
We still believe in supersymmetry
You must be joking

pMSSM Fits: Theory Persective(s)

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virtual only, 12/2020

1. Introduction

2. Which constraints? Why? When?

3. Some MasterCode experiences

4. Conclusions

1. Introduction

pMSSM scan: what do we want?

– full coverage
– no relevant phenomenology should remain uncovered . . .
  . . . at the LHC Run 3, HL-LHC, e^+e^- colliders, . . .
– constrain, but not overconstrain the parameter space
– . . .

pMSSM scan: what are (some of) the problems?

– parameter dependences from theory calculations
  (e.g. 3rd gen. slepton masses vs. 2nd gen. slepton masses)
– often now theory uncertainties available - but they can be crucial
– best evaluation vs. fast evaluation
– how to take the corresponding uncertainties into account?
– are theory predictions reliable for all corners of the parameter space?
  Simple and (nearly) always valid answer: No!
– . . .

2. Which constraints? Why? When?

– what data do we have?

– can we theoretically take all of that into account?

– what data do we want to take into account?

– theoretical prejudice?

– experimental prejudice?

– ...

$\Rightarrow$ some (hopefully) interesting examples

Existing data:

– Higgs boson mass/couplings/. . . (LHC) ⇒ FeynHiggs

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To be discussed:

– electroweak precision data, incl. $(g-2)_\mu$ ⇒ do you want this? How?

– flavor data ⇒ do you want this? How?

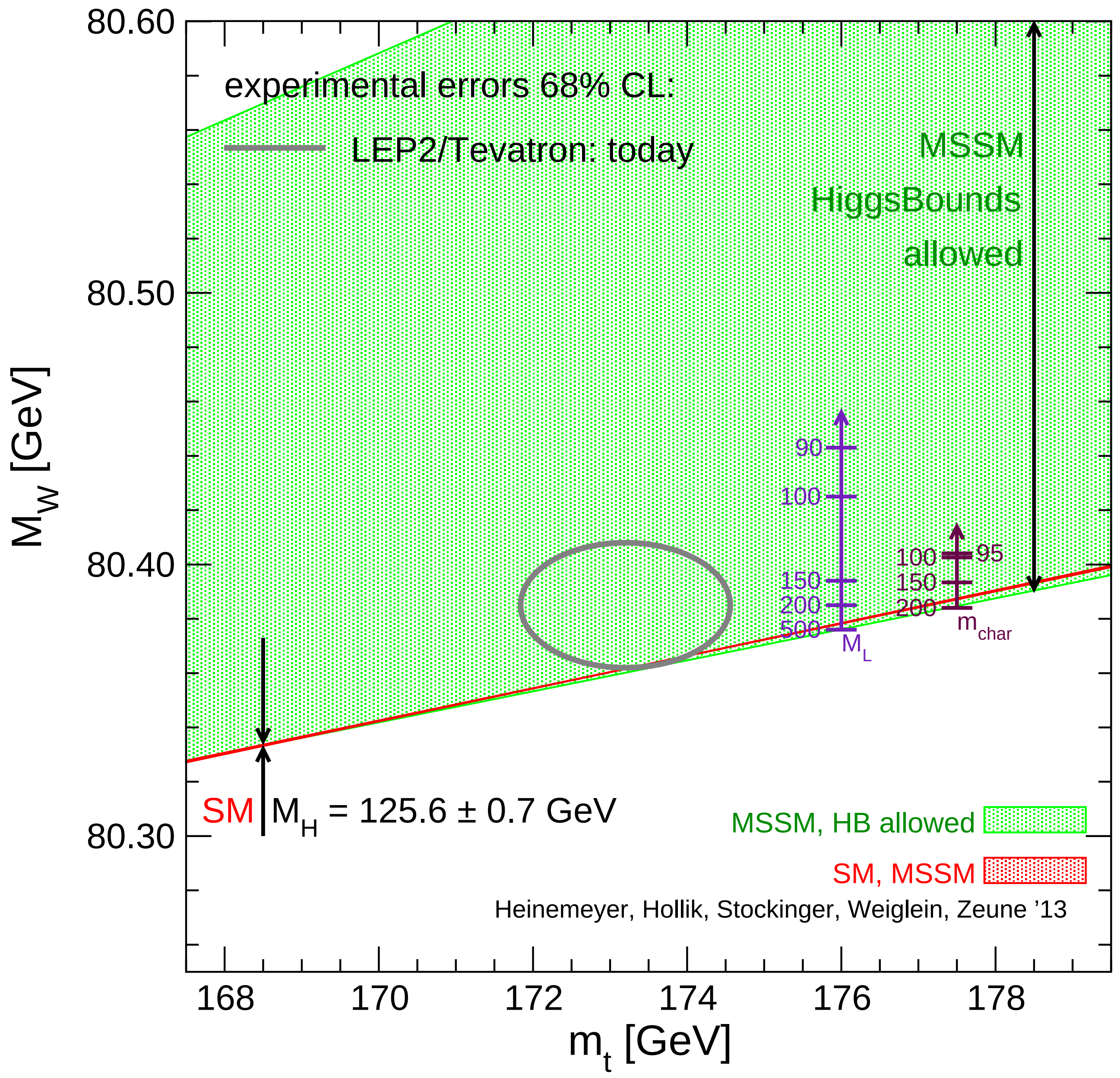
– astrophysical data (DM properties) ⇒ do you want this? How?

(Some) Electroweak precision observables:

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

$\Rightarrow$ largest impact: (1), (2), (3)
Problem: no public code exists, except for $M_W \Rightarrow$ FeynHiggs

Example MSSM scenario (I): effects beyond $\Delta\rho$: EW particles



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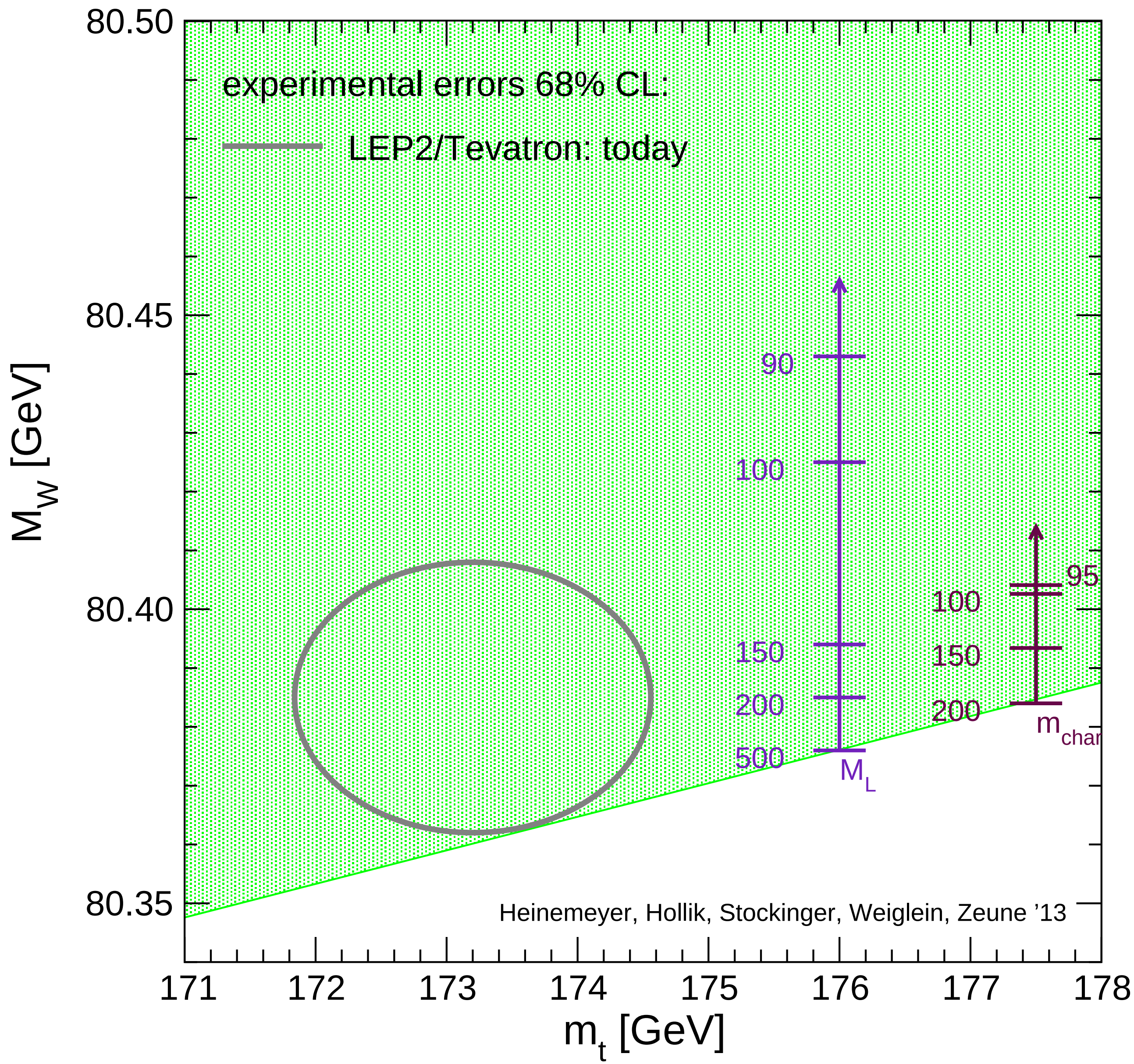
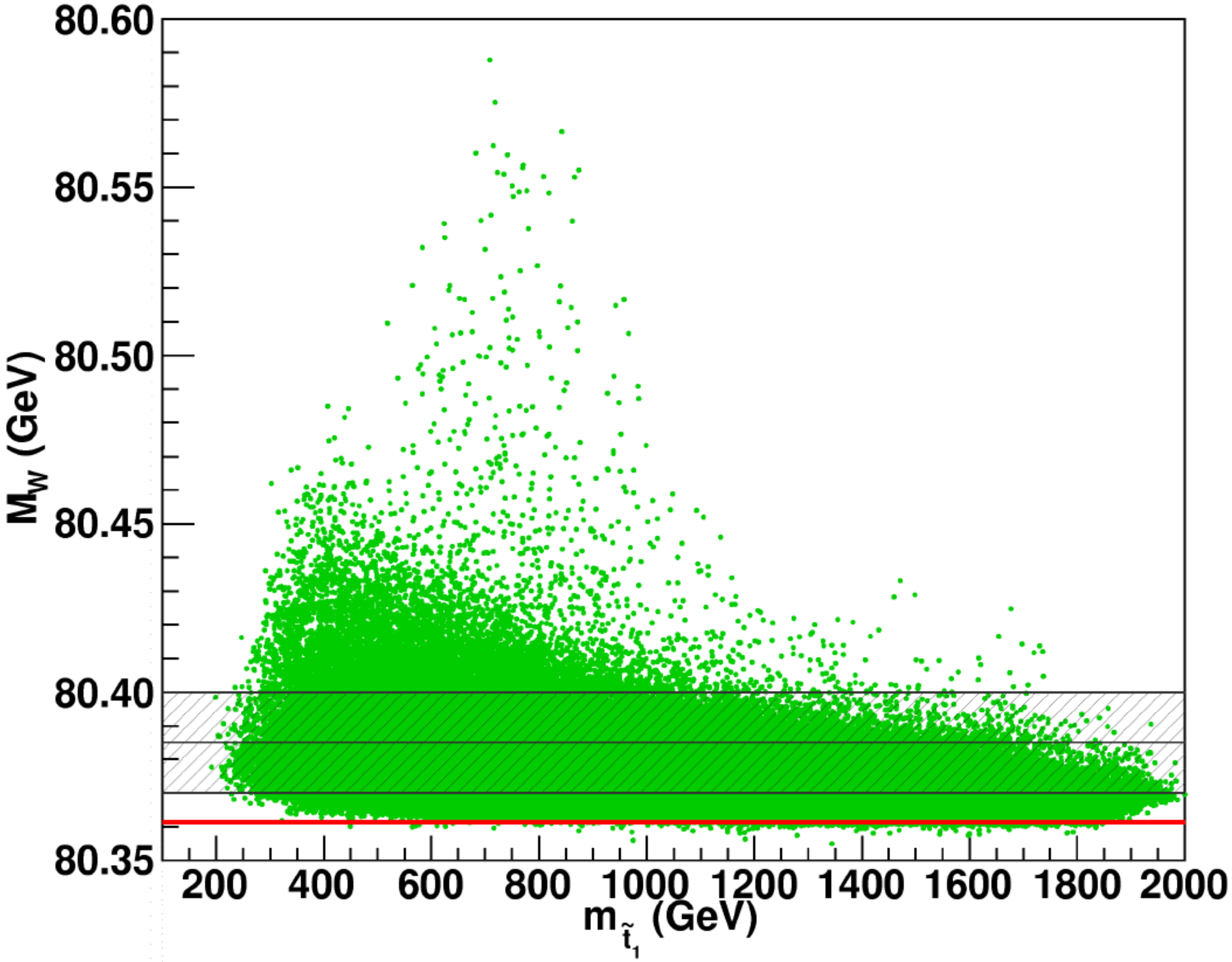


Effects of stops:

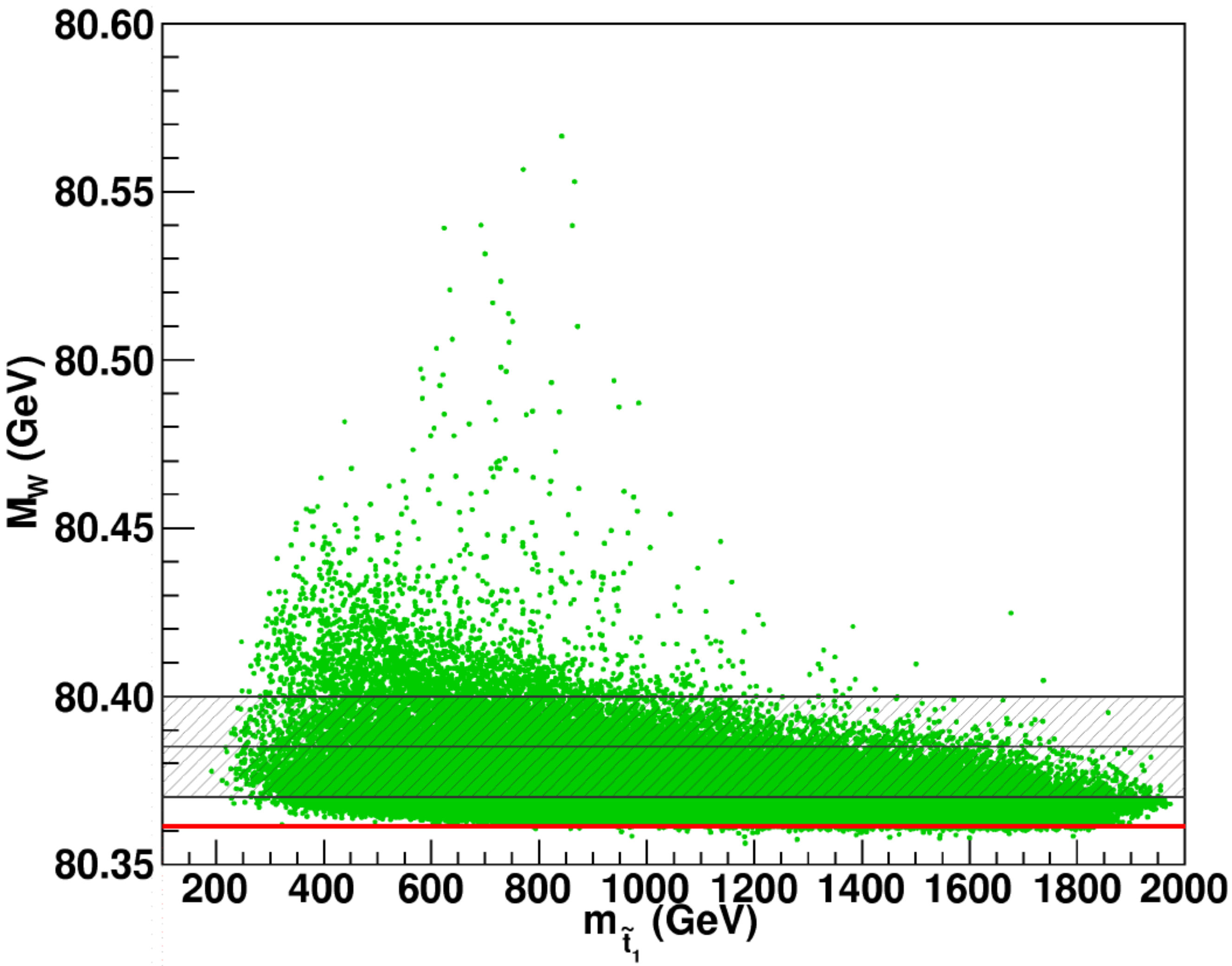
[*S.H., G. Weiglein, L. Zeune '13*]



All points HiggsBounds allowed

Effects of stops:

[S.H., G. Weiglein, L. Zeune '13]



$\ldots \oplus\ m_{\tilde{q}_{1,2}}, m_{\tilde{g}} > 1200$ GeV

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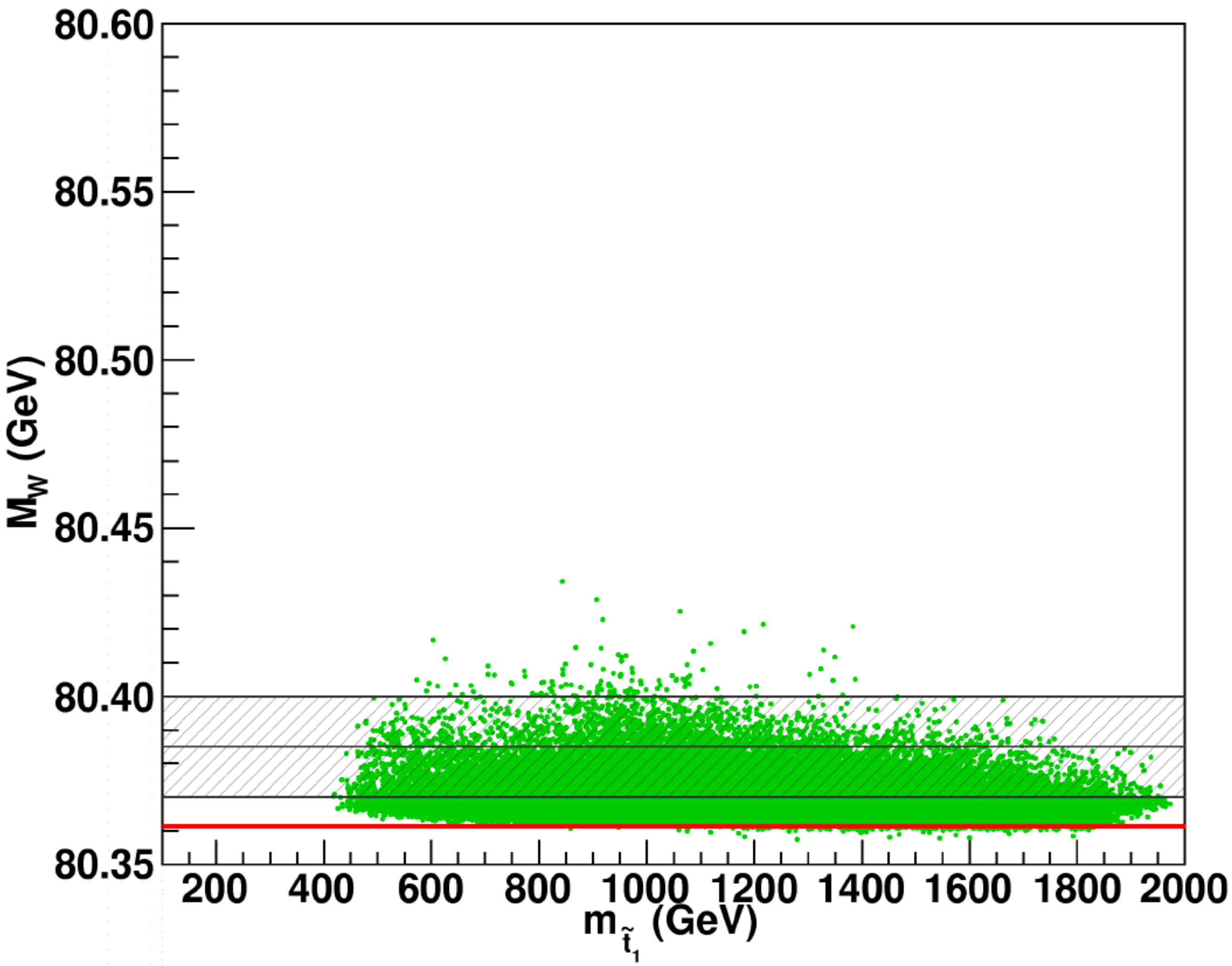
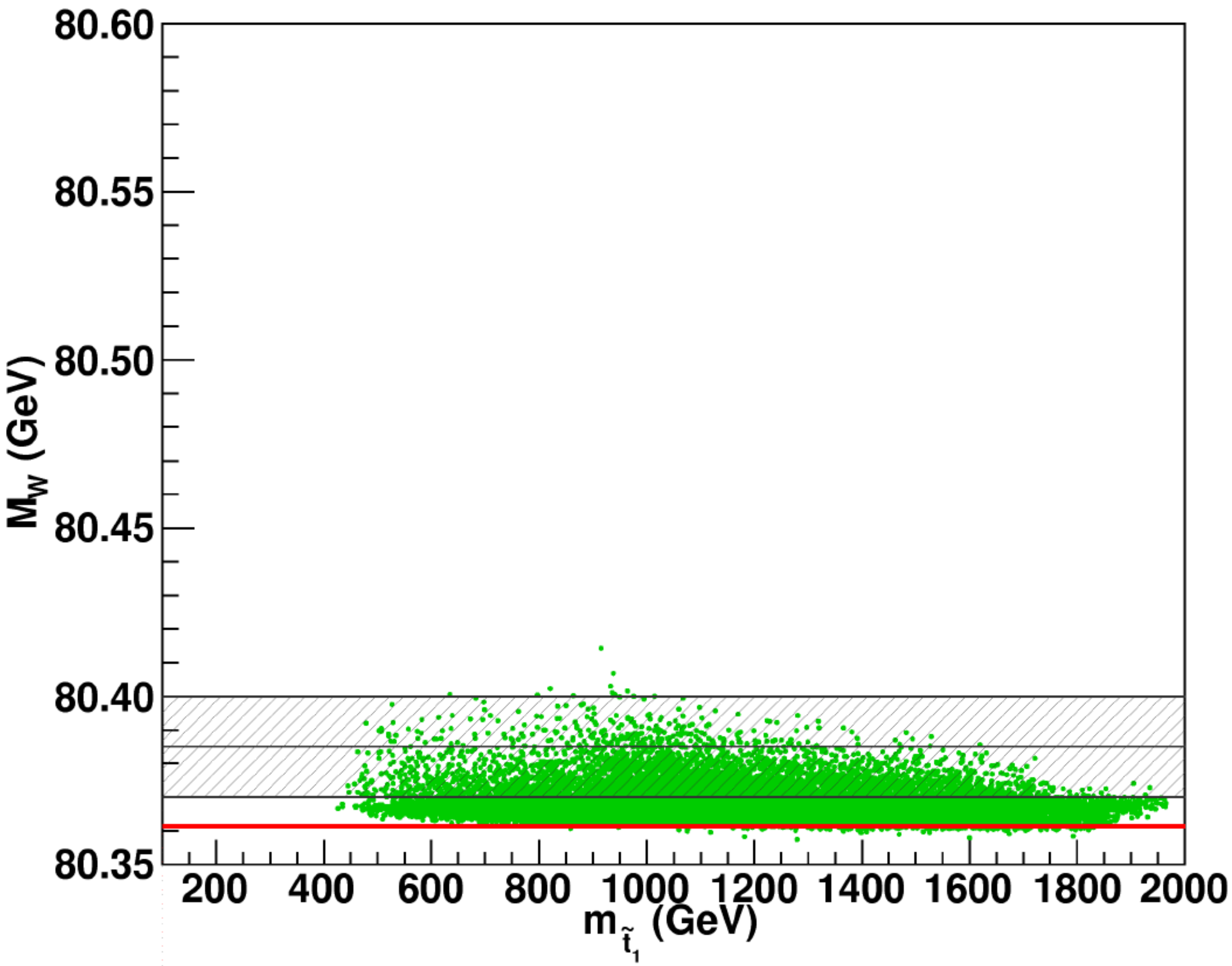


$\ldots \oplus m_{\tilde{b}_i} > 500$ GeV

Effects of stops: [S.H., G. Weiglein, L. Zeune '13]



$\ldots \oplus m_{\tilde{l}}, m_{\tilde{\chi}_i^\pm}, m_{\tilde{\chi}_j^0} > 500$ GeV $\Rightarrow M_W$ can be relevant for many parameters!

(Some) flavor physics observables:

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)

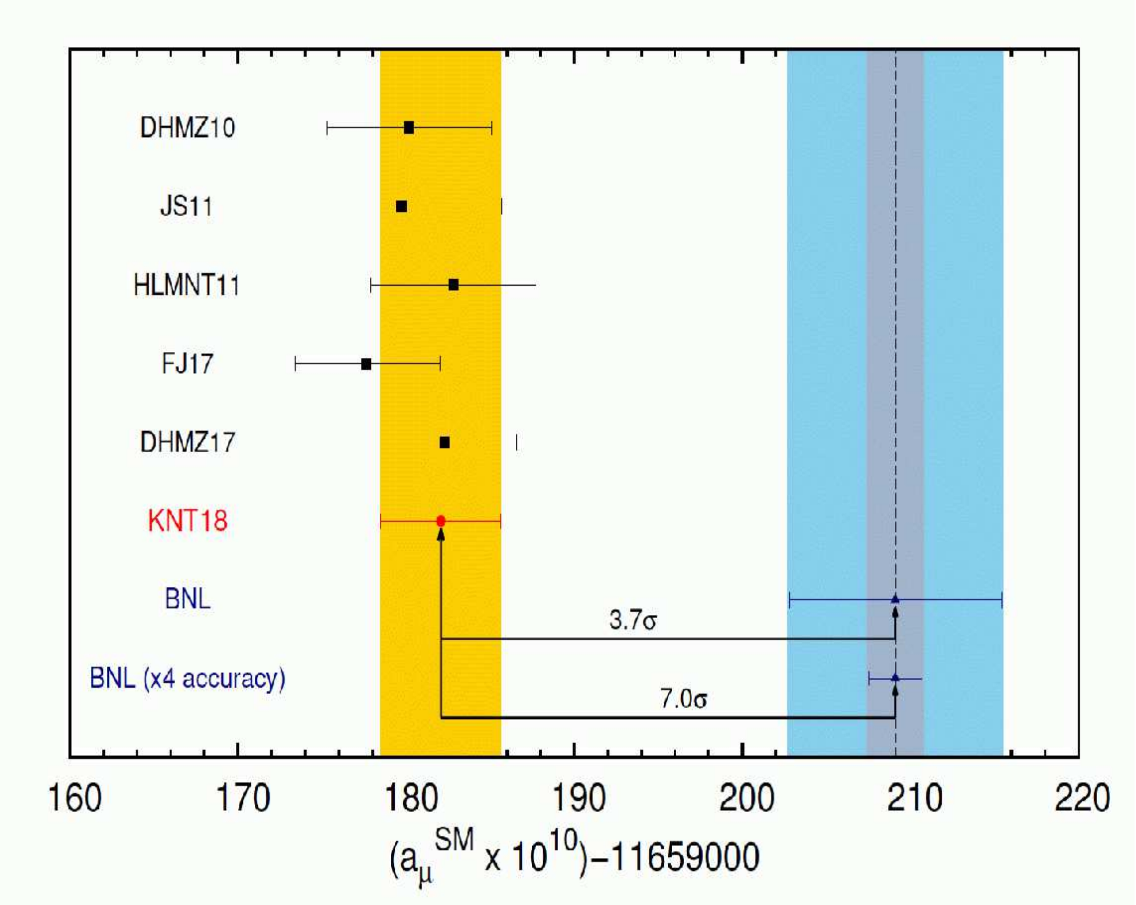
8. BR(ΔM_K) (MSSM/SM)

$\Rightarrow$ largest impact: (1) and (2)
$\Rightarrow$ public codes exist: SuperIso, ...
$\Rightarrow$ but no improvement for flavor anomalies! Ignore?

My favorite: $(g-2)_\mu$ (theoretical prejudice?)

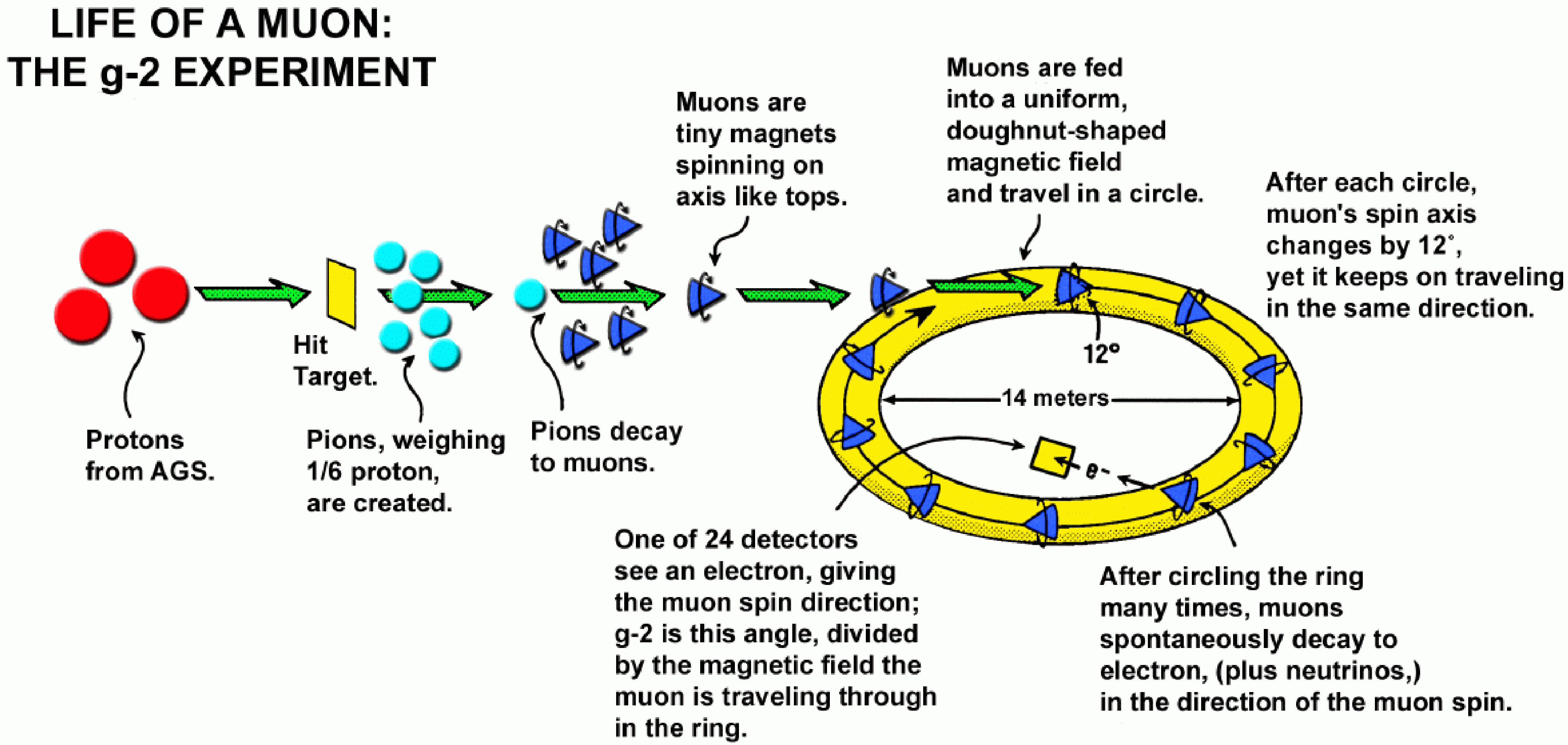
The anomalous magnetic moment of the muon: $a_\mu \equiv (g-2)_\mu/2$

Overview about the current experimental and SM (theory) result:
[*A. Keshavarzia, D. Nomura, T. Teubner '18, '20*]



$$a_\mu^{\text{exp}} - a_\mu^{\text{theo,SM}} \approx (28.02 \pm 7.37) \times 10^{-10} \quad : 3.8\,\sigma$$

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

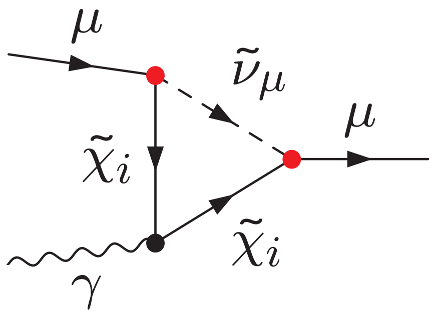


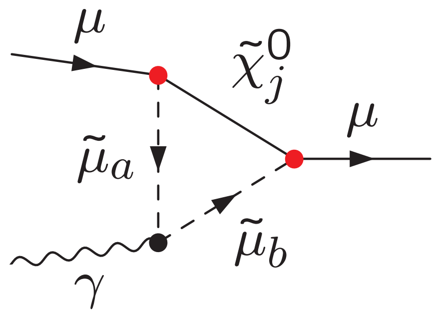
Coupling of muon to magnetic field : $\mu - \mu - \gamma$ coupling

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

SUSY can easily explain the deviation in a_μ:

Feynman diagrams for MSSM 1L corrections:





– Diagrams with chargino/sneutrino exchange

– Diagrams with neutralino/smuon exchange

Enhancement factor as compared to SM:

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

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

$$\begin{aligned} a_\mu^{\text{SUSY,1L}} &= (-100 \ldots + 100) \times 10^{-10} \\ a_\mu^{\text{exp}} - a_\mu^{\text{theo,SM}} &\approx (28 \pm 7.4) \times 10^{-10} \end{aligned}$$

$\Rightarrow$ SUSY could easily explain the “discrepancy”

$\Rightarrow$ a_μ can provide upper limits on the EW masses
(by requiering agreement at the 95% C.L.)

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

$(g-2)_\mu$ constraint: (GM2Calc)

$$\Delta a_\mu = (28.02 \pm 7.37) \times 10^{-10}$$

Possible situation in the near future:

Inclusion of anticipated MUON G-2 Run 1 data

$$\Delta a_\mu^{\text{fut}} = (28.02 \pm 5.2) \times 10^{-10}$$

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Inclusion of anticipated MUON G-2 Run 1 data

$$\Delta a_\mu^{\text{fut}} = (28.02 \pm 5.2) \times 10^{-10}$$

– do you want to ignore it when over $5\,\sigma$?

– if this region does not receive a dedicated scan, you will not find it!

– interplay with other EWPO (M_W, . . .)

– EW searches are crucial

$\Rightarrow$ important prospects for HL-LHC, e^+e^- colliders

Example results/impact:

[*M. Chakraborti, S.H., I. Saha '20*]

Parameter scan: (just one example out of a larger analysis)

$$100\ \text{GeV} \leq M_1 \leq 1\ \text{TeV}\ ,$$

$$M_1 \leq M_2 \leq 1.1 M_1\ ,$$

$$1.1 M_1 \leq \mu \leq 10 M_1,$$

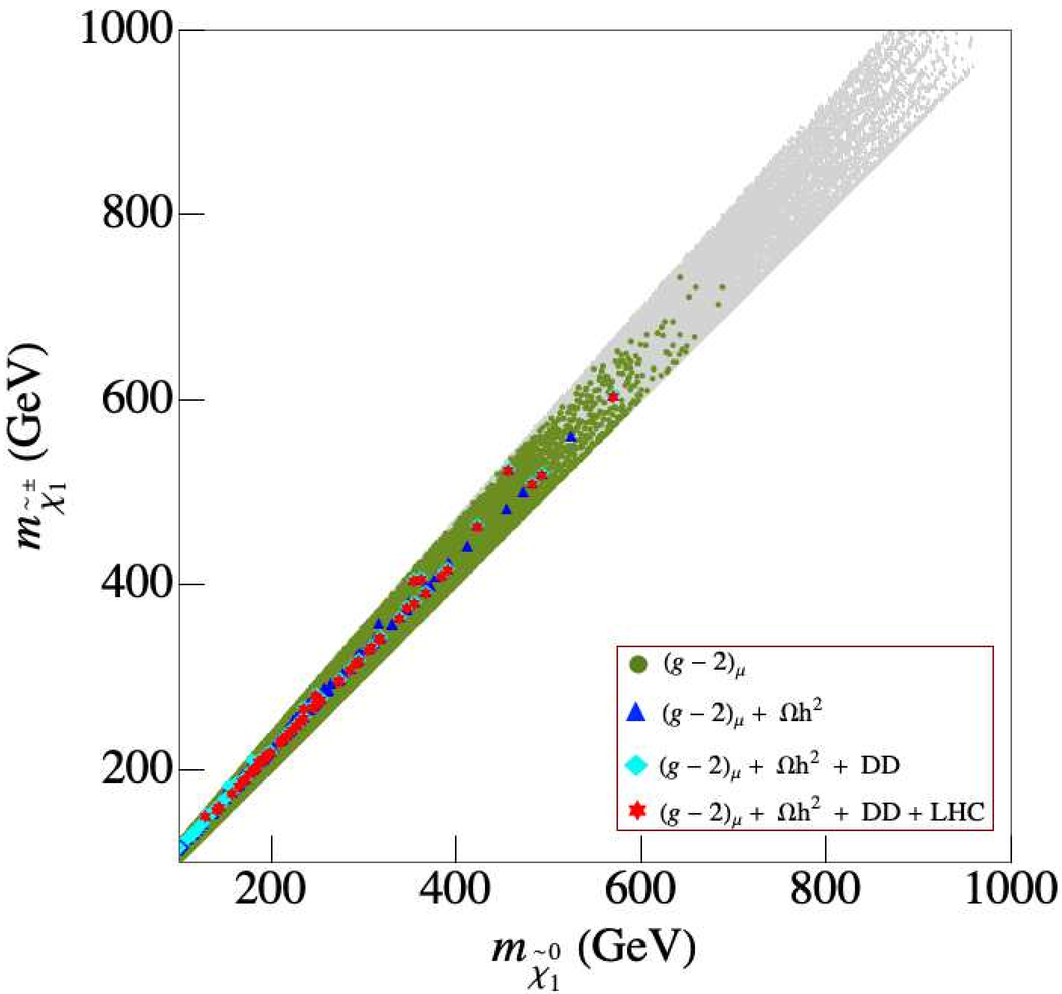
$$5 \leq \tan\beta \leq 60,$$

$$100\ \text{GeV} \leq m_{\tilde{L}} \leq 1\ \text{TeV},$$

$$m_{\tilde{R}} = m_{\tilde{L}}\ .$$

(latter condition only to make the analysis simpler, no relevant effect)

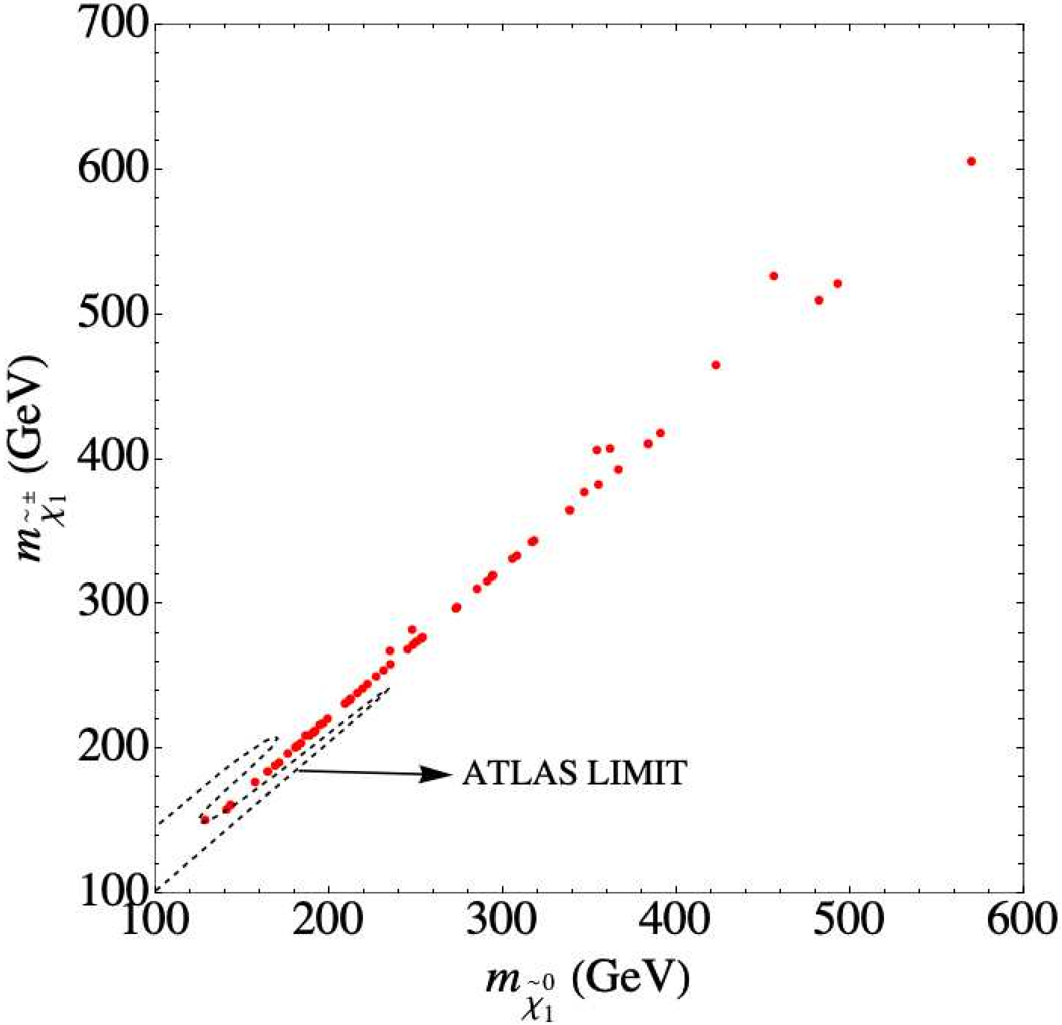
Results in the $m_{\tilde{\chi}_1^0}$-$m_{\tilde{\chi}_1^\pm}$ plane:



⇒ compressed spectrum as expected

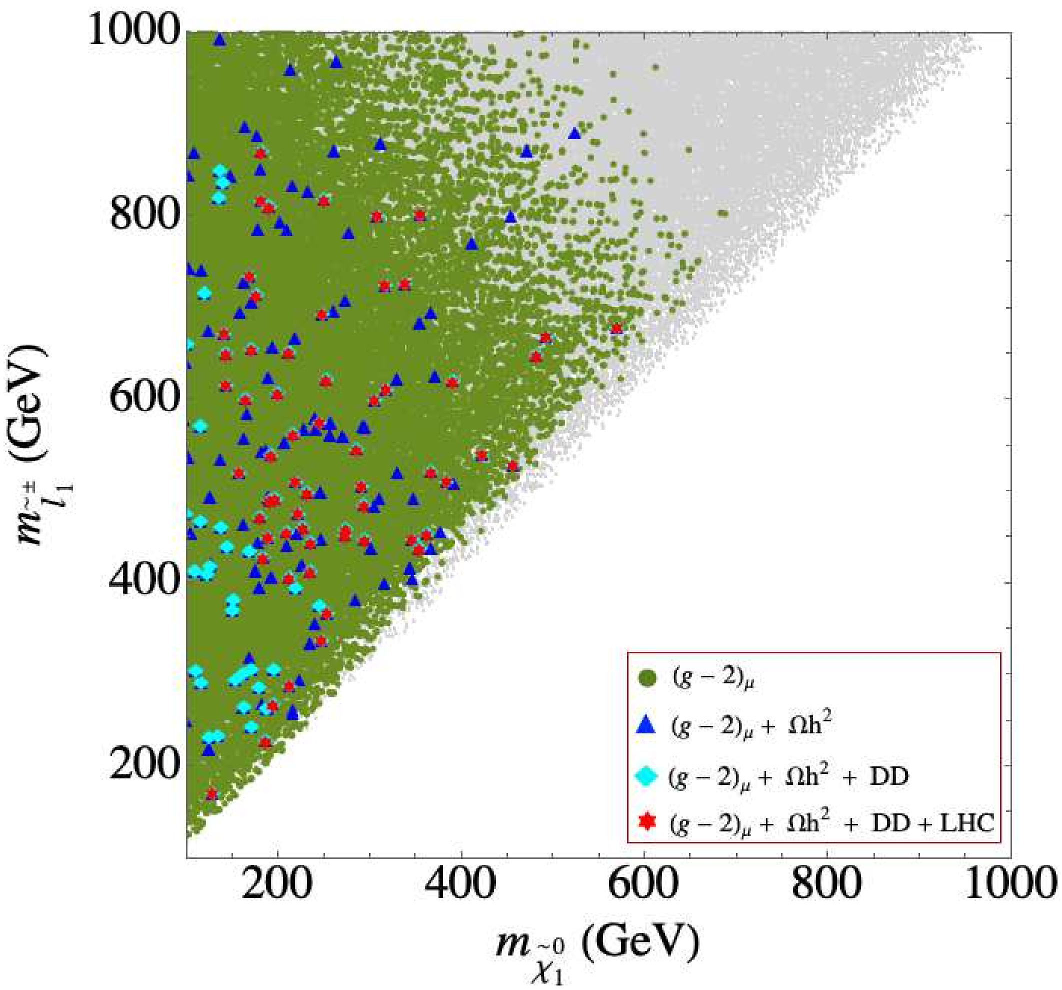
⇒ clear upper limits, $m_{(N)LSP} \lesssim 600$ GeV

Comparison with the compressed spectra searches:



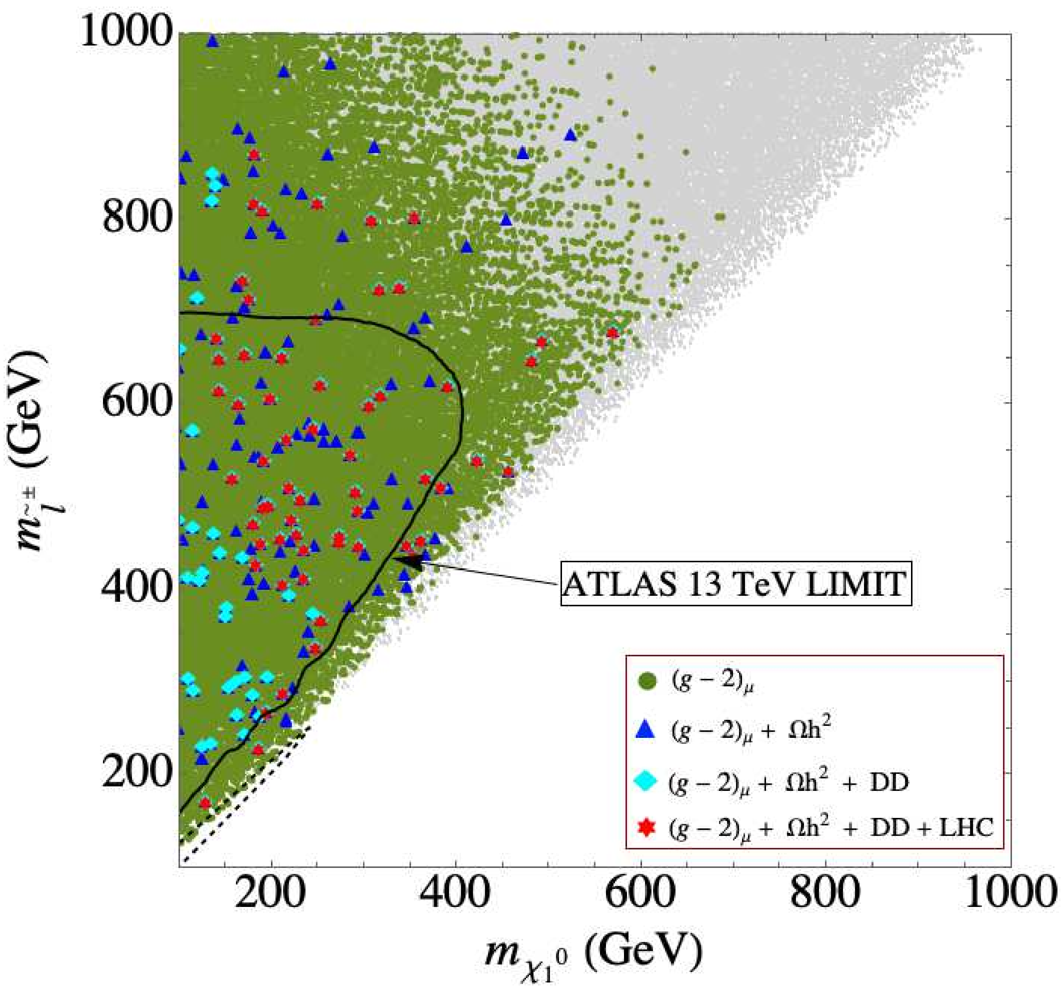
⇒ compressed spectrum avoids current bounds!

Results in the $m_{\tilde{\chi}_1^0}$-$m_{\tilde{l}_1}$ plane:



⇒ important: $\tilde{l}$-pair production searches (10)

Results in the $m_{\tilde{\chi}_1^0}$-$m_{\tilde{l}_1}$ plane:

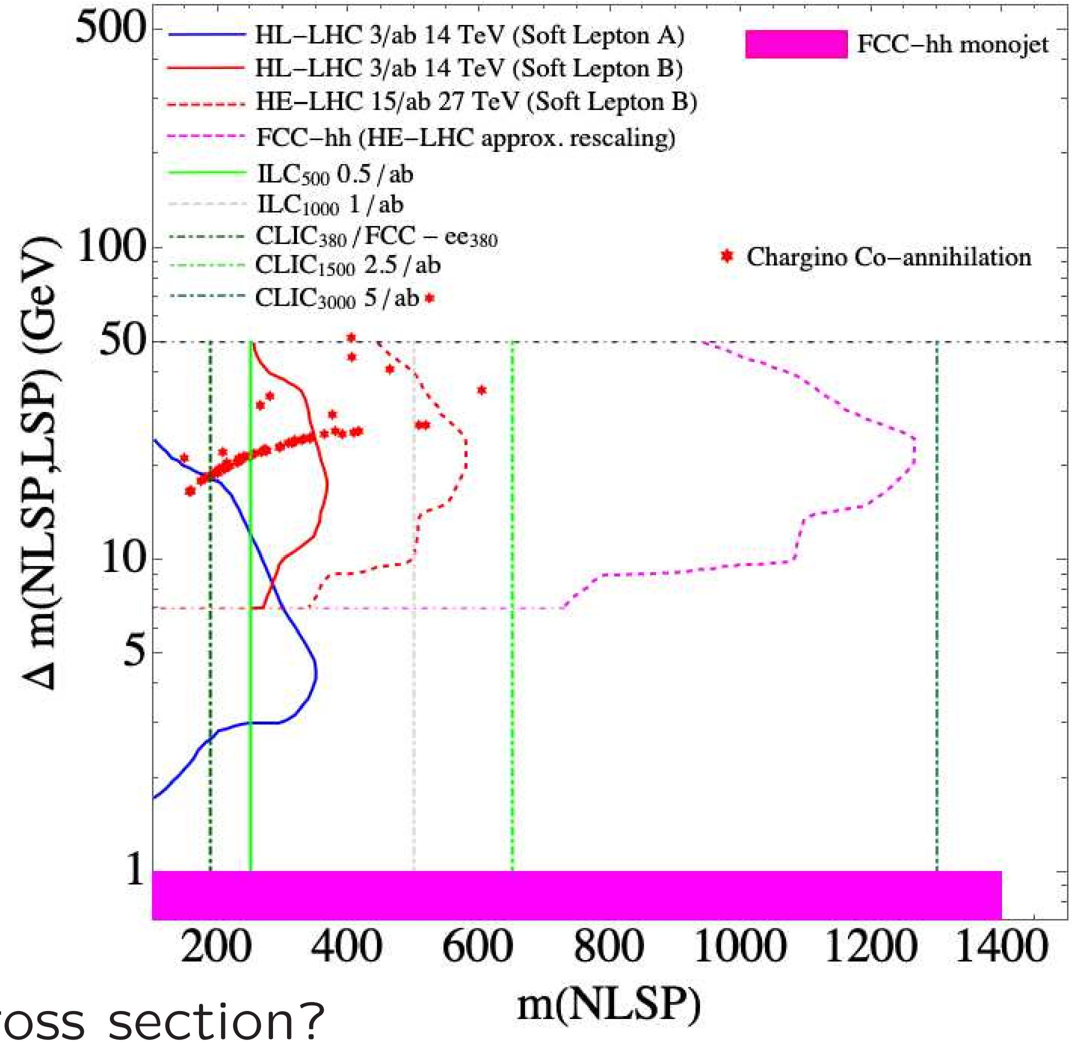


⇒ important: $\tilde{l}$-pair production searches (10)

⇒ naive application of LHC bounds fails

Future searches: available ONLY for higgsino LSP

⇒ naive inclusion of our points into the plot:



– scaling with cross section?

– possible problems?

– experimental projections for bino/wino/higgsino LSP?!

3. Some MasterCode experiences

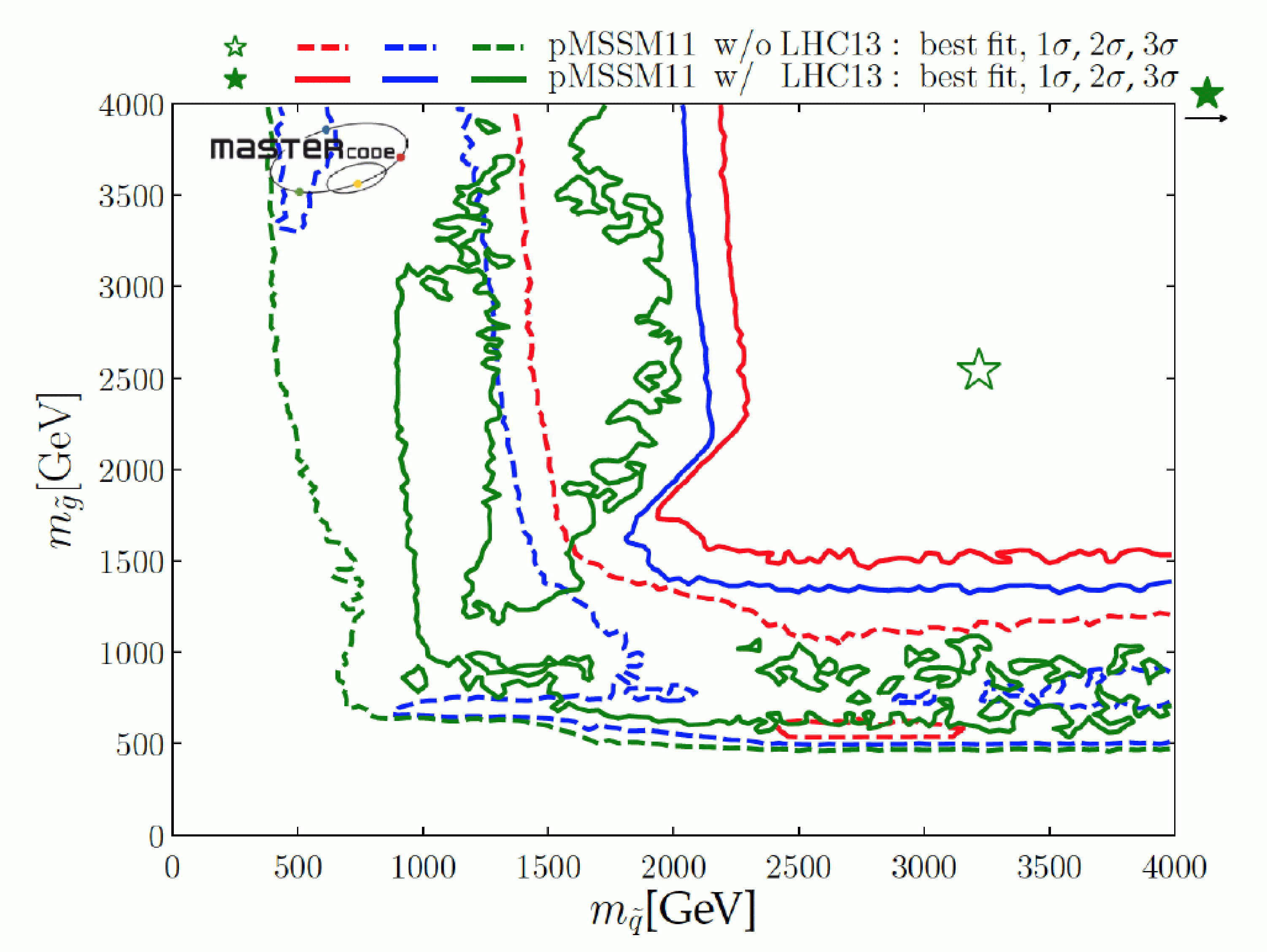
[2017]

Parameter	Range	# 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

$\Rightarrow$ I doubt that (many) more dimensions can reliably(!) be sampled

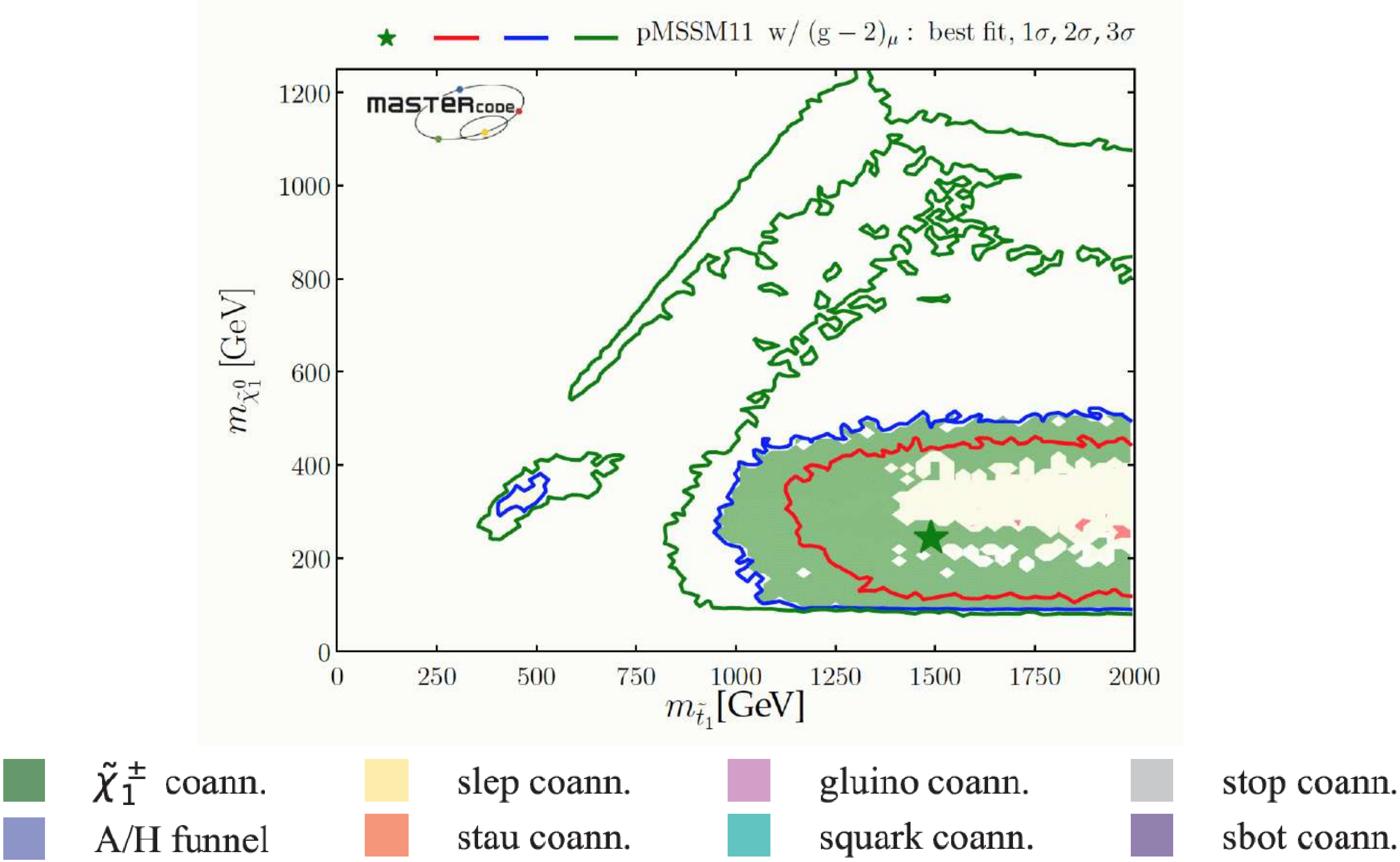
pMSSM11: Going from 8 TeV to 13 TeV (and adding latest DM limits)

[2017]



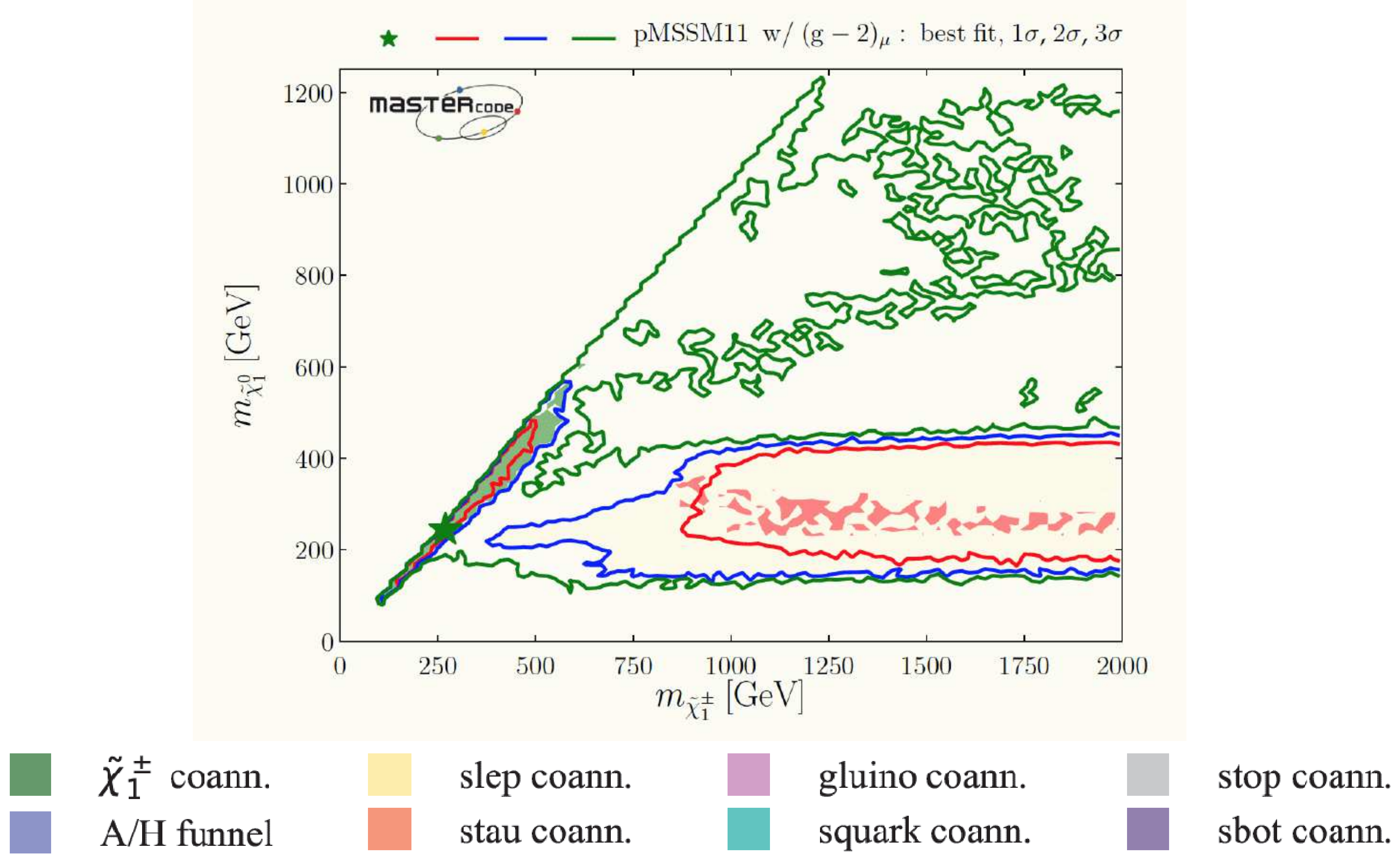
⇒ notice the "nose"! Do you have it?

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



⇒ notice the compressed region! Do you have it?

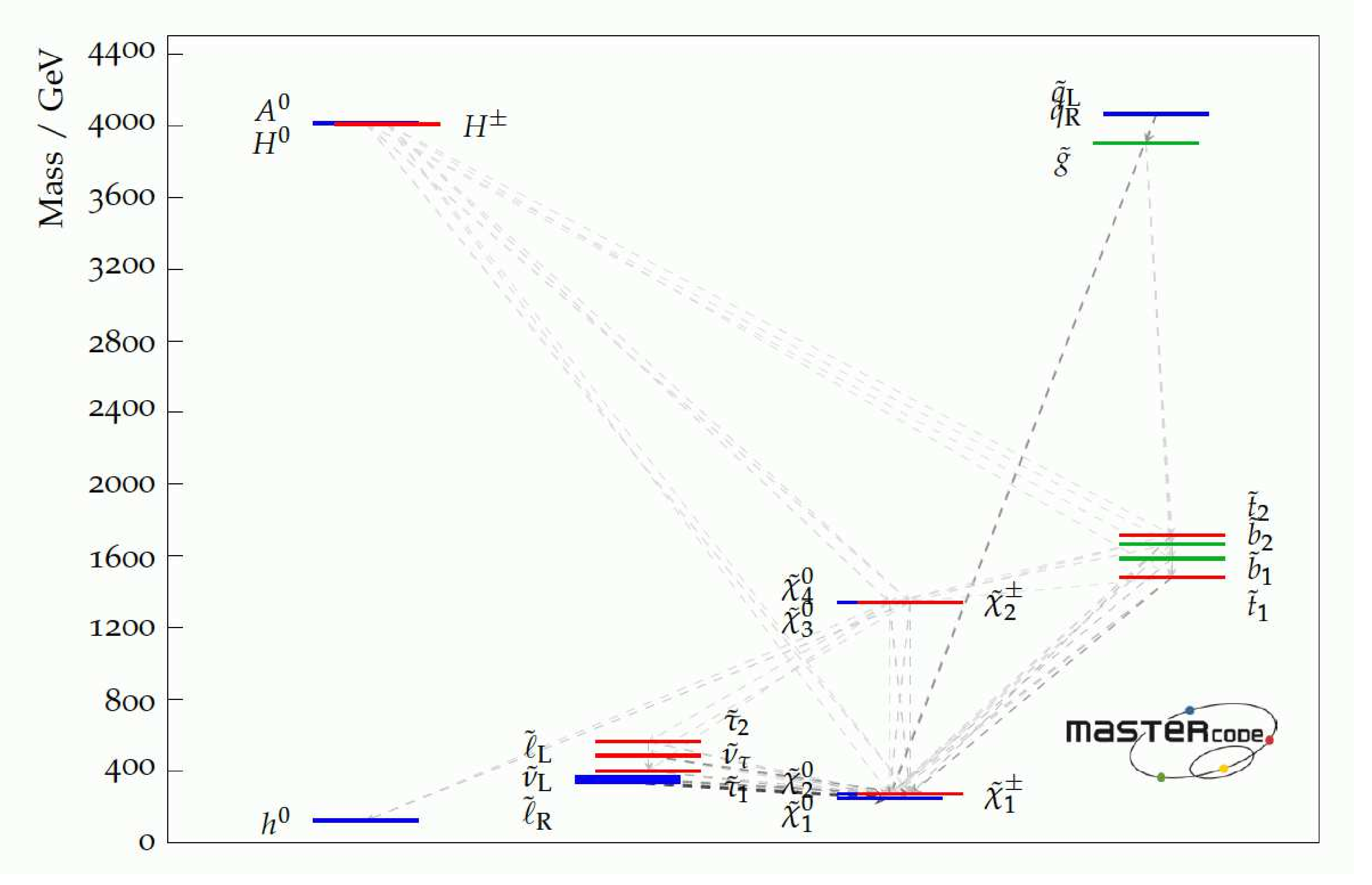
pMSSM11: $m_{\tilde{\chi}_1^\pm}$–$m_{\tilde{\chi}_1^0}$ plane



⇒ chargino co-annihilation ⇒ $M_1 \sim M_2$ Do you have it?

pMSSM11: best-fit point phenomenology

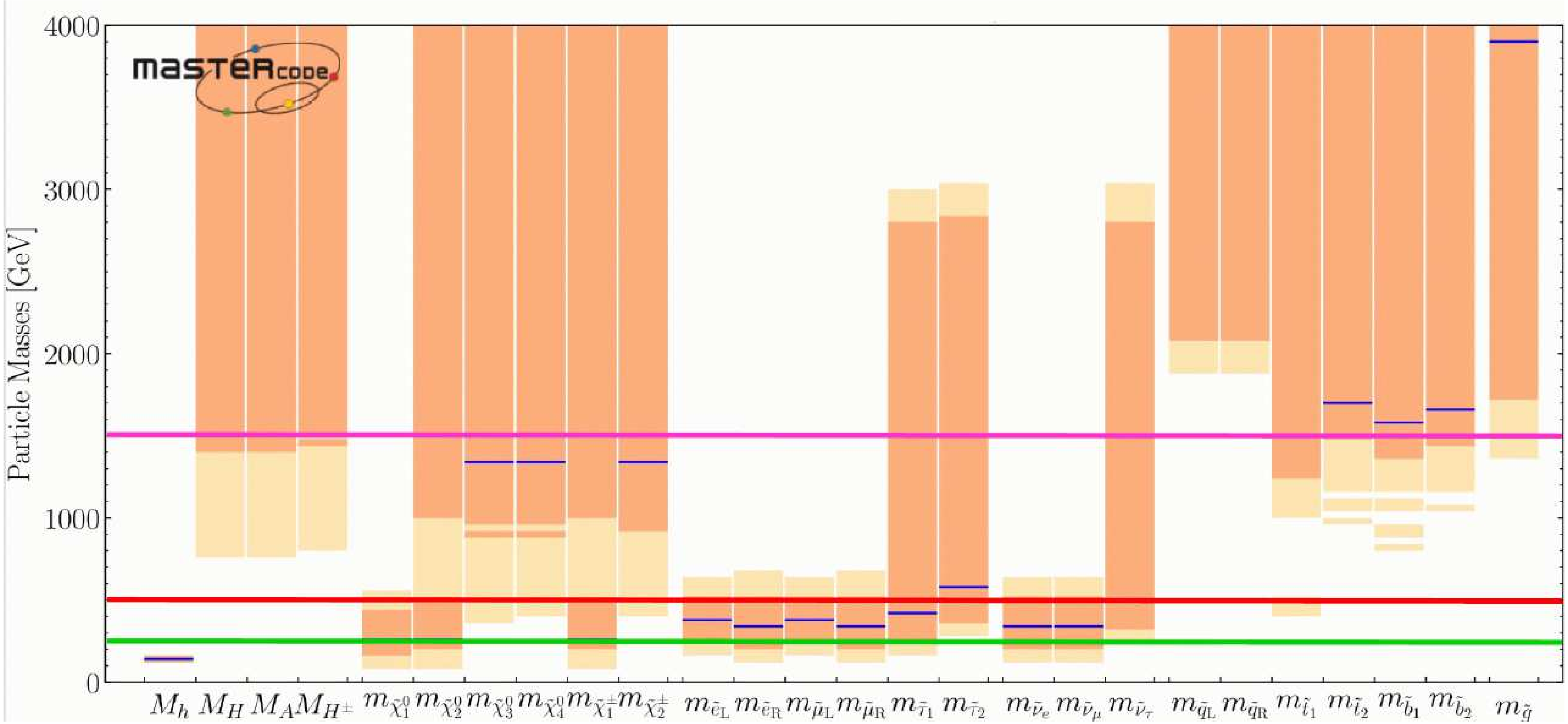
[2017]



⇒ heavy colored, light uncolored spectrum ⇒ effect of $(g-2)_\mu$

pMSSM11: full fit spectrum

[2017]



ILC: $\sqrt{s} = 500$ GeV ILC: $\sqrt{s} = 1000$ GeV CLIC: $\sqrt{s} = 3000$ GeV

LHC Run 3 reach?

HL-LHC reach?

How to evaluate?

4. Conclusinos

- pMSSM scan: THEO sees other problems/opportunities than EXP
- Higgs data: clarified / will be discussed later ⇒ talk by Jonas
- Electroweak precision observables: (FeynHiggs)
  - can be important for squarks, but also EWkinos
  - no public code, except for M_W
- Flavor observables: (SuperIso, . . .)
  - can be important for Higgs and/or SUSY partners
  - public codes exist / no improvement for the flavor anomalies
- The anomalous magnetic moment of the muon: (GM2Calc)
  - can set **upper** bounds on the EWkino mass scale
  - may be at $5\,\sigma$ in the near future
  - is fighting against (experimental) prejudice
- MasterCode results for the pMSSM11:
  - compressed spectra play a crucial role (squarks/LSP, stop/LSP, EWkinos/LSP)
  - clear effect of $(g-2)_\mu$
  - relatively easy: e^+e^- collider prospects
  - more complicted (how much?): HL-LHC prospects


Further Questions?

5. LHC rate measurements and BSM Higgs limits

HiggsBounds and HiggsSignals

Team: P. Bechtle, SH, T. Klingl, T. Stefaniak, G. Weiglein, J. Wittbrodt

HiggsBounds

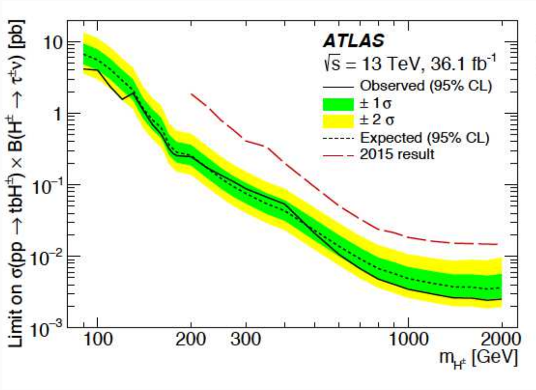
Confronts BSM Higgs sectors with exclusion limits from LEP, Tevatron and LHC Higgs searches.

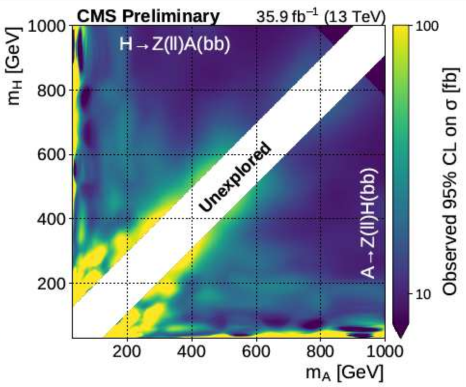
⇒ excluded/allowed at 95% C.L. ($\chi^2_{\tau\tau}$ ...)

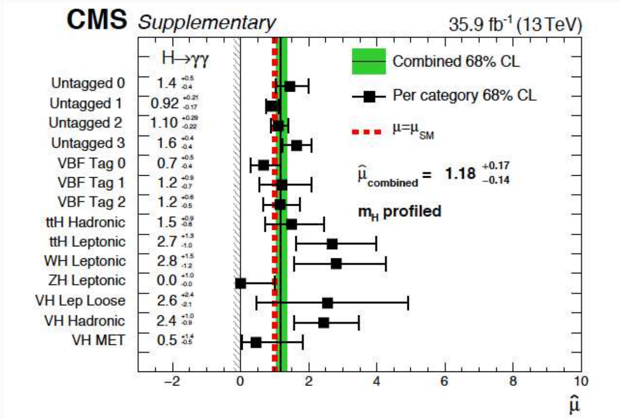
HiggsSignals

Confronts BSM Higgs sectors with LHC Higgs signal rate and mass measurements.

⇒ χ^2 (sep. for rates and mass)







Codes available at GitLab & hepforge.

Most important BSM Higgs searches for pMSSM scan:

$$pp \to H/A \to \tau^+\tau^-$$

ATLAS and CMS published $-2\ln\mathcal{L}$ values for 13 TeV
– ATLAS with full Run 2 data
– CMS (so far) for 36 fb^{-1}

Narrow resonance (ϕ) toy model in three dimensions: m_ϕ, $\sigma_{gg\phi}$, $\sigma_{bb\phi}$

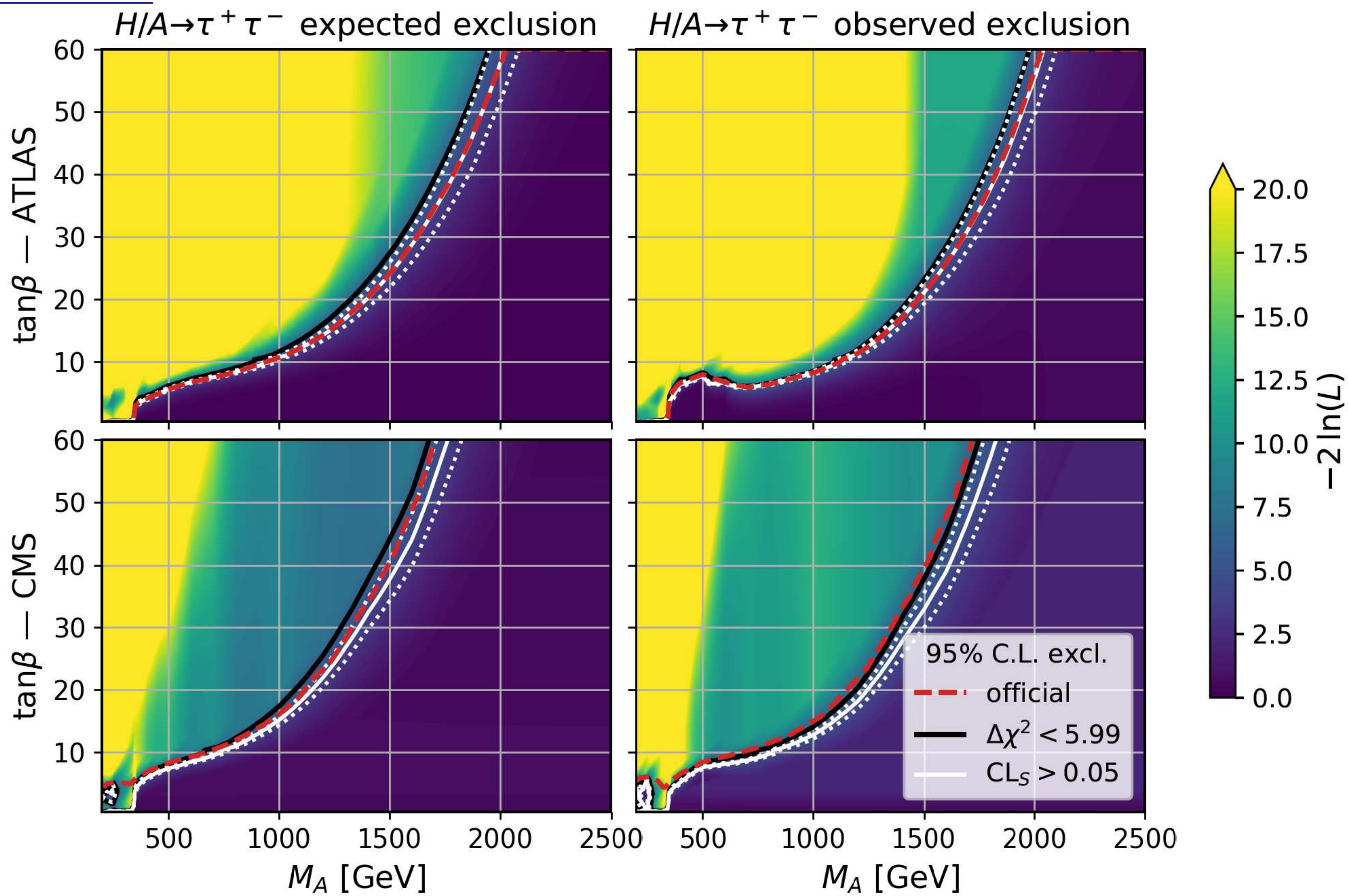
⇒ full $-2\ln\mathcal{L}$ result for many BSM models in HiggsBounds
via simple algorithm *[P. Bechtle, S.H., O. Stål, T. Stefaniak, G. Weiglein '15]*

⇒ re-interpretation in the MSSM possible

⇒ preferred over just a hard cut at 95% CL

Validation:

[*HiggsBounds 5 '20*]



⇒ $\chi^2(H/A \to \tau^+\tau^-)$ can reliably be used in the MSSM

HiggsSignals:

Is the h_{125} in agreement with the LHC rate measurements?

Included:

- 7, 8, 13 TeV data
- μ values
- STXS measurements
- correlations (where available)

$\Rightarrow$ overall χ^2 to all available channels

Validation:

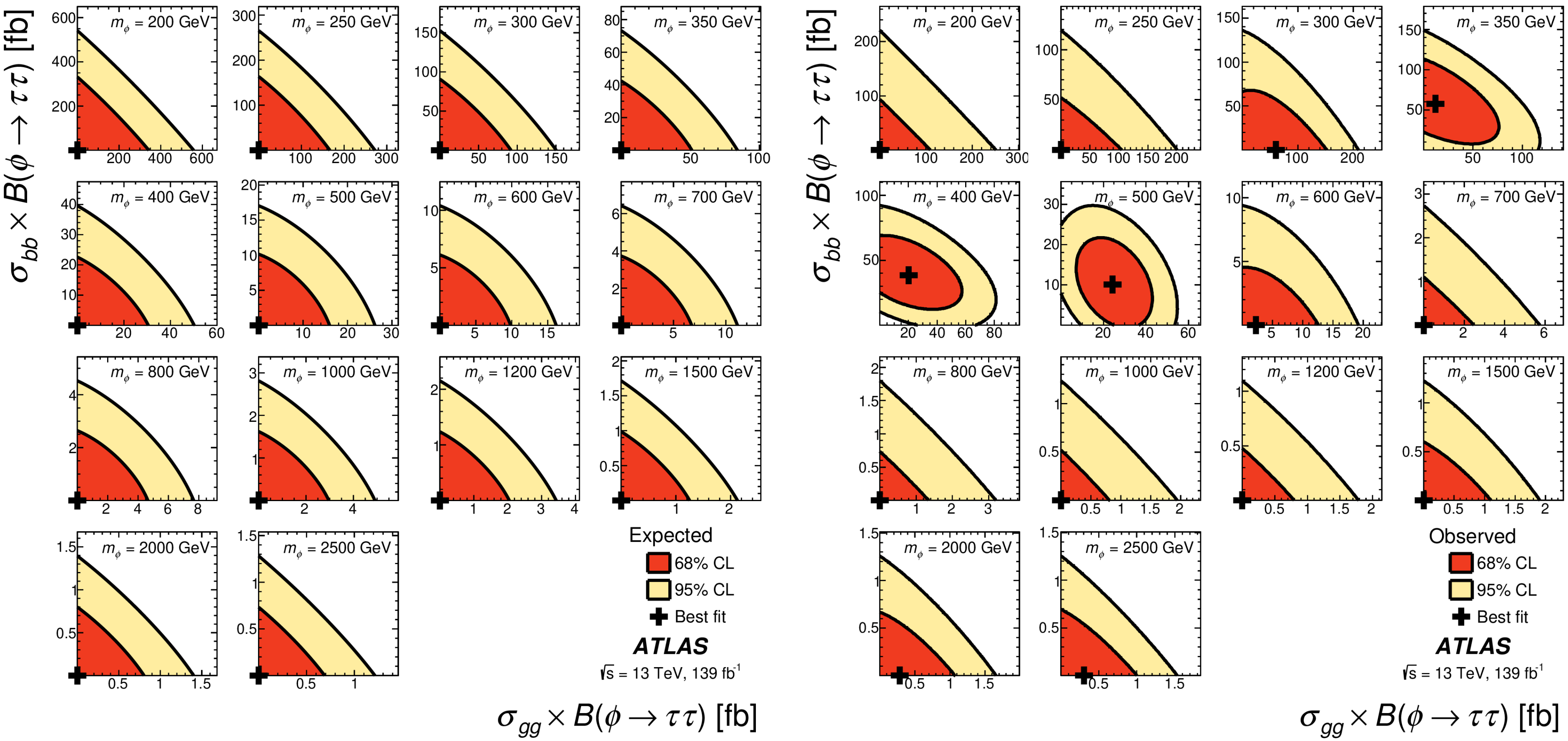
- 1-dim (μ, STXS)
- 2-dim κ-plots or μ-plots
- effect of correlations crucial

$\Rightarrow$ $\chi^2(h_{125})$ can reliably be used in the MSSM

Experimental data

[ATLAS '20]

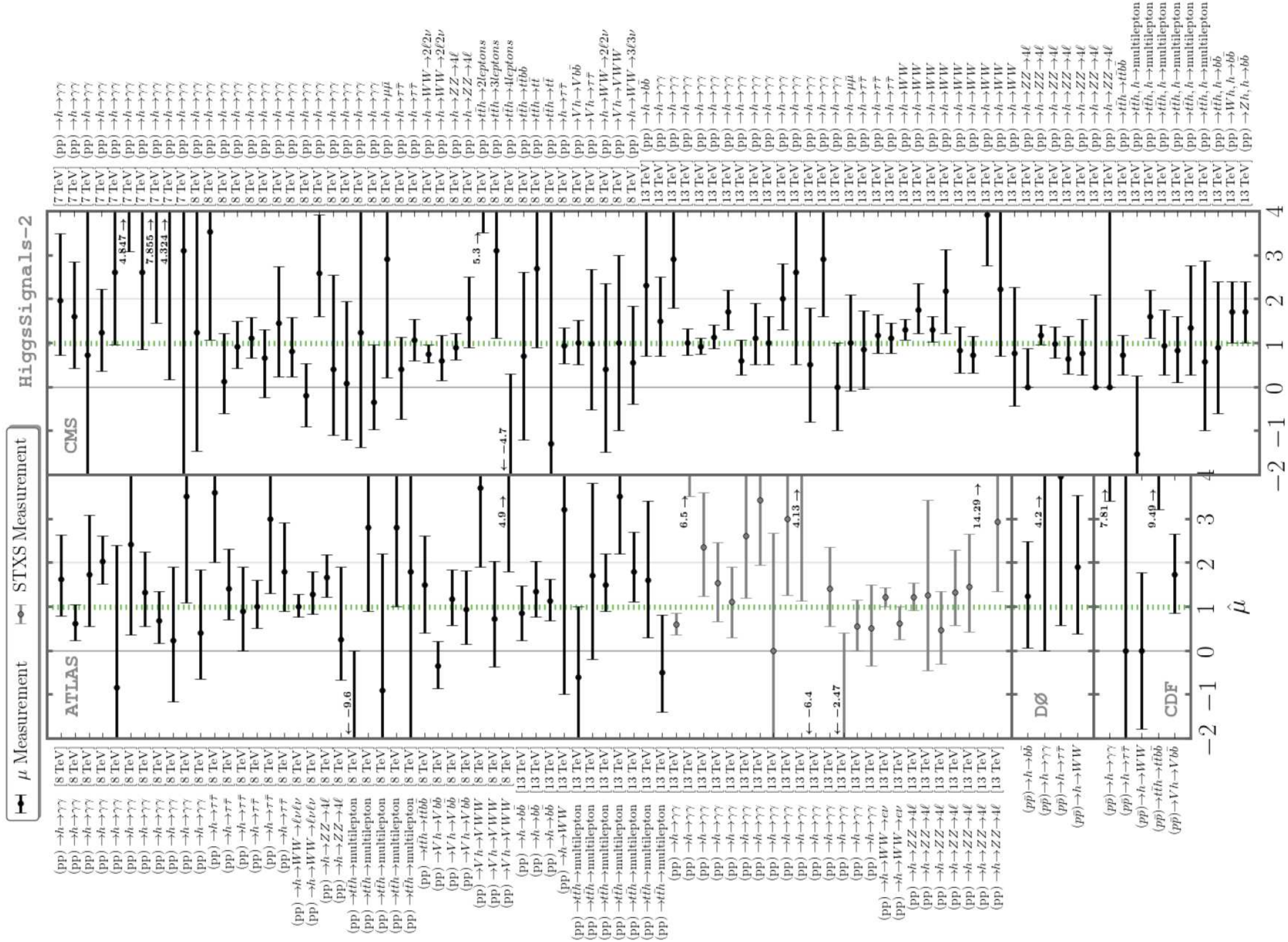
expected   observed



$\Rightarrow$ note the nice excess at $\sim$ 400 GeV :-)

All channels and their experimental input:

[*HiggsSignals 2 '20*]



Experimental constraints for $(g-2)_\mu$

LHC searches:

Decay via sleptons (3l)

$$\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \to (\tilde{l}^\pm \nu)(\tilde{l}^+ l^-) \to 3l + \not{E}_T \ ,$$
$$\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \to (l^\pm \tilde{\nu})(\tilde{l}^+ l^-) \to 3l + \not{E}_T \qquad (5)$$

Decay via sleptons (2l)

$$\tilde{\chi}_1^+ \tilde{\chi}_1^- \to (\tilde{l}^+ \nu)(\tilde{l}^- \nu) \to 2l + \not{E}_T \ ,$$
$$\tilde{\chi}_1^+ \tilde{\chi}_1^- \to (l^+ \tilde{\nu})(l^- \tilde{\nu}) \to 2l + \not{E}_T \qquad (6)$$

Decay via gauge bosons

$$\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \to (W \tilde{\chi}_1^0)(Z \tilde{\chi}_1^0) \to 3l + \not{E}_T \ , \qquad (7a)$$
$$\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \to (W \tilde{\chi}_1^0)(Z \tilde{\chi}_1^0) \to 2l + \text{jets} + \not{E}_T \ , \qquad (7b)$$
$$\tilde{\chi}_1^+ \tilde{\chi}_1^- \to (W^+ \tilde{\chi}_1^0)(W^- \tilde{\chi}_1^0) \to 2l + \not{E}_T \qquad (8)$$

Decay via Higgs bosons

$$\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \to (W \tilde{\chi}_1^0)(h \tilde{\chi}_1^0) \to l + b\bar{b} + \not{E}_T \qquad (9)$$

$\tilde{l}$-pair production (2l)

$$\tilde{l}^+ \tilde{l}^- \to (l^+ \tilde{\chi}_1^0)(l^- \tilde{\chi}_1^0) \to 2l + \not{E}_T \qquad (10)$$

Compressed spectra

$$\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \to (W^* \tilde{\chi}_1^0)(Z^* \tilde{\chi}_1^0) \to 2l + \not{E}_T \; + \text{ISR} \; , \qquad (11)$$

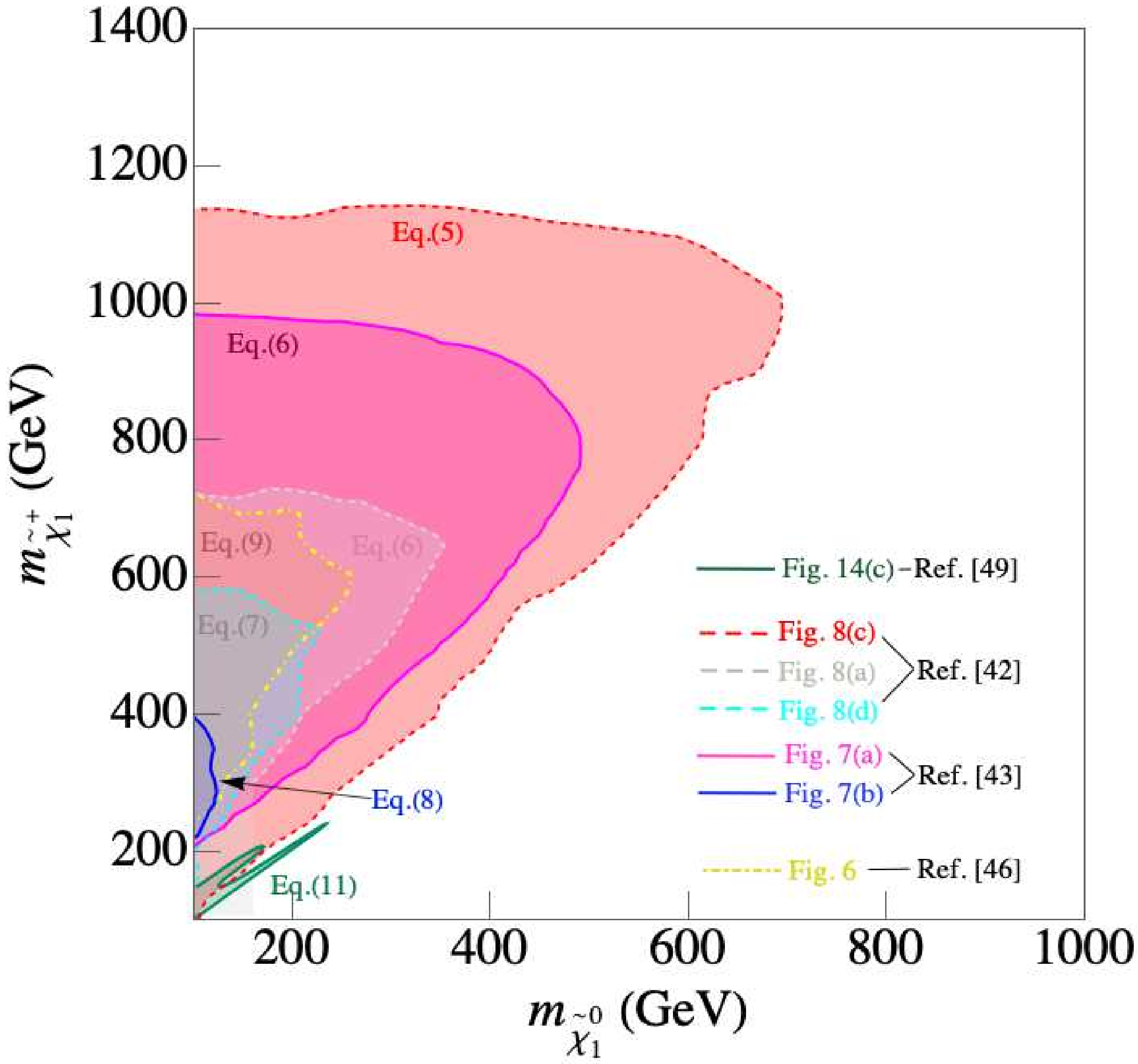
$$\tilde{l}^+ \tilde{l}^- \to (l^+ \tilde{\chi}_1^0)(l^- \tilde{\chi}_1^0) \to 2l + \not{E}_T \; + \text{ISR} \qquad (12)$$

Searches involving Staus

$\Rightarrow$ all newly included into CheckMate

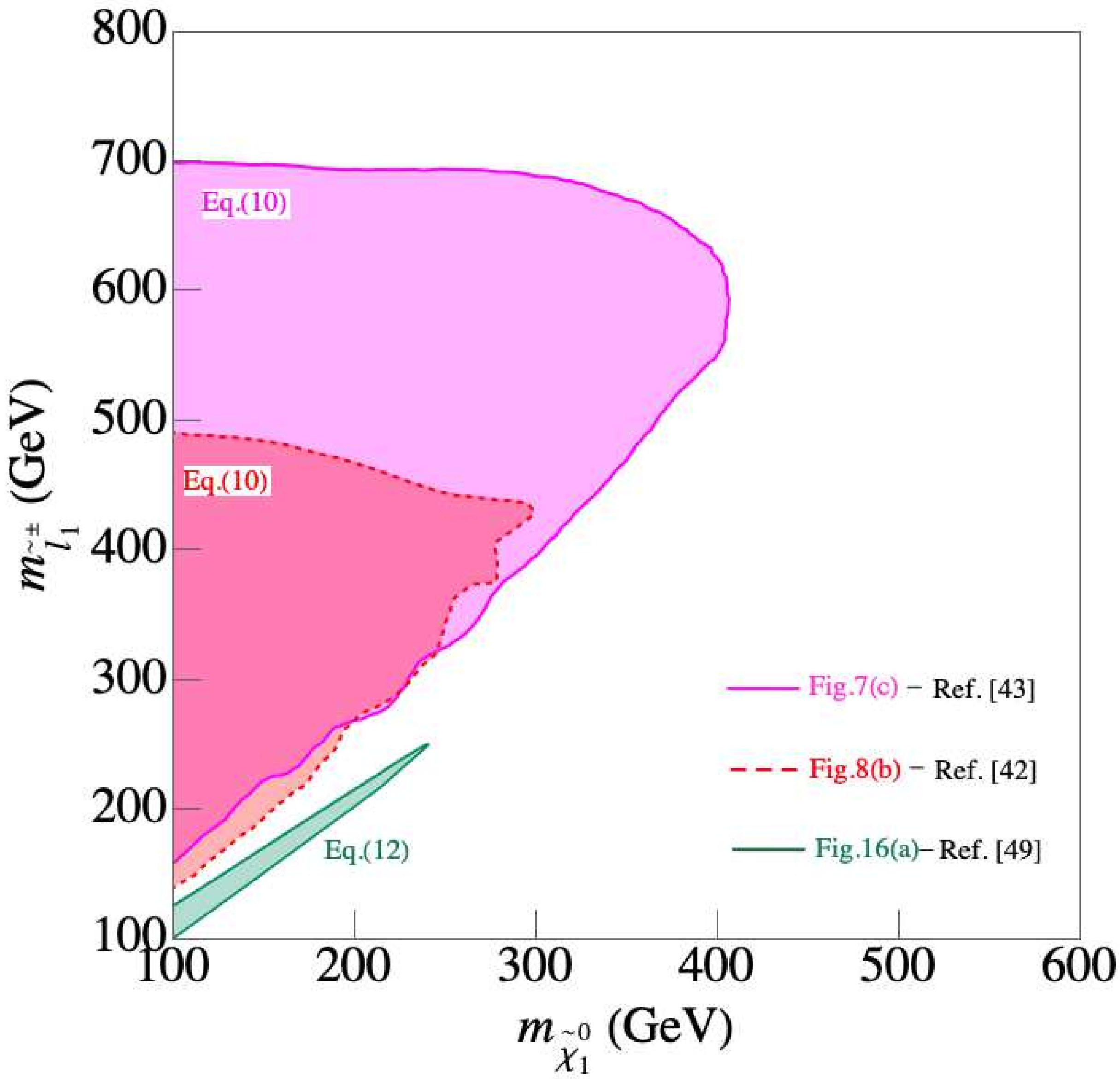
Exception: compressed spectra $\Rightarrow$ direct application

LHC exclusion bounds (I)



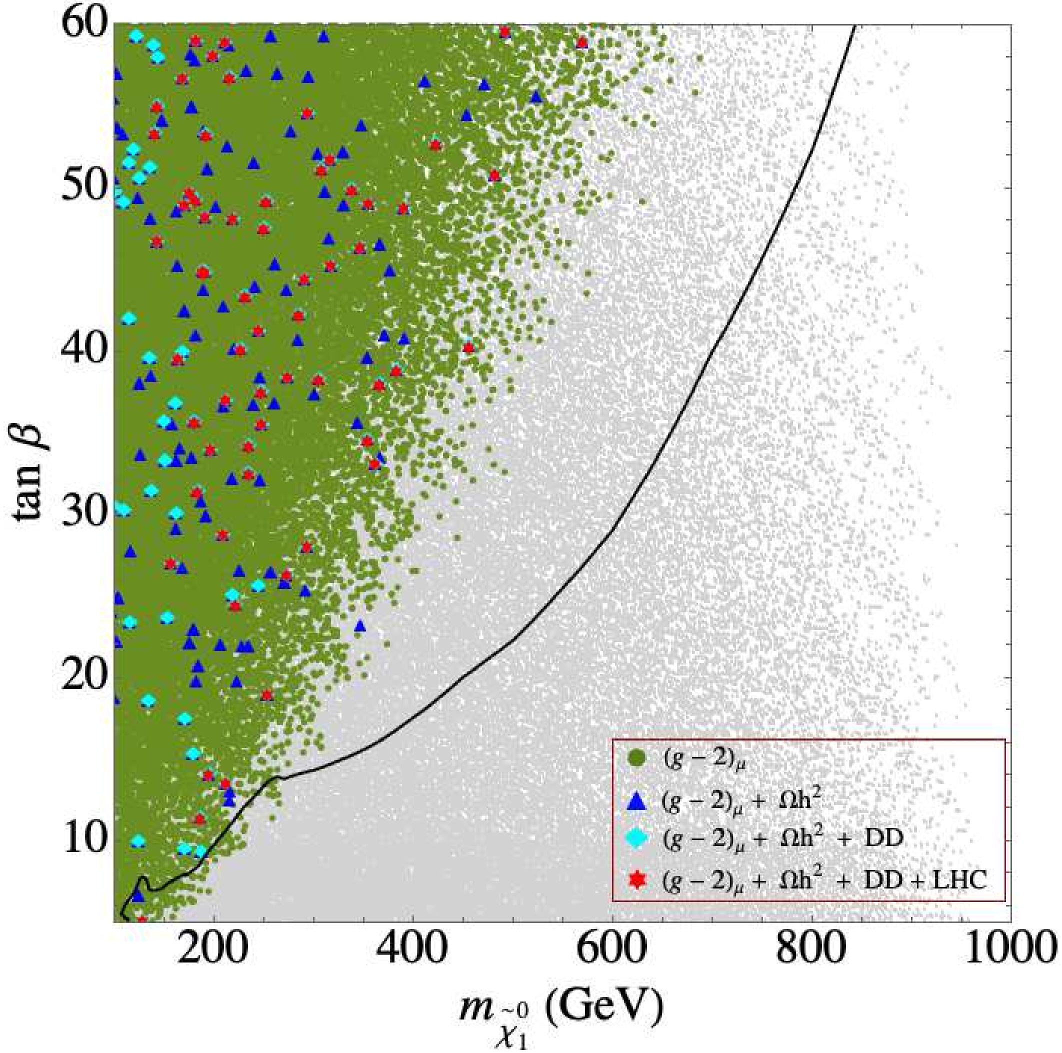
$\Rightarrow$ crucial to take latest bounds into account

LHC exclusion bounds (II)



⇒ crucial to take latest bounds into account

Results in the $m_{\tilde{\chi}_1^0}$-$\tan\beta$ plane:



black contour: (simplified) application of $H/A \to \tau^+\tau^-$

$\Rightarrow$ A-pole annihilation effectively excluded

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! $\Rightarrow$ Much better than in GUT based models!