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

SUSY Predictions for ILC and CLIC

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

SLAC, 06/2017

1. Introduction
2. The MasterCode
3. SUSY Fit Results for the ILC and CLIC
4. New Theory Predictions for the ILC and CLIC
5. Conclusions

1. Introduction

Some "recent" measurements:

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

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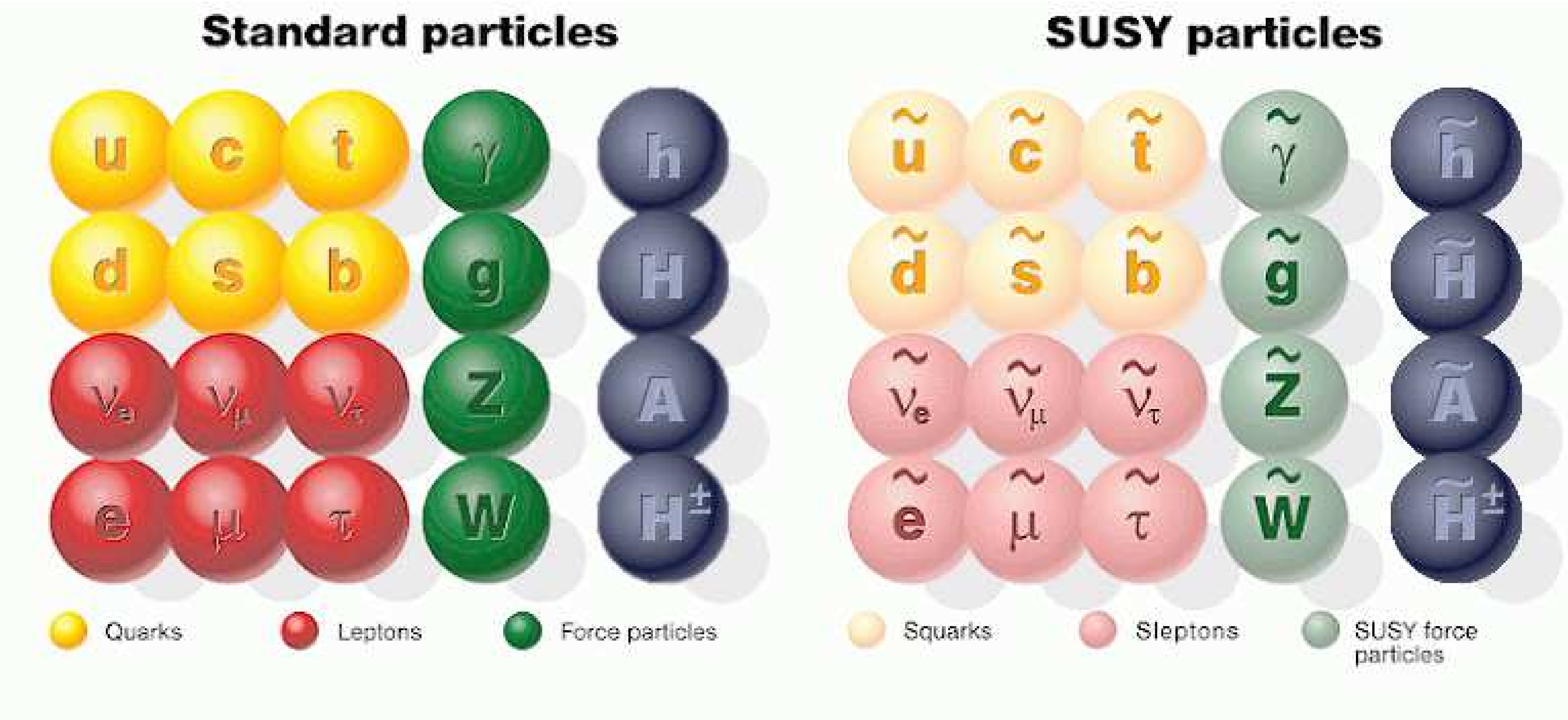
⇒ good motivation to look at SUSY!

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):

$\Rightarrow$ 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

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

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

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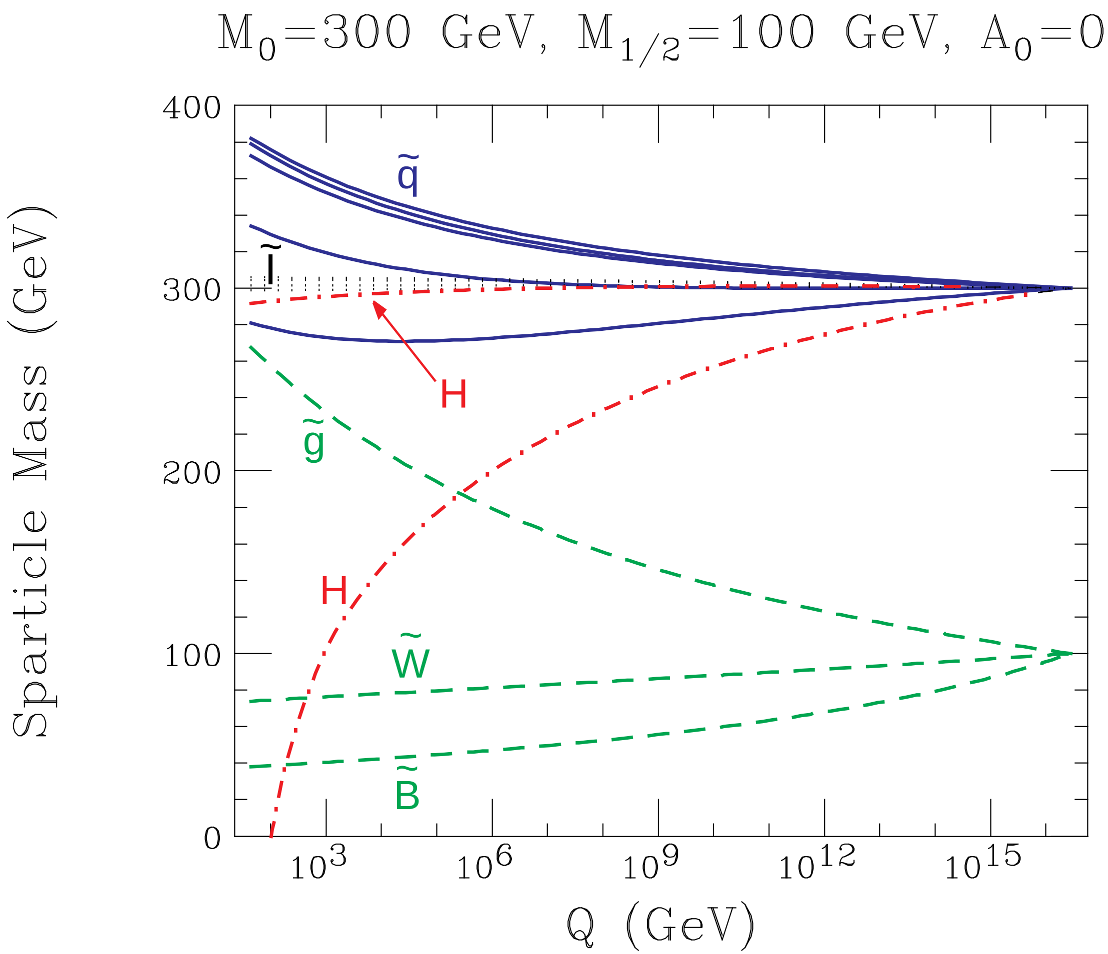


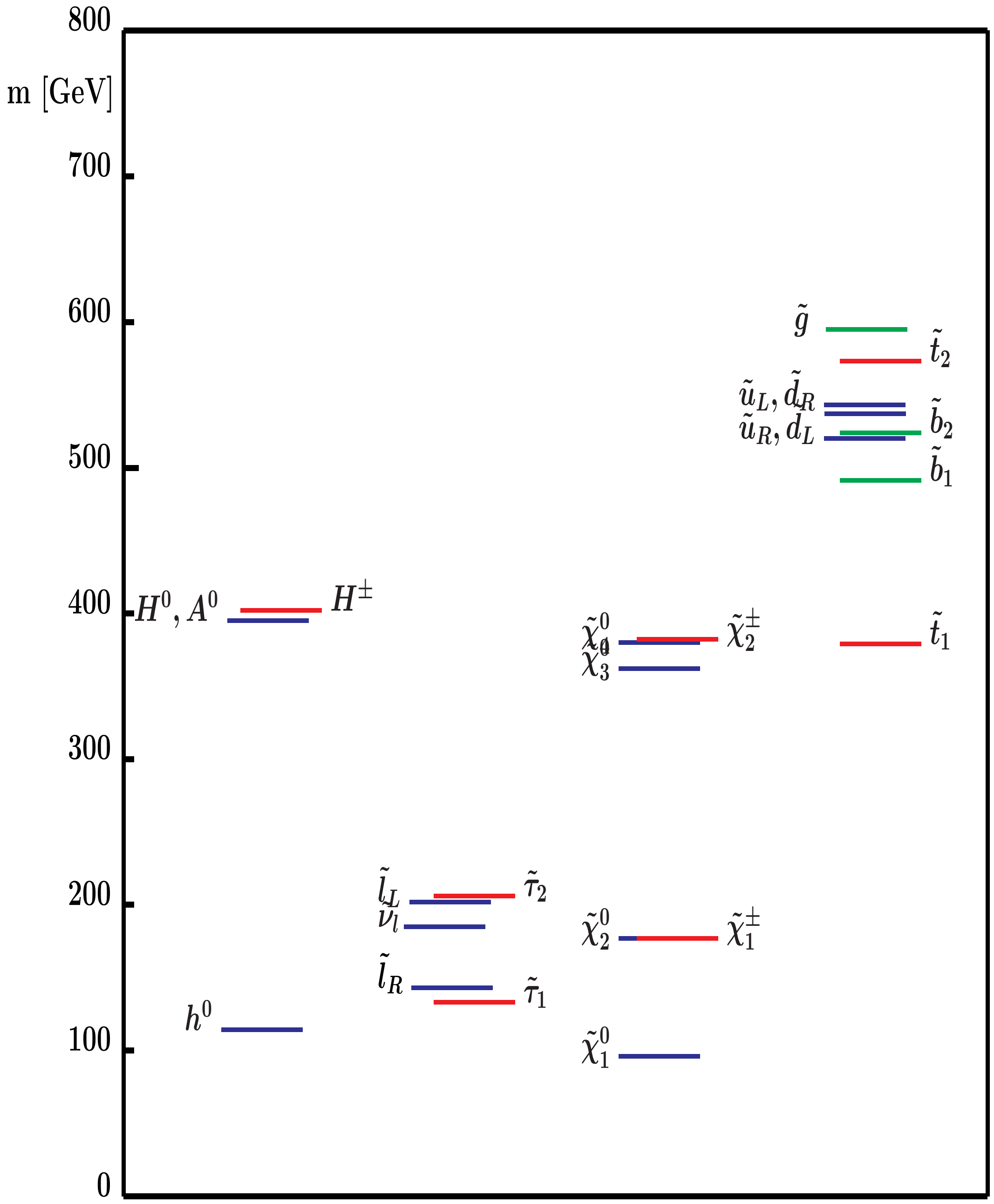
⇒ one parameter turns negative ⇒ Higgs mechanism for free

"Typical" CMSSM scenario

(SPS 1a benchmark scenario):

Strong connection between

all the sectors



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

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

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

⇒ Scenario characterized by

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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

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

⇒ it is possible that with the CMSSM, NUHM1, NUHM2, SU(5), mAMSB
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"

$\Rightarrow$ 10 parameters are manageable $\Rightarrow$ pMSSM10

- squark mass parameters: $m_{\tilde{q}_{1,2}} =: m_{\tilde{q}}$, $m_{\tilde{q}_3}$
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- 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, 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++

⇒ 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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– Higgs boson exclusion bounds (LHC, Tevatron, LEP) ⇒ HiggsBounds

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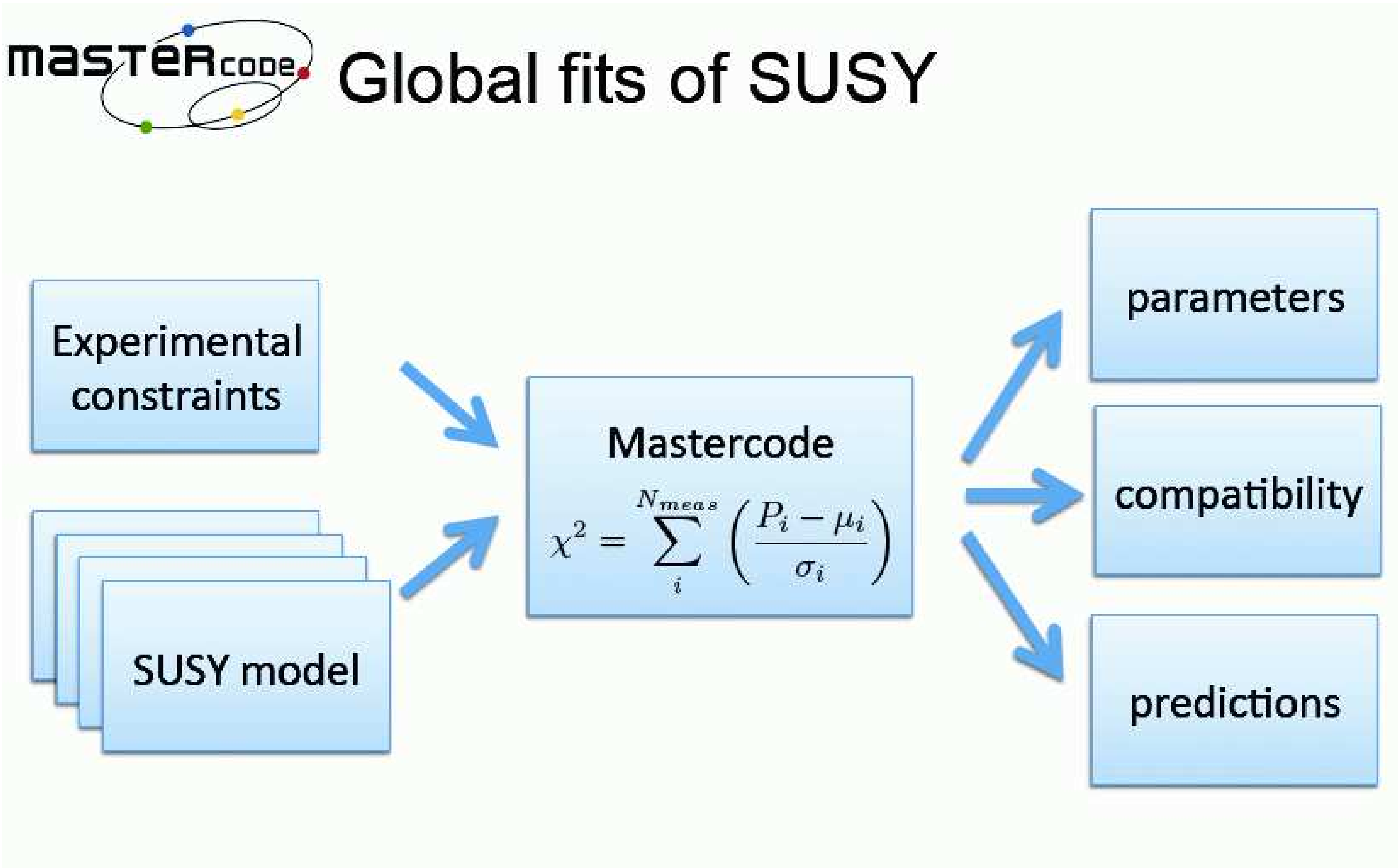
- electroweak precision data ⇒ FeynWZ, FeynHiggs
- flavor data ⇒ SuperIso, SuFla
- astrophysical data (DM properties) ⇒ MicrOMEGAs, SSARD

The χ^2 evaluation:

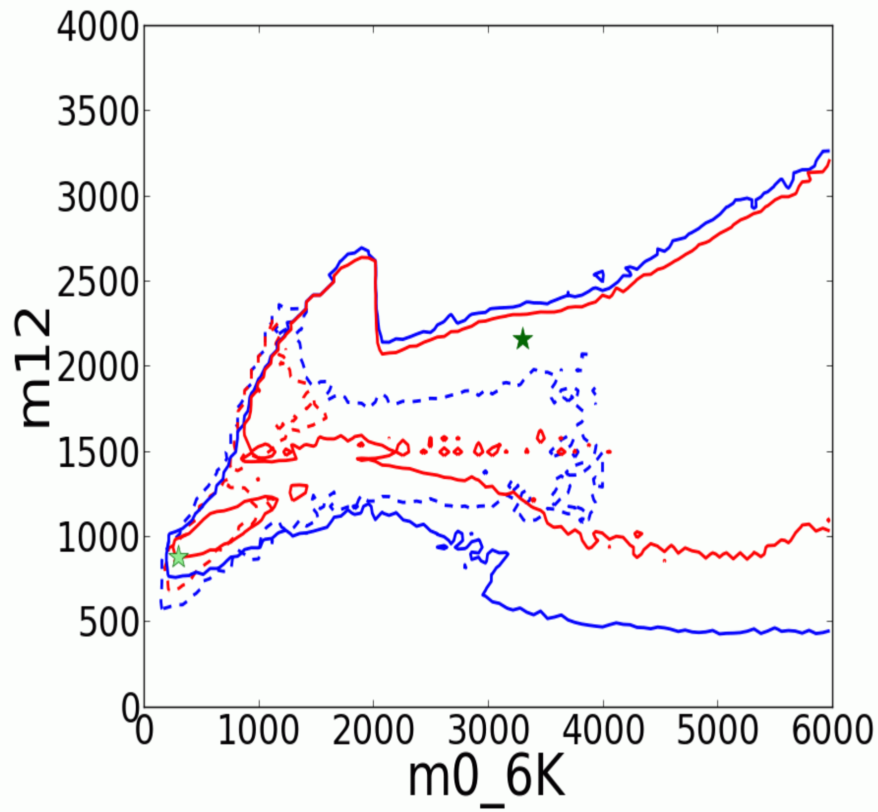


3. Predictions for the ILC and CLIC

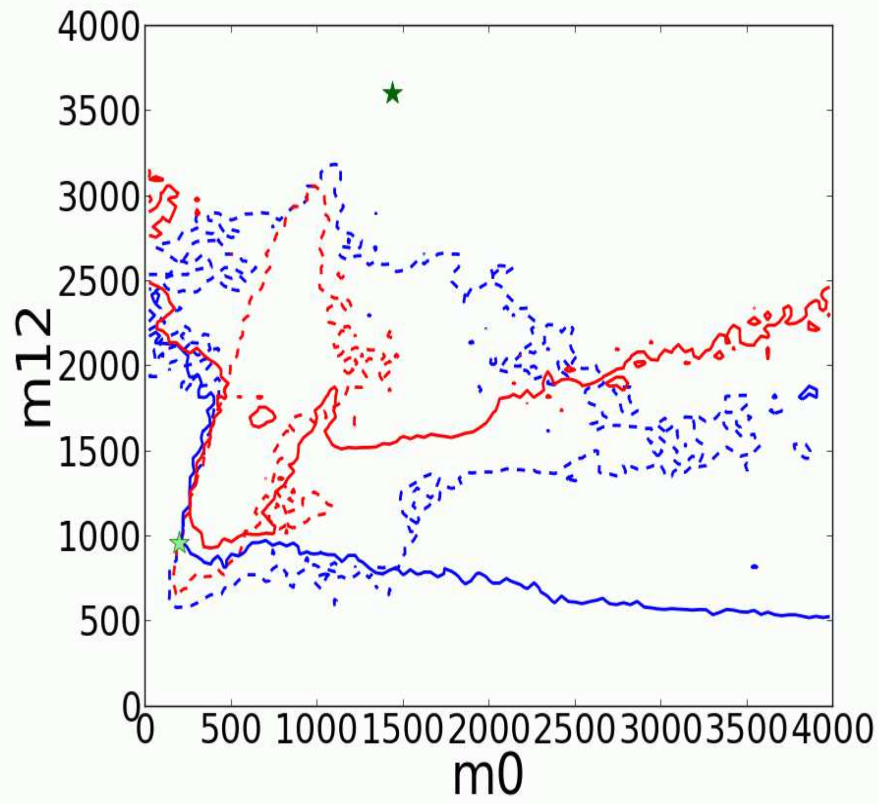
m_0-$m_{1/2}$ plane including LHC 20/fb:

[2013]

CMSSM



NUHM1



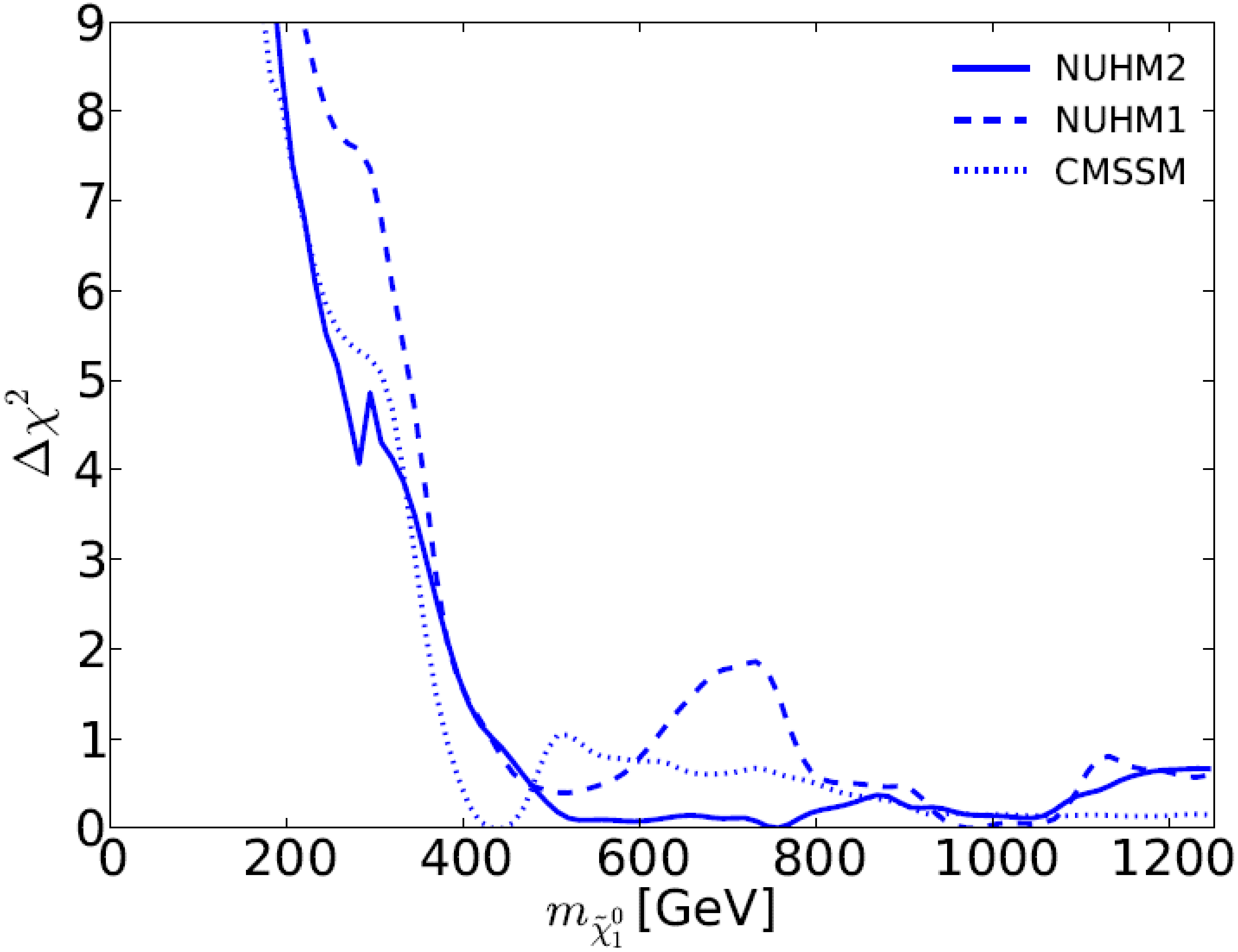
dotted: LHC 5/fb 7 TeV, solid: LHC 20/fb 8 TeV

⇒ very high masses favored!

⇒ prospects for ILC and CLIC?

LSP mass incl. 20/fb of LHC data

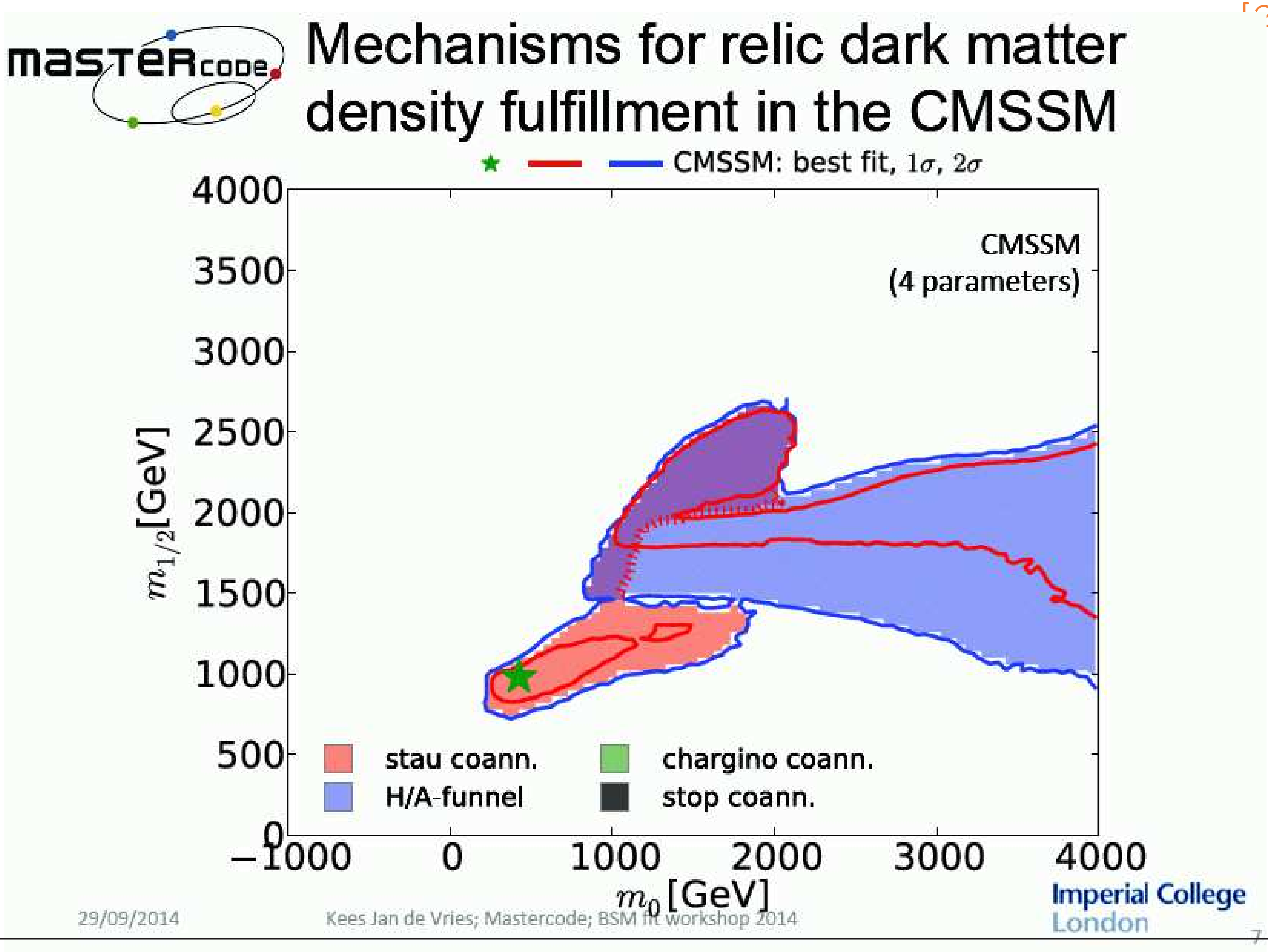
[2014]



⇒ only very large values are favored

CMSSM best-fit point prediction

[2014]



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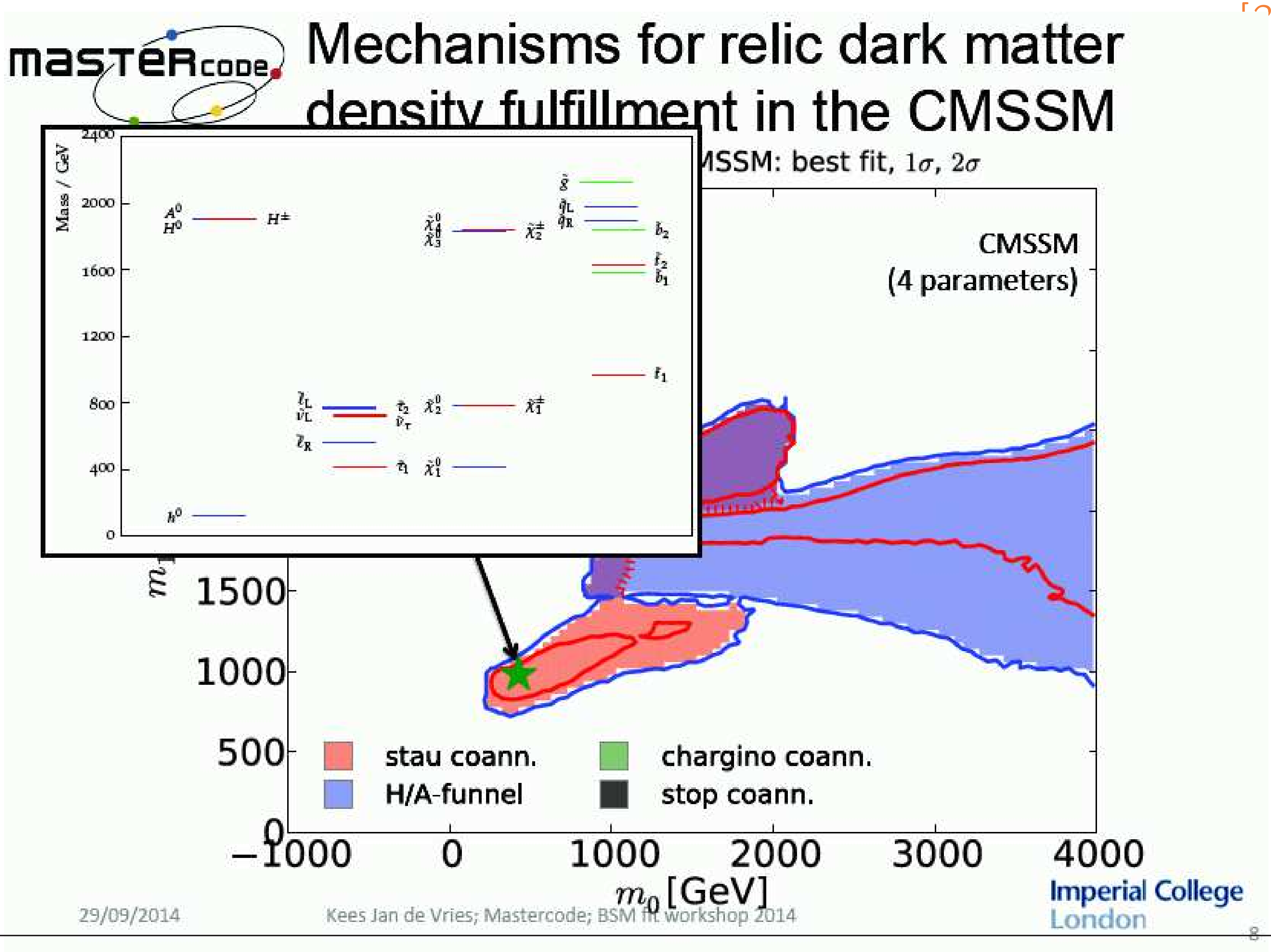

NUHM1 best-fit point prediction

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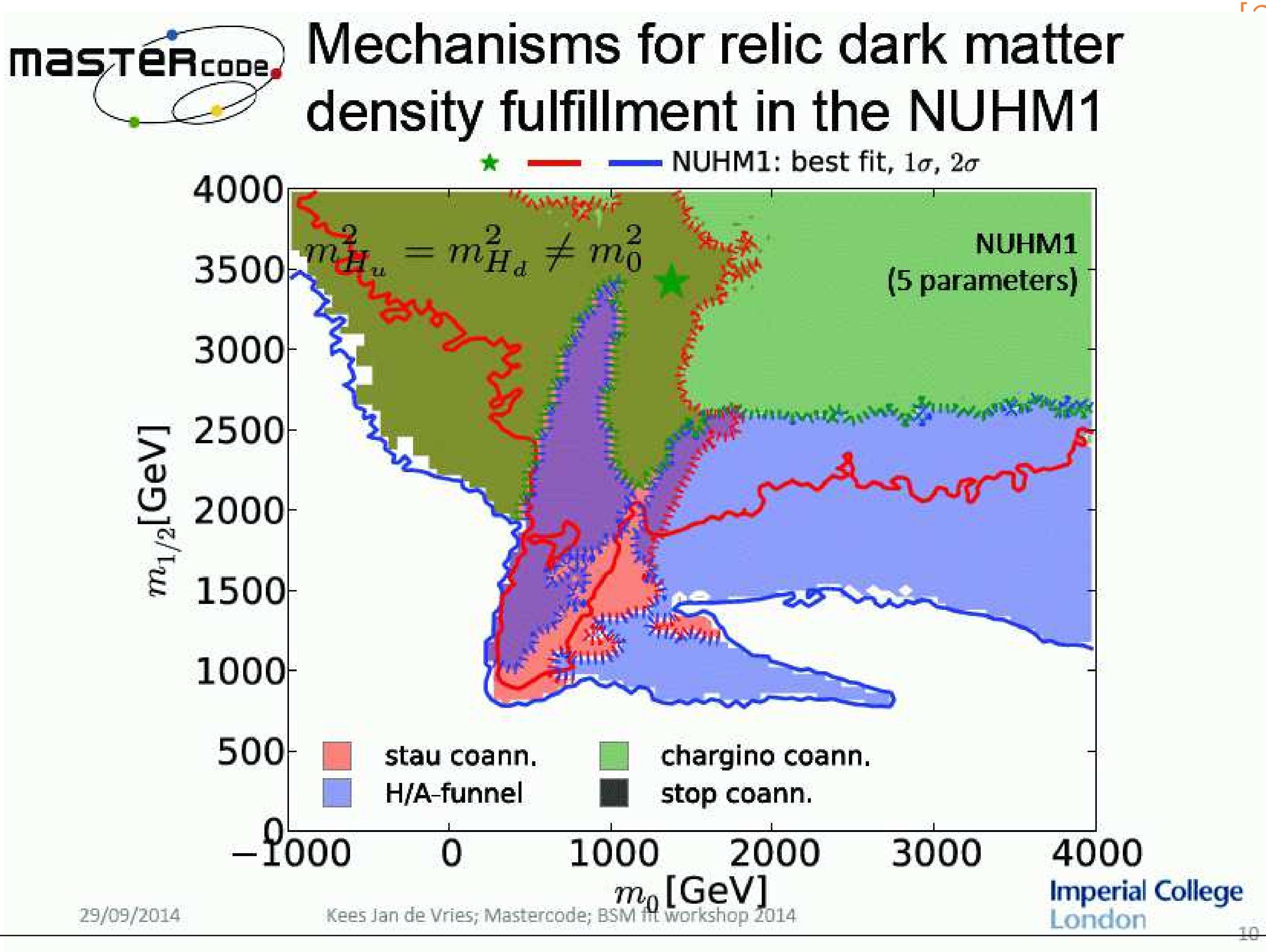

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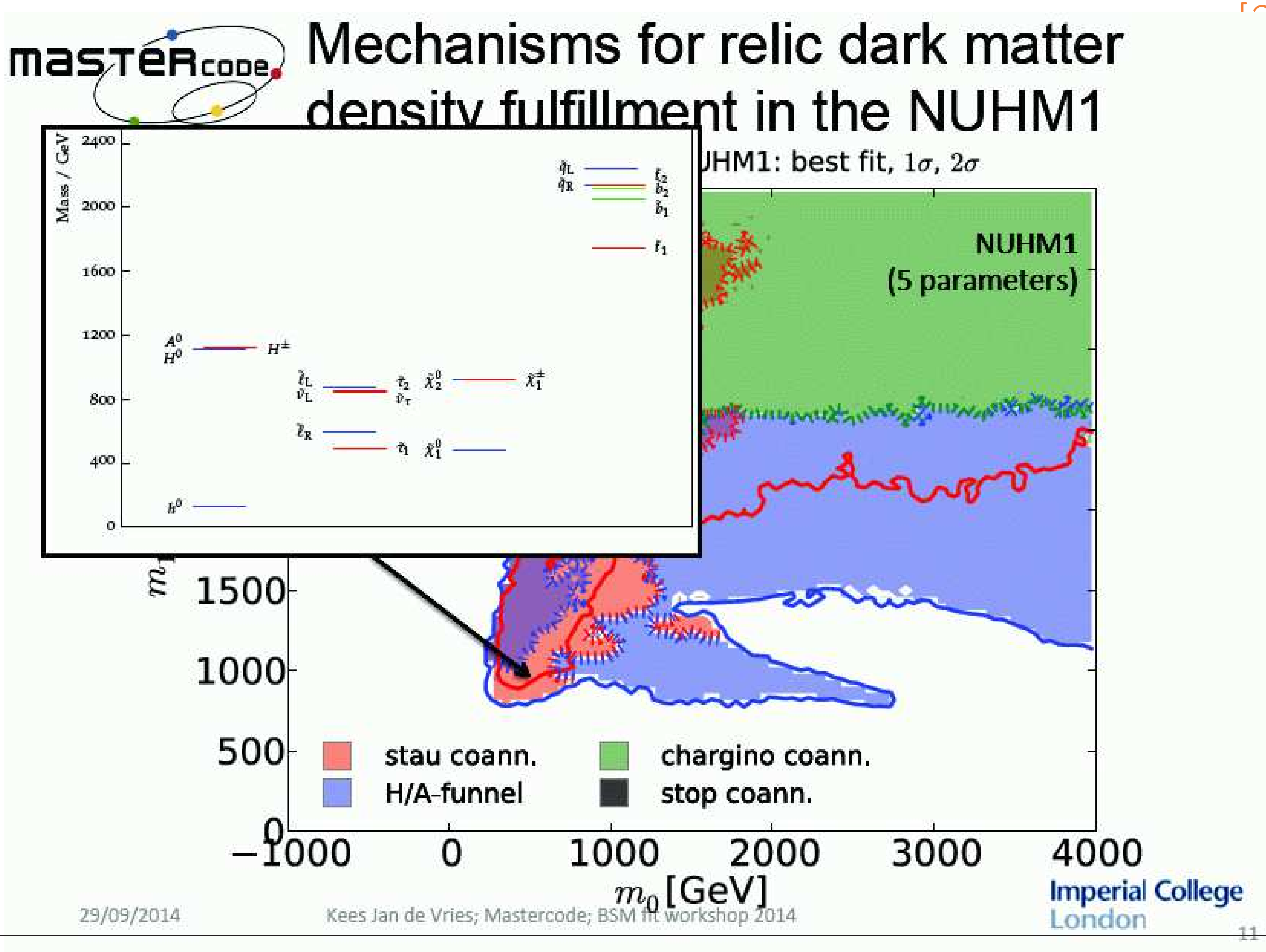
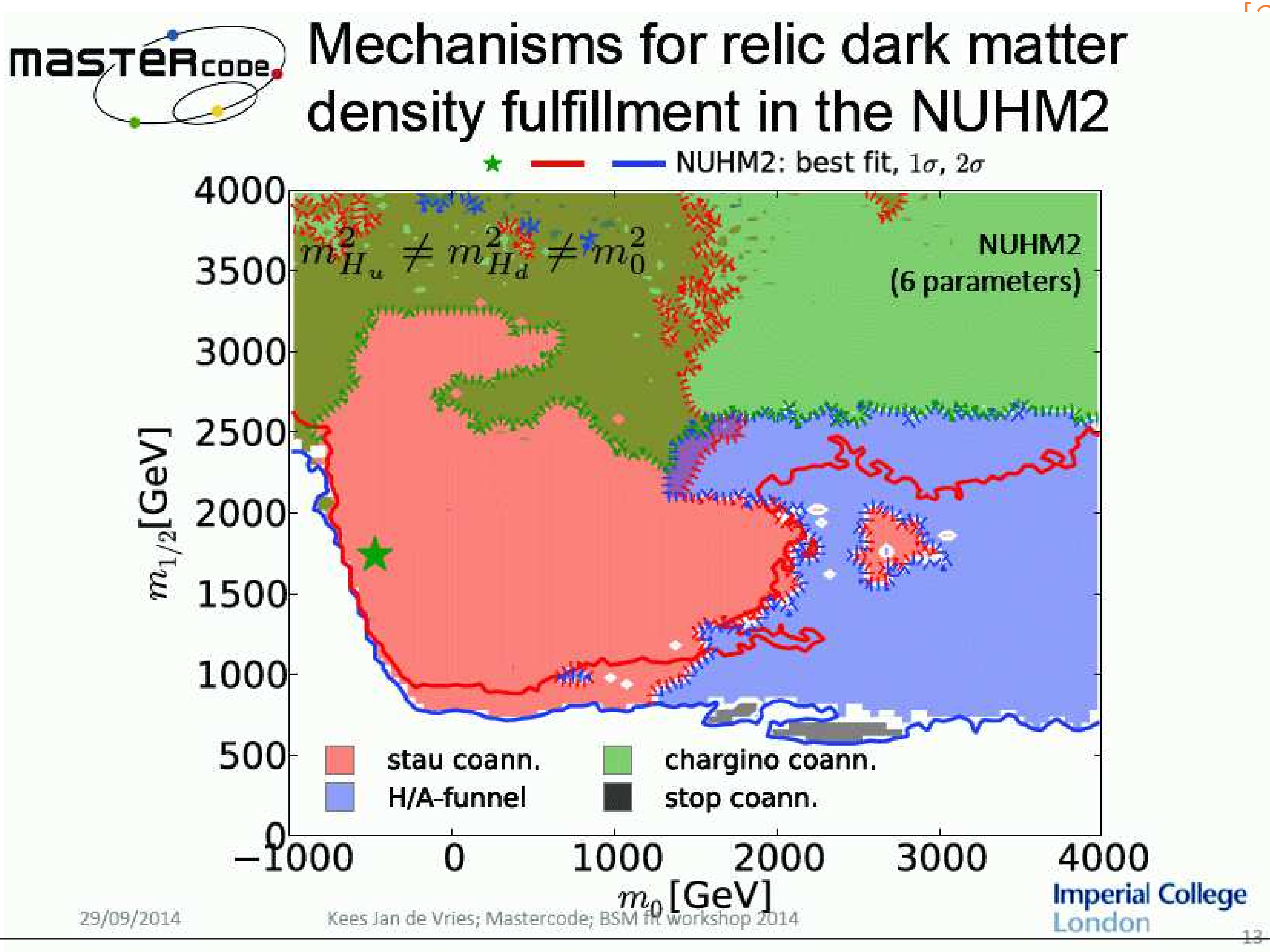


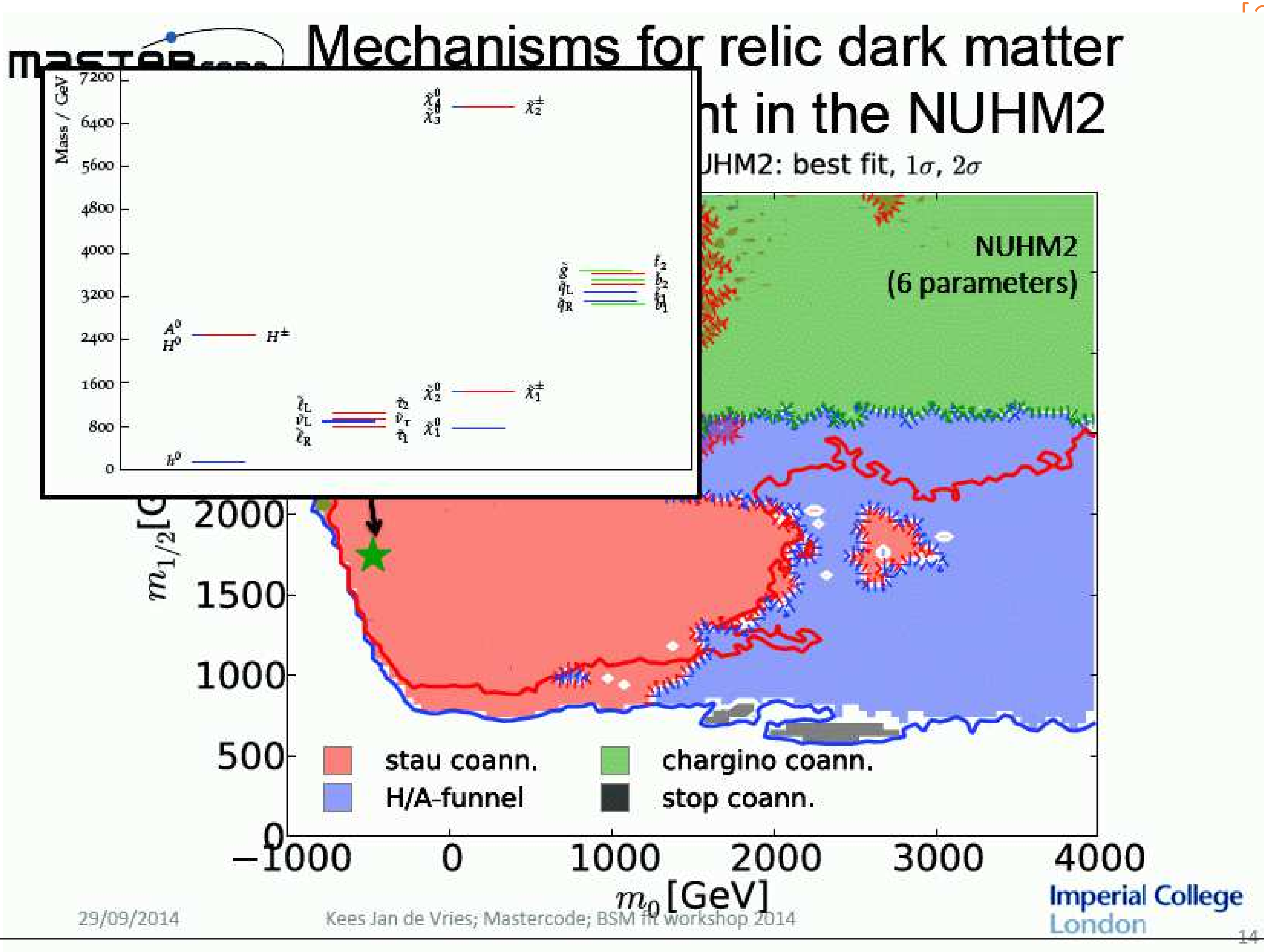
NUHM2 best-fit point prediction

[2014]



NUHM2 best-fit point prediction

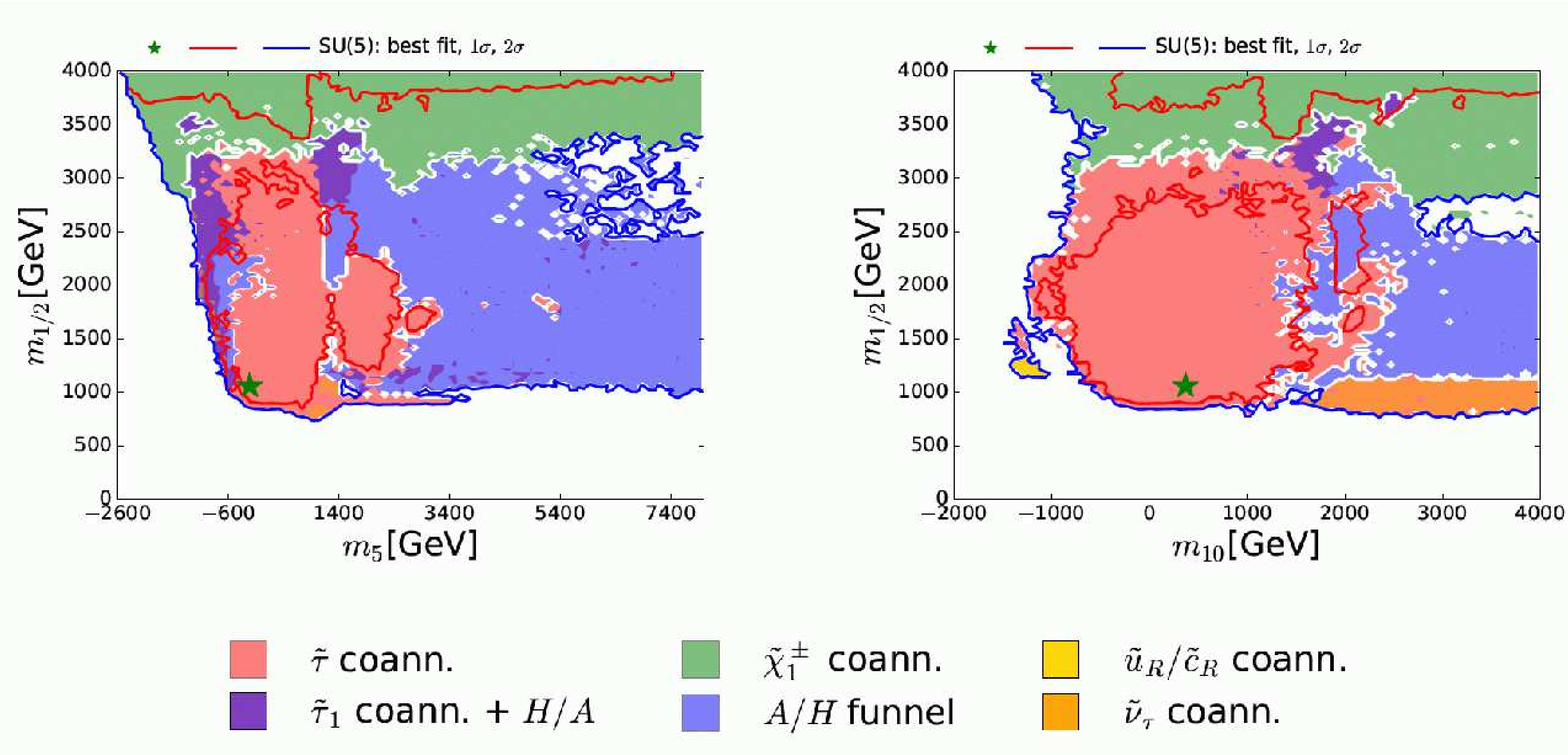
[?2014]



Results in the SU(5)

Dark Matter annihilation mechanism:

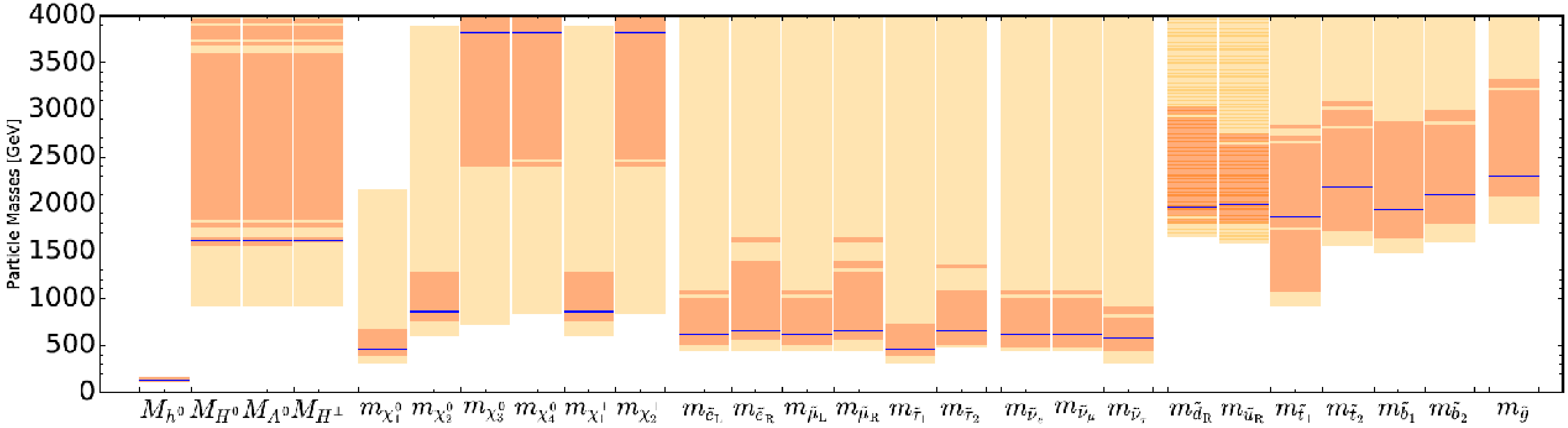
[2016]



$\Rightarrow \tilde{u}_R/\tilde{c}_R/\tilde{\nu}_\tau$ 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 σ ranges

⇒ clear prediction for ILC and CLIC

SU(5) prediction: best-fit masses

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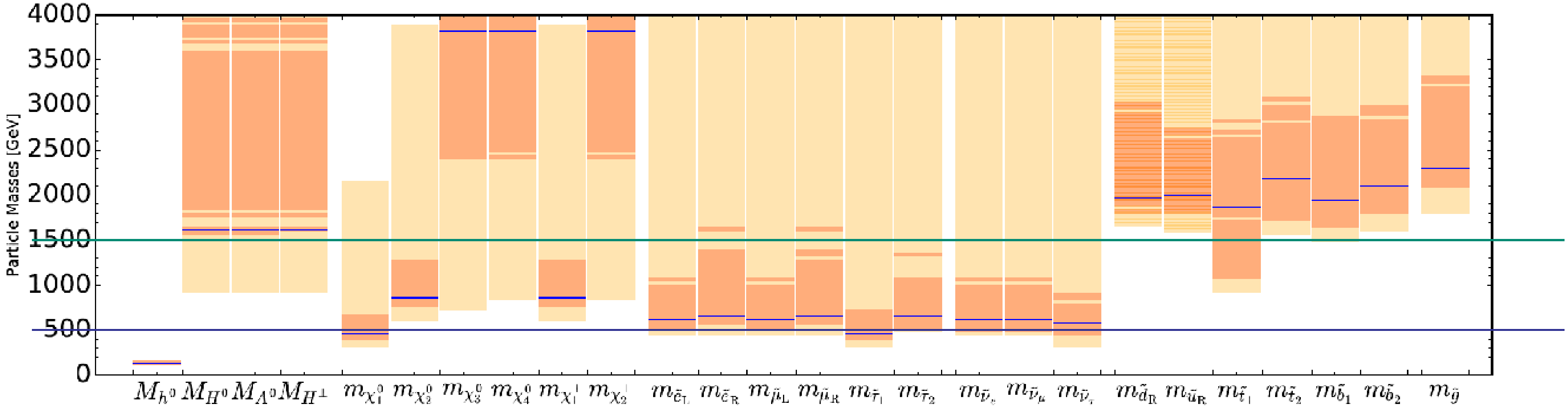


ILC: $\sqrt{s} = 1000$ GeV $\Rightarrow$ only few EW particles possibly accessible

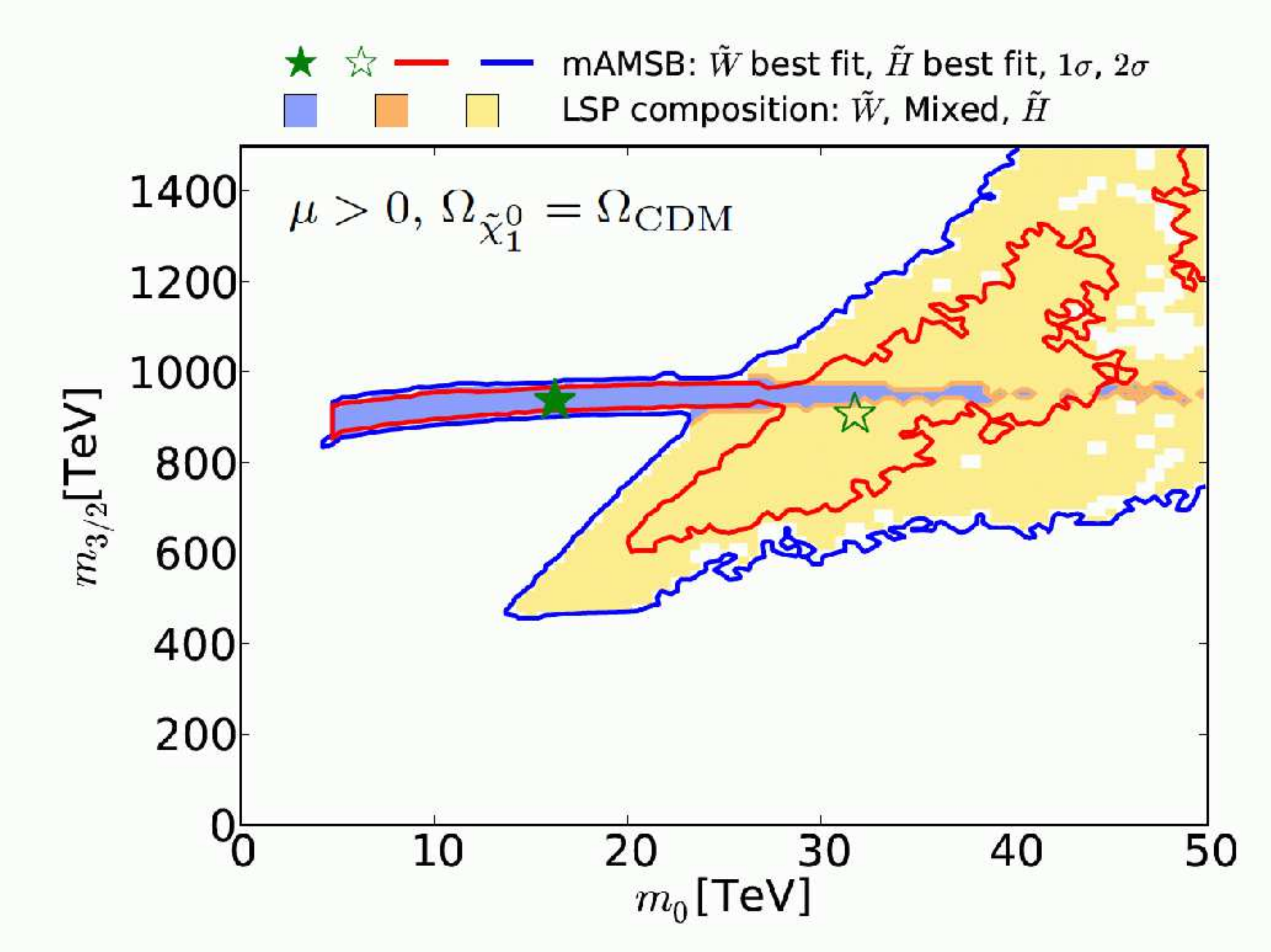
CLIC: $\sqrt{s} = 3000$ GeV $\Rightarrow$ pair production of many SUSY particles "likely"

$\Rightarrow$ no access to colored particles

Results in the mAMSB

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

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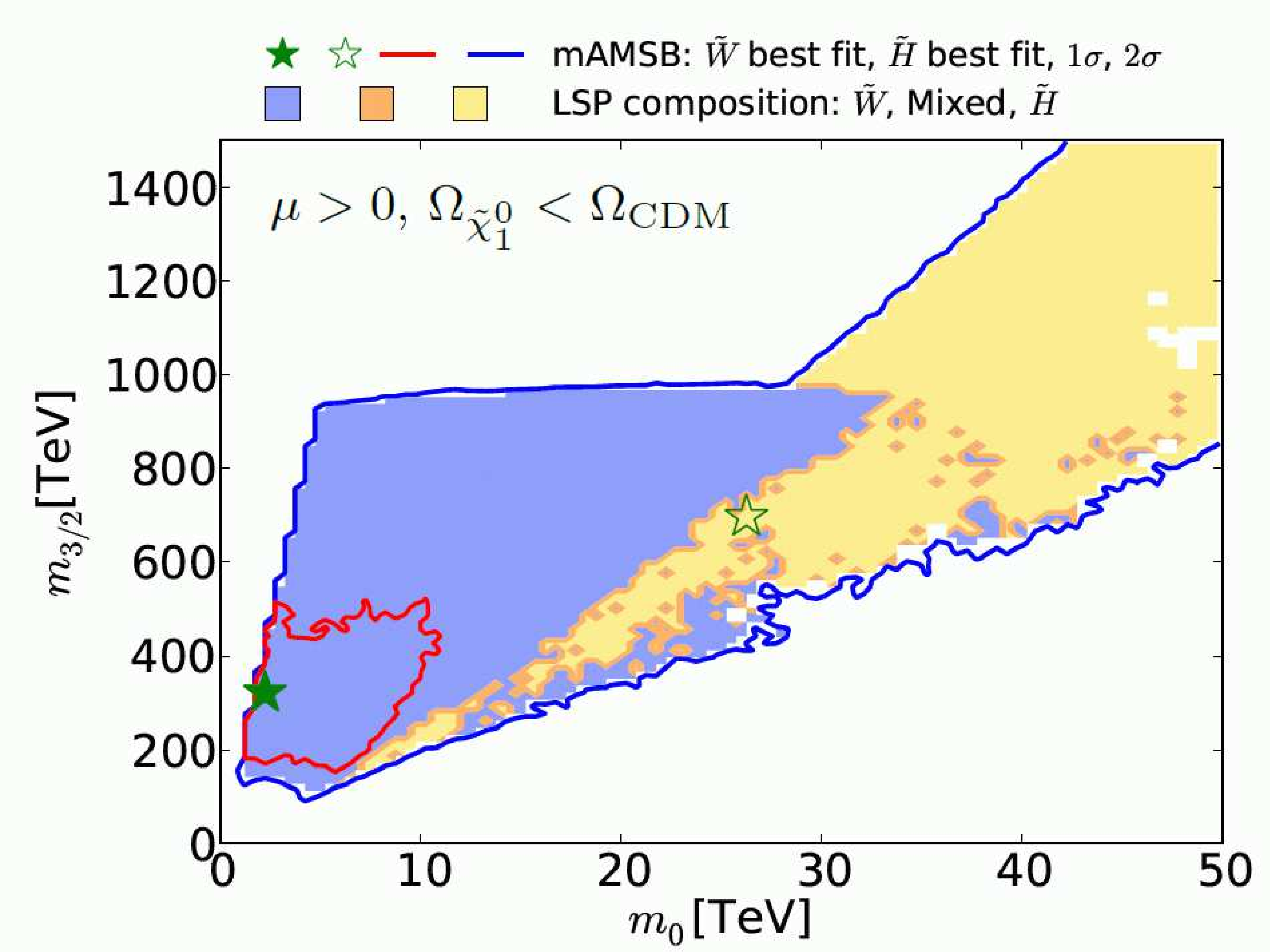
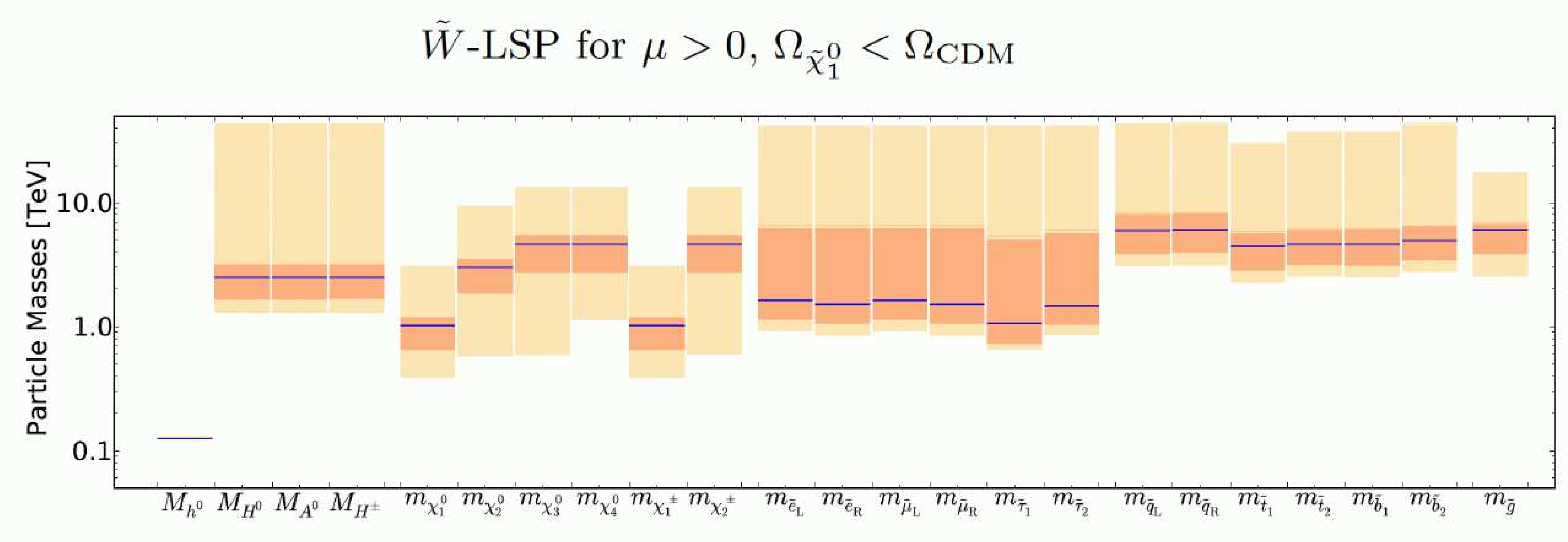
[2016]



⇒ very relaxed limits ⇒ lower masses

mAMSB prediction: best-fit masses (wino)

[2016]



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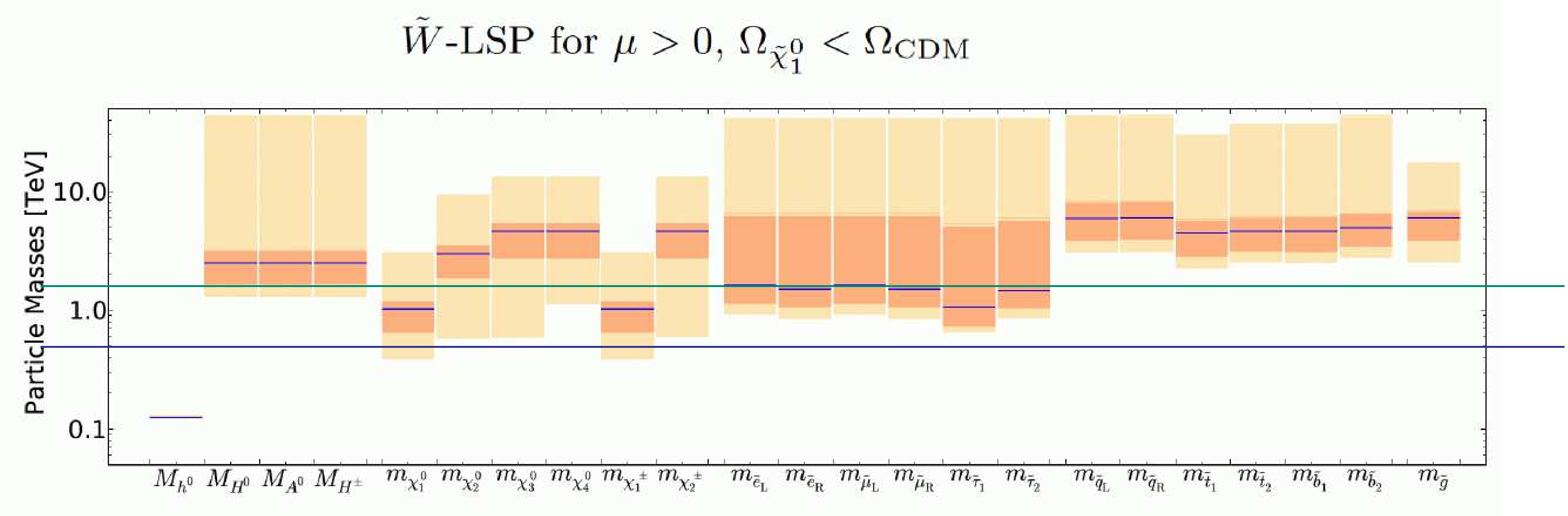
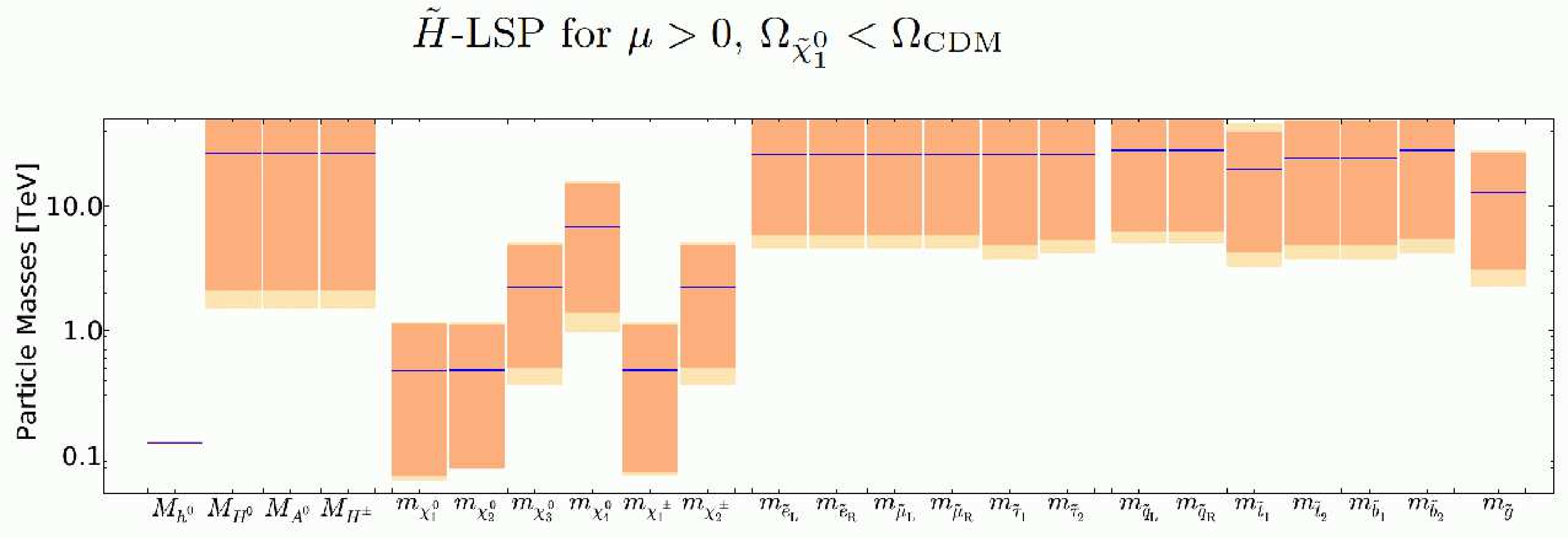


ILC: $\sqrt{s} = 1000$ GeV $\Rightarrow$ bad prospects

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

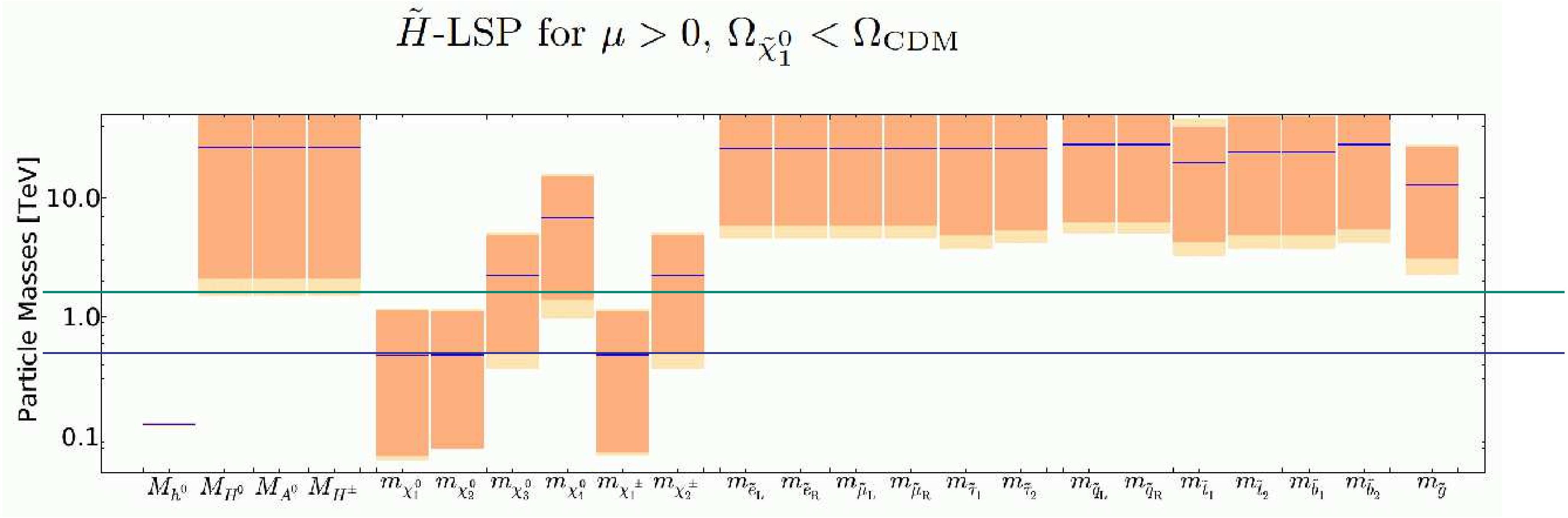
⇒ some(!) lower electroweak masses

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

⇒ clear prediction for ILC and CLIC

mAMSB prediction: best-fit masses (higgsino)

[2016]



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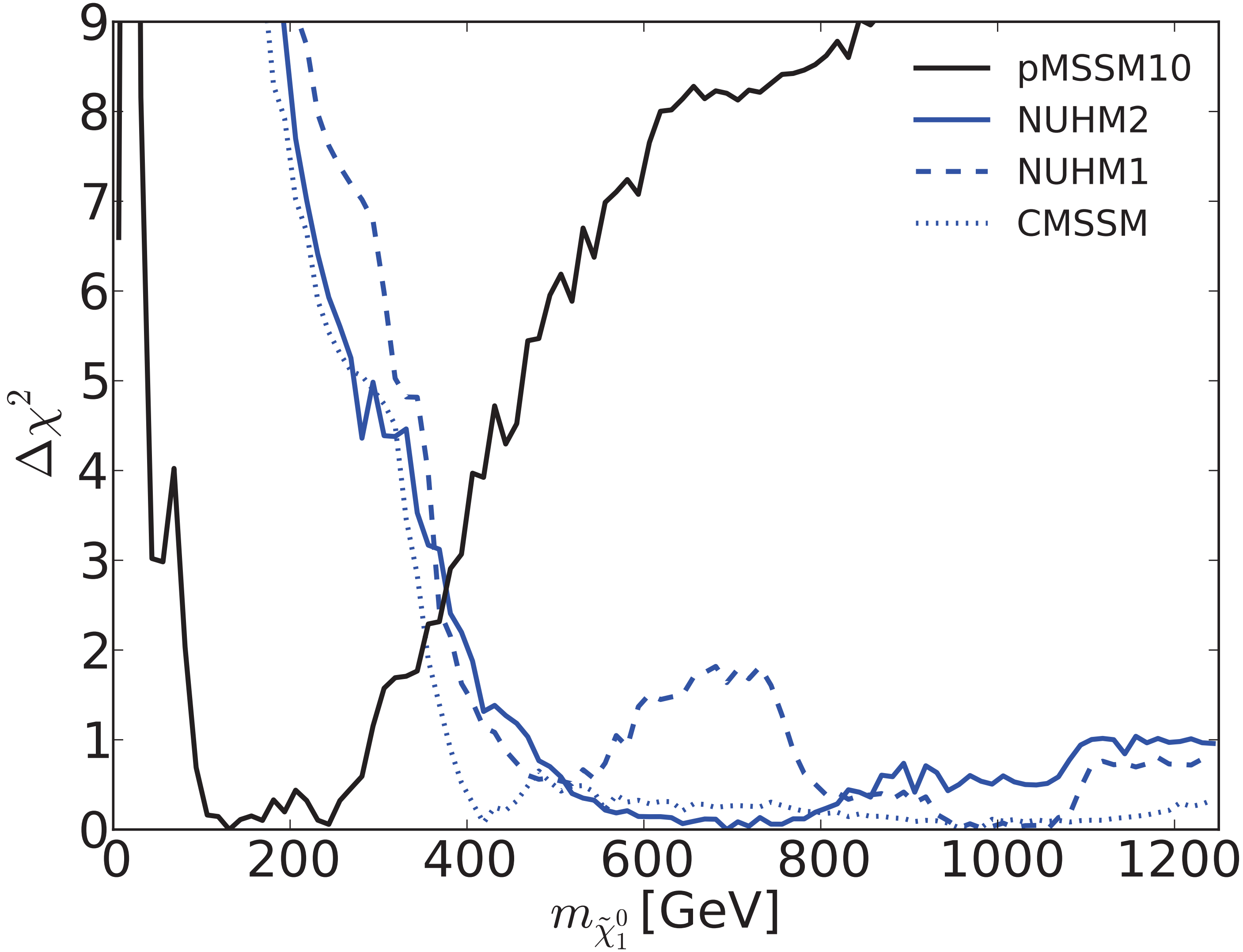
LSP mass incl. 20/fb of LHC data: pMSSM10 vs. GUT

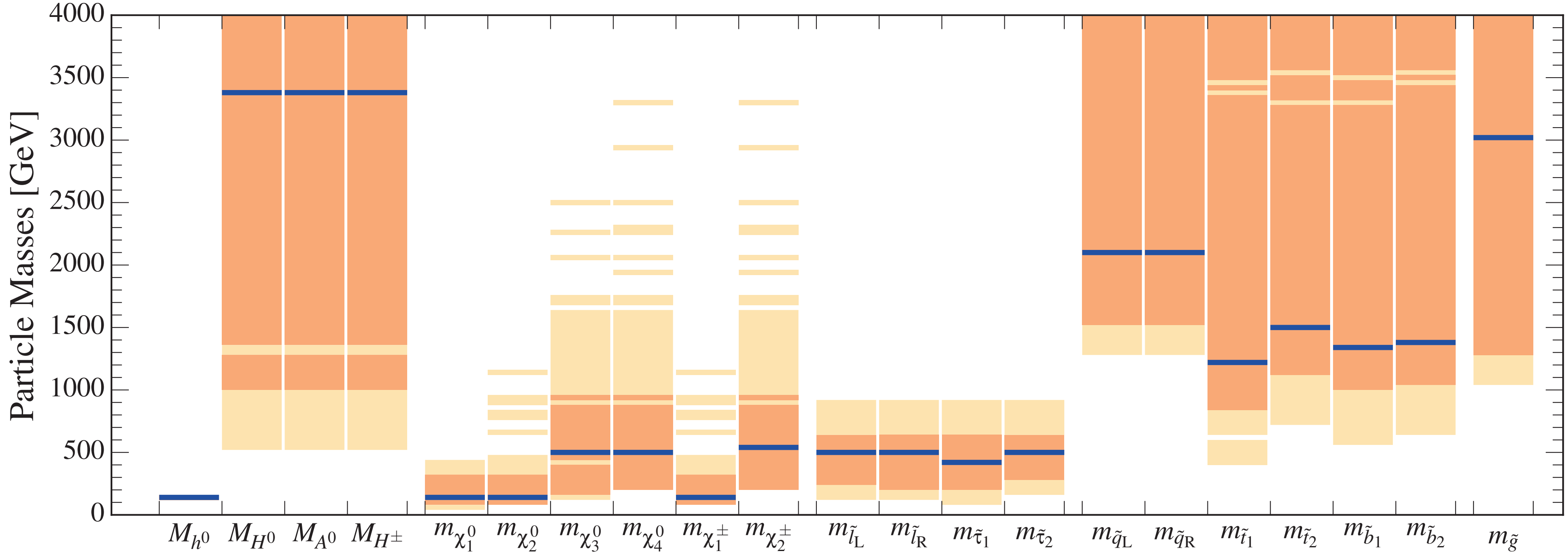
[2015]



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

pMSSM10 prediction: best-fit masses

[2015]



⇒ high colored masses

⇒ relatively low electroweak masses

partially with not too large ranges

⇒ clear prediction for ILC and CLIC

pMSSM10 prediction: best-fit masses

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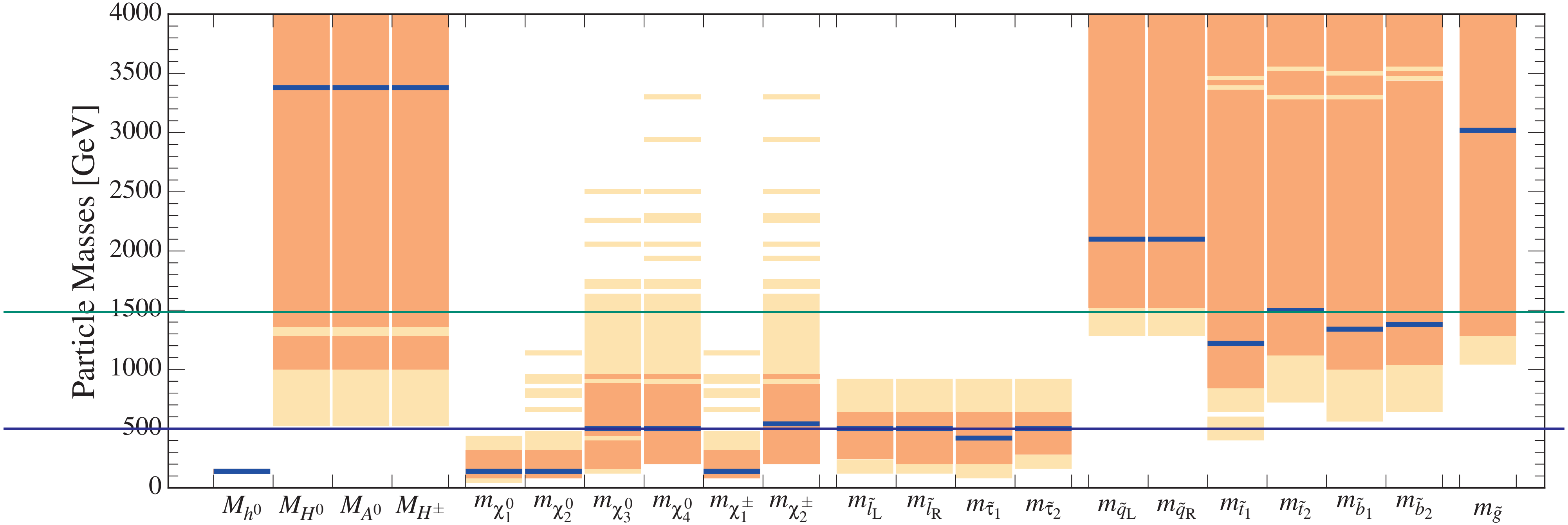


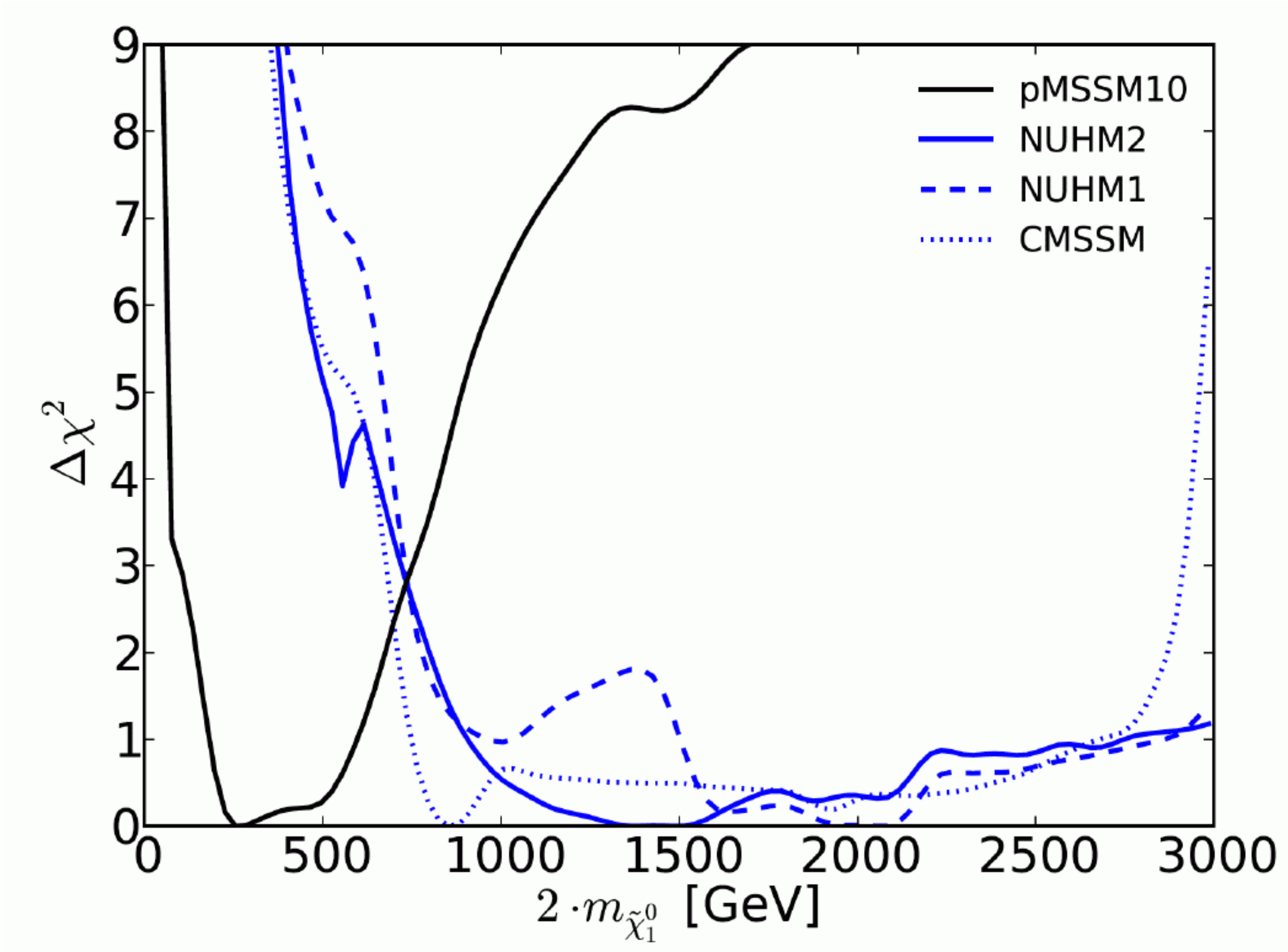
ILC: $\sqrt{s} = 1000$ GeV $\Rightarrow$ pair production of many SUSY particles possible

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

$\Rightarrow$ some colored particles possbile

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

[2014]



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

⇒ pMSSM10: easy at the ILC

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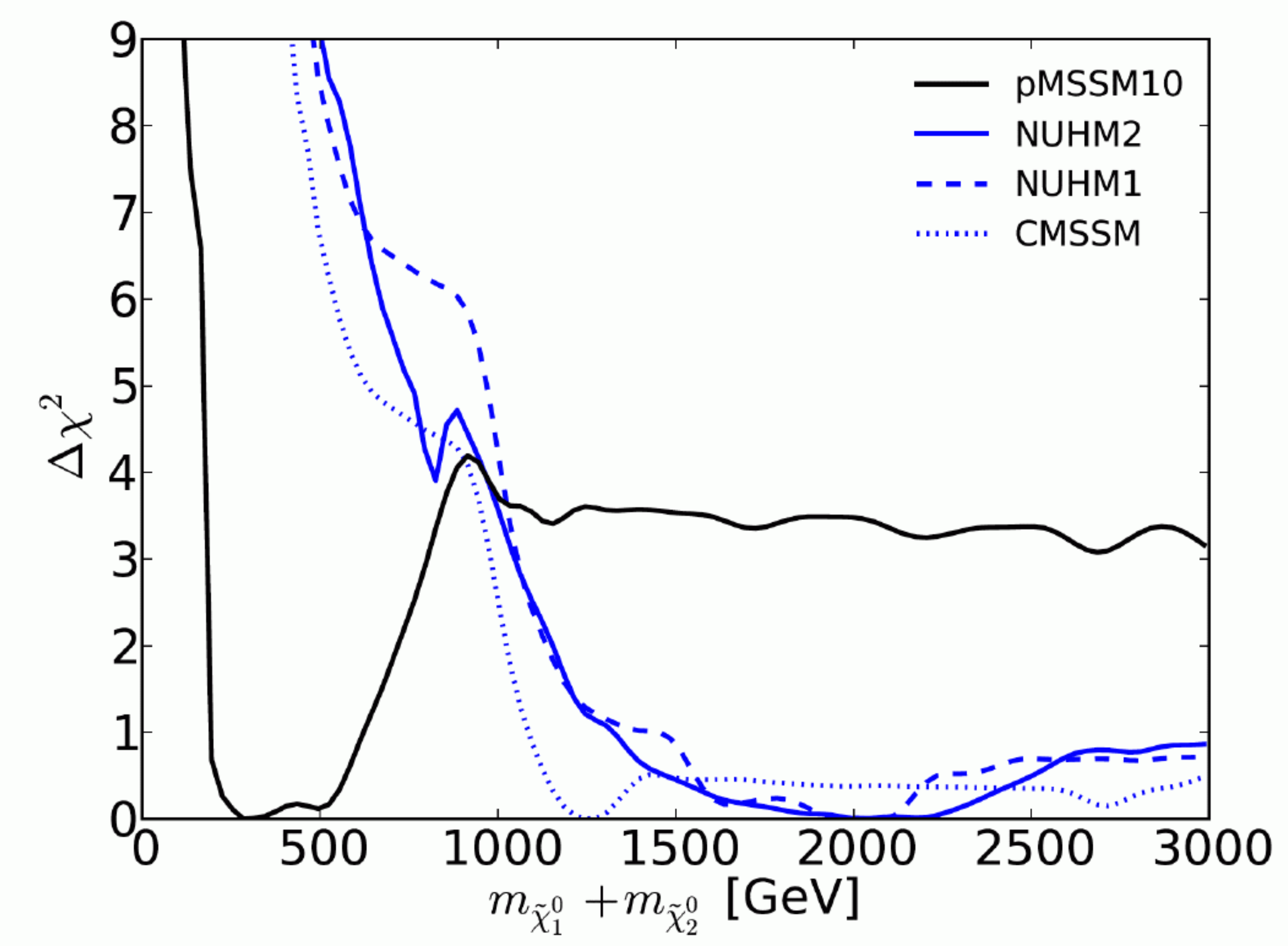

⇒ GUT based models: ILC :-(, CLIC possible

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

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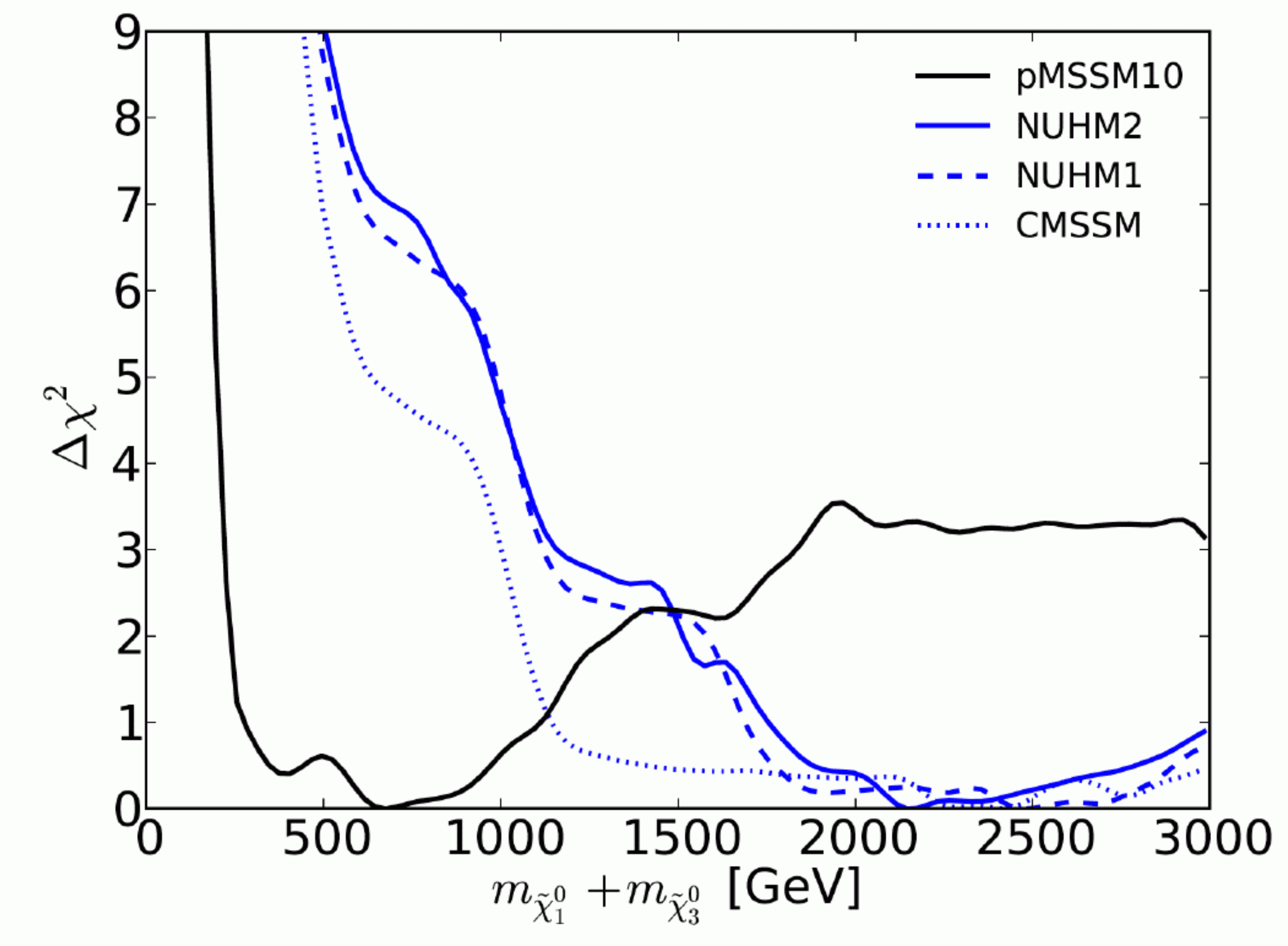
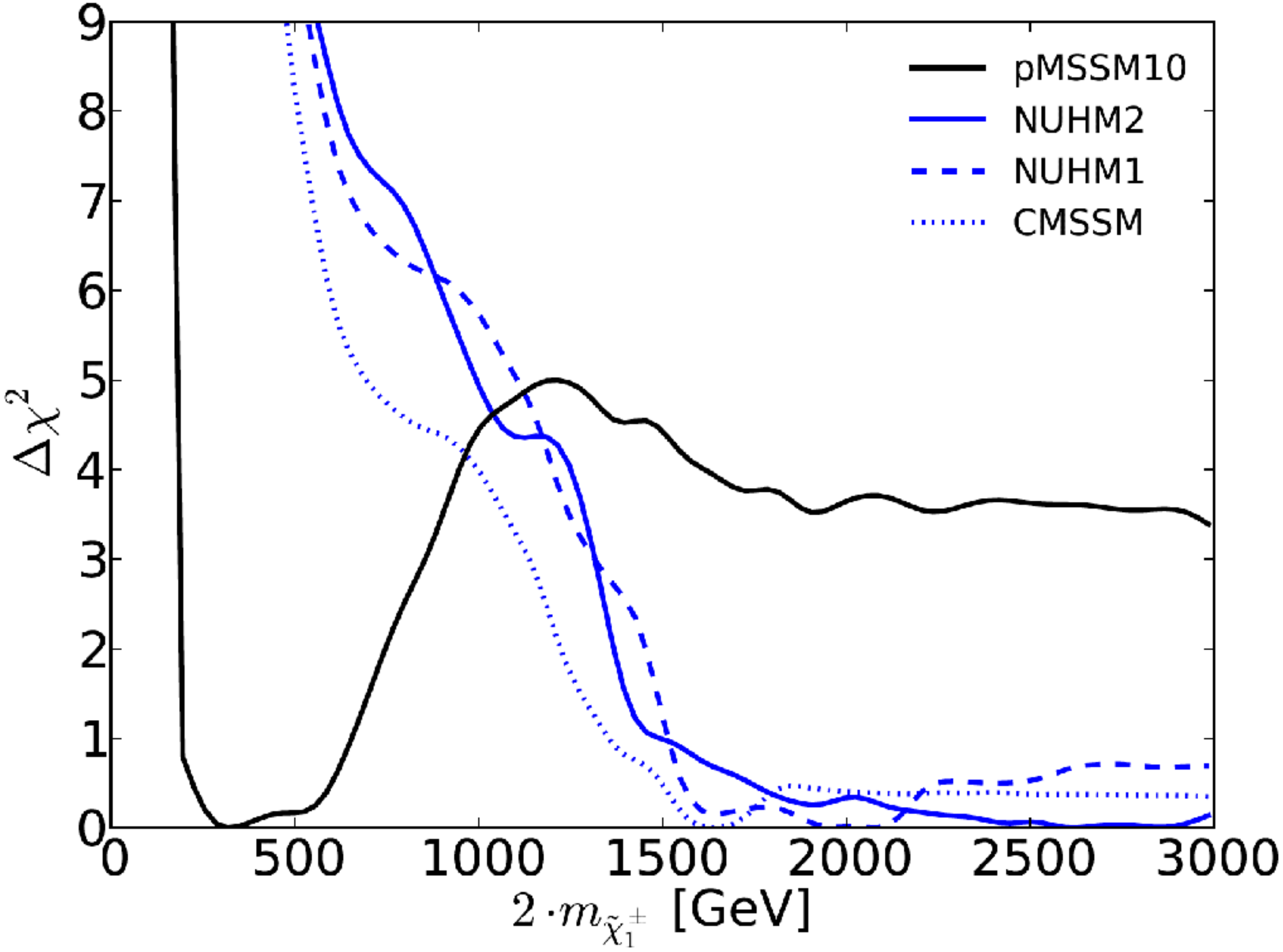


⇒ GUT based models: ILC :-(, CLIC possible

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

Some gaugino production cross sections: $e^+e^- \to \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$

[2014]



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What to conclude?

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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%
pMSSM10	20.5/18	31%

Which model is more likely??

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Which model is more likely??

⇒ pMSSM10: model with higher χ^2-probability
model with interesting ILC prospects
model with good CLIC prospects

What to conclude?

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Which model is more likely??

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model with interesting ILC prospects
model with good CLIC prospects

⇒ Are we ready (from the TH side) for EW particle production?

4. New Theory Predictions for the ILC and CLIC

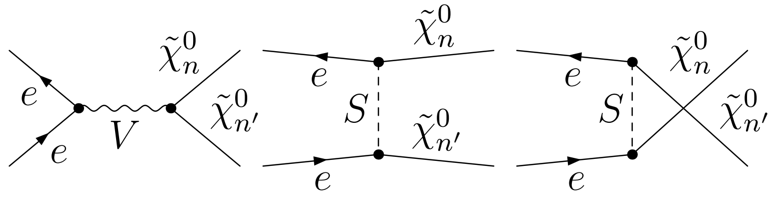
Extensive program for SUSY production and decay:

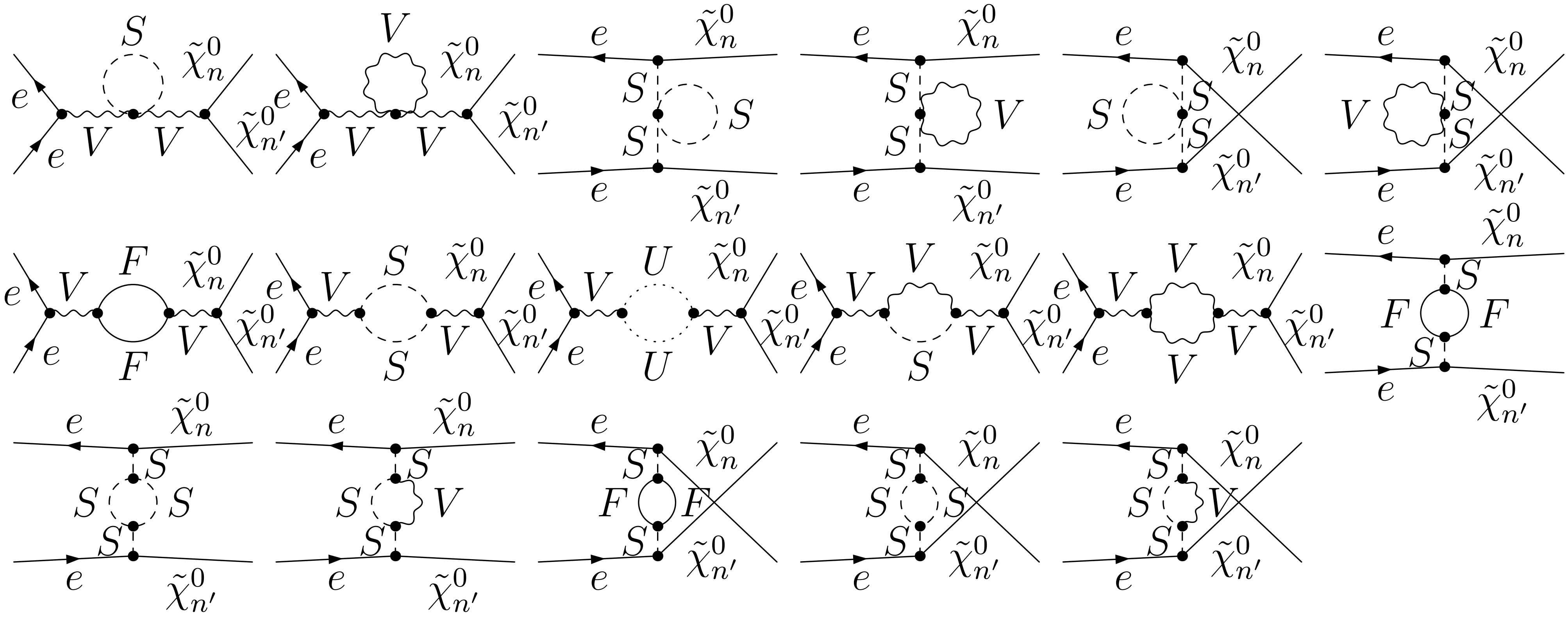
[*S.H., C. Schappacher et al. 08'-17'*]

– full one-loop
– real and complex parameters
– soft and hard (and collinear) QED/QCD radiation
– renormalization (finally) fully under control

– stop/sbottom/stau decays
– gluino/chargino/neutralino decays
– Higgs decays
– Higgs production ($2 \to 2$)
– chargino/neutralino production

$e^+e^- \to \tilde{\chi}^0_n \tilde{\chi}^0_{n'}$, ($e^+e^- \to \tilde{\chi}^\pm_c \tilde{\chi}^\mp_{c'}$ similar):





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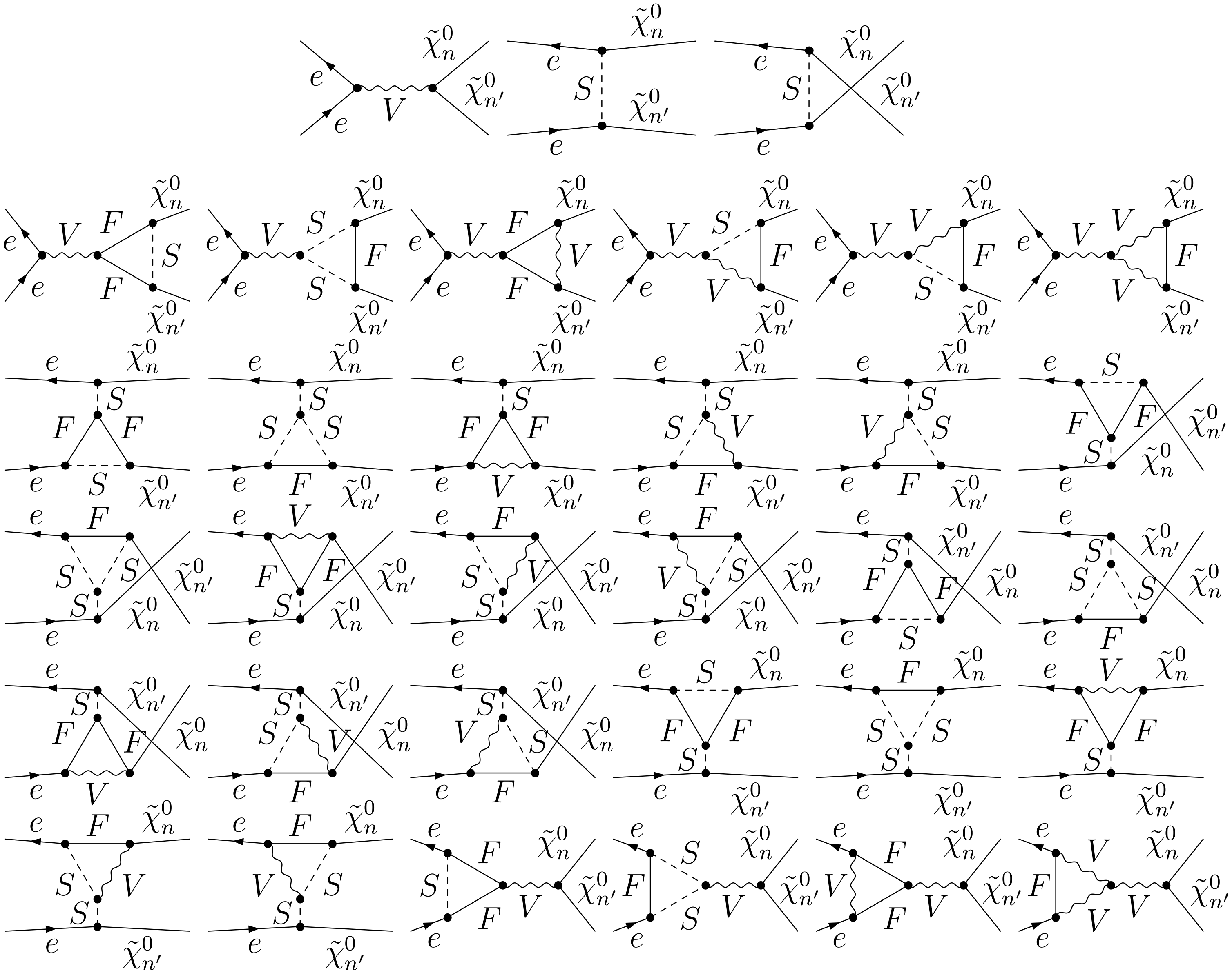

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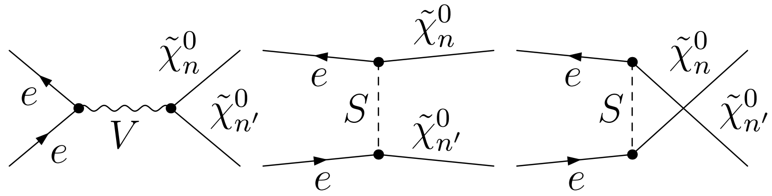

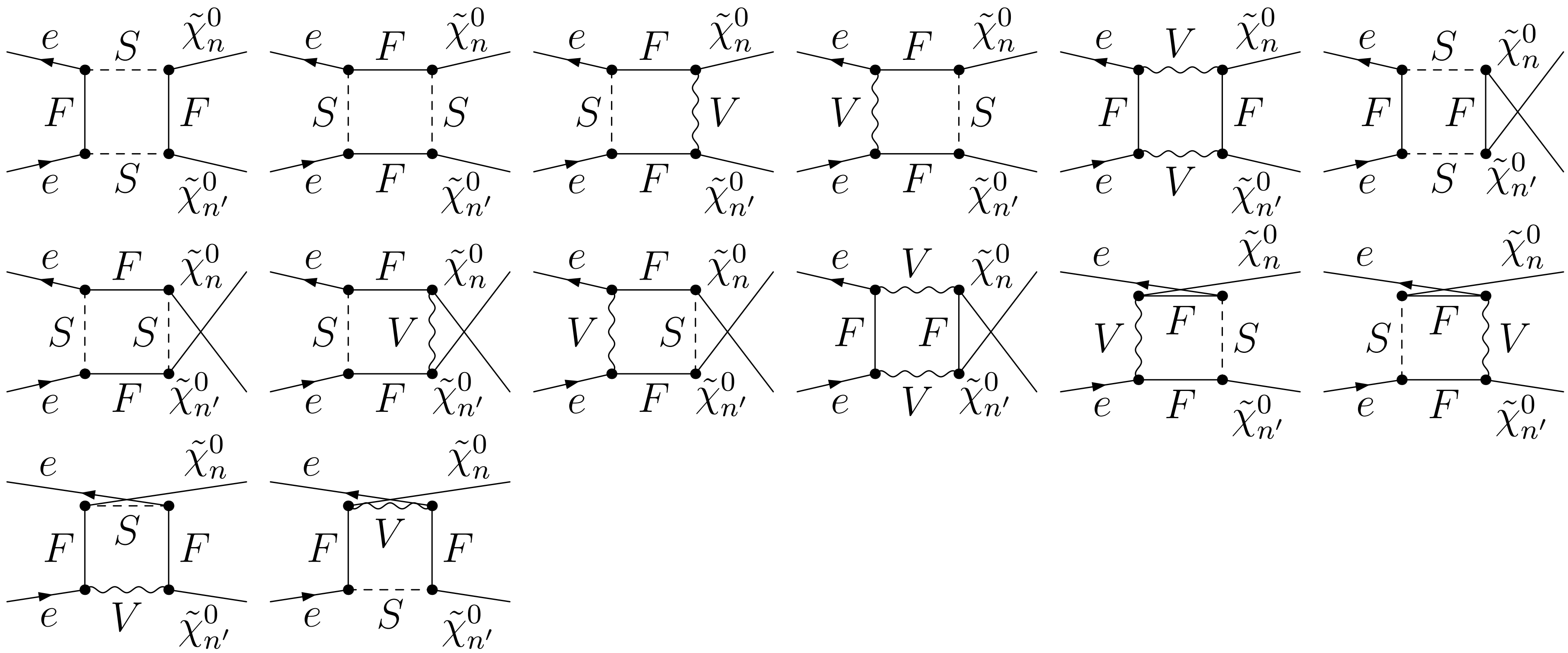

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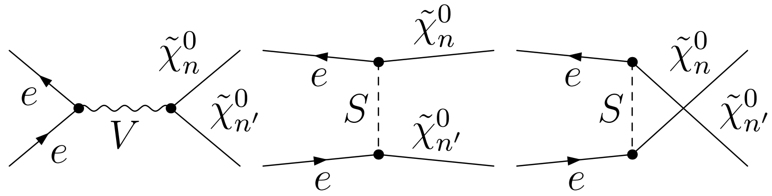
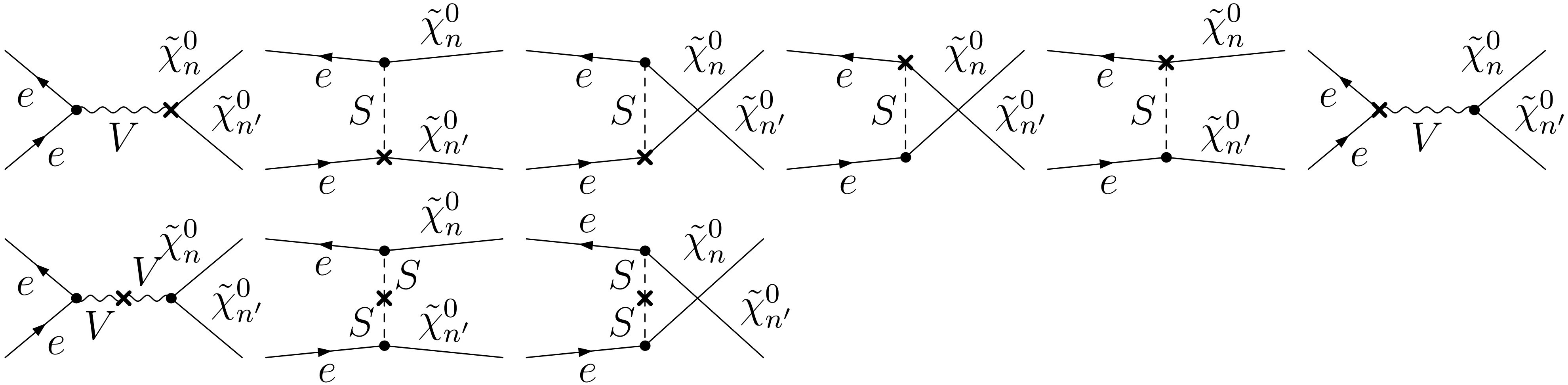




+ soft and hard QED radiation

cMSSM parameters:

Scen.	$\sqrt{s}$	t_β	μ	$M_{H^\pm}$	$M_{\tilde{Q},\tilde{U},\tilde{D}}$	$M_{\tilde{L},\tilde{E}}$	$\|A_t\|$	A_b	A_τ	$\|M_1\|$	M_2	M_3
$\mathcal{S}$	1000	10	450	500	1500	1500	2000	$\|A_t\|$	$M_{\tilde{L}}$	$\mu/4$	$\mu/2$	2000

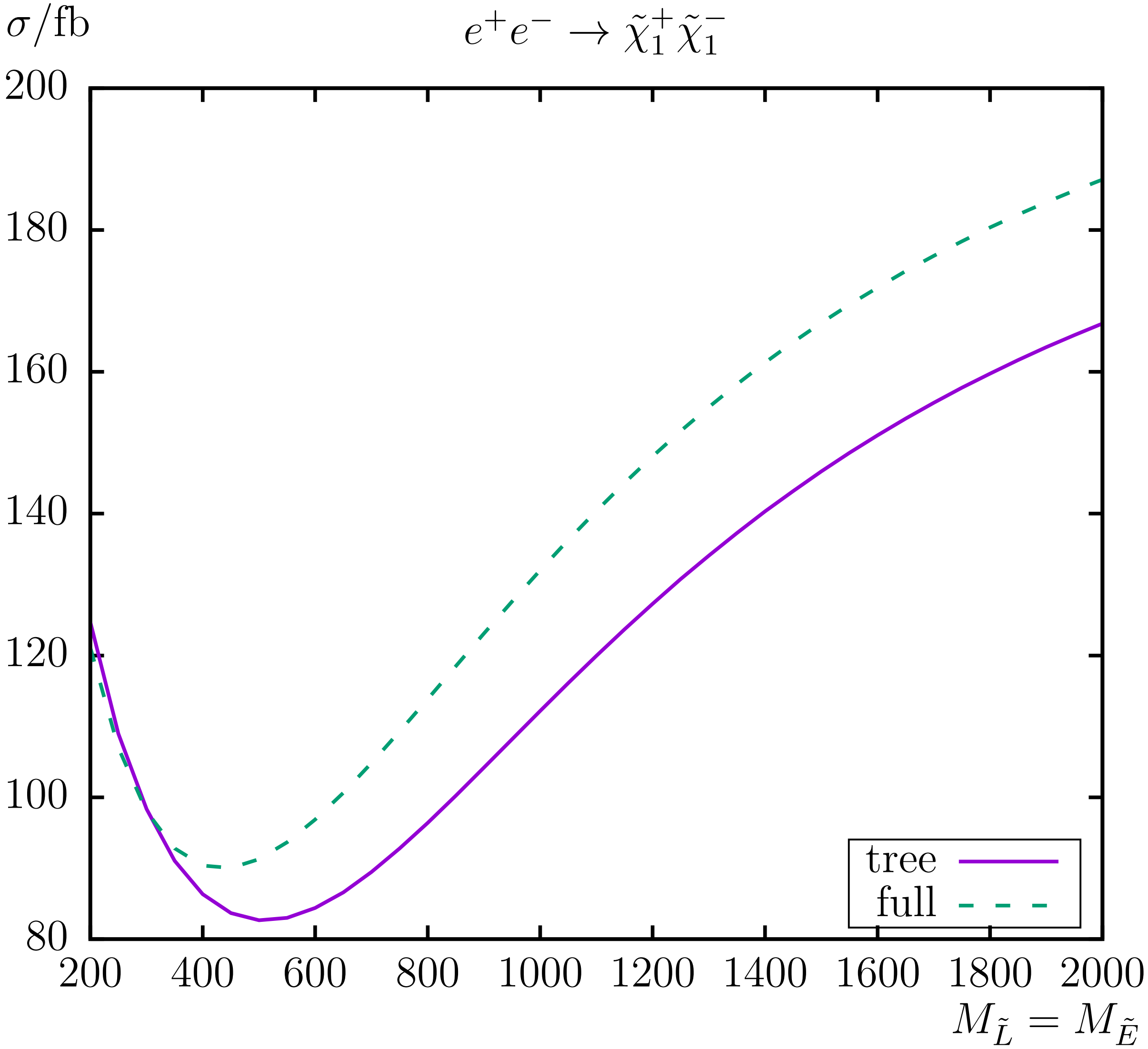
	$m_{\tilde{\chi}_1^\pm}$	$m_{\tilde{\chi}_2^\pm}$	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{\chi}_3^0}$	$m_{\tilde{\chi}_4^0}$
tree	212.760	469.874	110.434	213.002	455.162	469.226
CCN[1]	212.760	469.874	110.434	212.850	455.195	469.560

with $\sqrt{s}$, $M_{H^\pm}$, $\tan\beta$, $M_{\tilde{L}}$, φ_{M_1} varied

– Scenario chosen such that many processes are possible at the same time
– not chosen to maximize loop corrections

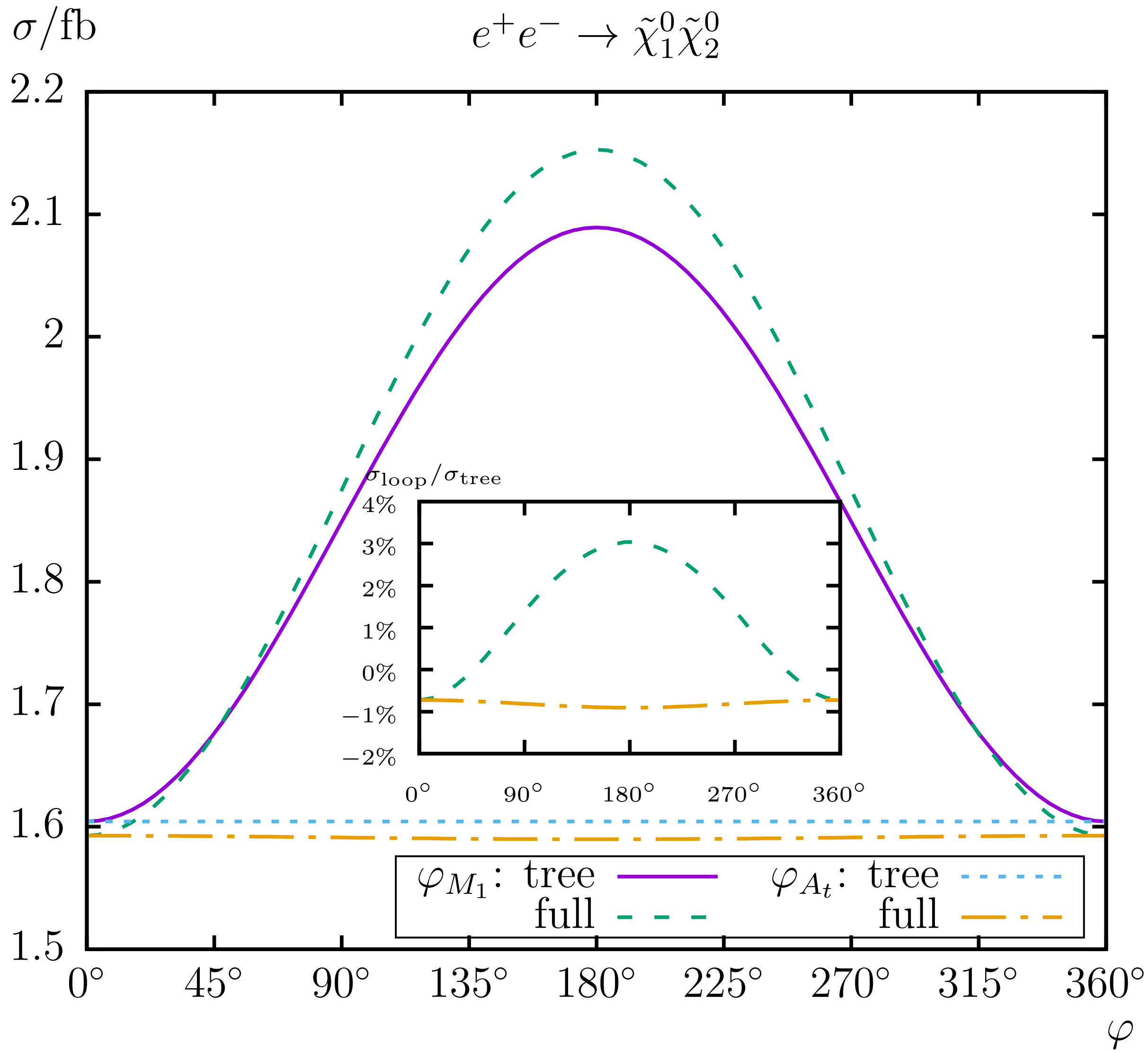
⇒ few example plots

$e^+e^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^-$:



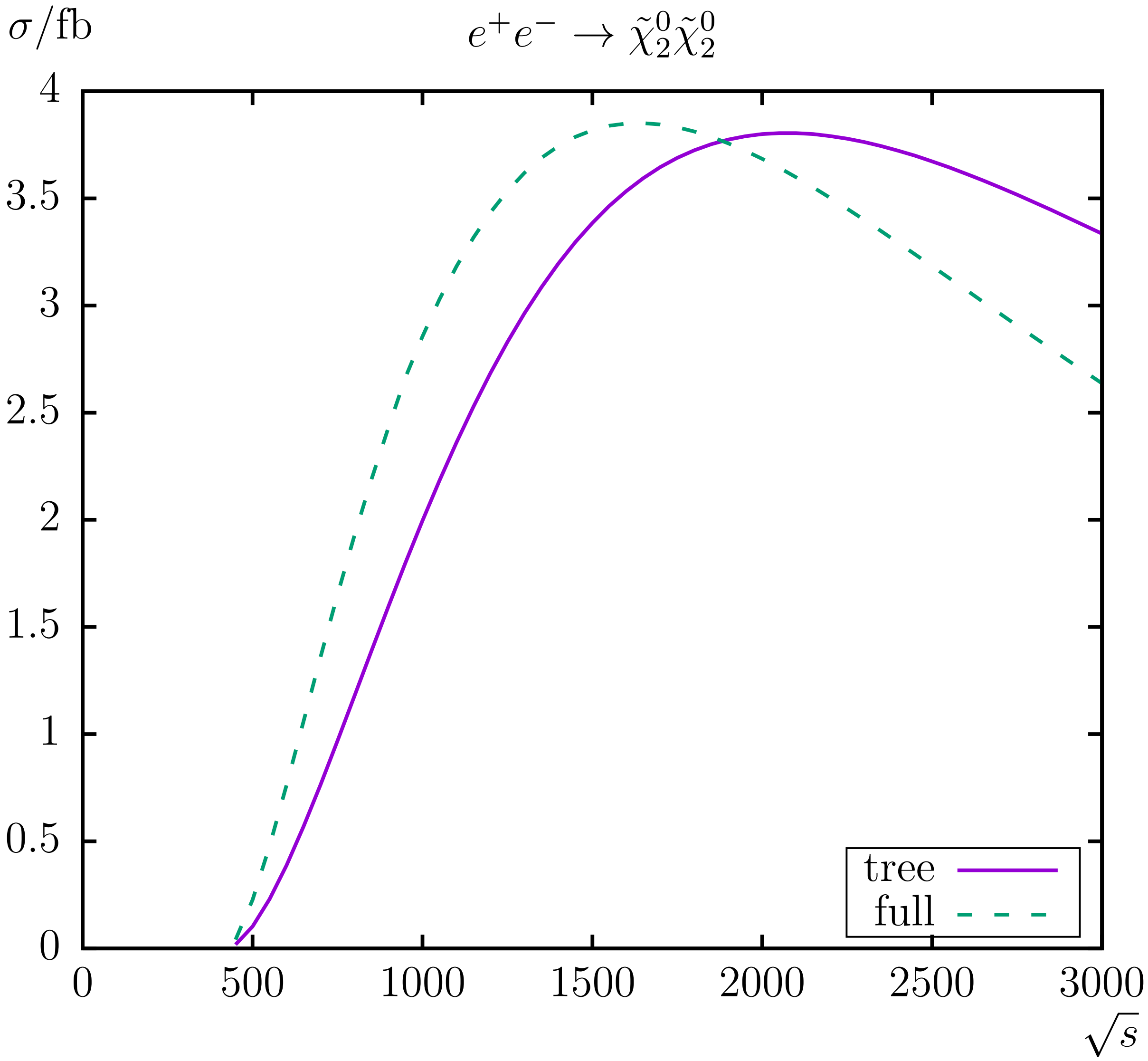
$\Rightarrow$ loop corrections crucial!

$e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2$:



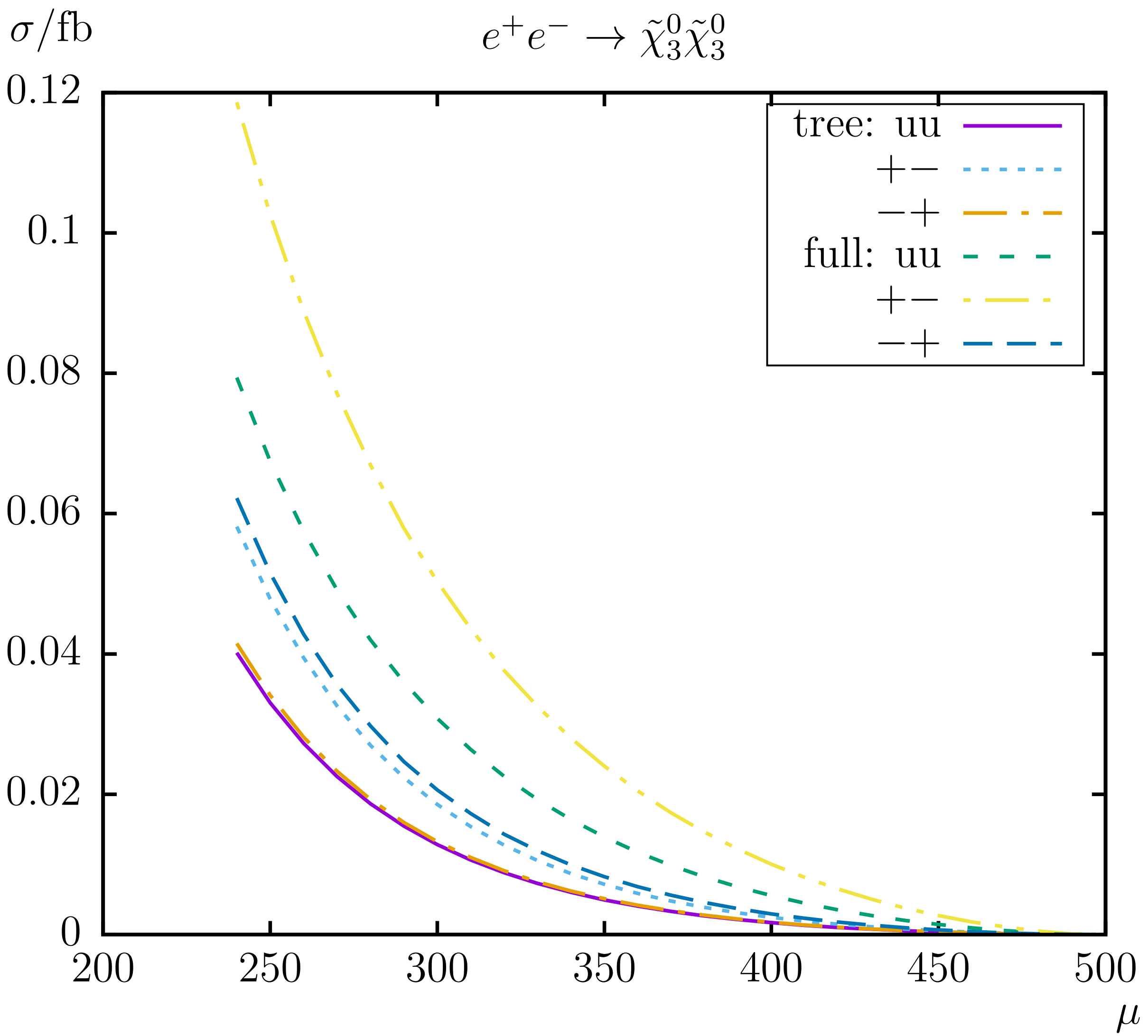
⇒ M_1 phase dependence large, loop corrections crucial!

$e^+e^- \to \tilde{\chi}^0_2\tilde{\chi}^0_2$:



$\Rightarrow$ loop corrections depend strongly on $\sqrt{s}$

$e^+e^- \to \tilde{\chi}^0_3\tilde{\chi}^0_3$:



$\Rightarrow$ polarization could be crucial for some processes!

5. Conclusinos

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

    $\Rightarrow$ other variants possible! Not (yet) analyzed!

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

- Fit results in CMSSM, NUHM1, NUHM2, pMSSM10:

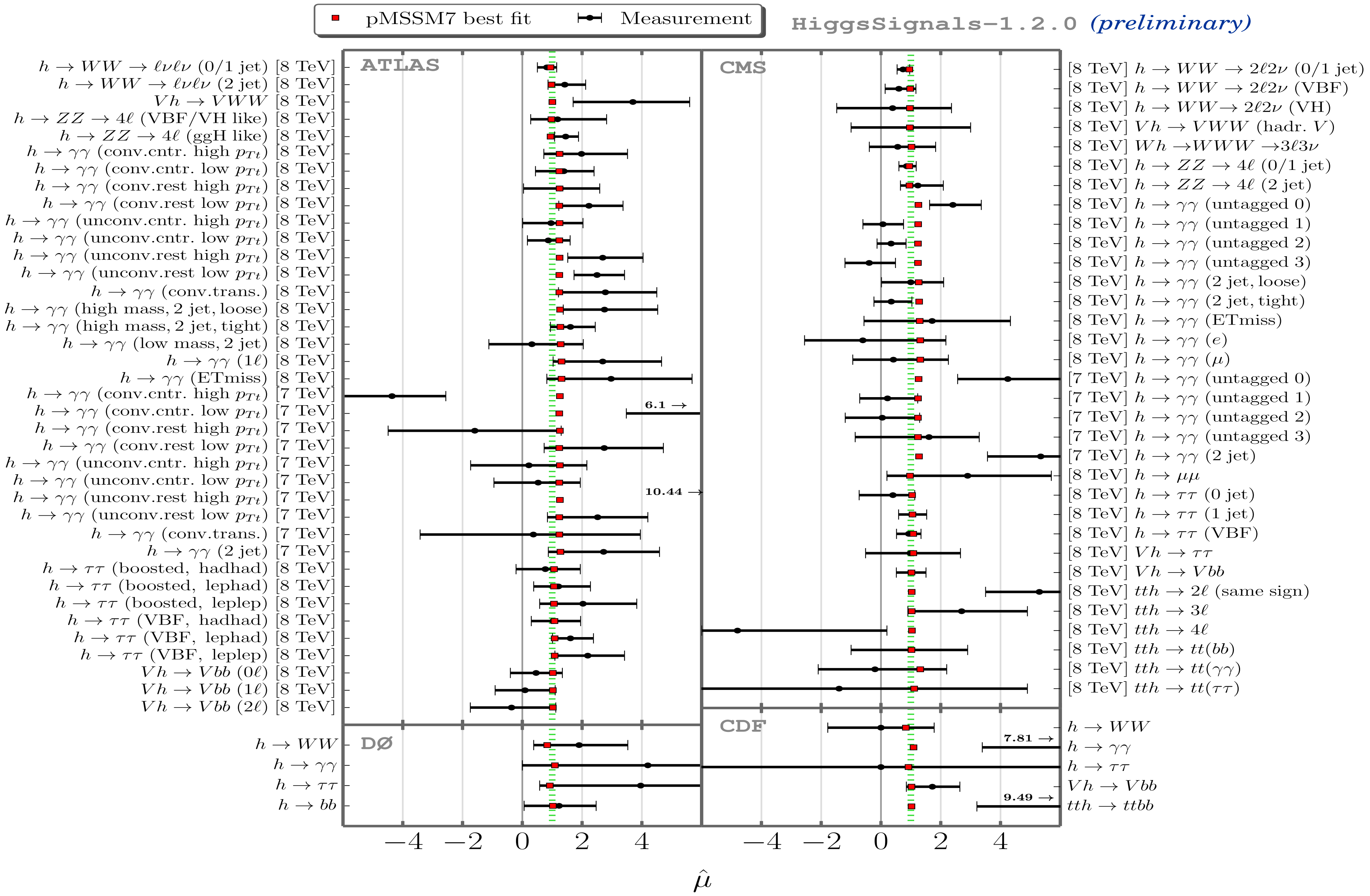
Particle	CMSSM/NUHM1/NUHM2	pMSSM10
gauginos	ILC CLIC	ILC CLIC
sleptons	CLIC	ILC CLIC
stops/sbottoms		CLIC
other		

χ^2-probabilities: CMSSM/NUHM1/NUHM2 = 11%, pMSSM10 = 31%

- SUSY production cross section: chargino/neutralino ready


Further Questions?

Higgs rate measurements: Implemented via HiggsSignals



(Some) Electroweak precision observables in the MasterCode

($\rightarrow$ as for blue band analysis, except Γ_W)

1. M_W (LEP/Tevatron)
2. $A^e_{\rm LR}$ (SLD)
3. $A^b_{\rm FB}$ (LEP)
4. $A^c_{\rm FB}$ (LEP)
5. $A^l_{\rm FB}$
6. A_b, A_c
7. R_b, R_c
8. $\sigma^0_{\rm had}$

$\Rightarrow$ largest impact: (1), (2), (3)

(Some) B/K physics observables in the MasterCode

1. BR($b \to s\gamma$) (MSSM/SM)

2. BR($B_s \to \mu^+\mu^-$)

3. ΔM_s

4. R($\Delta M_s/\Delta M_d$)

5. BR($B_u \to \tau\nu_\tau$) (MSSM/SM)

6. BR($B \to X_x\ell^+\ell^-$)

7. BR($K \to \ell\nu$) (MSSM/SM)

8. BR(ΔM_K) (MSSM/SM)

$\Rightarrow$ largest impact: (1) and (2)

Further low-energy observables

– anomalous magnetic moment of the muon: $(g-2)_\mu$

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Higgs physics observables in the MasterCode

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Dark Matter observables in the MasterCode

– CDM density: $\Omega_\chi h^2$

– Direct detection cross section: $\sigma_p^{\rm SI}$ (prediction; not incl. in the fit yet)

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– Direct detection cross section: σ_p^{SI} (prediction; not incl. in the fit yet)

SM parameters

– top mass: m_t

– Z boson mass: M_Z

– hadronic contribution to fine structure constant: $\Delta\alpha_{\text{had}}$