# NLO electroweak corrections to Higgs production in gluon-gluon fusion

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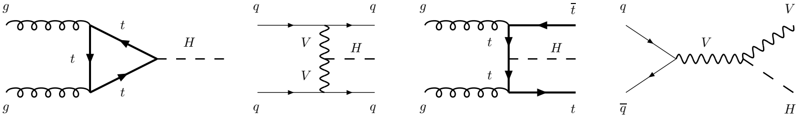
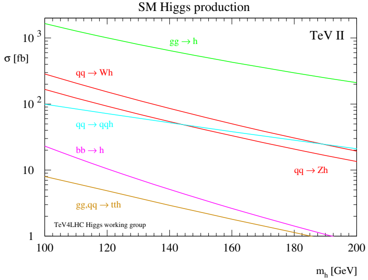
# Outline

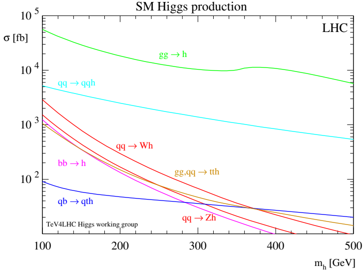
# Why $gg \to H$ at hadron colliders

Main production channels for the Standard Model Higgs in hadron collisions




Gluon-fusion production channel does not lead to the cleanest signal




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

Largest cross section both at the TEVATRON and the LHC

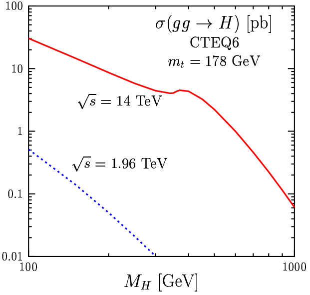
# LO production cross section for $gg \to H$

- Obtained from the interference ot (top) quark 1-loop diagrams

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

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

- Partonic $\sigma_{\rm LO} \Rightarrow \sigma_{\rm LO} \otimes$ PDFs $\Rightarrow$ LO total cross section for $h_1 h_2 \to H$




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

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

# QCD corrections to $\sigma_{tot}$

- 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

↖ full $M_H$, $M_q$ dependence

- NNLO at the LHC $+20\%$ NLO, uncertainty $\mu_{R,F}$ variation $\pm 10\%$

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

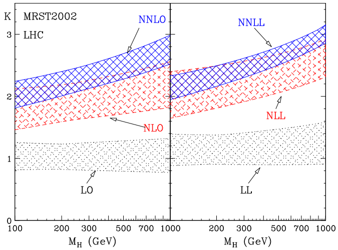
↖ large $M_t$ limit: integrate out top quark $\Rightarrow$ point-like $Hgg$ interaction

- large $M_t$ limit formally valid for $M_H < 2M_t$

good approximation for $M_H > 2M_t$ $\Rightarrow \sigma_{\mathrm{NNLO}} \simeq \sigma_{\mathrm{LO}}^{\mathrm{full}} \times K^{\mathrm{EFT}}$ $\quad K^{\mathrm{EFT}} = \sigma_{\mathrm{NNLO}}^{\mathrm{EFT}} / \sigma_{\mathrm{LO}}^{\mathrm{EFT}}$

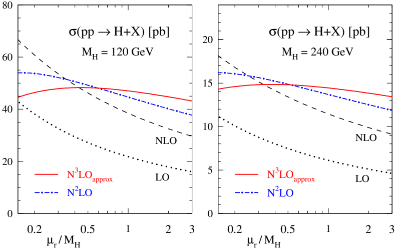
at NLO 90% complete result up to $M_H \simeq 1$ TeV    Krämer,Laenen,Spira'96

# QCD improvements




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

All-order large logarithms




Moch,Vogt [hep-ph/0508265]

stabilized $\mu_R$

$N^3LO$ soft limit

$\Rightarrow$ predictions for exclusive quantities

- differential cross section evaluated at NNLO in QCD
  Anastasiou,Melnikov,Petriello'04,Catani,Grazzini'07
- $\ldots \Rightarrow$ QCD corrections well under control

# EW corrections (I)

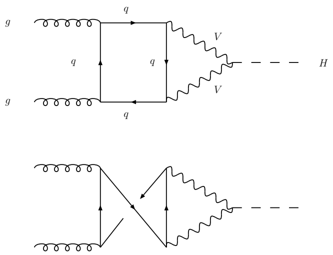
- Dominant contributions enhanced by $M_t^2$ Djouadi,Gambino'94

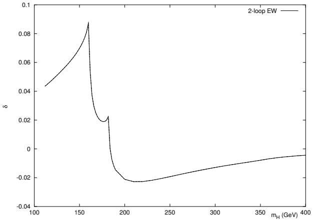
$$\sigma_{LO} \times [1 + G_F\, M_t^2 \sqrt{2}/(16\pi^2)] \qquad 0.4\,\%\ \text{accidental}$$

1) $< 0$ corrections to $\Pi_{gg} \Leftrightarrow V_{Hgg}$ through a low-energy theorem

2) $> 0$ " renormalization constants for the top and the Higgs

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



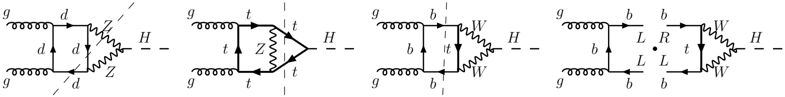




Aglietti,Bonciani,Degrassi,Vicini [hep-ph/0404071]

# 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: $M_H = 2 M_W \Rightarrow$ Taylor expansion in $q_H^2/(4M_W^2)$ allowed




Im: $q_H^2 = M_Z^2$ Im: $q_H^2 = 4\,M_t^2$ Im: $q_H^2 = 0 \;\Rightarrow$ no Taylor exp?

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

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

# Summary of NLO EW corrections below $WW$

| $M_H$ | 1 LQ | $3^{\text{rd}}$ 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

# Improving NLO EW corrections

SA,Passarino,Sturm,Uccirati'08

- 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 $2M_W$
- Top-quark terms evaluated only through Taylor expansion $\Rightarrow$ control reliability of the result close to the $WW$ threshold
- Threshold singularities show up at the amplitude level

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

$*$ 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

1. Generate all Feynman diagrams contributing to $gg \to H$
2. Projection of $\mathcal{A}$ on form factors $F_i$
3. Reduce $F_i$ to basis integrals $M_j$ by standard algebraic methods
4. $\mathcal{A}^{\rm NLO}$ shows UV poles $\Rightarrow$ renormalized, bare $\Leftrightarrow$ input data
5. $M_j$ divergent for $m_f \to 0$; $\mathcal{A}^{\rm NLO}$ finite for $m_f \to 0$

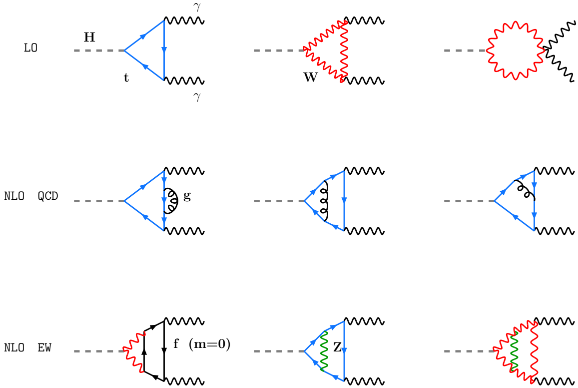
$$\Rightarrow \quad \boxed{M_j = \underbrace{c_j \ln(m_f^2/s)}_{\text{analytically}} + M_j^{\rm reg} \Rightarrow \underbrace{\sum c_j \ln(m_f^2/s) = 0}_{\text{amplitude}} \Rightarrow m_f = 0}$$

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

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

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

# NLO EW diagrams




- 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

- $\mathcal{A} = e_1^\mu \, e_2^\nu \, \mathcal{A}_{\mu\nu}$ $\quad \mathcal{A}_{\mu\nu} \longrightarrow$ Green's function
- $\mathcal{A}_{\mu\nu} = F_D \, \delta_{\mu\nu} + \sum F_P^{ij} \, p_{i\mu} \, p_{j\nu} + F_\epsilon \, \epsilon_{\mu\nu\alpha\beta} \, p_1^\alpha \, p_2^\beta$ $\qquad F_i = P_i^{\mu\nu} \mathcal{A}_{\mu\nu}$

Preliminary simplifications observing that:

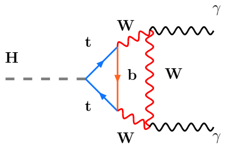
1) $e_i^\mu \, p_{i\mu} = 0$ $\Rightarrow$ $F_P^{11}, F_P^{12}, F_P^{22}$ do not contribute to $\mathcal{A}$

2) SM $H$ CP even $\Rightarrow$ $F_\epsilon$ 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.)

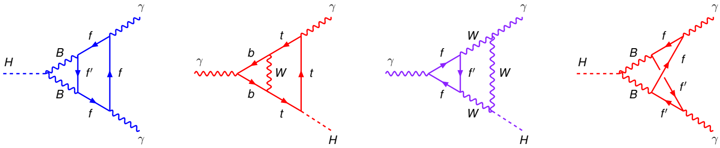
Single projection operator for extracting one form factor from $\mathcal{A}_{\mu\nu}$

$$F_D = \frac{1}{n-2} \left( \delta^{\mu\nu} - \frac{p_1^\mu p_2^\nu + p_2^\mu p_1^\nu}{p_1 \cdot p_2} \right) \mathcal{A}_{\mu\nu}$$

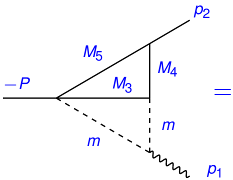



- prescription for $\gamma_5$ in DR
- $F_\epsilon = 0$ in $\mathcal{A}$
- use completely AC $\gamma_5$

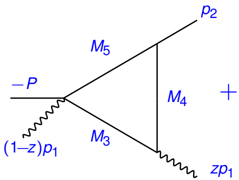
# Extraction of collinear logarithms




- Configurations with 2 massless quanta with same LF current cancel algebraically after reduction $\otimes$ symmetrization
- Integrals over Feynman parameters of well-known one-loop functions



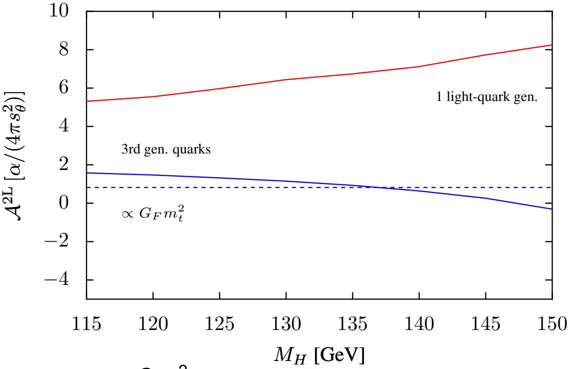

$$= \ln \frac{m^2}{s} \int_0^1 dz$$




$+$ 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

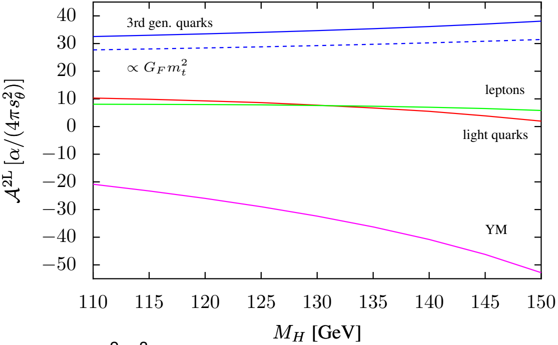



| $M_H$[Gev] | $\delta^{EW}$ [%] |
|---|---|
| 115 | +4.73 |
| 120 | +4.92 |
| 125 | +5.12 |
| 130 | +5.31 |
| 135 | +5.49 |
| 140 | +5.66 |
| 145 | +5.80 |
| 150 | +5.90 |

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

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

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




| $M_H$[Gev] | $\delta^{EW}$ [%] |
|---|---|
| 120 | −1.89 |
| 130 | −1.21 |
| 140 | −0.38 |
| 145 | +0.12 |
| 150 | +0.69 |

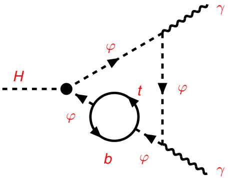
$$\Gamma = \frac{G_F \alpha^2 M_H^3}{128\sqrt{2}\pi^3} |\mathcal{A}^{1L} + \mathcal{A}^{2L} + \ldots|^2 = \sigma^{LO} \left(1 + \delta^{EW}\right) \qquad \mathcal{A}^{2L} = \mathcal{A}^{2L}_{YM} + \mathcal{A}^{2L}_{lq} + \mathcal{A}^{2L}_{lep} + \mathcal{A}^{2L}_{3gen}$$

- Agreement with lep / LQ Aglietti,Bonciani,Degrassi,Vicini'04 and corrected (1PR) $3^{rd}$ 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

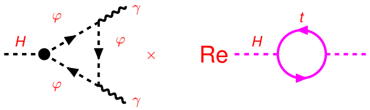
# Around the *WW* threshold: Ward identity

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 $M_H > 2\,M_W$
- Due to the relation between $\underbrace{m_H^2}_{\text{bare}}$ and $\underbrace{M_H^2}_{\text{on shell}}$ in scalar $V_{H\varphi^+\varphi^-} \propto \underbrace{m_H^2}_{\text{bare}}$
- At NLO there are two kinds of diagrams contributing to the Ward identity




$$\underbrace{m_H^2}_{\text{bare}} = \underbrace{M_H^2}_{\text{on shell}}$$




$$\underbrace{m_H^2}_{\text{bare}} = \underbrace{M_H^2}_{\text{on shell}} \left[1 + \frac{G_F M_W^2}{2\sqrt{2}\,\pi^2}\,\mathrm{Re}\,\Sigma_H^{(1)}(M_H^2)\right]$$

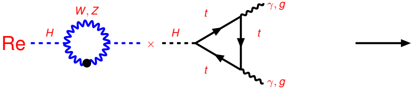
- Below $WW$ both classes of diagrams are real $\to$ the Ward identity holds
- Above $WW$ mismatch imaginary parts (Re) $\to$ the Ward identity $\neq 0$

# Around the $VV$ thresholds: square-root divergencies

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

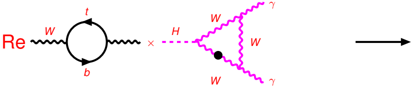
$H \to \gamma\gamma$ and $gg \to H$ ampls. $\Rightarrow$ terms proportional to $1/\beta_V$, $\beta_V = \sqrt{1 - 4\, M_V^2/M_H^2}$

1) (H WFR factor) $\otimes$ (1-loop diags., $\gamma\gamma$, $gg$) (see `Kniehl,Palisoc,Sirlin'00`)



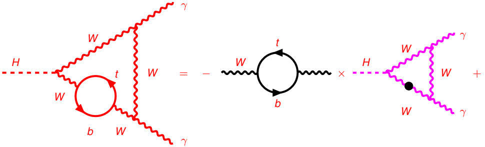

**H WF divergent for $M_H = 2M_{W,Z}$**

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




**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 $M_H = 2M_W$

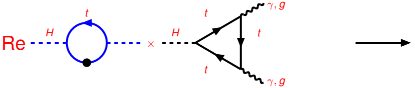
$\Rightarrow$ divergent part for $M_H = 2M_W$ can be represented as **1-loop $\otimes$ 1-loop**

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

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

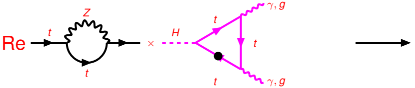
$H \to \gamma\gamma$ and $gg \to H$ ampls. $\Rightarrow$ terms potentially $\propto 1/\beta_t$, but multiplied by $\beta_t$ (spin)

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



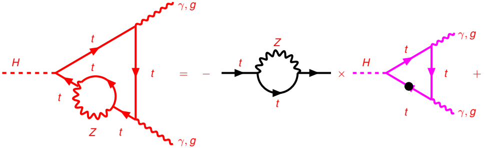

**H WF finite for $M_H = 2M_t$**

2) (1-loop counterterm diagrams, $\gamma\gamma$) $\otimes$ (t mass renormalization)




**der. finite for $M_H = 2M_t$**

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



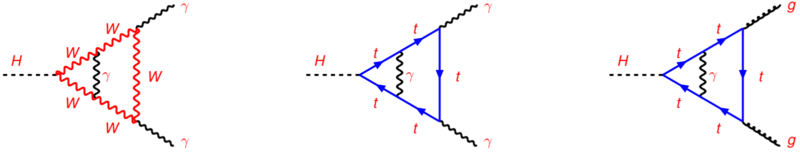

fin. part for $M_H = 2M_t$

$\Rightarrow$ finite for $M_H = 2M_t$ $\Rightarrow$ no problems for QCD

# 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




- no problem for $t\bar{t}$, since the ln is multiplied by $\beta_t^2$ (spin structure protects threshold behaviour); no $\sqrt{\phantom{x}}$, no ln divergencies $\Rightarrow$ $M_t = 170.9$ GeV
- open problems for $VV$: violation of Ward identity for $H \to \gamma\gamma$, ln divergency at the $WW$ threshold for $H \to \gamma\gamma$, $\sqrt{\phantom{x}}$ 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 $H \to \gamma\gamma$

2) "Minimal" introduction of the complex-mass scheme

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

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

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 $s_V = \mu_V(\mu_V - i\gamma_V)$
2. Trade the real parts of the $W$ and $Z$ self-energies (mass renormalization at 1 loop) for the complete self-energies, including imaginary parts

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

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

$\Rightarrow$ 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 $W$, $s_W$

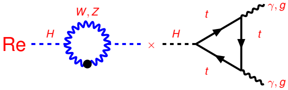
$$g = 2\left(\sqrt{2} G_F s_W\right)^{1/2} \left[ 1 - \frac{G_F s_W}{4\sqrt{2}\,\pi^2} \Delta \right], \Delta = \Sigma_W^{(1)}(0) - \Sigma_W^{(1)}(s_W) + 6 + \frac{7 - 4 s_\theta^2}{2 s_\theta^2} \ln c_\theta^2$$

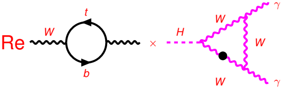
CMS $\to$ replacements done also at the level of the couplings $\Rightarrow s_\theta^2 = 1 - s_W/s_Z$

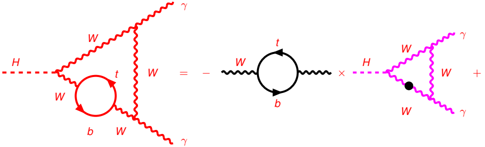
# Square-root divergencies in the CMS

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

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




fin. part for $M_H = 2M_W$

$\Rightarrow$ 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.)

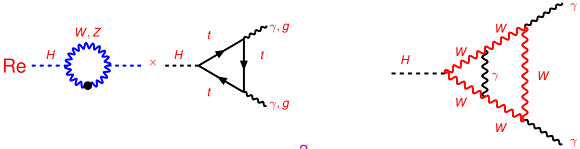
  $\Rightarrow$ divergent parts of bubble insertions $+$ $W$-mass renormalization terms cancel

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




- 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 $\beta_W^2$-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

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

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 $s_\theta^2$ through $s_Z$ and $s_W$, but simpler $g^2 s_\theta^2 = 4\pi\alpha$ (on-shell $\gamma$'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

- Internal masses complexified $\to$ no problems; the replacement $M^2 - i0 \Rightarrow s = \mu^2 - i\mu\gamma$ does not clash with the $-i0$ prescription
- External squared momenta are real quantities by construction
- $W$-mass renormalization at one-loop leads to a complication

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

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

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

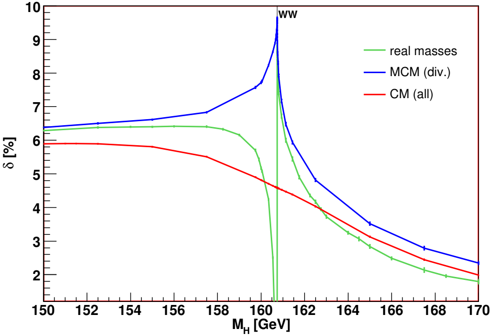
$\to$ 0-width limit of the complex-mass case doesn't reproduce the real-mass one

$\to$ 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 $gg \to H$

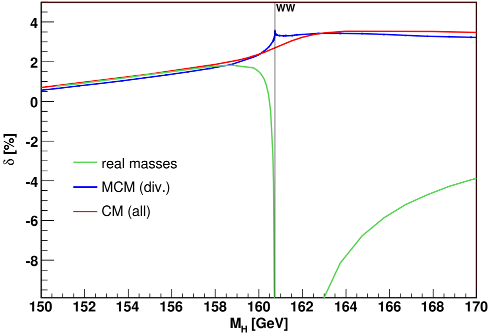
Comparison of EW corrections to $gg \to H$ around the $WW$ threshold, obtained using different schemes for treating unstable particles




- 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 $H \to \gamma\gamma$

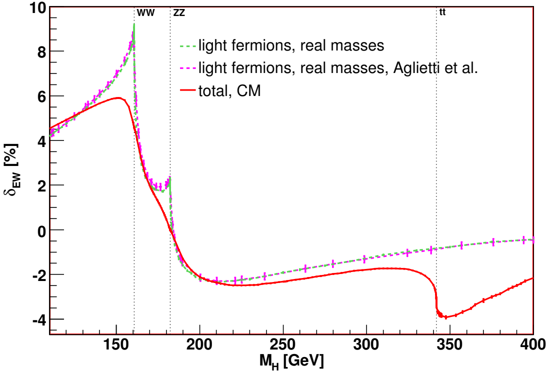
Comparison of EW corrections to $H \to \gamma\gamma$ around the $WW$ threshold, obtained using different schemes for treating unstable particles




- 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)

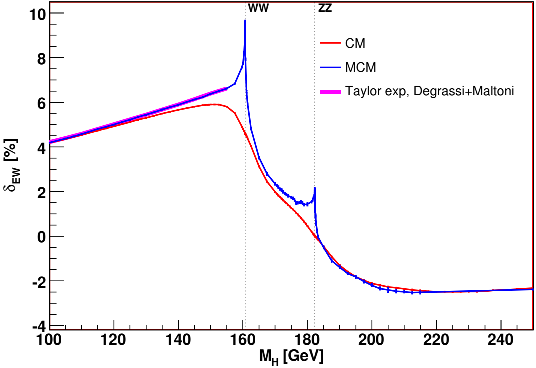
Summary of EW corrections to $gg \to H$ for $100\ \text{GeV} < M_H < 400\ \text{GeV}$




- 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)

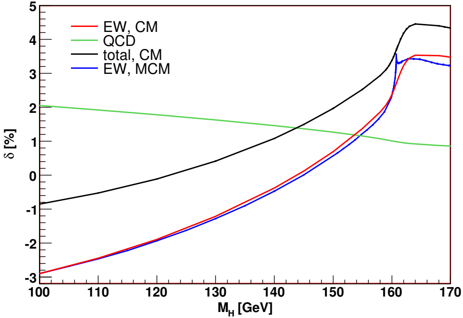
Summary of EW corrections to $gg \to H$ for $100\ \text{GeV} < M_H < 250\ \text{GeV}$




- 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

# 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 $M_H$

# Inclusion of NLO EW effects

Two factorization options for QCD/ EW:

$$\sigma(h_1 h_2 \to H) = \sum_{i,j} \int_0^1 dx_1\, dx_2\, f_{i,h_1}(x_1, \mu_F^2) f_{j,h_2}(x_2, \mu_F^2) \times$$

$$\times \int_0^1 dz \delta \left( z - \frac{M_H^2}{s x_1 x_2} \right) z \sigma^0 G_{ij}(z, \mu_R^2, \mu_F^2)$$

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

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

II) No factorization $G_{ij} \to G_{ij} + \alpha_S^2 \delta_{EW} G_{ij}^{(0)}$

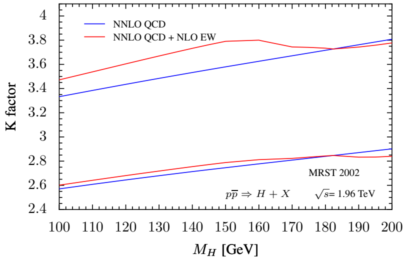
- Vary $\mu_{R,F}$ in $M_H/2 < \mu_{R,F} < 2M_H$ with $\mu_R/2 < \mu_F < 2\mu_R$

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

- Very conservative estimate, since in no fact. option the scale dependence is controlled by the LO QCD result (multiplied by $\delta_{EW}$)

# 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)

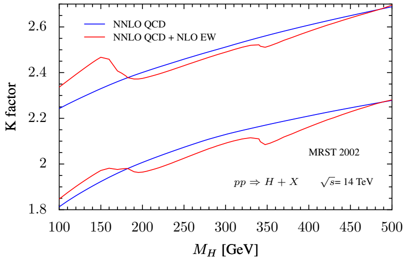



| $M_H$ [GeV] | $\delta_{\mathrm{CF}}$ [%] | $\delta_{\mathrm{PF}}$ [%] |
|---|---|---|
| 120 | $+4.9$ | $+1.6$ |
| 140 | $+5.7$ | $+1.8$ |
| 160 | $+4.8$ | $+1.5$ |
| 180 | $+0.5$ | $+0.1$ |
| 200 | $-2.1$ | $-0.6$ |

- 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)

# 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] | $\delta_{\rm CF}$ [%] | $\delta_{\rm PF}$ [%] |
|---|---|---|
| 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

- Completed the evaluation of NLO EW corrections to $gg \to H$ and $H \to \gamma\gamma$ below, around and above $VV$ thresholds
- For $H \to \gamma\gamma$, QCD+EW NLO effects well below the % level for $M_H = 120$ GeV, enhancement above the $WW$ threshold ($\delta = +4\%$ for $M_H = 170$ GeV)
- NLO EW corrections to $gg \to H$ range between $+6\%$ ($WW$) and $-4\%$ ($t\bar{t}$); for $M_H = 120$ GeV $\to \delta = +5\%$

# Ongoing activities

- Finite top mass effects at NNLO in QCD
  Harlander,Ozeren'09,Steinhauser,Pak,Rogal'09
- Mixed three-loop QCD / EW effects (effective theory)
  Anastasiou,Boughezal,Petriello'08
- Effect of bottom quarks Anastasiou,Boughezal,Petriello'08
  de Florian,Grazzini'09
- Defining the width at the Higgs complex pole
  Passarino,Sturm,Uccirati'10
- Updated predictions implemented in public codes: HIGLU Spira, HNNLO Catani,Grazzini, FEHiP Anastasiou,Melnikov, Petriello, available for LHC analyses