Two-loop corrections and techniques for Higgs production and decay with massless gauge bosons

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I. Introduction & Motivation
II. Calculation & Techniques
III. Results & Discussion
IV. Summary & Conclusion

In collaboration with: S. Actis, G. Passarino, S. Uccirati

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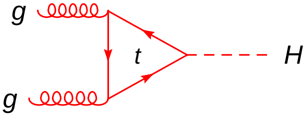
Phys. Lett. **B669**, 62, 2008, Phys. Lett. **B655**, 298, 2007.

Introduction & Motivation

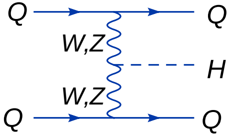
Higgs production

- Main production mechanisms:

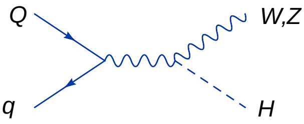
Gluon fusion:

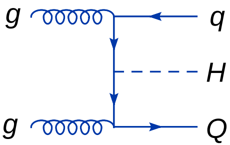


Vector boson fusion:



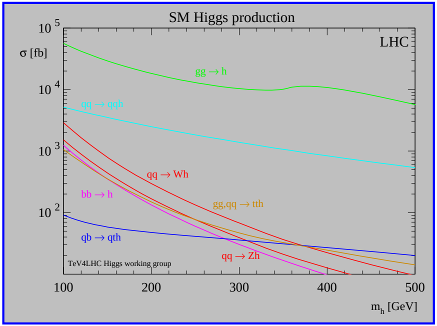
Associated production:





Introduction & Motivation

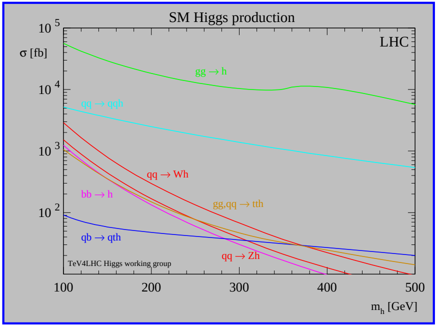
Higgs production



- Dominant production mechanism: Gluon fusion

Introduction & Motivation

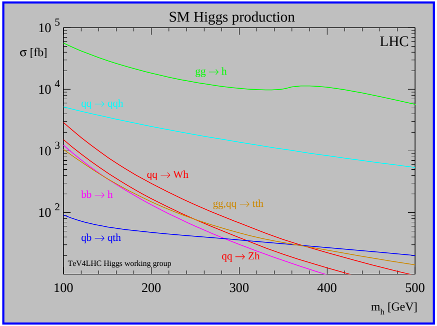
Higgs production



- 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

Introduction & Motivation

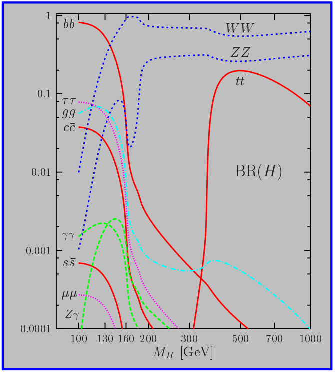
Higgs production



- Dominant production mechanism: Gluon fusion
- NLO EW
  - – Exact light-fermion contribution
    Aglietti, Bonciani, Degrassi, Vincini
  - – Contributions involving top-quark in terms of expansions
    Degrassi, Maltoni; Djouadi, Gambino, Kniehl
  - ↪ full EW corrections: in this talk with complete dependence on heavy particles M_H, M_W, M_Z, M_t
    S. Actis, G. Passarino, C.S., S. Uccirati
- Mixed QCD-EW corrections
  C. Anastasiou, R. Boughezal, F. Petriello

Introduction & Motivation

Higgs decay

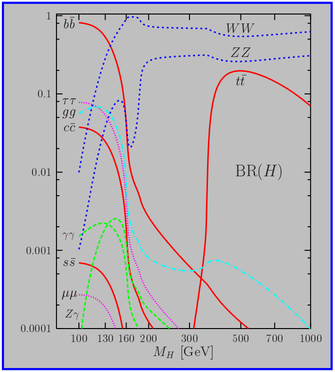


Djouadi, Graudenz, Spira, Zerwas

- $H \to WW, ZZ$ dominant process for heavy Higgs boson
- $H \to b\bar{b}$ dominant process for light Higgs, but huge QCD background.
- $H \to \gamma\gamma$ rare process Br$\sim 10^{-3}$, but experimentally clean

Introduction & Motivation

Higgs decay



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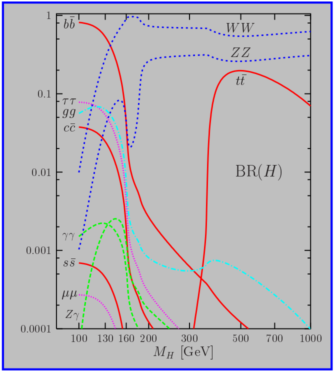
- $H \to \gamma\gamma$ rare process Br$\sim 10^{-3}$, but experimentally clean
- NLO QCD
  - Expansions below/above threshold
    Zheng, Wu; Djouadi, Spira, van der Bji, Zerwas; Dawson, Kauffman
    Djouadi, Spira, Zerwas; Melnikov, Yakovlev; Inoue, Najima, Oka, Saito
  - Analytical results
    Fleischer, Tarasov, Tarasov; Harlander, Kant; Anastasiou, Beerli, Bucherer, Daleo, Kunszt; Aglietti, Bonciani, Degrassi, Vicini

Introduction & Motivation

Higgs decay



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- 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

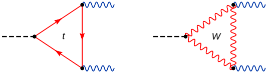
$\hookrightarrow$ full EW corrections: in this talk
Actis, Passarino, C.S., Uccirati

Calculation & Techniques

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

- $H \to \gamma\gamma$:

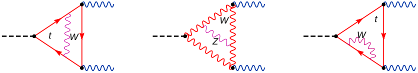
LO



, . . .

fermionic bosonic

NLO

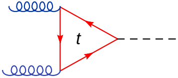


, . . .

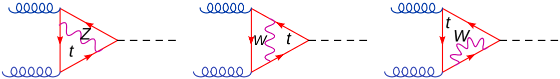
also unphysical Higgs-Kibble scalar fields and Fadeev-Popov ghost fields

- $gg \to H$:

LO



NLO



, . . . (subset)

Calculation & Techniques

The amplitude of $H(P) \to \gamma(p_1) + \gamma(p_2)$, (analog $gg \to H$)

- Decomposition of amplitude with respect to tensor structures:

$$\mathcal{A}^{\mu\nu}(H \to \gamma\gamma) = \frac{g^3 s_\theta^2}{16\pi^2}\left[F_D\,\delta^{\mu\nu} + \sum_{i,j=1}^{2} F_P^{(ij)}\,p_i^\mu\,p_j^\nu + F_\epsilon\,\epsilon(\mu,\nu,p_1,p_2)\right]$$

- Require interference of 2-loop with 1-loop amplitude,
  At 1-loop $F_\epsilon = 0$, need only F_D and F_P:

$$\mathcal{A}^{\mu\nu}(H \to \gamma\gamma) = \frac{g^3 s_\theta^2}{16\pi^2}\left(F_D\,\delta^{\mu\nu} + F_P^{(21)}\,p_2^\mu\,p_1^\nu\right).$$

- Introduce projectors for extraction of $F_D = P_D^{\mu\nu}\,\mathcal{A}_{\mu\nu}, F_P^{(21)} = P_P^{\mu\nu}\,\mathcal{A}_{\mu\nu}$

- Ward identity(WI): $p_1^\nu\,\mathcal{A}_{\mu\nu}\,p_2^\nu = 0$, $\quad F_D + p_1 \cdot p_2\,F_P = 0$
  - Valid order by order in perturbation theory
  - Only one form factor required (e.g. F_D) for computation of width
  - Can be used as a check of the calculation

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, extracts pole-part of loop diagrams, renormalization,...
- $\rightsquigarrow$ UV-finite amplitude,
  integrals classified into different topologies,
  subdivided in 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 behavior
  (For a moment consider $H \to \gamma\gamma$ without loss of generality)

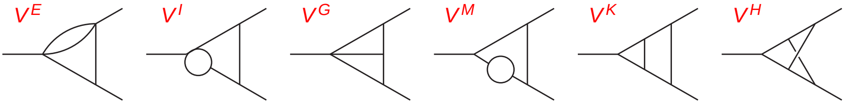
Calculation & Techniques

Classification different topologies

- 1-loop functions: well known A_0-, B_0-, C_0-functions
- 2-loop tadpoles (2 topologies, related by IBP)

- 2-loop self-energies (4 topologies)

- 2-loop vertices (6 topologies)

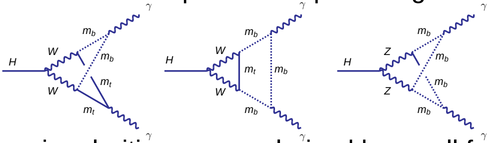


- We end with integrals up to rank 2

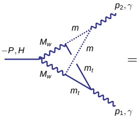
Calculation & Techniques

Collinear singularities

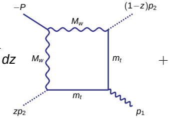
- Appear when external photon couples to light fermions, e.g.:



- Collinear singularities are regularized by small fermion mass
  $\rightsquigarrow$ singularities become manifest in $\log(m)$
- Verification of their cancellation:
  Requires universal representation of the coefficient
- Introduce integrals of one-loop functions:



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



$+$ coll. finite.

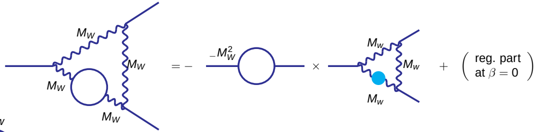
$\longrightarrow$ use their well-known properties to make cancellation explicit

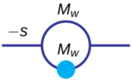
Calculation & Techniques

Threshold singularities, Behavior at WW-threshold ($H \to \gamma\gamma$)

Amplitude develops threshold singularities in $\beta_W = \sqrt{1 - 4M_W^2/s}$, when $s = M_h^2 \sim 4M_W^2$, possible sources:

I) Square-root singularities:



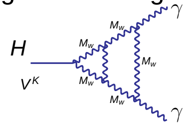


$= \dot{B}_0(-s, M_w, M_w) = -\frac{1}{\beta} \ln \frac{\beta+1}{\beta-1} \quad \Leftarrow$ **singular for $M_h = 2M_w$**

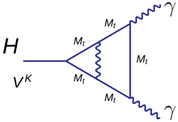
II) Finite W-mass renormalization (derivative of C-function)

III) Higgs wave function factor (derivative of B-function)

IV) Logarithmic singularities:



$\sim \log(\beta)$



same config. with top loop finite, log multiplied by β_t^2, (spin structure)

Calculation & Techniques

Complex poles Denner, Dittmaier, Roth, Wackeroth, Wieders

Cure problems with crossing of thresholds through complex poles:

- "Minimal" introduction of complex poles:

  Decompose Amplitude:

  $$\mathcal{A} = \mathcal{A}_{1,W}^{div}/\beta_W + \mathcal{A}_{1,Z}^{div}/\beta_Z + \mathcal{A}_2^{div}\log(-\beta_W^2 - i0) + \mathcal{A}^{fin}$$

  – $\mathcal{A}_1^{div}, \mathcal{A}_2^{div}$ form a gauge invariant subset

  – Replace M_V^2 with $s_V = \mu_V(\mu_V - i\gamma_V)$ in both $\mathcal{A}_1^{div}, \mathcal{A}_2^{div}$ and threshold factor β_V where $\mu_V^2 = M_V^2 - \Gamma_V^2, \gamma_V = \Gamma_V\left(1 - \frac{\Gamma_V^2}{2M_V^2}\right)$

  $\Rightarrow$ Regularize threshold singularities

  $\Rightarrow$ Square-root singularities originating from V_M and finite mass renormalization cancel($H \to \gamma\gamma$)

  $\Rightarrow$ Square-root sing. from wave function and log β survive

- "Complete" introduction of complex poles:

  Replace M_V^2 in all divergent and finite terms

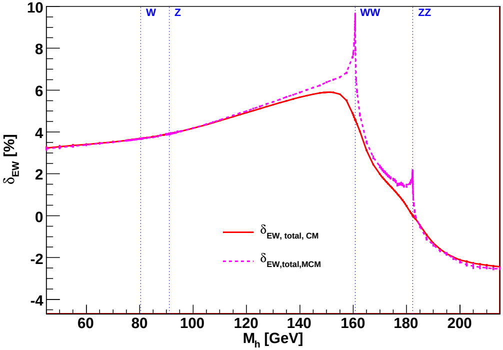
  $\rightsquigarrow$ Remove artificially large cusps coming from enhancements in finite contributions

Result:

The partonic process $gg \to H$

IPS: $M_W = 80.398$ GeV, $M_Z = 91.1876$ GeV, $m_t = 170.9$ GeV,
$G_F = 1.16637 \cdot 10^{-5}$ GeV^{-2}, $\Gamma_Z = 2.4952$ GeV, $\Gamma_W = 2.093$ GeV

- LO parton cross section
  $\sigma_{LO} = \sigma_0 M_H^2 \delta(s - M_H^2)$
- electroweak correction parametrized by
  $\sigma = \sigma_0 (1 + \delta_{EW})$
- MCM: minimal complex masses
  cures threshold singularity
  CM: complex masses
  avoids incongruent effects around thresholds
- Result obtained with real masses divergent at thr., good approx. below/above



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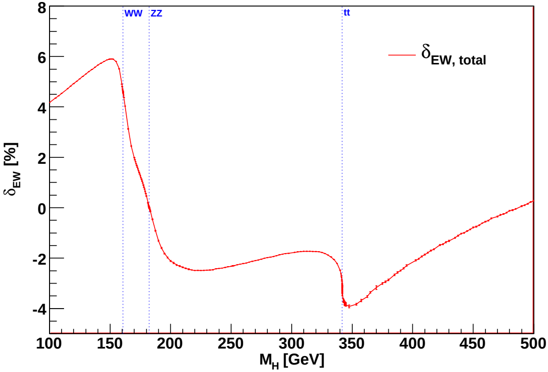


Maximum around WW-threshold, minimum around tt-threshold

$\to$ The percentage correction varies between +6% and -4%

Result:

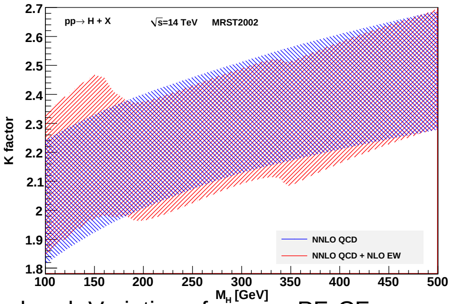
The hadronic process $pp \to H + X$

- Hadronic process:
$$\sigma\left(s, M_H^2\right) = \sum_{i,j} \int_0^1 dx_1 \int_0^1 dx_2 \, f_{i/h_1}\left(x_1, \mu_F^2\right) f_{j/h_2}\left(x_2, \mu_F^2\right) \times \int_0^1 dz \, \delta\left(z - \frac{M_H^2}{s\, x_1 x_2}\right) z \, \sigma^{(0)} \, G_{ij}\left(z; \alpha_s(\mu_R^2), M_H^2/\mu_R^2; M_H^2/\mu_F^2\right),$$
Parton densities: $f_{i/h_1}, f_{j/h_2}, \; i,j \in \{g, q, \bar{q}\}$
QCD corrections: $G_{ij} = \alpha_s^2(\mu_R)\delta_{ig}\delta_{jg}\delta(1-z) + \alpha_s^3(\mu_R) G_{ij}^{(1)} + \ldots$
- Complete factorization(CF): $\sigma^{(0)} \, G_{ij} \to \sigma^{(0)} \, (1 + \delta_{\text{EW}}) \, G_{ij}$
amounts to an overall re-scaling of QCD result,
consider electroweak correction point like
- Partial factorization(PF): $\sigma^{(0)} \, G_{ij} \to \sigma^{(0)} \left[G_{ij} + \alpha_s^2(\mu_R^2)\delta_{\text{EW}} \, G_{ij}^{(0)}\right]$
equivalent to add electroweak corrections to QCD ones

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
- Stronger dependence on H-mass, follows shape of partonic process
- $M_h < 180$GeV CF(PF) fixes upper(lower) bound, $M_h > 180$GeV inversely
- Central value for cross section is shifted by 2-5% ($M_H = 120$ GeV) (CF,PF)

Update with MSTW2008 PDF $\longrightarrow$ de Florian, Grazzini; Anastasiou, Boughezal, Petriello

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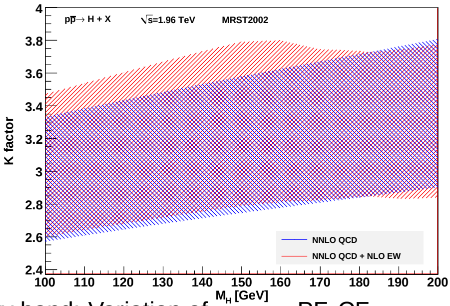

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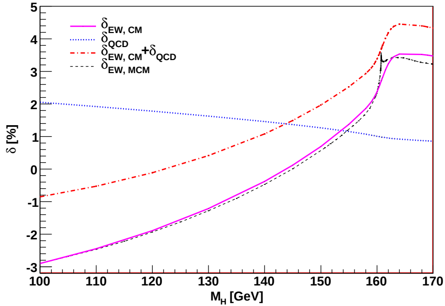
Result:

The decay $H \to \gamma\gamma$, correction in percent for the partial width



- QCD corrections > 0, ranging from $+1.8\%$(120 GeV) to $+0.9\%$(170 GeV)
- EW effects range from -1.9% (120 GeV) to 3.5%(170 GeV)
- EW effects directly below threshold small -0.47% (140 GeV) (cancellations)

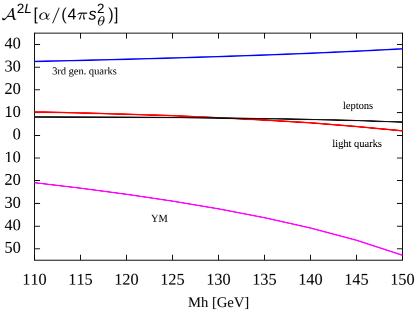
- Cancellation between δ_{QCD} and δ_{EW} below threshold -0.1%(120 GeV)
- Around the threshold both positive leading to a sizable total correction of about $+4\%$

Results:

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

Decompose 2-loop amplitude: $\mathcal{A}^{2L} = \mathcal{A}^{2L}_{lep} + \mathcal{A}^{2L}_{lq} + \mathcal{A}^{2L}_{YM} + \mathcal{A}^{2L}_{3gen}$

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



- Agreement with lep and lq Aglietti, Bonciani, Degrassi, Vicini, 3rd gen. quarks and YM Degrassi, Maltoni (expansion), corrected renormalization
- Analog for partonic $gg \to H$, decomposition in lq and 3rd gen. (contribution of 3rd gen. small below threshold)

Summary & Conclusion

- Gluon fusion ($gg \to H$) is the dominant production process for the Higgs boson at LHC
- The decay $H \to \gamma\gamma$ provides a clean environment for its discovery
- The two-loop electroweak corrections with complete dependence of all heavy particles(M_H, M_W, M_Z, M_t) have been computed:
- For $gg \to H$ the partonic cross section varies between

  $\delta \sim$-4% – 6% ($M_H = 100 - 500$ GeV)

  The had. cross section is shifted by +2%–5% ($M_H = 120$ GeV)
- For $H \to \gamma\gamma$ the relative corrections to the decay width are

  $\delta \sim$ -1% – 4% ($M_H = 100 - 170$ GeV)