Probing 2HDMs with top-quark observables

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Motivation

- Charged Higgs is a clear sign of new physics.
- Basic measurement: cross section of charged Higgs production.
- Detailed information on the interactions from particle polarization measurements.
- Polarization of heavy particles is related to the distributions of decay particles.
- Probe Charged Higgs' Yukawa couplings.

Determination of tW, tH couplings in single-top production:

Rindani, Sharma, JHEP 11 (2011) 082
Huitu, Rai, Rao, Rindani, Sharma, JHEP 04 (2011) 026
Godbole, Hartgring, Niessen, White, JHEP 01 (2012) 011.

top-quark observables

top polarization can be measured by studying the decay distribution of a decay fermion f in the rest frame of the top

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_f} = \frac{1}{2}(1 + P_t \kappa_f \cos\theta_f)$$

θ_f is the angle between the fermion f momentum and the top spin,
P_t is the degree of top polarization,
κ_f is the "analyzing power" of the final-state particle f.

$$P_t = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

$N_\uparrow$ Positive helicity tops

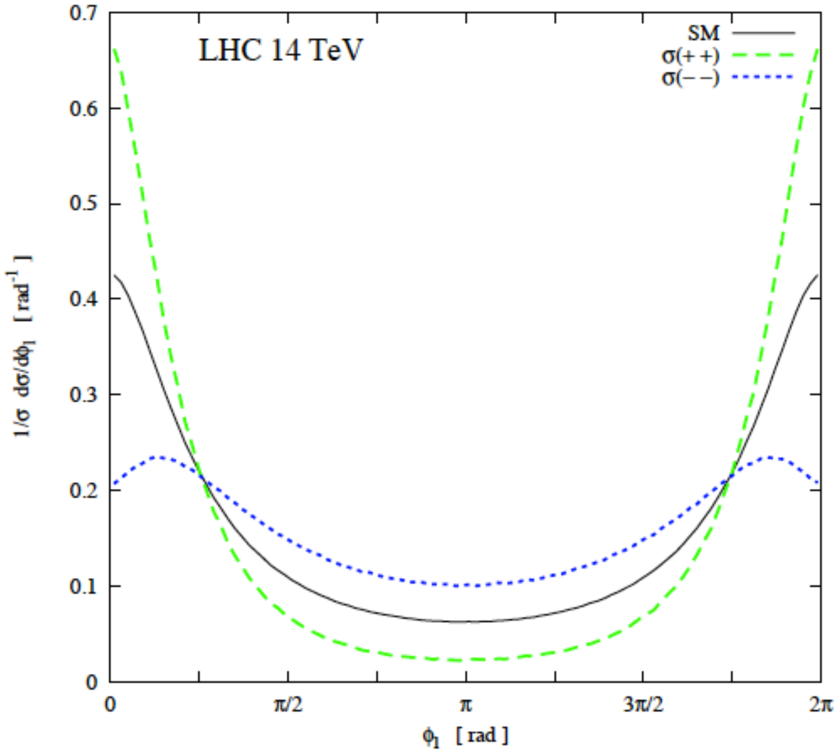
$N_\downarrow$ Negative helicity tops

These distributions are defined in top-quark rest frame. Reconstruction of top-rest frame is difficult at LHC

Lepton Azimuthal distribution

We can study a lab-frame distribution of top-decay products

$$pp \to t\,H^- \to b\,W\,H^- \to b\,l\,\nu\,H^-$$



Φ_l distribution is symmetric around $\Phi_l = \pi$. We define azimuthal asymmetry of charged lepton as

$$A_\phi = \frac{\sigma(\cos\phi_\ell > 0) - \sigma(\cos\phi_\ell < 0)}{\sigma(\cos\phi_\ell > 0) + \sigma(\cos\phi_\ell < 0)}$$

Z_2 symmetric CP-conserving 2HDM (softly broken)

$$V(\Phi_1,\Phi_2) = m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 - (m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c}) + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2$$
$$+ \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\lambda_5[(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}]$$

- m^2_{12} and λ_5 real, vacuum configuration

$$\langle\phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_1\end{pmatrix};\ \langle\phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_2\end{pmatrix}$$

7 free parameters + M_W: $m_h,\ m_H,\ m_A,\ m_{H\pm},\ \tan\beta,\ \alpha,\ M^2 = \frac{m_{12}^2}{\sin\beta\ \cos\beta}$

- $\tan\beta = \frac{v_2}{v_1}$ ratio of vacuum expectation values
- α rotation angle neutral CP-even sector

2HDM Lagrangian

- scalars-gauge bosons couplings

$$g_{SM}^{hVV}\sin(\beta-\alpha)$$ for the lightest CP-even Higgs

$$\cos(\beta-\alpha)$$ for the heavier CP-even Higgs

- Yukawa couplings

$$\sin\alpha \quad \tan\beta$$

Model	$g_{\bar{u}dH^+}$	$g_{l\bar{\nu}H^+}$
I	$\frac{ig}{\sqrt{2}\,M_W}V_{ud}\,[-m_d\cot\beta P_R+m_u\cot\beta P_L]$	$\frac{ig}{\sqrt{2}\,M_W}\,[-m_l\cot\beta P_R]$
II	$\frac{ig}{\sqrt{2}\,M_W}V_{ud}\,[m_d\,\tan\beta P_R+m_u\cot\beta P_L]$	$\frac{ig}{\sqrt{2}\,M_W}\,[m_l\,\tan\beta P_R]$
Y	$\frac{ig}{\sqrt{2}\,M_W}V_{ud}\,[m_d\,\tan\beta P_R+m_u\cot\beta P_L]$	$\frac{ig}{\sqrt{2}\,M_W}\,[-m_l\cot\beta P_R]$
X	$\frac{ig}{\sqrt{2}\,M_W}V_{ud}\,[-m_d\cot\beta P_R+m_u\cot\beta P_L]$	$\frac{ig}{\sqrt{2}\,M_W}\,[m_l\,\tan\beta P_R]$

III = I' = Y = Flipped=…

IV = II' = X = Lepton Specific= …

Experimental constraints on the charged Higgs mass

- **LEP** $e^+e^- \to H^+H^-$

ALEPH, DELPHI, L3 and OPAL Collaborations
The LEP working group for Higgs boson searches[1]

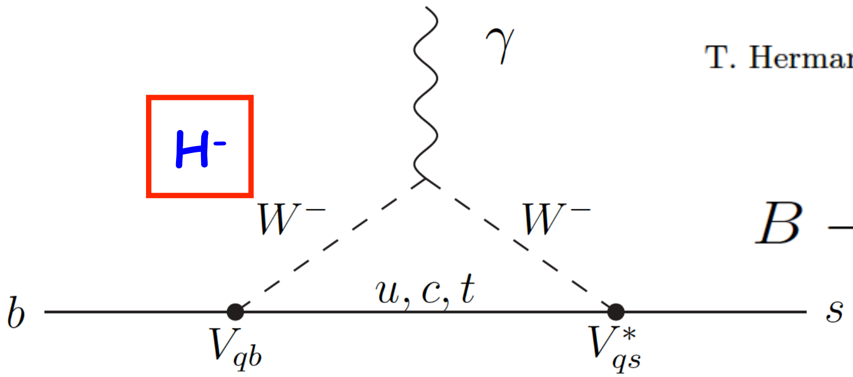
arXiv:1301.6065v1

Any $BR(H^+ \to \tau^+\nu)$ $m_{H^\pm} \gtrsim 80\ GeV$

$BR(H^+ \to \tau^+\nu) \approx 1$ $m_{H^\pm} \gtrsim 94\ GeV$ **(Model X)**

- **B factories**

T. Hermann, M. Misiak and M. Steinhauser, JHEP **1211** (2012) 036



$B \to X_s\gamma$

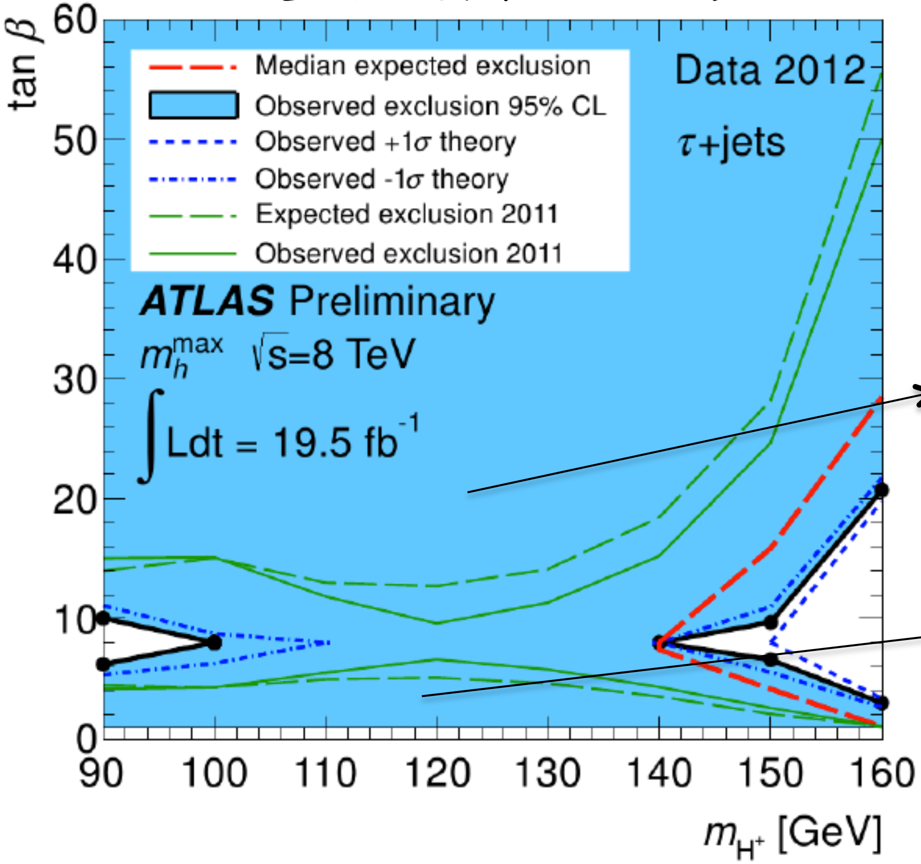
Models II and Y $m_{H^\pm} \gtrsim 360\ GeV$

Best available bound on the charged Higgs mass

Experimental (LHC)

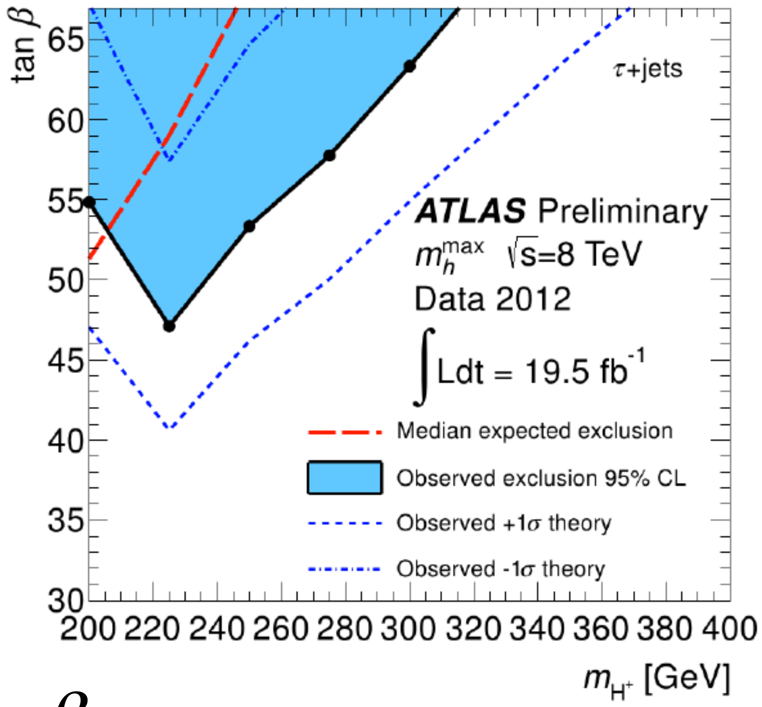
$$pp \to \bar{t}t \to \bar{b}bW^+H^-$$

ATLAS-CONF-2013-090



$$m_b \tan\beta$$

$$\frac{m_t}{\tan\beta}$$



G. Aad *et al.* [ATLAS Collaboration], JHEP **1206** (2012) 039

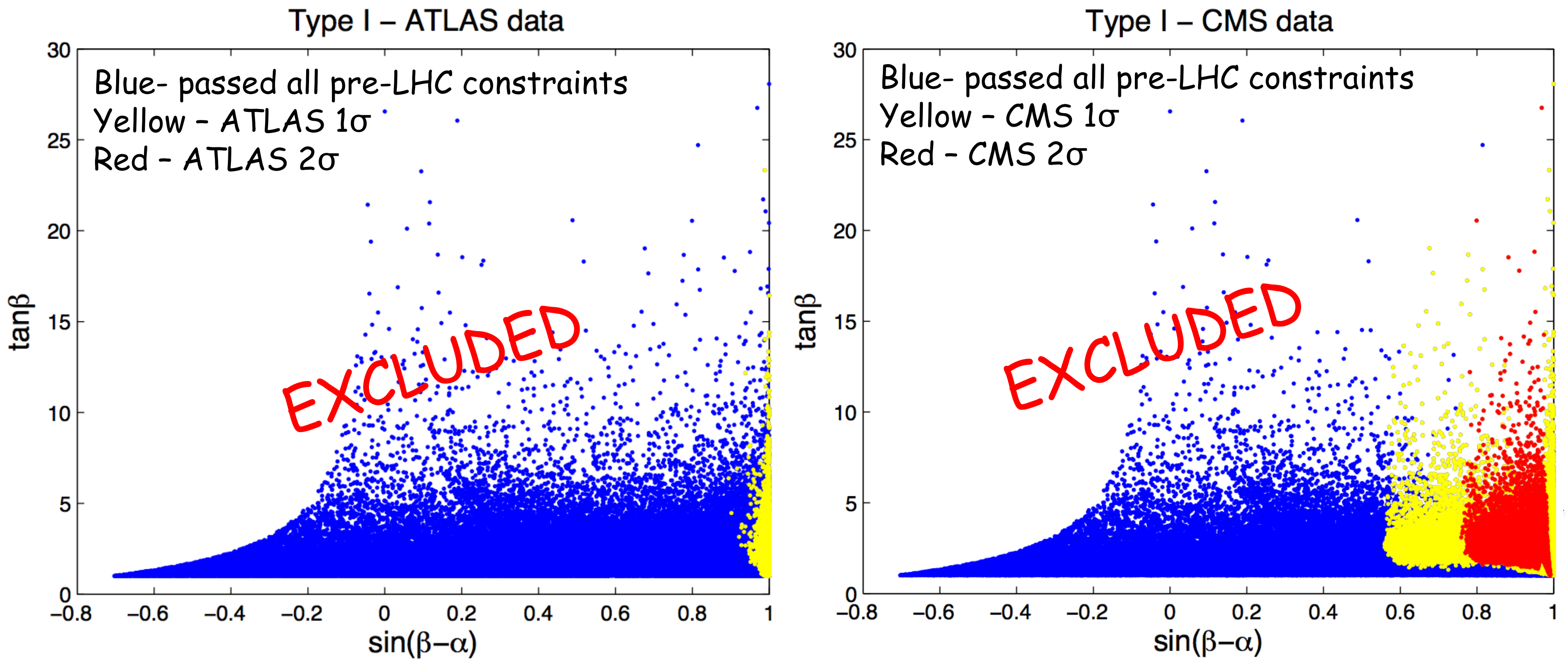
S. Chatrchyan *et al.* [CMS Collaboration], JHEP **1207** (2012) 143

Corrected for

$$BR(H^- \to \tau\bar{\nu})$$

$$m_{H^+} = 90 \text{ GeV}$$

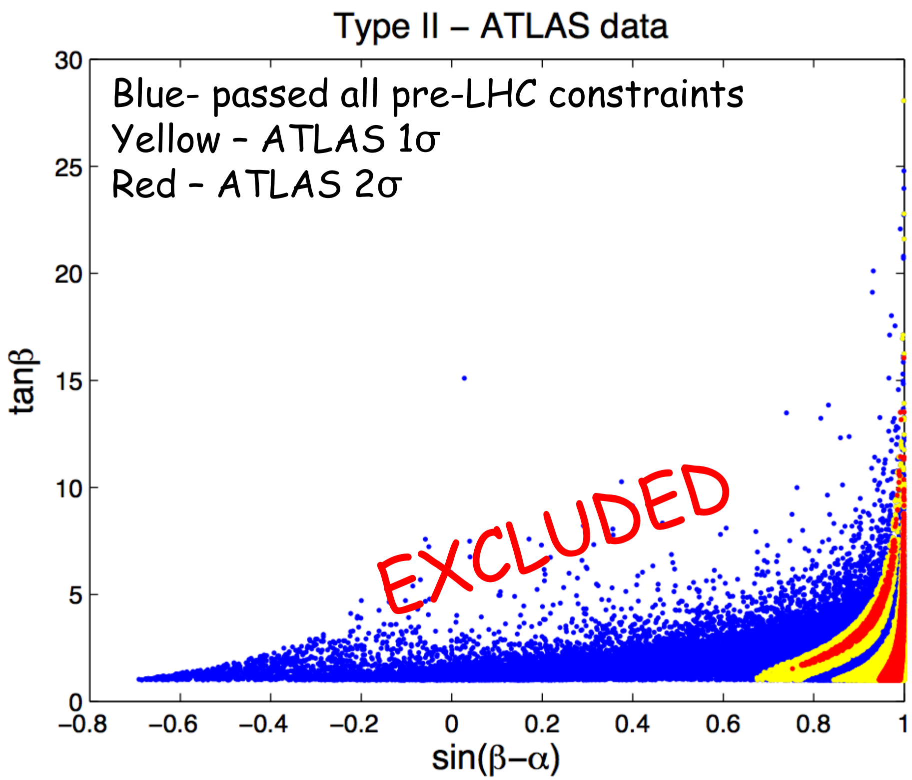
	I	II	Y	X
$\tan\beta$	4.3	6.4	3.2	5.2

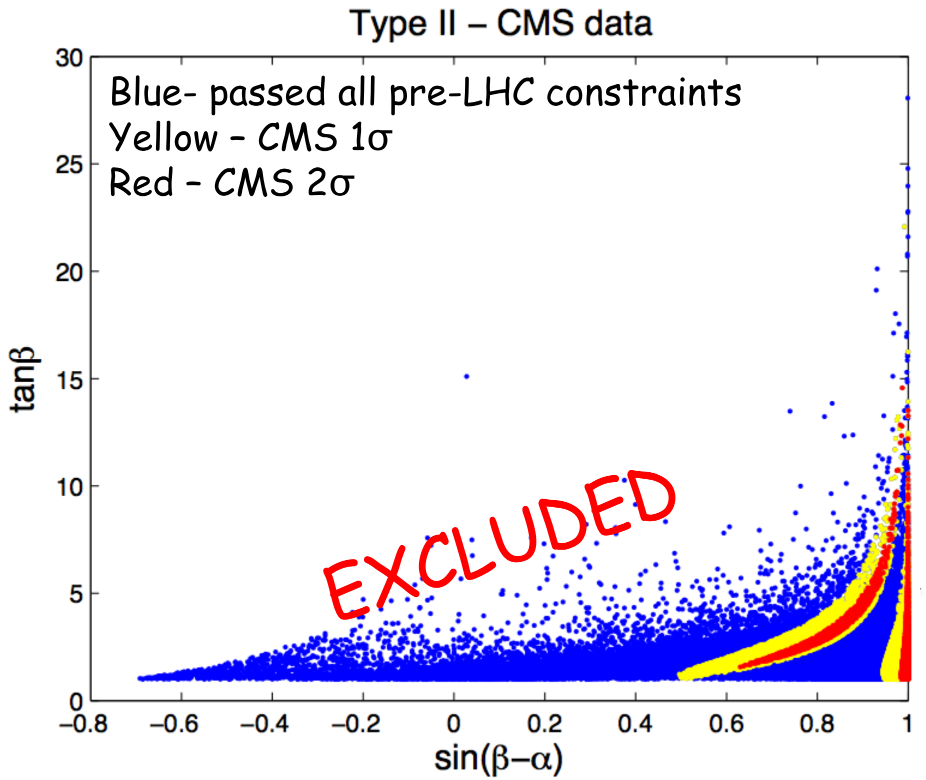


- $\sin(\beta - \alpha) < 0.5$ excluded at 2σ – <u>deviations of the light Higgs couplings to gauge bosons relative to the SM's</u>.

- As long as $\sin(\beta - \alpha)$ is in the allowed region, large values of tanβ are also allowed.

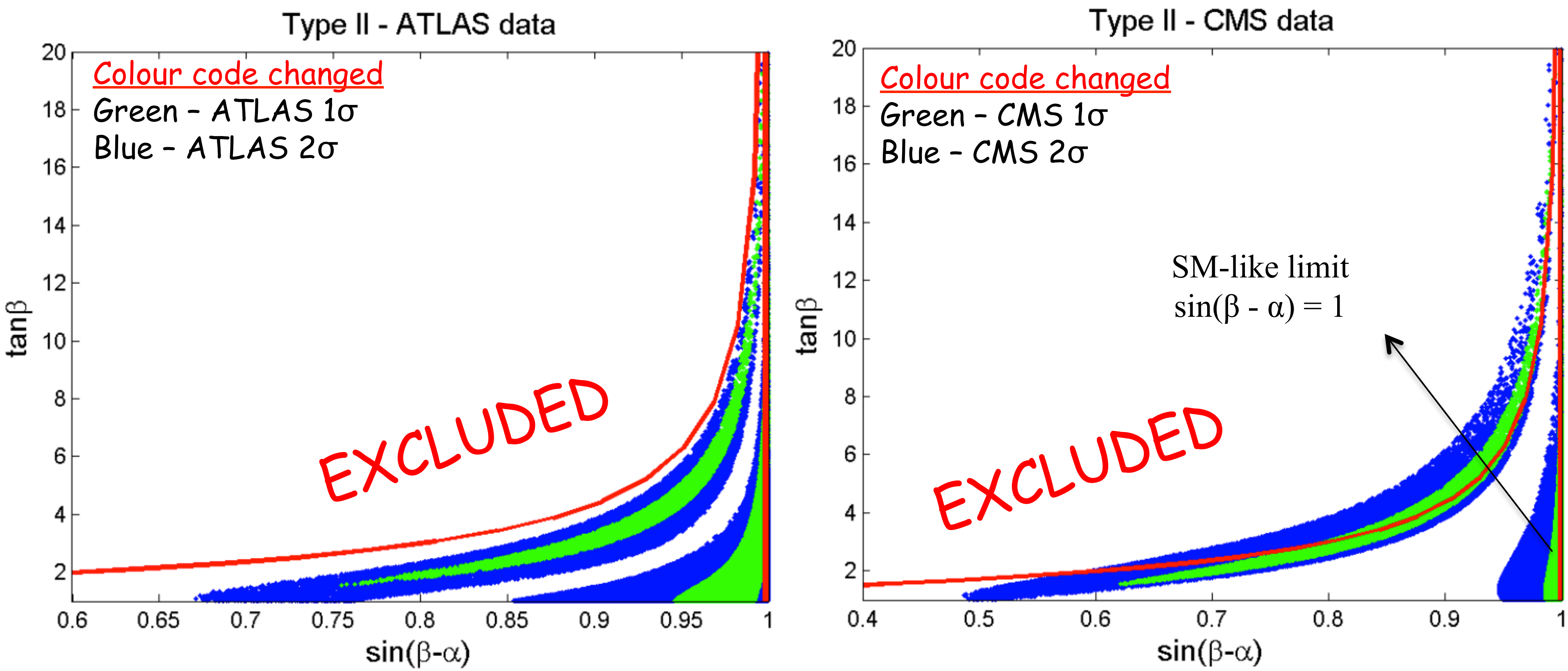
- In type I, μ_{XX} tend to be close to or below 1. That is why there are no red points in the ATLAS plot and the yellow points are the ones closer to the SM-like limit in the CMS plots.





- $\sin(\beta - \alpha) < 0.5$ excluded at 2σ – <u>deviations of the light Higgs couplings to gauge bosons relative to the SM's</u>.

- For $\sin(\beta - \alpha) < 0.8$, $\tan\beta < 4$ – <u>large $\tan\beta$ only close to $\sin(\beta - \alpha) = 1$</u>. This is a major difference relative to type I models.



- zoom on the previous plots for type II where we just show the allowed region at 1 and 2 sigma.

- In type II, μ_{XX} can be above 1. Because ATLAS results for VV are above the SM ones, the points are below/on the red lines. For CMS the μ_{VV} are below the SM ones so the points are on/above the red lines.

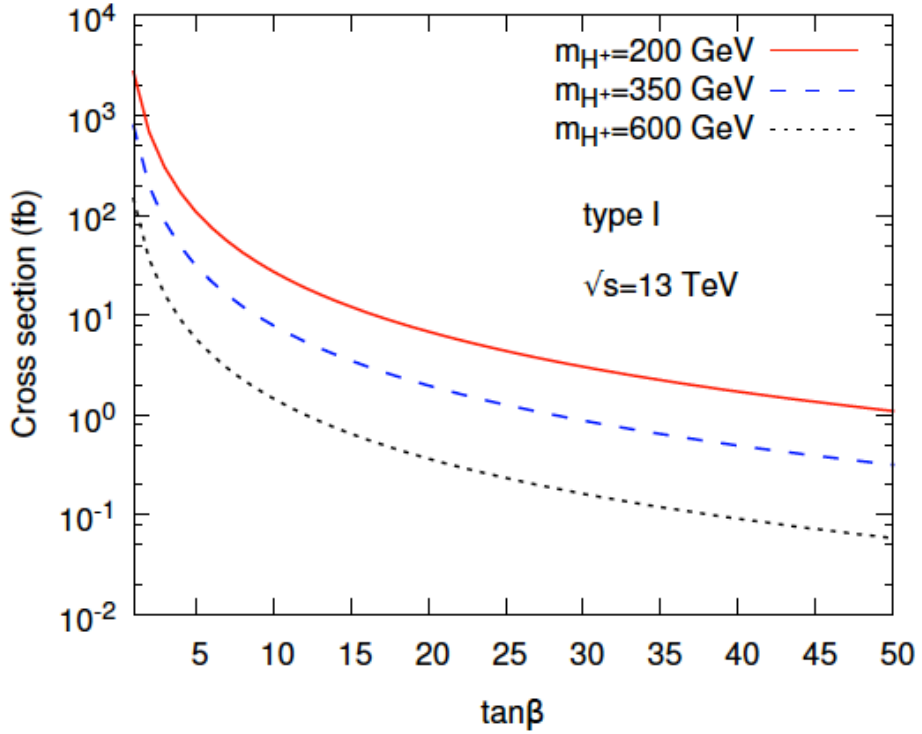
top Yukawa couplings

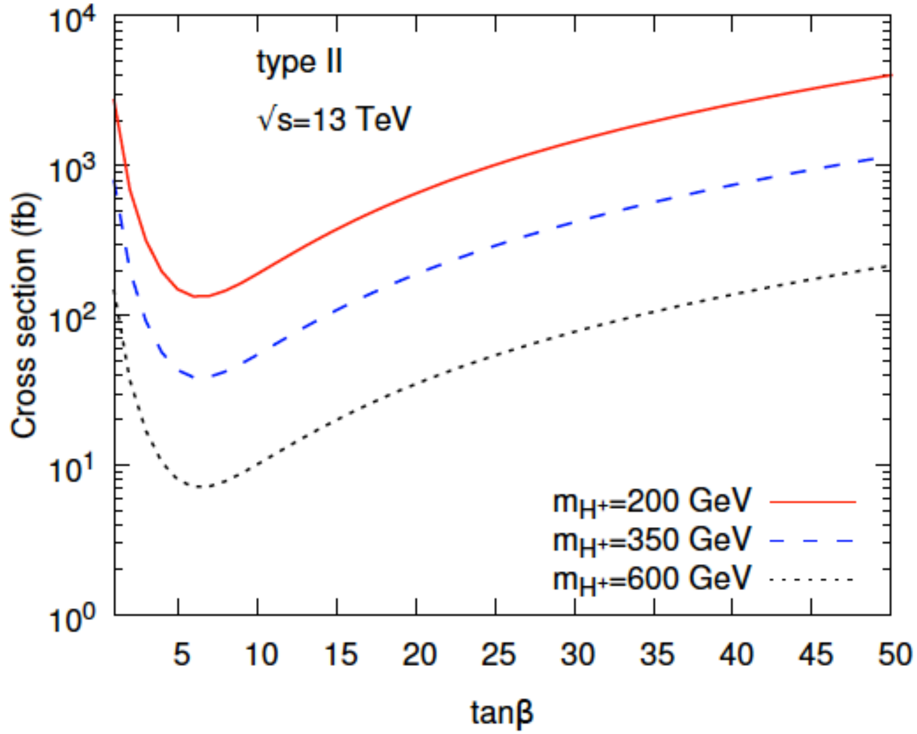
$$\bar{t}\, b H^+ \quad \longrightarrow \quad \boxed{A_t m_t \gamma_L + A_b m_b \gamma_R}$$

- $A_t\, m_t \gg A_b\, m_b$ — type I, X 2HDM, THM, and type II, Y 2HDM, (n)MSSM (low tanβ)
- $A_t\, m_t \ll A_b\, m_b$ — type II, Y 2HDM, (n)MSSM (high tanβ)
- $A_t\, m_t \sim A_b\, m_b$ — type II, Y 2HDM, (n)MSSM (medium tanβ)

Production cross sections

➡ $pp \to tH^-$

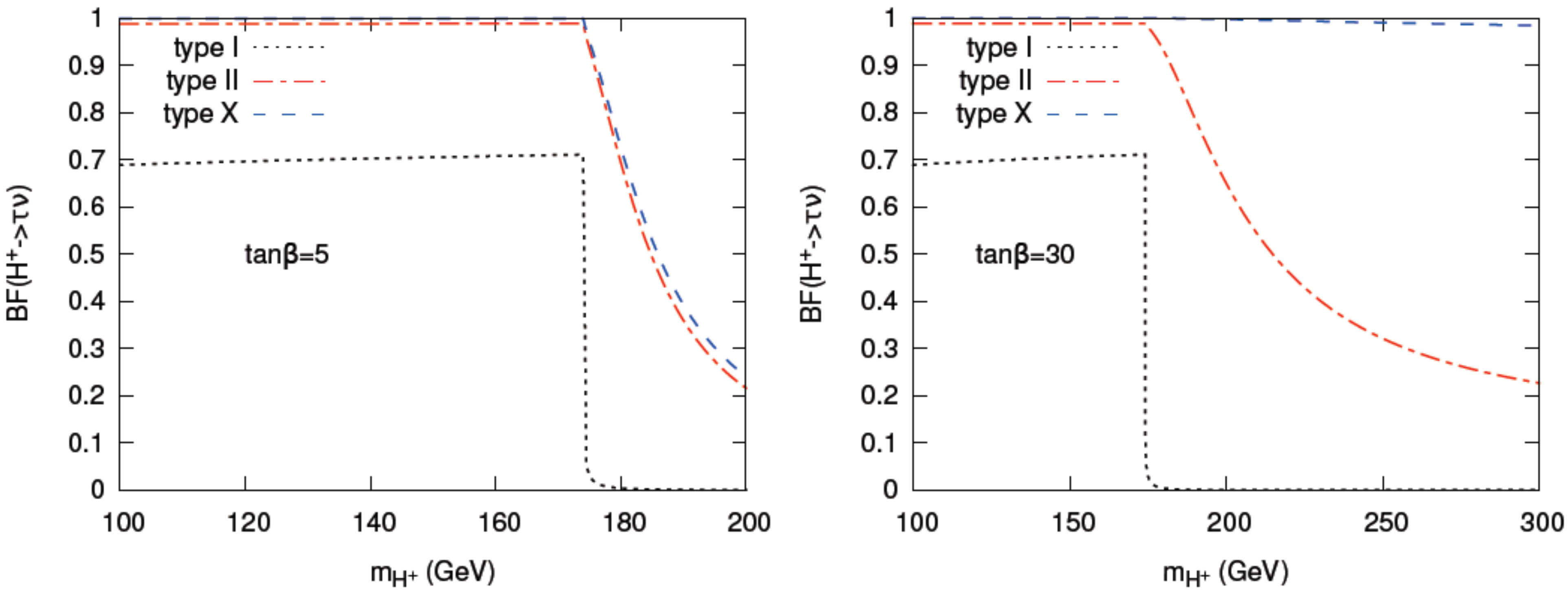




$$\sigma \propto \left(m_t^2 + m_b^2\right) \cot^2\beta$$

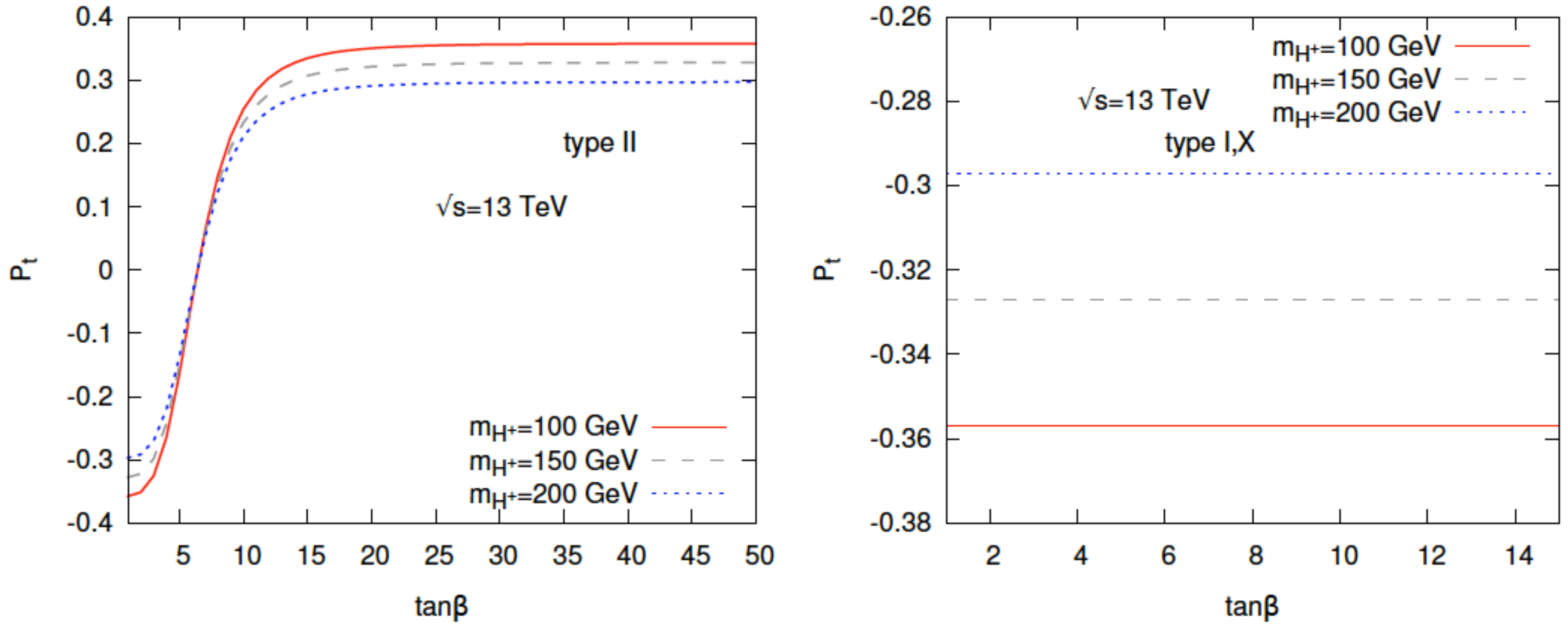
$$\sigma \propto \left(m_t^2 \cot^2\beta + m_b^2 \tan^2\beta\right)$$

Branching ratios



- $H^+ \to \tau\upsilon$, best way to search for a charged Higgs.
- $\sin(\beta - \alpha) \approx 1$ excludes $H^+ \to h\, W^+$ in all Yukawa types.
- In Type I all H^+ decays to fermions share the common $1/\tan\beta$ factor.
- For large $\tan\beta$ $H^+ \to tb$ is negligible in Type X.

Top polarization as a function of tanβ



- Used to measure tanβ in "type II".

- In many models (or regions of parameter space) P_t (or other asymmetries) is independent of the Yukawa coupling – it gives the charged Higgs mass.

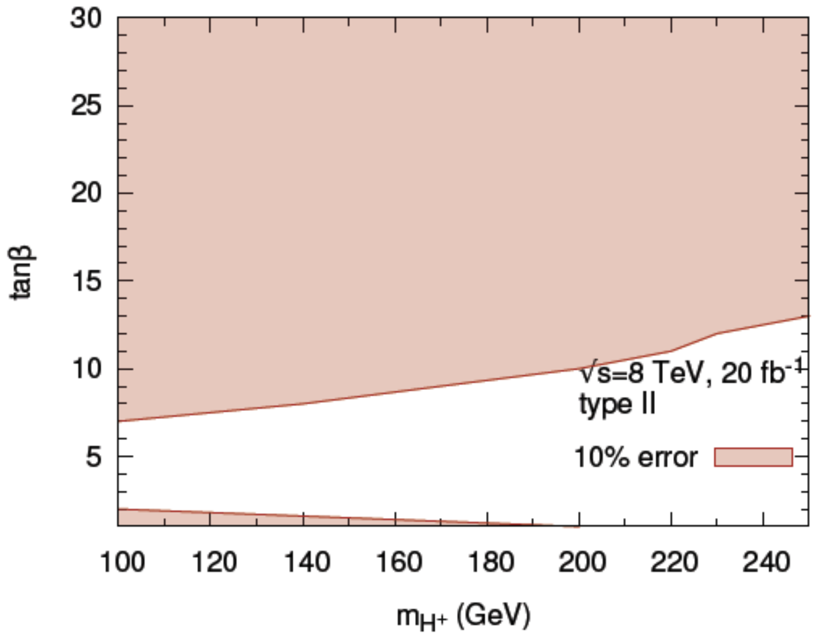
Huitu, Rai, Rao, Rindani, Sharma, JHEP 04 (2011) 026
Godbole, Hartgring, Niessen, White, JHEP 01 (2012) 011.

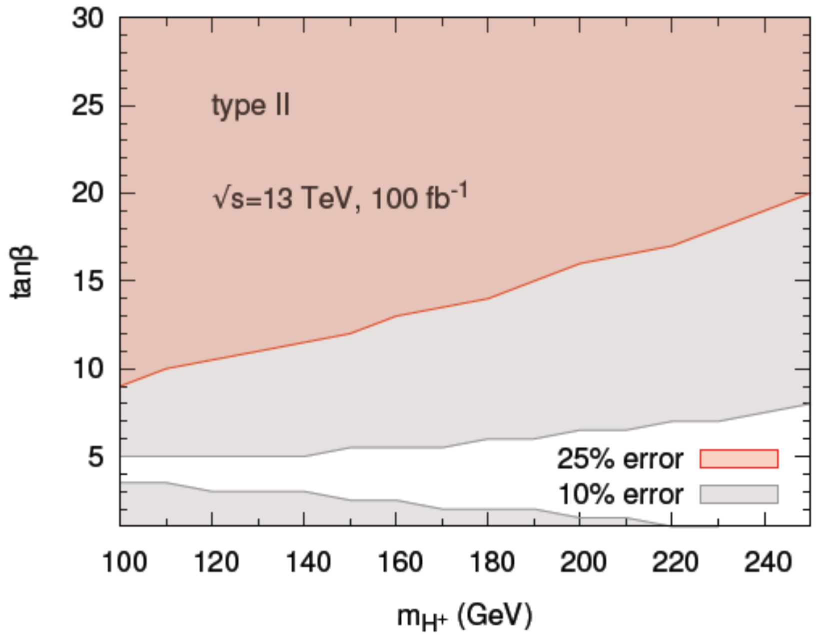
- Can it compete with cross section measurements in excluding the parameter space?

Exclusion with top polarization

- What if measured observables do not deviate from pp-> tW?
- In order to make this estimate we consider $pp \to t\,\tau\nu \to b\,l\,\tau\,\not{E}$
- Relate the experimentally measured values of observables with the SM and New Physics (NP) predictions Cao, McKeen, Rosner, Shaughnessy, Wagner, PRD81, 114004 (2010).

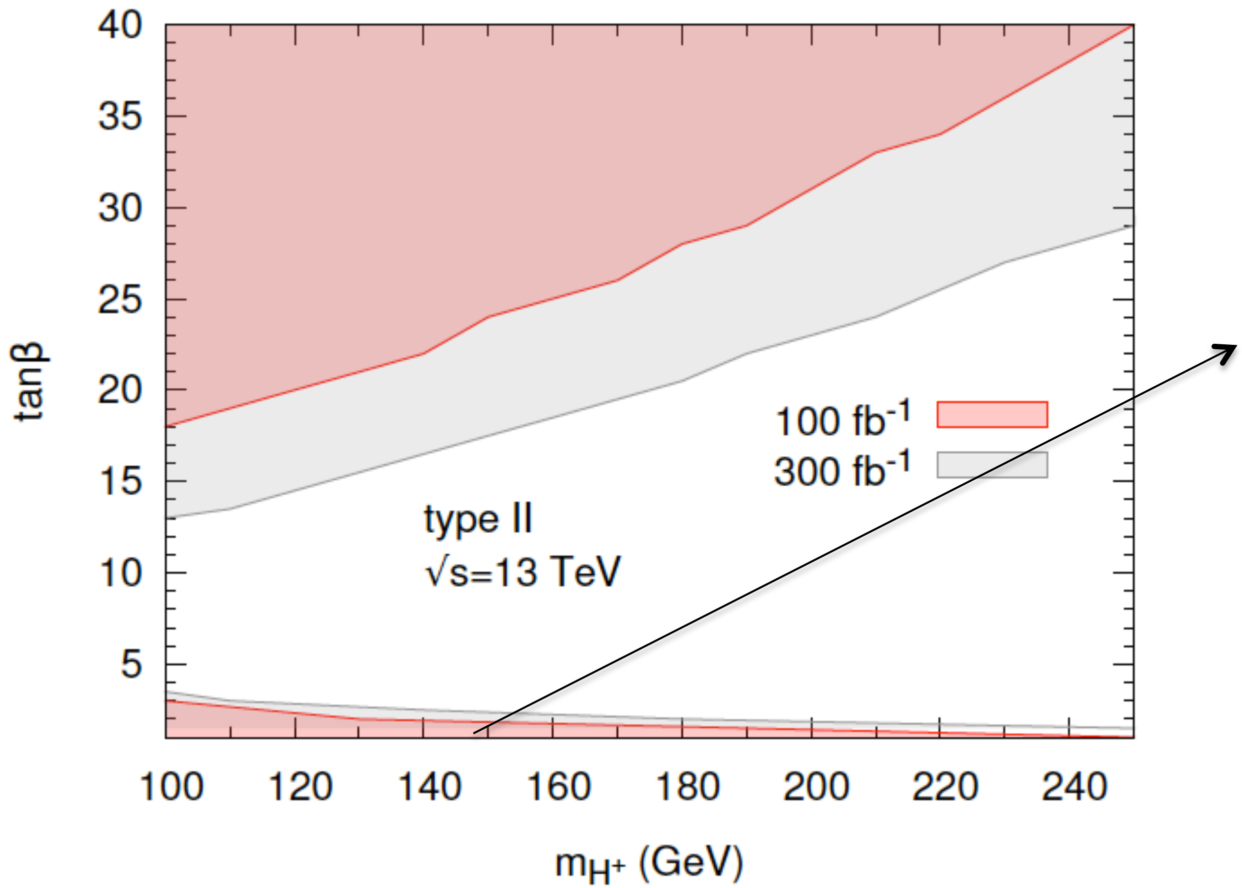
$$P_t^{tot} = P_t^{NP}\,R + P_t^{SM}\,(1-R) \qquad R = \frac{\sigma_{tot}^{NP}}{\sigma_{tot}^{SM} + \sigma_{tot}^{NP}}$$





Cannot compete with direct pp -> tt, but reach in charged Higgs mass higher.

Exclusion with left-right asymmetry

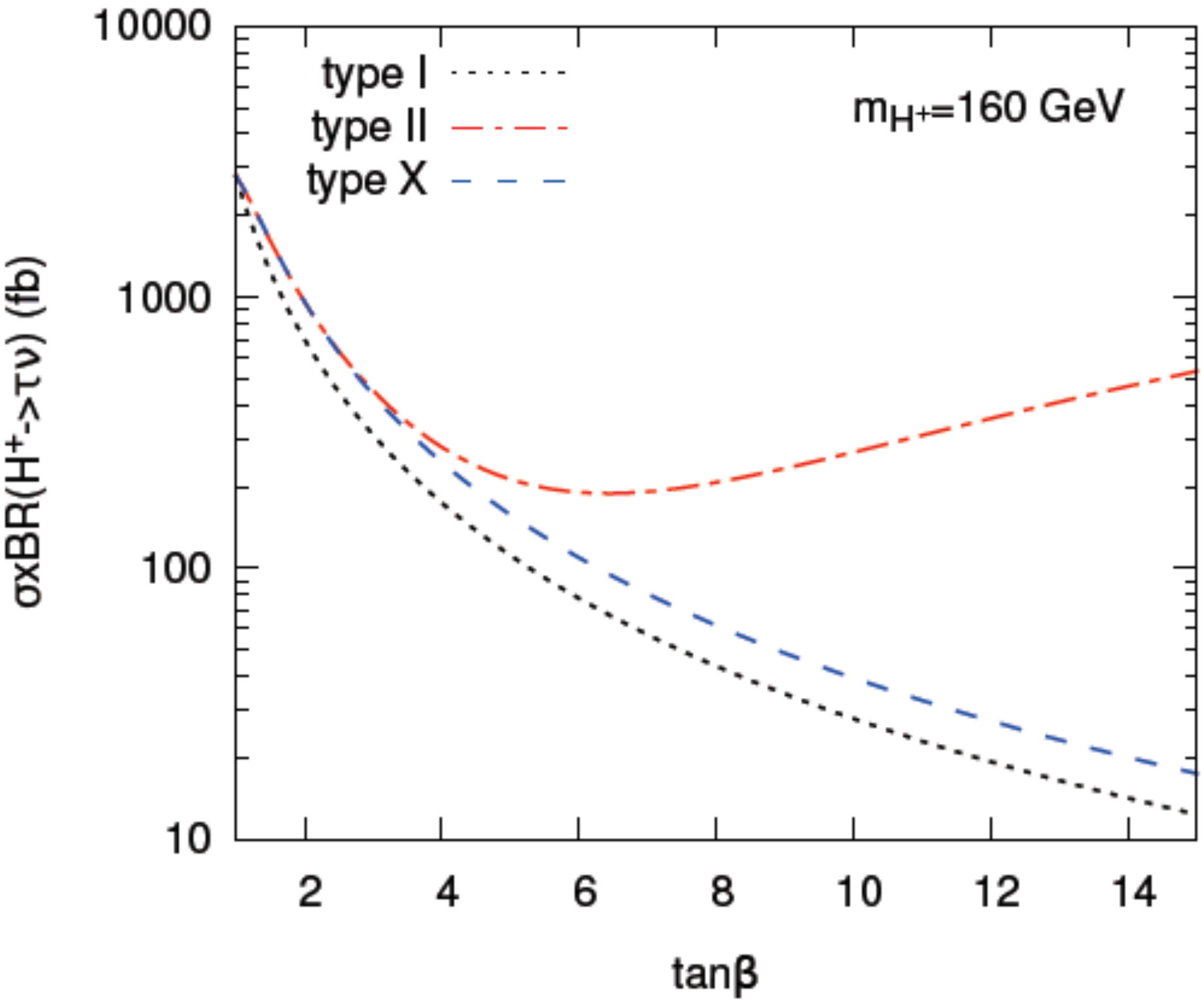


Also for type I and X when corrected for

$$BR(H^- \to \tau\bar{\nu})$$

This asymmetry is defined in the lab frame and thus expected to be measured with high precision. We have considered a 5 % systematic error. It shows that it should be further investigated.

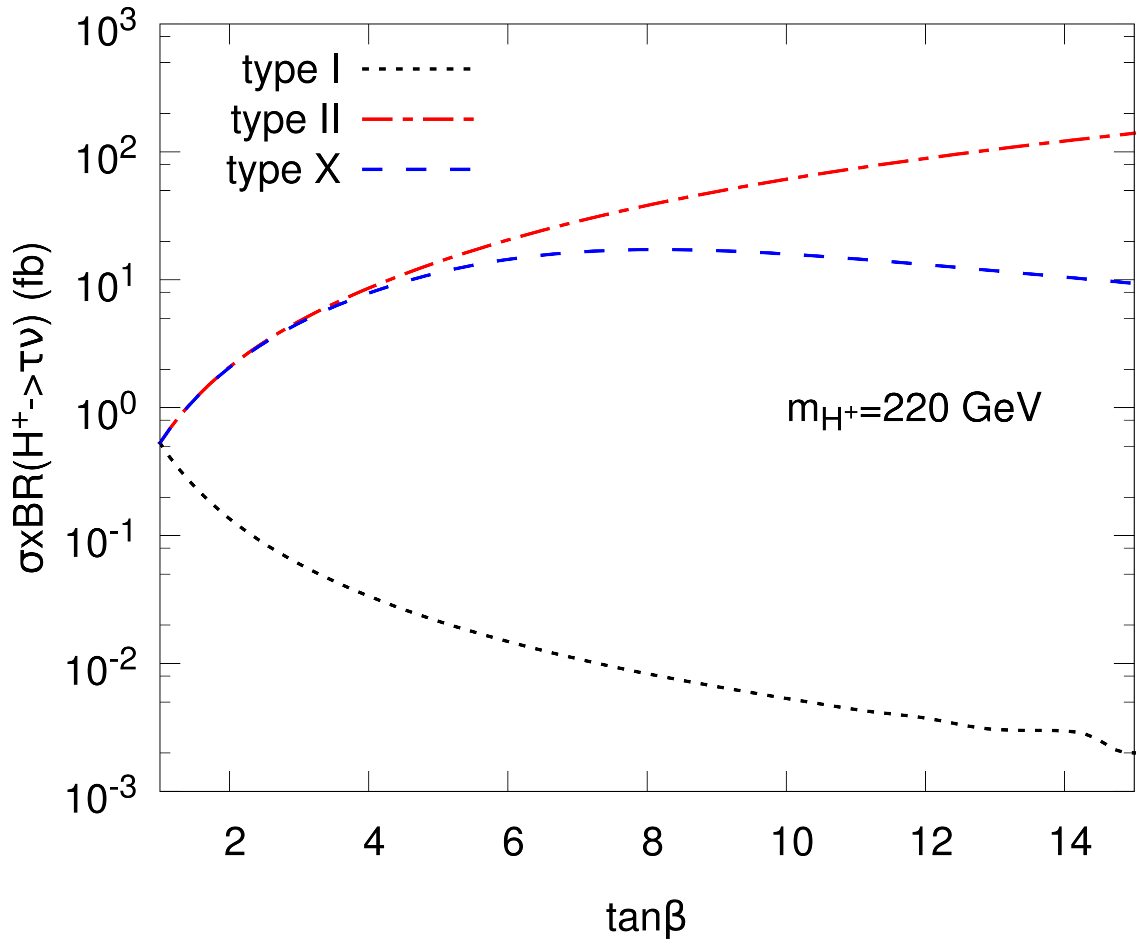
Discriminating models



Suppose we have two models that would give exactly the same number of charged Higgs events.

Taking the 2HDM as an example, for 160 GeV, for tan beta between 1 and 5 "type II" and type X would give very similar number of events.

Discriminating models

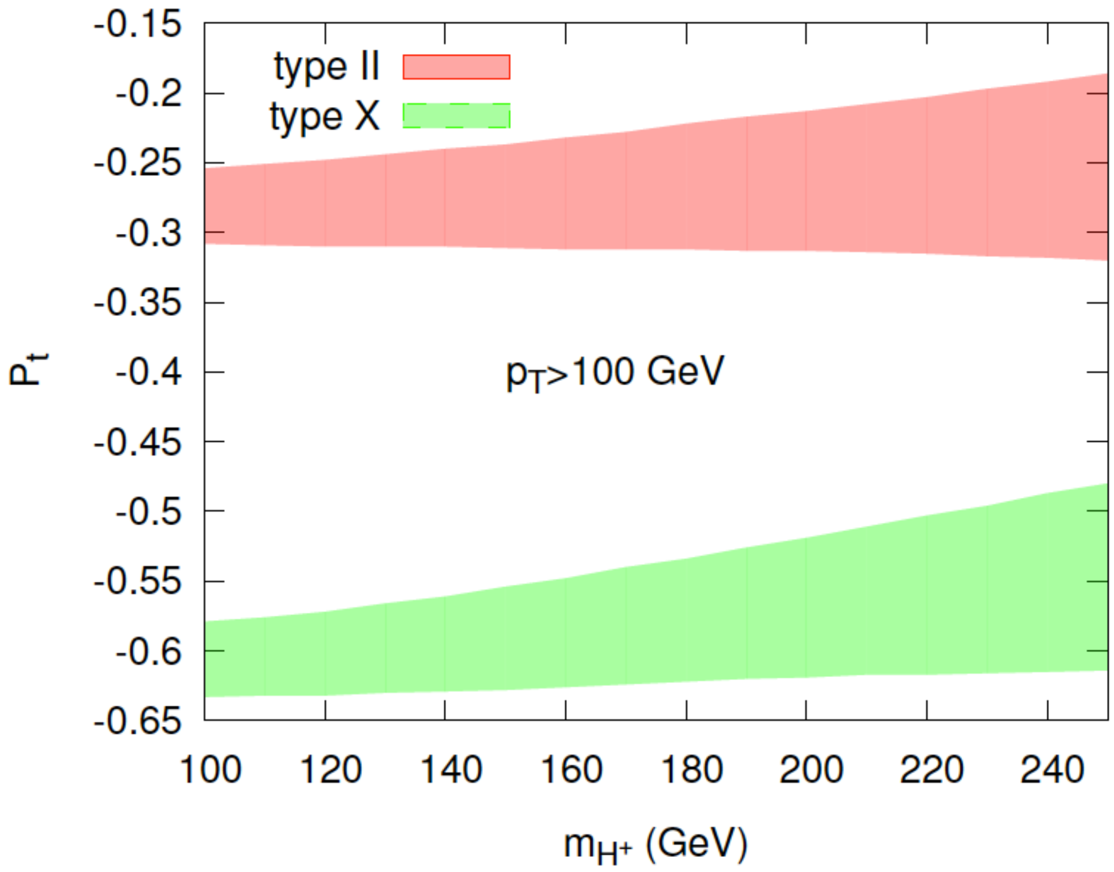


Same plot now for a charged Higgs mass of 220 GeV

When H^+ -> tb is possible it is dominant for low tanβ.

Therefore type I is now away from types "II" and X. Because BR to τν is much larger in type X there is again a region where the number of events is similar.

Discriminating type X and type II 2HDMs with P_t

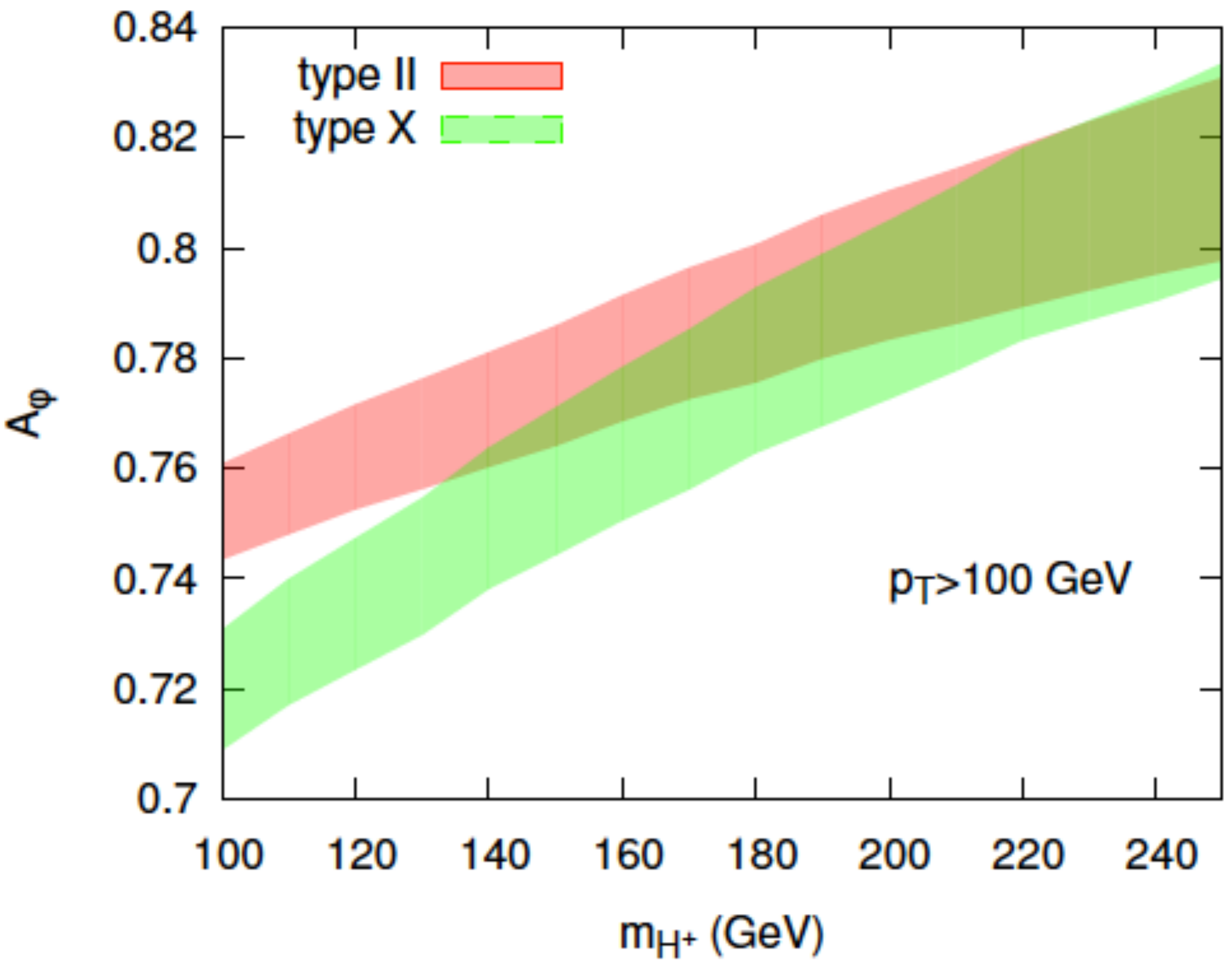


top polarization as a function of the charged Higgs mass for $\sqrt{s}$ = 13 TeV and tan β = 5 for type X and type "II" 2HDMs.

The error bands correspond to 10 % systematic uncertainty and the statistical uncertainty summed in quadrature.

Kinematical variables can be used to improve the differences in the top-polarisation between the two models.

Discriminating type X and type II 2HDMs with A_Φ



The error bands correspond to 5 % systematic uncertainty and the statistical uncertainty summed in quadrature.

Azimuthal asymmetry as a function of the charged Higgs mass for $\sqrt{s}$ = 13 TeV and tan β = 5 for type X and type “II” 2HDMs.

Conclusions

Top quark polarization together with other asymmetries provide an additional handle to probe new physics scenarios.

Associated-tH+ production is a good process to probe 2HDMs because top polarization proves to be a sensitive probe of $\tan\beta$ and the charged Higgs mass.

We have shown that in given regions of parameter space these observables could discriminate different Yukawa 2HDMs.

The end

The error

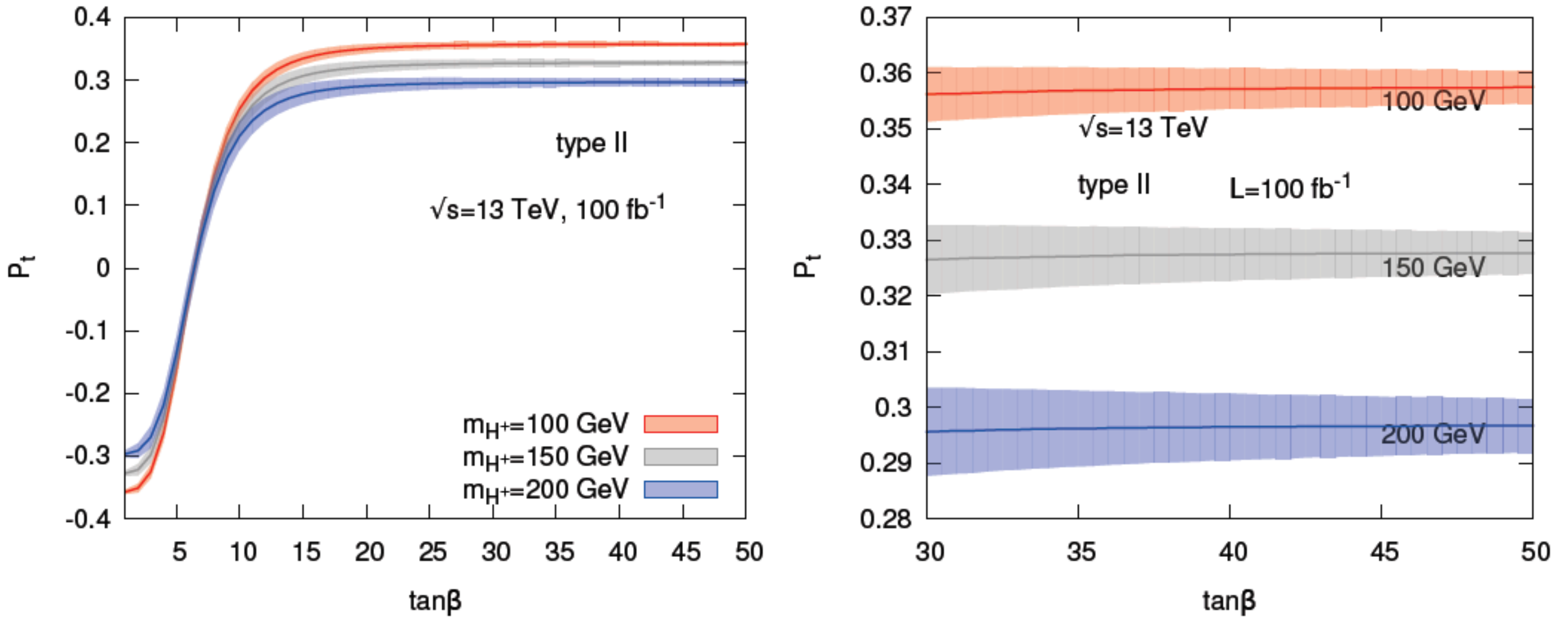
If A is the value of the asymmetry the statistical error is

$$\delta A_{stat} = \sqrt{\frac{1 - A^2}{\sigma_T L}}$$

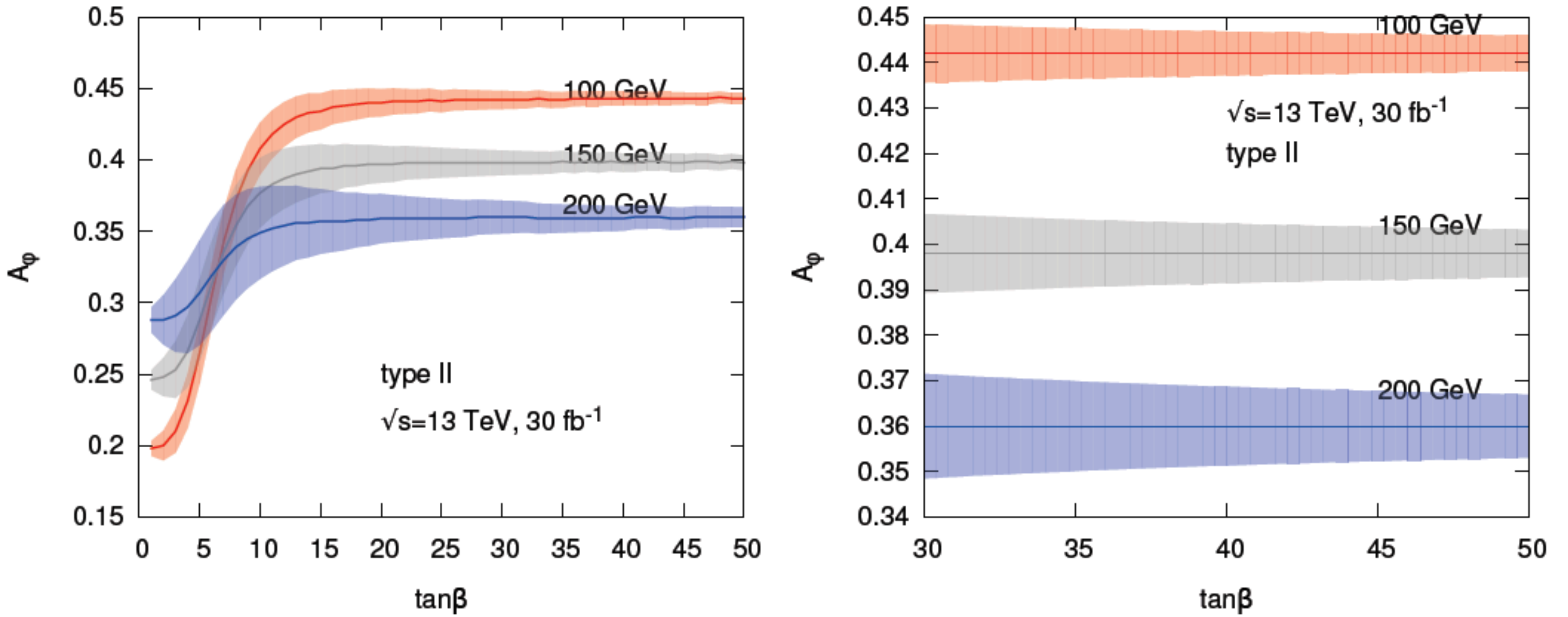
If δA_{syst} is the value of the systematical error

$$\delta A = \sqrt{\delta A_{stat}^2 + \delta A_{syst}^2}$$

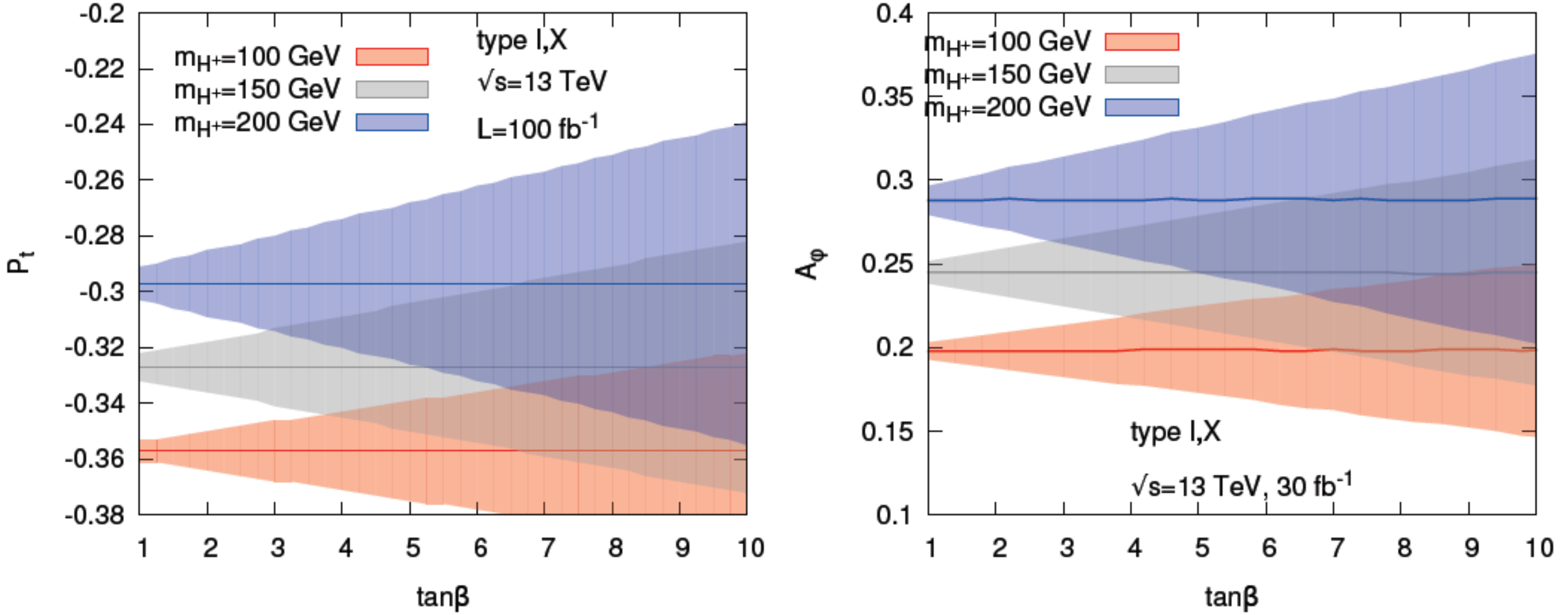
We have taken δA_{syst} = 10 % for top polarization and δA_{syst} = 5 % for the lepton azimuthal asymmetry.



P_t
tanβ
type II
√s=13 TeV, 100 fb^-1
mH+=100 GeV
mH+=150 GeV
mH+=200 GeV
√s=13 TeV
type II
L=100 fb^-1
100 GeV
150 GeV
200 GeV



100 GeV
150 GeV
200 GeV
type II
√s=13 TeV, 30 fb-1
Aφ
tanβ
100 GeV
√s=13 TeV, 30 fb-1
type II
150 GeV
200 GeV
Aφ
tanβ

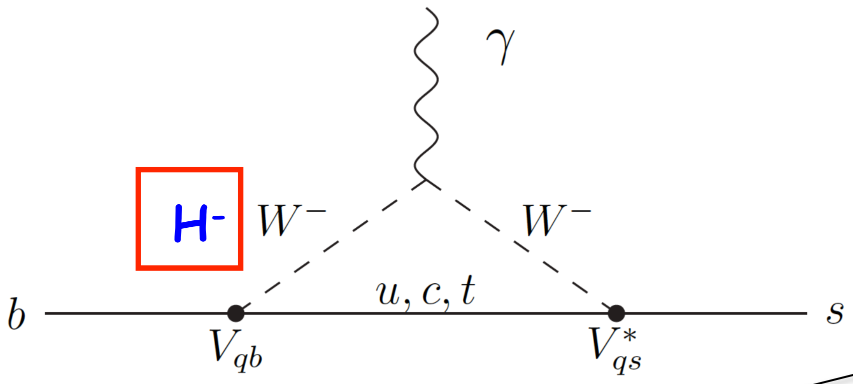


-0.2
-0.22
-0.24
-0.26
-0.28
-0.3
-0.32
-0.34
-0.36
-0.38
P_t
m_{H^+}=100 GeV
m_{H^+}=150 GeV
m_{H^+}=200 GeV
type I,X
√s=13 TeV
L=100 fb^{-1}
1 2 3 4 5 6 7 8 9 10
tanβ
0.4
0.35
0.3
0.25
0.2
0.15
0.1
A_φ
m_{H^+}=100 GeV
m_{H^+}=150 GeV
m_{H^+}=200 GeV
type I,X
√s=13 TeV, 30 fb^{-1}
1 2 3 4 5 6 7 8 9 10
tanβ

Experimental

• <u>INDIRECT BOUNDS</u> B factories

$$B \to X_s \gamma$$



Models II and Y $X_i Y_i = 1$

Models I and X $X_i Y_i = 1/\tan^2\beta$

$$\mathcal{L}_Y^{\pm} = (2\sqrt{2}G_F)^{1/2} \sum_{i=2}^{n} (X_i \overline{U}_L V M_D D_R + Y_i \overline{U}_R M_U V D_L + Z_i \overline{N}_L M_E E_R) H_i^+ + \text{h.c.}$$

$$\text{BR}(b \to s\gamma) = C|\eta_2 + G_W(x_t) + (|Y|^2/3)G_W(y_t) + (XY^*)G_H(y_t)|^2,$$

Models II and Y $m_{H^\pm} \gtrsim 300\ GeV$ **Best available bound on the charged Higgs mass**

Models I and X $\tan\beta > 1$ $m_{H^\pm} = 100\, GeV$

Theoretical

Potential has to be bounded from below:

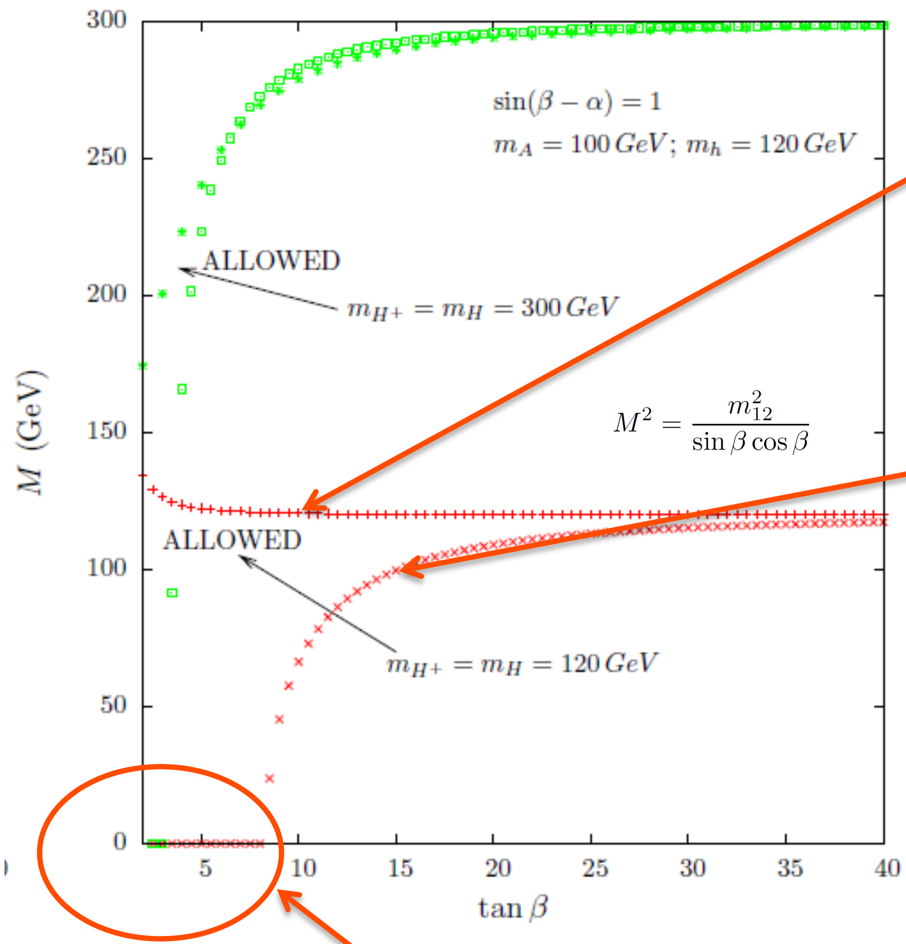
$$\lambda_1 \geq 0, \qquad \lambda_2 \geq 0,$$
$$\lambda_3 \geq -\sqrt{\lambda_1\lambda_2}, \qquad \lambda_3 + \lambda_4 - |\lambda_5| \geq -\sqrt{\lambda_1\lambda_2}$$

Theory must respect unitarity:

$$\begin{aligned}
a_\pm &= \frac{3}{2}(\lambda_1+\lambda_2) \pm \sqrt{\frac{9}{4}(\lambda_1-\lambda_2)^2 + (2\lambda_3+\lambda_4)^2},\\
b_\pm &= \frac{1}{2}(\lambda_1+\lambda_2) \pm \frac{1}{2}\sqrt{(\lambda_1-\lambda_2)^2 + 4\lambda_4^2},\\
c_\pm &= \frac{1}{2}(\lambda_1+\lambda_2) \pm \frac{1}{2}\sqrt{(\lambda_1-\lambda_2)^2 + 4\lambda_5^2},\\
e_1 &= \lambda_3 + 2\lambda_4 - 3\lambda_5\\
e_2 &= \lambda_3 - \lambda_5,\\
f_+ &= \lambda_3 + 2\lambda_4 + 3\lambda_5,\\
f_- &= \lambda_3 + \lambda_5,\\
f_1 &= \lambda_3 + \lambda_4,\\
p_1 &= \lambda_3 - \lambda_4.
\end{aligned}$$

$$|a_\pm|\,,\ |b_\pm|\,,\ |c_\pm|\,,\ |f_\pm|\,,\ |e_{1,2}|\,,\ |f_1|\,,\ |p_1| < 8\pi$$

Theoretical



potential bounded from below

unitarity limits for quartic Higgs couplings

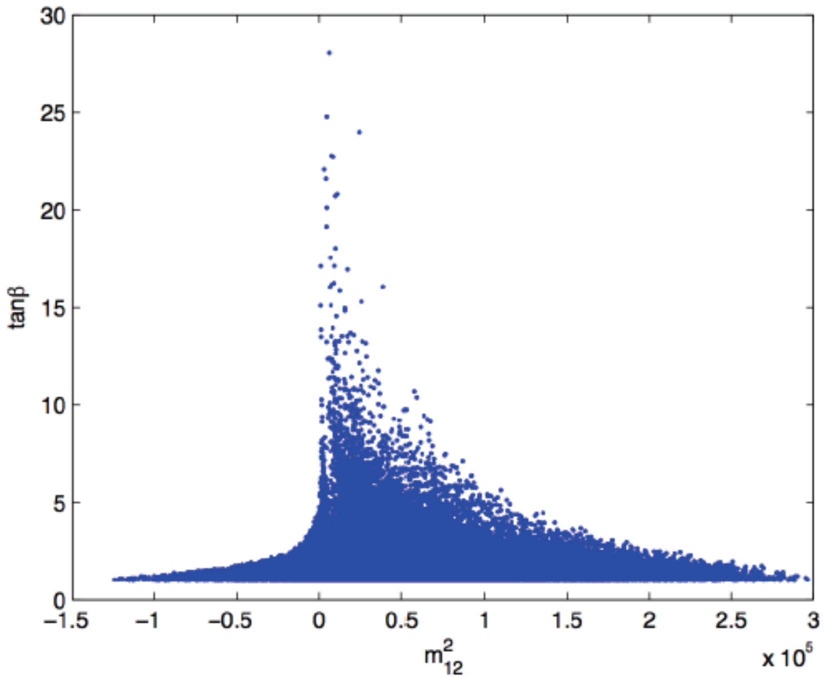
No soft breaking term = strong constraint on tanβ

$0.18 \lesssim \tan\beta \lesssim 5.59$

B. Gorczyca, M. Krawczyk, arXiv: 1112.5086

Z_2 symmetric potential

Theoretical



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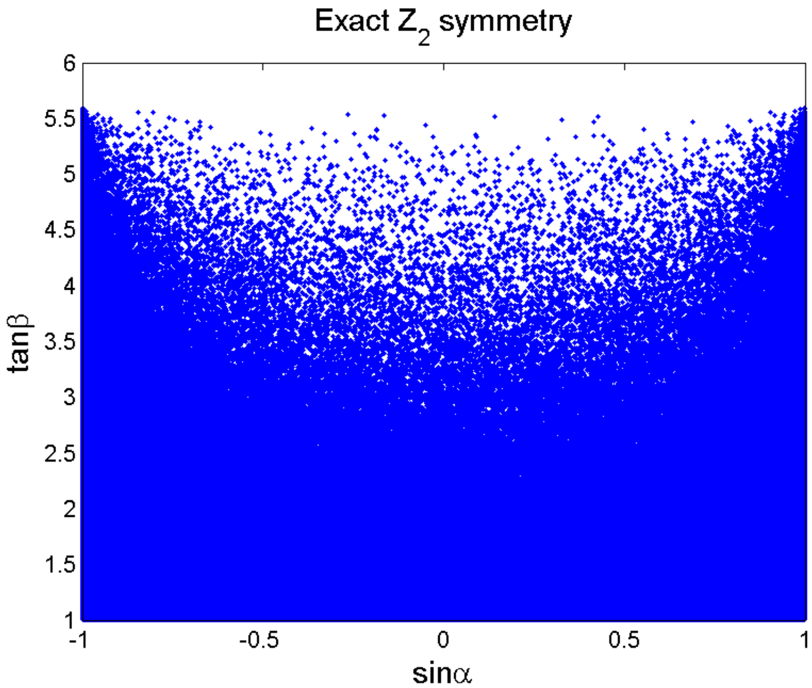
arXiv: 1112.5086
Z_2 symmetric potential



The decoupling limit

The decoupling limit of 2HDM

$M_{12}^2 \to \infty$, $\cos(\alpha - \beta) \to 0$

- In this limit, the masses of Φ=H, $H^{\pm}$, A:

$$m_{\Phi}^2 = M_{12}^2 + \sum_i \lambda_i v^2 + \mathcal{O}(v^4/M_{12}^2), \quad , \quad m_h^2 = \sum_i \lambda_i v^2$$

- When $M_{12}^2 \gg \lambda_i v^2$, $m_{H,A,H\pm}^2$ are determined by M_{12}^2, and are independent of λ_i. In this case $\alpha \longrightarrow \beta - \pi/2$, The effective theory below M_{12} is described by one Higgs doublet. In this limit:

$$h^0VV/(h_{SM}VV) = \sin(\beta-\alpha) \longrightarrow 1$$

$$h^0 b\bar{b}/h_{SM} b\bar{b} = -\frac{\sin\alpha}{\cos\beta} \longrightarrow 1 \ , \ (h^0\bar{t}t)/h_{SM}t\bar{t} = \frac{\cos\alpha}{\sin\beta} \longrightarrow 1$$

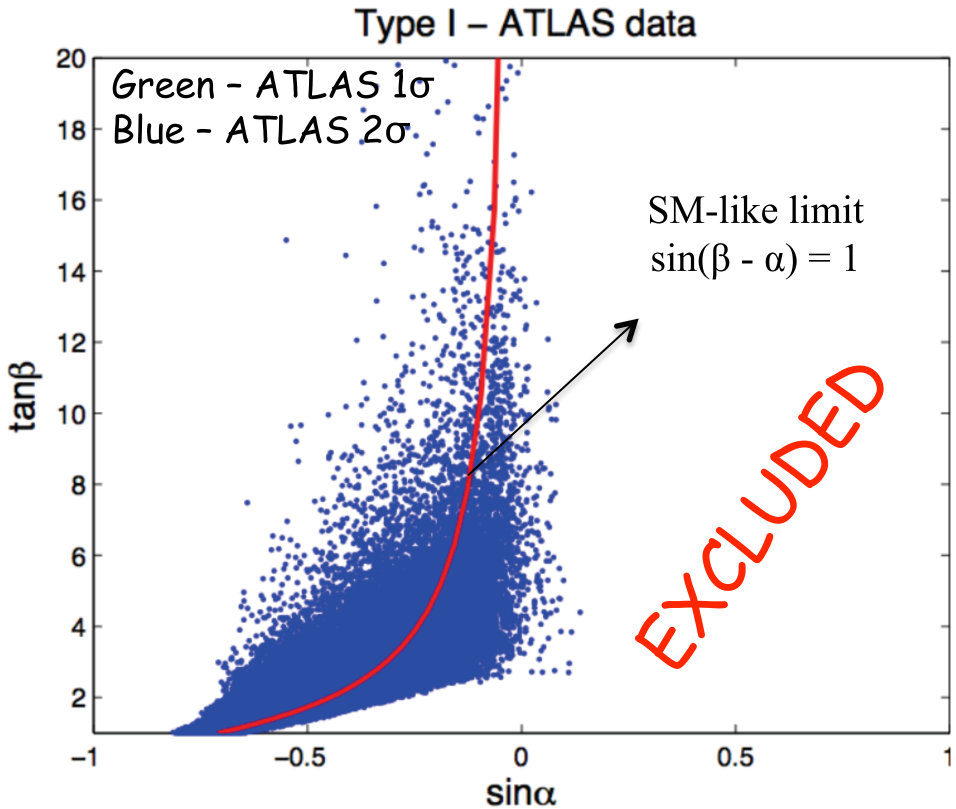
$$H^0VV \propto \cos(\beta-\alpha) \longrightarrow 0 \ , \ (hhh)/(hhh)_{SM} \longrightarrow 1$$

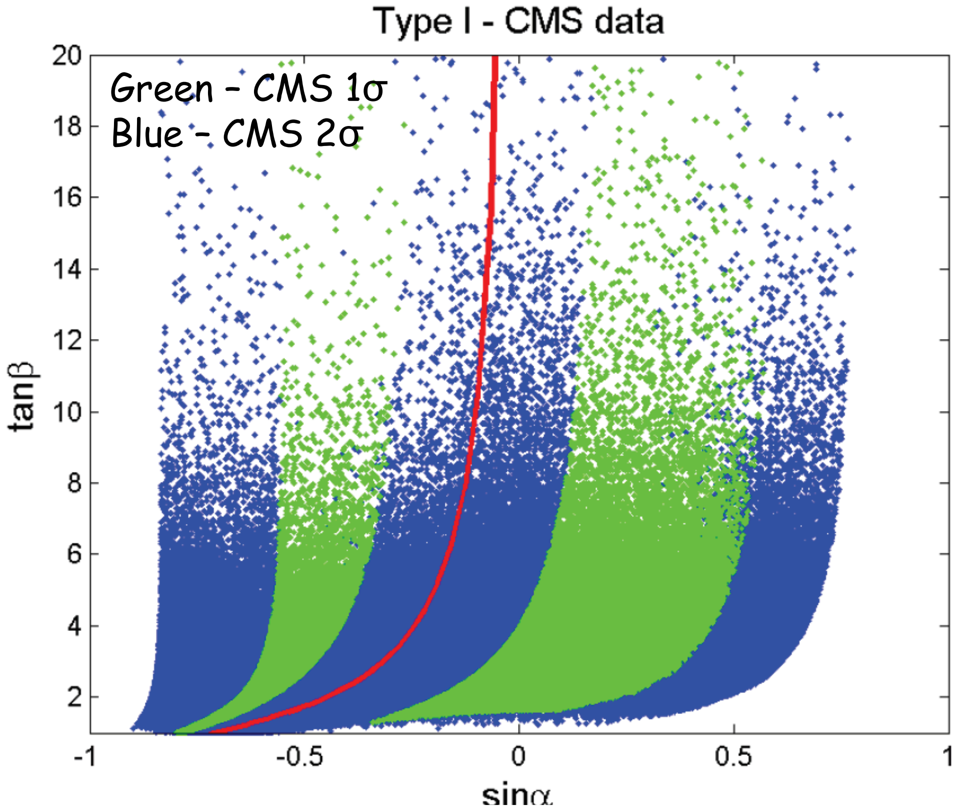
$$h^0H^+H^-, h^0A^0A^0, h^0H^0H^0, H^{\pm}t\bar{b}... \neq 0$$

Lepton angular distributions are independent of anomalous tbW couplings under following assumptions:
[Godbole, Rindani,Singh], [Grzadkowski,Hioki]

top is on-shell; narrow-width approximation for top,

couplings f_{1R}, f_{2L} and f_{2R} are small,





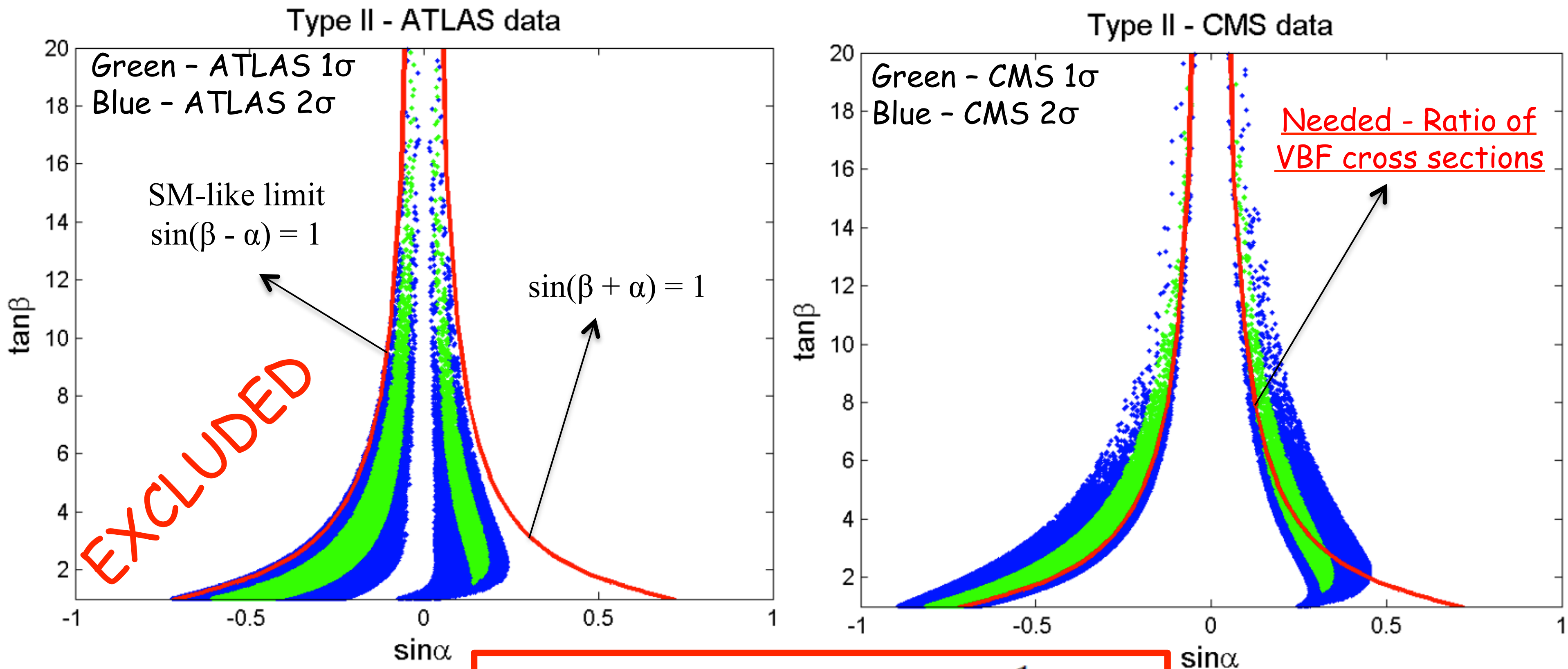
$$R_{ZZ}^{I,approx} = \frac{\cos^2\alpha}{\sin^2\beta}\sin^2(\alpha-\beta)\frac{\sin^2\beta}{\cos^2\alpha} = \sin^2(\alpha-\beta)$$

- The function $\sin^2(\beta - \alpha)$ is very sensitive to deviations from 1 – large dispersion.

- For ATLAS R_{ZZ} is above 1 – 1σ (green) excluded; 2σ (blue) allowed.

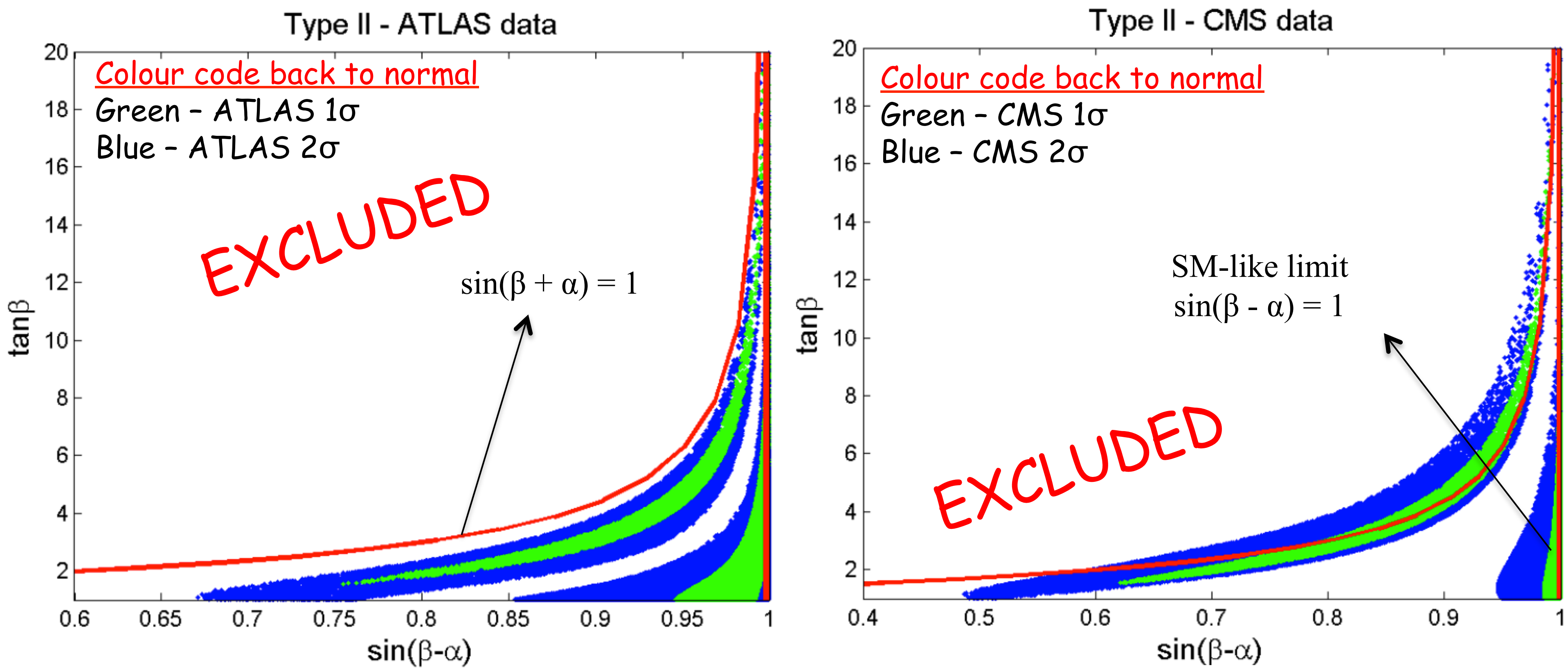
- For CMS R_{ZZ} is below 1 – 1σ (green) away from SM limit but allowed; 2σ (blue) allowed and with a large dispersion.

- Large positive values of sinα already excluded at 2σ.



$$R_{ZZ}^{II,approx} = \sin^2(\alpha - \beta)\frac{1}{\tan^2\alpha\,\tan^2\beta}$$

- This function is not sensitive to deviations from 1 – small dispersion.
- In both cases we have 1σ (green) and 2σ (blue) allowed regions.
- For CMS they are mostly above the red lines (R's below 1) and for ATLAS they are mostly below the red lines (R's above 1).
- Large positive values of sinα (and the ones close to -1) already excluded at 2σ.



• zoom on the previous plots for type II where we just show the allowed region at 1 and 2 sigma.

• In type II, R_{XX} can be above 1. Because ATLAS results for VV are above the SM ones the allowed regions, the points are below/on the red lines. For CMS the same results are below the SM ones so the points are on/above the red lines.