Dark Matter in the pMSSM

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

Durham, 11/2016

1. Motivation
2. The MasterCode
3. Results in the pMSSM10/11
4. Conclusions

1. Motivation

Some "recent" measurements:

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

1. Motivation

Some "recent" measurements:

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

Simple SUSY models predicted correctly:

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

1. Motivation

Some "recent" measurements:

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

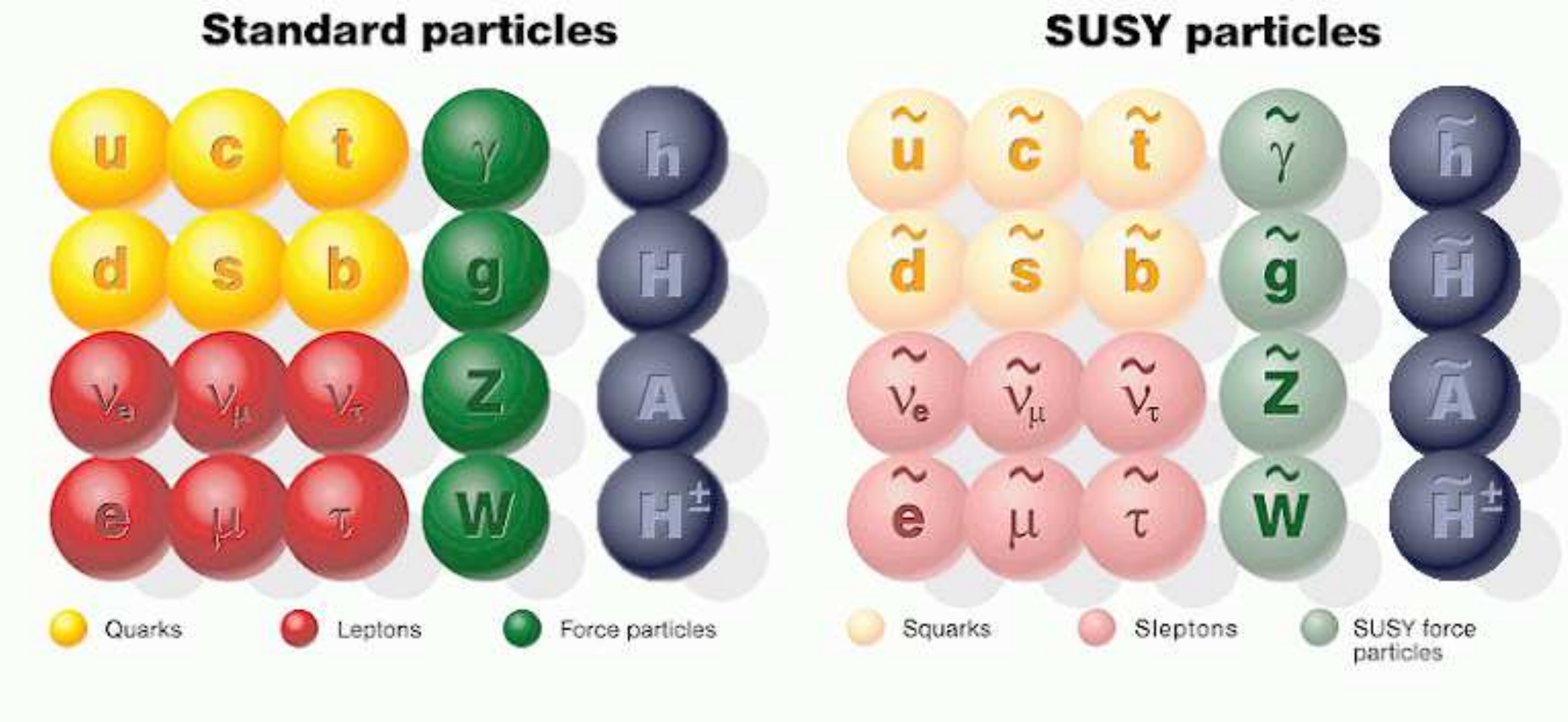
Simple SUSY models predicted correctly:

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

$\Rightarrow$ 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!

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

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

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

B. Constrained models (CMSSM, NUHM1, NUHM2, ...):

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

$\Rightarrow$ see Keith's talk

$\Rightarrow$ "easily possible": correct model missed

Have we missed the correct SUSY breaking mechanism?

Low energy data (mostly $(g-2)_\mu$) favors low SUSY mass scales

LHC data favors higher SUSY scales

$\Rightarrow$ tension, reflected in rising χ^2 in GUT based models:

Model	Min. χ^2	Prob.	$m_{1/2}$ (GeV)	m_0 (GeV)	A_0 (GeV)	$\tan\beta$
CMSSM	21.5/20	37%	360	90	-50	15
LHC $1\,\text{fb}^{-1} \oplus M_h$	30.6/23	13%	1800	1080	860	48
LHC $20\,\text{fb}^{-1} \oplus M_h$	35.1/23	5.1%	2100	5650	780	51
NUHM1	20.8/18	29%	340	110	520	13
LHC $1\,\text{fb}^{-1} \oplus M_h$	29.7/22	13%	830	290	660	33
LHC $20\,\text{fb}^{-1} \oplus M_h$	32.7/22	6.6%	3420	1380	3140	39

Model	Min. χ^2	Prob.	$m_{1/2}$ (GeV)	m_0 (GeV)	A_0 (GeV)	$\tan\beta$
CMSSM	21.5/20	37%	360	90	-50	15
LHC $1\,\text{fb}^{-1} \oplus M_h$	30.6/23	13%	1800	1080	860	48
LHC $20\,\text{fb}^{-1} \oplus M_h$	35.1/23	5.1%	2100	5650	780	51
NUHM1	20.8/18	29%	340	110	520	13
LHC $1\,\text{fb}^{-1} \oplus M_h$	29.7/22	13%	830	290	660	33
LHC $20\,\text{fb}^{-1} \oplus M_h$	32.7/22	6.6%	3420	1380	3140	39

Model	Min. χ^2	Prob.	$m_{1/2}$ (GeV)	m_0 (GeV)	A_0 (GeV)	$\tan\beta$
CMSSM	21.5/20	37%	360	90	-50	15
LHC $1\,\text{fb}^{-1} \oplus M_h$	30.6/23	13%	1800	1080	860	48
LHC $20\,\text{fb}^{-1} \oplus M_h$	35.1/23	5.1%	2100	5650	780	51
NUHM1	20.8/18	29%	340	110	520	13
LHC $1\,\text{fb}^{-1} \oplus M_h$	29.7/22	13%	830	290	660	33
LHC $20\,\text{fb}^{-1} \oplus M_h$	32.7/22	6.6%	3420	1380	3140	39

Probabilities still "so so", but this might change with LHC run II data.

Not finding SUSY now does not make SUSY prospects look bad,
makes some very constrained models look bad!

Model	Min. χ^2	Prob.	$m_{1/2}$ (GeV)	m_0 (GeV)	A_0 (GeV)	$\tan\beta$
CMSSM	21.5/20	37%	360	90	-50	15
LHC $1\,\text{fb}^{-1} \oplus M_h$	30.6/23	13%	1800	1080	860	48
LHC $20\,\text{fb}^{-1} \oplus M_h$	35.1/23	5.1%	2100	5650	780	51
NUHM1	20.8/18	29%	340	110	520	13
LHC $1\,\text{fb}^{-1} \oplus M_h$	29.7/22	13%	830	290	660	33
LHC $20\,\text{fb}^{-1} \oplus M_h$	32.7/22	6.6%	3420	1380	3140	39

Probabilities still "so so", but this might change with LHC run II data.

Not finding SUSY now does not make SUSY prospects look bad,
makes some very constrained models look bad!

And requires SUSY realizations that are in agreement with

– higher colored mass scales (LHC limits)

– lower uncolored mass scales (EWPO; $(g-2)_\mu$) $\Rightarrow$ DM predictions

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

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

Solution: investigate also the "general MSSM"

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

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

pMSSM10 scanned parameter ranges:

Parameter	Range	Number of segments
M_1	(-1 , 1) TeV	2
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_A	(0 , 4) TeV	2
A	(-5 , 5) TeV	1
μ	(-5 , 5) TeV	1
$\tan\beta$	(1 , 60)	1
Total number of boxes		128

Potential problem in "our" pMSSM10:

Only one soft SUSY-breaking parameter for the scalar lepton sector: $m_{\tilde{l}}$

- mass scale for staus $\Rightarrow$ stau co-annihilation
- mass scale for smuons $\Rightarrow (g-2)_\mu$

Potential problem in "our" pMSSM10:

Only one soft SUSY-breaking parameter for the scalar lepton sector: $m_{\tilde{l}}$

– mass scale for staus $\Rightarrow$ stau co-annihilation
– mass scale for smuons $\Rightarrow (g-2)_\mu$

Possible solution: pMSSM11

$\Rightarrow$ first investigations (and results) with $(m_{\tilde{l}_3} :=) m_{\tilde{\tau}} \neq m_{\tilde{\mu}} = m_{\tilde{e}} (=: m_{\tilde{l}})$

Parameter	Range	Number of segments
$m_{\tilde{l}_3}$	(0 , 2) TeV	1
$m_{\tilde{l}}$	(0 , 2) TeV	1

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

Status of the "MasterCode":

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

- tools included:
  - our own LHC SUSY search implementation
    (several searches: colored, electroweak, compressed stop, ...)
  - Higgs related observables, $(g-2)_\mu$ [*FeynHiggs*]
  - Higgs signal strengths [*HiggsSignals*]
  - Higgs exclusion bounds [*HiggsBounds*]
  - B-physics observables [*SuFla*]
  - more B-physics observables [*SuperIso*]
  - Electroweak precision observables [*FeynWZ*]
  - Dark Matter observables [*MicrOMEGAs, SSARD*]
  - BRs for SUSY decays [*SDecay*]
  - for GUT scale models: RGE running [*SoftSusy*]

$\Rightarrow$ all most-up-to-date codes on the market!

Status of the "MasterCode":

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

- tools included:
  - our own LHC SUSY search implementation
    (several searches: colored, electroweak, compressed stop, ...)
  - Higgs related observables, $(g-2)_\mu$ [*FeynHiggs*]
  - Higgs signal strengths [*HiggsSignals*]
  - Higgs exclusion bounds [*HiggsBounds*]
  - B-physics observables [*SuFla*]
  - more B-physics observables [*SuperIso*]
  - Electroweak precision observables [*FeynWZ*]
  - Dark Matter observables [*MicrOMEGAs, SSARD*]
  - BRs for SUSY decays [*SDecay*]
  - for GUT scale models: RGE running [*SoftSusy*]

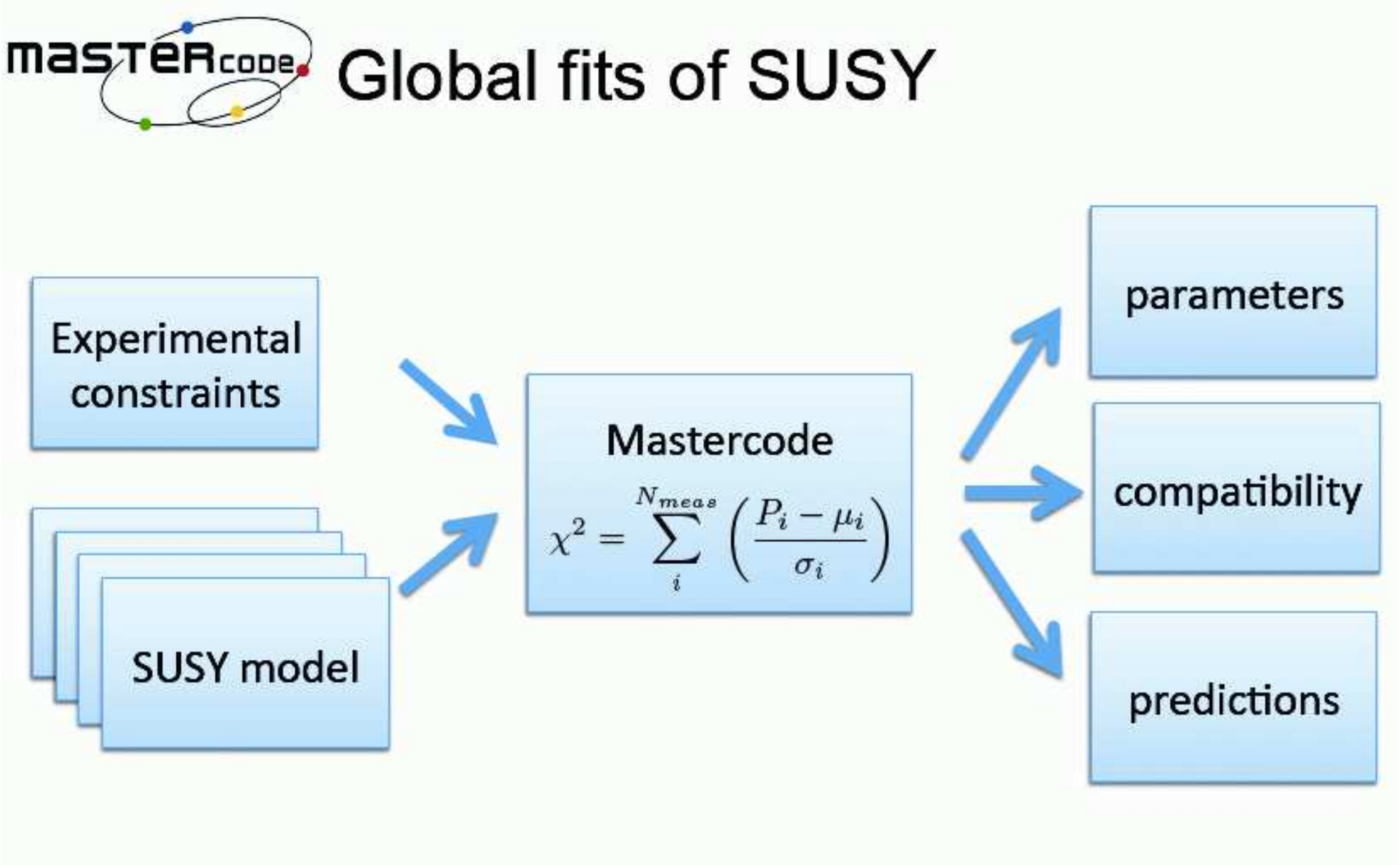
$\Rightarrow$ all most-up-to-date codes on the market! $\Rightarrow$ crucial for precision!

Latest updates in the "MasterCode":

- 13 TeV data for $\sigma(pp \to \tilde{g}\tilde{g})$ (recast)
- 13 TeV data for $\sigma(pp \to \tilde{q}\tilde{q}, \tilde{q}\bar{\tilde{q}})$ (recast)
- 13 TeV data for $pp \to H/A \to \tau\tau$ (preliminary)
  $\to$ waiting for "official" inclusion into [*HiggsBounds*]
- private combination of latest LUX and PandaX limits
- ...

$\Rightarrow$ included so far in SU(5), mABSB, pMSSM11

The χ^2 evaluation:



3. Results in the pMSSM10/11

– preferred pMSSM mass ranges

  in particular for $m_{\tilde{\chi}_1^0}$, our DM mass

– identification of DM annihilation mechanism

– prospects for (HL)-LHC, interplay with DM searches

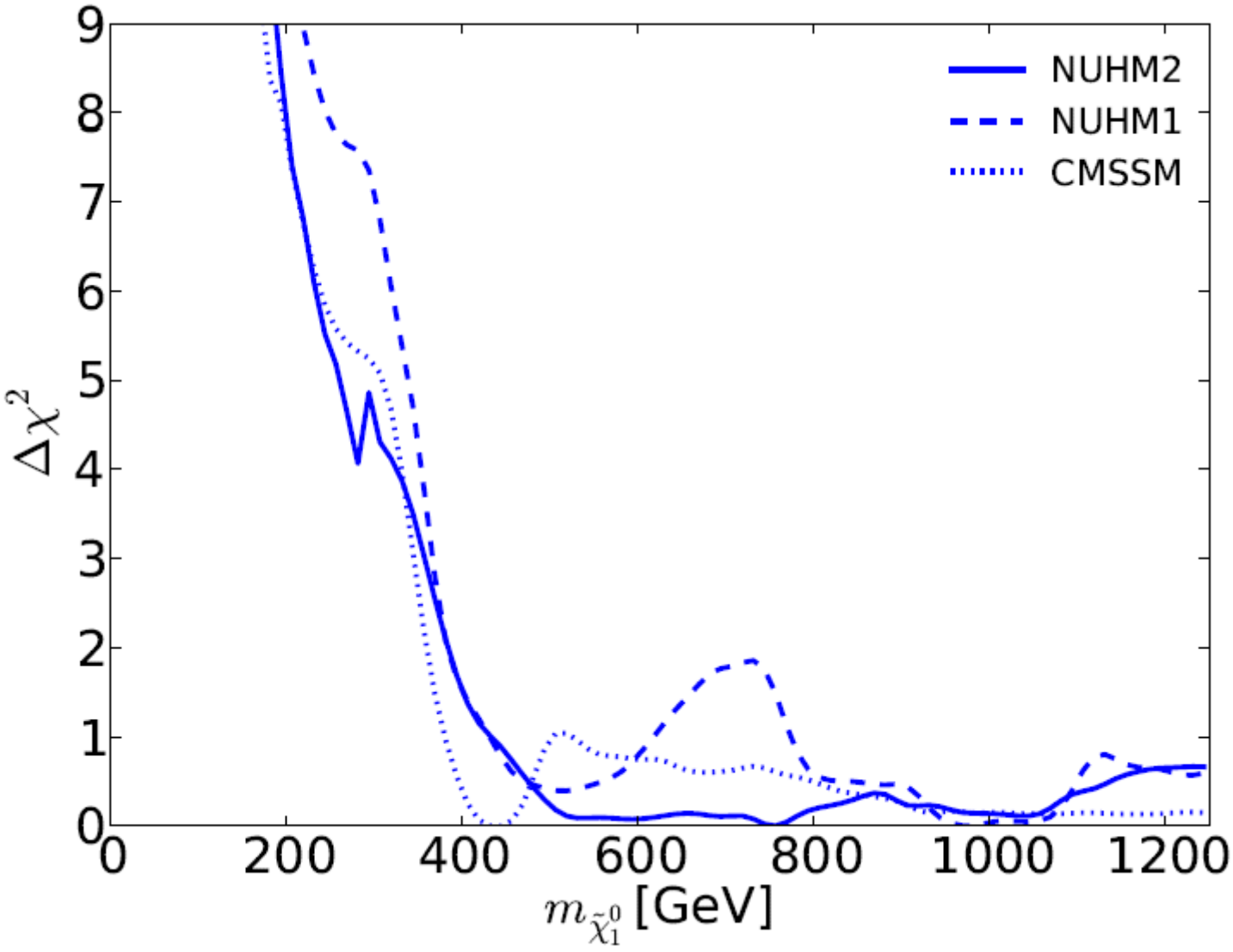
– results in the $m_{\tilde{\chi}_1^0}$–σ_p^{SI} plane for the pMSSM10

– no "no lose" theorem for DD experiments

– ...

LSP mass incl. 20/fb of LHC data in CMSSM, NUHM1/2

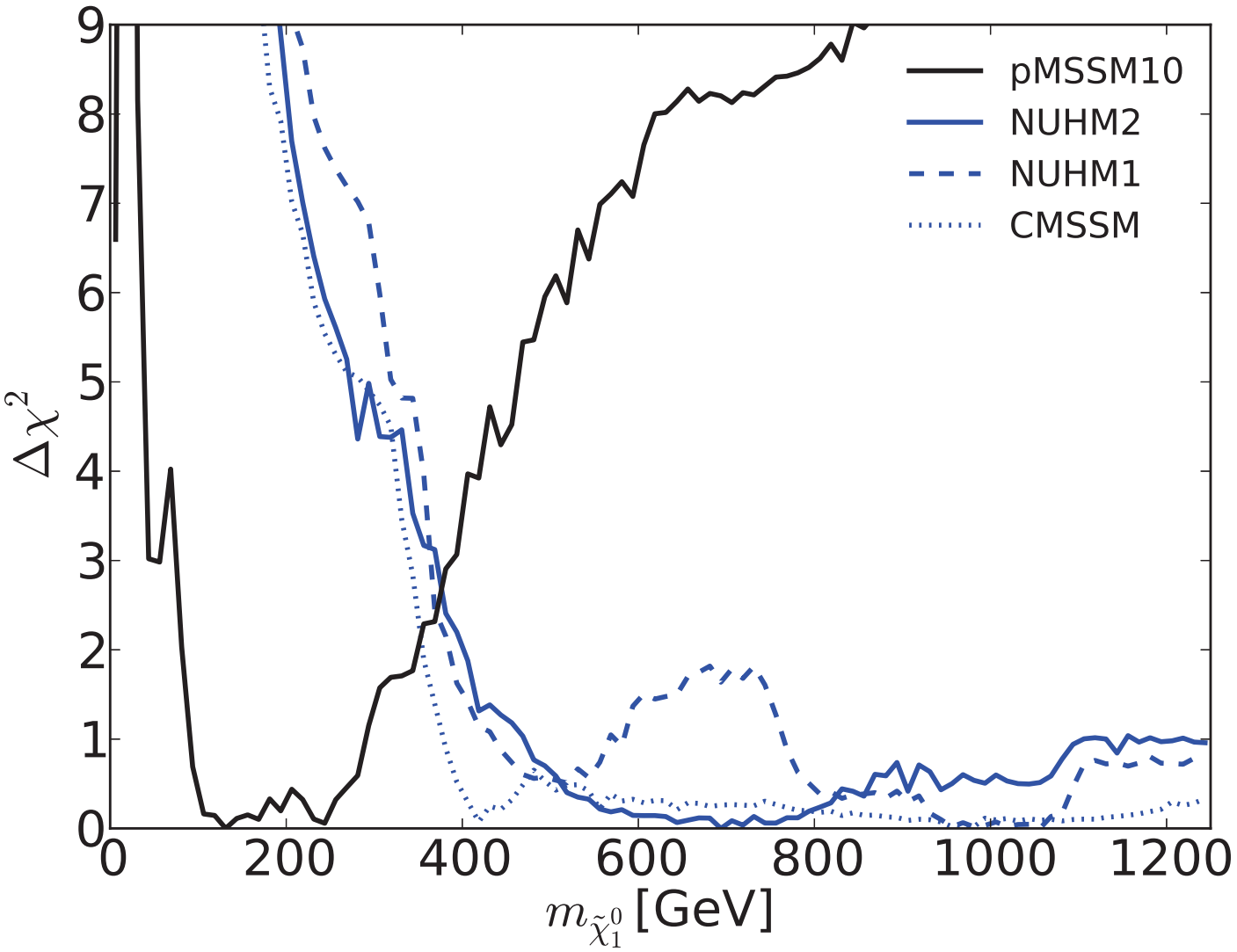
[2014]



⇒ only very large values are favored

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

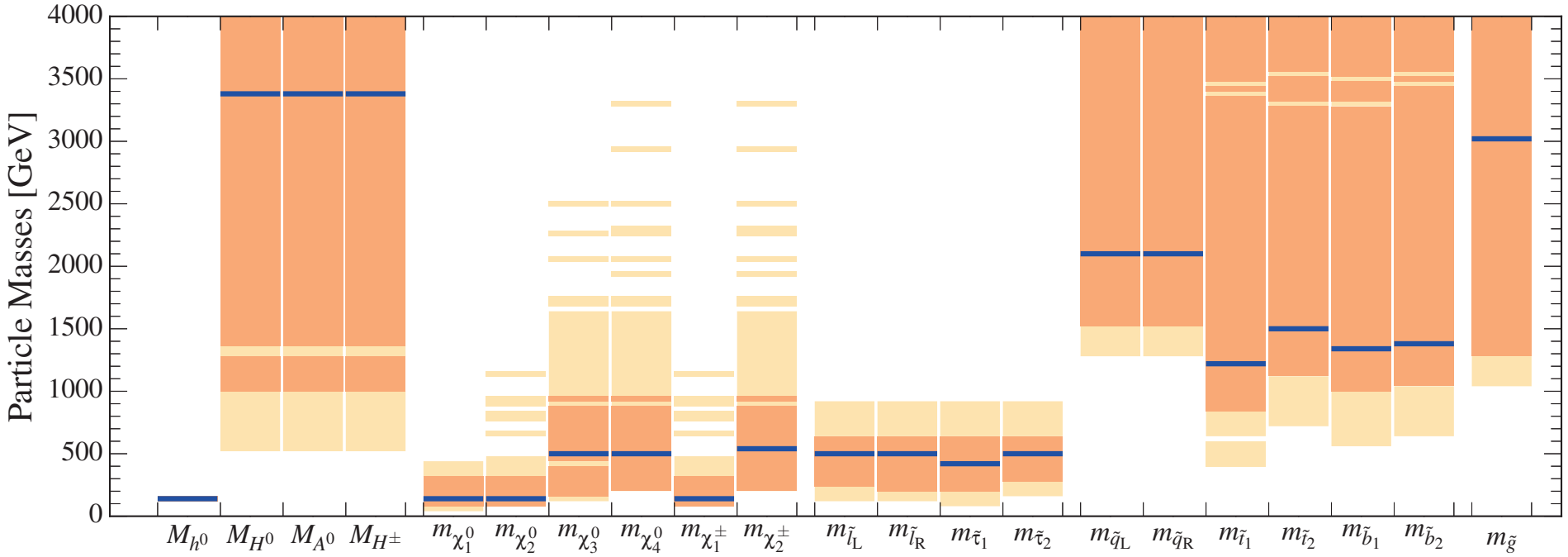
[2015]



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

pMSSM10 prediction: best-fit masses

[2015]



$\Rightarrow$ high colored masses

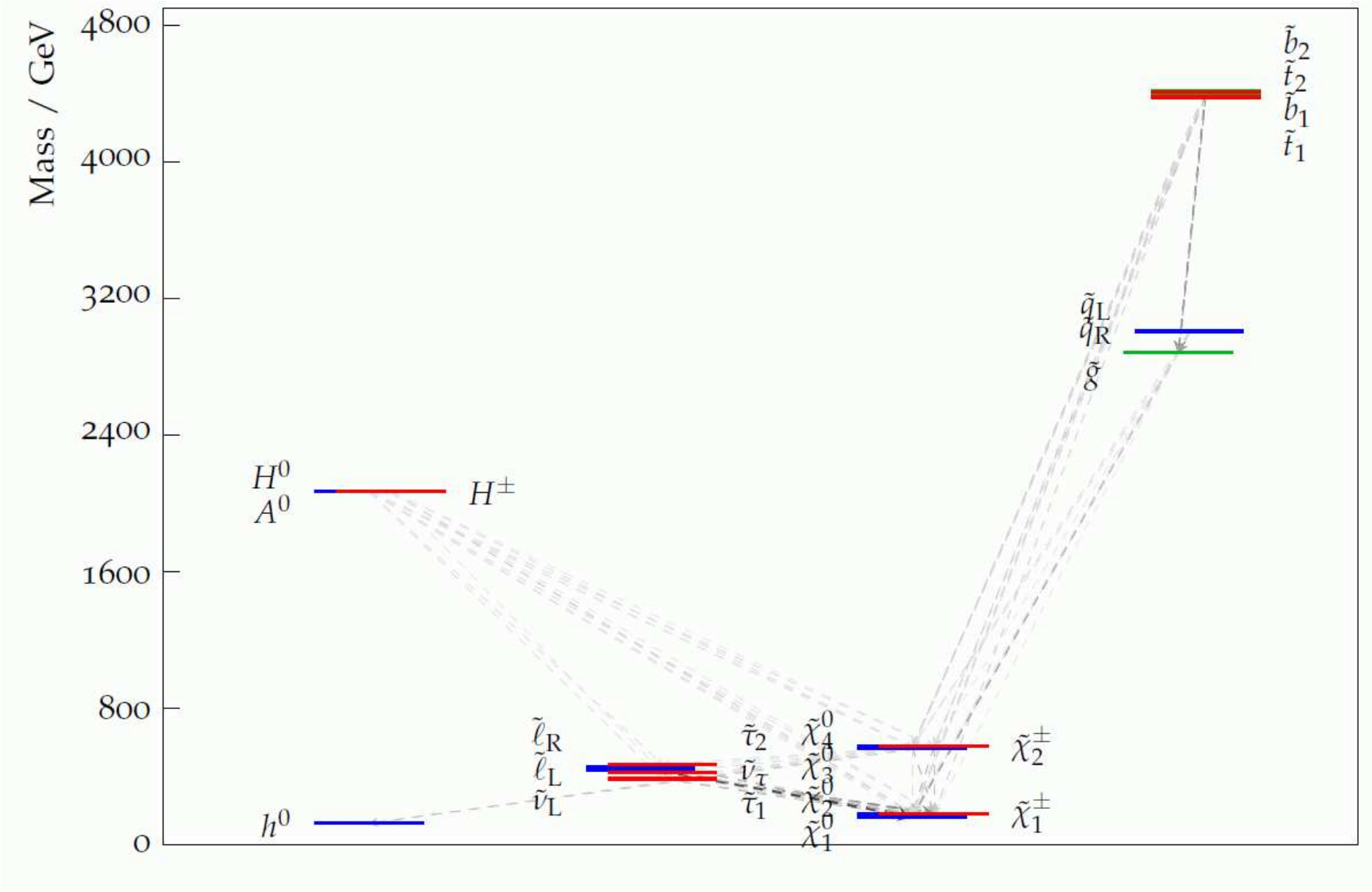
$\Rightarrow$ relatively low electroweak masses

partially with not too large ranges

$\Rightarrow$ clear prediction for $m_{\tilde{\chi}_1^0}$

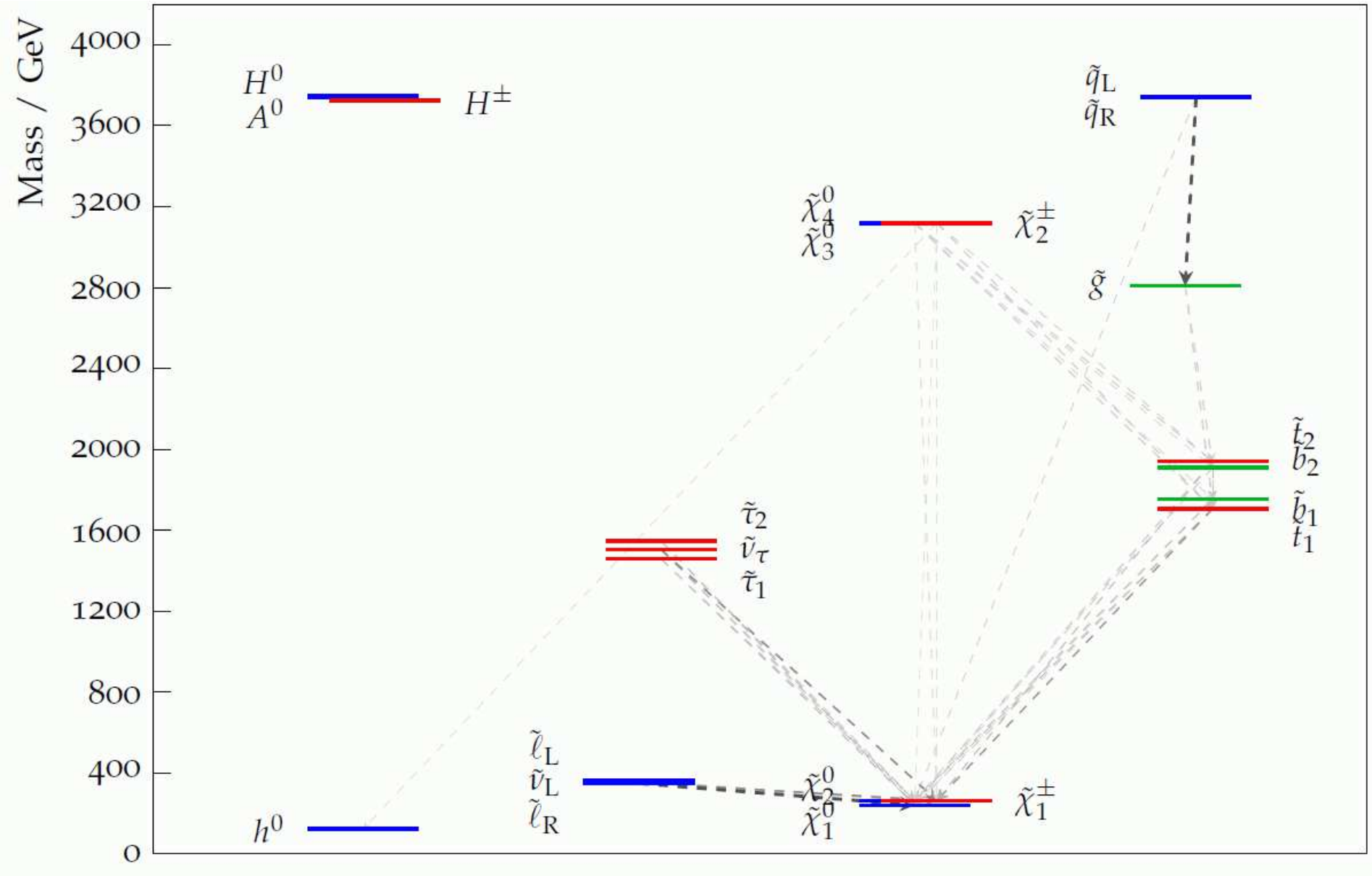
pMSSM10: best-fit masses

[2015]



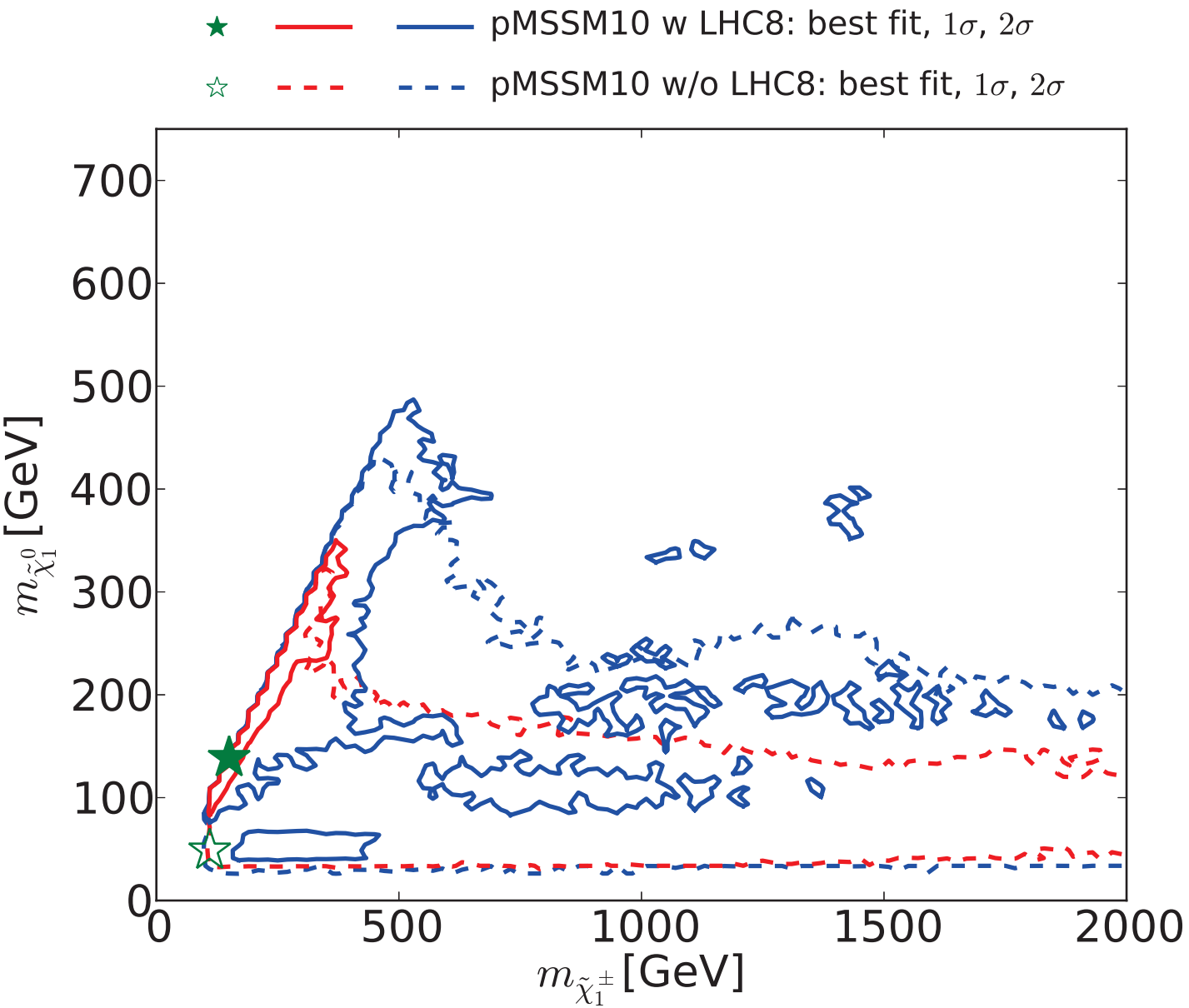
pMSSM11: best-fit masses [*PRELIMINARY*]

[*2016*]



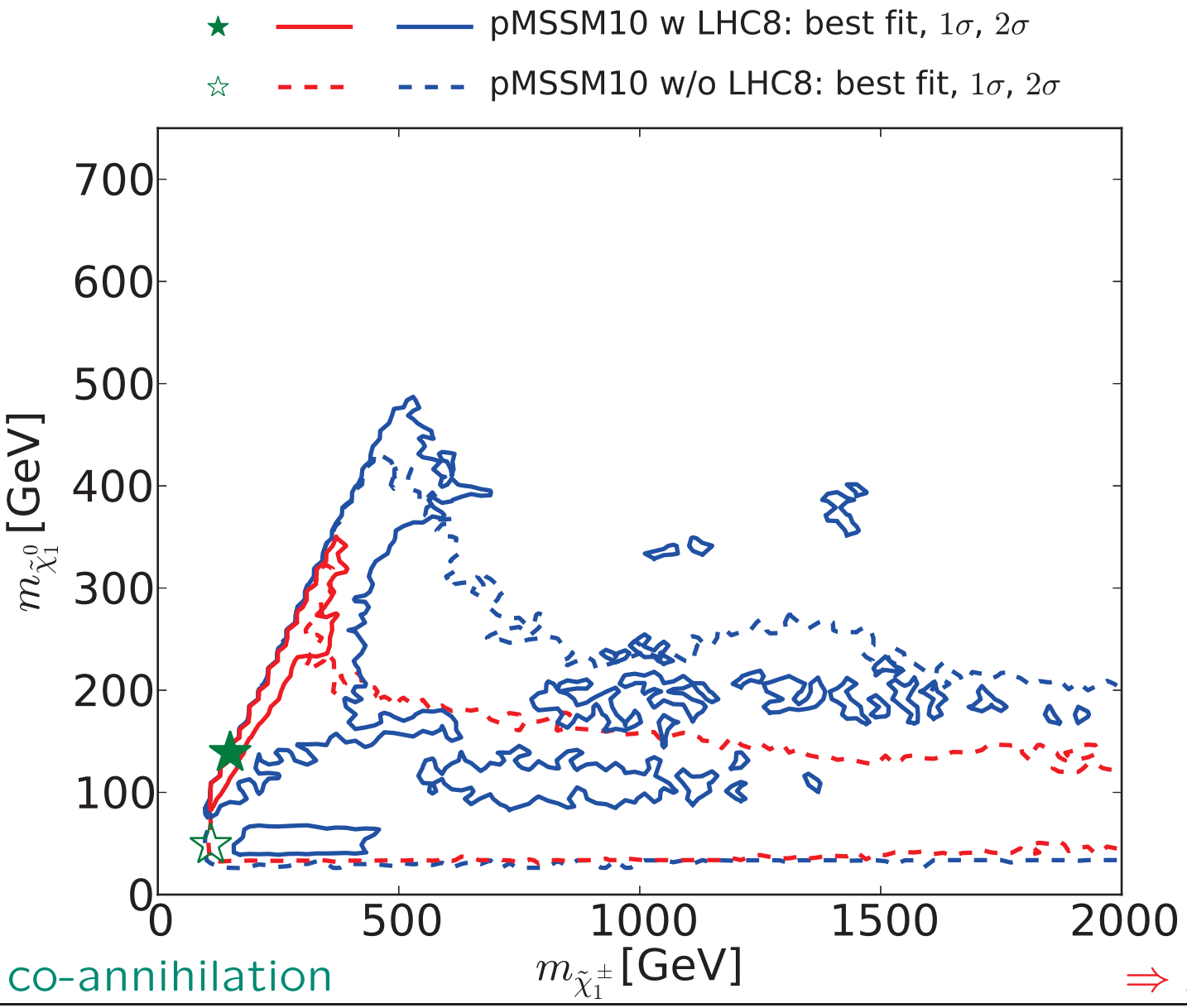
LHC search impact: DM mass vs. light chargino mass:

[2015]



LHC search impact: DM mass vs. light chargino mass:

[2015]

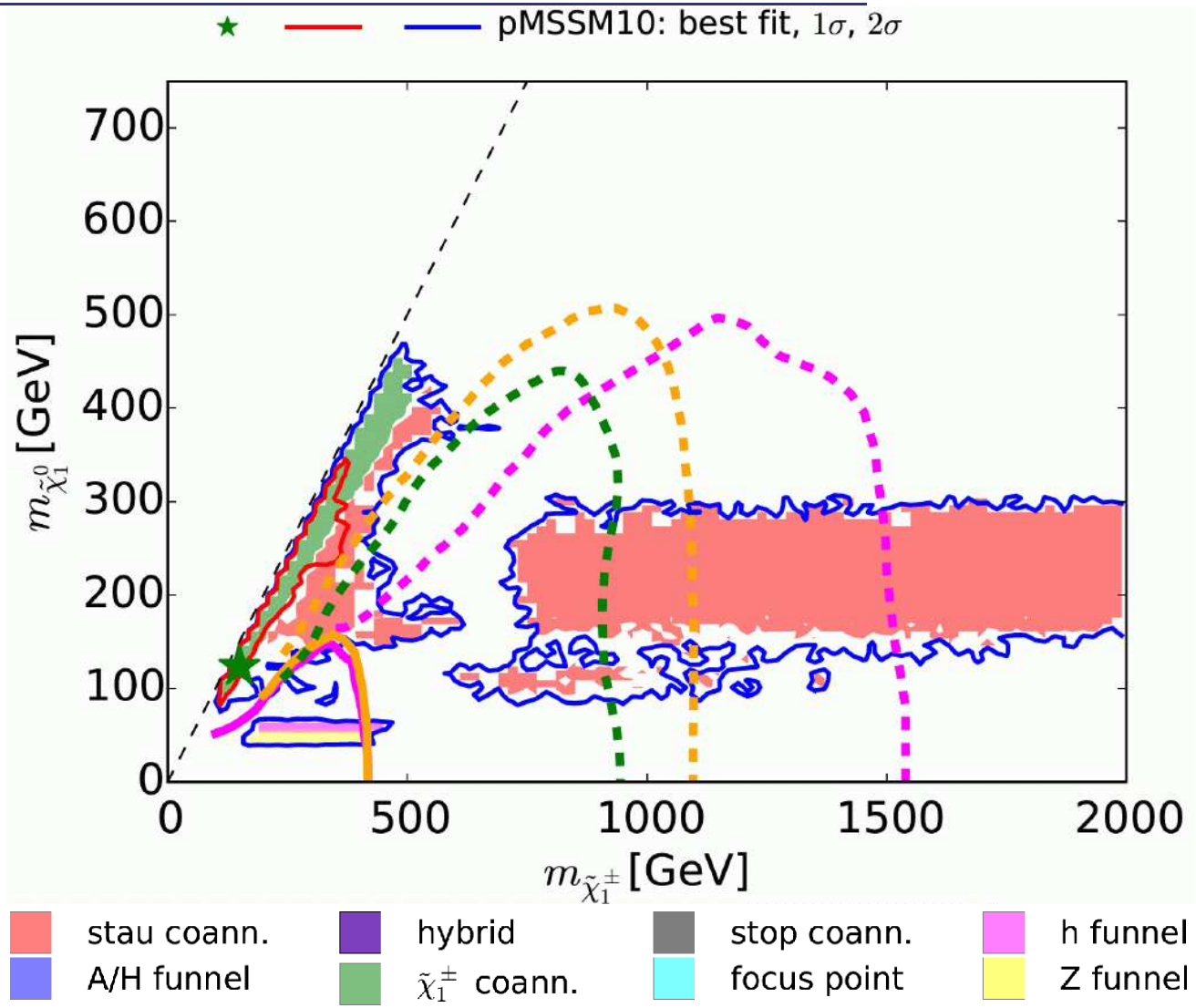


⇒ chargino co-annihilation

⇒ $M_1 \approx M_2$

pMSSM10: DM vs. LHC (electroweak searches)

[2015]

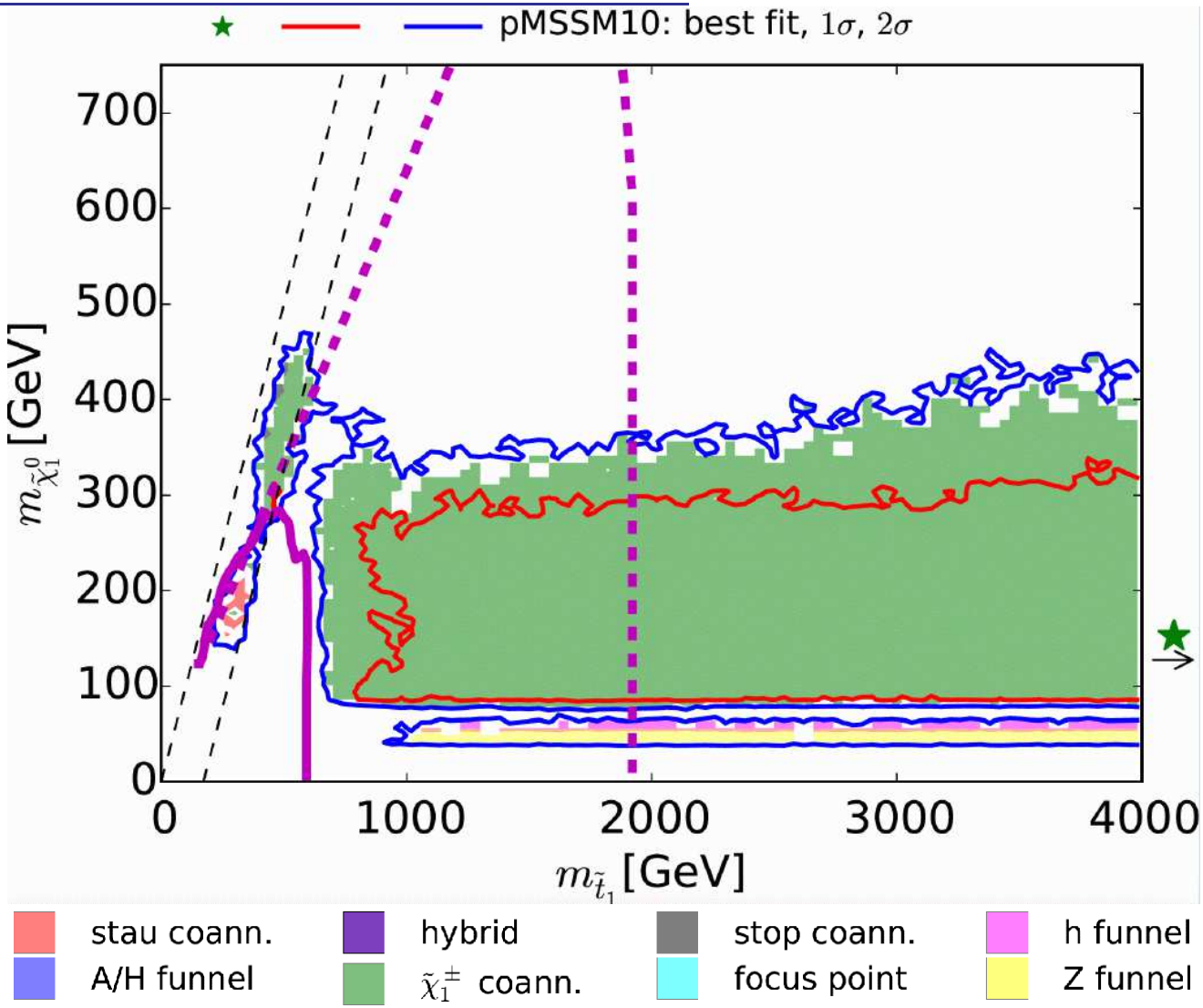


solid: current LHC limits, dashed: HL-LHC prospects

$\Rightarrow$ best-fit regions not covered! (in EW searches)

pMSSM10: DM vs. LHC (stop searches)

[2015]

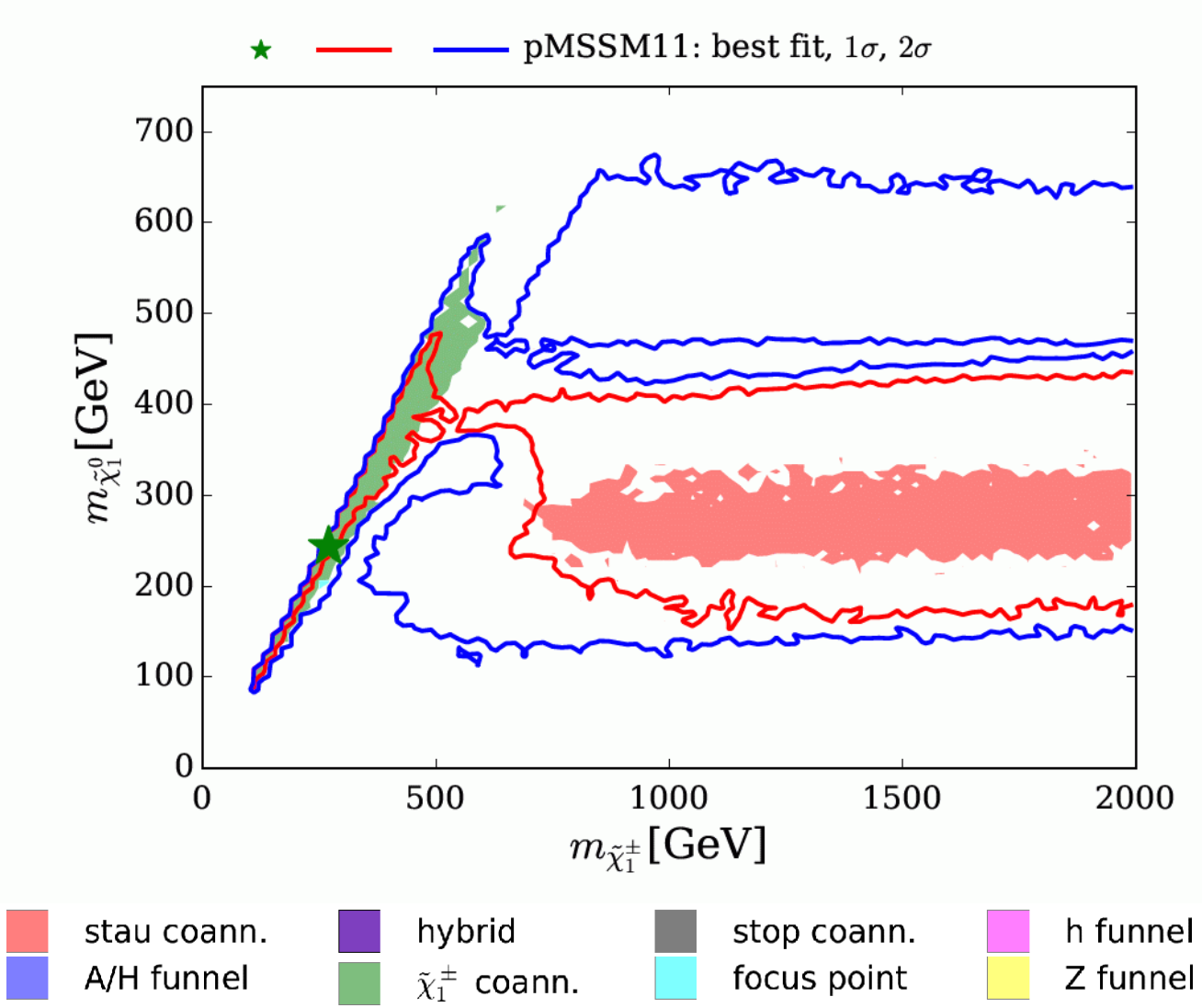


solid: current LHC limits, dashed: HL-LHC prospects

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

pMSSM11: light chargino mass [*PRELIMINARY*]

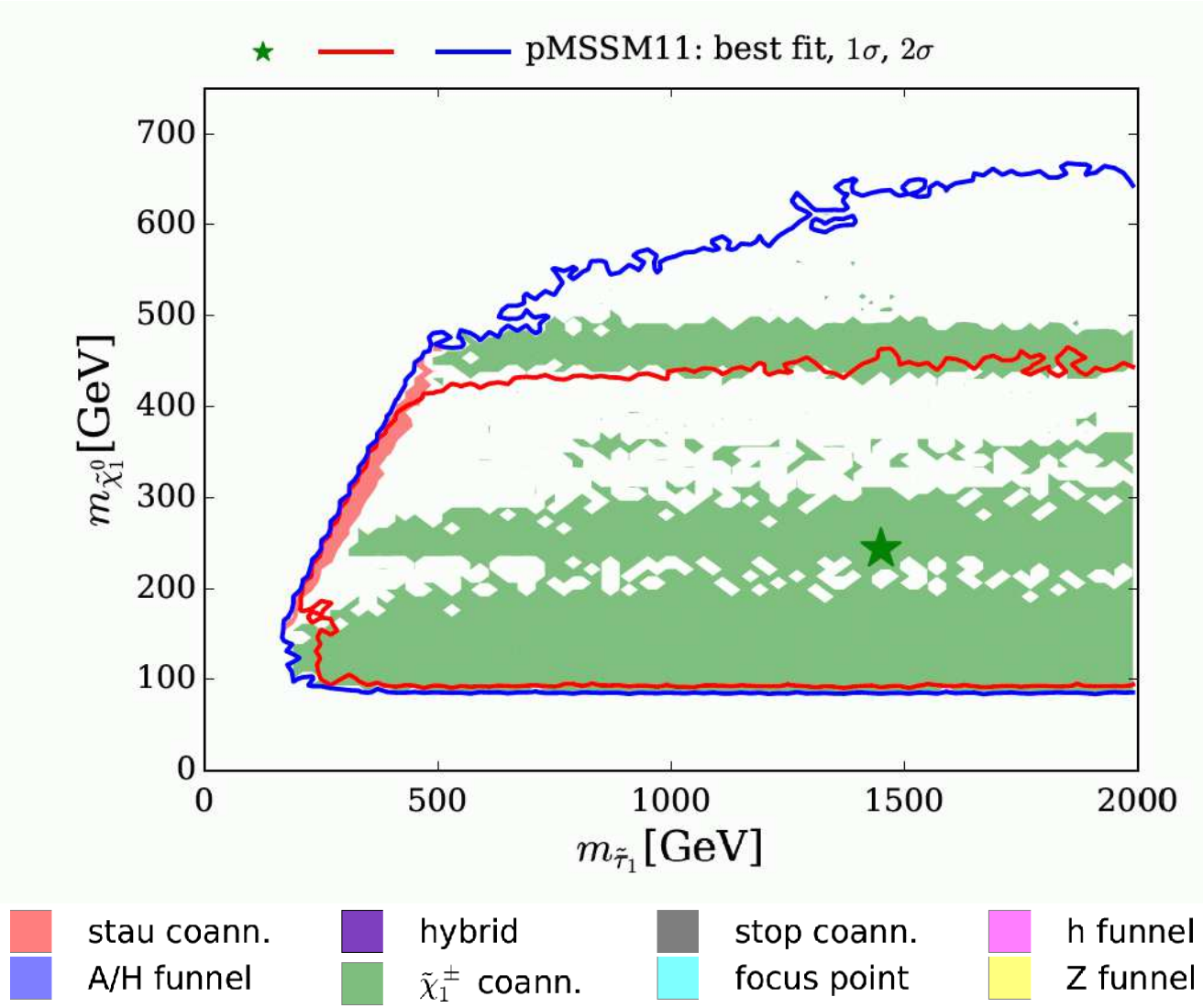
[*2016*]



⇒ larger preferred regions!

pMSSM11: light stau mass [*PRELIMINARY*]

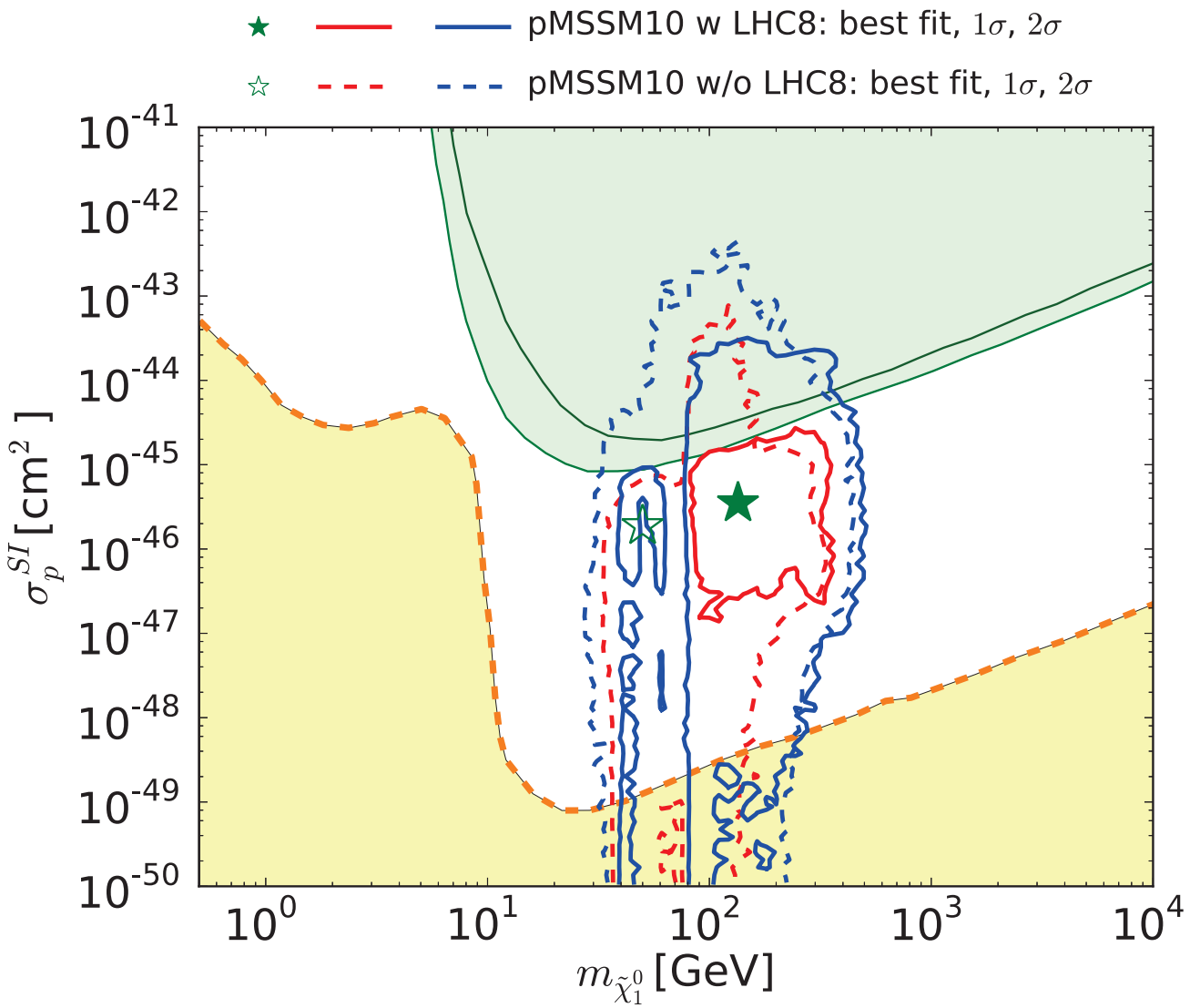
[*2016*]



⇒ shallow . . .

pMSSM10 prediction: $m_{\tilde{\chi}_1^0}$ vs. $\sigma_p^{\rm SI}$:

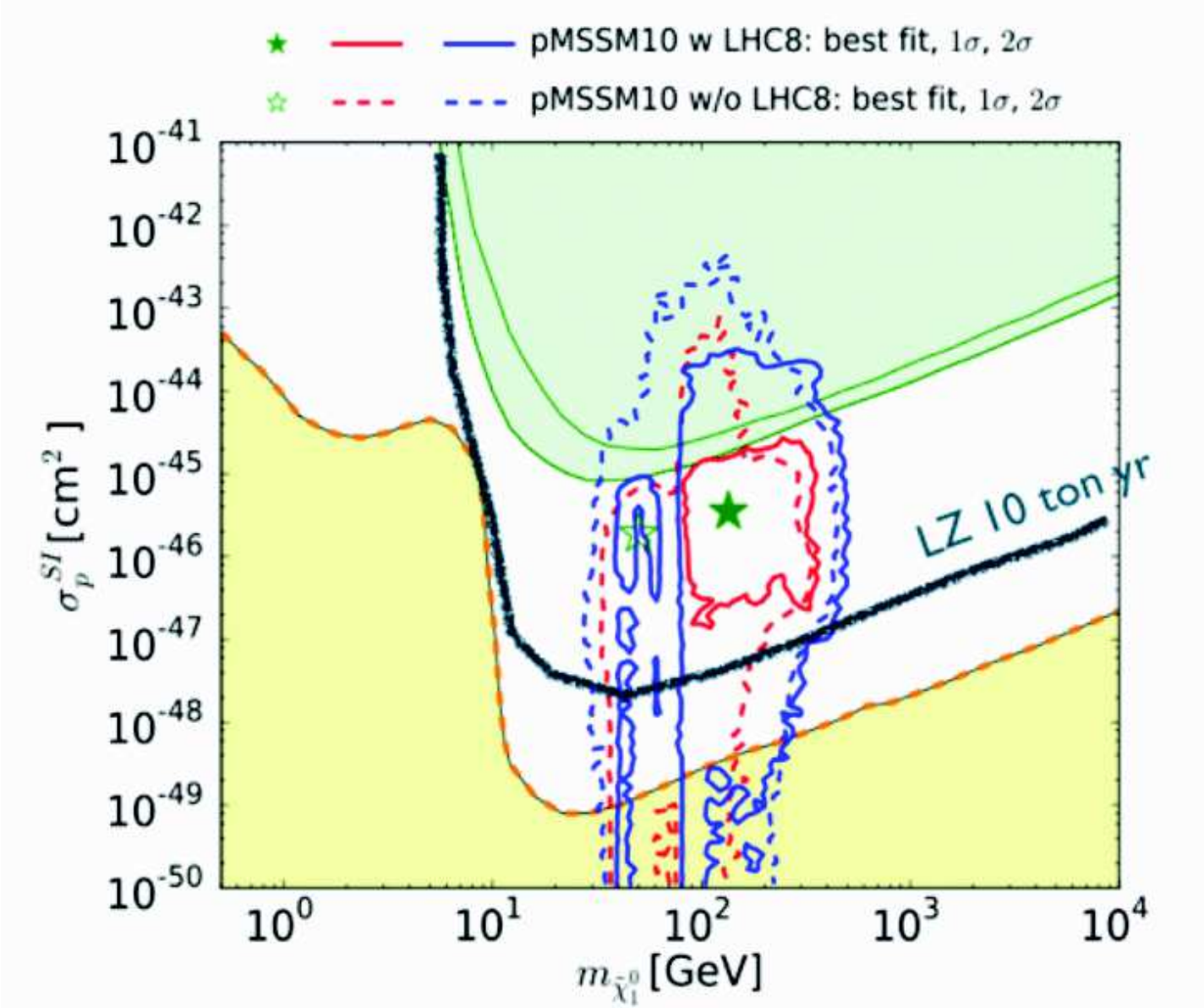
[2015]



$\Rightarrow$ LHC bounds try to "rescue" DD experiments!

pMSSM10 prediction: $m_{\tilde{\chi}_1^0}$ vs. $\sigma_p^{\rm SI}$: future expectations

[2015]



$\Rightarrow$ 68% CL areas covered by next round of DD experiments

pMSSM10 analysis: DD experiments: p- vs. n-scattering

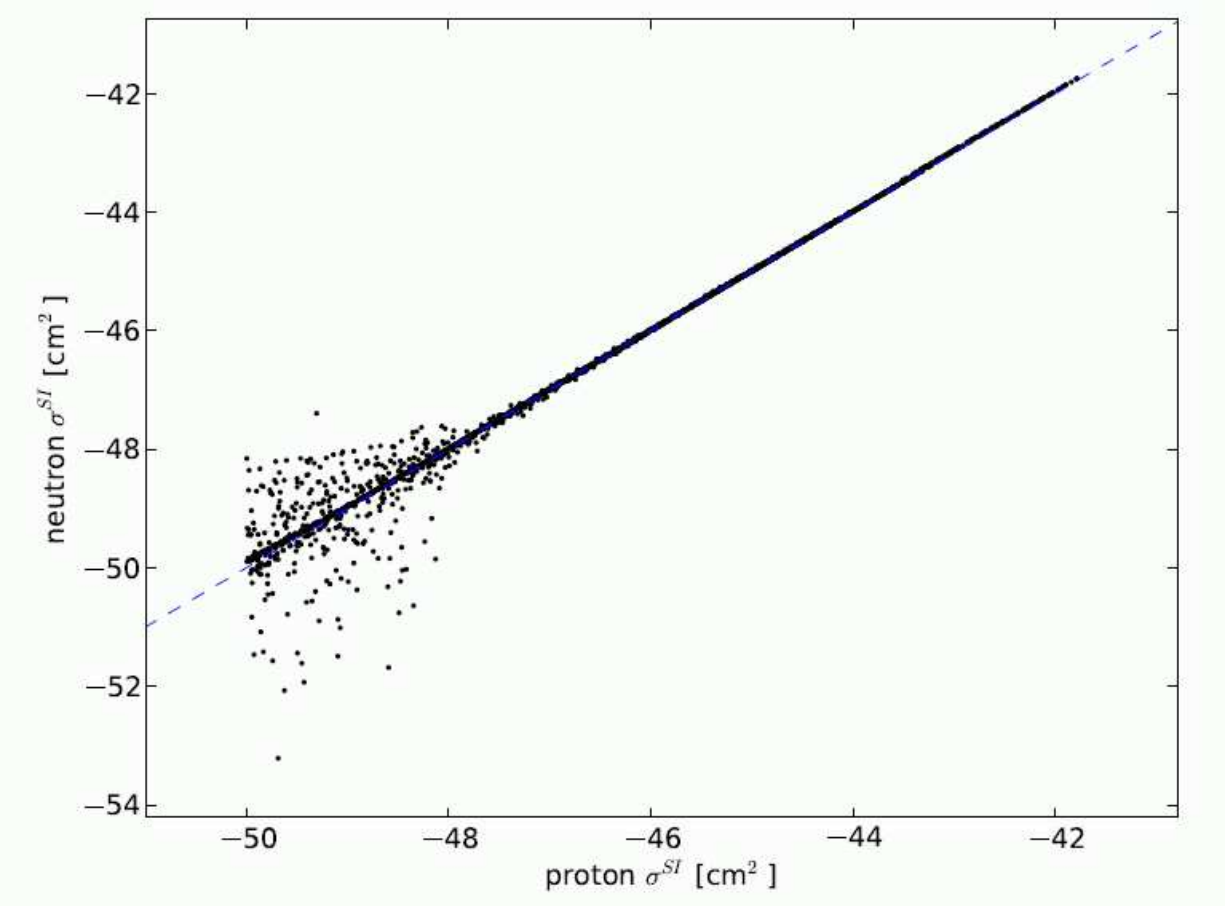
[2015]

$\sigma_p^{\rm SI}$ is evaluated for p-scattering

Can n-scattering come to rescue?

Some points with low $\sigma_p^{\rm SI}$ have even lower $\sigma_n^{\rm SI}$

$\Rightarrow$ no "no-lose theorem" for DD experiments!



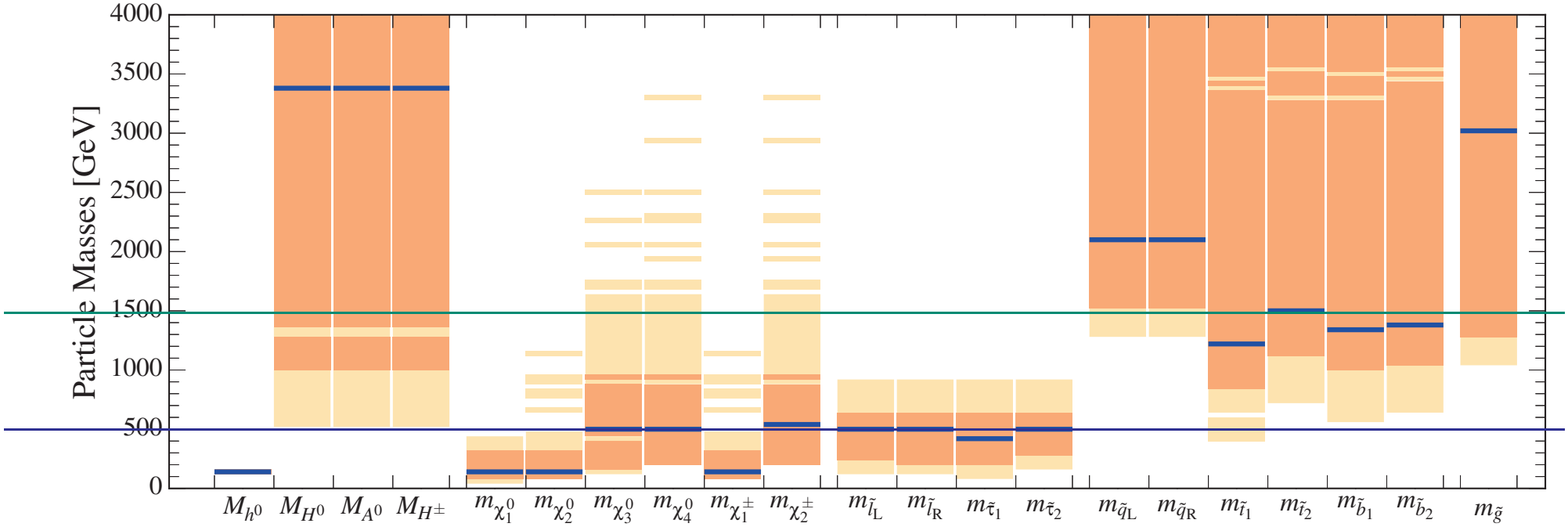
4. Conclusions

- SUSY is (still) the best-motivated BSM scenario
  - constrained models: CMSSM, NUHM1, NUHM2, ... $\Rightarrow$ Keith's talk
  - general models: pMSSM10, ...
- Our tool: MasterCode: combination of LHC searches
  Higgs measurements, EWPO, BPO, CDM $\Rightarrow$ χ^2 evaluation
- Preferred fit ranges in pMSSM10 (GUT): $m_{\tilde{\chi}_1^0} \lesssim (\gtrsim) 400$ GeV
  - important: chargino co-annihilation, $M_1 \sim M_2$ at the EW scale
  - many EW particles below $500 - 1000$ GeV
- Preliminary results in the pMSSM11:
  - stau decoupled, shallow in $m_{\tilde{\tau}_1}$
  - also other parameter ranges weaker constrained
- LHC prospects in the pMSSM10:
  - EW searches: best-fit regions only partially covered
  - colored searches: somewhat better prospects
- Predictions for DD experiments:
  - at the 68% CL accessible at the next generation of DD
  - at the 95% CL even below "neutrino floor"
  - no "no-loose theorem" for DD experiments


Further Questions?

e^+e^- prospects for pMSSM10:

[2015]

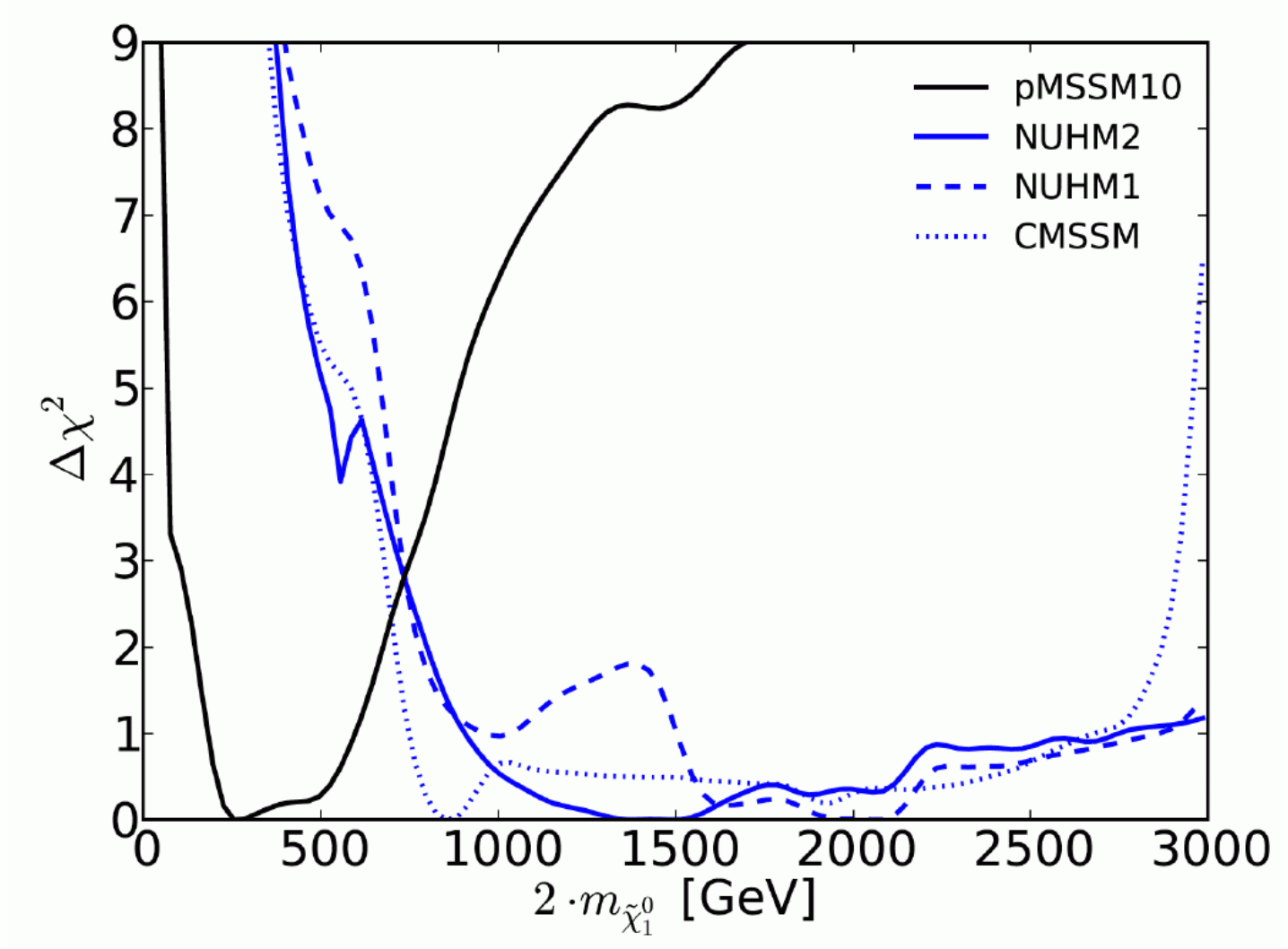


ILC: $\sqrt{s} = 1000$ GeV $\Rightarrow$ precision analysis of DM particle easy!

CLIC: $\sqrt{s} = 3000$ GeV $\Rightarrow$ precision analysis of DM particles easy!

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

[2014]

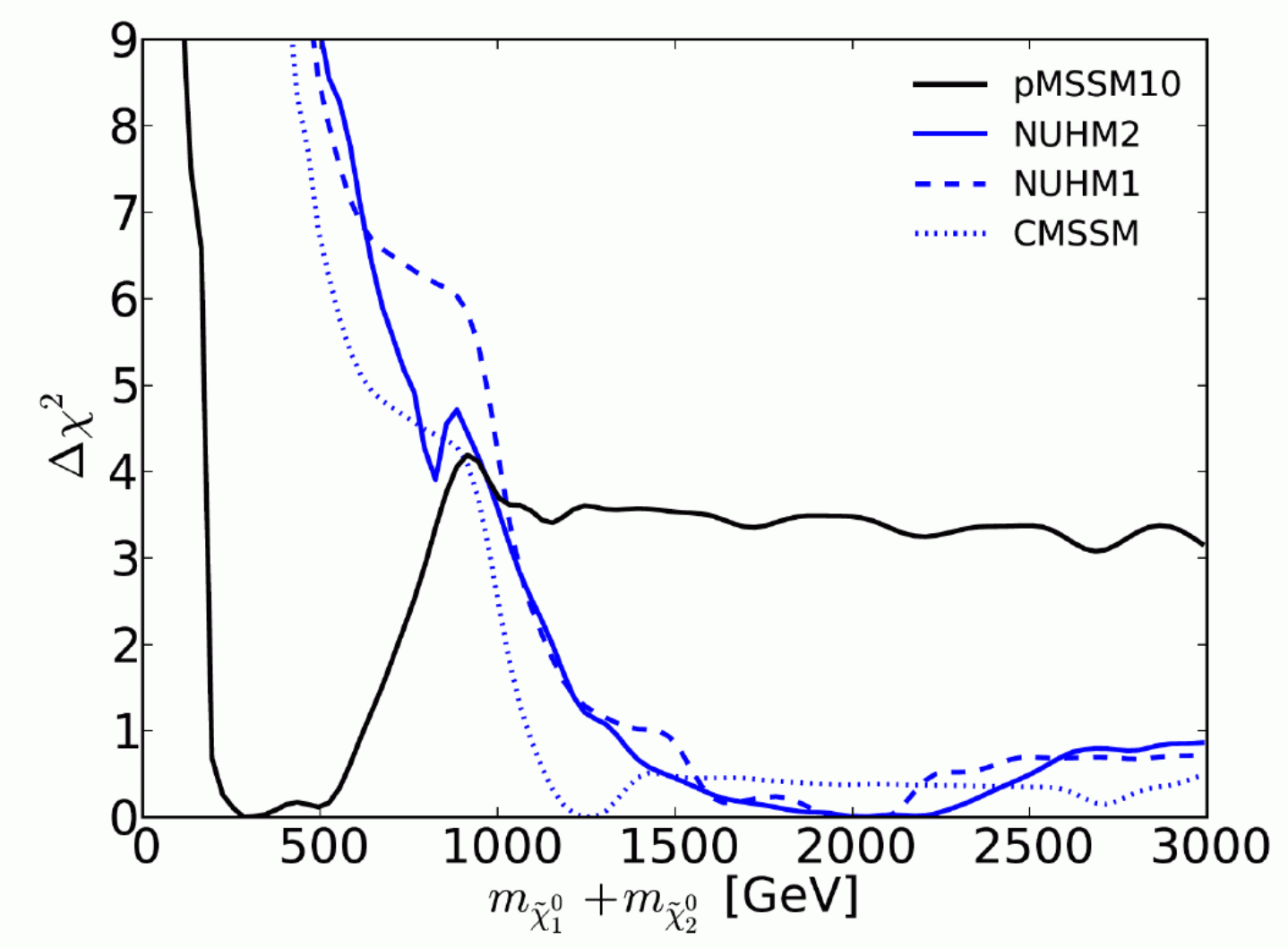


$\Rightarrow$ GUT based models: ILC :-(, CLIC possible

$\Rightarrow$ pMSSM10: easy at the ILC

DM production cross sections: $e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0$

[2014]



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

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