# SIGNIFICANCE OF NON-PERTURBATIVE INPUT TO TMD GLUON DENSITY IN HARD PROCESSES AT LHC


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*DESY, March 26, 2015*

# *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**

***DESY, March 26, 2015***

# SOFT PP -> h X

The inclusive spectrum is presented in the following form:

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

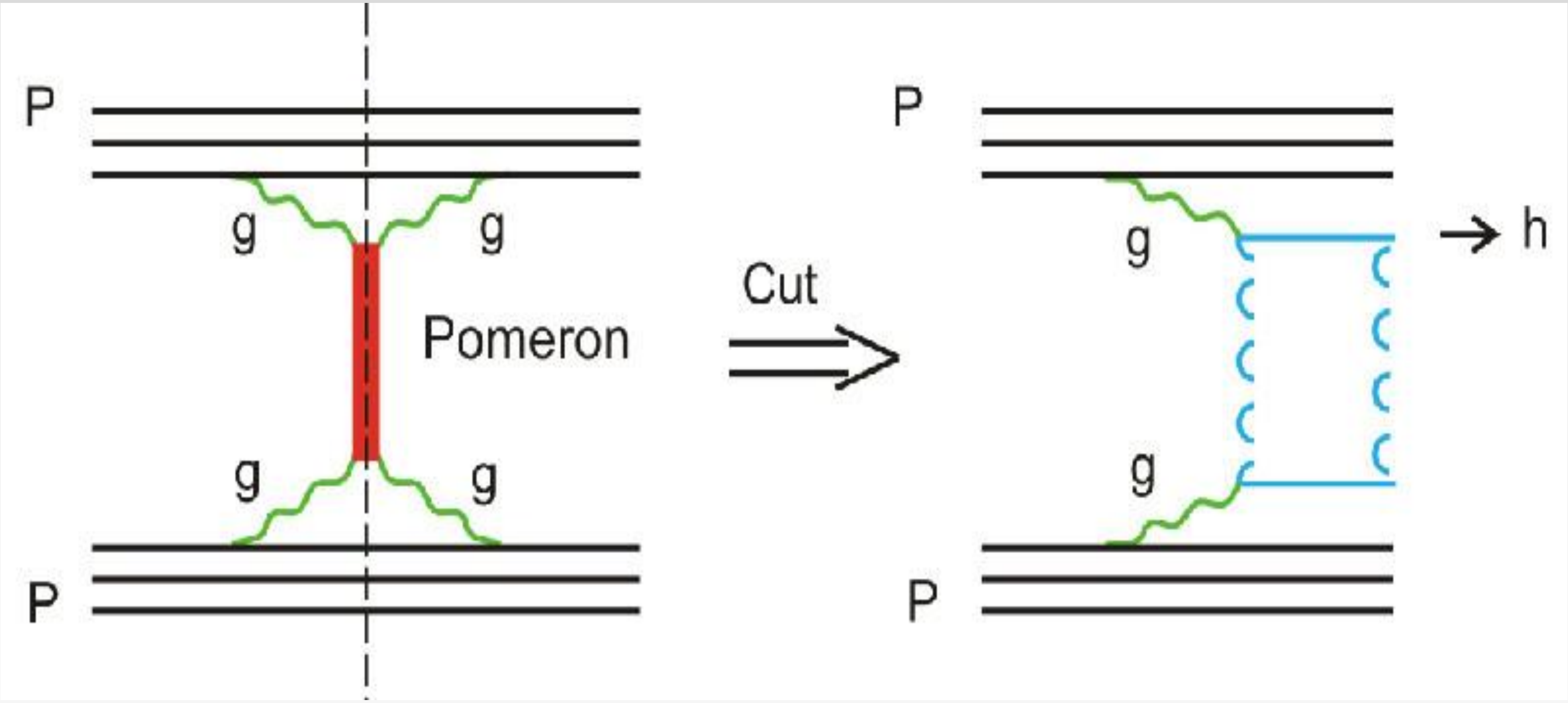
Here $\rho_q = g\left(\frac{s}{s_0}\right)^{\Delta}\varphi_q;\varphi_q(0,p_t)=A_q\exp(-b_q p_t)$

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

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

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

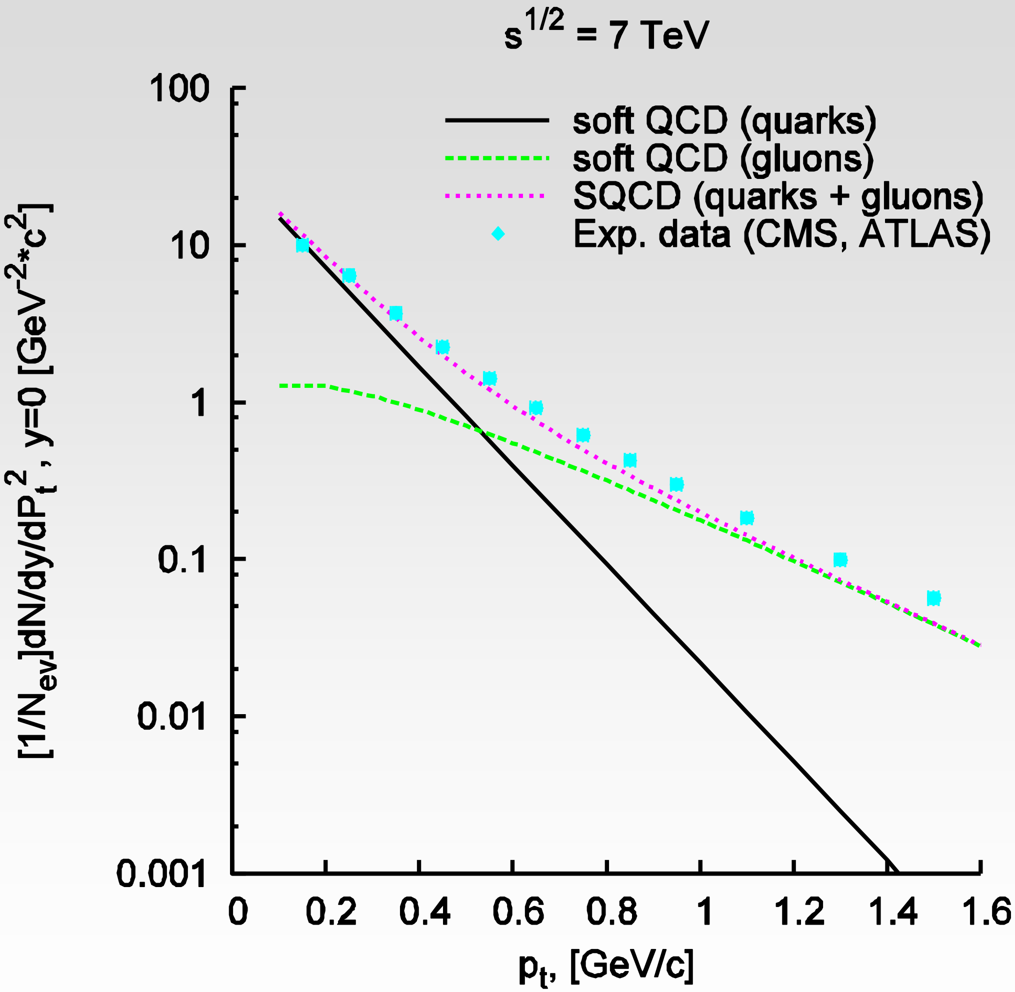
V.A. Bednyakov, A.V. Grinyuk, G.L., M. Poghosyan, Int. J.Mod.Phys. A 27 (2012) 1250012. hep-ph/11040532 (2011); hep-ph/1109.1469 (2011); Nucl.Phys. B 219 (2011) 225.




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.



s1/2 = 7 TeV
soft QCD (quarks)
soft QCD (gluons)
SQCD (quarks + gluons)
Exp. data (CMS, ATLAS)
[1/Nev]dN/dy/dPt2 , y=0 [GeV-2*c2]
pt, [GeV/c]
100
10
1
0.1
0.01
0.001
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6

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

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 $Q_0$

$$xg(x,k_t,Q_0)=C_0C_3(1-x)^{b_g}\left(R_0^2(x)k_t^2+C_2\left(R_0(x)k_t\right)^a\right)$$
$$\exp\left(-R_0(x)k_t-d\left(R_0(x)k_t\right)^3\right),$$

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

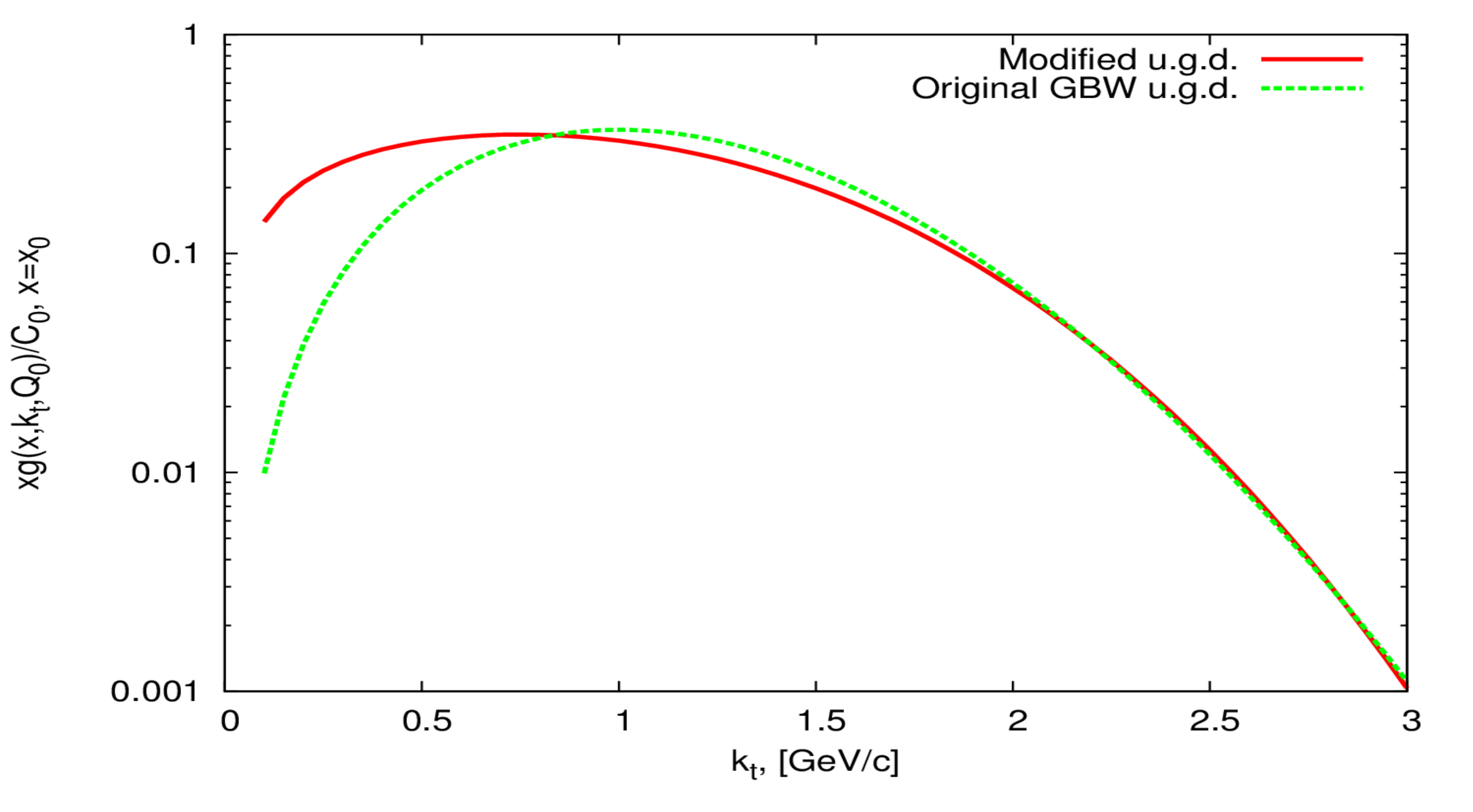
**The coefficient $C_3$ is found from the relation**

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

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)..***

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

***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)**

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

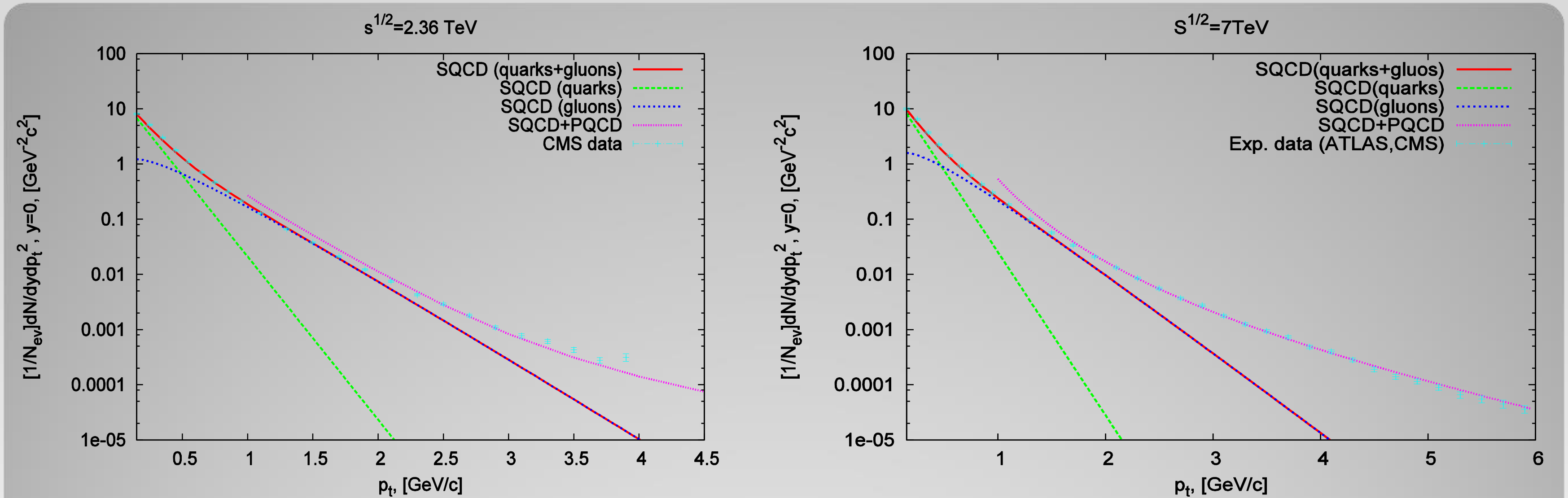
$\alpha_P$ **is the intercept of the subcritical Pomeron,** $Y = \ln(1/x)$

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

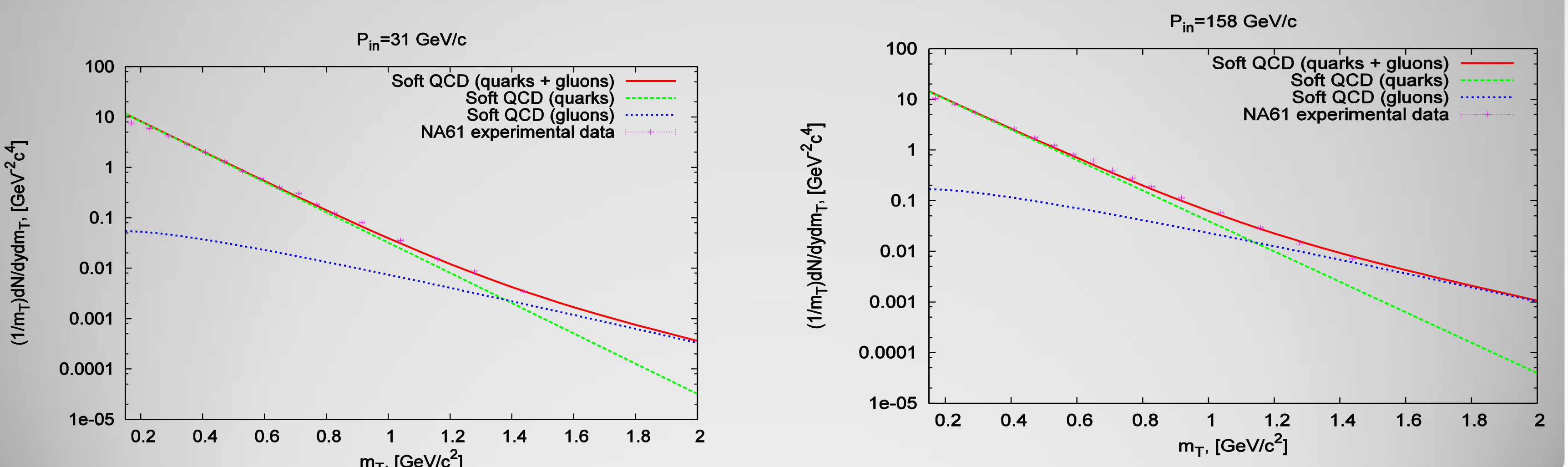
## Our matching function

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

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

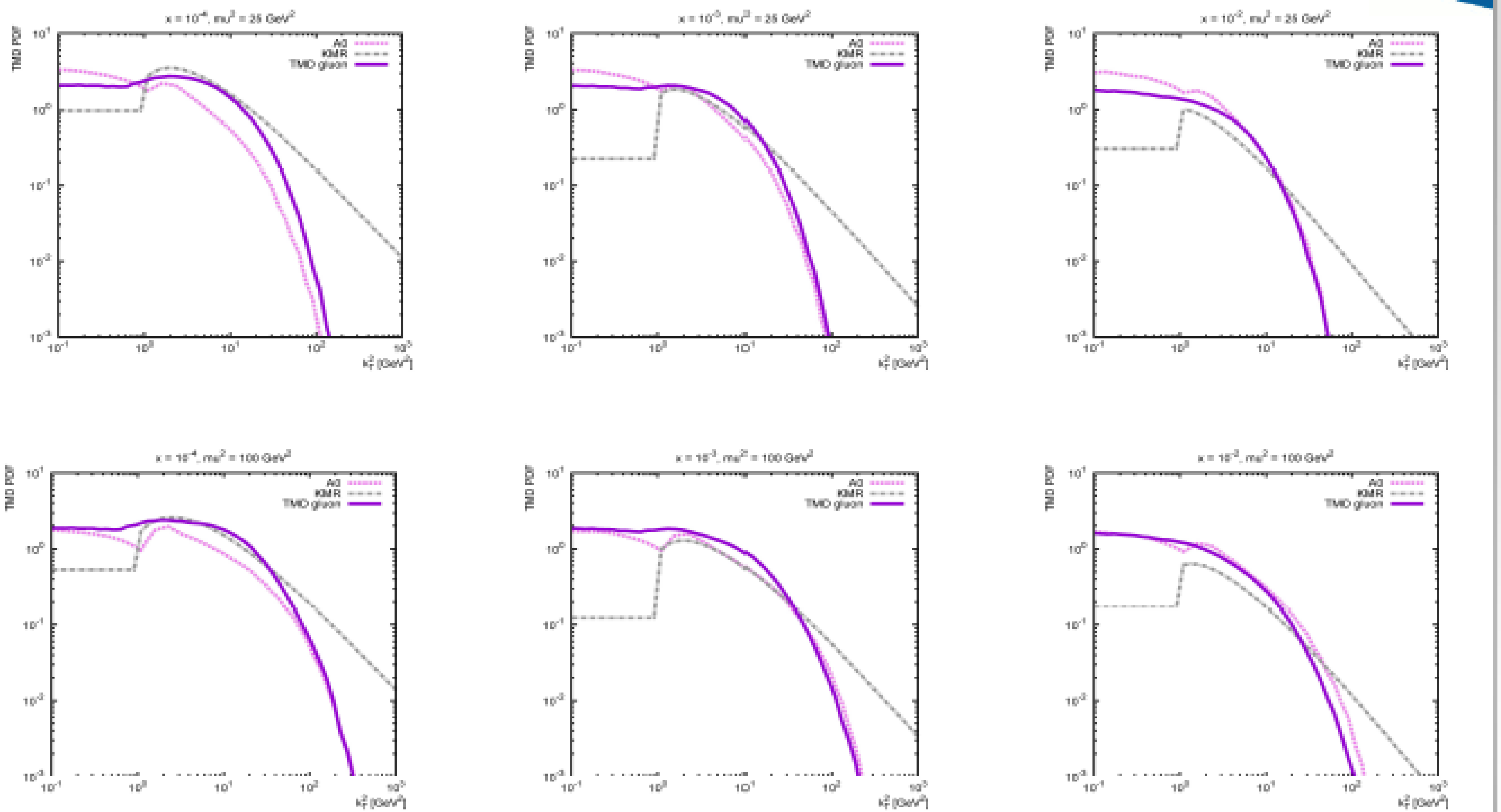



**Spectrum of charged hadrons produced in pp collision**



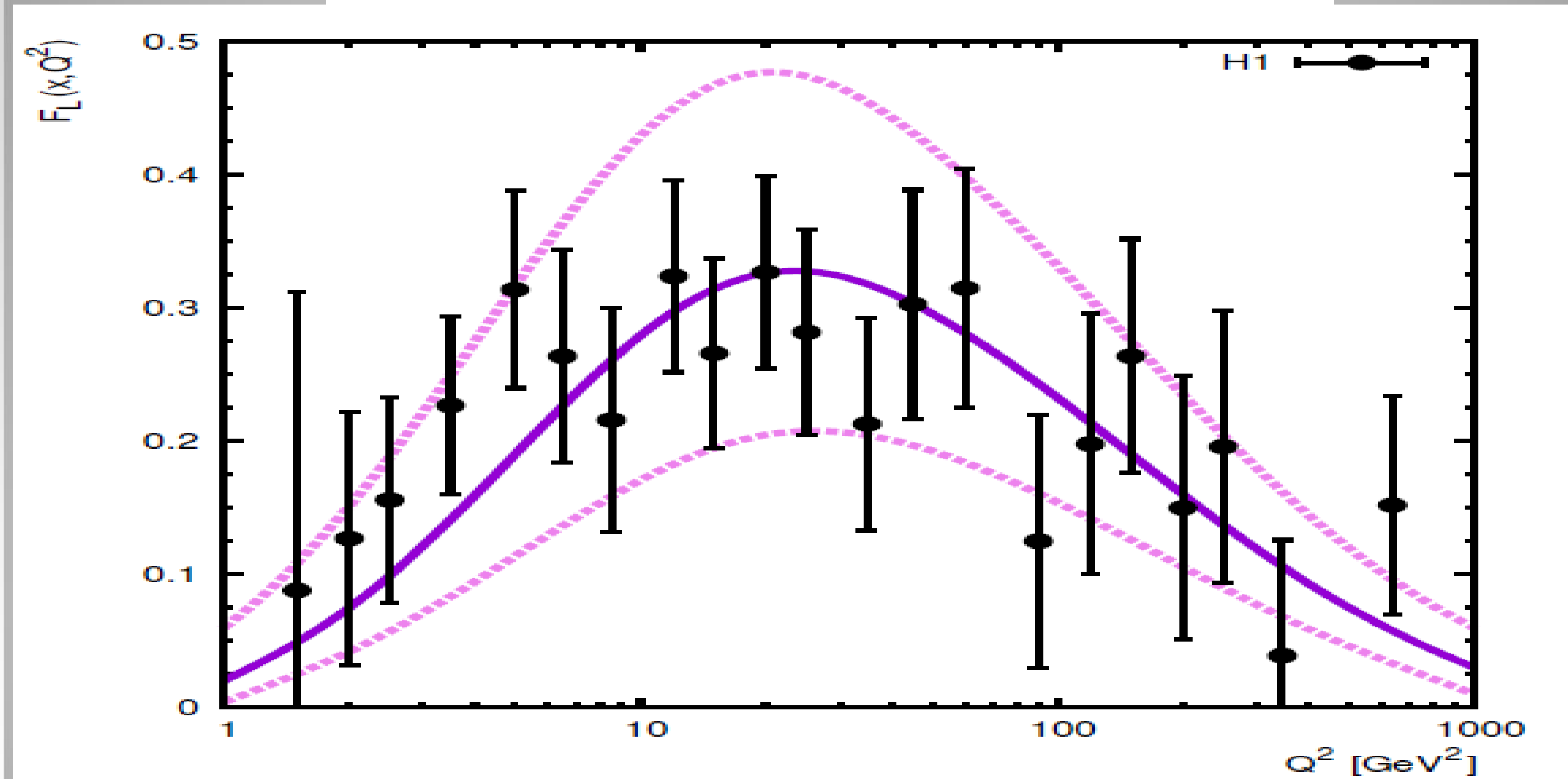

**Spectrum of $\pi^-$ - mesons produced in pp collision**

# Gluon distribution as a function of $k_T^2$



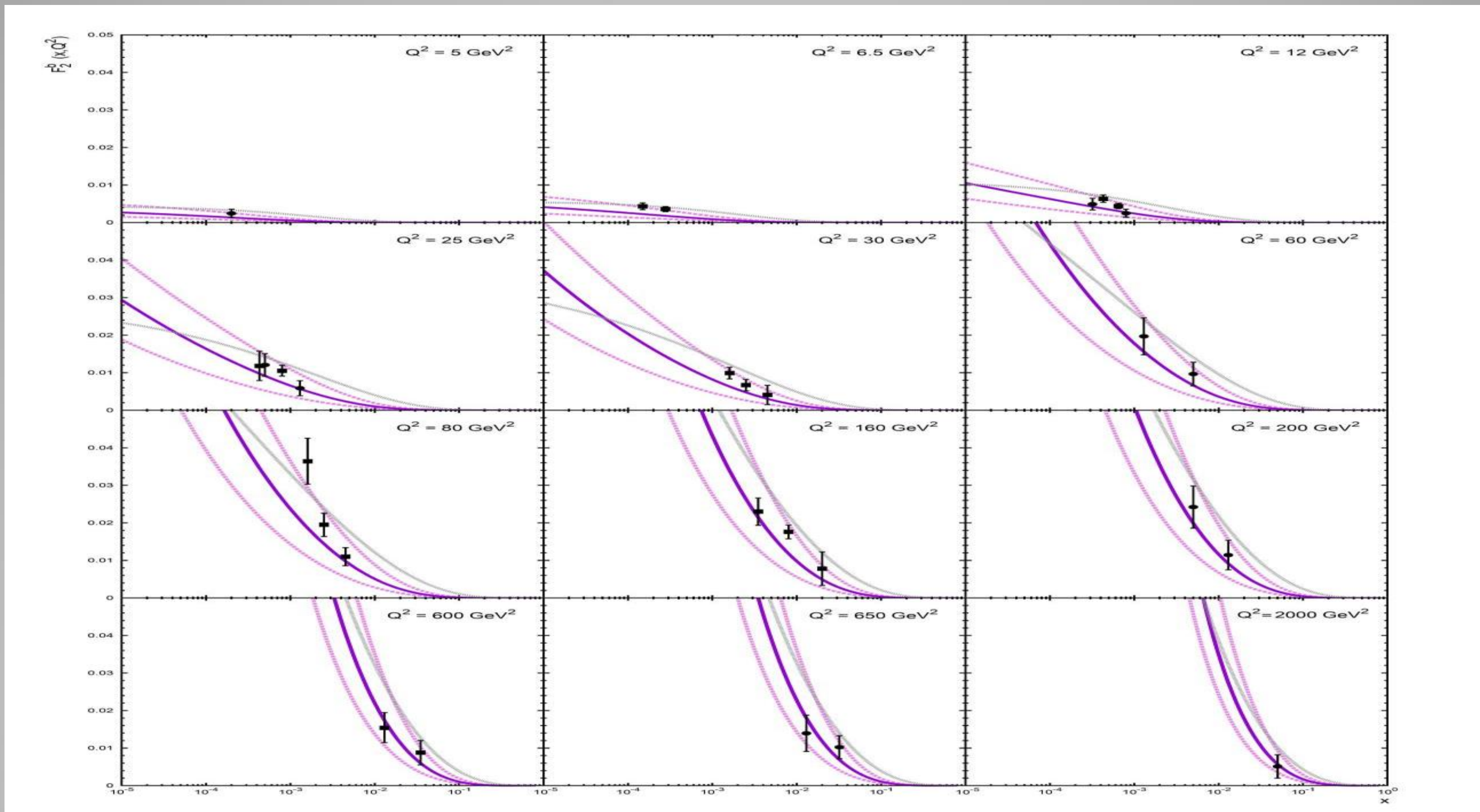

$$f_g^{(0)}(x, k_T^2, Q_0^2) \rightarrow f_g^{(0)}(x, k_T^2, Q_0^2) + f_g^{(k)}(x, k_T^2)$$

$$F_L(x,Q^2) = \sum_f e_f^2 \int \frac{dy}{y} \int d\mathbf{k}_T^2 \mathcal{C}_L(x/y, \mathbf{k}_T^2, Q^2, m_f^2, \mu^2) f_g(y, \mathbf{k}_T^2, \mu^2).$$




**Solid line corresponds to $\mu_R$= Q, the dash top line is for $\mu_R$=Q/2, the bottom line corresponds to $\mu_R$=2Q. Circles are the ZEUS data, squares are H1 data**

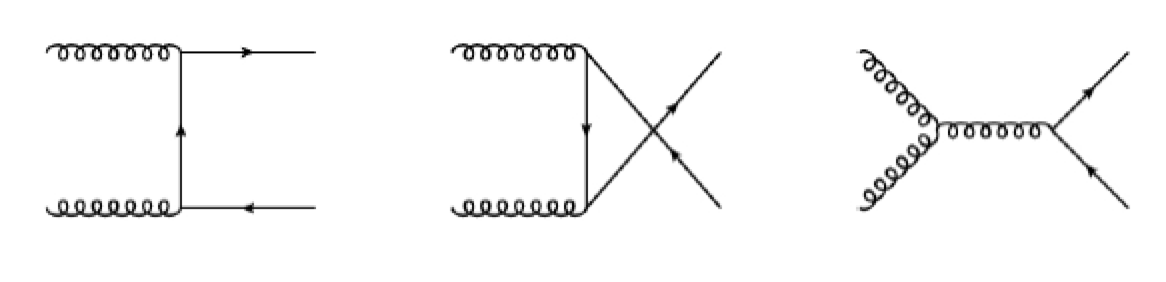
# $F_2^b\,(x,Q^2)$




**Solid line corresponds to $\mu_R$= Q, the dash top line is for $\mu_R$=Q/2, the bottom line corresponds to $\mu_R$=2Q. Circles are the H1 data, squares are H1 data.**

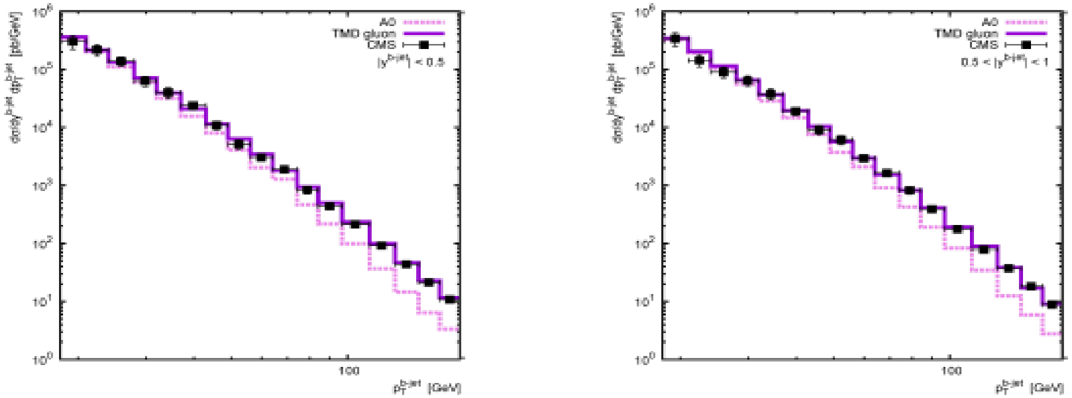
**Dotted line is the calculations using the set A0, Hannes Jung hep-ph/0411287**

# HEAVY FLAVOUR JET PRODUCTION



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

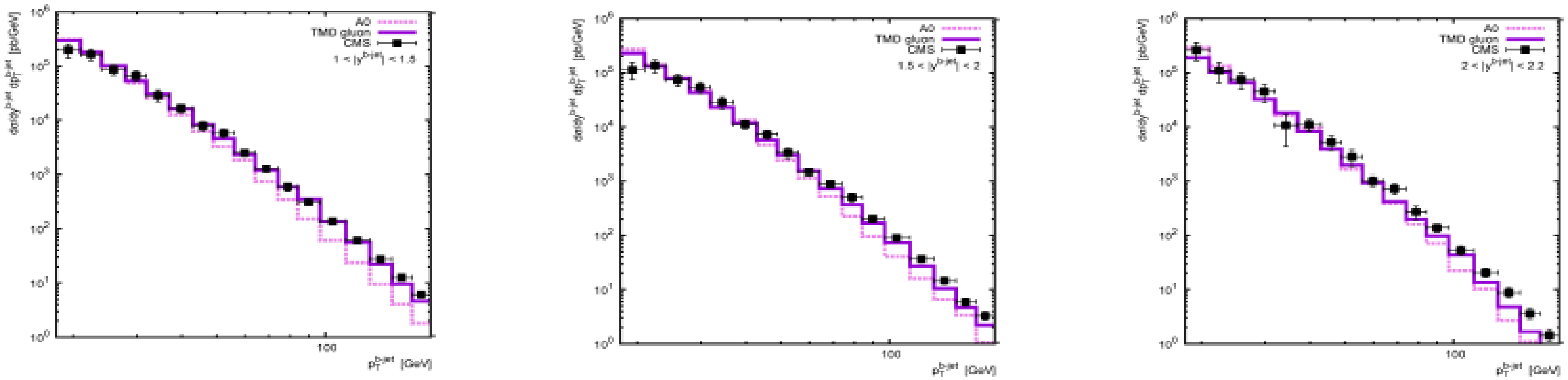
# b-Jets production in p-p collision at $s^{1/2}$ =7 TeV




$|y^b| < 2.2$

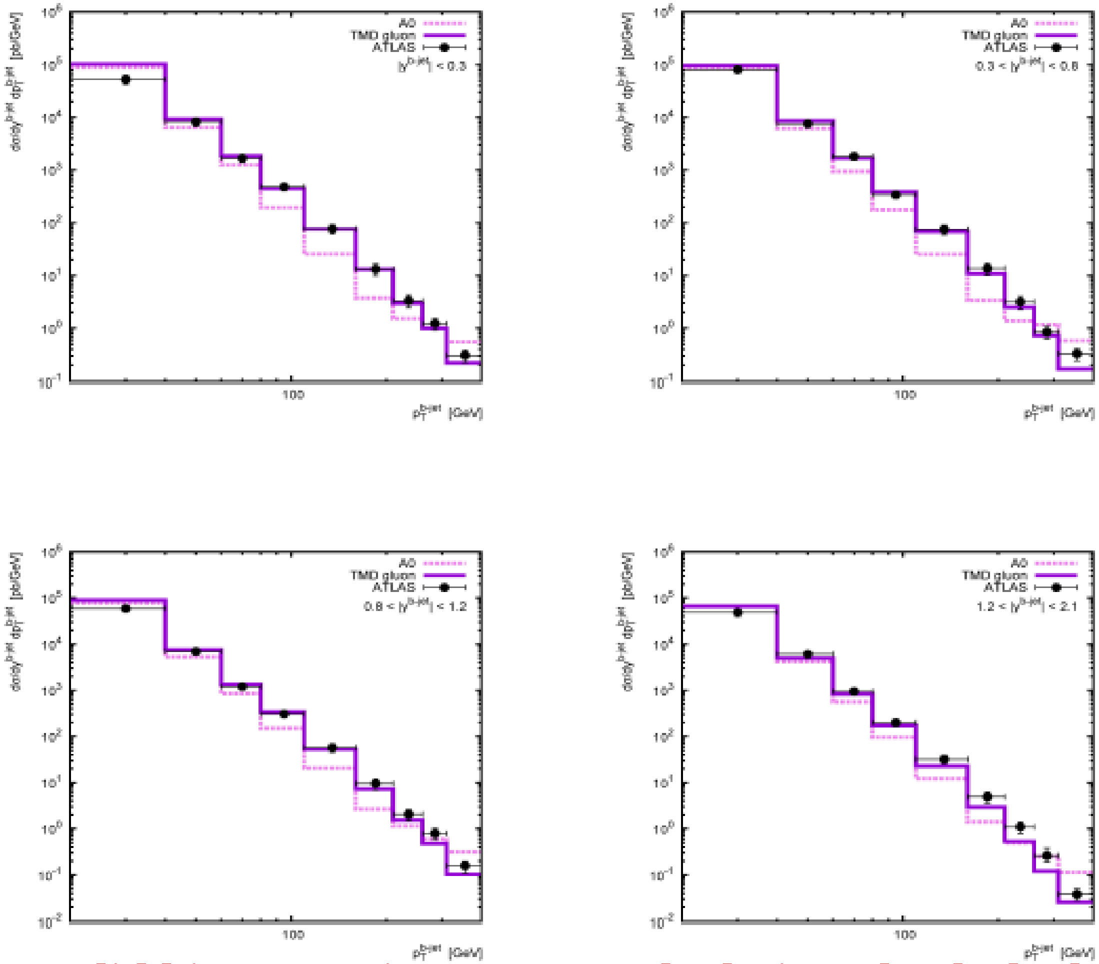
$18 < p_T^b < 196$ ГэВ

**CMS Collaboration, JHEP 1204, 084 (2012)**




**Solid histogram is our new calculation, the dashed one is results obtained using set A0, see Hannes Jung, Proc. 12th Int. Workshop DIS'2004, Strbske Pleso, Slovakia, 2004, hep-ph/0411287.**

# b-Jets production in p-p collision at $s^{1/2}$ =7 TeV



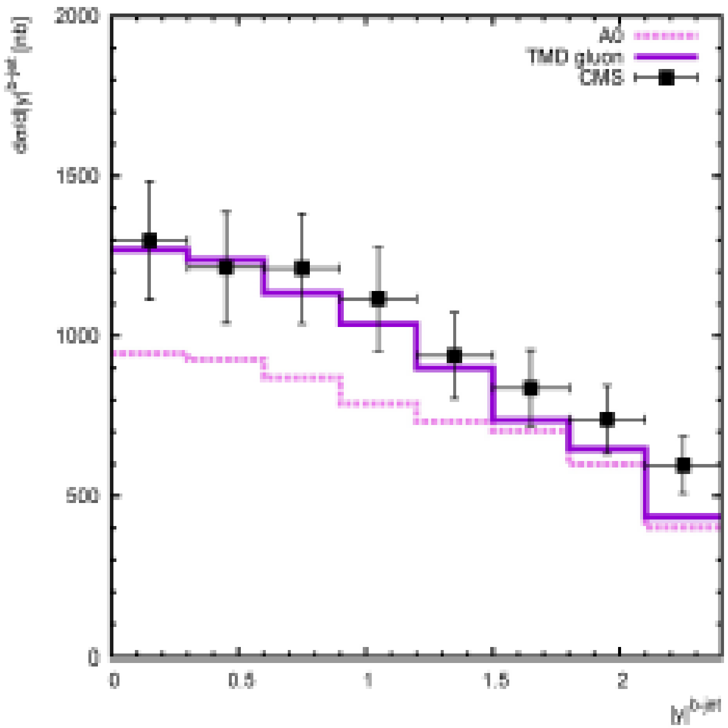

$|y^b| < 2.1$

$20 < p_T^b < 400$ ГэВ

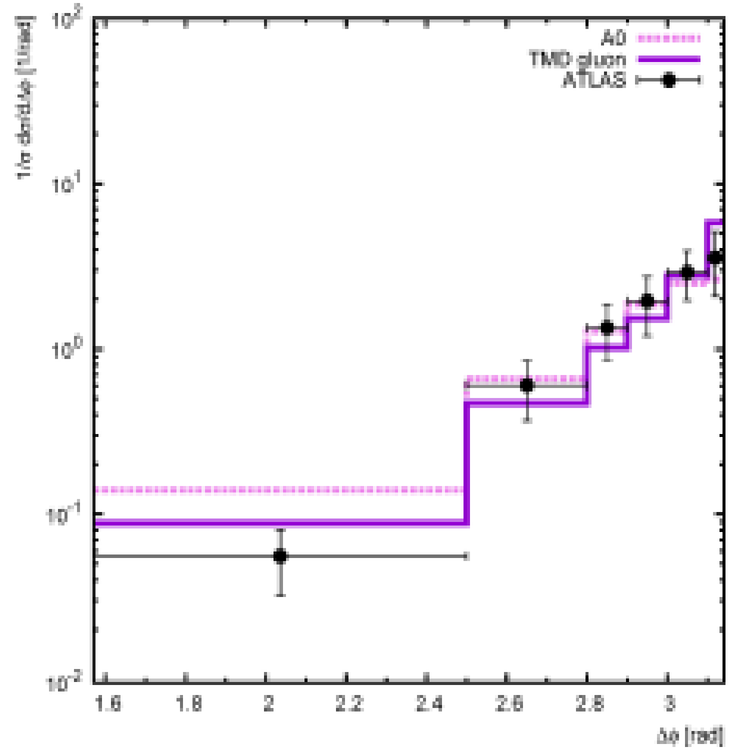
**ATLAS Collaboration, EPJ C 71, 1846 (2011)**

**Solid histogram is our new calculation, the dashed one is results obtained using set A0, see Hannes Jung, Proc. 12th Int. Workshop DIS'2004, Strbske Pleso, Slovakia, 2004. hep-ph/0411287.**

# Rapidity didtribution of b-jet produced in pp at $s^{1/2}$ =7 TeV




# Δφ-Distribution between b and b jets in pp collisions

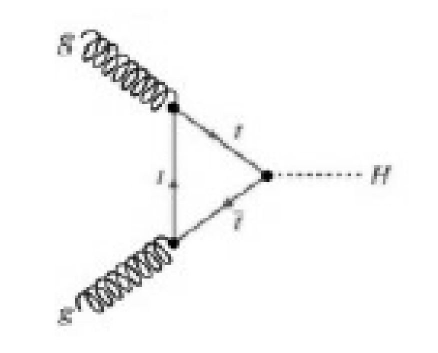



**Solid histogram is our new calculation, the dashed one is results obtained using set A0, see Hannes Jung, Proc. 12$^{th}$ Int. Workshop DIS'2004, Strbske Pleso, Slovakia, 2004. hep-ph/0411287.**

# Higgs-boson production in pp collision

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

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



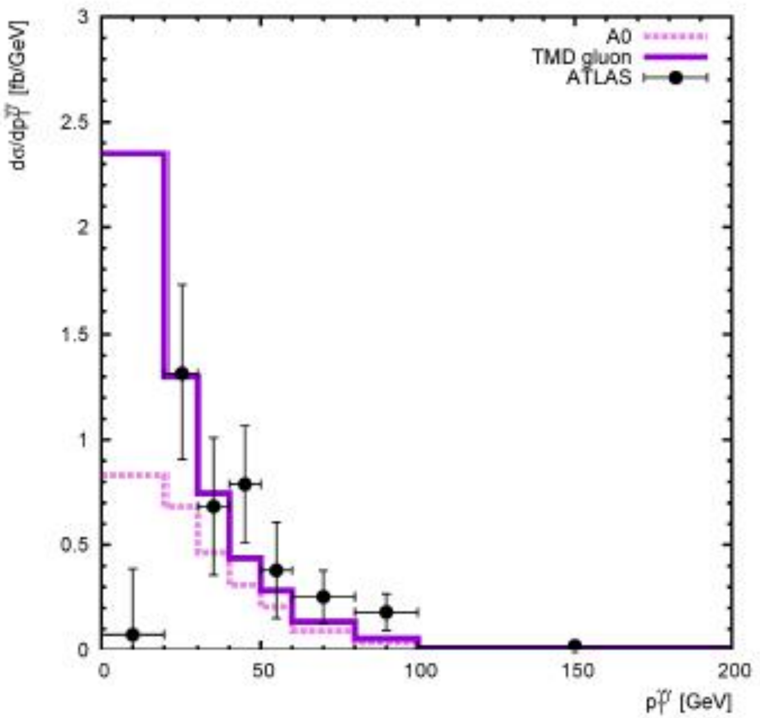

$$\mathcal{L}_{H\gamma\gamma} = \frac{\alpha}{8\pi}\mathcal{A}\left(G_F\sqrt{2}\right)^{1/2} F_{\mu\nu}F^{\mu\nu}H$$

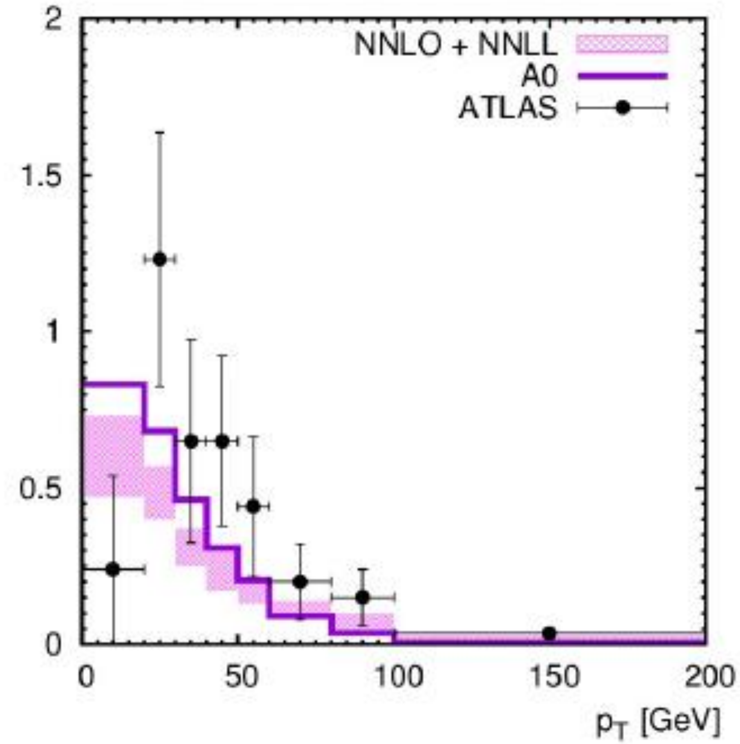
$$\mathcal{A} = \mathcal{A}_W(\tau_W) + N_c\sum_f Q_f^2\mathcal{A}_f(\tau_f)$$

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


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




Solid histogram is our calculation, the dashed one is results using set A0, see Hannes Jung, Proc. 12th Int. Workshop DIS'2004Strbske Pleso, Slovakia, 2004. he-ph/0411287.

Solid histogram is results of Hannes Jung, hep-ph/0411287; the light lilac area corresponds to NNLO+NNLL

# SUMMARY

1.The new TMD gluon density is proposed at initial $Q_0$ =1.1 GeV/c. 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 $\mathbf{F_L}$, $\mathbf{F_{2b}}$.

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

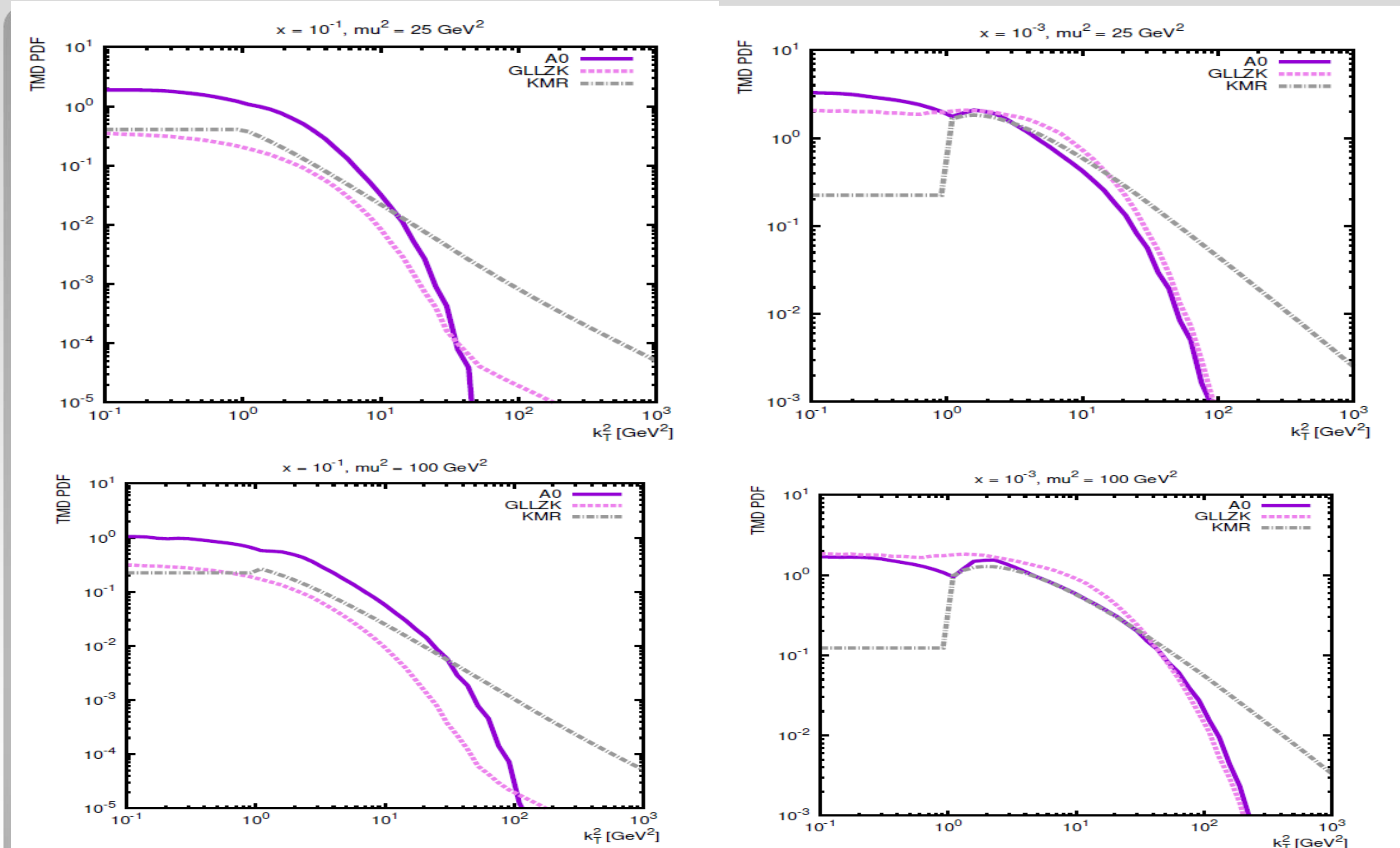
5. The CCFM-evolved new u.g.d. results in a satisfactory description of hard production of heavy flavour jets and Higgs bosons.

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.

7. **The connection between the soft processes at LHC and small x-physics at HERA has been confirmed using the new input for the gluon density**

***DESY, March 26, 2015***

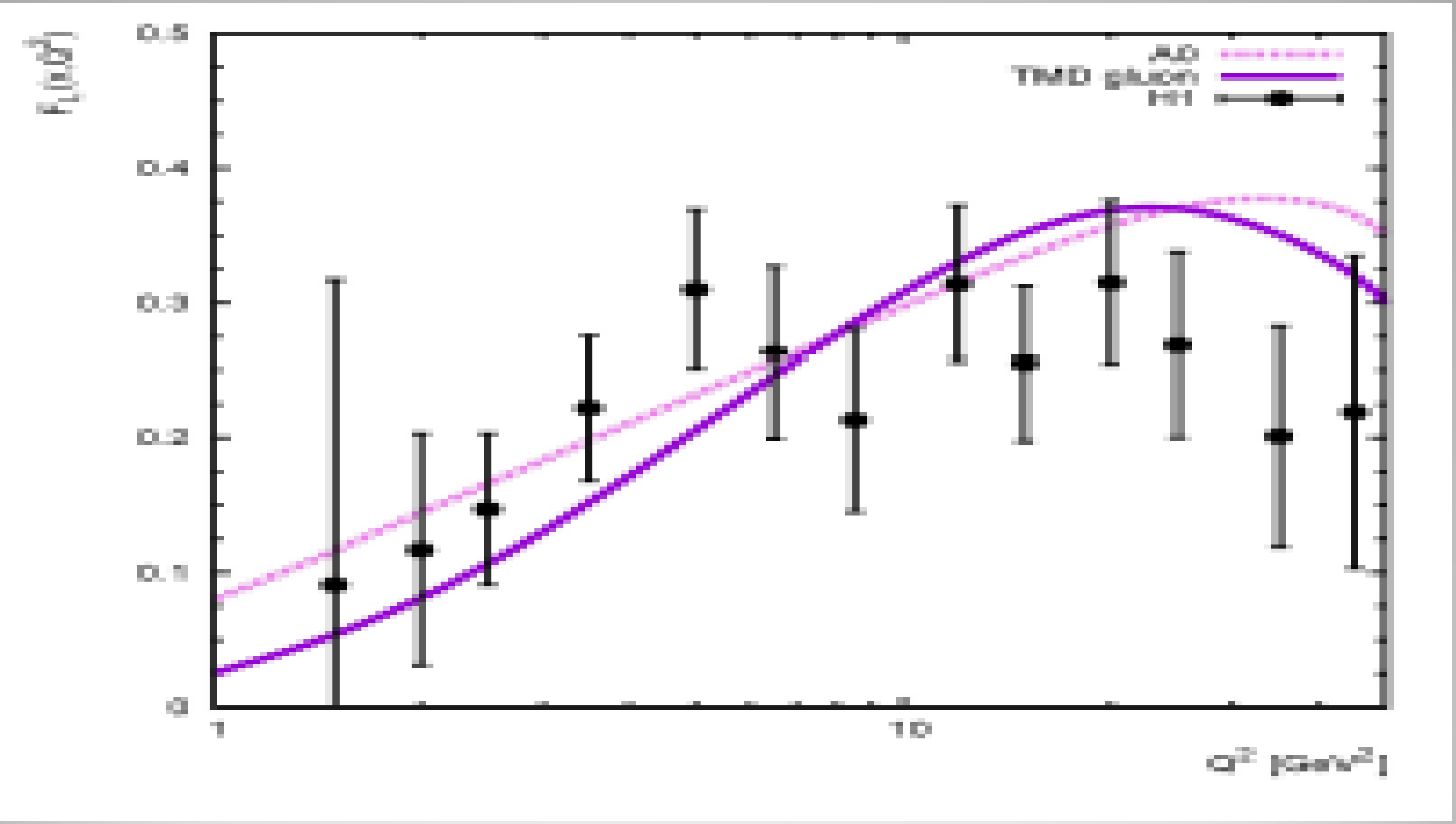
**THANK YOU VERY MUCH FOR YOUR ATTENTION !**



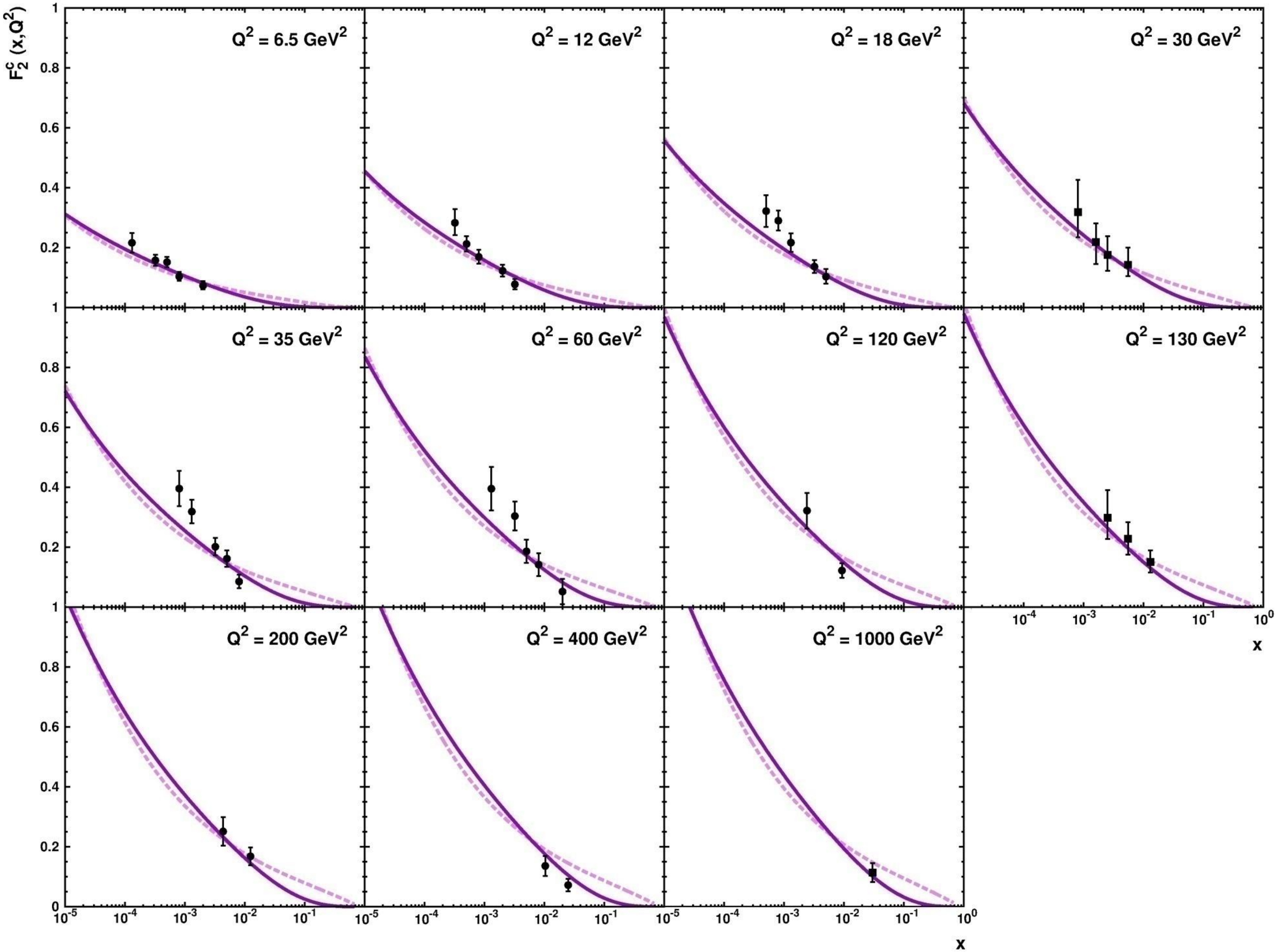

# *New input for TMD gluon density*

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

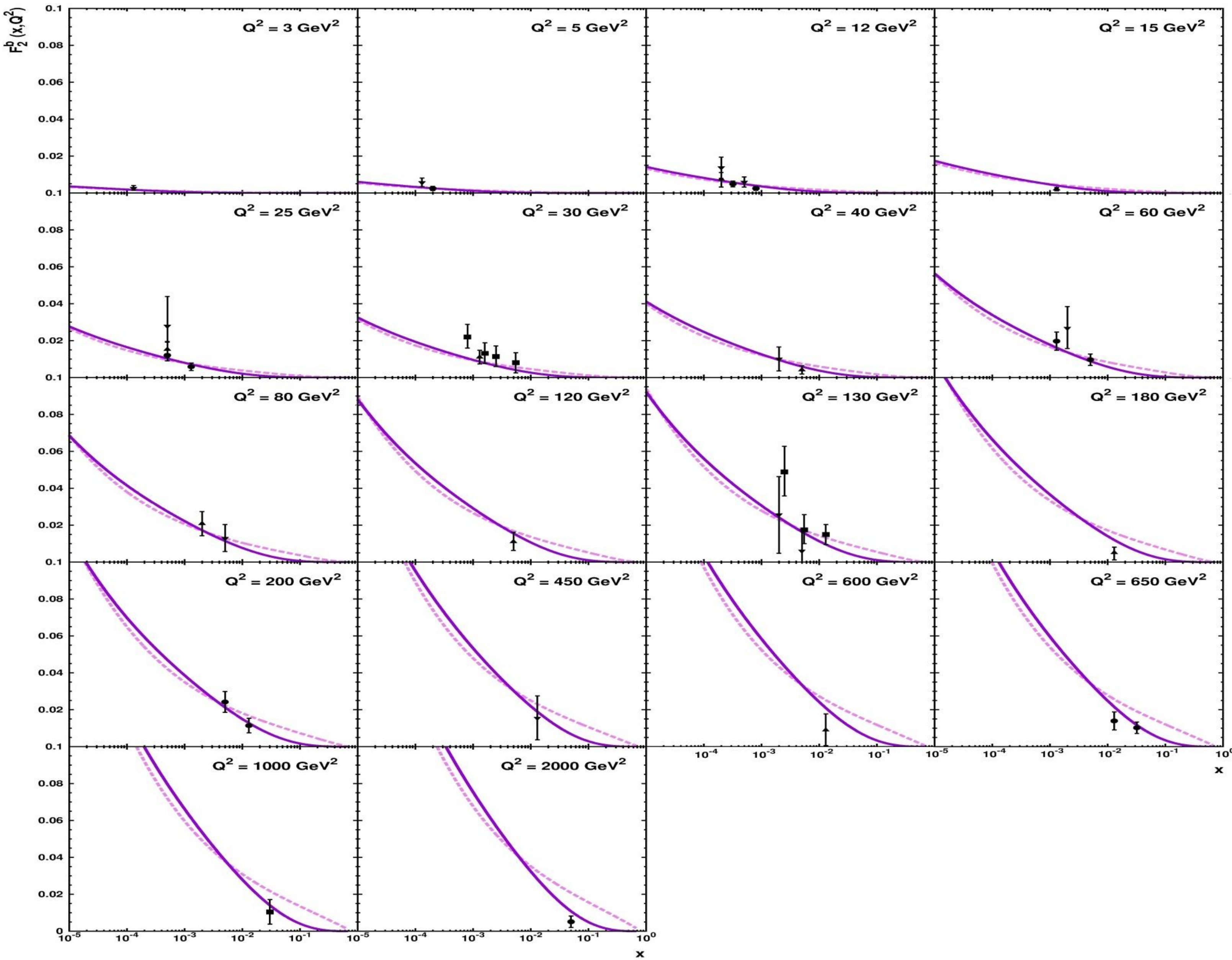
# Longitudinal structure function




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

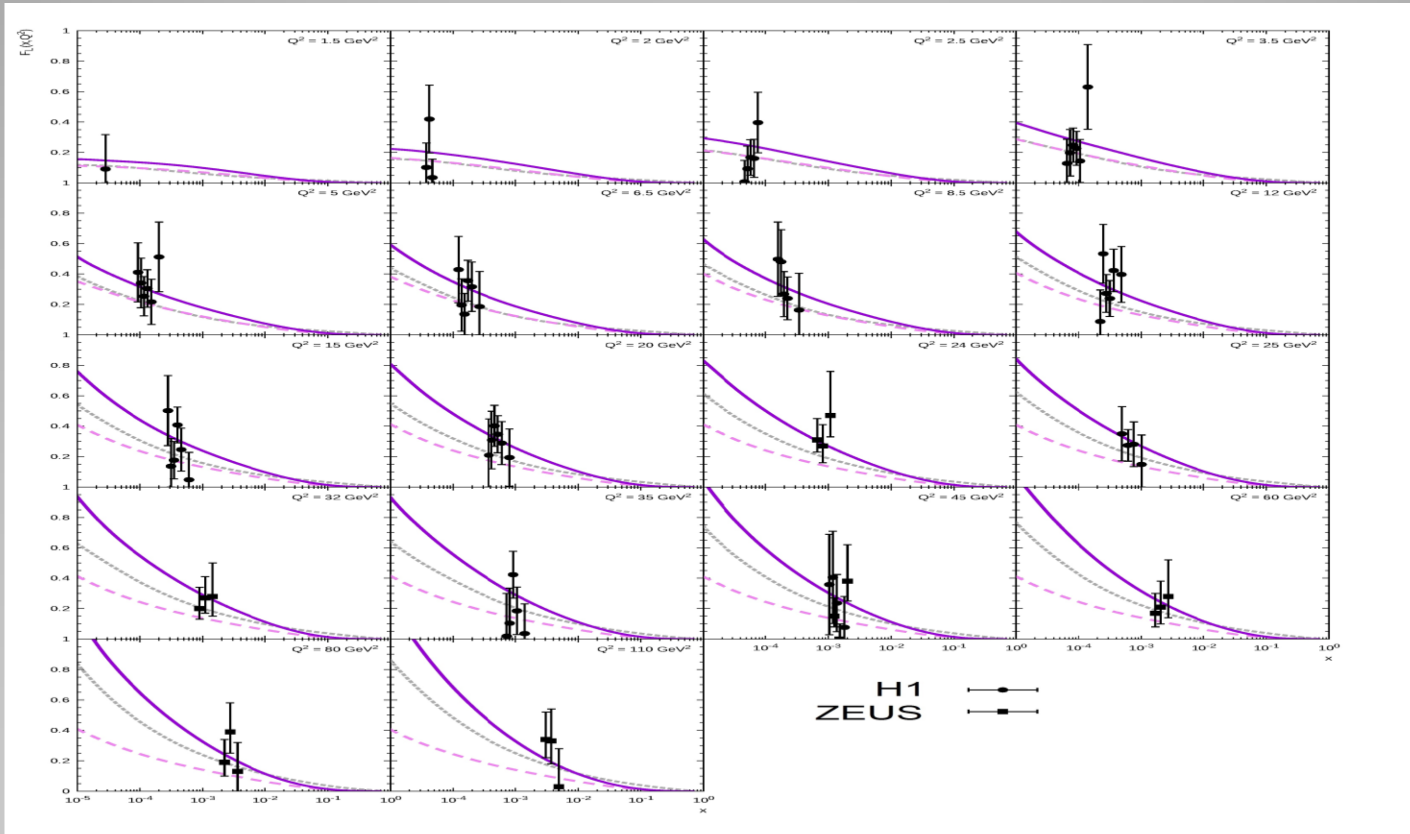


$F_2^c(x,Q^2)$
$Q^2$ = 6.5 GeV$^2$
$Q^2$ = 12 GeV$^2$
$Q^2$ = 18 GeV$^2$
$Q^2$ = 30 GeV$^2$
$Q^2$ = 35 GeV$^2$
$Q^2$ = 60 GeV$^2$
$Q^2$ = 120 GeV$^2$
$Q^2$ = 130 GeV$^2$
$Q^2$ = 200 GeV$^2$
$Q^2$ = 400 GeV$^2$
$Q^2$ = 1000 GeV$^2$
x



$F_2^b(x,Q^2)$
$Q^2$ = 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$^2$
0.1
0.08
0.06
0.04
0.02
0
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^{0}$
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 $\alpha_s\left(\bar{Q}^2\right) \leq 1$ )

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

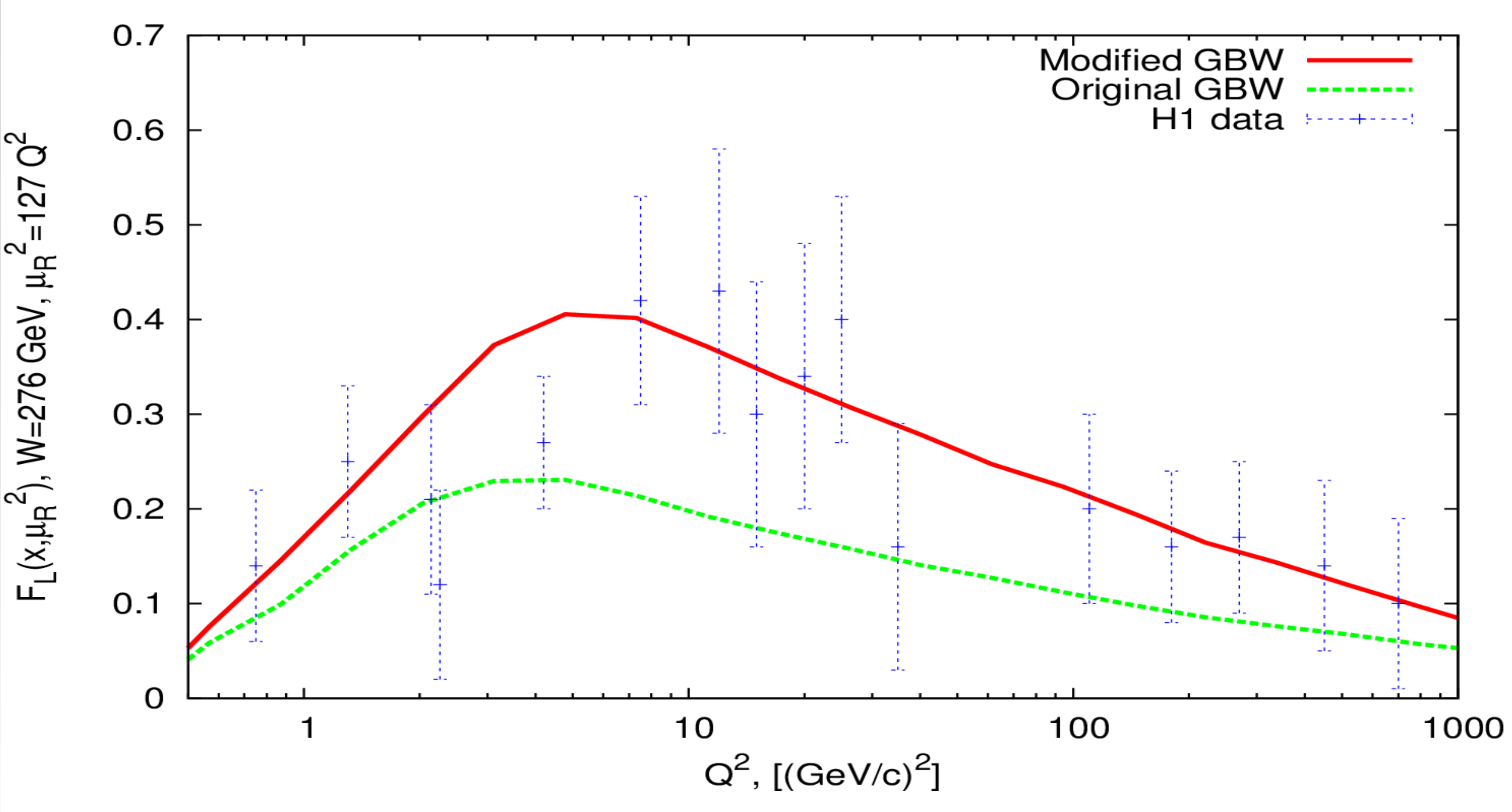
# Longitudinal structure function within the kt-factorization

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

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

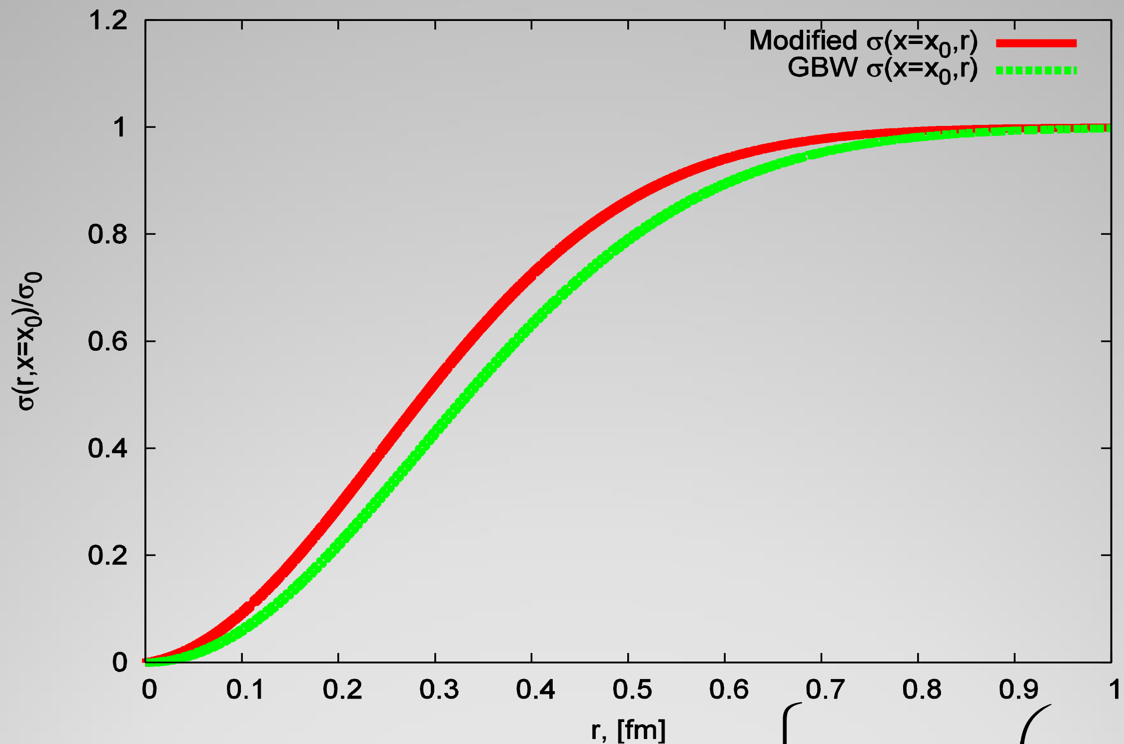


A.V. Kotikov, A.V. Lipatov, N.P. Zotov, Eur.Phys.J., C27 92003)219.
H. Jung, A.V. Kotikov, A.V. Lipatov, N.P. Zotov, DIS 2007, hep-ph/07063793.




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

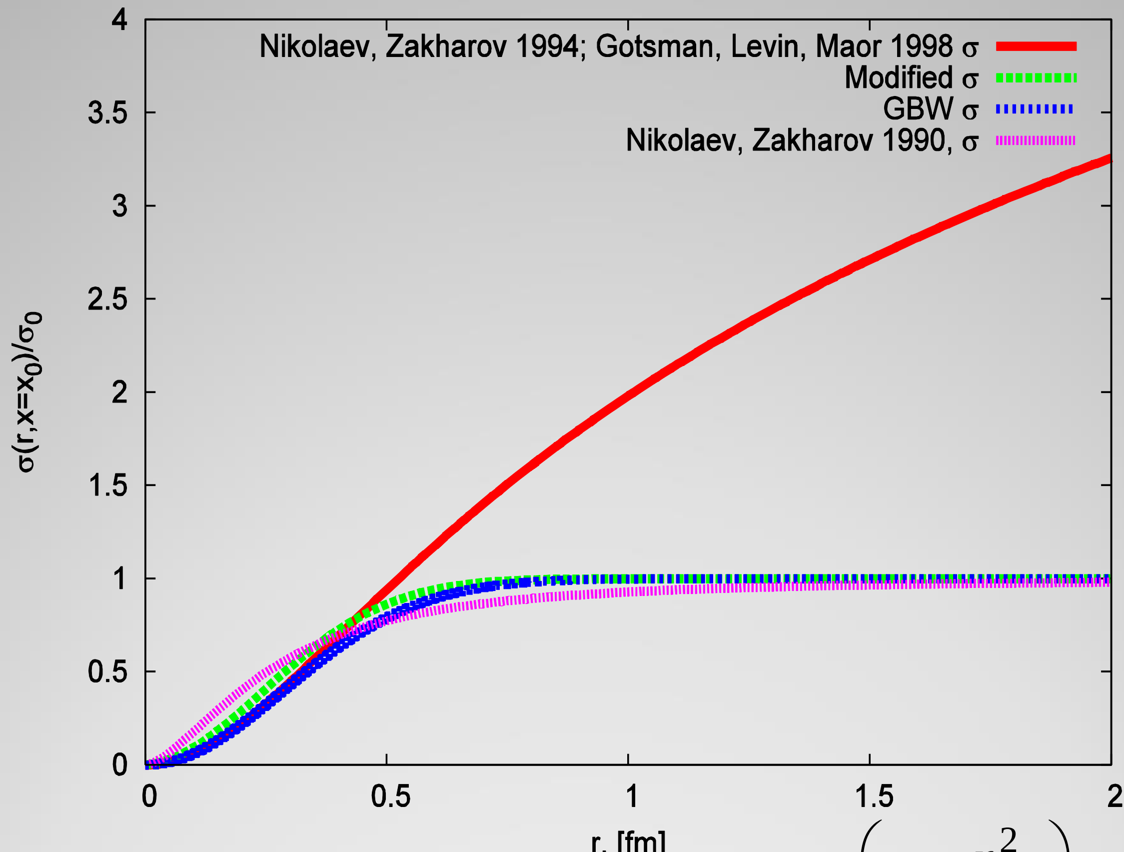
# Effective dipole cross section



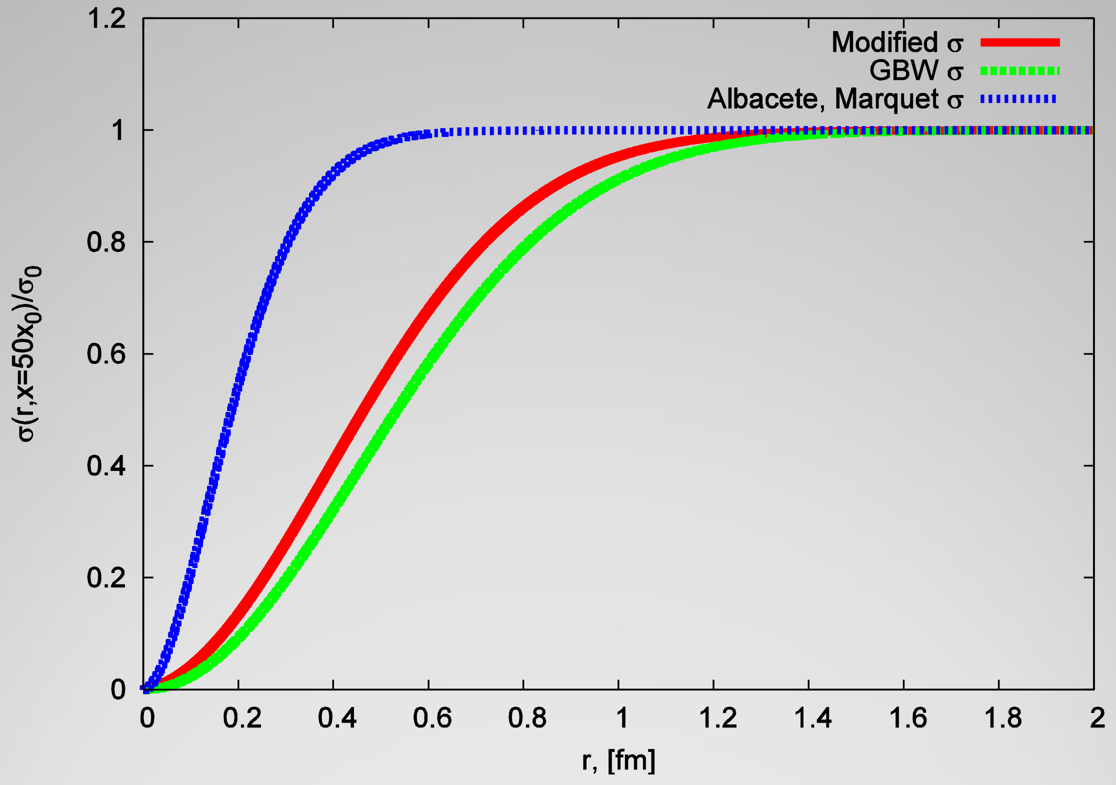

Green line: $\sigma_{dipole}^{GBW}(x,r) = \sigma_0 \left\{ 1 - \exp\left( -\frac{r^2}{4R_0^2(x)} \right) \right\}$

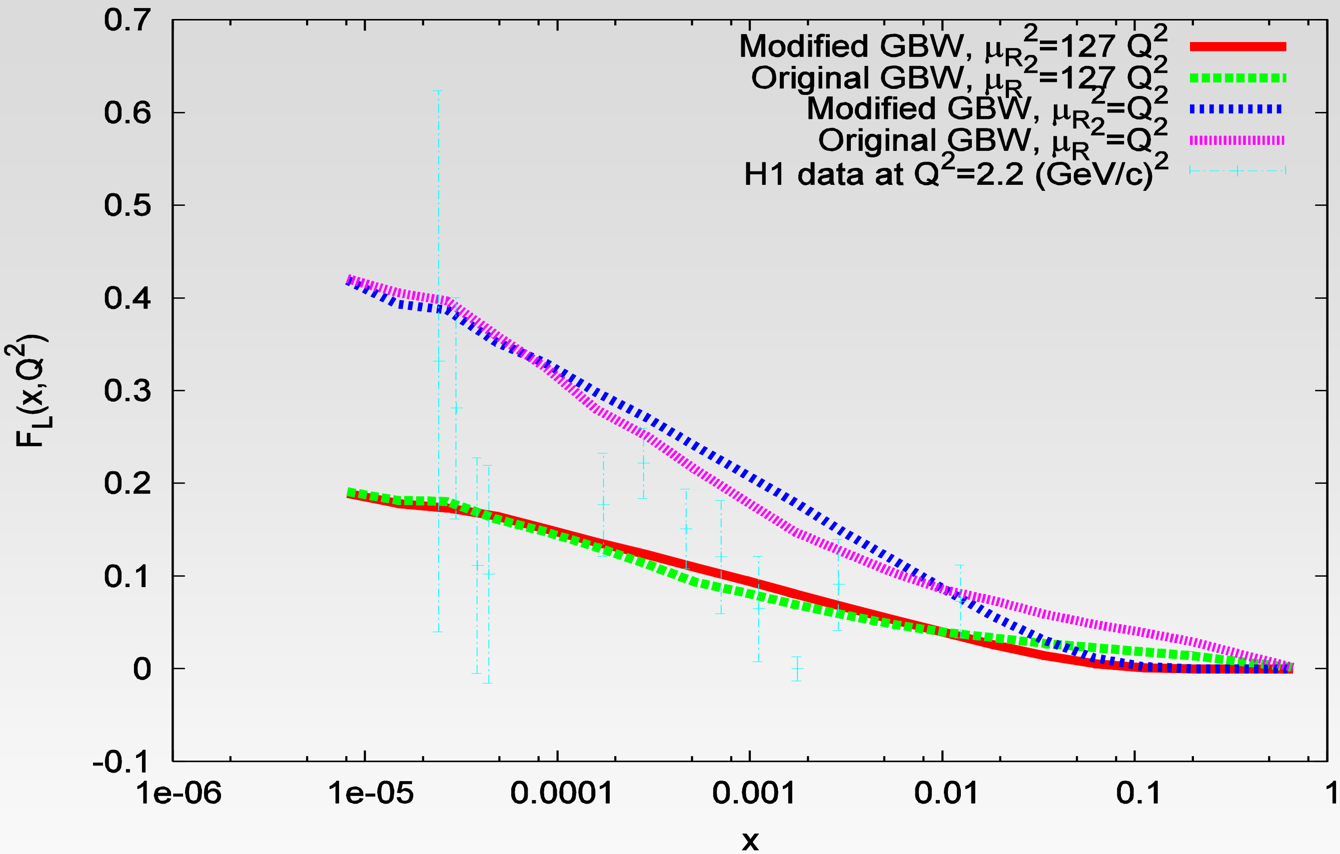
Red line: $\sigma_{dipole}^{GBW}(x,r) = \sigma_0 \left\{ 1 - \exp\left( -\frac{a_1 r}{R_0(x)} - \frac{a_2 r^2}{R_0^2(x)} \right) \right\}$

# Effective dipole cross section



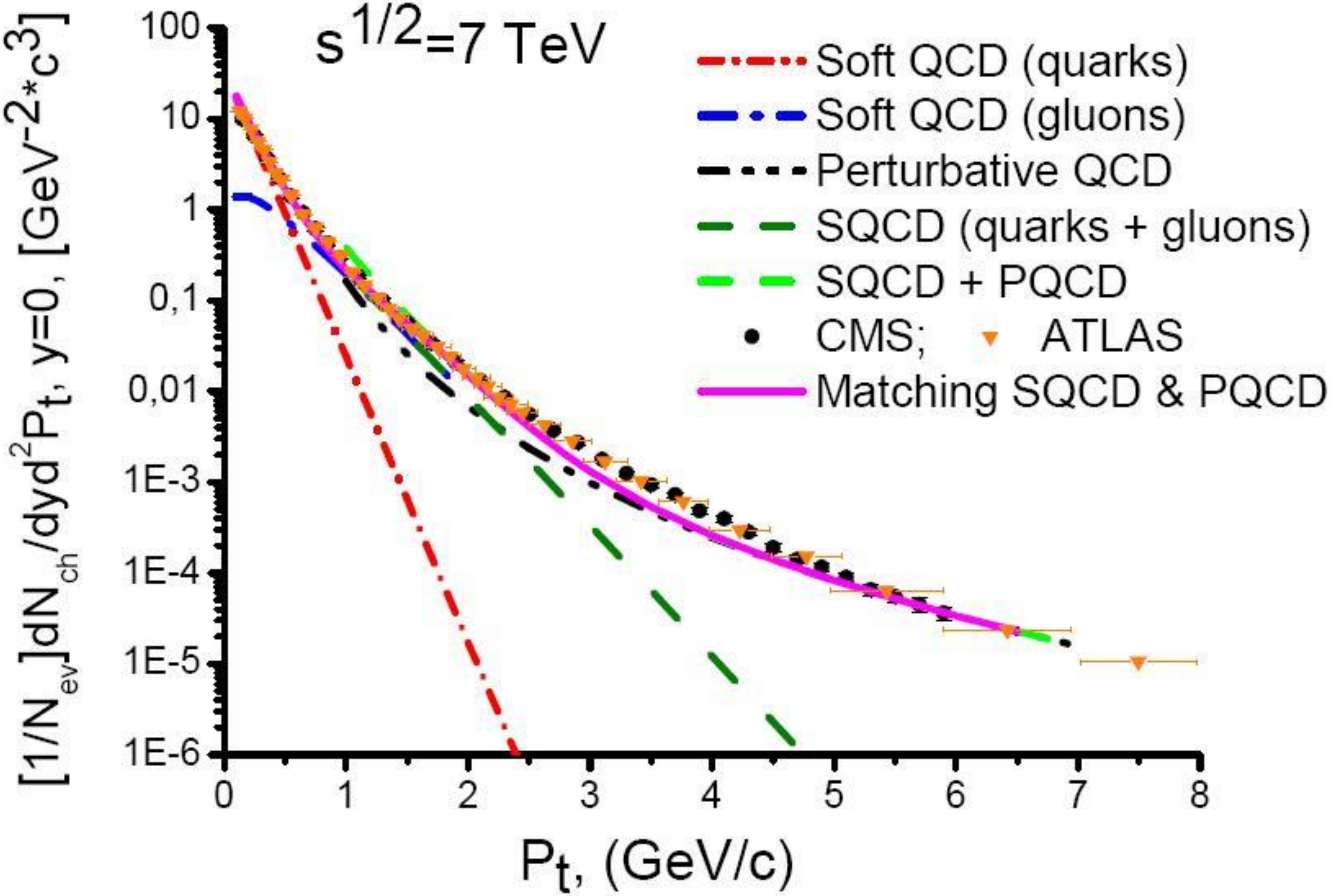

Red line corresponds to $\sigma_{dipole} = \sigma_0 \ln\left(1 + \frac{r^2}{4R_0^2}\right)$


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

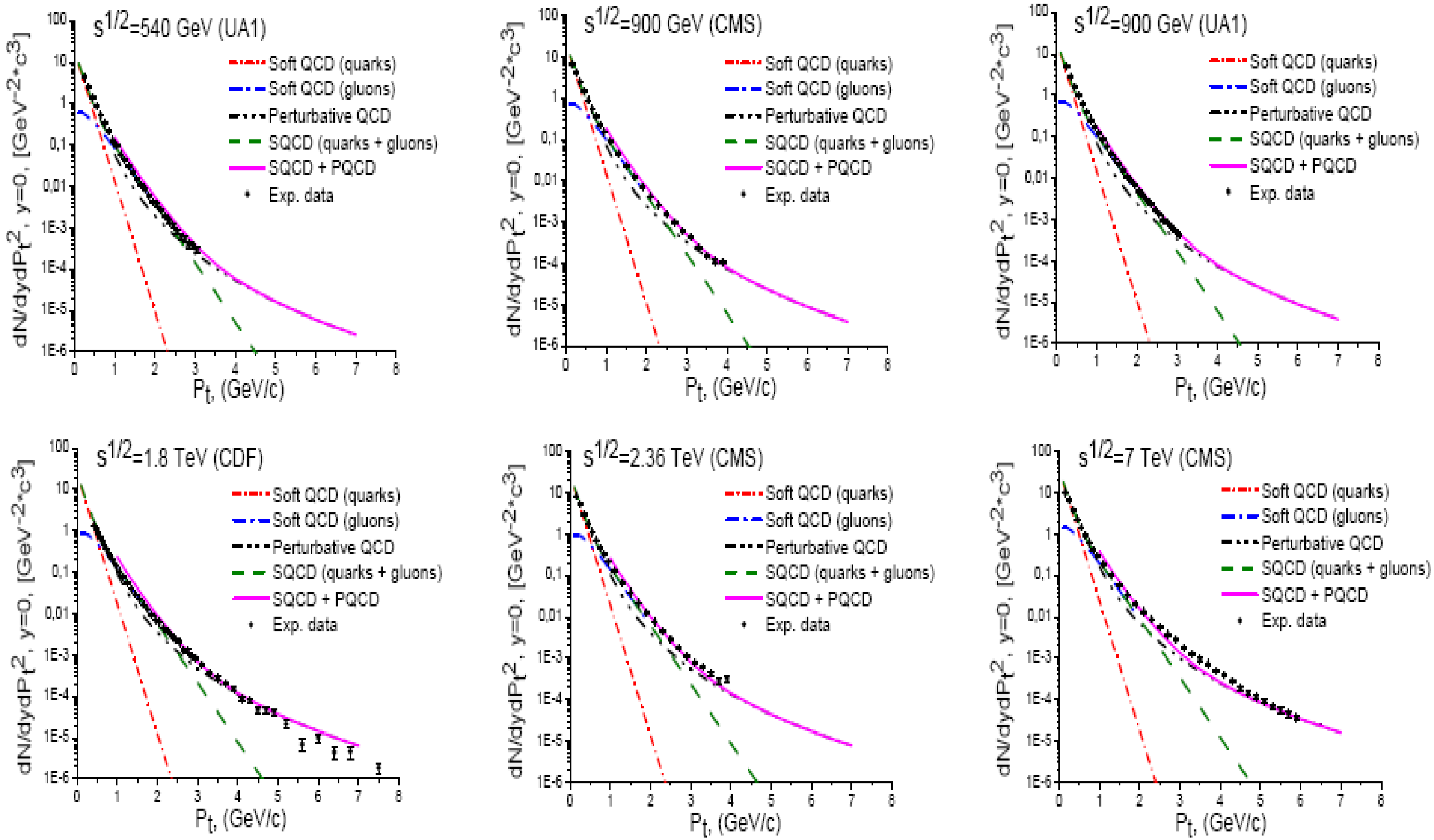



The x-dependence of $F_L$ at $Q^2 = 2.2 (GeV/c)^2$ assuming

$\mu_R^2 = KQ^2$ 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/dyd^2P_t, y=0, [GeV^-2*c^3]
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



s1/2=540 GeV (UA1)
s1/2=900 GeV (CMS)
s1/2=900 GeV (UA1)
s1/2=1.8 TeV (CDF)
s1/2=2.36 TeV (CMS)
s1/2=7 TeV (CMS)
Soft QCD (quarks)
Soft QCD (gluons)
Perturbative QCD
SQCD (quarks + gluons)
SQCD + PQCD
Exp. data
dN/dydPt2, y=0, [GeV-2*c3]
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.

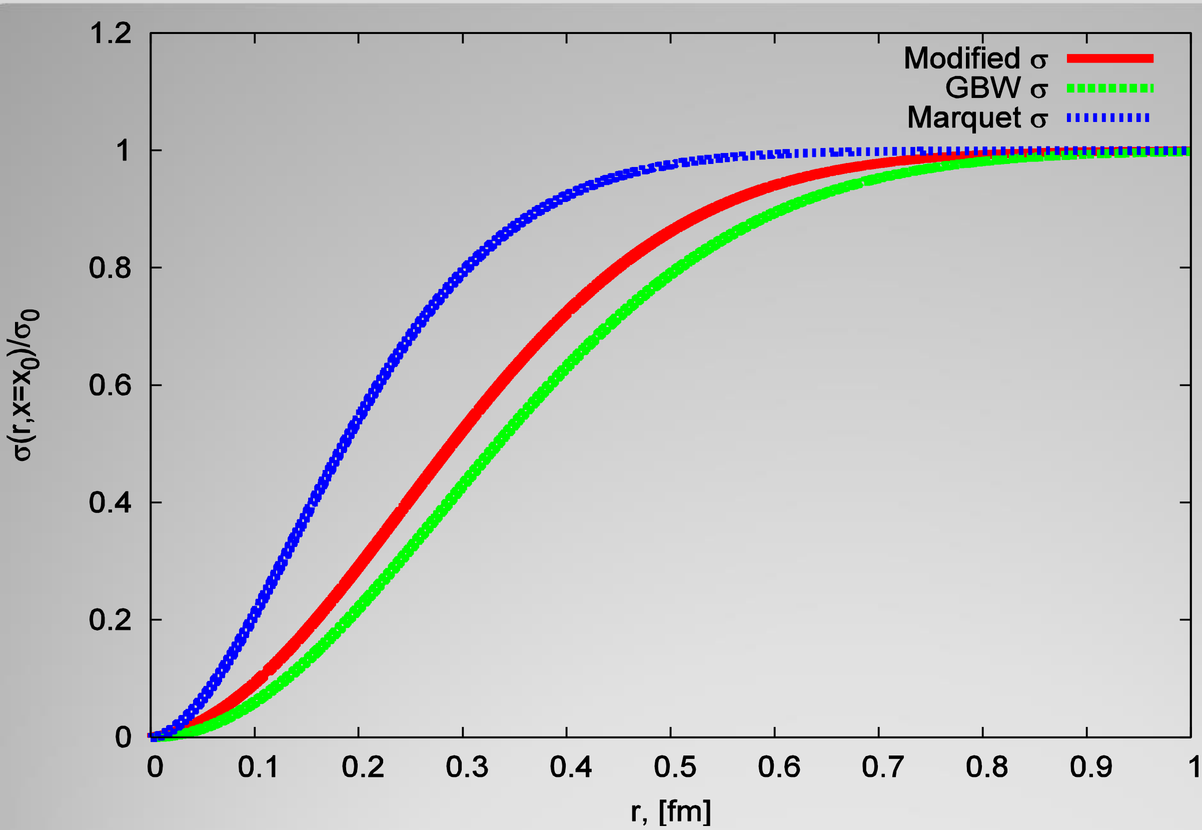
Using this AGK we estimate the inclusive spectrum of the charged hadrons produced in p-p at y=0 as a function of the transverse momentum including the quark and gluon components in the proton.

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

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

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

2012




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

# Blue line corresponds to

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

# Inclusive hadron production in central region and the AGK cancellation

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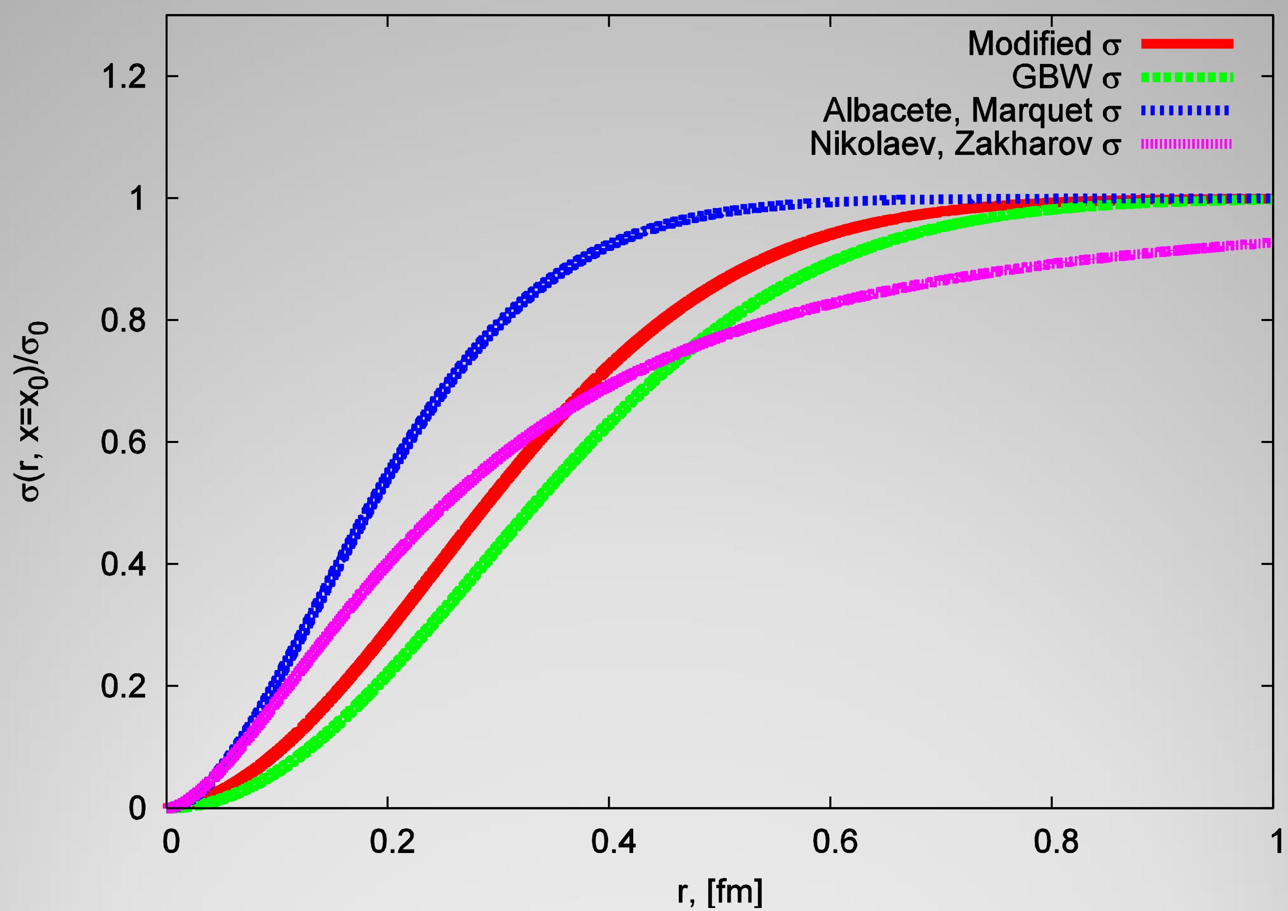
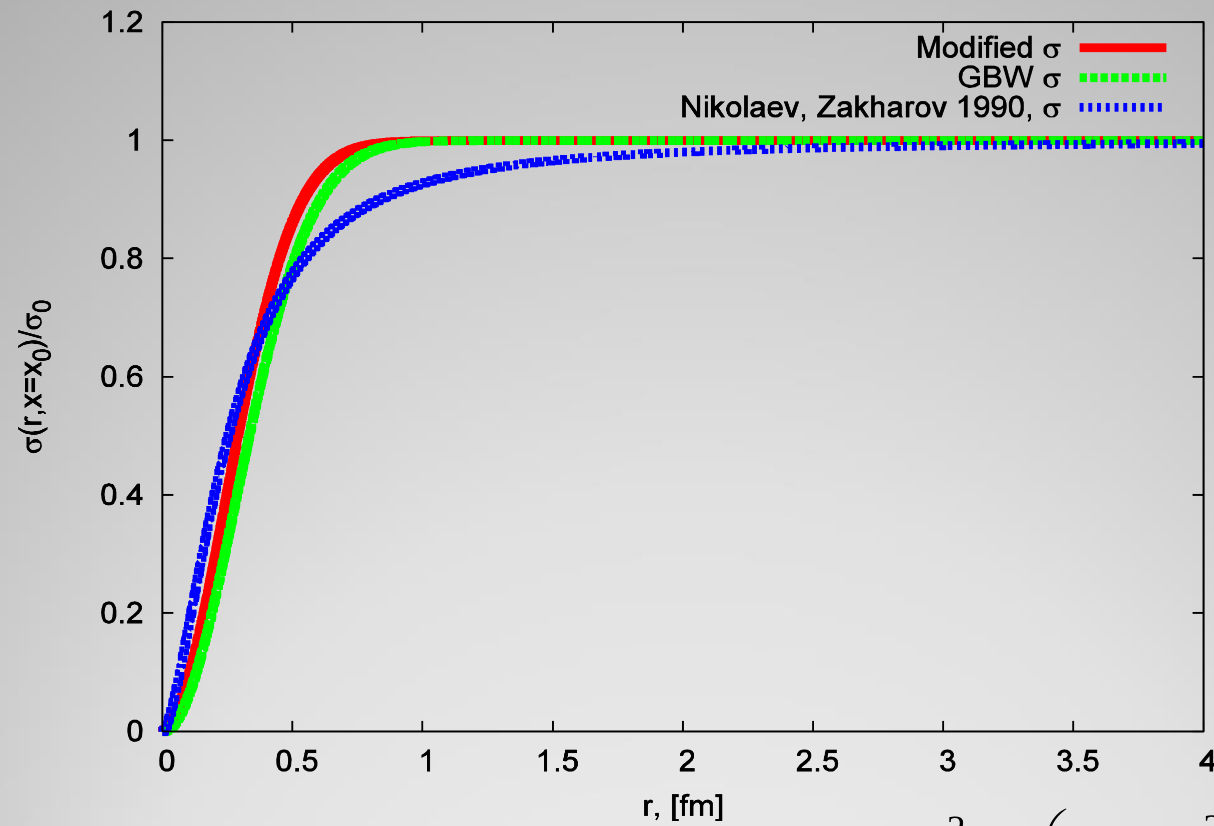
$$\varphi_g(0,p_t)(gs^{\Delta}-\sigma_{nd})$$



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

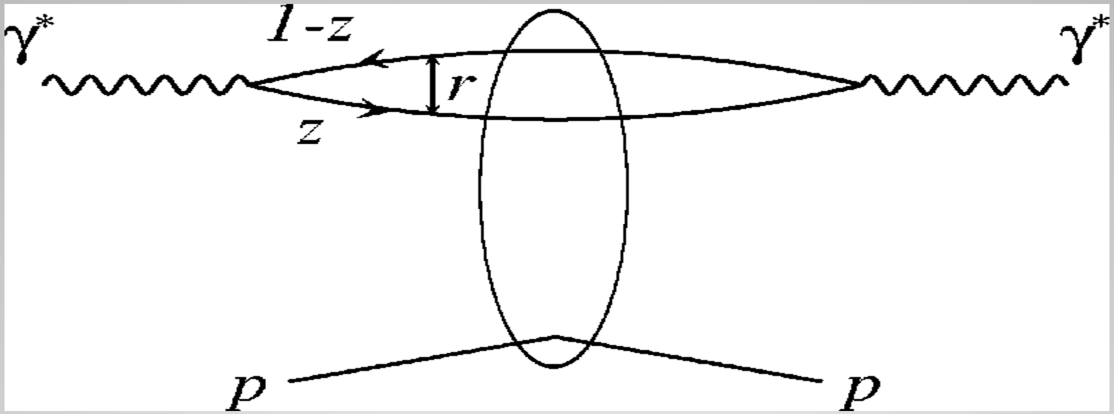



N.Nikolaev, B.Zakharov, Z.Phys.C49, 607 (1990)

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




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

$R_0 = GeV^{-1}(x/x_0)^{\lambda/2}$ 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 $\alpha_s$ is the QCD running constant, $J_0$ is the Bessel function of the zero order.

# Structure of an event

- Multiple parton-parton interactions