
We still believe in supersymmetry
You must be joking

Where is SUSY?

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

Corpus Cristi, 05/2019

1. Introduction
2. The MasterCode
3. GUT based predictions
4. pMSSM11 predictions
5. Conclusions

1. Introduction

Some “recent” measurements:

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

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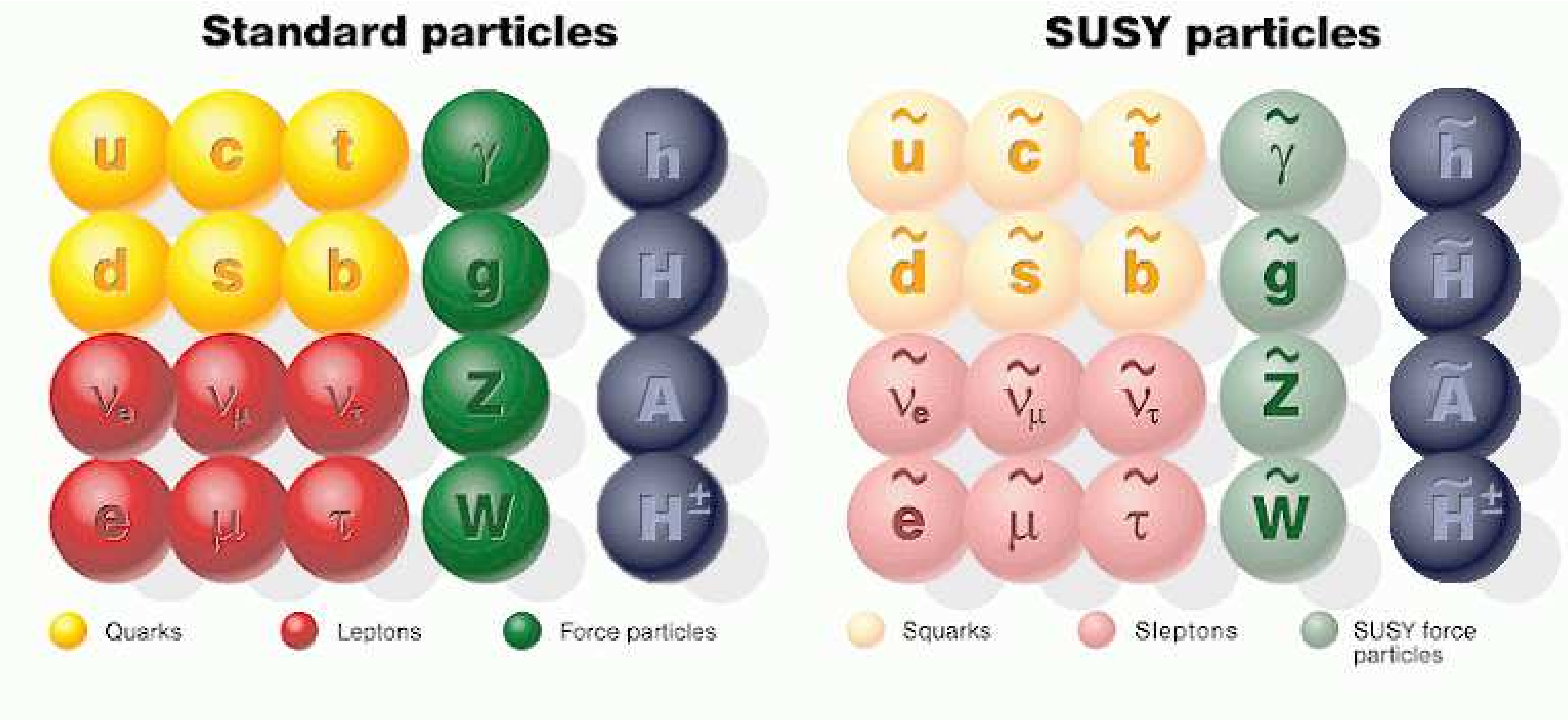
⇒ good motivation to look at SUSY!

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!

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!

Other GUT based models:

2.) NUHM1: CMSSM + 1 scalar mass parameter

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

3.) NUHM2: CMSSM + 2 scalar mass parameters

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

4.) SU(5): CMSSM + 3 scalar mass parameters

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

5.) mAMSB: different mechanism for SUSY breaking

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

6.) sub-GUT: CMSSM, but unification at lower scale

m_0, $m_{1/2}$, A_0, $\tan\beta$, sign μ and M_{in}

7.) . . .

$\Rightarrow$ wide variety of models covered!

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

⇒ it is possible that with the CMSSM, NUHM, SU(5), mAMSB, sub-GUT
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"

⇒ 11 parameters are manageable ⇒ pMSSM11

- squark mass parameters: $m_{\tilde{q}_{1,2}} =: m_{\tilde{q}}$, $m_{\tilde{q}_3}$
- slepton mass parameter(s): $m_{\tilde{l}}$, $m_{\tilde{\tau}}$
- 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

⇒ 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, 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++

⇒ evaluate observables of one parameter point consistently with various tools

cern.ch/mastercode

Data we have:

– Higgs boson mass/couplings/. . . (LHC) ⇒ FeynHiggs

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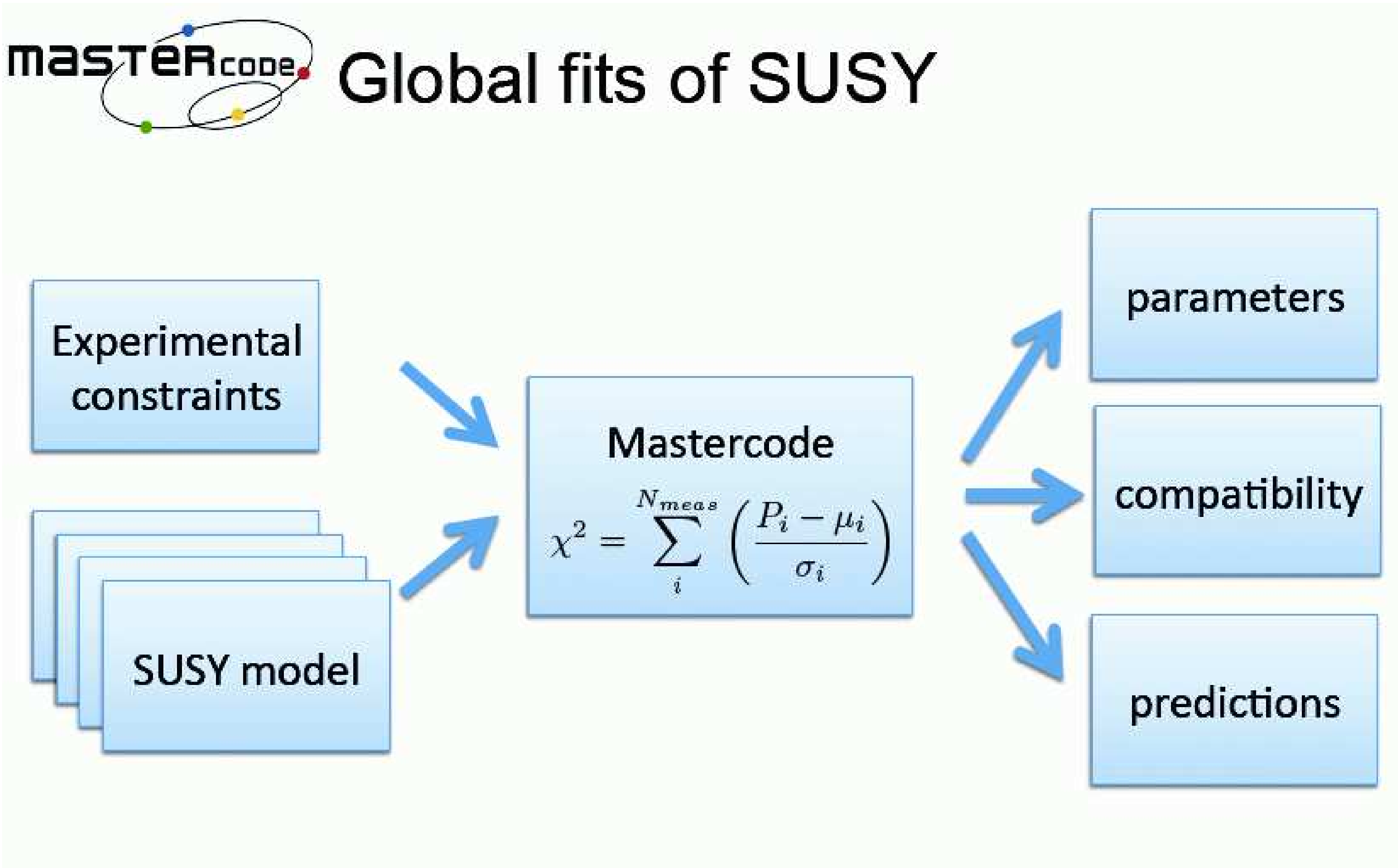
- electroweak precision data ⇒ FeynWZ, FeynHiggs
- flavor data ⇒ SuperIso, SuFla
- astrophysical data (DM properties) ⇒ MicrOMEGAs, SSARD

The χ^2 evaluation:

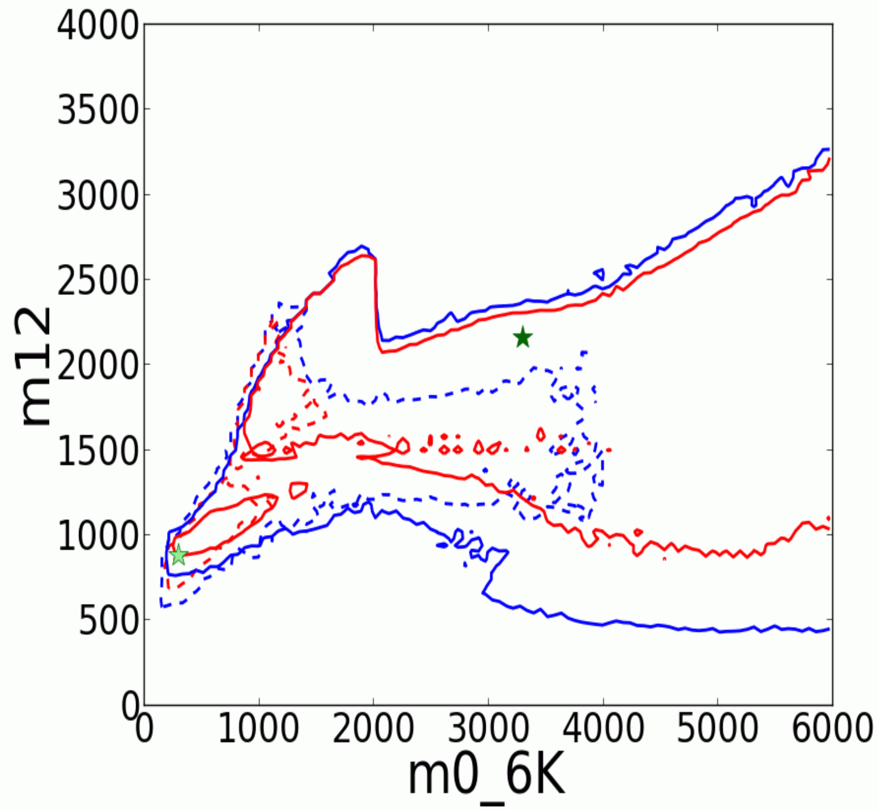


3. GUT based predictions

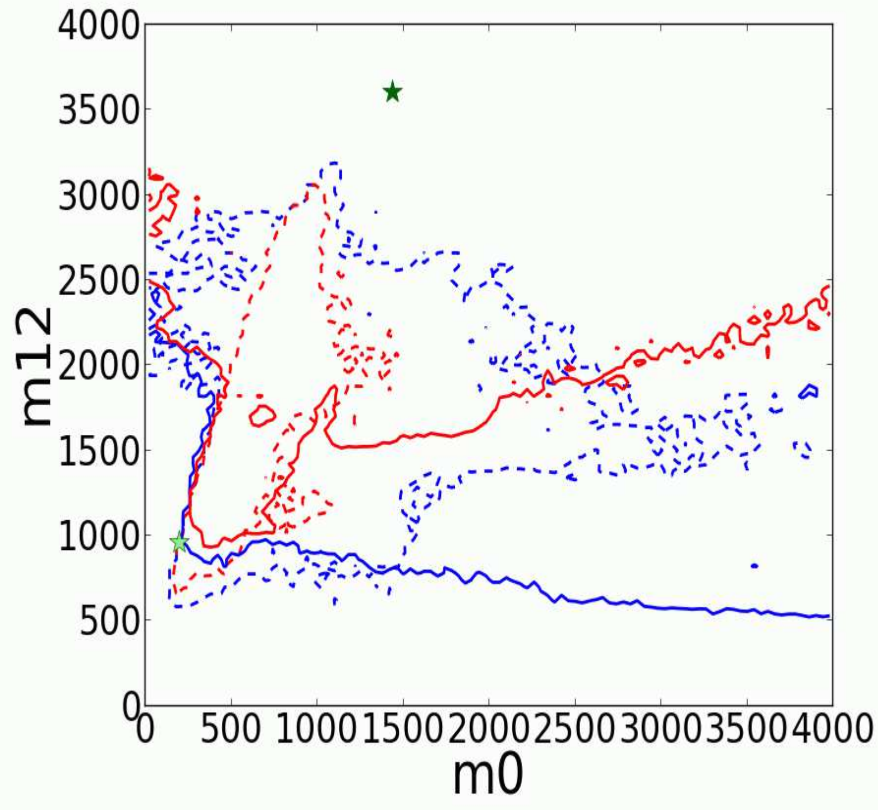
m_0-$m_{1/2}$ plane including LHC 20/fb:

[2013]

CMSSM



NUHM1

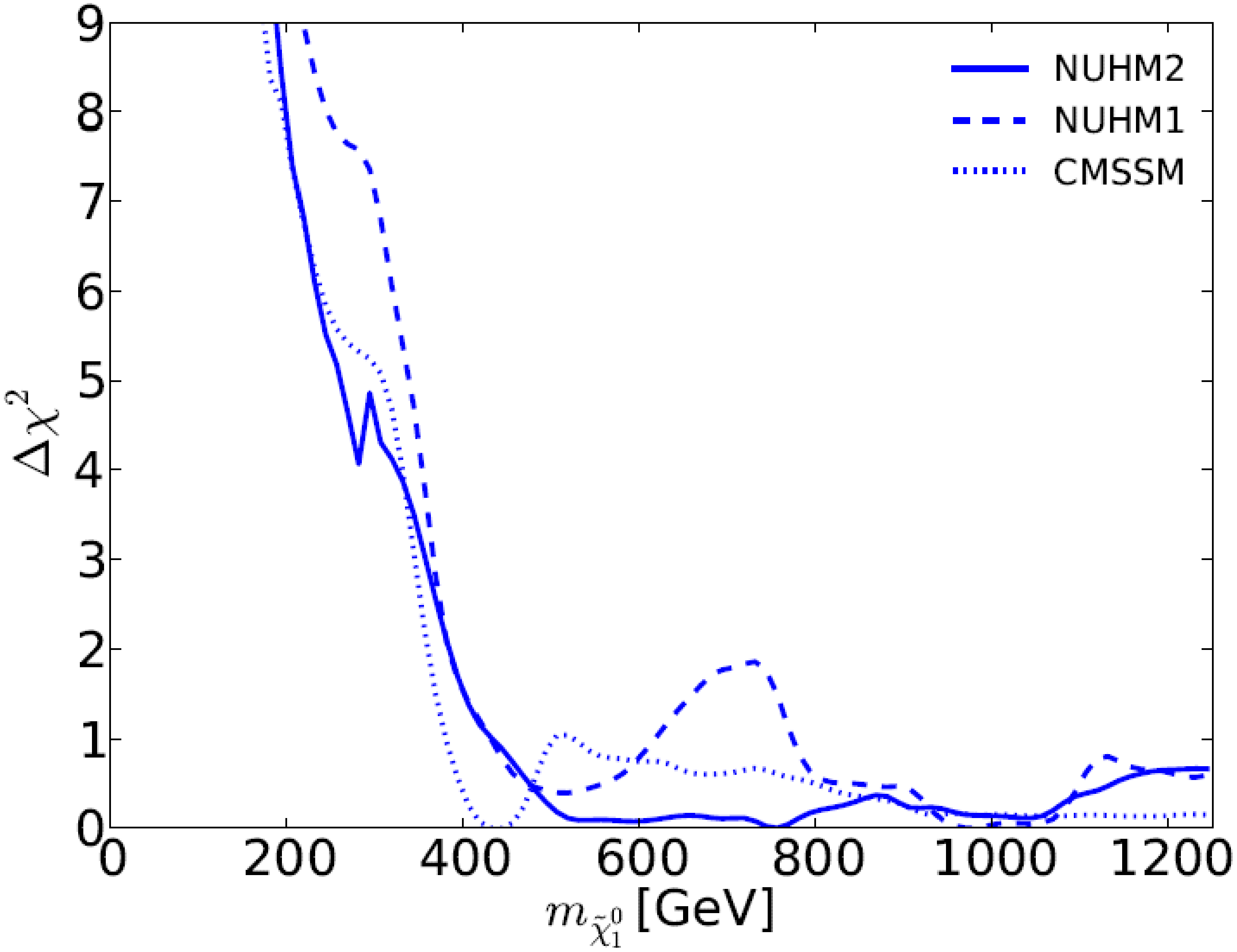


dotted: LHC 5/fb 7 TeV, solid: LHC 20/fb 8 TeV

⇒ very high masses favored!

LSP mass incl. 20/fb of LHC data

[2014]

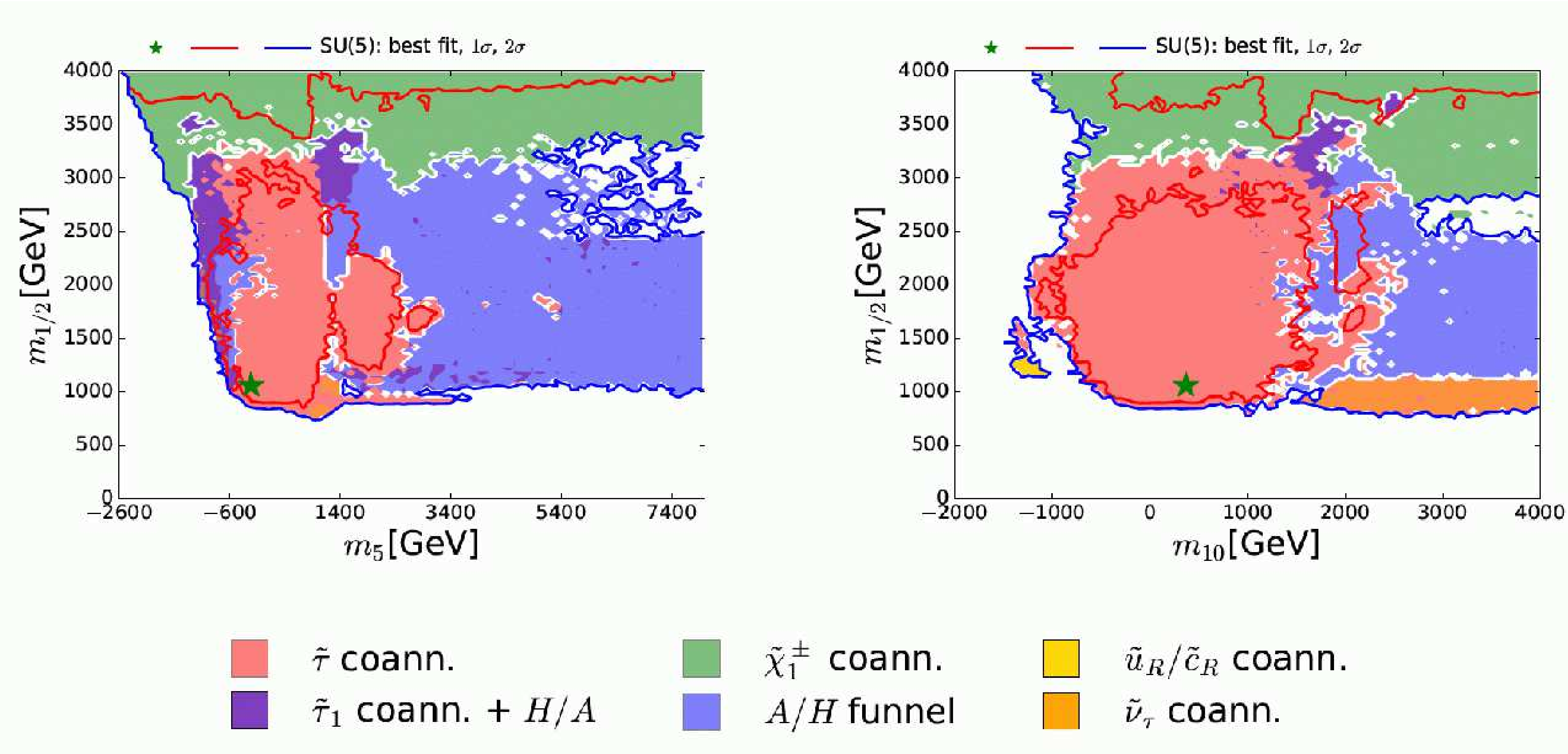


⇒ only very large values are favored

Results in the SU(5)

Dark Matter annihilation mechanism:

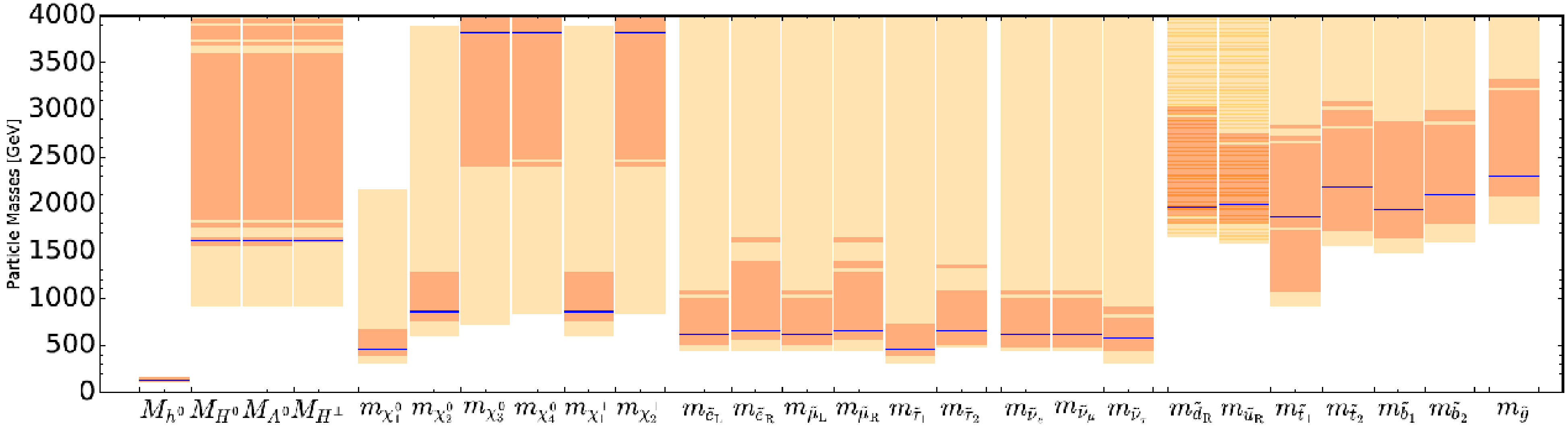
[2016]



$\Rightarrow$ $\tilde{u}_R/\tilde{c}_R/\tilde{\nu}_\tau$ co-ann. possible $\Rightarrow$ but $\tilde{\tau}_1$ co-ann. dominant!

SU(5) prediction: best-fit masses

[2016]



⇒ high colored masses

⇒ lower electroweak masses

partially with not too large $1\,\sigma$ ranges

⇒ clear prediction for future experiments?

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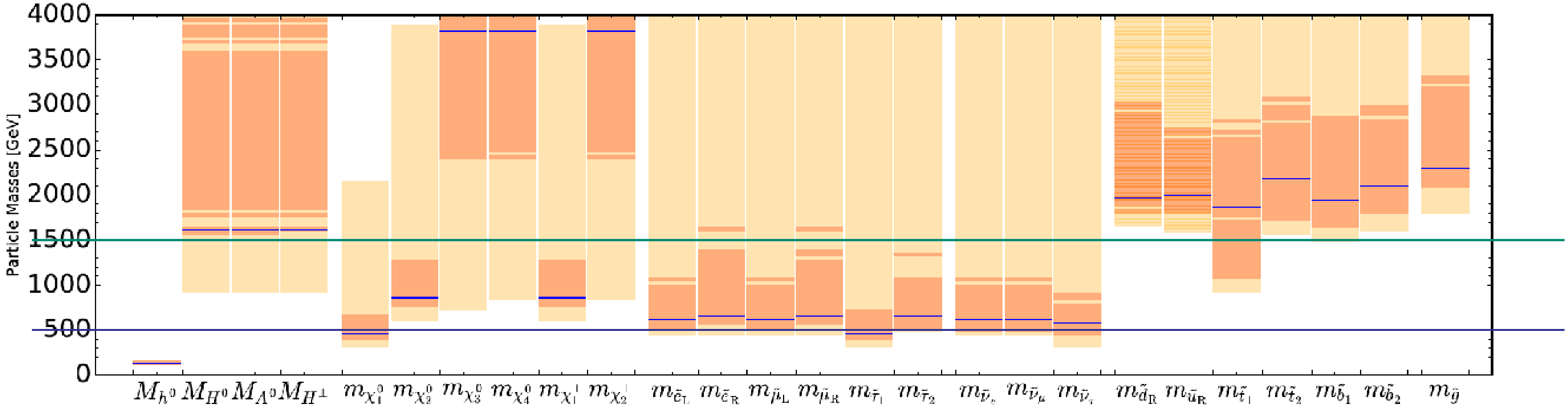


ILC: $\sqrt{s} = 1000$ GeV $\Rightarrow$ only few EW particles possibly accessible

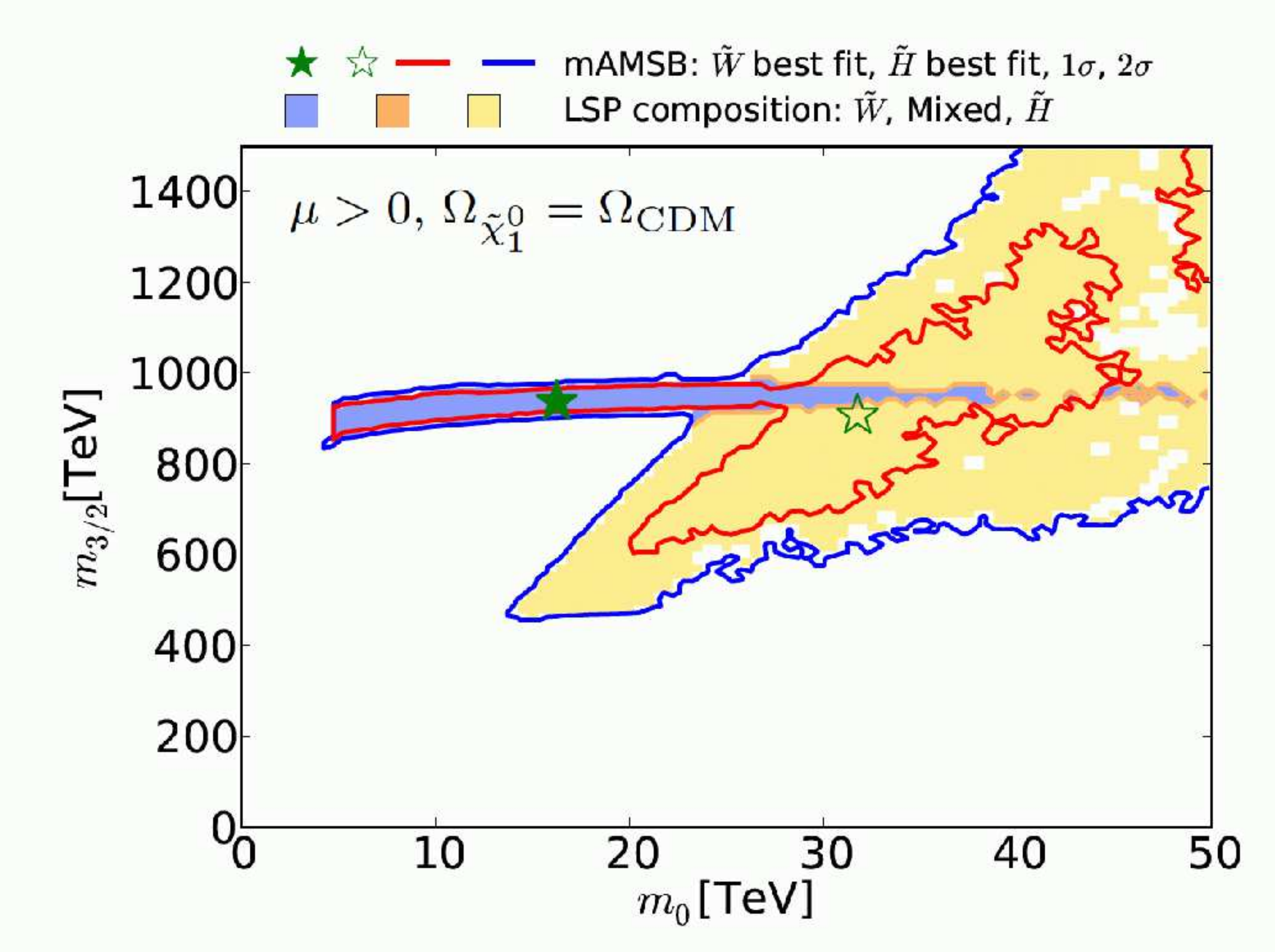
CLIC: $\sqrt{s} = 3000$ GeV $\Rightarrow$ pair production of many SUSY particles "likely"

$\Rightarrow$ no access to colored particles

Results in the mAMSB

[2016]

Dark Matter composition:

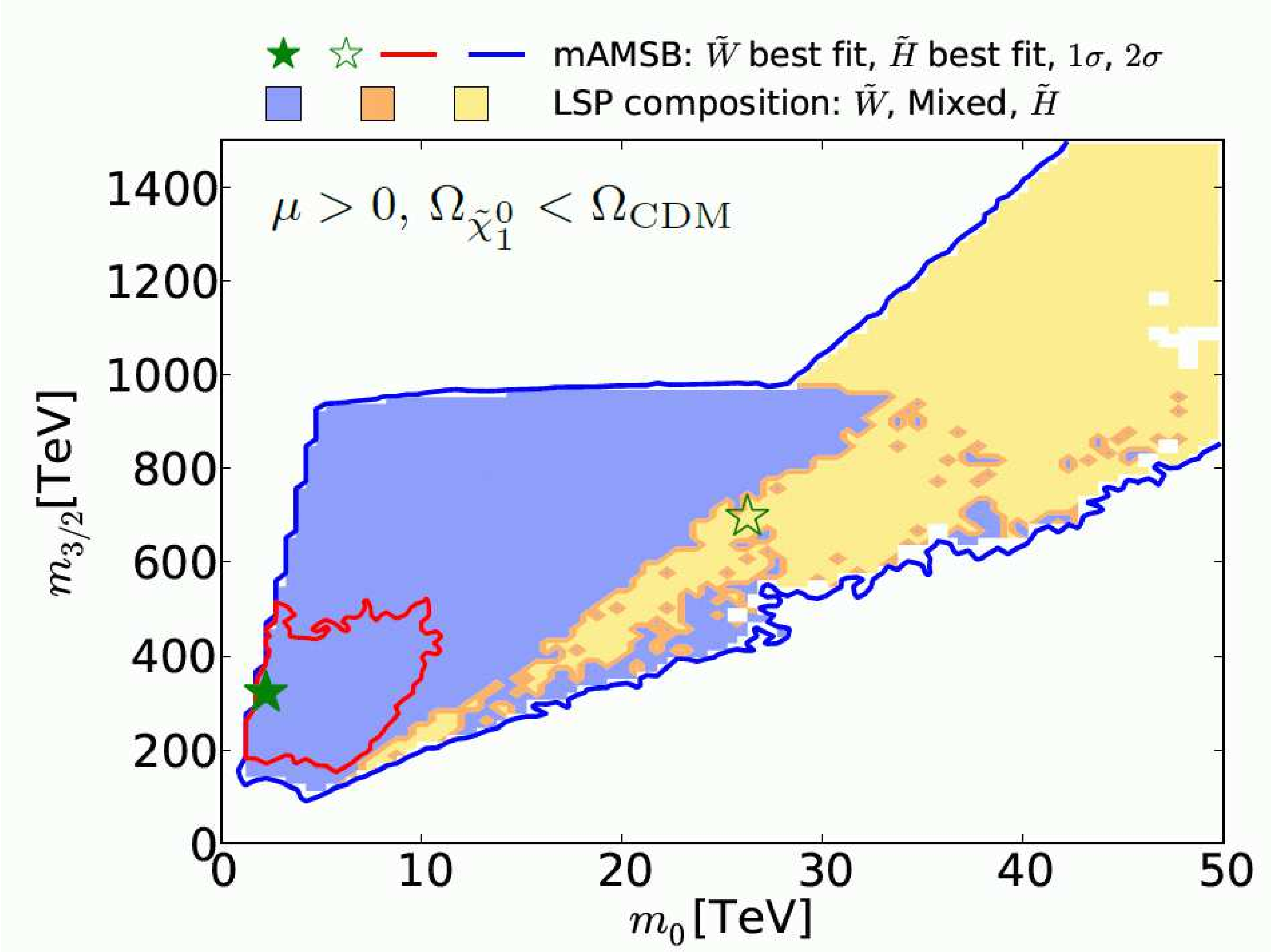


$\Rightarrow m_{\tilde{\chi}^0_1} \sim 2.9 \pm 0.1$ TeV (wino), $\sim 1.1 \pm 0.02$ TeV (higgsino)

Results in the mAMSB

Dark Matter composition:

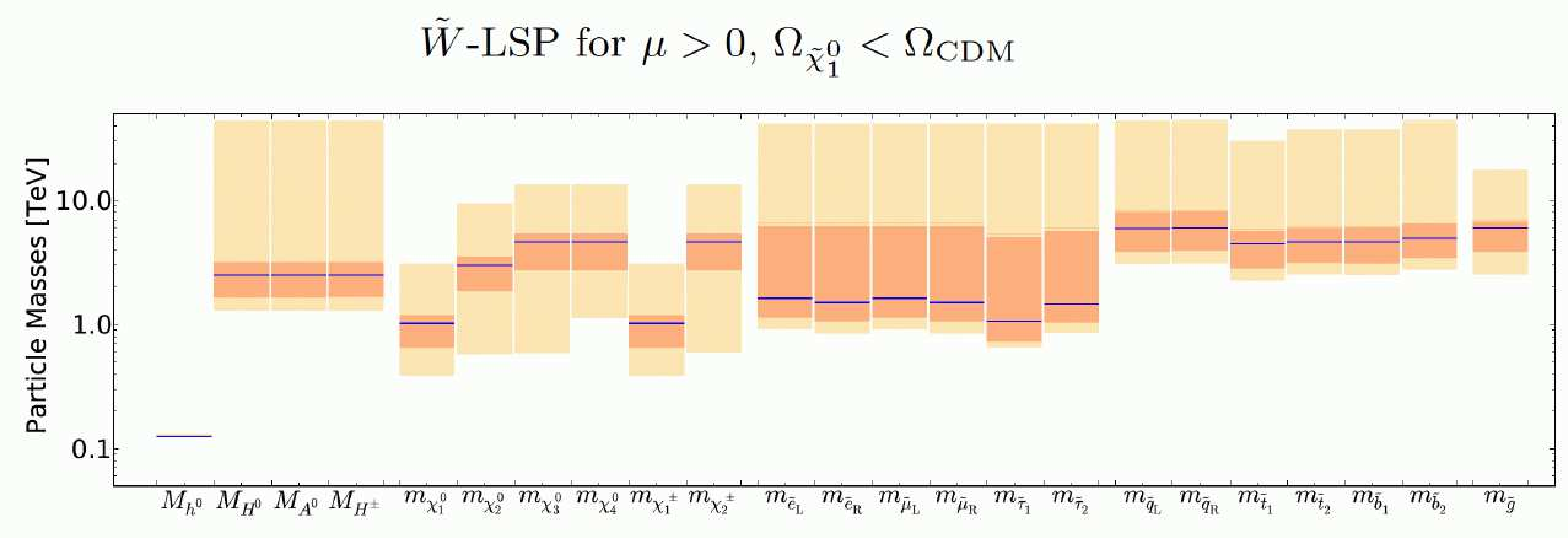
[2016]



⇒ very relaxed limits ⇒ lower masses

mAMSB prediction: best-fit masses (wino)

[2016]



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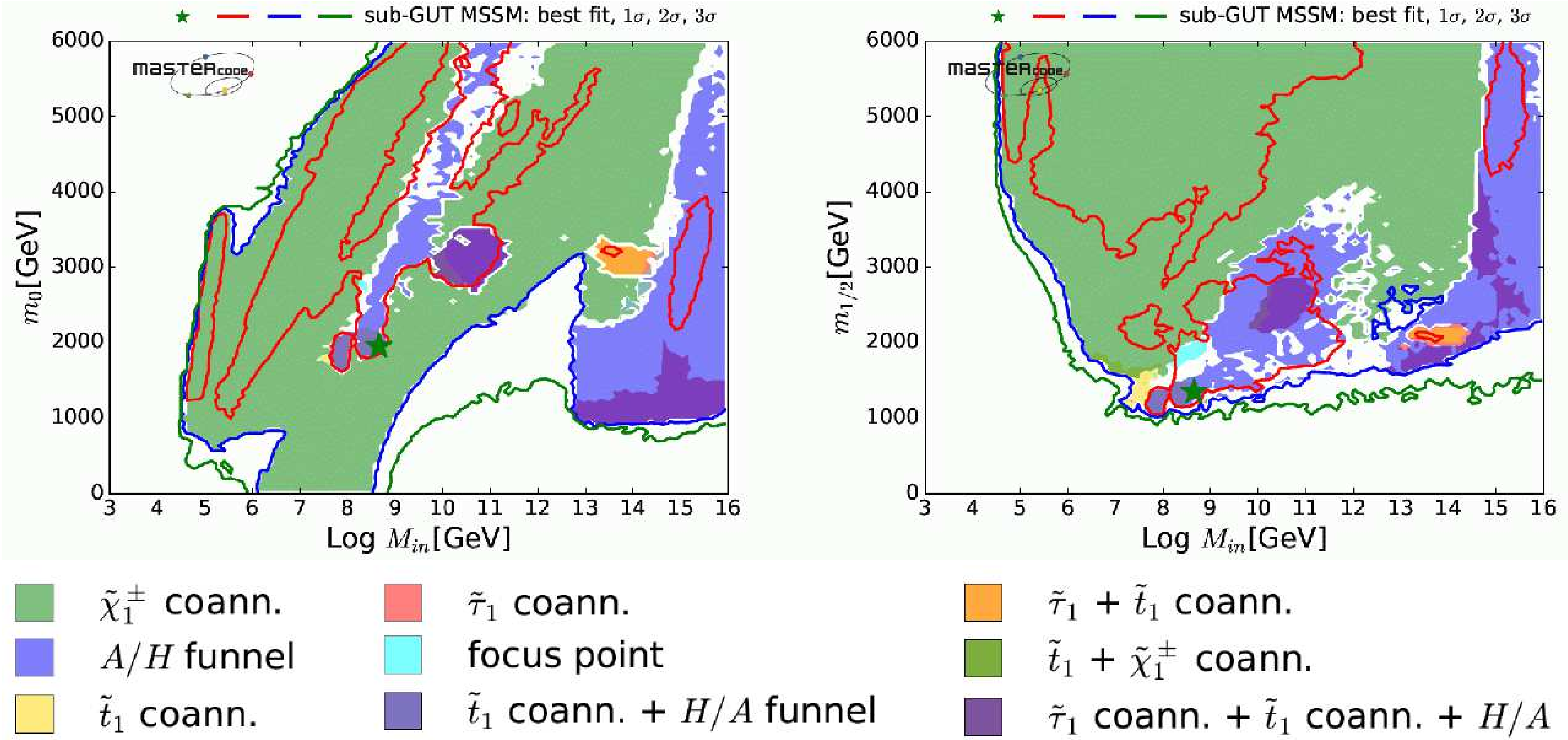
⇒ Higgsino case even heavier . . .

Results in sub-GUT

[2017]

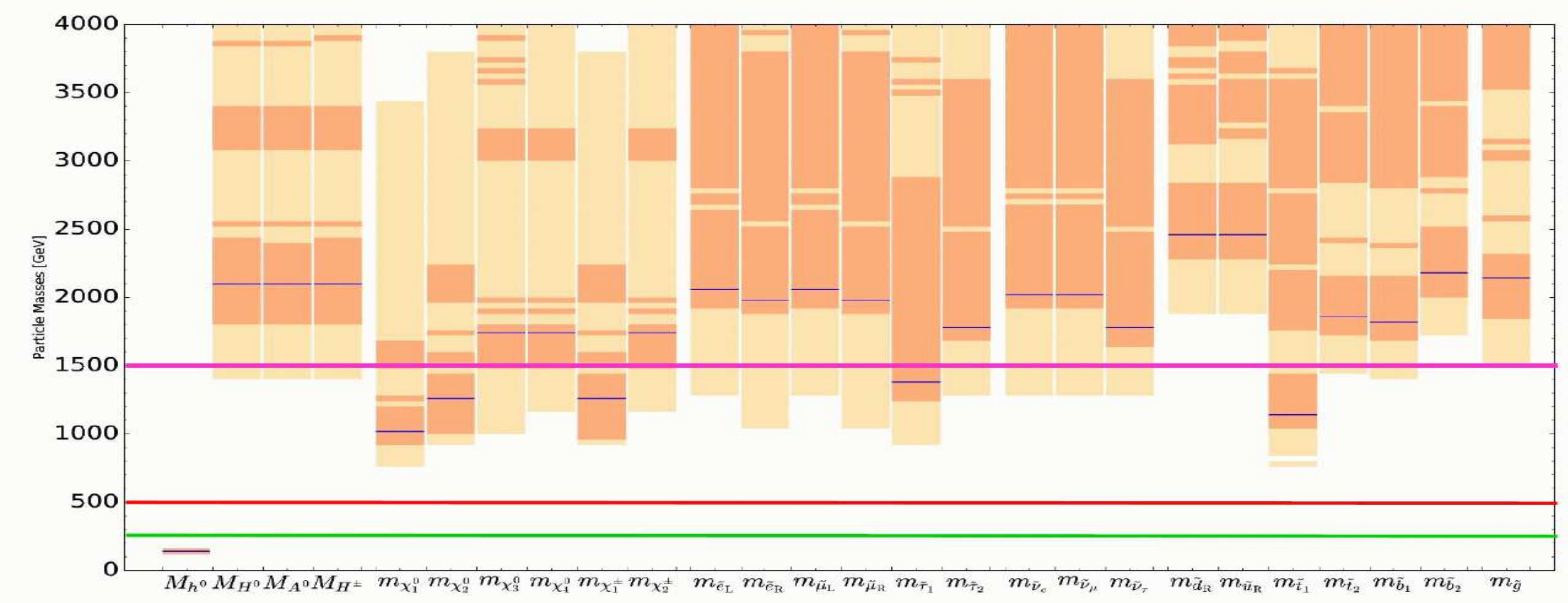


⇒ low M_{in} possible/favored

⇒ mainly due to BR($B_s \to \mu^+\mu^-$)

sub-GUT prediction: best-fit masses

[2017]



⇒ high colored masses
⇒ high electroweak masses

ILC: $\sqrt{s} = 1000$ GeV ⇒ nothing

CLIC: $\sqrt{s} = 3000$ GeV ⇒ pair production of few SUSY particles
⇒ no access to colored particles

Intermediate summary (simplified):

– data: Higgs, LHC searches, DM measurements/searches, EW, flavor

– GUT based models exhibit a heavy spectrum

– very difficult for the LHC

– ILC has to be “lucky” (I did not discuss it’s great Higgs/EW capabilities)

– CLIC has some particles in reach

– colored spectrum could partially be covered at FCC-hh

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ARE WE DEPRESSED?

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ARE WE DEPRESSED?

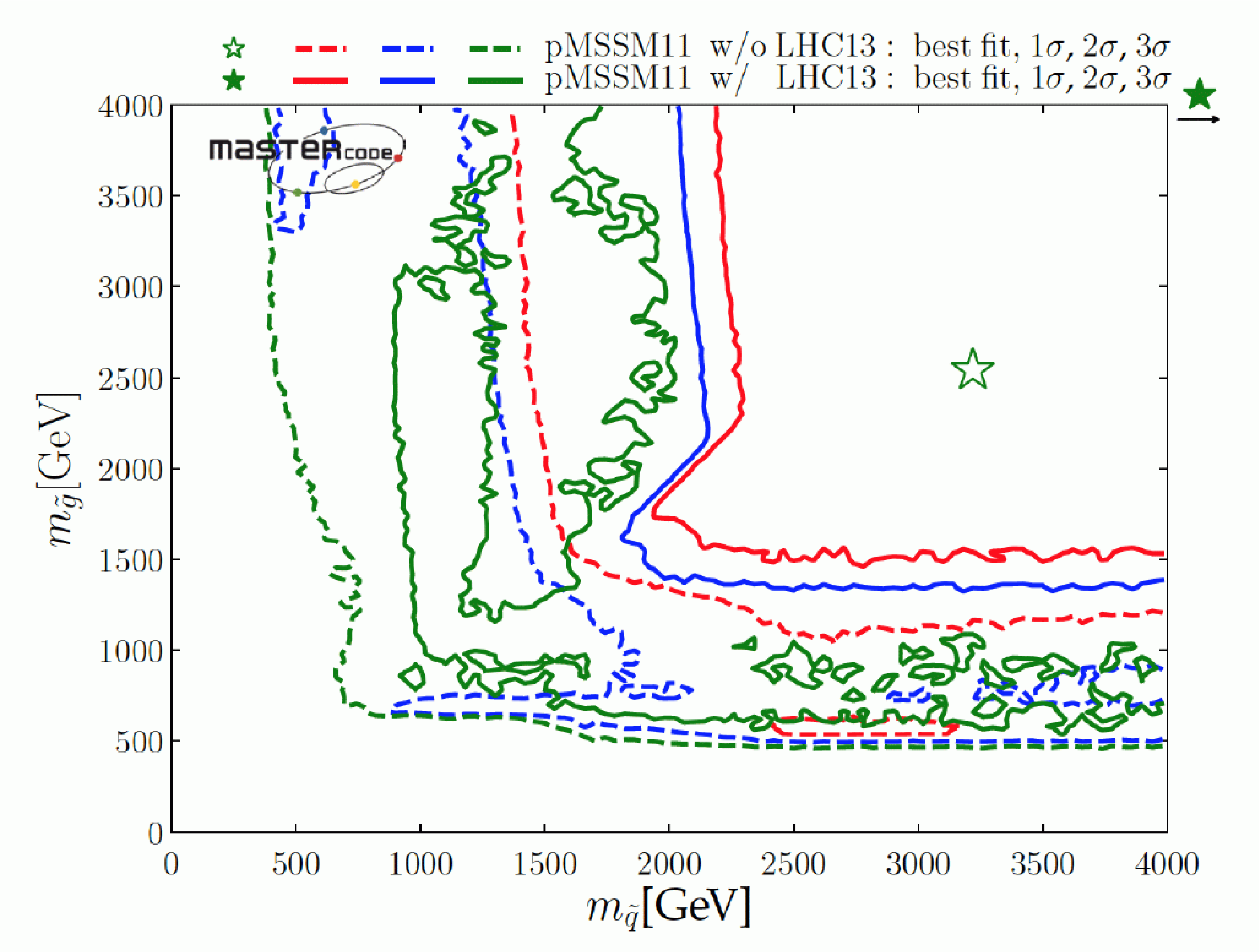
Let’s look at the more general pMSSM11!

4. pMSSM11 predictions

Parameter	Range	Number of segments
M_1	(-4 , 4) TeV	6
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
$m_{\tilde{\tau}}$	(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		384

pMSSM11: Going from 8 TeV to 13 TeV (and adding latest DM limits)

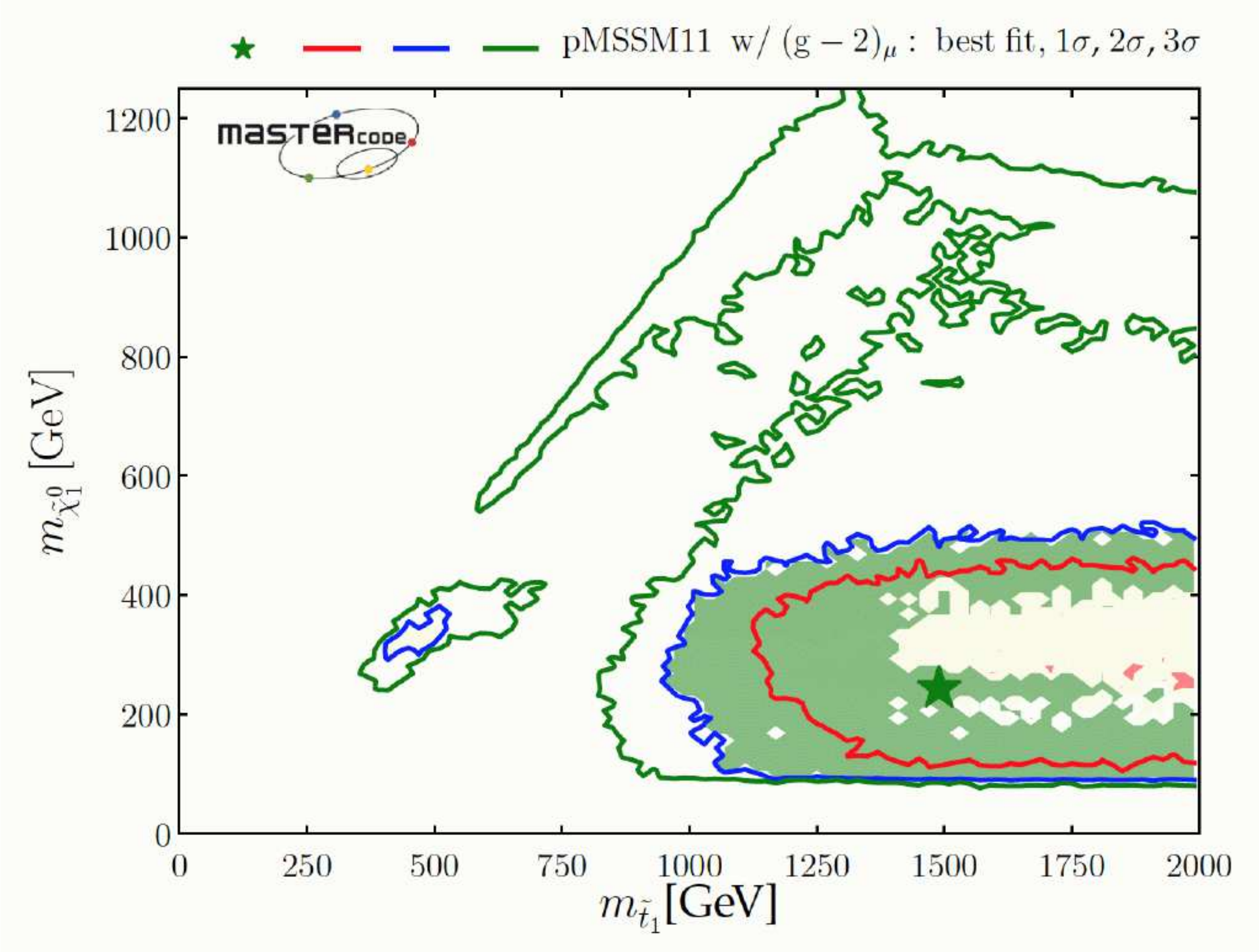
[2017]



⇒ substantial move to higher masses!

⇒ notice the "nose"!

pMSSM11: $m_{\tilde{t}_1}$–$m_{\tilde{\chi}_1^0}$ plane

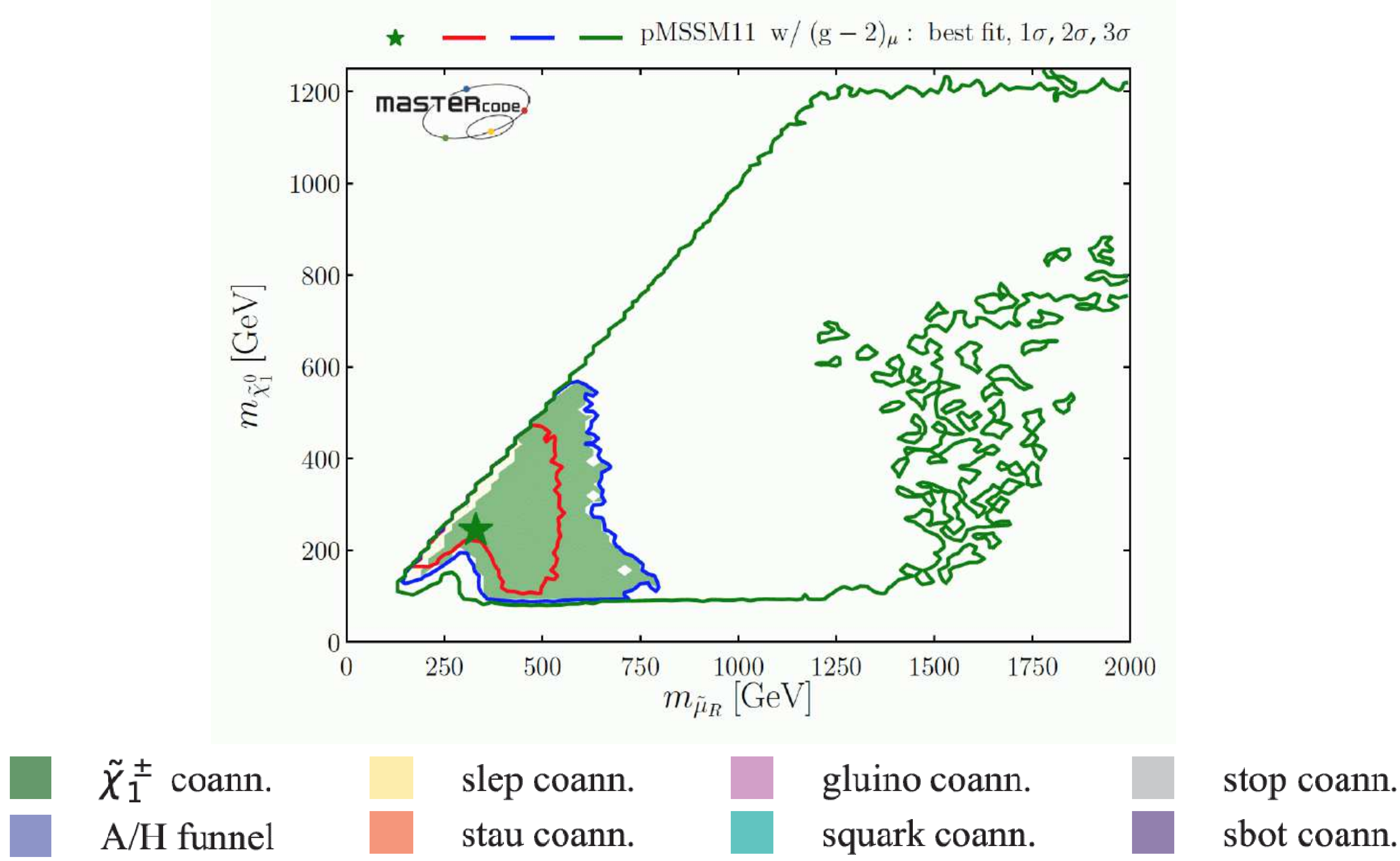


$\tilde{\chi}_1^\pm$ coann.	slep coann.	gluino coann.	stop coann.
A/H funnel	stau coann.	squark coann.	sbot coann.

⇒ high (low) stop (neutralino) masses ⇒ notice the compressed region!

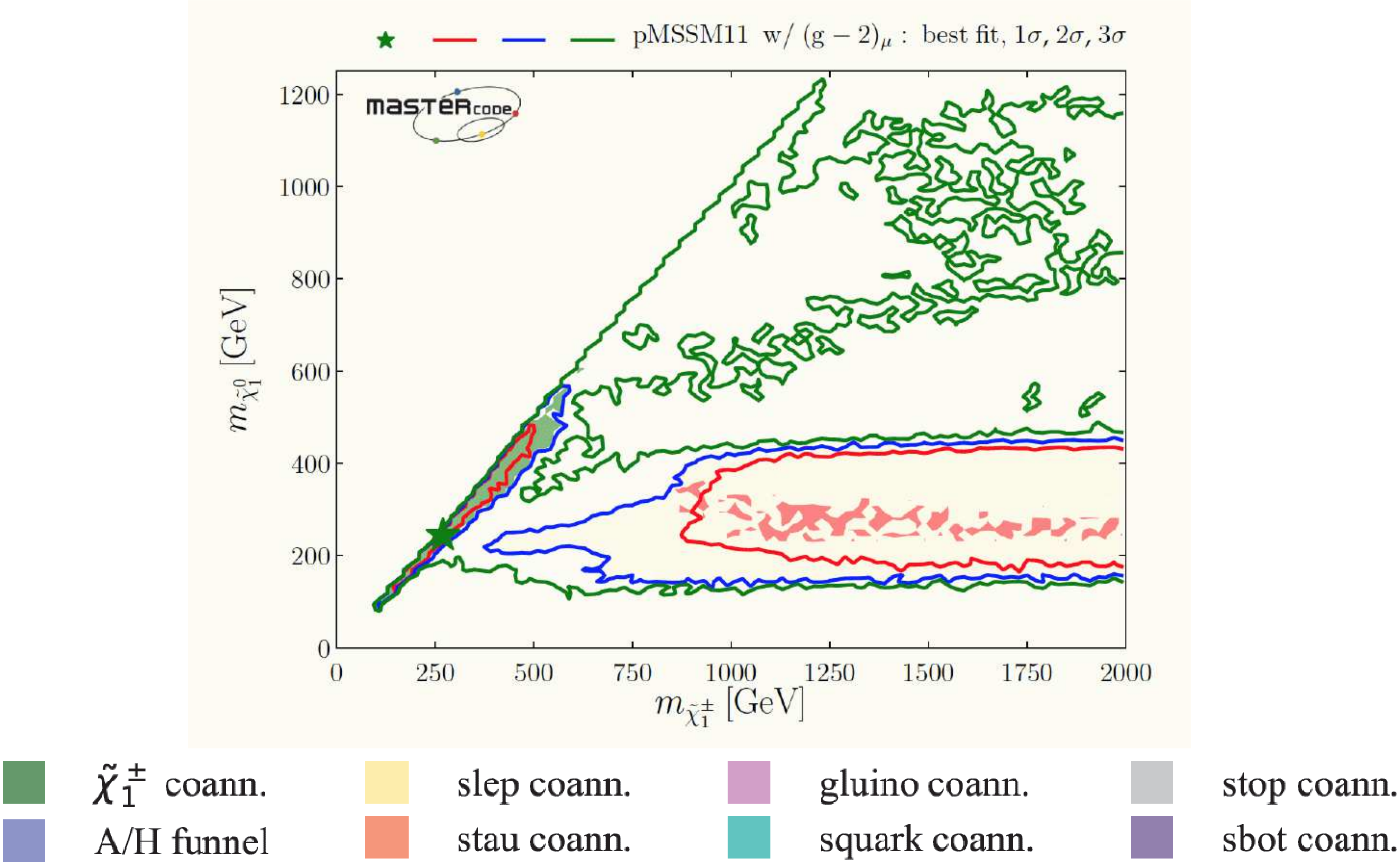
pMSSM11: $m_{\tilde{\mu}}$–$m_{\tilde{\chi}^0_1}$ plane

[2017]



⇒ all masses low!!

pMSSM11: $m_{\tilde{\chi}_1^\pm}$–$m_{\tilde{\chi}_1^0}$ planbe



⇒ chargino co-annihilation ⇒ $M_1 \sim M_2$

pMSSM11: best-fit point parameters

[2017]

Parameter	With LHC 13 TeV and $(g-2)_\mu$ Best fit	'Nose' region
M_1	0.25 TeV	- 0.39 TeV
M_2	0.25 TeV	1.2 TeV
M_3	- 3.86 TeV	- 1.7 TeV
$m_{\tilde{q}}$	4.0 TeV	2.00 TeV
$m_{\tilde{q}_3}$	1.7 TeV	4.1 TeV
$m_{\tilde{\ell}}$	0.35 TeV	0.36 TeV
$m_{\tilde{\tau}}$	0.46 TeV	1.4 TeV
M_A	4.0 TeV	4.2 TeV
A	2.8 TeV	5.4 TeV
μ	1.33 TeV	- 5.7 TeV
$\tan\beta$	36	19
χ^2/d.o.f.	22.1/20	24.46/20
p-value	0.33	0.22
$\chi^2(HS)$	68.01	67.97

$\Rightarrow$ excellent p value!

What to conclude?

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$\Rightarrow$ **Look at the p values!**

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Model	Min. χ^2/dof	χ^2-prob. (p-value)
CMSSM	32.8/18	11%
NUHM1	31.1/23	12%
NUHM2	30.3/22	11%
SU(5)	32.4/23	9%
mAMSB	36.5/27	11%
sub-GUT	28.9/24	23%
pMSSM11	21.0/20	33%

Which model is more likely??

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⇒ pMSSM11: model with higher χ^2-probability
model with good ILC/CLIC prospects
detailed LHC analysis tbd!

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⇒ Dark Matter prospects? ⇒ talk by S.H. later today

5. Conclusinos

- SUSY is (still) the best-motivated BSM scenario
  - constrained models: CMSSM, NUHM, SU(5), mAMSB, sub-GUT
  - general models: pMSSM11, ...
- MasterCode: LHC, Higgs, EWPO, BPO, CDM $\Rightarrow \chi^2$ evaluation
-

Model	Min. χ^2/dof	χ^2-prob. (p-value)
GUT based models	(30 . . . 33)/(18 . . . 23)	$\sim$ 11%
pMSSM11	21.0/20	33%

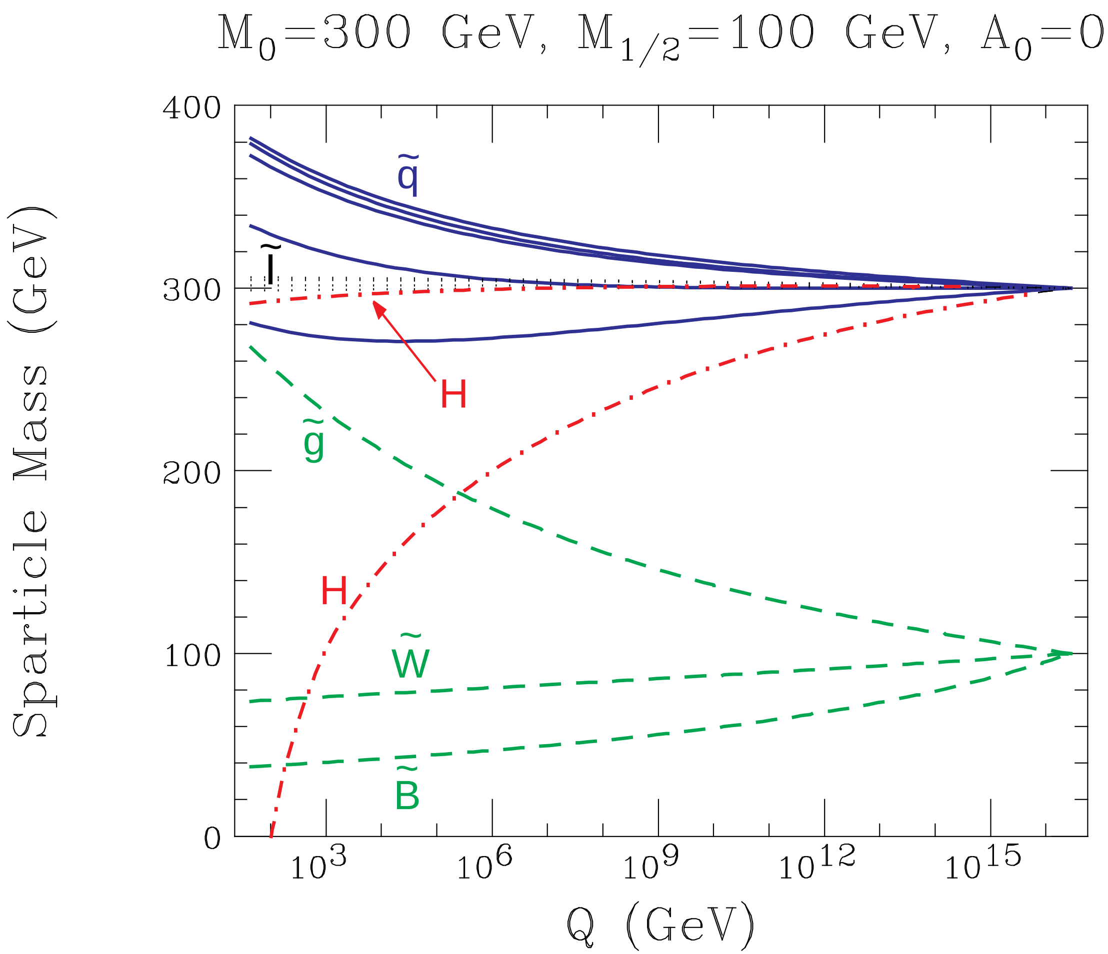
Particle	GUT-based models	pMSSM11
gauginos	ILC CLIC	ILC CLIC
sleptons	CLIC	ILC CLIC
stops/sbottoms		CLIC
other		

$\Rightarrow$ pMSSM11: model with higher χ^2-probability
model with good ILC/CLIC prospects


Further Questions?

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

⇒ particle spectra from renormalization group running to weak scale



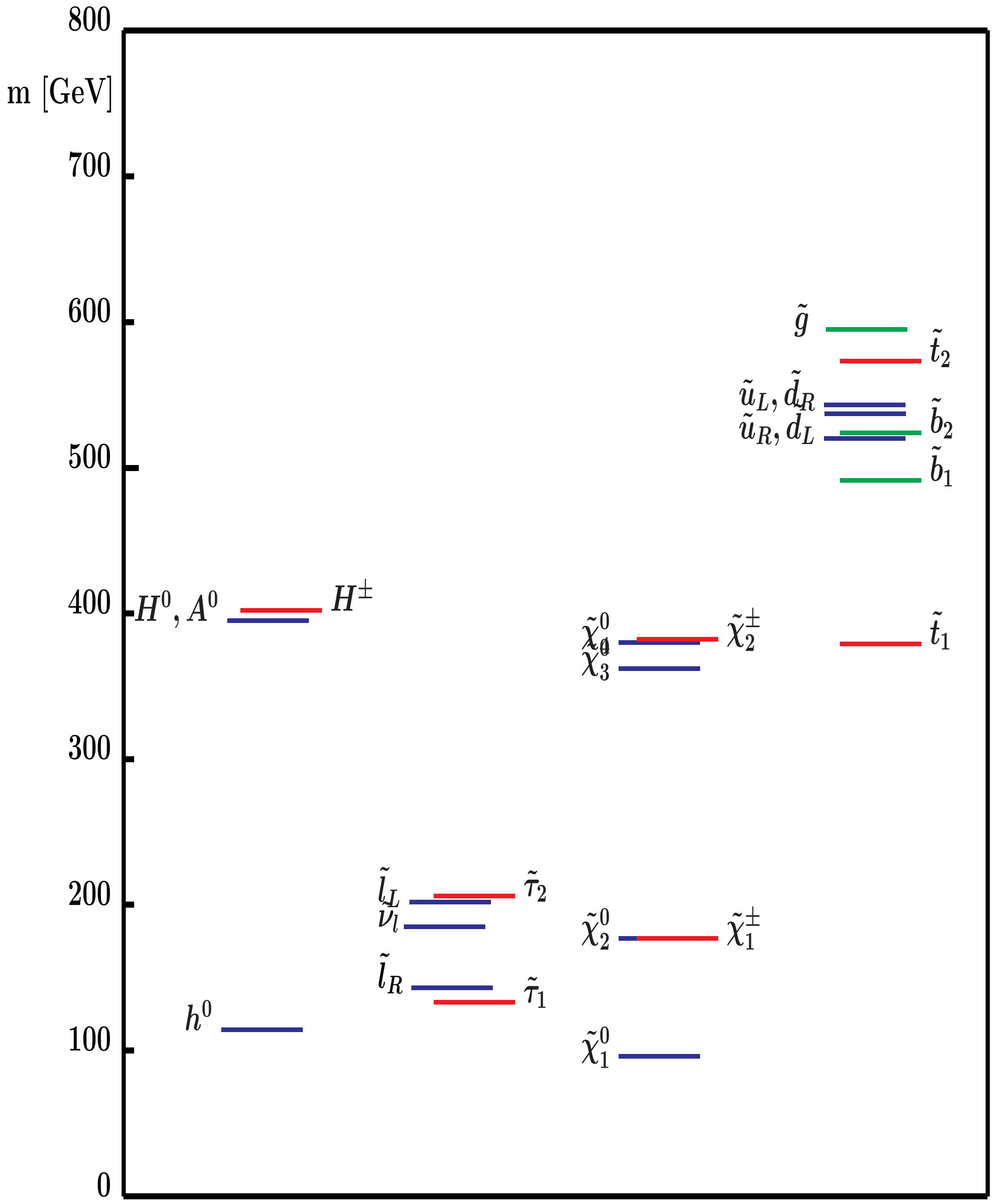
⇒ one parameter turns negative ⇒ Higgs mechanism for free

"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

⇒ effectively M_A as free parameters at the EW scale

> ⇒ 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

⇒ effectively M_A and μ as free parameters at the EW scale

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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:

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

$\Rightarrow$ Scenario characterized by

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

GUT based models: 5.) mAMSB:

mAMSB scenario characterized by

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

$m_{3/2} = \langle F \rangle / M_{\text{Planck}}$: 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

GUt based models: 6.) sub-GUT:

Based on CMSSM with unification at $M_{\text{GUT}} \sim 2 \cdot 10^{16}$ GeV:

> $\Rightarrow$ Scenario characterized by
>
> $$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \text{sign}\,\mu$$

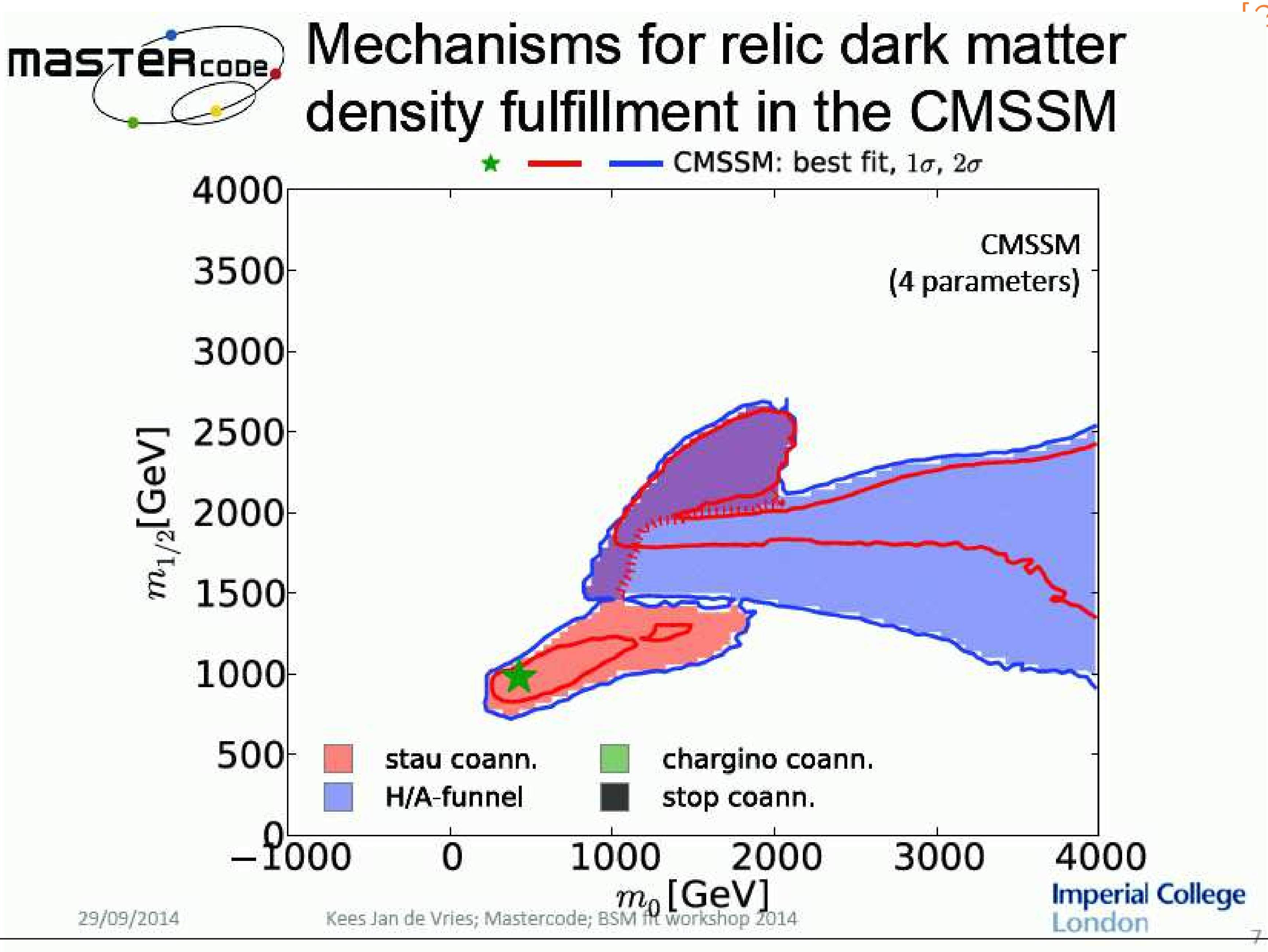
Unification is assumed at $M_{\text{in}} \leq M_{\text{GUT}}$:

> $\Rightarrow$ Scenario characterized by
>
> $$M_{\text{in}},\ m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \text{sign}\,\mu$$

Possible realization in "mirage unification"
warped extra dimensions
...

CMSSM best-fit point prediction

[2014]



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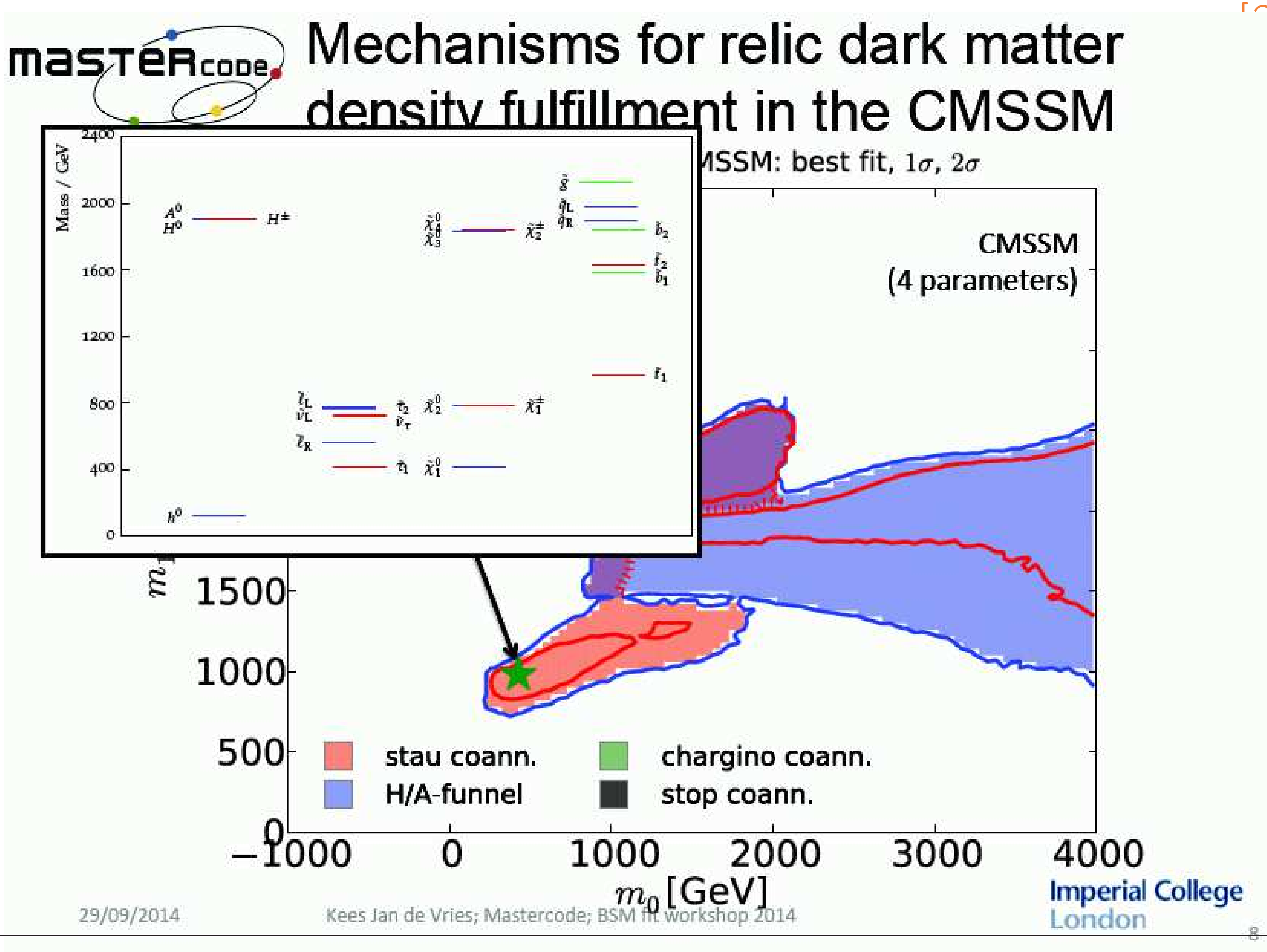

NUHM1 best-fit point prediction

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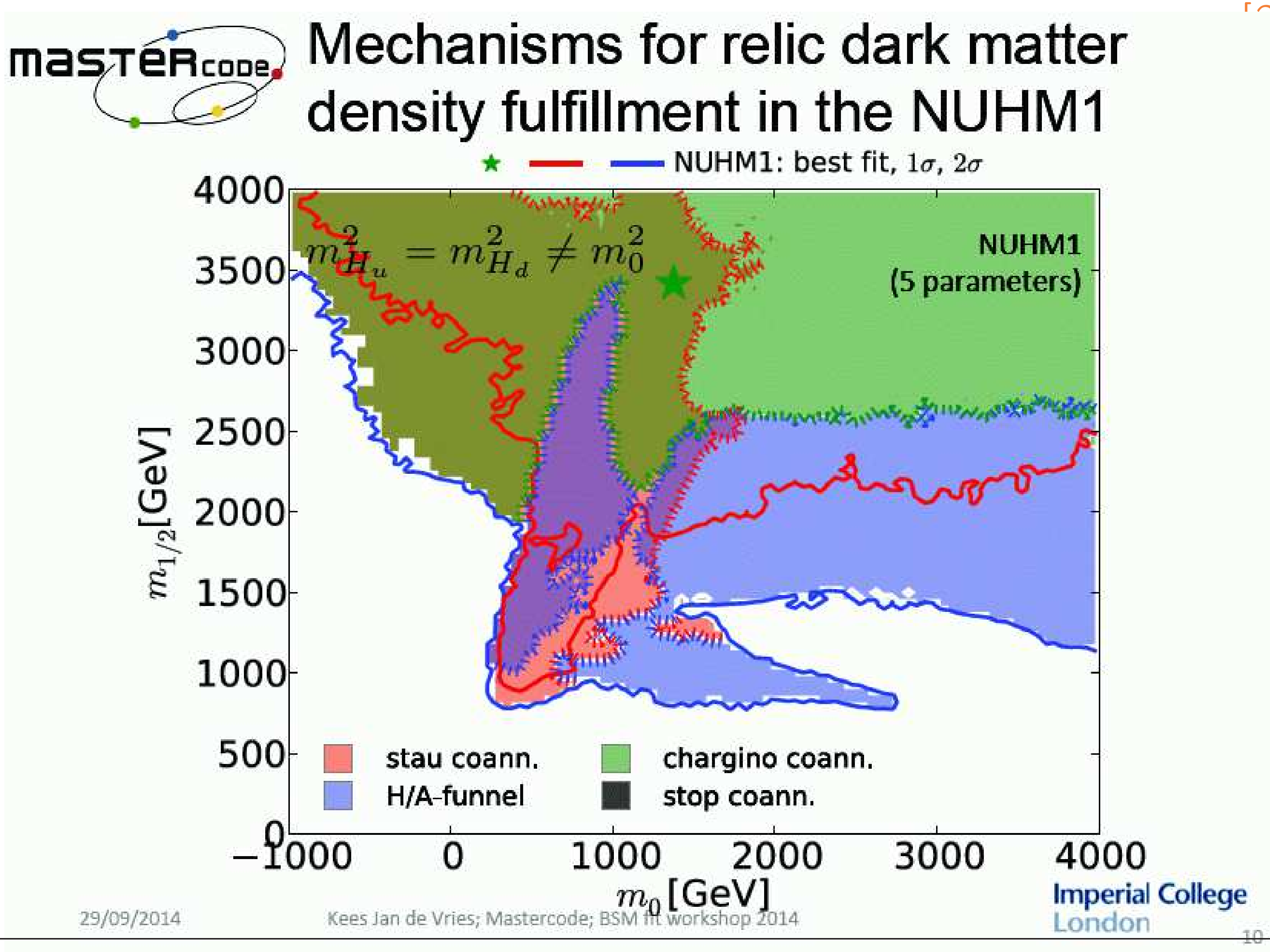

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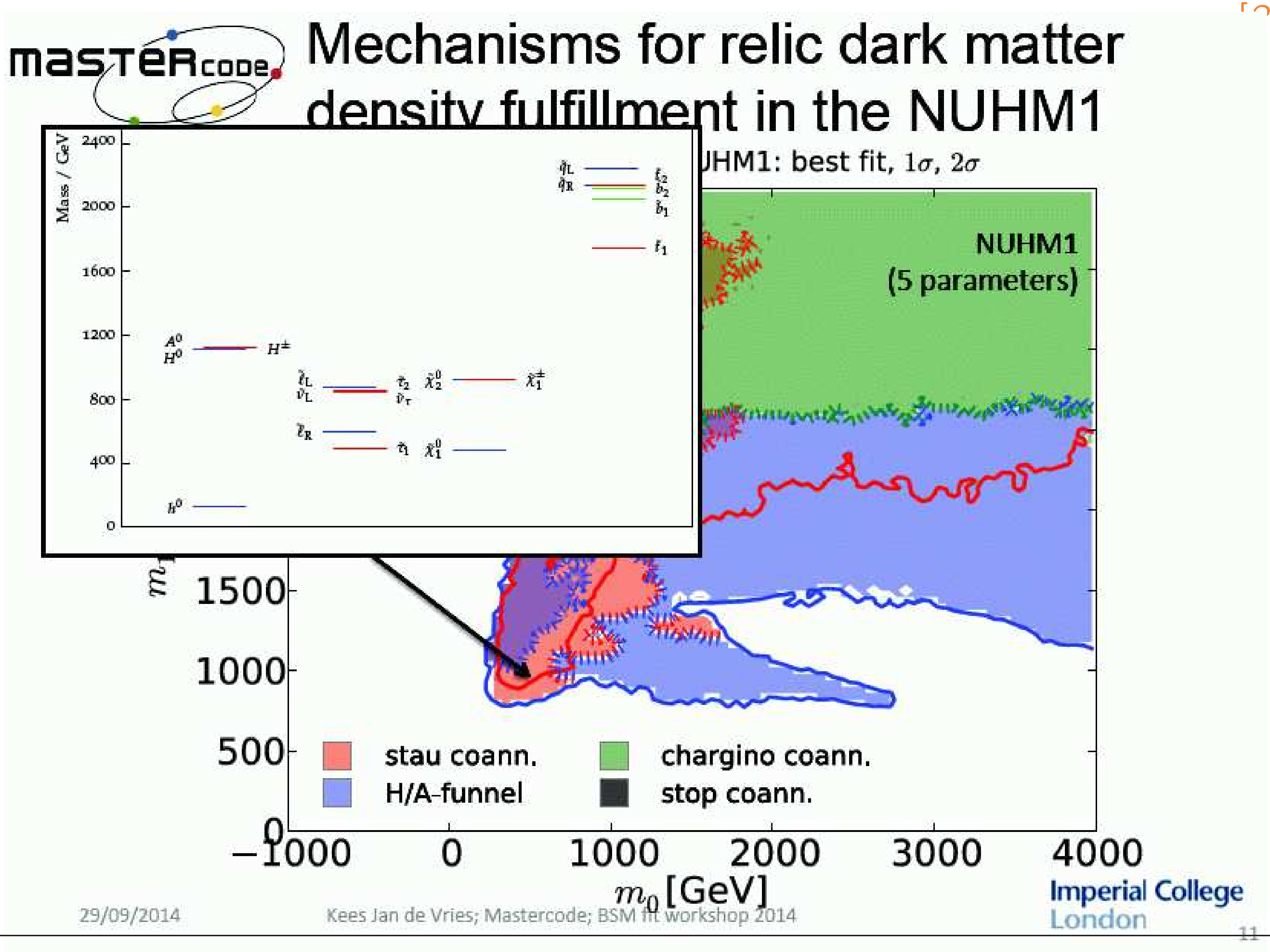

NUHM2 best-fit point prediction

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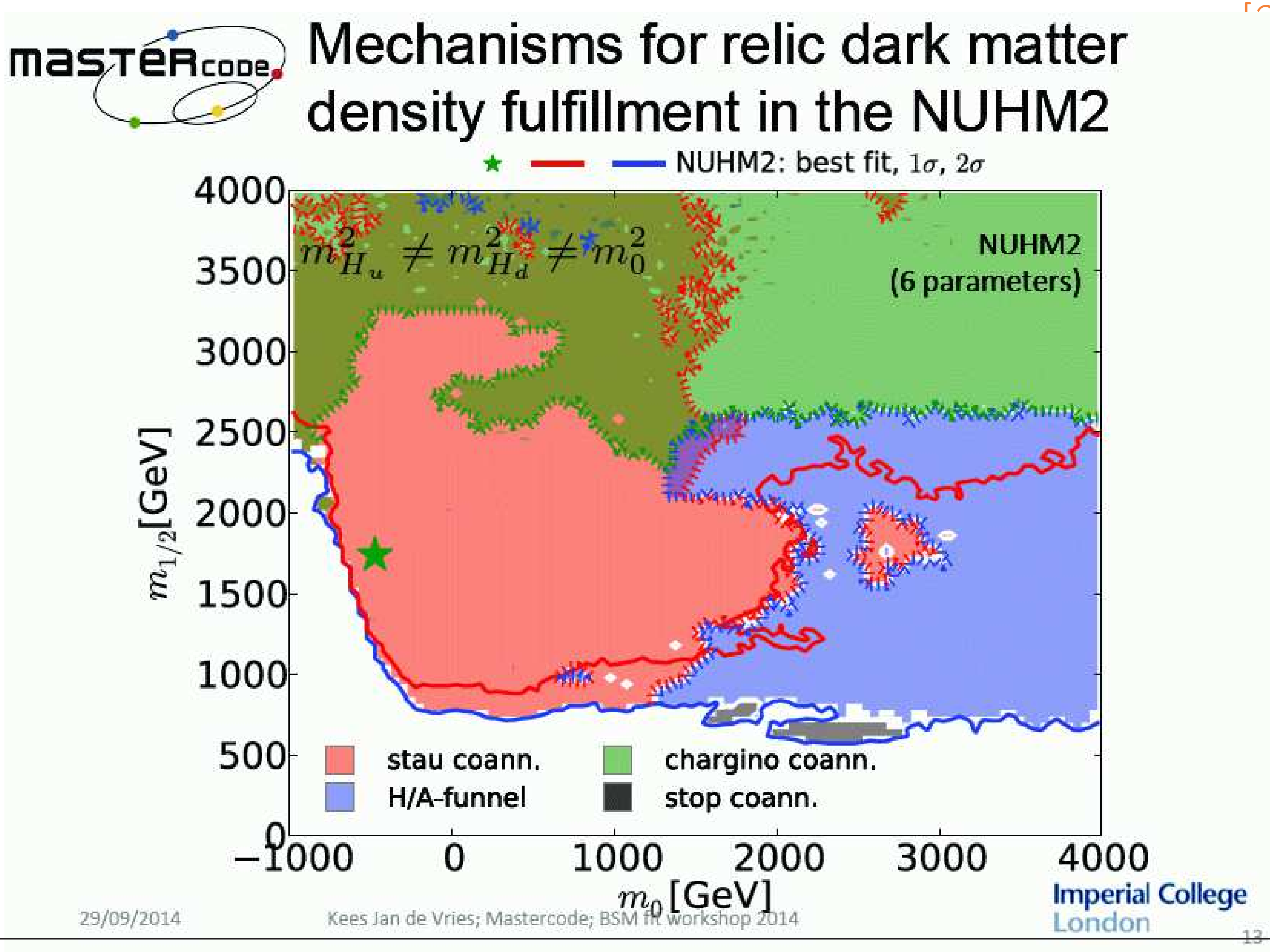

NUHM2 best-fit point prediction

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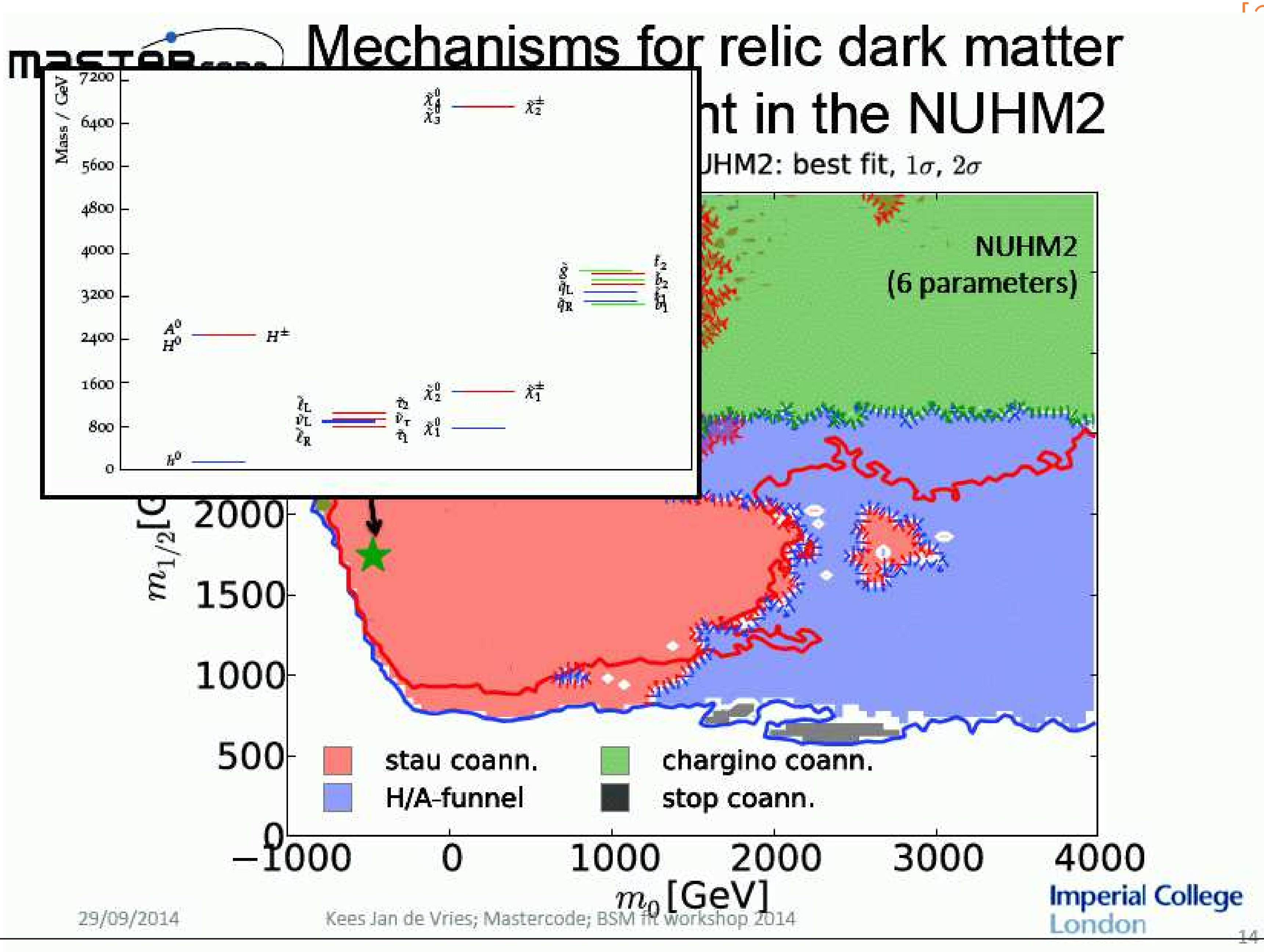

mAMSB prediction: best-fit masses (wino)

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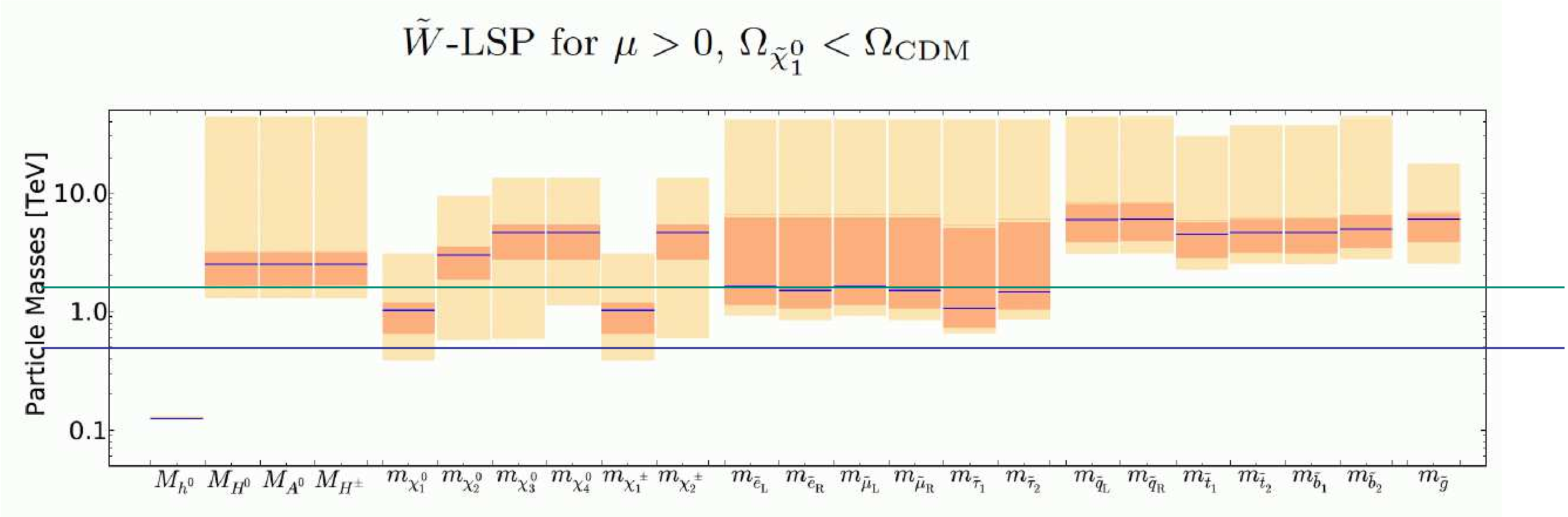

ILC: $\sqrt{s} = 1000$ GeV $\Rightarrow$ bad prospects

CLIC: $\sqrt{s} = 3000$ GeV $\Rightarrow$ pair production of few SUSY particles "likely"

$\Rightarrow$ no access to colored particles

mAMSB prediction: best-fit masses (higgsino)

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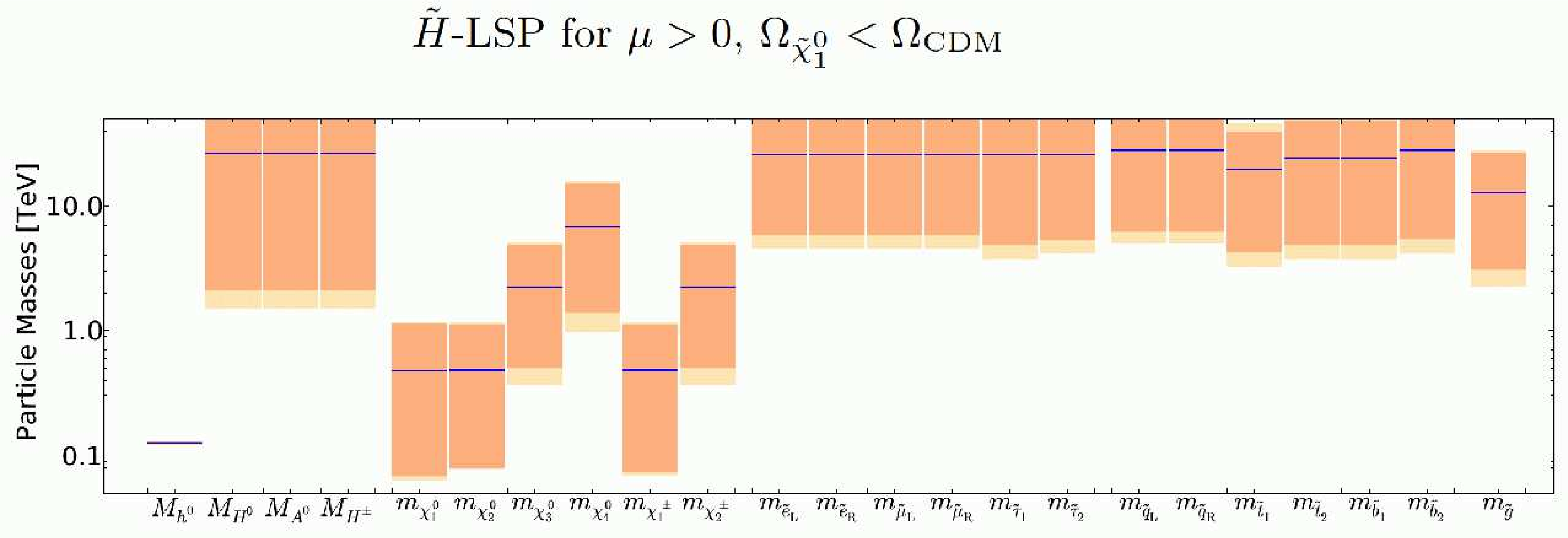

$\Rightarrow$ high colored masses

$\Rightarrow$ some(!) lower electroweak masses

partially with not too large $2\,\sigma$ ranges

$\Rightarrow$ clear prediction for ILC and CLIC

mAMSB prediction: best-fit masses (higgsino)

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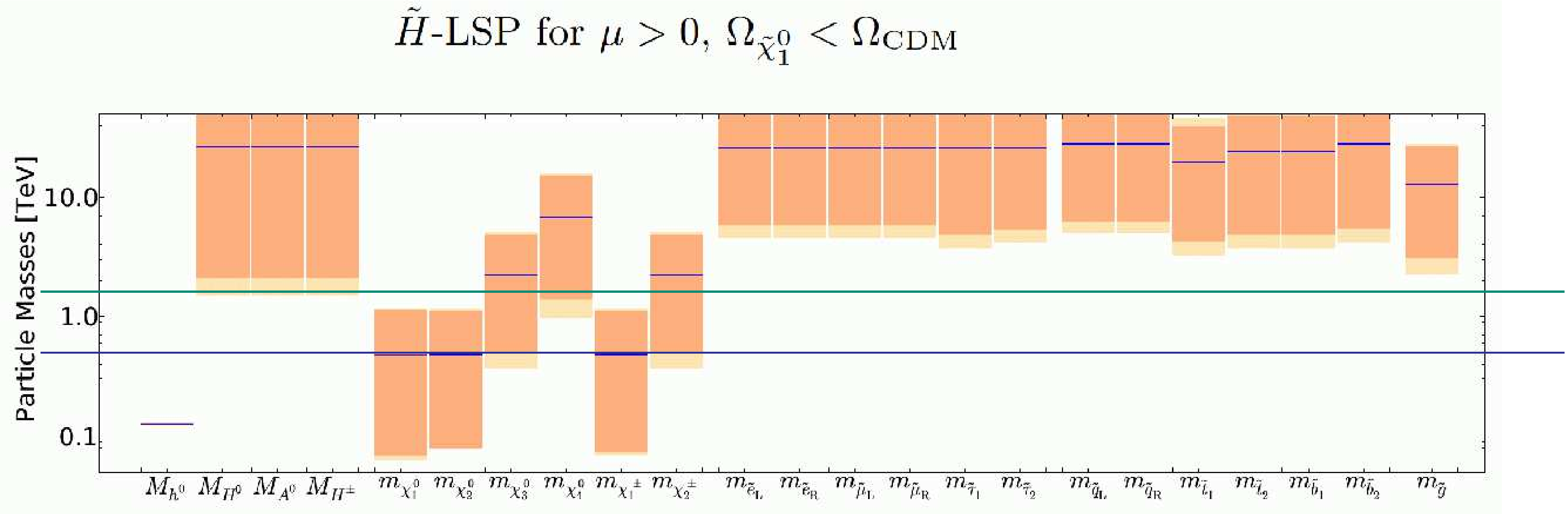

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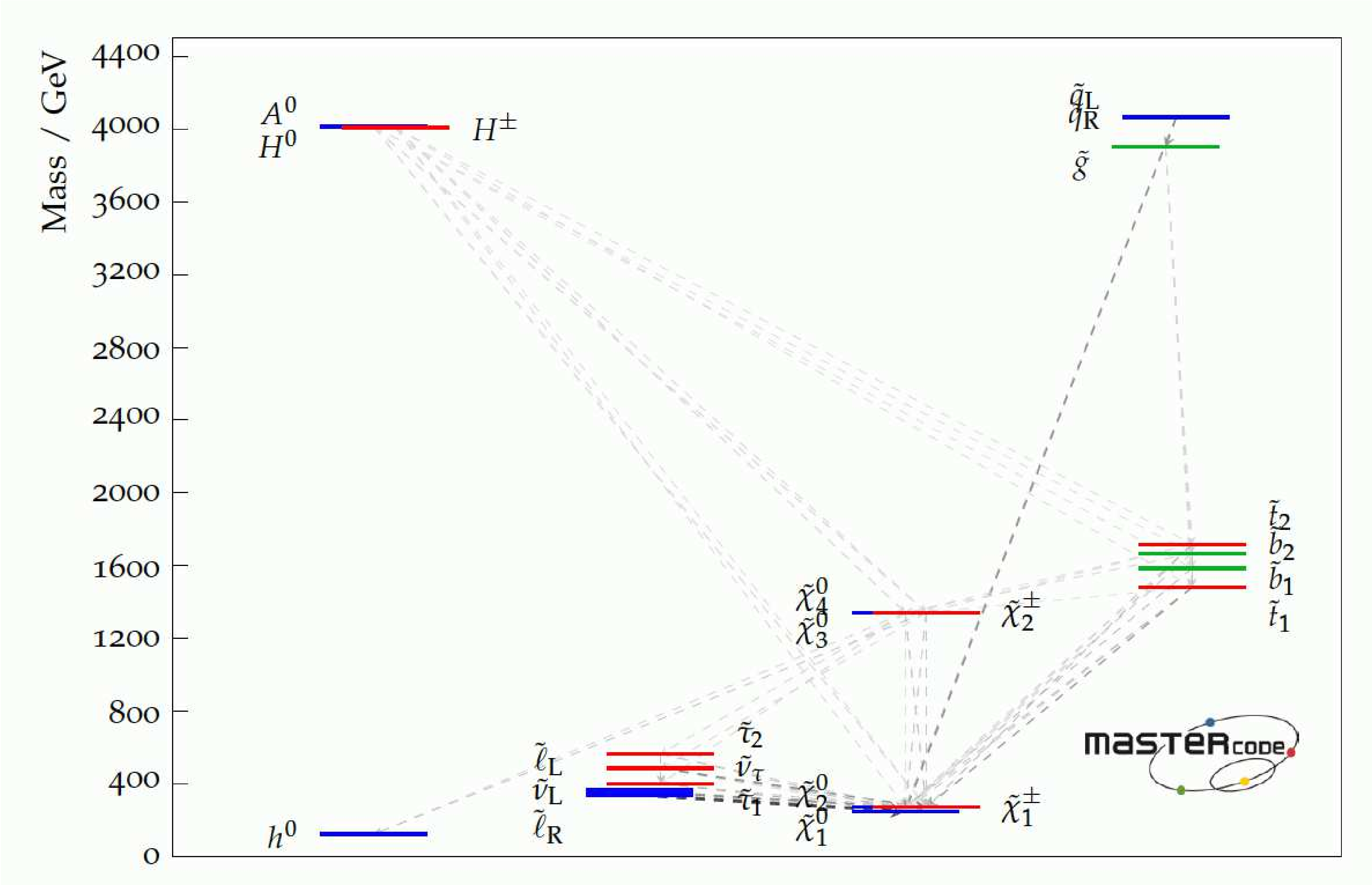
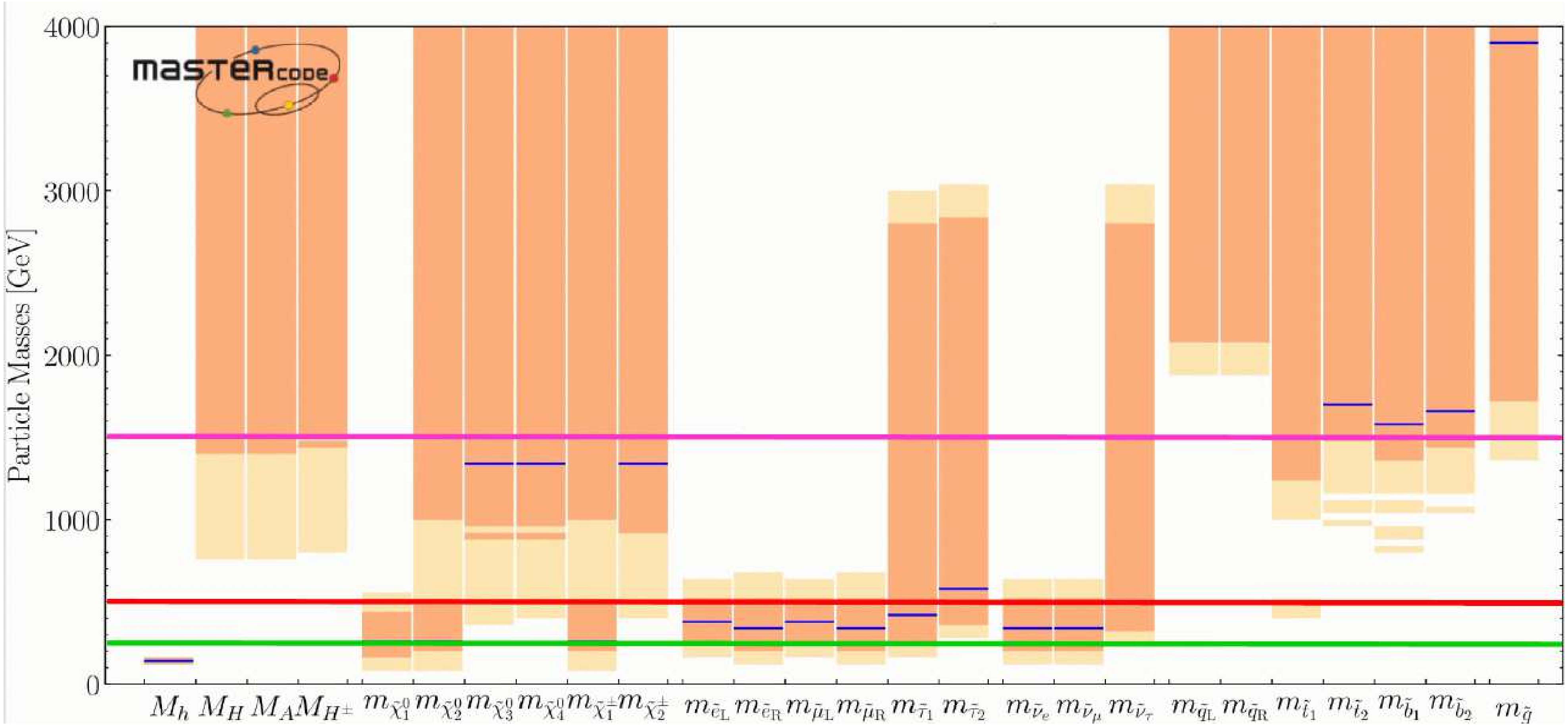
$\Rightarrow$ no access to colored particles

pMSSM11: best-fit point phenomenology [2017]



⇒ heavy colored, light uncolored spectrum

pMSSM11: prospects for ILC and CLIC [2017]



ILC: $\sqrt{s} = 500$ GeV $\Rightarrow$ some particles might be in reach

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

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