SM HIGGS THEORY

Michael Spira (PSI)

I Introduction

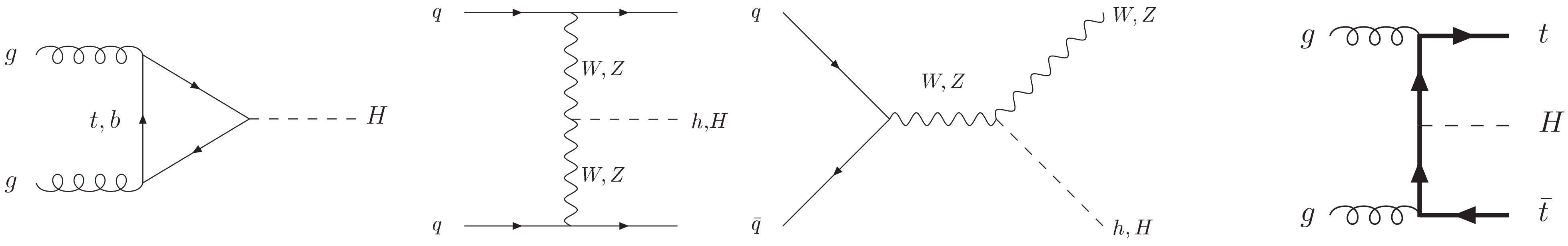
II Higgs Boson Decays

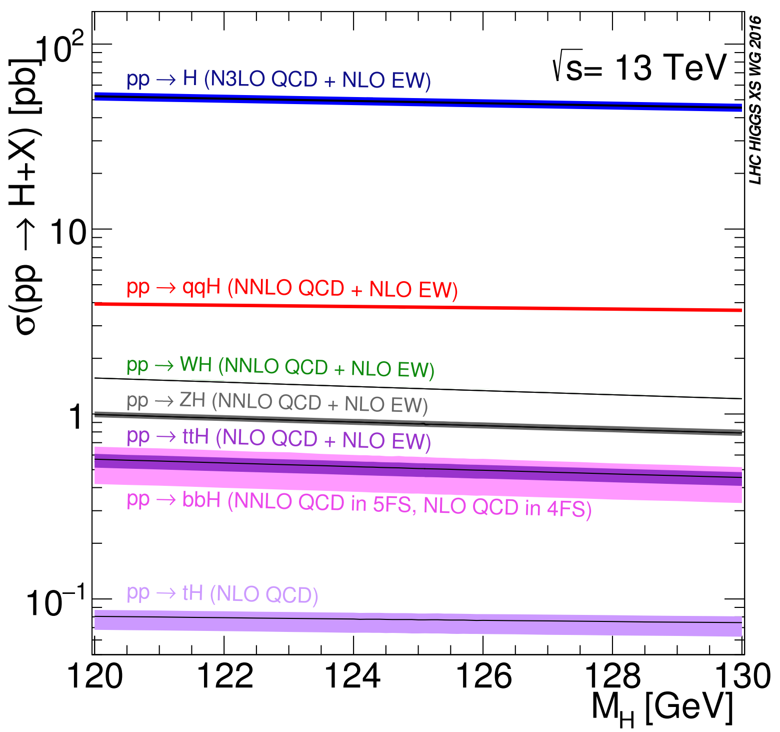
III Higgs Boson Production

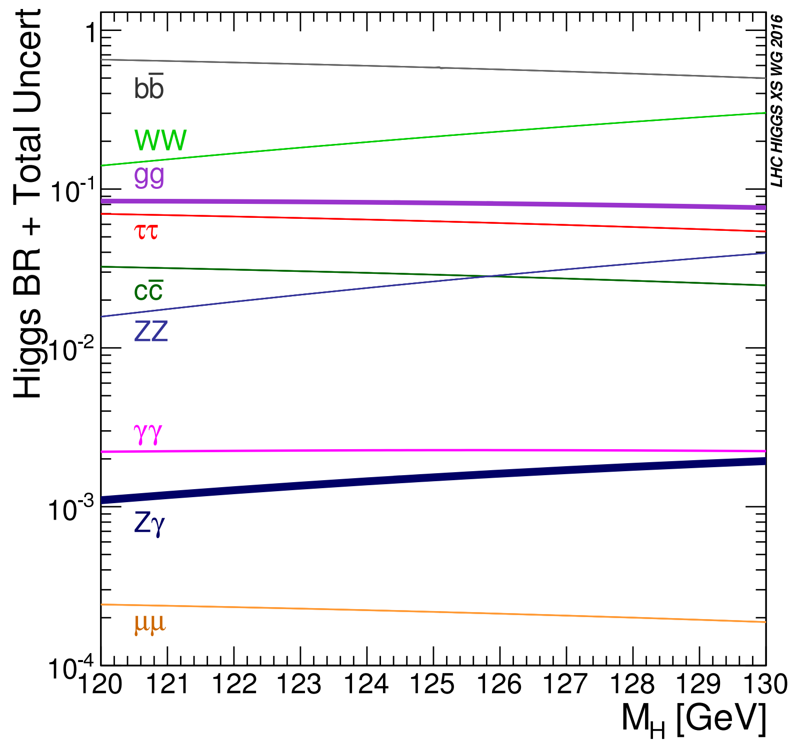
IV Conclusions

I INTRODUCTION

- Higgs Boson Production

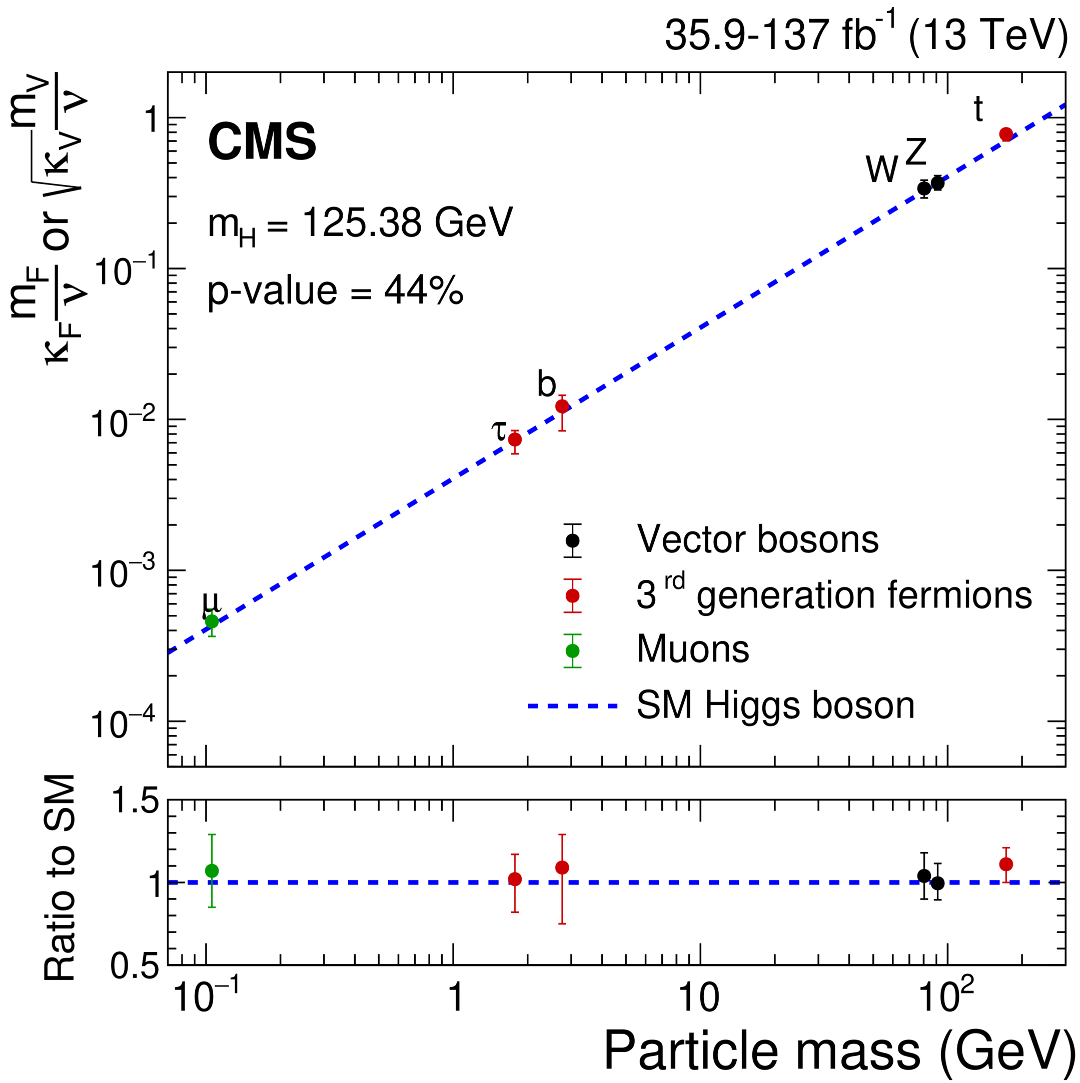






LHC Higgs XS WG

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



II *HIGGS BOSON DECAYS*

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
$H \to Z\gamma$	$< 1\%$	$\sim 5\%$	$\sim 5\%$	(N)LO / LO $\leftarrow$ NLO
$H \to WW/ZZ \to 4f$	$< 0.5\%$	$\sim 0.5\%$	$\sim 0.5\%$	(N)NLO

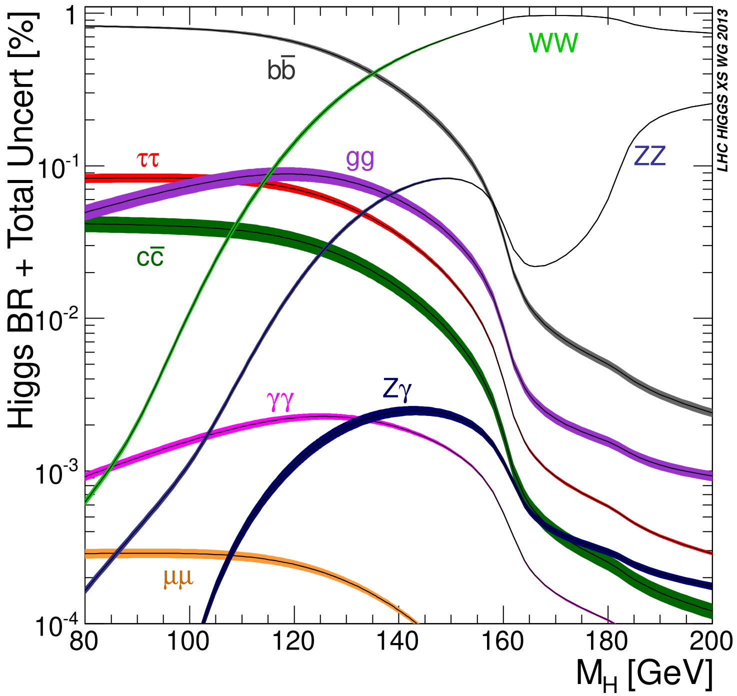
- QCD: variation $\mu_R = [1/2, 2]\mu_0$
  elw: missing HO estimated from known structure at NLO

- 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

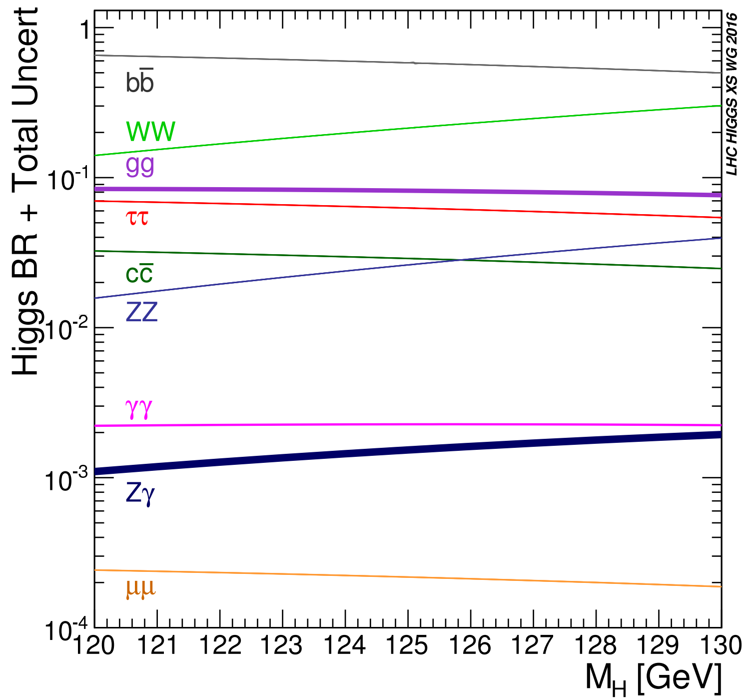
- total uncertainties: parametric & theor. uncertainties added linearly

YR3 HDECAY & Prophecy4f YR4

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



$\longrightarrow$

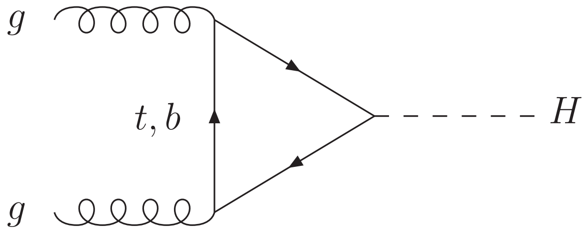


Denner, Heinemeyer, Puljak, Rebuzzi, S.

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

III *HIGGS BOSON PRODUCTION*

(i) $gg \to H$



Georgi,. . .

S., Djouadi, Graudenz, Zerwas
Dawson, Kauffman

- NLO QCD corrections: $\sim$ 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
Czakon, Harlander, Klappert, Niggetied

- 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: $\lesssim 1\%$

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

- impl. of $gg \to \phi$ in POWHEG including mass effects @ NLO (QCD also valid for 2HDM and other Higgs extensions)

Bagnaschi, Degrassi, Slavich, Vicini

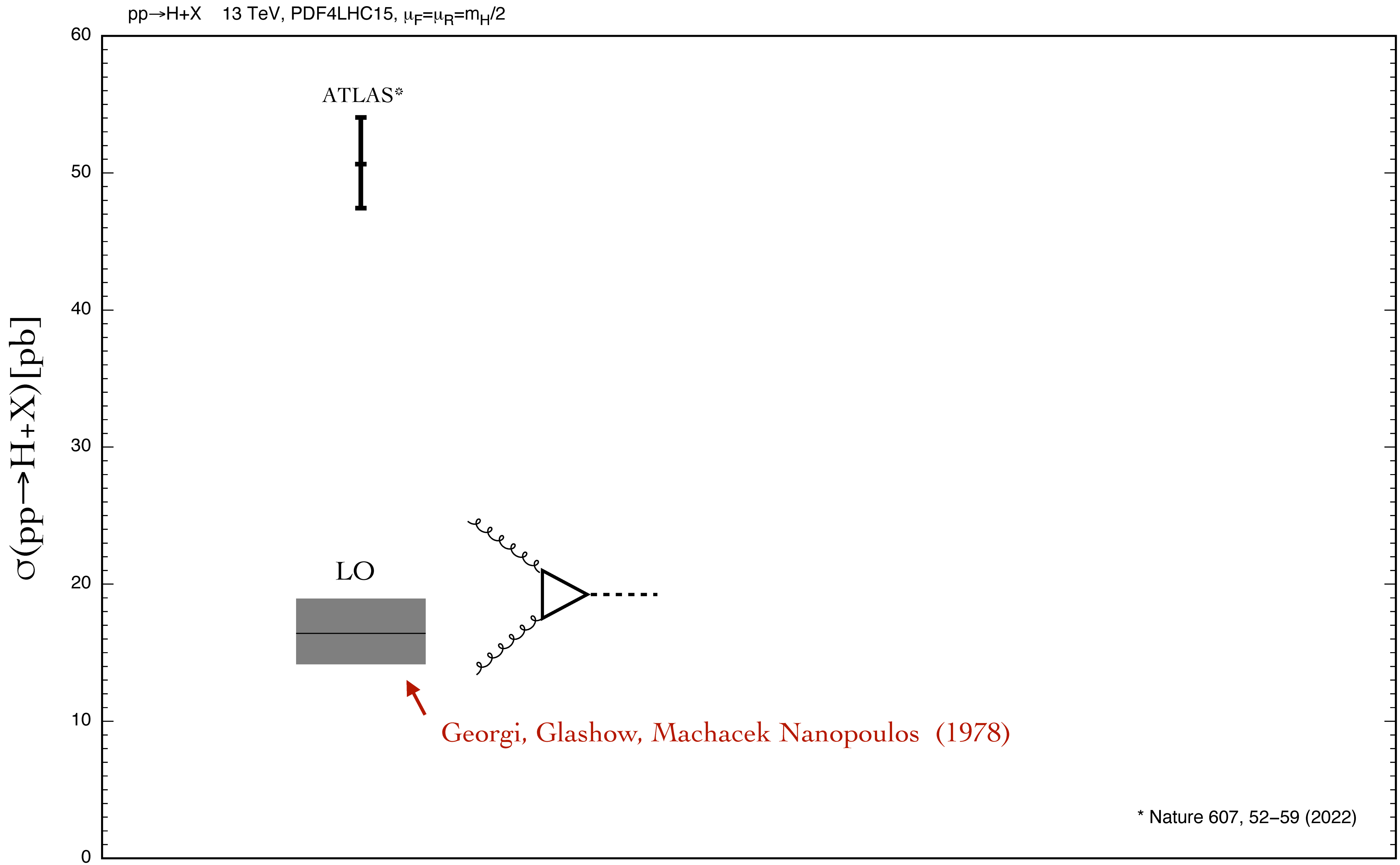
- elw. corrections: $\sim 5\%$

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

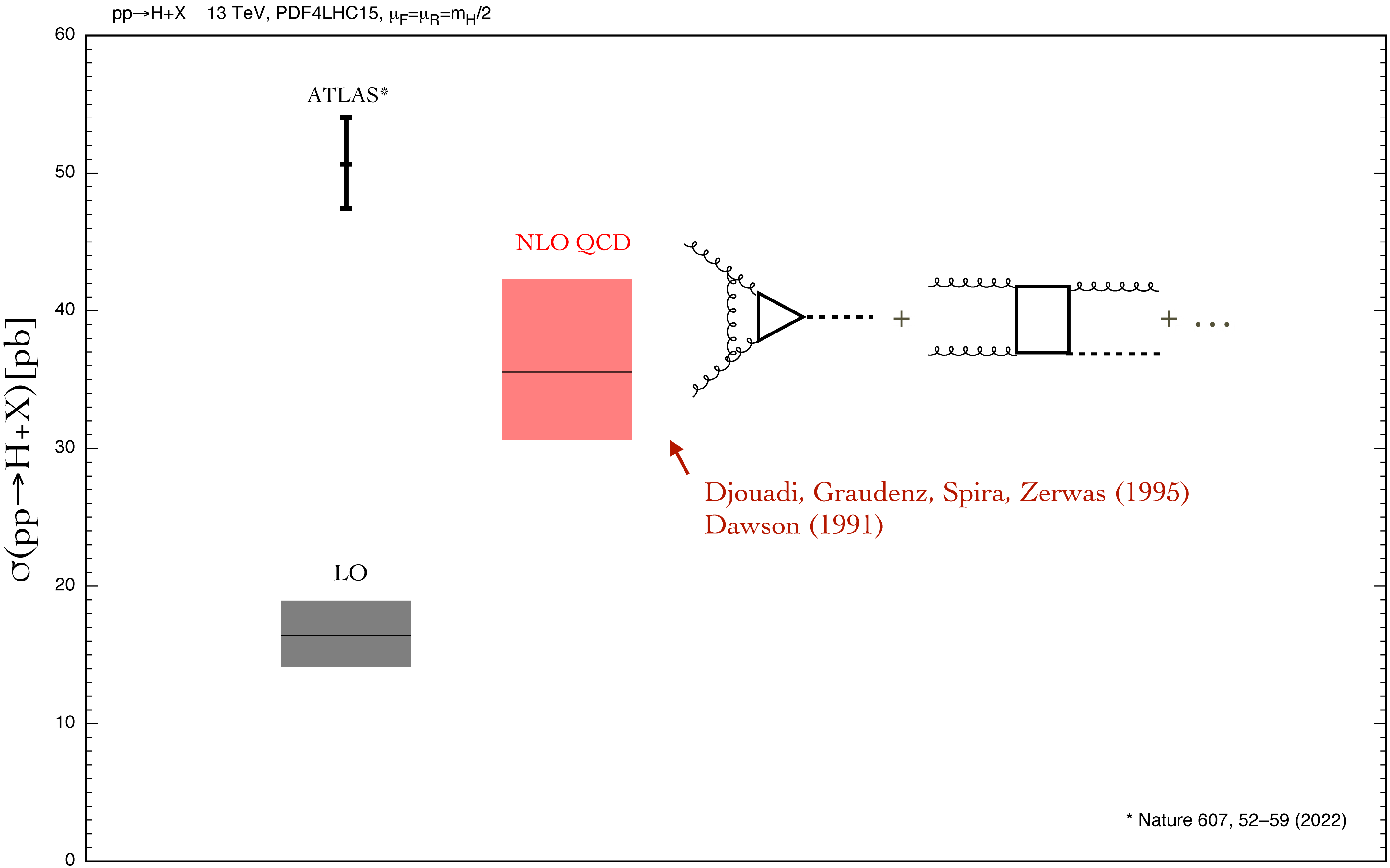
- $\sigma(gg \to H) = \left(54.72^{+4.3\%}_{-6.5\%}(TH) \pm 3.2\%(PDF, \alpha_s)\right)\ pb$ @ $\sqrt{s} = 14$ TeV

Anastasiou,...

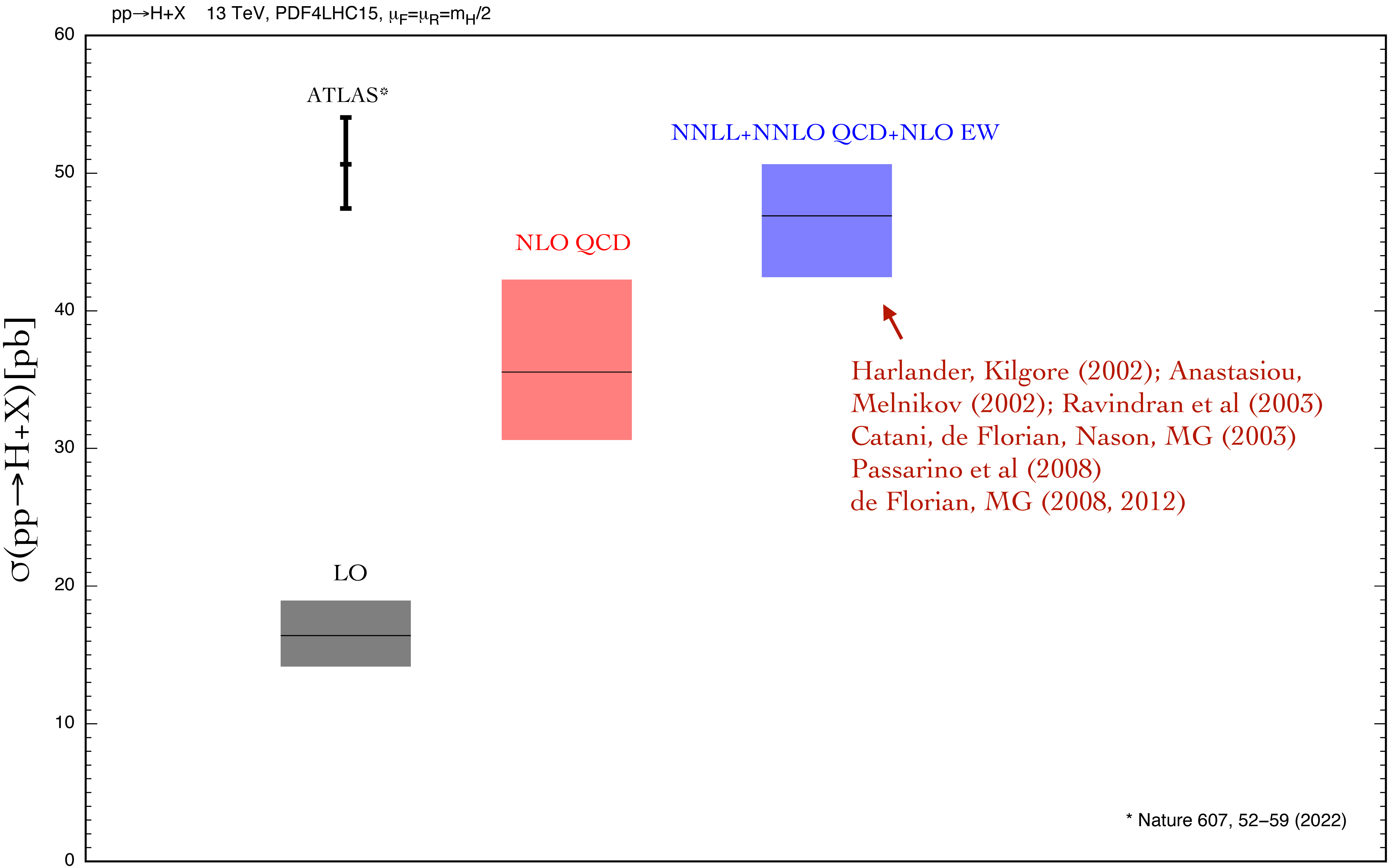
- uncertainties: PDF+α_s, renormalization/factorization scale top/bottom masses: $\sim \pm 0.8\% \leftarrow$ scale/scheme dependence



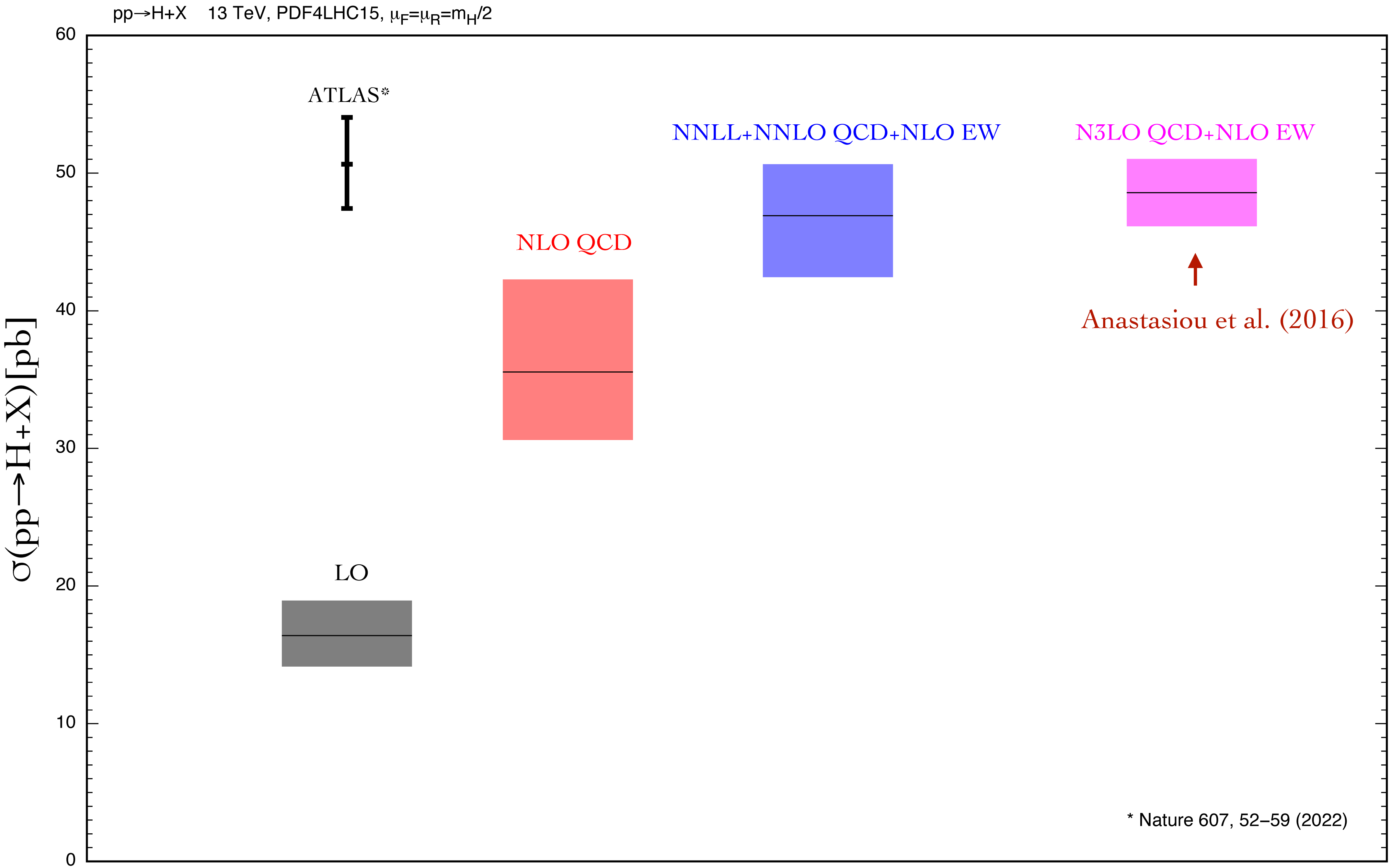
stolen from M. Grazzini@Higgs10



stolen from M. Grazzini@Higgs10



stolen from M. Grazzini@Higgs10



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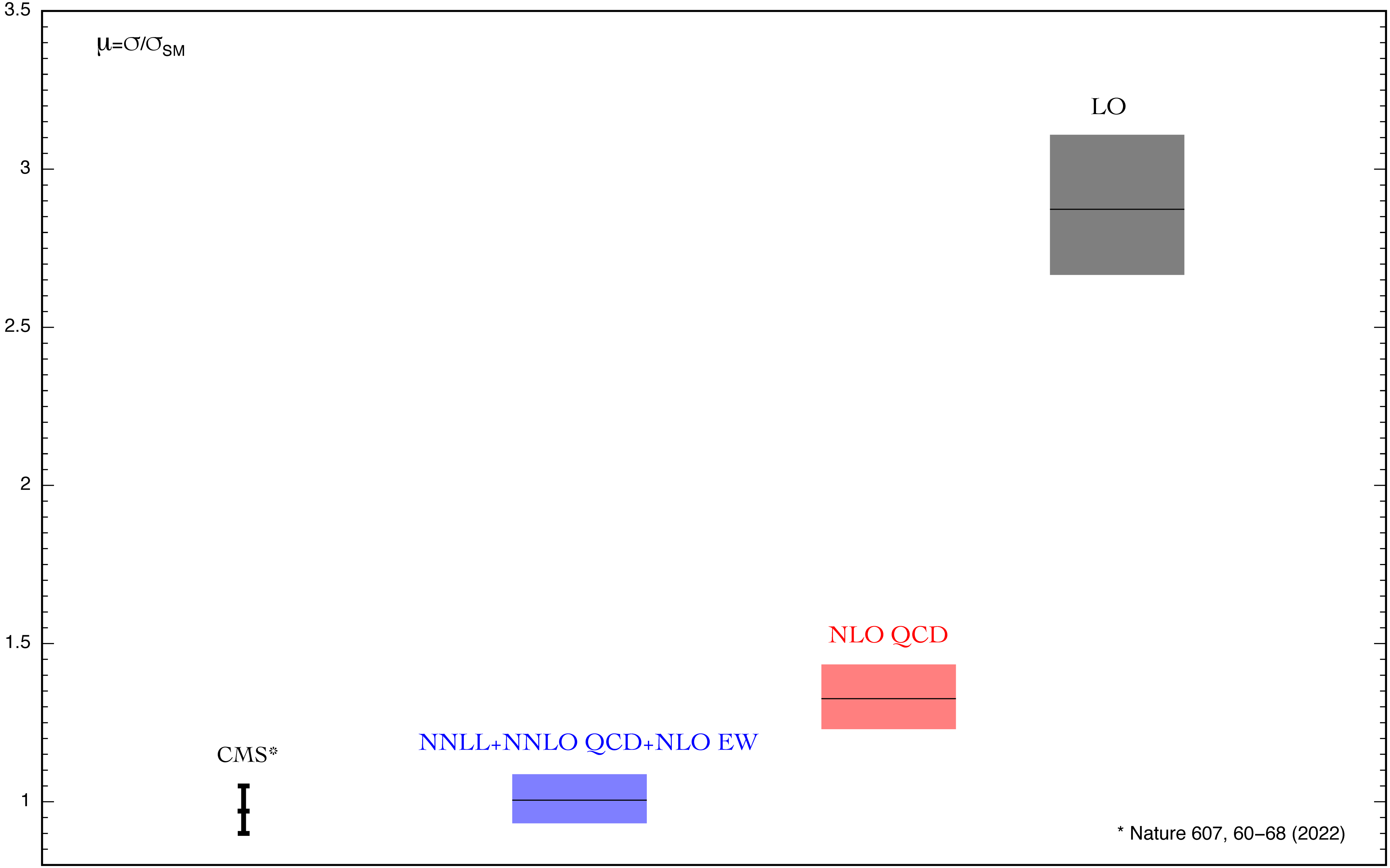
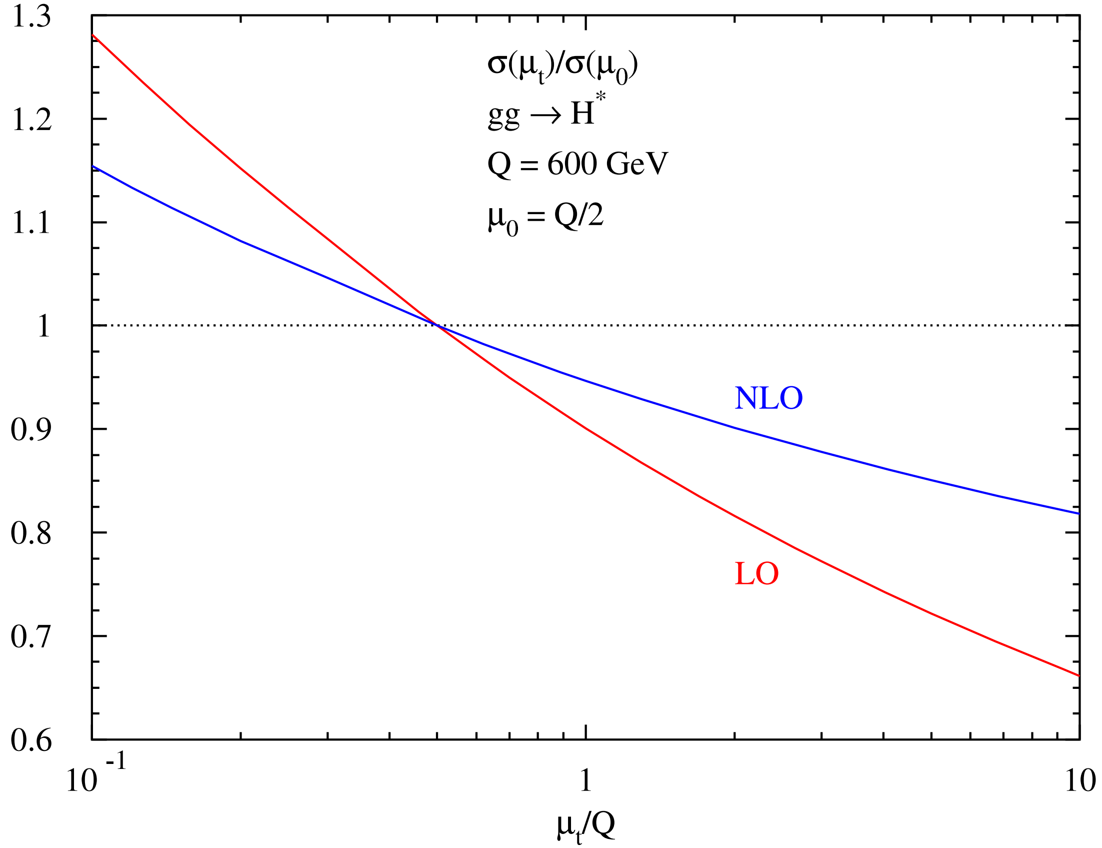


stolen from M. Grazzini@Higgs10

$\sigma(gg \to H)_{LO} = 18.43^{+0.8\%}_{-1.1\%}$ pb $\qquad \sigma(gg \to H)^{QCD}_{NLO} = 42.17^{+0.4\%}_{-0.5\%}$ pb



Jones, S.

m_t scheme/scale uncertainties only:

- LO:

$$\sigma(gg \to H^*)|_{Q=125\ \text{GeV}} = 18.43^{+0.8\%}_{-1.1\%}\ \text{pb}, \qquad \sigma(gg \to H^*)|_{Q=300\ \text{GeV}} = 4.88^{+23.1\%}_{-1.1\%}\ \text{pb}$$

$$\sigma(gg \to H^*)|_{Q=400\ \text{GeV}} = 4.94^{+1.2\%}_{-1.8\%}\ \text{pb}, \qquad \sigma(gg \to H^*)|_{Q=600\ \text{GeV}} = 1.13^{+0.0\%}_{-26.2\%}\ \text{pb}$$

$$\sigma(gg \to H^*)|_{Q=900\ \text{GeV}} = 0.139^{+0.0\%}_{-36.0\%}\ \text{pb}, \qquad \sigma(gg \to H^*)|_{Q=1200\ \text{GeV}} = 0.0249^{+0.0\%}_{-41.1\%}\ \text{pb}$$

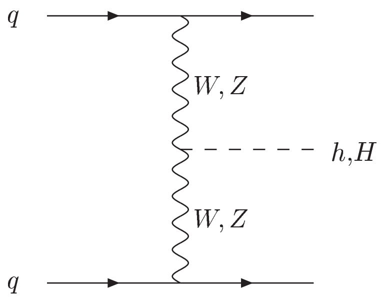
- NLO QCD:

$$\sigma(gg \to H^*)|_{Q=125\ \text{GeV}} = 42.17^{+0.4\%}_{-0.5\%}\ \text{pb}, \qquad \sigma(gg \to H^*)|_{Q=300\ \text{GeV}} = 9.85^{+7.5\%}_{-0.3\%}\ \text{pb}$$

$$\sigma(gg \to H^*)|_{Q=400\ \text{GeV}} = 9.43^{+0.1\%}_{-0.9\%}\ \text{pb}, \qquad \sigma(gg \to H^*)|_{Q=600\ \text{GeV}} = 1.97^{+0.0\%}_{-15.9\%}\ \text{pb}$$

$$\sigma(gg \to H^*)|_{Q=900\ \text{GeV}} = 0.230^{+0.0\%}_{-22.3\%}\ \text{pb}, \qquad \sigma(gg \to H^*)|_{Q=1200\ \text{GeV}} = 0.0402^{+0.0\%}_{-26.0\%}\ \text{pb}$$

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



Cahn, Dawson
Hikasa
Atarelli, Mele, Pitolli

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

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

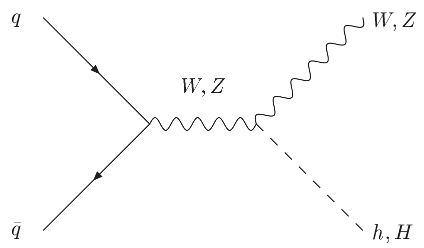
  [approx] 2–loop: $\lesssim 1\%$ — Bolzano, Maltoni, Moch, Zaro; Cacciari, Dreyer, Karlberg, Salam, Zanderighi

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

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

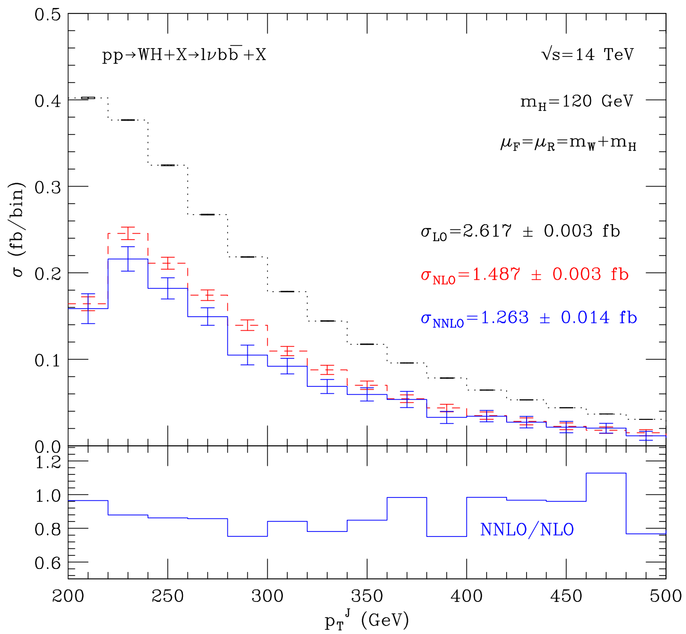
- fully exclusive @ NNLO QCD, NLO elw.

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

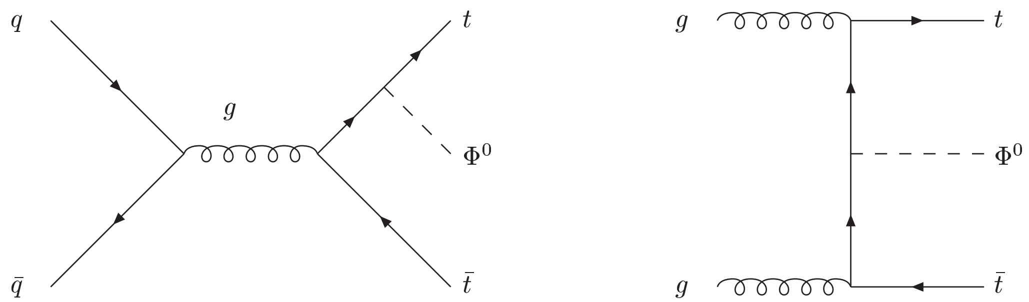


Glashow,...
Kunszt,...

- QCD corrections ← DY: $\sim 30\%$ — Han, Willenbrock
  - 2–loop: $\lesssim 5\%$ — Brein, Djouadi, Harlander
- 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

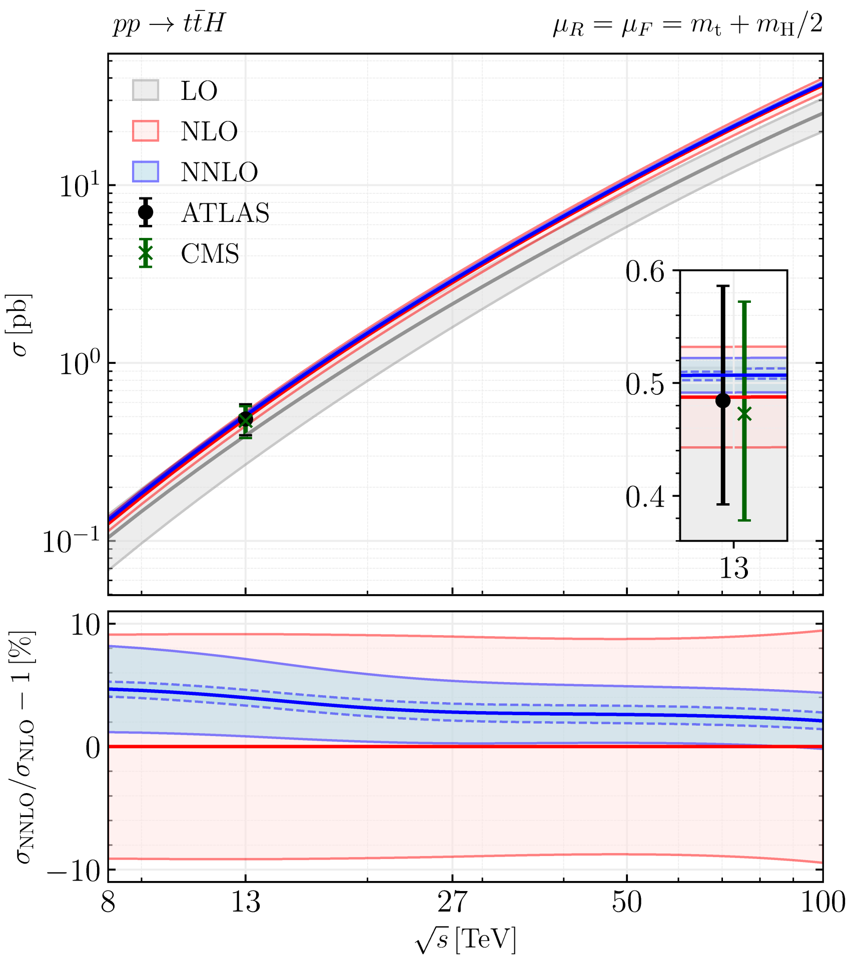
- link to parton showers: aMC@NLO, PowHel

Frederix et al.
Garzelli, Kardos, Papadopoulos, Trócsányi

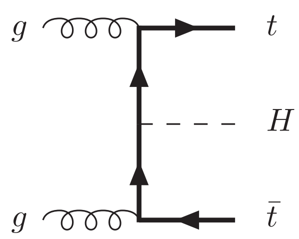
- important work on backgrounds $t\bar{t}b\bar{b}, t\bar{t}jj$, etc.

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

$pp \to t\bar{t}H$: approx. NNLO



$m_t = 173.3$ GeV

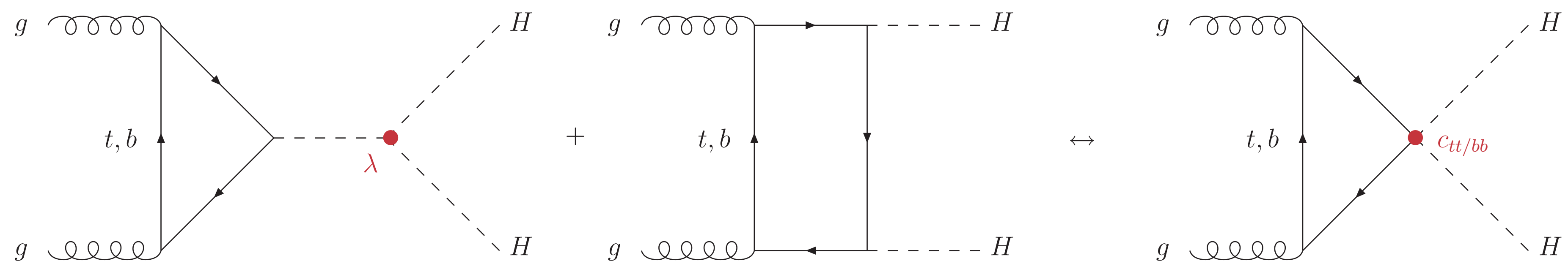


sensitive to top Yukawa coupling

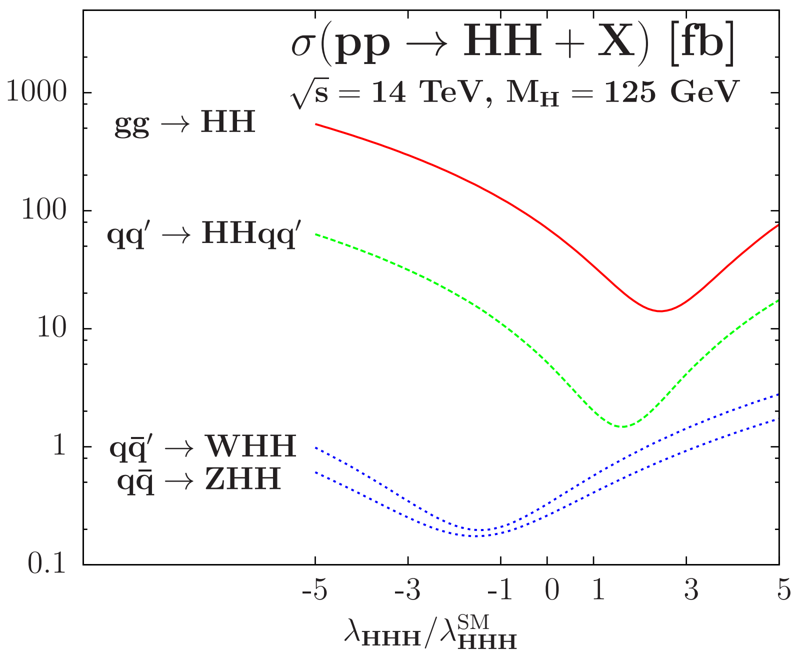
Catani, Devoto, Grazzini, Kallweit, Mazzitelli, Savoini

- 2-loop virtual corrections: soft Higgs approximation
  single + double real corrections: exact

(v) $gg \to HH$



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

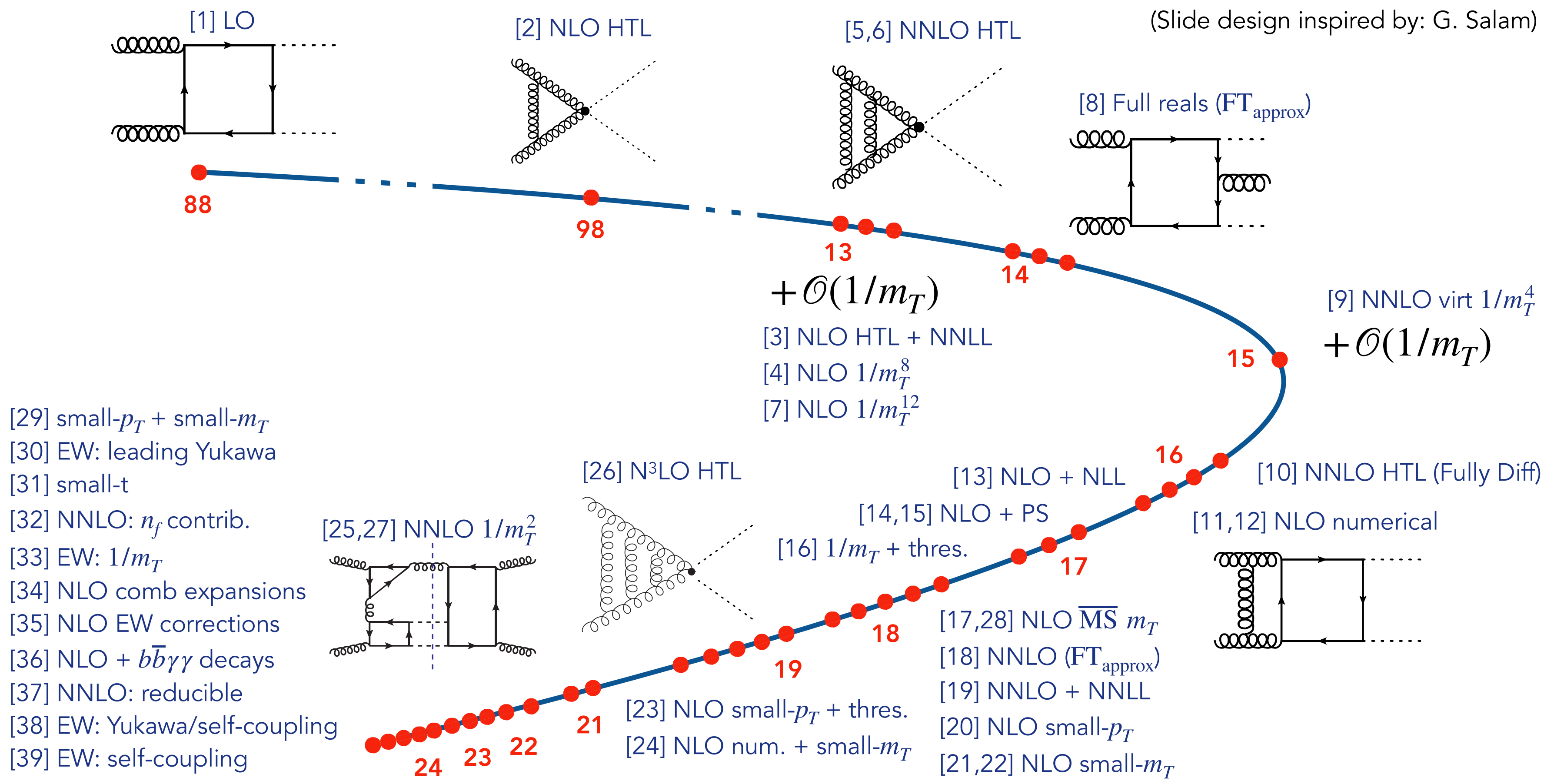


$$gg \to HH : \frac{\Delta\sigma}{\sigma} \sim -\frac{\Delta\lambda}{\lambda}$$

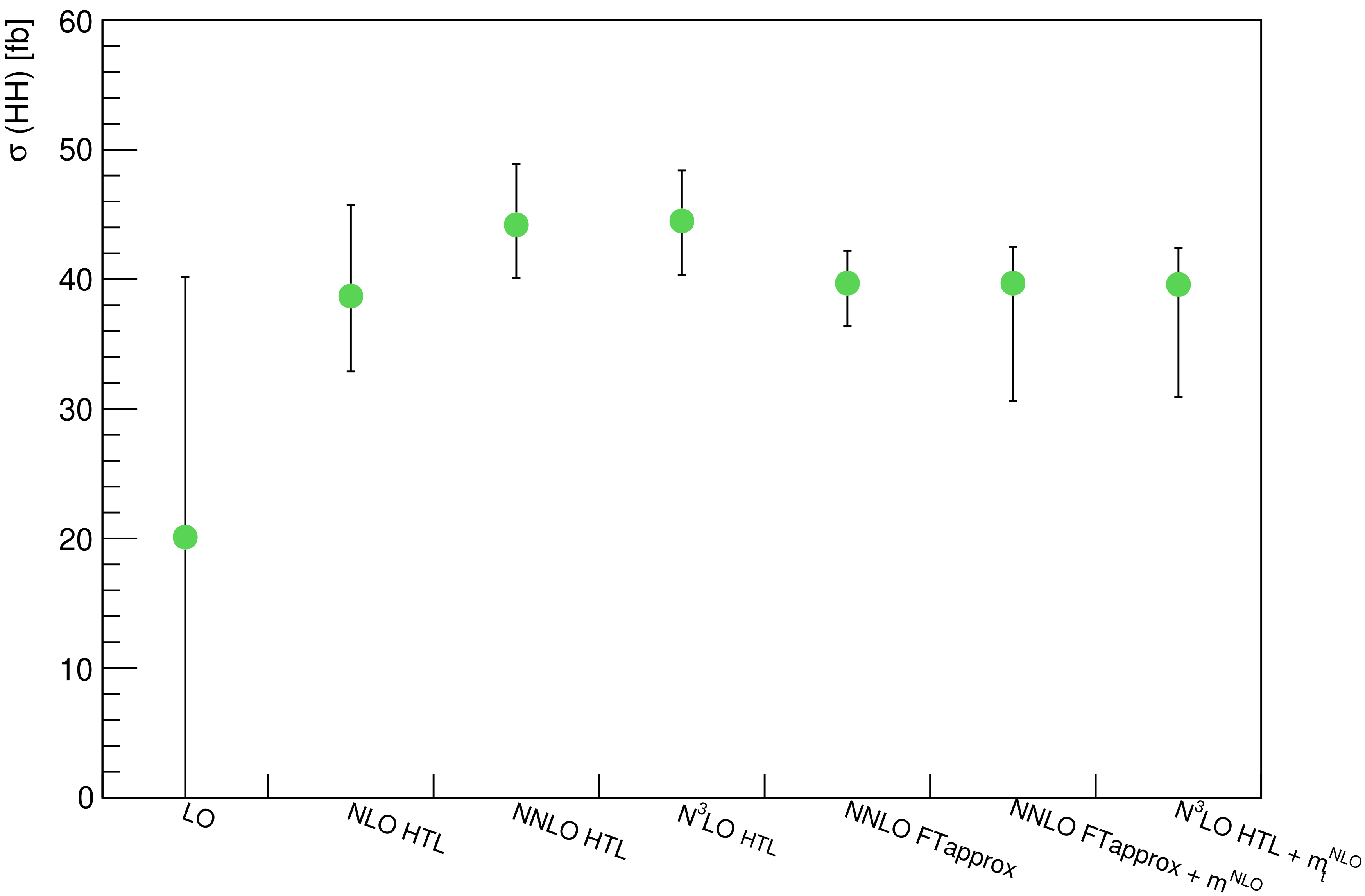
[decreasing with M_{HH}^2]

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

Overview



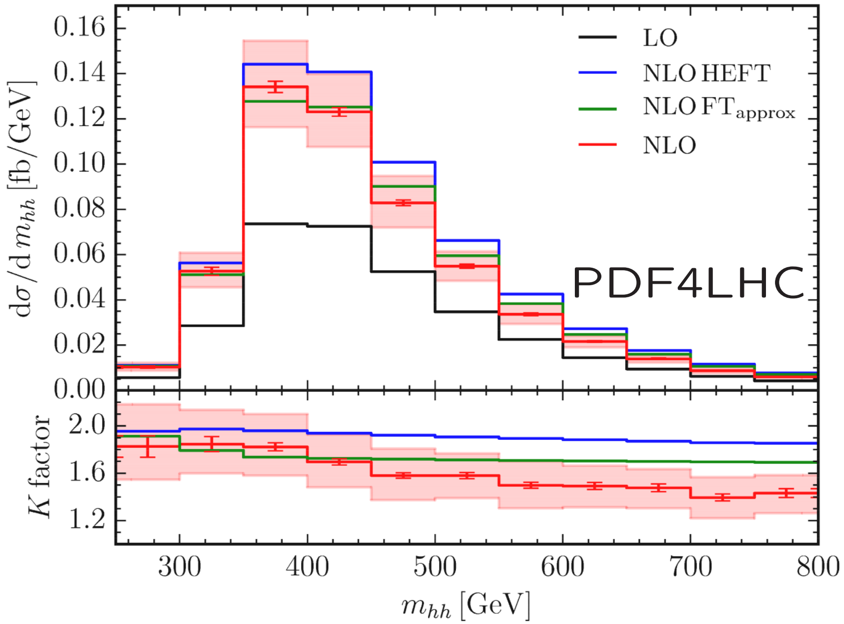
[1] Glover, van der Bij 88; [2] Dawson, Dittmaier, Spira 98; [3] Shao, Li, Li, Wang 13; [4] Grigo, Hoff, Melnikov, Steinhauser 13; [5] de Florian, Mazzitelli 13; [6] Grigo, Melnikov, Steinhauser 14; [7] Grigo, Hoff 14; [8] Maltoni, Vryonidou, Zaro 14; [9] Grigo, Hoff, Steinhauser 15; [10] de Florian, 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; [30] Davies, Mishima, Schönwald, Steinhauser, Zhang 22; [31] Davies, Mishima, Schönwald, Steinhauser 23; [32] Davies, Schönwald, Steinhauser 23; [33] Davies, Schönwald, Steinhauser, Zhang 23; [34] Bagnaschi, Degrassi, Gröber 23; [35] Bi, Huang, Huang, Ma Yu 23 [36] Li, Si, Wang, Zhang, Zhao 24; [37] Davies, Schönwald, Steinhauser, Vitti 24; [38] Heinrich, SPJ, Kerner, Stone, Vestner [39] Li, Si, Wang, Zhang, Zhao 24


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

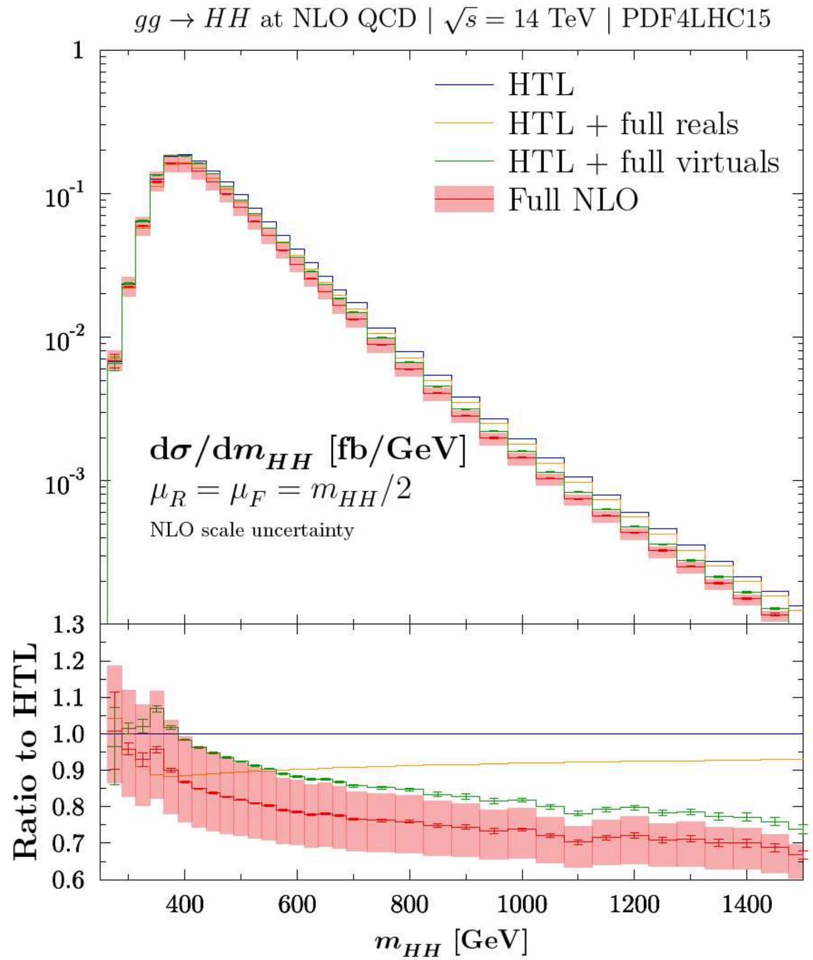
Full NLO calculation: top only, numerical integration

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



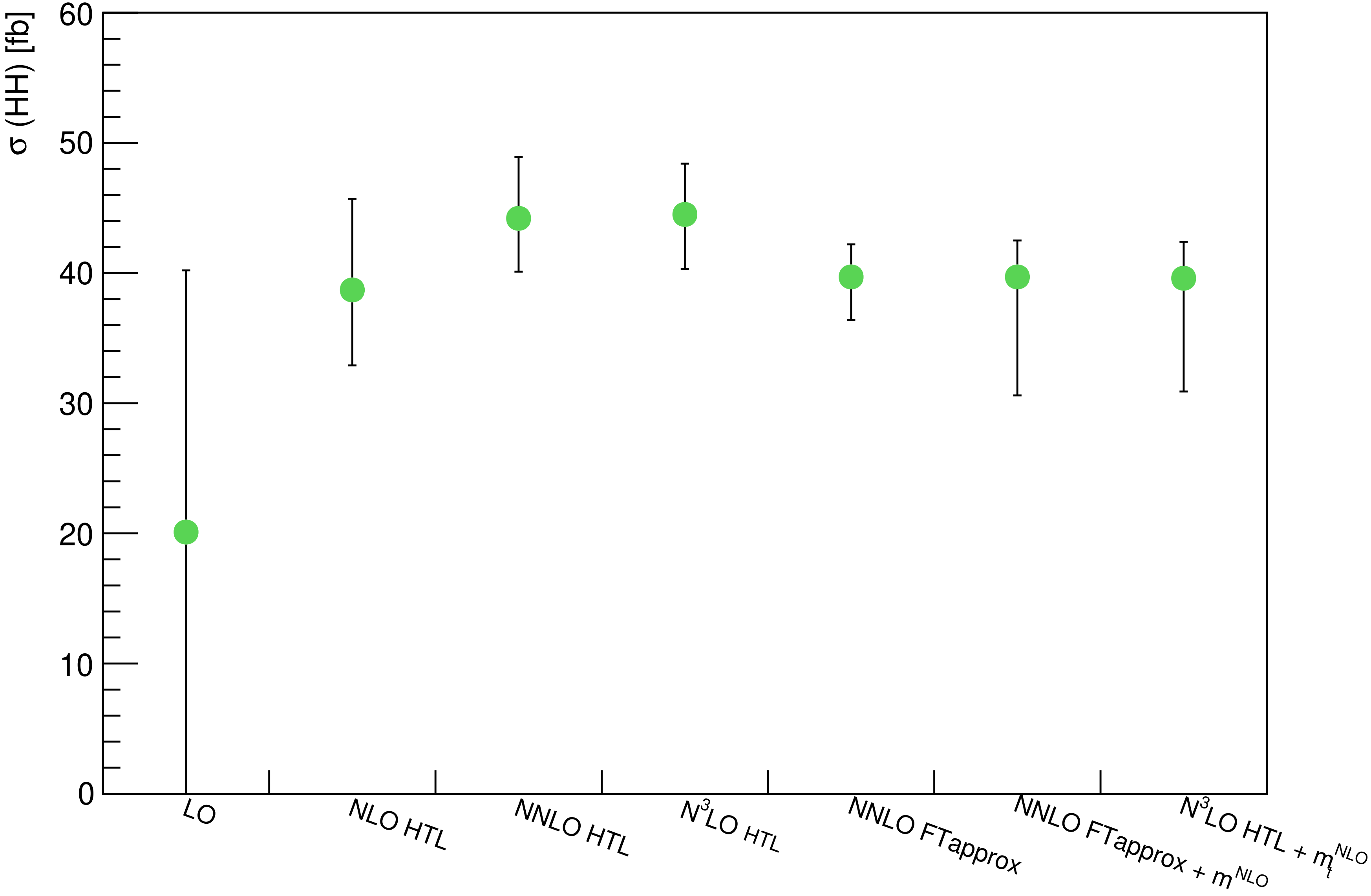
Borowka, Greiner, Heinrich, Jones, Kerner
Schlenk, Schubert, Zirke



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
40
30
20
10
0
LO
NLO HTL
NNLO HTL
N3LO HTL
NNLO FTapprox
NNLO FTapprox + m^NLO
N3LO 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:

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

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

$\leftarrow$ Davies, Mishima, Steinhauser, Wellmann

<u>pole mass m_t:</u>

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

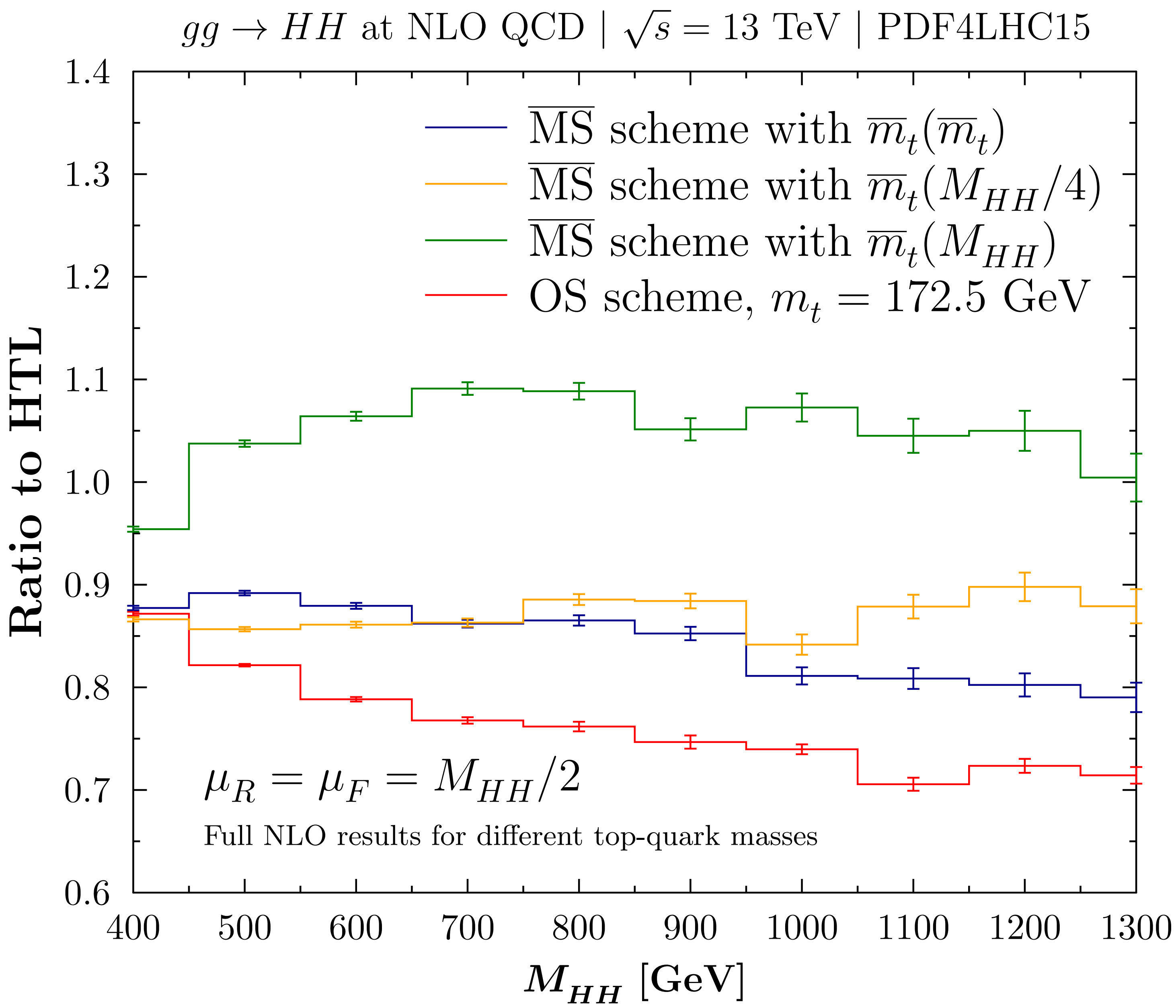
$$\Delta F_{2,mass} \rightarrow \frac{\alpha_s}{\pi}\left\{2F_{2,LO}\log\frac{m_t^2}{\hat{s}} + \frac{m_t^2}{\hat{s}}G_2(\hat{s},\hat{t})\right\}$$

<u>$\overline{\text{MS}}$ mass $\overline{m}_t(\mu_t)$:</u>

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

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

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



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

- renormalization/factorization scale uncertainties @ NLO:

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

- m_t scale/scheme uncertainties @ NLO:

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

• 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
combination $\to$ envelope $\sim$ linear sum (rel. err.)

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

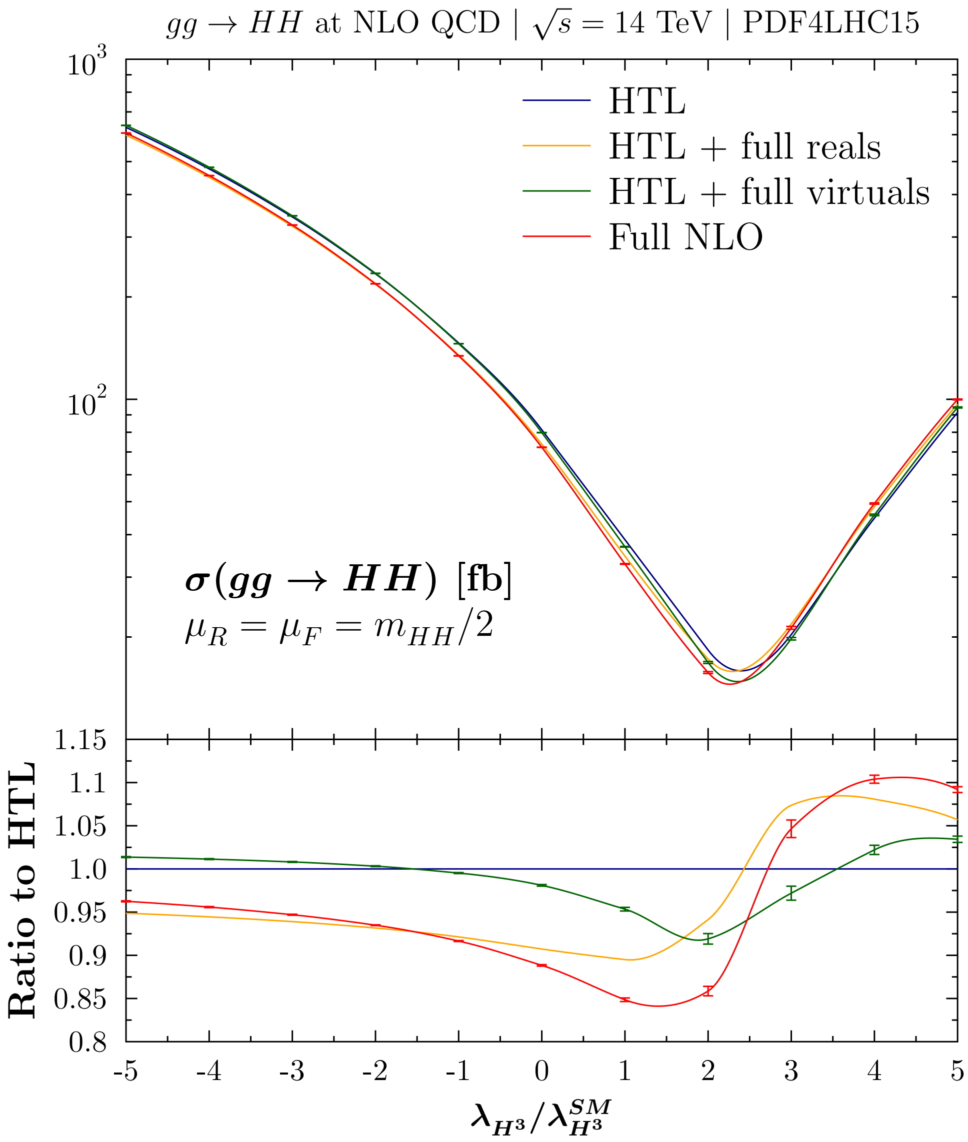
$$\sqrt{s} = 13 \text{ TeV}: \quad \sigma_{tot} = 31.05^{+6\%}_{-23\%} \text{ fb}$$

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

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

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

λ dependence



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

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

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

Is this everything?

Is this everything?

No. . .

Is this everything?

No. . .

electroweak corrections. . .

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

Mühlleitner, Schlenk, S.

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

Davies, Mishima, Schönwald, Steinhauser, Zhang

and close to the production threshold

Davies, Schönwald, Steinhauser, Zhang

(iii) λ: elw. corrections due to the Higgs self-interactions

Borowka, Duhr, Maltoni, Pagani, Shivaji, Zhao

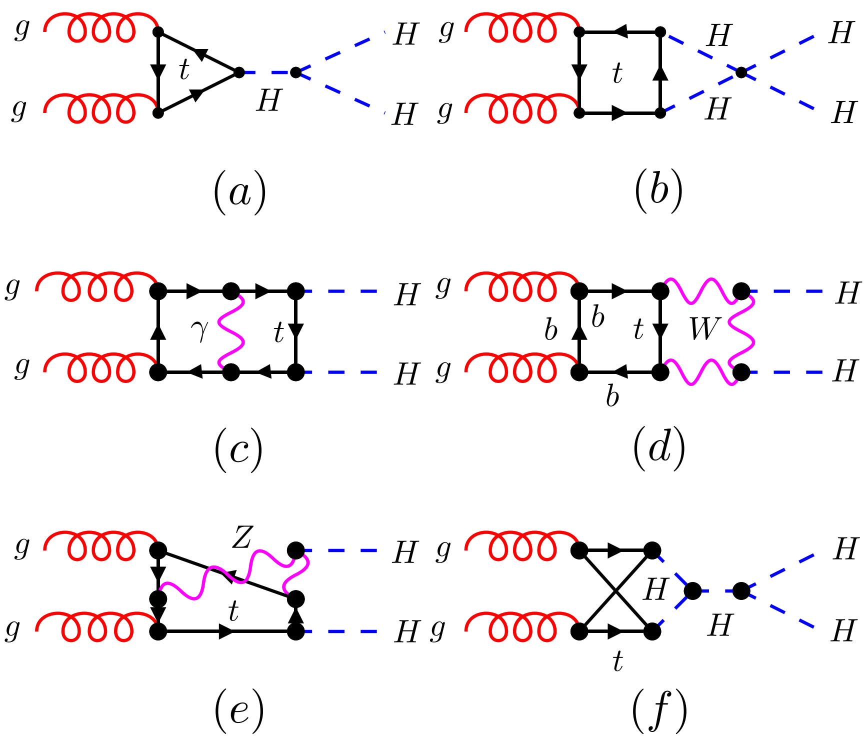
(iv) g_t, λ: elw. corrections due to the top Yukawa and Higgs self-interactions [only Higgs exchange diagrams]

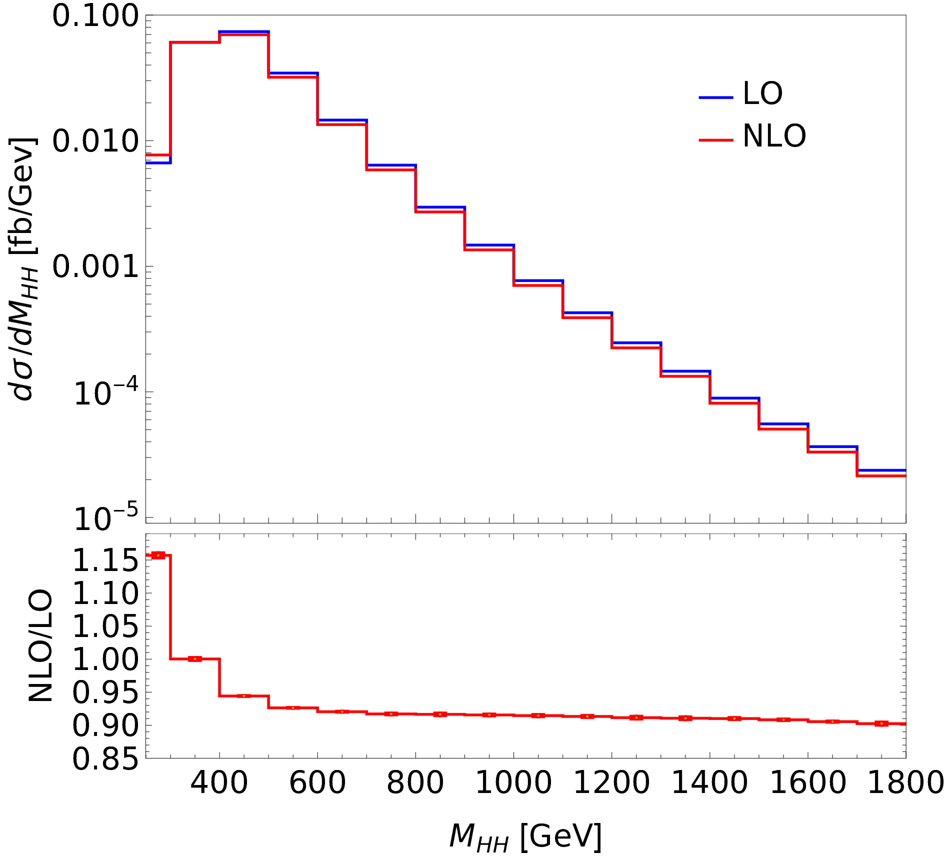
Heinrich, Jones, Kerner, Stone, Vestner

(v) full elw. corrections ($\leftarrow$ to be checked)

Bi, Huang, Huang, Ma, Yu

Full electroweak corrections



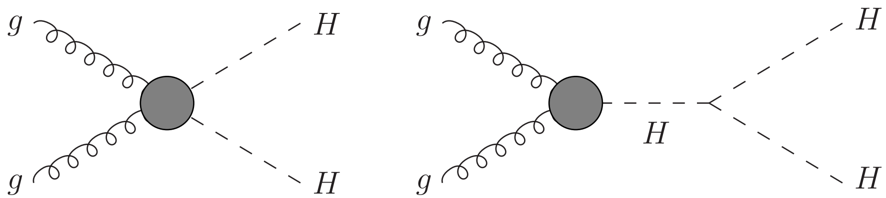


- -4.2% for total cross section

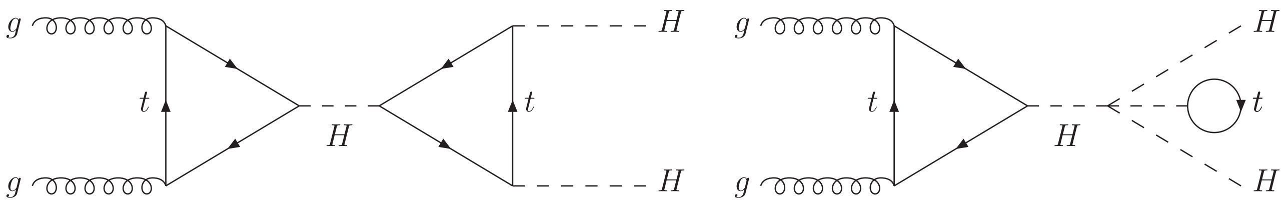
Bi, Huang, Huang, Ma, Yu

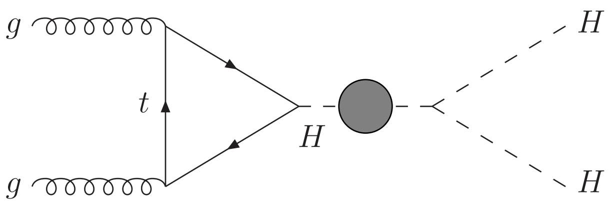
Top-Yukawa-induced elw. corrections

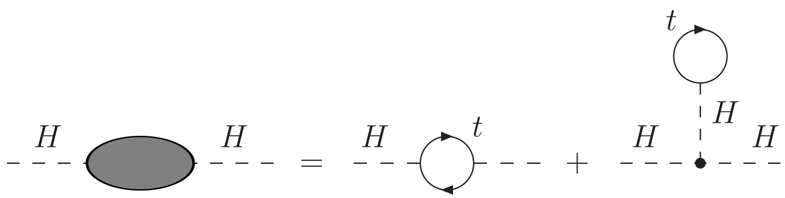
Mühlleitner, Schlenk, S.



← HTL

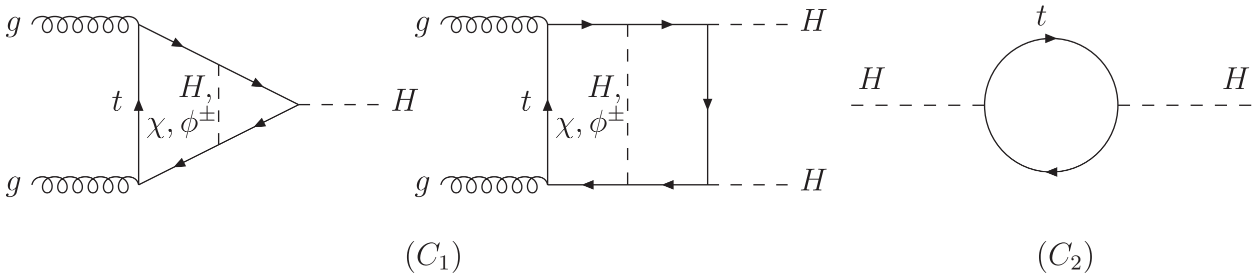






(i) effective $ggH(H)$ couplings:

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



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

Djoaudi, Gambino
Chetyrkin, Kniehl, Steinhauser

- $C_2 = 1 + 7x_t/2 \; [= 1 + \delta Z_H/2 - \delta v/v]$: universal corrections

Kniehl, Spira
Kwiatkowski, Steinhauser

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

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

elw. gaugeless limit + QCD = top-Yukawa model + QCD

$$\phi = \begin{pmatrix} G^+ \\ \frac{v + H + iG^0}{\sqrt{2}} \end{pmatrix}$$

$$\mathcal{L} = -\frac{1}{4} G^{a\mu\nu} G^a_{\mu\nu} + \bar{t} i \not{D} t + |\partial_\mu \phi|^2 - V(\phi) - g_t \bar{Q}_L \phi^c t_R$$

$$V(\phi) = -\mu^2 |\phi|^2 + \frac{\lambda}{2} |\phi|^4$$

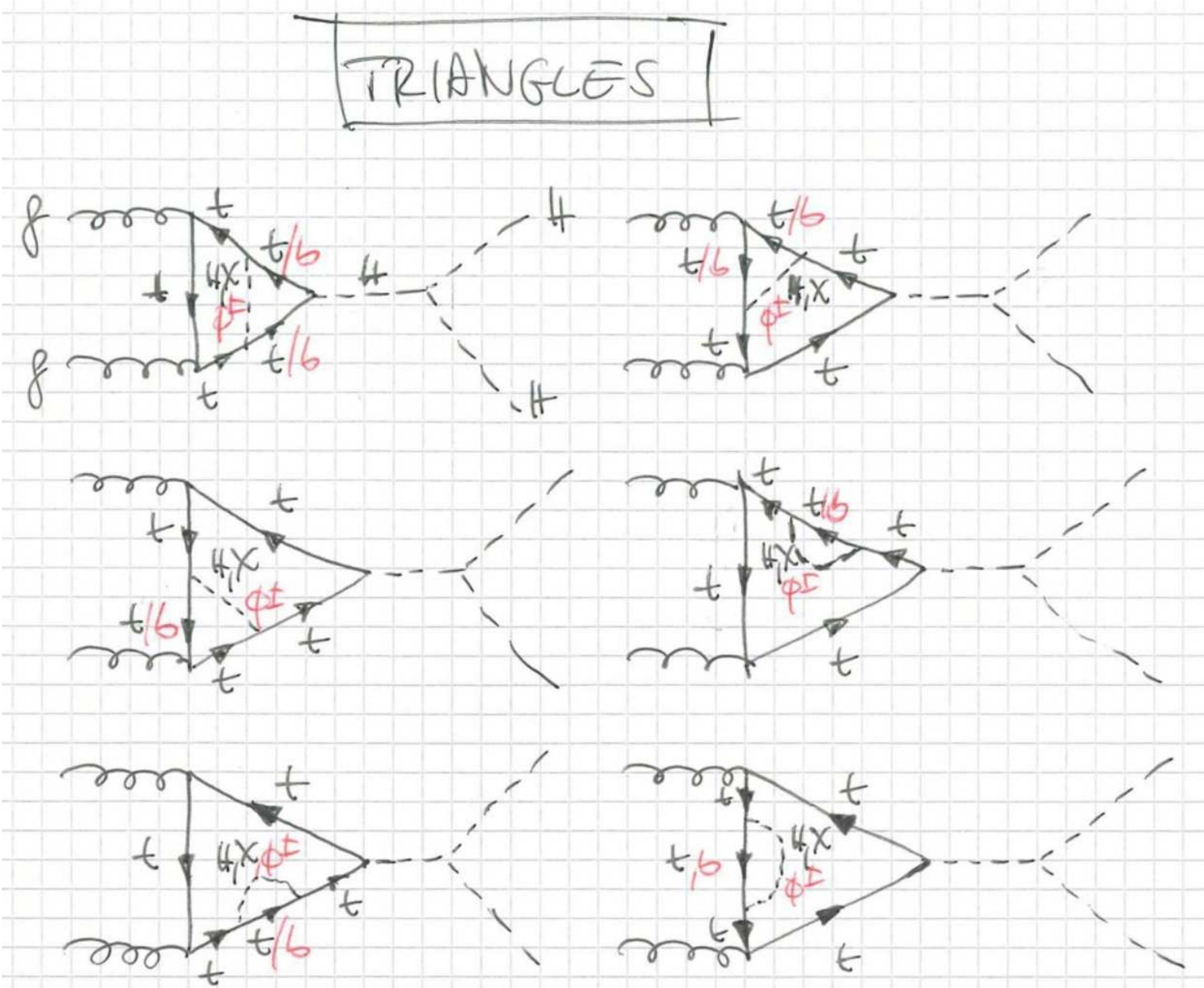
$$= -\frac{M_H^2}{8} v^2 + \frac{M_H^2}{2} H^2 + \frac{M_H^2}{v} \left[\frac{H^3}{2} + \frac{H}{2} (G^0)^2 + H G^+ G^- \right]$$

$$+ \frac{M_H^2}{2v^2} \left[\frac{H^4}{4} + \frac{H^2}{2} (G^0)^2 + H^2 G^+ G^- + (G^+ G^-)^2 + (G^0)^2 G^+ G^- + \frac{(G^0)^4}{4} \right]$$

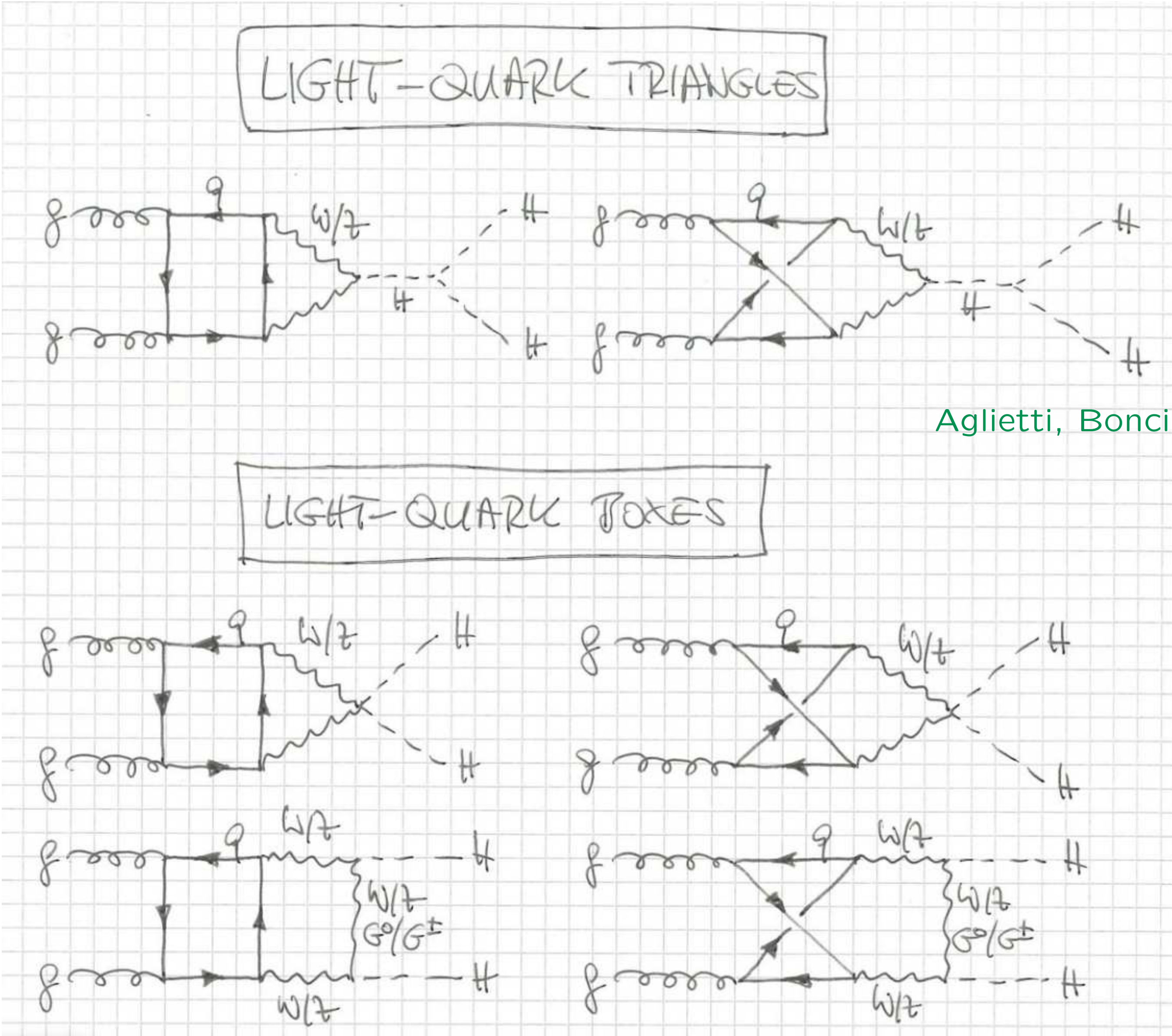
$$\Rightarrow M_{G^0} = M_{G^\pm} = 0$$

<u>INTERMEZZO</u>

Full top-mass dependence (wave-function ren. adjusted appropriately)

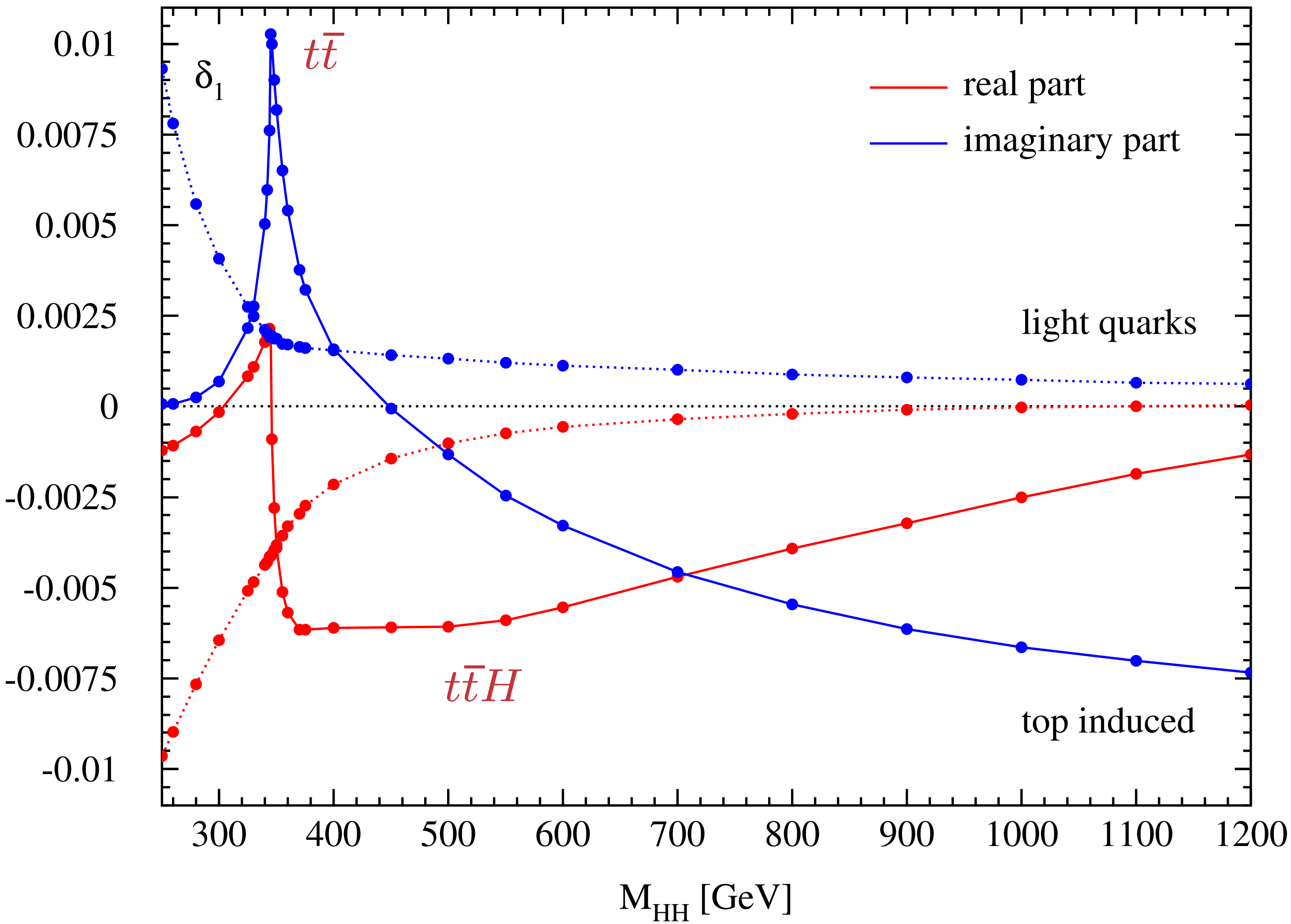


Light-quark loops



Aglietti, Bonciani, Degrassi, Vicini

$$\delta_1 = \delta_{2loop} + \delta Z_H/2 - \delta v/v$$

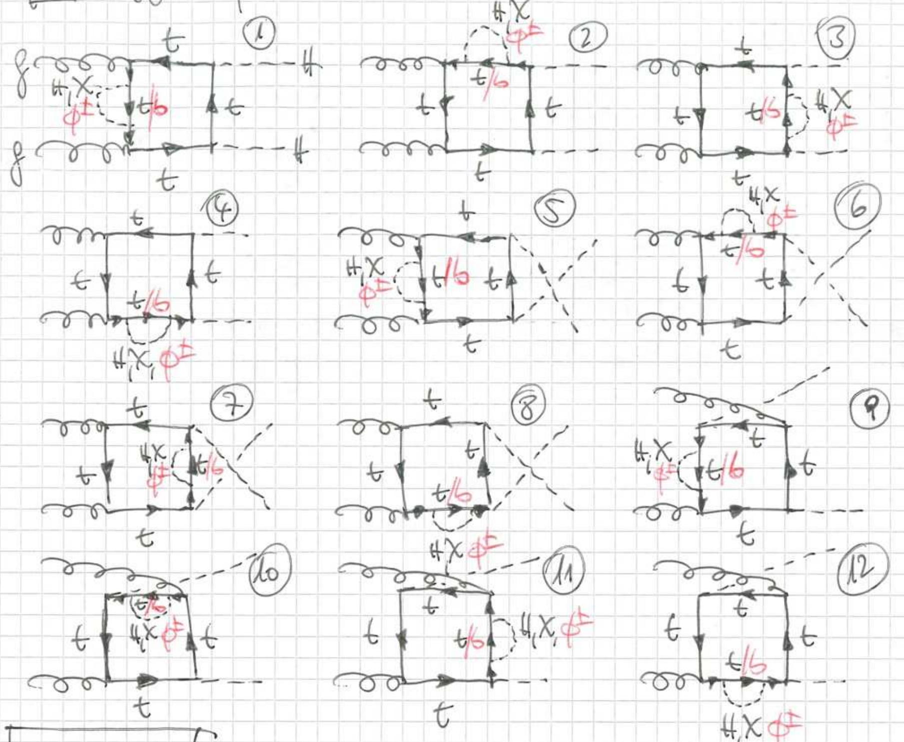


Bhattacharya, Campanario, Carlotti, Chang, Mazzitelli, Mühlleitner, Ronca, S.

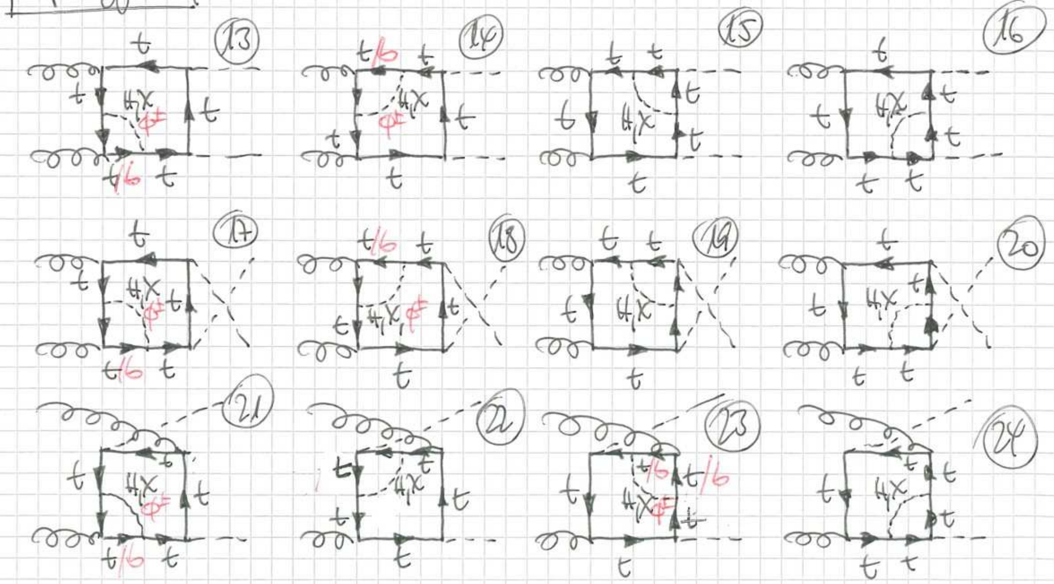
- box diagrams in the making...

Topology 1

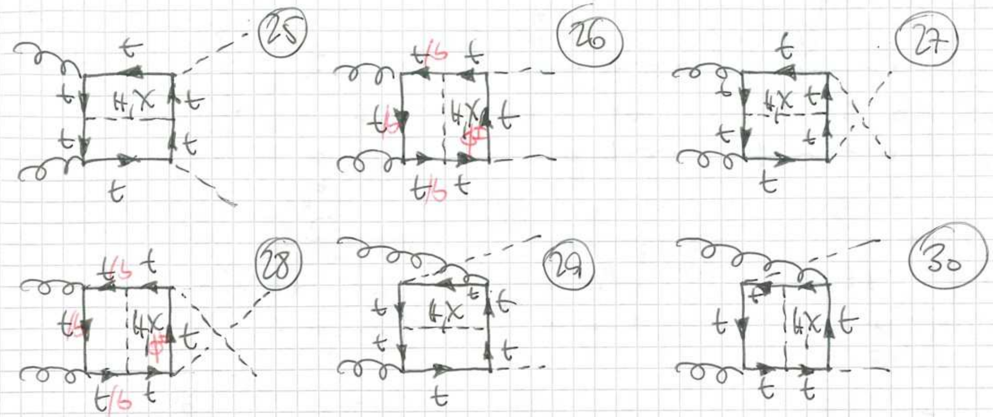
BOXES



Topology 2



TOPOLOGY 3



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

- effective Higgs potential: Coleman, Weinberg

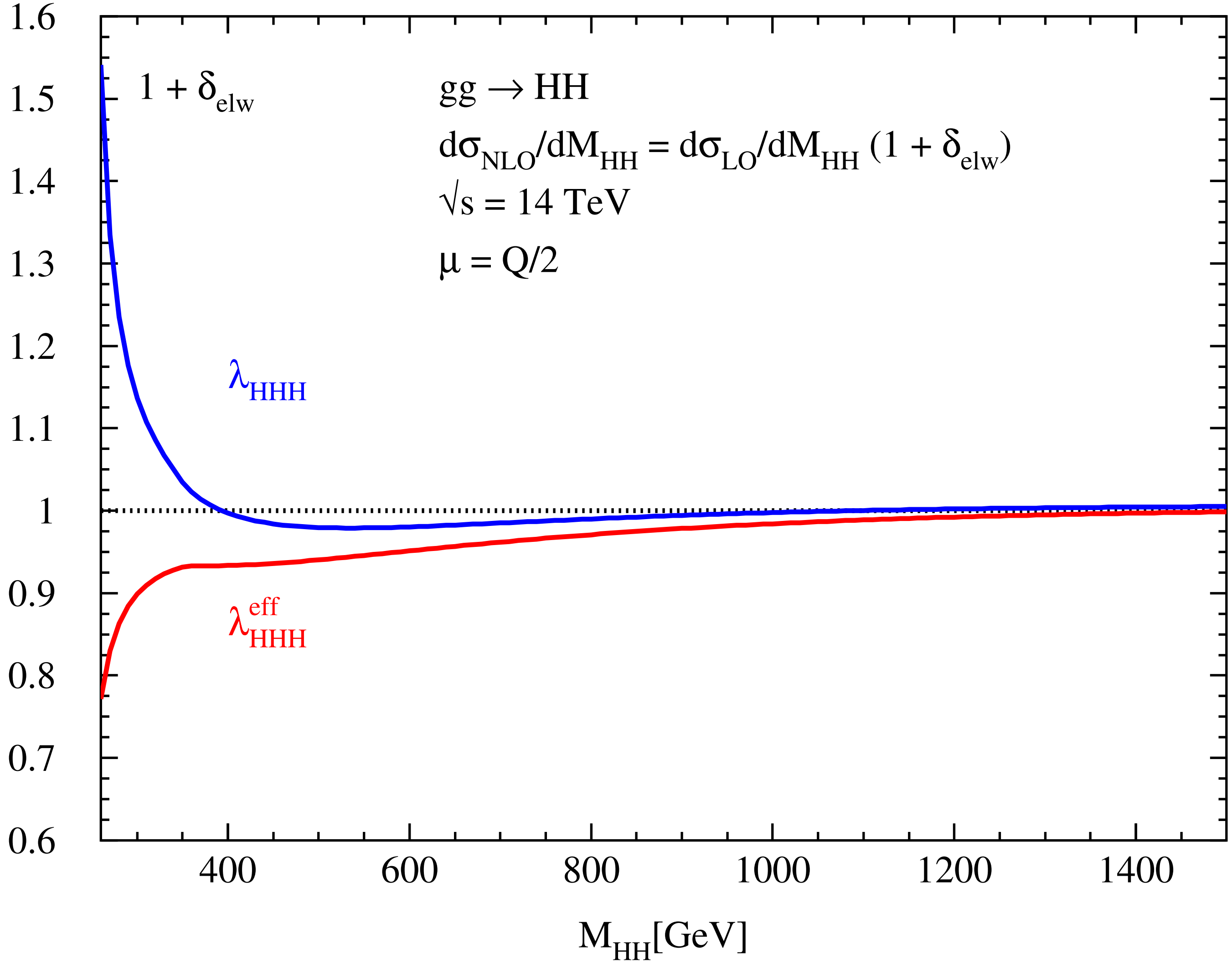
$$
\begin{aligned}
V_{eff} &= V_0 + V_1 \\
V_0 &= \mu_0^2|\phi|^2 + \frac{\lambda_0}{2}|\phi|^4 \\
V_1 &= \frac{3\overline{m}_t^4}{16\pi^2}\Gamma(1+\epsilon)(4\pi^2)^\epsilon\left(\frac{1}{\epsilon} + \log\frac{\bar{\mu}^2}{\overline{m}_t^2} + \frac{3}{2}\right) \\
\phi &= \frac{1}{\sqrt{2}}\begin{pmatrix}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

- after renormalization

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

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

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



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

Mühlleitner, Schlenk, S.

IV CONCLUSIONS

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

- important to develop NLO event generators [$\leftarrow$ backgrounds]

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

- significant uncertainties for off-shell Higgs production and decays

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

- factorization/renormalization scale uncertainties @NNLO$_{FTapprox}$ $\lesssim 5\%$

- uncertainties due to m_t scale/scheme choice sizeable $\lesssim 20\%$
  $\rightarrow$ linear combination of rel. uncertainties

- analogous issues in $gg \rightarrow H + 2jet, ZH, ZZ$ etc.

- small top-induced electroweak corrections

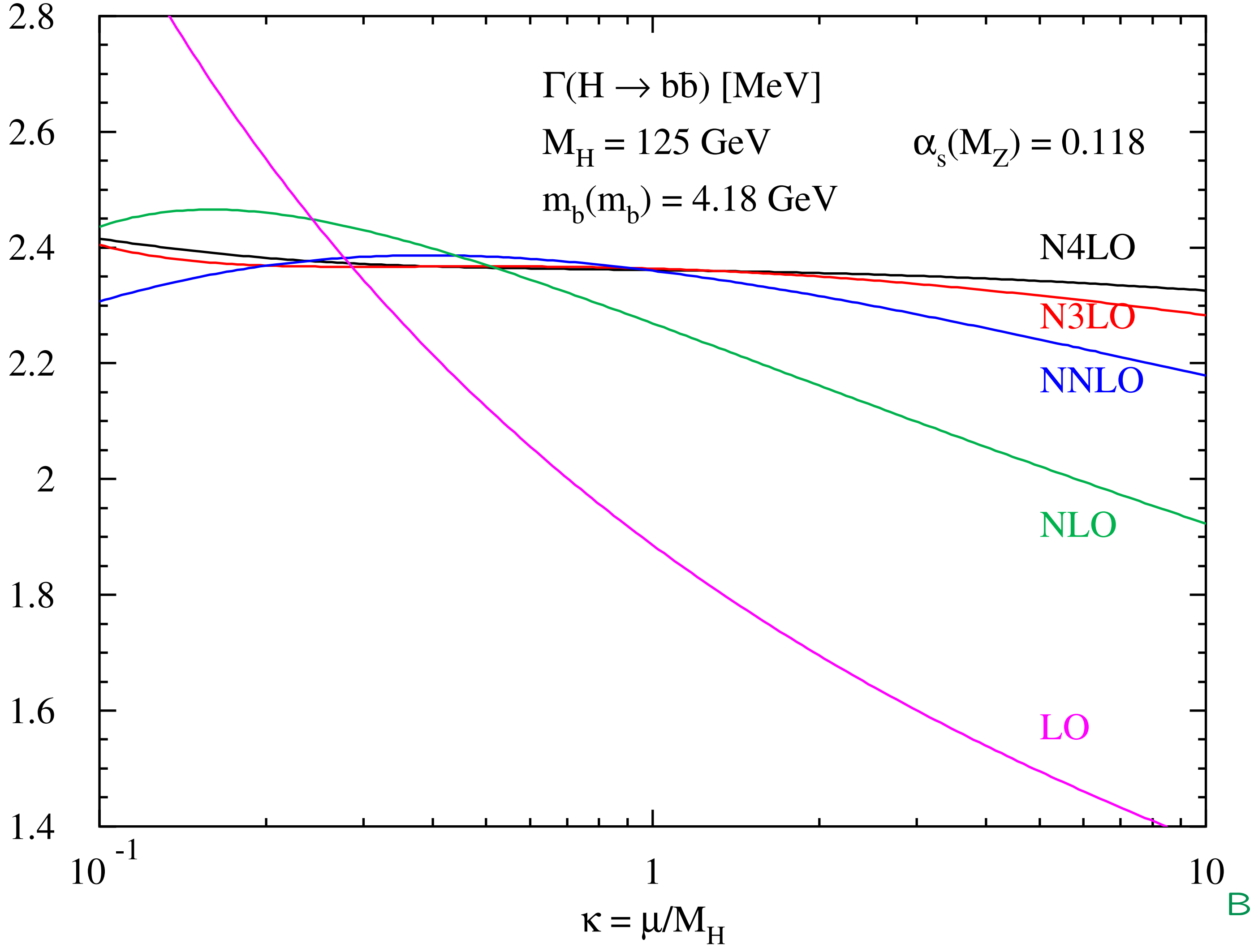
BACKUP SLIDES

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

$\uparrow$

log resummation $\to \sim$ factor 1/2

(larger than BSM effects!)



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

→ HDECAY

Djouadi, Kalinowski, Mühlleitner, S.

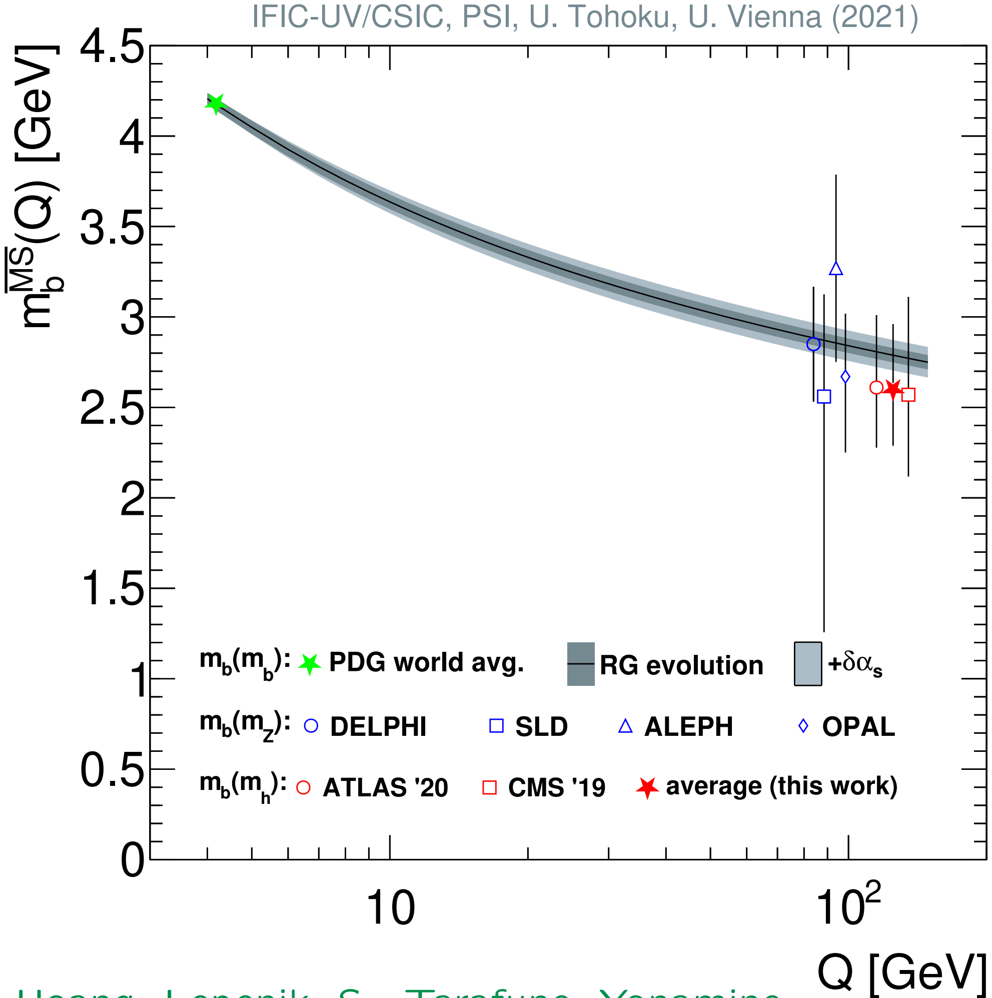
- ATLAS: $\mu_{bb}/\mu_{ZZ} = \Gamma(H \to bb)/\Gamma(H \to ZZ)|_{SM-norm} = 0.87^{+0.28}_{-0.21}$

- 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
(BLUE) Nisius

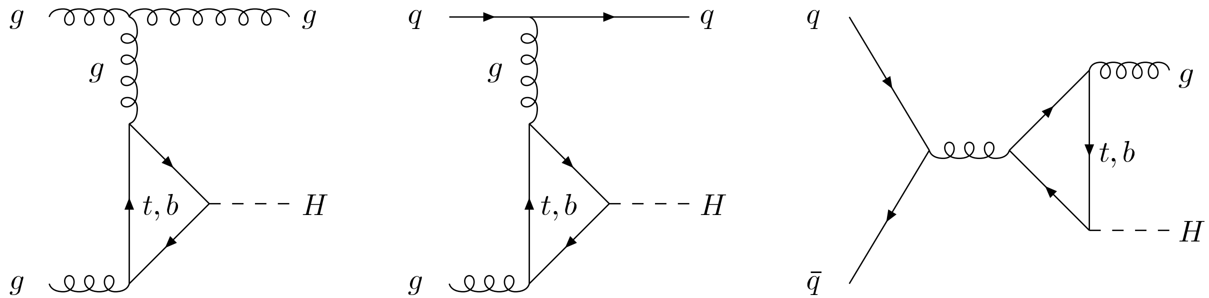
RG-evolution: REvolver

Hoang, Lepenik, Mateu

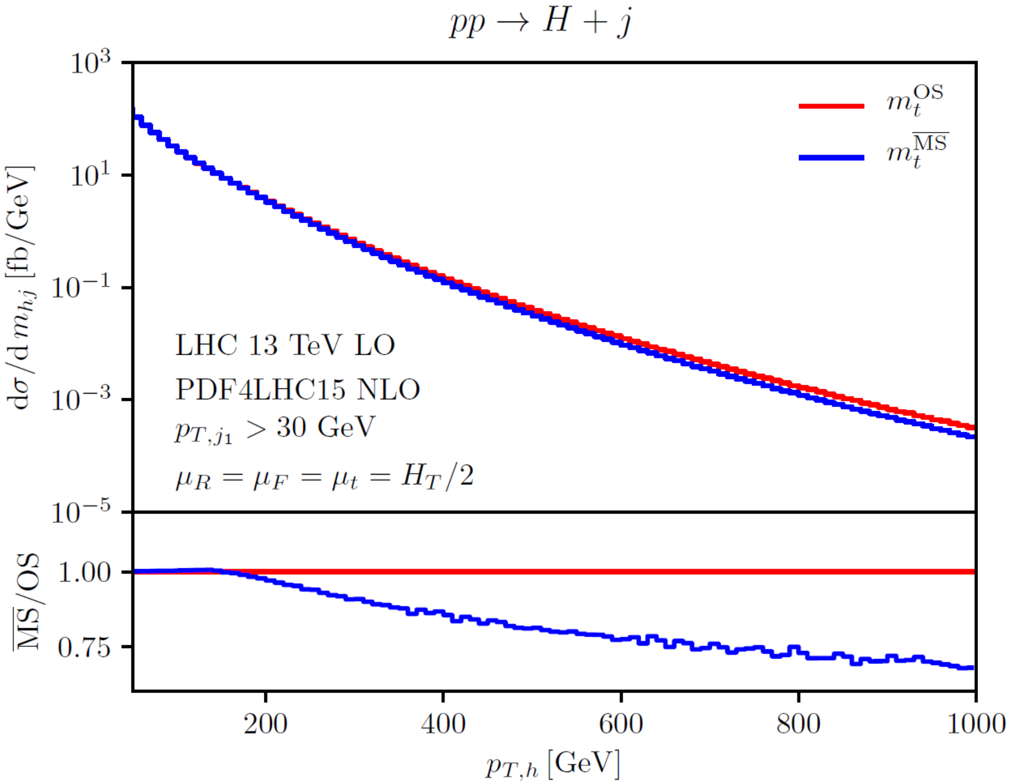


Aparisi, Fuster, Irles, Rodrigo, Vos, Yamamoto, Hoang, Lepenik, S., Tarafune, Yonamine

• Higgs + jet production: $gg \to H + j$



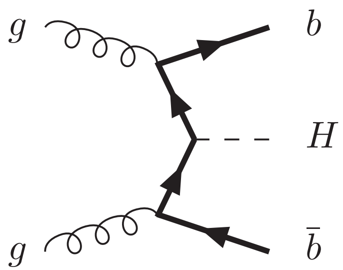
LO: $\mu_t = H_T/2 = (\sqrt{M_H^2 + p_T^2} + p_{Tj})/2$



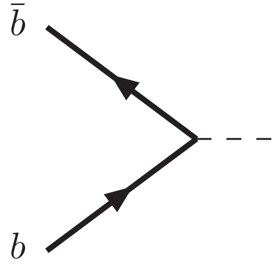
→ NLO? Jones, Kerner, Luisoni

Jones, S.

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



NLO



$[\leftarrow \Delta_b]$

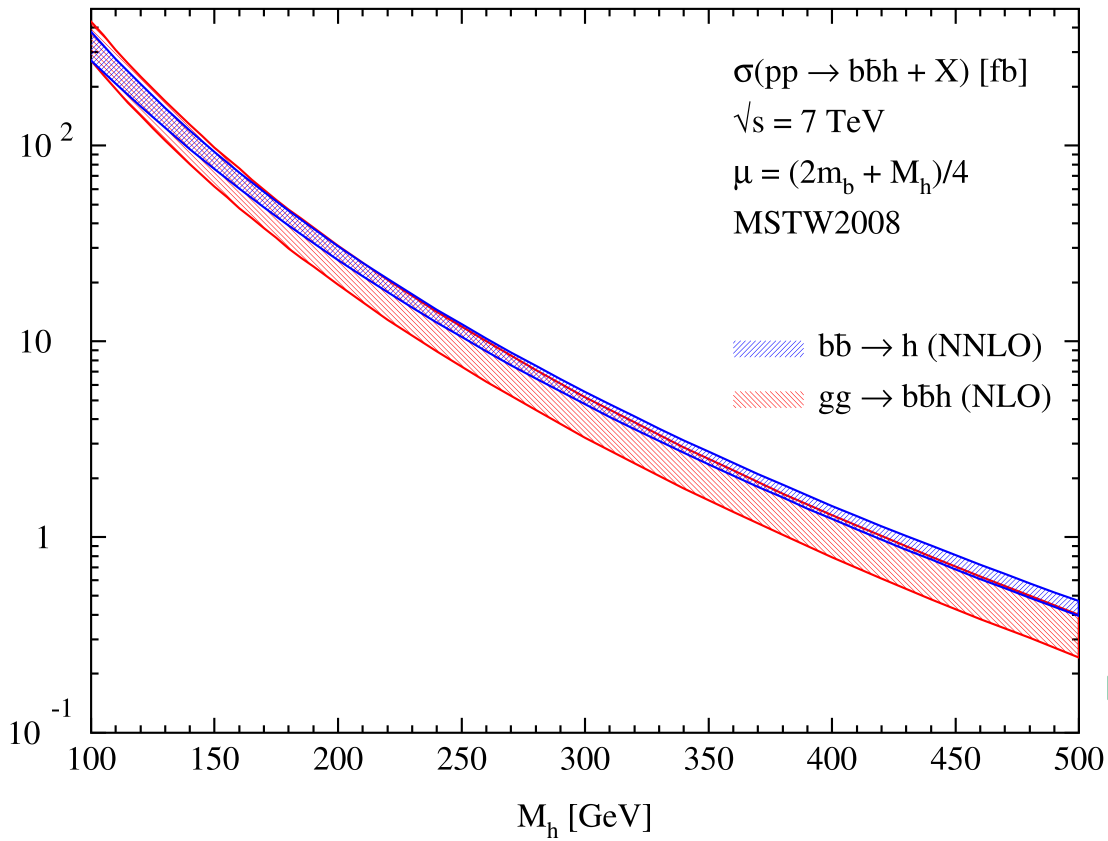
NNLO

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:

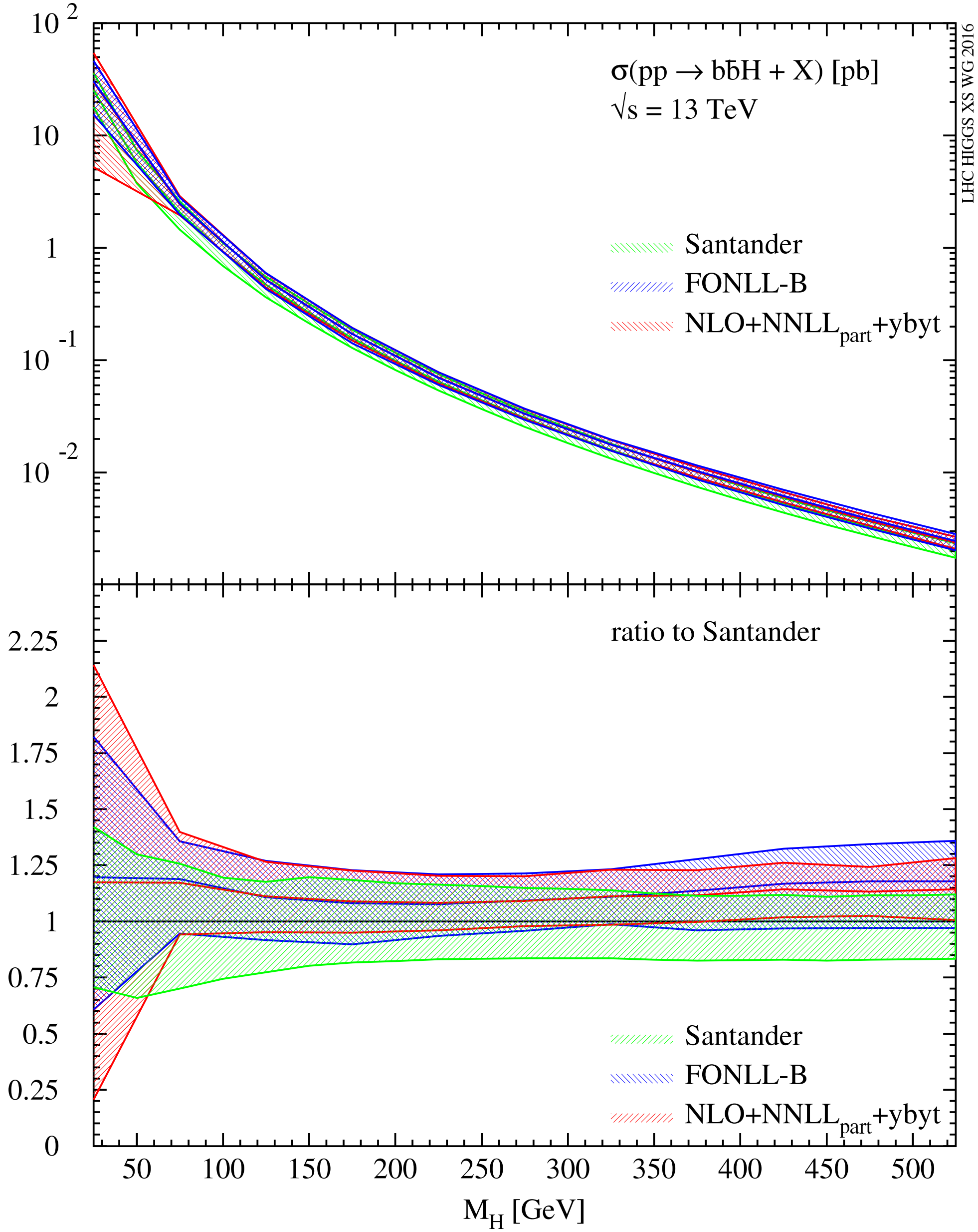
$$\sigma = \frac{\sigma^{4FS} + w\sigma^{5FS}}{1+w}$$

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

Harlander, Krämer, Schumacher

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

matching



Bonvini, Papanastasiou, Tackmann

Forte, Napoletano, Ubiali

Flavour-scheme comparison

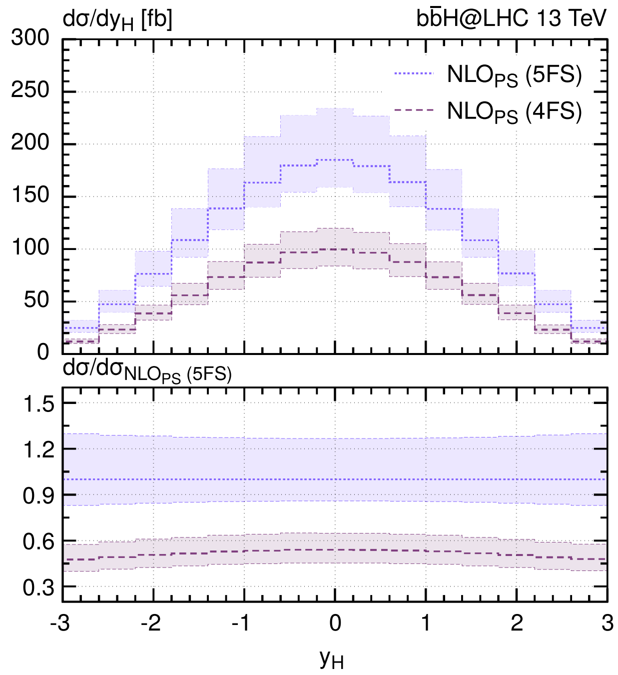
$$H_T = \sum_{i=b,\bar{b},H} \sqrt{m^2(i) + p_T^2(i)}$$

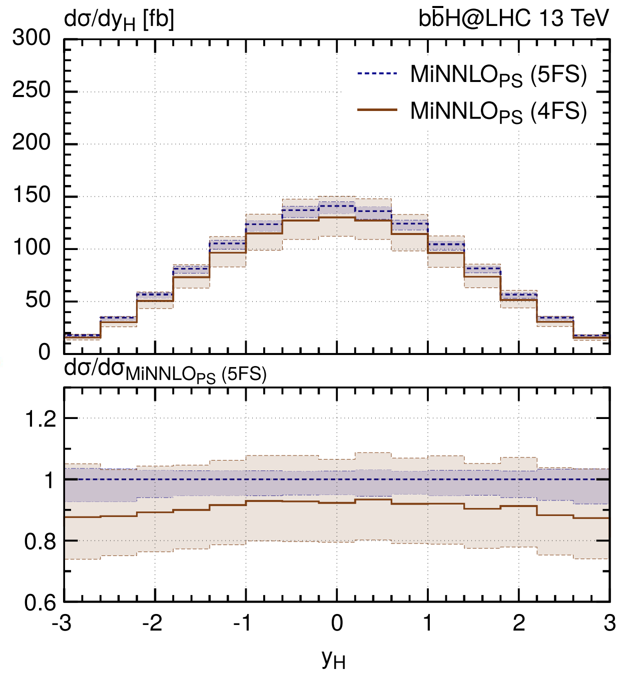
5FS $\mathrm{NLO_{PS}}(m_H)$	$0.676(4)^{+27\%}_{-15\%}$ pb
4FS $\mathrm{NLO_{PS}}(m_H)$	$0.355(3)^{+20\%}_{-16\%}$ pb
4FS $\mathrm{NLO_{PS}}(\frac{H_T}{4})$	$0.385(4)^{+16\%}_{-14\%}$ pb

5FS $\mathrm{MiNNLO_{PS}}$ (m_H)	$0.509(4)^{+2.9\%}_{-5.3\%}$ pb
4FS $\mathrm{MiNNLO_{PS}}$ (m_H)	$0.465(4)^{+16\%}_{-14\%}$ pb
4FS $\mathrm{MiNNLO_{PS}}$ $(\frac{H_T}{4})$	$0.492(3)^{+16\%}_{-14\%}$ pb

NNLO corrections solve the FS issue.

At NNLO QCD, the two predictions agree within the scale variation when using the most natural choice (m_H) as the central scale, without the need for artificial factors to improve the comparison.





CB, Mazzitelli, Sankar, Wiesemann, Zanderighi [to appear]

- m_t scale/scheme uncertainties @ NLO:

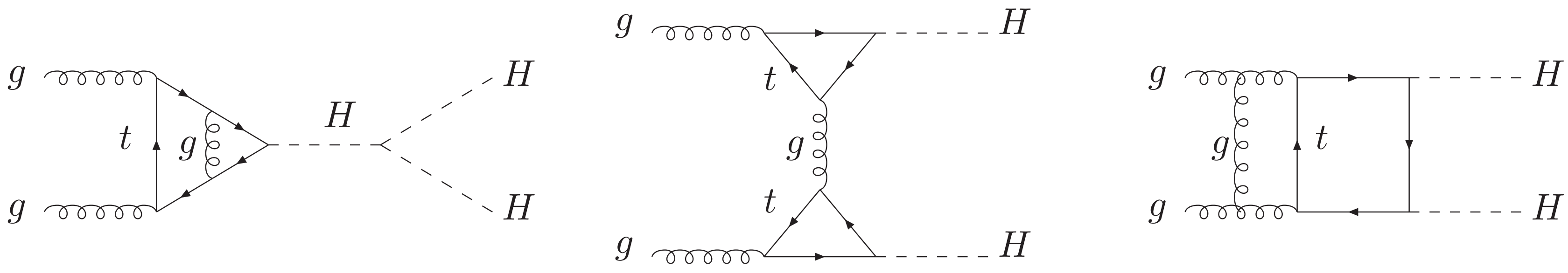
$$\kappa_\lambda = -10: \quad \sigma_{tot} = 1438(1)^{+10\%}_{-6\%} \text{ fb}$$
$$\kappa_\lambda = -5: \quad \sigma_{tot} = 512.8(3)^{+10\%}_{-7\%} \text{ fb}$$
$$\kappa_\lambda = -1: \quad \sigma_{tot} = 113.66(7)^{+8\%}_{-9\%} \text{ fb}$$
$$\kappa_\lambda = 0: \quad \sigma_{tot} = 61.22(6)^{+6\%}_{-12\%}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

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

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

(i) virtual corrections

47 gen. box diags, 8 triangle diags ($\leftarrow$ single Higgs), 1PR ($\leftarrow H \to Z\gamma$)



- full diagram w/o tensor reduction $\to$ 6-dim. Feynman integral (2 FF)
- UV-singularities: end-point subtractions

$$\int_0^1 dx\, \frac{f(x)}{(1-x)^{1-\epsilon}} = \int_0^1 dx\, \frac{f(1)}{(1-x)^{1-\epsilon}} + \int_0^1 dx\, \frac{f(x)-f(1)}{(1-x)^{1-\epsilon}} = \frac{f(1)}{\epsilon} + \int_0^1 dx\, \frac{f(x)-f(1)}{1-x} + \mathcal{O}(\epsilon)$$

- IR-sing.: IR-subtraction (based on struc. of integr. and rel. to HTL)
- thresholds: $Q^2 \geq 0, 4m_t^2 \to$ IBP $\to$ reduction of power of denominator $[m_t^2 \to m_t^2(1-ih)]$

$$\int_0^1 dx\, \frac{f(x)}{(a+bx)^3} = \frac{f(0)}{2a^2 b} - \frac{f(1)}{2b(a+b)^2} + \int_0^1 dx \frac{f'(x)}{2b(a+bx)^2}$$

- renormalization: α_s: $\overline{\text{MS}}$, 5 flavours
  m_t: on-shell

- PS-integration $\to$ 7-dim. integrals for $d\sigma/dQ^2$

- subtraction of HTL $\to$ IR-finite mass effects [adding back HTL results $\leftarrow$ HPAIR]

- extrapolation to NWA ($h \to 0$): Richardson extrapolation

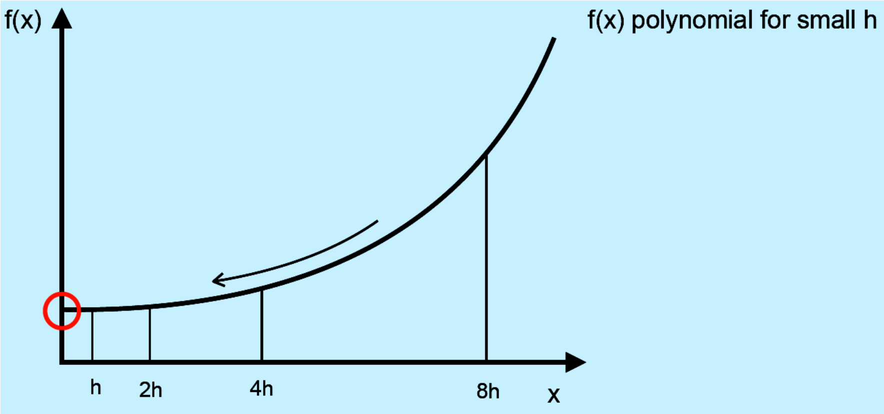
$M_2 = 2f(h) - f(2h) = f(0) + \mathcal{O}(h^2)$

$M_4 = \{8f(h) - 6f(2h) + f(4h)\}/3 = f(0) + \mathcal{O}(h^3)$

$M_8 = \{64f(h) - 56f(2h) + 14f(4h) - f(8h)\}/21 = f(0) + \mathcal{O}(h^4)$

etc.

[$h \geq 0.05$]



(ii) real corrections

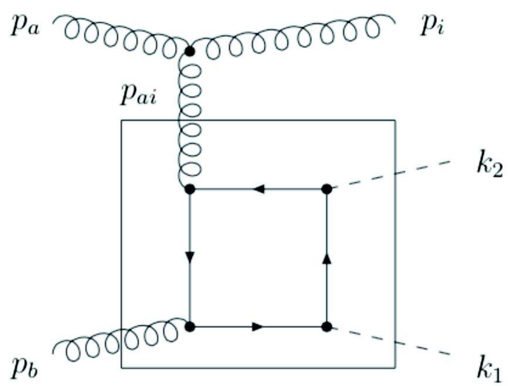
- full matrix elements generated with FeynArts and FormCalc

- matrix elements in HTL involving full LO sub-matrix elements subtracted $\to$ IR-, COLL-finite [adding back HTL results $\leftarrow$ HPAIR]

$$\sum \overline{|\mathcal{M}_{gg}|^2} = \sum \overline{\left|\tilde{\mathcal{M}}_{LO}\right|^2} \frac{24\pi^2}{Q^4}\frac{\alpha_s}{\pi}\left\{\frac{s^4+t^4+u^4+Q^8}{stu} - 4\frac{\epsilon}{1-\epsilon}Q^2\right\}$$

$$\sum \overline{|\mathcal{M}_{gq}|^2} = \sum \overline{\left|\tilde{\mathcal{M}}_{LO}\right|^2} \frac{32\pi^2}{3Q^4}\frac{\alpha_s}{\pi}\left\{\frac{s^2+u^2}{-t} + \epsilon\frac{(s+u)^2}{t}\right\}$$

$$\sum \overline{\left|\mathcal{M}_{q\bar{q}}\right|^2} = \sum \overline{\left|\tilde{\mathcal{M}}_{LO}\right|^2} \frac{256\pi^2}{9Q^4}\frac{\alpha_s}{\pi}(1-\epsilon)\left\{\frac{t^2+u^2}{s} - \epsilon\frac{(t+u)^2}{s}\right\}$$



$$
\begin{aligned}
F_i &= F_{i,LO} + \Delta F_i \\
\Delta F_i &= \Delta F_{i,HTL} + \Delta F_{i,mass}
\end{aligned}
$$

- pole mass:

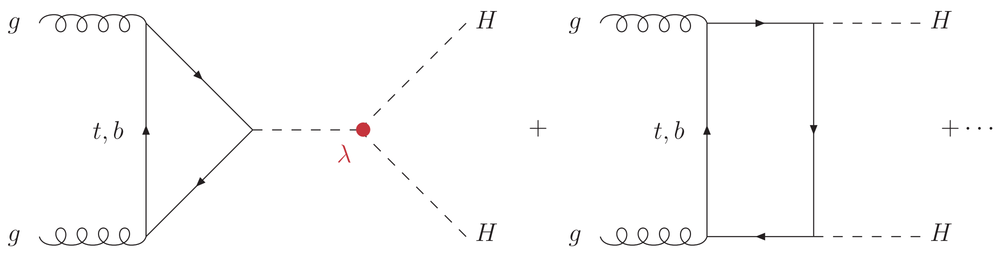
$$
\begin{aligned}
F_{1,LO} &\to 4\frac{m_t^2}{\hat{s}} \\
F_{2,LO} &\to -\frac{m_t^2}{\hat{s}\hat{t}(\hat{s}+\hat{t})}\{(\hat{s}+\hat{t})^2 L_{1ts}^2 + \hat{t}^2 L_{ts}^2 + \pi^2[(\hat{s}+\hat{t})^2 + \hat{t}^2]\}
\end{aligned}
$$

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

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

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

$\rightarrow$ has to hold at all orders



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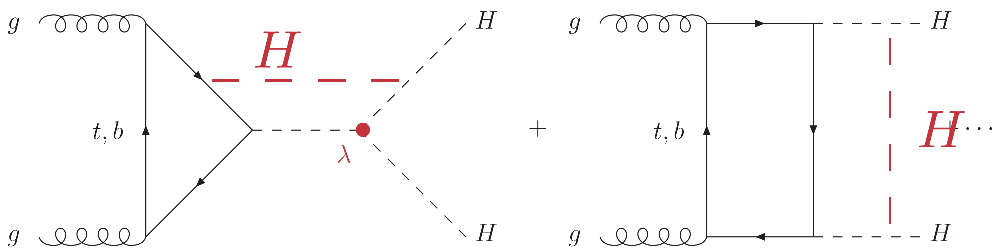

elw. corrections

$\Rightarrow$ same scales in all diagrams