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MSSM neutral Higgs production cross section via gluon fusion and bottom quark fusion at NNLO in QCD

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Abstract: MSSM Higgs production cross section in bottom-quark annihilation is evaluated at next-to-next-to-leading order (NNLO) in QCD. Scale dependence for both the factorization and renormalization scales for center of mass energies 7, 8 TeV was found. With the help of computer program HIGLU the neutral MSSM Higgs production cross section via gluon fusion at LHC with center of mass energies 7, 8, 14 TeV including next-to-next-to-leading order QCD corrections is presented. The result for neutral Higgs boson mass is in accordance with the last experimental data received at the LHC.

Keywords: Minimal Supersymmetric Standard Model, Cross Section of Higgs Boson Production, Renormalization and Factorization Scales

1. Introduction

Understanding the mechanism that leads to the breaking of the electroweak symmetry and that is responsible for the generation of the mass of the elementary particles is one of the major challenges of high energy physics. As the Higgs mass have already been set it requires an accurate control of all the Higgs production and decay mechanisms, including the effects due to radiative corrections [1].

The Standard Model (SM) provides very good description of experimental observables measured at high-energy colliders. The SM is the renormalizable theory and admits perturbative description at scales of the weak scale order. The Higgs boson [2, 3] is the last unobserved fundamental particle in Standard Model of particle physics, and its discovery would be the “ultimate verification” of the Standard Model. Dated August 2012, the search is widely considered to be in its final stages, a previously unknown boson has been found in July 2012, however it is not yet formally proven - whether or not this is the sought-after boson. On 4 July 2012, CMS announced the discovery of a previously unknown boson with mass 125.3±0.6 GeV [4, 5] and ATLAS of boson with mass 126.5 GeV [6, 7]. In this low mass region, the main search channel at the LHC comes from the Higgs production via gluon fusion and its rare decay into two photons [8-11]. Symmetry breaking is considered proven, but confirming exactly how this occurs in nature is the major unanswered question in physics. Proof of the Higgs field (by observing the associated particle), and evidence of its properties, is likely to greatly affect human understanding of the universe, validate the final unconfirmed part of Standard Model, as essentially correct, indicating - which of several current particle physics theories are more likely correct, and open up “new” physics beyond current theories. If the Higgs boson does not exist, other alternative sources for the Higgs mechanism would need to be considered and the same experimental equipment would be used for that purpose.

In the Standard Model the gluon fusion process [12] is the dominant Higgs production mechanism at the LHC. The total cross section receives very large next-to-leading order (NLO) QCD corrections, which were first computed in [13]. Later calculations [14, 15] retained the exact dependence on the masses of the top and bottom quarks running in the loops. The next-to-next-to-leading order (NNLO) QCD corrections are also large, and have been computed in [16]. The role of electroweak (EW) corrections has been discussed in [17]. The impact of mixed QCD-EW corrections has been discussed in [18]. The residual uncertainty on the total cross section depends on the uncomputed higher-order QCD effects and on the uncertainties that affect the parton distribution functions (PDF) of the proton [19].

The Higgs sector of the Minimal Supersymmetric Standard Model (MSSM) consists of two $SU(2)$ doublets, H_1 and H_2, whose relative contribution to electroweak symmetry breaking is determined by the ratio of vacuum expectation values of their neutral components, tan $\beta \equiv \upsilon_2/\upsilon_1$. The spectrum of physical Higgs bosons is richer than in the SM, consisting of two neutral CP-even bosons, h and H, one neutral CP-odd boson, A, and two charged bosons, $H^{\pm}$. The couplings of MSSM Higgs bosons to matter fermions differ from those of the SM Higgs, and they can be considerably enhanced depending on tan β. As in the SM, gluon fusion is one of the most important production mechanisms for the neutral Higgs bosons, whose couplings to the gluons are mediated by top and bottom quarks and supersymmetric partners.

In MSSM, the cross section for Higgs boson production in gluon fusion is currently known at the NLO. The contributions arising from diagrams with squarks and gluons were first computed under the approximation of vanishing Higgs mass in [20], and the full Higgs-mass dependence was included in later calculations [21].

The purpose of this article is the precise prediction of the total cross section for Higgs boson production in association with bottom quarks. We will present our calculations for the process $\left(pp \to \left(b\bar{b}\right)h + X\right)$ at NNLO. In these calculations we used last experimental data for Higgs boson mass and we also used new Martin-Stirling-Thorne-Watt (MSTW) parton distribution functions in order to remove the uncertainties that affect PDF of the proton. We considered energies of LHC $\sqrt{s} = 7, 8, 14$ TeV for calculations of the total Higgs production cross section. The results for the process $\left(pp \to \left(b\bar{b}\right)h + X\right)$ at NNLO meet all expectations concerning their dependence on the renormalization and factorization scales, thus providing a solid prediction for the total cross section at the LHC.

As a new scalar particle is discovered at the LHC, a major question will be to determine whether it is a Higgs boson and, in that case, whether it belongs to the particle spectrum of the SM, of the MSSM or of any other model. The spectacular discovery of a Higgs-like particle with a mass around 126 GeV and its decay in two photon channel, shows that the observed rate in two photon channel turns out to be considerably above the expectation for the SM Higgs both for ATLAS and CMS, whereas the $b\bar{b}$ and the $\tau^{+}\tau^{-}$ channels appear to be somewhat low in the LHC measurements [22]. While those possible deviations from the SM prediction are not statistically significant at present, in future the observed patterns could be a first indication of a non-SM nature of the new state. An example could be represented by a MSSM Higgs boson whose production cross section is close to the production cross section for a SM Higgs boson of equal mass. In this case, an accurate study of the production cross section for a Higgs boson might shed light on the underlying model.

In this article we concentrate on searches for neutral Higgs bosons in the MSSM [23]. In the following we will mainly focus on the production processes that are expected to be the most relevant for early searches of MSSM Higgs bosons at the LHC, namely Higgs production in gluon fusion and in association with bottom quarks.

The structure of the article is as following. In Sec. 2 we discuss the hadron cross section of Higgs boson production via gluon fusion pp→Φ+X including next-to-next-to-leading (NNLO) order of QCD corrections. In Sec. 3 we describe the actual calculation of the total cross section for Higgs production in bottom-quark annihilation $b\bar{b}$ at NNLO in QCD. Sec. 4 presents the results of our calculations.

2. Reaction pp → Φ + X

The next-to-leading order of QCD corrections to the production cross sections of scalar Higgs bosons have been calculated in [24,25]. They are significant for the theoretical prediction of the cross sections leading to the increase up to the factor of two compared to the lowest order results. In this paper the program HIGLU for the calculation of the Higgs production cross sections including next-to-next-to-leading order of QCD corrections will be presented. Possible options are minimal supersymmetric extension of Standard Model with various relevant input parameters. Within Standard Model as well as in most of the parameter space of MSSM the contribution of the top and bottom quarks in the loops provides the excellent approximation for all cases in practice.

The hadron cross section of Higgs boson production via gluon fusion gg → Φ (Φ=h, H, A) including next-to-next-to-leading order of QCD corrections, can be presented in the form:

$$\sigma\left(\mathrm{pp} \to \Phi + \mathrm{X}\right) = \sigma^{\Phi}_{\mathrm{LO}} + \Delta\sigma^{\Phi}_{\mathrm{virt}} + \Delta\sigma^{\Phi}_{\mathrm{gg}} + \Delta\sigma^{\Phi}_{\mathrm{gq}} + \Delta\sigma^{\Phi}_{\mathrm{q\bar{q}}} \tag{1}$$

with the lowest order of cross sections

$$\sigma\left(\mathrm{pp} \to \Phi + \mathrm{X}\right) = \sigma^{\Phi}_{0} \tau_{\Phi} \frac{\mathrm{d}L^{\mathrm{gg}}}{\mathrm{d}\tau_{\Phi}}$$

The coefficients are

$$\sigma_0^H = \frac{G_F \alpha_s^2\left(\mu^2\right)}{288\sqrt{2}\pi} \left| \sum_Q g_Q^H A_Q^H\left(\tau_Q\right) \right|^2,$$

$$\sigma_0^A = \frac{G_F \alpha_s^2\left(\mu^2\right)}{128\sqrt{2}\pi} \left| \sum_Q g_Q^A A_Q^A\left(\tau_Q\right) \right|^2.$$

They include the Yukawa coupling g_Q^{Φ} normalized to the SM couplings, and the quark amplitudes

$$A_Q^H\left(\tau_Q\right) = \frac{3}{2}\tau_Q\left[1 + \left(1 - \tau_Q\right) f\left(\tau_Q\right)\right], \quad A_Q^A\left(\tau_Q\right) = \tau_Q f\left(\tau_Q\right).$$

The function $f(\tau)$ is defined as

$$f(\tau) = \begin{cases} \arcsin^2 \dfrac{1}{\sqrt{\tau}} & \tau \geq 1 \\ -\dfrac{1}{4}\left[\log\dfrac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi\right]^2 & \tau \prec 1 \end{cases}$$

and the scaling variables are

$$\tau_Q = \frac{4m_Q^2}{m_\Phi^2}$$

and

$$\tau_\Phi = \frac{m_\Phi^2}{s}.$$

The parameter m_Q denotes the heavy quark mass, m_Φ is the Higgs boson mass and s is the total center of mass energy squared, G_F is the Fermi constant and α_s is the QCD coupling constant. The term $\Delta\sigma_{virt}^{\Phi}$ parametrizes the infrared regularized virtual two-loop corrections and the terms $\Delta\sigma_{ij}^{\Phi}\left(i,j=g,q,\bar{q}\right)$ the individual collinear regularized real one-loop corrections corresponding to the subprocesses

$$gg \to \Phi g,\ \ gq \to \Phi q,\ \ q\bar{q} \to \Phi g.$$

The expressions for $\Delta\sigma_{virt}^{\Phi}$ and $\Delta\sigma_{ij}^{\Phi}$ can be found in [24,25]. The gluon luminosity is defined by

$$\frac{dL^{gg}}{d\tau} = \int_{\tau}^{1} \frac{dx}{x} g\left(x,Q^2\right) g\left(\tau/x,Q^2\right),$$

where $g\left(x,Q^2\right)$ denotes the gluon density. The natural values to be chosen for the renormalization scale μ of the strong coupling $\alpha_s\left(\mu^2\right)$ and the factorization scale Q of the parton densities is given by the Higgs mass m_Φ.

The program HIGLU calculates five terms in formula (1) contributing to the total cross section separately, as well as their sum for all kinds of neutral Higgs boson Φ. Resulting cross sections for the light scalar MSSM Higgs boson h for energies $\sqrt{s} = 7, 8, 14$ TeV are shown in Figure 1.

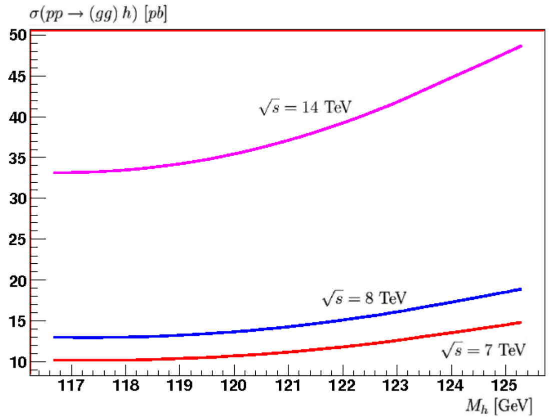

Figure 1. *Total gluon-fusion cross sections of the light scalar MSSM Higgs boson* h *for* $\sqrt{s} = 7, 8, 14$ *TeV.*

We can see that the total cross section for $\sqrt{s} = 14$ TeV is much more larger than for $\sqrt{s} = 7, 8$ TeV. From this figure it is possible to see that the mass of the light scalar MSSM Higgs boson h calculated with the help of HIGLU and recent experimental data for the Higgs boson mass $M_h = 125.3$ GeV received from LHC (CMS) are in good agreement.

3. Reaction $pp \to (b\bar{b})h+X$

Despite the fact that the dominant production mode for Higgs boson is gluon fusion, next-to-leading order (NLO) corrections have been also evaluated for Higgs boson production in association with top quarks [26-29]. These results can be used for supersymmetric Higgs boson production as well. However, due to the enriched particle spectrum in supersymmetric extensions of Standard Model, they provide only part of the full production rate in general. Additional contributions arise through intermediate supersymmetric partners and modified couplings of Standard Model particles. In order to avoid unnecessary generalizations, we will focus on MSSM [23]. MSSM contains after spontaneous symmetry breaking five physical Higgs bosons, where mass eigenstates are denoted by $h, H, H^{\pm}, A$. One interesting consequence of this more complicated Higgs sector is that compared to Standard Model, the bottom quark Yukawa coupling can be enhanced with respect to the top quark Yukawa coupling. In Standard Model, the ratio of the $t\bar{t}H$ and $b\bar{b}H$ couplings is given at the tree-level like

$$\lambda_t^{SM} / \lambda_b^{SM} = m_t / m_b \approx 35.$$

On the contrary, in MSSM, its depends on the value

$$\lambda_t^{MSSM} / \lambda_b^{MSSM}.$$

Such enhancement would have (at least) two important consequences. The first is that in the gluon fusion mode it is no longer sufficient to consider top quark loops as the only mediators between the Higgs boson and the gluons; one must also include the effects of bottom quark loops (see Figure 2). The second consequence is that Higgs boson production in association with bottom quarks can become an important channel: $pp \to b\bar{b}\phi,\ \phi \in h, H, A$. For the calculation one evaluates virtual and real corrections to Higgs production in $b\bar{b}, gb, gg, bb, qb, q\bar{q}$ scattering and then performs ultraviolet renormalization and mass factorization.

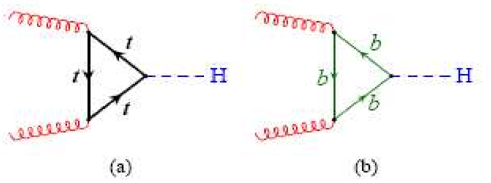

Figure 2. *The bottom quark contribution to the gluon fusion process (b) can be comparable to the top quark contribution (a).*

The subprocesses to be evaluated at the partonic level are given as following $(q \in u, d, c, s)$:

- up to two loops: $b\bar{b} \to \phi$;
- up to one loop: $b\bar{b} \to \phi g,\ g\bar{b} \to \phi b$;
- at tree level:

$$
\begin{aligned}
&b\bar{b} \to \phi\, gg,\;\; b\bar{b} \to \phi\, q\bar{q},\\
&b\bar{b} \to \phi\, b\bar{b},\;\; gb \to \phi\, gb,\\
&bb \to \phi\, bb,\;\; bq \to \phi\, bq,\\
&gg \to \phi\, b\bar{b},\\
&q\bar{q} \to \phi\, b\bar{b}\,.
\end{aligned}
$$

Let us now turn to the underlying interaction and the renormalization of the partonic results. We ignore the bottom quark mass and the electroweak interactions. So, for our purposes, the Lagrangian is:

$$L_{b\bar{b}\phi} = -\frac{1}{4}F^{a}_{\mu\nu}F^{a\mu\nu} + \sum_{q}\bar{q}iDq + \bar{b}iDb - \lambda_b^B \bar{b}\,\phi\, b\,,$$

where $F^{a}_{\mu\nu}$ is the gluon field strength tensor, D_μ is the QCD covariant derivative, and the sum runs over the quarks u,d,s,c. λ_b^B is a bare bottom Yukawa coupling constant. The renormalized partonic results have the dependence on the nonphysical scales μ_F and μ_R, both explicitly in terms of logarithms, and implicitly through the parameters $\alpha_s(\mu_R)$ and $\lambda_b(\mu_R)$. The variation of α_s and λ_b with μ_R is governed by the renormalization group equations (RGEs)

$$
\begin{aligned}
&\mu_R^2 \frac{d}{d\mu_R^2} a_s = \beta(a_s) a_s\,,\\
&\mu_R^2 \frac{d}{d\mu_R^2} \lambda_b = \gamma^m(a_s)\lambda_b\,,\\
&a_s \equiv \frac{\alpha_s}{\pi}\,,
\end{aligned}
$$

where

$$
\begin{aligned}
&\beta(a_s) = -a_s\beta_0 - a_s^2\beta_1 - a_s^3\beta_2 + \mathrm{O}(a_s^4),\\
&\beta_0 = \frac{11}{4} - \frac{1}{6}n_f\,,\quad \beta_1 = \frac{51}{8} - \frac{19}{24}n_f\,,\\
&\beta_2 = \frac{2857}{128} - \frac{5033}{1152}n_f + \frac{325}{3456}n_f^2\,,\\
&\gamma^m(a_s) = -a_s\gamma_0^m - a_s^2\gamma_1^m - a_s^3\gamma_2^m + \mathrm{O}(a_s^4),\\
&\gamma_0^m = 1\,,\quad \gamma_1^m = \frac{101}{24} - \frac{5}{36}n_f\,,\\
&\gamma_2^m = \frac{1249}{64} - \left(\frac{277}{216} + \frac{5}{6}\zeta_3\right)n_f - \frac{35}{1296}n_f^2\,.
\end{aligned}
$$

Here, $\zeta_n \equiv \zeta(n)$ is Riemann's ζ -function $(\zeta_3 \approx 1.20206)$. In order to evaluate $\alpha_s(\mu_R)$ from the initial value $\alpha_s(M_Z)$, $\beta(\alpha_s)$ is expanded up to α_s^l, with $l=1$ at LO, $l=2$ at NLO, and $l=3$ at NNLO. The resulting differential equation of the renormalization group equations (RGEs) is solved numerically. In order to evaluate $\lambda_b(\mu)$ from its initial value $\lambda(\mu_0)$, we combine two RGEs to obtain

$$\lambda_b(\mu) = \lambda_b(\mu_0)\frac{c(a_s(\mu))}{c(a_s(\mu_0))}$$

with

$$
\begin{aligned}
c(a) = a^{c_0}\{&1 + (c_1 - b_1c_0)a\\
&+ \frac{1}{2}\left[(c_1 - b_1c_0)^2 + c_2 - b_1c_1 + b_1^2c_0 - b_2c_0\right]a^2\\
&+ \mathrm{O}(a^3)\},\quad c_i \equiv \frac{\gamma_i^m}{\beta_0}\,,\quad b_i \equiv \frac{\beta_i}{\beta_0}\,.
\end{aligned}
$$

Working at LO (NLO, NNLO), we truncate the term in braces at order $a^0\left(a^1, a^2\right)$.

Convolution of the partonic cross section with the parton densities cancels the μ_F dependence up to higher orders and results in the physical hadronic cross section. The variation of the hadronic cross section with μ_F and μ_R is thus the indication of size of higher order effects. All the numerical results have been obtained using Martin-Stirling-Thorne-Watt (MSTW) parton distributions MSTW2008nnlo68cl.LHgrid [30]. In particular, we use the $[\alpha_s(M_Z) = 0.1171]$ at NNLO. These results can be seen from Figures 3, 4, 5.

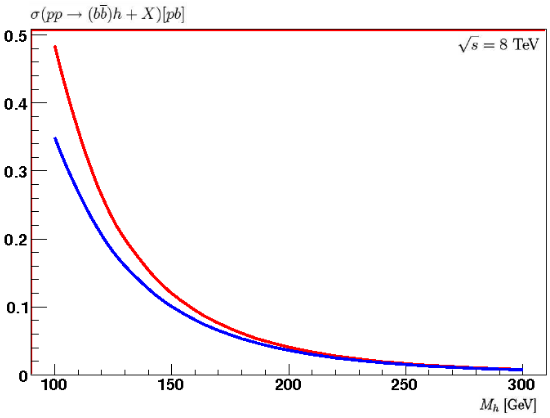

Figure 3. *Cross section for Higgs boson production in bottom quark annihilation at the LHC at NNLO. The upper (lower) line corresponds to a choice of the factorization scale of* $\mu_F = 0.7M_h$ $(\mu_F = 0.1M_h)$. *The renormalization scale is set to* $\mu_R = M_h$.

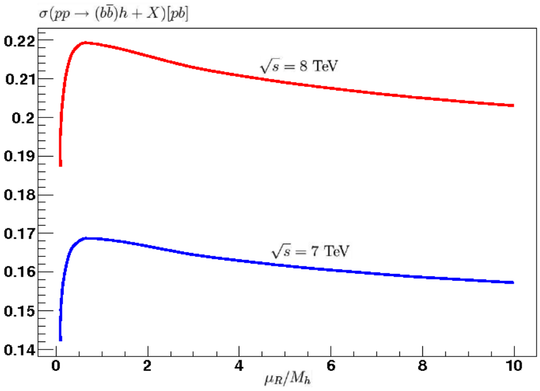

Figure 4. *Cross section for* $\left(pp \to \left(b\bar{b}\right)h + X\right)$ *at* $\sqrt{s} = 7{,}8$ *TeV,* $M_h = 125.3$ *GeV.* μ_R *dependence for* $\mu_F = 0.25M_h$.

Figure 3 shows the NNLO predictions for the cross section $\sigma\left(pp \to \left(b\bar{b}\right)h + X\right)$ at the LHC as a function of the

Higgs boson mass M_h. Two curves at each order correspond to two different choices of the factorization scale, $\mu_F = 0.1M_h$ and $\mu_F = 0.7M_h$ at $\sqrt{s} = 8$ TeV.

We study the behaviour of the NNLO result with respect to variations of the input parameters, in particular the Higgs boson mass and the collider energy. We put the Higgs boson mass $M_h = 125.3$ GeV in accordance with recent experimental data obtained at the LHC (CMS). Special emphasis is placed on the variation of the results with the renormalization (Figure 4) and factorization scale (Figure 5), from which we estimate the theoretical uncertainty of the prediction for Higgs boson production in $b\bar{b}$ annihilation. From Figures 4 and 5 we see that the magnitude of the cross sections for the neutral Higgs boson in $b\bar{b}$ annihilation is more for $\sqrt{s} = 8$ TeV than for $\sqrt{s} = 7$ TeV.

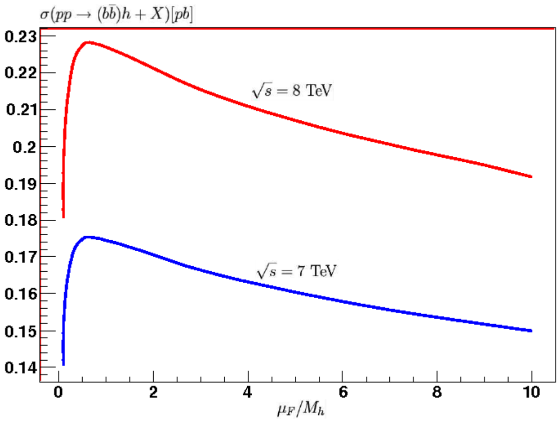

Figure 5. *Cross section for* $\left(pp \to \left(b\bar{b}\right)h + X\right)$ *at* $\sqrt{s} = 7,8$ *TeV,* $M_h = 125.3$ *GeV.* μ_F *dependence for* $\mu_R = M_h$.

4. Conclusion

The calculation of the total Higgs production cross section via gluon fusion at LHC with $\sqrt{s} = 7,8,14$ TeV including next-to-next-to-leading order QCD corrections is presented. It is suitable for the neutral Higgs particles of the minimal supersymmetric extension of the Standard Model. The corresponding couplings are implemented including the leading higher order corrections. The result for MSSM neutral Higgs boson mass is in accordance with the last experimental data at the LHC and equal approximately to $M_h = 125.3$ GeV. We have computed also the total cross section for Higgs boson production in $b\bar{b}$ fusion at NNLO in QCD. We have argued that the NNLO plays an exceptional role in this process. The results are very stable with respect to changes of the renormalization and factorization scales and differ only for the value of energies $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV. The contributions of two-loop diagrams to scalar Higgs production were computed with the full Higgs mass dependence for Higgs mass received at the LHC (CMS). We also tried to cut uncertainty on the total cross section of Higgs boson production connected with uncertainties that affect PDF. All the numerical results have been obtained using the last PDF MSTW2008nnlo68cl.LHgrid and Higgs mass $M_h = 125.3$ GeV. We conclude that the inclusive cross section for Higgs boson production in bottom quark annihilation is under good theoretical control.

New data from the ATLAS and CMS Higgs boson searches is rapidly emerging. It will be important to investigate on the one hand potential deviations of the rates from the SM predictions and on the other hand the outcome of searches for additional non SM-like Higgses. Confronting these results with predictions in MSSM will show whether this model, whose prediction of a light Higgs boson seems to be well supported by the data, will continue to provide a viable description of nature also in the future.

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