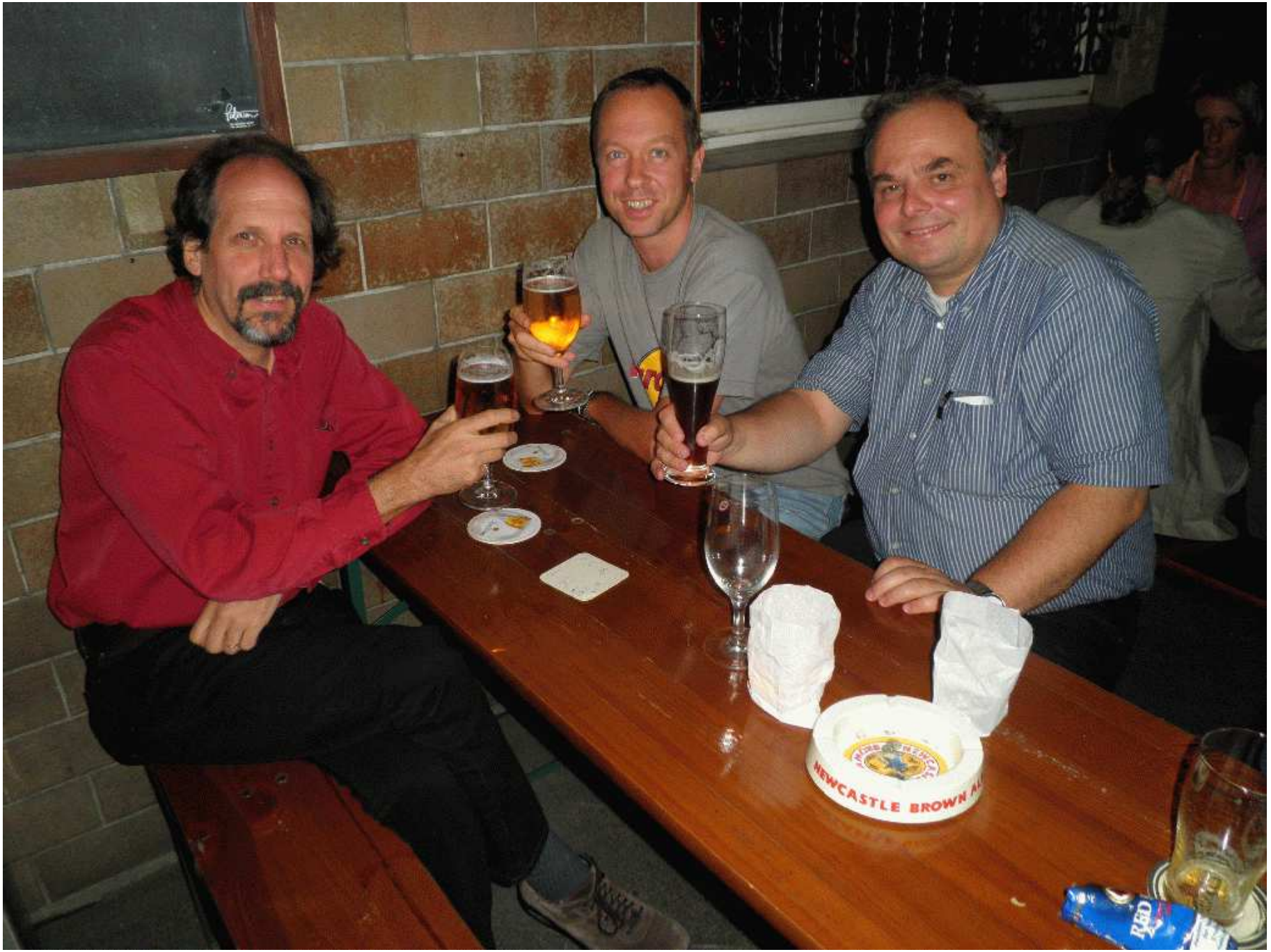
NEWCASTLE BROWN

Keith and the MasterCode

Sven Heinemeyer, IFT/IFCA (CSIC, Madrid/Santander)

Minneapolis, 05/2017

1. Introduction

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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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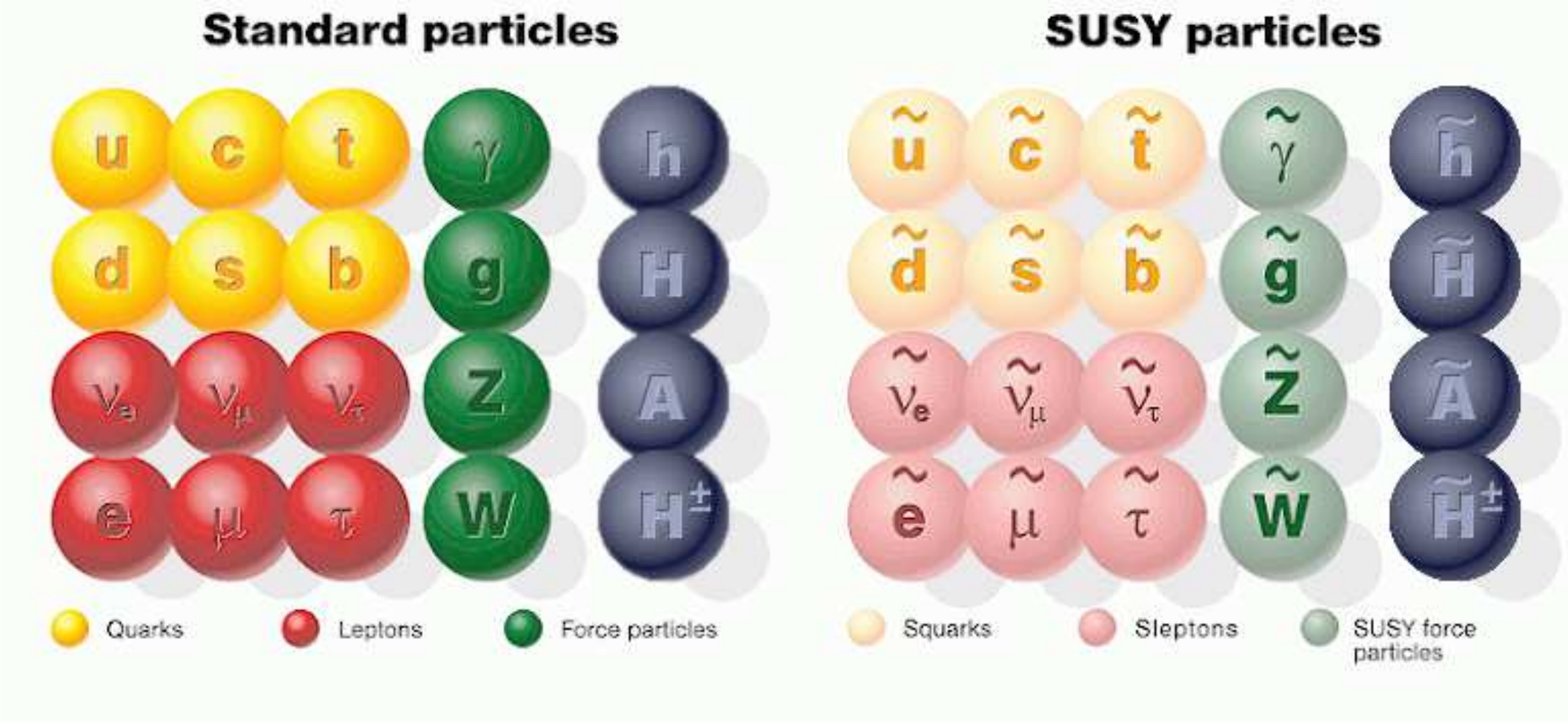
$\Rightarrow$ good motivation to look at SUSY!

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, SU(5), mAMSB, . . . :

assumption on the scenario that achieves spontaneous SUSY breaking

$\Rightarrow$ prediction for soft SUSY-breaking terms
in terms of small set of parameters

$\Rightarrow$ easy to handle

$\Rightarrow$ "likely": correct model missed

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

$\Rightarrow$ it is possible that with the CMSSM, NUHM1, NUHM2, SU(5), mAMSB we missed the "correct" mechanism

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

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tension between low-energy EW effects and (colored) LHC searches

Solution: investigate also the "general MSSM"

$\Rightarrow$ 10 parameters are manageable $\Rightarrow$ 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

2. The MasterCode

2. The Mastercode

$\Rightarrow$ collaborative effort of theorists and experimentalists

[*Bagnaschi, Borsato, Buchmüller, Cavanaugh, Chobanova, Citron, Costa, De Roeck, Dolan, Ellis, Flächer, SH, Isidori, Liu, Lucio, Martinez Santos, Olive, Richards, Sakurai, 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++

$\Rightarrow$ 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
    (3 search categories: colored, electroweak, compressed stop)
  – Higgs related observables, $(g-2)_\mu$ [*FeynHiggs*]
  – Higgs signal strengths [*HiggsSignals*]
  – Higgs exclusion bounds [*HiggsBounds*]
  – 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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60. Information about this code is available from K. A. Olive: it contains important contributions from J. Evans, T. Falk, A. Ferstl, G. Ganis, F. Luo, A. Mustafayev, J. McDonald, F. Luo, K. A. Olive, P. Sandick, Y. Santoso, V. Spanos, and M. Srednicki.

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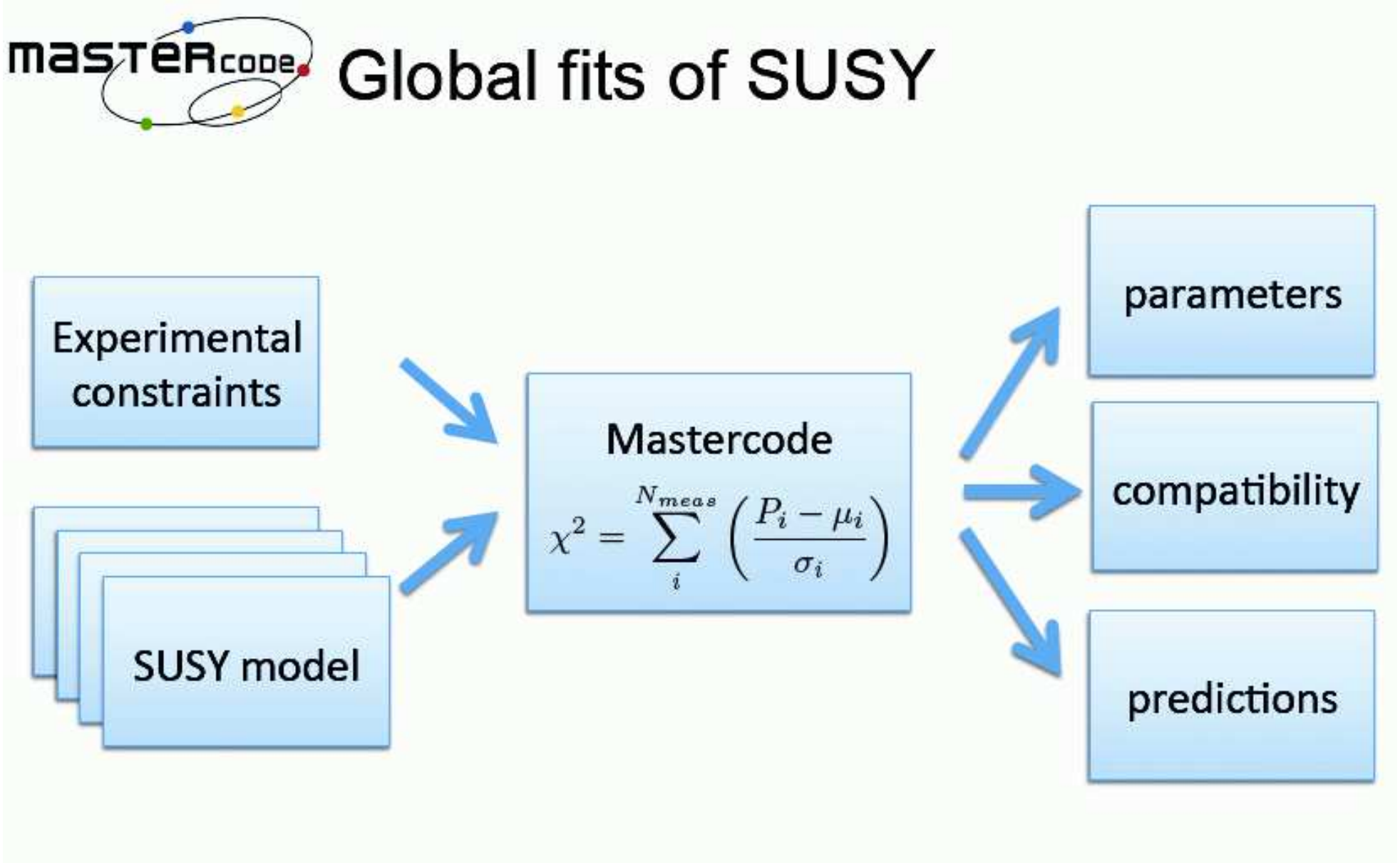
The χ^2 evaluation:



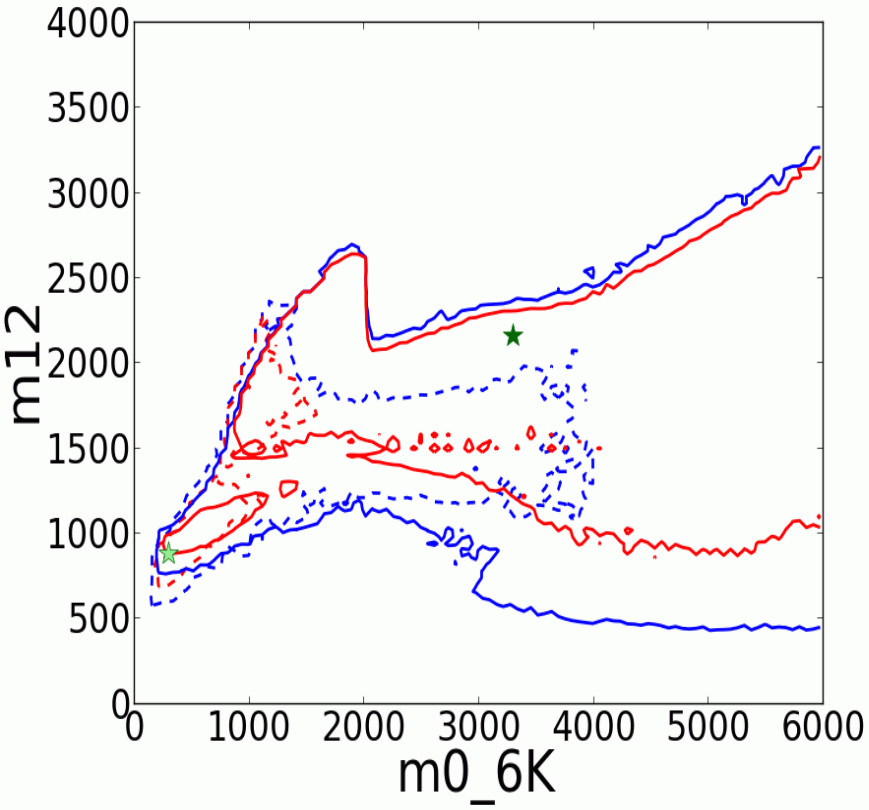
3. Keith and the MasterCode

Results in the CMSSM, NUHM1, NUHM2

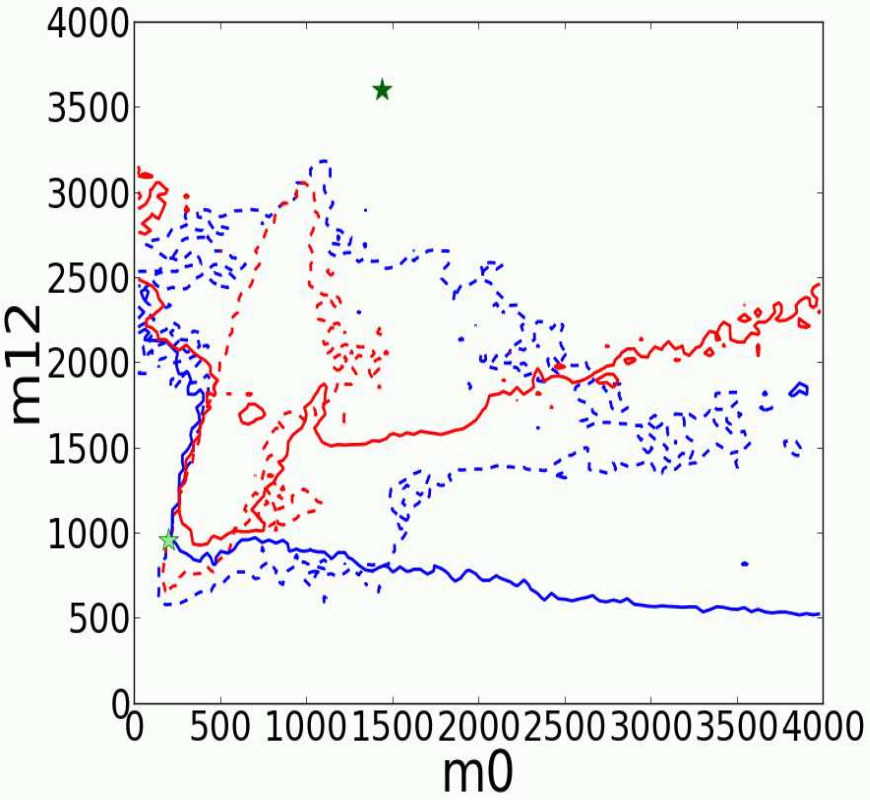
[2013]

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

CMSSM



NUHM1

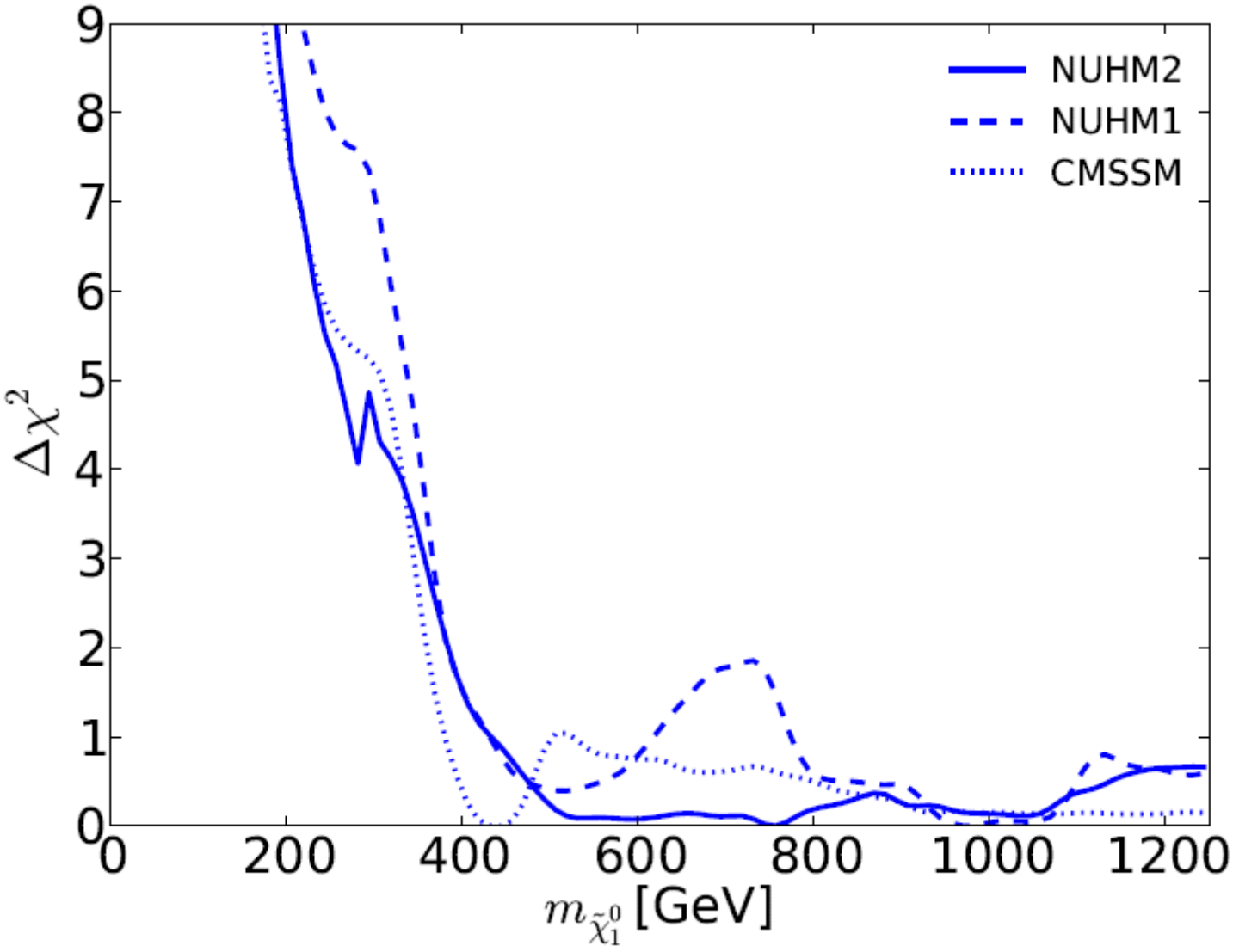


dotted: LHC 5/fb 7 TeV, solid: LHC 20/fb 8 TeV

$\Rightarrow$ only very high mass scales preferred

LSP mass incl. 20/fb of LHC data

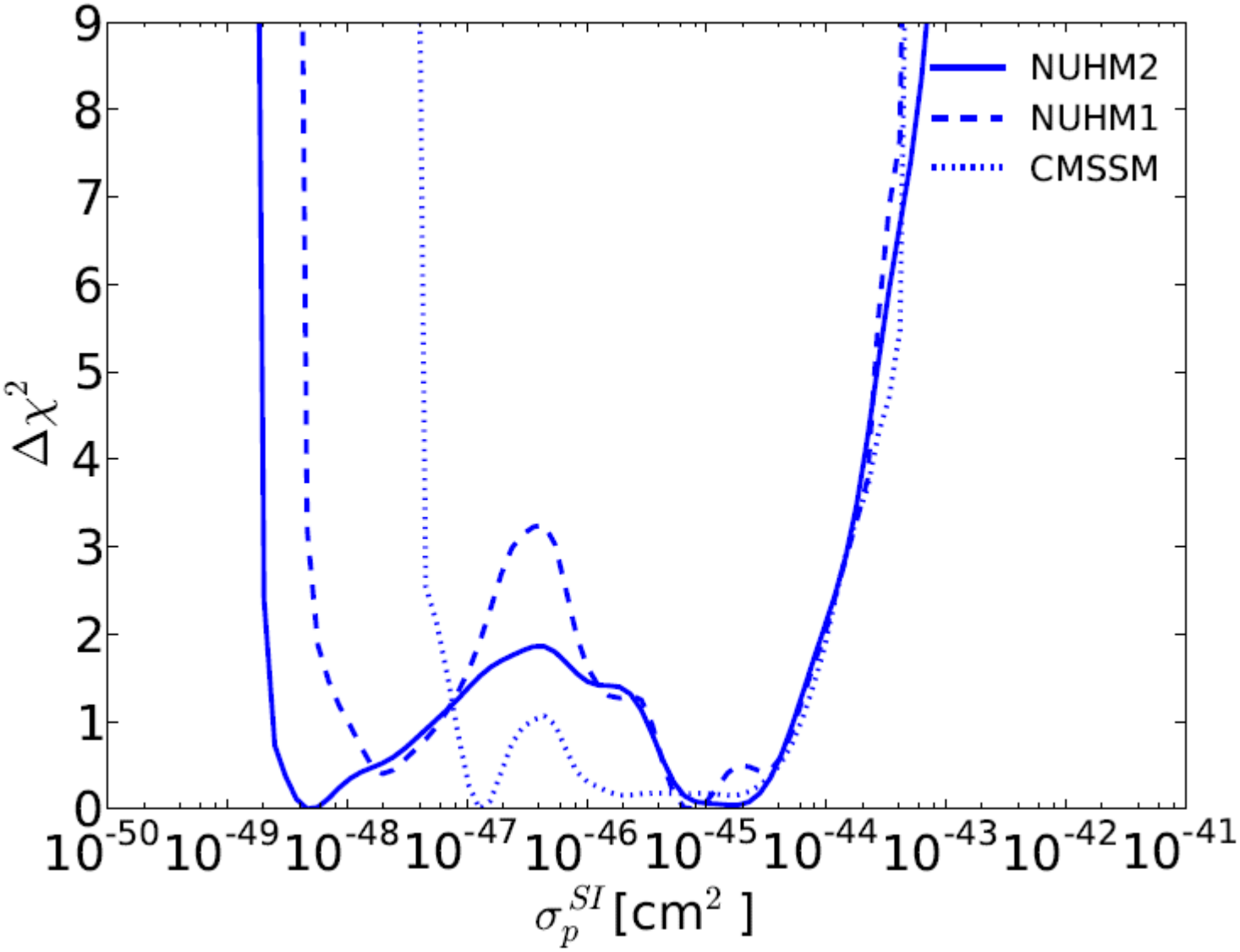
[2014]



⇒ only very large values are favored

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

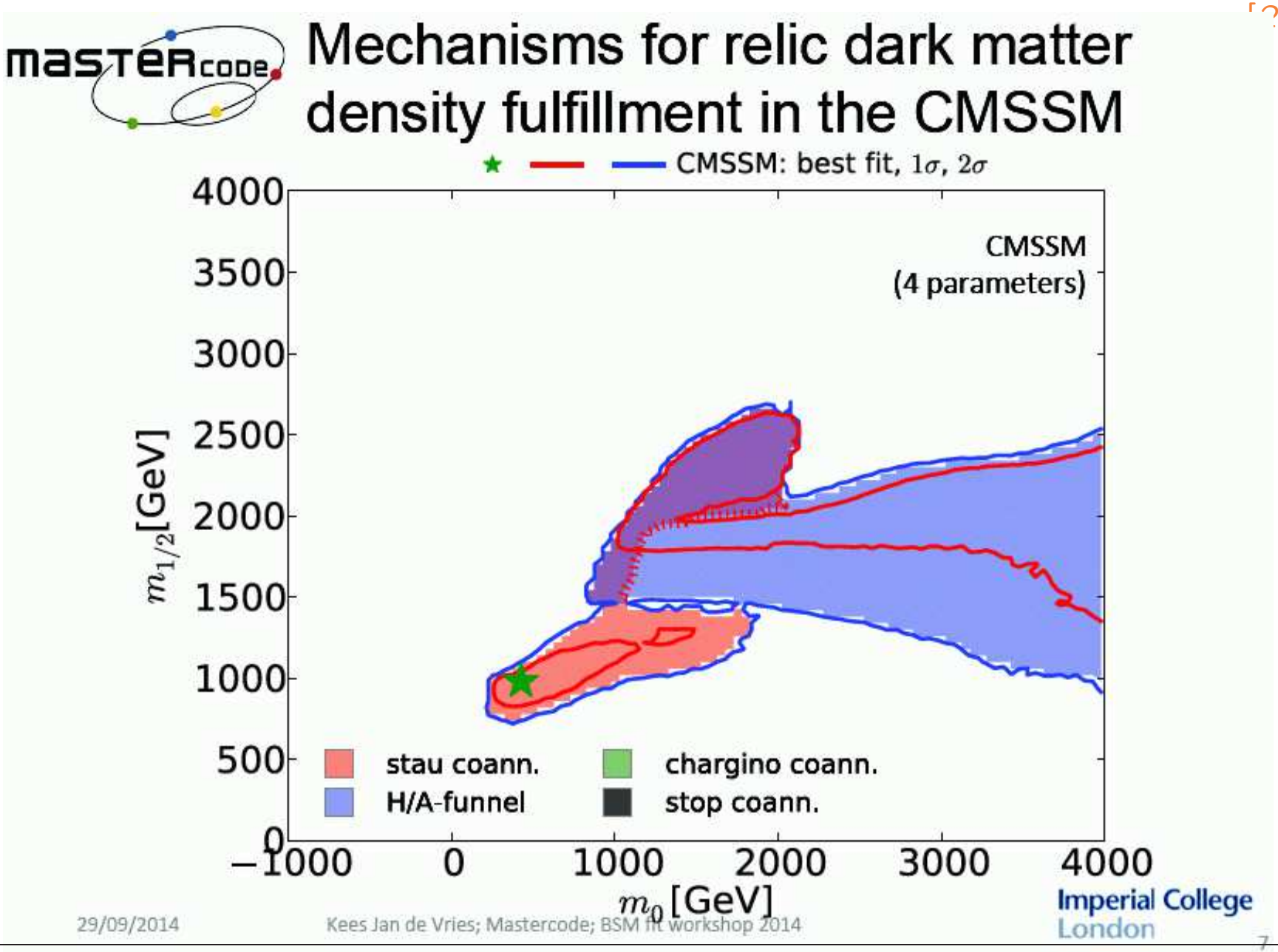
[2014]



$\Rightarrow$ only very small values are favored

CMSSM DM prediction

[?2014]



CMSSM DM prediction

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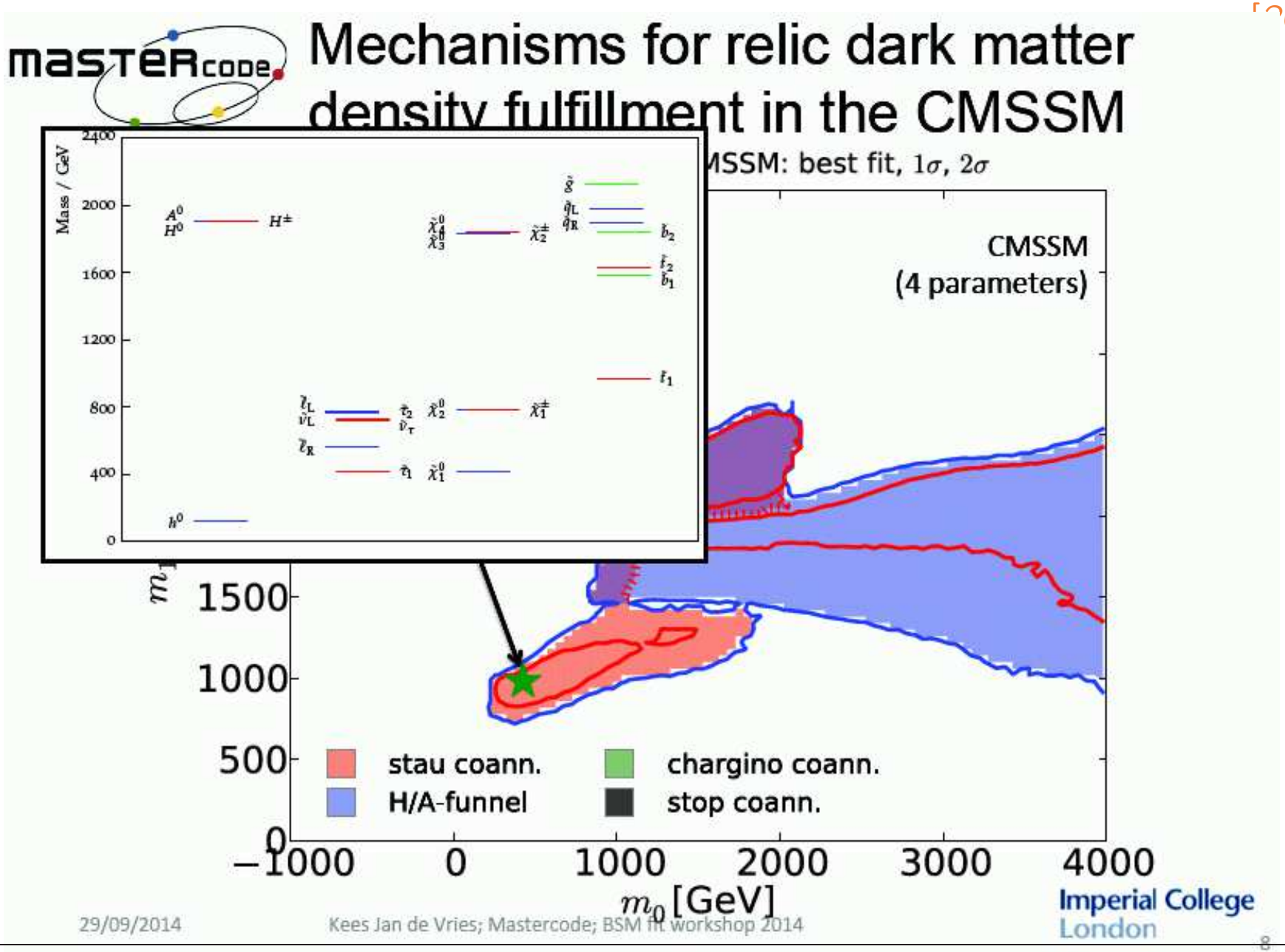

CMSSM DM prediction

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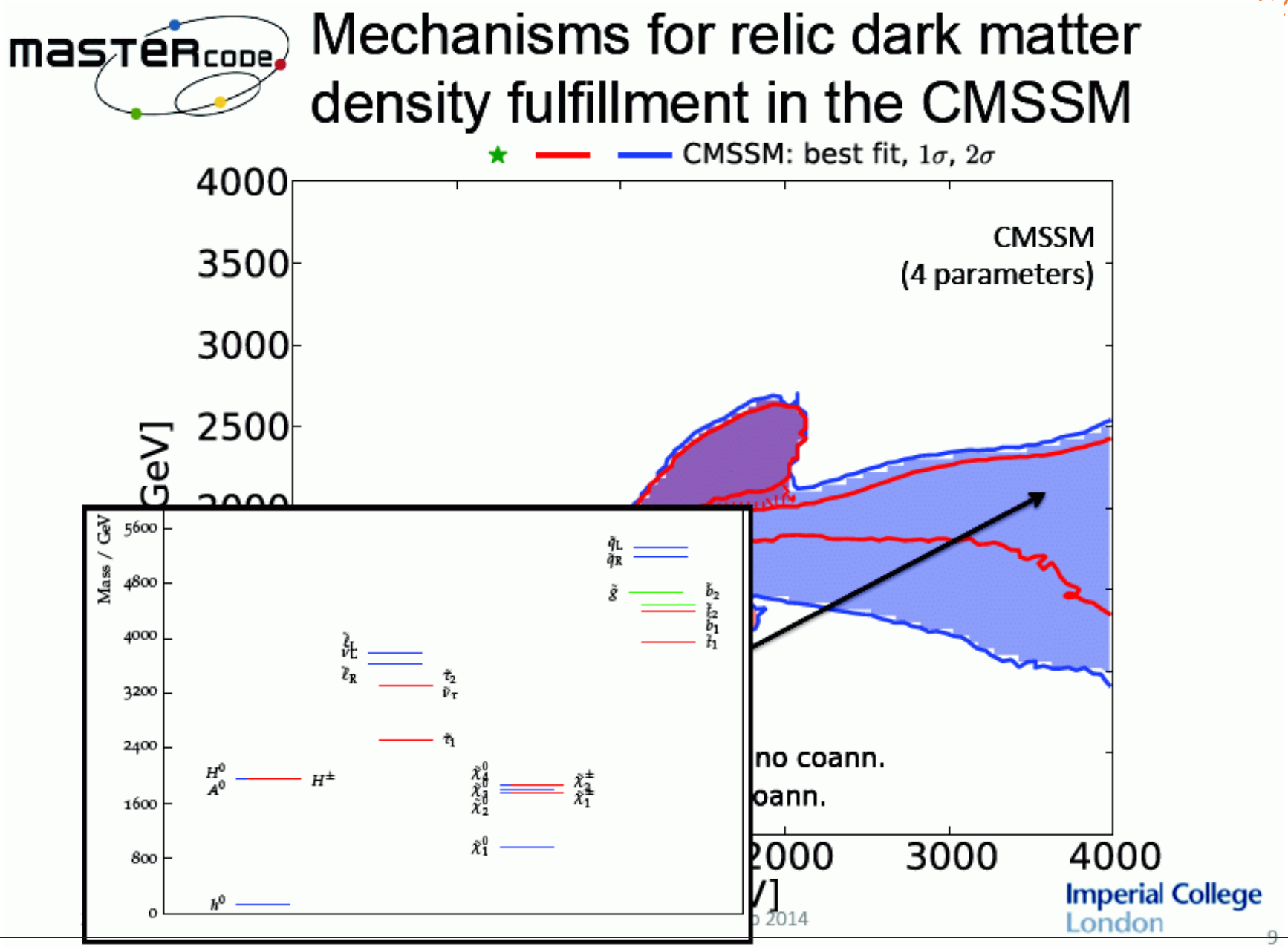
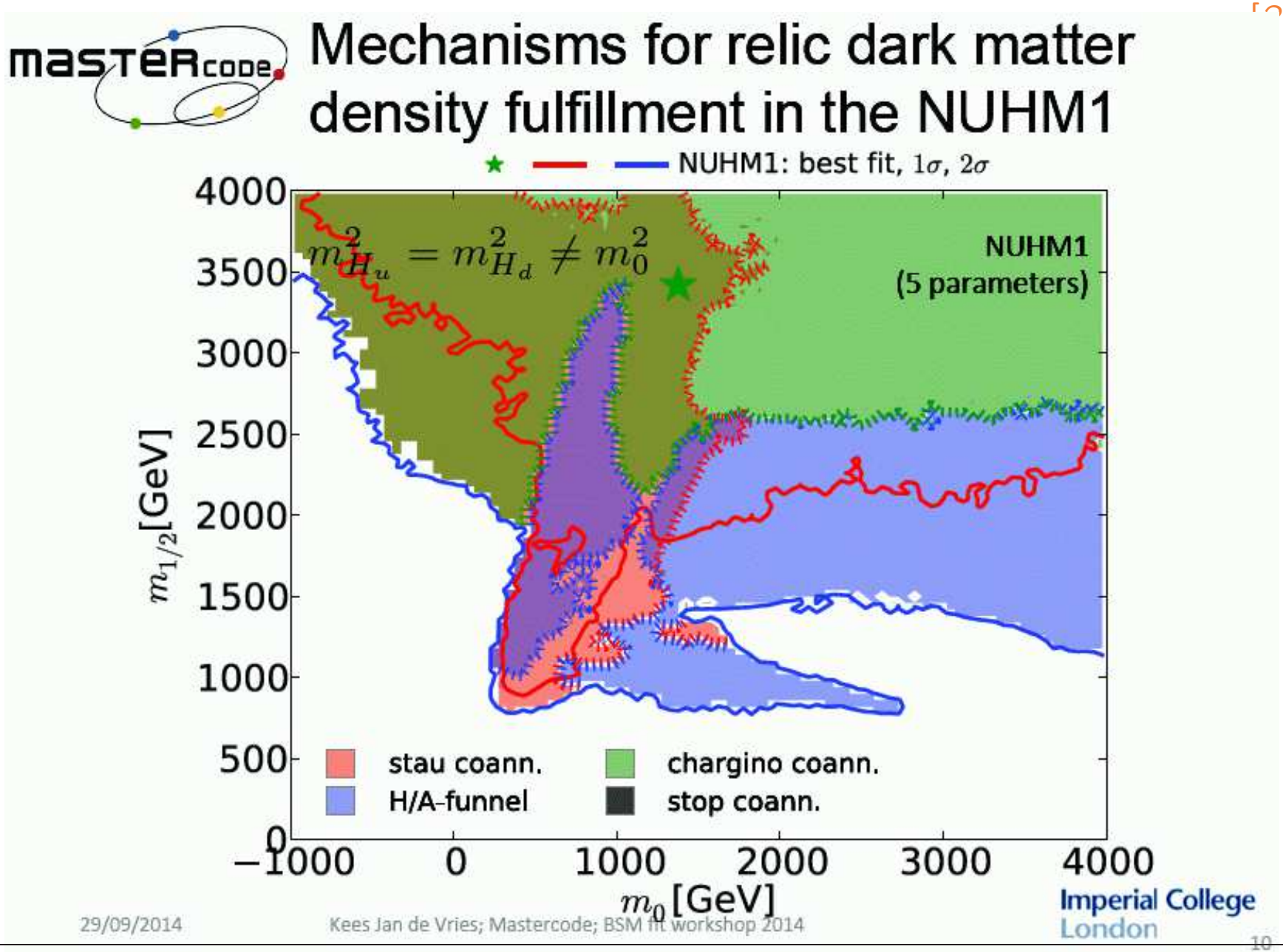


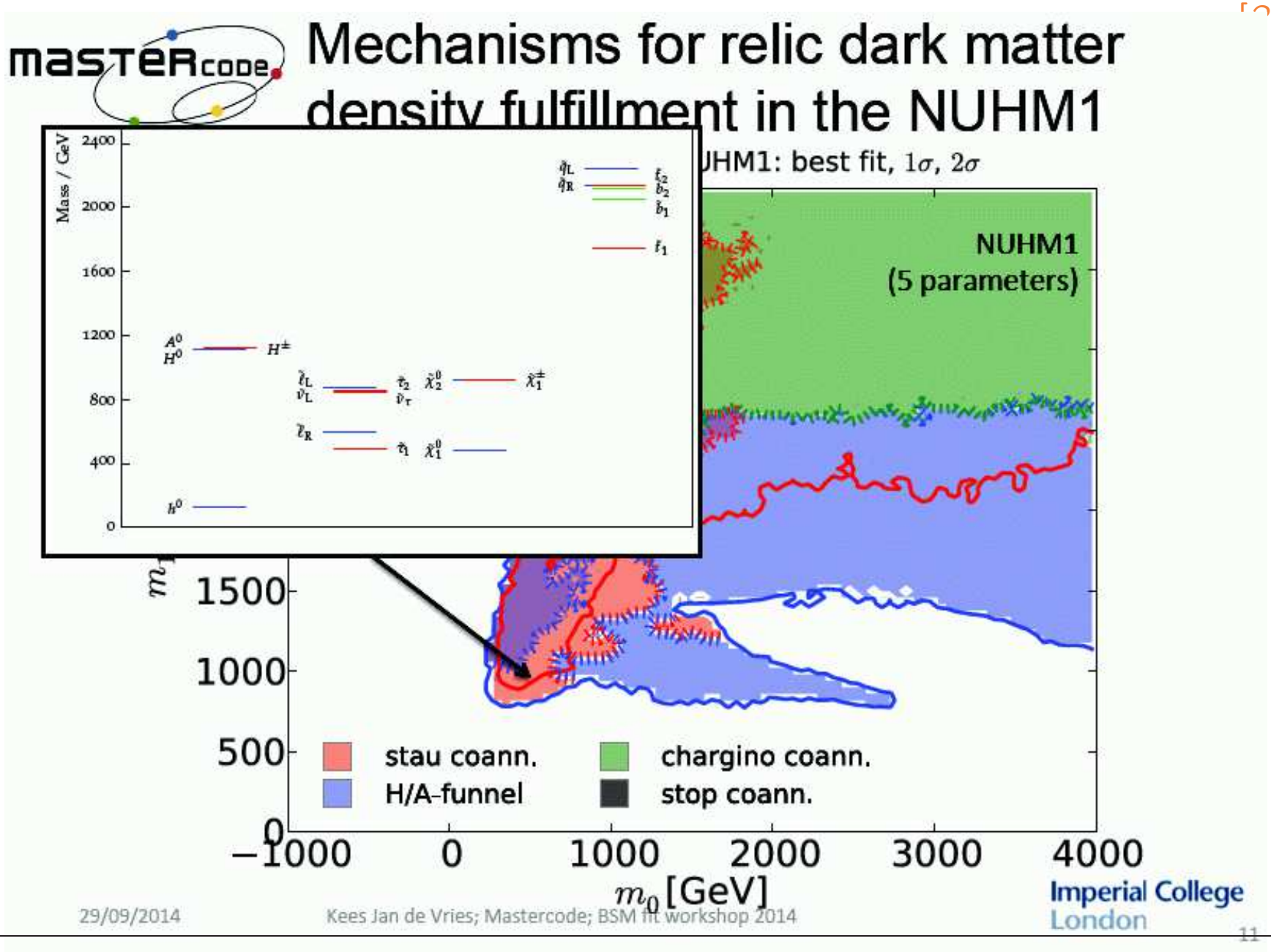
NUHM1 DM prediction

[2014]



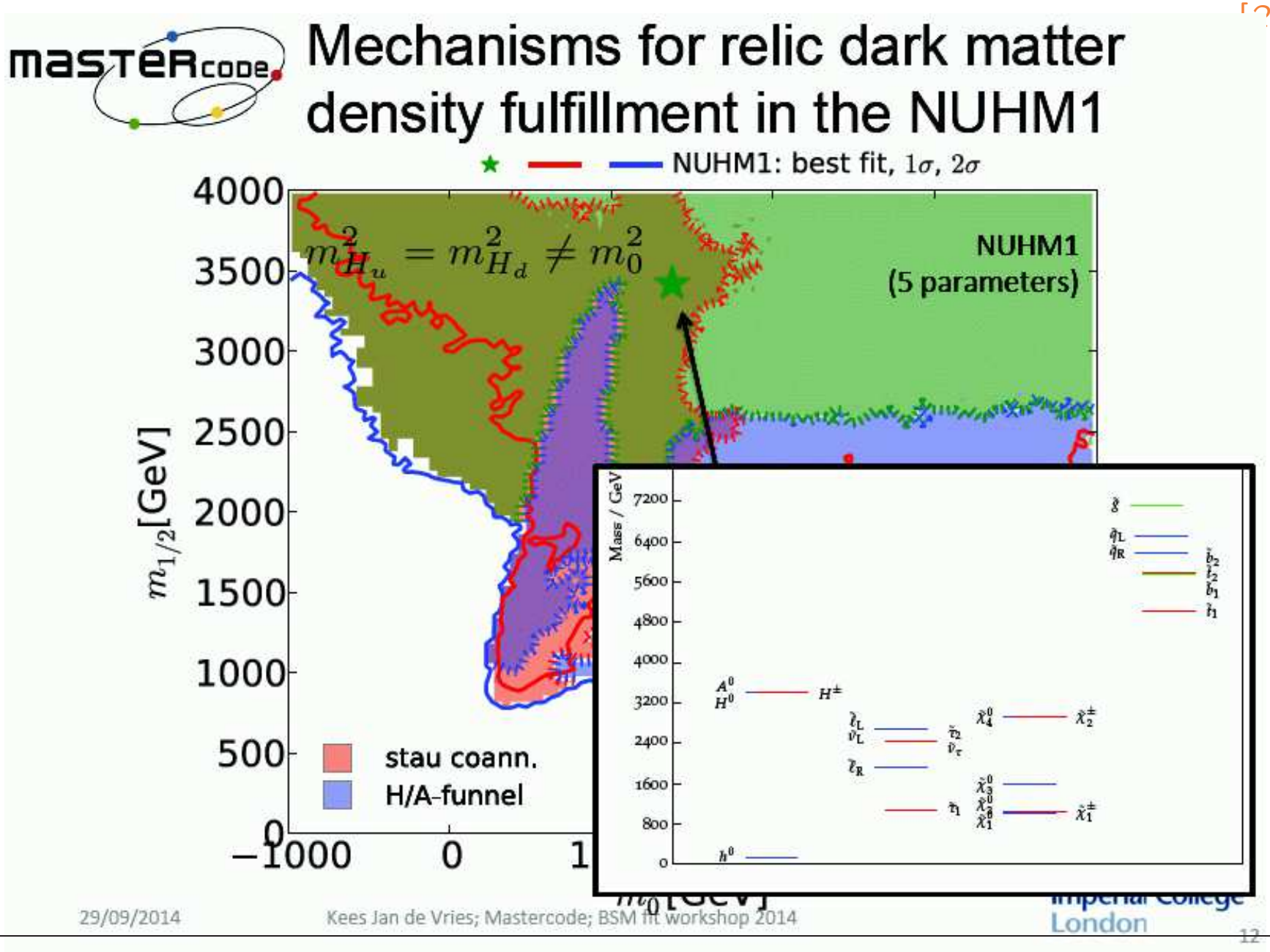
NUHM1 DM prediction

[2014]

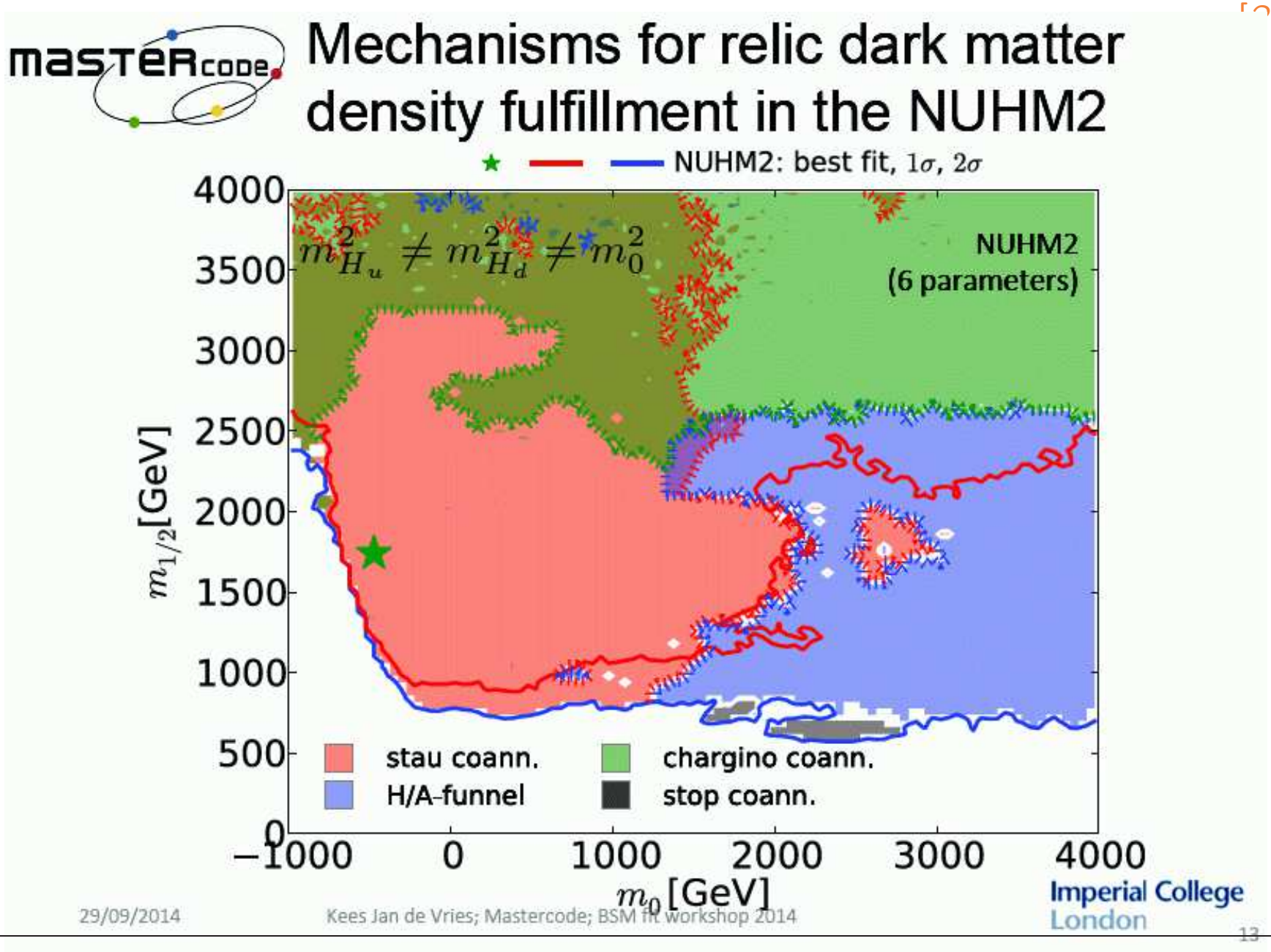


NUHM1 DM prediction

[2014]



[2014]


Mechanisms for relic dark matter density fulfillment in the NUHM2
NUHM2: best fit, 1σ, 2σ
$m^2_{H_u} \neq m^2_{H_d} \neq m^2_0$
NUHM2
(6 parameters)
stau coann.
chargino coann.
H/A-funnel
stop coann.
$m_{1/2}$[GeV]
m_0 [GeV]
4000
3500
3000
2500
2000
1500
1000
500
0
−1000
0
1000
2000
3000
4000
29/09/2014
Kees Jan de Vries; Mastercode; BSM fit workshop 2014
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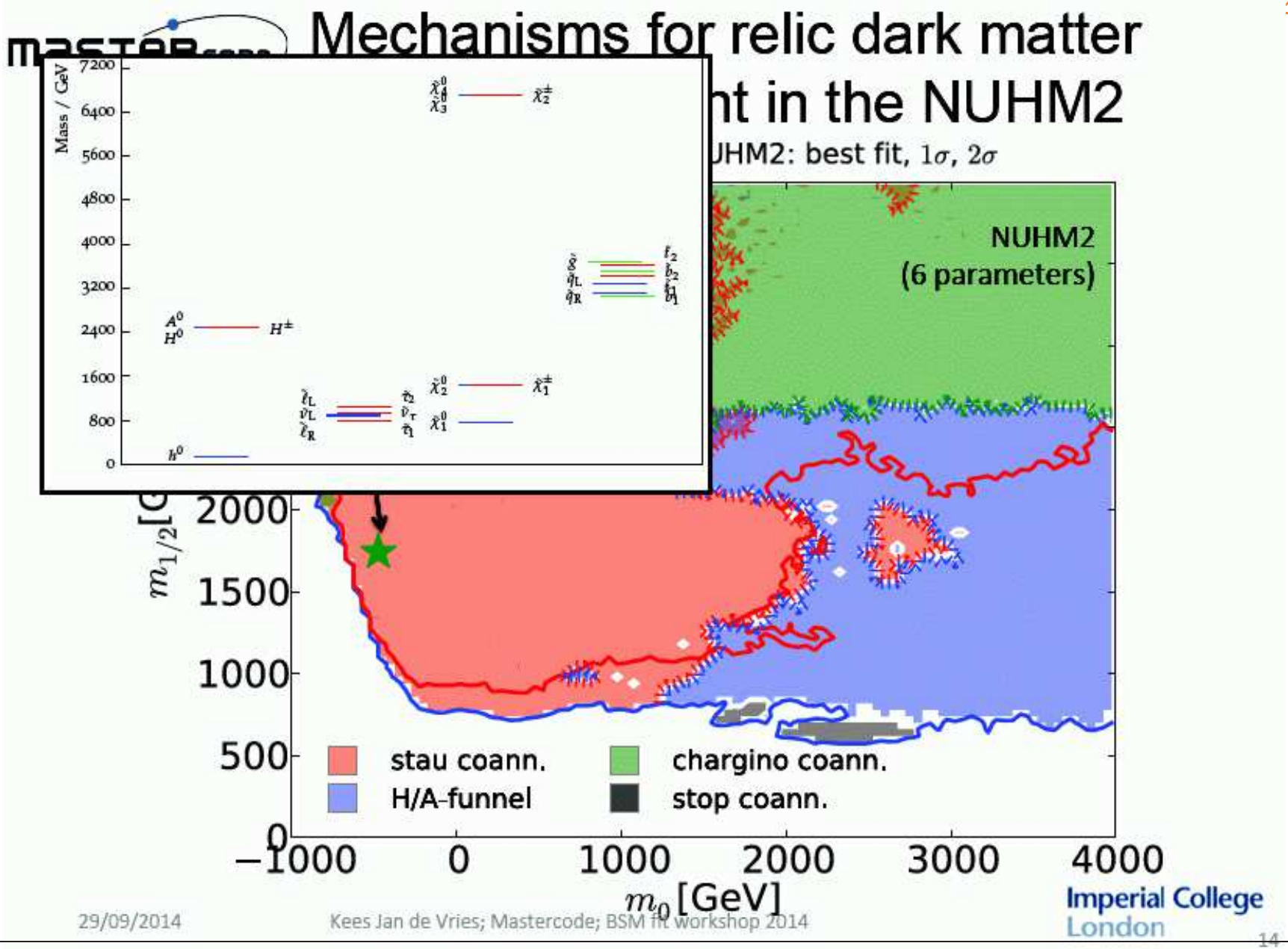
NUHM2 DM prediction

[?2014]



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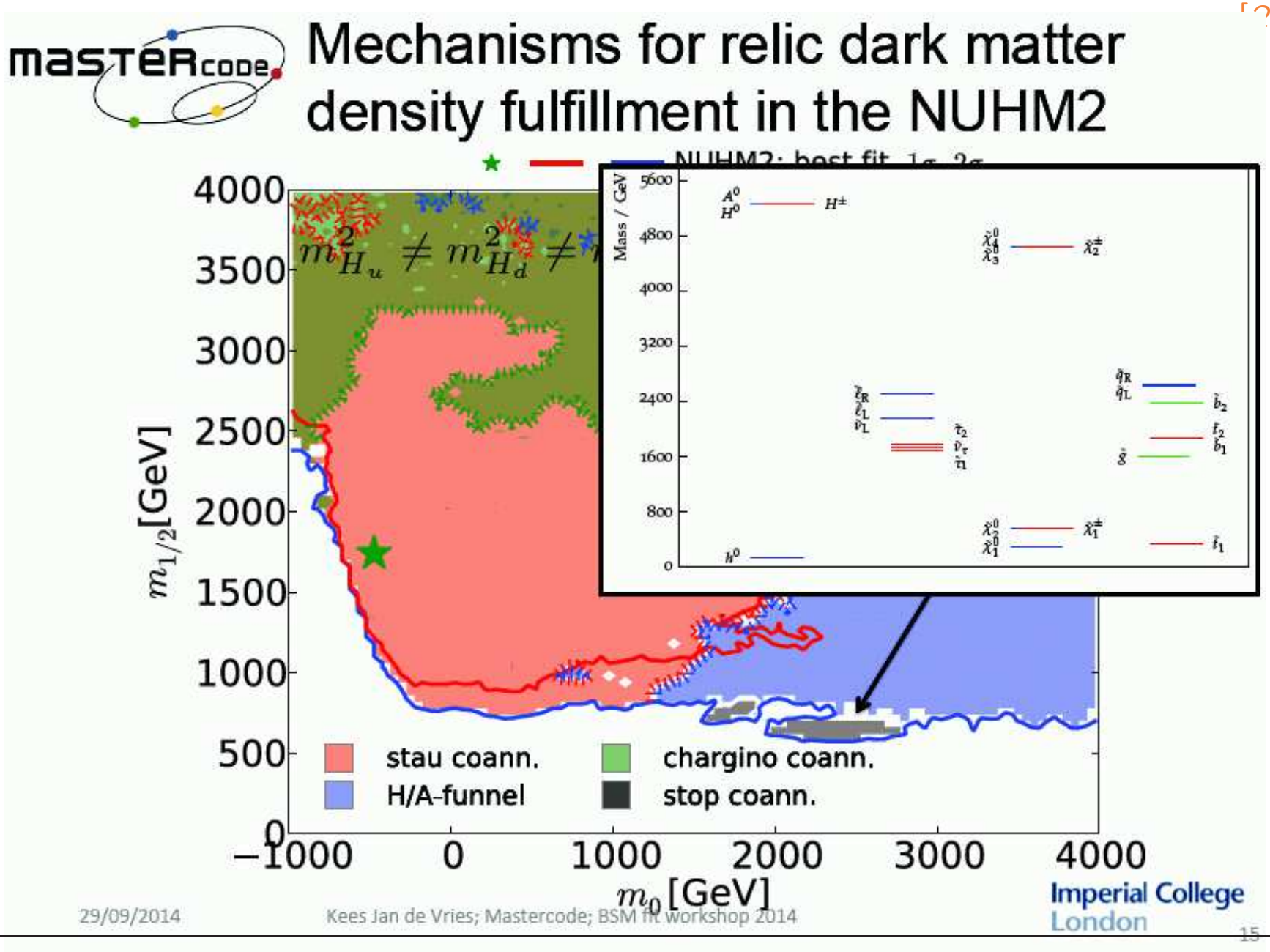
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$m^2_{H_u} \neq m^2_{H_d} \neq$
$m_{1/2}$[GeV]
m_0 [GeV]
4000
3500
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−1000
0
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2000
3000
4000
stau coann.
H/A-funnel
chargino coann.
stop coann.
Mass / GeV
5600
4800
4000
3200
2400
1600
800
0
A^0 H^0 $H^\pm$
h^0
$\tilde{\chi}^0_4$ $\tilde{\chi}^0_3$ $\tilde{\chi}^\pm_2$
$\tilde{\chi}^0_2$ $\tilde{\chi}^0_1$ $\tilde{\chi}^\pm_1$
$\tilde{e}_R$ $\tilde{e}_L$ $\tilde{\nu}_L$ $\tilde{\tau}_2$ $\tilde{\nu}_\tau$ $\tilde{\tau}_1$
$\tilde{q}_R$ $\tilde{q}_L$ $\tilde{b}_2$ $\tilde{t}_2$ $\tilde{b}_1$ $\tilde{g}$ $\tilde{t}_1$
29/09/2014
Kees Jan de Vries; Mastercode; BSM fit workshop 2014
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Results in the mAMSB

mAMSB scenario characterized by

$$m_{3/2}, m_0, \tan\beta, \text{sign}(\mu)$$

$m_{3/2} = \langle F \rangle / M_{\text{Planck}}$: overall scale of SUSY particle masses

m_0: phenomenological parameter: universal scalar mass term introduced in order to keep squares of slepton masses positive

typical feature: very small neutralino–chargino mass difference
$\Rightarrow \tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 + \pi^{\pm}$ with very soft pions

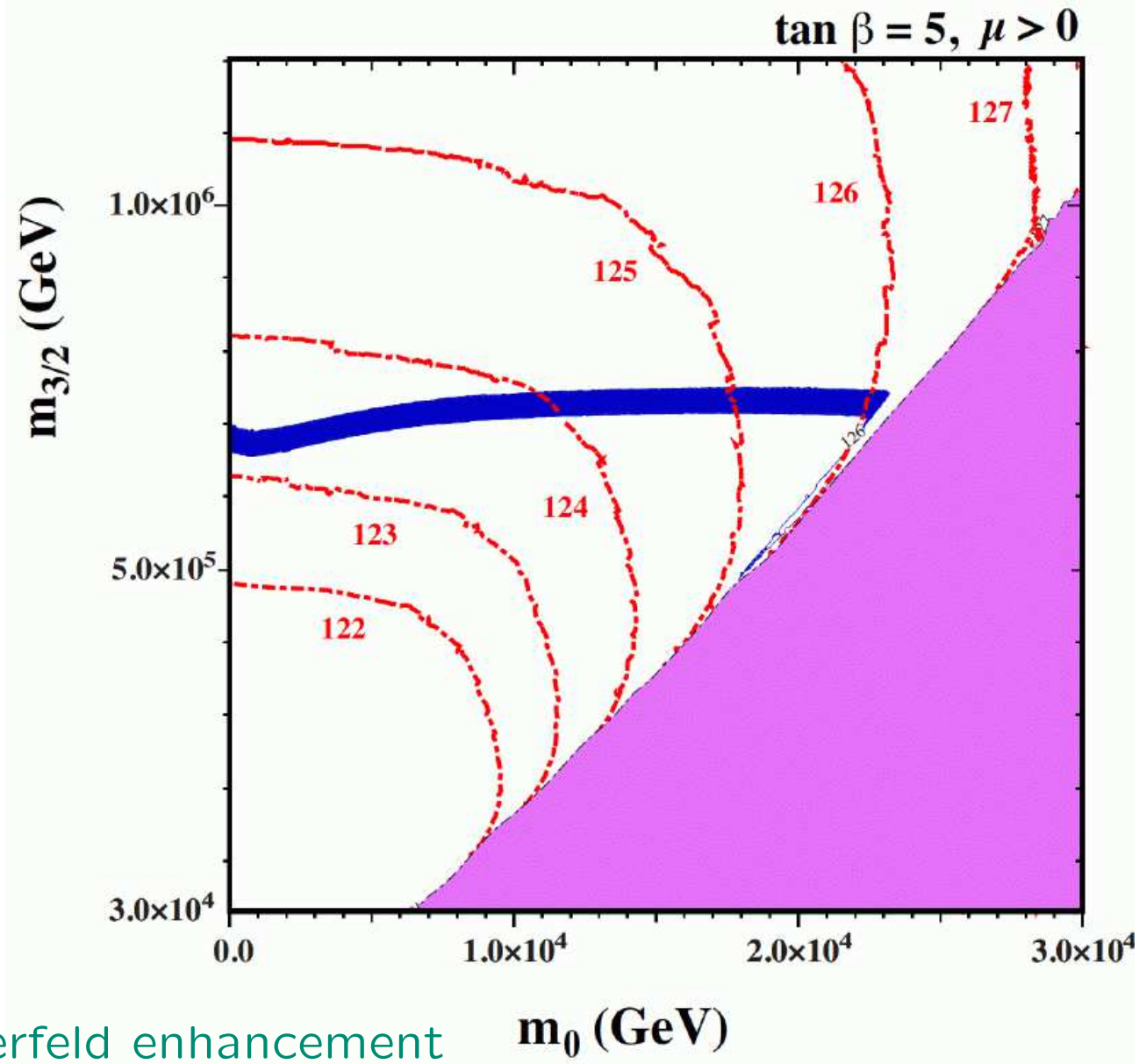
New LHC limit implementation: gluino decay modes:

$$\begin{aligned}
&\tilde{g}\tilde{g} \to (qq\tilde{\chi}_i^0)(qq\tilde{\chi}_j^0), \quad &&\tilde{g}\tilde{g} \to (tt\tilde{\chi}_i^0)(tt\tilde{\chi}_j^0),\\
&\tilde{g}\tilde{g} \to (bb\tilde{\chi}_i^0)(bb\tilde{\chi}_j^0), \quad &&\tilde{g}\tilde{g} \to (tb\tilde{\chi}_i^{\pm})(tb\tilde{\chi}_j^{\pm}),\\
&\tilde{g}\tilde{g} \to (tt\tilde{\chi}_i^0)(tb\tilde{\chi}_j^{\pm}), \quad &&\tilde{g}\tilde{g} \to (bb\tilde{\chi}_i^0)(tb\tilde{\chi}_j^{\pm}).
\end{aligned}$$

$\Rightarrow$ new LHC13 limits applied! $\to$ included into χ^2 evaluation

Known fact: Dark Matter requirement restricts $m_{3/2}$:

[2016]



⇒ no Sommerfeld enhancement

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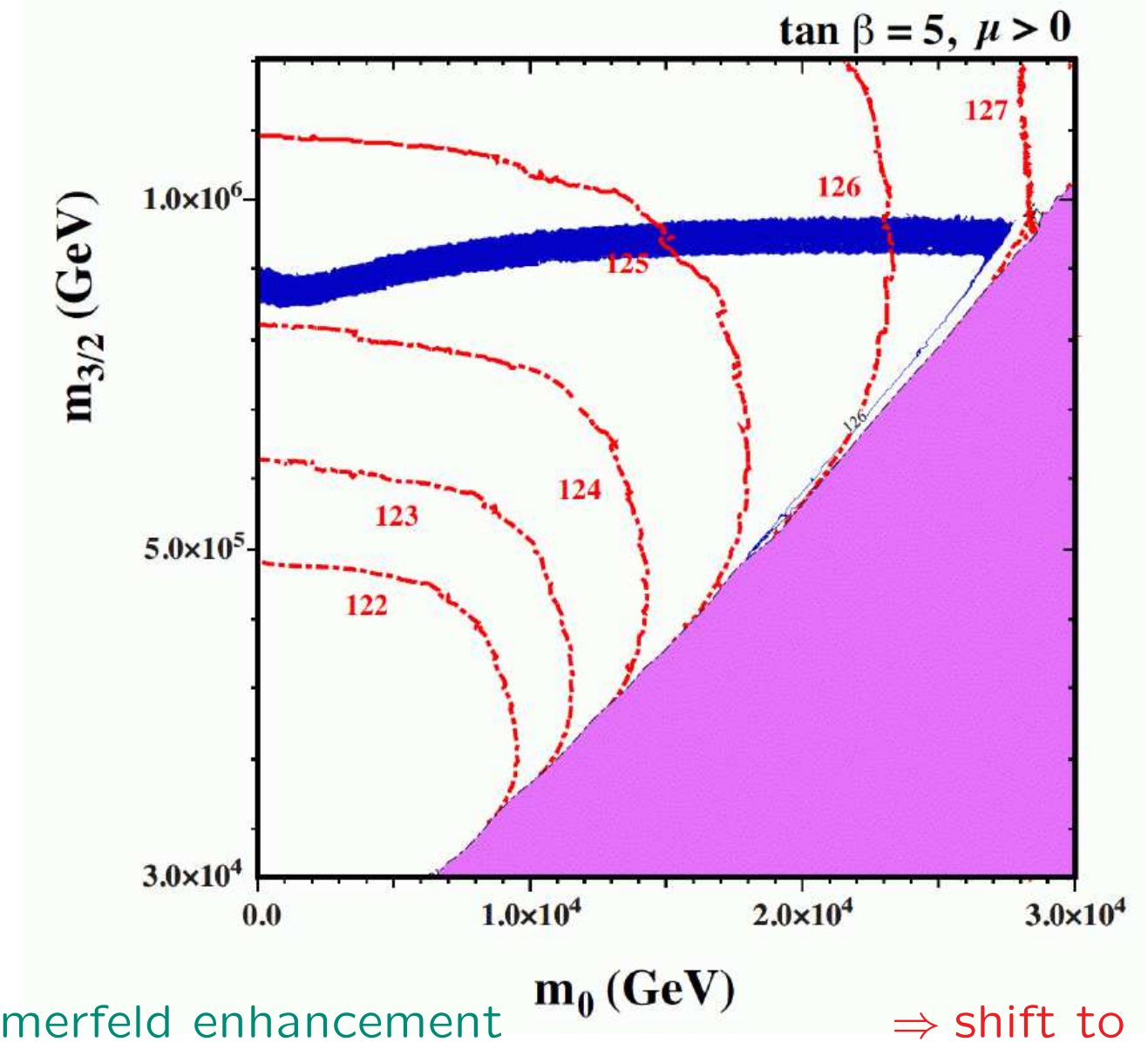
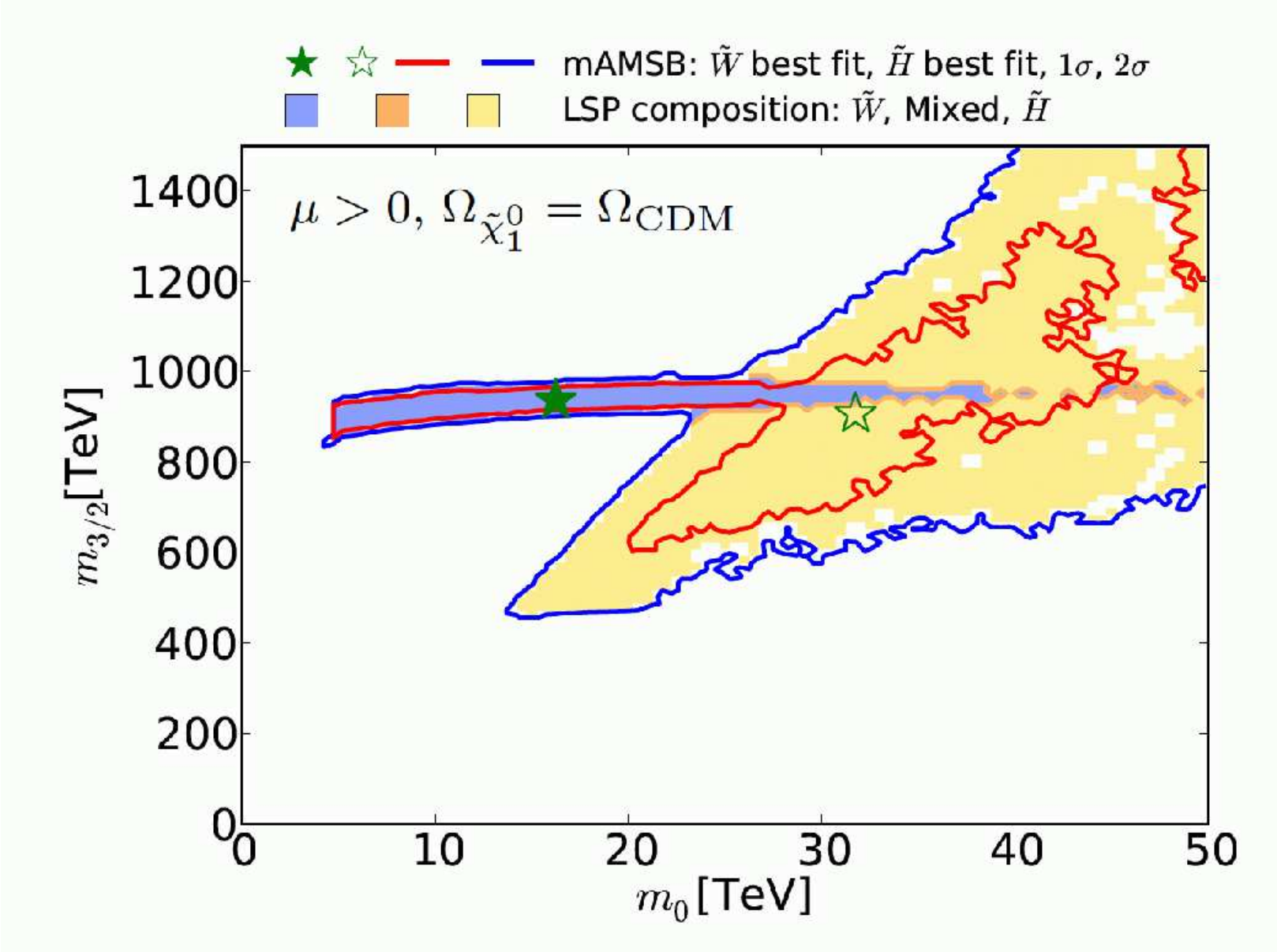
[2016]



⇒ with Sommerfeld enhancement ⇒ shift to higher $m_{3/2}$

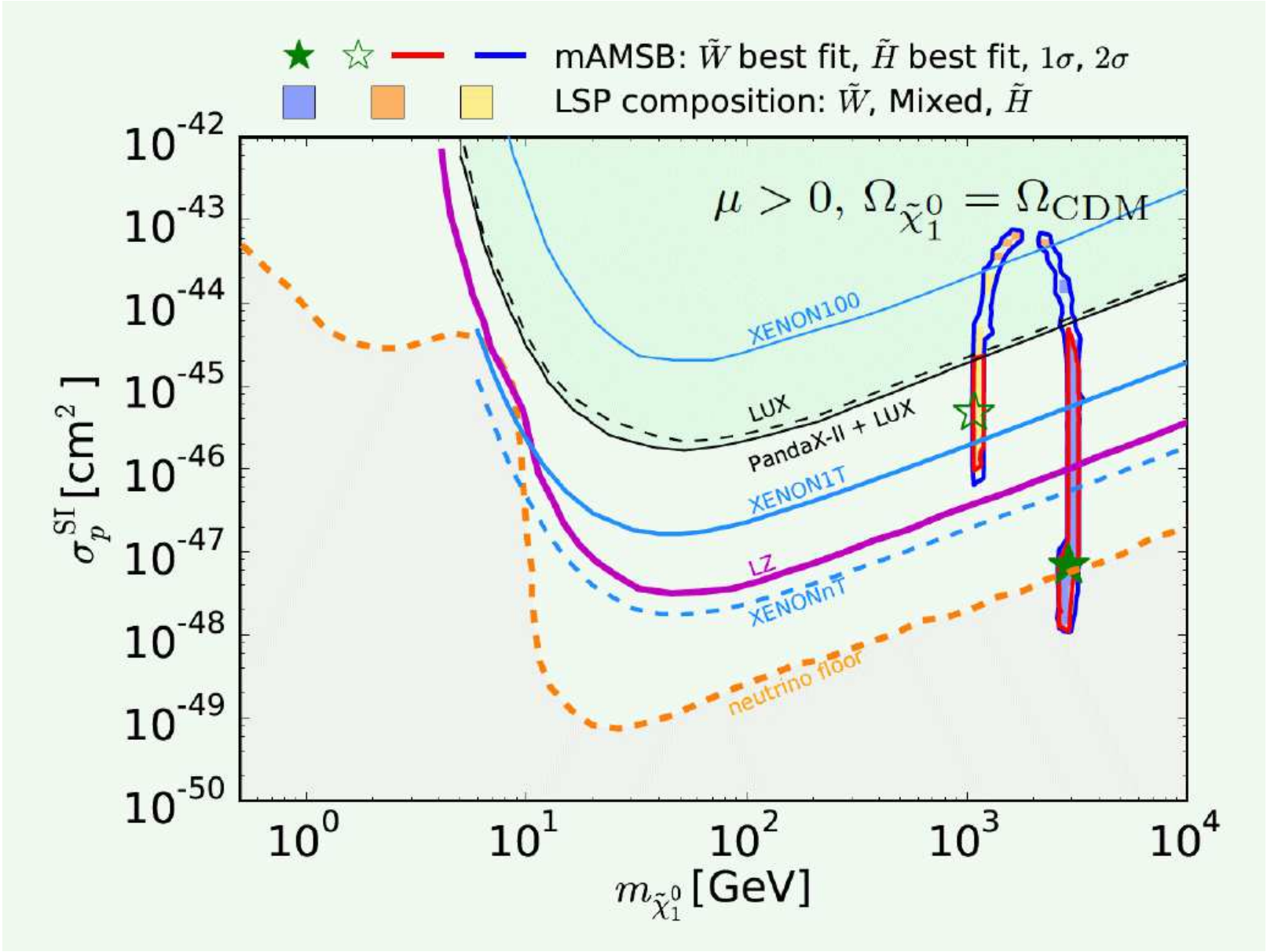
Dark Matter composition:

[2016]



Dark Matter Diret Detection prospects:

[2016]



Results in the SU(5)

SU(5) GUT:

Assumption I:

no unification of scalar Higgs parameter at the GUT scale

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

Assumption II:

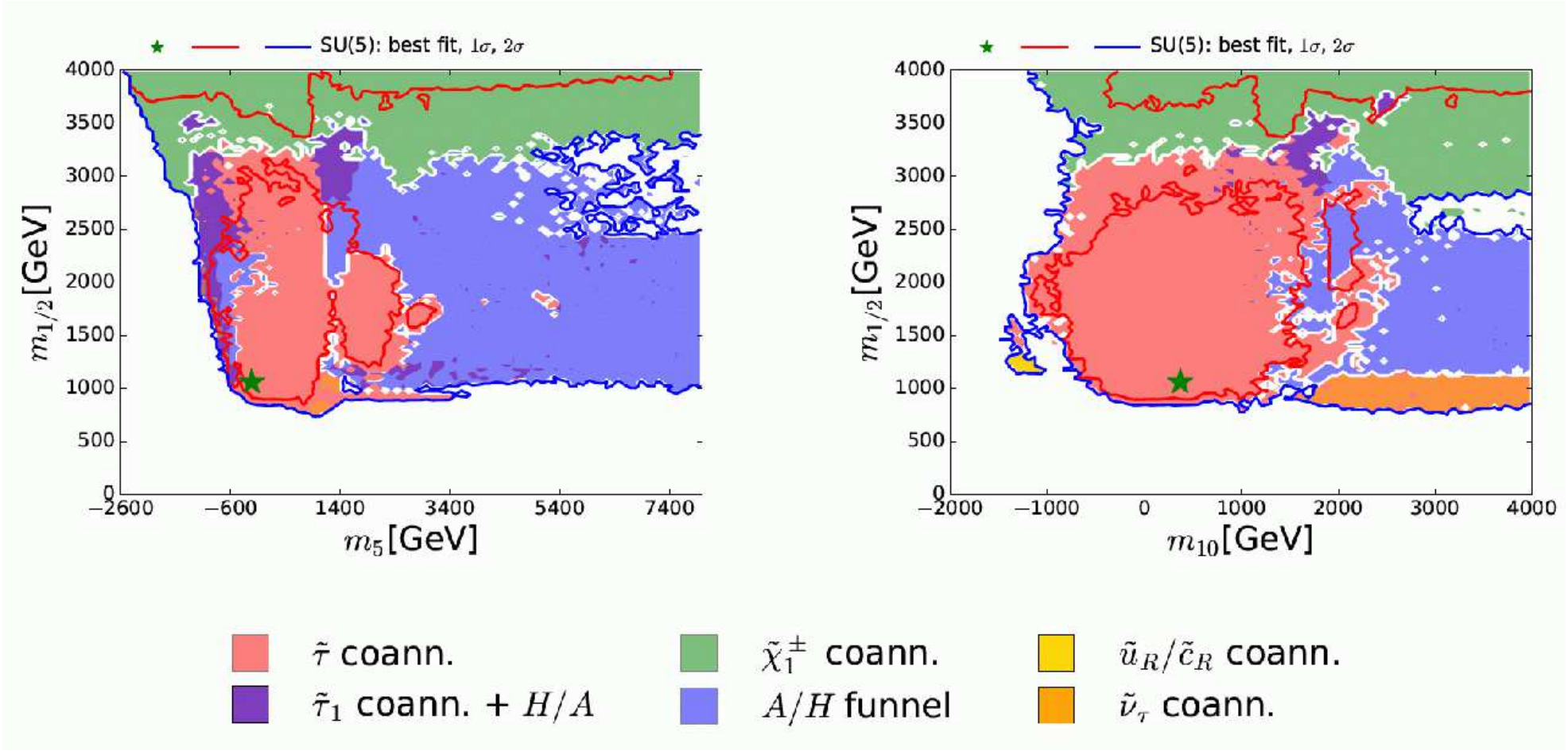
$$(q_L, u_L^c, e_L^c)_i \in \mathbf{10}_i, \quad (\ell_L, d_L^c)_i \in \bar{\mathbf{5}}_i$$

$\Rightarrow$ Scenario characterized by

$$m_5,\ m_{10},\ m_{1/2},\ A_0,\ \tan\beta,\ m_{H_u},\ m_{H_d}$$

Dark Matter annihilation mechanism:

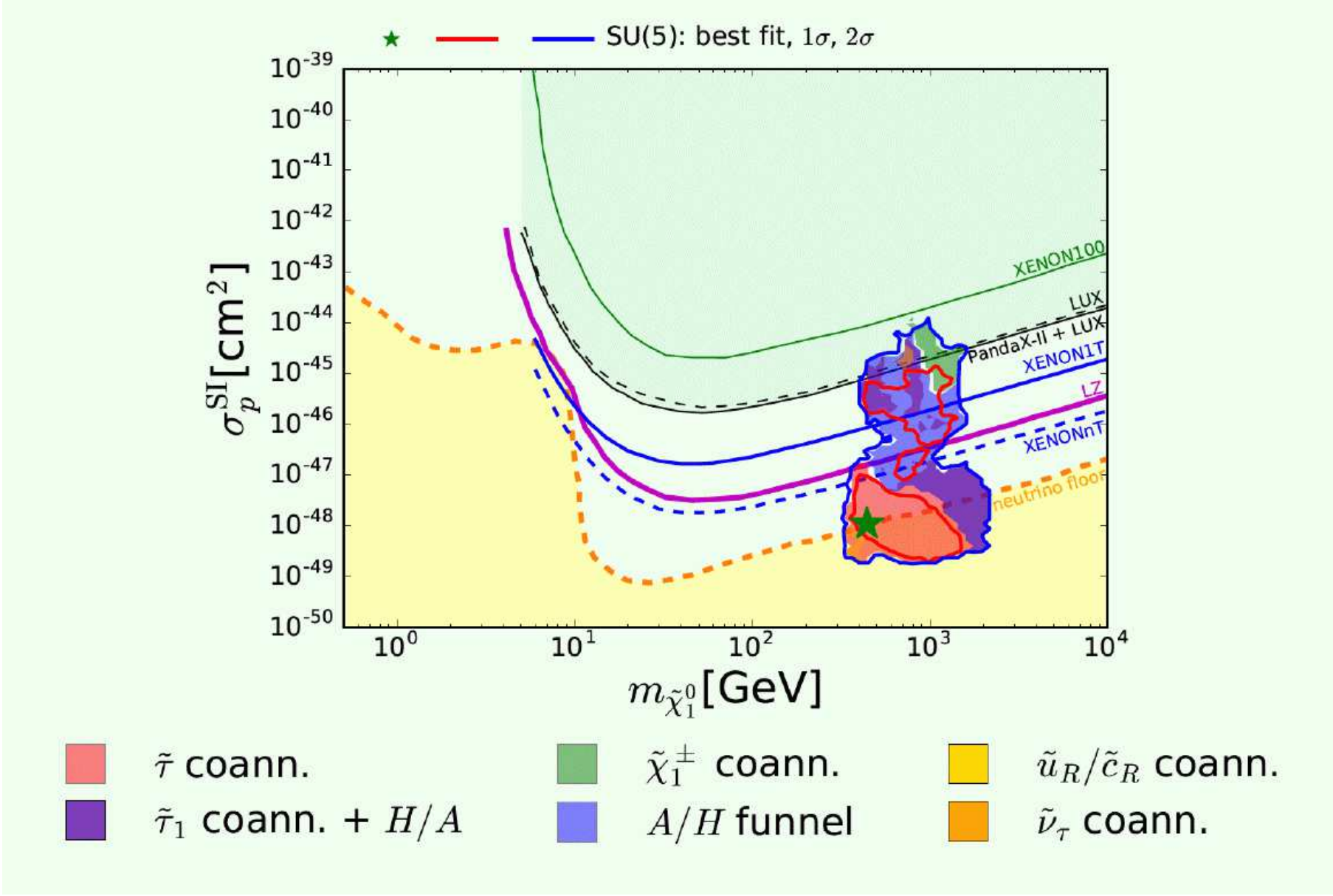
[2016]



$\Rightarrow \tilde{u}_R/\tilde{c}_R/\tilde{\nu}_\tau$ co-annihilation possible

Dark Matter Diret Detection prospects:

[2016]



Have we missed the correct SUSY-breaking mechanism?

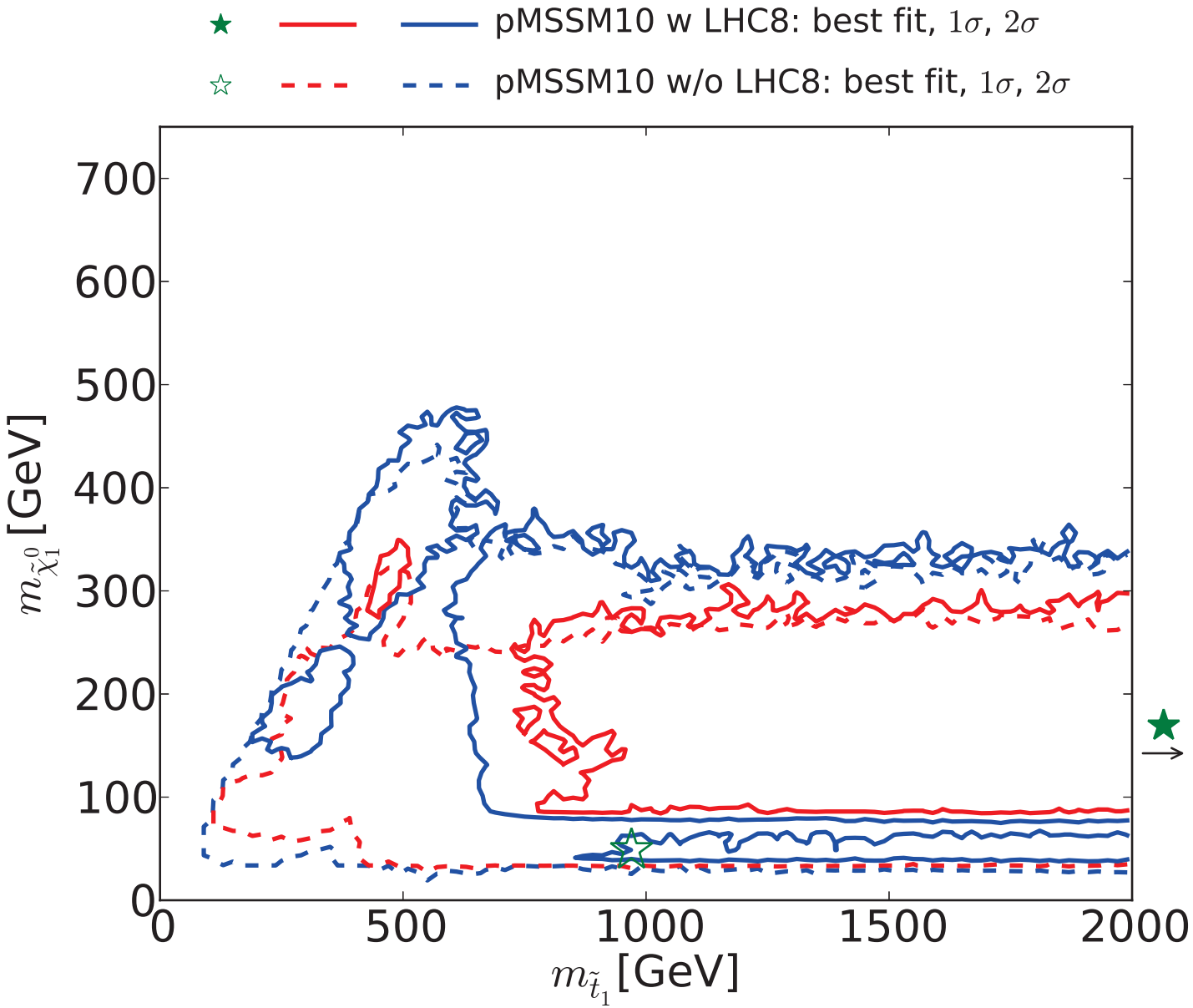
$\Rightarrow$ **pMSSM10!**

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

pMSSM10 prediction: DM mass vs. light stop mass:

[2015]



pMSSM10 prediction: DM mass vs. light stop mass:

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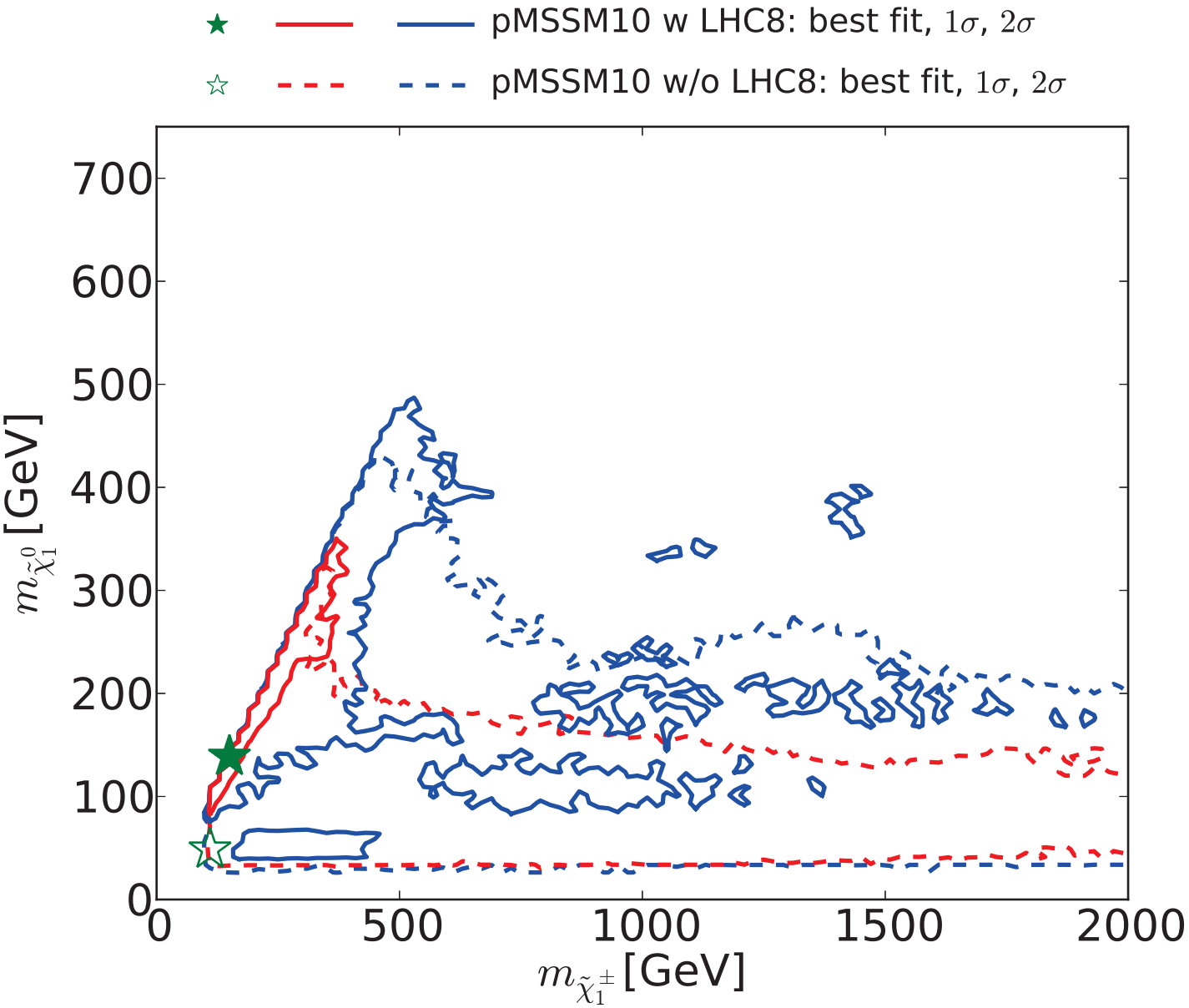

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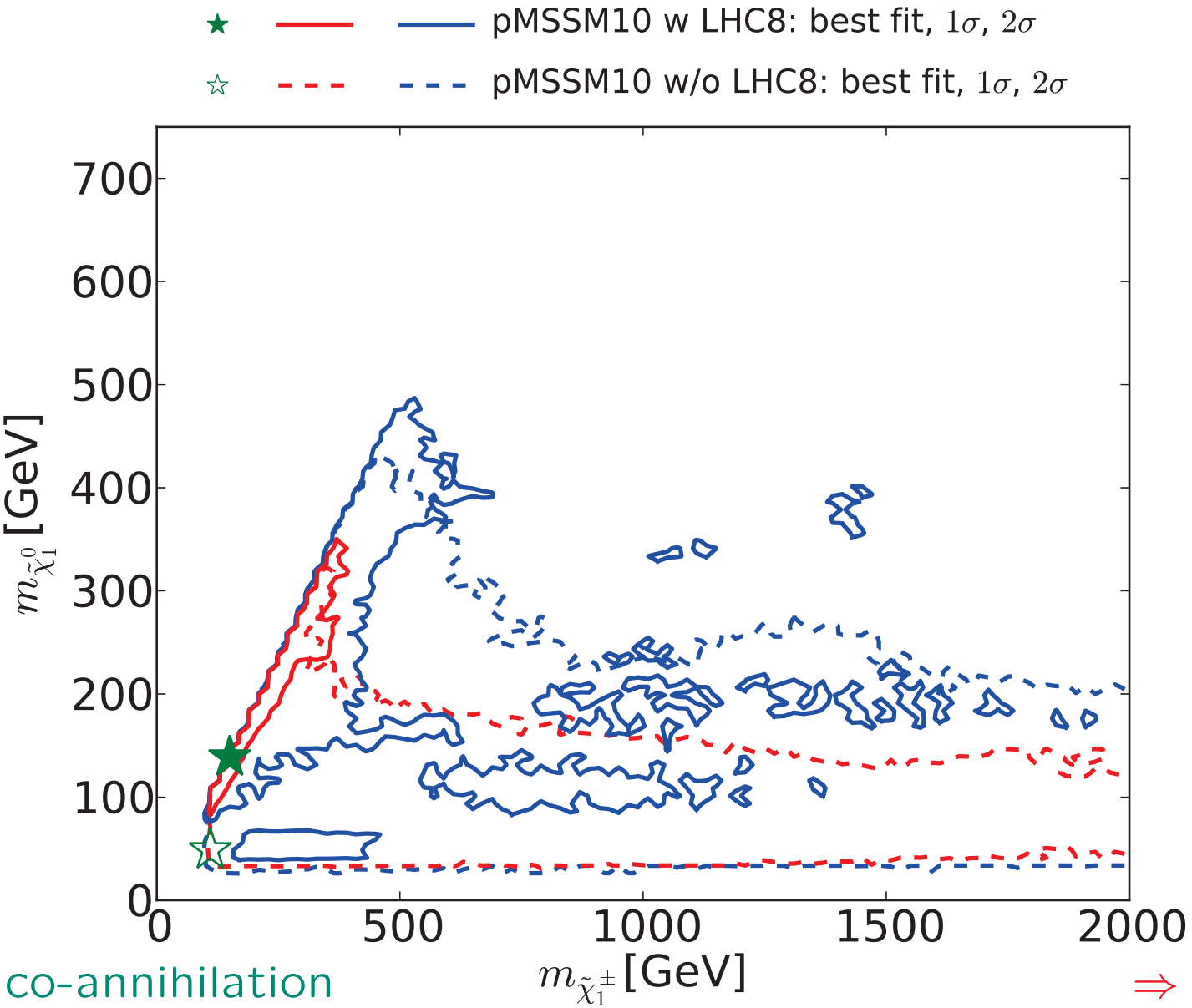
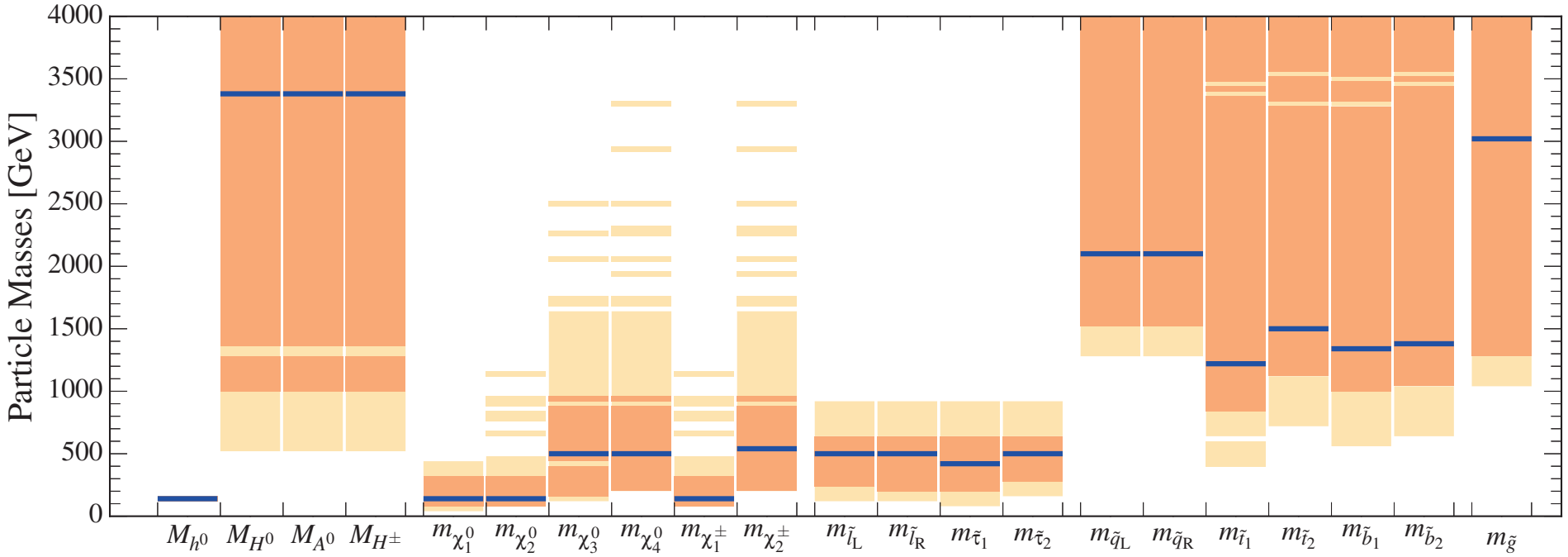


⇒ chargino co-annihilation

⇒ $M_1 \approx M_2$

pMSSM10 prediction: best-fit masses

[2015]



$\Rightarrow$ high colored masses

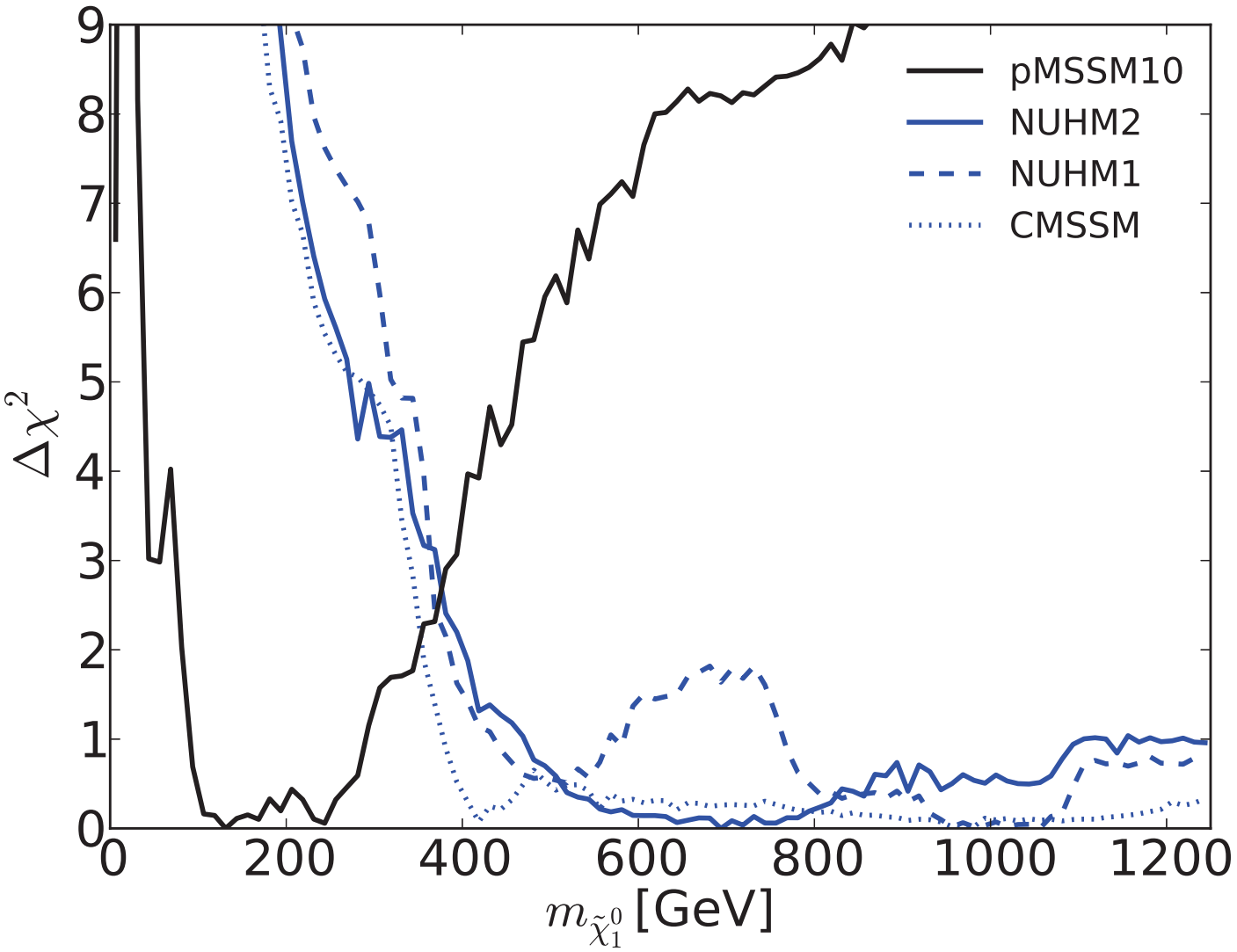
$\Rightarrow$ relatively low electroweak masses

partially with not too large ranges

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

DM mass: pMSSM10 vs. GUT based models prediction:

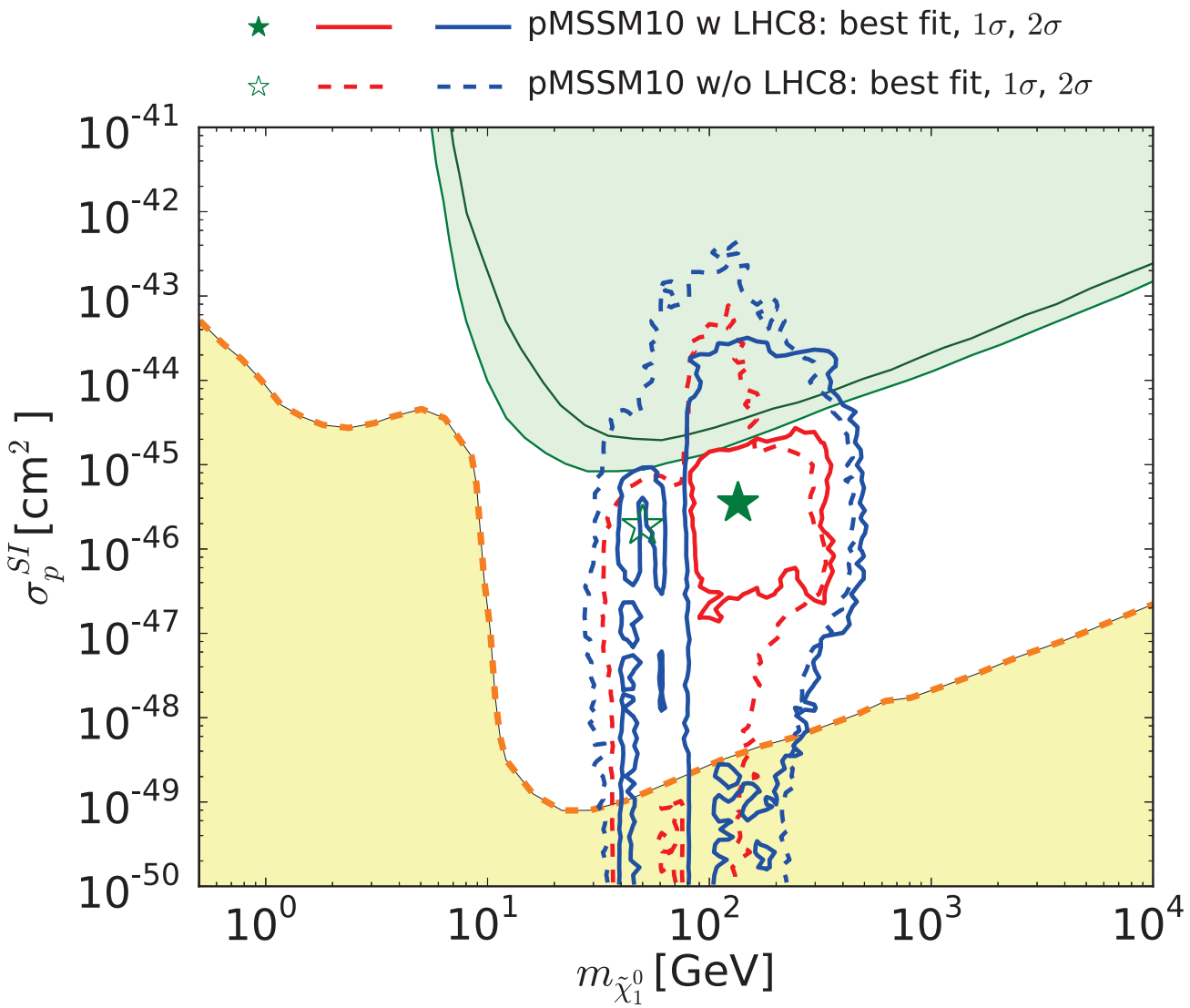
[2015]



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

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

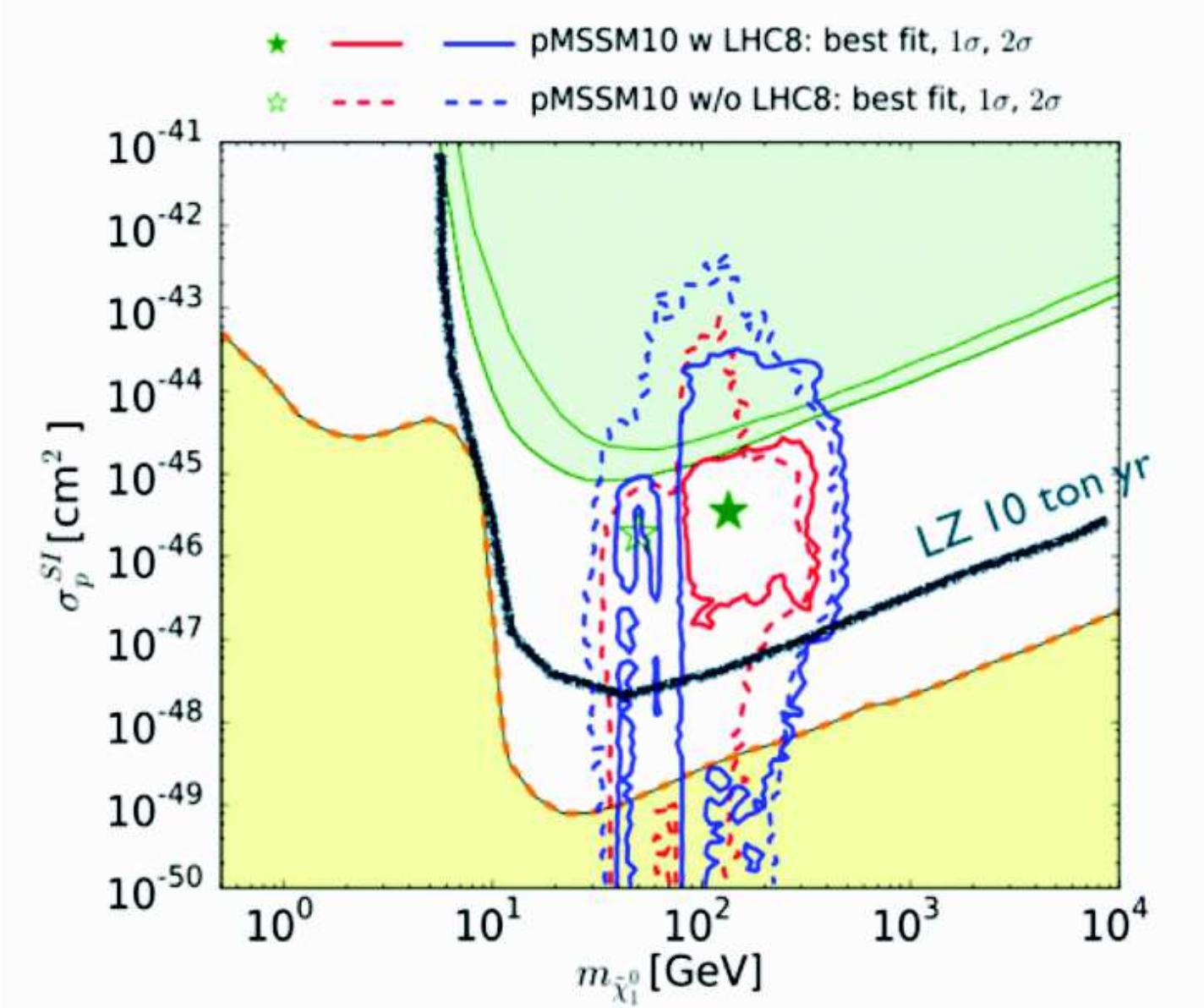
[2015]



$\Rightarrow$ LHC bounds try to "rescue" DD experiments!

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

[2015]



$\Rightarrow$ 68% CL areas covered by next round of DD experiments

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

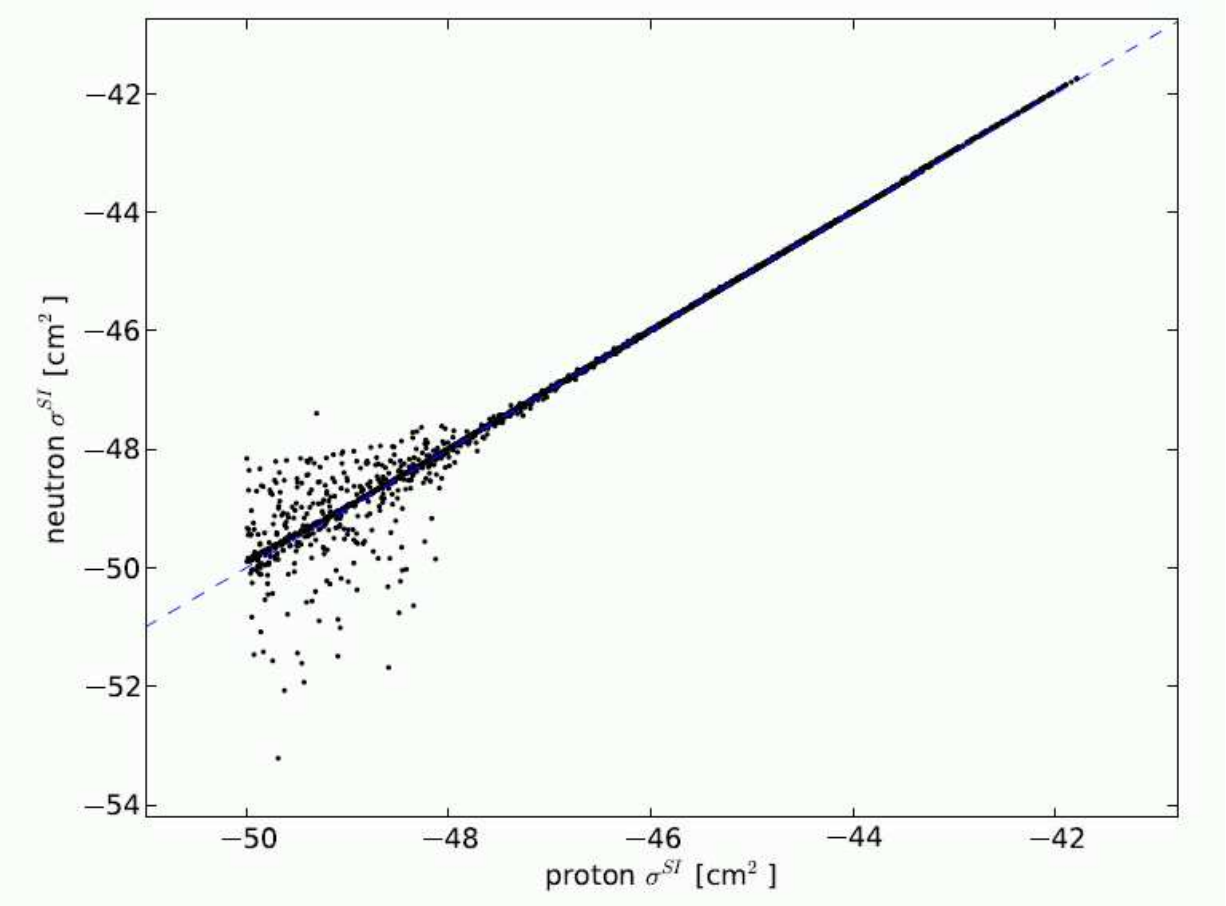
[2015]

$\sigma_p^{\rm SI}$ is evaluated for p-scattering

Can n-scattering come to rescue?

Some points with low $\sigma_p^{\rm SI}$ have even lower $\sigma_n^{\rm SI}$

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



4. Conclusinos

4. Conclusinos

- SUSY is (still) the best-motivated BSM scenario
  - constrained models: CMSSM, NUHM1, NUHM2, SU(5), mAMSB
  - general models: pMSSM10, . . .

- Our tool: MasterCode: combination of LHC searches, Higgs measurements, EWPO, BPO, CDM $\Rightarrow \chi^2$ evaluation

- Preferred ranges in GUT based models: $m_{\tilde{\chi}_1^0} \gtrsim 400$ GeV

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

- Predictions for DD experiments in pMSSM10:
  - 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


Further Questions?

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

$\Rightarrow$ Scenario characterized by

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

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

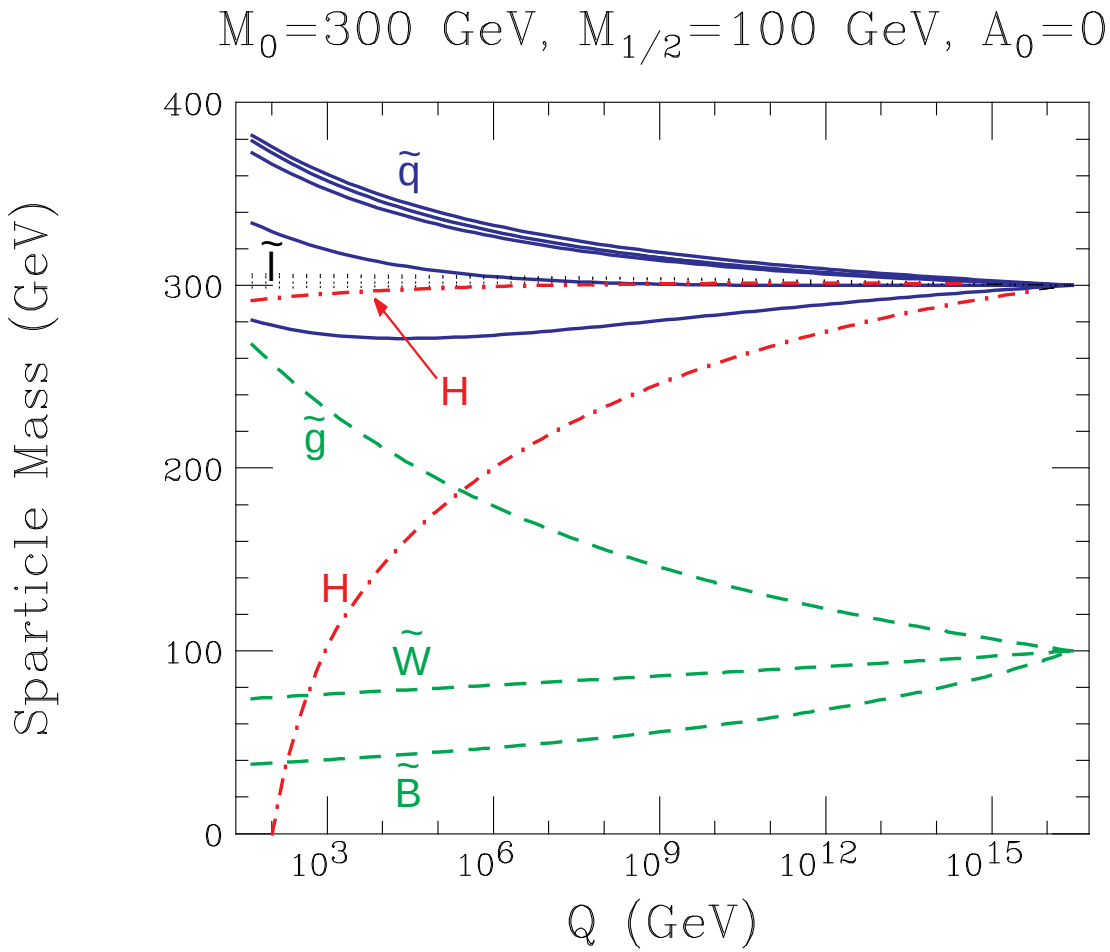
sign(μ) : sign of supersymmetric Higgs parameter

$\Rightarrow$ particle spectra from renormalization group running to weak scale

$\Rightarrow$ Lightest SUSY particle (LSP) is the lightest neutralino $\Rightarrow$ DM!

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

⇒ particle spectra from renormalization group running to weak scale



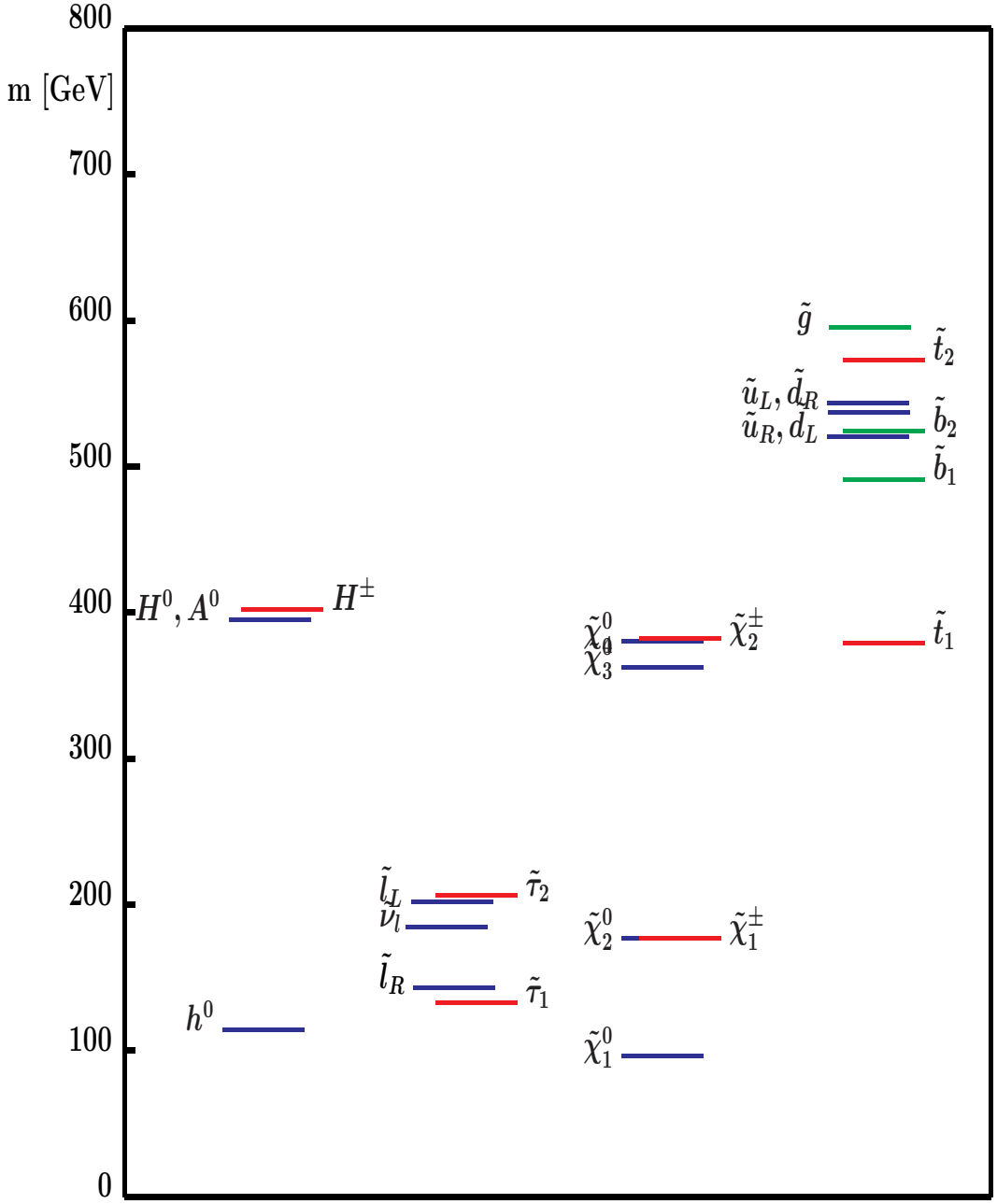
⇒ one parameter turns negative ⇒ Higgs mechanism for free

"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

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

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

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

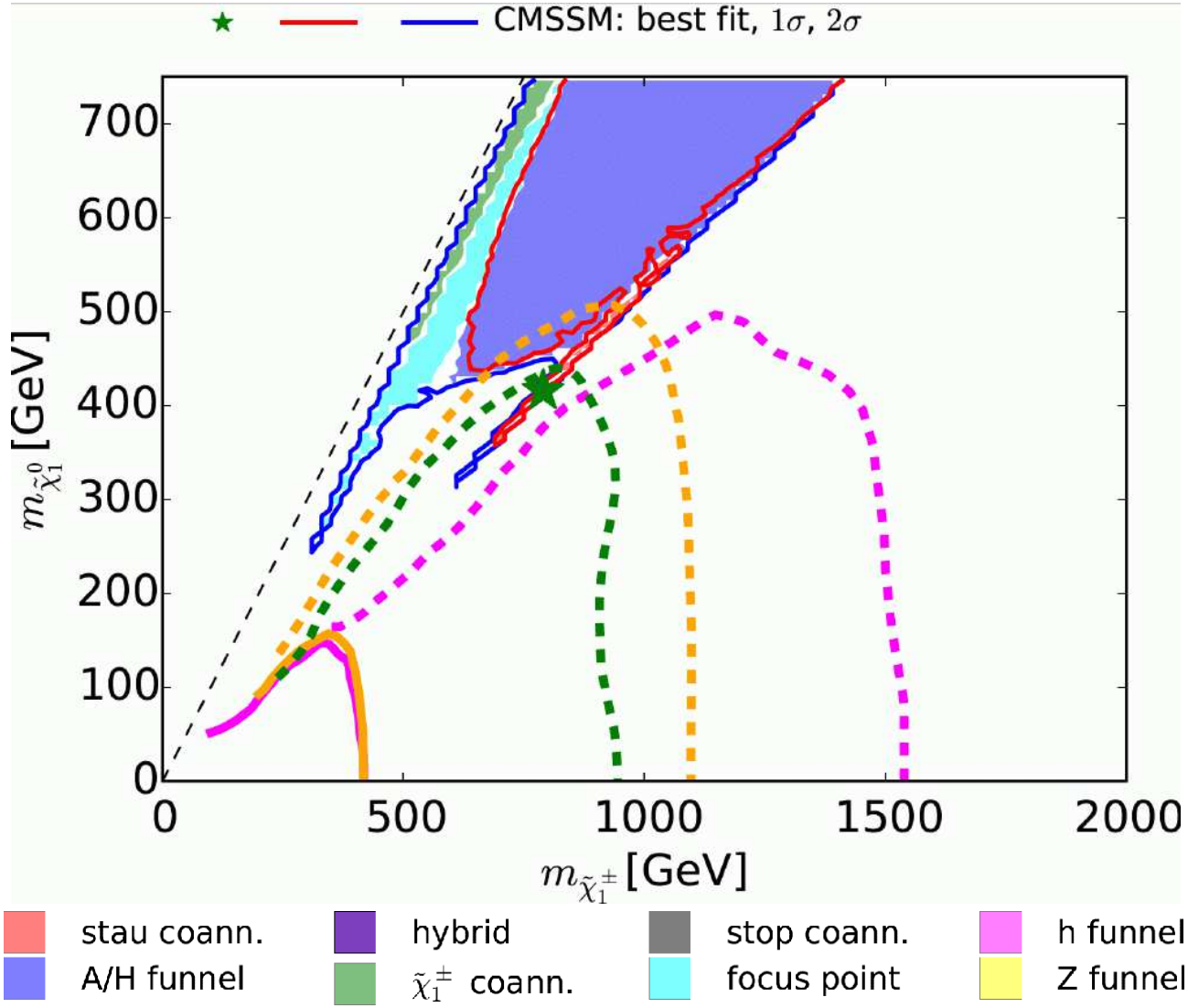
$\Rightarrow$ effectively M_A and μ as free parameters at the EW scale

$\Rightarrow$ Scenario characterized by

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

LHC prospects for CMSSM:

[2015]



solid: current LHC limits, dashed: HL-LHC prospects

⇒ best-fit regions can be covered! (in EW searches)

LHC prospects for CMSSM:

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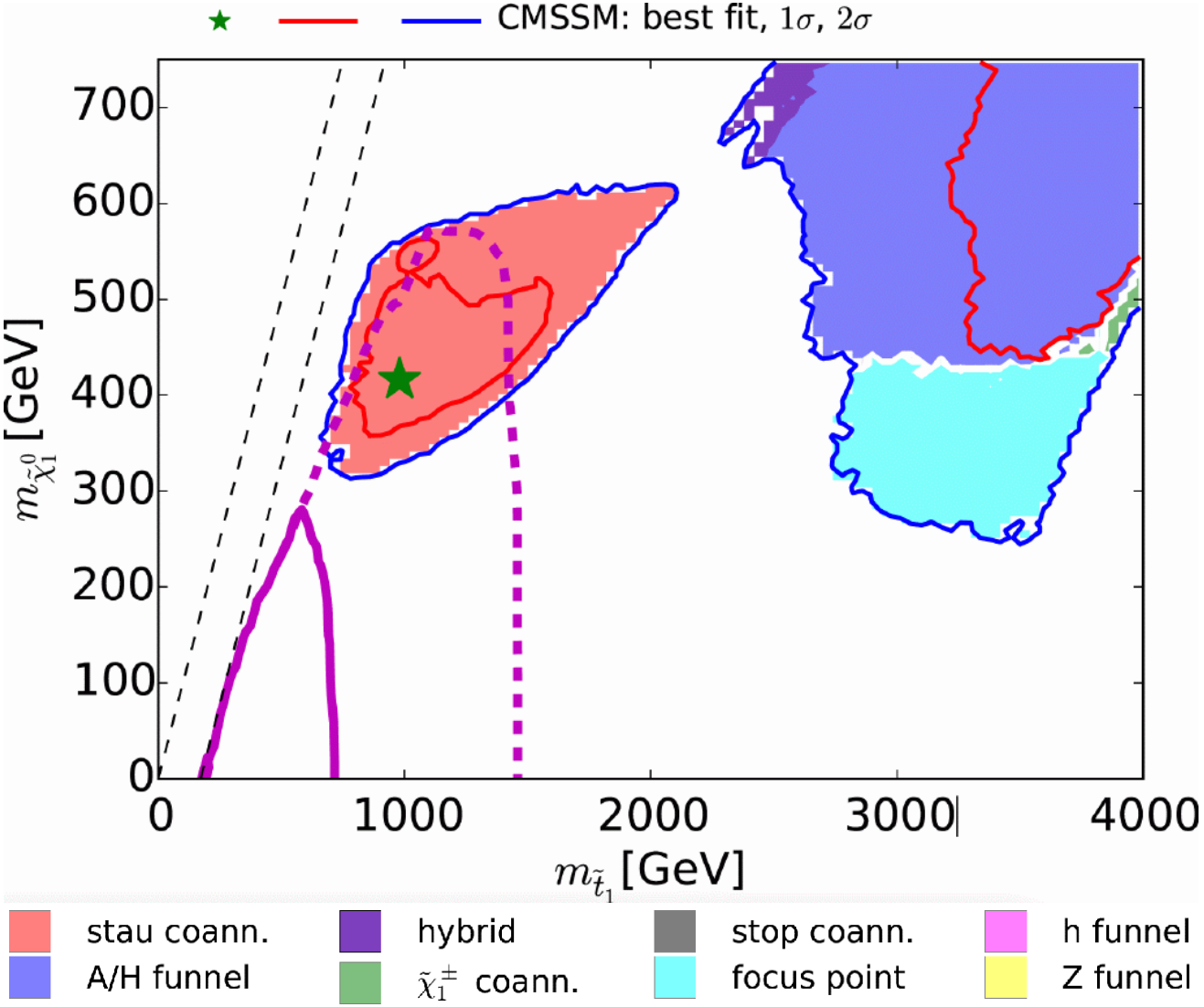
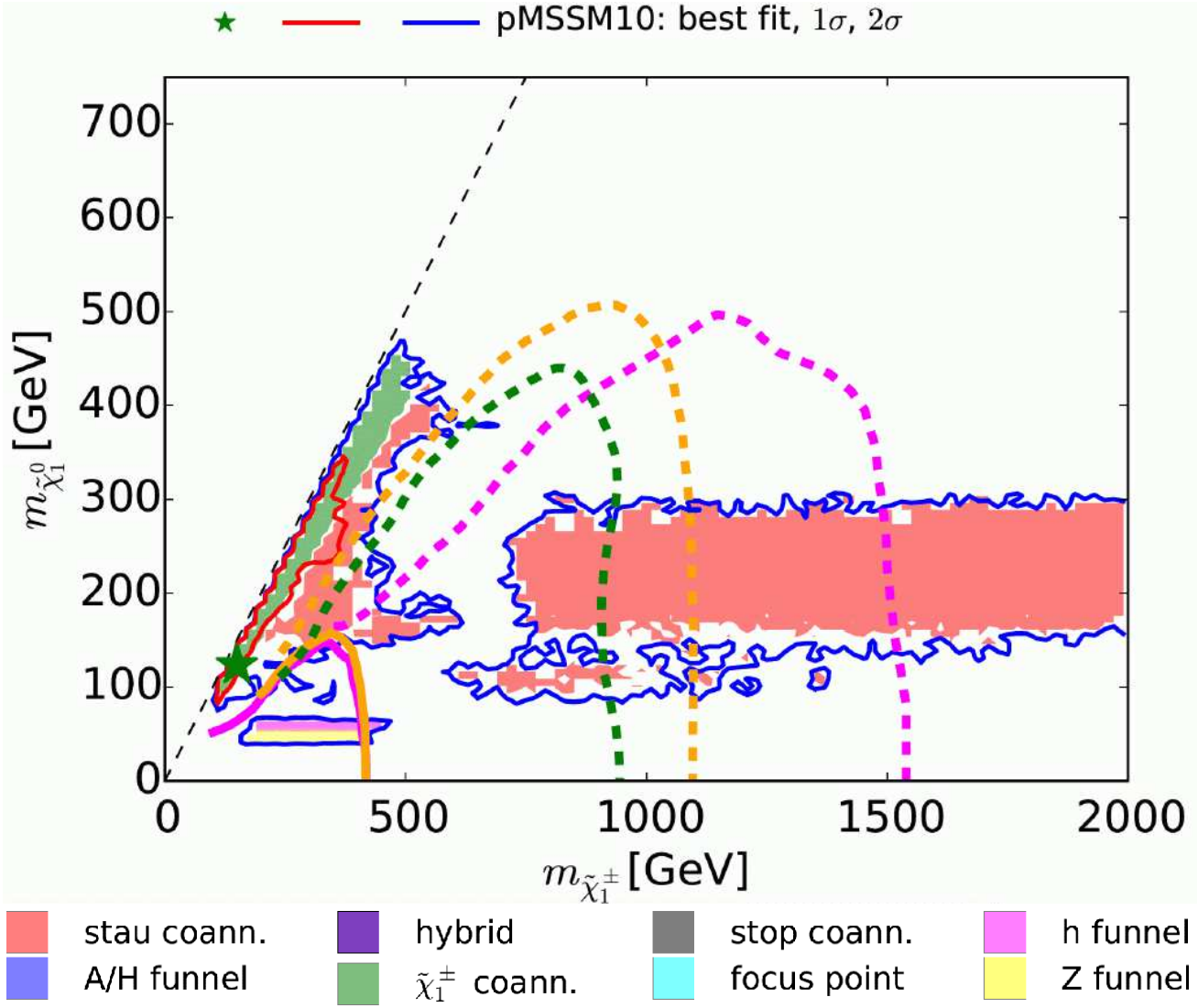


solid: current LHC limits, dashed: HL-LHC prospects

⇒ best-fit regions can partially be covered! (in colored searches)

LHC prospects for pMSSM10:

[2015]

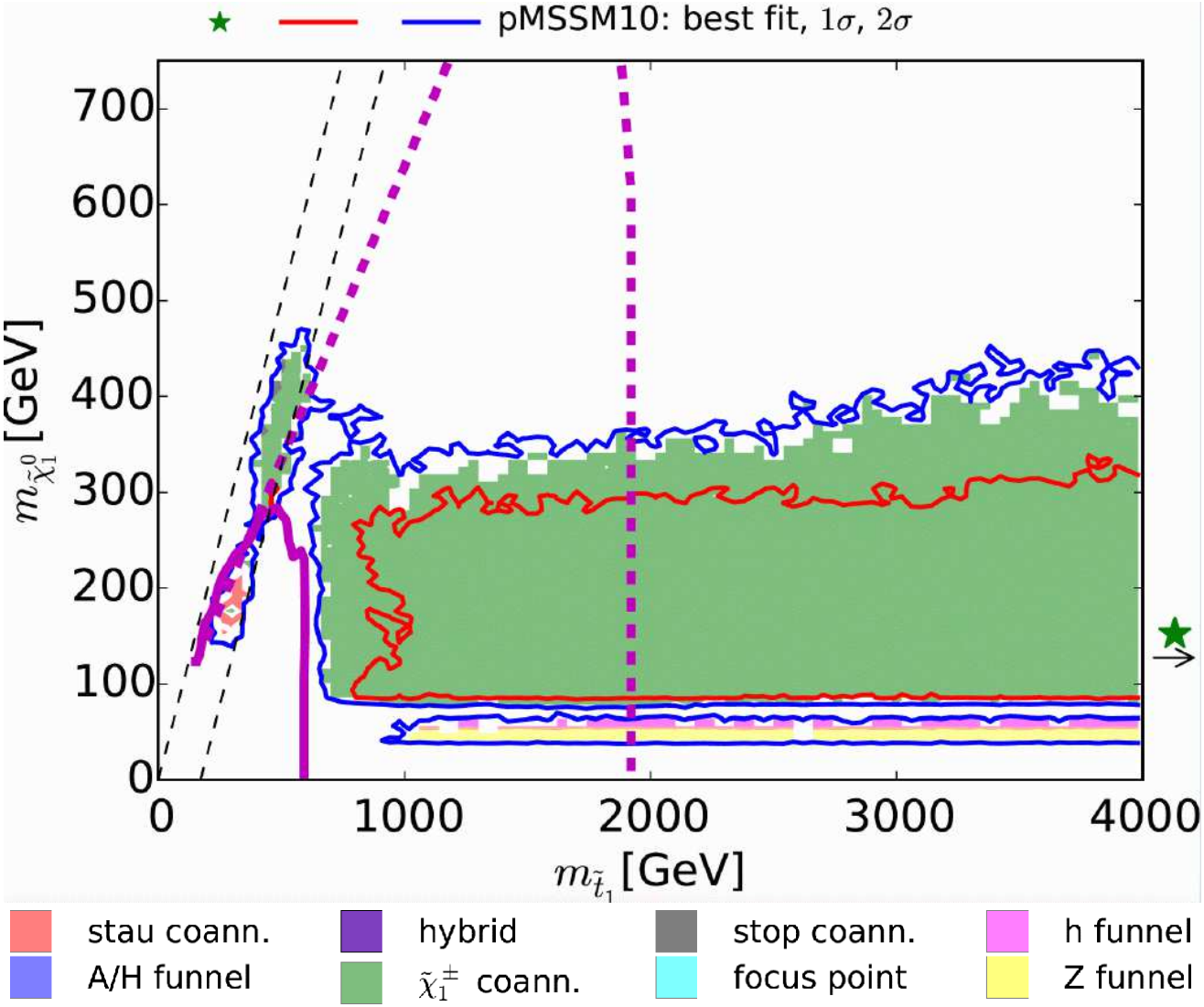


solid: current LHC limits, dashed: HL-LHC prospects

$\Rightarrow$ best-fit regions not covered! (in EW searches)

LHC prospects for pMSSM10:

[2015]



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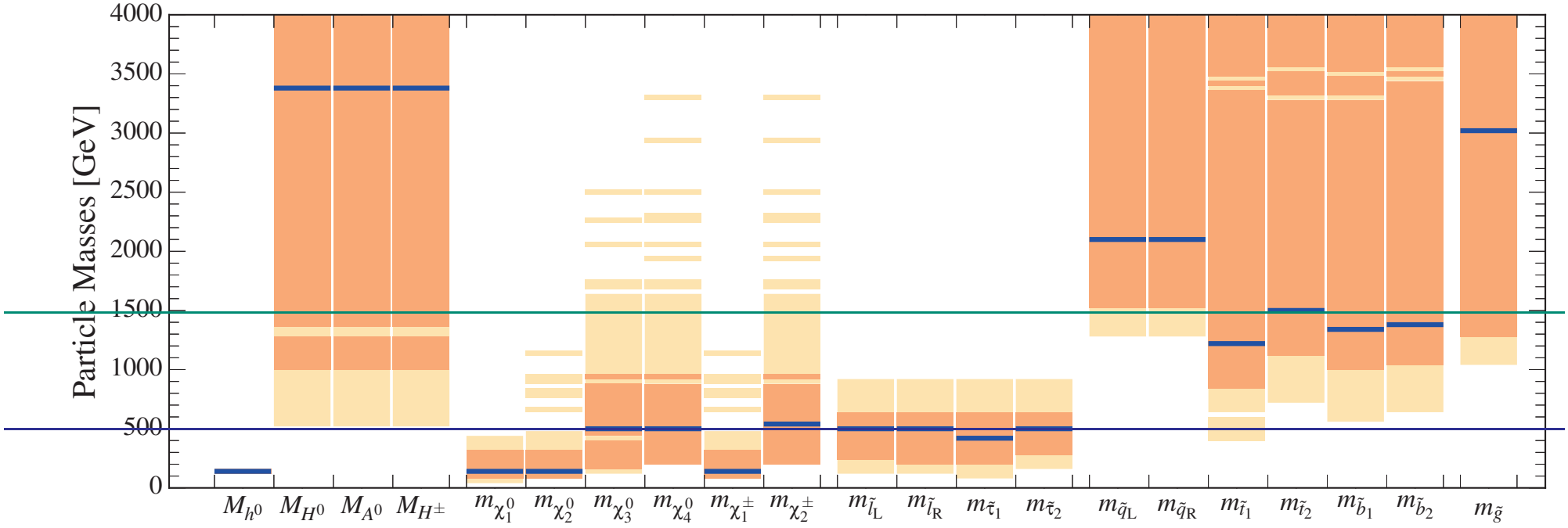
e^+e^- prospects for pMSSM10:

[2015]

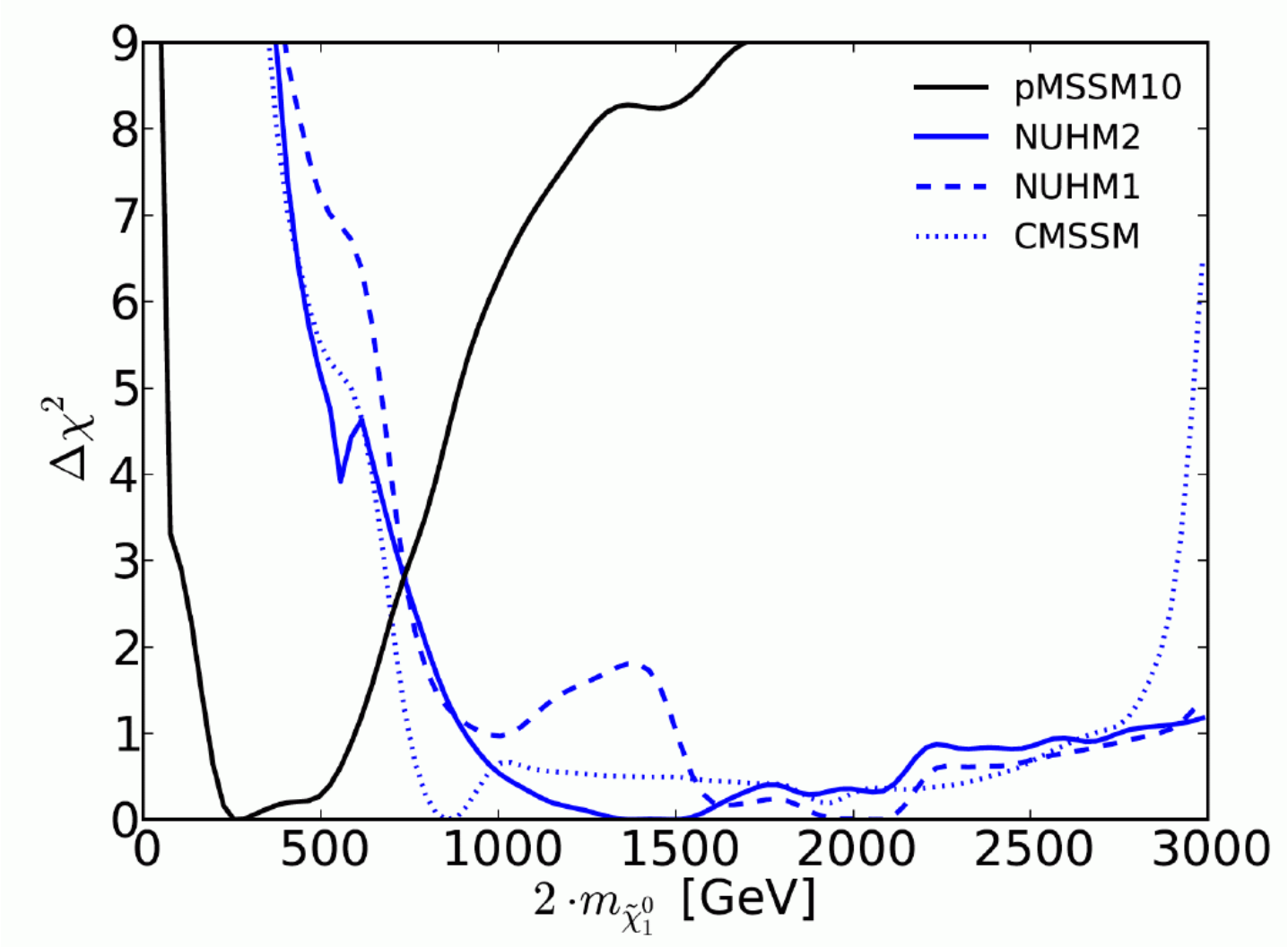


ILC: $\sqrt{s} = 1000$ GeV $\Rightarrow$ precision analysis of DM particle easy!

CLIC: $\sqrt{s} = 3000$ GeV $\Rightarrow$ precision analysis of DM particles easy!

DM production cross sections: $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0(+\gamma)$

[2014]

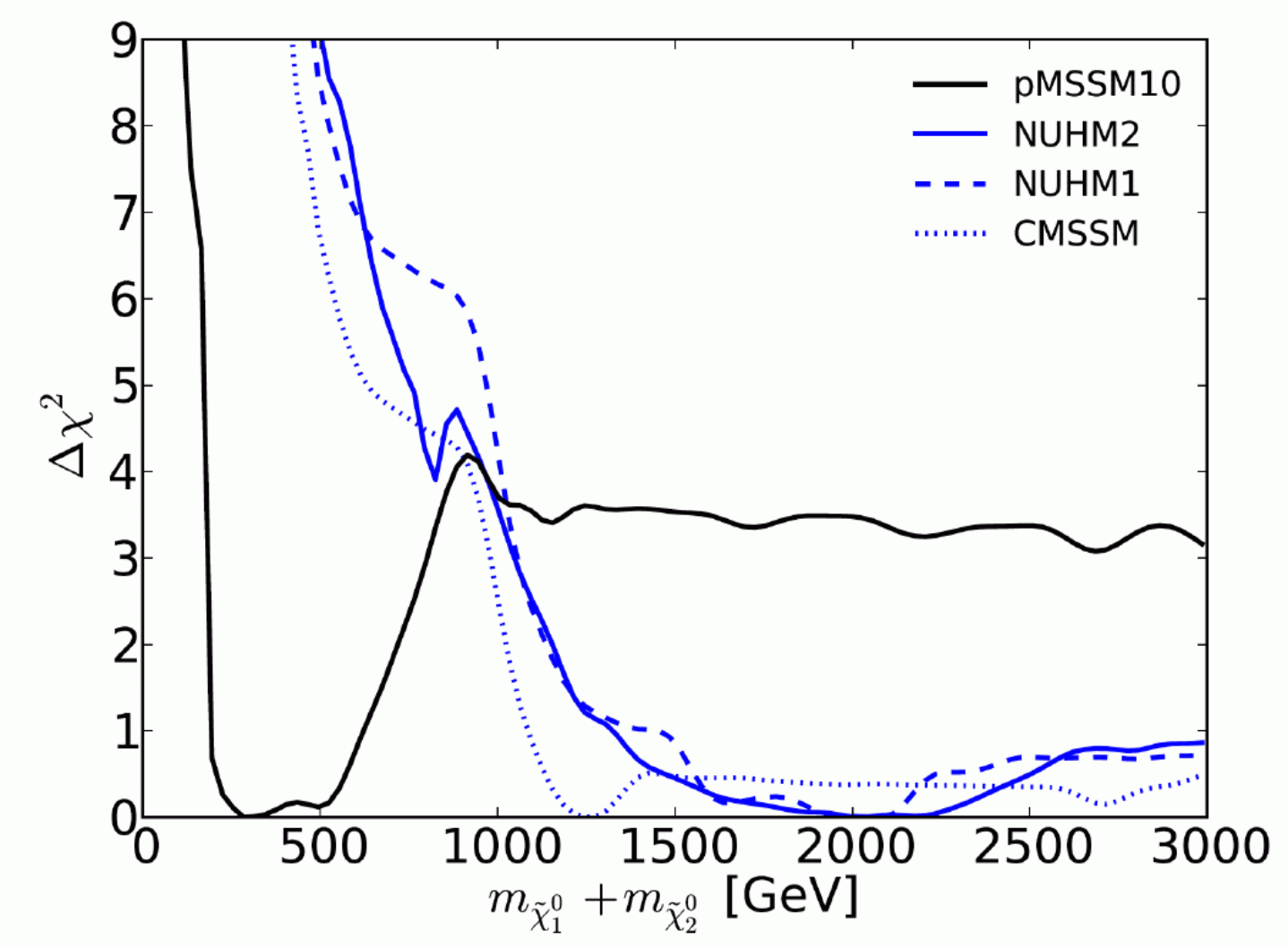


$\Rightarrow$ GUT based models: ILC :-(, CLIC possible

$\Rightarrow$ pMSSM10: easy at the ILC

DM production cross sections: $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0$

[2014]



⇒ GUT based models: ILC :-(, CLIC possible

⇒ pMSSM10: easy at the ILC - but no real upper limit

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

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

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)

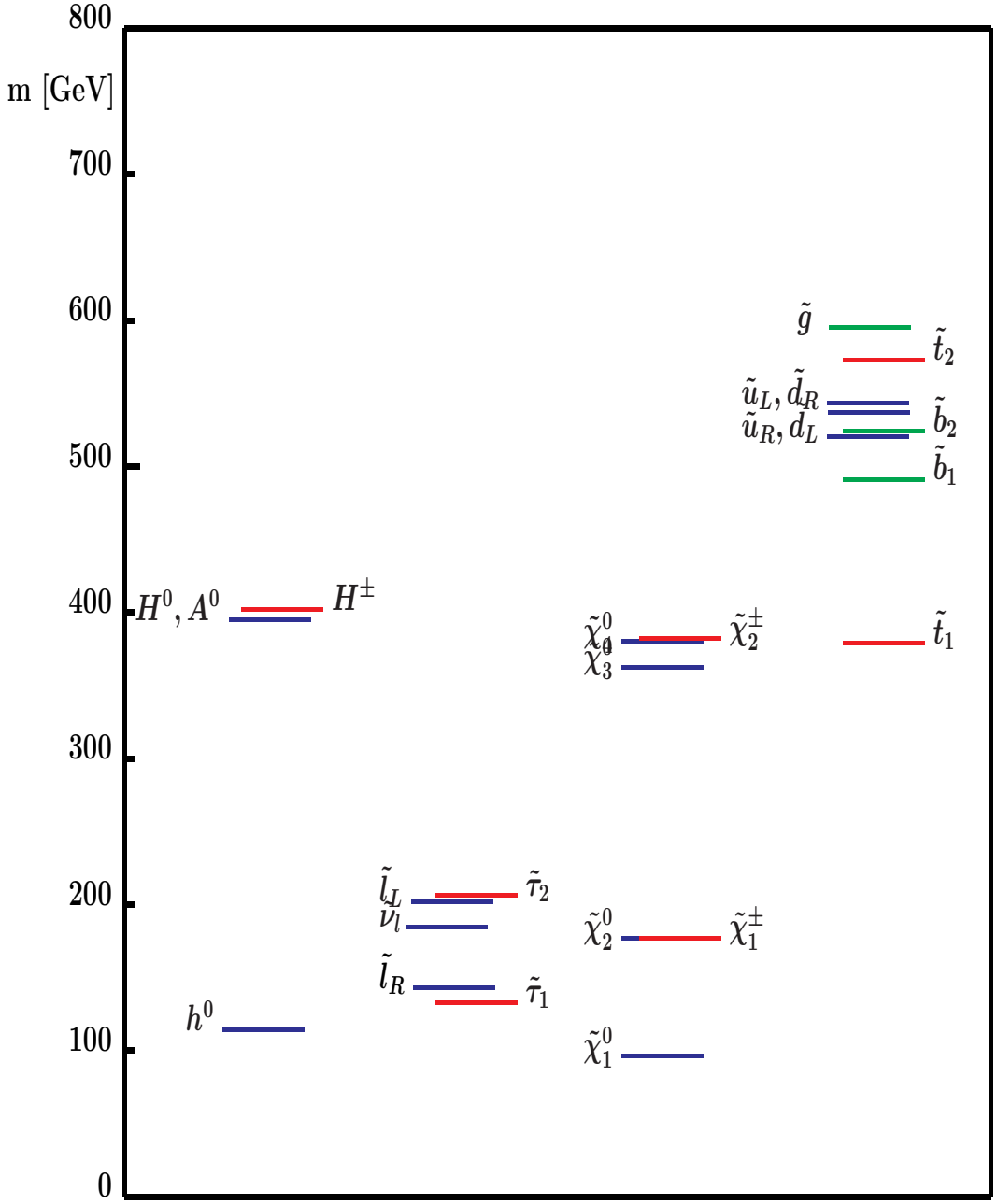
– lower uncolored mass scales (EWPO; $(g-2)_\mu$) $\Rightarrow$ DM predictions

"Typical" CMSSM scenario

(SPS 1a benchmark scenario):

Strong connection between

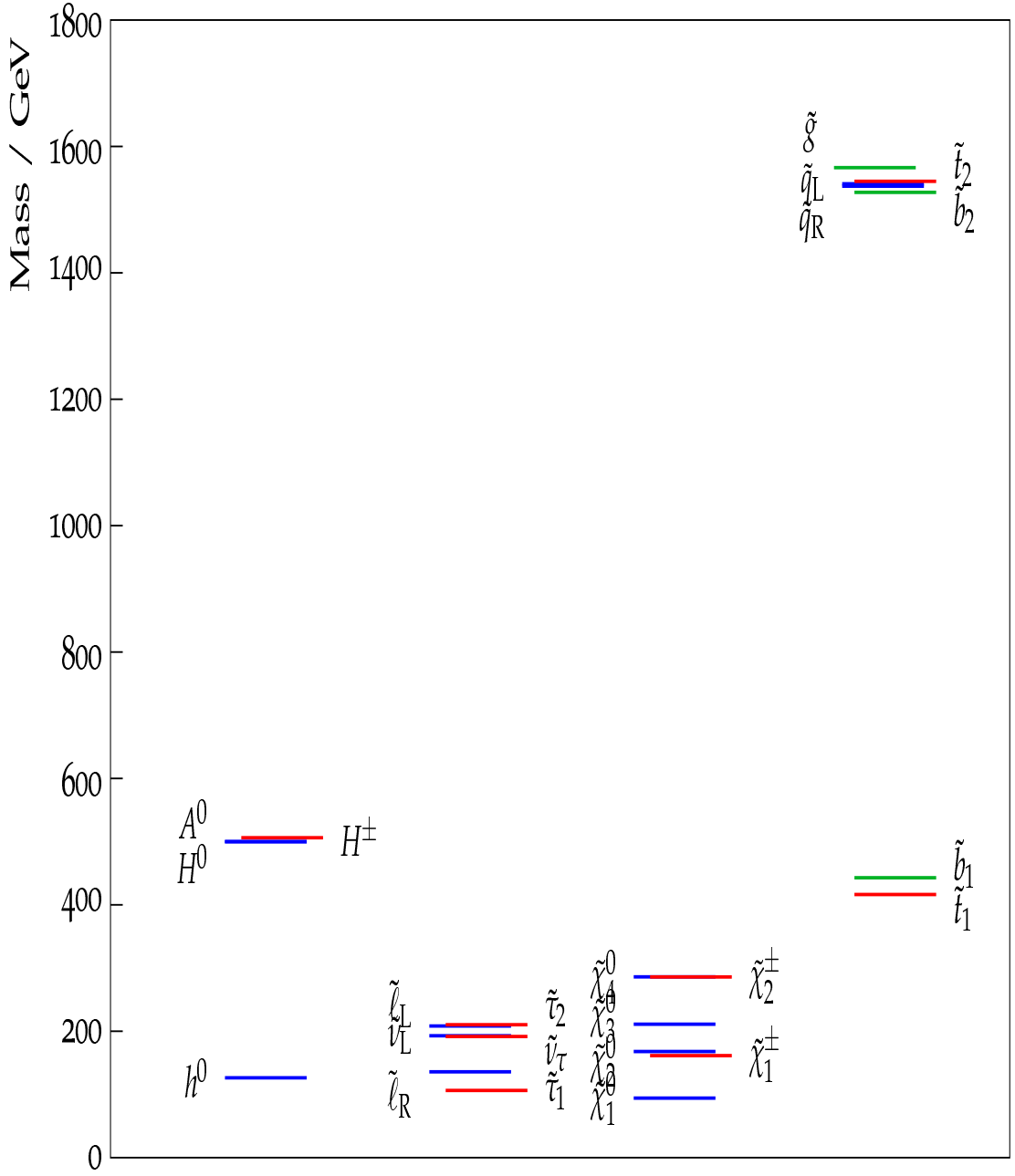
all the sectors



SPS1a variant (I)

colored and uncolored

sector decoupled:



SPS1a variant (II)

colored and uncolored

sector decoupled: