Higgs theory

Andrea Banfi

University of Sussex

Extensions of the SM Higgs

Outline

- A simple extension beyond the Standard Model: the 2 Higgs doublet model
- Differential distributions for BSM searches

Two-Higgs doublet model (2HDM)

Simplest extension of the SM, with two $SU(2)$ doublets with $Y = 1$

[Branco Ferreira Lavoura Rebelo Sher Silva Phys. Rep. 516 (2012) 1]

$$
\begin{aligned}
V = & \, m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi^\dagger 2 \Phi_2 - m_{12}^2 \left(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1 \right) + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 \\
& + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \frac{\lambda_5}{2} \left[(\Phi_1^\dagger \Phi_2)^2 + (\Phi_2^\dagger \Phi_1)^2 \right] \\
& + \left[(\Phi_1^\dagger \Phi_2) \left(\lambda_6 \Phi_1^\dagger \Phi_1 + \lambda_7 \Phi_2^\dagger \Phi_2 \right) + \text{h.c.} \right]
\end{aligned}
$$

The last term induces FCNC and is eliminated by setting $\lambda_6 = \lambda_7 = 0$, e.g. by imposing some extra symmetry

Minimising the potential one gets two VEVs, one for each doublet

$$
\langle \Phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix} \qquad \langle \Phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2 \end{pmatrix}
$$

To avoid sources of CP violation, we assume that both v_1 and v_2 are real

Particle content of the 2HDM

We expand each field around the corresponding VEV

$$\Phi_a = \begin{pmatrix} \phi_a^+ \\ \phi_a^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\phi_a^+ \\ v_a + \rho_a + i\eta_a^0 \end{pmatrix}$$

Three scalars become the longitudinal degrees of freedom of W and Z bosons

This leaves us with 5 physical states

$$\underbrace{h, H}_{\text{CP-even}}, \underset{\text{CP-odd}}{A}, \underset{\text{charged Higgs}}{H^{\pm}}$$

Higgs masses

Expanding the potential around the minimum one finds the masses of the physical Higgs bosons

Define $\tan\beta = v_2/v_1$

Pseudoscalar: $$m_A^2 = 2\left[\frac{m_{12}^2}{\sin 2\beta} - \lambda_5\right] v^2$$

$$v^2 = v_1^2 + v_2^2$$

Charged Higgs: $$m_{H^\pm}^2 = \left[2\frac{m_{12}^2}{\sin 2\beta} - \lambda_4 - \lambda_5\right] v^2$$

Note: $m_{H^\pm}^2 = m_A^2 + (\lambda_5 - \lambda_4)v^2$

Higgs masses

Expanding the potential around the minimum one finds the masses of the physical Higgs bosons

Define $\tan\beta = v_2/v_1$

Scalar: $\begin{pmatrix} m_{12}^2 \tan\beta + \lambda_1 v^2 \cos^2\beta & -m_{12}^2 + \frac{v^2}{2}\lambda_{345}\sin 2\beta \\ -m_{12}^2 + \frac{v^2}{2}\lambda_{345}\sin 2\beta & m_{12}^2 \cot\beta + \lambda_2 v^2 \sin^2\beta \end{pmatrix}$

Diagonalising the mass matrix introduces a mixing angle α

$$h = \rho_1 \sin\alpha - \rho_2 \cos\alpha$$
$$H = -\rho_1 \cos\alpha - \rho_2 \sin\alpha$$

Decoupling limit: for $m_A \gg v$ the heavy states $H, A, H^\pm$ decouple leaving a single neutral scalar h looking like the SM Higgs

Yukawa couplings

Most general Yukawa interactions, after diagonalisation of Yukawa couplings with CKM matrix

$$\mathcal{L} = \bar{u}_L \phi_a^{0*} h_a^u u_R - \bar{d}_L V_{\rm CKM}^\dagger \phi_a^- h_a^u u_R + \bar{u}_L V_{\rm CKM} \phi_a^+ h_a^{d\dagger} d_R + \bar{d}_L \phi_a^0 h_a^{d\dagger} d_R$$
$$+ \bar{\nu}_L \phi_a^+ h_a^{e\dagger} e_R + \bar{e}_L \phi_a^0 h_a^{e\dagger} e_R + \text{h.c.}$$

To avoid FCNC we have four options

Type I: $h_1^u = h_1^d = h_1^e = 0$, i.e. fermions couple only to Φ_2

Type II: $h_1^u = h_2^d = h_2^e = 0$, i.e. Φ_1 couples to down and leptons, Φ_2 to up

Type III: $h_1^u = h_1^d = h_2^e = 0$, i.e. Φ_1 couples to leptons, Φ_2 to quarks

Type IV: $h_1^u = h_2^d = h_1^e = 0$, i.e. Φ_1 couples to down, Φ_2 to up and leptons

Note. SUSY is a Type II 2HDM

2HDM couplings

Type I

ϕ	$g_{\phi u\bar{u}}/g_f$	$g_{\phi d\bar{d}}/g_f$	$g_{\phi VV}/g_V$	$g_{\phi ZA}/g_Z$
h	$\dfrac{\cos\alpha}{\sin\beta}$	$\dfrac{\cos\alpha}{\sin\beta}$	$\sin(\beta-\alpha)$	$\cos(\beta-\alpha)$
H	$\dfrac{\sin\alpha}{\sin\beta}$	$\dfrac{\sin\alpha}{\sin\beta}$	$\cos(\beta-\alpha)$	$\sin(\beta-\alpha)$
A	$i\gamma_5\cot\beta$	$-i\gamma_5\cot\beta$	0	0

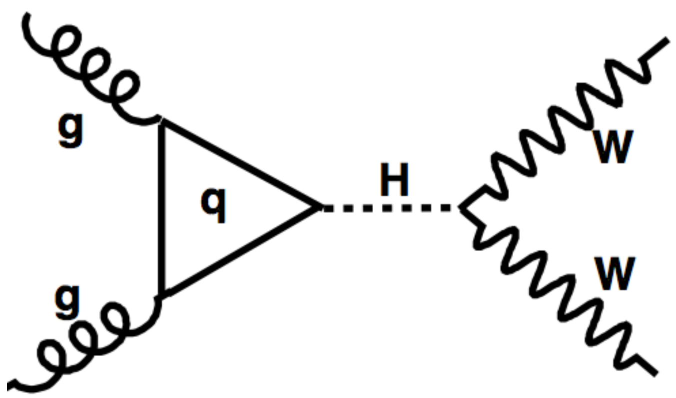
Type II

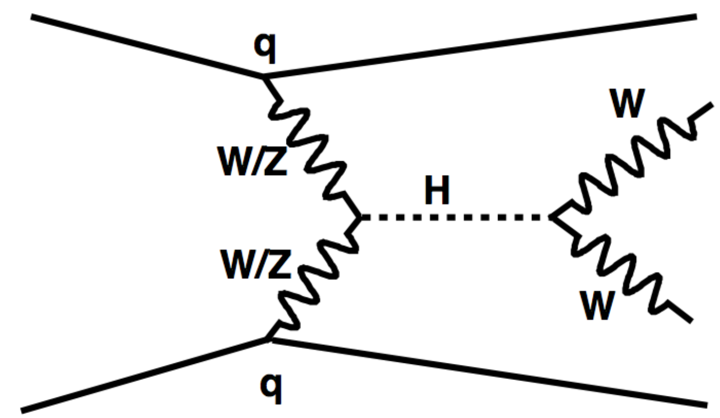
ϕ	$g_{\phi u\bar{u}}/g_f$	$g_{\phi d\bar{d}}/g_f$	$g_{\phi VV}/g_V$	$g_{\phi ZA}/g_Z$
h	$\dfrac{\cos\alpha}{\sin\beta}$	$-\dfrac{\sin\alpha}{\cos\beta}$	$\sin(\beta-\alpha)$	$\cos(\beta-\alpha)$
H	$\dfrac{\sin\alpha}{\sin\beta}$	$\dfrac{\cos\alpha}{\cos\beta}$	$\cos(\beta-\alpha)$	$\sin(\beta-\alpha)$
A	$i\gamma_5\cot\beta$	$i\gamma_5\cot\beta$	0	0

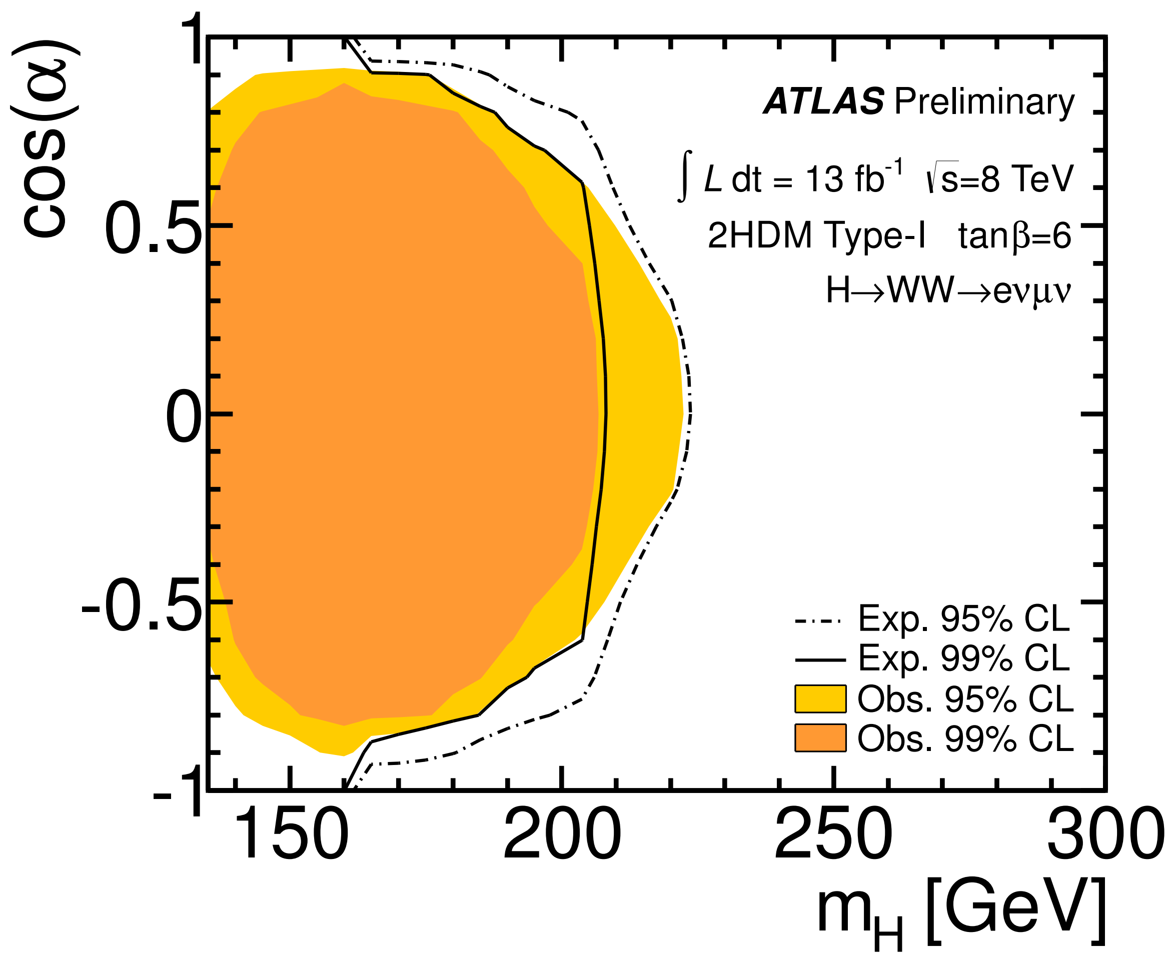
Type III and type IV have FCNC problems

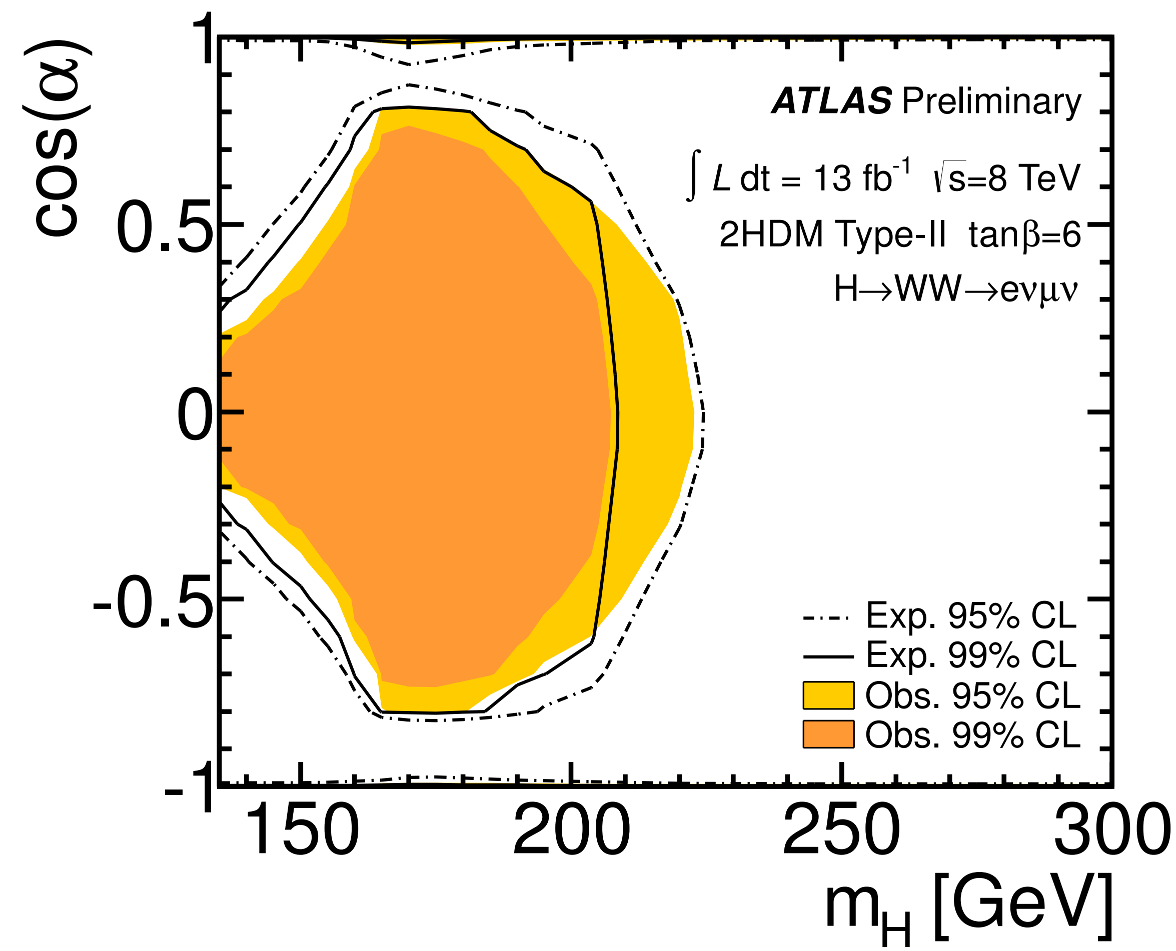
2HDM searches: CP-even

The scalar bosons are searched in the WW decay channel

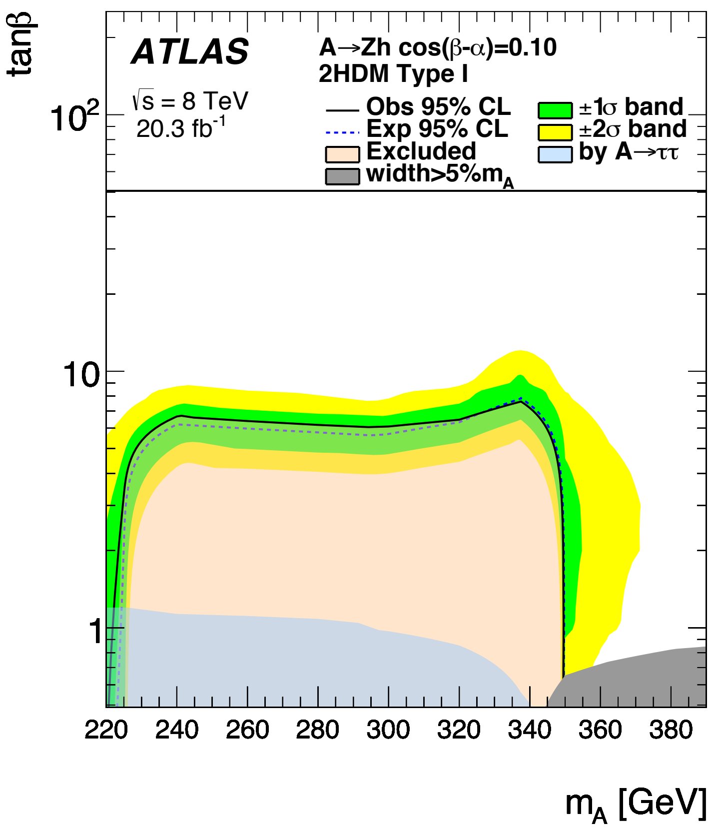


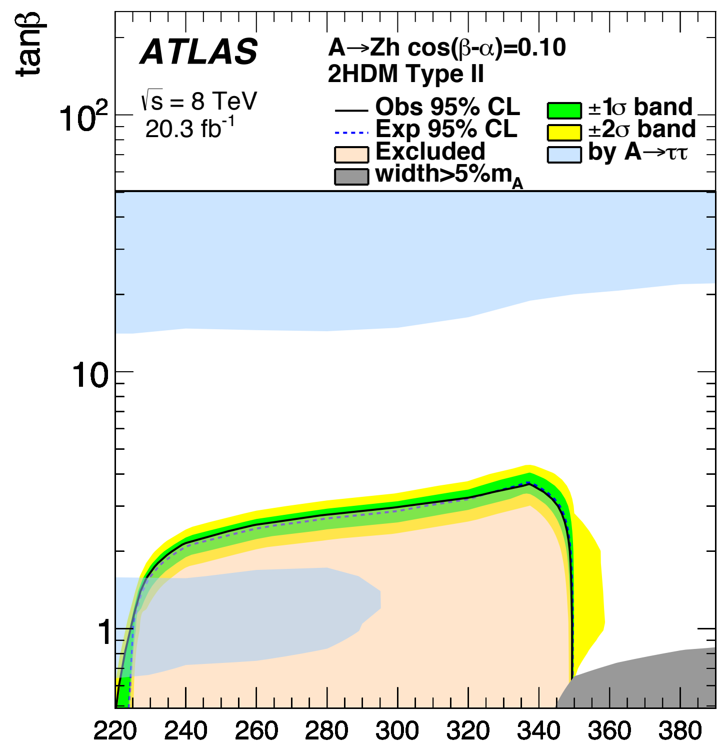


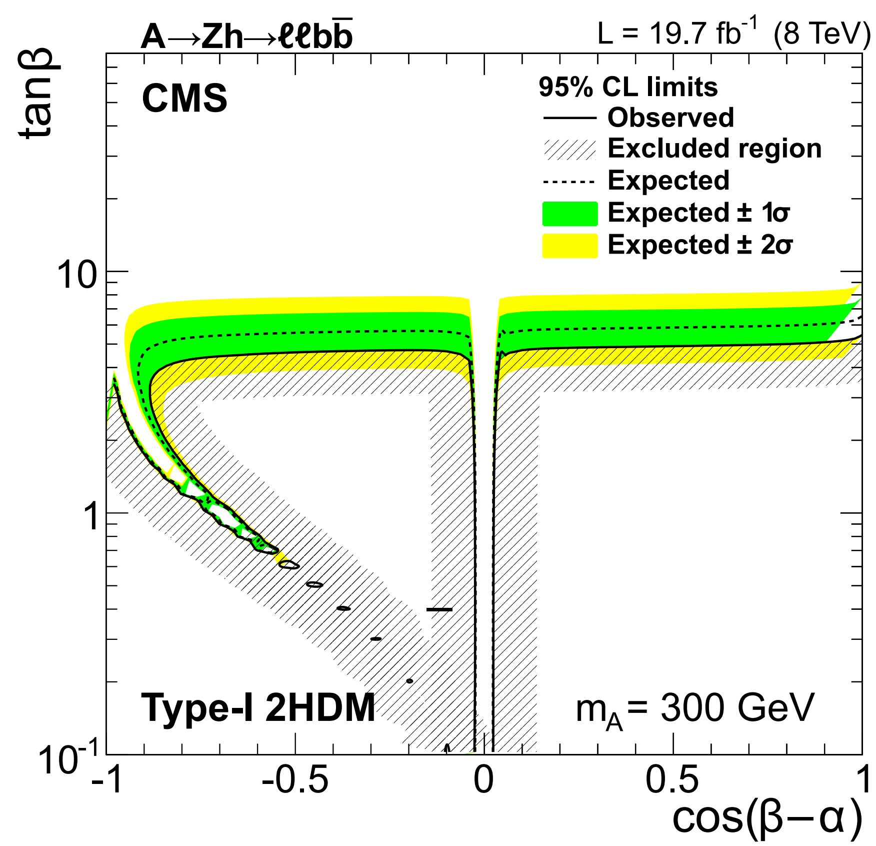


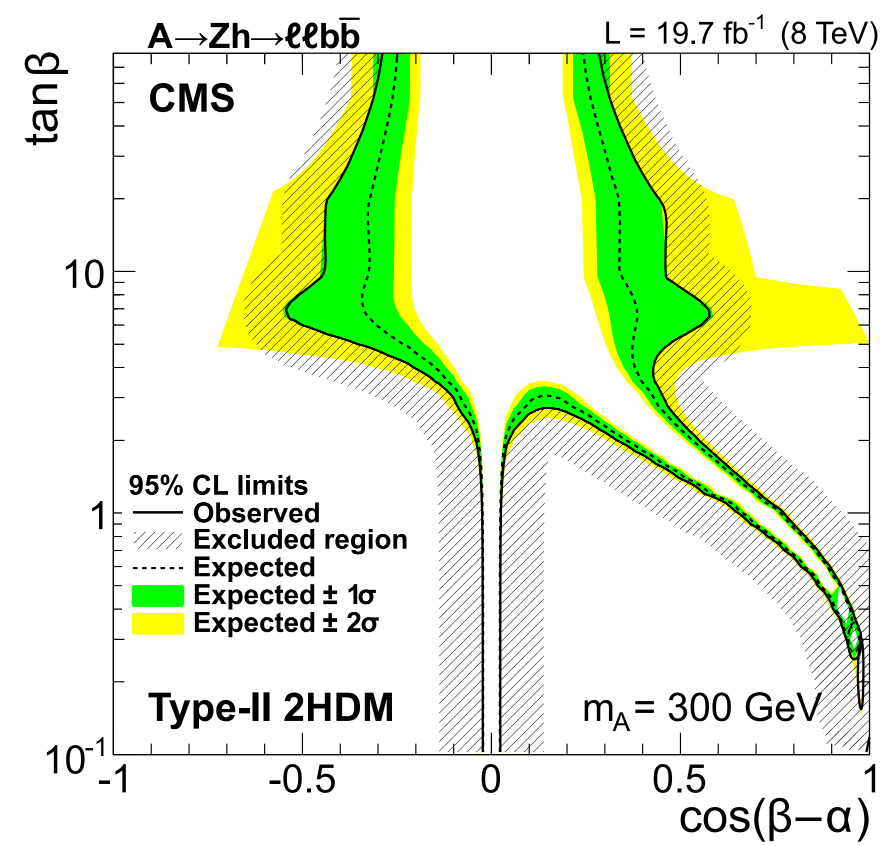


2HDM searches: CP-odd



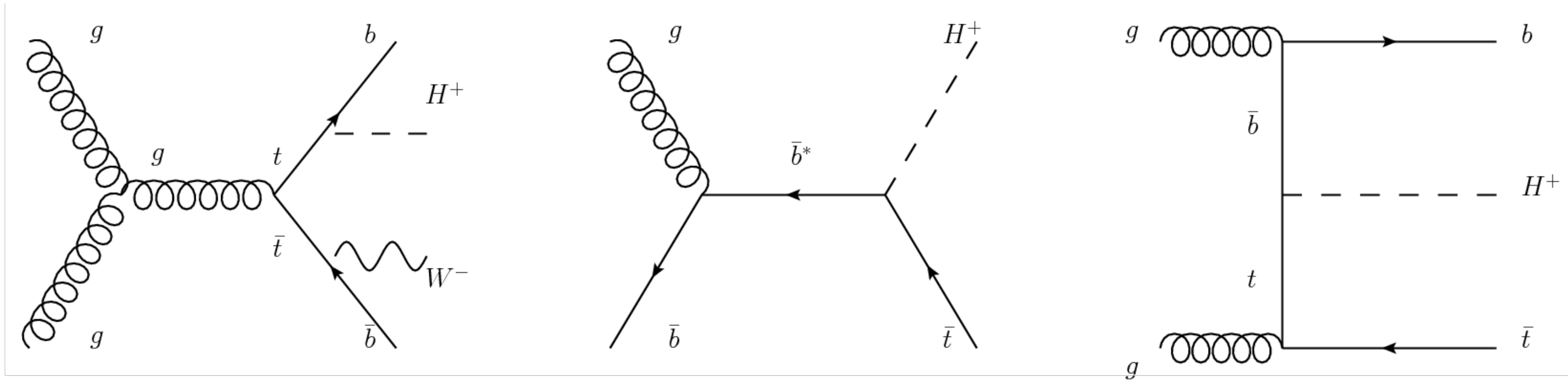


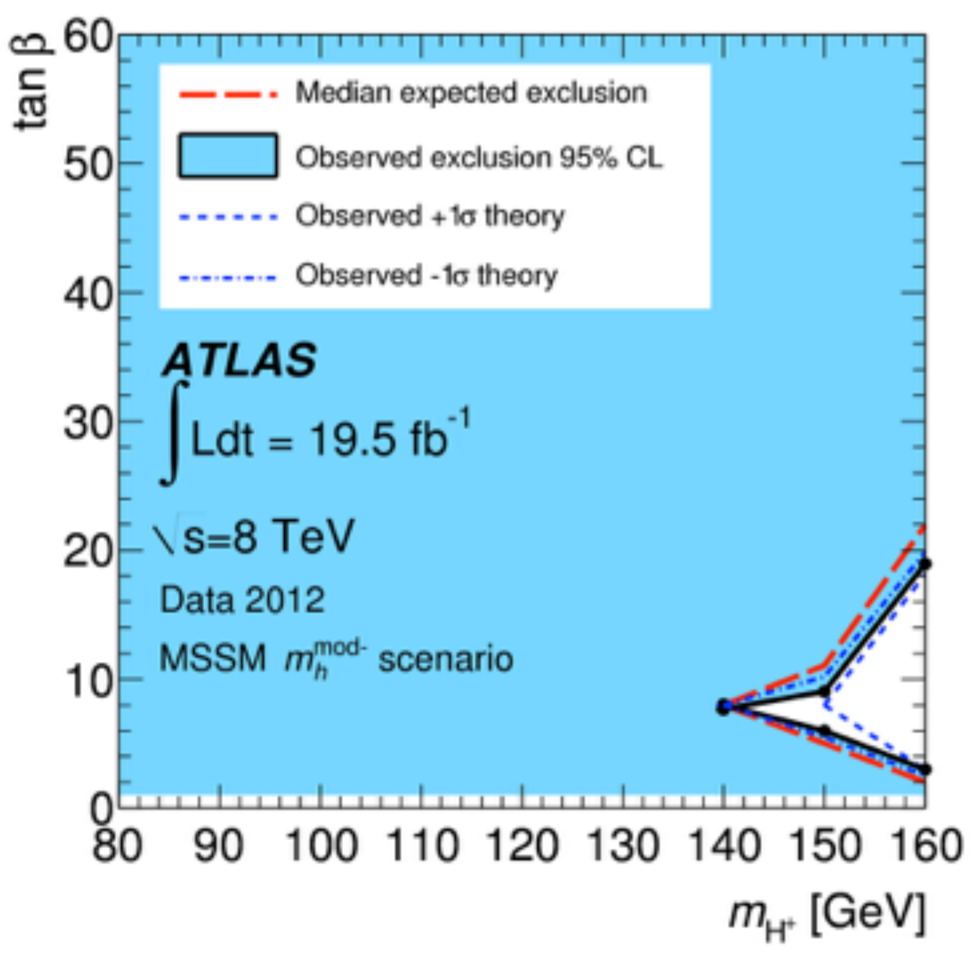


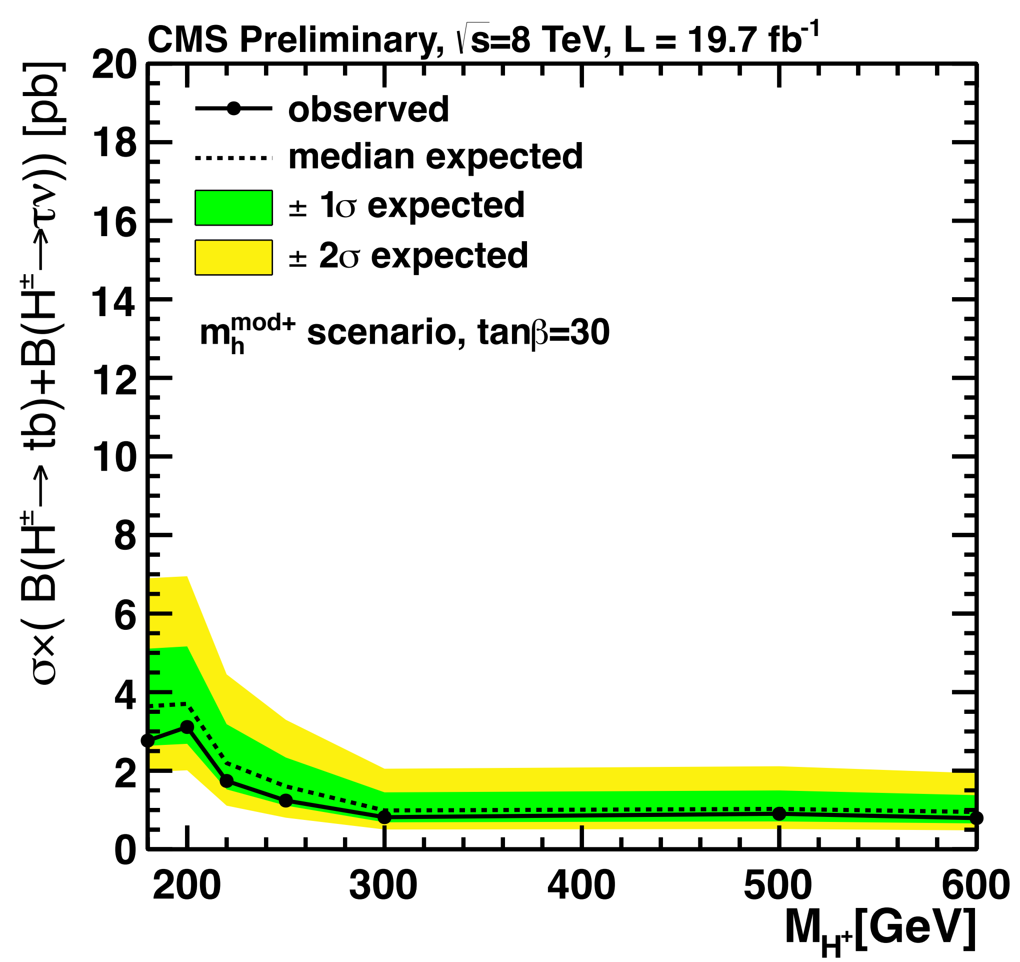


2HDM searches: charged higgs

Charged Higgs particles are searched in association with t and b quarks

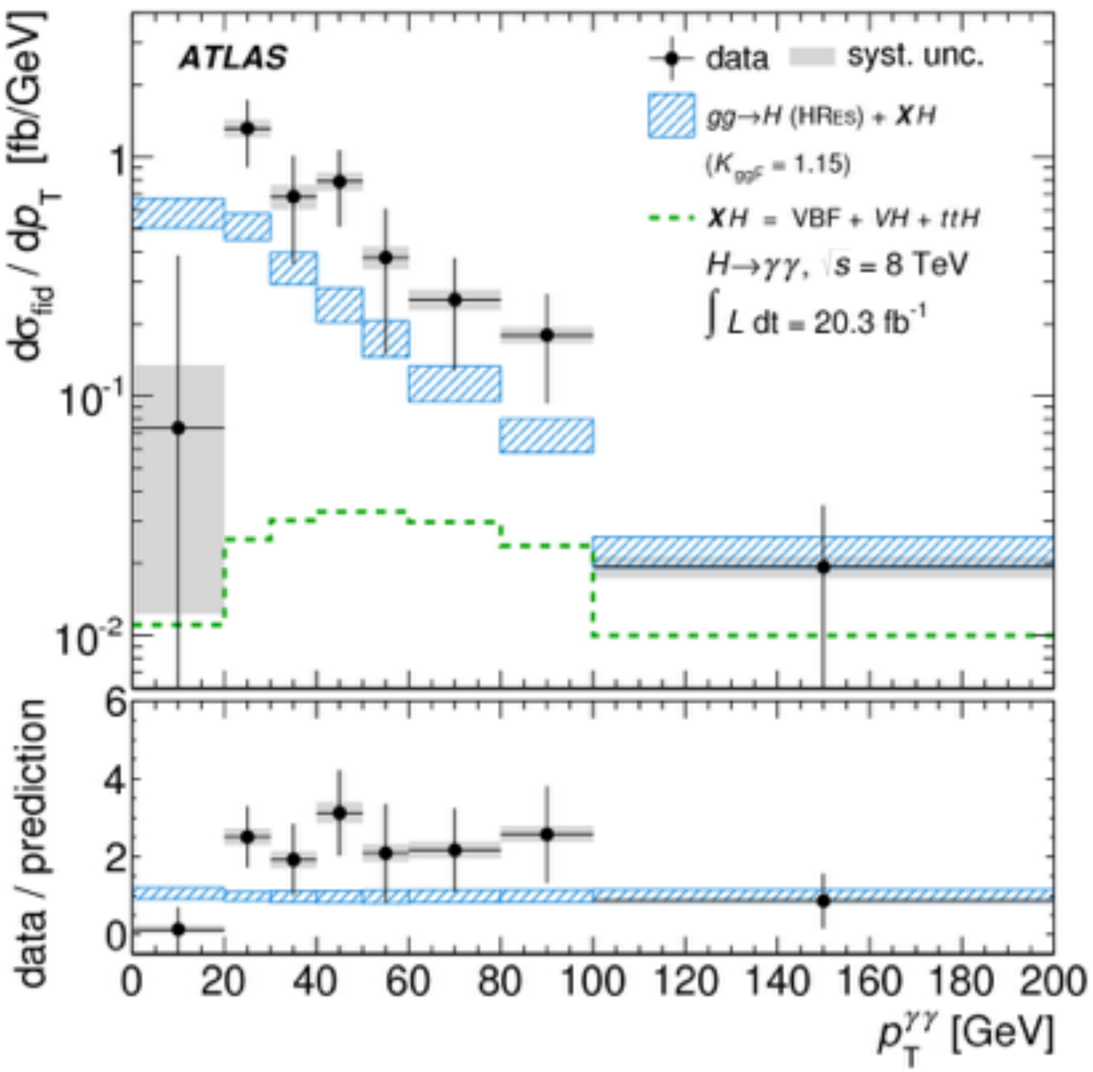


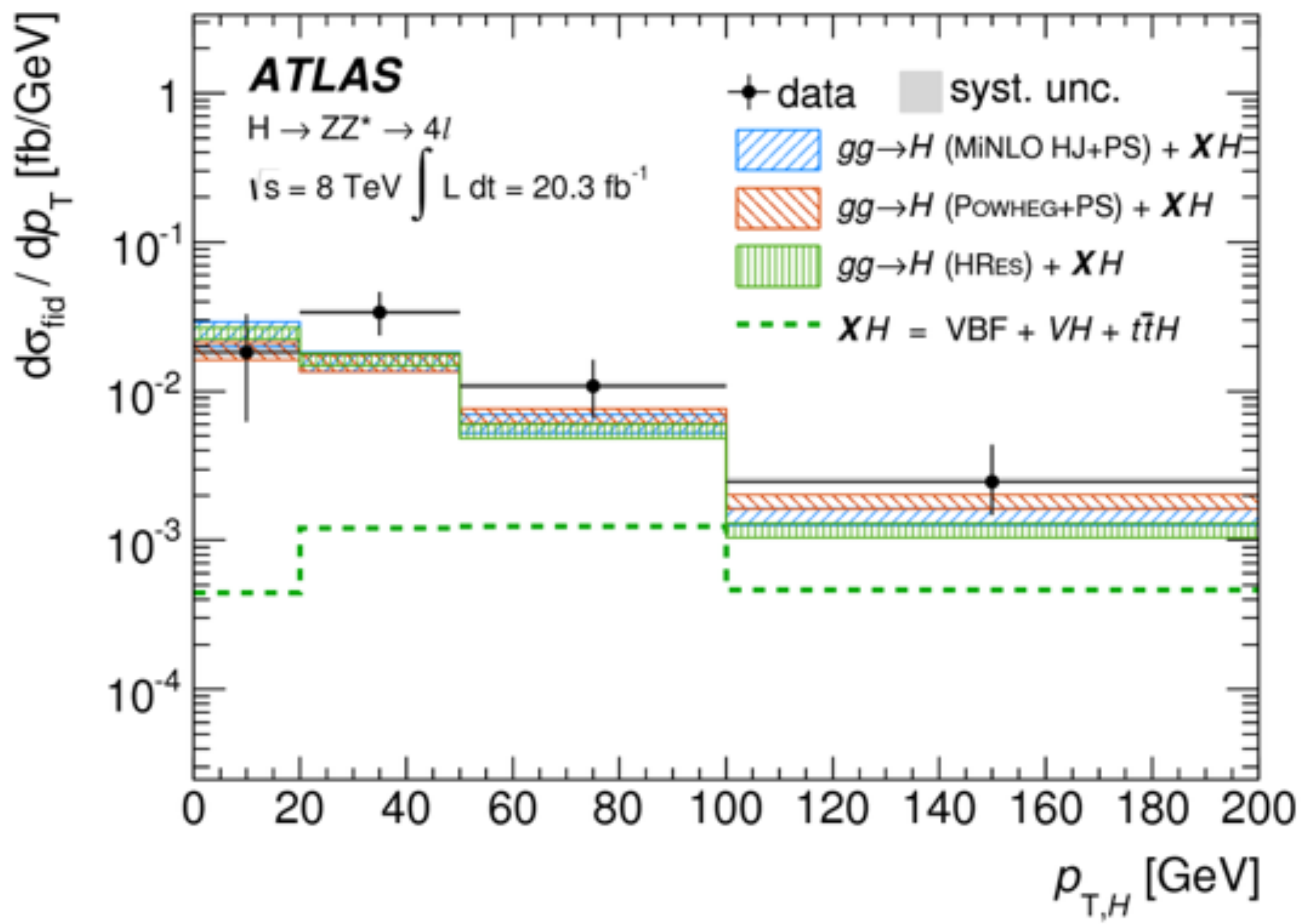




Differential distribution

Higgs differential cross sections have been recently measured



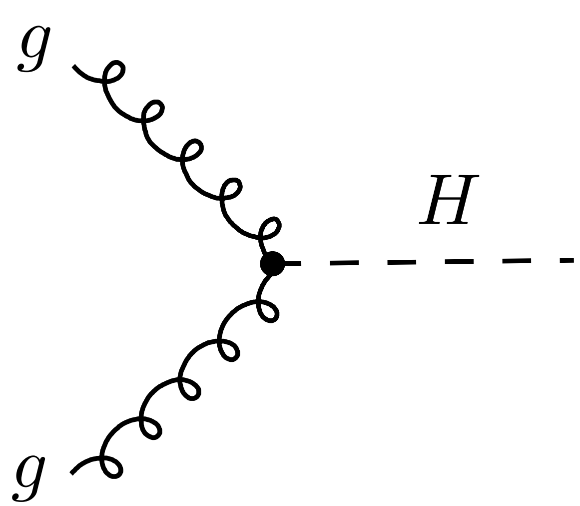


Differential distributions and top partners

Suppose you have a simple model in which the top quark is accompanied by a fermionic top-partner

$$\mathcal{L} = -\left(\frac{m_t}{v}\cos^2\theta\right)\bar{t}th - \left(\frac{M_T}{v}\sin^2\theta\right)\bar{T}Th$$

In the total cross section both the top and the top-partner decouple $m_t, M_T \gg v$

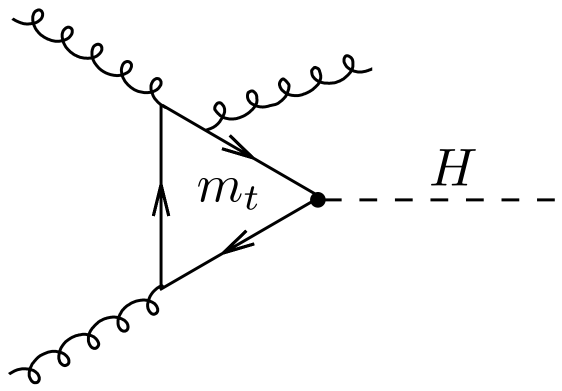


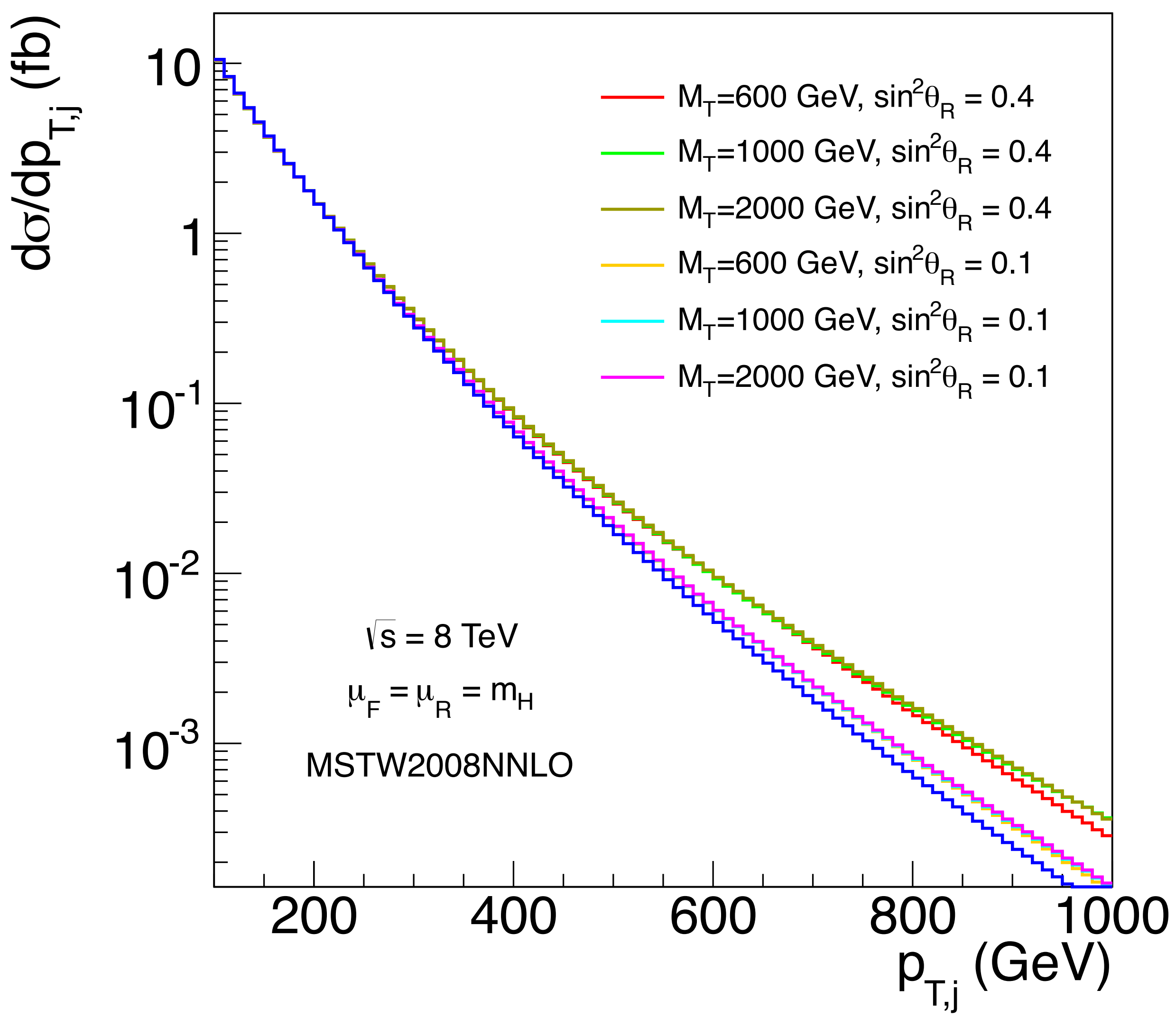
$$\mathcal{M}_{gg\to H} \simeq \mathcal{M}^{\rm SM}_{gg\to H}\Big|_{m_t\to\infty} \times \underbrace{\left(\cos^2\theta + \sin^2\theta\right)}_{=1}$$

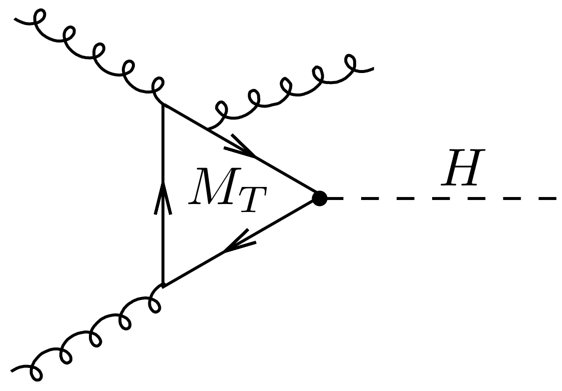
Differential distributions and top partners

A high-p_T gluon can resolve the top loop, thus giving a different functional behaviour for the top and the top-partner

[Banfi Martin Sanz JHEP 08 (2014) 053]







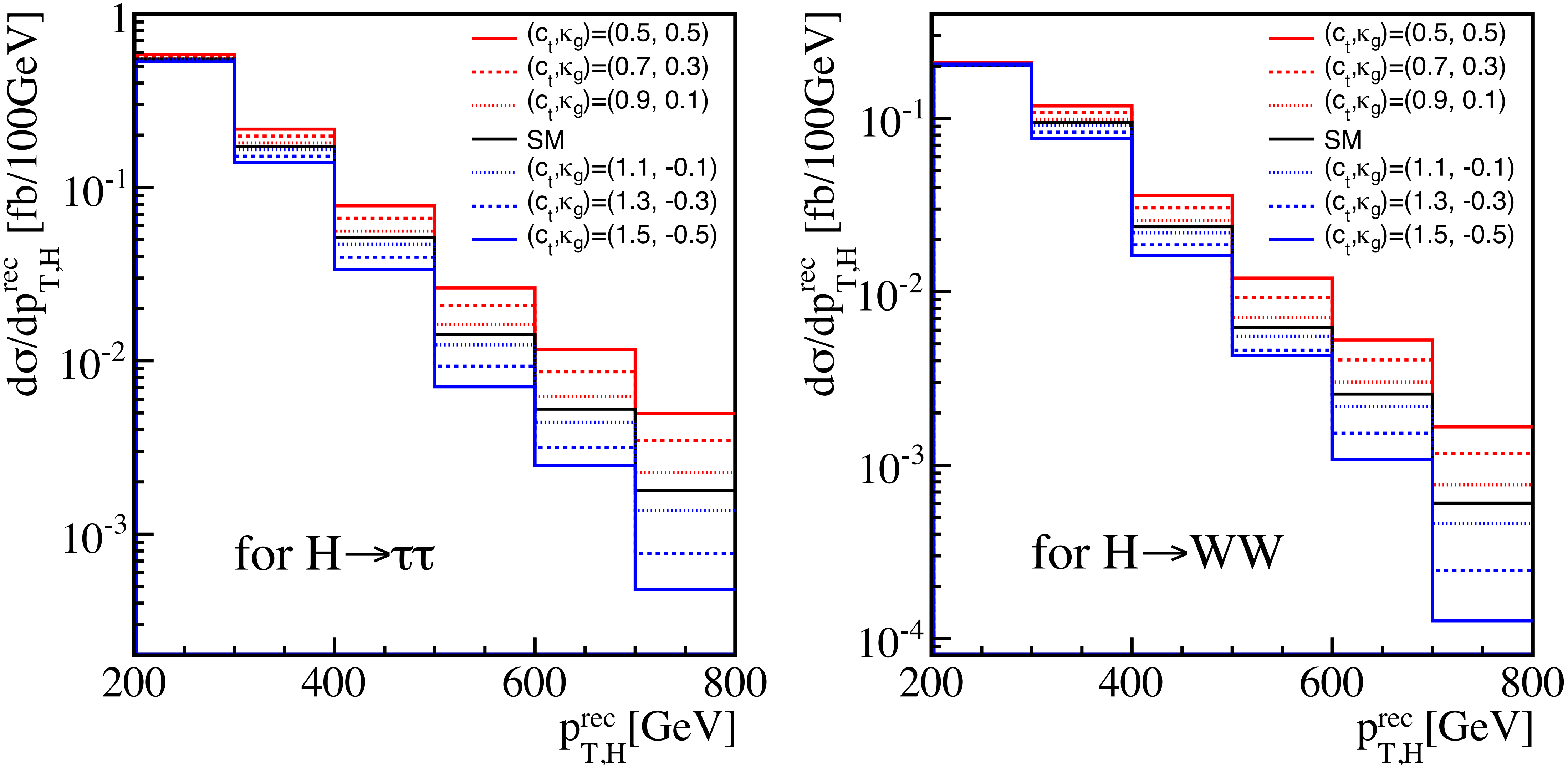
Need precision calculations to constrain SM background!

Differential distributions for BSM searches

The p_T-spectrum of the Higgs can be used to exclude various BSM scenarios, like composite Higgs or SUSY

The boosted nature of the Higgs makes it possible to discriminate signal from background in the WW and $\tau\tau$ channels

[Schlaffer Spannowsky Takeuchi Weyler Wymant EPJC 74 (2014) 10]



Learning outcomes

In this lecture we have learnt

- The 2HDM provides simple extension of the SM incorporating various BSM scenarios (including SUSY)
- Differential distributions can provide information that could not be accessed by measuring total cross sections only