New TMD gluon density in the proton from the LHC data

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in collaboration with

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Outline

- 1. Motivation
- 2. Non-perturbative input
- 3. Numerical results
- 4. Conclusion

Motivation

• TMD (unintegrated) parton distributions are an essential ingredient in the high energy, or $k_{\rm T}\text{-}$ factorization

$$d\sigma = \int \frac{dx_1}{x_1} f_g(x_1, \mathbf{k}_{1T}^2, \mu^2) d\mathbf{k}_{1T}^2 \frac{d\phi_1}{2\pi} \int \frac{dx_2}{x_2} f_g(x_2, \mathbf{k}_{2T}^2, \mu^2) d\mathbf{k}_{2T}^2 \frac{d\phi_2}{2\pi} d\hat{\sigma}(g^*g^* \to X)$$

• The number of such TMD PDFs is rather small.

• In the small-x region the main contribution comes from gluon PDFs.

• We search for a TMD applicable to processes in a quite large range of scales.

Recipe

$$f_g^{(0)}(x, \mathbf{k}_T^2, \mu_0^2) = c_g R_0^2(x) \mathbf{k}_T^2 e^{-R_0^2(x)\mathbf{k}_T^2}$$

Non-perturbative input $\mathcal{A}^{(0)}(x, \mathbf{k}_T^2, \mu_0^2) = A_1 x^{-A_2} (1-x)^{A_3} e^{-\mathbf{k}_T^2/\sigma^2}$

CCFM evolution

$$\mathcal{A}(x, k_t, p) = \mathcal{A}_0(x, k_t, p) + \int \frac{dz}{z} \int \frac{dq^2}{q^2} \Theta(p - zq)$$

$$\times \Delta(p, zq) \mathcal{P}(z, q, k_t) \mathcal{A}\left(\frac{x}{z}, k_t + (1 - z)q, q\right)$$

TMD at any scale



Non-perturbative input

The input can be determined from data on soft hadron production within modified quark-gluon string model (mQGSM), where we assume possible creation of non-perturbative gluons at low scales.

- Gluon density does not depend on scale at $\mu < \mu_{sat}$

- The nonperturbative gluon can be treated as a spectator during *pp* collision

$$\rho(x, p_T) = \rho_q(x, p_T) + \rho_g(x, p_T)$$

$$F_{pp} = f_{3q}^{(0)} \Psi_g$$

$$|\Psi_g|^2 \sim f_g^{(0)}(x, \mathbf{k}_T^2, \mu_0^2)$$

$$\rho_q(x, p_T) = |f_{3q}^{(0)}|^2 \otimes D_{q/qq \to h} \times \int d^2 k_T dz f_g^{(0)}(z, \mathbf{k}_T^2, \mu_0^2)$$

$$\rho_g(x, p_T) = f_g^{(0)} \otimes D_{g \to h} \times \sigma_{\text{in}}^{pp}$$

$$E \frac{d^3\sigma}{d^3p} = \sigma_1 \phi_g^{(1)}(s, x, p_T) + \sigma_{\text{in}} \phi_g^{(2)}(s, x, p_T)$$

Non-perturbative input

$$f_g^{(0)}(x,k_T^2,\mu_0^2) = c_g(1-x)^{b_g} \left(R_0^2(x)(k_T^2+m_g^2) + \sum_{n=1}^3 C_n(R_0(x)k_T)^n \right) e^{-R_0(x)k_T}$$

$$R_0(x) = \frac{1}{Q_0} \left(\frac{x}{x_0}\right)^{\lambda/2}$$

$$C_1 = 5, C_2 = 2, C_3 = 2, Q_0 = 1.23$$

$$b_g = b_g(0) + \frac{4C_A}{\beta_0} \log \frac{\alpha_s(\mu_0^2)}{\alpha_s(k_T^2)}$$

$$b_g(0) = 5.854$$

CCFM evolution

$$f_g(x, k_T, \mu) = f_g^{(0)}(x, k_T, \mu_0) + \int \frac{dz}{z} \int \frac{dq^2}{q^2} \Theta(\mu - zq)$$
$$\times \Delta(\mu, zq) \mathcal{P}(z, q, k_T) f_g\left(\frac{x}{z}, k_T + (1 - z)q, q\right)$$

$$P_g(z,q,k_T) = \bar{\alpha}_s(q^2(1-z)^2) \left(\frac{1}{1-z} - 1 + \frac{z(1-z)}{2}\right) + \bar{\alpha}_s(k_T^2) \left(\frac{1}{z} - 1 + \frac{z(1-z)}{2}\right) \Delta_{ns}(z,q^2,k_T^2)$$

Implemented with uPDFevolv [F. Hautmann et al. Eur. Phys. J. C74, 3082 (2014)]

10⁰

х

10⁰

х

New TMD PDF



10⁴

10³

10²

10¹

10⁰

10⁻¹

10⁻²

10-3

10-4

104

10³

10²

10¹

100

10-1

10⁻²

10⁻³

10-4

f_g(x, k²₇, μ²)

f_g(x, k²₇, μ²)



New TMD PDF

10

Soft hadron production spectra



b-jet production spectra



da/dpr [fb/GeV]

10¹

10⁰

10-1

10-2

10-3

100

80

60

40

20

0

0

0.5

1

da/d|y|[fb]

0

50

100

150

Higgs boson production spectra





0.25

Higgs boson production spectra





Q² = 12 GeV²

Q² = 60 GeV²

Q² = 200 GeV²

Structure functions



10⁰

10⁻¹

Reduced cross sections



Conclusion

New unintegrated TMD PDF has been presented.

- Good description of ATLAS data on hadron multiplicities at low $p_{\rm T}$ is obtained.

- The new function provides good decription at moderate and high p_T for *b*-jet and Higgs boson production at LHC.

- Structure functions $F_2^{c,b}$ and reduced cross sections are well described at different scales.

- The new TMD will be available soon in Monte-Carlo generator PEGASUS, library TMDlib and TMDPlotter.

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REF2022, November, 2, 2022

Back up

Off-shell gluon polarization sum

$$\epsilon_{\mu}\epsilon_{\nu}^{*} = \frac{k_{T}^{\mu}k_{T}^{\nu}}{\mathbf{k}_{T}^{2}}$$

Non-perturbative input

Input based on GBW unintegrated parton density

 $f_g^{(0)}(x, k_T^2, \mu_0^2) = c_g R_0^2(x) k_T^2 e^{-R_0^2(x)k_T^2}$

 $f_g^{(0)}(x,k_T^2,\mu_0^2) = c_g(1-x)^{b_g}(R_0^2(x)k_T^2 + C_2(R_0(x)k_T)^a)e^{-R_0(x)k_T - d(R_0(x)k_T)^3}$



Non-perturbative input

Input based on GBW unintegrated parton density + analytical solution of the linear BFKL equation at low x weighted with a matching function

 $f_g^{(0)}(x, k_T^2, \mu_0^2) = \tilde{f}_g^{(0)}(x, k_T^2, \mu_0^2) + \lambda(x, k_T^2, \mu_0^2) f_{\text{BFKL}}(x, k_T^2)$



N.A.Abdulov et al. Phys.Rev. **D98** 054010 (2018)

Some calculation details $\phi_{q}(s, x, p_{T}) = C_{q} \Big\{ \Phi_{q}(x_{+}, p_{T}) \Phi_{qq}(x_{-}, p_{T}) + \Phi_{qq}(x_{+}, p_{T}) \Phi_{q}(x_{-}, p_{T}) \Big\}$ $\phi_{g}(s, x, p_{T}) = C_{g} \Big\{ \Phi_{g}(x_{+}, p_{T}) + \Phi_{g}(x_{-}, p_{T}) \Big\}$ $x_{\pm} = \frac{1}{2} \Big(\pm x + \sqrt{x^{2} + 4(m_{h}^{2} + p_{T}^{2})/s} \Big), \quad x = 2\sqrt{\frac{m_{h}^{2} + p_{T}^{2}}{s}} \sinh y$

$$\Phi_q(x, p_T) = \int_x^1 d\xi \int_0^\infty d\mathbf{k}_T^2 \int_0^{2\pi} d\phi \times \left[\frac{2}{3} F_u(\xi, \mathbf{k}_T^2) G_{u \to h}\left(z, |\mathbf{p}_T - z\mathbf{k}_T|\right) + \frac{1}{3} F_d(\xi, \mathbf{k}_T^2) G_{d \to h}\left(z, |\mathbf{p}_T - z\mathbf{k}_T|\right) \right],$$

$$\Phi_{qq}(x, p_T) = \int_x^1 d\xi \int_0^\infty d\mathbf{k}_T^2 \int_0^{2\pi} d\phi \times \left[\frac{2}{3} F_{ud}(\xi, \mathbf{k}_T^2) G_{ud \to h}\left(z, |\mathbf{p}_T - z\mathbf{k}_T|\right) + \frac{1}{3} F_{uu}(\xi, \mathbf{k}_T^2) G_{uu \to h}\left(z, |\mathbf{p}_T - z\mathbf{k}_T|\right)\right],$$

$$\Phi_g(x, p_T) = \int_x^1 d\xi \int_0^\infty d\mathbf{k}_T^2 \int_0^{2\pi} d\phi F_g(\xi, \mathbf{k}_T^2) G_{g \to h}(z, |\mathbf{p}_T - z\mathbf{k}_T|)$$

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Some calculation details

$$F_q(x, \mathbf{k}_T^2) = \int_{x_{\pm}}^1 d\xi_1 d\xi_2 \delta(1 - x - \xi_1 - \xi_2) \int d^2 \mathbf{p}_T d^2 \mathbf{q}_T \delta^{(2)}(\mathbf{k}_T + \mathbf{p}_T + \mathbf{q}_T) \times$$

 $\times f_q(x)g_q(\mathbf{k}_T^2)f_{qq}(\xi_1)g_{qq}(\mathbf{p}_T^2)f_g(\xi_2,\mathbf{q}_T^2),$

$$F_{u}(x, \mathbf{k}_{T}^{2}) = f_{u}(x)g_{q}(\mathbf{k}_{T}^{2}) \int_{x_{\pm}}^{1-x} d\xi_{2} \int_{0}^{\infty} d\mathbf{q}_{T}^{2} \int_{0}^{2\pi} d\varphi \times \\ \times f_{ud}(1 - x - \xi_{2})g_{qq}(|\mathbf{k}_{T} + \mathbf{q}_{T}|^{2})f_{g}(\xi_{2}, \mathbf{q}_{T}^{2}), \\ F_{d}(x, \mathbf{k}_{T}^{2}) = f_{d}(x)g_{q}(\mathbf{k}_{T}^{2}) \int_{x_{\pm}}^{1-x} d\xi_{2} \int_{0}^{\infty} d\mathbf{q}_{T}^{2} \int_{0}^{2\pi} d\varphi \times \\ \times f_{uu}(1 - x - \xi_{2})g_{qq}(|\mathbf{k}_{T} + \mathbf{q}_{T}|^{2})f_{g}(\xi_{2}, \mathbf{q}_{T}^{2}), \end{cases}$$

$$\begin{split} F_{ud}(x,\mathbf{k}_{T}^{2}) &= f_{ud}(x)g_{qq}(\mathbf{k}_{T}^{2})\int_{x_{\pm}}^{1-x}d\xi_{2}\int_{0}^{\infty}d\mathbf{q}_{T}^{2}\int_{0}^{2\pi}d\varphi \times \\ &\times f_{u}(1-x-\xi_{2})g_{qq}(|\mathbf{k}_{T}+\mathbf{q}_{T}|^{2})f_{g}(\xi_{2},\mathbf{q}_{T}^{2}), \\ F_{uu}(x,\mathbf{k}_{T}^{2}) &= f_{uu}(x)g_{qq}(\mathbf{k}_{T}^{2})\int_{x_{\pm}}^{1-x}d\xi_{2}\int_{0}^{\infty}d\mathbf{q}_{T}^{2}\int_{0}^{2\pi}d\varphi \times \\ &\times f_{d}(1-x-\xi_{2})g_{qq}(|\mathbf{k}_{T}+\mathbf{q}_{T}|^{2})f_{g}(\xi_{2},\mathbf{q}_{T}^{2}). \\ F_{g}(x,\mathbf{k}_{T}^{2}) &= f_{g}(x,\mathbf{k}_{T}^{2})\int_{x_{\pm}}^{1-x}d\xi_{2}\int_{0}^{\infty}d\mathbf{q}_{T}^{2}\int_{0}^{2\pi}d\varphi \times \\ &\times \left\{\frac{2}{3}f_{u}(1-x-\xi_{2})g_{q}(|\mathbf{k}_{T}+\mathbf{q}_{T}|^{2})f_{ud}(\xi_{2})g_{qq}(\mathbf{q}_{T}^{2})+ \\ &+\frac{1}{3}f_{d}(1-x-\xi_{2})g_{q}(|\mathbf{k}_{T}+\mathbf{q}_{T}|^{2})f_{uu}(\xi_{2})g_{qq}(\mathbf{q}_{T}^{2})\right\}. \end{split}$$

Some calculation details

$$f_u(x) = C_u^p x^{-1/2} (1-x)^{3/2}, \quad f_d(x) = C_d^p x^{-1/2} (1-x)^{5/2}$$

 $f_{ud}(x) = C_{ud}^p (1-x)^{-1/2} x^{3/2}, \quad f_{uu}(x) = C_{ud}^p (1-x)^{-1/2} x^{5/2}$ $C_u^p = C_{ud}^p = \frac{\Gamma(2-1/2+3/2)}{\Gamma(1-1/2)\Gamma(1+3/2)} = 1/1.1781$ $C_d^p = C_{uu}^p = \frac{\Gamma(2-1/2+5/2)}{\Gamma(1-1/2)\Gamma(1+5/2)} = 1/1.01859$ $f_a(x, \mathbf{k}_T^2) = c_a f_a(x) g_a(\mathbf{k}_T^2), \quad g_a(\mathbf{k}_T^2) = \frac{B_a^2}{2\pi} e^{-B_a|\mathbf{k}_T|}$

Fragmentation functions

$$G_{g \to h}(z, |\mathbf{p}_T|) = 2G_{g \to \pi}(z)I_{\pi}^g(|\mathbf{p}_T|) + 2G_{g \to K}(z)I_K^g(|\mathbf{p}_T|)$$

$$G_{g \to \pi^+}(z) = G_{g \to \pi^-}(z), \quad G_{g \to K^+}(z) = G_{g \to K^-}(z)$$
$$G_{g \to \pi}(z) = 6.57 z^{0.54} (1-z)^{3.01}$$
$$G_{g \to K}(z) = 0.37 z^{0.79} (1-z)^{3.07}$$
$$I_{\pi}^g(|\mathbf{p}_T|) = I_K^g(|\mathbf{p}_T|) = I_h^g(|\mathbf{p}_T|) = \frac{(B_{f_h}^g)^2}{2\pi} e^{-B_{f_h}^g|\mathbf{p}_T|}$$

$$\begin{split} G_{u \to \pi^+}(z, |\mathbf{p}_T|) &= \left[a_0(1-z) + a_0(1-z)^2\right] I_{\pi}^q(|\mathbf{p}_T|) \\ G_{d \to \pi^+}(z, |\mathbf{p}_T|) &= (1-z)G_{u \to \pi^+}(z)I_{\pi}^q(|\mathbf{p}_T|) \\ G_{u \to K^+}(z, |\mathbf{p}_T|) &= a_k(1-z)^{1/2}(1+a_{1K}z)I_K^q(|\mathbf{p}_T|) \\ G_{u \to K^-}(z, |\mathbf{p}_T|) &= a_k(1-z)^{3/2}I_K^q(|\mathbf{p}_T|) \\ G_{d \to K^+}(z, |\mathbf{p}_T|) &= G_{u \to K^-}(z)I_K^q(|\mathbf{p}_T|) \\ G_{d \to K^-}(z, |\mathbf{p}_T|) &= G_{u \to K^+}(z)I_K^q(|\mathbf{p}_T|) \\ G_{uu \to \pi^+}(z, |\mathbf{p}_T|) &= a_0(1-z)^2I_{\pi}^{qq}(|\mathbf{p}_T|) \\ G_{uu \to \pi^+}(z, |\mathbf{p}_T|) &= a_0(1+(1-z)^2)(1-z)^2I_{\pi}^{qq}(|\mathbf{p}_T|) \\ G_{uu \to K^+}(z, |\mathbf{p}_T|) &= a_k(1-z)^{5/2}(1+a_{2K}z)I_K^{qq}(|\mathbf{p}_T|) \\ G_{ud \to K^+}(z, |\mathbf{p}_T|) &= a_k(1-z)^{5/2}(1+a_{2K}z+(1-z)^2)I_K^{qq}(|\mathbf{p}_T|) \\ G_{ud \to K^+}(z, |\mathbf{p}_T|) &= \frac{a_k}{2}(1-z)^{5/2}(1+(1-z)^2)I_K^{qq}(|\mathbf{p}_T|) \end{split}$$

*b*_g extraction



Non-perturbative input



PEGASUS

- parton level Monte-Carlo event generator for pp and pp processes with simple user-friendly grafical interface;
- can work with TMDs;
- a lot of implemented processes (heavy quarks, quarkonia, etc.);
- can generate an event record according to the Les Houches Event (*.lhe) format;
- an easy way to implement various kinematical restrictions;
- compatible with HEPData repository https://www.hepdata.net;
- built-in plotting tool PEGASUS Plotter

A.V. Lipatov, M.A. Malyshev, S.P. Baranov, Eur. Phys. J. **C80**, 4, 330 (2020); https://theory.sinp.msu.ru/doku.php/pegasus/overview

PEGASUS Particle Event Generator: A Simple-in-Use System

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A.V. Lipatov, S.P. Baranov, M.A. Malyshev, in preparation (2019)

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