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BEYOND THE STANDARD MODEL

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I Introduction

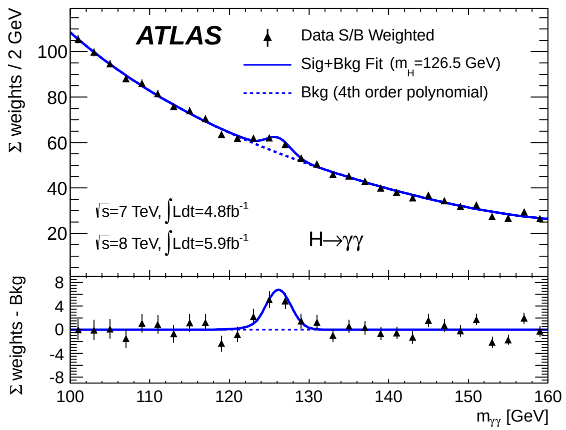
II Higgs Boson Production

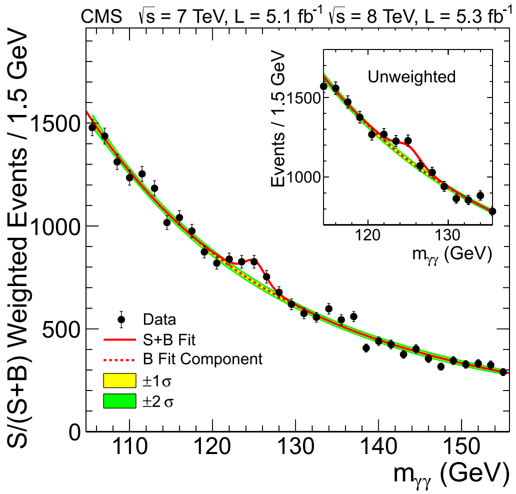
III Conclusions

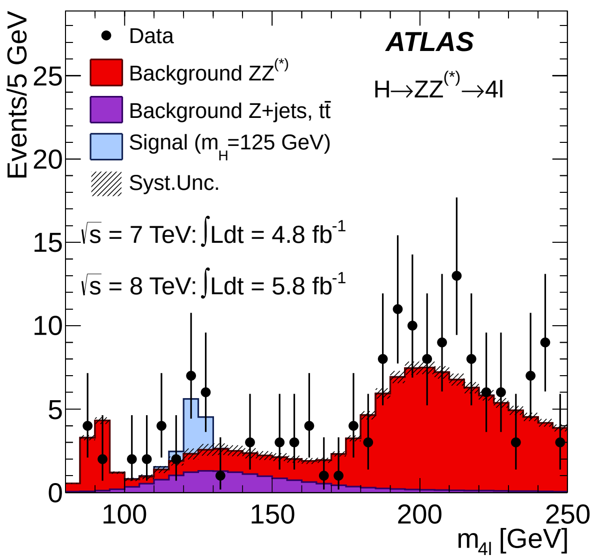
I INTRODUCTION

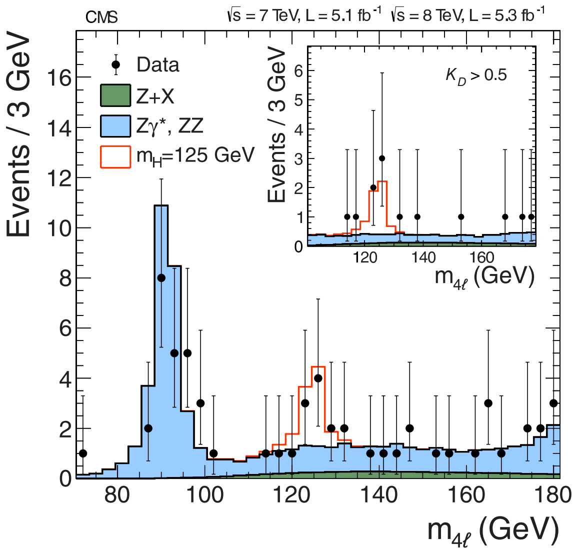
(i) Standard Model

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

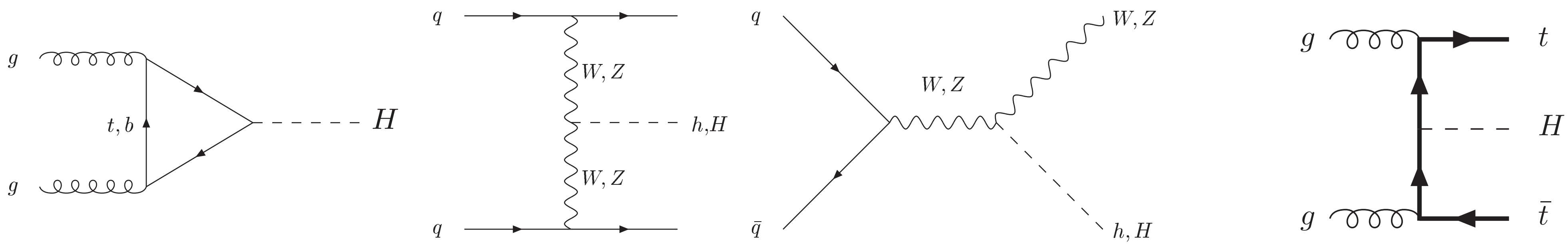


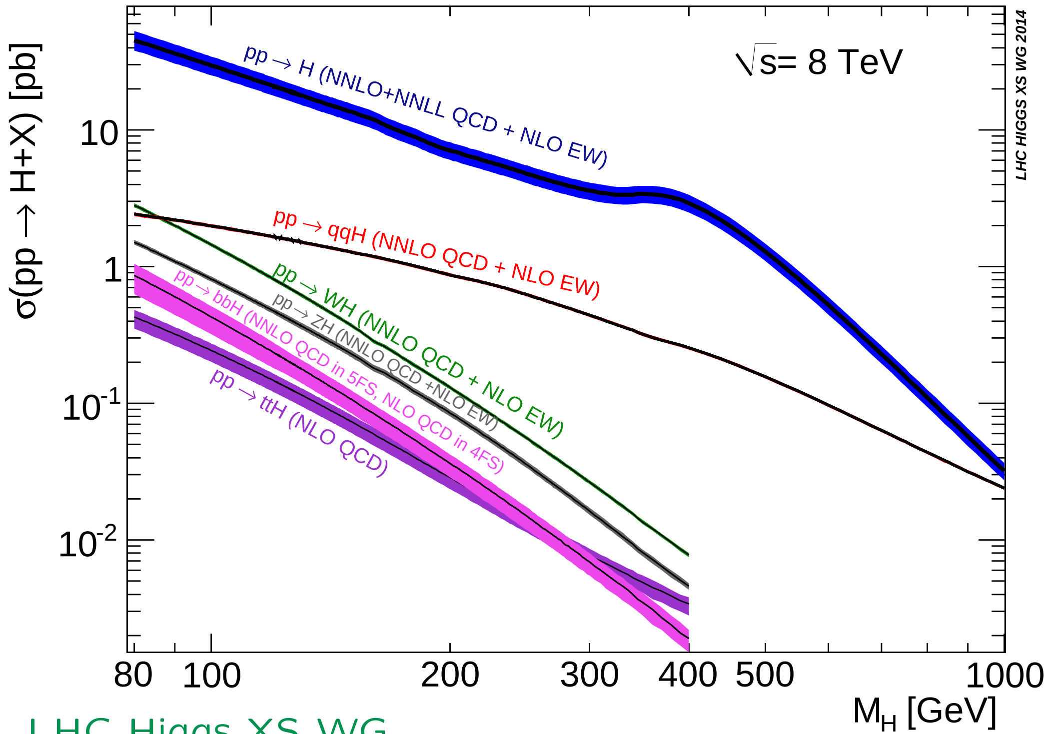




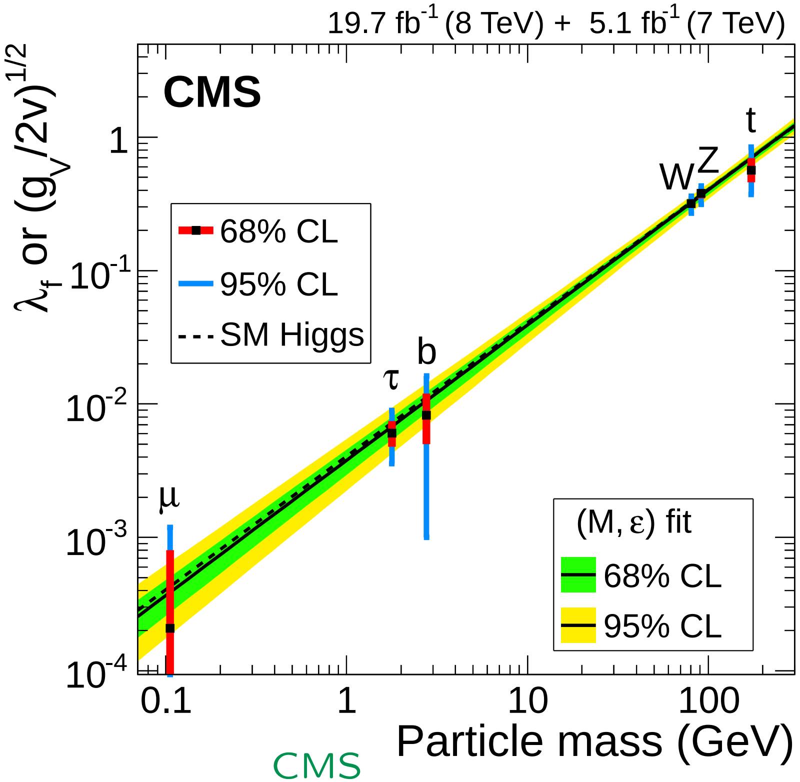


• Higgs Boson Production





LHC Higgs XS WG



CMS

• modifications: (i) higher-dim. operators → eff. Lagrangians
(ii) extended Higgs sectors (mixing, loop effects)

(ii) MSSM

- 2 Higgs doubletts $\stackrel{\text{ESB}}{\longrightarrow}$ 5 Higgs bosons: $h, H, A, H^\pm$

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

- radiative corrections $\propto m_t^4 \log \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}$ $\longrightarrow$ $\boxed{M_h \lesssim 135 \text{ GeV}}$

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

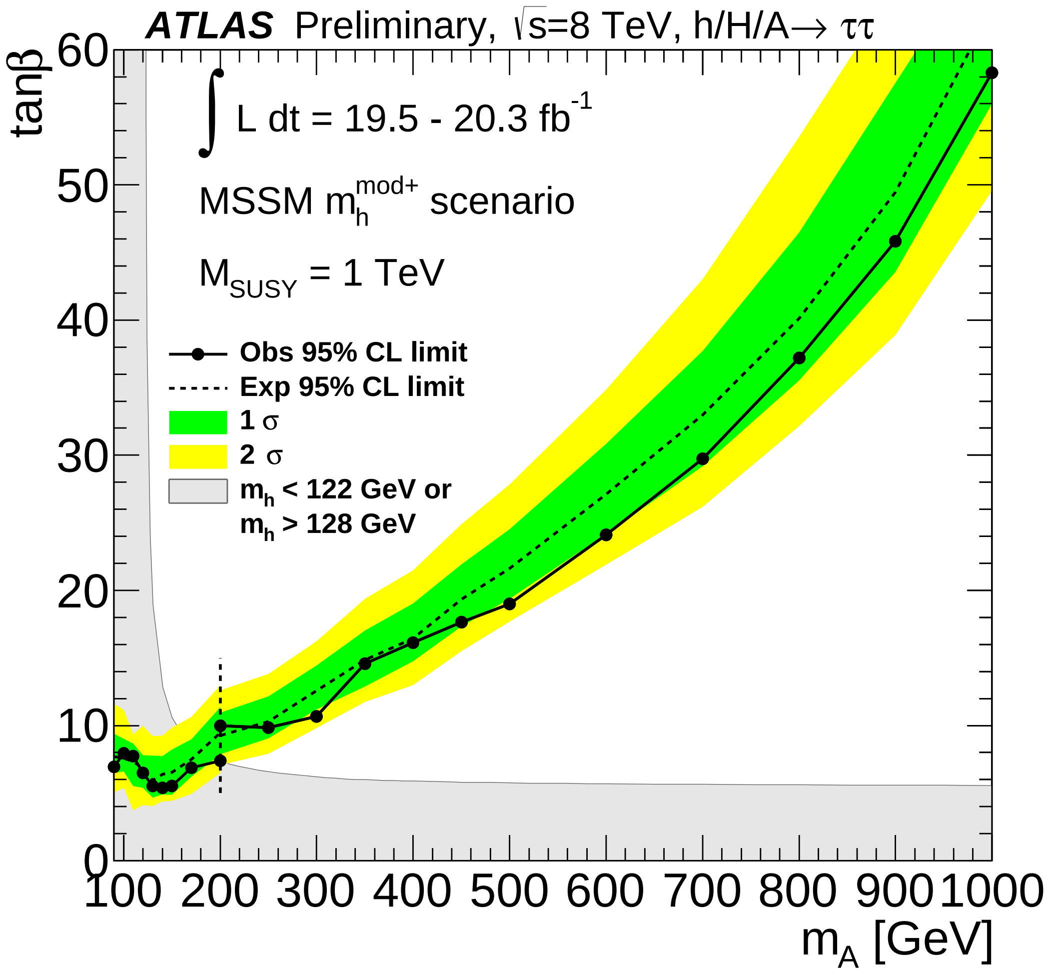
- Yukawa couplings: tg$\beta\uparrow$ $\Rightarrow$ $g_u^\phi\downarrow$ $g_d^\phi\uparrow$ $g_V^\phi\downarrow$

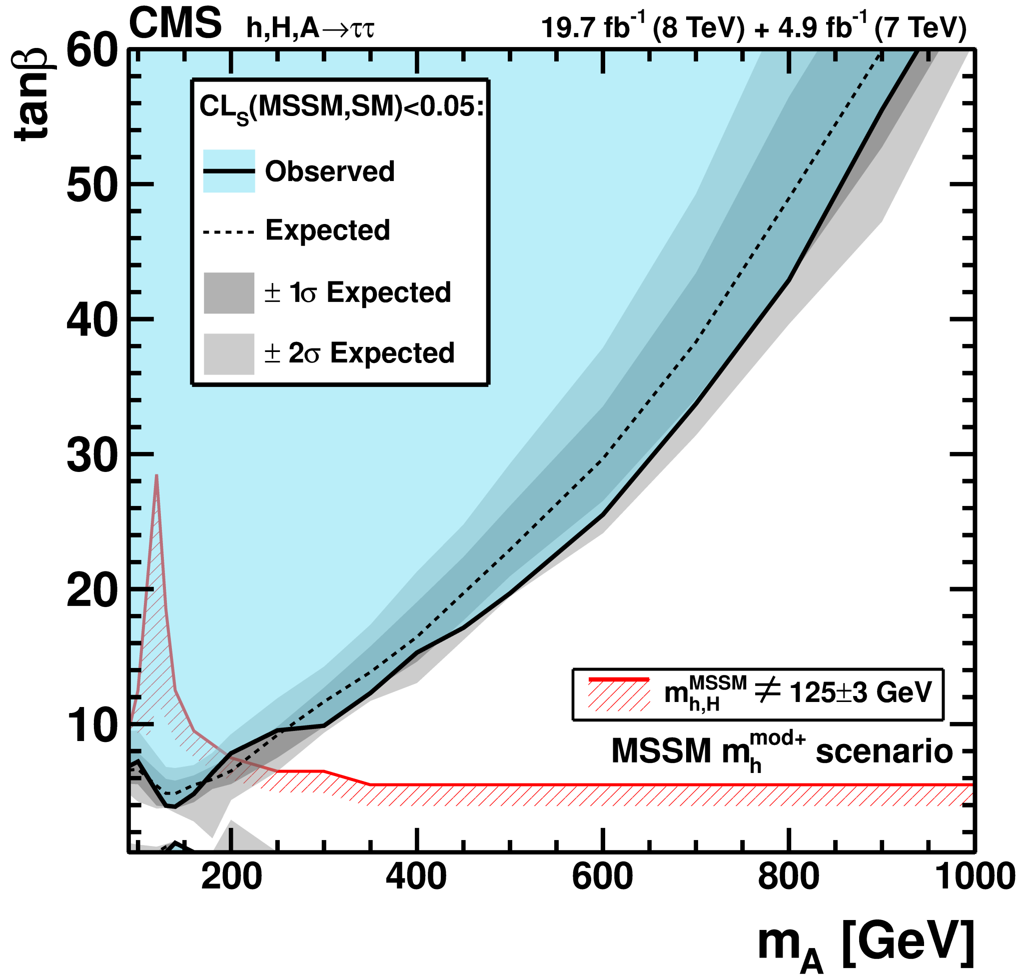
- LHC: $gg \to \phi$ dominant for tg$\beta \lesssim 10$
  $gg \to \phi b\bar{b}$ dominant for tg$\beta \gtrsim 10$

- [NMSSM: additional Higgs singlet $\to$ 7 Higgs bosons]

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

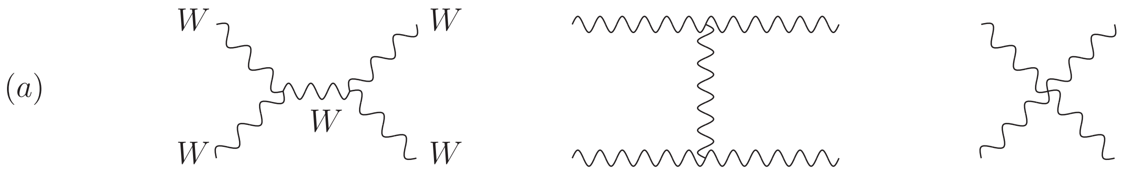
↓ ↓

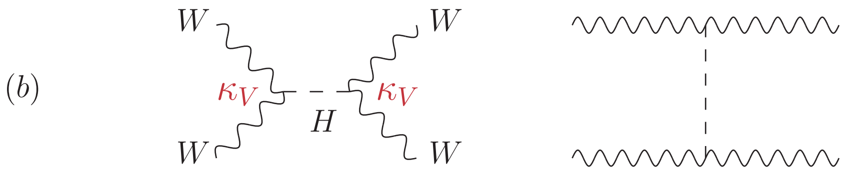




(iii) HEFT

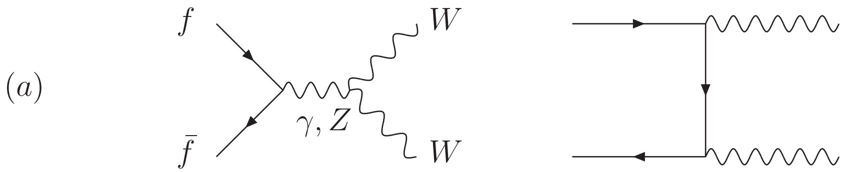
- $WW \to WW$ @ high energies

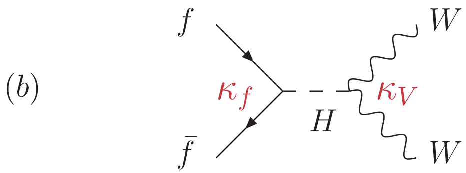




$$\mathcal{A} = \frac{s}{v^2}\left\{1 - \frac{\kappa_V^2 s}{s - M_H^2}\right\} \quad \Rightarrow \quad \kappa_V = 1$$

- $f\bar{f} \to WW$ @ high energies





$$\mathcal{A} = \frac{m_f\sqrt{s}}{v^2}\left\{1 - \frac{\kappa_f\kappa_V s}{s - M_H^2}\right\} \quad \Rightarrow \quad \kappa_f = \kappa_V = 1$$

- analogous for κ_H

weakly interacting theories

- effective higher dimension operators up to dim 6

Buchmüller, Wyler
Grzadkowski, Iskrzynski, Misiak, Rosiek
Giudice, Grojean, Pomarol, Rattazzi

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum_i \alpha_i O_i \\ &\equiv \mathcal{L}_{SM} + \sum_i \bar{c}_i O_i \\ &\equiv \mathcal{L}_{SM} + \Delta\mathcal{L}_{SILH} + \Delta\mathcal{L}_{F_1} + \Delta\mathcal{L}_{F_2} + \Delta\mathcal{L}_{bos} + \Delta\mathcal{L}_{4f} + \Delta\mathcal{L}_{\mathcal{CP}}\end{aligned}$$

[assume Λ large]

- assume Higgs $SU(2)$-doublet

$$H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

$$
\begin{aligned}
\Delta\mathcal{L}_{SILH} \;=\;& \frac{\bar{c}_H}{2v^2}\,\partial^\mu\Big(H^\dagger H\Big)\,\partial_\mu\Big(H^\dagger H\Big) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\Big(H^\dagger \overleftrightarrow{D}_\mu H\Big) - \frac{\bar{c}_6\,\lambda}{v^2}\Big(H^\dagger H\Big)^3 \\
& + \left(\frac{\bar{c}_u}{v^2}\,y_u\,H^\dagger H\,\bar{q}_L H^c u_R + \frac{\bar{c}_d}{v^2}\,y_d\,H^\dagger H\,\bar{q}_L H d_R + \frac{\bar{c}_l}{v^2}\,y_l\,H^\dagger H\,\bar{L}_L H l_R + h.c.\right) \\
& + \frac{i\bar{c}_W\,g}{2m_W^2}\left(H^\dagger\sigma^i\overleftrightarrow{D^\mu} H\right)(D^\nu W_{\mu\nu})^i + \frac{i\bar{c}_B\,g'}{2m_W^2}\left(H^\dagger\overleftrightarrow{D^\mu} H\right)(\partial^\nu B_{\mu\nu}) \\
& + \frac{i\bar{c}_{HW}\,g}{m_W^2}\,(D^\mu H)^\dagger\sigma^i(D^\nu H)W^i_{\mu\nu} + \frac{i\bar{c}_{HB}\,g'}{m_W^2}\,(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu} \\
& + \frac{\bar{c}_\gamma\,{g'}^2}{m_W^2}\,H^\dagger H B_{\mu\nu}B^{\mu\nu} + \frac{\bar{c}_g\,g_S^2}{m_W^2}\,H^\dagger H G^a_{\mu\nu}G^{a\mu\nu} \\
\Delta\mathcal{L}_{F_1} \;=\;& \frac{i\bar{c}_{Hq}}{v^2}\,(\bar{q}_L\gamma^\mu q_L)\Big(H^\dagger\overleftrightarrow{D}_\mu H\Big) + \frac{i\bar{c}'_{Hq}}{v^2}\Big(\bar{q}_L\gamma^\mu\sigma^i q_L\Big)\Big(H^\dagger\sigma^i\overleftrightarrow{D}_\mu H\Big) \\
& + \frac{i\bar{c}_{Hu}}{v^2}\,(\bar{u}_R\gamma^\mu u_R)\Big(H^\dagger\overleftrightarrow{D}_\mu H\Big) + \frac{i\bar{c}_{Hd}}{v^2}\Big(\bar{d}_R\gamma^\mu d_R\Big)\Big(H^\dagger\overleftrightarrow{D}_\mu H\Big) \\
& + \left(\frac{i\bar{c}_{Hud}}{v^2}\,(\bar{u}_R\gamma^\mu d_R)\Big(H^{c\,\dagger}\overleftrightarrow{D}_\mu H\Big) + h.c.\right) \\
& + \frac{i\bar{c}_{HL}}{v^2}\Big(\bar{L}_L\gamma^\mu L_L\Big)\Big(H^\dagger\overleftrightarrow{D}_\mu H\Big) + \frac{i\bar{c}'_{HL}}{v^2}\Big(\bar{L}_L\gamma^\mu\sigma^i L_L\Big)\Big(H^\dagger\sigma^i\overleftrightarrow{D}_\mu H\Big) \\
& + \frac{i\bar{c}_{Hl}}{v^2}\Big(\bar{l}_R\gamma^\mu l_R\Big)\Big(H^\dagger\overleftrightarrow{D}_\mu H\Big) \\
\Delta\mathcal{L}_{F_2} \;=\;& \frac{\bar{c}_{uB}\,g'}{m_W^2}\,y_u\,\bar{q}_L H^c\sigma^{\mu\nu}u_R\,B_{\mu\nu} + \frac{\bar{c}_{uW}\,g}{m_W^2}\,y_u\,\bar{q}_L\sigma^i H^c\sigma^{\mu\nu}u_R\,W^i_{\mu\nu} + \frac{\bar{c}_{uG}\,g_S}{m_W^2}\,y_u\,\bar{q}_L H^c\sigma^{\mu\nu}\lambda^a u_R\,G^a_{\mu\nu} \\
& + \frac{\bar{c}_{dB}\,g'}{m_W^2}\,y_d\,\bar{q}_L H\sigma^{\mu\nu}d_R\,B_{\mu\nu} + \frac{\bar{c}_{dW}\,g}{m_W^2}\,y_d\,\bar{q}_L\sigma^i H\sigma^{\mu\nu}d_R\,W^i_{\mu\nu} + \frac{\bar{c}_{dG}\,g_S}{m_W^2}\,y_d\,\bar{q}_L H\sigma^{\mu\nu}\lambda^a d_R\,G^a_{\mu\nu} \\
& + \frac{\bar{c}_{lB}\,g'}{m_W^2}\,y_l\,\bar{L}_L H\sigma^{\mu\nu}l_R\,B_{\mu\nu} + \frac{\bar{c}_{lW}\,g}{m_W^2}\,y_l\,\bar{L}_L\sigma^i H\sigma^{\mu\nu}l_R\,W^i_{\mu\nu} + h.c.
\end{aligned}
$$

$$\begin{aligned}
\Delta\mathcal{L}_{bos} &= \frac{\bar{c}_{3W}\, g^3}{m_W^2}\,\epsilon^{ijk}W_\mu^{i\,\nu}W_\nu^{j\,\rho}W_\rho^{k\,\mu} + \frac{\bar{c}_{3G}\, g_S^3}{m_W^2}\, f^{abc}G_\mu^{a\,\nu}G_\nu^{b\,\rho}G_\rho^{c\,\mu} \\
&+ \frac{\bar{c}_{2W}}{m_W^2}\,(D^\mu W_{\mu\nu})^i\,(D_\rho W^{\rho\nu})^i + \frac{\bar{c}_{2B}}{m_W^2}\,(\partial^\mu B_{\mu\nu})\,(\partial_\rho B^{\rho\nu}) + \frac{\bar{c}_{2G}}{m_W^2}\,(D^\mu G_{\mu\nu})^a\,(D_\rho G^{\rho\nu})^a \\
\Delta\mathcal{L}_{4f} &= \sum_{\psi,L/R,T^a} \bar{\psi}_i\gamma^\mu T^a\psi_j\bar{\psi}_k\gamma_\mu T^a\psi_l + \bar{\psi}_i T^a\psi_j\bar{\psi}_k T^a\psi_l \\
\Delta\mathcal{L}_{\mathcal{CP}} &= \frac{i\tilde{c}_{HW}\, g}{m_W^2}\,(D^\mu H)^\dagger\sigma^i(D^\nu H)\tilde{W}_{\mu\nu}^i + \frac{i\tilde{c}_{HB}\, g'}{m_W^2}\,(D^\mu H)^\dagger(D^\nu H)\tilde{B}_{\mu\nu} \\
&\quad + \frac{\tilde{c}_\gamma\, g'^2}{m_W^2}\, H^\dagger H B_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{\tilde{c}_g\, g_S^2}{m_W^2}\, H^\dagger H G_{\mu\nu}^a\tilde{G}^{a\mu\nu} \\
&\quad + \frac{\tilde{c}_{3W}\, g^3}{m_W^2}\,\epsilon^{ijk}W_\mu^{i\,\nu}W_\nu^{j\,\rho}\tilde{W}_\rho^{k\,\mu} + \frac{\tilde{c}_{3G}\, g_S^3}{m_W^2}\, f^{abc}G_\mu^{a\,\nu}G_\nu^{b\,\rho}\tilde{G}_\rho^{c\,\mu}
\end{aligned}$$

$$\tilde{V}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\alpha\beta}V^{\alpha\beta}$$

- after using EOM: 53 (59) independent dim6 operators

- power counting: $H \to \mathcal{O}(g_*/M = 1/f)$, $\partial_\mu \to \mathcal{O}(1/M)$

$\Rightarrow$ expansion in H/f and E/M

$$\bar{c}_H, \bar{c}_T, \bar{c}_6, \bar{c}_\psi \sim O\left(\frac{v^2}{f^2}\right), \quad \bar{c}_W, \bar{c}_B \sim O\left(\frac{m_W^2}{M^2}\right), \quad \bar{c}_{HW}, \bar{c}_{HB}, \bar{c}_\gamma, \bar{c}_g \sim O\left(\frac{m_W^2}{16\pi^2 f^2}\right)$$

$$\bar{c}_{H\psi}, \bar{c}'_{H\psi} \sim O\left(\frac{\lambda_\psi^2}{g_*^2}\frac{v^2}{f^2}\right), \quad \bar{c}_{Hud} \sim O\left(\frac{\lambda_u \lambda_d}{g_*^2}\frac{v^2}{f^2}\right), \quad \bar{c}_{\psi W}, \bar{c}_{\psi B}, \bar{c}_{\psi G} \sim O\left(\frac{m_W^2}{16\pi^2 f^2}\right)$$

Giudice, Grojean, Pomarol, Rattazzi

- canonical normalization, unitary gauge:

$$\begin{aligned} v^2 &= v_{SM}^2\left(1 + \frac{3}{4}\bar{c}_6\right) \\ h_{SM} &= h\left[1 - \frac{\bar{c}_H}{2} - \frac{\bar{c}_T}{8}\right] - \frac{3}{8}\bar{c}_6 v \\ m_h^2 &= m_{h_{SM}}^2\left[1 - \bar{c}_H + \frac{3}{2}\bar{c}_6 - \frac{1}{2}\bar{c}_T\right] \end{aligned}$$

etc.

$$\mathcal{L} = \frac{1}{2}\partial_\mu h\, \partial^\mu h - \frac{1}{2}m_h^2 h^2 - c_3 \frac{1}{6}\left(\frac{3m_h^2}{v}\right) h^3 - \sum_{\psi=u,d,l} m_{\psi^{(i)}}\, \bar{\psi}^{(i)}\psi^{(i)} \left(1 + c_\psi \frac{h}{v} + \ldots\right)$$
$$+ m_W^2\, W_\mu W^\mu \left(1 + 2c_W \frac{h}{v} + \ldots\right) + \frac{1}{2}m_Z^2\, Z_\mu Z^\mu \left(1 + 2c_Z \frac{h}{v} + \ldots\right) + \ldots$$
$$+ \left(c_{WW}\, W^+_{\mu\nu}W^{-\mu\nu} + \frac{c_{ZZ}}{2}\, Z_{\mu\nu}Z^{\mu\nu} + c_{Z\gamma}\, Z_{\mu\nu}\gamma^{\mu\nu} + \frac{c_{\gamma\gamma}}{2}\,\gamma_{\mu\nu}\gamma^{\mu\nu} + \frac{c_{gg}}{2}\, G^a_{\mu\nu}G^{a\mu\nu}\right)\frac{h}{v}$$
$$+ \left(c_{W\partial W}\left(W^-_\nu D_\mu W^{+\mu\nu} + h.c.\right) + c_{Z\partial Z}\, Z_\nu \partial_\mu Z^{\mu\nu} + c_{Z\partial\gamma}\, Z_\nu \partial_\mu \gamma^{\mu\nu}\right)\frac{h}{v} + \ldots$$

Higgs couplings	$\Delta\mathcal{L}_{SILH}$	MCHM4	MCHM5
c_W	$1 - \bar{c}_H/2$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$
c_Z	$1 - \bar{c}_H/2 - 2\bar{c}_T$	$\sqrt{1-\xi}$	$\sqrt{1-\xi}$
$c_\psi \quad (\psi = u,d,l)$	$1 - (\bar{c}_H/2 + \bar{c}_\psi)$	$\sqrt{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$
c_3	$1 + \bar{c}_6 - 3\bar{c}_H/2$	$\sqrt{1-\xi}$	$\frac{1-2\xi}{\sqrt{1-\xi}}$
c_{gg}	$8\,(\alpha_s/\alpha_2)\,\bar{c}_g$	0	0
$c_{\gamma\gamma}$	$8\sin^2\theta_W\,\bar{c}_\gamma$	0	0
$c_{Z\gamma}$	$\left(\bar{c}_{HB} - \bar{c}_{HW} - 8\,\bar{c}_\gamma \sin^2\theta_W\right)\tan\theta_W$	0	0
c_{WW}	$-2\,\bar{c}_{HW}$	0	0
c_{ZZ}	$-2\left(\bar{c}_{HW} + \bar{c}_{HB}\tan^2\theta_W - 4\bar{c}_\gamma \tan^2\theta_W \sin^2\theta_W\right)$	0	0
$c_{W\partial W}$	$-2(\bar{c}_W + \bar{c}_{HW})$	0	0
$c_{Z\partial Z}$	$-2(\bar{c}_W + \bar{c}_{HW}) - 2\,(\bar{c}_B + \bar{c}_{HB})\tan^2\theta_W$	0	0
$c_{Z\partial\gamma}$	$2\,(\bar{c}_B + \bar{c}_{HB} - \bar{c}_W - \bar{c}_{HW})\tan\theta_W$	0	0

Contino, Ghezzi, Grojean, Mühlleitner, S.

strongly interacting theories

$$\mathcal{L} = \frac{1}{2}\partial_\mu h\ \partial^\mu h - \frac{1}{2}m_h^2 h^2 - c_3\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 - \sum_{\psi=u,d,l} m_{\psi^{(i)}}\,\bar{\psi}^{(i)}\psi^{(i)}\left(1 + c_\psi\frac{h}{v} + \dots\right)$$
$$+m_W^2\,W_\mu W^\mu\left(1 + 2c_W\frac{h}{v} + \dots\right) + \frac{1}{2}m_Z^2\,Z_\mu Z^\mu\left(1 + 2c_Z\frac{h}{v} + \dots\right) + \dots$$
$$+\left(c_{WW}\,W^+_{\mu\nu}W^{-\mu\nu} + \frac{c_{ZZ}}{2}Z_{\mu\nu}Z^{\mu\nu} + c_{Z\gamma}\,Z_{\mu\nu}\gamma^{\mu\nu} + \frac{c_{\gamma\gamma}}{2}\gamma_{\mu\nu}\gamma^{\mu\nu} + \frac{c_{gg}}{2}G^a_{\mu\nu}G^{a\mu\nu}\right)\frac{h}{v}$$
$$+\left(c_{W\partial W}\left(W^-_\nu D_\mu W^{+\mu\nu} + h.c.\right) + c_{Z\partial Z}\,Z_\nu\partial_\mu Z^{\mu\nu} + c_{Z\partial\gamma}\,Z_\nu\partial_\mu\gamma^{\mu\nu}\right)\frac{h}{v} + \dots$$

- also valid in case of a non-linear Lagrangian for a light Higgs-like scalar [h generic $\mathcal{CP}$-even scalar]

$\Rightarrow$ expansion in E/M (derivatives) only, large deviations from SM couplings

> SILH: expansion in $v^2/f^2, E^2/M^2, \alpha_s/\pi, \alpha/\pi$
>
> non-lin.: expansion in $E^2/M^2, \alpha_s/\pi$

$\mathcal{eHDECAY}$ http://www.itp.kit.edu/~maggie/eHDECAY/

- $h \to f\bar{f}$:

$$\Gamma(\bar\psi\psi)\big|_{SILH} = \Gamma_0^{SM}(\bar\psi\psi)\left[1 - \bar{c}_H - 2\bar{c}_\psi + \frac{2}{|A_0^{SM}|^2}\mathrm{Re}\left(A_0^{*SM} A_{1,ew}^{SM}\right)\right]\left[1 + \delta_\psi\,\kappa^{QCD}\right] + \mathcal{O}\left(\frac{v^4}{f^4}, \frac{v^2\alpha}{f^2\pi}, \frac{\alpha^2}{\pi^2}\right)$$

$$\Gamma(\bar\psi\psi)\big|_{NL} = c_\psi^2\,\Gamma_0^{SM}(\bar\psi\psi)\left[1 + \delta_\psi\,\kappa^{QCD}\right] + \mathcal{O}\left(\frac{m_h^2}{M^2}, \frac{\alpha}{\pi}\right)$$

A_0^{SM}: SM tree-level amplitude
$A_{1,ew}^{SM}$: SM elw. amplitude [real corrections treated analogously]

- factorization of QCD $\leftrightarrow$ elw. [limit small m_h]

- NL: no elw. corrections!

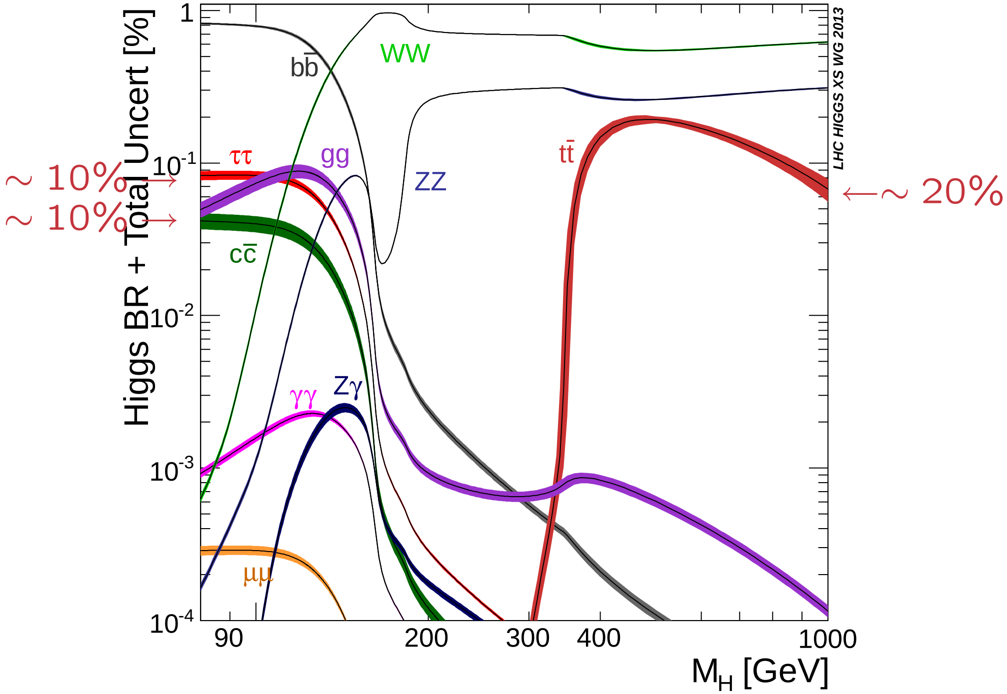
Partial Width	QCD	Electroweak	Total	
$H \to b\bar{b}/c\bar{c}$	$\sim 0.1\%$	~ 1–2% for $M_H \lesssim 135$GeV	$\sim 2\%$	NNNNLO / NLO
$H \to \tau^+\tau^-/\mu^+\mu^-$		~ 1–2% for $M_H \lesssim 135$GeV	$\sim 2\%$	NLO
$H \to t\bar{t}$	$\lesssim 5\%$	$\lesssim 2$–5% for $M_H < 500$GeV	$\sim 5\%$	(NNN)NLO / LO
		$\sim 0.1(\frac{M_H}{1\text{TeV}})^4$ for $M_H > 500$GeV	~ 5–10%	
$H \to gg$	$\sim 3\%$	$\sim 1\%$	$\sim 3\%$	NNNLO approx. / NLO
$H \to \gamma\gamma$	$< 1\%$	$< 1\%$	$\sim 1\%$	NLO / NLO
$H \to Z\gamma$	$< 1\%$	$\sim 5\%$	$\sim 5\%$	(N)LO / LO
$H \to WW/ZZ \to 4f$	$< 0.5\%$	$\sim 0.5\%$ for $M_H < 500$GeV	$\sim 0.5\%$	(N)NLO
		$\sim 0.17(\frac{M_H}{1\text{TeV}})^4$ for $M_H > 500$GeV	~ 0.5–15%	

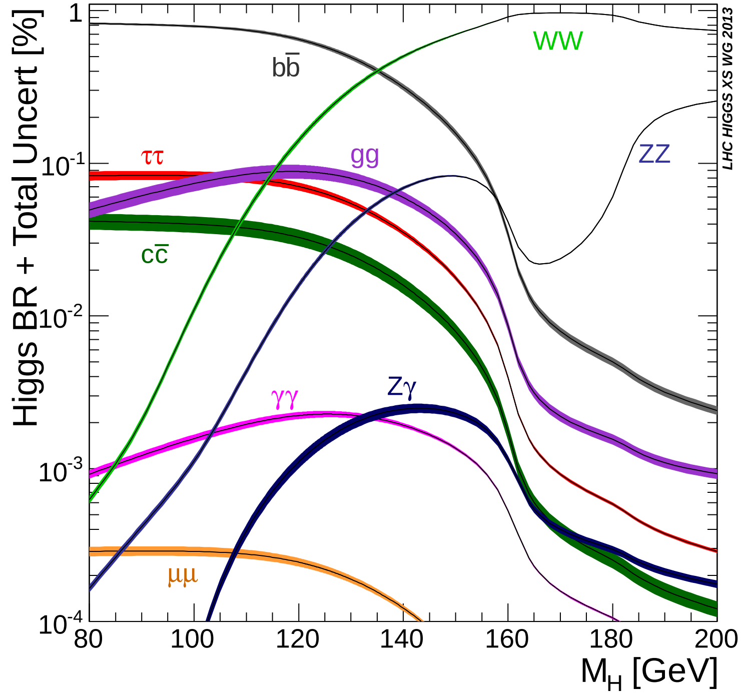
- QCD: variation of Higgs widths for scale by factor 2 and 1/2
  elw: missing HO estimated from known structure at NLO
  $M_H \gtrsim 500$ GeV: Higgs self-interactions dominate error
  different uncertainties added linearly for each channel

- parametric uncertainties:
  $m_t = 172.5 \pm 2.5$ GeV $\qquad \alpha_s(M_Z) = 0.119 \pm 0.002$
  $m_b(m_b) = 4.16 \pm 0.06$ GeV $\qquad m_c(m_c) = 1.28 \pm 0.03$ GeV
  different uncertainties added quadratically for each channel

- total uncertainties: parametric & theor. uncertainties added linearly

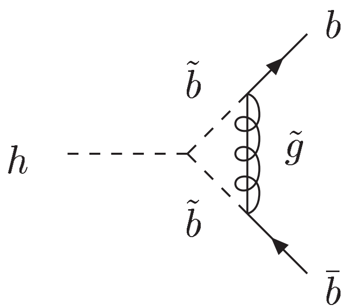
HDECAY & Prophecy4f





Denner, Heinemeyer, Puljak, Rebuzzi, S.

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



$$\propto \frac{\alpha_s}{\pi}\, \frac{m_{\tilde g}\mu \mathrm{tg}\beta}{M^2_{SUSY}} \sim \Delta_b$$

Hall,. . .
Carena,. . .
Nierste,. . .
Häfliger,. . .
Noth, S.
Mihaila, Reisser
etc.

SUSY-QCD Corrections to $b\bar{b}\phi^0$ $[\Delta \lesssim 1\%]$

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

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

$$\left. + g_b^H\left(1 + \Delta_b \frac{\text{tg}\alpha}{\text{tg}\beta}\right) H - g_b^A\left(1 - \frac{\Delta_b}{\text{tg}^2\beta}\right) i\gamma_5 A\right] b$$

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

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

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

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

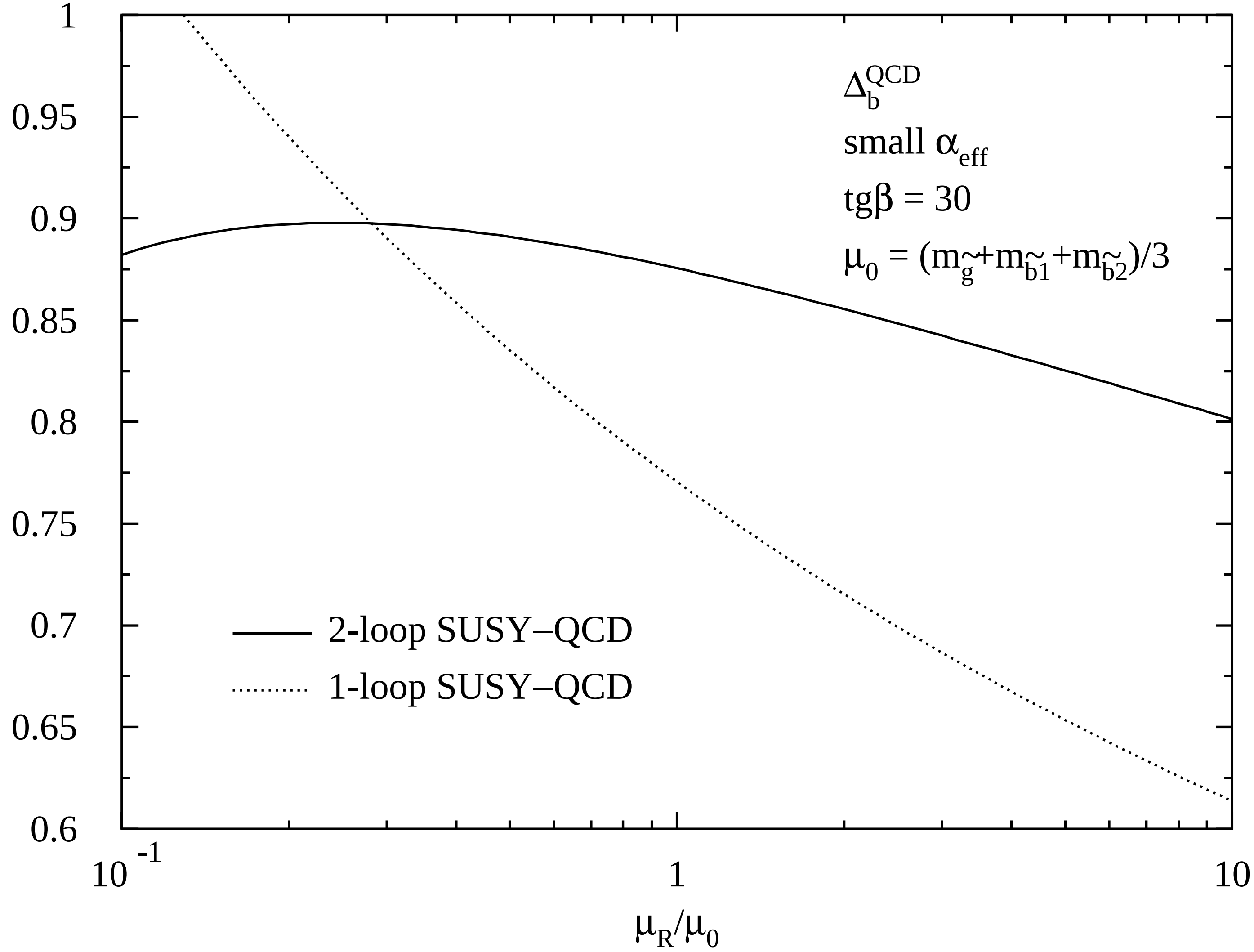
Carena, Garcia, Nierste, Wagner
Guasch, Häfliger, S.

$\Rightarrow$ resummed Yukawa couplings $\tilde{g}_b^\Phi$
[analogous for NMSSM]

small α_{eff} scenario [modified]

$$
\begin{aligned}
\text{tg}\beta &= 30 \\
M_{\tilde{Q}} &= 800 \text{ GeV} \\
M_{\tilde{g}} &= 1000 \text{ GeV} \qquad \longleftarrow \\
M_2 &= 500 \text{ GeV} \\
A_b = A_t &= -1.133 \text{ TeV} \\
\mu &= 2 \text{ TeV}
\end{aligned}
$$

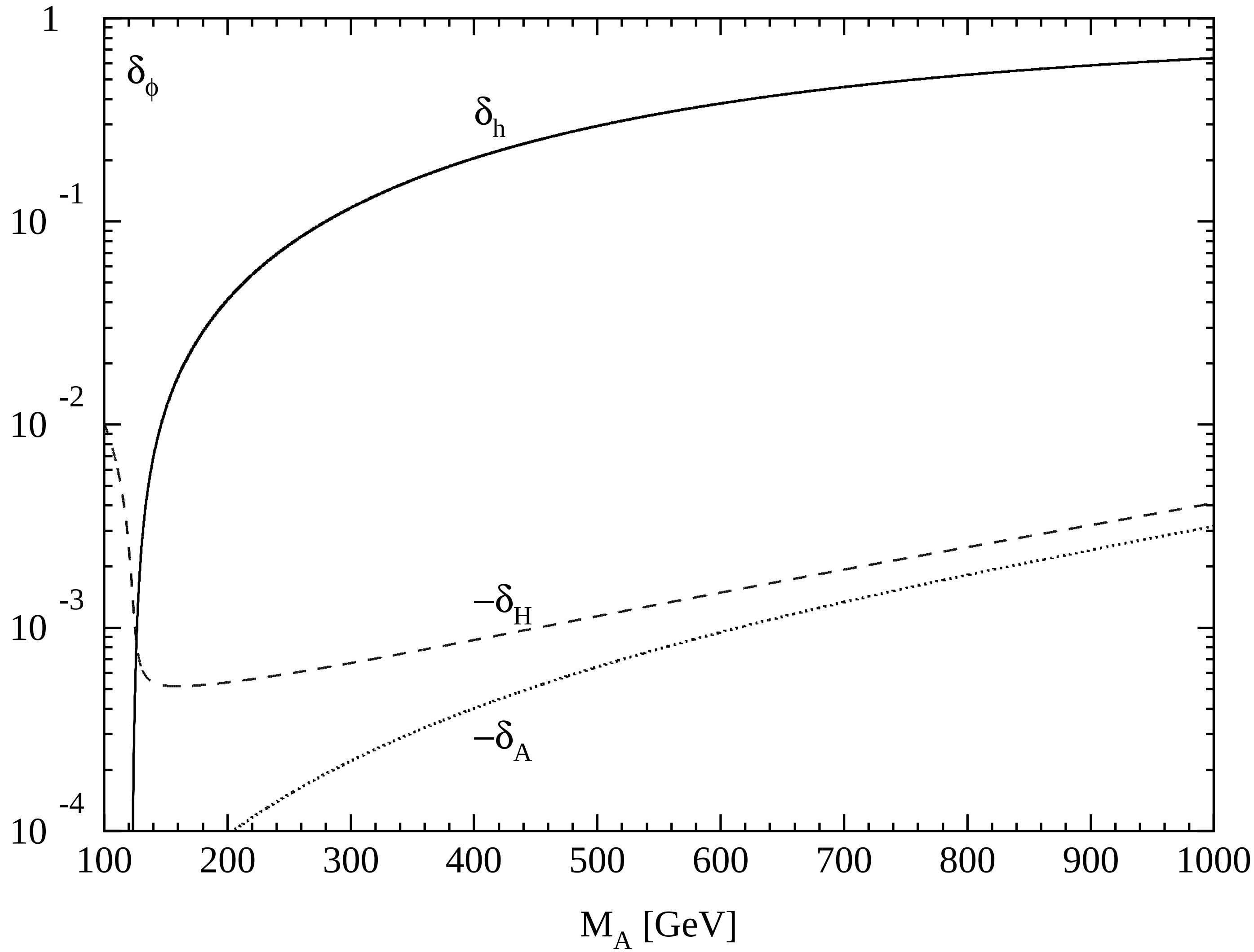
$$
\begin{aligned}
m_{\tilde{t}_1} &= 679 \text{ GeV} \qquad & m_{\tilde{t}_2} = 935 \text{ GeV} \\
m_{\tilde{b}_1} &= 601 \text{ GeV} \qquad & m_{\tilde{b}_2} = 961 \text{ GeV}
\end{aligned}
$$



Noth, S.
(Mihaila, Reisser)

$$\Gamma[\Phi \to b\bar{b}] = \frac{3G_F M_\Phi}{4\sqrt{2}\pi}\overline{m}_b^2(M_\Phi)\ \Delta_{\rm QCD}\ \tilde{g}_b^{\Phi 2}\,[1 + \delta_\Phi]$$

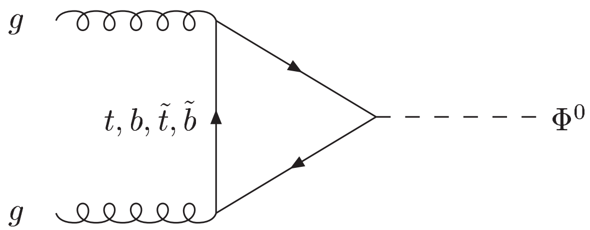
$$M_A^2 \gg M_Z^2 : \text{tg}\alpha \to -\frac{1}{\text{tg}\beta} \quad \Rightarrow \quad \tilde{g}_b^h \to \frac{1}{1+\Delta_b}\left(1 - \frac{\Delta_b}{\text{tg}\alpha\ \text{tg}\beta}\right) \to 1$$



Guasch, Häfliger, S.

II *HIGGS BOSON PRODUCTION*

(i) $gg \to h/H/A$



Georgi,...

Gamberini,...

S., Djouadi, Graudenz, Zerwas
Dawson, Kauffman

• NLO QCD corrections: $\sim 10 \ldots 100\%$

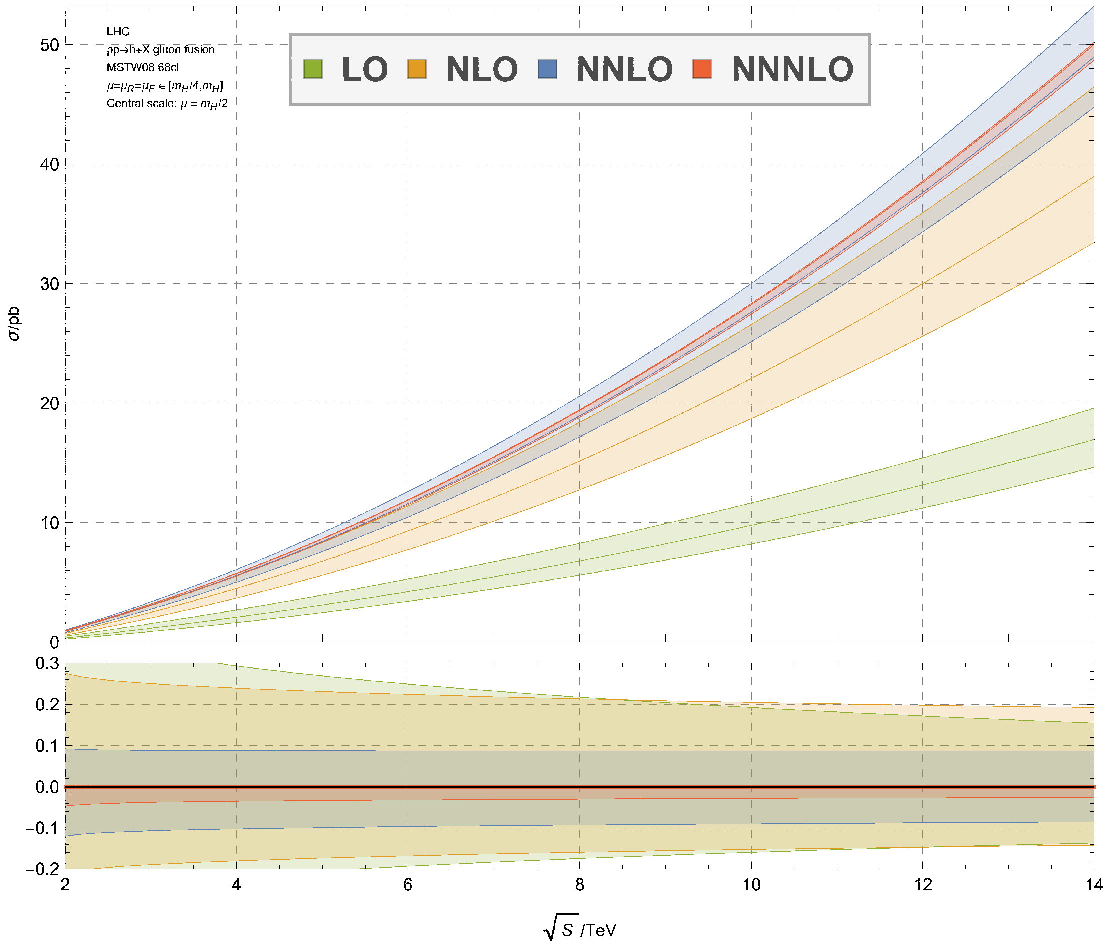
• NNLO calculated for $m_t \gg M_\phi \Rightarrow$ further increase by 20–30%
[mass effects small]

Harlander, Kilgore
Anastasiou, Melnikov
Ravindran, Smith, van Neerven

Marzani, Ball, Del Duca, Forte, Vicini
Harlander, Ozeren
Pak, Rogal, Steinhauser

• N^{3}LO for $m_t \gg M_\phi$ $\Rightarrow$ scale stabilization
scale dependence: $\Delta \lesssim 5\%$

Moch, Vogt
Ravindran
de Florian, Mazzitelli, Moch, Vogt
Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Mistlberger
Ball, Bonvini, Forte, Marzani, Ridolfi
Anastasiou, Duhr, Dulat, Herzog, Mistlberger



Anastasiou, Duhr, Dulat, Herzog, Mistlberger

- N^{3}LL soft gluon resummation $[m_t \gg M_\phi]$: $\lesssim$ 5%

Catani, de Florian, Grazzini, Nason
Ravindran
Ahrens, Becher, Neubert, Yang
Ball, Bonvini, Forte, Marzani, Ridolfi
Schmidt, S.

- elw. corrections: $\sim$ 5%

Aglietti,. . .
Degrassi, Maltoni
Actis, Passarino, Sturm, Uccirati

- QCD corrections to squark loops: 10–100%

Mühlleitner, S.
Bonciani, Degrassi, Vicini

- impl. of $gg \to \phi$ in POWHEG including mass effects @ NLO

Bagnaschi, Degrassi, Slavich, Vicini

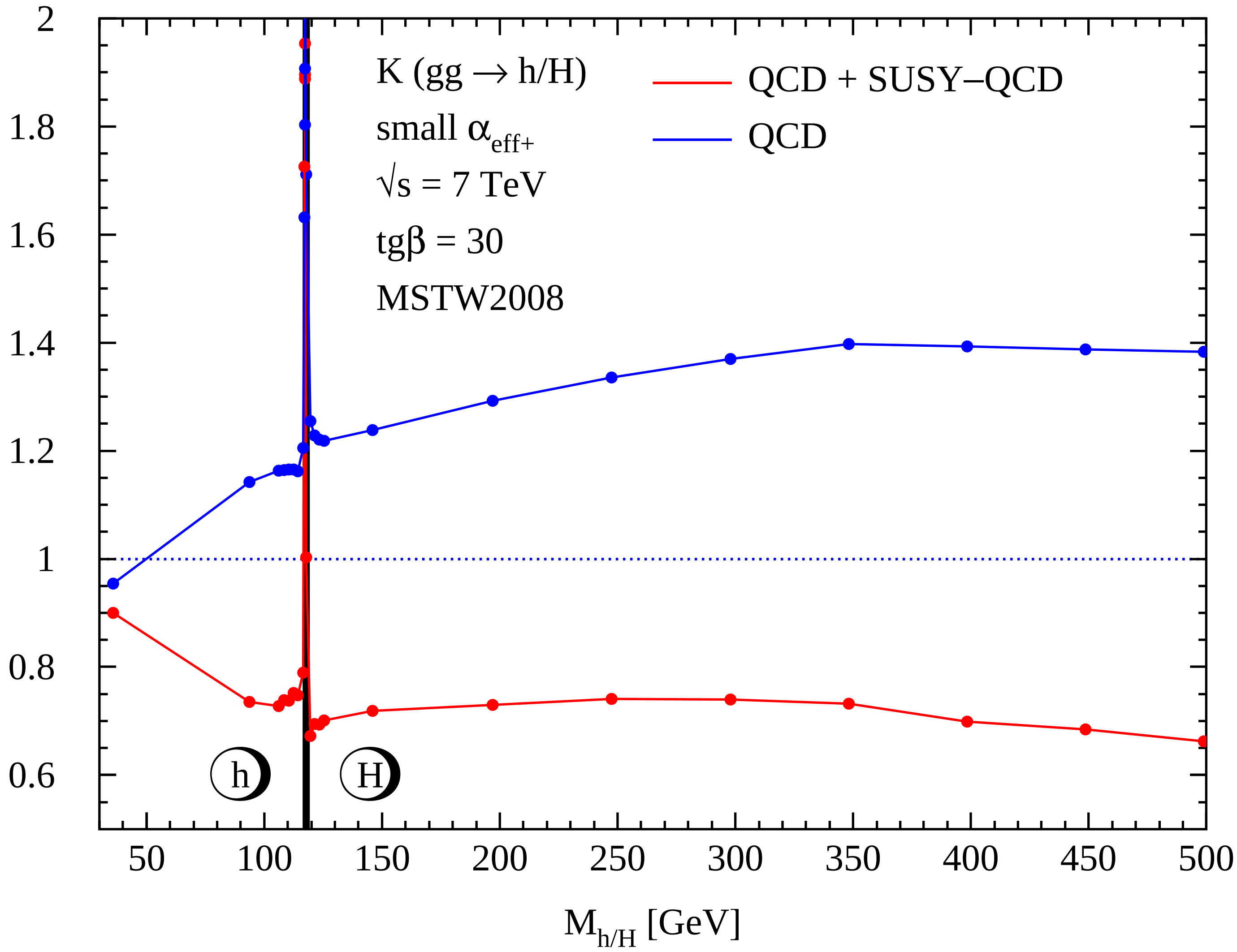
- genuine SUSY–QCD corrections: 10–100%
  [$\leftarrow \Delta_b$ @ large tgβ]

Harlander, Steinhauser, Hofmann
Degrassi, Slavich
Anastasiou, Beerli, Daleo
Mühlleitner, Rzehak, S.

- SUSY-elw. corrections unknown

$$\sigma(gg \to \Phi) = \sigma_{LO}(g_t^\Phi, \tilde{g}_b^\Phi)\left[1 + \delta_{QCD} + \delta_{SQCD}\right]$$

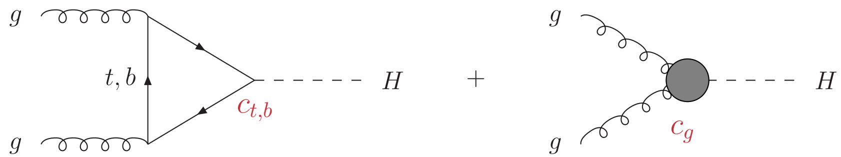
PRELIMINARY



Mühlleitner, Rzehak, S.

Dim 6

$$\mathcal{L} = \quad -\sum_{\psi=u,d,l} m_{\psi^{(i)}}\, \bar{\psi}^{(i)}\psi^{(i)} \left(1 + c_\psi \tfrac{h}{v} + \dots\right) + \tfrac{\alpha_s}{\pi}\, c_g\, G^a_{\mu\nu} G^{a\mu\nu} \tfrac{h}{v} + \dots$$



$$\sigma_{LO} \sim |c_t F_t + 12 c_g|^2 \to |c_t + 12 c_g|^2 \qquad (m_t^2 \gg M_H^2)$$

$$\begin{aligned} \mathcal{L}_{eff} &= \frac{\alpha_s}{12\pi} \{c_t(1+\delta_t) + 12 c_g\}\, G^a_{\mu\nu} G^{a\mu\nu} \frac{h}{v} \\ \delta_t &= \frac{11}{4}\frac{\alpha_s}{\pi} + \left[\frac{2777}{288} - \frac{67}{96} N_F + \left(\frac{19}{16} + \frac{N_F}{3}\right) \log \frac{\mu^2}{\overline{m}_t^2(\mu^2)}\right] \left(\frac{\alpha_s}{\pi}\right)^2 + \dots \end{aligned}$$

$$\frac{\partial c_g(\mu^2)}{\partial \log \mu^2} = \left(\alpha_s \frac{\partial}{\partial \alpha_s} \frac{\beta(\alpha_s)}{\alpha_s} - \frac{\beta(\alpha_s)}{\alpha_s}\right) c_g = -\left(\frac{\alpha_s}{\pi}\right)^2 \left(\beta_1 + 2\beta_2 \frac{\alpha_s}{\pi} + \dots\right) c_g \qquad (\leftarrow \text{trace anomaly})$$

$$\beta(\alpha_s) = -\frac{\alpha_s^2}{\pi} \left(\beta_0 + \beta_1 \frac{\alpha_s}{\pi} + \beta_2 \left(\frac{\alpha_s}{\pi}\right)^2 + \dots\right)$$

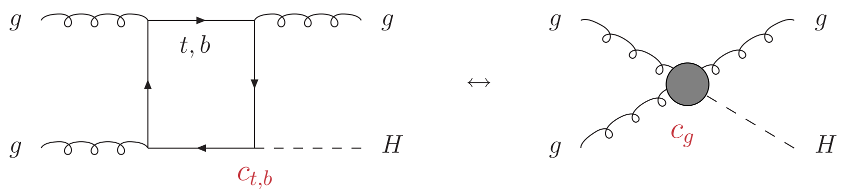
$$\beta_0 = \frac{33 - 2N_F}{12} \qquad \beta_1 = \frac{153 - 19 N_F}{24} \qquad \beta_2 = \frac{1}{128}\left[2857 - \frac{5033}{9} N_F + \frac{325}{27} N_F^2\right]$$

$\Rightarrow$ c_g renormalized @ NNLO, scale dependent @ NLL

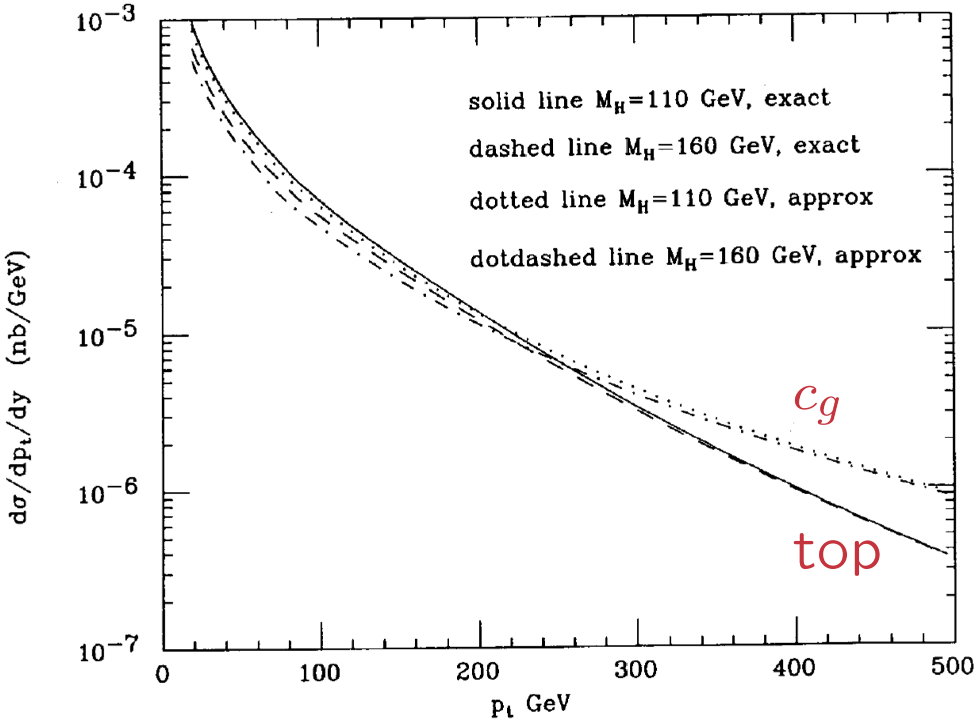
$$\Theta^\mu_\mu = [1 + \gamma_m(\alpha_s)]\, m_t \bar{t} t + \frac{\beta(\alpha_s)}{2\alpha_s} G^{a\mu\nu} G^a_{\mu\nu}$$

Higgs p_T (or how to prove that ggF is loop-mediated)

$$\mathcal{L} = \quad -\sum_{\psi=u,d,l} m_{\psi^{(i)}} \bar{\psi}^{(i)}\psi^{(i)} \left(1 + c_\psi \frac{h}{v} + \dots\right) + \frac{\alpha_s}{\pi} c_g \, G^a_{\mu\nu} G^{a\mu\nu} \frac{h}{v} + \dots$$



- distinction dim4 ↔ dim5: shape of p_T distribution

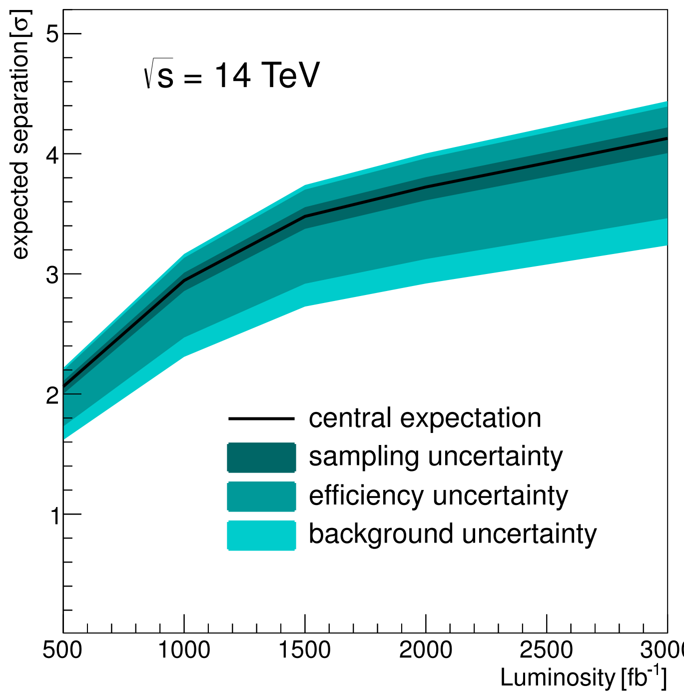


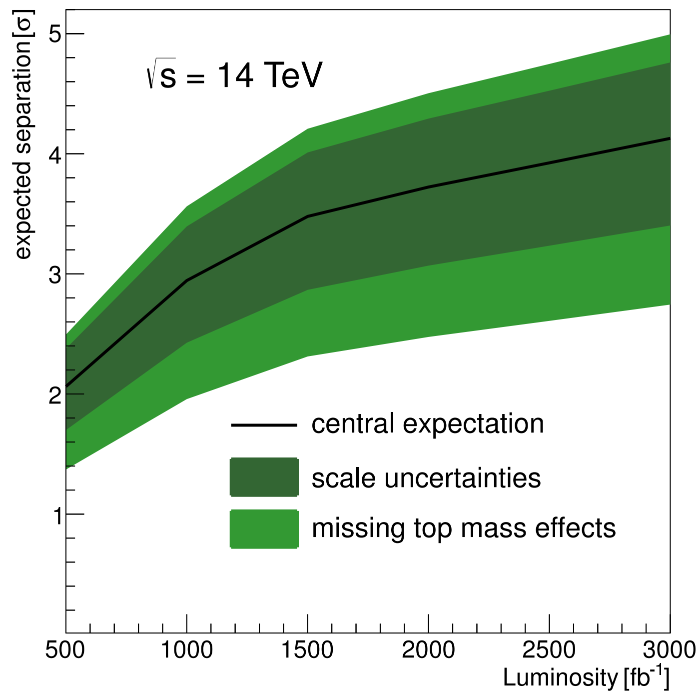
$m_t = 160$ GeV

Ellis, Hinchliffe, Soldate, van der Bij (1987!)

- QCD corrections only known for $m_t \gg M_H, p_{TH}$

Glosser, Schmidt
de Florian, Grazzini, Kunszt
Anastasiou, Melnikov, Petriello
Boughezal, Caola, Melnikov, Petriello, Schulze
Chen, Gehrmann, Glover, Jaquier
Boughezal, Focke, Giele, Liu, Petriello
Harlander, Neumann, Ozeren, Wiesemann

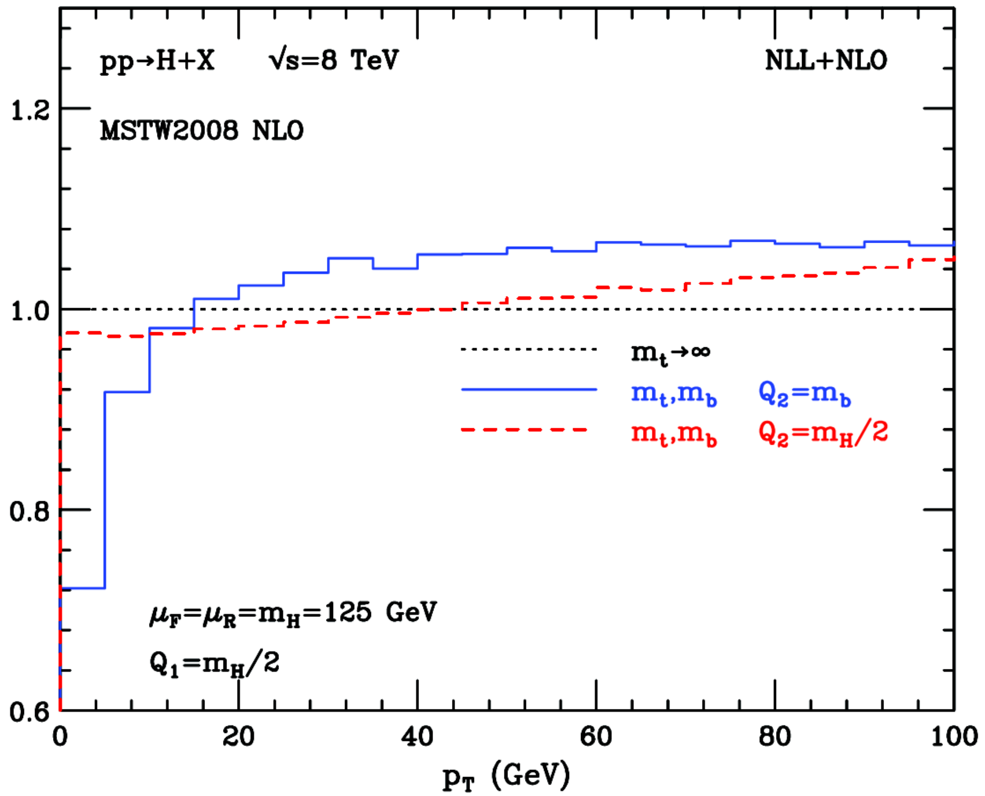




Langenegger, S., Strebel

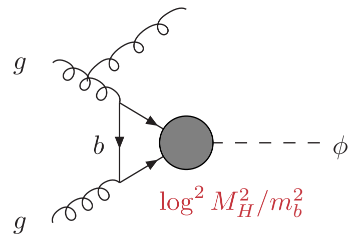
- large p_{TH}: elw. Sudakov logs $\sim \log^2 M_{W/Z}^2/p_{TH}^2$

- factorization: $p_T \ll 2m_b \to Q \sim m_b$ [← POWHEG, MC@NLO]

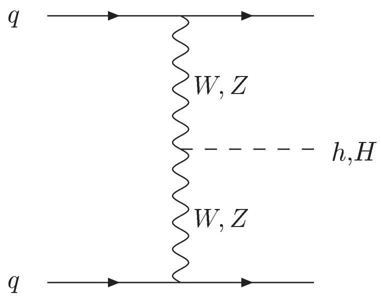


Grazzini, Sargsyan

- Sudakov form factor → unresummed logs



(ii) W/Z fusion: $pp \to W^*W^*/Z^*Z^* \to h/H$



Cahn, Dawson
Hikasa
Atarelli, Mele, Pitolli

- QCD corrections ← DIS: $\sim 10\%$

Han, Valencia, Willenbrock
Figy, Oleari, Zeppenfeld
Berger, Campbell

2–loop: $\lesssim 1\%$ [approx]

Bolzano, Maltoni, Moch, Zaro

- elw. corrections: $\sim 10\%$ → HAWK

Ciccolini, Denner, Dittmaier

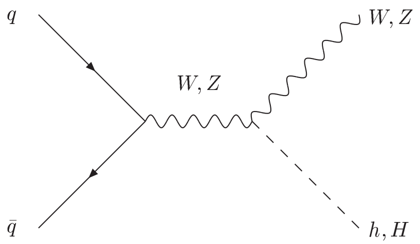
- full NLO SUSY-elw. corrections

Hollik, Rzehak, Plehn, Rauch
Figy, Palmer, Weiglein

- implemented in VBFNLO

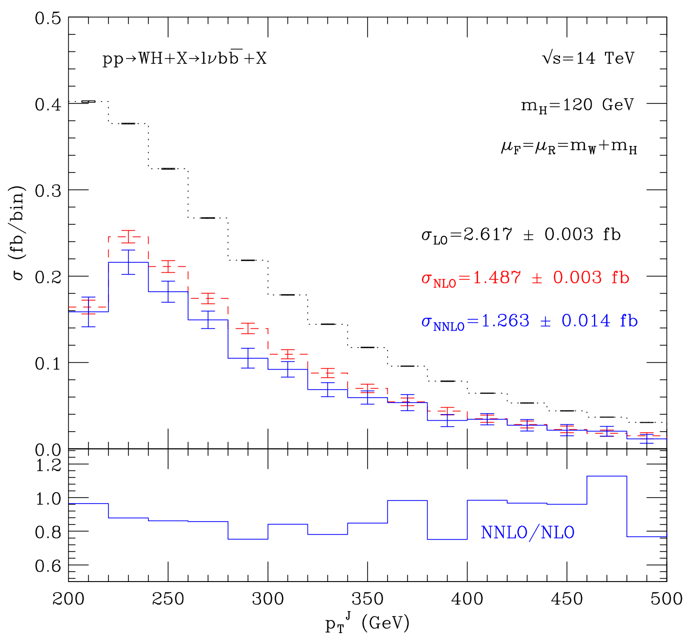
- Dim 6: new tensor structures ← implemented @ LO

(iii) Higgs–strahlung: $pp \to W^*/Z^* \to W/Z + h/H$



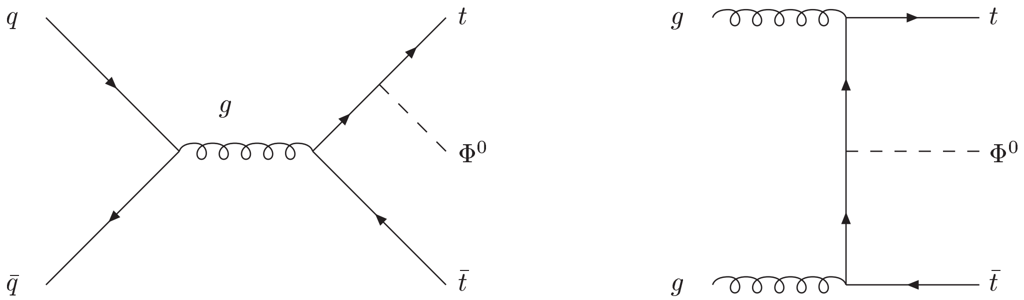
Glashow, . . .
Kunszt, . . .

- QCD corrections ← DY: $\sim 30\%$ — Han, Willenbrock
  2–loop: $\lesssim 5\%$ — Brein, Djouadi, Harlander
- SUSY-QCD corrections small — Djouadi, S.
- electroweak corrections: $\sim -10\% \to$ HAWK — Ciccolini, Dittmaier, Krämer
- WH/ZH: fully exclusive @ NNLO QCD — Ferrera, Grazzini, Tramantano



- Dim 6: new tensor structures ← implemented @ LO

(iv) Bremsstrahlung: $pp \to t\bar{t} + h/H/A$



dominant

Kunszt
Gunion
Marciano, Paige

- $t\bar{t}h \to t\bar{t}b\bar{b}$ important @ LHC $\to$ top Yukawa cplg.

- QCD corrections [SM]: $\sim 20\%$

Beenakker,. . .
Dawson, . . .
Broggio, Ferroglia, Pecjak, Signer, Yang
Kulesza, Motyka, Stebel, Theeuwes

- link to parton showers: aMC@NLO, PowHel

Frederix et al.
Garzelli, Kardos, Papadopoulos, Trócsányi

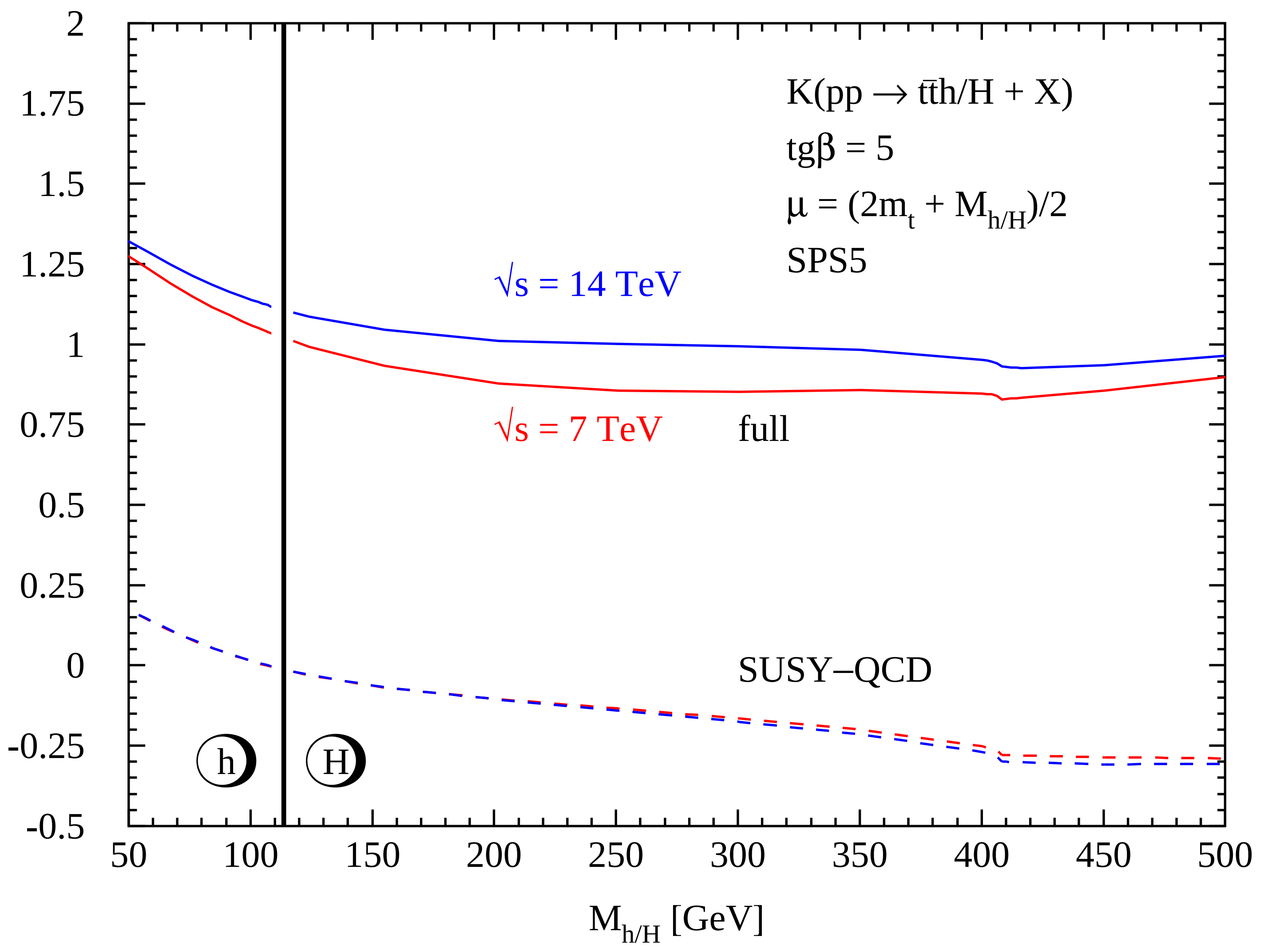
- elw. corrections: $\sim 1-2\%$

Yu, Wen-Gan, Ren-You, Chong, Lei
Frixione, Hirschi, Pagani, Shao, Zaro
Denner, Feger

- dim 6: $c_t, c_g \to c_t$ dominant

- SUSY-QCD corrections: moderate

Dittmaier, Häfliger, Krämer, S., Walser



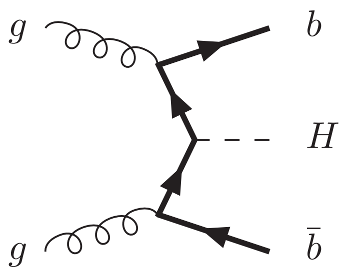
Dittmaier, Häfliger, Krämer, S., Walser

SPS 5

$$
\begin{aligned}
\text{tg}\beta &= 5 \\
\mu &= 639.8 \text{ GeV} \\
A_t &= -1671.4 \text{ GeV} \\
A_b &= -905.6 \text{ GeV} \\
m_{\tilde{g}} &= 710.3 \text{ GeV} \\
m_{\tilde{q}_L} &= 535.2 \text{ GeV} \\
m_{\tilde{b}_R} &= 620.5 \text{ GeV} \\
m_{\tilde{t}_R} &= 360.5 \text{ GeV}
\end{aligned}
$$

$$\longrightarrow m_{\tilde{t}_1} = 204.1 \text{ GeV}, m_{\tilde{t}_2} = 656.1 \text{ GeV}, m_{\tilde{b}_1} = 533.3 \text{ GeV}, m_{\tilde{b}_2} = 625.2 \text{ GeV}$$

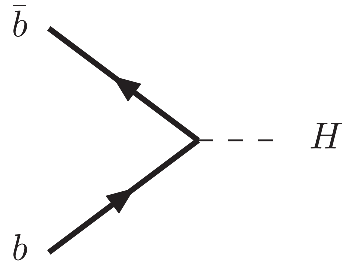
(v) $b\bar{b}$+Higgs production



NLO

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

no resummation of $\log M_H^2/m_b^2$ terms

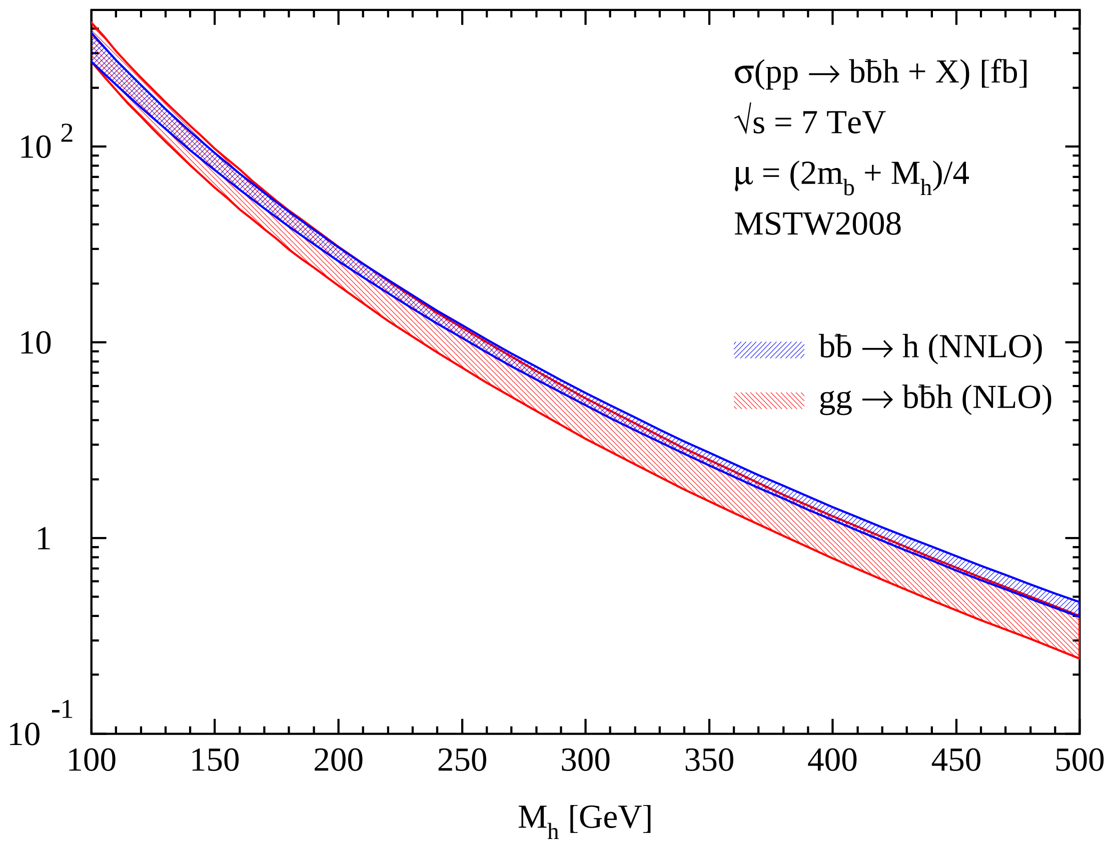


$[\leftarrow \Delta_b]$

NNLO

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

resummation of $\log M_H^2/m_b^2$ terms



Santander matching:

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

$$w = \log \frac{M_H}{m_b} - 2$$

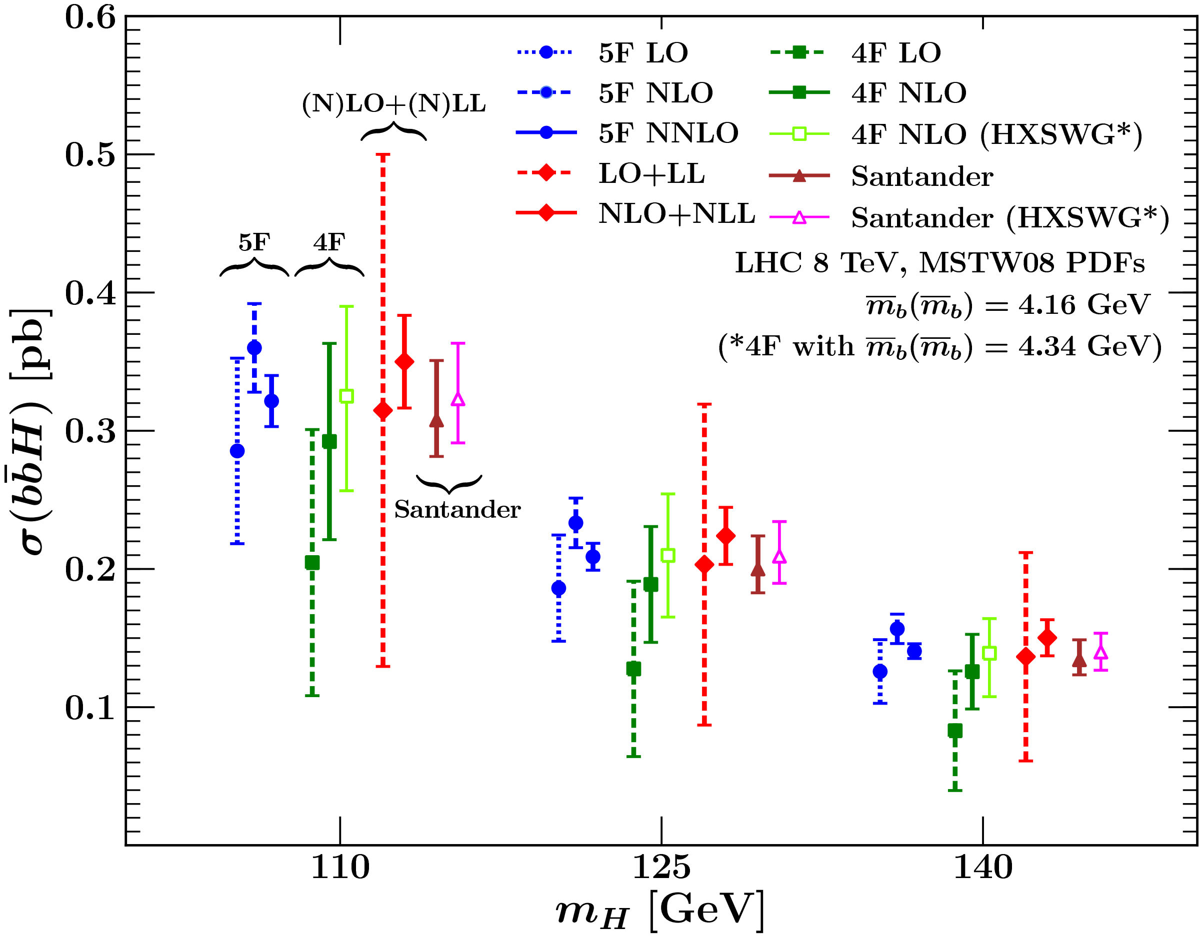
Harlander, Krämer, Schumacher

Dittmaier, Krämer, S.
Dawson, Jackson, Reina, Wackeroth
Harlander, Kilgore

- two approaches for proper matching 4FS + 5FS

Bonvini, Papanastasiou, Tackmann

Forte, Napoletano, Ubiali



Bonvini, Papanastasiou, Tackmann

	M_A	M_H [GeV]	δ^A_{QCD}	δ^A_{SUSY}	$\delta^A_{SUSYrem}$	δ^H_{QCD}	δ^H_{SUSY}	$\delta^H_{SUSYrem}$
7 TeV	100	113.9	0.23	-0.30	0.4×10^{-4}	0.27	-0.38	0.3×10^{-4}
	200	200	0.38	-0.30	2.9×10^{-4}	0.39	-0.30	5.8×10^{-4}
	300	300	0.46	-0.30	6.7×10^{-4}	0.47	-0.30	9.3×10^{-4}
	400	400	0.53	-0.30	1.3×10^{-3}	0.53	-0.30	1.5×10^{-3}
	500	500	0.57	-0.30	2.0×10^{-3}	0.59	-0.30	2.2×10^{-3}
14 TeV	100	113.9	0.14	-0.30	0.4×10^{-4}	0.17	-0.38	0.5×10^{-4}
	200	200	0.28	-0.30	2.7×10^{-4}	0.29	-0.30	5.7×10^{-4}
	300	300	0.37	-0.30	6.5×10^{-4}	0.39	-0.30	9.3×10^{-4}
	400	400	0.45	-0.30	1.2×10^{-3}	0.45	-0.30	1.5×10^{-3}
	500	500	0.50	-0.30	2.1×10^{-3}	0.49	-0.30	2.3×10^{-3}

	tgβ	M_A	M_H [GeV]	δ^A_{SUSY}	$\delta^A_{SUSYrem}$	δ^H_{SUSY}	$\delta^H_{SUSYrem}$
7 TeV	3	200	209.7	-0.04	2.1×10^{-4}	-0.04	5.7×10^{-4}
	5	200	204.0	-0.06	2.4×10^{-4}	-0.06	5.3×10^{-4}
	7	200	202.1	-0.08	2.5×10^{-4}	-0.09	3.9×10^{-4}
	10	200	200.9	-0.12	2.5×10^{-4}	-0.12	3.8×10^{-4}
	20	200	200.1	-0.21	2.6×10^{-4}	-0.21	4.4×10^{-4}
	30	200	200.0	-0.30	2.9×10^{-4}	-0.30	5.8×10^{-4}
14 TeV	3	200	209.7	-0.04	2.0×10^{-4}	-0.04	7.2×10^{-4}
	5	200	204.0	-0.06	2.2×10^{-4}	-0.06	5.0×10^{-4}
	7	200	202.1	-0.08	2.4×10^{-4}	-0.09	4.4×10^{-4}
	10	200	200.9	-0.12	2.5×10^{-4}	-0.12	4.1×10^{-4}
	20	200	200.1	-0.21	2.7×10^{-4}	-0.21	4.4×10^{-4}
	30	200	200.0	-0.30	2.7×10^{-4}	-0.30	5.7×10^{-4}

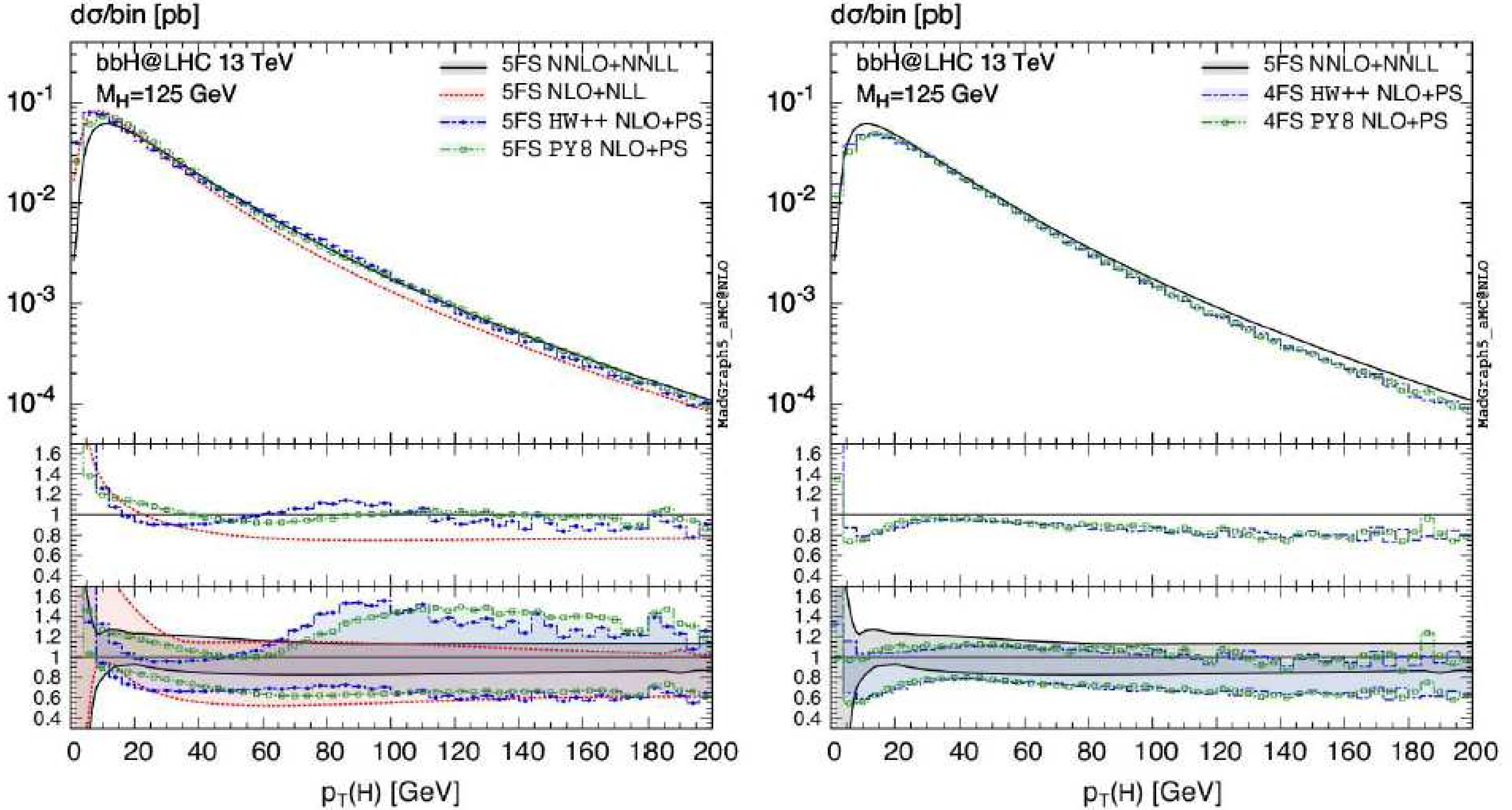
SPS1b

SPS 1b

$$\begin{aligned} \mathrm{tg}\beta &= 30 \\ \mu &= 495.6 \text{ GeV} \\ A_t &= -729.3 \text{ GeV} \\ A_b &= -987.4 \text{ GeV} \\ m_{\tilde{g}} &= 916.1 \text{ GeV} \\ m_{\tilde{q}_L} &= 762.5 \text{ GeV} \\ m_{\tilde{b}_R} &= 780.3 \text{ GeV} \\ m_{\tilde{t}_R} &= 670.7 \text{ GeV} \end{aligned}$$

$$\longrightarrow m_{\tilde{t}_1} = 631.8 \text{ GeV}, m_{\tilde{t}_2} = 829.1 \text{ GeV}, m_{\tilde{b}_1} = 721.8 \text{ GeV}, m_{\tilde{b}_2} = 820.7 \text{ GeV}$$

distributions



Wiesemann, Frederix, Frixione, Hirschi, Maltoni, Torrielli MG5_aMC@NLO

[POWHEG Jäger, Reina, Wackeroth]

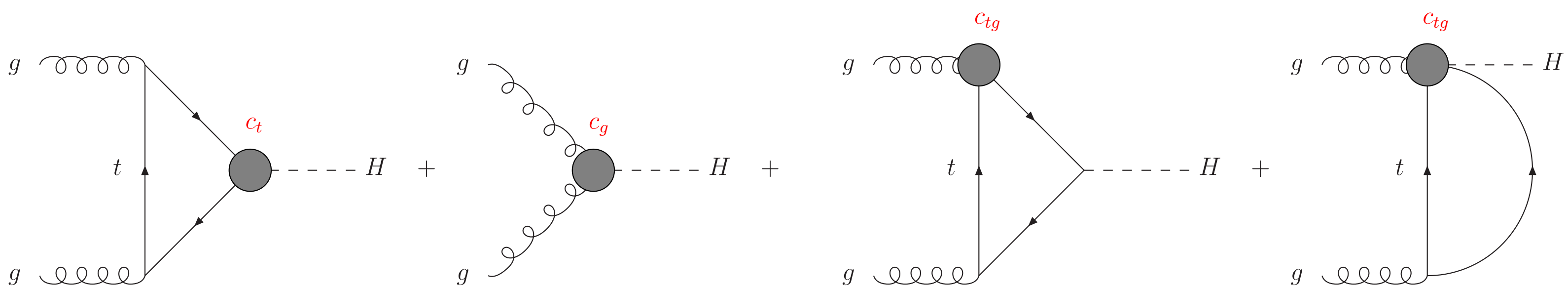
III *CONCLUSIONS*

- Higgs boson searches/studies at LHC belong to major endeavours
- most QCD and elw. corrections known in SM & MSSM
  $\to \Delta \lesssim 10-15\%$ @ LHC
- QCD & elw. corrections to dim 6 contributions in the making
  ($\to$ Ghezzi, Gomez-Ambrosio, Passarino, Uccirati
  Berthier, Hartmann, Trott)
- important to develop NLO event generators [$\leftarrow$ backgrounds]

BACKUP SLIDES

$gg \longrightarrow H$

- chromomagnetic dipole operator



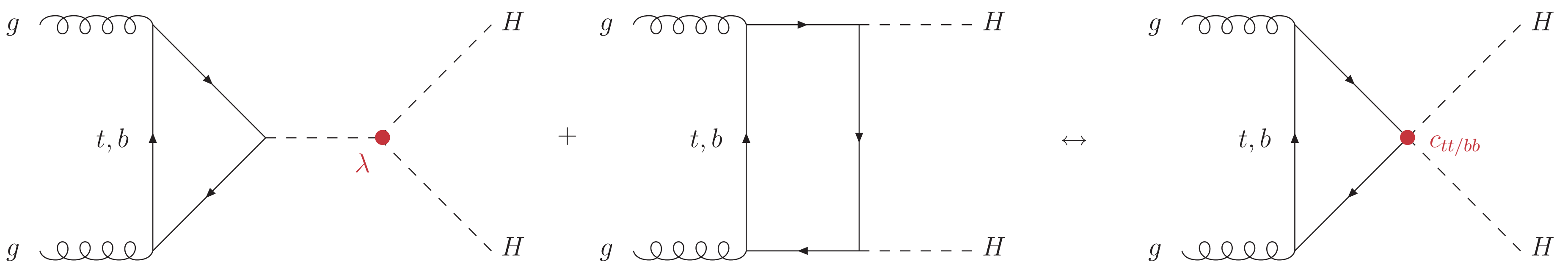
$$\mathcal{L}_{eff} = -c_t m_t \bar{t}t \frac{H}{v} + c_g \frac{g_s^2}{4\pi^2} G^{a\,\mu\nu} G^a_{\mu\nu} \frac{H}{v} + c_{tg} \frac{g_s m_t}{2v^3} (v+H) G^a_{\mu\nu} \left[\overline{t_L} \sigma^{\mu\nu} T^a t_R + h.c. \right]$$

$\longrightarrow$ mixing of operators, renormalization @ 'LO':

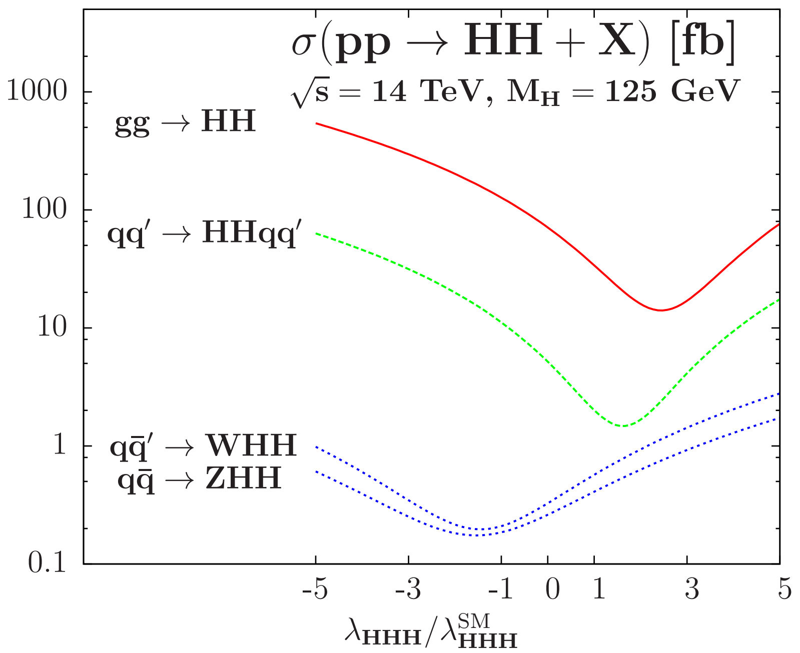
$$\delta c_g = \frac{\alpha_t}{2\pi} \Re e(c_{tg}) \Gamma(1+\epsilon) \left(\frac{4\pi\mu^2}{\mu_R^2} \right)^{\epsilon} \frac{1}{\epsilon} \qquad \left(\alpha_t = \frac{y_t^2}{4\pi} = \frac{m_t^2}{2\pi v^2} \right)$$

Degrande, Gérard, Grojean, Maltoni, Servant

$gg \to HH$



- threshold region: sensitive to λ
  large M_{HH}: sensitive to $c_{tt/bb}$ [e.g. boosted Higgs pairs]



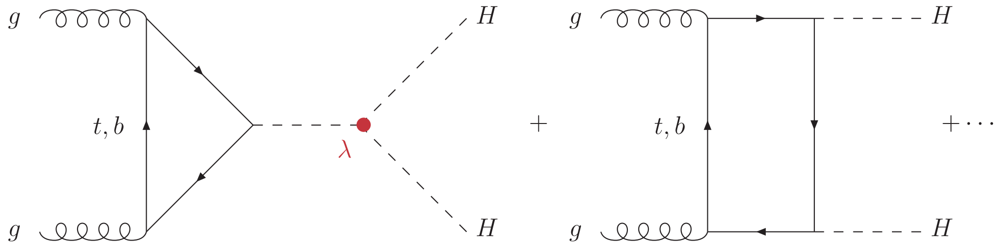
$$gg \to HH : \frac{\Delta\sigma}{\sigma} \sim -\frac{\Delta\lambda}{\lambda}$$

[decreasing with M_{HH}^2]

Baglio, Djouadi, Gröber, Mühlleitner, Quevillon, S.

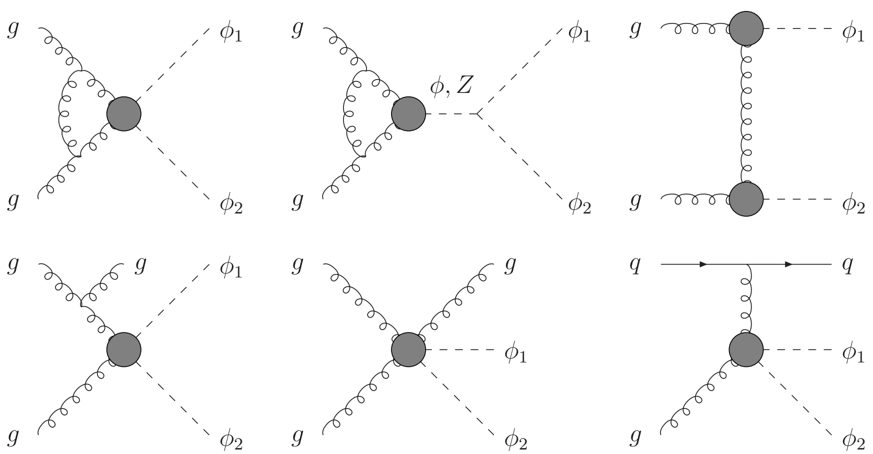
$gg \to HH$

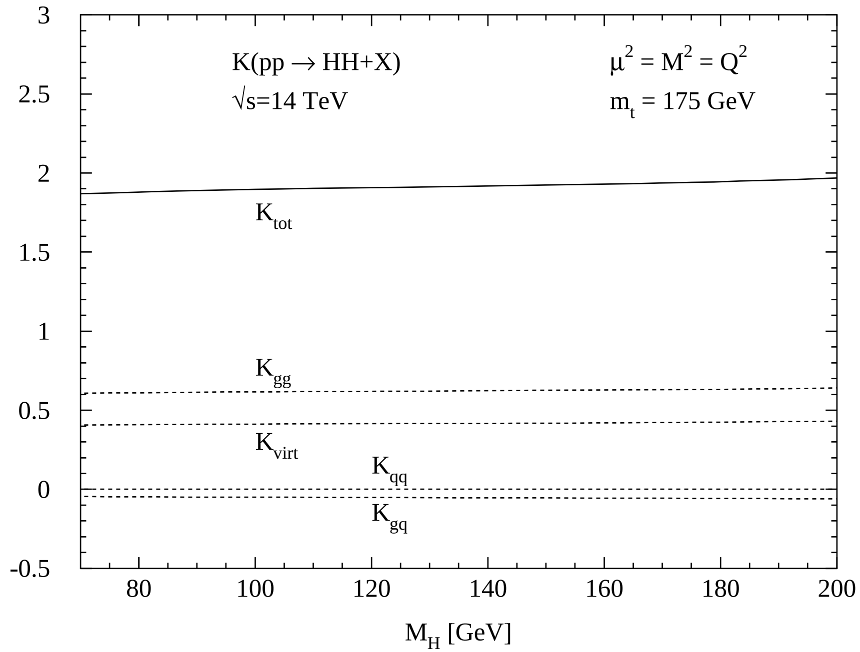
SM



- third generation dominant $\to t, b$

- 2-loop QCD corrections: $\sim 90 - 100\%$
  $[M_H^2 \ll 4m_t^2, \qquad \mu = M_{HH}]$

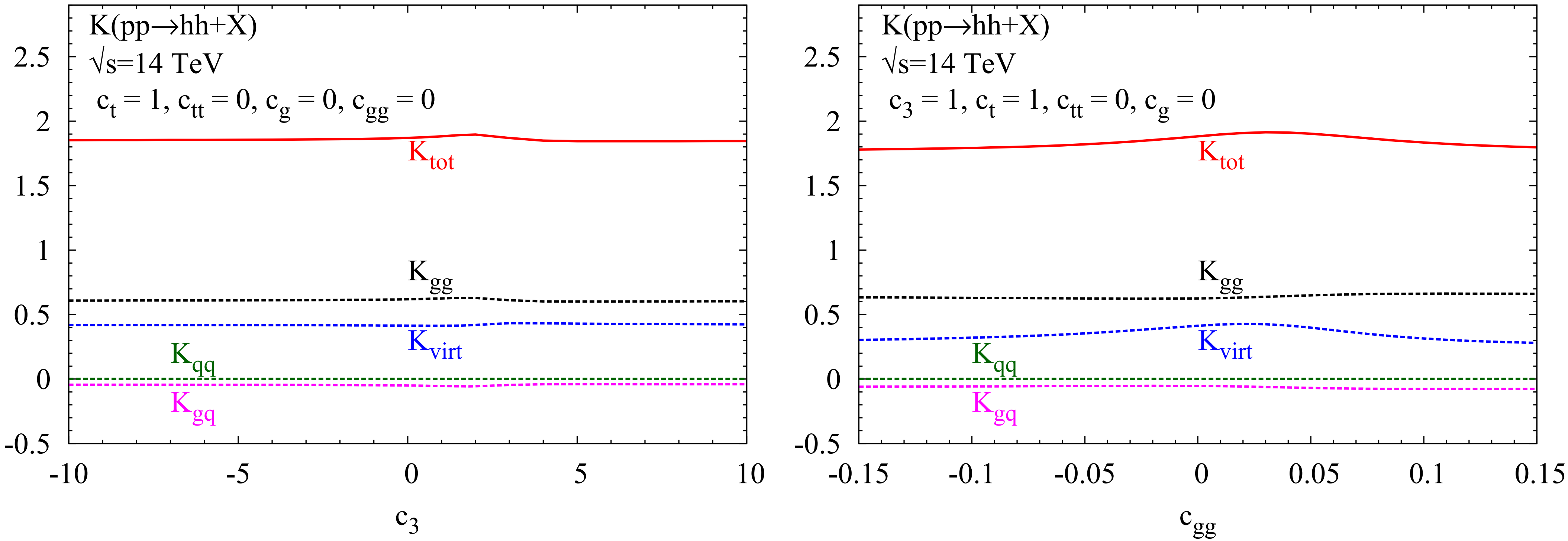




Dawson, Dittmaier, S.

- extended to dim6 → large impact on cxn
  small impact on K-factor

$$\mathcal{L}_{eff} = -m_t\bar{t}t\left(c_t\frac{h}{v} + c_{tt}\frac{h^2}{2v^2}\right) - c_3\frac{1}{6}\left(\frac{3M_h^2}{v}\right)h^3 + \frac{\alpha_s}{\pi}G^{a\,\mu\nu}G^a_{\mu\nu}\left(c_g\frac{h}{v} + c_{gg}\frac{h^2}{2v^2}\right)$$

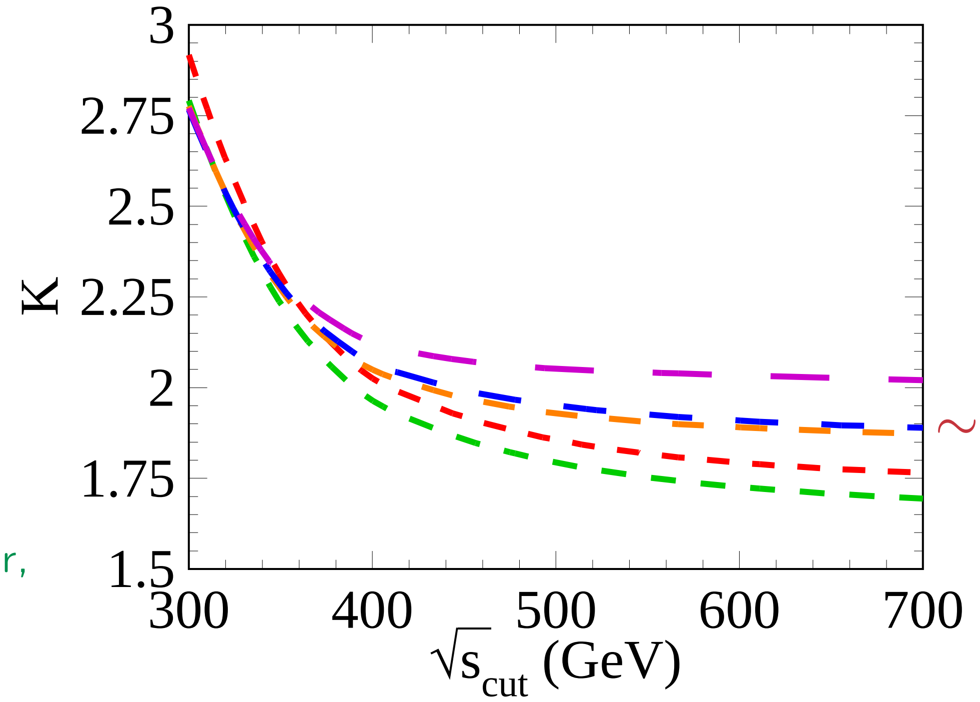


Gröber, Mühlleitner, S., Streicher

• 2-loop QCD corrections:

$$\sigma = \sigma_0 + \frac{\sigma_1}{m_t^2} + \cdots + \frac{\sigma_4}{m_t^8}$$

Grigo, Hoff, Melnikov, Steinhauser



$\sim +10\%$

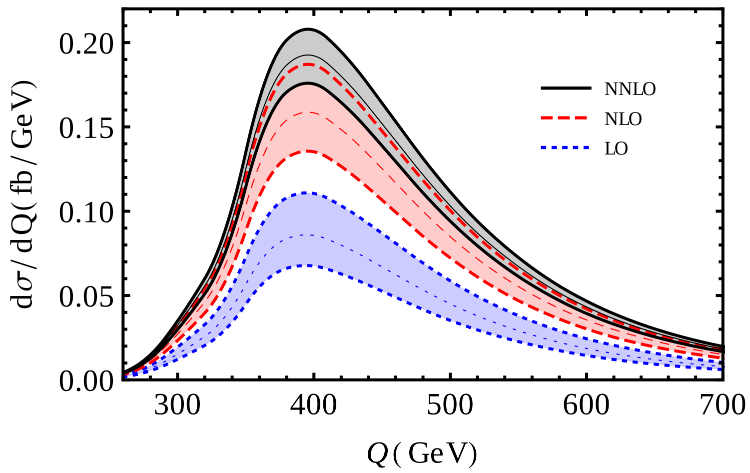
• NLO mass effects @ NLO in real corrections: $\sim -10\%$

Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Torrielli, Vryonidou, Zaro

→ large virtual mass effects

• NNLO QCD corrections: $\sim 20\%$ $[M_H^2 \ll 4m_t^2]$

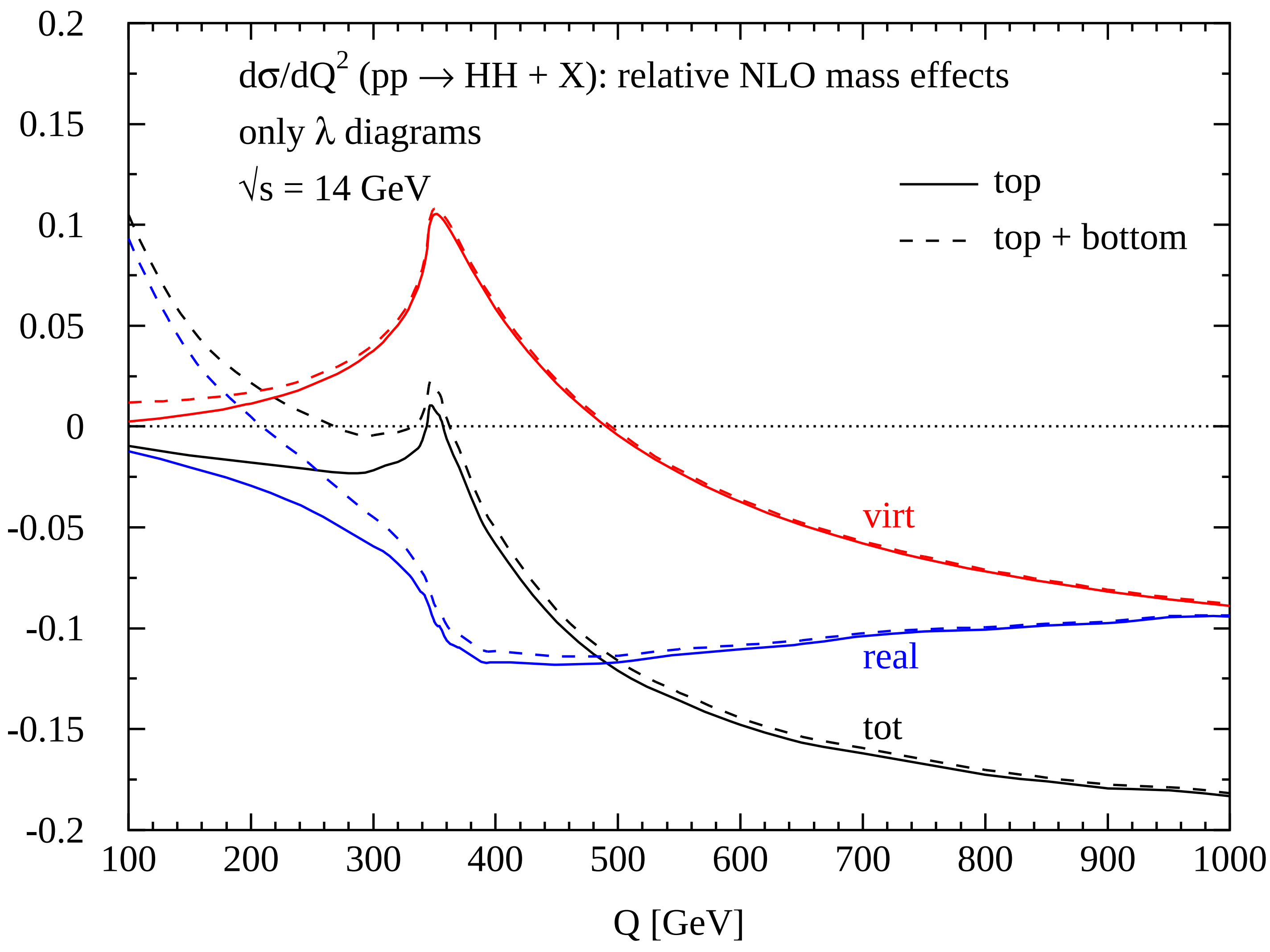
de Florian, Mazzitelli
Grigo, Melnikov, Steinhauser



• soft gluon resummation: $\sim 10\%$ $[M_H^2 \ll 4m_t^2]$

Shao, Li, Li, Wang
de Florian, Mazzitelli

Diagrams with λ only:



- situation unclear $\leftarrow$ boxes different?