PAUL SCHERRER INSTITUT

HIGGS BOSON PRODUCTION AT THE LHC

Michael Spira (PSI)

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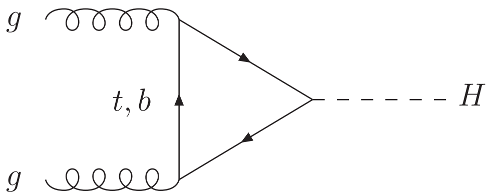
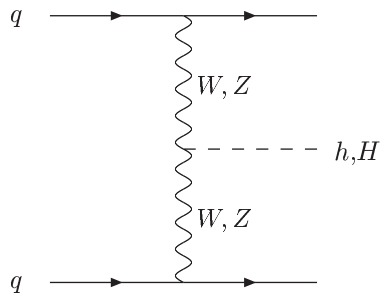
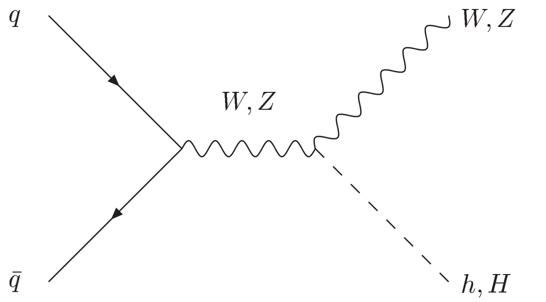
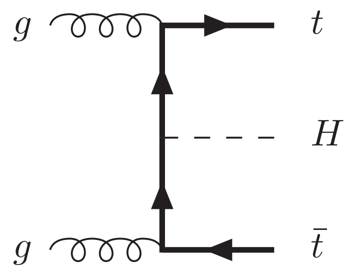
I INTRODUCTION

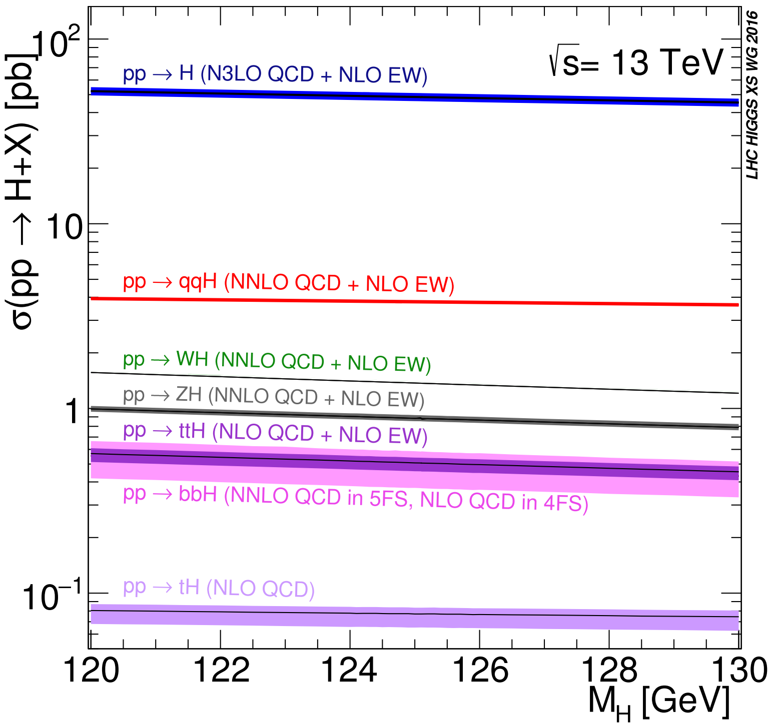
- Higgs Boson Production

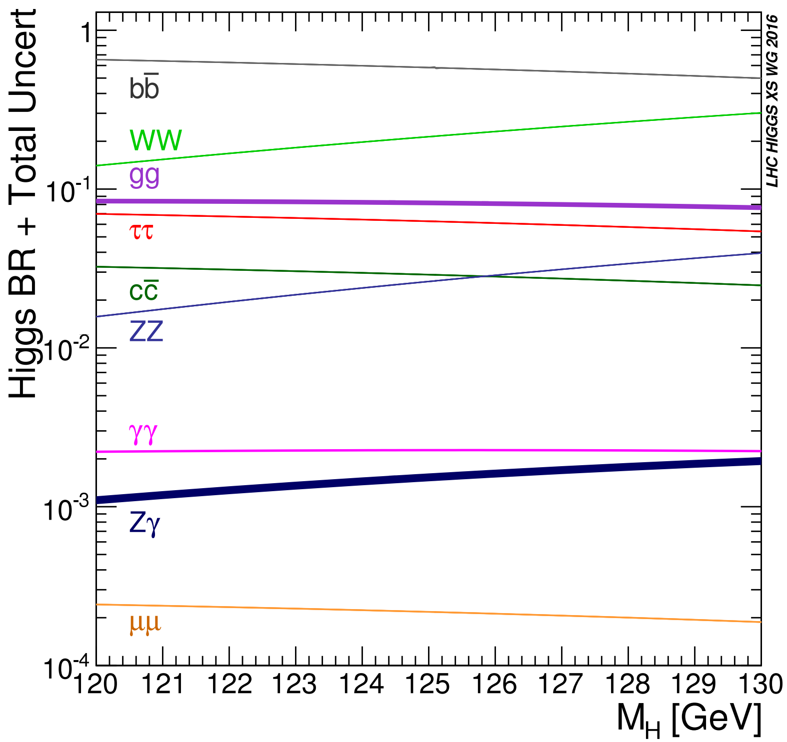






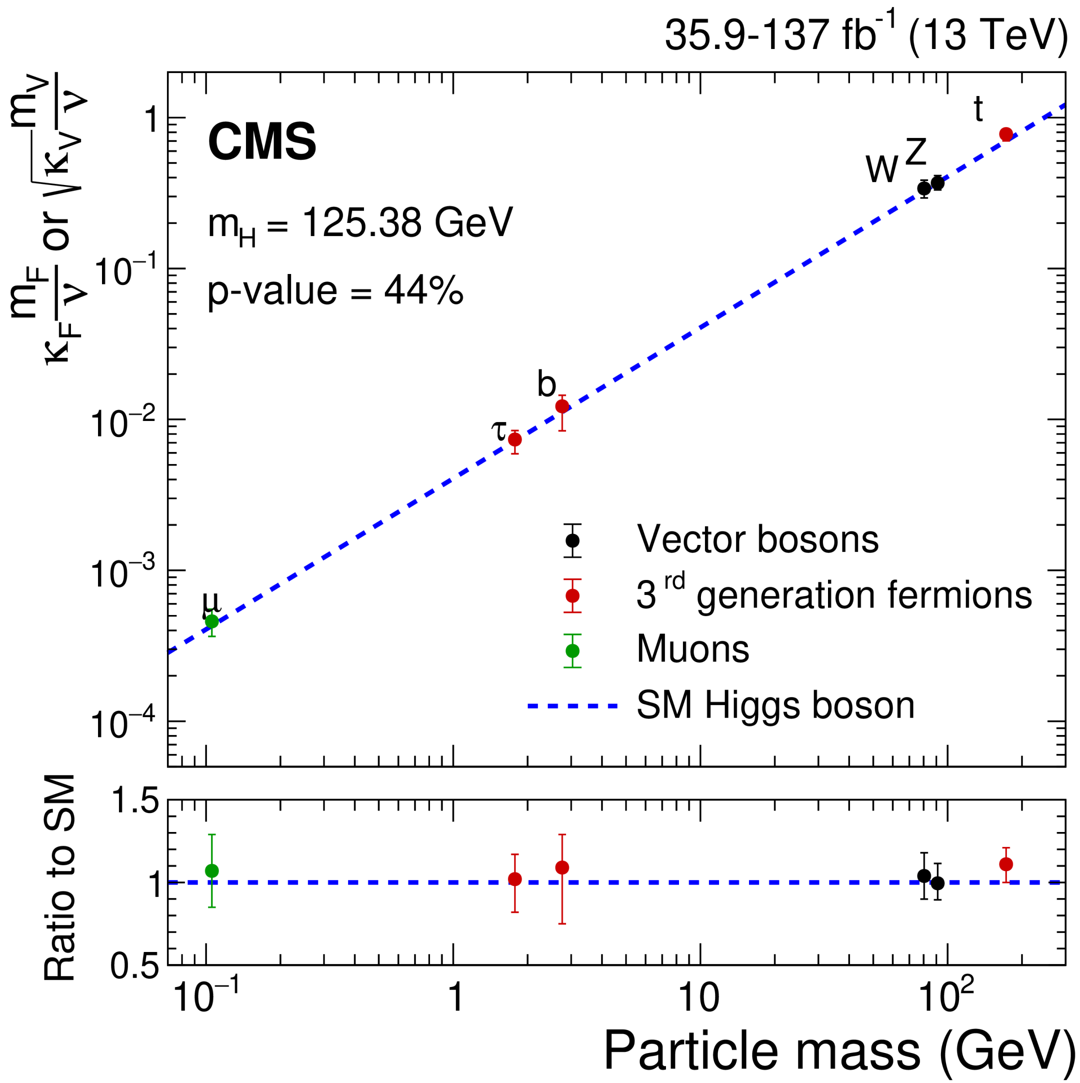






LHC Higgs XS WG

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



MSSM

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

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

- radiative corrections $\propto m_t^4 \log \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}$ $\rightarrow$ $M_h \lesssim 130$ 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	ctgβ	tgβ $[-\mathrm{ctg}\beta]$	0

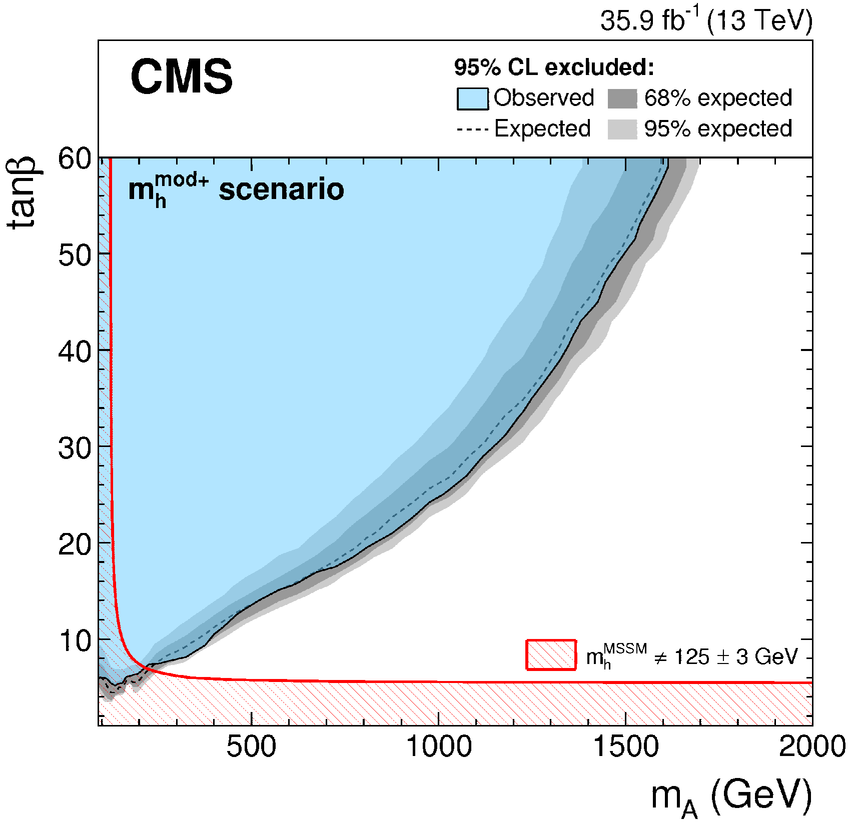
2HDM type II [type I]

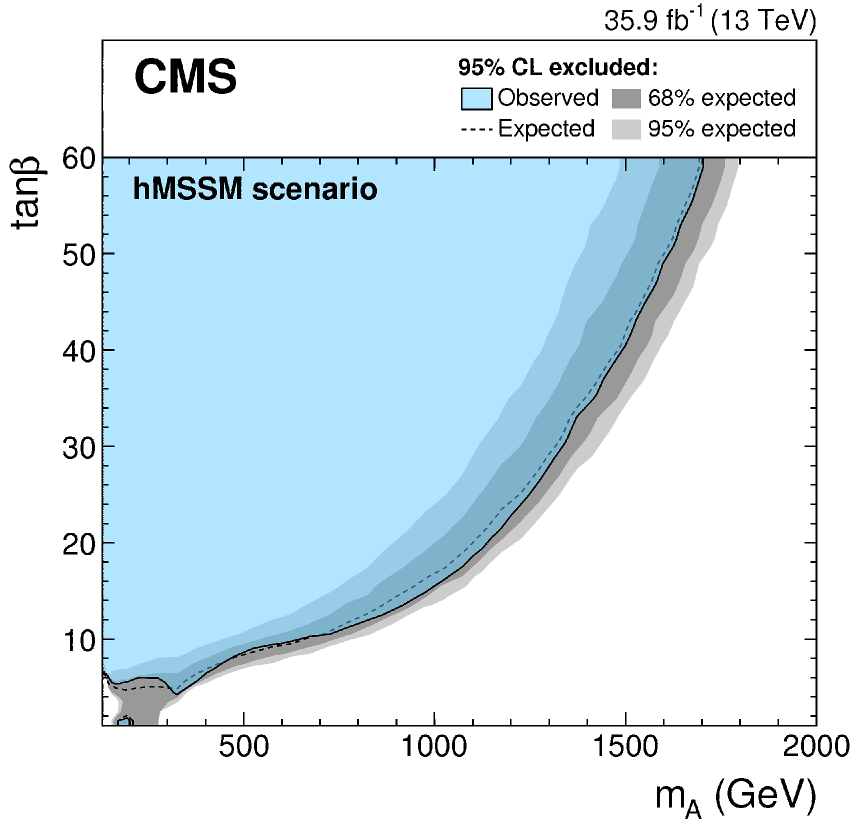
- Yukawa couplings: tg$\beta\uparrow$ $\Rightarrow$ $g_u^\phi\downarrow$ $g_d^\phi\uparrow$ $g_V^\phi\downarrow$

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

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

↓ ↓



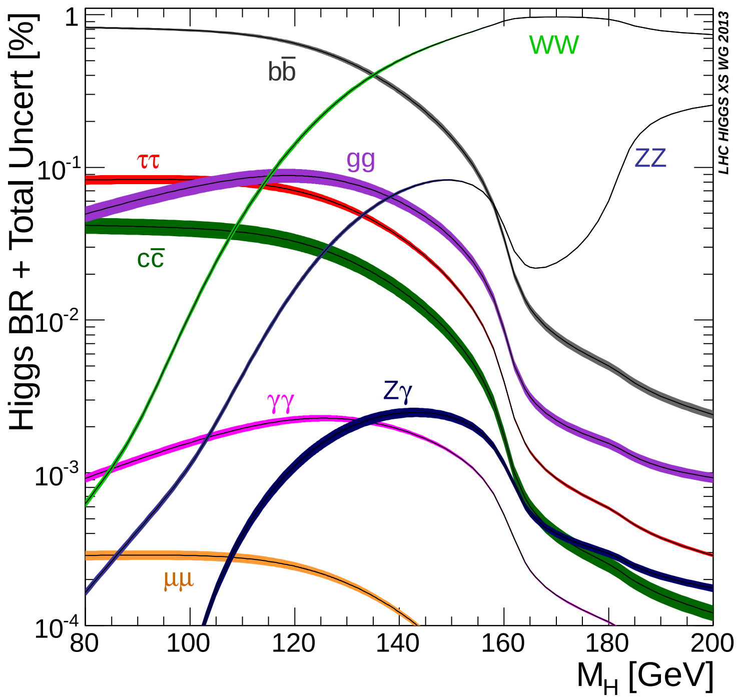


ATLAS: similar results

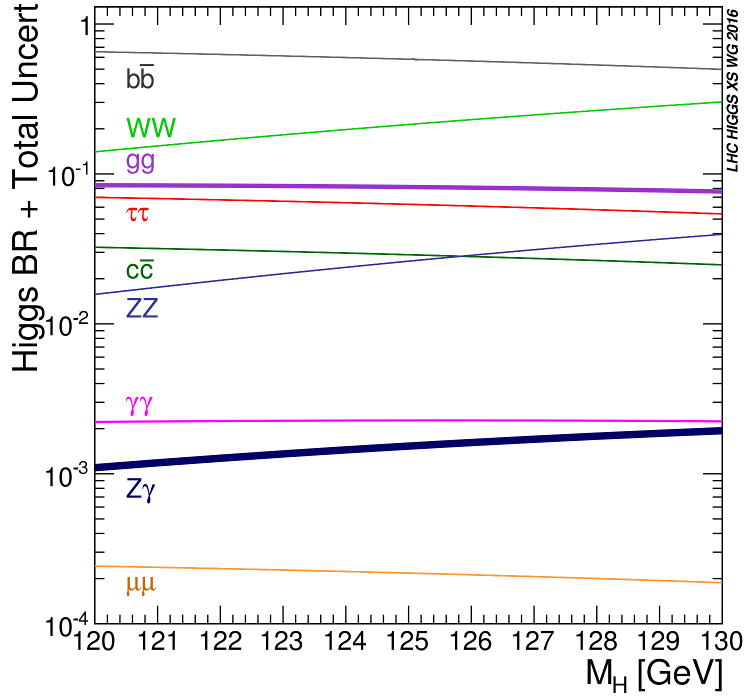
II HIGGS BOSON DECAYS

YR3 HDECAY & Prophecy4f YR4

~ 10% →
~ 10% →



⟶

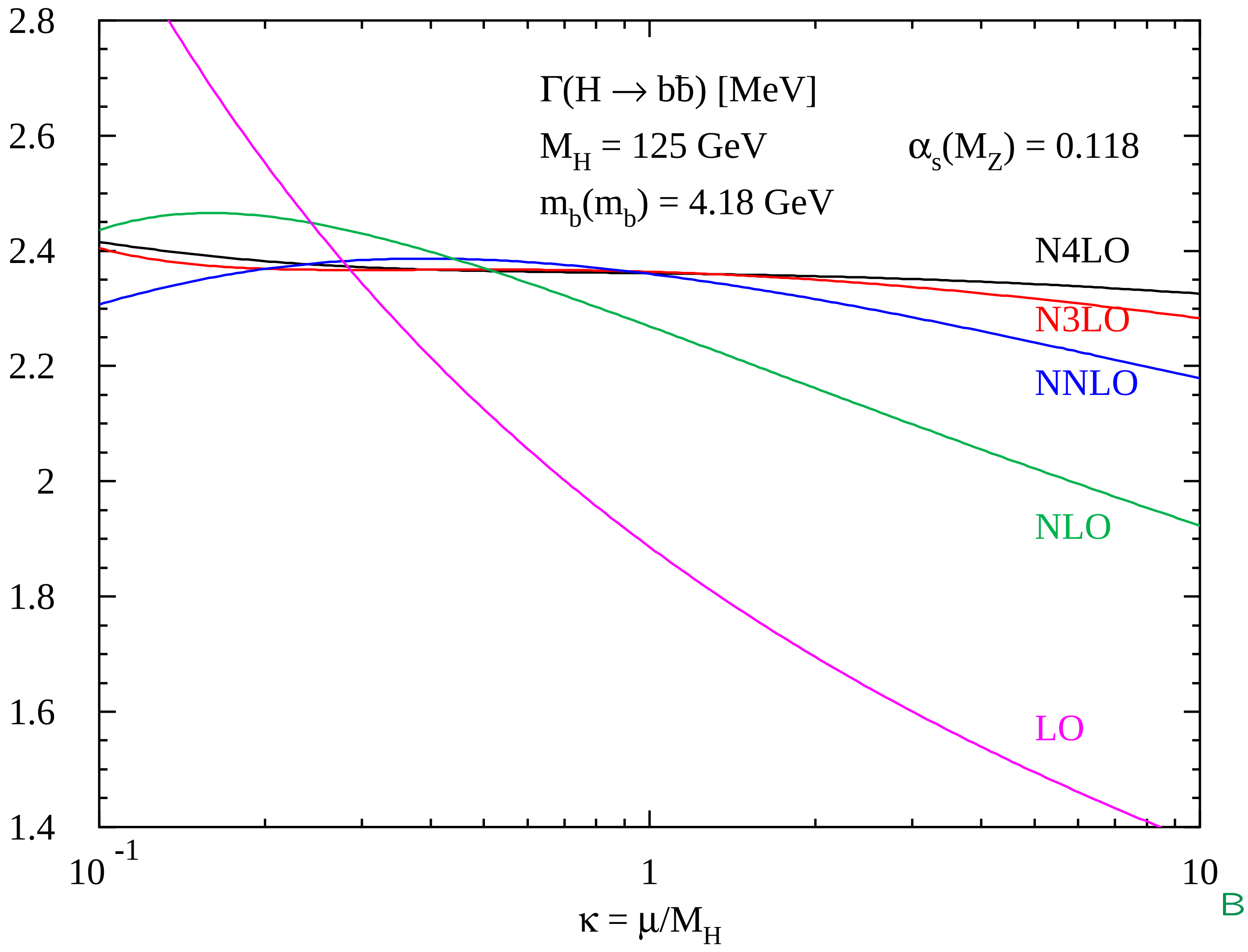


Denner, Heinemeyer, Puljak, Rebuzzi, S.

$$\Gamma[H \to b\bar{b}] = \frac{3G_F M_H}{4\sqrt{2}\pi} \, \overline{m}_b^2(M_H) \, \Delta_{\rm QCD}$$

↑

log resummation → ~ factor 1/2
(larger than BSM effects!)



Braaten, Leveille
Drees, Hikasa
Kataev,. . .
Chetyrkin,. . .
etc.

→ HDECAY

Djouadi, Kalinowski, Mühlleitner, S.

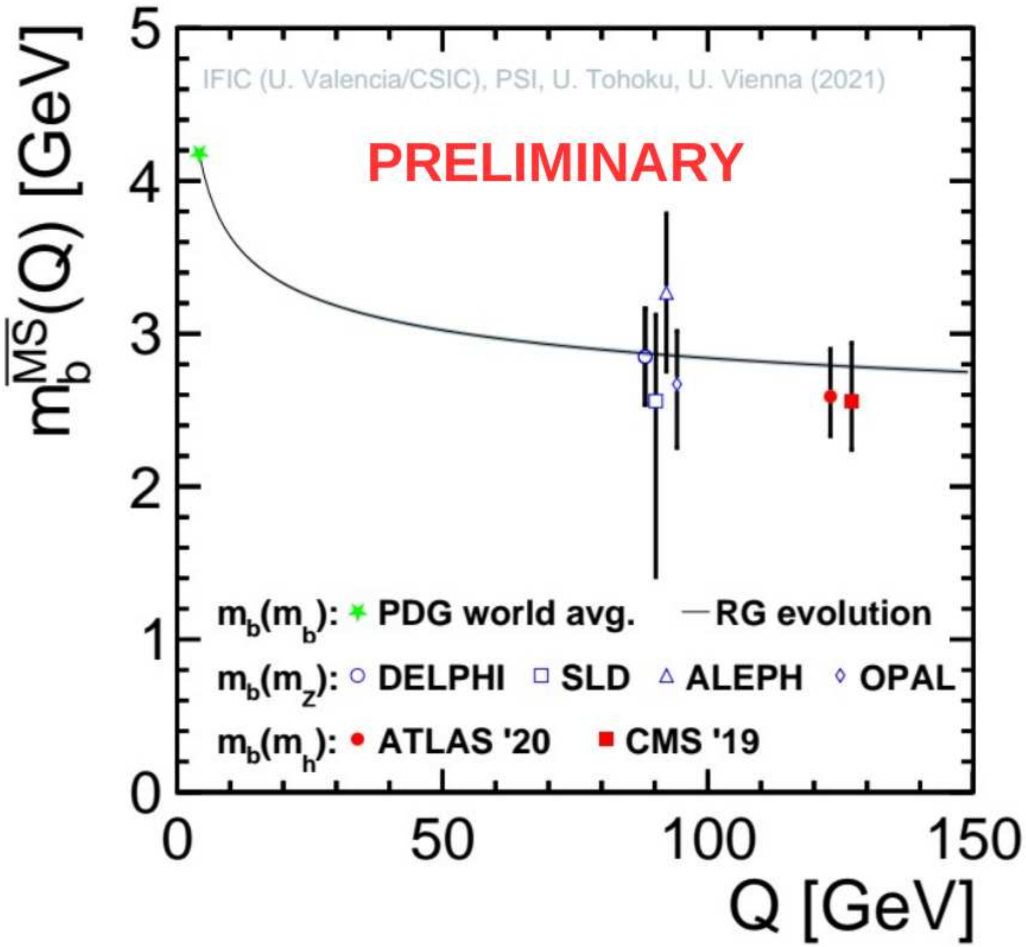
- ATLAS: $\mu_{bb}/\mu_{ZZ} = \Gamma(H \to bb)/\Gamma(H \to ZZ)|_{SM-norm} = 0.87^{+0.28}_{-0.21}$
  $\to \overline{m}_b(M_H) = 2.59^{+0.31}_{-0.26}(\text{stat})^{+0.26}_{-0.18}(\text{syst})$ GeV

- CMS: $\mu_{bb}/\mu_{ZZ} = \Gamma(H \to bb)/\Gamma(H \to ZZ)|_{SM-norm} = 0.84^{+0.37}_{-0.27}$
  $\to \overline{m}_b(M_H) = 2.55^{+0.38}_{-0.32}(\text{stat})^{+0.37}_{-0.26}(\text{syst})$ GeV

$\Rightarrow \overline{m}_b(M_H) = 2.58^{+0.35}_{-0.27}$ GeV
(BLUE) Nisius

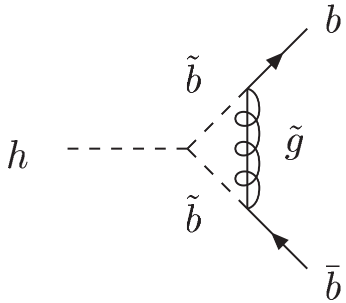
RG-evolution: REvolver

Hoang, Lepenik, Mateu



Aparisi, Fuster, Irles, Rodrigo, Vos, Yamamoto, Hoang, Lepenik, S., Tarafune, Yonamine

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



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

(known at NNLO)

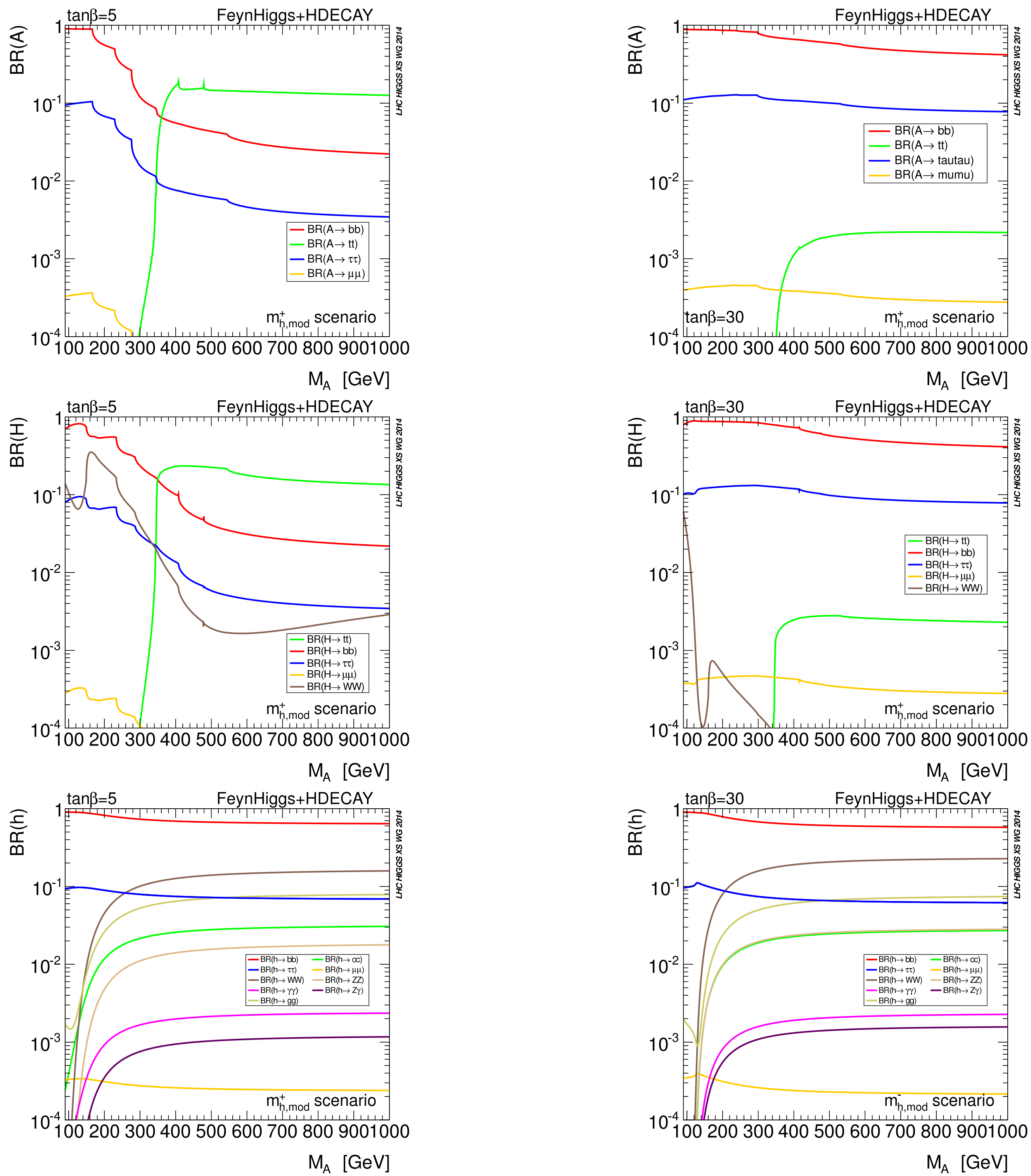
Hall,. . .
Carena,. . .
Nierste,. . .
Häfliger,. . .
etc.
Noth, S.
Mihaila, Reisser
Ghezzi, Glaus,. . .

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

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

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

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



[2HDM: HDECAY, 2HDMC]

Djouadi, Kalinowski, Mühlleitner, S.

Eriksson, Rathsman, Stal

[new: 2HDECAY (+elw)]

Krause, Mühlleitner, S.

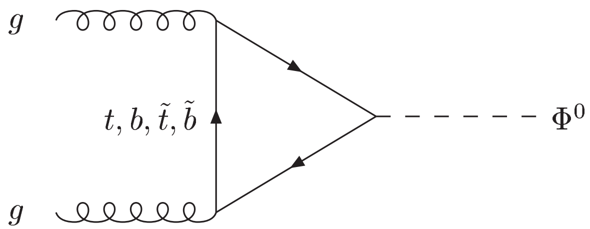
[new: H-COUP (+elw)]

Kanemura, Kikuchi, Mawatari, Sakurai, Yagyu

+ charged Higgs decays

III 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%
  [top mass effects small in SM]

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

- N^{3}LL soft gluon resummation: $\lesssim 2\%$

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

- SM + 2HDM elw. corrections: $\sim 5\%$

Aglietti,...
Degrassi, Maltoni
Actis, Passarino, Sturm, Uccirati
Jenniches, 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
  (QCD also valid for 2HDM and other Higgs extensions)

Bagnaschi, Degrassi, Slavich, Vicini

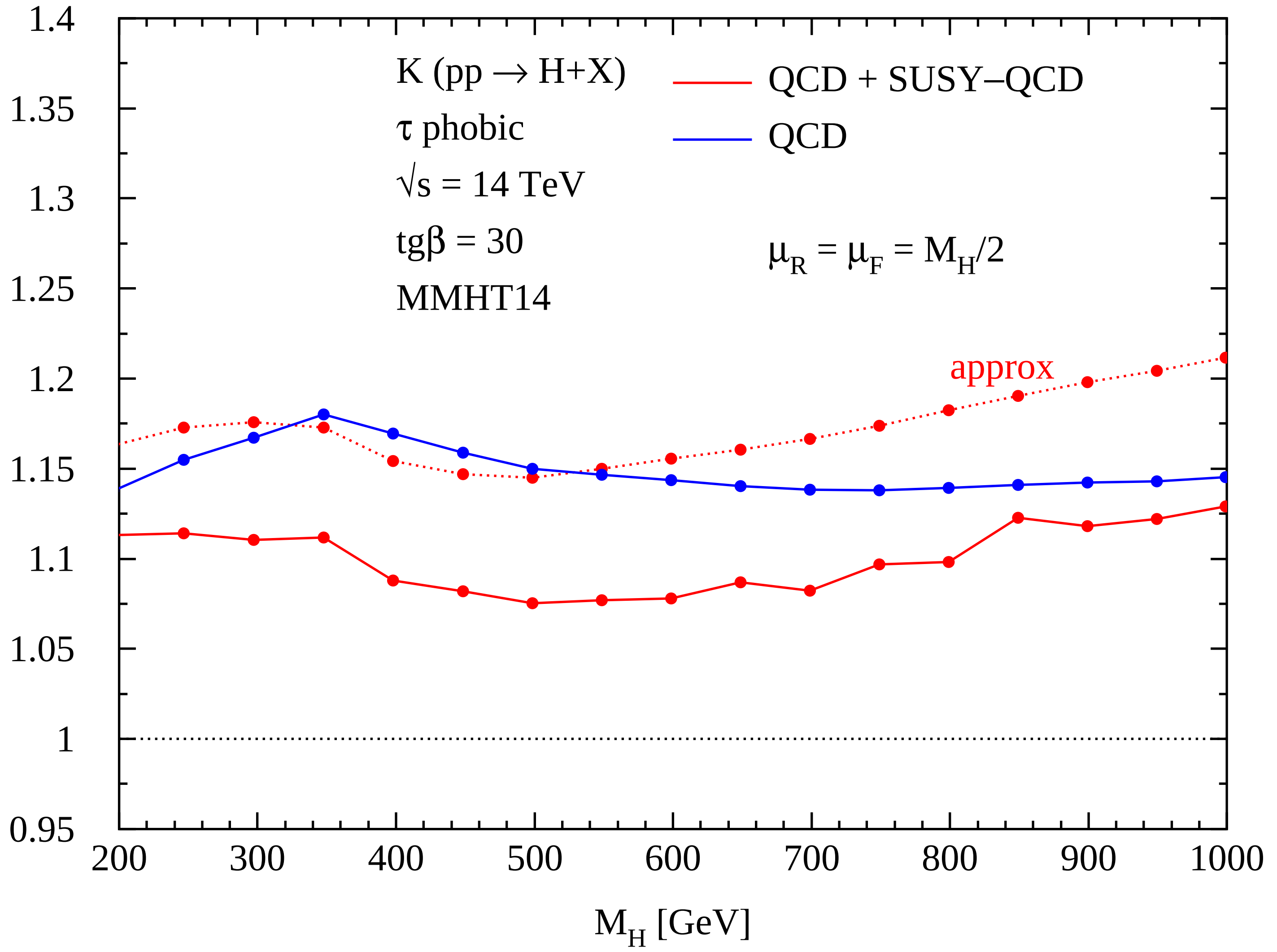
- SUSY-elw. corrections unknown

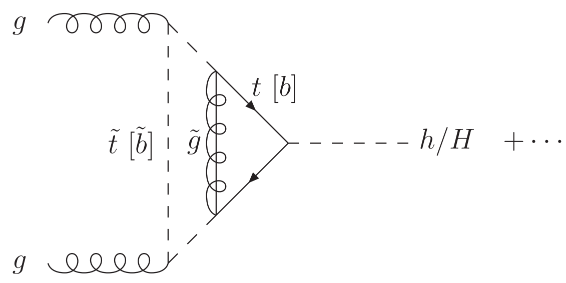
- genuine SUSY–QCD corrections: 10–100%
  [$\leftarrow \Delta_b$ @ large tgβ]

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

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

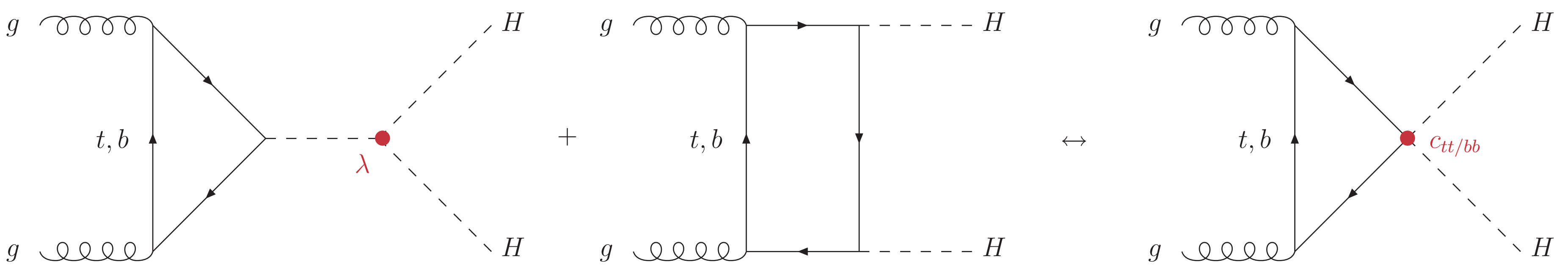
PRELIMINARY





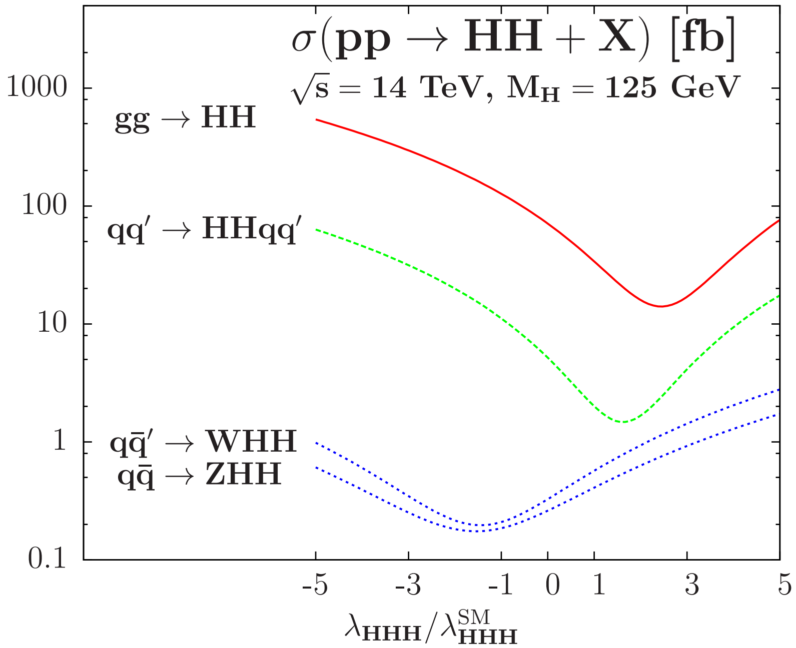
Fritz, Mühlleitner, Rzehak, S.

(ii) $gg \to HH$



- threshold region: sensitive to λ

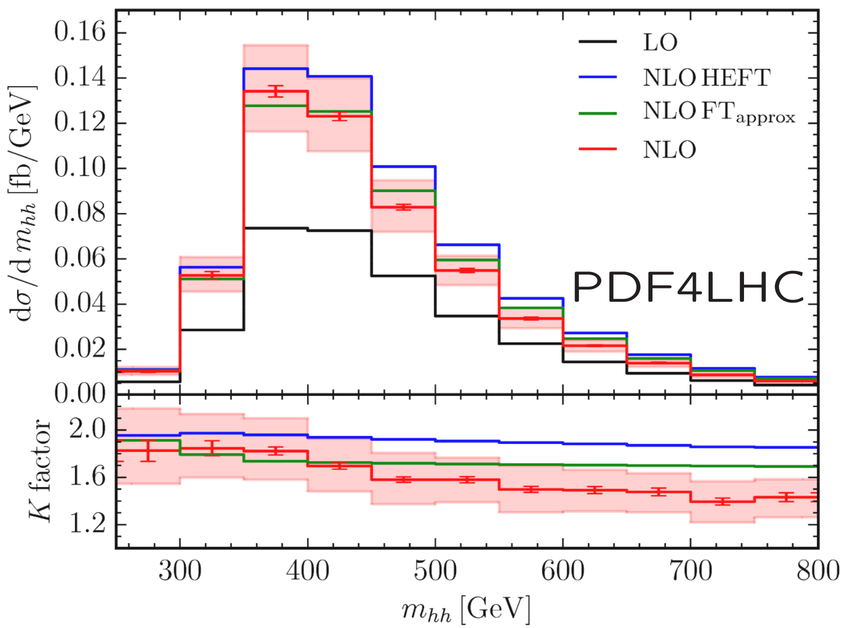
  large M_{HH}: sensitive to $c_{tt/bb}$ [e.g. boosted Higgs pairs]



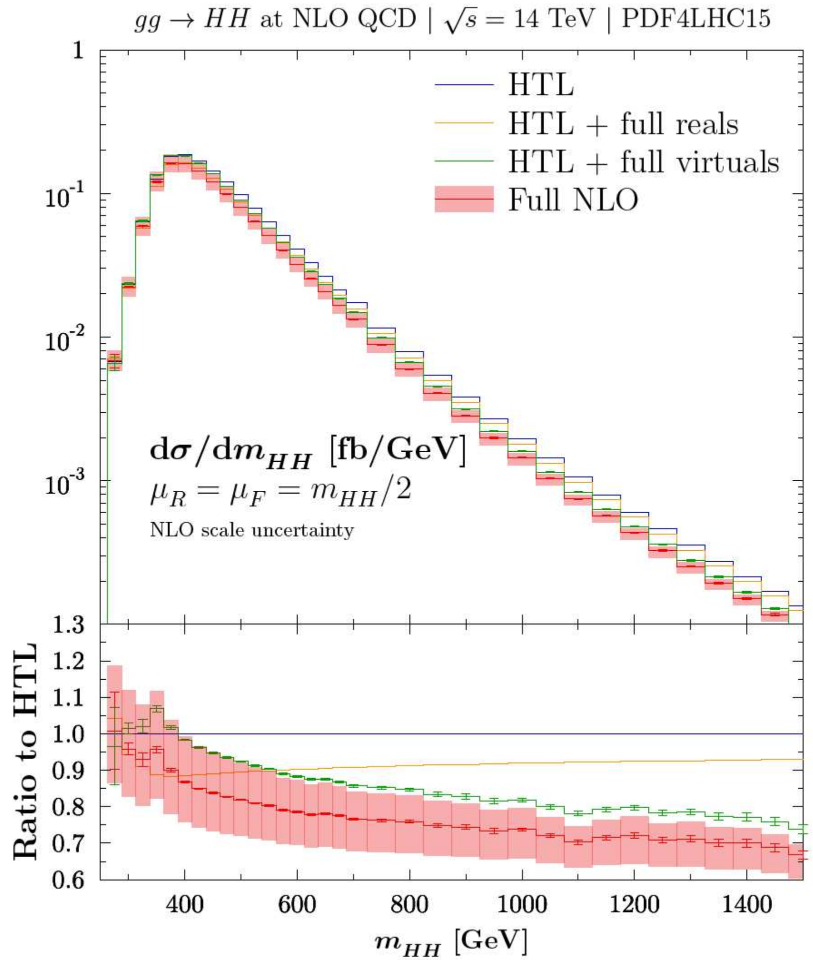
$$gg \to HH : \frac{\Delta\sigma}{\sigma} \sim -\frac{\Delta\lambda}{\lambda}$$

[decreasing with M_{HH}^2]

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



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



Baglio, Campanario, Glaus,
Mühlleitner, Ronca, S., Streicher

$\sigma_{NLO} =$	$32.91(10)^{+13.8\%}_{-12.8\%}\ fb$	$32.81(7)^{+13.5\%}_{-12.5\%}\ fb$
$\sigma^{HTL}_{NLO} =$	$38.75^{+18\%}_{-15\%}\ fb$	$38.66^{+18\%}_{-15\%}\ fb$
$m_t =$	173 GeV	172.5 GeV

$\Rightarrow$ -15% mass effects on top of LO

uncertainties due to m_t

- use m_t, $\overline{m}_t(\overline{m}_t)$ and scan $Q/4 < \mu < Q$ $\rightarrow$ uncertainty = envelope:

$$\frac{d\sigma(gg \rightarrow HH)}{dQ}\Big|_{Q=300\text{ GeV}} = 0.02978(7)^{+6\%}_{-34\%}\text{ fb/GeV},$$

$$\frac{d\sigma(gg \rightarrow HH)}{dQ}\Big|_{Q=400\text{ GeV}} = 0.1609(4)^{+0\%}_{-13\%}\text{ fb/GeV},$$

$$\frac{d\sigma(gg \rightarrow HH)}{dQ}\Big|_{Q=600\text{ GeV}} = 0.03204(9)^{+0\%}_{-30\%}\text{ fb/GeV},$$

$$\frac{d\sigma(gg \rightarrow HH)}{dQ}\Big|_{Q=1200\text{ GeV}} = 0.000435(4)^{+0\%}_{-35\%}\text{ fb/GeV}$$

- bin-by-bin interpolation:

$$\sigma(gg \rightarrow HH) = 32.81^{+4\%}_{-18\%}\text{ fb}$$

- why a dynamical scale $\sim Q$?
  large momentum expansion ($\hat{s} = Q^2 \gg m_t^2$), two FF:

← Davies, Mishima, Steinhauser, Wellmann

pole mass m_t:

$$\Delta F_{1,mass} \;\to\; \frac{\alpha_s}{\pi}\left\{2F_{1,LO}\log\frac{m_t^2}{\hat{s}} + \frac{m_t^2}{\hat{s}}G_1(\hat{s},\hat{t})\right\},$$

$$\Delta F_{2,mass} \;\to\; \frac{\alpha_s}{\pi}\left\{2F_{2,LO}\log\frac{m_t^2}{\hat{s}} + \frac{m_t^2}{\hat{s}}G_2(\hat{s},\hat{t})\right\}$$

$\overline{\text{MS}}$ mass $\overline{m}_t(\mu_t)$:

$$\Delta F_{1,mass} \;\to\; \frac{\alpha_s}{\pi}\left\{2F_{1,LO}\left[\log\frac{\mu_t^2}{\hat{s}} + \frac{4}{3}\right] + \frac{\overline{m}_t^2(\mu_t)}{\hat{s}}G_1(\hat{s},\hat{t})\right\},$$

$$\Delta F_{2,mass} \;\to\; \frac{\alpha_s}{\pi}\left\{2F_{2,LO}\left[\log\frac{\mu_t^2}{\hat{s}} + \frac{4}{3}\right] + \frac{\overline{m}_t^2(\mu_t)}{\hat{s}}G_2(\hat{s},\hat{t})\right\}$$

⇒ scale $\mu_t \sim Q$ preferred at large Q

- renormalization/factorization scale uncertainties @ NLO:

$$\sqrt{s} = 13\text{ TeV}: \quad \sigma_{tot} = 27.73(7)^{+13.8\%}_{-12.8\%}\text{ fb}$$
$$\sqrt{s} = 14\text{ TeV}: \quad \sigma_{tot} = 32.81(7)^{+13.5\%}_{-12.5\%}\text{ fb}$$
$$\sqrt{s} = 27\text{ TeV}: \quad \sigma_{tot} = 127.0(2)^{+11.7\%}_{-10.7\%}\text{ fb}$$
$$\sqrt{s} = 100\text{ TeV}: \quad \sigma_{tot} = 1140(2)^{+10.7\%}_{-10.0\%}\text{ fb}$$

- m_t scale/scheme uncertainties @ NLO:

$$\sqrt{s} = 13\text{ TeV}: \quad \sigma_{tot} = 27.73(7)^{+4\%}_{-18\%}\text{ fb}$$
$$\sqrt{s} = 14\text{ TeV}: \quad \sigma_{tot} = 32.81(7)^{+4\%}_{-18\%}\text{ fb}$$
$$\sqrt{s} = 27\text{ TeV}: \quad \sigma_{tot} = 127.8(2)^{+4\%}_{-18\%}\text{ fb}$$
$$\sqrt{s} = 100\text{ TeV}: \quad \sigma_{tot} = 1140(2)^{+3\%}_{-18\%}\text{ fb}$$

- how to combine them? $\rightarrow$ envelope $\sim$ linear sum (rel. err.)

- renormalization/factorization scale uncertainties @ NNLO$_{FTapprox}$:

$$
\begin{aligned}
\sqrt{s} = 13 \text{ TeV}: \quad \sigma_{tot} &= 31.05^{+2.2\%}_{-5.0\%} \text{ fb} \\
\sqrt{s} = 14 \text{ TeV}: \quad \sigma_{tot} &= 36.69^{+2.1\%}_{-4.9\%} \text{ fb} \\
\sqrt{s} = 27 \text{ TeV}: \quad \sigma_{tot} &= 139.9^{+1.3\%}_{-3.9\%} \text{ fb} \\
\sqrt{s} = 100 \text{ TeV}: \quad \sigma_{tot} &= 1224^{+0.9\%}_{-3.2\%} \text{ fb}
\end{aligned}
$$

- HO corrections: dominated by universal S+V+C corrections

$\Rightarrow \sim$ rescaling of rel. m_t scale/scheme uncertainties final combined ren./fac. scale and m_t scale/scheme unc. @ NNLO$_{FTapprox}$:

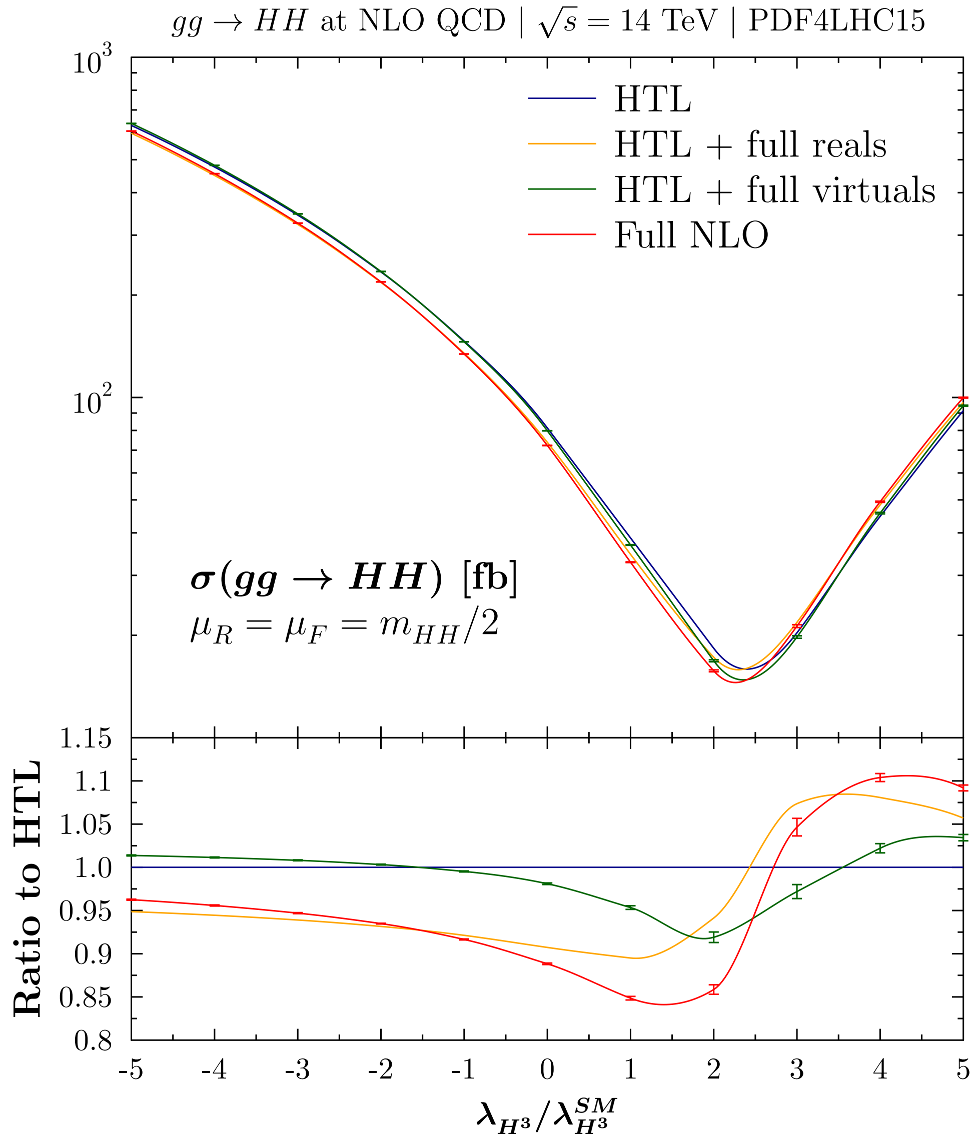
$$\sqrt{s} = 13\ \text{TeV}: \quad \sigma_{tot} = 31.05^{+6\%}_{-23\%}\ \text{fb}$$

$$\sqrt{s} = 14\ \text{TeV}: \quad \sigma_{tot} = 36.69^{+6\%}_{-23\%}\ \text{fb}$$

$$\sqrt{s} = 27\ \text{TeV}: \quad \sigma_{tot} = 139.9^{+5\%}_{-22\%}\ \text{fb}$$

$$\sqrt{s} = 100\ \text{TeV}: \quad \sigma_{tot} = 1224^{+4\%}_{-21\%}\ \text{fb}$$

λ dependence



Baglio, Campanario, Glaus, Mühlleitner, Ronca, S.

- final combined uncertainties @ $\text{NNLO}_{FTapprox}$ ($\sqrt{s} = 14$ TeV):

$$
\begin{aligned}
\kappa_\lambda = -10: &\quad \sigma_{tot} = 1680^{+13\%}_{-14\%} \text{ fb} \\
\kappa_\lambda = -5: &\quad \sigma_{tot} = 598.9^{+13\%}_{-15\%} \text{ fb} \\
\kappa_\lambda = -1: &\quad \sigma_{tot} = 131.9^{+11\%}_{-16\%} \text{ fb} \\
\kappa_\lambda = 0: &\quad \sigma_{tot} = 70.38^{+8\%}_{-18\%} \text{ fb} \\
\kappa_\lambda = 1: &\quad \sigma_{tot} = 31.05^{+6\%}_{-23\%} \text{ fb} \\
\kappa_\lambda = 2: &\quad \sigma_{tot} = 13.81^{+3\%}_{-28\%} \text{ fb} \\
\kappa_\lambda = 2.4: &\quad \sigma_{tot} = 13.10^{+6\%}_{-27\%} \text{ fb} \\
\kappa_\lambda = 3: &\quad \sigma_{tot} = 18.67^{+12\%}_{-22\%} \text{ fb} \\
\kappa_\lambda = 5: &\quad \sigma_{tot} = 94.82^{+18\%}_{-13\%} \text{ fb} \\
\kappa_\lambda = 10: &\quad \sigma_{tot} = 672.2^{+16\%}_{-13\%} \text{ fb}
\end{aligned}
$$

IV CONCLUSIONS

- Higgs boson searches/studies at LHC belong to major endeavours

- most (SUSY–)QCD and –elw. corrs known → $\Delta \lesssim 10 - 15\%$ @ LHC

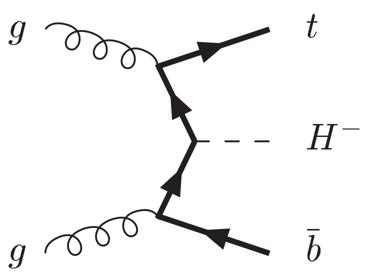
- several dedicated HO–tools available for SM, 2HDM, MSSM [NMSSM,. . .]

- important to develop NLO event generators [← backgrounds]

BACKUP SLIDES

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

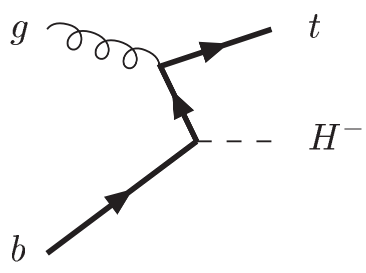
- $M_{H^\pm} < m_t - m_b$: $\sigma_{t\bar{b}H^-} = \sigma_{t\bar{t}} \times BR(\bar{t} \to \bar{b}H^-)$
- $M_{H^\pm} \sim m_t - m_b$: new NLO calculation — Degrande, Frederix, Wiesemann, Zaro
- $M_{H^\pm} > m_t - m_b$:



NLO

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

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



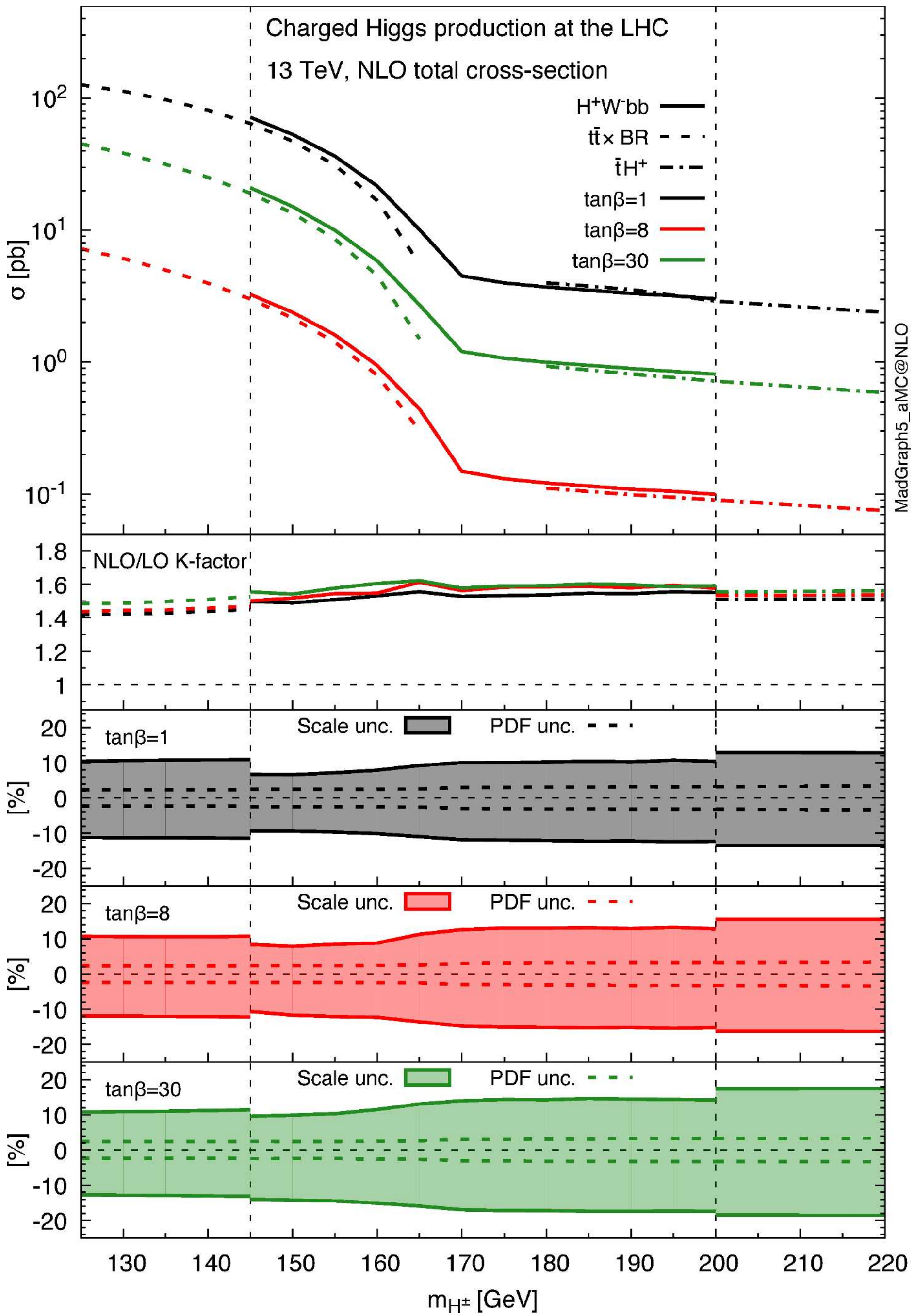
NLO

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

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

→ Santander matching

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



Degrande, Frederix, Wiesemann, Zaro

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

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

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

$\leftarrow g_t^{H^\pm}$

Dittmaier, Krämer, S., Walser

uncertainties due to m_t for single Higgs

- transform $m_t \to \overline{m}_t(\mu)$ ($\overline{\text{MS}}$)

  $\to$ modification of mass CT

- use m_t, $\overline{m}_t(\overline{m}_t)$ and scan $Q/4 < \mu < Q$ $\to$ uncertainty = envelope:

$$\begin{aligned}
\sigma(gg \to H)|_{M_H=125\ \text{GeV}} &= 42.17^{+0.4\%}_{-0.5\%}\ \text{pb} \\
\sigma(gg \to H)|_{M_H=300\ \text{GeV}} &= 9.85^{+7.5\%}_{-0.3\%}\ \text{pb} \\
\sigma(gg \to H)|_{M_H=400\ \text{GeV}} &= 9.43^{+0.1\%}_{-0.9\%}\ \text{pb} \\
\sigma(gg \to H)|_{M_H=600\ \text{GeV}} &= 1.97^{+0.0\%}_{-15.9\%}\ \text{pb} \\
\sigma(gg \to H)|_{M_H=900\ \text{GeV}} &= 0.230^{+0.0\%}_{-22.3\%}\ \text{pb} \\
\sigma(gg \to H)|_{M_H=1200\ \text{GeV}} &= 0.0402^{+0.0\%}_{-26.0\%}\ \text{pb}
\end{aligned}$$

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

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

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

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

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

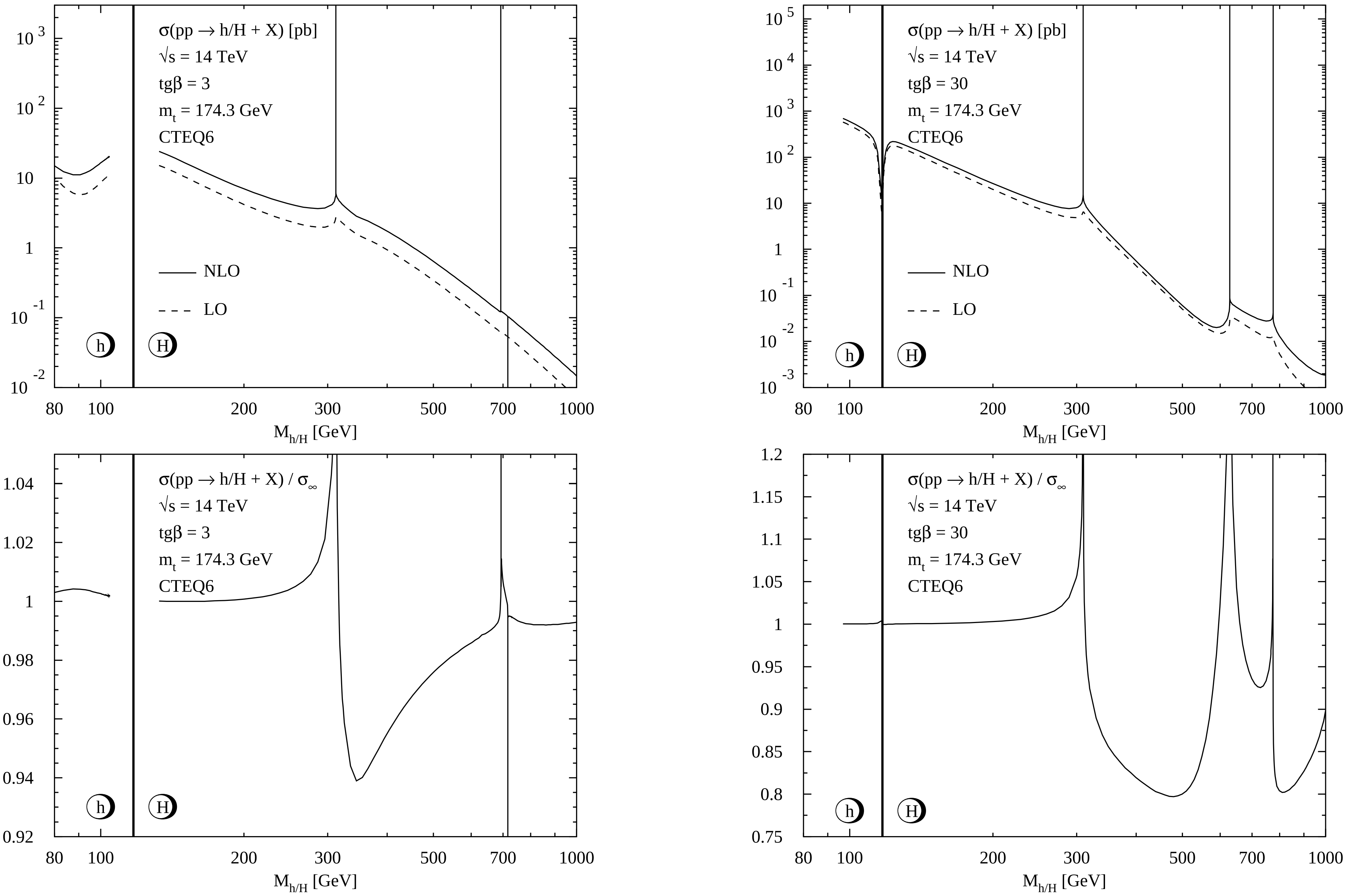
$$\Delta_b^{elw(1)} = \frac{\lambda_t^2(\mu_R)}{(4\pi)^2}\ \mu\ A_t\ \text{tg}\beta\ I(m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2, \mu^2)$$

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

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

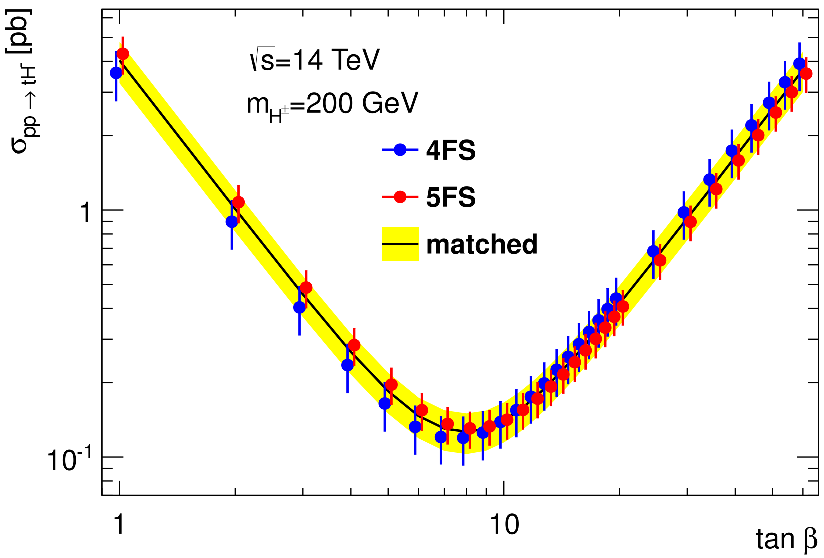
Carena, Garcia, Nierste, Wagner
Guasch, Häfliger, S.

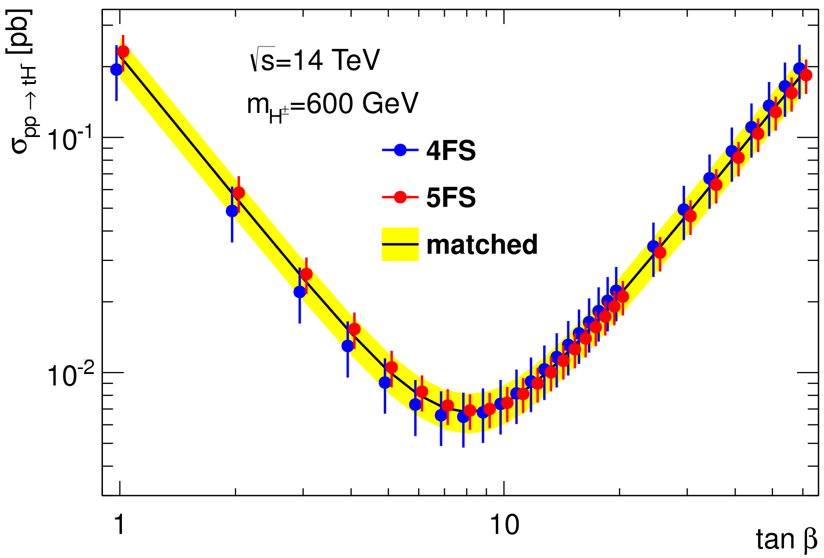
- QCD corrections to squark loops: Mühlleitner, S.



• Santander matching

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





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

SPS 1b

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

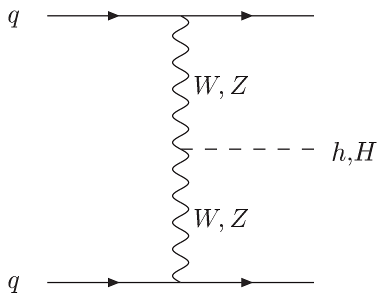
$$\longrightarrow m_{\tilde{t}_1} = 631.8 \text{ GeV}, m_{\tilde{t}_2} = 829.1 \text{ GeV}, m_{\tilde{b}_1} = 721.8 \text{ GeV}, m_{\tilde{b}_2} = 820.7 \text{ GeV}$$

SPS 5

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

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

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



Cahn, Dawson
Hikasa
Atarelli, Mele, Pitolli

- QCD corrections $\leftarrow$ DIS: $\sim$ 10%

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

[approx] 2–loop: $\lesssim$ 1% — Bolzano, Maltoni, Moch, Zaro; Cacciari, Dreyer, Karlberg, Salam, Zanderighi

[approx] 3–loop: $\lesssim$ 0.3% — Dreyer, Karlberg

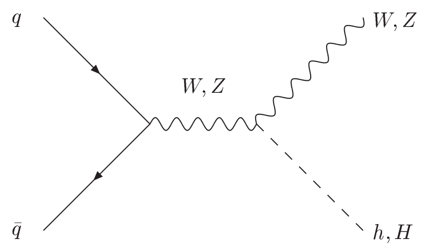
- elw. corrections: $\sim$ 10% — Ciccolini, Denner, Dittmaier

- genuine SUSY-QCD corrections small — Djouadi, S.

- genuine SUSY-elw. corrections: $\lesssim$ 5%
  [implemented in VBFNLO]

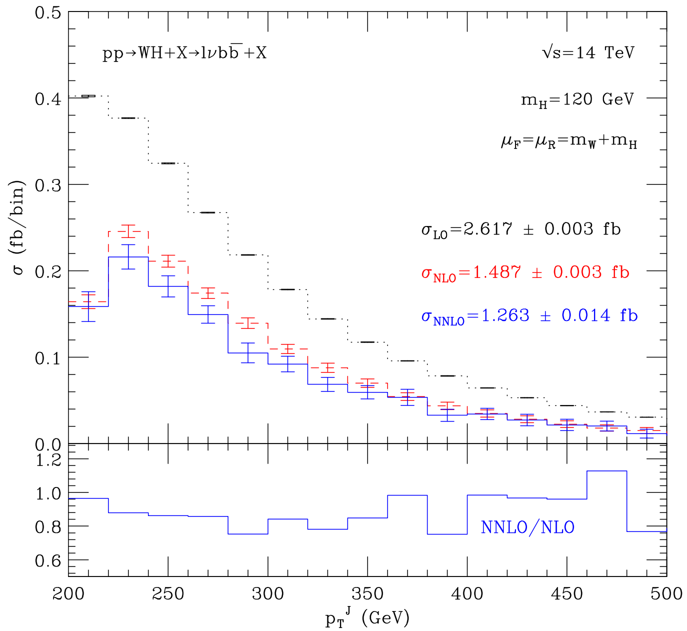
Hollik, Rzehak, Plehn, Rauch
Figy, Palmer, Weiglein

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

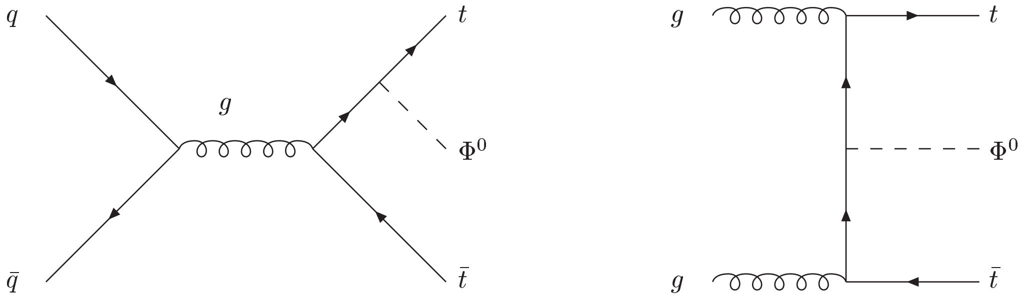


Glashow,. . .
Kunszt,. . .

- QCD corrections ← DY: $\sim 30\%$ — Han, Willenbrock
  2–loop: $\lesssim 5\%$ — Brein, Djouadi, Harlander
- SUSY-QCD corrections small — Djouadi, S.
- electroweak corrections: $\sim -10\%$ — Ciccolini, Dittmaier, Krämer
- $W/Z + H$: 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]: $\sim 20\%$
  [threshold suppressed: $\sigma_{LO} \sim \beta^4$]

  Beenakker, Dittmaier, Krämer, Plümper, S., Zerwas
  Dawson, Orr, Reina, Wackeroth
  Broggio, Ferroglia, Pecjak, Signer, Yang

- SUSY-QCD corrections: moderate

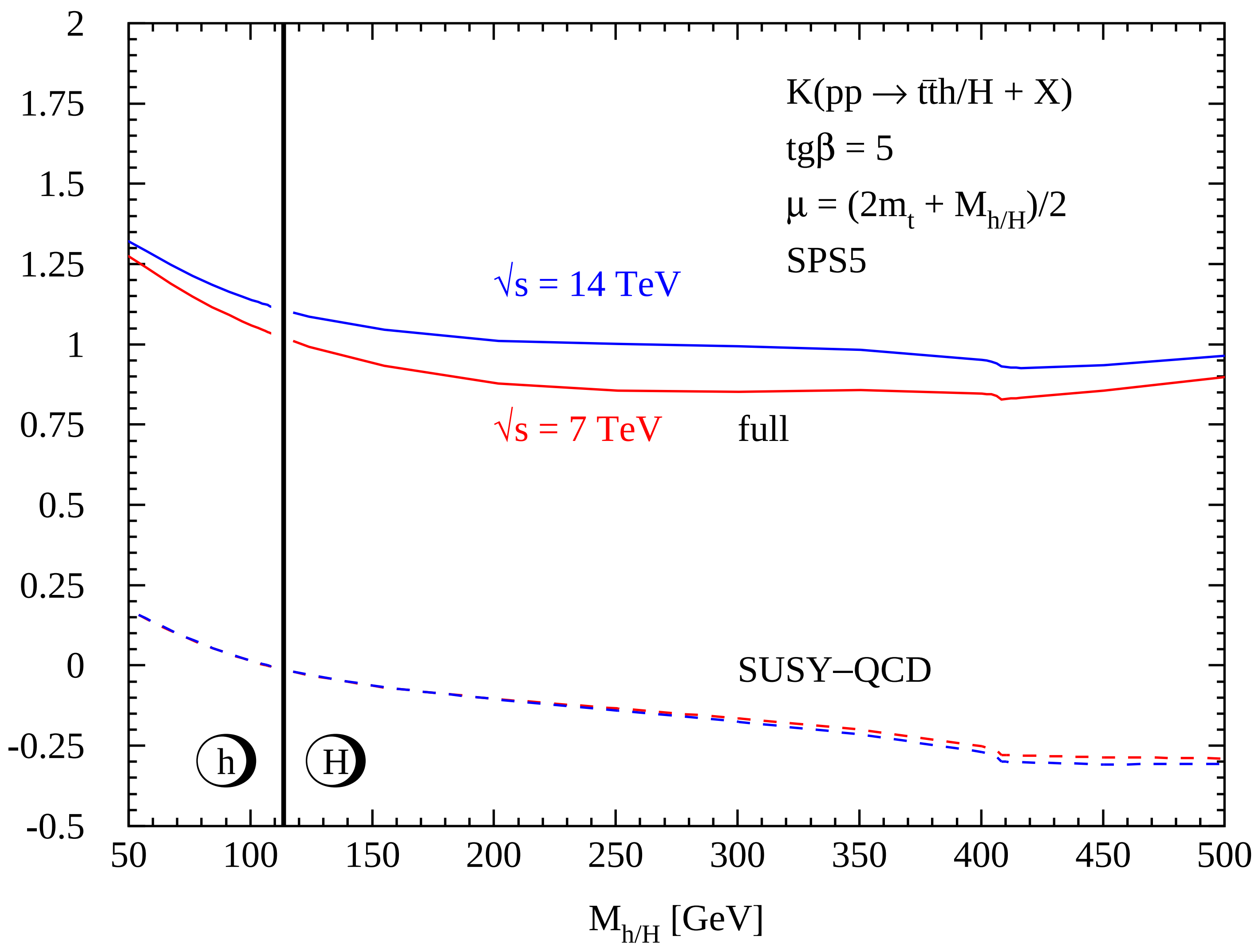
  Dittmaier, Häfliger, Krämer, S., Walser

- link to parton showers: aMC@NLO, PowHel

  Frederix et al.
  Garzelli, Kardos, Papadopoulos, Trócsányi

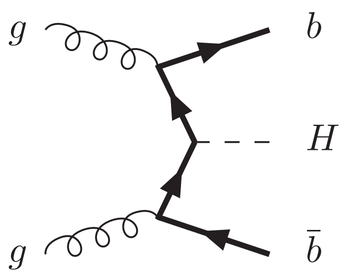
- important work on backgrounds $t\bar{t}b\bar{b}, t\bar{t}jj$, etc.

  Bredenstein, Denner, Dittmaier, Pozzorini
  Bevilacqua, Czakon, Papadopoulos, Pittau, Worek
  Cascioli, Maierhofer, Pozzorini

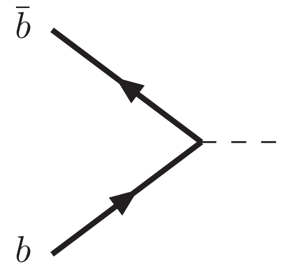


Dittmaier, Häfliger, Krämer, S., Walser

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



NLO



$[\leftarrow \Delta_b]$

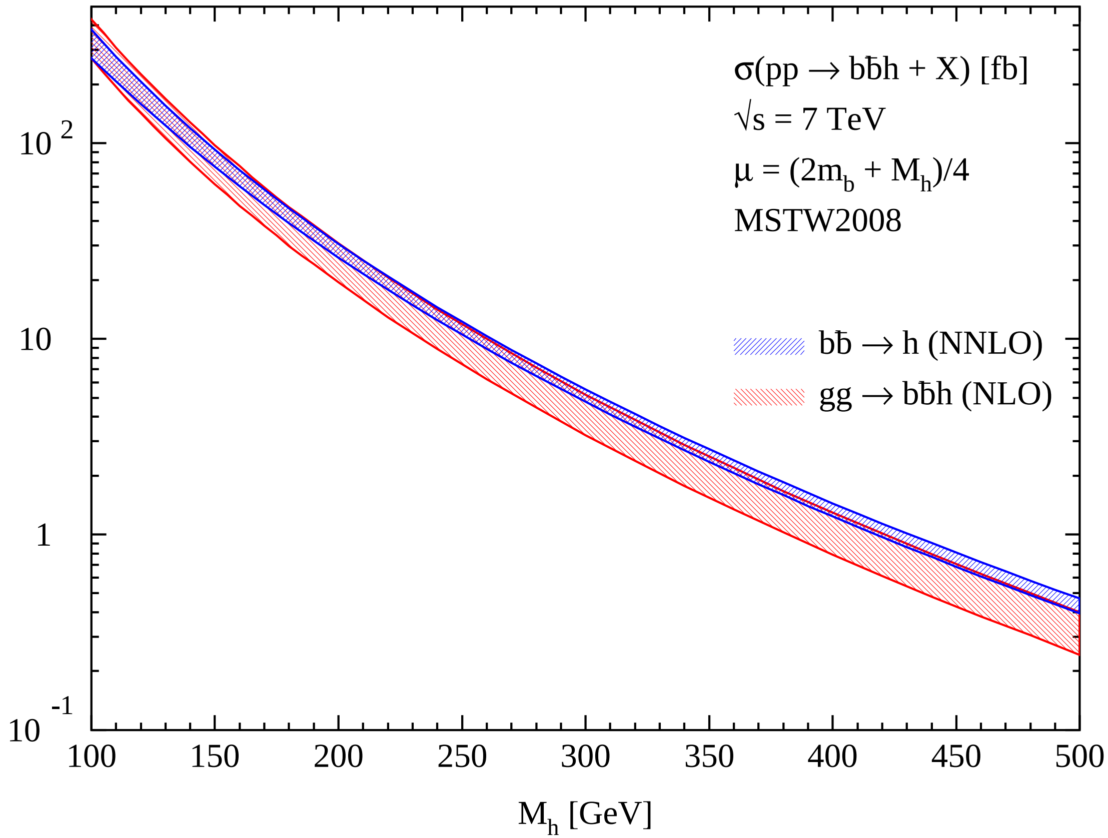
NNLO

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:

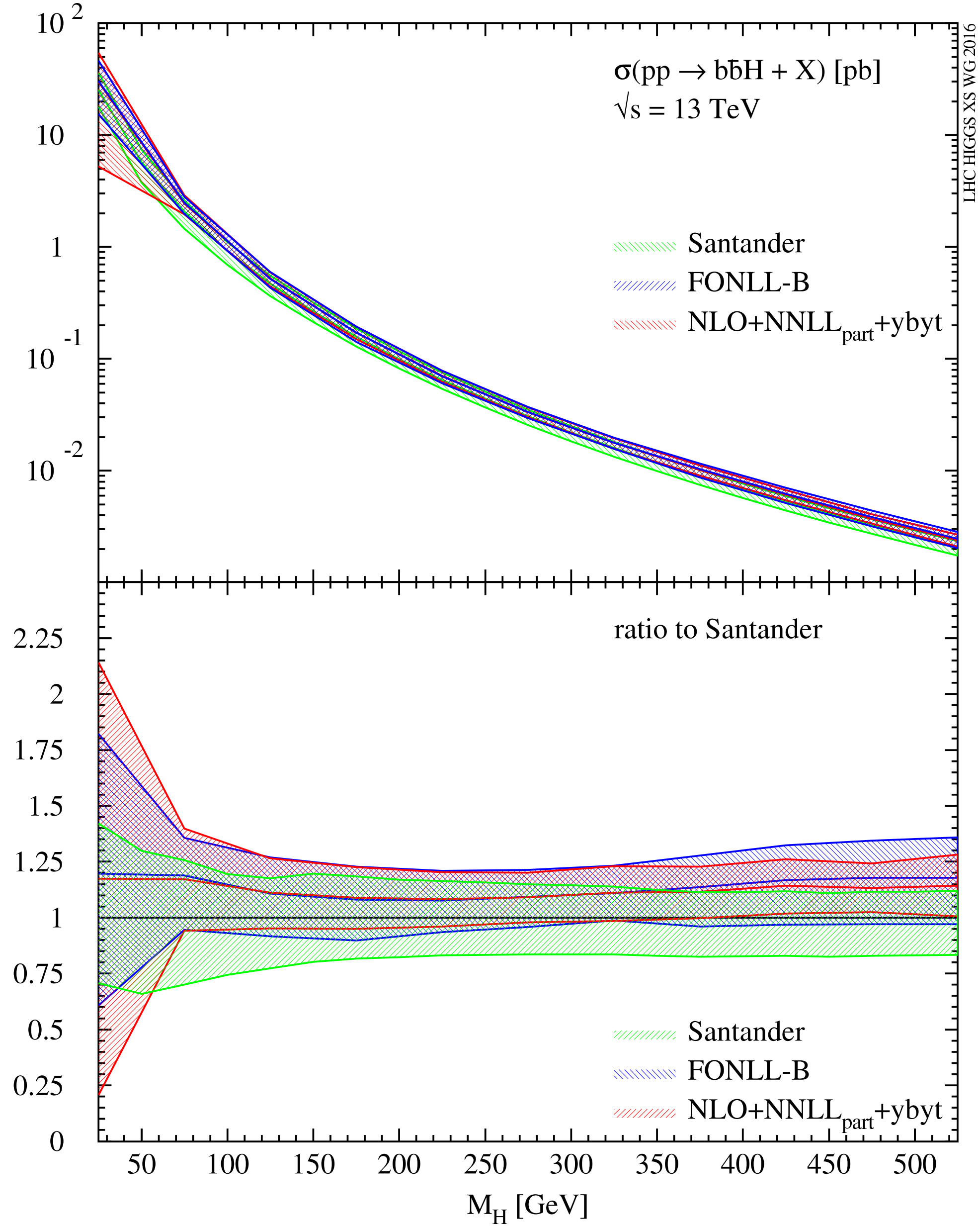
$$\sigma = \frac{\sigma^{4FS} + w\sigma^{5FS}}{1+w}$$

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

Harlander, Krämer, Schumacher

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

matching



Bonvini, Papanastasiou, Tackmann

Forte, Napoletano, Ubiali

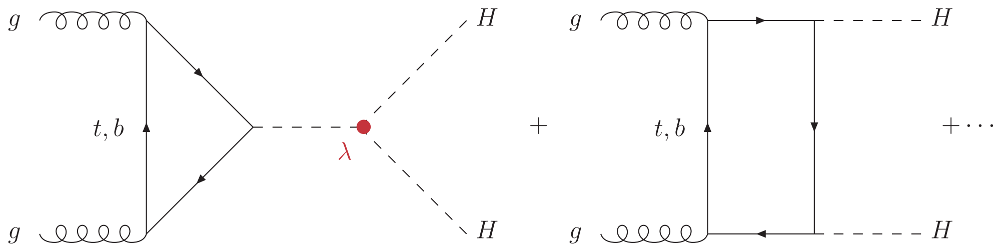
	M_A	M_H [GeV]	δ^A_{QCD}	δ^A_{SUSY}	$\delta^A_{SUSY rem}$	δ^H_{QCD}	δ^H_{SUSY}	$\delta^H_{SUSY rem}$
7 TeV	100	113.9	0.23	-0.30	0.4×10^{-4}	0.27	-0.38	0.3×10^{-4}
	200	200	0.38	-0.30	2.9×10^{-4}	0.39	-0.30	5.8×10^{-4}
	300	300	0.46	-0.30	6.7×10^{-4}	0.47	-0.30	9.3×10^{-4}
	400	400	0.53	-0.30	1.3×10^{-3}	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}

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

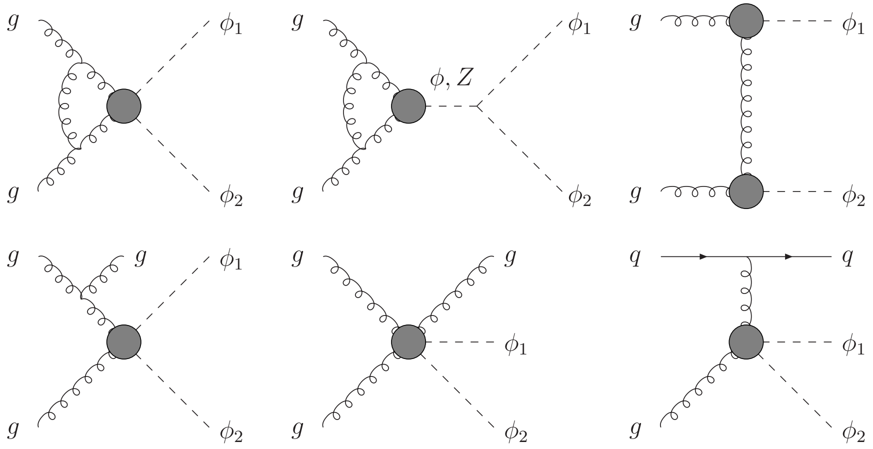
Dittmaier, Häfliger, Krämer, S., Walser

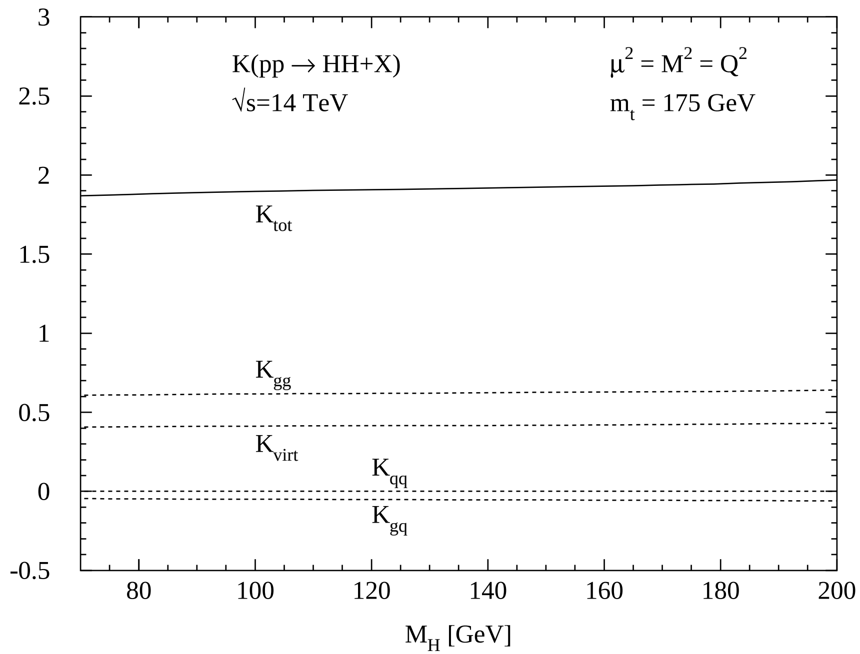
SM



- third generation dominant $\longrightarrow t, b$

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



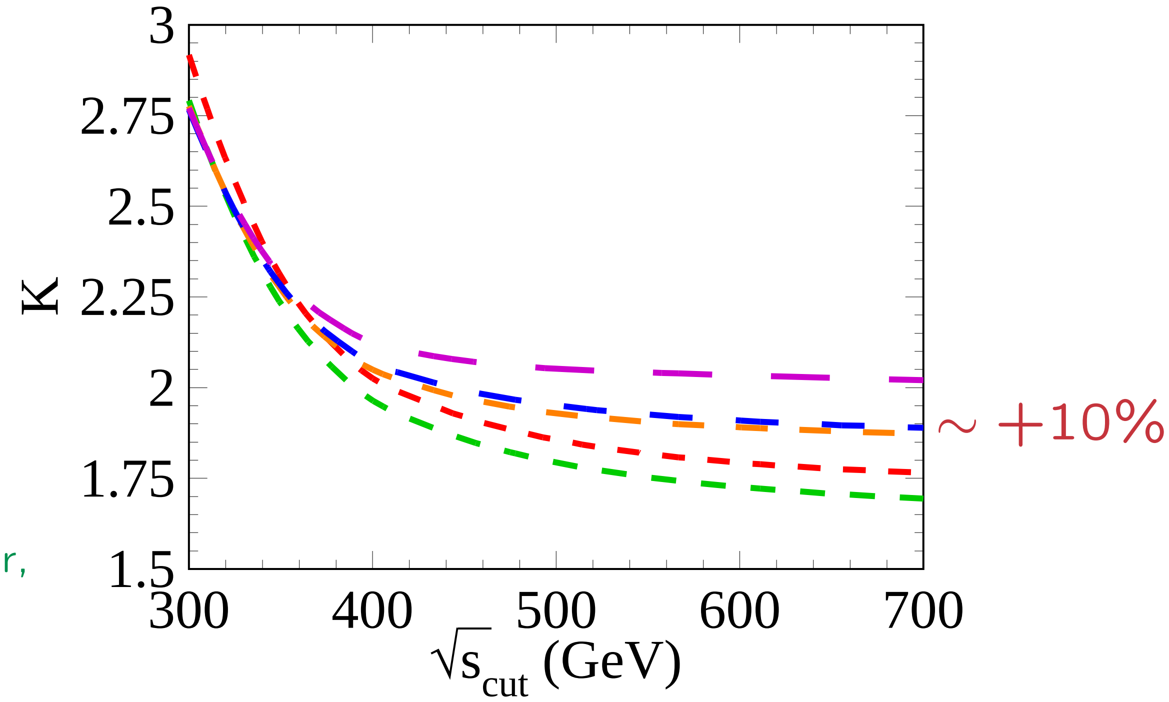


Dawson, Dittmaier, S.

- 2-loop QCD corrections:

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

Grigo, Hoff, Melnikov, Steinhauser



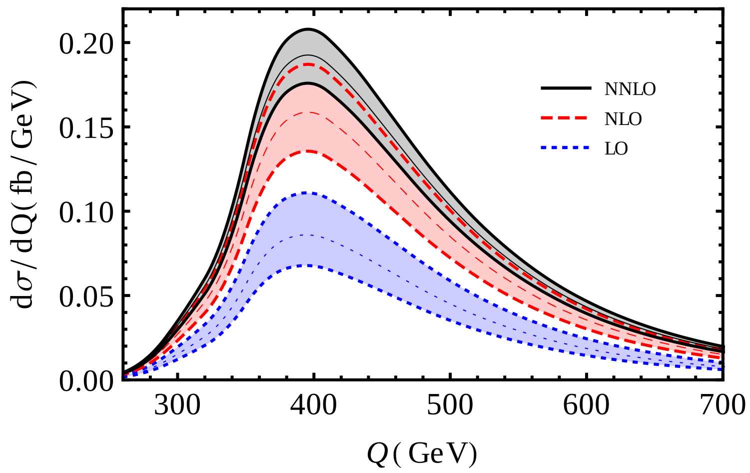
- NLO mass effects @ NLO in real corrections: $\sim -10\%$

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

→ sizeable 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

uncertainties due to m_t

- transform $m_t \to \overline{m}_t(\mu)$ ($\overline{\text{MS}}$)

  $\to$ modification of mass CT

- use m_t, $\overline{m}_t(\overline{m}_t)$ and scan $Q/4 < \mu < Q$ $\to$ uncertainty = envelope:

$$\frac{d\sigma(gg \to HH)}{dQ}\Big|_{Q=300 \text{ GeV}} = 0.0298(7)^{+6\%}_{-34\%} \text{ fb/GeV},$$

$$\frac{d\sigma(gg \to HH)}{dQ}\Big|_{Q=400 \text{ GeV}} = 0.1609(4)^{+0\%}_{-13\%} \text{ fb/GeV},$$

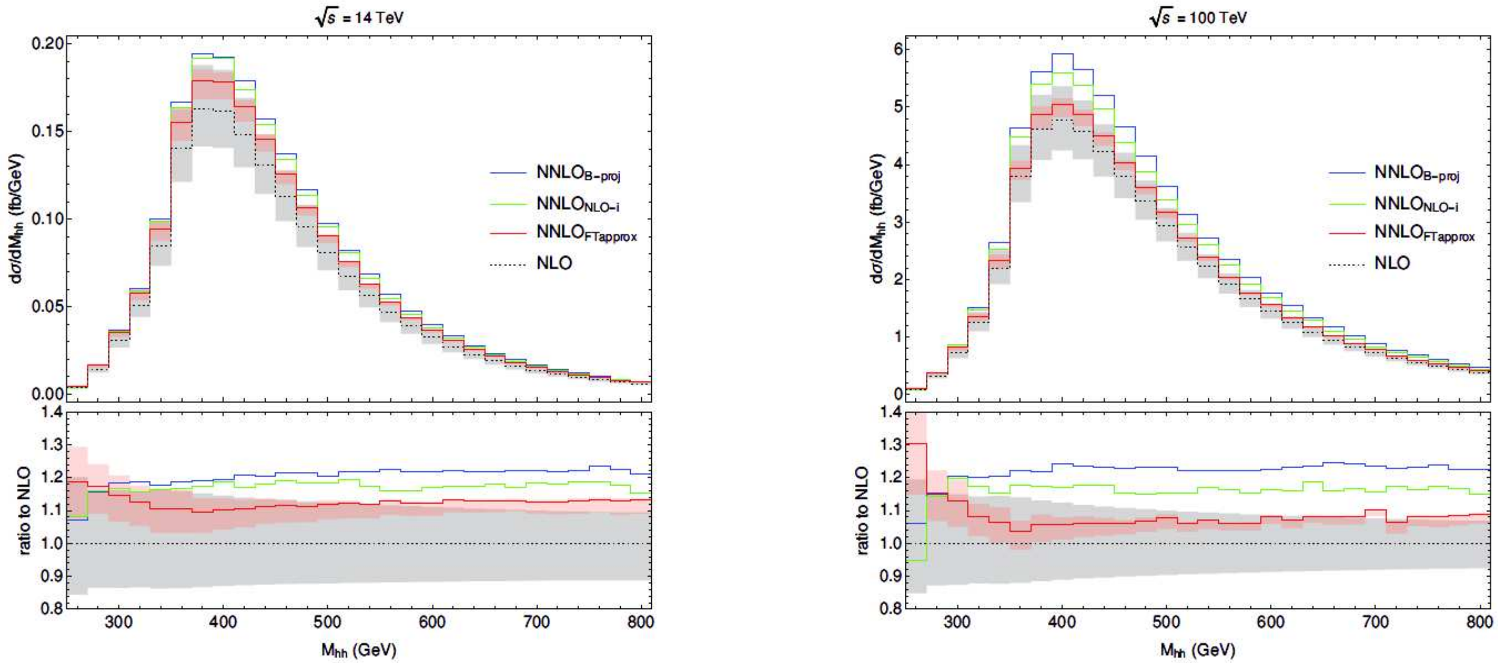
$$\frac{d\sigma(gg \to HH)}{dQ}\Big|_{Q=600 \text{ GeV}} = 0.03204(9)^{+0\%}_{-30\%} \text{ fb/GeV},$$

$$\frac{d\sigma(gg \to HH)}{dQ}\Big|_{Q=1200 \text{ GeV}} = 0.000435(4)^{+0\%}_{-35\%} \text{ fb/GeV}$$

- preliminary interpolation:

$$\sigma(gg \to HH) = 32.78^{+4\%}_{-17\%} \text{ fb} \qquad \text{(preliminary)}$$

NNLO Monte Carlo:



Grazzini, Heinrich, Jones, Kallweit, Kerner, Lindert, Mazzitelli

- 20% effects beyond NLO

- m_t scale/scheme uncertainties @ NLO:

$$
\begin{aligned}
\kappa_\lambda = -10: &\quad \sigma_{tot} = 1438(1)^{+10\%}_{-6\%} \text{ fb} \\
\kappa_\lambda = -5: &\quad \sigma_{tot} = 512.8(3)^{+10\%}_{-7\%} \text{ fb} \\
\kappa_\lambda = -1: &\quad \sigma_{tot} = 113.66(7)^{+8\%}_{-9\%} \text{ fb} \\
\kappa_\lambda = 0: &\quad \sigma_{tot} = 61.22(6)^{+6\%}_{-12\%} \text{ fb} \\
\kappa_\lambda = 1: &\quad \sigma_{tot} = 27.73(7)^{+4\%}_{-18\%} \text{ fb} \\
\kappa_\lambda = 2: &\quad \sigma_{tot} = 13.2(1)^{+1\%}_{-23\%} \text{ fb} \\
\kappa_\lambda = 2.4: &\quad \sigma_{tot} = 12.7(1)^{+4\%}_{-22\%} \text{ fb} \\
\kappa_\lambda = 3: &\quad \sigma_{tot} = 17.6(1)^{+9\%}_{-15\%} \text{ fb} \\
\kappa_\lambda = 5: &\quad \sigma_{tot} = 83.2(3)^{+13\%}_{-4\%} \text{ fb} \\
\kappa_\lambda = 10: &\quad \sigma_{tot} = 579(1)^{+12\%}_{-4\%} \text{ fb}
\end{aligned}
$$

- renormalization/factorization scale uncertainties @ NNLO$_{FTapprox}$:

$$\begin{aligned}
\kappa_\lambda = -10: \quad \sigma_{tot} &= 1680^{+3.0\%}_{-7.7\%}\ \text{fb}\\
\kappa_\lambda = -5: \quad \sigma_{tot} &= 598.9^{+2.7\%}_{-7.5\%}\ \text{fb}\\
\kappa_\lambda = -1: \quad \sigma_{tot} &= 131.9^{+2.5\%}_{-6.7\%}\ \text{fb}\\
\kappa_\lambda = 0: \quad \sigma_{tot} &= 70.38^{+2.4\%}_{-6.1\%}\ \text{fb}\\
\kappa_\lambda = 1: \quad \sigma_{tot} &= 31.05^{+2.2\%}_{-5.0\%}\ \text{fb}\\
\kappa_\lambda = 2: \quad \sigma_{tot} &= 13.81^{+2.1\%}_{-4.9\%}\ \text{fb}\\
\kappa_\lambda = 2.4: \quad \sigma_{tot} &= 13.10^{+2.3\%}_{-5.1\%}\ \text{fb}\\
\kappa_\lambda = 3: \quad \sigma_{tot} &= 18.67^{+2.7\%}_{-7.3\%}\ \text{fb}\\
\kappa_\lambda = 5: \quad \sigma_{tot} &= 94.82^{+4.9\%}_{-8.8\%}\ \text{fb}\\
\kappa_\lambda = 10: \quad \sigma_{tot} &= 672.2^{+4.2\%}_{-8.5\%}\ \text{fb}
\end{aligned}$$