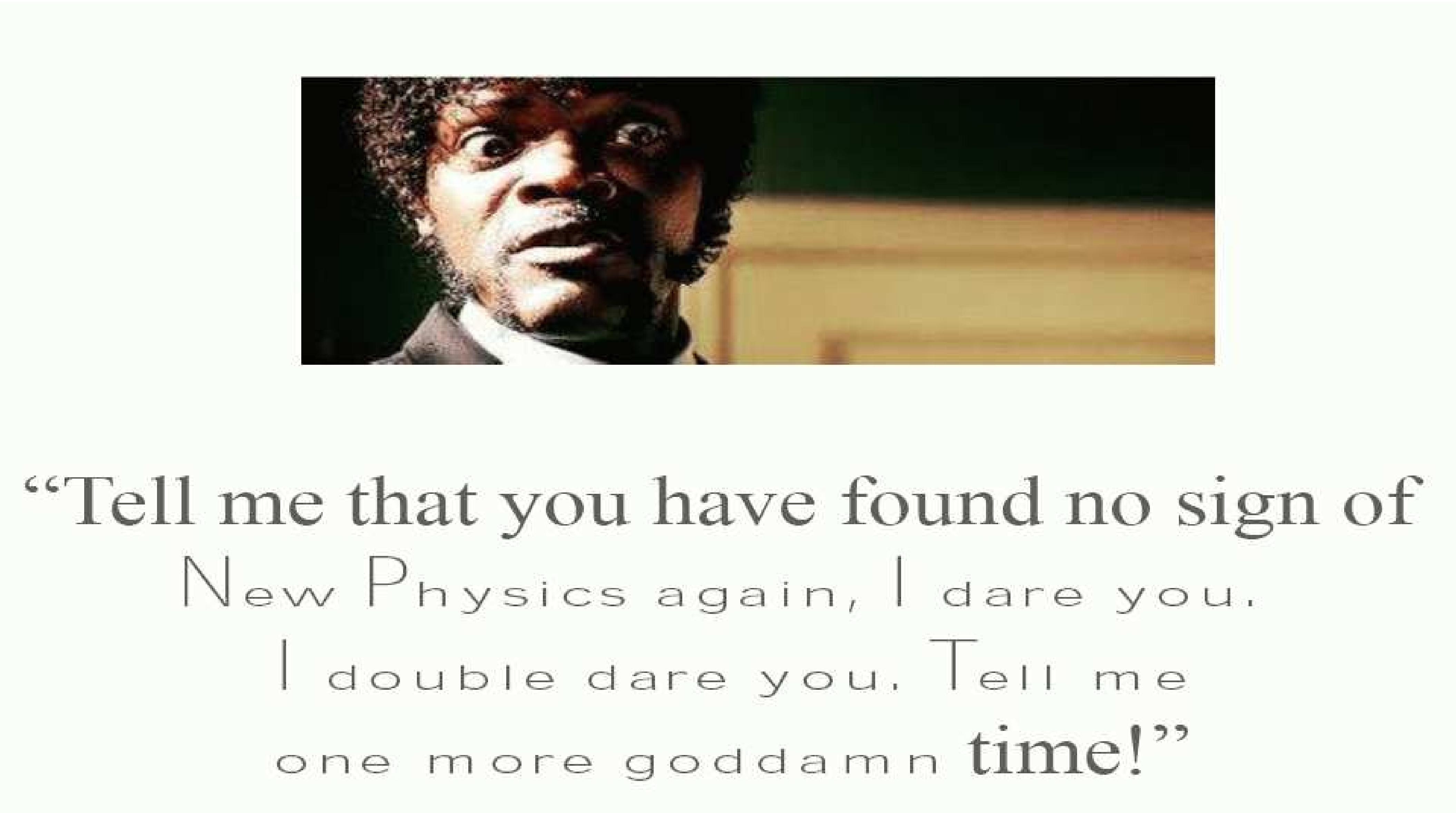
"Tell me that you have found no sign of
New Physics again, I dare you.
I double dare you. Tell me
one more goddamn time!"

Theory review of W mass measurement and its implications

Sven Heinemeyer, IFT (CSIC, Madrid)

virtual, 05/2022

1. Introduction: the mass of the W-boson
2. Implications for the Standard Model
3. Implications for Multi-Higgs models
4. Implications for SUSY
5. Conclusions

Disclaimer

What I will NOT talk about: (not my area of expertise)

- calculations needed to measure M_W
- tools/codes that are used to measure M_W
- PDFs
- related uncertainties
- CDF's uncertainty estimate
- ...

I will take the CDF measurement simply at face value

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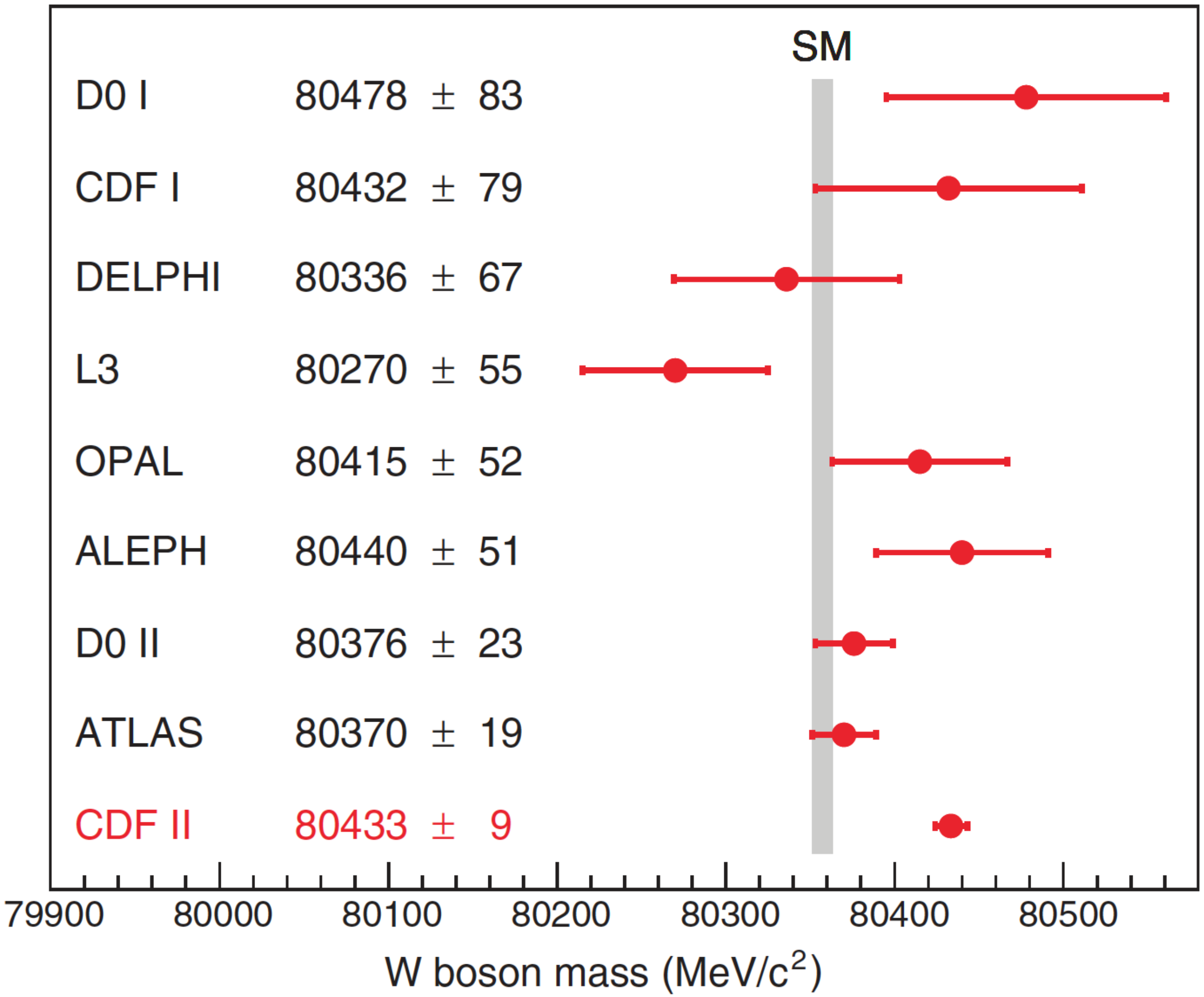
- CDF's uncertainty estimate
- ...

I will take the CDF measurement simply at face value
well, nearly ...

1. Introduction: the mass of the W-boson

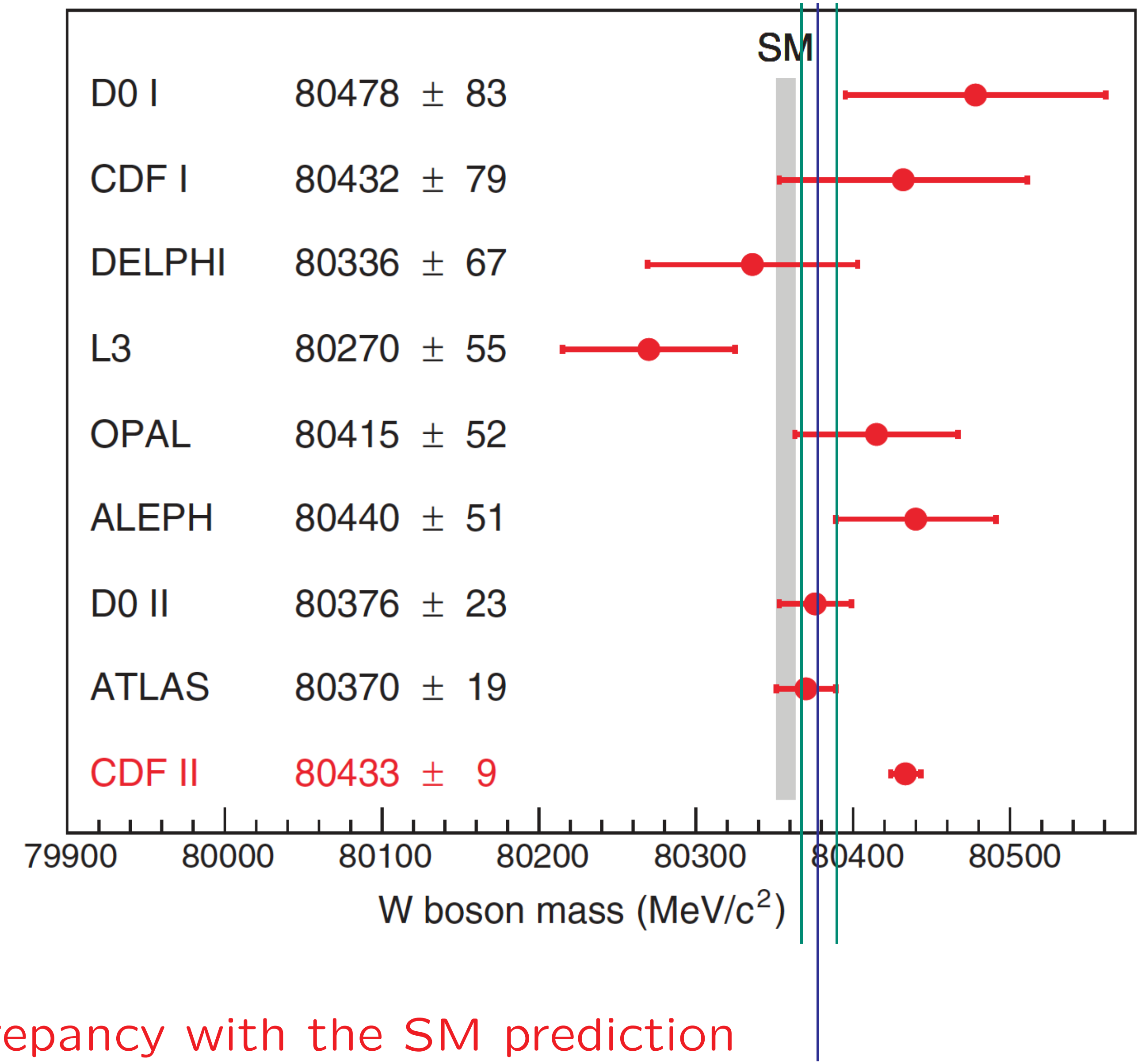
[*CDF '22*]



$\Rightarrow$ large discrepancy with the SM prediction

1. Introduction: the mass of the W-boson

[*CDF '22*]

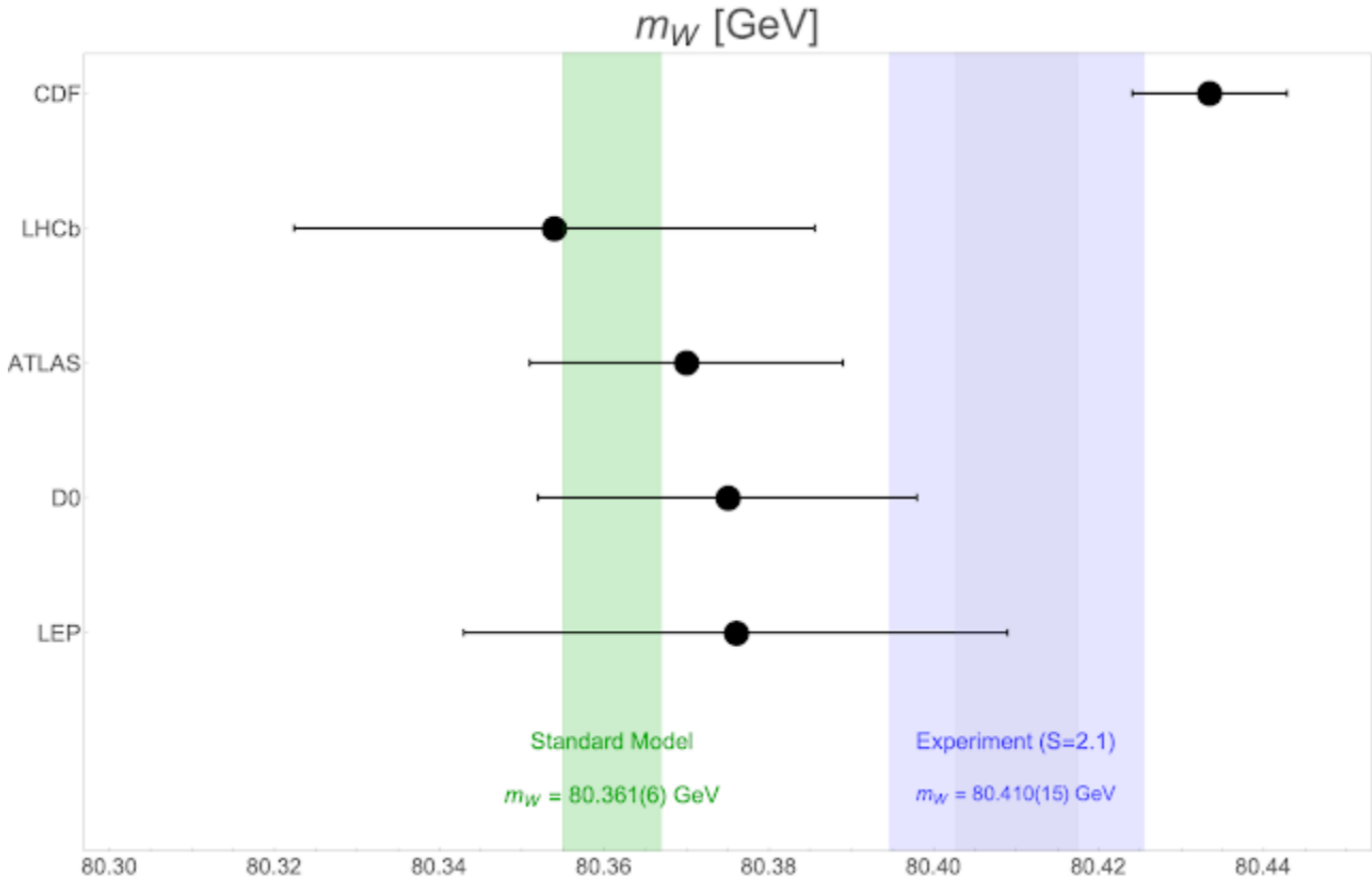


⇒ large discrepancy with the SM prediction

⇒ large discrepancy with other measurements: $M_W^{\text{PDG}} = 80379 \pm 12$ MeV

Approximation for a new world average:

[A. Falkowski '22]



$\Rightarrow$ approximation yields $M_W^{\text{approx-av.}} = 80410 \pm 15$ MeV $\sim 3\,\sigma$

$\Rightarrow$ enlarged uncertainty because of "bad agreement" between older and new measurements $\Rightarrow$ PDG prescription

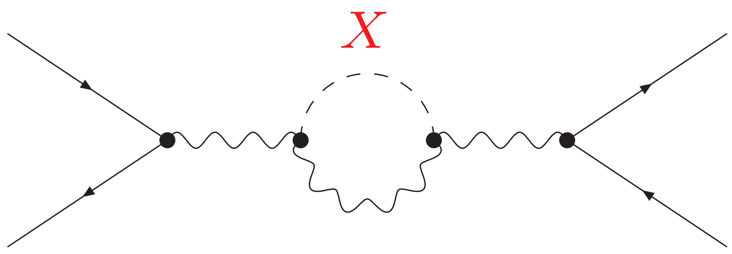
Search for BSM physics via EWPO:

Comparison of observables with theory:

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

$\Downarrow$

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
$\Rightarrow$ models "ready" so far: SM, MSSM, "pure multi-Higgs" models (?)

Precision observables in the SM and the BSM models

M_W, $\sin^2\theta_{\text{eff}}$, ...

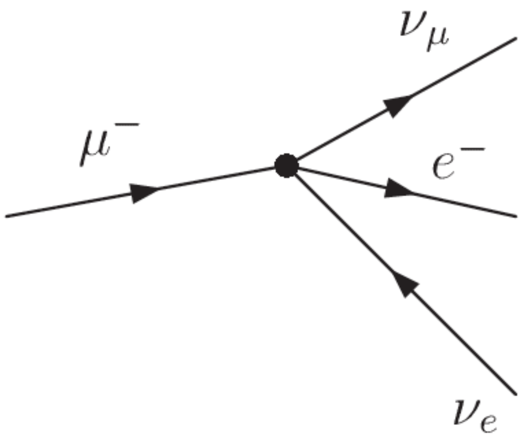
A) Theoretical prediction for M_W in terms

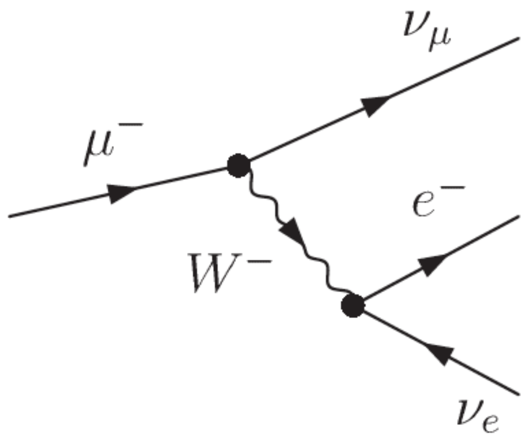
of $M_Z, \alpha, G_\mu, \Delta r$:

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

$\Updownarrow$

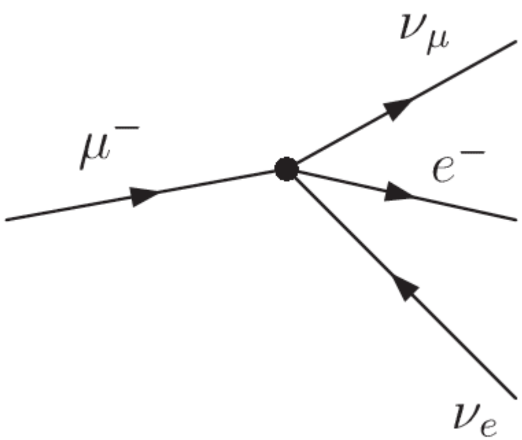
loop corrections

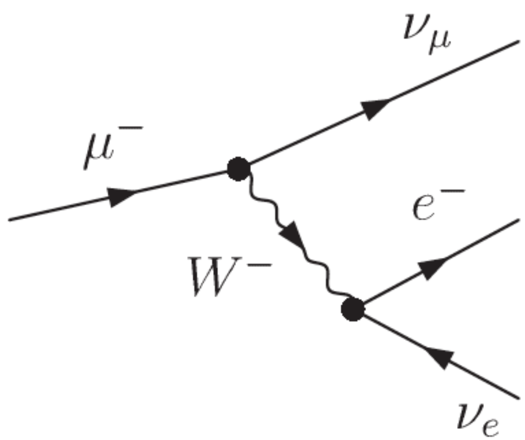




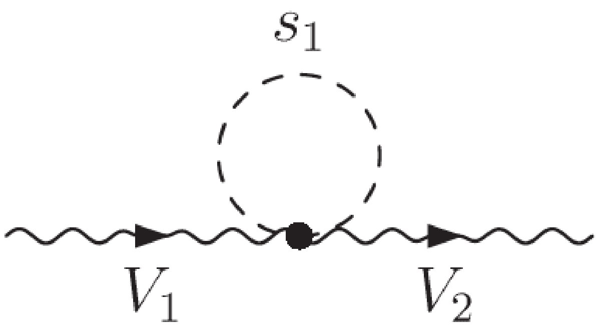
μ decay:

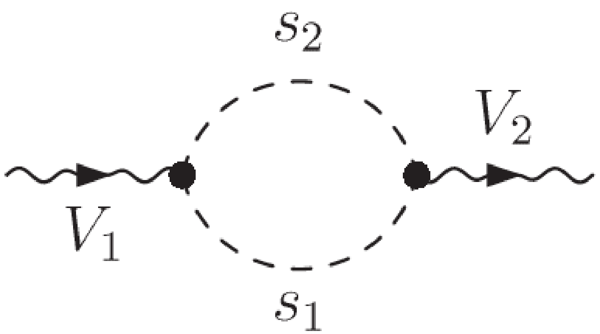
tree:

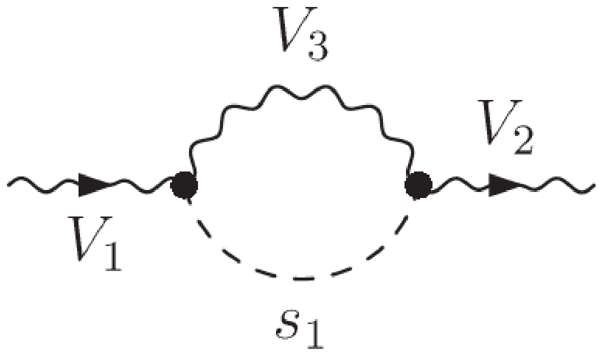




gauge-boson self-energy corrections:

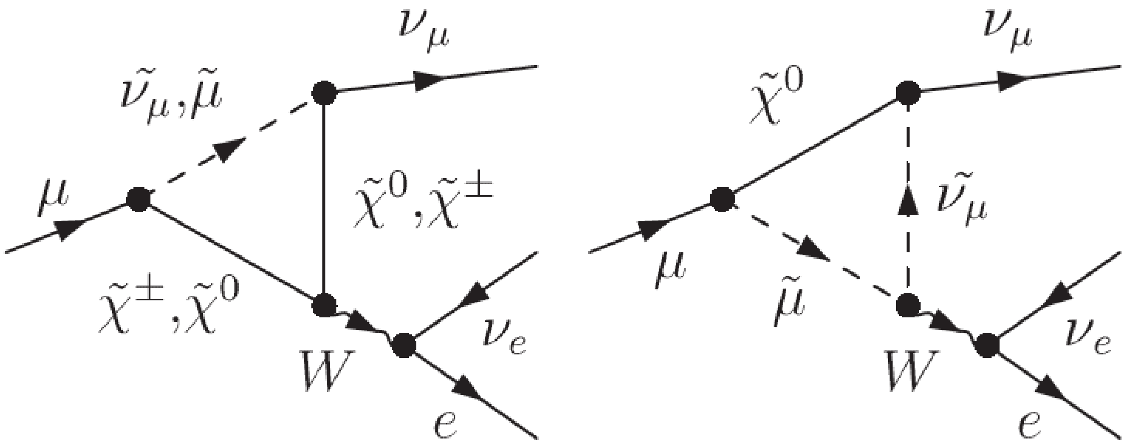




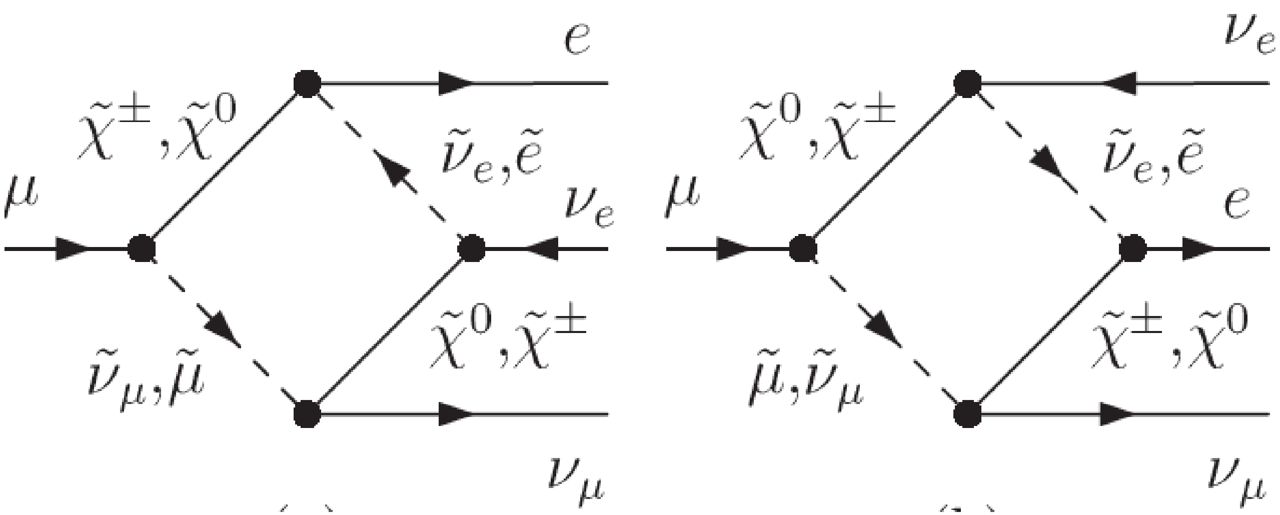


μ decay:

vertex corrections:



box corrections:



Precision observables in the SM and the BSM models

M_W, $\sin^2\theta_{\text{eff}}$, ...

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*]

$$\begin{array}{llllll} \Delta r_{1-\text{loop}} = & \Delta\alpha & - & \frac{c_W^2}{s_W^2}\Delta\rho & + & \Delta r_{\text{rem}}(M_H) \\ & \sim \log\frac{M_Z}{m_f} & & \sim m_t^2 & & \log(M_H/M_W) \\ & \sim 6\% & & \sim 3.3\% & & \sim 1\% \end{array}$$

Precision observables in the SM and the BSM models

M_W, $\sin^2\theta_{\text{eff}}$, ...

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

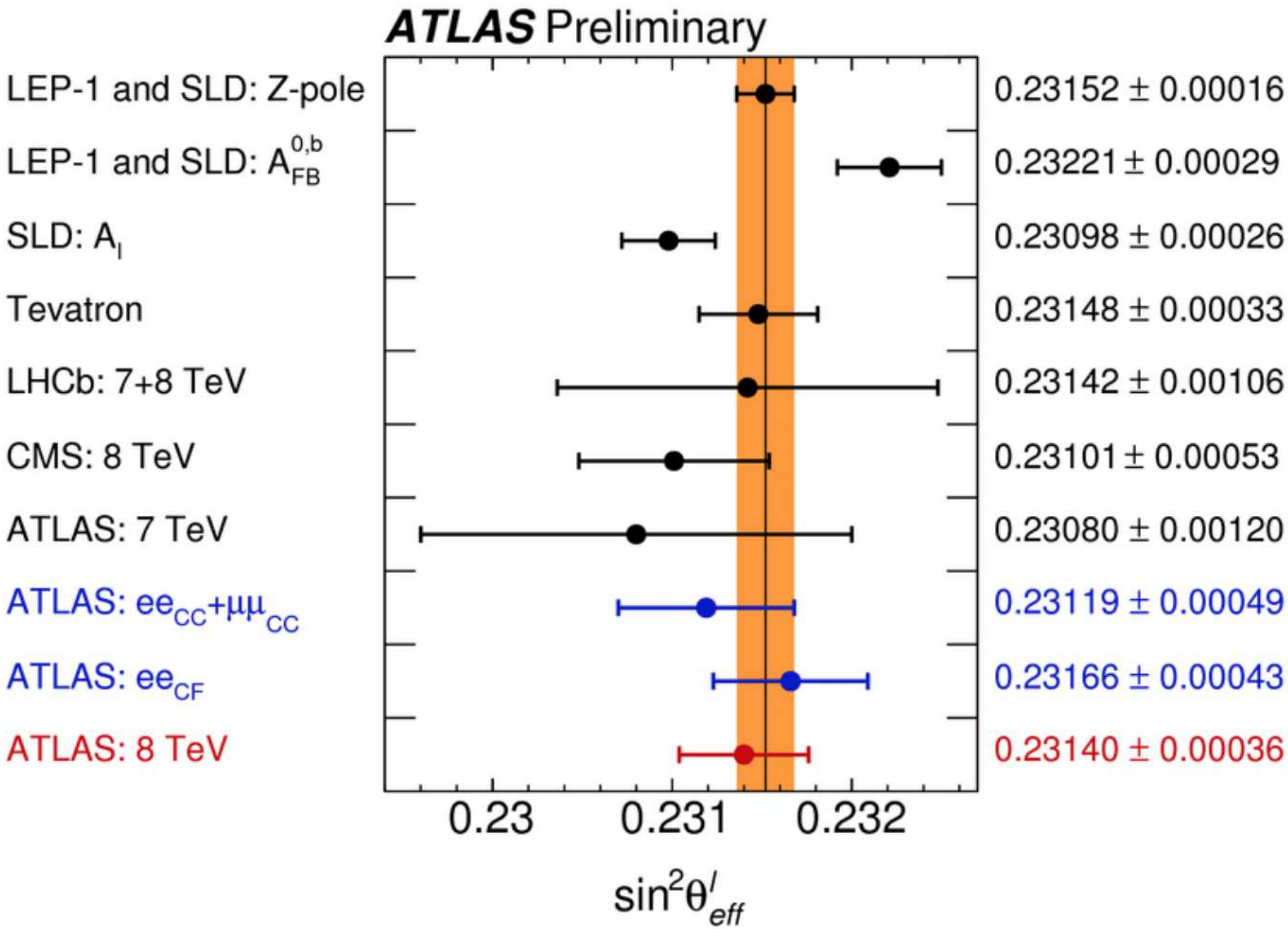
B) Effective mixing angle:

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

Higher order contributions:

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

Effective weak mixing angle: experimental results:



$\Rightarrow$ only average of A^b_{FB}(LEP) and A^e_{LR}(SLD) agrees with SM prediction

Calculation of M_W:

$$\Delta r^{(\alpha)} = \frac{\Sigma_T^{WW}(0)}{M_W^2} + (\text{vertex}) + (\text{box}) - \frac{\mathrm{Re}\,\Sigma_T^{WW}(M_W^2)}{M_W^2}$$
$$+ \left[\frac{\partial \Sigma_T^{\gamma\gamma}(k^2)}{\partial k^2}\right]_{k^2=0} - \frac{s_\mathrm{w}}{c_\mathrm{w}} \frac{\Sigma_T^{\gamma Z}(0)}{M_Z^2} - \frac{c_\mathrm{w}^2}{s_\mathrm{w}^2} \mathrm{Re}\left[\frac{\Sigma_T^{ZZ}(M_Z^2)}{M_Z^2} - \frac{\Sigma_T^{WW}(M_W^2)}{M_W^2}\right]$$
$$-\Sigma_L^e(0) - \Sigma_L^\mu(0) - \Sigma_L^{\nu_e}(0) - \Sigma_L^{\nu_\mu}(0)\,,$$

Main contribution:

$$- \frac{c_\mathrm{W}^2}{s_\mathrm{W}^2} \mathrm{Re}\left[\frac{\Sigma_Z(M_Z^2)}{M_Z^2} - \frac{\Sigma_W(M_W^2)}{M_W^2}\right]$$
$$\approx -\frac{c_\mathrm{W}^2}{s_\mathrm{W}^2}\left[\frac{\Sigma_Z(0)}{M_Z^2} - \frac{\Sigma_W(0)}{M_W^2}\right]$$
$$=: -\frac{c_\mathrm{W}^2}{s_\mathrm{W}^2} \Delta\rho$$

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

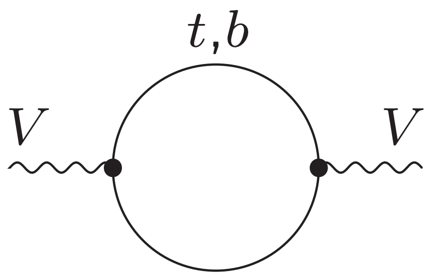
ρ measures the relative strength between
neutral current interaction and charged current interaction

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

(leading, process independent terms)

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

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



Remember: $\Delta\rho$ goes up $\Rightarrow$ M_W goes up, $\sin^2\theta_{\text{eff}}$ goes down

Calculation of M_W with S, T, U: [M. Peskin, T.Takeuchi '90]

$\to$ capture the gauge boson self-energies

$\Rightarrow$ good approximation in multi-Higgs models

$$M_W^2 = M_W^2\Big|_{\rm SM}\left(1 + \frac{s_w^2}{c_w^2 - s_w^2}\Delta r'\right) ,$$

$$\Delta r' = \frac{\alpha}{s_w^2}\left(-\frac{1}{2}S + c_w^2 T + \frac{c_w^2 - s_w^2}{4 s_w^2}U\right) .$$

Main contribution:

$$\begin{aligned} & + \frac{\alpha c_\mathrm{W}^2}{s_\mathrm{W}^2}\frac{s_\mathrm{W}^2}{c_\mathrm{W}^2 - s_\mathrm{W}^2}T \\ =: & + \frac{c_\mathrm{W}^2}{c_\mathrm{W}^2 - s_\mathrm{W}^2}(\alpha T) \\ =: & + \frac{c_\mathrm{W}^2}{c_\mathrm{W}^2 - s_\mathrm{W}^2}\Delta\rho \qquad \alpha T \equiv \Delta\rho \end{aligned}$$

2. Implications for the Standard Model

SM result for M_W (and $\sin^2\theta_{\text{eff}}$):

- full one-loop
- full two-loop
- leading 3-loop via $\Delta\rho$
- leading 4-loop via $\Delta\rho$

Remaining theory uncertainties from unknown higher-orders:

intrinsic today: $\delta M_W^{\text{SM,theo}} = 4$ MeV

parametric today: $\delta m_t = 0.9$ GeV, $\delta(\Delta\alpha_{\text{had}}) = 10^{-4}$, $\delta M_Z = 2.1$ MeV

$\delta M_W^{\text{para},m_t} = 5.5$ MeV, $\delta M_W^{\text{para},\Delta\alpha_{\text{had}}} = 2$ MeV, $\delta M_W^{\text{para},M_Z} = 2.5$ MeV

Results for M_H from other EWPO: [GFitter '18]

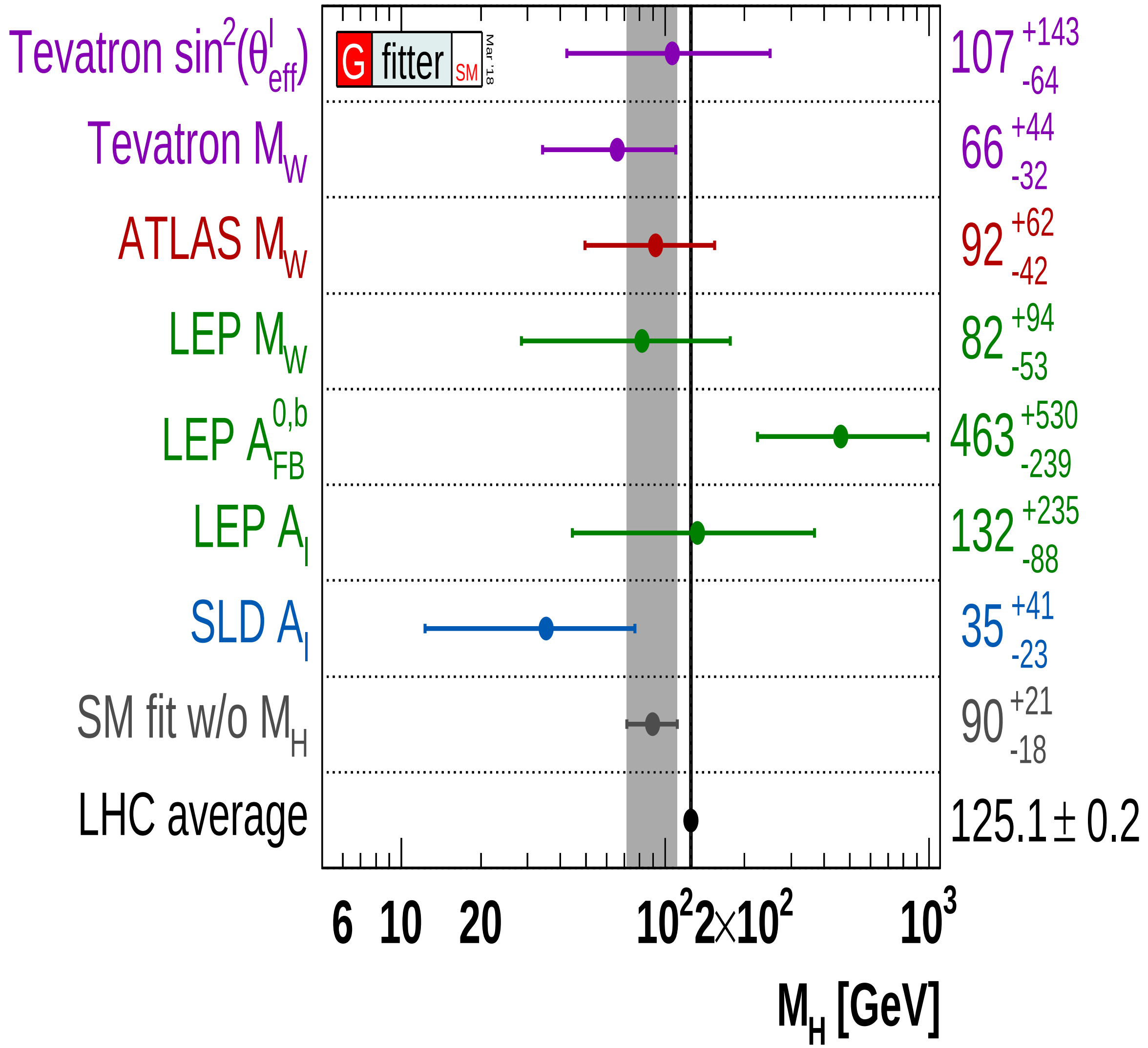
light Higgs preferred by:

M_W, $A^l_{\rm LR}$ (SLD)

heavier Higgs preferred by:

$A^b_{\rm FB}$ (LEP)

$\Rightarrow$ keeps SM alive

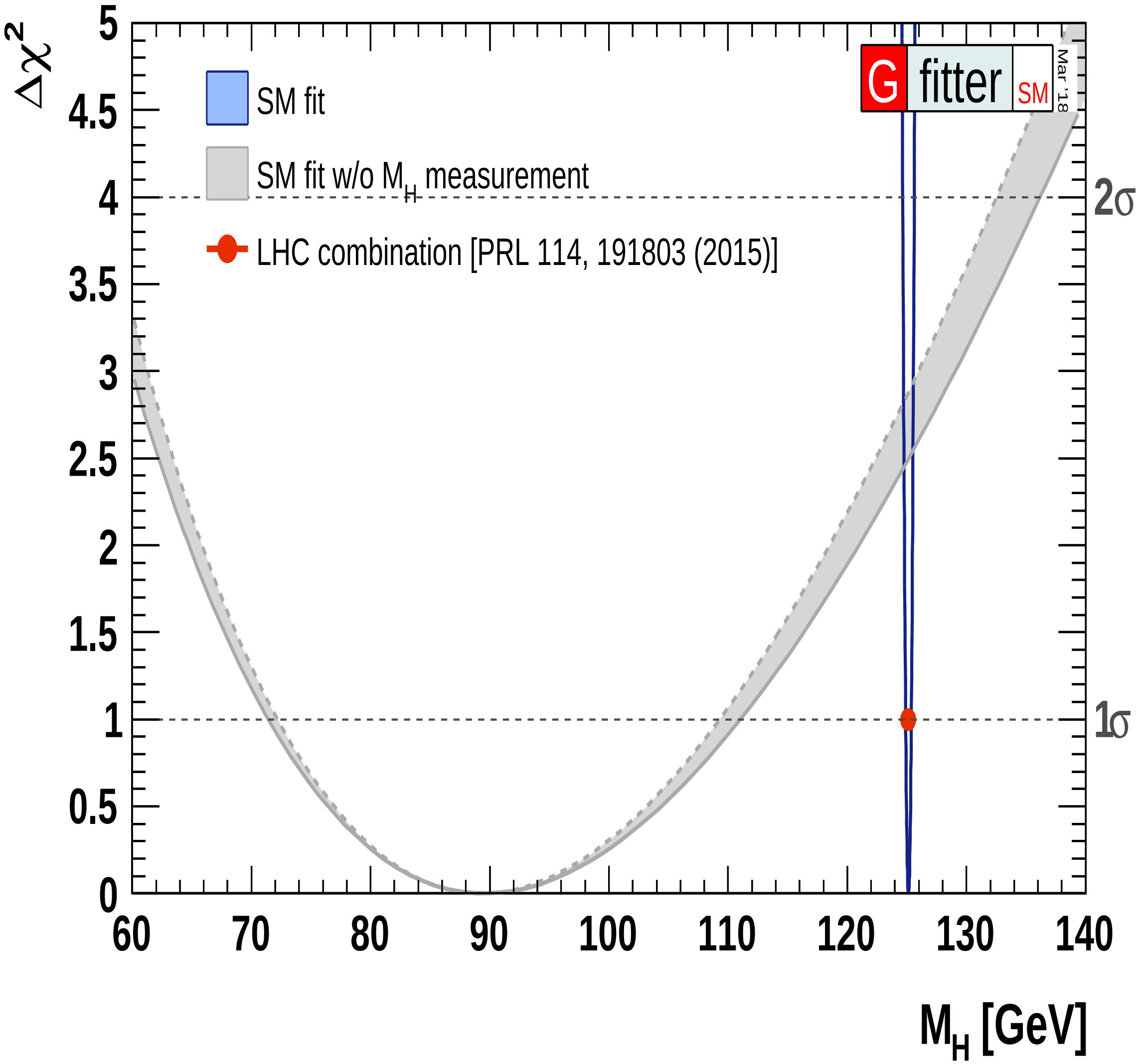


$\Rightarrow M_W^{\rm CDF}$ prefers a too light Higgs mass

Global fit to all SM data:
[*GFitter '18*]

$\Rightarrow M_H = 90^{+21}_{-18}$ GeV

"agreement" at $1.8\,\sigma$



Assumption for the fit:
SM incl. Higgs boson

$\Rightarrow$ no confirmation of
Higgs mechanism

$\Rightarrow M_W^{\text{CDF}}$ would move the fit down substantially

3. Implications for Multi-Higgs models

Models with extended Higgs sectors:

1. SM with addional Higgs singlet
2. Two Higgs Doublet Model (2HDM): type I, II, III, IV
3. 2HDM with singlet extensions: N2HDM, S2HDM, 2HDMS, . . .
4. Minimal Supersymmetric Standard Model (MSSM)
5. MSSM with one extra singlet (NMSSM)
6. MSSM with more extra singlets ($\mu\nu$SSM)
7. SM/MSSM with Higgs triplets
8. . . .

Extended Higgs sectors

Compatibility with the experimental results requires:

- A SM-like Higgs at $\sim$ 125 GeV
- Properties of the other Higgs bosons (masses, couplings,...) have to be such that they are in agreement with the present bounds

The "sum rule": $\sum_i g^2_{h_i VV} = g^2_{H_{\mathrm{SM}} VV}$ – and we know $g^2_{h_{125} VV} \sim g^2_{H_{\mathrm{SM}} VV}$

$\Rightarrow$ not much room left for BSM Higgs couplings to gauge bosons

Sum rule "violated" only by triplets or higher representations ...

Two Higgs Doublet Model (2HDM):

Fields:

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix}$$

Potential:

$$\begin{aligned} V &= m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 \\ &\quad + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + h.c.] \end{aligned}$$

Physical states: h, H, ($\mathcal{CP}$-even), A ($\mathcal{CP}$-odd), $H^\pm$ (charged)

"Physical" input parameters:

$$c_{\beta-\alpha}\,, \quad \tan\beta\,, \quad v\,, \quad M_h, \quad M_H\,, \quad M_A\,, \quad M_{H^\pm}\,, \quad m_{12}^2$$

Assumption (for now): $h \sim h_{125}$

Z_2 symmetry to avoid FCNC:

$$\Phi_1 \to \Phi_1\,,\ \Phi_2 \to -\Phi_2\,,\ \Phi_S \to \Phi_S$$

Extension of the Z_2 symmetry to fermions determines four types:

	u-type	d-type	leptons	
type I	Φ_2	Φ_2	Φ_2	
type II	Φ_2	Φ_1	Φ_1	$\to$ MSSM type
type III (lepton-specific)	Φ_2	Φ_2	Φ_1	
type IV (flipped)	Φ_2	Φ_1	Φ_2	

Sum rule (with h SM-like): $\sin(\beta - \alpha) \approx 1$, $\cos(\beta - \alpha) \approx 0$

Unitarity/perturbativity and EWPO (so far): $\Rightarrow M_A \sim M_H \sim M_{H^\pm}$

Next-Two Higgs Doublet Model (N2HDM): → (nearly) NMSSM type

Fields:

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix}, \; \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix}, \; \Phi_S = v_S + \rho_S$$

Potential:

$$\begin{aligned} V \;=\; & m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 \\ & + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + h.c.] \\ & + \frac{1}{2}m_S^2\Phi_S^2 + \frac{\lambda_6}{8}\Phi_S^4 + \frac{\lambda_7}{2}(\Phi_1^\dagger\Phi_1)\Phi_S^2 + \frac{\lambda_8}{2}(\Phi_2^\dagger\Phi_2)\Phi_S^2 \end{aligned}$$

Z_2 symmetry: $\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2$, $\Phi_S \to \Phi_S$

Z_2' symmetry: $\Phi_1 \to \Phi_1$, $\Phi_2 \to \Phi_2$, $\Phi_S \to -\Phi_S$ (broken by $v_S \Rightarrow$ no DM)

Physical states: h_1, h_2, h_3 ($\mathcal{CP}$-even), A ($\mathcal{CP}$-odd), $H^\pm$ (charged)

Contribution from 2HDM Higgs sector to $\Delta\rho$:

$$\Delta\rho^{(1)}_{\text{non-SM}} = \frac{\alpha}{16\pi^2 s_W^2 M_W^2} \left\{ \frac{m_A^2 m_H^2}{m_A^2 - m_H^2} \ln \frac{m_A^2}{m_H^2} - \frac{m_A^2 m_{H^\pm}^2}{m_A^2 - m_{H^\pm}^2} \ln \frac{m_A^2}{m_{H^\pm}^2} - \frac{m_H^2 m_{H^\pm}^2}{m_H^2 - m_{H^\pm}^2} \ln \frac{m_H^2}{m_{H^\pm}^2} + m_{H^\pm}^2 \right\}$$

$\Rightarrow$ large $\Delta\rho$ needed to accomodate M_W^{CDF}

Before M_W^{CDF}:

$\Rightarrow$ small mass splittings between $m_{H^\pm}$-m_H and $m_{H^\pm}$-m_A

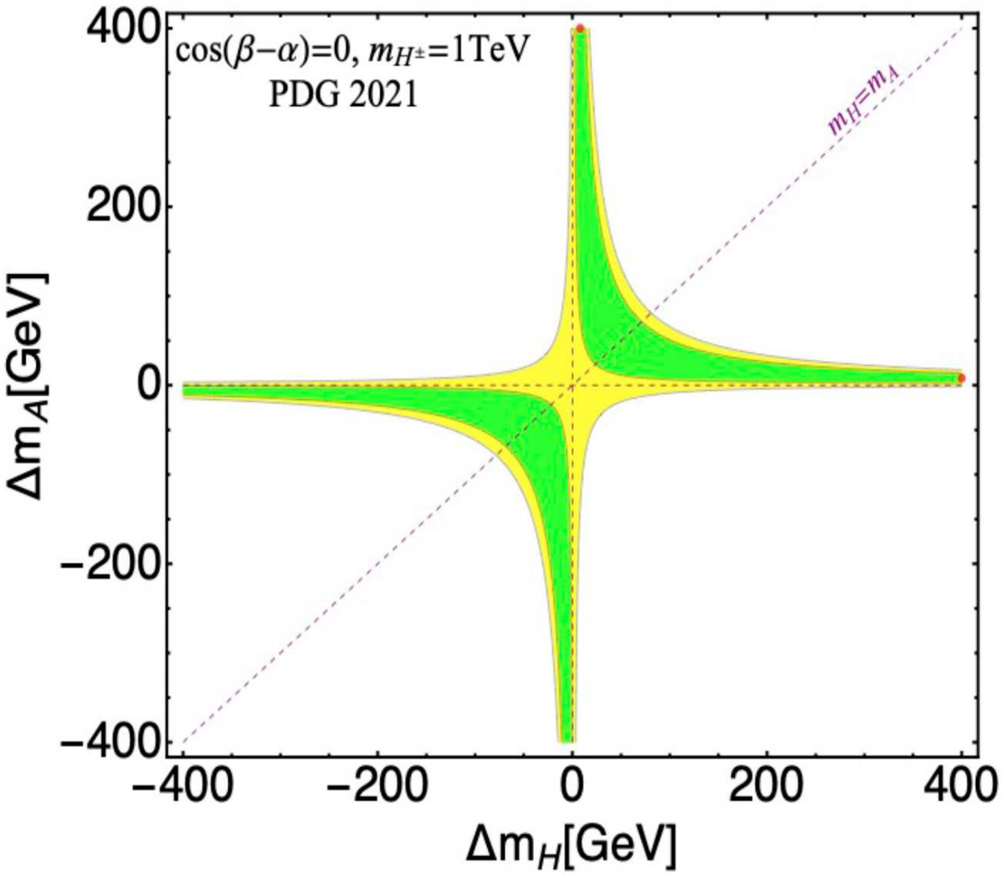
After M_W^{CDF}:

$\Rightarrow$ increased mass splittings to accomodate M_W^{CDF}

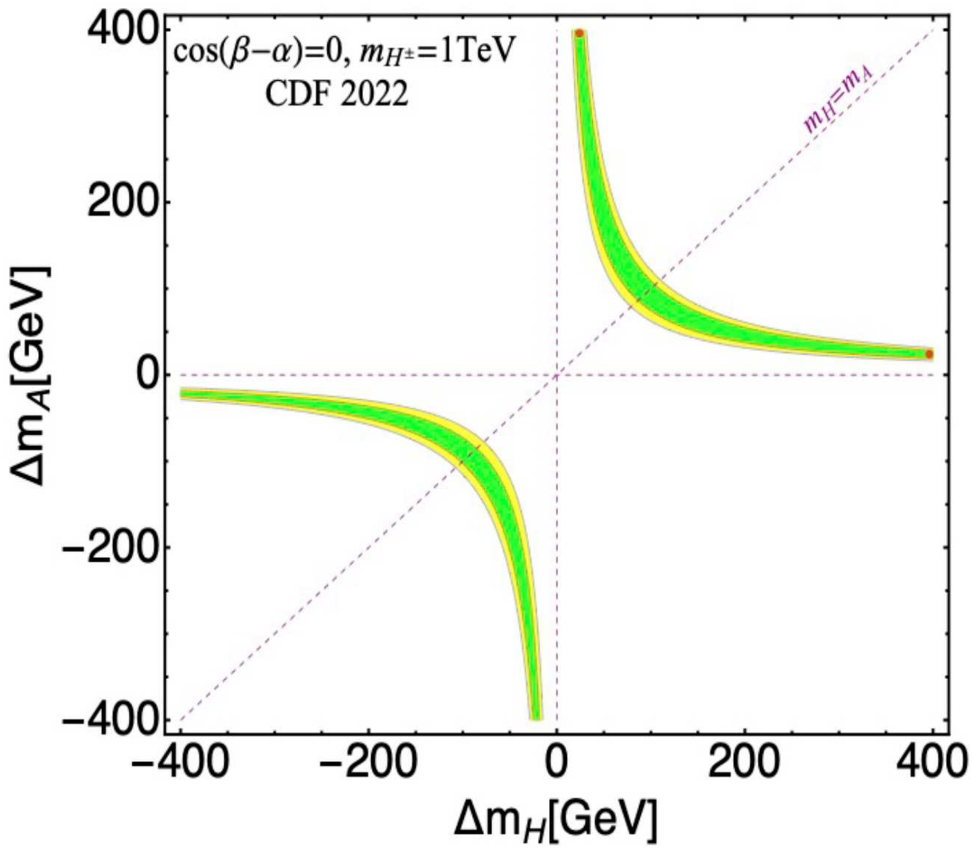
Example: $m_{H^\pm} = 1000$ GeV, $\cos(\beta - \alpha) = 0$

[C. Lu, L. Wu, Y. Wu, B. Zhu '22]

PDG 2021



M_W^{CDF}



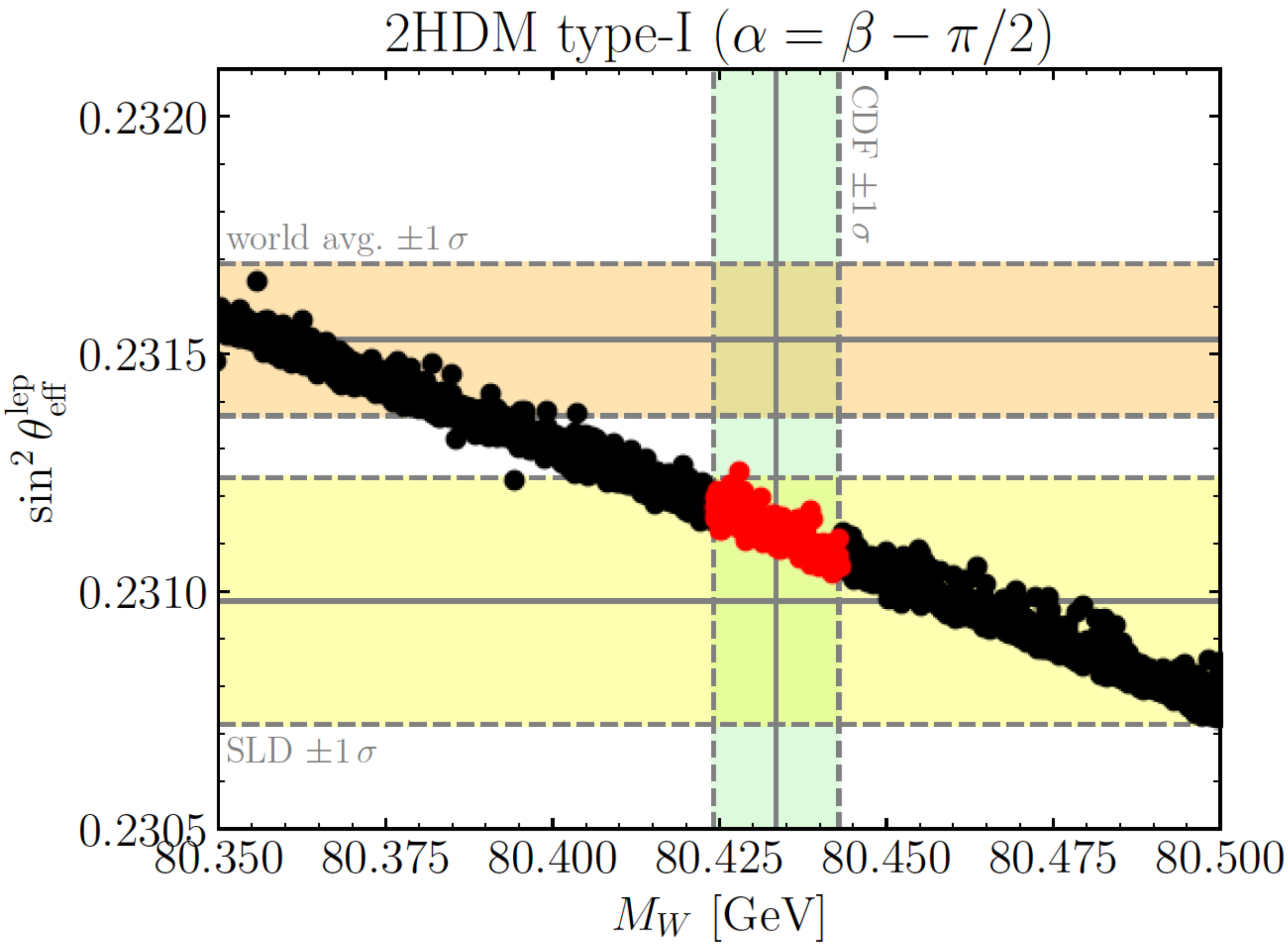
$\Rightarrow$ nearly no overlap of the $2\,\sigma$ regions

$\Leftrightarrow$ new CDF value lies substantially above the PDG value

$\Rightarrow$ new CDF value requires relatively large BSM Higgs mass splitting

M_W^{CDF} vs. $\sin^2\theta_{\text{eff}}$ in the 2HDM

[H. Bahl, J. Braathen, G. Weiglein '22]

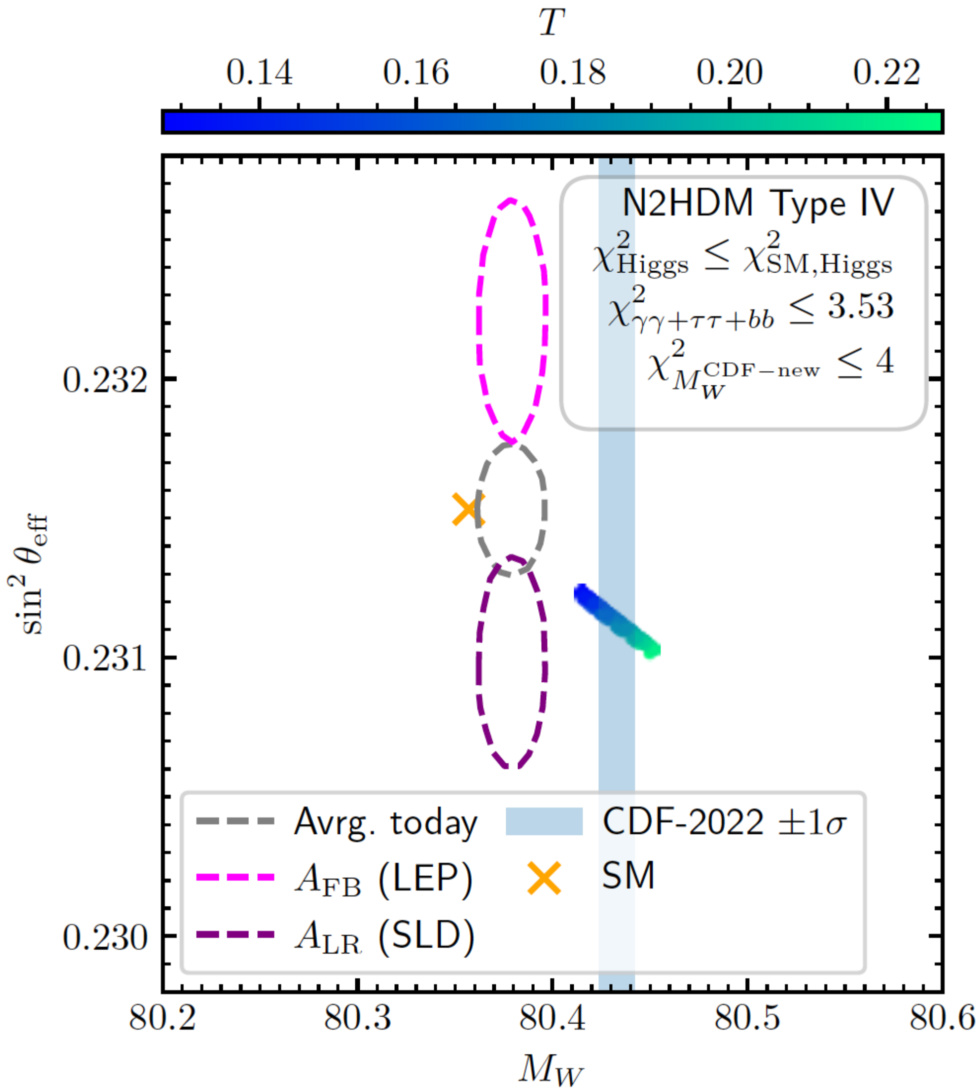


Remember: $\Delta\rho$ goes up $\Rightarrow$ M_W goes up, $\sin^2\theta_{\text{eff}}$ goes down
$\Rightarrow$ agreement only with SLD value of $\sin^2\theta_{\text{eff}}$

M_W^{CDF} vs. $\sin^2\theta_{\text{eff}}$ in the N2HDM

[*T. Biekötter, S.H., G. Weiglein '22*]

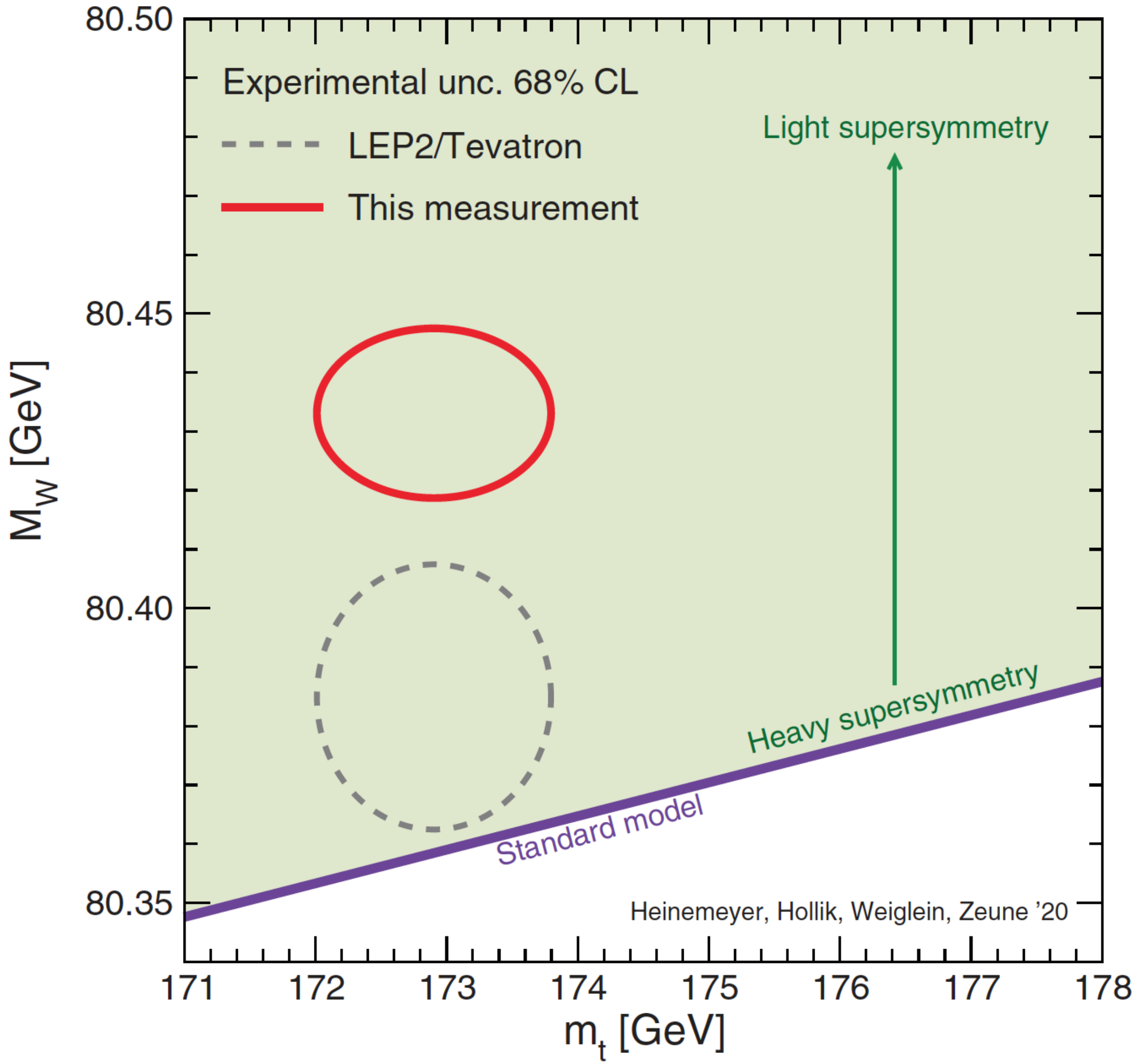
$\Rightarrow$ N2HDM favored by 3 independent excesses in Higgs searches at $\sim$ 95 GeV



Remember: $\Delta\rho$ goes up $\Rightarrow M_W$ goes up, $\sin^2\theta_{\text{eff}}$ goes down

$\Rightarrow$ agreement only with SLD value of $\sin^2\theta_{\text{eff}}$

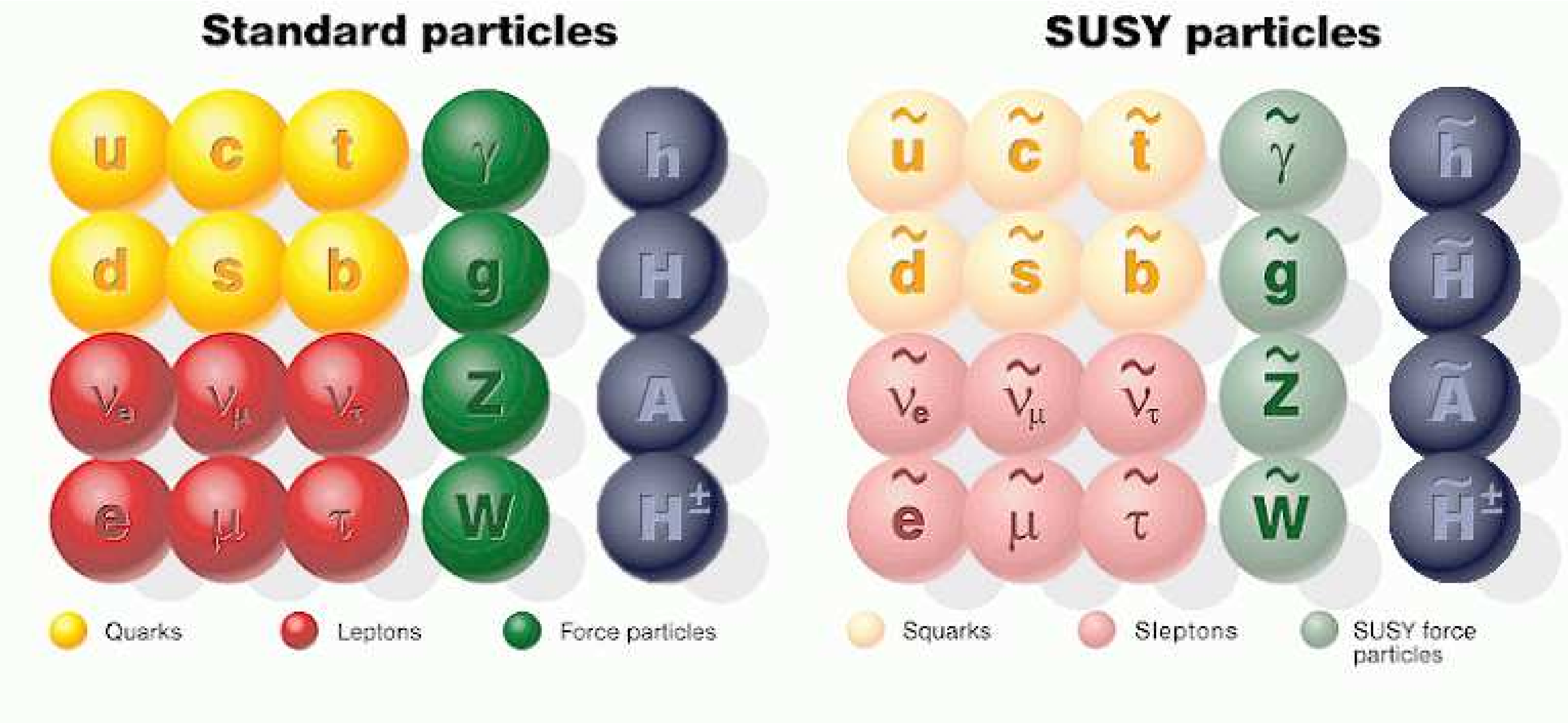
4. Implications for SUSY [CDF / S.H., W. Hollik, G. Weiglein, L. Zeune '20]



Q: Can SUSY fit the new CDF value of M_W?

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles



⇒ SUSY partners for SM particles

⇒ Important here: scalar tops and scalar bottoms

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

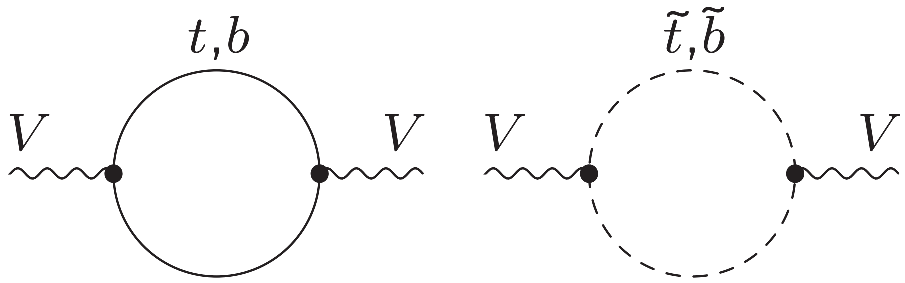
ρ measures the relative strength between
neutral current interaction and charged current interaction

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

(leading, process independent terms)

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

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



$\Delta\rho^{\rm SUSY}$ from $\tilde{t}/\tilde{b}$ loops > 0 $\quad\Rightarrow M_W^{\rm SUSY} \gtrsim M_W^{\rm SM}$

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

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

– full one-loop
– full two-loop
– leading 3-loop via $\Delta\rho$
– leading 4-loop via $\Delta\rho$

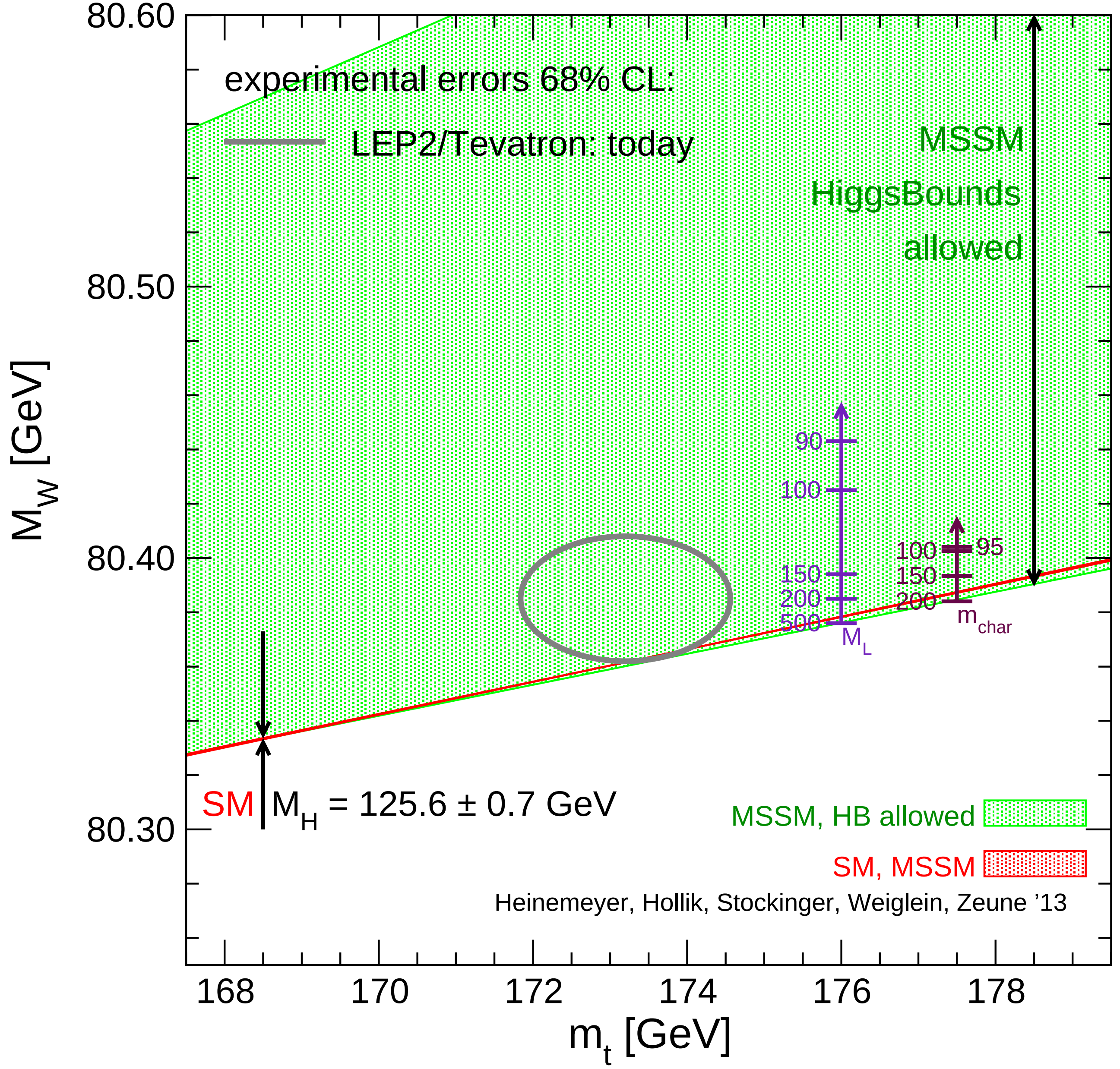
Our MSSM result for M_W and $\sin^2\theta_{\text{eff}}$:

– full SM result (via fit formel)
– full MSSM one-loop (incl. complex phases)
– all existing two-loop $\Delta\rho$ contributions

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

Effects of charginos and sleptons:

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



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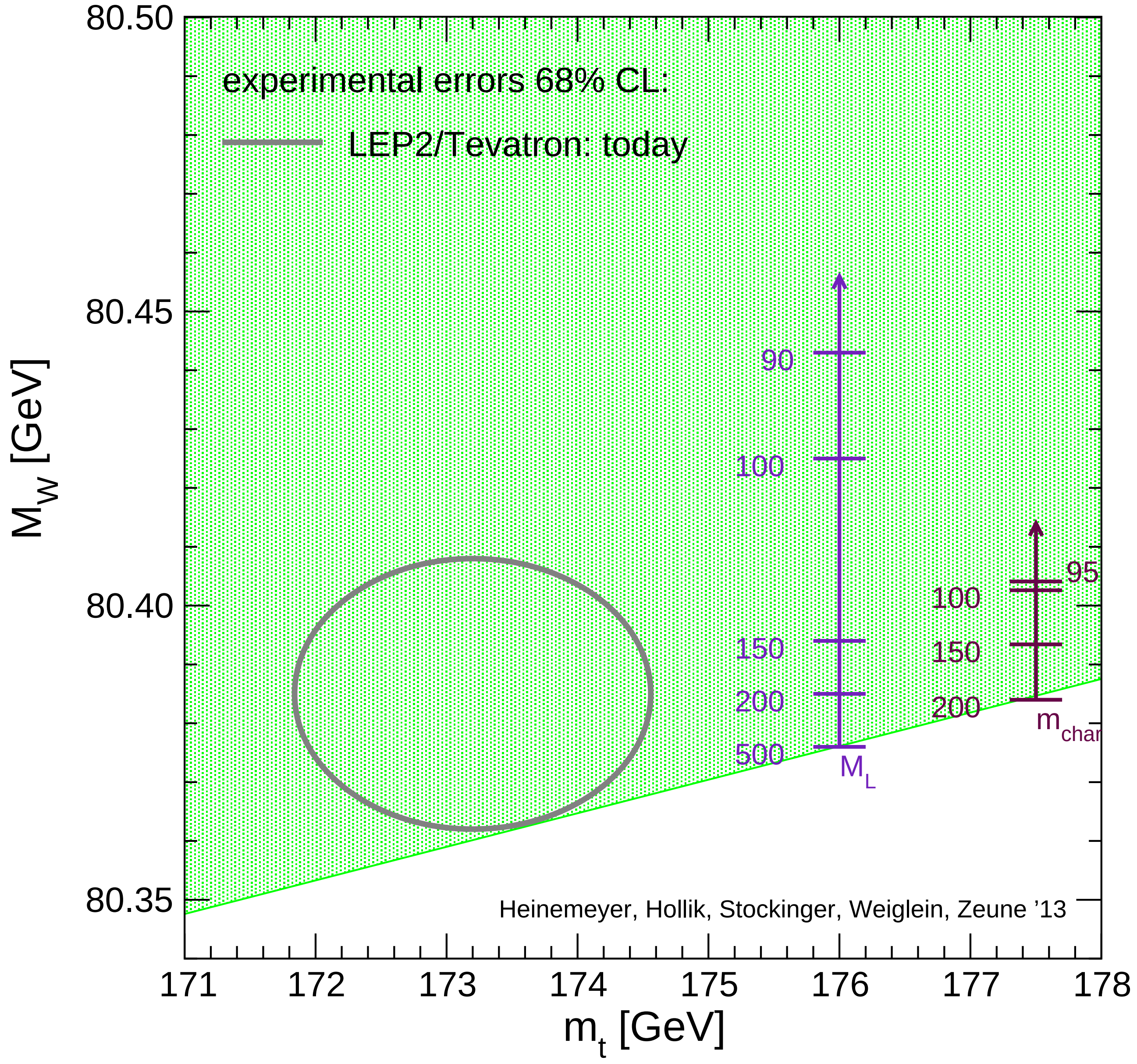


The general idea: [E. Bagnaschi, M. Chakraborti, S.H., I. Saha, G. Weiglein '20-'22]

1. What are the limits on the EW SUSY sector?
2. What does this say about M_W?

– scan the relevant EW SUSY parameter space

– impose all relevant experimental constraints:
  – $(g-2)_\mu$
  – Dark Matter relic density
  – Dark Matter direct detection
  – LHC searches for EW particles

– Dark Matter relic density requires a mechanism to reduce the density in the early universe
  – bino/wino DM with chargino co-annihilation
  – bino DM with slepton co-annihilation
  – higgsino DM
  – wino DM

– obtain lower and upper limits on the various EW particle masses

⇒ evaluate M_W

Results for (nearly) all SUSY scenarios

A) bino/wino DM with chargino co-annihilation ($M_1 \sim M_2 \lesssim \mu$)
relic DM density 100% fulfilled
$\Rightarrow m_{\text{(N)LSP}} \lesssim$ 650(700) GeV

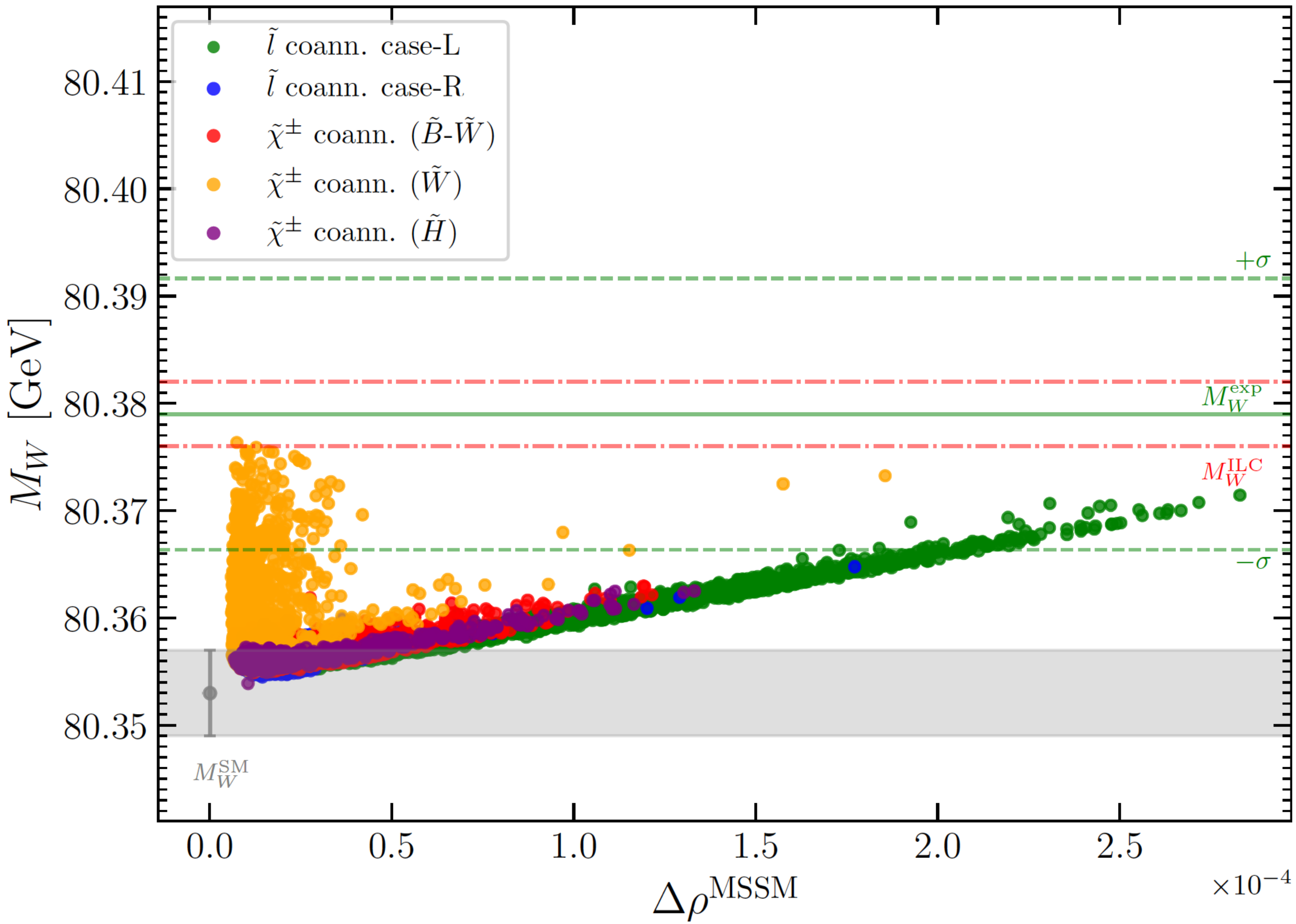
B/C) bino DM with slepton co-annihilation ($M_1 \lesssim M_2, \mu$)
relic DM density 100% fulfilled
$\Rightarrow m_{\text{(N)LSP}} \lesssim$ 650(700) GeV

D) higgsino DM: $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_2^0} \sim m_{\tilde{\chi}_1^\pm} \sim \mu$ ($\mu \lesssim M_1, M_2$)
relic DM density as upper limit (otherwise $m_{\tilde{\chi}_1^0} \sim 1$ TeV)
$\Rightarrow m_{\text{(N)LSP}} \lesssim$ 500 GeV

E) wino DM: $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_1^\pm} \sim M_2$ ($M_2 \lesssim M_1, \mu$)
relic DM density as upper limit (otherwise $m_{\tilde{\chi}_1^0} \sim 3$ TeV)
$\Rightarrow m_{\text{(N)LSP}} \lesssim$ 600 GeV

$\Rightarrow$ predictions for M_W?

Prediction for M_W: [E. Bagnaschi, M. Chakraborti, S.H., I. Saha, G. Weiglein '20-'22]



⇒ EW sector gives a large contribution to M_W

⇒ but far away from $M_W^{\rm CDF}$ ⇒ contributions from stops/sbottoms needed!

M_W: Effects of SUSY masses: [S.H., G. Weiglein, L. Zeune '13]

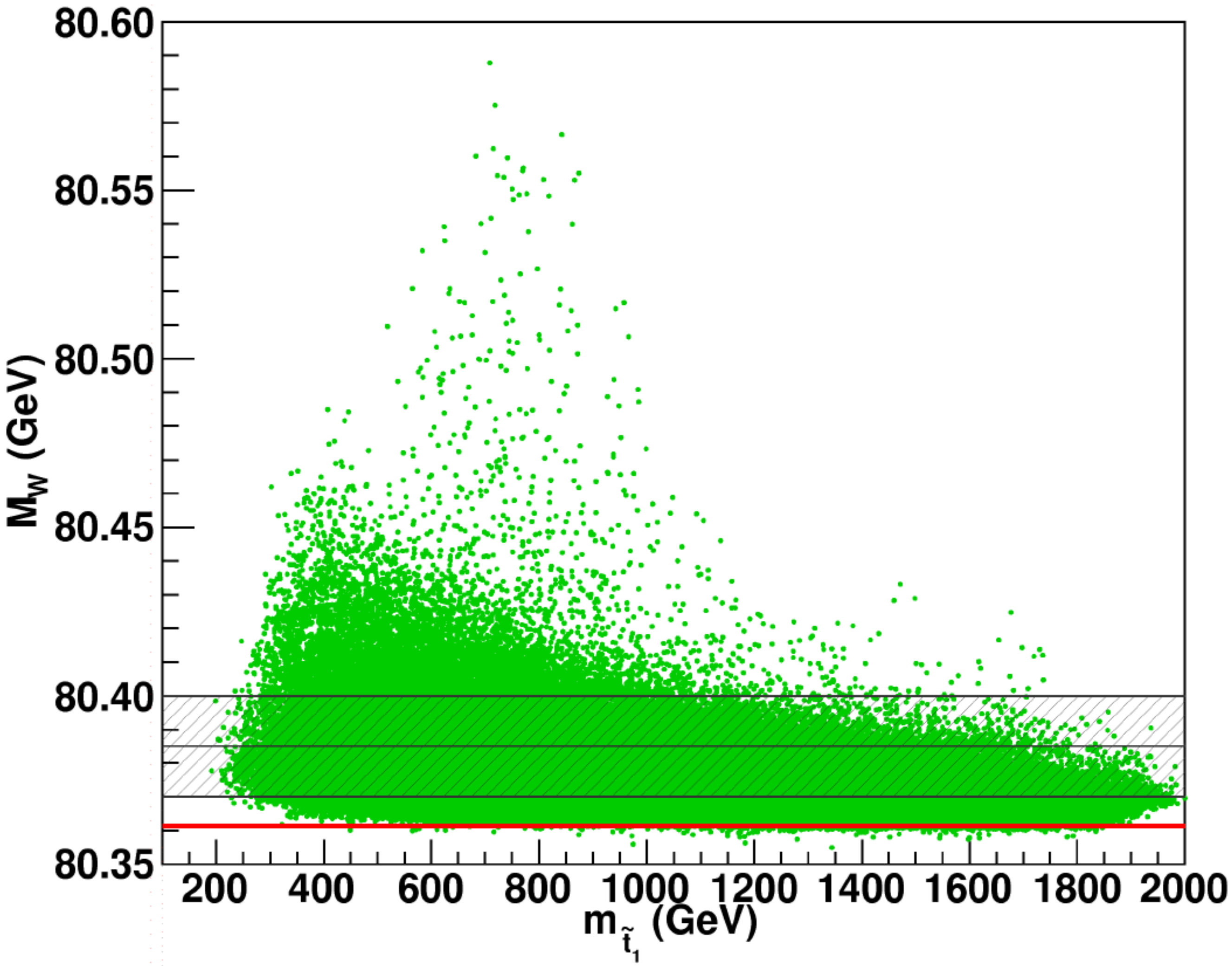
$\Rightarrow$ extensive parameter scan:

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

Additional (artificial) requirement: $2/5 \leq m_{\tilde{t}_i}/m_{\tilde{b}_j} \leq 5/2$

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

$\Rightarrow$ larger M_W without $(2/5 \leq m_{\tilde{t}_i}/m_{\tilde{b}_j} \leq 5/2)$

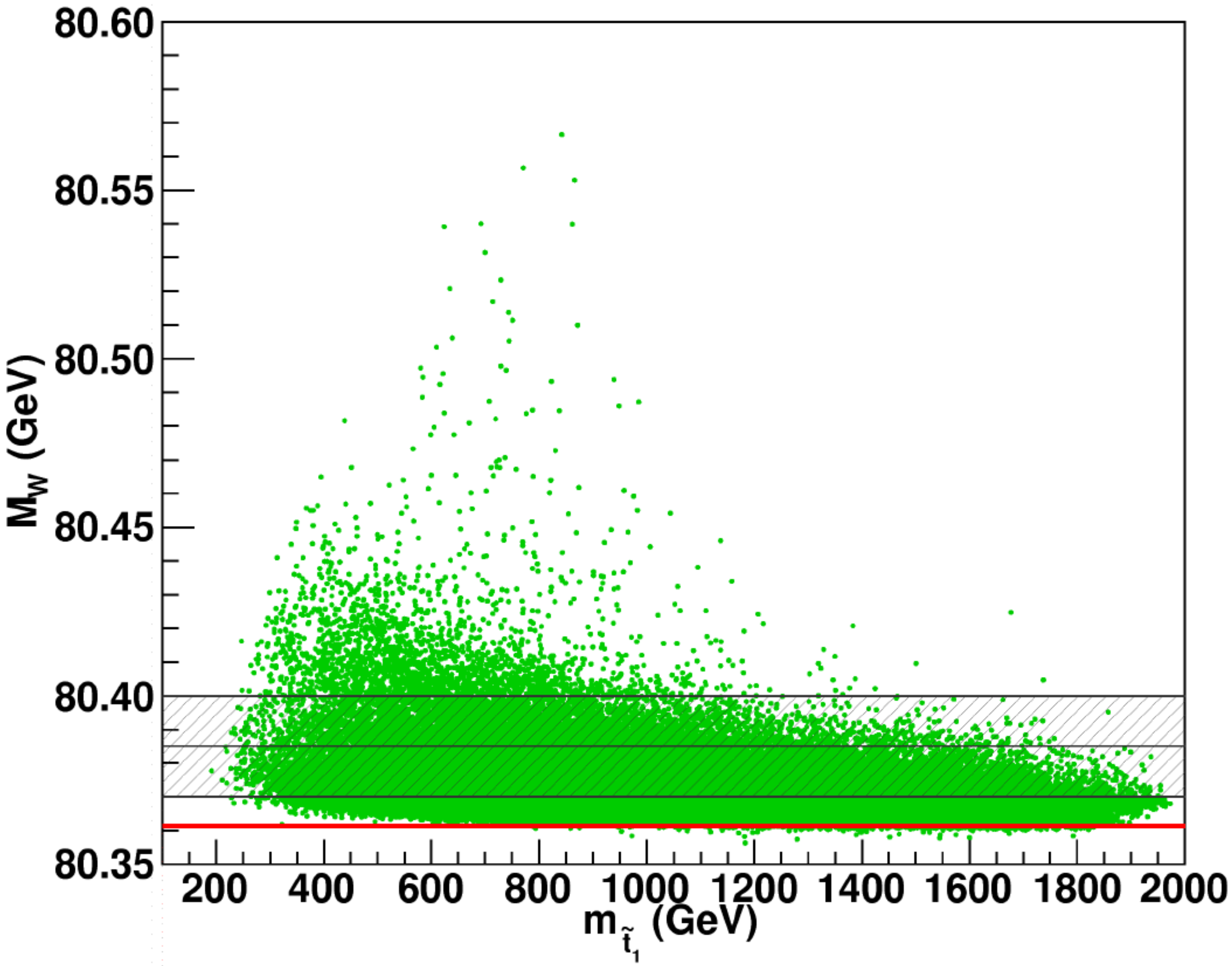


All points HiggsBounds allowed

Effects of stops:

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

$\Rightarrow$ larger M_W without $(2/5 \leq m_{\tilde{t}_i}/m_{\tilde{b}_j} \leq 5/2)$

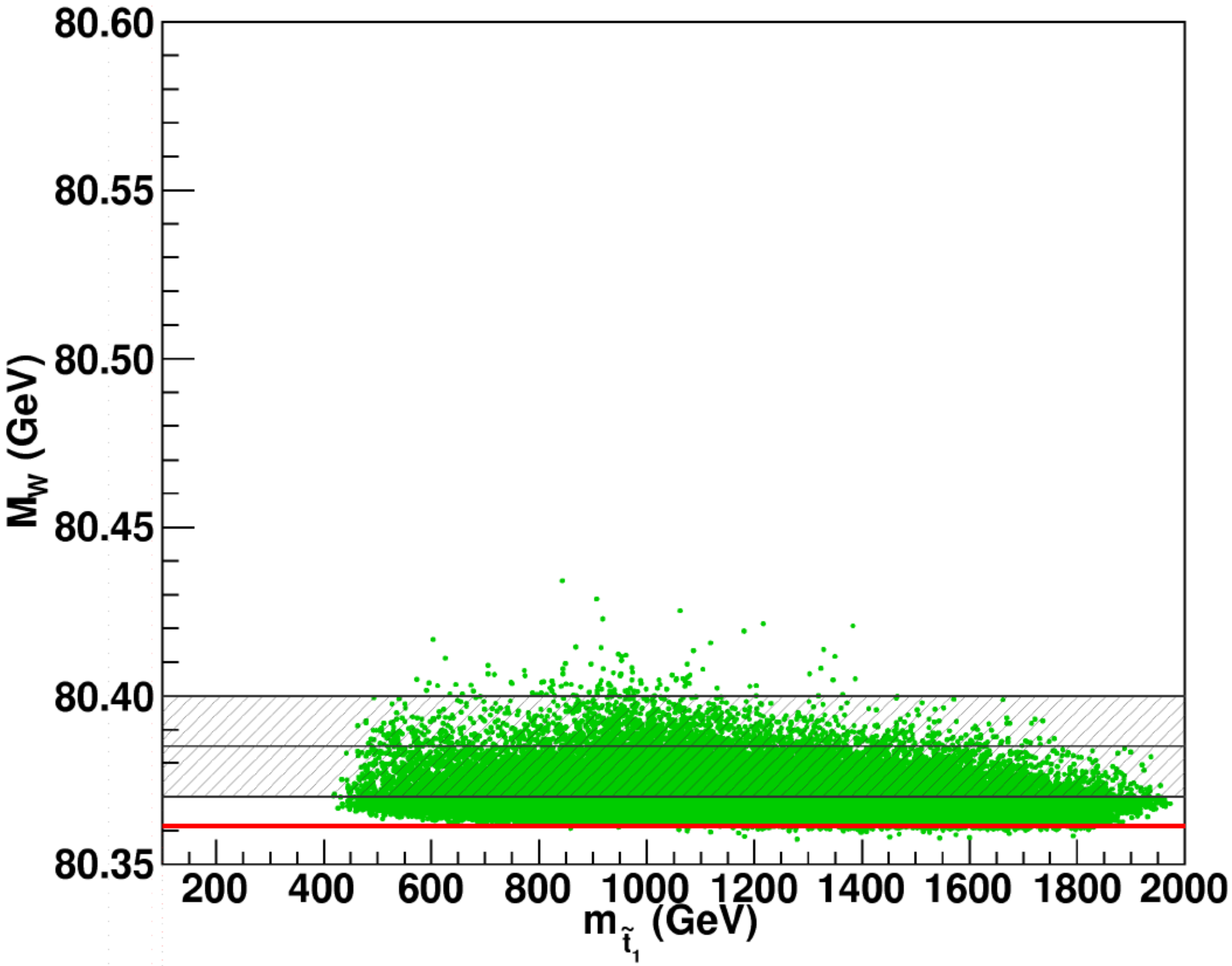


$\ldots \oplus\ m_{\tilde{q}_{1,2}}, m_{\tilde{g}} > 1200$ GeV

Effects of stops:

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

$\Rightarrow$ larger M_W without $(2/5 \le m_{\tilde{t}_i}/m_{\tilde{b}_j} \le 5/2)$



$\ldots \oplus\ m_{\tilde{b}_i} > 500$ GeV $\Rightarrow$ stop/sbottom effects can give rise to M_W^{CDF}!

Final example: MRSSM

[P. Diessner, J. Kalinowski, W. Kotlarski, D. Stöckinger '14]

$\Rightarrow$ minimal R-symmetric SUSY model (MRSSM)

$\to$ contains Dirac gauginos and higgsinos
and a $Y = 0$, $SU(2)_L$ Higgs triplet T

v_T: vev of the triplet

$\Rightarrow$ tree-level contribution to M_W:

$$M_W^2 := M_Z^2 c_\mathrm{W}^2 + g_2^2 v_T$$

or equivalently

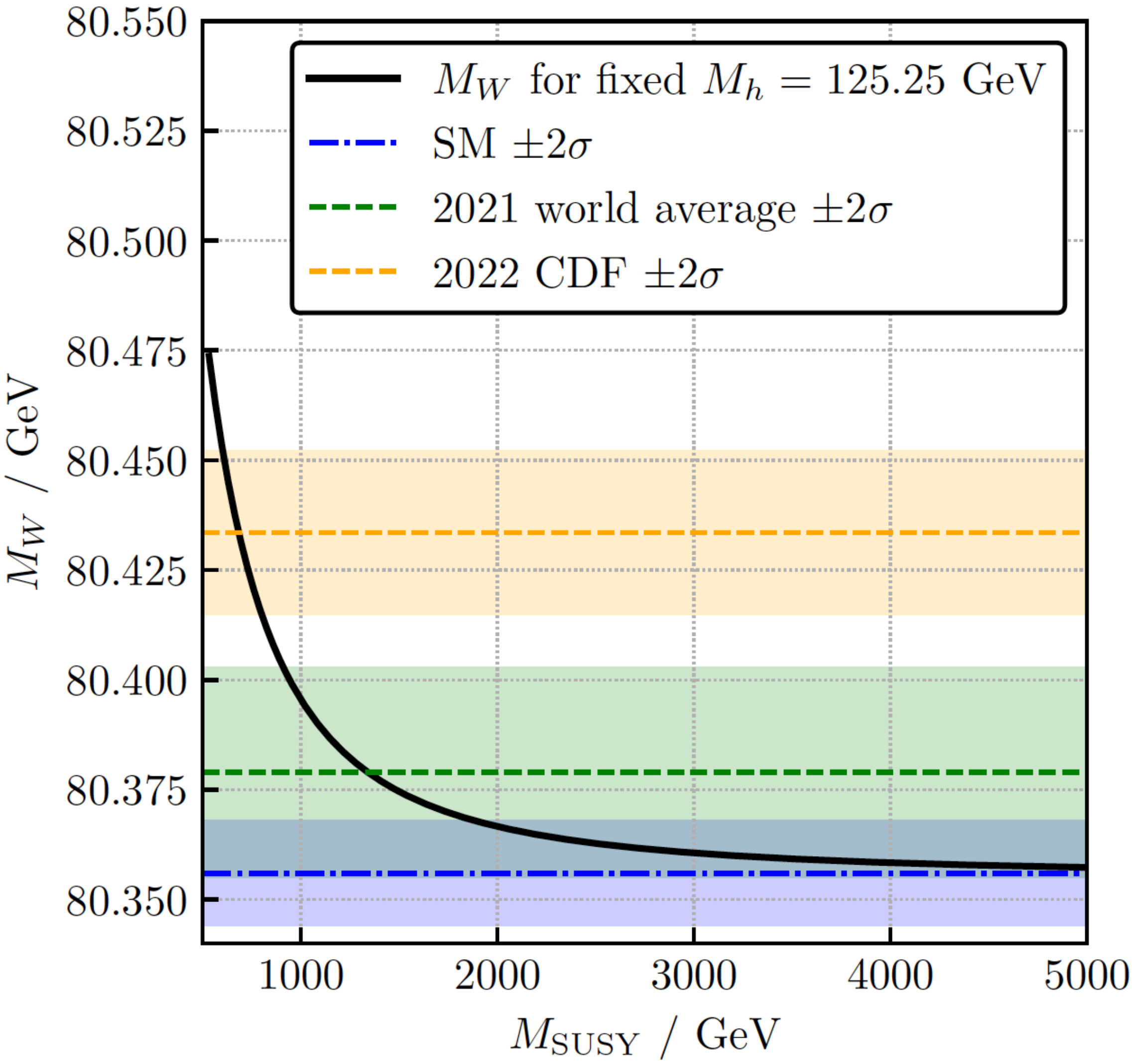
$$\rho_\mathrm{tree} := 1 + \frac{4v_T^2}{v_1^2 + v_2^2}$$

$\Rightarrow$ easier to reach M_W^CDF

M_W prediction in the MRSSM:

[*P. Athron, M. Bach, D. Jacob, W. Kotlarski, D. Stöckinger, A. Voigt '22*]

$\Rightarrow$ point with small "genuine SUSY" contributions to M_W:



$\Rightarrow$ large tree-level effects possible

5. Conclusions

- M_W^{CDF} shows a large discrepancy with the SM prediction
  but also with other experimental measurements

- SM and BSM: M_W can be calculated from μ decay
  Approximations: S, T, U or only $\alpha T \equiv \Delta\rho$
  $\Rightarrow$ large $\Delta\rho$ required to describe M_W^{CDF}

- SM is inconsistent with M_W^{CDF} $\Leftrightarrow$ too low M_H required

- 2HDM/N2HDM: large BSM Higgs mass splitting needed
  to describe M_W^{CDF}
  $\Rightarrow$ possible, but then potential problems with $\sin^2\theta_{\text{eff}}$

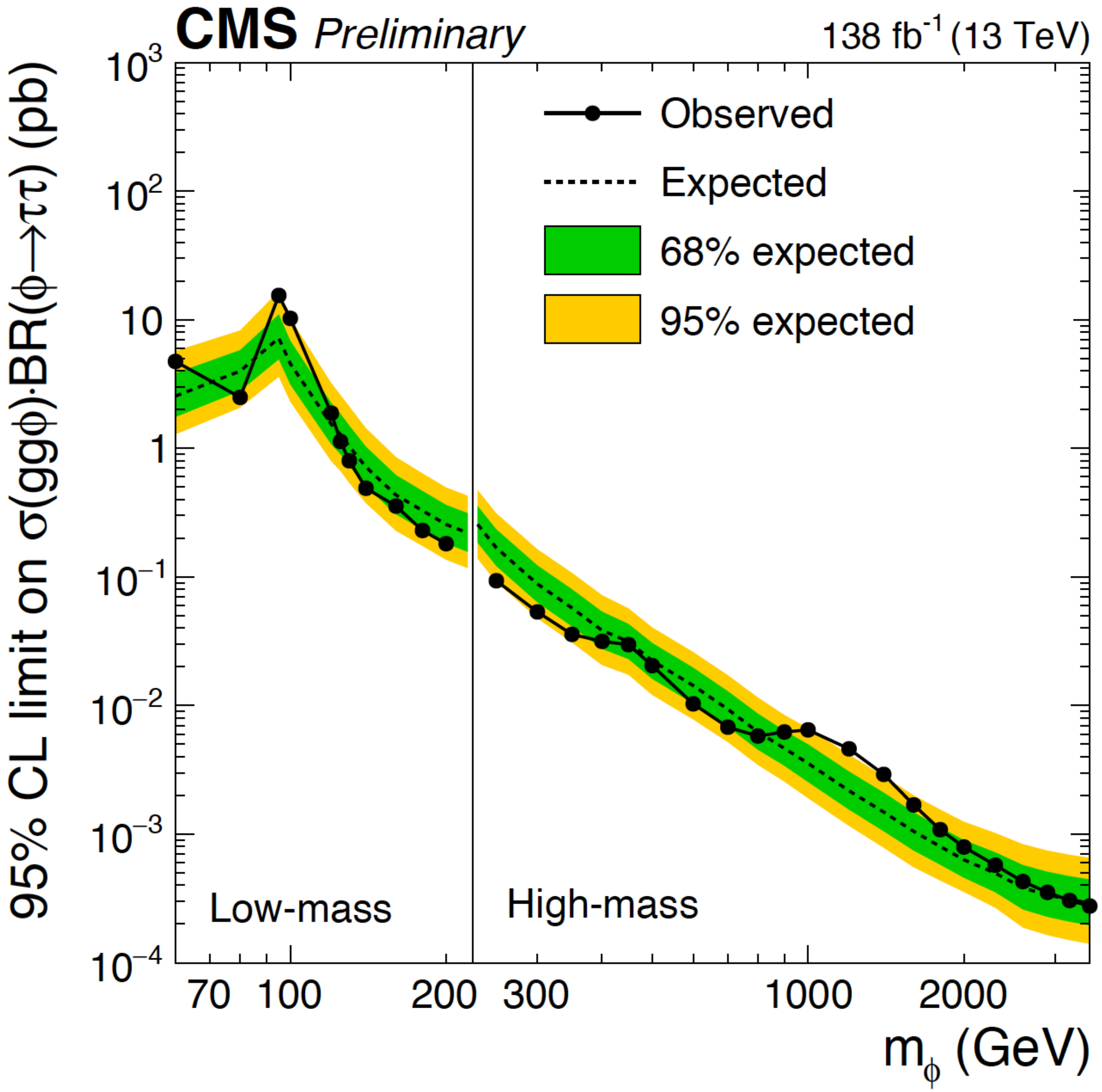
- MSSM: large stop/sbottom contributions can accommodate M_W^{CDF}
  $\Rightarrow$ possible, but then potential problems with $\sin^2\theta_{\text{eff}}$

- More work from **ALL** sides needed to clarify the situation


Further Questions?

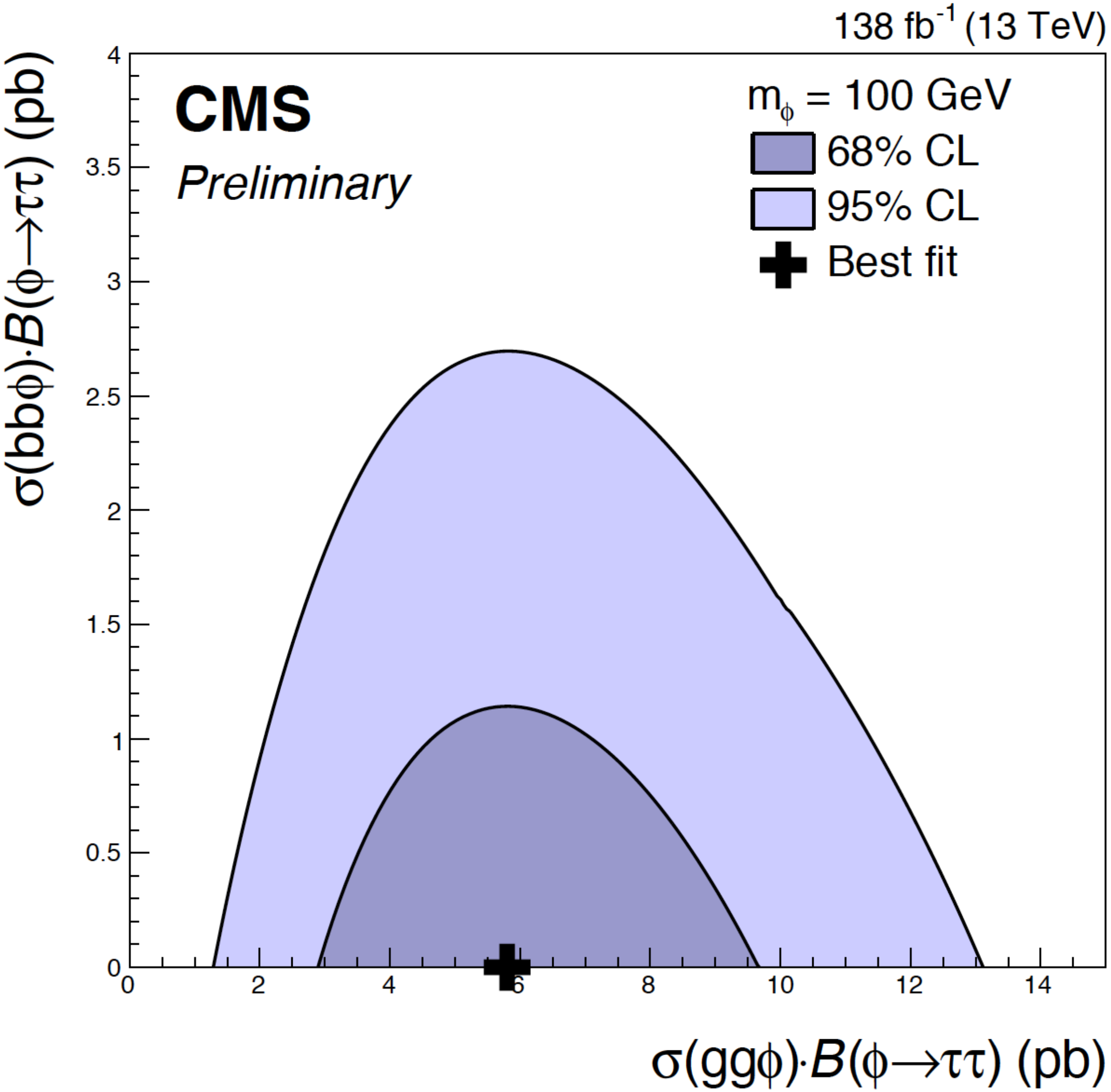
The new $\tau^+\tau^-$ excess

[CMS '22]



Can you spot the excess? At 95 – 100 GeV?

Better visible here, focusing on 100 GeV: [*CMS '22*]



$\Rightarrow$ clear excess of $\sim 3\,\sigma$ at ~ 100 GeV

Now we have three excesses at ~ 95 GeV

$$\mu_{bb}^{\text{exp}} = 0.117 \pm 0.057, \quad {\mu_{\gamma\gamma}}^{\text{exp}} = 0.6 \pm 0.2, \quad {\mu_{\tau\tau}}^{\text{exp}} = 1.2 \pm 0.5$$

corresponding to

$$\mu_{bb}^{\text{exp}} \sim 2\,\sigma, \quad \mu_{\gamma\gamma}^{\text{exp}} \sim 3\,\sigma, \quad \mu_{\tau\tau}^{\text{exp}} \sim 2.4\,\sigma$$

Three (effectively) independent channels

$\Rightarrow$ no LEE (as theorist I am allowed to add naively)

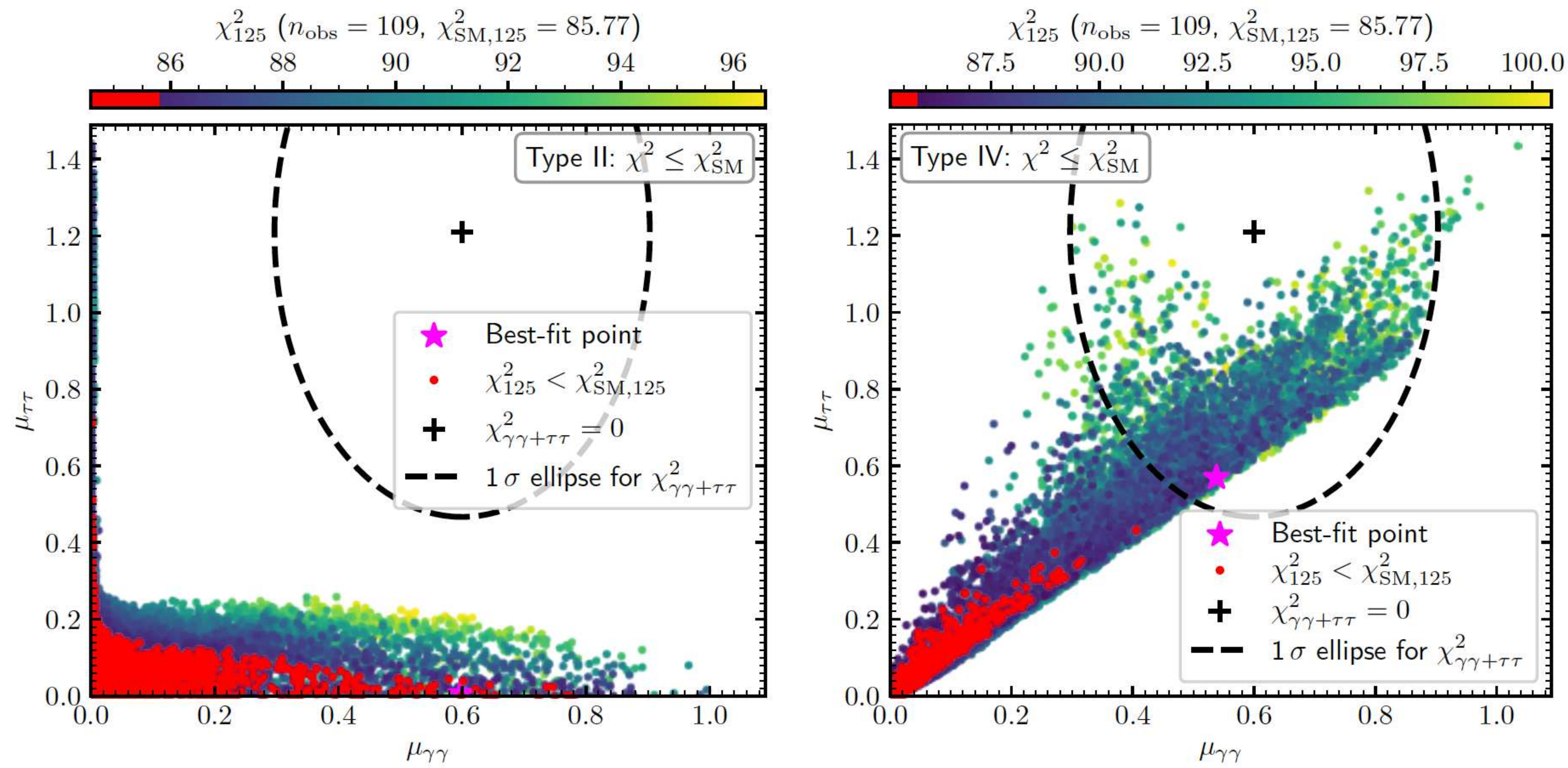
$$\boxed{\Rightarrow \sim 4.3\,\sigma}$$

$$\chi^2_{95} = \frac{(\mu_{bb}^{\text{theo}} - 0.117)^2}{(0.057)^2} + \frac{(\mu_{\gamma\gamma}^{\text{theo}} - 0.6)^2}{(0.2)^2} + \frac{(\mu_{\tau\tau}^{\text{theo}} - 1.2)^2}{(0.5)^2}$$

Can we fit all excesses together?

N2HDM type II vs. type IV

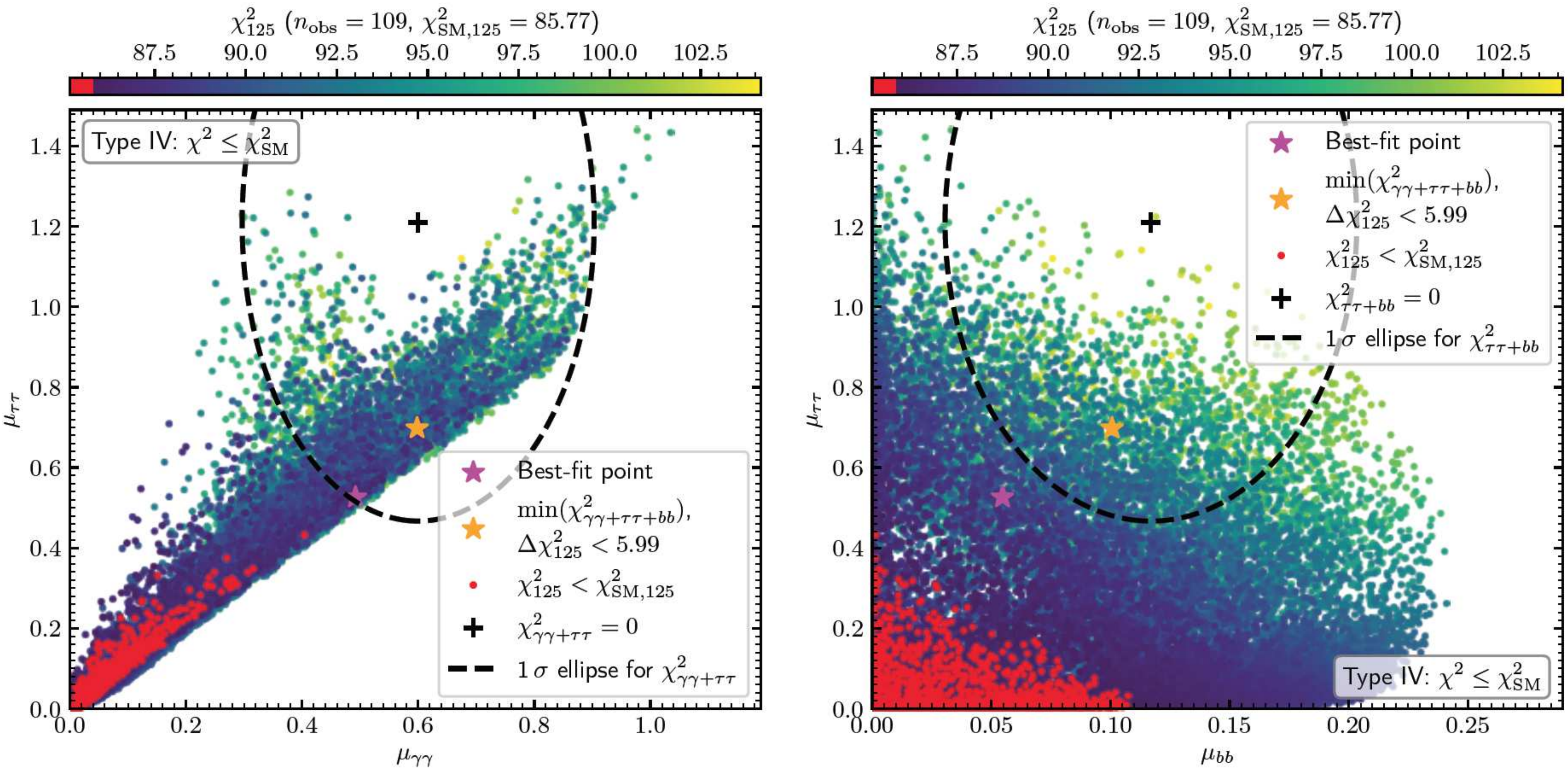
[*T. Biekötter, S.H., G. Weiglein '22*]



Color coding: χ^2_{125} from HiggsSignals

$\Rightarrow$ only type IV can fit the $\gamma\gamma$ and $\tau\tau$ excesses

N2HDM type IV: fitting all three excesses: [*T. Biekötter, S.H., G. Weiglein '22*]

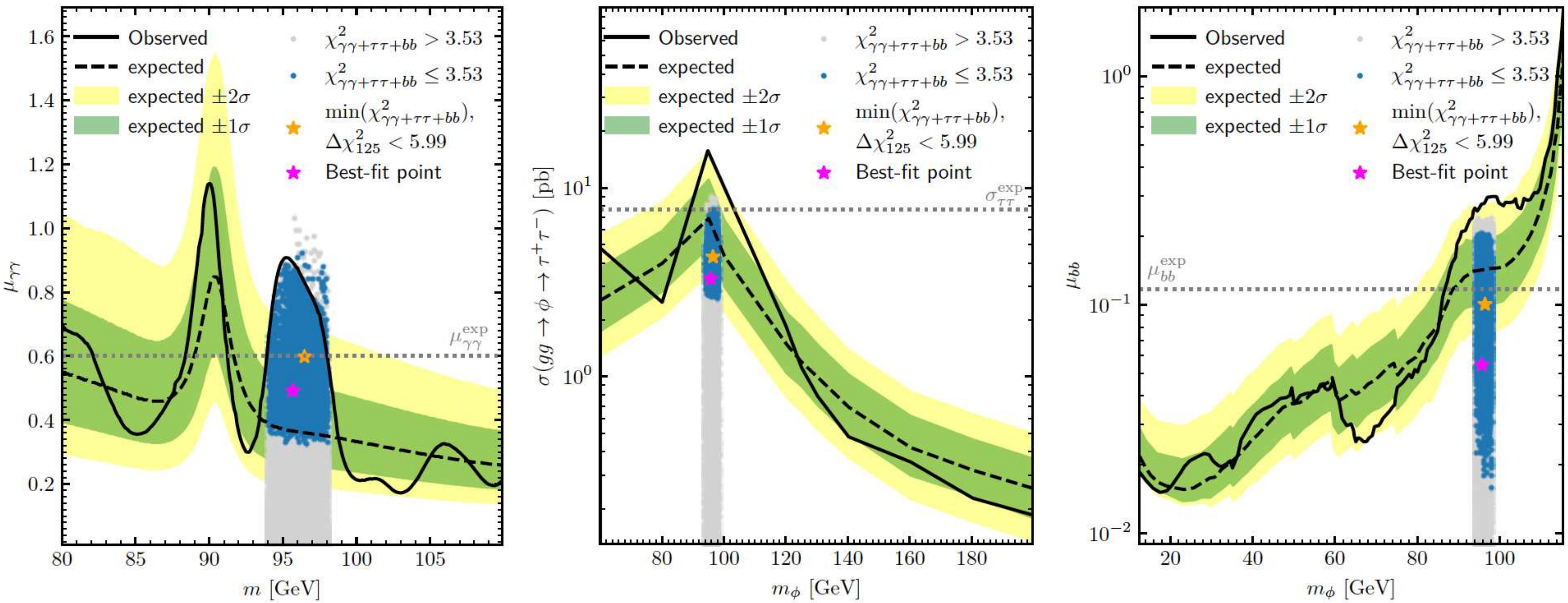


Color coding: χ^2_{125} from HiggsSignals

$\Rightarrow$ type IV can fit the $\gamma\gamma$, $\tau\tau$ and bb excesses

N2HDM type IV: fitting all three excesses: [*T. Biekötter, S.H., G. Weiglein '22*]

$pp \to h_{95} \to \gamma\gamma$ $\quad$ $gg \to h_{95} \to \tau^+\tau^-$ $\quad$ $e^+e^- \to Zh_{95} \to Zb\bar{b}$



gray lines: central values of excesses

$\Rightarrow$ type IV can fit the $\gamma\gamma$, $\tau\tau$ and bb excesses very well