PHENOMENOLOGY OF CHARGED HIGGS BOSONS

Michael Spira (PSI)

I *INTRODUCTION*

- SM very successful ← precision data [LEP, Tevatron, LHC]

- open problems: – mechanism of electroweak symmetry breaking
  – unification of forces
  – space-time structure @ short distances

- LHC: fundamental discoveries: Higgs boson(s?)
  Supersymmetry ?
  Extra space dimensions ?

- electroweak symmetry breaking: two classes of realization:
  – standard Higgs mechanism [SM, SUSY,. . .]
  – strong elw. symmetry breaking [TC, LH, Higgsless, ED,. . .]

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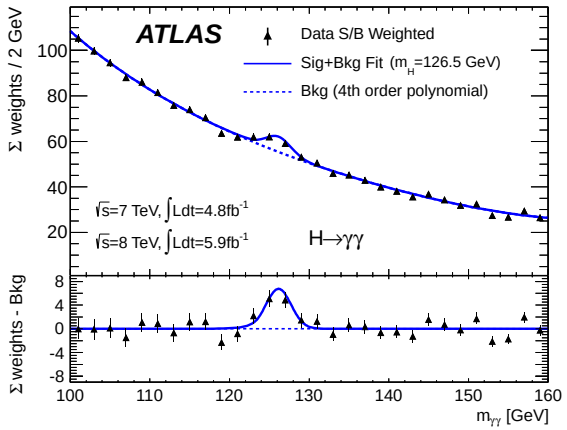
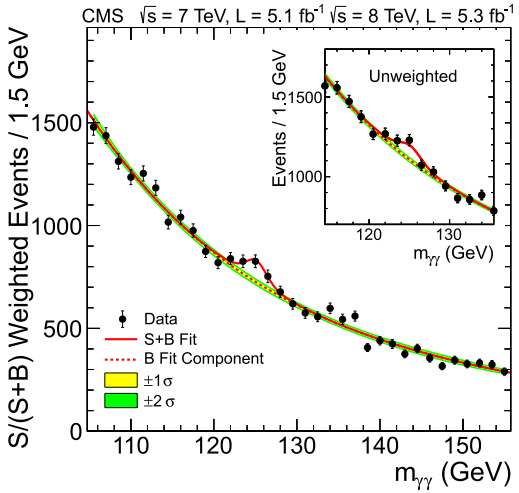
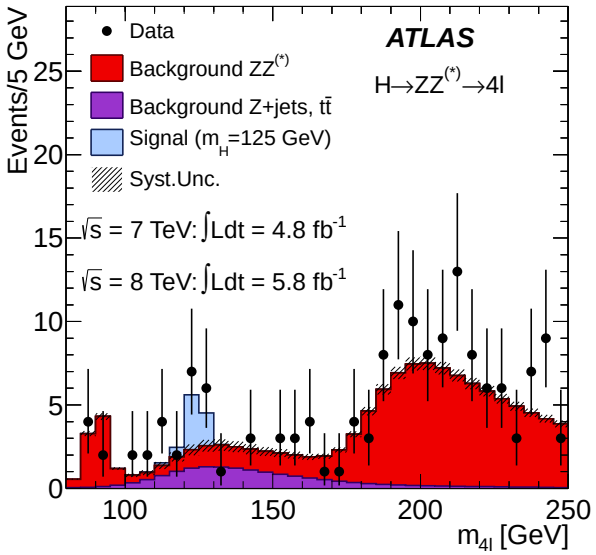
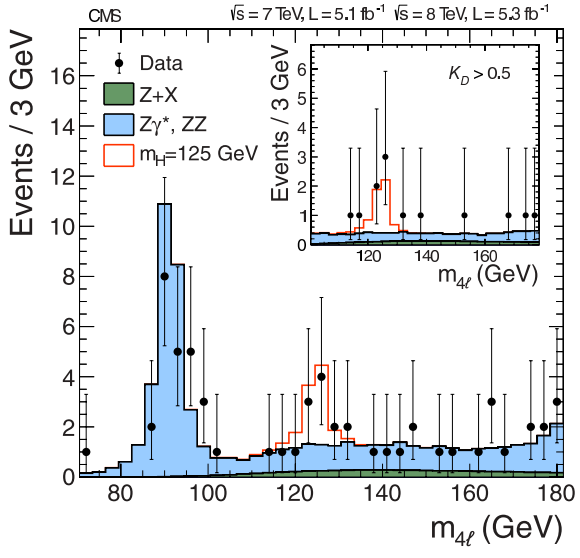
(i) Standard Model

- we have found the Higgs: $M_H \sim 125$ GeV
- $gg \to H$ dominant

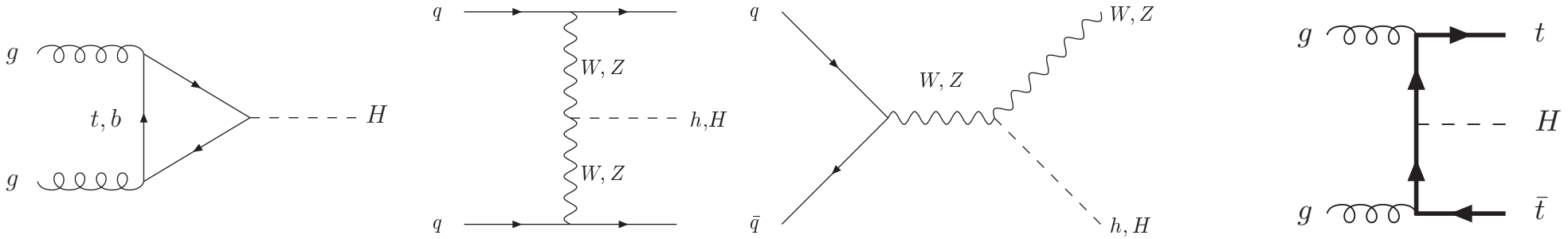


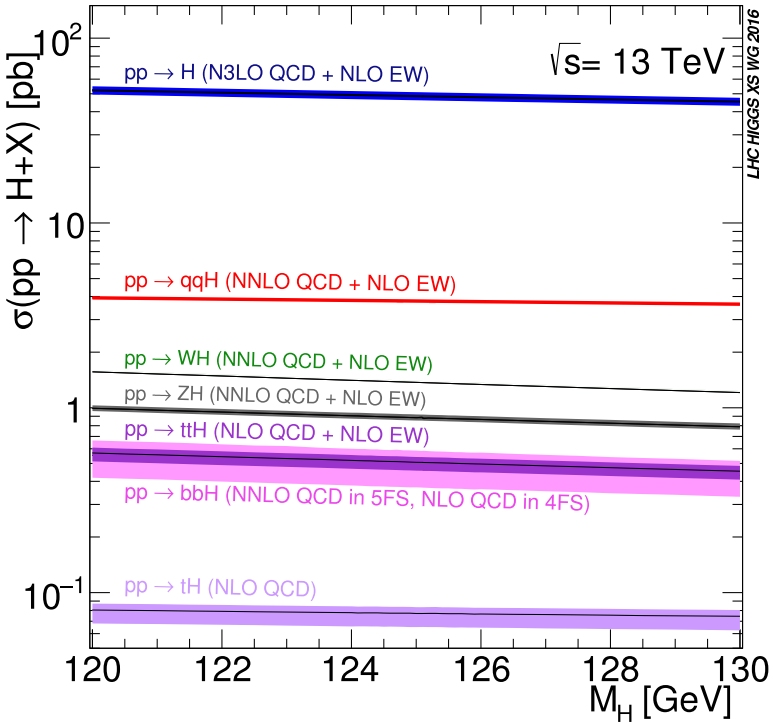


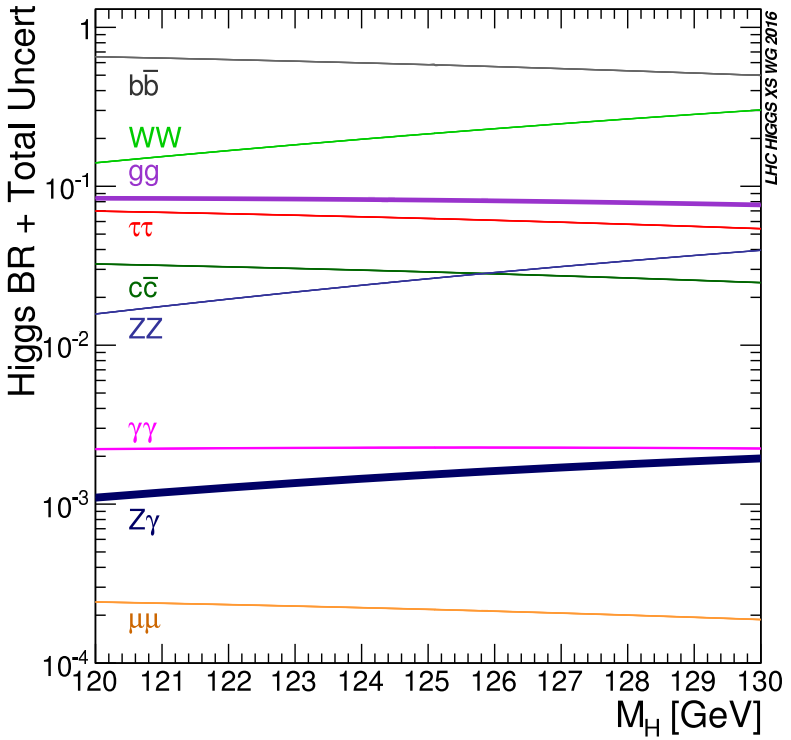




- Higgs Boson Production & Decay

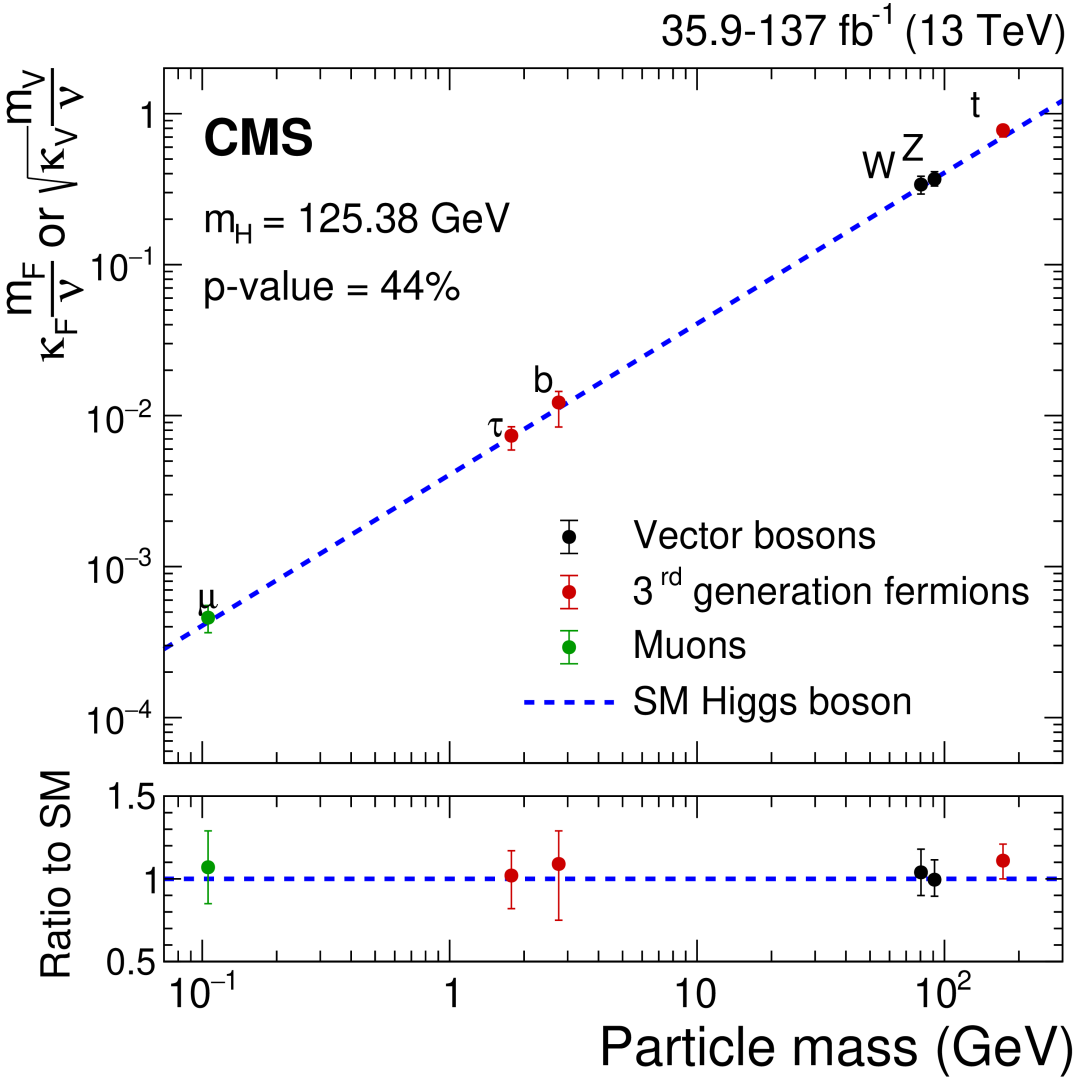




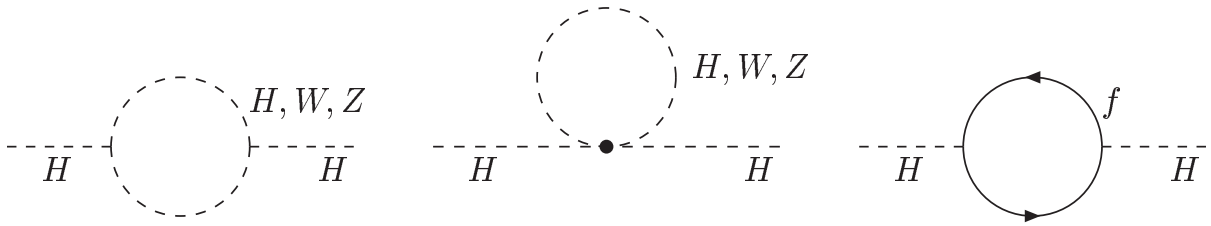


LHC Higgs XS WG

- Discovery: LHC [Tevatron]
  → Higgs mass
  couplings
  spin
  $\mathcal{CP}$
  λ ?



- GUT: hierarchy problem



$$\Delta M_H^2 \sim \alpha \Lambda^2 \sim \mathcal{O}(\alpha M_{GUT}^2) \gg M_H^2$$

[quadratic divergence]

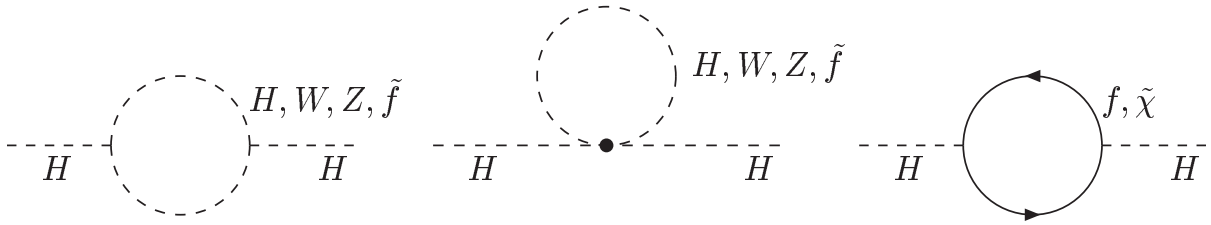
absorbed in counter term: $M_H^2 \to M_H^2 + \Delta M_H^2 - \delta M_H^2$

$\Rightarrow$ unnatural fine tuning [$\sim$ 28 digits]

(ii) MSSM [2HDM]

- SUSY: fermions $\leftrightarrow$ bosons

- no quadratic divergences $\Rightarrow$ solution to the hierarchy problem



$$\Delta M_H^2 \sim \alpha(\tilde{m}^2 - m^2) \log \frac{\Lambda^2}{m^2} \Rightarrow \tilde{m} \lesssim \mathcal{O}(1 \text{ TeV})$$

- SUSY-GUT: $\sin^2\theta_W = 0.2334 \pm 0.0026$ Langacker

  LEP: $\sin^2\theta_W = 0.2317 \pm 0.0002$ LEP/SLC

- 2 Higgs doublets $\overset{\text{ESB}}{\rightarrow}$ 5 Higgs bosons: $h, H, A, H^{\pm}$

- LO: 2 input parameters: $M_A, \text{tg}\beta = \frac{v_2}{v_1}$

- radiative corrections $\propto m_t^4 \log \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}$ $\rightarrow$ $\boxed{M_h \lesssim 130 \text{ GeV}}$

Haber
Carena,...
Heinemeyer,...
Zhang
Slavich,...
...

- modified couplings:

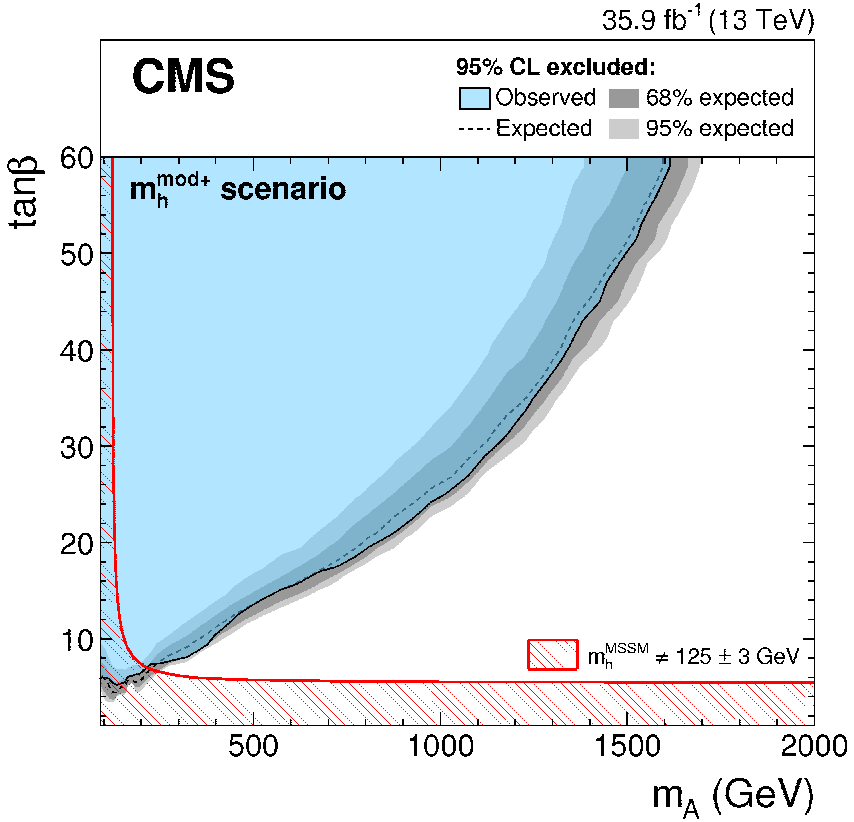
ϕ	g_u^ϕ	g_d^ϕ	g_V^ϕ
h	c_α/s_β	$-s_\alpha/c_\beta$ $[c_\alpha/s_\beta]$	$s_{\beta-\alpha}$
H	s_α/s_β	c_α/c_β $[s_\alpha/s_\beta]$	$c_{\beta-\alpha}$
A	$\text{ctg}\beta$	$\text{tg}\beta$ $[-\text{ctg}\beta]$	0

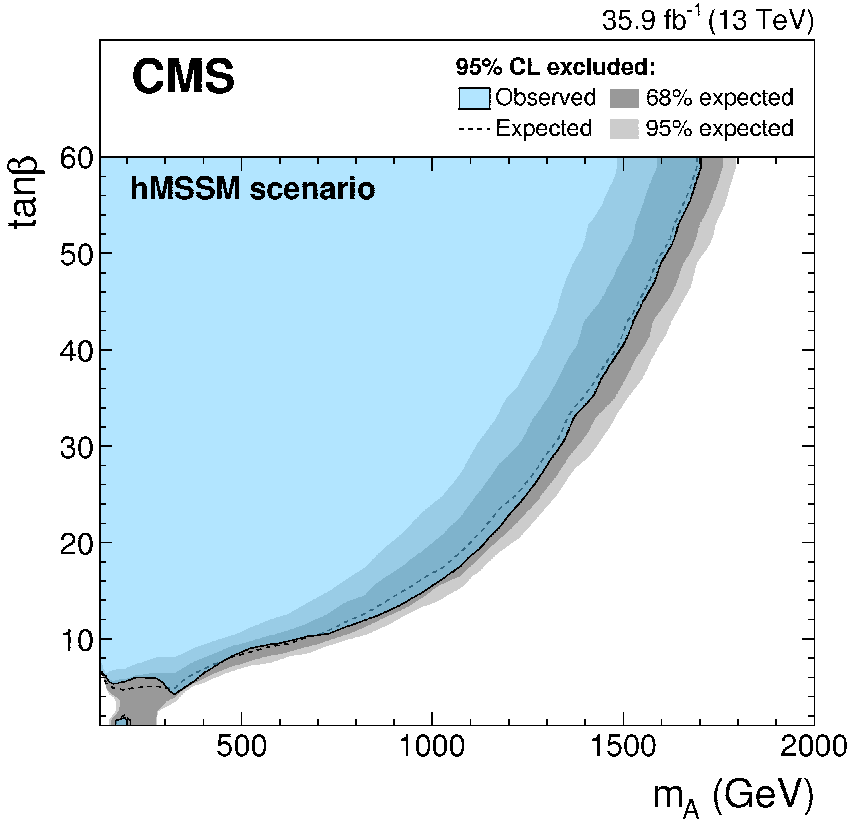
2HDM type II [type I]

- Yukawa couplings: $\text{tg}\beta\uparrow \quad \Rightarrow \quad g_u^\phi\downarrow \quad g_d^\phi\uparrow \quad g_V^\phi\downarrow$

- LHC: $gg \rightarrow \phi$ dominant for $\text{tg}\beta \lesssim 10$
  $gg \rightarrow \phi b\bar{b}$ dominant for $\text{tg}\beta \gtrsim 10$

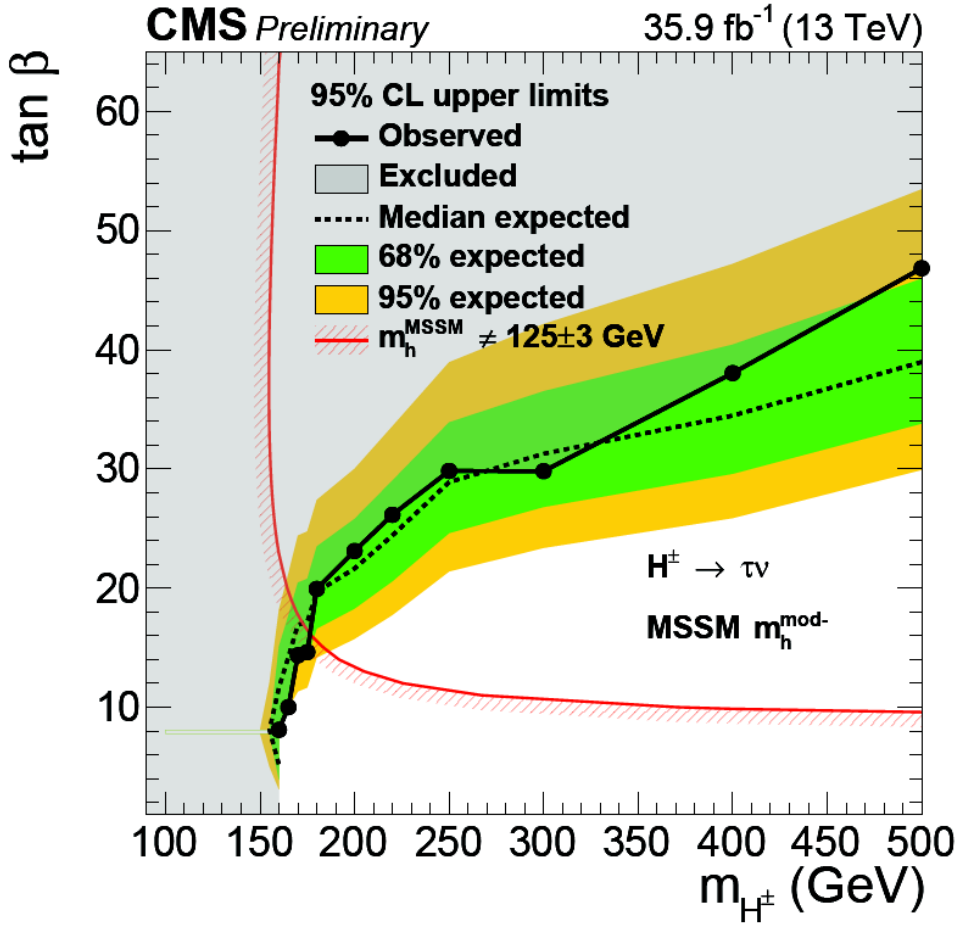
$$gg \to b\bar{b}\phi^0,\ gg \to \phi^0 \qquad \phi^0 \to \tau^+\tau^-$$

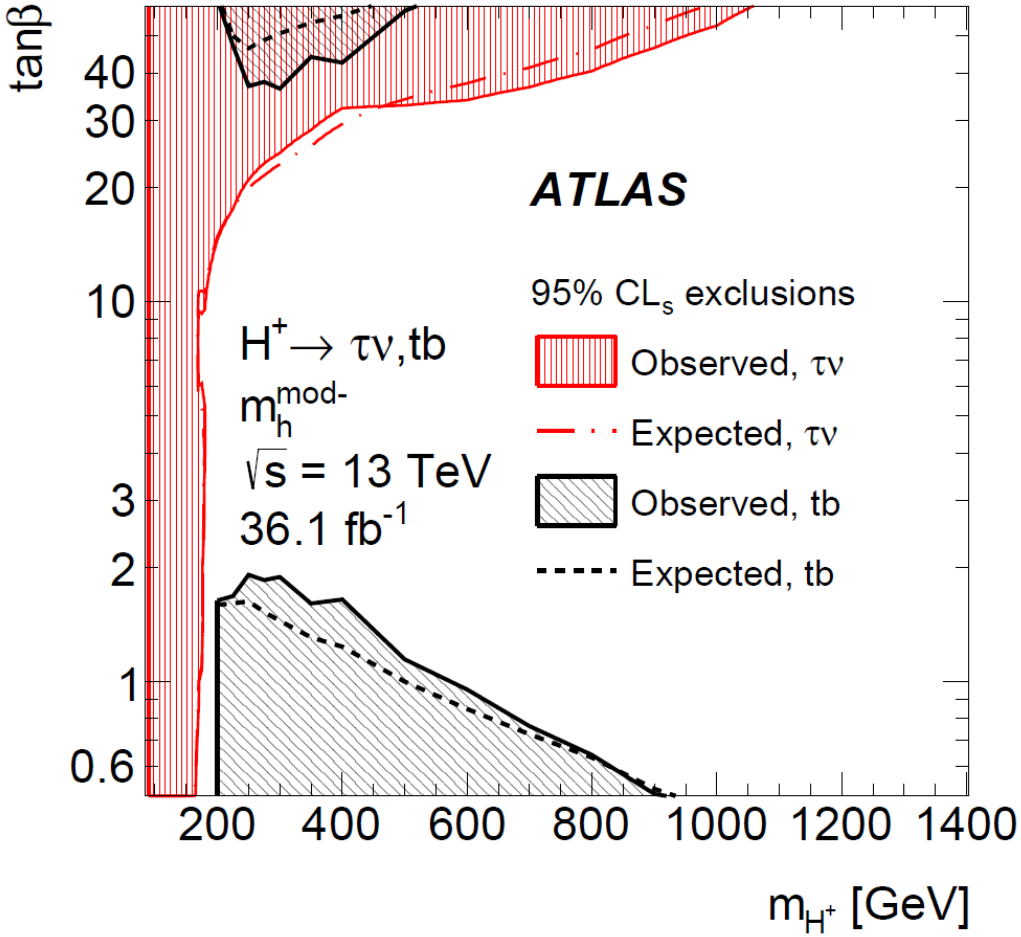




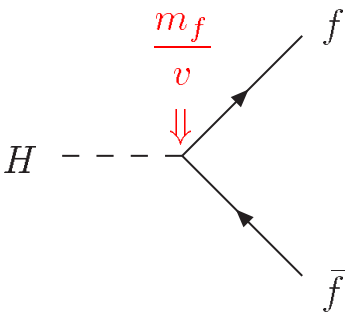
ATLAS: similar results

$$gg, q\bar{q} \rightarrow t\bar{b}H^- \qquad H^+ \rightarrow \tau^+\bar{\nu}_\tau(, t\bar{b})$$





II CHARGED HIGGS BOSON DECAYS



$$BR(H^+ \to t\bar{b}) \lesssim 100\%$$
$$BR(H^+ \to \tau^+\bar{\nu}\tau) \lesssim 100\%$$
$$BR(H^+ \to c\bar{b}) \lesssim 2\%$$
$$BR(H^+ \to c\bar{s}) \lesssim 1\%$$
$$BR(H^+ \to \mu^+\bar{\nu}_\mu) \lesssim 0.04\%$$

- $H^+ \to t\bar{b}, \tau\bar{\nu}_\tau$ dominant

$$\Gamma(H^+ \to U\overline{D}) = \frac{N_c G_F M_{H^\pm}}{4\sqrt{2}\pi}|V_{UD}|^2 \left[m_U^2 (g_U^A)^2 + m_D^2 (g_D^A)^2\right] (1 + \delta_{\rm QCD})$$

- δ_{QCD} ($M_{H^+} \gg m_{U,D}$): large QCD corrections $\sim -50 \ldots -80\%$
  (known to 4 loops - scalar correlator)

Braaten, Leveille
Drees, Hikasa
Gorishnii, Kataev, Larin, Surguladze
Chetyrkin, Kwiatkowski, Steinhauser, Baikov

- dominant effect: $m_{U,D} \to \overline{m}_{U,D}(M_{H^\pm}) \Rightarrow \sim 25\%$ remaining

- NLO mass effects: ($\mu_i = M_i^2/M_{H^\pm}$)

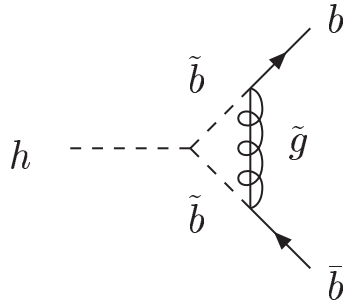
$$\Gamma[H^+ \to U\bar{D}] = \frac{3G_F M_{H^\pm}}{4\sqrt{2}\pi}|V_{UD}|^2\,\lambda^{1/2}\left\{(1-\mu_U-\mu_D)\left[\frac{M_U^2}{\mathrm{tg}^2\beta}\left(1+\frac{4}{3}\frac{\alpha_s}{\pi}\delta_{UD}^+\right)\right.\right.$$
$$\left.\left.+M_D^2\mathrm{tg}^2\beta\left(1+\frac{4}{3}\frac{\alpha_s}{\pi}\delta_{DU}^+\right)\right]-4M_UM_D\sqrt{\mu_U\mu_D}\left(1+\frac{4}{3}\frac{\alpha_s}{\pi}\delta_{UD}^-\right)\right\}$$

Li, Oakes
Mendez, Pomarol
Djouadi, Gambino

- SUSY-QCD corrections: dominated by $\Delta_{b,t} \to$ effective Yukawa couplings (SUSY-remainder small)

Dabelstein
Coarasa Perez, Jimenez, Sola

- large SUSY–QCD corrections to $\phi^0 b\bar{b}$ coupling



$+\cdots \qquad \propto \frac{\alpha_s}{\pi}\,\frac{m_{\tilde{g}}\mu\mathrm{tg}\beta}{m_{\tilde{b}}^2}$

Hall,. . .
Carena,. . .
Nierste,. . .
Guasch,. . .
etc.

$$\mathcal{L}_{eff} = -\lambda_b \overline{b_R} \left[\phi_1^0 + \frac{\Delta_b}{\mathrm{tg}\beta} \phi_2^{0*} \right] b_L + h.c. \quad \text{valid to all orders in } \Delta_b$$

$$= -m_b \bar{b} \left[1 + i\gamma_5 \frac{G^0}{v} \right] b - \frac{m_b/v}{1+\Delta_b} \bar{b} \left[g_b^h \left(1 - \frac{\Delta_b}{\mathrm{tg}\alpha \ \mathrm{tg}\beta} \right) h \right.$$
$$\left. + g_b^H \left(1 + \Delta_b \frac{\mathrm{tg}\alpha}{\mathrm{tg}\beta} \right) H - g_b^A \left(1 - \frac{\Delta_b}{\mathrm{tg}^2\beta} \right) i\gamma_5 A \right] b$$

$$\Delta_b = \Delta_b^{QCD(1)} + \Delta_b^{elw(1)}$$

$$\Delta_b^{QCD(1)} = \frac{2}{3} \frac{\alpha_s(\mu_R)}{\pi} M_{\tilde{g}} \ \mu \ \mathrm{tg}\beta \ I(m^2_{\tilde{b}_1}, m^2_{\tilde{b}_2}, M^2_{\tilde{g}})$$

$$\Delta_b^{elw(1)} = \frac{\lambda_t^2(\mu_R)}{(4\pi)^2} \ \mu \ A_t \ \mathrm{tg}\beta \ I(m^2_{\tilde{t}_1}, m^2_{\tilde{t}_2}, \mu^2)$$

$$I(a,b,c) = -\frac{ab \log \frac{a}{b} + bc \log \frac{b}{c} + ca \log \frac{c}{a}}{(a-b)(b-c)(c-a)}$$

$\Rightarrow$ resummed Yukawa couplings $\tilde{g}_b^\Phi$

Carena, Garcia, Nierste, Wagner
Guasch, Häfliger, S.

- analogous resummed couplings for $H^\pm$

- extension to A_b terms:

$$\mathcal{L}_{eff} = -\lambda_b^0 \overline{b_R} \left[(1 + \Delta_{b,1}) \phi_1^0 + \frac{\Delta_{b,2}}{\mathrm{tg}\beta} \phi_2^{0*} \right] b_L + h.c.$$

$$\mathcal{L}_{eff} = -\lambda_b \overline{b_R} \left[\phi_1^0 + \frac{\Delta_b}{\mathrm{tg}\beta} \phi_2^{0*} \right] b_L + h.c.$$

$$\Rightarrow \qquad \Delta_b = \frac{\Delta_{b,2}}{1 + \Delta_{b,1}}$$

Guasch, Häfliger, S.
Ghezzi, Glaus, Müller, Schmidt, S.

$$\Delta_{b,1} = -\frac{2}{3} \frac{\alpha_s(\mu_R)}{\pi} M_{\tilde{g}} \, A_b \, I(m^2_{\tilde{b}_1}, m^2_{\tilde{b}_2}, M^2_{\tilde{g}}) \qquad \rightarrow \text{NNLO}$$

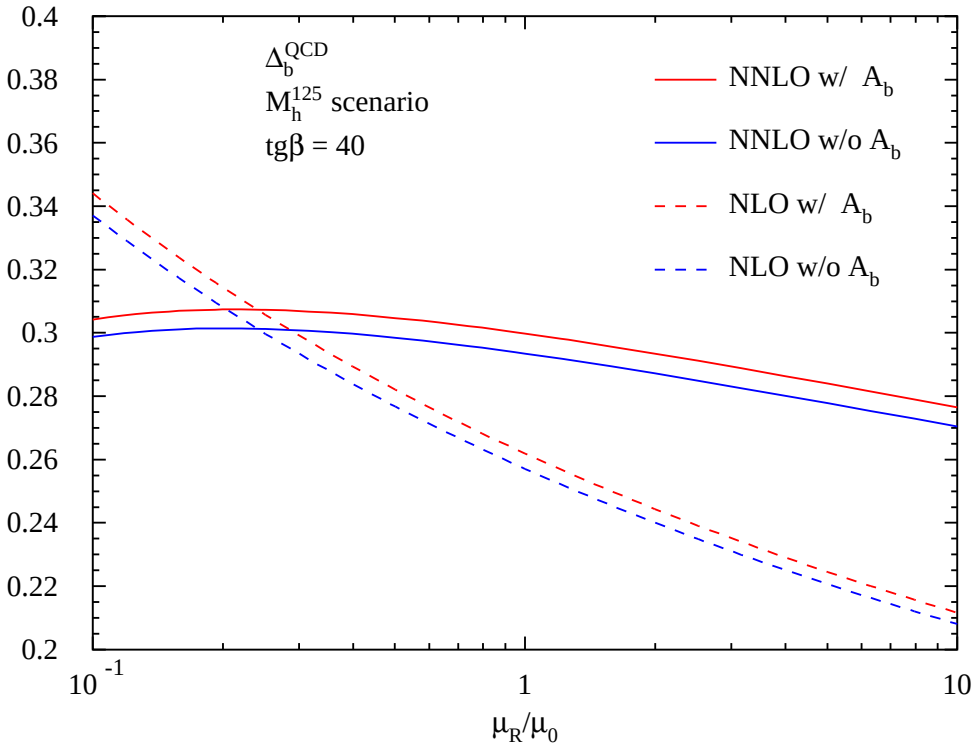
- strange Yukawa couplings:

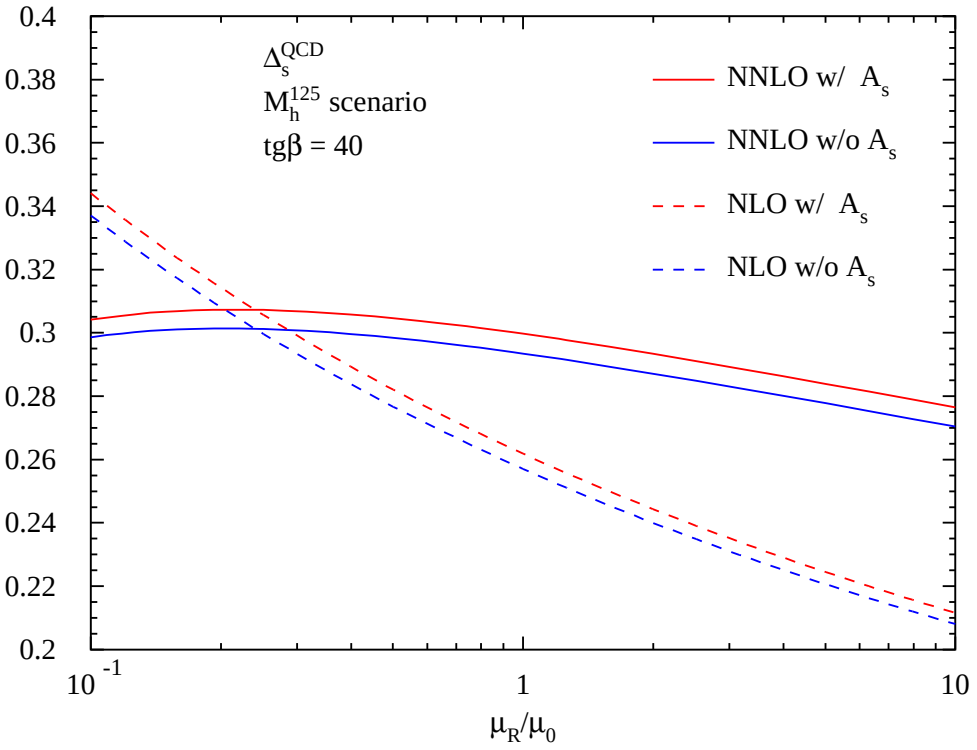
$$\Delta_{s,1} = -\frac{2}{3} \frac{\alpha_s(\mu_R)}{\pi} M_{\tilde{g}} \, A_s \, I(m^2_{\tilde{s}_1}, m^2_{\tilde{s}_2}, M^2_{\tilde{g}})$$

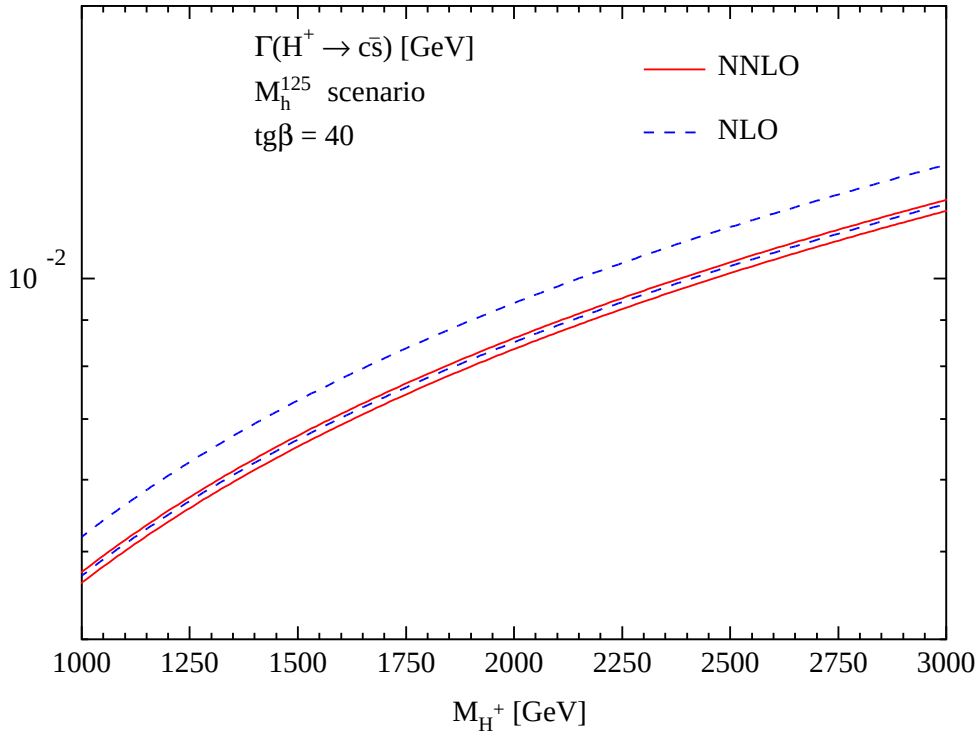
$$\Delta_{s,2} = \frac{2}{3} \frac{\alpha_s(\mu_R)}{\pi} M_{\tilde{g}} \, \mu \mathrm{tg}\beta \, I(m^2_{\tilde{s}_1}, m^2_{\tilde{s}_2}, M^2_{\tilde{g}})$$

$$\Delta_s = \frac{\Delta_{s,2}}{1 + \Delta_{s,1}} \qquad \rightarrow \text{NNLO}$$

Ghezzi, Glaus, Müller, Schmidt, S.

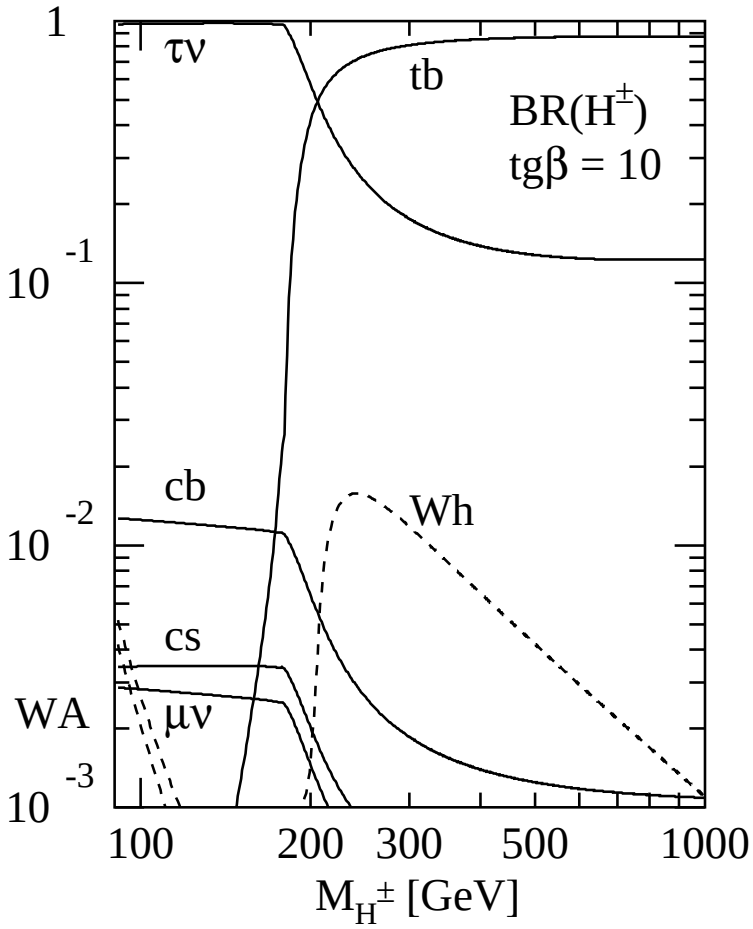


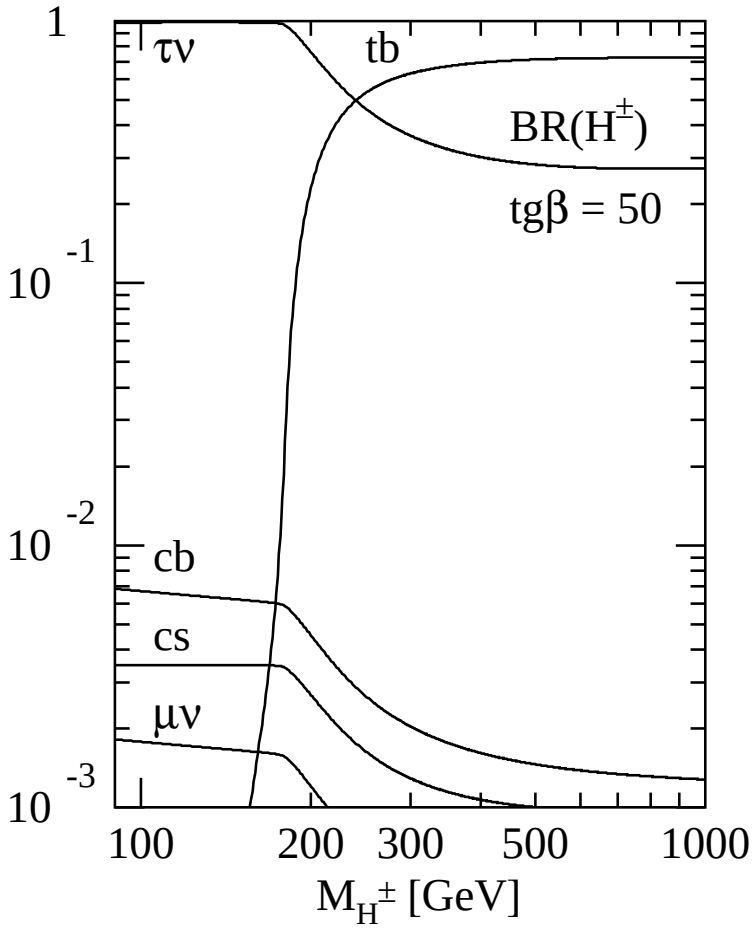




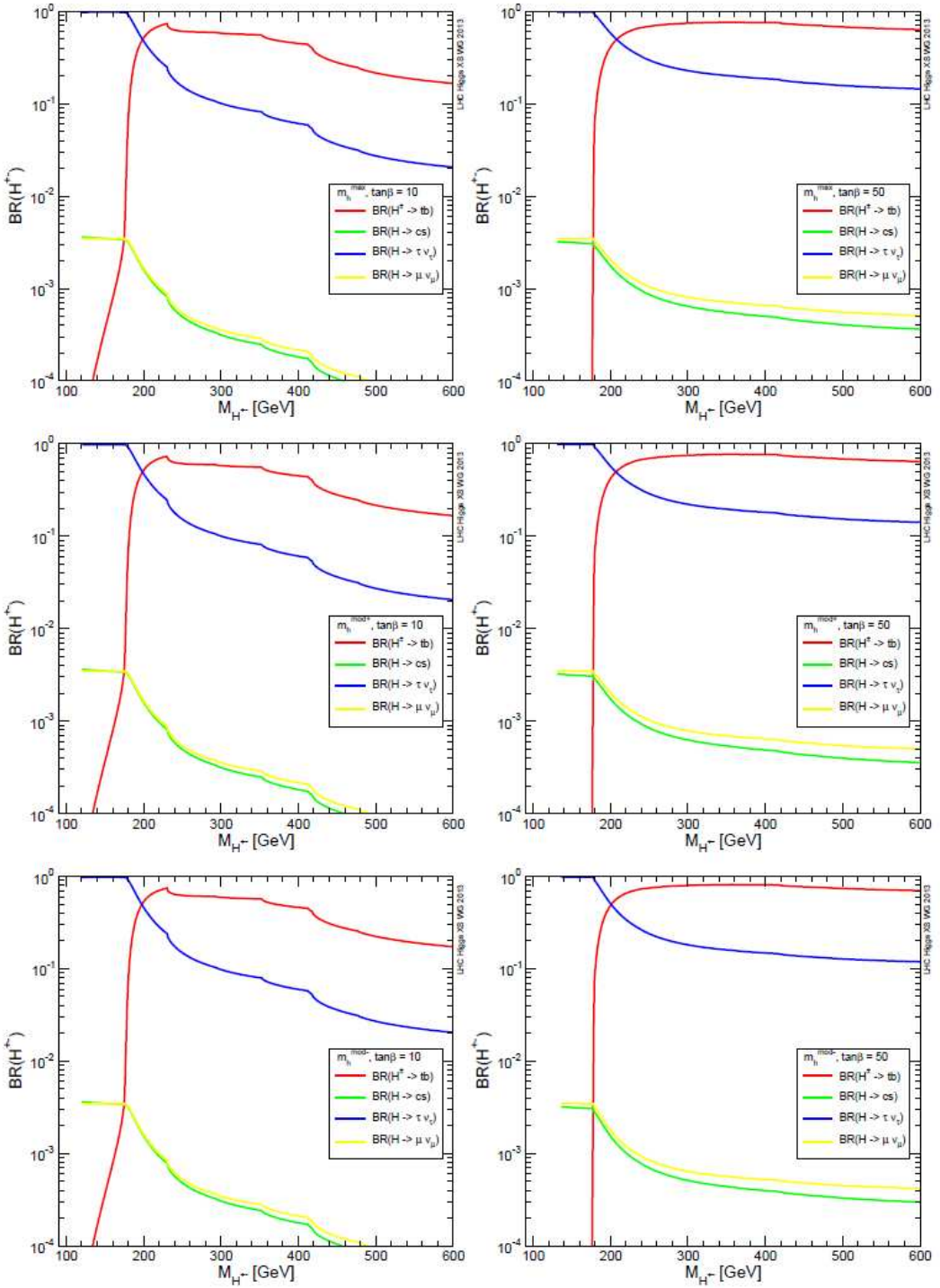
Ghezzi, Glaus, Müller, Schmidt, S.

→ charged Higgs Yukawa couplings


1
10 -1
10 -2
10 -3
WA
τν
tb
BR(H±)
tgβ = 10
cb
Wh
cs
μν
100
200
300
500
1000
M_H± [GeV]


1
10 -1
10 -2
10 -3
τν
tb
BR(H±)
tgβ = 50
cb
cs
μν
100
200
300
500
1000
M_H± [GeV]

HDECAY

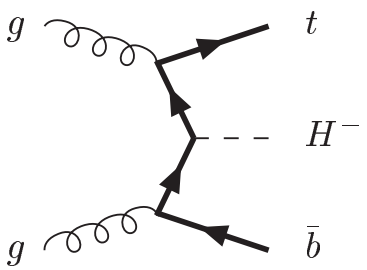

BR(H+)
M_H+ [GeV]
m_h^max, tanβ = 10
m_h^max, tanβ = 50
m_h^mod+, tanβ = 10
m_h^mod+, tanβ = 50
m_h^mod-, tanβ = 10
m_h^mod-, tanβ = 50
BR(H+ -> tb)
BR(H -> cs)
BR(H -> τ ν_τ)
BR(H -> μ ν_μ)
LHC Higgs XS WG 2013

LHCHWG (YR3)

III CHARGED HIGGS BOSON PRODUCTION

(i) $pp \to t\bar{b}H^- + X$

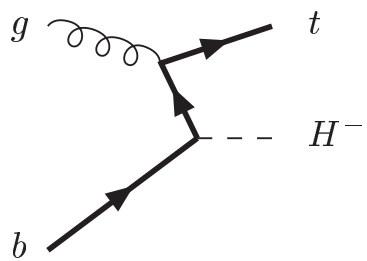
- $M_{H^\pm} < m_t - m_b$: $\sigma_{t\bar{b}H^-} = \sigma_{t\bar{t}} \times BR(\bar{t} \to \bar{b}H^-)$
- $M_{H^\pm} \sim m_t - m_b$: new NLO calculation — Degrande, Frederix, Wiesemann, Zaro
- $M_{H^\pm} > m_t - m_b$:



NLO

exact $g \to b\bar{b}$ splitting & mass/off-shell effects

no resummation of log $M^2_{H^\pm}/m^2_b$ terms



NLO

massless/on-shell b's, no p_{Tb}

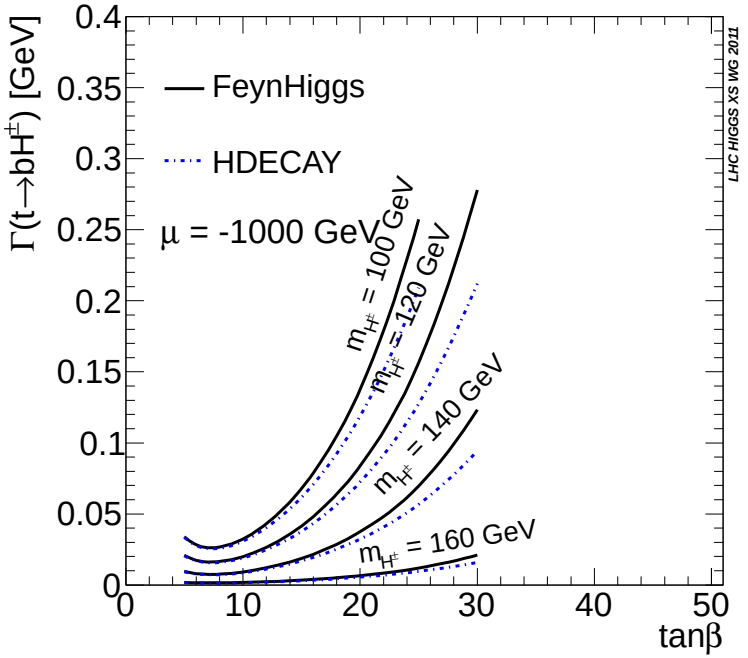
resummation of log $M^2_{H^\pm}/m^2_b$ terms

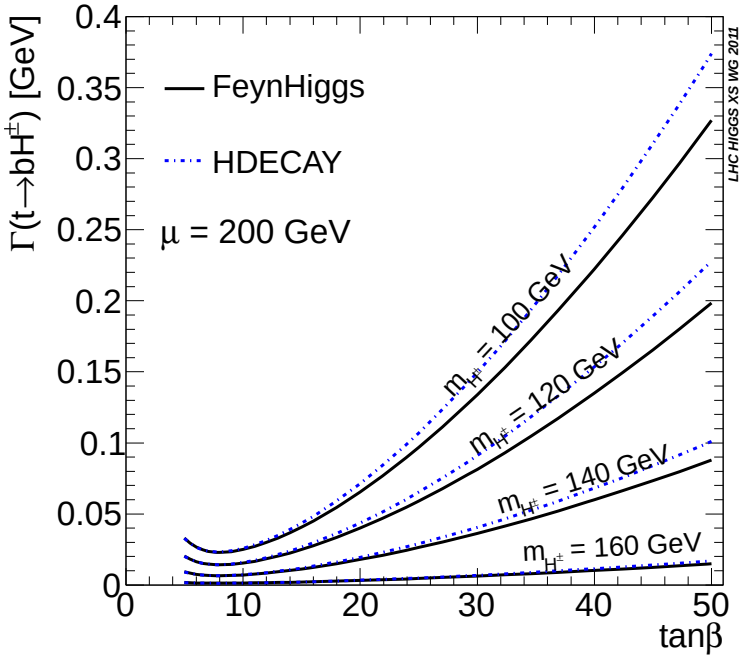
$\to$ Santander matching

Dittmaier, Krämer, S., Walser
Plehn
Flechl, Klees, Krämer, Spira, Ubiali

$t \to bH^+$

- $M_{H^\pm} < m_t - m_b$: $\sigma_{b\bar{t}H+} = \sigma_{t\bar{t}} \times BR(t \to bH^+)$





HDECAY: NLO QCD + Δ_b

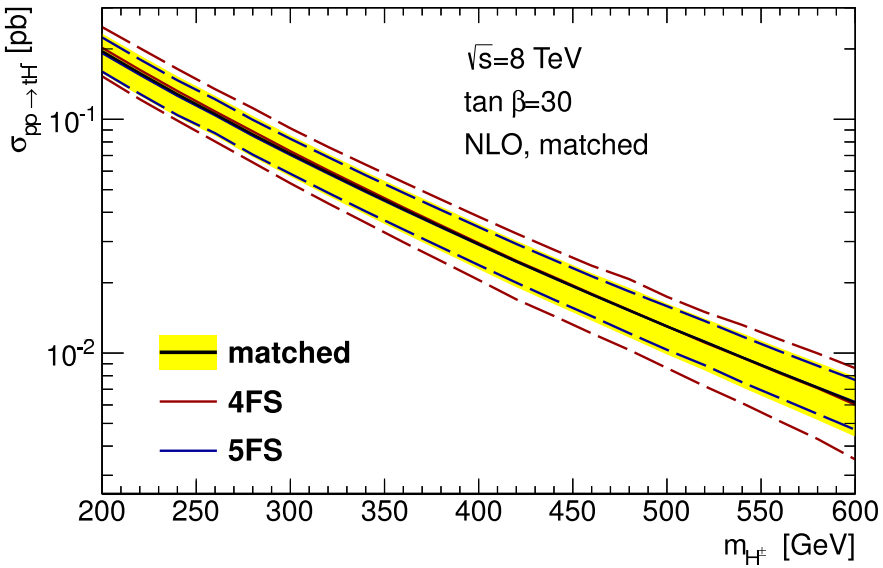
FeynHiggs: NLO QCD + Δ_b

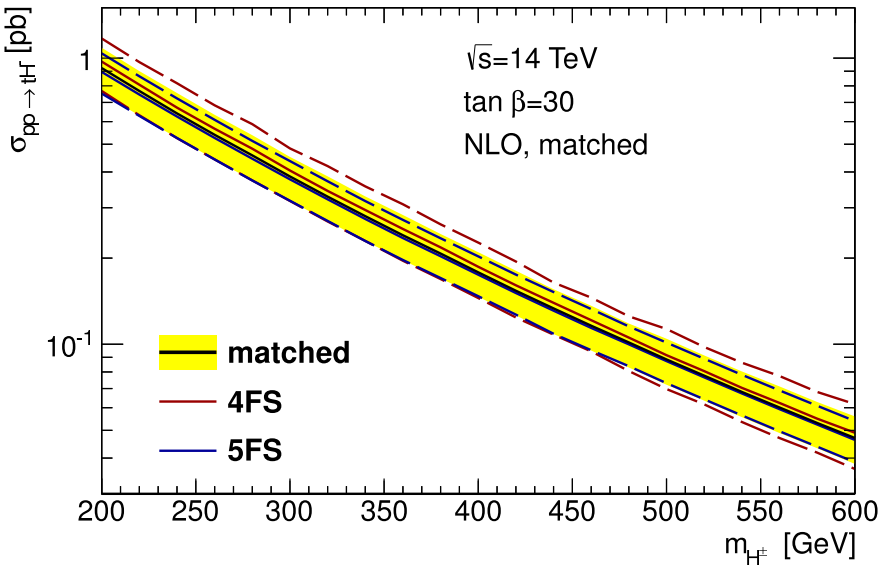
Santander matching:

$$\sigma = \frac{\sigma^{4FS} + w\sigma^{5FS}}{1+w}$$

$$w = \log \frac{M_{H^\pm}}{m_b} - 2$$

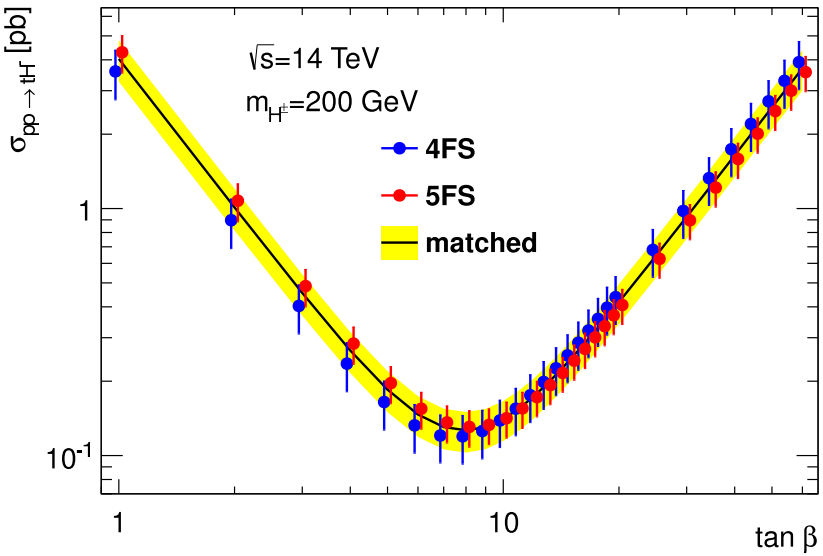
Harlander, Krämer, Schumacher

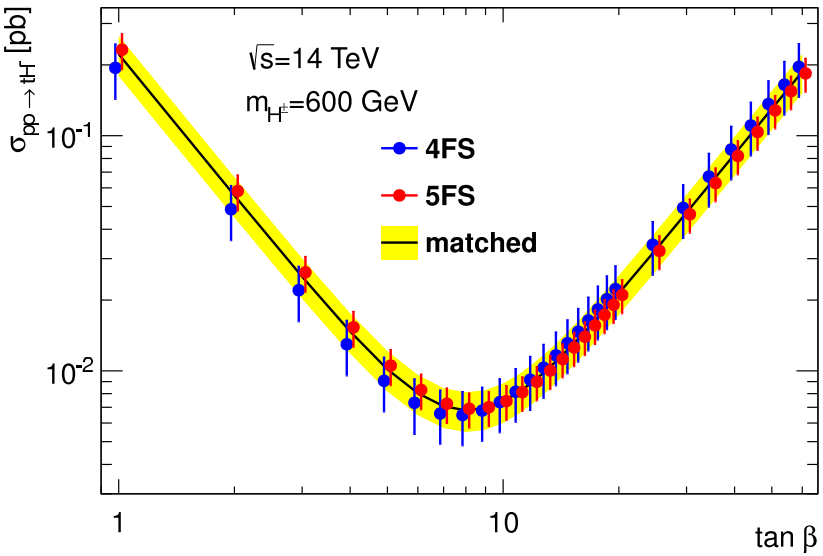




Dittmaier, Krämer, S., Walser
Plehn
Flechl, Klees, Ubiali

minimum: $\mathrm{tg}\beta \sim \sqrt{\frac{m_t}{\overline{m}_b}} \sim 8$





Dittmaier, Krämer, S., Walser
Plehn
Flechl, Klees, Ubiali

SUSY-QCD Corrections to $b\bar{b}\phi^0$

$$\mathcal{L}_{eff} = -\frac{m_b/v}{1+\Delta_b}\bar{b}\left[g_b^h\left(1-\frac{\Delta_b}{\mathrm{tg}\alpha\ \mathrm{tg}\beta}\right)h + g_b^H\left(1+\Delta_b\frac{\mathrm{tg}\alpha}{\mathrm{tg}\beta}\right)H - g_b^A\left(1-\frac{\Delta_b}{\mathrm{tg}^2\beta}\right)i\gamma_5 A\right]b$$

$$\Delta_b = \frac{2}{3}\frac{\alpha_s}{\pi}\, m_{\tilde{g}}\ \mu\ \mathrm{tg}\beta\ I(m^2_{\tilde{b}_1}, m^2_{\tilde{b}_2}, m^2_{\tilde{g}}) \qquad I(a,b,c) = \frac{ab\log\frac{a}{b}+bc\log\frac{b}{c}+ca\log\frac{c}{a}}{(a-b)(b-c)(a-c)}$$

Carena, Garcia, Nierste, Wagner
Guasch, Häfliger, S.
Noth, S.
Mihaila, Reisser

$\Rightarrow$ resummed Yukawa couplings

- NNLO: $\mathcal{O}(10\%)$, $\mu = M_{SUSY}$
- approximation of NLO SUSY-QCD corrections $< 1\%$ @ large $\mathrm{tg}\beta$

Dittmaier, Krämer, S., Walser

- analogous for charged Higgs: $\tilde{g}_b^{H^\pm} = \frac{\mathrm{tg}\beta}{1+\Delta_b}\left(1-\frac{\Delta_b}{\mathrm{tg}^2\beta}\right) = \rho \times \mathrm{tg}\beta$

$$\sigma(\mathrm{tg}\beta) = \rho\ \sigma(\mathrm{tg}\beta_{eff}) = \frac{\sigma_{tt}}{\mathrm{tg}^2\beta} + \sigma_{tb}\times\rho + \sigma_{bb}\mathrm{tg}^2\beta\times\rho^2$$

$$\mathrm{tg}\beta_{eff} = \sqrt{\rho}\ \mathrm{tg}\beta$$

- charged Higgs: $\tilde{g}_b^{H^\pm} = \dfrac{\mathrm{tg}\beta}{1+\Delta_b}\left(1 - \dfrac{\Delta_b}{\mathrm{tg}^2\beta}\right)$

$$\sigma_{NLO} = \sigma_{LO}|_{g_b^{H^\pm} \to \tilde{g}_b^{H^\pm}} \times \left\{1 + \delta_{QCD} + \delta_{SQCD}^{rem}\right\}$$

$\mathrm{tg}\beta$	δ_{SUSY}^{rem} [%]
3	-5.7%
5	-7.9%
10	-4.8%
30	-0.13%

$\leftarrow g_t^{H^\pm}\ (\Delta_t)$

Dittmaier, Krämer, S., Walser

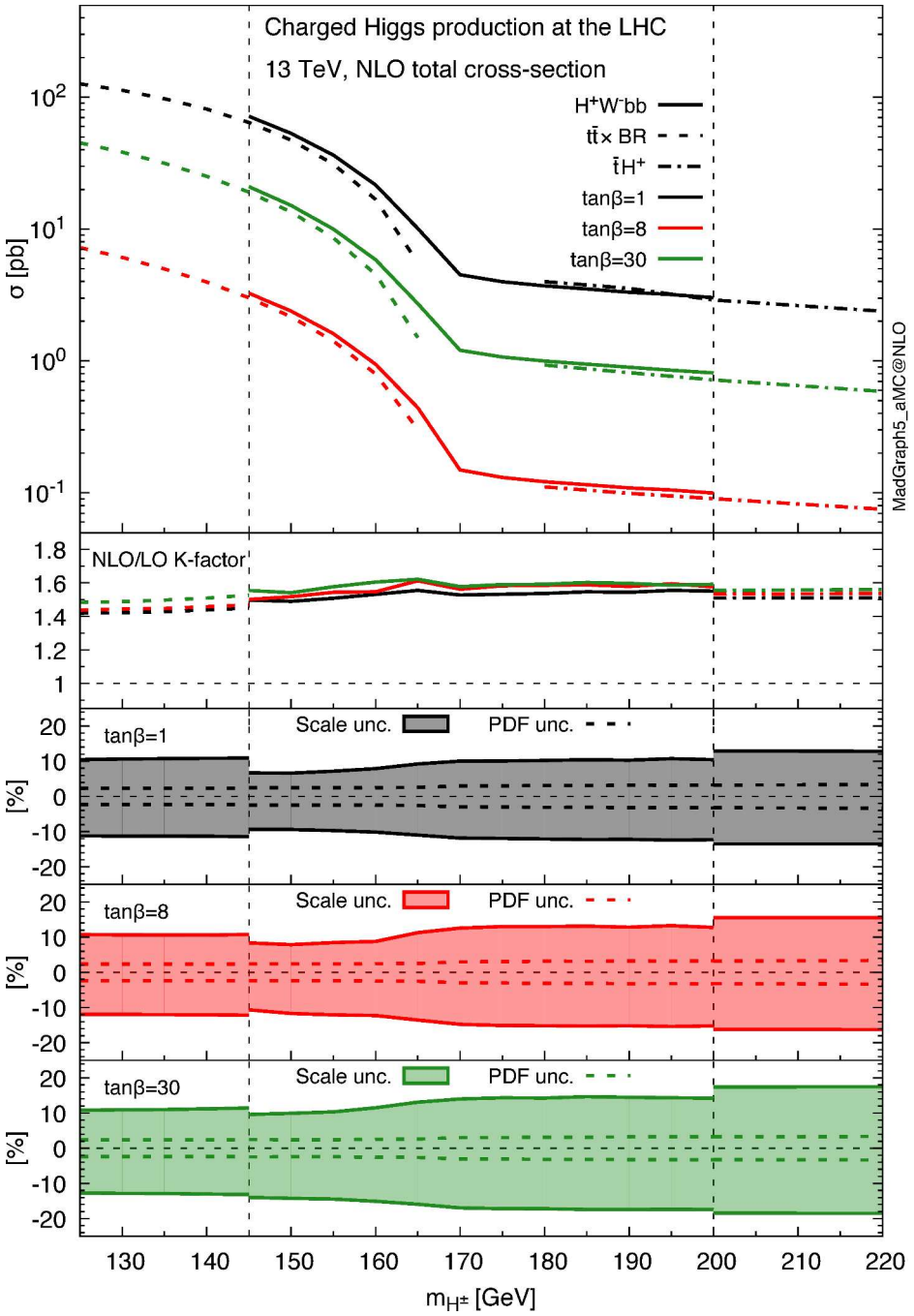
2HDM [III = lepton-specific, IV = flipped]

- charged 2HDM couplings:

type	g_u	g_d
I/III	$\mathrm{ctg}\beta$	$-\mathrm{ctg}\beta$
II/IV	$\mathrm{ctg}\beta$	$\mathrm{tg}\beta$

$$\Rightarrow \sigma_{I/III} \approx \frac{\sigma(\mathrm{tg}\beta = 1)}{\mathrm{tg}^2\beta}$$

at per-mille accuracy [or fit of $\sigma_{tt/tb/bb}$ from grid $\leftarrow$ exact]



complex-mass scheme, 4FS

Degrande, Frederix, Wiesemann, Zaro

- $q\bar{q} \to H^+H^-$ ($\leftarrow$ DY): SUSY-QCD small — Djouadi, S.

- $b\bar{b} \to H^+H^-$: NLO QCD + SUSY-QCD (Δ_b) — Hong-Shen, Wen-Gan, Ren-You, Liang, Li-Rong; Alves, Plehn

- $gg \to H^+H^-$: loop-induced, NLO unknown — Foot, Lew, Joshi; Willenbrock; Krause, Plehn, S., Zerwas; Brein, Hollik; Bendezu, Kniehl

- $b\bar{b} \to H^+W^-$: NLO QCD — Hollik, Zhu; Zhao, Li, Li

- $gg \to H^+W^-$: loop-induced, NLO unknown — Bendezu, Kniehl; Brein, Hollik, Kanemura

- VBF: $qq \to qqH^+H^-$: improvement required (γ exchange) — Moretti

IV DOUBLY CHARGED HIGGS BOSONS

- simplest model: SM Higgs doublet + Higgs triplet ($\rightarrow H^+ZW^-$ cpl.)

$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$

- neutrino mass w/o right-handed ν's:

$$\mathcal{L} = h_{ij} L_{iL}^T C i\sigma_2 \Delta L_{jL} + h.c.$$

$\Delta^0 = (v_\Delta + \delta^0)/\sqrt{2}$: $m_{ij} = \sqrt{2} h_{ij} v_\Delta$

$$V(H,\Delta) = -m_H^2 H^\dagger H + \lambda (H^\dagger H)^2 + M_\Delta^2 Tr(\Delta^\dagger \Delta) + (\mu H^T i\sigma_2 \Delta^\dagger H + h.c.)$$
$$+\lambda_1 (H^\dagger H) Tr(\Delta^\dagger \Delta) + \lambda_2 (Tr(\Delta^\dagger \Delta))^2 + \lambda_3 Tr(\Delta^\dagger \Delta)^2 + \lambda_4 H^\dagger \Delta \Delta^\dagger H$$

- $M_\Delta \gg v \gg v_\Delta$: $v_\Delta \sim \dfrac{\mu v^2}{\sqrt{2} M_\Delta^2}$ + stability/unitarity constraints

Arhrib, Benrik, Chabab,. . .

$$\rho = \frac{1+2x^2}{1+4x^2} \qquad (x = v_\Delta/v) \qquad \Rightarrow v_\Delta \lesssim 8\text{GeV}$$

$\Rightarrow \Delta^{\pm\pm}$ coupling to W suppressed ($\propto v_\Delta$)

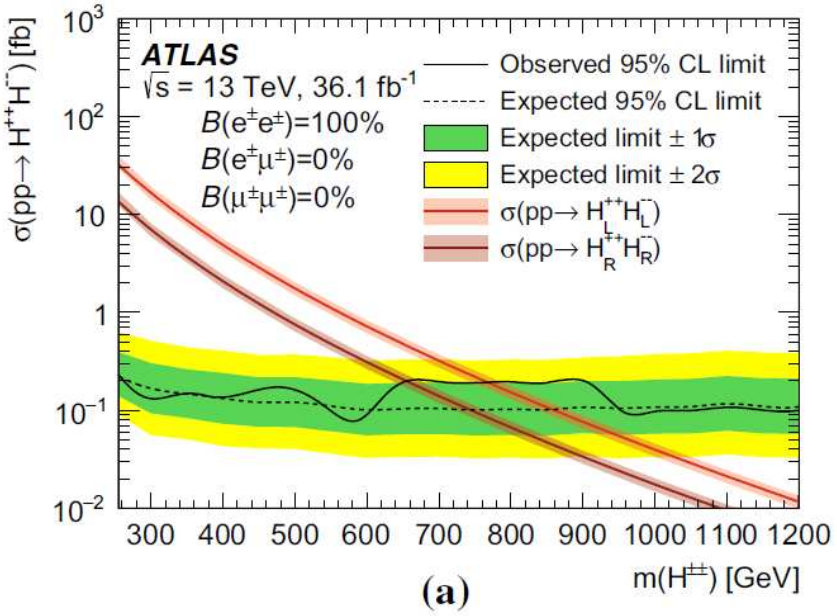
$\Rightarrow pp \rightarrow \Delta^{\pm\pm}\Delta^{\mp\mp}, \Delta^{\pm\pm}\Delta^{\mp}$ leading (for not too large $M_{\Delta^{\pm\pm}}$)

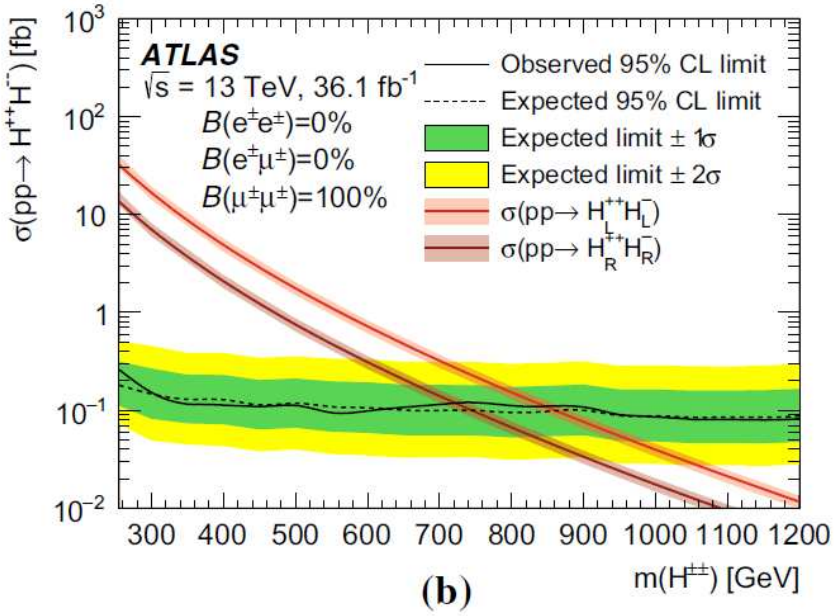
- $gg \rightarrow H^0 \rightarrow \Delta^{\pm\pm}\Delta^{\mp\mp}$ relevant in special scenarios

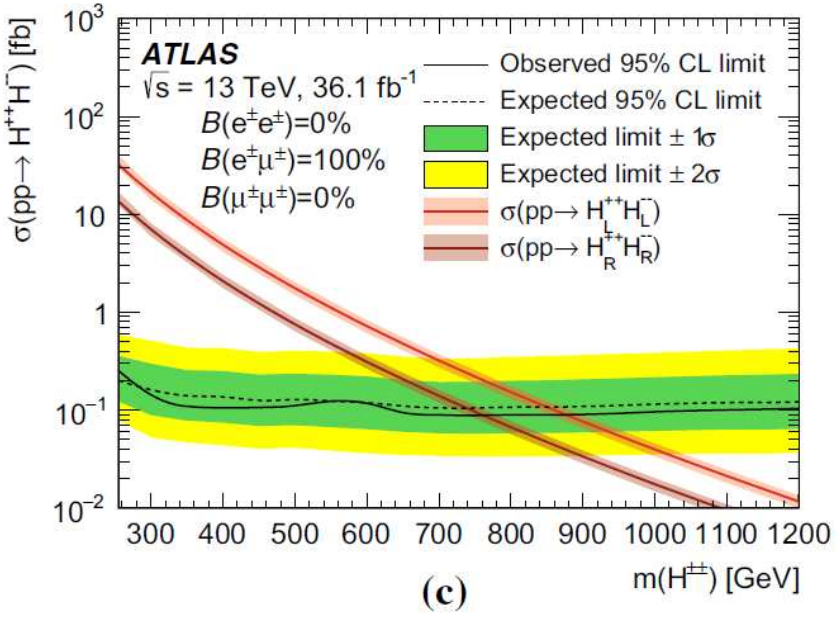
Akeroyd, Moretti

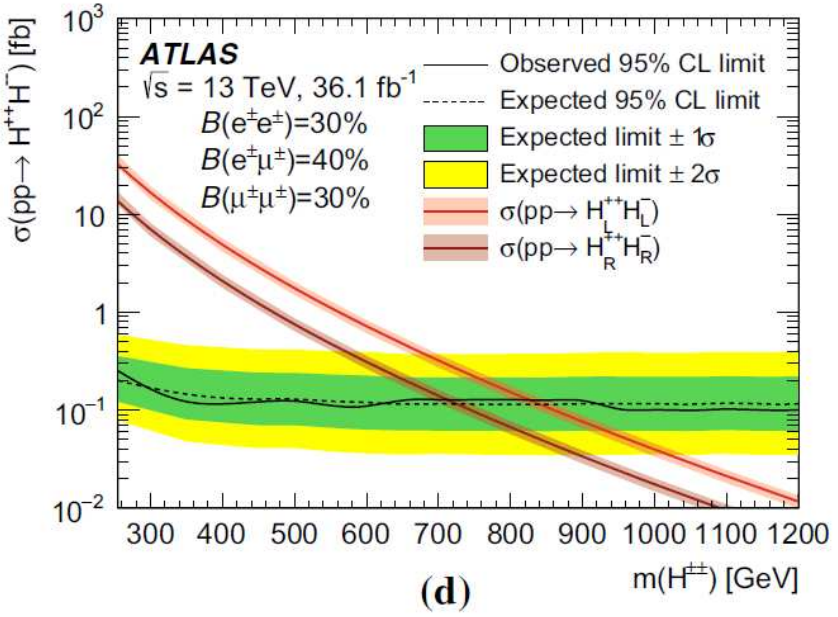
$H_L^{\pm\pm} = \Delta_L^{\pm\pm}$: $I_3^{--} = -1$

$H_R^{\pm\pm} = \Delta_R^{\pm\pm}$: $I_3^{--} = 0$

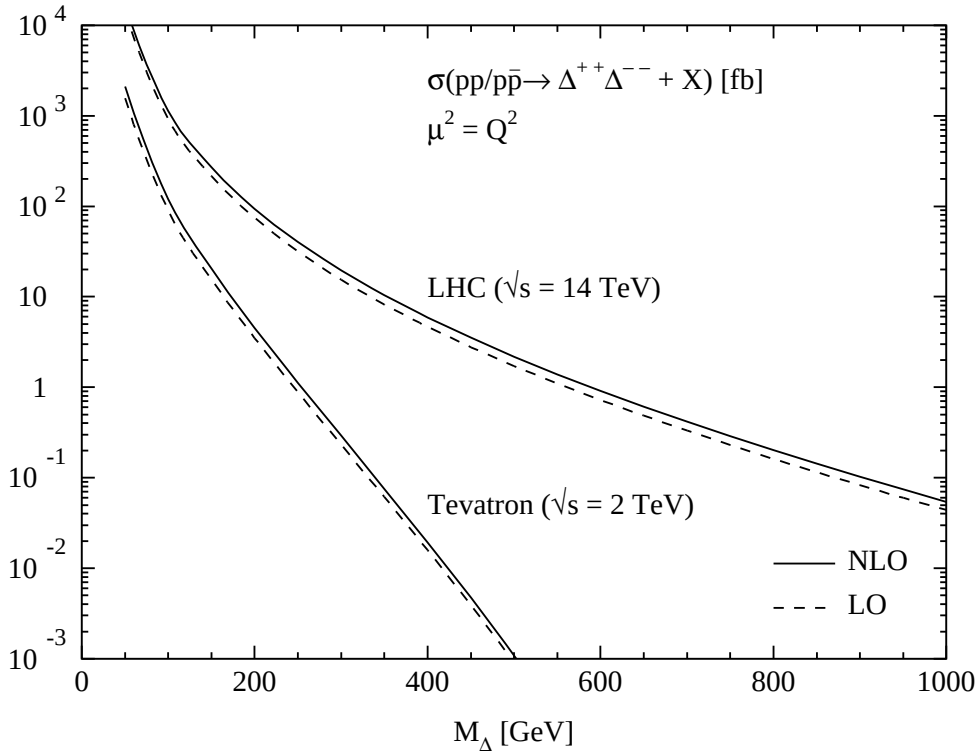


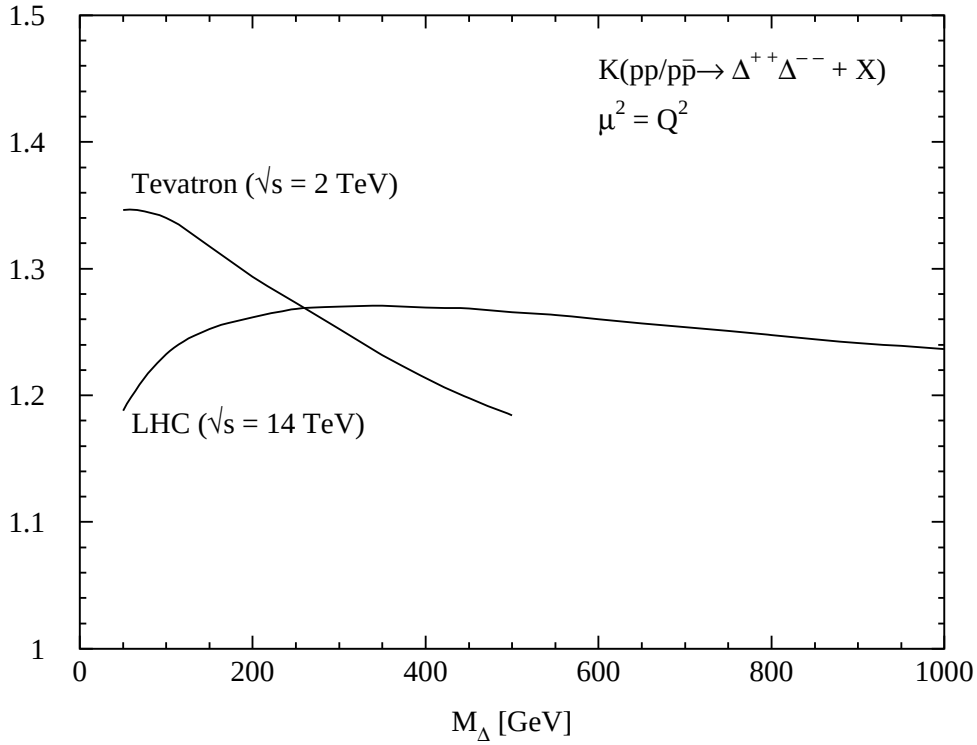






$pp \to \Delta_L^{\pm\pm}\Delta_L^{\mp\mp}$





Mühlleitner, S.

- similar: $pp \to \Delta^{\pm\pm}\Delta^{\mp}$ ($\leftarrow$ DY)
- decays: $\Delta^{\pm\pm} \to \ell^{\pm}\ell^{\pm}, W^{\pm}H^{\pm}$ $(, W^{\pm}W^{\pm}, H^{\pm}H^{\pm})$

V *CONCLUSIONS*

- Higgs boson searches/studies at LHC belong to major endeavours
  $\rightarrow$ charged Higgs!

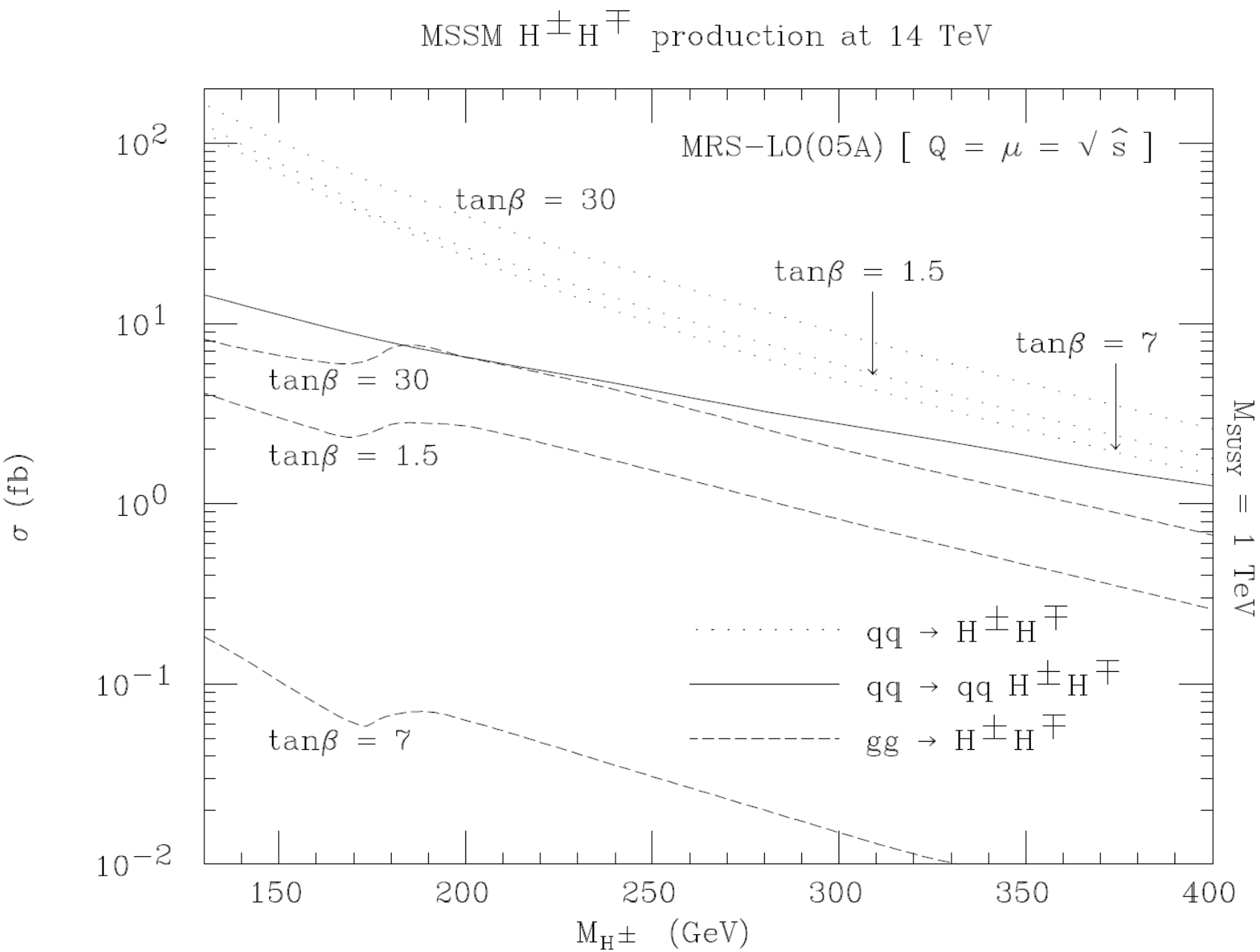
- doubly charged unique signature beyond Higgs doublets

- most (SUSY–)QCD corrs known

- several HO–tools available for inclusive cxn and BR

- important to develop NLO event generators [$\leftarrow$ backgrounds]

BACKUP SLIDES


MSSM $H^{\pm}H^{\mp}$ production at 14 TeV
MRS-LO(05A) [Q = μ = $\sqrt{\hat{s}}$]
tanβ = 30
tanβ = 1.5
tanβ = 7
tanβ = 30
tanβ = 1.5
tanβ = 7
qq → $H^{\pm}H^{\mp}$
qq → qq $H^{\pm}H^{\mp}$
gg → $H^{\pm}H^{\mp}$
M_{SUSY} = 1 TeV
σ (fb)
$M_{H^{\pm}}$ (GeV)
10^2
10^1
10^0
10^{-1}
10^{-2}
150
200
250
300
350
400

Moretti