



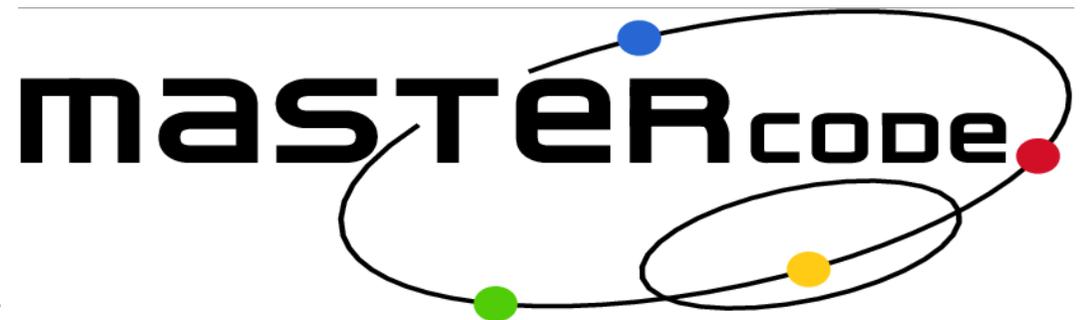
Sometimes I drive recklessly, just to kill off close copies of me in the multiverse.

SUSY fits and their Implications for ILC and CLIC

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

Whistler, 11/2015

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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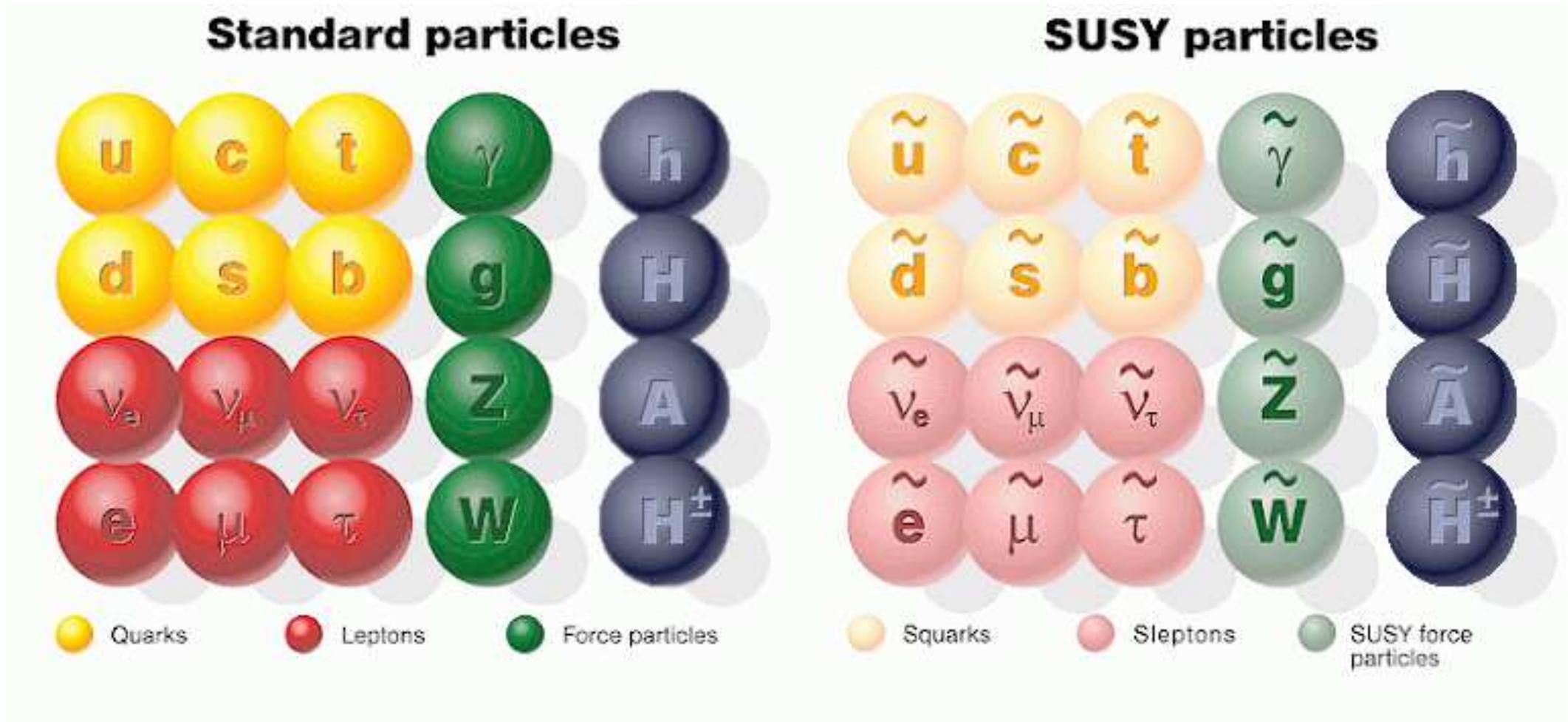
Simple SUSY models predicted correctly:

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

⇒ 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

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

$\text{sign}(\mu)$: sign of supersymmetric Higgs parameter

} at the GUT scale

⇒ particle spectra from renormalization group running to weak scale

⇒ Lightest SUSY particle (LSP) is the lightest neutralino ⇒ 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

⇒ 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

⇒ Scenario characterized by

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

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

⇒ it is possible that with the CMSSM, NUHM1, NUHM2, . . . 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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- ⇒ it is possible that with the CMSSM, NUHM1, NUHM2, . . . we missed the “correct” mechanism
- ⇒ hint: strong connection between colored and uncolored sector
tension between low-energy EW effects and (colored) LHC searches

Solution: investigate also the “general MSSM”

⇒ 10 parameters are manageable ⇒ 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 parameter: μ

Scanned parameter ranges in the pMSSM10:



parameter ranges 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

⇒ other pMSSM10 variants possible! Not (yet) analyzed!

2. The Mastercode



⇒ collaborative effort of theorists and experimentalists

[*Bagnaschi, Buchmüller, Cavanaugh, Citron, De Roeck, Dolan, Ellis, Flücher, 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 \Rightarrow NEW
(3 search categories: colored, electroweak, compressed stop)
 - Higgs related observables, $(g - 2)_\mu$ [*FeynHiggs*]
 - Higgs signal strengths [*HiggsSignals*] \Rightarrow NEW
 - Higgs exclusion bounds [*HiggsBounds*] \Rightarrow NEW
 - *B*-physics observables [*SuFla*]
 - more *B*-physics observables [*SuperIso*]
 - Electroweak precision observables [*FeynWZ*]
 - Dark Matter observables [*MicrOMEGAs*, *SSARD*]
 - for GUT scale models: RGE running [*SoftSusy*]
- \Rightarrow all most-up-to-date codes on the market!

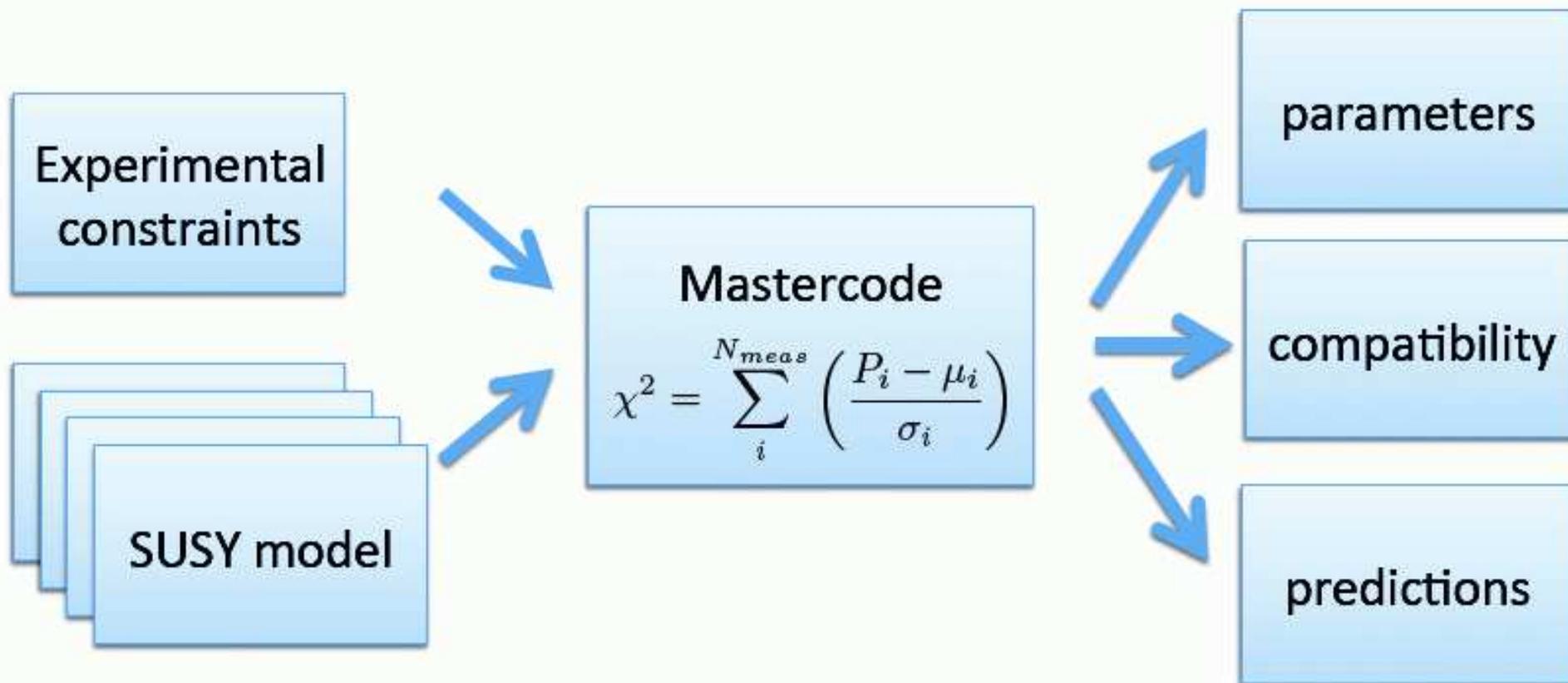
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The χ^2 evaluation:



Global fits of SUSY



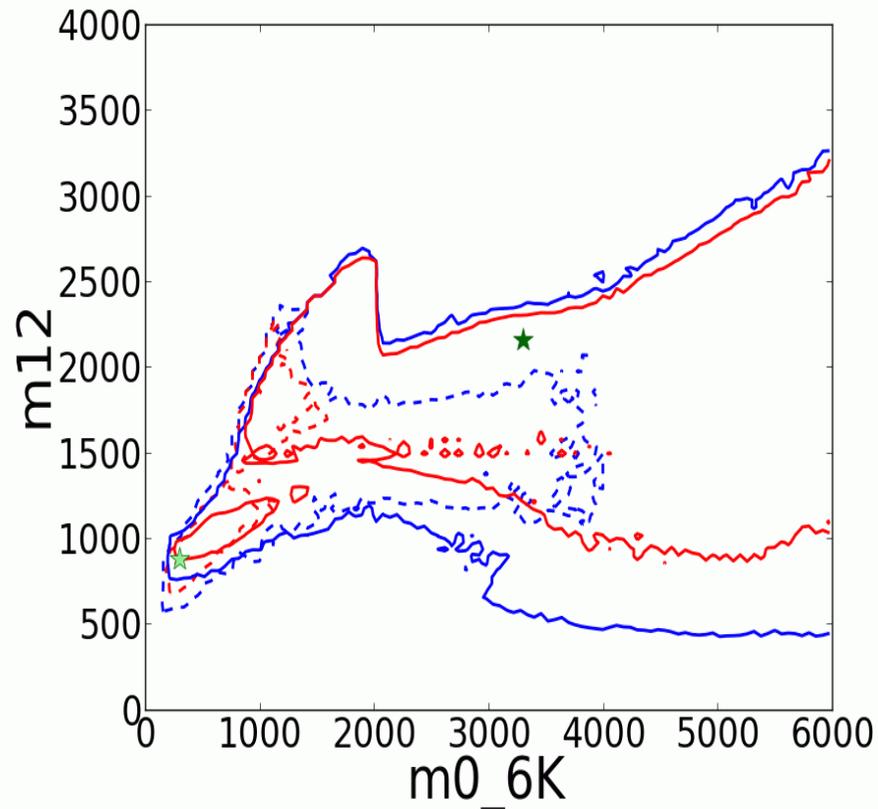
3. Predictions for the ILC and CLIC



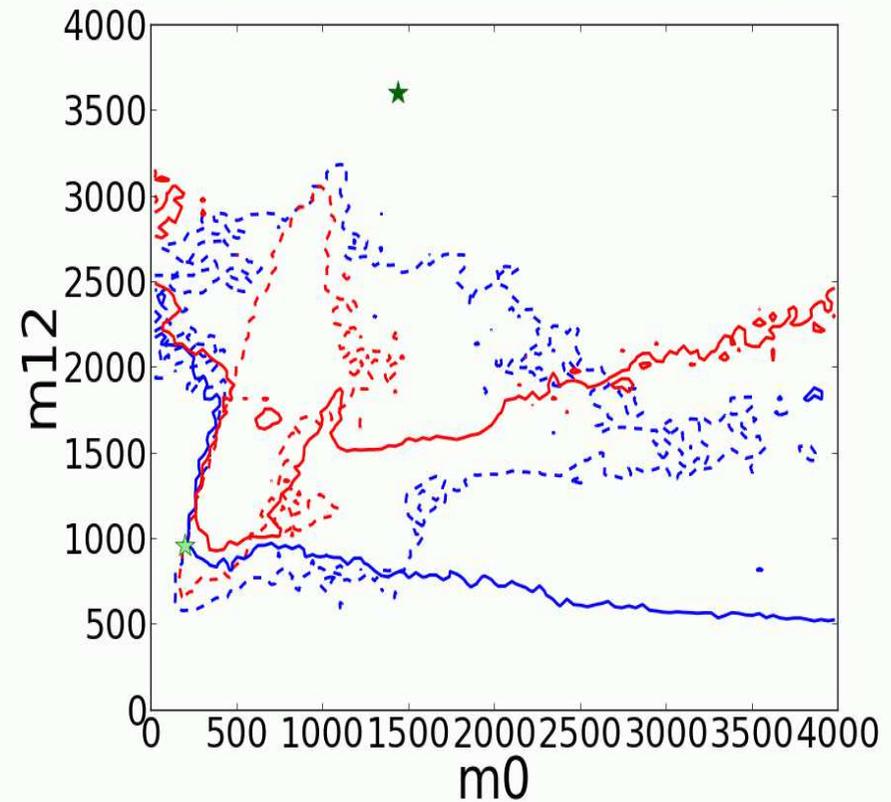
m_0 - $m_{1/2}$ plane including LHC 20/fb:

[2013]

CMSSM



NUHM1



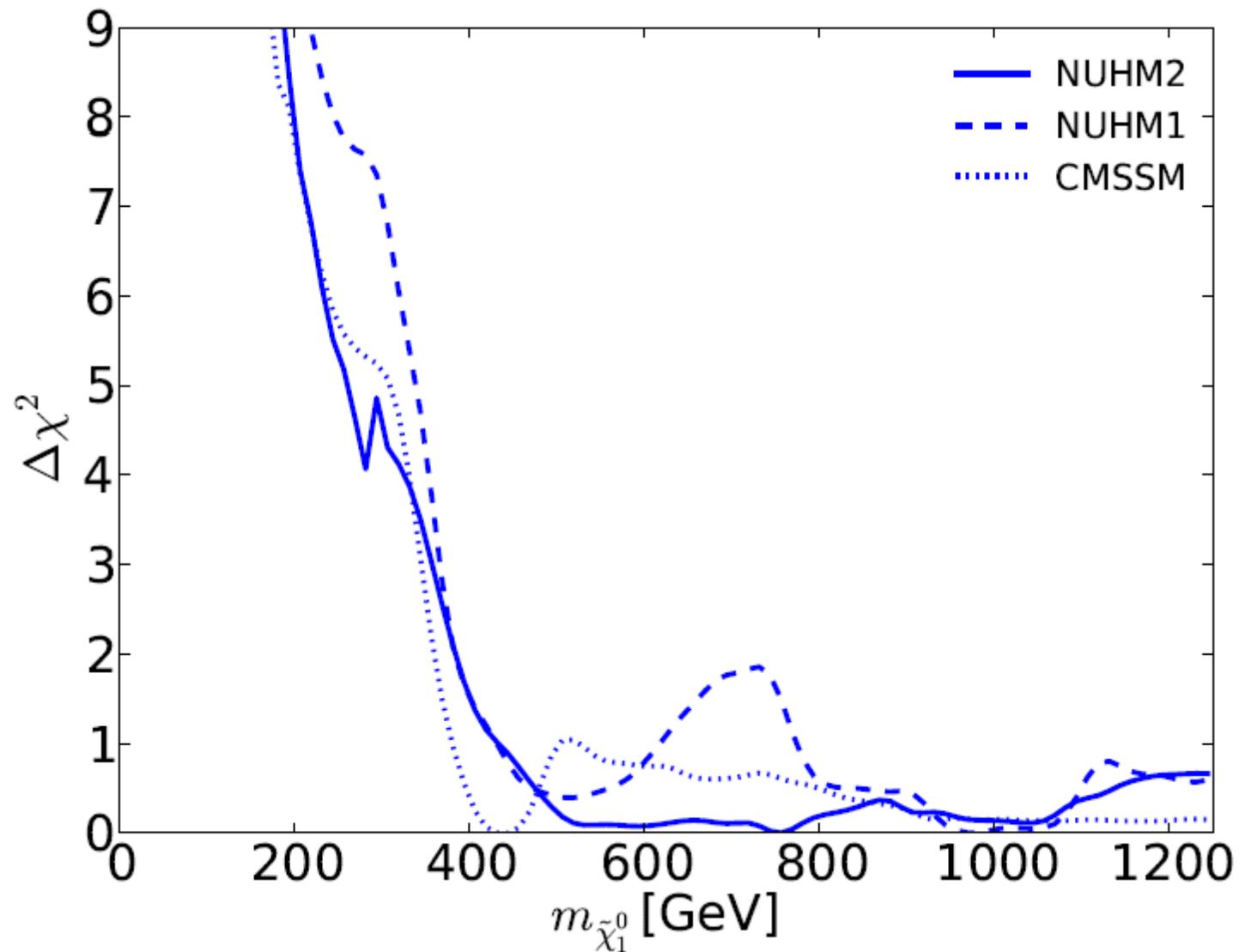
dotted: LHC 5/fb 7 TeV, solid: LHC 20/fb 8 TeV

⇒ very high masses favored!

⇒ prospects for ILC and CLIC?

LSP mass incl. 20/fb of LHC data

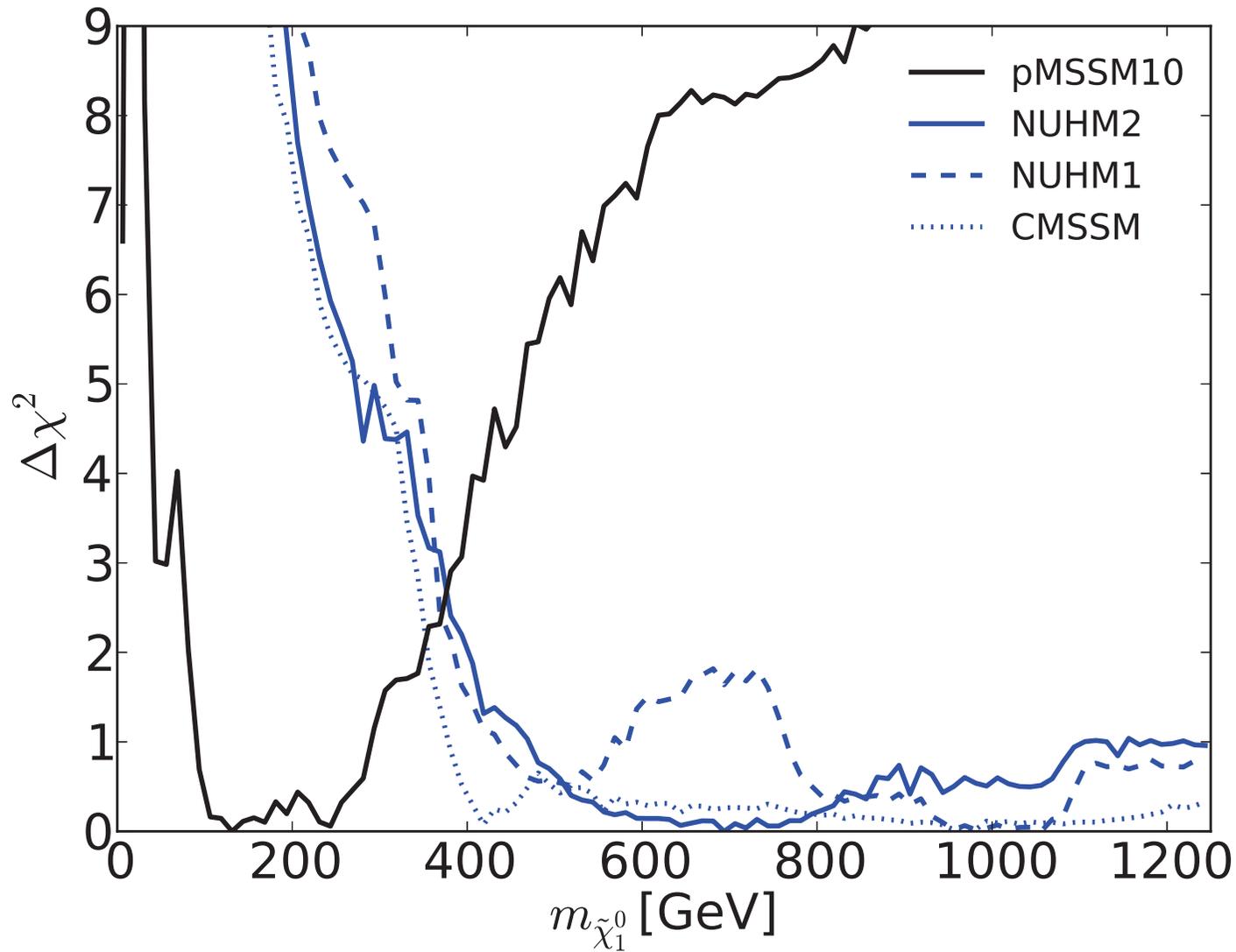
[2014]



⇒ only very large values are favored

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

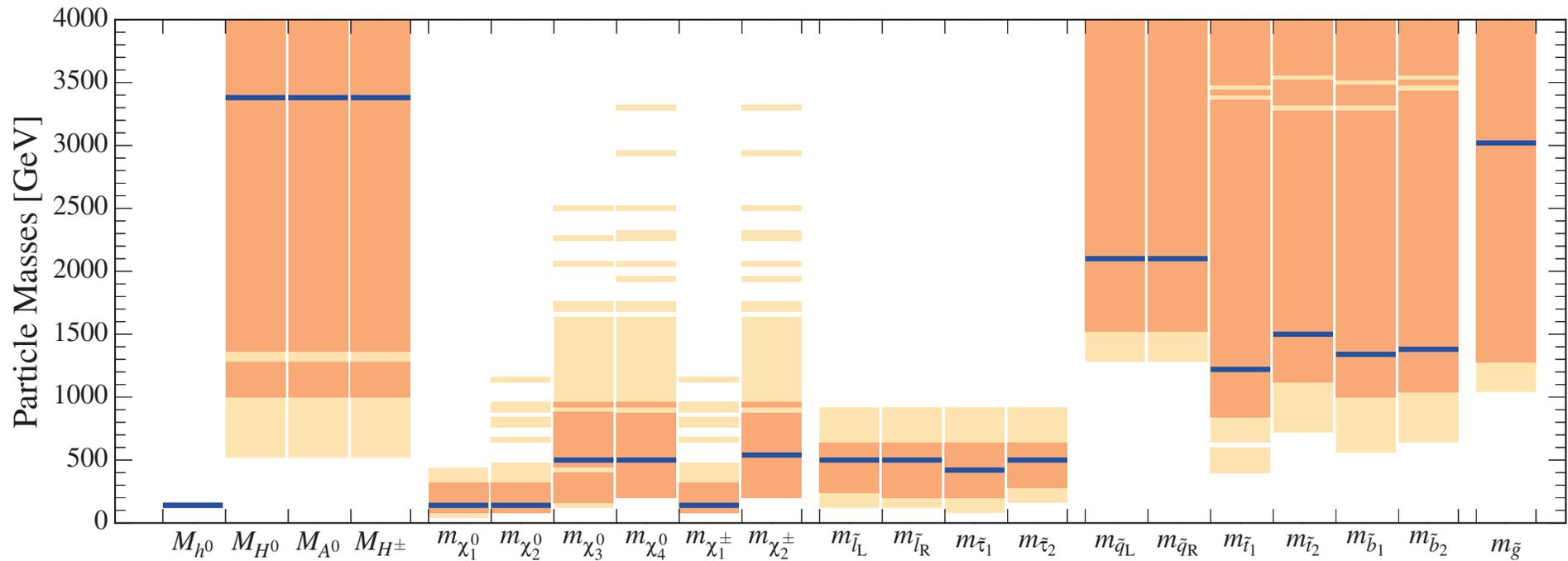
[2015]



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

pMSSM10 prediction: best-fit masses

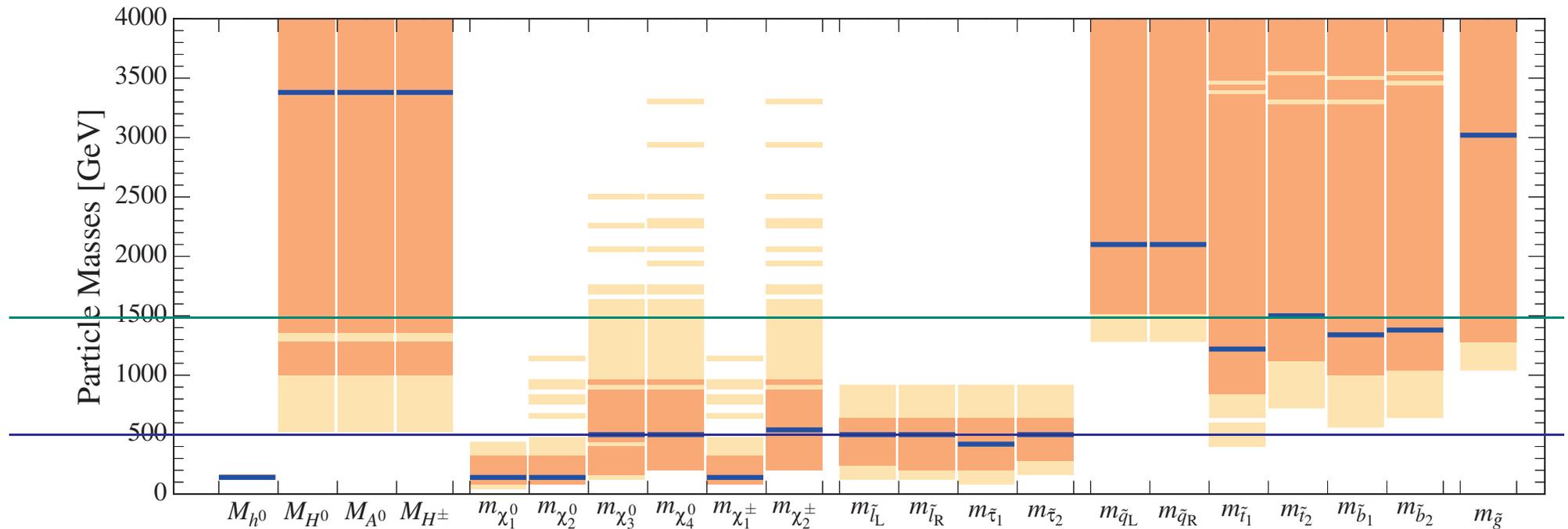
[2015]



- ⇒ 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]

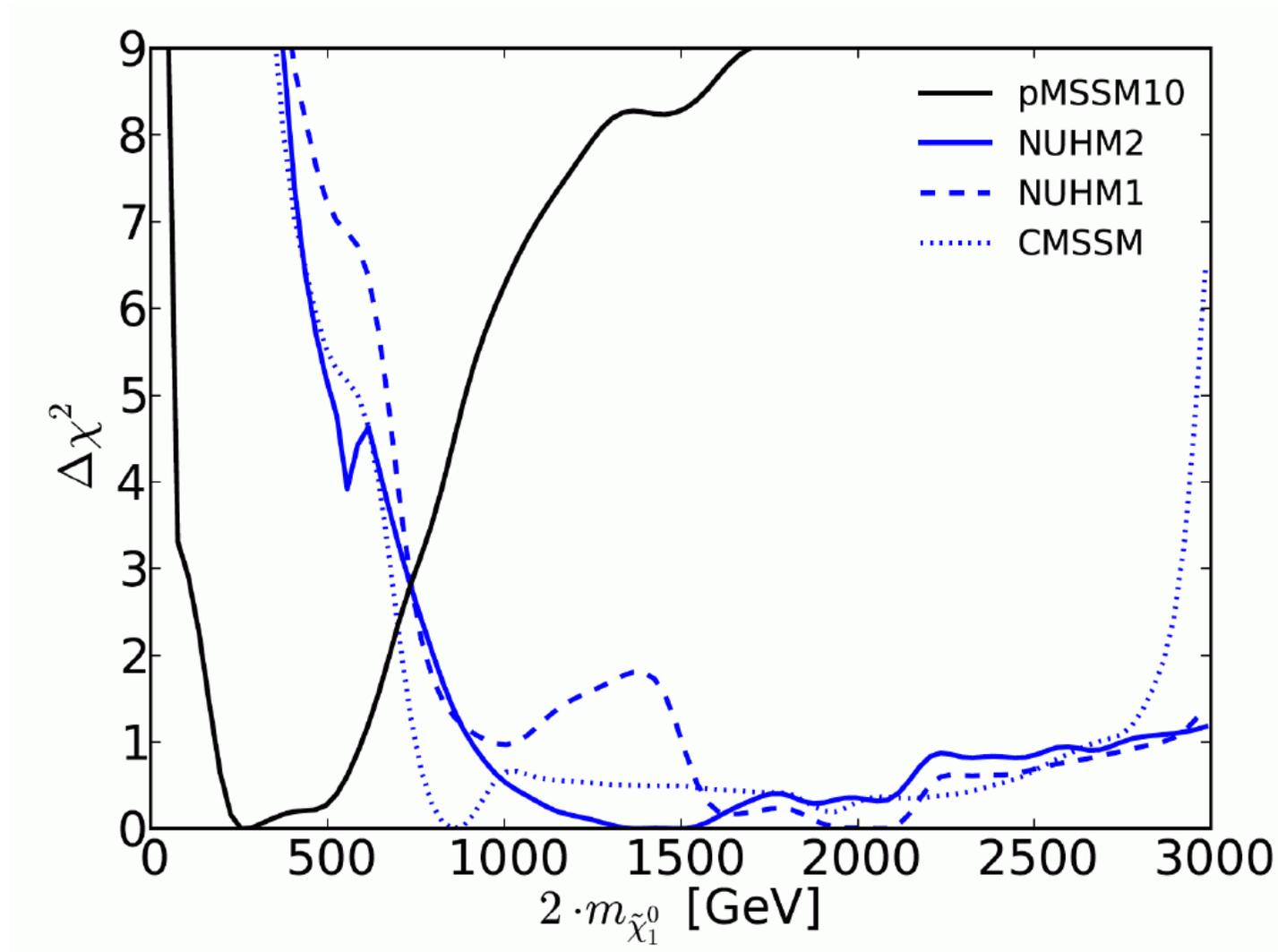


ILC: $\sqrt{s} = 1000$ GeV \Rightarrow pair production of many SUSY particles possible

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

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

[2014]

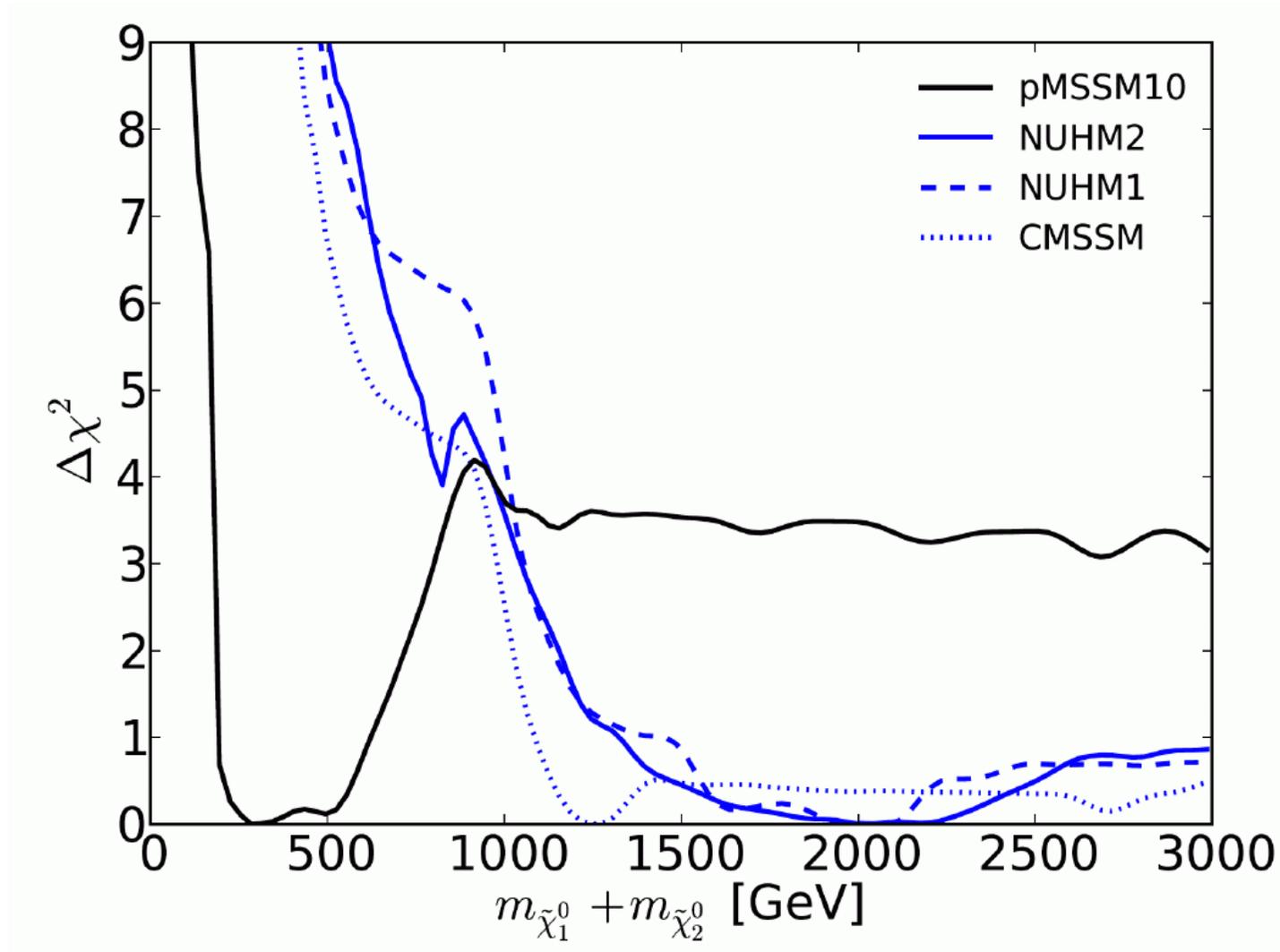


⇒ GUT based models: ILC :-(, CLIC possible

⇒ pMSSM10: easy at the ILC

Some gaugino production cross sections: $e^+e^+ \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_2^0$

[2014]

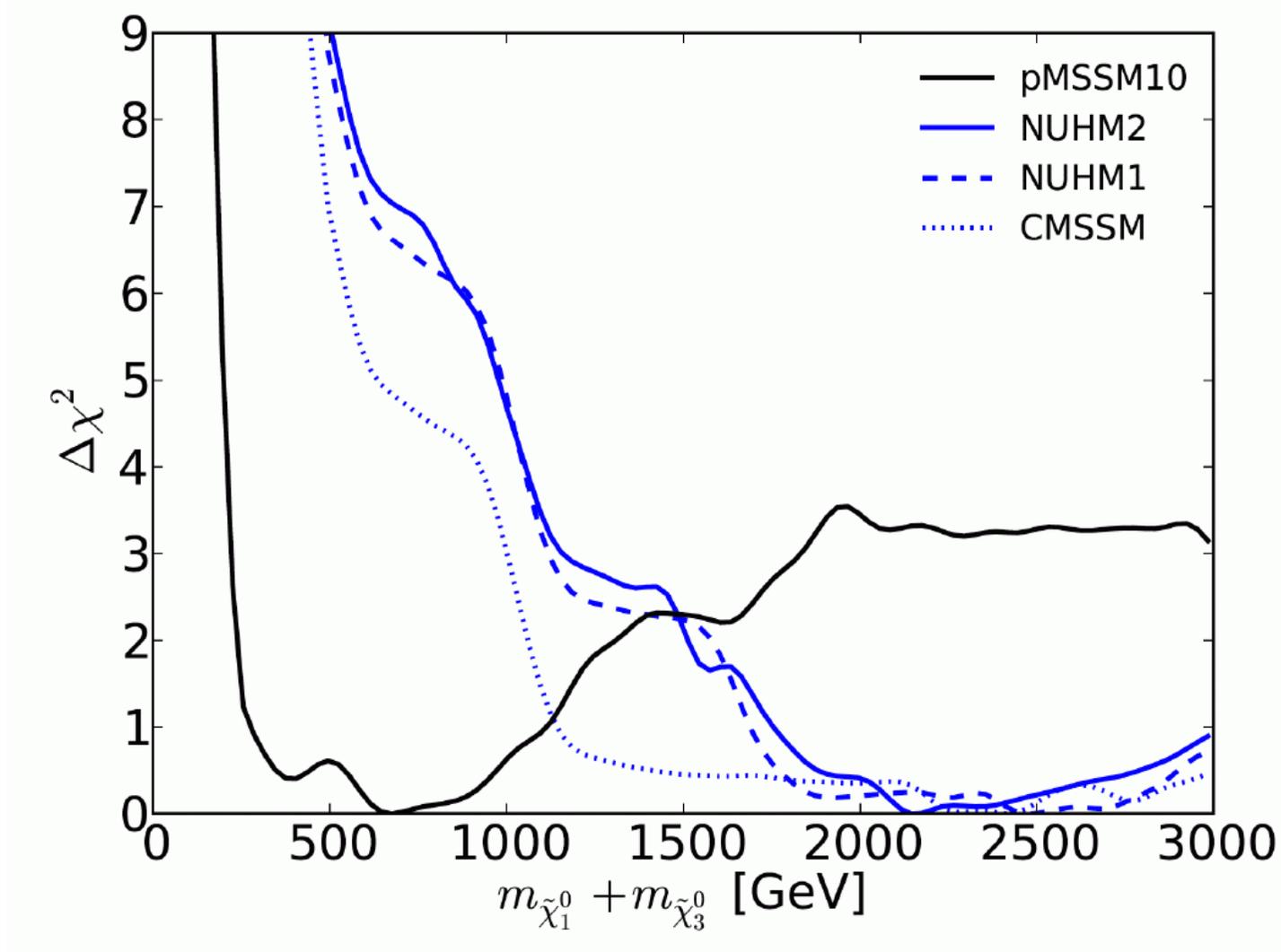


⇒ GUT based models: ILC :- (, CLIC possible

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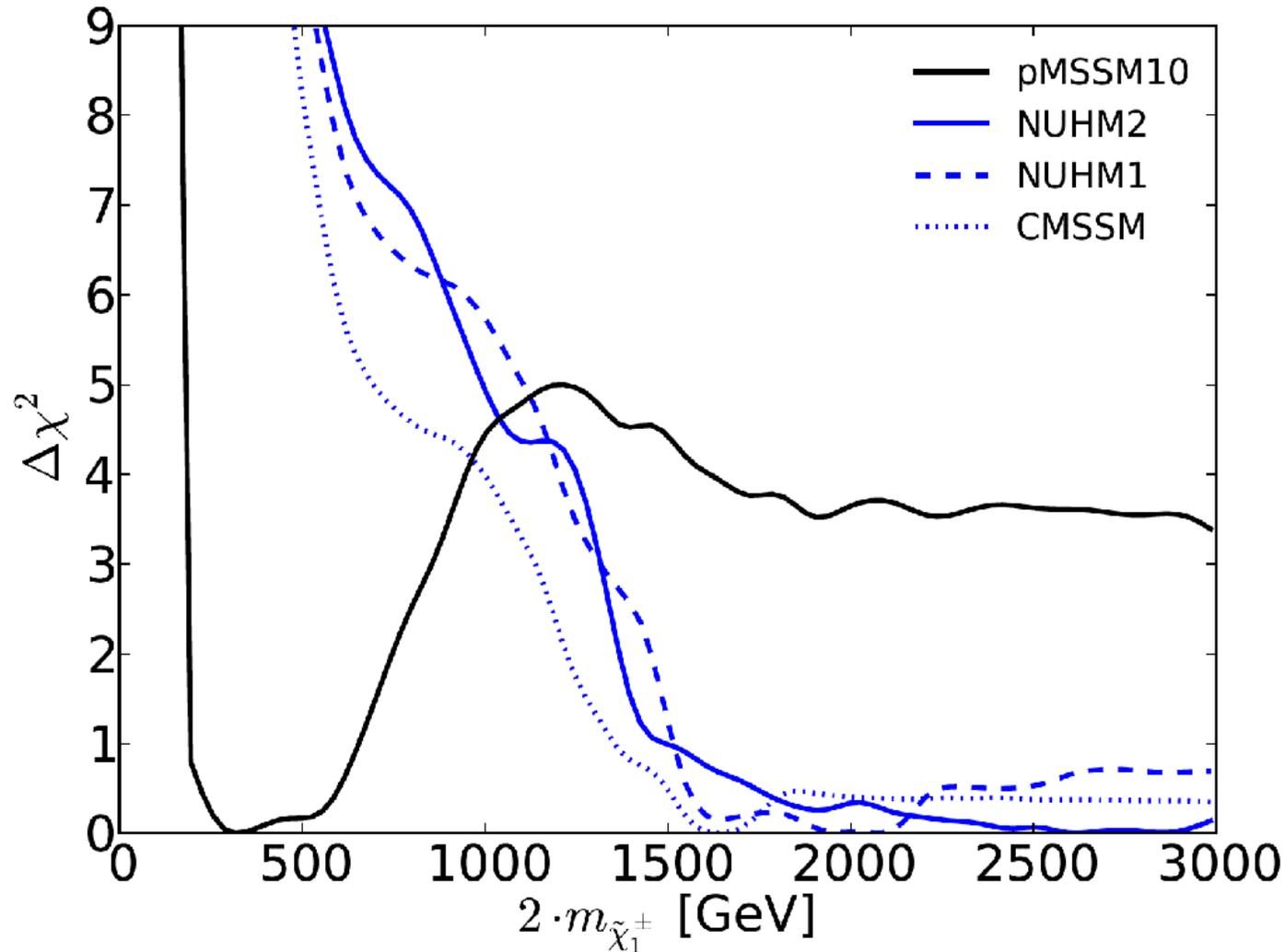


⇒ GUT based models: ILC :- (, CLIC possible

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

[2014]



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

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What to conclude?

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⇒ **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%
pMSSM10	20.5/18	31%

Which model is more likely??

What to conclude?

⇒ **Look at the p values!**

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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

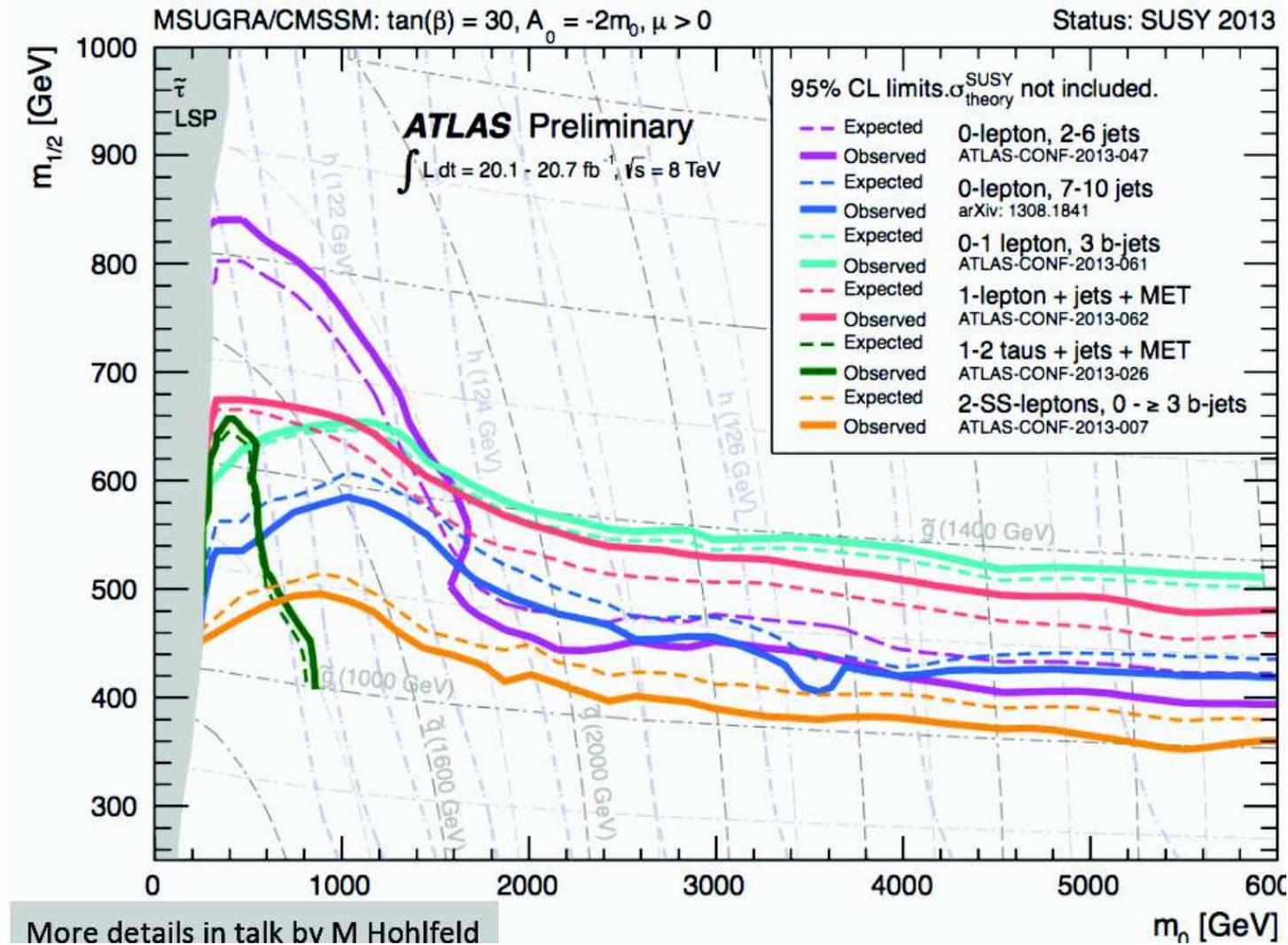
- **SUSY** is (still) the best-motivated BSM scenario
 - constrained models: CMSSM, NUHM1, NUHM2, ...
 - general models: pMSSM10, ...
 - ⇒ other variants possible! Not analyzed!
- Our tool: **MasterCode**
 combination of LHC searches, Higgs measurements, EWPO,
 BPO, CDM ⇒ χ^2 evaluation
- Fit results 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%

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 $m_{\tilde{\chi}_1^0}$, $m_{\tilde{q}}$, $m_{\tilde{g}}$, $m_{\tilde{q}_3}$, $m_{\tilde{g}}$

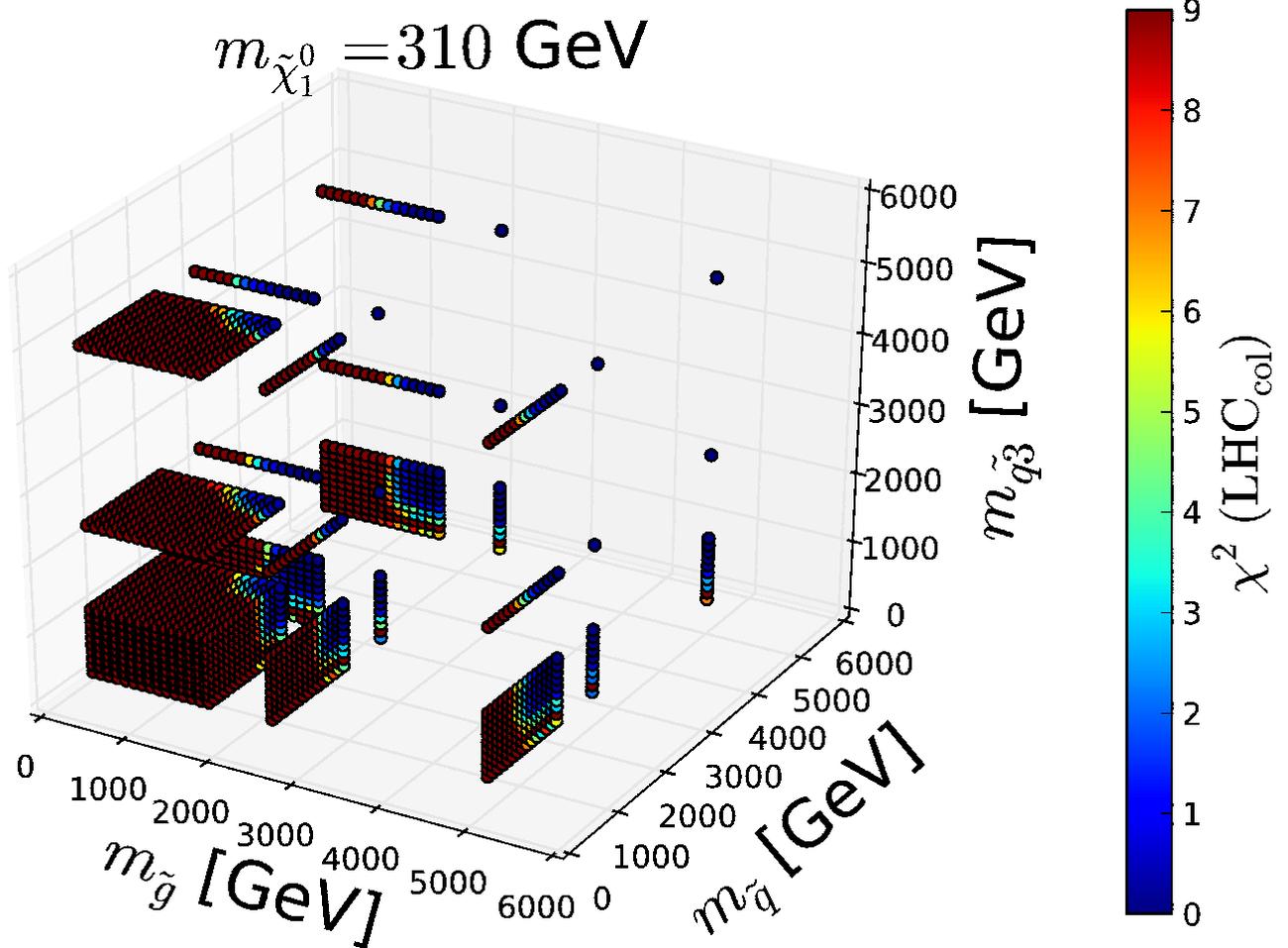
2. searches for compressed stop spectra

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

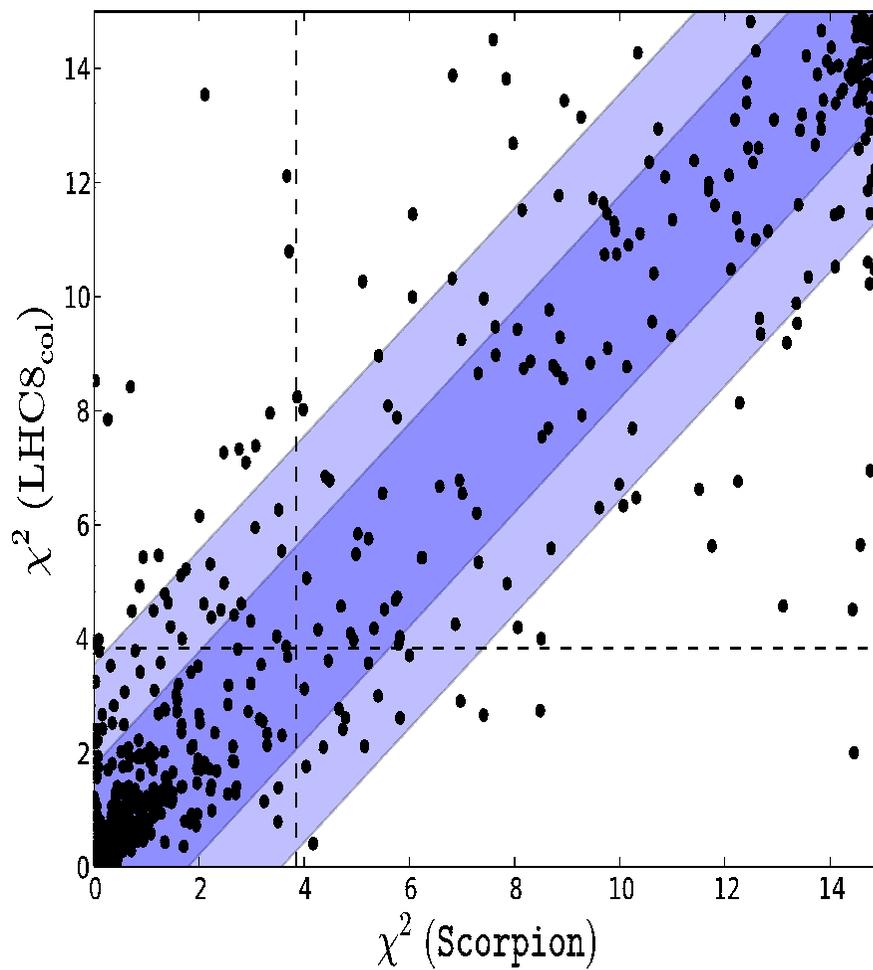
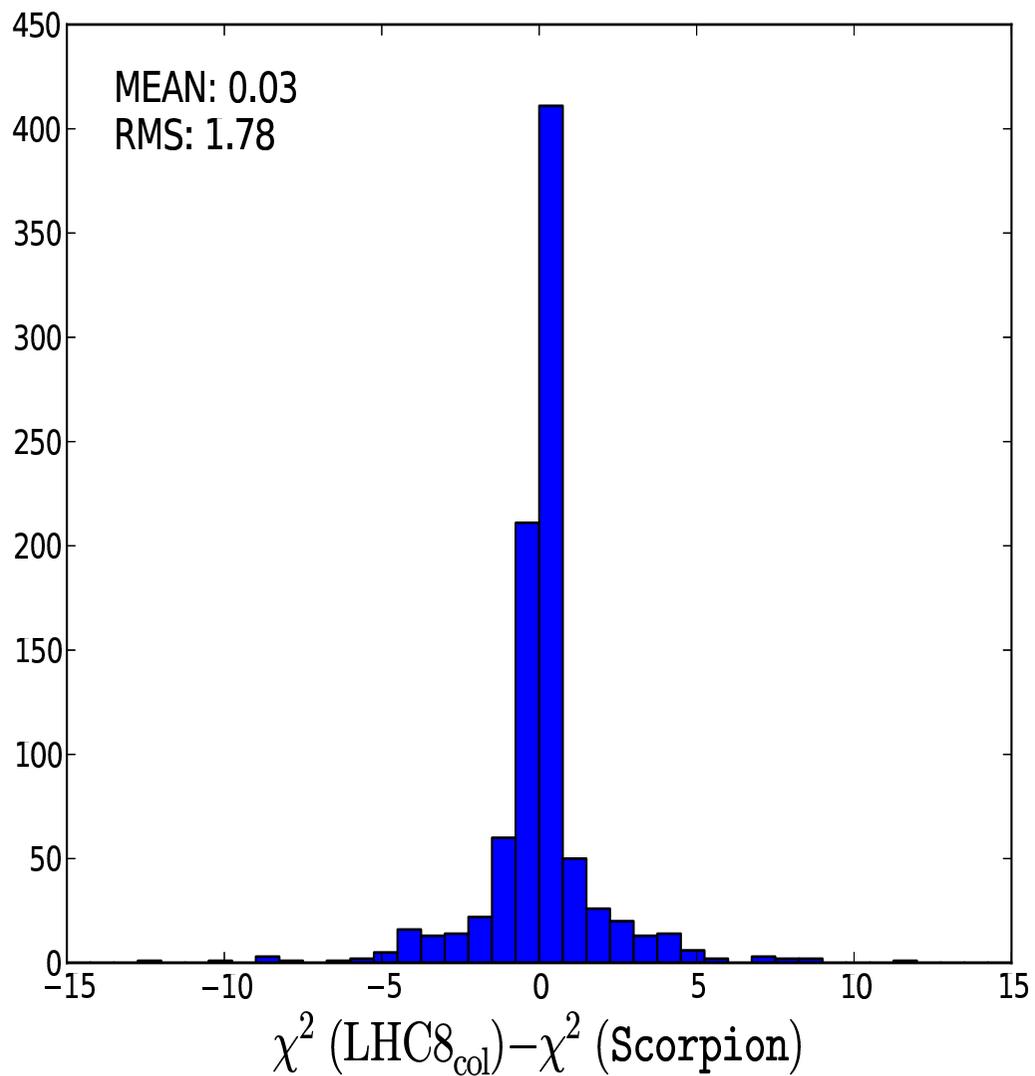
3. searches for light EW particles

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

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



χ^2 comparison for colored searches



⇒ tested with Scopion (home made code “a la Atom”)

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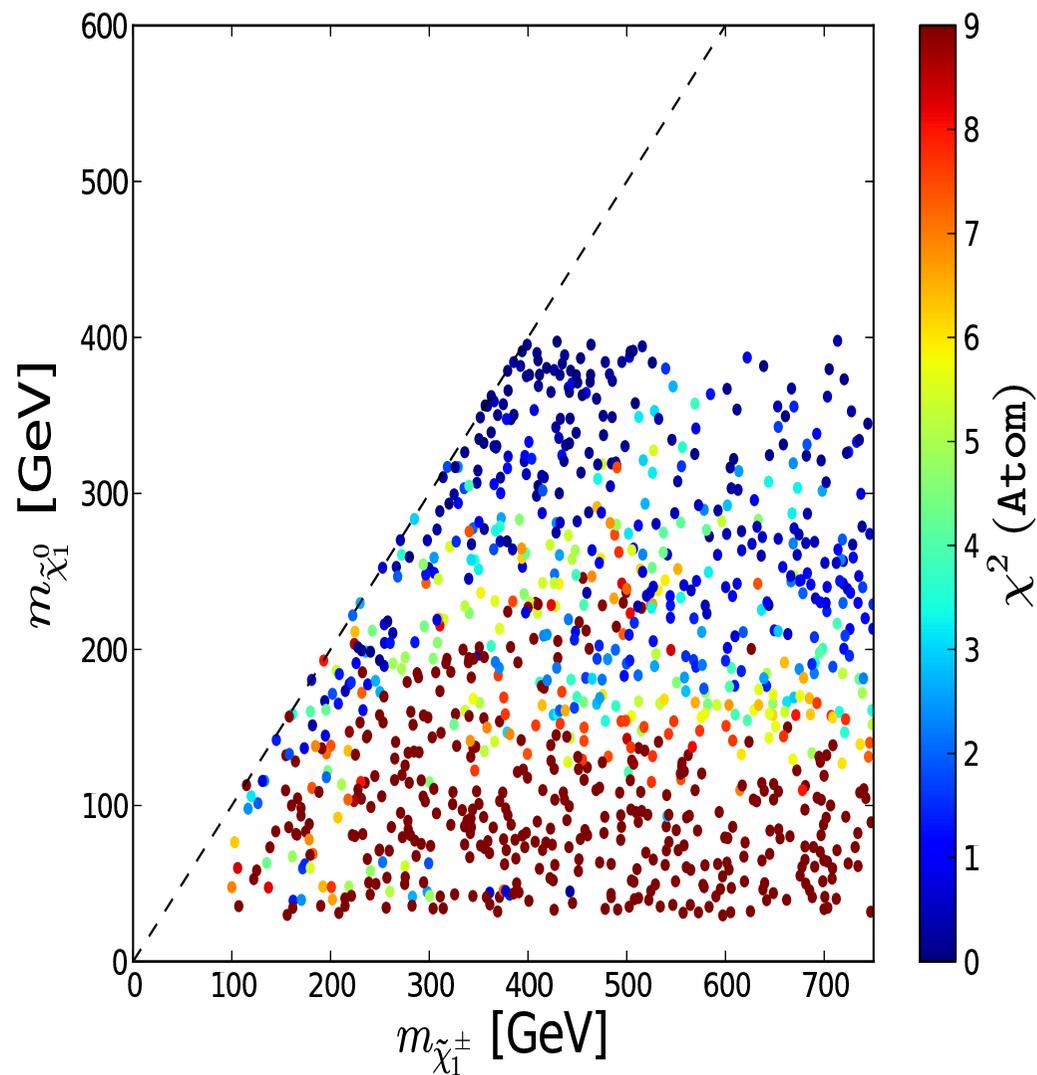
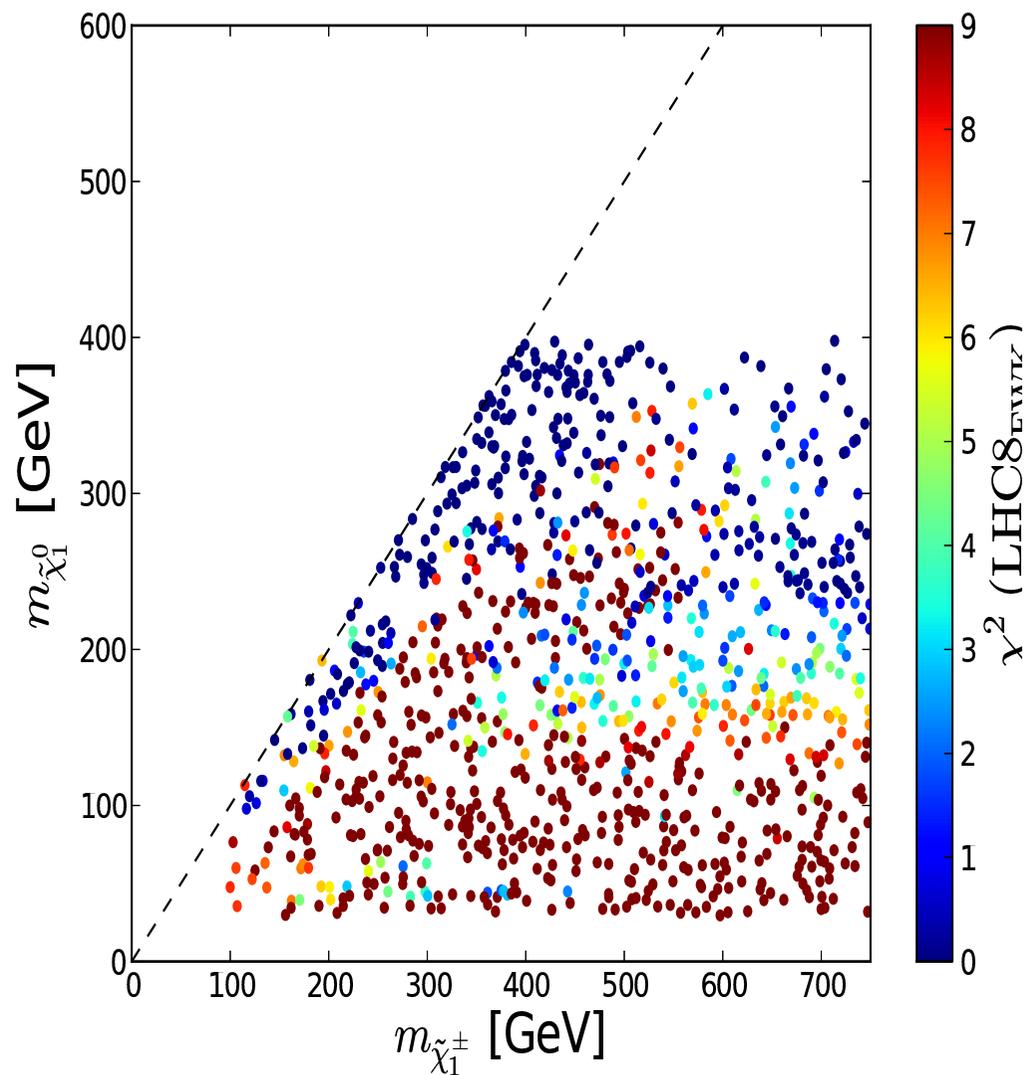
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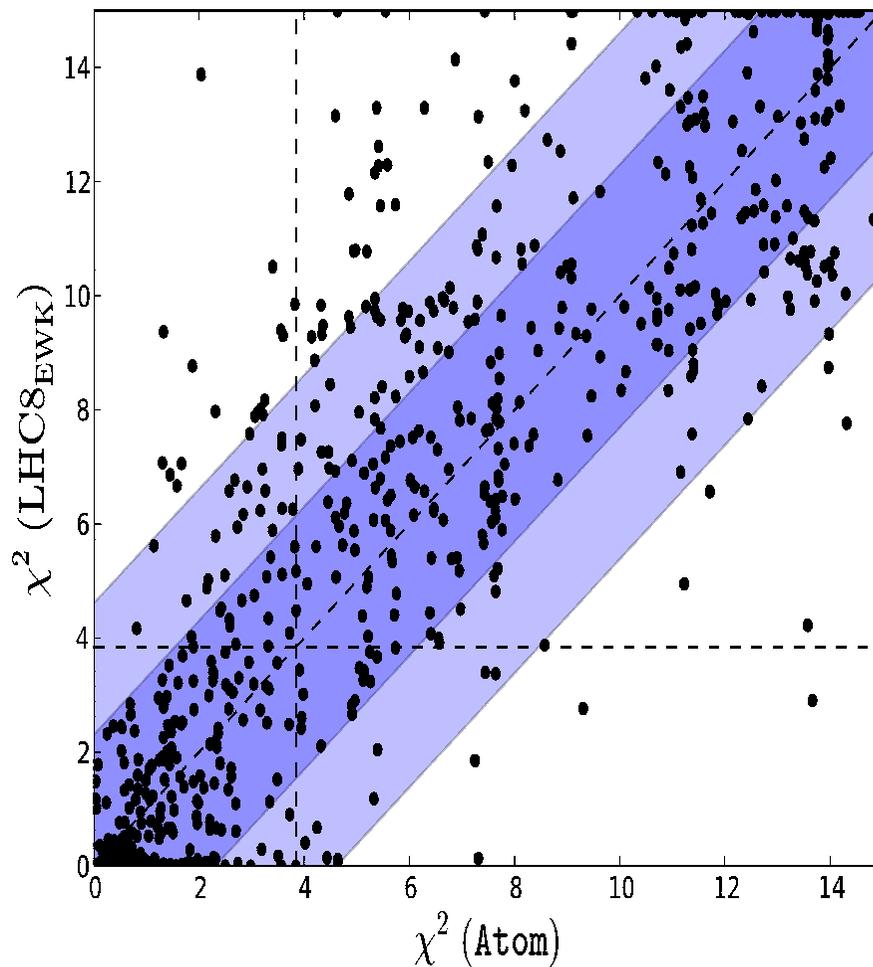
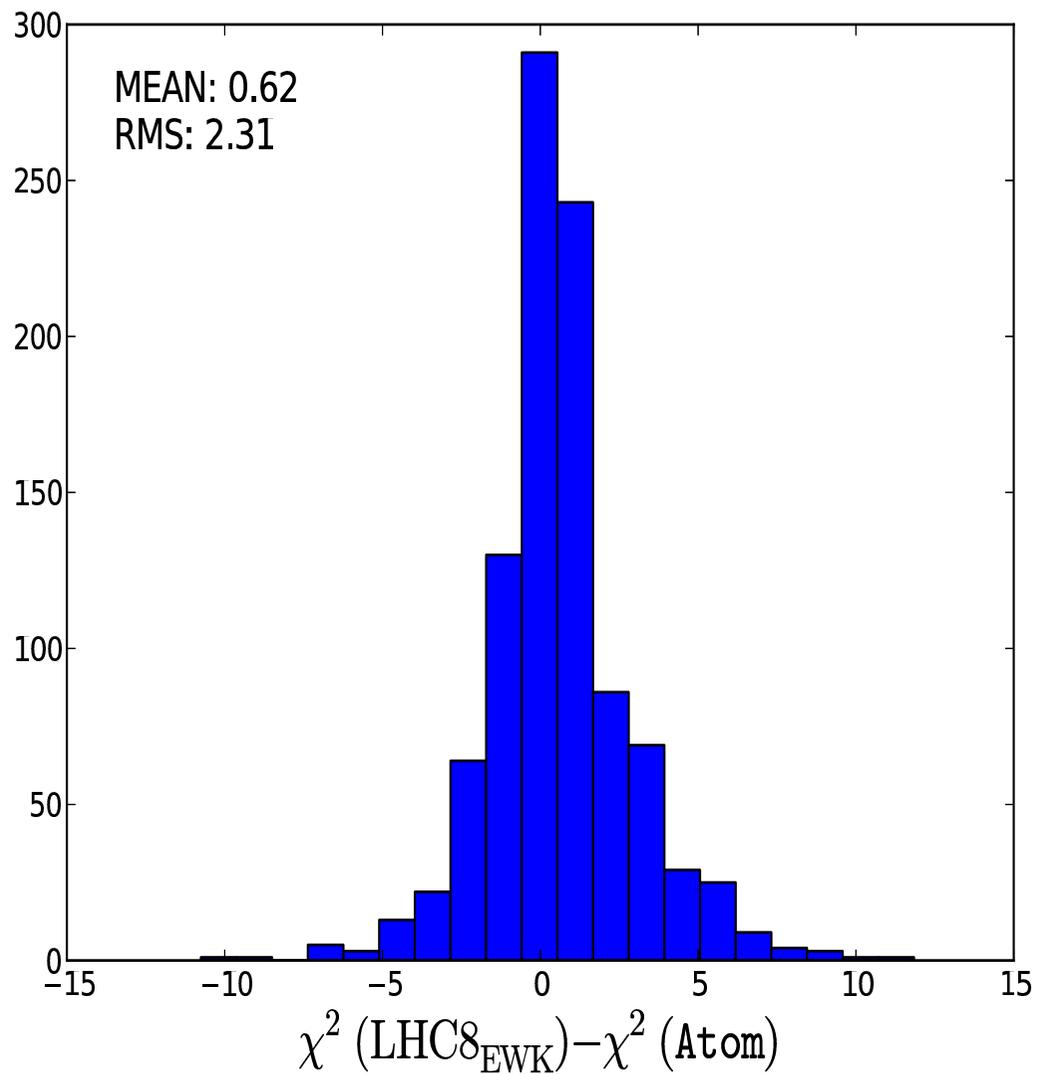
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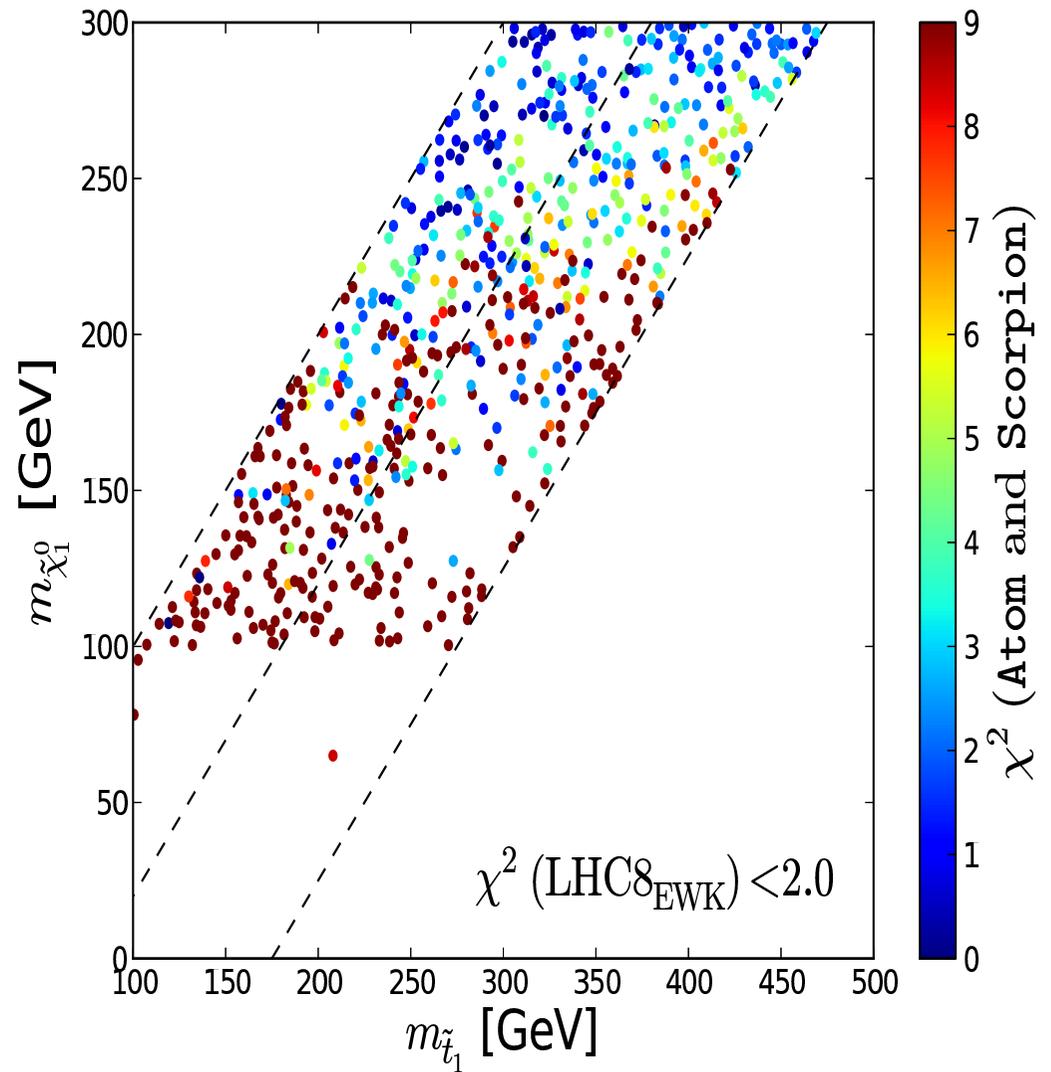
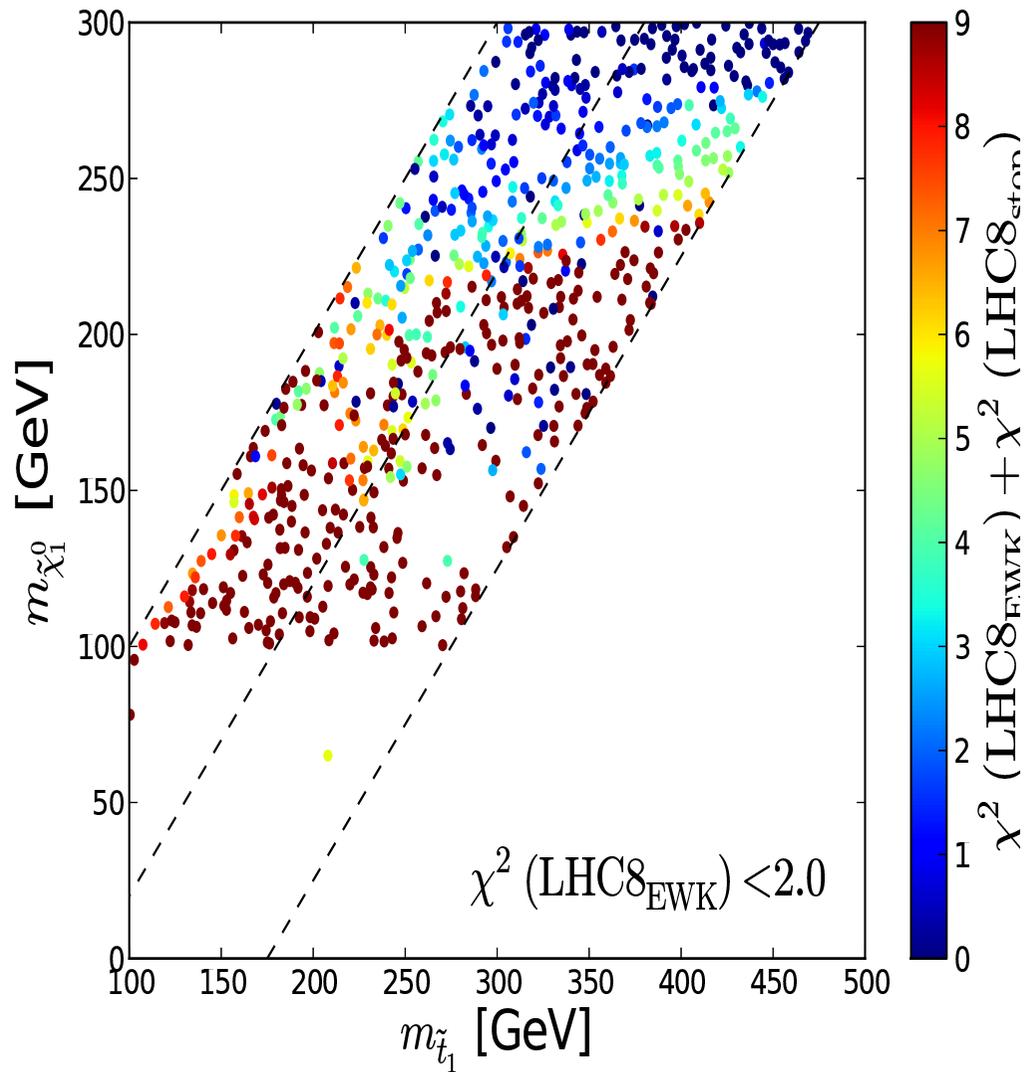
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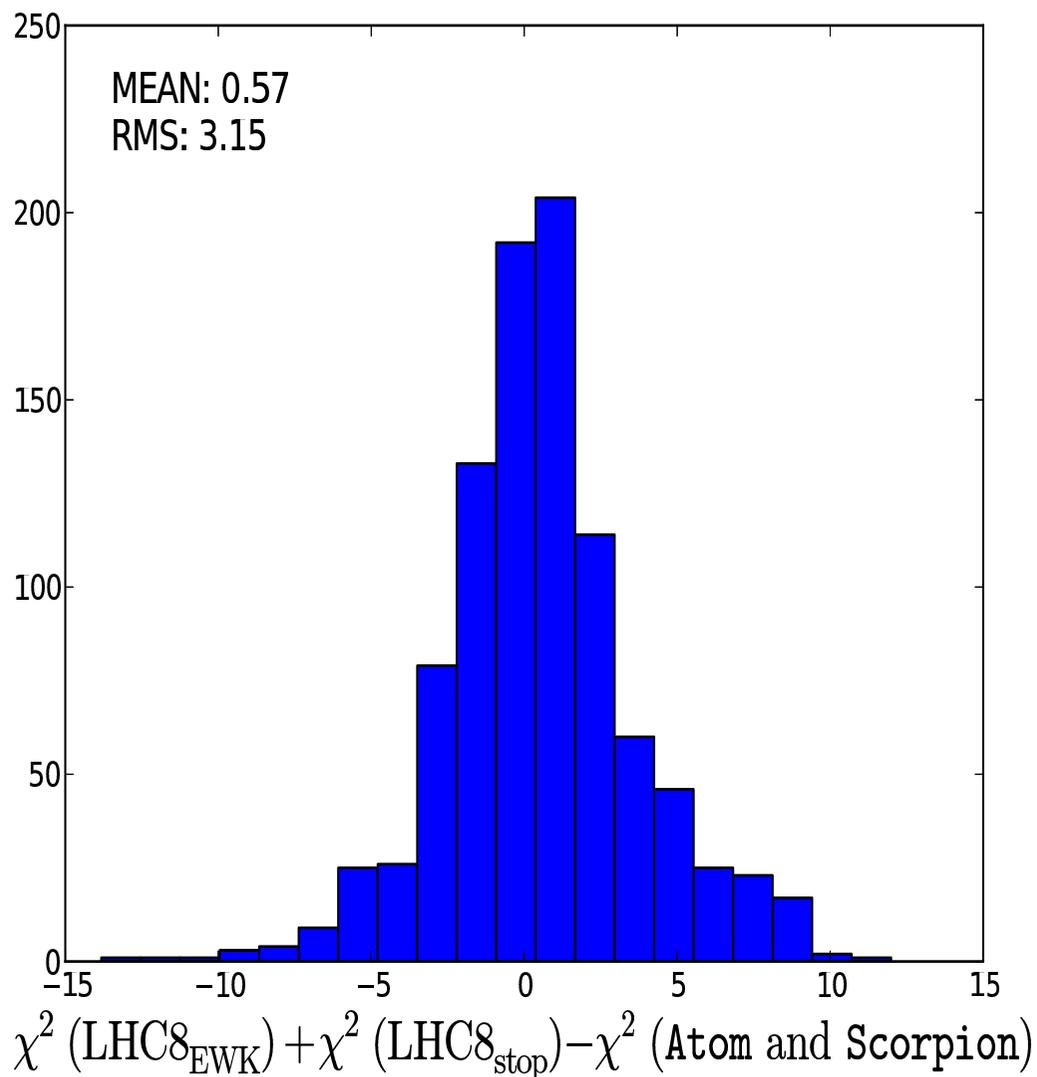
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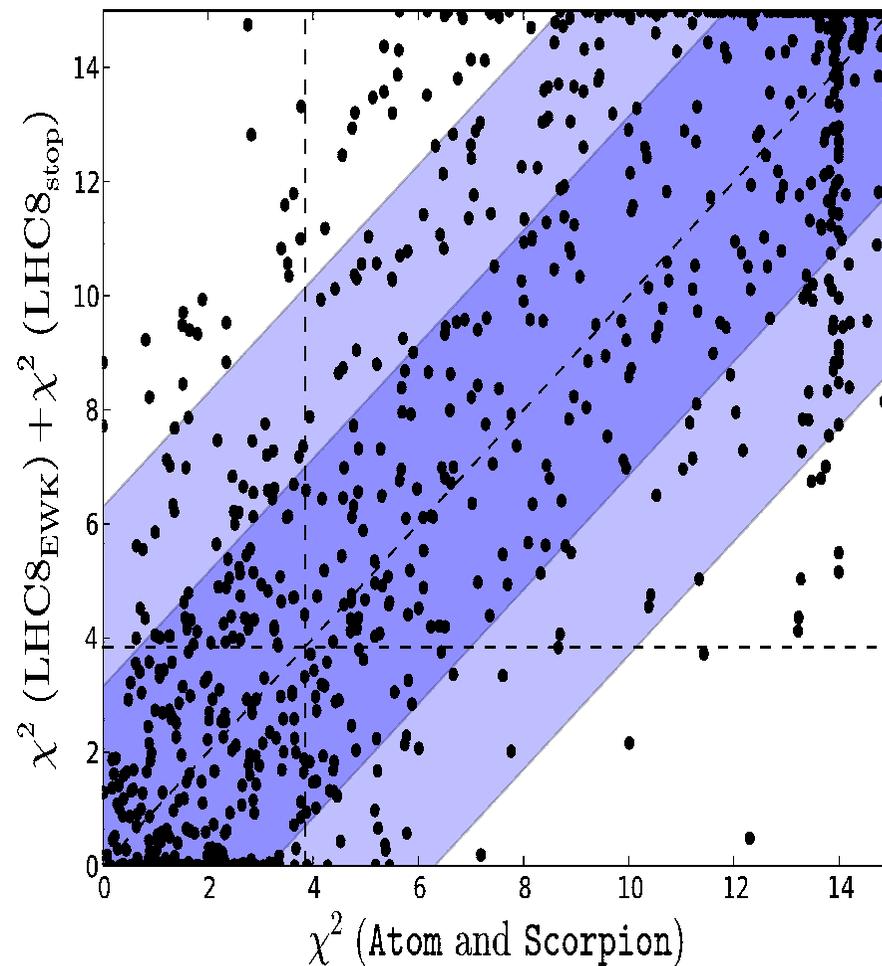


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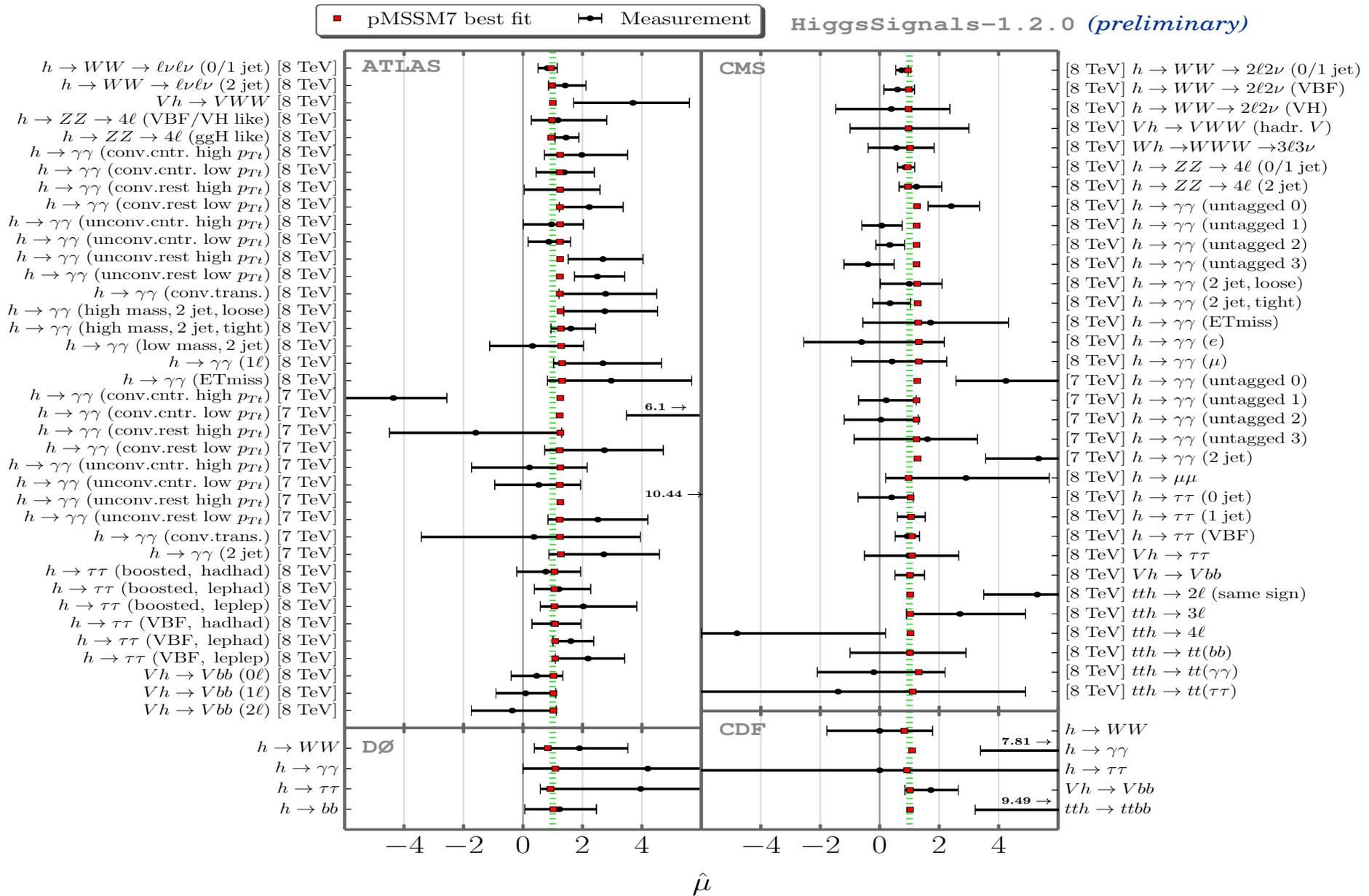
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Higgs rate measurements: Implemented via HiggsSignals



(Some) Electroweak precision observables in the MasterCode

(→ as for blue band analysis, except Γ_W)

1. M_W (LEP/Tevatron)

2. A_{LR}^e (SLD)

3. A_{FB}^b (LEP)

4. A_{FB}^c (LEP)

5. A_{FB}^l

6. A_b, A_c

7. R_b, R_c

8. σ_{had}^0

⇒ largest impact: (1), (2), (3)

(Some) B/K physics observables in the MasterCode

1. $\text{BR}(b \rightarrow s\gamma)$ (MSSM/SM)
2. $\text{BR}(B_s \rightarrow \mu^+\mu^-)$
3. ΔM_s
4. $R(\Delta M_s/\Delta M_d)$
5. $\text{BR}(B_u \rightarrow \tau\nu_\tau)$ (MSSM/SM)
6. $\text{BR}(B \rightarrow X_x\ell^+\ell^-)$
7. $\text{BR}(K \rightarrow \ell\nu)$ (MSSM/SM)
8. $\text{BR}(\Delta M_K)$ (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: $\Omega_\chi h^2$
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SM parameters

- top mass: m_t
- Z boson mass: M_Z
- hadronic contribution to fine structure constant: $\Delta\alpha_{\text{had}}$