"Tell me that you have found no sign of New Physics again, I dare you. I double dare you. Tell me one more goddamn time!"

Electroweak Precision Observables and BSM Physics

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virtual only, 07/2020

1. Introduction: Electroweak Precision Observables
2. EWPOs in concrete BSM theories
3. Why not (only) EFT?
4. Conclusions

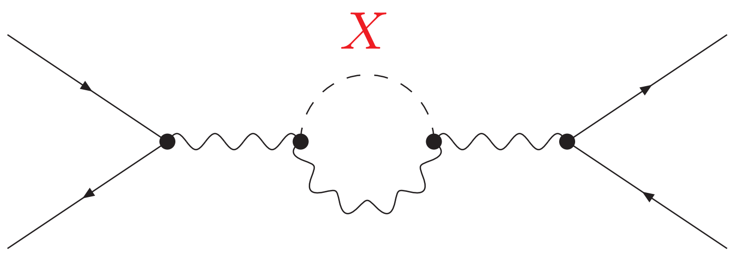
1. Introduction: Electroweak Precision Observables

Comparison of observables with theory:

Precision data:		Theory:
$M_W, \sin^2\theta_{\rm eff}, a_\mu, M_h$	$\leftrightarrow$	SM, BSM , EFT?

$\Downarrow$

Test of theory at quantum level: Sensitivity to loop corrections, e.g. X



$\Downarrow$

SM: limits on M_H, BSM: limits on M_X

Very high accuracy of measurements and theoretical predictions needed
$\Rightarrow$ only models "ready" so far: SM, MSSM and maybe pure Higgs extensions

The "classical" EWPO:

M_W (best from e^+e^- threshold scan)

$$\sigma^0_{\text{had}} = \sum_q \sigma_q(M_Z^2),$$

$$\Gamma_Z = \sum_f \Gamma[Z \to f\bar{f}],$$ (from a fit to $\sigma_f(s)$ at various values of s)

$$R_\ell = \left[\sum_q \sigma_q(M_Z^2)\right] / \sigma_\ell(M_Z^2), \qquad (\ell = e, \mu, \tau)$$

$$R_q = \sigma_q(M_Z^2) / \left[\sum_q \sigma_q(M_Z^2)\right], \qquad (q = b, c)$$

$$A^f_{\text{FB}} = \frac{\sigma_f(\theta < \frac{\pi}{2}) - \sigma_f(\theta > \frac{\pi}{2})}{\sigma_f(\theta < \frac{\pi}{2}) + \sigma_f(\theta > \frac{\pi}{2})} \equiv \frac{3}{4}\mathcal{A}_e\mathcal{A}_f,$$

$$A^f_{\text{LR}} = \frac{\sigma_f(P_e < 0) - \sigma_f(P_e > 0)}{\sigma_f(P_e < 0) + \sigma_f(P_e > 0)} \equiv \mathcal{A}_e|P_e|$$

$$\mathcal{A}_f = 2\frac{g_{V_f}/g_{A_f}}{1 + (g_{V_f}/g_{A_f})^2} = \frac{1 - 4|Q_f|\sin^2\theta^f_{\text{eff}}}{1 - 4|Q_f|\sin^2\theta^f_{\text{eff}} + 8(|Q_f|\sin^2\theta^f_{\text{eff}})^2} \quad (f = \ell, b, \ldots)$$

More "possible" EWPO:

- the anomalous magnetic moment of the muon: a_μ

- Higgs boson masses $\sim$ 125 GeV
  $\Rightarrow$ if M_h is not a free parameter
  Challenge: before the end of this talk think of a non-SUSY BSM theory that predicts M_h!

- new couplings between SM and BSM

- . . .

$\Rightarrow$ focus here mostly on the "classical" EWPO

Evaluation of “classical” EWPO in the SM (and BSM)

A) Theoretical prediction for M_W in terms

of $M_Z, \alpha, G_\mu, \Delta r$:

$$M_W^2 \left(1 - \frac{M_W^2}{M_Z^2}\right) = \frac{\pi\,\alpha}{\sqrt{2}\,G_\mu}(1 + \Delta r)$$

$\Updownarrow$

loop corrections

Evaluate Δr from μ decay $\Rightarrow M_W$

One-loop result for M_W in the SM:

[*A. Sirlin '80*] , [*W. Marciano, A. Sirlin '80*]

$$\Delta r_{1-\text{loop}} = \Delta\alpha - \frac{c_W^2}{s_W^2}\Delta\rho + \Delta r_{\text{rem}}(M_H)$$

$$\sim \log\frac{M_Z}{m_f} \qquad \sim m_t^2 \qquad \log(M_H/M_W)$$

$$\sim 6\% \qquad \sim 3.3\% \qquad \sim 1\%$$

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$\Updownarrow$

loop corrections

B) Effective mixing angle:

$$\sin^2 \theta_{\text{eff}} = \frac{1}{4\,|Q_f|} \left(1 - \frac{\text{Re}\, g_V^f}{\text{Re}\, g_A^f}\right)$$

Higher order contributions:

$$g_V^f \to g_V^f + \Delta g_V^f, \quad g_A^f \to g_A^f + \Delta g_A^f$$

2. EWPOs in concrete BSM models

The by far best worked out model: SM

Intrinsic uncertainties:

Quantity	current experimental unc.	current intrinsic unc.
M_W [MeV]	12	4 $(\alpha^3, \alpha^2\alpha_s)$
$\sin^2\theta^\ell_{\text{eff}}$ [10^{-5}]	16	4.5 $(\alpha^3, \alpha^2\alpha_s)$
Γ_Z [MeV]	2.3	0.5 $(\alpha^3, \alpha^2\alpha_s, \alpha\alpha_s^2)$
R_b [10^{-5}]	66	15 $(\alpha^3, \alpha^2\alpha_s)$
R_l [10^{-3}]	25	5 $(\alpha^3, \alpha^2\alpha_s)$

Parametric uncertainties:

Quantity	$\delta m_t = 0.9$ GeV	$\delta(\Delta\alpha_{\text{had}}) = 10^{-4}$	$\delta M_Z = 2.1$ MeV
δM_W^{para} [MeV]	5.5	2	2.5
$\delta \sin^2\theta^{\ell,\text{para}}_{\text{eff}}$ [10^{-5}]	3.0	3.6	1.4

$\Rightarrow$ Current intrinsic/parametric uncertainties are substantially smaller than current experimental uncertainties :-) in the SM!

Which BSM theories have been sufficiently worked out?

What means "sufficiently"?

– several/all EWPOs are available at full 1-loop
– at best: leading 2-loop
– uncertainty estimate available

MSSM: all EWPO at full 1-loop, $\Delta\rho$ 2-loop: $\Delta\rho^{\alpha\alpha_s}$, $\Delta\rho^{\alpha_t^2,\alpha_t\alpha_b,\alpha_b^2}$
rough uncertainty estimate available

NMSSM: only M_W, $\Delta\rho^{\text{1-loop}}$, $\Delta\rho^{\alpha\alpha_s}$, no uncertainty estimate

xSM: only S, T, U at 1-loop, no uncertainty estimate

2HDMs: only S, T, U at 1-loop, T at 2-loop, no uncertainty estimate

$\Rightarrow$ better overview necessary! $\Rightarrow$ Snowmass 2021?

Pure Higgs sector extensions:
S, T, U probably sufficient, still uncertainty estimate needed

⇒ better overview necessary! ⇒ Snowmass 2021? (my EF04 LoI :-)

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– What BSM models have been worked out?

– . . . and to what extent?

– Uncertainty estimate?

– What has to be calculated to have them "sufficiently" under control?
(. . . any volunteers? :-)

– Any possible predictions about other parts of the BSM spectrum?

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– What BSM models have been worked out?

– ... and to what extent?

– Uncertainty estimate?

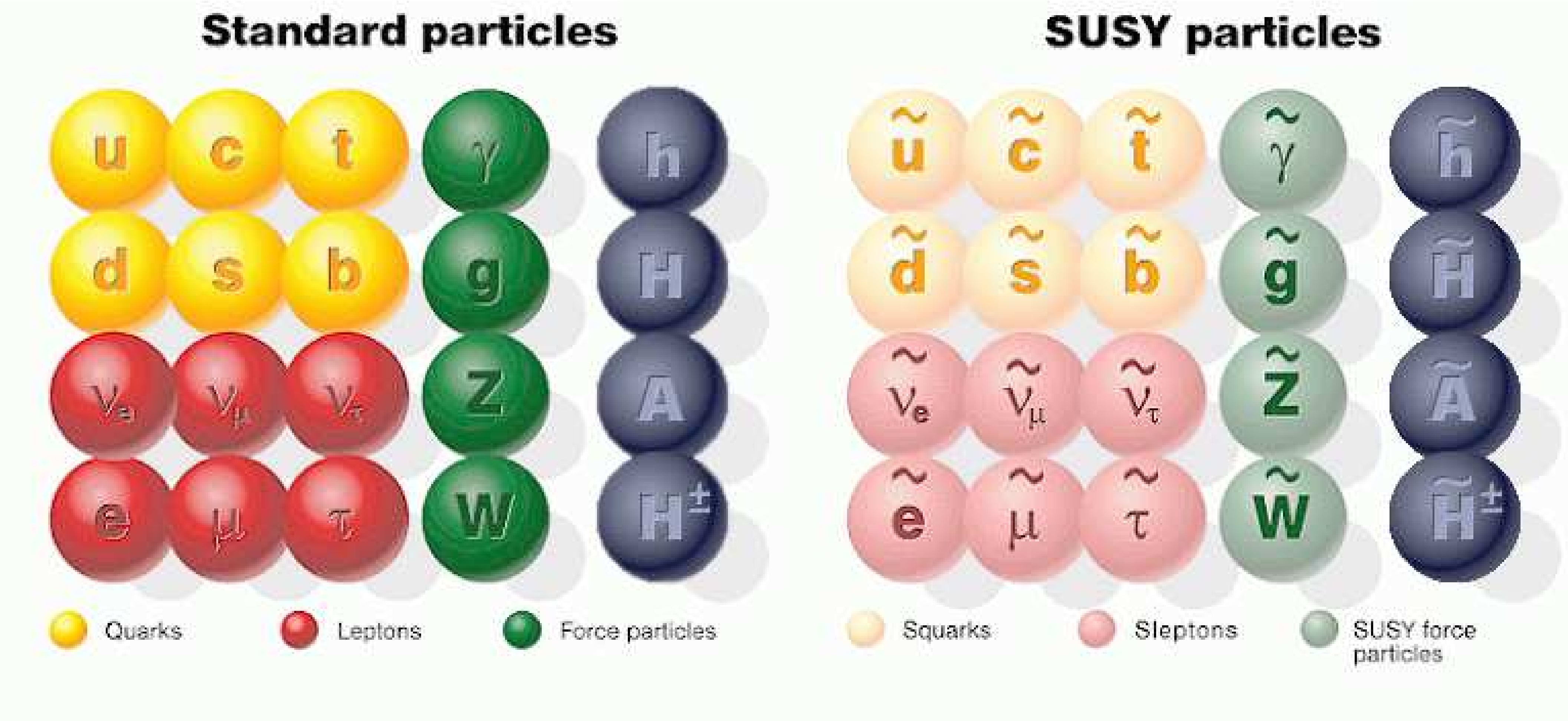
– What has to be calculated to have them "sufficiently" under control?
(... any volunteers? :-)

– Any possible predictions about other parts of the BSM spectrum?

– Are there some clear patterns arising?
... that can be compared to future data?

EWPOs in the MSSM

Superpartners for Standard Model particles



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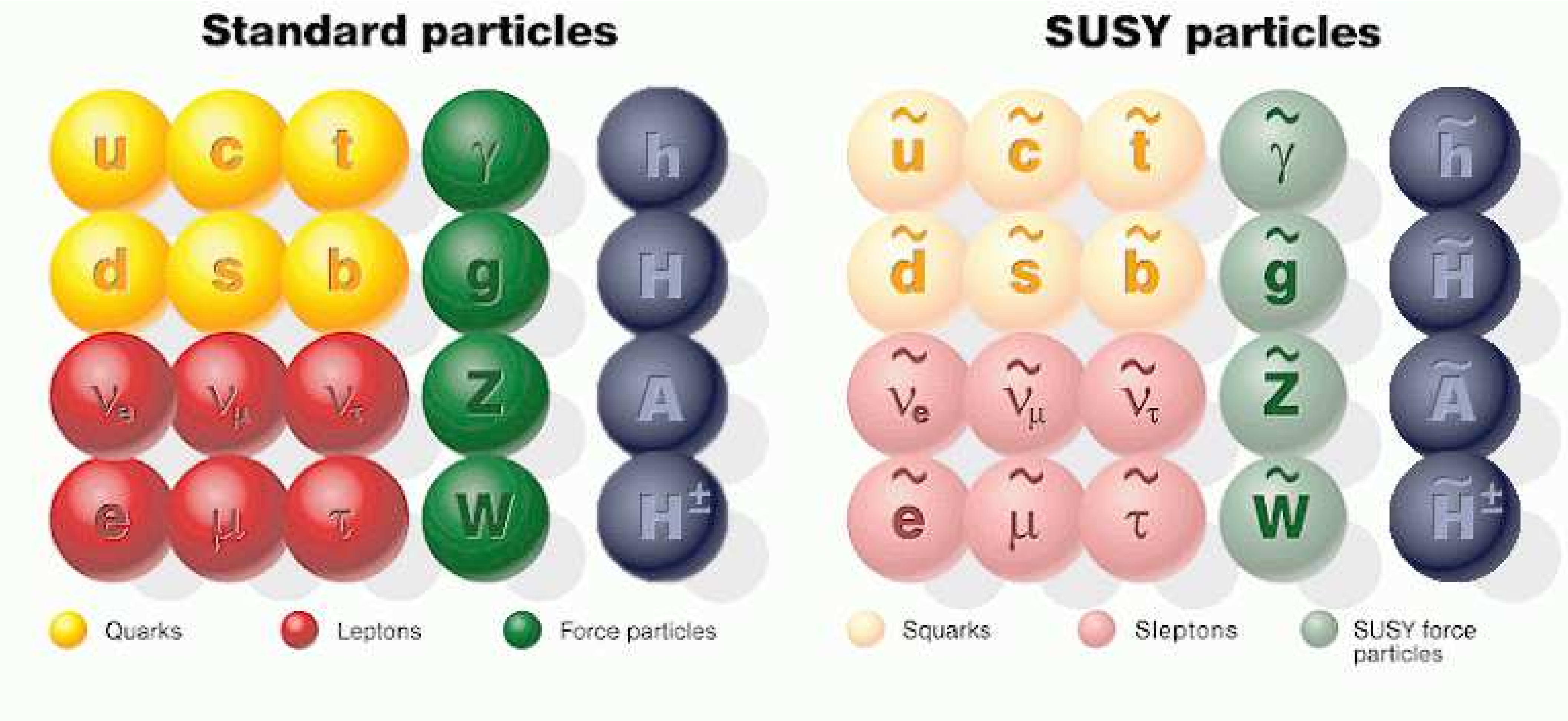
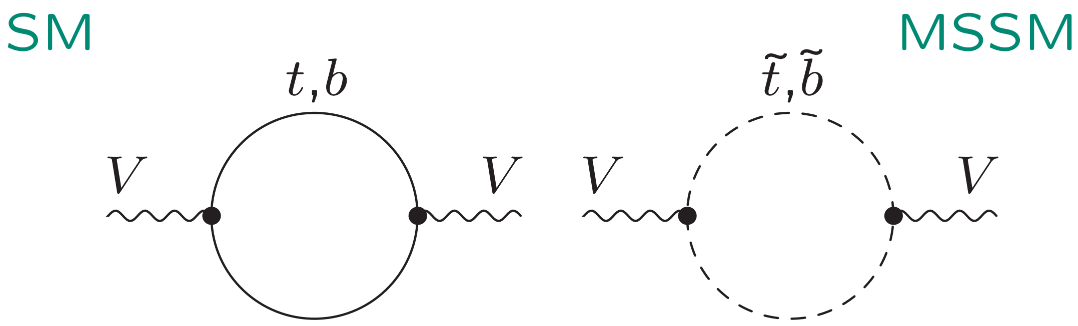


Repeat the following excercises in your favorite BSM theory!

Differences between the MSSM and the SM:

1.) New contributions from SUSY particles:



2.) CPV effects via new CPV phases

3.) large Yukawa corrections: $\sim m_t^4 \log \left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} \right)$

4.) large corrections from the $b/\tilde{b}$ sector for large $\tan\beta$

5.) non-decoupling SUSY effects: $\sim \log \frac{M_{\text{SUSY}}}{M_W}$

Corrections to M_W, $\sin^2\theta_{\rm eff}$ → approximation via the ρ-parameter:

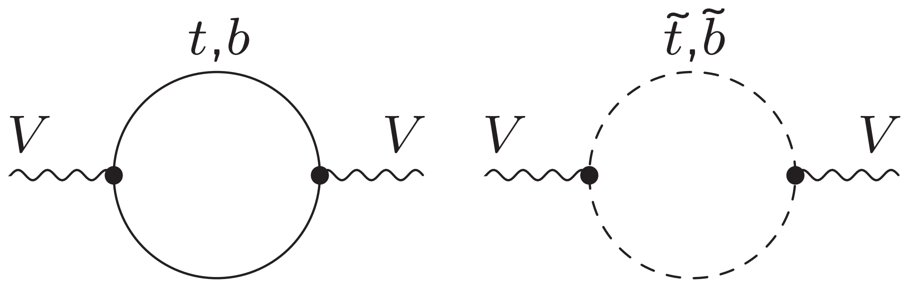
ρ measures the relative strength between
neutral current interaction and charged current interaction

$$\rho = \frac{1}{1 - \Delta\rho} \qquad \Delta\rho = \frac{\Sigma_Z(0)}{M_Z^2} - \frac{\Sigma_W(0)}{M_W^2}$$

(leading, process independent terms)

$\Delta\rho$ gives the main contribution to EW observables:

$$\Delta M_W \approx \frac{M_W}{2}\frac{c_{\rm W}^2}{c_{\rm W}^2 - s_{\rm W}^2}\Delta\rho, \qquad \Delta\sin^2\theta_W^{\rm eff} \approx -\frac{c_{\rm W}^2 s_{\rm W}^2}{c_{\rm W}^2 - s_{\rm W}^2}\Delta\rho$$



$\Delta\rho^{\rm SUSY}$ from $\tilde{t}/\tilde{b}$ loops > 0 $\Rightarrow M_W^{\rm SUSY} \gtrsim M_W^{\rm SM}$, $\sin^2\theta_{\rm eff}^{\rm SUSY} \lesssim \sin^2\theta_{\rm eff}^{\rm SM}$

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SM result for M_W, $\sin^2\theta_{\text{eff}}$:

– full one-loop
– full two-loop
– leading 3-loop via $\Delta\rho$ (not yet n_f^3 ;-)
– leading 4-loop via $\Delta\rho$

Best MSSM result for M_W: [S.H., W. Hollik, G. Weiglein, L. Zeune '13]

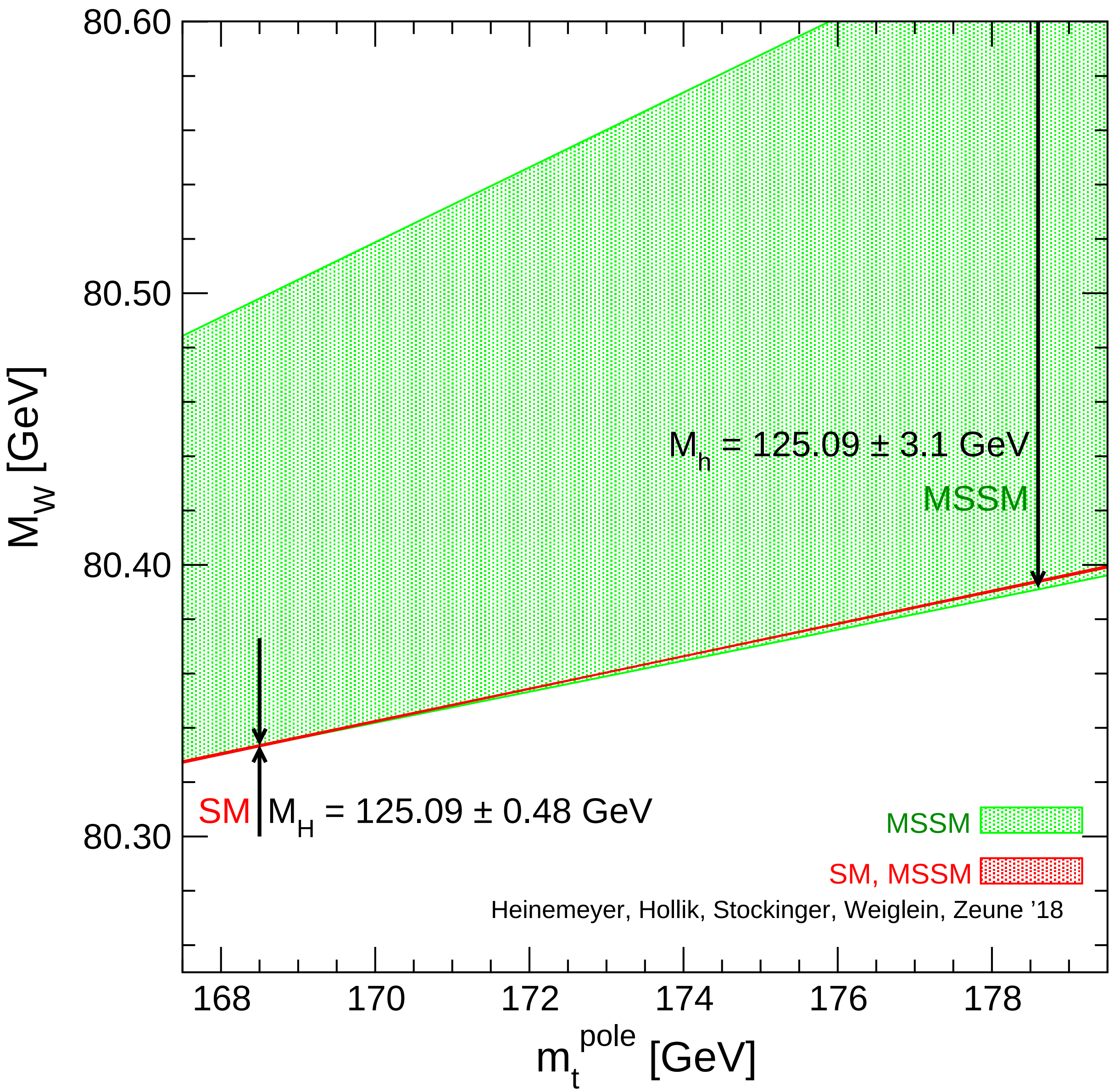
– full SM result (via fit formel)
– full MSSM one-loop (incl. CPV phases)
– all existing two-loop $\Delta\rho$ contributions ($\Delta\rho^{\alpha\alpha_s}$, $\Delta\rho^{\alpha_t^2,\alpha_t\alpha_b,\alpha_b^2}$)

$\Delta\rho$ does not contain: – effects from sleptons
– effects from charginos/neutralinos

$\Rightarrow$ non-$\Delta\rho$ one-loop and $\Delta\rho$ two-loop contributions sometimes non-negligible!

Example: Prediction for M_W in the SM and the MSSM :

[S.H., W. Hollik, D. Stockinger, G. Weiglein, L. Zeune '18]



MSSM band:
scan over
SUSY masses

overlap:
SM is MSSM-like
MSSM is SM-like

SM band:
variation of M_H^{SM}

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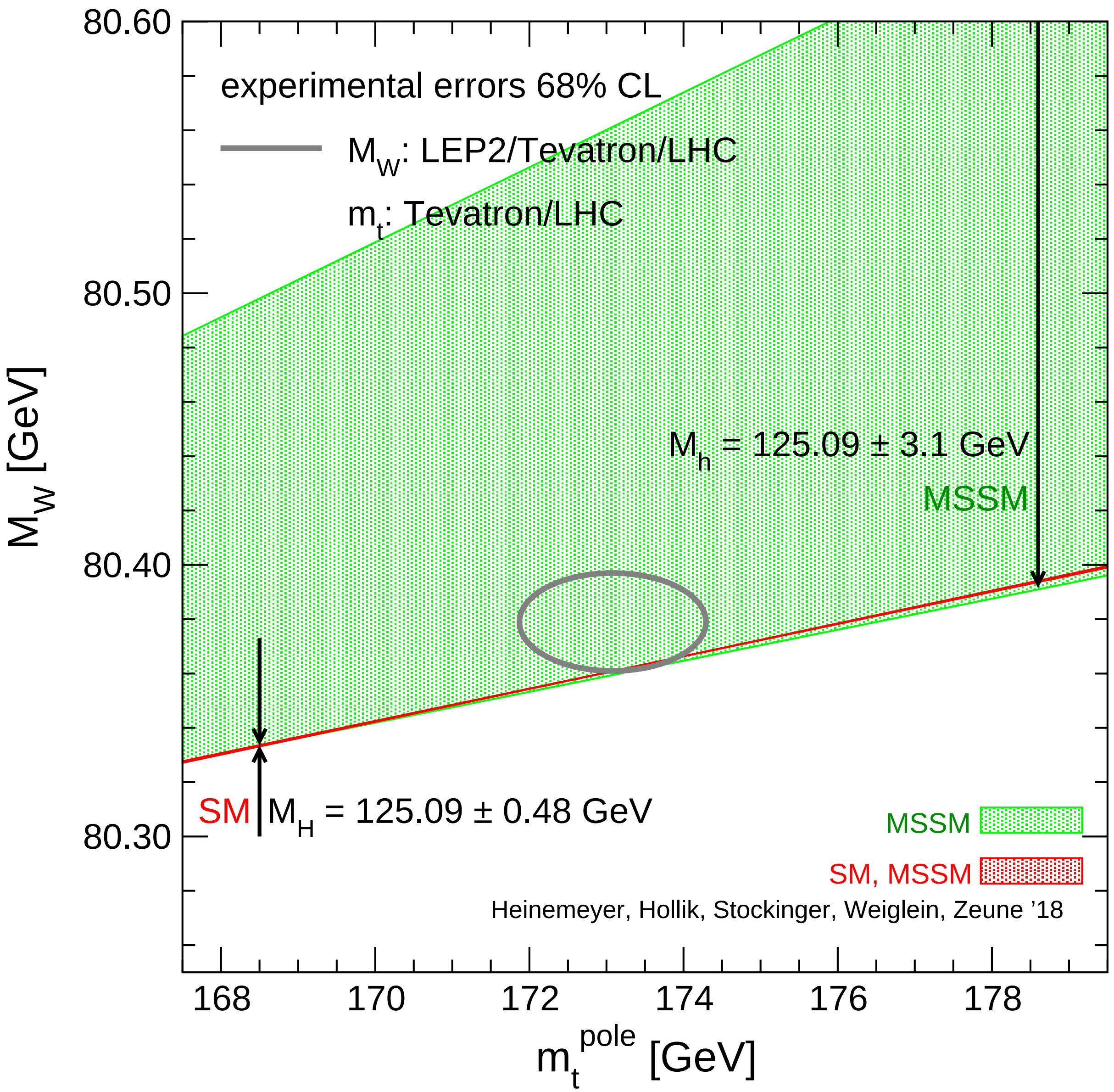

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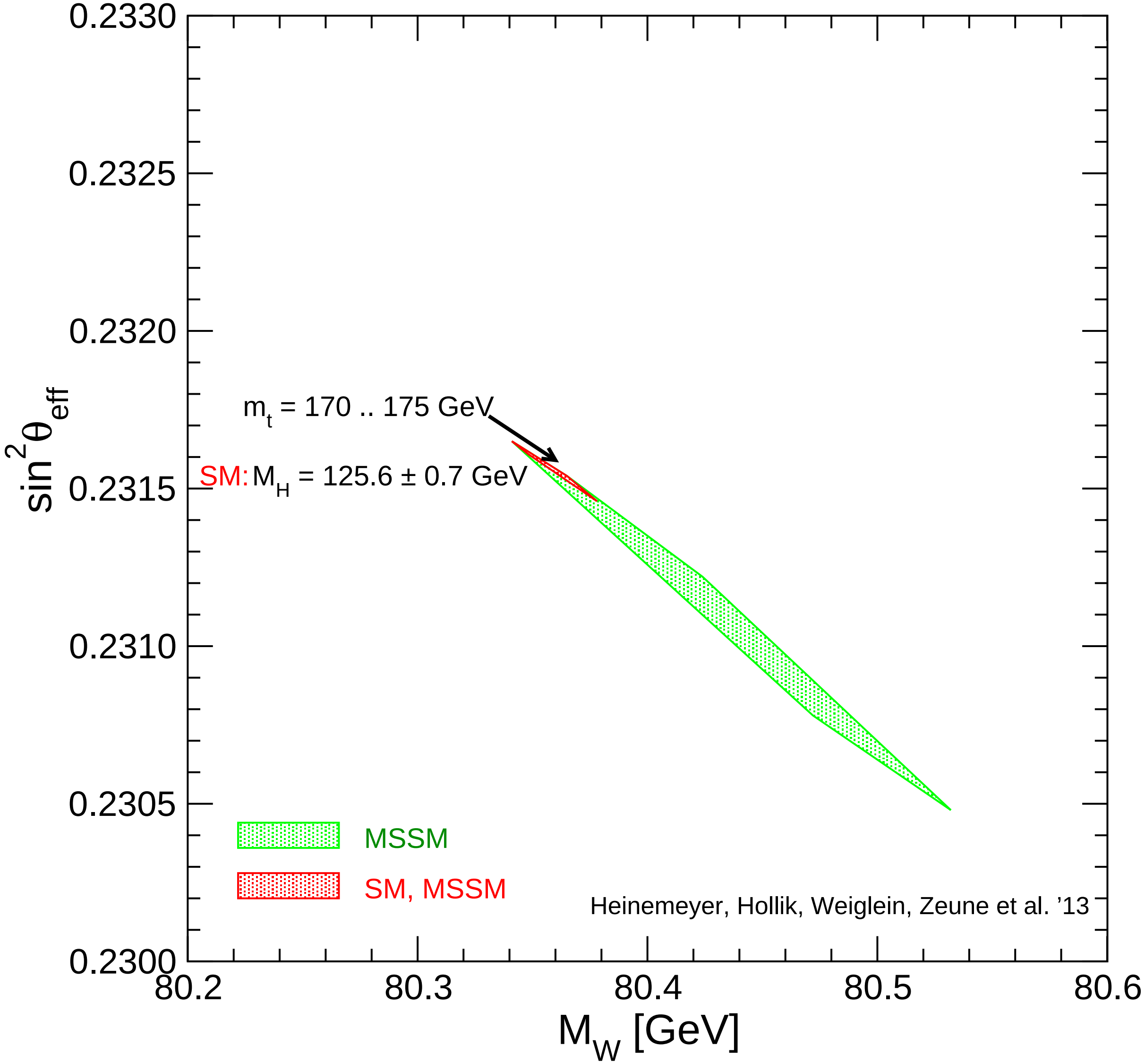
Example: Prediction for M_W and $\sin^2\theta_{\rm eff}$ in the SM and the MSSM :

[*S.H., W. Hollik, G. Weiglein, L. Zeune et al. '13*]



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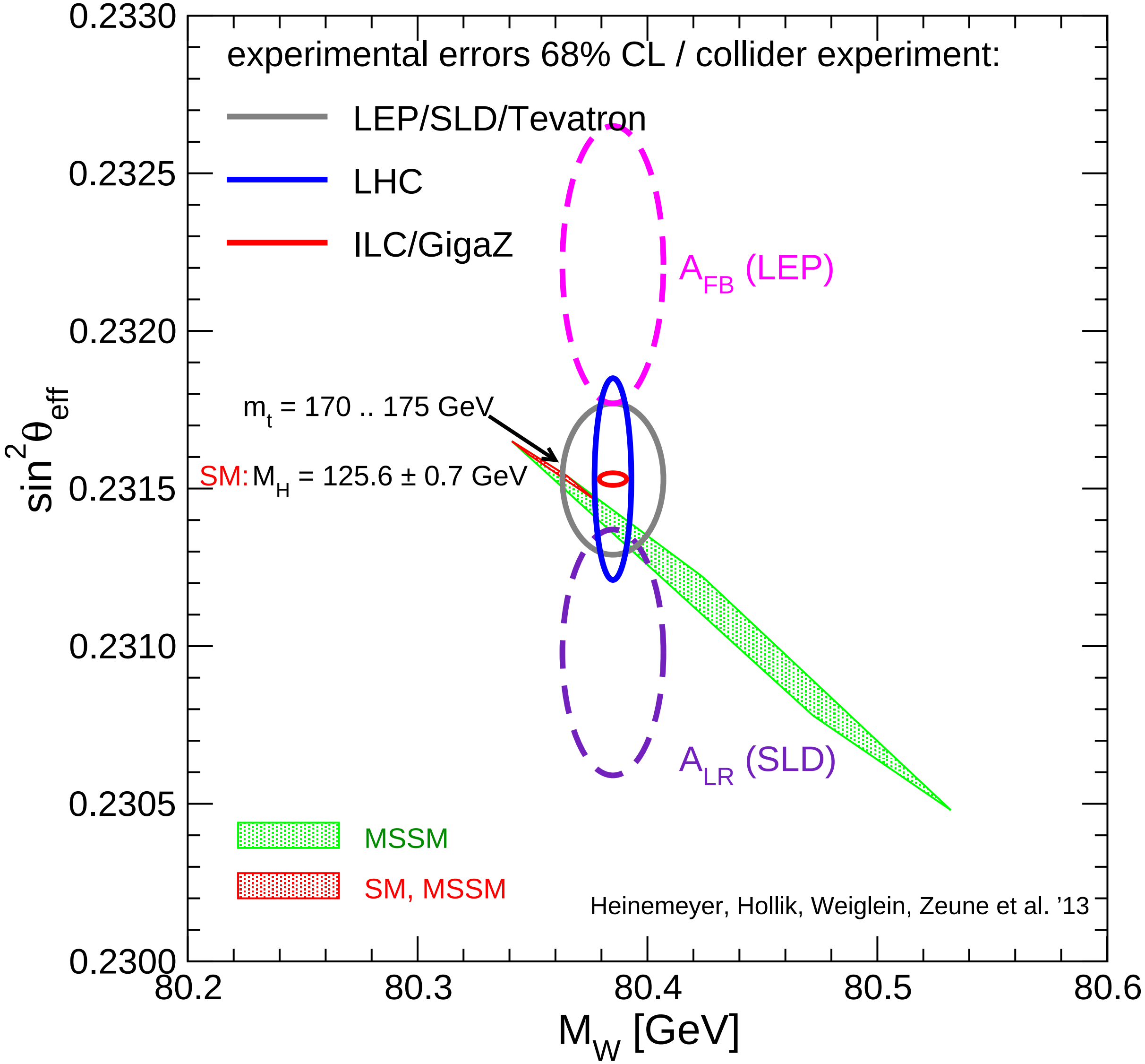

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SM band:
variation of M_H^{SM}

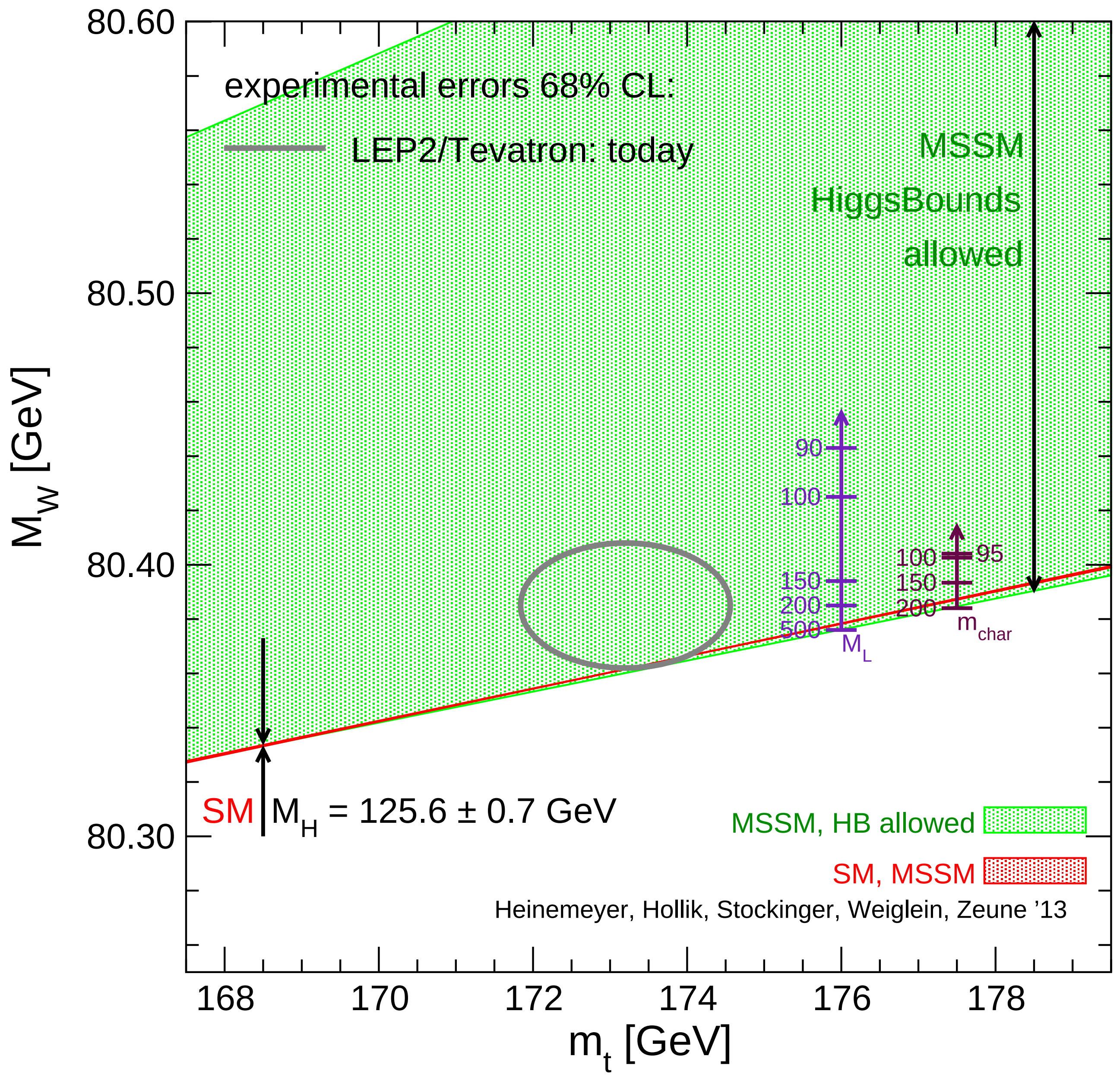
Example MSSM scenario (I):

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

⇒ extensive parameter scan:

Parameter	Minimum	Maximum
μ	-2000	2000
$M_{\tilde{E}_{1,2,3}} = M_{\tilde{L}_{1,2,3}}$	100	2000
$M_{\tilde{Q}_{1,2}} = M_{\tilde{U}_{1,2}} = M_{\tilde{D}_{1,2}}$	500	2000
$M_{\tilde{Q}_3}$	100	2000
$M_{\tilde{U}_3}$	100	2000
$M_{\tilde{D}_3}$	100	2000
$A_e = A_\mu = A_\tau$	-3 $M_{\tilde{E}}$	3 $M_{\tilde{E}}$
$A_u = A_d = A_c = A_s$	-3 $M_{\tilde{Q}_{12}}$	3 $M_{\tilde{Q}_{12}}$
A_b	-3 max$(M_{\tilde{Q}_3}, M_{\tilde{D}_3})$	3 max$(M_{\tilde{Q}_3}, M_{\tilde{D}_3})$
A_t	-3 max$(M_{\tilde{Q}_3}, M_{\tilde{U}_3})$	3 max$(M_{\tilde{Q}_3}, M_{\tilde{U}_3})$
tan β	1	60
M_3	500	2000
M_A	90	1000
M_2	100	1000

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



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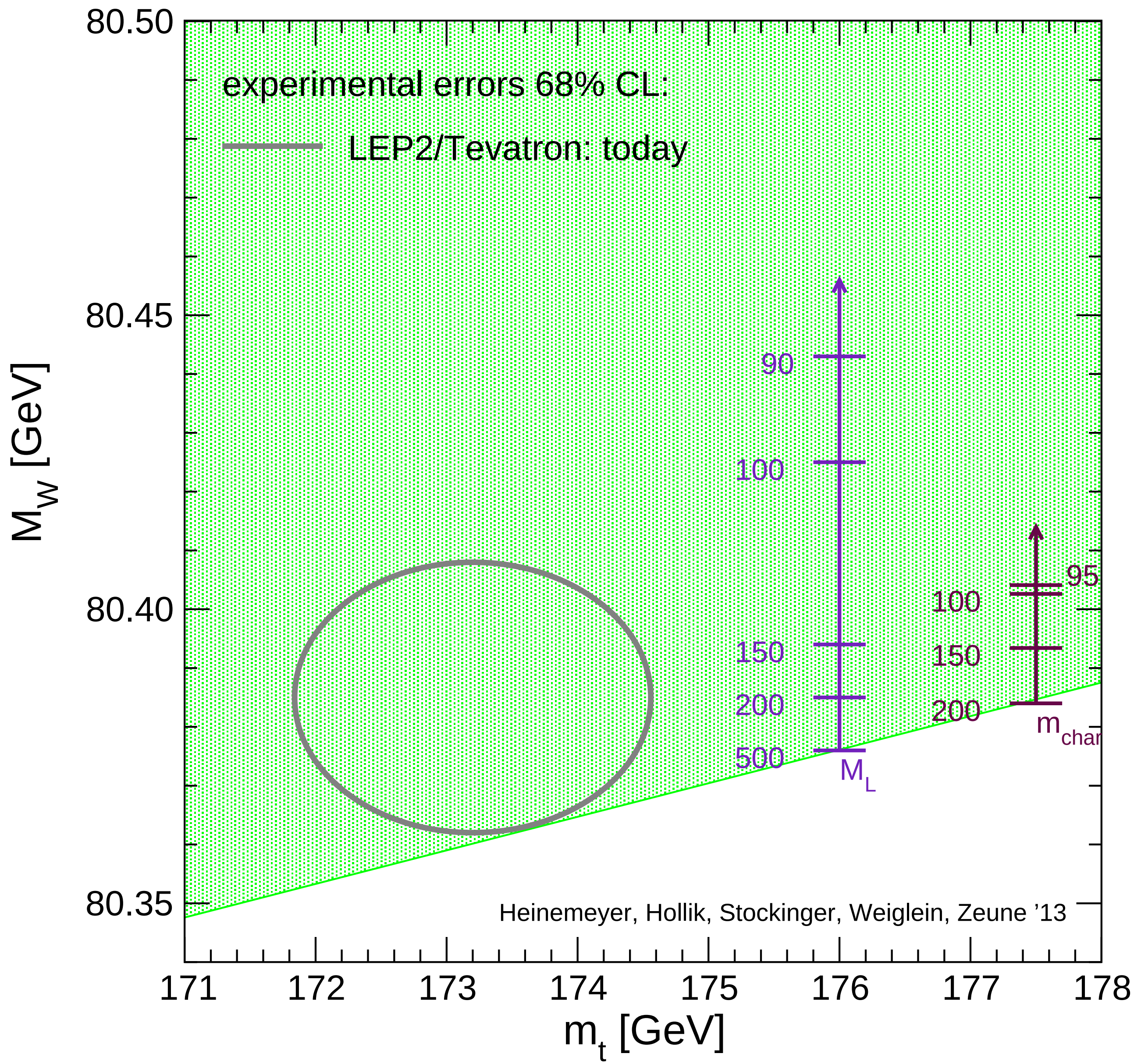
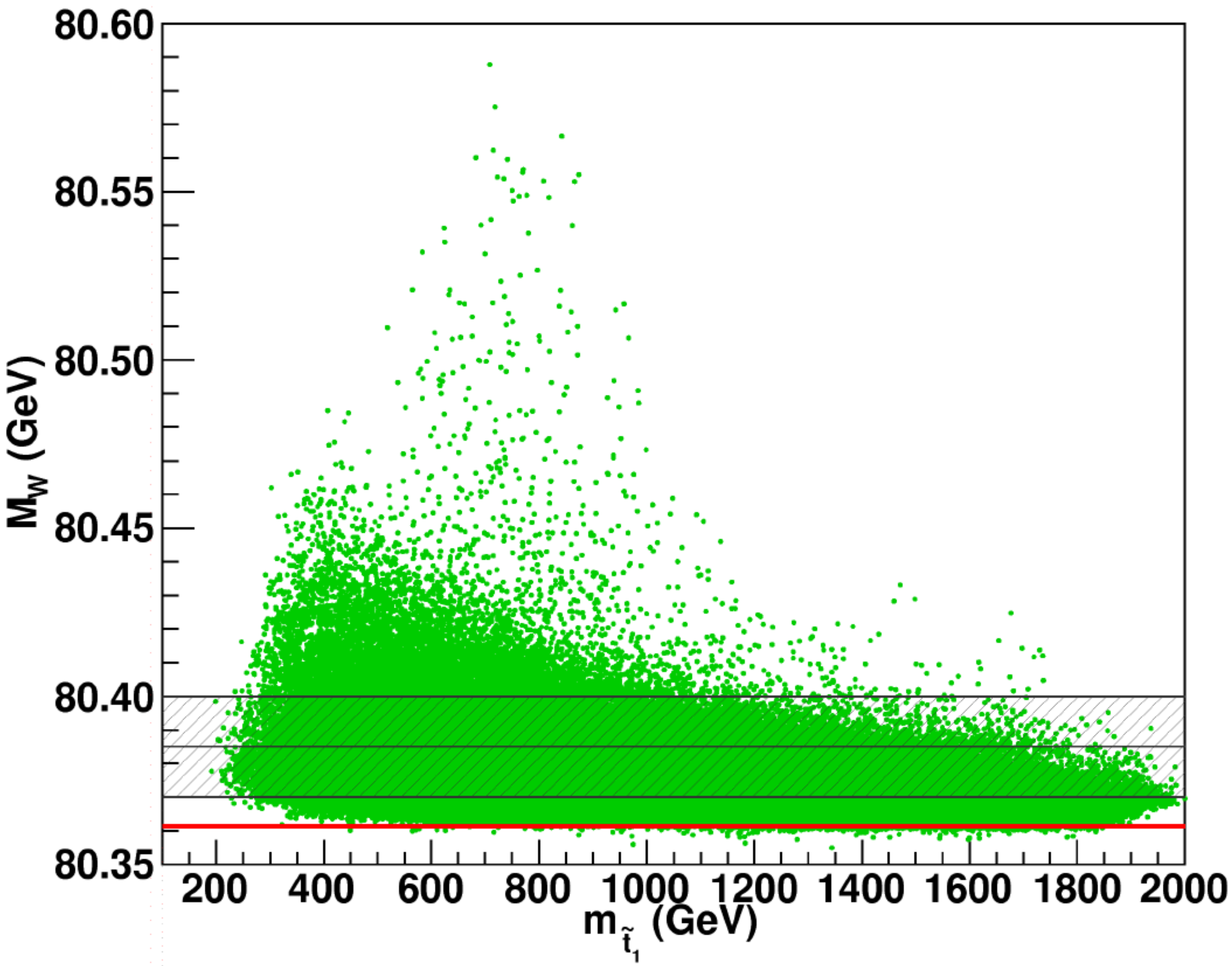


Effects of stops: [S.H., G. Weiglein, L. Zeune '13]



All points HiggsBounds allowed

Effects of stops:

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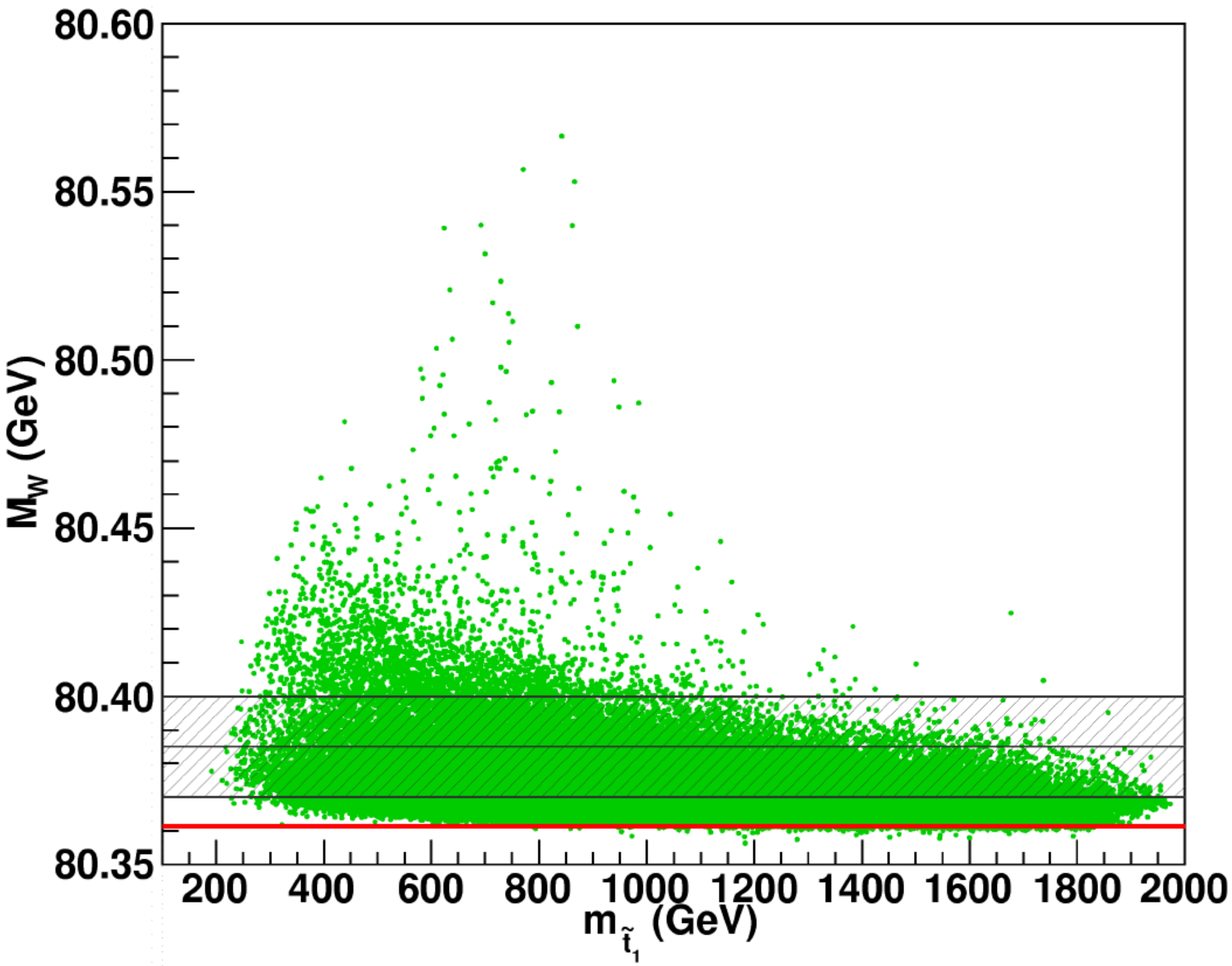
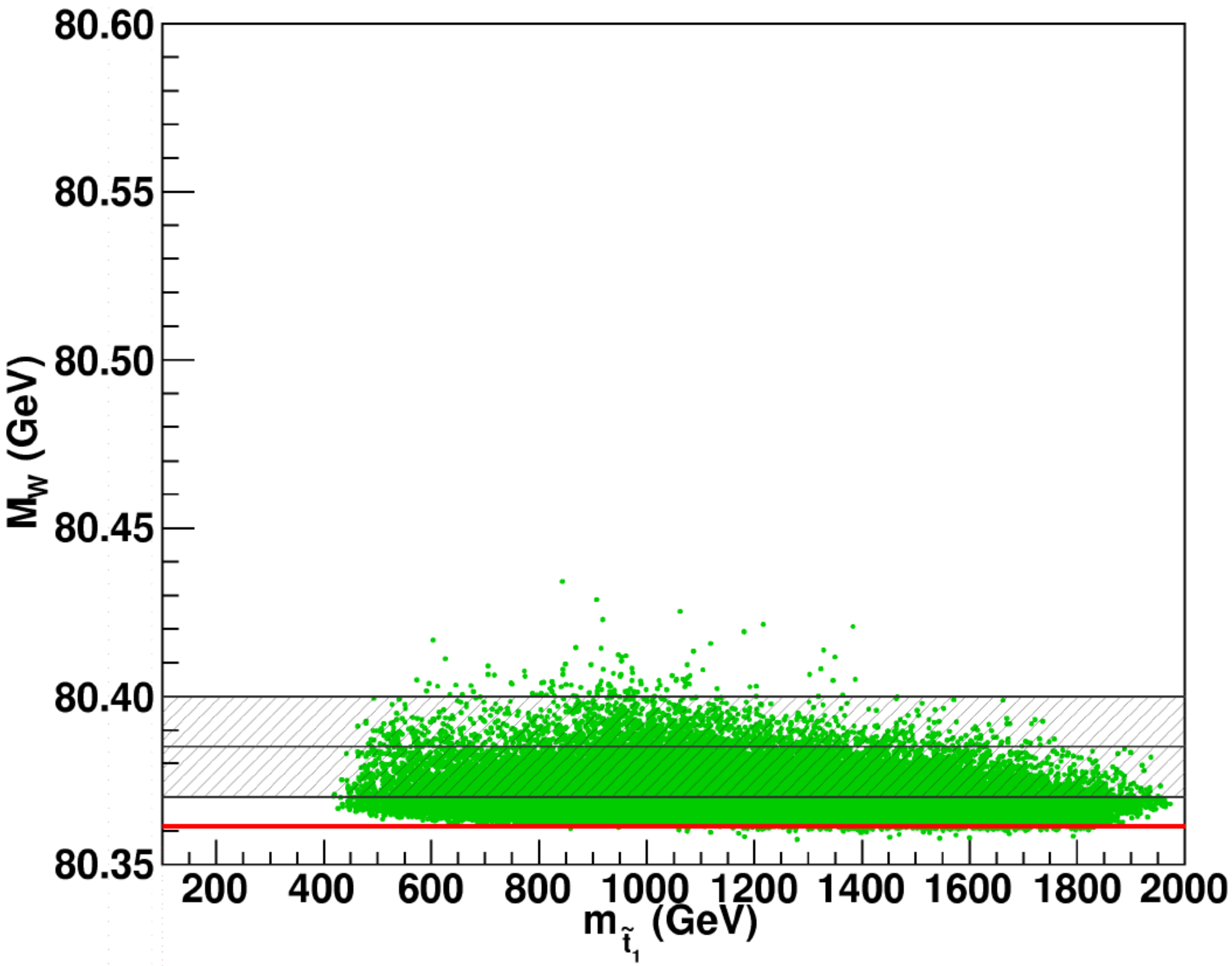


$\ldots \oplus\ m_{\tilde{q}_{1,2}}, m_{\tilde{g}} > 1200$ GeV

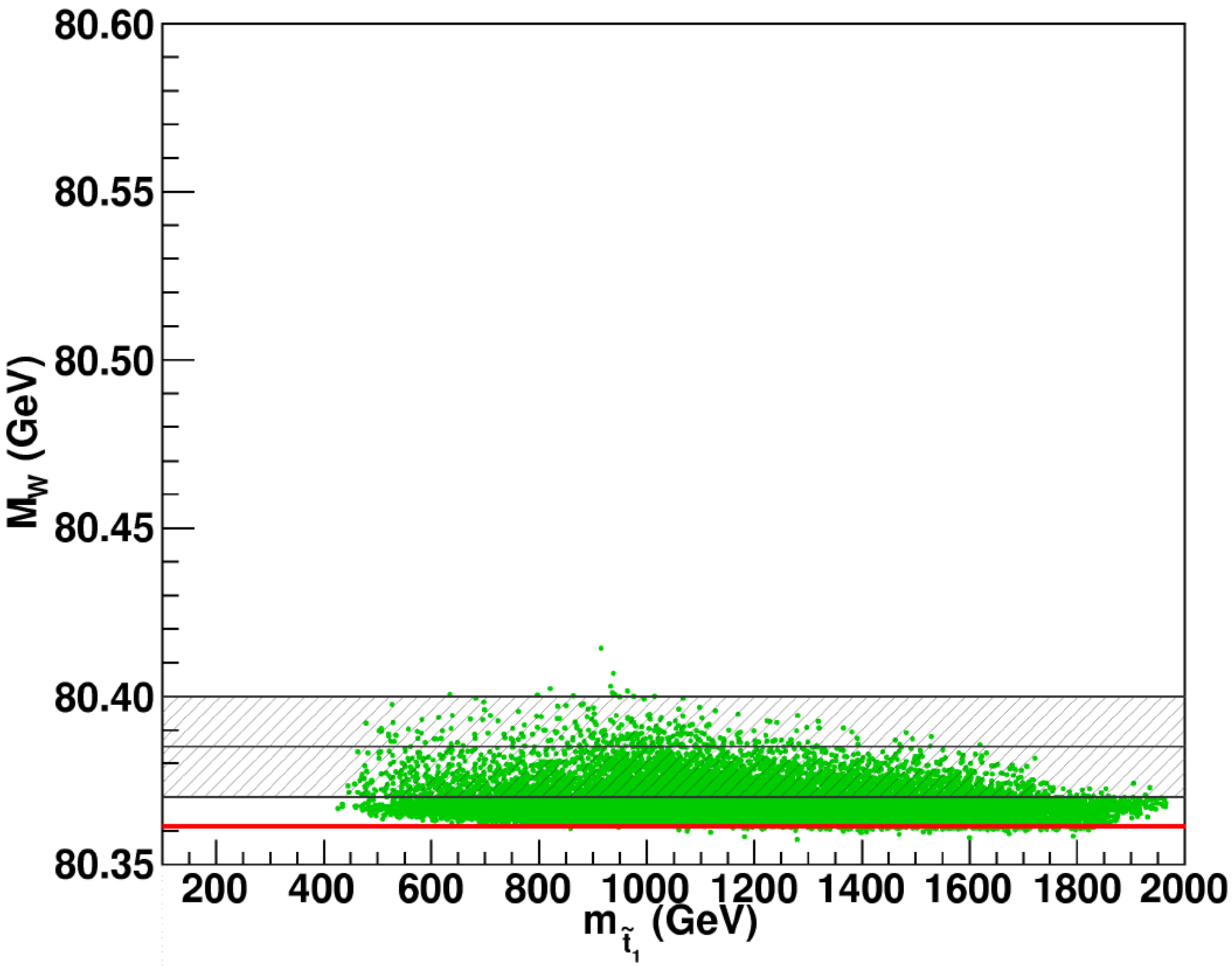
Effects of stops:

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



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

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

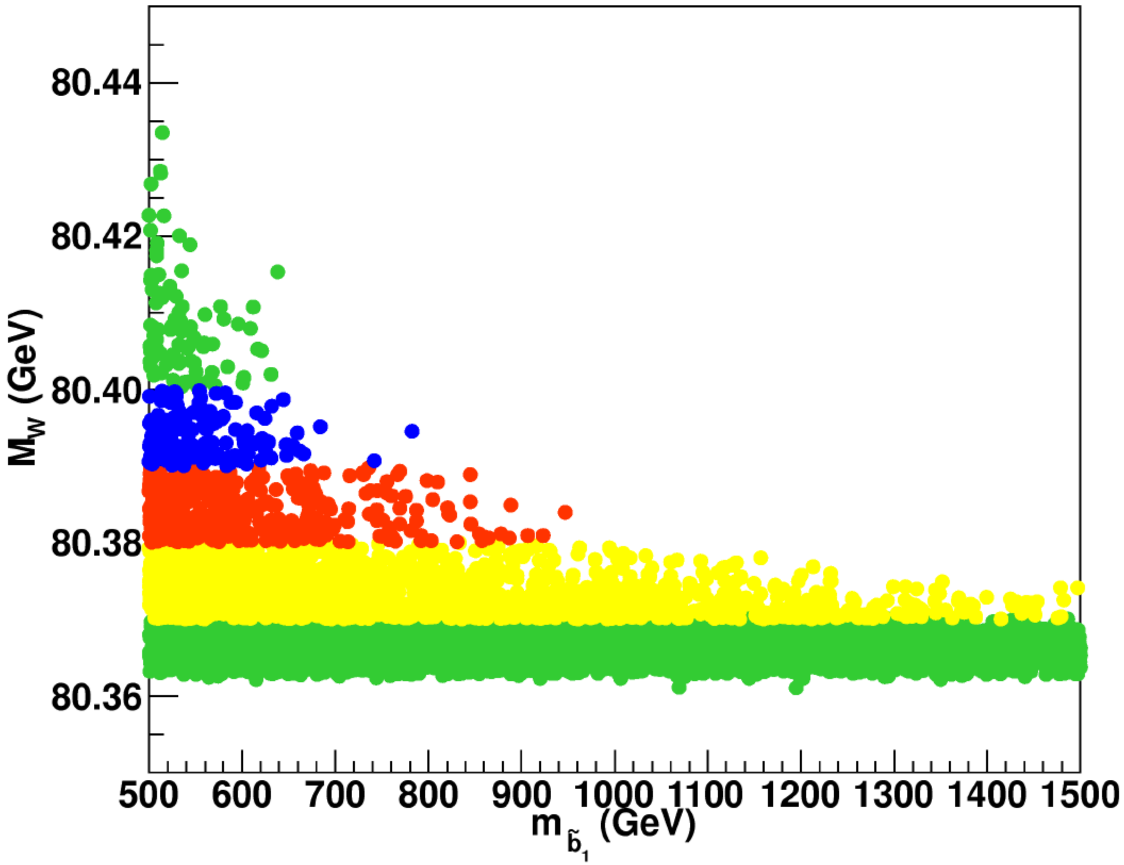


$\ldots \oplus\ m_{\tilde{l}}, m_{\tilde{\chi}_i^\pm}, m_{\tilde{\chi}_j^0} > 500$ GeV $\Rightarrow$ update worthwhile?!

Example MSSM scenario (II): [S.H., G. Weiglein, L. Zeune '15]

$m_{\tilde{t}_1} = 400 \pm 40$ GeV, Other masses $\gtrsim 500$ GeV

$M_W^{\rm exp} = 80.375 \pm 0.005$ GeV, 80.385 ± 0.005 GeV, 80.395 ± 0.005 GeV



⇒ precision below 5 MeV required! ⇒ update worthwhile?!

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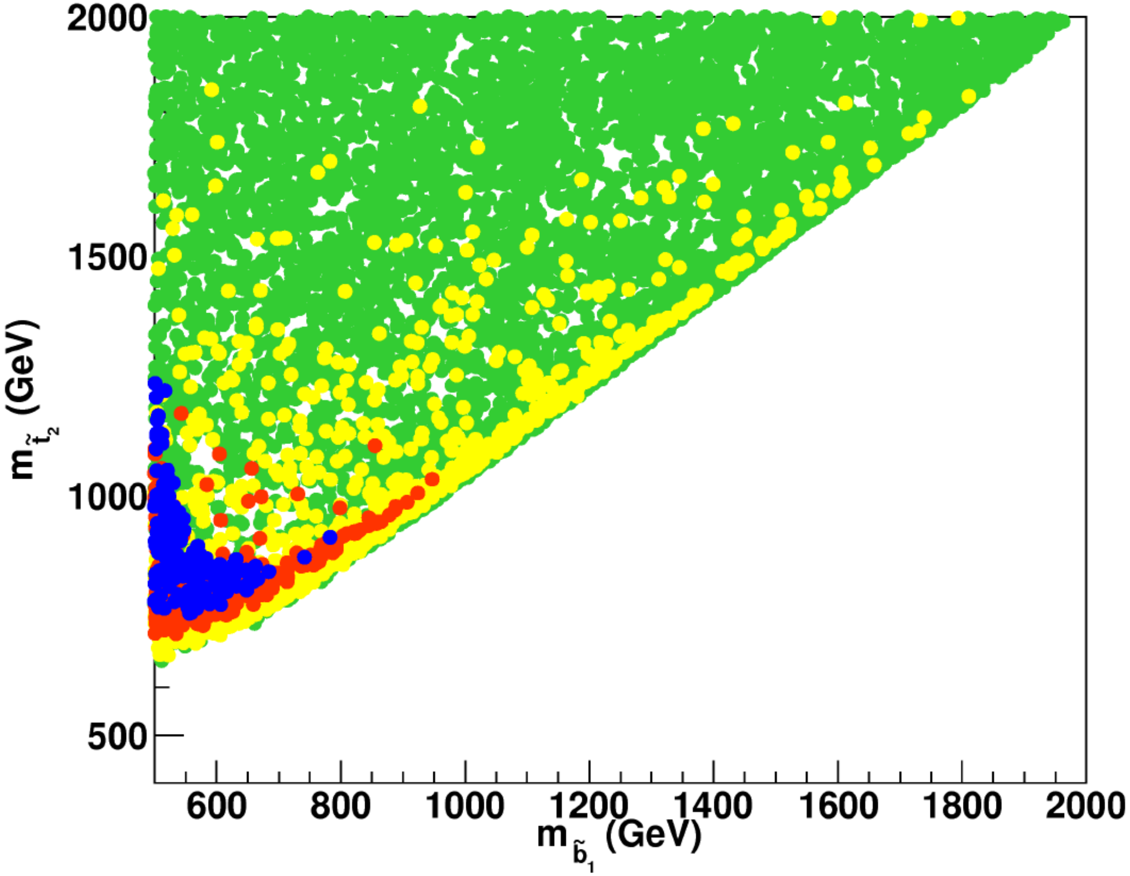

⇒ precision below 5 MeV required!

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3. Why not (only) EFTs?

EFTs have many virtues!

But they also have many (un?)known short-comings:

– all BSM physics is assumed to be very heavy,
  out of the direct reach of current/future colliders
  (Not my favorite future physics scenario ...)

– if one finds large effects in the EFT predictions,
  it is not clear whether this can be reproduced by any real model

– EFTs as such leave unclear to what underlying real model
  a certain effect corresponds
  $\Rightarrow$ this requires a "model by model" prediction for the EFT

– ...

Let us assume that we do see a deviation from the SM

What do we learn from that?
How do we learn something from that?

⇒ We have to compare the observed deviation with predicted deviations

⇒ Preferrably with the predicted deviations in a concrete models

We want to learn which physics is responsible for the deviations
⇒ A comparison with an EFT result subsequently requires the mapping to concrete models anyway!

Needed:
– sufficiently precise predictions in BSM model
– . . . including uncertainty estimates
– Analysis of patterns of deviations?!

4. Conclusinos

- EWPOs are a powerful tool to learn about unknown physics scales
  $\Rightarrow$ top mass and Higgs mass were predicted correctly (within the SM)
- "Classical" EWPO: M_W, $\sin^2\theta_{\rm eff}$, Γ_Z, R_l, R_q, ...
  Do not forget possible new EWPOs: a_μ, M_h, ...
- Current predictions within the SM are sufficiently under control for now
- Situation is less clear for BSM models
  $\Rightarrow$ better overview necessary! $\Rightarrow$ Snowmass 2021?
  $\Rightarrow$ Analysis of patterns of deviations?!
- MSSM as a showcase:
  - sufficiently worked out, including rough uncertainty estimate
  - possible clear patterns
  - $\Delta\rho$ not sufficient to cover the possible effects
  - EWPOs can tell us about other unknown scales of the MSSM
- Assume an observed deviation from the SM:
  - compre observed deviations with predicted deviations
  - preferrably in a concrete model
  - Comp. with EFT requires subsequent mapping to concrete models


Further Questions?