

Production of the Higgs Boson via b-quark Fusion in the Regge Limit of QCD

Saleev V.A.

Samara State University and Samara State Aerospace University

In collaboration with

A. Shipilova (Samara State University)

Many thanks to Organizing
Committee for invitation!

I am very glad to be in Dubna
each time.

Quantum Field Theory Community from Samara

(
Us at least five !)

congratulate Dmitry Kazakov
with an anniversary !!!

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MOTIVATIONS

I. Why we study "Production of the Higgs Boson in SM and beyond" at the LHC?

- 1) We can do predictions beyond collinear parton model and fixed order QCD calculations.
- 2) We will check QCD in high-energy limit.

II. Why we consider "b-quark Fusion" $b\bar{b} \rightarrow \Phi$ ($\Phi = H, h, A$)?

- 1) $g_{Hb\bar{b}} = m_b(\sqrt{2}G_F)^{\frac{1}{2}}$ is not small in SM and $g_{\Phi b\bar{b}} \sim m_b \tan \beta$ should be enhanced in MSSM ($\tan \beta \sim 30 - 50$, $\Phi = A$).
- 2) Associated production of $\Phi b\bar{b}$ should be clean signal experimentally.
- 3) $m_b \ll m_\Phi$ and we can consider b-quark as an active parton and use so-called "five-flavor scheme" with b-quark in the proton structure function $F_b(x, \mu^2)$, $\mu \sim m_\Phi$.

Higgs-boson production via bottom-quark fusion in the collinear parton model was studied in papers

- 1) *D.A.Discus and S.Willebrock*, Phys.Rev.D39, 751 (1989); **LO**
- 2) *D.Discus, T.Stelzer, Z.Sullivan, and S.Willebrock*, Phys.Rev.D59, 094016 (1999); **LO+NLO**
- 3) *F.Maltoni, Z.Sullivan and S.Willebrock*, Phys.Rev.D67, 093005 (2003); **LO+NLO**
- 4) *R.V.Harlander and W.B.Kilgore*, Phys.Rev.D68, 013001 (2003); **LO+NLO+NNLO**.

For the LHC it was obtained

$$\frac{\sigma^{pp \rightarrow HX}(b\bar{b} \rightarrow H)}{\sigma^{pp \rightarrow HX}(gg \rightarrow Hb\bar{b})} \approx 5$$

$$K = \frac{LO + NLO + NNLO}{LO} \approx 3$$

The additional large logs $\ln(m_H/m_b)$ are included in this scheme.

III. Why we deal with QCD in the Regge limit?

In the fusion subprocess $(b(x_1)\bar{b}(x_2) \rightarrow H)$ parton momentum fractions are equal to

$$x_{1,2} = \frac{m_H}{\sqrt{S}} \exp(\pm y)$$

and one has $x_{1,2} \simeq 0.1$ at the $m_H \sim 100$ GeV, $y \simeq 0$ and $\sqrt{S} = 7 - 14$ TeV.

We will show that it is small enough to realize multi-Regge kinematics (MRK), which lead to parton Reggeization in this high-energy limit of QCD.

The effective action for QCD in high-energy limit contains field of Reggeized gluons, it has been found by [*L.N.Lipatov, 1995*](#). Effective action with Reggeized quarks was written by [*Lipatov and Vyazovsky in 2001*](#). The effective Feynman rules for Reggeized partons are presented in paper by [*Antonov, Kuraev, Lipatov, Cherednikov, 2005*](#).

Process $pp \rightarrow H(b\bar{b})X$ at the LHC in fixed-number flavor scheme of collinear parton model

In the leading order (LO) of QCD the main contribution is

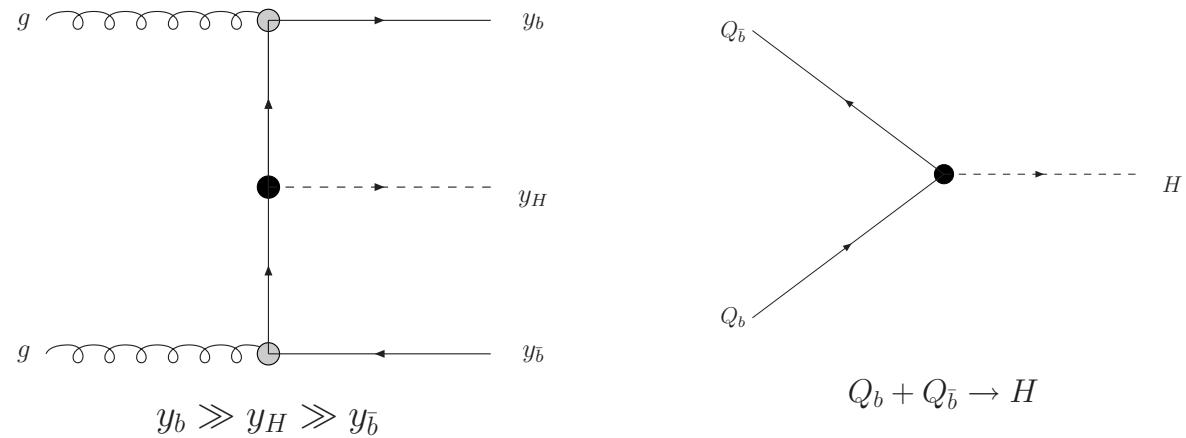
$$g + g \rightarrow H + b + \bar{b}$$

We consider following kinematical region:

$$y_H \simeq 0, \quad |y_b, y_{\bar{b}}| > 2.$$

We found, using **COMPHEP** package, that

$$\frac{\sigma(pp \rightarrow Hb\bar{b}X, |y_b, y_{\bar{b}}| > 2)}{\sigma(pp \rightarrow Hb\bar{b}X, |y_b, y_{\bar{b}}| < 2)} \sim 1.$$

Figure 1: The effective vertex $Q_b \bar{Q}_b \rightarrow H$.

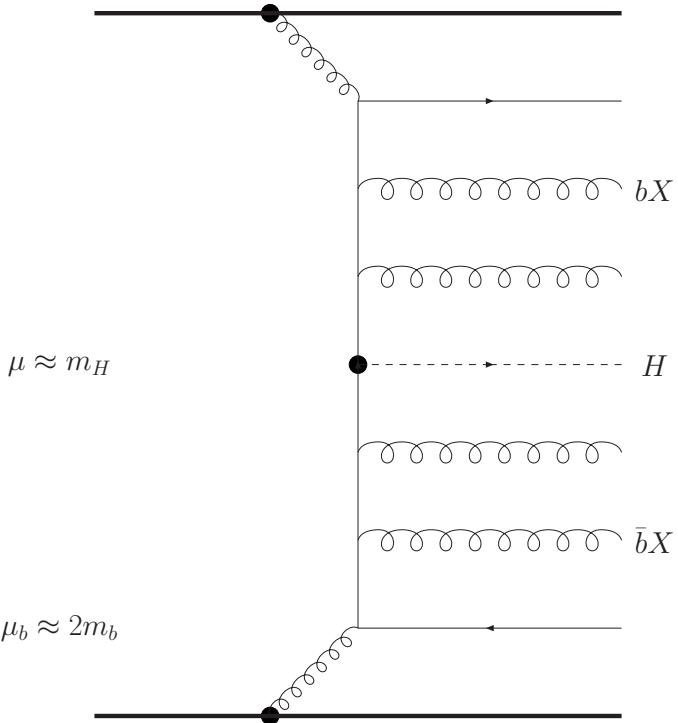
$$d\sigma (pp \rightarrow H(b\bar{b})X) = \int \frac{dx_1}{x_1} \int \frac{d^2 q_{1T}}{\pi} \int \frac{dx_2}{x_2} \int \frac{d^2 q_{2T}}{\pi} \times \\ \times \Phi_b^p(x_1, t_1, \mu^2) \Phi_b^p(x_2, t_2, \mu^2) d\hat{\sigma}(Q_b Q_{\bar{b}} \rightarrow H)$$

$$t_{1,2} = |\vec{q}_{(1,2)T}|^2$$

In our numerical analysis, we adopt the prescriptions proposed by [Kimber, Martin, and Ryskin \(2001\)](#) and by [Blumlein \(1994\)](#) to obtain unintegrated gluon and quark distribution functions for the proton from the conventional integrated ones. As input for this procedure, we use the [Martin-Roberts-Stirling-Thorne](#) proton PDFs.

KMR PDF base on [DGLAPP](#) equation with large logarithms $\log(\frac{\mu^2}{\Lambda_{QCD}^2})$ and include additionally dependence on parton transverse momentum.

Blumlein gluon PDF bases on [BFKL](#) equation with large logarithms $\log(\frac{S}{\mu^2}) \simeq \log(\frac{1}{x})$.

Figure 2: Scheme of b -quark Reggeization in QCD evolution.

The b -quark distribution function at the scale $\mu_b \approx 2m_b$:

$$F_b(x, \mu) = \frac{\alpha_s(\mu)}{2\pi} \log\left(\frac{\mu^2}{m_b^2}\right) \int_x^1 \frac{dy}{y} P_{qg}\left(\frac{x}{y}\right) F_g(y, \mu)$$

The valence-like QCD evolution for $b(x, \mu)$ from $\mu = \mu_b$ to $\mu = m_H$:

$$\frac{dF_b(x, \mu)}{d \log \mu^2} = \frac{\alpha_s(\mu)}{2\pi} \int_x^1 \frac{dy}{y} P_{qq}\left(\frac{x}{y}\right) F_b(y, \mu)$$

Finally, one has

$$\Phi_b(x, \vec{q}_T^2, \mu^2) = F_b(y, \mu^2) \bigotimes K^{KMR, B}(z, \vec{q}_T^2, \mu^2), \quad x = yz$$

RELEVANT EXAMPLES

1. Inclusive (gluon) jet production at the LHC in MRK via *Fadin-Kuraev-Lipatov (1974)* effective vertex $RR \rightarrow g$.

$$C_{\mathcal{R}\mathcal{R}}^{g,\mu}(q_1, q_2) = -\sqrt{4\pi\alpha_s} f^{abc} \frac{q_1^+ q_2^-}{2\sqrt{t_1 t_2}} \left[(q_1 - q_2)^\mu + \frac{(n^+)^{\mu}}{q_1^+} (q_2^2 + q_1^+ q_2^-) - \frac{(n^-)^{\mu}}{q_2^-} (q_1^2 + q_1^+ q_2^-) \right]$$

2. Prompt photon production at the LHC in MRK via *Fadin-Sherman (1974)* effective vertex $Q\bar{Q} \rightarrow \gamma$.

$$C_{\mathcal{Q}\bar{\mathcal{Q}}}^{\gamma,\mu}(q_1, q_2) = -i\sqrt{4\pi\alpha} e_q \left[\gamma^\mu - \hat{q}_1 \frac{(n^-)^{\mu}}{q_1^- + q_2^-} - \hat{q}_2 \frac{(n^+)^{\mu}}{q_1^+ + q_2^+} \right]$$

B.A. Kniehl, V.A. Saleev, A.V. Shipilova, E.V. Yatsenko.

”Single jet and prompt-photon inclusive production with multi-Regge kinematics: From Tevatron to LHC.”

DESY-11-115, NSF-KITP-11-119. Jul 2011. 24 pp. e-Print: arXiv:1107.1462 [hep-ph]
To be published in PRD.

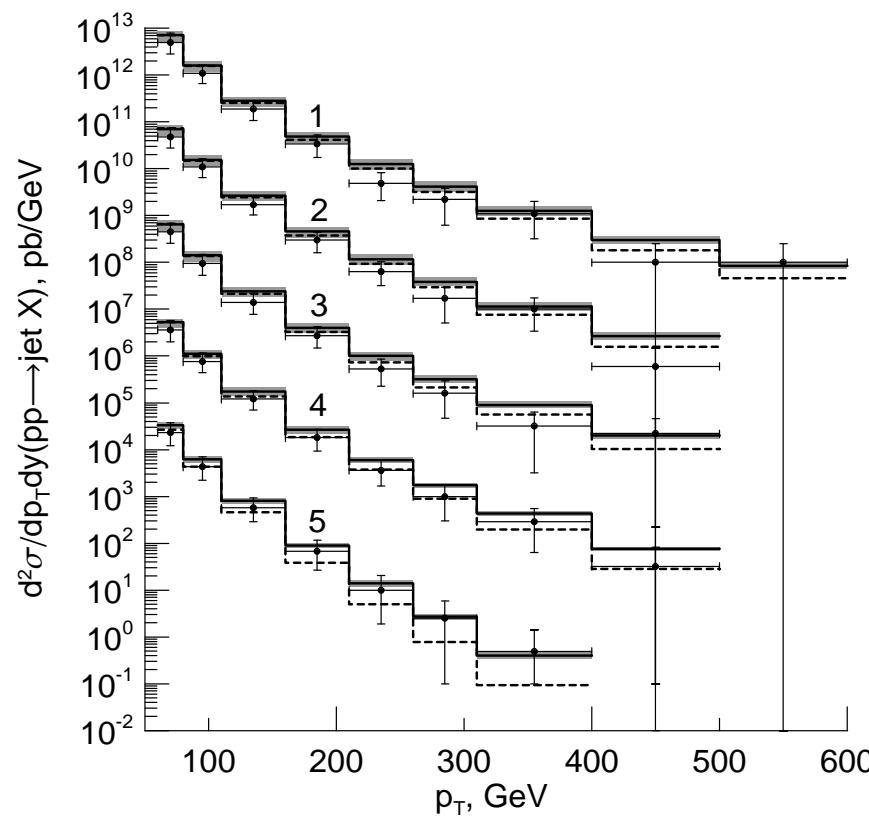


Figure 3: LHC, $\sqrt{s} = 7$ TeV, ATLAS. Solid lines - KMR unPDF, dashed lines - Blumlein unPDF. (1) $|y| < 0.3$ ($\times 10^8$), (2) $0.3 < |y| < 0.8$ ($\times 10^6$), (3) $0.8 < |y| < 1.2$ ($\times 10^4$), (4) $1.2 < |y| < 2.1$ ($\times 10^2$), and (5) $2.1 < |y| < 2.6$

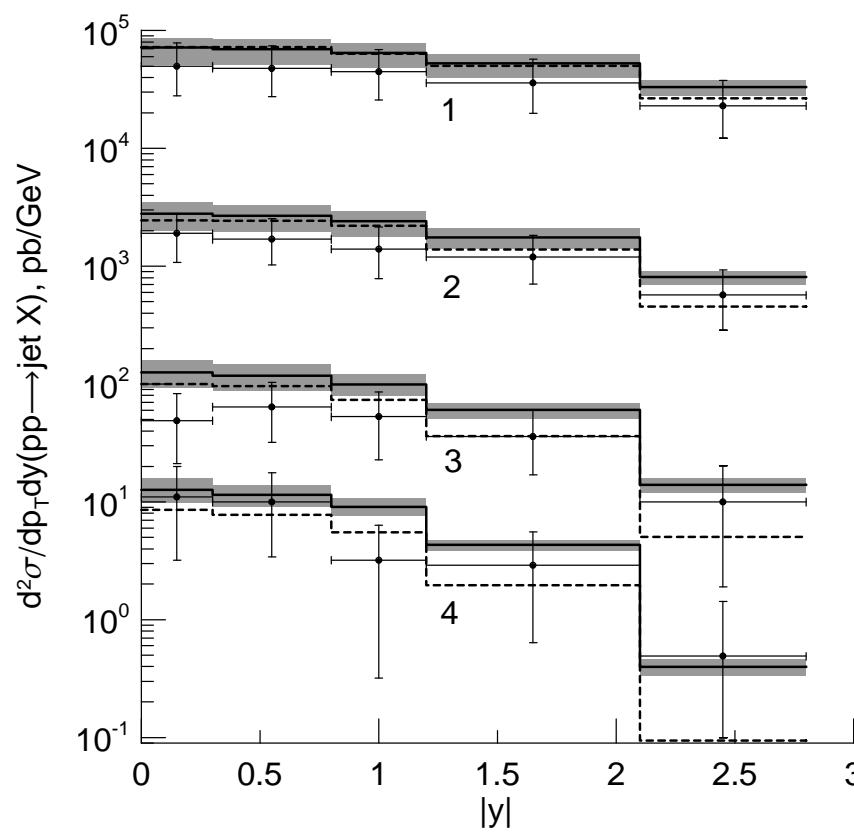


Figure 4: LHC, \sqrt{s} TeV, ATLAS. Solid lines - KMR unPDF, dashed lines - Blumlein unPDF. (1) $60 \text{ GeV} < p_T < 80 \text{ GeV}$, (2) $110 \text{ GeV} < p_T < 160 \text{ GeV}$, (3) $210 \text{ GeV} < p_T < 250 \text{ GeV}$, and (4) $310 \text{ GeV} < p_T < 400 \text{ GeV}$

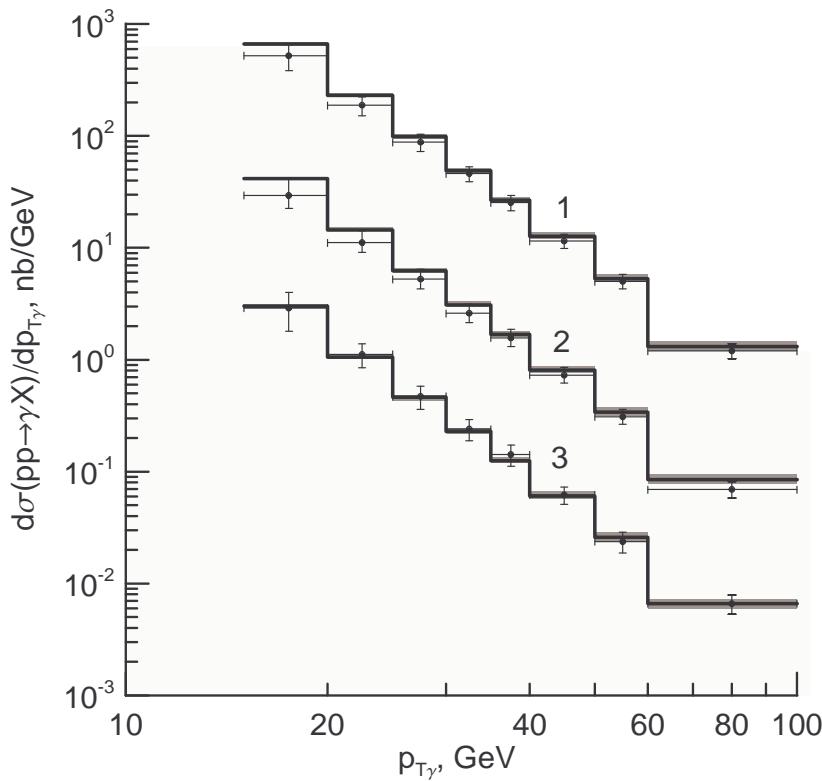


Figure 5: LHC, $\sqrt{7}$ TeV, ATLAS. Solid lines - KMR unPDF. (1) $|\eta| < 0.6$ ($\times 10^2$), (2) $0.6 < |\eta| < 1.37$ ($\times 5$), and (3) $1.52 < |\eta| < 1.81$

SM Higgs boson production

$$\frac{d\sigma(pp \rightarrow H(b\bar{b})X)}{dp_T} = \frac{p_T}{(m_H^2 + p_T^2)^2} \int d\phi_1 \int dt_1 \int \frac{dx_1}{x_1} \overline{|M(Q_b\bar{Q}_b \rightarrow H)|^2} \\ \left(\Phi_b(x_1, t_1, \mu^2) \Phi_{\bar{b}}(x_2, t_2, \mu^2) + \Phi_{\bar{b}}(x_1, t_1, \mu^2) \Phi_b(x_2, t_2, \mu^2) \right)$$

$$\overline{|M(Q_b\bar{Q}_b \rightarrow H)|^2} = \frac{\sqrt{2}G_F m_b^2}{6} (m_H^2 + p_T^2)$$

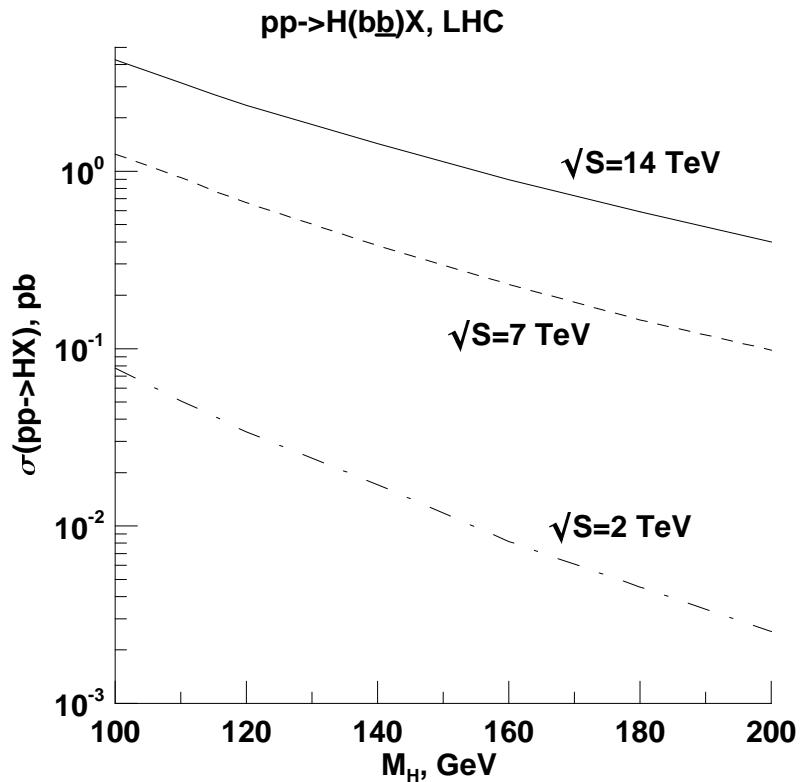


Figure 6: $\sigma(pp \rightarrow H(\bar{b}b)X)$ as function of Higgs boson mass.

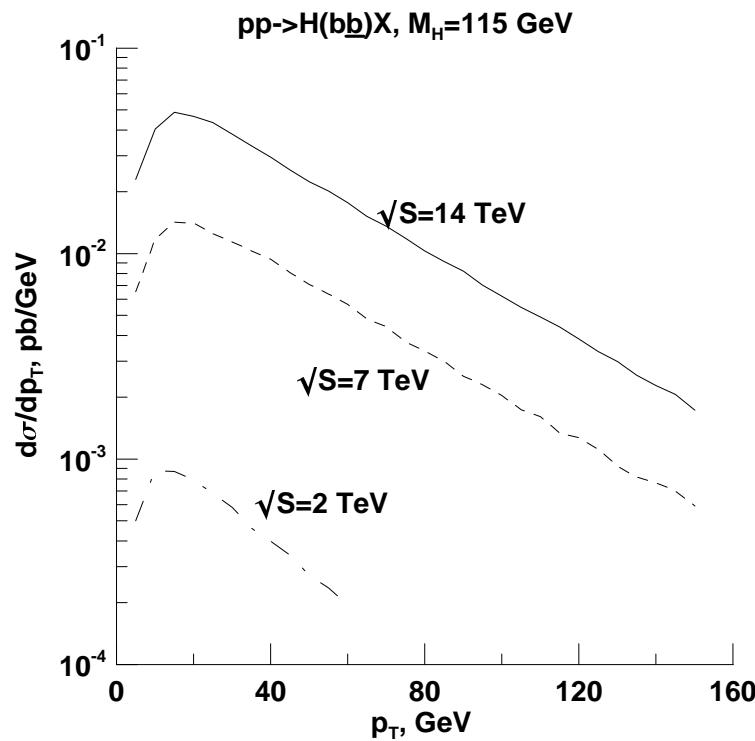


Figure 7: Transverse momentum spectrum of Higgs boson at the $m_H = 115 \text{ GeV}$.

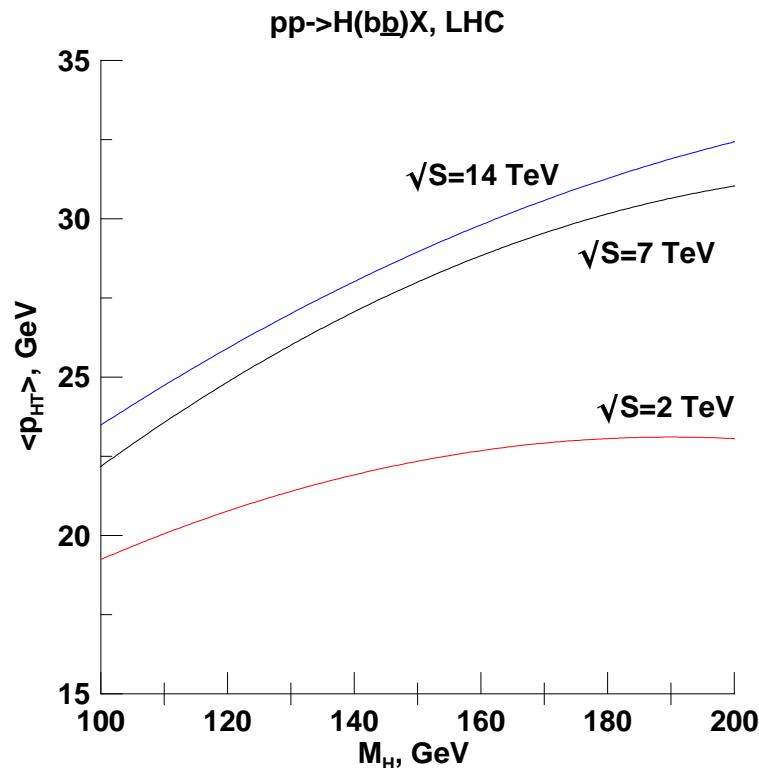


Figure 8: Average Higgs boson transverse momentum as function of mass m_H .

SIGNAL/BACKGROUND: $H \rightarrow b\bar{b}$

1. For $m_H \simeq 100$ GeV one has $Br(H \rightarrow b\bar{b}) \simeq 0.7$, and we should consider process

$$pp \rightarrow H(b\bar{b})X \quad \text{with the decay} \quad H \rightarrow b\bar{b}.$$

Using Feynman rules for effective action with Reggeized quarks ([Lipatov-Vyazovsky, 2001](#)), we find effective vertices for signal (*) and background (**) subprocesses

$$Q_b + \bar{Q}_b \rightarrow H \rightarrow b + \bar{b} \quad (*)$$

$$Q_b + \bar{Q}_b \rightarrow b + \bar{b} \quad (**) \quad$$

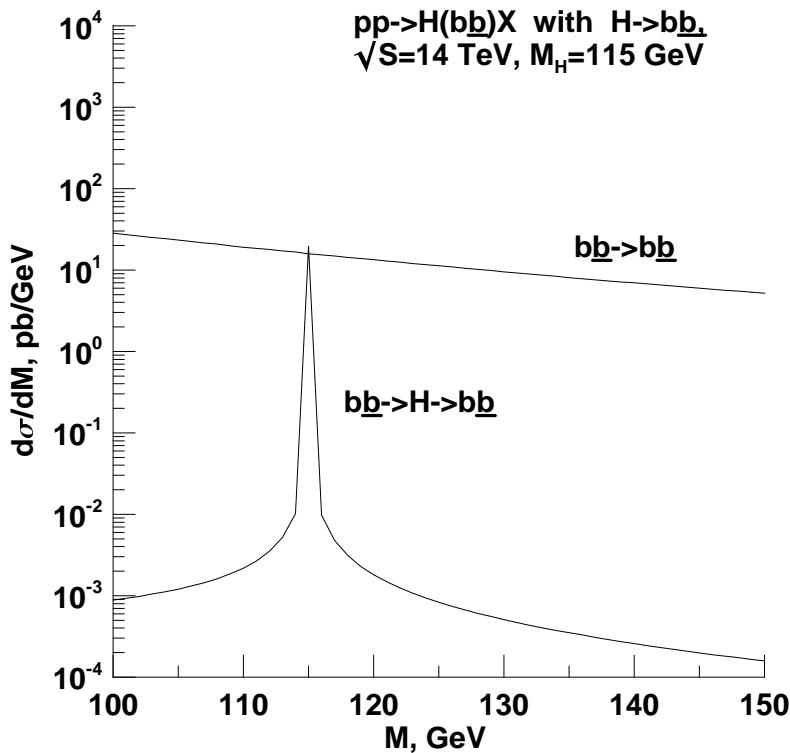


Figure 9: $b\bar{b}$ Invariant mass spectrum for process $pp \rightarrow b\bar{b}(b\bar{b}X)$ at the $m_H = 115 \text{ GeV}$.

SIGNAL/BACKGROUND: $H \rightarrow \gamma\gamma$

1. For $m_H \sim 100$ GeV one has $Br(H \rightarrow \gamma\gamma) \simeq 0.07$, and we should consider process

$$pp \rightarrow H(b\bar{b})X \quad \text{with the decay} \quad H \rightarrow \gamma\gamma.$$

We find effective vertices for signal (*) and background (**) subprocesses

$$Q_b + \bar{Q}_b \rightarrow H \rightarrow \gamma + \gamma \quad (*)$$

$$Q_b + \bar{Q}_b \rightarrow \gamma + \gamma \quad (**)$$

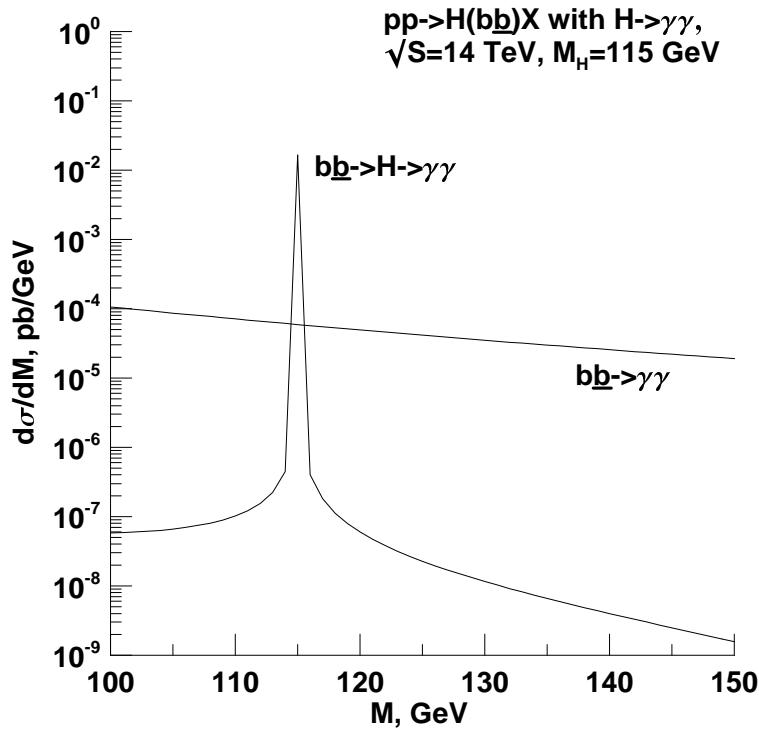


Figure 10: $\gamma\gamma$ Invariant mass spectrum for process $pp \rightarrow \gamma\gamma(b\bar{b}X)$ at the $m_H = 115$ GeV.

NEUTRAL HIGGS BOSONS IN MSSM

$$g_{\Phi b\bar{b}} = \begin{cases} -\sqrt{2} \frac{m_b}{v} \frac{\sin \alpha}{\cos \beta}, & \Phi = h \\ \sqrt{2} \frac{m_b}{v} \frac{\cos \alpha}{\cos \beta}, & \Phi = H \\ \sqrt{2} \frac{m_b}{v} \tan \beta, & \Phi = A \end{cases}$$

$$\frac{\sigma(b\bar{b} \rightarrow A_{MSSM})}{\sigma(b\bar{b} \rightarrow H_{SM})} \approx \tan^2 \beta \approx 10^3, \text{ if } \tan \beta \approx 30$$

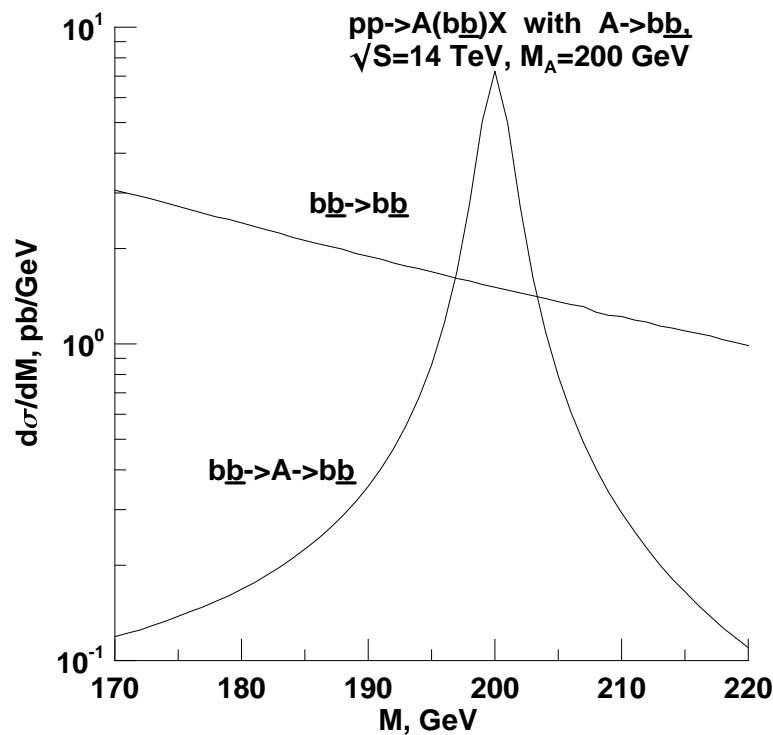


Figure 11: $b\bar{b}$ Invariant mass spectrum for process $pp \rightarrow b\bar{b}(b\bar{b}X)$ at the $m_A = 200$ GeV.

CONCLUSIONS

- Production of Higgs bosons in SM and in MSSM under multi-Regge-kinematics at high-energy colliders, such as the LHC, can be described successfully using parton Reggeization approach in the high-energy factorization scheme.
- We found Reggeized b-quark fusion is essential mechanism of scalar Higgs boson production, especially in the MSSM.
- Our LO calculations in the parton Reggeization approach are in agreement with data for inclusive jet and prompt photon production at the LHC and, we see, they are correct predictions for Higgs bosons production. By contrast, in the collinear parton model of QCD, it is necessary to take into account NLO+NNLO corrections and to perform soft-gluon resummation in order to obtain an adequate predictions.

OUR RELEVANT PUBLICATIONS

- B. A. Kniehl, V. A. Saleev, A. V. Shipilova, E. V. Yatsenko, DESY-11-115, NSF-KITP-11-119, e-Print: arXiv:1107.1462 [hep-ph];
- B. A. Kniehl, A. V. Shipilova and V. A. Saleev, Phys. Rev. D **79**, 034007 (2009); Phys. Rev. D **81**, 094010 (2010);
- V. A. Saleev, Phys. Rev. D **78**, 034033 (2008); Phys. Rev. D **78**, 114031 (2008); Phys. Rev. D **80**, 114016 (2009);
- B. A. Kniehl, D. V. Vasin, and V. A. Saleev, Phys. Rev. D **73**, 074022 (2006); Phys. Rev. D **74**, 014024 (2006).

Thank you for attention!