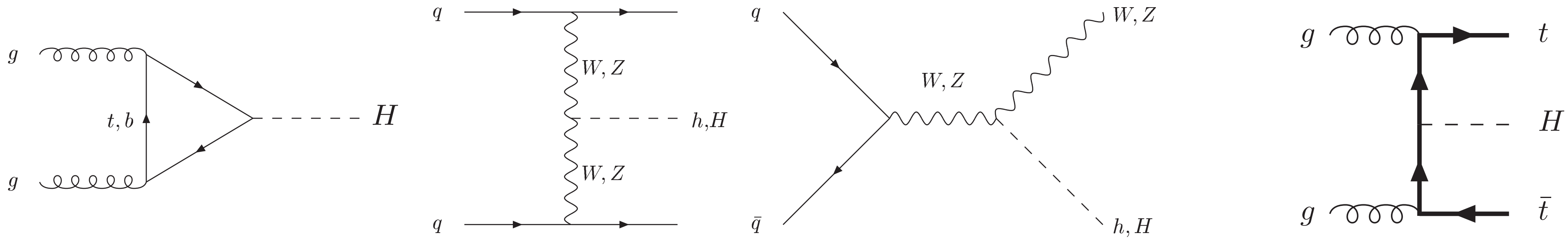
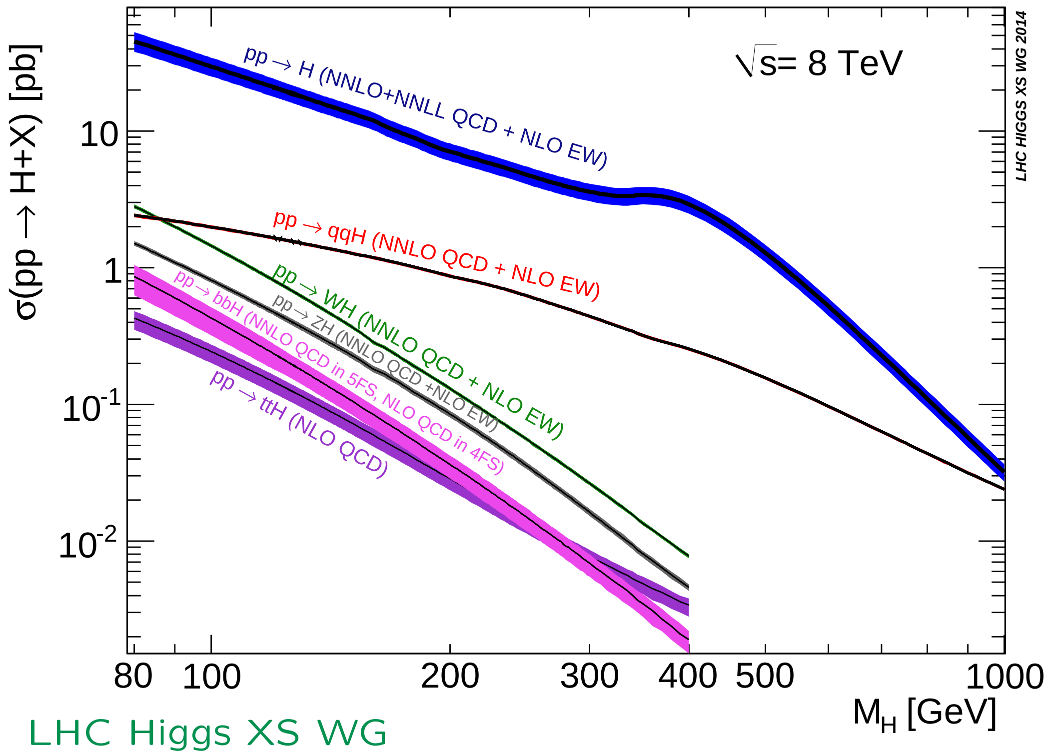
ZURICH ACTS

Michael Spira (PSI)

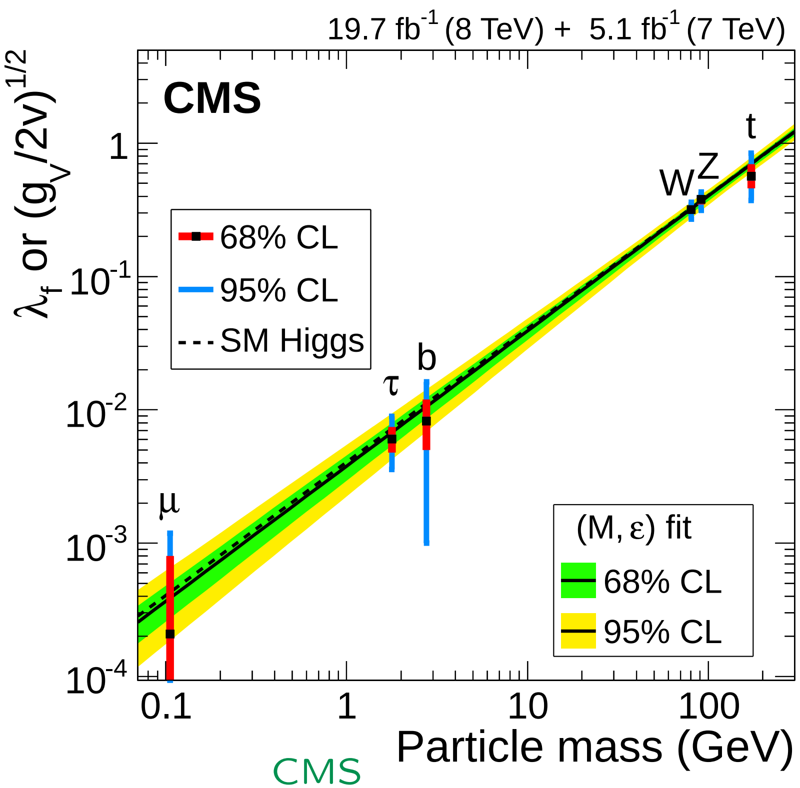
I *PRELUDE*

(i) Standard Model: Higgs Boson Production





LHC Higgs XS WG



CMS

(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 $\propto m_t^4 \log \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}$ $\rightarrow$ $\boxed{M_h \lesssim 135 \text{ GeV}}$

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

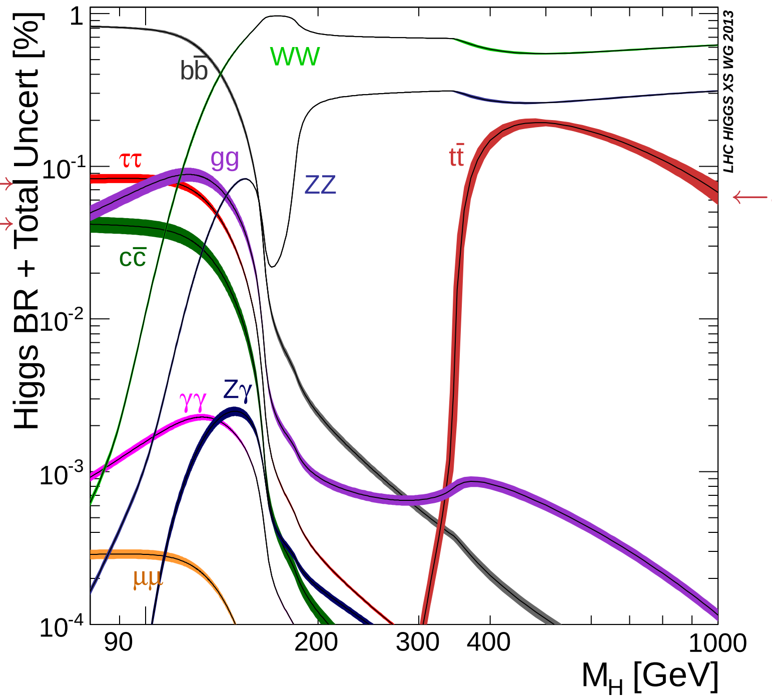
- Yukawa couplings: $\text{tg}\beta\uparrow \quad \Rightarrow \quad g_u^\phi\downarrow \quad g_d^\phi\uparrow \quad g_V^\phi\downarrow$

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

HDECAY & Prophecy4f

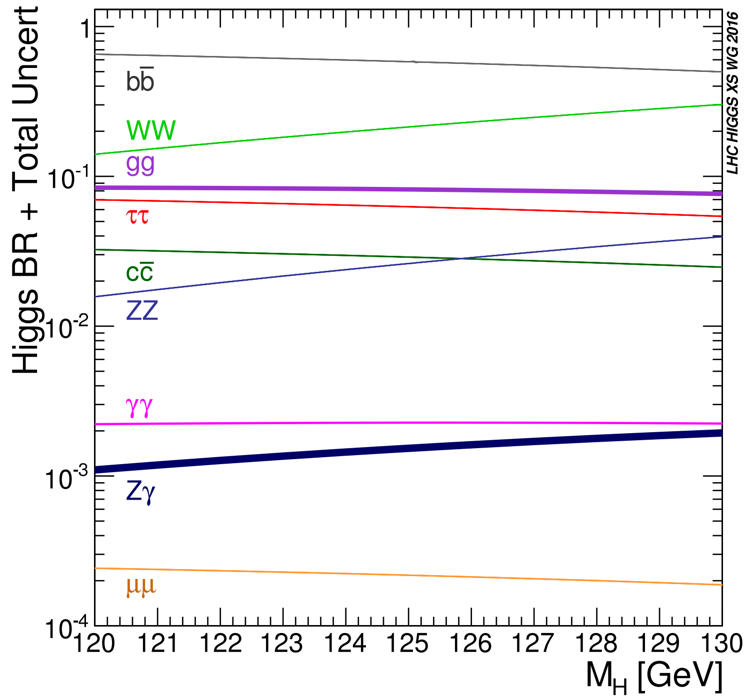
$\sim$ 10% →

$\sim$ 10% →



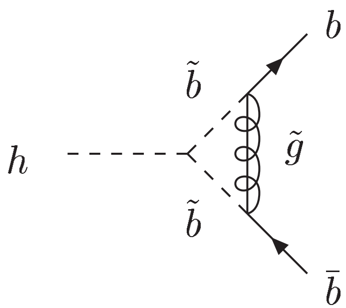
←$\sim$ 20%

$\longrightarrow$



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 $b\bar{b}\phi^0$ $[\Delta \lesssim 1\%]$

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

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

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

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

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

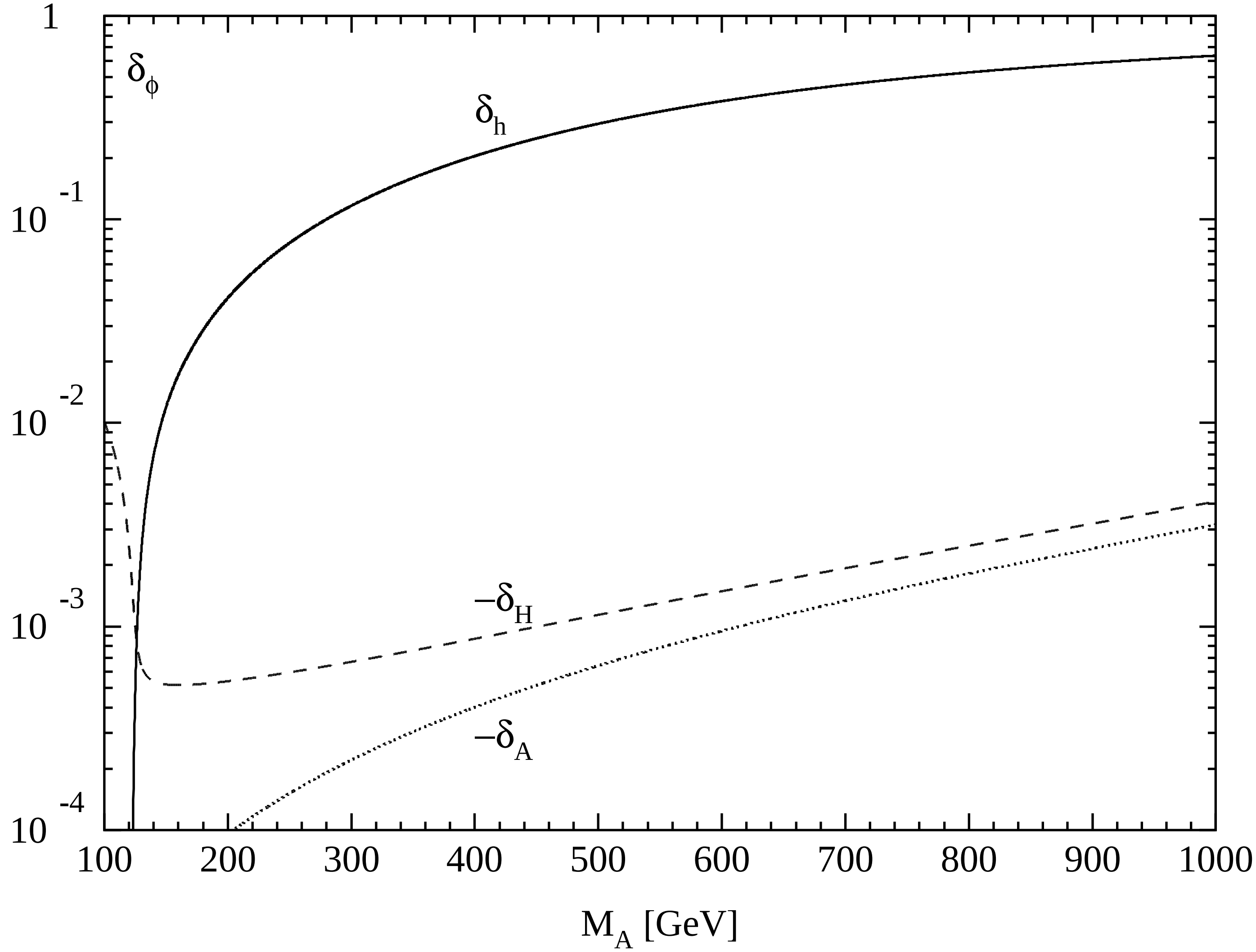
$$I(a,b,c) = -\frac{ab \log\frac{a}{b} + bc \log\frac{b}{c} + ca \log\frac{c}{a}}{(a-b)(b-c)(c-a)}$$

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

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

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

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

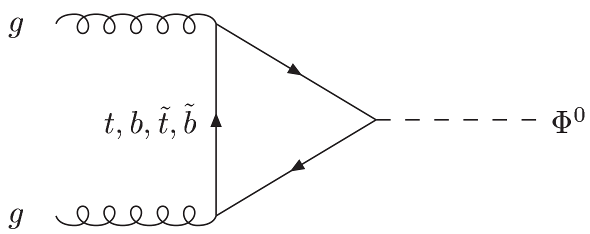


$$\delta_\Phi = \frac{\delta_{rem}}{\delta_{SQCD}}$$

Guasch, Häfliger, S.

II *FIRST ACT*

$gg \to \Phi$



Georgi, . . .

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

S., Djouadi, Graudenz, Zerwas
Dawson, Kauffman
Aglietti, . . .
Degrassi, Maltoni
Actis, Passarino, Sturm, Uccirati

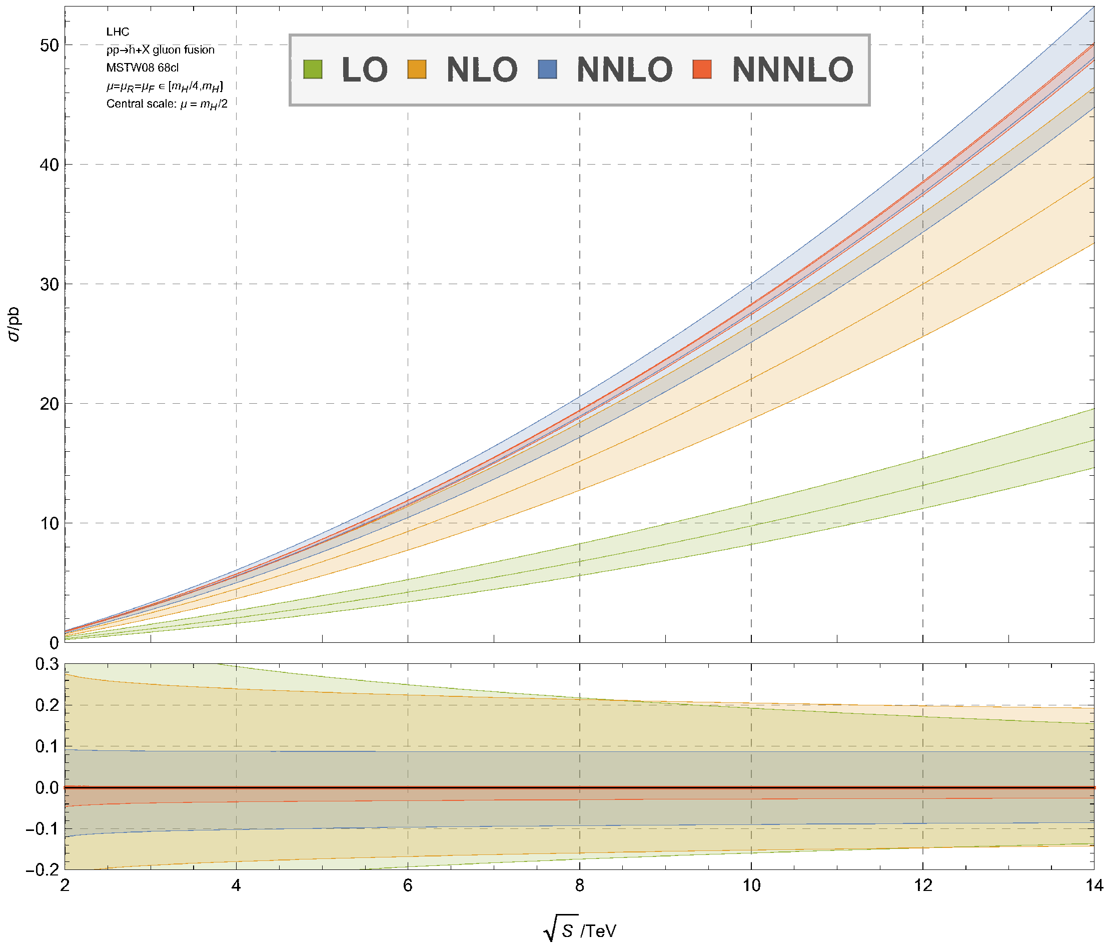
- elw. corrections: $\sim 5\%$

- NNLO QCD for $m_t \gg M_\phi \Rightarrow +$ 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

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, Furlan, Gehrmann, Herzog, Lazopoulos, Mistlberger



Anastasiou, Duhr, Dulat, Herzog, Mistlberger

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

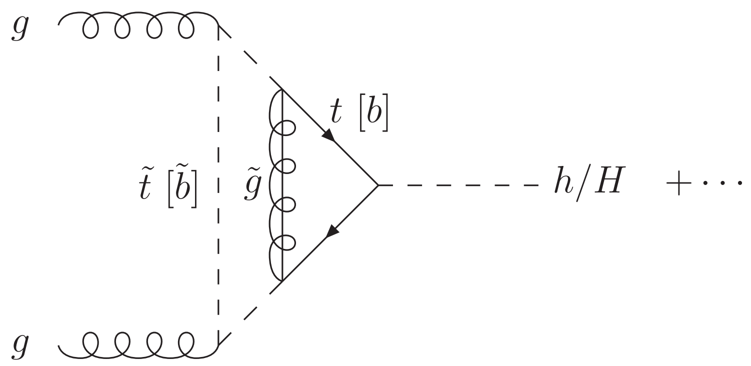
Catani, de Florian, Grazzini, Nason
Ravindran
Ahrens, Becher, Neubert, Yang
Ball, Bonvini, Forte, Marzani, Ridolfi
Schmidt, S.

- QCD corrections to squark loops: 10–100%

Mühlleitner, S.
Bonciani, Degrassi, Vicini

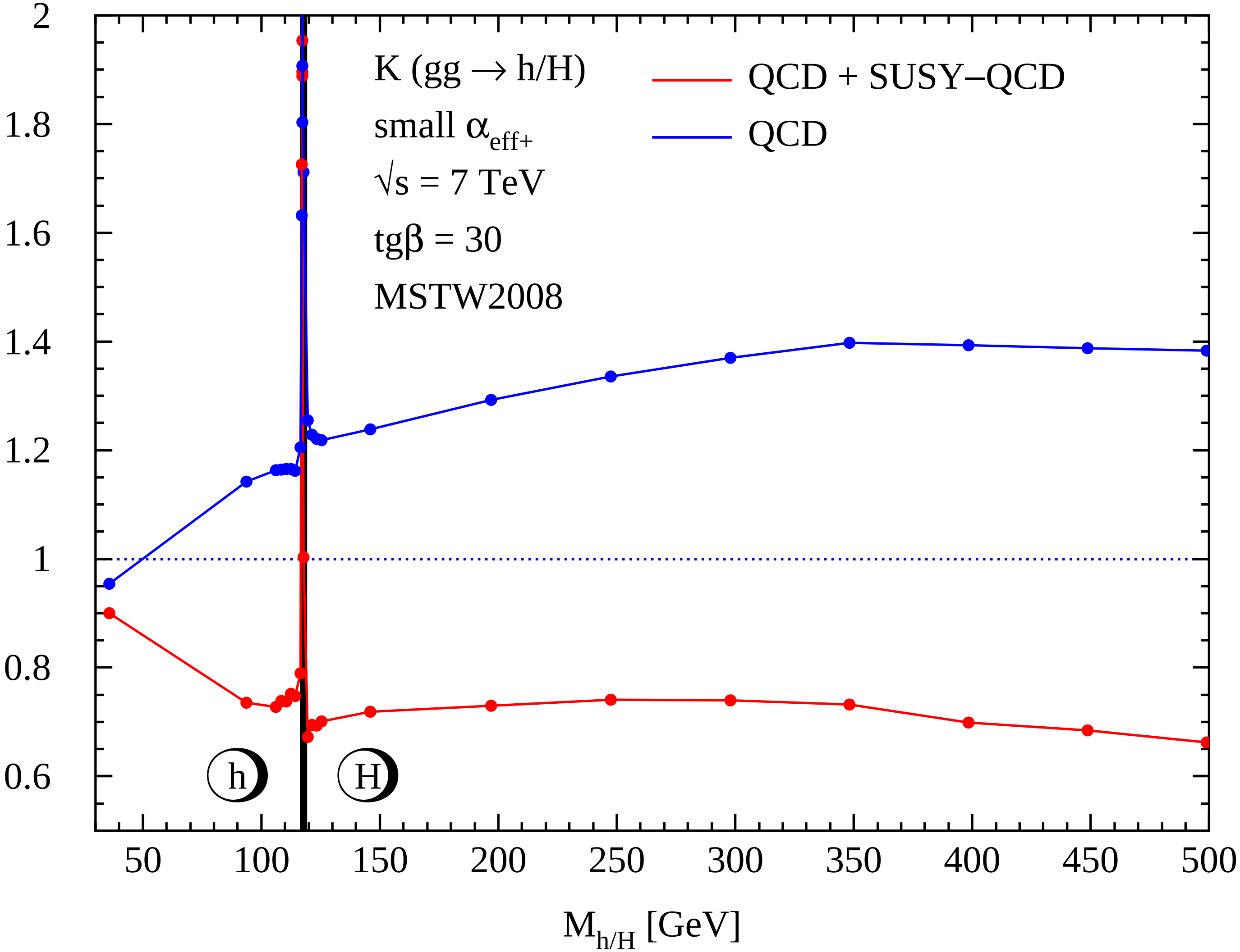
- genuine SUSY–QCD corrections: 10–100%
  [$\leftarrow \Delta_b$ @ large tgβ]

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



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

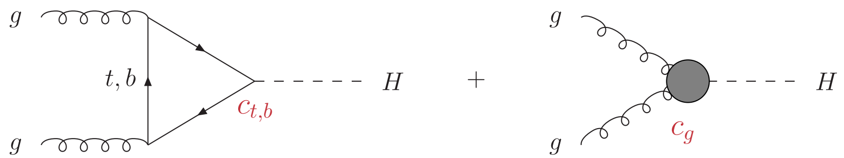
PRELIMINARY



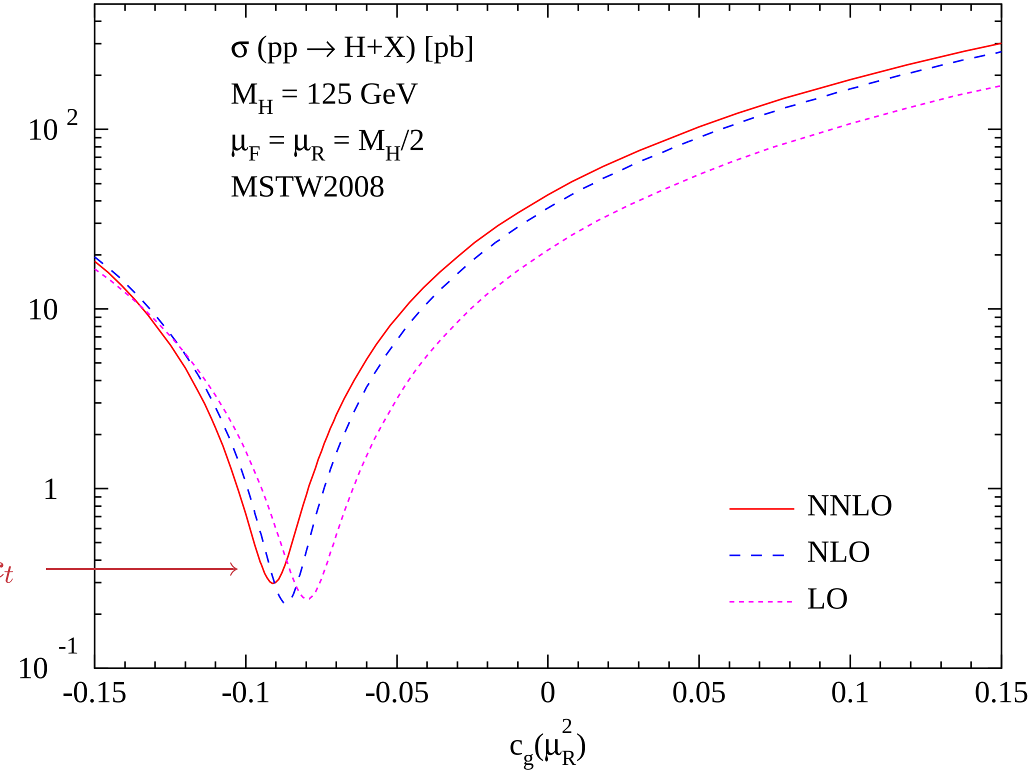
Mühlleitner, Rzehak, S.

Dim 6

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



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



$12 c_g \sim -c_t$

Schmidt, S.

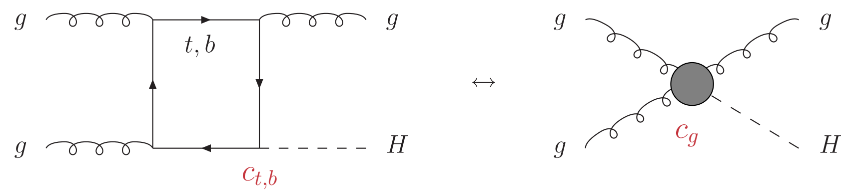
- extended to N^{3}LO

Harlander, Liebler, Mantler

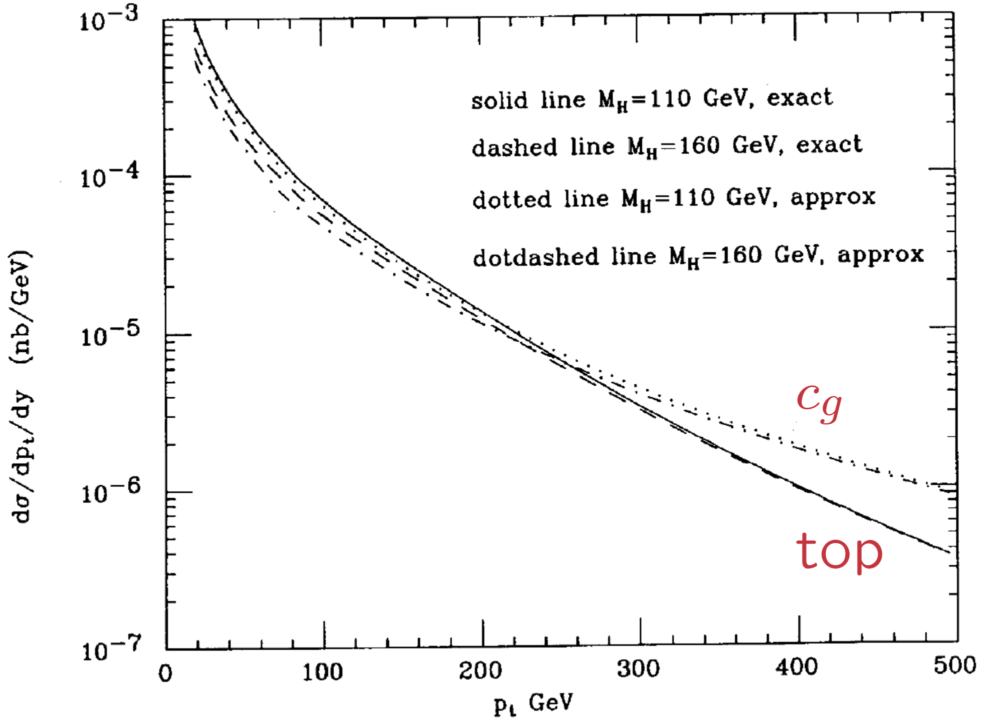
Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Lazopoulos, Mistlberger

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

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



- distinction dim4 ↔ dim5: shape of p_T distribution

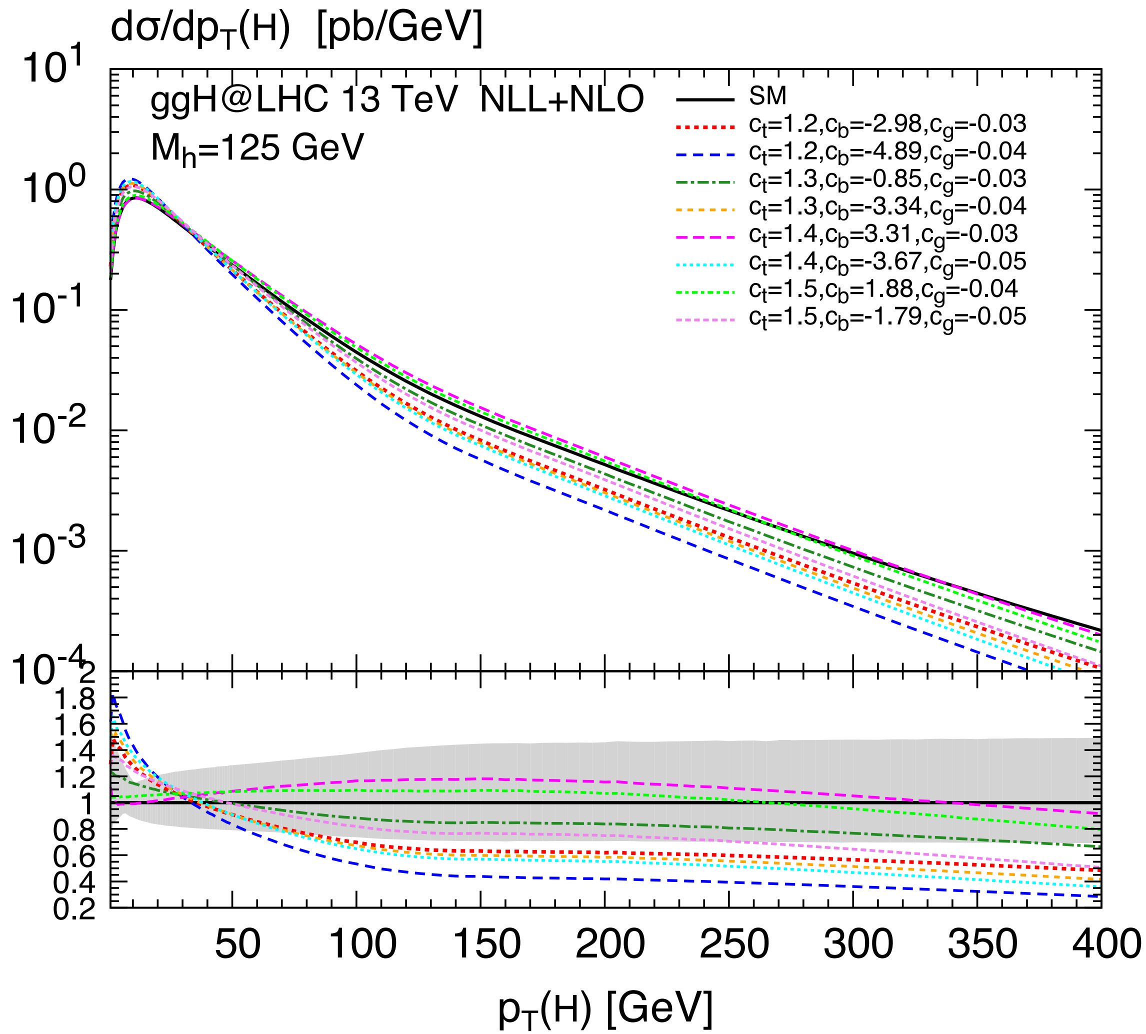


$m_t = 160$ GeV

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



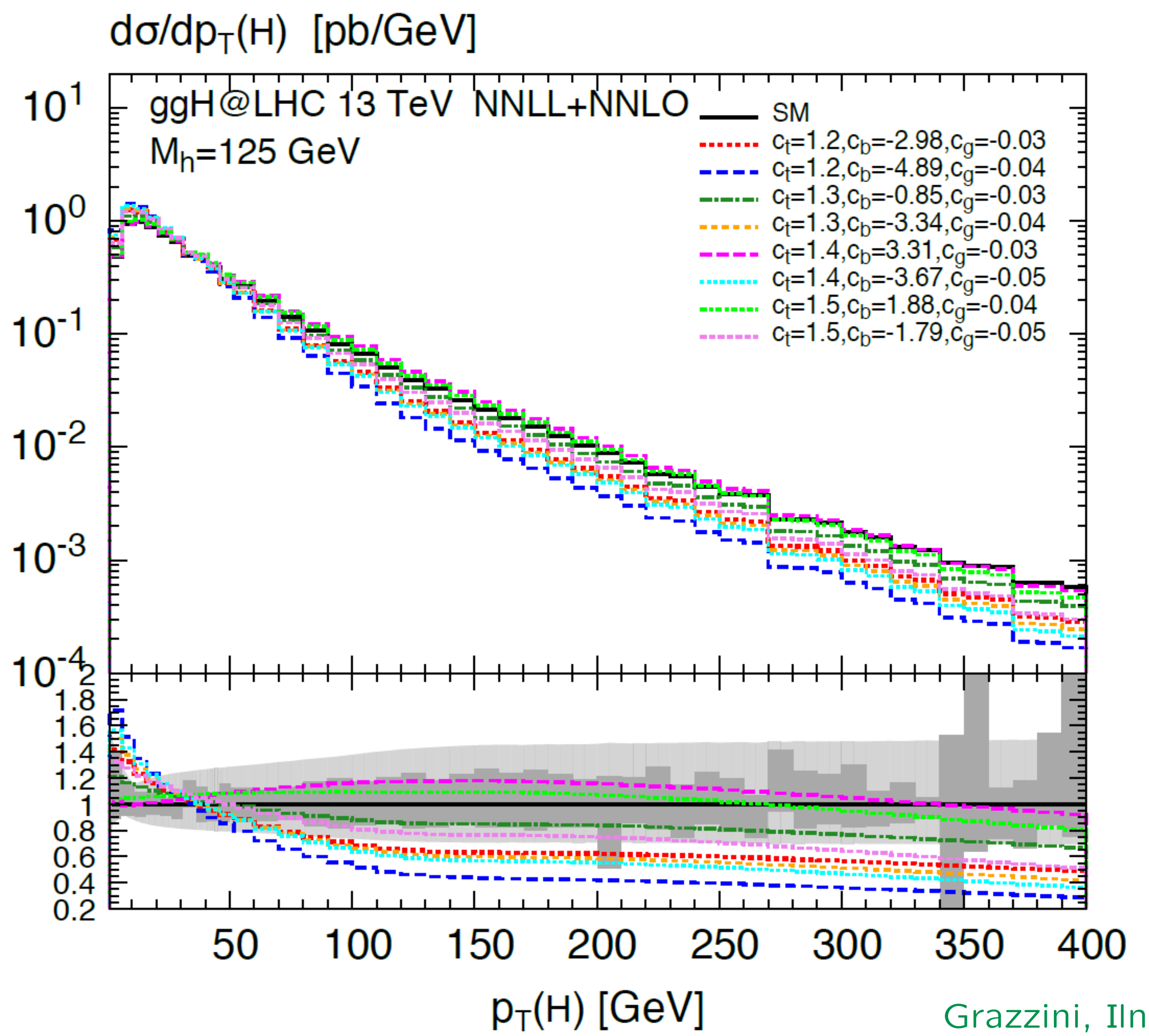
NLL+NLO

Grazzini, Ilnicka, S., Wiesemann

- A. Ilnicka: secondment @ MapleSoft

$$\left(\frac{d\sigma}{dp_t}\right)^{SMEFT}_{NNLL+NNLO}(p_T) = \frac{\left(\frac{d\sigma}{dp_t}\right)^{SMEFT}_{NLL+NLO}(p_T)}{\left(\frac{d\sigma}{dp_t}\right)^{SM}_{NLL+NLO}(p_T)} \cdot \left(\frac{d\sigma}{dp_t}\right)^{SM}_{NNLL+NNLO}(p_T)$$

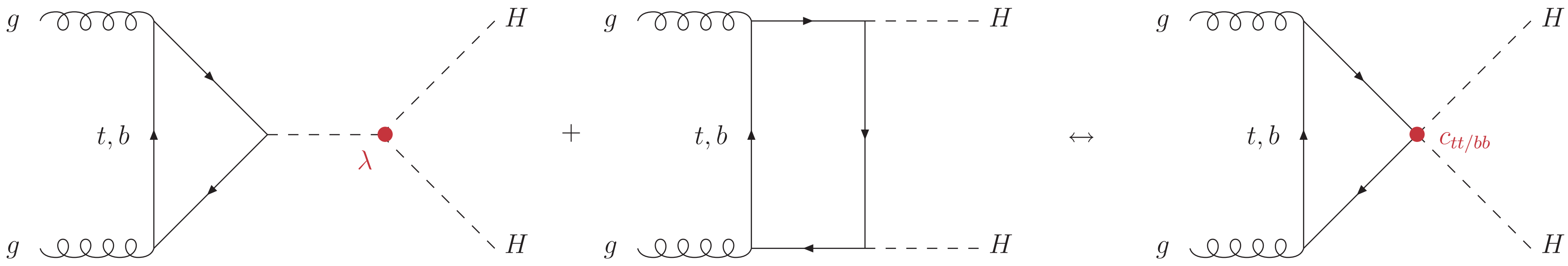
NNLL+NNLO



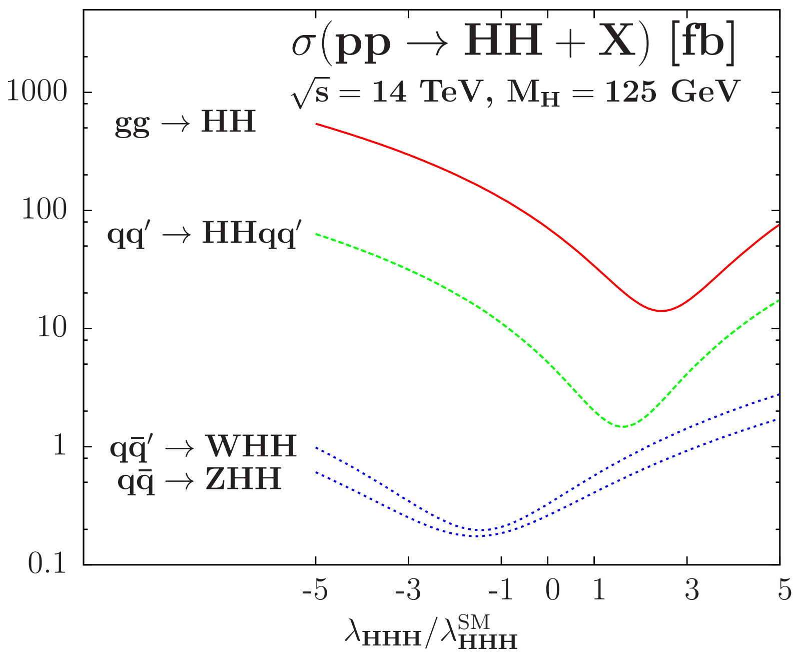
Grazzini, Ilnicka, S., Wiesemann

III *SECOND ACT*

$gg \longrightarrow HH$



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



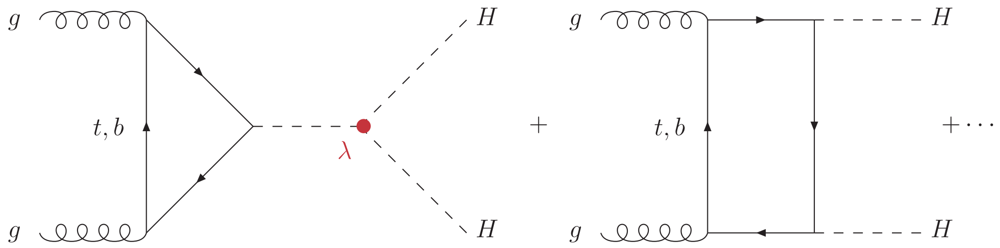
$$gg \longrightarrow HH : \frac{\Delta\sigma}{\sigma} \sim -\frac{\Delta\lambda}{\lambda}$$

[decreasing with M_{HH}^2]

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

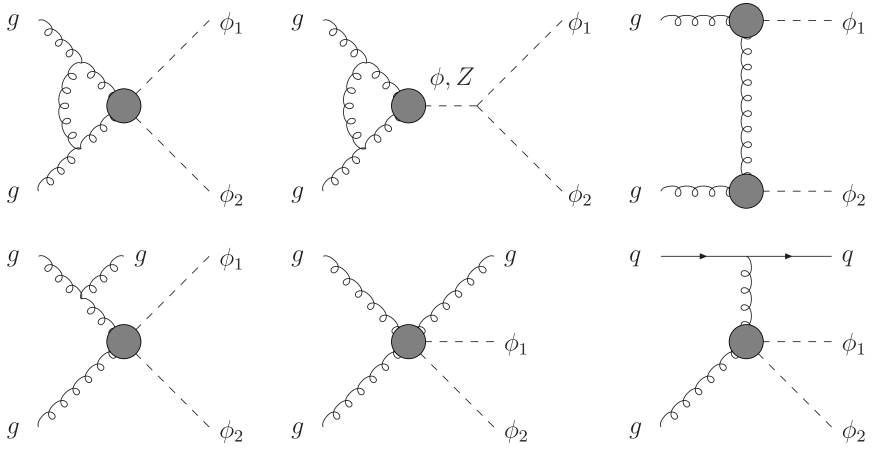
$gg \to HH$

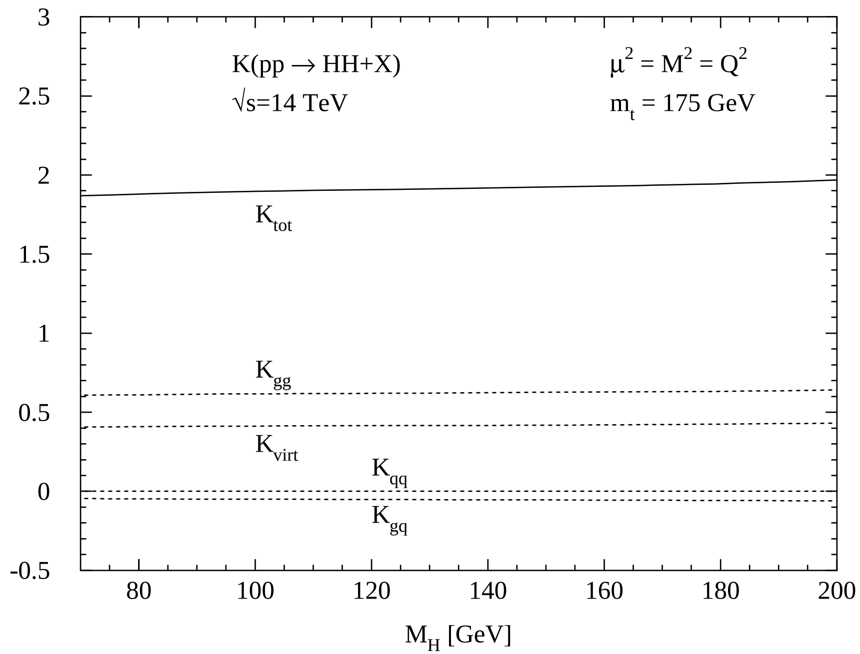
SM



- third generation dominant $\to t, b$

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





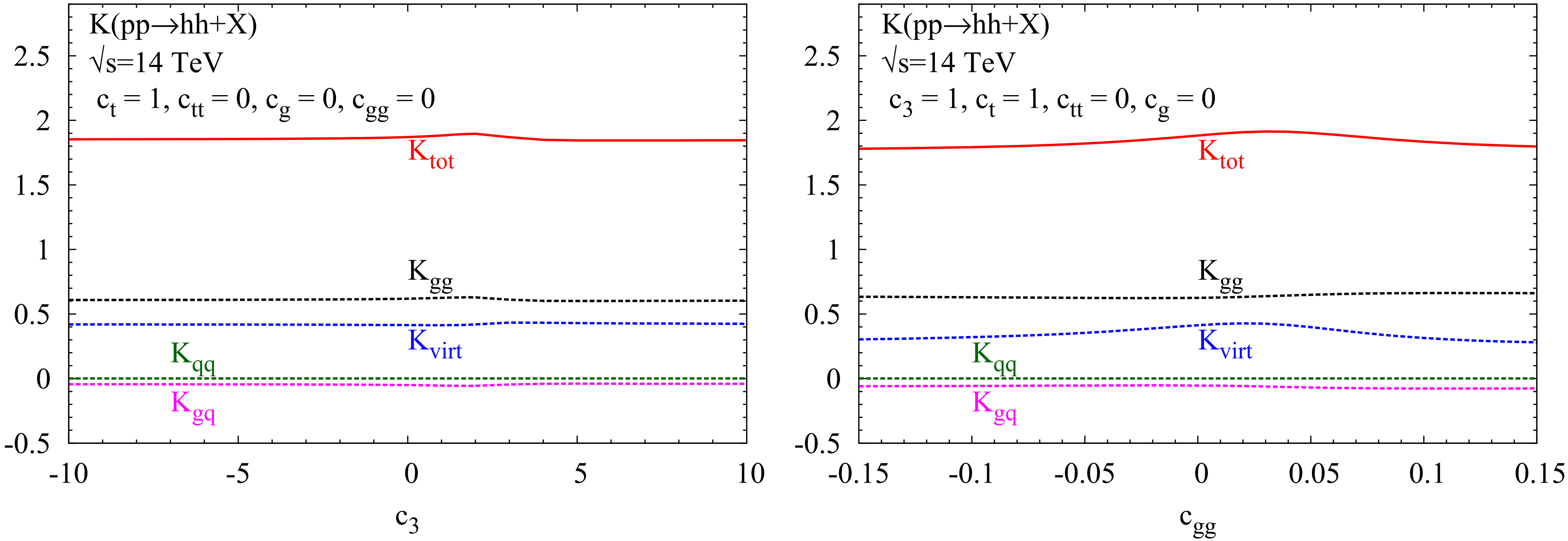
Dawson, Dittmaier, S.

- mass effects @ NLO: -14%

Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke

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

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



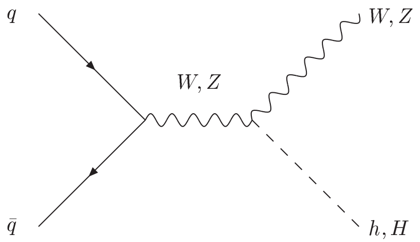
Gröber, Mühlleitner, S., Streicher

- extended to NNLO

de Florian, Fabre, Mazzitelli

IV *THIRD ACT*

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



Glashow,. . .
Kunszt,. . .

- QCD corrections ← DY: ∼ 30%
  2–loop: ≲ 5%

Han, Willenbrock

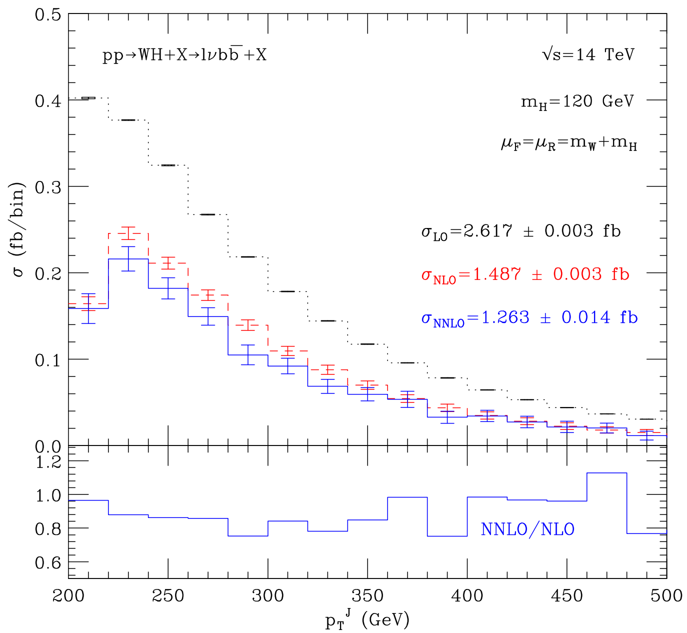
Brein, Djouadi, Harlander

- electroweak corrections: ∼ −10% → HAWK

Ciccolini, Dittmaier, Krämer

- WH/ZH: fully exclusive @ NNLO QCD

Ferrera, Grazzini, Tramantano



NNLO calculations with MATRIX

M.Grazzini et al.

The q_T subtraction method has been used to perform a number of important NNLO calculations where a coloured singlet final state is produced in hadron collisions

We have started an effort to provide a new NNLO parton level generator which implements all these calculations in a unique framework and includes all the vector-boson pair production processes plus single vector and Higgs bosons

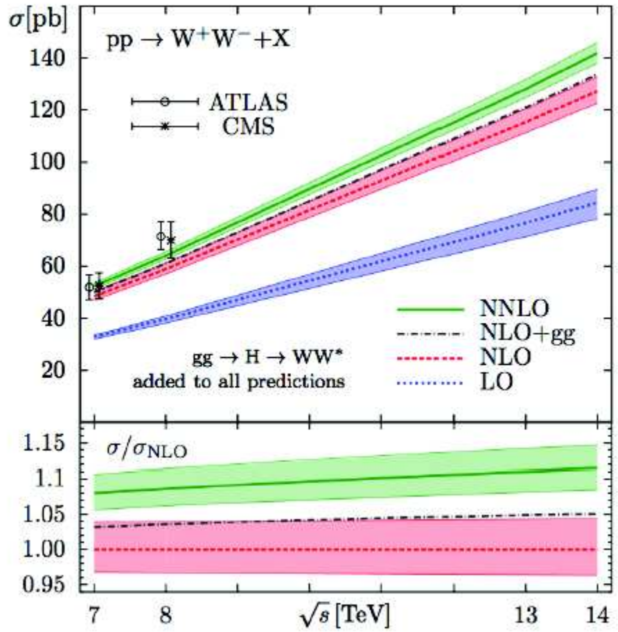
→ MATRIX

The program combines the MUNICH Monte Carlo framework with amplitudes from Openloops and q_T subtraction

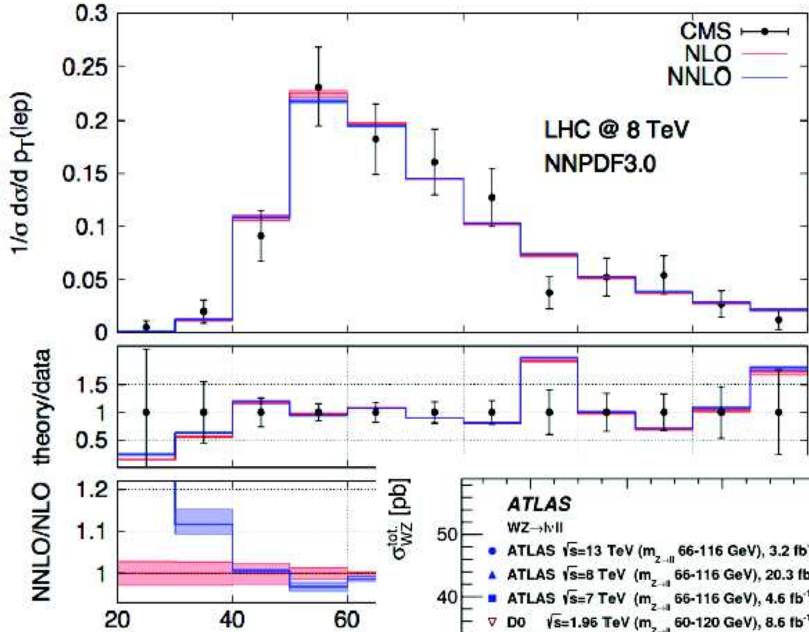
NNLO calculations with MATRIX

M.Grazzini et al.

All diboson fully differential NNLO calculations completed

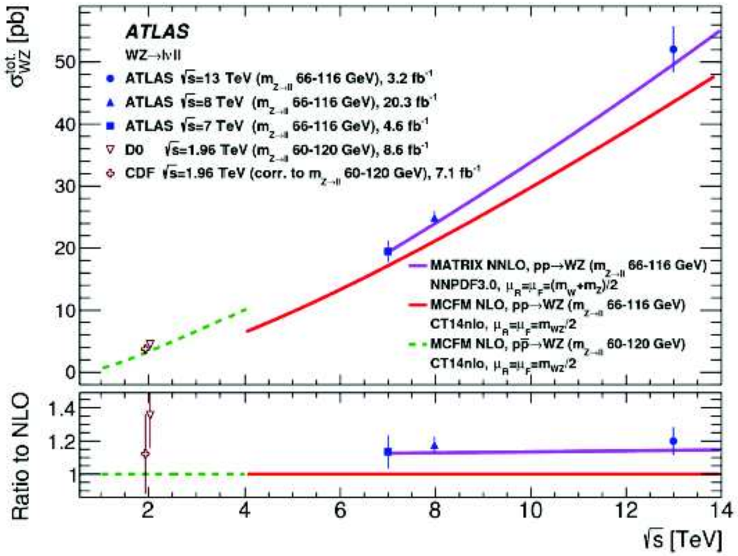


WW



ZZ

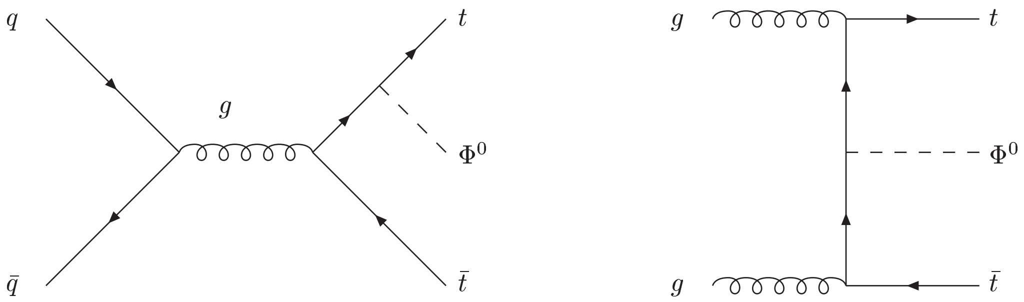
WZ



Public release imminent !

V *FINALE*

Bremsstrahlung: $pp \to t\bar{t} + \Phi$



dominant

Kunszt
Gunion
Marciano, Paige

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

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

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

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

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

- SUSY-QCD corrections: moderate

Dittmaier, Häfliger, Krämer, S., Walser

Joseep Pata, Günther Dissertori

Work on ttH(bb)

- Progressing on the full CMS analysis in the CMS ttH(bb) team with full 13 TeV data beyond HiggsCouplings'16, aiming for paper in Summer-Fall 2017 (modulo secondment)
- Significant speedups in the CMS/ETH ttH(bb) MEM code
- **new:** Improved the systematic uncertainty modelling, especially for jet-related uncertainties
- **new:** Implemented approximation technique for Matrix Element Method (MEM) uncertainty evaluation, reducing CPU requirements on the grid by ~100x [CMS internal report]
- Final training and validation of the official CMS Combined MVA V2 b-tagging algorithm for Phase I/II, possible to incorporate to ttH(bb) analysis

Secondment at Lingvist Technologies

- Industrial secondment at Lingvist in Tallinn, Estonia between 01.05.17 - 30.07.17 in the data science team

- Working on statistical models of human learning: ***based on your test results, what do you know?*** [ref]

- Improving the adaptive teaching algorithm in order to speed up individual learning: ***what and how should we teach you so that you learn faster and are happy?***

- Contributing machine learning & statistical analysis techniques: maximum likelihood, decision trees, ...

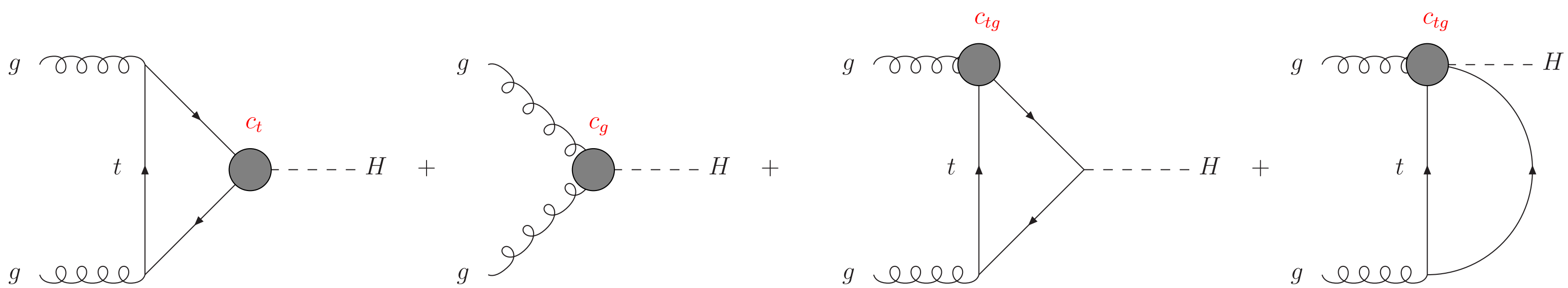
- Learning about cognitive models for learning; database technologies & software development

- Just the first week, a lot of interesting material...

BACKUP SLIDES

$gg \to H$

- 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':

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

Degrande, Gérard, Grojean, Maltoni, Servant

$$\sigma_{LO}(pp \to H) = \sigma_0 \tau_H \frac{d\mathcal{L}^{gg}}{d\tau_H}$$

$$\sigma_0 = \frac{G_F \alpha_s^2(\mu_R)}{288\sqrt{2}\pi} \; |F(\tau_Q)|^2 \qquad \tau_Q = 4\frac{m_t^2}{M_H^2}$$

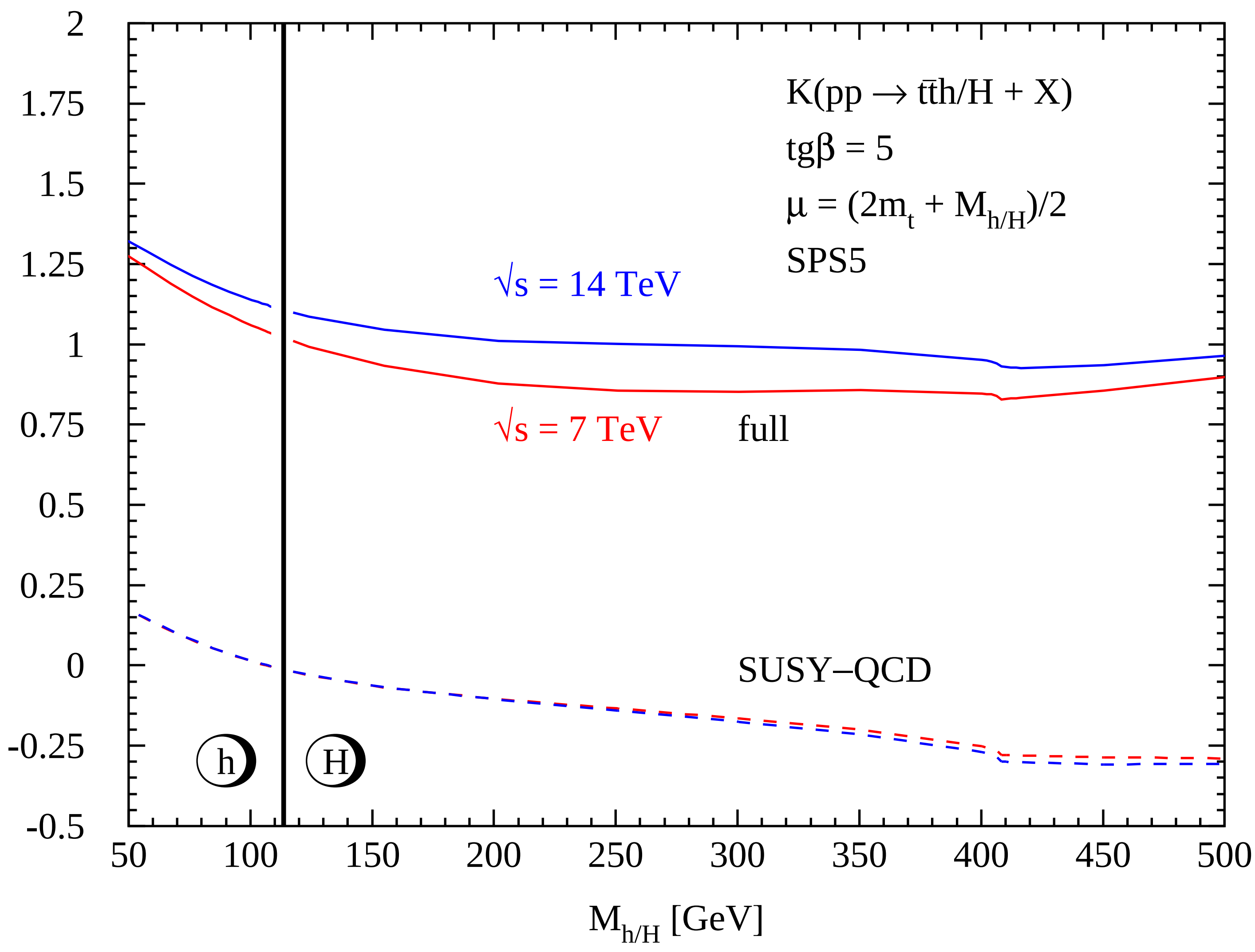
$$F(\tau) = c_t F_1(\tau) + 12 c_g(\mu_R) + \Re e(c_{tg}) \frac{m_t^2}{v^2} F_3(\tau)$$

$$F_1(\tau) = \frac{3}{2}\tau[1 + (1-\tau) f(\tau)] \qquad \to 1$$

$$F_3(\tau) = 3\left(1 - \tau f(\tau) - 2g(\tau) + 2\log\frac{\mu_R^2}{m_t^2}\right) \qquad \to 6\left(\log\frac{\mu_R^2}{m_t^2} - 1\right)$$

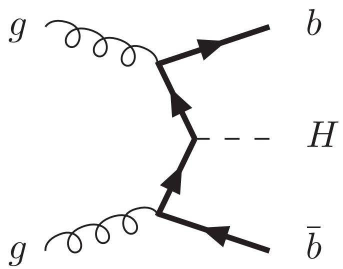
$$f(\tau) = \begin{cases} \arcsin^2 \frac{1}{\sqrt{\tau}} & \tau \geq 1 \\ -\frac{1}{4}\left[\log\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi\right]^2 & \tau < 1 \end{cases}$$

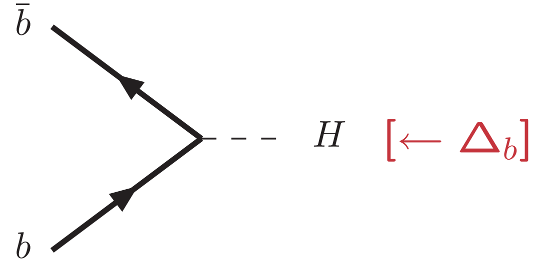
$$g(\tau) = \begin{cases} \sqrt{\tau - 1}\arcsin\frac{1}{\sqrt{\tau}} & \tau \geq 1 \\ \frac{\sqrt{1-\tau}}{2}\left[\log\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi\right] & \tau < 1 \end{cases}$$



Dittmaier, Häfliger, Krämer, S., Walser

$b\bar{b}$+Higgs production





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

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

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

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

	M_A	M_H [GeV]	δ^A_{QCD}	δ^A_{SUSY}	$\delta^A_{SUSY rem}$	δ^H_{QCD}	δ^H_{SUSY}	$\delta^H_{SUSY rem}$
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}

SPS1b

Dittmaier, Häfliger, Krämer, S., Walser

SPS 5

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

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

SPS 1b

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

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

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