

Color Class Condensate from electron-proton DIS to proton-nucleus collisions

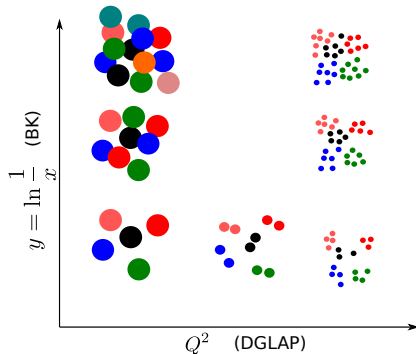
IS 2013

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Introduction



- Study QCD at high energies
- Evolution in x (energy):
BK equation
- Saturation phenomena
described by CGC
- Saturation scale $Q_s =$
characteristic momentum scale

pA is interesting as $Q_s^2 \sim A^{1/3}$.

Setting up the baseline

CGC offers a consistent framework to describe small- x data.

- Non-perturbative input: dipole amplitude at $x = x_0$
- rcBK equation gives energy (Bjorken x) evolution

Compute

- DIS
- Single inclusive hadron production in pp and pA
- Dihadron correlations, ...

In this talk: Use only HERA DIS data as an input and go consistently to pA collisions

T. Lappi, H.M, in preparation

Solve rcBK with modified MV model initial condition

$$N_p(r, y = 0) = 1 - \exp \left[\frac{-(r^2 Q_{sp}^2)^\gamma}{4} \ln \left(\frac{1}{r \Lambda_{\text{QCD}}} + e_c \cdot e \right) \right],$$

$$\alpha_s(r^2) = \frac{12\pi}{(33 - 2N_f) \ln \frac{4C^2}{r^2 \Lambda_{\text{QCD}}^2}}.$$

Compute σ_r (or F_2), assume factorizable proton impact parameter profile

$$\sigma_{T,L}^{\gamma^* p} = \sigma_0 \int dz |\Psi_{\gamma^* \rightarrow q\bar{q}}^{T,L}|^2 N(r, y)$$

Fit different models:

- MV with $\gamma \equiv 1, e_c \equiv 1$.
- MV^γ with $e_c \equiv 1$, fit γ (AAMQS collaboration, arXiv:1012.4408).
- MV^e with $\gamma \equiv 1$, fit e_c (NEW).

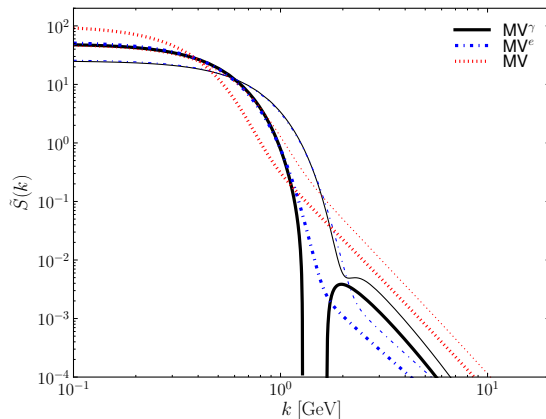
Fit result

Fit to HERA σ_r data at $Q^2 < 50 \text{ GeV}^2, x < 0.01$ (MV^γ fit by AAMQS).

	$\frac{\chi^2}{\text{d.o.f}}$	$Q_{s0}^2 [\text{GeV}^2]$	$Q_s^2 [\text{GeV}^2]$	γ	C^2	e_c	$\sigma_0/2 [\text{mb}]$
MV	2.76	0.104	0.139	1	14.5	1	18.81
MV^γ	1.18	0.165	0.245	1.135	6.35	1	16.45
MV^e	1.15	0.060	0.238	1	7.2	18.9	16.36

- Fit quality is significantly improved when also fitting γ or e_c .
- MV^γ : Fourier transform of $N(r)$ (\sim single inclusive yield) becomes negative at large k
- + MV^e : Positive (next slide)
- + MV^e without γ is easier to generalize for nuclei.

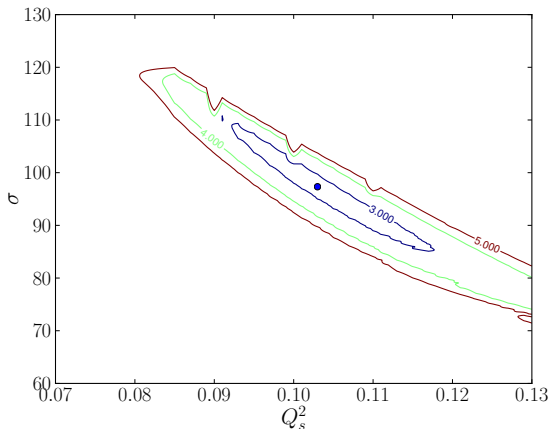
Fourier transform of the ICs



- Thick lines: Fundamental representation
- Thin lines: Adjoint representation

Correlations

Fit parameters are correlated. More detailed analysis is required to obtain error sets (in progress).



Example: MV model, initial saturation scale Q_s^2 and proton size σ_0 .

Single inclusive hadron production from CGC

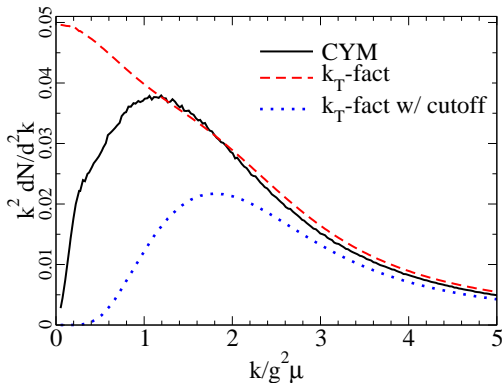
Single inclusive particle production in pp using the k_T factorization:

$$\frac{d\sigma}{d^2p_T dy} = \frac{2\alpha_s}{C_F p_T^2} \int d^2q_T \frac{\varphi_{x_1}(q_T)}{q_T^2} \frac{\varphi_{x_2}(k_T - q_T)}{(k_T - q_T)^2}$$

- Agrees with CYM for $p_T \gtrsim Q_s$
- $\varphi_{x_{1,2}}$: dipole (not WW) UGD of hadron 1/2.

$$\varphi(k_T) \sim \frac{\sigma_0}{2} k^4 \int d^2r e^{ikr} [1 - N(r)]$$

Blaizot, Lappi, Mehtar-Tani, arXiv:1005.0955



Single inclusive hadron production from CGC

$$\frac{d\sigma}{d^2p_T dy} = \frac{2\alpha_s}{C_F p_T^2} \int d^2q_T \frac{\varphi_{x_1}(q_T)}{q_T^2} \frac{\varphi_{x_2}(p_T - q_T)}{(p_T - q_T)^2}$$

Assuming that $p_T \gg Q_s$ we get the hybrid formalism

(Note: $\varphi \sim \sigma_0/2 =$ proton DIS area).

$$\frac{dN}{dy d^2p_T} = \frac{\sigma_0/2}{\sigma_{\text{inel}}} \frac{1}{(2\pi)^2} xg(x, Q^2) \tilde{S}(p_T),$$

where

$$xg(x, Q^2) = \frac{C_F \sigma_0/2}{2\pi^2 \alpha_s} \int^{Q^2} \frac{d^2q_T}{(2\pi)^2} q_T^2 \tilde{S}(q_T),$$

(or e.g. CTEQ) and \tilde{S} is Fourier transform of $1 - N(r)$ (adj. rep.).

Normalization factor

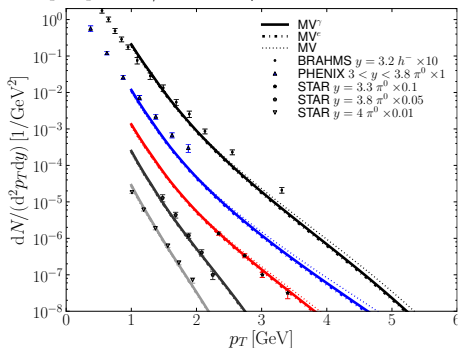
At RHIC (LHC) $(\sigma_0/2)/\sigma_{\text{inel}} \sim 0.4$ (0.3)

Single inclusive hadron production from CGC

MV^γ and MV^e models work with the LHC data, MV does not.

RHIC

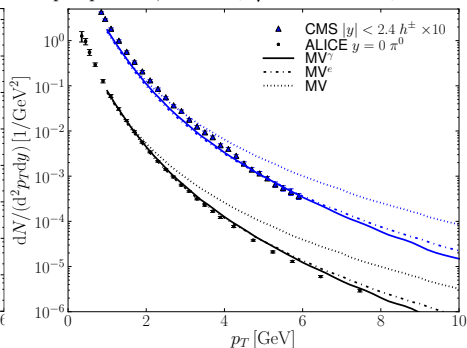
$p + p \rightarrow \pi^0/h^- + X, \sqrt{s} = 200 \text{ GeV}, K = 2.5$



Hybrid formalism, LO CTEQ&DSS

LHC

$p + p \rightarrow \pi^0, h^\pm + X, \sqrt{s} = 7000 \text{ GeV}, K = 1$



k_T factorization, LO DSS

From proton to nucleus

Initial condition for nuclei: Glauber (dilute limit $\sigma_{\text{dip}}^A \sim A\sigma_{\text{dip}}^p$)

$$N_A(b, r) = 1 - \exp \left[-A T_A(b) \frac{\sigma_0}{2} \frac{(r^2 Q_{sp}^2)^\gamma}{4} \ln \left(\frac{1}{\Lambda_{\text{QCD}} r} + e_c \cdot e \right) \right].$$

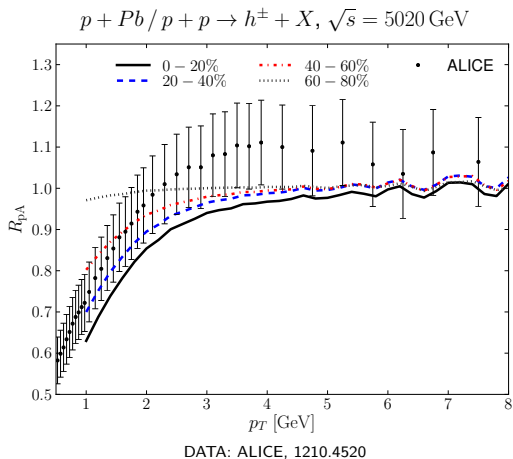
No additional nuclear parameters

- σ_0 from DIS
- T_A : standard Woods-Saxon

\Rightarrow prediction for Q_s^2 .

From proton to nucleus: R_{pA}

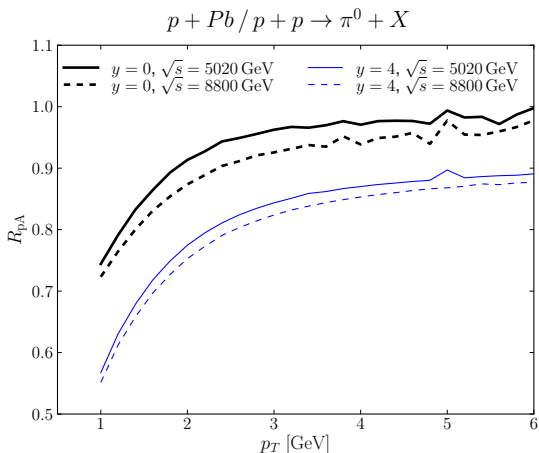
Consistent with ALICE pA data (k_T factorization, LO-DSS fragfun)



MV , MV^γ and MV^e give \approx same R_{pA}

Energy dependence of R_{pA}

$R_{pA} \rightarrow 1$ at large p_T independently of $\sqrt{s_{NN}}$!

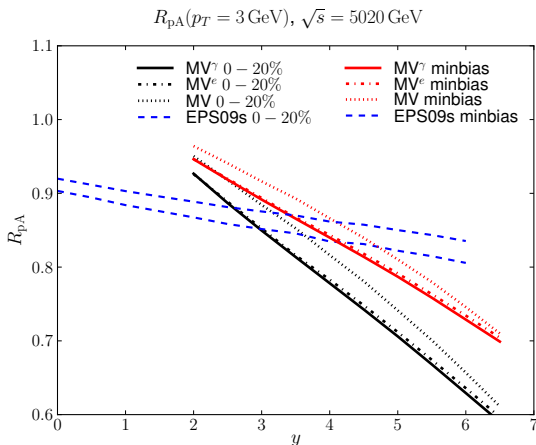


R_{pA} at $y = 0$ (k_T factorization) and at $y = 4$ (hybrid formalism)

CGC vs pQCD (EPS09s)

CGC predicts faster centrality and especially rapidity evolution than
EPS09s-NLO pQCD

EPS09s calculations by I. Helenius



CGC: Hybrid formalism, LO-CTEQ PDF, LO DSS FF.

- New initial condition MV^e fitted to HERA data.
- MV model must be modified (include γ or e_c) in order describe LHC pp and pA spectra
- Using only ep DIS as an input we compute single particle production in pp and pA.
- Single inclusive spectrum: absolute normalization
- Centrality and rapidity dependent predictions for R_{pA}
 - Faster rapidity evolution than predicted by NLO pQCD calculations (EPS09s).

BACKUPS

Value of Λ_{QCD}

$$\alpha_s(r^2) = \frac{12\pi}{(33 - 2N_f) \ln \frac{4C^2}{r^2 \Lambda_{\text{QCD}}^2}}.$$

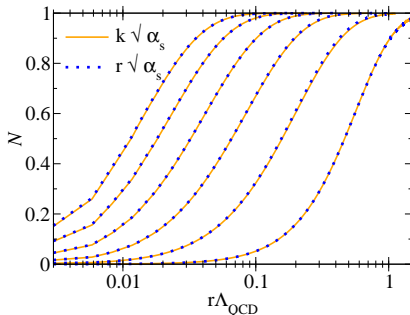
Fit result: $C^2 \sim 6$.

Analytically (Kovchegov, Weigert, 2007): $4C^2 = 4e^{-2\gamma E}$

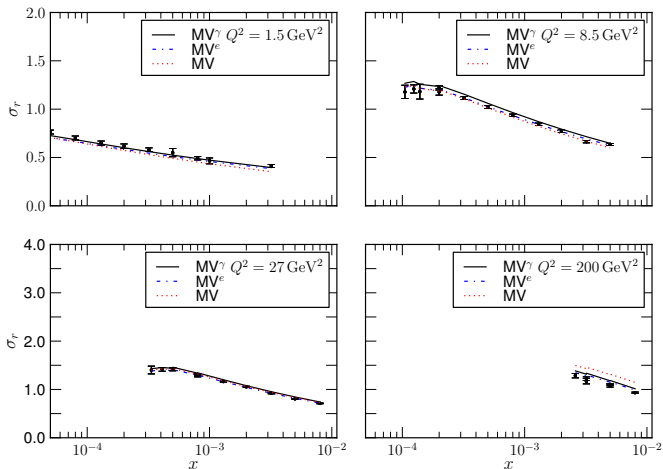
\Rightarrow Effectively $\Lambda_{\text{QCD}} \sim 50 \text{ MeV}??$ (NLO effects \rightarrow slower evolution?)

Dipole amplitude at various y
from JIMWLK

- Solid: $\alpha_s(k)$ (standard)
- Dashed: $\alpha_s(r)$,
 $4C^2 = 4e^{-2\gamma E}$

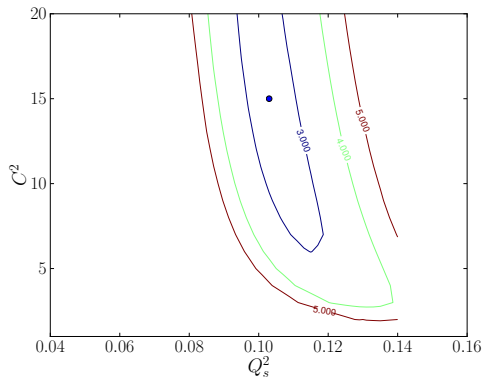


Fit result



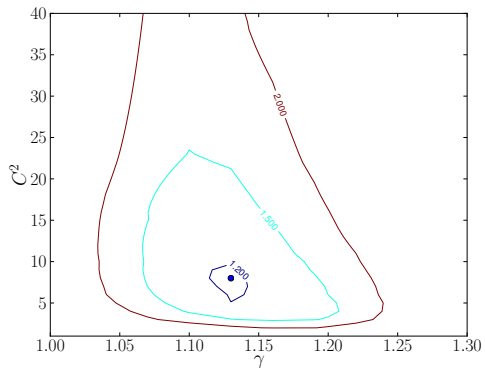
MV fitted to $Q^2 < 50 \text{ GeV}^2$ HERA data (arXiv:0911.0884)

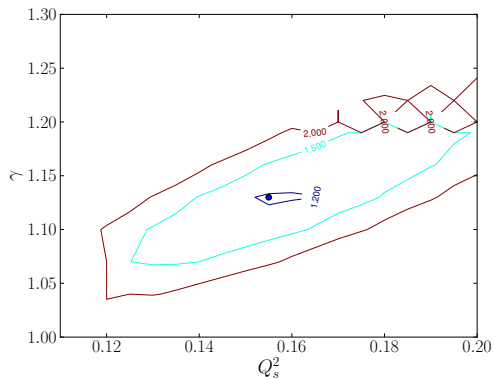
Example: MV^γ



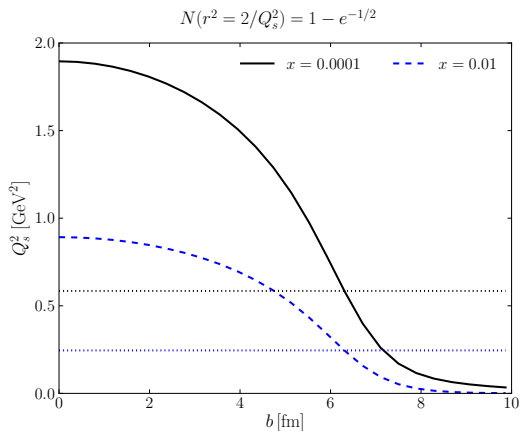
- Initial saturation scale Q_s^2 and α_s scale C^2 are slightly correlated.

Correlations: MV^γ



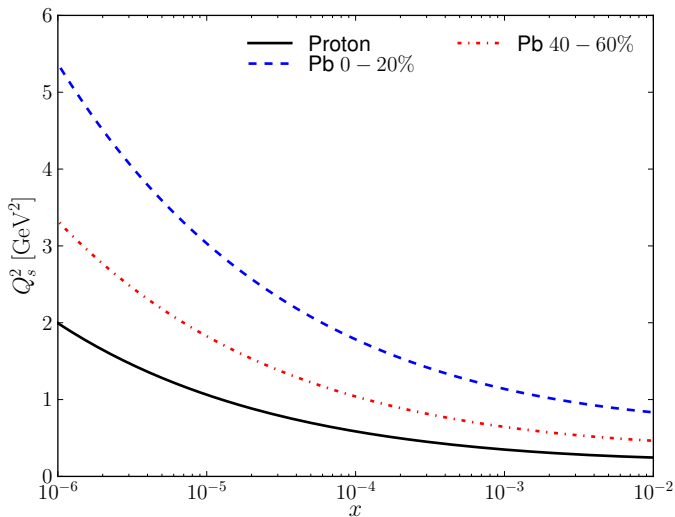


Impact parameter dependence of the saturation scale

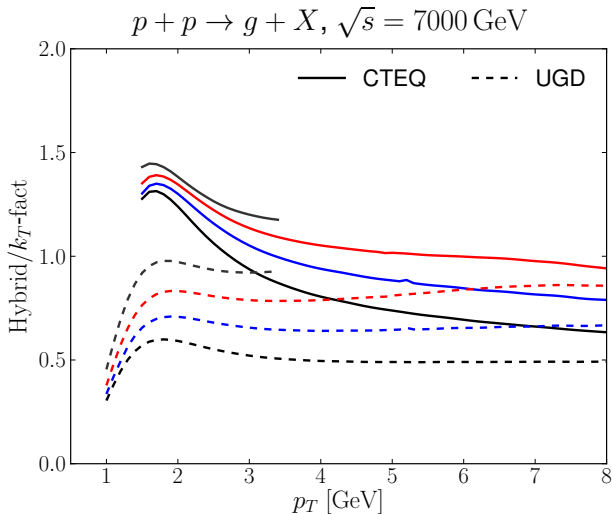


From proton to nucleus: saturation scale

$$N(r^2 = 2/Q_s^2) = 1 - e^{-1/2}$$

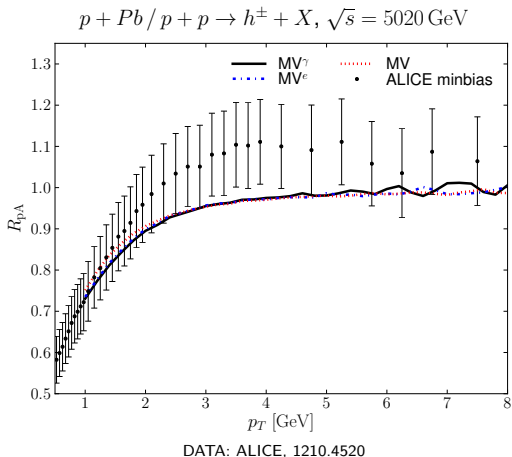


k_T factorization vs hybrid formalism



From proton to nucleus

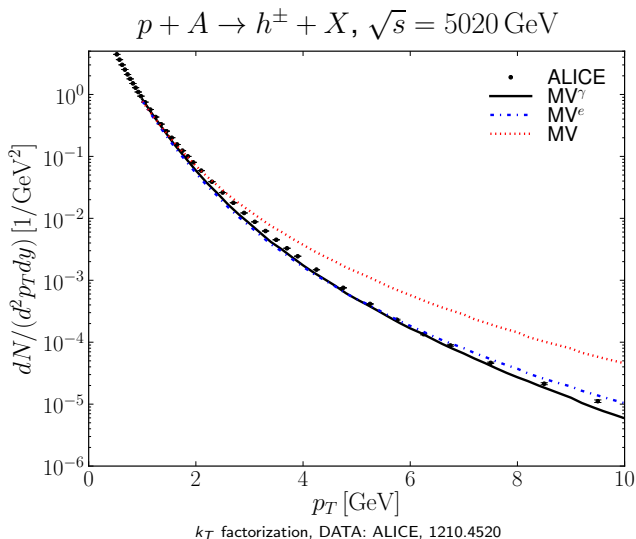
Consistent with ALICE pA data (k_T factorization, LO-DSS fragfun)



Minimum bias, small dependence on initial condition (also MV model works).

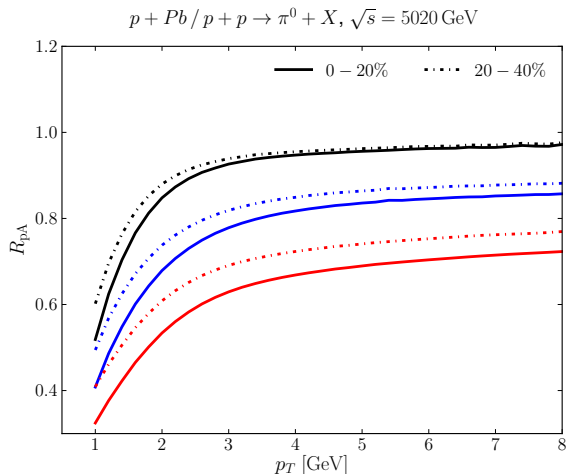
ALICE $p + Pb$ spectrum, k_T factorization

MV^γ and MV^e model ICs work with ALICE data, MV does not.



Rapidity dependence of R_{pA} : 0 – 20% vs 20 – 40%

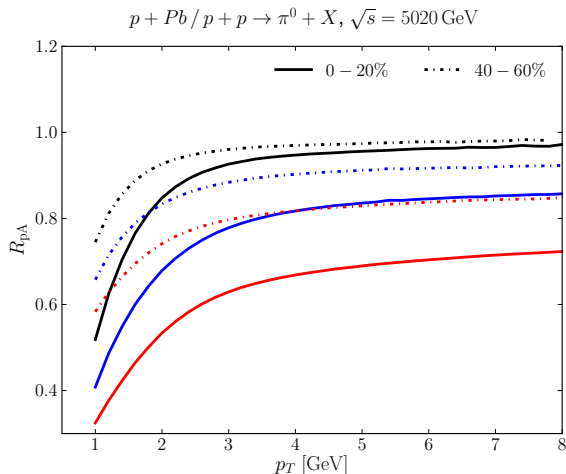
Centrality dependence increases at forward rapidities ($y = 2, 4, 6$)



Hybrid formalism, LO-CTEQ PDF, LO DSS FF.

Rapidity dependence of R_{pA} : 0 – 20% vs 40 – 60%

Centrality dependence increases at forward rapidities ($y = 2, 4, 6$)



Hybrid formalism, LO-CTEQ PDF, LO DSS FF.