
We still believe in supersymmetry
You must be joking

SUSY Predictions for ILC and CLIC

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Arlington, 10/2017

1. Introduction

2. The MasterCode

3. SUSY Fit Results for the ILC and CLIC in GUTs

4. SUSY Fit Results for the ILC and CLIC in the pMSSM

5. Conclusions

1. Introduction

Some "recent" measurements:

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

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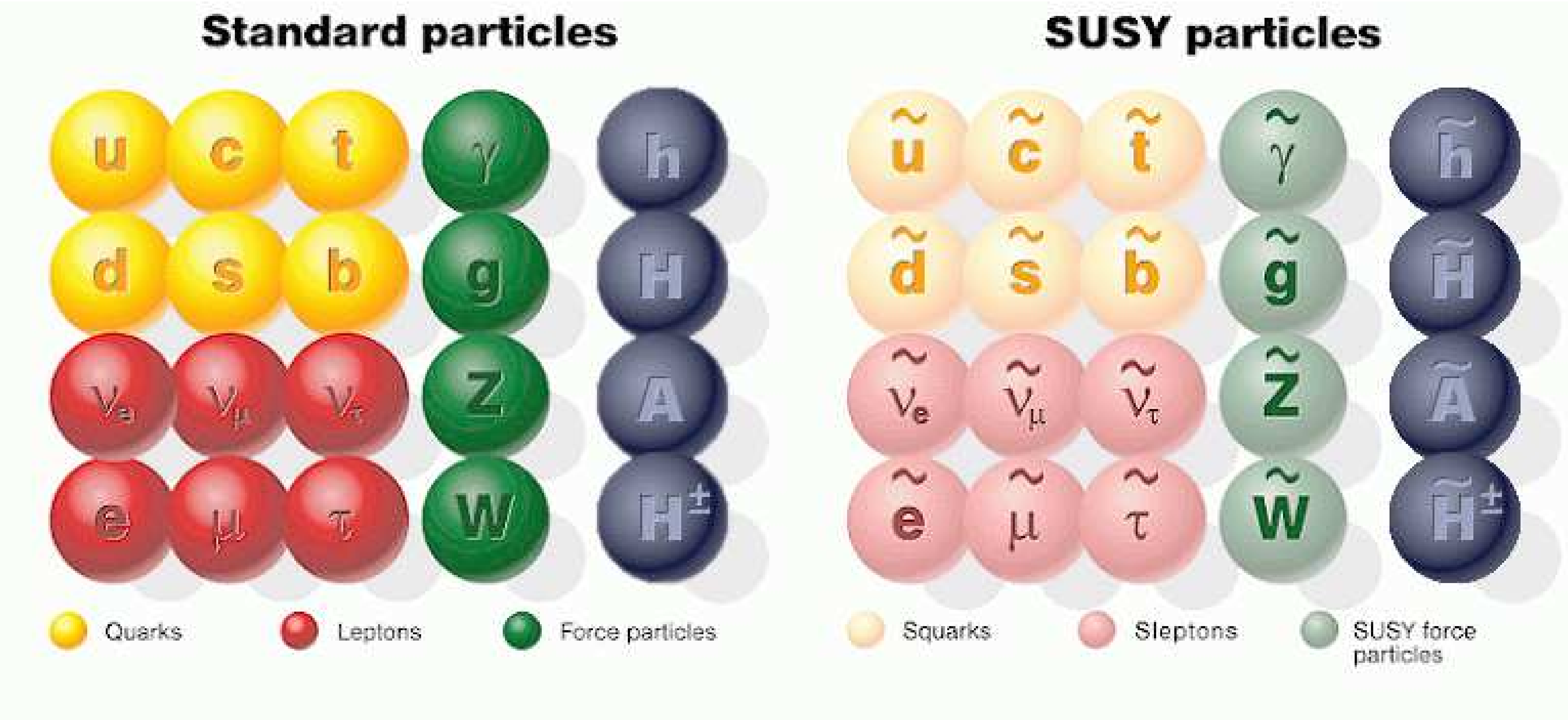
⇒ good motivation to look at SUSY!

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!

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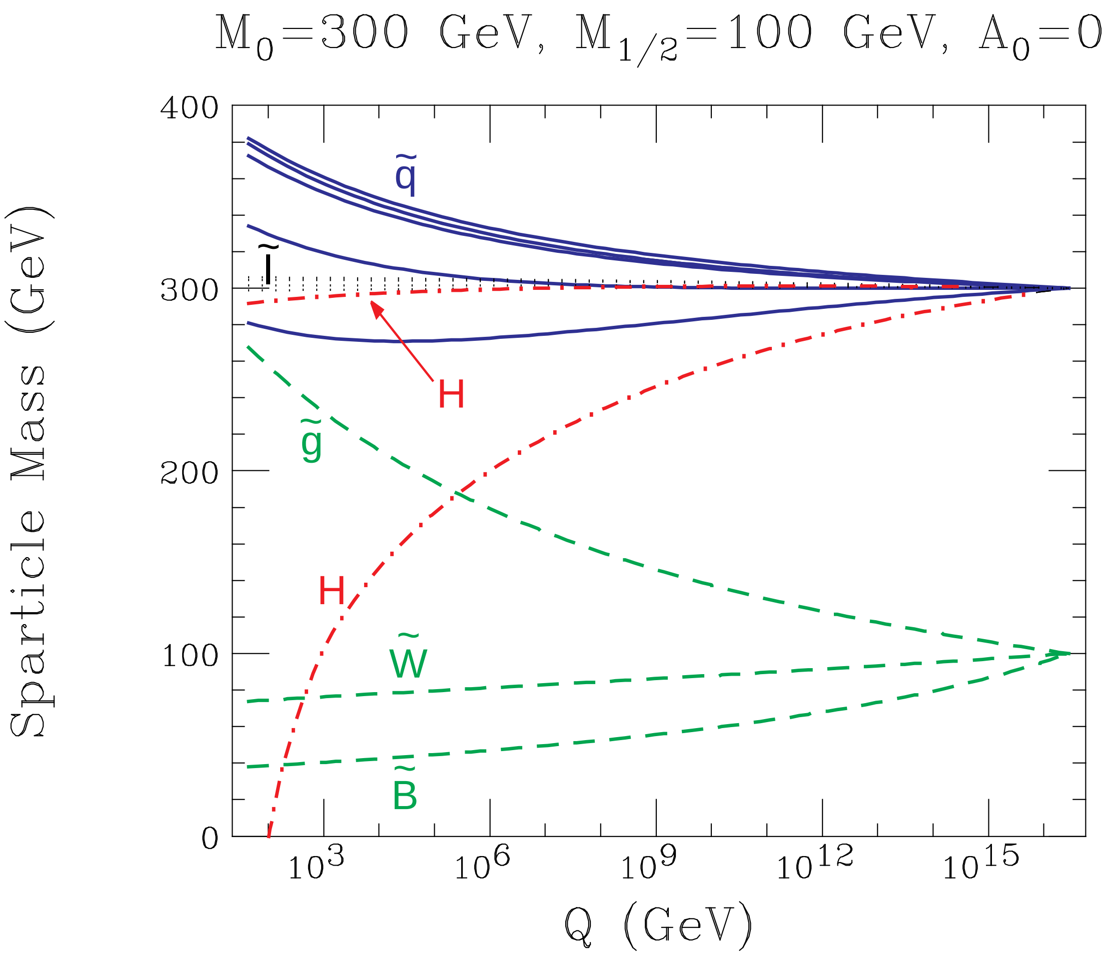


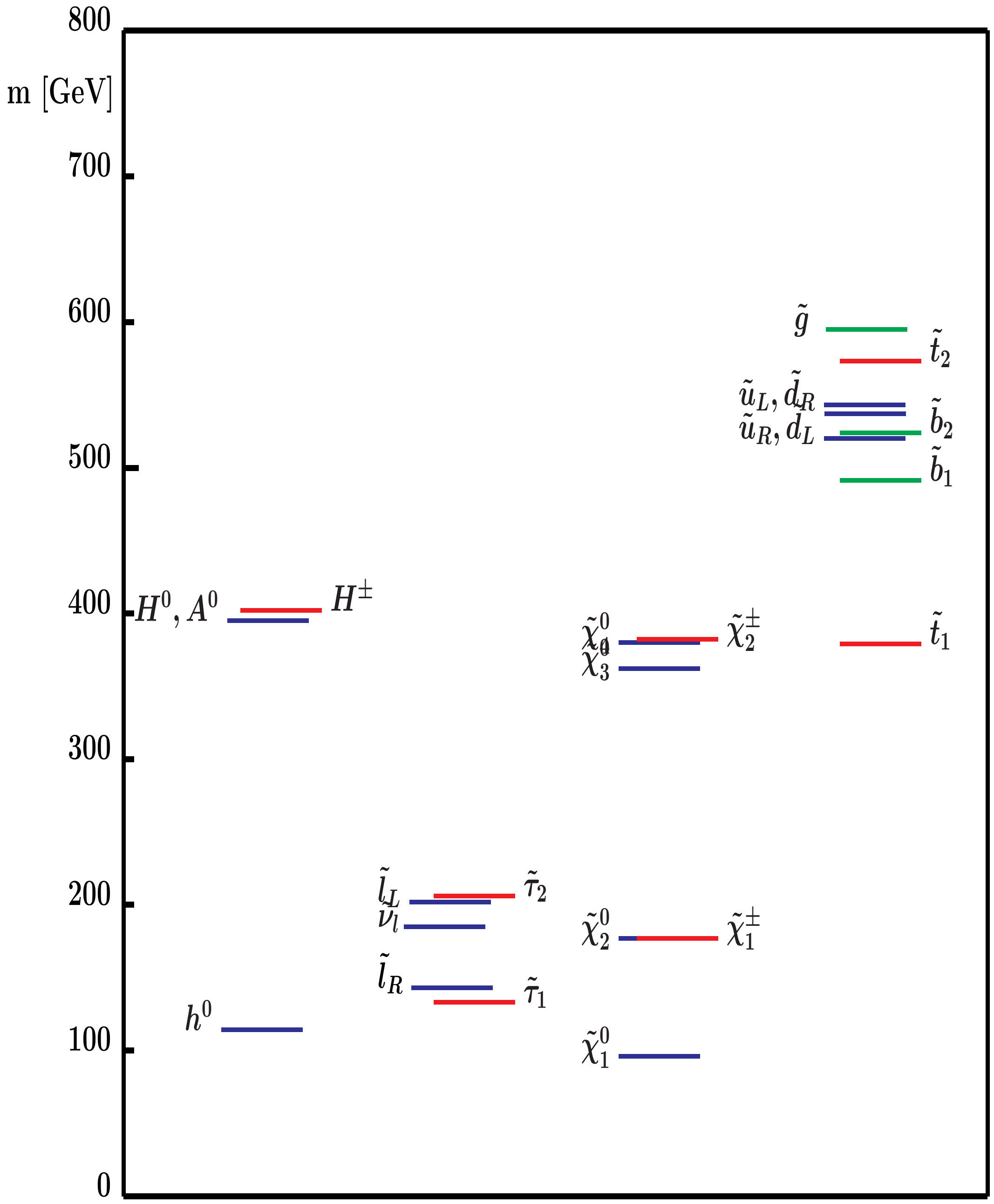
⇒ one parameter turns negative ⇒ Higgs mechanism for free

"Typical" CMSSM scenario

(SPS 1a benchmark scenario):

Strong connection between

all the sectors



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.) ...

⇒ 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) $\Rightarrow$ FeynHiggs

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- Higgs boson exclusion bounds (LHC, Tevatron, LEP) $\Rightarrow$ HiggsBounds

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– SUSY searches (LHC) ⇒ own re-cast (fast-lim approach)

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– Higgs boson exclusion bounds (LHC, Tevatron, LEP) $\Rightarrow$ HiggsBounds

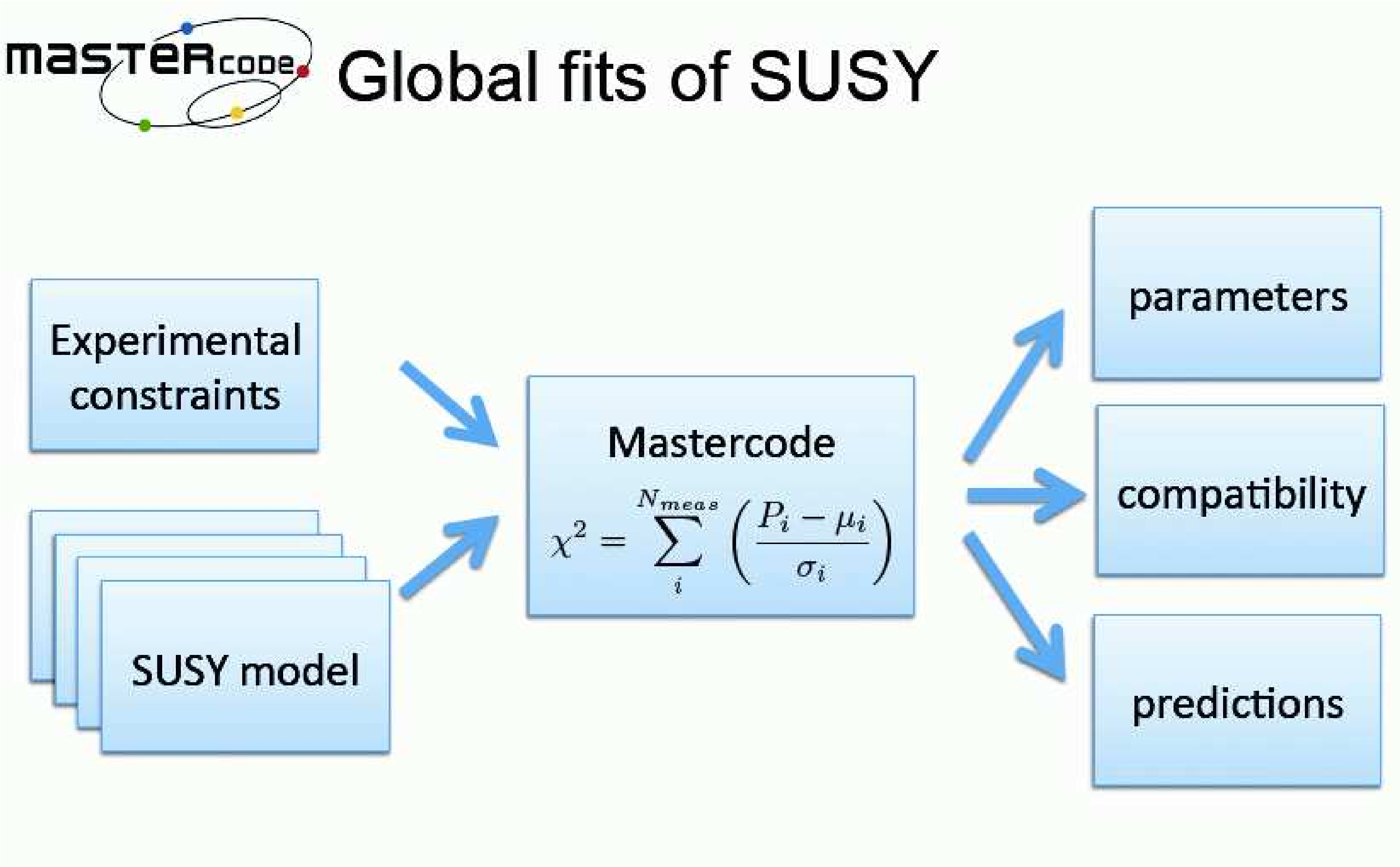
– SUSY searches (LHC) $\Rightarrow$ own re-cast (fast-lim approach)

– electroweak precision data $\Rightarrow$ FeynWZ, FeynHiggs

– flavor data $\Rightarrow$ SuperIso, SuFla

– astrophysical data (DM properties) $\Rightarrow$ MicrOMEGAs, SSARD

The χ^2 evaluation:

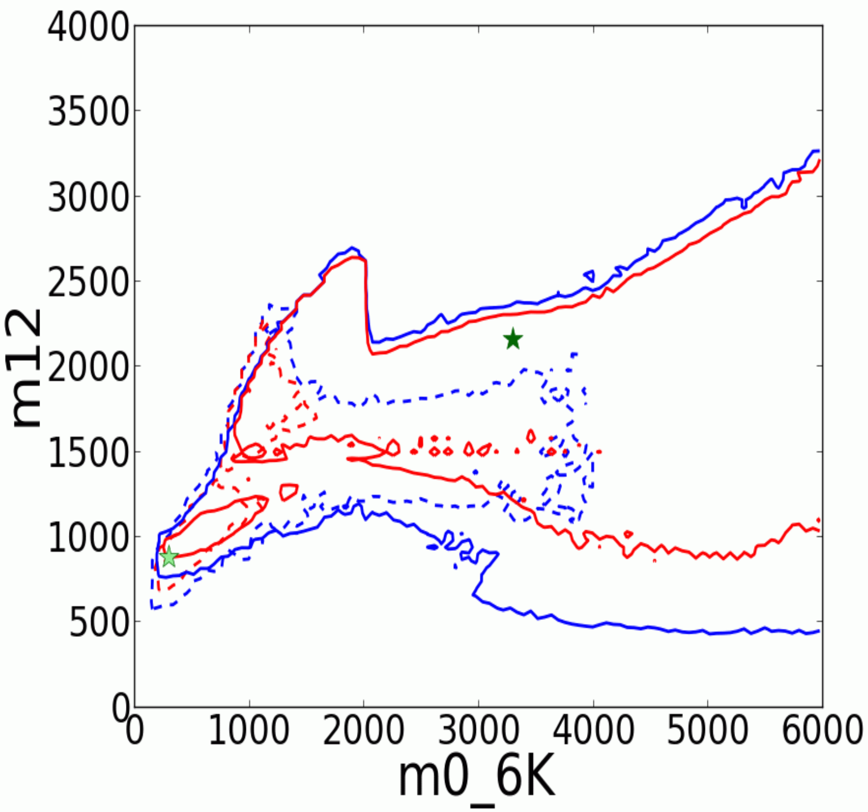


3. Predictions for the ILC and CLIC in GUTs

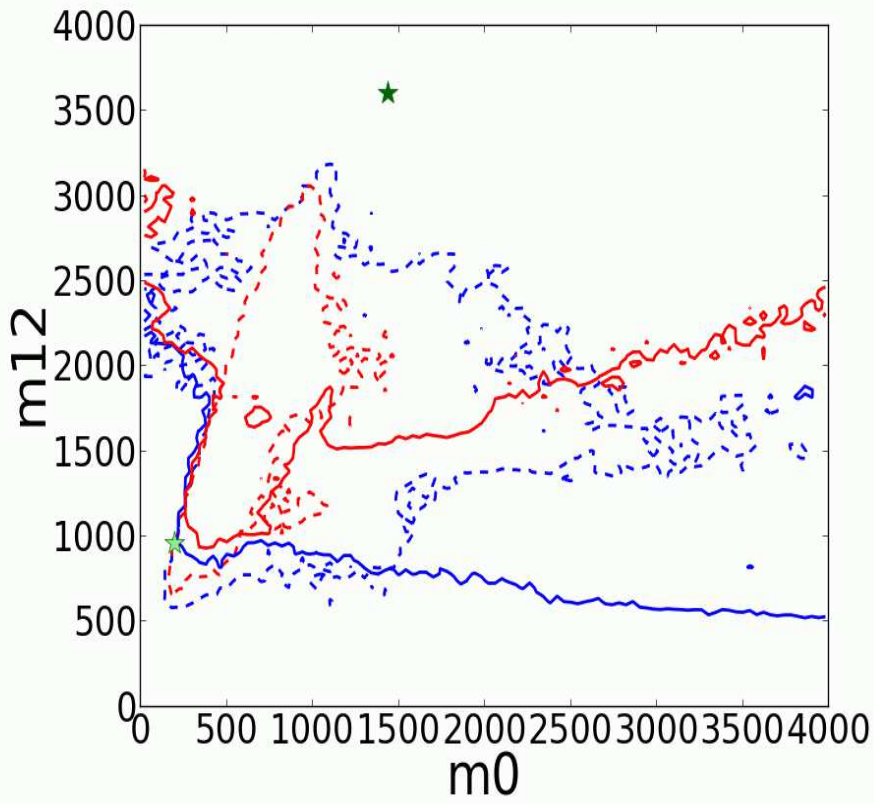
m_0-$m_{1/2}$ plane including LHC 20/fb:

[2013]

CMSSM



NUHM1



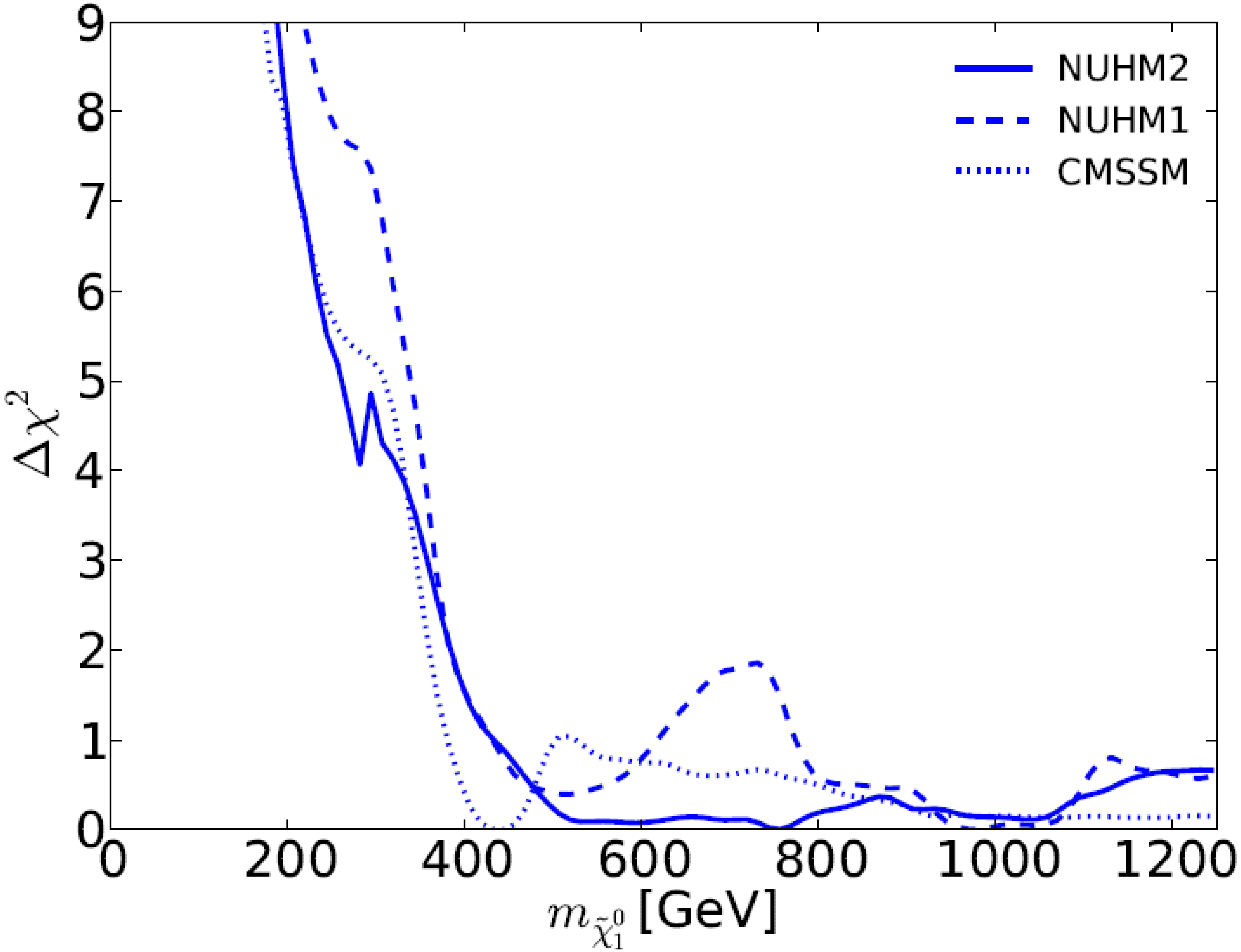
dotted: LHC 5/fb 7 TeV, solid: LHC 20/fb 8 TeV

⇒ very high masses favored!

⇒ prospects for ILC and CLIC?

LSP mass incl. 20/fb of LHC data

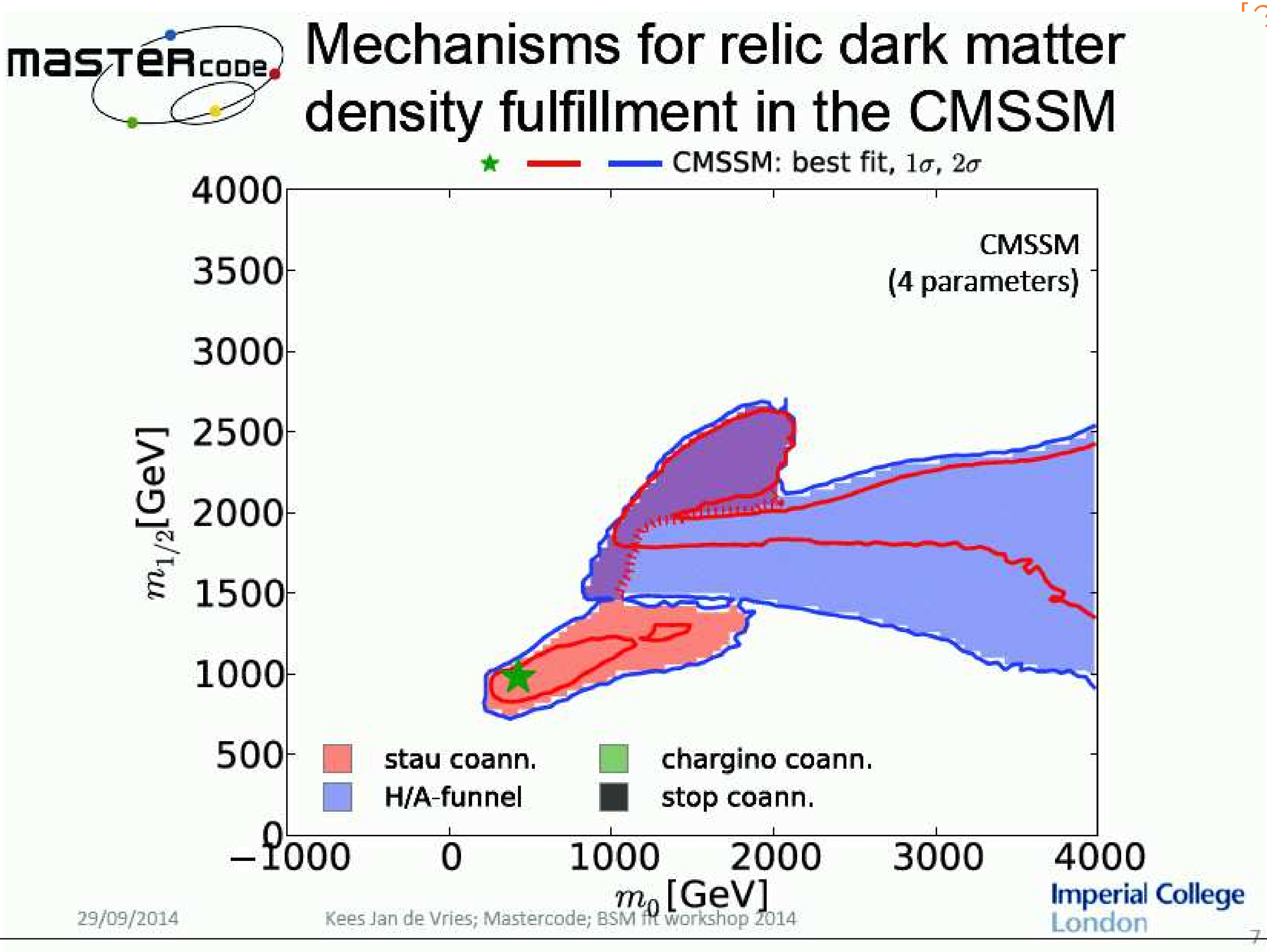
[2014]



⇒ only very large values are favored

CMSSM best-fit point prediction

[2014]



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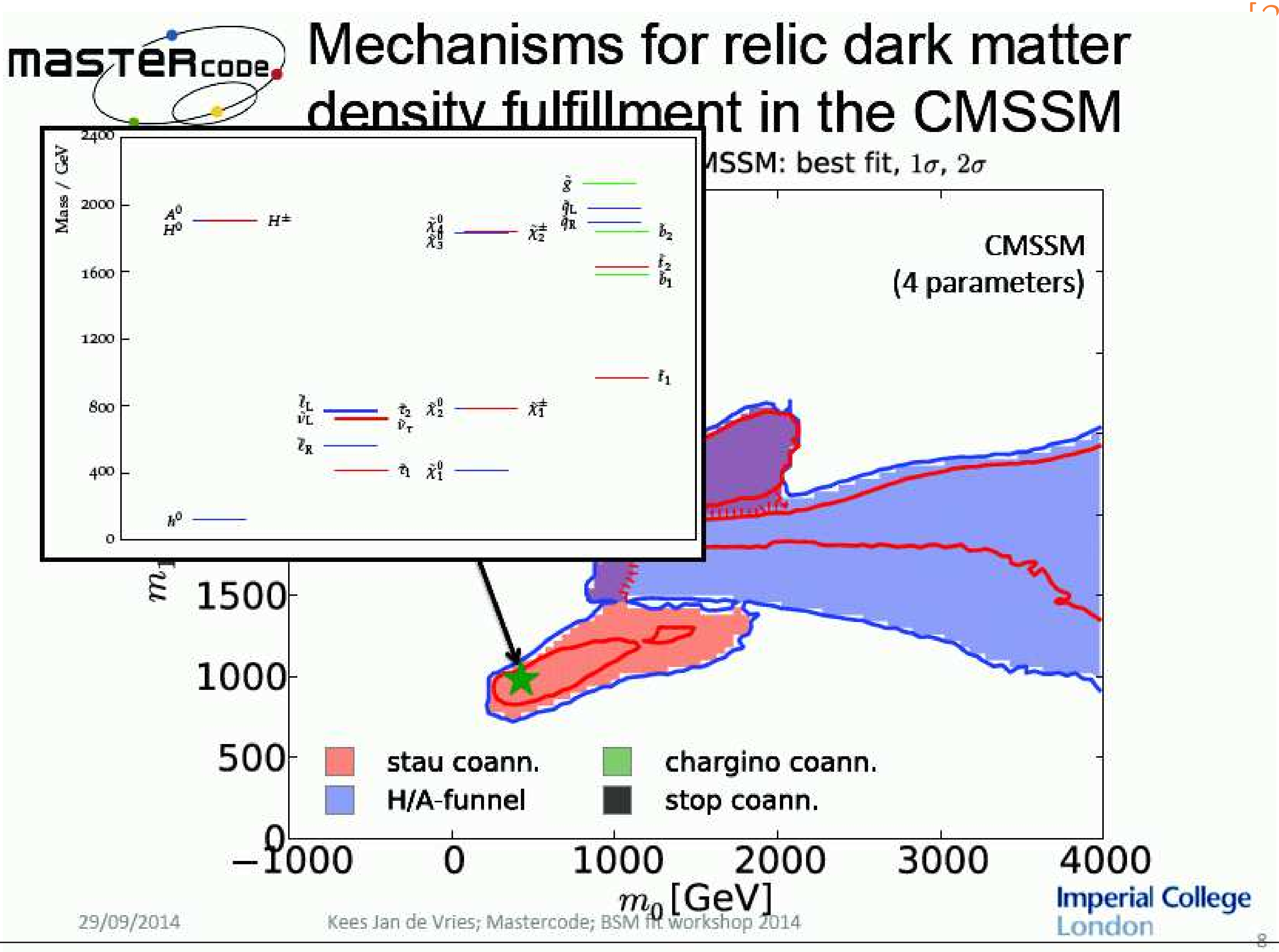
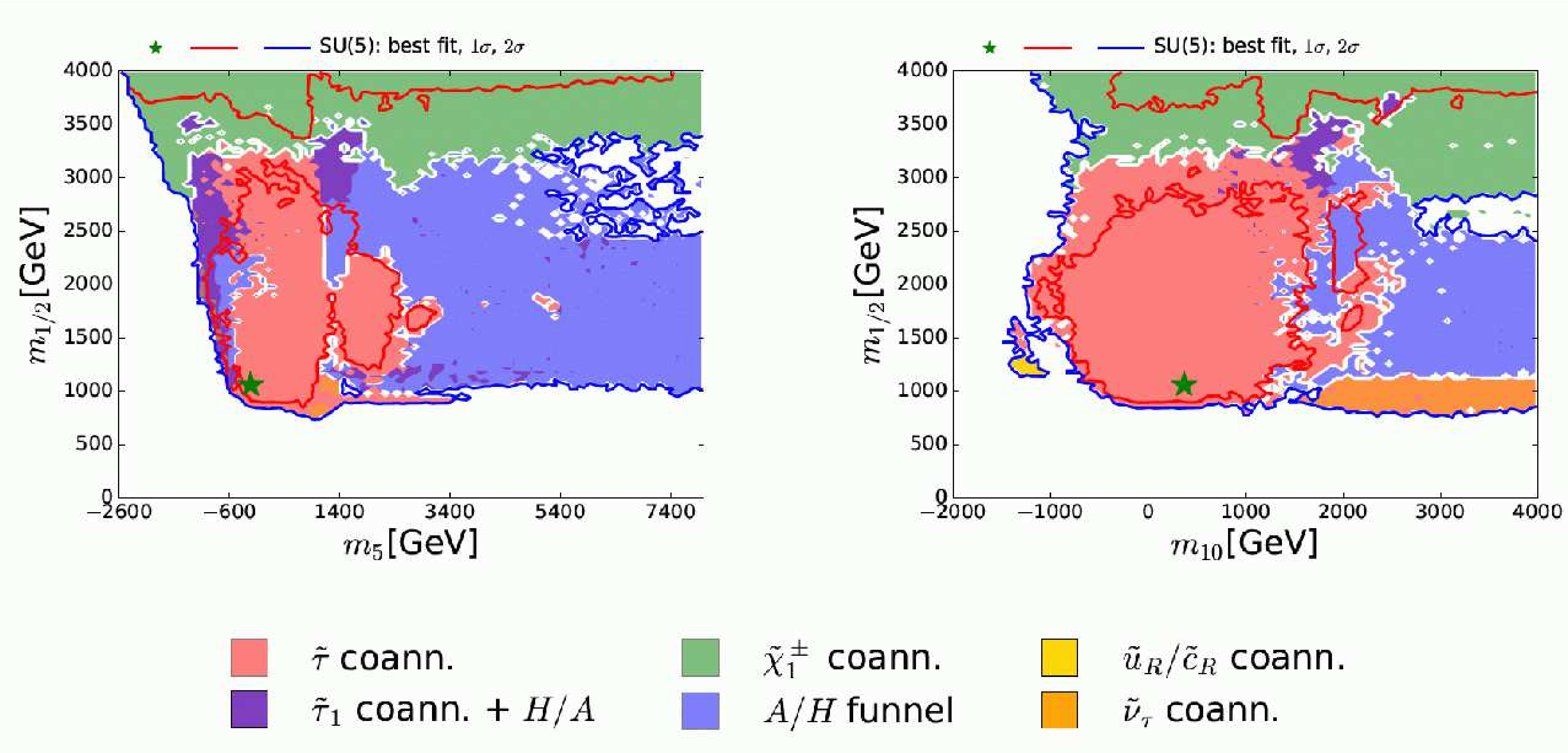

mastercode
Mechanisms for relic dark matter density fulfillment in the CMSSM
CMSSM: best fit, 1σ, 2σ
CMSSM
(4 parameters)
Mass / GeV
A^0
H^0
$H^\pm$
h^0
$\tilde{g}$
$\tilde{q}_L$
$\tilde{q}_R$
$\tilde{b}_2$
$\tilde{t}_2$
$\tilde{b}_1$
$\tilde{t}_1$
$\tilde{\chi}_4^0$
$\tilde{\chi}_3^0$
$\tilde{\chi}_2^\pm$
$\tilde{\chi}_2^0$
$\tilde{\chi}_1^\pm$
$\tilde{\chi}_1^0$
$\tilde{l}_L$
$\tilde{\nu}_L$
$\tilde{l}_R$
$\tilde{\tau}_2$
$\tilde{\nu}_\tau$
$\tilde{\tau}_1$
stau coann.
H/A-funnel
chargino coann.
stop coann.
m_0 [GeV]
29/09/2014
Kees Jan de Vries; Mastercode; BSM fit workshop 2014
Imperial College London
8

Results in the SU(5)

Dark Matter annihilation mechanism:

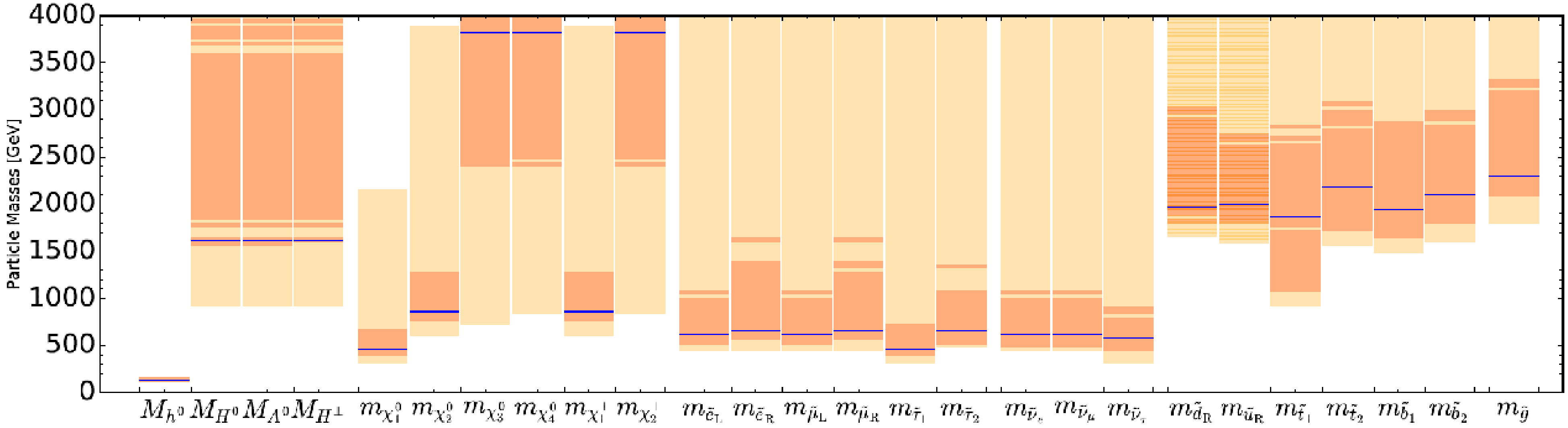
[2016]



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

SU(5) prediction: best-fit masses

[2016]



$\Rightarrow$ high colored masses

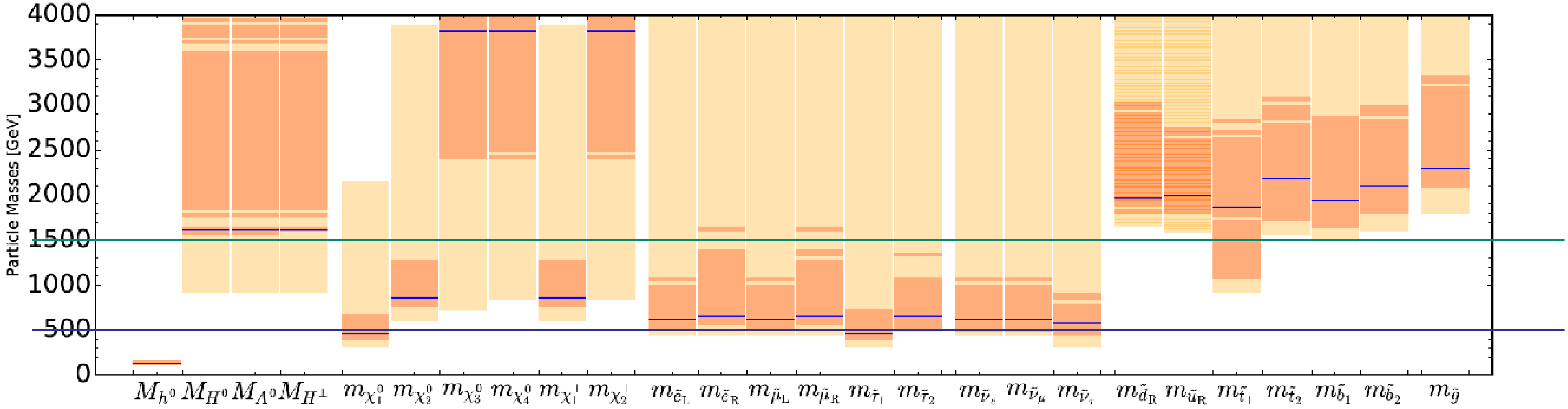
$\Rightarrow$ lower electroweak masses

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

$\Rightarrow$ clear prediction for ILC and CLIC

SU(5) prediction: best-fit masses

[2016]



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

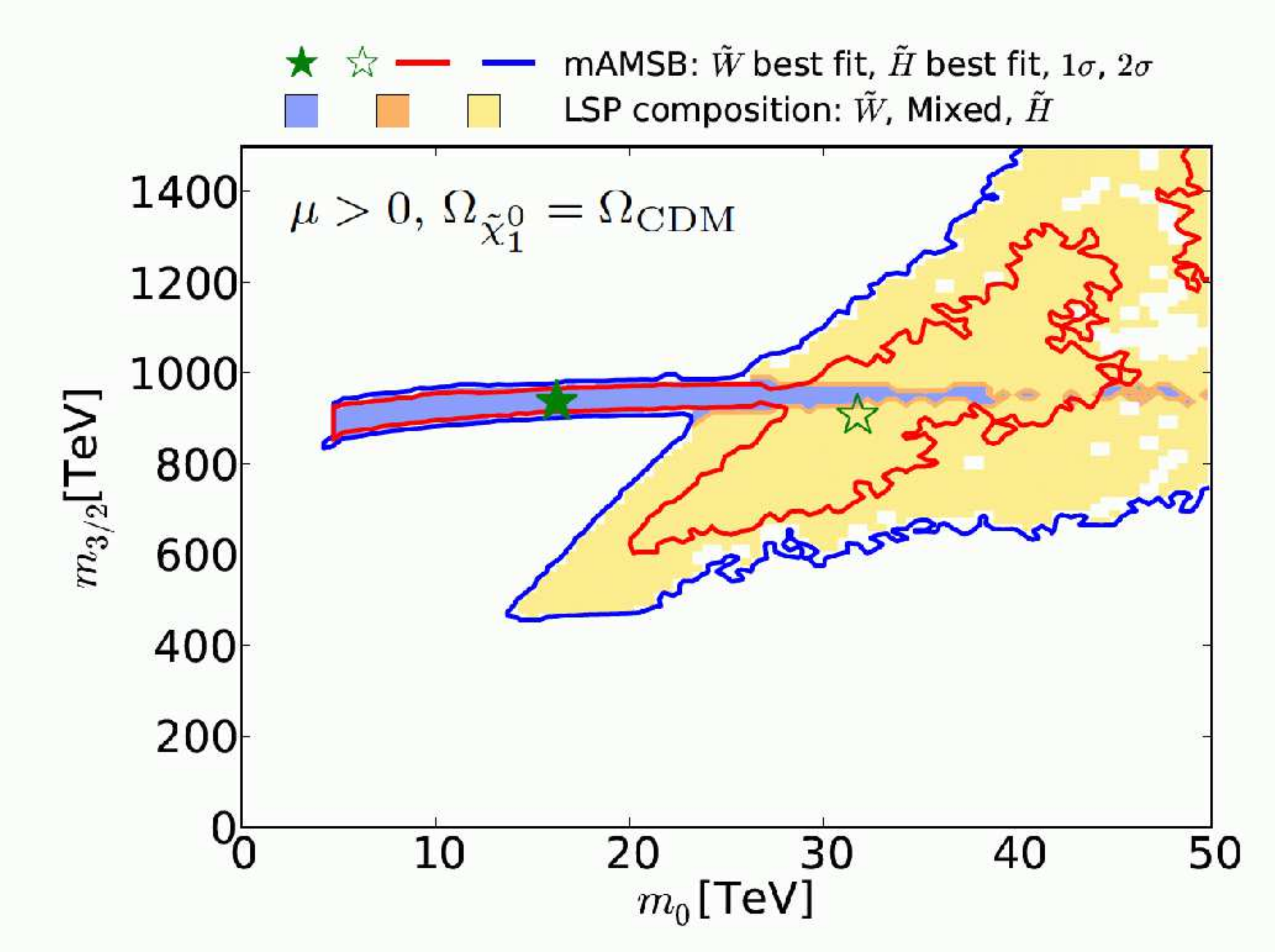
CLIC: $\sqrt{s} = 3000$ GeV $\Rightarrow$ pair production of many SUSY particles “likely”

$\Rightarrow$ no access to colored particles

Results in the mAMSB

Dark Matter composition:

[2016]

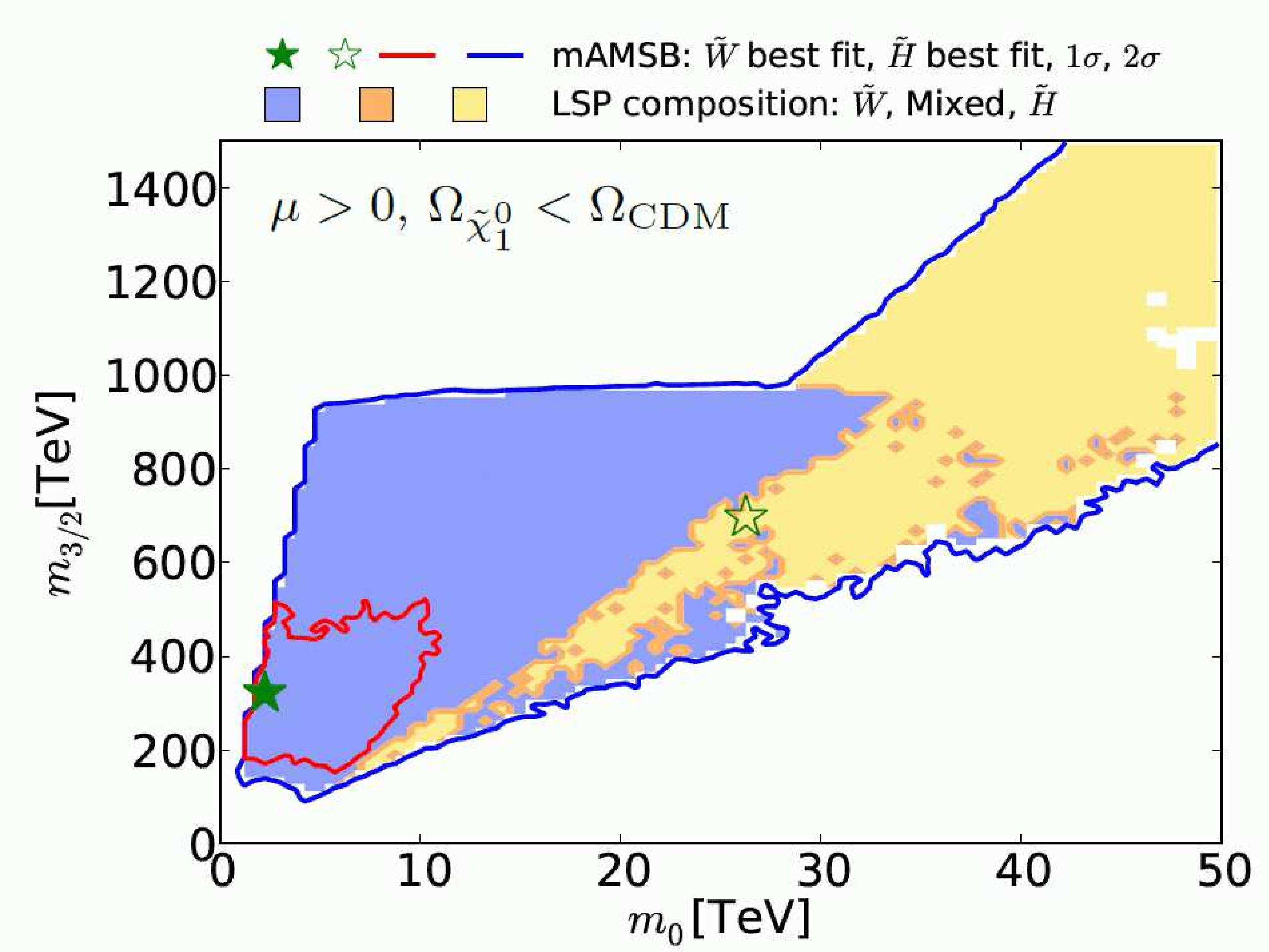


$\Rightarrow m_{\tilde{\chi}_1^0} \sim 2.9 \pm 0.1$ TeV (wino), $\sim 1.1 \pm 0.02$ TeV (higgsino)

Results in the mAMSB

Dark Matter composition:

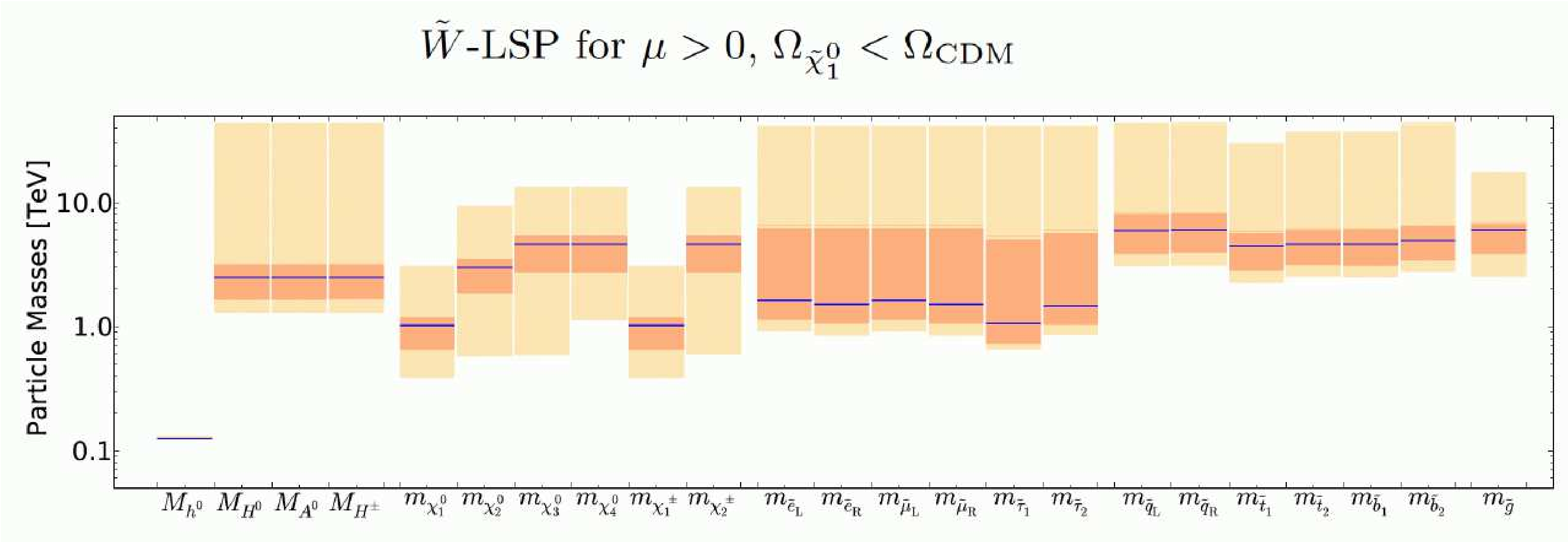
[2016]



⇒ very relaxed limits ⇒ lower masses

mAMSB prediction: best-fit masses (wino)

[2016]



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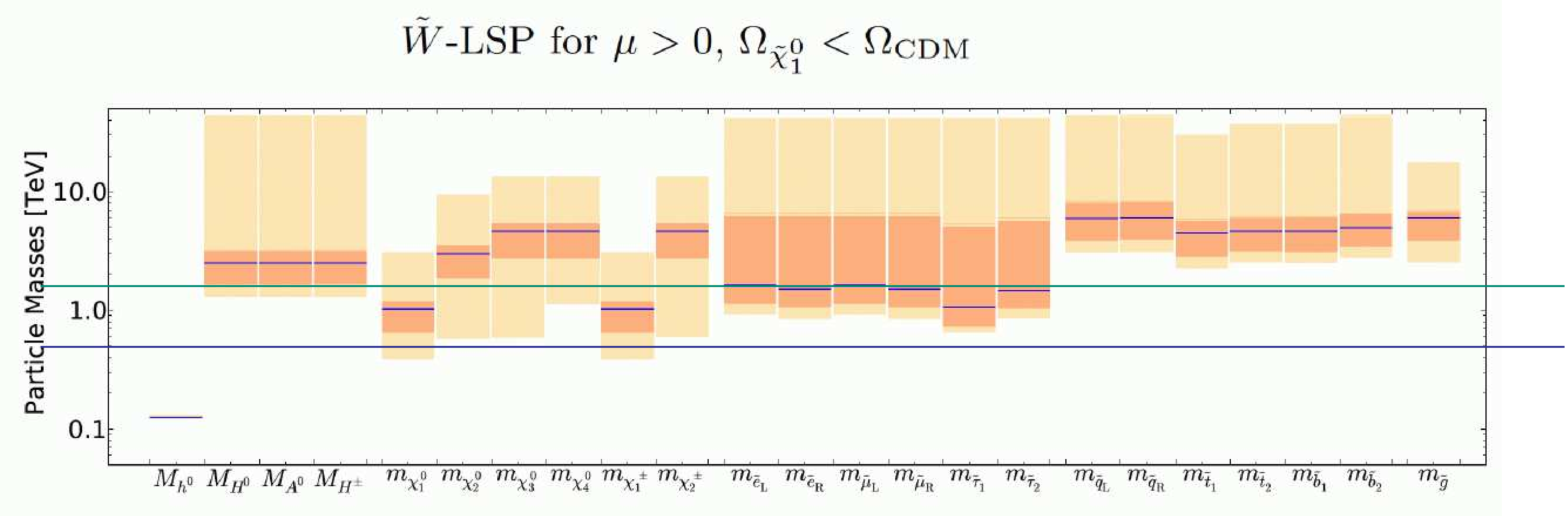
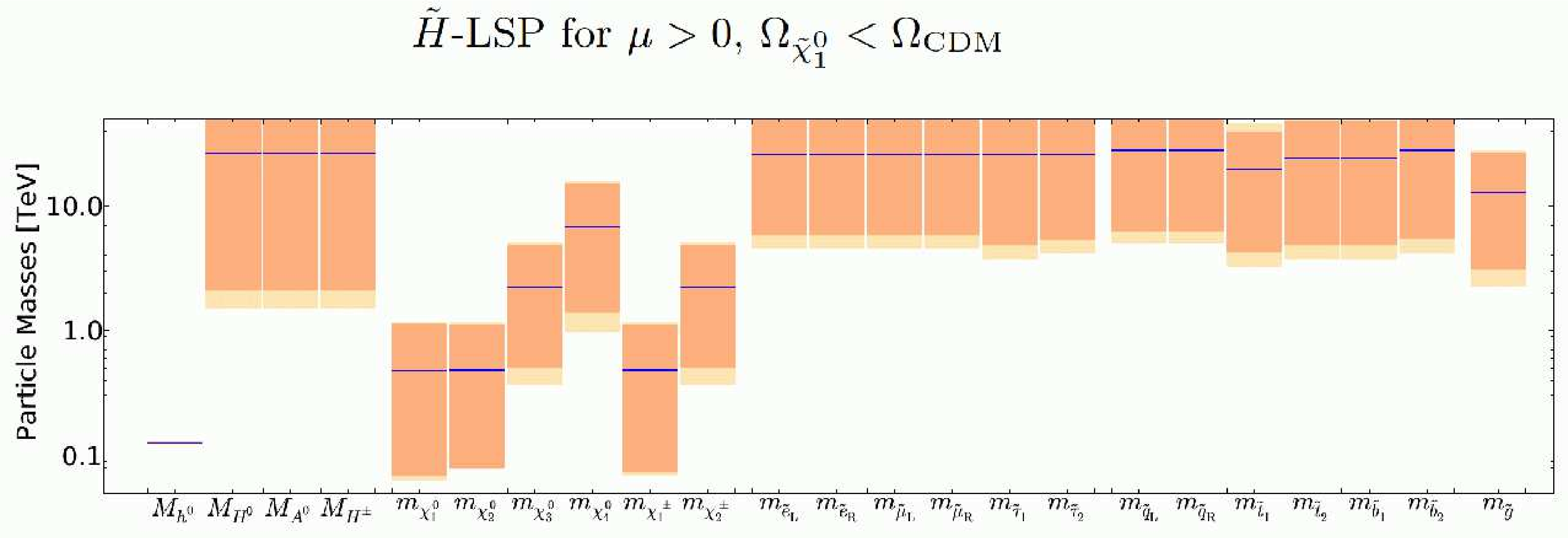


ILC: $\sqrt{s} = 1000$ GeV $\Rightarrow$ bad prospects

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)

[2016]



⇒ high colored masses

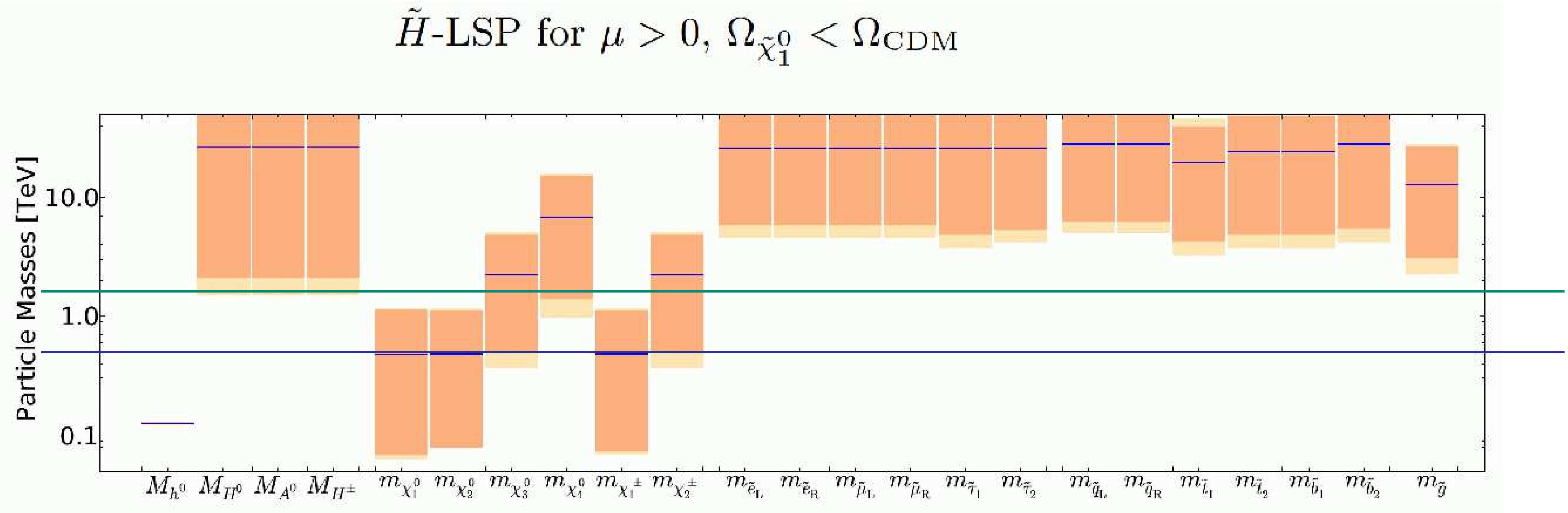
⇒ some(!) lower electroweak masses

partially with not too large 2σ ranges

⇒ clear prediction for ILC and CLIC

mAMSB prediction: best-fit masses (higgsino)

[2016]

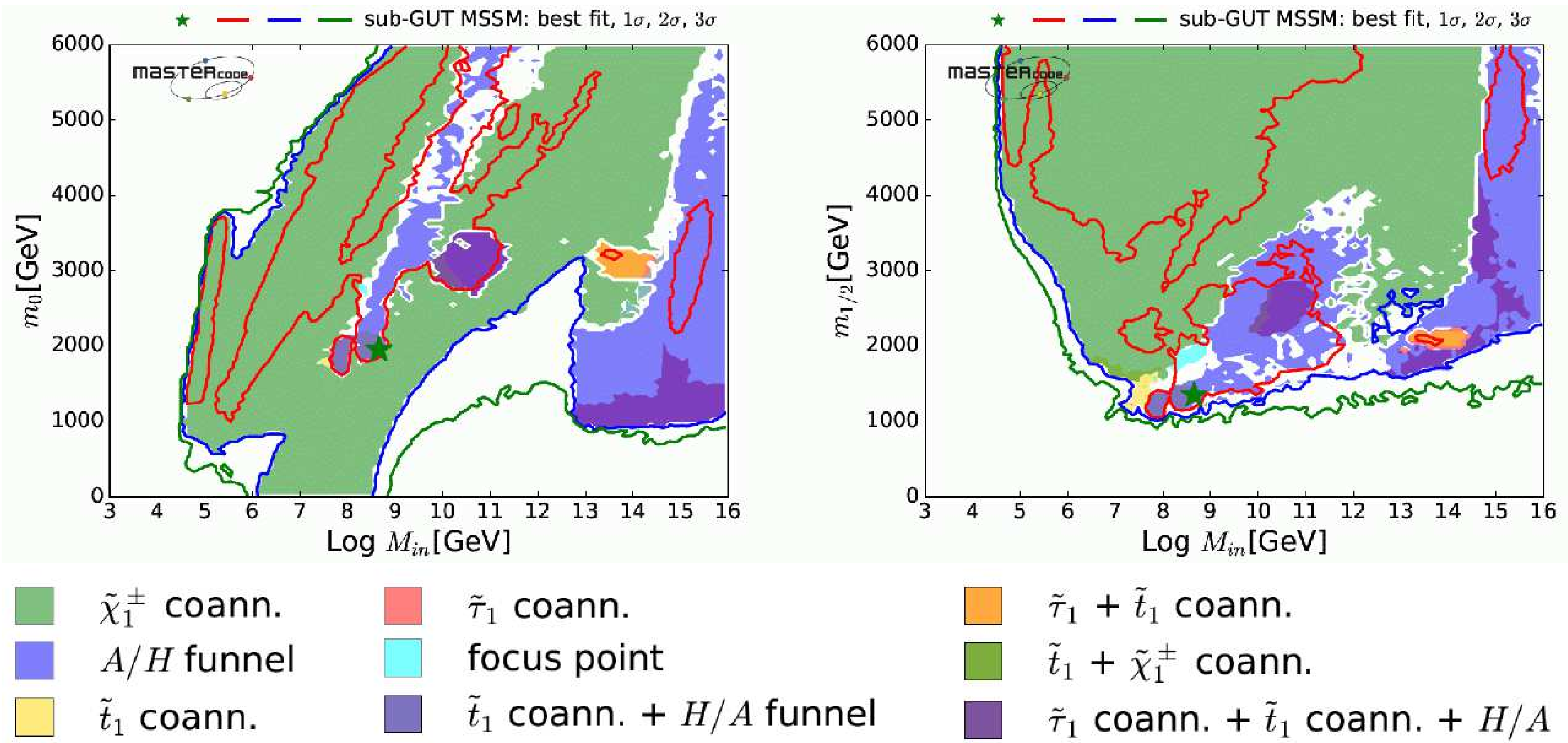


ILC: $\sqrt{s} = 1000$ GeV $\Rightarrow$ few EW particles possibly accessible

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

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]

$\Rightarrow$ high colored masses

$\Rightarrow$ high electroweak masses

ILC: $\sqrt{s} = 1000$ GeV $\Rightarrow$ nothing

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

$\Rightarrow$ 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?

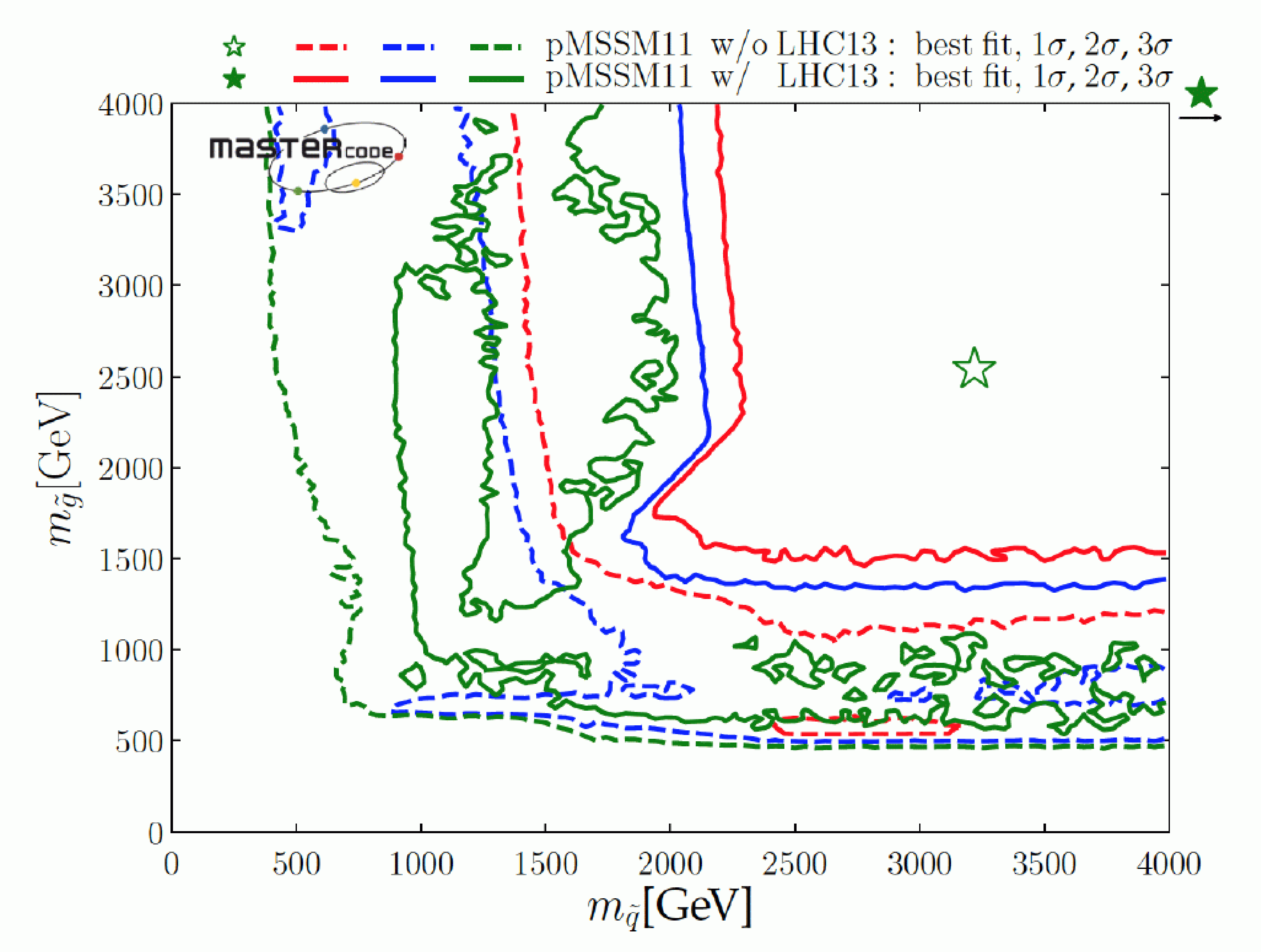
Let's look at the more general pMSSM11!

4. SUSY fit results for ILC and CLIC in the pMSSM11

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]

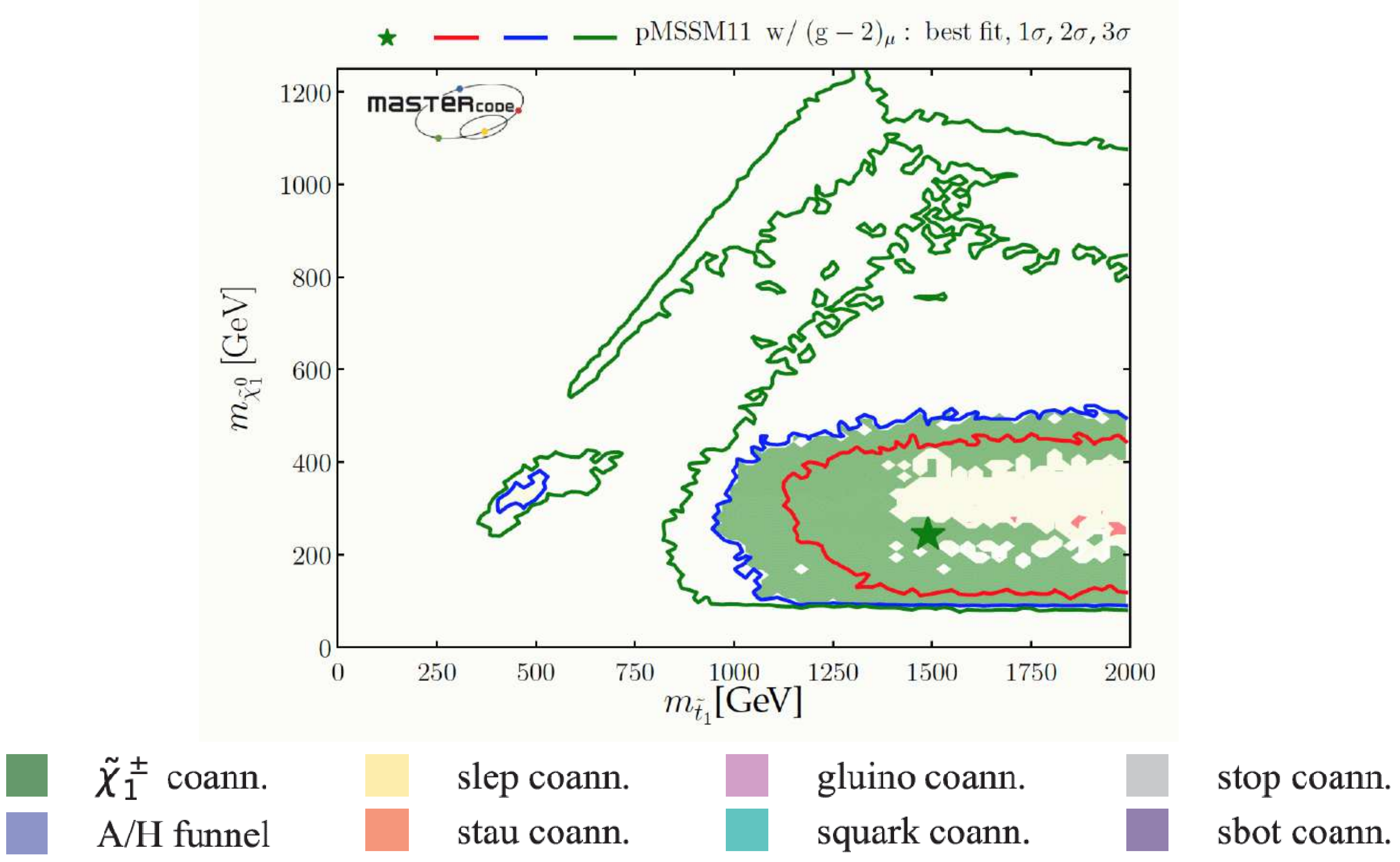


⇒ substantial move to higher masses!

⇒ notice the "nose"!

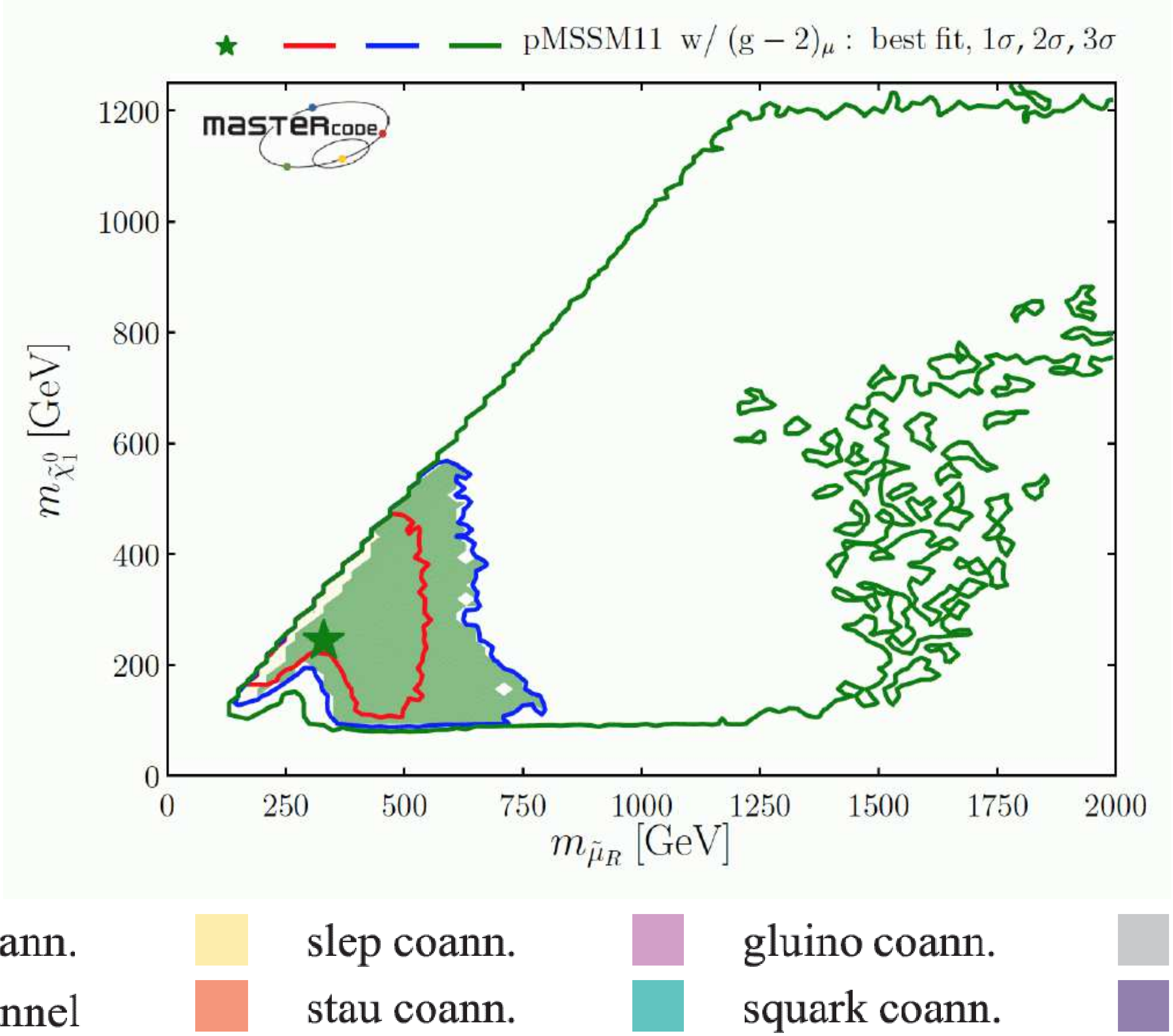
pMSSM11: $m_{\tilde{t}_1}$–$m_{\tilde{\chi}_1^0}$ plane

[2017]



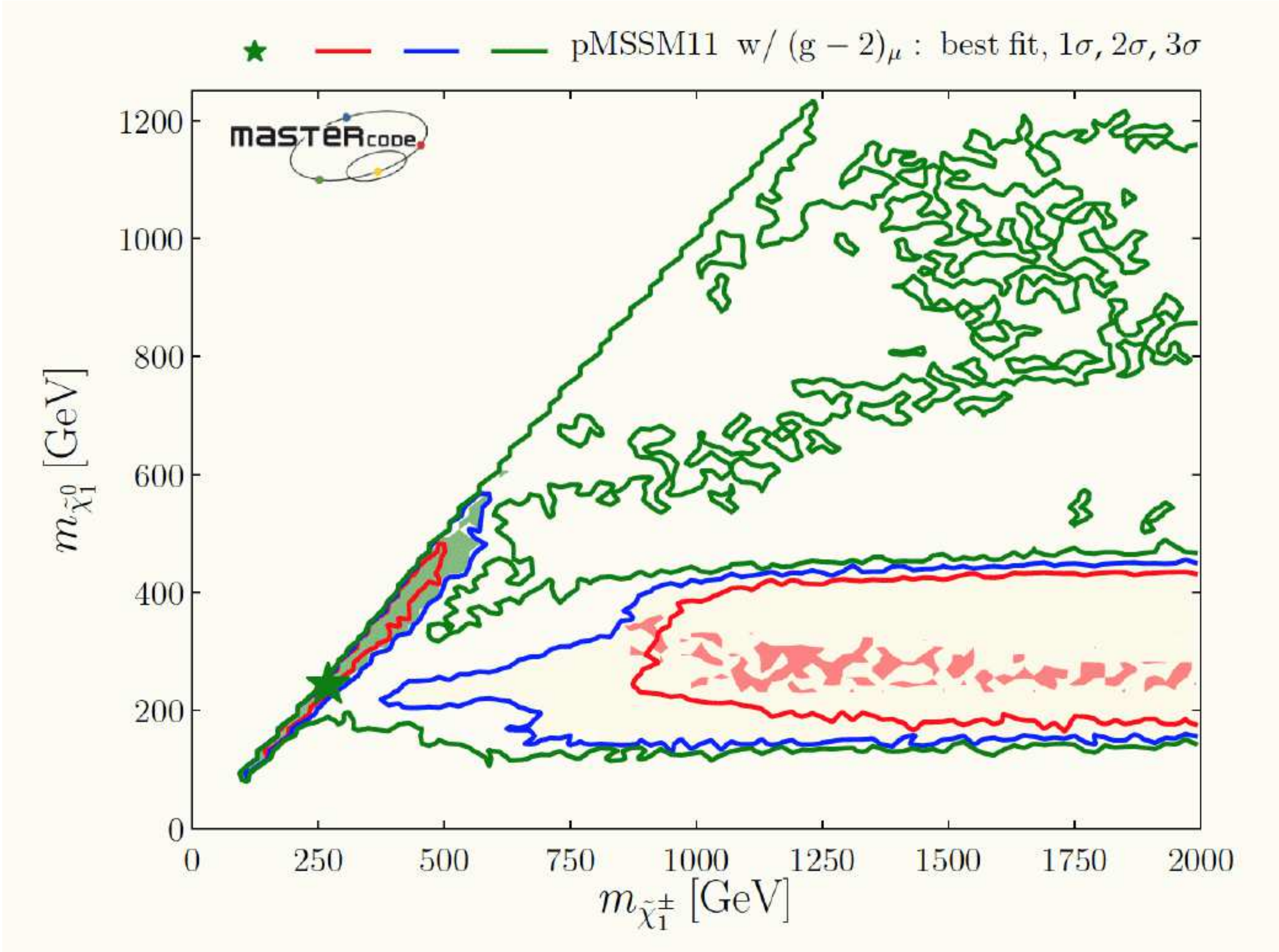
⇒ high (low) stop (neutralino) masses ⇒ notice the compressed region!

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



⇒ all masses low!!

pMSSM11: $m_{\tilde{\chi}_1^\pm}$–$m_{\tilde{\chi}_1^0}$ planbe [2017]



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

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

pMSSM11: best-fit point parameters

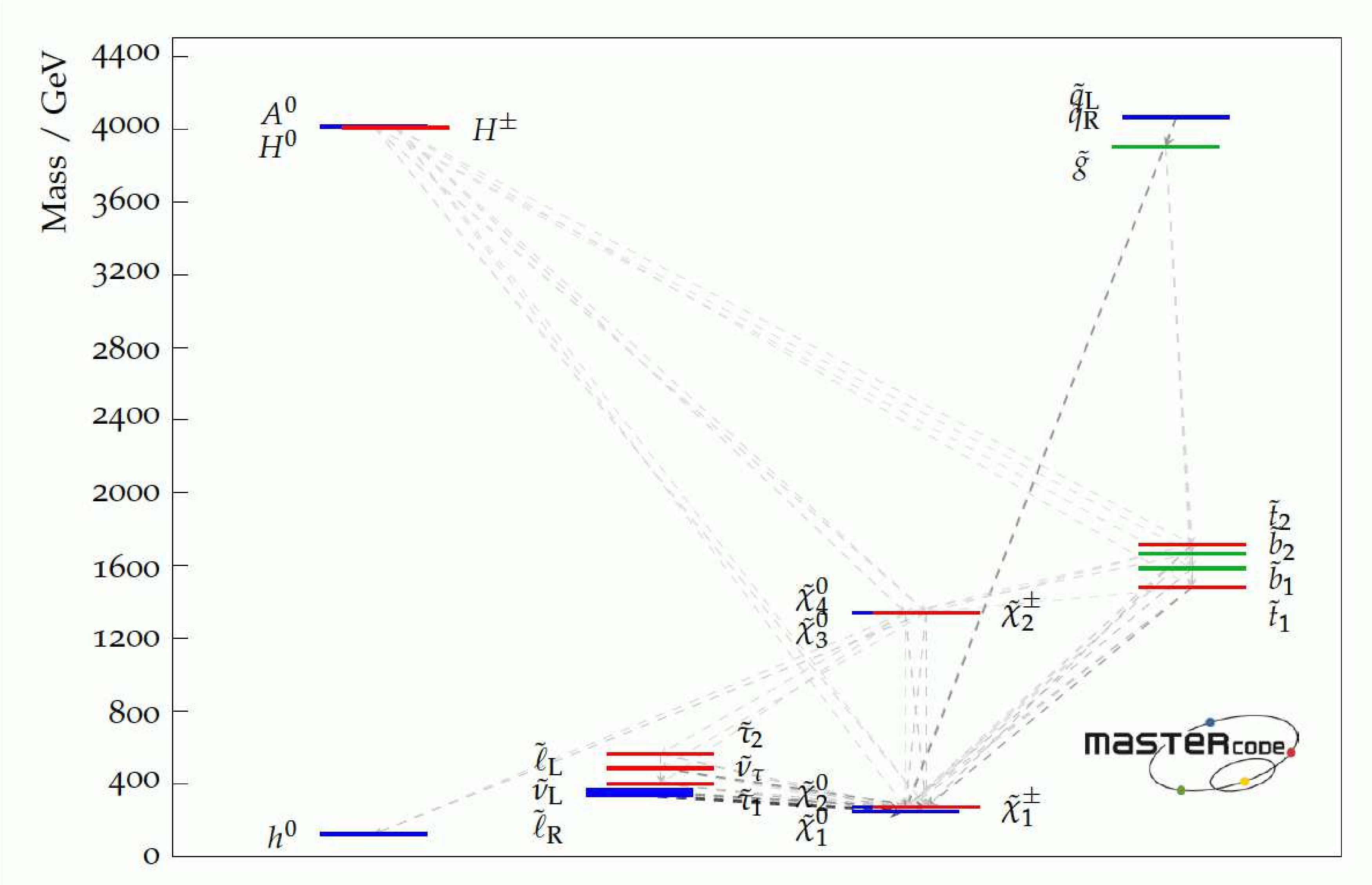
[2017]

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!

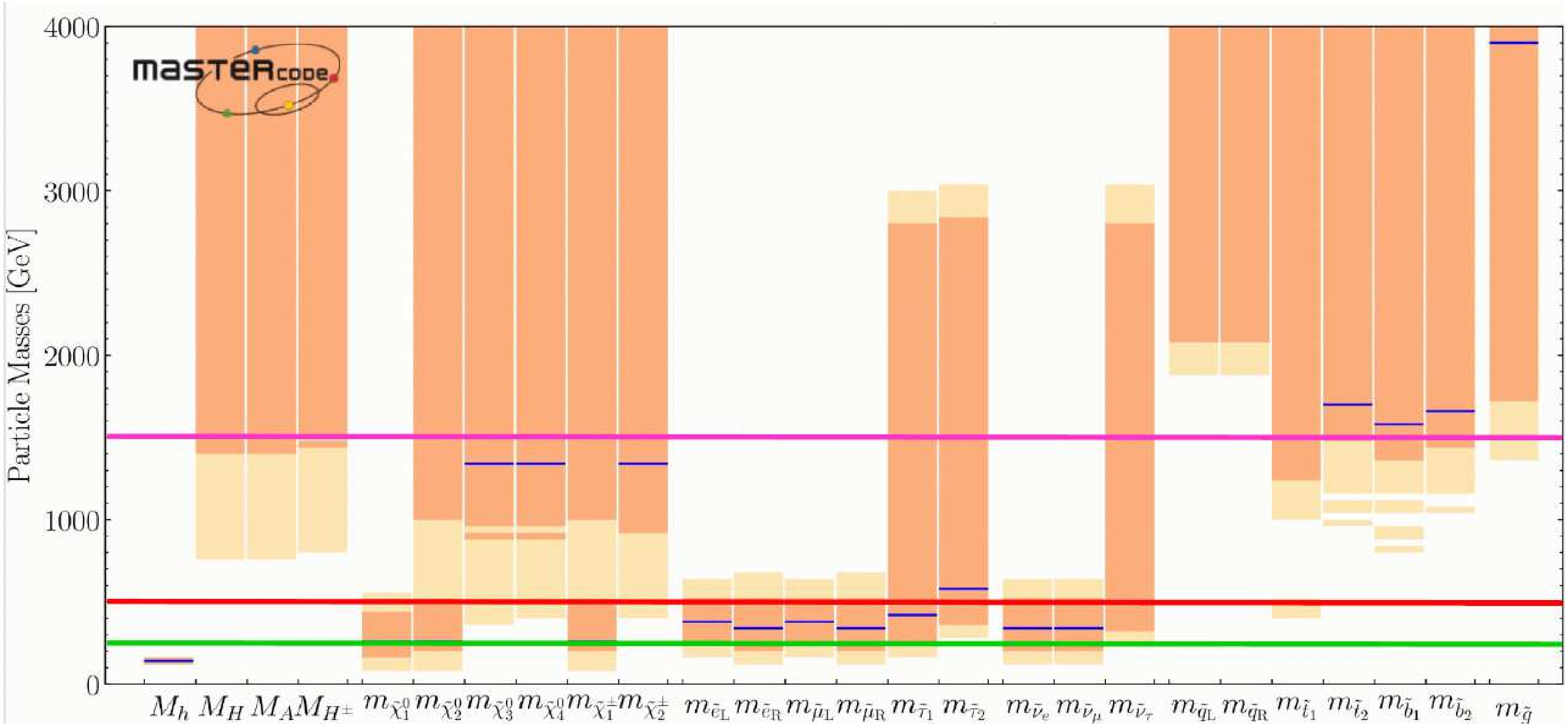
pMSSM11: best-fit point phenomenology

[2017]



⇒ heavy colored, light uncolored spectrum

pMSSM11: prospects for ILC and CLIC



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!

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??

What to conclude?

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Which model is more likely??

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

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detailed LHC analysis tbd!

⇒ Is TH ready for EW particle production? ⇒ talk by S.H. tomorrow

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	$(30\ldots33)/(18\ldots23)$	$\sim$ 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: 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

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

GUT based models: 4.) 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:

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

$\Rightarrow$ 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

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

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

⇒ Scenario characterized by

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

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

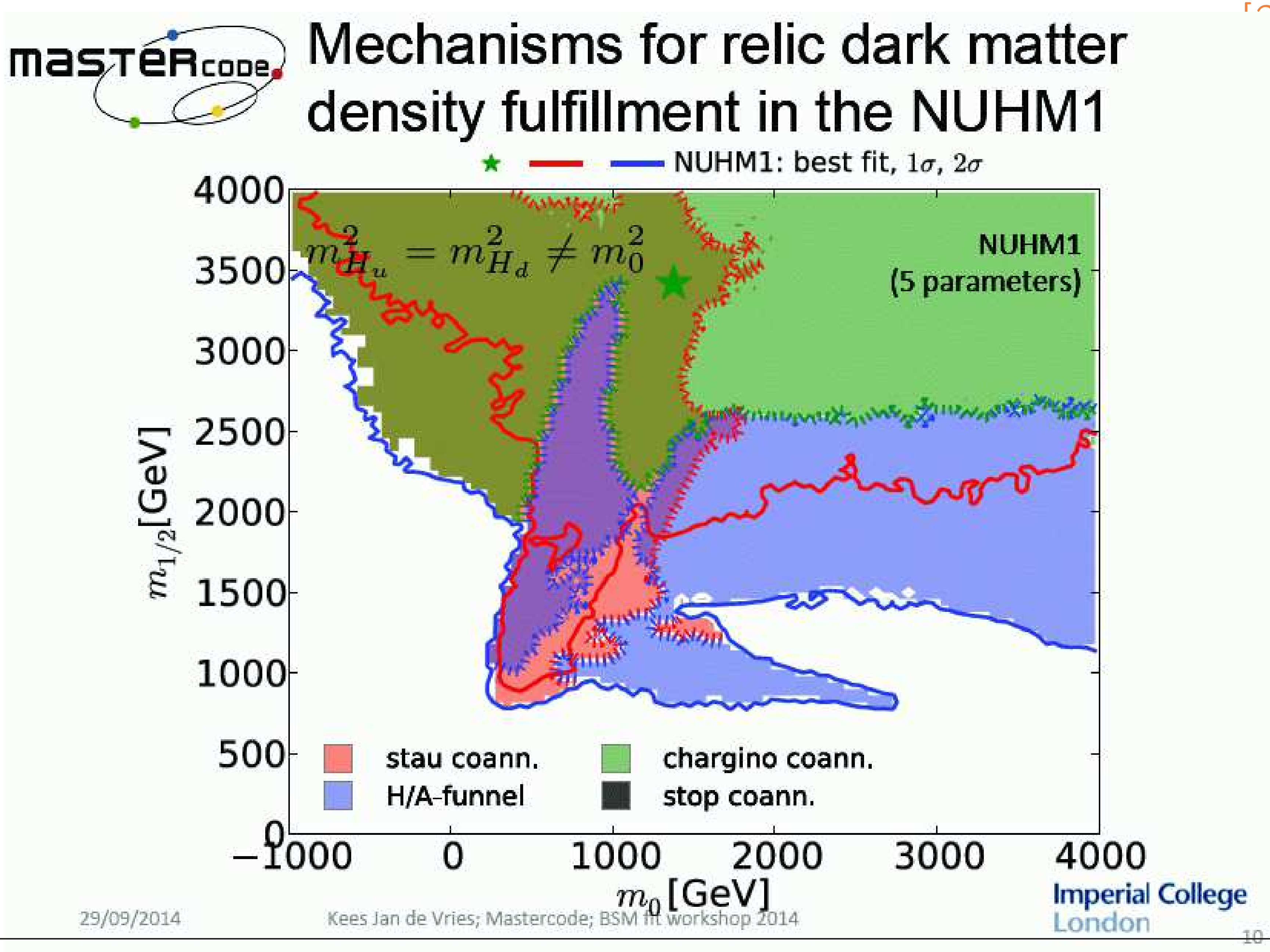
⇒ Scenario characterized by

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

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

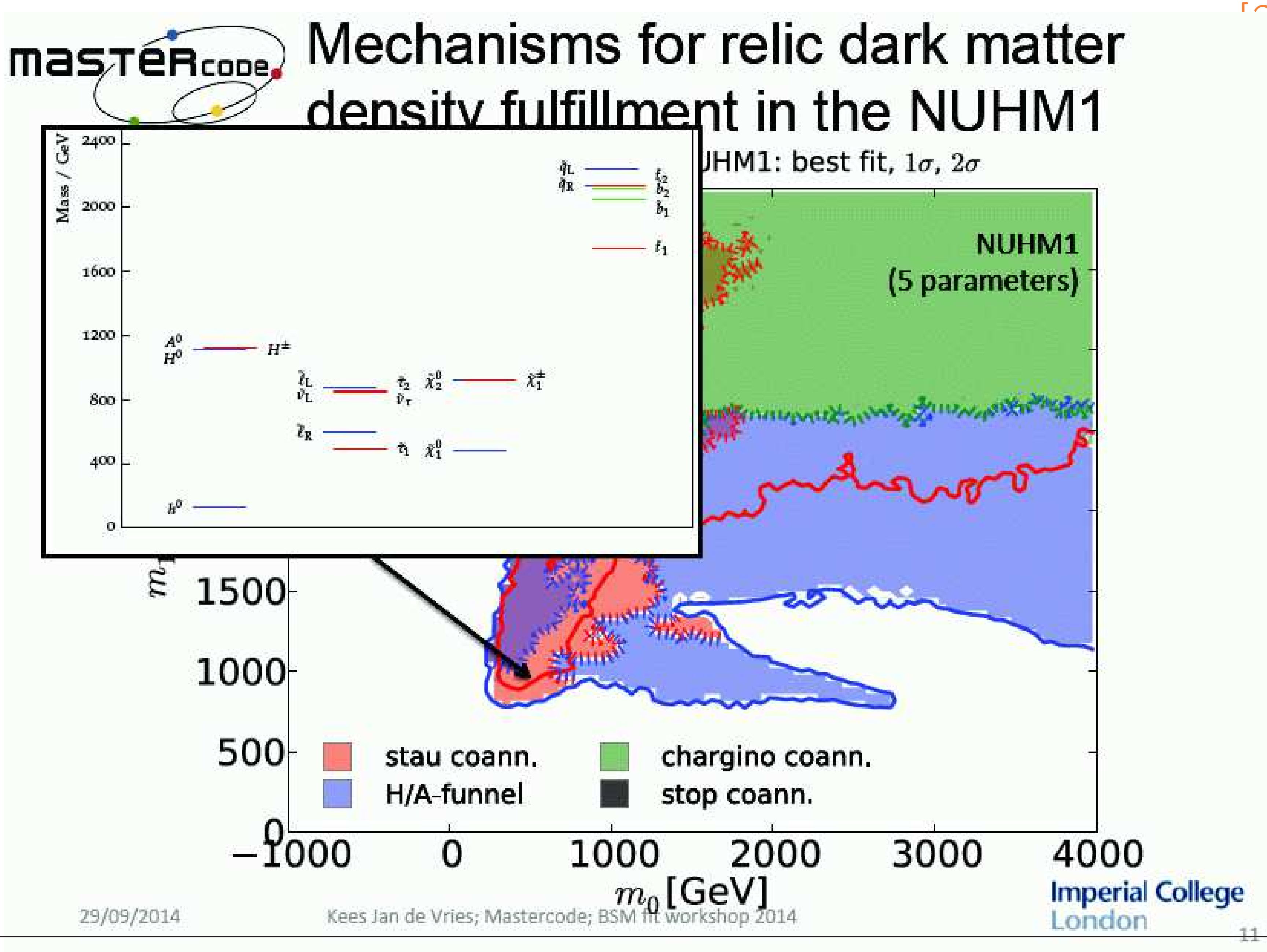
NUHM1 best-fit point prediction

[2014]



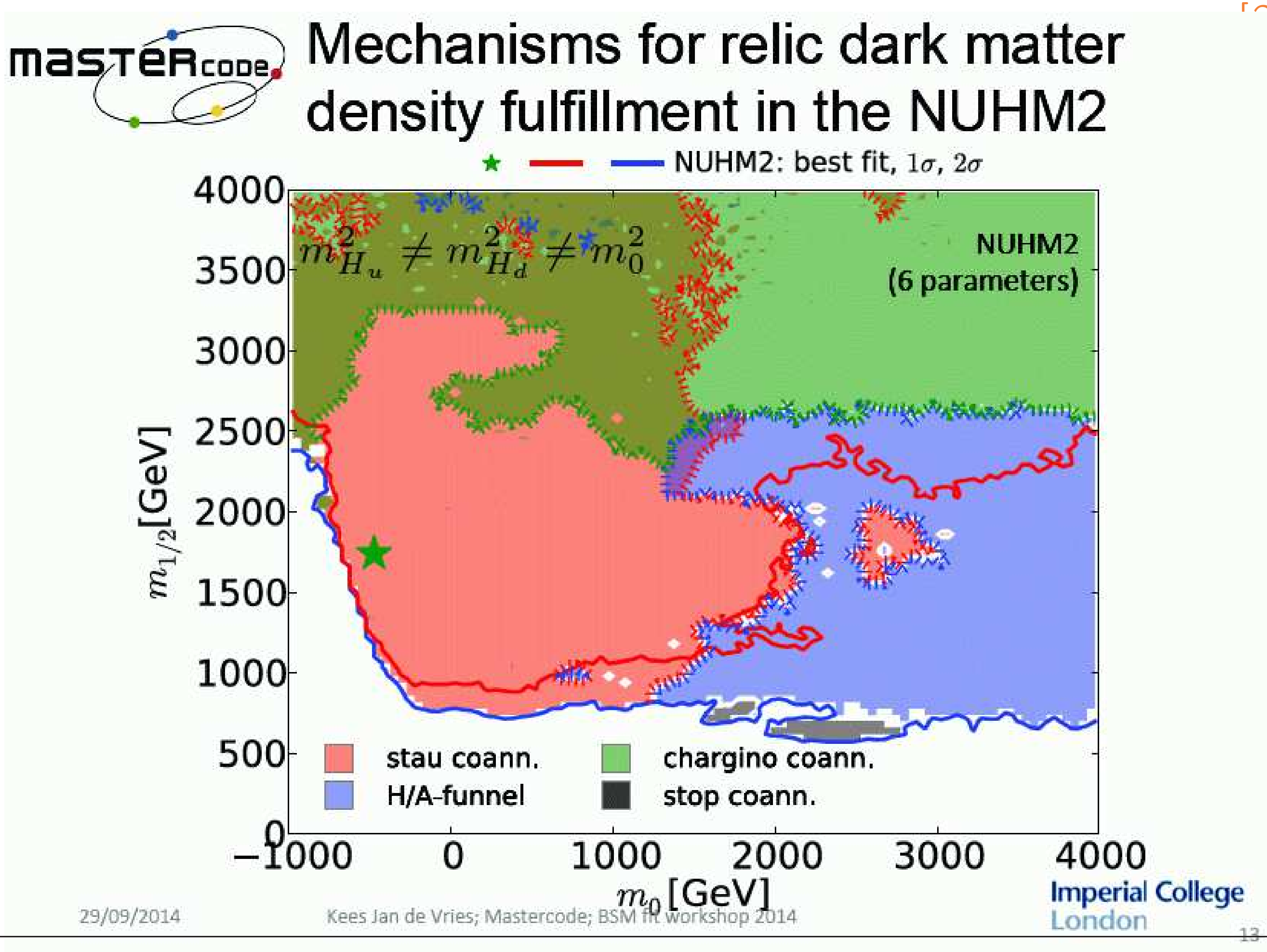
NUHM1 best-fit point prediction

[2014]

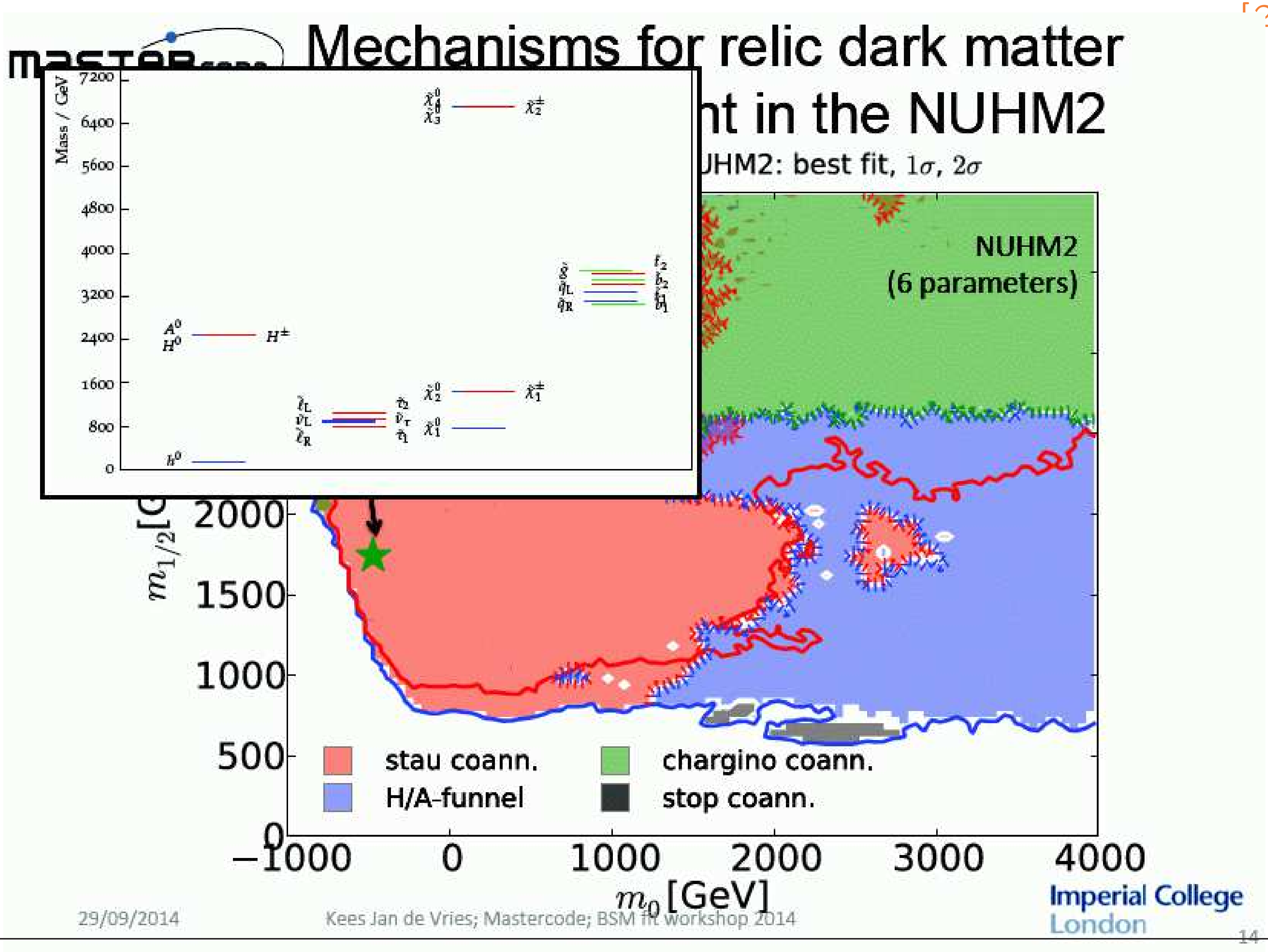


NUHM2 best-fit point prediction

[2014]



[?2014]


Mechanisms for relic dark matter
...nt in the NUHM2
...UHM2: best fit, 1σ, 2σ
NUHM2
(6 parameters)
stau coann.
chargino coann.
H/A-funnel
stop coann.
m_0 [GeV]
$m_{1/2}$ [G...
Mass / GeV
29/09/2014
Kees Jan de Vries; Mastercode; BSM fit workshop 2014
Imperial College London
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