New TMD gluon density in the proton from the LHC data

Maxim Malyshev

in collaboration with

Artem Lipatov,
Gennady Lykasov

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_T-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

Non-perturbative input

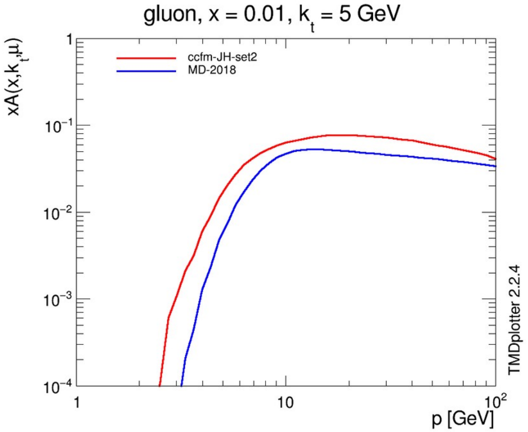
$$f_g^{(0)}(x, \mathbf{k}_T^2, \mu_0^2) = c_g R_0^2(x) \mathbf{k}_T^2 e^{-R_0^2(x)\mathbf{k}_T^2}$$

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

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

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

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

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

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

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

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

Non-perturbative input

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

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

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

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

$$b_g(0) = 5.854$$

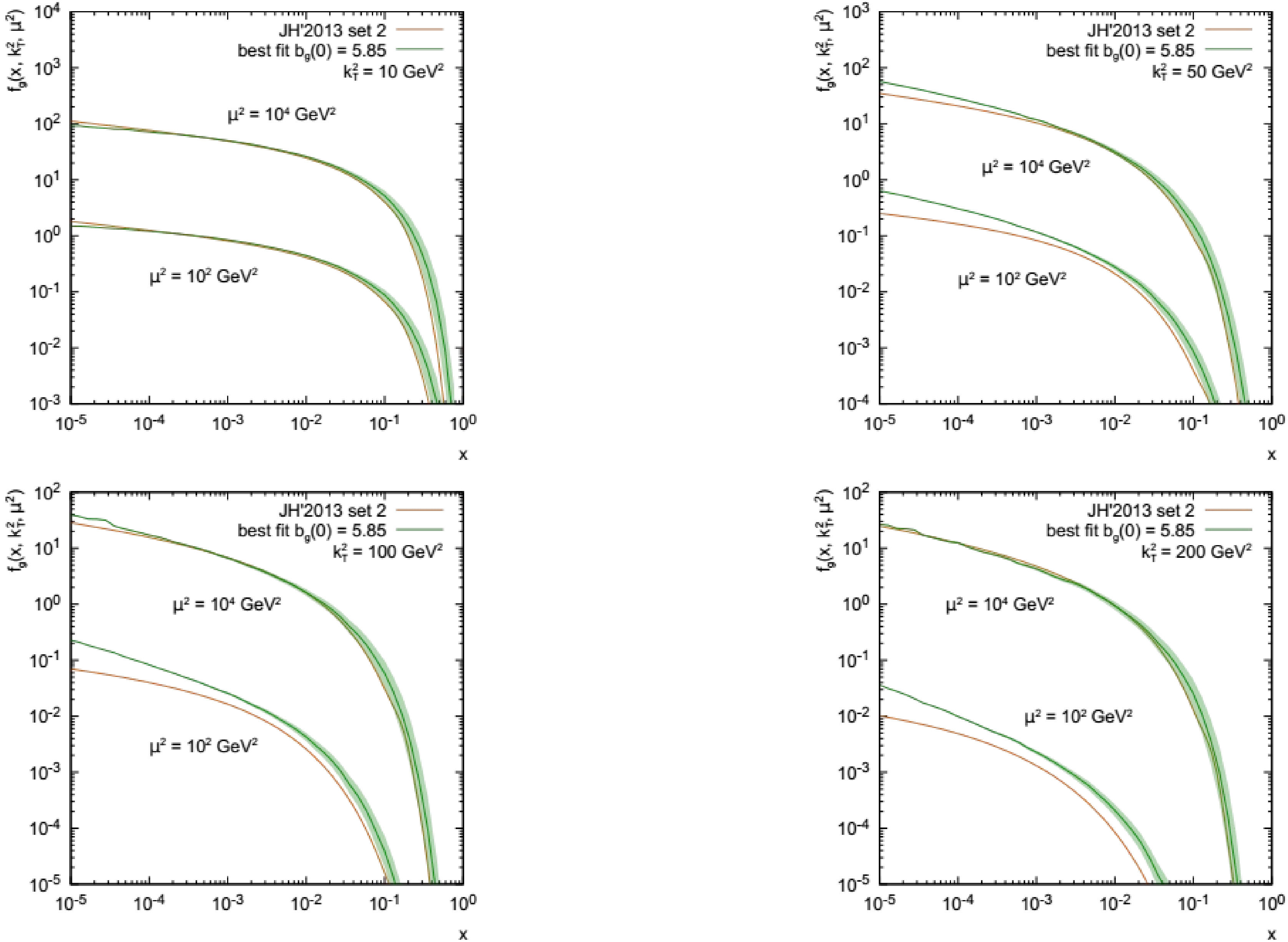
CCFM evolution

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

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

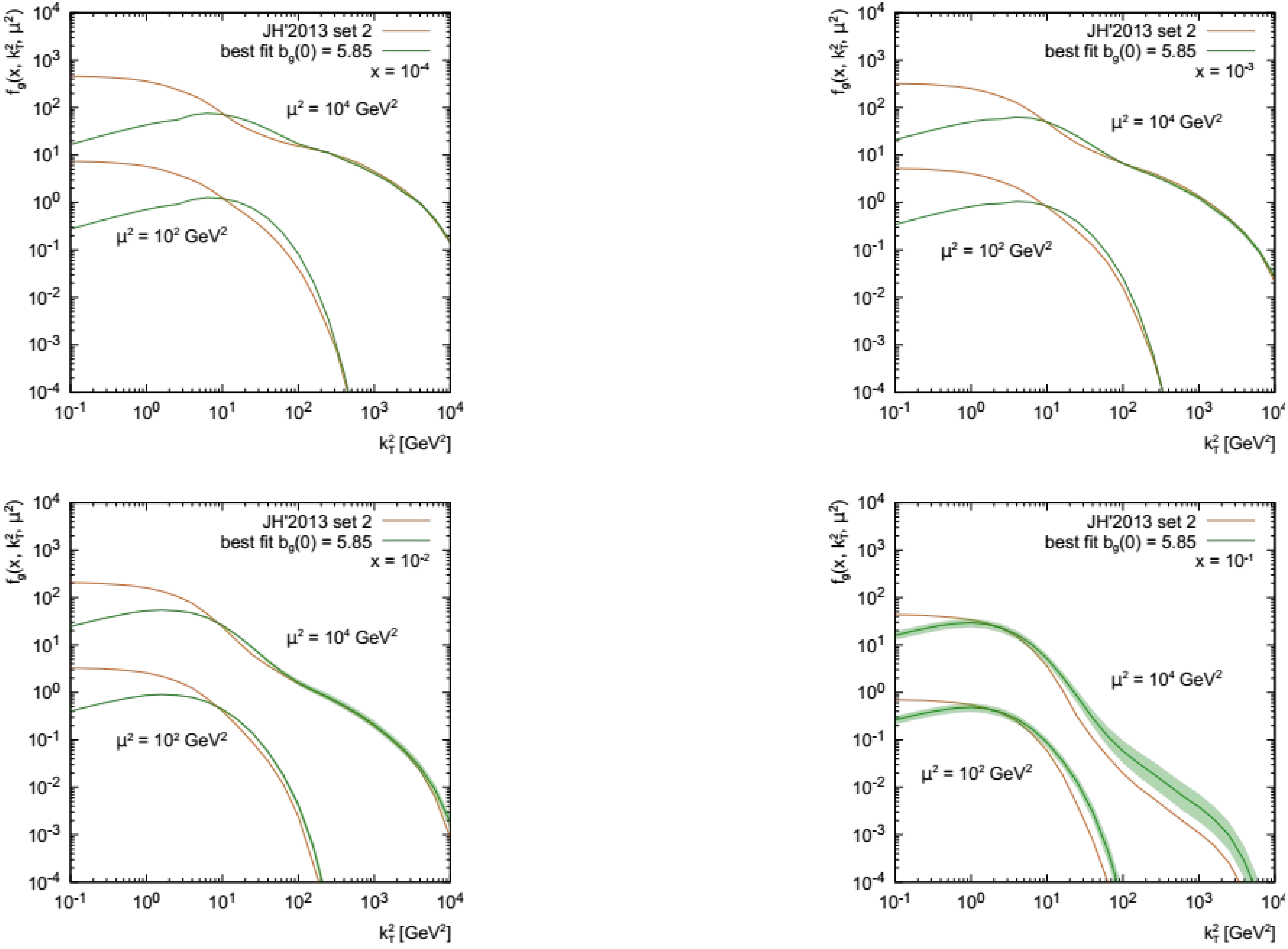
Implemented with uPDFevolv [F. Hautmann et al. Eur. Phys. J. **C74**, 3082 (2014)]

New TMD PDF



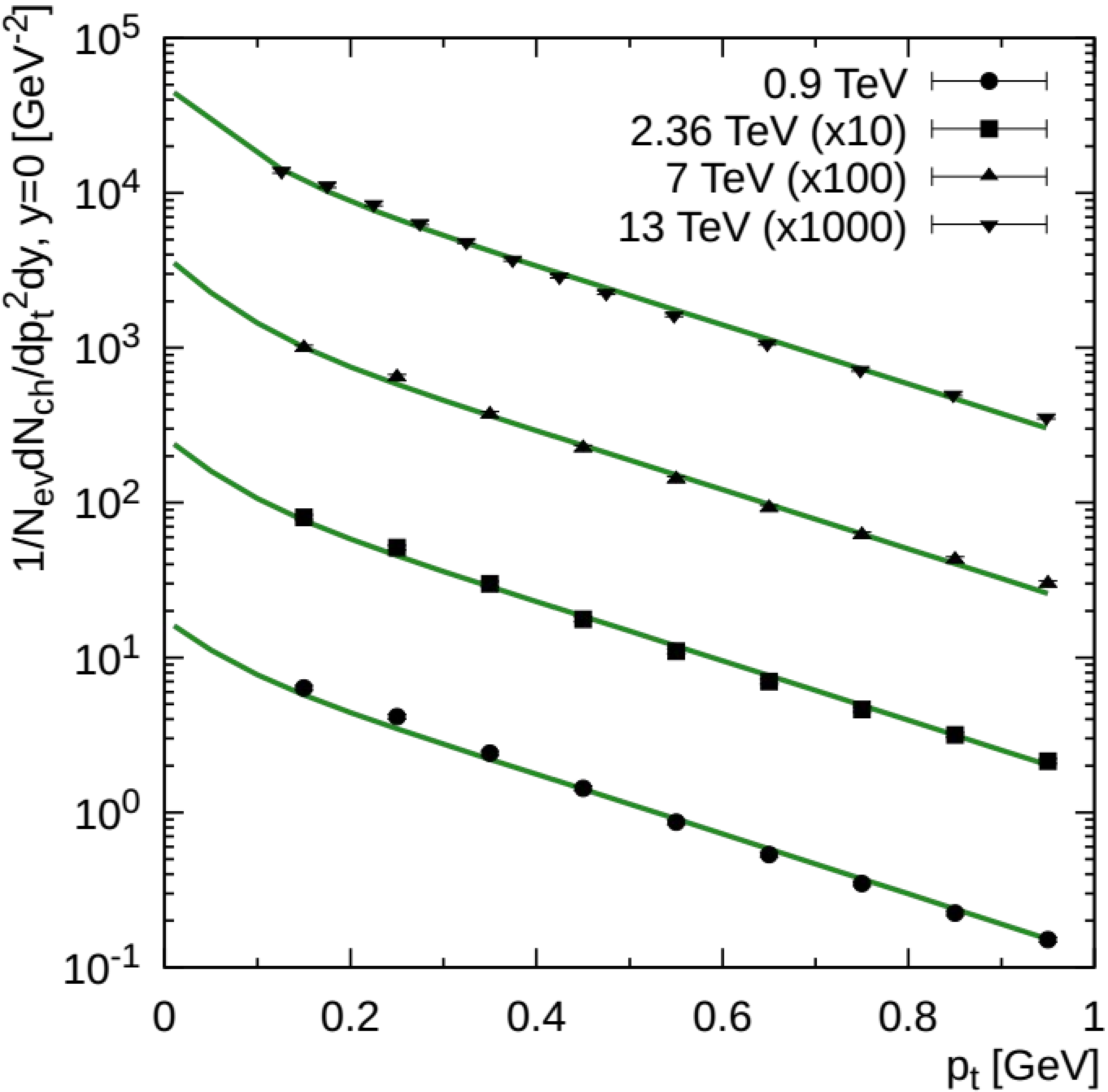
JH'2013 set 2
best fit b_g(0) = 5.85
k_T^2 = 10 GeV^2
μ^2 = 10^4 GeV^2
μ^2 = 10^2 GeV^2
f_g(x, k_T^2, μ^2)
x
JH'2013 set 2
best fit b_g(0) = 5.85
k_T^2 = 50 GeV^2
μ^2 = 10^4 GeV^2
μ^2 = 10^2 GeV^2
f_g(x, k_T^2, μ^2)
x
JH'2013 set 2
best fit b_g(0) = 5.85
k_T^2 = 100 GeV^2
μ^2 = 10^4 GeV^2
μ^2 = 10^2 GeV^2
f_g(x, k_T^2, μ^2)
x
JH'2013 set 2
best fit b_g(0) = 5.85
k_T^2 = 200 GeV^2
μ^2 = 10^4 GeV^2
μ^2 = 10^2 GeV^2
f_g(x, k_T^2, μ^2)
x

New TMD PDF

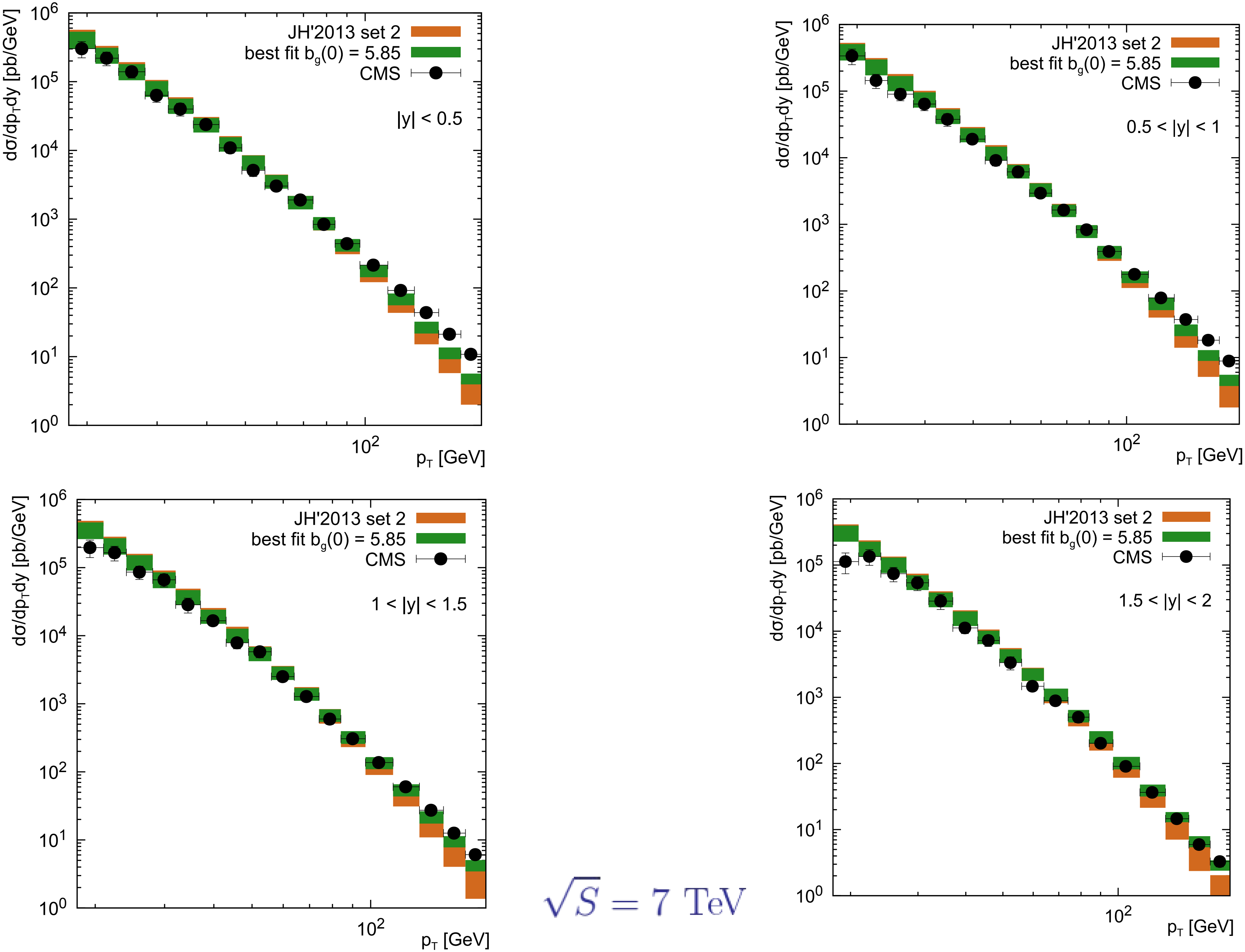


$f_g(x, k_T^2, \mu^2)$
JH'2013 set 2
best fit $b_g(0) = 5.85$
$x = 10^{-4}$
$\mu^2 = 10^4$ GeV^2
$\mu^2 = 10^2$ GeV^2
k_T^2 [GeV^2]
JH'2013 set 2
best fit $b_g(0) = 5.85$
$x = 10^{-3}$
$\mu^2 = 10^4$ GeV^2
$\mu^2 = 10^2$ GeV^2
k_T^2 [GeV^2]
JH'2013 set 2
best fit $b_g(0) = 5.85$
$x = 10^{-2}$
$\mu^2 = 10^4$ GeV^2
$\mu^2 = 10^2$ GeV^2
k_T^2 [GeV^2]
JH'2013 set 2
best fit $b_g(0) = 5.85$
$x = 10^{-1}$
$\mu^2 = 10^4$ GeV^2
$\mu^2 = 10^2$ GeV^2
k_T^2 [GeV^2]

Soft hadron production spectra

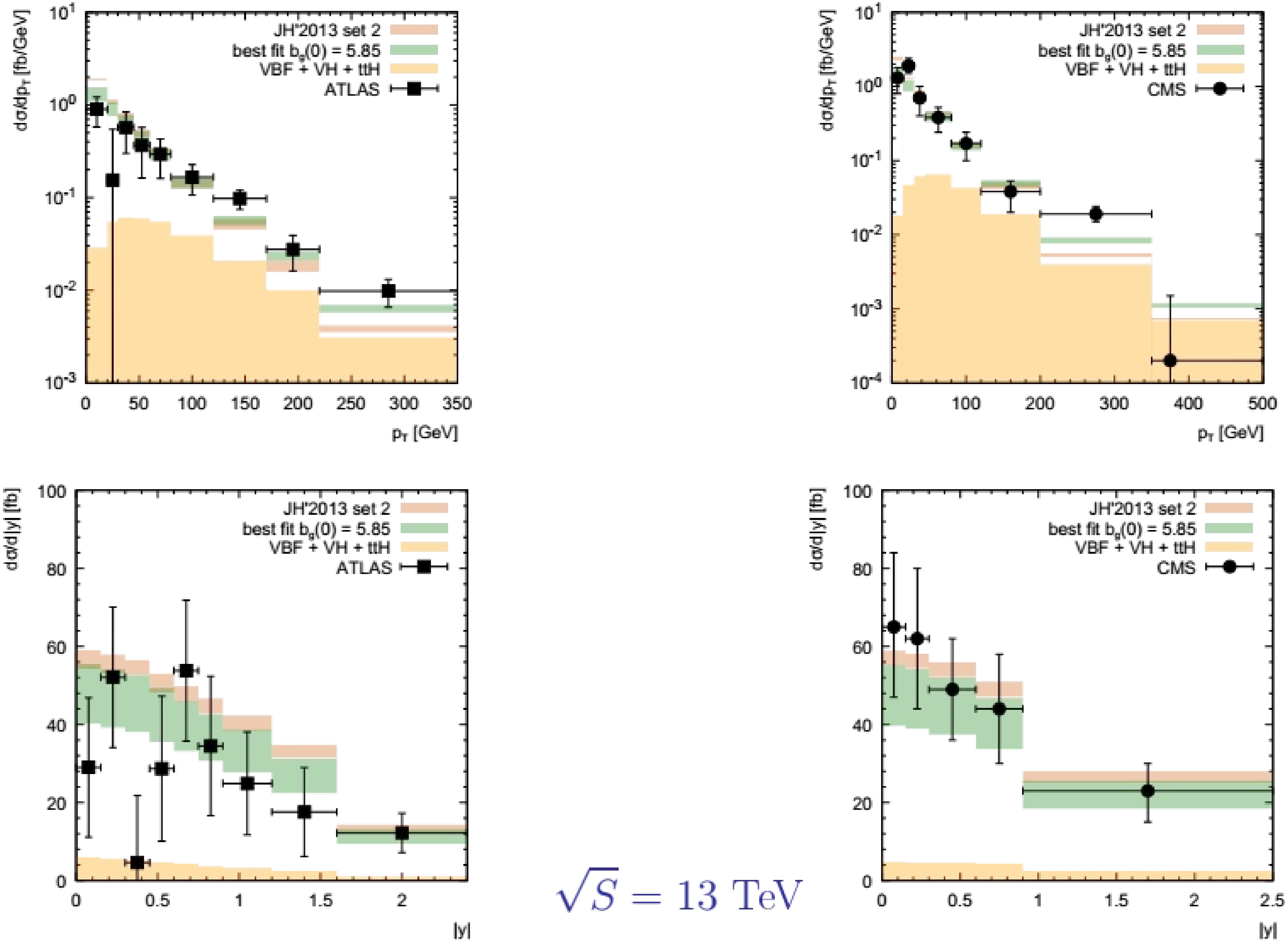


b-jet production spectra



$$\sqrt{S} = 7 \text{ TeV}$$

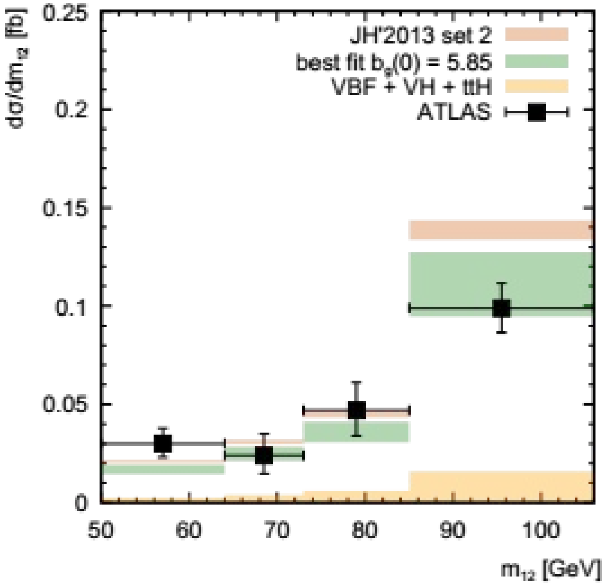
Higgs boson production spectra

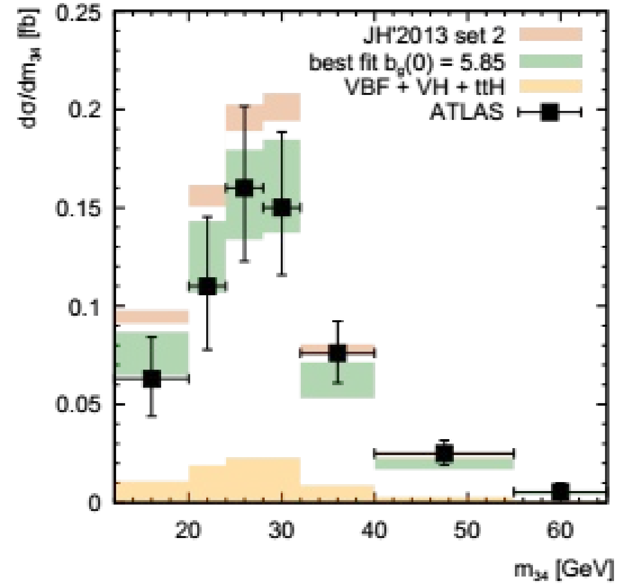


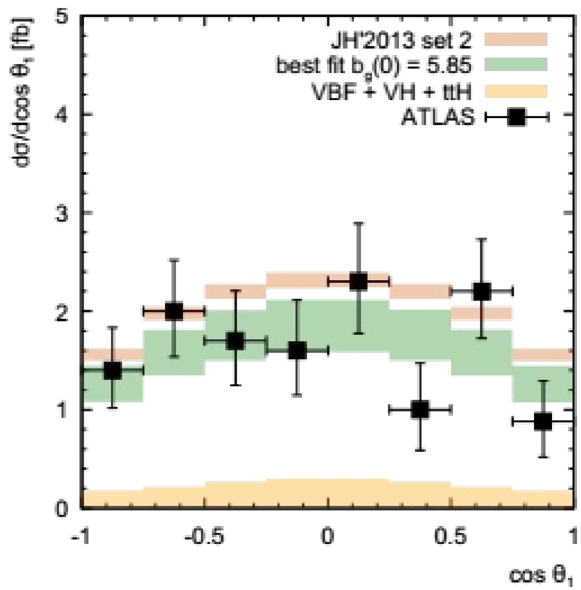
$\sqrt{S} = 13$ TeV

$pp \to H \to \gamma\gamma$

Higgs boson production spectra

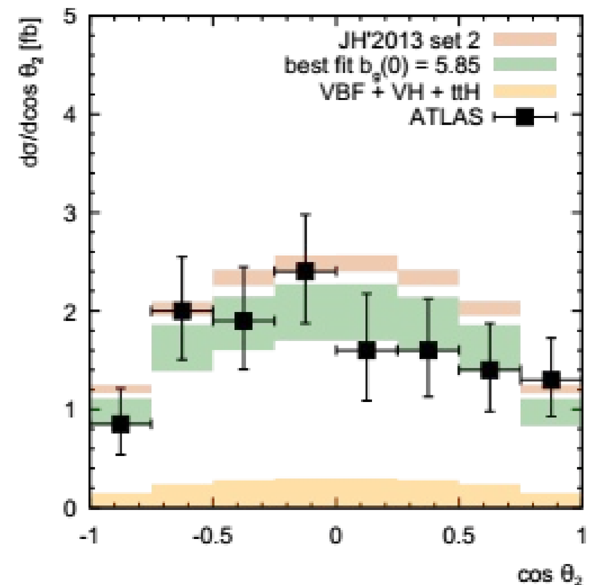




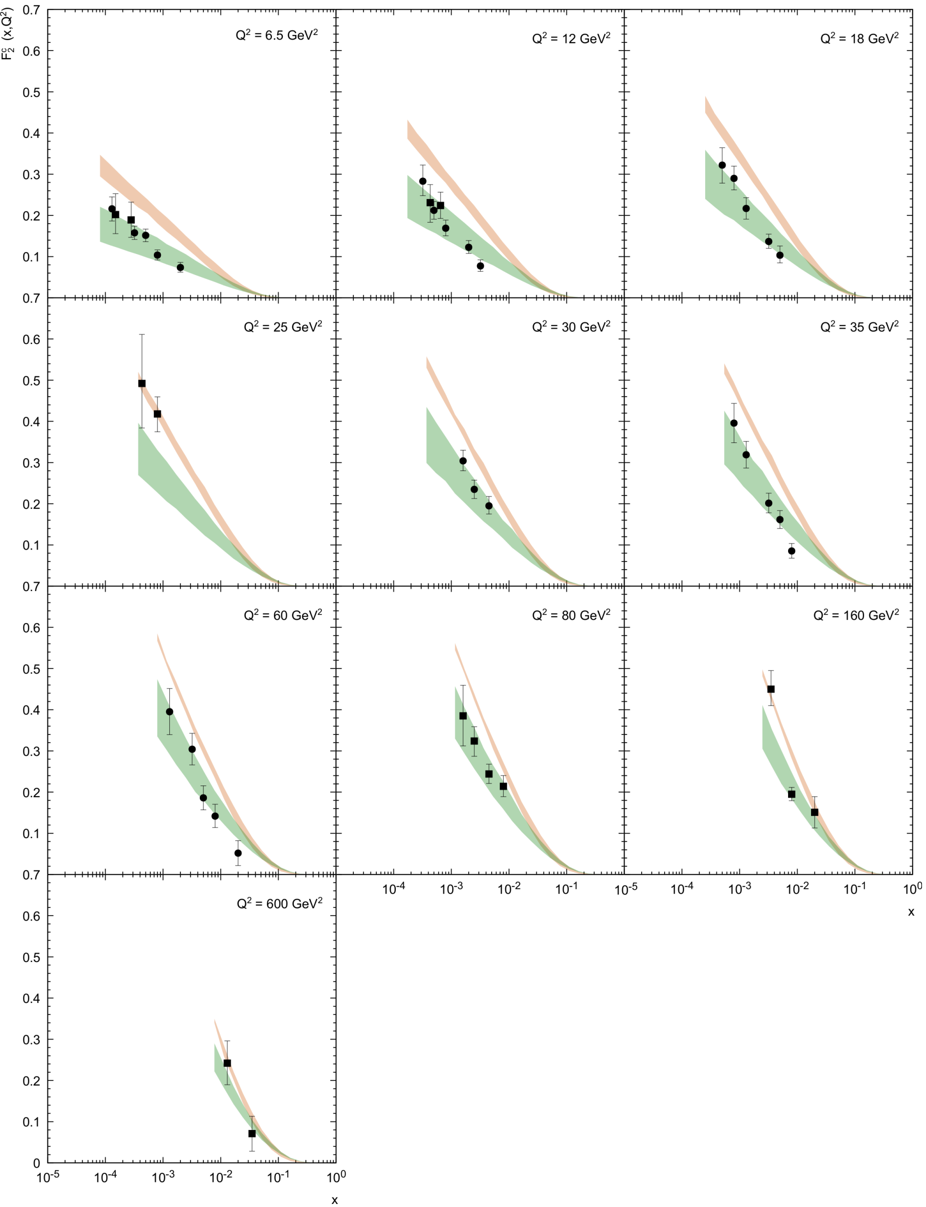


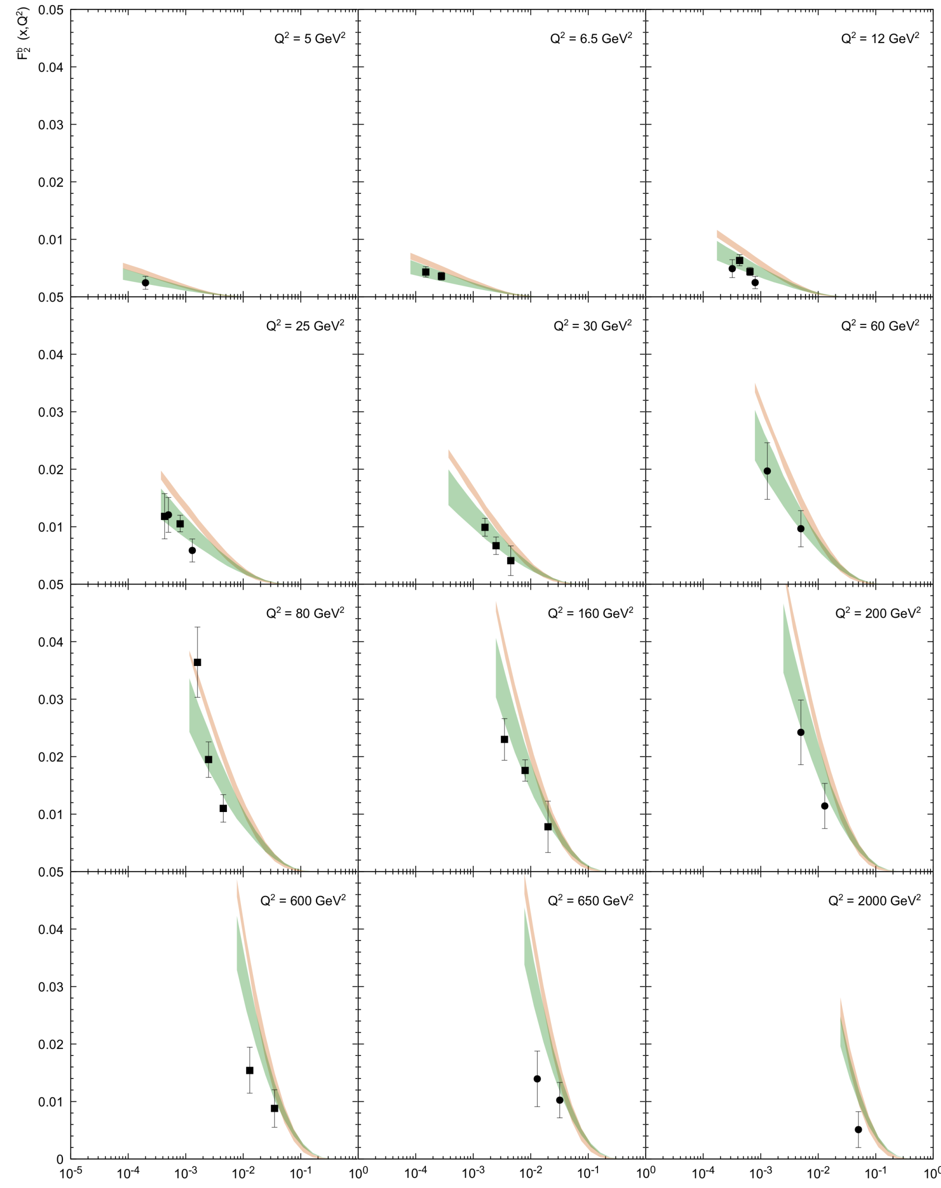
$$\sqrt{S} = 13 \text{ TeV}$$

$$pp \to H \to 4l$$

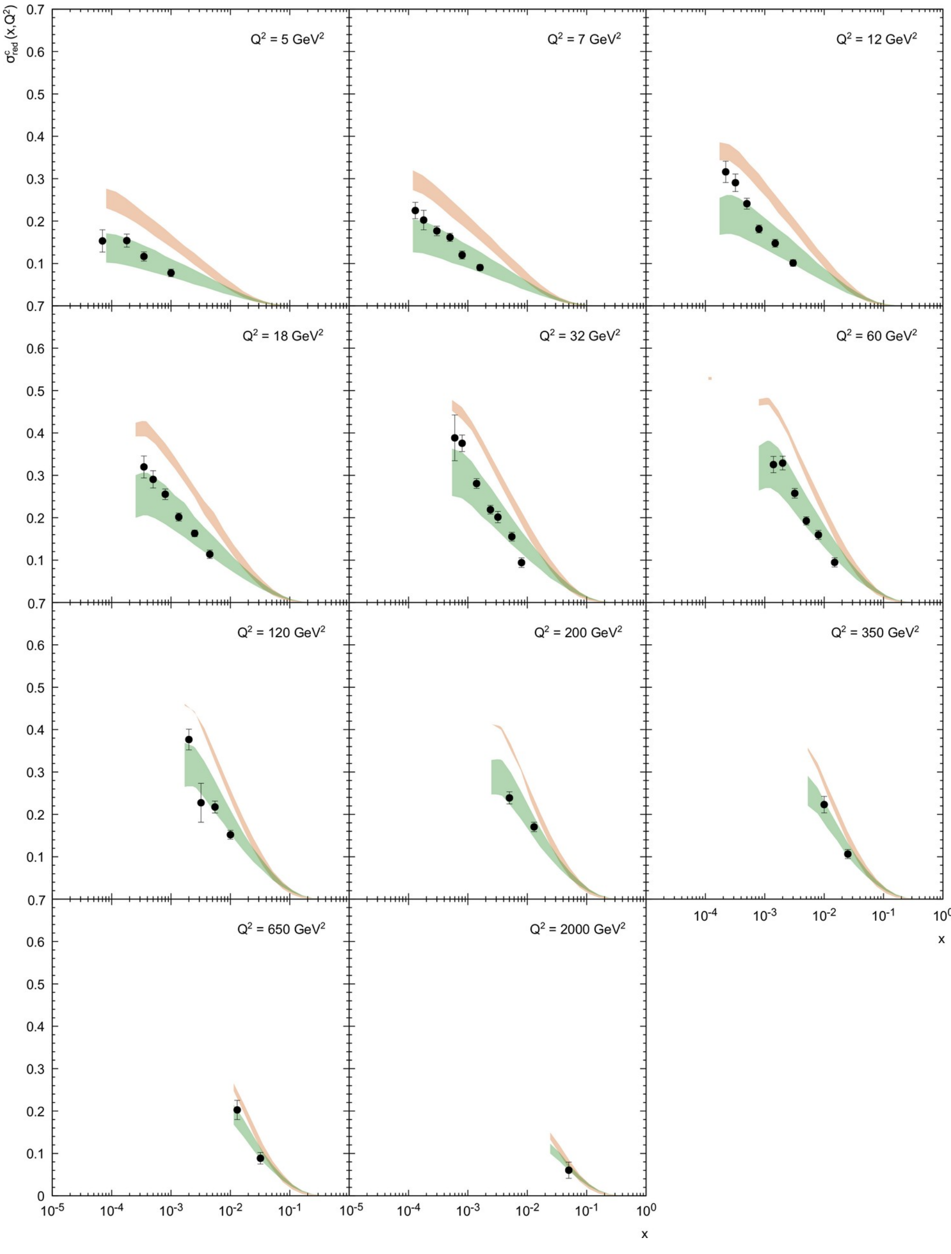


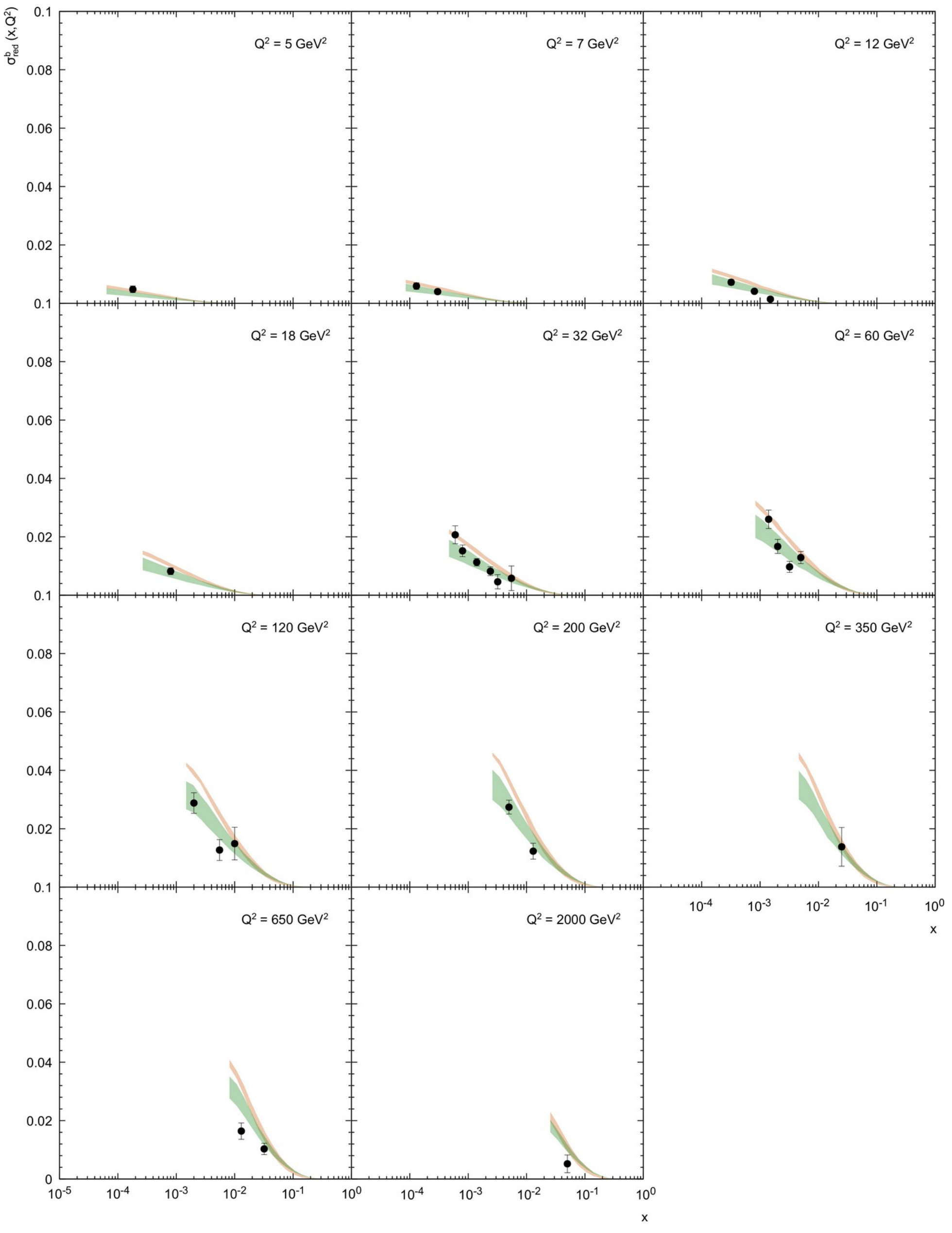
Structure functions





Reduced cross sections





$$\sigma^Q_{\rm red}(x,Q^2) = F^Q_2(x,Q^2) - \frac{y^2}{1+(1-y)^2} F^Q_L(x,Q^2)$$

Conclusion

New unintegrated TMD PDF has been presented.

- Good description of ATLAS data on hadron multiplicities at low p_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.

Back up

Off-shell gluon polarization sum

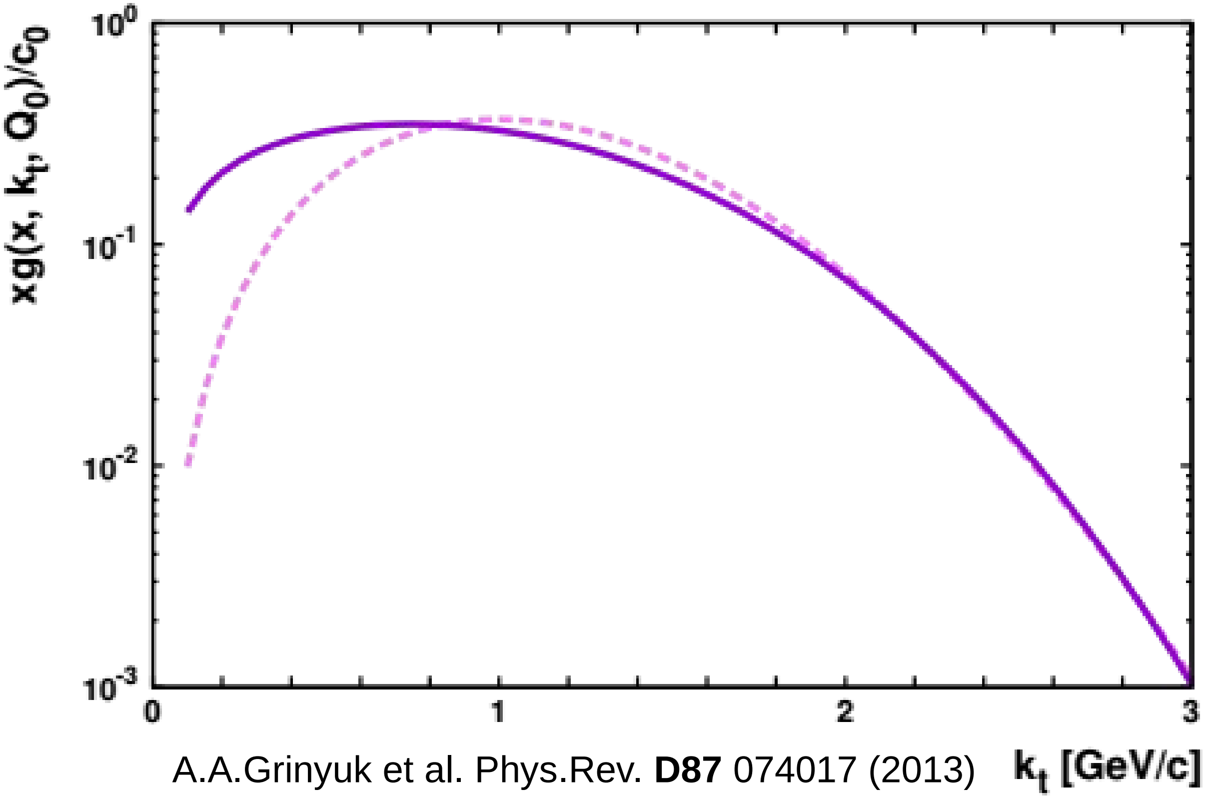
$$\epsilon_\mu \epsilon_\nu^* = \frac{k_T^\mu k_T^\nu}{\mathbf{k}_T^2}$$

Non-perturbative input

Input based on GBW unintegrated parton density

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

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

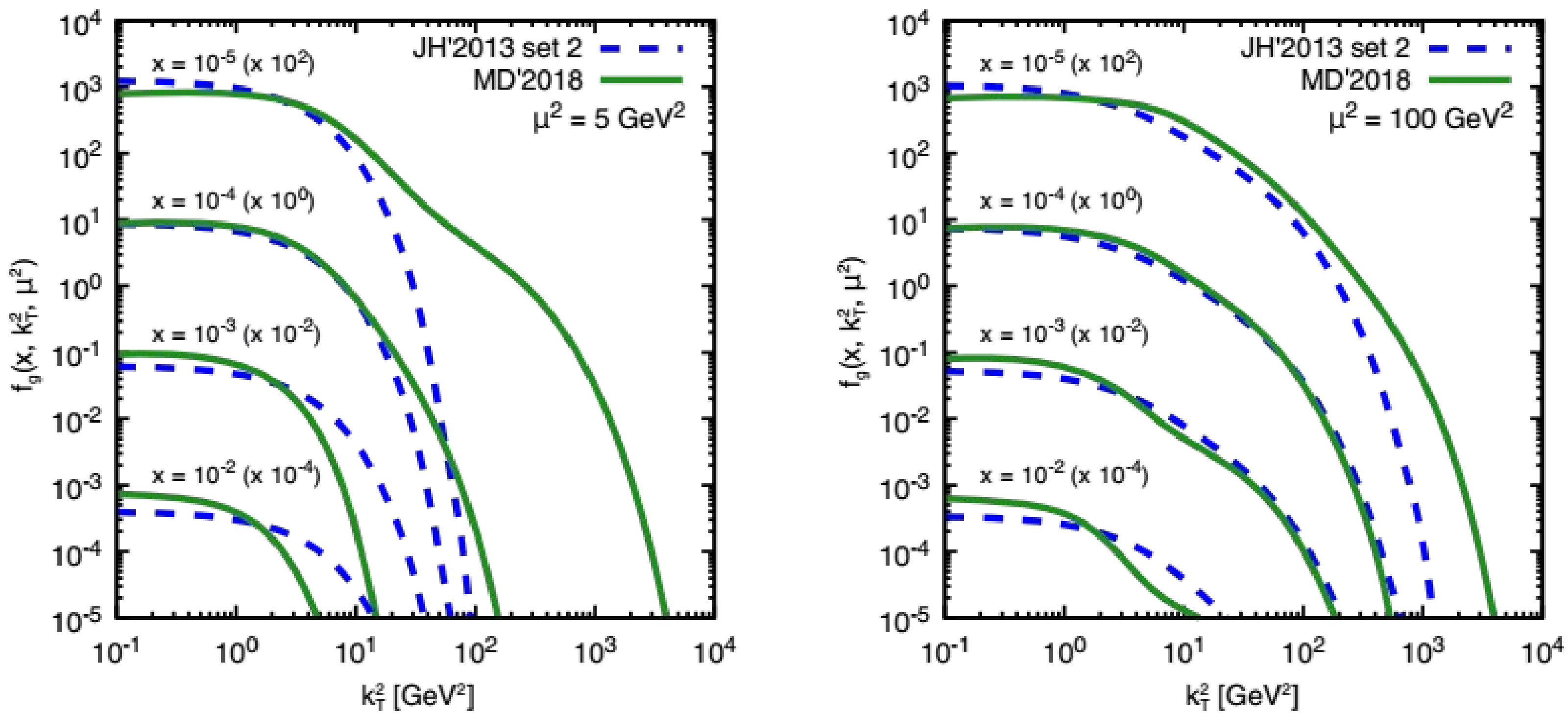


A.A.Grinyuk et al. Phys.Rev. **D87** 074017 (2013)

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

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



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

Some calculation details

$$\phi_q(s,x,p_T) = C_q\Big\{\Phi_q(x_+,p_T)\Phi_{qq}(x_-,p_T) + \Phi_{qq}(x_+,p_T)\Phi_q(x_-,p_T)\Big\}$$

$$\phi_g(s,x,p_T) = C_g\Big\{\Phi_g(x_+,p_T) + \Phi_g(x_-,p_T)\Big\}$$

$$x_\pm = \frac{1}{2}\left(\pm x + \sqrt{x^2 + 4(m_h^2 + p_T^2)/s}\right), \quad x = 2\sqrt{\frac{m_h^2 + p_T^2}{s}}\sinh y$$

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

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

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

Some calculation details

$$F_q(x,\mathbf{k}_T^2) = \int\limits_{x_\pm}^{1} d\xi_1 d\xi_2 \delta(1-x-\xi_1-\xi_2) \int d^2\mathbf{p}_T d^2\mathbf{q}_T \delta^{(2)}(\mathbf{k}_T+\mathbf{p}_T+\mathbf{q}_T)\times$$
$$\times f_q(x) g_q(\mathbf{k}_T^2) f_{qq}(\xi_1) g_{qq}(\mathbf{p}_T^2) f_g(\xi_2,\mathbf{q}_T^2),$$

$$F_u(x,\mathbf{k}_T^2) = f_u(x) g_q(\mathbf{k}_T^2) \int\limits_{x_\pm}^{1-x} d\xi_2 \int\limits_0^\infty d\mathbf{q}_T^2 \int\limits_0^{2\pi} d\varphi \times$$
$$\times f_{ud}(1-x-\xi_2) g_{qq}(|\mathbf{k}_T+\mathbf{q}_T|^2) f_g(\xi_2,\mathbf{q}_T^2),$$

$$F_d(x,\mathbf{k}_T^2) = f_d(x) g_q(\mathbf{k}_T^2) \int\limits_{x_\pm}^{1-x} d\xi_2 \int\limits_0^\infty d\mathbf{q}_T^2 \int\limits_0^{2\pi} d\varphi \times$$
$$\times f_{uu}(1-x-\xi_2) g_{qq}(|\mathbf{k}_T+\mathbf{q}_T|^2) f_g(\xi_2,\mathbf{q}_T^2),$$

$$F_{ud}(x,\mathbf{k}_T^2) = f_{ud}(x) g_{qq}(\mathbf{k}_T^2) \int\limits_{x_\pm}^{1-x} d\xi_2 \int\limits_0^\infty d\mathbf{q}_T^2 \int\limits_0^{2\pi} d\varphi \times$$
$$\times f_u(1-x-\xi_2) g_{qq}(|\mathbf{k}_T+\mathbf{q}_T|^2) f_g(\xi_2,\mathbf{q}_T^2),$$

$$F_{uu}(x,\mathbf{k}_T^2) = f_{uu}(x) g_{qq}(\mathbf{k}_T^2) \int\limits_{x_\pm}^{1-x} d\xi_2 \int\limits_0^\infty d\mathbf{q}_T^2 \int\limits_0^{2\pi} d\varphi \times$$
$$\times f_d(1-x-\xi_2) g_{qq}(|\mathbf{k}_T+\mathbf{q}_T|^2) f_g(\xi_2,\mathbf{q}_T^2).$$

$$F_g(x,\mathbf{k}_T^2) = f_g(x,\mathbf{k}_T^2) \int\limits_{x_\pm}^{1-x} d\xi_2 \int\limits_0^\infty d\mathbf{q}_T^2 \int\limits_0^{2\pi} d\varphi \times$$
$$\times \left\{ \frac{2}{3} f_u(1-x-\xi_2) g_q(|\mathbf{k}_T+\mathbf{q}_T|^2) f_{ud}(\xi_2) g_{qq}(\mathbf{q}_T^2) + \right.$$
$$\left. + \frac{1}{3} f_d(1-x-\xi_2) g_q(|\mathbf{k}_T+\mathbf{q}_T|^2) f_{uu}(\xi_2) g_{qq}(\mathbf{q}_T^2) \right\}.$$

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

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

$$G_{g\to\pi^+}(z) = G_{g\to\pi^-}(z), \quad G_{g\to K^+}(z) = G_{g\to K^-}(z)$$

$$G_{g\to\pi}(z) = 6.57z^{0.54}(1-z)^{3.01}$$

$$G_{g\to K}(z) = 0.37z^{0.79}(1-z)^{3.07}$$

$$I_\pi^g(|\mathbf{p}_T|) = I_K^g(|\mathbf{p}_T|) = I_h^g(|\mathbf{p}_T|) = \frac{(B_{f_h}^g)^2}{2\pi}e^{-B_{f_h}^g|\mathbf{p}_T|}$$

J. Binnewies et al., Phys.Rev. **D52**, 4947

$$G_{u\to\pi^+}(z,|\mathbf{p}_T|) = \left[a_0(1-z) + a_0(1-z)^2\right] I_\pi^q(|\mathbf{p}_T|)$$

$$G_{d\to\pi^+}(z,|\mathbf{p}_T|) = (1-z)G_{u\to\pi^+}(z)I_\pi^q(|\mathbf{p}_T|)$$

$$G_{u\to K^+}(z,|\mathbf{p}_T|) = a_k(1-z)^{1/2}(1+a_{1K}z)I_K^q(|\mathbf{p}_T|)$$

$$G_{u\to K^-}(z,|\mathbf{p}_T|) = a_k(1-z)^{3/2}I_K^q(|\mathbf{p}_T|)$$

$$G_{d\to K^+}(z,|\mathbf{p}_T|) = G_{u\to K^-}(z)I_K^q(|\mathbf{p}_T|)$$

$$G_{d\to K^-}(z,|\mathbf{p}_T|) = G_{u\to K^+}(z)I_K^q(|\mathbf{p}_T|)$$

$$G_{uu\to\pi^+}(z,|\mathbf{p}_T|) = a_0(1-z)^2 I_\pi^{qq}(|\mathbf{p}_T|)$$

$$G_{ud\to\pi^+}(z,|\mathbf{p}_T|) = a_0(1+(1-z)^2)(1-z)^2 I_\pi^{qq}(|\mathbf{p}_T|)$$

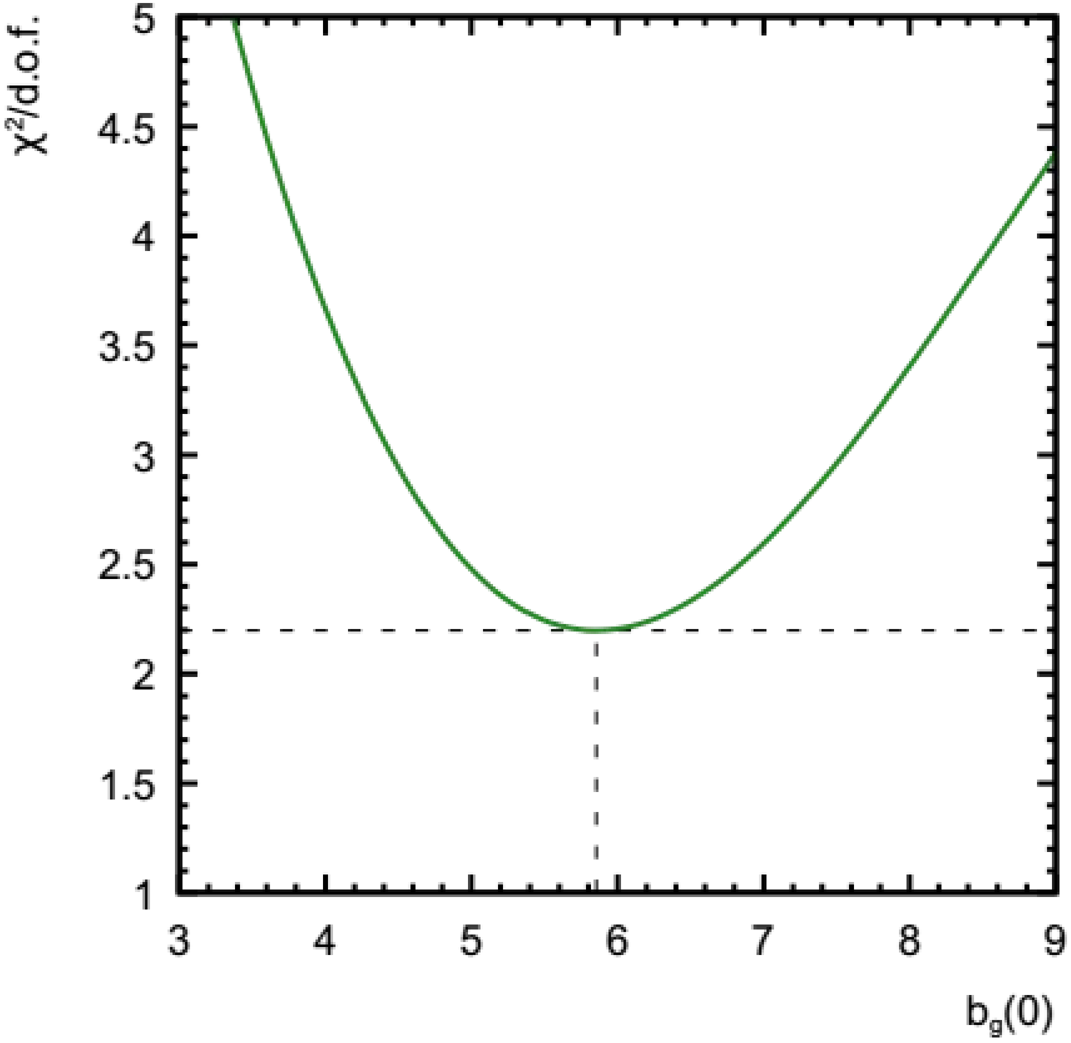
$$G_{uu\to K^+}(z,|\mathbf{p}_T|) = a_k(1-z)^{5/2}(1+a_{2K}z)I_K^{qq}(|\mathbf{p}_T|)$$

$$G_{uu\to K^-}(z,|\mathbf{p}_T|) = a_k(1-z)^{7/2}I_K^{qq}(|\mathbf{p}_T|)$$

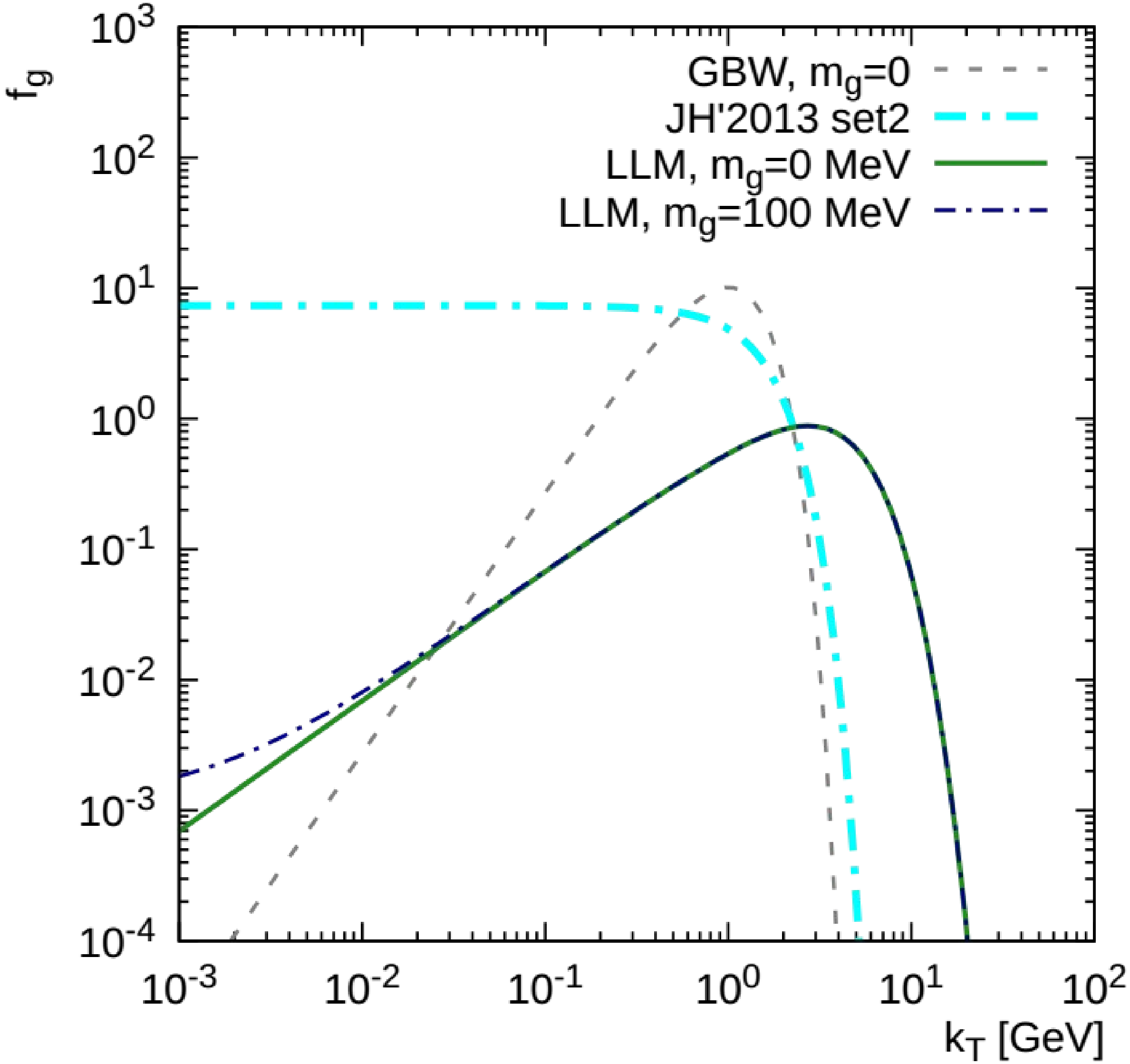
$$G_{ud\to K^+}(z,|\mathbf{p}_T|) = \frac{a_k}{2}(1-z)^{5/2}(1+a_{2K}z+(1-z)^2)I_K^{qq}(|\mathbf{p}_T|)$$

$$G_{ud\to K^-}(z,|\mathbf{p}_T|) = \frac{a_k}{2}(1-z)^{7/2}(1+(1-z)^2)I_K^{qq}(|\mathbf{p}_T|)$$

b_g extraction



Non-perturbative input



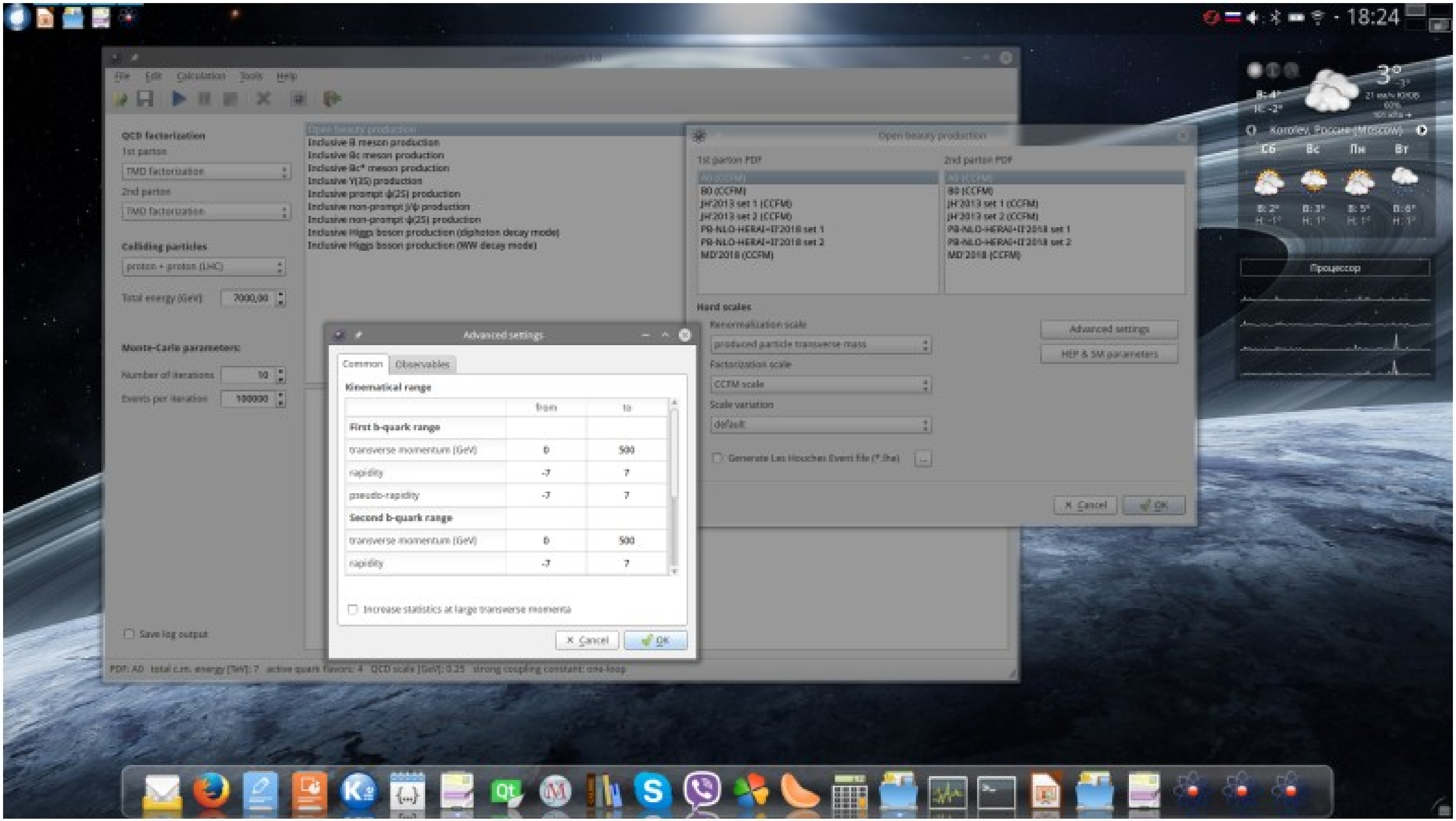
x=4·10^{-5}
μ=1.2 GeV

PEGASUS

- parton level Monte-Carlo event generator for pp and $p\bar{p}$ 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

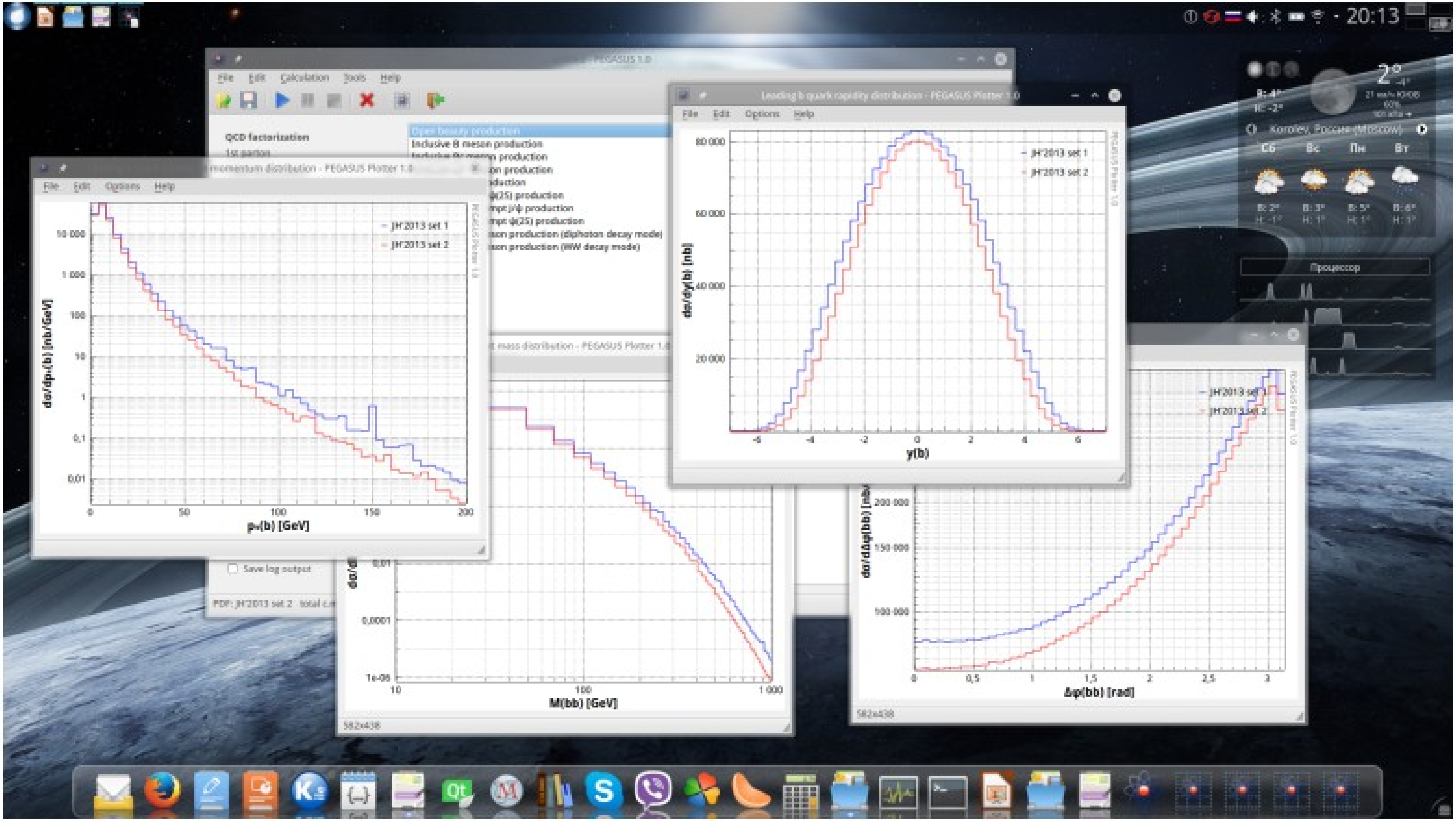
A.V. Lipatov, M.A. Malyshev, S.P. Baranov, Eur. Phys. J. **C80**, 4, 330 (2020);
https://theory.sinp.msu.ru/doku.php/pegasus/overview

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



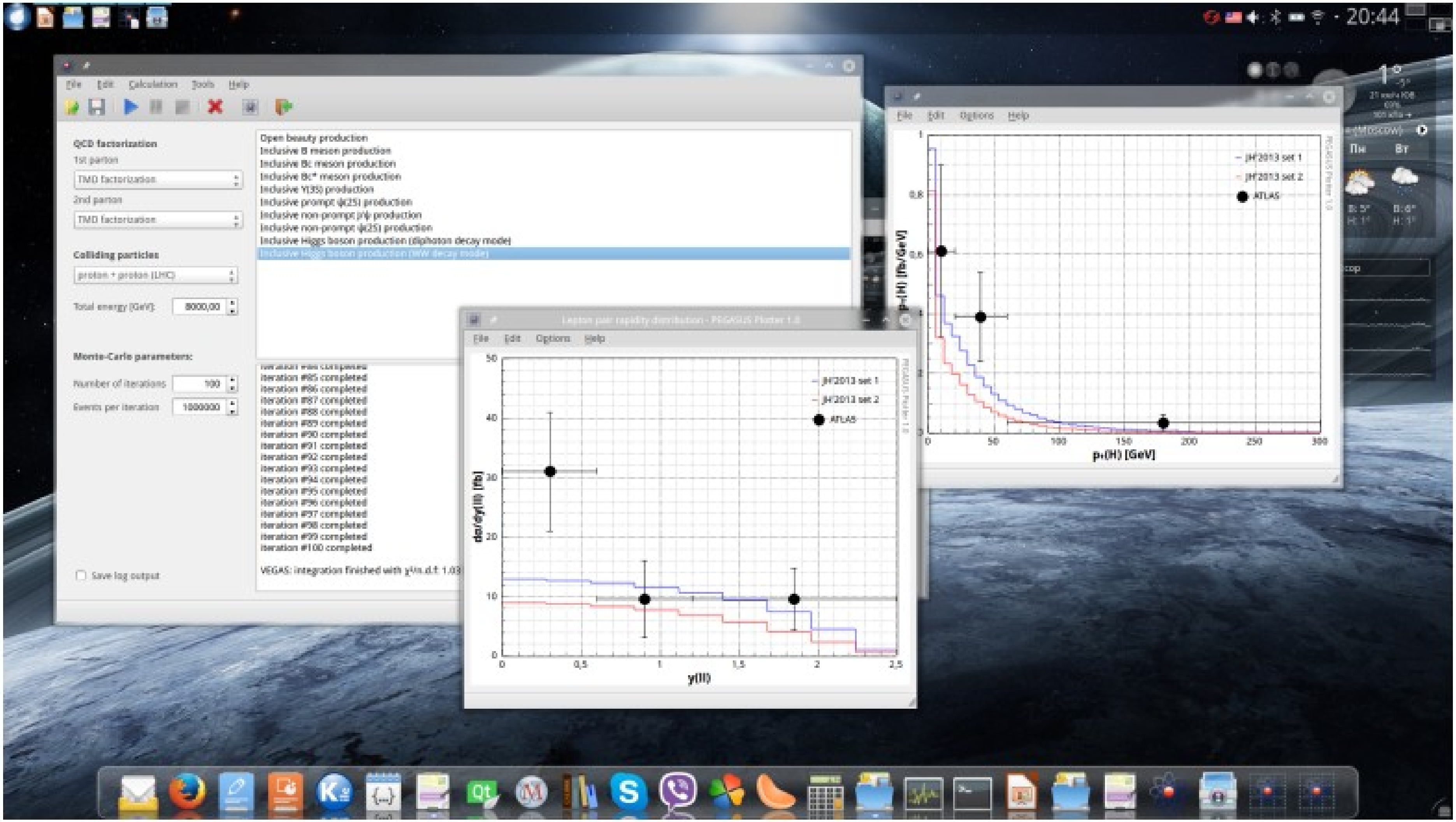
A.V. Lipatov, S.P. Baranov, M.A. Malyshev, in preparation (2019)

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



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

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



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