When Higgs Production & Decay QCD Dressed, Met EW

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Based on work done in collaboration with
Stefano Actis, Christian Sturm and Sandro Uccirati

Thanks: M. Grazzini, M. Spira, P. Kant

Outlines

(1 , 2 ,)

1. *From the analytical structure of EW NNLOs*
2. *to their numerical evaluation and their interplay with QCD,*

what else, but the inevitable!

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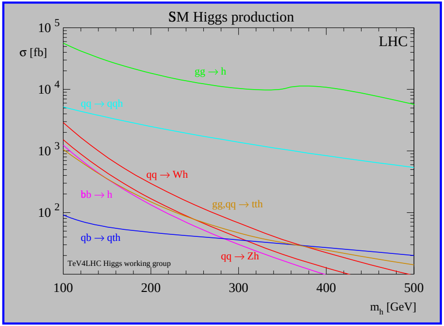
Part I

Preludio

Introduction & Motivation

Higgs production

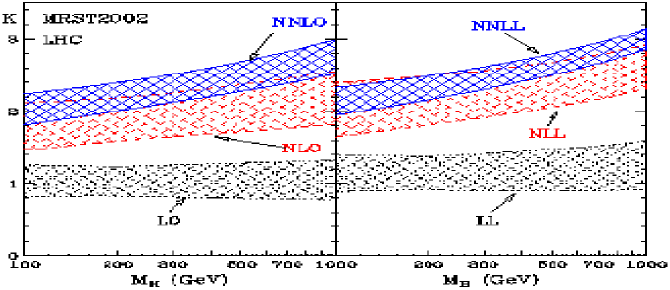


- Dominant production mechanism: Gluon fusion
- NLO QCD
  - – Heavy top-quark limit:
    Dawson; Djouadi, Spira, Zerwas
  - – Entire Higgs-mass range:
    Djouadi, Graudenz, Spira, Zerwas; Harlander, Kant; Anastasiou, Beerli, Bucherer, Daleo, Kunszt; Aglietti, Bonciani, Degrassi, Vincini
- NNLO QCD
  Harlander; Catani, Florian, Grazzini; Harlander, Kilgore; Anastasiou, Melnikov; Ravindran, Smith, Neerven; Anastasiou, Melnikov, Petriello; Catani, Grazzini

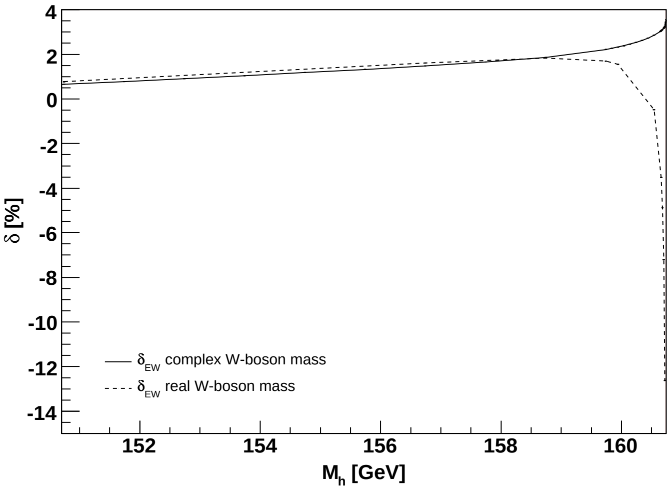
QCD & K - factor(s)

The bulk

From LO to NNLO and NNLL

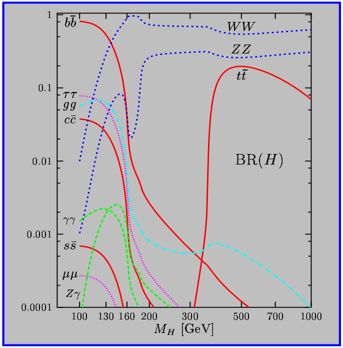


What about EW? NLO for $\gamma\gamma$



$\downarrow -\infty$

Introduction & Motivation
Higgs decay



Djouadi, Graudenz, Spira, Zerwas

- $H \rightarrow WW, ZZ$ dominant process for heavy Higgs boson
- $H \rightarrow b\bar{b}$ dominant process for light Higgs, but huge QCD background.
- $H \rightarrow \gamma\gamma$ rare process Br$\sim 10^{-3}$, but experimentally clean
- NLO EW
  - – corrections of $\mathcal{O}(G_f\, m_t^2)$
    Liao,Li; Fugel, Kniehl, Steinhauser
  - – corrections of $\mathcal{O}(G_f\, m_h^2)$
    Korner, Melnikov, Yakovlev
  - – exact light-fermion contribution
    Aglietti, Bonciani, Degrassi, Vincini
  - – Contributions involving top-quark and weak bosons exp. in $M_h^2/(4M_w^2)$
    Degrassi, Maltoni
  - $\hookrightarrow$ full EW corrections: in this talk
    Actis, Passarino, C.S., Uccirati

Synopsis

From PO to RO

from $gg \to H$ to $pp \to gg(\to H) + X$

QCD, light Higgs $\rightsquigarrow$

NLO K-fact.	$\approx$	$1.7 - 1.9$
NNLO K-fact.	$\approx$	$2.0 - 2.2$

EW $<$ 2008 $\neg$

- approximate
- incomplete
- divergent

$\exists$ Uncertainty

Remaining sources of large corrections?

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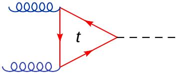
Part II

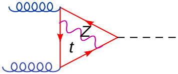
Intermezzo

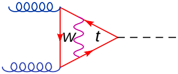
Calculation & Techniques

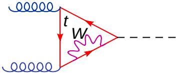
...some diagrams contributing to the EW 2-loop corrections

- $gg \to H$:

LO 

NLO 





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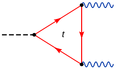
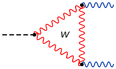
- $H \to \gamma\gamma$:

LO 



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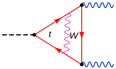
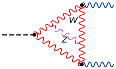
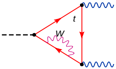
fermionic   bosonic

NLO 





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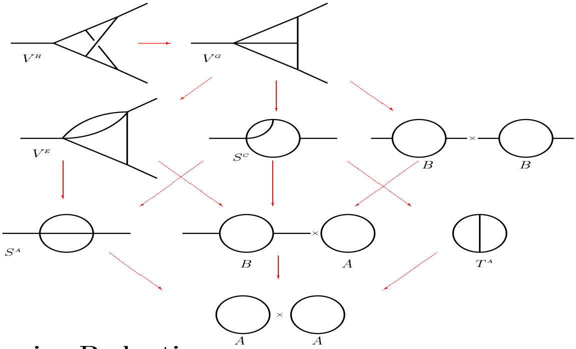
Calculation & Techniques

2-loop contributions are computed numerically:

- Diagrams: *GraphShot*
  S. Actis, A. Ferroglia, G. Passarino, M. Passera, C.S., S. Uccirati
  Form3 based package for automatic generation and manipulation of 1- and 2-loop Feynman diagrams:
  insert Feynman-rules, perform traces, remove reducible scalar products, symmetrize integrals, reduction, counter terms, renormalization,...
- $\rightsquigarrow$ UV-finite integrals classified into:
  scalar, vector and tensor type integrals
  $\rightsquigarrow$ mapped on form factors
- Form factors are evaluated numerically in parametric space
- Before num. integration: Cancel collinear sing. + Study threshold

For a moment consider $H \to \gamma\gamma$ without loss of generality

Generating the Amplitude: reduction



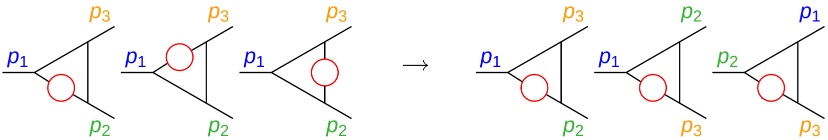
Recursive Reduction

Generic child topologies of the V^H parent topology. The five-line V^G diagram is obtained by removing one line of the V^H diagram; the second line contains the child topologies of V^G (V^E, S^C and $B \times B$). The third line contains the topologies S^A, $B \times A$ and T^A, obtained by removing one line from the diagrams above. The arrows indicate the correspondences between parent and child topologies.

Generating the Amplitude

Strategy

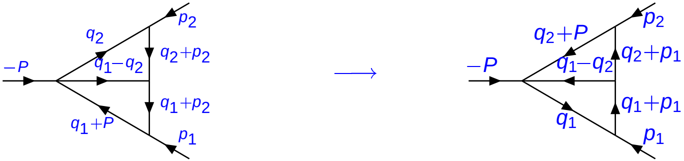
group diagrams into families, paying attention to permutation of external legs



Rooting

Strategy

mapping onto a standard rooting for loop momenta

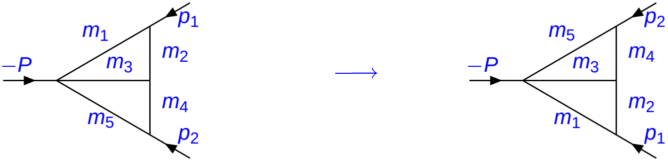


$$\begin{pmatrix} q_1 \to -q_1 - P \\ q_2 \to -q_2 - P \end{pmatrix}$$

Symmetry

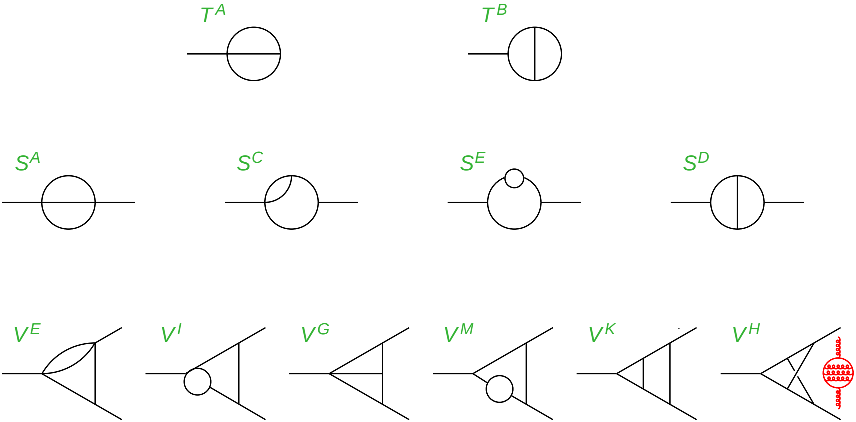
Strategy

apply symmetries to identify identical objects



$$\begin{pmatrix} q_1 \to -q_2 - P \\ q_2 \to -q_1 - P \end{pmatrix}$$

List-of-diagrams: all what is needed



All-you-can-do-analytic

rule-of-the-game

Adelante Numerics, cum judicio

UV

- UV poles, of course
- beware, *overlapping divergencies*

IR/Coll

- IR poles, of course
- Collinear logs, of course

upshot

Cancellations, if any, enforced analytically

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upshot

Cancellations, if any, enforced analytically

Collinear

Example

double divergency $\rightsquigarrow$ double subtraction

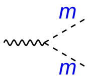
$$\int_0^1 dxdy \frac{1}{xyA(x,y)+\lambda B(x,y)} = \int_0^1 dxdy \left\{ \frac{1}{xyA(x,y)+\lambda B(x,y)}\Big|_{++} + \frac{1}{xyA(x,0)+\lambda B(x,0)}\Big|_{+} + \frac{1}{xyA(0,y)+\lambda B(0,y)}\Big|_{+} + \frac{1}{xyA(0,0)+\lambda B(0,0)} \right\}, \quad \lambda \to 0$$

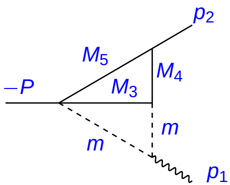
- First term $\rightarrow$ set $\lambda = 0$
- Second (third) term $\rightarrow$ integrate in $y(x)$ $\rightsquigarrow$ $\ln \lambda$
- Last term $\rightarrow$ integrate in x and y $\rightsquigarrow$ $\ln^2 \lambda$

Extracting Collinear divergencies

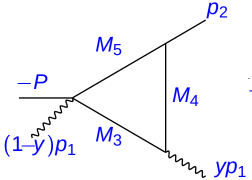
Theorem

Coefficients of collinear logarithms are integrals of one-loop functions





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

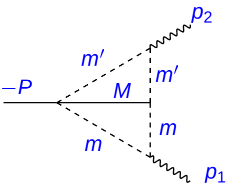


$$+ \text{ finite part}$$

Extracting Collinear divergencies

Example

Sometimes the answer is explicit



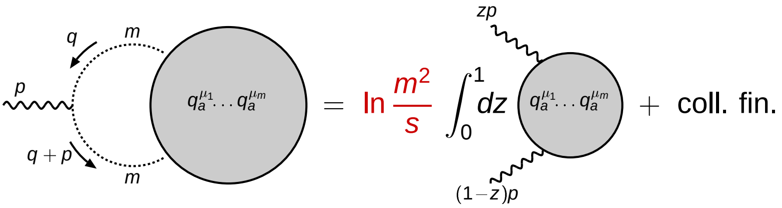
$$= \ln\frac{m^2}{s}\ln\frac{m'^2}{s}\mathrm{Li}_2\left(\frac{s}{M^2}\right) + \left(\ln\frac{m^2}{s} + \ln\frac{m'^2}{s}\right)$$

$$\left[\mathrm{Li}_3\left(\frac{s}{M^2}\right) + 2\,S_{12}\left(\frac{s}{M^2}\right)\right.$$

$$\left. -\ln\frac{M^2}{s}\,\mathrm{Li}_2\left(\frac{s}{M^2}\right)\right] + \text{ finite part}$$

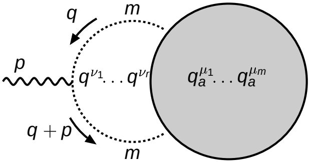
General results I

Coll. behavior of arbitrary two-loop q-scalar, UV-finite diagrams



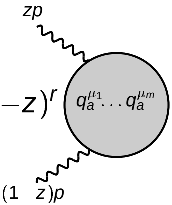
General results II

Generalization to tensor integrals



$$= \ln\frac{m^2}{s}\left[1-\frac{\epsilon}{2}\Delta_{UV}(s)-\frac{\epsilon}{4}\ln\frac{m^2}{s}\right]$$

$$\times \int_0^1 dz\,(-z)^r$$

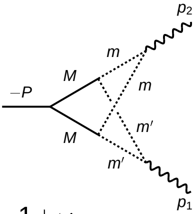


$$p^{\nu_1}\ldots p^{\nu_r} + \text{c. f.}$$

General results III

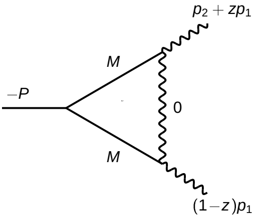
$$\omega = -P^2/M^2,\ l_\omega = \ln(1-\omega)$$

$$V^H_{\mathrm{dc}} = \left[P^2M^2 + 2P^2 q_1\cdot p_1 - 4(q_1\cdot p_1)^2\right]$$



$$= 2\left(1-\frac{1+\omega}{\omega}\, l_\omega\right) L\, L' + 2\left[1+\frac{1+\omega}{\omega}\, l_\omega\,(l_\omega - 1) + \mathrm{Li}_2(\omega)\right](L + L')$$

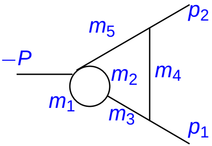
$$- \quad 2\int_0^1 dz\, \left[(1-z)P^2 L + (P^2 + 2\, q\cdot p_2)\, L'\right]$$



$+$

Extracting Ultraviolet divergencies

$V^l =$



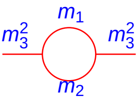
$$= \frac{1}{\pi^4} \int \frac{d^n q_1\, d^n q_2}{\underbrace{\underbrace{[1]\,[2]}_{x}\,[3]\,[4]\,[5]}_{y_1, y_2, y_3}},$$

$$[1] = q_1^2 + m_1^2$$
$$[2] = (q_1 - q_2)^2 + m_2^2$$
$$[3] = q_2^2 + m_3^2$$
$$[4] = (q_2 + p_1)^2 + m_4^2$$
$$[5] = (q_2 + P)^2 + m_5^2$$

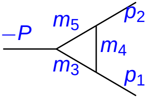
$$= C_\epsilon \int_0^1 dx \int dS_3(y_1, y_2, y_3)\, [x\,(1 - x)]^{-\epsilon/2}\, (1 - y_1)^{\epsilon/2 - 1}\, V^{-1-\epsilon}$$

The single pole can always be expressed in terms of 1L.

$V^l =$



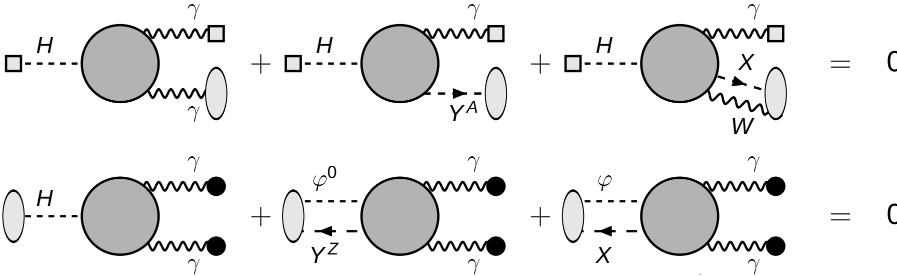
$\times$



$+$ finite part.

Checks

Off-shell WSTIs involving special sources
contracted sources → black circles
physical ones → gray boxes



Tasting numerical evaluation

Finite parts

Write the **finite part** of a FD in one of the following forms:

1. $\int dx \, \frac{Q(x)}{V(x)} \qquad V(x) > 0;$
2. $\int dx \, Q(x) \ln^n V(x);$
3. $\int dx \, \frac{Q(x)}{V(x)} f\left(\frac{V(x)}{P(x)}\right) \qquad f(x) = ln^n(1+x),\ Li_n(x),\ S_{n,p}(x)$

Typical integrand with k Feynman variables:

$$z_1^{n_1} \cdots z_k^{n_k} V^{\mu}(z_1, \ldots, z_k) \ln^m V(z_1, \ldots, z_k),$$

$$\mu = -1, -2, \ \{z\} \subseteq [0,1]^k$$

V quadratic with respect to a subset of $\{z\}$ in which each z_i^2 is proportional to one squared external momentum.

bite-and-run strategy I

Multivariate Polylogs

- V is not complete
  - $\mu = -1$ and $m = 0$ ($m > 0$ similar)

$$\frac{1}{a\,x + b} = \partial_x \frac{1}{a} \ln\left(1 + \frac{a}{b}\,x\right)$$

  - $\mu = -2$ and $m = 0$ ($m > 0$ similar)

$$\frac{1}{(a\,x\,y + b\,x + c\,y + d)^2} = -\frac{\partial_x\,\partial_y}{a\,d - b\,c} \times \ln\left\{1 + \frac{(a\,d - b\,c)\,x}{b\,(axy + bx + cy + d)}\right\}$$

bite-and-run strategy II

Multivariate PolyLogs

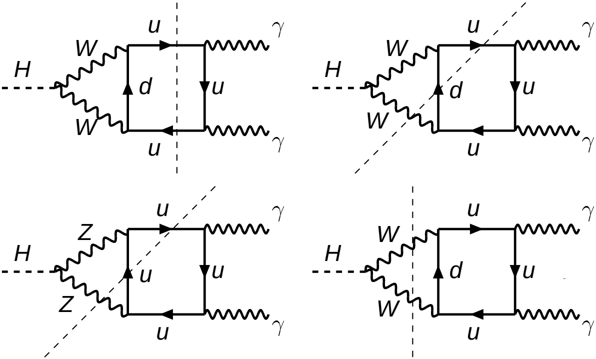
- V is complete

$$
\begin{aligned}
V(z) &= z^t\, H\, z + 2\, K^t\, z + L = (z^t - Z^t)\, H\, (z - Z) + B \\
&= Q(z) + B, \\
Z &= -K^t H^{-1},\ B = L - K^t H^{-1} K, \\
\mathcal{P}^t \partial_z\, Q(z) &= -Q(z),\ \mathcal{P} = -(z - Z)/2, \\
V^\mu(z) &= (\beta - \mathcal{P}^t\, \partial_z) \int_0^1 dy\, y^{\beta-1} \left[Q(z)\, y + B\right]^\mu \\
\text{e.g. } V^{-1} &= (1 - \mathcal{P}^t\, \partial_z)\, \frac{1}{Q}\, \ln\left(1 + \frac{Q}{B}\right)
\end{aligned}
$$

Part III

Andante

Around threshold



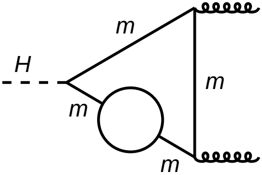
Singularities

- FD have a complicated analytical structure

- A frequently encountered singular behavior is associated with the so-called normal thresholds: the leading Landau singularities of self-energy-like diagrams

- which can appear, in more complicated diagrams, as sub-leading singularities.

$1/\beta$ -behavior



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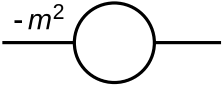

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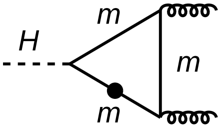
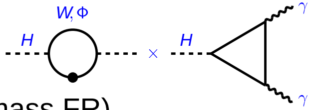


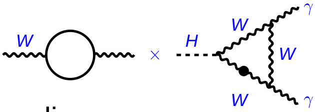
$+$ $\left(\begin{array}{c} \text{reg. part} \\ \text{at } \beta = 0 \end{array} \right)$

Origin of $1/\beta$

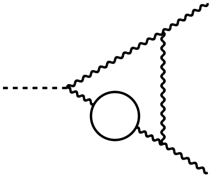
- (1-loop diagrams) $\otimes$ (H wave-function FR)



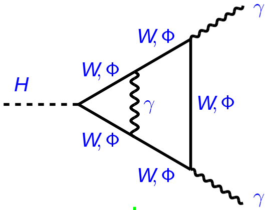
- (1-loop diagrams) $\otimes$ (W mass FR)



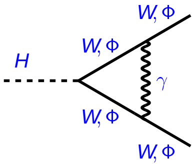
- Pure 2-loop diagrams



Logarithmic singularities



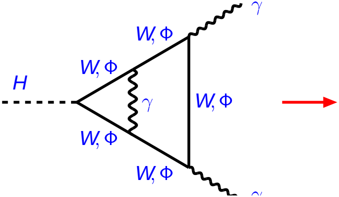
Remnant of Coulomb singularity



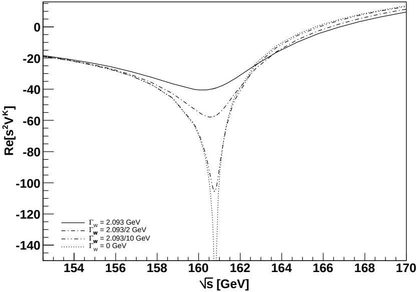
$\sim \ln \beta_W$

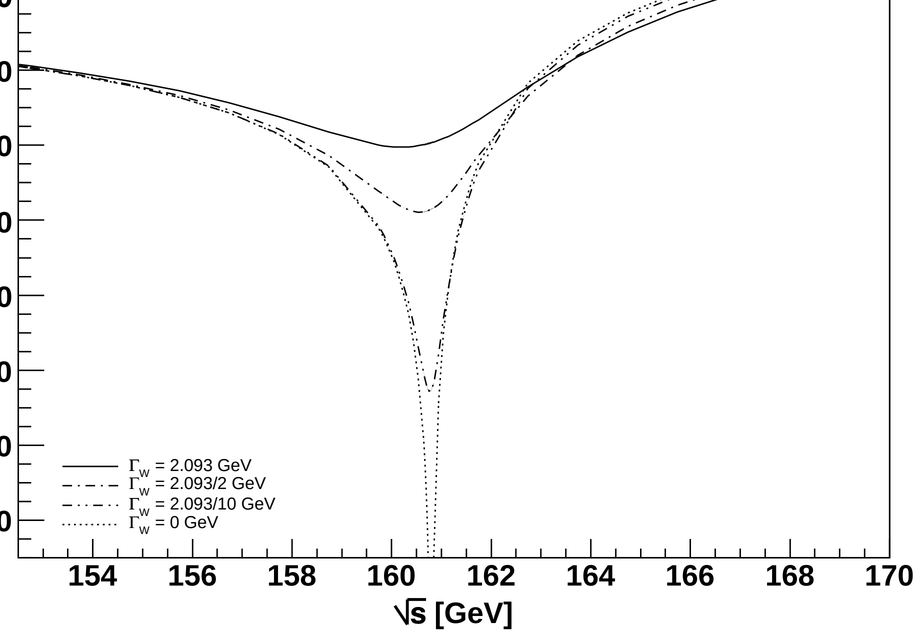
$\sim 1/\beta_W$

Cure for logarithmic singularities



Complex W Mass





Γ_W = 2.093 GeV
Γ_W = 2.093/2 GeV
Γ_W = 2.093/10 GeV
Γ_W = 0 GeV
154
156
158
160
162
164
166
168
170
$\sqrt{s}$ [GeV]

Part IV

Impetuoso

Solutions

RM scheme - none

- where masses are the real on-shell ones; it gives the extension of the generalized minimal subtraction scheme up to two loop level.

MCM scheme - minimal

- start by removing the Re label in those terms that, coming from finite renormalization, violate WSTIs.
- split the amplitude

$$\mathcal{A}^{\mathrm{NLO}} = \sum_{i=W,Z} \frac{A_{\mathrm{SR},i}}{\beta_i} + A_{\mathrm{LOG}} \ln\left(-\beta_W^2 - i0\right) + A_{\mathrm{REM}},$$

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Solutions

MCM scheme - minimal

- After proving that all coefficients, gauge-parameter independent by construction, satisfy the WST identities, we minimally modify the amplitude introducing the complex-mass scheme of for the divergent terms.

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

Solutions

pitfalls

A nice feature of the MCM scheme is its simplicity

MCM scheme - minimal

- The MCM, however, does not deal with cusps associated with the crossing of normal thresholds.

MCM scheme - minimal

- The large and artificial effects arising around normal thresholds in the MCM scheme (or in RM scheme) are aesthetically unattractive.
- In addition, they represent a concrete problem in assessing the impact of two-loop EW corrections on processes

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Solutions

CM scheme - complete

- The procedure described for the divergent terms has been extended to the remainder A_{REM}. In particular, all two-loop diagrams have been computed with complex masses for the internal vector bosons.

CM scheme - complete

- In the full CM setup, the real parts of the W and Z self-energies induced by one-loop renormalization of the masses and the couplings have to be traded for the associated complex expressions.

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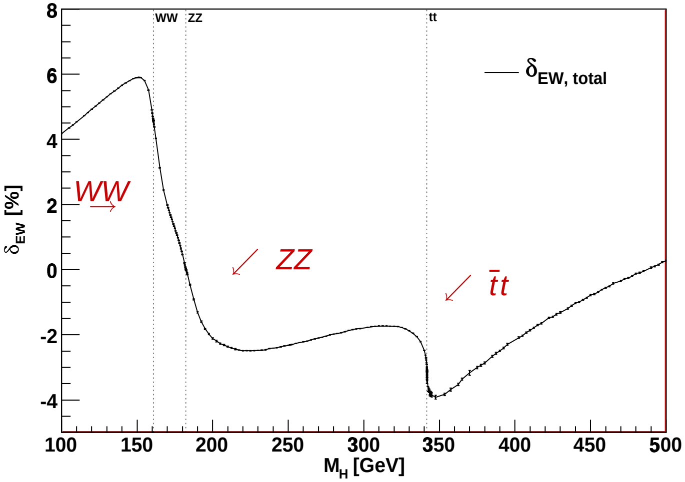
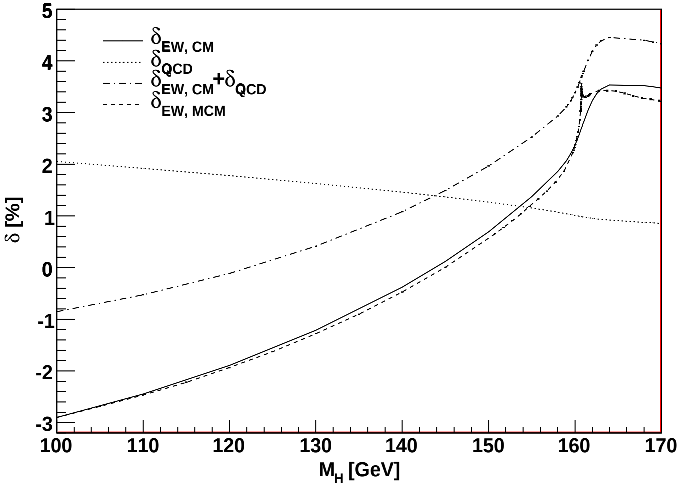
Part V

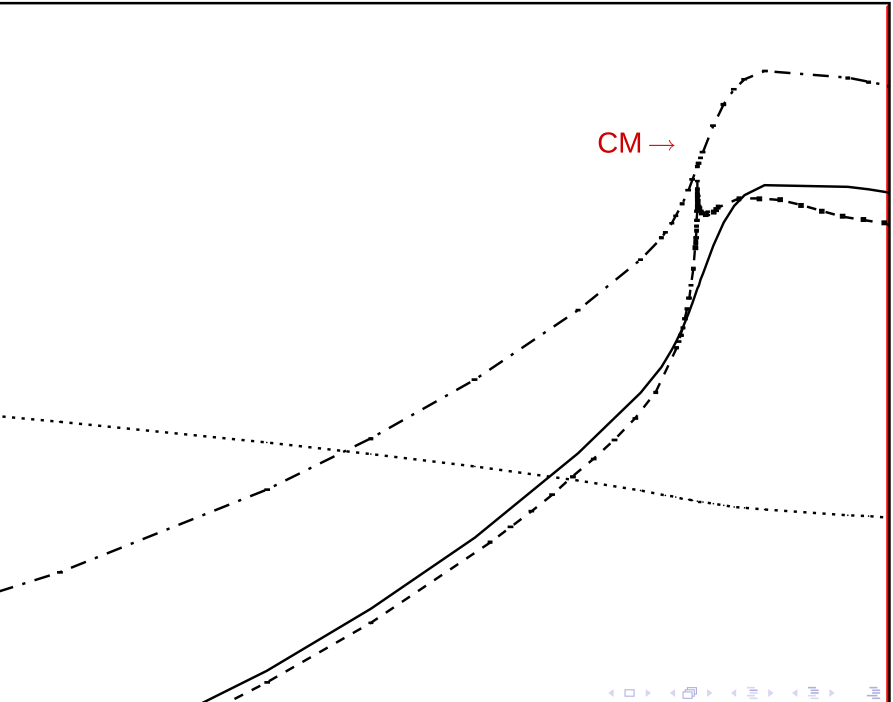
Allegro

EW on gluon-gluon fusion

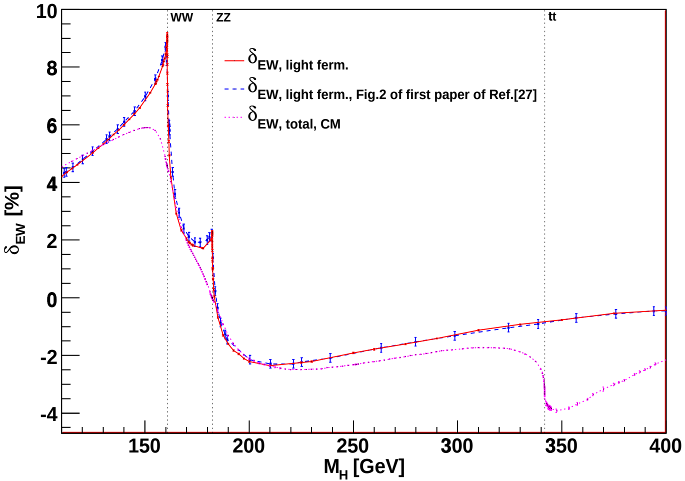


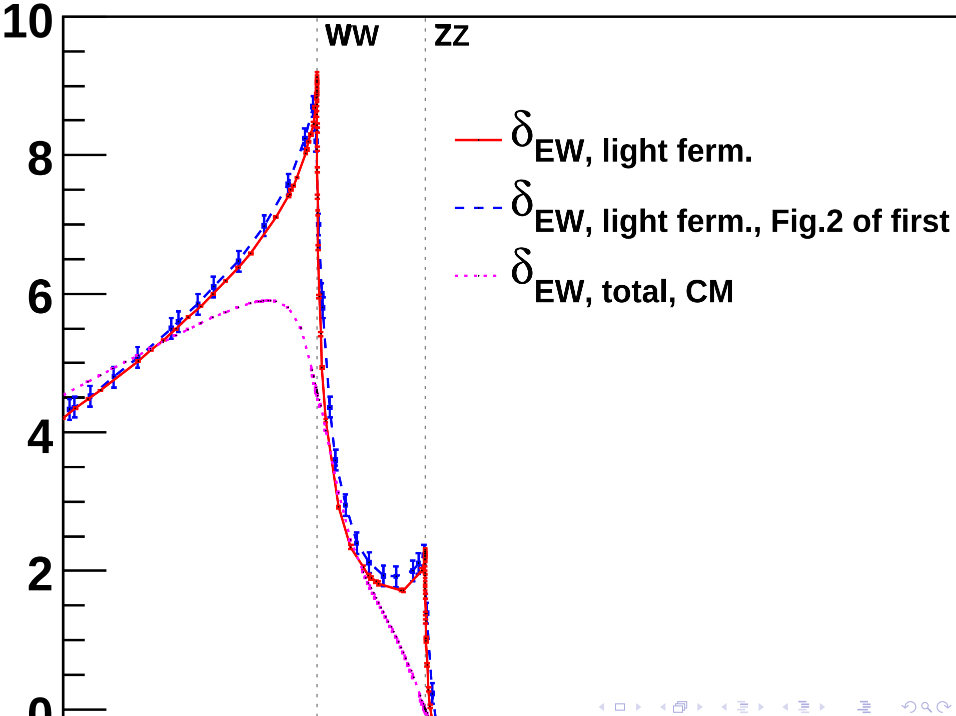
EW on decay ($\gamma\gamma$)




CM →

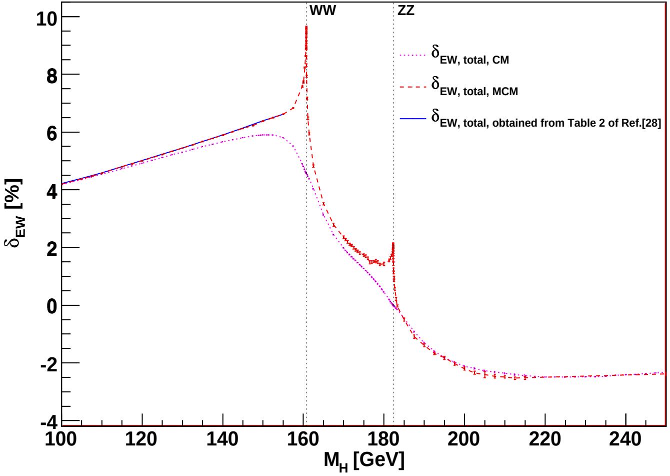
Comparing


10
8
6
4
2
0
-2
-4
WW
ZZ
tt
δ EW, light ferm.
δ EW, light ferm., Fig.2 of first paper of Ref.[27]
δ EW, total, CM
δ EW [%]
150
200
250
300
350
400
M H [GeV]



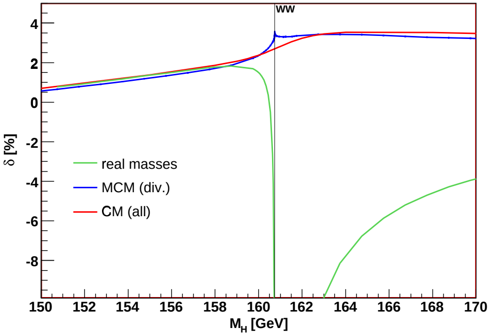
10
8
6
4
2
0
WW
ZZ
δ EW, light ferm.
δ EW, light ferm., Fig.2 of first
δ EW, total, CM

Comparing


WW
ZZ
δEW, total, CM
δEW, total, MCM
δEW, total, obtained from Table 2 of Ref.[28]
δEW [%]
10
8
6
4
2
0
-2
-4
100
120
140
160
180
200
220
240
MH [GeV]

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

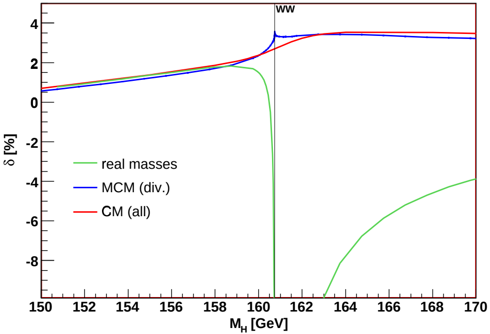


- Result obtained with real masses divergent at WW; good approx. below; completely off above threshold, since no cancellation mechanism occurs
- Result in MCM setup finite, shows cusp; result in CM setup is smooth
- At threshold, result in MCM setup $\to$ 3.5%; result in CM setup $\to$ 2.7%

  $\Rightarrow$ prediction at the % level requires complete CMS implementation

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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Part VI

Allegro Con Brio

EW on K-factors - uncertainty

We introduce two options for including NLO electroweak corrections

- CF (Complete Factorization):

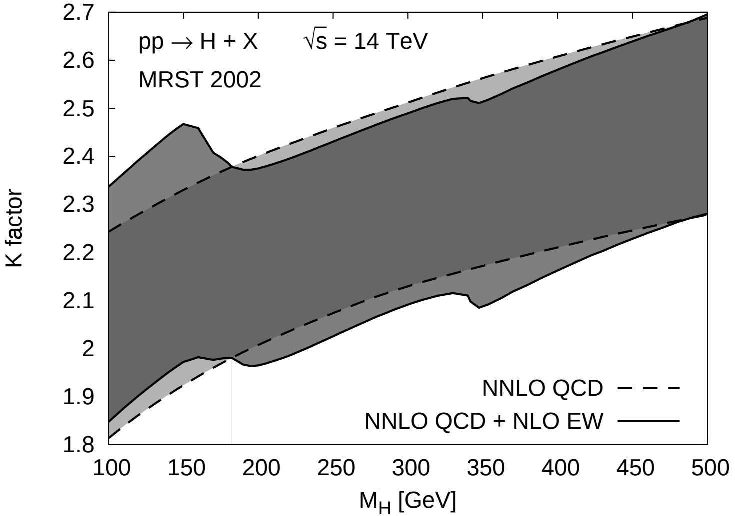
$$\sigma^{(0)}\, G_{ij} \to \sigma^{(0)}\, \Big(1 + \delta_{\rm EW}(M_H^2)\Big)\, G_{ij}\,;$$

- PF (Partial Factorization):

$$\sigma^{(0)}\, G_{ij} \to \sigma^{(0)}\, \Big[G_{ij} + \alpha_S^2(\mu_R^2)\delta_{\rm EW}(M_H^2)\, G_{ij}^{(0)}\Big],$$

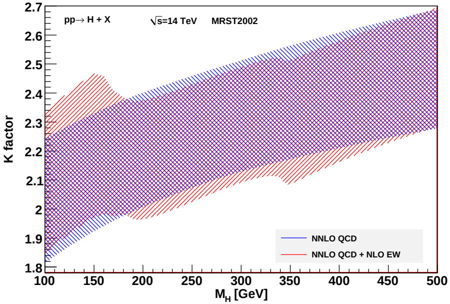
Can we do it better? Babis, Radja and Frank say yes

EW on K-factors - LHC



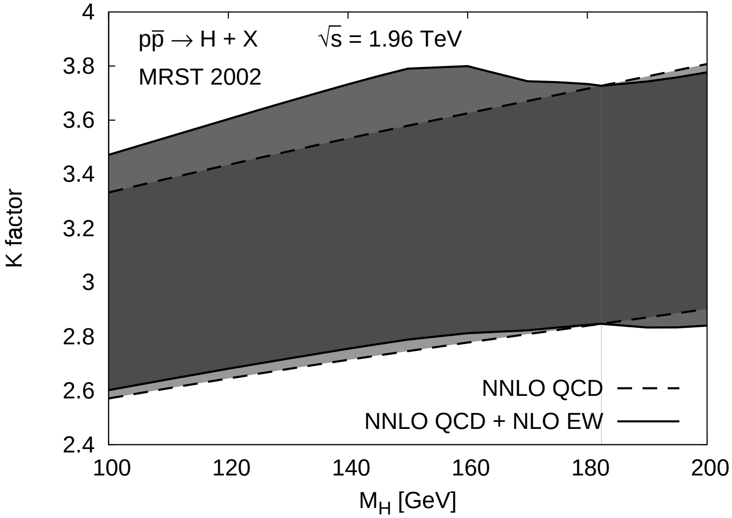
Result:
The hadronic process $pp \to H + X$

- Use Fortran program HiggsNNLO by M. Grazzini
- K-factor: Ratio cross section with higher orders over LO result



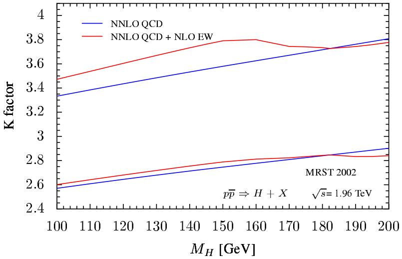
- Uncertainty band: Variation of μ_R, μ_F, PF, CF
- Central value for cross section is shifted by 2-5% (M_H = 120 GeV)

EW on K-factors - Tevatron



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)

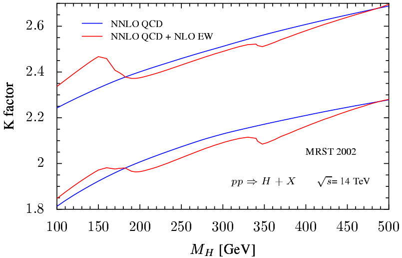


M_H [GeV]	δ_{CF} [%]	δ_{PF} [%]
120	$+4.9$	$+1.6$
140	$+5.7$	$+1.8$
160	$+4.8$	$+1.5$
180	$+0.5$	$+0.1$
200	-2.1	-0.6

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

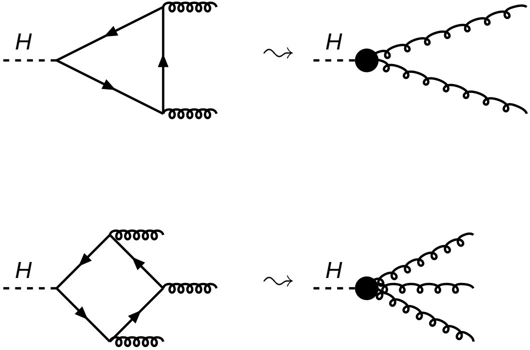
- Uncertainty band shows stronger sensitivity on the Higgs mass, once NLO EW effects are included
- WW and $t\bar{t}$ thresholds visible, but smooth having introduced everywhere CMs
- Impact of NLO EW corrections comparable to that of NNLL resummation `Catani,de Florian,Grazzini,Nason'03` ($+6\,\%$ for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

Part VII

Crescendo

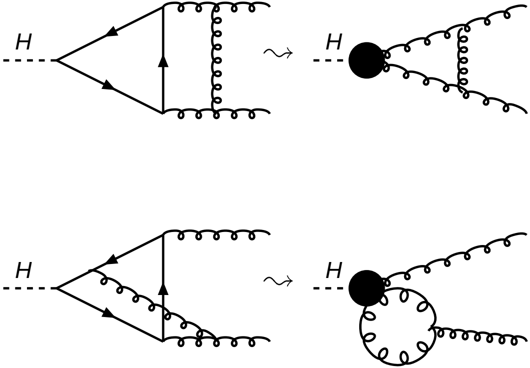
yes is thre loops at $M_H = 0$: effective theory

Operator expansion plus matching
or brute force tadpoles



Building with Effective theory

$$m_t \to \infty \equiv m_H \to 0$$



Missing the real McCoy I

Define

- σ^M the mixed three-loop σ;
- σ^{EW} the two-loop EW σ.

- How good is $\sigma^M(0)$? wrt $\sigma^M(M_H)$? Assume it is

$$\sigma^M(M_H) = \sigma^M(0) + E \quad \text{with } E \text{ small}$$

- What is usually done:

$$\sigma^M(M_H) \to \frac{\sigma^M(0)}{\sigma^{\mathrm{EW}}(0)}\, \sigma^{\mathrm{EW}}(M_H)$$

- the difference is

$$\frac{\sigma^M(0)\, \sigma^{\mathrm{EW}}(M_H) - \sigma^M(M_H)\, \sigma^{\mathrm{EW}}(0)}{\sigma^{\mathrm{EW}}(0)}$$

Missing the real McCoy II

- If E is almost zero this difference is

$$\frac{\sigma^{M}(0)}{\sigma^{\mathrm{EW}}(0)}\left[\sigma^{\mathrm{EW}}(M_H)-\sigma^{\mathrm{EW}}(0)\right]$$

- so, the effective error is in

$$\sigma^{M}(M_H)=\sigma^{M}(0)\,(1+e)$$

- with

$$e=\frac{\sigma^{\mathrm{EW}}(M_H)}{\sigma^{\mathrm{EW}}(0)}-1.$$

- at $M_H = 170\,\mathrm{GeV}$ this difference is not tiny at all which, contradicts the *assumption* that E is small.

$M_H = 0$ versus finite M_H

However

the altrenative is

$$\sigma^{M}(x) = \sigma^{\rm EW}(x)\,(1+\delta)$$

where δ doesn't depend on x.

How zero is $\sigma^{\rm EW}(M_H)\left[\delta(0) - \delta(M_H)\right]$?

- impossible to prove it with just one point, $x = 0$;
- plausible, soft gluon dominance;
- more difficult than before, if the top triangle is *almost* point-like, here there is a structure with openings of thresholds etc.

Facts or Misfits?

Example

How good is heavy-top NLO QCD wrt complete NLO QCD?

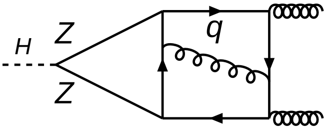
- from literature: *excellent,* $\cdots$
- From the Lion's Mouth (Spira):
  - the deviations of the heavy top mass limit from the fully massive result is in the range of 6% for 170 GeV Higgs mass at the Tevatron.
  - less than 15% for Higgs masses below $\approx$ 700 GeV
- from Harlander & Kant $\delta(170\,\mathrm{GeV})/\delta(0) - 1 = 5.25\%$

Difficult to say at NNLO

Example

Approximation is fair enough if it remains $\approx$ 10% of our 6%

- The main source of difference could come from diagrams without top: is $M_H \ll m_t$ & M_W a good approximation?



Conclusions

Recapitulation

No matter what, NLO EW corrections to $gg \to H$ are under control without incongruent large effects around EW thresholds

Refrain

Next update of Tevatron analysis with higher luminosity should appear in February/March, $\cdots$, it looks like the old times with the two communities busy to fill a gap $\cdots$

Or, if I create a negative Higgs field and bombard the rest of the community with a stream of Higgs anti-bosons, it might disintegrate (free adaptation from Stephen Soderbergh's Solaris, 2002).

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