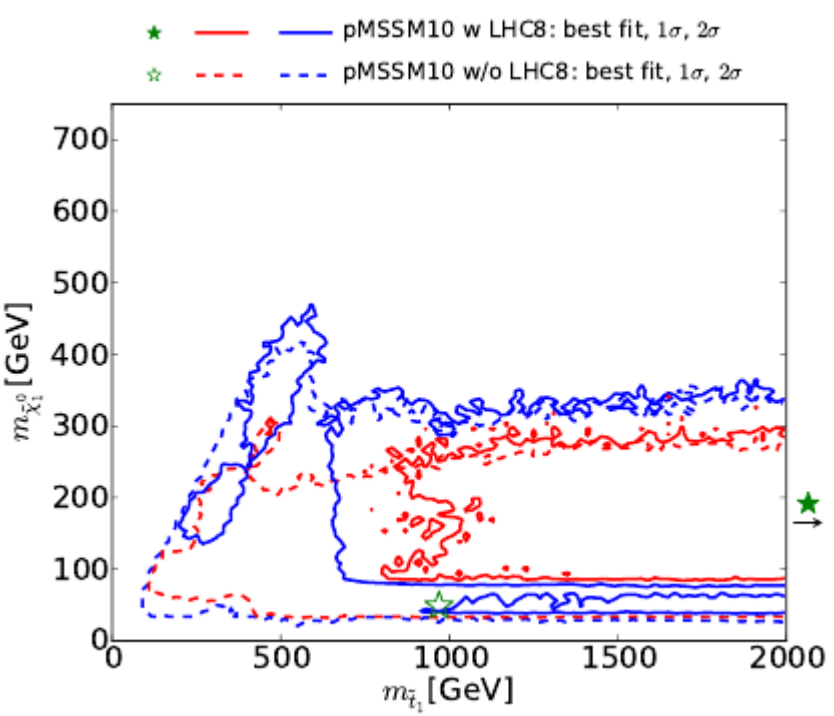
Constraints on pMSSM10

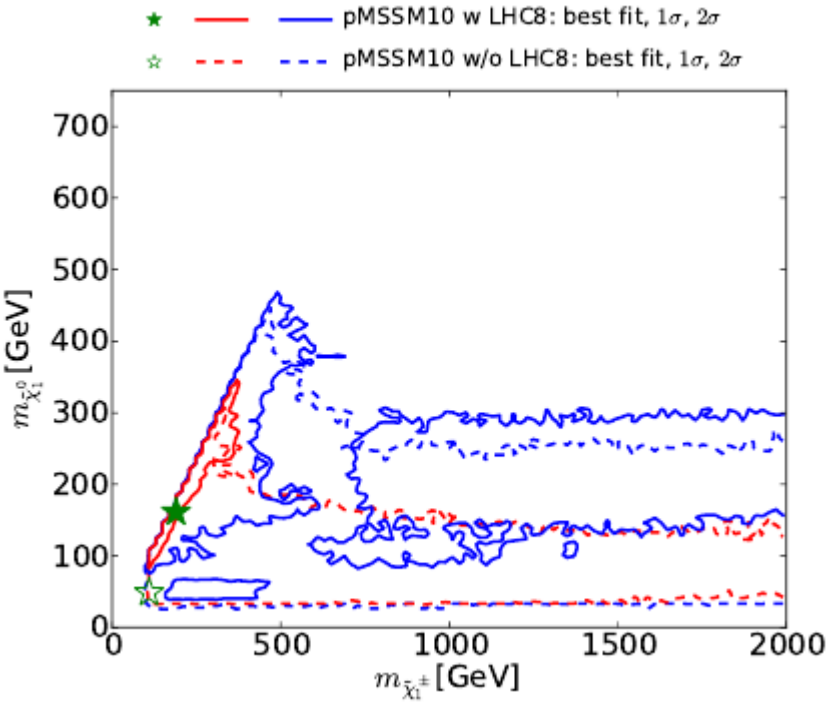
Squark/Gluino – LSP mass planes



Constraints on pMSSM10

Stop/Chargino – LSP mass planes

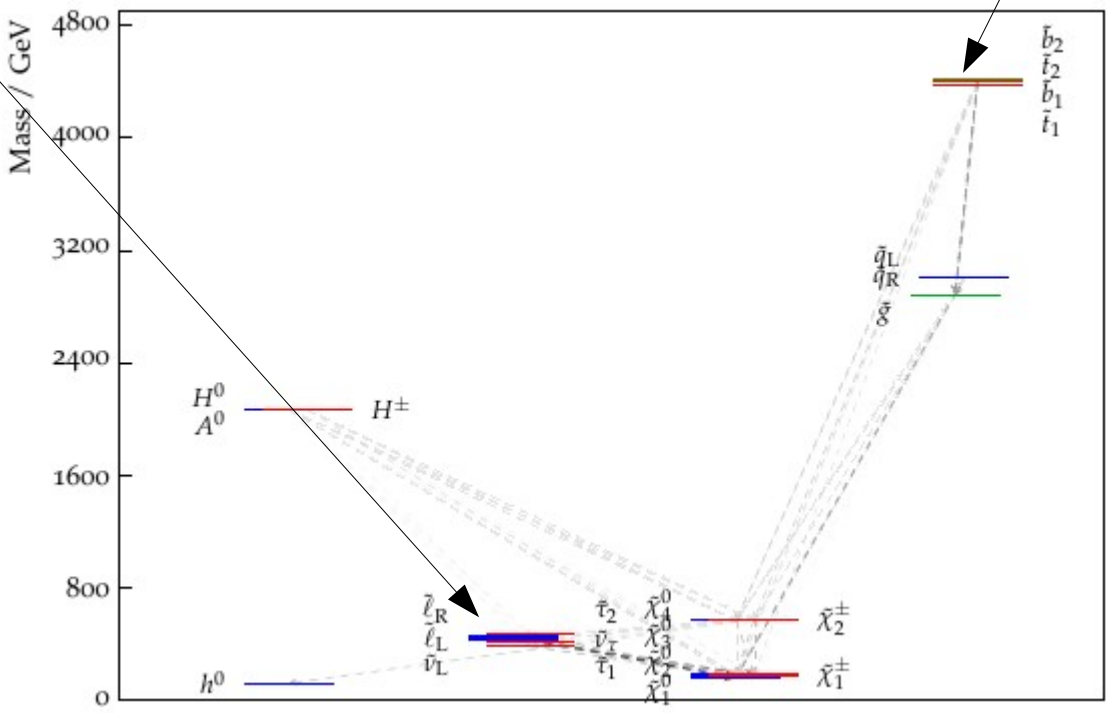




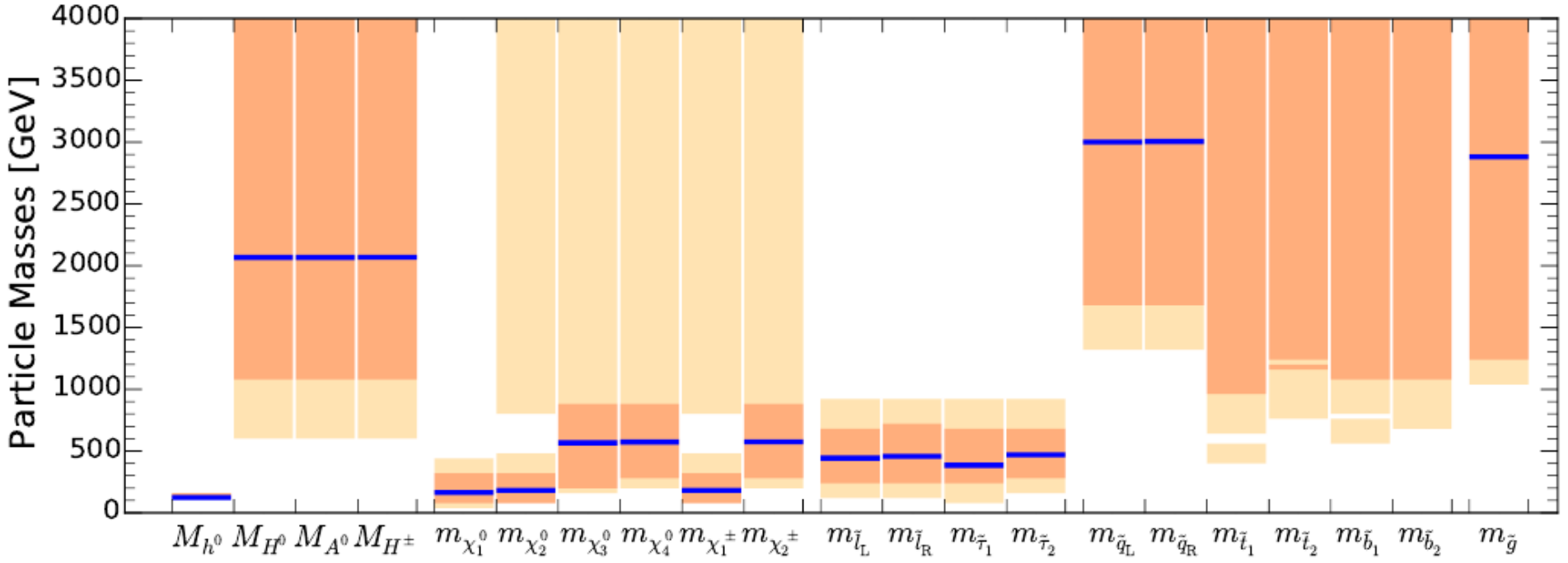
Best-Fit Point Spectrum

Light EW for DM/g-2

Heavy stops for Higgs mass



Predicted Mass Ranges

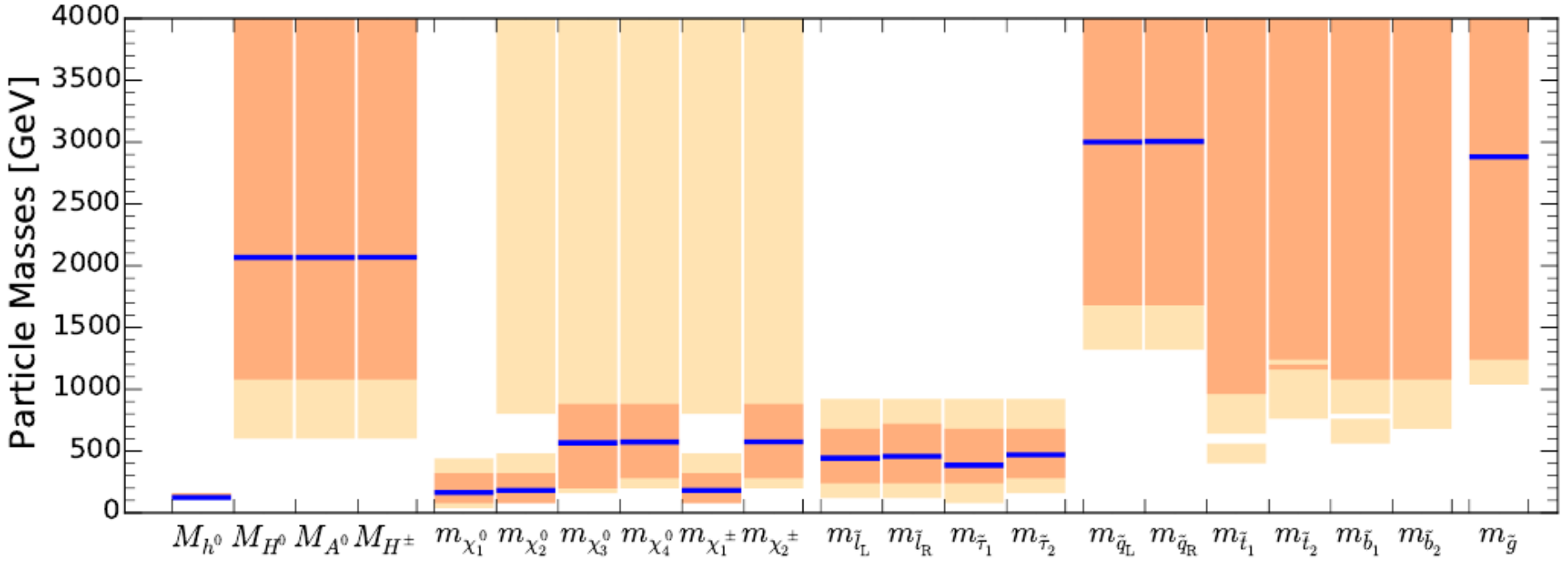


Heavy coloured particles

Heavy Higgses

Light Ewinos and leptons

Predicted Mass Ranges



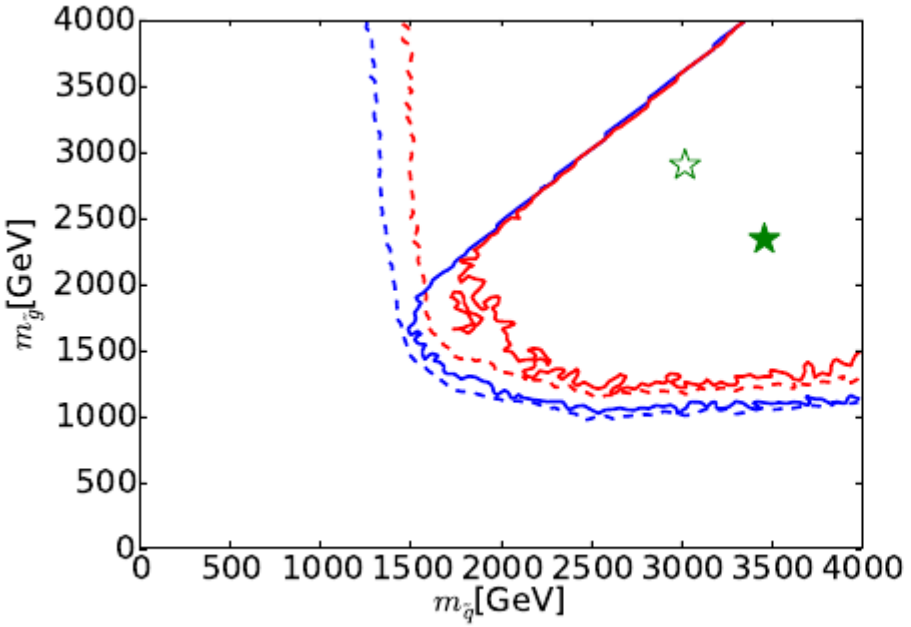
g-2 driving light Ewinos and DM

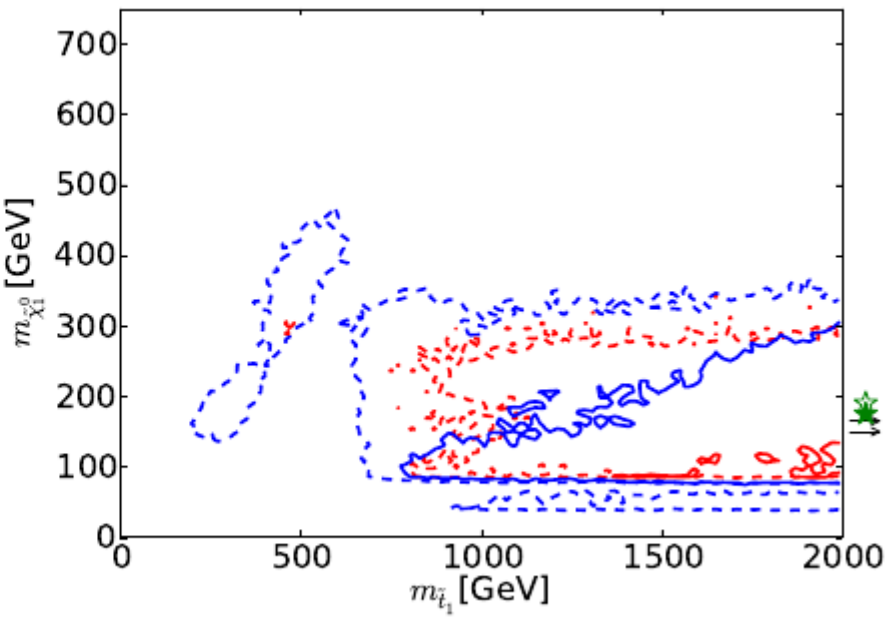
Light coloured states not required by any observables

To rule-out/increase chi^2: target EW states below 1 TeV

Extrapolation to High Scales

- What happens if we run the pMSSM up to the GUT ($2 \cdot 10^{16}$ GeV) scale?
- Impose an anti-tachyon cut $m_0^2 > 0$

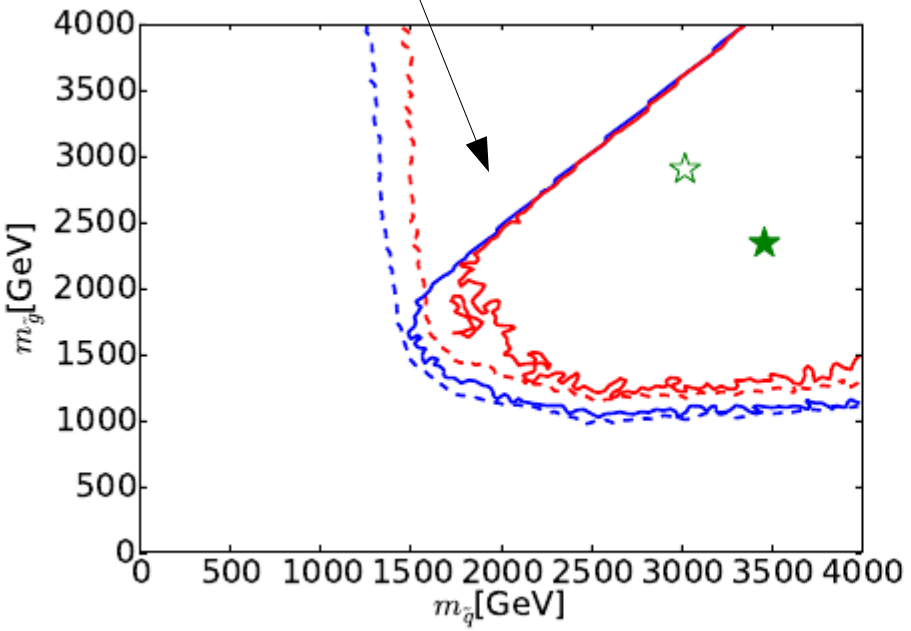




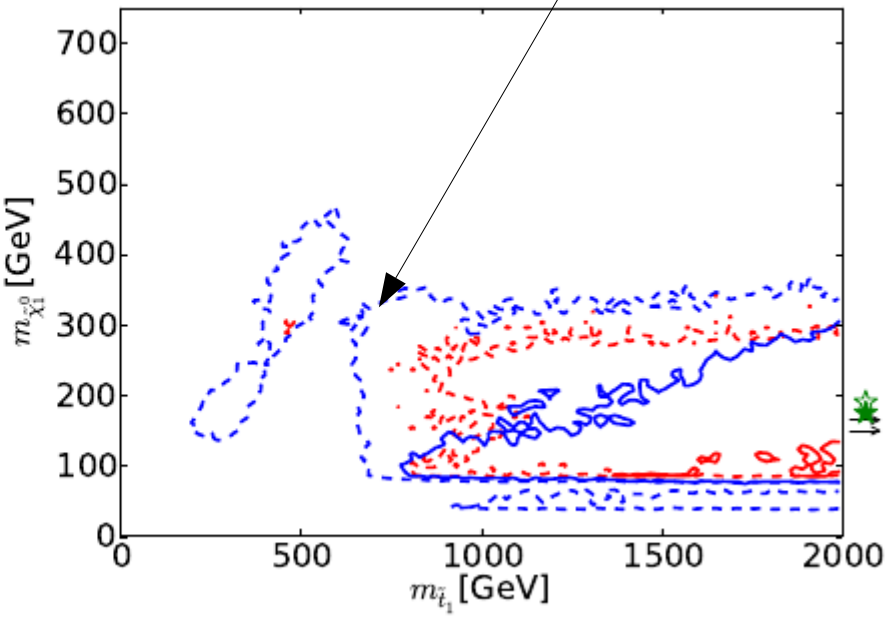
Solid: with cut. Dashed: without cut

Extrapolation to High Scales

Heavy gluino and light squarks not stable RG trajectory



Hard to get hierarchy between stops and gluinos/other squarks



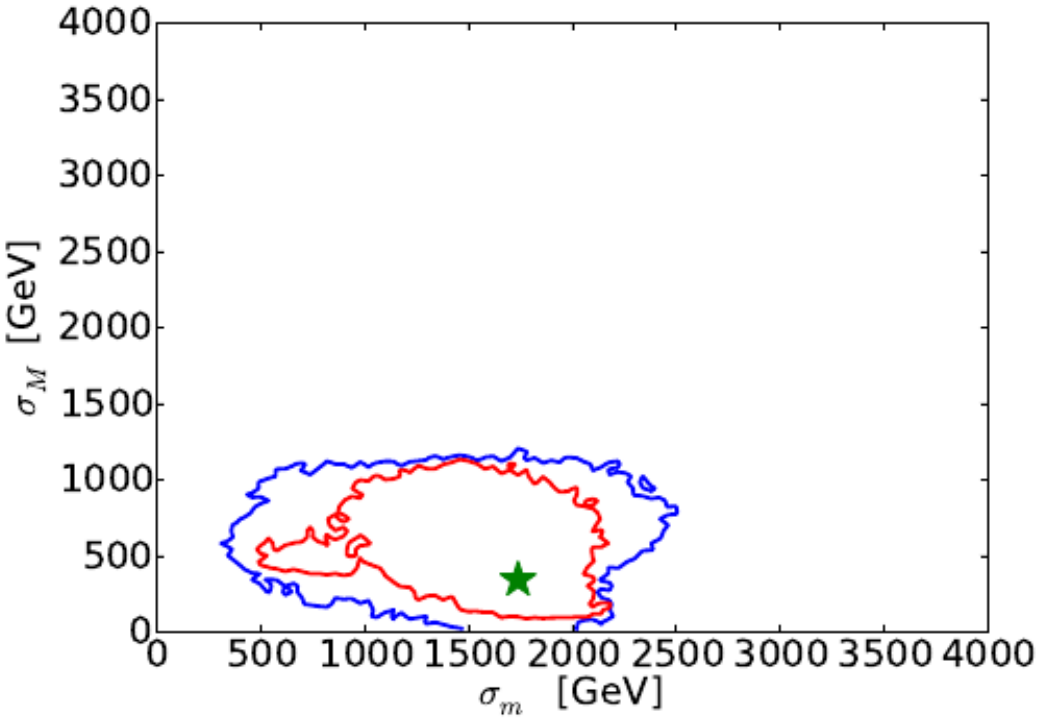
Solid: with cut. Dashed: without cut

Mass Universality

- Run up to GUT scale and ask: how far from soft-breaking universality are we?
- PMSSM10 disfavouring gaugino mass universality

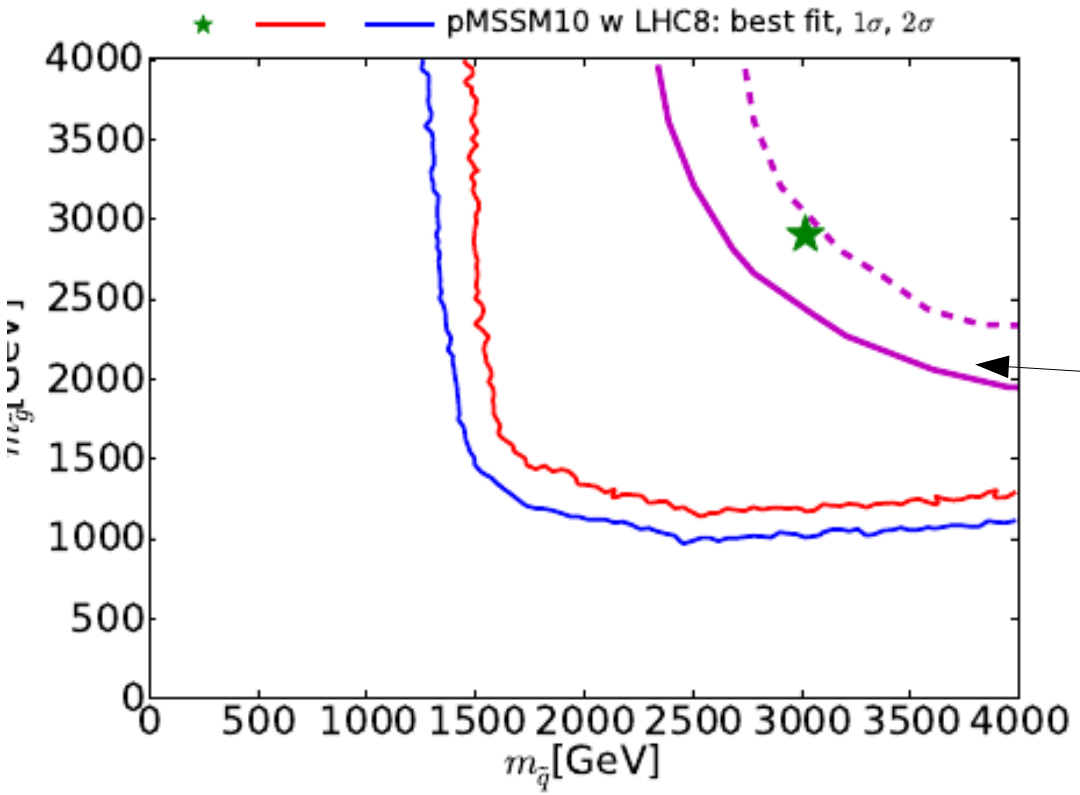
Define RMS deviation of sum over gaugino/ scalar masses

$$\sigma_{M,m} \equiv \sqrt{\sum_i^N (m_i - \bar{m})^2 / N}\,,$$



Future Search Prospects

How much of the best-fit region can we cover at 13/14 TeV?

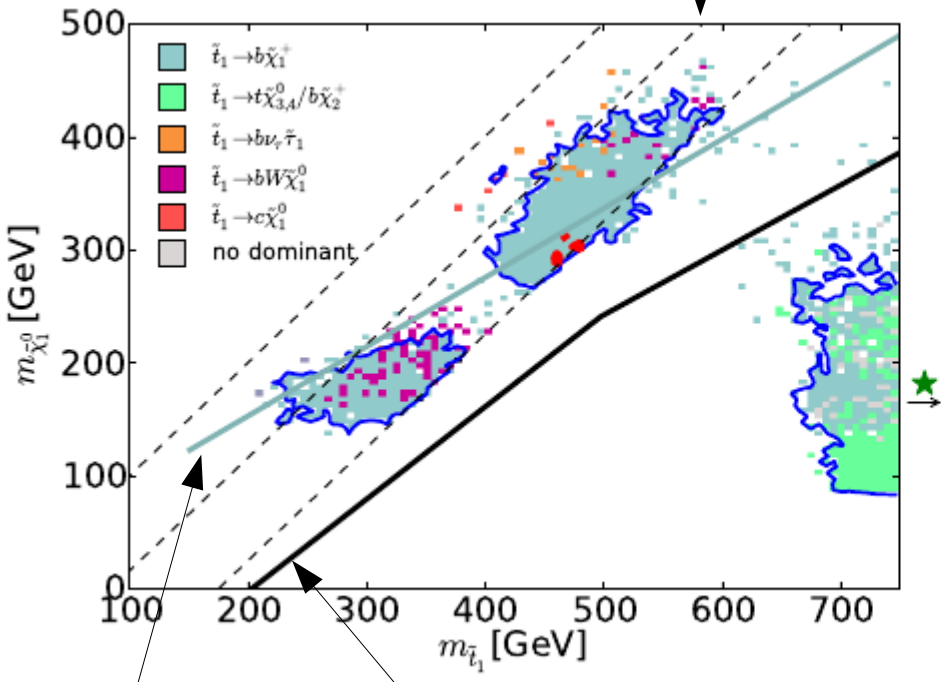


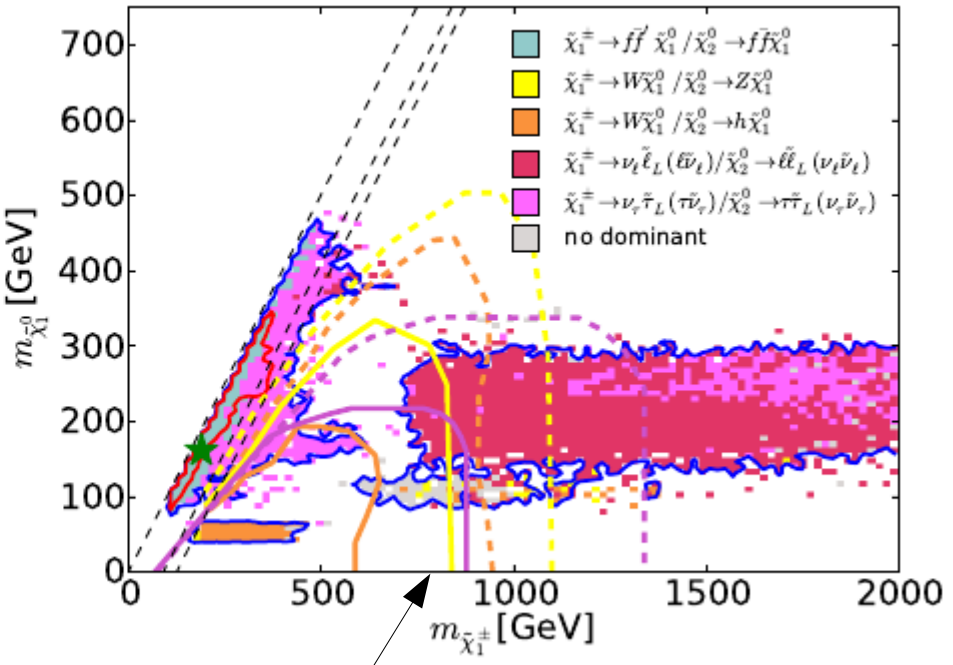
ATLAS 5 sigma discovery and 95% exclusion limits for 300/fb at 14 TeV

Future Search Prospects

Coloured by dominant decay branching ratio

$$\Delta m \equiv m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} = 0, M_W + m_b \text{ and } m_t.$$





$\tilde{t}_1 \to \tilde{\chi}_1^\pm b$
300/fb

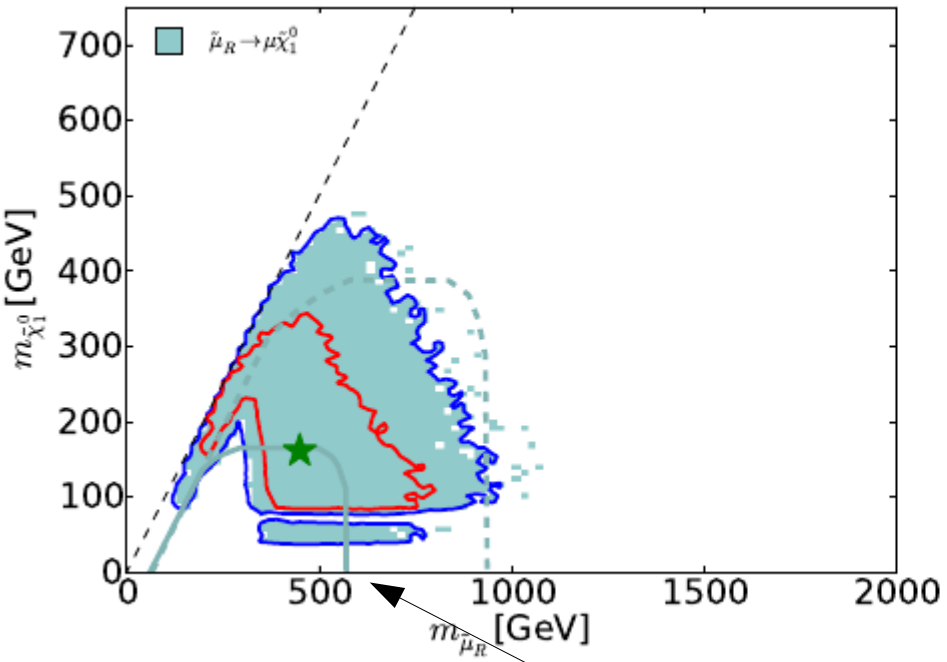
$\tilde{t}_1 \to \tilde{\chi}_1^0 + t$
300/fb

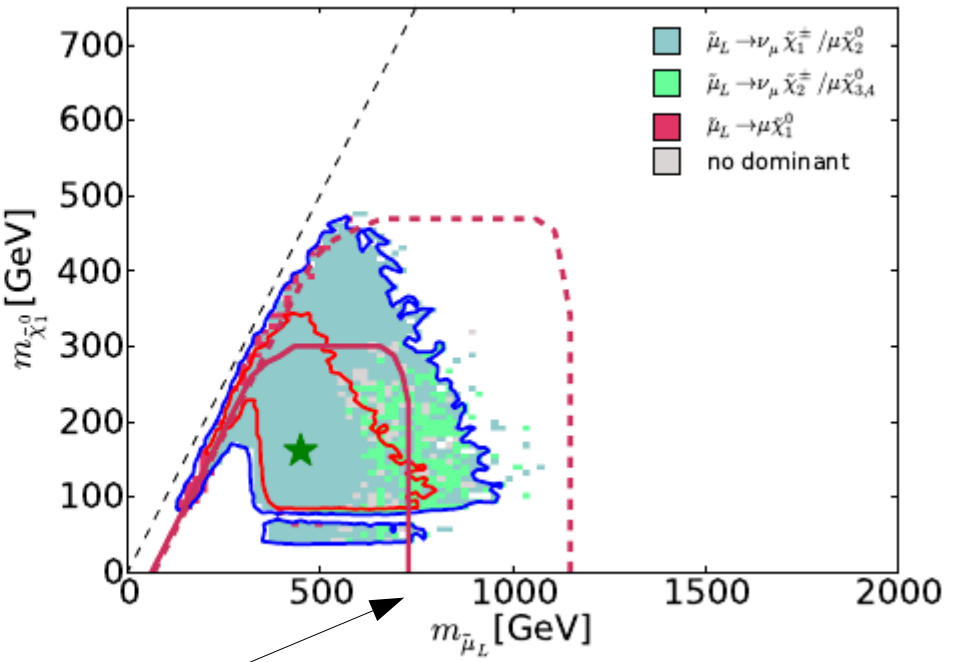
Reach estimates for 300 and 3000/fb

Assume performance is maintained and rescale: Collider Reach

Future Search Prospects

Low smuon masses favoured by g-2 will be probed

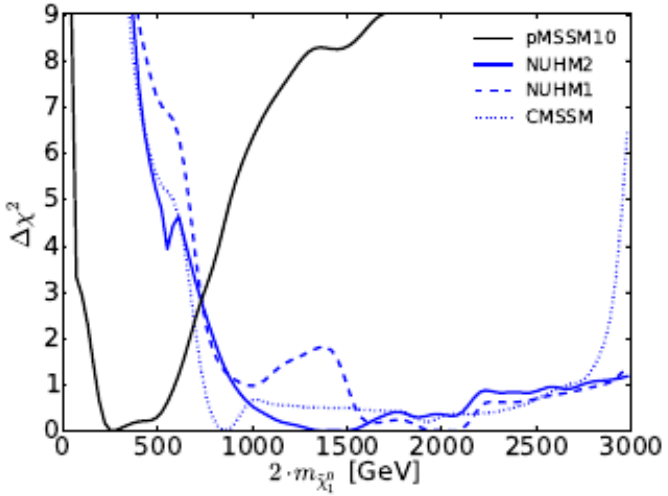


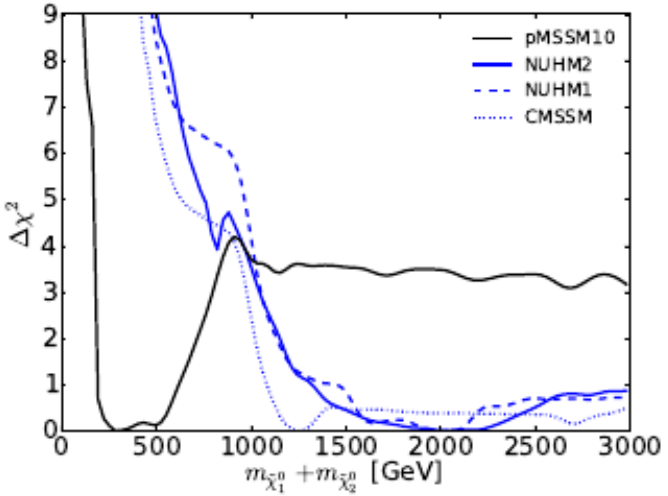


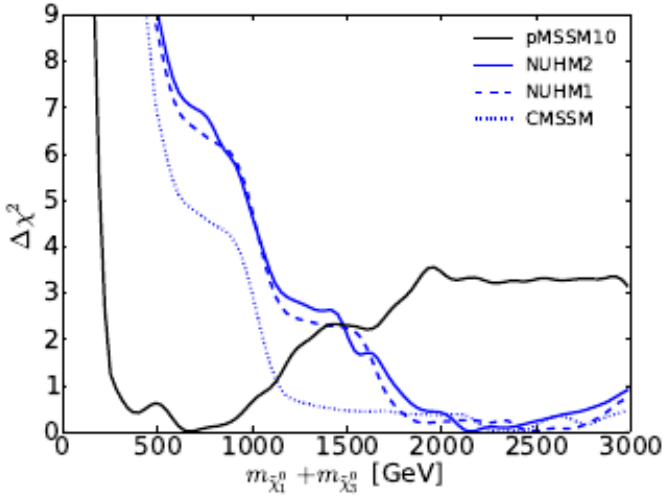
Estimates of smuon search bounds with 300 and 3000/fb

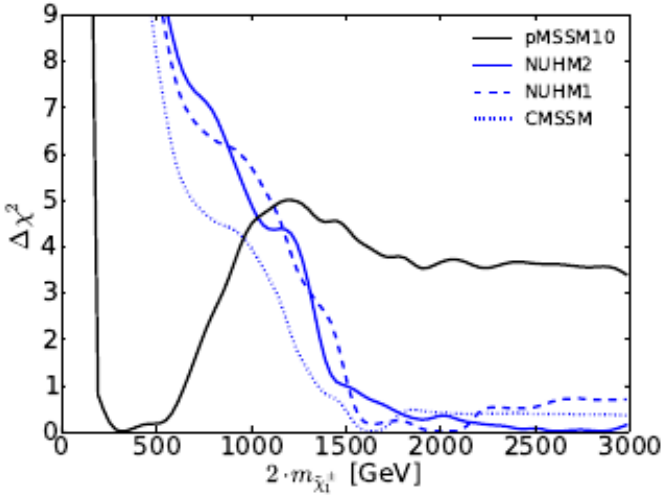
New g-2 results from 2019(?)

Linear Collider Prospects









Likelihood functions for various thresholds

Dark Matter Phenomenology

Fits provide a rich dataset

How is relic density set in pMSSM?

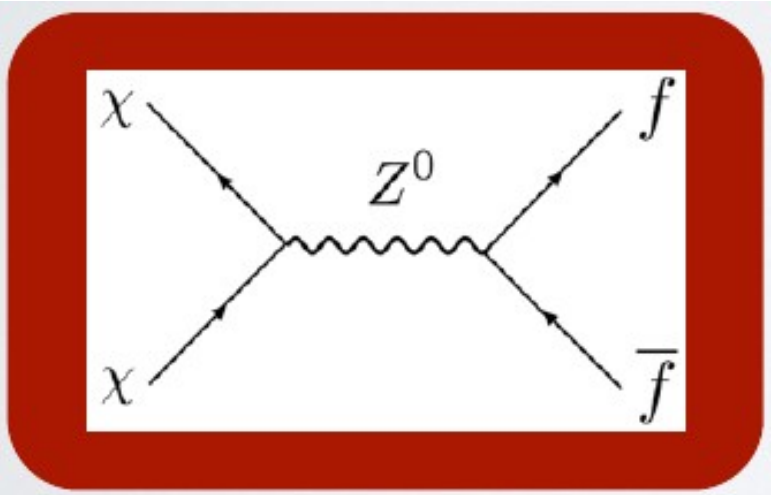
How does LHC probe pMSSM by mechanism?

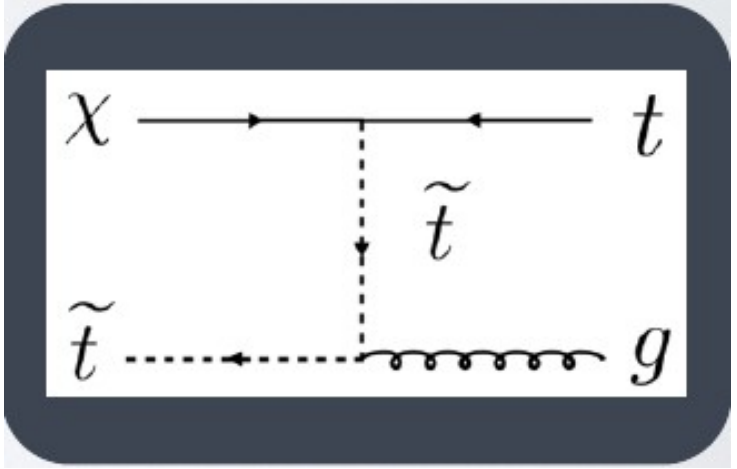
Direct detection prospects?

Relic Density Mechanisms

Relic density depletion requires relations between sparticle masses

In the MSSM this happens through resonant DM annihilation ('funnel') or co-annihilation





Resonant/funnel/s-channel

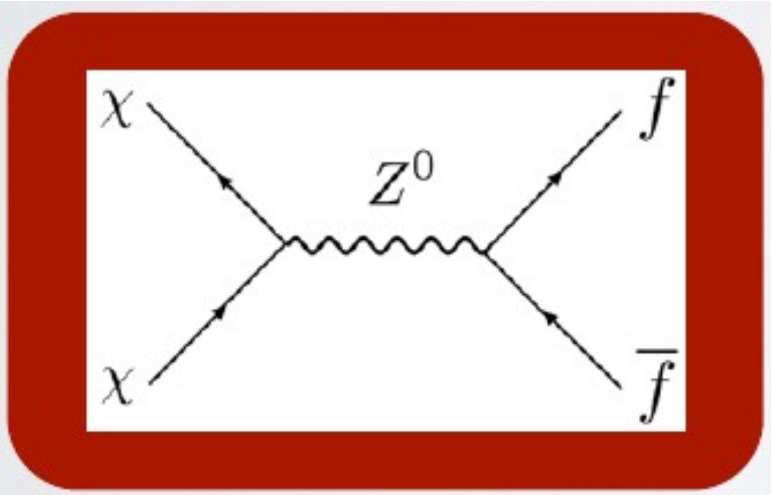
Co-annihilation/t-channel

Credit: Cohen/Wacker 2013

Relic Density Mechanisms

Also for

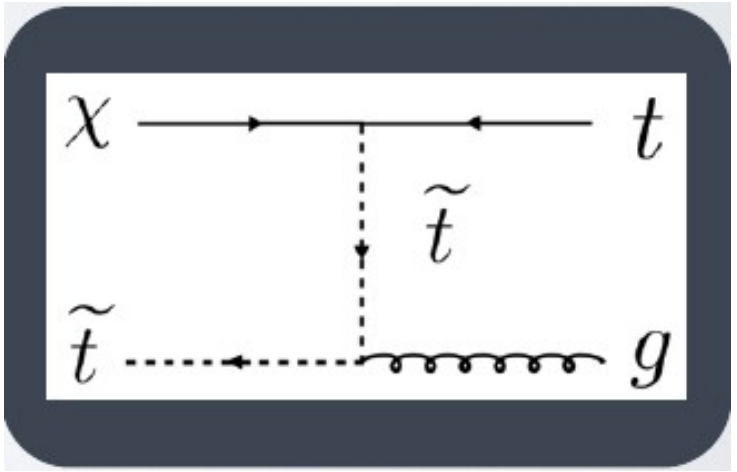
- Light Higgs h
- Heavy Higgs A/H



Resonant/funnel/s-channel

Also for

- Stau co-annihilation
- Chargino Co-annihilation



Co-annihilation/t-channel

Credit: Cohen/Wacker 2013

Relic Density Mechanisms

How to quantify this?

$$\tilde{\tau}_1 \text{ coann. (pink)}: \quad \left(\frac{m_{\tilde{\tau}_1}}{m_{\tilde{\chi}_1^0}} - 1\right) < 0.15\,,$$

$$\tilde{\chi}_1^{\pm} \text{ coann. (green)}: \quad \left(\frac{m_{\tilde{\chi}_1^{\pm}}}{m_{\tilde{\chi}_1^0}} - 1\right) < 0.1\,,$$

$$\tilde{t}_1 \text{ coann. (grey)}: \quad \left(\frac{m_{\tilde{t}_1}}{m_{\tilde{\chi}_1^0}}\right) - 1 < 0.2\,,$$

$$A/H \text{ funnel (blue)}: \quad \left|\frac{M_A}{m_{\tilde{\chi}_1^0}} - 2\right| < 0.4\,,$$

$$\text{focus point (cyan)}: \quad \left(\frac{\mu}{m_{\tilde{\chi}_1^0}}\right) - 1 < 0.3\,.$$

$$h \text{ funnel (magenta)}: \quad \left|\frac{M_h}{m_{\tilde{\chi}_1^0}} - 2\right| < 0.4\,,$$

$$Z \text{ funnel (orange)}: \quad \left|\frac{M_Z}{m_{\tilde{\chi}_1^0}} - 2\right| < 0.4\,.$$

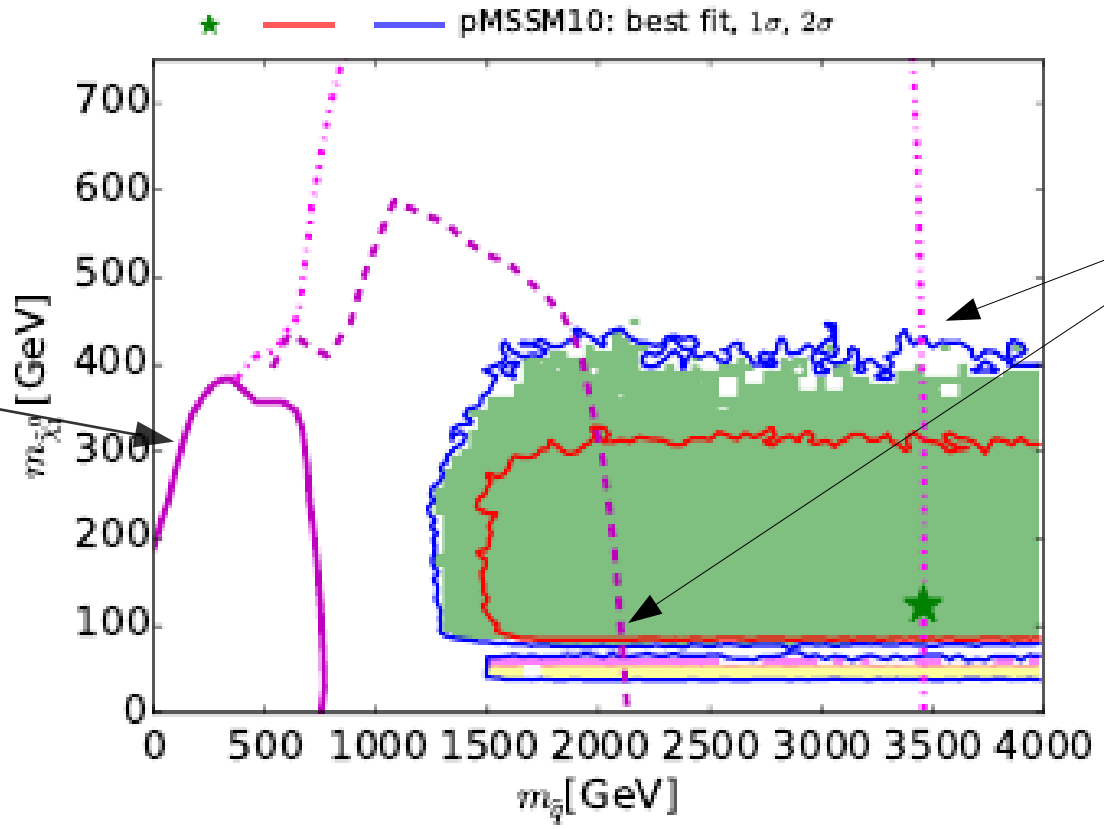
Conditions cross-checked from MicroMegas output

pMSSM results

Squark-neutralino mass plane

8 TeV LHC exclusion with decoupled gluinos

Estimate of 3/ab reach with and w/out decoupled gluinos



stau coann.
A/H funnel
hybrid
$\tilde{\chi}_1^{\pm}$ coann.
stop coann.
focus point
h funnel
Z funnel

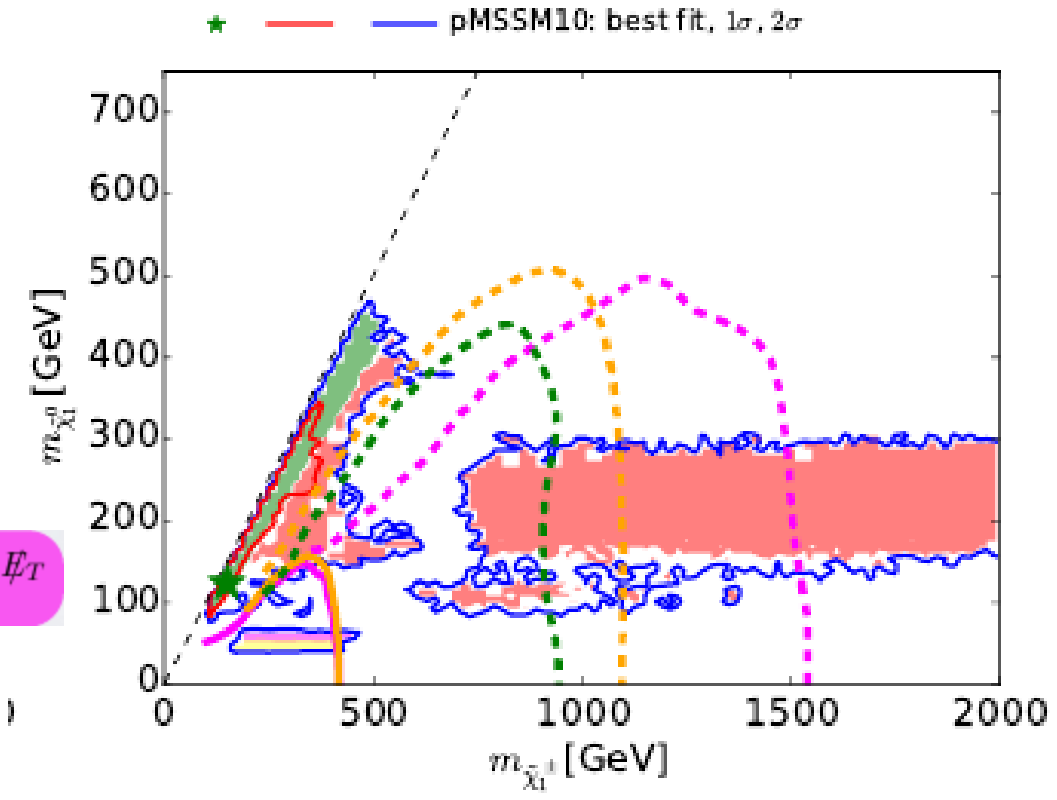
pMSSM results

Lightest chargino-neutralino mass plane

$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow W/Z + \not{E}_T$

$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow W/h + \not{E}_T$

$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0, \tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\pm} \rightarrow \tau, \tilde{\tau} \rightarrow 2, 3\tau's + \not{E}_T$



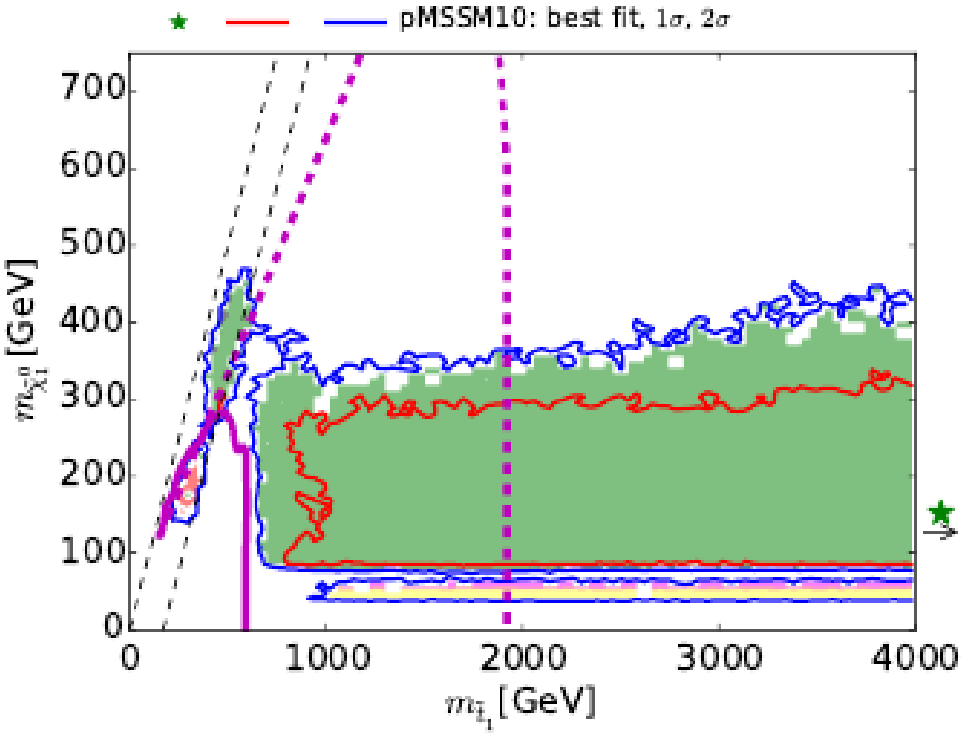
Current and projected SMS limits for different decay channels

stau coann.
A/H funnel
hybrid
$\tilde{\chi}_1^{\pm}$ coann.
stop coann.
focus point
h funnel
Z funnel

pMSSM results

Stop neutralino mass plane

$\tilde{t}_1 \rightarrow b\tilde{\chi}_1^{\pm}$



Current and projected SMS limits for different decay channels

stau coann.
A/H funnel
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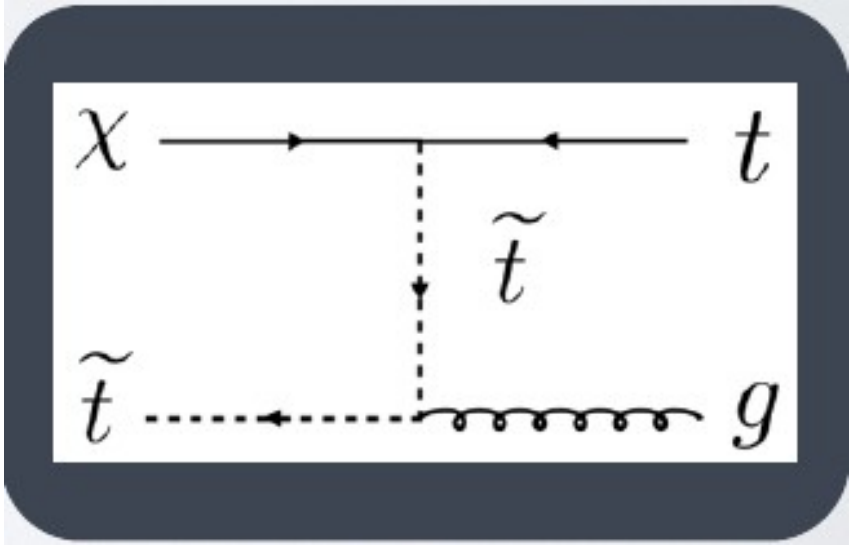
pMSSM results

Co-annihilation requires LSP and other sparticle to be degenerate.

Possibility of long-lived particles?



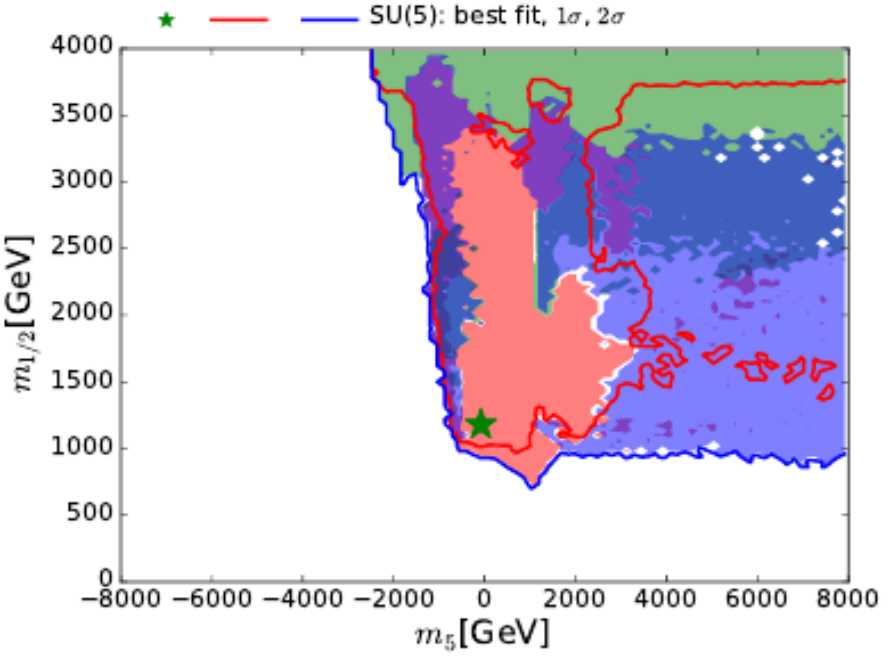
We don't find this in the pMSSM10

Work in Progress: SU5 GUTs

- Embed matter fields in SU5 GUT

$$(q_L, u_L^c, e_L^c)_i \in \mathbf{10}_i, \quad (\ell_L, d_L^c)_i \in \bar{\mathbf{5}}_i \,,$$

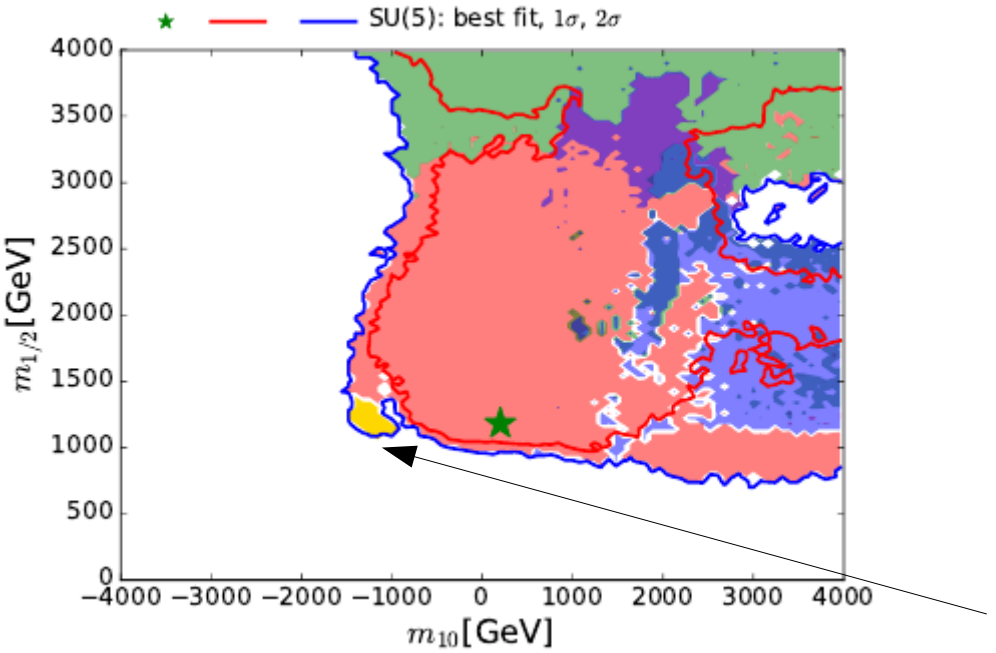
- Scan over $m_{1/2},\ m_5,\ m_{10},\ m_{H_u},\ m_{H_d},\ A_0$



$\tilde{\tau}$ coann.
$\tilde{\tau}_1$ coanni. + H/A
$\tilde{\chi}_1^\pm$ coann.
$\tilde{\chi}_1^\pm$ coann. + H/A
A/H-funnel
$\tilde{\tau}_1$ coanni. + $\tilde{\chi}_1^\pm$ coann. + H/A
$\tilde{u}_R/\tilde{c}_R$ coann.

Work in Progress: SU5 GUTs

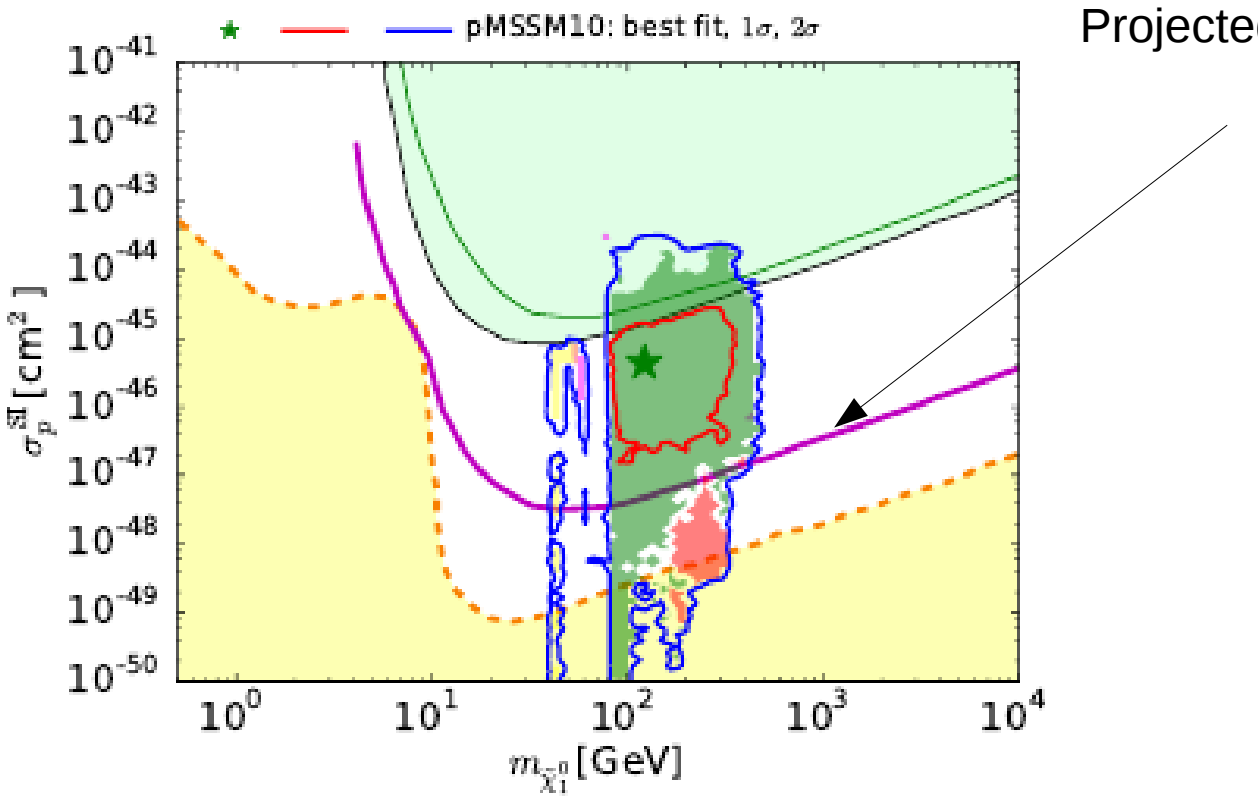
- New co-annihilation mechanism pops out
- Can be understood with RGE cancellations



Haven't seen this before in constrained models

$\tilde{\tau}$ coann.
$\tilde{\tau}_1$ coanni. + H/A
$\tilde{\chi}_1^{\pm}$ coann.
$\tilde{\chi}_1^{\pm}$ coann. + H/A
A/H-funnel
$\tilde{\tau}_1$ coanni. + $\tilde{\chi}_1^{\pm}$ coann. + H/A
$\tilde{u}_R/\tilde{c}_R$ coann.

Direct Detection Phenomenology



stau coann.
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Work in Progress: SU5 GUTs

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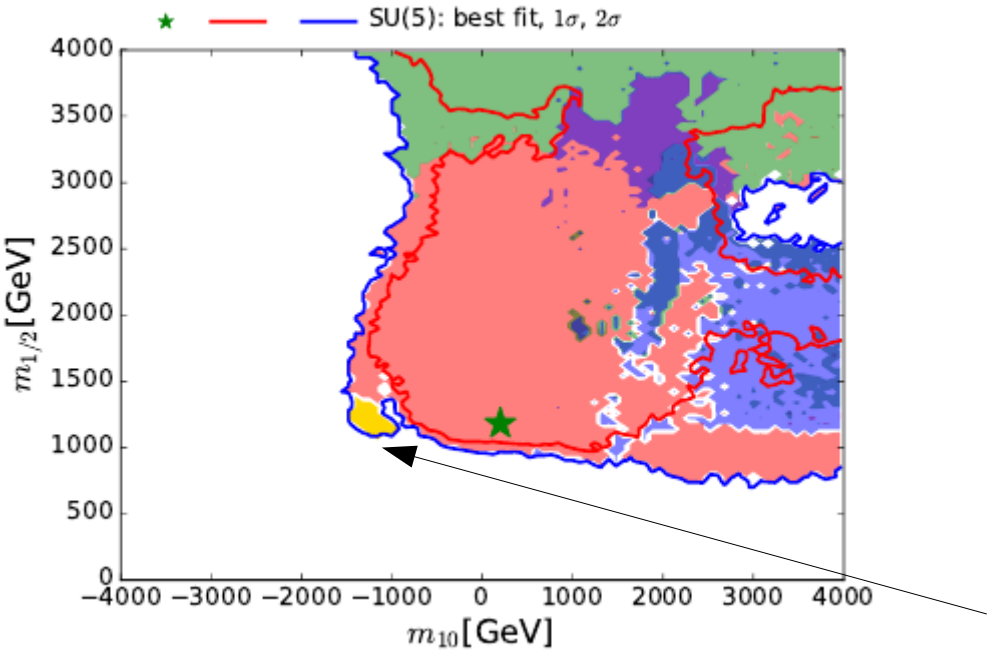
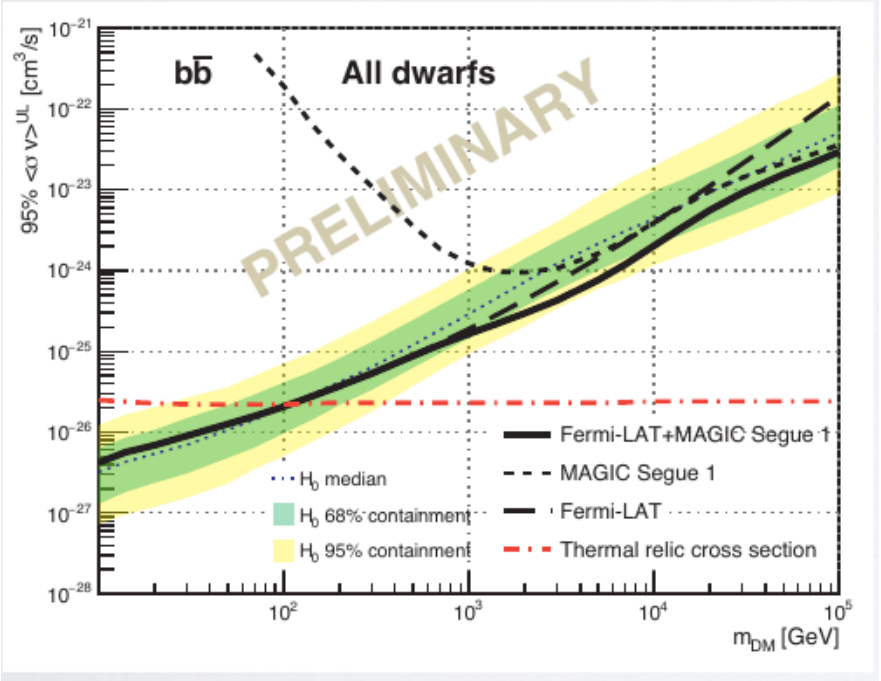


Haven't seen this before in constrained models

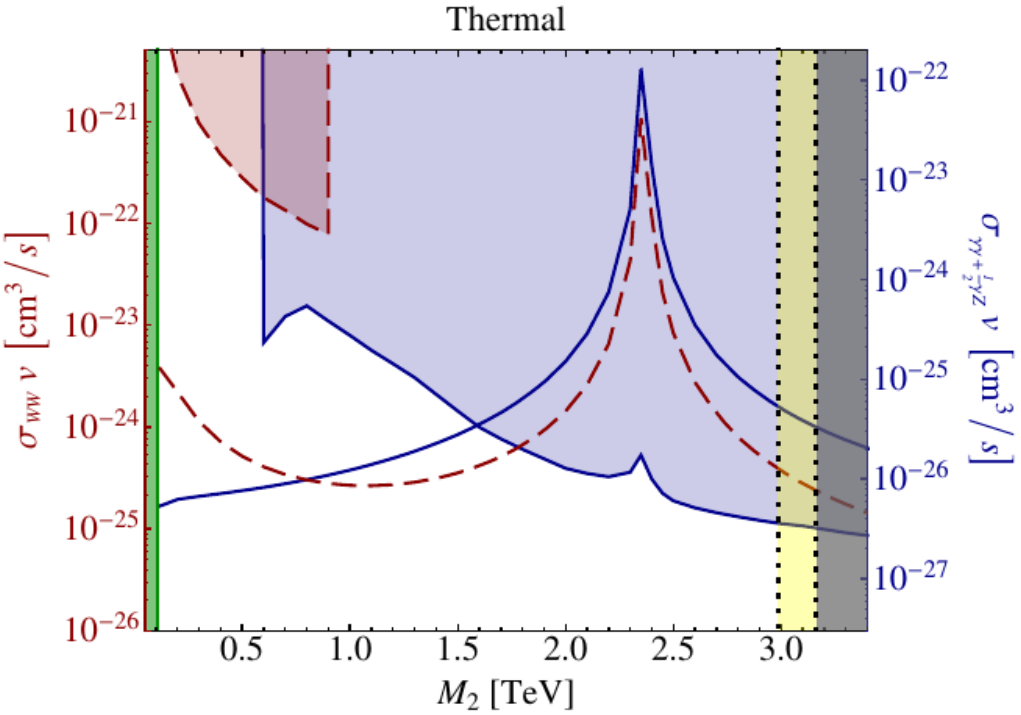
$\tilde{\tau}$ coann.
$\tilde{\tau}_1$ coanni. + H/A
$\tilde{\chi}_1^{\pm}$ coann.
$\tilde{\chi}_1^{\pm}$ coann. + H/A
A/H-funnel
$\tilde{\tau}_1$ coanni. + $\tilde{\chi}_1^{\pm}$ coann. + H/A
$\tilde{u}_R/\tilde{c}_R$ coann.

Indirect Detection

Interesting to include recent Fermi-LAT dwarf limits



Indirect detection constraints from Fermi-HESS constrain heavier (wino) states



Work in Progress: pMSSM11

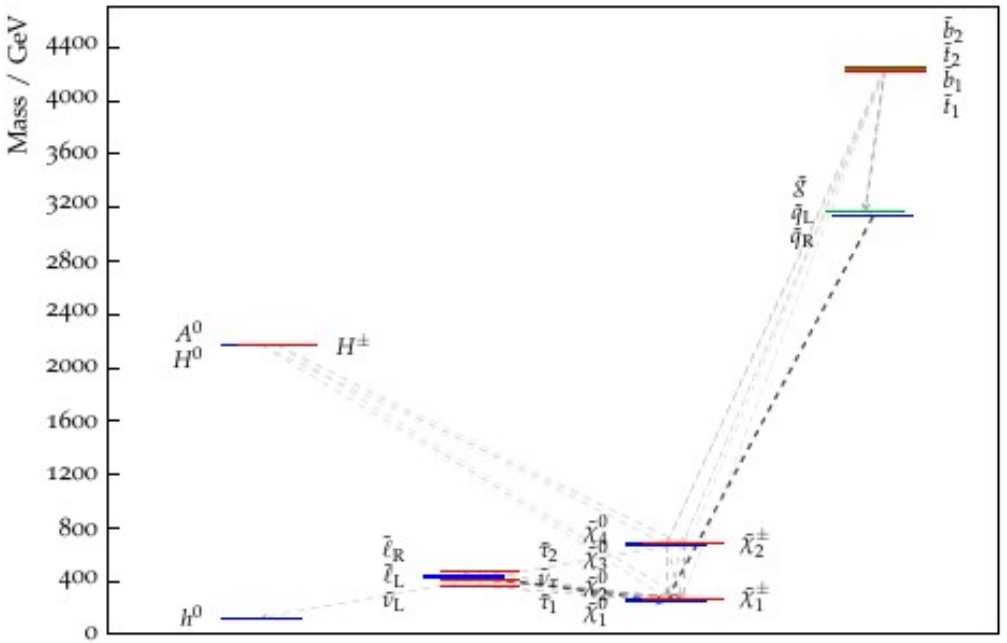
- As for pMSSM10 but with non-universal slepton masses $m_{\tilde{l}_1} = m_{\tilde{l}_2} \neq m_{\tilde{l}_3}$
- Implementing 13/fb results from ICHEP 2016
- Although note 30/fb and counting on tape...
- Also currently looking at SU5 GUTs and mAMSB

Work in Progress: pMSSM11

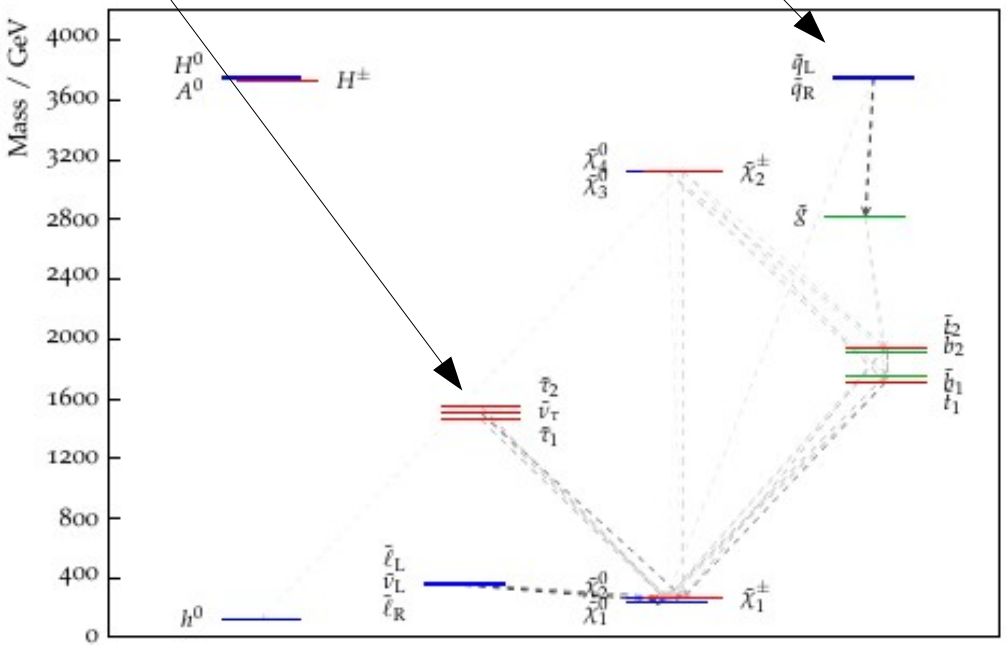
Best-fit points

Similar coloured spectrum to pMSSM10

Heavier staus



pMSSM10

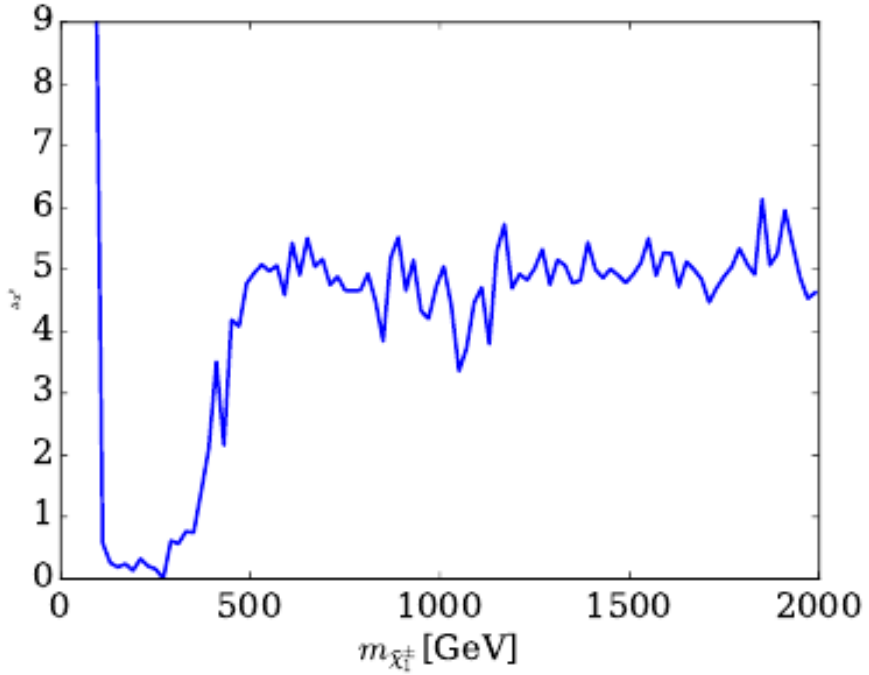


pMSSM11

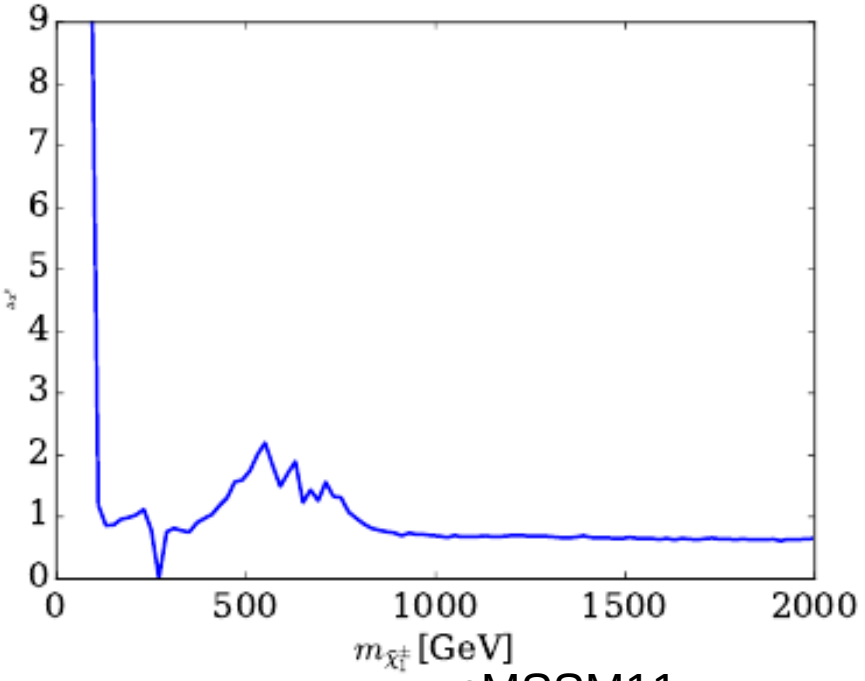
Work in Progress: pMSSM11

Lightest chargino mass

Much larger range: richer possibilities for co-annihilation?



pMSSM10

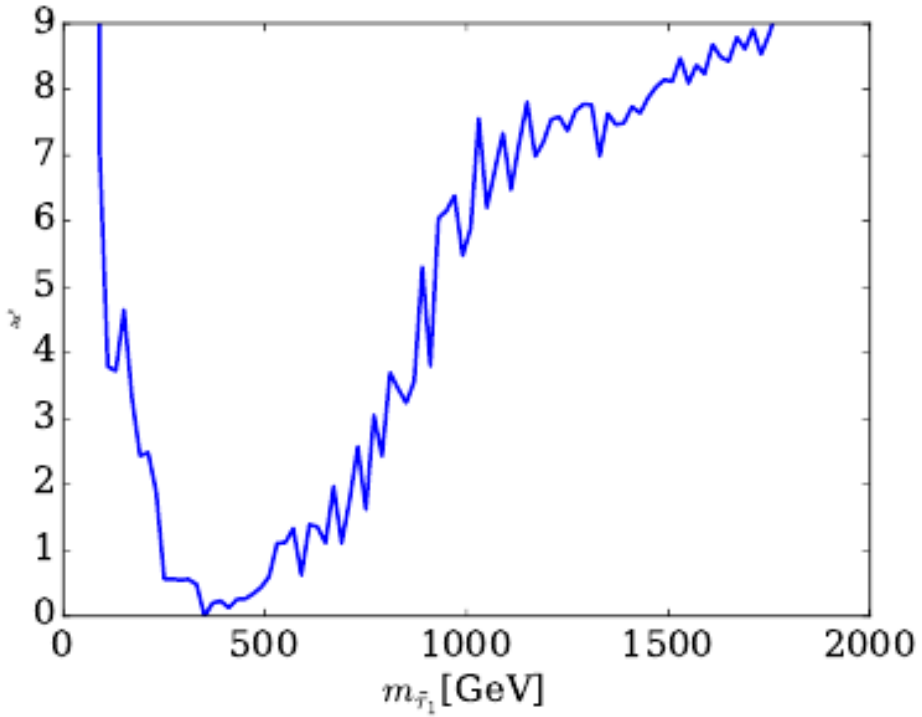


pMSSM11

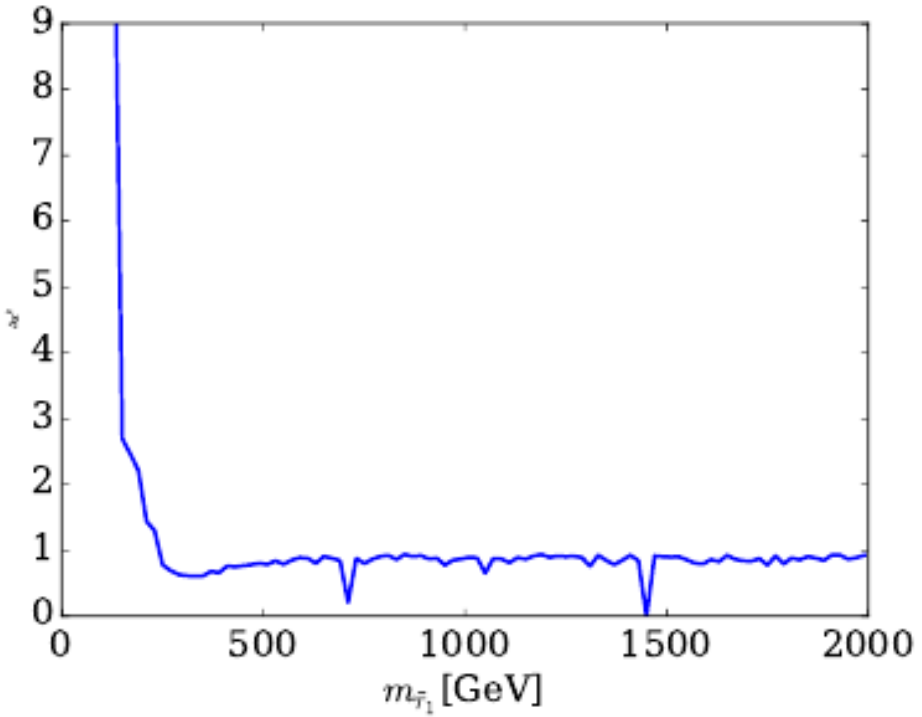
Work in Progress: pMSSM11

Lightest stau mass

Much larger range: richer possibilities for co-annihilation?



pMSSM10

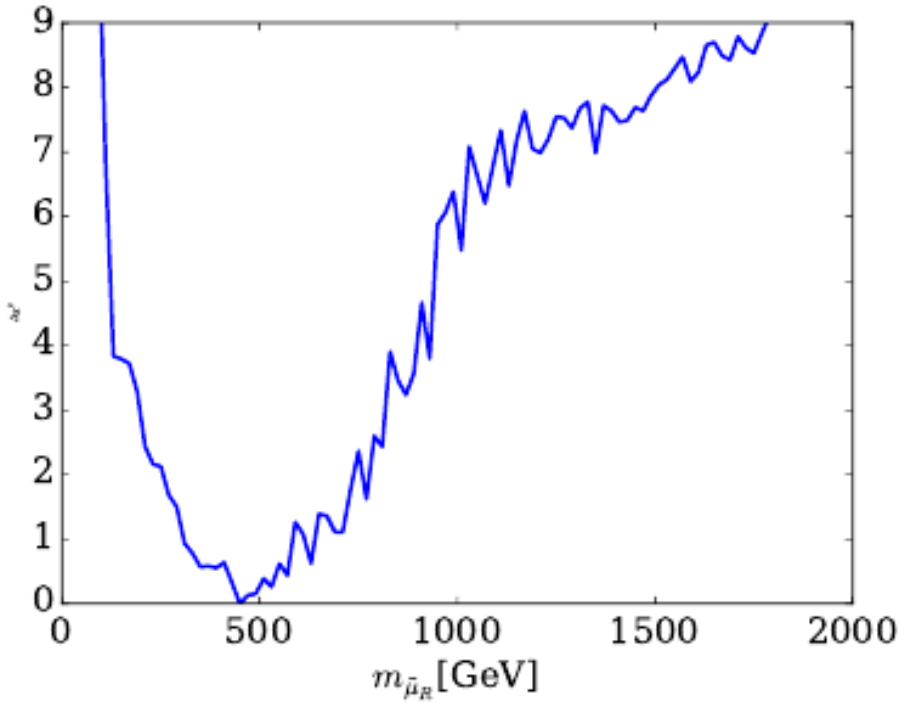


pMSSM11

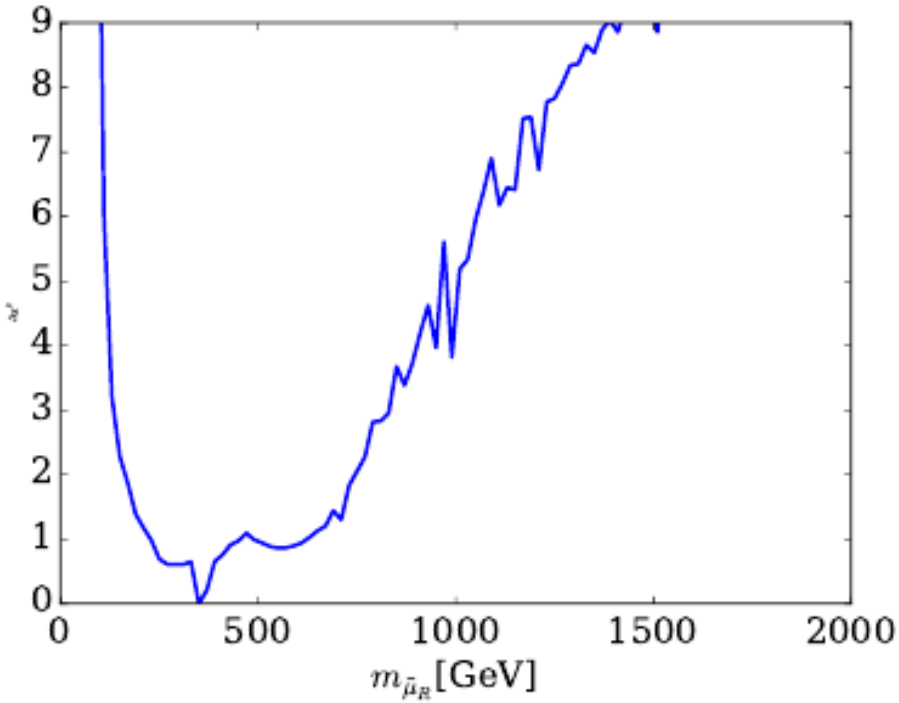
Work in Progress: pMSSM11

Lightest smuon mass

Very similar: driven by g-2



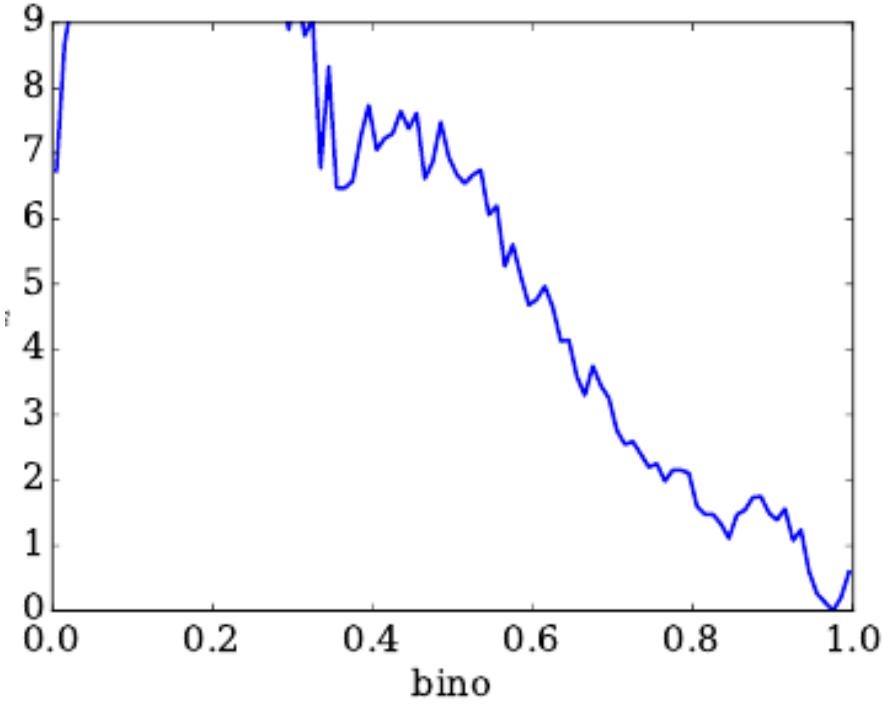
pMSSM10



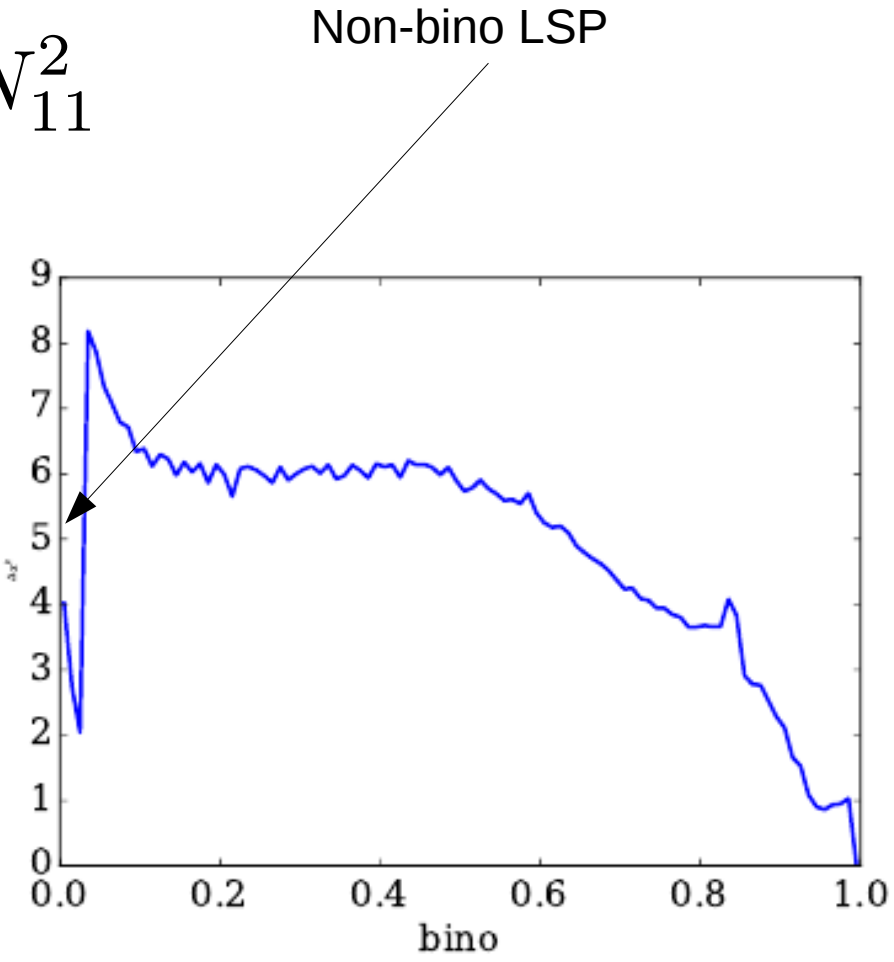
pMSSM11

Work in Progress: pMSSM11

- Bino component of LSP, N_{11}^2



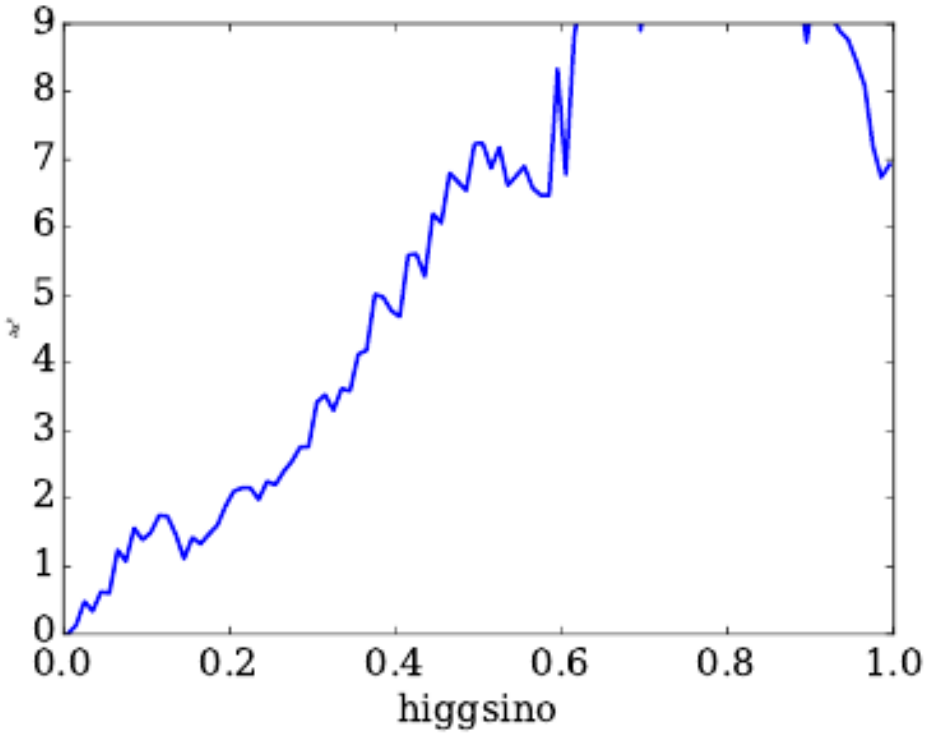
pMSSM10



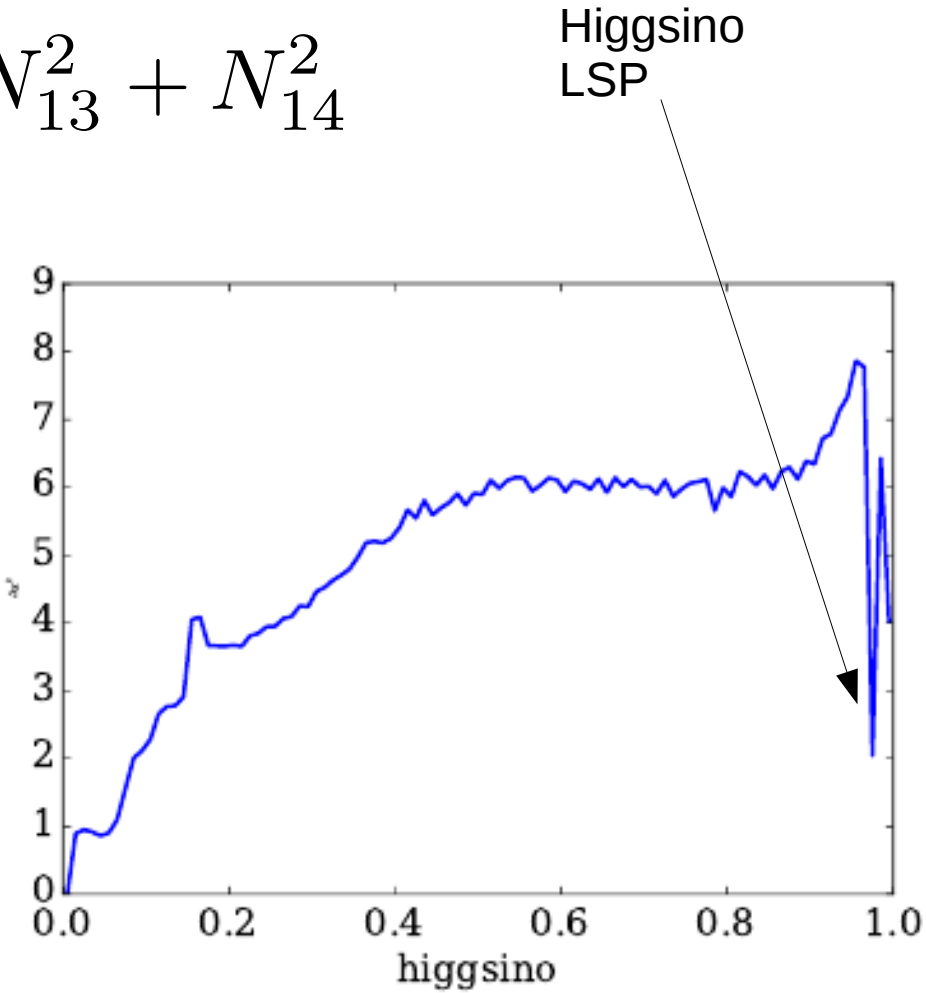
pMSSM11

Work in Progress: pMSSM11

- Bino component of LSP, $N_{13}^2 + N_{14}^2$



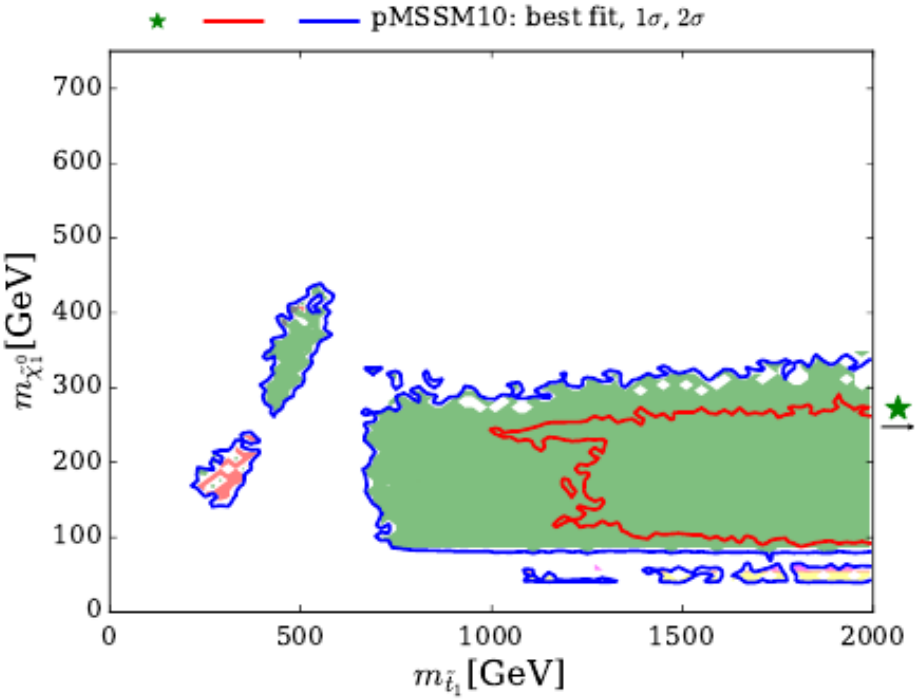
pMSSM10



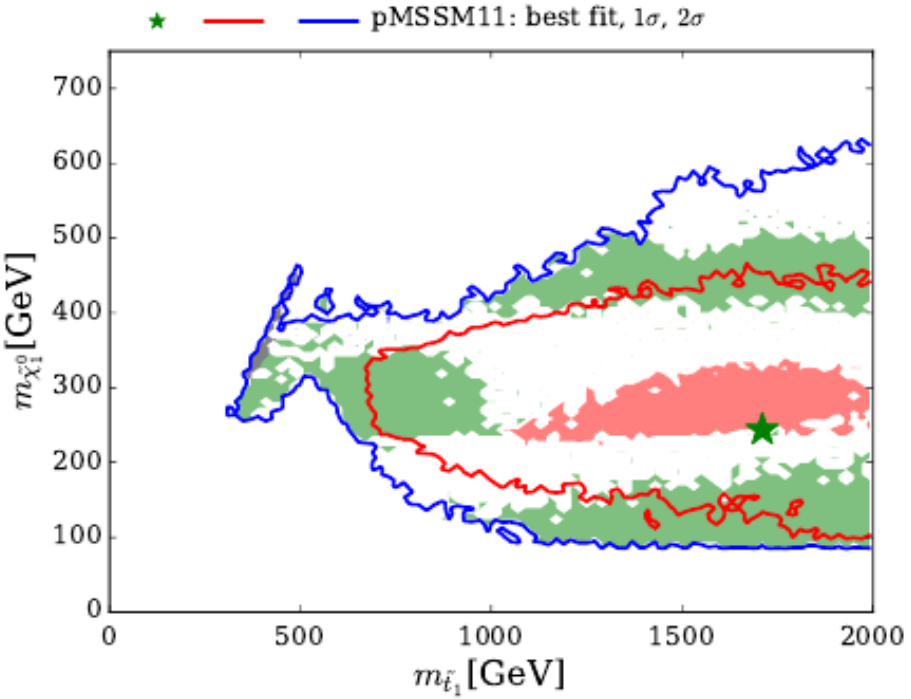
pMSSM11

Work in Progress: pMSSM11

- Stop masses: light stop window more closed (FeynHiggs?)



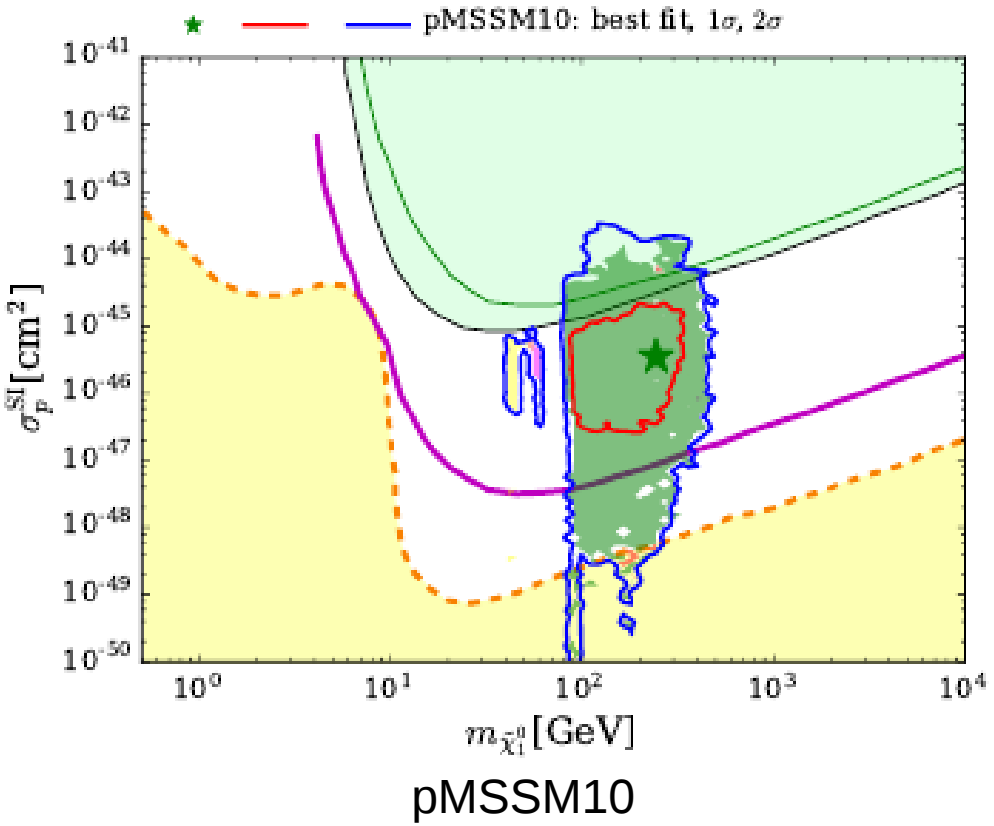
pMSSM10



pMSSM11

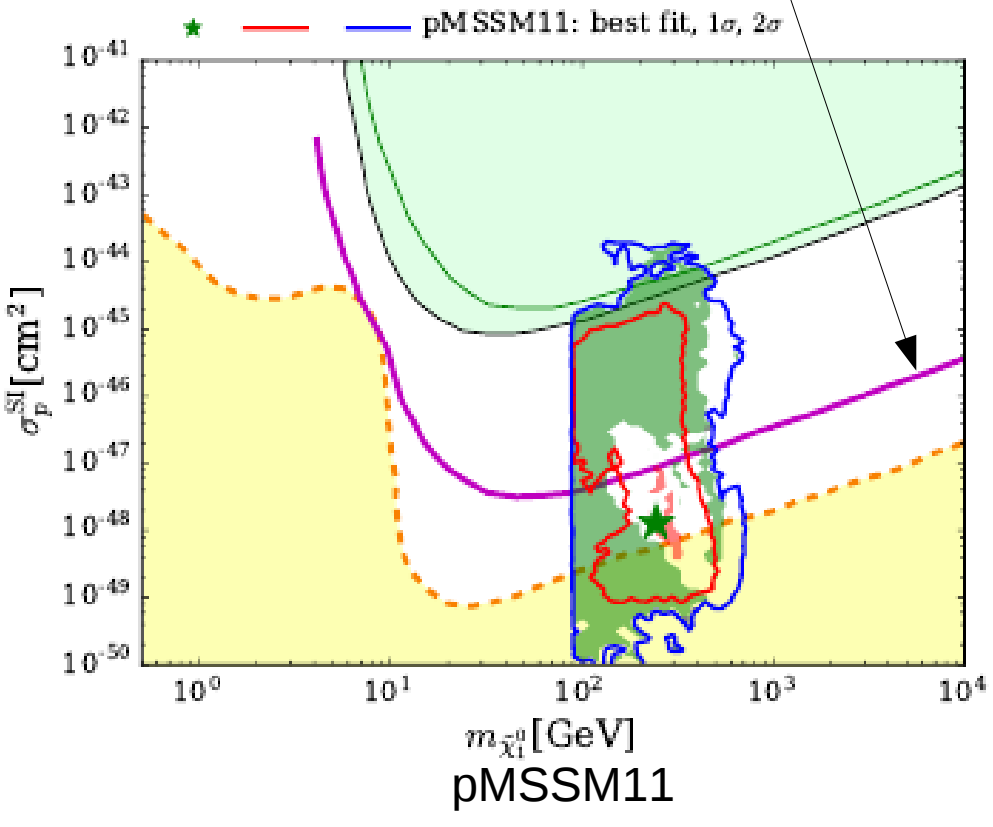
Work in Progress: pMSSM11

- Direct detection projections



pMSSM10

LZ projected reach
(early 2020s)



pMSSM11

Future Plans

- Vacuum stability constraints (vevacious?)
- Stau production limits
- Heavy Higgs production and other ICHEP results (low mass gluinos?)
- LUX + PandaX DD constraints
- Metastable charged particle searches: co-annihilation regions
- Indirect detection?

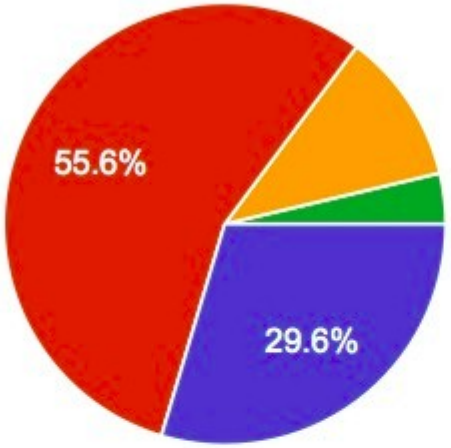
Shameless Advertising: (Re)Interpreting LHC Results Forum

- Recasting tools, infrastructure, physics studies
- Platform for theory/experiment interaction
- 2nd workshop to be held at CERN 12-14 December

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/InterpretingLHCresults

Summary

Is SUSY alive and well?



Alive and well	**16**	29.6%
Alive but not well	**30**	55.6%
Almost dead	**6**	11.1%
Well dead	**2**	3.7%

- 2.96 of out 10 cats think SUSY is alive and well
- The rest: SUSY needs a doctor or a priest
- PMSSM fits: expect a rich spectrum of EW states below 1 TeV
- Coloured states could be anywhere

https://workshops.ift.uam-csic.es/susyaaw/Survey