Electroweak Corrections to Higgs Production and Decay

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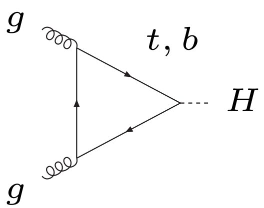
Plan of the Talk

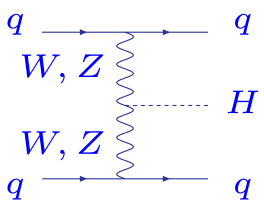
- Introduction
- Theoretical Predictions: QCD Radiative Corrections
- Theoretical Predictions: EW Radiative Corrections
  - Production: gg-Fusion and VBF
  - Decay: $H \to \gamma\gamma$ and $H \to WW/ZZ$
- Summary

SM Higgs production at the LHC

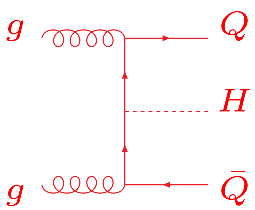
- Large gluon luminosity $\Longrightarrow$ dominant production mech.



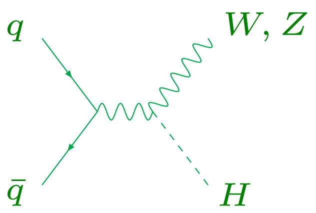
- VBF:

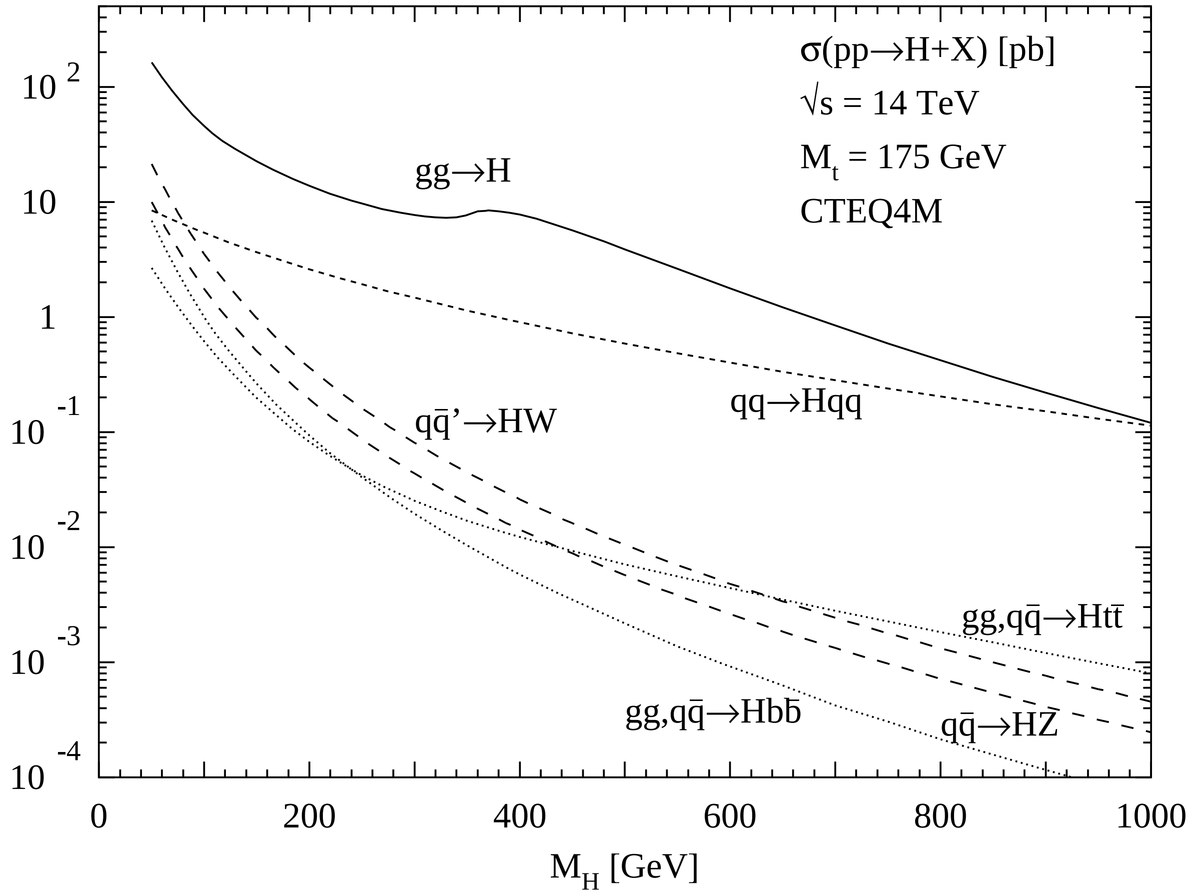


- Associated prod. with $Q\bar{Q}$:



- Associated prod. with W, Z:

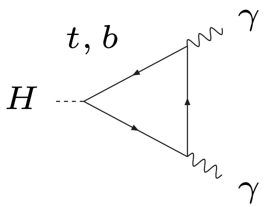




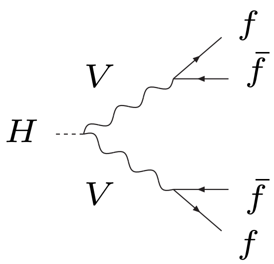
(Djouadi-Spira-Zerwas)

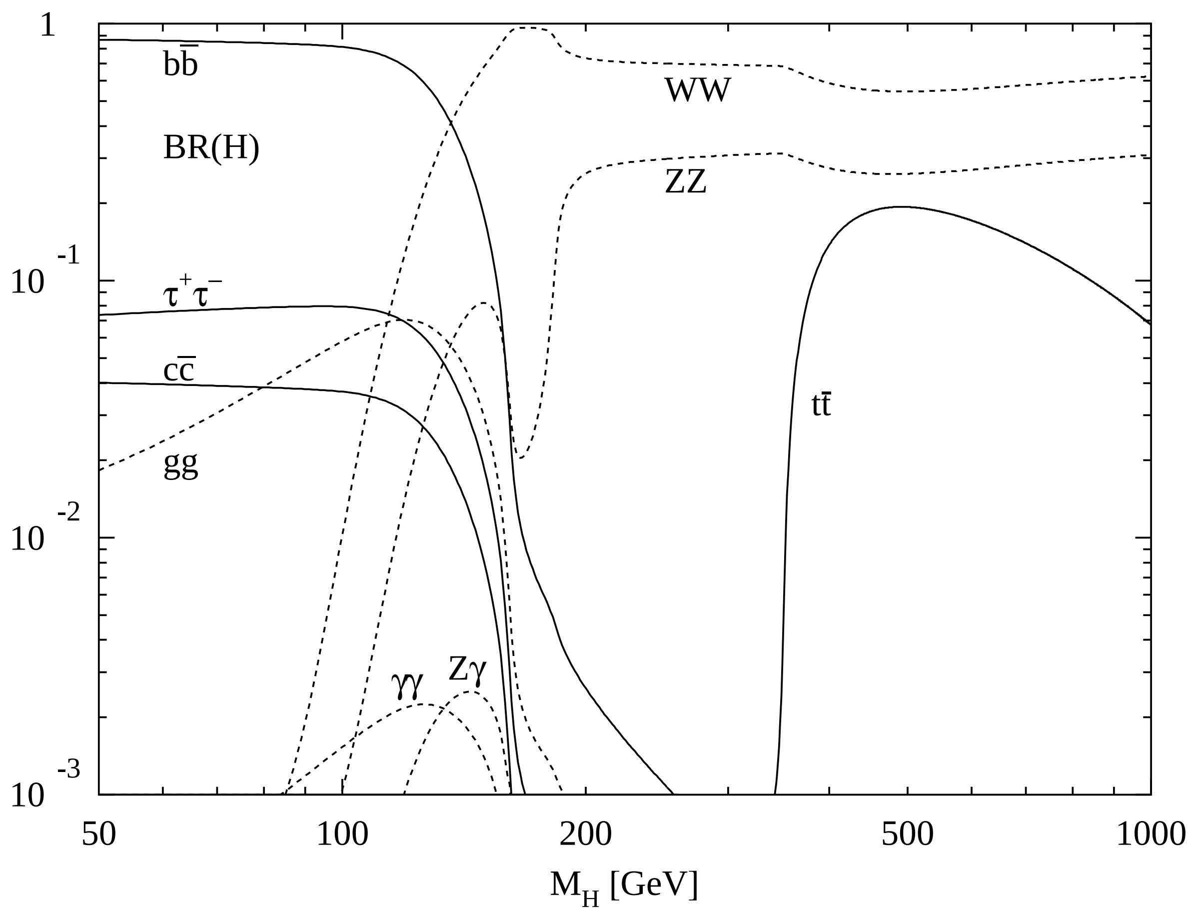
SM Higgs decays (BR)

- $\boxed{m_H < 140 \text{ GeV}}$ $H \to b\bar{b}$ dominant process, but at LHC huge QCD background!
  $H \to \gamma\gamma$ is a rare process ($BR \sim 10^{-3}$), but experimentally clean



- $\boxed{m_H > 140 \text{ GeV}}$ dominant decay channels are $H \to WW, ZZ$





(Djouadi-Spira-Zerwas)

SM predictions for Higgs production

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- LO corrections
  - Georgi-Glashow-Machacek-Nanopoulos ’78

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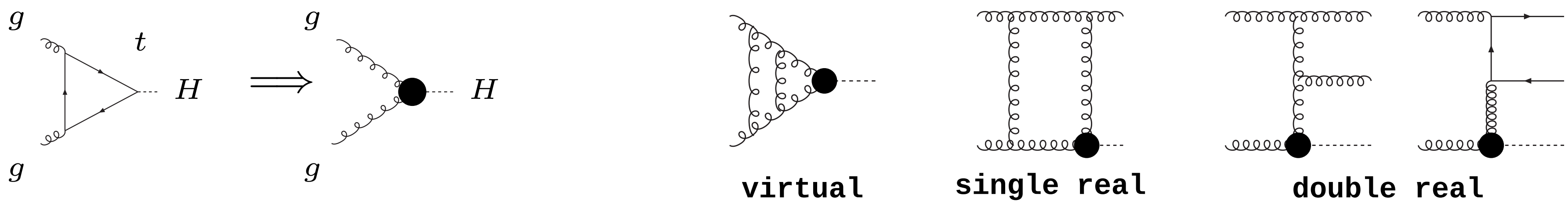

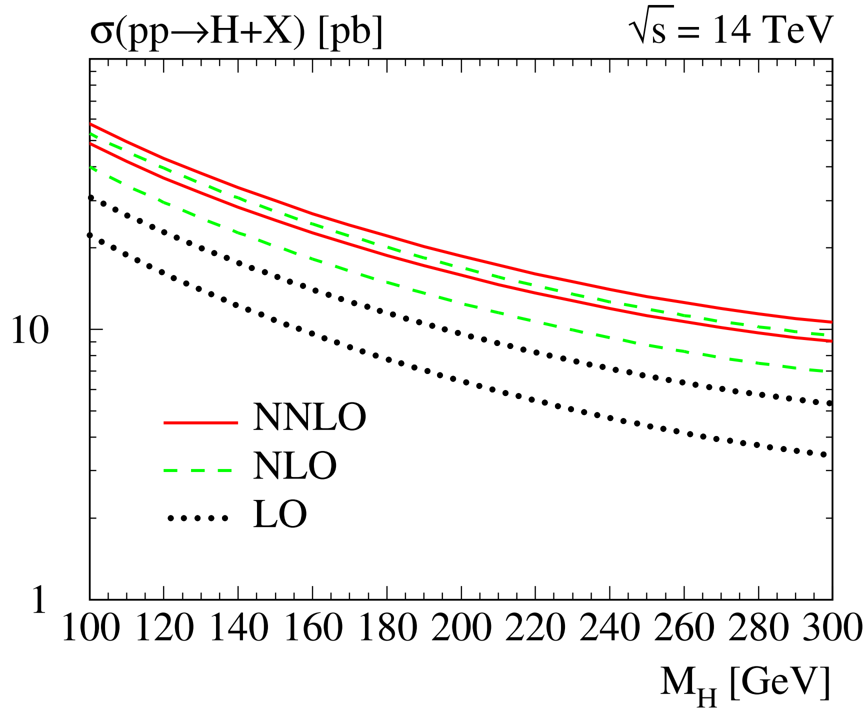

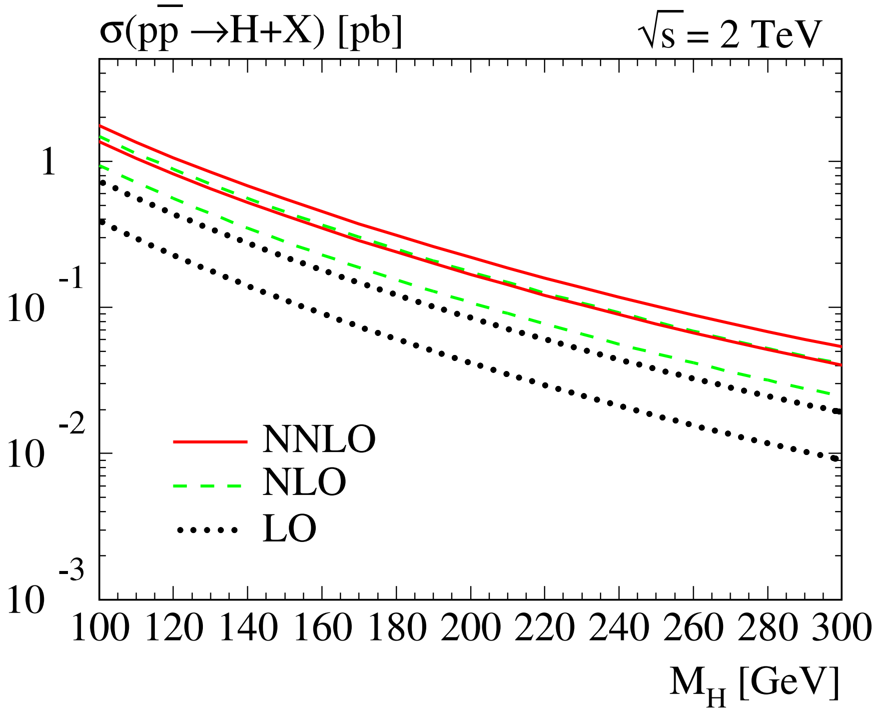

Gluon-fusion production cross section for a Standard Model Higgs boson at the LHC (14 TeV) and at the Tevatron (2 TeV) at leading, next-to-leading, and next-to-next-to-leading order.

Increase of 15-20% of the cross section.

(R. Harlander)

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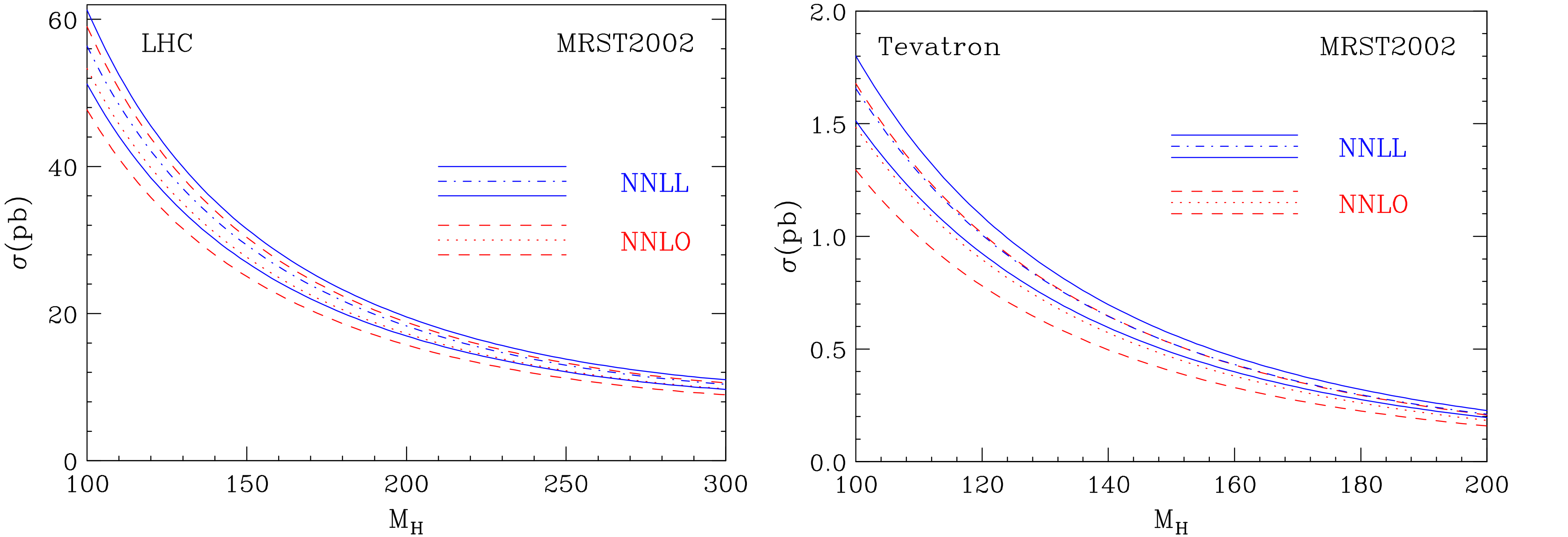
  - Catani-De Florian-Grazzini-Nason ’03

SM predictions for Higgs production



NNLL and NNLO cross-sections at the LHC (left) and Tevatron (right) using MRST2002 parton densities.

- Additional increase of the cross section $\sim 6\%$.
- Decrease in the scale dependence $\Longrightarrow$ Theoretical uncertainty $< 10\%$.

(Catani, de Florian, Grazzini and Nason)

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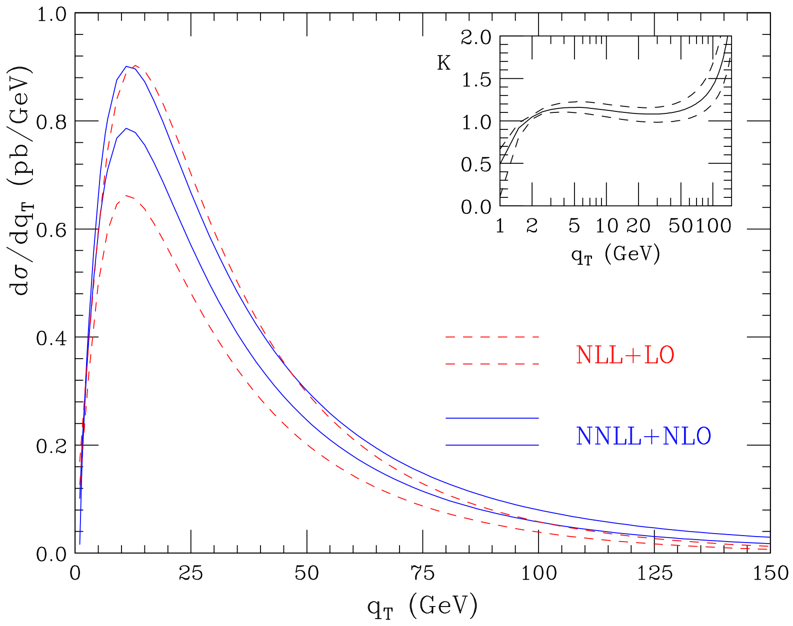
- Higher order corrections p_T distributions
  - De Florian-Grazzini-Kunst ’99, Del Duca-Kilgore-Oleari-Schmidt-Zeppenfeld ’01, Bozzi-Catani-De Florian-Grazzini ’03/’06

SM predictions for Higgs production

- For small transverse momentum ($q_T \ll m_H$) the q_T-spectrum is affected by large logarithms of the form $\alpha_S^n \ln^{2n}(m_H^2/q_T^2)$.
- They spoil the reliability of the perturbative series and they must be resummed.

LO+NLL and NLO+NNLL q_T-spectra for $m_H = 125$ GeV



(Bozzi, Catani, de Florian, Grazzini)

- Note that the NLO+NNLL band lies in the one of LO+NLL
- Enhancement of central value and reduction of the scale dependence

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- Rapidity distribution
  - Anastasiou-Dixon-Melnikov '03, Anastasiou-Melnikov-Petriello '04-'05, Catani-Grazzini '07

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- VBF:One Loop QCD corrections (NLO) increase the LO by 5-10%
  - Han-Valencia-Willenbrock ’91, Figy-Oleari-Zeppenfeld ’03, Campbell-Ellis ’03

SM predictions for Higgs Decay

$$\Gamma(H \to \gamma\gamma)$$

- One Loop (LO)
  - Ellis-Gaillard-Nanopoulos ’76, Shifman-Vainshtein-Voloshin-Zakharov ’79,
- Two-Loop QCD corrections (NLO)
  - Zheng-Wu ’90, Djouadi-Spira-van der Bij-Zerwas ’91, Dawson-Kauffman ’93, Djouadi-Spira-Zerwas ’93, Melnikov-Yakovlev ’93, Inoue-Najima-Oka-Saito ’94, Steinhauser ’96
  - Fleischer-Tarasov-Tarasov ’04, Harlander-Kant ’05, Anastasiou-Beerli-Bucherer-Daleo-Kunst ’06, Aglietti-B.-Degrassi-Vicini ’06, Passarino-Sturm-Uccirati ’07

Status of QCD Corrections

The message is that QCD is ok: corrections are known at the level of NNLO and the theoretical errors are under control (at the level of $< 10\%$ in the best cases).

Electroweak Corrections start to be important since

- They range around 5-8% (ore more) ad therefore they are comparable with the QCD theoretical error

So, consider the Electroweak corrections is now mandatory!

Brief overview of gg-fusion and VBF for the production and $H \to \gamma\gamma$ and $H \to WW, ZZ$ for the decay.

EW Corrections

SM predictions for Higgs production

Gluon fusion

- NLO EW corrections
  - Heavy-m_t expansion (Djouadi-Gambino ’94, Djouadi-Gambino-Kniehl ’98)
  - Light-fermions (Aglietti-B-Degrassi-Vicini ’04)
  - Top-quark contribution (Degrassi-Maltoni ’04)

Vector-Boson Fusion

- NLO EW corrections
  - Complete NLO EW (and QCD) corrections (Ciccolini-Denner-Dittmeier ’07)

Partonic Cross Section $\sigma(\mathrm{gg} \to \mathrm{H})$

Partonic Cross Section $\sigma(\mathrm{gg} \to \mathrm{H})$

The amplitude has the following structure:

$$T^{\mu\nu} = \left[q_1^{\nu}\, q_2^{\mu} - (q_1 \cdot q_2)\, g^{\mu\nu} \right] T_5$$

The cross-section is given by:

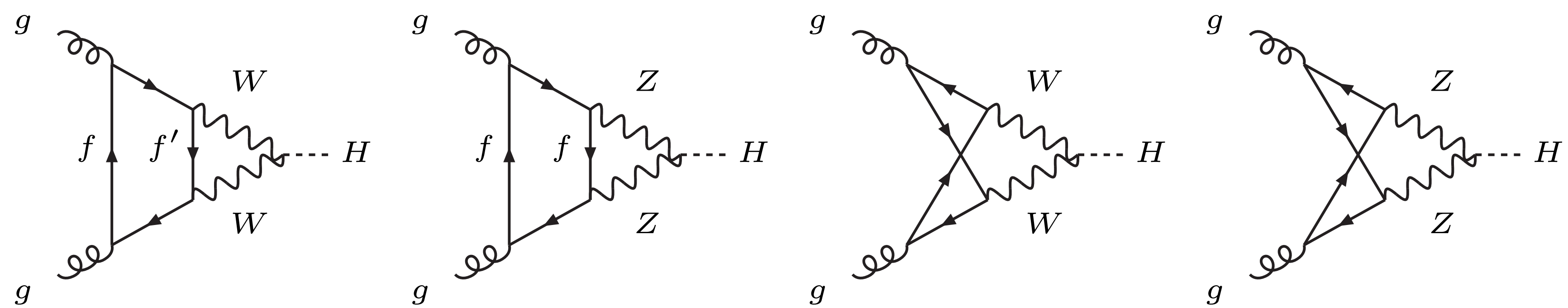
$$\boxed{\sigma(gg \to H) = \frac{G_\mu {\alpha_S}^2}{512\sqrt{2}\pi} \left| \mathcal{G} \right|^2}$$

- G_μ, α_S are respectively the Fermi constant and the strong coupling constant
- $\mathcal{G} = T_5$

The form factor $\mathcal{G}$ can be calculated in perturbation theory:

$$\mathcal{G} = \mathcal{G}^{(1l)}_{QCD} + \frac{\alpha_S}{\pi} \mathcal{G}^{(2l)}_{QCD} + \frac{\alpha m_W^2}{2\pi m_H^2 s_W^2} \mathcal{G}^{(2l)}_{EW} + \left(\frac{\alpha_S}{\pi} \right)^2 \mathcal{G}^{(3l)}_{QCD}$$

Light-fermion Contributions to $\mathcal{G}^{(2l)}_{\mathrm{EW}}$

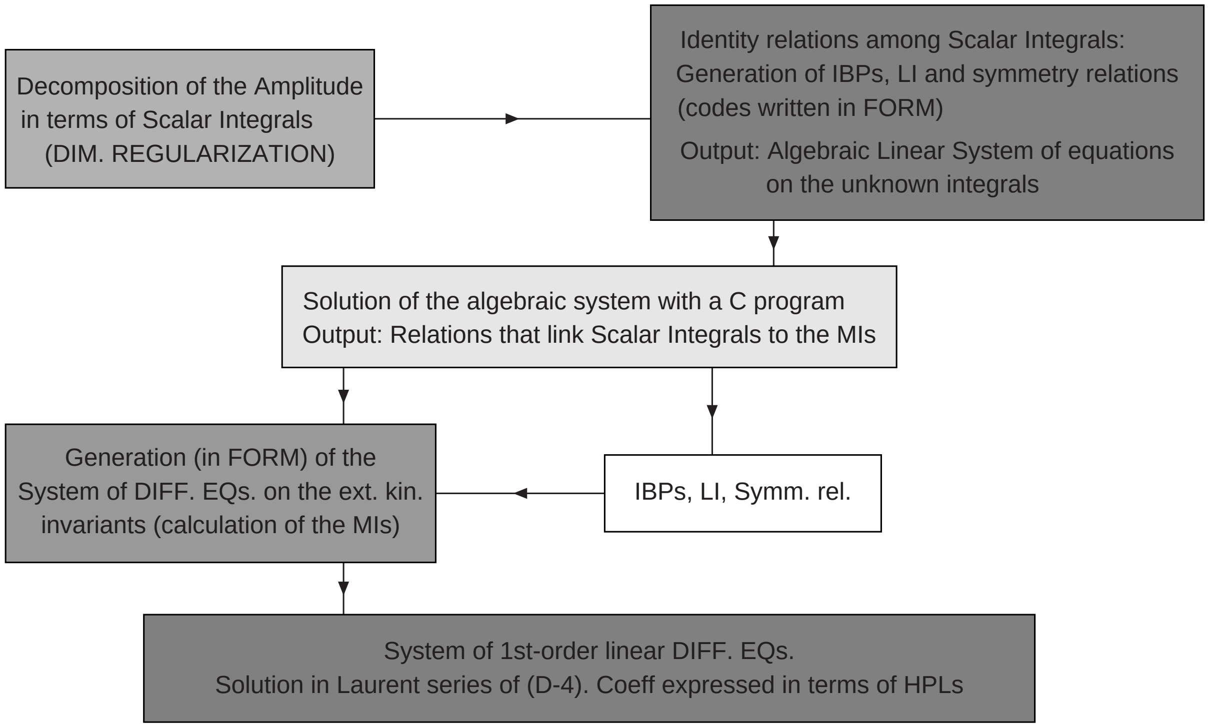


Laporta Algorithm

- Reduction to the MIs

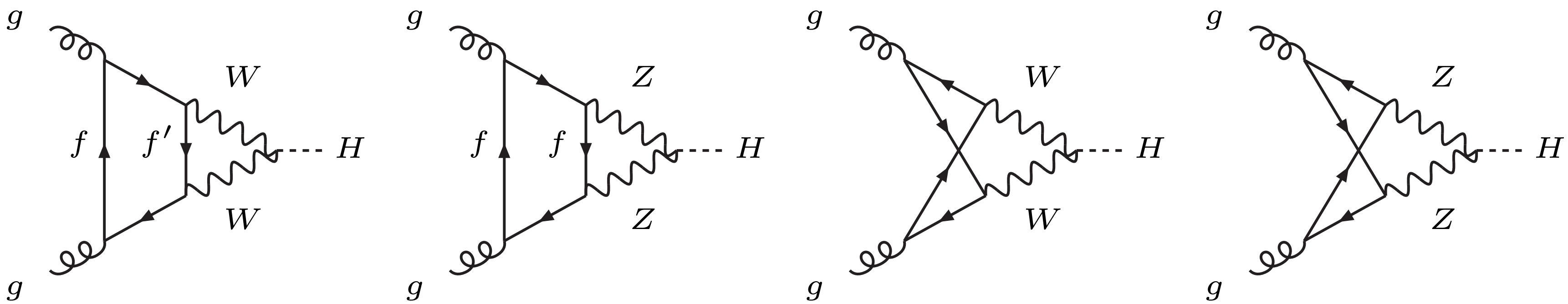
Differential Equations

- Analytic evaluation of the MIs



(Aglietti-B-Degrassi-Vicini ’04)

Light-fermion Contributions to $\mathcal{G}^{(2l)}_{\rm EW}$



$$\mathcal{G}^{2l}_{EW} = \frac{2}{c^4}\left(\frac{5}{4} - \frac{7}{3}\,s^2 + \frac{22}{9}\,s^4\right) A_1\,[z_H] + 4\,A_1\,[w_H]$$

Laporta Algorithm

- Reduction to the MIs

$$w_H \equiv m_W^2/m_H^2\,,\quad z_H \equiv m_Z^2/m_H^2\,,\quad s^2 \equiv \sin^2\theta_W\,,\quad c^2 = 1 - s^2$$

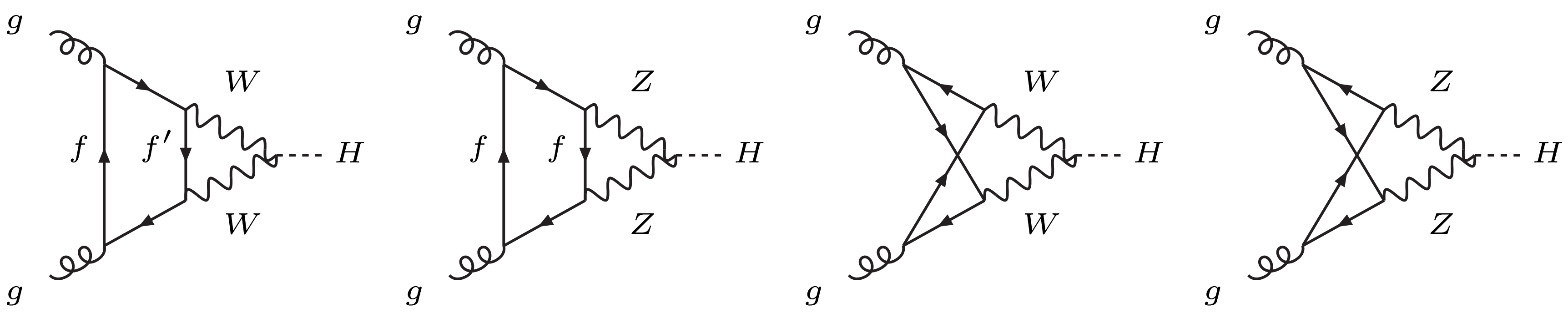
Differential Equations

- Analytic evaluation of the MIs

$$\begin{aligned} A_1\,[x] = {} & -4 + 2(1-x)H\left(-1; -\frac{1}{x}\right) - 2\,x\,H\left(0,-1;-\frac{1}{x}\right) + 2(1-3x)H\left(0,0,-1;-\frac{1}{x}\right) \\ & + 2\,(1-2\,x)\;H\left(0,-r,-r;-\frac{1}{x}\right) - 3\,(1-2\,x)\;H\left(-r,-r,-1;-\frac{1}{x}\right) \\ & - \sqrt{1-4\,x}\,\left[2\,H\left(-r;-\frac{1}{x}\right) - 3\,(1-2\,x)\;H\left(-4,-r,-1;-\frac{1}{x}\right)\right. \\ & \left. + 2\,(1-2\,x)\,H\left(-r,0,-1;-\frac{1}{x}\right) + 2\,(1-2\,x)\,H\left(-r,-r,-r;-\frac{1}{x}\right)\right] \end{aligned}$$

(Aglietti-B-Degrassi-Vicini ’04)

Light-fermion Contributions to $\mathcal{G}_{\mathrm{EW}}^{(2l)}$



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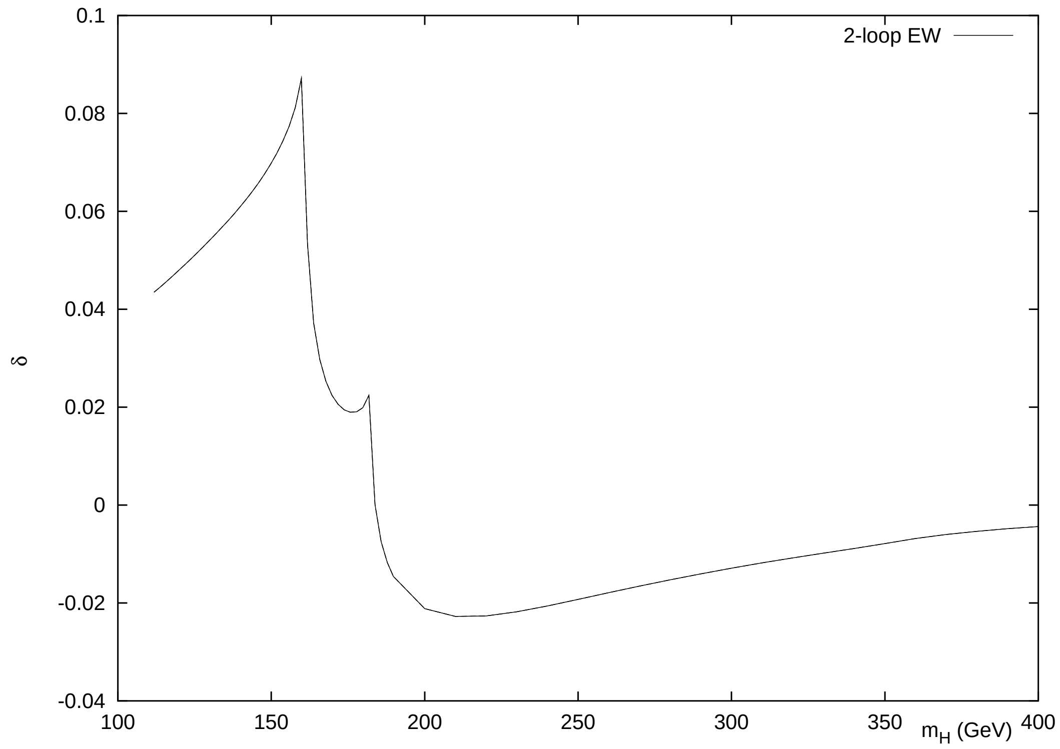
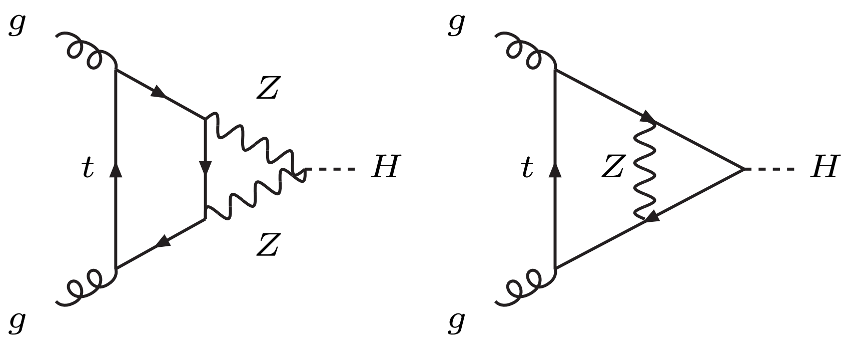


(Aglietti-B-Degrassi-Vicini ’04)

Remaining EW Contributions to $\mathcal{G}^{(2l)}_{\mathrm{EW}}$



Evaluation of the Feynman diagrams in Taylor expansion in the variable $h_{4w} = q^2/(4m_W^2)$.
The leading term is

$$\mathcal{G}^{2l}_{EW} = \frac{1}{w_t}\left[1 + \frac{2t_H+1}{4(4t_H-1)} + \frac{t_H(2t_H-5)}{2(4t_H-1)^2}\log t_H - \frac{t_H(2t_H^2+1)}{2(4t_H-1)^2}\phi\left(\frac{1}{4t_H}\right)\right] - \frac{28}{9} - \frac{7}{18c^2}$$
$$+\frac{1}{w_H}\left[\frac{w_t-1-\log w_t}{3(w_t-1)^2} + \frac{5z_t-2}{12(z_t-4)^2} + \frac{46-19z_t}{6(z_t-4)^3}\log z_t + \frac{z_t^2-6}{2z_t(z_t-4)^3}\phi\left(\frac{z_t}{4}\right)\right]$$
$$+\mathcal{O}(h_{4w})$$

where $z_t = m_Z^2/m_t^2$ and $\phi(z) = 4\sqrt{\frac{z}{1-z}}\,Cl_2(2\arcsin\sqrt{z})$,

(Degrassi-Maltoni '04)

The Hadronic Cross Section

Fortran code by S. Catani, D. de Florian, M. Grazzini, *JHEP* 0105:025 (2001); *JHEP* 0201:015 (2002)
Evaluation of the hadronic cross-section with pdf MRST 2002 at NLO and NNLO

$$\sigma(p+p \to H+X) = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_{a,p}(x_1,\mu_F^2)\, f_{b,p}(x_2,\mu_F^2) \times$$
$$\times \int_0^1 dz\, \delta\left(z - \frac{\tau_H}{x_1 x_2}\right) (1+\delta_{EW}(m_H))\, \hat{\sigma}_{ab}(z)$$

$$\hat{\sigma}(z) = \hat{\sigma}_0 \left[1 + K_{ab}^{QCD\,only}(\alpha_s(\mu^2),\mu^2,\mu_F^2)\right]$$
$$K_{ab}^{QCD\,only} = \left[c_1 \frac{\alpha_s(\mu^2)}{\pi} + c_2 \left(\frac{\alpha_s(\mu^2)}{\pi}\right)^2\right] \delta(m_H^2 - x_1 x_2 S) +$$
$$+ \left[k_1 \frac{\alpha_s(\mu^2)}{\pi} + k_2 \left(\frac{\alpha_s(\mu^2)}{\pi}\right)^2\right]$$

- c_1, c_2 describe the 2-, 3-loop QCD corrections to $gg \to H$
- k_1, k_2 describe the effect of radiation of real gluons

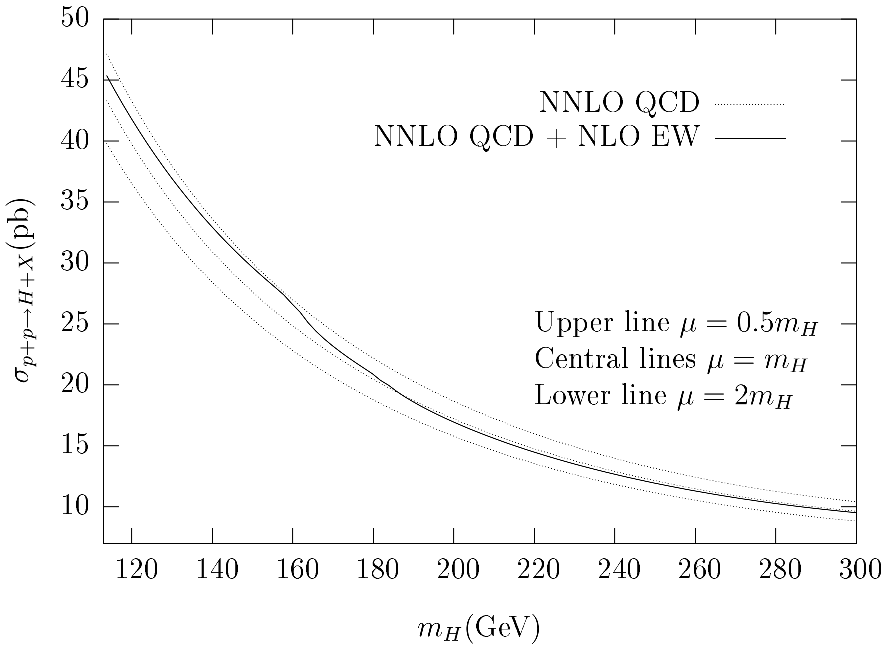
The Electroweak Corrections

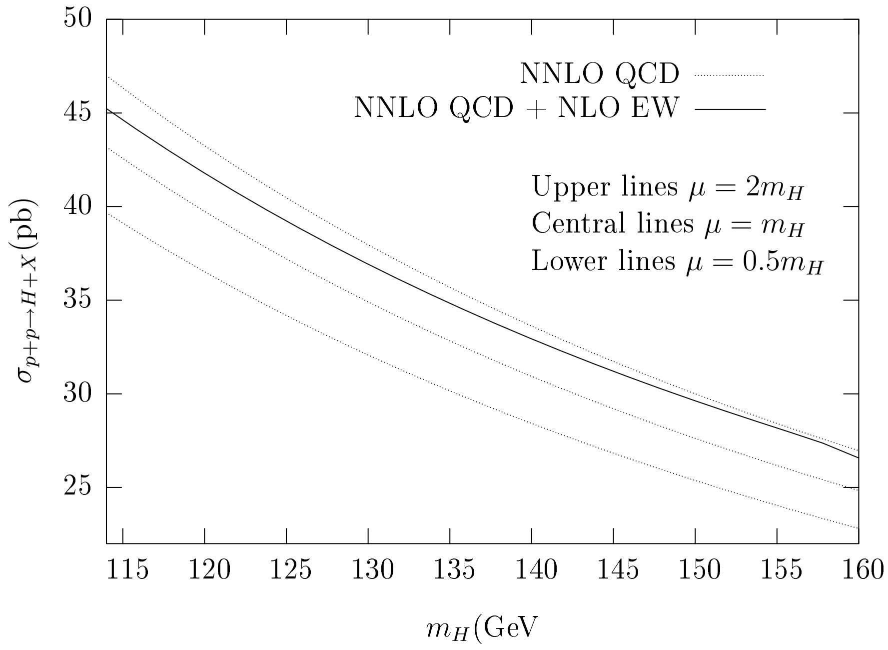
The EW corrections in the “intermediate mass range” ($114\,$GeV $< m_H < 155\,$GeV) can be parametrized by the following simple formula:

$$\delta_{EW}(m_H) = 0.00961 + 6.9904 \cdot 10^{-5}\, m_H + 2.31508 \cdot 10^{-6}\, m_H^2$$

m_H (GeV)	δ_{EW}	m_H (GeV)	δ_{EW}	m_H (GeV)	δ_{EW}	m_H (GeV)	δ_{EW}
114	0.048	136	0.062	158	0.077	180	0.020
116	0.049	138	0.063	160	0.069	182	0.010
118	0.050	140	0.065	162	0.063	184	0.010
120	0.051	142	0.066	164	0.049	186	0.002
122	0.053	144	0.068	166	0.041	188	0.997
124	0.054	146	0.069	168	0.035	190	0.994
126	0.055	148	0.071	170	0.031	192	0.991
128	0.056	150	0.073	172	0.028	194	0.989
130	0.058	152	0.074	174	0.026	196	0.987
132	0.059	154	0.076	176	0.024	198	0.986
134	0.060	156	0.077	178	0.022	200	0.985

The Electroweak Corrections





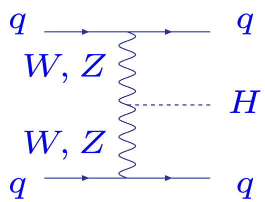
- Enhancement of the cross section of about 6-8% in the intermediate mass range (it has to be taken into account for reliable analysis) $\sim$ of the order of the QCD theoretical error.
- Full EW corrections available in the region $m_H < 2m_W$. For $m_H > 2m_W$ EW corrections negligible.

Vector Boson Fusion

Vector Boson Fusion

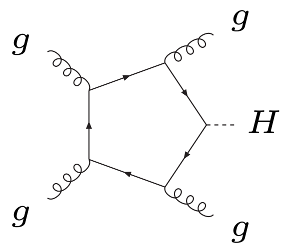
Process: $pp \longrightarrow H + 2jets$

- VBF (Vector Boson Fusion)



(jets forward-backward)

- “Other” contributions



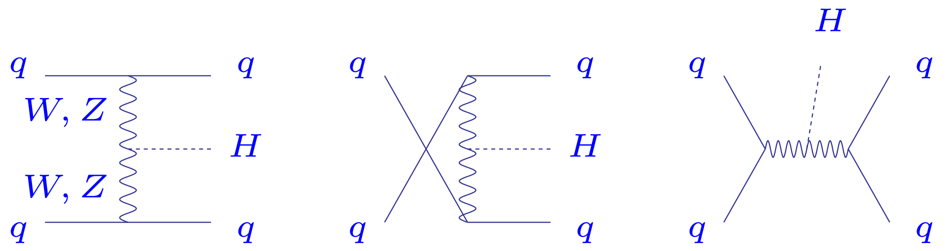
(Campbell-Ellis-Zanderighi)

⇒ VBF can be easily resolved over the background (imposing suitable cuts: p_T, central-jet veto ...)

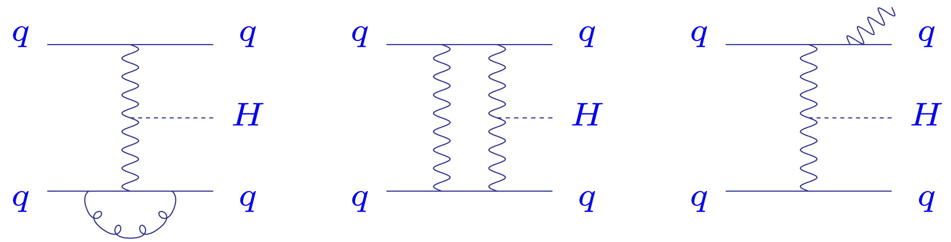
After VBF cuts, the “Other” contributions are reduced to the 4-5% of the channel $pp \longrightarrow H + 2jets$.

Vector Boson Fusion

- LO



- NLO



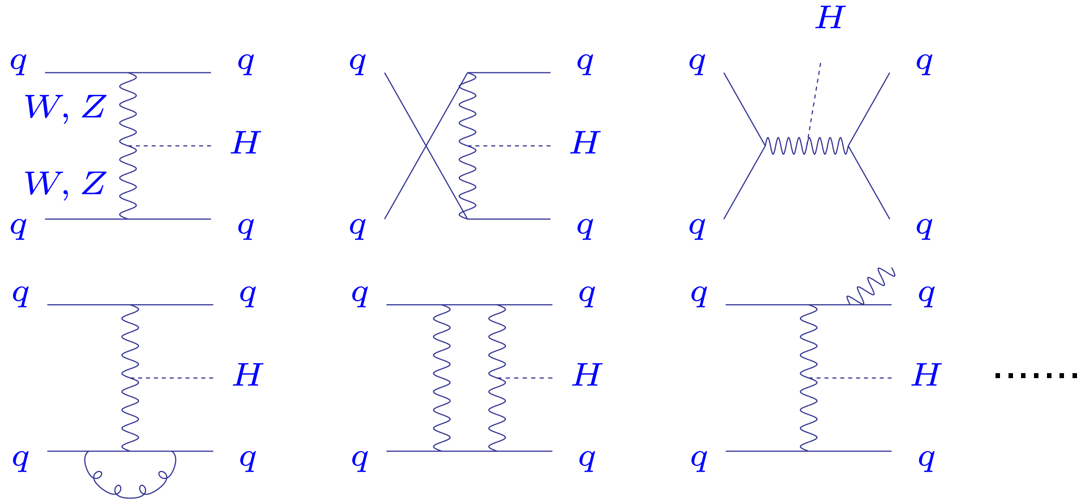
....

- all the diagrams related by crossing symmetry to $H \to q\bar{q}q\bar{q}$ (Bredenstein-Denner-Dittmaier-Weber)
- Masses of q neglected except in the logs
- W and Z in the complex mass scheme (Denner-Dittmaier-Roth-Wieders)
- Reduction to the scalar MIs with Passarino-Veltman for 2-, 3-, and 4-point functions; Denner-Dittmaier NPB734(2006)62 for the pentagons

(Ciccolini-Denner-Dittmaier '07)

Vector Boson Fusion

- LO
- NLO



m_H[GeV]	120	150	170	200
σ_{LO} [fb]	5936(1)	4271(2)	3536(1)	2743(1)
σ_{NLO} [fb]	5890(2)	4219(2)	3538(1)	2775(1)
δ_{QCD} [%]	4.04(3)	3.47(2)	3.72(2)	4.48(2)
δ_{EW} [%]	−4.81(2)	−4.70(2)	−3.65(1)	−3.33(1)
$\delta_{\gamma-induced}$ [%]	0.86(1)	1.04(1)	1.14(1)	1.27(1)

(Ciccolini-Denner-Dittmaier '07)

SM predictions for Higgs decay

$$\Gamma(H \to \gamma\gamma)$$

- Two-Loop EW corrections (NLO)
  - corrections at $\mathcal{O}(G_\mu m_t^2)$ (Liao-Li '97)
  - corrections at $\mathcal{O}(G_\mu m_H^2)$ (Korner-Melnikov-Yakovlev '96)
  - exact light-fermion contribution (Aglietti-B.-Degrassi-Vicini '04)
  - contributions involving top and weak bosons below W thr. (Degrassi-Maltoni '05)
  - full EW contributions (Passarino-Sturm-Uccirati '07)

$$\Gamma(H \to WW, ZZ)$$

- LO (W,Z on shell)
  - Pocsik-Torma '80, Rizzo '80, Keung-Marciano '84
- NLO and higher orders (W,Z on shell)
  - Fleischer-Jegerlehner '81, Kniehl '91, Kniehl-Spira '95, Kniehl-Steinhouser '96, Djouadi-Gambino-Kniehl '98
- One-Loop EW corrections (NLO), Z,W off-shell
  - QED corrections (Carloni Calame-Moretti-Montagna-Nicrosini-Piccinini-Polosa '06)
  - full EW corrections $H \to 4f$ (Bredenstein-Denner-Dittmaier-Weber '06/'07)

Decay width $\Gamma(\mathrm{H} \to \gamma\gamma)$

The amplitude has the following structure:

$$T^{\mu\nu} = \left[q_1^\nu \, q_2^\mu \; - (q_1 \cdot q_2) \, g^{\mu\nu} \right] \mathcal{F}$$

Once the form factor $\mathcal{F}$ is known, the Decay width can be expressed as follows:

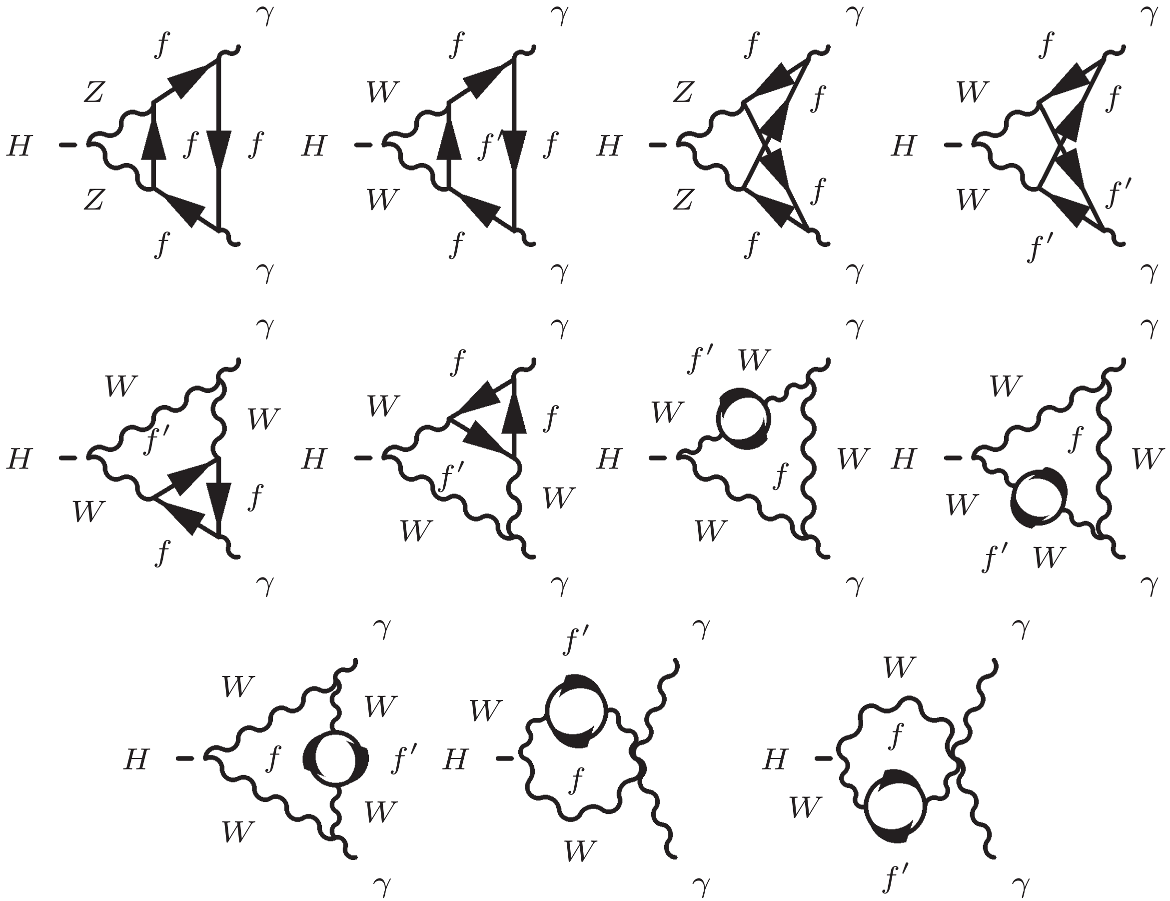
$$\boxed{\Gamma(H \to \gamma\gamma) = \frac{G_\mu \alpha^2 m_H^3}{128\sqrt{2}\pi^3} \, |\mathcal{F}|^2}$$

- G_μ, α and m_H are respectively the Fermi constant, fine-structure constant and mass of the Higgs boson

The form factor $\mathcal{F}$ can be calculated in perturbation theory:

$$\mathcal{F} = \mathcal{F}_{QCD}^{(1l)} + \mathcal{F}_{EW}^{(1l)} + \frac{\alpha_S}{\pi} \mathcal{F}_{QCD}^{(2l)} + \frac{\alpha m_W^2}{2\pi m_H^2 s_W^2} \mathcal{F}_{EW}^{(2l)}$$

Light-fermion contr to H $\to \gamma\gamma$



Light-fermion contr to H $\to \gamma\gamma$

$$\mathcal{F}^{2l}_{EW} = 2N_c A_2\left[-2/9, w_H\right] + 3A_2\left[0, w_H\right] + \frac{2N_c}{c^4}\left(\frac{11}{36} - \frac{19}{27}s^2 + \frac{70}{81}s^4\right) A_1\left[z_H\right]$$
$$+\frac{3}{c^4}\left(\frac{1}{2} - 2s^2 + 4s^4\right) A_1\left[z_H\right]$$

where: $w_H = m_W^2/m_H^2$, $t_H = m_t^2/m_H^2$

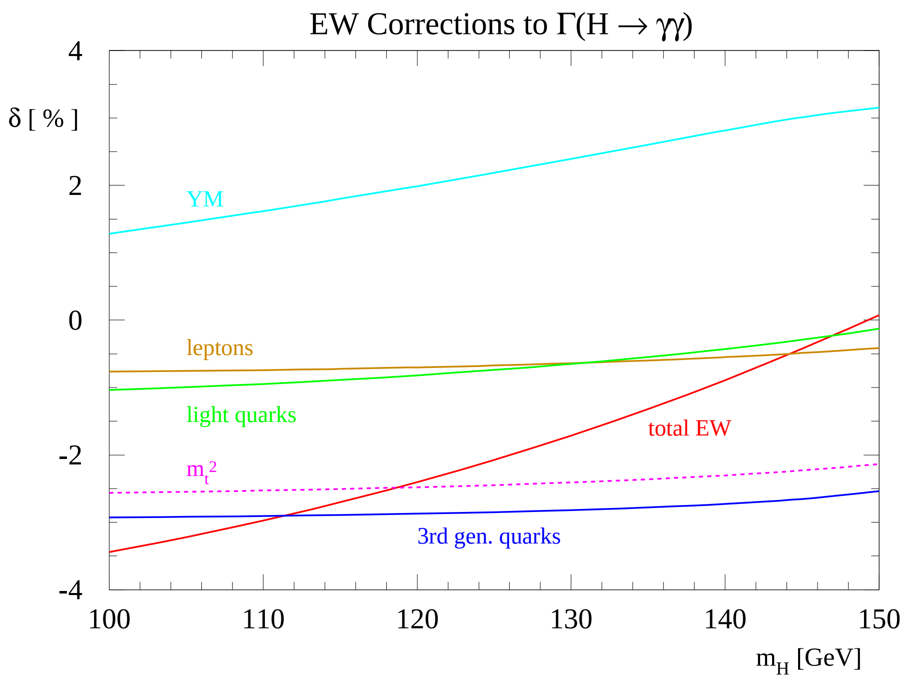
$$A_2[q,x] = -8(1+q)+4(1+q)(1-x)H\left(-1;-\frac{1}{x}\right) - 2(1+2qx)H\left(0,-1;-\frac{1}{x}\right) - \frac{2}{3}(5-12x)H\left(-r,-r;-\frac{1}{x}\right)$$
$$-6(1+q-3x-2qx)H\left(-r,-r,-1;-\frac{1}{x}\right)+2(1+2q)\Bigg[(1-2x)H\left(0,-r,-r;-\frac{1}{x}\right)$$
$$+(1-3x)H\left(0,0,-1;-\frac{1}{x}\right)\Bigg] - \sqrt{1-4x}\Bigg\{2(1+2q)H\left(-r;-\frac{1}{x}\right) - 6q(1-2x)H\left(-4,-r,-1;-\frac{1}{x}\right)$$
$$+4q(1-2x)\left[H\left(-r,0,-1;-\frac{1}{x}\right) + H\left(-r,-r,-r;-\frac{1}{x}\right)\right]\Bigg\} + \frac{6(1-2x)^2}{\sqrt{1-4x}} H\left(-r,-1;-\frac{1}{x}\right)$$

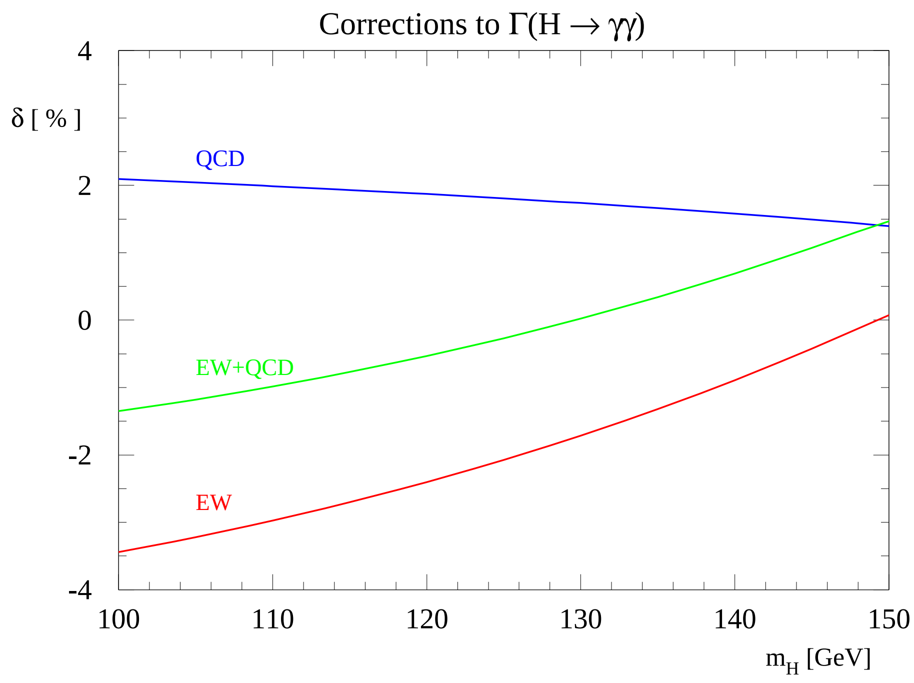
$$A_1[x] = -4+2(1-x)H\left(-1;-\frac{1}{x}\right)-2xH\left(0,-1;-\frac{1}{x}\right)+2(1-3x)H\left(0,0,-1;-\frac{1}{x}\right)$$
$$+2(1-2x)H\left(0,-r,-r;-\frac{1}{x}\right)-3(1-2x)H\left(-r,-r,-1;-\frac{1}{x}\right) - \sqrt{1-4x}\Bigg[2H\left(-r;-\frac{1}{x}\right)$$
$$-3(1-2x)H\left(-4,-r,-1;-\frac{1}{x}\right)+2(1-2x)H\left(-r,0,-1;-\frac{1}{x}\right)+2(1-2x)H\left(-r,-r,-r;-\frac{1}{x}\right)\Bigg]$$

Decay H $\rightarrow \gamma\gamma$: Complete EW Corrections

In the intermediate mass range (100GeV $< m_H < 150$GeV) the EW corrections to the decay process $H \rightarrow \gamma\gamma$ are known analytically and they are complete.

- The net effect is a cancellation between the QCD and EW NLO corrections



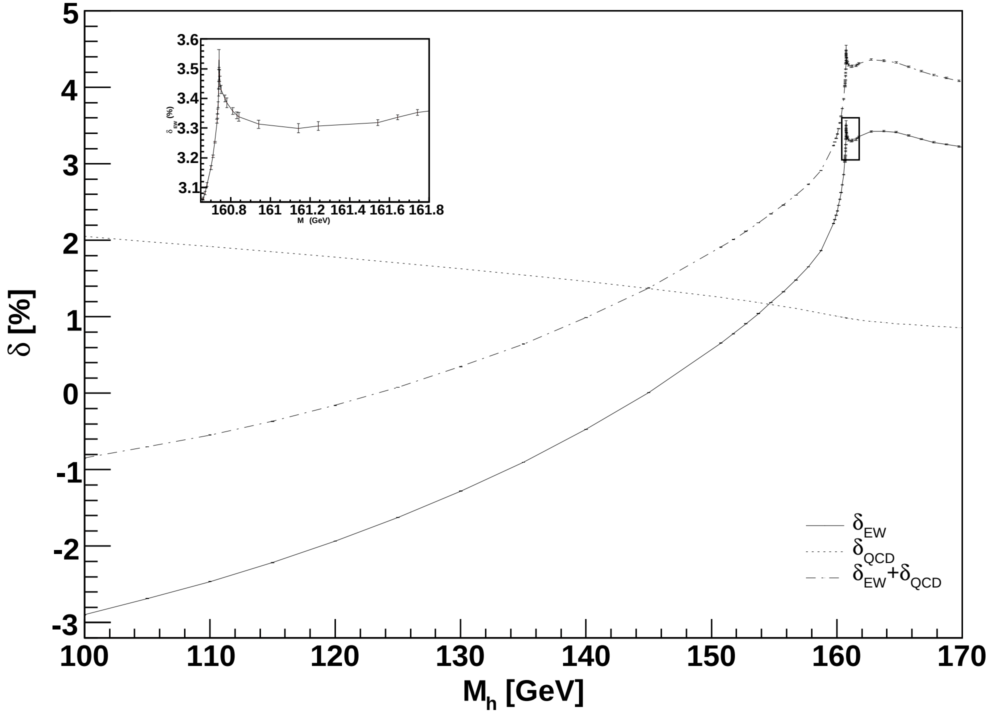


In the plots $m_t = 178$ GeV.

(Degrassi-Maltoni '05)

$\Gamma(\mathrm{H} \to \gamma\gamma)$: Numerical Approach

- Numerical method (but eventual divergencies extracted analitycally)
- W,Z in the complex-mass scheme (Denner et al.)
- The numerics for the $\Gamma(H \to \gamma\gamma)$ is in agreement with the existing results



In the plot $m_t = 170.9$ GeV

(Passarino-Sturm-Uccirati '07)

Decay H $\rightarrow$ 4f

- $\boxed{155\text{GeV} < m_H < 180\text{GeV}}$ highest discovery potential $H \rightarrow WW \rightarrow l\nu l\nu$
- $\boxed{m_H > 130\text{GeV}}$ “golden-plated” channel $H \rightarrow ZZ \rightarrow 4l$

Signals with lepton are preferable for LHC because of the huge QCD background

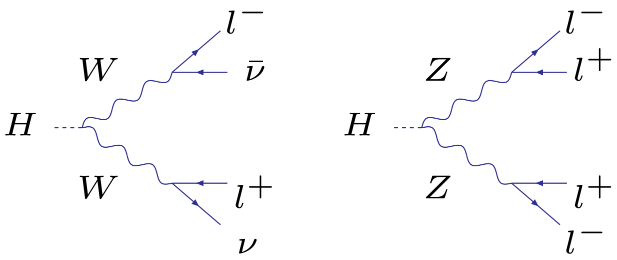
$H \rightarrow 4l$ allows a very accurate determination of the Higgs mass, because of the narrow invariant-mass peak

$H \rightarrow l\nu l\nu$ is basically 2 leptons + missing p_T (no narrow mass peak)

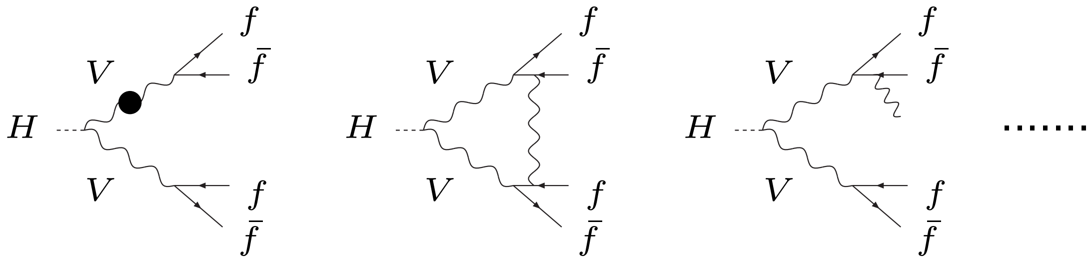
Very important the distributions for investigate the properties of the Higgs (for instance the ϕ angle between the two plains of the Z decays is connected to the spin and CP properties of the Higgs)

Decay width $\Gamma(H \to 4f)$

- LO



- NLO

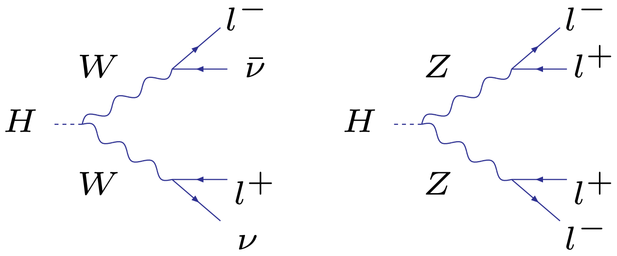


- W and Z in the complex mass scheme (Denner-Dittmaier-Roth-Wieders)
- Reduction to the scalar MIs with Passarino-Veltman for 2-, 3-, and 4-point functions; Denner-Dittmaier NPB734(2006)62 for the pentagons
- partial decay width, invariant-mass distributions, angular distributions

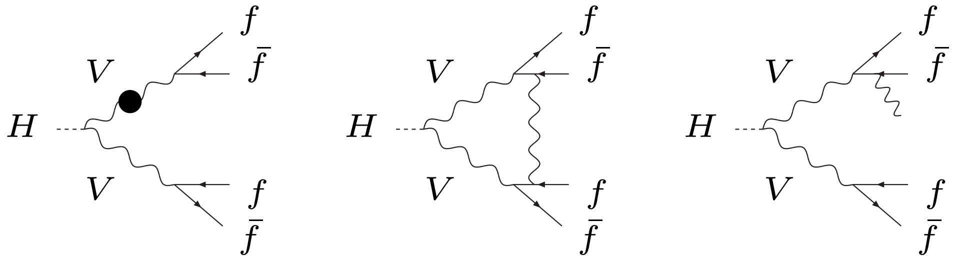
(Bredenstein-Denner-Dittmaier-Weber '07)

Decay width $\Gamma(H \to 4f)$

- LO



- NLO



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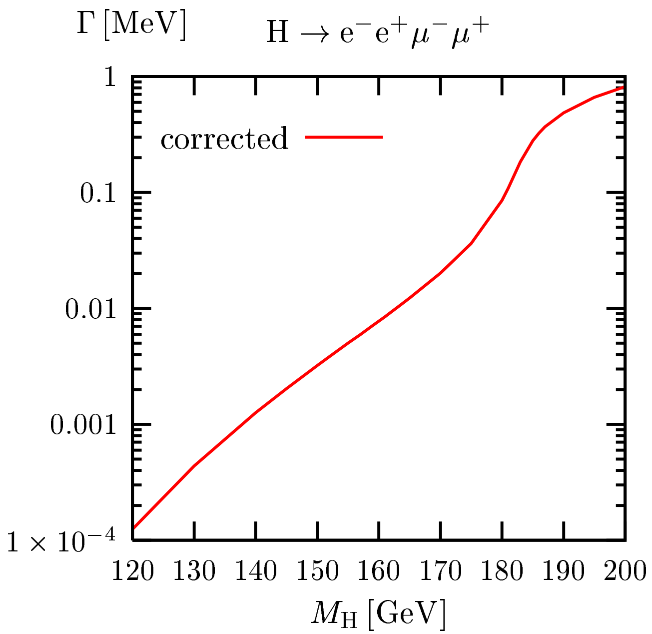

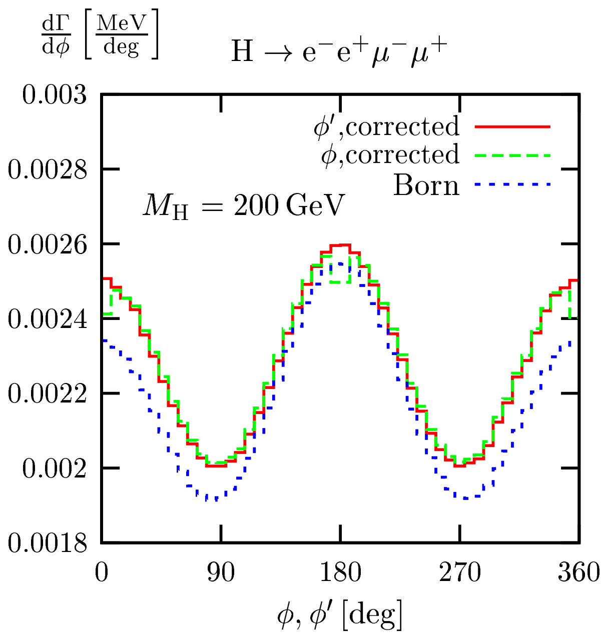

(Bredenstein-Denner-Dittmaier-Weber ’07)

Summary

- In the last 6-7 years there was a big activity in the study of the theoretical predictions for the Higgs boson at LHC.
- QCD corrections are now known at the level of NNLO (in the heavy-m_t limit). For some observables the resummation of large logarithms was carried out at the level of NNLL. The theoretical errors are at the level of < 10% in the best cases.
- In this situation, having an appropriate description of the EW effects is mandatory.
- I presented the calculation of the two-loop EW corrections to gg-fusion and $H \to \gamma\gamma$. As a net effect we register an enhancement of the total cross section $\sigma(pp \to H + X)$ of up to 8% in the intermediate mass range and a substantial cancellation of QCD and EW corrections in the decay width $\Gamma(H \to \gamma\gamma)$.
- Very recently the PSI-MPI group completed the calculation the NLO EW (and QCD) corrections for the VBF and the decay $H \to 4f$. For the VBF they find a cancellation between the NLO QCD and EW corrections in the intermediate mass range. For $H \to 4l$ they find an enhancement of the Γ of 2-5% when m_H ranges between 140 and 200 GeV. For $H \to 4f$ the EW and QCD corrections interfere constructively and they can be large.
- For the processes considered, the EW corrections are under control and they will be used together with the corresponding QCD for analysis (HWG meeting, June 2007: Mellado-Nisati-Rebuzzi-Rosati-Unal-Sau Lan Wu)