New transverse momentum dependent gluon distribution in proton and nuclei

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in collaboration with

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A.V. Lipatov, G.I. Lykasov, M.A. Malyshev, Phys.Lett. **B 848** (2024) 138390
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Outline

1. Motivation
2. LLM-2024 TMD gluon distribution in proton
3. LLM-2024 TMD gluon distribution in nuclei
4. Conclusion

Motivation

- High energy, or k_T-factorization is a powerful tool to study processes in *ep* and *pp* collisions. Monte-Carlo implementations: CASCADE, KaTie, PEGASUS.

- k_T-factorization employs transverse momentum dependent (TMD), or unintegrated parton densities, which obey non-collinear evolution equations.

- TMD parton distributions in nuclei are barely studied; very few are available.

- Since k_T-factorization is valid at small *x*, we study ***gluon*** TMD distributions.

$$\sigma = \hat{\sigma}^* \otimes f(x, \mathbf{k}_T^2, \mu^2)$$

Unintegrated TMD in proton: LLM-2024

The initial distribution for the gluon TMD at low Q^2 and small x was chosen in a way to describe data on soft hadrons (π and K-mesons) multiplicity spectra within the modified quark-gluon string model.

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

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

$$Q_0 = 2.2 \text{ GeV}$$

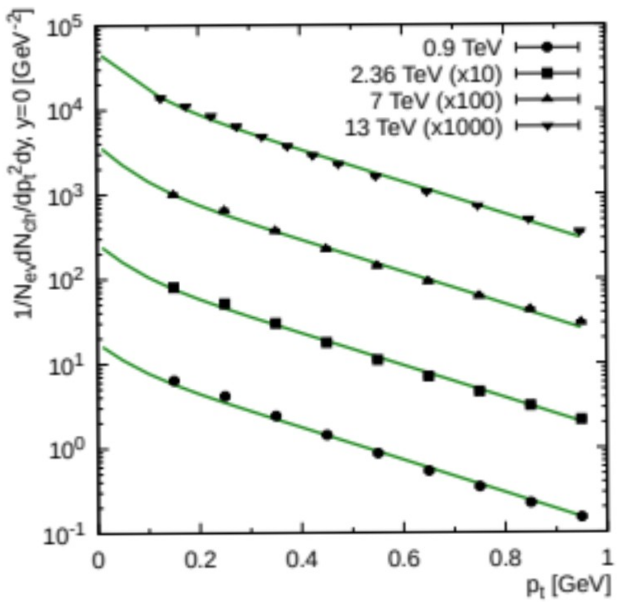
$$b_g = b_g(0) + \frac{4C_A}{\beta_0}\log\frac{\alpha_S(\mu_0^2)}{\alpha_S(k_T^2)}$$

Modified quark-gluon string model

Non-perturbative gluons are added at low scales:

- The gluon distribution does not depend on the scale at $Q<Q_s$

- The non-perturbative gluon distribution is taken as a spectator in *pp* collisions



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

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

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

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

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

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

$F_2(x,Q^2)$ in color dipole model

At small Q^2 the proton and nuclear structure function $F_2(x,Q^2)$ can be calculated in the color dipole model [Golec-Biernat, Wusthoff, Phys. Rev. **D 59**, 014017 (1998)]:

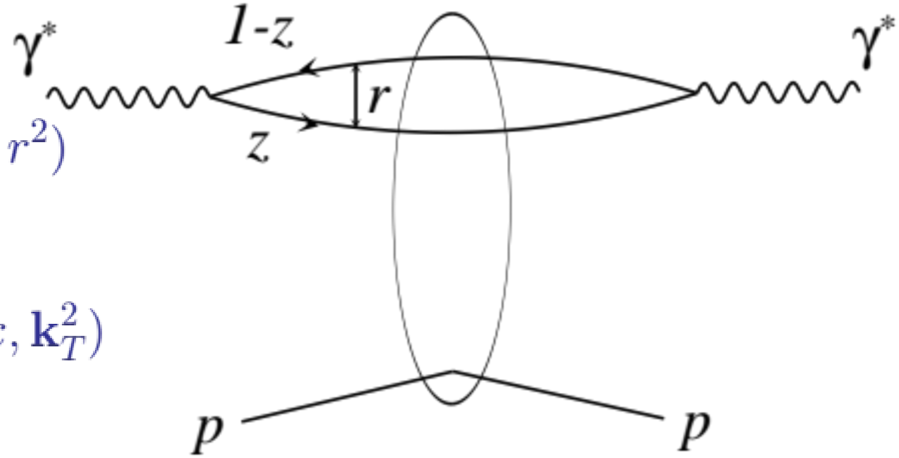
$$\sigma_{T,L}(x,Q^2) = \int d^2\mathbf{r} \int_0^1 dz |\Psi_{T,L}(z,r)|^2 \, \hat{\sigma}(x,r^2)$$

$$\hat{\sigma}(x,r^2) = \frac{4\pi^2\alpha_s}{3} \int \frac{d\mathbf{k}_T^2}{\mathbf{k}_T^2} \{1 - J_0(|\mathbf{k}_T|r)\} \, f_g(x,\mathbf{k}_T^2)$$

$$F_2(x,Q^2) = F_T(x,Q^2) + F_L(x,Q^2)$$

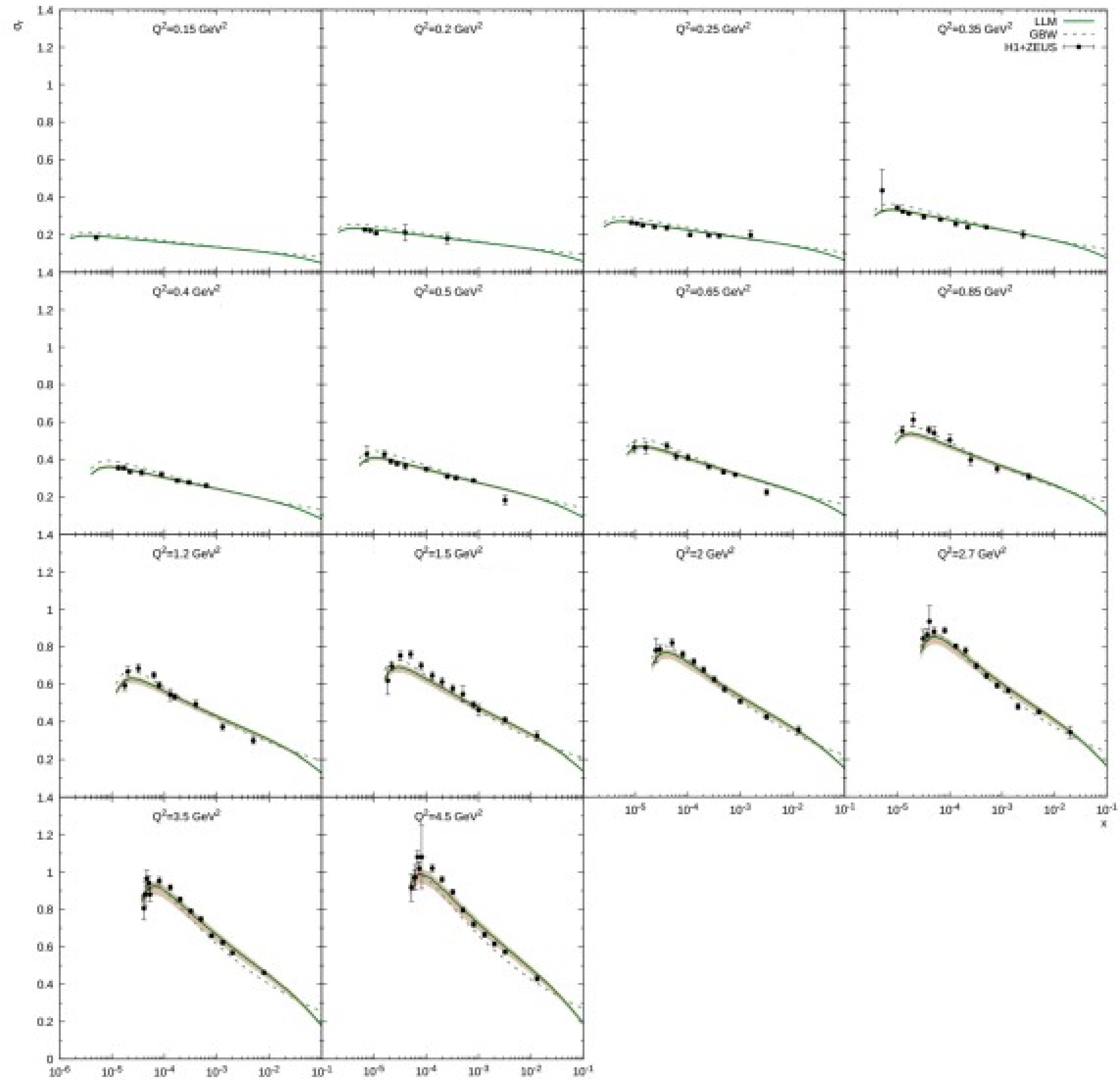
$$F_{T,L}(x,Q^2) = \frac{Q^2}{4\pi^2\alpha_{em}} \sigma_{T,L}(x,Q^2)$$

$$\sigma_r(x,Q^2) = \frac{Q^4 x}{2\pi\alpha^2(1-y^2)} \frac{d^2\sigma}{dx dQ^2} = F_2(x,Q^2) - f(y) F_L(x,Q^2)$$



Unintegrated TMD: LLM-2024

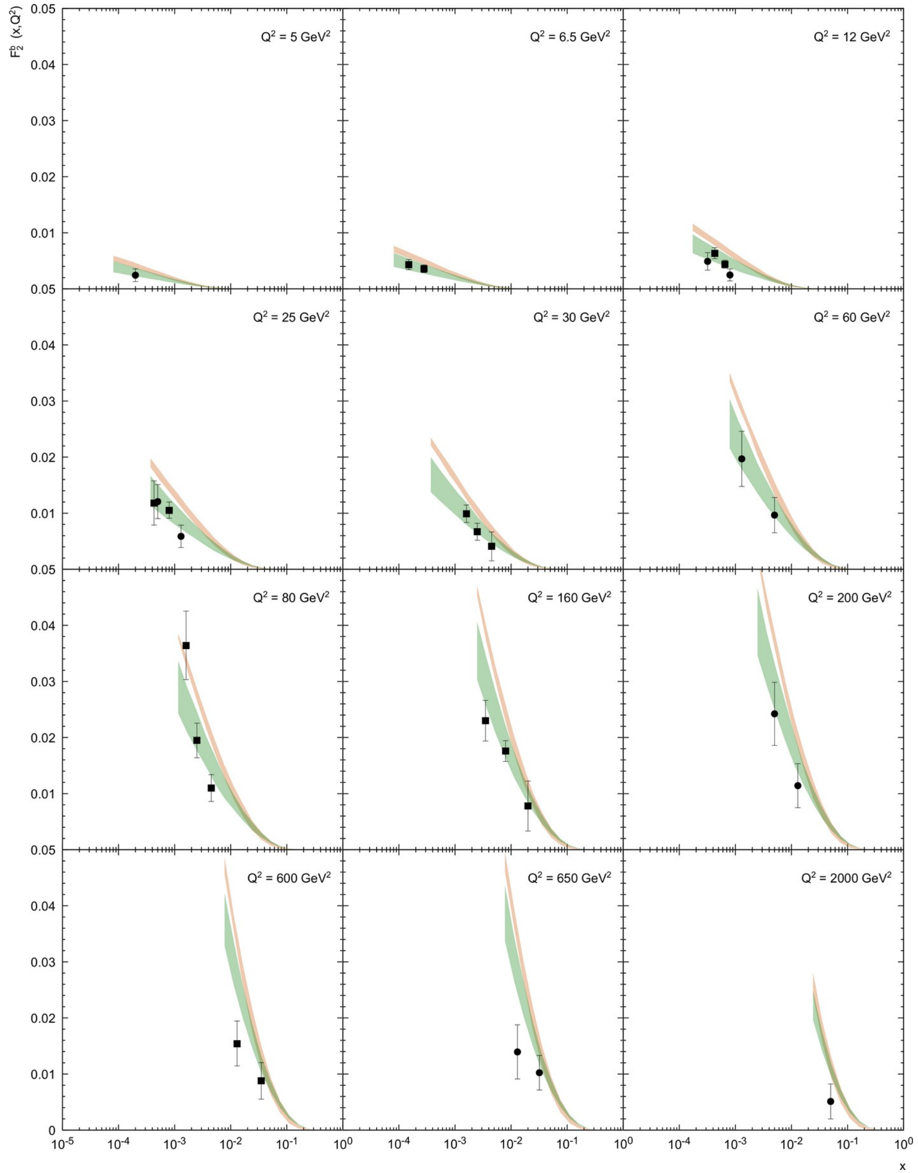
Parameters important at small x were determined from a fit on $\sigma_{red}(x,Q^2)$ data taken by HERA at low scales using the color dipole model.



Unintegrated TMD: LLM-2024

- The TMD was expanded to higher Q^2 using the CCFM evolution equation.

- Parameters important at large x were determined from a comparison with higher energies HERA and LHC data on *b*-jet, Higgs boson production and $F_2^{c,b}(x,Q^2)$ data

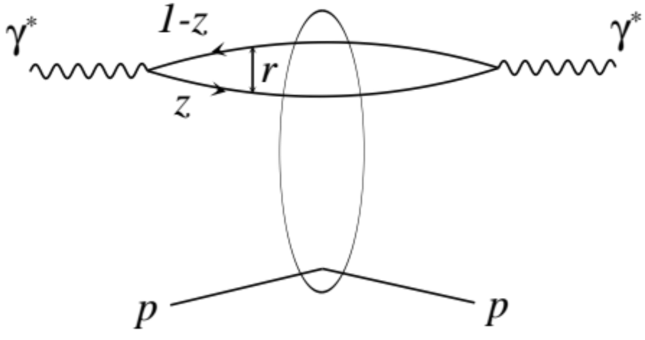


Unintegrated TMD: LLM-2024

Experiment	Collaboration	Year	Reference	Collision	$\sqrt{s}$/GeV	Number of points
Inclusive c-jet	CMS	2017	[60]	pp	2.76	5
Inclusive c-jet	CMS	2017	[60]	pp	5.02	5
Inclusive b-jet	ATLAS	2011	[59]	pp	7	46
Inclusive b-jet	CMS	2012	[63]	pp	7	98
$F_2^c(x,Q^2)$	H1	2010, 2011	[64, 65]	ep	0.319	25
$F_2^c(x,Q^2)$	ZEUS	2014	[66]	ep	0.319	18
$F_2^b(x,Q^2)$	H1	2014	[64]	ep	0.319	12
$F_2^b(x,Q^2)$	ZEUS	2014	[66]	ep	0.319	17
$\sigma_{red}^c(x,Q^2)$	H1, ZEUS	2018	[67]	ep	0.319	51
$\sigma_{red}^b(x,Q^2)$	H1, ZEUS	2018	[67]	ep	0.319	27
Inclusive $H \to \gamma\gamma$	CMS	2023	[68]	pp	13	37
Inclusive $H \to \gamma\gamma$	ATLAS	2018	[68]	pp	13	27
Inclusive $H \to ZZ^*$	CMS	2023	[69]	pp	13	54
Inclusive $H \to ZZ^*$	ATLAS	2020	[70]	pp	13	54
Inclusive γ	H1	2010	[61]	ep, low Q^2	0.319	25
Inclusive γ	ZEUS	2014	[62]	ep, low Q^2	0.319	8

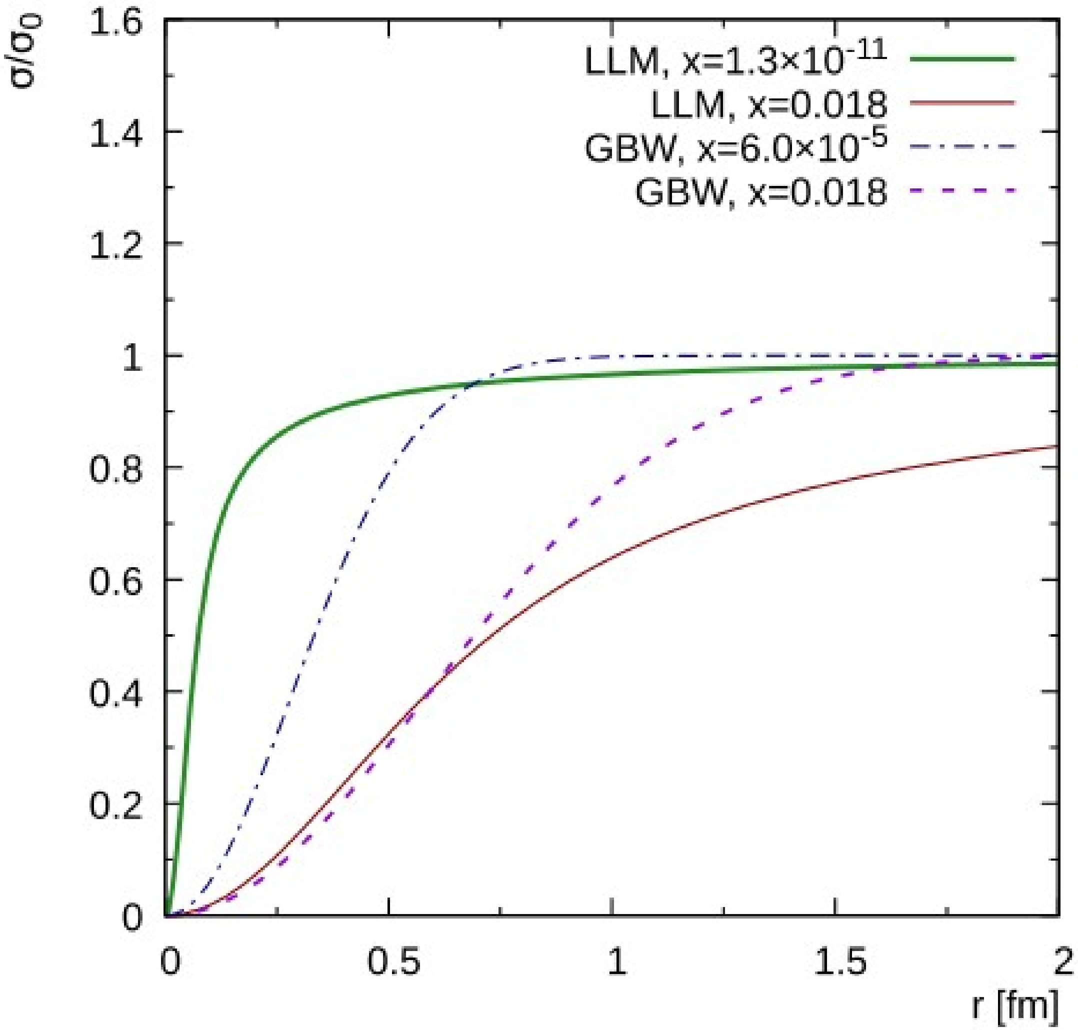
χ^2/n.d.f.=1,773

Saturation for LLM-2024



$$\hat{\sigma}(x,r^2) = \frac{4\pi^2\alpha_s}{3}\int \frac{d\mathbf{k}_T^2}{\mathbf{k}_T^2}(1 - J_0(|\mathbf{k}_T|r))f_g(x,\mathbf{k}_T^2)$$

$$Q_s(x) = \frac{1}{R_0(x)}$$



Shadowing in nucleus

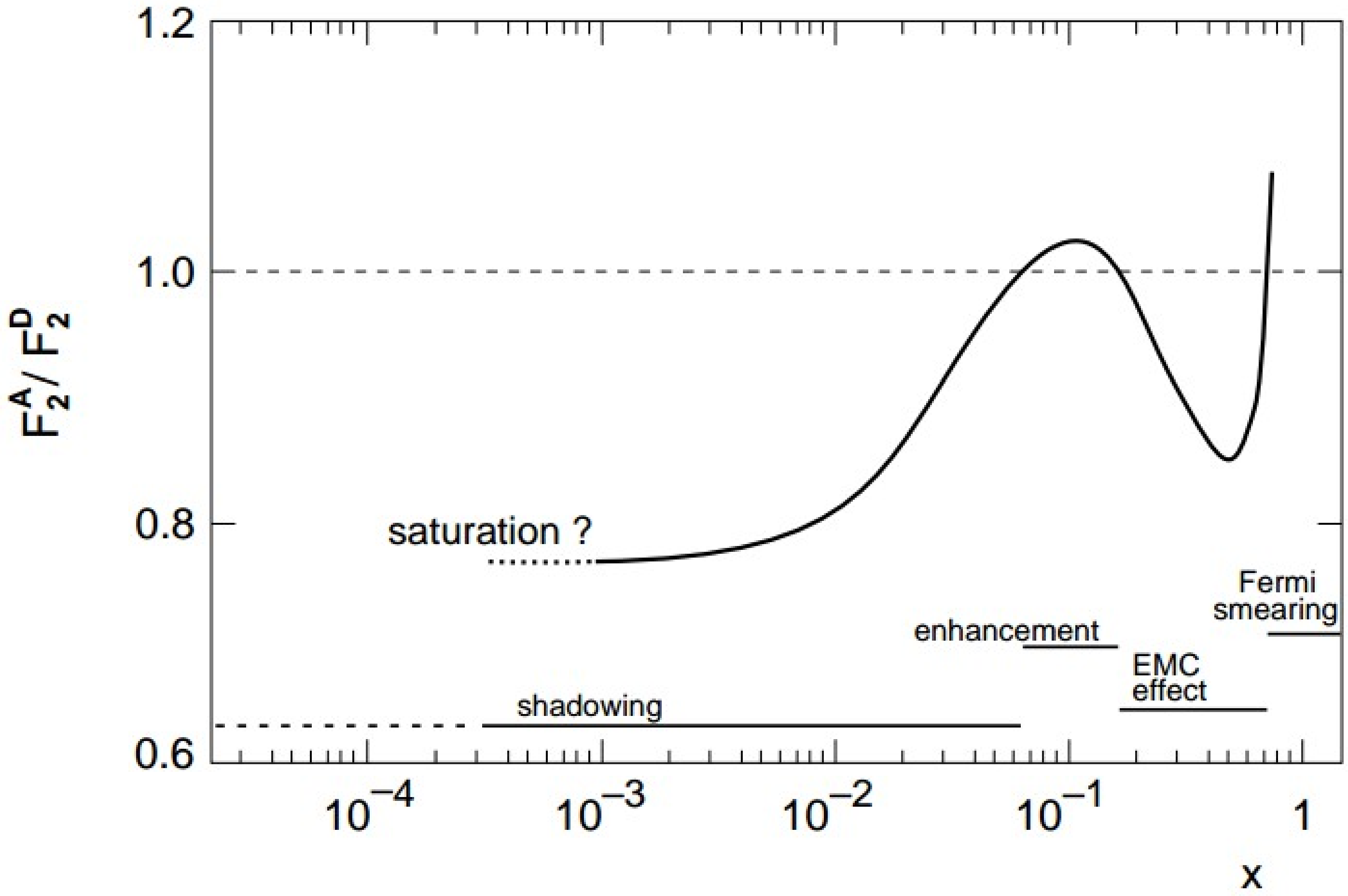


Fig. from [NMC, Nucl. Phys. **B 441** (1995) 12]

Geometric scaling

$$\frac{\sigma^{\gamma^* A}(\tau_A)}{\pi R_A^2} = \frac{\sigma^{\gamma^* p}(\tau_p)}{\pi R_p^2}$$

$$\tau_{p,A} = Q^2/Q^2_{s\,p,A}$$

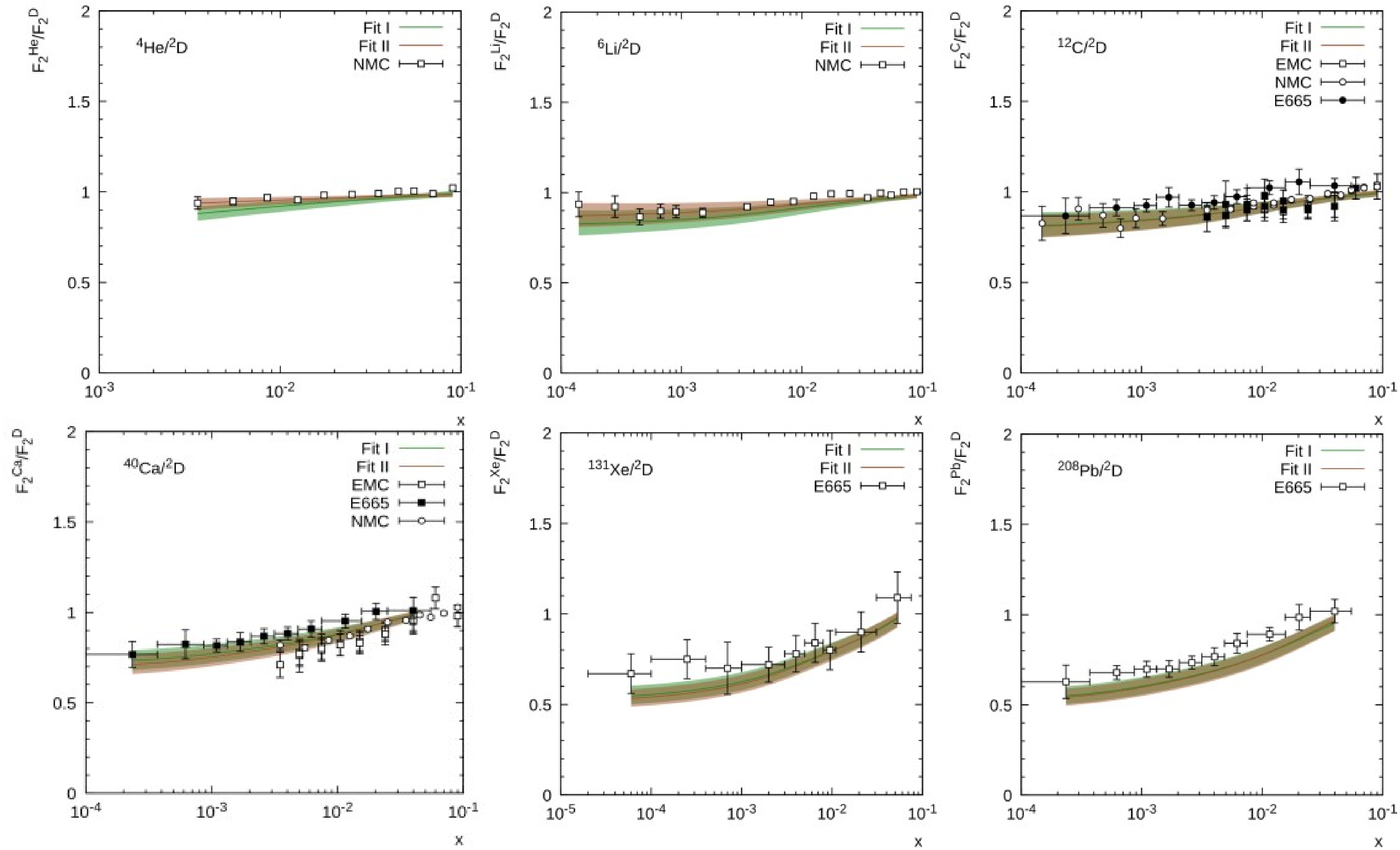
$$Q^2_{s,\,A}(x) = Q^2_s(x)\left(\frac{A\pi R_p^2}{\pi R_A^2}\right)^{\frac{1}{\delta}}$$

[Armesto et al., Phys. Rev. Lett. **94** (2005) 022002]

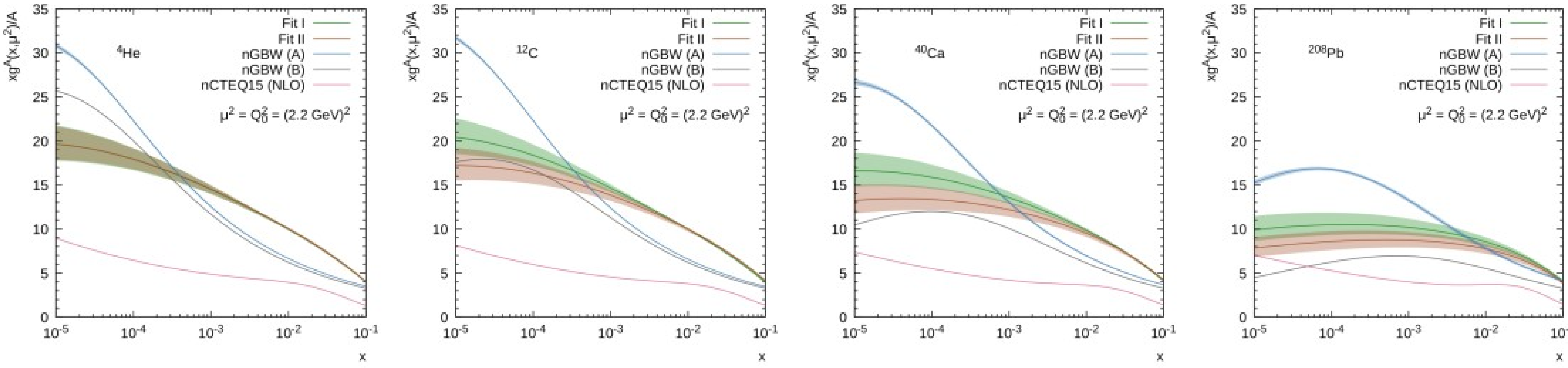
$R_A = \left(1.12A^{1/3} - 0.86A^{-1/3}\right)\ \mathrm{fm}$ ➡ Fit I: πR_p^2=1.74 fm^2, δ=0.751 (χ^2/n.d.f.=2.28)

$R_A = \left(1.12A^{1/3} - 0.5\right)\ \mathrm{fm}$ ➡ Fit II: πR_p^2=1.86 fm^2, δ=0.740 (χ^2/n.d.f.=2.19)

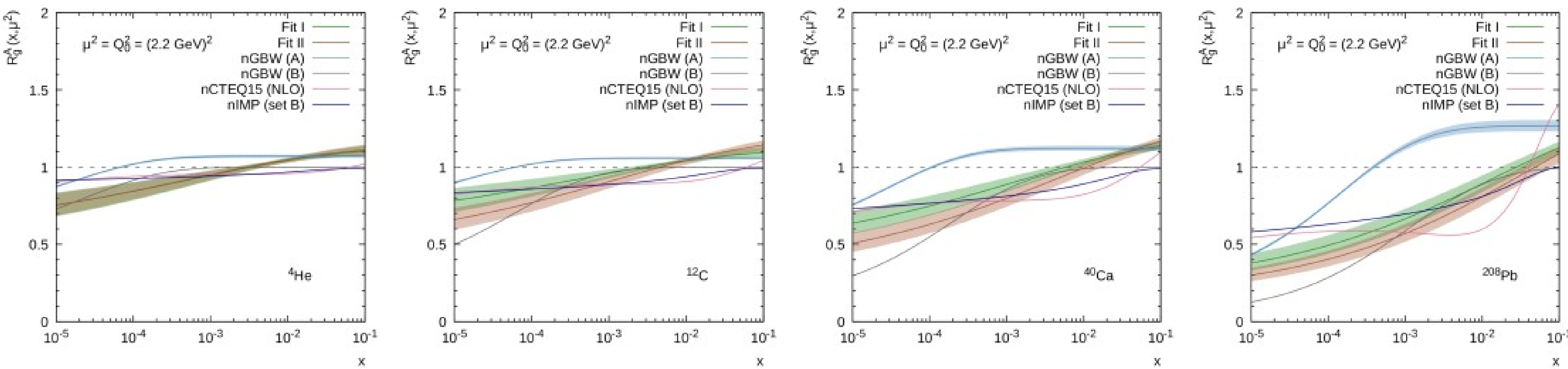
TMD in nucleus: fit results



Integrated TMD in nucleus: comparison with other gluon distributions



Nuclear modification factors:



Conclusion

A new TMD gluon distribution in proton and nuclei has been proposed

- The new LLM-2024 TMD can simultaneously describe LHC data on charged hadrons multiplicities at small p_T and a number of HERA and LHC data ($F_2(x,Q^2)$, *b*-jet production, Higgs production etc.).

- Using geometric scaling one can obtain a TMD gluon distribution in nucleus, which takes into account shadowing at small x.

- LLM-2024 gluon TMD is now available via TMDlib and PEGASUS Monte-Carlo generator

https://theory.sinp.msu.ru/doku.php/pegasus/overview.

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Back up

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)]

k_T-factorization: TMDs

CCFM-based unintegrated distributions

Numerical solutions of Catani-Ciafaloni-Fiorani-Marchesini evolution equation.

The starting distribution is chosen to satisfy data on proton structure functions $F_2(x,\mu^2)$ only (A0, JH2013-set-1) or both $F_2(x,\mu^2)$ and $F_2^c(x,\mu^2)$ (JH2013-set-2)

[H. Jung, hep-ph/0411287, F. Hautmann, H. Jung, Nucl. Phys. **B883** (2014) 1]**.**

Only gluons and valence quarks. Sea quarks can be obtained from gluons in the last splitting.

Golec-Biernat — Wusthoff TMD gluon distribution

$$f_g^p(x, \mathbf{k}_T^2) = \frac{3\sigma_0}{4\pi^2} R_0^2(x)\mathbf{k}_T^2 \exp\left[-R_0^2(x)\mathbf{k}_T^2\right]$$

$$\hat{\sigma}^p(x, r^2) = \sigma_0 \left\{1 - \exp\left[-\frac{r^2}{R_0^2(x)}\right]\right\}$$

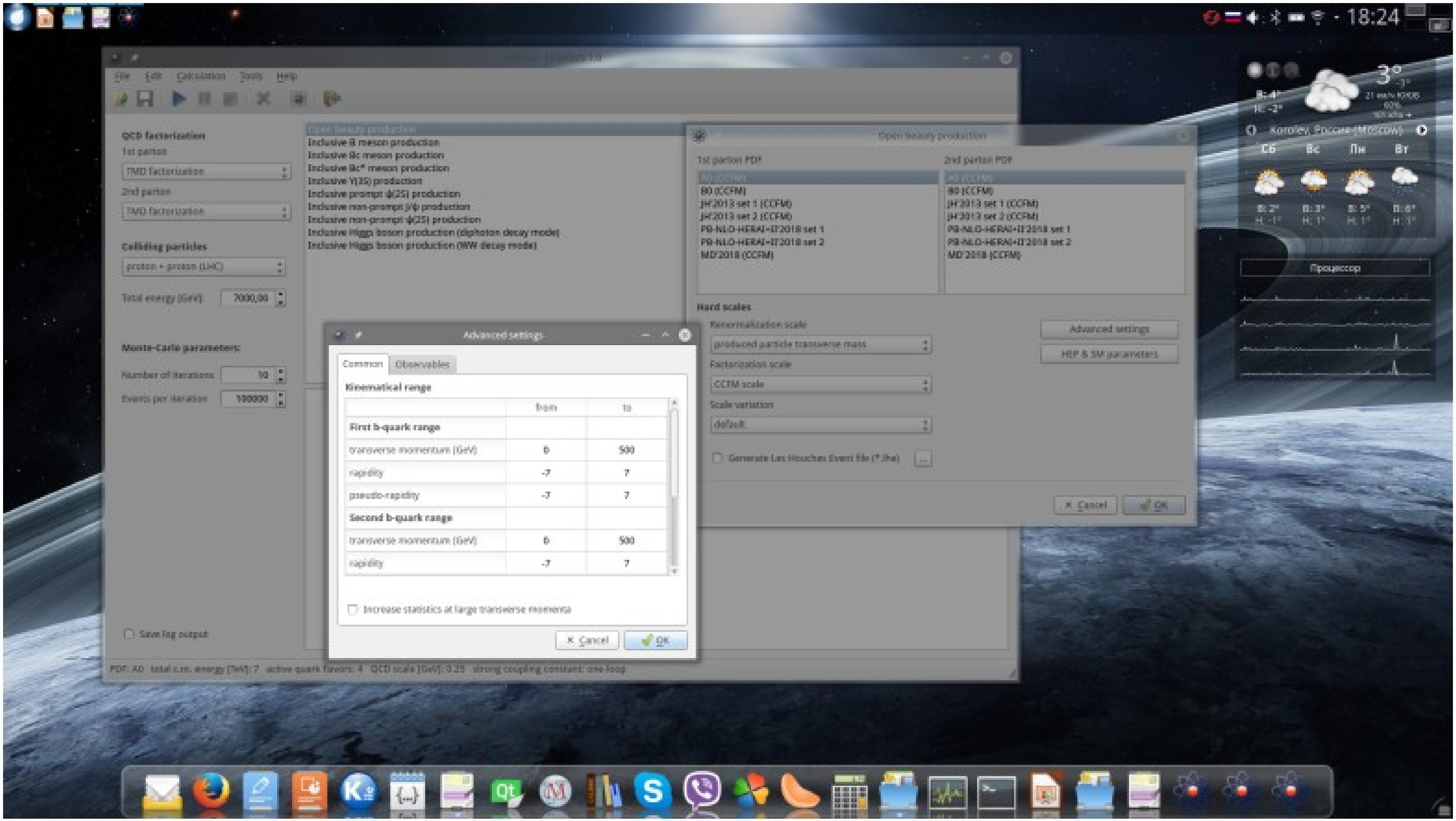
[Golec-Biernat, Wusthoff, Phys. Rev. **D 60**, 114023 (1999)]

PEGASUS

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

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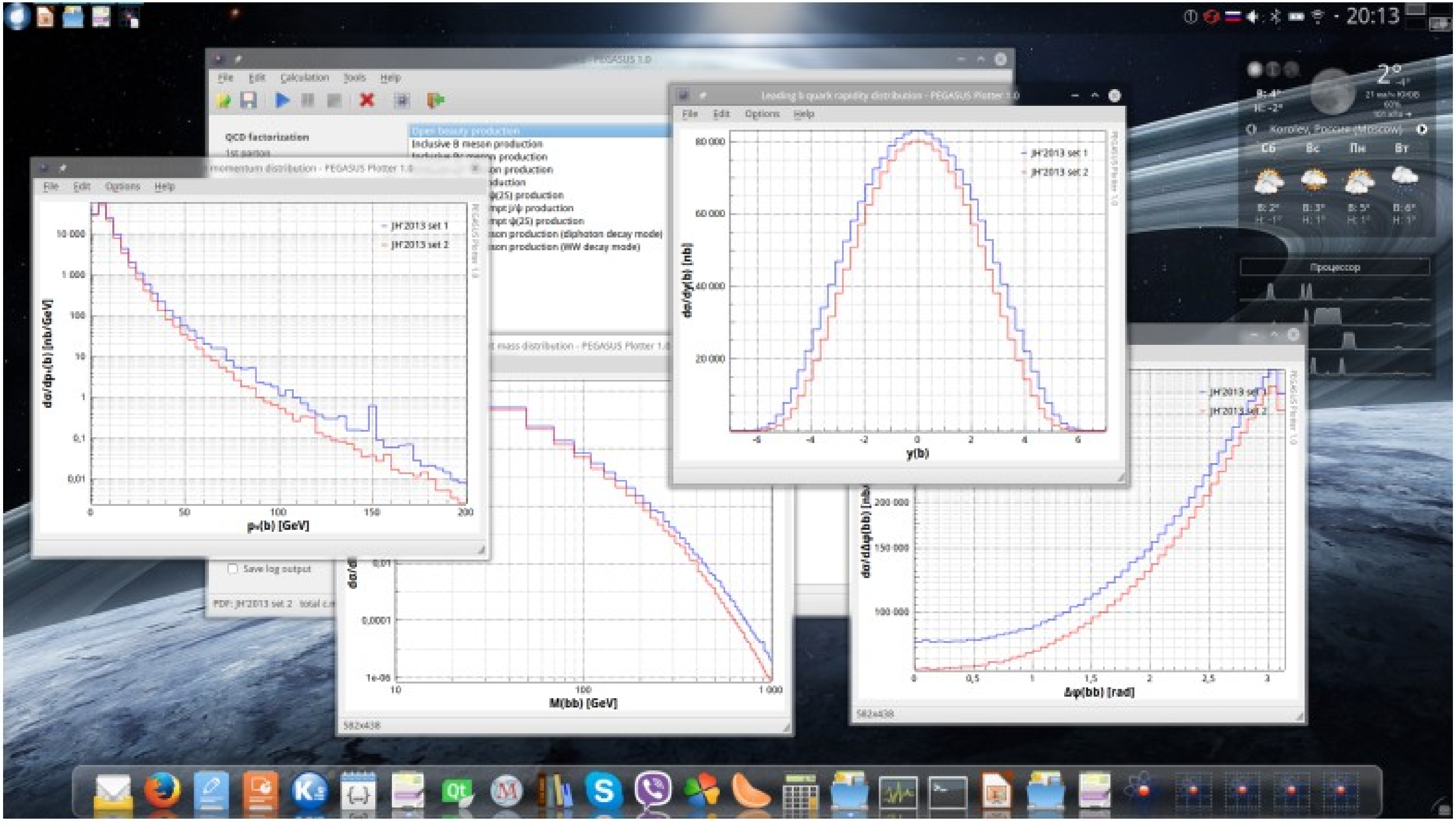

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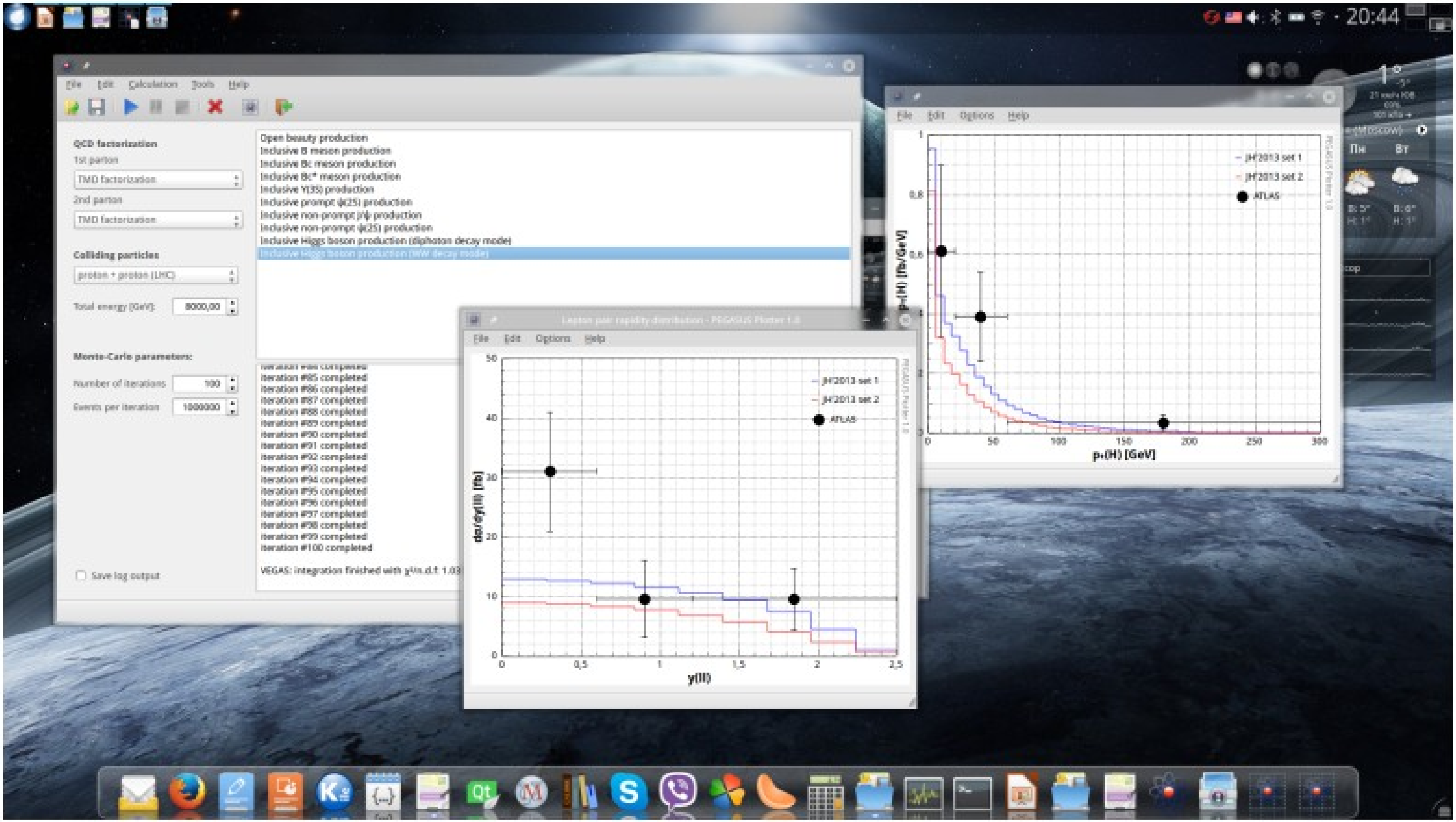

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