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

SUSY fits and their Implications for ILC and CLIC

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

Madrid, 01/2016

1. Introduction
2. The MasterCode
3. Predictions for the ILC and CLIC
4. Conclusions

1. Introduction

Some "recent" measurements:

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

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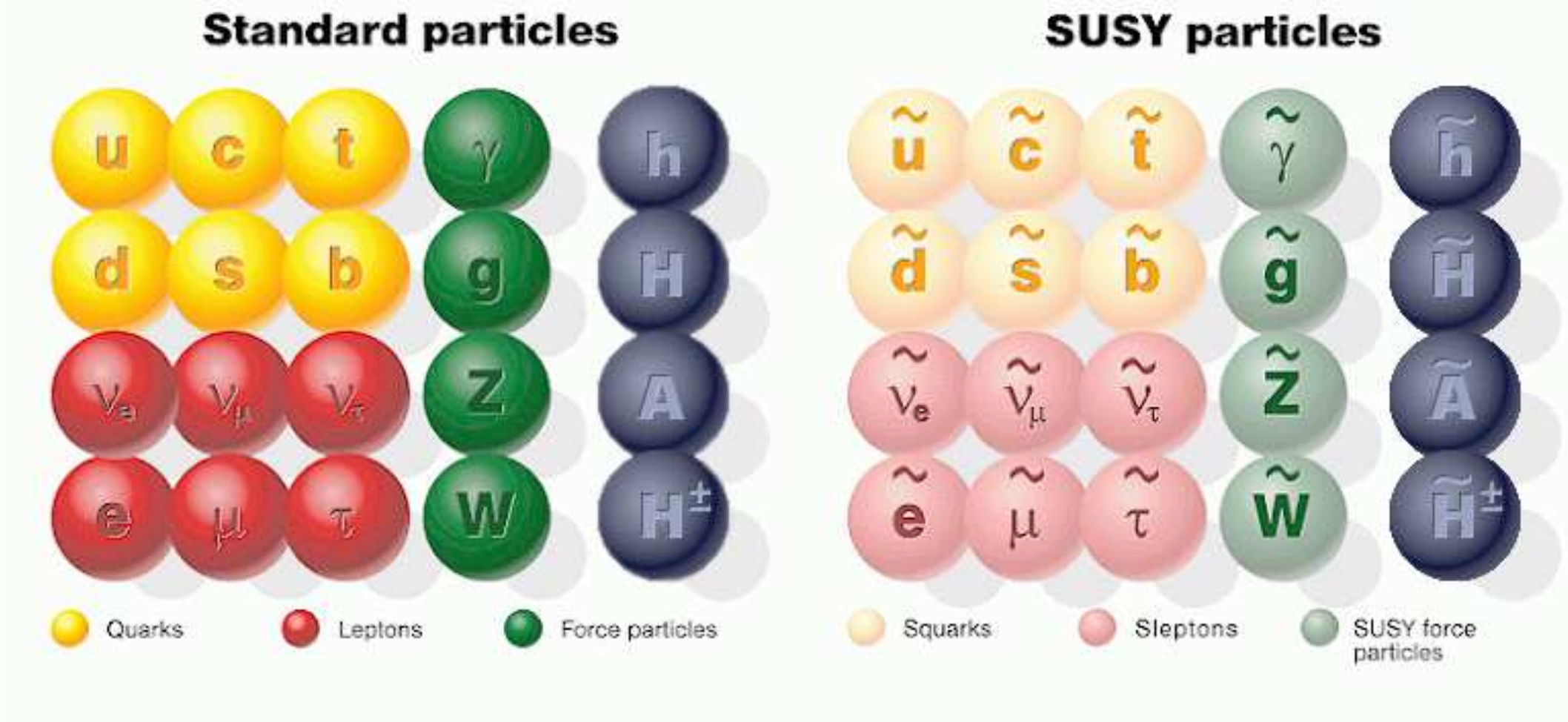
$\Rightarrow$ good motivation to look at SUSY!

$\Rightarrow$ also $gg \to \phi_{750} \to \gamma\gamma$ can be accomodated!

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! $\Rightarrow gg \to \phi_{750} \to \gamma\gamma$ cannot be accomodated!

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

$\Rightarrow$ Scenario characterized by

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

m_0 : universal scalar mass parameter

$m_{1/2}$: universal gaugino mass parameter

A_0 : universal trilinear coupling

} at the GUT scale

$\tan\beta$: ratio of Higgs vacuum expectation values

sign(μ) : sign of supersymmetric Higgs parameter

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

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

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

$\Rightarrow$ it is possible that with the CMSSM, NUHM1, NUHM2, . . . we missed the "correct" mechanism

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

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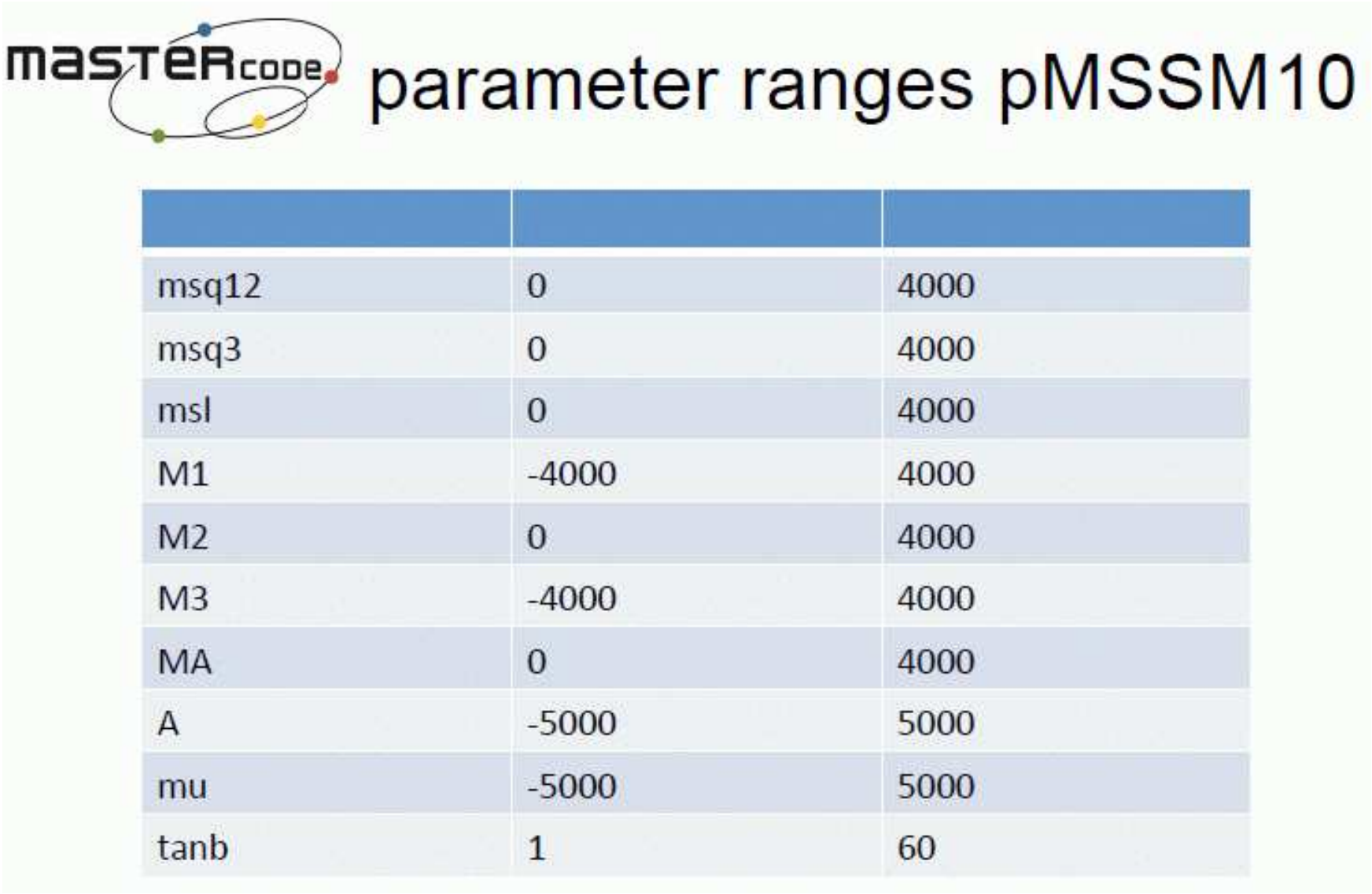
tension between low-energy EW effects and (colored) LHC searches

Solution: investigate also the "general MSSM"

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

- squark mass parameters: $m_{\tilde{q}_{12}}$, $m_{\tilde{q}_3}$
- slepton mass parameter: $m_{\tilde{l}}$
- gaugino masses: M_1, M_2, M_3
- trilinear coupling: A
- Higgs sector parameters: M_A, $\tan\beta$
- Higgs mixing paramter: μ

Scanned parameter ranges in the pMSSM10:



msq12	0	4000
msq3	0	4000
msl	0	4000
M1	-4000	4000
M2	0	4000
M3	-4000	4000
MA	0	4000
A	-5000	5000
mu	-5000	5000
tanb	1	60

$\Rightarrow$ other pMSSM10 variants possible! Not (yet) analyzed!

2. The Mastercode

⇒ collaborative effort of theorists and experimentalists

[*Bagnaschi, Buchmüller, Cavanaugh, Citron, De Roeck, Dolan, Ellis, Flächer, SH, Isidori, Mallik, Marouche, Martinez Santos, Olive, Sakurai, de Vries, 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

Status of the "MasterCode":

- (so far) one model: (MFV) MSSM

- tools included:
  - our own LHC SUSY search implementation ⇒ NEW
    (3 search categories: colored, electroweak, compressed stop)
  - Higgs related observables, $(g-2)_\mu$ [*FeynHiggs*]
  - Higgs signal strengths [*HiggsSignals*] ⇒ NEW
  - Higgs exclusion bounds [*HiggsBounds*] ⇒ NEW
  - B-physics observables [*SuFla*]
  - more B-physics observables [*SuperIso*]
  - Electroweak precision observables [*FeynWZ*]
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  - for GUT scale models: RGE running [*SoftSusy*]

⇒ all most-up-to-date codes on the market!

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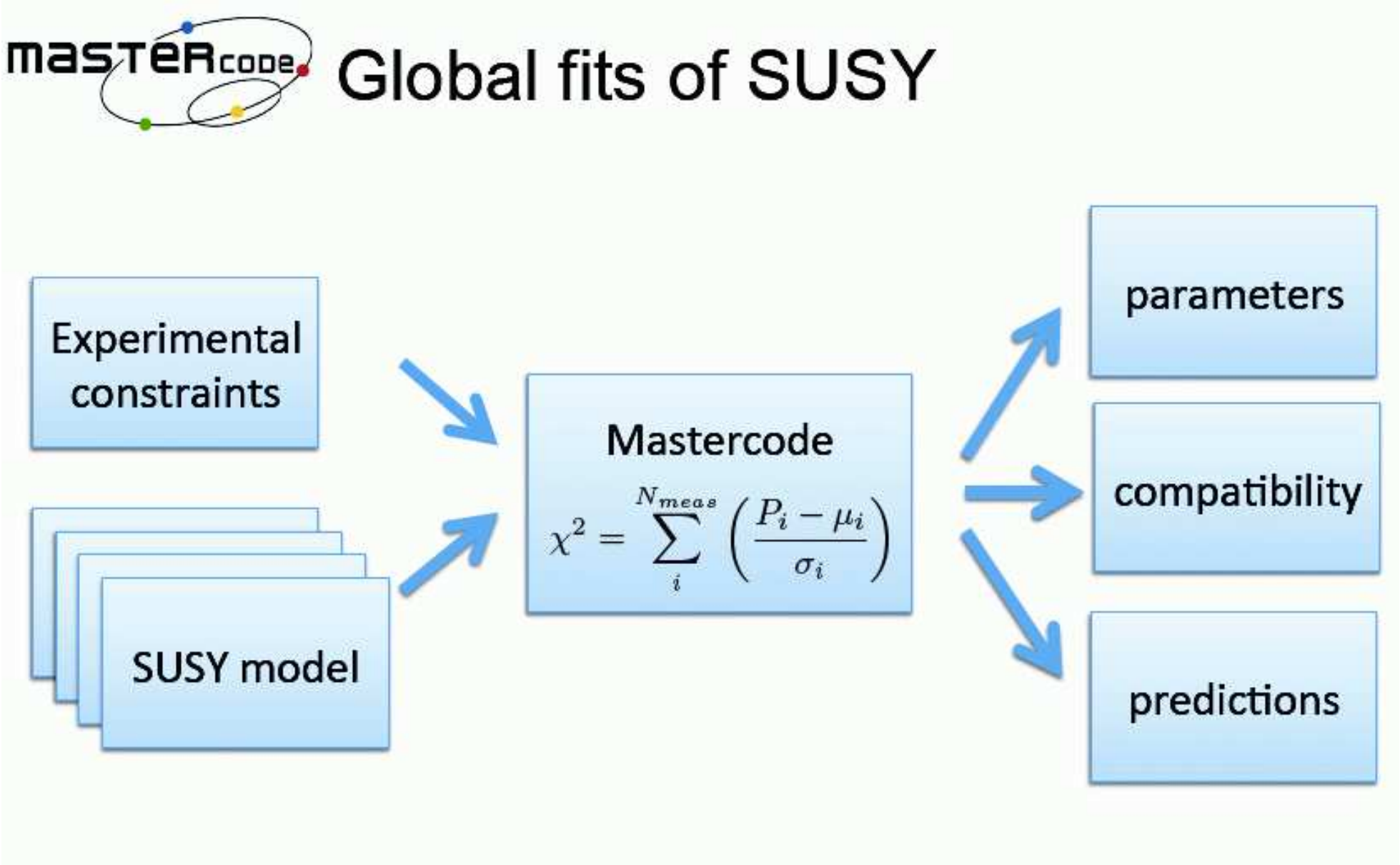
⇒ all most-up-to-date codes on the market! ⇒ crucial for precision!

The χ^2 evaluation:

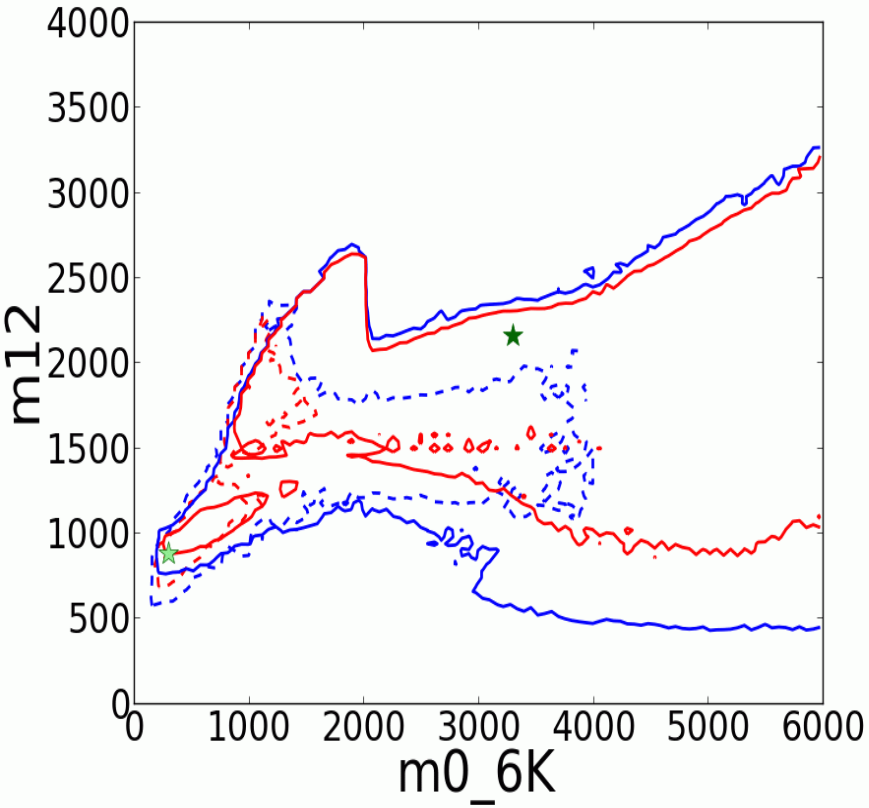


3. Predictions for the ILC and CLIC

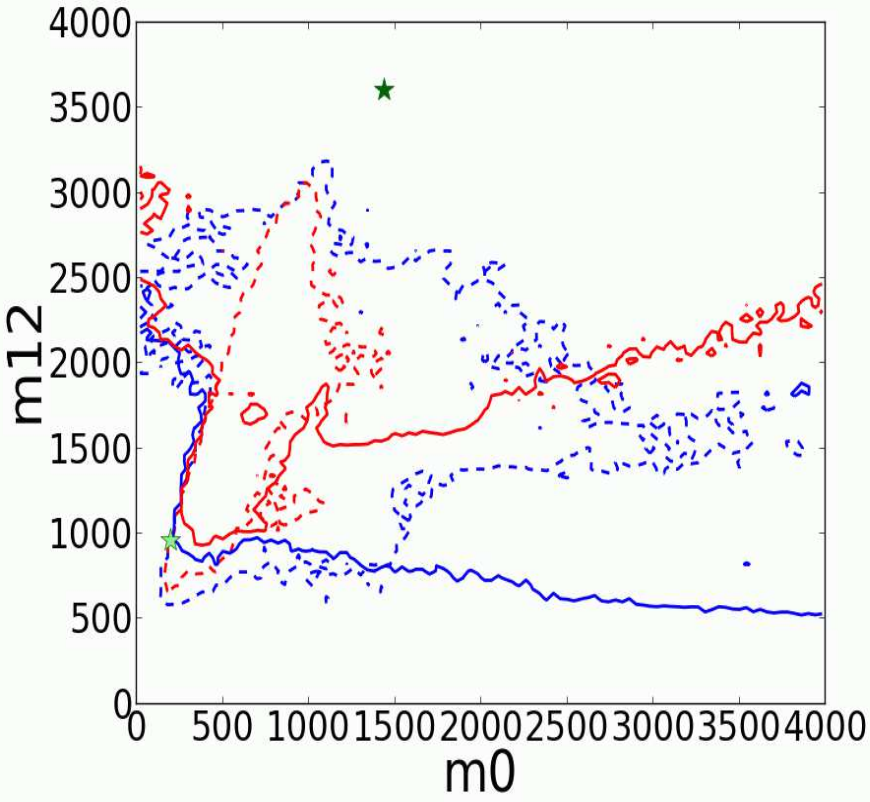
m_0-$m_{1/2}$ plane including LHC 20/fb:

[2013]

CMSSM



NUHM1



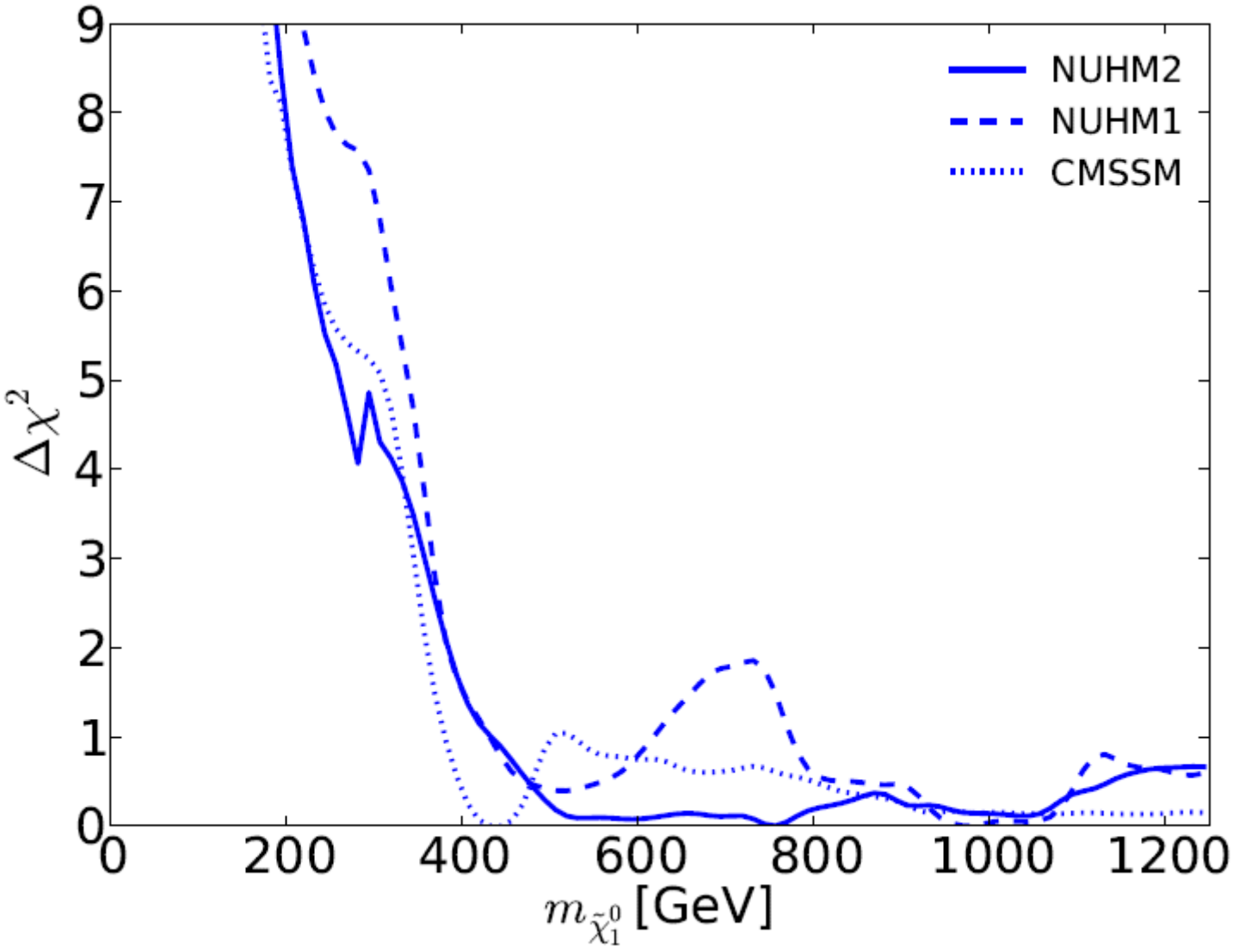
dotted: LHC 5/fb 7 TeV, solid: LHC 20/fb 8 TeV

$\Rightarrow$ very high masses favored!

$\Rightarrow$ prospects for ILC and CLIC?

LSP mass incl. 20/fb of LHC data

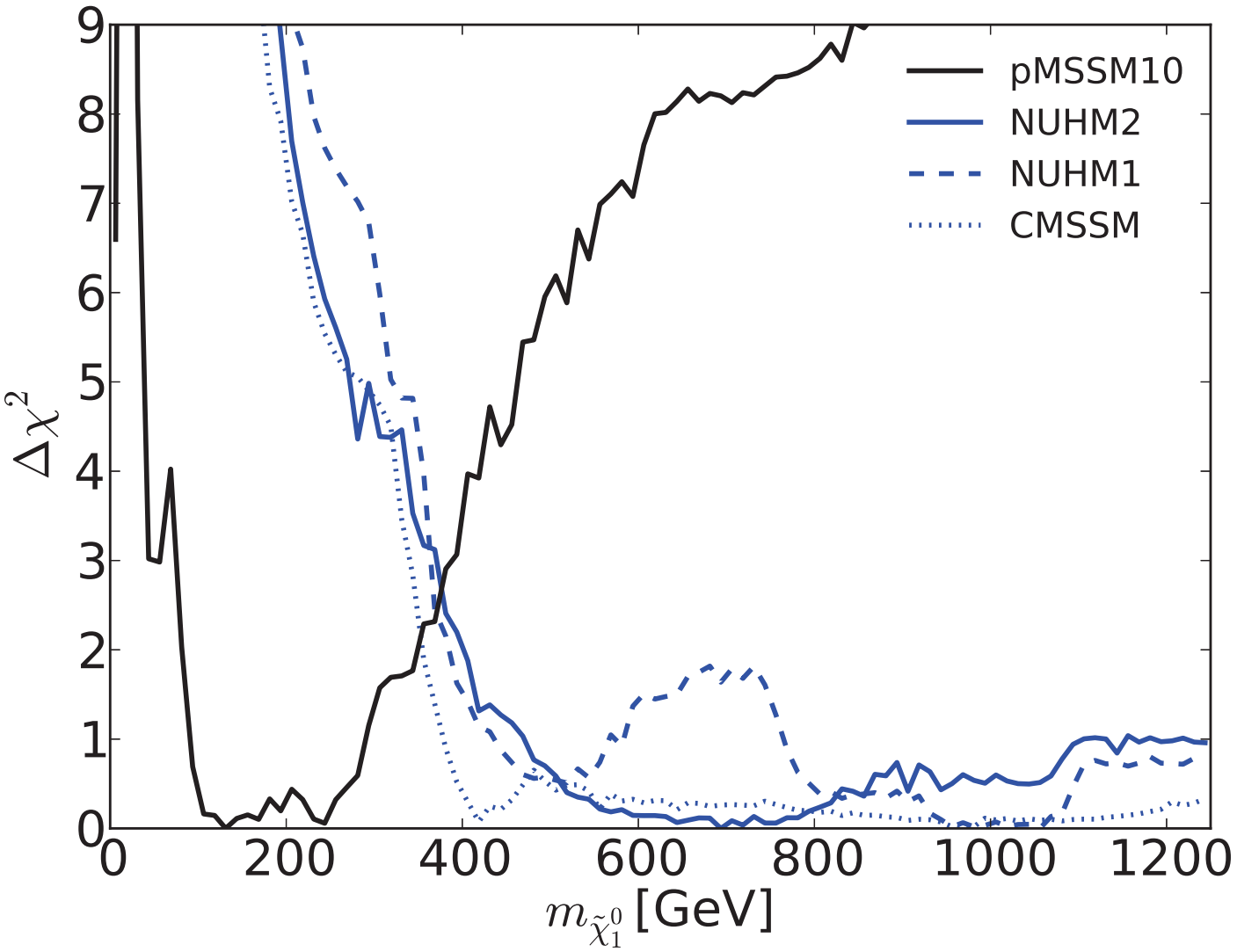
[2014]



⇒ only very large values are favored

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

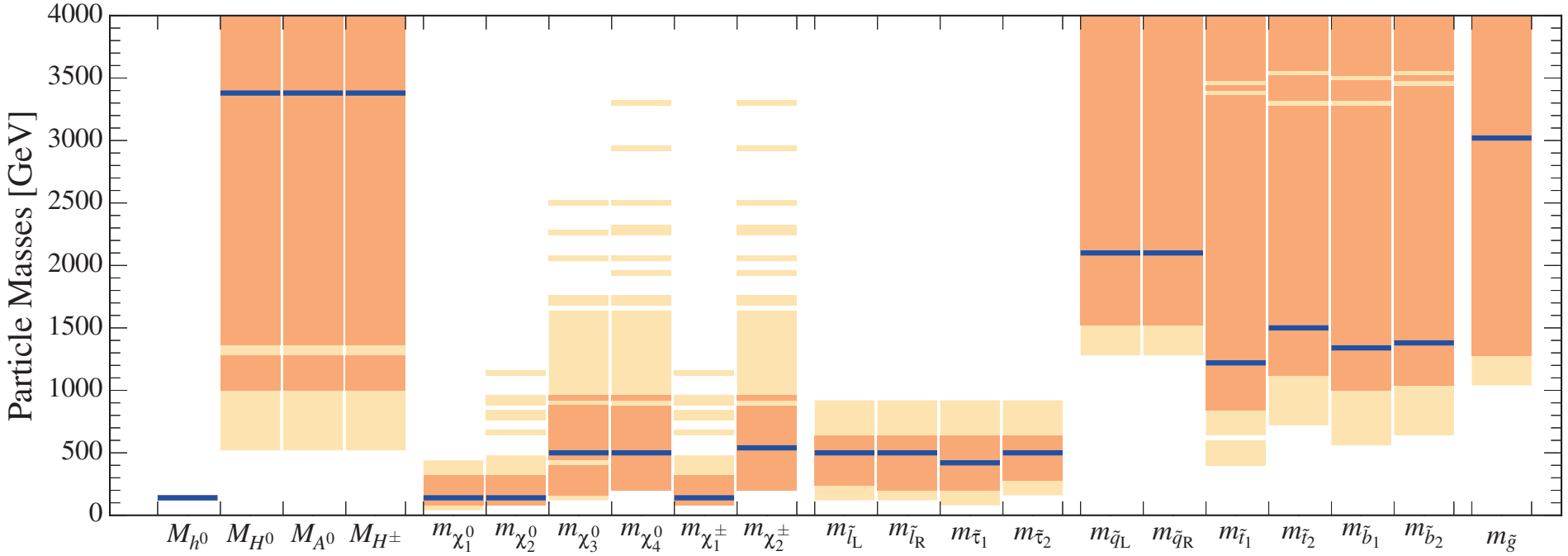
[2015]



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

pMSSM10 prediction: best-fit masses

[2015]



⇒ high colored masses

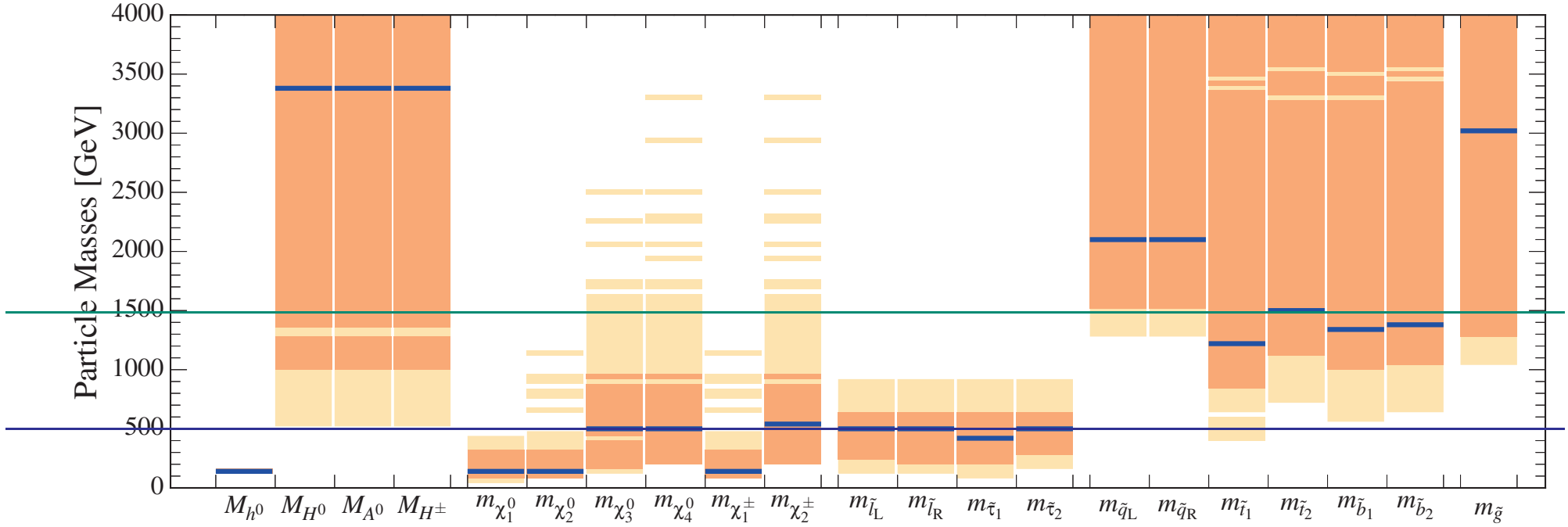
⇒ relatively low electroweak masses

partially with not too large ranges

⇒ clear prediction for ILC and CLIC

pMSSM10 prediction: best-fit masses

[2015]



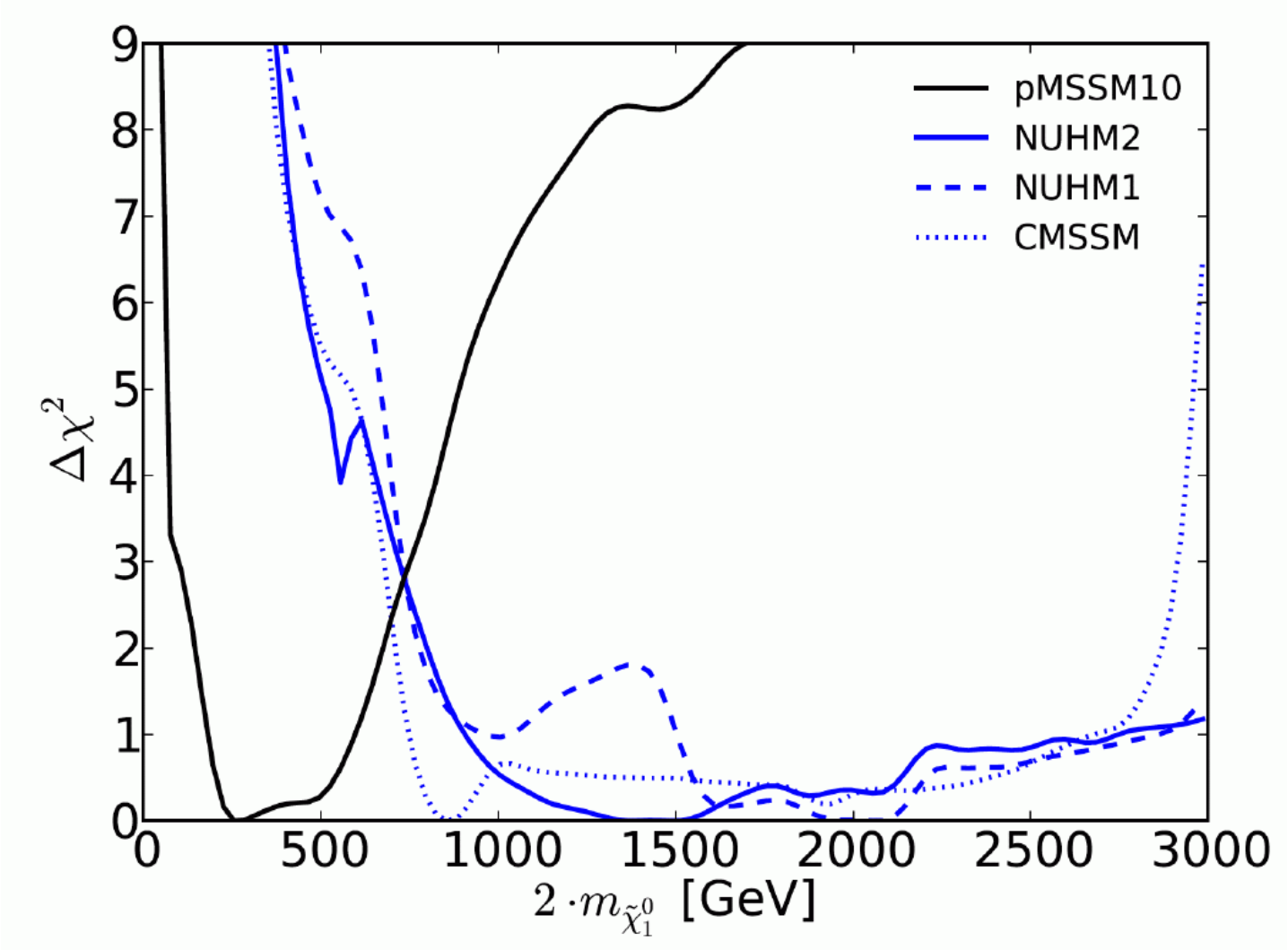
ILC: $\sqrt{s} = 1000$ GeV $\Rightarrow$ pair production of many SUSY particles possible

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

$\Rightarrow$ some colored particles possbile

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

[2014]



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

$\Rightarrow$ pMSSM10: easy at the ILC

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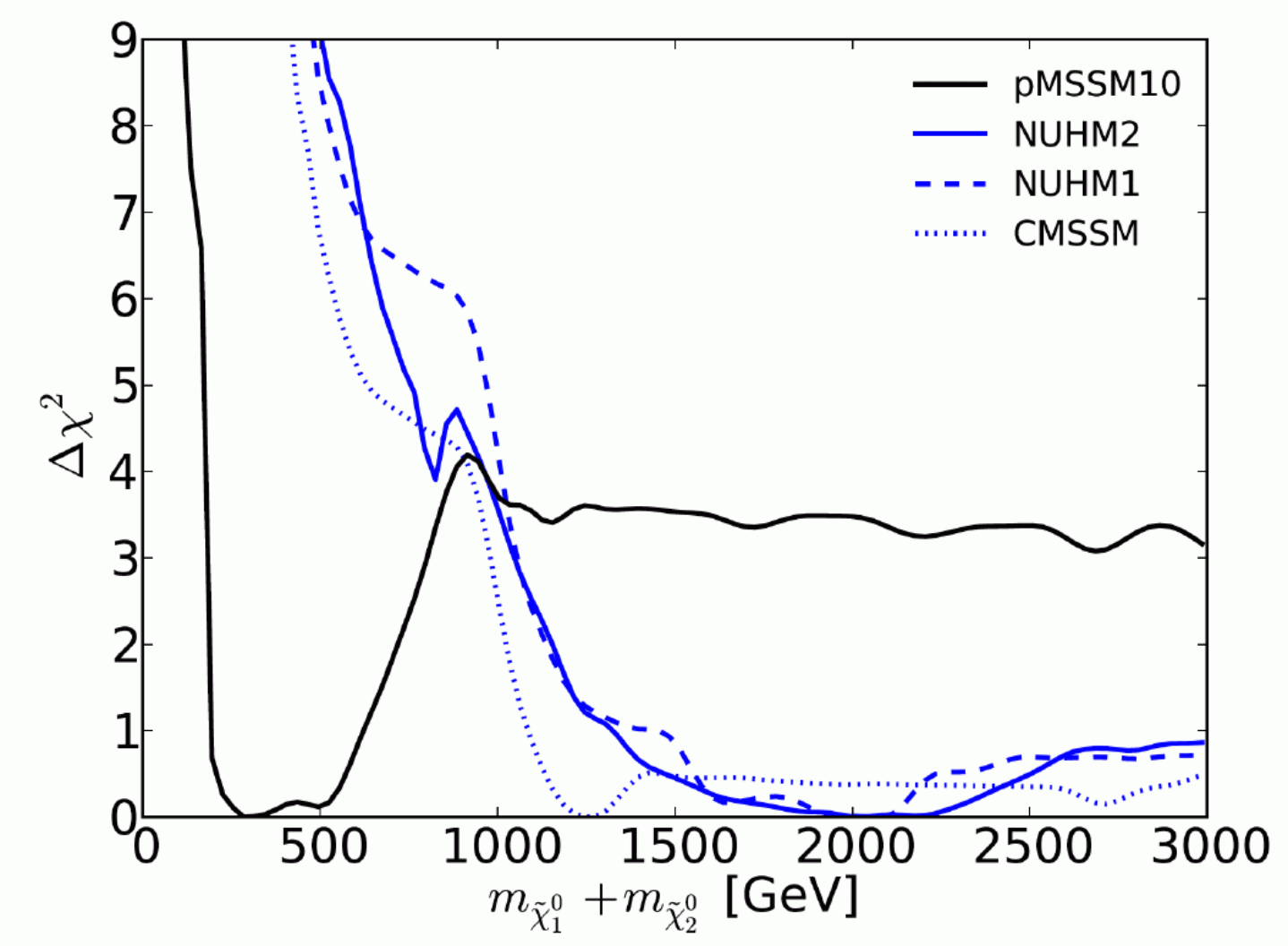

⇒ GUT based models: ILC :-(, CLIC possible

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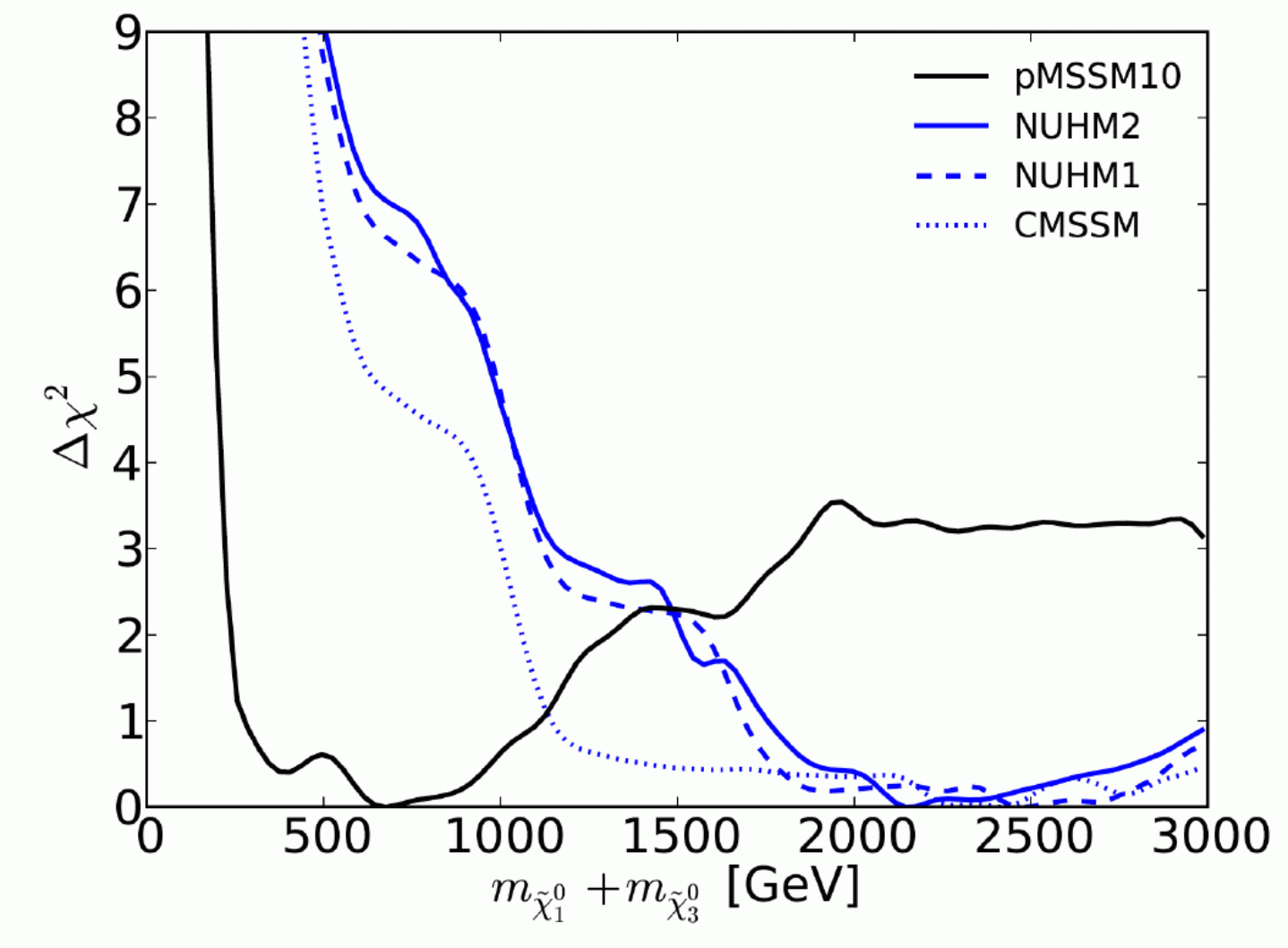

⇒ GUT based models: ILC :-(, CLIC possible

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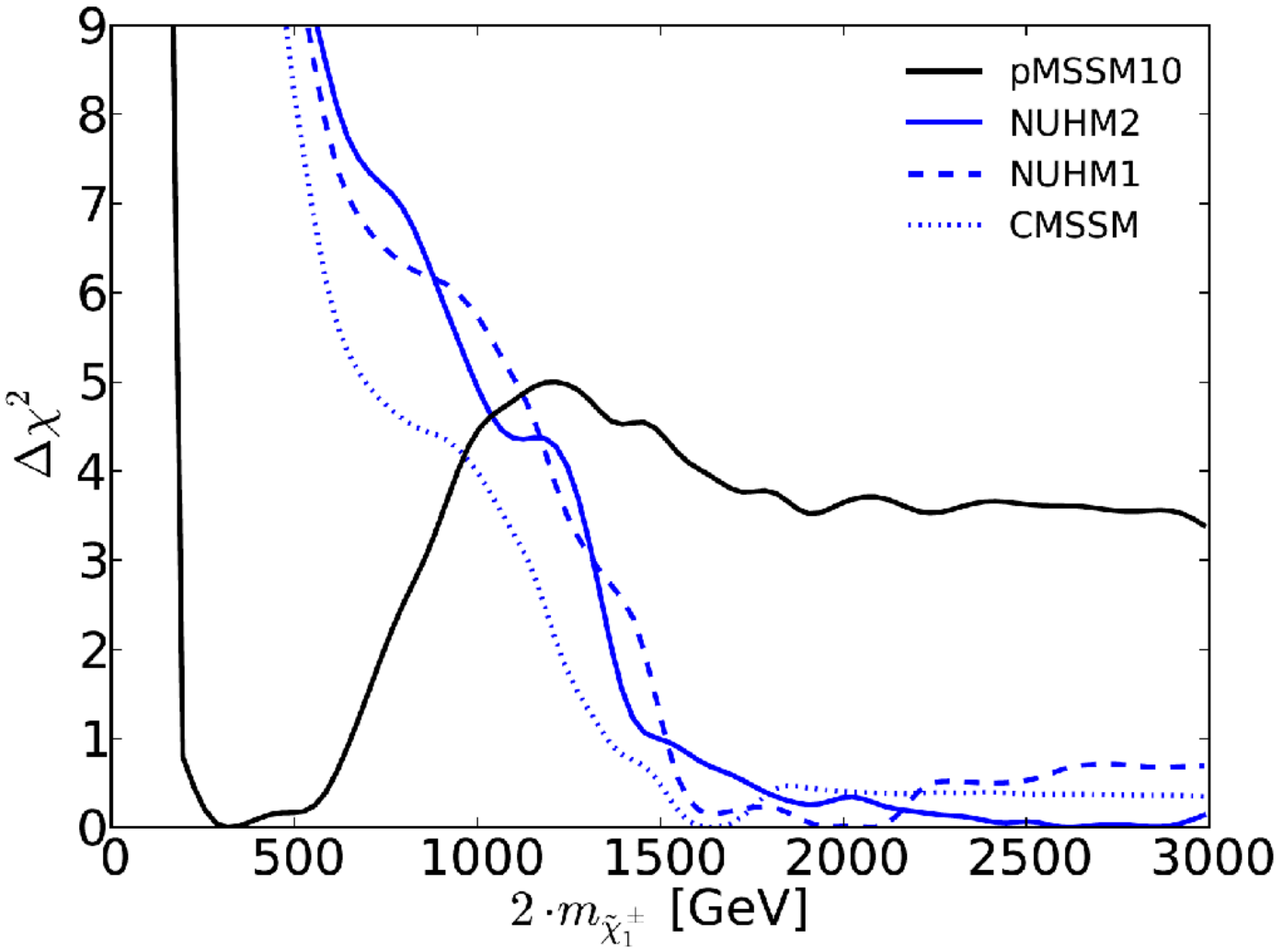
Some gaugino production cross sections: $e^+e^+ \to \tilde{\chi}_1^\pm \tilde{\chi}_1^\pm$

[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%
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

4. Conclusinos

- SUSY is (still) the best-motivated BSM scenario
  - constrained models: CMSSM, NUHM1, NUHM2, ...
  - general models: pMSSM10, ...
    $\Rightarrow$ other variants possible! Not analyzed!

- Our tool: MasterCode

  combination of LHC searches, Higgs measurements, EWPO, BPO, CDM $\Rightarrow \chi^2$ evaluation

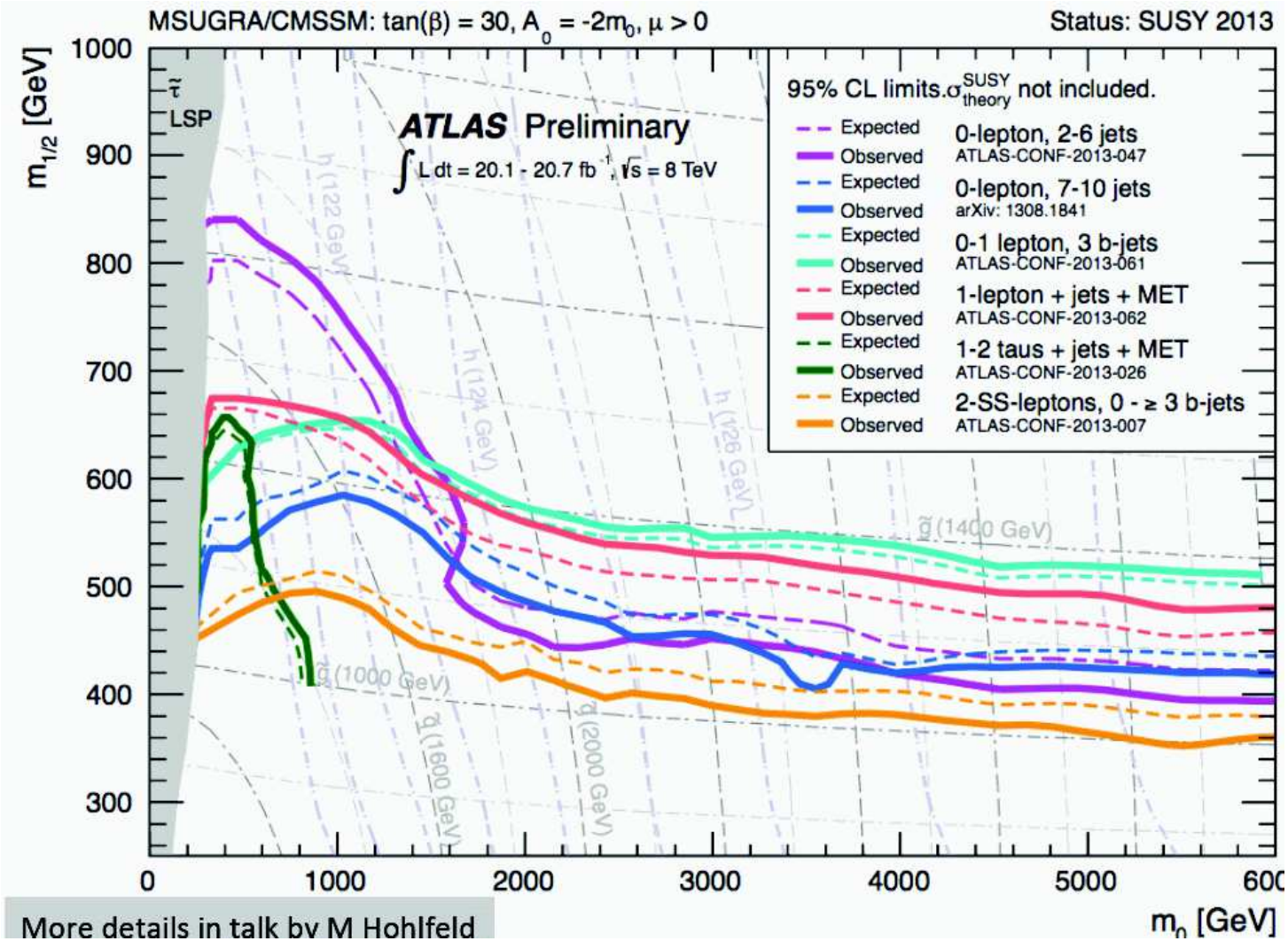
- Fit results in CMSSM, NUHM1, NUHM2, pMSSM10:

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%

Back-up

LHC searches for SUSY particles: ATLAS/CMS results for CMSSM, . . .



⇒ Results given in CMSSM

⇒ can be taken over to NUHM1, NUHM2

⇒ not applicable to the pMSSM

LHC searches for SUSY particles in the pMSSM:

3 limits:

1. searches for colored particles
   4-dim grid in $m_{\tilde{\chi}_1^0}$, $m_{\tilde{q}}$, $m_{\tilde{q}}$, $m_{\tilde{q}_3}$, $m_{\tilde{g}}$

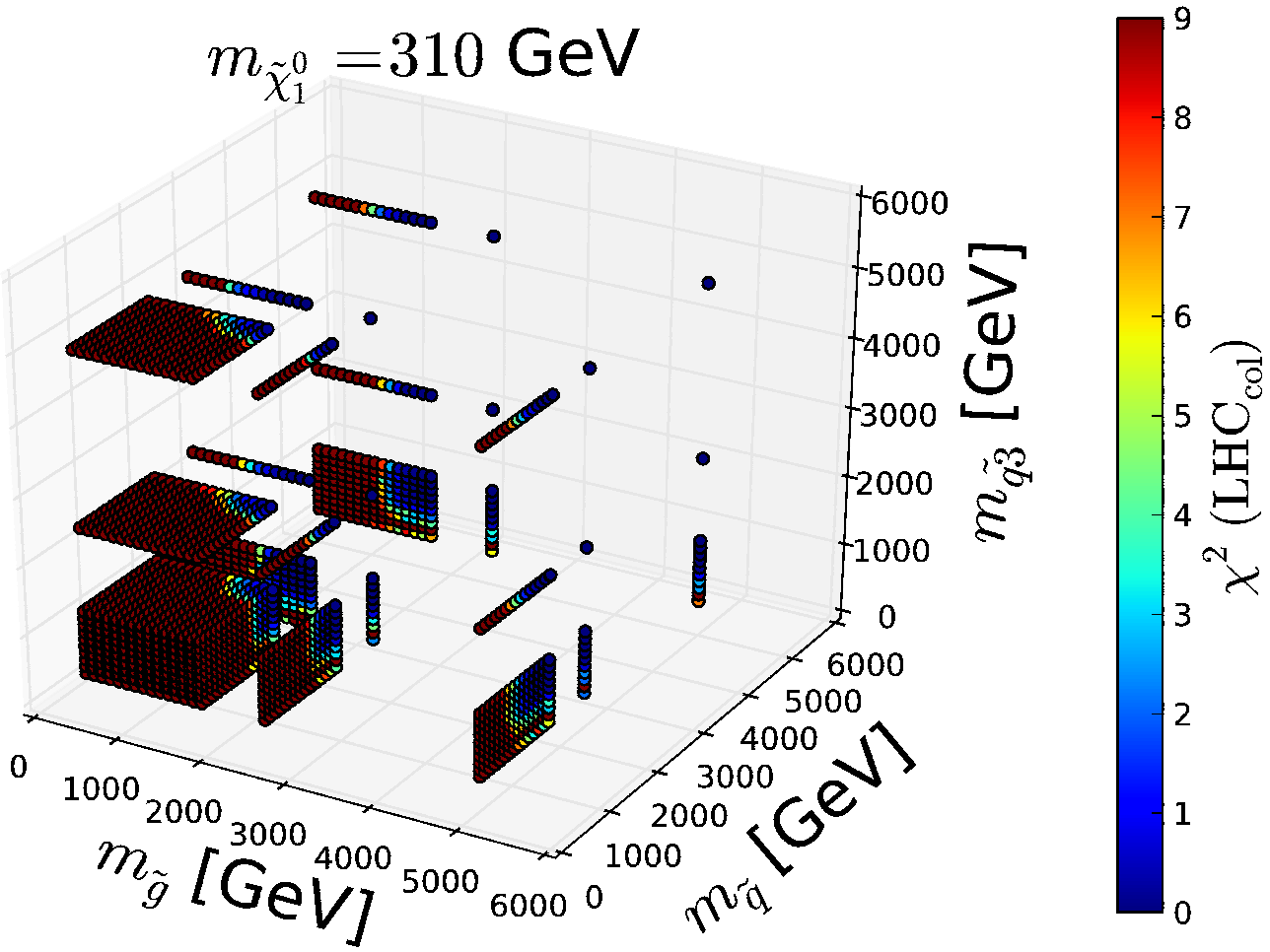
2. searches for compressed stop spectra

$$\tilde{t} \to b\tilde{\chi}_1^{\pm}\,, \quad \tilde{t} \to bW\tilde{\chi}_1^0\,, \quad \tilde{t} \to b\nu\tilde{\tau}_1\,, \quad \tilde{t} \to c\tilde{\chi}_1^0$$

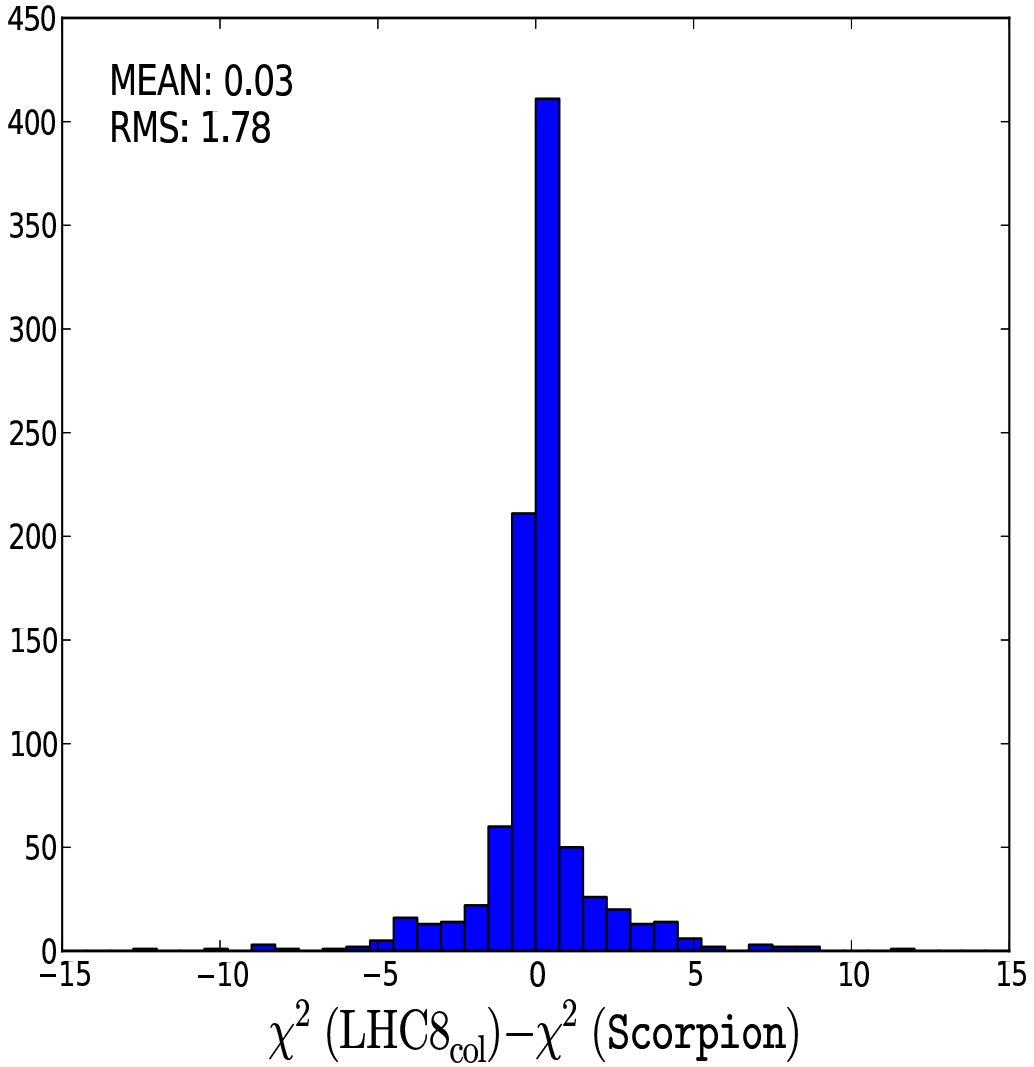
3. searches for light EW particles

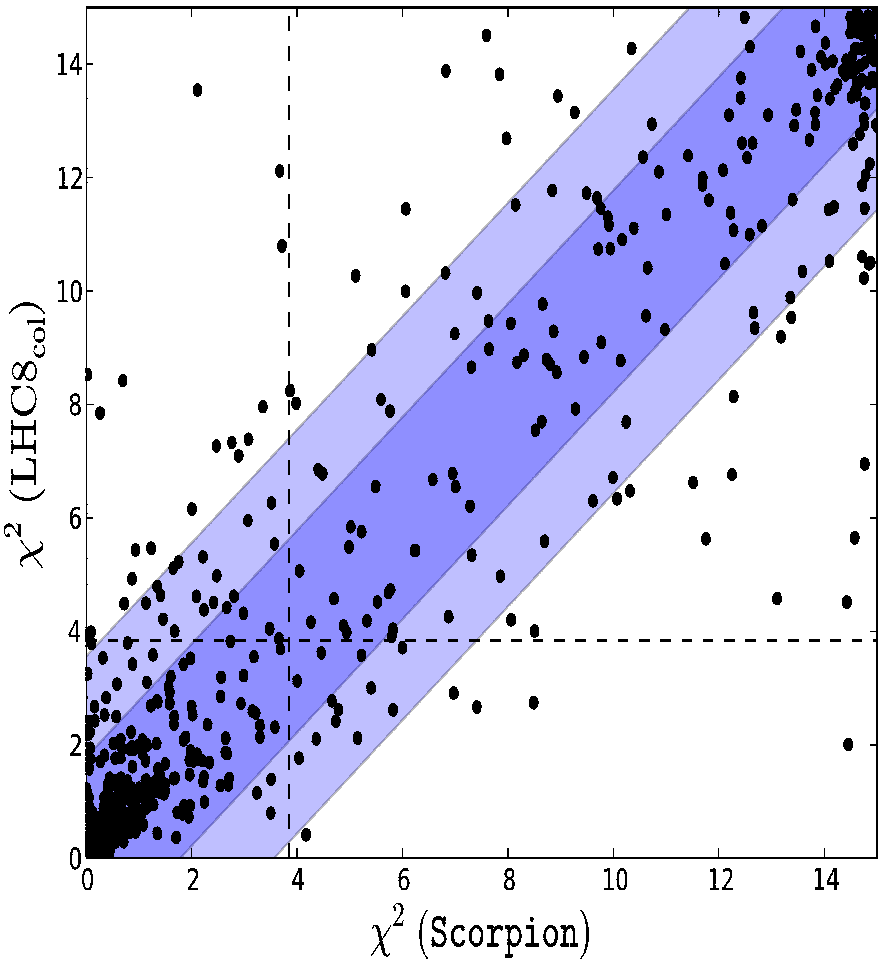
$$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \text{ via } \tilde{l}, \quad \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \text{ via } WZ\,, \quad \tilde{l} \to l\tilde{\chi}_{1,2}^0, \nu_l\tilde{\chi}_1^{\pm}$$

Example for $m_{\tilde{\chi}_1^0} = 310$ GeV:



χ^2 comparison for colored searches





$\Rightarrow$ tested with Scopion (home made code "a la Atom")

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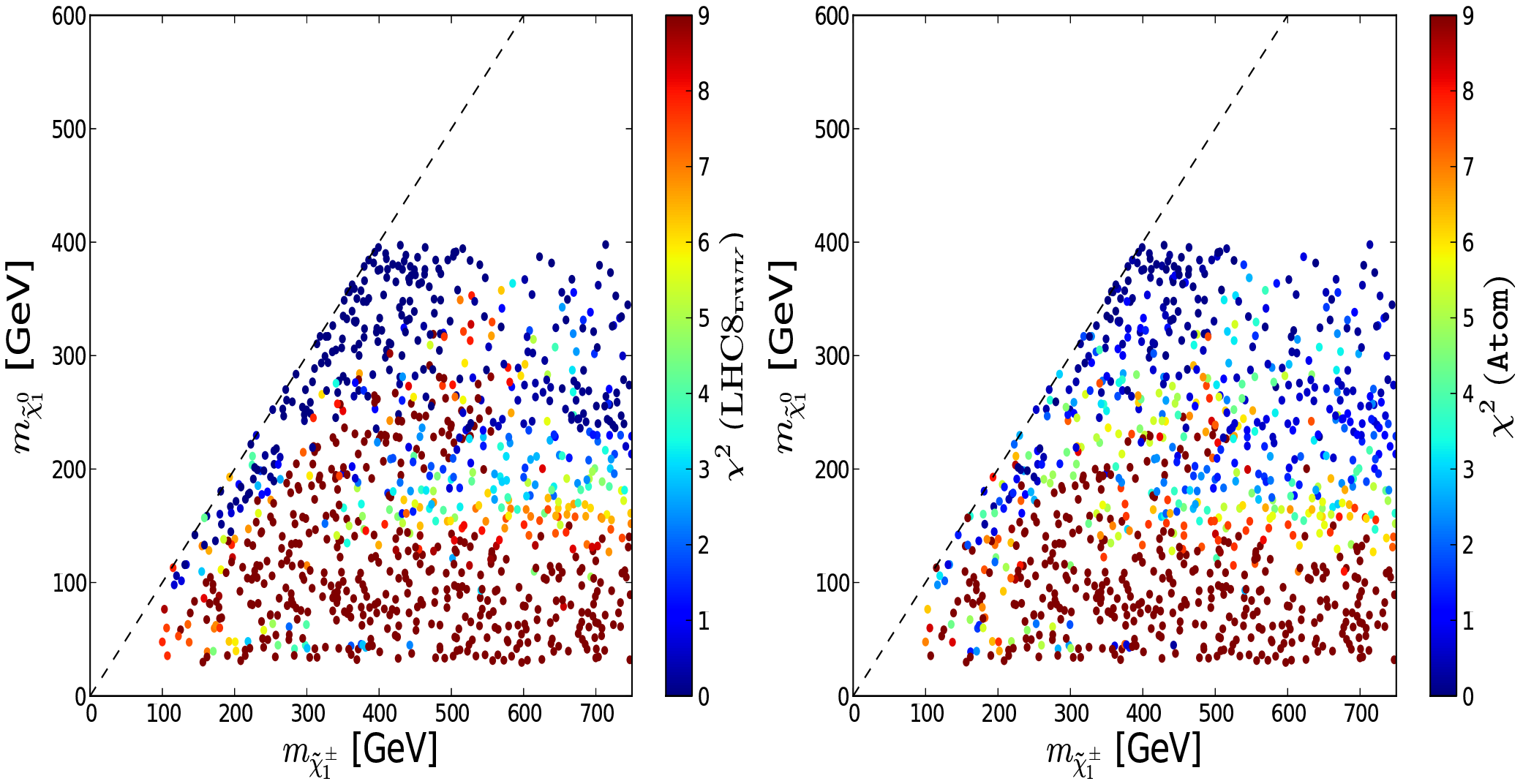

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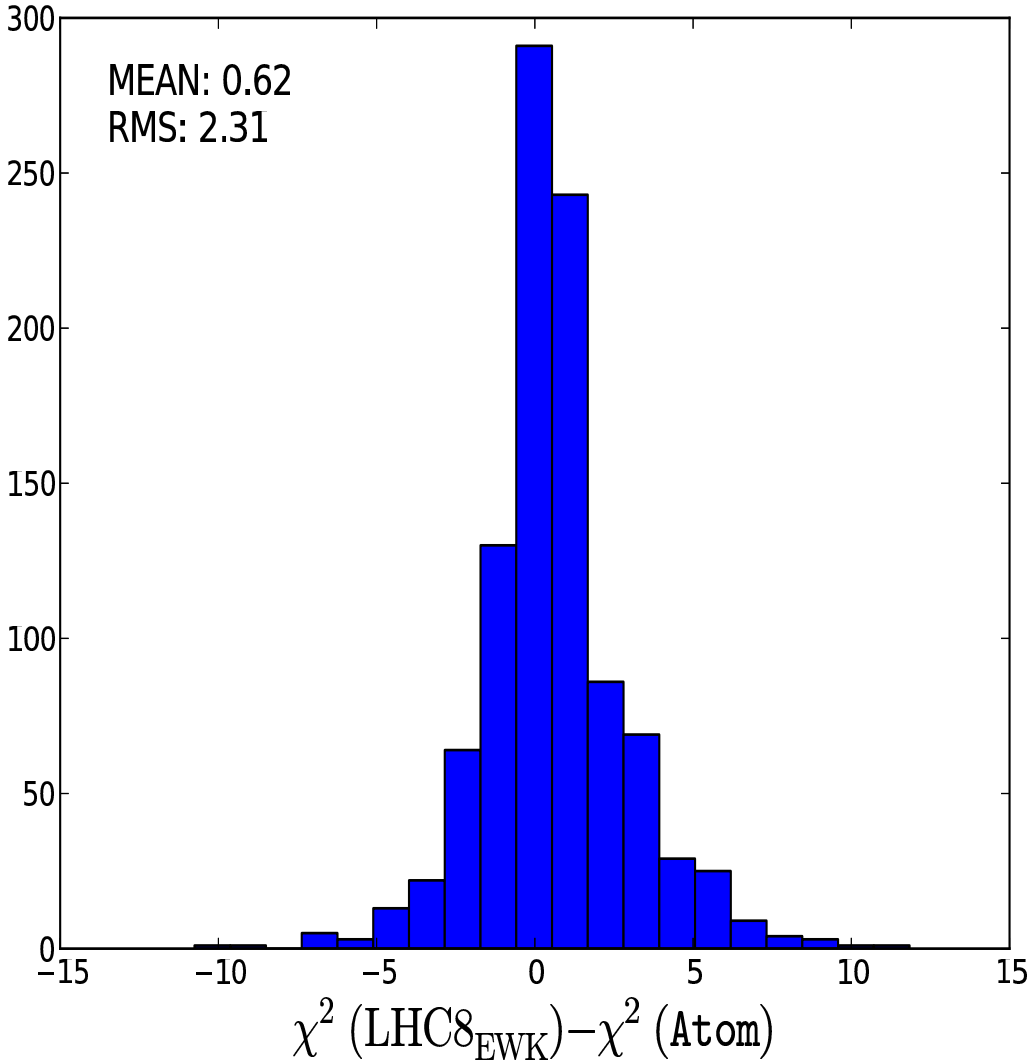

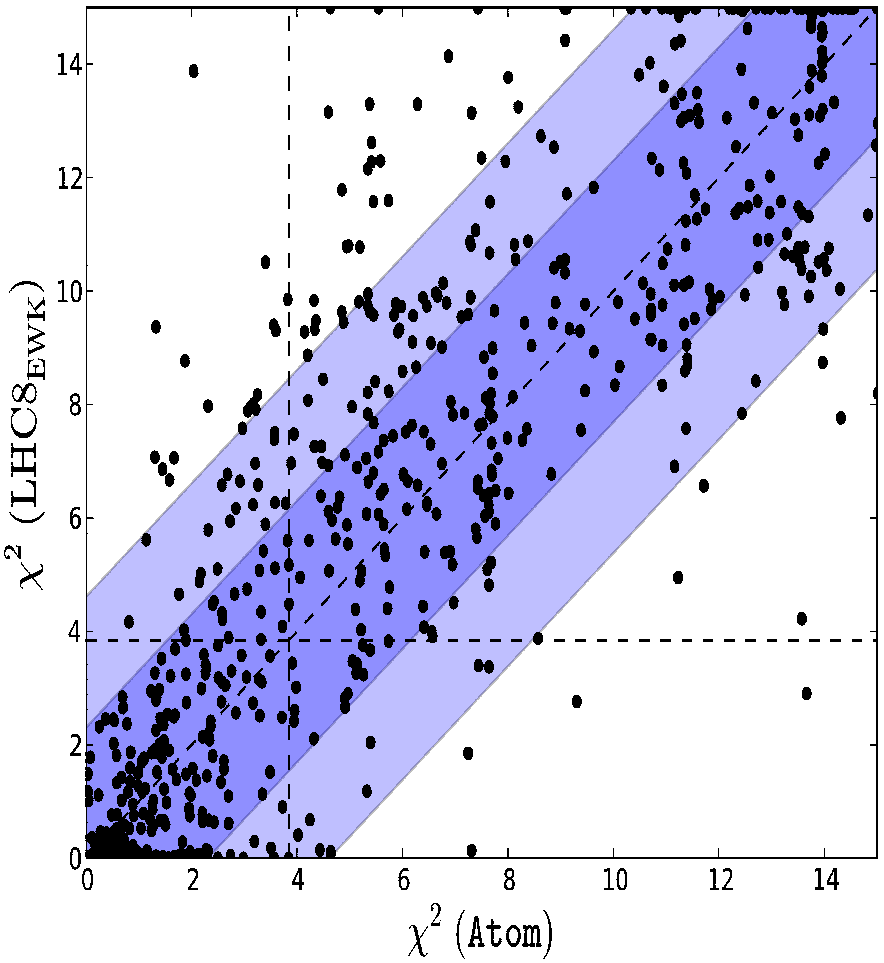

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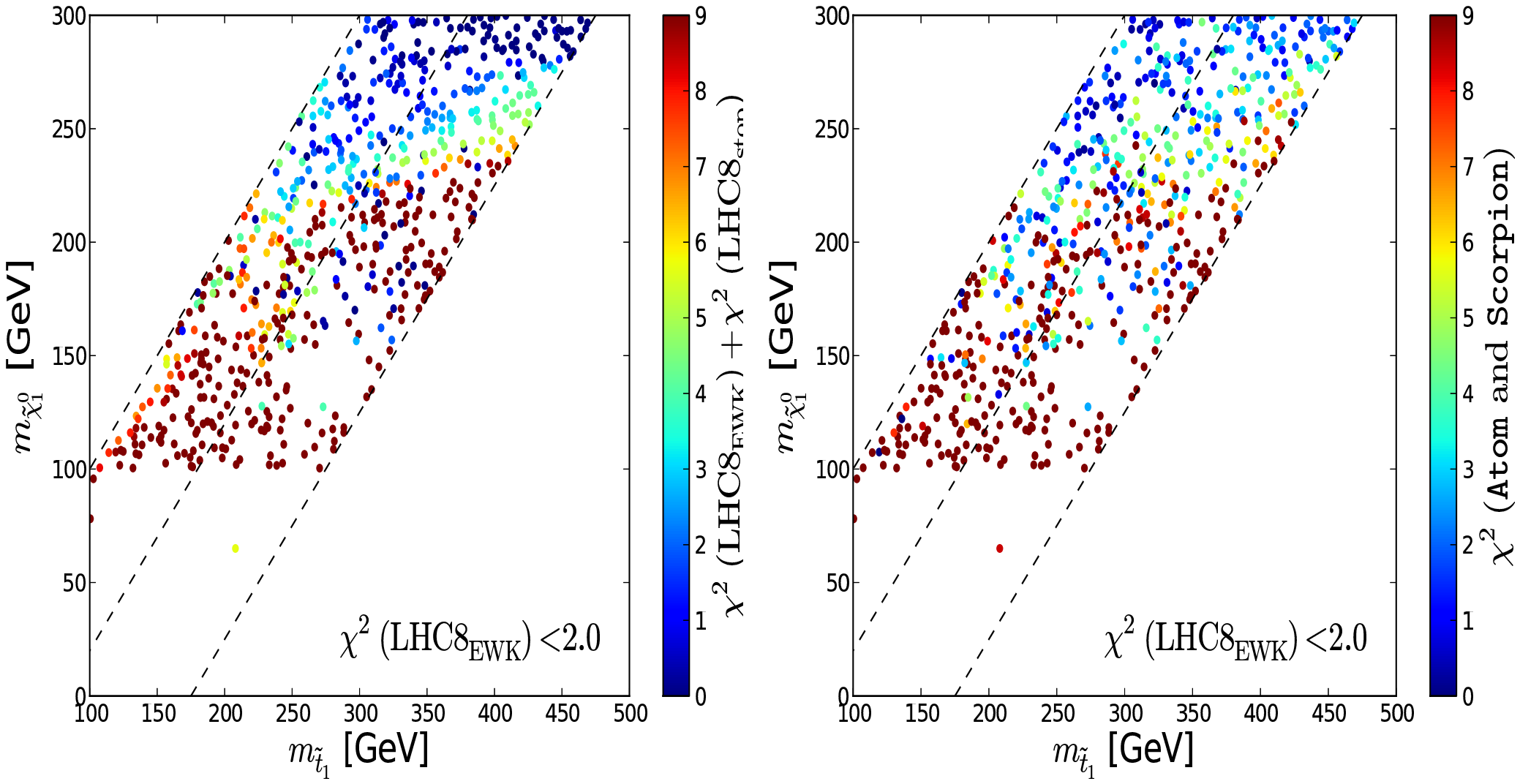

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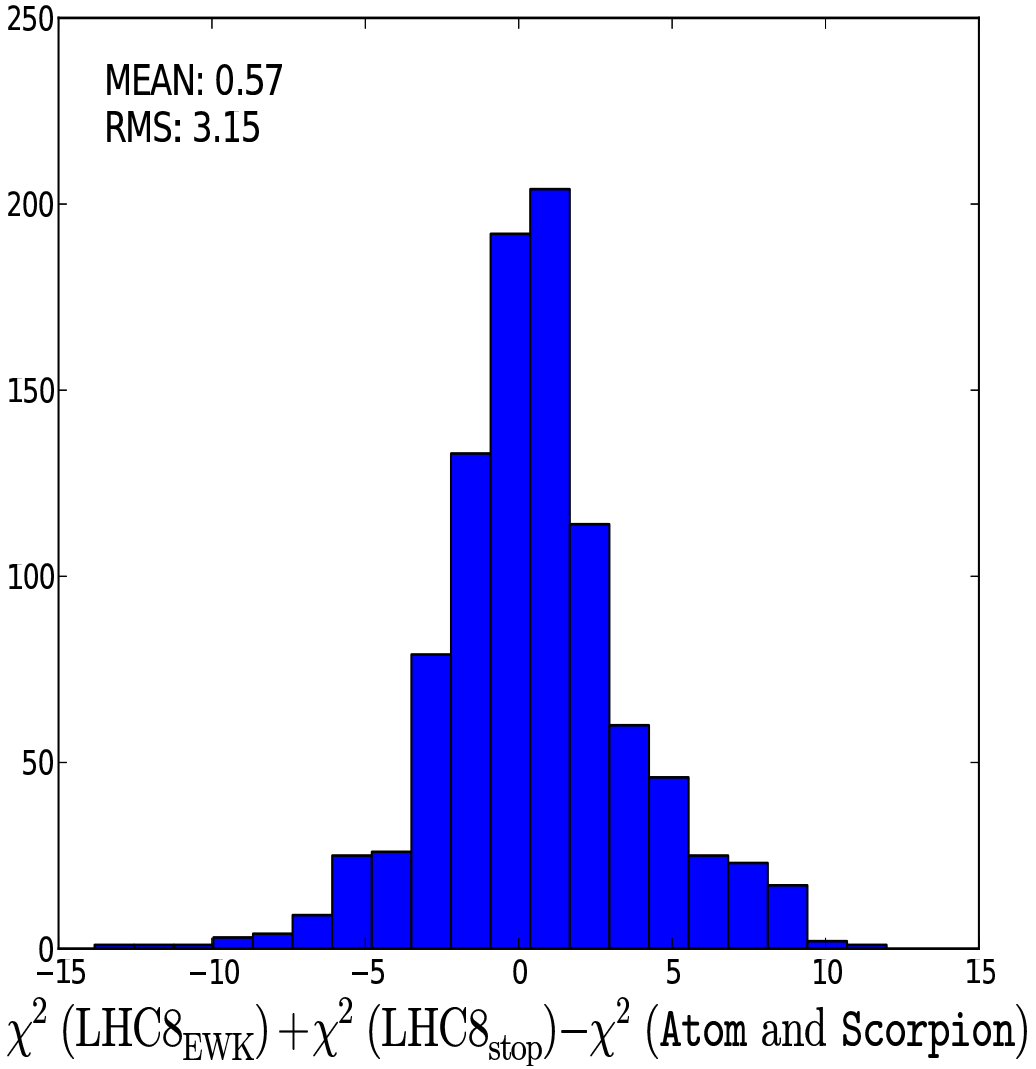

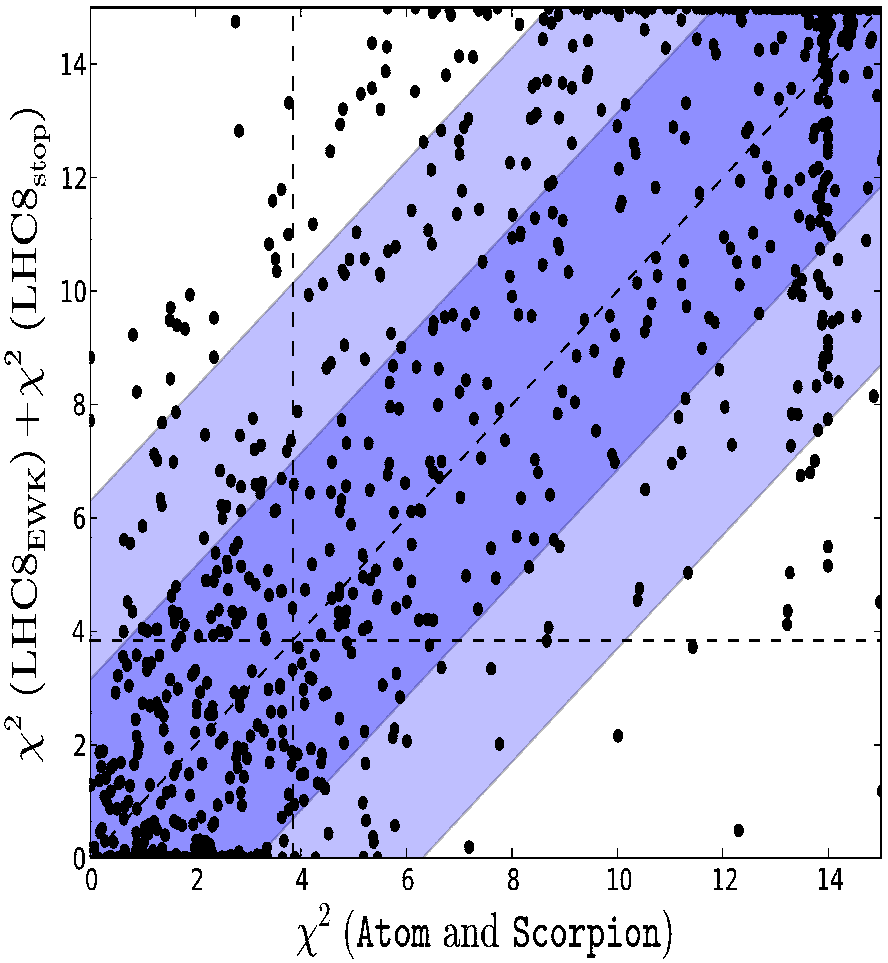

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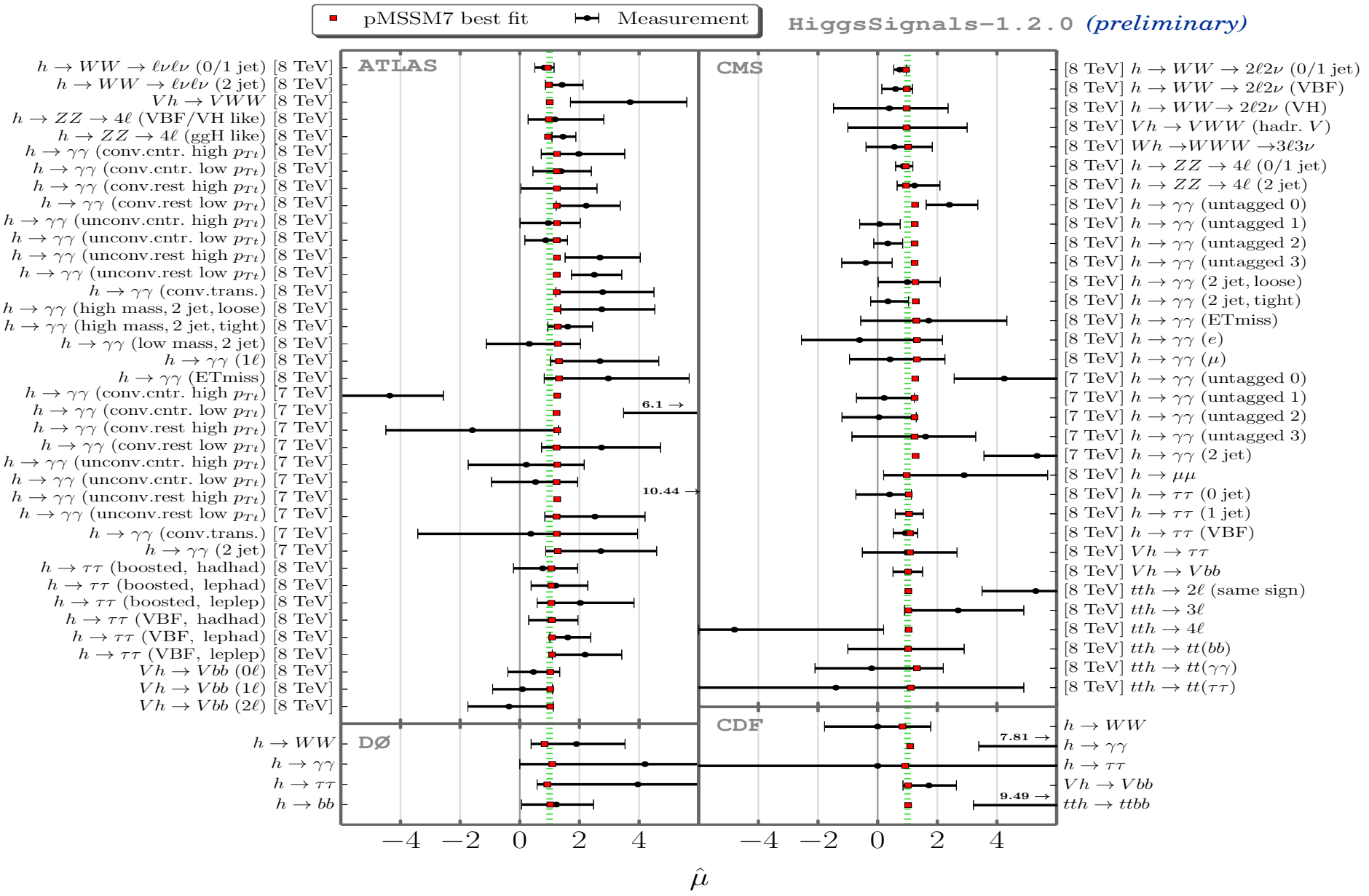
Higgs rate measurements: Implemented via HiggsSignals



(Some) Electroweak precision observables in the MasterCode

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

1. M_W (LEP/Tevatron)
2. $A_{\rm LR}^e$ (SLD)
3. $A_{\rm FB}^b$ (LEP)
4. $A_{\rm FB}^c$ (LEP)
5. $A_{\rm FB}^l$
6. A_b, A_c
7. R_b, R_c
8. $\sigma_{\rm had}^0$

$\Rightarrow$ 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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SM parameters

– top mass: m_t

– Z boson mass: M_Z

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