Sometimes I drive recklessly, just to kill off close copies of me in the multiverse.

SUSY Dark Matter at the LHC

Sven Heinemeyer, IFCA (CSIC, Santander)

Heidelberg, 06/2015

1. Introduction

2. Preparations

3. Results in GUT based models

4. Results in the pMSSM10

5. Conclusions

1. Introduction

Some “recent” measurements:

– top quark mass
– Higgs boson mass
– Higgs boson “couplings”
– Dark Matter (properties)

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Simple SUSY models predicted correctly:

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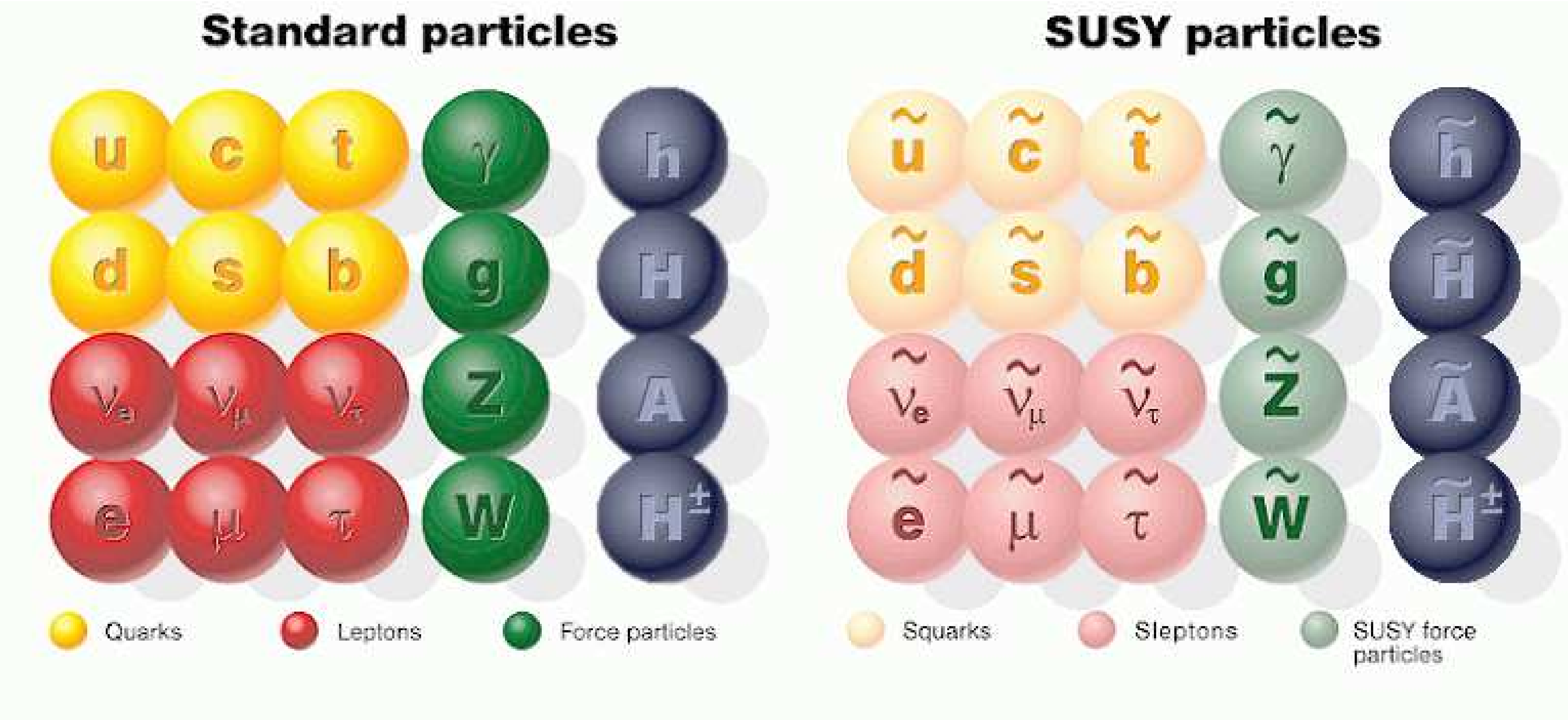
$\Rightarrow$ good motivation to look at SUSY!

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles



Problem in the MSSM: more than 100 free parameters

Nobody(?) believes that a model describing nature
has so many free parameters!

A. Unconstrained models (MSSM):

agnostic about how SUSY breaking is achieved
no particular SUSY breaking mechanism assumed, parameterization of possible soft SUSY-breaking terms

most general case:

$\Rightarrow$ 105 new parameters: masses, mixing angles, phases

$\Rightarrow$ no model missed (within the MSSM)

$\Rightarrow$ $\mathcal{O}(100)$ parameters difficult to handle

B. Constrained models (CMSSM, NUHM1, NUHM2, . . .):

assumption on the scenario that achieves spontaneous SUSY breaking
$\Rightarrow$ prediction for soft SUSY-breaking terms
in terms of small set of parameters

- CMSSM: m_0, $m_{1/2}$, A_0, $\tan\beta$
- NUHM1: m_0, $m_{1/2}$, A_0, $\tan\beta$, m_H
- NUHM2: m_0, $m_{1/2}$, A_0, $\tan\beta$, m_{H_u}, m_{H_d}

$\Rightarrow$ easy to handle $\Rightarrow$ "likely": correct model missed??

Problem: We cannot be sure about the SUSY-breaking mechanism

⇒ it is possible that with the CMSSM, NUHM1, NUHM2, . . . we missed the “correct” mechanism

⇒ hint: strong connection between colored and uncolored sector
tension between low-energy EW effects and (colored) LHC searches

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Solution: investigate also the "general MSSM"

⇒ 10 parameters are manageable ⇒ pMSSM10

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

pMSSM10 scanned parameter ranges:

Parameter	Range	Number of segments
M_1	(-1 , 1) TeV	2
M_2	(0 , 4) TeV	2
M_3	(-4 , 4) TeV	4
$m_{\tilde{q}}$	(0 , 4) TeV	2
$m_{\tilde{q}_3}$	(0 , 4) TeV	2
$m_{\tilde{l}}$	(0 , 2) TeV	1
M_A	(0 , 4) TeV	2
A	(-5 , 5) TeV	1
μ	(-5 , 5) TeV	1
$\tan\beta$	(1 , 60)	1
Total number of boxes		128

2. Preparations Our tool: Mastercode

⇒ collaborative effort of theorists and experimentalists
[*Bagnaschi, Buchmüller, Cavanaugh, Citron, De Roeck, Dolan, Ellis, Flächer, SH, Isidori, Mallik, Marouche, Martinez Santos, Olive, Sakurai, de Vries, Weiglein*]

Über-code for the combination of different tools:

– Über-code original in Fortran, now re-written in C++
– tools are included as subroutines
– compatibility ensured by collaboration of authors of "MasterCode" and authors of "sub tools" /SLHA(2)
– sub-codes in Fortran or C++

⇒ evaluate observables of one parameter point consistently with various tools

cern.ch/mastercode

Status of the "MasterCode":

– (so far) one model: (MFV) MSSM

– tools included:
  - our own LHC SUSY search implementation ⇒ NEW
    (3 search categories: colored, electroweak, compressed stop)
  - Higgs related observables, $(g-2)_\mu$ [*FeynHiggs*]
  - Higgs signal strengths [*HiggsSignals*] ⇒ NEW
  - Higgs exclusion bounds [*HiggsBounds*] ⇒ NEW
  - B-physics observables [*SuFla*]
  - more B-physics observables [*SuperIso*]
  - Electroweak precision observables [*FeynWZ*]
  - Dark Matter observables [*MicrOMEGAs, SSARD*]
  - for GUT scale models: RGE running [*SoftSusy*]

⇒ all most-up-to-date codes on the market!

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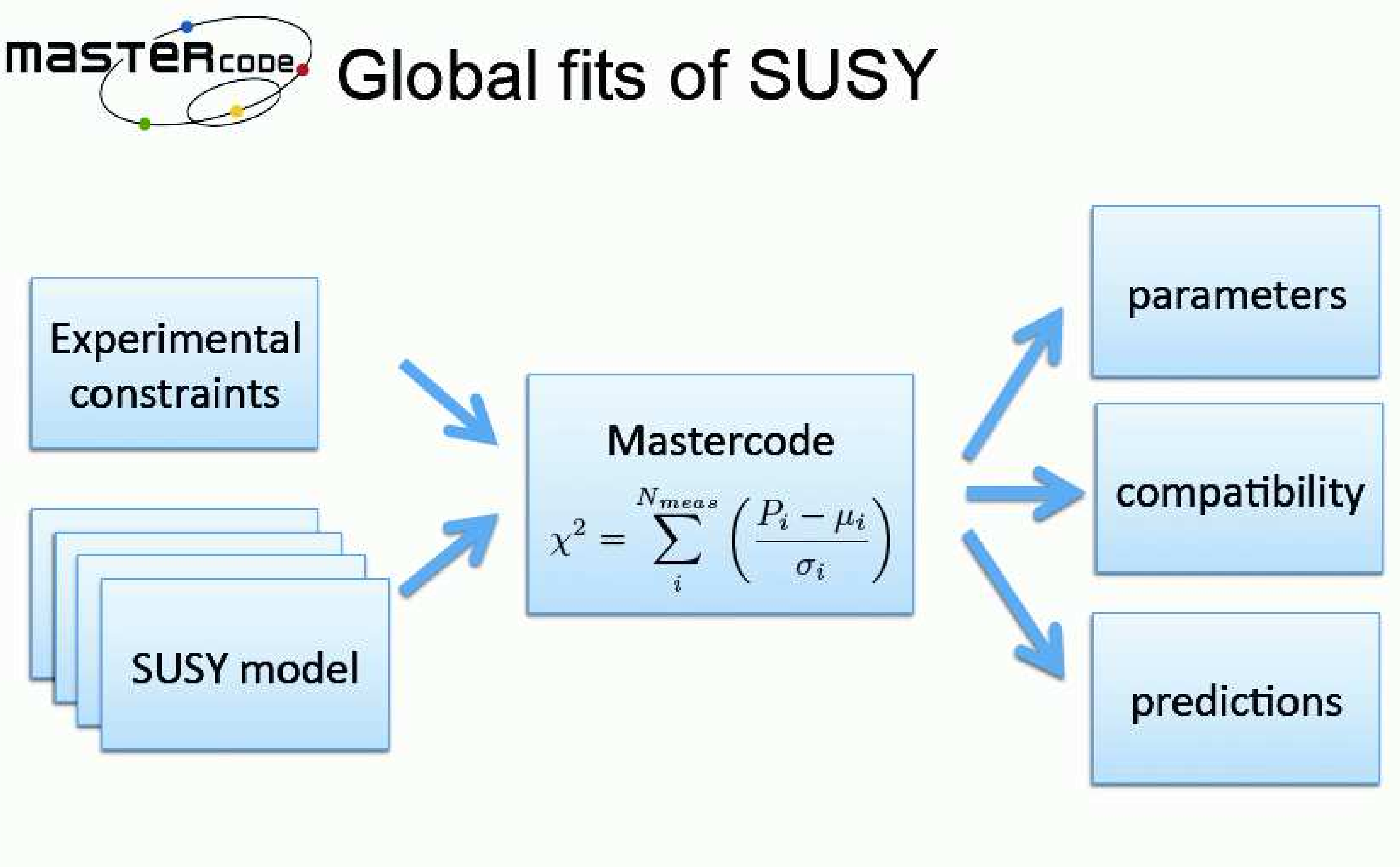
⇒ all most-up-to-date codes on the market!   ⇒ crucial for precision!

The χ^2 evaluation:



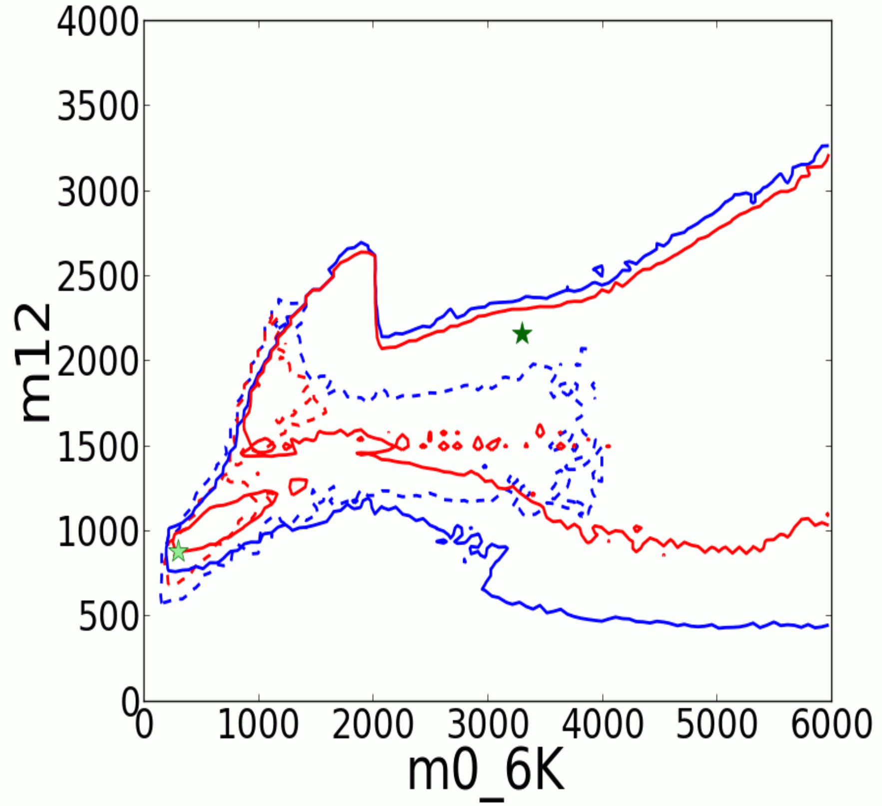
3. Results in GUT based models

- evolution of results in the CMSSM, NUHM1
- results for the DM mass predictions in the CMSSM, NUHM1
- results in the $m_{\tilde{\chi}_1^0}$–$\sigma_p^{\rm SI}$ plane for the CMSSM, NUHM1, NUHM2
- analysis of DM anihilation processes
- ...

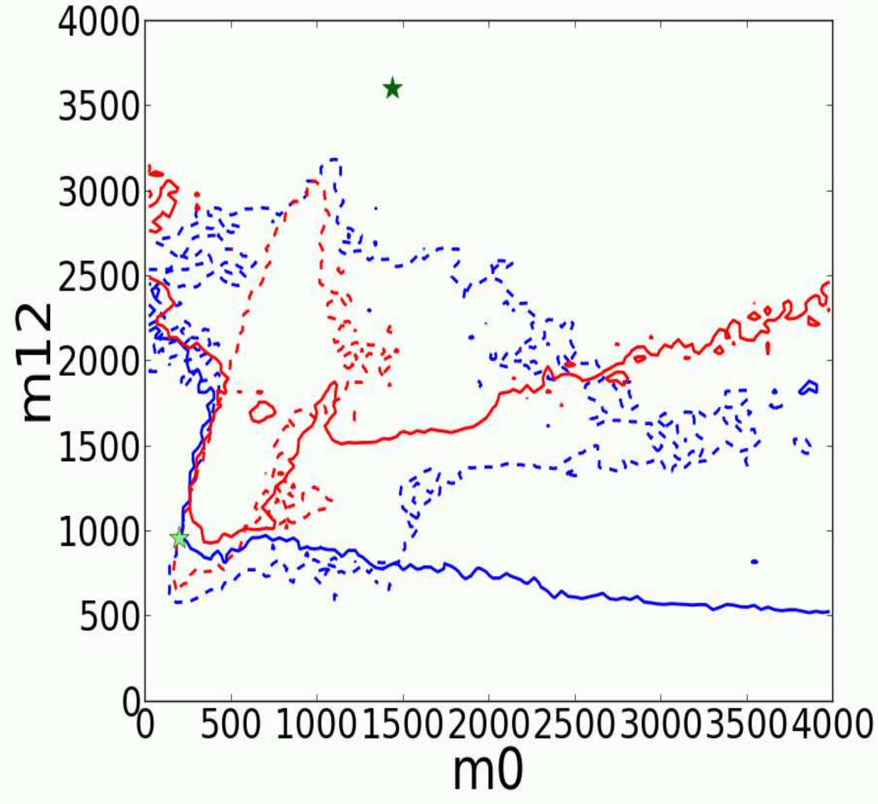
m_0-$m_{1/2}$ plane including LHC 20/fb:

[2013]

CMSSM



NUHM1



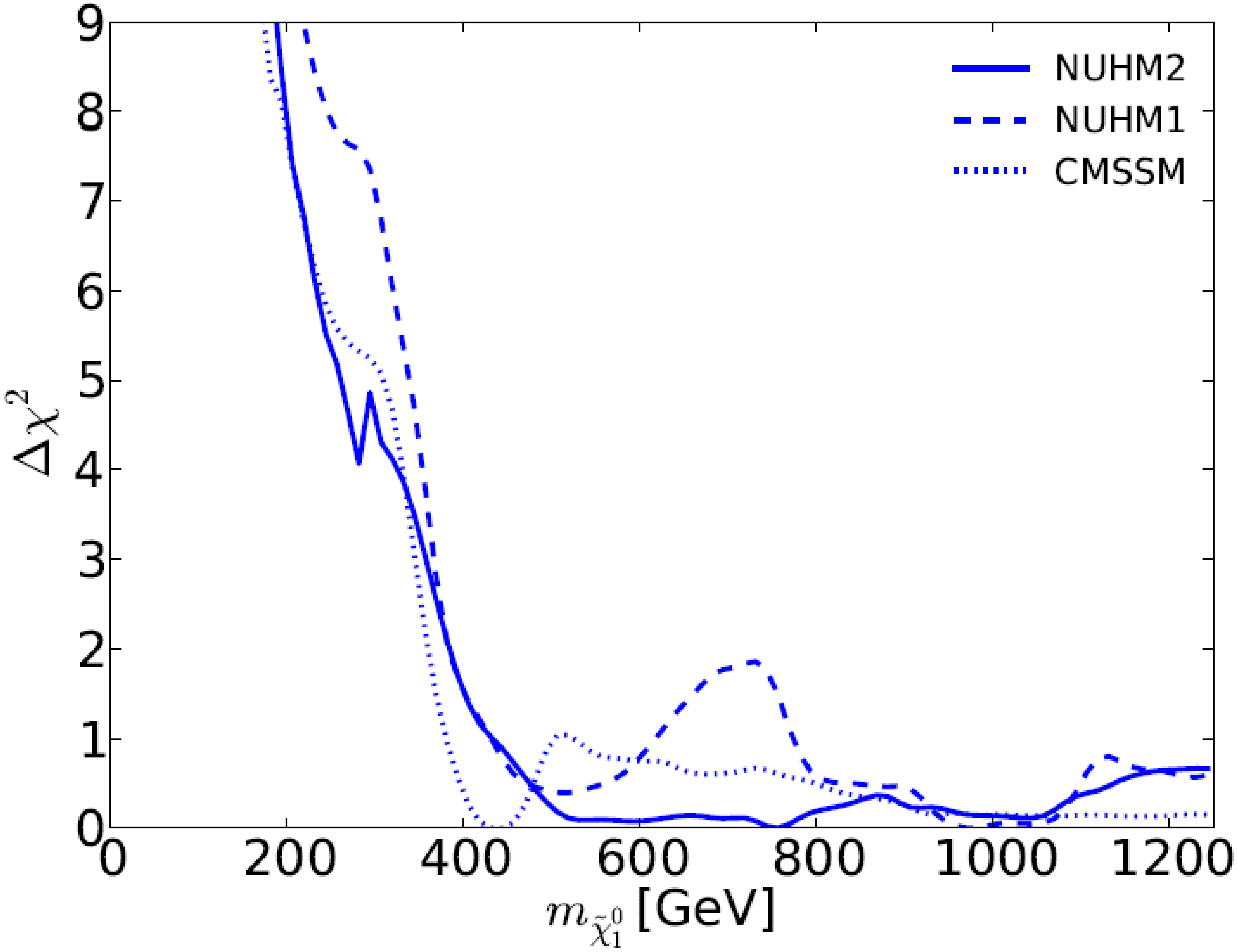
dotted: LHC 5/fb 7 TeV, solid: LHC 20/fb 8 TeV

⇒ shift to even higher masses

even larger allowed ranges . . .

LSP mass incl. 20/fb of LHC data

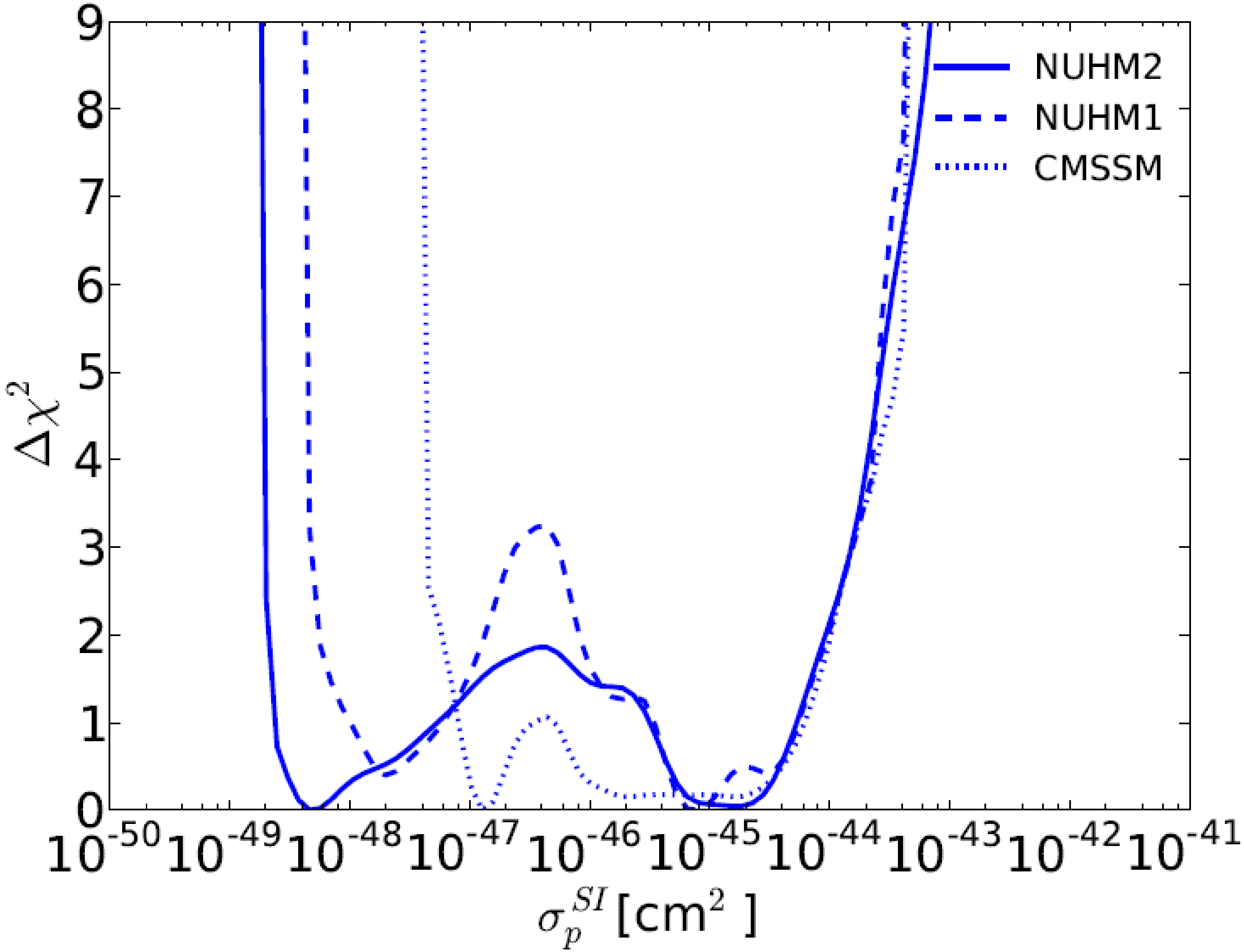
[2014]



⇒ only very large values are favored

$\sigma_p^{\rm SI}$ incl. 20/fb of LHC data

[2014]



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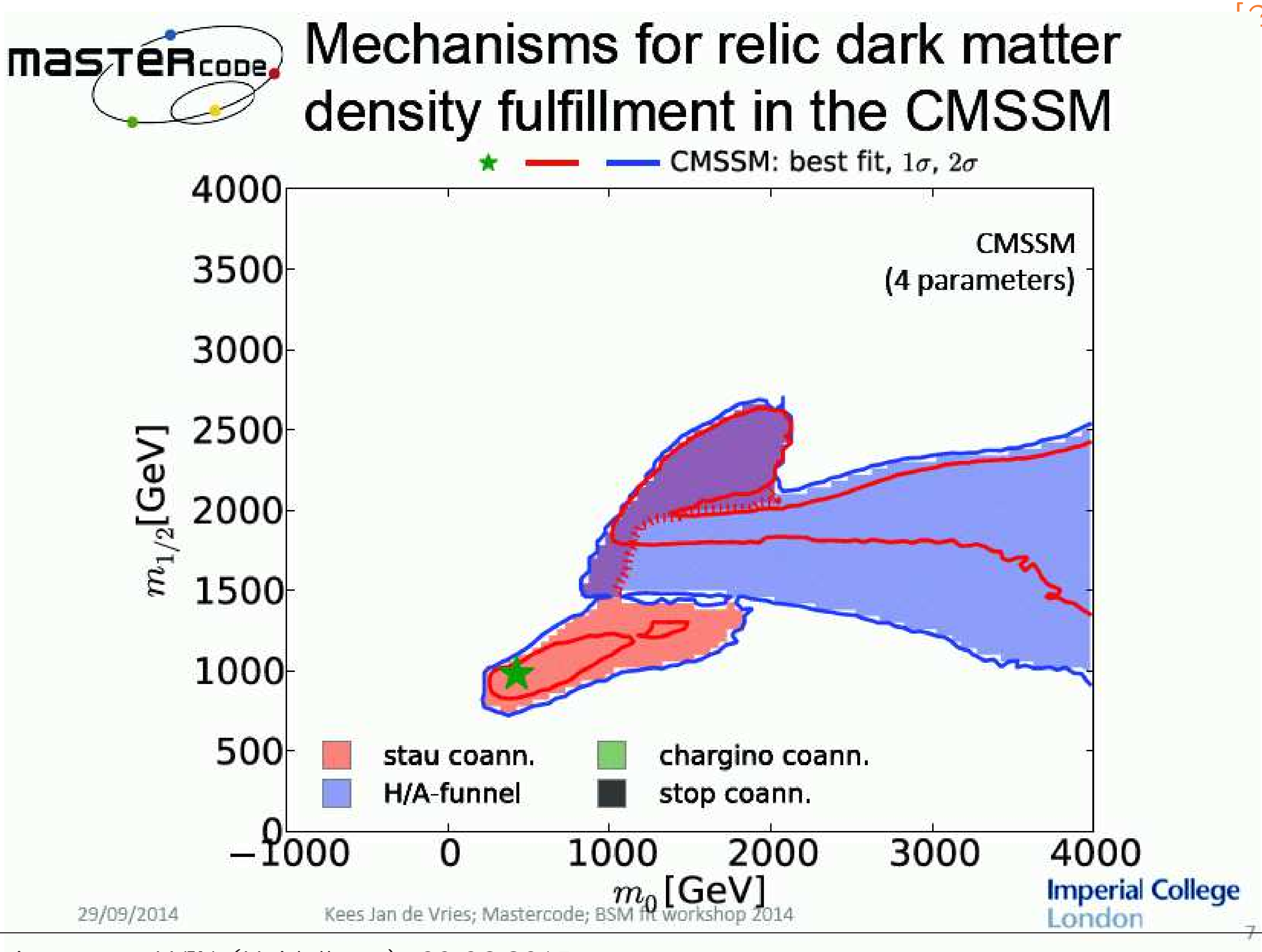
CMSSM DM prediction

[2014]



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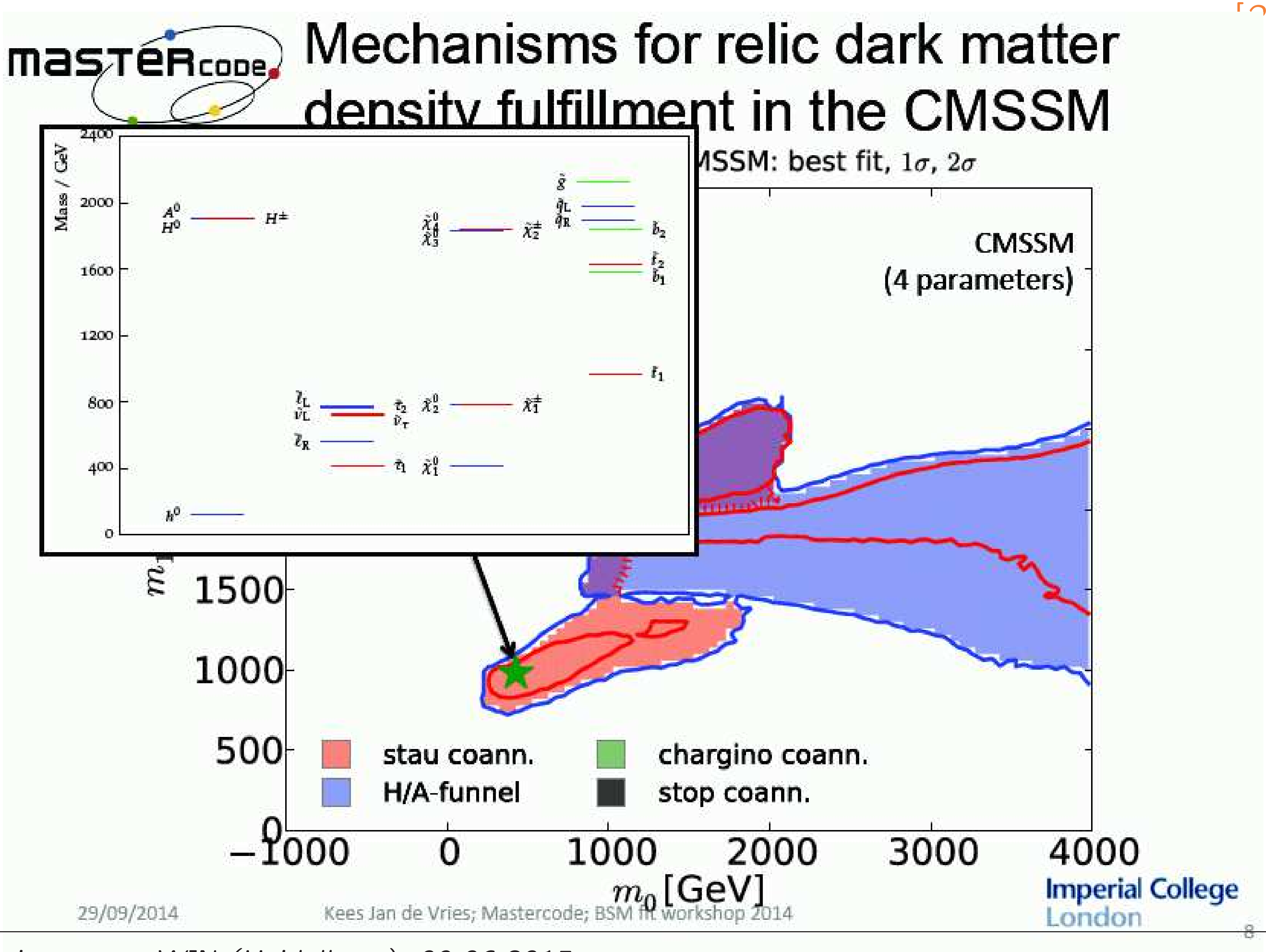

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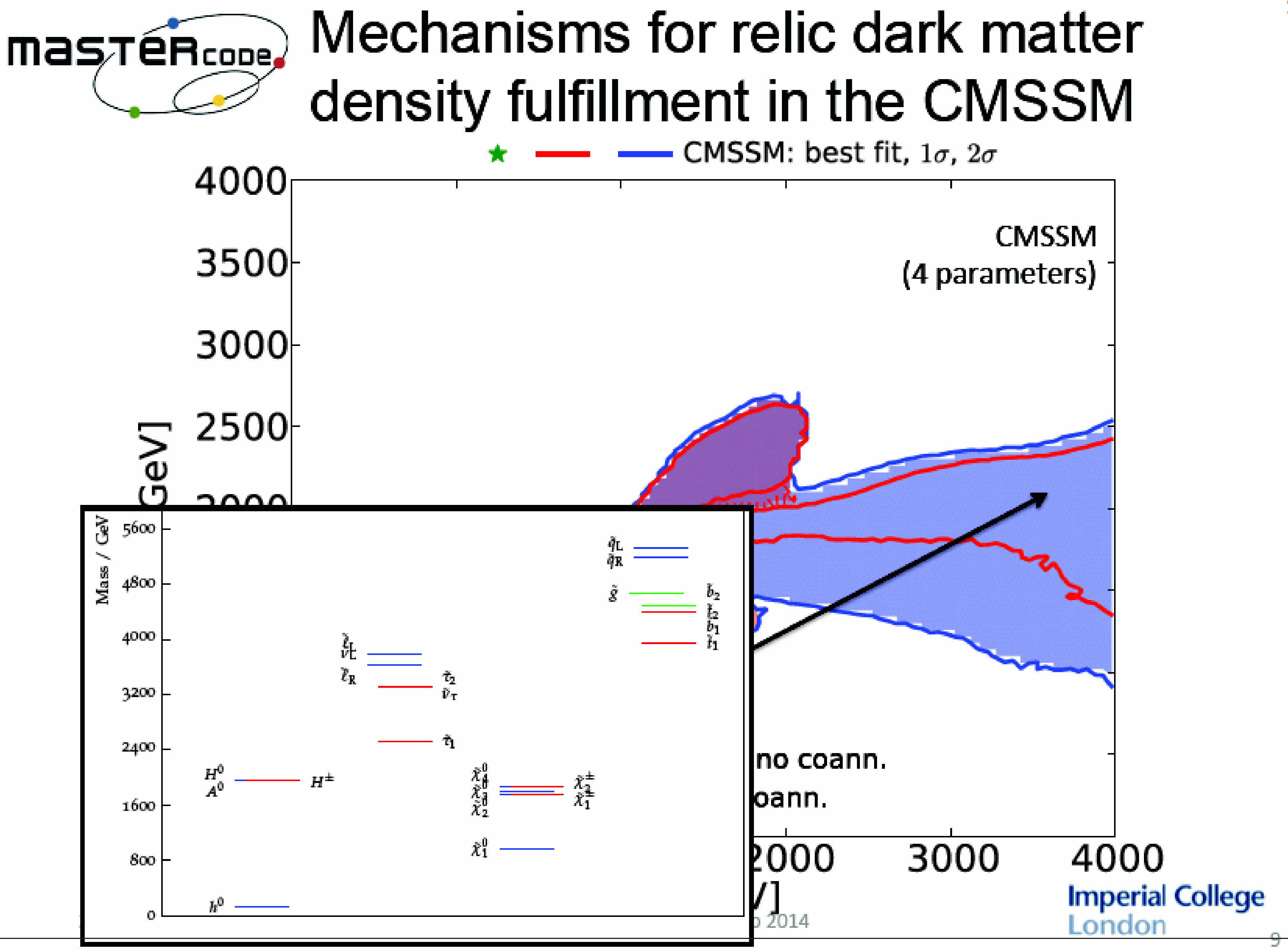
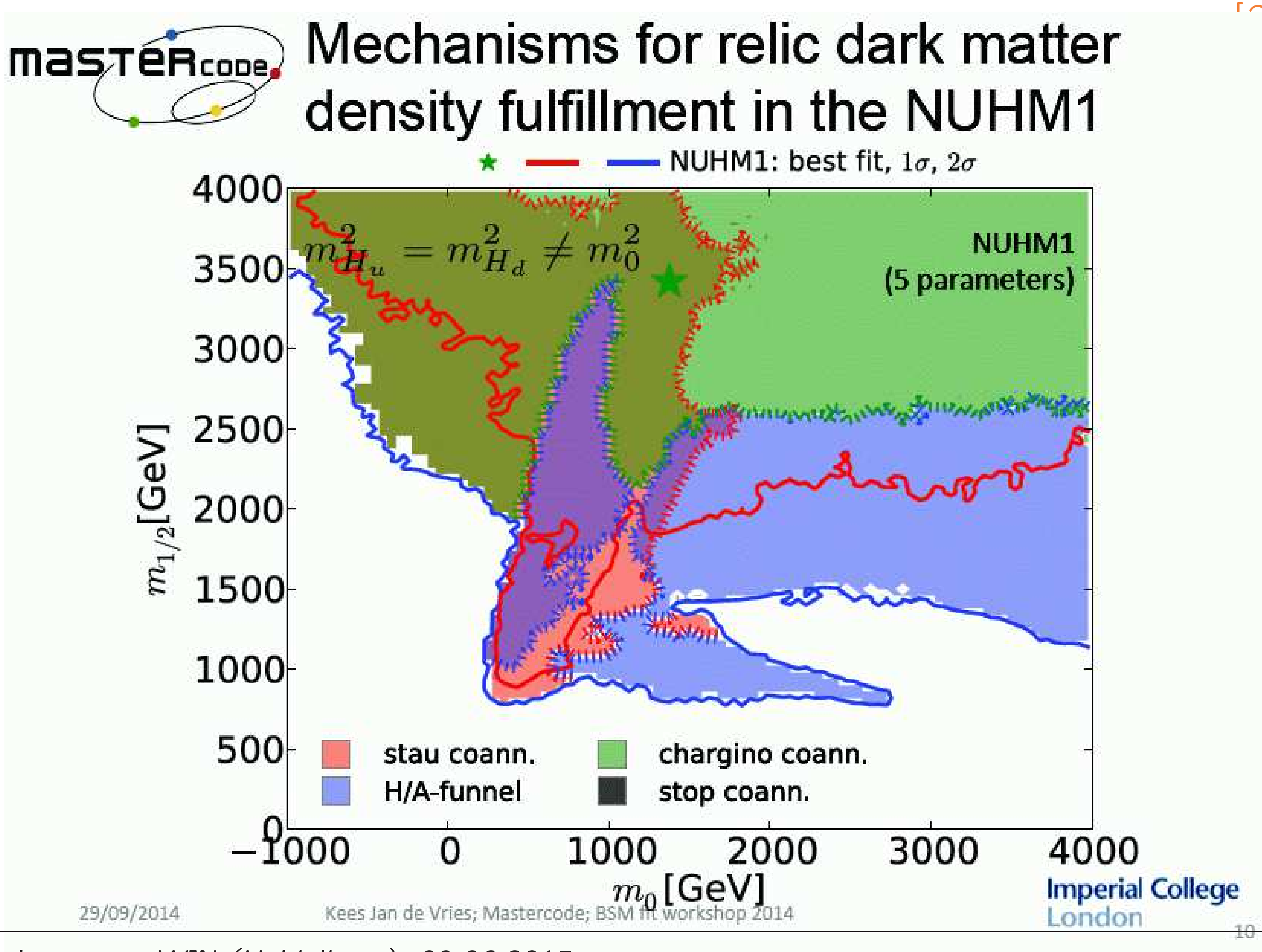


NUHM1 DM prediction

[2014]



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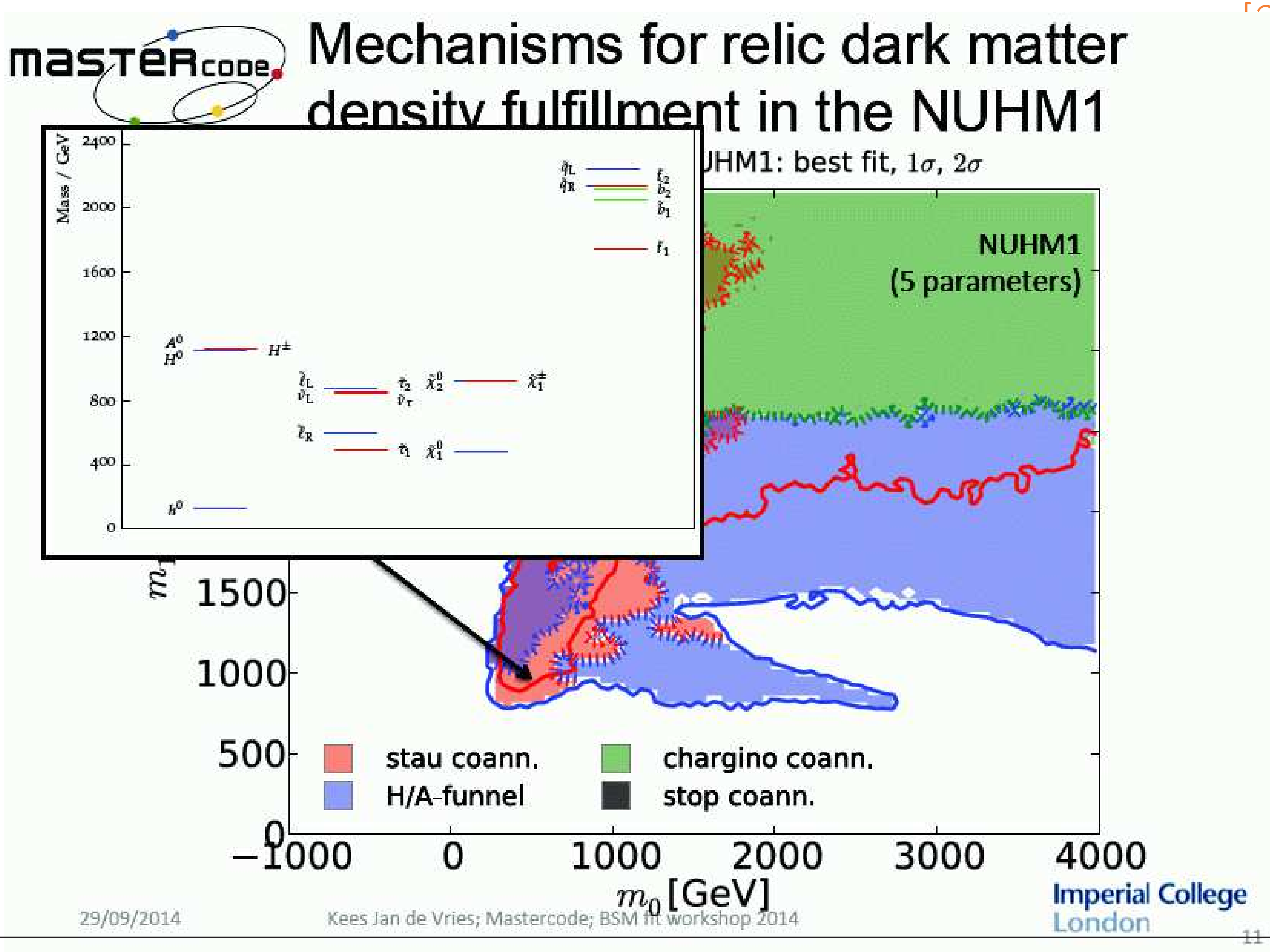
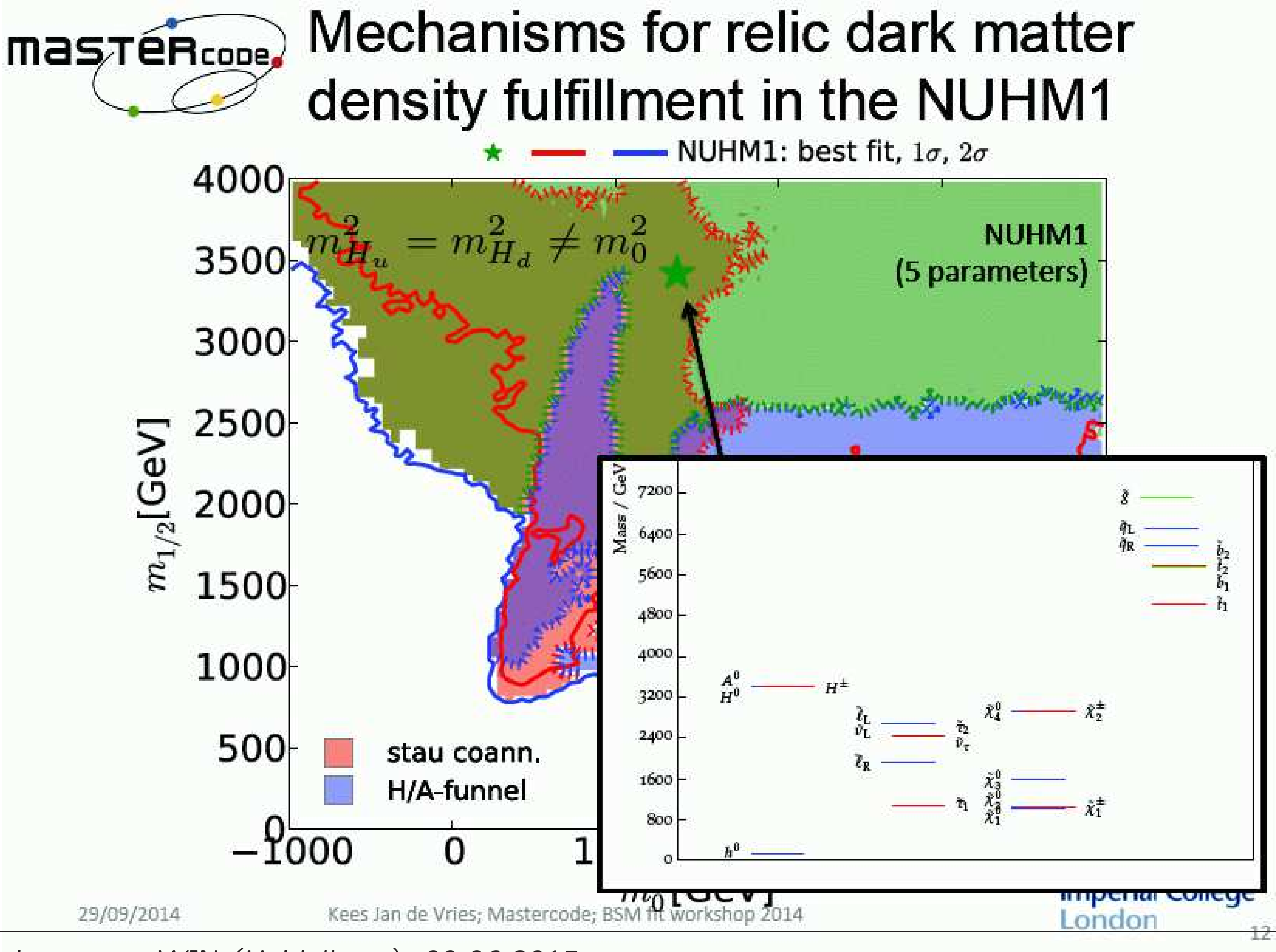


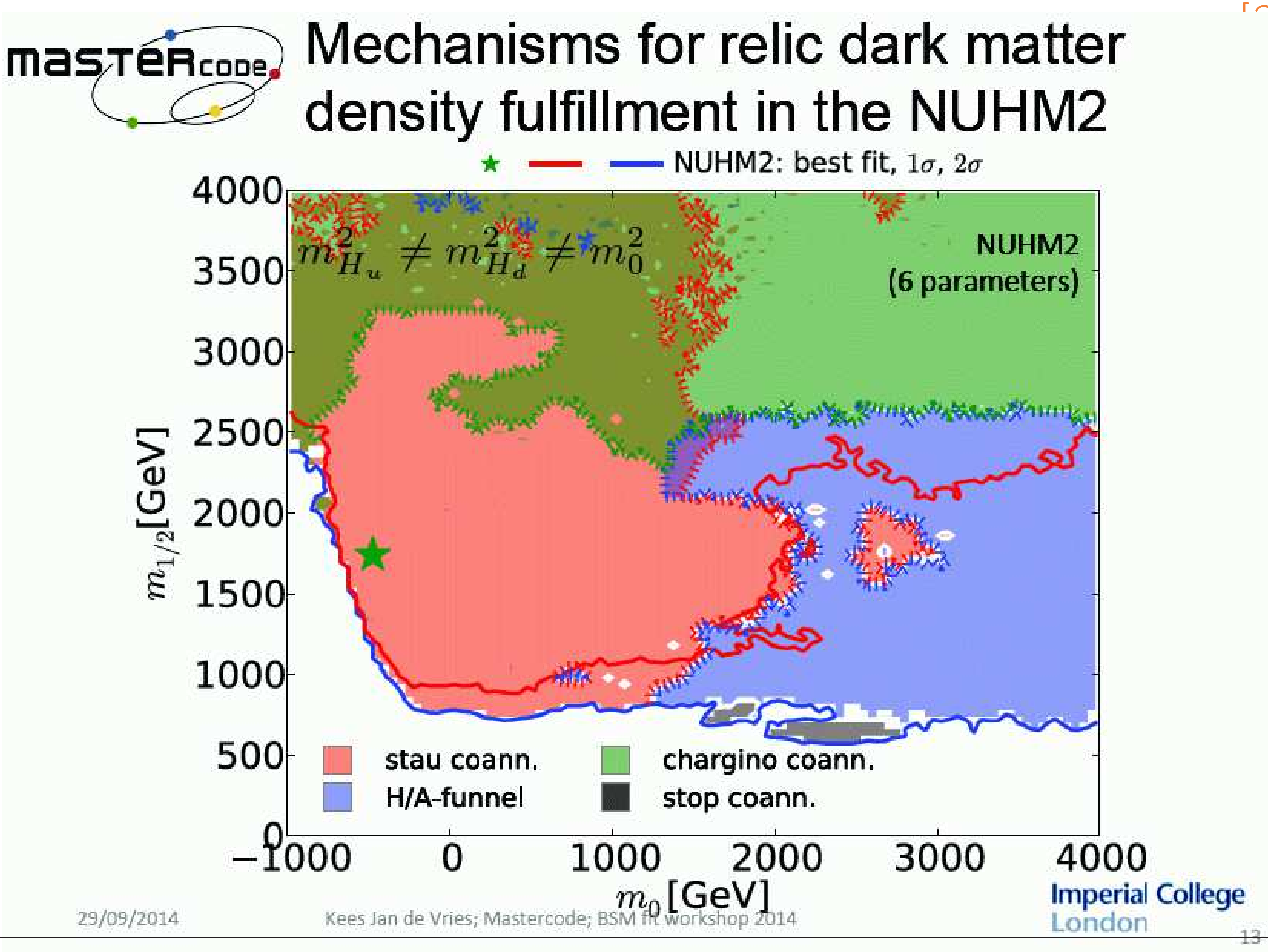
NUHM1 DM prediction

[2014]



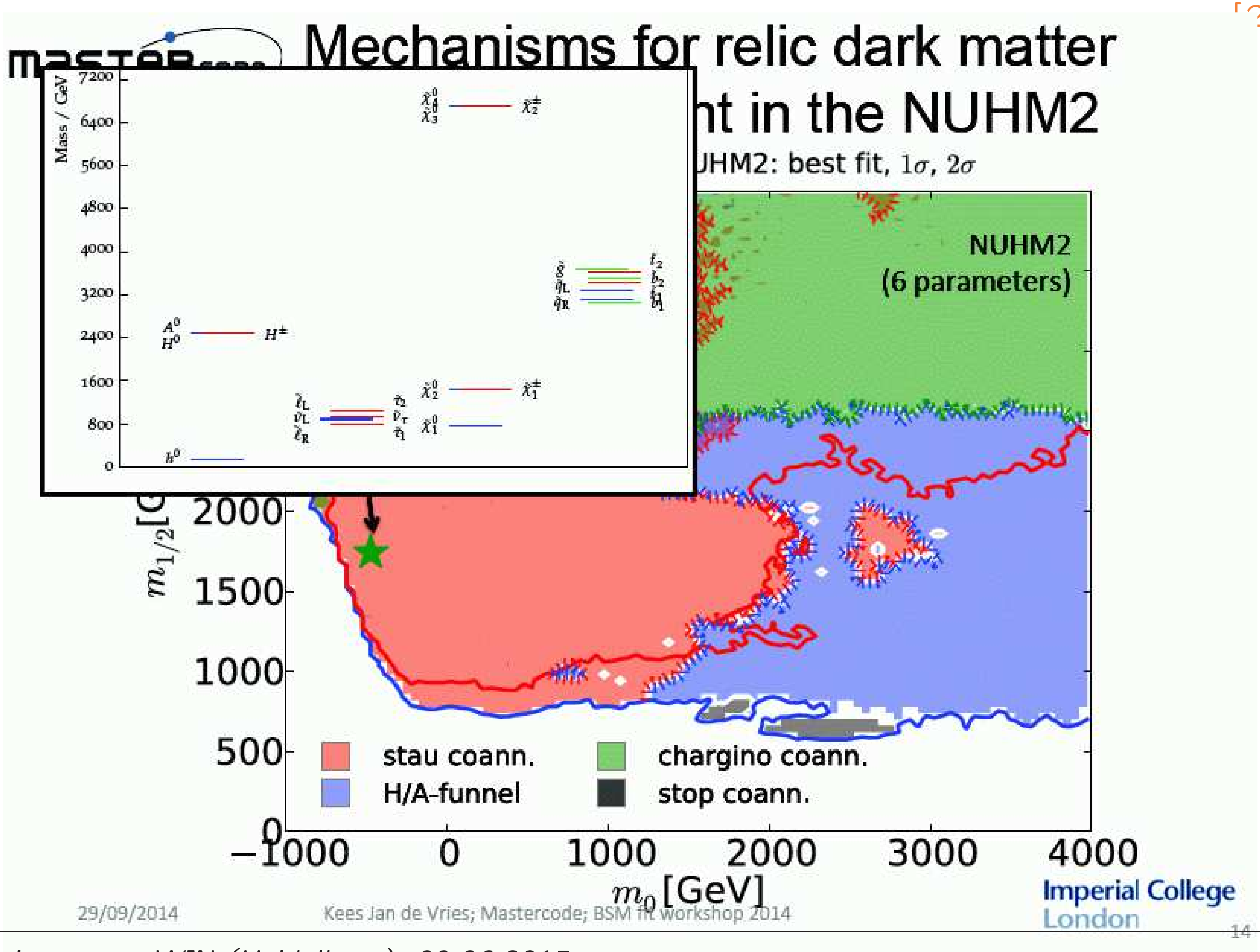
NUHM2 DM prediction

[2014]

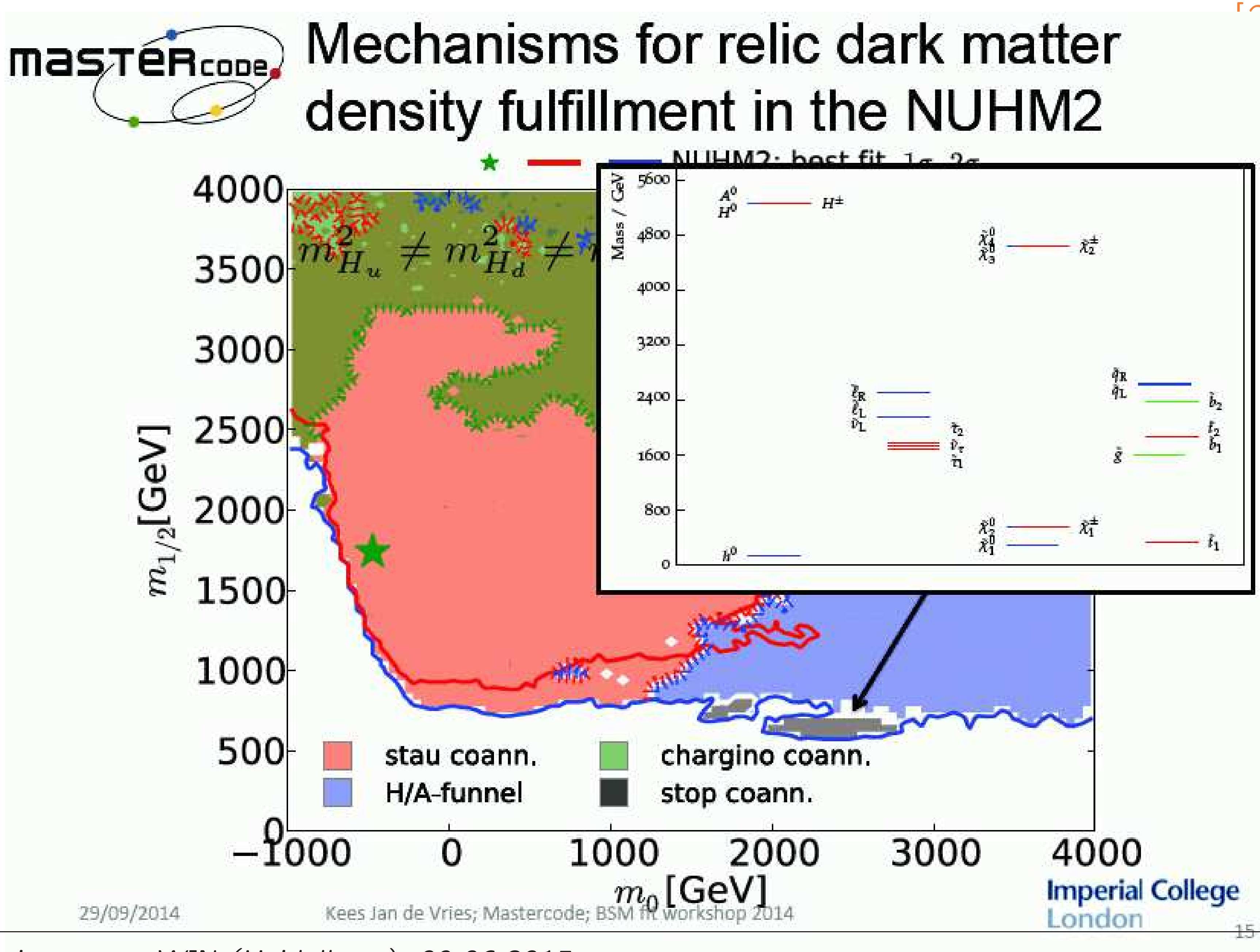


NUHM2 DM prediction

[?2014]

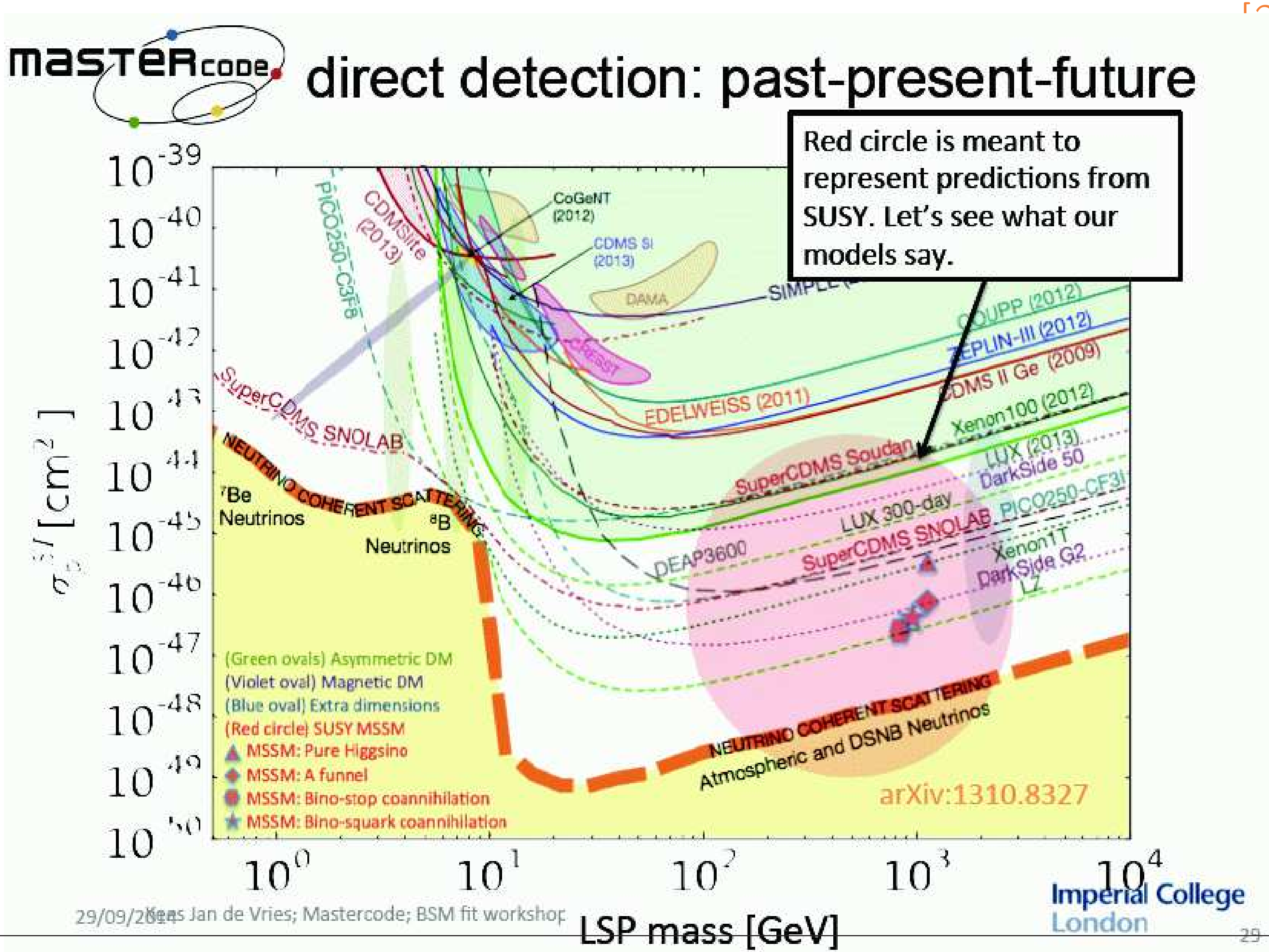


[2014]


Mechanisms for relic dark matter density fulfillment in the NUHM2
NUHM2: best fit, 1σ, 2σ
$m^2_{H_u} \neq m^2_{H_d} \neq$
$m_{1/2}$[GeV]
m_0[GeV]
stau coann.
chargino coann.
H/A-funnel
stop coann.
Mass / GeV
29/09/2014
Kees Jan de Vries; Mastercode; BSM fit workshop 2014
Imperial College London
15

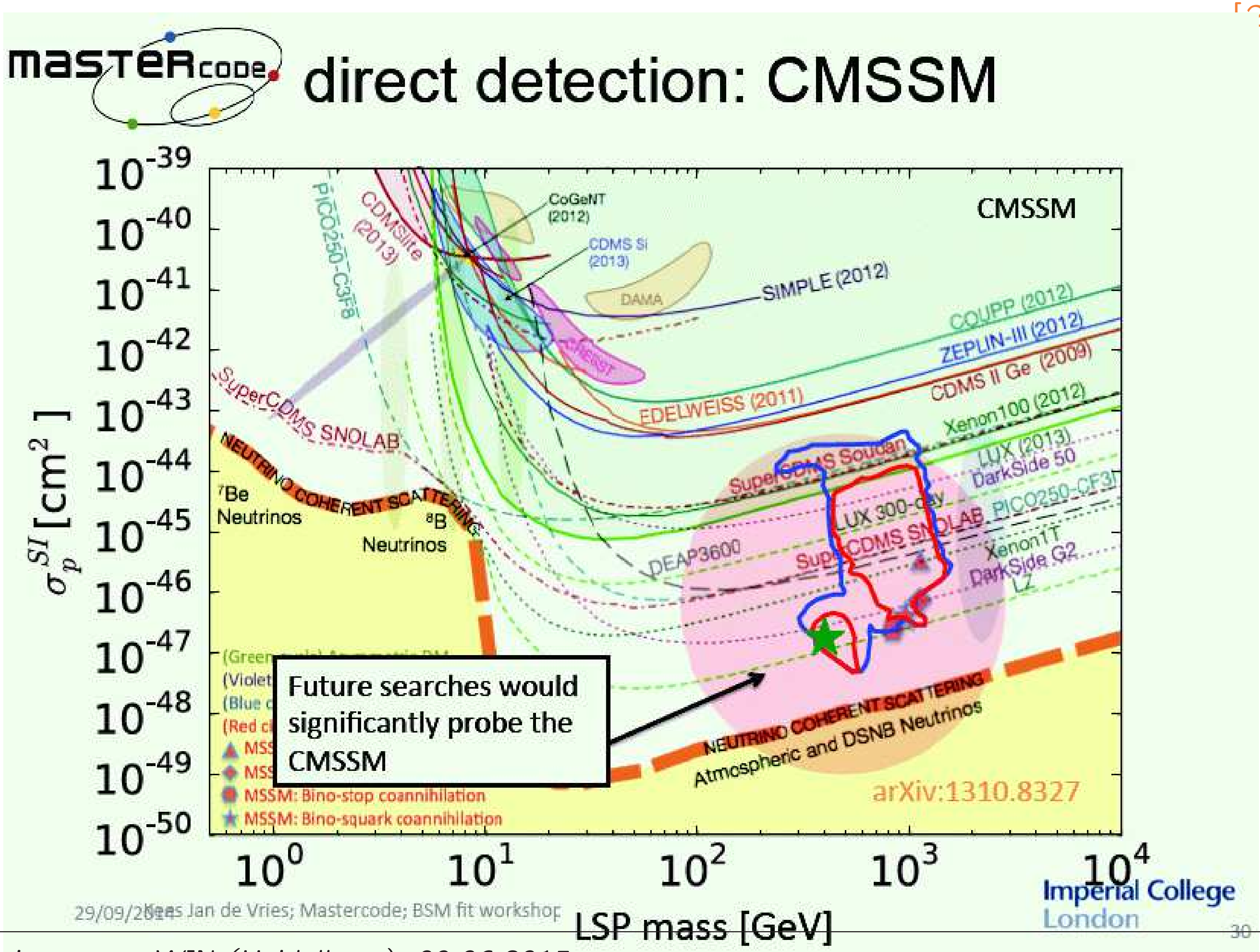
MSSM DM prediction

[2014]



MSSM DM prediction

[2014]



MSSM DM prediction

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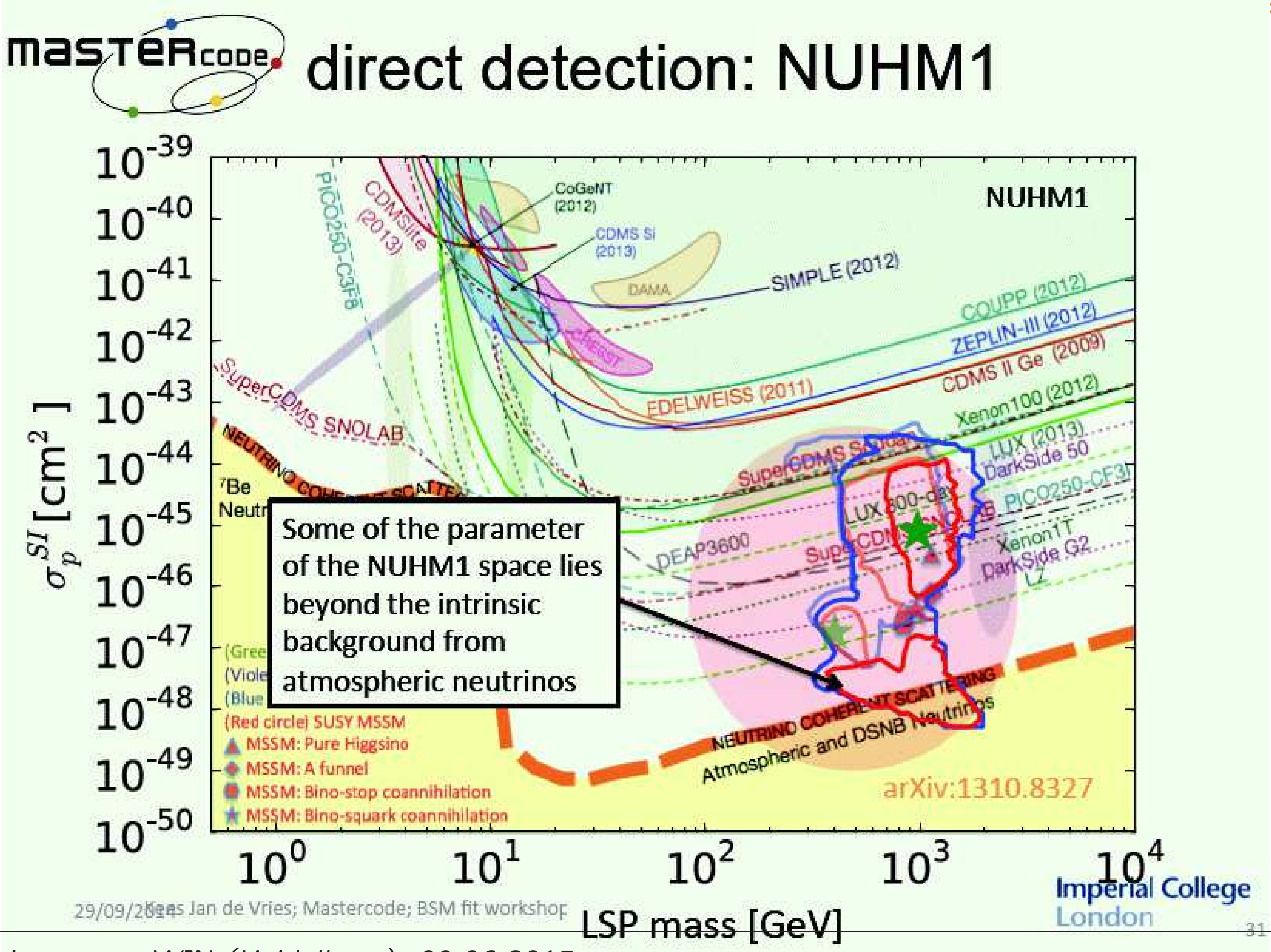
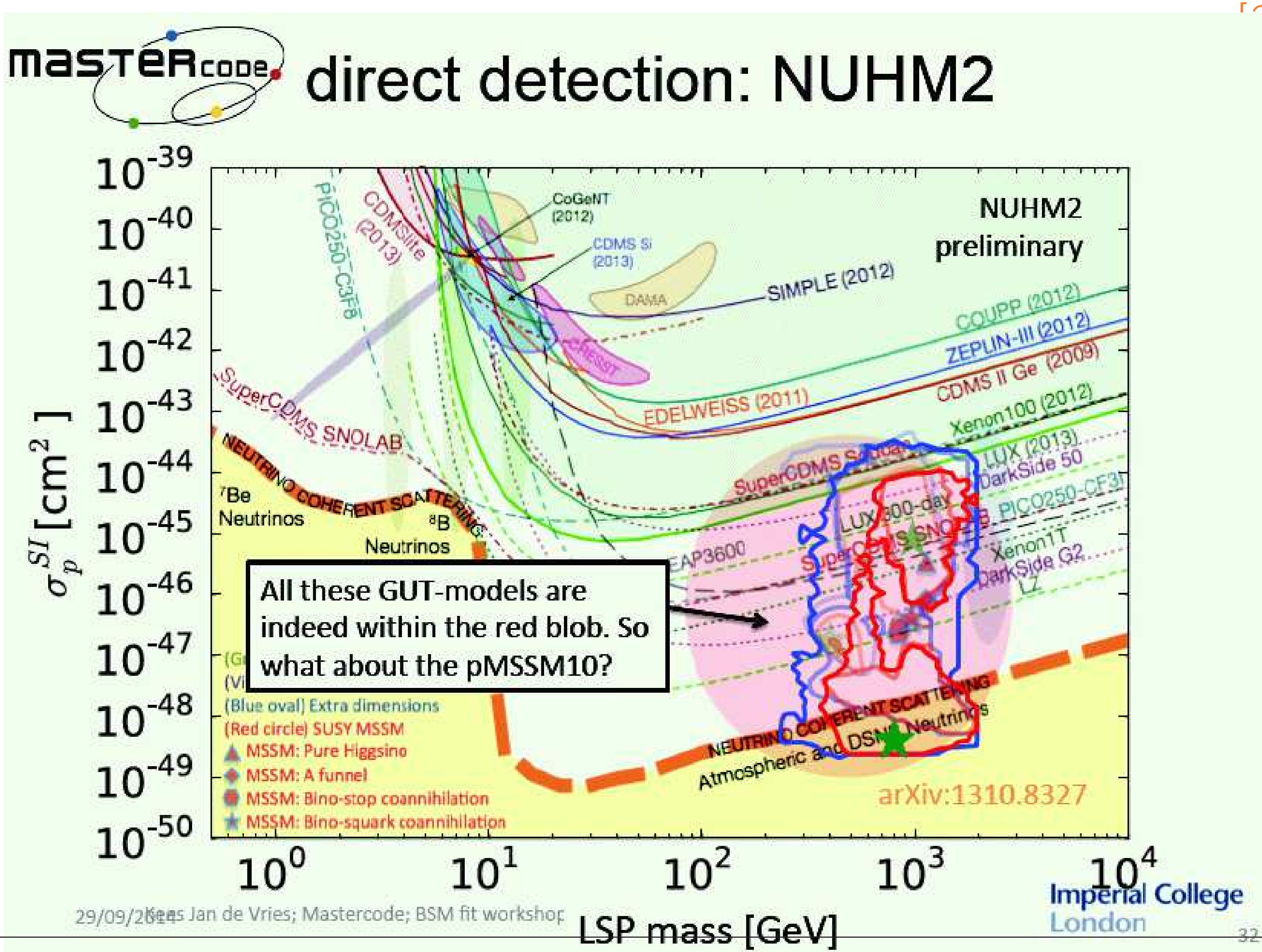


MSSM DM prediction

[?2014]



4. Results in the pMSSM

– preferred pMSSM mass ranges

  in particular for $m_{\tilde{\chi}_1^0}$, our DM mass

– identification of DM annihilation mechanism

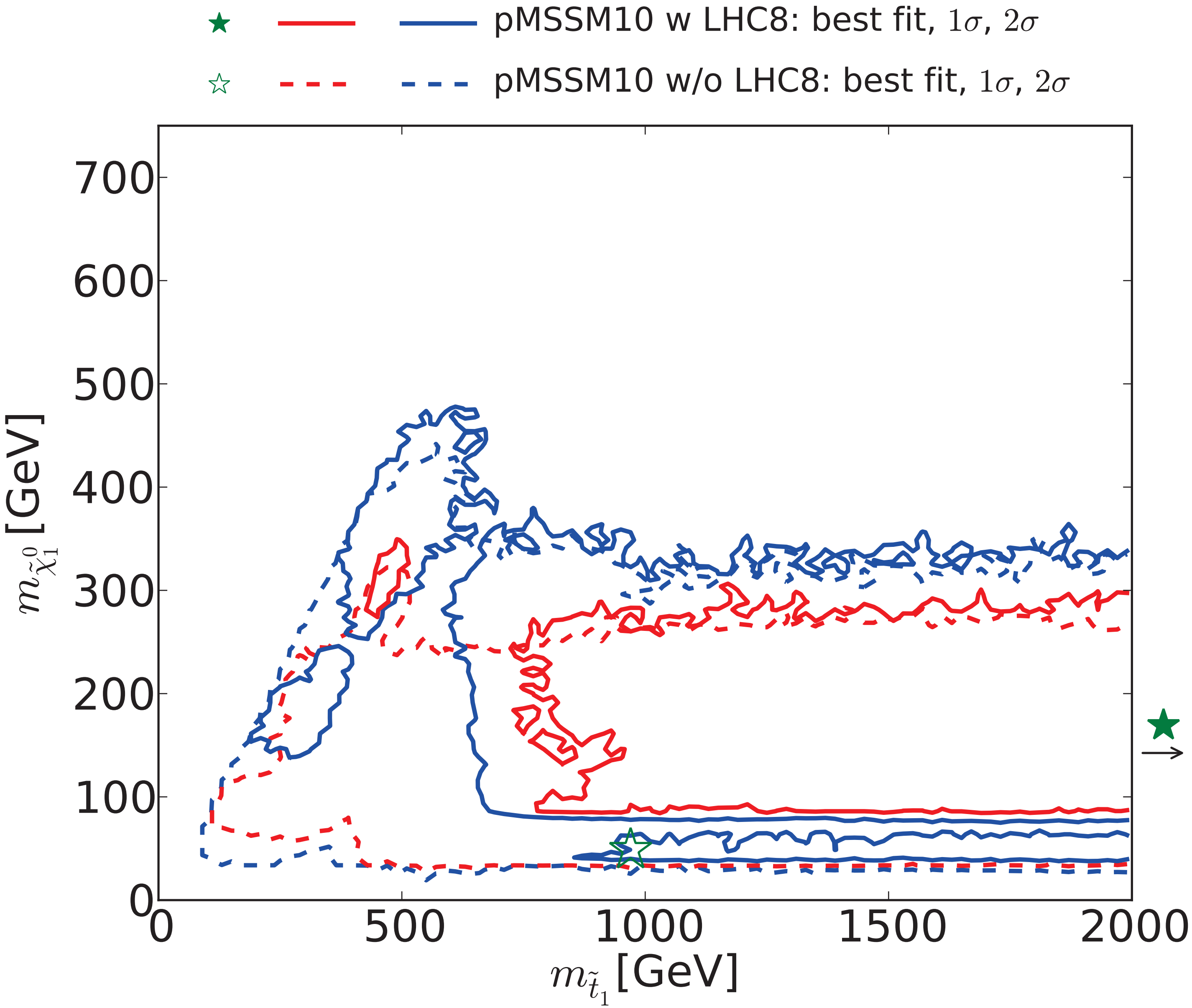
– results in the $m_{\tilde{\chi}_1^0}$–σ_p^{SI} plane for the pMSSM10

– no "no lose" theorem for DD experiments

– . . .

pMSSM10 prediction: DM mass vs. light stop mass:

[2015]



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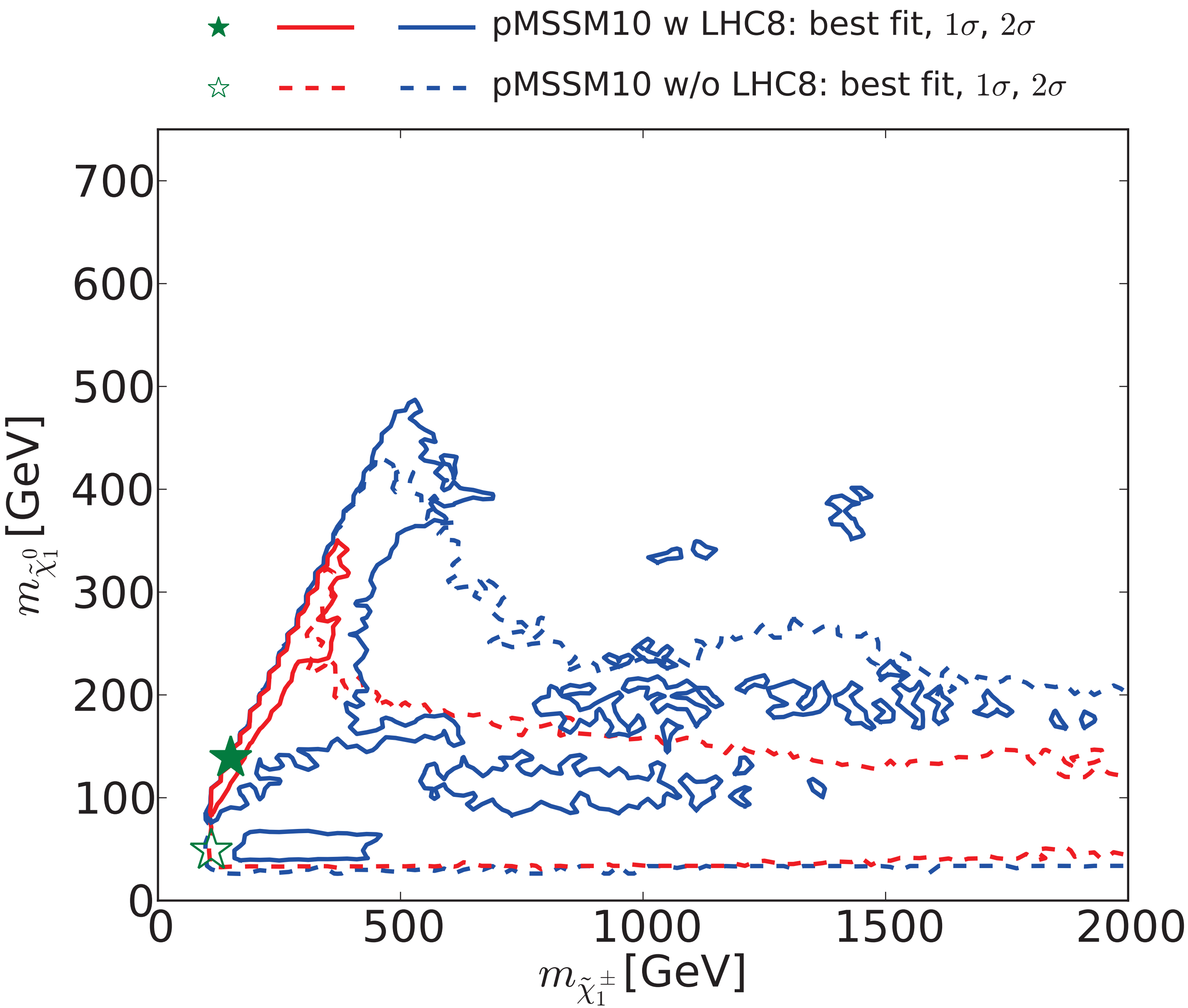

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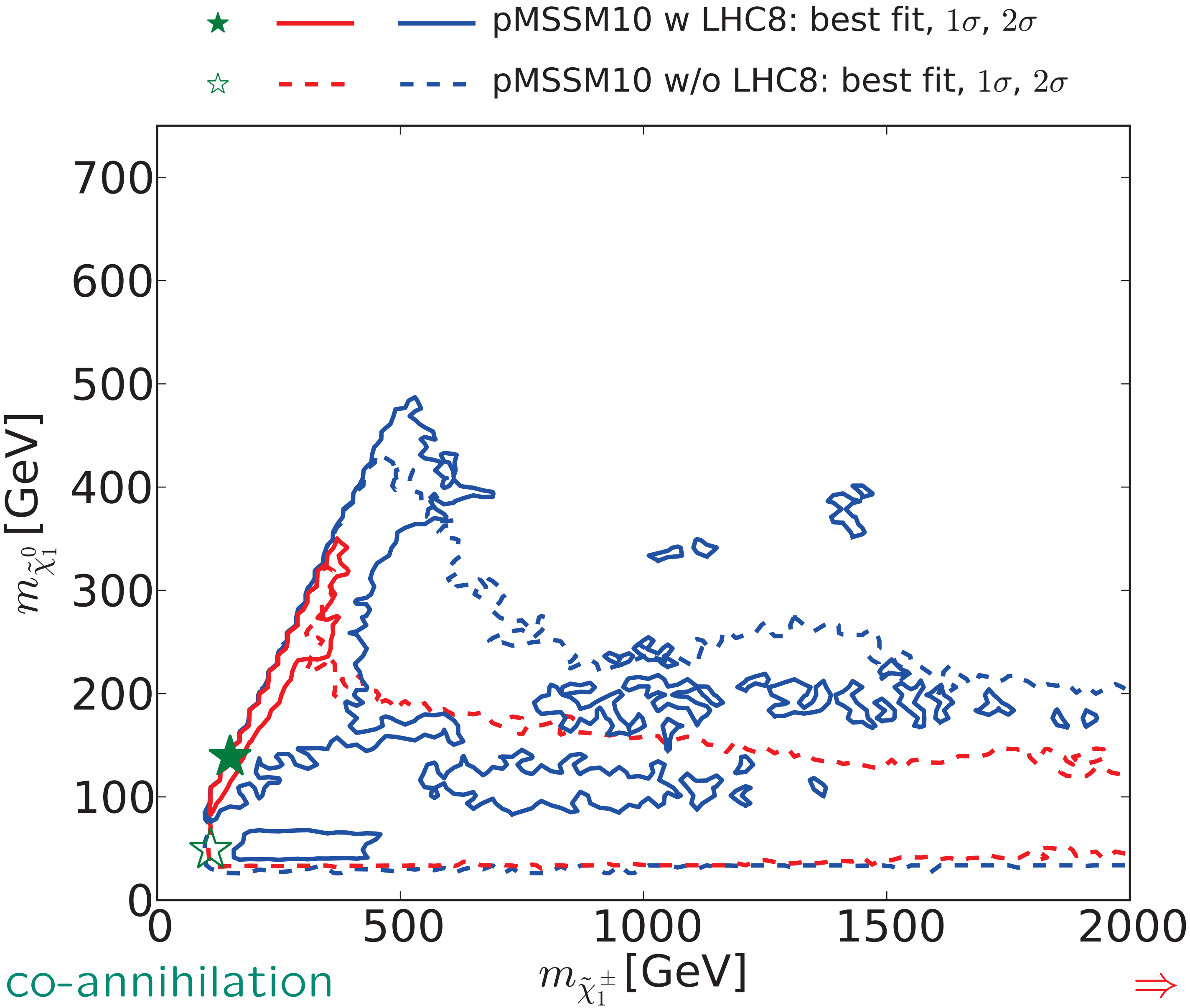
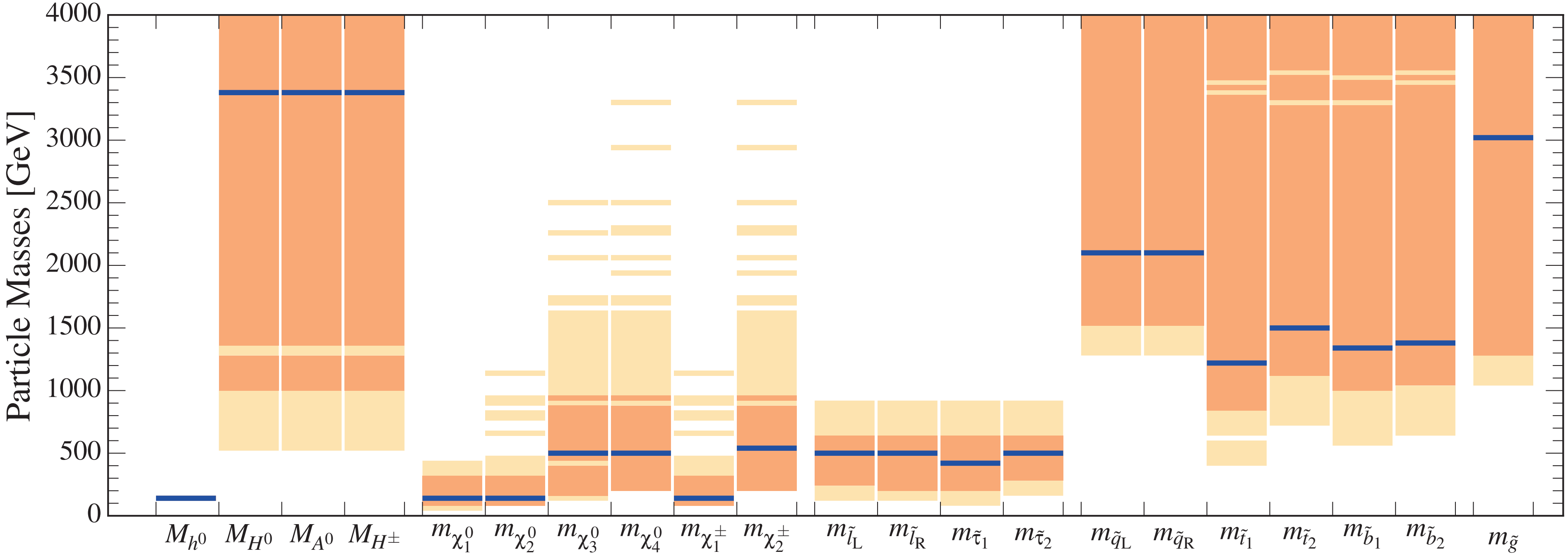
[2015]



$\Rightarrow$ chargino co-annihilation $\Rightarrow M_1 \approx M_2$

pMSSM10 prediction: best-fit masses

[2015]



⇒ high colored masses

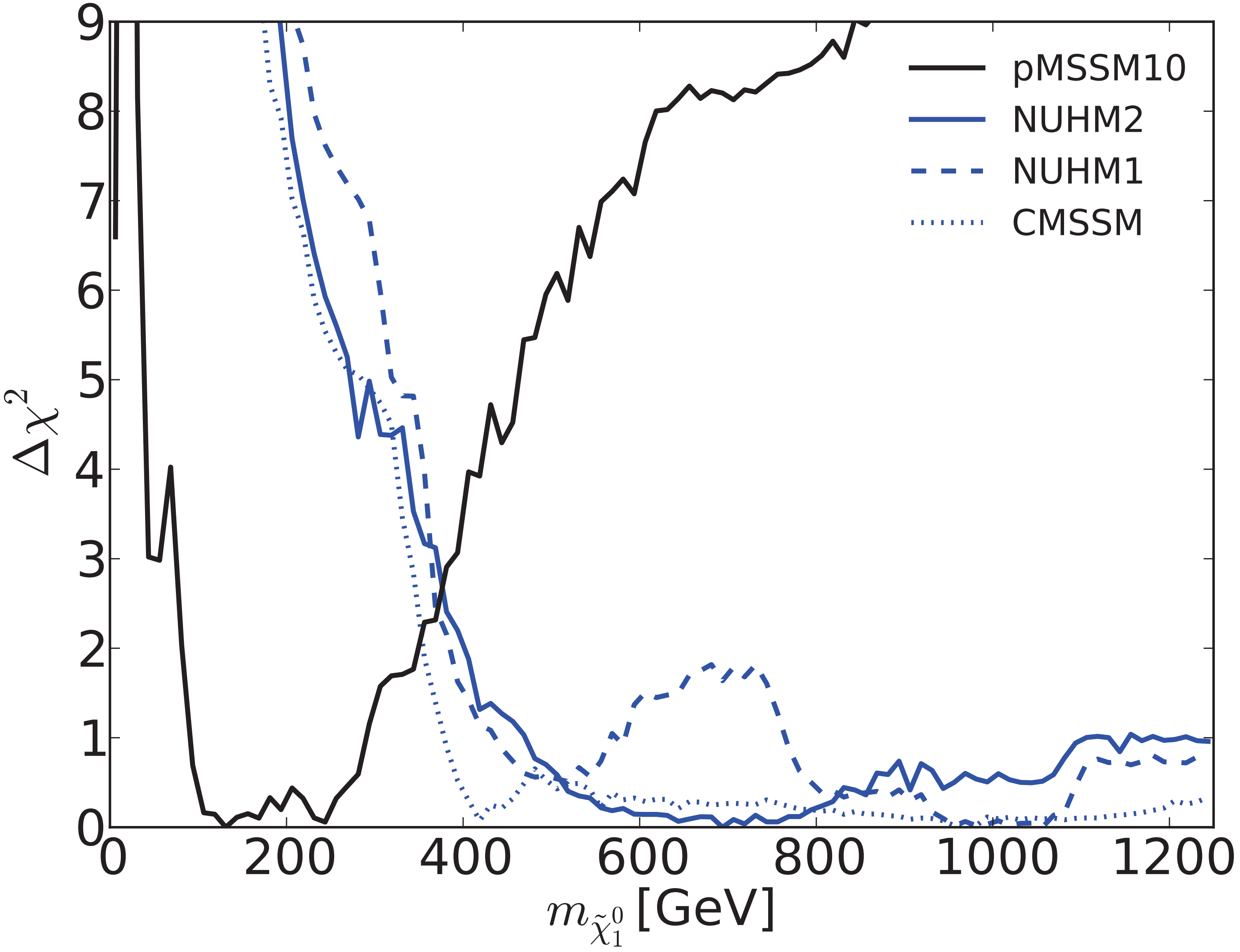
⇒ relatively low electroweak masses

partially with not too large ranges

⇒ clear prediction for $m_{\tilde{\chi}_1^0}$

pMSSM10 prediction: DM mass

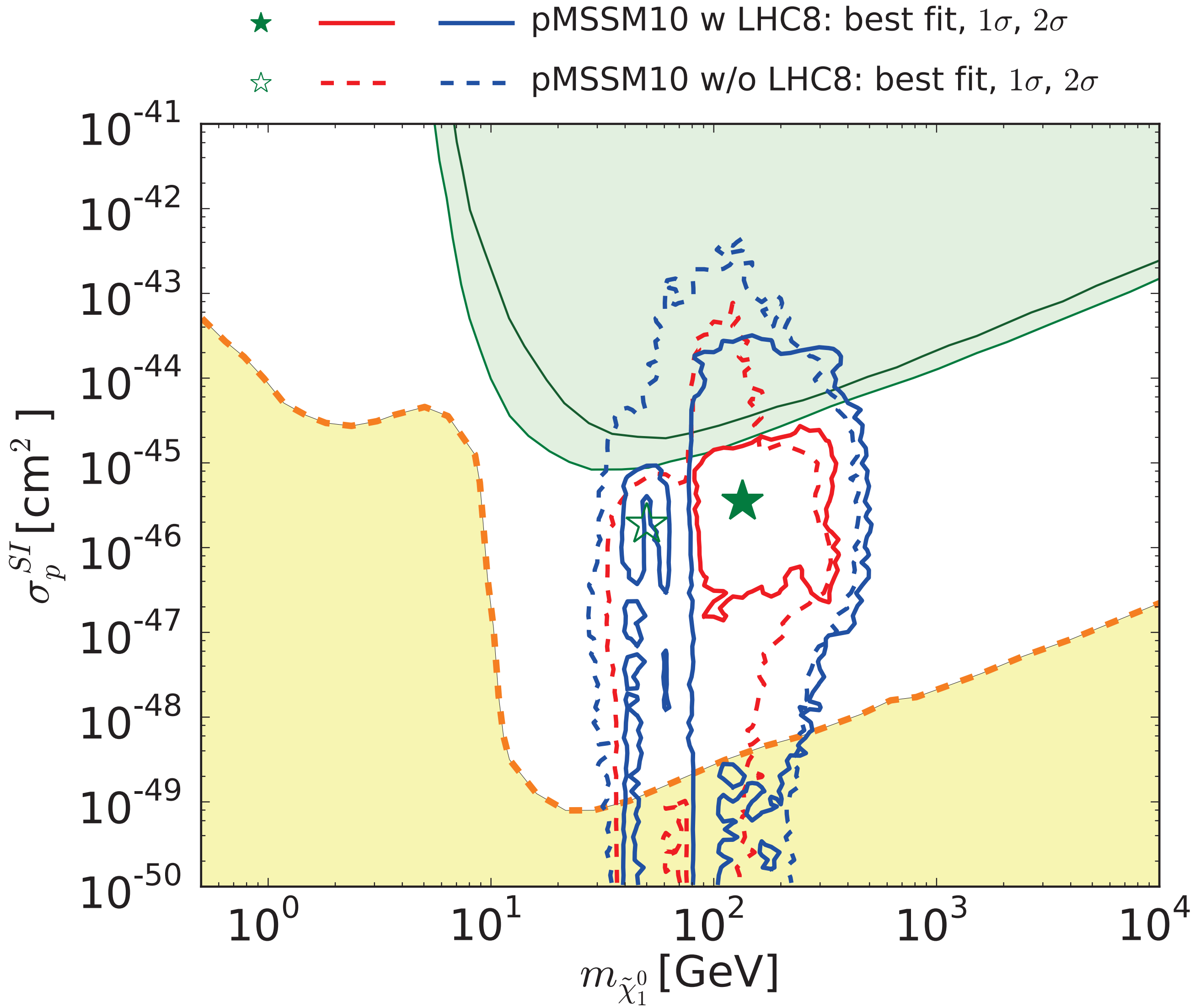
[2015]



⇒ pMSSM10 predicts much lower DM mass than GUT-based models

pMSSM10 prediction: $m_{\tilde{\chi}^0_1}$ vs. $\sigma_p^{\rm SI}$:

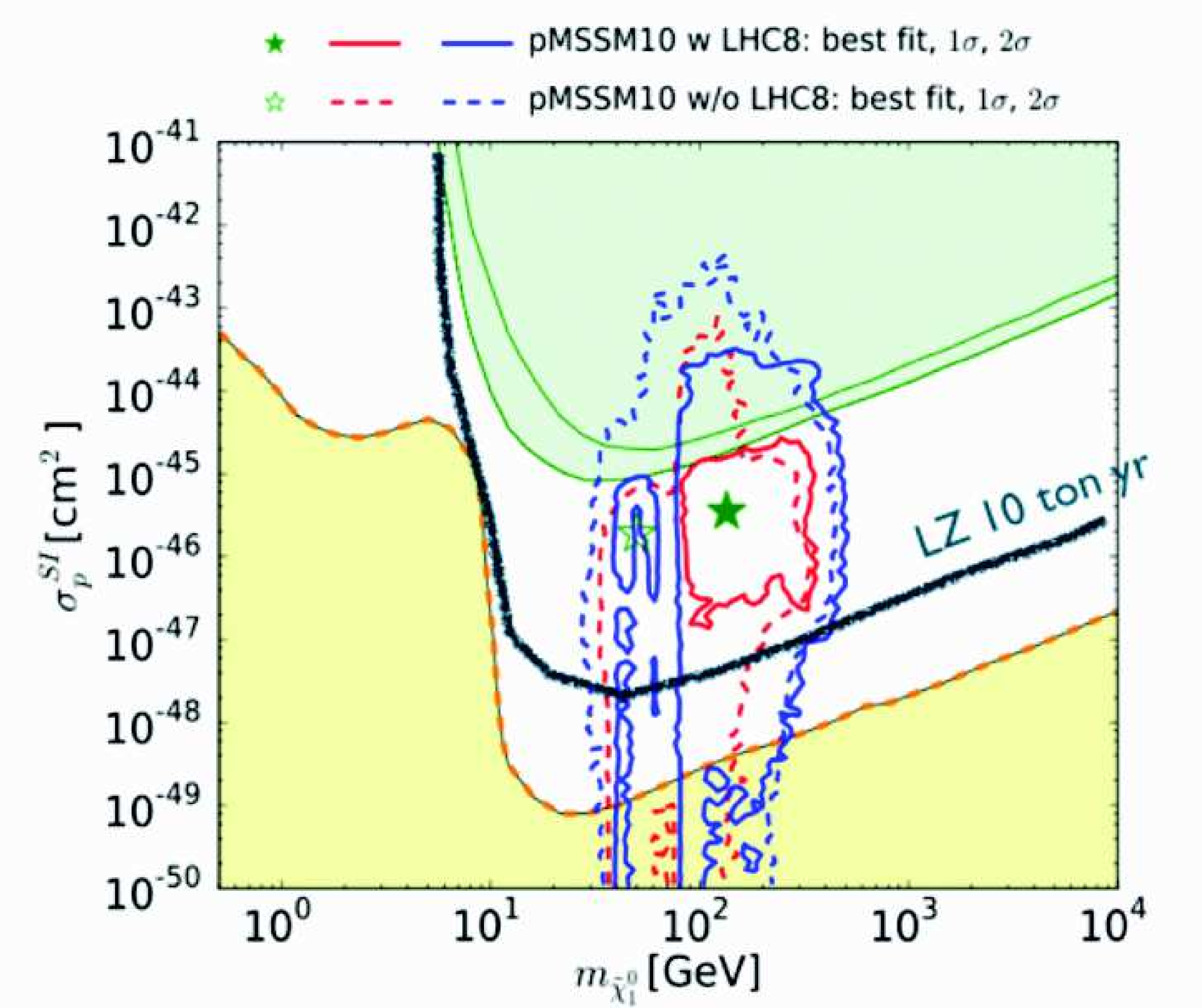
[2015]



⇒ LHC bounds try to "rescue" DD experiments!

pMSSM10 prediction: $m_{\tilde{\chi}^0_1}$ vs. $\sigma_p^{\rm SI}$: future expectations

[2015]



⇒ 68% CL areas covered by next round of DD experiments

pMSSM10 analysis: DD experiments: p- vs. n-scattering

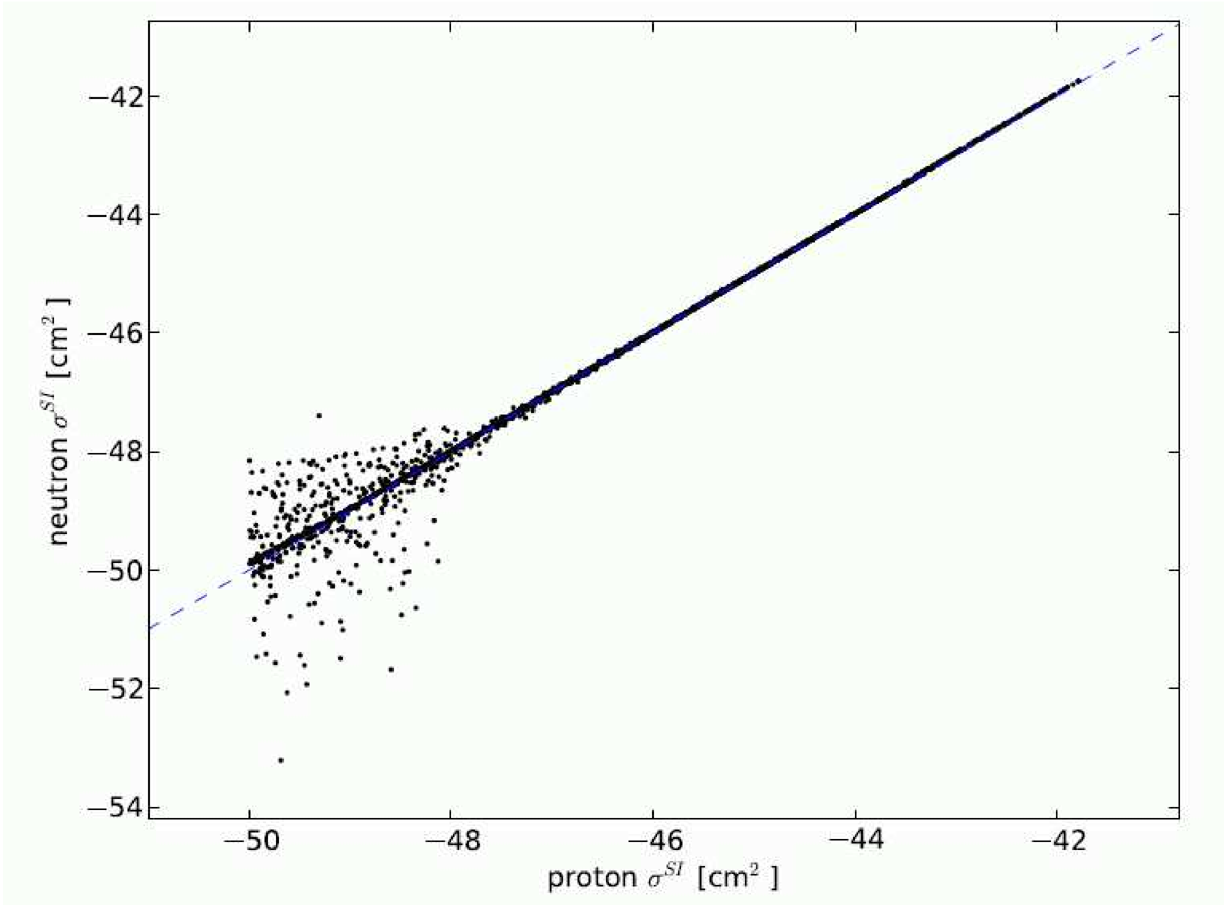
[2015]

σ_p^{SI} is evaluated for p-scattering

Can n-scattering come to rescue?

Some points with low σ_p^{SI} have even lower σ_n^{SI}

$\Rightarrow$ no "no-lose theorem" for DD experiments!



5. Conclusions

- SUSY is (still) the best-motivated BSM scenario
  - constrained models: CMSSM, NUHM1, NUHM2, . . .
  - general models: pMSSM10, . . .

- Our tool: MasterCode

  combination of LHC searches, Higgs measurements, EWPO, BPO, CDM $\Rightarrow \chi^2$ evaluation

- Preferred fit ranges in the pMSSM10:
  - $m_{\tilde{\chi}^0_1} \lesssim 400$ GeV
  - important: chargino co-annihilation
  - $M_1 \sim M_2$ at the EW scale

- Predictions for DD experiments:
  - at the 68% CL accessible at the next generation of DD
  - at the 95% CL even below "neutrino floor"
  - no "no-loose theorem" for DD experiments

Back-up

GUT based models: 1.) CMSSM (sometimes wrongly called mSUGRA):

⇒ Scenario characterized by

$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \text{sign}\,\mu$$

m_0 : universal scalar mass parameter

$m_{1/2}$: universal gaugino mass parameter

A_0 : universal trilinear coupling

} at the GUT scale

$\tan\beta$: ratio of Higgs vacuum expectation values

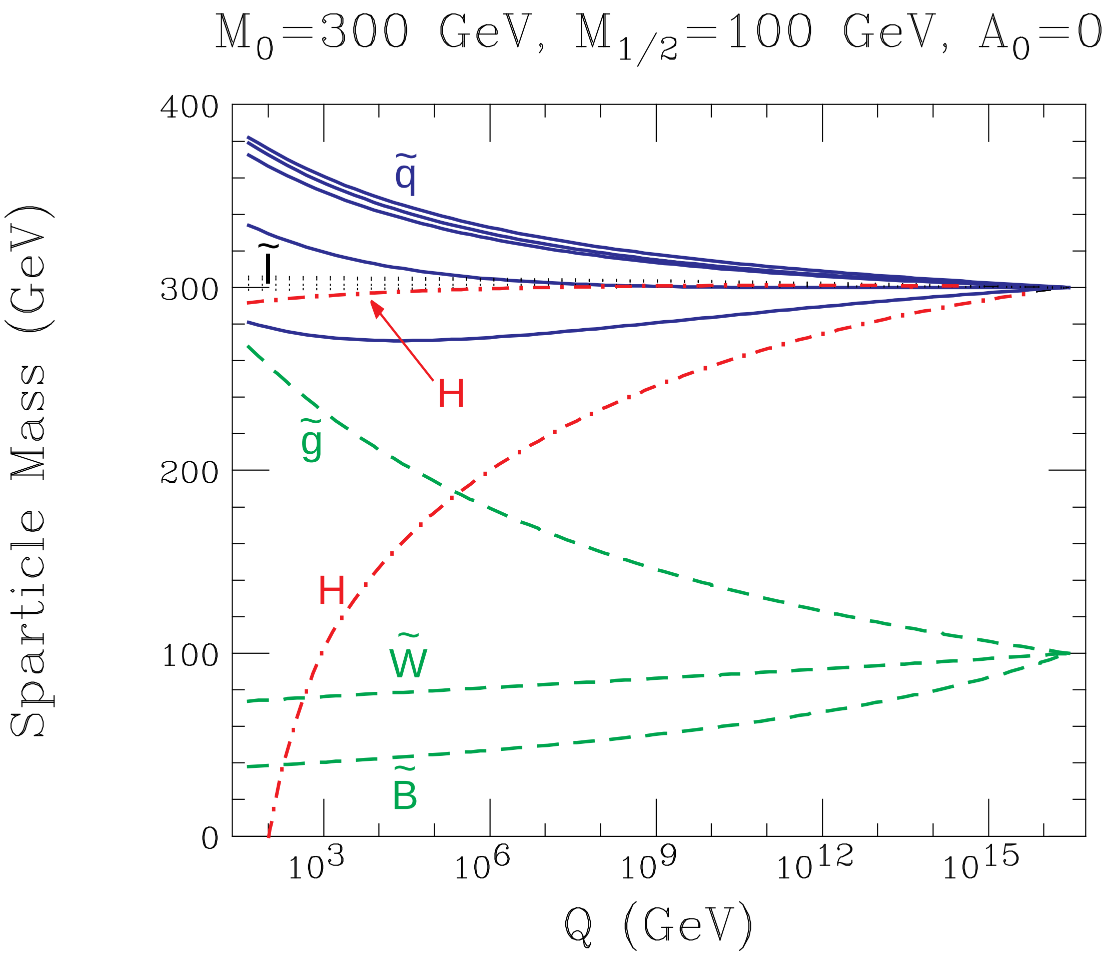
sign(μ) : sign of supersymmetric Higgs parameter

⇒ particle spectra from renormalization group running to weak scale

⇒ Lightest SUSY particle (LSP) is the lightest neutralino ⇒ DM!

GUT based models: 1.) CMSSM (sometimes wrongly called mSUGRA):

⇒ particle spectra from renormalization group running to weak scale



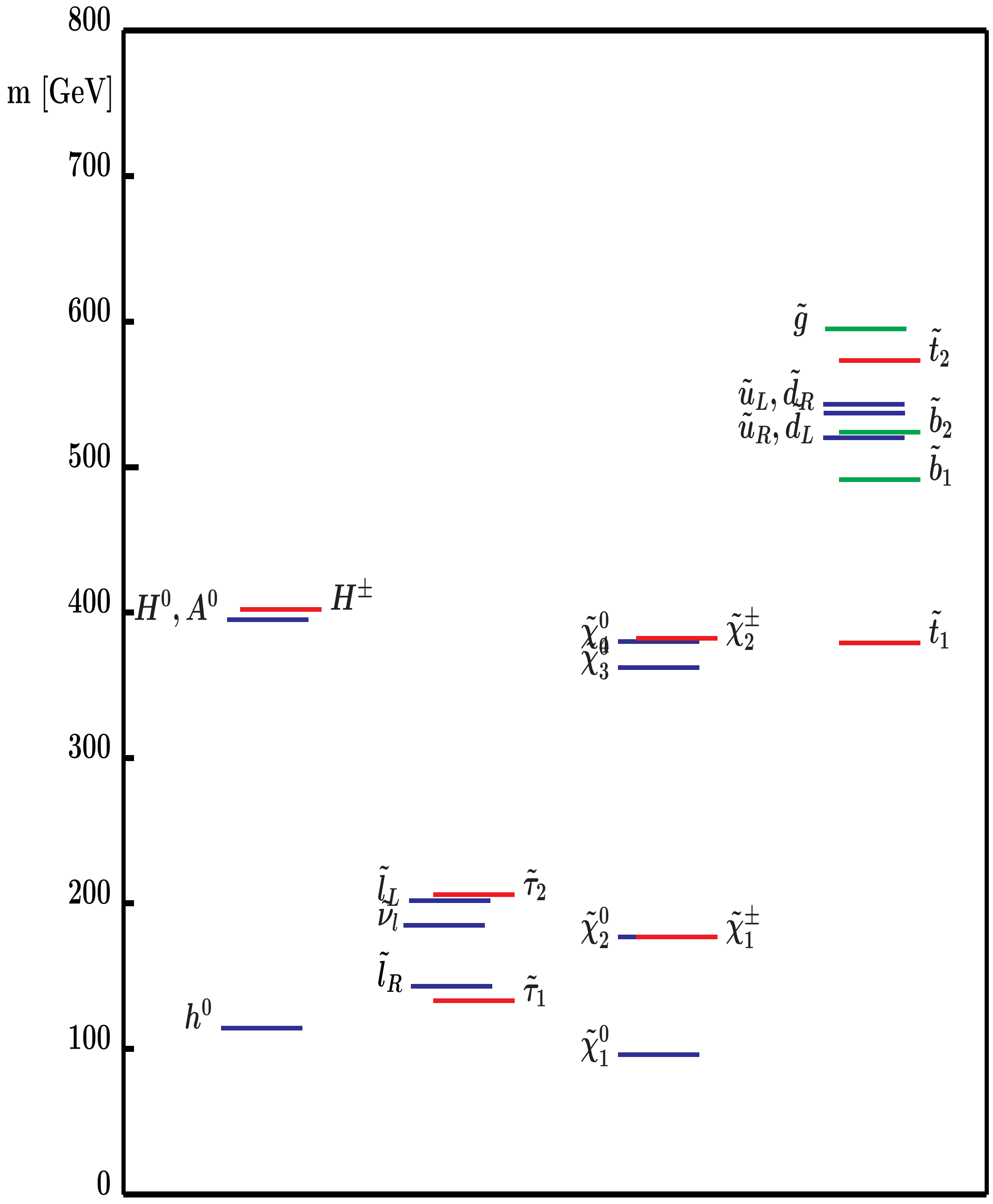
⇒ one parameter turns negative ⇒ Higgs mechanism for free

"Typical" CMSSM scenario

(SPS 1a benchmark scenario):

Strong connection between

all the sectors



GUT based models: 2.) NUHM1: (Non-universal Higgs mass model)

Assumption: no unification of scalar fermion and scalar Higgs parameter at the GUT scale

$\Rightarrow$ effectively M_A as free parameters at the EW scale

> $\Rightarrow$ Scenario characterized by
>
> m_0, $m_{1/2}$, A_0, $\tan\beta$, sign μ and M_A

GUT based models: 3.) NUHM2: (Non-universal Higgs mass model 2)

Assumption: no unification of scalar Higgs parameter at the GUT scale

$\Rightarrow$ effectively M_A and μ as free parameters at the EW scale

> $\Rightarrow$ Scenario characterized by
>
> m_0, $m_{1/2}$, A_0, $\tan\beta$, μ and M_A

What is happening to the χ^2?

Low energy data (mostly $(g-2)_\mu$) favors low SUSY mass scales

LHC data favors higher SUSY scales

M_h "measurement" moves the fit to even higher scales

$\Rightarrow$ tension, reflected in rising χ^2:

Model	Min. χ^2	Prob.	$m_{1/2}$ (GeV)	m_0 (GeV)	A_0 (GeV)	$\tan\beta$
CMSSM	21.5/20	37%	360	90	-50	15
LHC 1 $\text{fb}^{-1} \oplus M_h$	30.6/23	13%	1800	1080	860	48
LHC 20 $\text{fb}^{-1} \oplus M_h$	35.1/23	5.1%	2100	5650	780	51
NUHM1	20.8/18	29%	340	110	520	13
LHC 1 $\text{fb}^{-1} \oplus M_h$	29.7/22	13%	830	290	660	33
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Probabilities still "so so", but this might change with LHC run II data.

Not finding SUSY now does not make SUSY prospects look bad,
makes some very constrained models look bad!

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An MSSM Higgs at 125 GeV makes CMSSM/NUHM1 less likely

And requires SUSY realizations that are in agreement with

– higher colored mass scales (LHC limits)

– lower uncolored mass scales (EWPO; $(g-2)_\mu$) $\Rightarrow$ DM predictions

“Typical” CMSSM scenario

(SPS 1a benchmark scenario):

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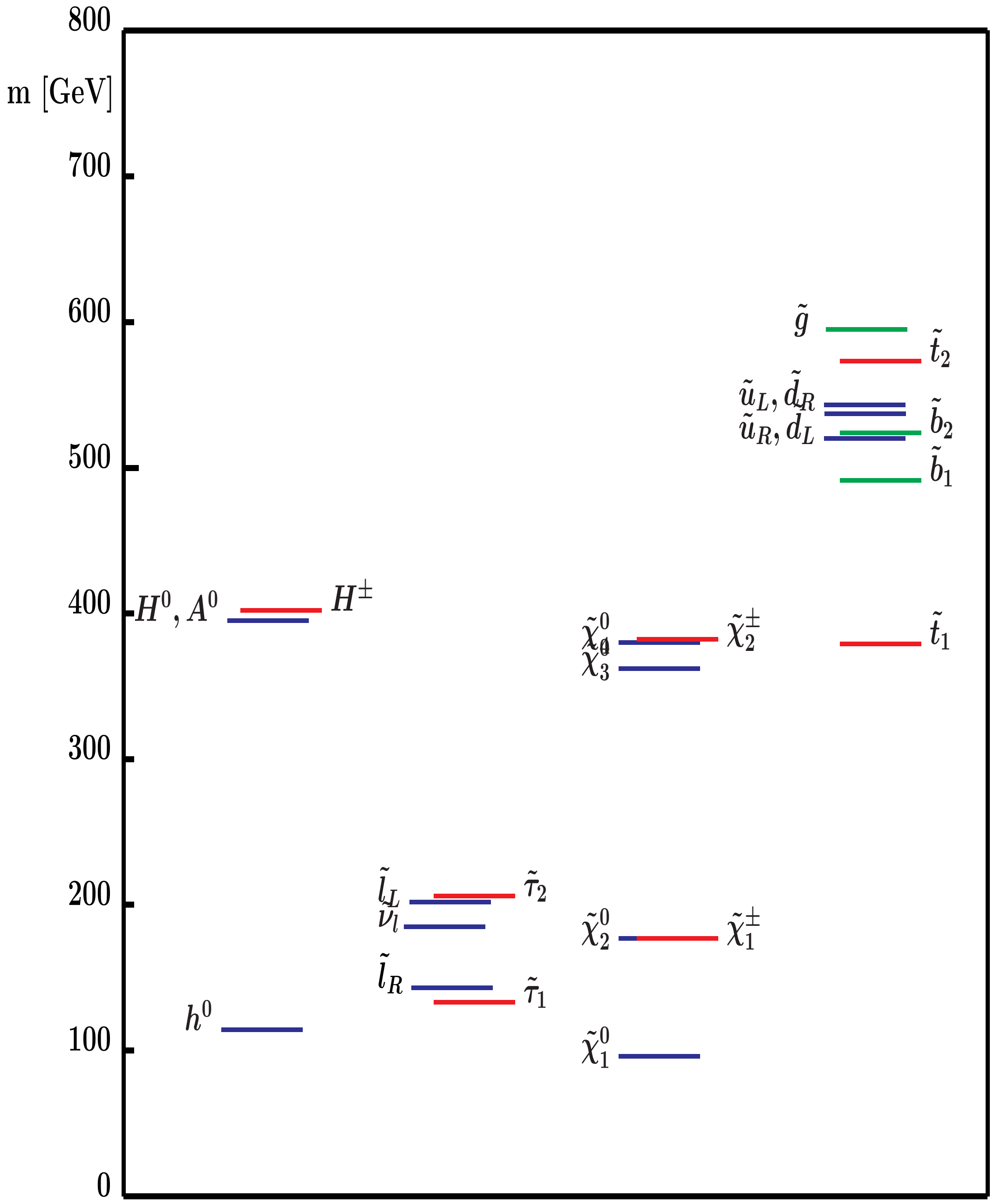
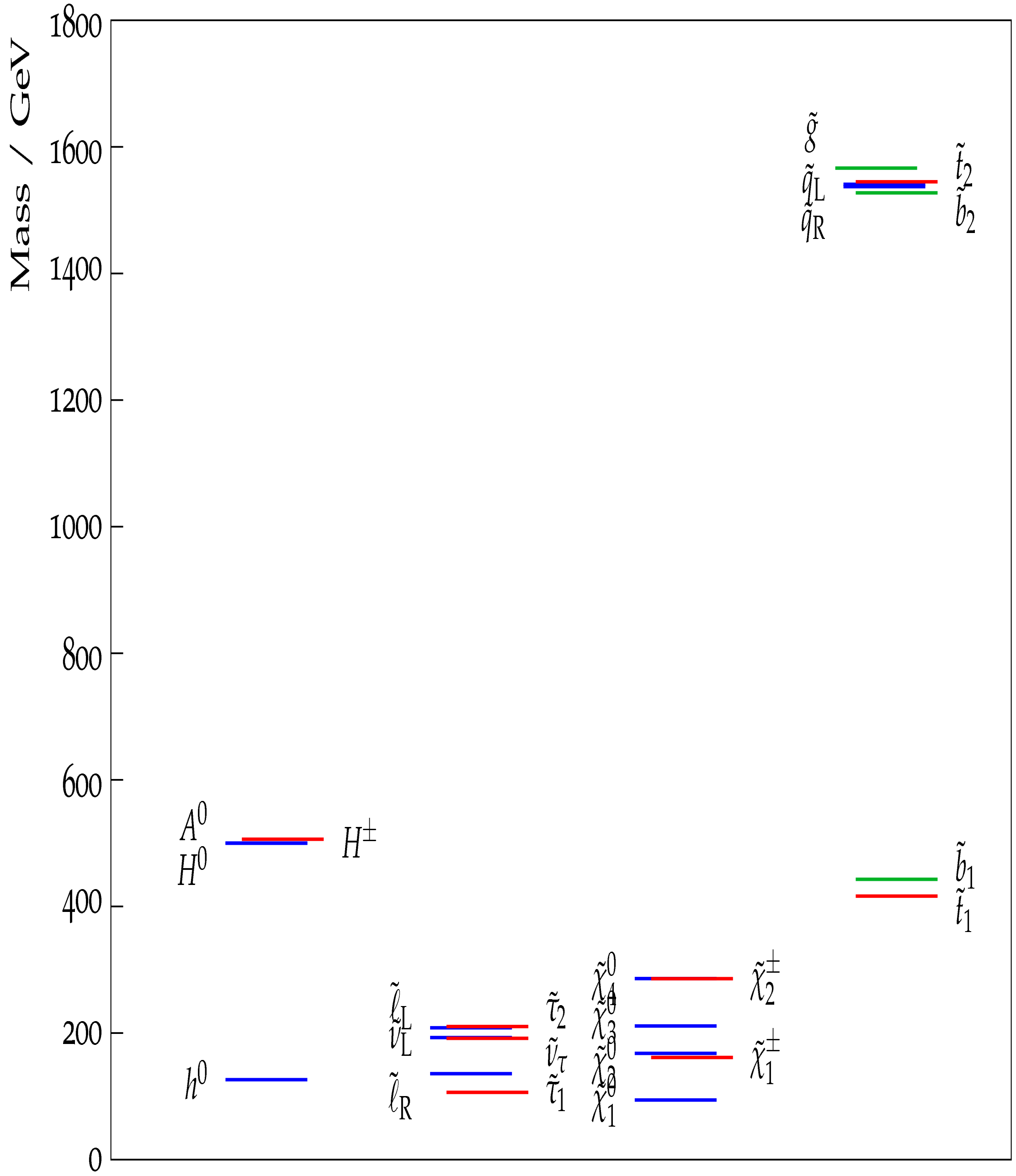
all the sectors



SPS1a variant (I)

colored and uncolored

sector decoupled:



SPS1a variant (II)

colored and uncolored

sector decoupled: