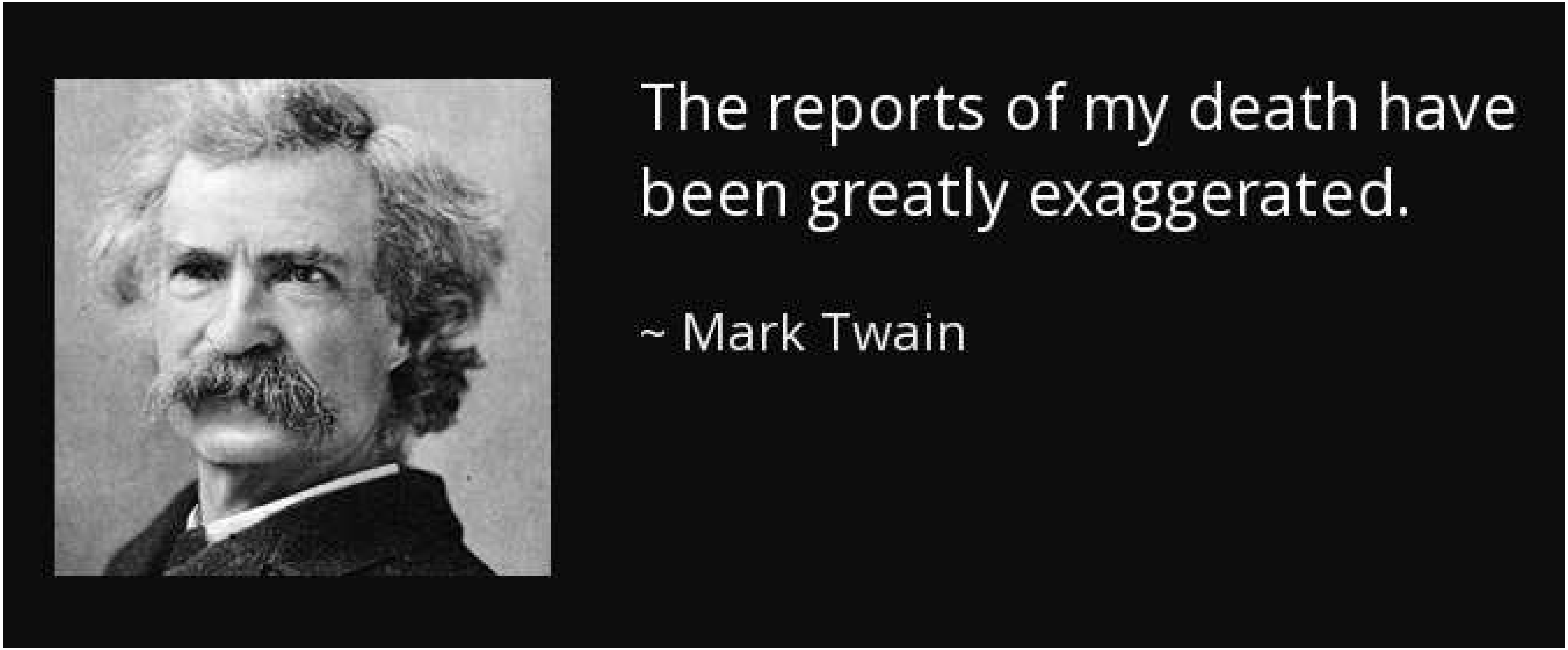
Some original SUSY literature:



Higgs and BSM Phenomenology

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

Cosener's house, 07/2019

1. Basics of the Higgs

2. BSM Higgs physics (theory)

3. Higgs boson(s) at the LHC

4. Further BSM phenomenology

Higgs and BSM Phenomenology

Further BSM phenomenology

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

Cosener's house, 07/2019

1. Some models

2. SUSY at the LHC

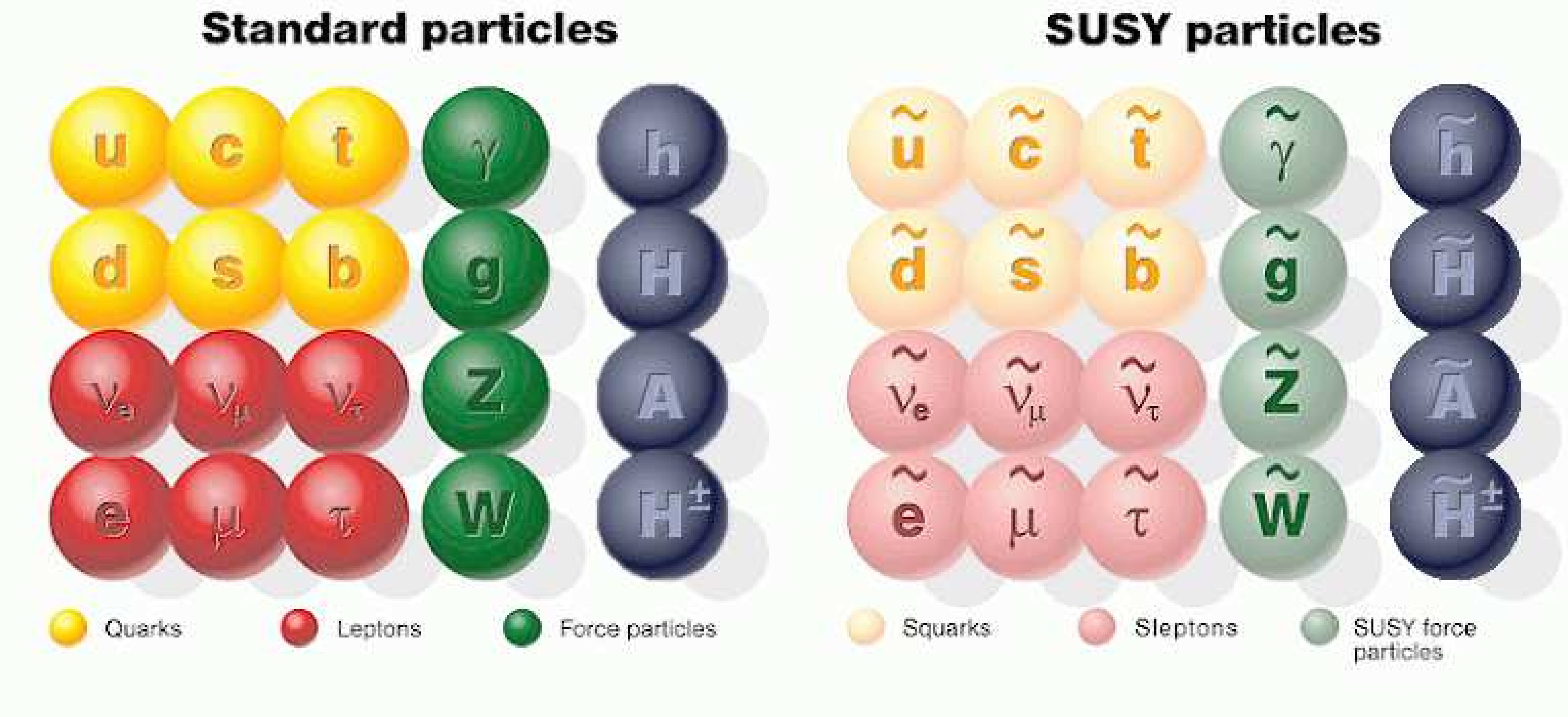
3. Where are the SUSY particles?

4. Where is the Dark Matter?

1. Some Models

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

($\Rightarrow$ many (close to) zero according to experimental data)

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

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

B. Constrained models: ($\rightarrow$ details in a moment)

CMSSM, NUHM1, NUHM2, SU(5), mAMSB, sub-GUT, . . . :

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

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

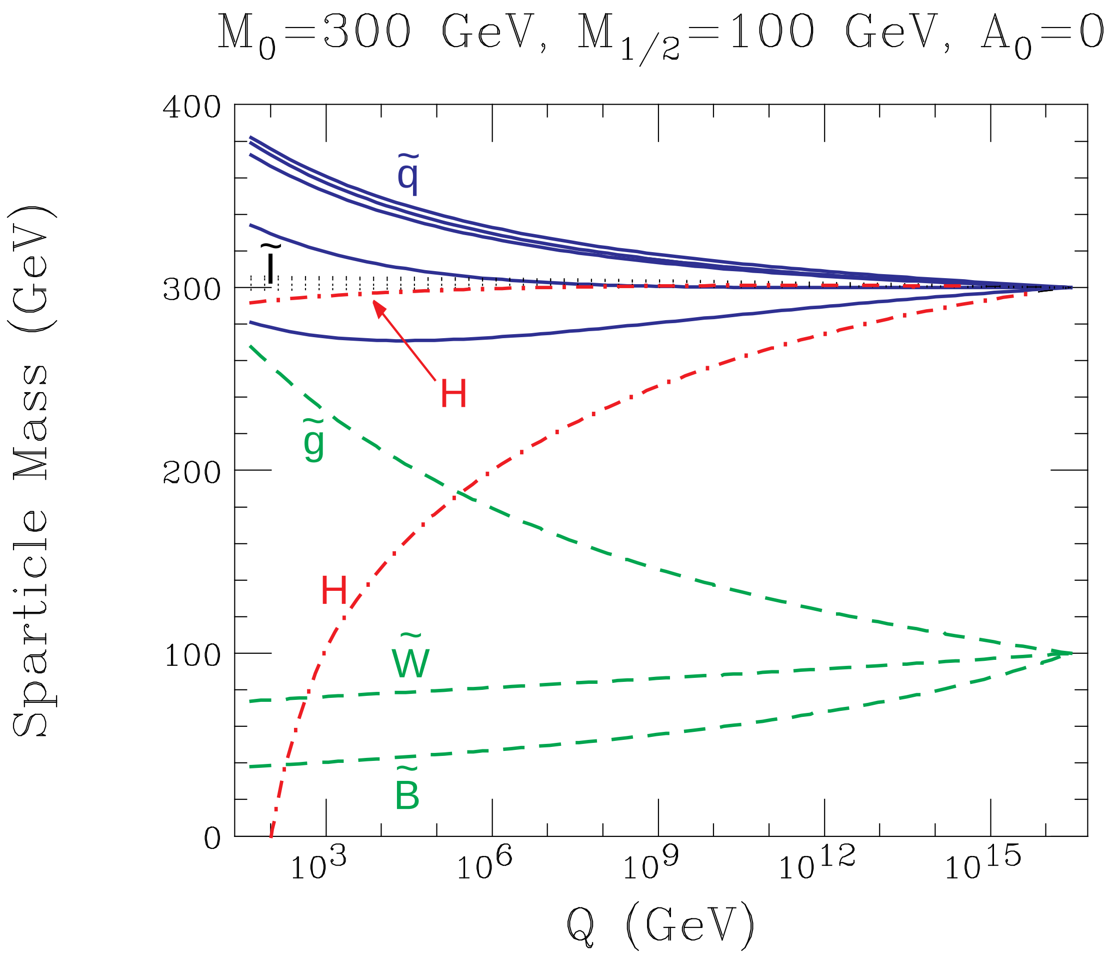
sign(μ) : sign of supersymmetric Higgs parameter

⇒ 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



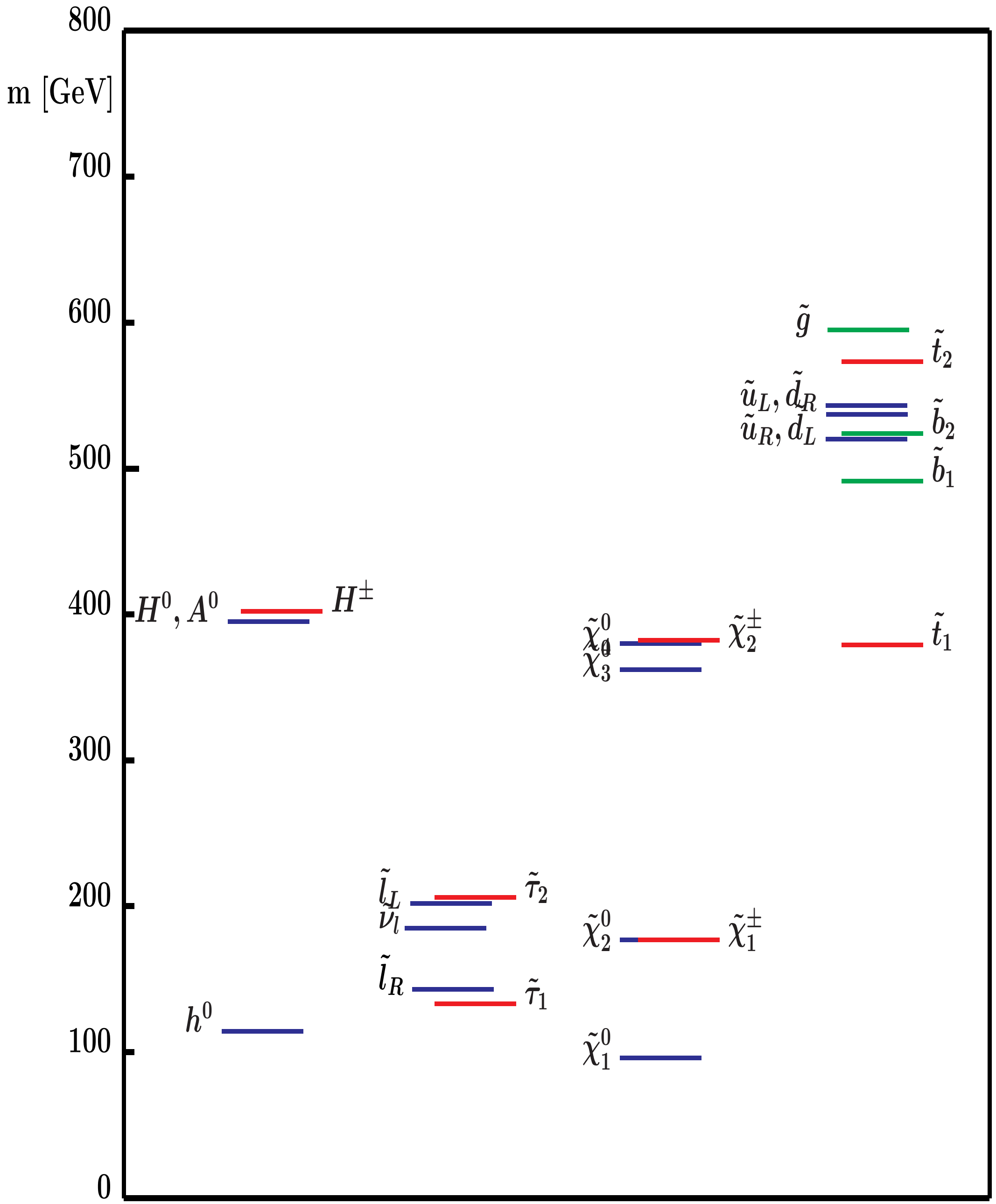
⇒ one parameter turns negative ⇒ Higgs mechanism for free

“Typical” CMSSM scenario

(SPS 1a benchmark scenario):

Close 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

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

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

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

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

GUt based models: 6.) sub-GUT:

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

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

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

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

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

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

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

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

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

Current at future collider experiments:

LHC (Large Hadron Collider): running

pp collisions at 13 TeV

HL-LHC final high-luminosity phase: approved

HE-LHC new magnets $\Rightarrow$ 27 TeV possible?

ILC (International Linear Collider) decision 2018 in Japan

e^+e^- collisions at 250 GeV (final stage 1000 GeV)

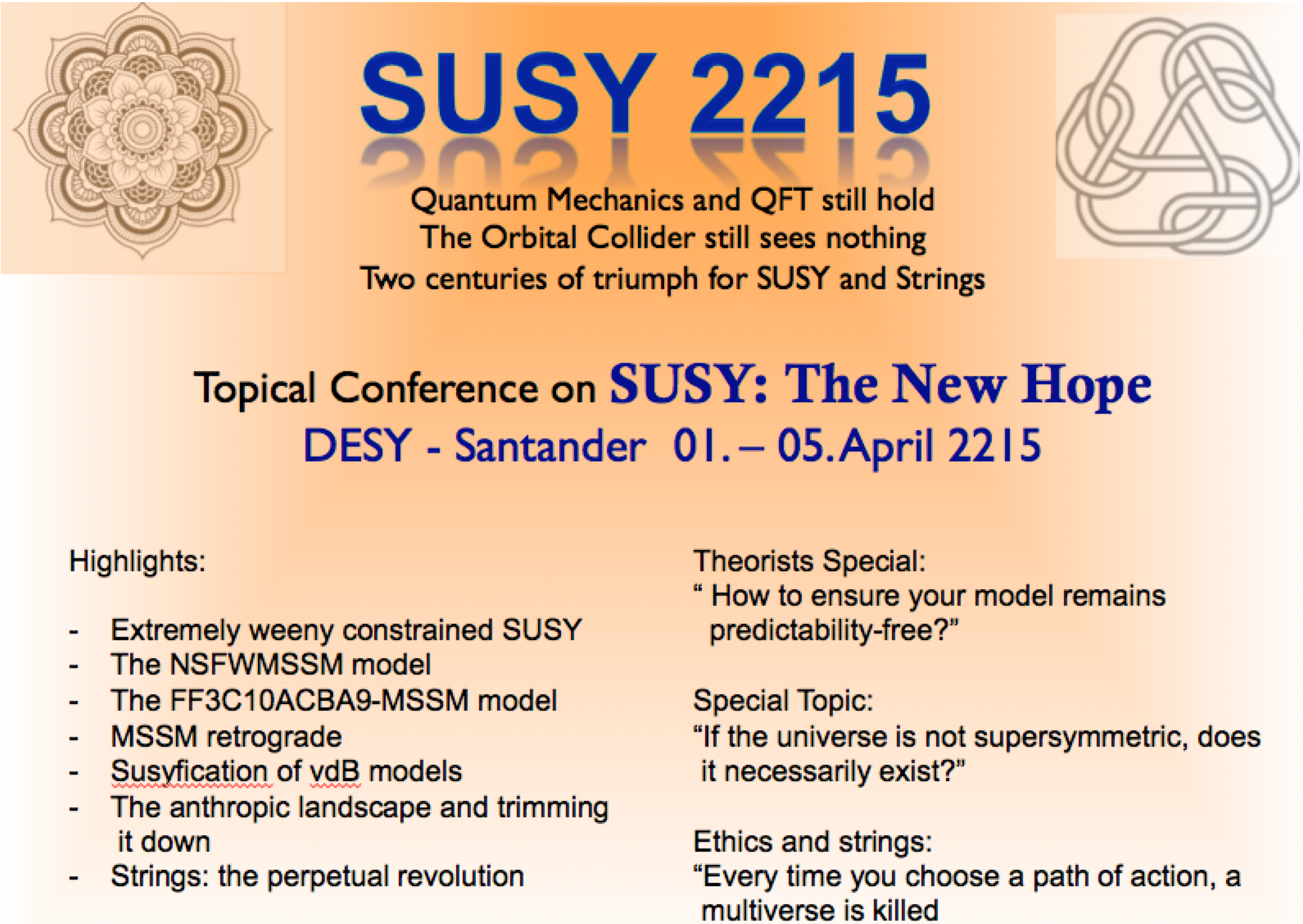
CLIC (Compact LInear Collider)

e^+e^- collisions at 380 GeV (final stage 3000 GeV)

FCC-hh (Future Circular Collider)

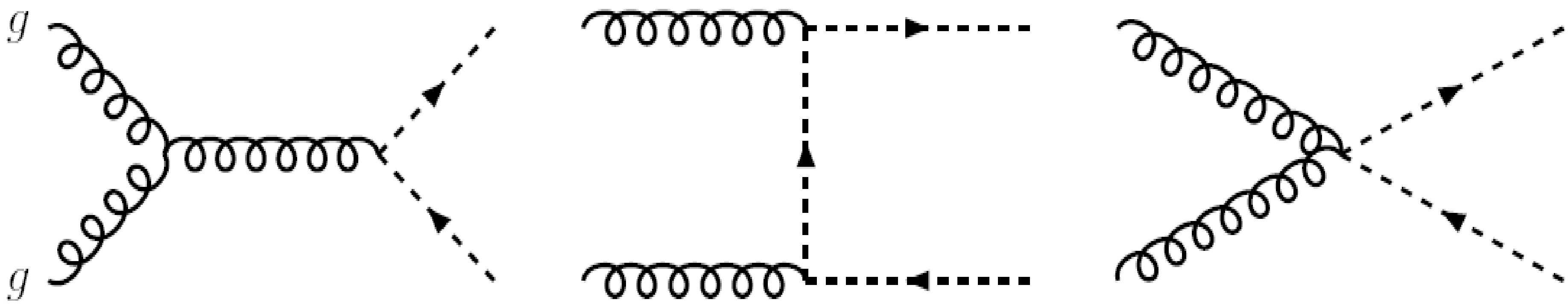
pp collisions at 100 TeV

2. SUSY at the LHC



SUSY particle production at the LHC:

⇒ colored (s)particles are copiously produced

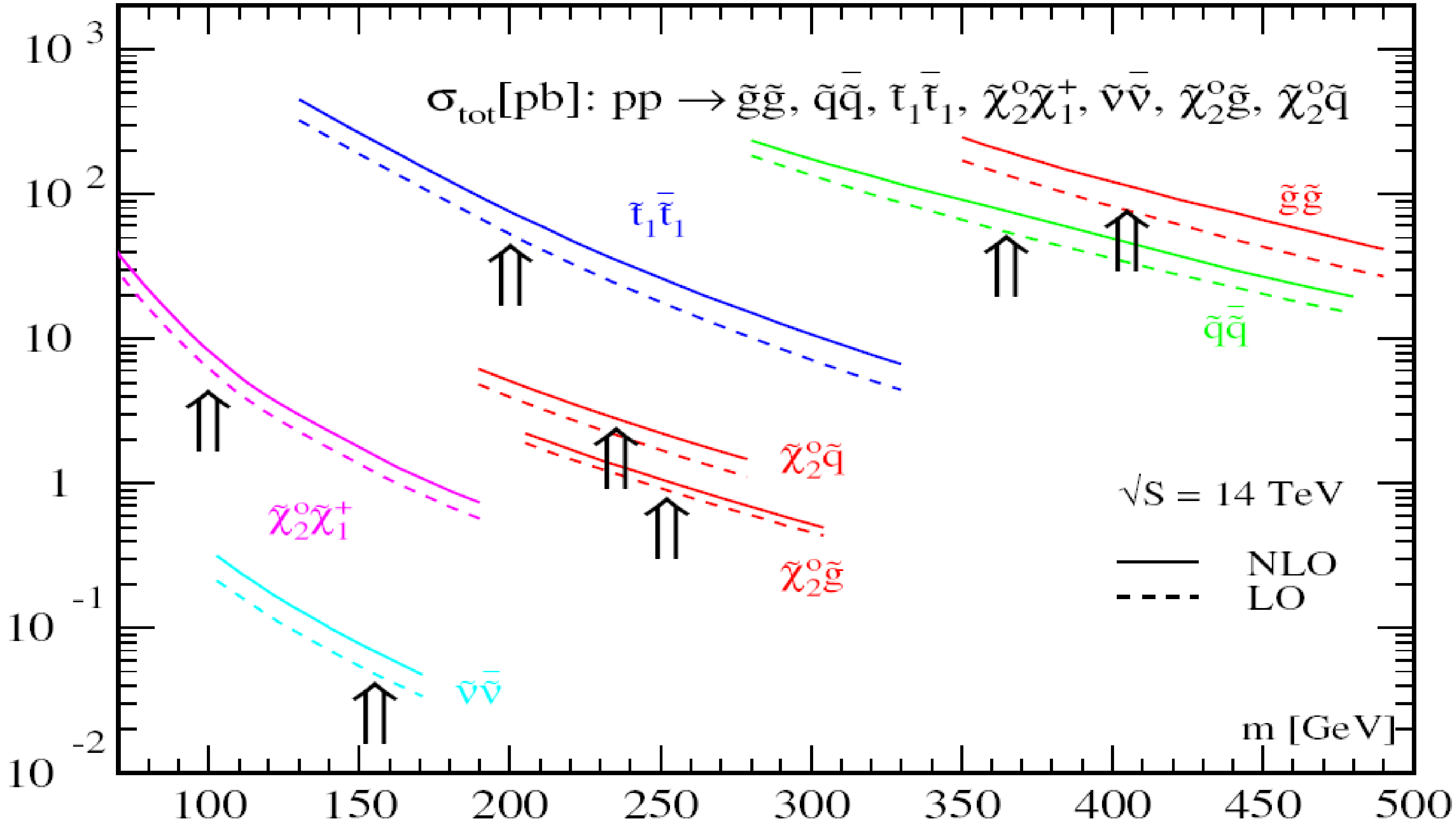


⇒ production of gluinos, squarks, . . .

As in QCD: NLO corrections are crucial!

Example for SUSY production:

[*Prospino collaboration*]



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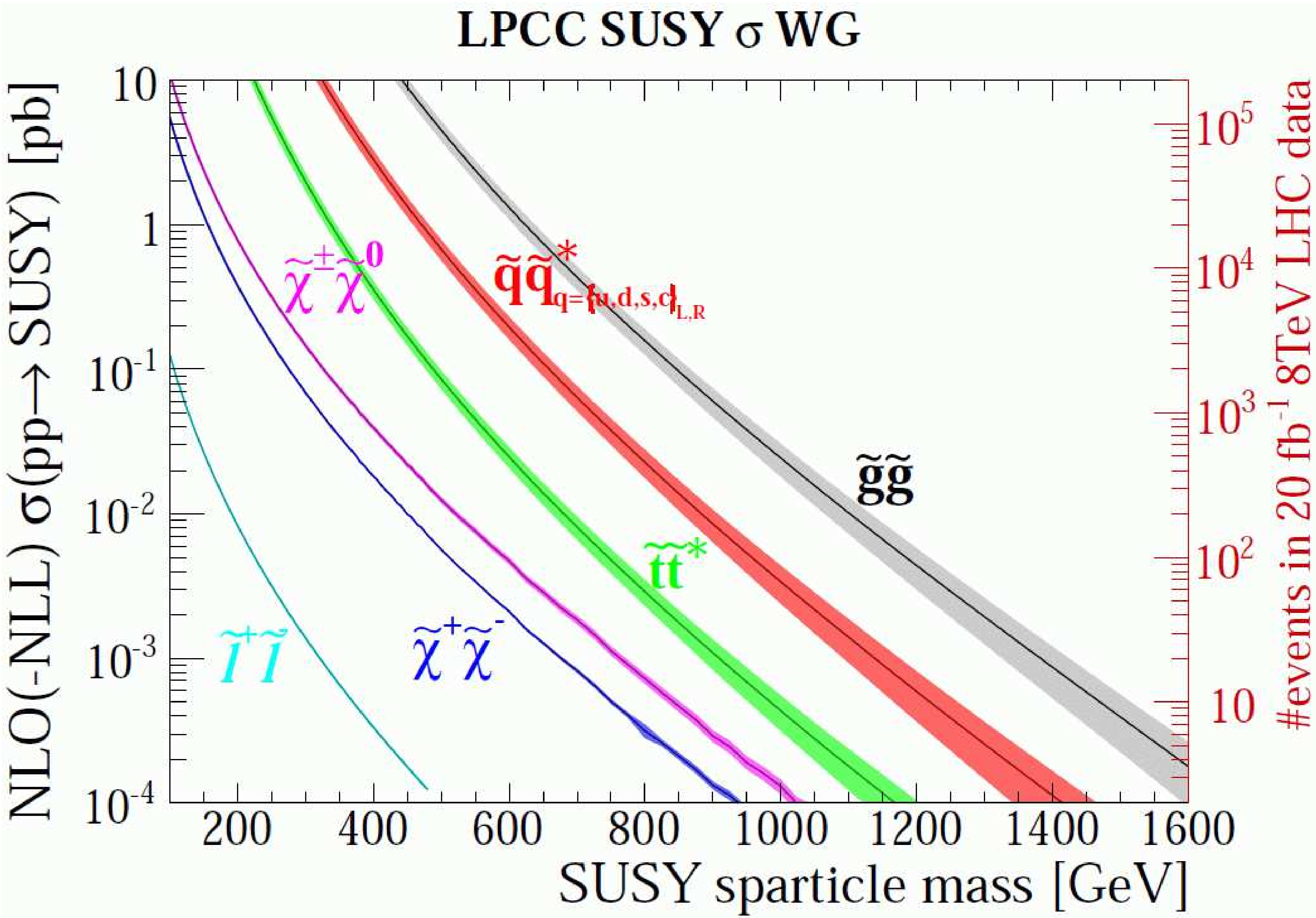


⇒ uncertainties crucial!

Production of SUSY particles at the LHC

will in general result in complicated final states

⇒ cascade decays

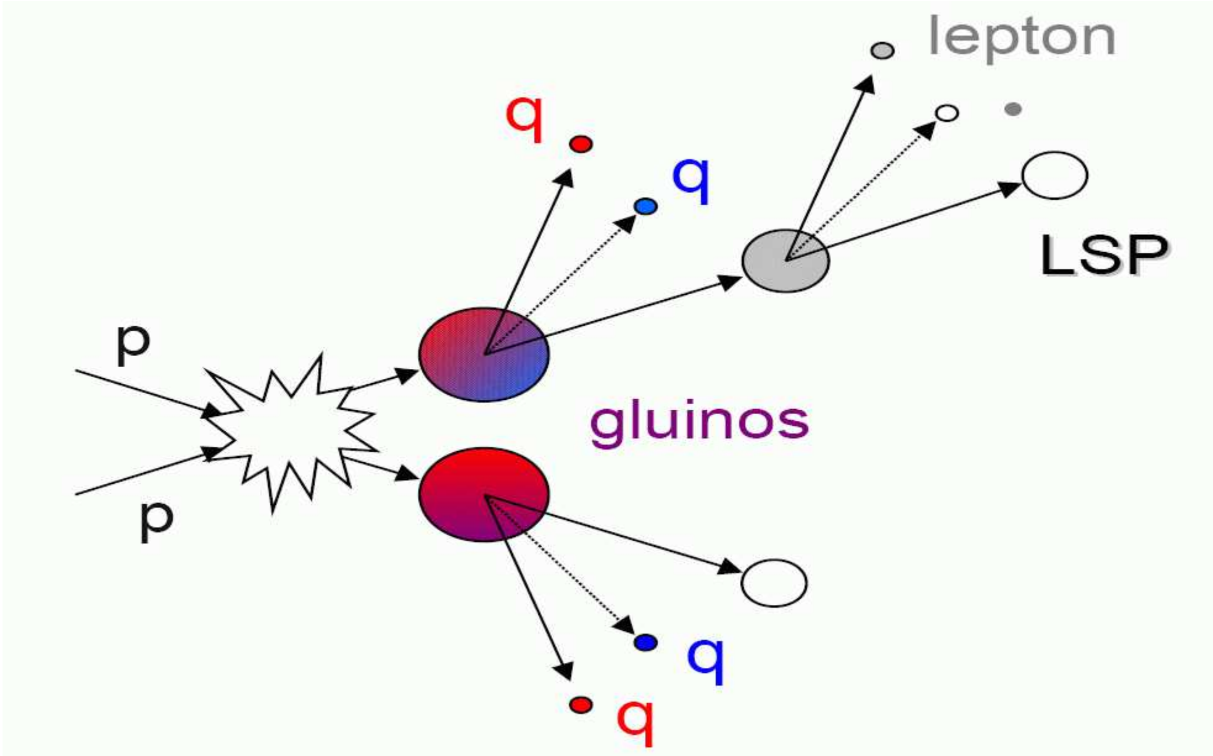
$$\tilde{g} \to \bar{q}\tilde{q} \to \bar{q}q\tilde{\chi}_2^0 \to \bar{q}q\tilde{\tau}\tau \to \bar{q}q\tau\tau\tilde{\chi}_1^0$$

Production of SUSY particles at the LHC

will in general result in complicated final states

⇒ cascade decays

$$\tilde{g} \to \bar{q}\tilde{q} \to \bar{q}q\tilde{\chi}^0_2 \to \bar{q}q\tilde{\tau}\tau \to \bar{q}q\tau\tau\tilde{\chi}^0_1$$



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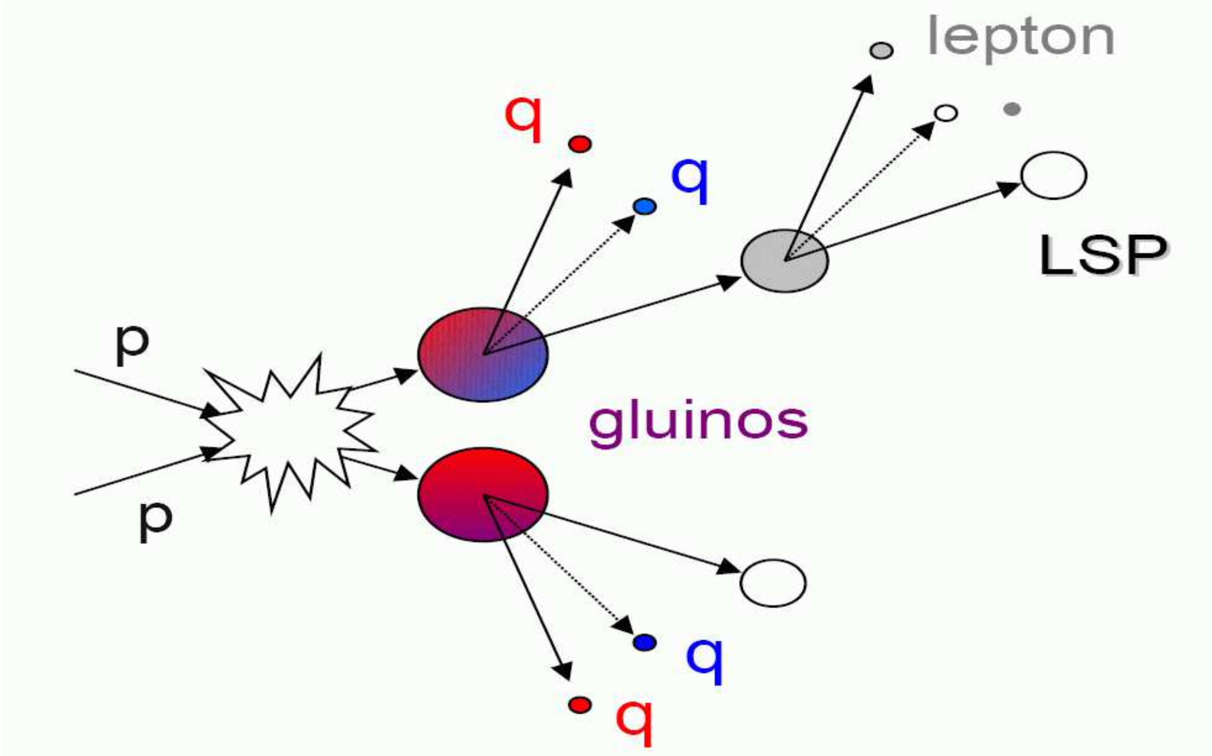


Production of uncolored particles via cascade decays often dominates over direct production – Many states are produced at once

⇒ **Main background for SUSY is SUSY itself!**

Cascade decays: taken from talk by [A. Farbin '11]

different patterns due to different SM particles "coming out":

Signature	Motivating Model(s)	Comments
1 Jet + 0 Lepton + MET 70/nb	• Large Extra Dim (ExoGraviton) • strong qG production, G propagate in extra Dim • Planck Scale is MD in 4+δ dim • Normal Gravity >> R • SUSY • qg→ISR + 2 Neutralino or squark + Neutralino	• Not primary discovery channel for SUGRA, GMSB, AMSB... but helps in characterization • Possible leading discovery for neutralino NLSP with nearly degenerate gluino
NEW 2,3,4 [b]-Jet + 0 Lepton + MET 310/nb for b-jets 35/pb	• squark/gluino production • squark→q+LSP, gluino→q+squark+LSP	• Possible leading squark/ gluino discovery channel • Must manage QCD bkg
NEW 2,3,4 [b]-Jet + 1 Lepton + MET 310/nb for b-jets 35/pb	• squark/gluino production with cascades which include electroweak (or partner) decays • high tan β leads to more τ's	• Lepton requirement suppresses QCD • τ's partially covered by e/μ
2 lepton + MET 70/nb	• Same sign: gluino cascade can have either sign lepton... squark/gluino prod can produce same sign. • Opposite sign: squark/gluino decay dediated by Z (or partner) • Same flavor: 2 leptons from same sparticle cascade must be same flavor	• Reduced SM backgrounds for same sign • Opposite Sign-Flavor Subtraction
3 lepton + MET	• SUSY events ending in Chargino/neutralino pair decays • Weak Chargino/Neutralino production • Exotic sources	• Low SM bkgs
2 photon + MET 3.1/pb	• GMSB models with gravitino LSP and neutralino or stau NLSP • UED- each KK partons cascade to LKP which decays to graviton + γ	• No SUSY limit (not sensitive at the time)

Example: $\tilde{t}$ sector of the MSSM

Stop mass matrices

$$\mathbf{M}_{\tilde{t}}^2 = \begin{pmatrix} M_{\tilde{t}_L}^2 + m_t^2 + DT_{t_1} & m_t X_t \\ m_t X_t & M_{\tilde{t}_R}^2 + m_t^2 + DT_{t_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{t}}} \begin{pmatrix} m_{\tilde{t}_1}^2 & 0 \\ 0 & m_{\tilde{t}_2}^2 \end{pmatrix}$$

with

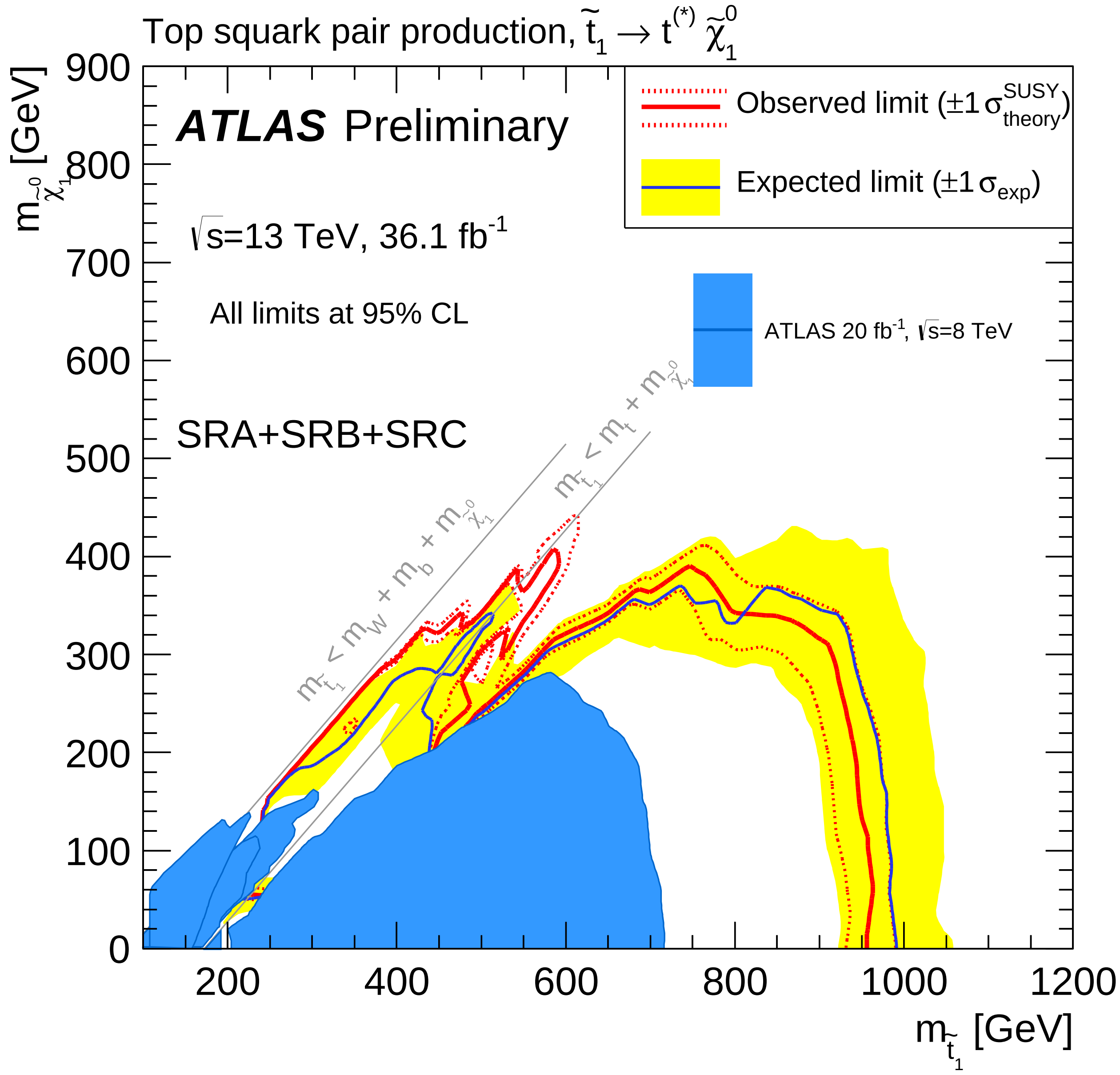
$$X_t = A_t - \mu / \tan\beta$$

$\Rightarrow$ mixing important in stop sector!

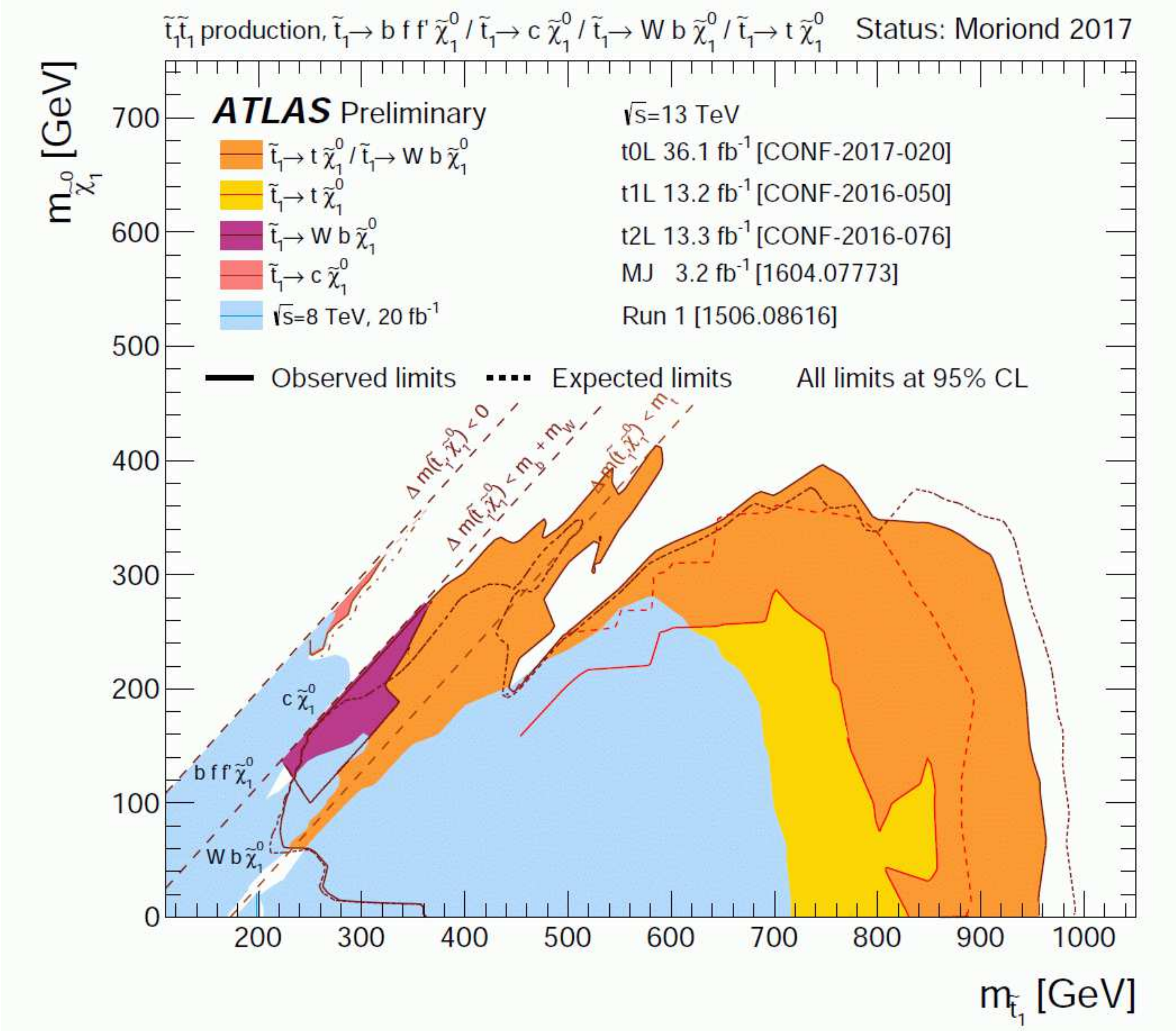
Simplifying abbreviation:

$$M_{\mathrm{SUSY}} = M_S := M_{\tilde{t}_L} = M_{\tilde{t}_R}$$

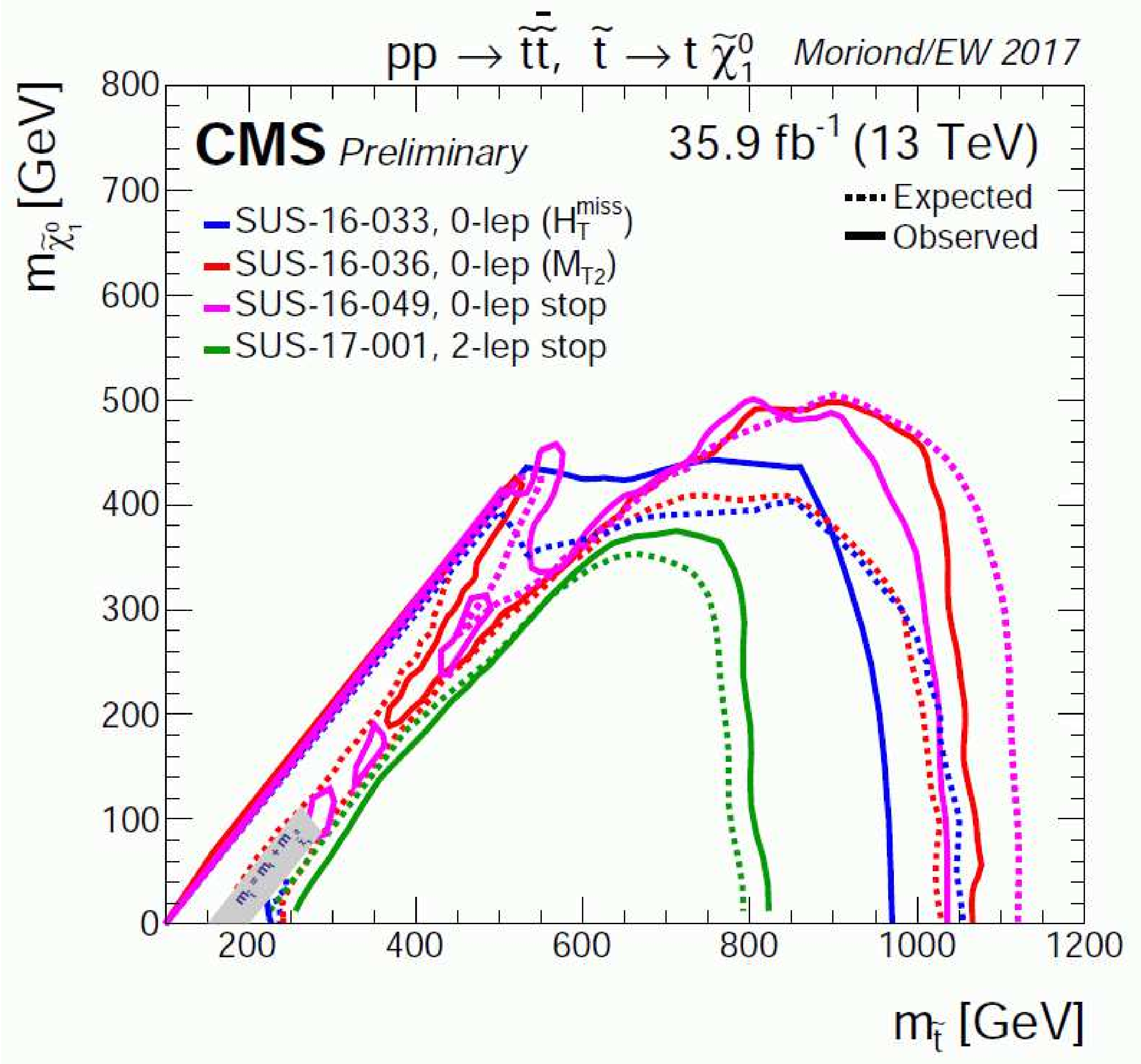
Direct stop production:



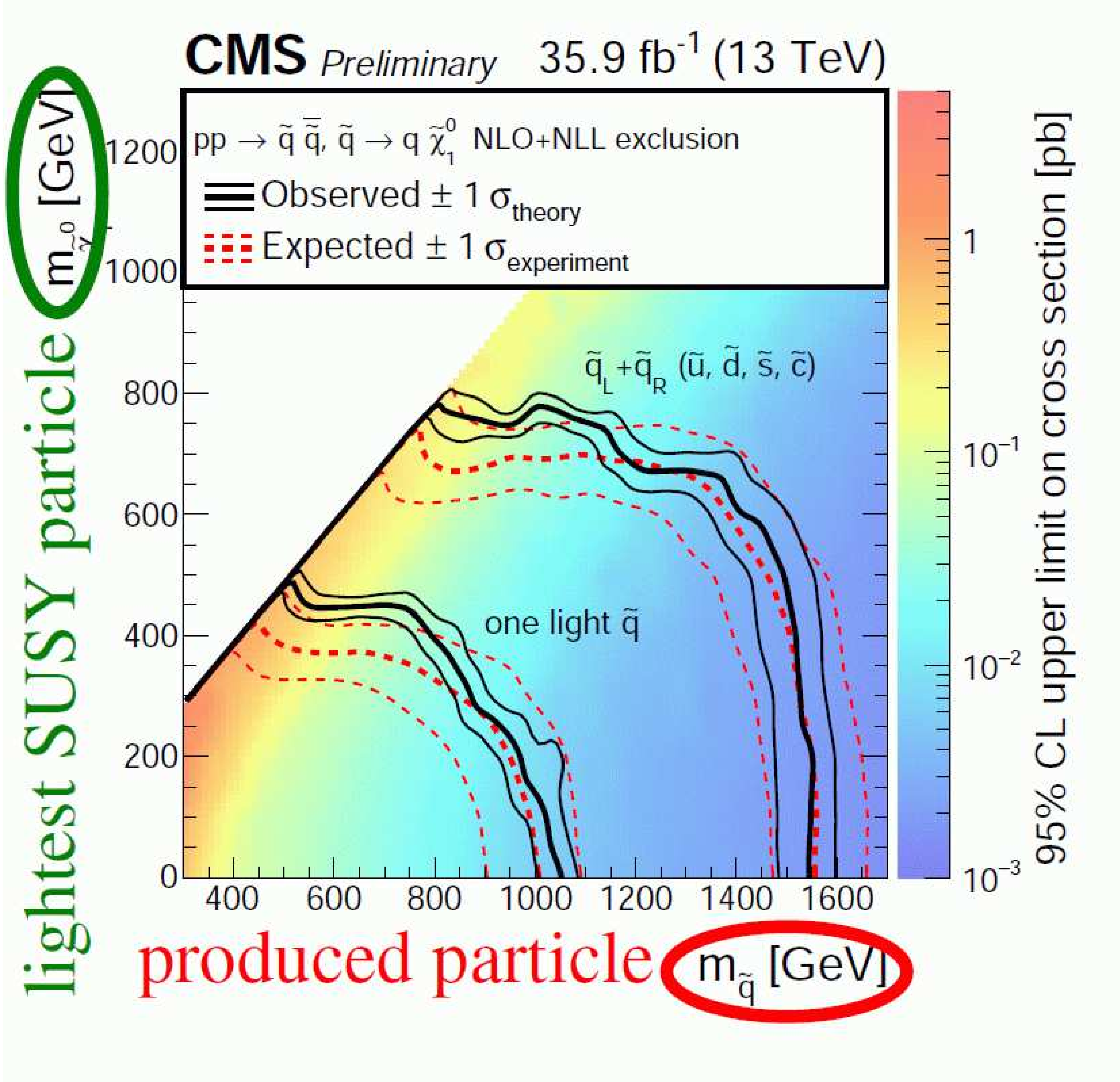
Stop overview ATLAS:



Stop overview CMS:



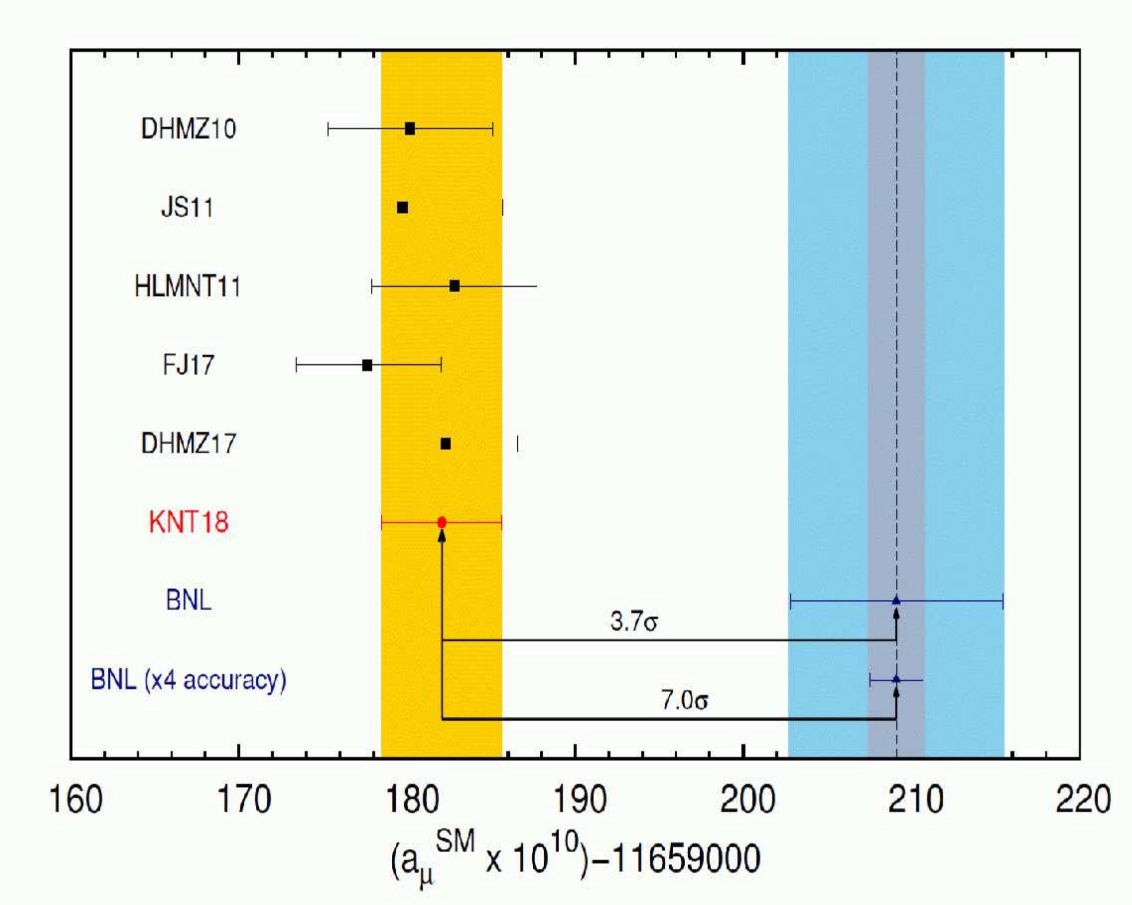
Be aware about squark limits:



The anomalous magnetic moment of the muon

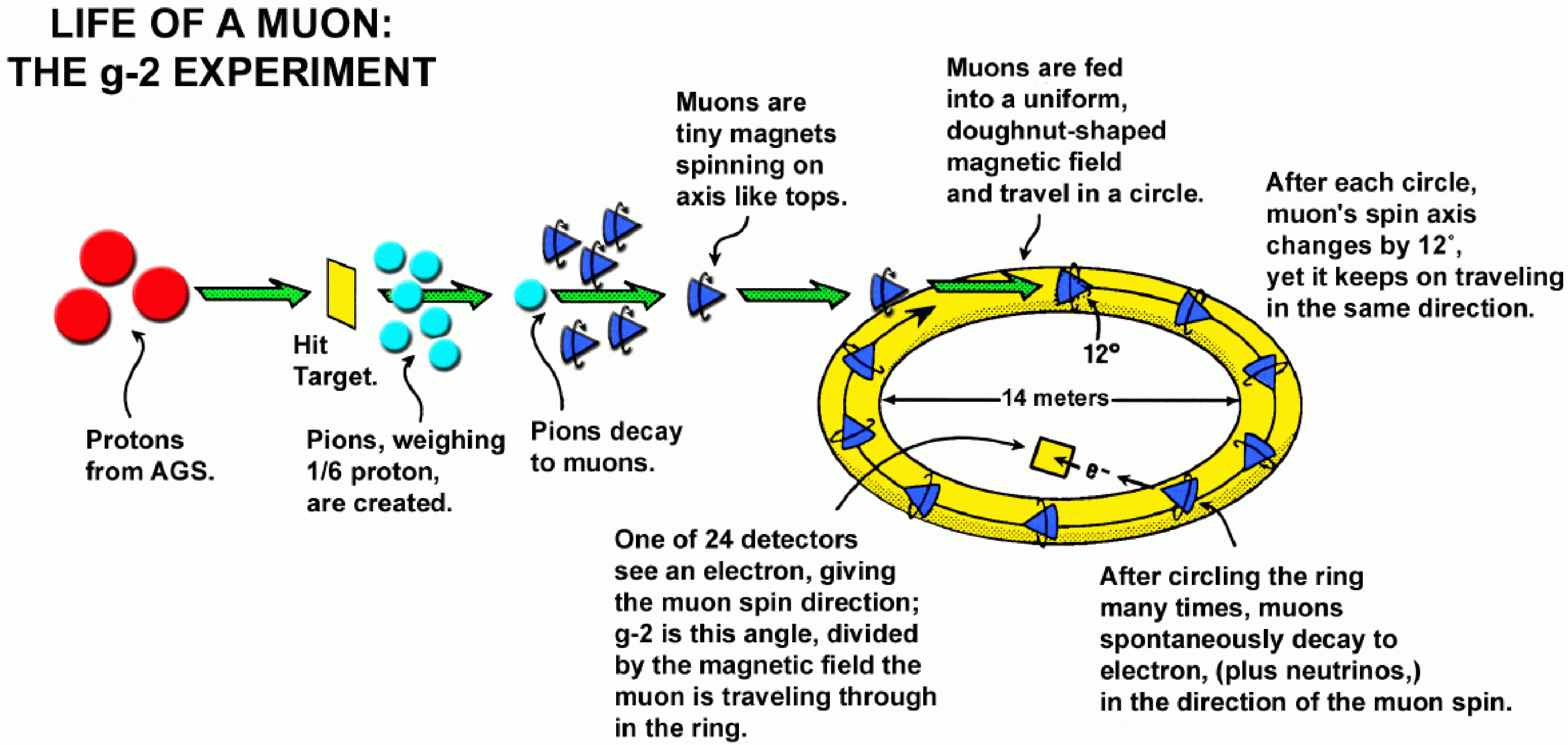
$$a_\mu \equiv (g-2)_\mu/2$$

Overview about the current experimental and SM (theory) result:
[A. Keshavarzia, D. Nomura, T. Teubner '18]



$$a_\mu^{\text{exp}} - a_\mu^{\text{theo,SM}} \approx (27.05 \pm 7.26) \times 10^{-10} \quad : 3.7\,\sigma$$

The $(g-2)_\mu$ experiment:



Coupling of muon to magnetic field : $\mu - \mu - \gamma$ coupling

$$\bar{u}(p') \left[\gamma^\mu F_1(q^2) + \frac{i}{2m_\mu} \sigma^{\mu\nu} q_\nu F_2(q^2) \right] u(p) A_\mu \qquad F_2(0) = a_\mu$$

SUSY can easily explain the deviation:

Feynman diagrams for MSSM 1L corrections:

– Diagrams with chargino/sneutrino exchange

– Diagrams with neutralino/smuon exchange

Enhancement factor as compared to SM:

$$\mu - \tilde{\chi}_i^{\pm} - \tilde{\nu}_\mu \quad : \quad \sim m_\mu \tan\beta$$
$$\mu - \tilde{\chi}_j^{0} - \tilde{\mu}_a \quad : \quad \sim m_\mu \tan\beta$$

SM, EW 1L: $\frac{\alpha}{\pi} \frac{m_\mu^2}{M_W^2}$

MSSM, 1L: $\frac{\alpha}{\pi} \frac{m_\mu^2}{M_{\text{SUSY}}^2} \times \tan\beta$

SUSY corrections at 1L:

$$a_\mu^{\text{SUSY,1L}} \approx 13 \times 10^{-10} \left(\frac{100 \text{ GeV}}{M_{\text{SUSY}}}\right)^2 \tan\beta \, \text{sign}(\mu)$$

$M_{\text{SUSY}} (= m_{\tilde\mu} = m_{\tilde\nu} = m_{\tilde\chi})$: generic SUSY mass scale

$$a_\mu^{\text{SUSY,1L}} = (-100 \ldots +100) \times 10^{-10}$$
$$a_\mu^{\text{exp}} - a_\mu^{\text{theo,SM}} \approx (27 \pm 7.25) \times 10^{-10}$$

⇒ SUSY could easily explain the "discrepancy"

⇒ a_μ can provide bounds on SUSY parameter space
(by requiering agreement at the 95% C.L.)

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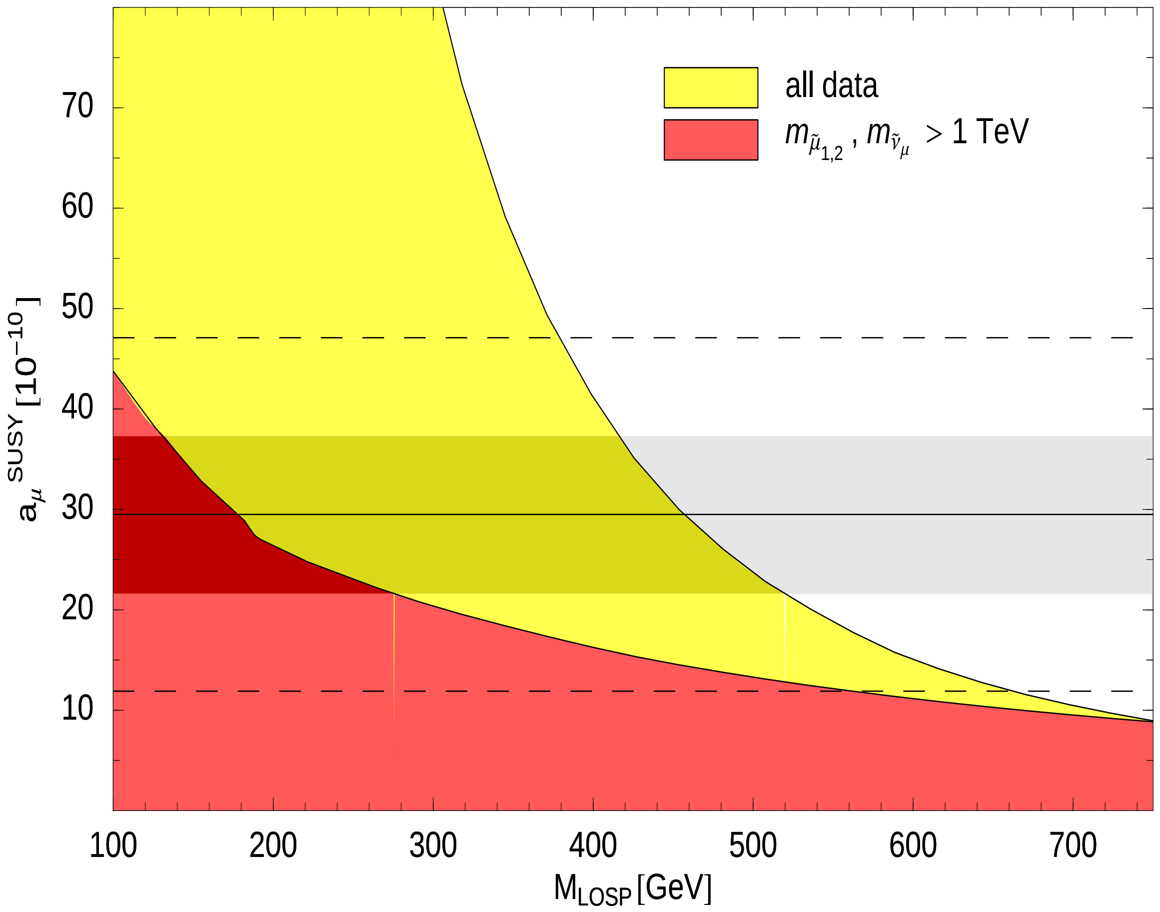
If SUSY exists, it should fix $(g-2)_\mu$!
⇒ there must be light EW SUSY particles!

Example: Scan over SUSY parameter space



Scan over

μ, M_2, $m_{\tilde{\mu}}$, A_μ

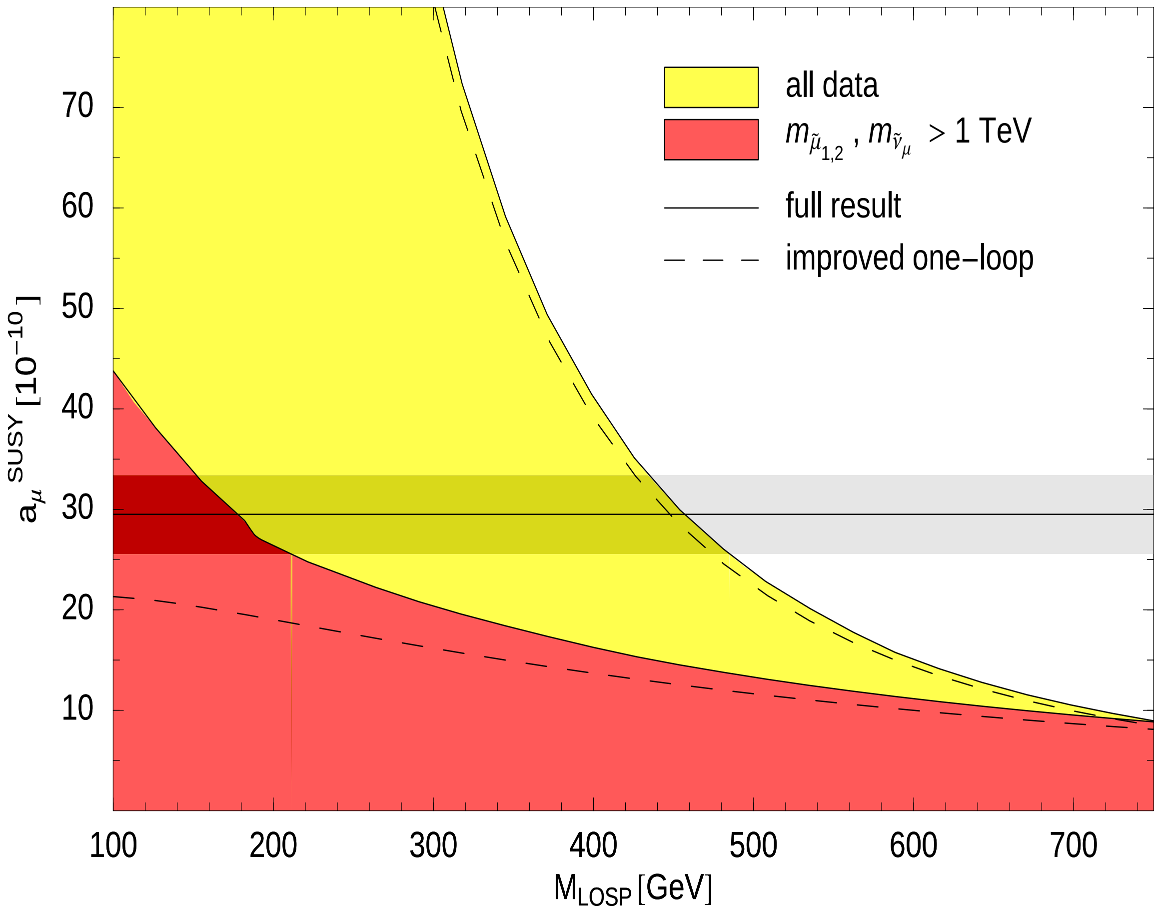
LOSP = lightest observable SUSY particle

LOSP = $\tilde{\mu}$ or $\tilde{\chi}$

[*D. Stöckinger '06*]

SUSY could easily explain discrepancy

New example: Scan over SUSY parameter space

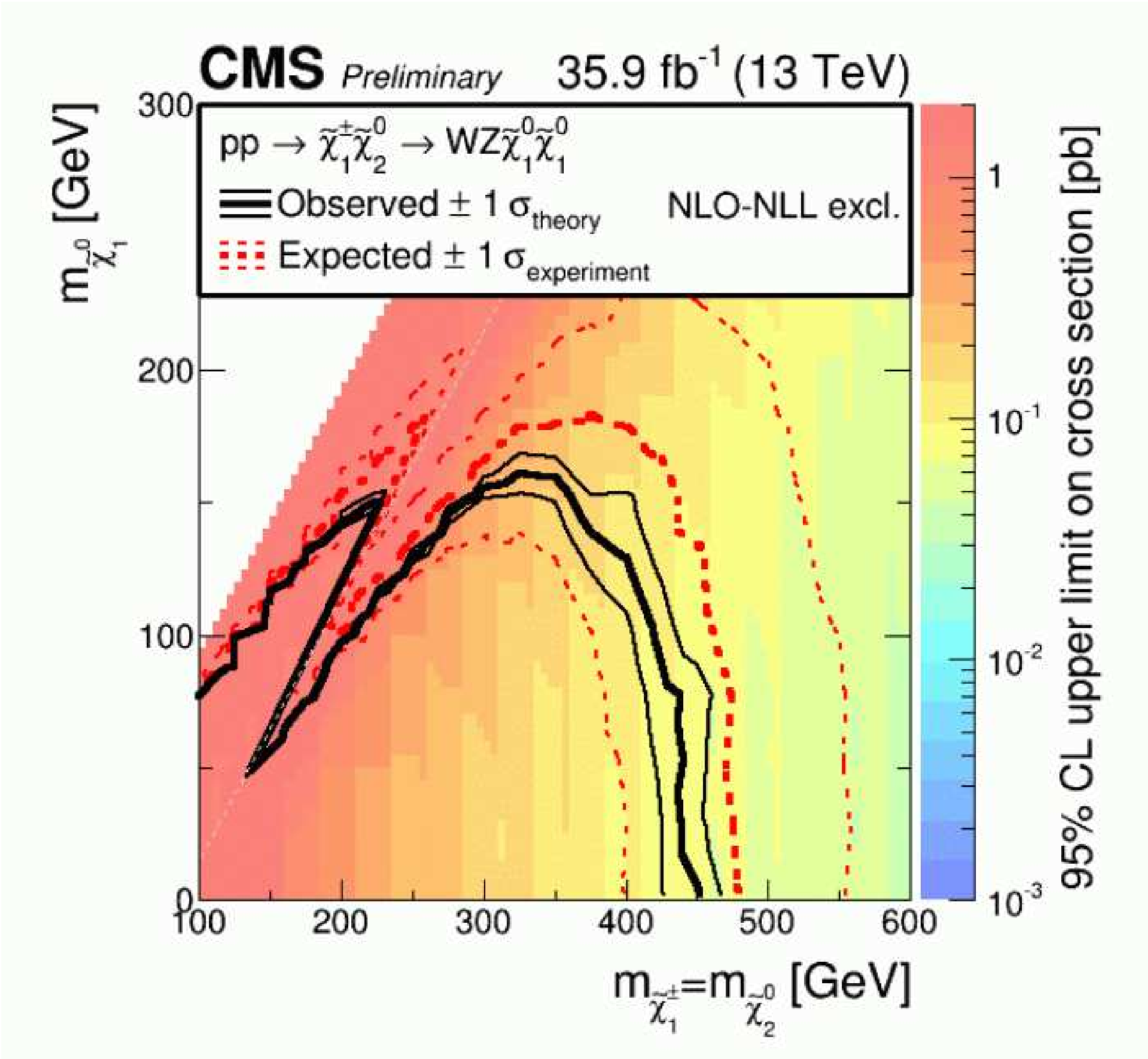


Scan over
μ, M_2, $m_{\tilde{\mu}}$, A_μ
LOSP = lightest observable SUSY particle
LOSP = $\tilde{\mu}$ or $\tilde{\chi}$
[*D. Stöckinger '06*]

SUSY could easily explain discrepancy

With improved precision (and similar central value):
$\Rightarrow$ strong bounds on the MSSM parameter space

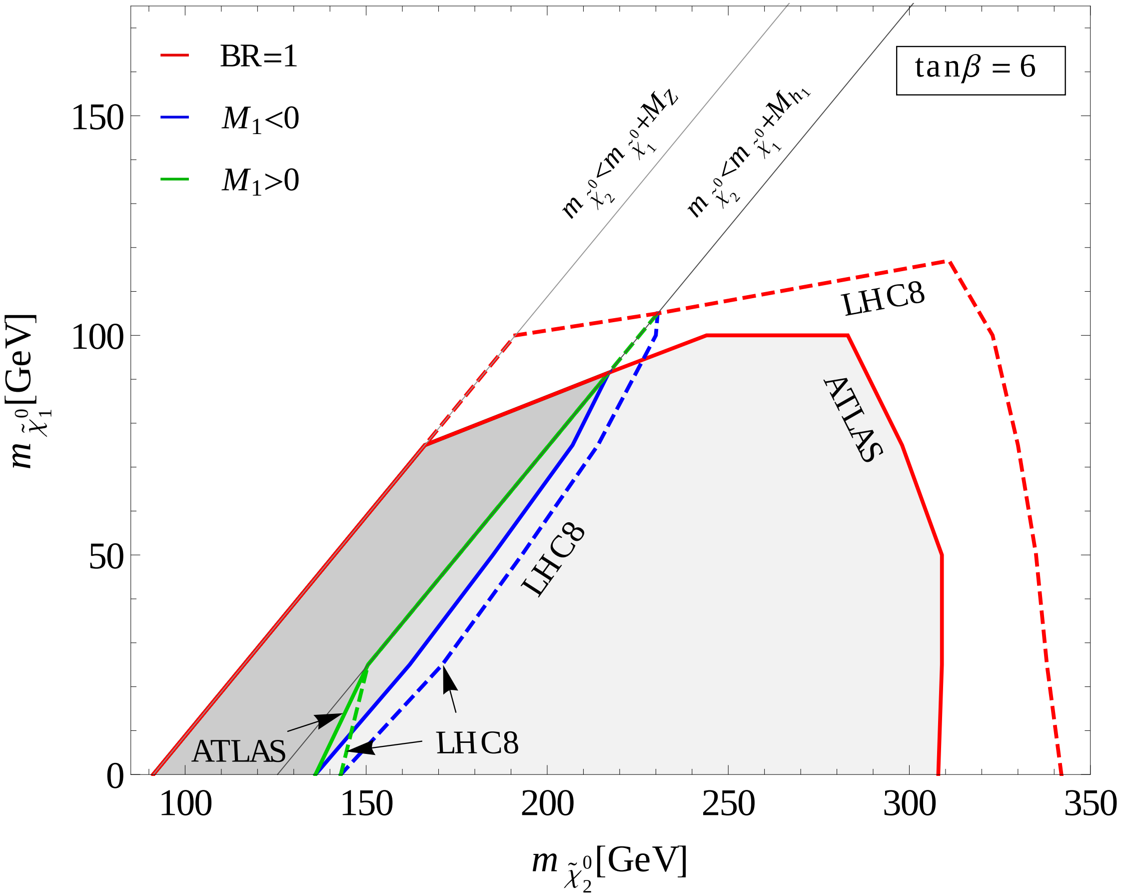
Electroweak searches:



LHC is looking for $pp \to \tilde{\chi}_1^\pm \, \tilde{\chi}_2^0 \to W^\pm \tilde{\chi}_1^0 \, Z \tilde{\chi}_1^0$

Reality: $\text{BR}(\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0) = 1$ is NEVER correct because $\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0$ is possible

[A. Bharucha, S.H., F. v.d. Pahlen '13]

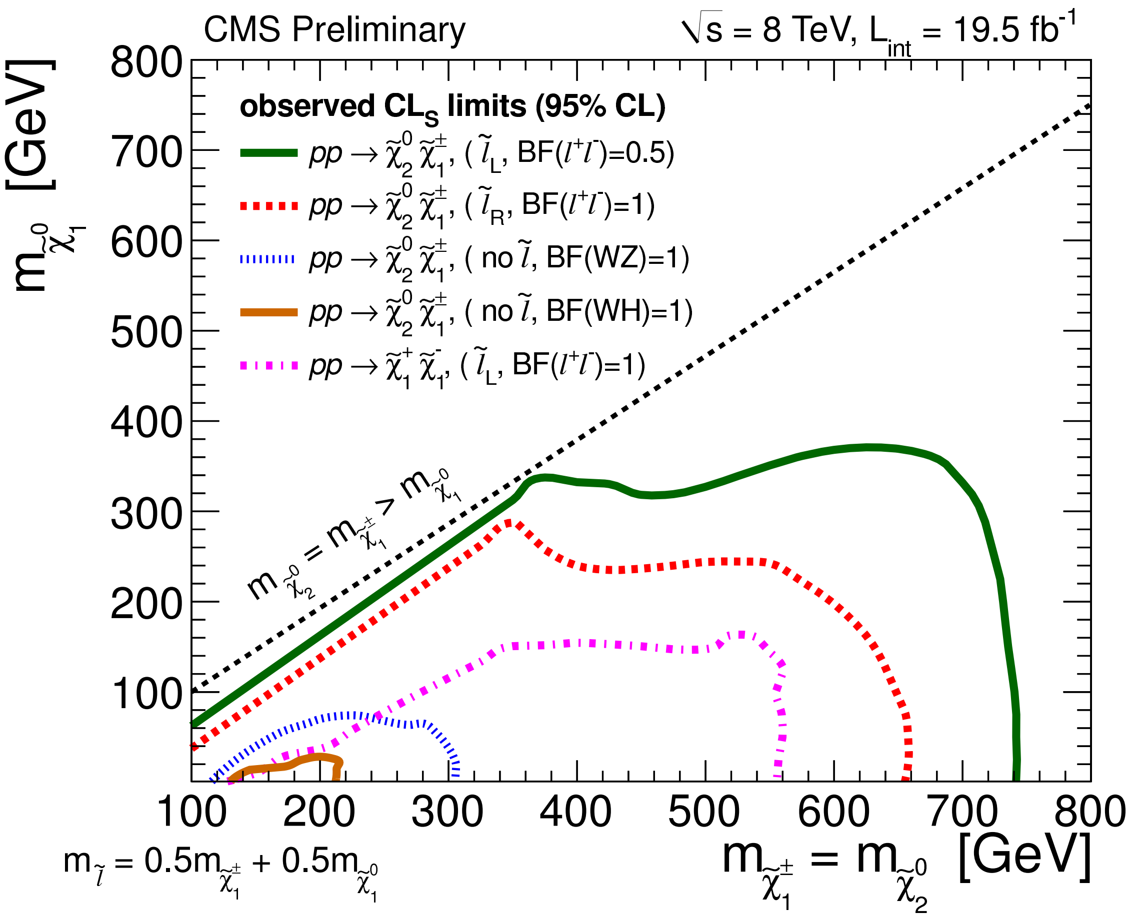


⇒ huge reduction of exclusion region (where $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h$ allowed)

More recently:

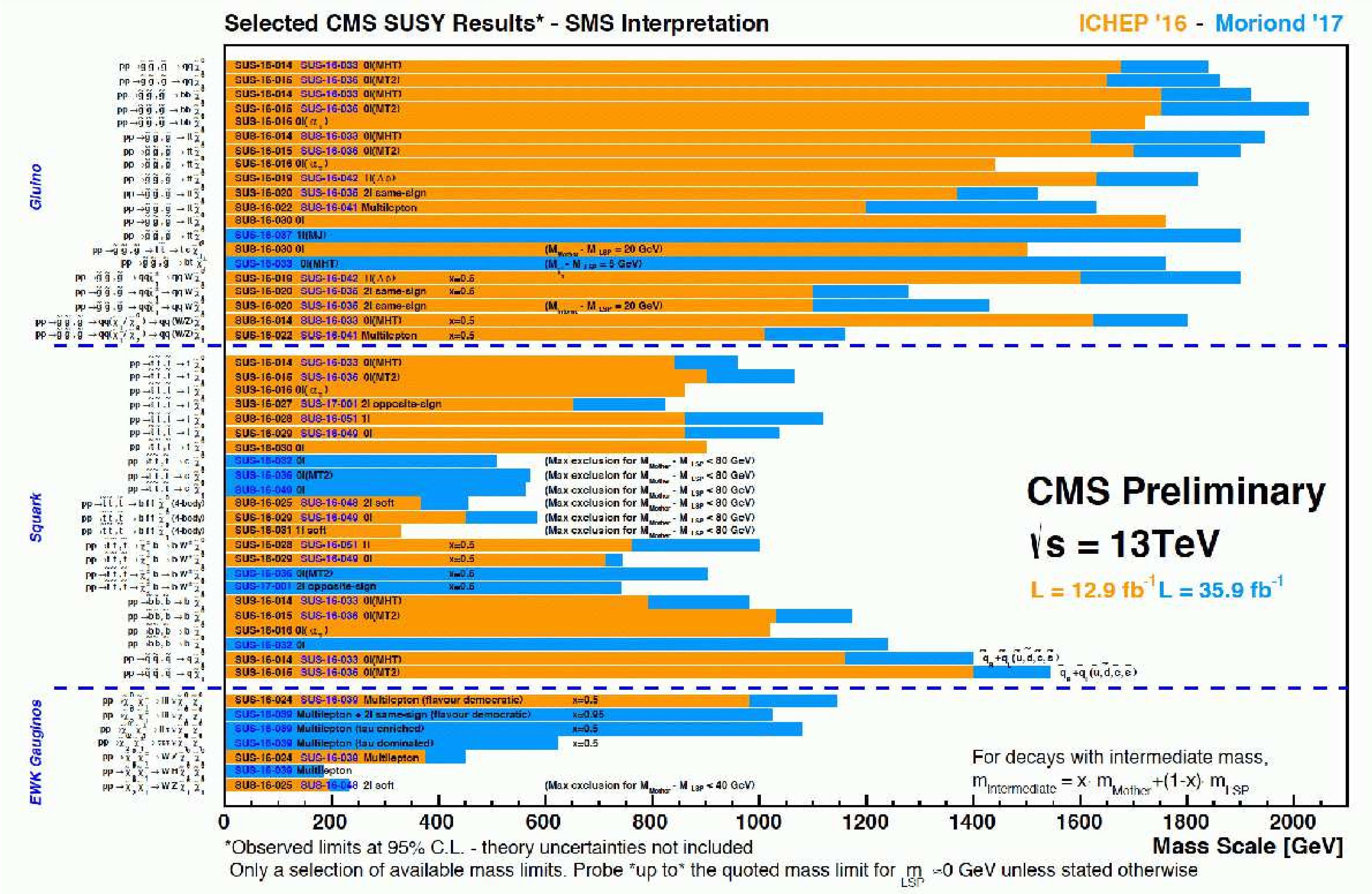
ATLAS and CMS are now also searching for

$$pp \to \tilde{\chi}_1^{\pm}\, \tilde{\chi}_2^0 \to W^{\pm}\tilde{\chi}_1^0\, \tilde{\chi}_2^0 \to W^{\pm}\tilde{\chi}_1^0\, h\tilde{\chi}_1^0 \to W^{\pm}\tilde{\chi}_1^0\, b\bar{b}\tilde{\chi}_1^0$$



⇒ strongly reduced bounds!

Overview about SUSY limits: [*CMS '17*]



⇒ all limits require special assumptions!


SUSY 2020
The 28th International Conference on
Supersymmetry and Unification
of Fundamental Interactions,
Beijing, P. R. China
SUSY 2020: July 6-11, 2020
Pre-SUSY 2020: June 29-July 3, 2020
Institute of Theoretical Physics (ITP), Chinese Academy of Sciences (CAS)

Tool for combined SUSY analysis: MasterCode

⇒ collaborative effort of theorists and experimentalists

[Bagnaschi, Borsato, Buchmüller, Chobanova, Citron, Costa, De Roeck, Dolan, Ellis, Flächer, SH, Isidori, Lucio, Luo, Martinez Santos, Olive, Sakurai, Weiglein]

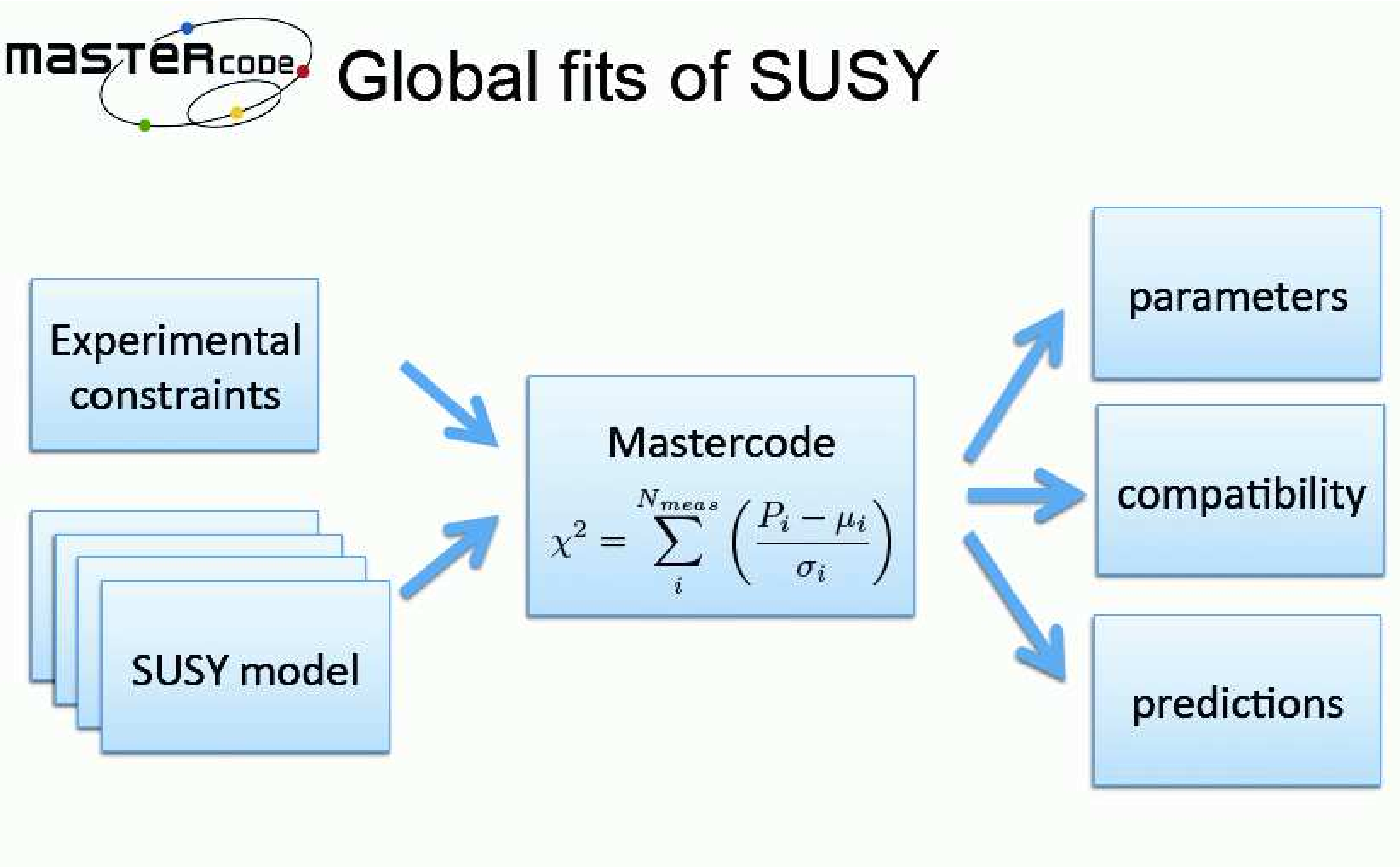
Über-code for the combination of different tools:

– 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

The χ^2 evaluation:



Data we have:

– Higgs boson mass (LHC) $\Rightarrow$ FeynHiggs

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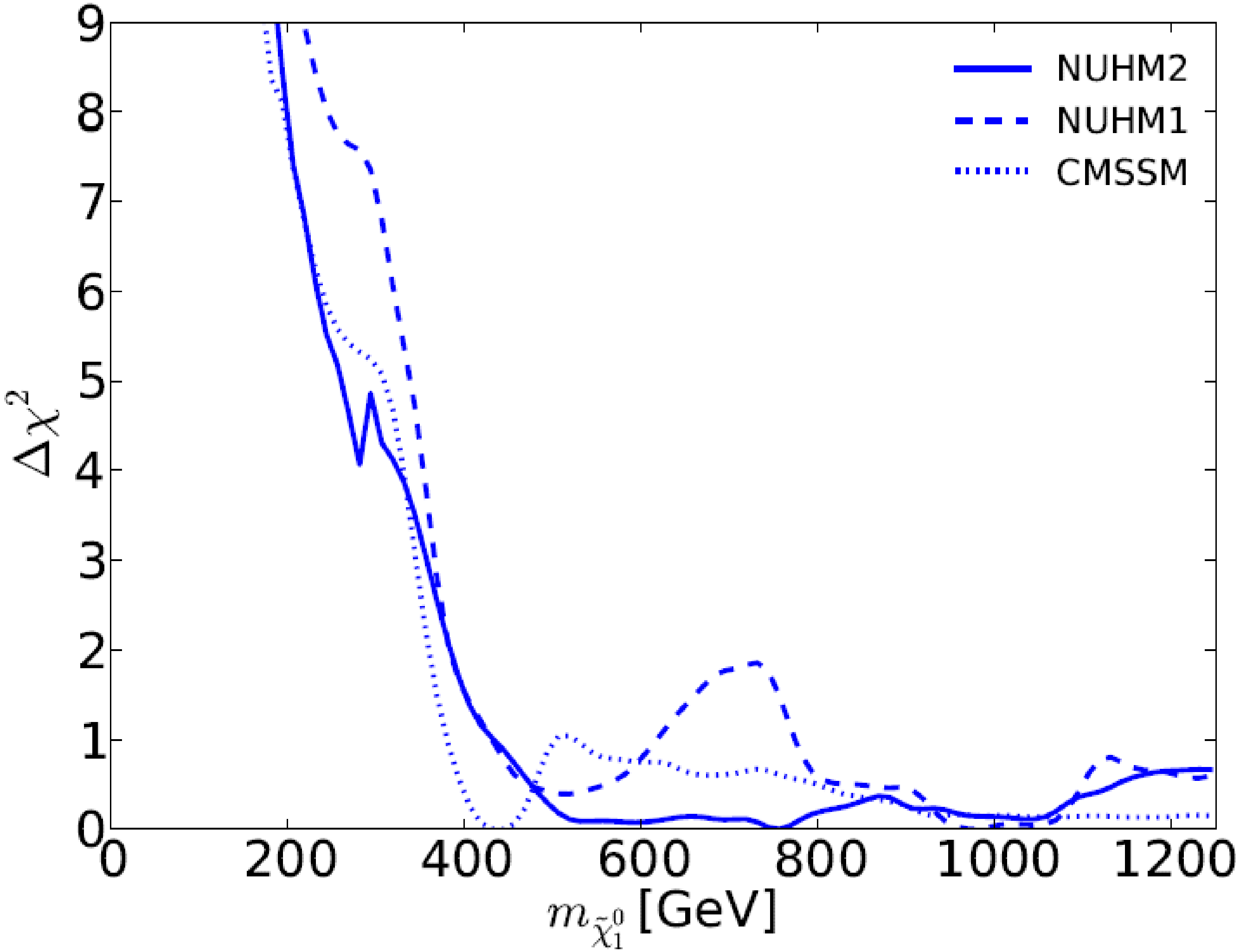
- electroweak precision data $\Rightarrow$ FeynWZ, FeynHiggs
- flavor data $\Rightarrow$ SuperIso, SuFla
- astrophysical data (DM properties) $\Rightarrow$ MicrOMEGAs, SSARD

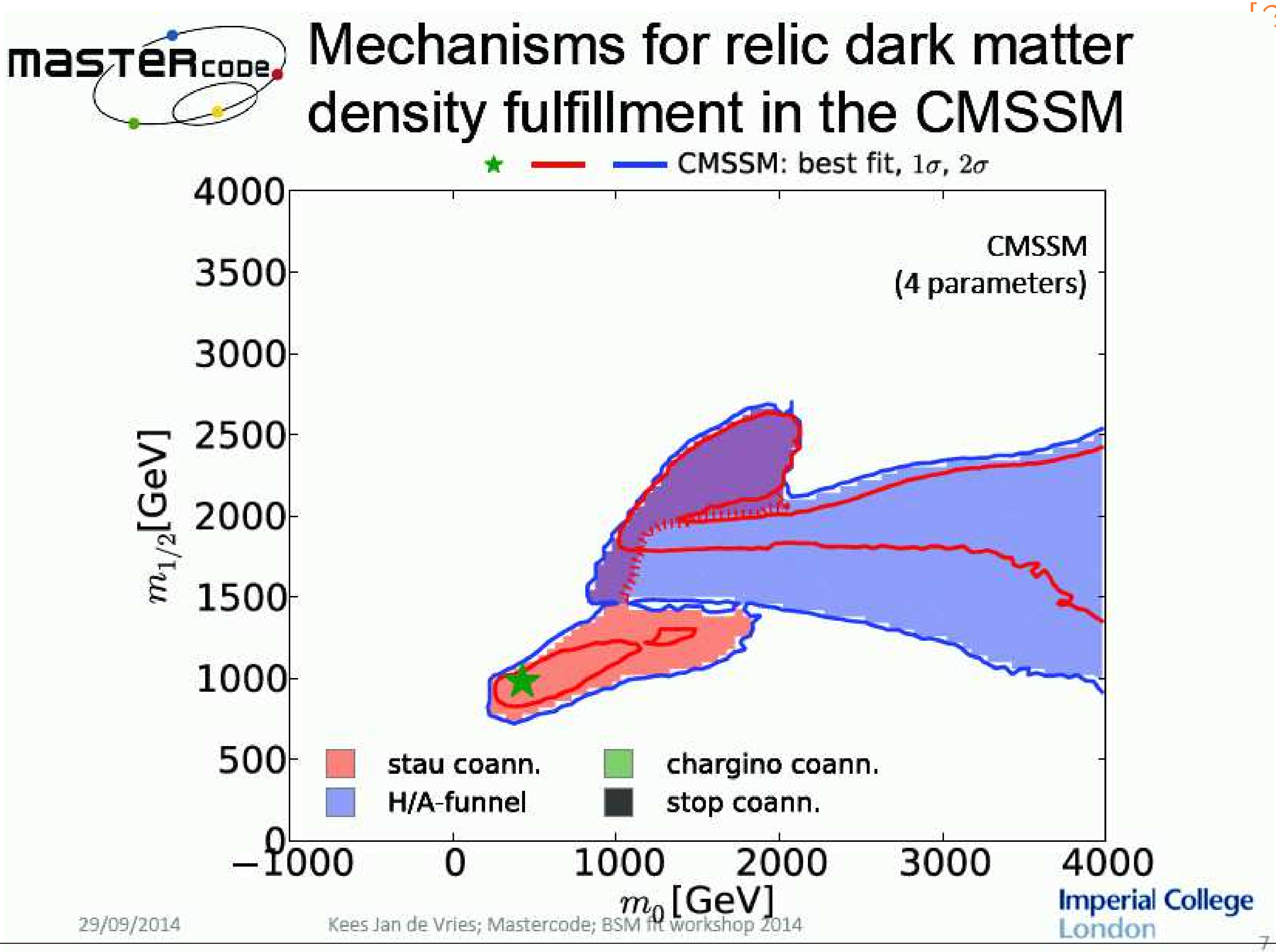
Results in the CMSSM, NUHM1, NUHM2

[2014]



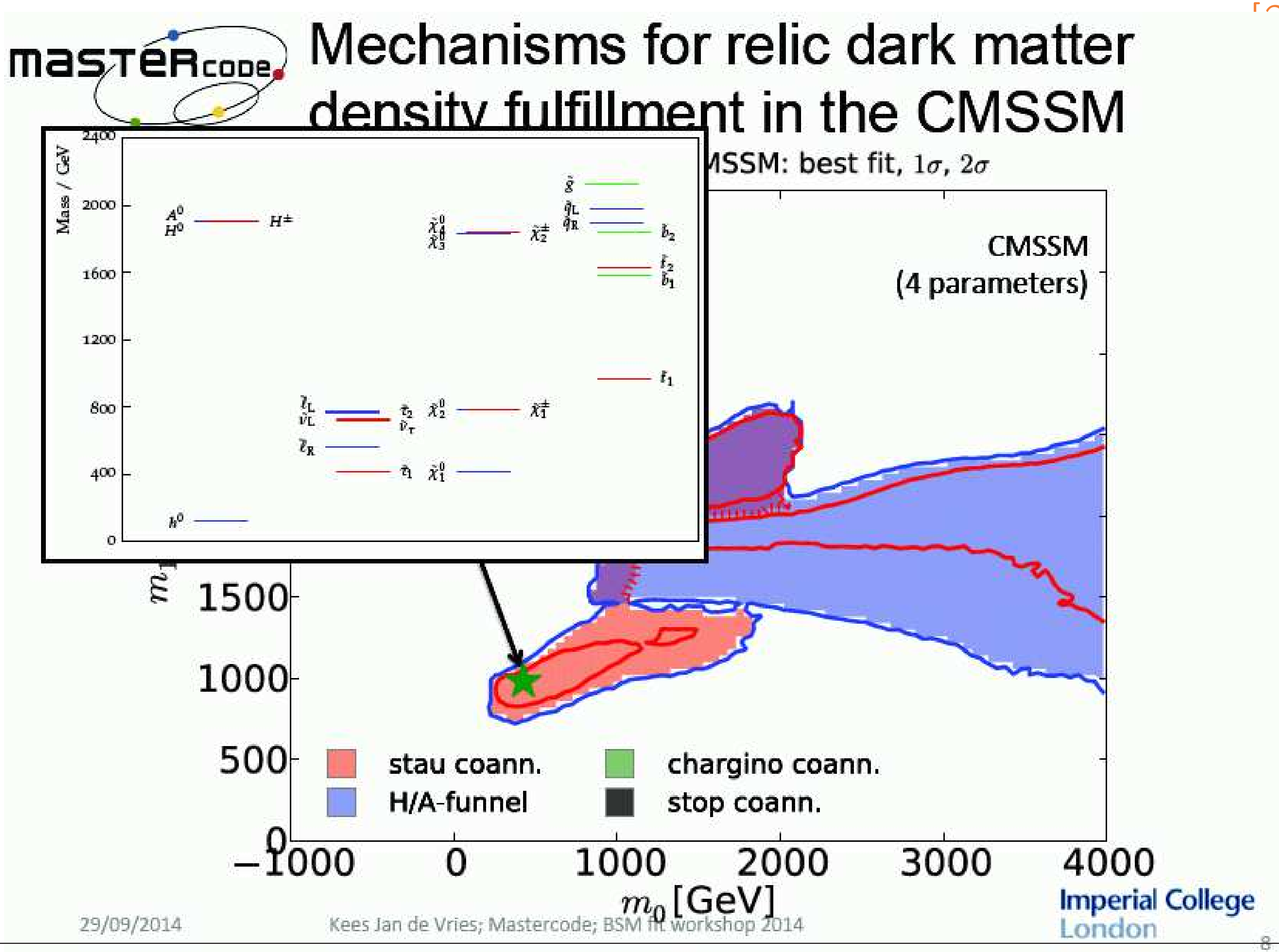
⇒ only very large values are favored

[2014]


Mechanisms for relic dark matter density fulfillment in the CMSSM
CMSSM: best fit, 1σ, 2σ
CMSSM
(4 parameters)
stau coann.
H/A-funnel
chargino coann.
stop coann.
$m_{1/2}$[GeV]
m_0 [GeV]
29/09/2014
Kees Jan de Vries; Mastercode; BSM fit workshop 2014
Imperial College London
7

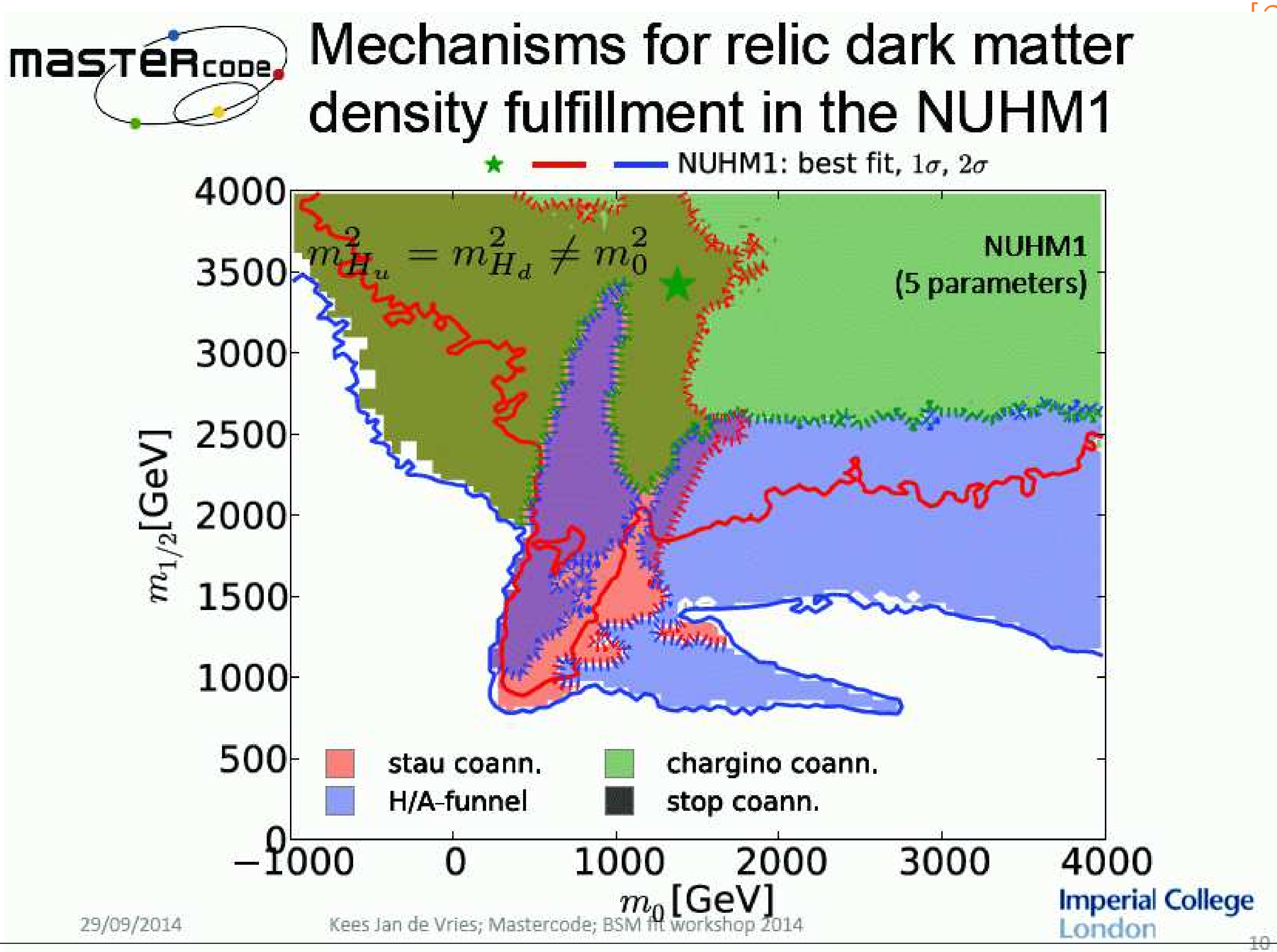
CMSSM DM prediction

[2014]



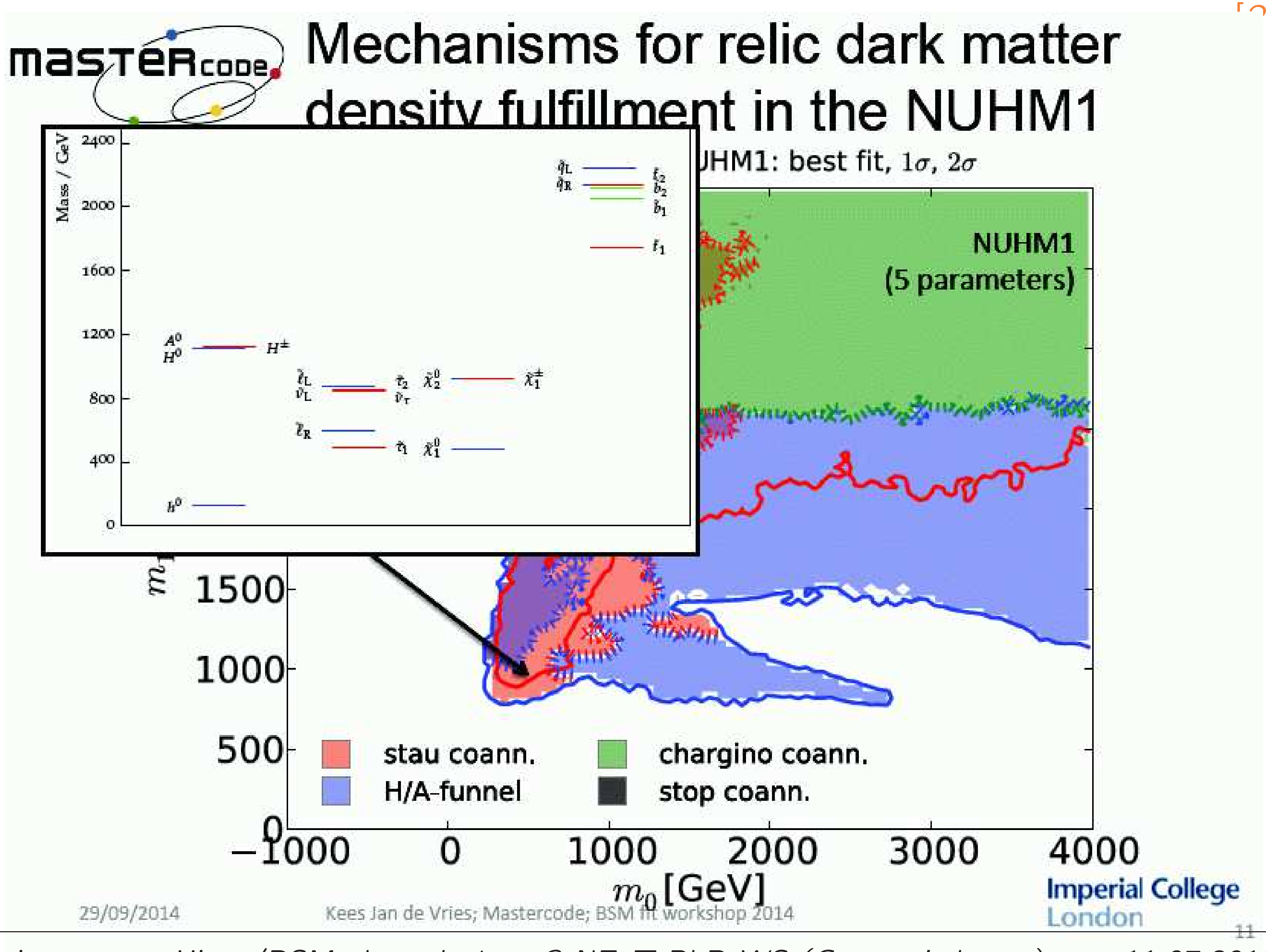
NUHM1 DM prediction

[2014]



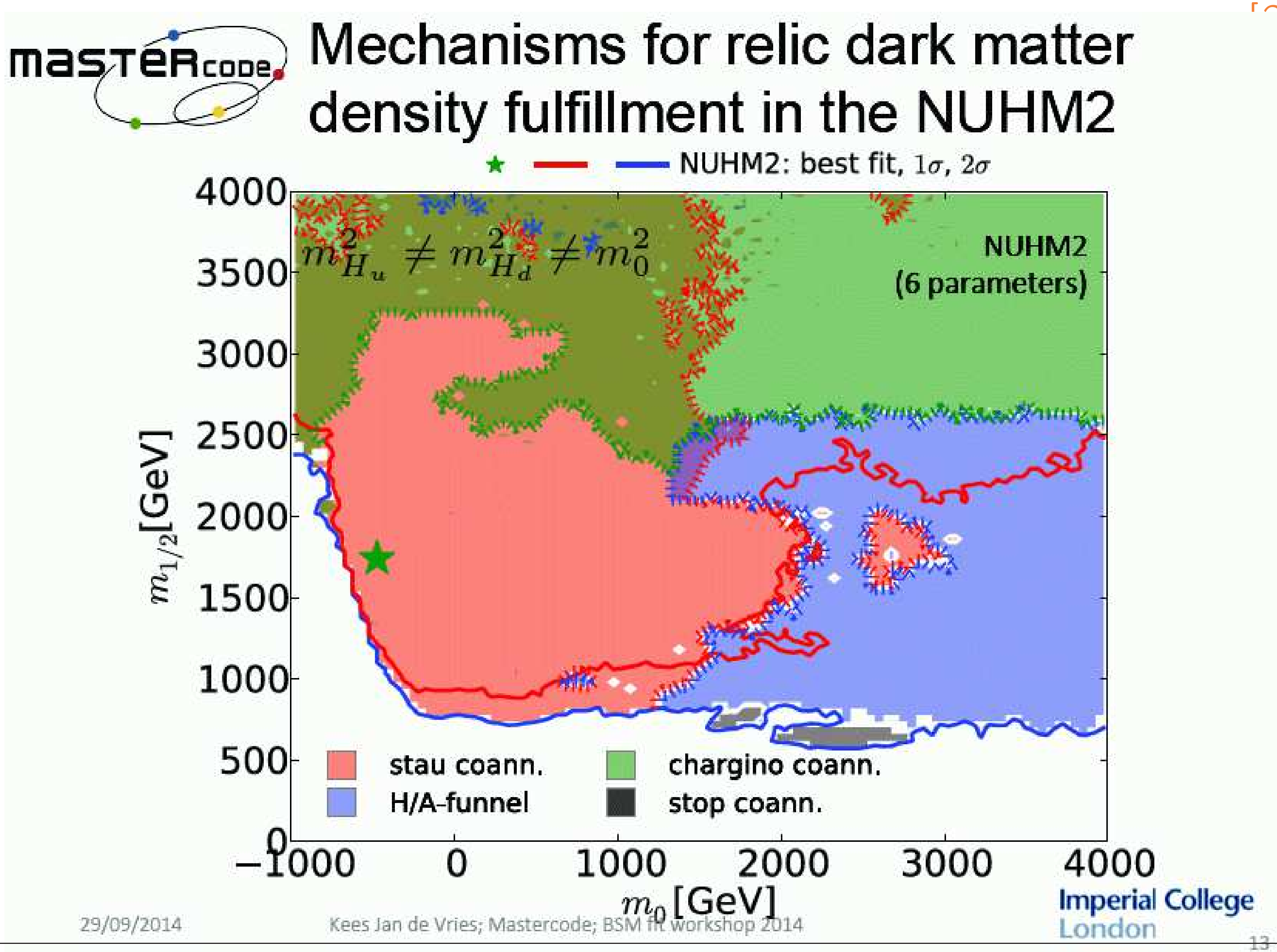
NUHM1 DM prediction

[2014]



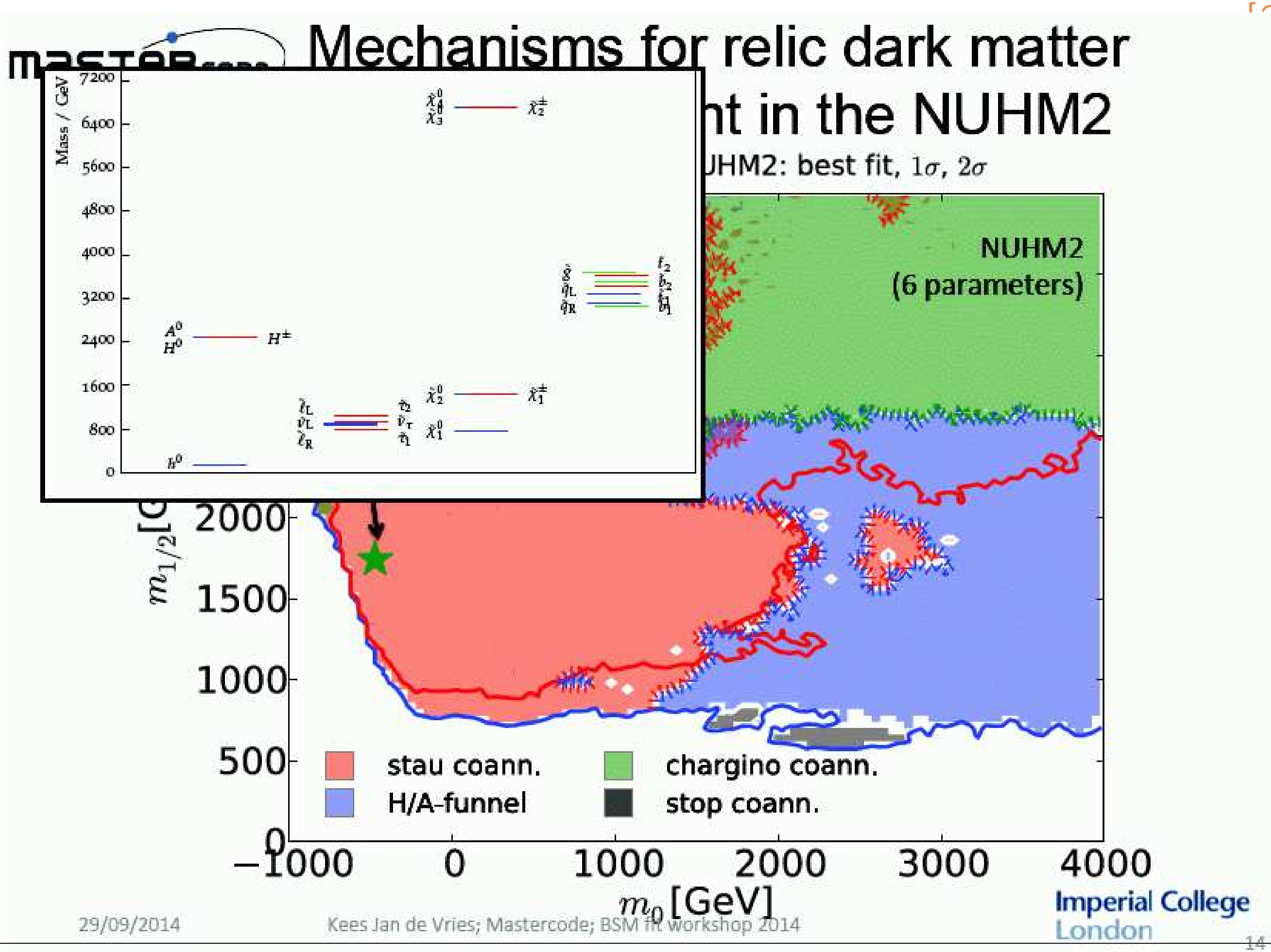
NUHM2 DM prediction

[2014]



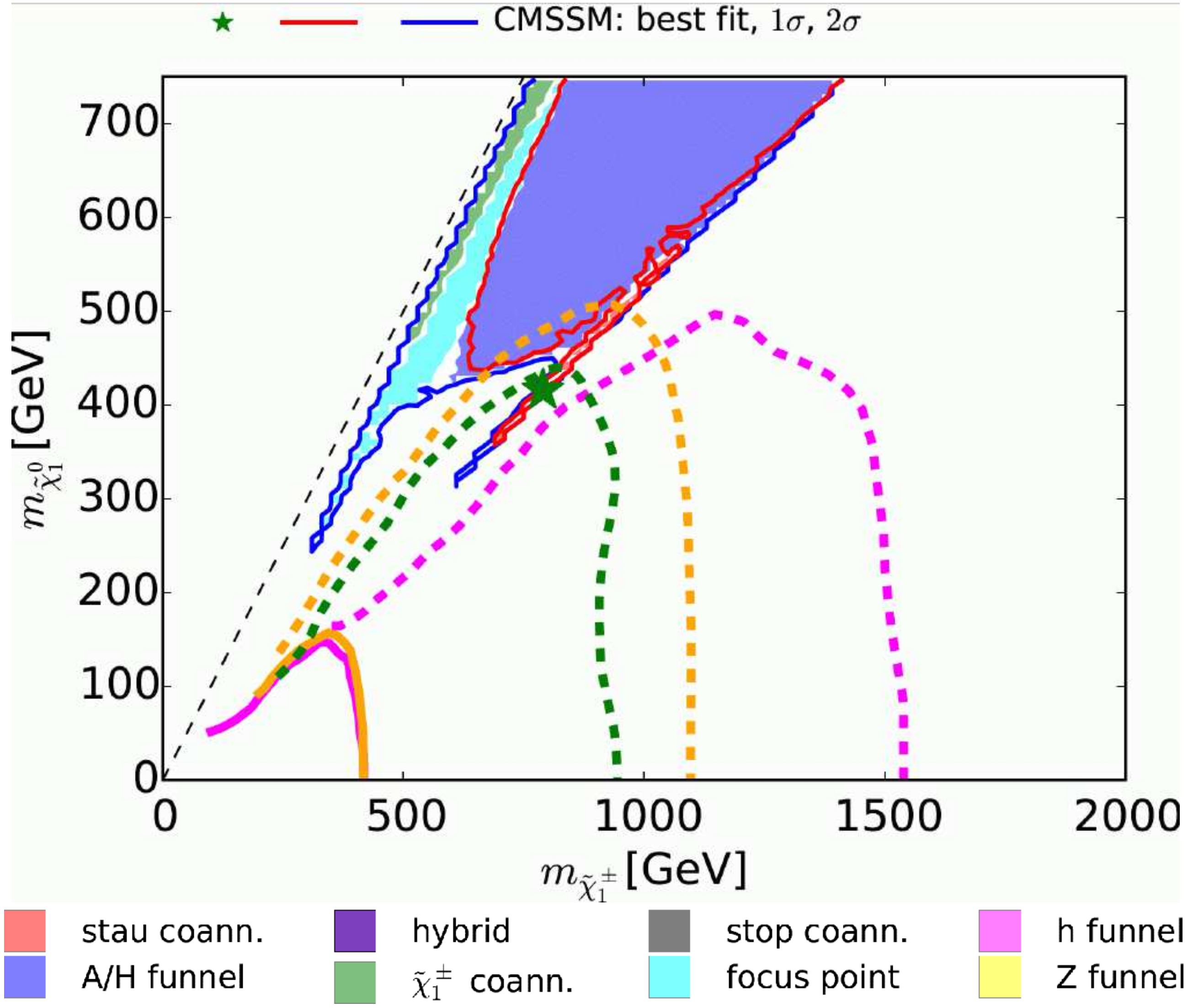
NUHM2 DM prediction

[?2014]



LHC prospects for CMSSM:

[2015]

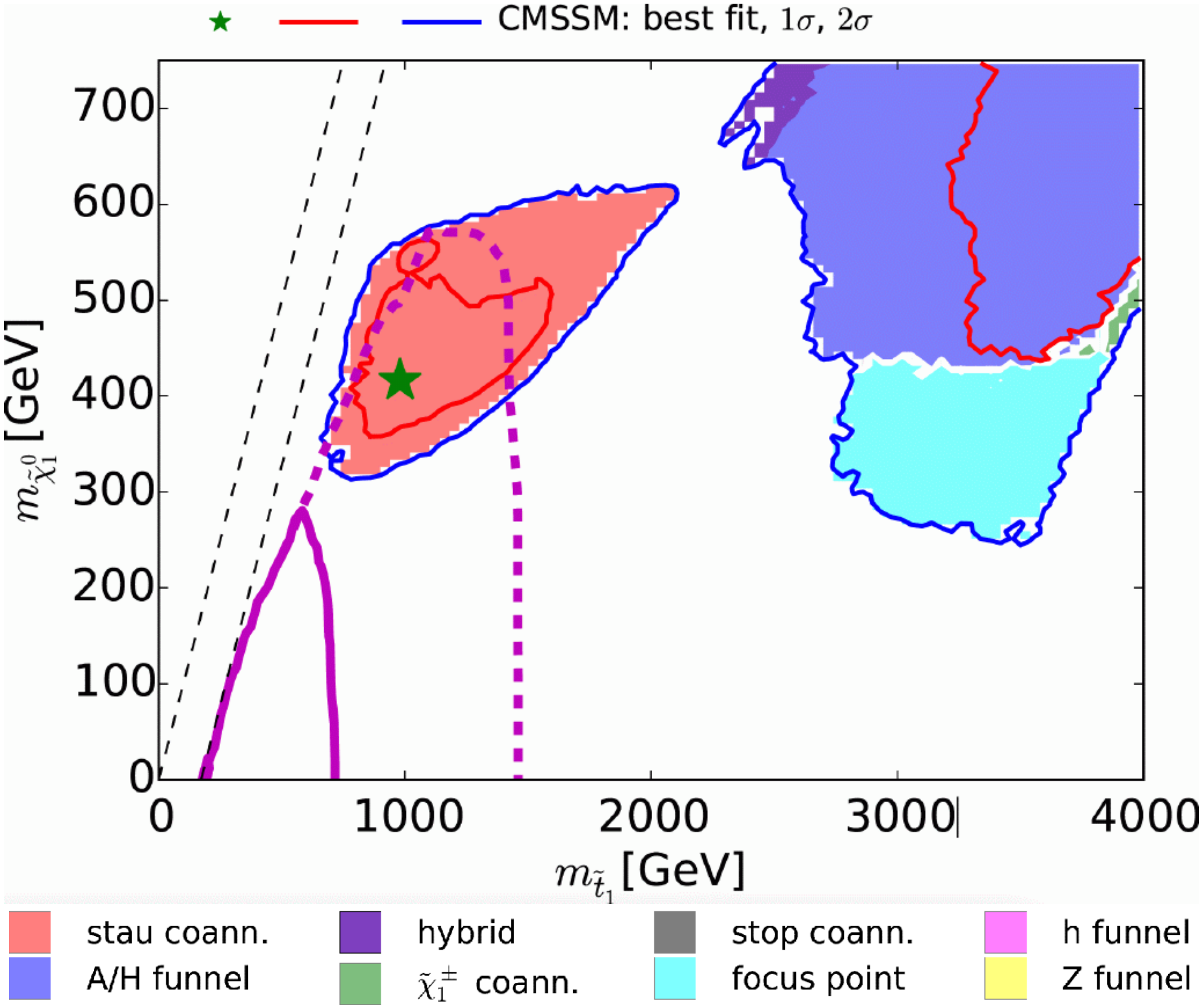


solid: current LHC limits, dashed: HL-LHC prospects

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

LHC prospects for CMSSM:

[2015]



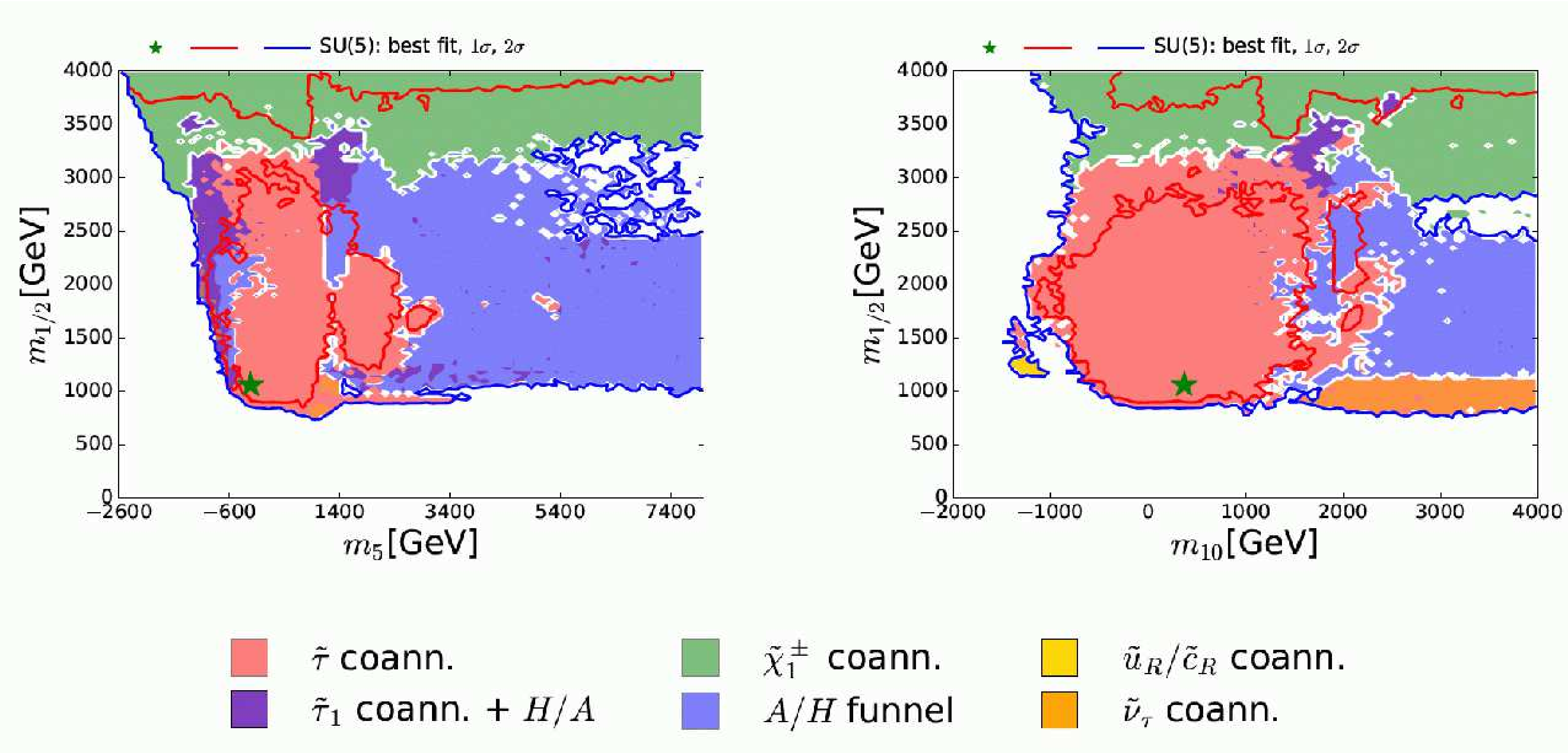
solid: current LHC limits, dashed: HL-LHC prospects

$\Rightarrow$ best-fit regions can partially be covered! (in colored searches)

Results in the SU(5)

GUT Mass planes:

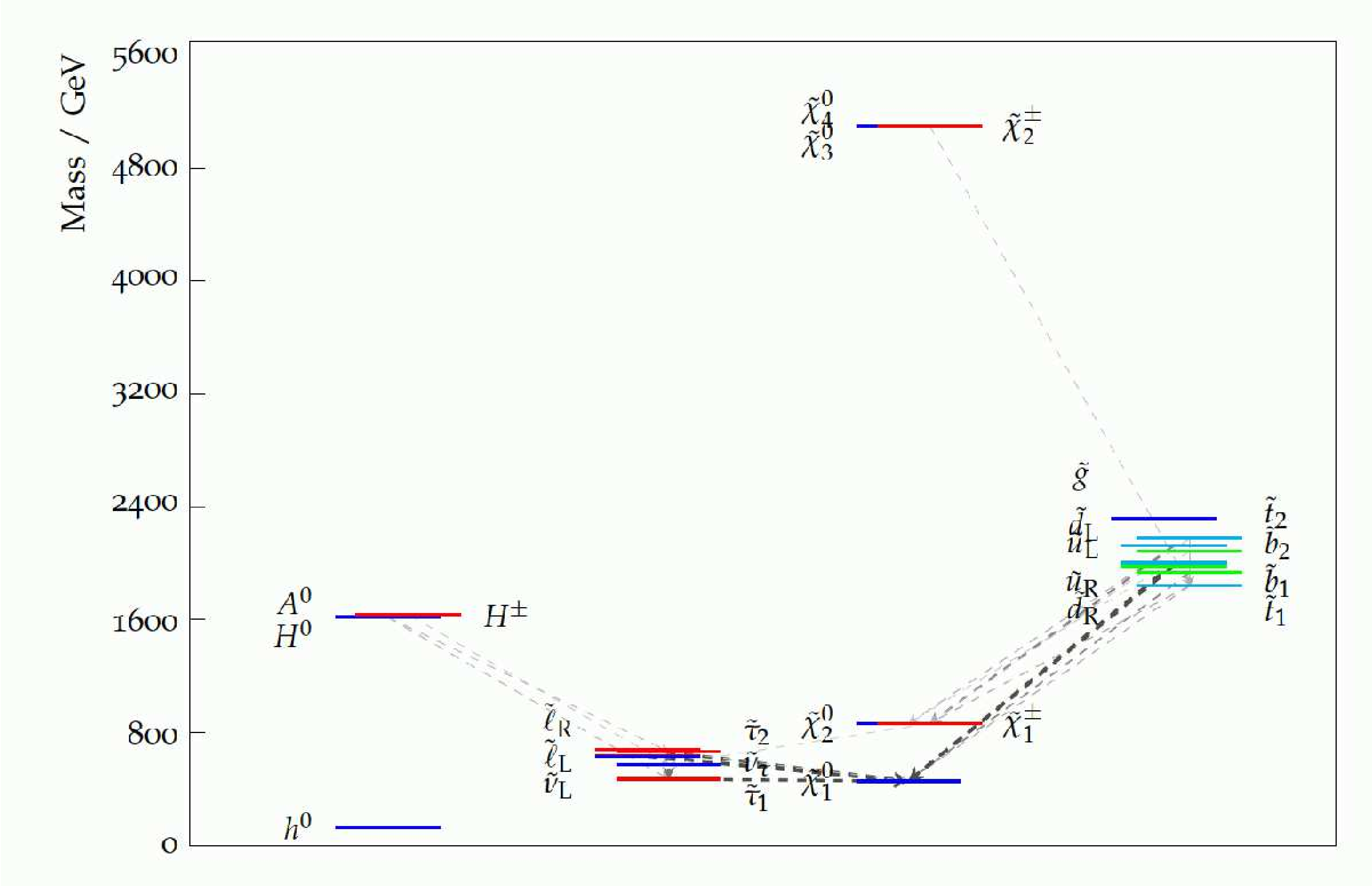
[2016]



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

SU(5) best-fit point:

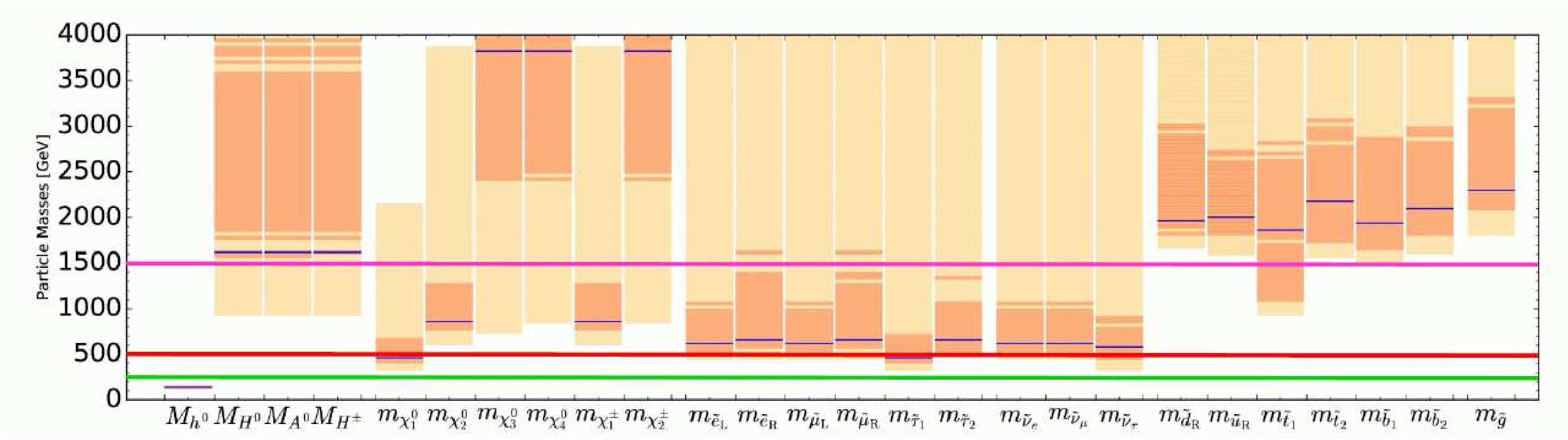
[2016]



⇒ not too heavy uncolored spectrum, colored within LHC reach?

SU(5) prediction: best-fit masses

[2016]



$\Rightarrow$ high colored masses

$\Rightarrow$ lower electroweak masses

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

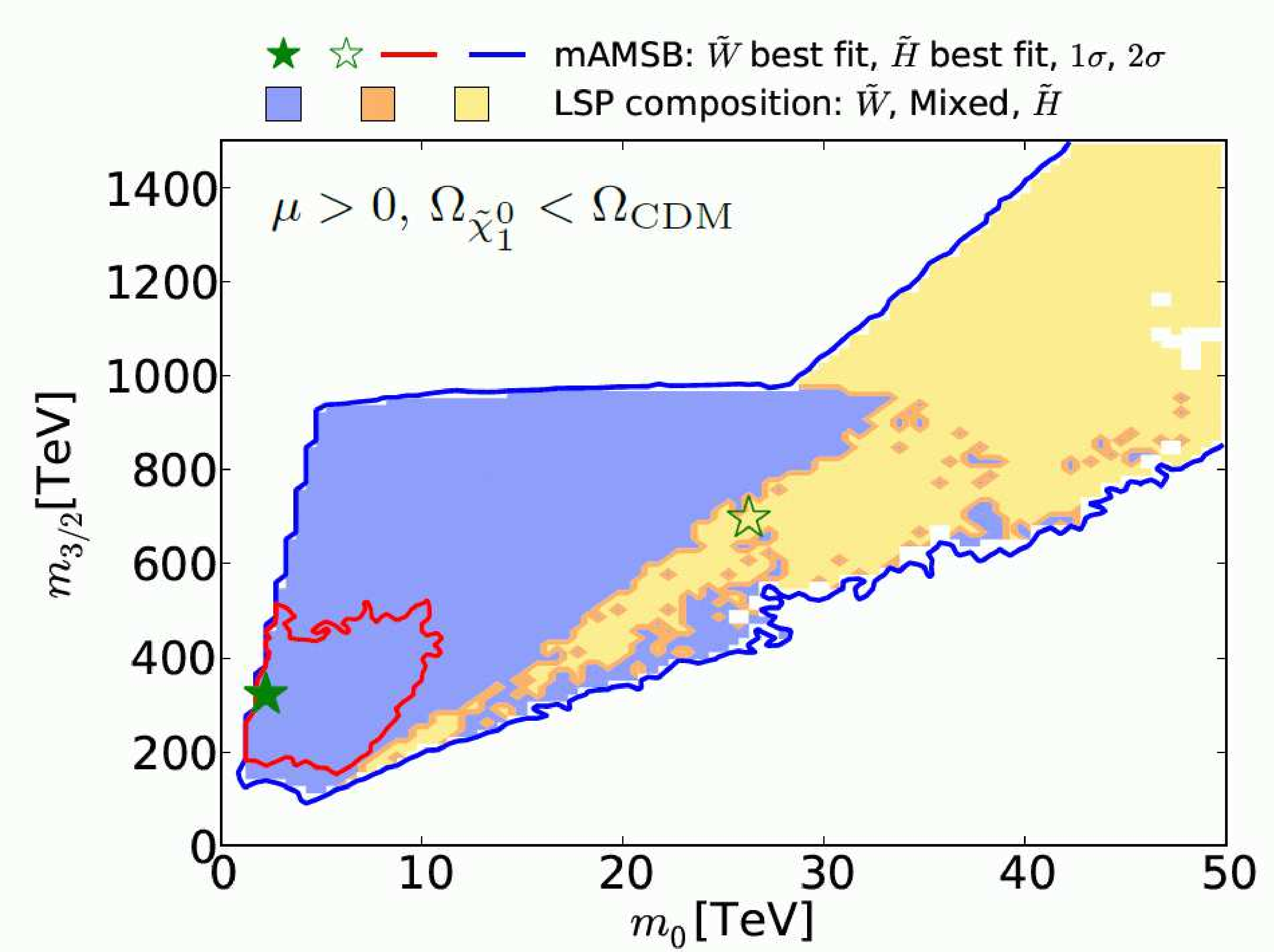
CLIC: $\sqrt{s} = 3000$ GeV $\Rightarrow$ pair production of many SUSY particles "likely"

$\Rightarrow$ no access to colored particles

Results in the mAMSB

[2016]

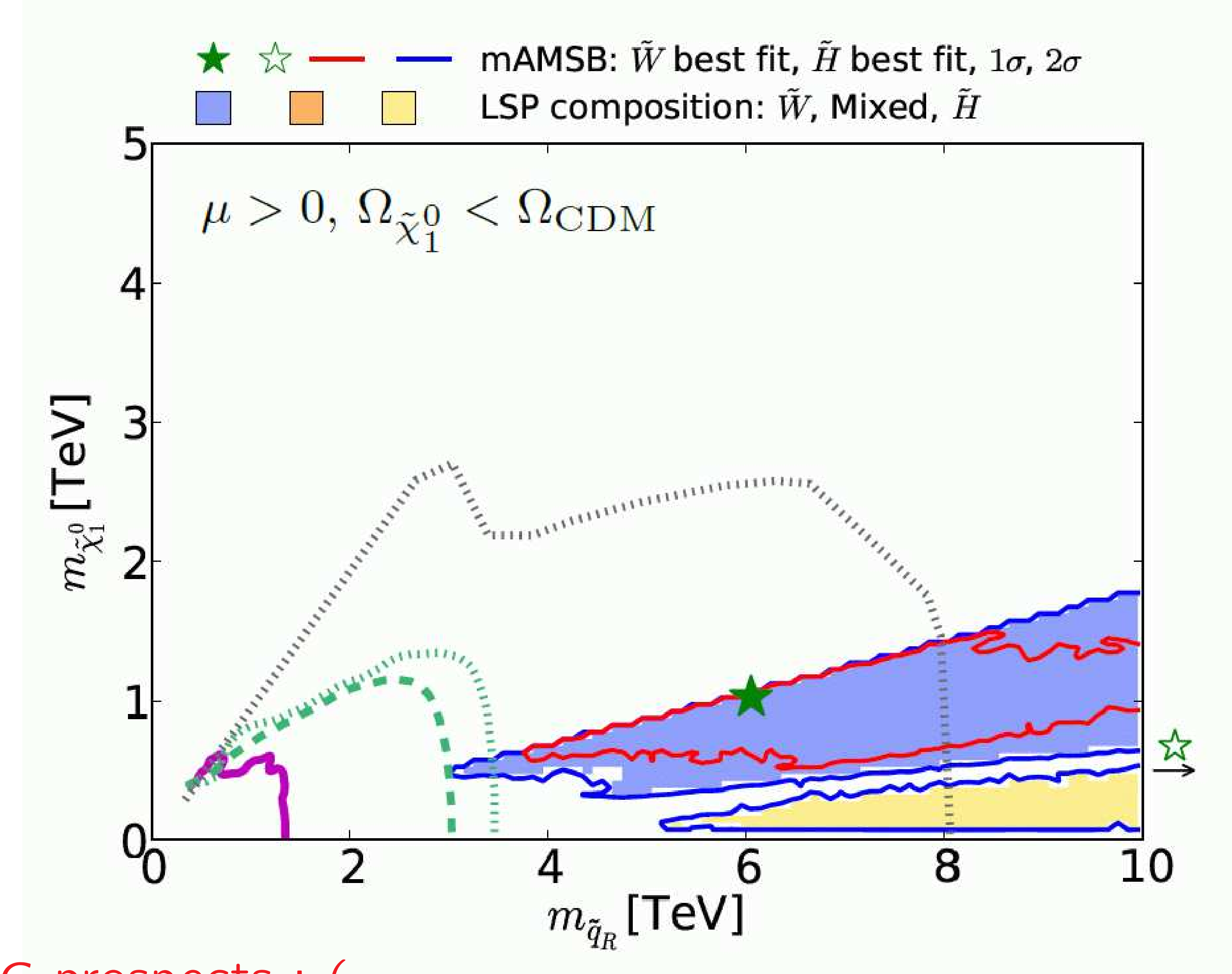
Dark Matter composition:



⇒ very relaxed limits ⇒ lower masses

Squark mass vs. DM mass:

[2016]

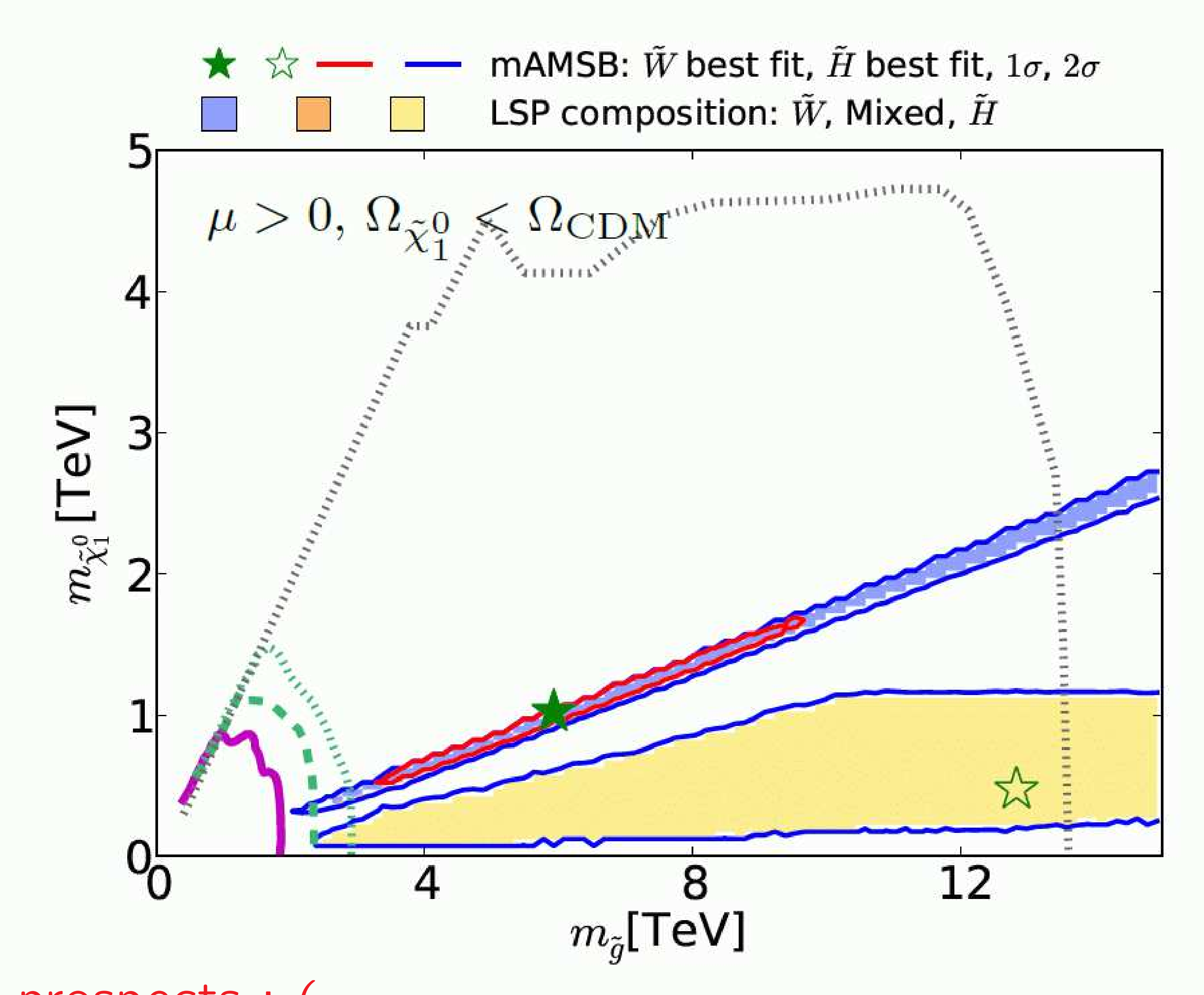


⇒ bad LHC prospects :-(

⇒ better FCC-hh prospects :-)

Gluino mass vs. DM mass:

[2016]

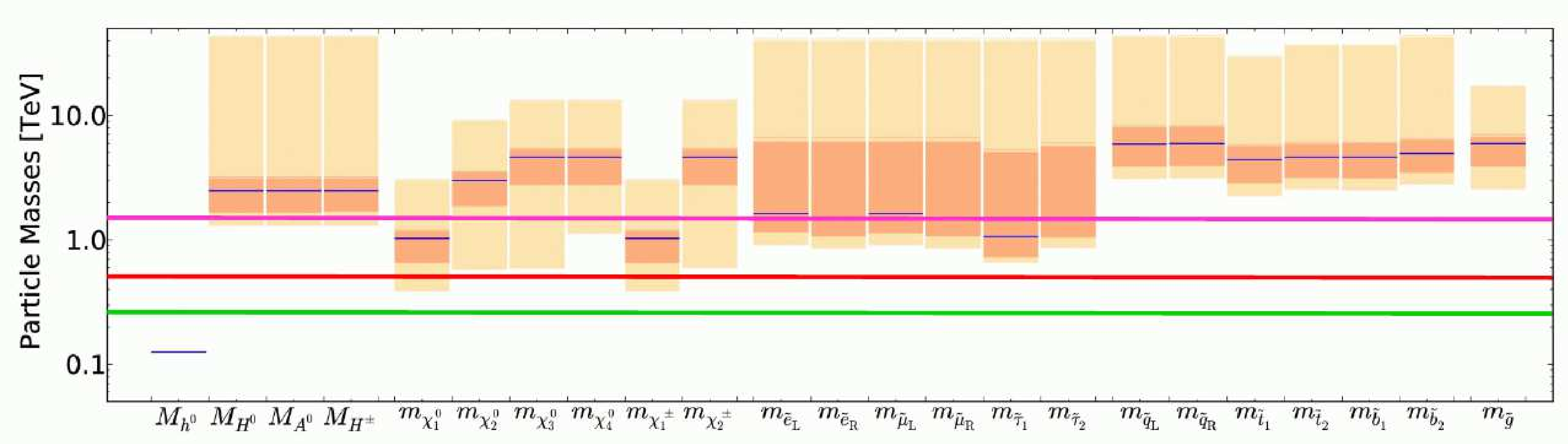


⇒ bad LHC prospects :-(

⇒ better FCC-hh prospects :-)

mAMSB prediction: best-fit masses (wino)

[2016]



$\Rightarrow$ high colored masses

$\Rightarrow$ lower electroweak masses

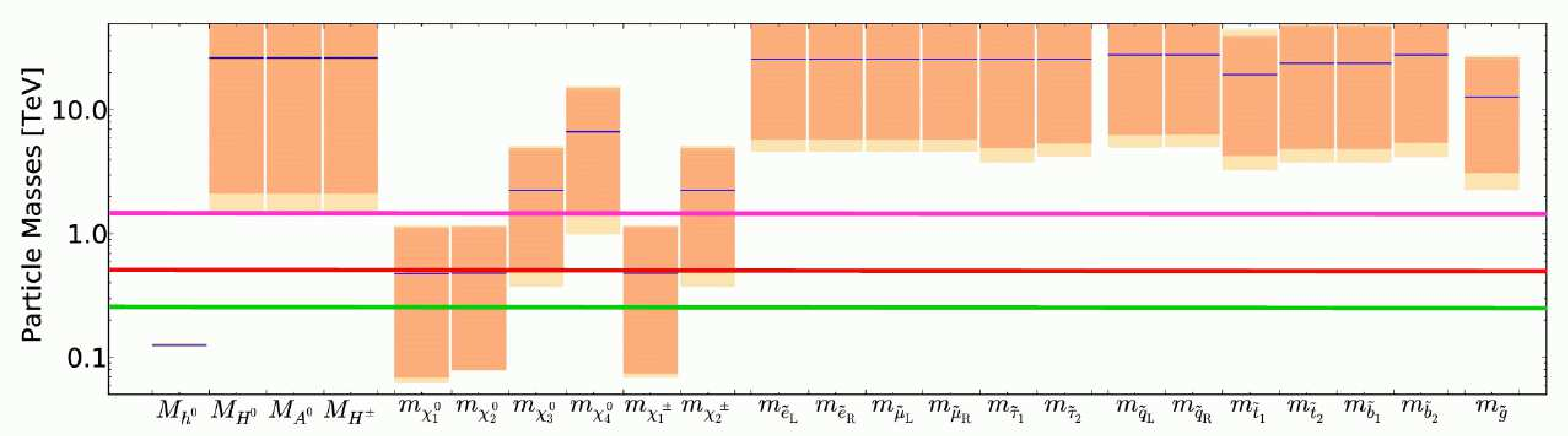
ILC: $\sqrt{s} = 1000$ GeV $\Rightarrow$ bad prospects

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

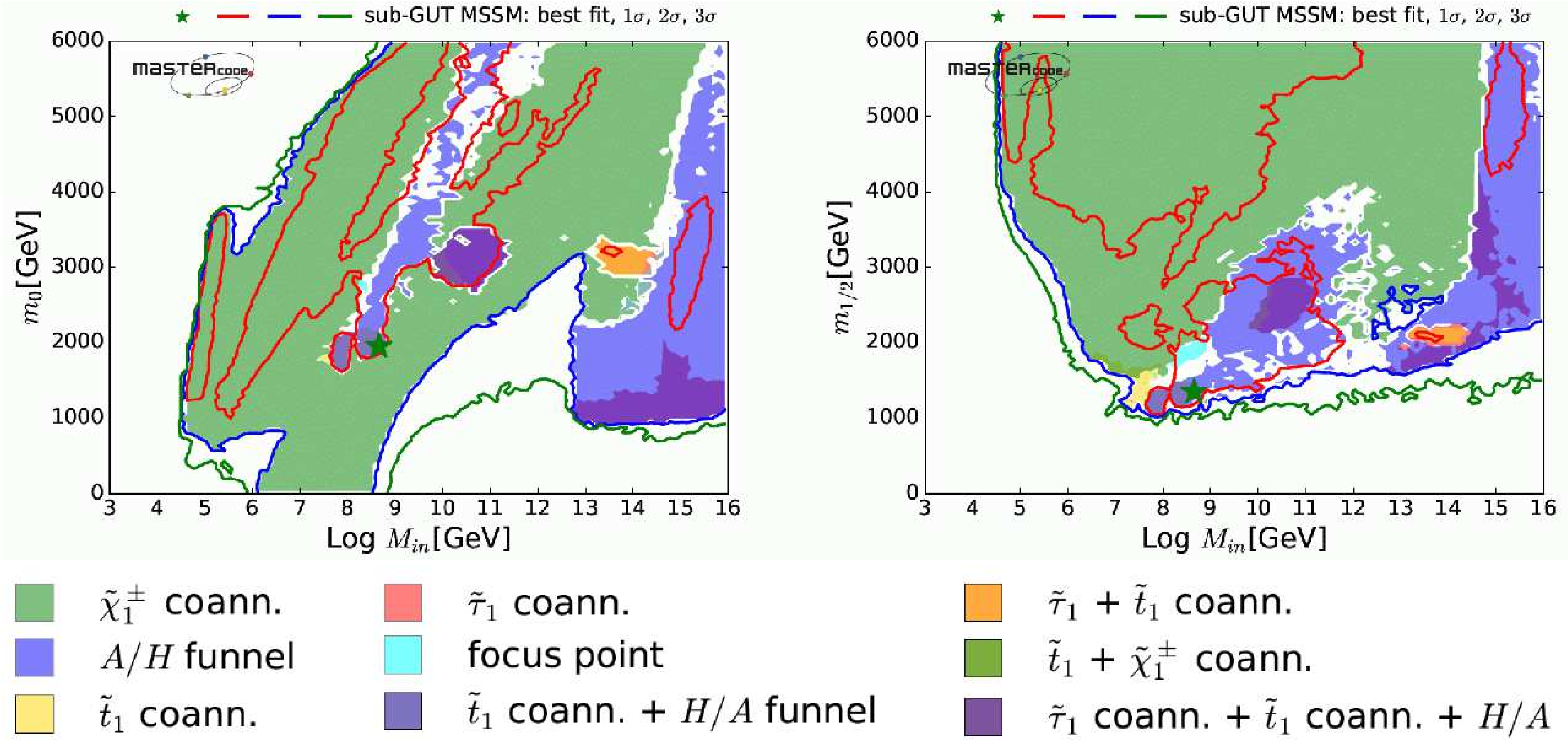
⇒ lower electroweak masses

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

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

Results in sub-GUT

[2017]

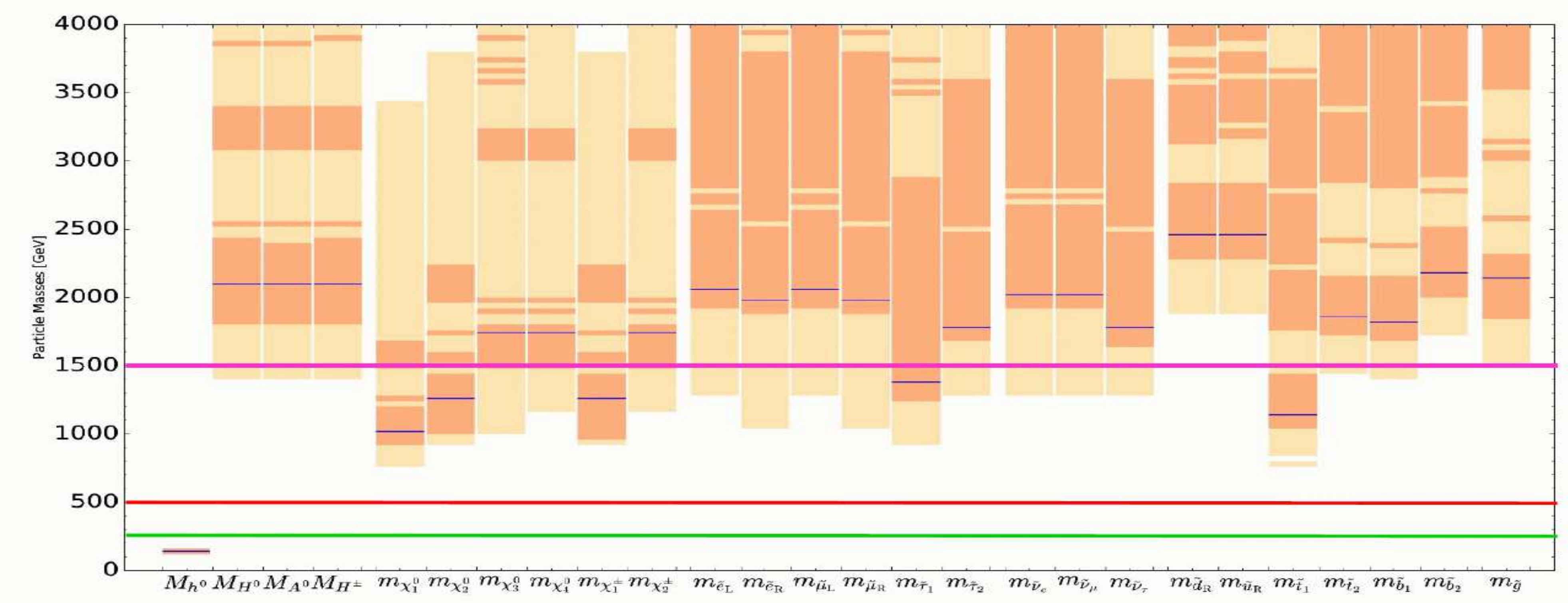


⇒ low M_{in} possible/favored

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

sub-GUT prediction: best-fit masses

[2017]



⇒ 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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– colored spectrum could partially be covered at FCC-hh

ARE WE DEPRESSED?

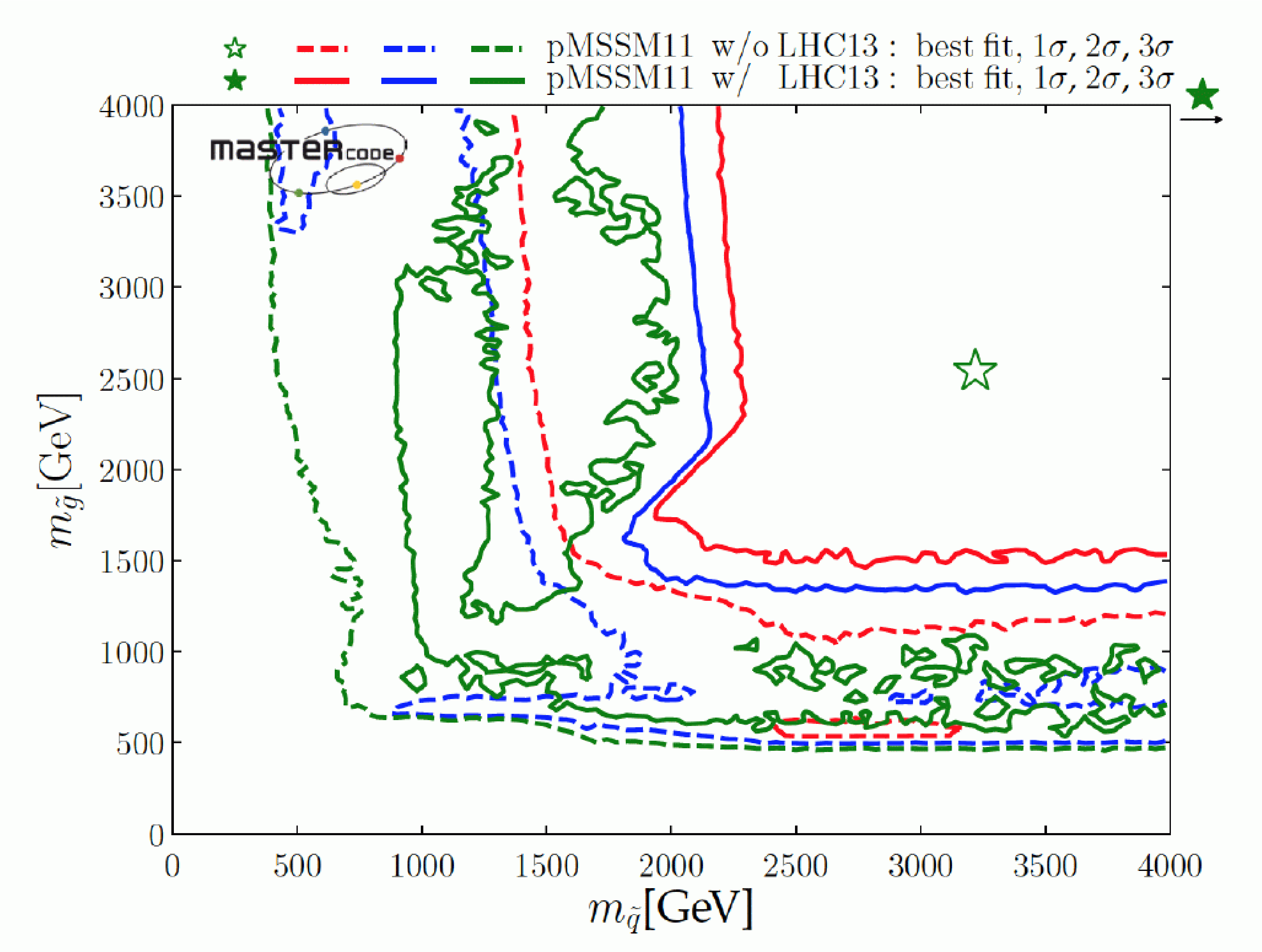
Let's look at the more general pMSSM11!

Results and predictions 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)

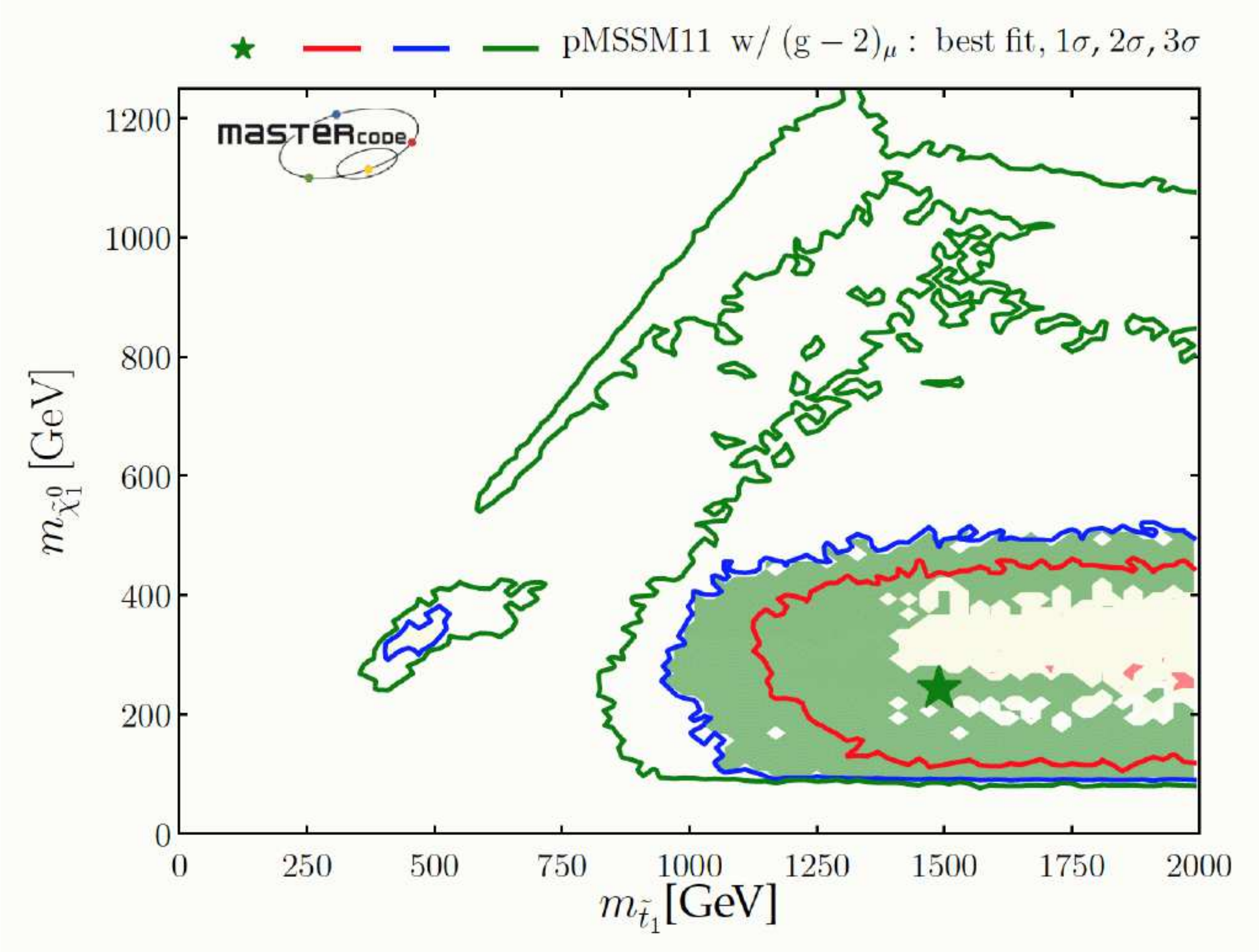
[2017]



⇒ substantial move to higher masses!

⇒ notice the "nose"!

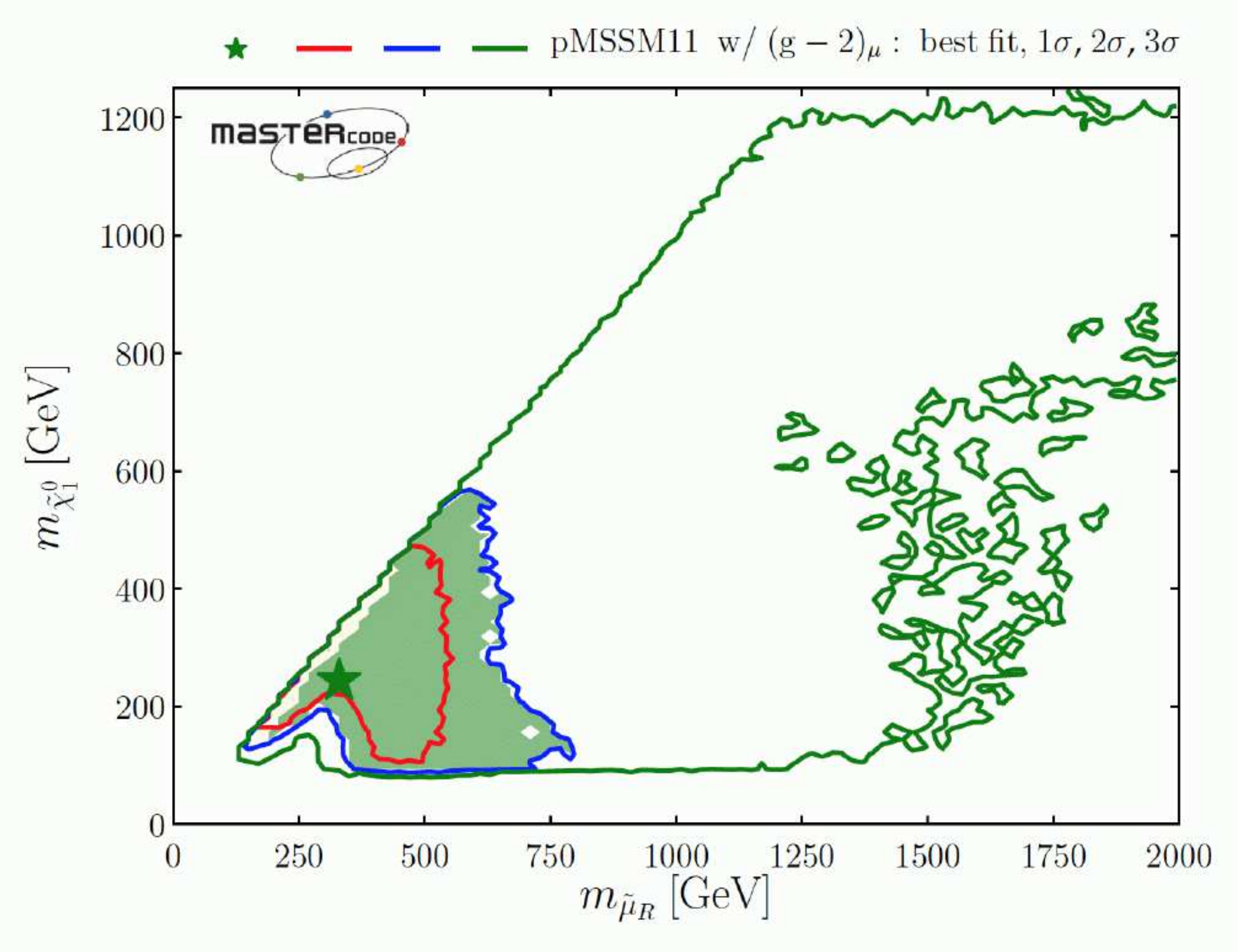
pMSSM11: $m_{\tilde{t}_1}$–$m_{\tilde{\chi}^0_1}$ plane



■	$\tilde{\chi}^\pm_1$ coann.	■	slep coann.	■	gluino coann.	■	stop coann.
■	A/H funnel	■	stau coann.	■	squark coann.	■	sbot coann.

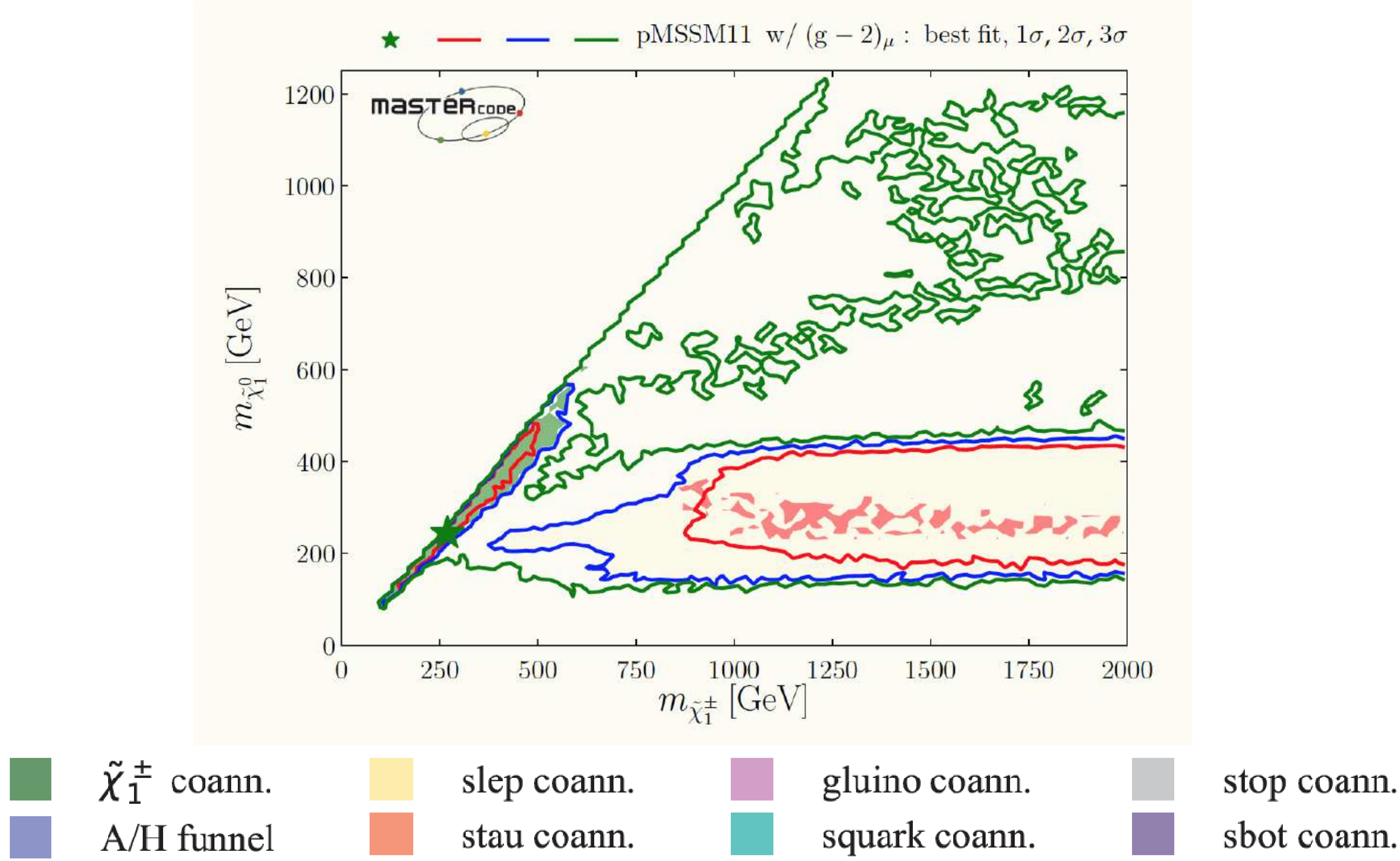
⇒ high (low) stop (neutralino) masses ⇒ notice the compressed region!

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

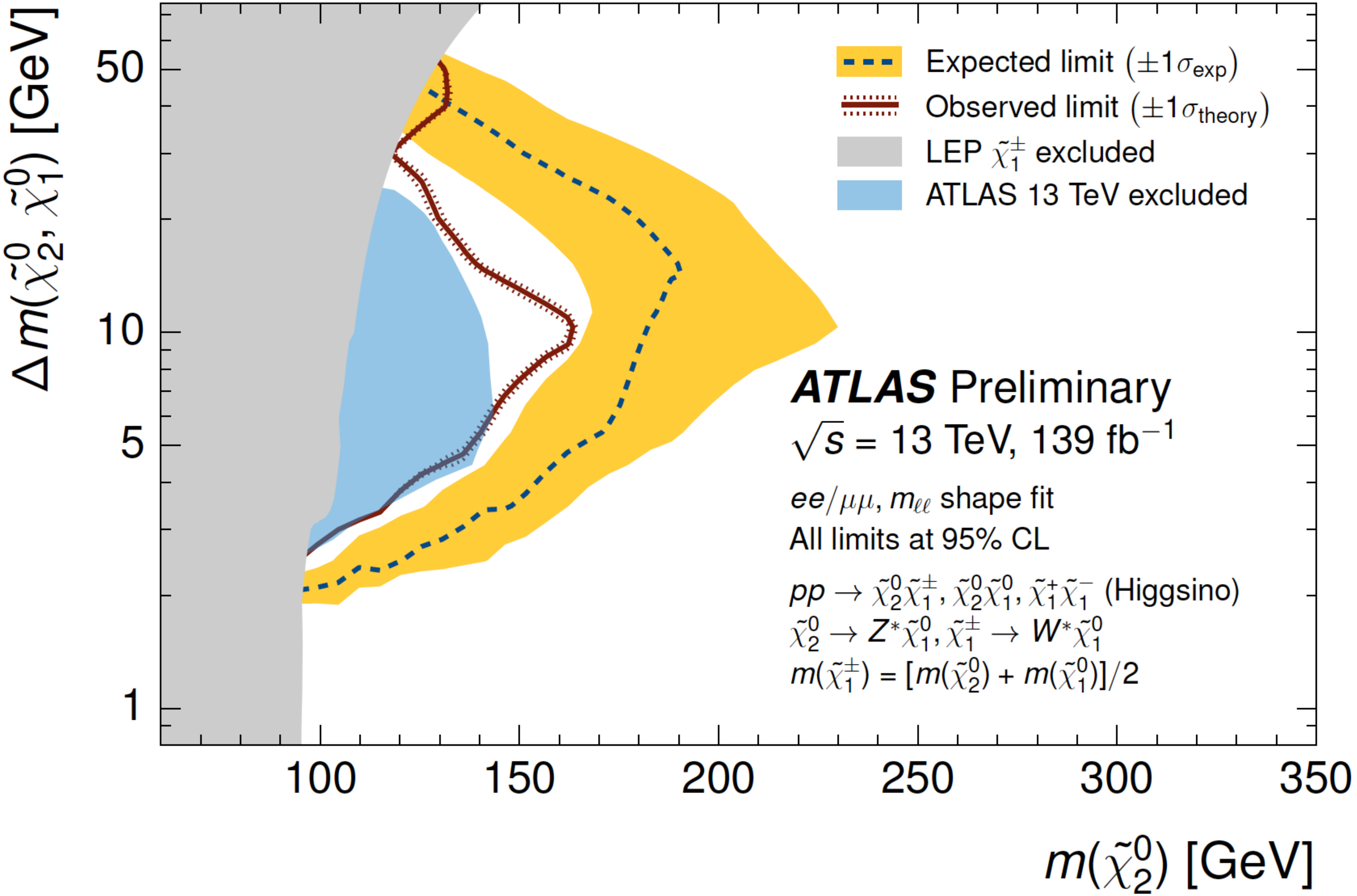


	$\tilde{\chi}_1^\pm$ coann.		slep coann.		gluino coann.		stop coann.
	A/H funnel		stau coann.		squark coann.		sbot coann.

⇒ all masses low!!

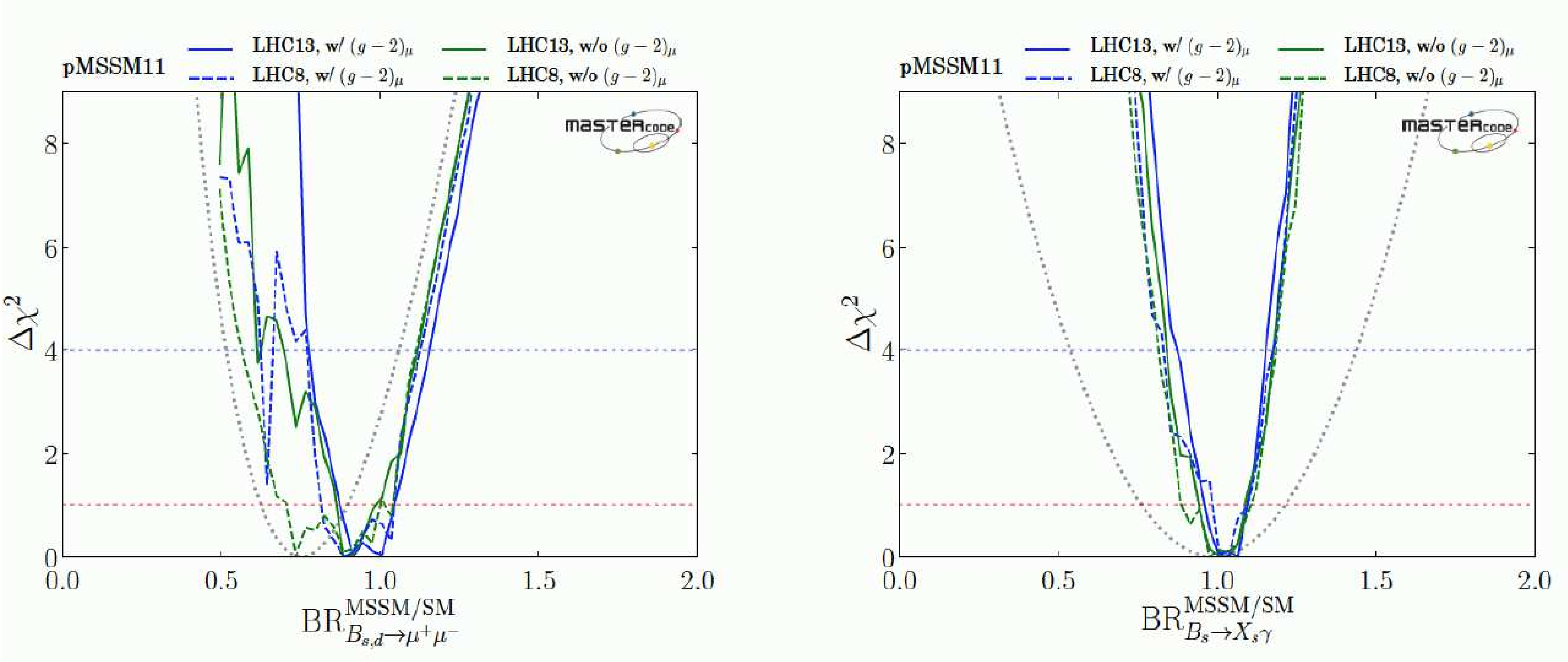


⇒ chargino co-annihilation ⇒ $M_1 \sim M_2$



Expected limit $(\pm 1\sigma_{exp})$
Observed limit $(\pm 1\sigma_{theory})$
LEP $\tilde{\chi}_1^\pm$ excluded
ATLAS 13 TeV excluded
ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
$ee/\mu\mu$, $m_{\ell\ell}$ shape fit
All limits at 95% CL
$pp \to \tilde{\chi}_2^0\tilde{\chi}_1^\pm, \tilde{\chi}_2^0\tilde{\chi}_1^0, \tilde{\chi}_1^+\tilde{\chi}_1^-$ (Higgsino)
$\tilde{\chi}_2^0 \to Z^*\tilde{\chi}_1^0, \tilde{\chi}_1^\pm \to W^*\tilde{\chi}_1^0$
$m(\tilde{\chi}_1^\pm) = [m(\tilde{\chi}_2^0) + m(\tilde{\chi}_1^0)]/2$
$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ [GeV]
50
10
5
1
100
150
200
250
300
350
$m(\tilde{\chi}_2^0)$ [GeV]

pMSSM11: B physics observables



⇒ follows the experimental data

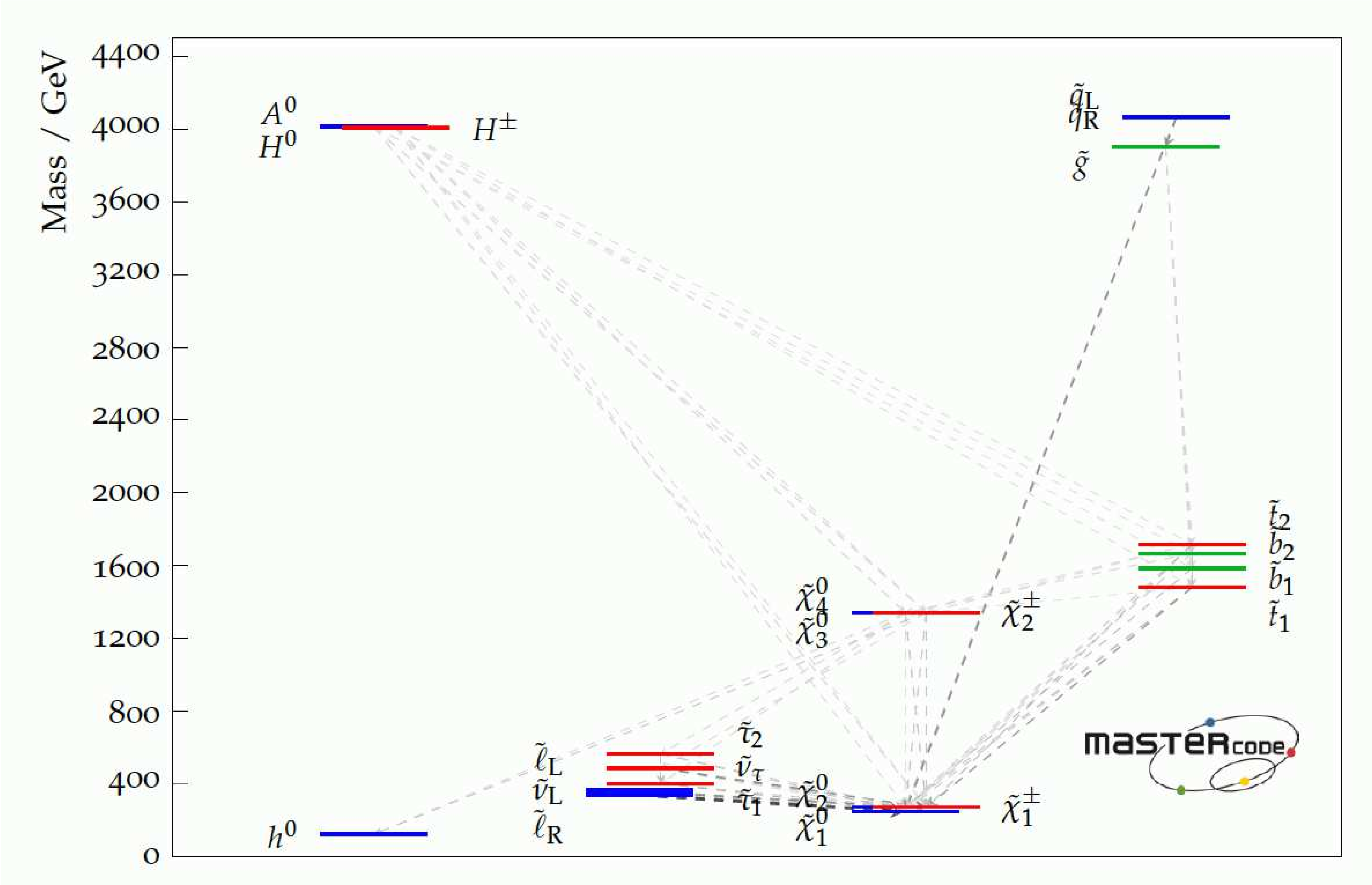
⇒ BR($B_s \to \mu^+\mu^-$): below the SM value

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

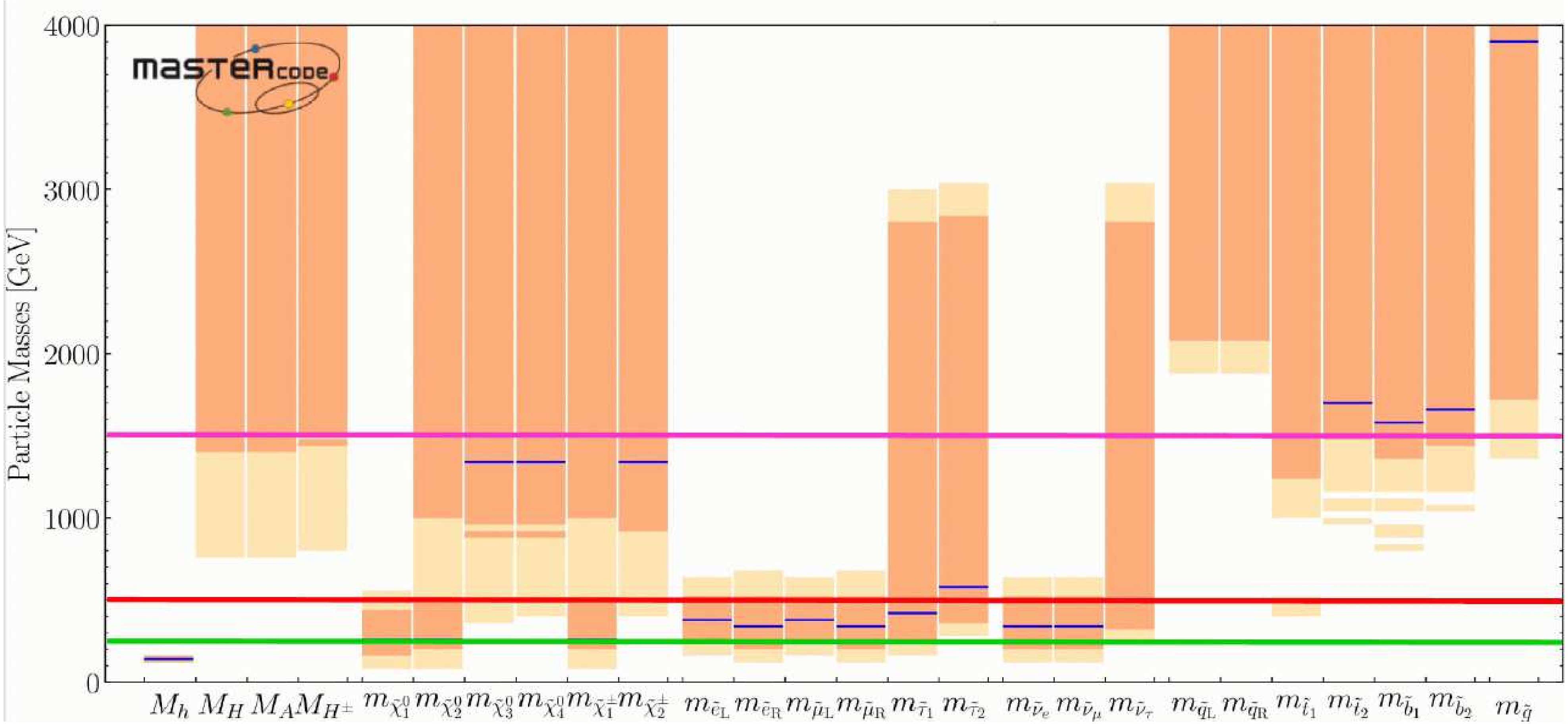
$\Rightarrow$ excellent p value!



⇒ heavy colored, light uncolored spectrum

pMSSM11: prospects for ILC and CLIC

[2017]



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?

What to conclude?

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

What to conclude?

⇒ **Look at the p values!**

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?

⇒ **Look at the p values!**

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mAMSB	36.5/27	11%
sub-GUT	28.9/24	23%
pMSSM11	21.0/20	33%

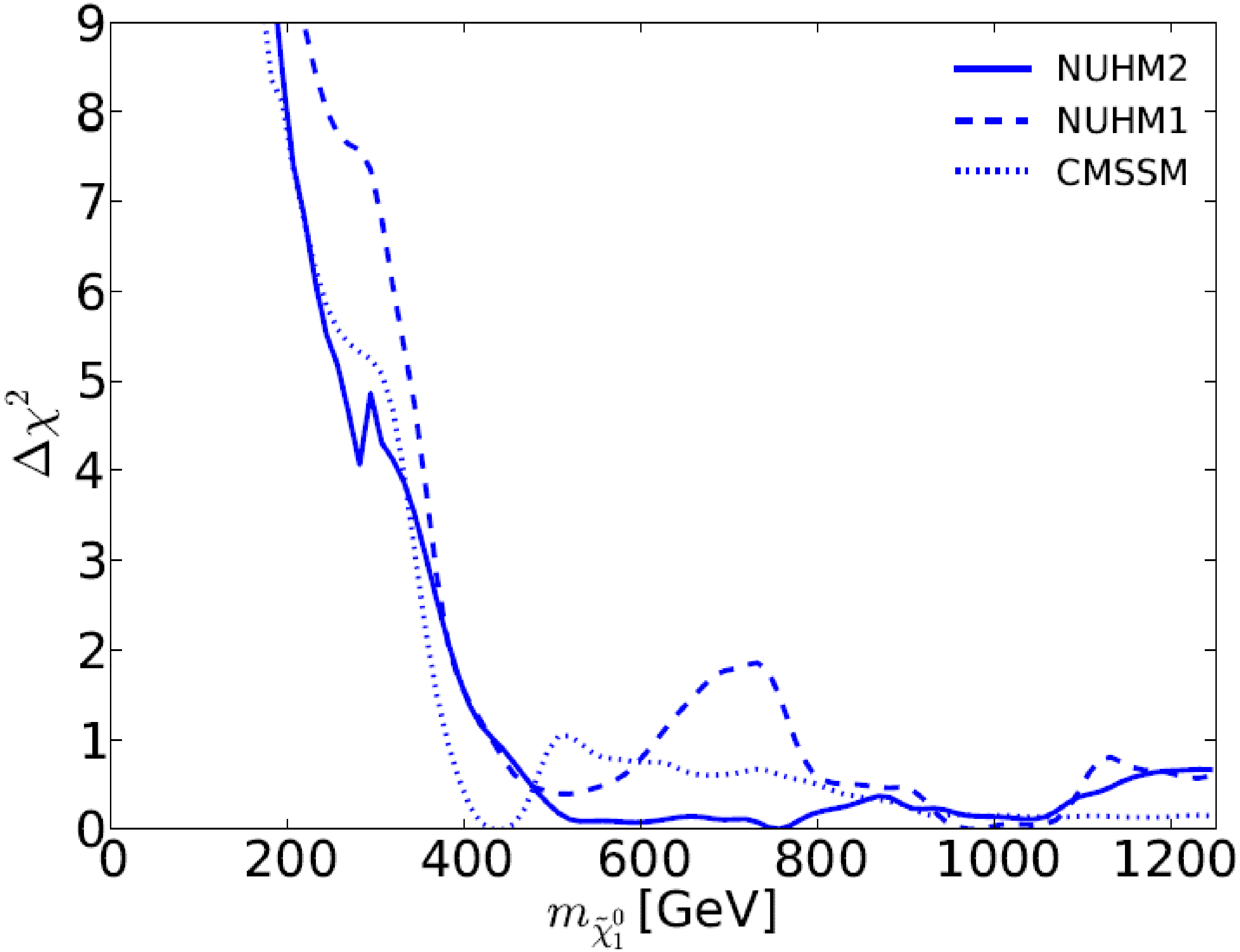
Which model is more likely??

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

4. Where is the Dark Matter

Results in the CMSSM, NUHM1, NUHM2

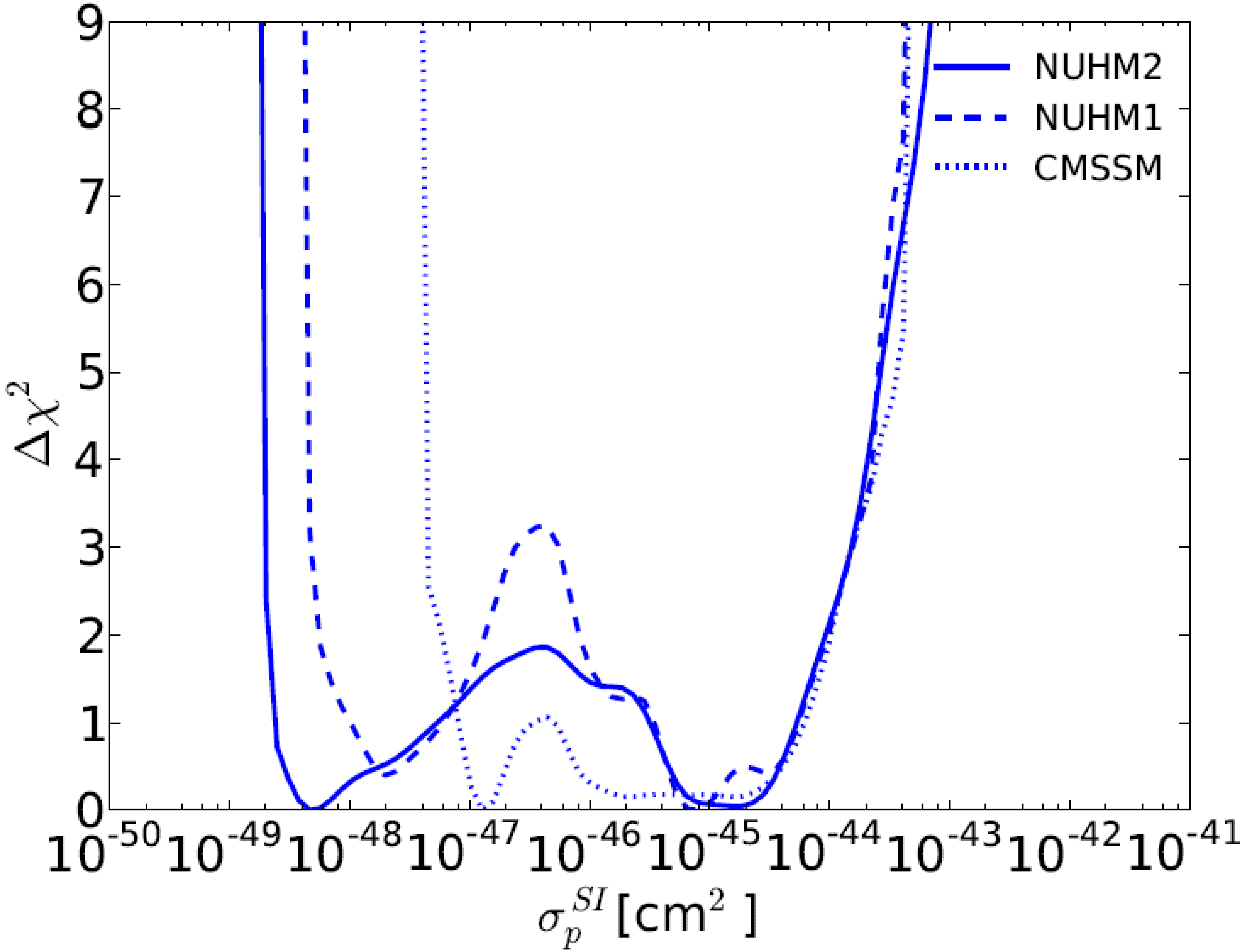
[2014]



⇒ only very large values are favored

σ_p^{SI} incl. 20/fb of LHC data

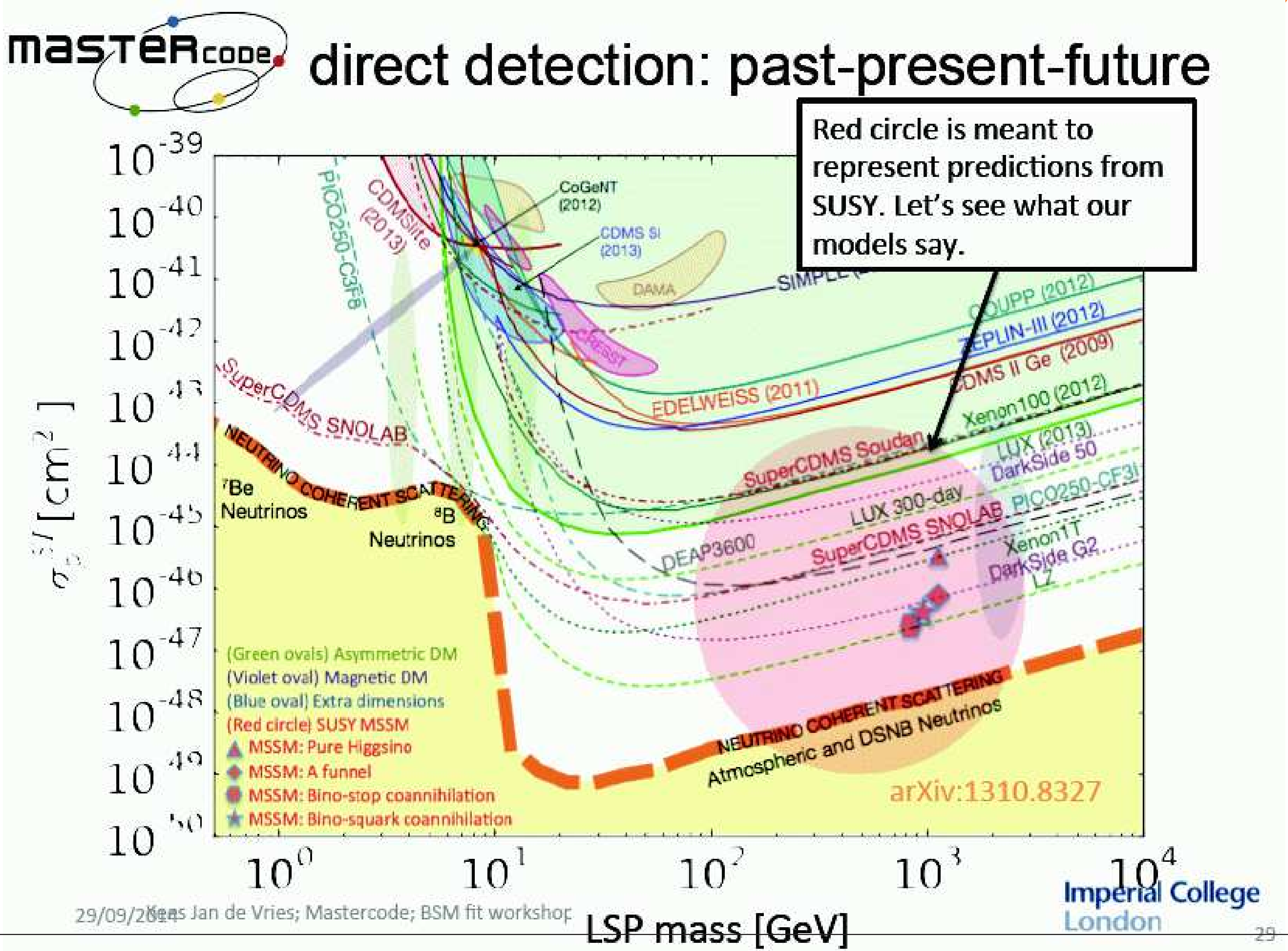
[2014]



$\Rightarrow$ only very small values are favored

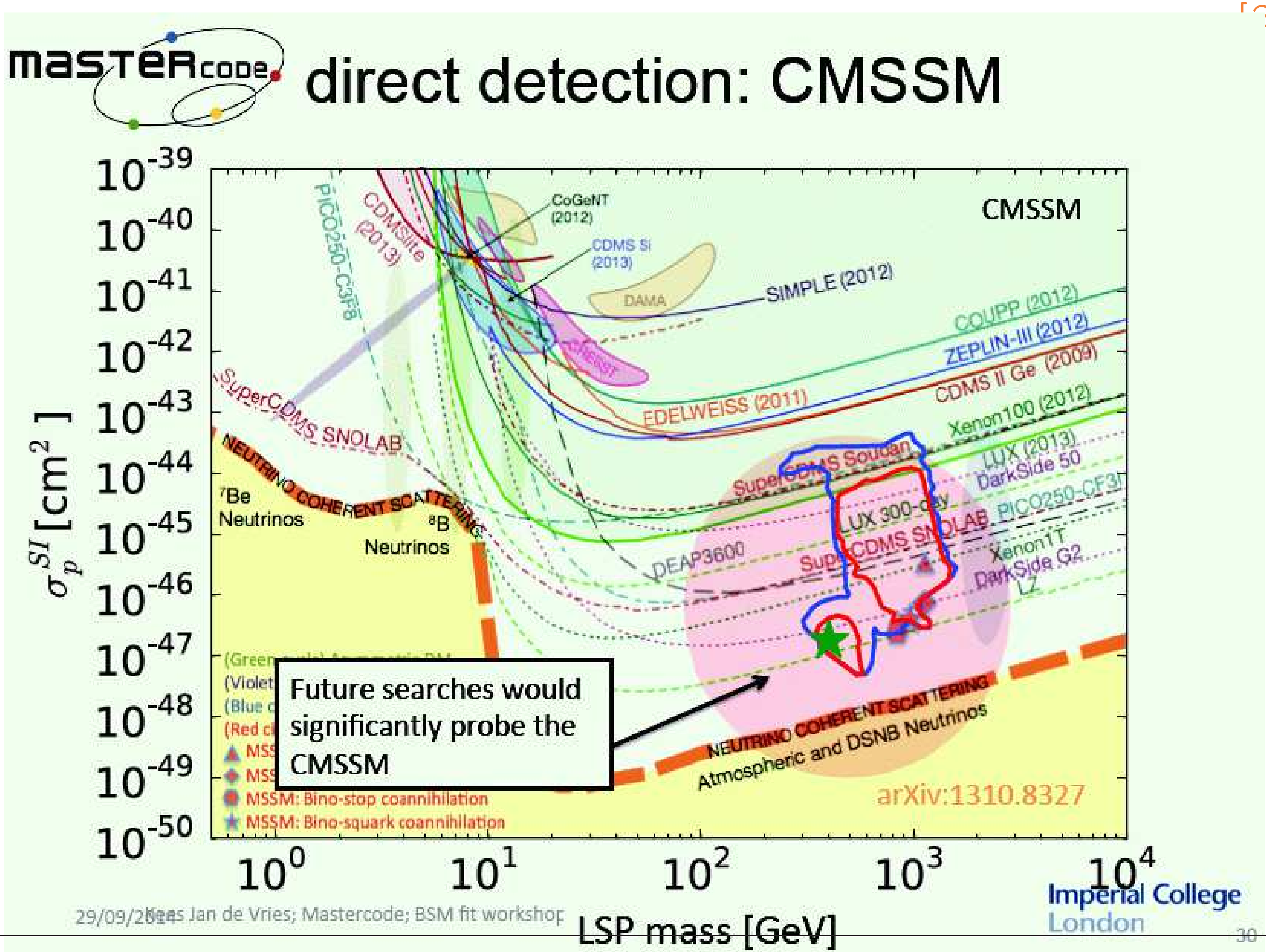
MSSM DM prediction

[2014]



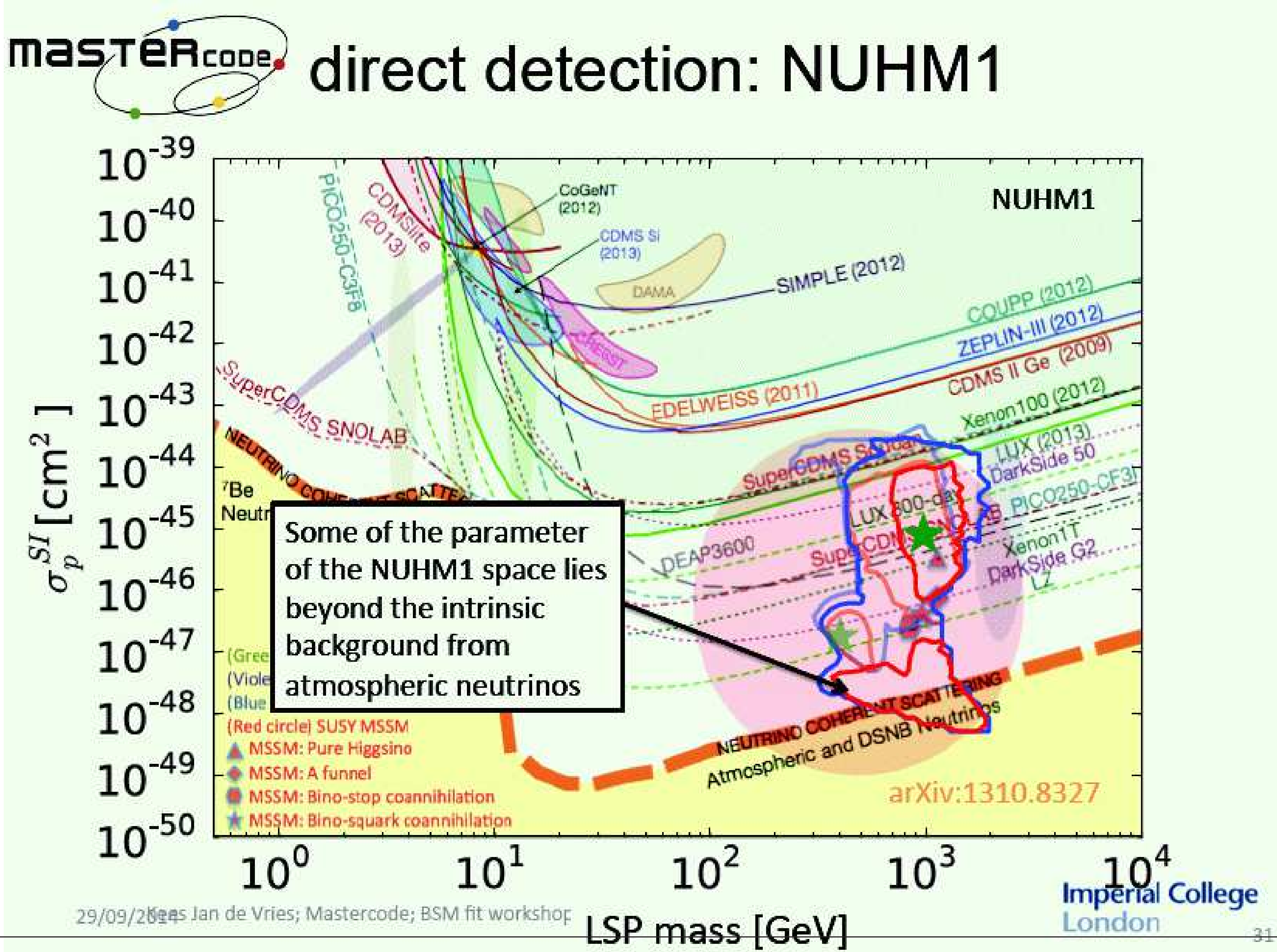
MSSM DM prediction

[2014]



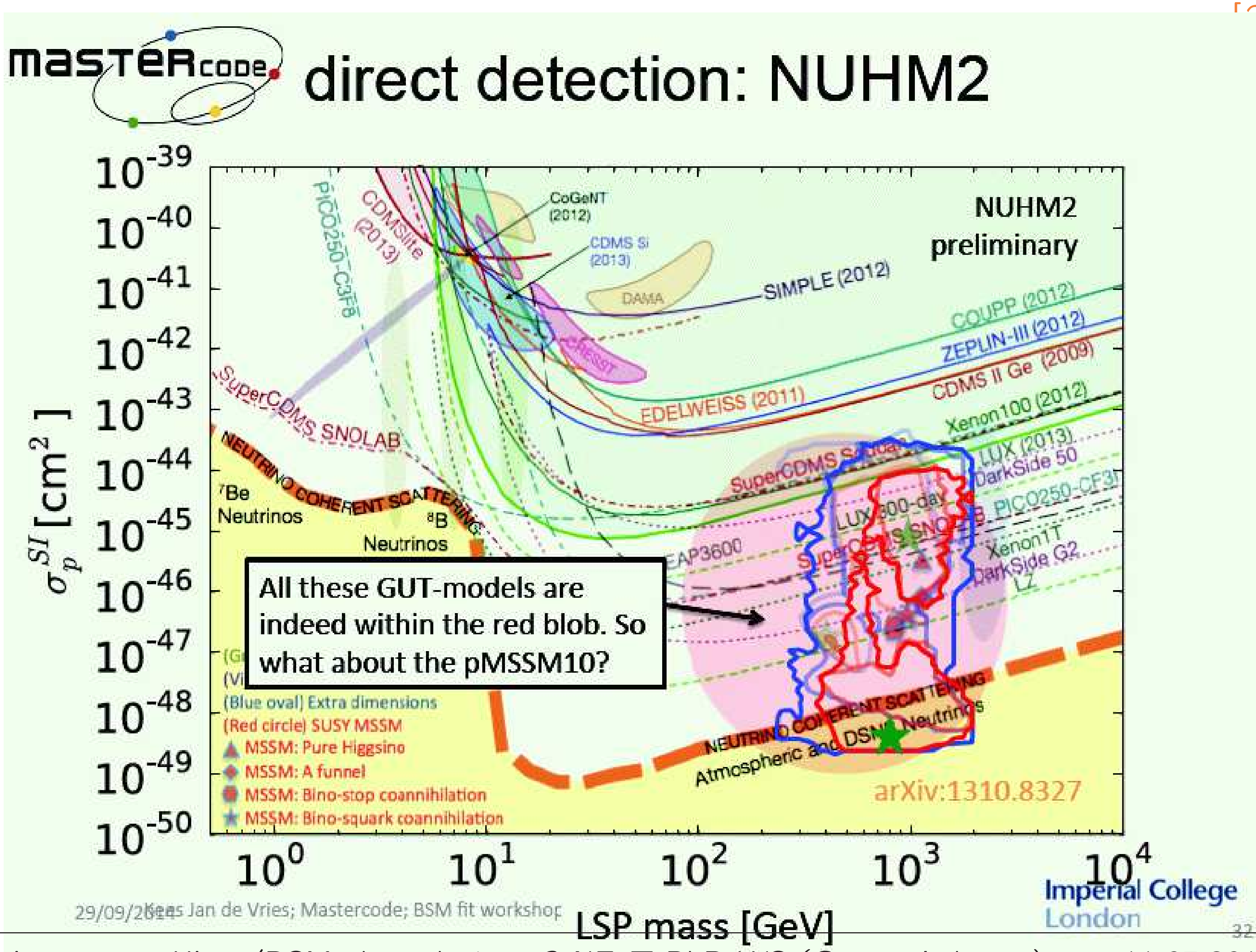
MSSM DM prediction

[2014]



MSSM DM prediction

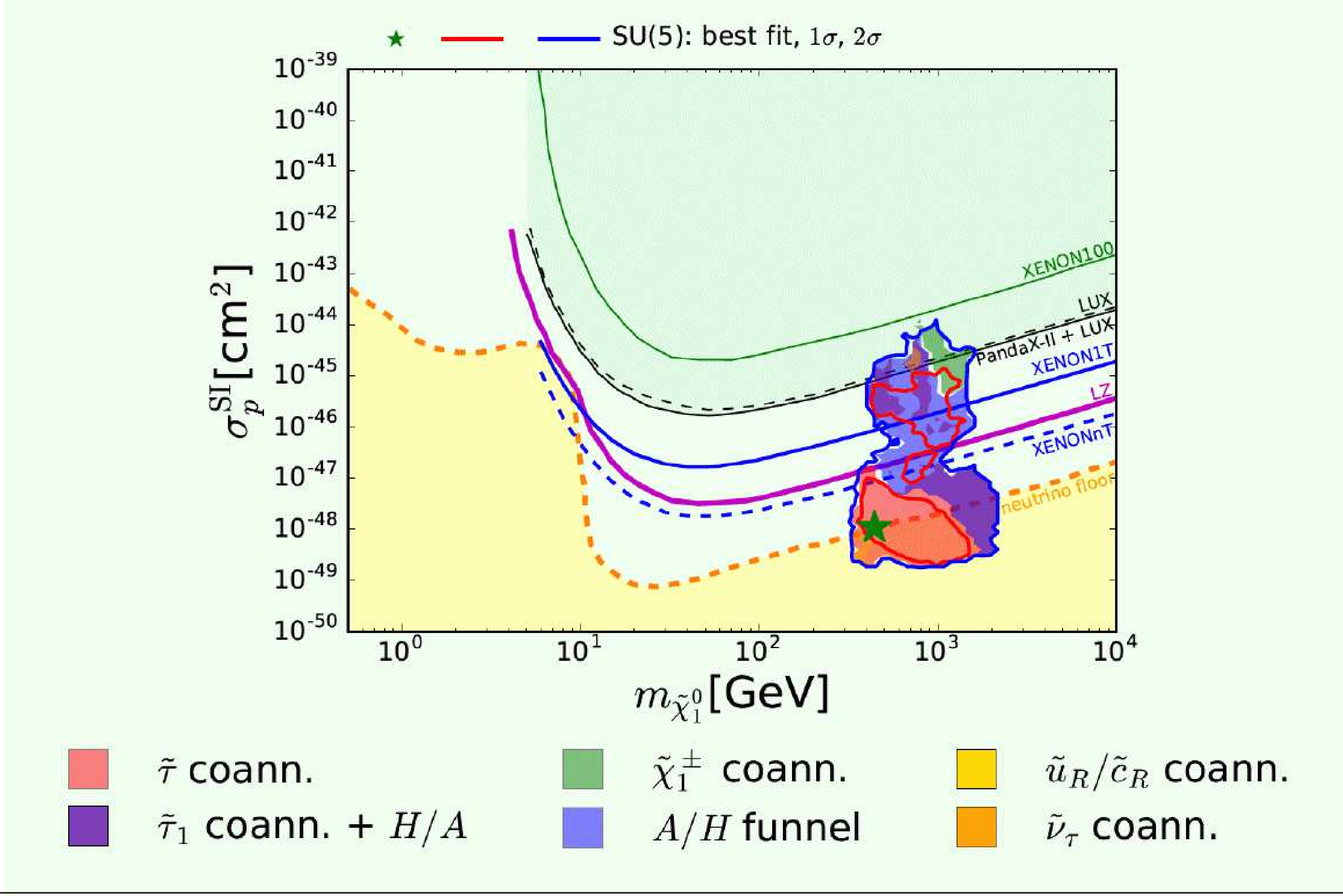
[?2014]



Results in the SU(5)

Dark Matter Diret Detection prospects:

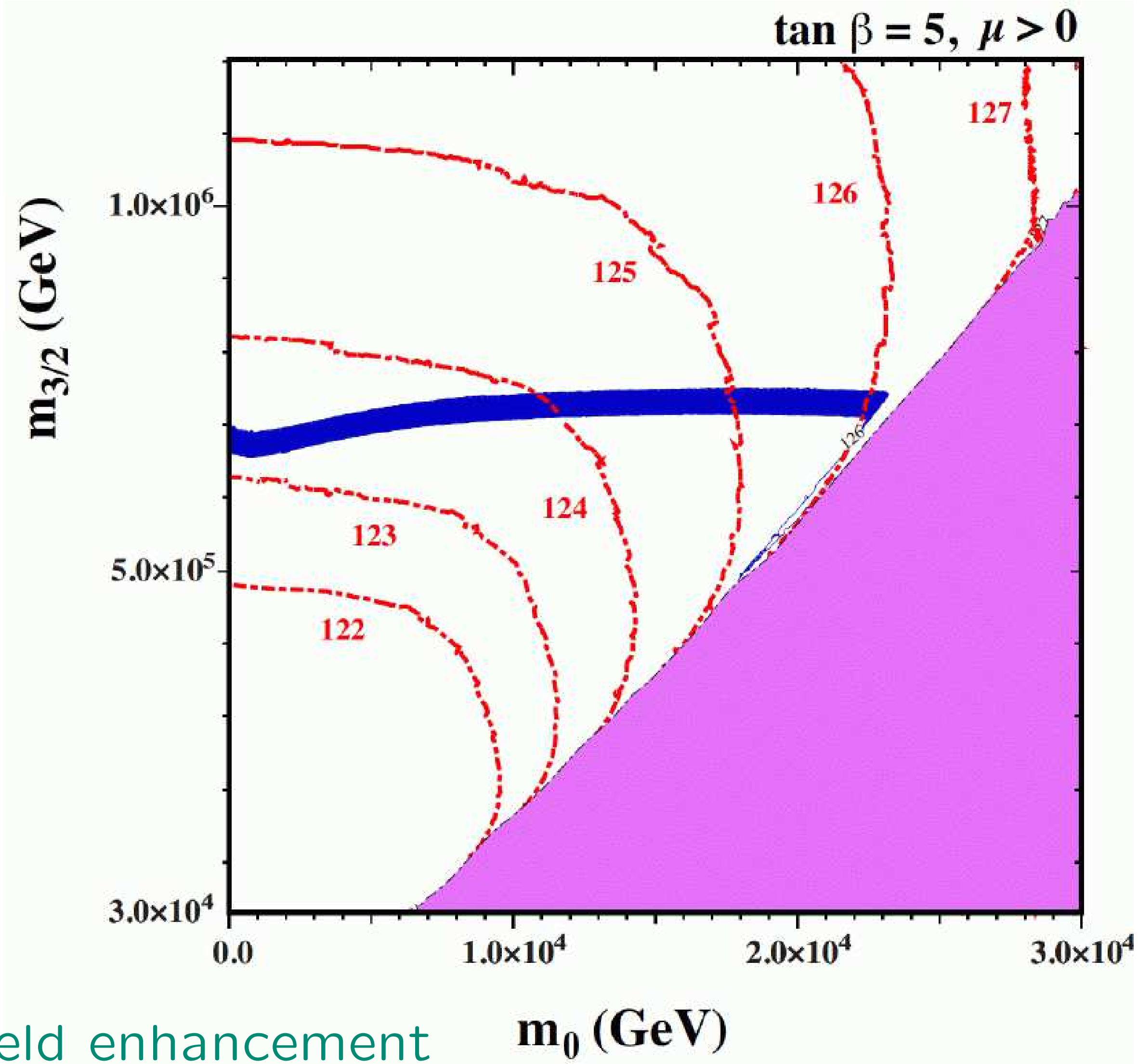
[*2016*]



Results in the mAMSB

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

[2016]

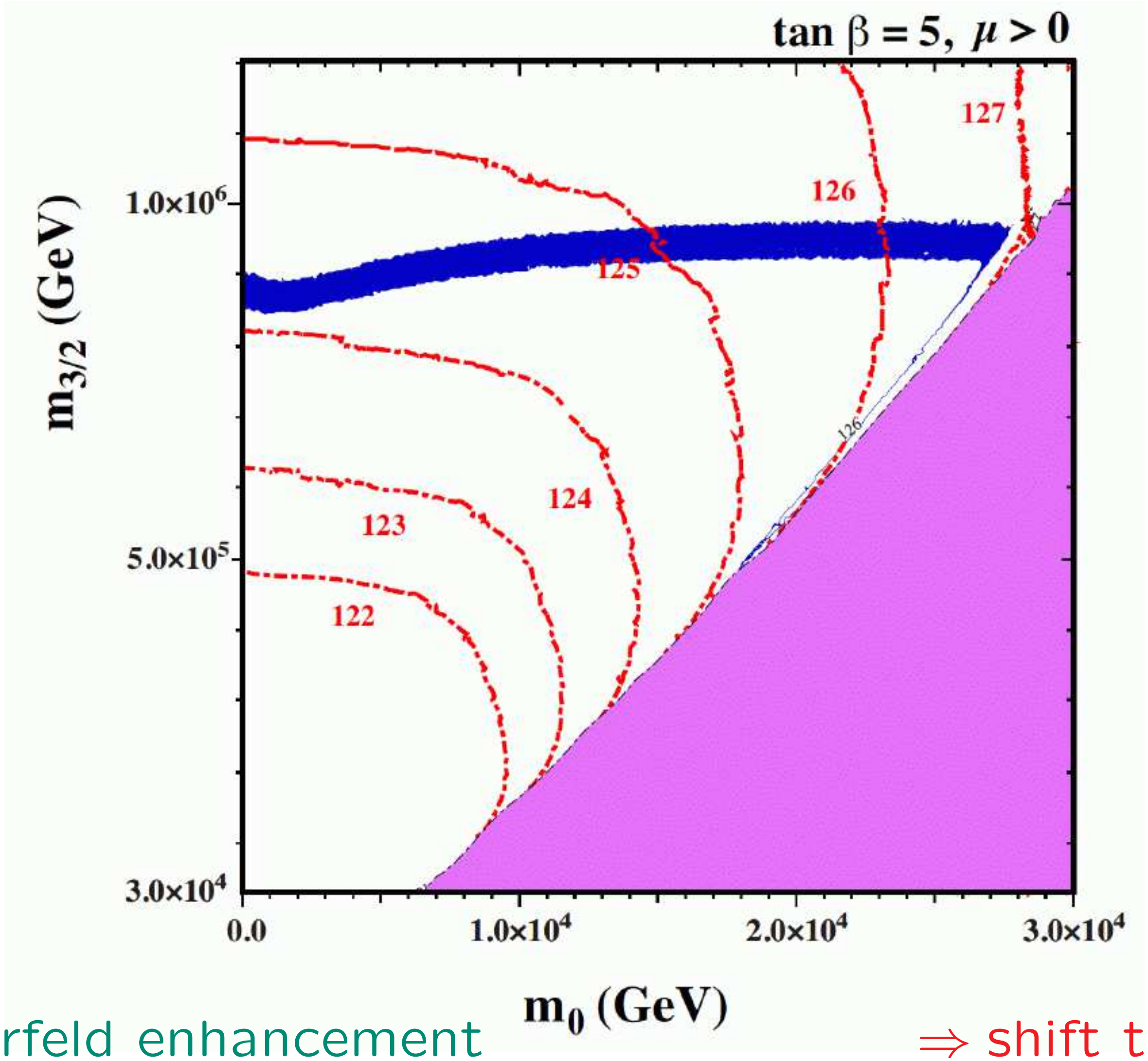


⇒ no Sommerfeld enhancement

Results in the mAMSB

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

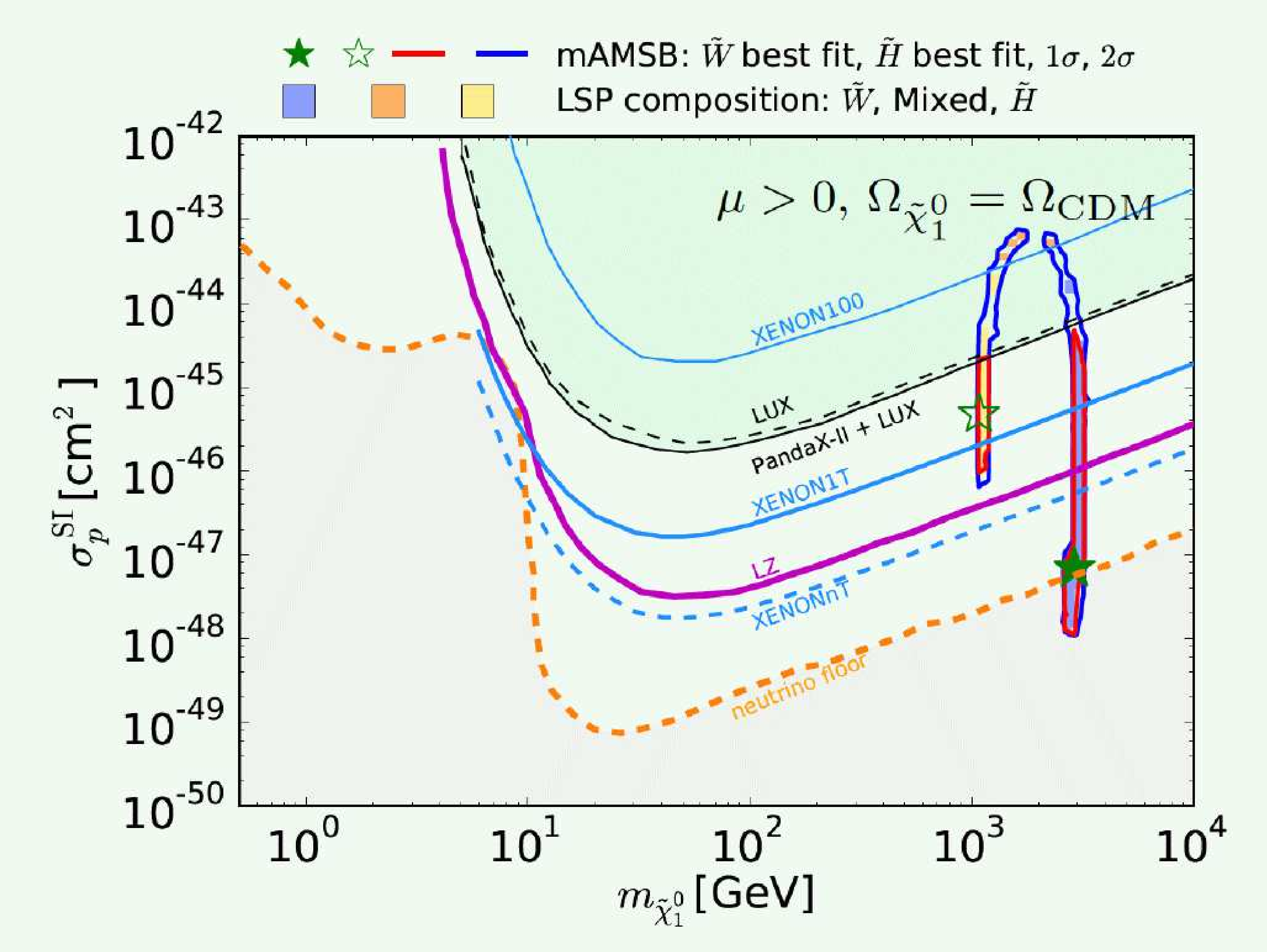
[2016]



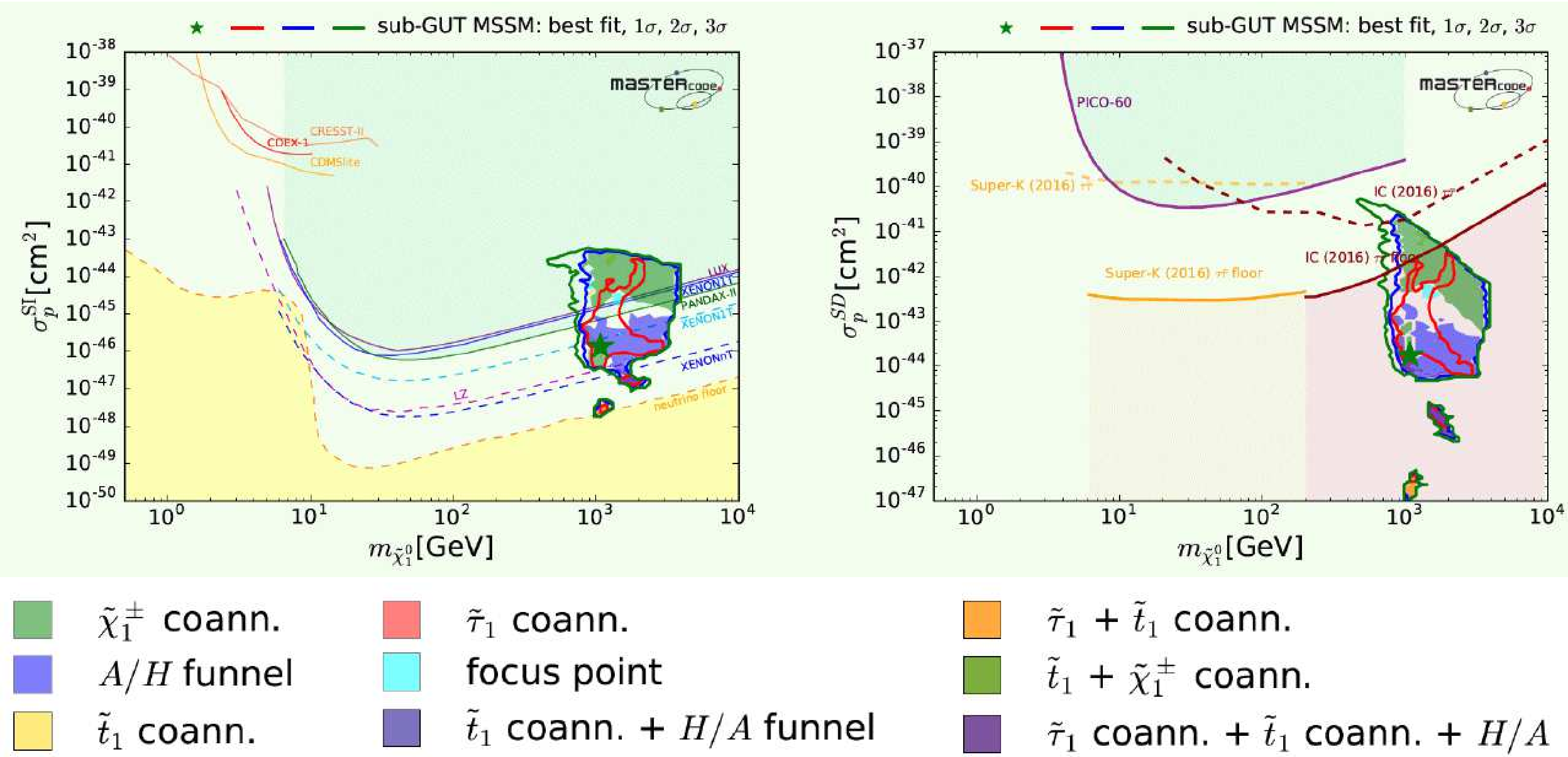
⇒ with Sommerfeld enhancement ⇒ shift to higher $m_{3/2}$

Dark Matter Diret Detection prospects:

[2016]



Results in sub-GUT



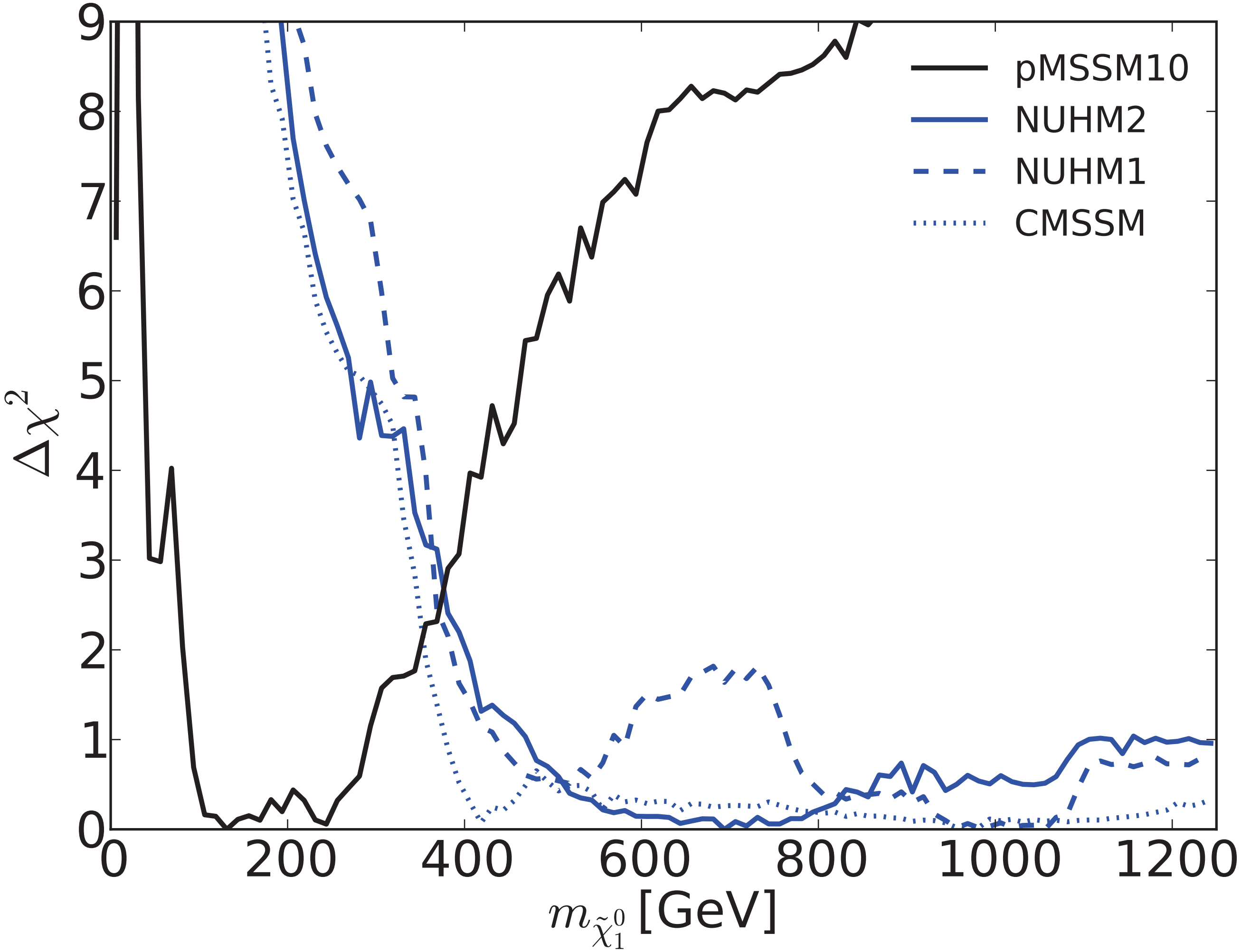
$\sigma_p^{\rm SI}$: good prospects, all above the neutrino floor

$\sigma_p^{\rm SD}$: unclear prospects, best-fit regions below the neutrino floor

Results in the pMSSM11

DM mass: pMSSM10 vs. GUT based models prediction:

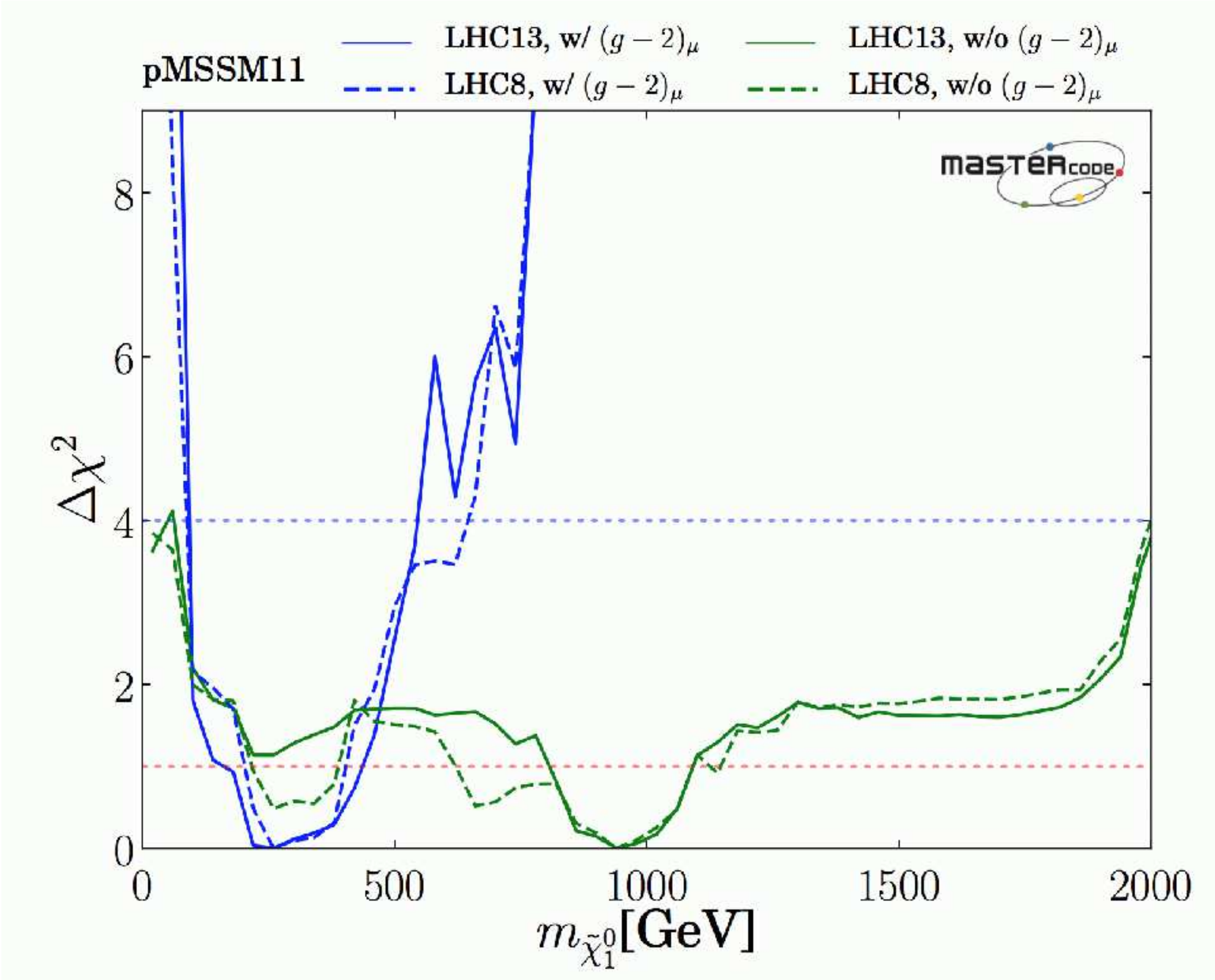
[2015]



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

Results in the pMSSM11

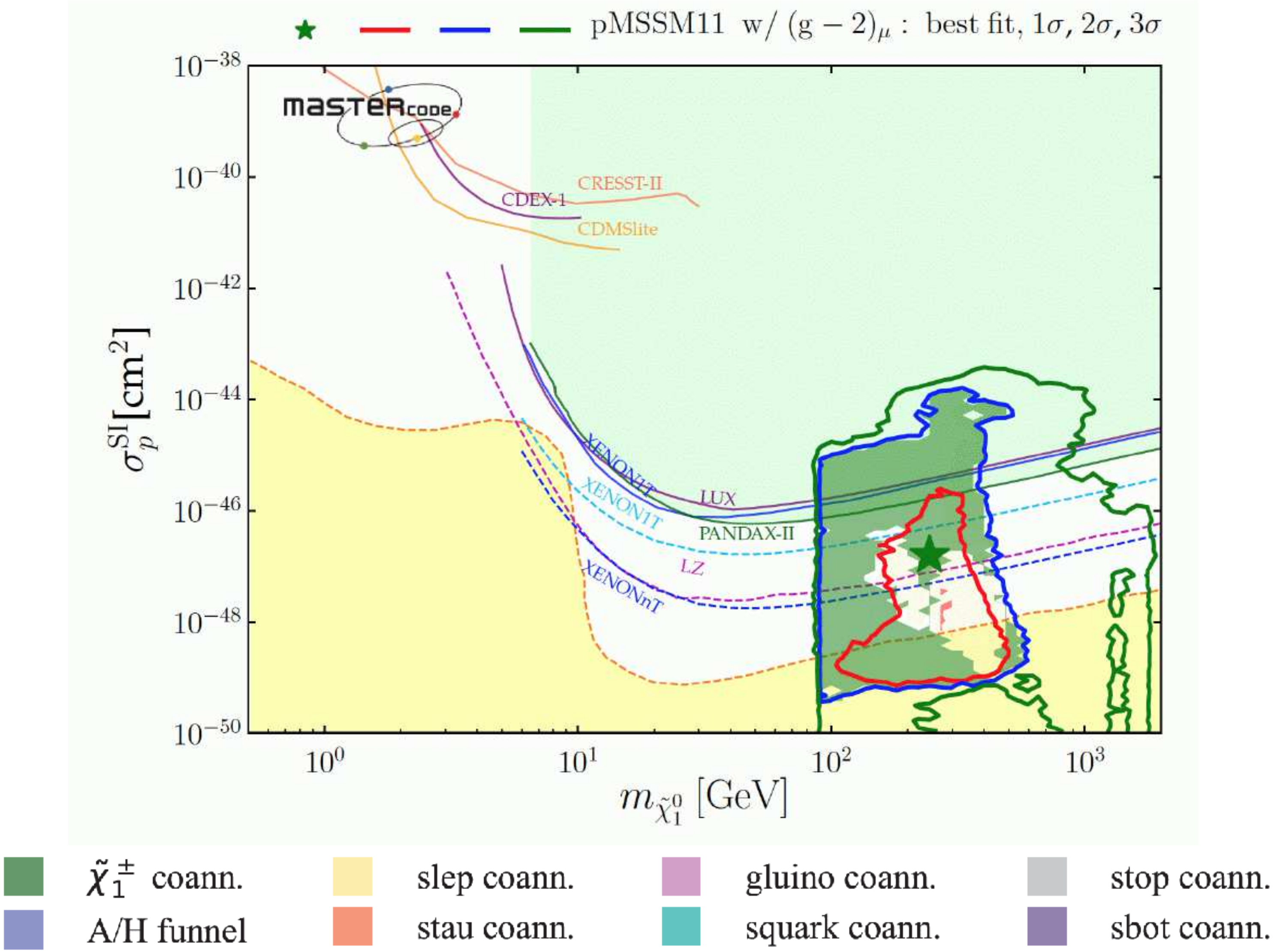
DM mass: similar in the pMSSM11:



⇒ pMSSM11 predicts much lower DM mass than GUT-based models

pMSSM11 prediction: $m_{\tilde{\chi}^0_1}$ vs. $\sigma_p^{\rm SI}$:

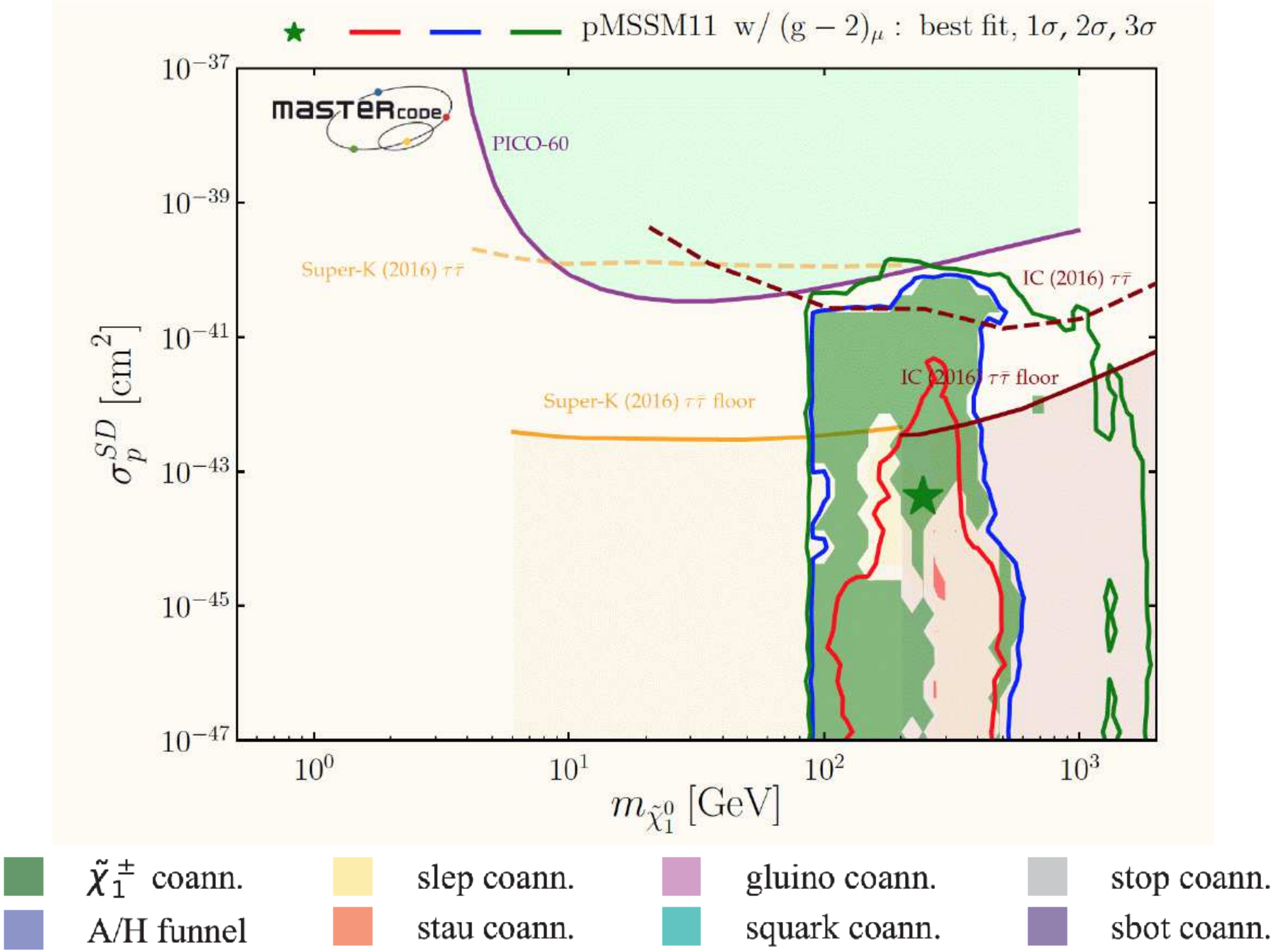
[2017]



⇒ best-fit point covered by future experiments

⇒ but very low cross sections possible at $1\,\sigma$, below neutrino floor

pMSSM11 prediction: $m_{\tilde{\chi}^0_1}$ vs. $\sigma_p^{\rm SD}$: [2017]



⇒ slim prospects for future experiments

⇒ large regions allowed at 1 σ, below neutrino floor

5. Conclusinos

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Further Questions?