PAUL SCHERRER INSTITUT

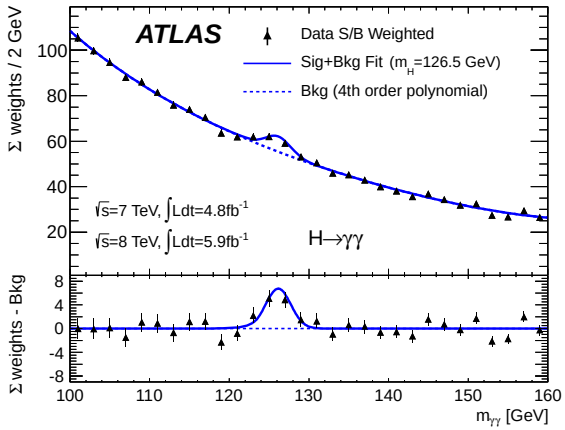
HIGGS THEORY

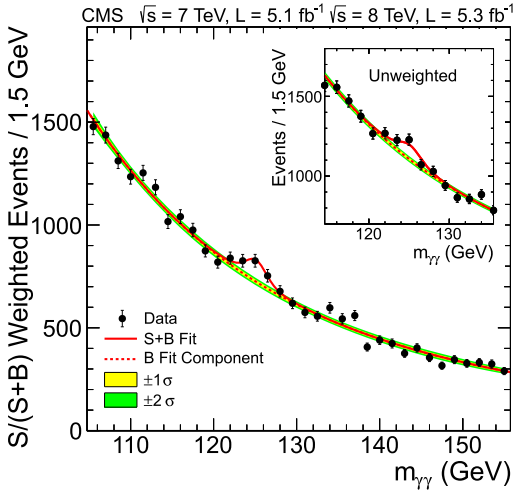
Michael Spira (PSI)

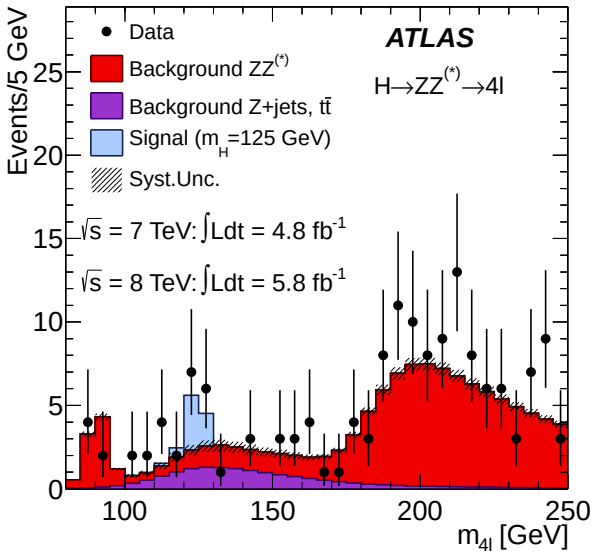
I INTRODUCTION

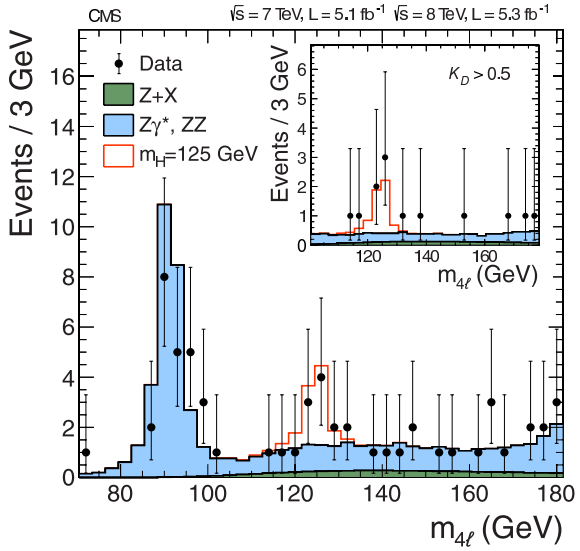
(i) Standard Model

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

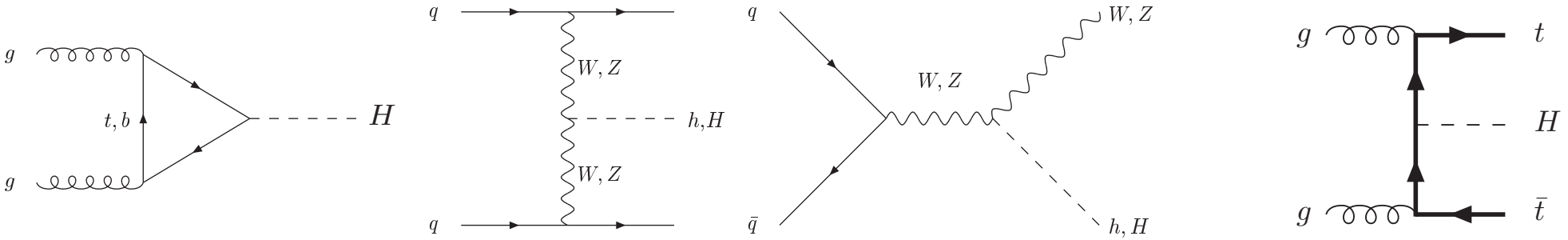


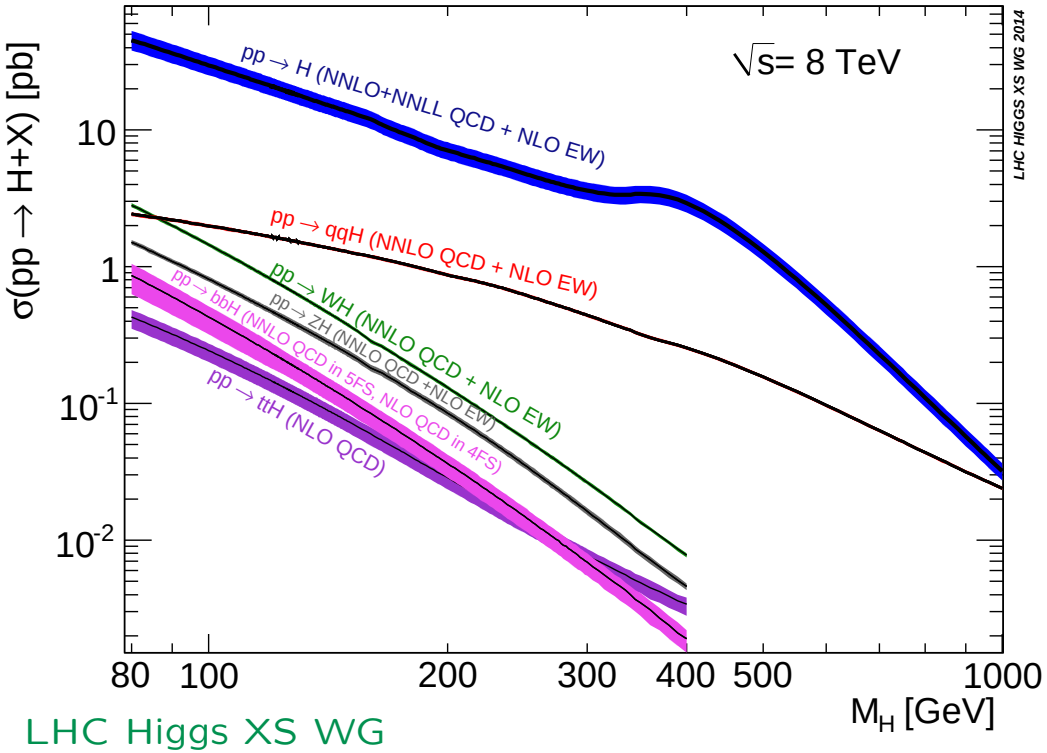




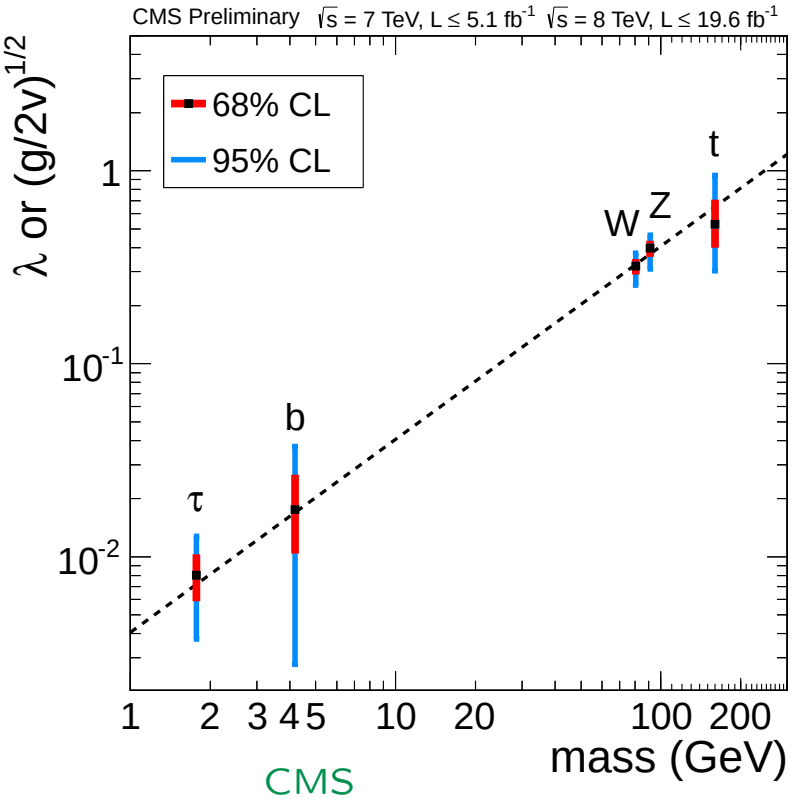


- Higgs Boson Production

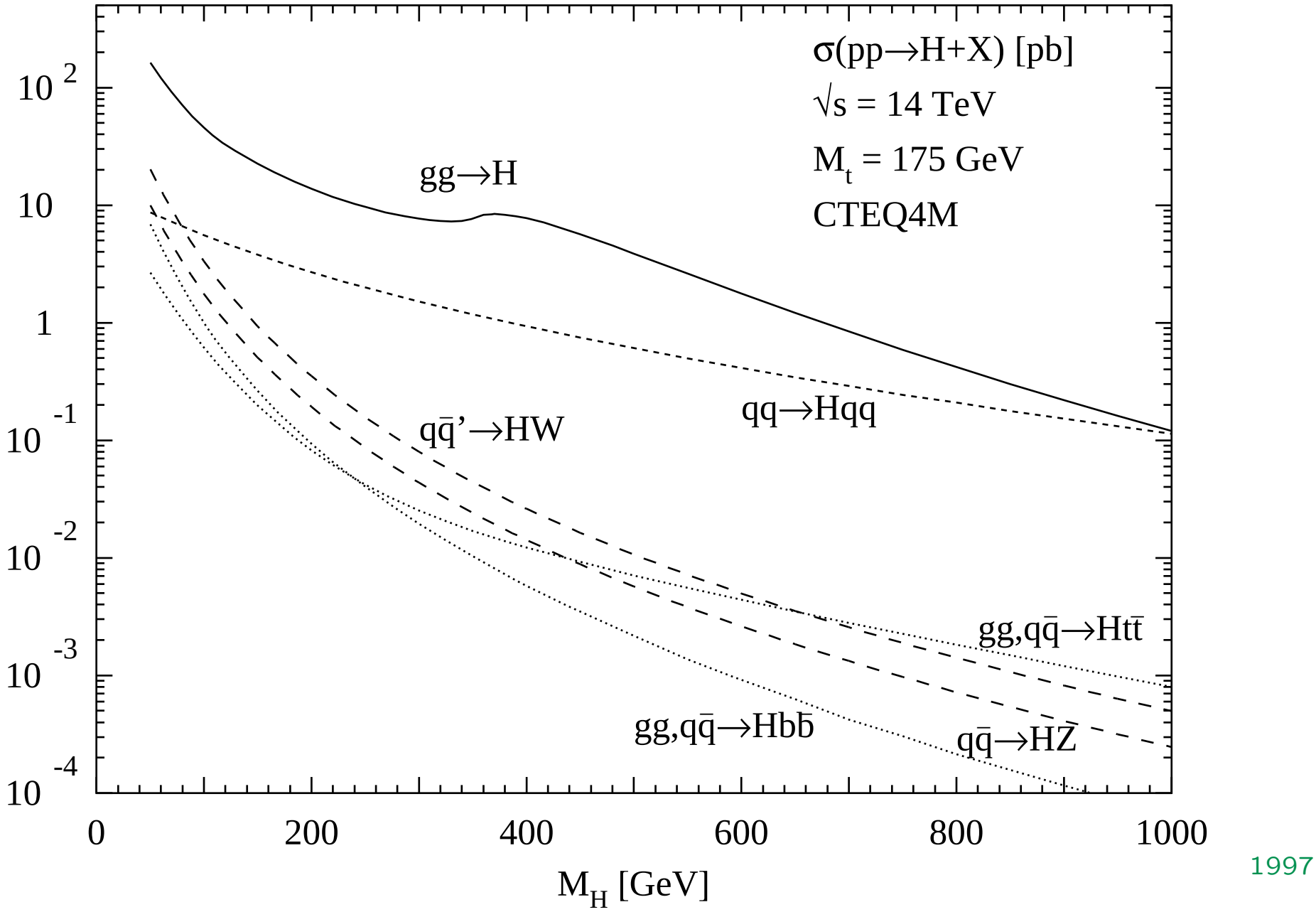




LHC Higgs XS WG



CMS


σ(pp→H+X) [pb]
√s = 14 TeV
M_t = 175 GeV
CTEQ4M
gg→H
qq→Hqq
qq̄'→HW
gg,qq̄→Htt̄
gg,qq̄→Hbb̄
qq̄→HZ
10 2
10
1
10 -1
10 -2
10 -3
10 -4
0
200
400
600
800
1000
M_H [GeV]

1997

(ii) MSSM

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

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

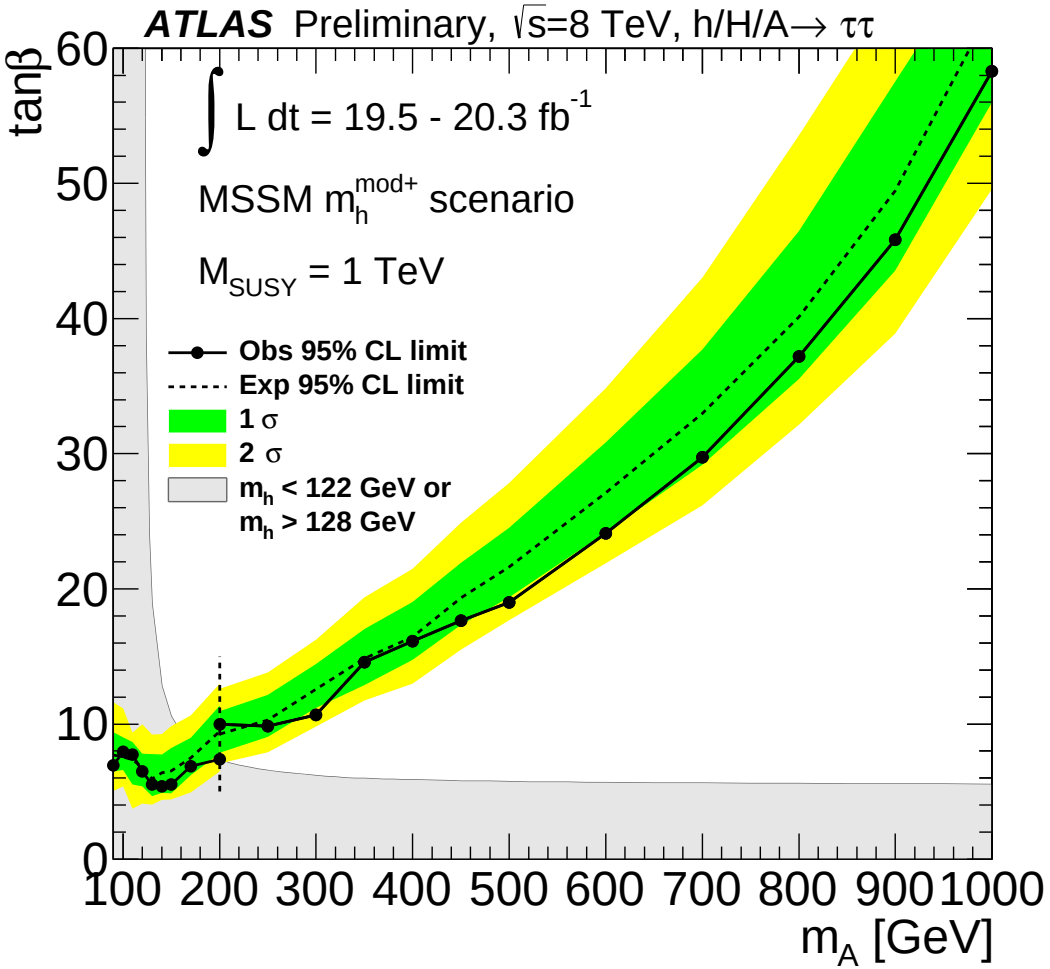
- radiative corrections $\propto m_t^4 \log \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}$ $\rightarrow$ $\boxed{M_h \lesssim 135 \text{ GeV}}$

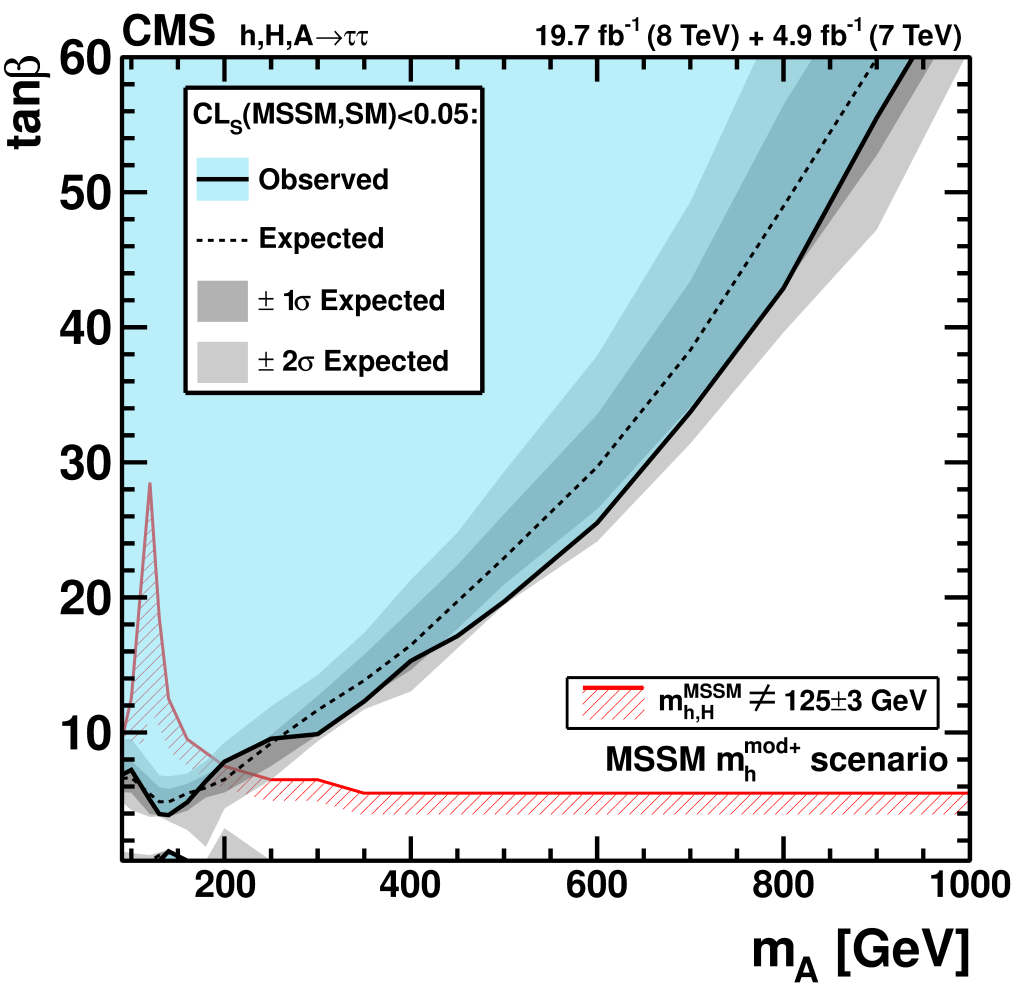
Haber
Carena,...
Heinemeyer,...
Zhang
Slavich,...
...

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

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

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





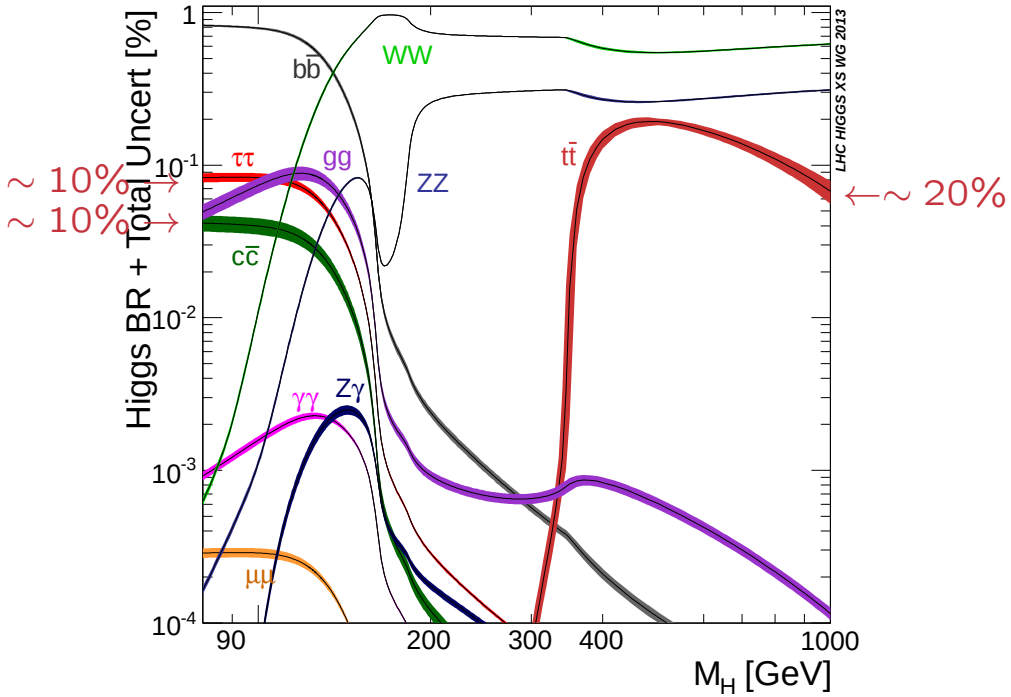
Partial Width	QCD	Electroweak	Total	
$H \to b\bar{b}/c\bar{c}$	$\sim 0.1\%$	$\sim$ 1–2% for $M_H \lesssim 135$GeV	$\sim 2\%$	NNNNLO / NLO
$H \to \tau^+\tau^-/\mu^+\mu^-$		$\sim$ 1–2% for $M_H \lesssim 135$GeV	$\sim 2\%$	NLO
$H \to t\bar{t}$	$\lesssim 5\%$	$\lesssim$ 2–5% for $M_H < 500$GeV	$\sim 5\%$	(NNN)NLO / LO
		$\sim 0.1(\frac{M_H}{1\text{TeV}})^4$ for $M_H > 500$GeV	$\sim$ 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	$\sim$ 0.5–15%	

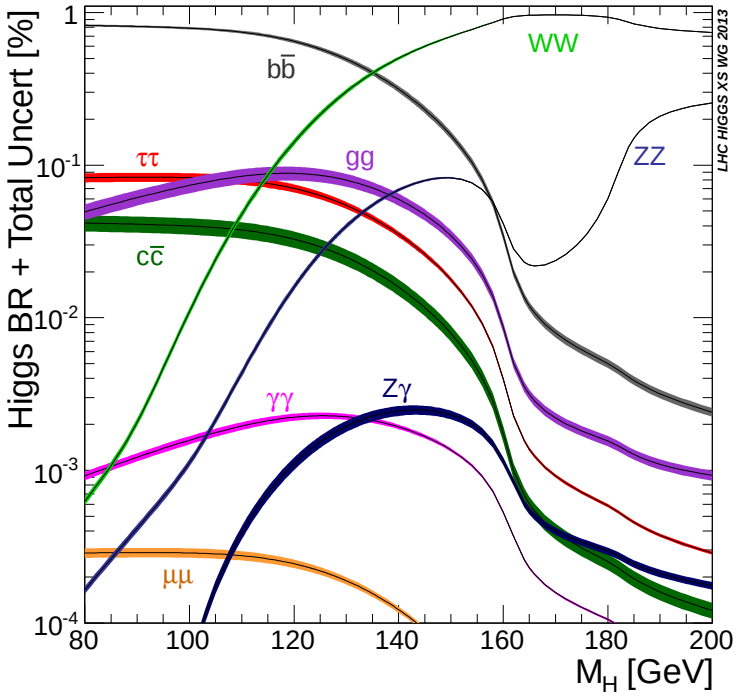
- QCD: variation of Higgs widths for scale by factor 2 and 1/2
  elw: missing HO estimated from known structure at NLO
  $M_H \gtrsim 500$ GeV: Higgs self-interactions dominate error
  different uncertainties added linearly for each channel

- 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

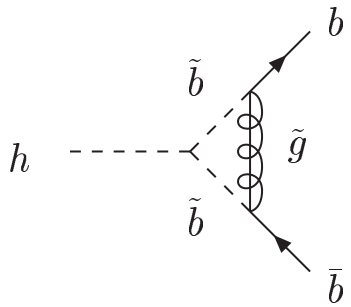
HDECAY & Prophecy4f





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

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

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

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

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

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

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

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

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

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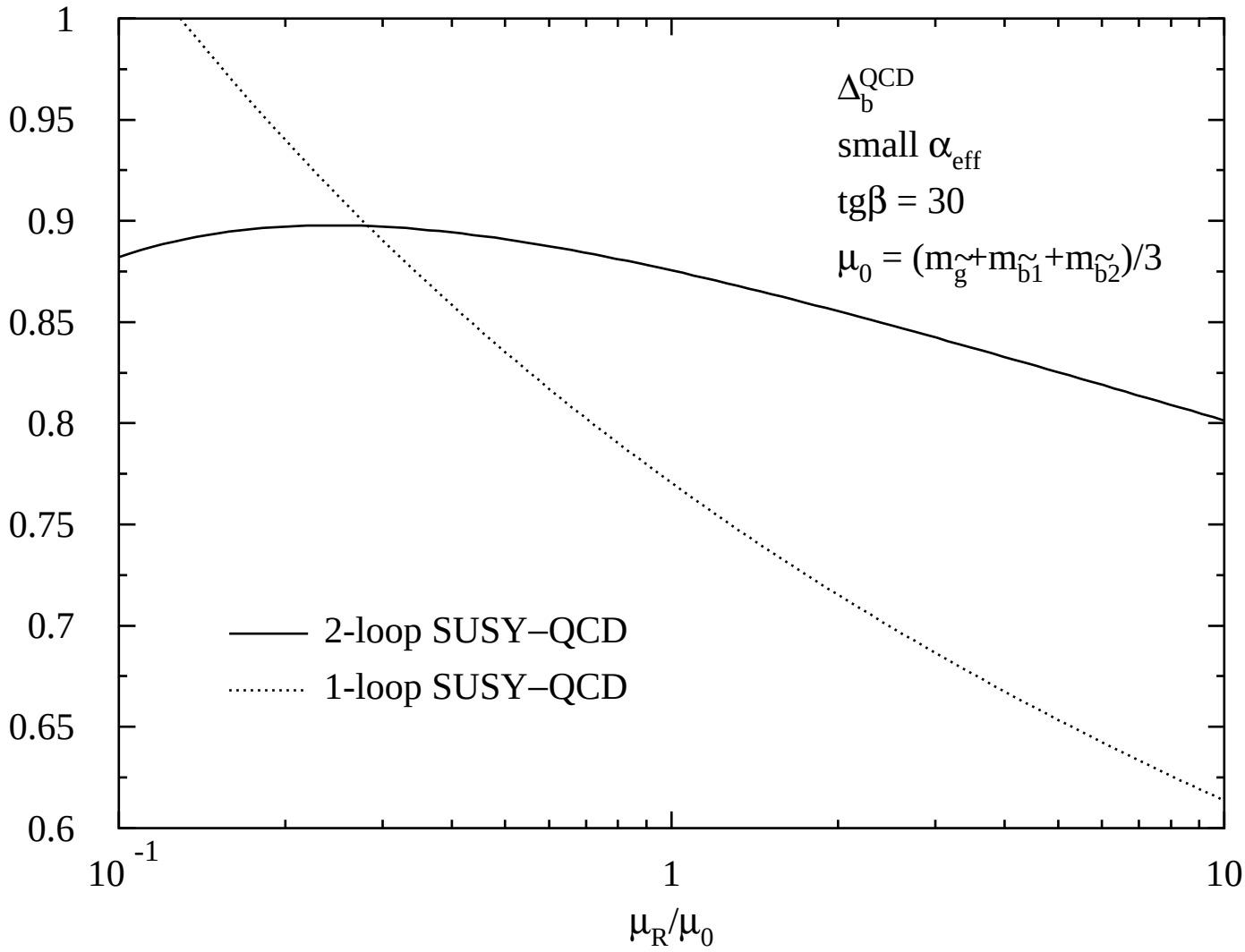
small α_{eff} scenario [modified]

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

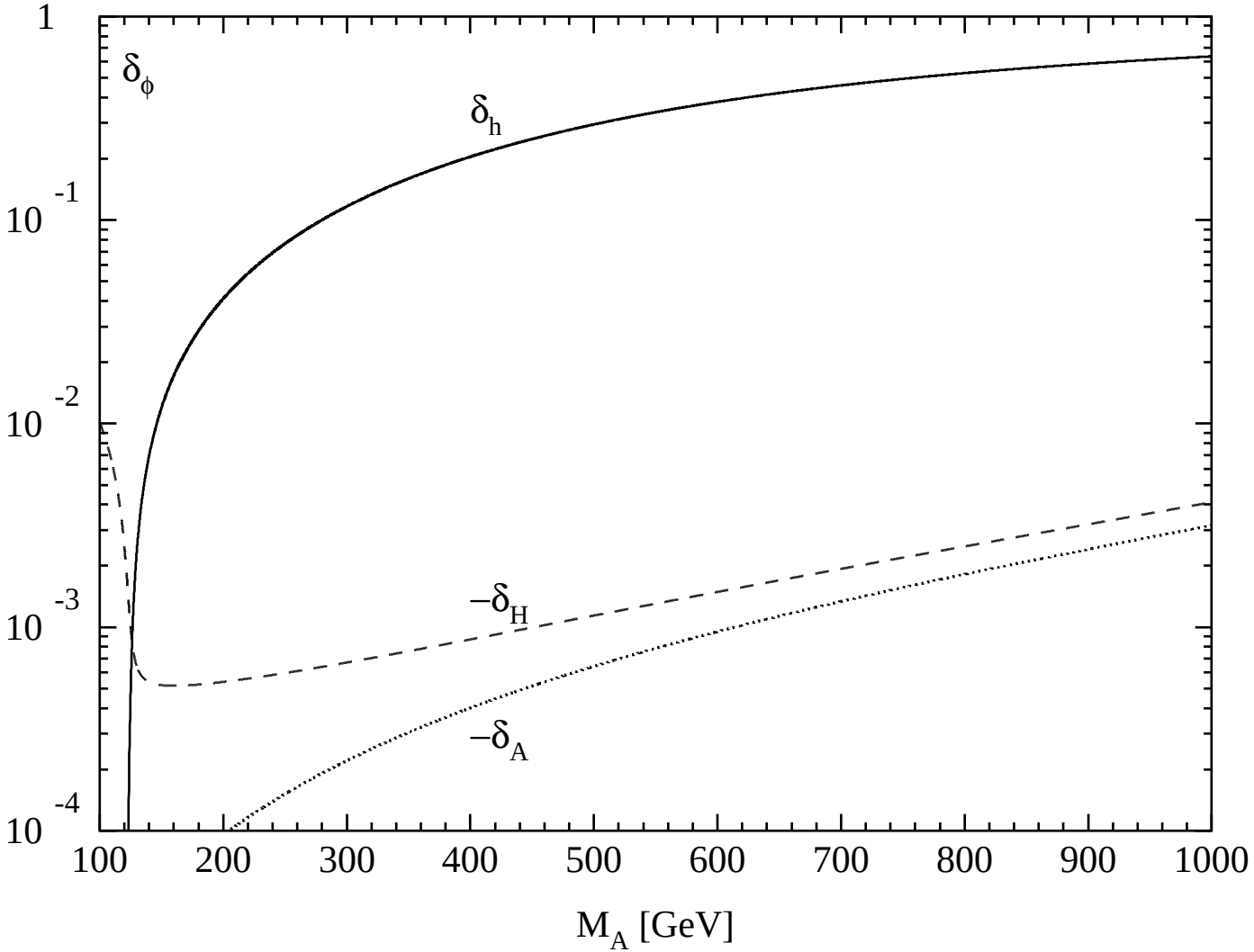
$$
\begin{aligned}
m_{\tilde{t}_1} &= 679 \text{ GeV} \qquad & m_{\tilde{t}_2} &= 935 \text{ GeV} \\
m_{\tilde{b}_1} &= 601 \text{ GeV} \qquad & m_{\tilde{b}_2} &= 961 \text{ GeV}
\end{aligned}
$$



Noth, S.
(Mihaila, Reisser)

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

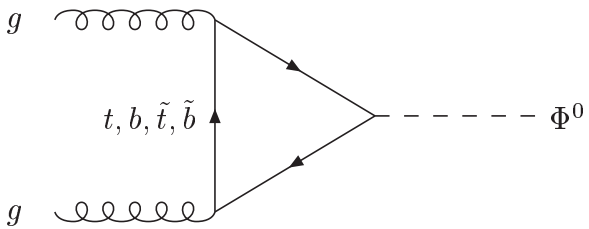
$$M_A^2 \gg M_Z^2 : \mathrm{tg}\alpha \to -\frac{1}{\mathrm{tg}\beta} \quad \Rightarrow \quad \tilde{g}_b^h \to \frac{1}{1+\Delta m_b}\left(1 - \frac{\Delta m_b}{\mathrm{tg}\alpha\ \mathrm{tg}\beta}\right) \to 1$$



Guasch, Häfliger, S.

II HIGGS BOSON PRODUCTION

(i) $gg \to h/H$



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

- NNNLO estimated for $m_t \gg M_\phi \quad \Rightarrow$ scale stabilization
  scale dependence: $\Delta \lesssim 10 - 15\%$

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

- NNLL soft gluon resummation: $5 - 10\%$

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

- elw. corrections: -4% – 6%

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

- 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.

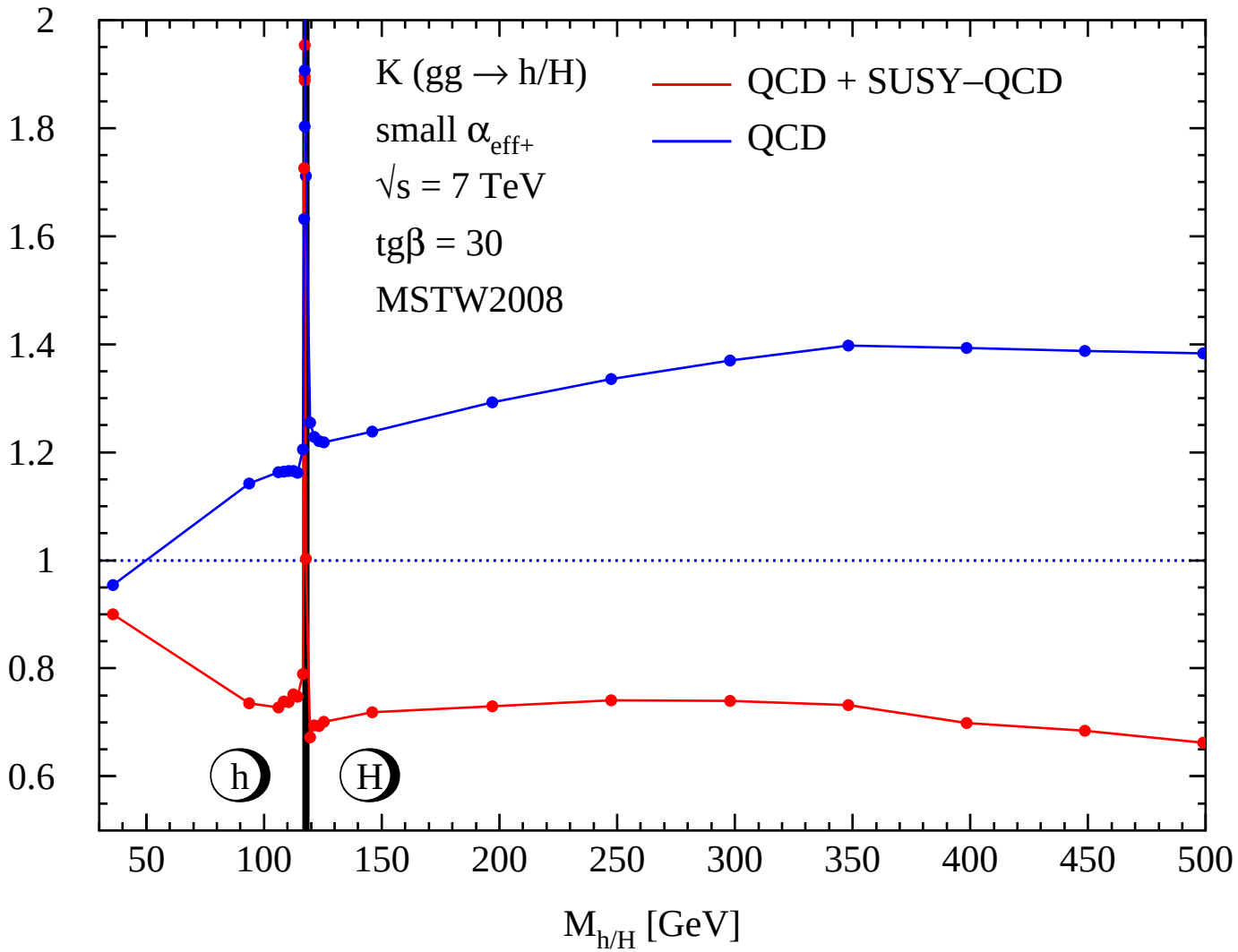
- SUSY-elw. corrections unknown

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

  Bagnaschi, Degrassi, Slavich, Vicini

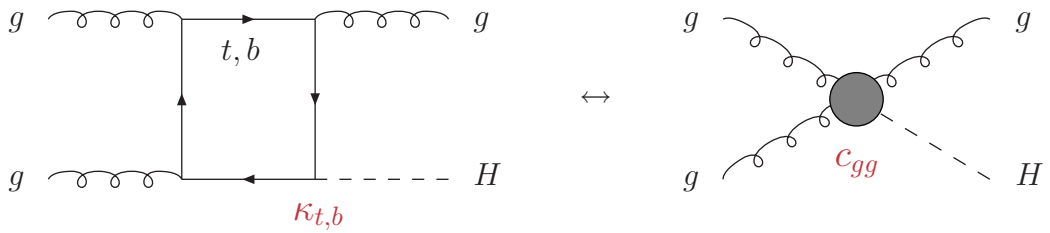
$$\sigma(gg \to \Phi) = \sigma_{LO}(g_t^{\Phi}, \tilde{g}_b^{\Phi}) \left[1 + \delta_{QCD} + \delta_{SQCD}\right]$$

PRELIMINARY

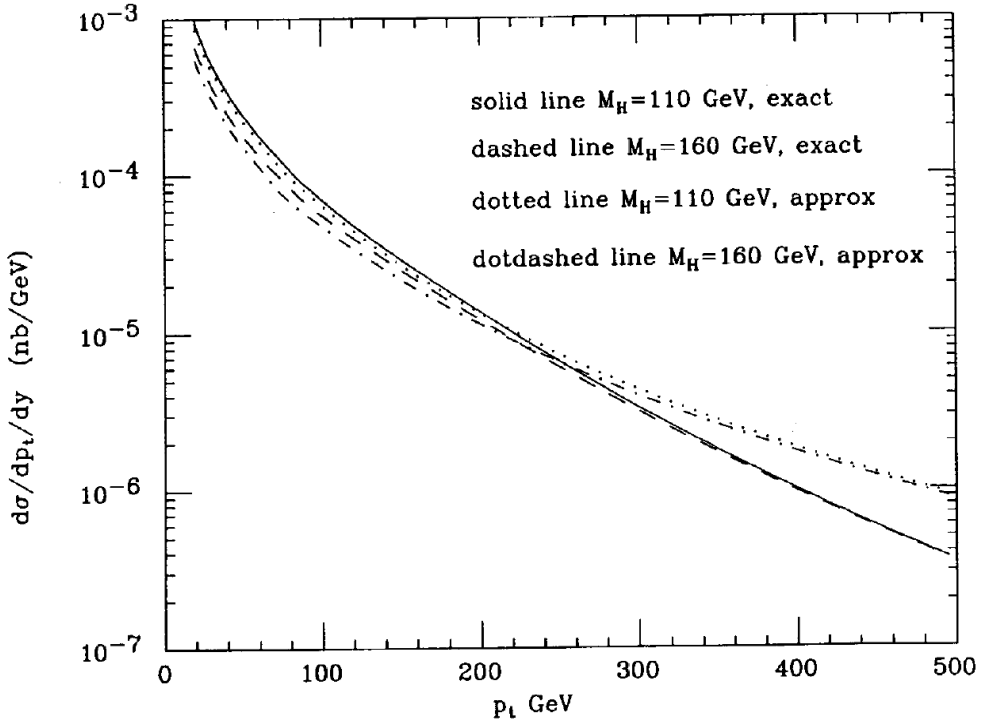


Mühlleitner, Rzehak, S.

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



- distinction dim4 $\leftrightarrow$ dim5



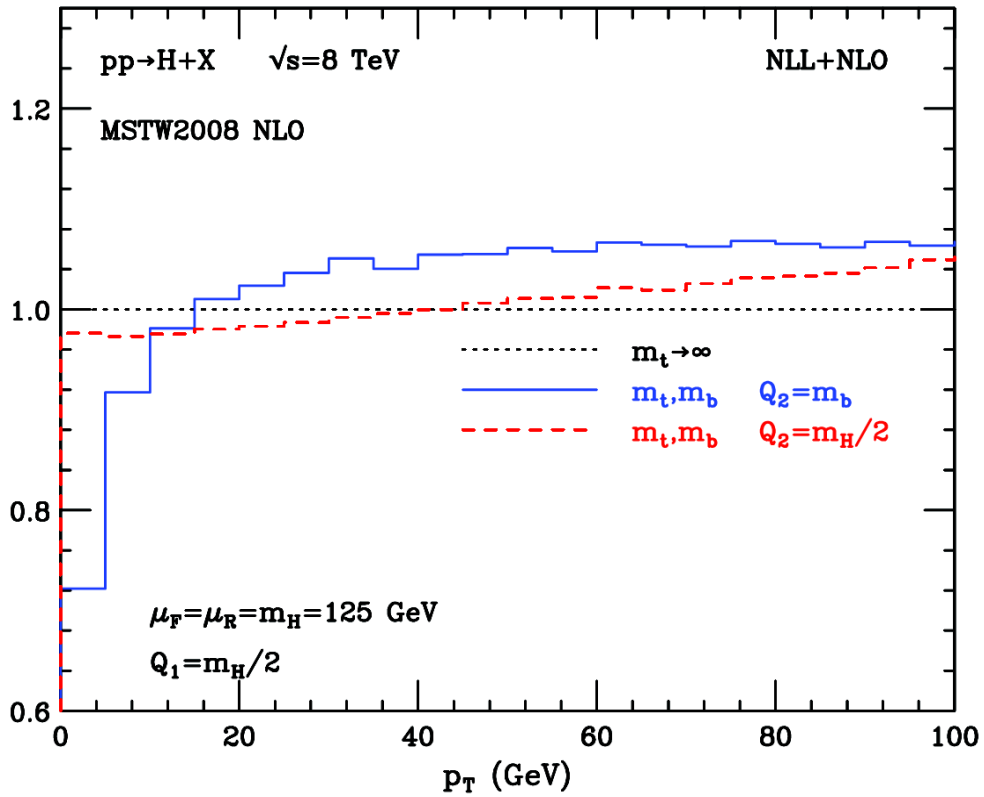
$m_t = 160$ GeV

Ellis, Hinchliffe, Soldate, van der Bij

- QCD corrections large $[m_t^2 \gg M_H^2, p_{TH}^2]$
  $[\leftarrow b$ @ large tgβ: LO, soft spectrum]

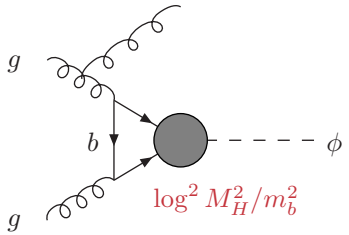
Schmidt
de Florian, Grazzini, Kunszt
Ravindran, Smith, van Neerven
Kauffman
Balazs, Yuan
Bozzi, Catani, de Florian, Grazzini

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

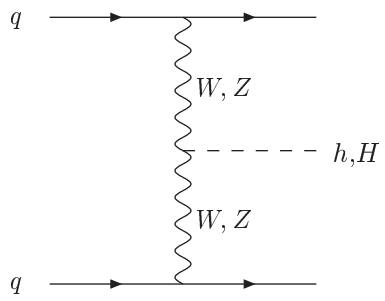


Grazzini, Sargsyan

- 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: $\sim 10\%$

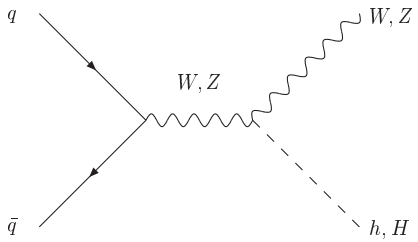
Ciccolini, Denner, Dittmaier

- full NLO SUSY-elw. corrections

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

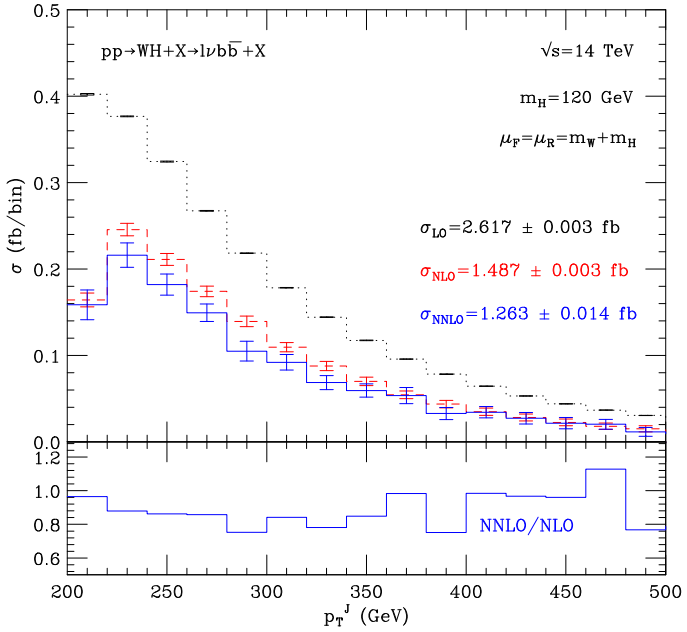
- implemented in VBFNLO

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

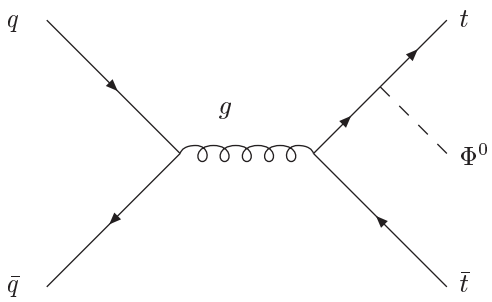


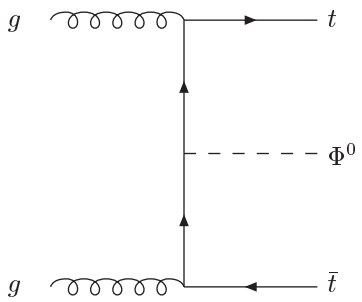
Glashow,. . .
Kunszt,. . .

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



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





dominant

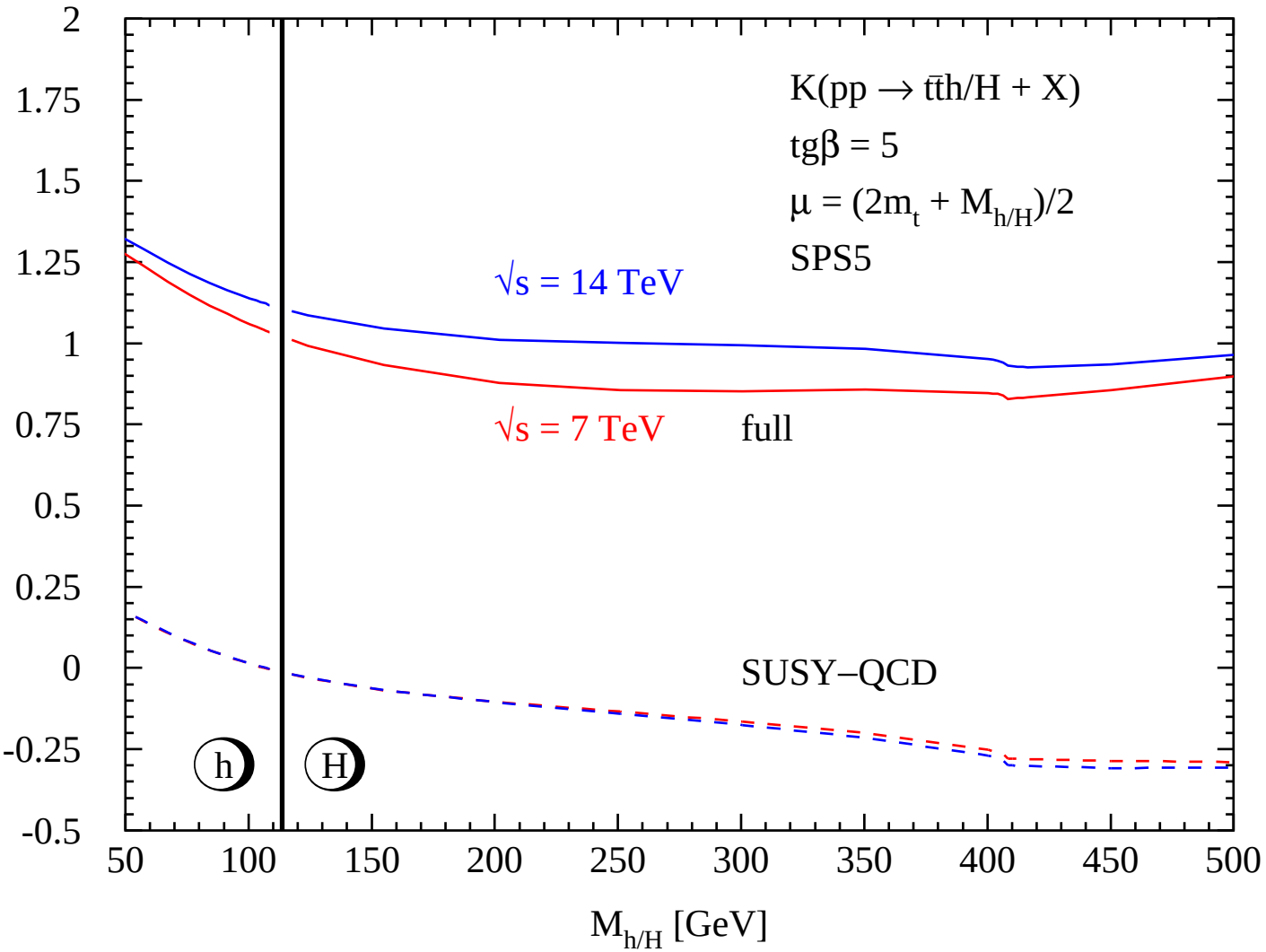
Kunszt
Gunion
Marciano, Paige

- $t\bar{t}h \to t\bar{t}b\bar{b}$ important @ LHC $\to$ top Yukawa cplg.
- QCD corrections [SM]: $\sim 20\%$

  Beenakker,. . .
  Dawson, . . .
- SUSY-QCD corrections: moderate

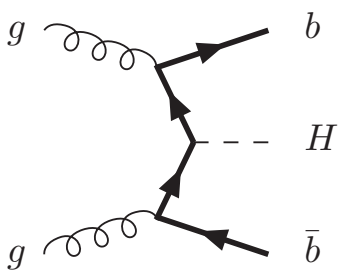
  Dittmaier, Häfliger, Krämer, S., Walser
- link to parton showers: aMC@NLO, PowHel

  Frederix et al.
  Garzelli, Kardos, Papadopoulos, Trócsányi

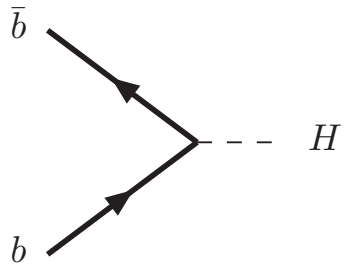


Dittmaier, Häfliger, Krämer, S., Walser

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



NLO



$[\leftarrow \Delta_b]$

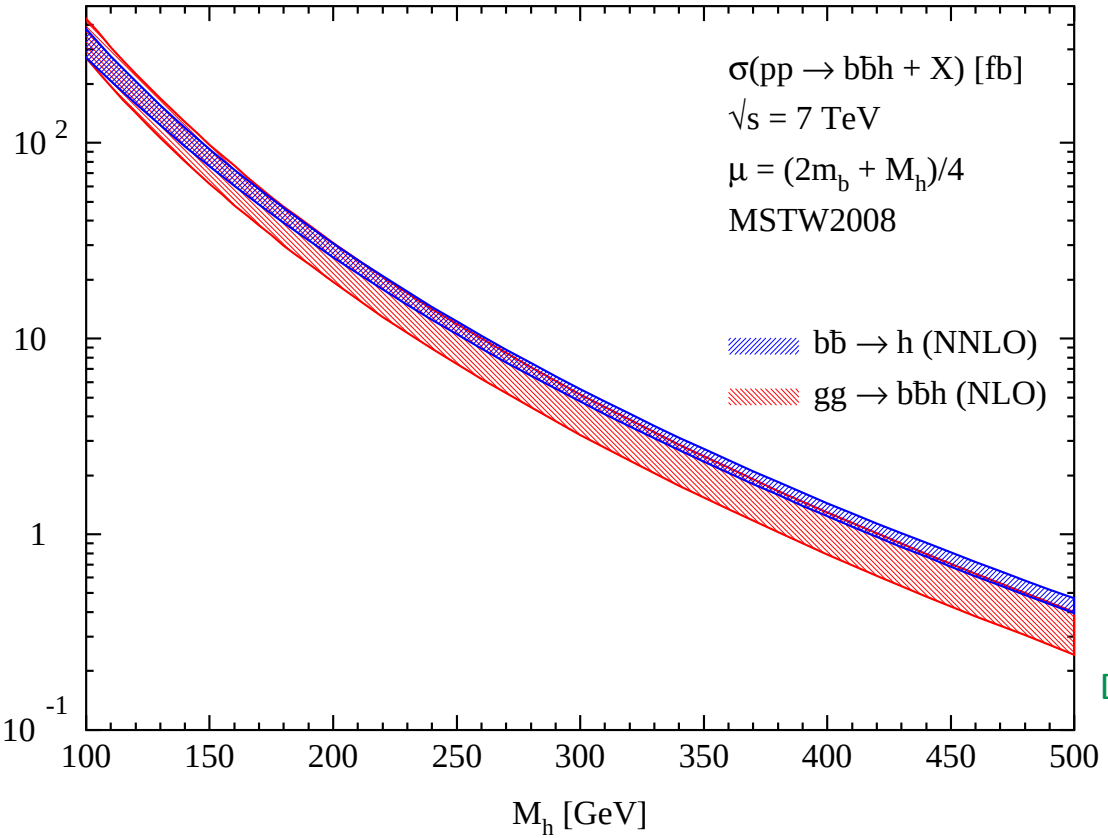
NNLO

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



Santander matching:

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

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

Harlander, Krämer, Schumacher

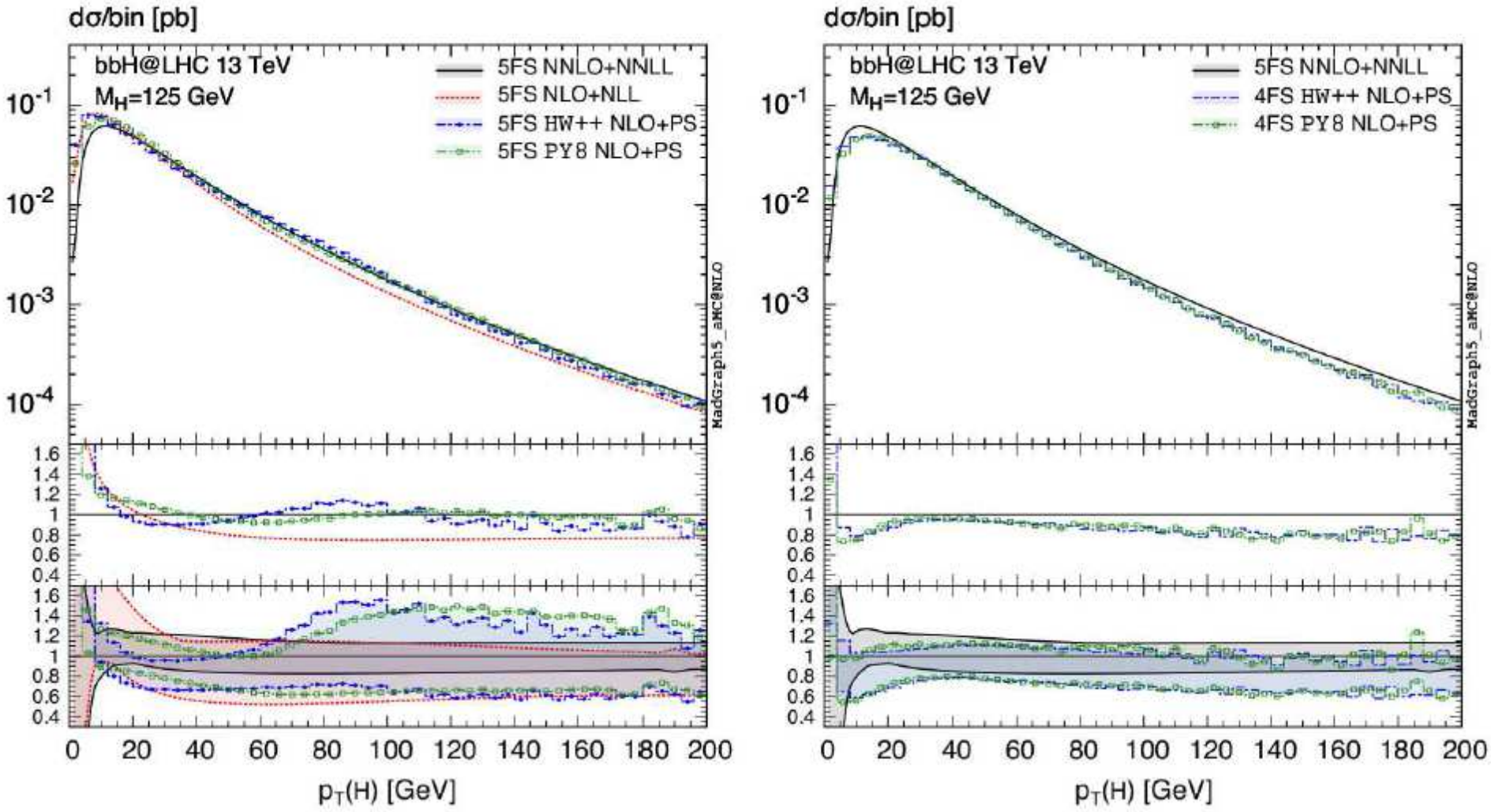
Dittmaier, Krämer, S.
Dawson, Jackson, Reina, Wackeroth
Harlander, Kilgore

	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}

Dittmaier, Häfliger, Krämer, S., Walser

distributions



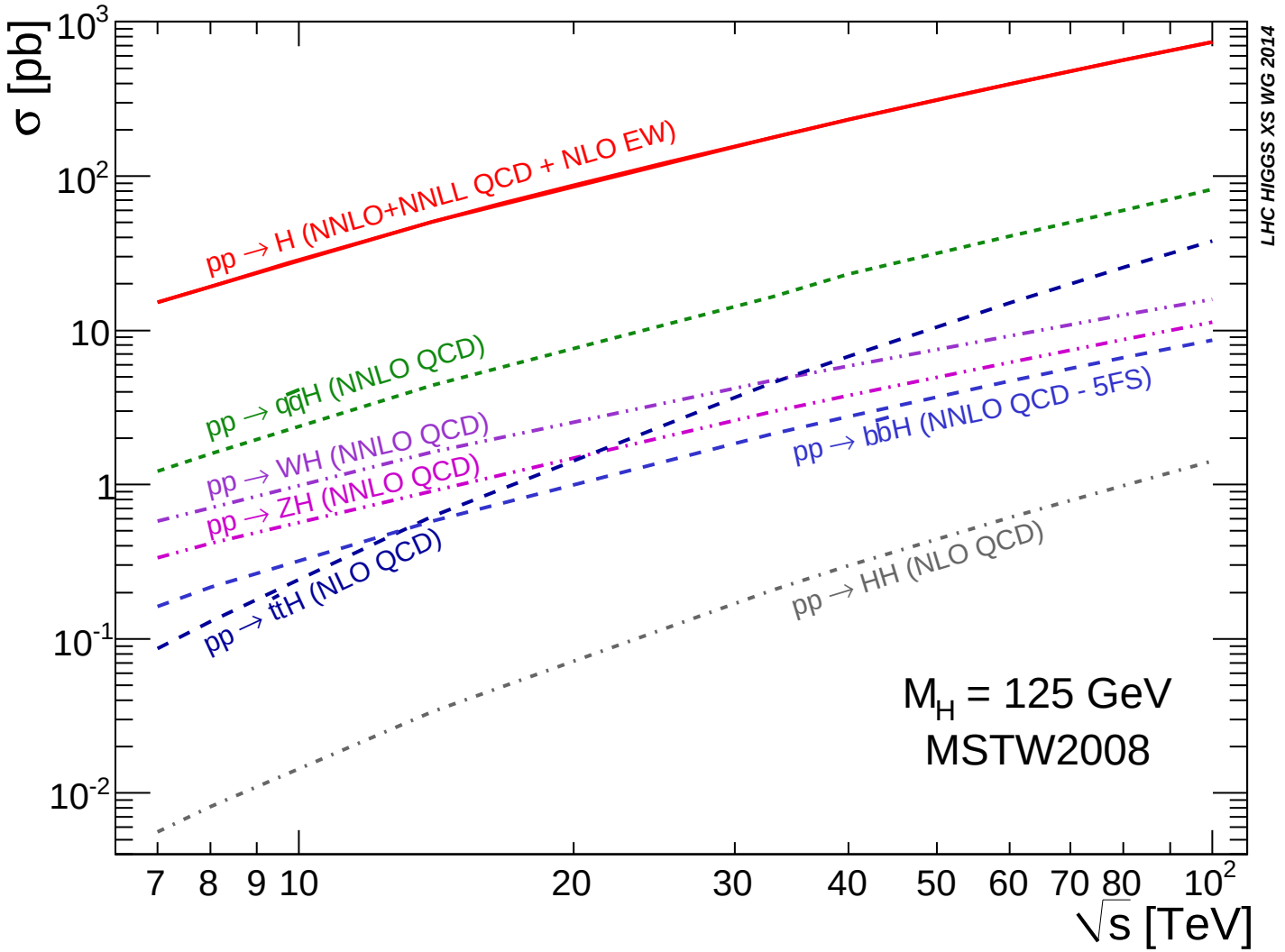
Wiesemann, Frederix, Frixione, Hirschi, Maltoni, Torrielli

III *CONCLUSIONS*

- Higgs boson searches/studies at LHC belong to major endeavours
- most QCD and elw. corrections known $\rightarrow \Delta \lesssim 10 - 15\%$ @ LHC
- important to develop NLO event generators [$\leftarrow$ backgrounds]

BACKUP SLIDES

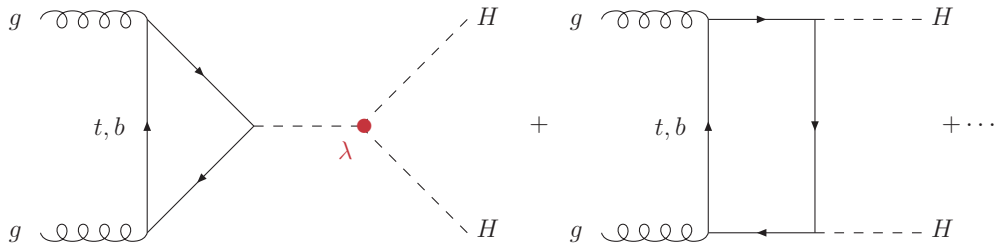
Energy Dependence → VLHC



LHC Higgs XS WG

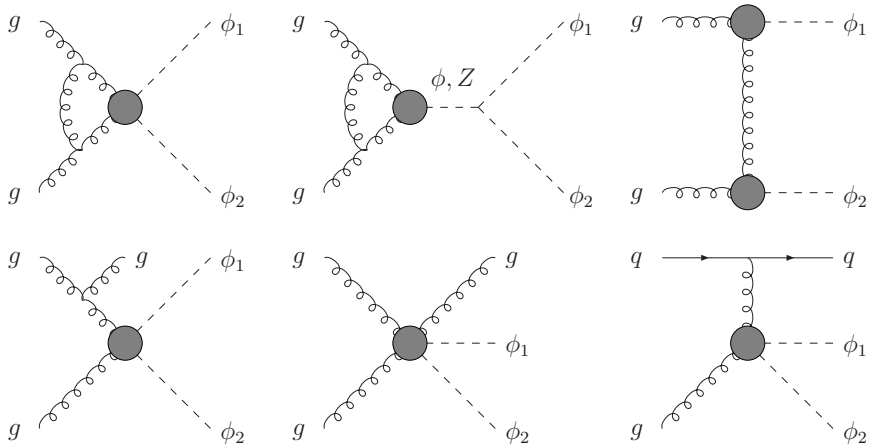
$(i)\ gg \to HH$

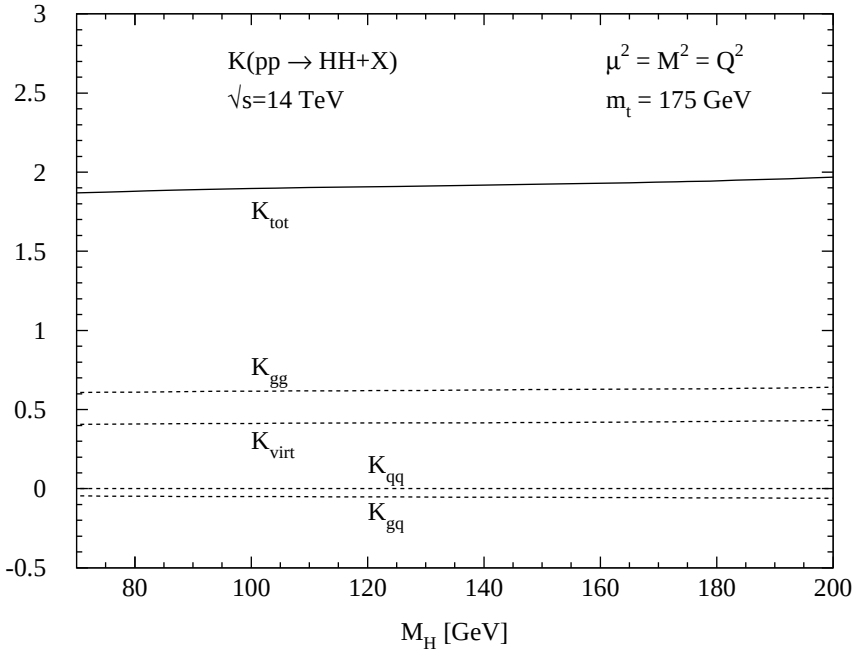
SM



- 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, Djouadi, S.

- 2-loop QCD corrections:

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

Grigo, Hoff, Melnikov, Steinhauser

- NLO mass effects @ NLO in real corrections

Frederix,. . .

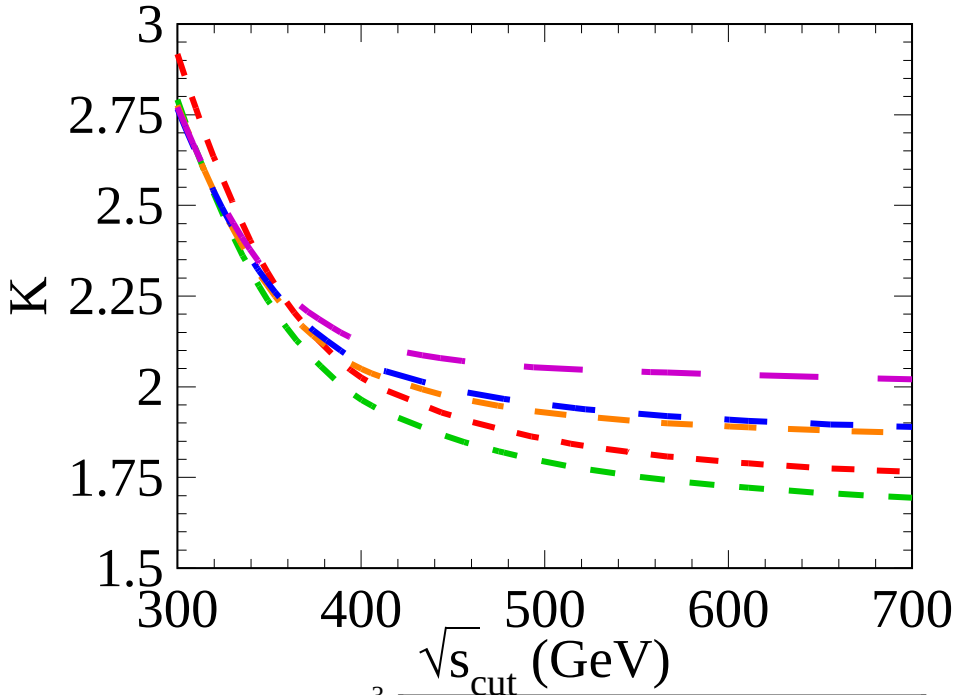
- NNLO QCD corrections: $\sim 20\%$

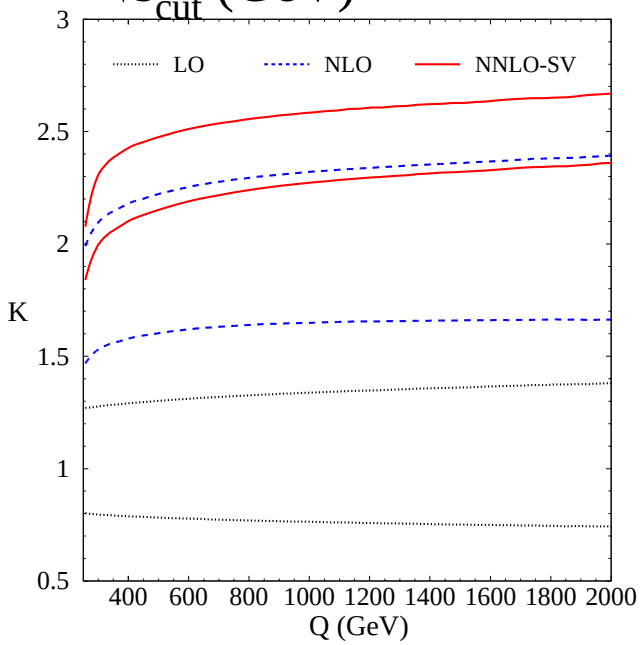
$[M_H^2 \ll 4m_t^2]$ de Florian, Mazzitelli

- soft gluon resummation [SCET]: $\sim 30\%$

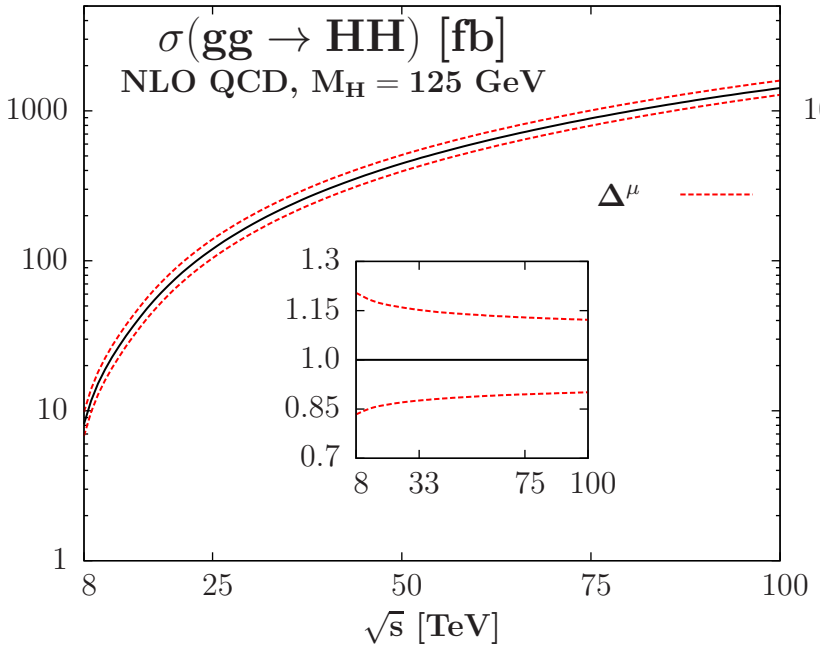
$[M_H^2 \ll 4m_t^2]$

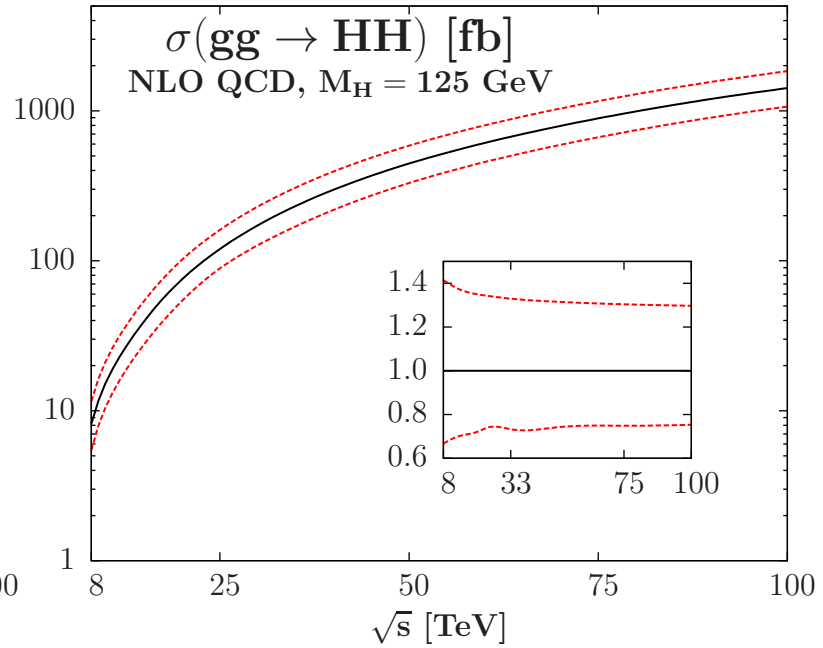
Shao, Li, Li, Wang





Uncertainties:





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

- scale: $\sim 15 - 20\%$
- PDF+α_s: $\sim 6 - 7\%$ [MSTW2008]
- EFT: $\sim 10\%$
- total: $\sim 30 - 40\%$

Channels: need 3 ab^{-1}

$HH \to b\bar{b}\gamma\gamma$: low signal rate, most promising?
$HH \to b\bar{b}\tau^+\tau^-$: mass reconstruction difficult
$HH \to b\bar{b}W^*W^{(*)}$: hopeless?

- $b\bar{b}\gamma\gamma$: $^{+160\%}_{-190\%}$ @ 600 fb^{-1}

  $^{+74\%}_{-62\%}$ @ 6 ab^{-1}

  Baur, Plehn, Rainwater

- boosted kinematics: less sensitivity to λ Dolan, Englert, Spannowsky

- $HH + jet \to b\bar{b}b\bar{b}j, b\bar{b}\tau^+\tau^-j$ promising? Dolan, Englert, Spannowsky

- reduction of THUs by ratio $\dfrac{\sigma(gg \to HH)}{\sigma(gg \to H)} \to \dfrac{\delta\lambda}{\lambda} \sim 30\%$?

  Goertz, Papaefstathiou, Yang, Zurita