TOP – YUKAWA – INDUCED CORRECTIONS TO HIGGS PAIR PRODUCTION

Michael Spira (PSI)

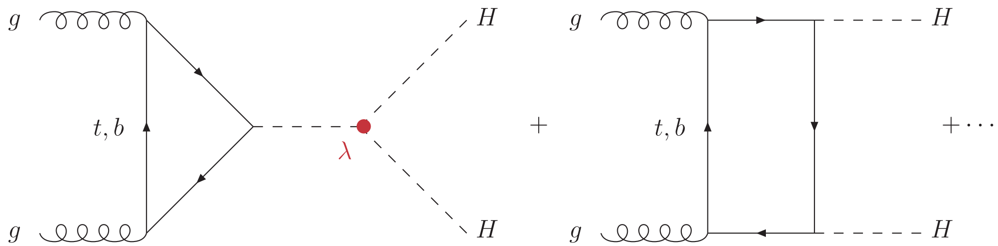
I Introduction

II $gg \to HH$

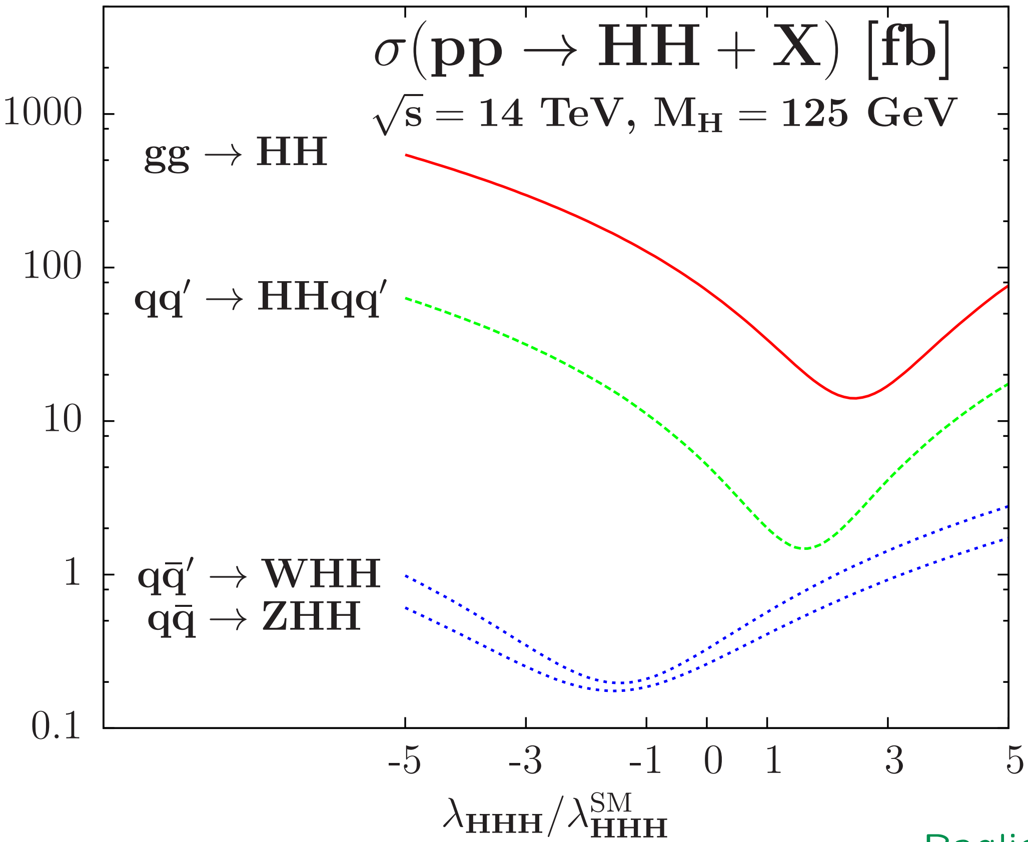
III Conclusions

in collaboration with J. Baglio, F. Campanario, S. Glaus, J. Ronca, M. Mühlleitner and J. Schlenk

I INTRODUCTION



- third generation dominant: $t\,(b)$



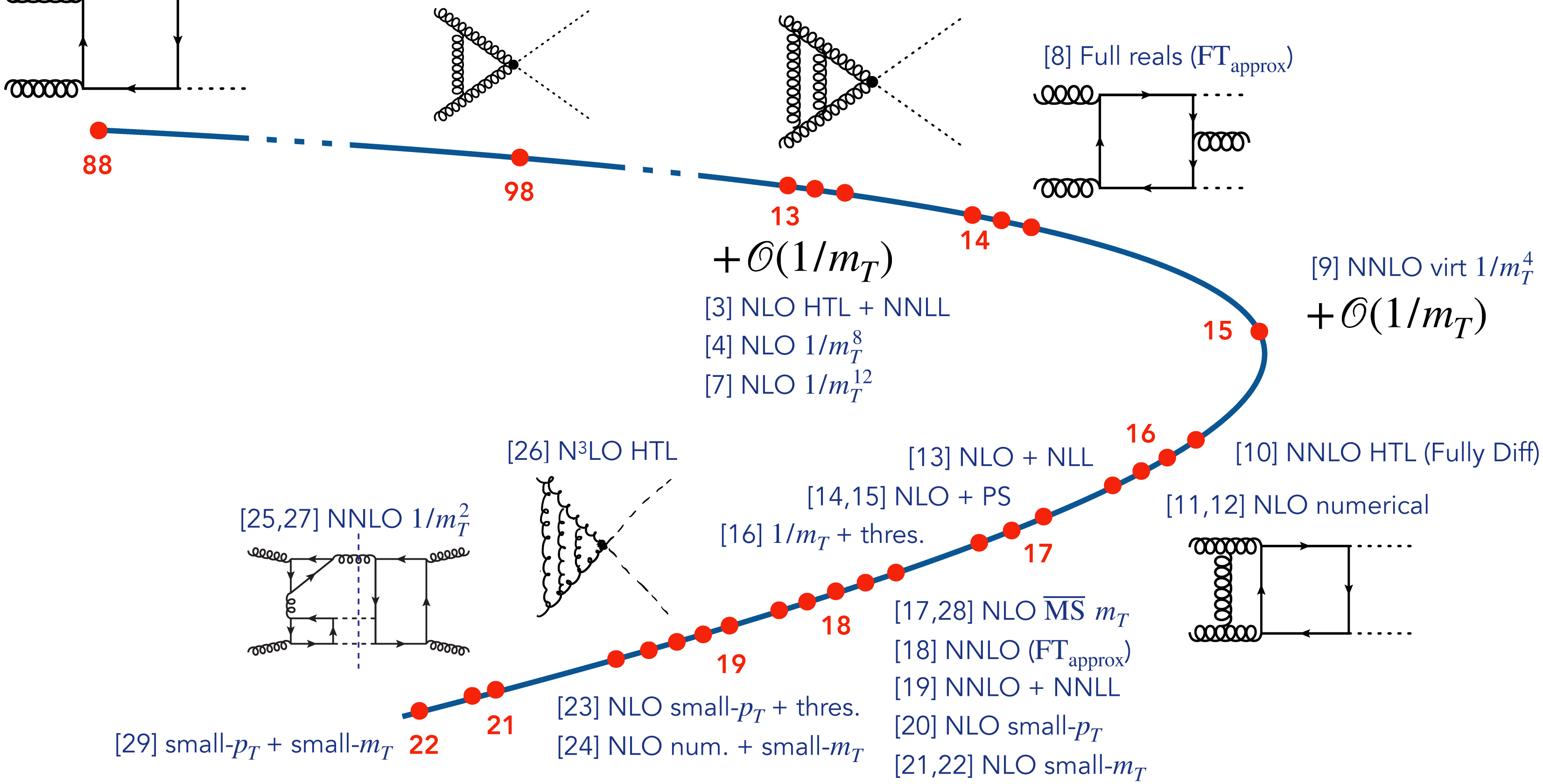
$gg \to HH:$

$$\frac{\Delta\sigma}{\sigma} \sim -\frac{\Delta\lambda}{\lambda}$$

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

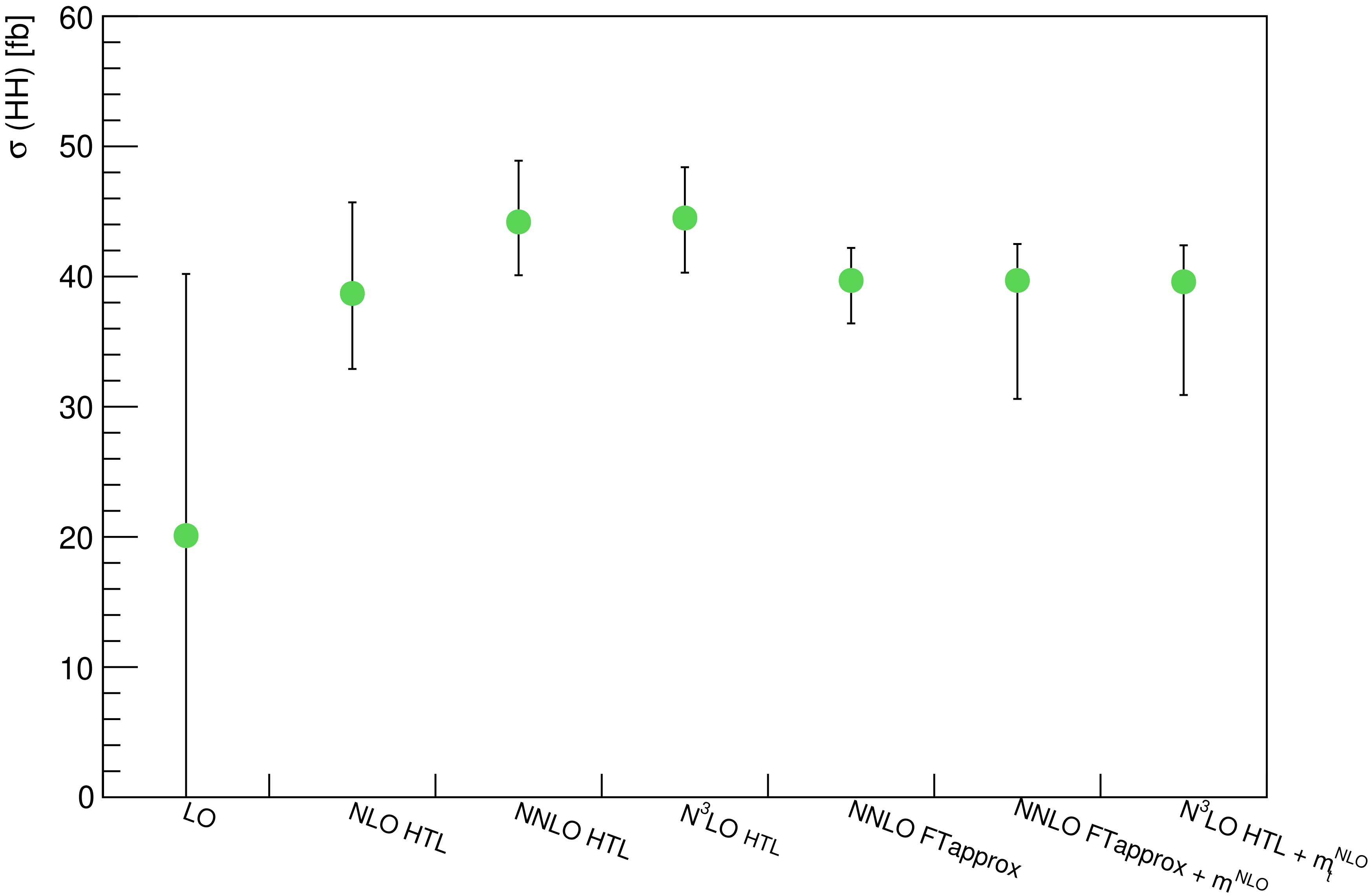
An approximate history (30 years in 30 seconds)

(Slide design shamelessly stolen from G. Salam)



[1] Glover, van der Bij 88; [2] Dawson, Dittmaier, Spira 98; [3] Shao, Li, Li, Wang 13; [4] Grigo, Hoff, Melnikov, Steinhauser 13; [5] de Florian, Mazzitelli 13; [6] Grigo, Melnikov, Steinhauser 14; [7] Grigo, Hoff 14; [8] Maltoni, Vryonidou, Zaro 14; [9] Grigo, Hoff, Steinhauser 15; [10] de Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev 16; [11] Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Schubert, Zirke 16; [12] Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Zirke 16; [13] Ferrera, Pires 16; [14] Heinrich, SPJ, Kerner, Luisoni, Vryonidou 17; [15] SPJ, Kuttimalai 17; [16] Gröber, Maier, Rauh 17; [17] Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher 18; [18] Grazzini, Heinrich, SPJ, Kallweit, Kerner, Lindert, Mazzitelli 18; [19] de Florian, Mazzitelli 18; [20] Bonciani, Degrassi, Giardino, Gröber 18; [21] Davies, Mishima, Steinhauser, Wellmann 18, 18; [22] Mishima 18; [23] Gröber, Maier, Rauh 19; [24] Davies, Heinrich, SPJ, Kerner, Mishima, Steinhauser, David Wellmann 19; [25] Davies, Steinhauser 19; [26] Chen, Li, Shao, Wang 19, 19; [27] Davies, Herren, Mishima, Steinhauser 19, 21; [28] Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira 21; [29] Bellafronte, Degrassi, Giardino, Gröber, Vitti 22;

S. Jones

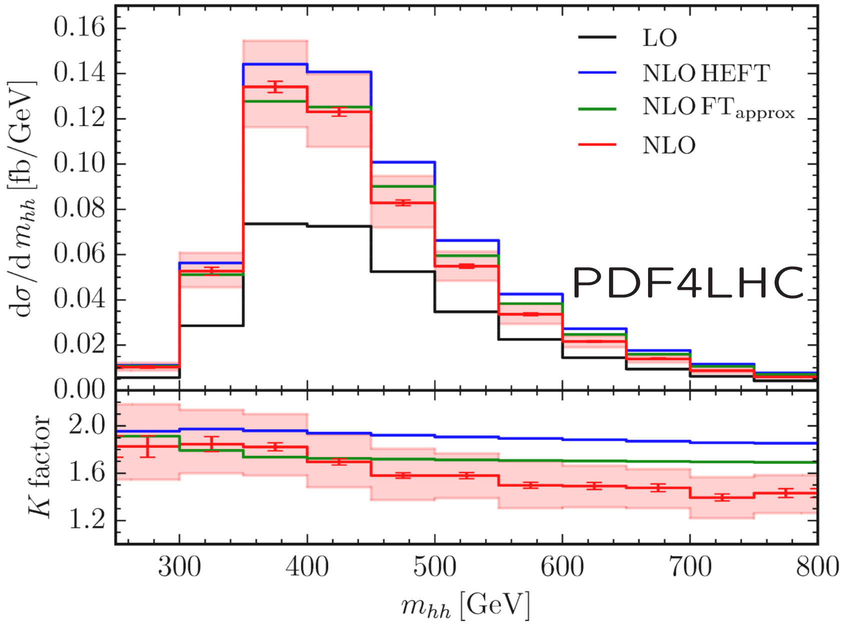


σ (HH) [fb]
60
50
40
30
20
10
0
LO
NLO HTL
NNLO HTL
N3LO HTL
NNLO FTapprox
NNLO FTapprox + mt NLO
N3LO HTL + mt NLO

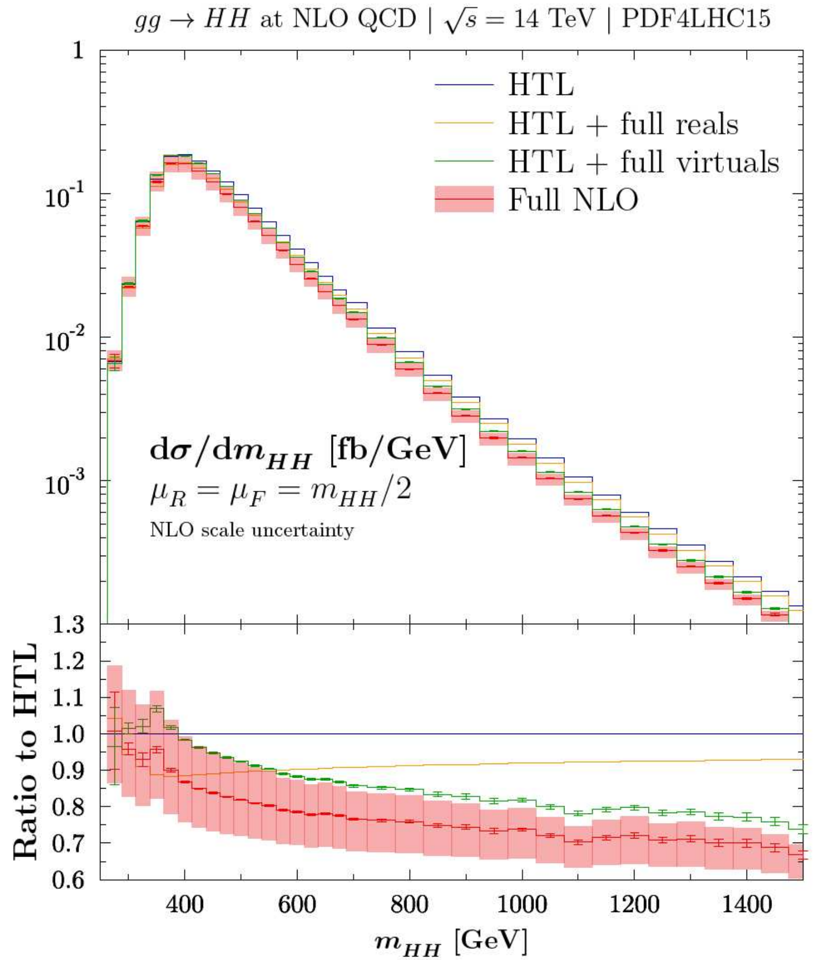
Full NLO calculation: top only, numerical integration

Borowka *et al.*	Baglio *et al.*
tensor reduction	no tensor reduction
sector decomposition	IR, end-point subtraction
contour deformation	IBP, Richardson extrapolation
$m_t = 173$ GeV	$m_t = 172.5$ GeV

Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke
Baglio, Campanario, Glaus, Mühlleitner, Ronca, S., Streicher



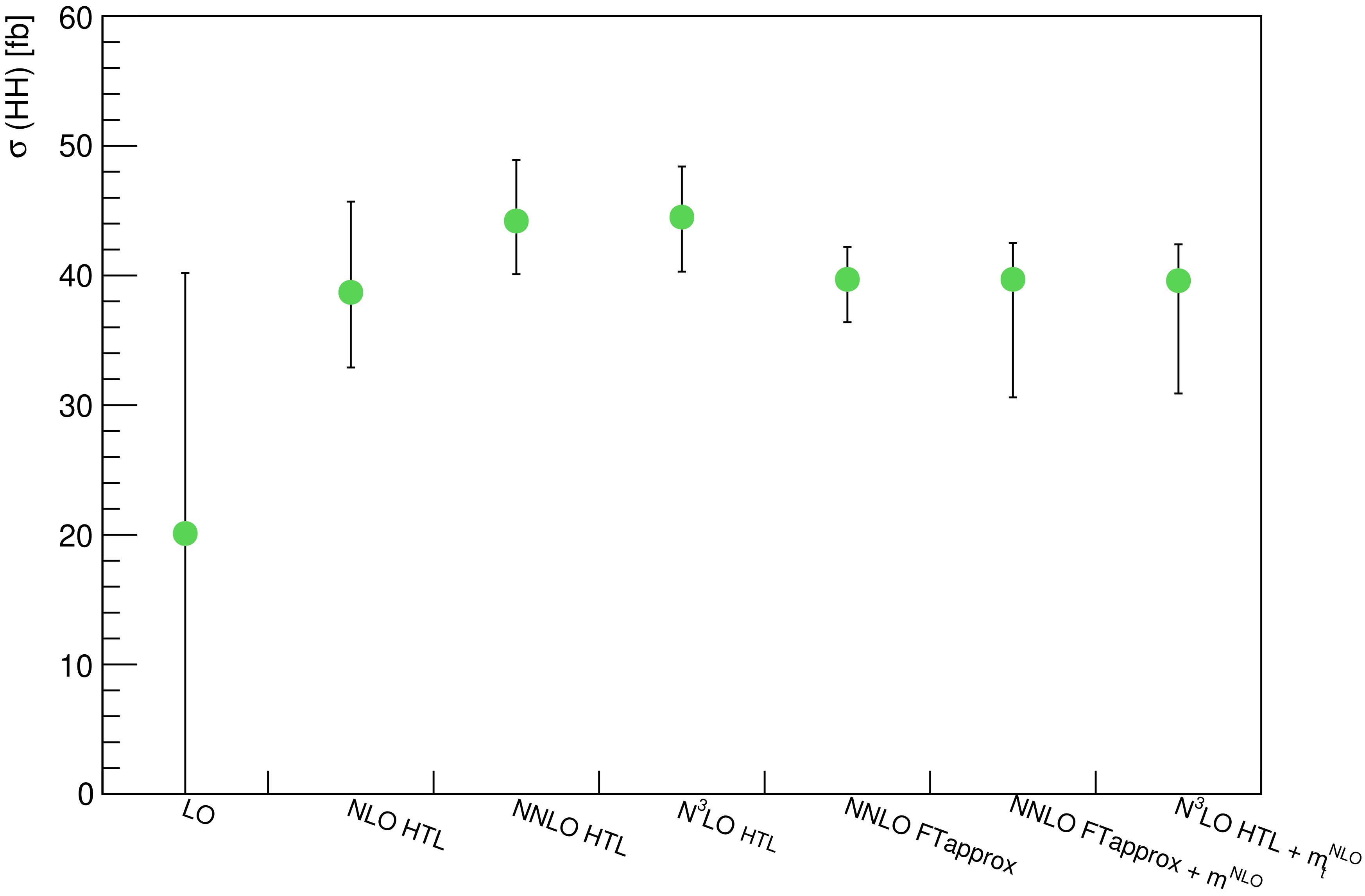
Borowka, Greiner, Heinrich, Jones, Kerner
Schlenk, Schubert, Zirke



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



σ (HH) [fb]
60
50
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NLO HTL
NNLO HTL
N^3LO HTL
NNLO FTapprox
NNLO FTapprox + m_t^{NLO}
N^3LO HTL + m_t^{NLO}

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:

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

final combined ren./fac. scale and m_t scale/scheme unc. @ NNLO$_{FTapprox}$:

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

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

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

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

Is this everything?

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No. . .

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No. . .

electroweak corrections. . .

- two works: top-Yukawa-induced as first step

  (i) HTL for $ggH(H)$ coupling + full corrections to HHH vertex

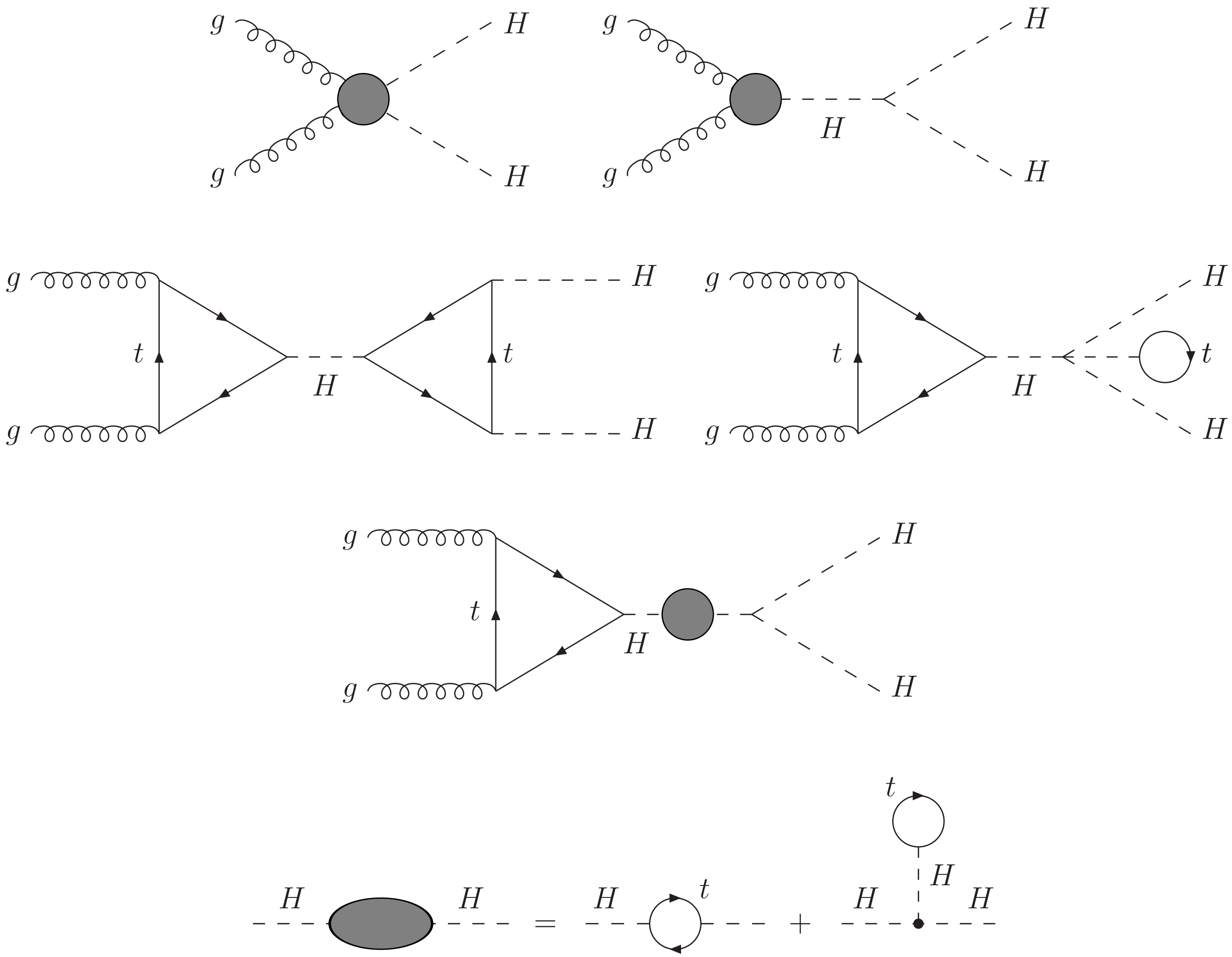
  Mühlleitner, Schlenk, S.

  (ii) analytical results for $ggHH$ coupling in the HEL

  Davies, Mishima, Schönwald, Steinhauser, Zhang

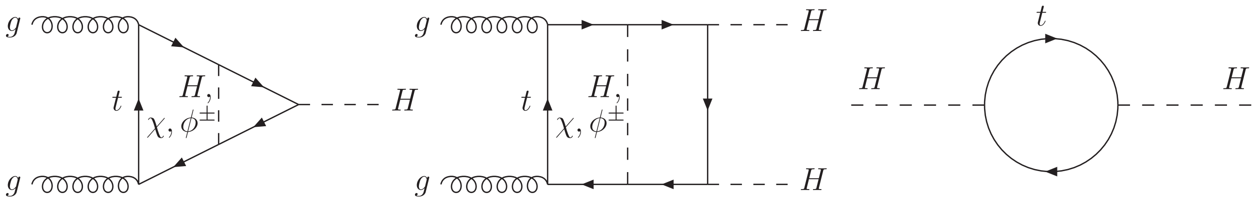
Top-induced elw. corrections

Mühlleitner, Schlenk, S.



(i) effective $ggH(H)$ couplings:

$$\mathcal{L}_{eff} = C_1 \frac{\alpha_s}{12\pi} G^{a\mu\nu} G^a_{\mu\nu} \log\left(1 + C_2 \frac{H}{v}\right)$$



(C_1) (C_2)

- $C_1 = 1 - 3x_t$: genuine vertex corrections $[x_t = G_F m_t^2/(8\sqrt{2}\pi^2)]$

Djoaudi, Gambino
Chetyrkin, Kniehl, Steinhauser

- $C_2 = 1 + 7x_t/2$: universal corrections

Kniehl, Spira
Kwiatkowski, Steinhauser

$$\mathcal{L}_{eff} = \frac{\alpha_s}{12\pi} G^{a\mu\nu} G^a_{\mu\nu} \left\{ (1+\delta_1)\frac{H}{v} + (1+\eta_1)\frac{H^2}{2v^2} + \mathcal{O}(H^3) \right\}$$

$$\delta_1 = \frac{x_t}{2} + \mathcal{O}(x_t^2) \qquad \eta_1 = 4x_t + \mathcal{O}(x_t^2)$$

[HEL: Davies, Mishima, Schönwald, Steinhauser, Zhang]

(ii) effective $HHH(H)$ couplings:

- effective Higgs potential: Coleman, Weinberg

$$
\begin{aligned}
V_{eff} &= V_0 + V_1 \\
V_0 &= \mu_0^2 |\phi|^2 + \frac{\lambda_0}{2} |\phi|^4 \\
V_1 &= \frac{3\overline{m}_t^4}{16\pi^2} \Gamma(1+\epsilon)(4\pi^2)^\epsilon \left(\frac{1}{\epsilon} + \log \frac{\bar{\mu}^2}{\overline{m}_t^2} + \frac{3}{2} \right) \\
\phi &= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix} \\
\overline{m}_t &= m_t \left(1 + \frac{H}{v} \right)
\end{aligned}
$$

- renormalize bare μ_0, λ_0 parameters:

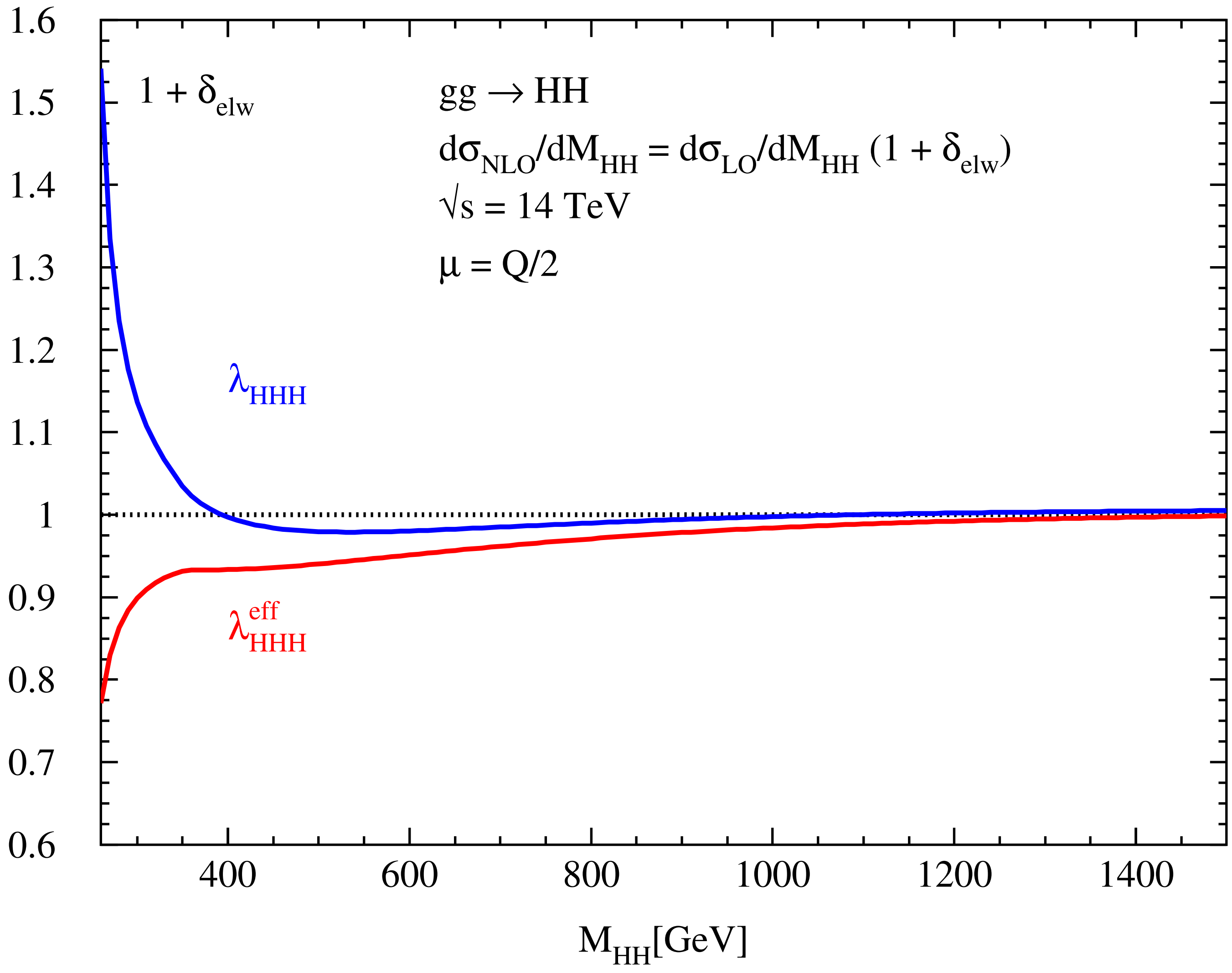
$$
\begin{aligned}
\mu_0^2 &= -\frac{\lambda_0}{2} v^2 + \delta\mu^2 \qquad\qquad M_{H0}^2 = \lambda_0 v^2 = \lambda v^2 + (\delta\lambda) v^2 = \lambda v^2 + \delta M_H^2 \\
\delta\mu^2 &= -\frac{3m_t^4}{4\pi^2 v^2} C_\epsilon \left\{ \frac{1}{\epsilon} + \log \frac{\bar{\mu}^2}{m_t^2} + 1 \right\} \\
\delta M_H^2 &= -\frac{3m_t^4}{2\pi^2 v^2} C_\epsilon \left\{ \frac{1}{\epsilon} + \log \frac{\bar{\mu}^2}{m_t^2} \right\}
\end{aligned}
$$

- radiatively corrected Higgs self-couplings:

$$\lambda_{HHH}^{eff} = 3\frac{M_H^2}{v} + \Delta\lambda_{HHH}\,, \qquad \lambda_{HHHH}^{eff} = 3\frac{M_H^2}{v^2} + \Delta\lambda_{HHHH}$$

$$\Delta\lambda_{HHH} = -\frac{3m_t^4}{\pi^2 v^3}\,, \qquad \Delta\lambda_{HHHH} = -\frac{12m_t^4}{\pi^2 v^4}$$

$$\boxed{\lambda_{HHH}^{eff} = 3\frac{M_H^2}{v} - \frac{3m_t^4}{\pi^2 v^3} \approx 0.91 \times 3\frac{M_H^2}{v}}$$



$$\sigma = 1.002 \times \sigma_{LO} \qquad (\lambda_{HHH})$$
$$\sigma = 0.938 \times \sigma_{LO} \qquad (\lambda^{eff}_{HHH})$$

Mühlleitner, Schlenk, S.

IV *CONCLUSIONS*

- scale and scheme uncertainties due to m_t relevant for large momenta

- Higgs pair production: m_t effects on top of LO $\sim -15\%$ for σ_{tot}
  [larger for distributions]

- uncertainties due to factorization/renormalization scale and m_t scale/scheme choice @NNLO$_{FTapprox}$ $\lesssim$ 25%

- combined uncertainties available for λ dependence, too.

- top-induced electroweak corrections: small for total cxn, larger for distributions

- uncertainties due to unknown full elw. corrections $\sim 10 - 20\%$

BACKUP SLIDES

$$\sigma_{\mathrm{NLO}}(pp \to HH + X) = \sigma_{\mathrm{LO}} + \Delta\sigma_{\mathrm{virt}} + \Delta\sigma_{gg} + \Delta\sigma_{gq} + \Delta\sigma_{q\bar{q}}$$

$$\sigma_{\mathrm{LO}} = \int_{\tau_0}^{1} d\tau \, \frac{d\mathcal{L}^{gg}}{d\tau} \, \hat{\sigma}_{\mathrm{LO}}(Q^2 = \tau s)$$

$$\Delta\sigma_{\mathrm{virt}} = \frac{\alpha_s(\mu)}{\pi} \int_{\tau_0}^{1} d\tau \, \frac{d\mathcal{L}^{gg}}{d\tau} \, \hat{\sigma}_{\mathrm{LO}}(Q^2 = \tau s) \; C$$

$$\Delta\sigma_{gg} = \frac{\alpha_s(\mu)}{\pi} \int_{\tau_0}^{1} d\tau \, \frac{d\mathcal{L}^{gg}}{d\tau} \int_{\tau_0/\tau}^{1} \frac{dz}{z} \, \hat{\sigma}_{\mathrm{LO}}(Q^2 = z\tau s) \left\{ -zP_{gg}(z) \log \frac{M^2}{\tau s} + d_{gg}(z) + 6[1 + z^4 + (1-z)^4] \left(\frac{\log(1-z)}{1-z} \right)_+ \right\}$$

$$\Delta\sigma_{gq} = \frac{\alpha_s(\mu)}{\pi} \int_{\tau_0}^{1} d\tau \sum_{q,\bar{q}} \frac{d\mathcal{L}^{gq}}{d\tau} \int_{\tau_0/\tau}^{1} \frac{dz}{z} \, \hat{\sigma}_{\mathrm{LO}}(Q^2 = z\tau s) \left\{ -\frac{z}{2} P_{gq}(z) \log \frac{M^2}{\tau s (1-z)^2} + d_{gq}(z) \right\}$$

$$\Delta\sigma_{q\bar{q}} = \frac{\alpha_s(\mu)}{\pi} \int_{\tau_0}^{1} d\tau \sum_{q} \frac{d\mathcal{L}^{q\bar{q}}}{d\tau} \int_{\tau_0/\tau}^{1} \frac{dz}{z} \, \hat{\sigma}_{\mathrm{LO}}(Q^2 = z\tau s) \; d_{q\bar{q}}(z)$$

$$C \to \pi^2 + \frac{11}{2} + C_{\triangle\triangle}, \quad d_{gg} \to -\frac{11}{2}(1-z)^3, \quad d_{gq} \to \frac{2}{3}z^2 - (1-z)^2, \quad d_{q\bar{q}} \to \frac{32}{27}(1-z)^3$$

- m_t scale/scheme uncertainties at LO:

$$\frac{d\sigma(gg \to HH)}{dQ}\Big|_{Q=300\text{ GeV}} = 0.01656^{+62\%}_{-2.4\%}\,\text{fb/GeV}$$

$$\frac{d\sigma(gg \to HH)}{dQ}\Big|_{Q=400\text{ GeV}} = 0.09391^{+0\%}_{-20\%}\,\text{fb/GeV}$$

$$\frac{d\sigma(gg \to HH)}{dQ}\Big|_{Q=600\text{ GeV}} = 0.02132^{+0\%}_{-48\%}\,\text{fb/GeV}$$

$$\frac{d\sigma(gg \to HH)}{dQ}\Big|_{Q=1200\text{ GeV}} = 0.0003223^{+0\%}_{-56\%}\,\text{fb/GeV}$$

$$F_i = F_{i,LO} + \Delta F_i$$
$$\Delta F_i = \Delta F_{i,HTL} + \Delta F_{i,mass}$$

- pole mass:

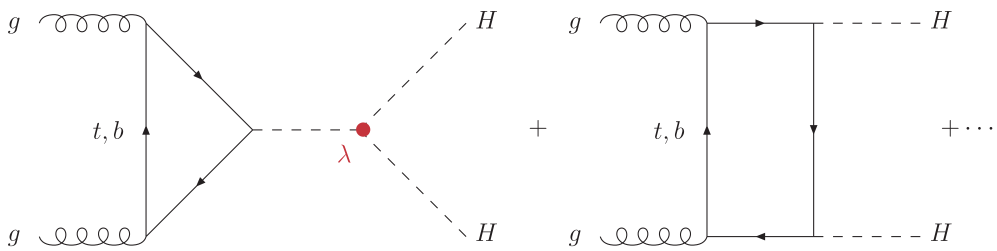
$$F_{1,LO} \rightarrow 4\frac{m_t^2}{\hat{s}}$$
$$F_{2,LO} \rightarrow -\frac{m_t^2}{\hat{s}\hat{t}(\hat{s}+\hat{t})}\{(\hat{s}+\hat{t})^2 L_{1ts}^2 + \hat{t}^2 L_{ts}^2 + \pi^2[(\hat{s}+\hat{t})^2 + \hat{t}^2]\}$$

- $\overline{\text{MS}}$ mass:

$$F_{1,LO} \rightarrow 4\frac{\overline{m}_t^2(\mu_t)}{\hat{s}}$$
$$F_{2,LO} \rightarrow -\frac{\overline{m}_t^2(\mu_t)}{\hat{s}\hat{t}(\hat{s}+\hat{t})}\{(\hat{s}+\hat{t})^2 L_{1ts}^2 + \hat{t}^2 L_{ts}^2 + \pi^2[(\hat{s}+\hat{t})^2 + \hat{t}^2]\}$$

- different scales for y_t in triangle (Q) and box (M_H) diagrams?

$\rightarrow$ has to hold at all orders



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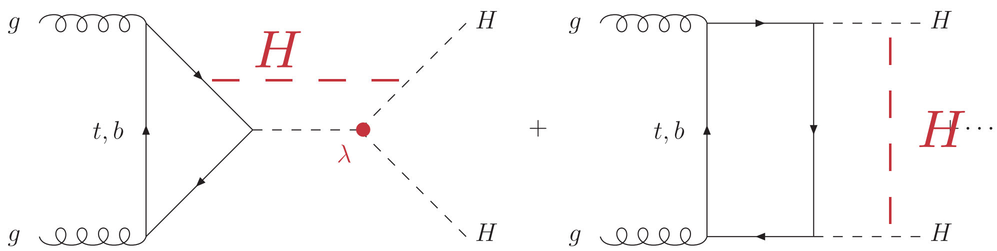

elw. corrections

$\Rightarrow$ same scales in all diagrams

$$\sigma_{\text{LO}} = \int_{\tau_0}^{1} d\tau \; \frac{d\mathcal{L}^{gg}}{d\tau} \; \hat{\sigma}_{\text{LO}}(Q^2 = \tau s)$$

$$\frac{d\mathcal{L}^{gg}}{d\tau} = \int_{\tau}^{1} \frac{dx}{x} g(x, \mu_F) g\left(\frac{\tau}{x}, \mu_F\right)$$

$$\hat{\sigma}_{LO} = \frac{G_F^2 \alpha_s^2(\mu_R)}{512(2\pi)^3} \int_{\hat{t}_-}^{\hat{t}_+} d\hat{t} [|C_\triangle F_\triangle + F_\Box|^2 + |G_\Box|^2]$$

$$\hat{t}_\pm = -\frac{1}{2}\left[Q^2 - 2M_H^2 \mp Q^2 \sqrt{1 - 4\frac{M_H^2}{Q^2}}\right]$$

$$\lambda_{HHH} = 3\frac{M_H^2}{v}$$

$$C_\triangle = \frac{\lambda_{HHH} v}{(Q^2 - M_H^2)}$$

$$\text{HTL: } F_\triangle \to 2/3, \qquad F_\Box \to -2/3, \qquad G_\Box \to 0$$

$$C_\triangle F_\triangle \to C_\triangle F_\triangle (1 + \Delta_\triangle)$$

$$F_\Box \to F_\Box (1 + \Delta_\Box)$$

$$\Delta_\triangle = \delta_1 + \Delta_{HHH}$$

$$\Delta_\Box = \eta_1$$

$$
\begin{aligned}
\Delta_{HHH} &= \Delta_{vertex} + \Delta_{self} + \Delta_{CT} \\
\Delta_{vertex} &= \frac{m_t^4}{v^2 M_H^2} \frac{8}{(4\pi)^2} \Big\{ B_0(Q^2; m_t, m_t) + 2B_0(M_H^2; m_t, m_t) \\
&\quad + \left(4m_t^2 - \frac{Q^2 + 2M_H^2}{2} \right) C_0(Q^2, M_H^2, M_H^2; m_t, m_t, m_t) \Big\} + \frac{T_1}{v M_H^2} \\
\Delta_{self} &= \frac{\Sigma_H(Q^2)}{Q^2 - M_H^2} + \frac{1}{2} \Sigma'_H(M_H^2) \\
\Delta_{CT} &= \frac{\delta M_H^2}{Q^2 - M_H^2} + \frac{\delta \lambda_{HHH}}{\lambda_{HHH}} \\
\Sigma_H(Q^2) &= 3\, \frac{T_1}{v} + 6\, \frac{m_t^2}{(4\pi)^2 v^2} \left\{ 2A_0(m_t) + (4m_t^2 - Q^2) B_0(Q^2; m_t, m_t) \right\} + \mathcal{O}(m_t^0) \\
\Sigma'_H(Q^2) &= 6\, \frac{m_t^2}{(4\pi)^2 v^2} \left\{ (4m_t^2 - Q^2) B'_0(Q^2; m_t, m_t) - B_0(Q^2; m_t, m_t) \right\} + \mathcal{O}(m_t^0) \\
\frac{T_1}{v} &= -12\, \frac{m_t^2}{(4\pi)^2 v^2} A_0(m_t) \\
\frac{\delta \lambda_{HHH}}{\lambda_{HHH}} &= \frac{\delta M_H^2}{M_H^2} + \frac{1}{2} \frac{\Sigma_W(0)}{M_W^2} \\
\frac{\Sigma_W(0)}{M_W^2} &= 2\, \frac{T_1}{v M_H^2} + \frac{2m_t^2}{(4\pi)^2 v^2} \left\{ B_0(0; m_t, 0) + 2B_0(0; m_t, m_t) + m_t^2 B'_0(0; m_t, 0) \right\} + \mathcal{O}(m_t^0) \\
\delta M_H^2 &= -\Sigma_H(M_H^2)
\end{aligned}
$$

M_HH	mt(M_HH/4)	mt(M_HH/2)	mt(M_HH)
125	189.209370262526	176.772460597358	166.501914700149
260	176.139964023672	165.972836934324	156.889554725476
275	175.247098219568	165.224863654266	156.188624671063
300	173.888433241807	164.084218616097	155.118481503625
350	171.556916171559	162.101622772544	153.272150436136
375	170.543285547792	161.158290295641	152.465560631846
400	169.611142167793	160.289697463114	151.721739637882
500	166.501914700149	157.384965182267	149.226383426185
600	164.084218616097	155.118481503625	147.270941230420
700	162.101622772544	153.272150436136	145.672596390682
800	160.289697463114	151.721739637882	144.326704798025
900	158.737886290123	150.390138497802	143.168060367441
1000	157.384965182267	149.226383426185	142.153427561240
1100	156.188624671063	148.195135247933	141.252743160739
1200	155.118481503625	147.270941230420	140.444302478362
1300	154.152026867353	146.434896300904	139.711950260189
1400	153.272150436136	145.672596390682	139.043354388391
1500	152.465560631846	144.972828986822	138.428898934501