NLO electroweak corrections to SM Higgs production $gg \to H$ and decay $H \to \gamma\gamma$

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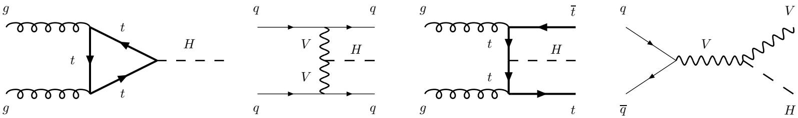
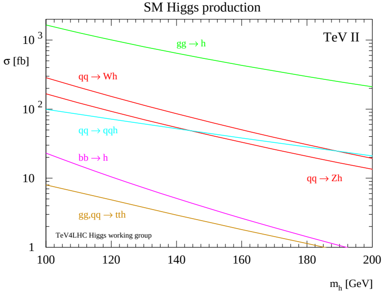
Outline

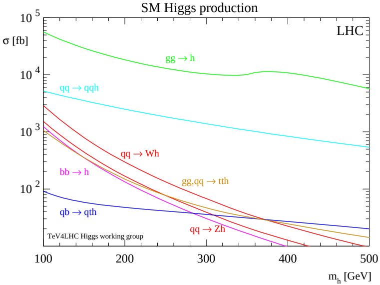
1. Corrections to $gg \longrightarrow H$
2. Method for NLO EW
3. Threshold behaviour
4. Results
5. Conclusions

Hadronic SM Higgs production

Main production channel for the Standard Model Higgs in hadron collisions







Hahn,Heinemeyer,Maltoni,Weiglein,Willenbrock [hep-ph/0607308]

Gluon-fusion production channel does not lead to the cleanest signal, but it has by far the largest cross section both at the TEVATRON and the LHC

LO production cross section through gluon fusion

- LO cross section for $gg \to H$ by interfering quark 1-loop diagrams

$$\sigma_{\mathrm{LO}} = \frac{G_F \alpha_S{}^2(\mu_R^2)}{288\sqrt{2}\pi} \left| \frac{3}{2} \sum_q \frac{1}{\tau_q} \left[1 + \left(1 - \frac{1}{\tau_q} \right) f(\tau_q) \right] \right|^2 \qquad \tau_q = M_H^2/(4M_q^2)$$

$f = \text{arcsin}, \ln$ Georgi, Glashow, Machacek, Nanopoulos'78

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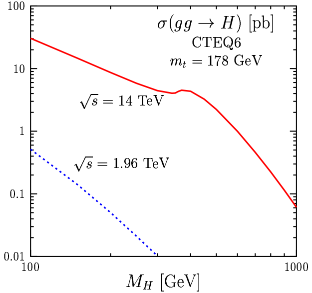

$\Leftarrow$ Djouadi [hep-ph/0503172]

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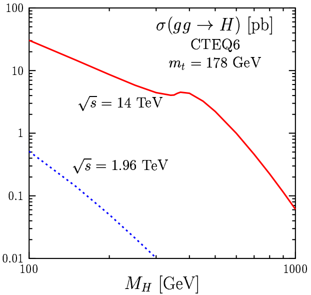

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- both setting $\mu_R = \mu_F = M_H$
- LO $\to$ strong dependence on $\mu_{R,F}$
- QCD corrections for reliability

QCD corrections (I)

QCD corrections to the total cross section very well under control

- NLO at the LHC $+80\%$ LO, uncertainty $\mu_{R,F}$ variation $\pm 20\%$

Dawson'91,Djouadi,Spira,Zerwas'91

↖ large M_t limit

Spira,Djouadi,Graudenz,Zerwas'95,Harlander,Kant'05,Anastasiou, Beerli,Bucherer,Daleo,Kunszt'06,Aglietti,Bonciani,Degrassi,Vicini'06

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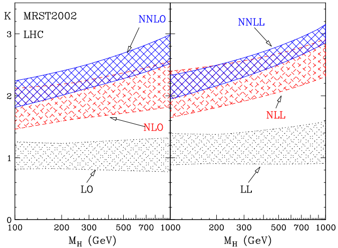
- Total cross section dominated by long-wavelength gluon effects, insensitive to the reduction to an effective vertex

$\Rightarrow \sigma_{\text{NNLO}} \simeq \sigma_{\text{LO}} \times K_{\text{EFT}}$ NLO 90% result up to $M_H \simeq 1$ TeV

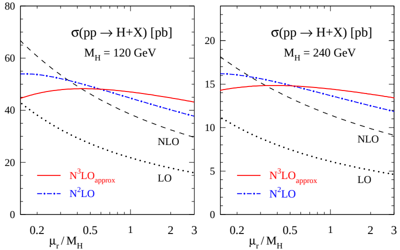
Krämer,Laenen,Spira'96

QCD corrections (II)

QCD corrections improved beyond FO and for exclusive quantities



Catani,de Florian,Grazzini,Nason [hep-ph/0306211] NNLL = +6% NNLO



Moch,Vogt [hep-ph/0508265] N^3LO soft limit $\Rightarrow$ stabilized μ_R

- effect of a jet veto on total CS Catani,de Florian,Grazzini'01
- differential cross section evaluated at NNLO in QCD Anastasiou,Melnikov,Petriello'04,Catani,Grazzini'07
- . . .

EW corrections (I)

NLO EW corrections for matching the precision of QCD predictions

- "Dominant" contributions enhanced by M_t^2 Djouadi,Gambino'94

$$\sigma_{LO} \times [1 + G_F \sqrt{2}/(16\pi^2)\, M_t^2] \qquad 0.4\,\% \text{ accidental}$$

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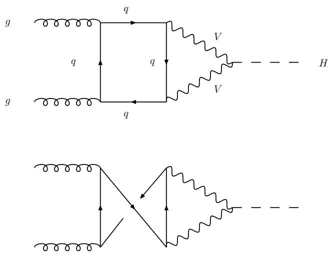
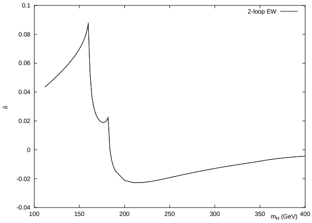
- Light-quark analytically Aglietti,Bonciani,Degrassi,Vicini'04



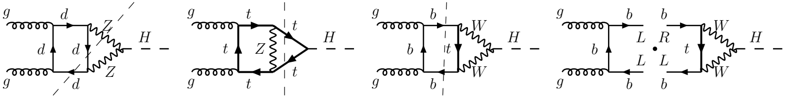


Aglietti,Bonciani,Degrassi,Vicini [hep-ph/0404071]

EW corrections (II)

Top diagrams by a Taylor expansion in q_H Degrassi,Maltoni'04

- for $M_H < 2\,M_W \Rightarrow$ check the cuts of each Feynman diagram
- Im: $M_H = 2M_W \Rightarrow$ Taylor expansion in $q_H^2/(4M_W^2)$ allowed



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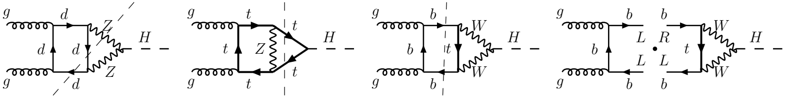

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$*$ Cut vanishes because helicites on two sides cannot match

$\Rightarrow$ "naive" Taylor expansion allowed for top-quark diagrams

EW corrections (III)

Summary of EW corrections to $gg \to H$ at NLO below WW threshold

M_H	1 LQ	3rd gen		$\delta_{ew}(\%)$
115	-5.28	-0.78	- 0.22	4.7
120	-5.62	-0.82	- 0.06	4.9
125	-5.98	-0.87	+ 0.12	5.1
130	-6.36	-0.93	+ 0.33	5.4
135	-6.76	-0.98	+ 0.58	5.6
140	-7.20	-1.04	+ 0.88	5.8
145	-7.69	-1.10	+ 1.26	6.1
150	-8.26	-1.16	+ 1.78	6.4
155	-9.01	-1.23	+ 2.68	6.6
160	-10.4	-1.30	+ 3.43	7.5

Amplitude in units $\alpha/(4\pi \sin^2\theta)$

Aglietti,Bonciani,Degrassi,Vicini’04

Degrassi,Maltoni’04 (Taylor expansion)

$\sigma_{ew} = \sigma_0(1 + \delta_{ew}) \Rightarrow +5\%/+8\%$

$\Leftarrow$ Degrassi,Maltoni [hep-ph/0407249]

NLO EW corrections match the uncertainty related to HO QCD corrections, estimated to be 5% at the LHC Moch,Vogt’05

Missing NLO EW corrections

EW corrections less known respect to QCD ones (each subset of them evaluated by one group only) and not completely under control

- Light-fermion terms known for all values of M_H, top-quark part computed only for $M_H < 2\,M_W \Rightarrow$ extend the result above $2M_W$

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- Top-quark terms evaluated only through Taylor expansion (BFM) $\Rightarrow$ control reliability of the result close to the WW threshold
- Threshold singularities show up at the amplitude level

$$\mathcal{A}^{\text{top}}_{\text{NLO}}(gg \to H) = \underbrace{\mathcal{A}_{1\text{PR}}}_{\text{exactly}} + \underbrace{\mathcal{A}_{1\text{PI}}}_{\text{expansion}} \qquad \mathcal{A}_{1\text{PR}} = \ldots + \underbrace{\frac{f(4M_W^2/M_H^2)}{\sqrt{4M_W^2 - M_H^2}}}_{M_H = 2M_W \to \infty} + \ldots$$

∗ Minimal solution by Degrassi,Maltoni'04: $M_W^2 \Rightarrow M_W^2 - i\Gamma_W M_W$ only in the singular terms only to cure the divergent behaviour

What does it happen if complex poles instead of real masses are used everywhere?

Outline of the computation

Computation of the complete NLO EW corrections through six steps implemented in in-house FORM and FORTRAN codes

1. Generate all Feynman diagrams contributing to $gg \to H$
2. Projection of $\mathcal{A}$ on form factors F_i (Ward identity $\Rightarrow$ 1 form factor)
3. Reduce F_i to basis integrals M_j by standard algebraic methods
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$$\Rightarrow \boxed{M_j = \underbrace{c_j \ln(m_f^2/s)}_{\text{analytically}} + M_j^{\mathrm{reg}} \Rightarrow \underbrace{\sum c_j \ln(m_f^2/s) = 0}_{\text{amplitude}} \Rightarrow m_f = 0}$$

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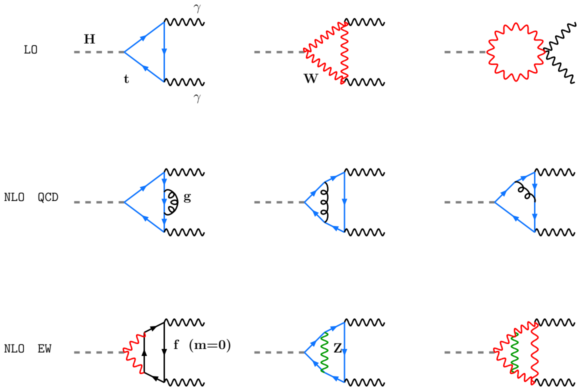
$\ast$ No details about numerical part; focus on the threshold behaviour

$\ast$ Treat simultaneously $gg \to H$ and $H \to \gamma\gamma$ (couplings, YM fields)

NLO EW diagrams

Representative diagrams for the processes $H \to \gamma\gamma$ and $gg \to H$



- Light fermions (topologies not present at LO); also for $gg \to H$
- Top-quark QCD-like configurations, present also for $gg \to H$
- Pure Yang-Mills diagrams; specific only of the $H \to \gamma\gamma$ decay

Projection of the amplitude

Project the amplitude for simplifying the calculation (ex. $H \to \gamma\gamma$)

- $\mathcal{A} = \mathcal{Z}_A^{-1} \mathcal{Z}_H^{-1/2} e_1^{\mu} e_2^{\nu} \mathcal{A}_{\mu\nu}$ $\mathcal{A}_{\mu\nu} \to$ Green's function $\mathcal{Z}_K \to$ WFR factors
- $\mathcal{A}_{\mu\nu} = F_D \, \delta_{\mu\nu} + \sum F_P^{ij} \, p_{i\mu} \, p_{j\nu} + F_\epsilon \, \epsilon_{\mu\nu\alpha\beta} \, p_1^{\alpha} \, p_2^{\beta}$ tensor decomposition

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Preliminary simplifications observing that:

1) $e_i^\mu \, p_{i\mu} = 0$ $\Rightarrow$ $F_P^{11}, F_P^{12}, F_P^{22}$ do not contribute to $\mathcal{A}$

2) SM H CP even $\Rightarrow$ F_ϵ vanishes in the full $\mathcal{A}$ (not each diag.)

3) WI $p_1^\mu \mathcal{A}_{\mu\nu} p_2^\nu = 0$ $\Rightarrow$ $F_D + p_1 \cdot p_2 F_P^{21} = 0$ (not linearly indep.)

Projection operators for extracting the two form factors from $\mathcal{A}_{\mu\nu}$

$$\Rightarrow \quad F_D = \frac{1}{n-2} \left(\delta^{\mu\nu} - \frac{p_1^\mu p_2^\nu + p_2^\mu p_1^\nu}{p_1 \cdot p_2} \right) \mathcal{A}_{\mu\nu} \,, \qquad F_P^{21} = \frac{1}{(2-n) p_1 \cdot p_2} \left[\delta^{\mu\nu} - \frac{(n-1) p_1^\mu p_2^\nu + p_2^\mu p_1^\nu}{p_1 \cdot p_2} \right] \mathcal{A}_{\mu\nu}$$

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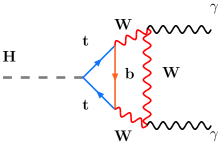

- prescription for γ_5 in DR
- $F_\epsilon = 0$ in $\mathcal{A}$
- use completely AC γ_5

Reduction to basis integrals

After projection, no free Lorentz indices $\Rightarrow$ standard algebr. reduction

- Trivial reduction of scalar products in numerators with propagators

$$\frac{2q\cdot p}{(q^2+m^2)[(q+p)^2+M^2]} = \frac{1}{q^2+m^2} - \frac{1}{(q+p)^2+M^2} - \frac{p^2-m^2+M^2}{(q^2+m^2)[(q+p)^2+M^2]}$$

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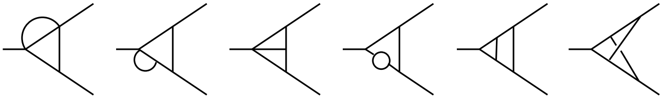

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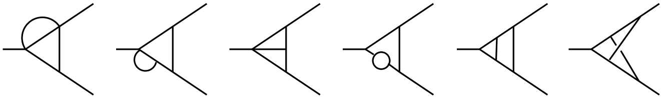

- IBPIs [Chetyrkin, Tkachov'81] for tadpole integrals (no ext. scales)

One-loop renormalization

Renormalization at one loop, no tree-level $H\gamma\gamma$ and Hgg couplings

- $p_B = \left(1 + \frac{g_R^2}{16\pi^2}\delta Z_p\right) p_R$ $\delta Z_p \Rightarrow \overline{\mathrm{MS}}^{1\mathrm{L}}$ $1/\epsilon, \gamma_E$, no fin. parts

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- WFRs $\neq 1 \quad \Rightarrow \quad \mathcal{Z}_H = 1 - \frac{g_R^2}{16\pi^2} \underbrace{\mathrm{Re}\Sigma_H^{(1)\prime}(M_H^2)}_{\text{derivative}}$

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- $p_R \neq p_{EXP}$ $\quad \Rightarrow \quad m_W^2 = M_W^2 \left[1 + \underbrace{\frac{G_F M_W^2}{2\sqrt{2}\,\pi^2}\,\mathrm{Re}\Sigma_W^{(1)}(M_W^2)}_{\text{finite shift}}\right]$

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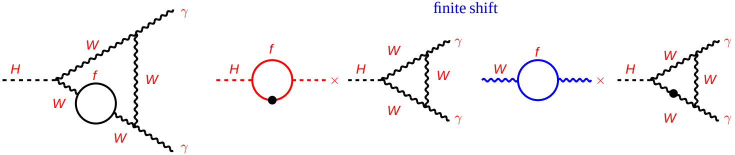
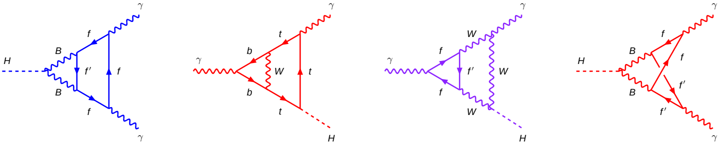
- $p_B = \left(1 + \frac{g_R^2}{16\pi^2}\delta Z_p\right) p_R \qquad \delta Z_p \Rightarrow \overline{\mathrm{MS}}^{\mathrm{1L}} \qquad 1/\epsilon, \gamma_E$, no fin. parts
- WFRs $\neq 1 \quad \Rightarrow \quad \mathcal{Z}_H = 1 - \frac{g_R^2}{16\pi^2} \underbrace{\mathrm{Re}\Sigma_H^{(1)\prime}(M_H^2)}_{\text{derivative}}$
- $p_R \neq p_{EXP} \quad \Rightarrow \quad m_W^2 = M_W^2 \left[1 + \underbrace{\frac{G_F M_W^2}{2\sqrt{2}\,\pi^2}\mathrm{Re}\Sigma_W^{(1)}(M_W^2)}_{\text{finite shift}}\right]$



$\Rightarrow$ trivial but important for the analysis of the threshold behaviour

Extraction of collinear logarithms

Before evaluating the $\mathcal{A}$ numerically, control cancellation of mass divs.



- Configurations with 2 massless quanta with same LF current cancel algebraically after reduction ⊗ symmetrization

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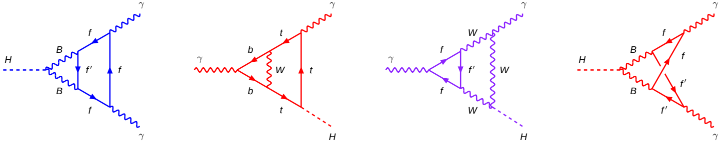
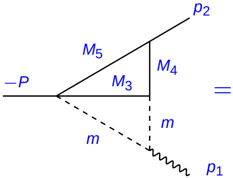
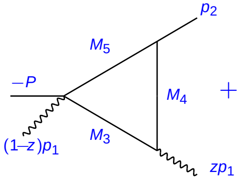


- Configurations with 2 massless quanta with same LF current cancel algebraically after reduction $\otimes$ symmetrization
- All two-loop collinear-divergent configurations can be represented as integrals over Feynman parameters of one-loop functions



$$= \ln \frac{m^2}{s} \int_0^1 dz$$

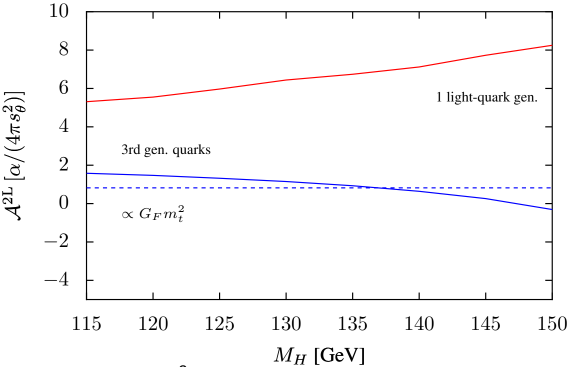


$$+ \text{finite part}$$

Check algebraically that $\ln m^2/s \to 0$ in $\mathcal{A}$ $\to$ evaluate num. rest for $m = 0$

EW corrections to $gg \to H$ below 150 GeV

Anatomy of EW corrections to $gg \to H$ for $115\text{ GeV} < M_H < 150\text{ GeV}$



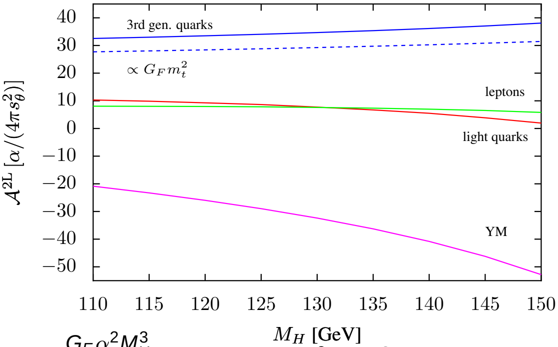
M_H[Gev]	δ^{EW} [%]
115	+4.73
120	+4.92
125	+5.12
130	+5.31
135	+5.49
140	+5.66
145	+5.80
150	+5.90

$$\sigma = \frac{G_F \alpha_S^2}{512\sqrt{2}\pi} |\mathcal{A}^{1L} + \mathcal{A}^{2L} + \dots|^2 = \sigma^{LO}\left(1 + \delta^{EW}\right) \qquad \mathcal{A}^{2L} = \mathcal{A}^{2L}_{lq} + \mathcal{A}^{2L}_{3gen}$$

- Agreement with light quarks Aglietti,Bonciani,Degrassi,Vicini'04 and corrected (1PR) 3rd gen. quarks Degrassi,Maltoni'04
- Light quarks dominate respect to $\propto G_F m_t^2$ Djouadi,Gambino'94

EW corrections to $H \to \gamma\gamma$ below 150 GeV

Anatomy of EW corrections to $\underline{H \to \gamma\gamma}$ for 110 GeV $< M_H <$ 150 GeV



M_H[Gev]	δ^{EW} [%]
120	−1.89
130	−1.21
140	−0.38
145	+0.12
150	+0.69

$$\Gamma = \frac{G_F \alpha^2 M_H^3}{128\sqrt{2}\pi^3} |\mathcal{A}^{1L} + \mathcal{A}^{2L} + \dots|^2 = \sigma^{LO}\left(1 + \delta^{EW}\right) \qquad \mathcal{A}^{2L} = \mathcal{A}^{2L}_{YM} + \mathcal{A}^{2L}_{lq} + \mathcal{A}^{2L}_{lep} + \mathcal{A}^{2L}_{3gen}$$

- Agreement with lep / LQ Aglietti,Bonciani,Degrassi,Vicini'04 and corrected (1PR) 3rd gen. quarks / YM Degrassi,Maltoni'05
- Contributions $\propto G_F m_t^2$ Liao,Li'96,Djouadi,Gambino,Kniehl'97 Fugel,Kniehl,Steinhauser'04 large but not dominant

Around the WW threshold: Ward identity

1st problem with the crossing of WW: violation of a Ward identity for $\underline{H \to \gamma\gamma}$

- WI $\to$ $p_1^{\mu} \mathcal{A}_{\mu\nu} p_2^{\nu} = 0$, but explicitly $\to$ $p_1^{\mu} \mathcal{A}_{\mu\nu} p_2^{\nu} \neq 0$ for $M_H > 2\,M_W$

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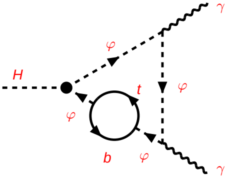
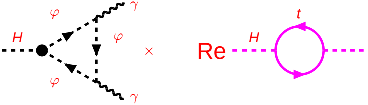
- At NLO there are two kinds of diagrams contributing to the Ward identity





$$\underbrace{m_H^2}_{\overline{\text{MS}}\text{ ren.}} = \underbrace{M_H^2}_{\text{on shell}}$$

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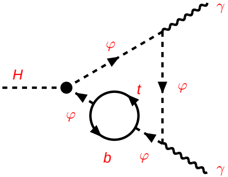

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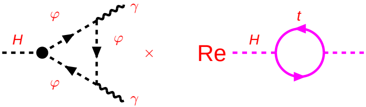

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- Below WW both classes of diagrams are real $\to$ the Ward identity holds
- Above WW mismatch imaginary parts (Re) $\to$ the Ward identity $\neq 0$

Around the VV thresholds: square-root divergencies

2nd problem with the crossing of both WW and ZZ: square-root divergencies

$H \to \gamma\gamma$ and $gg \to H$ ampls. $\Rightarrow$ terms proportional to $1/\beta_V$, $\beta_V = \sqrt{1 - 4\,M_V^2/M_H^2}$

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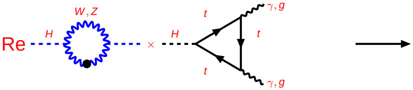

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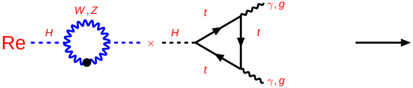

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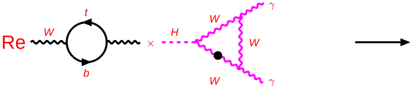
2) (W mass renormalization) $\otimes$ (derivatives 1-loop diagrams, $\gamma\gamma$)



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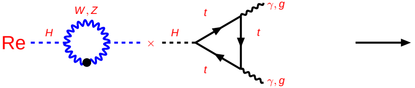

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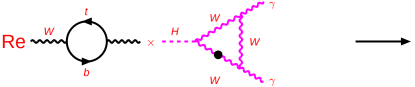
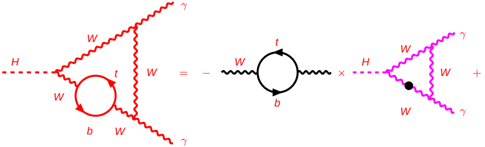


der. divergent for $M_H = 2M_W$

3) (irreducible 2-loop diagrams with a bubble insertion in an internal W line, $\gamma\gamma$)



fin. part for $M_H = 2M_W$

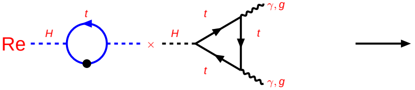
$\Rightarrow$ divergent part for $M_H = 2M_W$ can be represented as **1-loop $\otimes$ 1-loop**

Around the $t\bar{t}$ threshold: square-root divergencies?

No problem with the crossing of $t\bar{t}$: square-root divergencies 'protected'

$H \to \gamma\gamma$ and $gg \to H$ ampls. $\Rightarrow$ terms potentially $\propto 1/\beta_t$, but multiplied by β_t (spin)

1) (H WFR factor) $\otimes$ (1-loop diags., $\gamma\gamma, gg$)



H WF finite for $M_H = 2M_t$

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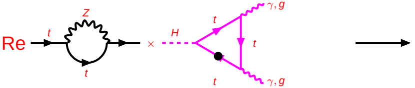

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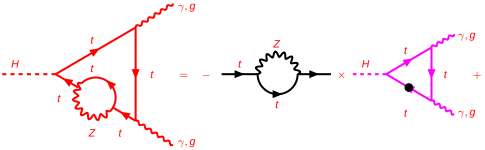

fin. part for $M_H = 2M_t$

$\Rightarrow$ would-be divergency for $M_H = 2M_t$ as 1-loop $\otimes$ 1-loop, finite as in class 2)

Logarithmic singularity at the WW threshold

3rd problem with the crossing of WW / $t\bar{t}$: logarithmic divergencies

$H \to \gamma\gamma$ and $gg \to H$ ampls. $\Rightarrow$ terms proportional to $\ln(-\beta_i^2 - i0)$, i=W,t

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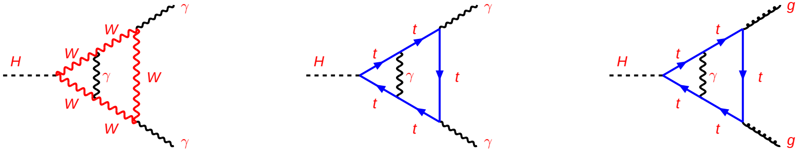

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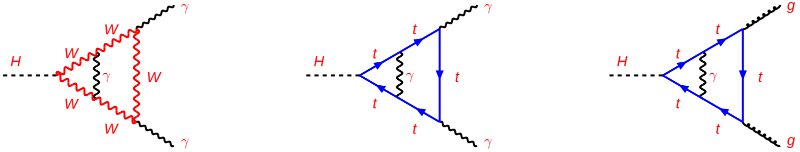

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- open problems: violation of Ward identity for $H \to \gamma\gamma$, ln divergency at the WW threshold for $H \to \gamma\gamma$, $\sqrt{}$ divergencies at the WW and ZZ thresholds for both $H \to \gamma\gamma$ and $gg \to H$

Complex poles

Cure problems with crossing of thresholds implementing the complex-mass scheme at 1 loop Denner,Dittmaier,Roth,Wieders'05

1) Avoid the selection of the Re part for H self-energy (mass renormalization) in order to restore the Ward identity for $H \to \gamma\gamma$

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Decompose $A = A_{\text{div}}^{1,\text{W}}/\beta_W + A_{\text{div}}^{1,\text{Z}}/\beta_Z + A_{\text{div}}^{2} \ln(-\beta_W^2 - i0) + A_{\text{fin}}$

Introduce the CMS in both threshold factors β_V and coefficients $A_{\text{div}}^{1,2}$

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3) Complete introduction of the complex-mass scheme

Introduce the CMS in all divergent and finite terms of the amplitude

Practical implementation of the CMS

Practical implementation of the complex-mass scheme through two steps:

1. Replace on-shell masses M_V^2 with complex poles $s_V = \mu_V(\mu_V - i\gamma_V)$

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⇒ Replace the conventional on-shell mass renormalization equations with the associated expressions for the complex poles of the W and Z bosons

$$m_i^2 = M_i^2 \left[1 + \frac{G_F M_W^2}{2\sqrt{2}\,\pi^2} \mathrm{Re}\Sigma_i^{(1)}(M_i^2)\right] \quad \Rightarrow \quad m_i^2 = s_i \left[1 + \frac{G_F s_W}{2\sqrt{2}\,\pi^2} \Sigma_i^{(1)}(s_i)\right]$$

⇒ Insert the full self-energy for the W boson in the renormalization equation for the Fermi-coupling constant, expressed through the complex mass of the W, s_W

$$g = 2\left(\sqrt{2} G_F s_W\right)^{1/2}\left[1 - \frac{G_F s_W}{4\sqrt{2}\,\pi^2}\Delta\right], \Delta = \Sigma_W^{(1)}(0) - \Sigma_W^{(1)}(s_W) + 6 + \frac{7 - 4s_\theta^2}{2s_\theta^2} \ln c_\theta^2$$

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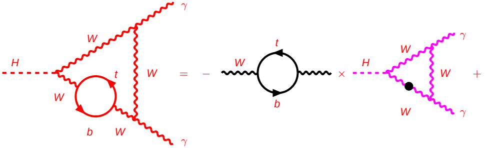
CMS $\to$ replacements done also at the level of the couplings $\Rightarrow s_\theta^2 = 1 - s_W/s_Z$

Square-root divergencies in the CMS

In the CMS square-root divergencies are confined to the H WFR factor

- Using on-shell masses as input data $\Rightarrow$ three sources of $\sqrt{}$ divergencies



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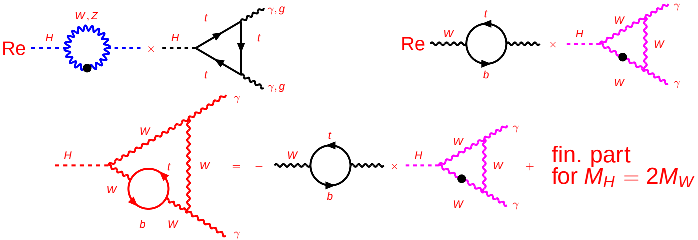


$\Rightarrow$ divergent part for $M_H = 2M_W$ represented as 1-loop $\otimes$ 1-loop $+$ finite

- Using complex masses as input data (Re tag removed from W-mass ren.)

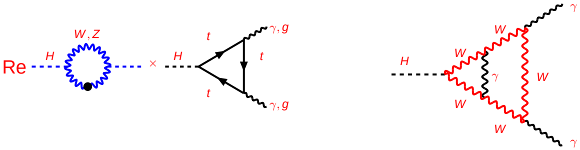
$\Rightarrow$ divergent parts of bubble insertions $+$ W-mass renormalization terms cancel

$\Rightarrow$ all square-root divergencies arise only from the Higgs WFR factor at one-loop

Minimal implementation of the CMS

Minimal implementation of the CMS involves only two classes of diagrams

- Decompose $A = A_{\mathrm{div}}^{1,\mathrm{W}}/\beta_W + A_{\mathrm{div}}^{1,\mathrm{Z}}/\beta_Z + A_{\mathrm{div}}^{2}\ln(-\beta_W^2 - i0) + A_{\mathrm{fin}}$



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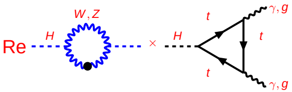

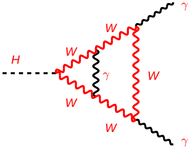

- Replace on-shell masses M_V^2 with complex poles $s_V = \mu_V(\mu_V - i\gamma_V)$ in terms involving the derivative of the Higgs self-energy at one loop and in the two-loop diagram with a Coulomb exchange

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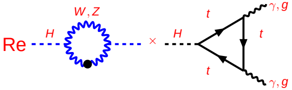
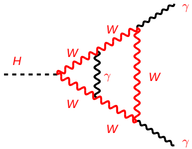
- Decompose $A = A_{\rm div}^{1,W}/\beta_W + A_{\rm div}^{1,Z}/\beta_Z + A_{\rm div}^2 \ln(-\beta_W^2 - i0) + A_{\rm fin}$





- Replace on-shell masses M_V^2 with complex poles $s_V = \mu_V(\mu_V - i\gamma_V)$ in terms involving the derivative of the Higgs self-energy at one loop and in the two-loop diagram with a Coulomb exchange

- Problem of resumming Coulomb singularities not addressed; In terms are not β_W^2-protected at threshold, large enhancement expected as for pseudo-scalar H decay for $M_H = 2M_t$ (Melnikov,Spira,Yakovlev'94)

Complete implementation of the CMS

Complete implementation of the CMS in principle much more complicated

1. Replace on-shell masses M_V^2 with complex poles s_V in all diagrams
2. Trade the Re parts of the W and Z self-energies for the full self-energies

$$A = \underbrace{A^{1,\mathrm{W}}_{\mathrm{div}}/\beta_W}_{\mathrm{cancell.\ irrelevant}} + A^{1,\mathrm{Z}}_{\mathrm{div}}/\beta_Z + A^2_{\mathrm{div}} \ln(-\beta_W^2 - i0) + \underbrace{A_{\mathrm{fin}}}_{\mathrm{complex\ masses}}$$

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Practically the second step can be in most cases avoided

- Z-mass renormalization only for $H \to \gamma\gamma$, because of the coupling $g^2 s_\theta^2$ at LO, with s_θ^2 through s_Z and s_W, but simpler $g^2 s_\theta^2 = 4\pi\alpha$ (on-shell γ's)
- W-mass renormalization also for $gg \to H$, because of the coupling g/m_W at LO, but the W self-energy at s_W drops out when combining mass renormalization with the equation for the Fermi-coupling constant

2. needed only concerning W-mass renormalization for $H \to \gamma\gamma$

Introduction of complex masses in loop integrals

Loop integrals have to be evaluated with complex masses

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$$B_0(p^2; 0, 0) \Rightarrow \int_0^1 dx \ln \chi(x), \qquad \chi(x) = p^2 x(1-x) - i0$$

real M_W^2 $\Rightarrow$ $\mathrm{Re}\chi(x) = -M_W^2 x(1-x) < 0, \quad \mathrm{Im}\chi(x) = -0 < 0$

complex s_W $\Rightarrow$ $\mathrm{Re}\chi(x) = -\mu_W^2 x(1-x) < 0, \quad \mathrm{Im}\chi(x) = +\mu_W \gamma_W x(1-x) > 0$

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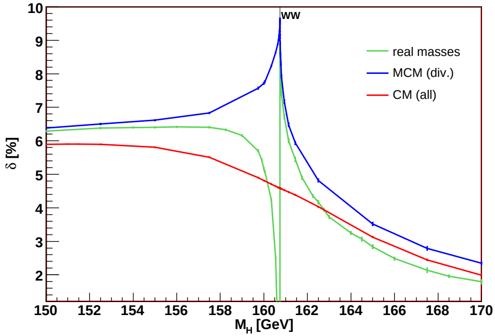
$\to$ define an analytic continuation of ln such that the value for a stable gauge boson is smoothly approached when the coupling tends to zero

$$\ln(z_R + iz_I) \Rightarrow \ln(z_R + iz_I) - 2i\pi\theta(-z_R), \qquad \lim_{z_I \to 0} = \underbrace{\ln(z_R - i0)}_{\text{real mass}}$$

Threshold behaviour for $gg \to H$

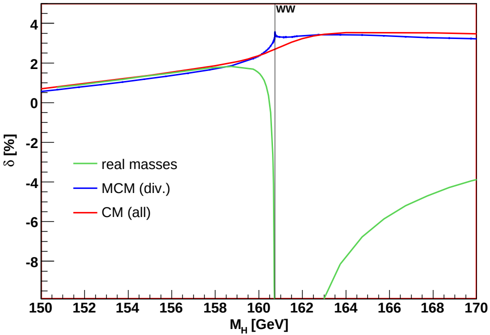
Comparison of EW corrections to $gg \to H$ around the WW threshold, obtained using different schemes for treating unstable particles



- Result obtained with real masses divergent at WW; good approx. below/above
- MCM setup gives finite result at WW; large effect 9.6 % associated with cusp
- CM setup smoothens singular behaviour; effects at threshold reduced to 4.6 %

Threshold behaviour for $H \to \gamma\gamma$

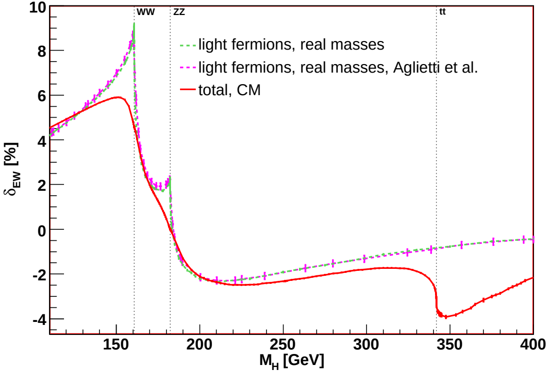
Comparison of EW corrections to $H \to \gamma\gamma$ around the *WW* threshold, obtained using different schemes for treating unstable particles



- Result obtained with real masses divergent at *WW*; good approx. below; completely off above threshold, since no cancellation mechanism occurs
- Result in MCM setup finite, shows cusp; result in CM setup is smooth
- At threshold, result in MCM setup $\to$ 3.5%; result in CM setup $\to$ 2.7%
  $\Rightarrow$ prediction at the % level requires complete CMS implementation

EW corrections to $gg \to H$ (I)

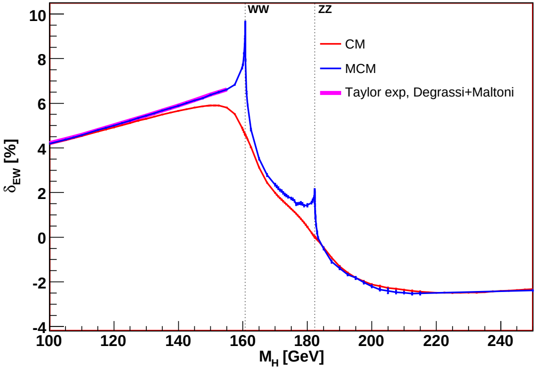
Summary of EW corrections to $gg \to H$ for $100\ \mathrm{GeV} < M_H < 400\ \mathrm{GeV}$



- Full agreement with `Aglietti,Bonciani,Degrassi,Vicini'04` using RMs as input data; light fermions dominate up to 300 GeV (max $+9\%$)
- CMs change the result around WW and ZZ thresholds, where cusps disappear
- Top-quark diagrams relevant at $t\bar{t}$ threshold, with relative correction $\delta_{ew} \sim -4\%$

EW corrections to $gg \to H$ (II)

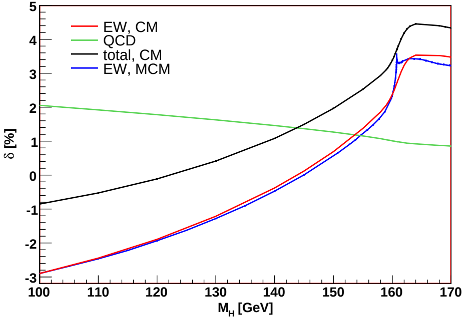
Summary of EW corrections to $gg \to H$ for $100\text{ GeV} < M_H < 250\text{ GeV}$



- Full agreement below *WW* with Taylor expansion `Degrassi,Maltoni'04` using CMs as input data in divergent terms only
- Implementation of CMs everywhere smoothens the result around *WW* and *ZZ* thresholds and leads to a -4% shift respect to MCM at 140 GeV

EW/QCD corrections to $H \to \gamma\gamma$

Summary of EW/QCD corrections to $H \to \gamma\gamma$ for $100\ \text{GeV} < M_H < 170\ \text{GeV}$



- QCD corrections > 0, ranging from $+1.8\%$ (120 GeV) to $+0.9\%$ (170 GeV)
- CMs in non-divergent terms smoothen threshold behaviour of EW effects; numerically they range from -1.9% (120 GeV) to $+3.5\%$ (170 GeV)
- EW effects compensate QCD ones for light Higgs masses, -0.1% (120 GeV); strong enhancement above threshold, $+4.4\%$ (170 GeV)

Total cross section in hadron collisions

- Insert the partonic result for EW corrections to $gg \to H$ in the total cross section $\sigma(h_1 h_2 \to H)$
- Fold PDFs with partonic cross section

$$\sigma(h_1 h_2 \to H) = \sum_{i,j} \int_0^1 dx_1 dx_2 f_{i,h_1}(x_1, \mu_F^2) f_{j,h_2}(x_2, \mu_F^2) \times$$
$$\times \int_0^1 dz\, \delta\left(z - \frac{M_H^2}{s x_1 x_2}\right) z \underbrace{\sigma^0}_{\text{Born}} \underbrace{G_{ij}(z, \mu_R^2, \mu_F^2)}_{\text{pQCD}}$$

- Estimate theoretical uncertainty controlling the dependence of $\sigma(h_1 h_2 \to H)$ on $\mu_{R,F}$ for fixed values of M_H; define uncertainty band around central values for $\mu_R = \mu_F = M_H$

Inclusion of NLO EW effects

Two factorization options for QCD/ EW:

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I) Complete factorization $G_{ij} \to (1 + \delta_{EW}) G_{ij}$

analogous to Aglietti,Bonciani,Degrassi,Vicini'06 light Higgs

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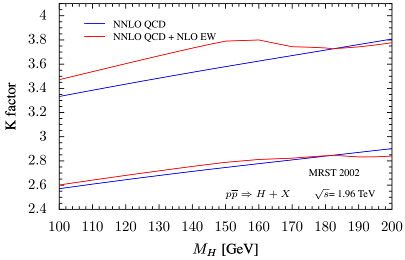
- Vary $\mu_{R,F}$ sim./indep. in $M_H/2 < \mu_{R,F} < 2M_H$ with $\mu_R/2 < \mu_F < 2\mu_R$

$\Rightarrow$ For each $M_H \to \sigma_{ref}, \sigma_{max}, \sigma_{min}$, uncertertainty band $\sigma_{max} - \sigma_{min}$

- Very conservative estimate, since in PF option the scale dependence is controlled by the LO QCD result (multiplied by δ_{EW})

NLO EW corrections at the Tevatron

Impact of NLO EW effects at Tevatron II, $\sqrt{s} = 1.96$ TeV,
100 GeV $< M_H <$ 200 GeV (using HIGGSNNLO, by M.Grazzini)

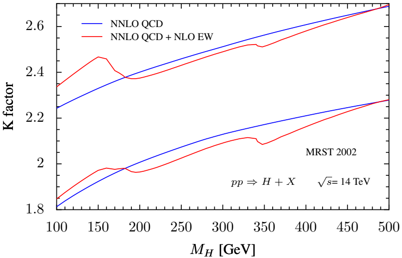


M_H [GeV]	δ_{CF} [%]	δ_{PF} [%]
120	$+4.9$	$+1.6$
140	$+5.7$	$+1.8$
160	$+4.8$	$+1.5$
180	$+0.5$	$+0.1$
200	-2.1	-0.6

- Uncertainty band shows stronger sensitivity on the Higgs mass, once NLO EW effects are included
- Impact of NLO EW corrections smaller respect to NNLL resummation `Catani,de Florian,Grazzini,Nason'03` ($+12$ % for $M_H = 120$ GeV)
- 95 % CL exclusion of a SM Higgs for $M_H = 170$ GeV, % effects relevant; CM result employed by `Anastasiou,Boughezal,Petriello'08`, prediction σ is $7 - 10$% larger than σ used by TEVNPH WG

NLO EW corrections at the LHC

Impact of NLO EW effects at LHC, $\sqrt{s} = 14$ TeV,
100 GeV $< M_H <$ 500 GeV (using HIGGSNNLO, by M.Grazzini)



M_H [GeV]	δ_{CF} [%]	δ_{PF} [%]
120	$+4.9$	$+2.4$
150	$+5.9$	$+2.8$
200	-2.1	-1.0
310	-1.7	-0.9
410	-0.8	-0.8

- Uncertainty band shows stronger sensitivity on the Higgs mass, once NLO EW effects are included
- WW and $t\bar{t}$ thresholds visible, but smooth having introduced everywhere CMs
- Impact of NLO EW corrections comparable to that of NNLL resummation Catani, de Florian, Grazzini, Nason'03 ($+6\,\%$ for $M_H = 120$ GeV); for large M_H NLO EW corrections turn negative, screening effect with NNLL resummation

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- NLO EW corrections to $gg \to H$ range between $+6\%$ (WW) and -4% ($t\bar{t}$); for $M_H = 120$ GeV $\to \delta = +5\%$