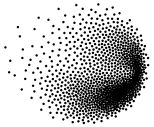


PSI

STATUS AND PROPECTS FOR HIGGS DECAY CALCULATIONS

Michael Spira (PSI)

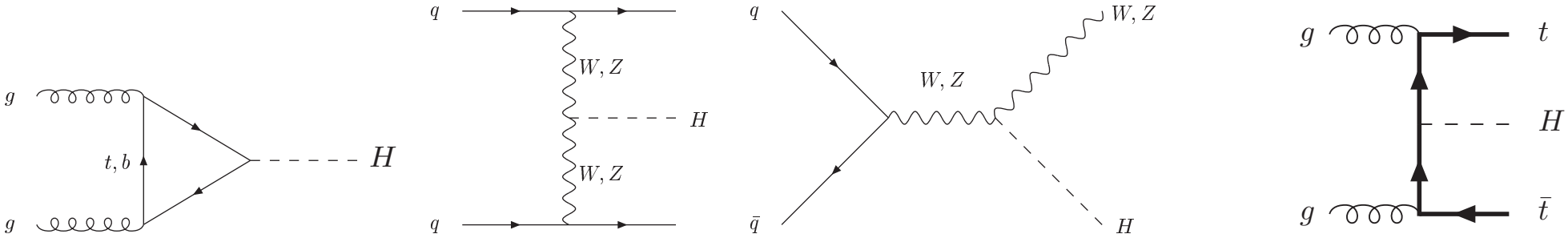
I Introduction

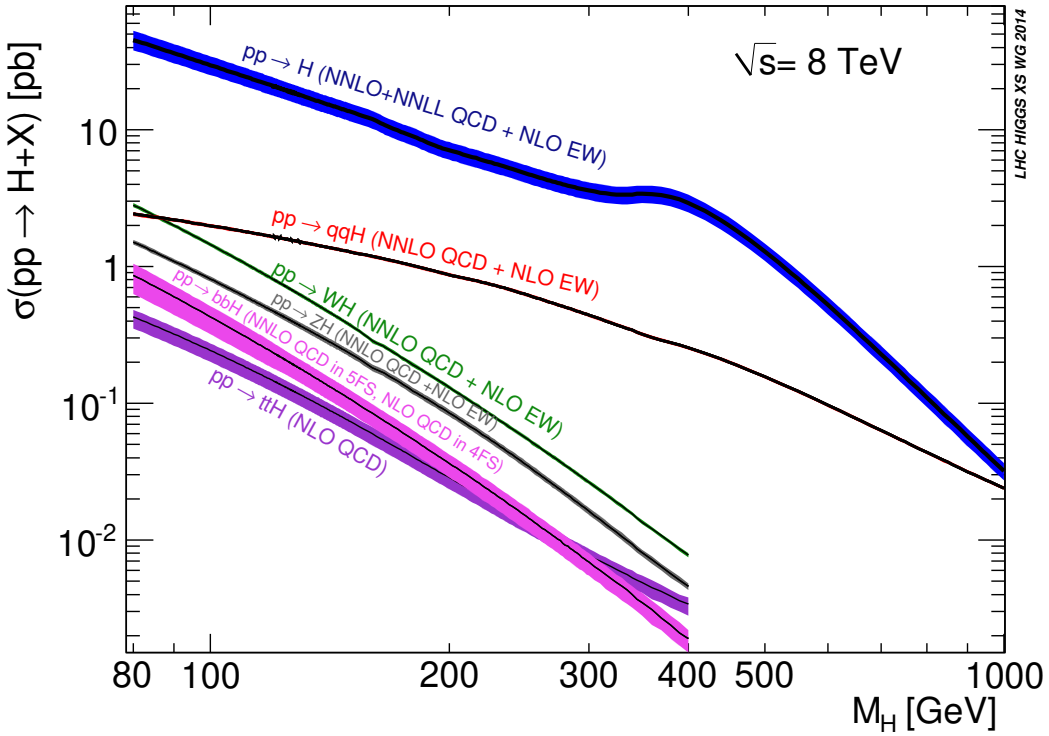
II Higgs Boson Decays

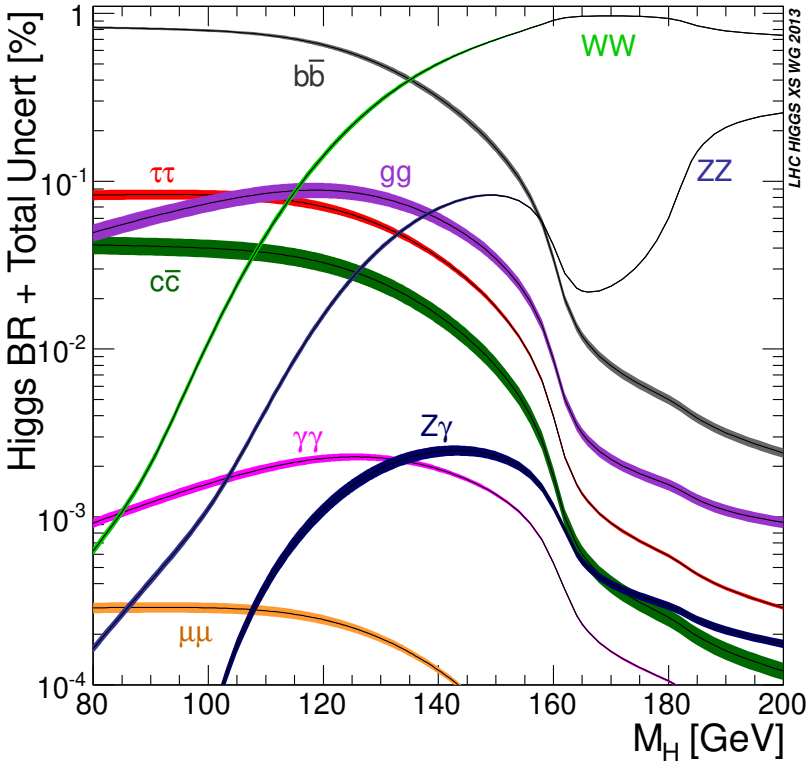
III Summary

I *INTRODUCTION*

- Higgs Boson Production & Decay

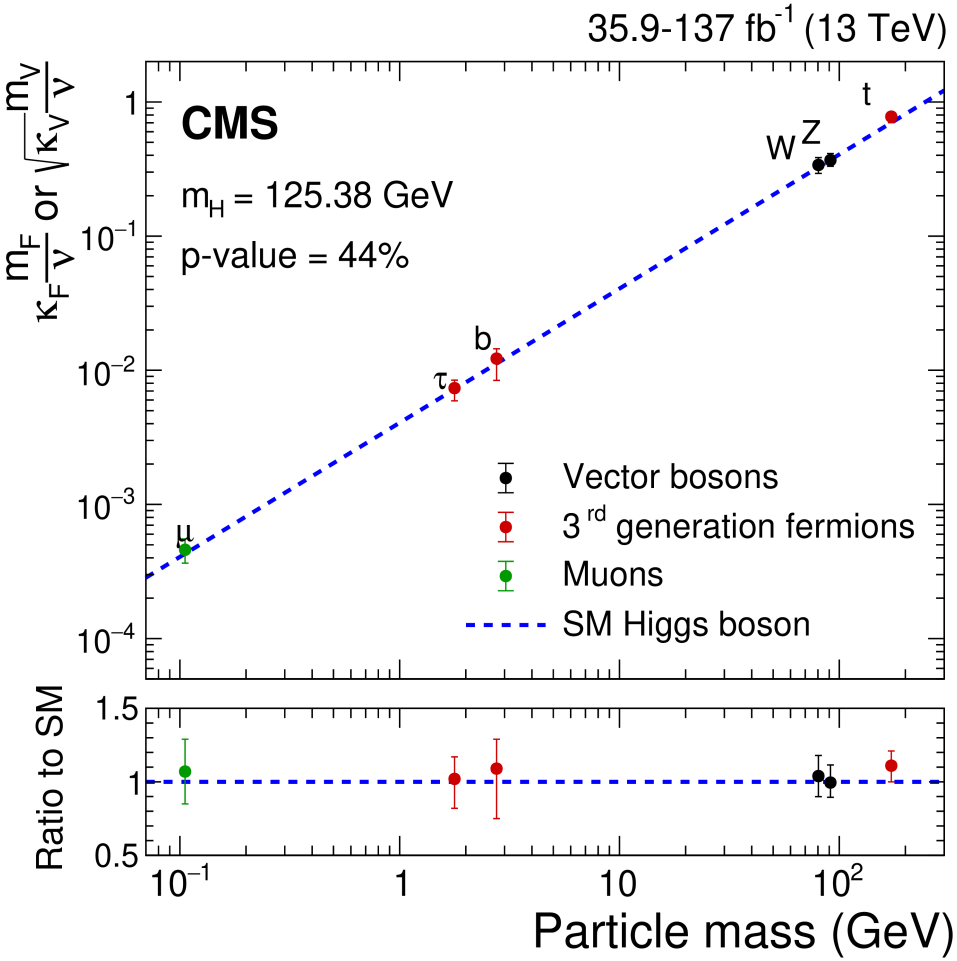




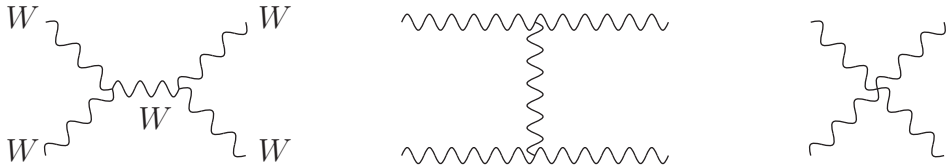


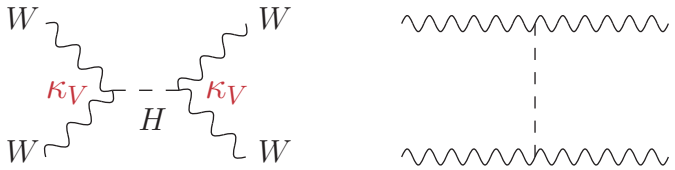
LHC Higgs XS WG

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



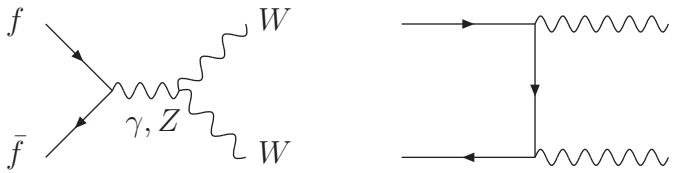
- $WW \to WW$ @ high energies

(a) 

(b) 

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

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

(a) 

(b)

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

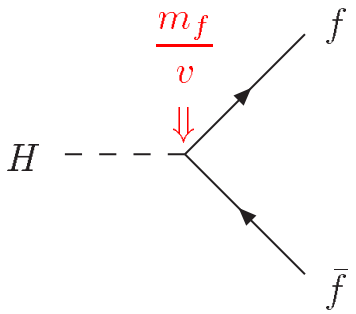
[analogously for κ_H]

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

- $\Gamma = \Gamma_{SM} + \Delta\Gamma_{BSM} \quad \rightsquigarrow \quad \Gamma = \Gamma_{SM} \pm \delta\Gamma_{SM} + \Delta\Gamma_{BSM} \pm \delta\Delta\Gamma_{BSM}$

II HIGGS BOSON DECAYS

Standard Model



$$BR(H \to b\bar{b}) \sim 58\%$$
$$BR(H \to \tau^+\tau^-) \sim 6\%$$
$$BR(H \to c\bar{c}) \sim 3\%$$
$$BR(H \to \mu^+\mu^-) \sim 0.02\%$$

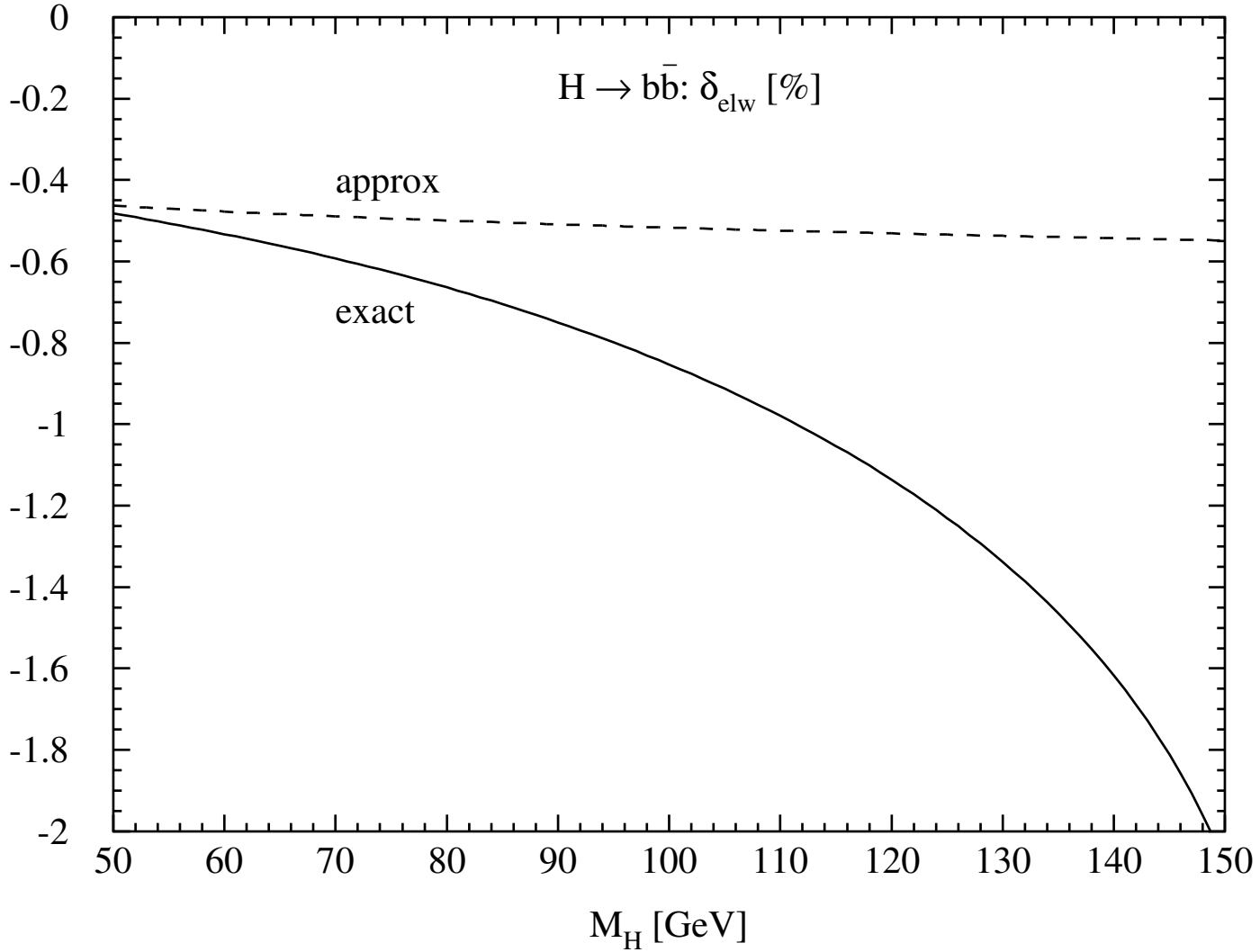
- $H \to b\bar{b}$ dominant

$$\Gamma(H \to f\overline{f}) = \frac{N_c G_F M_H}{4\sqrt{2}\pi}\, m_f^2\, (1 + \delta_{\rm QCD} + \delta_t + \delta_{mixed})\,(1 + \delta_{elw})$$

- elw. corr. δ_{elw}: moderate in interm. mass range

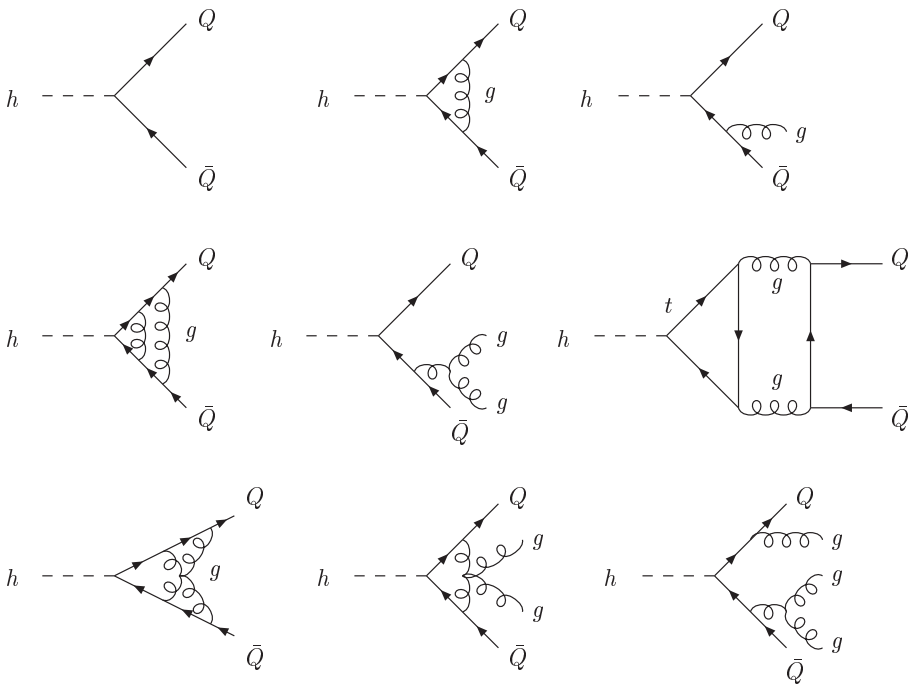
Fleischer, Jegerlehner
Bardin,...
Dabelstein, Hollik
Kniehl

$$\delta_{\rm elw} \approx \frac{3}{2}\frac{\alpha}{\pi} e_f^2 \left(\frac{3}{2} - \log\frac{M_H^2}{M_f^2}\right) + \frac{G_F}{8\pi^2\sqrt{2}} \left\{ k_f M_t^2 + M_W^2 \left[-5 + \frac{3}{s_W^2}\log c_W^2\right] - M_Z^2 \frac{6v_f^2 - a_f^2}{2} \right\}$$



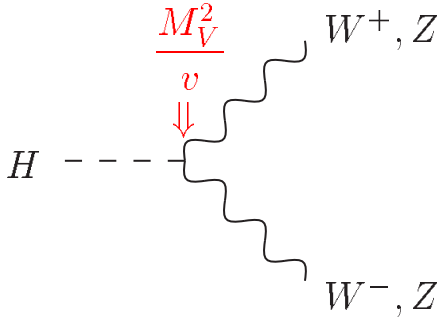
- -0.5% shift from approx $\to$ exact

- δ_{QCD}: large QCD corrections to $H \to b\bar{b}, c\bar{c}$: $\sim -50 \ldots -80\%$ (known to 4 loops)



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

- dominant effect: $m_b \to \overline{m}_b(M_h) \Rightarrow \sim 25\%$ remaining
- δ_t: top-Yukawa induced QCD corrections: $\sim 1\%$
- δ_{mixed}: mixed QCD-elw. corrections: $\sim 0.1\%$ Mihaila, Schmidt, Steinhauser
- finite m_b effects at NNLO $\sim 0.3\% \to 0.026\%$ Bernreuther, Chen, Si
- HDECAY: $(1+\delta_{QCD}+\delta_t)(1+\delta_{elw})$ (full elw., no mixed & NNLO m_b)
- differential @ NNLO Anastasiou, Herzog, Lazopoulos
Del Duca, Duhr, Somogyi, Tramontano, Trocsanyi



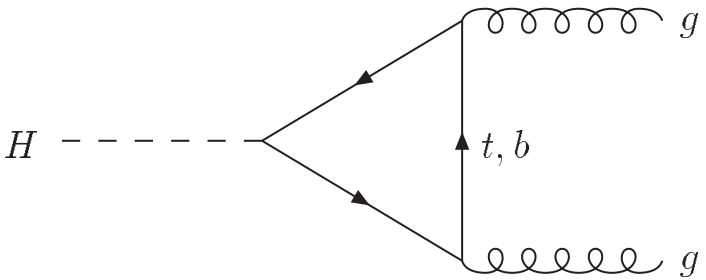
$$BR(H \to W^{+(*)}W^{-(*)}) \sim 21\%$$
$$BR(H \to Z^{(*)}Z^{(*)}) \sim 3\%$$

below threshold: $H \to V^{(*)}V^*$ important for $M_H \gtrsim M_V$ Rizzo, Keung, Marciano, Cahn

- elw. corr.: $\sim 5\%$ Fleischer, Jegerlehner, Bardin,..., Kniehl, Bredenstein, Denner, Dittmaier, Weber

- HDECAY: approx. NLO elw. corrections
  $\to$ Prophecy4f Bredenstein, Denner, Dittmaier, Weber

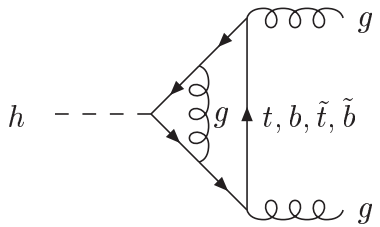
- Hto4l: NLO elw. matched to parton showers Boselli, Carloni Calame, Montagna, Nicrosini, Piccinini

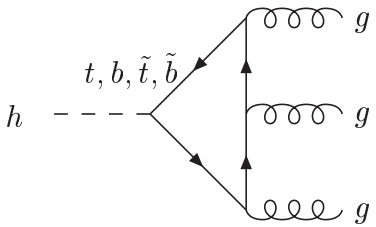


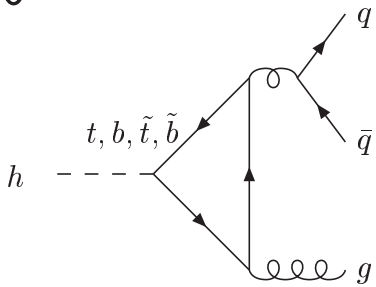
$$BR(H \to gg) \sim 8\%$$

- large QCD corrections: $\sim +90\%$

Inami, Kubota, Okada
S., Djouadi, Graudenz, Zerwas







$$\Gamma\left(H \to gg\right) \approx \Gamma_{LO}\left\{1 + 0.67 + 0.20 + 0.02\right\}$$

- 3/4/5-loop corr. $(M_H \ll 4m_t)$: $\mathcal{O}(20\%) \Rightarrow$ perturbatively stable

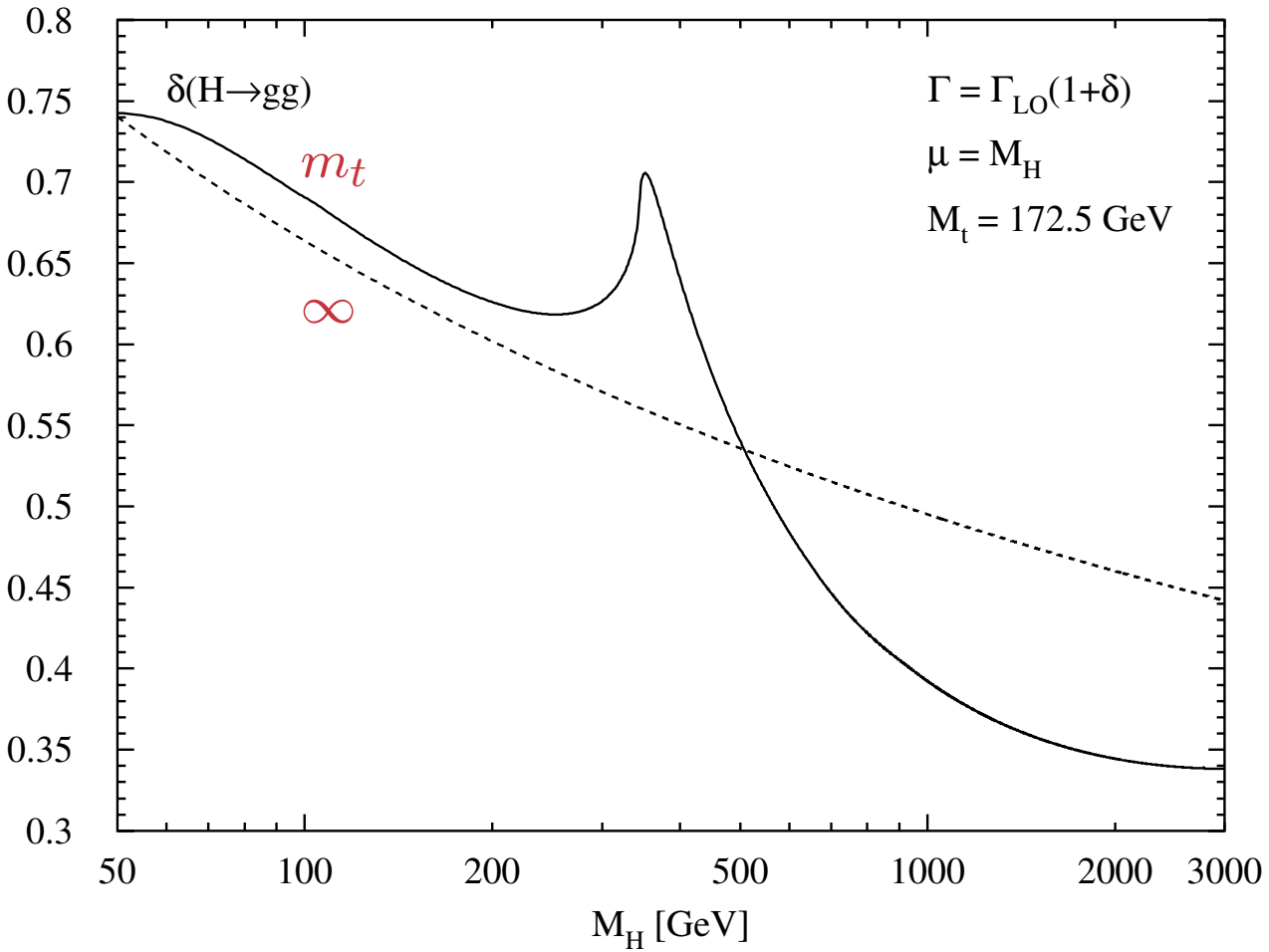
Chetyrkin, Kniehl, Steinhauser
Baikov, Chetyrkin
Herzog, Ruijl, Ueda, Vermaseren, Vogt

- can be obtained from

$$\mathcal{L}_{eff} = \frac{\alpha_s}{12\pi}\left\{1 + \frac{11}{4}\frac{\alpha_s}{\pi} + \cdots\right\} G^{a\mu\nu} G^a_{\mu\nu} \frac{H}{v}$$

Inami, Kubota, Okada
S., Djouadi, Graudenz, Zerwas
Chetyrkin, Kniehl, Steinhauser
Baikov, Chetyrkin

$$\Gamma(H \to gg) = \kappa_t^2 \Gamma_{tt} + \kappa_t \kappa_b \Gamma_{tb} + \kappa_b^2 \Gamma_{bb} \; [+\Gamma_{rem}]$$

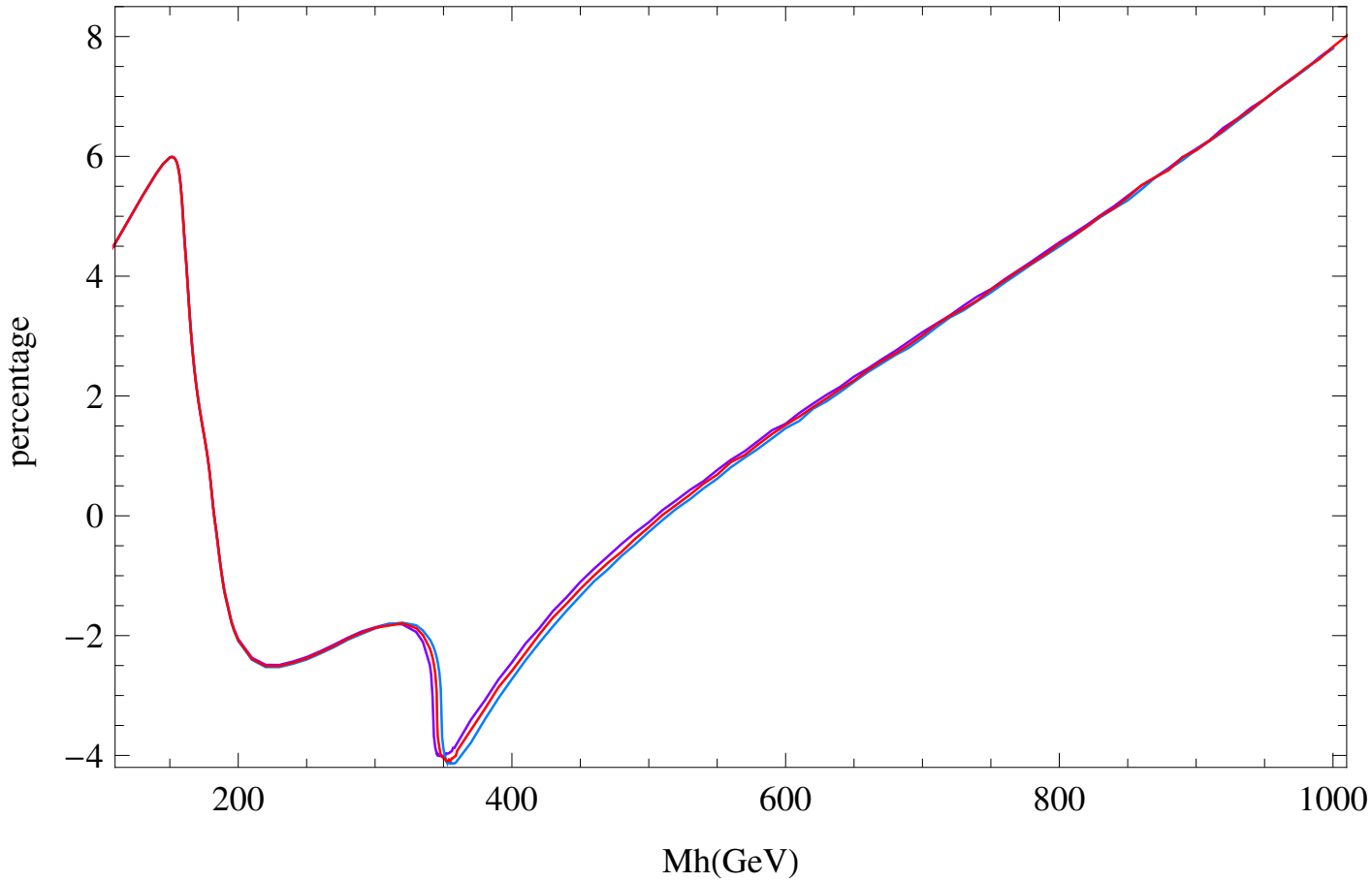


S., Djouadi, Graudenz, Zerwas

NLO QCD: full mass dependence $\to$ HDECAY

charm loops: $\sim 2\% \to$ HDECAY

$H \to gg$

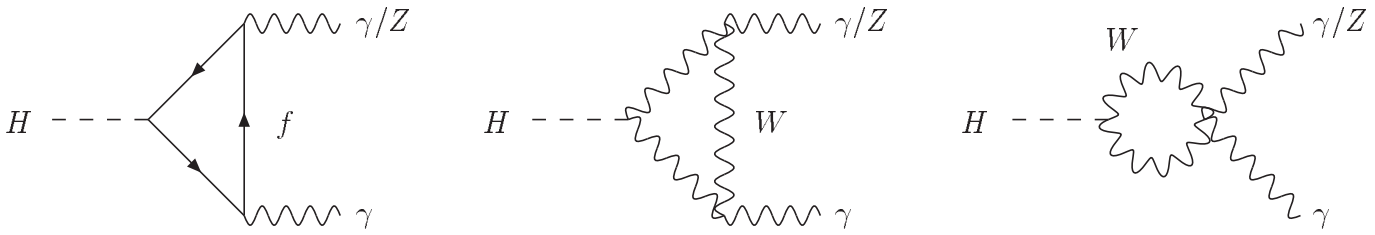


Actis, Passarino, Sturm, Uccirati

moderate elw. corrections: $\mathcal{O}(5\%)$

Aglietti, Bonciani, Degrassi, Vicini
Degrassi, Maltoni
Actis, Passarino, Sturm, Uccirati

HDECAY: 4-loop QCD corrections + NLO elw. corrections



$$BR(H \to \gamma\gamma, Z\gamma) \lesssim 2 \times 10^{-3}$$

- $H \to \gamma\gamma$ extremely important decay channel @ LHC
- W–loop dominant
- QCD corrections: $\sim 2\%$ in intermediate mass range

  Zheng, Wu
  Djouadi, S., Zerwas
  Melnikov, Yakovlev
  Inoue,. . .

  NNLO QCD: per-mille range

  Steinhauser
  Maierhöfer, Marquard
  Sturm

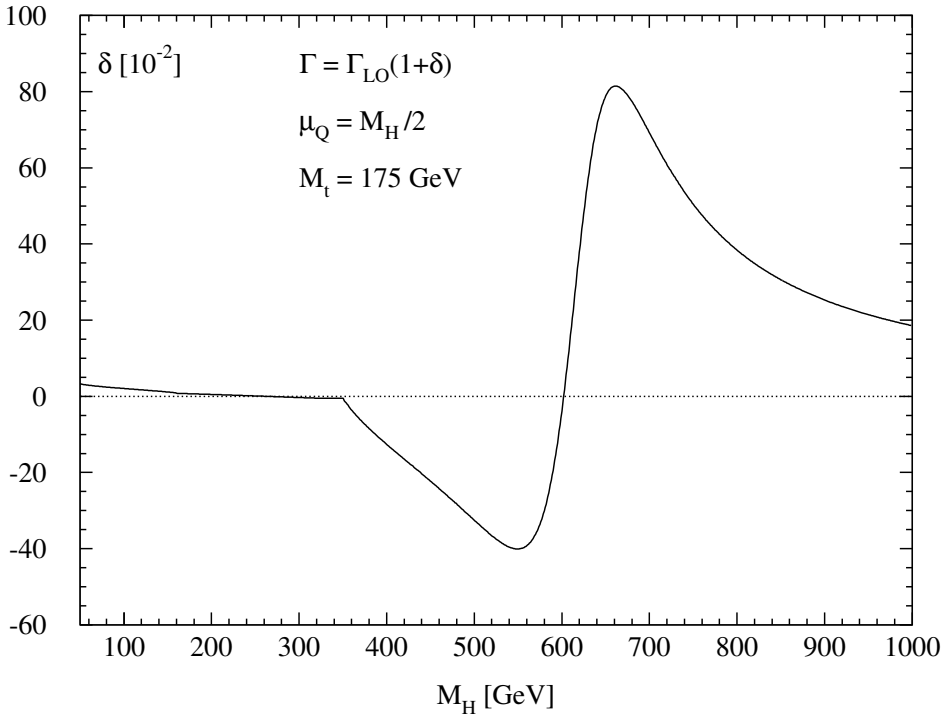
- elw. corr.: $\sim -2\%$ $(H \to \gamma\gamma)$

  Aglietti, Bonciani, Degrassi, Vicini
  Degrassi, Maltoni
  Actis, Passarino, Sturm, Uccirati

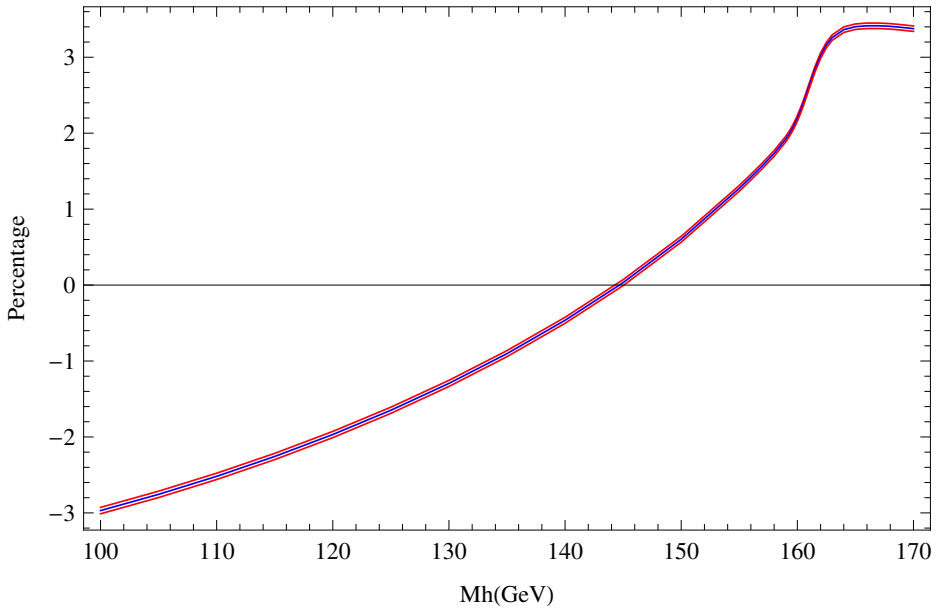
  $\sim -0.75\%$ $(H \to Z\gamma)$

  Chen, Chen, Qiao, Zhu
  Sang, Feng, Jia

$H \to \gamma\gamma$



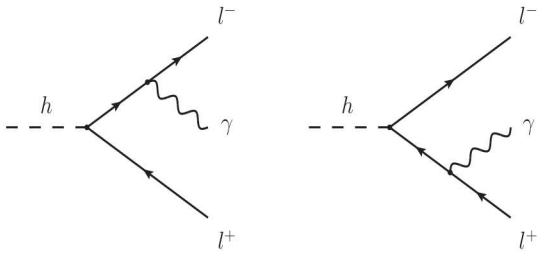
S., Djouadi, Zerwas



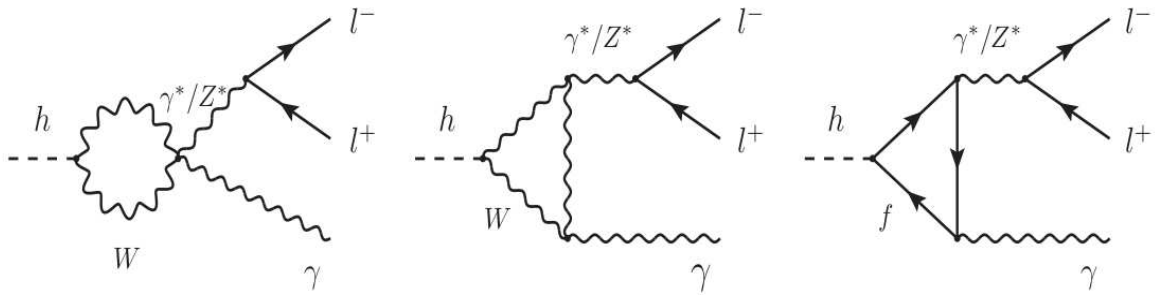
Actis, Passarino, Sturm, Uccirati

NLO QCD + elw.: full mass dependence → HDECAY

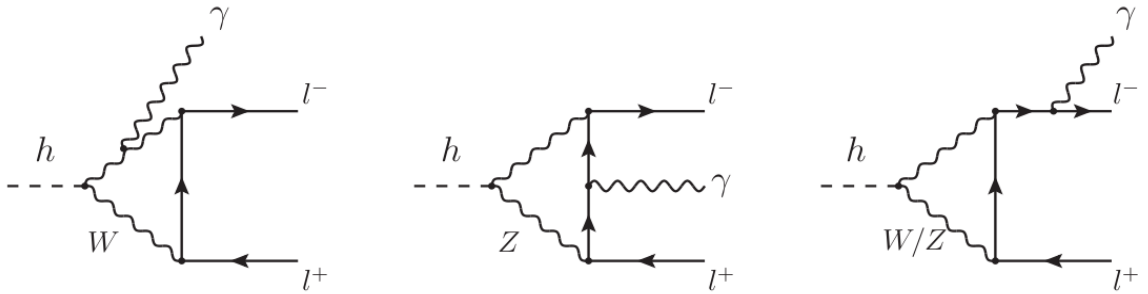
HIGGS DALITZ DECAYS



tree



off-shell



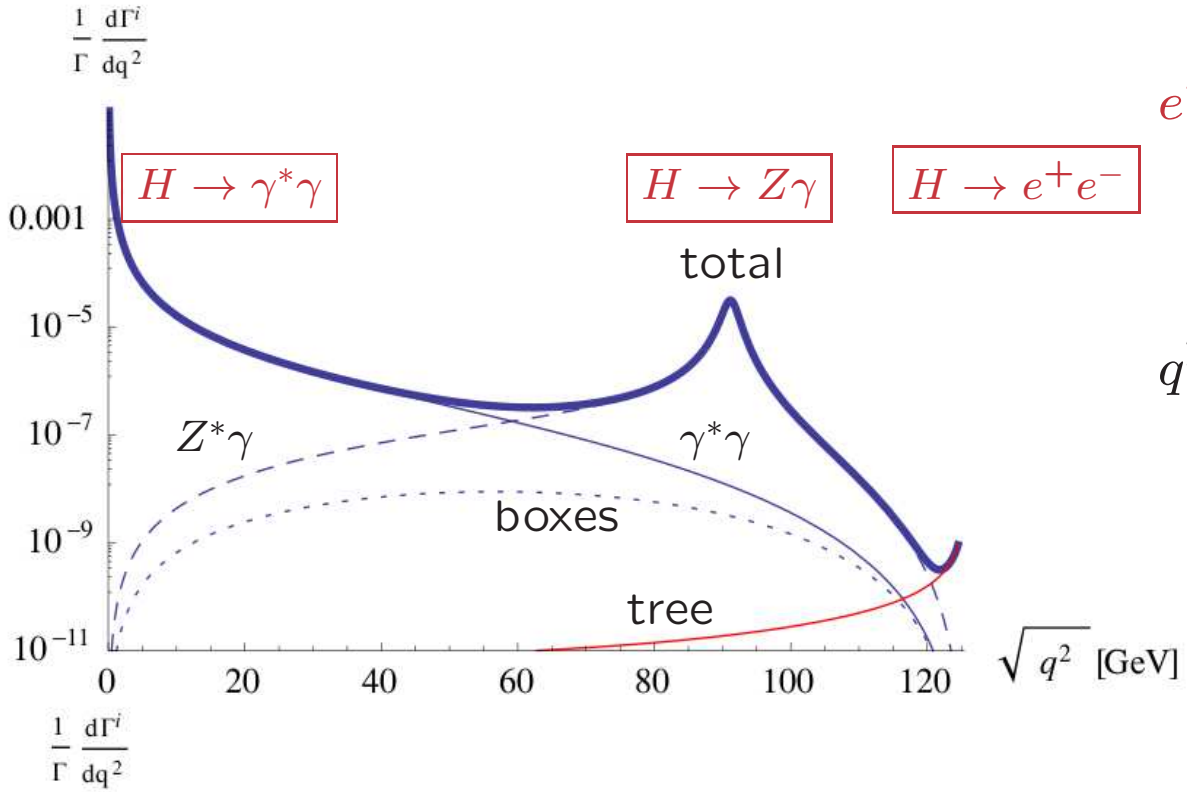
boxes

Abbasabadi, Bowser–Chao, Dicus, Repko
Sun, Chang, Gao
Passarino
Kachanovich, Nierste, Nišandžić

$$\frac{\Gamma(h \to \gamma e^+ e^-)}{\Gamma(h \to \gamma\gamma)} = 5.7\%$$

$$\frac{\Gamma(h \to \gamma \mu^+ \mu^-)}{\Gamma(h \to \gamma\gamma)} = 5.8\% \qquad (E_\gamma > 1 \text{ GeV})$$

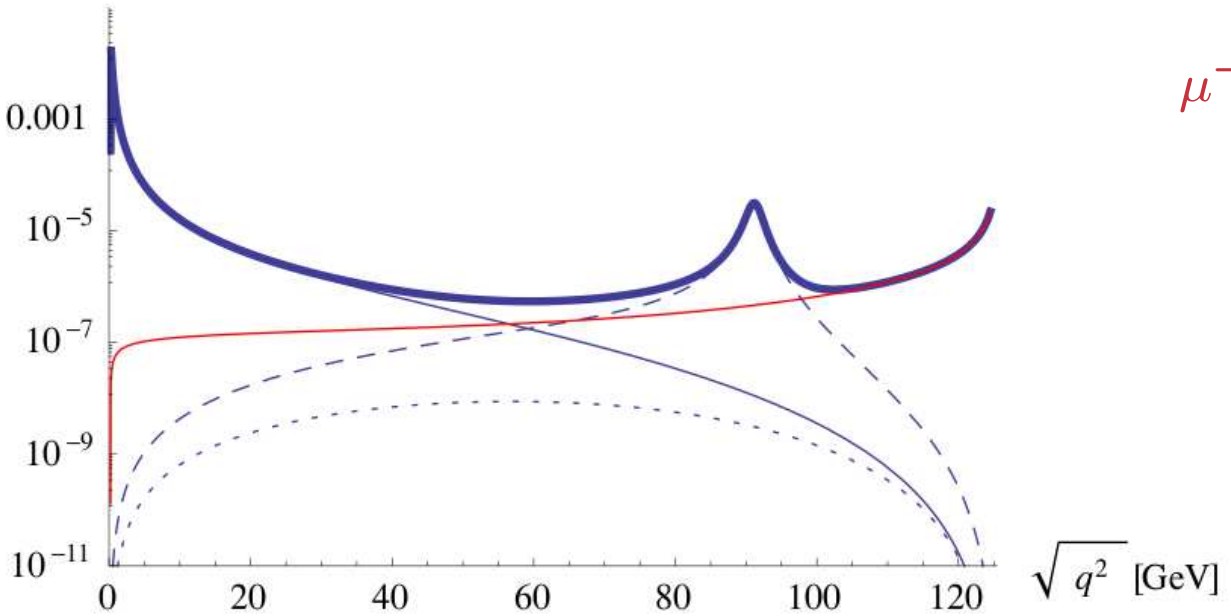
$$\frac{\Gamma(h \to \gamma \tau^+ \tau^-)}{\Gamma(h \to \gamma\gamma)} = 3.04$$



$e^+e^-\gamma$

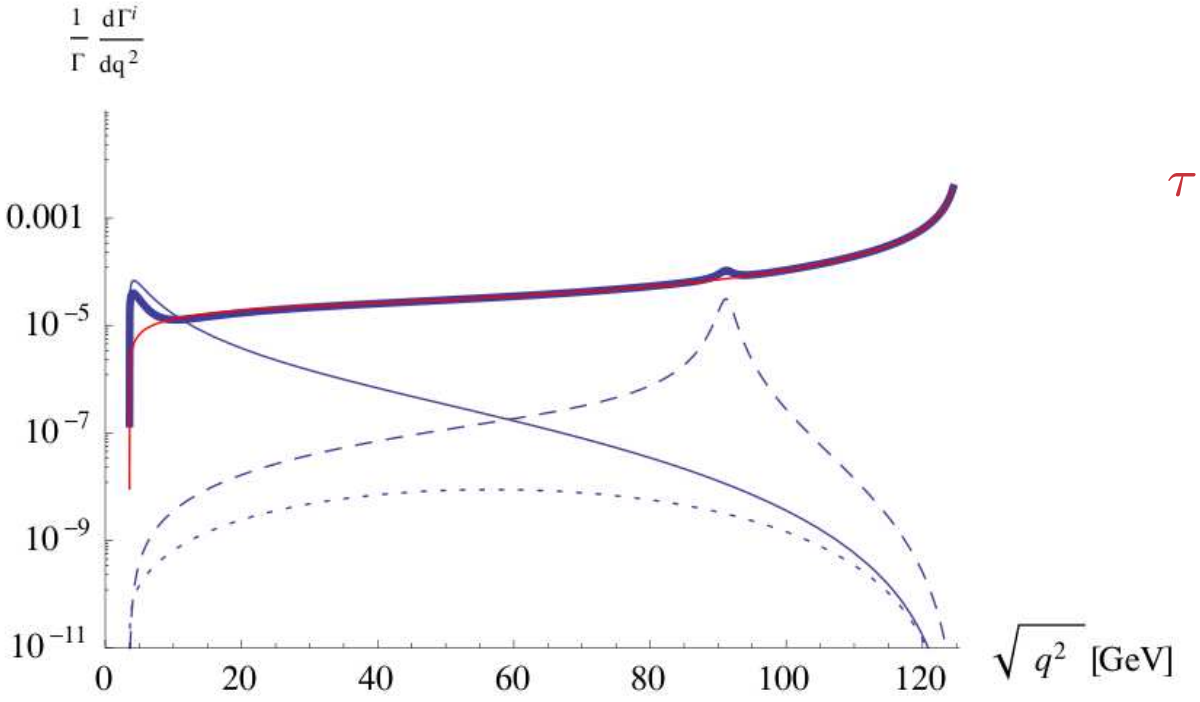
$q^2 = M^2_{\ell^+\ell^-}$

Sun, Chang, Gao



$\mu^+\mu^-\gamma$

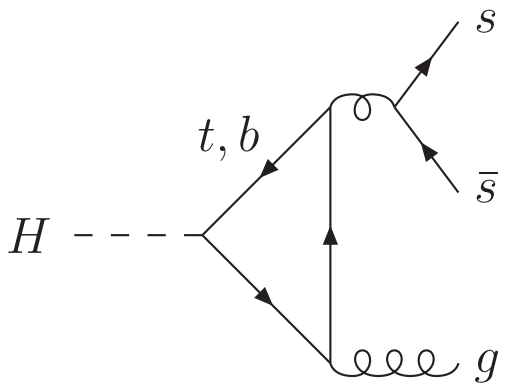
- $H \to \gamma\gamma \Leftrightarrow H \to \ell^+\ell^-\gamma \Leftrightarrow H \to Z\gamma \Leftrightarrow H \to \ell^+\ell^-$



$\tau^+\tau^-\gamma$

Sun, Chang, Gao

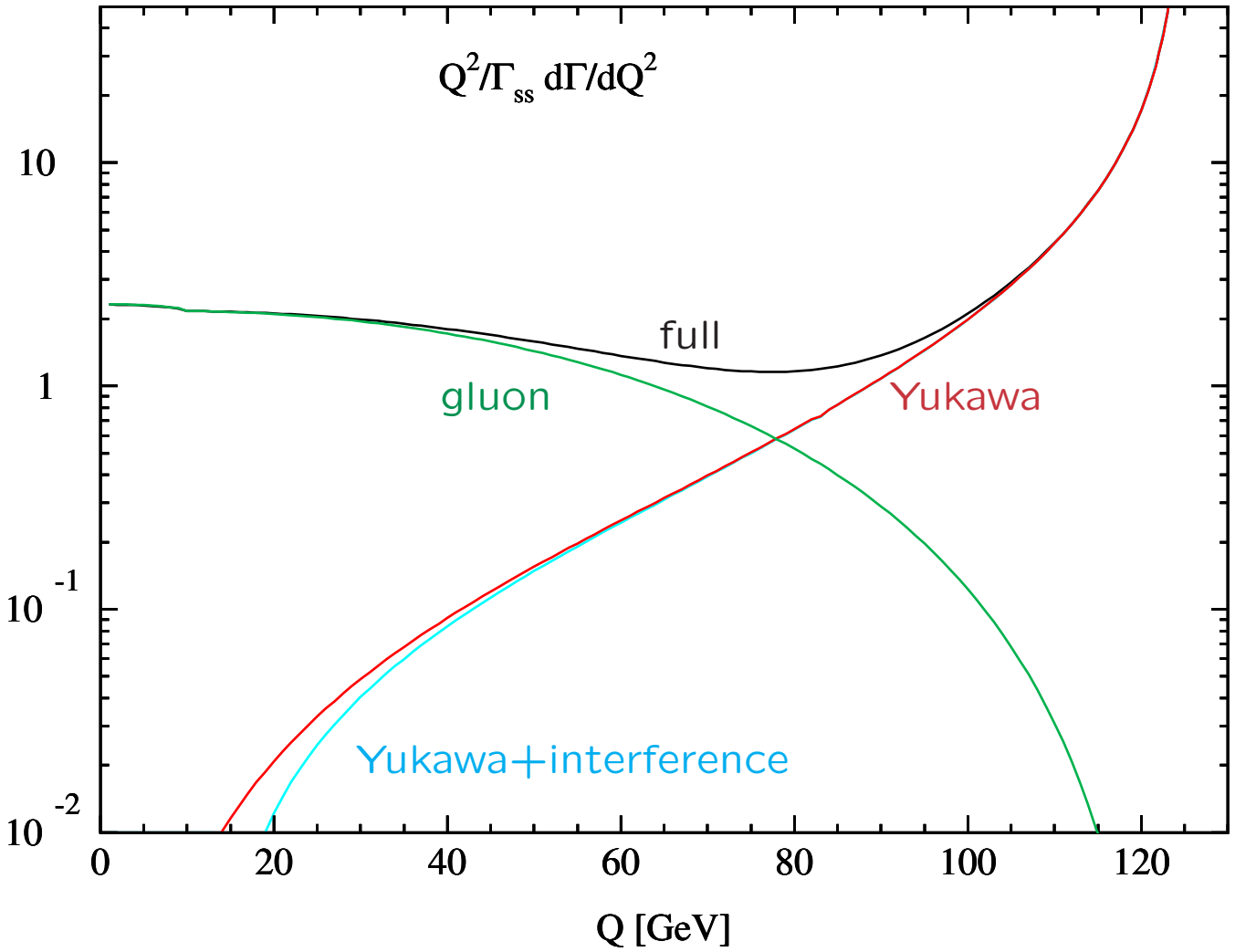
INTERMEZZO: strong Dalitz decays: $H \to s\bar{s}g$

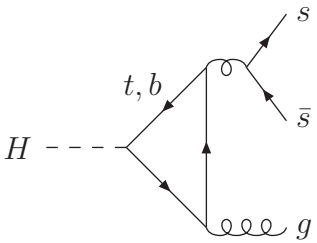


$$\delta_s = \left\{ -\frac{7}{6} + \frac{1}{3} \log \frac{M_H^2}{m_s^2} \right\} \frac{\alpha_s}{\pi}$$

- $\delta\Gamma = \Gamma(H \to gg)(1 + \delta_s)$
- $BR(H \to g^* g \to s\bar{s}g) \lesssim 1\%$
- $BR(H \to s\bar{s}) \sim 0.021\%$ (Yukawa-induced, $\overline{\text{MS}}$ mass)
- constrain y_s within less than a factor of 2?

$H \to s\bar{s}g$

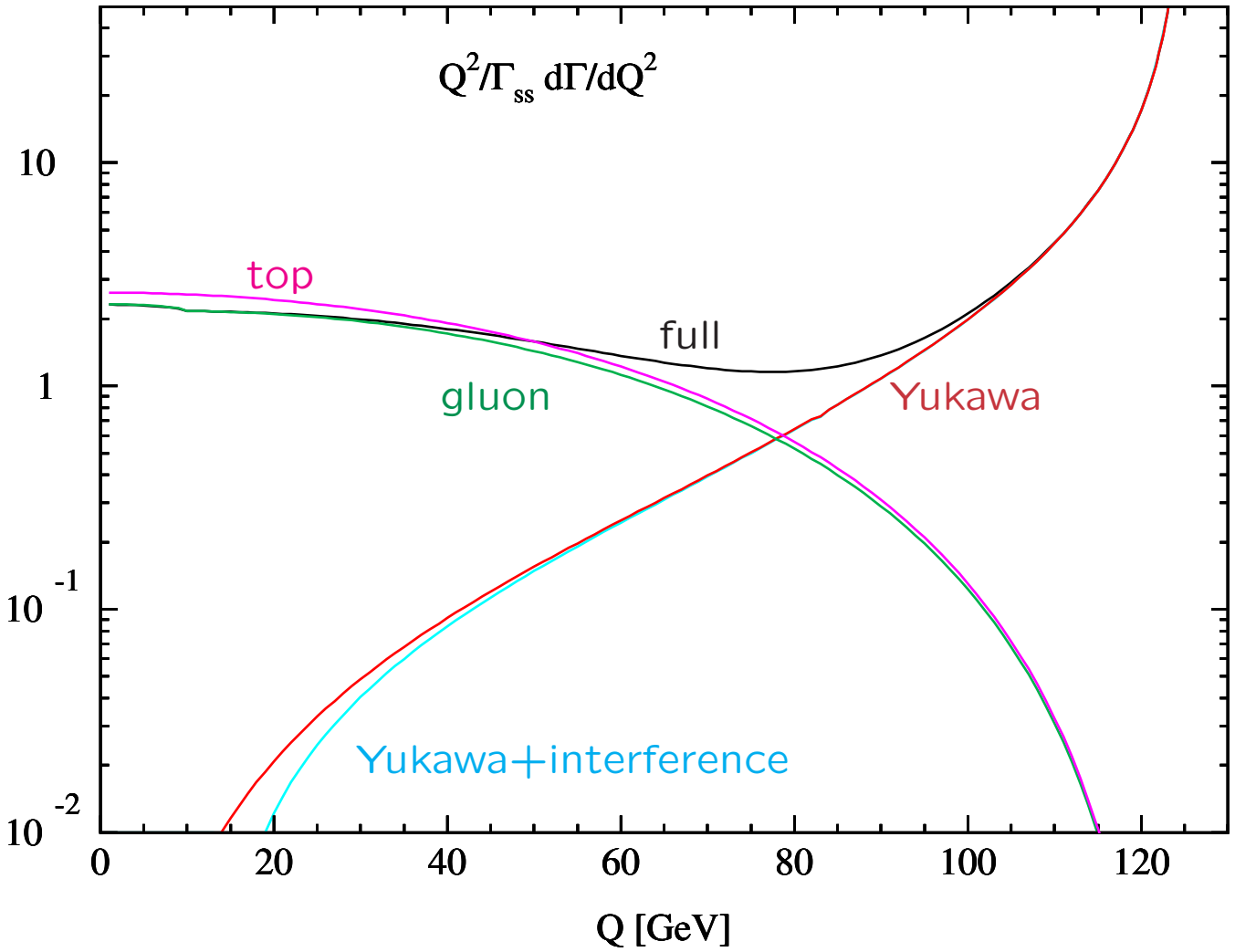


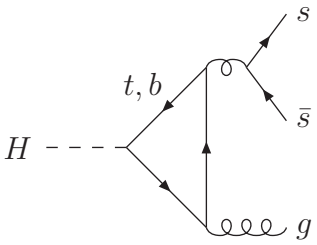


Bagnaschi, Biermann, S.

- using $\overline{m}_s(M_H)$ (neglecting regular mass effects)
- no resummation towards the end-point

$H \to s\bar{s}g$

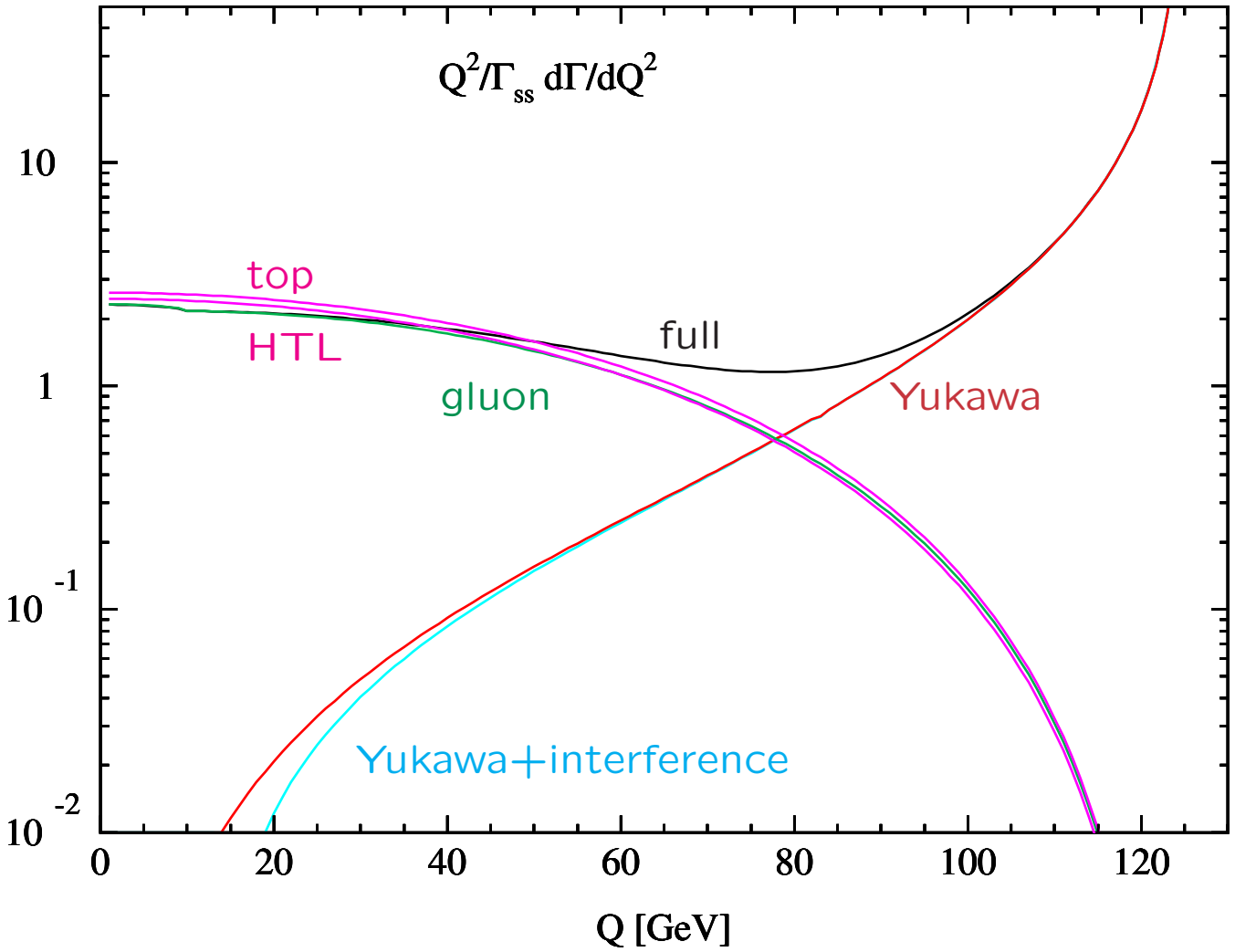


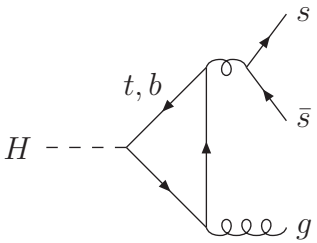


Bagnaschi, Biermann, S.

- using $\overline{m}_s(M_H)$ (neglecting regular mass effects)
- no resummation towards the end-point

$H \to s\bar{s}g$

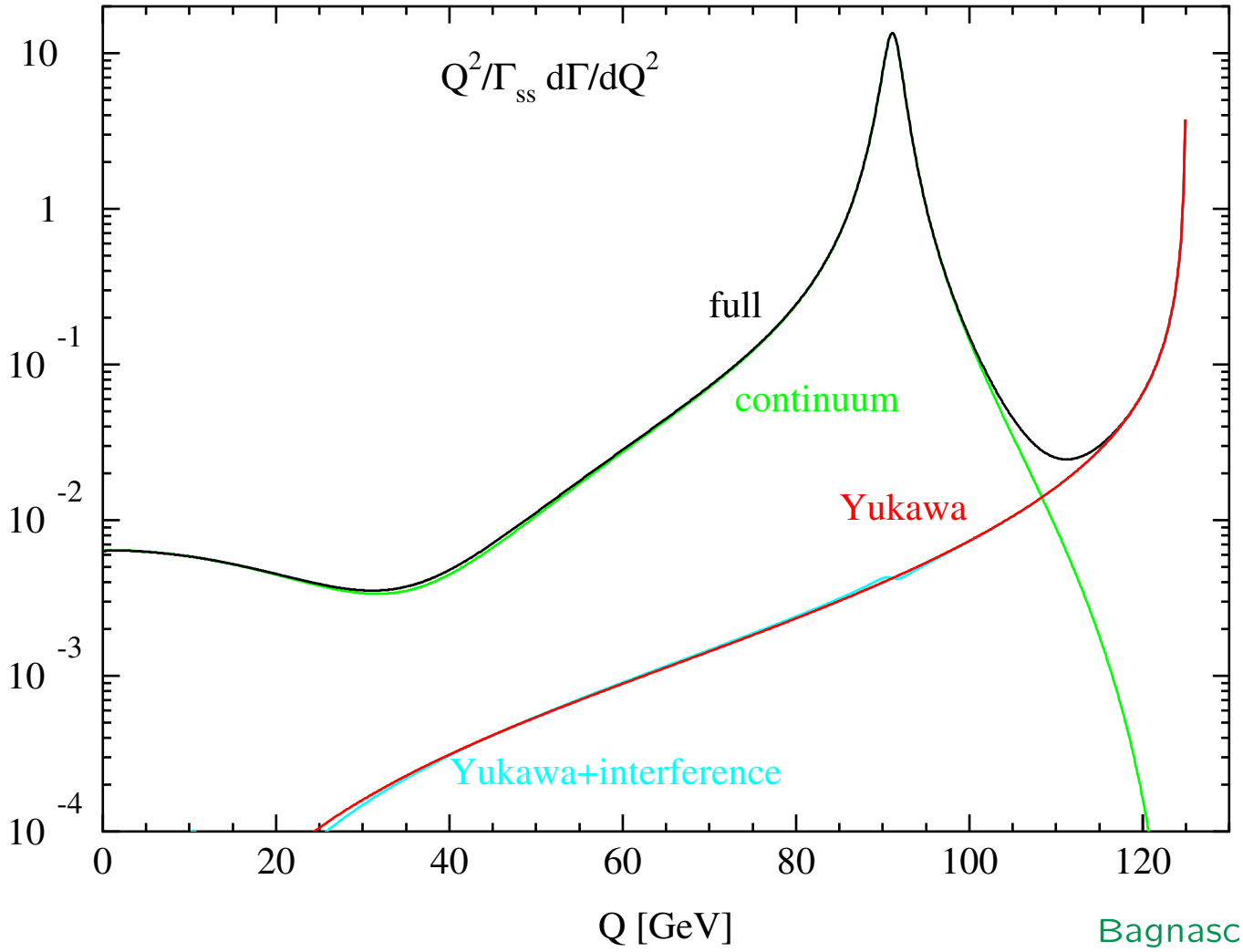




Bagnaschi, Biermann, S.

- using $\overline{m}_s(M_H)$ (neglecting regular mass effects)
- no resummation towards the end-point

weak:



$s\bar{s}\gamma$

Bagnaschi, Biermann, S.

- using $\overline{m}_s(M_H)$ (neglecting regular mass effects)
- no resummation towards the end-point

Partial Width	QCD	Electroweak	Total	on-shell Higgs
$H \to b\bar{b}/c\bar{c}$	$\sim 0.2\%$	$\sim 0.5\%$	$\sim 0.5\%$	NNNNLO / NLO
$H \to \tau^+\tau^-/\mu^+\mu^-$		$\sim 0.5\%$	$\sim 0.5\%$	NLO
$H \to gg$	$\sim 3\%$	$\sim 1\%$	$\sim 3\%$	NNNLO approx. / NLO
$H \to \gamma\gamma$	$< 1\%$	$< 1\%$	$\sim 1\%$	NLO / NLO
$H \to Z\gamma$	$< 1\%$	$< 1\%$	$\sim 1\%$	(N)LO / NLO
$H \to WW/ZZ \to 4f$	$< 0.5\%$	$\sim 0.5\%$	$\sim 0.5\%$	(N)NLO

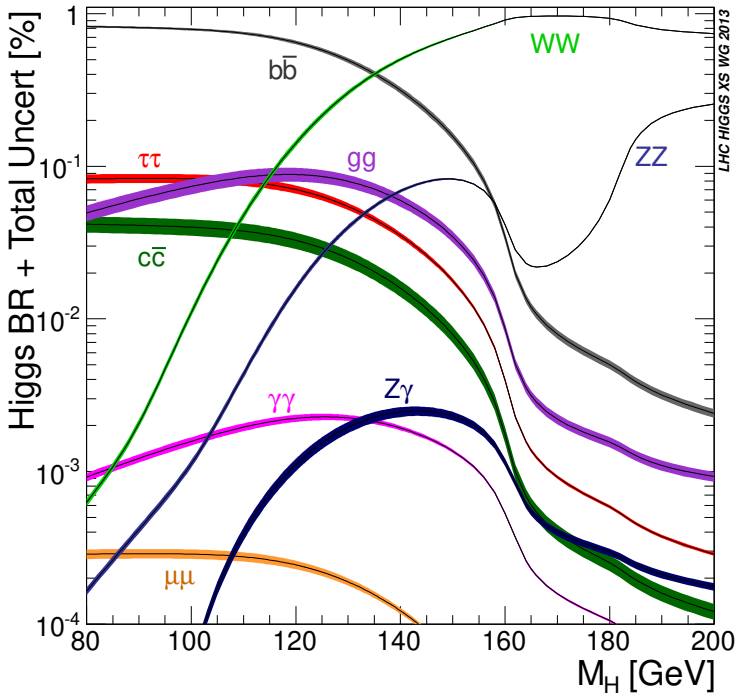
- QCD: variation $\mu_R = [1/2, 2]\mu_0$
  elw: missing HO estimated from known structure at NLO
  different uncertainties added linearly for each channel

- parametric uncertainties:
  $m_t = 172.5 \pm 1$ GeV $\qquad \alpha_s(M_Z) = 0.118 \pm 0.0015$
  $m_b(m_b) = 4.18 \pm 0.03$ GeV $\qquad m_c(3\text{GeV}) = 0.986 \pm 0.025$ GeV
  different uncertainties added quadratically for each channel

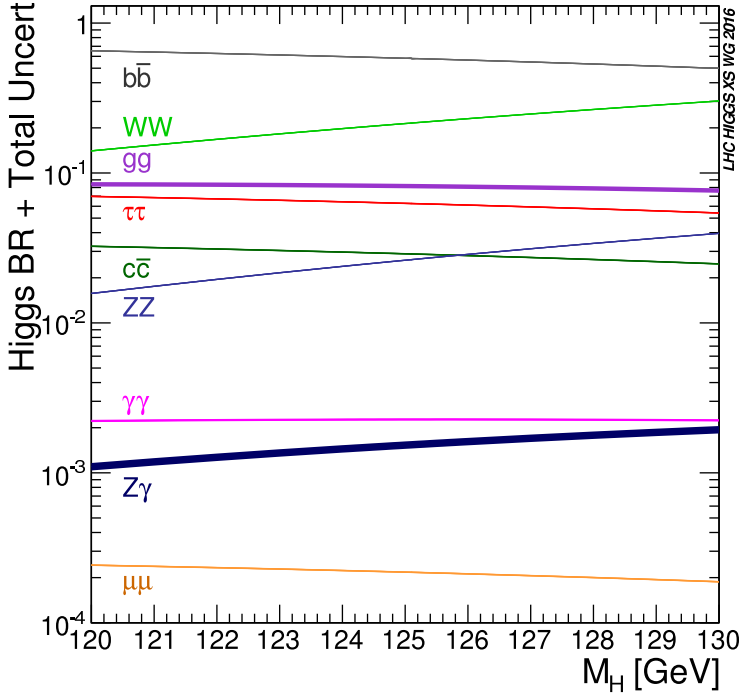
- total uncertainties: parametric & theor. uncertainties added linearly

YR3 HDECAY & Prophecy4f YR4

$\sim \sim$ 10% $\rightarrow$
$\sim$ 10% $\rightarrow$



$\longrightarrow$



Denner, Heinemeyer, Puljak, Rebuzzi, S.

- refinements input parameters
- full NLO elw. corrections to $H \to f\bar{f}$
- NLO quark-mass effects in $H \to gg$

- ATLAS: $\mu_{bb}/\mu_{ZZ} = \Gamma(H \to bb)/\Gamma(H \to ZZ)|_{SM-norm} = 0.87^{+0.28}_{-0.21}$

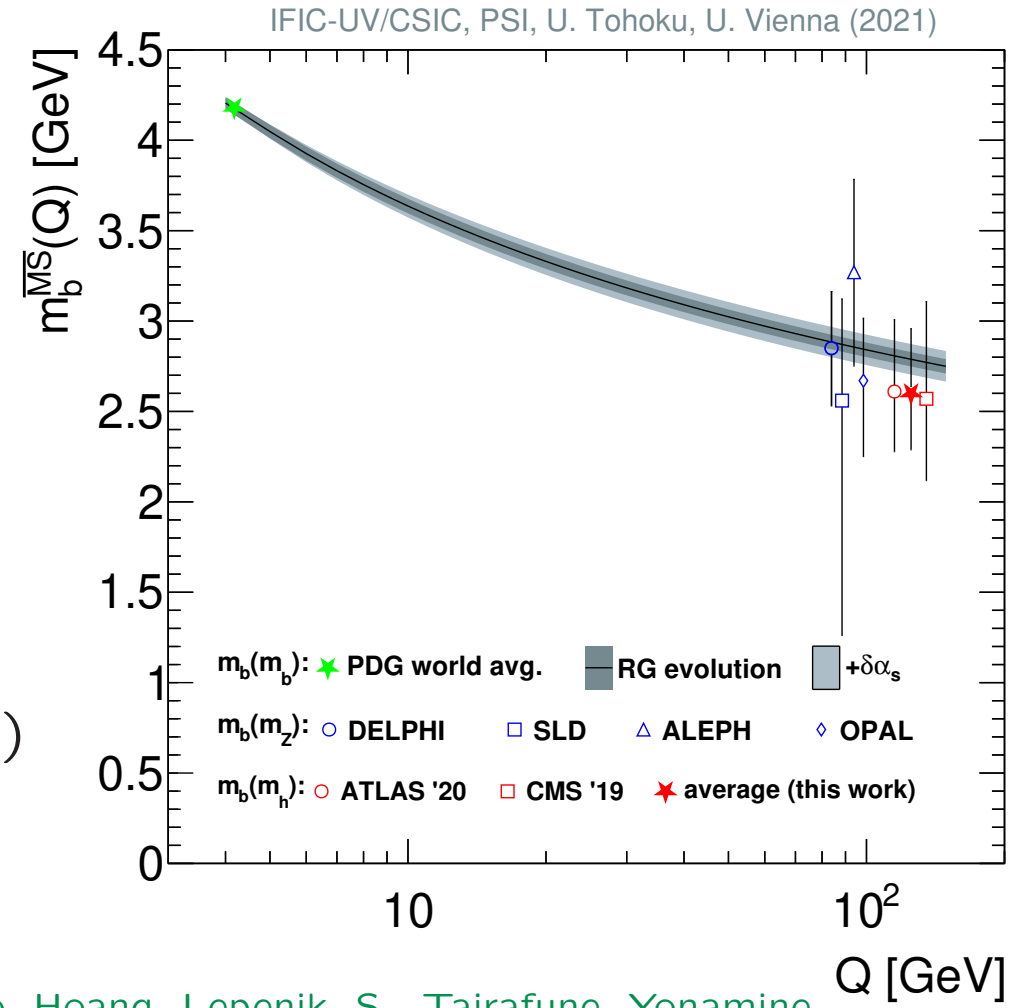
- CMS: $\mu_{bb}/\mu_{ZZ} = \Gamma(H \to bb)/\Gamma(H \to ZZ)|_{SM-norm} = 0.84^{+0.37}_{-0.27}$

$\Rightarrow \overline{m}_b(M_H) = 2.60^{+0.36}_{-0.31}$ GeV
(Convino) Kieseler

RG-evolution: REvolver

Hoang, Lepenik, Mateu

$\alpha_s(M_Z) = 0.1179 \pm 0.001$ (0.004)



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

	FCC$_{ee}$	current th.	current par.
$H \to b\bar{b}$	0.4%	0.5%	2.2%
$H \to c\bar{c}$	0.7%	0.5%	5.5%
$H \to \tau^+\tau^-$	0.5%	0.5%	$< 0.1\%$
$H \to \mu^+\mu^-$	3.3%	0.5%	$< 0.1\%$
$H \to gg$	0.5%	3.2%	3.0%
$H \to \gamma\gamma$	1.1%	1.0%	$< 0.1\%$
$H \to Z\gamma$	4.3%	1.0%	$< 0.1\%$
$H \to WW$	0.3%	0.5%	$< 0.1\%$
$H \to ZZ$	0.1%	0.5%	$< 0.1\%$

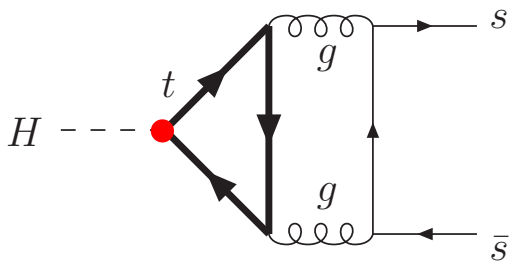
III *SUMMARY*

Standard Model

- decay widths and BRs known with sufficient accuracy for the LHC
- sizeable corrections from QCD
- elw. corrections required for high precision
- bottle neck: parametric uncertainties $\leftarrow m_b, \alpha_s, m_c, m_t$
  [non-perturbative to a large extent $\leftarrow$ lattice?]

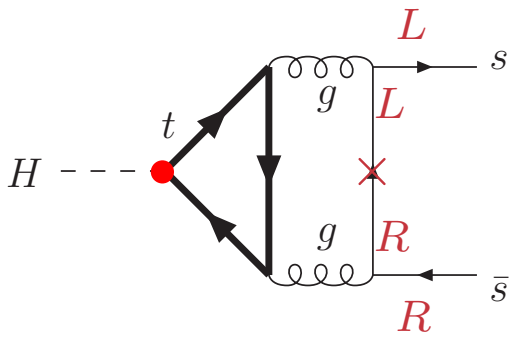
BACKUP SLIDES

QCD corrections



- involves top Yukawa coupling, part of the NNLO QCD corrections

QCD corrections



- involves top Yukawa coupling, part of the NNLO QCD corrections

- helicity flip $\Rightarrow$ develops factor $m_s \rightarrow$ small correction ($\sim 3\%$)

[You cannot perturbatively generate a Yukawa coupling for a massless fermion]

- weak and strong Dalitz decays: **no** helicity flip!