The CMSSM and NUHM1* after Run I of the LHC

*and NUHM2 and pMSSM10

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Experiment: O. Buchmueller, R. Cavanaugh, M. Citron, A. De Roeck, H. Flaecher, S. Malik, J. Marrouche, D. Martinez-Santos, S. Rogerson, F.J. Ronga, K.J. de Vries

Theory: M. Dolan, J. Ellis, S. Heinemeyer, G. Isidori, K. Olive, G. Weiglein

Eur. Phys. J. C (2014) 74:292 (arXiv:1312.5250) and work in progress

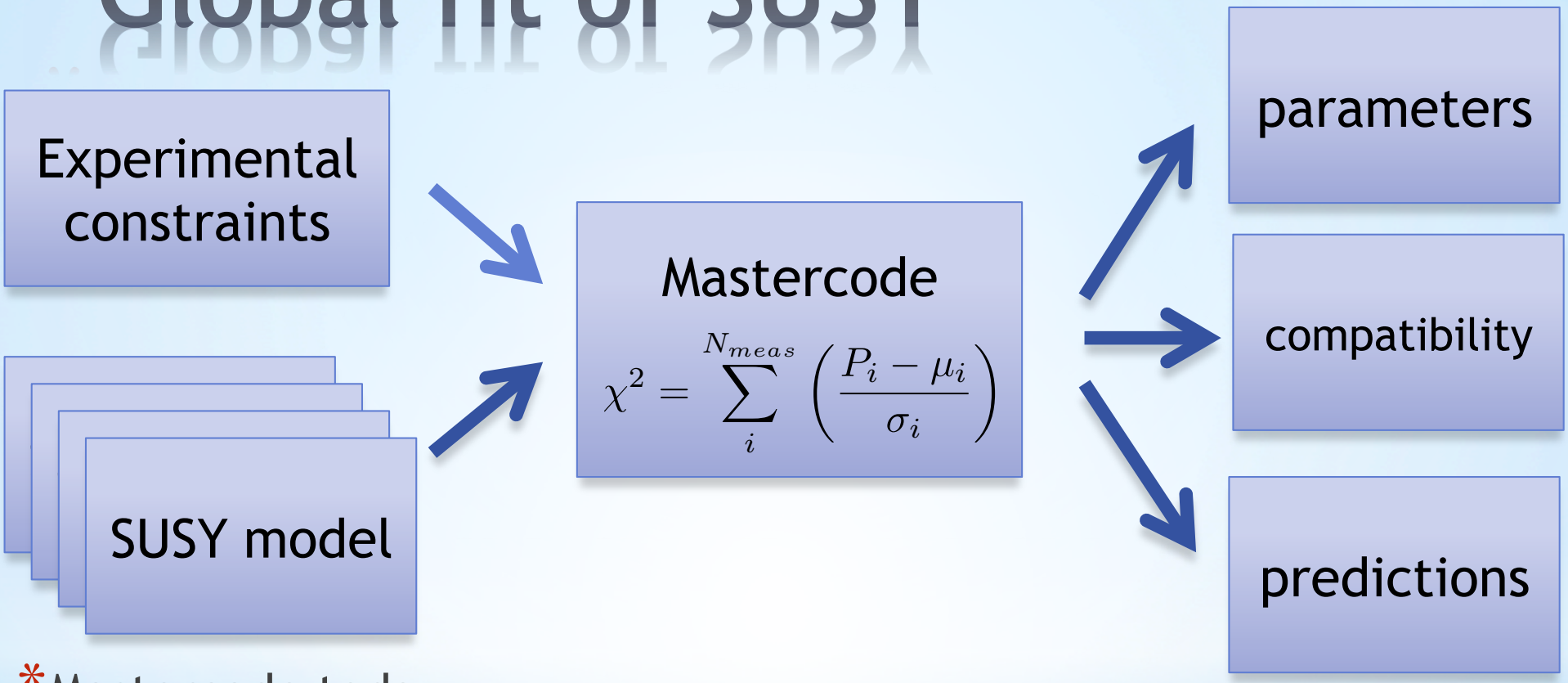
Introduction

- What can we say about the allowed parameter space of supersymmetric models?
  - best exploited by combining as much experimental information as possible
  - Famous example: Standard Model fit to electroweak precision data
- Equivalent framework for physics beyond the Standard Model, in particular the Minimal SuperSymmetic Standard Model (MSSM)

- Necessary tools:
  - state-of-the-art calculations of experimental observables

  and
  - a common framework that interfaces between the different calculations and combines the obtained information
- Objectives/Outcome:
  - Fit model parameters in some MSSM scenarios
  - Explore sensitivity of different observables to parameter space

*Global fit of SUSY



* Mastercode today
  * supergravity: CMSSM, NUHM1, NUHM2 NEW

$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ (m_{H_u}^2,\ m_{H_d}^2)$$

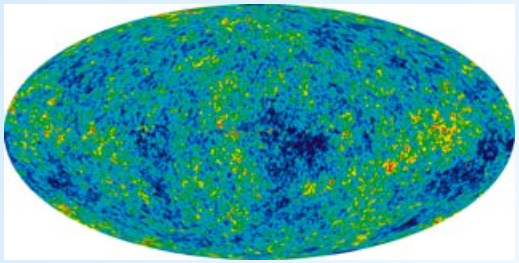
  * phenomenological: pMSSM10 NEW

$$m_{\tilde{q}_{12}},\ m_{\tilde{q}_3},\ m_{\tilde{l}},\ M_1,\ M_2,\ M_3,\ A,\ M_A,\ \tan\beta,\ \mu$$

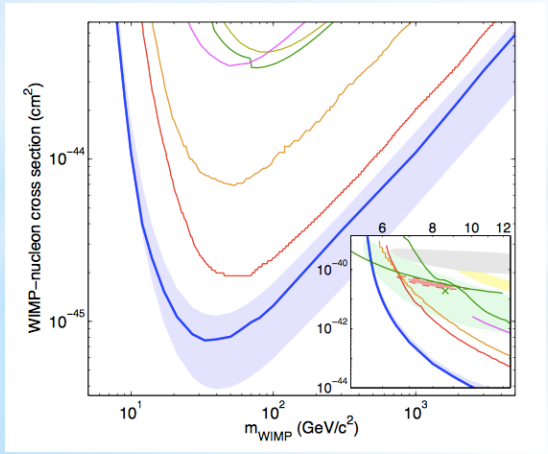
*Experimental constraints

$$\chi^2 = \sum_i^{N_{meas}} \left(\frac{P_i - C_i}{\sigma_i} \right)^2$$

Dark matter



relic density



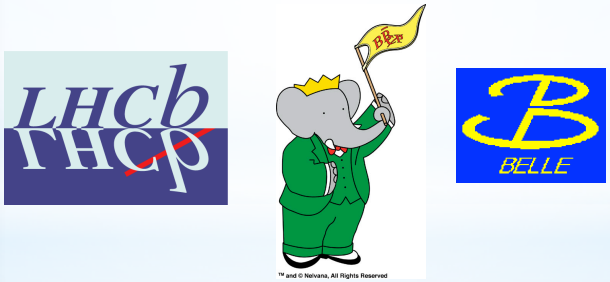
Direct Detection

Indirect searches

$$M_W,\ \Gamma_Z,\ A_{fb}(b),\ \ldots$$

$$(g-2)_\mu$$

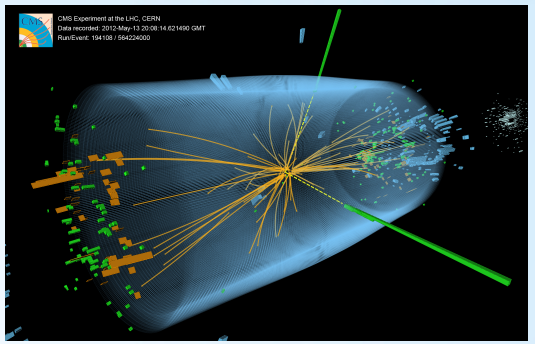
Electroweak observables



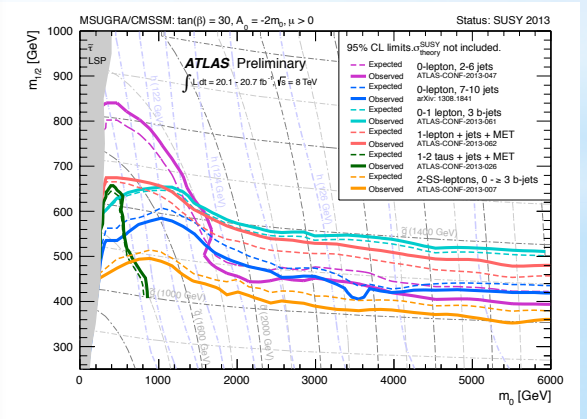
$$B_s \to \mu\mu,\ b \to s\gamma,\ \ldots$$

Flavour observables

Direct searches



Lightest Higgs



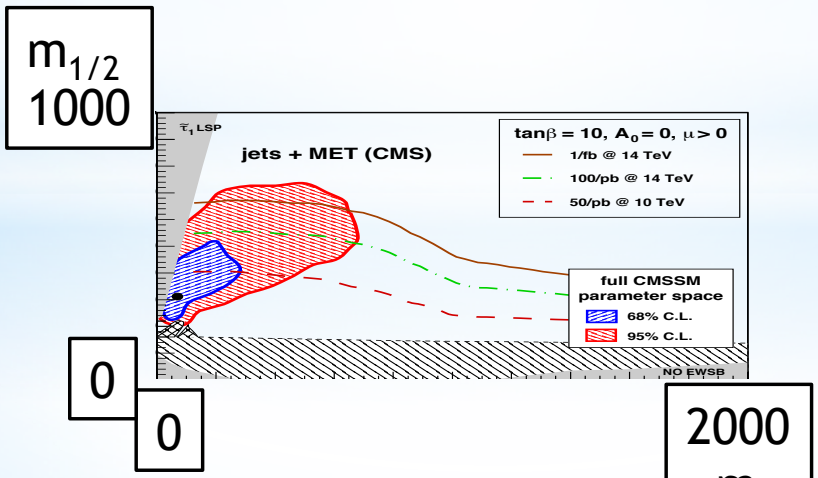
LHC SUSY searches

Overview

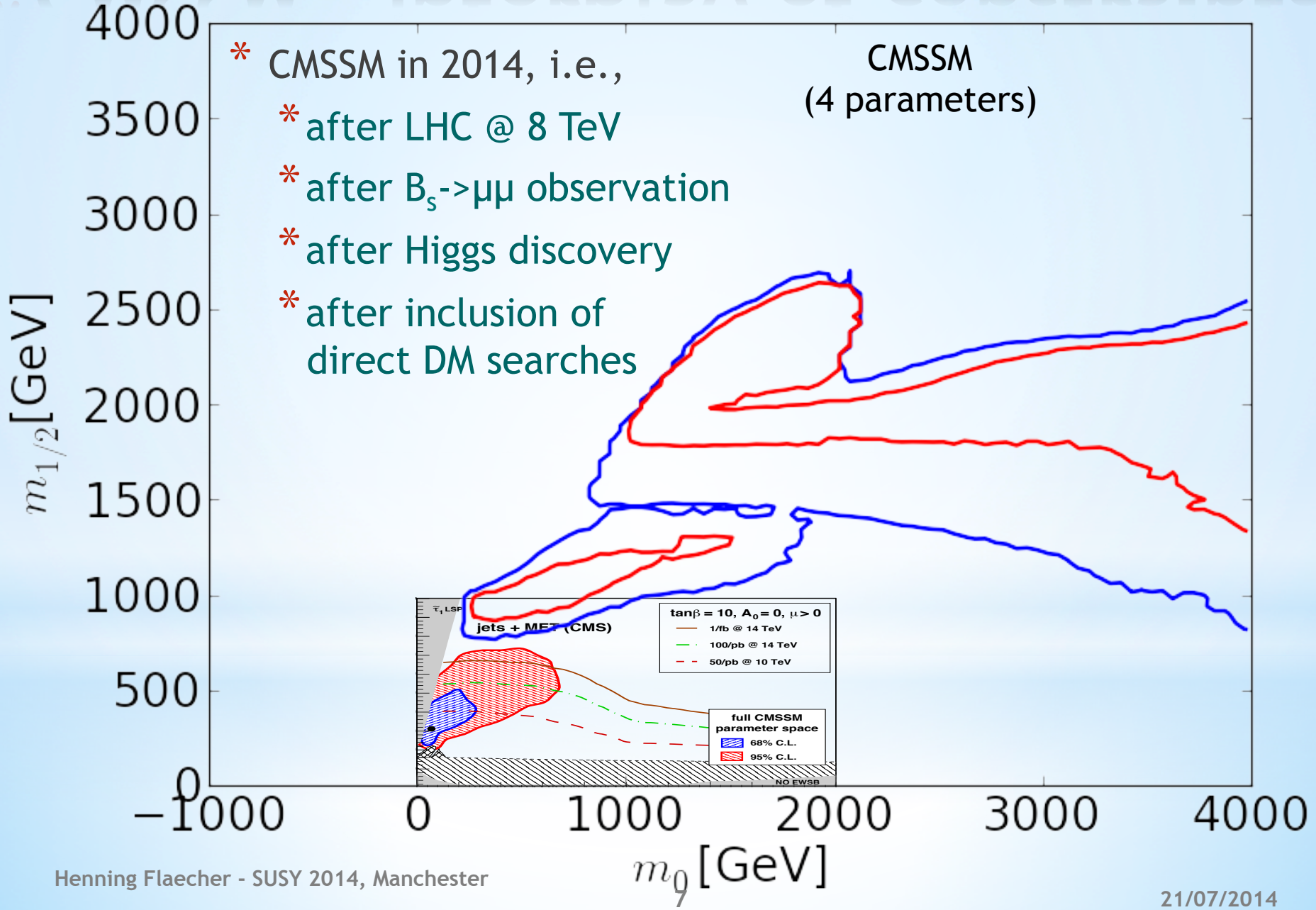
- Scans of parameter spaces with multinest algorithm
  - $O(10^7)$ points per model
- Frequentist interpretation by calculating an overall χ^2 and relative $\Delta\chi^2$
- Construct 1-D or 2-D projections of multidimensional parameter space for interpretation
- Study influence of individual experimental constraints
- Make predictions for favoured regions of unknown quantities
  - e.g. m_h, $BR(B_s \to \mu\mu)$, σ_p^{SI}

Interplay of constraints

- Status of CMSSM in 2009, i.e.,
  - before LHC
  - before B_s->μμ observation
  - before Higgs discovery
  - before inclusion of direct DM searches



*CMSSM - Interplay of constraints



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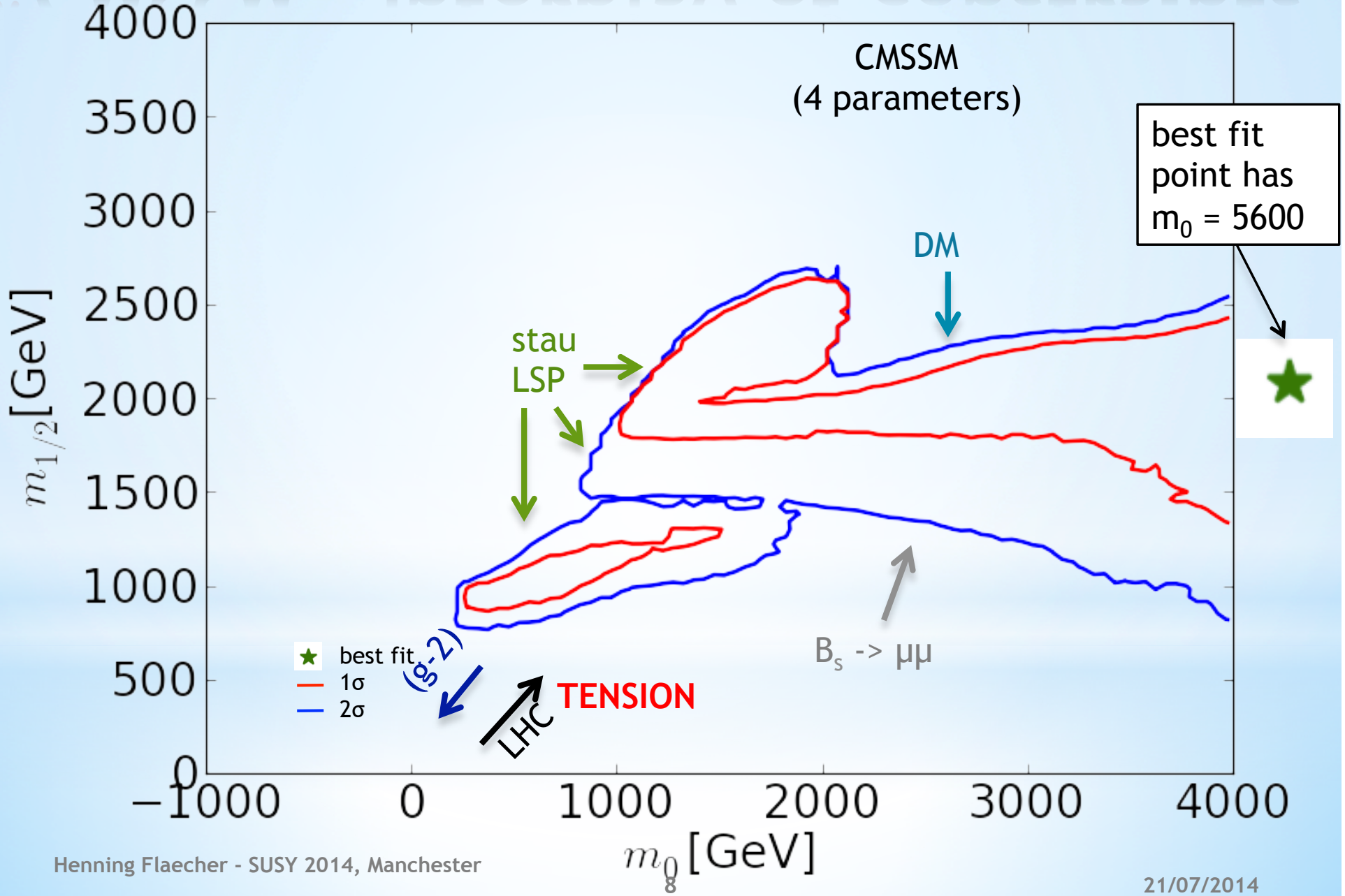
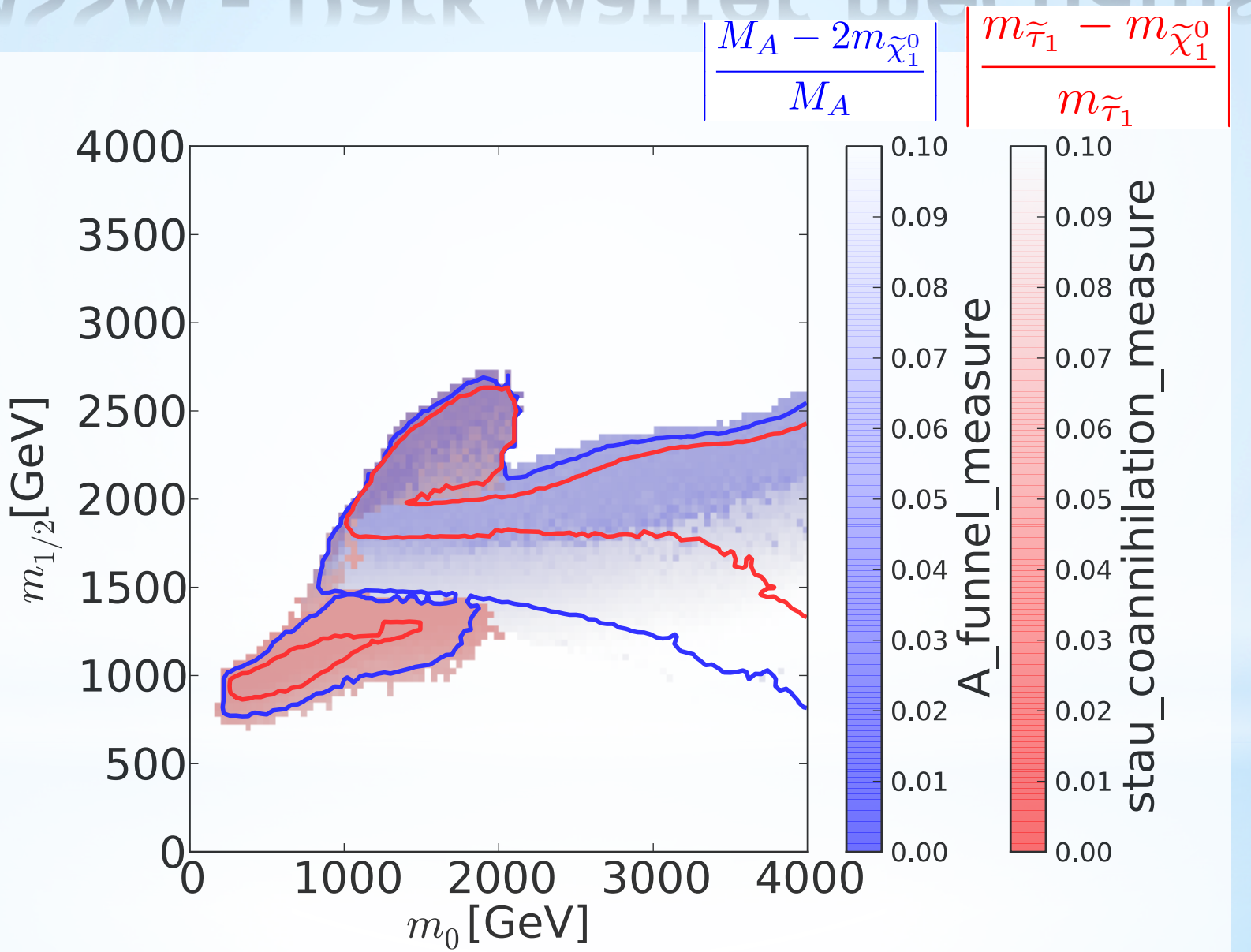
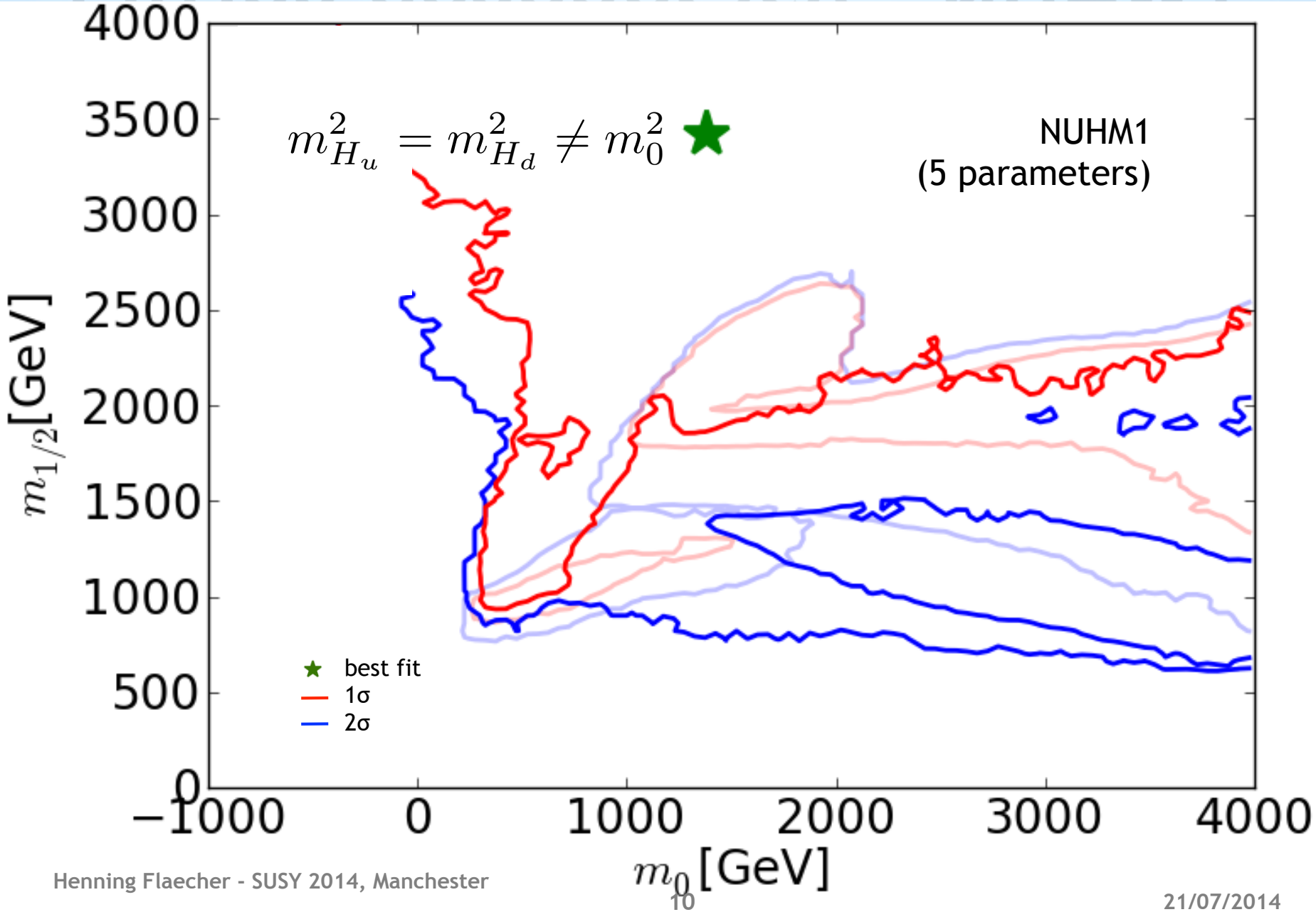


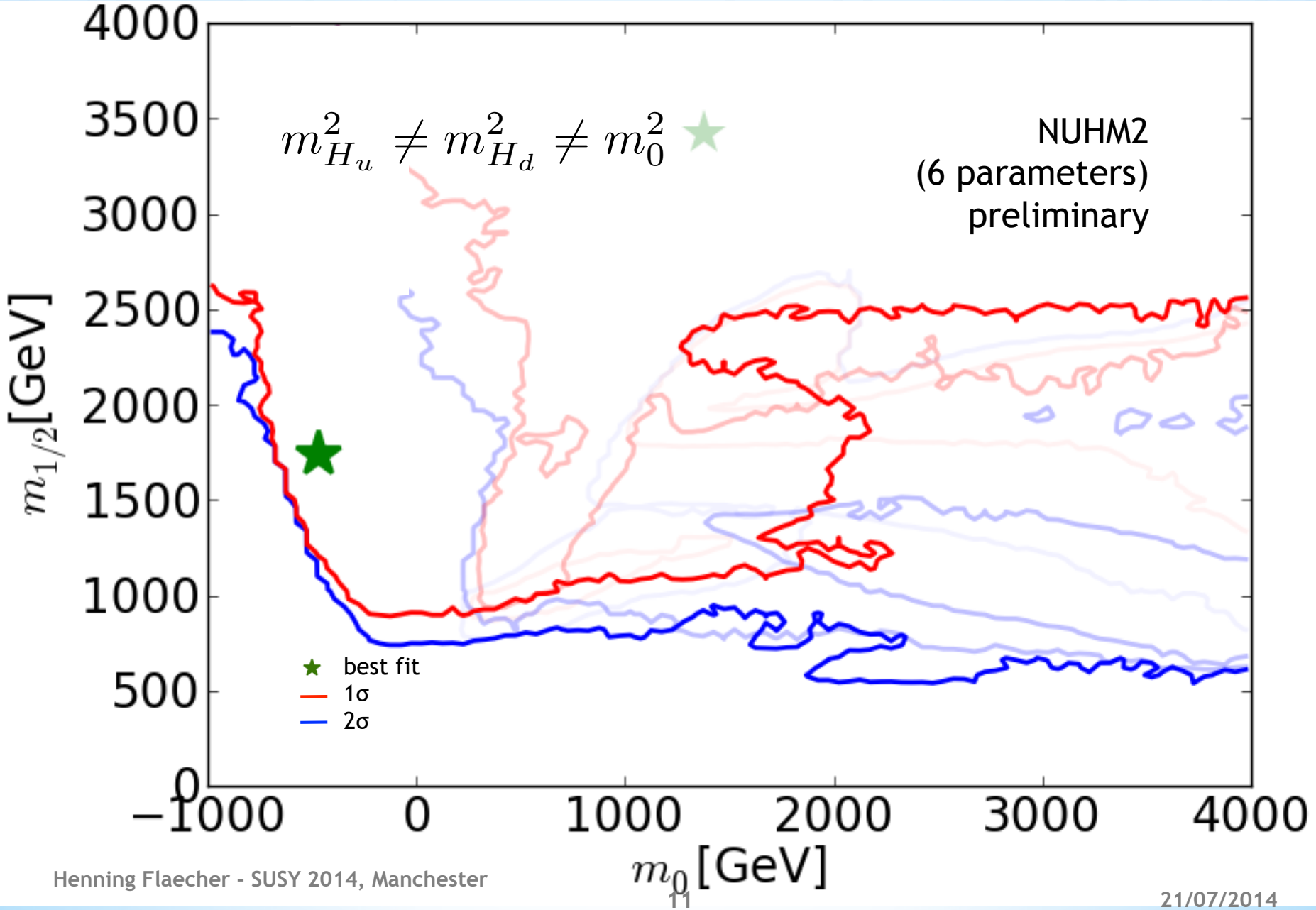
*CMSSM - Dark Matter mechanism



*Lifting degeneracy - NUHM1



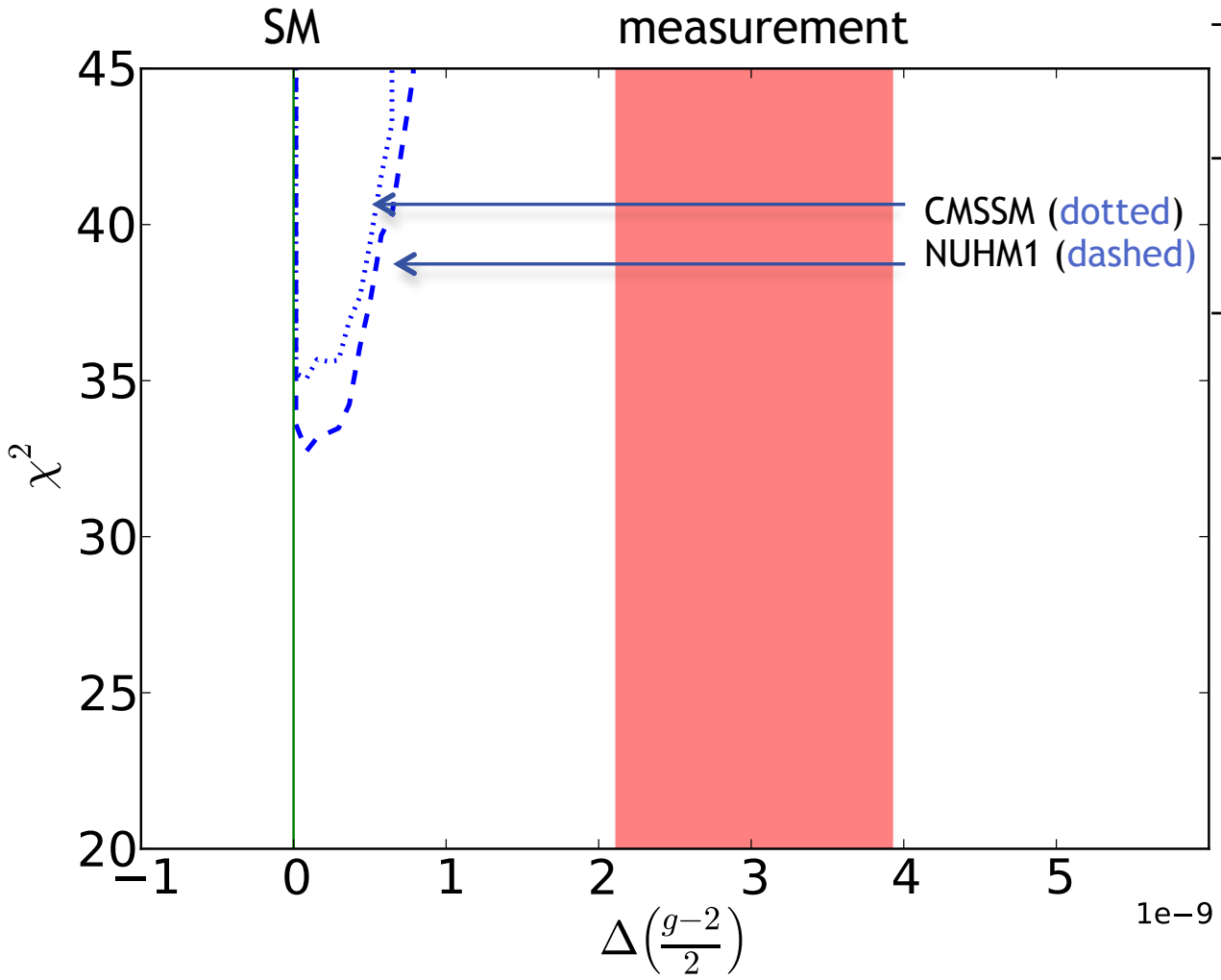
*Lifting degeneracy further - NUHM2



$(g-2)_\mu$ vs LHC exclusions

- Additional freedom in NUHM1 and NUHM2 opens up allowed parameter space
- Tension between g-2 and LHC searches remains
- Explore models with more freedom, e.g. pMSSM10

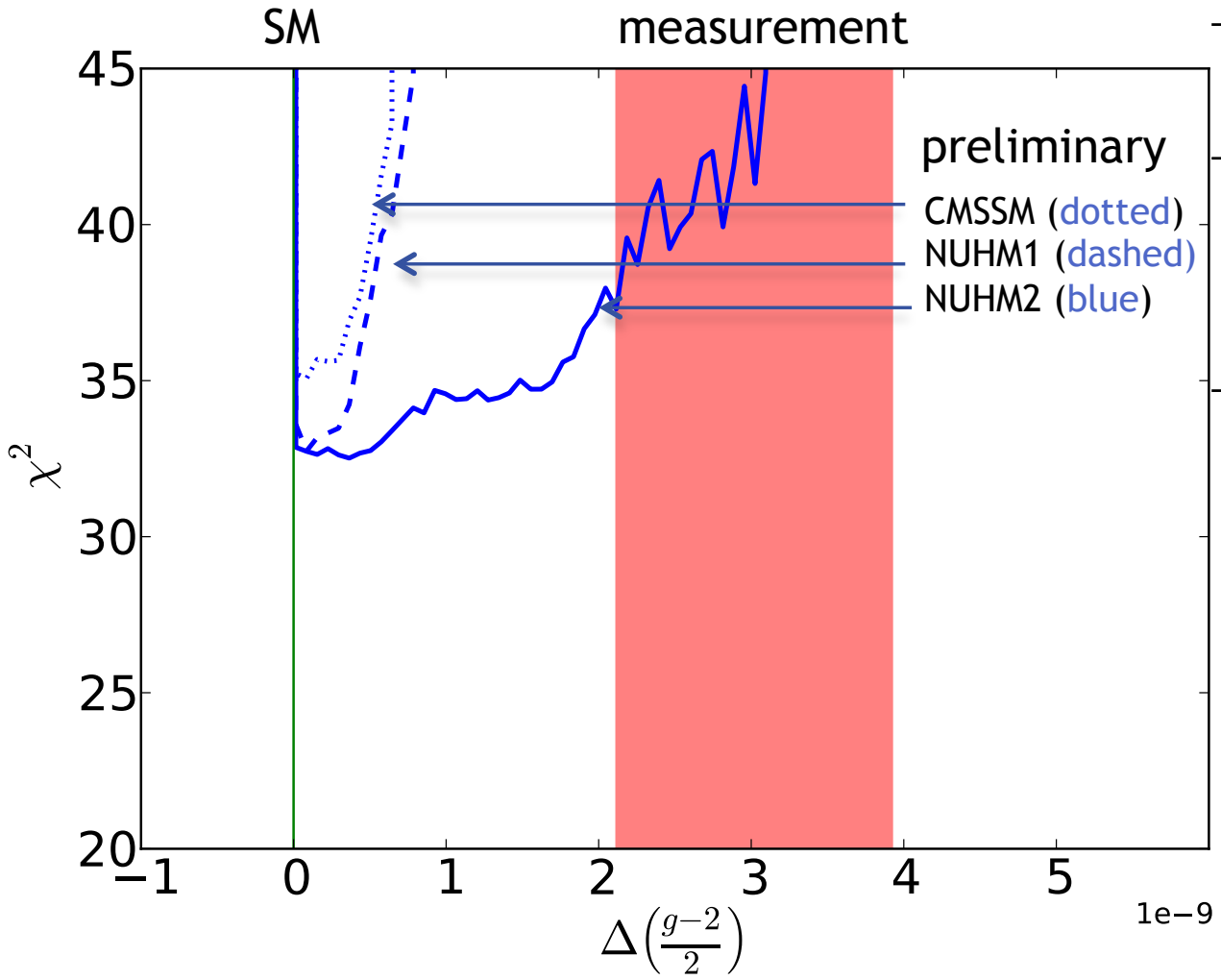
* Resolving tension between (g-2) and LHC



	X^2/n_{dof}	p-value
CMSSM	35.1/23	5.1 %
NUHM1	32.7/22	6.6 %

Can adding extra parameters resolve the tension between (g-2) and LHC constraints?

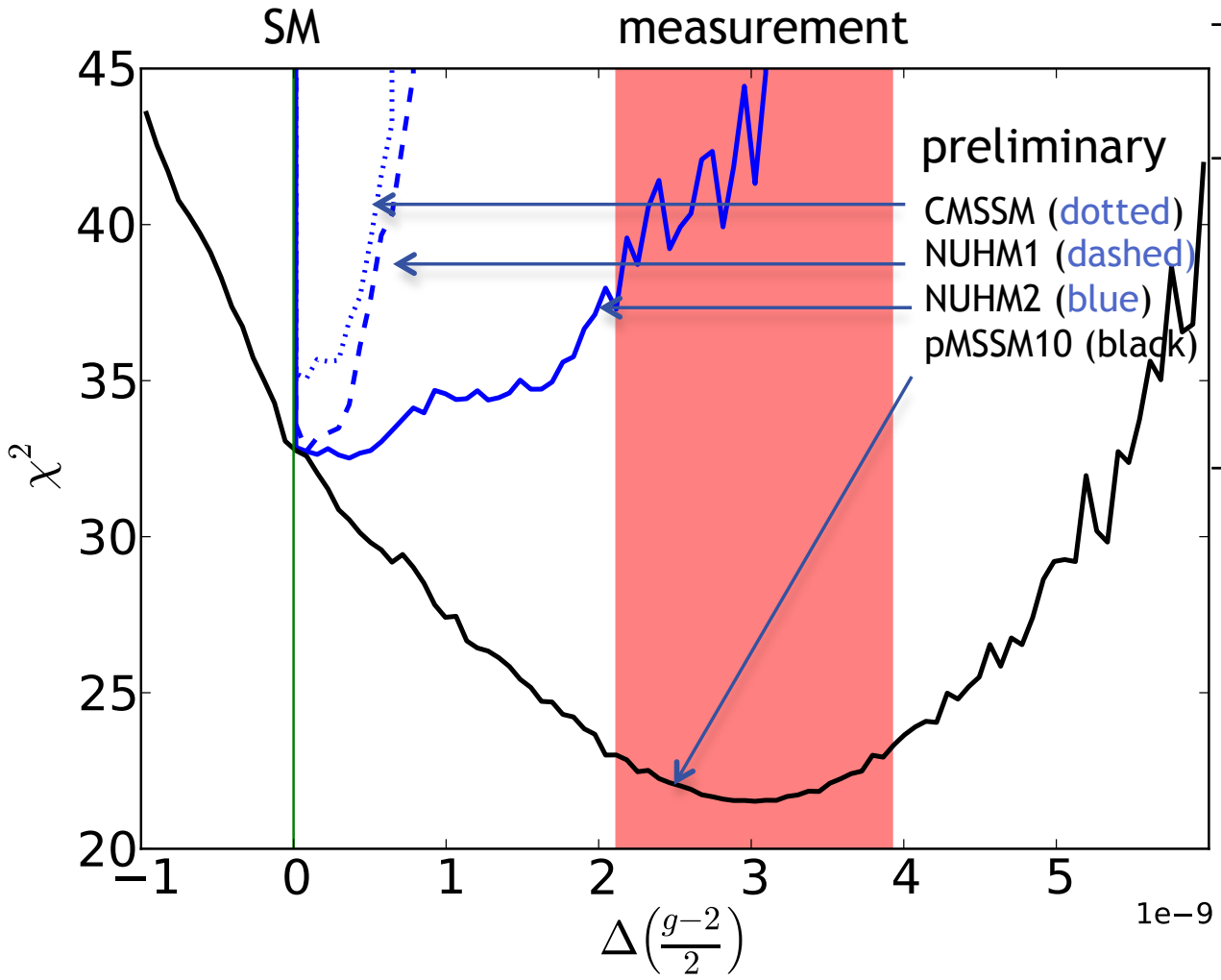
* Resolving tension between (g-2) and LHC



	X^2/n_{dof}	p-value
CMSSM	35.1/23	5.1 %
NUHM1	32.7/22	6.6 %
NUHM2	32.5/21	5.2 %

NUHM2 can get (g-2) right but only at the cost of other constraints.

* Resolving tension between (g-2) and LHC

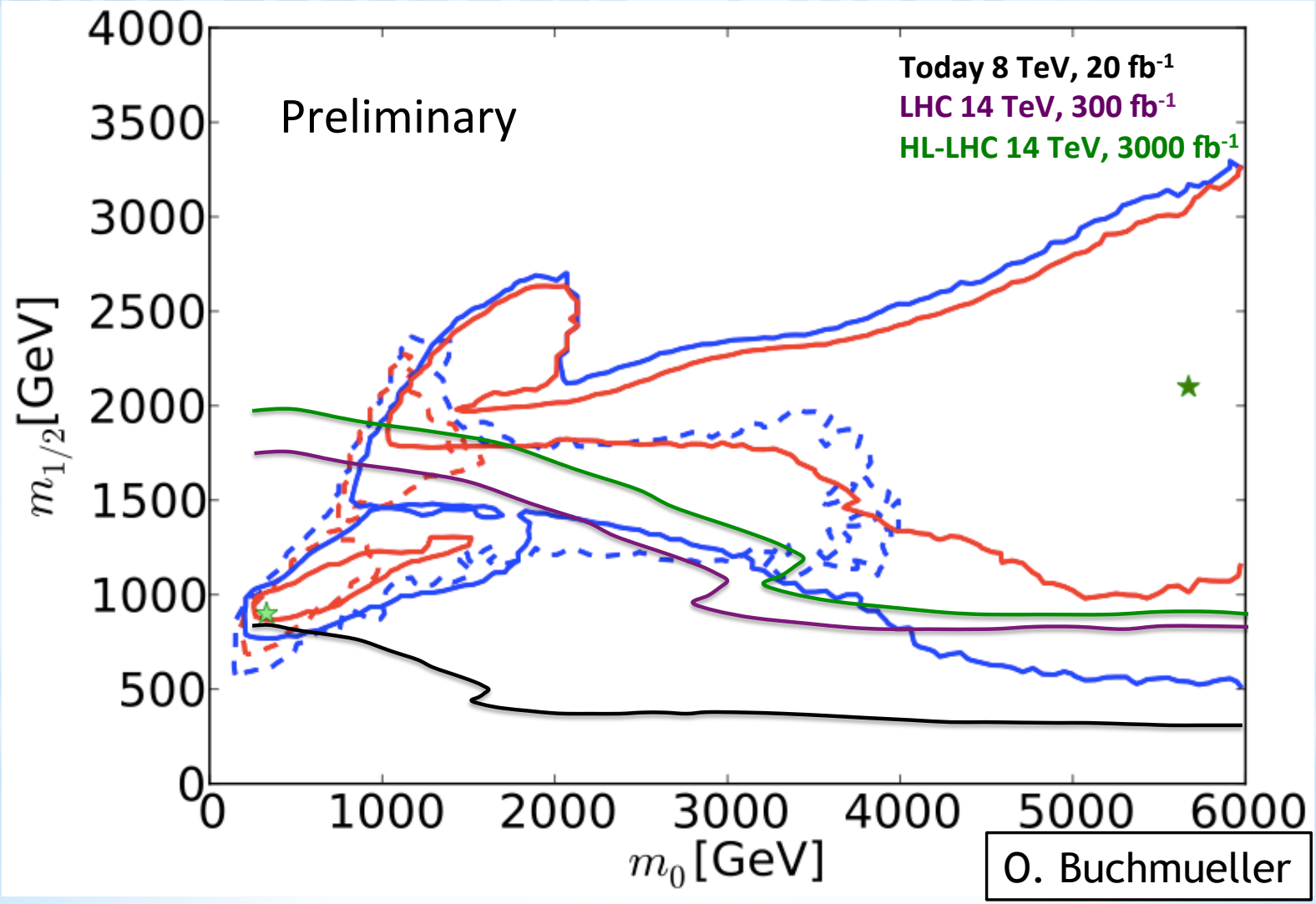


	X^2/n_{dof}	p-value
CMSSM	35.1/23	5.1 %
NUHM1	32.7/22	6.6 %
NUHM2	32.5/21	5.2 %
pMSSM10	21.1/17	22 %

pMSSM10 resolves the **tension** between (g-2) and LHC constraints. This **significantly improves** the **fit**.

Future prospects for LHC in 2015 and beyond

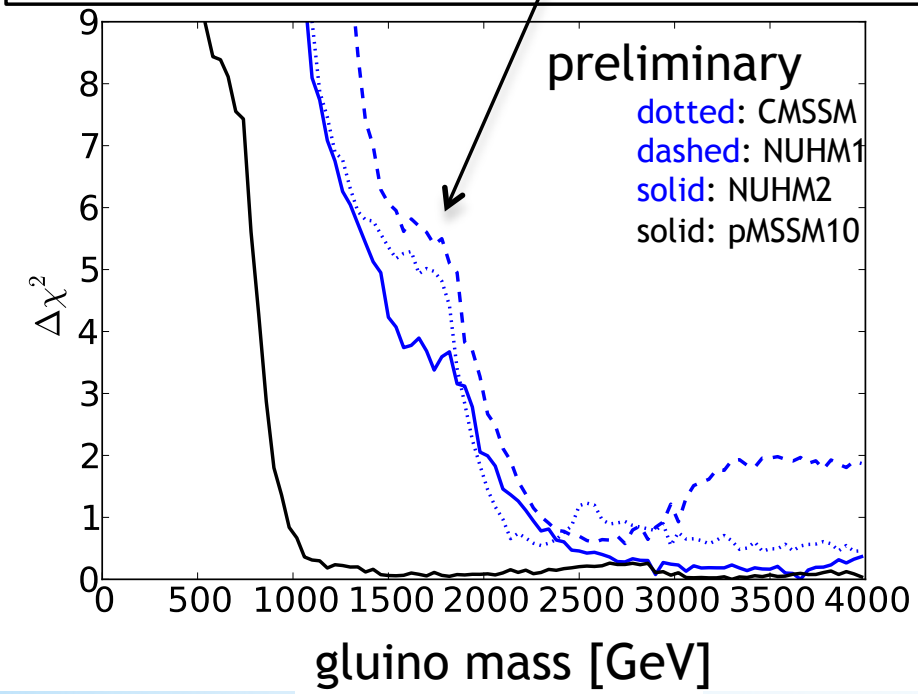
*Future prospects - CMSSM

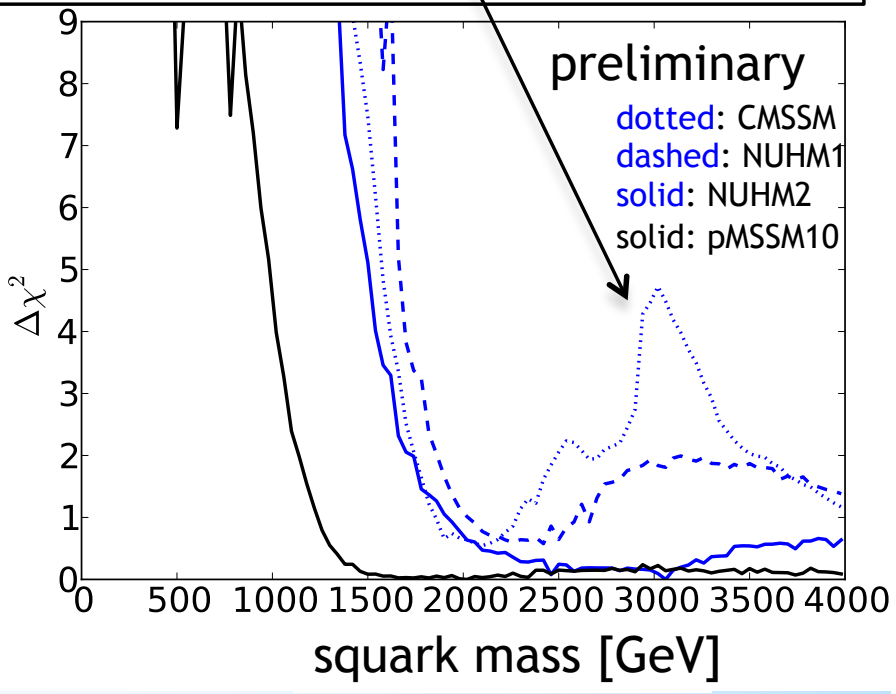


LHC has sensitivity to the lower isolated region

*Prospects for LHC in 2015 & beyond

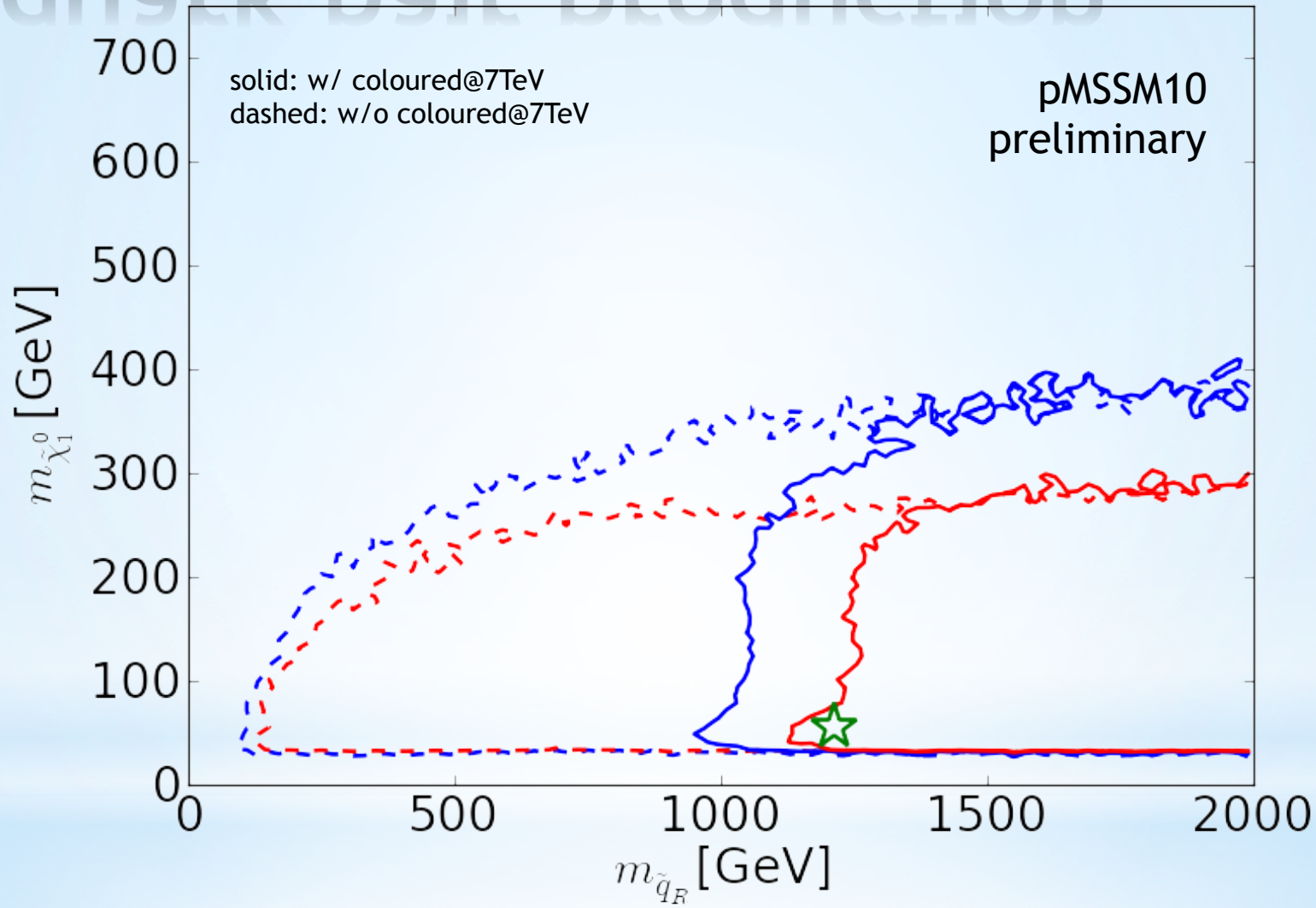
The **CMSSM**, **NUHM1** and **NUHM2** give very **comparable** mass ranges. For the squark mass, the two-modal structure is quite visible in the CMSSM, and less so in the other models.



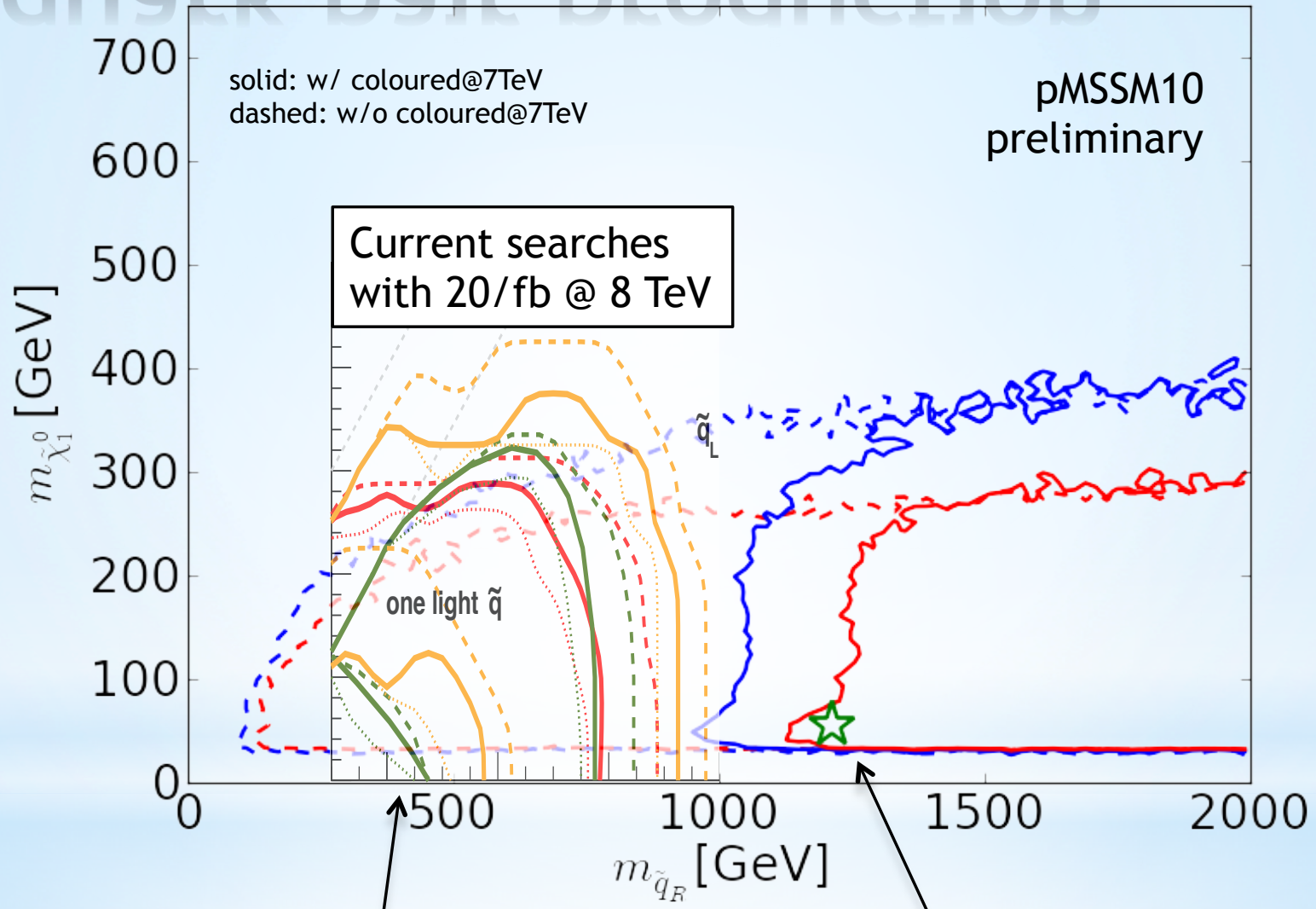


We currently apply 7TeV searches in the pMSSM10. The searches at 8TeV are work in progress.

*squark pair production

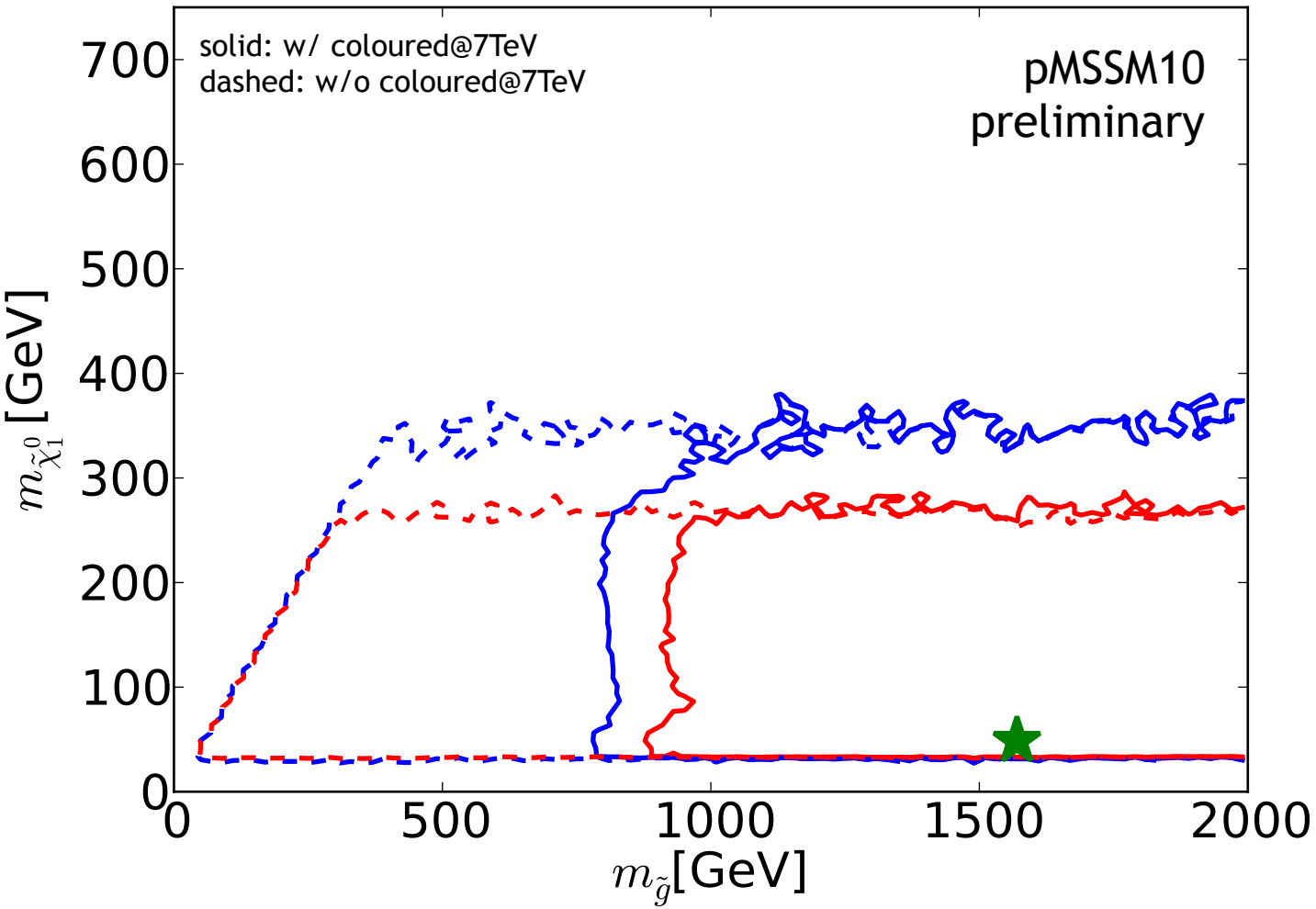


*squark pair production



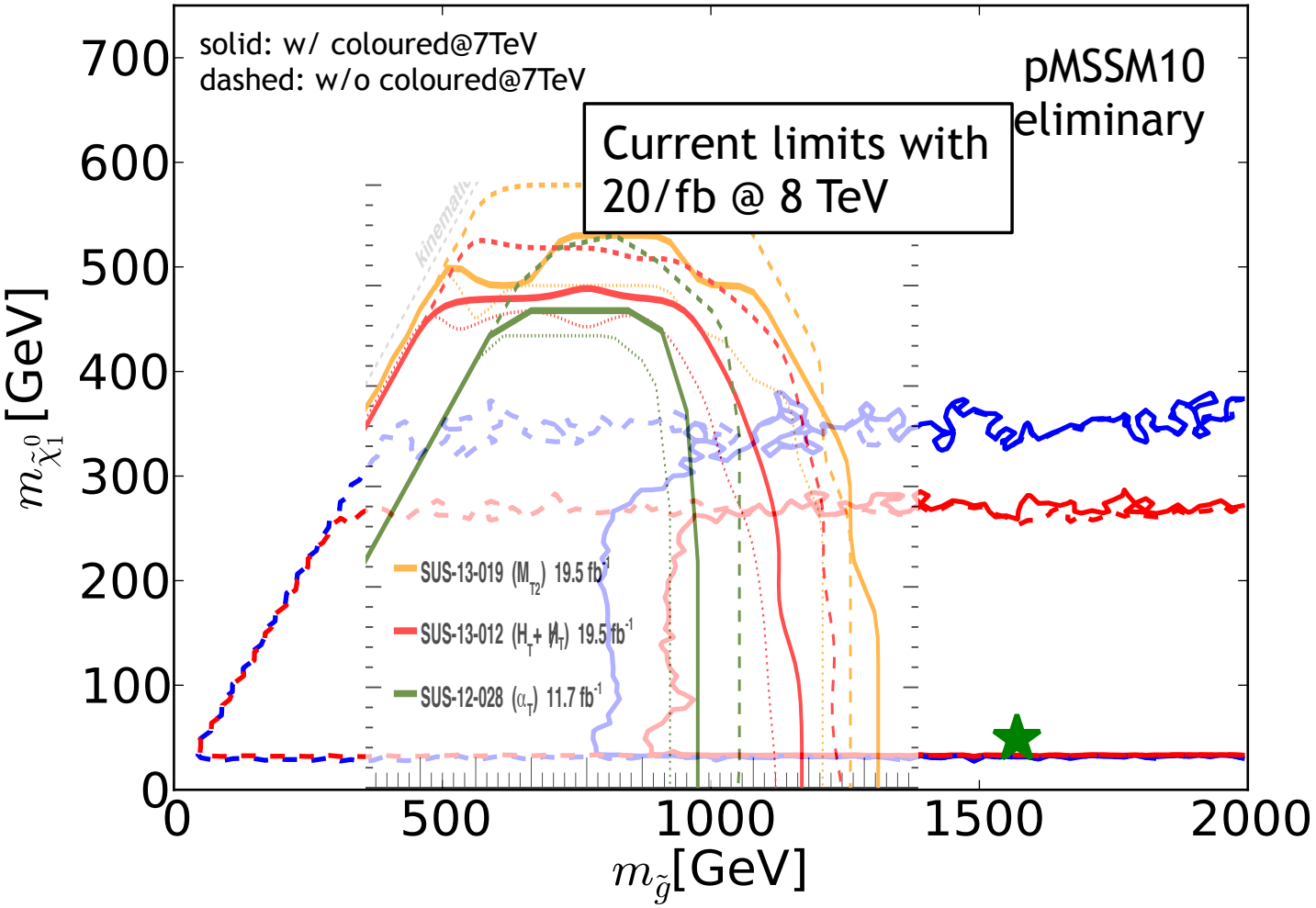
A lot of the parameter space, including the current best fit point, lies outside the reach of 8 TeV searches.

*gluino pair production



*gluino pair production

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS



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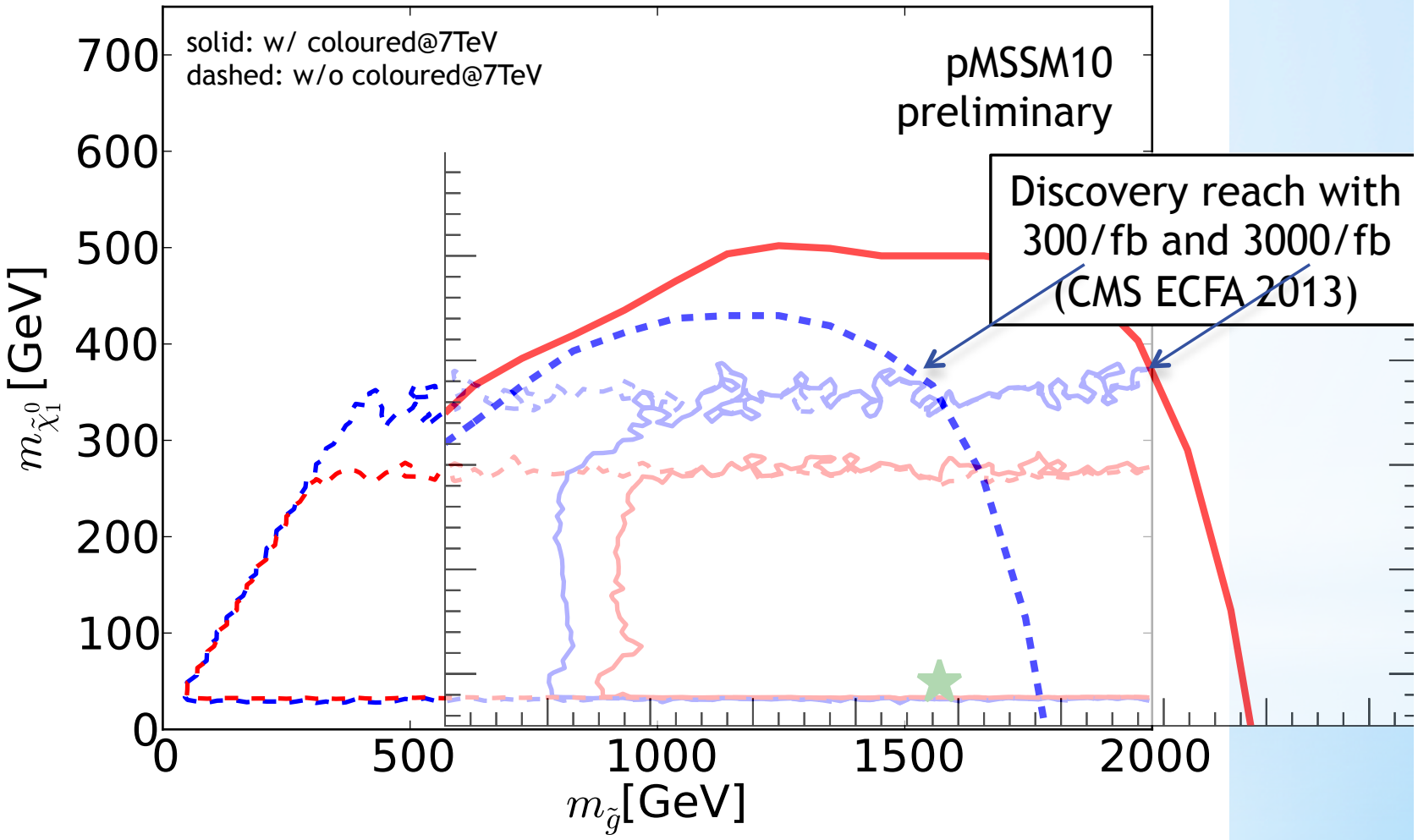
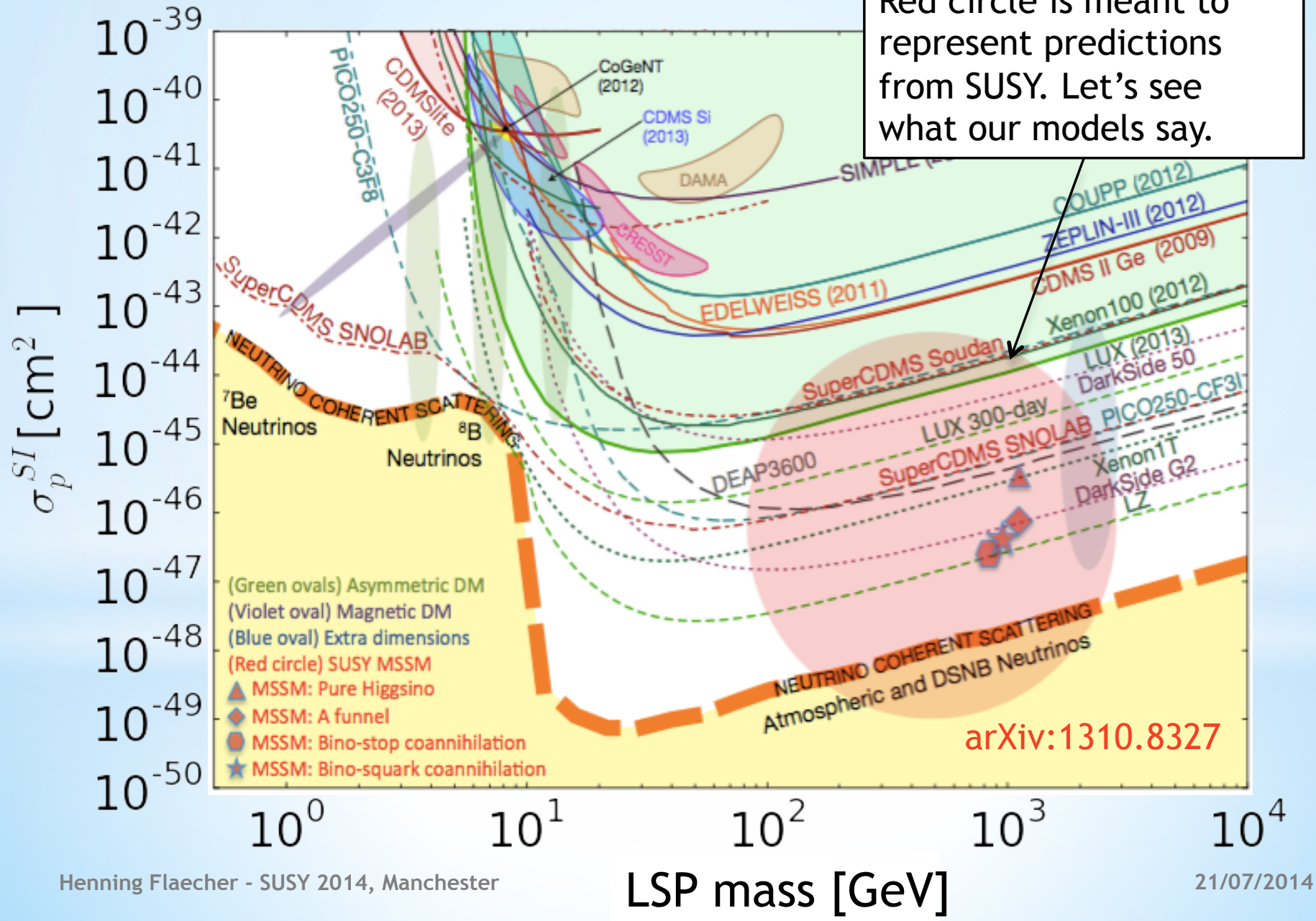


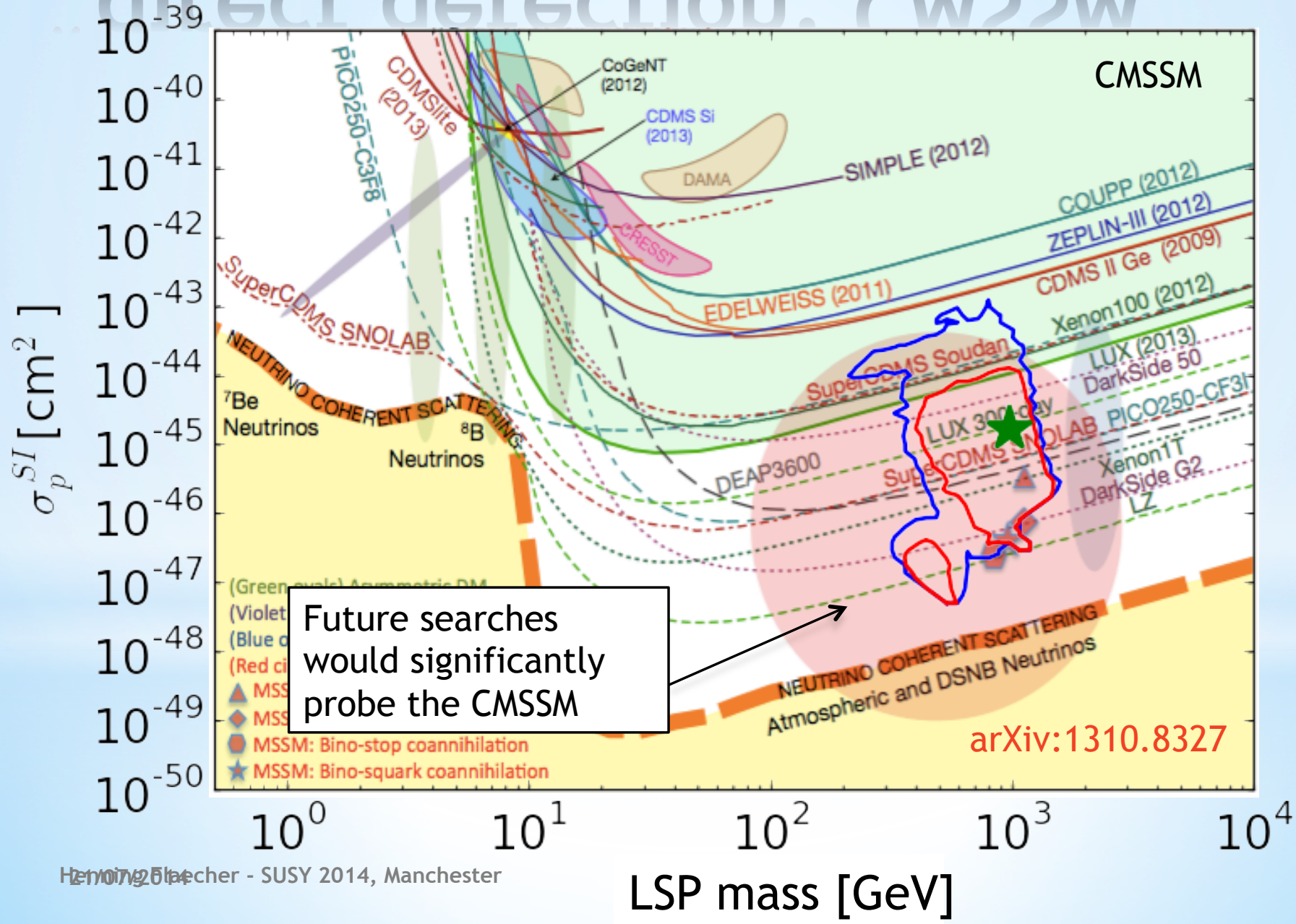
Current best fit point is within reach of 13 TeV LHC @ 300/fb

Direct dark matter detection: spin-independent scattering cross section

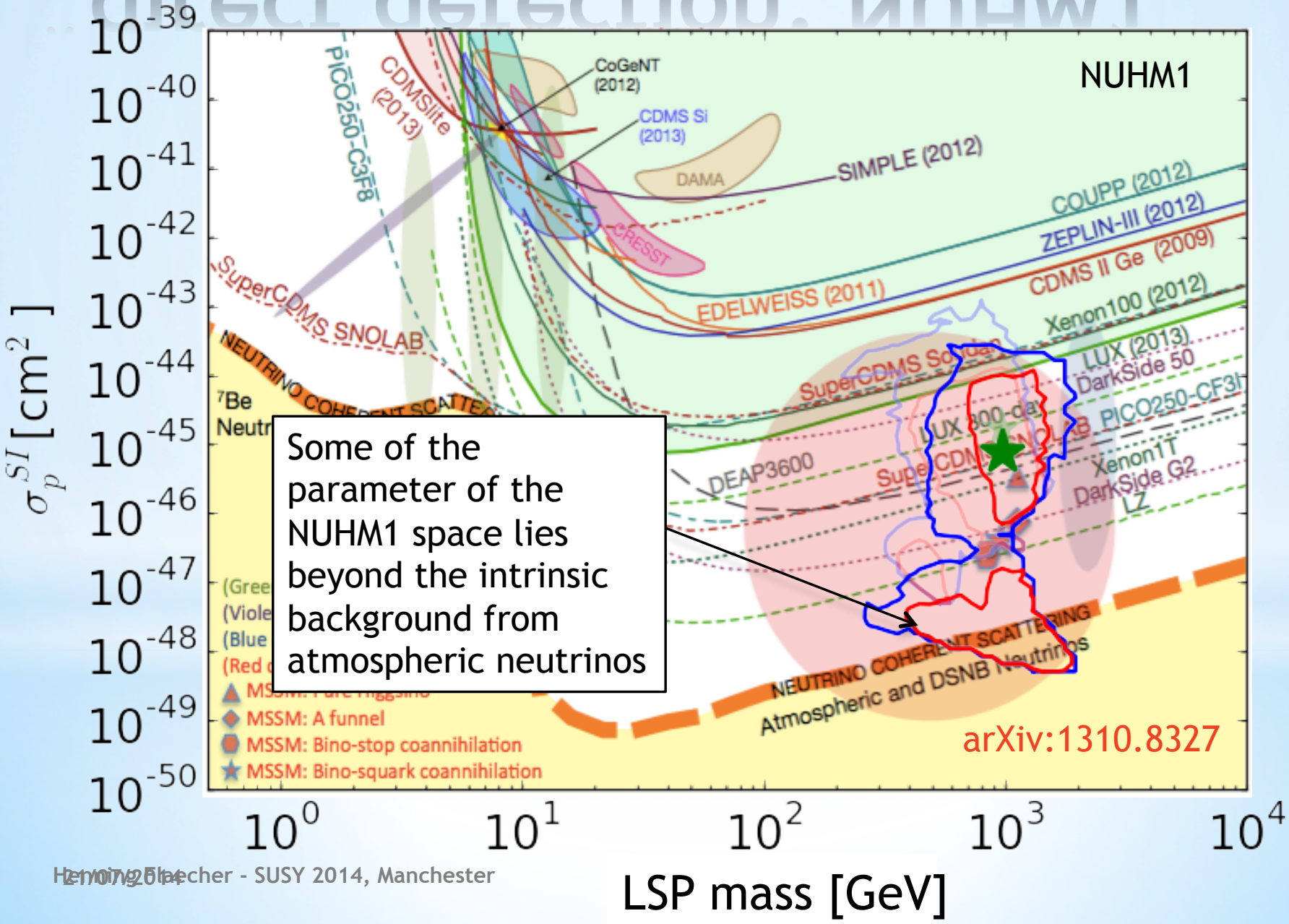
* direct detection: past-present-future



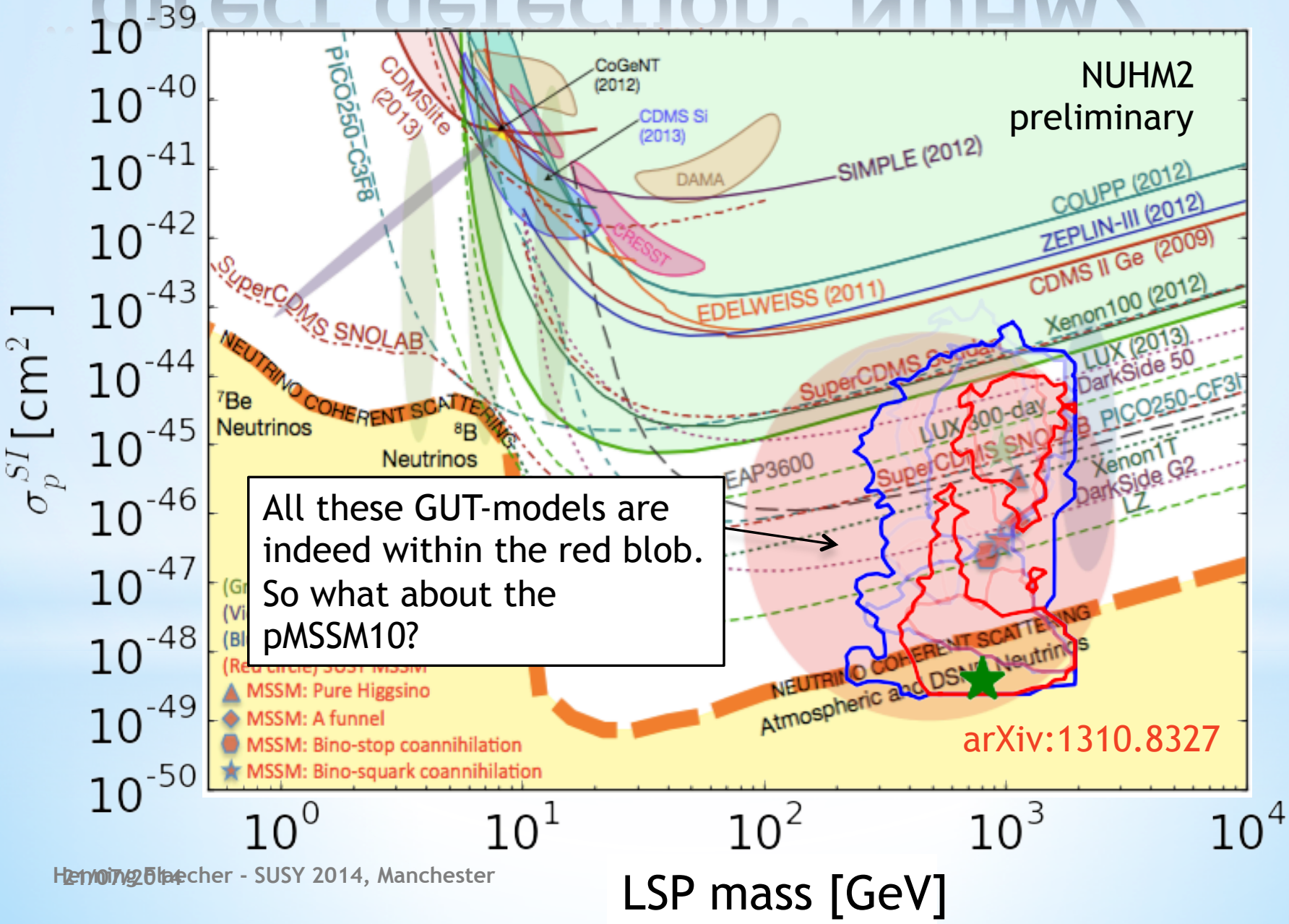
* direct detection: CMSSM



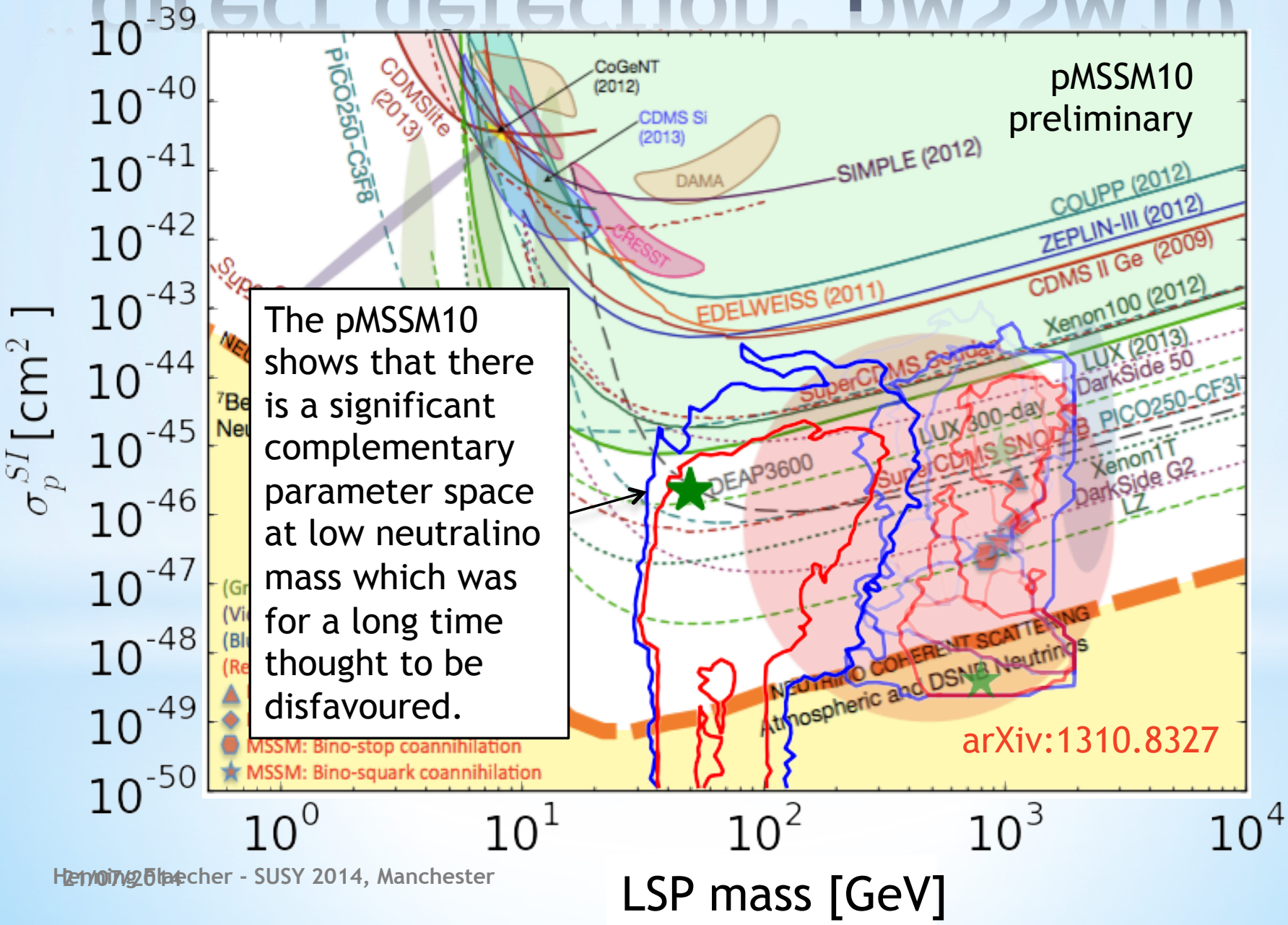
*direct detection: NUHM1



*direct detection: NUHM2

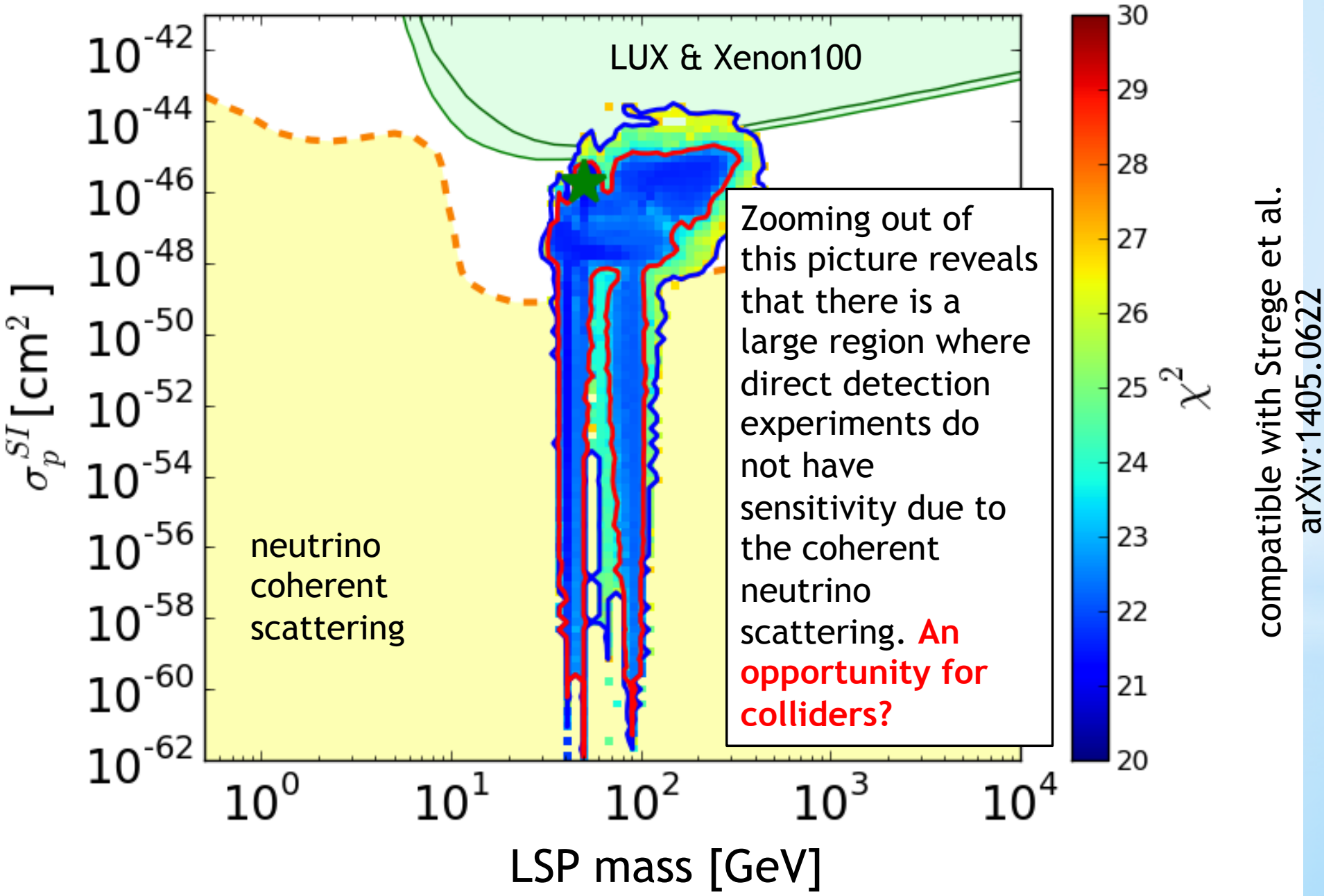


*direct detection: pMSSM10



The pMSSM10 shows that there is a significant complementary parameter space at low neutralino mass which was for a long time thought to be disfavoured.

*direct detection: pMSSM10



compatible with Strege et al.
arXiv:1405.0622

Conclusion & Outlook

- Comparison of our models
  - **CMSSM**, **NUHM1** and **NUHM2** show **tension** between the searches at the **LHC** and **(g-2)**
  - **pMSSM10** seems to **resolve** this **tension** and provides a significantly **better fit**
- Discovery potential at the LHC
  - In the pMSSM10 there is a huge parameter space "just around the corner" at low neutralino masses. **Early discovery?**
- Direct detection experiments
  - Future direct detection experiments will have access to a significant part of the parameter space of the CMSSM, NUHM1 and NUHM2
  - The pMSSM10 reveals a complimentary region with a large fraction below the neutrino floor. **An opportunity for colliders?**
- Outlook
  - Finish implementation of LHC searches for coloured and electroweak sparticles at 8 TeV for pMSSM10 and update our results

*backup

Mastercode: global fits of SUSY

- Models
  - **supergravity:** CMSSM, NUHM1, NUHM2 NEW
  - **phenomenological:** pMSSM10 NEW
- Experimental constraints
  - **cosmology:** Dark Matter density, direct detection
  - **indirect searches:** Flavour and Electroweak Precision observables
  - **direct searches:** Higgs, coloured sparticles, electroweakinos
- Predictor codes
  - **public:** SoftSUSY, FeynHiggs, Micromegas, SuperIso
  - **private:** SuFla, FeynWZ, SSARD
- Sampling algorithm
  - Multinest

The **implementation** of the **experimental constraints** follows arXiv:1312.5250. Some details can be found in the backup slides

*parameter ranges

	CMSSM	NUHM1	NUHM2
m_0	(0, 6000) GeV	(0, 4000) GeV	(-1000, 4000) GeV
m^2_H	-	$(-5\times10^7, 5\times10^7)$ GeV^2	-
m^2_{Hu}	-	-	$(-5\times10^7, 5\times10^7)$ GeV^2
m^2_{Hu}	-	-	$(-5\times10^7, 5\times10^7)$ GeV^2
$m_{1/2}$	(0,4000) GeV	(0,4000) GeV	(0,4000) GeV
A_0	(-5000, 5000) GeV	(-5000, 5000) GeV	(-8000, 8000) GeV
tanβ	(2, 68)	(2, 68)	(2, 68)
sign(μ)	1	1	1

Note: these parameter ranges were chosen to examine relevant parameter space for the LHC. As we will see, the **1σ and 2σ contours do not always** close for this choice of ranges. This should be kept in mind when interpreting the results.

*pMSSM10: parameter ranges

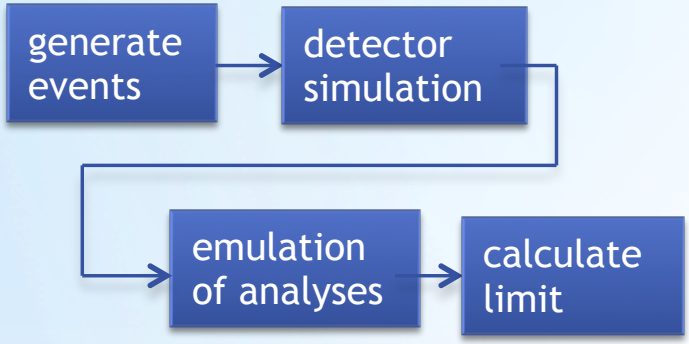
			#segments
msq12	0	4000	2
msq3	0	4000	2
msl	0	4000	2
M1	-4000	4000	4
M2	0	4000	2
M3	-4000	4000	4
MA	0	4000	2
A	-5000	5000	1
mu	-5000	5000	1
tanb	1	60	1

This set of parameters is chosen to allow uncorrelated neutralino, gluino, stop and squark masses, whilst keeping the number of fit parameters low.

*LHC limits on coloured production

challenge: establish level of exclusion for O(10^8) points

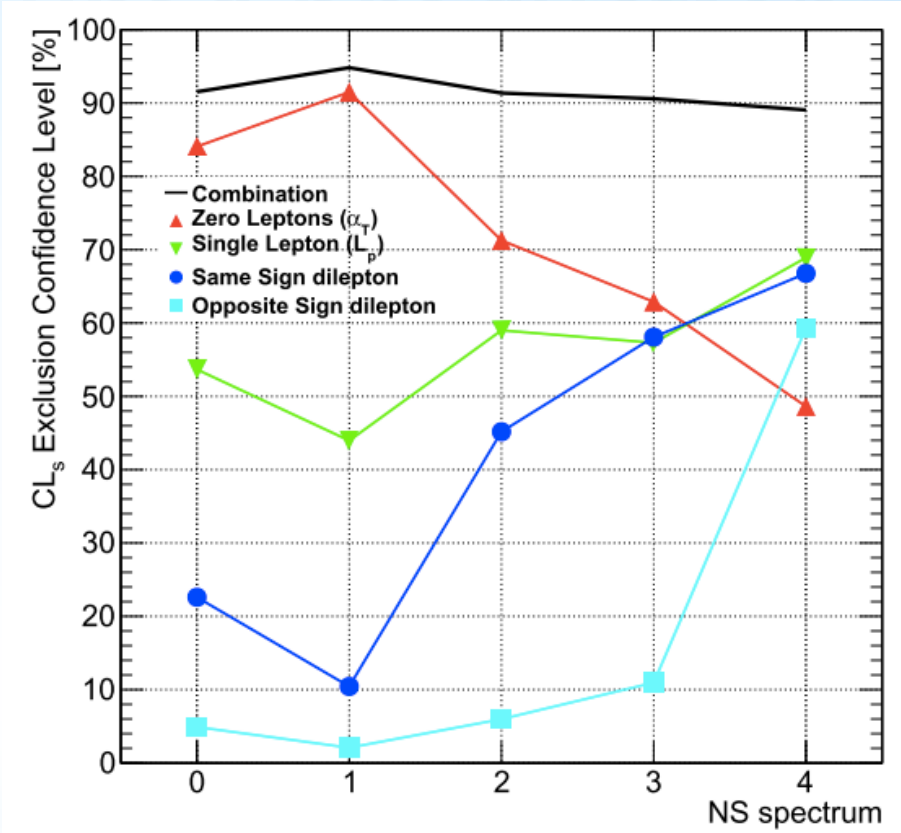
if one had infinite CPU time, one could run for each point in parameter space



but NOT computationally feasible (6 years on 1000 cores)

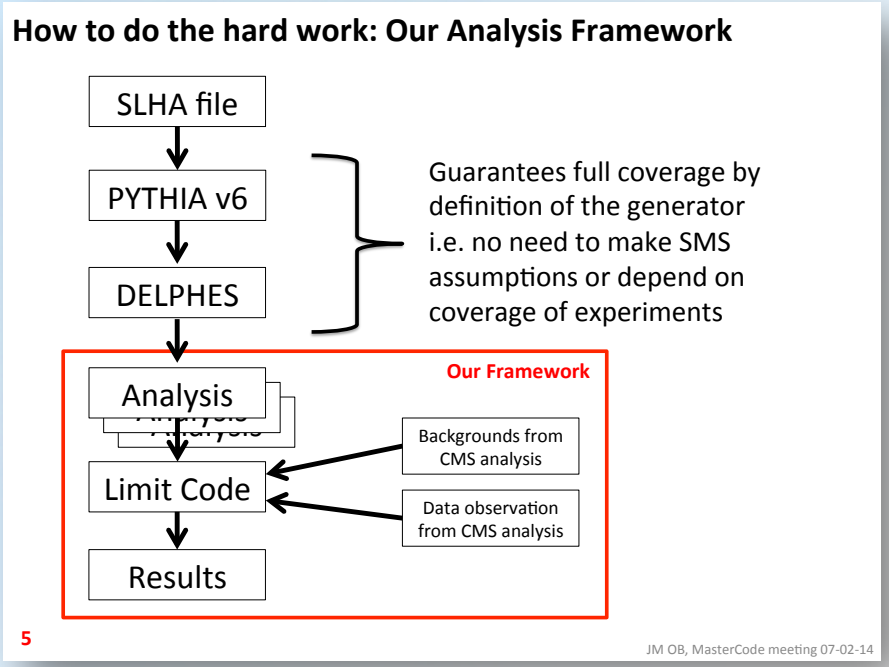
an alternative is to combine all SMS models **but**

1. **not all relevant SMS limits are available (problem)**
2. **would need to evaluate for each point in parameter space (NOT computationally feasible)**

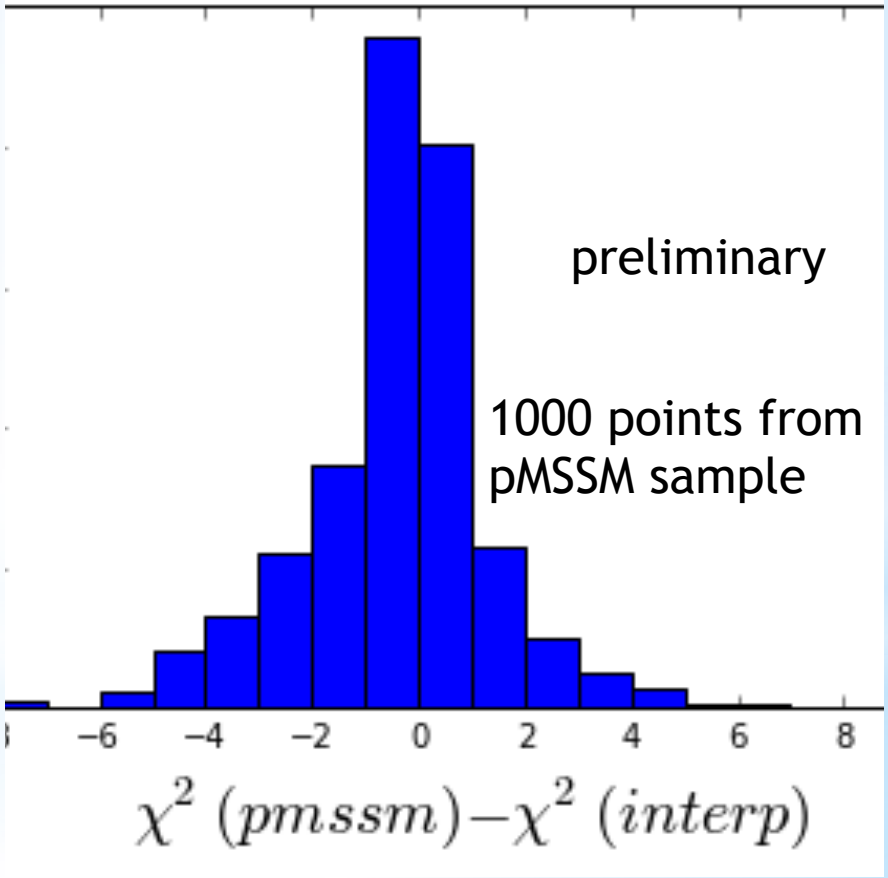


In our approach we make use of the finding by OB and JM in **1304.2185** that if one **combines sufficiently inclusive searches**, then the exclusion is mainly driven by the masses of **1) neutralino; 2) gluino; 3) 1st and 2nd generation squark; 4) 3rd generation squark**

*LHC limits on coloured production



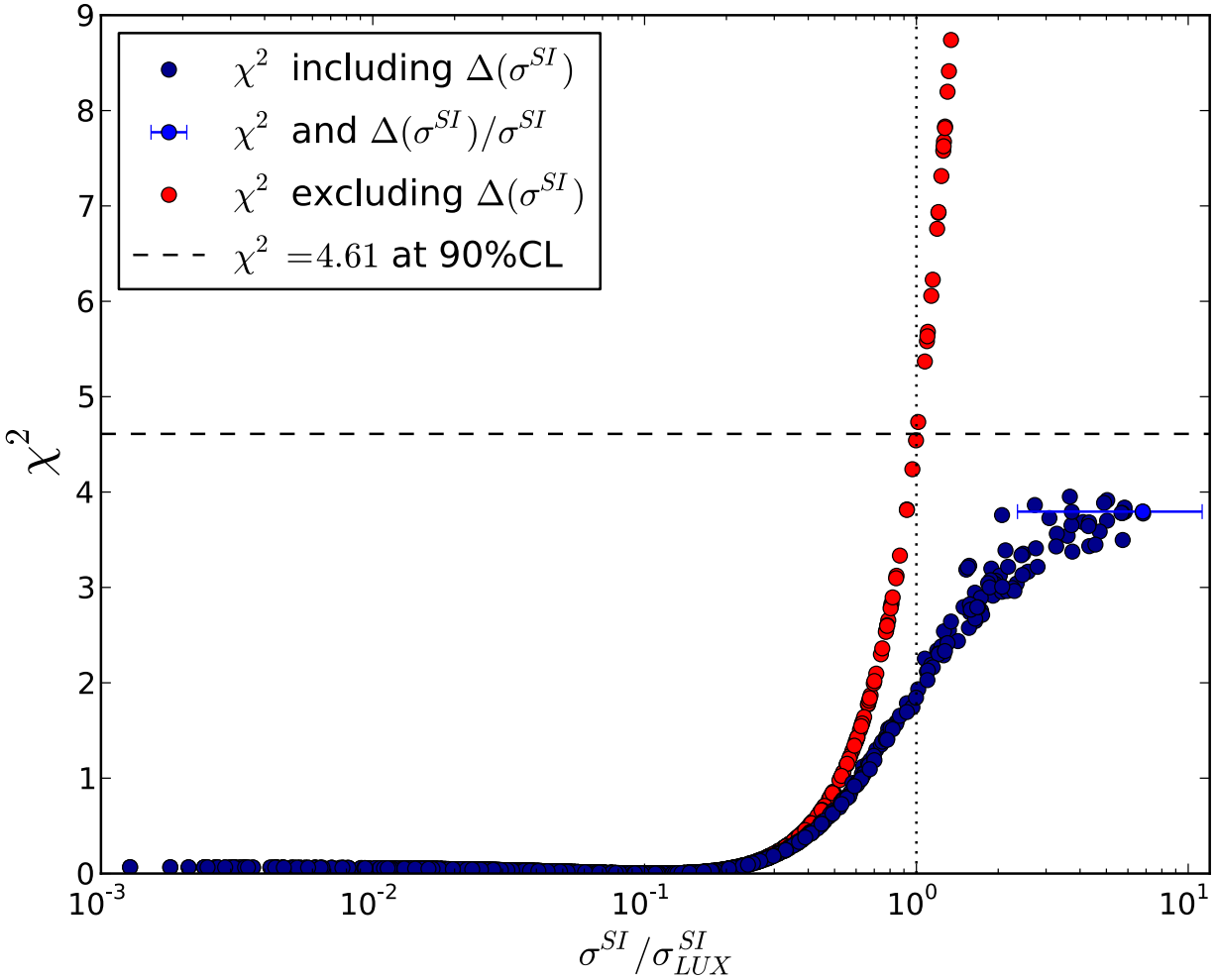
note: we have implemented and validated the 7 TeV searches. The 8 TeV searches are work in progress.



we generate a 4-d grid using **inclusive** searches for

- 0 leptons + MET
- 1 leptons + MET
- 2 leptons (OS & SS) + MET
- >=3 leptons + MET

we linearly interpolate based on this grid


χ^2 including $\Delta(\sigma^{SI})$
χ^2 and $\Delta(\sigma^{SI})/\sigma^{SI}$
χ^2 excluding $\Delta(\sigma^{SI})$
χ^2 =4.61 at 90%CL
χ^2
$\sigma^{SI}/\sigma^{SI}_{LUX}$
0
1
2
3
4
5
6
7
8
9
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}