DI – HIGGS PRODUCTION IN THE 2HDM : THEORY UPDATE

Michael Spira (PSI)

I Introduction

II Calculation

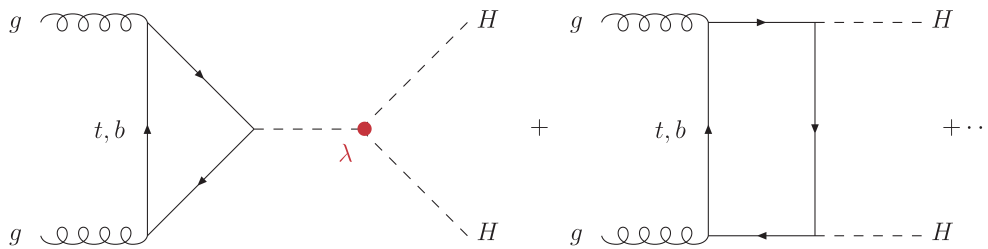
III Conclusions

in collaboration with J. Baglio, F. Campanario, S. Glaus, M. Mühlleitner, J. Streicher

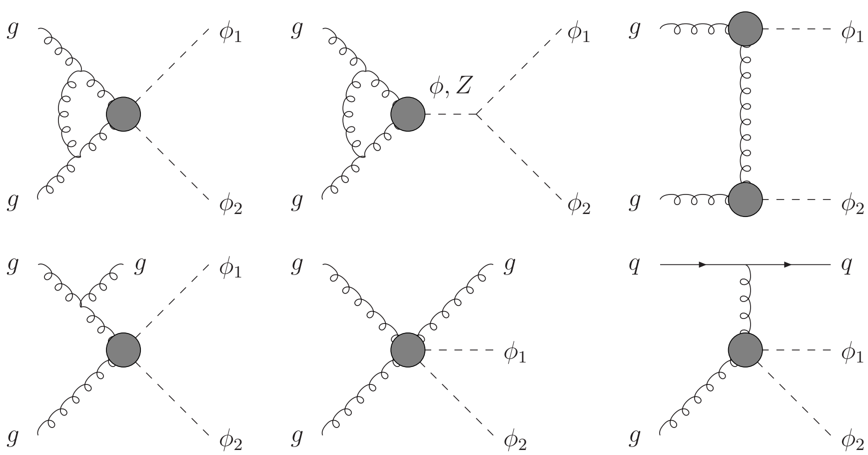
I INTRODUCTION

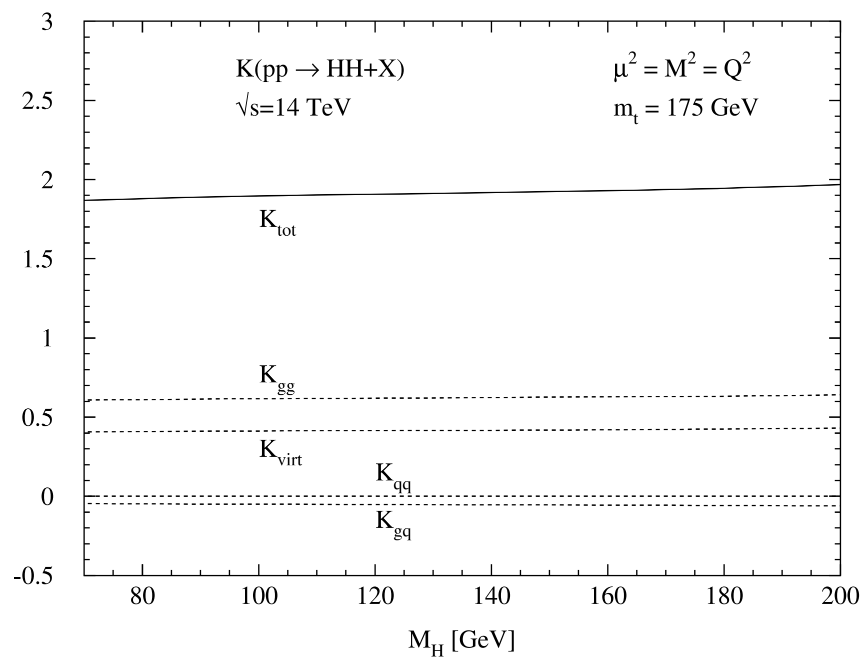
$gg \to HH$

(B)SM



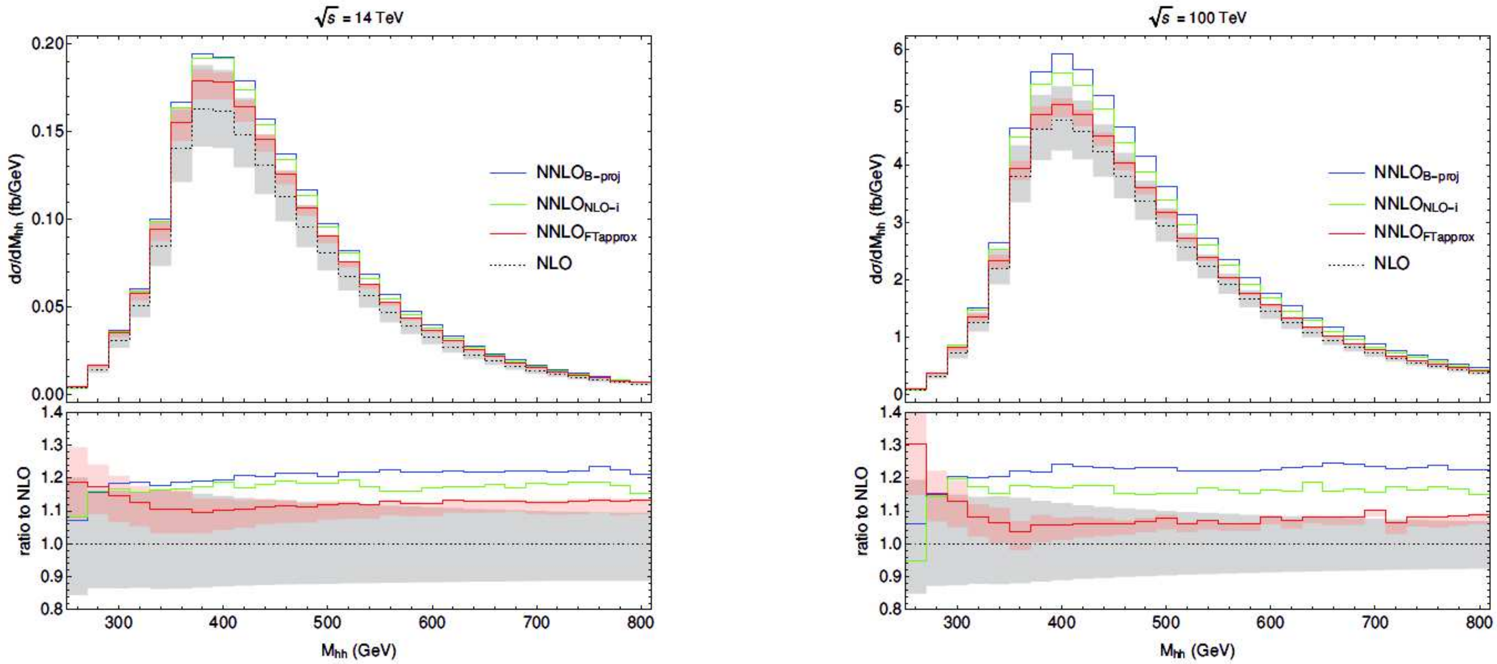
- third generation dominant $\to t, b$
- 2-loop QCD corrections: $\sim 90 - 100\%$
  $[M_H^2 \ll 4m_t^2, \qquad \mu = M_{HH}]$





Dawson, Dittmaier, S.

• NNLO Monte Carlo: inclusion of full top-mass effects @ NLO



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

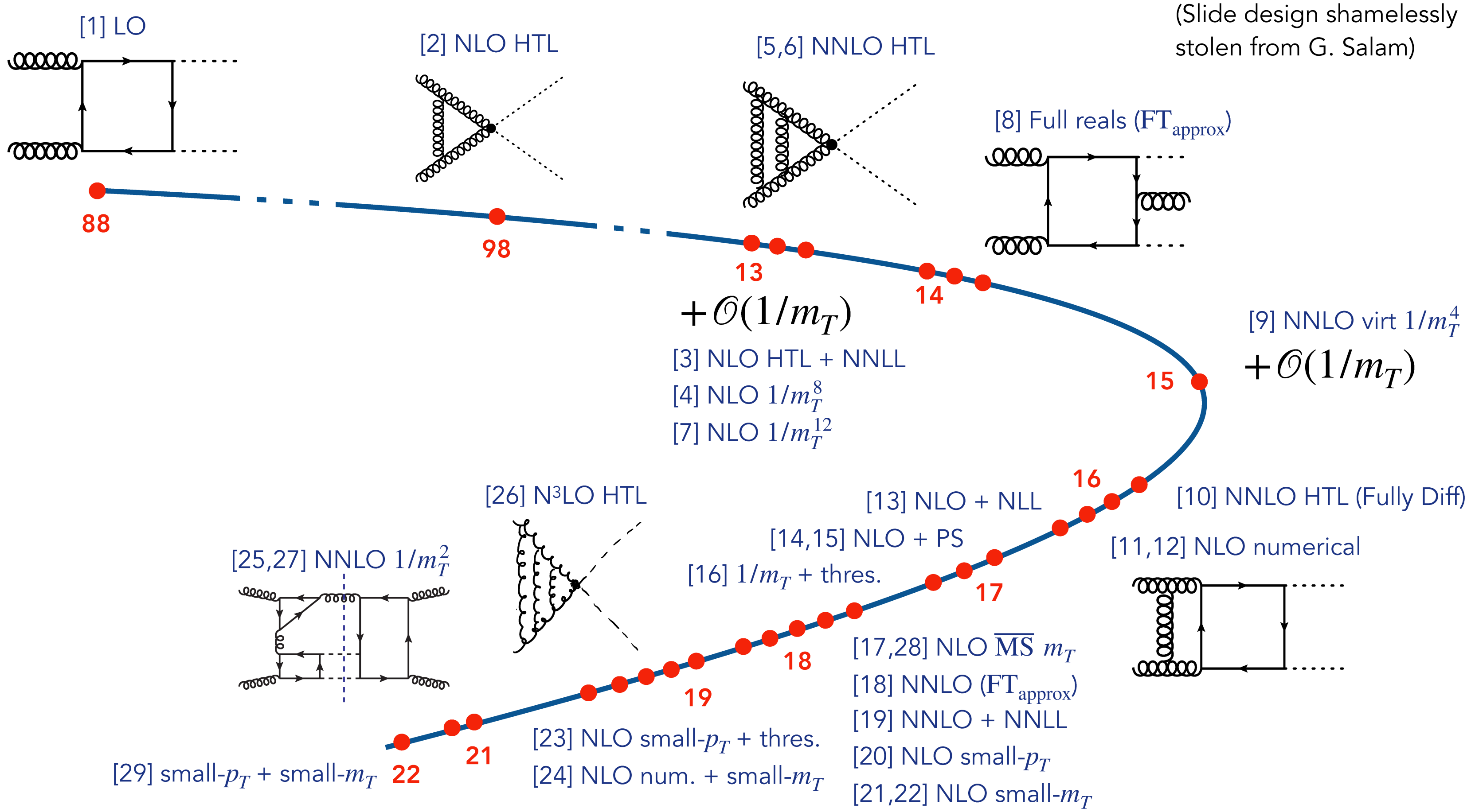
⇒ 20% effects beyond NLO

• NLO: matching to parton showers

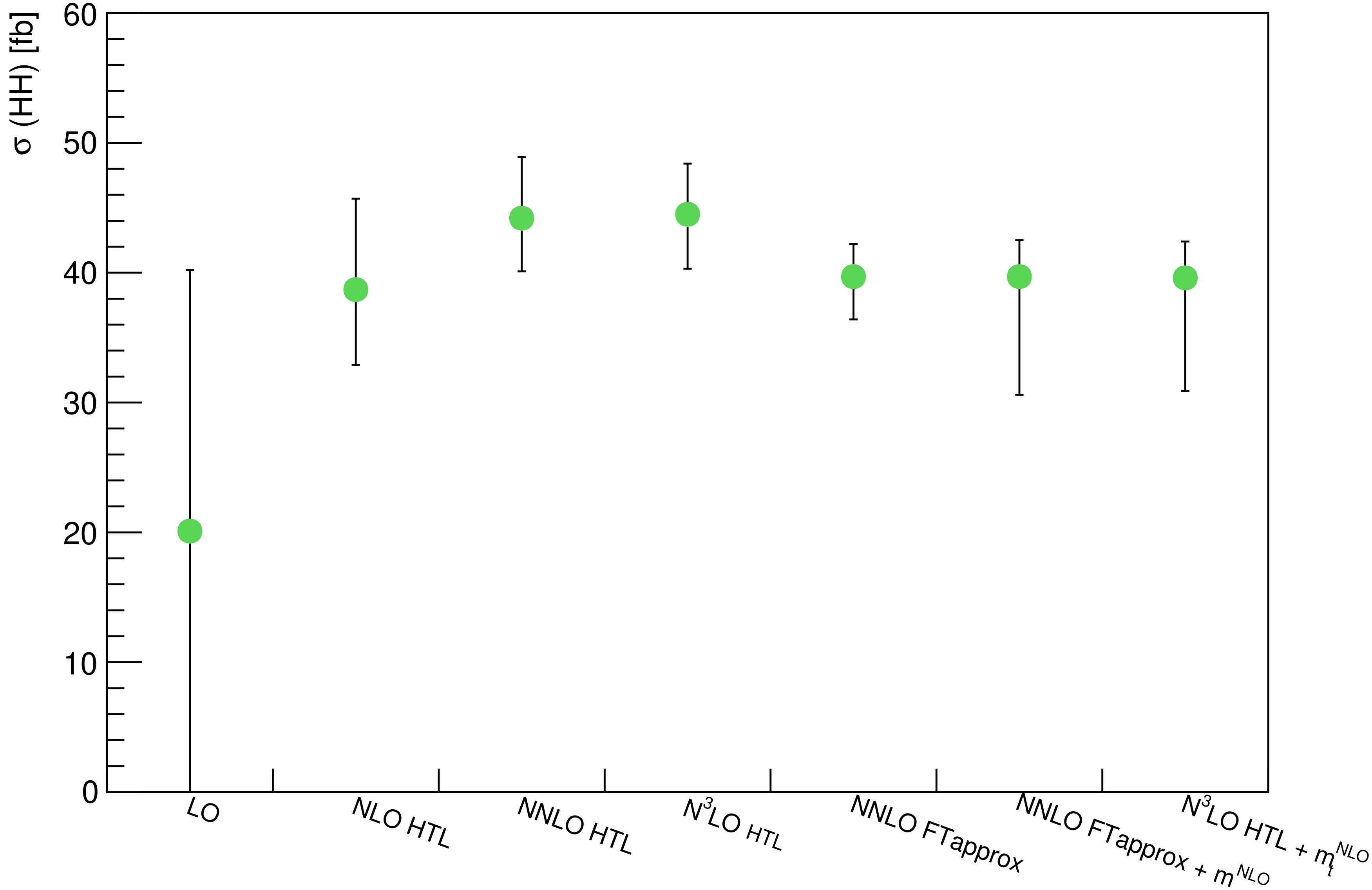
Heinrich, Jones, Kerner, Luisoni, Vryonidou

An approximate history (30 years in 30 seconds)

(Slide design shamelessly stolen from G. Salam)



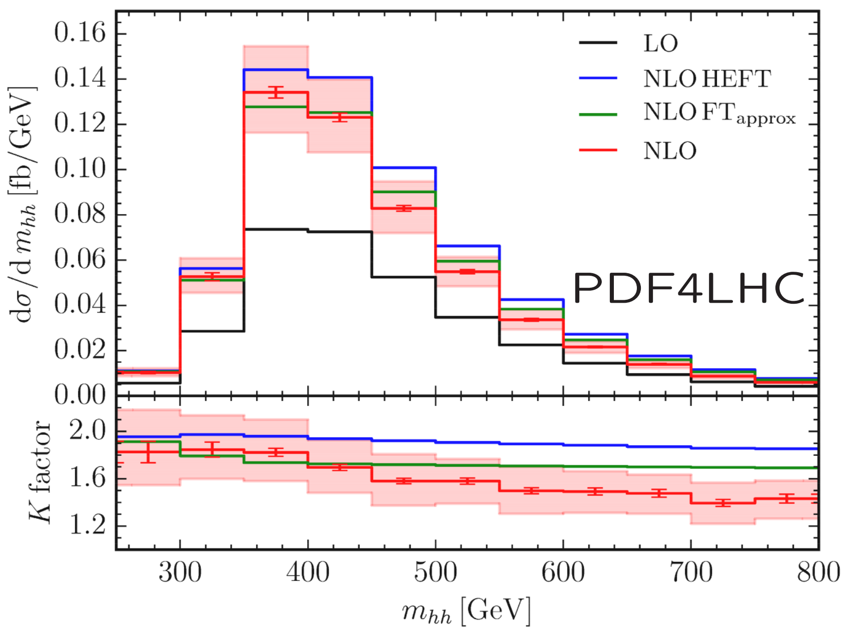
[1] Glover, van der Bij 88; [2] Dawson, Dittmaier, Spira 98; [3] Shao, Li, Li, Wang 13; [4] Grigo, Hoff, Melnikov, Steinhauser 13; [5] de Florian, Mazzitelli 13; [6] Grigo, Melnikov, Steinhauser 14; [7] Grigo, Hoff 14; [8] Maltoni, Vryonidou, Zaro 14; [9] Grigo, Hoff, Steinhauser 15; [10] de Florian, 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;


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

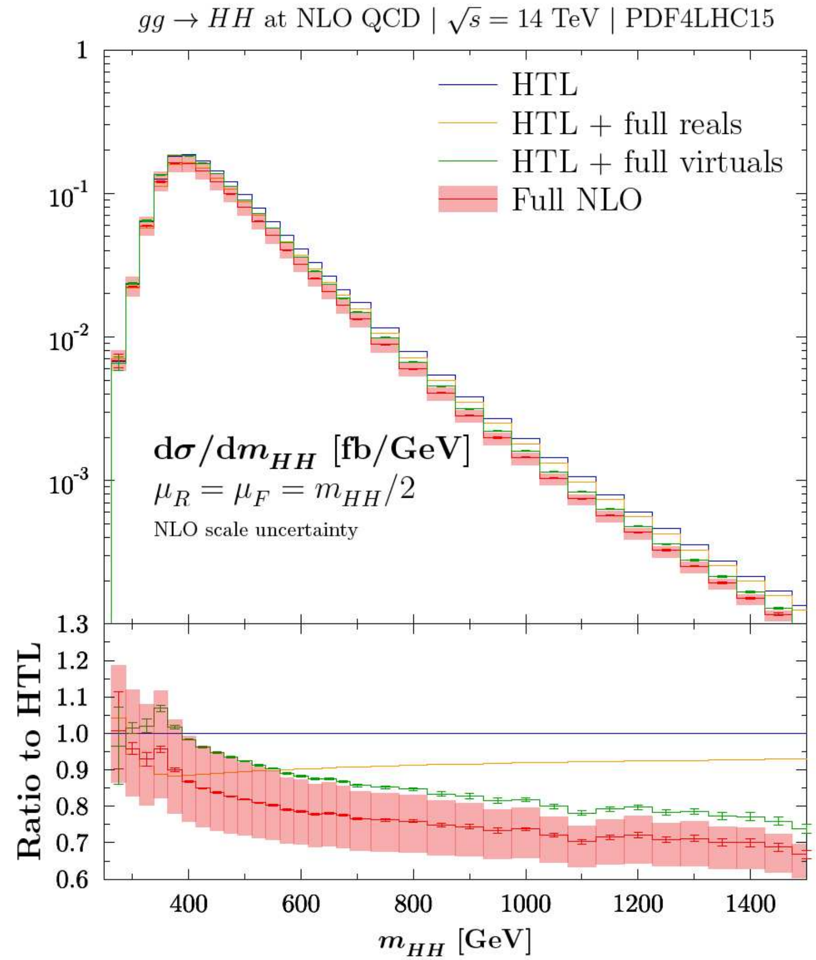
Full NLO calculation: top only, numerical integration

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

⇒ -15% mass effects on top of LO

uncertainties due to m_t

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

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

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

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

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

- bin-by-bin interpolation:

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

2HDM

$$
\begin{aligned}
V &= m_{11}|\phi_1|^2 + m_{22}^2|\phi_2|^2 - m_{12}^2(\phi_1^\dagger\phi_2 + \text{h.c}) + \lambda_1|\phi_1|^4 + \lambda_2|\phi_2|^4 \\
&+ \lambda_3|\phi_1|^2|\phi_2|^2 + \lambda_4|\phi_1^\dagger\phi_2|^2 + \frac{1}{2}\lambda_5[(\phi_1^\dagger\phi_2)^2 + \text{h.c}]
\end{aligned}
$$

- modified couplings: 2HDM type II [I]

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 [$-$ctgβ]	0

- heavy 2nd Higgs doublet $A, H, H^\pm$ and h SM-like

- $gg \to hh, hH, HH, AA$
  [$gg \to hA, HA$ overwhelmed by DY-like $q\bar{q} \to hA, HA$]

II CALCULATION

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

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

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

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

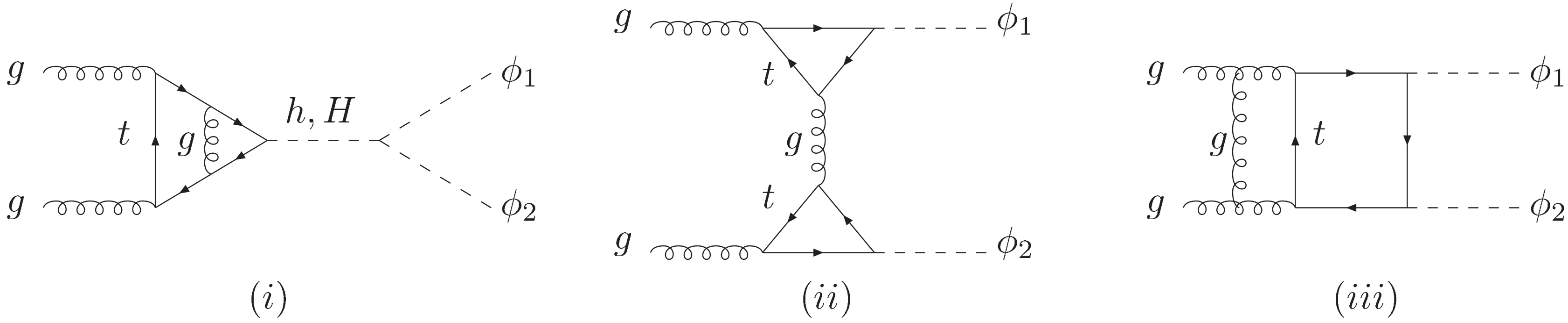
$$\Delta\sigma_{gq} = \frac{\alpha_s(\mu)}{\pi} \int_{\tau_0}^{1} d\tau \sum_{q,\bar{q}} \frac{d\mathcal{L}^{gq}}{d\tau} \int_{\tau_0/\tau}^{1} \frac{dz}{z} \, \hat{\sigma}_{\rm LO}(Q^2 = z\tau s) \left\{ -\frac{z}{2} P_{gq}(z) \log \frac{M^2}{\tau s (1-z)^2} + d_{gq}(z) \right\}$$

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

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

(i) virtual corrections

47 gen. box diags, 8 tria diags (← single Higgs), 1PR (← $H, A \to Z\gamma$)



- two formfactors:

$$\mathcal{A}^{\mu\nu} = F_1 T_1^{\mu\nu} + F_2 T_2^{\mu\nu} \qquad F_1 = C_\triangle F_\triangle + F_\Box \qquad F_2 = G_\Box$$

$$T_1^{\mu\nu} = g^{\mu\nu} - \frac{q_1^\nu q_2^\mu}{(q_1 q_2)},$$

$$T_2^{\mu\nu} = g^{\mu\nu} + \frac{M_H^2 q_1^\nu q_2^\mu}{p_T^2 (q_1 q_2)} - 2\frac{(q_2 p_1) q_1^\nu p_1^\mu}{p_T^2 (q_1 q_2)} - 2\frac{(q_1 p_1) p_1^\nu q_2^\mu}{p_T^2 (q_1 q_2)} + 2\frac{p_1^\nu p_1^\mu}{p_T^2}$$

$$P_1^{\mu\nu} = \frac{(1-\epsilon) T_1^{\mu\nu} + \epsilon T_2^{\mu\nu}}{2(1-2\epsilon)} \qquad P_2^{\mu\nu} = \frac{\epsilon T_1^{\mu\nu} + (1-\epsilon) T_2^{\mu\nu}}{2(1-2\epsilon)}$$

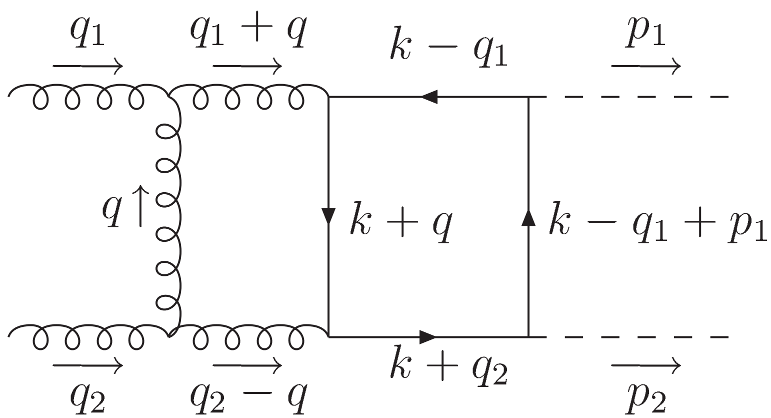
$$P_1^{\mu\nu} \mathcal{A}_{\mu\nu} = F_1 \qquad P_2^{\mu\nu} \mathcal{A}_{\mu\nu} = F_2$$

- full diagram w/o tensor reduction → 6-dim. Feynman integrals

- 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)



$$\rho_s = \hat{s}/m_t^2 = Q^2/m_t^2$$
$$\rho_t = (\hat{t} - M_H^2)/m_t^2$$
$$\rho_u = (\hat{u} - M_H^2)/m_t^2$$
$$\rho_H = M_H^2/m_t^2$$
$$d^6x = dx\,dy\,dz\,dr\,ds\,dt$$

$$\begin{aligned}
\Delta F_i &= \Gamma(1+2\epsilon)\left(\frac{4\pi\mu_0^2}{m_t^2}\right)^{2\epsilon} \int_0^1 d^6x\, \frac{x^{1+\epsilon}(1-x)^{\epsilon} r^{1+\epsilon} s^{-\epsilon} H_i(\vec{x})}{N^{3+2\epsilon}(\vec{x})} \\
N(\vec{x}) &= ar^2 + br + c \\
a &= x(1-x)ys\Big[-\rho_s(1-y-t) + \rho_t yz - \rho_u z(1-y-t) + \rho_H yz^2\Big] \\
b &= 1 - \rho_s x\Big\{xy(1-y) + (1-x)[(1-s)(1-y-t) + yst]\Big\} - \rho_H xyz(1-xyz) \\
&\quad -\rho_t xyz[1 - xy - (1-x)(1-s)] - \rho_u xyz[x(1-y) + (1-x)st] \\
c &= -\rho_s x(1-x)(1-s)t
\end{aligned}$$

- subtract integrand with linear denominator

$$\Delta F_i = \frac{\alpha_s}{\pi}\,\Gamma(1+2\epsilon)\left(\frac{4\pi\mu_0^2}{m_t^2}\right)^{2\epsilon}(G_1+G_2)$$

$$G_1 = \int_0^1 d^6x\; x^{1+\epsilon}(1-x)^{\epsilon} r^{1+\epsilon} s^{-\epsilon}\left\{\frac{H_i(\vec{x})}{N^{3+2\epsilon}(\vec{x})} - \frac{H_i(\vec{x})|_{r=0}}{(br+c)^{3+2\epsilon}}\right\}$$

$$G_2 = \int_0^1 d^6x\; x^{1+\epsilon}(1-x)^{\epsilon} r^{1+\epsilon} s^{-\epsilon}\frac{H_i(\vec{x})|_{r=0}}{(br+c)^{3+2\epsilon}}$$

- $G_2 \to$ hypergeom. fct. after r-integration [arg $\to$ 1/arg]

- thresholds: $Q^2 \geq 0, 4m_t^2 \to$ IBP $\to$ reduction of power of denominator [$m_t^2 \to m_t^2(1-ih)$]

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

- extrapolation to NWA ($h \to 0$): Richardson extrapolation 1911

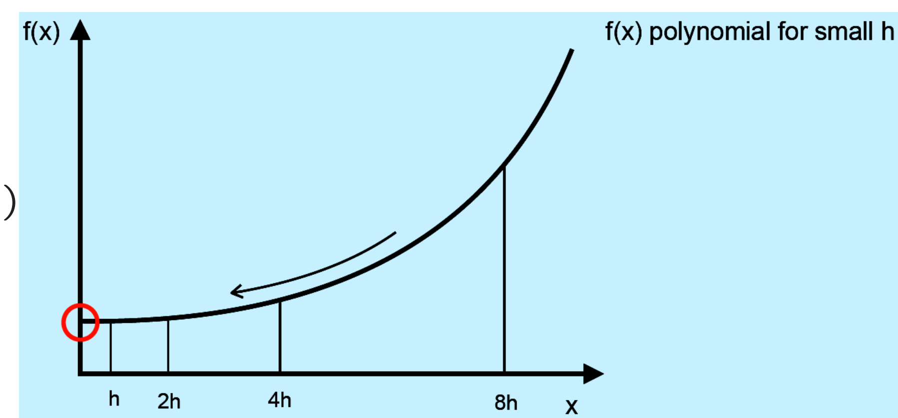
$M_2 = 2f(h) - f(2h) = f(0) + \mathcal{O}(h^2)$

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

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

etc.

[$h \geq 0.05$]



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

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

- subtraction of HTL $\rightarrow$ IR-finite mass effects

- add back HTL results $\leftarrow$ HPAIR

(ii) real corrections

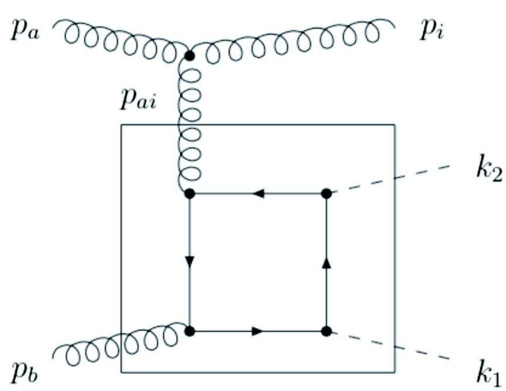
• full matrix elements generated with FeynArts and FormCalc

• matrix elements in HTL involving full LO sub-matrix elements subtracted → IR-, COLL-finite [adding back HTL results ← HPAIR]

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

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

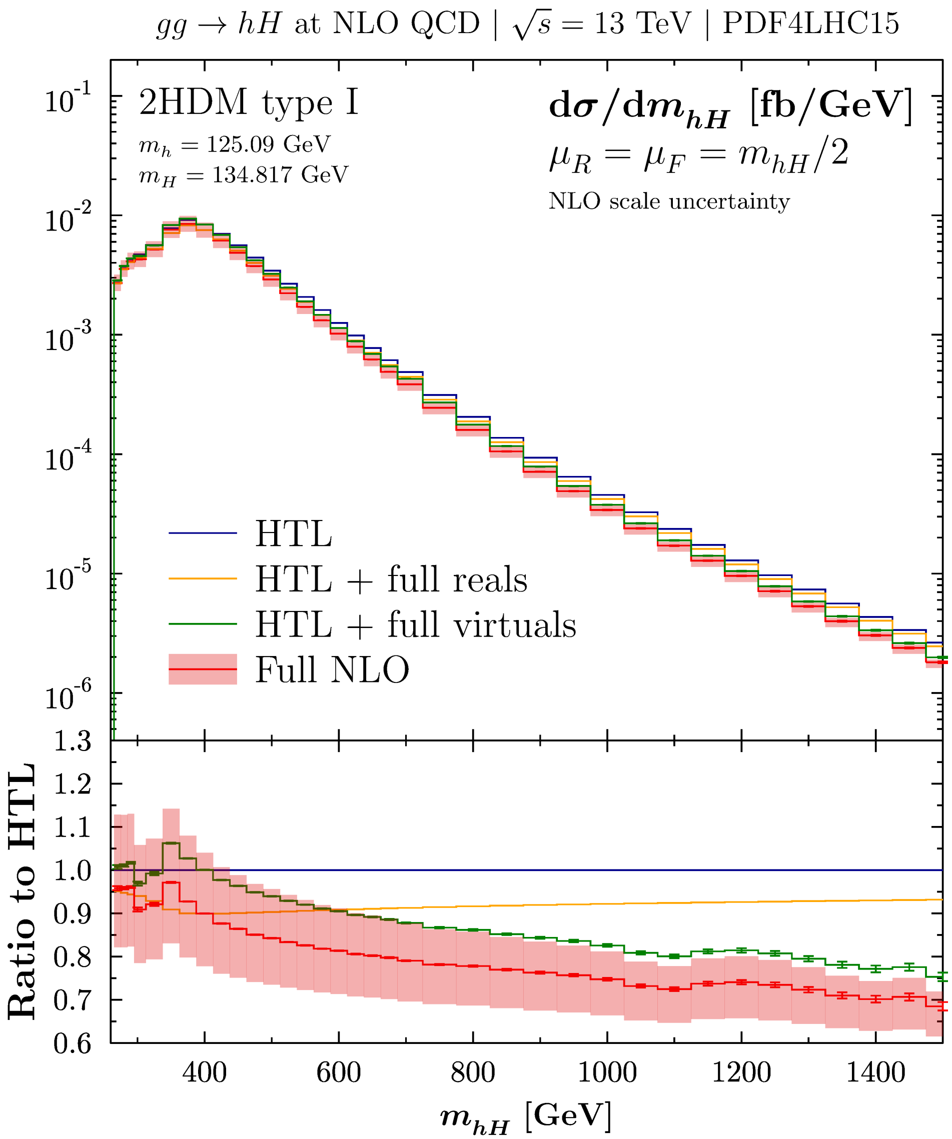
$$\sum \overline{\left|\mathcal{M}_{q\bar{q}}\right|^2} = \sum \overline{\left|\tilde{\mathcal{M}}_{LO}\right|^2} \frac{256\pi^2}{9Q^4}\frac{\alpha_s}{\pi}(1-\epsilon)\left\{\frac{t^2+u^2}{s} - \epsilon\frac{(t+u)^2}{s}\right\}$$

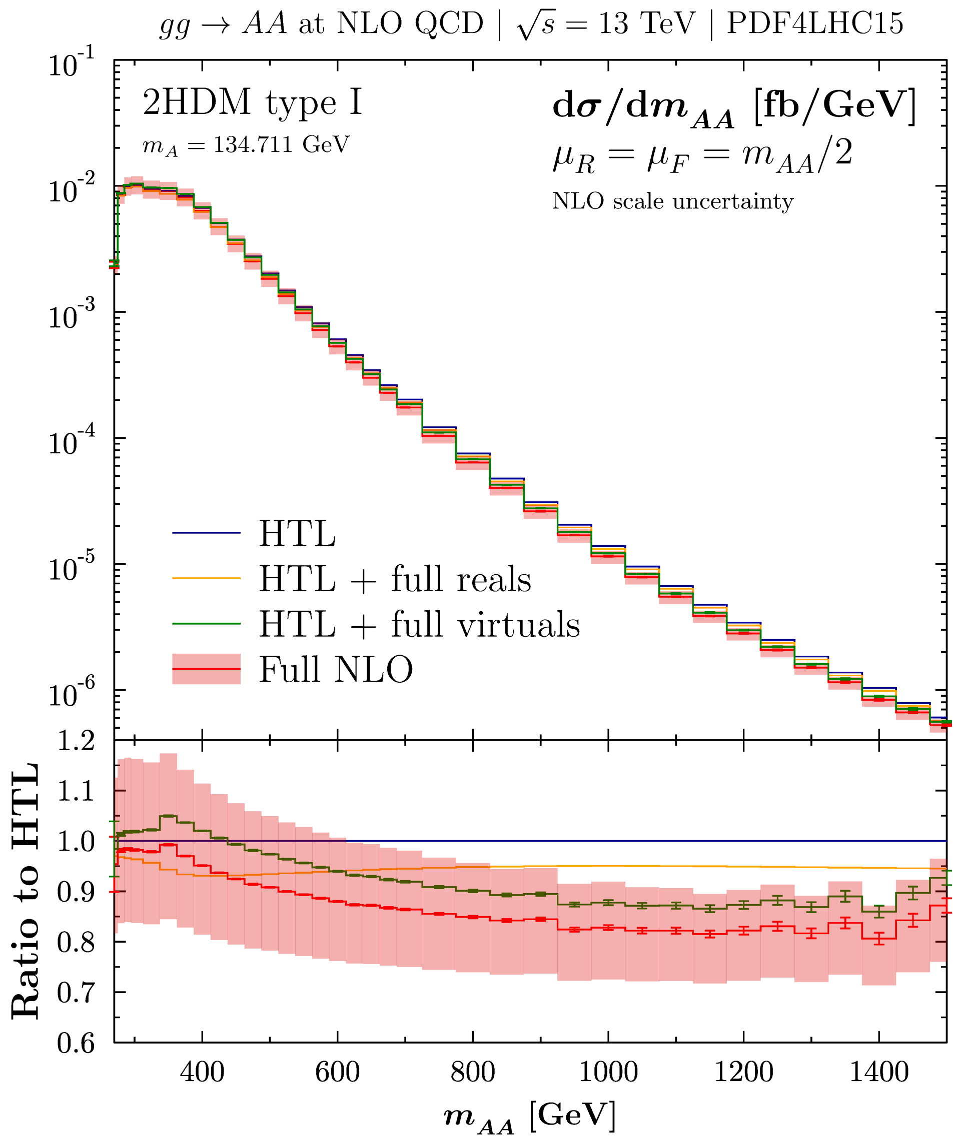


(iii) results: 2HDM [type I]

$M_h = 125.09$ GeV $\quad M_H = 134.817$ GeV $\quad M_A = 134.711$ GeV

$\mathrm{tg}\beta = 3.759 \quad \alpha = -0.102 \quad m_{12}^2 = 4305\ \mathrm{GeV}^2 \quad \Rightarrow \cos(\beta-\alpha) = 0.157$





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

(iv) factorization/renormalization scale uncertainties

- 7-point variation, 13 TeV

$$\left.\frac{d\sigma(gg \to hH)}{dQ}\right|_{Q=300\ \text{GeV}} = 0.004278(2)^{+16.4\%}_{-13.6\%}\ \text{fb/GeV},$$

$$\left.\frac{d\sigma(gg \to hH)}{dQ}\right|_{Q=400\ \text{GeV}} = 0.007522(5)^{+15.6\%}_{-13.6\%}\ \text{fb/GeV},$$

$$\left.\frac{d\sigma(gg \to hH)}{dQ}\right|_{Q=600\ \text{GeV}} = 0.0010217(9)^{+12.1\%}_{-12.3\%}\ \text{fb/GeV},$$

$$\left.\frac{d\sigma(gg \to hH)}{dQ}\right|_{Q=1200\ \text{GeV}} = 0.00000956(6)^{+8.1\%}_{-11.3\%}\ \text{fb/GeV}$$

- interpolation:

$$\sigma(gg \to hH) = 1.592(1)^{+15.2\%}_{-13.4\%}\ \text{fb}$$

(iv) factorization/renormalization scale uncertainties

- 7-point variation, 13 TeV

$$\left.\frac{d\sigma(gg \to AA)}{dQ}\right|_{Q=300\ \text{GeV}} = 0.01005(2)^{+18.3\%}_{-14.7\%}\ \text{fb/GeV},$$

$$\left.\frac{d\sigma(gg \to AA)}{dQ}\right|_{Q=400\ \text{GeV}} = 0.006346(6)^{+17.1\%}_{-14.4\%}\ \text{fb/GeV},$$

$$\left.\frac{d\sigma(gg \to AA)}{dQ}\right|_{Q=600\ \text{GeV}} = 0.0005328(7)^{+14.4\%}_{-13.4\%}\ \text{fb/GeV},$$

$$\left.\frac{d\sigma(gg \to AA)}{dQ}\right|_{Q=1200\ \text{GeV}} = 0.00000280(2)^{+9.7\%}_{-12.0\%}\ \text{fb/GeV}$$

- interpolation:

$$\sigma(gg \to AA) = 1.643(1)^{+17.4\%}_{-14.4\%}\ \text{fb}$$

(iv) factorization/renormalization scale uncertainties

- 7-point variation

$$13\ \text{TeV}: \quad \sigma(gg \to hH) = 1.592(1)^{+15.2\%}_{-13.4\%}\ \text{fb}$$

$$14\ \text{TeV}: \quad \sigma(gg \to hH) = 1.876(1)^{+14.9\%}_{-13.2\%}\ \text{fb}$$

$$27\ \text{TeV}: \quad \sigma(gg \to hH) = 7.036(4)^{+13.1\%}_{-11.4\%}\ \text{fb}$$

$$100\ \text{TeV}: \quad \sigma(gg \to hH) = 60.49(4)^{+12.4\%}_{-10.9\%}\ \text{fb}$$

$$13\ \text{TeV}: \quad \sigma(gg \to AA) = 1.643(1)^{+17.4\%}_{-14.4\%}\ \text{fb}$$

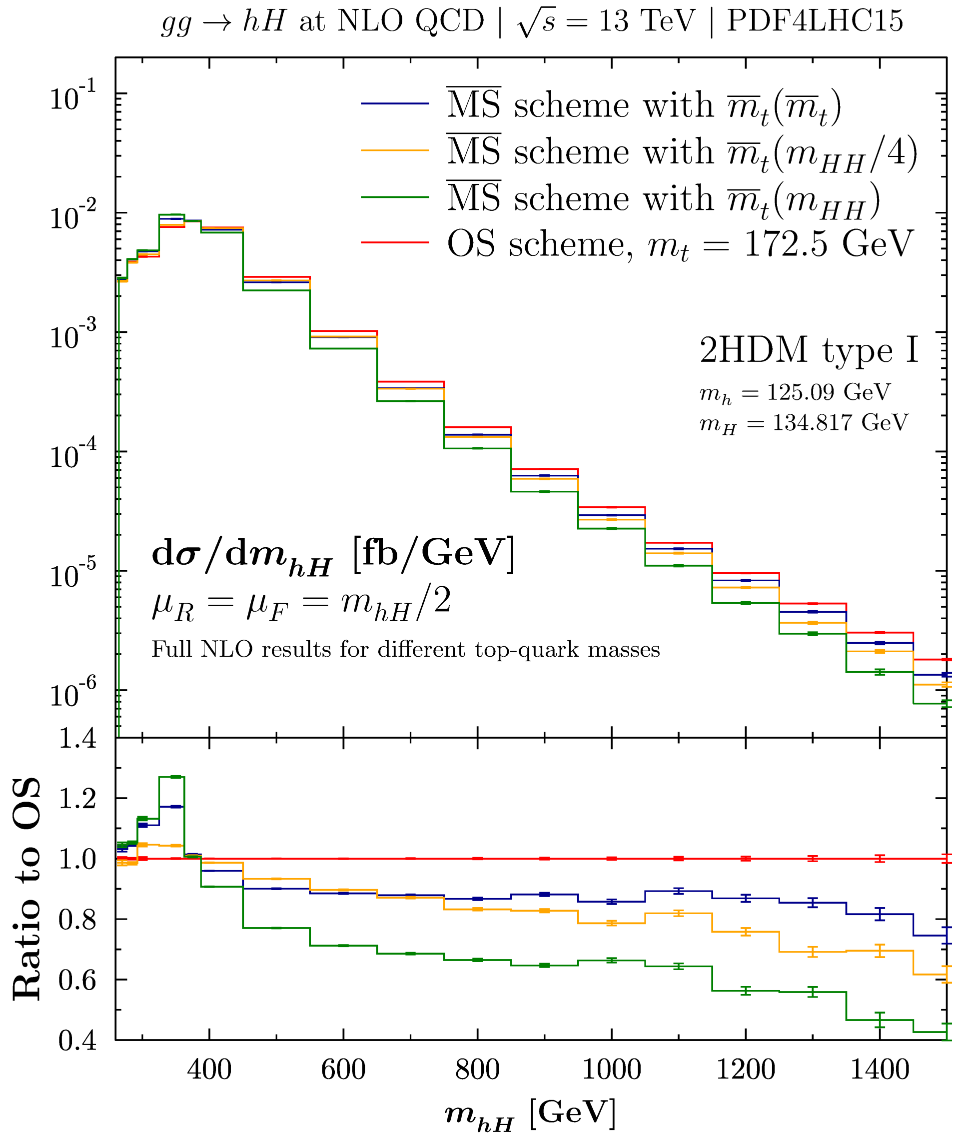
$$14\ \text{TeV}: \quad \sigma(gg \to AA) = 1.927(1)^{+17.1\%}_{-14.2\%}\ \text{fb}$$

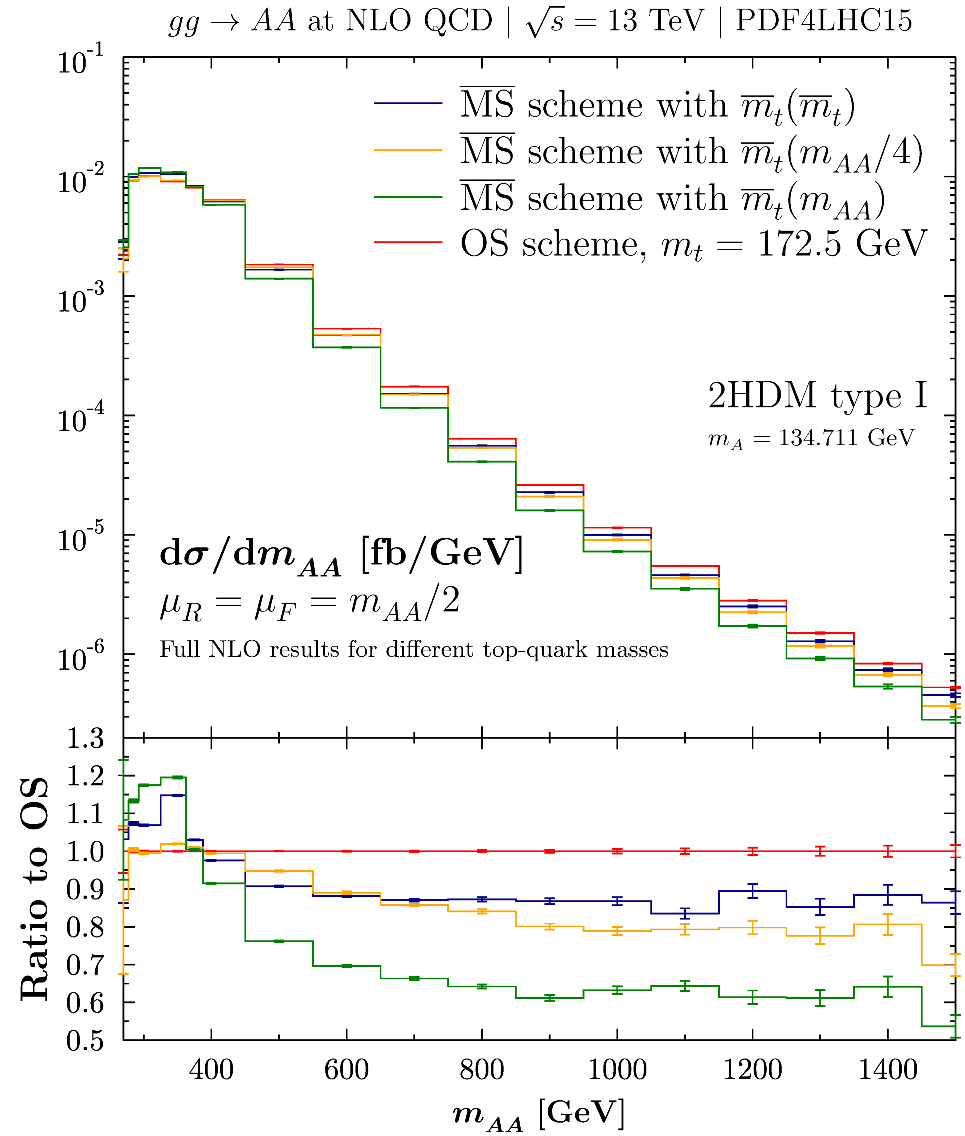
$$27\ \text{TeV}: \quad \sigma(gg \to AA) = 7.012(4)^{+15.3\%}_{-12.7\%}\ \text{fb}$$

$$100\ \text{TeV}: \quad \sigma(gg \to AA) = 58.12(3)^{+15.2\%}_{-12.6\%}\ \text{fb}$$

(v) uncertainties due to m_t

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





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

(v) uncertainties due to m_t

- transform $m_t \to \overline{m}_t(\mu)$ ($\overline{\mathrm{MS}}$) $\to$ modification of mass CT
- use m_t, $\overline{m}_t(\overline{m}_t)$ and scan $Q/4 < \mu < Q$ $\to$ uncertainty = envelope:

$$\left.\frac{d\sigma(gg \to hH)}{dQ}\right|_{Q=300\ \mathrm{GeV}} = 0.004278(2)^{+13\%}_{-0\%}\ \mathrm{fb/GeV},$$

$$\left.\frac{d\sigma(gg \to hH)}{dQ}\right|_{Q=400\ \mathrm{GeV}} = 0.007522(5)^{+0\%}_{-9\%}\ \mathrm{fb/GeV},$$

$$\left.\frac{d\sigma(gg \to hH)}{dQ}\right|_{Q=600\ \mathrm{GeV}} = 0.0010217(9)^{+0\%}_{-29\%}\ \mathrm{fb/GeV},$$

$$\left.\frac{d\sigma(gg \to hH)}{dQ}\right|_{Q=1200\ \mathrm{GeV}} = 0.00000956(6)^{+0\%}_{-44\%}\ \mathrm{fb/GeV}$$

- interpolation:

$$\sigma(gg \to hH) = 1.592(1)^{+6\%}_{-11\%}\ \mathrm{fb}$$

(v) 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:

$$\left.\frac{d\sigma(gg \to AA)}{dQ}\right|_{Q=300\text{ GeV}} = 0.01005(2)^{+17\%}_{-1\%}\ \text{fb/GeV},$$

$$\left.\frac{d\sigma(gg \to AA)}{dQ}\right|_{Q=400\text{ GeV}} = 0.006346(6)^{+0\%}_{-9\%}\ \text{fb/GeV},$$

$$\left.\frac{d\sigma(gg \to AA)}{dQ}\right|_{Q=600\text{ GeV}} = 0.0005328(7)^{+0\%}_{-30\%}\ \text{fb/GeV},$$

$$\left.\frac{d\sigma(gg \to AA)}{dQ}\right|_{Q=1200\text{ GeV}} = 0.00000280(2)^{+0\%}_{-37\%}\ \text{fb/GeV}$$

- interpolation:

$$\sigma(gg \to AA) = 1.643(1)^{+9\%}_{-7\%}\ \text{fb}$$

(v) uncertainties due to m_t

$$13 \text{ TeV}: \quad \sigma(gg \to hH) = 1.592(1)^{+6\%}_{-11\%} \text{ fb}$$

$$14 \text{ TeV}: \quad \sigma(gg \to hH) = 1.876(1)^{+6\%}_{-11\%} \text{ fb}$$

$$27 \text{ TeV}: \quad \sigma(gg \to hH) = 7.036(4)^{+5\%}_{-12\%} \text{ fb}$$

$$100 \text{ TeV}: \quad \sigma(gg \to hH) = 60.49(4)^{+4\%}_{-14\%} \text{ fb}$$

$$13 \text{ TeV}: \quad \sigma(gg \to AA) = 1.643(1)^{+9\%}_{-7\%} \text{ fb}$$

$$14 \text{ TeV}: \quad \sigma(gg \to AA) = 1.927(1)^{+9\%}_{-8\%} \text{ fb}$$

$$27 \text{ TeV}: \quad \sigma(gg \to AA) = 7.012(4)^{+8\%}_{-8\%} \text{ fb}$$

$$100 \text{ TeV}: \quad \sigma(gg \to AA) = 58.12(3)^{+7\%}_{-9\%} \text{ fb}$$

(vi) combined uncertainties

$$13\ \text{TeV}: \quad \sigma(gg \to hH) = 1.592(1)^{+21\%}_{-24\%}\ \text{fb}$$
$$14\ \text{TeV}: \quad \sigma(gg \to hH) = 1.876(1)^{+21\%}_{-24\%}\ \text{fb}$$
$$27\ \text{TeV}: \quad \sigma(gg \to hH) = 7.036(4)^{+18\%}_{-23\%}\ \text{fb}$$
$$100\ \text{TeV}: \quad \sigma(gg \to hH) = 60.49(4)^{+16\%}_{-25\%}\ \text{fb}$$

$$13\ \text{TeV}: \quad \sigma(gg \to AA) = 1.643(1)^{+26\%}_{-21\%}\ \text{fb}$$
$$14\ \text{TeV}: \quad \sigma(gg \to AA) = 1.927(1)^{+26\%}_{-22\%}\ \text{fb}$$
$$27\ \text{TeV}: \quad \sigma(gg \to AA) = 7.012(4)^{+23\%}_{-21\%}\ \text{fb}$$
$$100\ \text{TeV}: \quad \sigma(gg \to AA) = 58.12(3)^{+22\%}_{-22\%}\ \text{fb}$$

III *CONCLUSIONS*

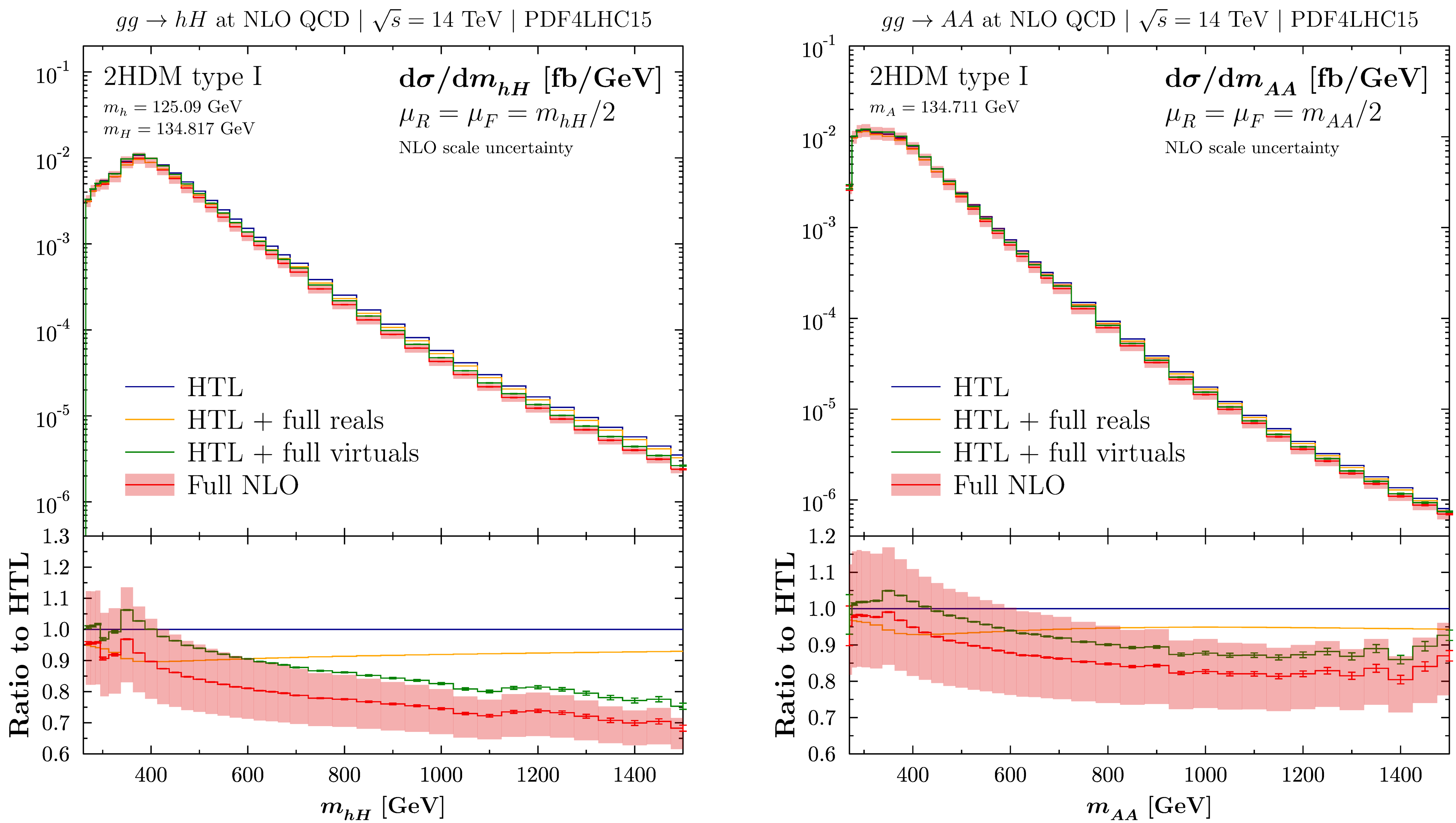
- Higgs pair production at full NLO for variable top/Higgs masses [SM, 2HDM: top loops]

- top mass effects on top of LO up to 20–30%

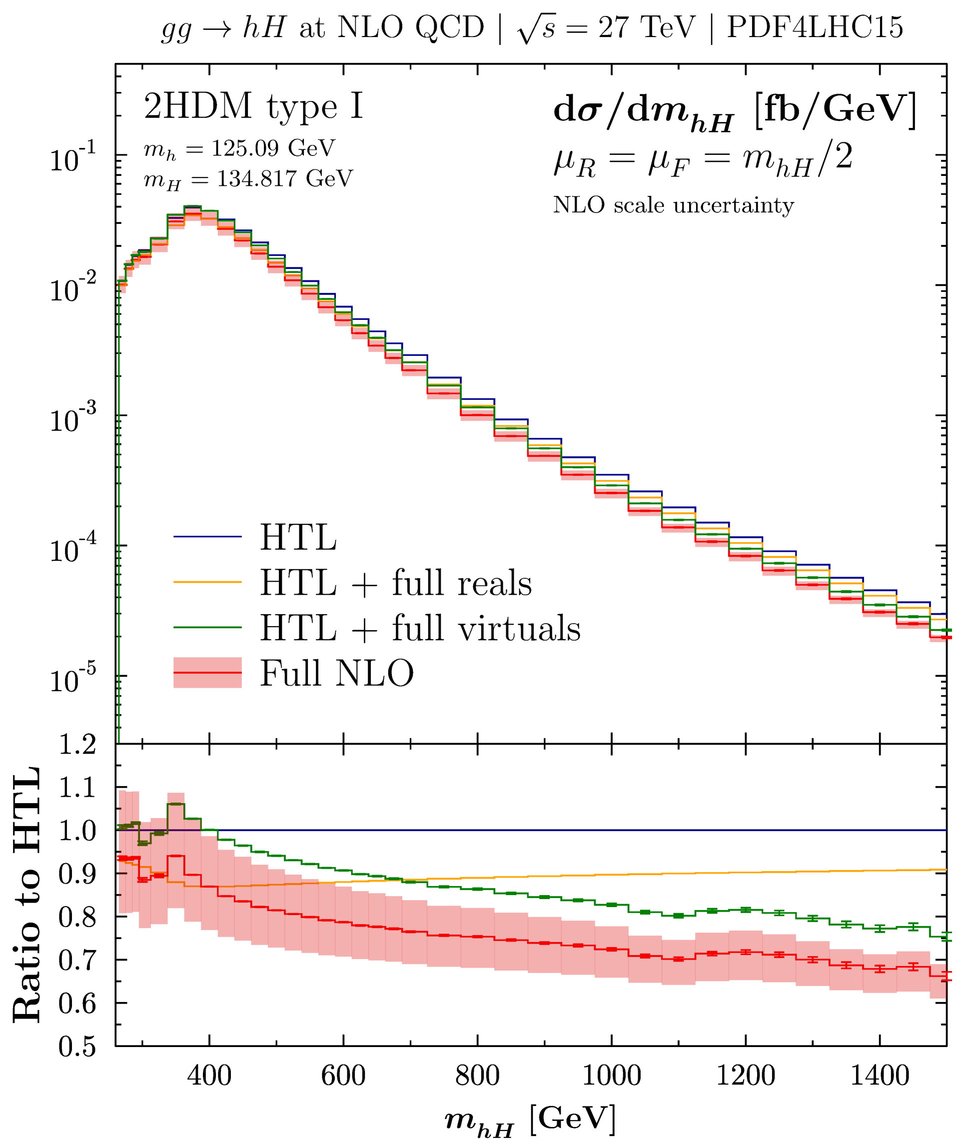
- factorization/renormalization scale uncertainties $\sim$ 15%

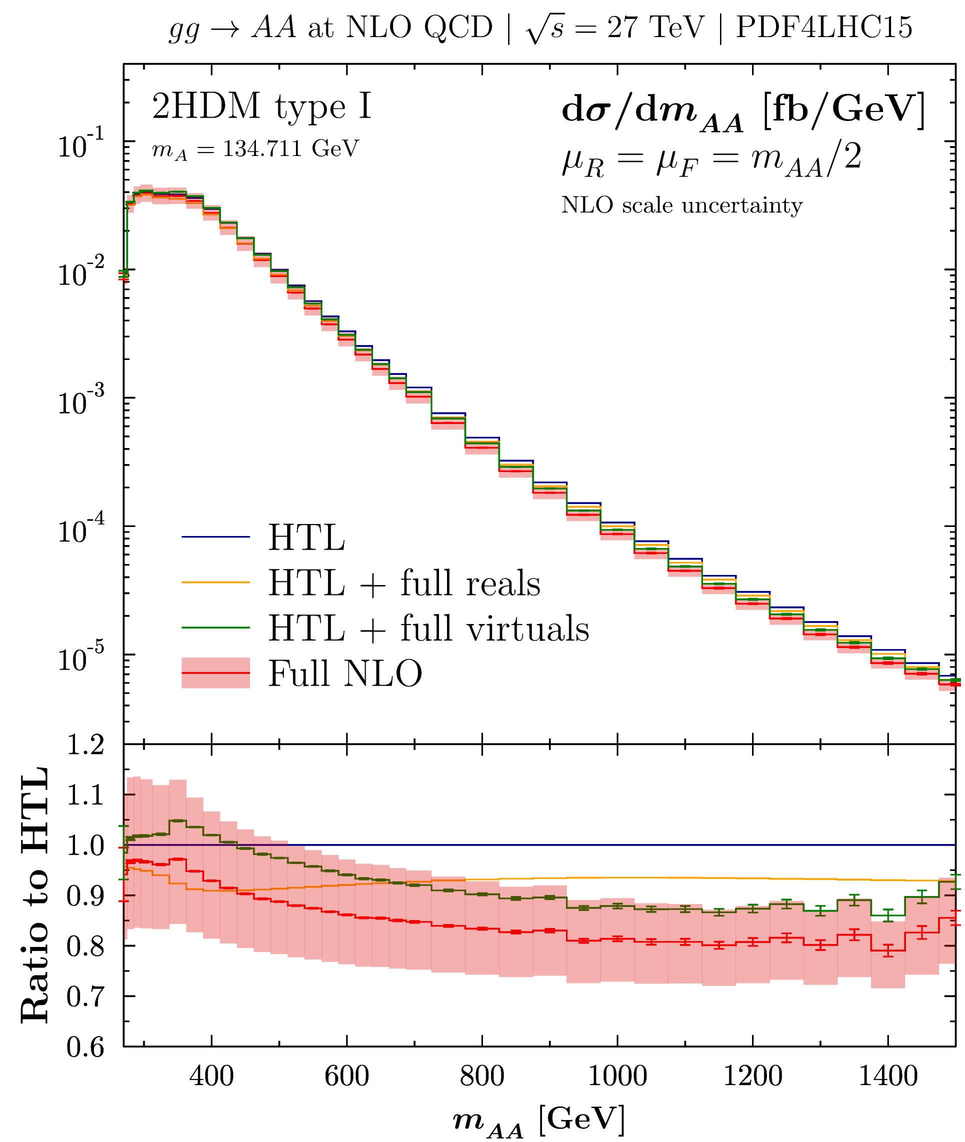
- uncertainties due to scale/scheme choice of m_t sizeable $\lesssim$ 40%

BACKUP SLIDES

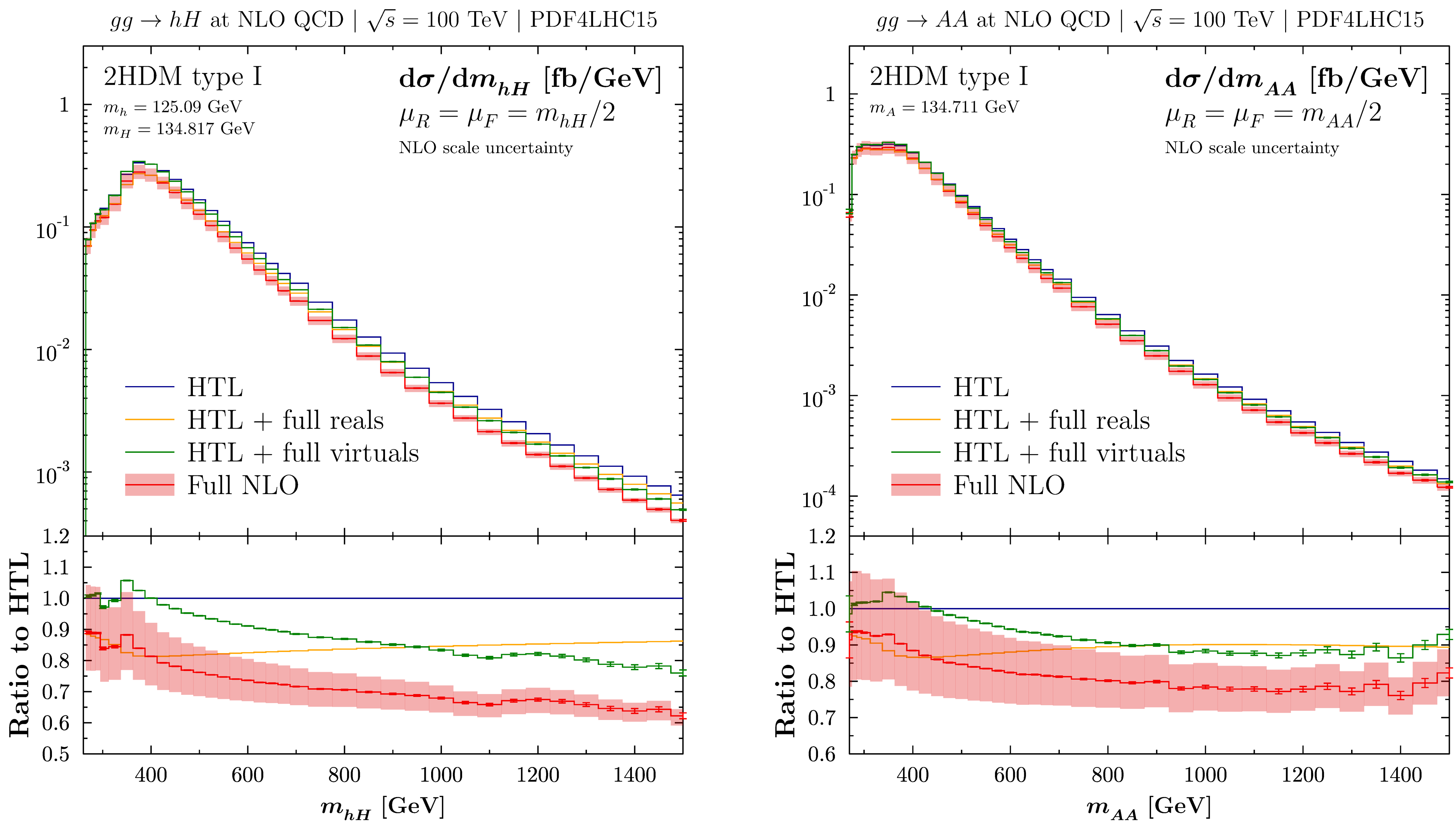


Baglio, Campanario, Glaus, Mühlleitner, Ronca, S.





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



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

Box 45

$$\Delta F_i = \frac{\alpha_s}{\pi}\,\Gamma(1+\epsilon)\frac{\Gamma(1-\epsilon)}{\Gamma(1-2\epsilon)}\left(\frac{4\pi\mu_0^2}{m_t^2}\right)^{2\epsilon}\sum_{j=1}^{6} S_j$$

$$S_1 = \int_0^1 d^6x\; xr\left\{\frac{H_i(\vec{x})}{N^3(\vec{x})}\left[1+\epsilon L+\epsilon^2\left(\frac{L^2}{2}+3\zeta_2\right)\right]\right.$$
$$\left. - \frac{H_i(\vec{x})|_{r=0}}{(c+br)^3}\left[1+\epsilon L_0+\epsilon^2\left(\frac{L_0^2}{2}+3\zeta_2\right)\right]\right\}$$

$$S_2 = -\int_0^1 d^6x\; x\frac{H_i(\vec{x})|_{r=0}}{(b+cr)^3}\left\{1+\epsilon L_1+\epsilon^2\left(\frac{L_1^2}{2}+3\zeta_2\right)+\epsilon^3\left(\frac{L_1^3}{6}+3\zeta_2 L_1\right)\right\}$$

$$S_3 = -\int_0^1 \frac{d^5x}{2\rho_s(1-x)(1-s)t}\left\{\frac{H_i(\vec{x})|_{r=0}}{b^2}\left[1-\epsilon(L_2+2)+\epsilon^2\left(\frac{L_2^2}{2}+2L_2+2\zeta_2+4\right)\right]\right.$$
$$+\frac{H_i(\vec{x})|_{r,t=0,s=1}}{b_0^2}\left[1-\epsilon(L_3+2)+\epsilon^2\left(\frac{L_3^2}{2}+2L_3+2\zeta_2+4\right)\right]$$
$$-\frac{H_i(\vec{x})|_{r=0,s=1}}{b_1^2}\left[1-\epsilon(L_4+2)+\epsilon^2\left(\frac{L_4^2}{2}+2L_4+2\zeta_2+4\right)\right]$$
$$\left.-\frac{H_i(\vec{x})|_{r,t=0}}{b_2^2}\left[1-\epsilon(L_5+2)+\epsilon^2\left(\frac{L_5^2}{2}+2L_5+2\zeta_2+4\right)\right]\right\}$$

$$S_4 = -\int_0^1 \frac{dx\,dy\,dz\,ds}{2\rho_s(1-x)(1-s)}\left\{\frac{H_i(\vec{x})|_{r,t=0}}{b_2^2}\left[-\frac{1}{\epsilon}+L_6+2-\epsilon\left(\frac{L_6^2}{2}+2L_6+2\zeta_2+4\right)\right.\right.$$
$$\left.+\epsilon^2\left(\frac{L_6^3}{6}+L_6^2+2(\zeta_2+2)L_6-2\zeta_3+4\zeta_2+8\right)\right]$$
$$-\frac{H_i(\vec{x})|_{r,t=0,s=1}}{b_0^2}\left[-\frac{1}{\epsilon}+L_7+2-\epsilon\left(\frac{L_7^2}{2}+2L_7+2\zeta_2+4\right)\right.$$
$$\left.\left.+\epsilon^2\left(\frac{L_7^3}{6}+L_7^2+2(\zeta_2+2)L_7-2\zeta_3+4\zeta_2+8\right)\right]\right\}$$

$$
\begin{aligned}
S_5 \;=\; & -\int_0^1 \frac{dx\,dy\,dz\,dt}{2\rho_s(1-x)t}\left\{\frac{H_i(\vec{x})|_{r=0,s=1}}{b_1^2}\left[-\frac{1}{\epsilon}+L_8+2-\epsilon\left(\frac{L_8^2}{2}+2L_8+\zeta_2+4\right)\right.\right.\\
& \left.+\epsilon^2\left(\frac{L_8^3}{6}+L_8^2+(\zeta_2+4)L_8+2\zeta_2+8\right)\right]\\
& -\frac{H_i(\vec{x})|_{r,t=0,s=1}}{b_0^2}\left[-\frac{1}{\epsilon}+L_9+2-\epsilon\left(\frac{L_9^2}{2}+2L_9+\zeta_2+4\right)\right.\\
& \left.\left.+\epsilon^2\left(\frac{L_9^3}{6}+L_9^2+(\zeta_2+4)L_9+2\zeta_2+8\right)\right]\right\}\\
S_6 \;=\; & -\int_0^1 dx\,dy\,dz\;\frac{H_i(\vec{x})|_{r,t=0,s=1}}{2\rho_s(1-x)b_0^2}\left\{\frac{1}{\epsilon^2}-\frac{1}{\epsilon}(L_{10}+2)+\frac{L_{10}^2}{2}+2L_{10}+\zeta_2+4\right.\\
& \left.-\epsilon\left(\frac{L_{10}^3}{6}+L_{10}^2+(\zeta_2+4)L_{10}+2\zeta_2+8\right)\right\}
\end{aligned}
$$

$$
L = \log\left(\frac{x(1-x)r}{s}\right)-2\log N \qquad L_0=\log\left(\frac{x(1-x)r}{s}\right)-2\log(c+br)
$$

$$
L_1 = \log\left(\frac{x(1-x)r}{s}\right)-2\log(b+cr) \qquad L_2=\log\left[-\rho_s s(1-s)t\right]+\log b
$$

$$
L_3 = \log\left[-\rho_s s(1-s)t\right]+\log b_0 \qquad L_4=\log\left[-\rho_s s(1-s)t\right]+\log b_1
$$

$$
L_5 = \log\left[-\rho_s s(1-s)t\right]+\log b_2 \qquad L_6=\log\left[-\rho_s s(1-s)\right]+\log b_2
$$

$$
L_7 = \log\left[-\rho_s s(1-s)\right]+\log b_0 \qquad L_8=\log\left(-\rho_s t\right)+\log b_1
$$

$$
L_9 = \log\left(-\rho_s t\right)+\log b_0\,, \qquad L_{10}=\log\left(-\rho_s\right)+\log b_0
$$

$$
b_0 = b|_{t=0,s=1} \qquad b_1=b|_{s=1} \qquad b_2=b|_{t=0}
$$

(v) 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:

$$\sigma(gg \to H)\Big|_{M_H=125\text{ GeV}} = 42.17^{+0.4\%}_{-0.5\%}\text{ pb}$$

$$\sigma(gg \to H)\Big|_{M_H=300\text{ GeV}} = 9.85^{+7.5\%}_{-0.3\%}\text{ pb}$$

$$\sigma(gg \to H)\Big|_{M_H=400\text{ GeV}} = 9.43^{+0.1\%}_{-0.9\%}\text{ pb}$$

$$\sigma(gg \to H)\Big|_{M_H=600\text{ GeV}} = 1.97^{+0.0\%}_{-15.9\%}\text{ pb}$$

$$\sigma(gg \to H)\Big|_{M_H=900\text{ GeV}} = 0.230^{+0.0\%}_{-22.3\%}\text{ pb}$$

$$\sigma(gg \to H)\Big|_{M_H=1200\text{ GeV}} = 0.0402^{+0.0\%}_{-26.0\%}\text{ pb}$$

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

$$\overline{m}_t(M_t) = \frac{M_t}{1 + \frac{4}{3}\frac{\alpha_s(M_t)}{\pi} + 10.9\left(\frac{\alpha_s(M_t)}{\pi}\right)^2}$$

$$\overline{m}_t\,(\mu) \;=\; \overline{m}_t\,(M_t)\,\frac{c\,[\alpha_s\,(\mu)/\pi]}{c\,[\alpha_s\,(M_t)/\pi]}$$

$$c(x) = \left(\frac{7}{2}\,x\right)^{\frac{4}{7}}\;[1 + 1.398x + 1.793\,x^2 - 0.6834\,x^3]$$

$$M_t \;=\; 172.5 \text{ GeV}$$

$$\overline{m}_t(\overline{m}_t) \;=\; 163.0 \text{ GeV}$$

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