TMD GLUON DENSITY AT SMALL X

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in collaboration with

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REF-2014, Antwerp, 08.12.14-11.12.14

OUTLINE

1. **Inclusive spectra of charge hadrons in p-p within soft QCD model including gluon**

2. **Gluon distribution in proton**

3. **Modified un-integrated gluon distribution**

4. **CCFM-evolution and structure functions**

5. **Summary**

REF-2014, Antwerp, 08.12.14-11.12.14

SOFT PP -> h X

The inclusive spectrum is presented in the following form:

$$\rho(x=0, p_t) = \rho_q(x=0, p_t) + \rho_g(x=0, p_t)$$

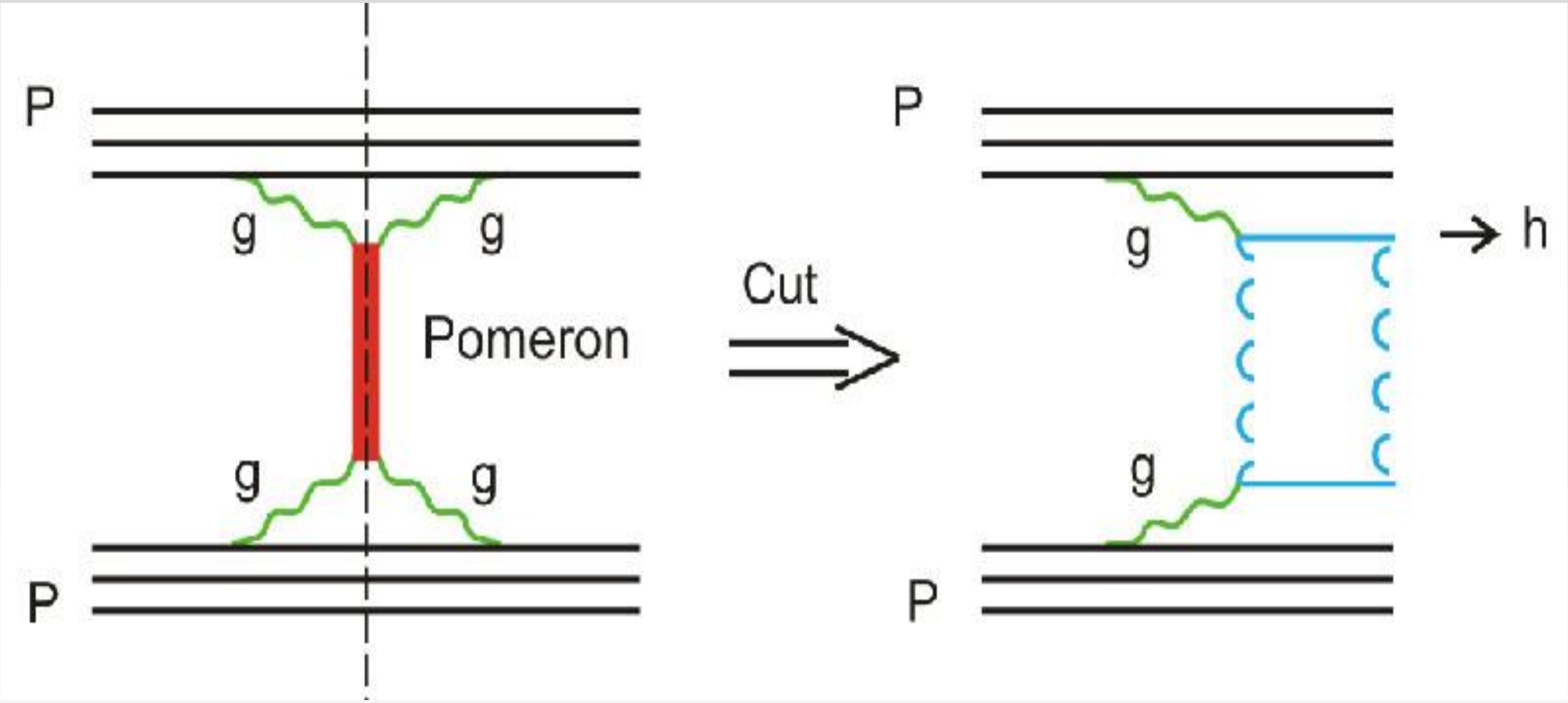
Here $\rho_q = g\left(\frac{s}{s_0}\right)^{\Delta} \varphi_q ; \varphi_q(0, p_t) = A_q \exp(-b_q p_t)$

$$\rho_g = g\left[\left(\frac{s}{s_0}\right)^{\Delta} - \sigma_{nd}\right] \varphi_g ; \varphi_g(0, p_t) = \sqrt{p_t} A_g \exp(-b_g p_t)$$

$A_q = 11.91 \pm 0.39$, $b_q = 7.29 \pm 0.11$ $\quad g \approx 21$ mb

$A_g = 3.76 \pm 0.13$ $\quad b_g = 3.51 \pm 0.02$ $\quad \Delta \approx 0.12$

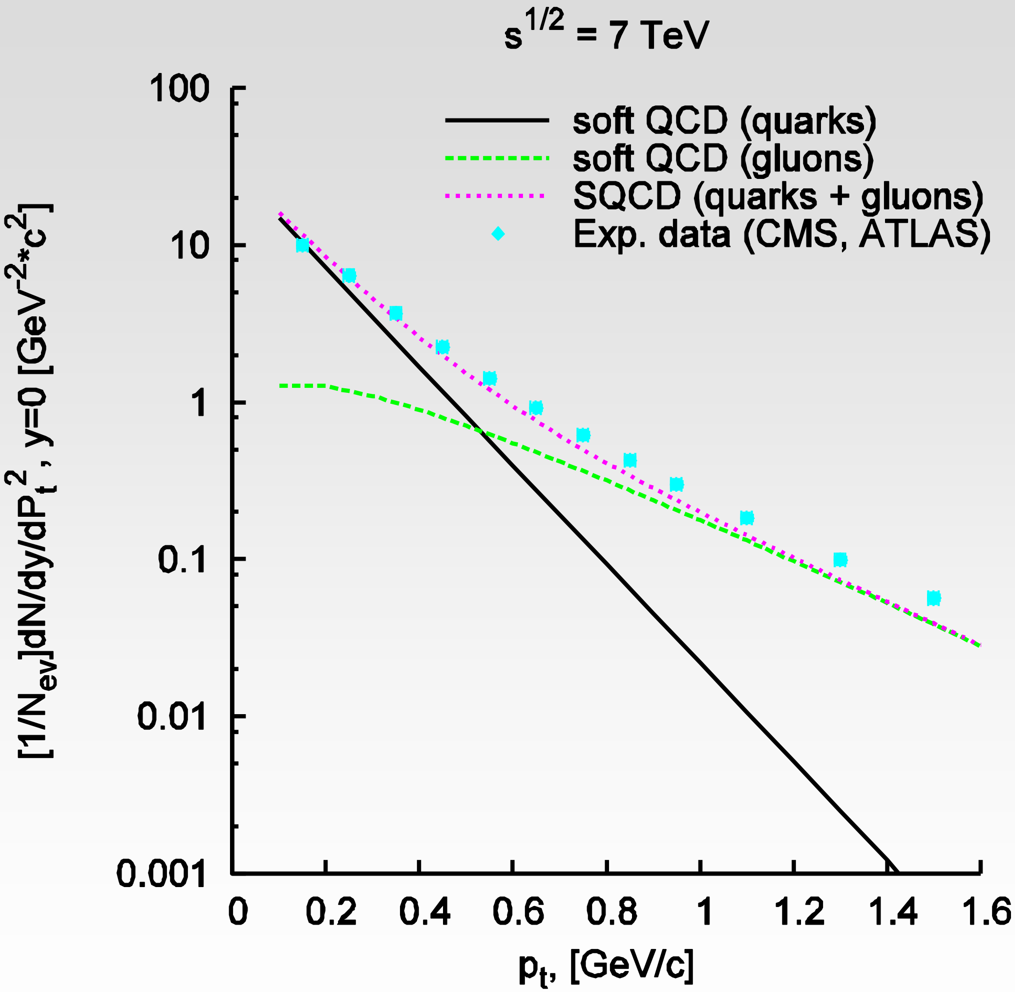
V.A. Bednyakov, A.V. Grinyuk, G.L., M. Poghosyan, Int. J.Mod.Phys. A 27 (2012) 1250012. hep-ph/11040532 (2011); hep-ph/1109.1469 (2011); Nucl.Phys. B 219 (2011) 225.



One-Pomeron exchange (left) and the cut one-Pomeron exchange (right); P-proton, g-gluon, h-hadron produced in PP

In the light cone dynamics the proton has a general decomposition:

$|uud\rangle, |uudg\rangle, |uudq\bar{q}\rangle, \ldots$ S.J.Brodsky, C.Peterson, N.Sakai, Phys.Rev. D 23 (1981) 2745.



$s^{1/2}$ = 7 TeV
soft QCD (quarks)
soft QCD (gluons)
SQCD (quarks + gluons)
Exp. data (CMS, ATLAS)
100
10
1
0.1
0.01
0.001
[1/N$_{ev}$]dN/dy/dP$_t^2$, y=0 [GeV^{-2}*c^2]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
p$_t$, [GeV/c]

THE CUT ONE-POMERON EXCHANGE

$$\rho(x, p_{ht}) = F(x_+, p_{ht}) F(x_-, p_{ht})$$

Here

$$F(x_+, p_{ht}) = \int dx_1 \int d^2 k_{1t} \, f_q(x_1, k_{1t}) G_q^h\left(\frac{x_+}{x_1}, p_{ht} - k_{1t}\right)$$

where

$$G_q^h(z, k_t) = z D_q^h(z, k_t) \qquad f_q = g \otimes P_{g-q\bar{q}}$$

where $P_{g-q\bar{q}}$ is the splitting function of a gluon to the quark-antiquark pair

A.A.Grinyuk, A.V.Lipatov, G.L., N/P/Zotov, Phys.Rev. D87, 074017 (2013).

UN-INTEGRATED GLUON DISTRIBUTION IN PROTON

$$xA\left(x,k_t^2,Q_0^2\right)=\frac{3\sigma_0}{4\pi^2\alpha_s}R_0^2(x)k_t^2\exp\left(-R_0^2(x)k_t^2\right),$$

where $R_0=C_1(x/x_0)^{\lambda/2}$, $C_1=1/\mathrm{GeV}$

K.Golec-Biernat & M.Wuesthoff, Phys.Rev. D60, 114023 (1999); Phys.Rev. D59, 014017 (1998)

H.Jung, hep-ph/0411287, Proc. DIS'2004 Strbske Pleco, Slovakia

MODIFIED UGD AT Q_0

$$xg(x,k_t,Q_0)=C_0C_3(1-x)^{b_g}\left(R_0^2(x)k_t^2+C_2(R_0(x)k_t)^a\right)$$

$$\exp\left(-R_0(x)k_t-d\,(R_0(x)k_t)^3\right),$$

where $C_0=3\sigma_0/\left(4\pi^2\alpha_s(Q_0^2)\right)$

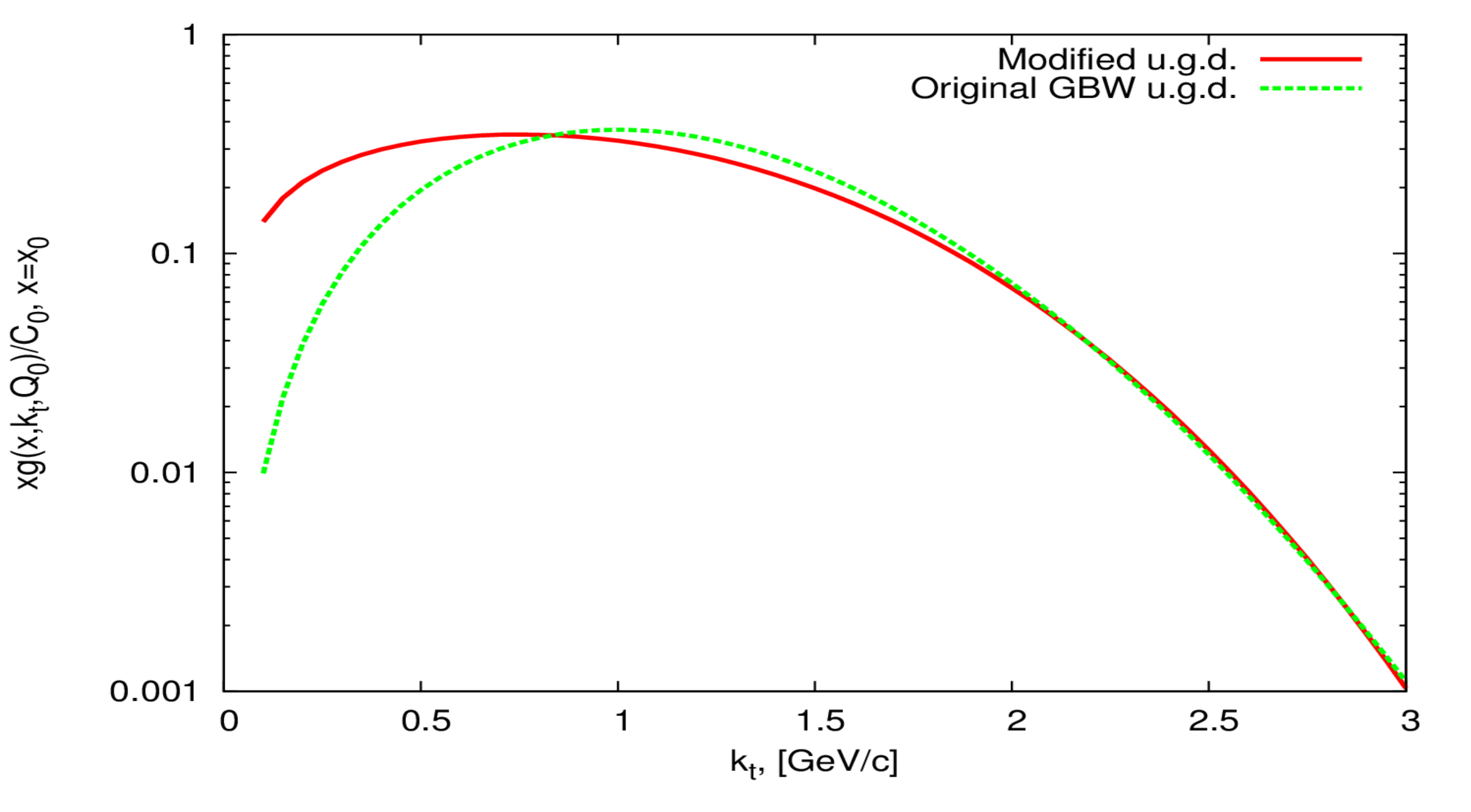
The coefficient C_3 is found from the relation

$$xg(x,Q_0^2)=\int_0^{Q_0^2} xg(x,k_t^2,Q_0^2)\,dk_t^2$$

A.Grinyuk, H.Jung, G.L., A.Lipatov, N.Zotov, hep-ph/1203.0939; Proc.MPI-11, DESY, Hamburg, 2012.

At $k_t -> 0$ our UGD goes to zero as k_t^a where $a<1$

It has been confirmed by B.I.Ermolaev, V.Greco, S.I.Troyan, Eur.Phys.J. C 72 (2012) 1253; hep-ph/1112.1854.



Green line is the GBW u.g.d. K. Golec-Biernat & M. Wuesthoff, Phys.Rev.D60, 114023 (1999).Red line is the modified u.g.d. A.Grinyuk, H.Jung, G.L., A.Lipatov, N.Zotov, hep-ph/1203.0939; Proc.MPI-11, DESY, Hamburg, 2012; A.A.Grinyuk, A.V.Lipatov, G.L., N.P.Zotov, Phys.Rev. D87, 074017 (2013); hep-ph/1301.45

CCFM evolution equation

$$f_g(x,k_T^2,\bar{q}^2) = f_g^0(x,k_T^2,Q_0^2)\Delta_s(\bar{q}^2,Q_0^2) + \int\frac{dz}{z}\int\frac{dq^2}{q^2}\times$$

$$\theta(\bar{q}-zq)\Delta_s(\bar{q}^2,q^2)P_{gq\bar{q}}(z,q^2,k_T^2)f_g\left(\frac{x}{z},k_T'^2,q^2\right)$$

Here $k_T' = q(1-z)/z + k_T$ and the Sudakov form factor $\Delta_s(q_1^2,q_2^2)$ describes the probability of no radiation between q_2 and q_1, $P_{gq\bar{q}}$ is the splitting function, f_g is the gluon density.

The first term means the contribution of non resolvable branchings between the starting scale Q_0 and the factorization scale $\bar{q}$.

A.V.Lipatov, G.L., N.P.Zotov, Phys.Rev. D89 (2014) 1, 014001

MODIFICATION OF U.G.D. AT LARGE k_T

We construct the new U.G.D. matching their form at low k_T (k_T <2-3 GeV/c) to the one, which is the exact solution of the BFKL outside of the saturation region obtained by Yuri V. Kovchegov (Phys.Rev.D61 (2000) 074018). The multiple Pomeron exchanges were included, the unitarization of the total deep inelastic scattering cross section and $F_2(x,Q^2)$ was satisfied.

$$xg_1(x,k_T,Q_0) = xg_0(x,k_T,Q_0) + F_M(x,k_T,Q_0)P_1(x,k_T)$$

Here xg_1 is the new U.G.D., xg_0 is our old U.G.D., $\boldsymbol{P_1}$ is the Kovchegov's solution at $k_T > 1.GeV/c$, F_M is the matching function of xg_0 to $\boldsymbol{P_1}$

Kovchegov's solution

(Yri V. Kovchegov, Phys.Rev.D61 (2000) 074018)

$$P_1\left(k_T, Y\right) = C_{-1} \frac{\Lambda}{k_T} \frac{\exp\left[\left(\alpha_P - 1\right)Y\right]}{\sqrt{14\alpha_s N_c \varsigma(3) Y}} \exp\left(-\frac{\pi}{14\alpha_s N_c \varsigma(3) Y} \ln^2 \frac{k_T}{\Lambda}\right)$$

α_P ***is the intercept of the subcritical Pomeron,*** $Y = \ln(1/x)$

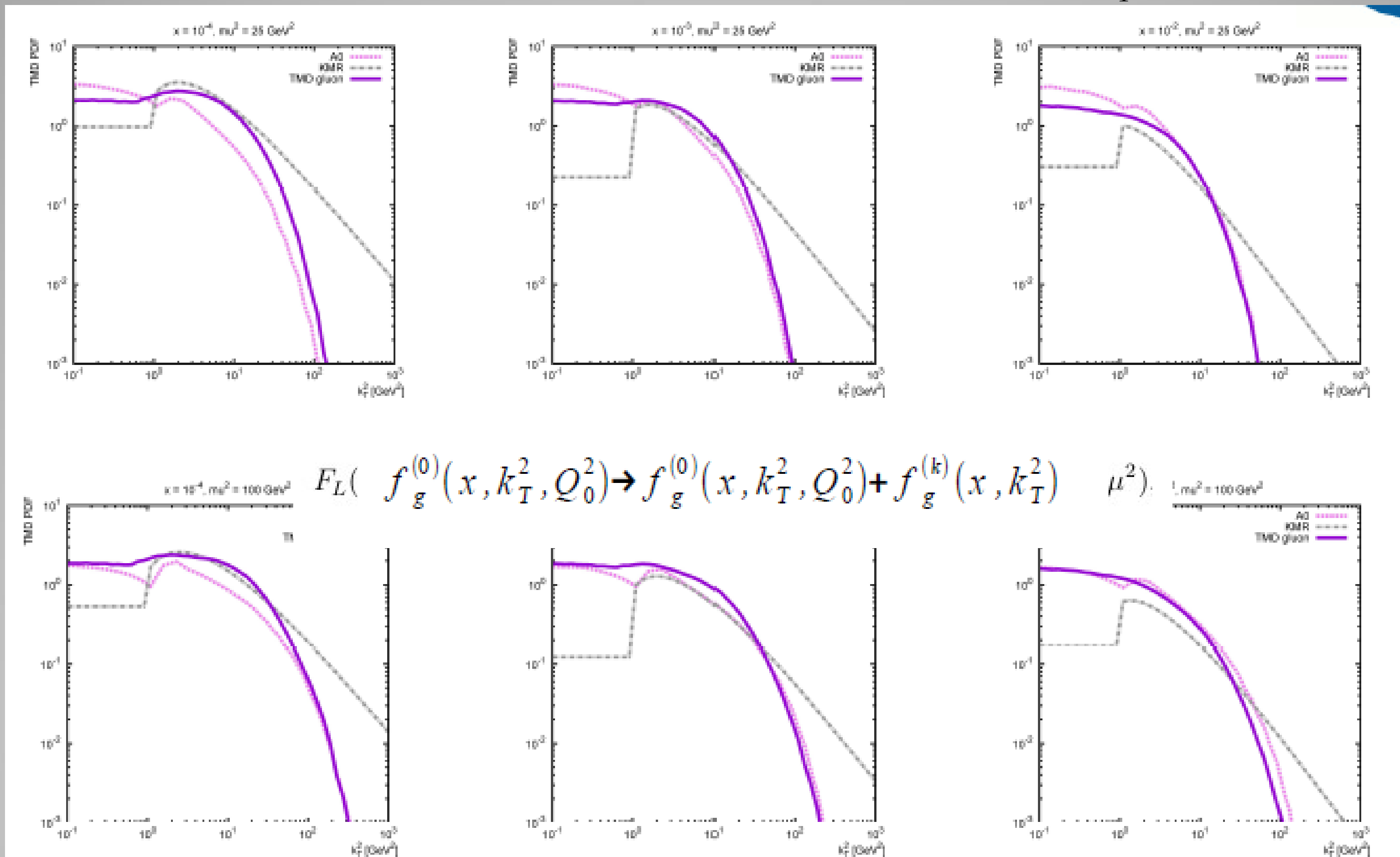
For the initial conditions, as the two gluon exchange approximation $C_{-1} \sim \alpha_s^2$

Our matching function

$$F_M\left(x, k_T, Q_0\right) = B\left(x/x_0\right)^d \exp\left(-aR_0/k_T\right)$$

where $R_0 = \left(x/x_0\right)^\lambda$ **,** B, d, a ***are parameters, which were found from matching of our old U.G.D. to the Kovchegov's solution***

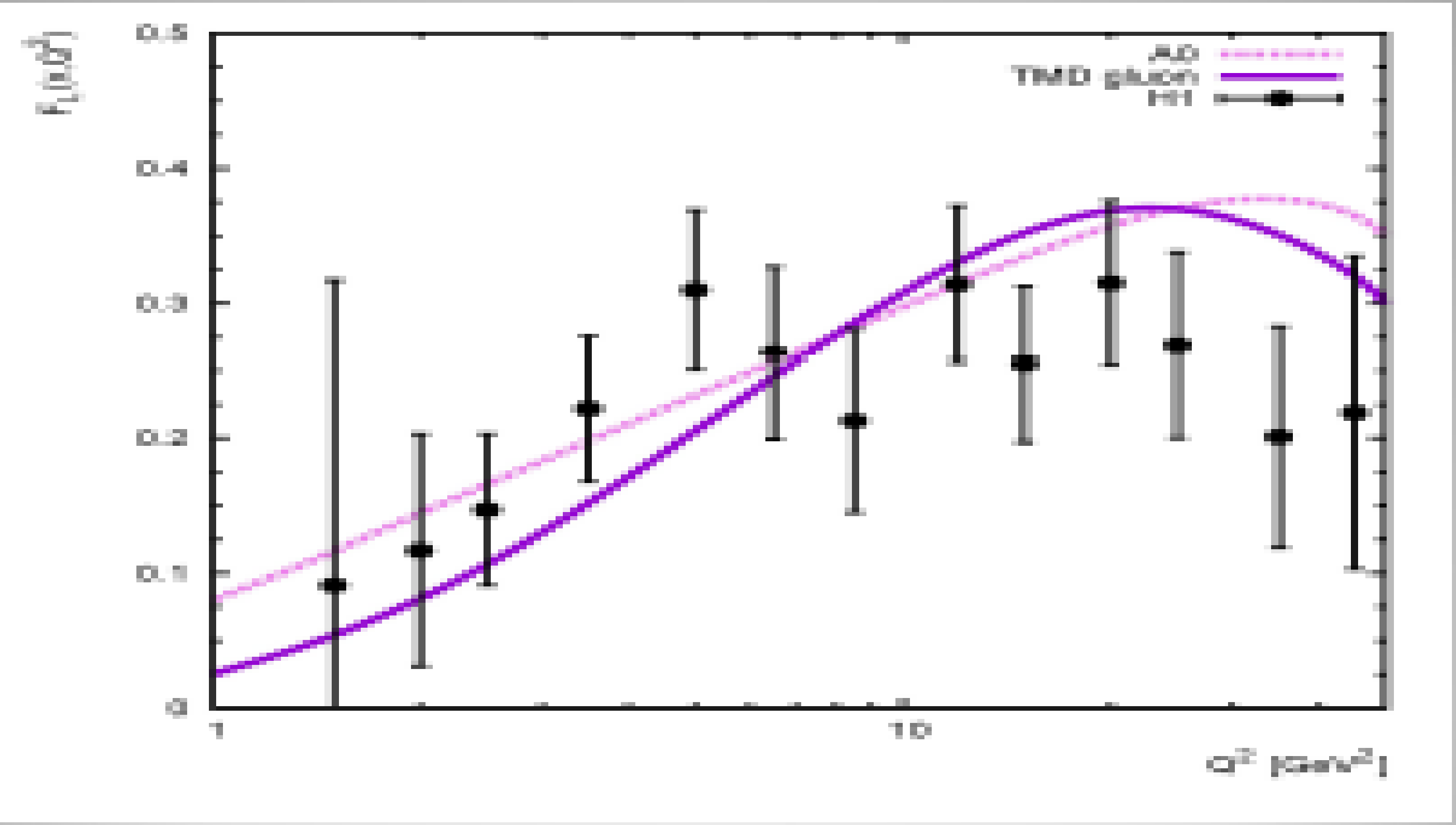
Gluon distribution as a function of k_T^2



$$F_L(\quad f_g^{(0)}(x,k_T^2,Q_0^2) \rightarrow f_g^{(0)}(x,k_T^2,Q_0^2) + f_g^{(k)}(x,k_T^2) \quad \mu^2).$$

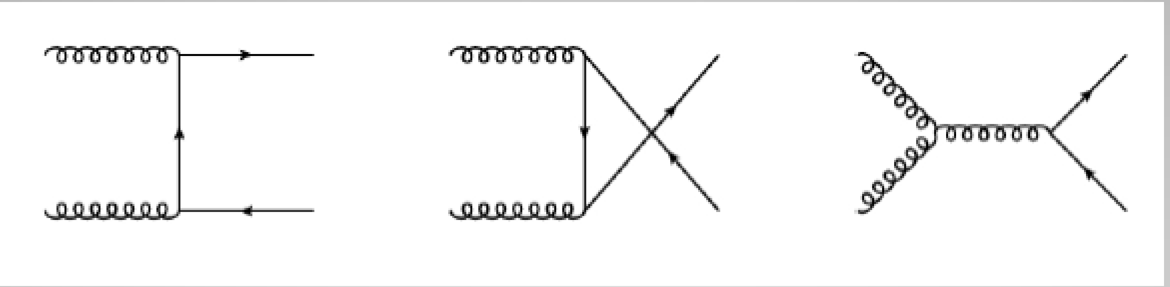
$$f_g^{(0)}(x,k_T^2,Q_0^2) \rightarrow f_g^{(0)}(x,k_T^2,Q_0^2) + f_g^{(k)}(x,k_T^2)$$

Longitudinal structure function



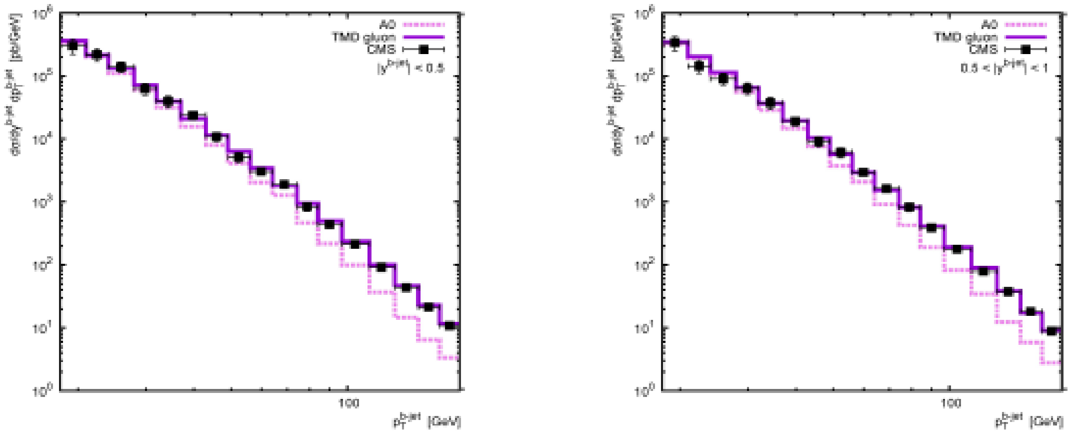
$$f_g^{(0)}(x,k_T^2,Q_0^2) \rightarrow f_g^{(0)}(x,k_T^2,Q_0^2) + f_g^{(k)}(x,k_T^2)$$

HEAVY FLAVOUR JET PRODUCTION



$$\sigma = \int \frac{|\bar{\mathcal{M}}|^2}{16\pi\,(x_1 x_2 s)^2} f_g(x_1, \mathbf{k}_{1T}^2, \mu^2) f_g(x_2, \mathbf{k}_{2T}^2, \mu^2) d\mathbf{p}_{1T}^2 d\mathbf{k}_{1T}^2 d\mathbf{k}_{2T}^2 dy_1 dy_2 \frac{d\phi_1}{2\pi}\frac{d\phi_2}{2\pi}$$

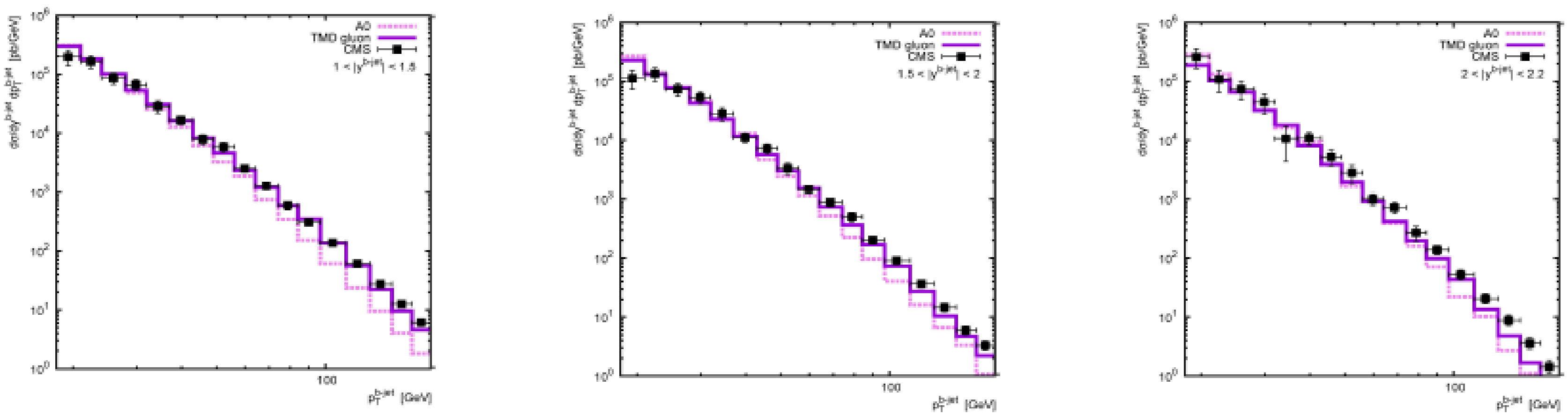
b-Jets production in p-p collision at $s^{1/2}$ =8 TeV



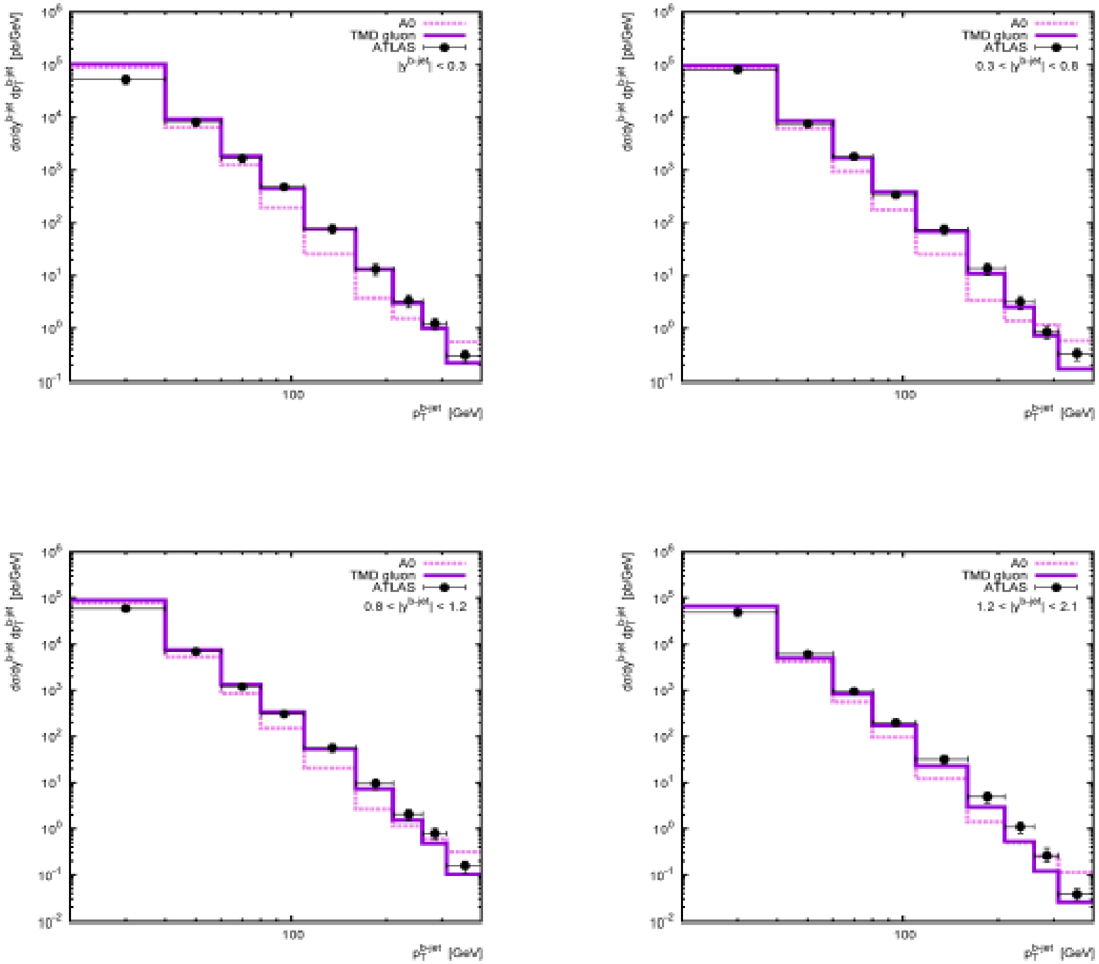
$|y^b|<2.2$

$18<p_T^b<196$ ГэВ

CMS Collaboration, JHEP 1204, 084 (2012)



b-Jets production in p-p collision at $s^{1/2}$ =8 TeV

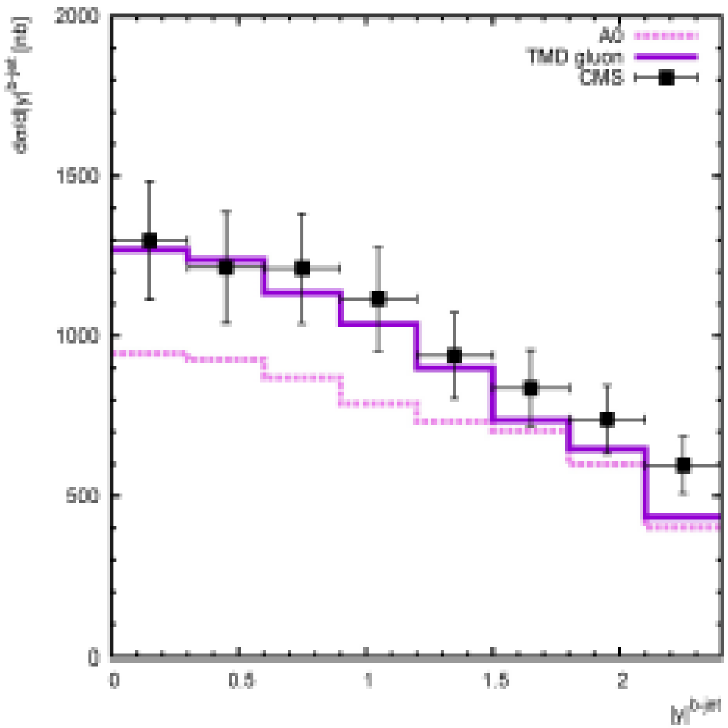


$|y^b| < 2.1$

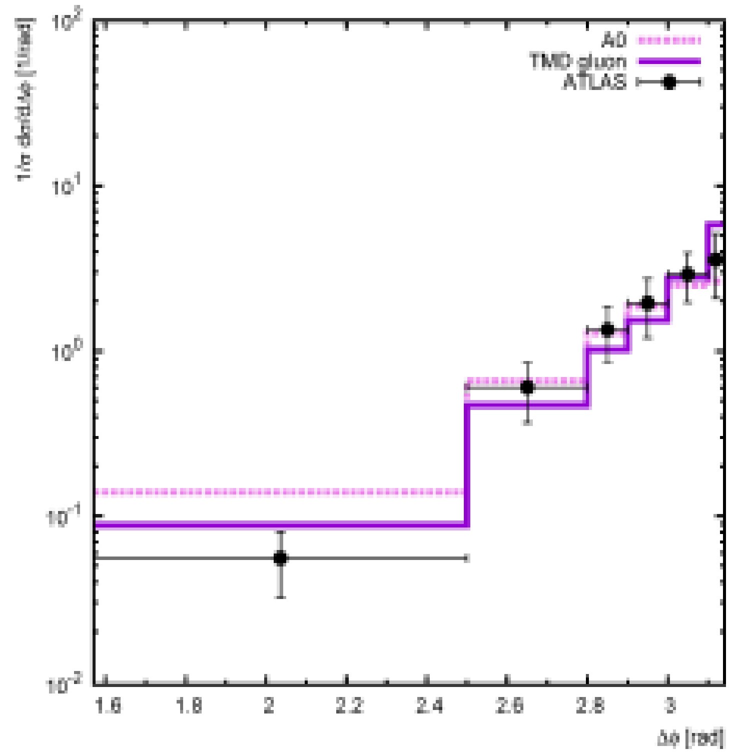
$20 < p_T^b < 400$ ГэВ

ATLAS Collaboration, EPJ C 71, 1846 (2011)

Rapidity didtribution of b-jet produced in pp at $s^{1/2}$ =8 TeV



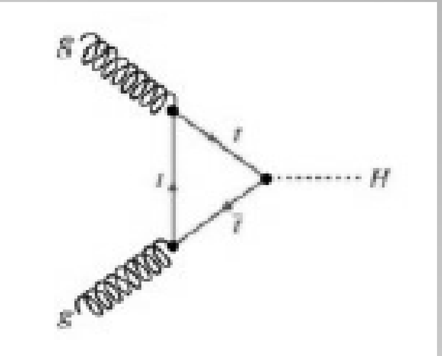
Δφ-Distribution between b and b jets in pp collisions



Higgs-boson production in pp at $s^{1/2}$ =8 TeV

$$\mathcal{L}_{ggH} = \frac{\alpha_s}{12\pi}\left(G_F\sqrt{2}\right)^{1/2} G^a_{\mu\nu}G^{a\,\mu\nu}H.$$

$$T^{\mu\nu,ab}_{ggH}(k_1,k_2) = i\delta^{ab}\frac{\alpha_s}{3\pi}\left(G_F\sqrt{2}\right)^{1/2}\left[k_2^\mu k_1^\nu - (k_1\cdot k_2)g^{\mu\nu}\right]$$



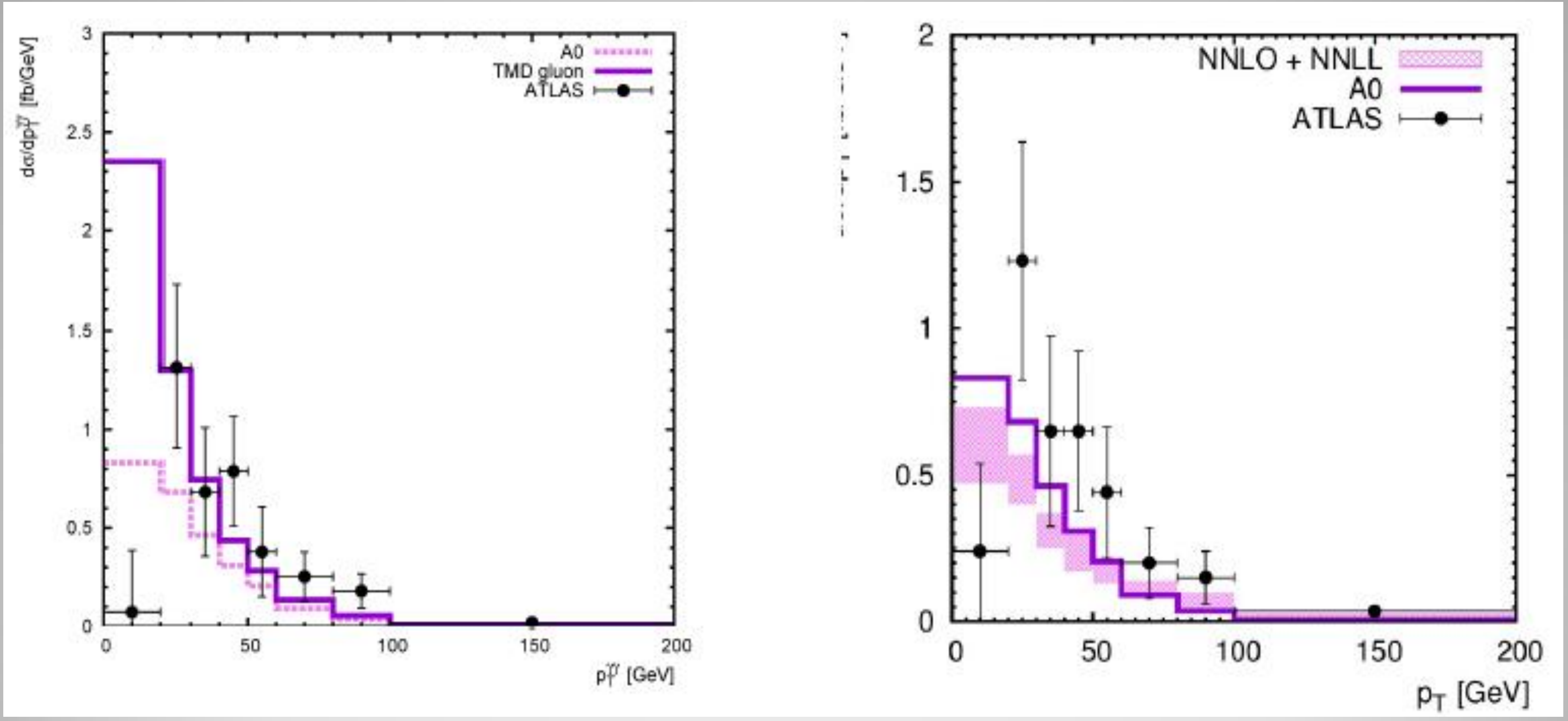
$$\mathcal{L}_{H\gamma\gamma} = \frac{\alpha}{8\pi}\mathcal{A}\left(G_F\sqrt{2}\right)^{1/2} F_{\mu\nu}F^{\mu\nu}H$$

$$\mathcal{A} = \mathcal{A}_W(\tau_W) + N_c\sum_f Q_f^2\mathcal{A}_f(\tau_f)$$

$$\tau_f = \frac{m_H^2}{4m_f^2}, \quad \tau_W = \frac{m_H^2}{4m_W^2}$$

J.R. Ellis, M.K. Gaillard, D.V. Nanopulos, NPB 106, 292 (1976)
M.A. Shifman, A.I. Vainstein, M.B. Voloshin, V.I. Zakharov, Sov. J. Nucl. Phys. 30, 711 (1979)

Higgs-boson production in pp at $s^{1/2}$ =8 TeV



SUMMARY

1.The TMD gluon density is proposed at initial $Q_0^2 = 1(GeV/c)^2$ and their parameters are verified by the description of the LHC data on the hadron spectra in the soft kinematical region.

2. The CCFM evolution equation was solved using the proposed TMD g.d. at starting Q_0^2.

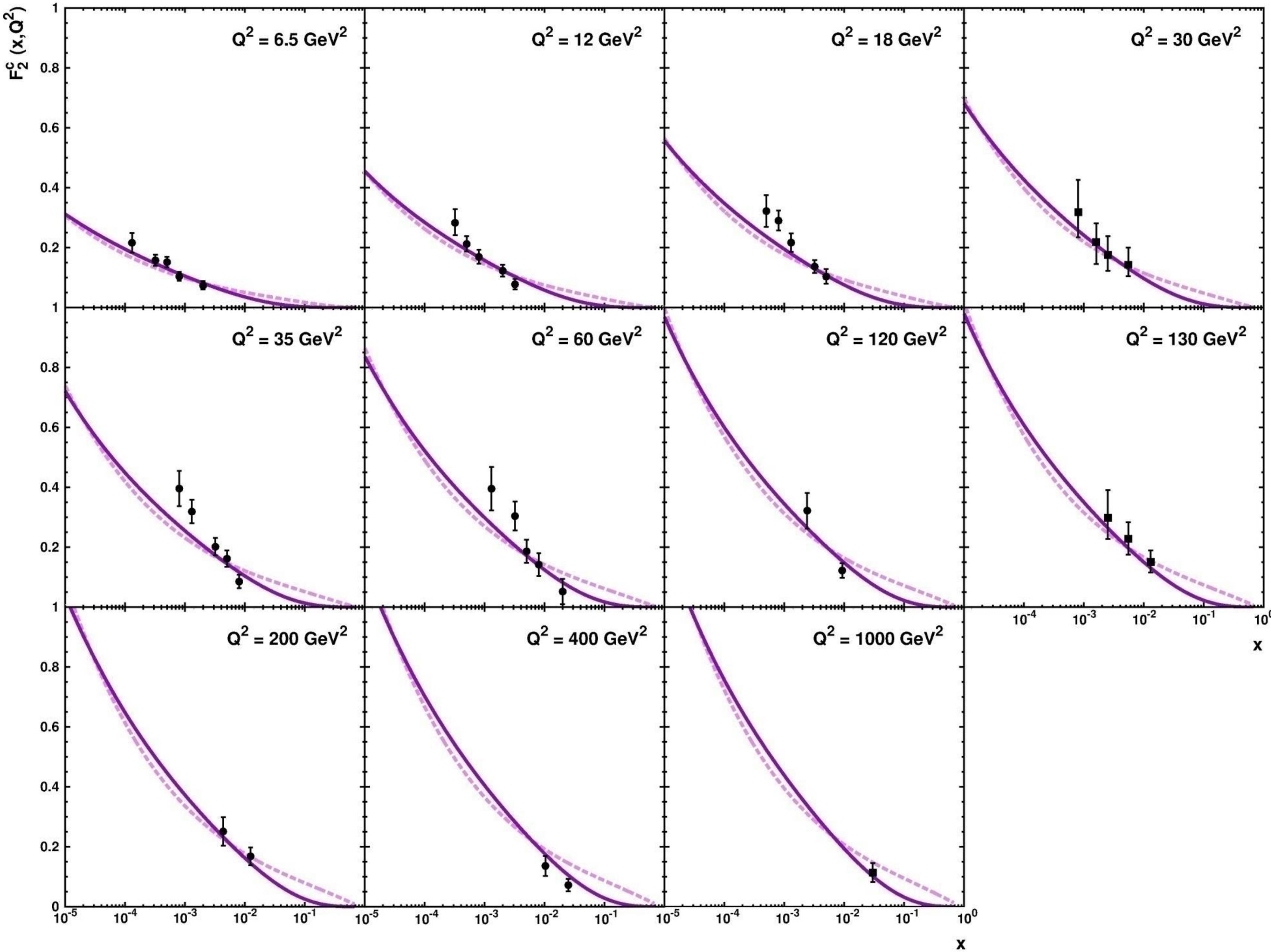
3. The CCFM-evolved u.g.d. results in a satisfactory description of the H1 and ZEUS data on the longitudinal structure function .

4. The modification of the u.g.d. at large k_T is suggested matching the exact solution of the BFKL obtained by Kovchegov at k_T > 1GeV/c and our u.g.d. at k_T < 1GeV/c.

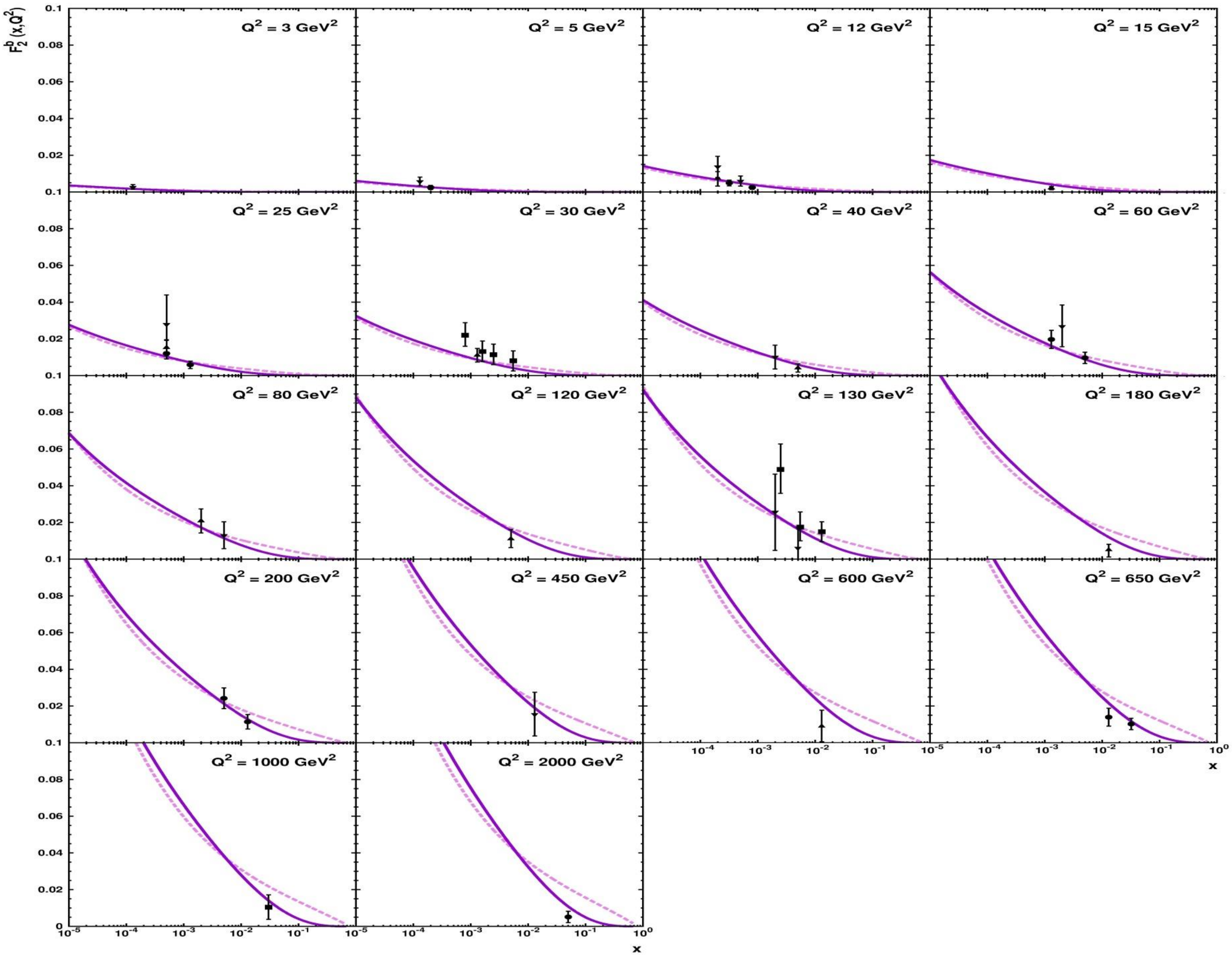
5. The CCFM-evolved new u.g.d. results in a satisfactory description of hard production of heavy flavour jets and Higgs bosons.

6.The application of the new u.g.d. to the analysis of these processes allows us to describe rather well the azimuthal correlations of two b-jets.

THANK YOU VERY MUCH FOR YOUR ATTENTION !

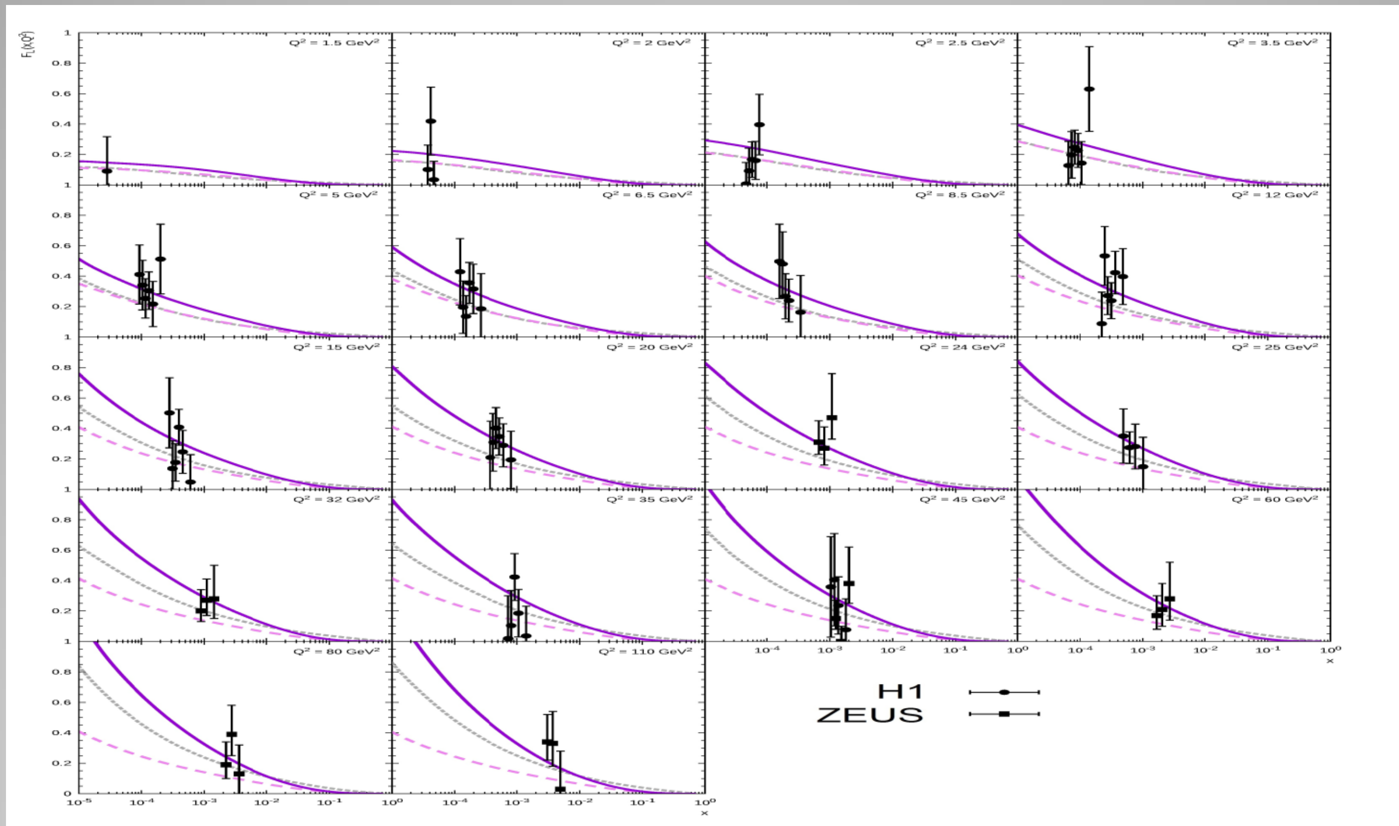


$F_2^c(x,Q^2)$
$Q^2 = 6.5\ GeV^2$
$Q^2 = 12\ GeV^2$
$Q^2 = 18\ GeV^2$
$Q^2 = 30\ GeV^2$
$Q^2 = 35\ GeV^2$
$Q^2 = 60\ GeV^2$
$Q^2 = 120\ GeV^2$
$Q^2 = 130\ GeV^2$
$Q^2 = 200\ GeV^2$
$Q^2 = 400\ GeV^2$
$Q^2 = 1000\ GeV^2$
x



$F_2^b(x,Q^2)$
$Q^2 = 3\ GeV^2$
$Q^2 = 5\ GeV^2$
$Q^2 = 12\ GeV^2$
$Q^2 = 15\ GeV^2$
$Q^2 = 25\ GeV^2$
$Q^2 = 30\ GeV^2$
$Q^2 = 40\ GeV^2$
$Q^2 = 60\ GeV^2$
$Q^2 = 80\ GeV^2$
$Q^2 = 120\ GeV^2$
$Q^2 = 130\ GeV^2$
$Q^2 = 180\ GeV^2$
$Q^2 = 200\ GeV^2$
$Q^2 = 450\ GeV^2$
$Q^2 = 600\ GeV^2$
$Q^2 = 650\ GeV^2$
$Q^2 = 1000\ GeV^2$
$Q^2 = 2000\ GeV^2$
x

Longitudinal structure function as a function of x



The solid lines correspond to the proposed CCFM – evolved TMD gluon density; the dashed curves mean the contribution from the our non evolved gluon density; the dottet lines correspond to the CCFM-evolved GBW g.d

A.V.Lipatov, G.L., N.P.Zotov, Phys.Rev. D89 (2014) 1, 014001

Kt-factorization

Photo-production cross section

$$\sigma = \int \frac{dz}{z} d^2 k_t \, \sigma_{part}\left(\frac{x}{z}, k_t^2\right) F\left(z, k_t^2\right)$$

Here $F\left(z, k_t^2\right)$ is the un-integrated parton density function,
$\sigma_{part}\left(x/z, k_t^2\right)$ is the partonic cross section.

Classification scheme:

$xF\left(x, k_t^2\right)$ is used by BFKL

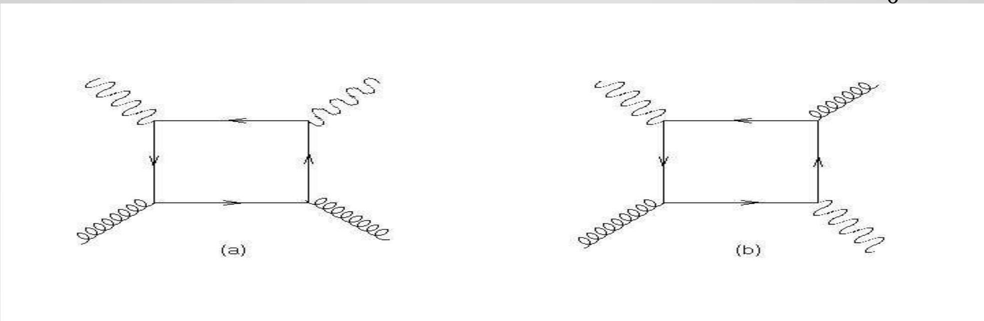
$xA\left(x, k_t^2, \bar{Q}^2\right)$ describes the CCFM type UGD with an additional factorization scale $\bar{Q}$ (such as $\alpha_s\left(\bar{Q}^2\right) \le 1$)

$xG\left(x, k_t^2\right)$ describes the DGLAP type UGD

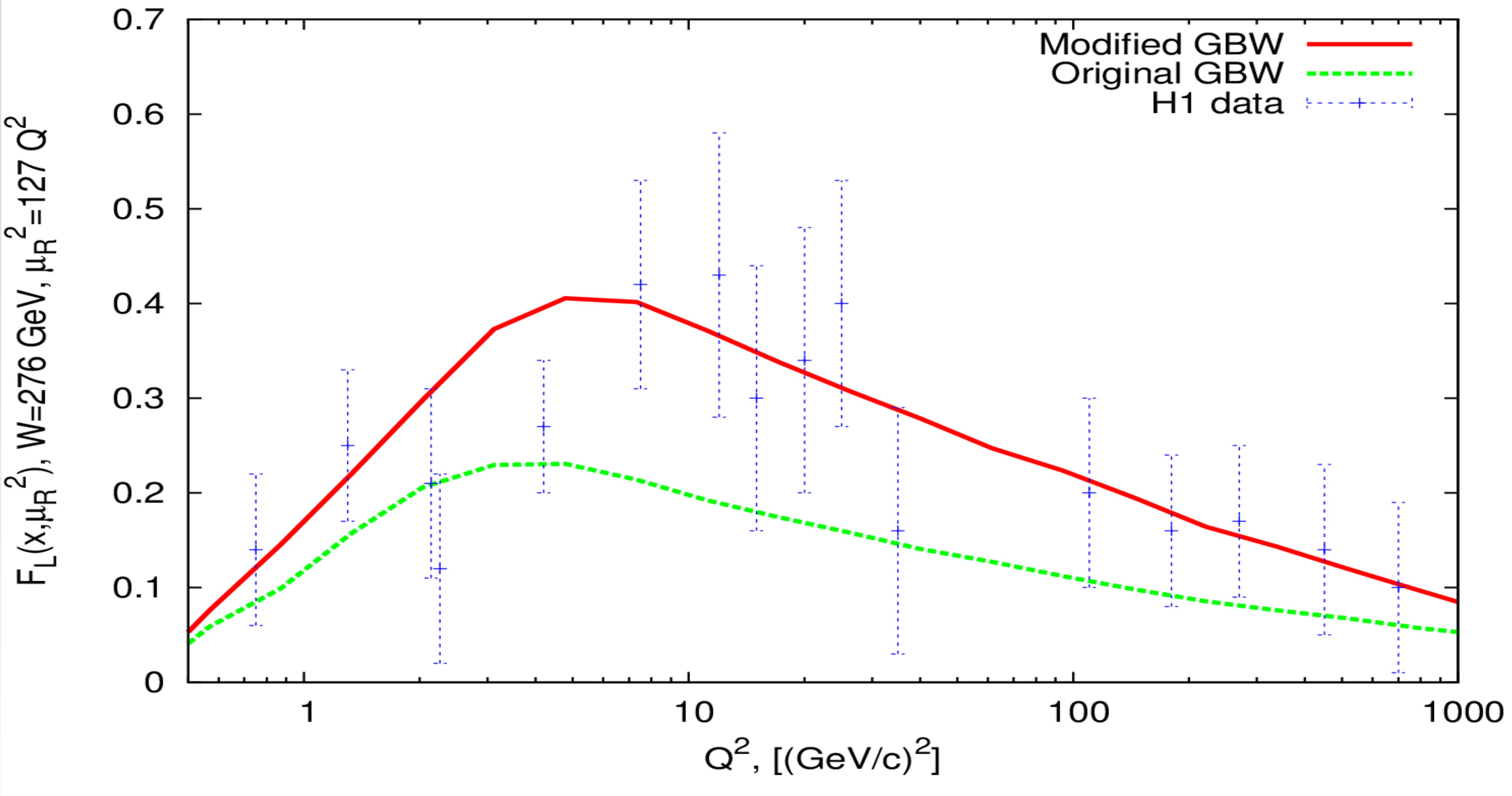
Longitudinal structure function within the kt-factorization

$$F_L(x,Q^2)=\int_x^1\frac{dz}{z}\int_0^{Q^2}dk_t^2\sum_{i=u,d,s}e_i^2C_L^g\left(\frac{x}{z},Q^2,m_i^2,k_t^2\right)\phi_g(z,k_t^2),$$

$$\phi_g(x,k_t^2)=xg(x,k_t^2),\quad xg(x,Q^2)=xg(x,Q_0^2)+\int_{Q_0^2}^{Q^2}dk_t^2\phi_g(x,k_t^2)$$

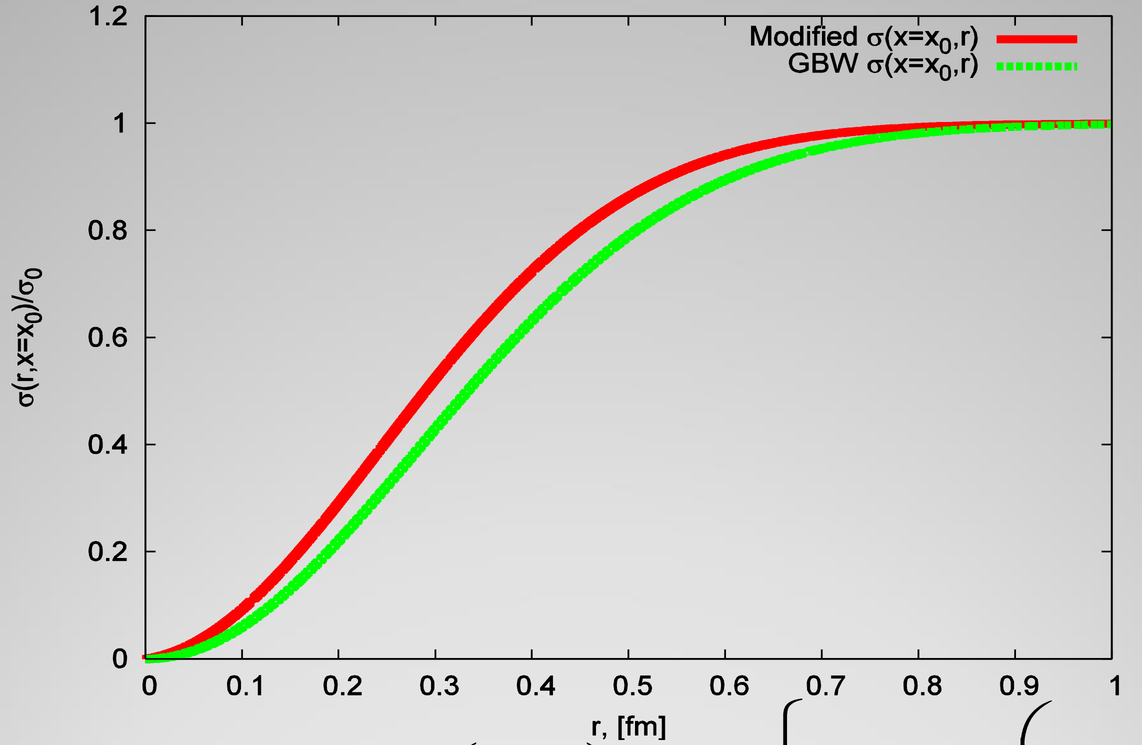


A.V. Kotikov, A.V. Lipatov, N.P. Zotov, Eur.Phys.J., C27 92003)219.
H. Jung, A.V. Kotikov, A.V. Lipatov, N.P. Zotov, DIS 2007, hep-ph/07063793.



F_L as a function of Q^2 at W=276 GeV and $\mu_R^2 = 127\,Q^2$

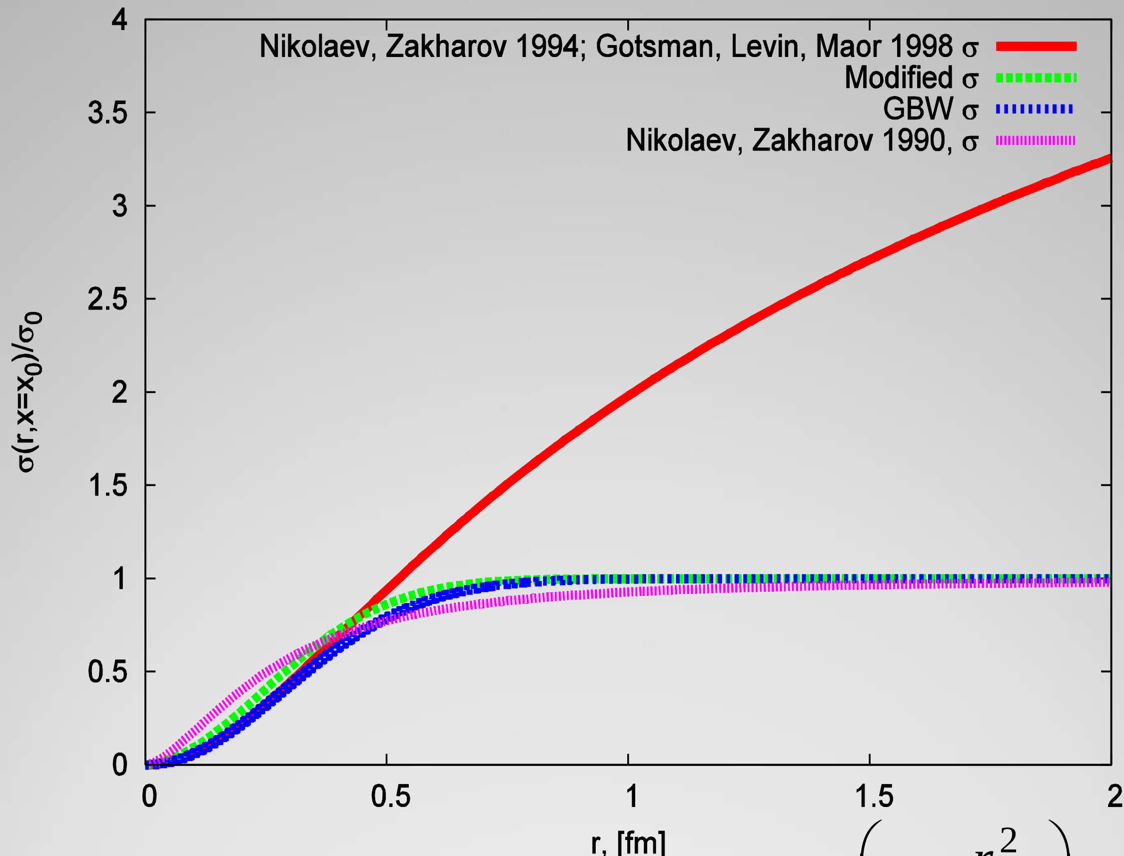
Effective dipole cross section



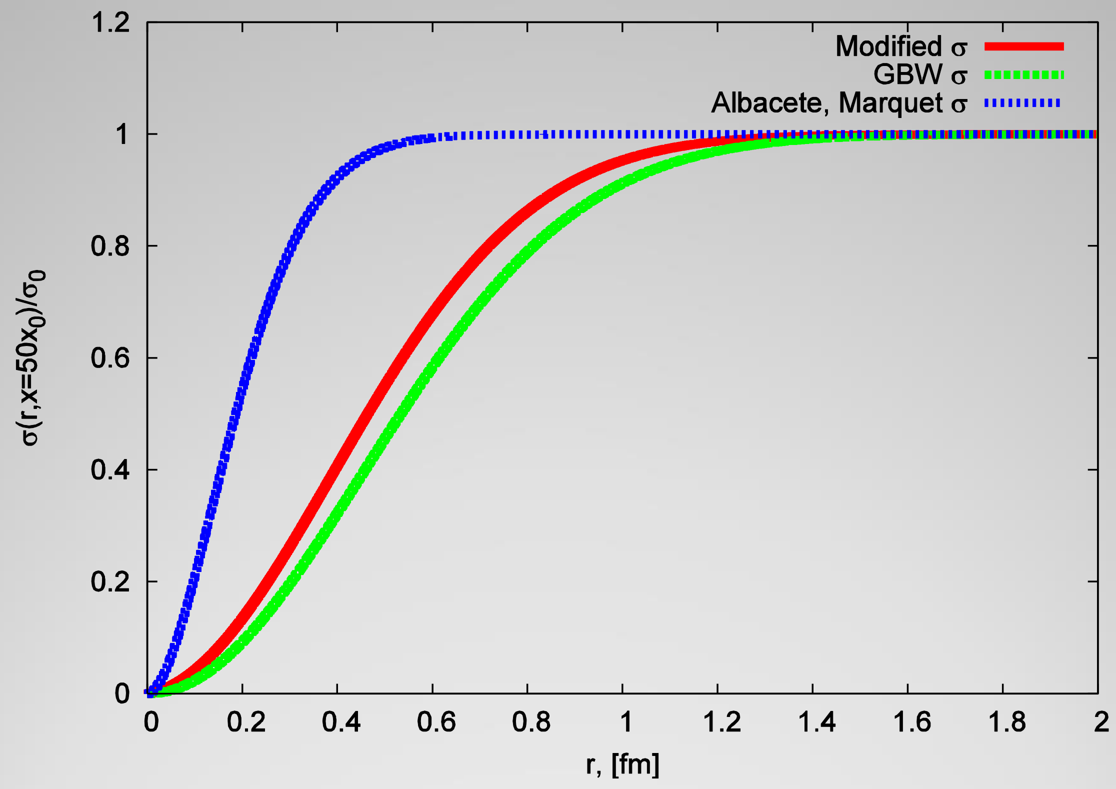
Green line: $\sigma_{dipole}^{GBW}(x,r) = \sigma_0 \left\{ 1 - \exp\left(-\frac{r^2}{4R_0^2(x)} \right) \right\}$

Red line: $\sigma_{dipole}^{GBW}(x,r) = \sigma_0 \left\{ 1 - \exp\left(-\frac{a_1 r}{R_0(x)} - \frac{a_2 r^2}{R_0^2(x)} \right) \right\}$

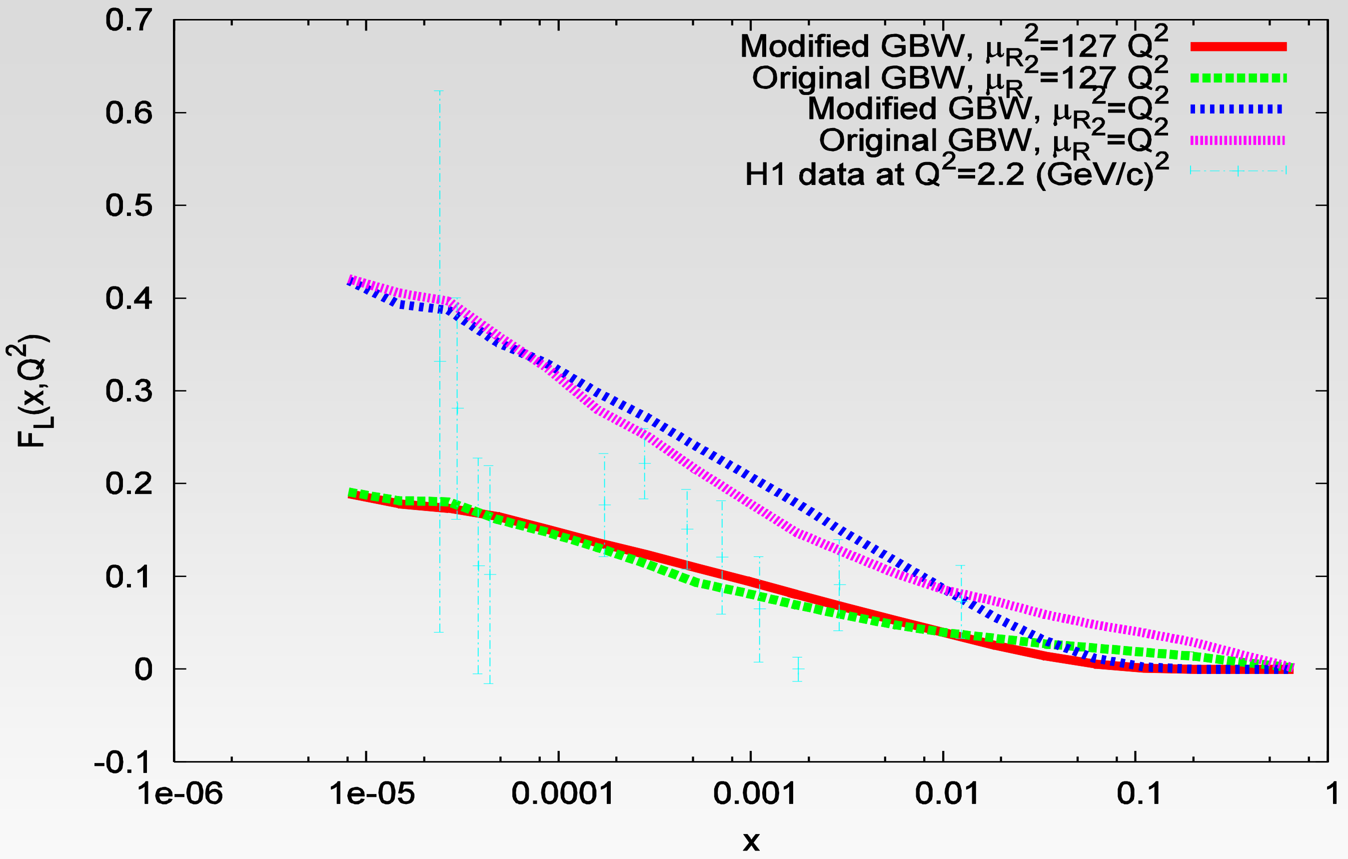
Effective dipole cross section



Red line corresponds to $\sigma_{dipole} = \sigma_0 \ln\left(1 + \frac{r^2}{4R_0^2}\right)$

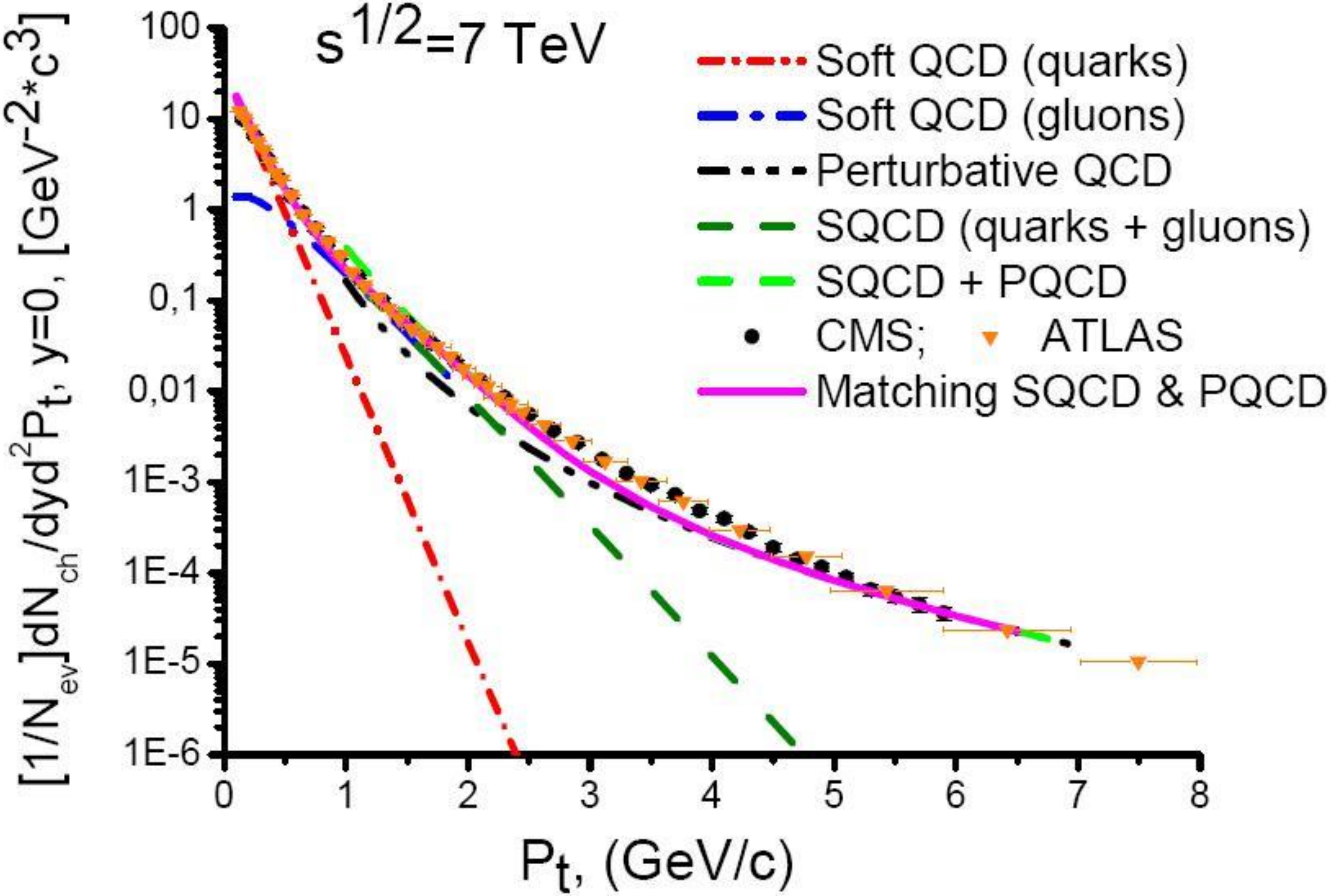


Modified σ
GBW σ
Albacete, Marquet σ
σ(r,x=50x0)/σ0
r, [fm]
1.2
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2



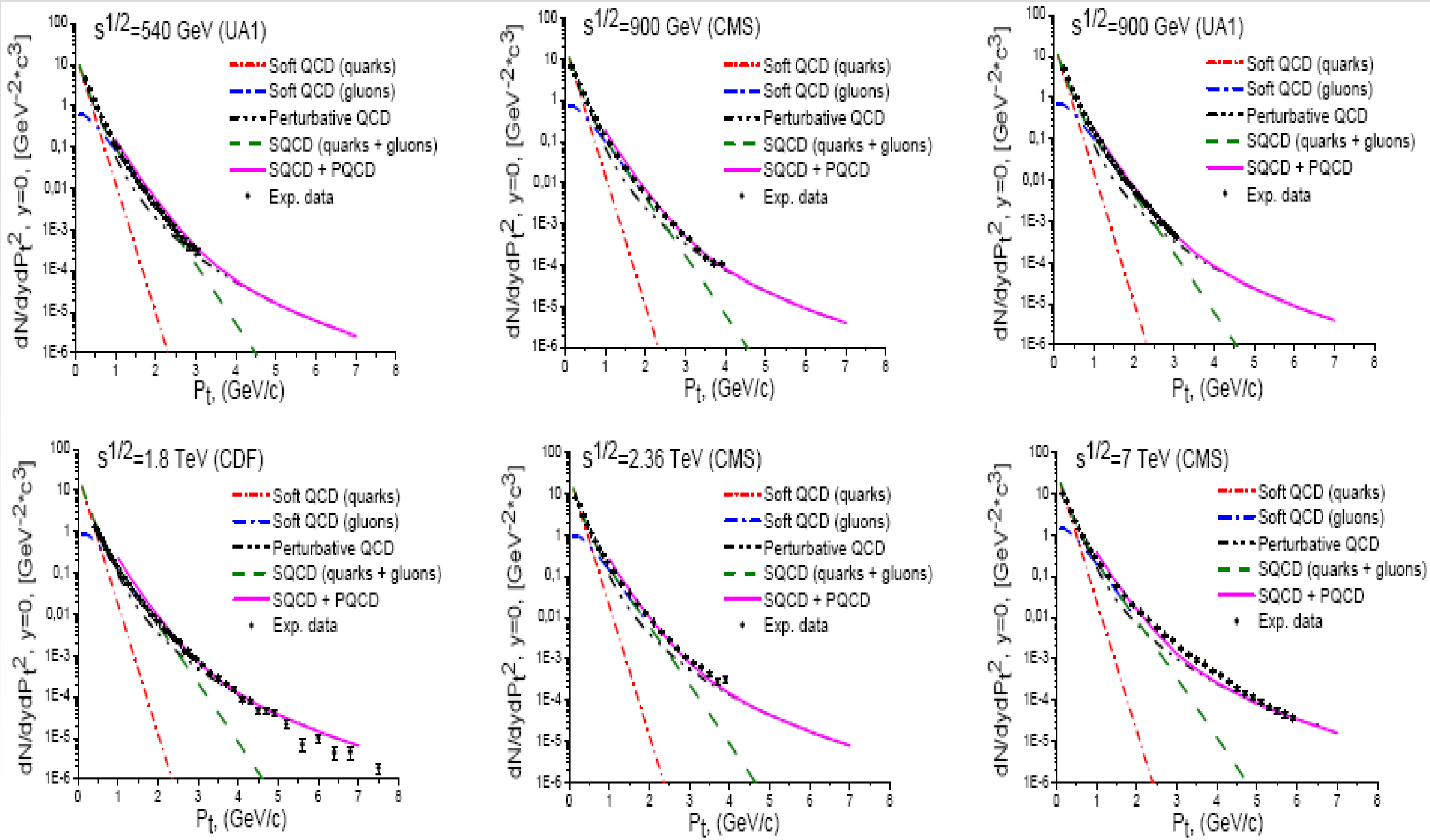
The x-dependence of F_L at $Q^2 = 2.2 (GeV/c)^2$ assuming

$\mu_R^2 = KQ^2$ and $\mu_R^2 = Q^2$, where $K = 127$



$s^{1/2}$=7 TeV
Soft QCD (quarks)
Soft QCD (gluons)
Perturbative QCD
SQCD (quarks + gluons)
SQCD + PQCD
CMS; ATLAS
Matching SQCD & PQCD
[1/N_ev]dN_ch/dyd²P_t, y=0, [GeV⁻²*c³]
100
10
1
0,1
0,01
1E-3
1E-4
1E-5
1E-6
0
1
2
3
4
5
6
7
8
P_t, (GeV/c)

2012


s^1/2=540 GeV (UA1)
Soft QCD (quarks)
Soft QCD (gluons)
Perturbative QCD
SQCD (quarks + gluons)
SQCD + PQCD
Exp. data
dN/dydPt^2, y=0, [GeV^-2*c^3]
Pt, (GeV/c)
s^1/2=900 GeV (CMS)
Soft QCD (quarks)
Soft QCD (gluons)
Perturbative QCD
SQCD (quarks + gluons)
SQCD + PQCD
Exp. data
dN/dydPt^2, y=0, [GeV^-2*c^3]
Pt, (GeV/c)
s^1/2=900 GeV (UA1)
Soft QCD (quarks)
Soft QCD (gluons)
Perturbative QCD
SQCD (quarks + gluons)
SQCD + PQCD
Exp. data
dN/dydPt^2, y=0, [GeV^-2*c^3]
Pt, (GeV/c)
s^1/2=1.8 TeV (CDF)
Soft QCD (quarks)
Soft QCD (gluons)
Perturbative QCD
SQCD (quarks + gluons)
SQCD + PQCD
Exp. data
dN/dydPt^2, y=0, [GeV^-2*c^3]
Pt, (GeV/c)
s^1/2=2.36 TeV (CMS)
Soft QCD (quarks)
Soft QCD (gluons)
Perturbative QCD
SQCD (quarks + gluons)
SQCD + PQCD
Exp. data
dN/dydPt^2, y=0, [GeV^-2*c^3]
Pt, (GeV/c)
s^1/2=7 TeV (CMS)
Soft QCD (quarks)
Soft QCD (gluons)
Perturbative QCD
SQCD (quarks + gluons)
SQCD + PQCD
Exp. data
dN/dydPt^2, y=0, [GeV^-2*c^3]
Pt, (GeV/c)

2012

Inclusive hadron production in central region and the AGK cancellation

According to the AGK, the n-Pomeron contributions to the inclusive hadron spectrum at y=0 are cancelled and only the one-Pomeron contributes. This was proved asymptotically, i.e., at very high energies.

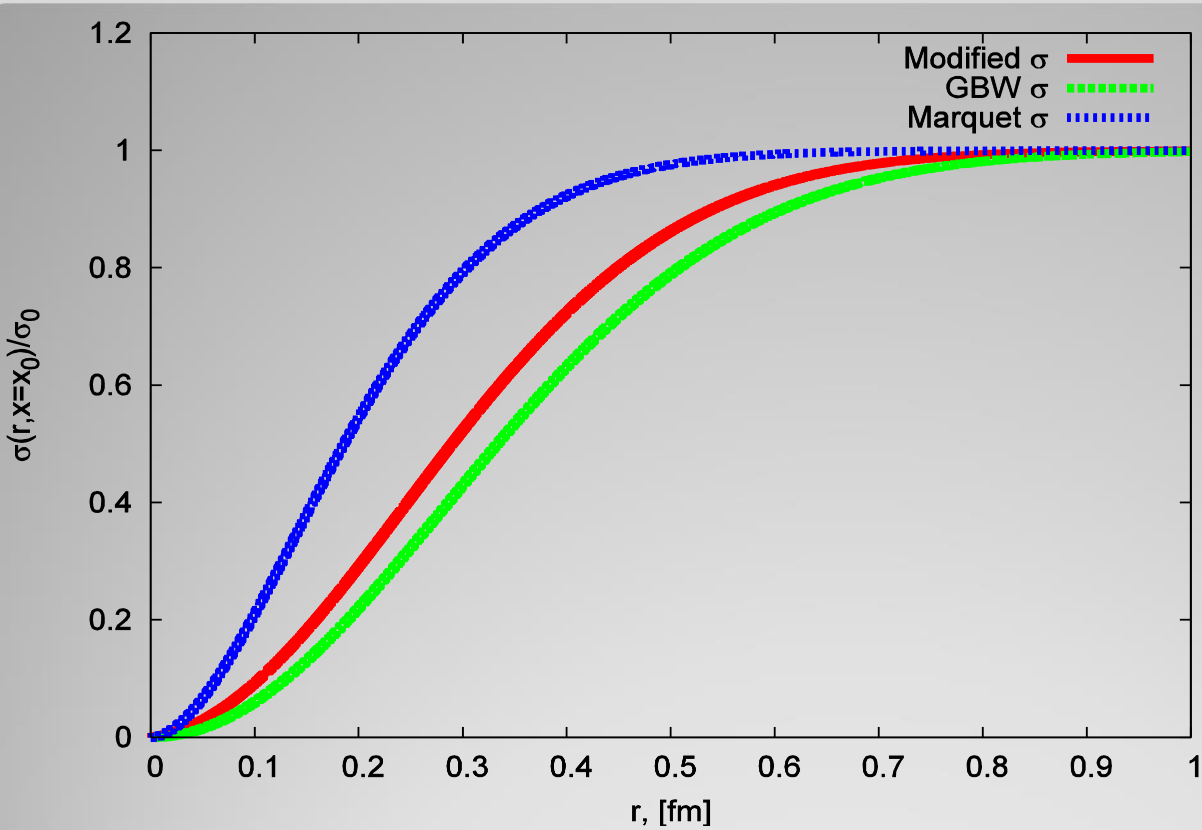
Using this AGK we estimate the inclusive spectrum of the charged hadrons produced in p-p at y=0 as a function of the transverse momentum including the quark and gluon components in the proton.

$$\rho_q(x=0,p_t) = \phi_q(0,p_t)\sum_{n=1}^{\infty} n\sigma_n(s) = gs^{\Delta}\phi_q(0,p_t)$$

$$\rho_g(x=0,p_t) = \varphi_g(0,p_t)\sum_{n=2}(n-1)\sigma_n(s) =$$

$$\varphi_g(0,p_t)(gs^{\Delta}-\sigma_{nd})$$

2012



Javier L. Albacete, Cyrille Marquet, arXiv:1001.137 [hep-ph]

Blue line corresponds to

$$\sigma_{dipole}^{AM} = \sigma_0 \left\{ 1 - \exp\left[-\frac{r^2}{4R_0^2} \ln\left(\frac{1}{\Lambda r} + e \right) \right] \right\}; \Lambda = 0.24 GeV = 1.2\, fm^{-1}; R_0 = 1 GeV^{-1} = 0.2\, fm$$

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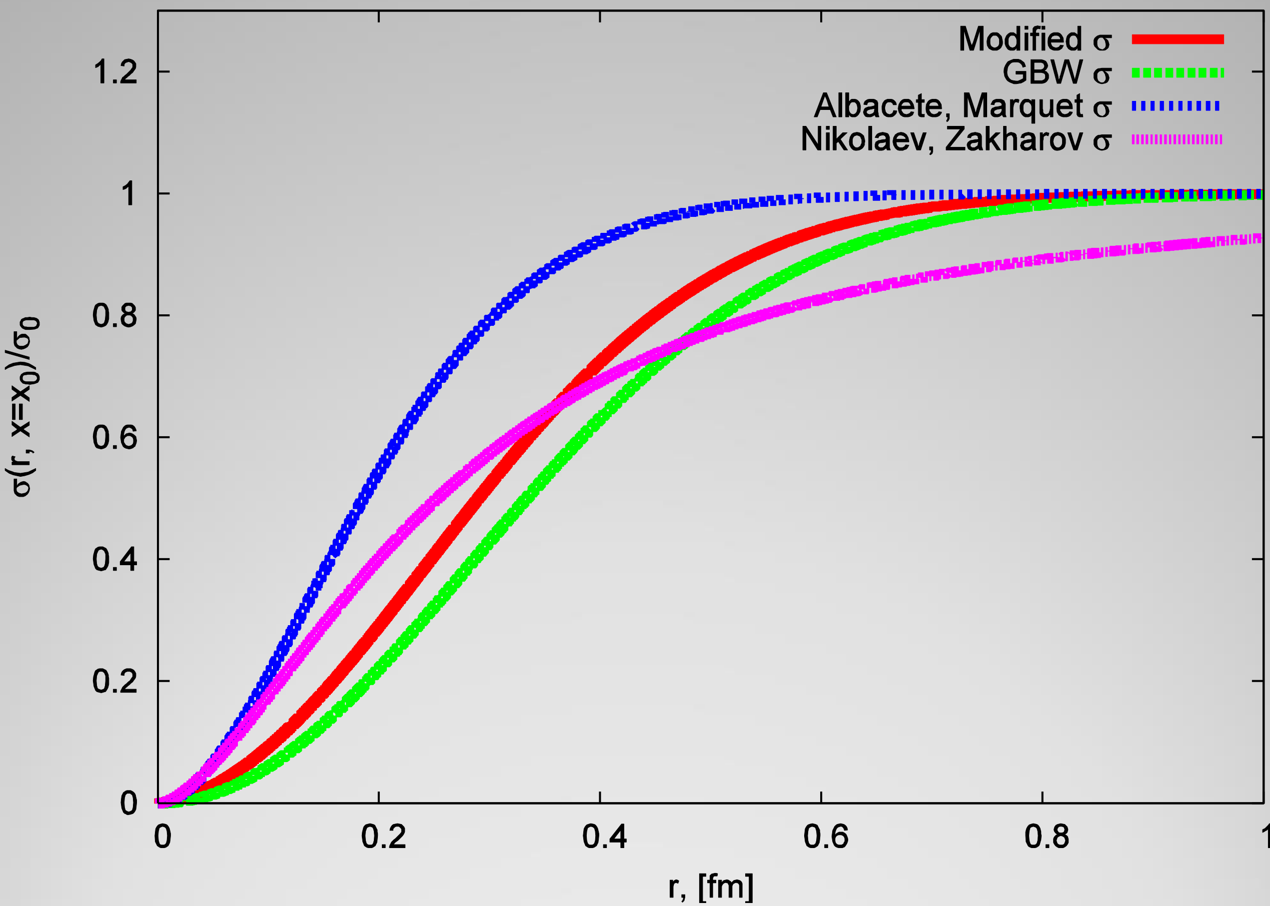
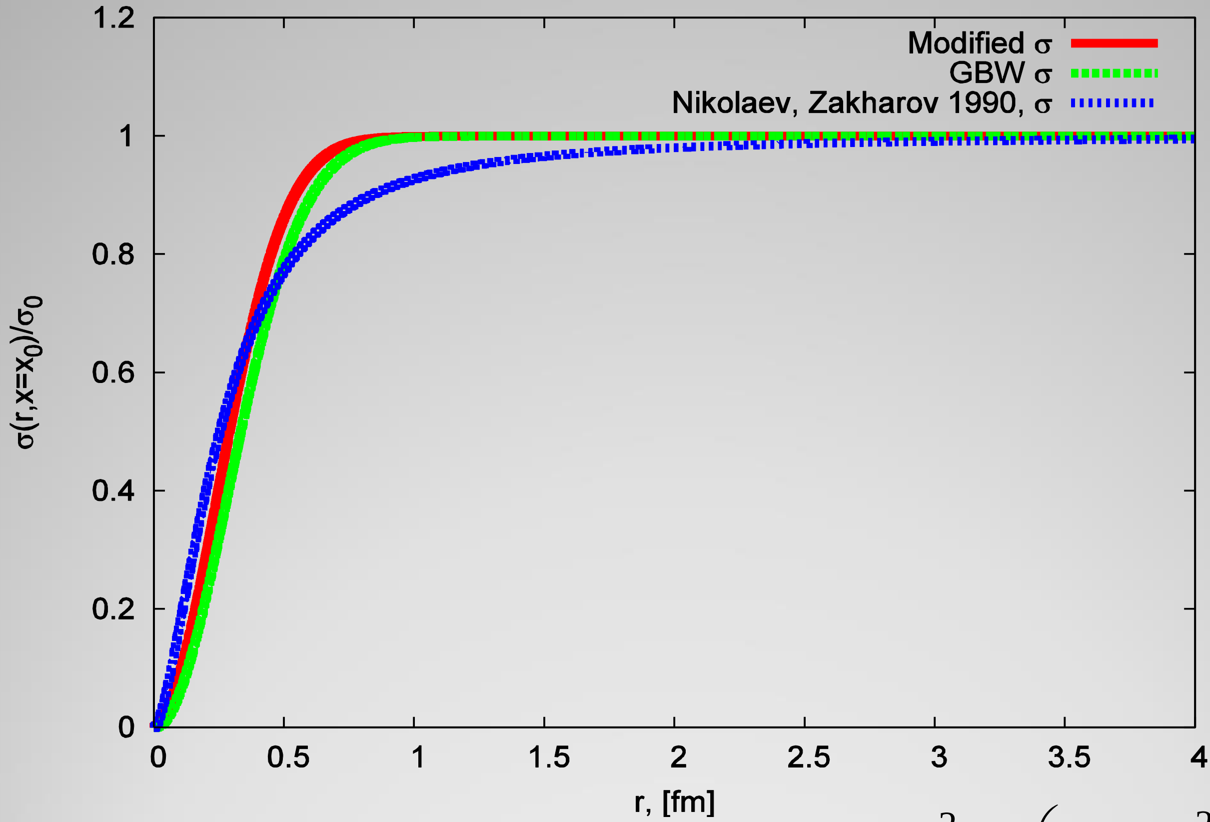
$$\varphi_g(0,p_t)(gs^{\Delta}-\sigma_{nd})$$

2012


Modified σ
GBW σ
Albacete, Marquet σ
Nikolaev, Zakharov σ
1.2
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
σ(r, x=x0)/σ0
r, [fm]

Effective dipole cross section

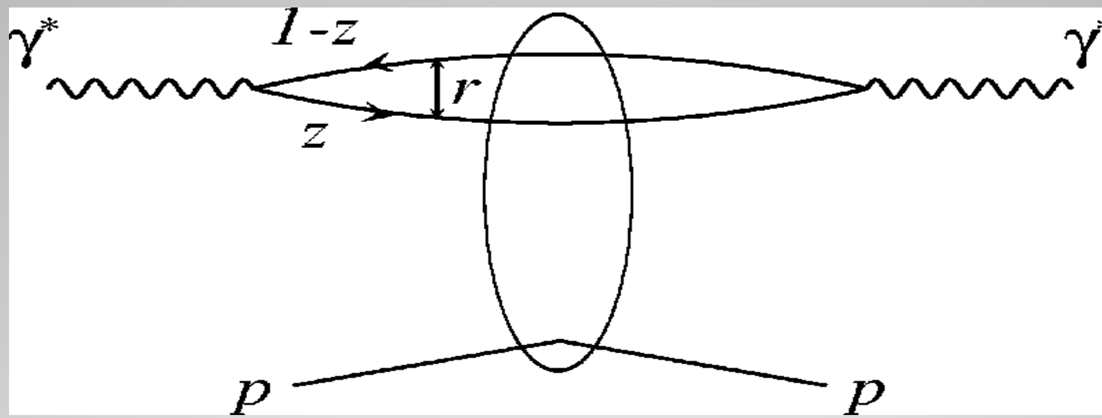


N.Nikolaev, B.Zakharov, Z.Phys.C49, 607 (1990)

Blue line corresponds to $\sigma_{dipole} = \sigma_0 \frac{r^2}{4R_0^2} \ln\left(1 + \frac{4R_0^2}{r^2}\right)$

K. Golec-Biernat, M Wuesthoff , Phys.Rev. D60, 114023 (1999); D59, 014017 (1998)

Saturation dynamics



$$\sigma^{GBW}_{dipole}(x,r) = \sigma_0 \left\{ 1 - \exp\left(-\frac{r^2}{4R_0^2} \right) \right\}$$

$R_0 = GeV^{-1}(x/x_0)^{\lambda/2}$ at $x < x_0$ we have $\sigma_{dipole} \approx \sigma_0$

Saturation becomes when $r \sim 2R_0$. It leads to $\sigma_T \sim \sigma_0$ when $QR_0 < 1$ or $Q < 1/R_0$

Effective dipole cross section and unintegrated gluon distribution

$$\sigma_{dipole}(x,r) = \frac{4\pi}{3}\int \frac{dk_t^2}{k_t^2}\left[1 - J_0(k_t, r)\right]\alpha_s xg(x, k_t)$$

Here α_s is the QCD running constant, J_0 is the Bessel function of the zero order.

Structure of an event

- Multiple parton-parton interactions