(B)SM Higgs Boson Production via Gluon Fusion

Timo Schmidt

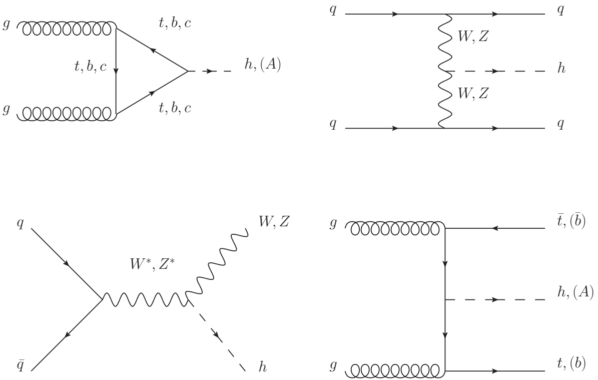
in collaboration with
Michael Spira

University of Freiburg

Buffalo, August 15, 2016

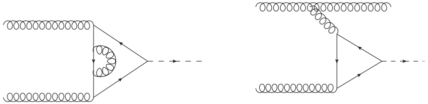
Higgs boson production

- At the LHC there are mainly 4 relevant production mechanism for a single SM Higgs h and pseudoscalar Higgs A

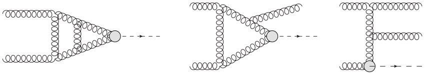


Gluon Fusion: Fixed order calculations

- Leading order (LO)
  - Due to large Yukawa coupling and large gluon luminosities gluon fusion dominant production mechanism in the SM [*Georgi et. al.* (1978)]
- NLO-calculations (next-to-leading order)
  - Effective theory in the limit of a heavy top quark [*Dawson* (1991), *Spira et al.* (1991)]
  - Massive calculation [*Spira et al.* (1993,1995), *Harlander, Kant* (2005), *Anastasiou et al.* (2007), *Aglietti et el.* (2007)]



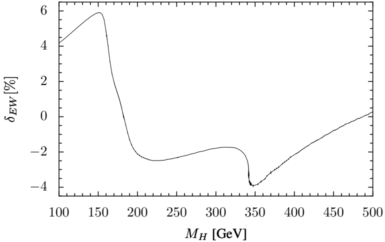
  - Increase of the hadronic cross section by about 50 − 90% ⇒ K-factor $K_\infty = \frac{\sigma^{NLO}}{\sigma^{LO}}|_{M_t \to \infty}$ huge!
  - Effective calculation is in accordance with the full massive calculation of K-factor within $\mathcal{O}(5\%)$ for $M_H = 125$ GeV
  - NLO cross section can be expressed in good approximation by K_∞-factor rescaled by massive Born term
- Effective NNLO calculation in the limit $M_t^2 \gg M_H^2$ [*Harlander, Kilgore* (2001), *Anastasiou, Melnikov* (2002), *Ravindran et al.* (2003)]



  - Further increase of the cross section by about ≈ 30%
  - Scale dependence at NNLO reduces by a factor of 2 with respect to NLO

NNLO and N^3LO QCD corrections / NLO electroweak corrections

- Massive NNLO calculation only partly available [*Harlander et al.*, *Steinhauser et al.* (2009)] in asymptotic mass expansion. Mass effects below $\mathcal{O}(1\%)$ in K-factor.
- State-of-the-art calculation at N^3LO [*Anastasiou et al.* (2014,2015,2016),*Li et al.* (2014)]
  - Soft + virtual approximation or threshold expansion (singular terms in the limit $z \to \infty$)
  - Terms originating from collinear region $\sim \ln^m(1-z)$, $0 \leq m \leq 5$
  - Quite recently: Full three loop result
  - N^3LO results lead to a further increase of the cxn by +3.2% for $\mu_R = \mu_F = m_H/2$ in the effective theory approach,
- NLO electroweak corrections $\mathcal{O}(\alpha_s^2\alpha)$ in the completely factorizated scheme $\sigma_{tot} = \sigma_{QCD}(1+\delta_{elw})$, [*Degrassi et al.* (2004), *Aglietti et al.* (2006), *Actis et al.* (2008,2009)]
- approximate mixed QCD and elw NNLO corrections $\mathcal{O}(\alpha_s^3\alpha)$ [*Anastasiou et al.* (2009)]



Dim-6 Operators

- Higher-dimension operators of weakly interacting theories up to certain scale Λ generate deviation of the effective Higgs coupling to gluons

$$\mathcal{L}_{\rm eff} = \frac{\alpha_s}{\pi} \left\{ \frac{c_t}{12}(1+\delta) + c_g \right\} G^{a,\mu\nu} G^a_{\mu\nu} \frac{h}{v}$$

- Novel coupling c_g does not receive QCD corrections but develops a RGE as of the trace anomaly $\Theta^\mu_\mu = [1+\gamma_m(\alpha_s)] m_t t\bar{t} + \frac{\beta(\alpha_s)}{2\alpha_s} G^{a,\mu\nu} G^a_{\mu\nu} \frac{h}{v}$ [*Adler et al.* (1979)]

$$c_g(\mu^2) = c_g(\mu_0^2) \frac{\beta_0 + \beta_1 \frac{\alpha_s(\mu^2)}{\pi} + \beta_2 \left(\frac{\alpha_s(\mu^2)}{\pi}\right)^2}{\beta_0 + \beta_1 \frac{\alpha_s(\mu_0^2)}{\pi} + \beta_2 \left(\frac{\alpha_s(\mu_0^2)}{\pi}\right)^2}$$

- Results into a rescaling of the t, b, c Yukawa couplings and effective Hgg coupling [*S., Spira* (2016), *Liebler et al.* (2016), *Anastasiou et al.* (2016)]

Threshold-resummation, part 1

- Partonic cross sections contain singular plus distributions

$$\mathcal{D}_i = \left[\frac{\ln^i(1-z)}{1-z} \right]_+$$

  at every perturbative order
- These logarithmically enhanced terms spoil the convergence of the perturbative expansion in the kinematical region $z \to 1$
- Physical explanation: Near partonic threshold the phase space only permits the emission of soft gluons.
- First observation: Leading Plus distributions show a recurrent pattern [*Parisi* (1980)]
  $\Rightarrow$ Possibility to resum these large contributions

Threshold-resummation, part 2

- Transformation into Laplace- or Mellin-space N.

$$\sigma_N(m_h^2) = \int_0^1 \mathrm{d}\tau_h \tau_h^{N-1} \sigma(s, m_h^2)$$

- Limit $z \to 1$ corresponds to limit $N \to \infty$
- $\mathcal{D}_i \to c_i \ln^{i+1} N + \mathcal{O}(\ln^i N)$
- Renormalization group method:
  - Factorization of divergent hard scattering cross section in the soft region into a soft, soft-collinear and hard part
  - Solution of the RG equations leads to the Sudakov exponentiation [*Sterman et al.* (1986,1997), *Catani et al.* (1989)]

$$\begin{aligned} \hat{\sigma}_{gg\to h} &= \alpha_S^2(\mu_R) C_{gg}\left(\alpha_S^2(\mu_R), \frac{m_h^2}{\mu_R^2}, \frac{m_h^2}{\mu_F^2}\right) \\ &\times \exp\left[\mathcal{G}_h\left(\alpha_S^2(\mu_R), \ln N, \frac{m_h^2}{\mu_R^2}, \frac{m_h^2}{\mu_F^2}\right)\right] \end{aligned}$$

Threshold resummation in inclusive Higgs production via Gluon-Fusion

- Conventional QCD resummation
  - Threshold resummation at NLO+NLL $m_t^2 \gg M_H^2$ [*Krämer, Laenen, Spira* (1997)]
  - Soft-gluon resummation at NNLO+NNLL in the limit of a heavy top-quark [*Catani et al.* (2003)], [*de Florian, Grazzini* (2009)]
  - Inclusion of finite mass effects in the resummation [*de Florian, Grazzini* (2012)]
  - Resummation large-x + small-x + approximate N^{3}LO [*Ball et al.*, *Bonvini et al.* (2014)]
  - Approximate N^{3}LO [*deFlorian et al.* (2014)]
  - Approx. N^{3}LO [*Catani et al.* (2014)]
  - N^{3}LO+N^{3}LL [*Bonvini et al.* (2015,2016), *Anastasiou et al.* (2016)]
- SCET
  - SCET resummation at NNLO+NNLL [*Ahrens et al.* (2009)]
  - SCET resummation at N^{3}LO+N^{3}LL [*Anastasiou et al.* (2016)]

Inclusion of mass effects into resummed kernel

- Soft+virtual gg-channel contains mass dependent NLO contribution $c(\tau_q)$ [*de Florian, Grazzini* (2012)]

$$C_{gg}^{(1)}(\tau_q^\phi) = \pi^2 + c_\phi(\tau_q^\phi) + \frac{33-2N_F}{6}\log\frac{\mu_R^2}{\mu_F^2} + 6\gamma_E^2 + \frac{\zeta_2}{6} - 6\gamma_E \ln\frac{M_H^2}{\mu_F^2}$$

$$c_H(\tau_t^H) \overset{\tau_t^H\to\infty}{\to} \frac{11}{2}\,, \tau_t^\phi = \frac{4m_t^2}{m_\phi^2}$$

- Real gg-, gq- und qq-channels have the same limit $z \to 1$ as for $m_t \to \infty$ relative to Born term (universal factorization) $\Rightarrow$ mass effects can be included in resummation
- Since no massive NNLO calculation available mass effects at NNLL unknown

Collinear Logarithms

- Universal collinear effects $\ln^k N/N \sim \ln^k(1-z)$ are numerically relevant.
- At NLL they exponentiate together with the constant terms $\Leftarrow$ conjecture [*Krämer, Laenen, Spira* (1997)]
- Alternative: Inclusion into constant terms $C_{gg}^{(1)} \to C_{gg}^{(1)} + 2C_A \frac{\ln N}{N}$ [*Catani et al.* (2001,2003)]
- Alternative approach [*S., Spira* (2015)]

$$C_{gg}^{(1)} \to C_{gg}^{(1)} + 2C_A \frac{\tilde{L}}{N},\ C_{gg}^{(2)} \to C_{gg}^{(2)} + (48 - N_F)\frac{\tilde{L}^2}{N} \text{ with } \tilde{L} = \ln \frac{N e^{\gamma_E} \mu_F}{M_\Phi}$$

  - correctly predicts leading logarithms $((\alpha_s/\pi)^{2n-1} \ln^n N/N)$ as well as subleading logarithms $\ln^2 N/N$ at NNLO and $\ln^4 N/N$ at N^{3}LO.
- Next-to-eikonal approach [*Laenen, Magnea, Stavenga (2008,2015)*]
- Physical kernel evolution resums the next-to-soft terms by altering the soft function [*Moch, Vogt* (2014)]

Minimal prescription

- Mellin inversion

$$\sigma^{(\mathrm{res})} = \sigma^{(0)} \int_{C_{MP}-i\infty}^{C_{MP}+i\infty} \frac{dN}{2\pi i} \left(\frac{M_H^2}{s}\right)^{-N+1} f_{g/h_1,\,N}(\mu_F^2)\, f_{g/h_2\,N}(\mu_F^2)$$
$$\times\, \hat{\sigma}_{gg\to\phi,\,N}(\alpha_s(\mu_R^2), M_H^2/\mu_R^2; M_H^2/\mu_F^2)$$

- Minimal Prescription = choosing carefully the integration contour in order to avoid non-perturbative poles
- Necessity for N-space PDF's $\Rightarrow$ Fitting linear combinations of $x^\alpha(1-x)^\beta$ to x-space PDF's for different μ_F and transforming results to N-space [*de Florian, Vogelsang*]
- Alternative: QCD-PEGASUS. Takes PDF's at input scale $\mu_{F,0}$ in the 9-parameter form and evolves them with DGLAP-equations in Mellin-space up to higher scales

Usage of x-space PDF's

- Parton derivatives / Fake parton luminosities [*Kulesza et al.* (2002)]
  - Multiplication of the cross section by one:

$$\sigma^{(\mathrm{res})} = \sigma^{(0)} \int_{C_{MP}-i\infty}^{C_{MP}+i\infty} \frac{dN}{2\pi i}\, \rho^{-N+1}$$

$$\times\ f_{g/h_1,\,N}(\mu_F^2)\, (N-1)^2\, f_{g/h_2\,N}(\mu_F^2)\, (N-1)^2\, \hat{\sigma}_{gg\to\phi,\,N}/(N-1)^4$$

$$= \sigma^{(0)} \int_{\rho}^{1} \frac{\mathrm{d}z}{z} \int_{\rho/z}^{1} \frac{\mathrm{d}y}{y} \mathcal{G}^{(2)}(y, \mu_F^2) \mathcal{G}^{(2)}(\frac{\rho}{y \cdot z}, \mu_F^2)$$

$$\times\ \frac{1}{2\pi i} \int_{C_{MP}-i\infty}^{C_{MP}+i\infty} \mathrm{d}z\, z^{-N} \hat{\sigma}_{gg\to\phi,\,N}/(N-1)^4$$

  - Second derivative

$$\mathcal{G}^{(2)}(x, \mu_F^2) = \frac{\mathrm{d}}{\mathrm{d}x} \left\{ x\, \frac{\mathrm{d}}{\mathrm{d}x} \left(x\, g(x, \mu_F^2) \right) \right\}$$

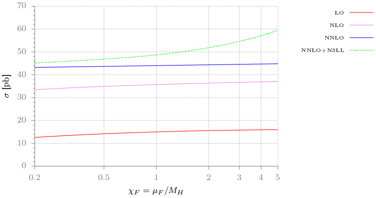
stabilizes numerical integration over the phase space. Good agreement with QCD-PEGASUS.

Matching by including mass effects

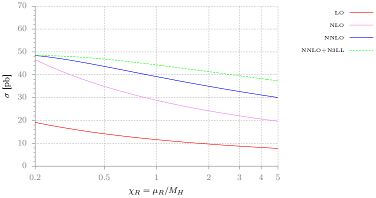
- Improved matching by only incorporating top mass effects in the resummed kernel
  - Large double logarithms (DL) $\ln^2 \frac{M_H^2}{m_q^2}$ in the case of bottom and charm quarks $\Rightarrow$ Numerically relevant, no soft gluon dominance
  - For MSSM Higgs DL's of bottom quarks scale with $\tan\beta$ $\Rightarrow$ Resummation only relevant for moderate $\tan\beta \lesssim 10-15$

$$
\begin{aligned}
\sigma_{tt}^{(NNLO+N^3LL)} = & \left[\sigma_{tt}^{(0)} K_{tt,\infty}^{(NNLO)}\right]^{x-space} + \left[\sigma_{tt}^{(0)} K_{tt,\infty}^{(N3LL)} - \sigma_{tt}^{(0)} K_{tt,\infty}^{(NNLO)}\right]^{N-space} \\
& + \left[\sigma_{t+b+c}^{(NLO)} - \sigma_{tt}^{(0)} K_{tt,\infty}^{(NLO)}\right]^{x-space} \\
& + \left[\sigma_{tt}^{(0)} K_{tt}^{(NLL)} - \sigma_{tt}^{(0)} K_{tt}^{(NLO)}\right]^{N-space} \\
& - \left[\sigma_{tt}^{(0)} K_{tt,\infty}^{(NLL)} - \sigma_{tt}^{(0)} K_{tt,\infty}^{(NLO)}\right]^{N-space}
\end{aligned}
$$

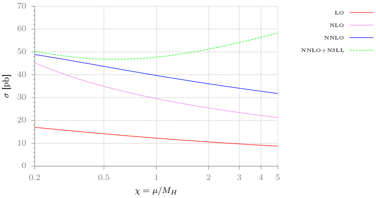
Scale variation: SM Higgs



(a) Scale variation with respect to the factorization scale $\chi_F = \mu_F/M_H$



(b) Scale variation with respect to the renormalization scale $\chi_R = \mu_R/M_H$



(c) Scale variation with identified scales $\chi = \mu/M_H$

Total cross section: SM Higgs

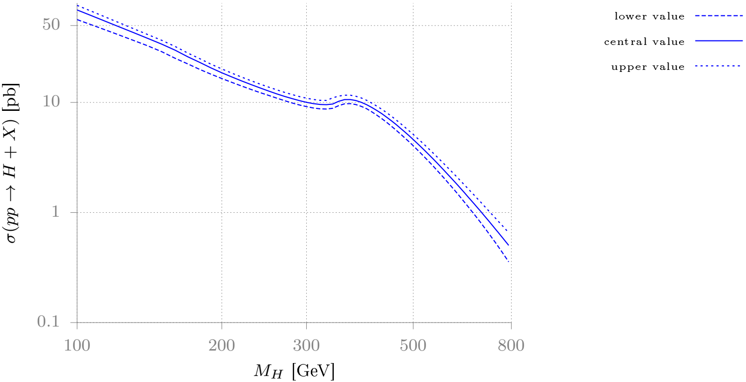
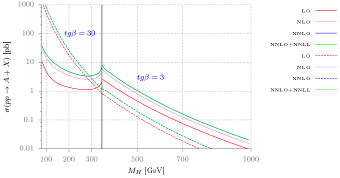
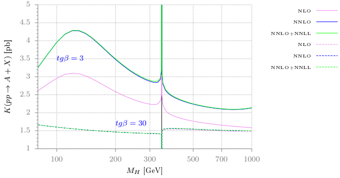


Figure : Total hadronic cross section with uncertainty band due to 7-point scale variation and PDF+α_S uncertainties according to the PDF4LHC15 recommendations

Pseudoscalar Higgs: Total hadronic cross section and K-Factor



(a) Total hadr. cxn in the m_h^{mod+} scenario

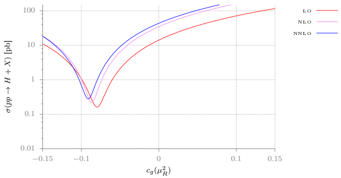


(b) K-factor in the m_h^{mod+} scenario

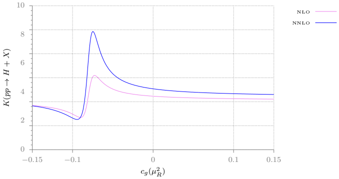
- Resummation effects amount to about 5% for tg$\beta = 3$ and are small for large tg$\beta = 30$.
- Bumbs and spikes at $M_A \sim 2M_t$ related to $t\bar{t}$ threshold that generates Coulomb singularity
- Squark loops [*Anastasiou et al.* (2007), *Aglietti et al.* (2007)], SUSY-QCD corrections [*Anastasiou et al.* (2008), *Mühlleitner et al.* (2010)] and N^{3}LO threshold effects [*Ahmed et al.* (2015,2016)] not yet included

Dim-6 Operator: Total hadronic cross section and K-Factor

- Novel coupling c_g consistently included at NNLO in HIGLU [*Spira et al.* (1995)], resummation effects not yet examined.
- SM value recovered for $c_g(\mu_R^2)=0$.
- Large constructive and destructive effects depending on the value of c_g due to Born term interference.
- Hadronic cross section becomes minimal where c_g cancels the quark-loop contributions.



(a) Total hadr. cxn by variation of the novel coupling c_g



(b) K-factor by variation of the novel coupling c_g

Conclusions

- Gluon fusion dominant production mechanism over the entire energy spectrum at the LHC
- Higher order corrections in pQCD and elw. theory are sizeable
- Threshold resummation proves to permit insight into higher orders in QCD
- Inclusion of mass effects in resummation turns out to be small
- Collinear effects not negligible
- Matched result at NNLO+N^{3}LL agrees with full N^{3}LO within $\mathcal{O}(2\%)$ for $\mu_R = \mu_F = M_H/2$ for $\overline{\mathrm{MS}}$-masses (no inclusion of missing mass effects)
- Dim-6 Operator included at NNLO

Thank you for your attention!