UNCONVENTIONAL PHENOMENOLOGY OF A MINIMAL 2HDM

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FLASHBACK

$$m_t = 169^{+16+17}_{-18-20}\ \mathrm{GeV}$$

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- PDG value, best fit of all indirect EW data
- First top candidate events:

$$m_t = 174 \pm 10^{+13}_{-12}\ \mathrm{GeV}$$

MASS PREDICTION

- In the Standard Model, at one loop:

$$\hat{\rho} \equiv \frac{M_W^2}{\hat{c}_Z^2 M_Z^2} \neq 1$$

mainly due to the non degenerate top/bottom doublet

$$\Delta_t \hat{\rho} = \frac{3G_F}{8\sqrt{2}\pi^2}\left(m_t^2 + m_b^2 - \frac{4m_t^2 m_b^2}{m_t^2 - m_b^2}\log\frac{m_t}{m_b}\right)$$

AND THE HIGGS ?

$$\Delta_H \hat{\rho} = -\frac{3\alpha}{16\pi \hat{c}_W^2}\left(\log\frac{m_{h^0}^2}{m_W^2} + \frac{1}{6} + \frac{1}{\hat{s}_W^2}\log\frac{m_W^2}{m_Z^2}\right)$$

but only logarithmic, so

$$m_t^{pred} = 149^{+16}_{-18} \text{ GeV for } m_h = 60 \text{ GeV}$$
$$m_t^{pred} = 186^{+16}_{-18} \text{ GeV for } m_h = 1 \text{ TeV}$$

WHY NOT QUADRATIC ?

- Accidental custodial symmetry in the SM scalar sector

$$SU(2)_L \times SU(2)_R \rightarrow SU(2)_{L+R}$$

- Broken in the gauge sector, restored if

$$g_Y \longrightarrow 0 \text{ or } g_L \longrightarrow 0$$

- Broken in the Yukawa sector

$$\mathrm{L}_Y \ni \lambda_d \overline{Q}_L \phi d_R + \lambda_u \overline{Q}_L \tilde{\phi} u_R$$

OUTLINE

- A minimal 2HDM
- Possible constraints
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"If you are out to describe the truth, leave elegance to the tailor."

Albert Einstein (1879-1955)

A GENERIC 2HDM

- Two Higgs doublets with Y=+1 $\phi_1,\ \phi_2$

- Arbitrarily choose a "Higgs basis"

$$\langle\phi_1^0\rangle = v \text{ and } \langle\phi_2^0\rangle = 0$$

- Use the convenient representation

$$M_i \equiv \begin{pmatrix} \phi_i^0 & \phi_i^+ \\ -(\phi_i^+)^* & (\phi_i^0)^* \end{pmatrix} \quad \phi_1^\dagger\phi_1 = \mathrm{Tr}(M_1^\dagger M_1), \ldots$$

CUSTODIAL SYMMETRY

Phys. Rev. Lett. 98: 251802, 2007. hep-ph/0703051, J.-M. Gérard and M.H.

- Invariance under the transformation

$$SU(2)_L \times SU(2)_R : \quad M_1 \to U_L M_1 U_R^\dagger$$

is sufficient to guarantee $\hat{\rho} = 1$

- But only $SU(2)_L \times U(1)_Y$ is gauged, such that one can still freely choose

$$M_2 \to U_L M_2 V_R^\dagger \qquad V_R = X^\dagger U_R X$$

$$X = \begin{pmatrix} \exp(i\frac{\gamma}{2}) & 0 \\ 0 & \exp(-i\frac{\gamma}{2}) \end{pmatrix}$$

CP SYMMETRY

- If the CP transformation of the doublets reads

CP Violation, G. C. Branco, L. Lavoura and J. P. Silva, Oxford U. Press, 1999

$$\begin{aligned} (\mathcal{CP})\phi_1(t,\vec{r})(\mathcal{CP})^\dagger &= \phi_1^*(t,-\vec{r}) \\ (\mathcal{CP})\phi_2(t,\vec{r})(\mathcal{CP})^\dagger &= e^{i\delta}\phi_2^*(t,-\vec{r}). \end{aligned}$$

- If $\delta = \gamma$ then $\hat{\rho} = 1 \leftrightarrow m_{H^\pm} = m_{A^0}$
- If $\delta = \gamma - \pi$ then $\hat{\rho} = 1 \leftrightarrow m_{H^\pm} = m_{H^0}$

and h^0 is purely SM-like

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TWISTED

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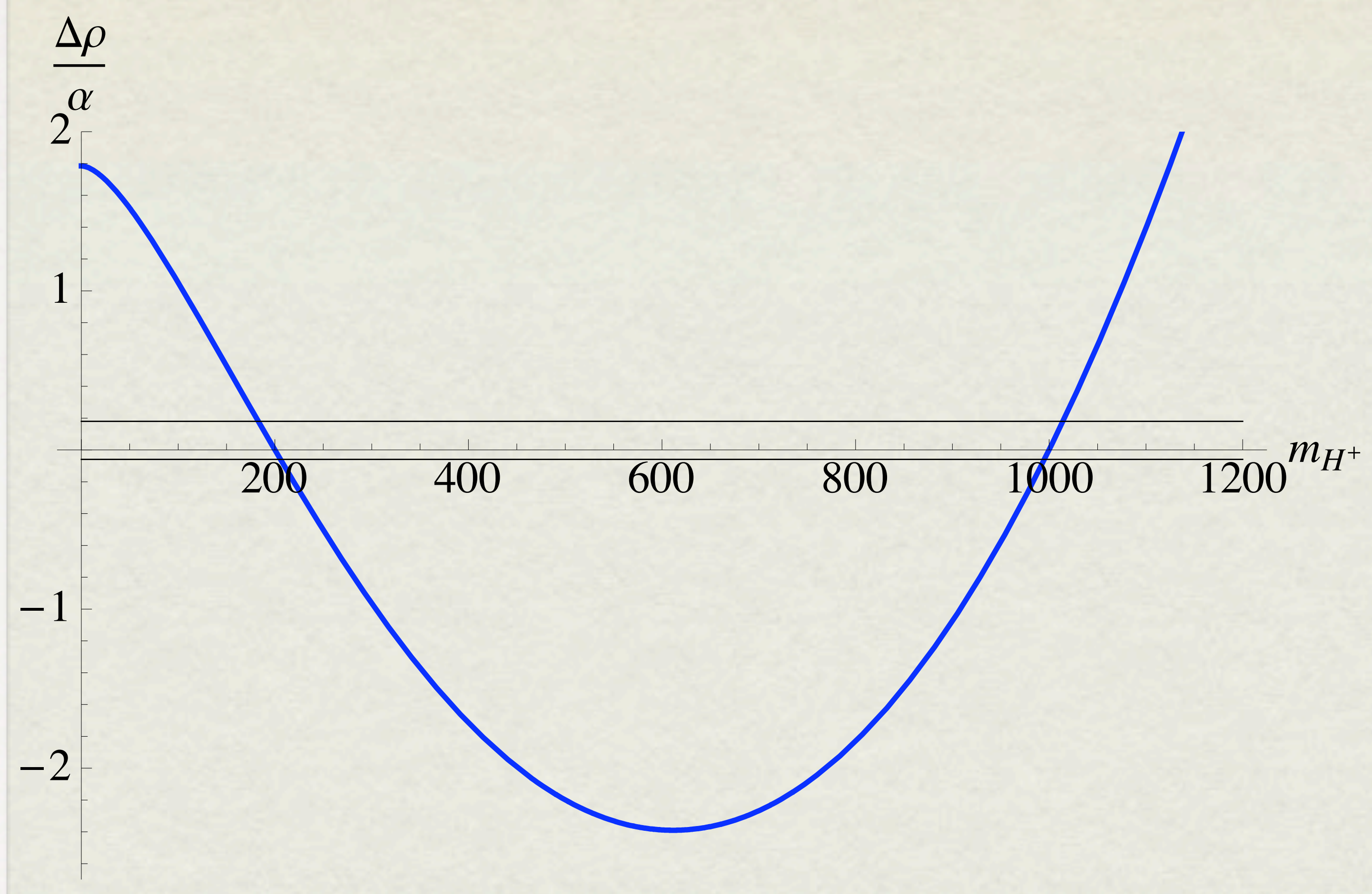
2 CUSTODIAL CASES



$(\hat{\rho} - 1)/\alpha$ as a function of $m_{H^\pm}$

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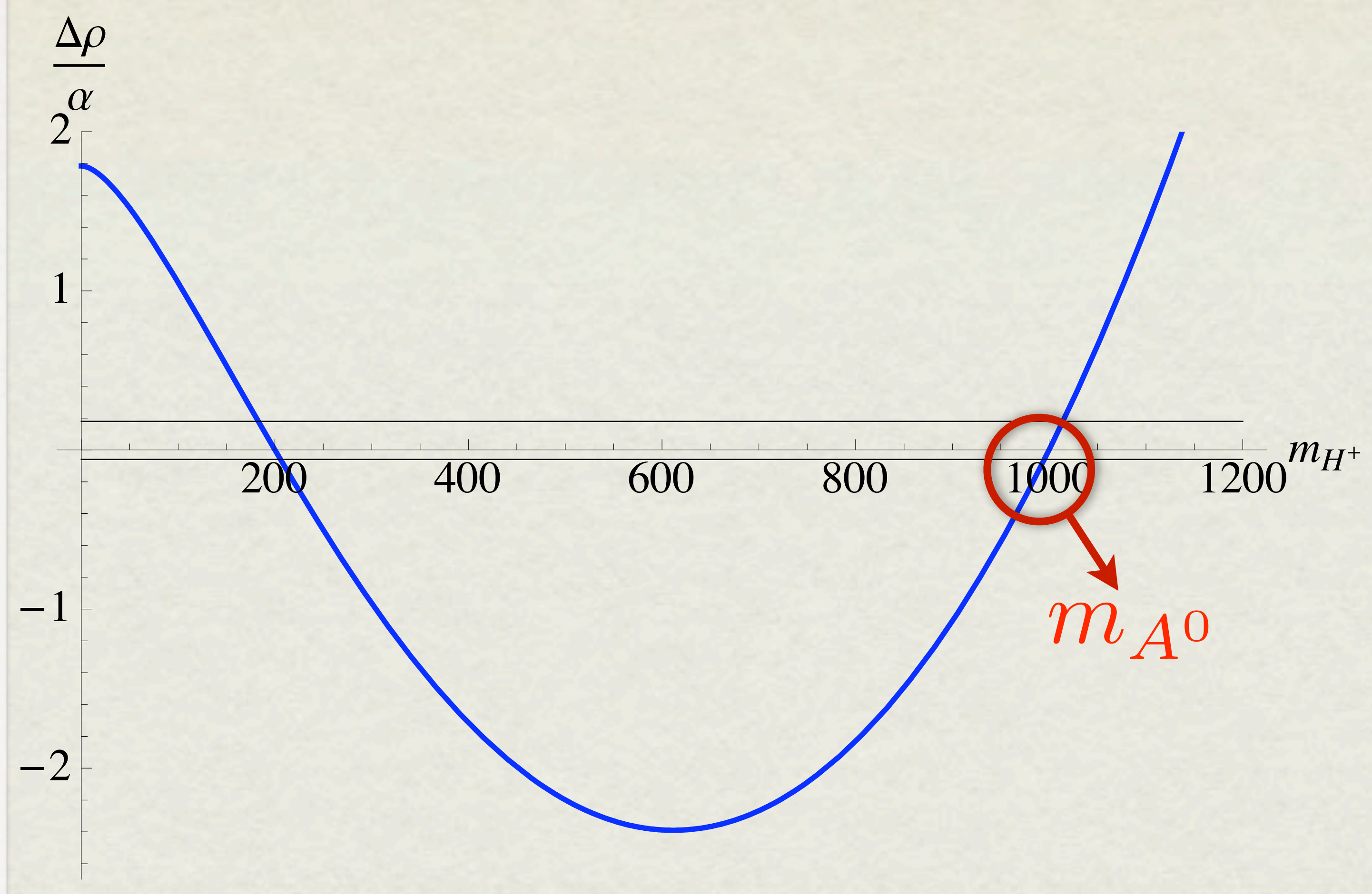

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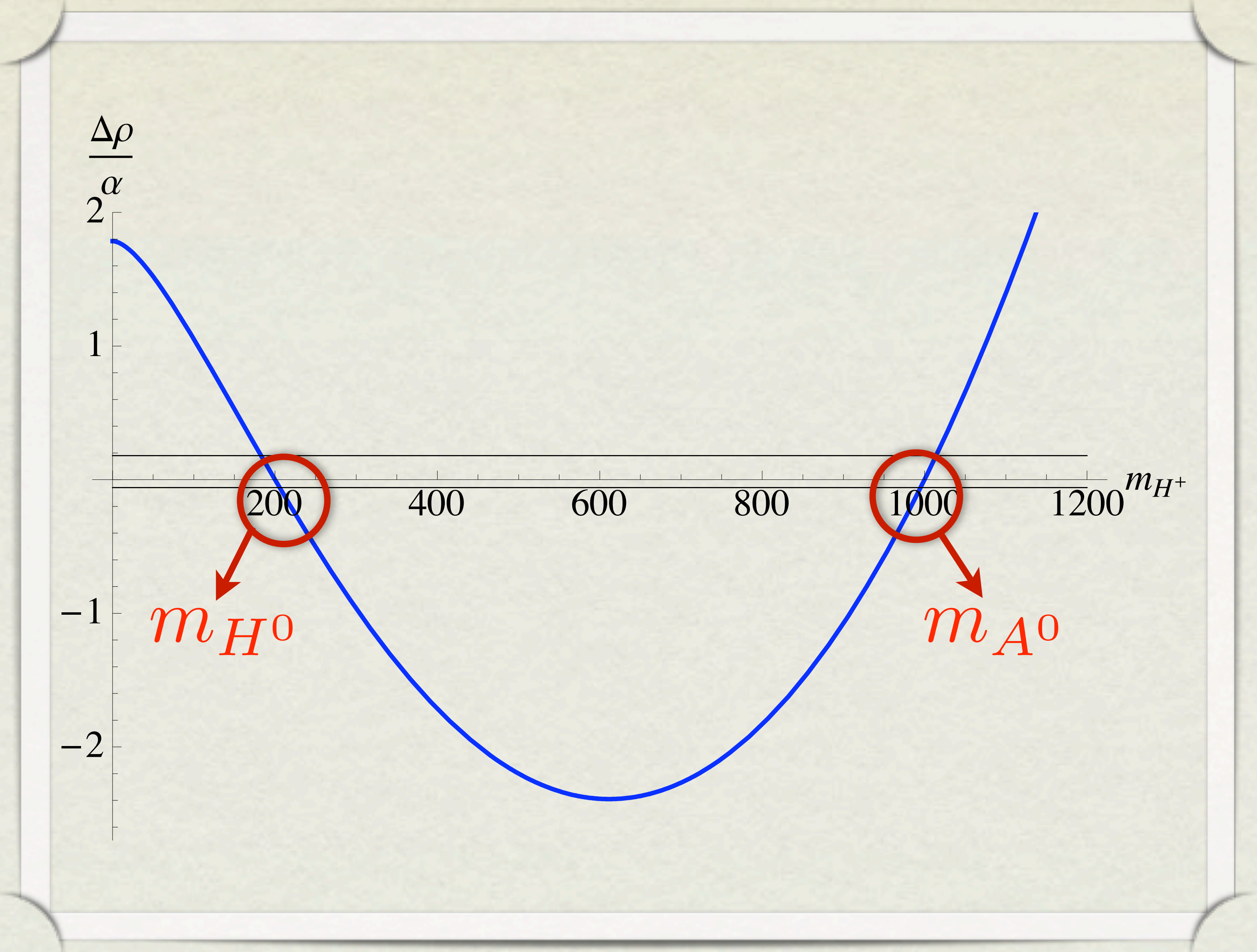

$(\hat{\rho} - 1)/\alpha$ as a function of $m_{H^\pm}$

ALTERNATIVE POV

H. Haber, private communication, 2007
Thesis, D. O'Neil, arXiv:0908.1363, 2009

- In terms of invariants, the minimal 2HDM corresponds to a subclass of $Z_6 = Z_7 = 0$, where two equivalent definitions of CP can coexist
- In the absence of Yukawa couplings, those definitions are physically indistinguishable (both A^0 and H^0 have vanishing couplings to $Z^0 Z^0$)
- The two cases considered here can be described without the "twisting" formalism, but it enlightens an interplay between CP and custodial for this specific model.

YUKAWA COUPLINGS

- Due to CP+custodial symmetries, there is already an accidental $\mathbb{Z}_2$ symmetry in the Higgs basis
- One can promote the real rotation from the Higgs to a generic basis to be a (softly broken) symmetry of the potential
- Type I & II can be defined as usual, the SM-like Higgs h^0 has purely SM couplings to SM particles

M2HDM: SUMMARY

- A “minimal” two-Higgs-doublet model:

$$V = -m_1^2\phi_1^\dagger\phi_1 - m_2^2\phi_2^\dagger\phi_2 + \frac{\lambda_S}{2}(\phi_1^\dagger\phi_2 + \phi_2^\dagger\phi_2)^2 + \frac{\lambda_{AS}}{2}(\phi_1^\dagger\phi_2 - \phi_2^\dagger\phi_1)^2$$

- Built naturally **by imposing** CP/custodial symmetries
- Invariant under a $\mathbb{Z}_2$ symmetry ➡ Yukawa type I & II
- 4 free parameters: $m_{h^0}, m_{A^0}, m_{H^\pm} = m_{H^0}, \tan\beta$

How to choose them ?

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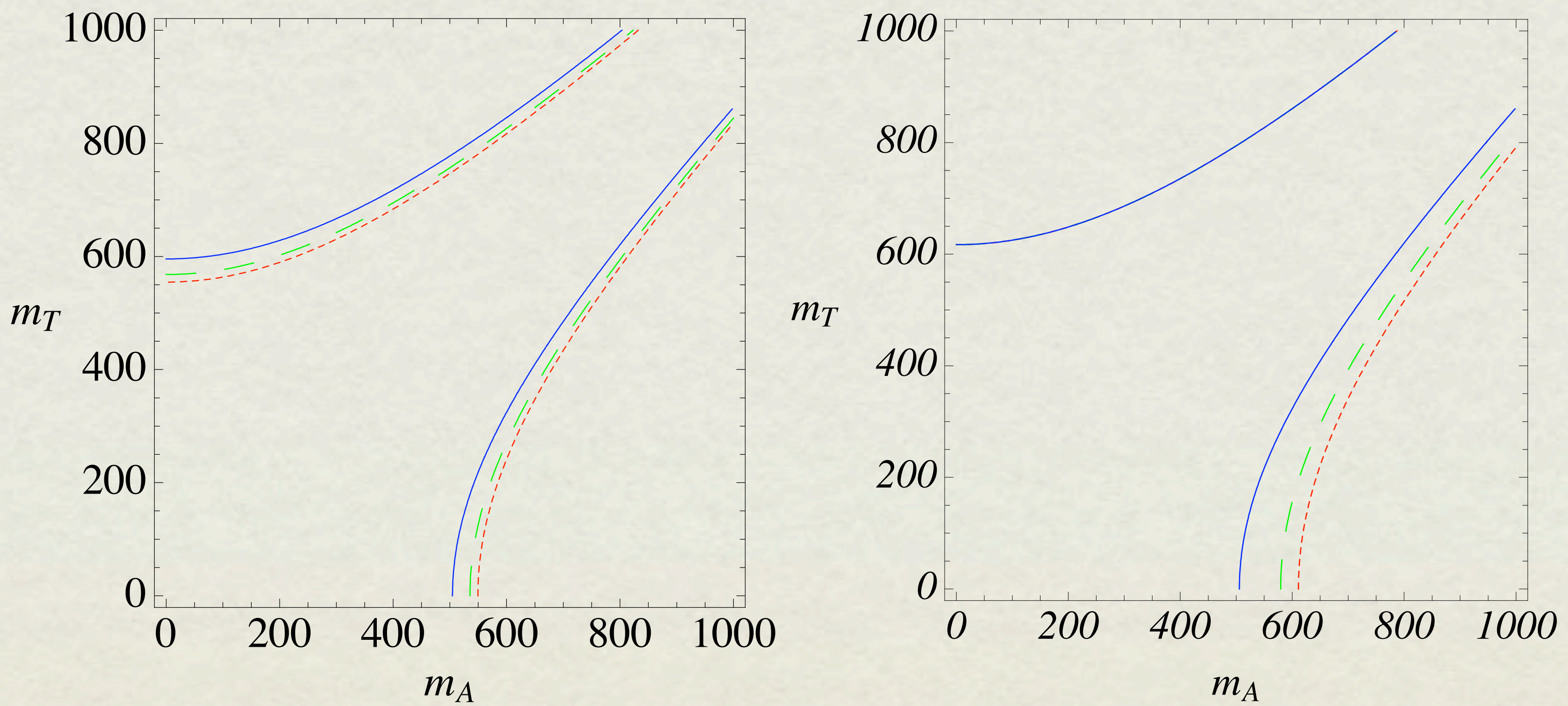
"We live on an island surrounded by a sea of ignorance. As our island of knowledge grows, so does the shore of our ignorance."

John A. Wheeler (1911 - 2008)

TH. CONSTRAINTS

- Vacuum stability : $m_{h^0}^2 > m_T^2 - m_{A^0}^2$
- Unitarity ($|\Lambda^{\mathbb{Z}_2}_{YI^3}| < 8\pi$) and perturbativity ($\lambda \lesssim 4\pi$)



(a) Unitarity (b) Perturbativity

EW PRECISION S,T,U

- The T parameter is naturally free of quadratic contributions thanks to the custodial symmetry.
- The log contribution of an heavy h^0 (> 300 GeV) has to be compensated by an O(10%) CS breaking (only 1% expected from radiative corrections)
- S and U are naturally small, and both slightly favors a light pseudoscalar A^0 and an heavy triplet $(H^0, H^\pm)$

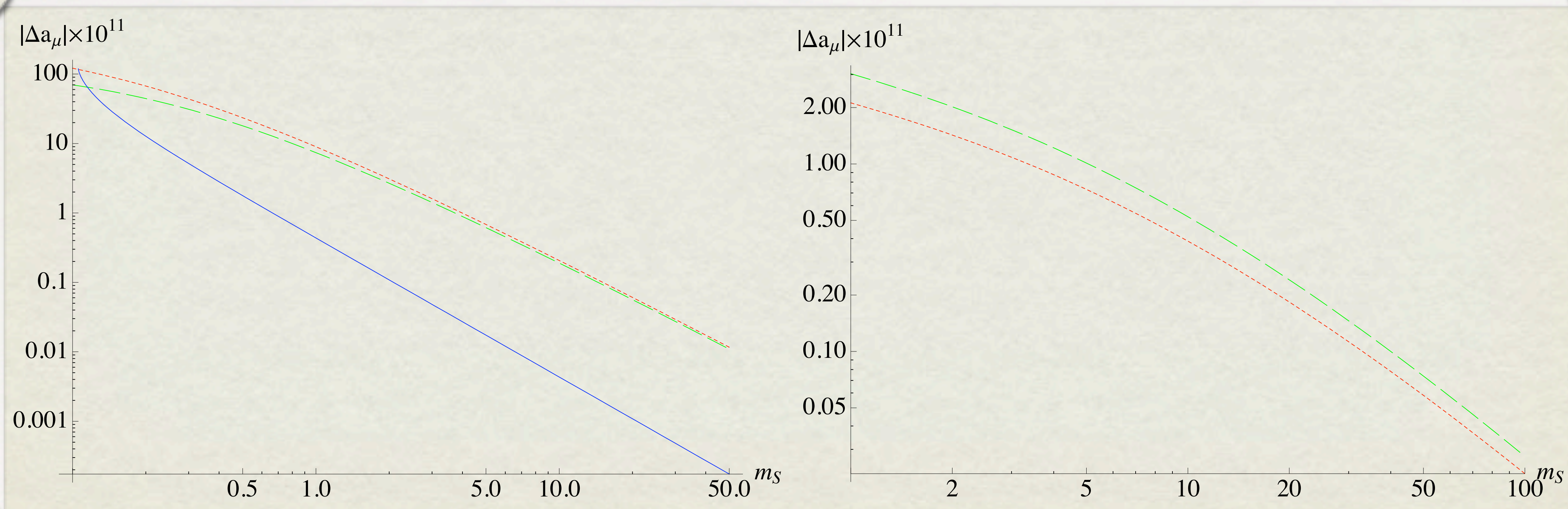
B PHYSICS

- In type II, $b \to s\gamma$ favors high charged Higgs masses (>300 GeV)
- $B \to D\tau\nu_\tau$ is not really restrictive but $B \to \tau\nu_\tau$ strongly favors low values: $\tan\beta \lesssim 30$
- The $B_0 - \overline{B_0}$ mixing forbids extreme $\tan\beta$ values in both type I and II
- The $Zb\bar{b}$ vertex tends to forbid very large m_{A^0}/m_{H^0} splitting

MUON ANOMALOUS MAGNETIC MOMENT

hep-ph/0103223, M. Krawczyk, 2001.

- Even if discrepancies are weaker than in the past, still tends to favor the presence of a light pseudoscalar in type II models (two-loop effect)

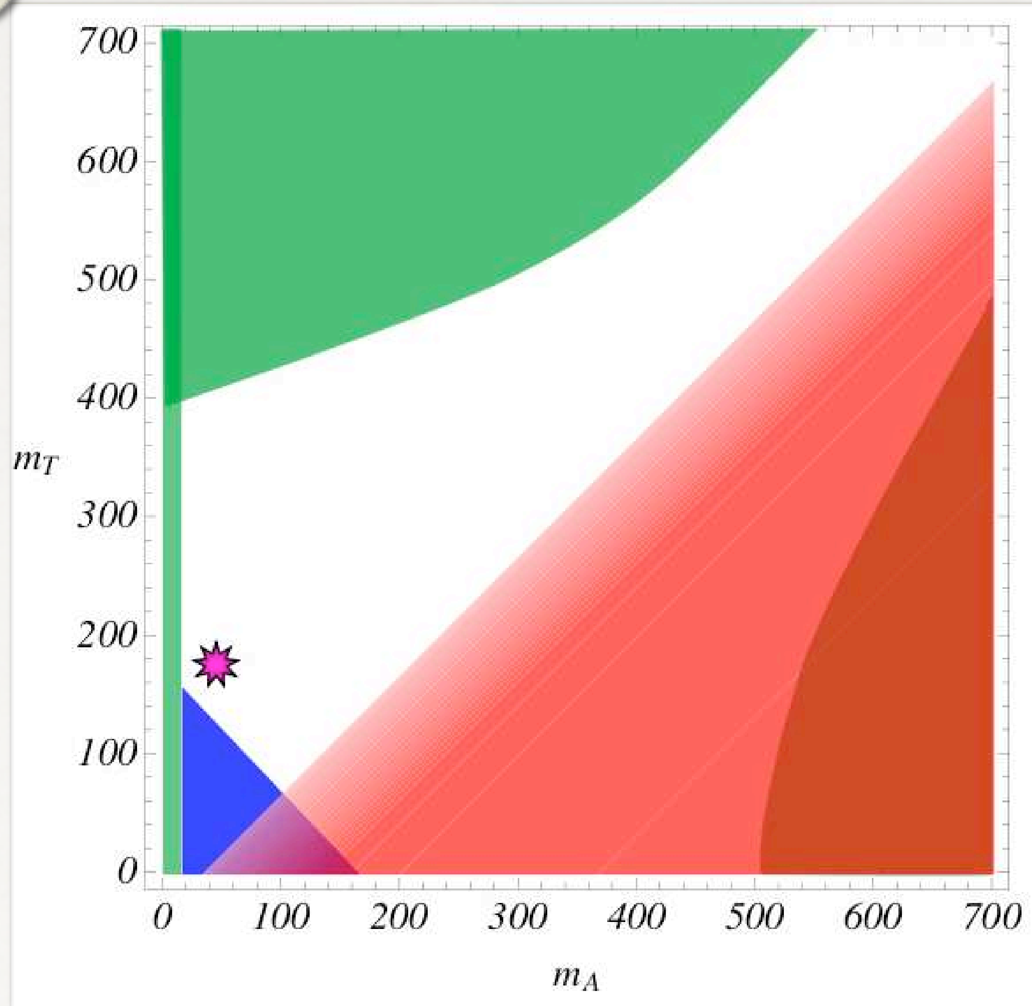


LEP AND TEVATRON

- LEP: $m_{h^0} > 114\,\mathrm{GeV}$(SM searches), $m_{H^0} + m_{A^0} \gtrsim 180\,\mathrm{GeV}$ (pair production), $m_{A^0} \gtrsim 20\,\mathrm{GeV}$ (Yukawa process type II), model independent searches: $m_{H^\pm} > 75\,\mathrm{GeV}$

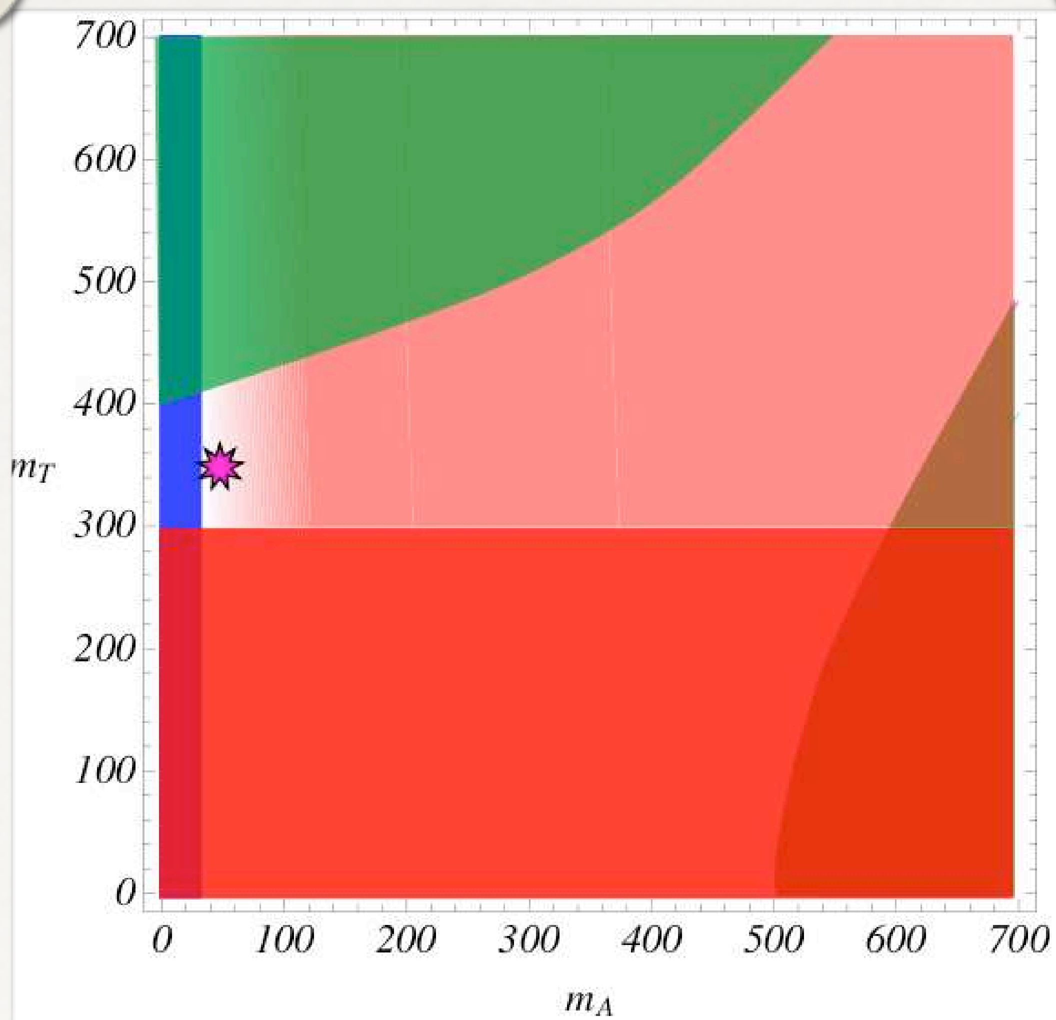
- Tevatron: $\tan\beta < 35$ (if $m_{A^0} > 70\,\mathrm{GeV}$, from MSSM searches), $BR(t \to H^+ b) \lesssim 0.2$ (model independent searches)

SUMMARY



$\tan\beta < 0.4$

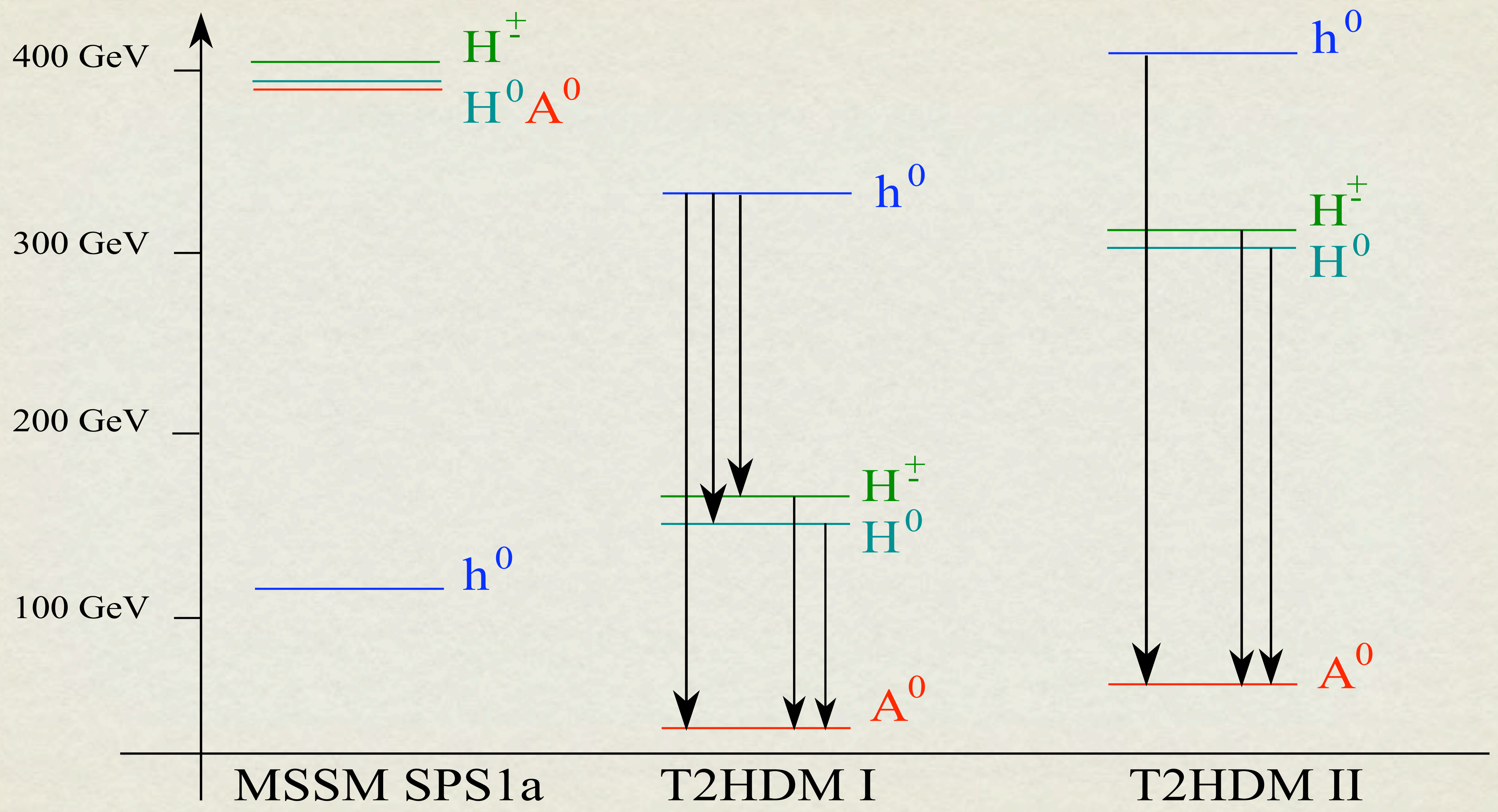
Type I



$\tan\beta < 30$

Type II

UNUSUAL SPECTRUM



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"The true method of knowledge is experiment."

William Blake (1757-1827)

PRODUCTION & DECAY

JHEP 0908:042,2009, S. de Visscher, J.-M. Gérard, V. Lemaitre, F. Maltoni and M.H.

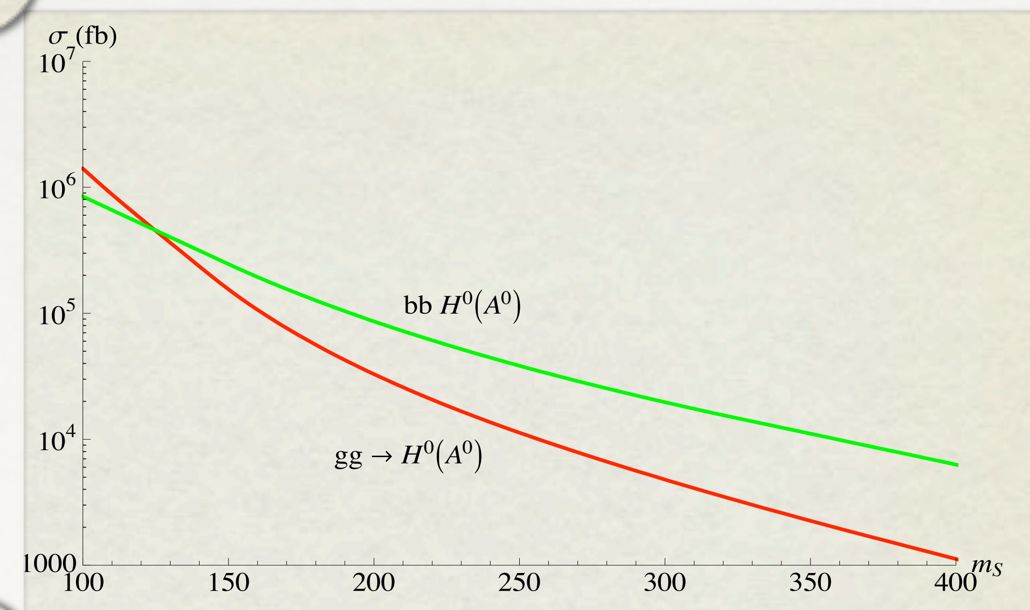
- Usual production for h^0
- Alternatives for $H^0, A^0, H^\pm$

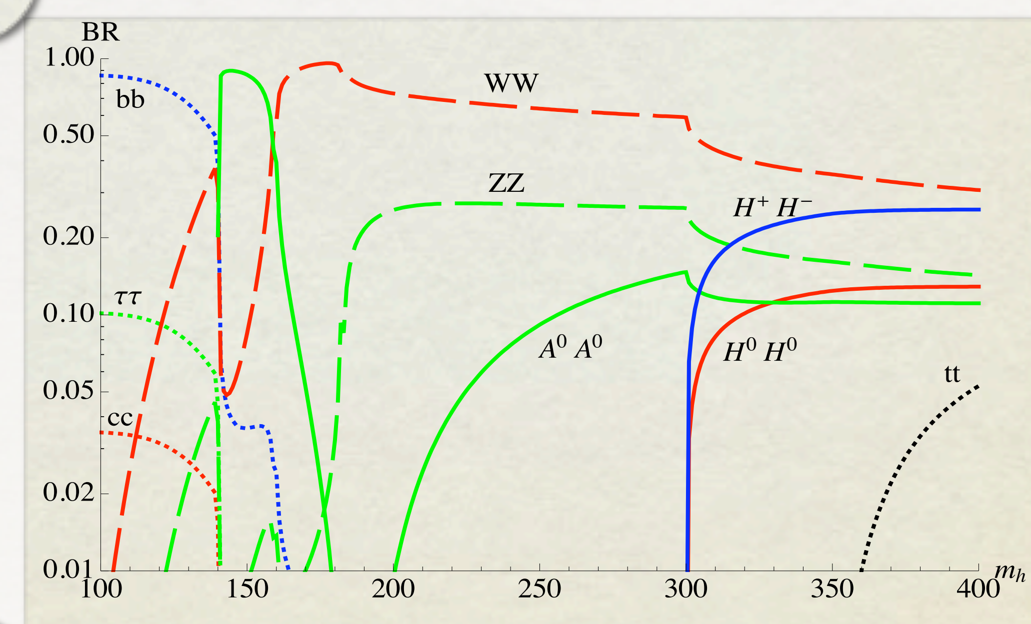
$$\begin{aligned} gg &\rightarrow b\bar{b}H^0(A^0) \\ gb &\rightarrow tH^-,\ t\rightarrow H^+b \end{aligned}$$

- Exotic decays

$$\begin{aligned} h^0 &\rightarrow H^0H^0, H^+H^-, A^0A^0 \\ H^0 &\rightarrow Z^0A^0 \\ H^\pm &\rightarrow W^\pm A^0 \end{aligned}$$

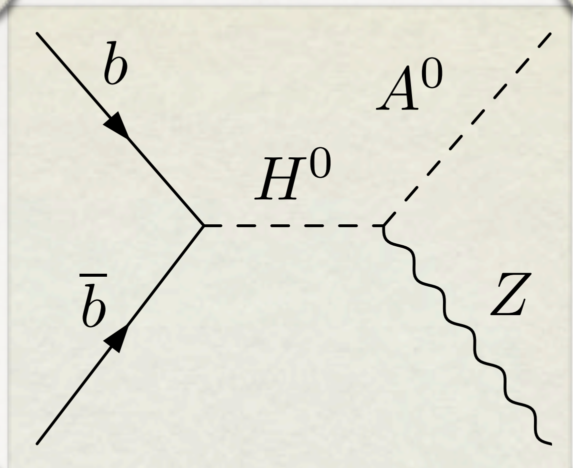
often dominant

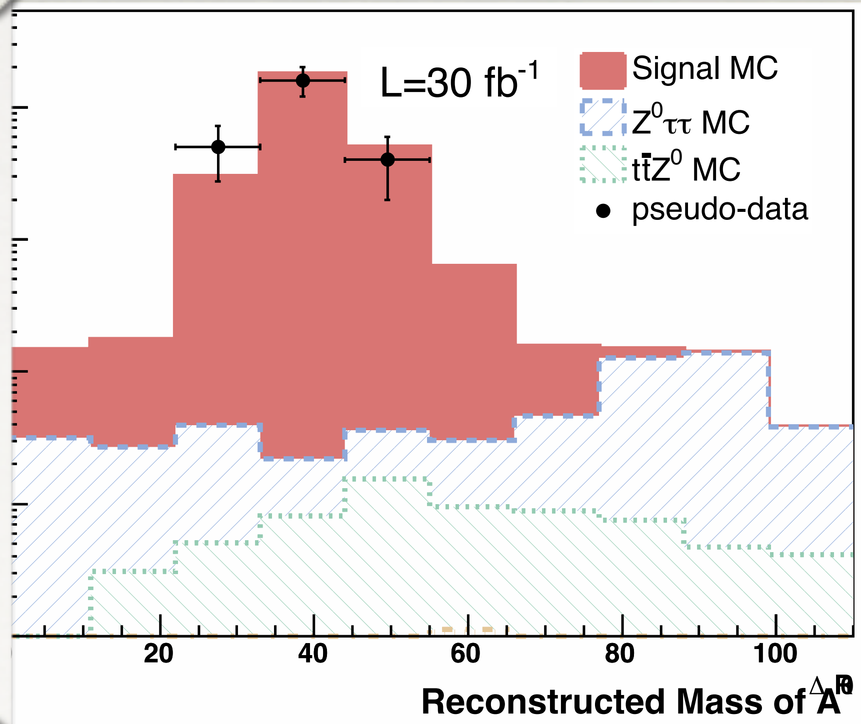




PROCESS $b\bar{b} \to H^0 \to ZA^0$

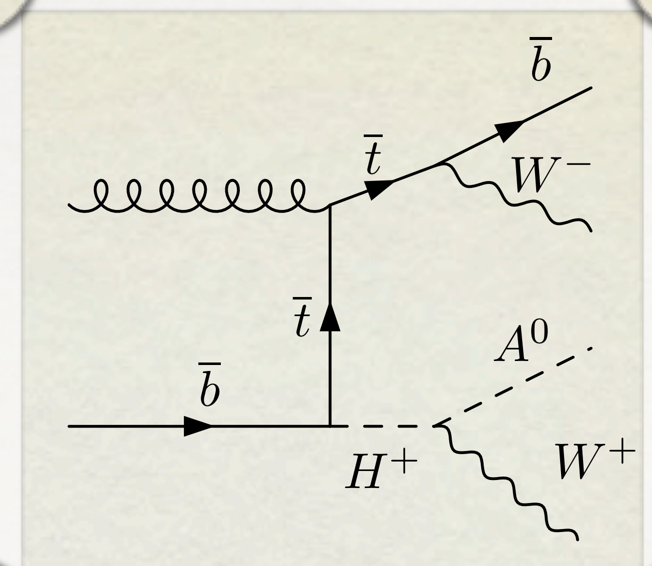
- Large production cross section (type II)
- If $A^0 \to \tau^+\tau^-$ and the taus decay leptonically, very clear
- Low SM background (ZZ, WWZ and ttZ)
- Realistic studies have shown discovery possibility after $20\,\mathrm{fb}^{-1}$

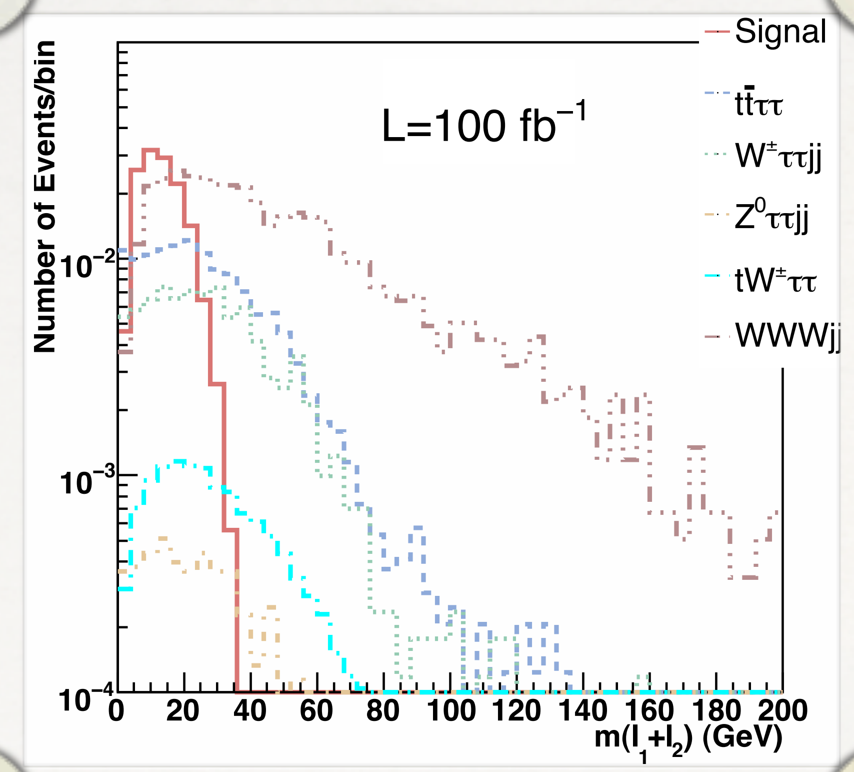




PROCESS $g(b/\bar{b}) \rightarrow (t/\bar{t})H^{\pm} \rightarrow W^{-}(b/\bar{b})W^{+}A^{0}$

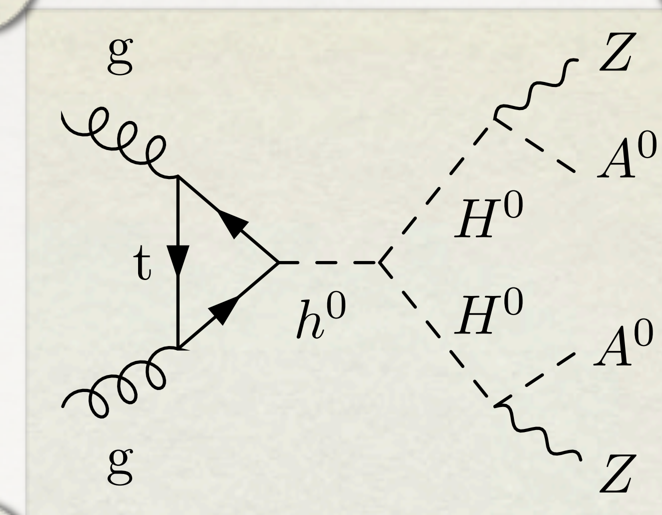
- Crucial to identify an extended Higgs sector
- Again, $A^0 \rightarrow \tau^+\tau^-$ and the taus decay leptonically
- Difficult SM background (ttZ and WWWjj)
- Discovery is only possible at very high luminosity

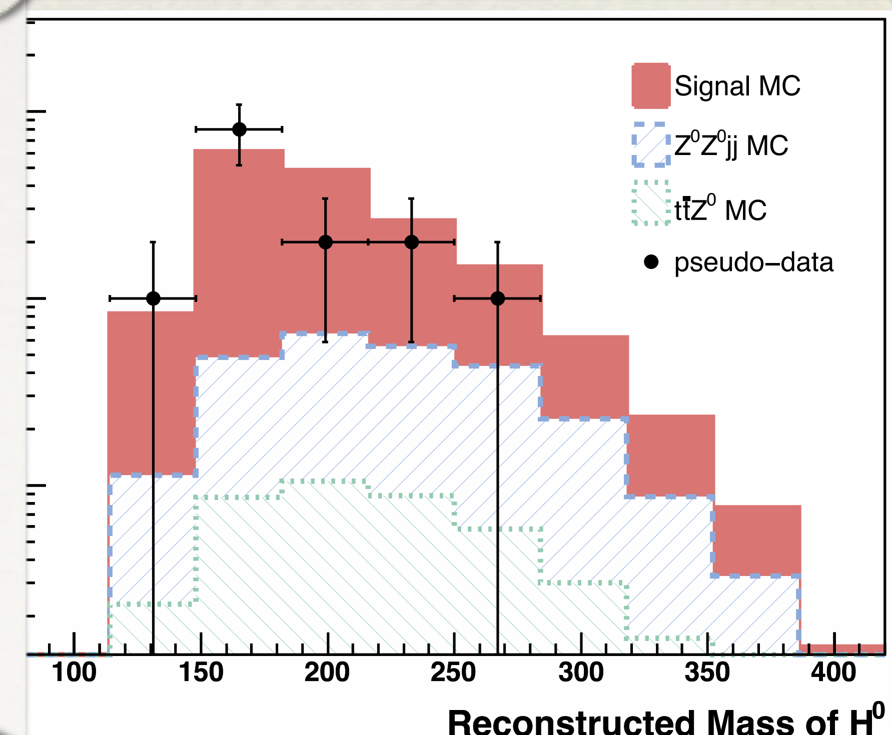




PROCESS $gg \to h^0 \to H^0 H^0 \to Z A^0 Z A^0$

- Signature of an inverted spectrum
- $A^0 \to b\bar{b}$ due to relatively low cross section (considered as one single jet)
- Very low SM background (ttZ and ZZjj)
- Discovery and mass reconstruction possible at 30fb^{-1}





CONCLUSION

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- It can be implemented as a “minimal”, yet viable, 2HDM
- Unusual and challenging phenomenology may appear at hadron collider

THANKS FOR YOUR ATTENTION