M_W in the 2HDM in light of the CDF II result

Based on

arXiv:2204.05269 in collaboration with Henning Bahl and Georg Weiglein

Johannes Braathen

2HDM Working Group | May 12, 2022

Outline of the talk

- Why the interest for M_W ?
- The CDF measurement of M_W
- Computing the W-boson mass in the SM and beyond
- Solving the W-boson mass discrepancy at loop level → case of the 2HDM
- Our results in the 2HDM
- Conclusions

M_W and the CDF result

M_W as an Electroweak Precision Observable (EWPO)

- **Electroweak precision observables**, including
  - **W-boson mass M_W**
  - (Squared sine of) Effective leptonic weak mixing angle $\sin^2\theta_{eff}^{lep}$
  - Z-boson decay width Γ_Z
  - Muon anomalous magnetic moment $(g-2)_\mu$

  etc.

  are **measured** very precisely, and can also be **computed** to high level of accuracy in terms of **G_F, $\alpha(0)$, M_Z** (most precisely measured EW quantities) and m_h, m_t, α_S, $\Delta\alpha_{had}$, $\Delta\alpha_{lept}$, m_b, etc.

- Allow testing the SM as well as BSM models

- Before April, experimental *world average* was [PDG 2020]
  M_W^{exp} = 80 379 ± 12 MeV

- *SM prediction* (full 1L+2L, partial 3L and 4L, see e.g. [Awramik, Czakon, Freitas, Weiglein '03])
  M_W^{SM} = 80 353 ± 4 MeV (taken from [Bagnaschi, Chakraborti, Heinemeyer, Saha, Weiglein '22])
  → **already a small discrepancy!**

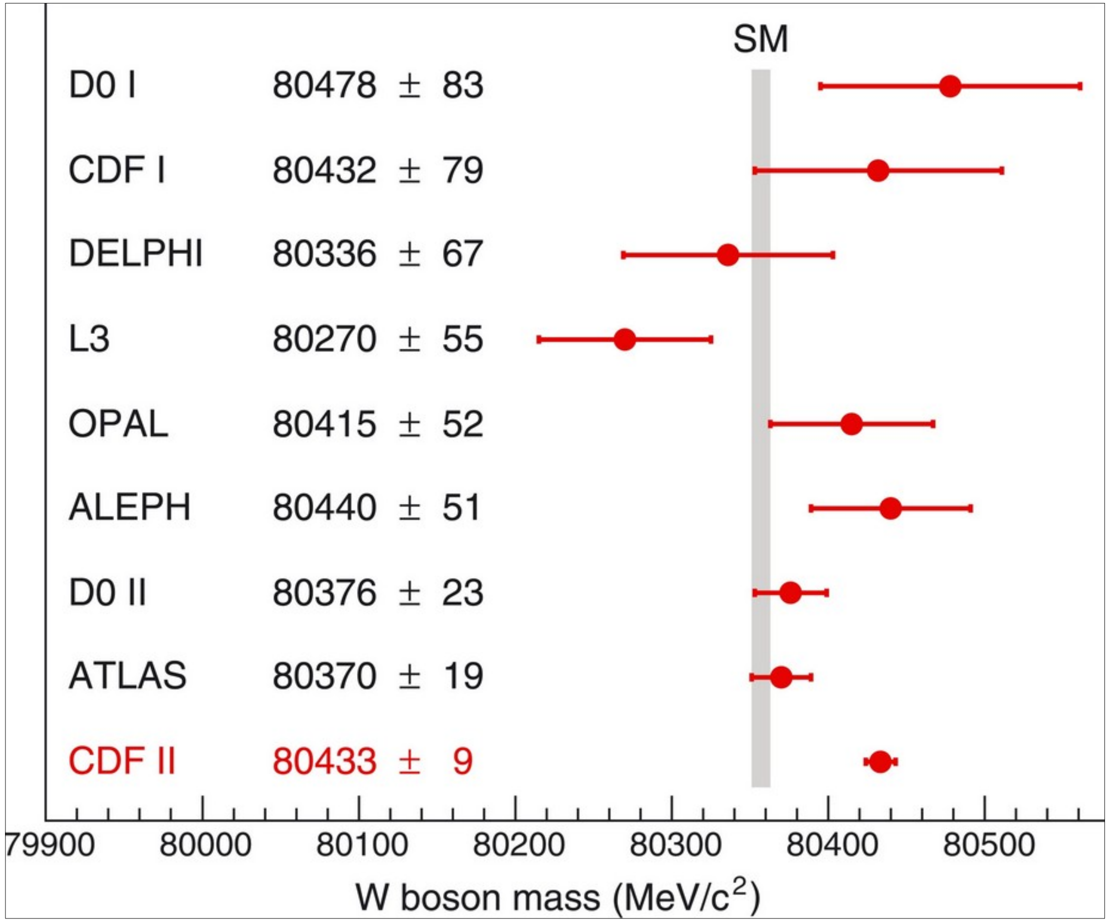
CDF measurement of M_W

Science **376**, 170 (2022)

- April 7, 2022: CDF collaboration at Fermilab Tevatron released a measurement of MW, using 8.8fb^{-1} of data taken between 2002 and 2011

$$M_W = 80\,433 \pm 9 \text{ MeV}$$

- Most precise result from a *single experiment*
- **CDF value is ~7σ away from SM prediction!**
- Tevatron (claimed) advantages over LHC
  - $p\bar{p}$ collisions rather than pp → processes involve mainly (anti)quark momentum distributions (PDFs), which are better known than that of gluons → lower uncertainty than processes at LHC
  - Lower centre-of-mass energy
    → PDFs known more precisely at low √s
    → less QCD backgrounds



Some concerns raised about the CDF measurement of M_W

- Several points in the CDF analysis have drawn criticisms/skepticisms (see also colloquium by J. Ellis on 3/5)
  - Measurement of lepton momenta
  - Version of ResBos used to model p_T (v1 used rather than v2)
  - Version of PDF and their uncertainties

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  - Version of PDF and their uncertainties

ResBos2 and the CDF W Mass Measurement

Joshua Isaacson,[1,*] Yao Fu,[2] and C.-P. Yuan[3]

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[3] *Department of Physics and Astronomy, Michigan State University, 567 Wilson Road, East Lansing, MI 48824, USA*

The recent CDF W mass measurement of 80,433 ± 9 MeV is the most precise direct measurement. However, this result deviates from the Standard Model predicted mass of 80,359.1 ± 5.2 MeV by 7σ. The CDF experiment used an older version of the ResBos code that was only accurate at NNLL+NLO, while the state-of-the-art ResBos2 code is able to make predictions at N^{3}LL+NNLO accuracy. We determine that the data-driven techniques used by CDF capture most of the higher order corrections, and using higher order corrections would result in a decrease in the value reported by CDF by at most 10 MeV.

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Understanding PDF uncertainty on the W boson mass measurements in CT18 global analysis

Jun Gao,[1,2,*] DianYu Liu,[1,2,†] and Keping Xie[3,‡]

δM_W in MeV	sta.	NNPDF3.1	CT18	MMHT14	NNPDF4.0	MSHT20	CTEQ6M
$\langle M_T\rangle$(LO)	–	$0^{+8.3}_{-8.3}$	$-1.0^{+8.3}_{-11.4}$	$-3.3^{+7.4}_{-4.2}$	$+7.8^{+5.1}_{-5.1}$	$-3.1^{+6.7}_{-5.7}$	$-7.3^{+8.4}_{-12.0}$
χ^2 fit (LO)	8.0	$0^{+7.6}_{-7.6}$	$-1.0^{+5.4}_{-8.6}$	$-3.3^{+6.1}_{-3.0}$	$+8.0^{+3.7}_{-3.7}$	$-3.0^{+5.0}_{-4.0}$	$-7.3^{+5.6}_{-9.3}$
$\langle M_T\rangle$(NLO)	–	$0^{+5.9}_{-5.9}$	$-4.2^{+8.8}_{-13.3}$	$-5.0^{+6.7}_{-5.3}$	$+6.9^{+6.2}_{-6.2}$	$-7.6^{+7.9}_{-6.7}$	$-14.0^{+9.0}_{-11.9}$
χ^2 fit (NLO)	8.0	$0^{+4.2}_{-4.2}$	$-4.3^{+5.4}_{-10.1}$	$-5.1^{+4.8}_{-3.4}$	$+7.1^{+4.5}_{-4.5}$	$-7.8^{+5.7}_{-4.5}$	$-14.6^{+5.8}_{-5.4}$
CDF	9.2	$0^{+3.9}_{-3.9}$	–	–	–	–	−3.3

TABLE I. Estimated shifts and PDF uncertainties at 68% C.L. on the extracted W boson mass for the CDF scenario for various PDF sets with respect to a common reference of using NNPDF3.1 NNLO central PDF. We show results using the simplified prescription, compared to those from a χ^2 fit as well as results reported in the CDF analysis. In the case of the χ^2 fit, we also show the expected experimental statistical error of the extracted W boson mass compared to the actual one in the CDF analysis.

Thus we suggest analyzing the experimental data using up-to-date PDFs could be highly desirable, especially considering tensions between different W boson mass measurements. We

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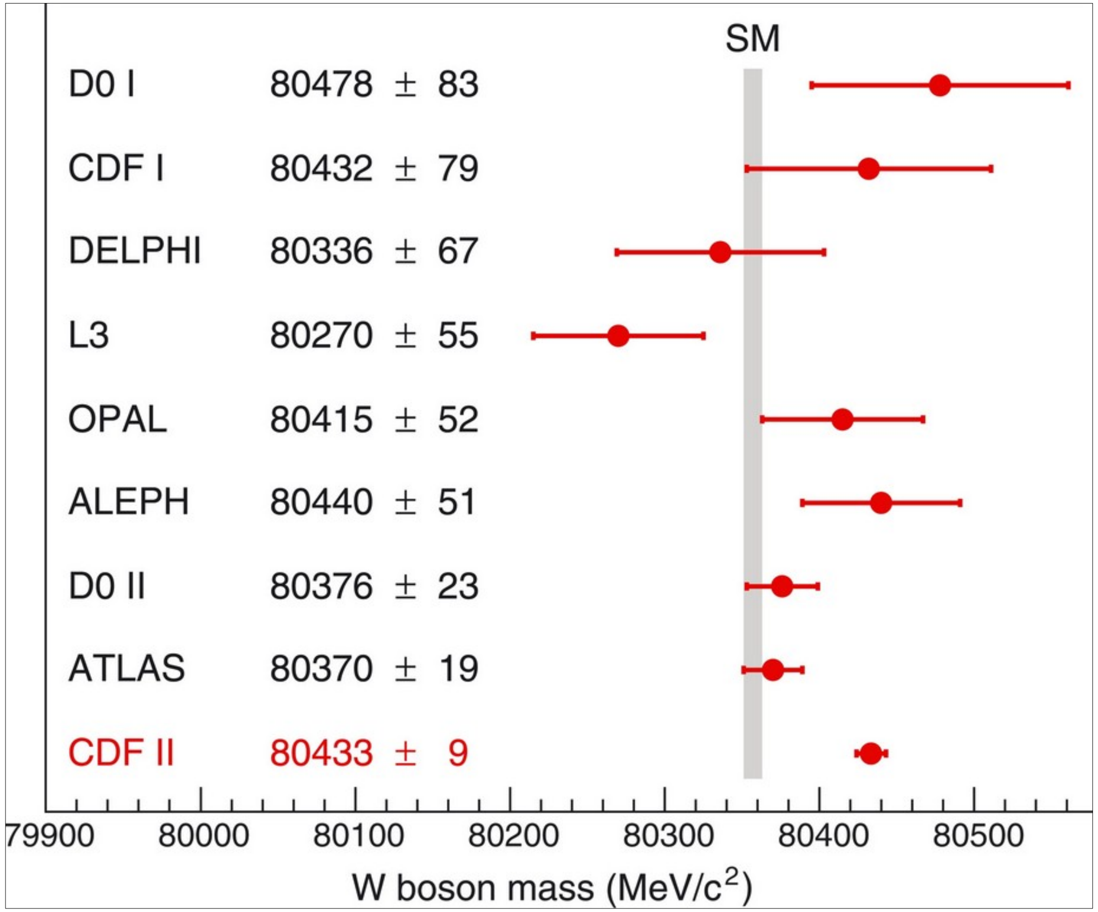
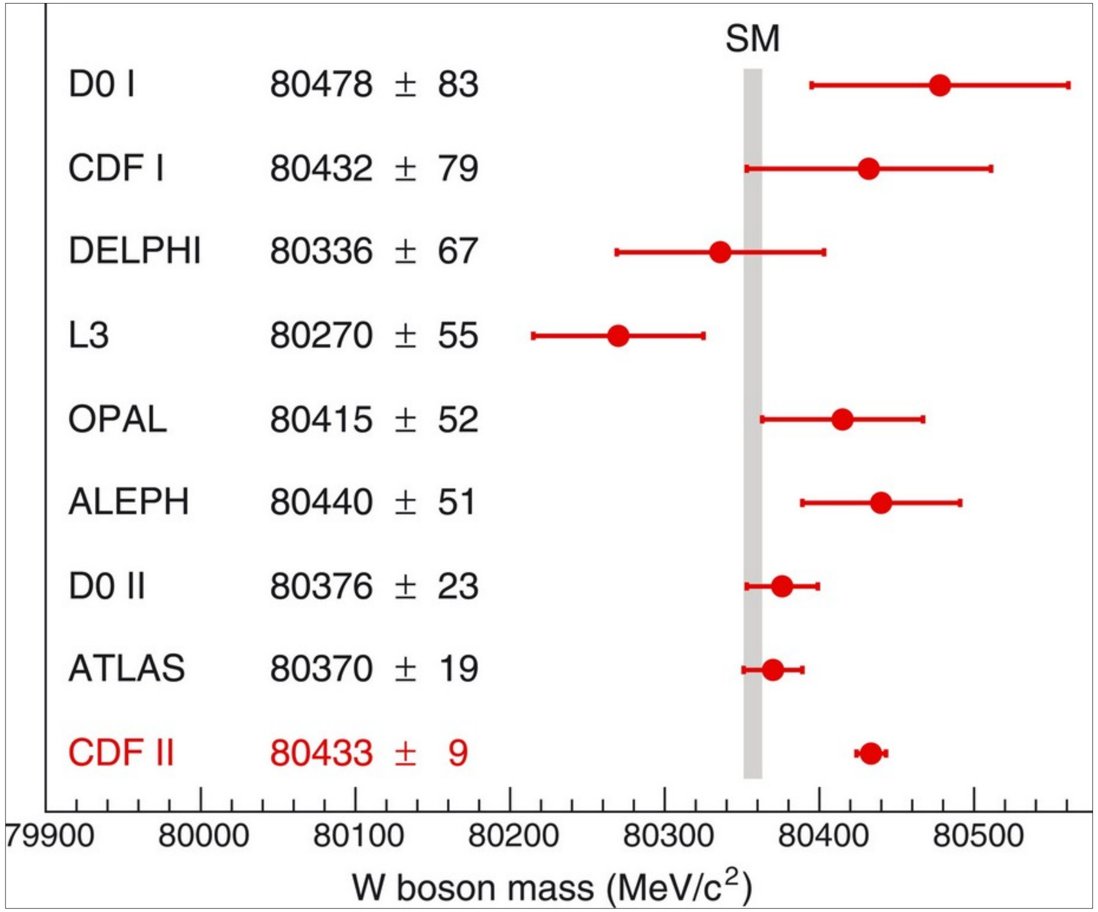
- CDF value is in tension with several of the earlier results (esp. LEP, ATLAS) → at least some of the experiments might have underestimated their uncertainties

- *Note*: pre-CDF II, measurements from LEP, Tevatron, and ATLAS were not yet combined, and investigation/evaluation of uncertainties was ongoing



What to do of the CDF measurement as phenomenologists?

- Not for us to say “the CDF measurement is right/wrong” or “the other measurements are right/wrong”
- Possible issues remain to be discussed about the CDF measurement and its compatibility with previous results → central value could decrease and/or uncertainty could be augmented
- Even so, **inclusion of CDF II into world average will most certainly increase the *already existing* pull from the SM prediction**
- **Strong motivation to investigate BSM contributions to W-boson mass**



Calculating M_W

1) In the SM

2) In BSM theories

M_W calculation in the SM I

See e.g. [Awramik, Czakon, Freitas, Weiglein '03], [Hessenberger TUM thesis '18]

- Base for MW calculation is the decay of the muon
  - **Extract G_F from muon lifetime τ_μ** by computing τ_μ in the **Fermi theory**

$$\frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^3} F(m_e^2/m_\mu^2)\left(1+\frac{3}{5}\frac{m_\mu^2}{M_W^2}\right)(1+\Delta q)$$

with $F(x) \equiv 1 - 8x - 12x^2 \ln x + 8x^3 - x^4$

Tree-level W propagator contributions (not in Fermi th. but numerically tiny)

QED corrections (known to 1L+2L)

  - Relate M_W, M_Z, α, G_F by **computing muon decay in SM**, and **matching to Fermi theory result**

$$\frac{G_F}{\sqrt{2}} = \frac{e^2}{8M_W^2 s_W^2}(1+\Delta r) \quad \Rightarrow \quad M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right) = \frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$

OS scheme

$\Delta r \equiv \Delta r(M_W, M_Z, m_h, m_t, \ldots)$ denotes corrections to muon decay (w/o finite QED effects)

  - Previous relation used to determine M_W as solution, via iterations, of

$$M_W^2 = M_Z^2\left[\frac{1}{2}+\sqrt{\frac{1}{4}-\frac{\pi\alpha}{\sqrt{2}G_F M_Z^2}\left(1+\Delta r(M_W^2, M_Z^2, m_h^2, m_t^2, \cdots)\right)}\right]$$

OS scheme

M_W calculation in the SM II

$$\frac{G_F}{\sqrt{2}} = \frac{e^2}{8M_W^2 s_W^2}(1+\Delta r) \quad \Rightarrow \quad M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right) = \frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$

$$M_W^2 = M_Z^2\left[\frac{1}{2}+\sqrt{\frac{1}{4}-\frac{\pi\alpha}{\sqrt{2}G_F M_Z^2}\left(1+\Delta r(M_W^2, M_Z^2, m_h^2, m_t^2, \cdots)\right)}\right]$$

- At one loop

$$\Delta r^{(1)} = 2\delta^{(1)}Z_e + \frac{\Sigma_{WW}^{(1)}(p^2=0)-\delta^{(1)}M_W^2}{M_W^2} - \frac{\delta^{(1)}s_W^2}{s_W^2} + \{\text{vertex} + \text{box corrections}\}$$

Σ_{WW}: transverse part of the W-boson self-energy, $\delta^{(1)}X$: 1L counterterm to quantity X

- One can show that

$$\delta^{(1)}Z_e \simeq \frac{1}{2}\Delta\alpha + \cdots \quad \text{and} \quad \frac{\delta^{(1)}s_W^2}{s_W^2} \simeq \frac{c_W^2}{s_W^2}\Delta\rho^{(1)}$$

$$\text{with} \quad \Delta\alpha = \frac{\partial}{\partial p^2}\Sigma_{\gamma\gamma}\Big|_{p^2=0} - \frac{\text{Re}\Sigma_{\gamma\gamma}(p^2=M_Z^2)}{M_Z^2}$$

- Leading terms can be rewritten as [Sirlin '80]

$$\Delta r^\alpha = \Delta\alpha - \frac{c_W^2}{s_W^2}\Delta\rho^{(1)} + \Delta r_{\text{remainder}}(m_h)$$

with $\Delta\alpha$: contribution from light fermion loops to photon vacuum polarisation

$\Delta\rho$: corrections to the ρ parameter

$$\rho \equiv \frac{G_{\text{NC}}}{G_{\text{CC}}} \quad \Rightarrow \quad \rho^{(0)} = \frac{M_W^2}{c_W^2 M_Z^2} = 1 \text{ and } \Delta\rho^{(1)} = \frac{\Sigma_{ZZ}^{(1)}(p^2=0)}{M_Z^2} - \frac{\Sigma_{WW}^{(1)}(p^2=0)}{M_W^2}$$

M_W calculation in the SM III

$$\frac{G_F}{\sqrt{2}} = \frac{e^2}{8M_W^2 s_W^2}(1+\Delta r) \quad \Rightarrow \quad M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right) = \frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$

$$M_W^2 = M_Z^2\left[\frac{1}{2}+\sqrt{\frac{1}{4}-\frac{\pi\alpha}{\sqrt{2}G_F M_Z^2}\left(1+\Delta r(M_W^2, M_Z^2, m_h^2, m_t^2, \cdots)\right)}\right]$$

- At higher orders

$$\Delta r = \Delta r^{\alpha} + \Delta r^{\alpha\alpha_s} + \Delta r^{\alpha\alpha_s^2} + \Delta r^{\alpha\alpha_s^3 m_t} + \Delta r^{\alpha^2}_{\text{ferm}} + \Delta r^{\alpha^2}_{\text{bos}} + \Delta r^{G_F^2\alpha_s m_t^4} + \Delta r^{G_F^3 m_t^6}$$

QCD (2L+3L+approx.4L) *EW (2L)* *leading 3L corr. to Δρ*

- [Awramik, Czakon, Freitas, Weiglein '03] gives a parametrisation as

$$M_W = M_W^0 - c_1\,\mathrm{dH} - c_2\,\mathrm{dH}^2 + c_3\,\mathrm{dH}^4 + c_4(\mathrm{dh}-1) - c_5\,\mathrm{d}\alpha + c_6\,\mathrm{dt} - c_7\,\mathrm{dt}^2 - c_8\,\mathrm{dH}\,\mathrm{dt} + c_9\,\mathrm{dh}\,\mathrm{dt} - c_{10}\,\mathrm{d}\alpha_s + c_{11}\,\mathrm{dZ},$$

with

$$\mathrm{dH} = \ln\left(\frac{M_H}{100\text{ GeV}}\right), \quad \mathrm{dh} = \left(\frac{M_H}{100\text{ GeV}}\right)^2, \quad \mathrm{dt} = \left(\frac{m_t}{174.3\text{ GeV}}\right)^2 - 1,$$

$$\mathrm{dZ} = \frac{M_Z}{91.1875\text{ GeV}} - 1, \quad \mathrm{d}\alpha = \frac{\Delta\alpha}{0.05907} - 1, \quad \mathrm{d}\alpha_s = \frac{\alpha_s(M_Z)}{0.119} - 1,$$

$M_W^0 = 80.3779$ GeV, $c_1 = 0.05263$ GeV, $c_2 = 0.010239$ GeV,
$c_3 = 0.000954$ GeV, $c_4 = -0.000054$ GeV, $c_5 = 1.077$ GeV,
$c_6 = 0.5252$ GeV, $c_7 = 0.0700$ GeV, $c_8 = 0.004102$ GeV,
$c_9 = 0.000111$ GeV, $c_{10} = 0.0774$ GeV, $c_{11} = 115.0$ GeV,

- *Note*: Δr also serves to extract the Higgs VEV from G_F

$$v^2 = \frac{1}{\sqrt{2}G_F}(1+\Delta r)$$

M_W calculation beyond the SM

- Idea of the calculation remains the same, but full theory calculation (that is matched with the Fermi theory one) is now done in the **BSM model**

- In BSM models, M_W ($\leftrightarrow$ muon decay) can receive contributions both at **tree level** and at **loop level**. Considering a model with both sources (and turning to $\overline{\text{MS}}$ for simplicity just here), one can write at 1L [Athron et al. 1710.03760, 2204.05285]

$$M_W^2\big|^{\overline{\text{MS}}} = (M_W^{\text{SM}}|^{\overline{\text{MS}}})^2\left\{1+\frac{s_W^2}{c_W^2-s_W^2}\left[\frac{c_W^2}{s_W^2}(\Delta\rho_{\text{tree}}+\Delta\rho_{\text{loop}}^{\text{BSM}})-\Delta r_{\text{remainder}}^{\text{BSM}}-\Delta\alpha^{\text{BSM}}\right]\right\}$$

- In the following, we will only discuss models with **$\rho^{(0)}$=1**, and we stay in **OS scheme**

- Some 2L corrections to Δρ known in BSM models
  - $O(\alpha\alpha_S)$ SUSY corrections in [Djouadi et al. '96, '98]
  - $O(\alpha_t^2,\alpha_t\alpha_b,\alpha_b^2)$ in MSSM in [Heinemeyer, Weiglein '02], [Hastier, Heinemeyer, Stöckinger, Weiglein '05]
  - BSM scalar + top quark corrections in (aligned) 2HDM and IDM [Hessenberger, Hollik '16]
- Inclusion of known higher-order SM corrections crucial $\Delta r = \Delta r^{\text{SM}} + \Delta r^{\text{BSM}}$
- Calculations of M_W with Δr to full BSM 1L + partial BSM 2L (from resummation and Δρ) + SM up to 4L
  - MSSM [Heinemeyer, Hollik, Weiglein, Zeune '13]
  - NMSSM [Stål, Weiglein, Zeune '15]
  - MRSSM [Diessner, Weiglein '19]
  - **2HDM & IDM** [Hessenberger '18] (TUM thesis and code `THDM_EWPOS`)

Brief comment: fixed vs running width

- OS renormalisation conditions: W- (and Z-) boson mass defined as **real part of the complex pole of the propagator** → gauge invariant definition

- Expanding propagator around complex pole → Breit-Wigner shape with a **fixed width**

- W- (and Z-) boson mass measured experimentally corresponds (usually) to a definition of the mass with a Breit-Wigner shape with **running width**

- Comparison of theory and experiment requires a conversion:

$$M_W^{\text{run. width}} = M_W^{\text{fix. width}} + \frac{\Gamma_W^2}{2M_W^{\text{run. width}}}$$

  where for the W decay width one uses a result parametrised in terms of G_F and including 1L QCD corrections

$$\Gamma_W = \frac{3G_F(M_W^{\text{run. width}})^3}{2\sqrt{2}\pi}\left(1 + \frac{2\alpha_s}{3\pi}\right)$$

- Resulting shift of **~27 MeV**

Solving the M_W discrepancy at loop level

$M_W^{CDF} = 80\,433 \pm 9$ MeV

Note 1: solutions at tree level are also possible, e.g. contribution from a triplet scalar
See for instance colloquium by John Ellis (3/5)
https://physikseminar.desy.de/hamburg/colloquia_in_2022/03_may_2022/

Note 2: many models have been considered at loop level (large number of papers compute the S, T, U parameters at 1L and check if they can reproduce the preferred values obtained by a global fit including the CDF result)

Some models work, some don't

e.g. singlet extension, c.f. [Sakurai, Takahashi, Yin 2204.04770] which found that $\Delta M_W \leq 5$ MeV

→ in what follows, we will consider the **2HDM**

The Two-Higgs-Doublet Model (2HDM)

- 2 $SU(2)_L$ doublets $\Phi_{1,2}$ of hypercharge 1

$$V(\Phi_1,\Phi_2) = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - \left(m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}\right) + \frac{1}{2}\Lambda_1\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{1}{2}\Lambda_2\left(\Phi_2^\dagger\Phi_2\right)^2 + \Lambda_3\left(\Phi_2^\dagger\Phi_2\right)\left(\Phi_1^\dagger\Phi_1\right) + \Lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) + \left[\frac{1}{2}\Lambda_5\left(\Phi_1^\dagger\Phi_2\right)^2 + \left(\Lambda_6\Phi_1^\dagger\Phi_1 + \Lambda_7\Phi_2^\dagger\Phi_2\right)\Phi_1^\dagger\Phi_2 + \text{h.c.}\right].$$

$$v_1^2 + v_2^2 = v^2 \simeq (246\ \text{GeV})^2$$

- CP-conserving 2HDM, with softly-broken Z_2 symmetry $\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2$ to avoid tree-level FCNCs → m_{12}^2 and Λ_5 real, $\Lambda_6=\Lambda_7=0$
- **Mass eigenstates**:
  - h, H: CP-even Higgs bosons *(h → 125-GeV SM-like state)*
  - A: CP-odd Higgs boson
  - $H^\pm$: charged Higgs boson
  - α: CP-even Higgs mixing angle
- **BSM parameters**: 3 BSM masses m_H, m_A, $m_{H\pm}$, BSM mass scale M (defined by $M^2 \equiv m_{12}^2/c_\beta s_\beta$), angles α and β (defined by $\tan\beta = v_2/v_1$)
- We take the **alignment limit α=β-π/2** → all Higgs couplings are SM-like at tree level
  → compatible with current experimental data + no mixing of CP-even scalars!

Custodial symmetry in the scalar sector of the 2HDM I

- In SM (and at 0L) the Higgs potential is *invariant under global transformations of $SU(2)_L x SU(2)_R$*
- After EWSB, this invariance group is *broken by the Higgs VEV down to* ***$SU(2)_{L+R}$***

  → **custodial symmetry**, which ensures **$\rho^{(0)}=1$**

  → quark sector breaks the custodial symmetry → **$\Delta\rho_{tb}^{SM}\neq 0$**
- What about the 2HDM? → let's follow the the discussion in [Hessenberger '18]
- Using the Higgs basis Φ_{SM}, Φ_{NS} one can first rewrite the scalar potential as

$$V = V_{\rm I} + V_{\rm II} + V_{\rm III} + V_{\rm IV};$$

$$V_{\rm I} = \frac{m_{h^0}^2}{2v^2}\left(\Phi_{\rm SM}^\dagger \Phi_{\rm SM}\right)^2 - \frac{1}{2}m_{h^0}^2\left(\Phi_{\rm SM}^\dagger \Phi_{\rm SM}\right),$$

$$V_{\rm II} = \left[\frac{1}{2v^2}\left(m_{h^0}^2 + \frac{4}{t_{2\beta}^2}\left(m_{H^0}^2 - \frac{m_{12}^2}{s_\beta c_\beta}\right)\right) + \frac{\Lambda_6\left(2c_{2\beta}-1\right)}{4c_\beta s_\beta^3} - \frac{\Lambda_7\left(2c_{2\beta}+1\right)}{4c_\beta^3 s_\beta}\right]\left(\Phi_{\rm NS}^\dagger \Phi_{\rm NS}\right)^2$$
$$+ \left(\frac{m_{12}^2}{c_\beta s_\beta} - \frac{m_{h^0}^2}{2}\right)\left(\Phi_{\rm NS}^\dagger \Phi_{\rm NS}\right),$$

$$V_{\rm III} = \left(\frac{m_{A^0}^2}{v^2} - \frac{2m_{H^\pm}^2}{v^2} + \frac{m_{H^0}^2}{v^2}\right)\left(\Phi_{\rm SM}^\dagger \Phi_{\rm NS}\right)\left(\Phi_{\rm NS}^\dagger \Phi_{\rm SM}\right)$$
$$+ \left(\frac{m_{H^0}^2}{2v^2} - \frac{m_{A^0}^2}{2v^2}\right)\left(\left(\Phi_{\rm NS}^\dagger \Phi_{\rm SM}\right)^2 + \left(\Phi_{\rm SM}^\dagger \Phi_{\rm NS}\right)^2\right)$$
$$+ \left(\Phi_{\rm NS}^\dagger \Phi_{\rm NS}\right)\left(\Phi_{\rm SM}^\dagger \Phi_{\rm SM}\right)\left(\frac{2m_{H^\pm}^2}{v^2} + \frac{m_{h^0}^2}{v^2} - \frac{2m_{12}^2}{v^2 c_\beta s_\beta}\right),$$

$$V_{\rm IV} = \left(\frac{2}{v^2 t_{2\beta}}\left(m_{H^0}^2 - \frac{m_{12}^2}{c_\beta s_\beta}\right) - \frac{\Lambda_7}{2c_\beta^2} + \frac{\Lambda_6}{2s_\beta^2}\right)\left(\Phi_{\rm NS}^\dagger \Phi_{\rm NS}\right)\left(\Phi_{\rm NS}^\dagger \Phi_{\rm SM} + \Phi_{\rm SM}^\dagger \Phi_{\rm NS}\right).$$

with

$$\Phi_{\rm SM} = \begin{pmatrix}\phi_{\rm SM}^+ \\ \phi_{\rm SM}^0\end{pmatrix} = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG)\end{pmatrix}$$

$$\Phi_{\rm NS} = \begin{pmatrix}\phi_{\rm NS}^+ \\ \phi_{\rm NS}^0\end{pmatrix} = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(-H + iA)\end{pmatrix}$$

Custodial symmetry in the scalar sector of the 2HDM II

- Then one can construct bidoublets transforming under $SU(2)_L xSU(2)_R$ as $\mathcal{M}_{\rm SM,NS} = \left(i\sigma_2\Phi^*_{\rm SM,NS}|\Phi_{\rm SM,NS}\right) = \begin{pmatrix} \phi^{0\ *}_{\rm SM,NS} & \phi^+_{\rm SM,NS} \\ -\phi^-_{\rm SM,NS} & \phi^0_{\rm SM,NS}\end{pmatrix}$

$$\mathcal{M}_{\rm SM} \to L\mathcal{M}_{\rm SM}R^\dagger \quad \text{and} \quad \mathcal{M}_{\rm NS} \to L\mathcal{M}_{\rm NS}R'^{\ \dagger} \text{ with } L \in SU(2)_L,\ R, R' \in SU(2)_R$$

- 2 custodial symmetric invariant quantities $\mathrm{tr}\left(\mathcal{M}^\dagger_{\rm X}\mathcal{M}_{\rm X}\right) = 2\Phi^\dagger_{\rm X}\Phi_{\rm X} \text{ with X} = \text{SM or NS}$
→ V_I and V_{II} respect custodial invariance!

- V_{III} and V_{IV} involve the non-invariant combinations $\Phi^\dagger_{\rm NS}\Phi_{\rm SM} \pm \Phi^\dagger_{\rm SM}\Phi_{\rm NS}$
→ break custodial symmetry
→ enter scalar corrections to Δρ at 1L and 2L respectively → potential contributions to Δρ and hence Δr and M_W!

- Φ_{SM} and Φ_{NS} have same hypercharge Y=1 → R and R' are related as $R=X^{-1}R'X$ and due to CP invariance, X=Id or $X=-i\sigma_3$
    - X=Id → $\mathrm{tr}\left(\mathcal{M}^\dagger_{\rm SM}\mathcal{M}_{\rm NS}X\right) = \Phi^\dagger_{\rm NS}\Phi_{\rm SM} + \Phi^\dagger_{\rm SM}\Phi_{\rm NS}$ is invariant → **V_{IV} invariant and V_{III} invariant if $m_A=m_{H\pm}$**
    - $X=-i\sigma_3$ → $\mathrm{tr}\left(\mathcal{M}^\dagger_{\rm SM}\mathcal{M}_{\rm NS}X\right) = -i\Phi^\dagger_{\rm NS}\Phi_{\rm SM} + i\Phi^\dagger_{\rm SM}\Phi_{\rm NS}$ is invariant → **V_{III} invariant if $m_H=m_{H\pm}$**
    while **V_{IV} must vanish → imposes either $m_H^2=m_{12}^2/(s_\beta c_\beta)=M^2$ or $t_\beta=1$**

- E.g. at 1L, explicitly

$$\Delta\rho^{(1)}_{\text{non-SM}} = \frac{\alpha}{16\pi^2 s_W^2 M_W^2}\left\{\frac{m_A^2 m_H^2}{m_A^2-m_H^2}\ln\frac{m_A^2}{m_H^2} - \frac{m_A^2 m_{H\pm}^2}{m_A^2-m_{H\pm}^2}\ln\frac{m_A^2}{m_{H\pm}^2} - \frac{m_H^2 m_{H\pm}^2}{m_H^2-m_{H\pm}^2}\ln\frac{m_H^2}{m_{H\pm}^2} + m_{H\pm}^2\right\} \xrightarrow{m_{H\pm}\to m_H \text{ or } m_A} 0$$

THDM_EWPOS

- Private code written by Stefan Hessenberger, based on [Hessenberger, Hollik '16] and [Hessenberger '18]
- Computes Δρ and EWPOs in (aligned) 2HDM as well as IDM to full 1L + leading 2L BSM (+ higher SM)
- Specifically, the computed EWPOs are $\mathbf{M_W}$ and observables at Z pole, namely
  - **Z-boson width** $\Gamma_Z = \Sigma_f\, \Gamma(Z \to f\bar{f})$ with $\Gamma(Z \to f\bar{f}) = \frac{G_F M_Z^3}{6\sqrt{2}\pi} N_c^f \left[(g_V^f)^2 R_V^f + (g_A^f)^2 R_A^f \right]$
  - **Effective leptonic weak mixing angle** $\sin^2\theta_{\rm eff}^{\rm lep} \equiv \frac{1}{4}\left(1 - \frac{g_V^{\rm lep}}{g_A^{\rm lep}}\right)$

    (assuming lepton universality)

N_c^f: colour factor
$g_{V,A}^f$: eff. vector/axial coup. of Z boson to fermion f
$R_{V,A}^f$: radiation factors (final state QCD & QED corr.)

- Corrections to Δρ:
  - **1L**: SM-like top quark piece + BSM scalar piece
  - **2L**: (1L)^2 pieces + **genuine pieces**, i.e. *{top+SM scalars}*, *{top+BSM scalars}*, *{BSM scalars only}*, *{SM+BSM scalars}* – all computed in gaugeless limit
- 2L BSM corrections to Δr, Γ_Z, $\sin^2\theta_{\rm eff}^{\rm lep}$ can always be split between a **reducible part** (i.e. (1L)^2 terms) and an **irreducible part**, which is **proportional to 2L BSM corrections to Δρ**
- Higher order SM corrections to Δr, Γ_Z, $\sin^2\theta_{\rm eff}^{\rm lep}$ included via known parametrisations

  → see details in [Hessenberger '18]

A parameter scan to investigate EWPOs

[Bahl, JB, Weiglein 2204.05269]

- *Here*: we consider an **aligned 2HDM of type-I**, but similar results expected for other 2HDM types
- Constraints in our parameter scan (all except the last are checked with `ScannerS`)

experimental

  - SM-like Higgs measurements with `HiggsSignals`
  - Direct searches for BSM scalars with `HiggsBounds`
  - b-physics constraints, using results from [Gfitter group 1803.01853]

theoretical

  - Vacuum stability
  - Boundedness-from-below of the potential
  - NLO perturbative unitarity, using results from [Grinstein et al. 1512.04567], [Cacchio et al. 1609.01290]

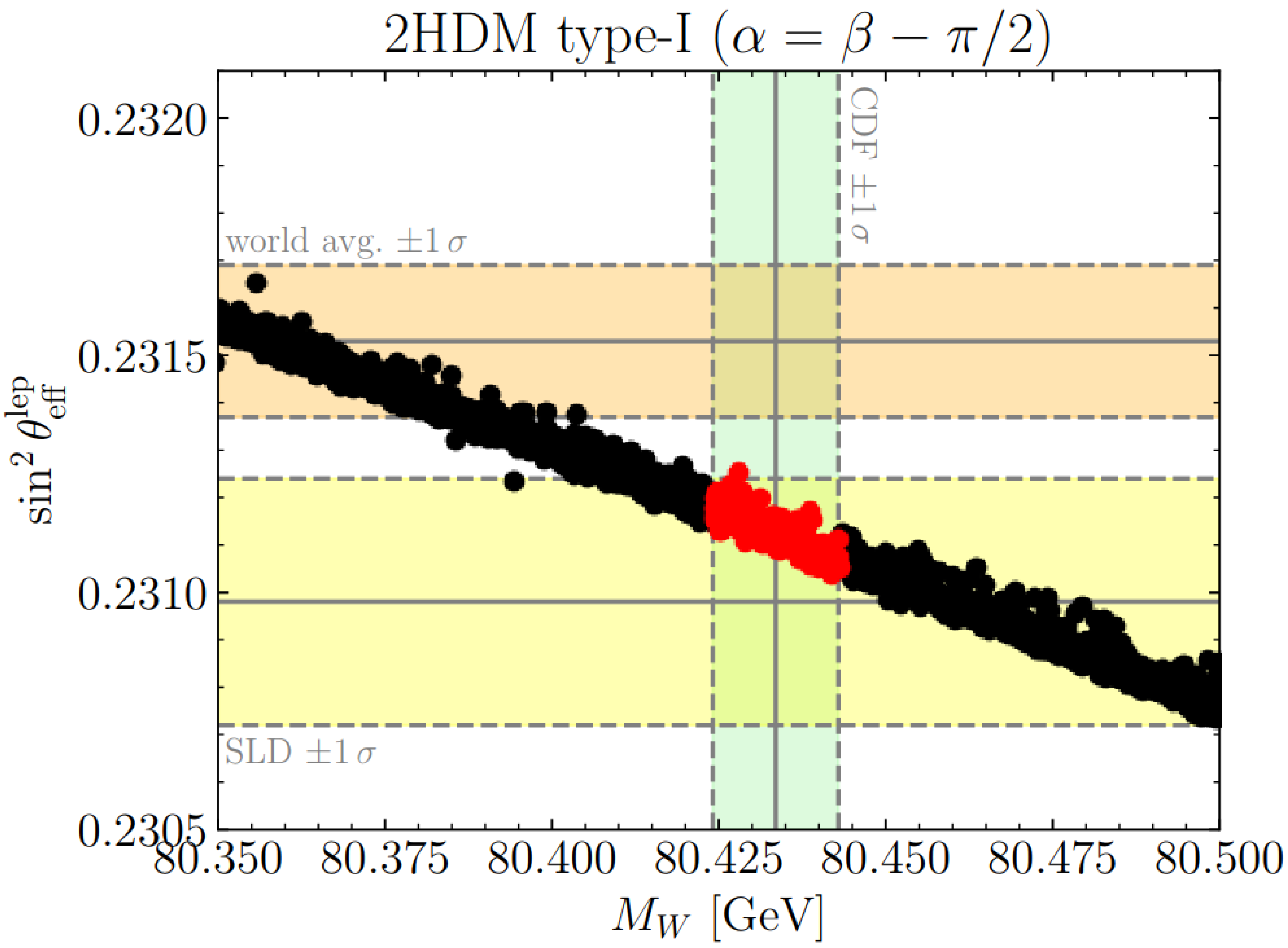
- For points passing these constraints, we compute M_W, $\sin^2\theta_{\text{eff}}^{\text{lep}}$ and Γ_Z using `THDM_EWPOS`
  - **red points** ≡ parameter points that reproduce CDF value for M_W within 1σ, i.e.

$$80\,424\text{ MeV} \leq (M_W^{(2)})^{\text{2HDM}} \leq 80\,442\text{ MeV}$$

  - **black points** ≡ all other points

Results: M_W vs $\sin^2\theta_{eff}^{lep}$

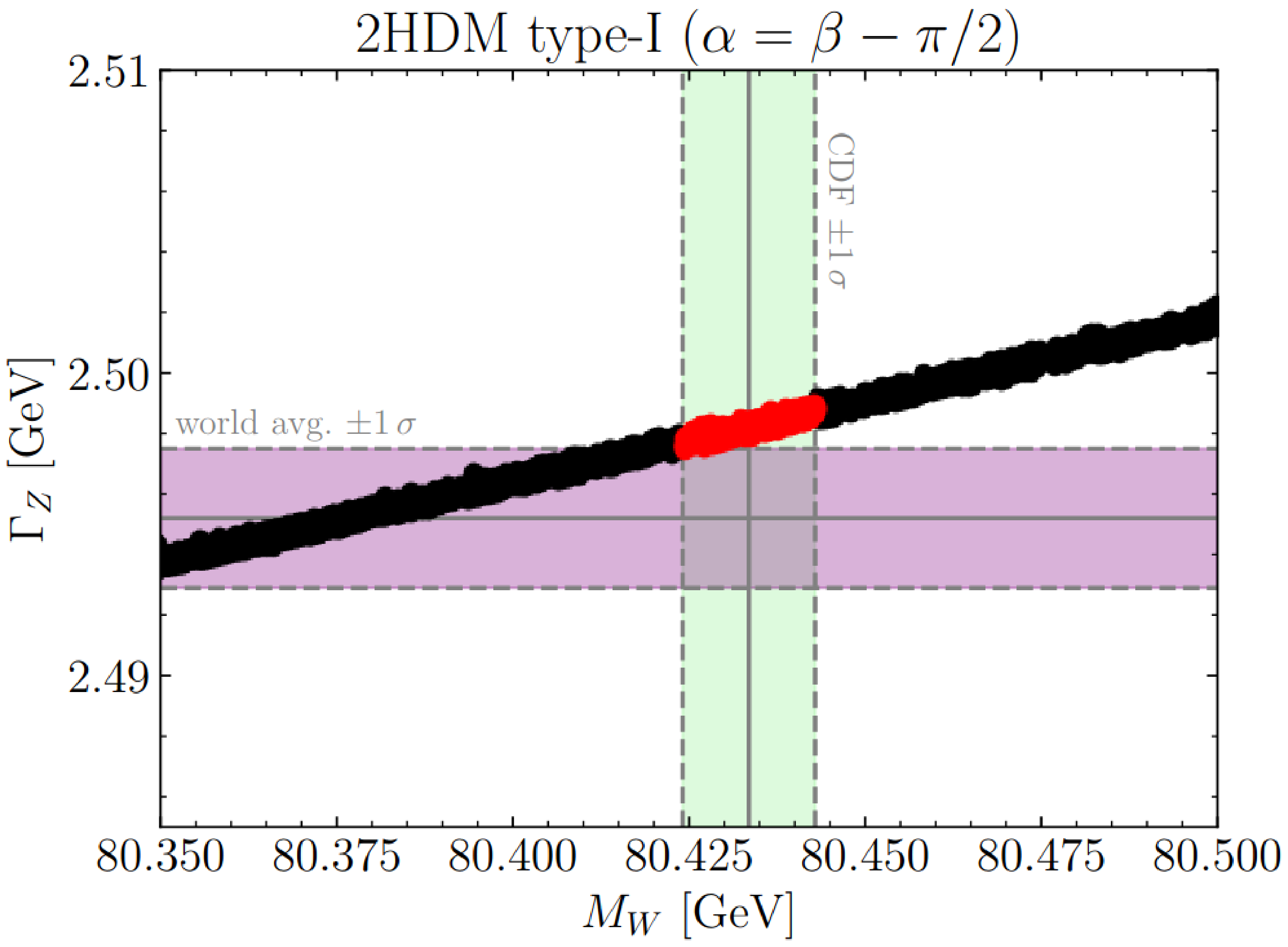
[Bahl, JB, Weiglein 2204.05269]



- **2HDM can explain the discrepancy in M_W!**
- Light tension with world average for $\sin^2\theta_{eff}^{lep}$ but good agreement with SLD result
- ***World average***: using both LEP result (based on forward-backward asymmetry of bottom quarks) + SLD result (based on left-right asymmetry) which show a *3σ discrepancy* between each other
- ***SLD***: most precise *single* measurement of $\sin^2\theta_{eff}^{lep}$ and only depends on leptonic couplings

Results: M_W vs Γ_Z

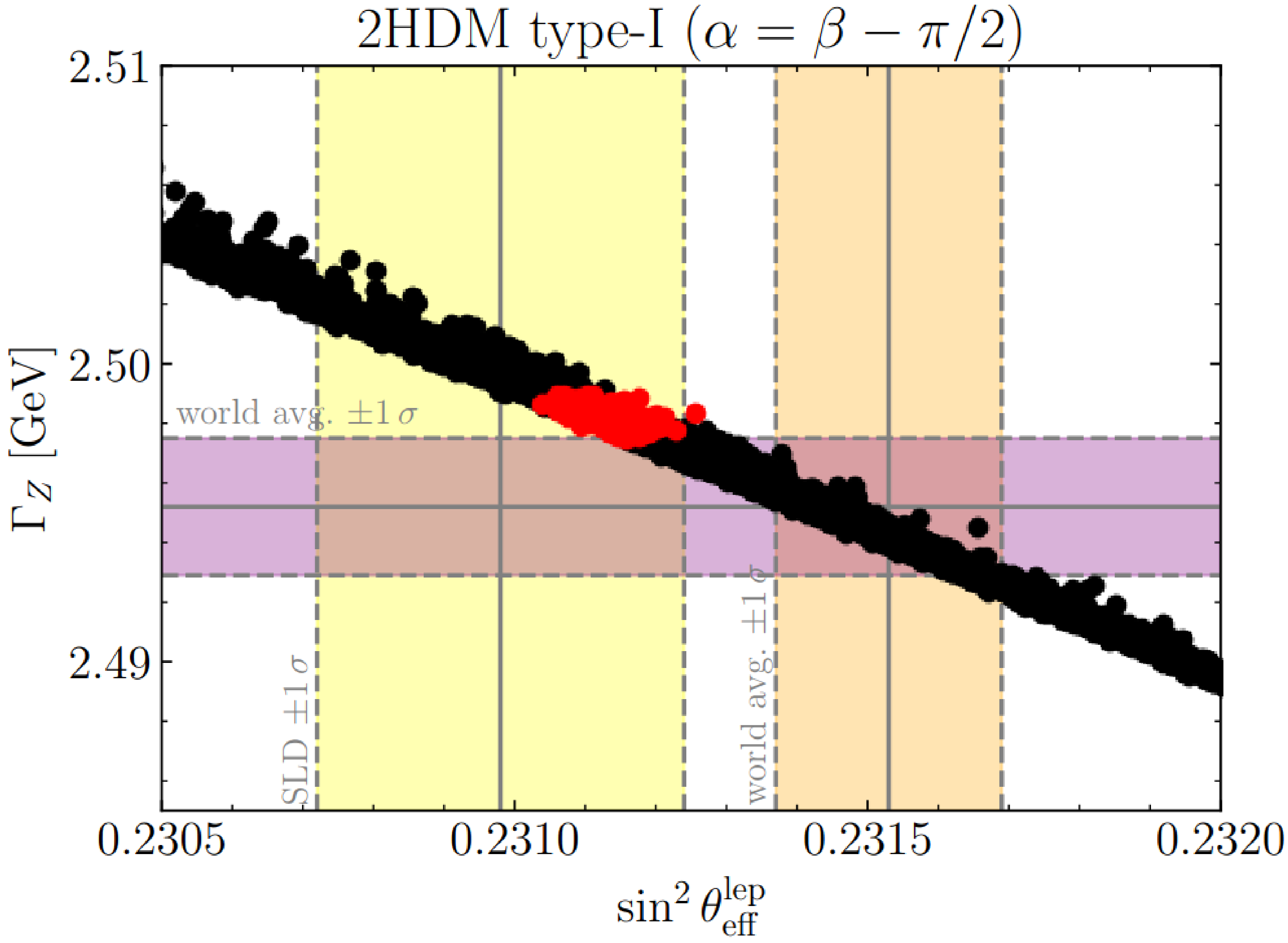
[Bahl, JB, Weiglein 2204.05269]



- Result for Γ_z compatible within 1 – 1.5σ of world average

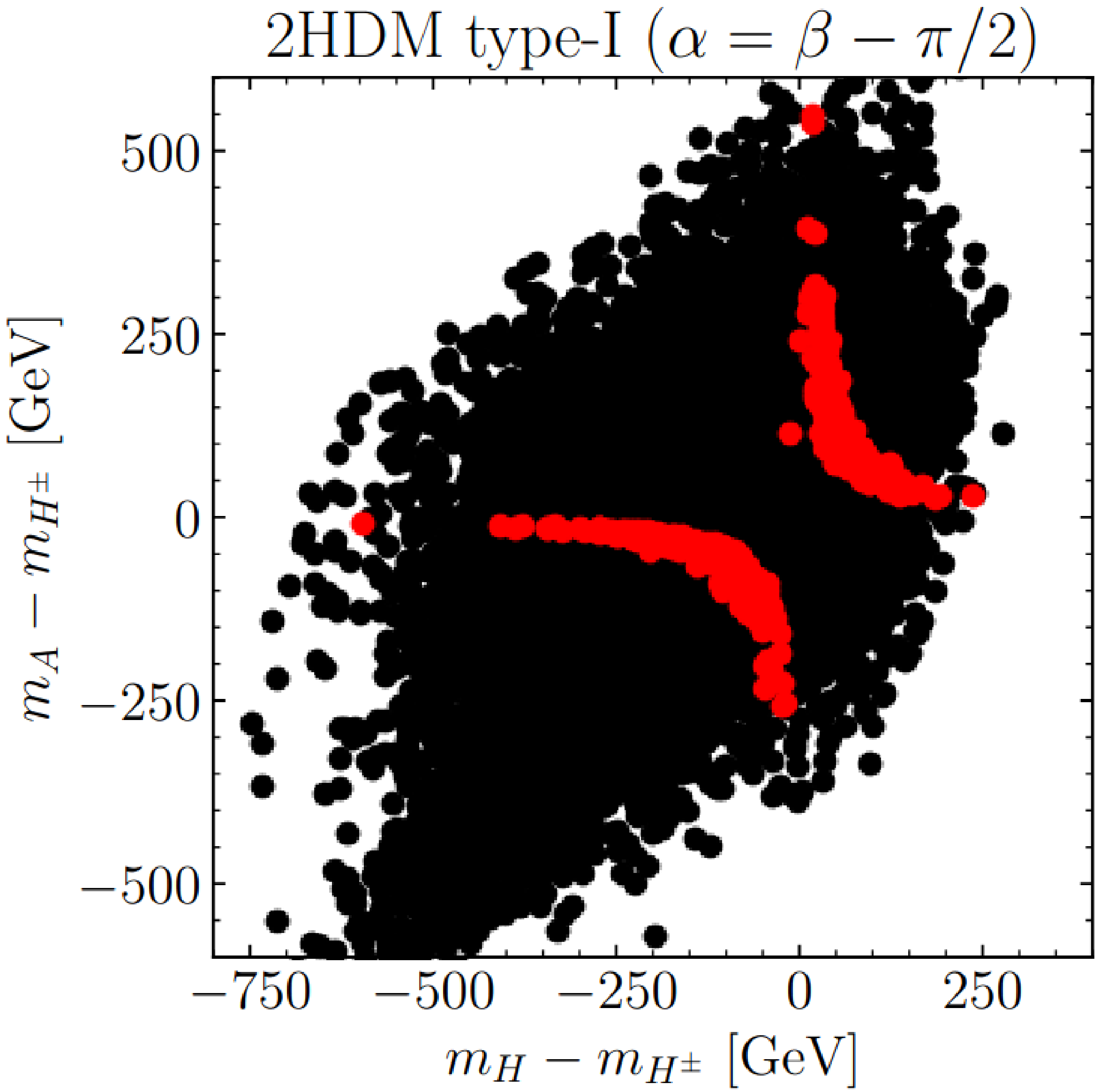
Results: $\sin^2\theta_{eff}^{lep}$ vs Γ_Z

[Bahl, JB, Weiglein 2204.05269]



Results in the (M_H-$M_{H\pm}$, M_A-$M_{H\pm}$) plane I

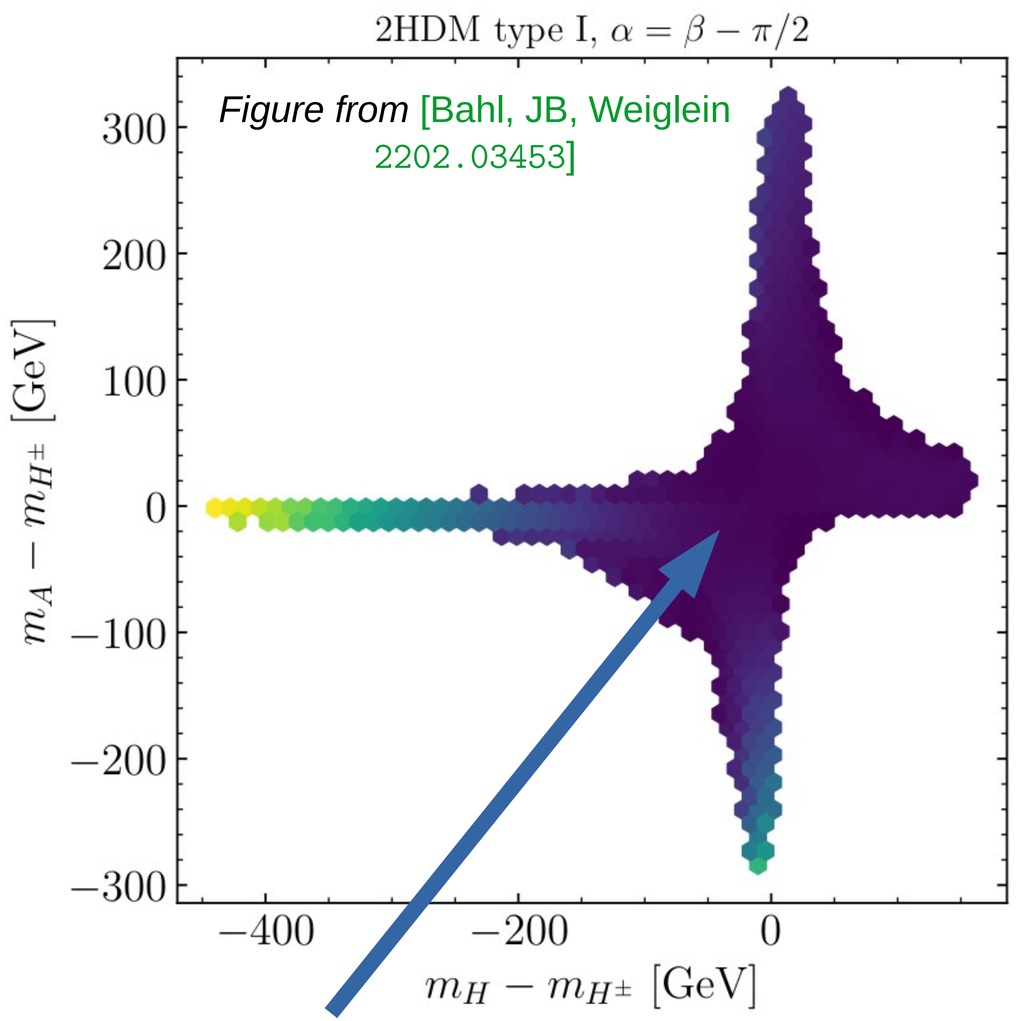
[Bahl, JB, Weiglein 2204.05269]

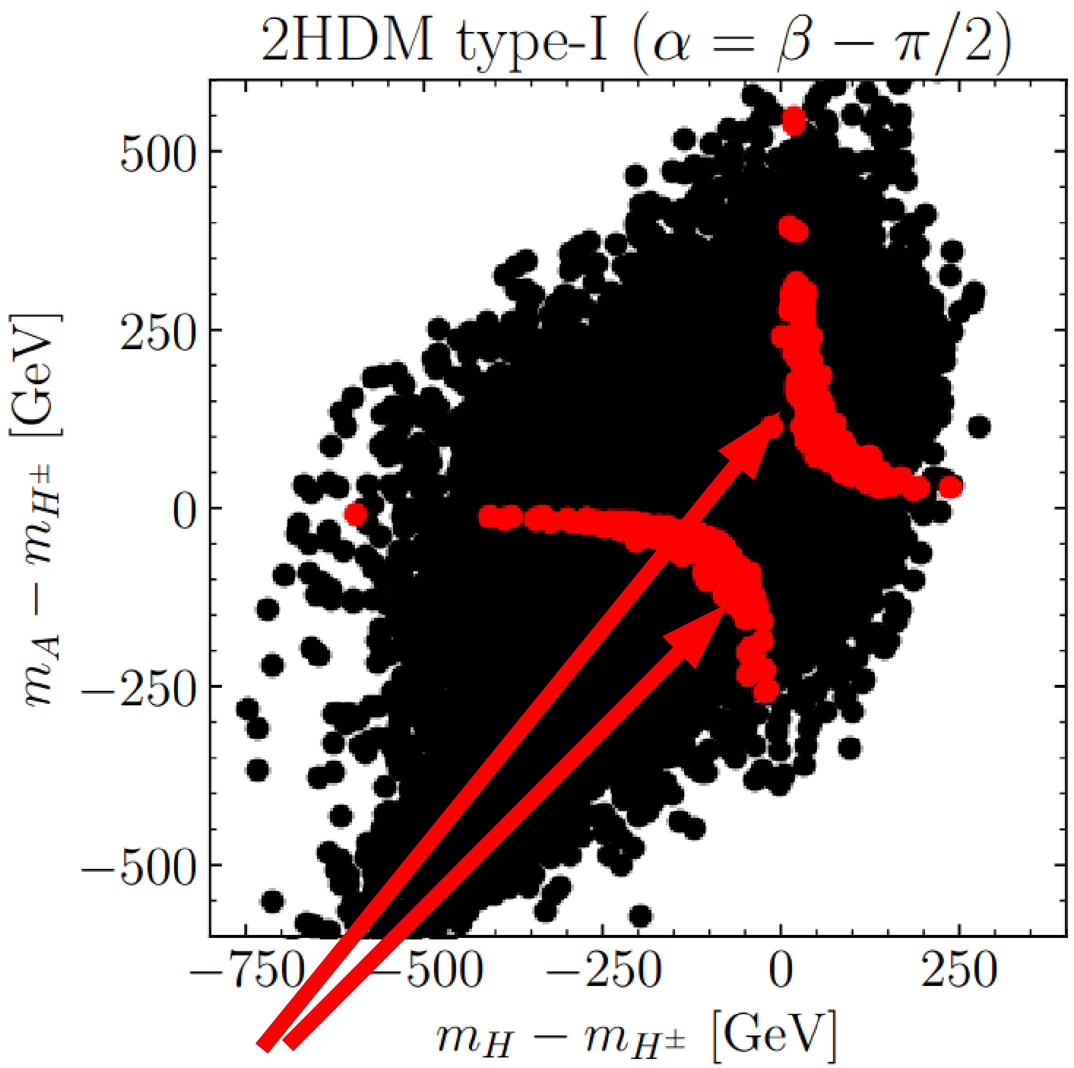


- **Mass hierarchy where m_H=m_A=$m_{H\pm}$ is no longer allowed because it cannot reproduce M_W!**
- The reason is that in this limit, the *custodial symmetry is restored in the 2HDM scalar sector*
  → scalar contributions to Δρ *vanish*
  → no way of getting a large enough contribution to M_W!
- Need **m_H-$m_{H\pm}$ < 0 and m_A-$m_{H\pm}$ < 0** or **m_H-$m_{H\pm}$ > 0 and m_A-$m_{H\pm}$ > 0** to have a **positive** contribution to Δρ

Results in the (M_H-$M_{H\pm}$, M_A-$M_{H\pm}$) plane II

[Bahl, JB, Weiglein 2204.05269]



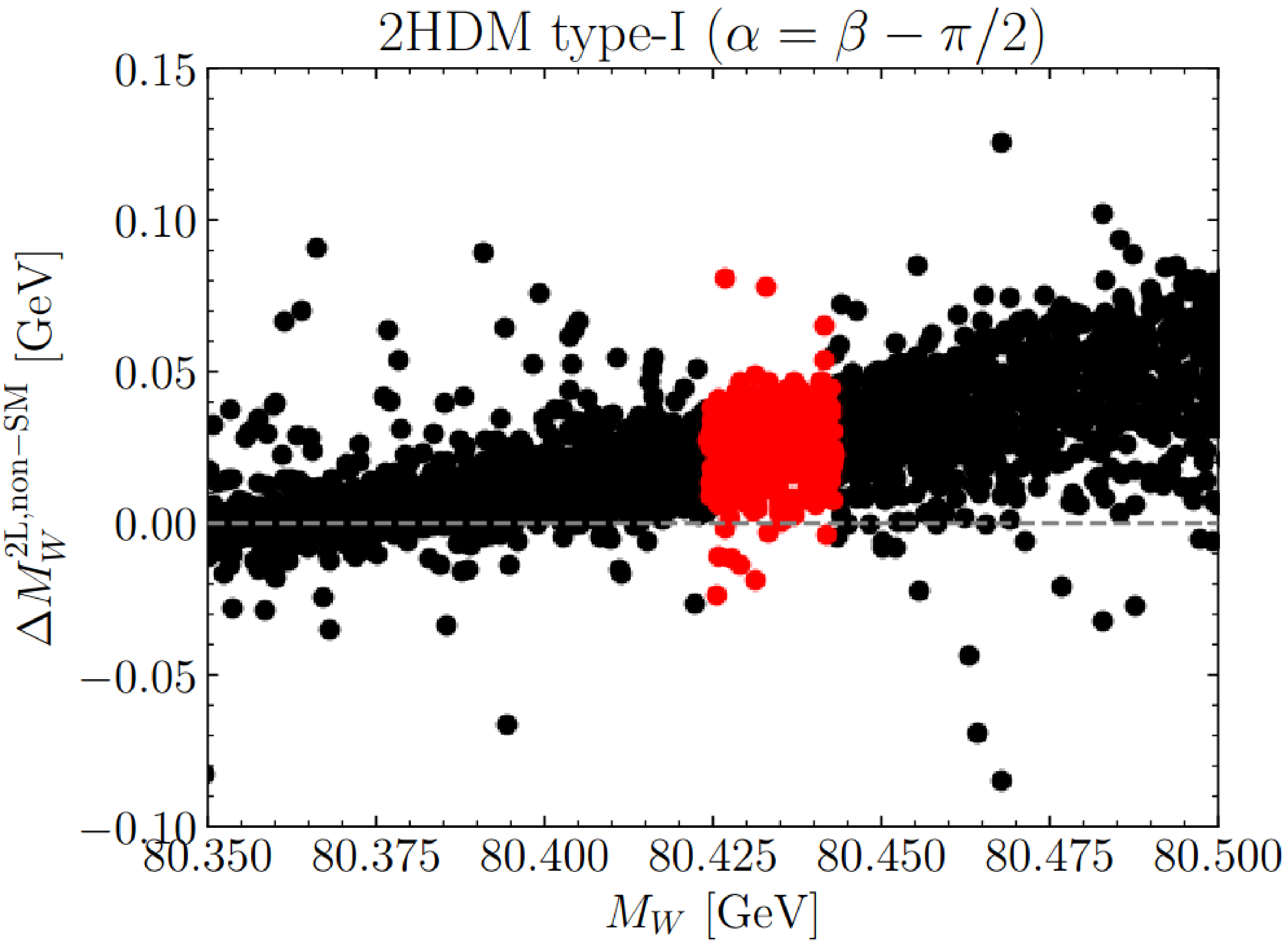


Reproducing the world average value for M_W (w/o CDF)

Reproducing the CDF result for M_W

Impact of two-loop corrections to M_W I

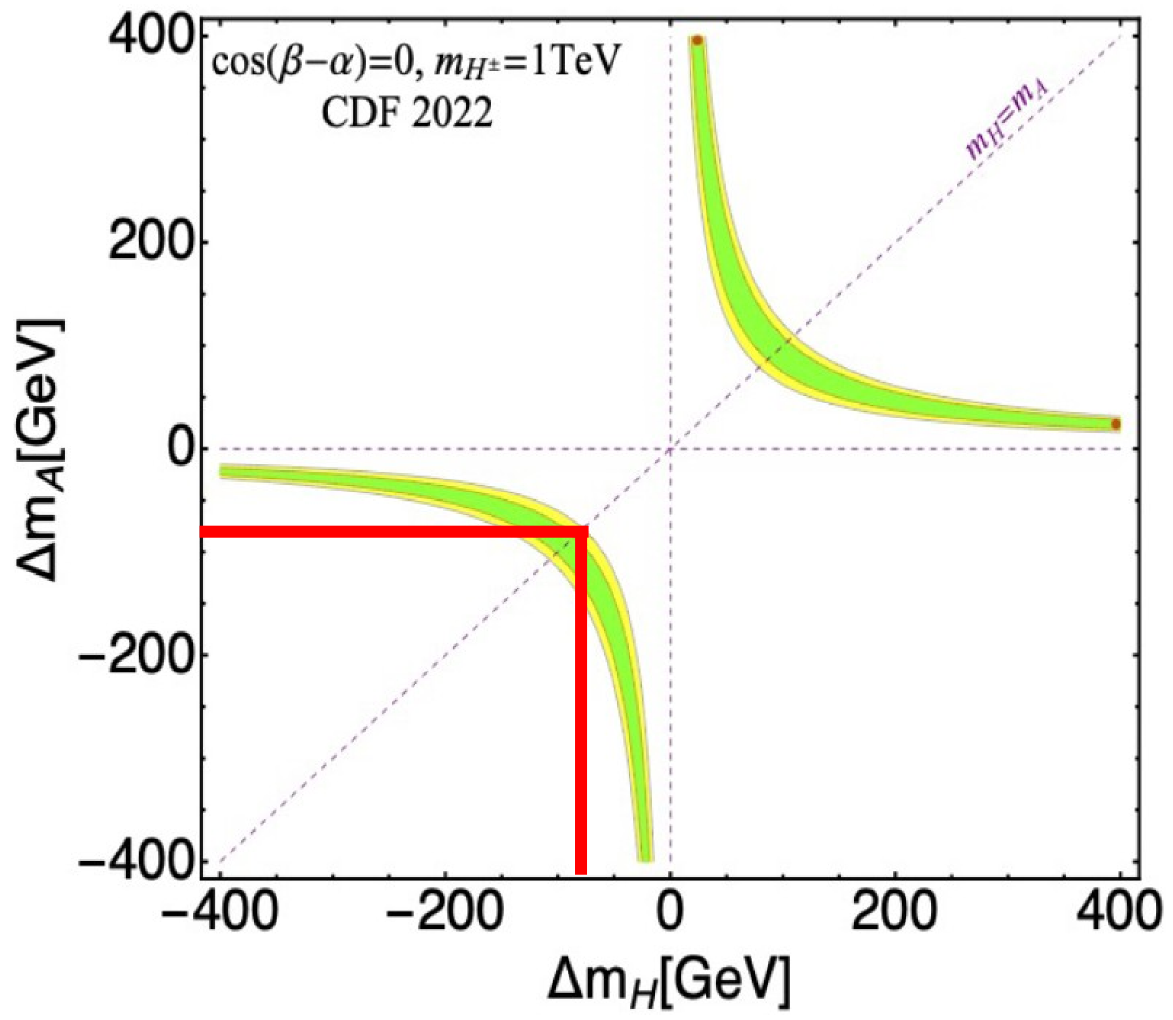
[Bahl, JB, Weiglein 2204.05269]

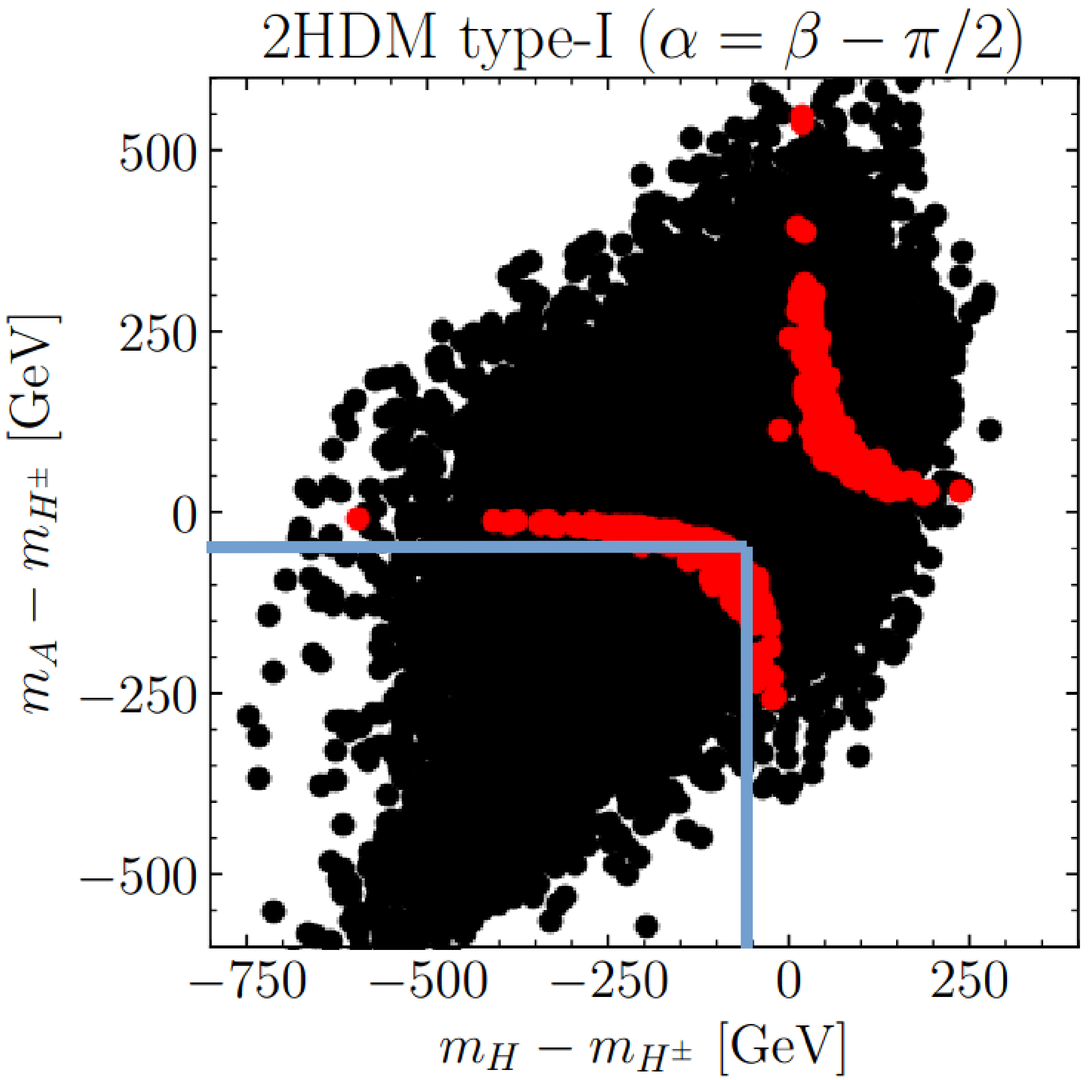


- 2L correction to M_W often significant, and can play an important role in reaching the values of M_W compatible with the CDF result
- **Shows the importance of including 2L effects!**

Impact of two-loop corrections to M_W II

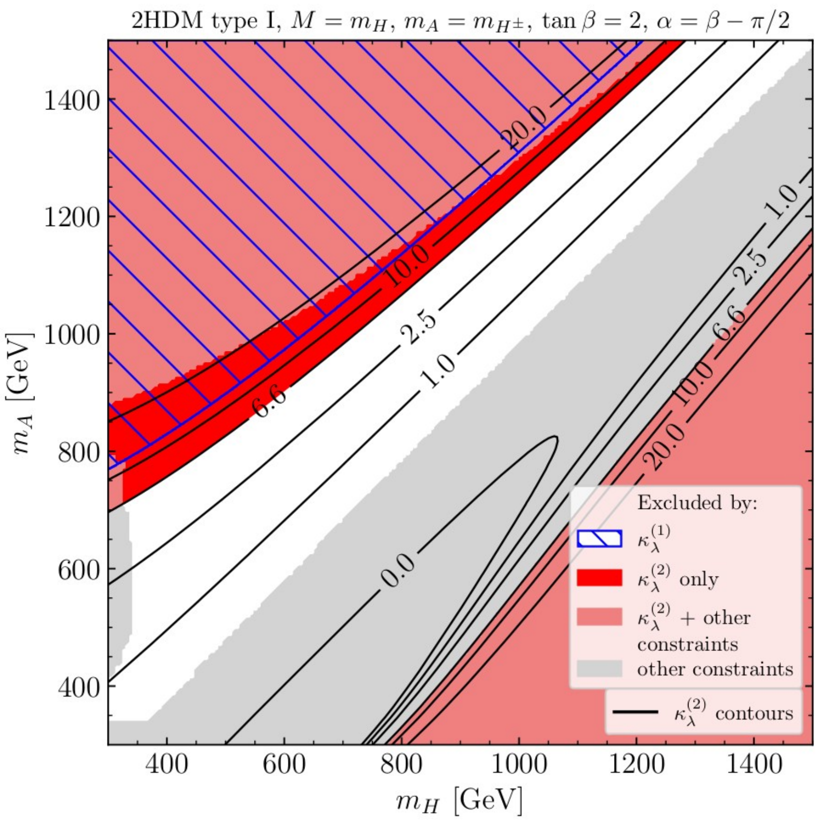
[Bahl, JB, Weiglein 2204.05269]



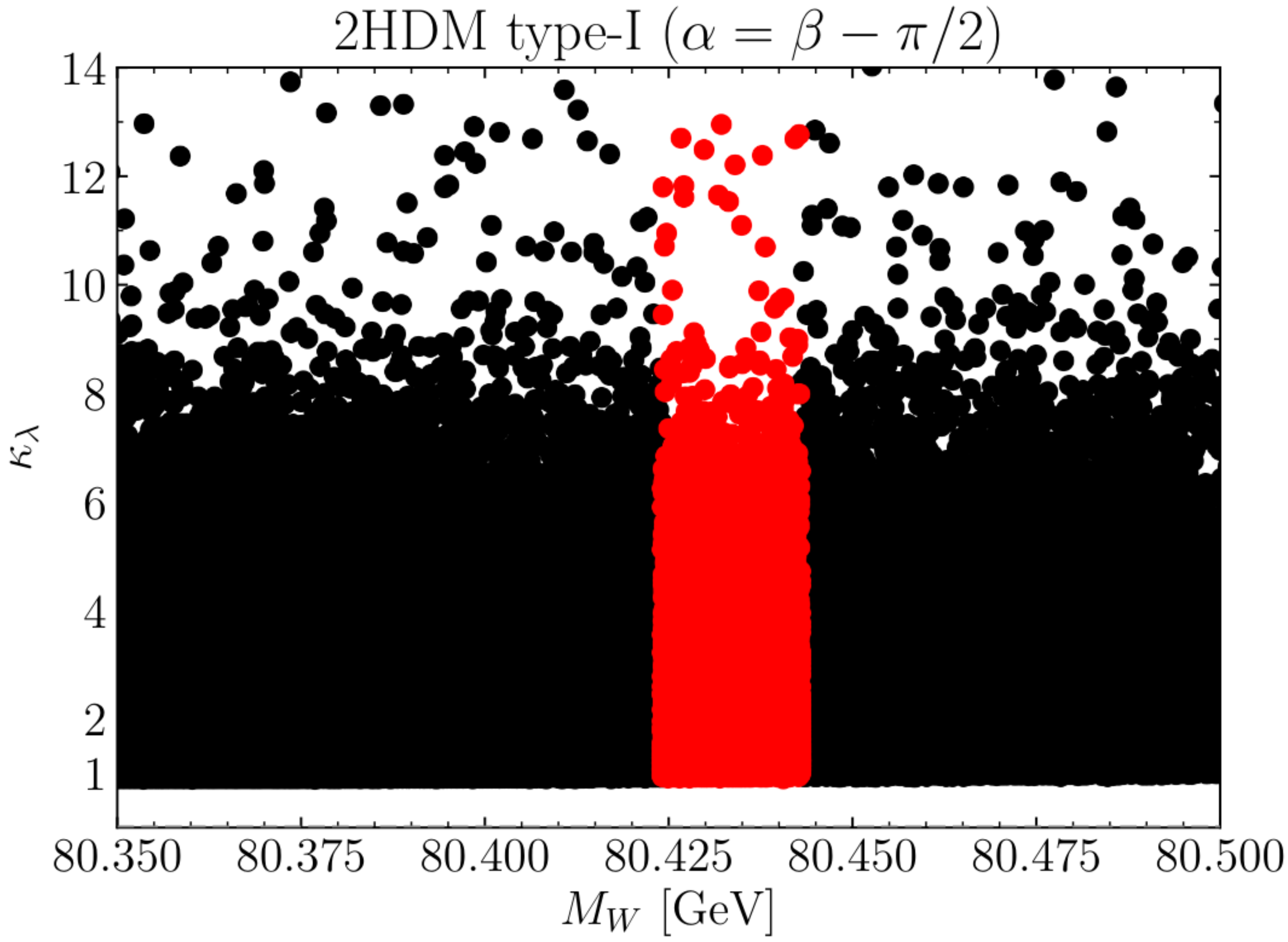


Plot from [Lu, Wu, Wu, Zhu 2204.03796] using 1L S, T, U

Correlation between M_W and κ_λ



[Bahl, JB, Weiglein 2202.03453]



- No apparent correlation between M_W and κ_λ
- Only few points excluded by $-1.0 < \kappa_\lambda < 6.6$ [ATLAS-CONF-2021-052]

Summary

- M_W is one of the best measured EWPO, and comparison of theory prediction and experimental results allow stringent tests of SM as well as BSM theories
- Recent excitement related to **CDF result**, seemingly **7σ away from SM → strong motivation to consider BSM contributions to M_W**
- [Bahl, JB, Weiglein 2204.05269] investigated situation in 2HDM, with calculation of M_W including leading 2L BSM (+ h.o. SM) effects using `THDM_EWPOS` → **2HDM can accommodate M_W discrepancy while keeping satisfactory agreement for $\sin^2\theta_{eff}^{lep}$ and Γ_Z**
- M_W discrepancy can also be explained in N2HDM scenarios that also accommodate the 95 GeV excesses → [Biekötter, Heinemeyer, Weiglein 2204.05975]
- See also colloquia by John Ellis (3/5) and Chris Hays (24/5): http://physikseminar.desy.de/hamburg

Thank you for your attention!

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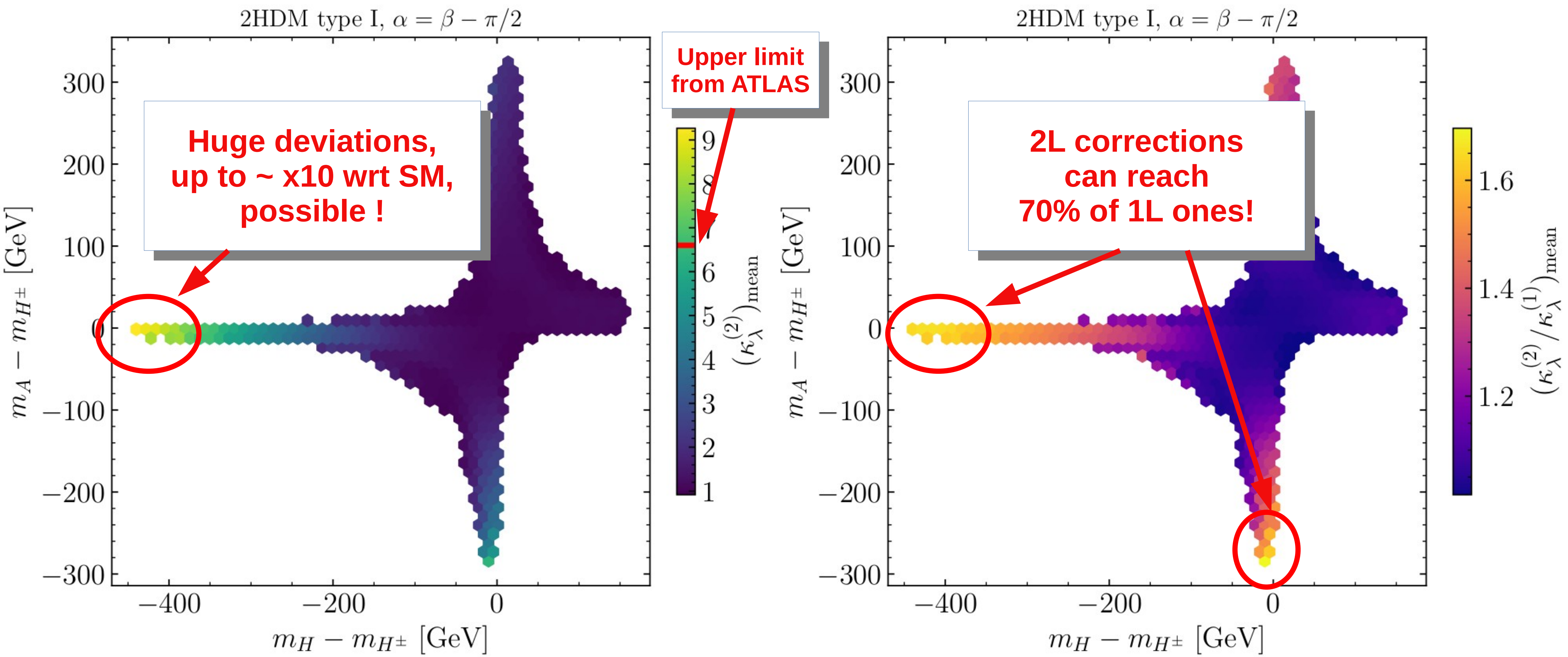
Parameter scan results

[Bahl, JB, Weiglein 2202.03453]

Mean value for $\kappa_\lambda^{(2)} = (\lambda_{hhh}^{(2)})^{2HDM}/(\lambda_{hhh}^{(0)})^{SM}$ [left] and $\kappa_\lambda^{(2)}/\kappa_\lambda^{(1)} = (\lambda_{hhh}^{(2)})^{2HDM}/(\lambda_{hhh}^{(1)})^{2HDM}$ [right] in $\{m_H - m_{H\pm}, m_A - m_{H\pm}\}$ plane



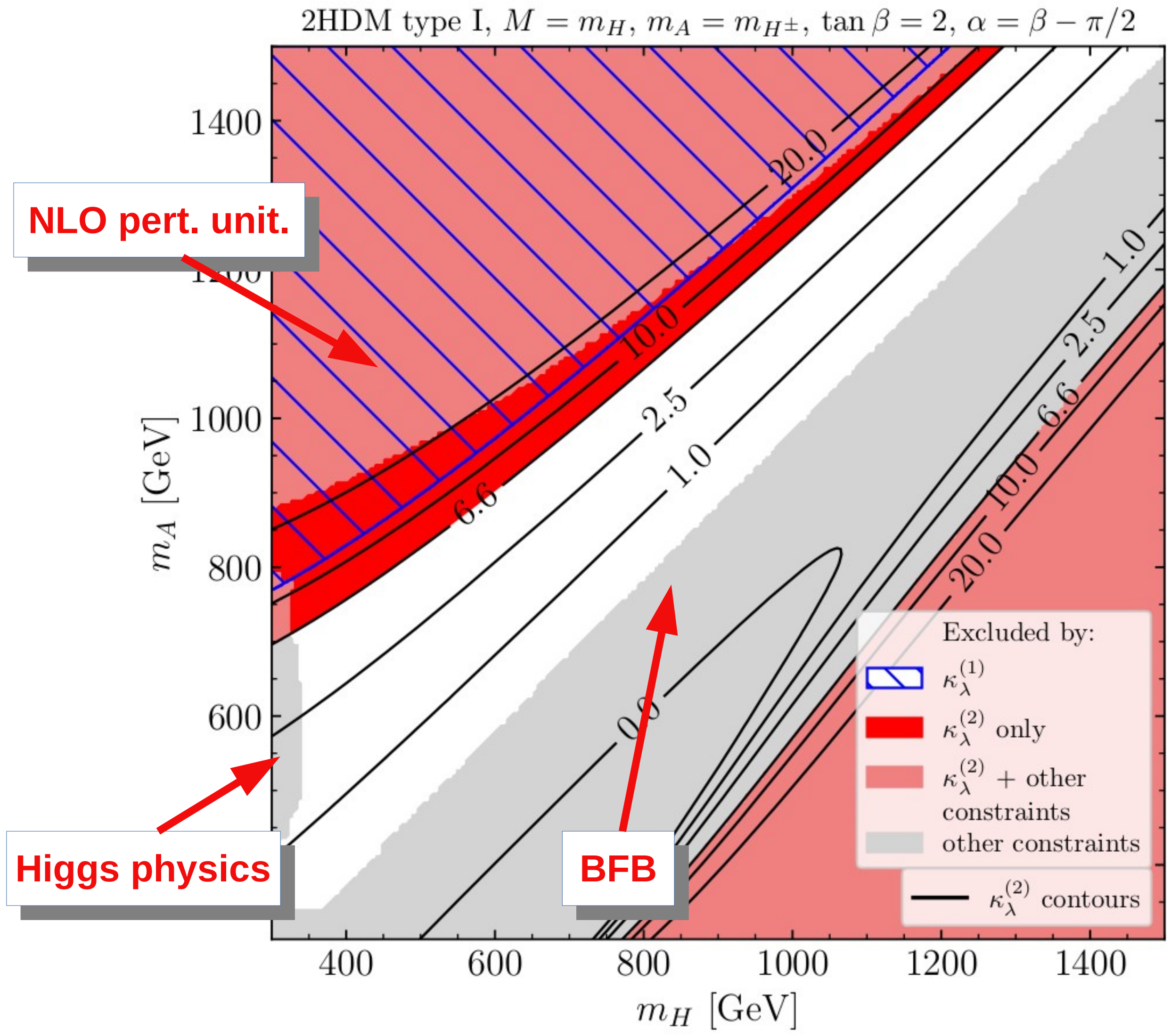
- 2L corrections can become **significant** (up to ~70% of 1L)
- **Huge enhancements** (by a factor ~10) of λ_{hhh} possible for $m_A \sim m_{H\pm}$ and $m_H \sim M$

A benchmark plane in the aligned 2HDM

[Bahl, JB, Weiglein 2202.03453]

Results shown for aligned 2HDM of type-I, similar for other types (*available in backup*)

We take $m_A=m_{H\pm}$, $M=m_H$, $\tan\beta=2$



- ***Grey area:*** area excluded by other constraints, in particular Higgs physics, boundedness-from-below (BFB), perturbative unitarity
- ***Light red area:*** area excluded both by other constraints (BFB, perturbative unitarity) and by $\kappa_\lambda^{(2)} > 6.6$ [in region where $\kappa_\lambda^{(2)} < -1.0$ the calculation isn't reliable]
- ***Dark red area:*** new area that is **excluded ONLY by $\kappa_\lambda^{(2)} > 6.6$**. Would otherwise not be excluded!
- ***Blue hatches:*** area excluded by $\kappa_\lambda^{(1)} > 6.6$ → impact of including 2L corrections is significant!