NLO electroweak corrections to Higgs production through gluon-gluon fusion

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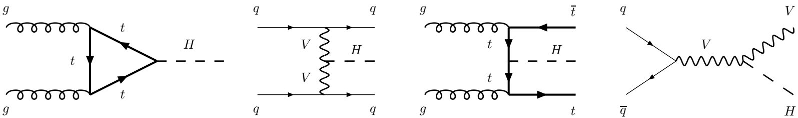
Outline

1. EW corrections to $\sigma(gg \to H)$ below WW threshold
2. Crossing of double vector-boson thresholds
3. Numerical results

Hadronic SM Higgs production

Main production channels for the Standard Model Higgs in hadron collisions



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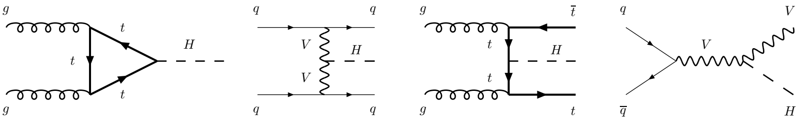

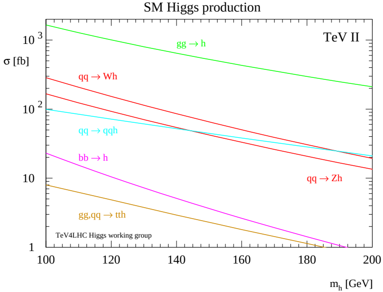

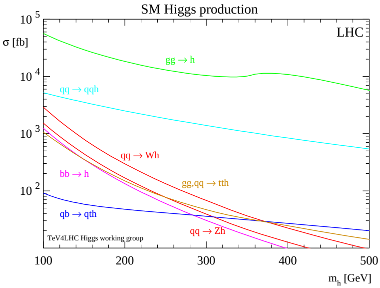

Hahn,Heinemeyer,Maltoni,Weiglein,Willenbrock [hep-ph/0607308]

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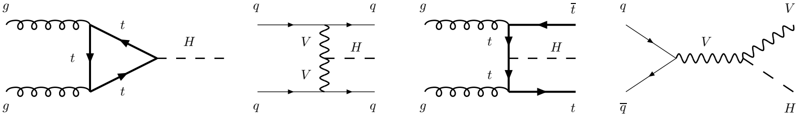
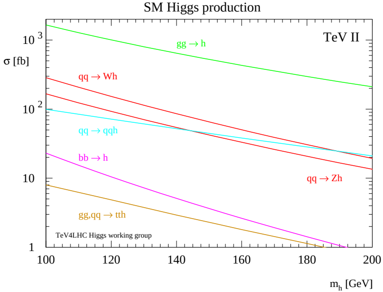
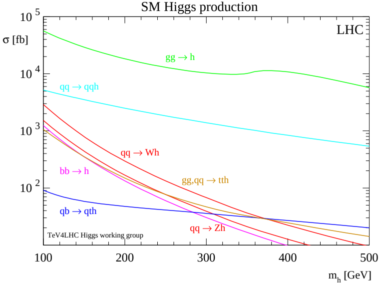






Hahn, Heinemeyer, Maltoni, Weiglein, Willenbrock [hep-ph/0607308]

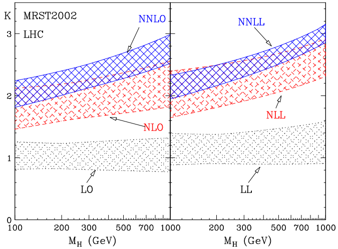
Gluon-fusion production channel does not lead to the cleanest signal, but it has by far the largest cross section both at the TEVATRON and the LHC

QCD corrections

NLO and NNLO QCD corrections to the cross section extremely large

Dawson'91,Djouadi,Spira,Zerwas'91,Spira,Djouadi,Graudenz,Zerwas'95
Harlander,Kant'05,Anastasiou,Beerli,Bucherer,Daleo,Kunszt'06,
Aglietti,Bonciani,Degrassi,Vicini'06

Harlander'00,Catani,de Florian,Grazzini'01,Harlander,Kilgore'01,
Anastasiou,Melnikov'02,Ravindran,Smith,van Neerven'03



Catani,de Florian,Grazzini,Nason
[hep-ph/0306211]

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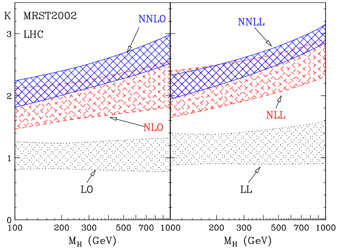

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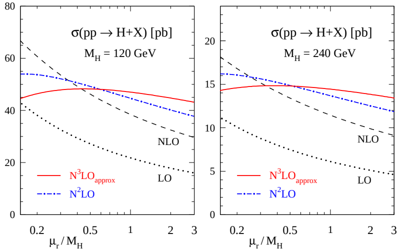

Moch, Vogt [hep-ph/0508265]

N^3LO soft limit $\Rightarrow$ 5% uncertainty

EW corrections

NLO EW corrections needed for matching the precision of QCD predictions, but not very well known

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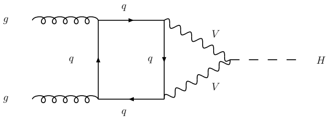
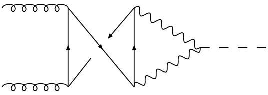
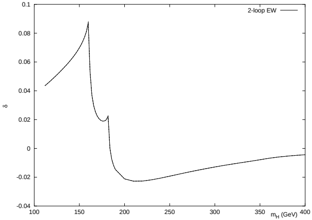
- Light-quark analytically Aglietti,Bonciani,Degrassi,Vicini'04







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

Outline of the computation

NLO EW corrections not complete $\Rightarrow$ extend the results above the WW threshold (after checking below)

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3. Reduce F_i to basis integrals M_j by standard algebraic methods
4. M_j divergent for $m_f \to 0$; $\mathcal{A}^{\mathrm{NLO}}$ finite for $m_f \to 0$

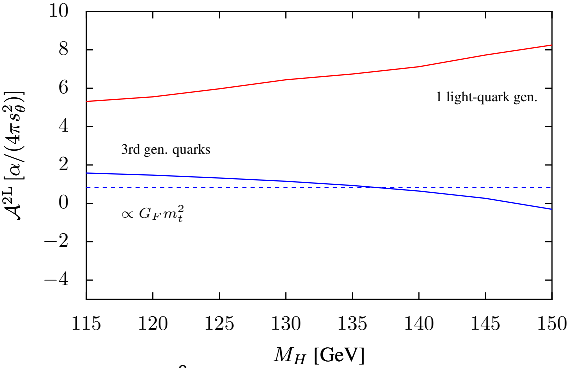
$$\Rightarrow \boxed{M_j = \underbrace{c_j \ln(m_f^2/s)}_{\text{analytically}} + M_j^{\mathrm{reg}} \Rightarrow \underbrace{\sum c_j \ln(m_f^2/s) = 0}_{\text{amplitude}} \Rightarrow m_f = 0}$$

5. Renormalized $\mathcal{A}^{\mathrm{NLO}} = \sum a_j M_j^{\mathrm{reg}}$ evaluated numerically

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

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

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

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

- 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

Around the VV thresholds: square-root divergencies

Problem with the crossing of both WW and ZZ: square-root divergencies

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

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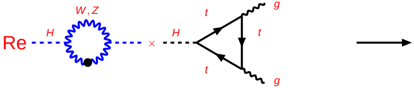

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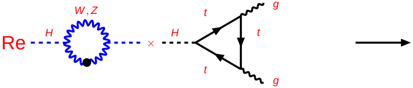

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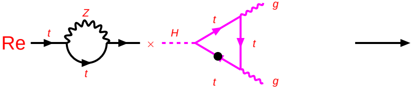

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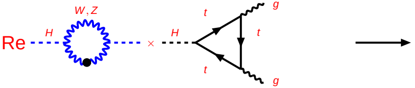

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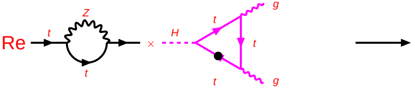

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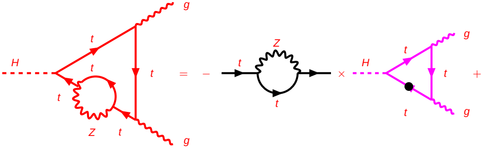
3) (irreducible 2-loop diagrams with a bubble insertion in an internal t line)



fin. part
for $M_H = 2M_t$

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

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2) Complete introduction of the complex-mass scheme

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

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

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$\Rightarrow$ 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

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

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

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

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

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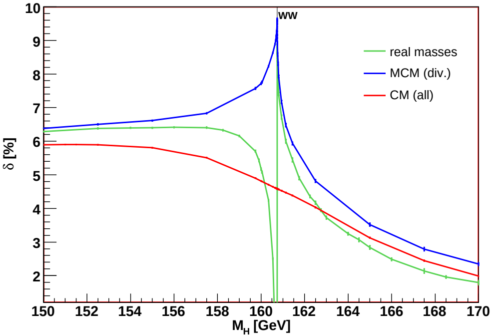
$\rightarrow$ 0-width limit of the complex-mass case doesn't reproduce the real-mass one

$\rightarrow$ 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 $gg \to H$

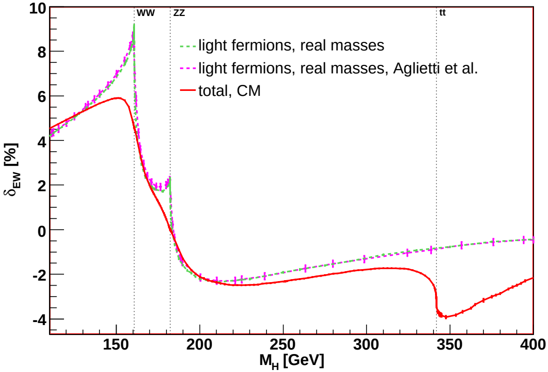
Comparison of EW corrections to $gg \to H$ around the WW threshold, obtained using different schemes for treating unstable particles



- 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 %

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

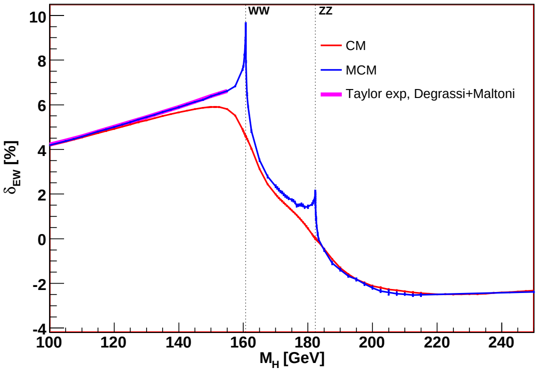
Summary of EW corrections to $gg \to H$ for $100\text{ GeV} < M_H < 400\text{ GeV}$



- 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

Inclusion of NLO EW effects

Partonic result convoluted with the PDFs:

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

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

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II) Partial factorization $G_{ij} \to G_{ij} + \alpha_S^2 \delta_{EW} G_{ij}^{(0)}$

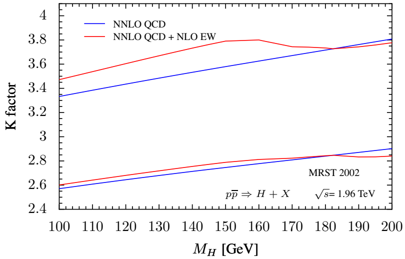
- Vary $\mu_{R,F}$ for $M_H/2 < \mu_{R,F} < 2M_H$ with $\mu_R/2 < \mu_F < 2\mu_R$

$\Rightarrow$ 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)

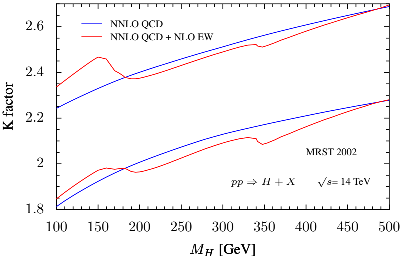


M_H [GeV]	δ_{CF} [%]	δ_{PF} [%]
120	+4.9	+1.6
140	+5.7	+1.8
160	+4.8	+1.5
180	+0.5	+0.1
200	−2.1	−0.6

- 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)
- Effective-theory computation of mixed three-loop EW and QCD effects by `Anastasiou,Boughezal,Petriello'08` supports the hypothesis of a complete factorization

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

Conclusions

- Performed a complete computation of the NLO EW corrections to $gg \to H$; all contributions evaluated for any value of M_H; result used by `de Florian-Grazzini ’09` for updating σ_H

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- Corrections range between $+6\%$ for $M_H = 150$ GeV (light fermions) and -4% for $M_H \sim 2\,M_t$ (top-quark diagrams)
- Full implementation of the complex-mass scheme needed to avoid large effects at two-particle thresholds; for $M_H = 2\,M_W$, corrections reduced from $+10\%$ (almost naive introduction of finite-width effects) to $+5\%$ (CMS in all terms)