NLO electroweak corrections to Higgs production in $\gamma\gamma$ fusion

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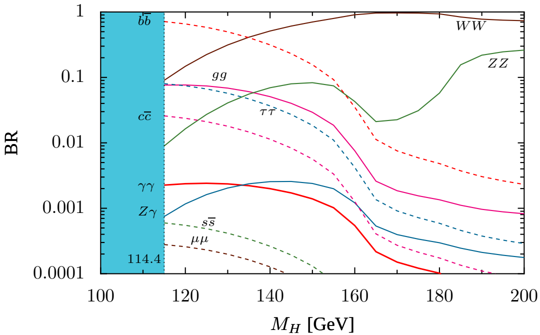
Outline

1. Why EW corrections to $\gamma\gamma \to H$
2. Method for NLO EW (thresholds)
3. Numerical results
4. Conclusions

Higgs branching ratios

Branching ratios of the SM Higgs for 100 GeV $< M_H <$ 200 GeV obtained using HDECAY [Djouadi, Kalinowski, Mühlleitner, Spira]



- $M_H \gtrsim 140$ GeV $\Rightarrow$ $H \rightarrow WW\,/\,ZZ$
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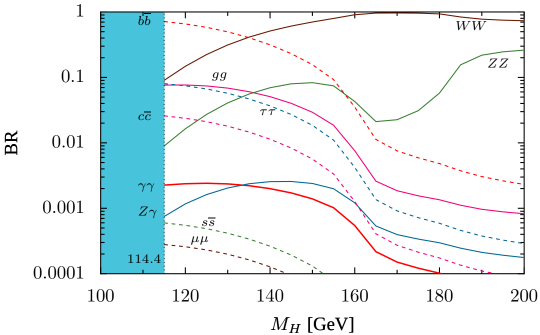

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QCD **background**

$H \to \gamma\gamma$ for light H at the LHC

- **rare** $\sim 2 \cdot 10^{-3}$ for $M_H = 120$ GeV
- **exp. clean** $\Leftarrow \gamma\,\gamma$ **stable**

Higgs production through $\gamma\gamma$ collisions at the ILC

Reverse process ($\gamma\gamma \to H$) even more interesting at the ILC operating in the $\gamma\gamma$ mode for precision physics $\Rightarrow$ measure decay width $\Gamma_{H\to\gamma\gamma}$

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  $\Rightarrow$ $\Gamma_{H\to\gamma\gamma} \to 2.3\%$ assuming $\mathrm{Br}_{H\to b\bar{b}} \to 1.5\%$

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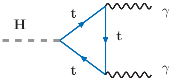
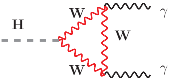
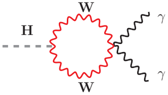
Theory side: SM radiative corrections to $\Gamma_{H\to\gamma\gamma}$ needed to match the % experimental accuracy, to distinguish between standard/non standard Higgs, to reveal possible unknown charged particles in loops

LO decay width

Ellis,Gaillard,Nanopoulos’76,Vainshtein,Voloshin,Zakharov,Shifman’79







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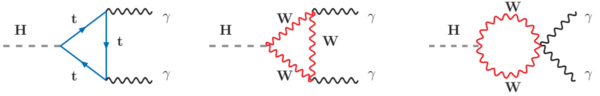
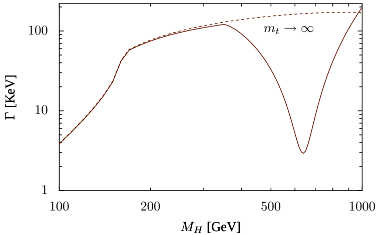
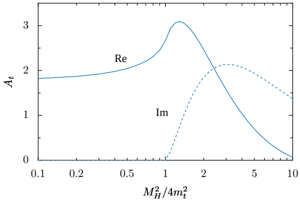
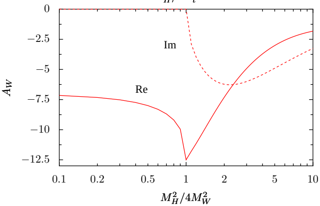


$$\Gamma = \underbrace{\frac{G_F\,\alpha^2\,M_H^3}{128\,\sqrt{2}\,\pi^3}}_{\text{loop suppressed}} \,\Big|\underbrace{A_t + A_W}_{\text{compensation}}\Big|^2$$

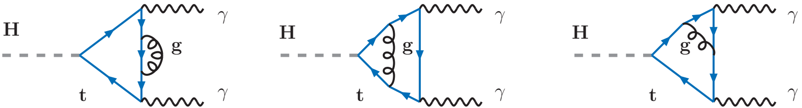






NLO QCD corrections

Two-loop (NLO) QCD corrections very well known since the '90s



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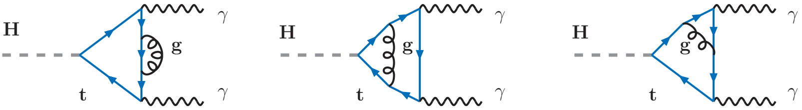

1) computed below the $t\bar{t}$ threshold, for $M_H < 2M_t$

Zheng,Wu'90,Djouadi,Spira,v.d.Bij,Zerwas'91,Dawson,Kauffmann'93

$\Rightarrow$ improved including 3 loops Steinhauser'96

2) result extended to the complete Higgs-mass range

Melnikov,Yakovlev'93,Djouadi,Spira,Zerwas'93,Inoue,Najima, Oka,Saito'94 $\Rightarrow$ analytic form Fleischer,Tarasov,Tarasov'04, Harlander,Kant'05,Aglietti,Bonciani,Degrassi,Vicini'06

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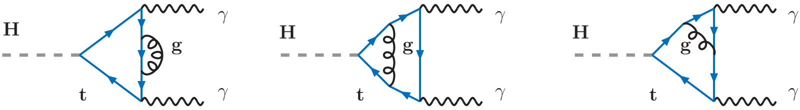

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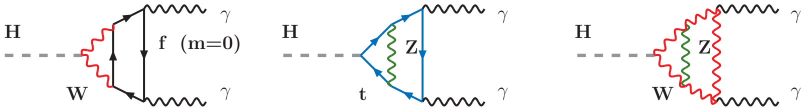
$M_H < 170\,\text{GeV}$ $\delta^{QCD} > 0$, monotonically decreasing, $\delta^{QCD} < 2\,\%$

NLO EW corrections

Two-loop (NLO) electroweak corrections recently studied



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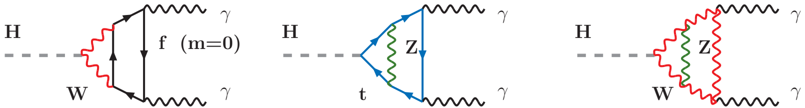

⇒ $G_F M_t^2$ with asymptotic expansion Liao,Li'96,Djouadi,Gambino, Kniehl'97,Fugel,Kniehl,Steinhauser'04

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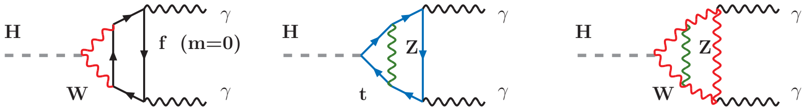

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Each result matches the size of QCD corrections, and should be taken into account when comparing with experiment for a % accuracy

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

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- Threshold singularities show up at the amplitude level

$$\mathcal{A}_{\rm NLO}(H \to \gamma\gamma) = \ldots + \underbrace{\frac{f(4M_W^2/M_H^2)}{\sqrt{4M_W^2 - M_H^2}}}_{M_H = 2M_W \to \infty} + \ldots$$

$\ast$ Minimal solution in known results: $M_W^2 \Rightarrow M_W^2 - i\Gamma_W M_W$ only in the square root to cure the divergent behaviour

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

Steps of the computation

Computation of all NLO EW corrections through 6 standard steps

1. Generate all Feynman diagrams contributing to $H \to \gamma\gamma$
2. Projection of $\mathcal{A}_{\rm NLO}$ on form factors F_i (Ward identity $\Rightarrow$ 1 FF)
3. Reduce F_i to basis integrals M_j ($\neq$ math. sense, no IBPIs)
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5. M_j divergent for $m_f \to 0$; $\mathcal{A}_{\rm NLO}$ finite for $m_f \to 0$

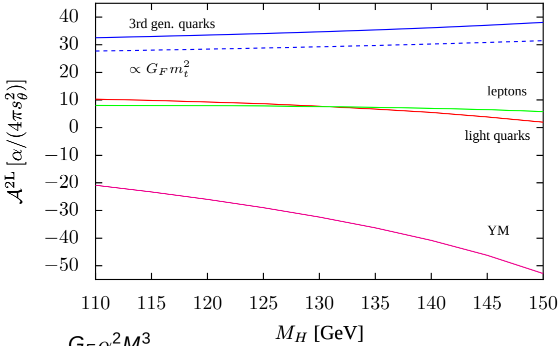
$$\Rightarrow \quad M_j = \underbrace{c_j \ln(m_f^2/s)}_{\rm analytically} + M_j^{\rm fin} \Rightarrow \underbrace{\sum c_j \ln(m_f^2/s) = 0}_{\rm amplitude} \Rightarrow m_f = 0$$

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

- FORM/FORTRAN [SA, Ferroglia, Passarino, Passera, Sturm, Uccirati]
- No special conceptual problems appear before crossing the *WW* threshold

EW corrections below 150 GeV

Anatomy of EW corrections to $\Gamma(H \to \gamma\gamma)$ for $110\text{ GeV} < M_H < 150\text{ GeV}$



M_H [GeV]	δ_{EW} [%]
115	−2.22
120	−1.93
125	−1.63
130	−1.28
135	−0.90
140	−0.47

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

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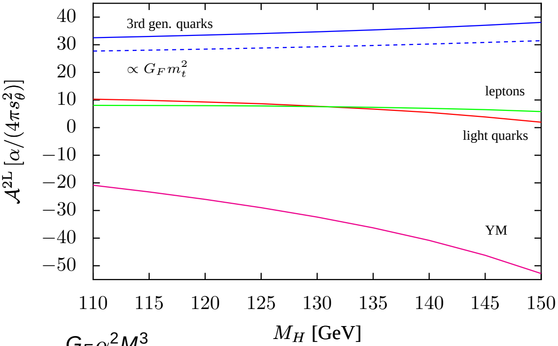

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- Agreement with lep and lq Aglietti, Bonciani, Degrassi, Vicini'04; corrected (renormalization) 3_{rd} gen. quarks and YM Degrassi, Maltoni'05
- 'Dominant' contributions $\propto G_F m_t^2$ Liao, Li'96, Djouadi, Gambino Kniehl'97, Fugel, Kniehl, Steinhauser'04 large but not dominant

Around the WW threshold: WI

1st problem with crossing of WW: WI violation for $H \to \gamma\gamma$

- WI $\to p_1^\mu \mathcal{A}_{\mu\nu} p_2^\nu = 0$ explicitly $\Rightarrow p_1^\mu \mathcal{A}_{\mu\nu} p_2^\nu \neq 0$ $(M_H^2 > 4\,M_W^2)$

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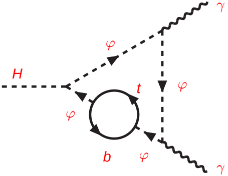
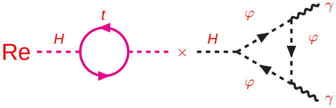
- Due to H mass renormalization $\Rightarrow \underbrace{m_H^2}_{\text{bare}} = \underbrace{M_H^2}_{\text{exp.}} \left[1 + \frac{G_F M_W^2}{2\sqrt{2}\,\pi^2}\, \mathrm{Re}\Sigma_H^{(1)}(M_H^2)\right]$
- At NLO there are two kinds of diagrams contributing to the Ward identity





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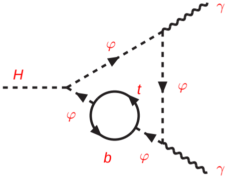

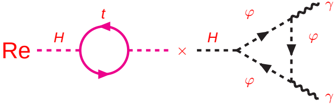

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- Below *WW* $\Rightarrow$ both diagrams are real, and the Ward id. is fulfilled
- Above *WW* $\Rightarrow$ mismatch imaginary parts (Re), and the Ward id. $\neq 0$

Around the VV threshold: square-root singularities

2nd problem with crossing of WW and ZZ: square-root singularities

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

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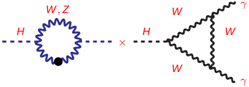

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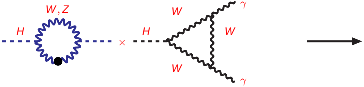

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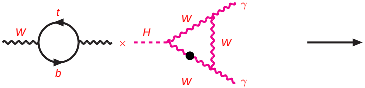

divergent for $\beta_W = 0$

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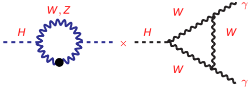

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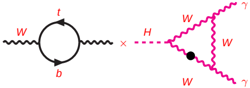
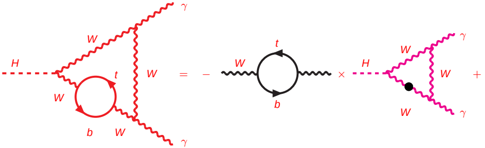


$\longrightarrow$ **divergent for** $\beta_W = 0$

3) (irr. 2-loop diagrams div.) $\Rightarrow$ sum 2) + 3) finite for $\beta_W = 0$ $\Rightarrow$ H WFR divergent

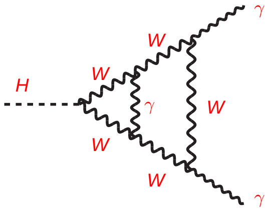


$\left(\begin{array}{l}\text{fin. part}\\ \text{for } \beta_W = 0\end{array}\right)$

Logarithmic singularity at the WW threshold

3rd problem with crossing of WW: logarithmic singularity

$\Rightarrow$ terms proportional to $\ln(-\beta_W^2 - i0)$ $\beta_W = \sqrt{1 - 4\,M_W^2/s}$



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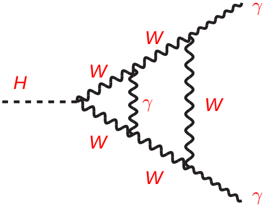

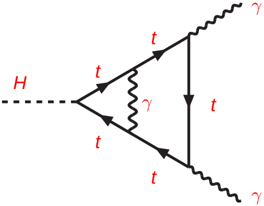

- same config. with t loop finite, ln multiplied by β_t^2 (spin structure)
- well known problem, studied beyond perturbation theory (resummation of Coulomb photons) Melnikov,Spira,Yakovlev'94

Complex poles

Cure problems with crossing of thresholds through complex poles:

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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 M_V^2 with $s_V = \mu_V(\mu_V - i\gamma_V)$ in both $A^{1,2}_{\mathrm{div}}$ and threshold factor β_V

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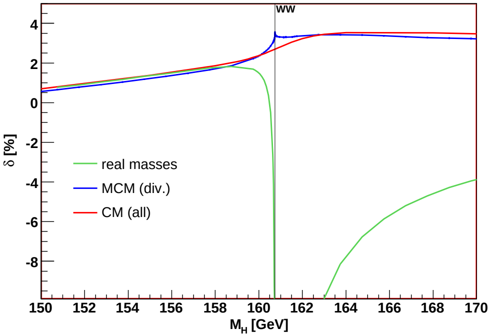
3) "Complete" introduction of complex poles

Replace M_V^2 with $s_V = \mu_V(\mu_V - i\gamma_V)$ in all divergent and finite terms

Replacement also at the level of the couplings in order to preserve gauge invariance CMS `Denner,Dittmaier,Roth,Wackeroth,Wieders'99-'05`

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



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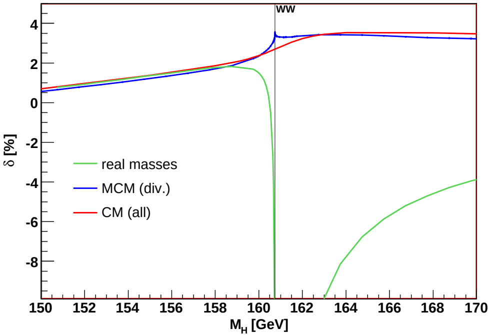
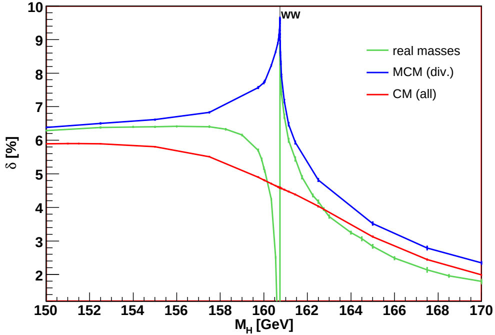


- Result obtained with real masses divergent at *WW*; good approx. below; completely off above threshold, since no cancellation mechanism occurs
- Result in MCM setup finite, shows cusp; result in CM setup is smooth
- At threshold, result in MCM setup $\to$ 3.5%; result in CM setup $\to$ 2.7%
  $\Rightarrow$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

Threshold behaviour for $gg \to H$

Threshold effects can be even artificially larger for other processes

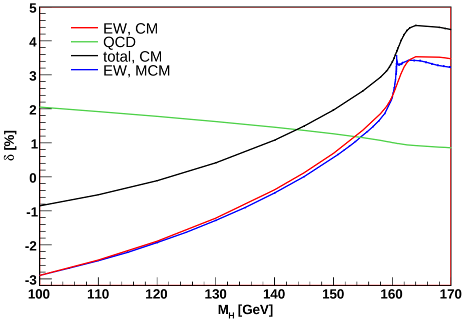
Comparison of EW corrections to $gg \to H$ around the WW threshold, obtained using different schemes for treating unstable particles



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

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



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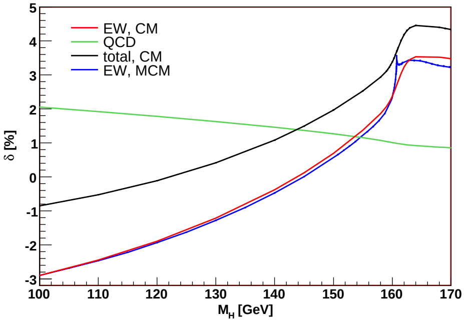

- QCD corrections > 0, ranging from $+1.8\%$ (120 GeV) to $+0.9\%$ (170 GeV)
- CMs in non-divergent terms smoothen threshold behaviour of EW effects; numerically they range from -1.9% (120 GeV) to $+3.5\%$ (170 GeV)
- EW effects compensate QCD ones for light Higgs masses, -0.1% (120 GeV); strong enhancement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

Conclusions

- The complete set of NLO EW corrections to $H \to \gamma\gamma$ ($gg \to H$) has been computed, compared with the existing results and extended around and above the WW threshold

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- Light Higgs, screening between QCD and EW NLO effects: $\boxed{M_H = 120\text{ GeV} \Rightarrow \delta = -0.1\%}$ $\to$ one order of magnitude less than the expected experimental accuracy at the ILC

Conclusions

- The complete set of NLO EW corrections to $H \rightarrow \gamma\gamma$ ($gg \rightarrow H$) has been computed, compared with the existing results and extended around and above the WW threshold
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- Light Higgs, screening between QCD and EW NLO effects: $\boxed{M_H = 120\text{ GeV} \Rightarrow \delta = -0.1\%}$ $\rightarrow$ one order of magnitude less than the expected experimental accuracy at the ILC
- Heavier Higgs, enhancement between QCD and EW NLO effects: $\boxed{M_H = 170\text{ GeV} \Rightarrow \delta = +4.4\%}$