CGC Fit to HERA DIS and Forward Hadron Production in p+p Collisions

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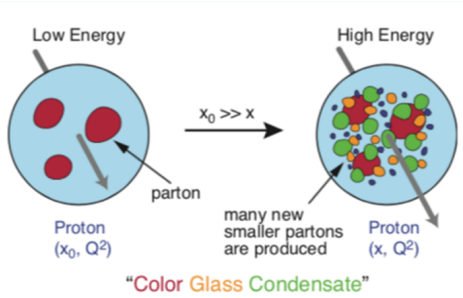
Gluon Saturation

Hints of gluon saturation:

- Suppression of forward particle yields in d+Au collisions relative to p+p collisions at RHIC. [Arsene et al., 2004, Adams et al., 2006]
- Suppression of away-side peaks in di-hadron correlations at forward rapidities in proton-nucleus collisions at RHIC and the LHC. [Abdallah et al., 2022]

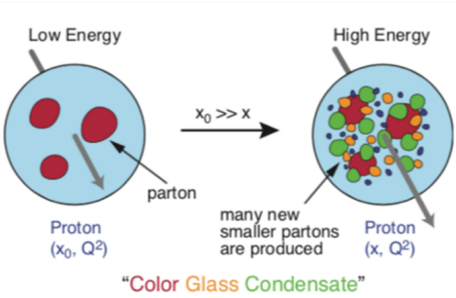
CGC Framework



Properties:

- Characterized by scale $Q_s^2 \rightarrow$ many studies
- Universal property

CGC Framework



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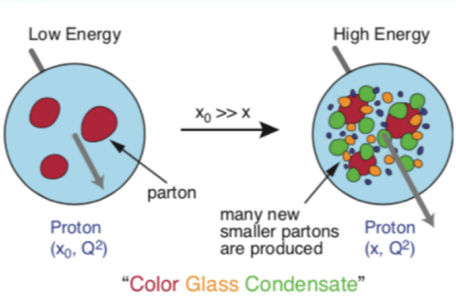
CGC Framework



Properties:

- Characterized by scale $Q_s^2 \rightarrow$ many studies
- Universal property $\rightarrow$ our goal
- Non-linear dynamic, governed by BK/JIMWLK

LO BK equation

The Balitsky-Kovchegov (BK) equation is: [Balitsky, 1996, Kovchegov, 1999]

$$\frac{\partial \mathcal{N}(r,Y)}{\partial Y} = \int d^2\boldsymbol{r}\, K_{\rm run}(r,r_1,r_2)\left[\mathcal{N}(r_1,Y)+\mathcal{N}(r_2,Y)-\mathcal{N}(r,Y)+\mathcal{N}(r_1,Y)N(r_2,Y)\right] \quad (1)$$

where $Y = \ln 1/x$.

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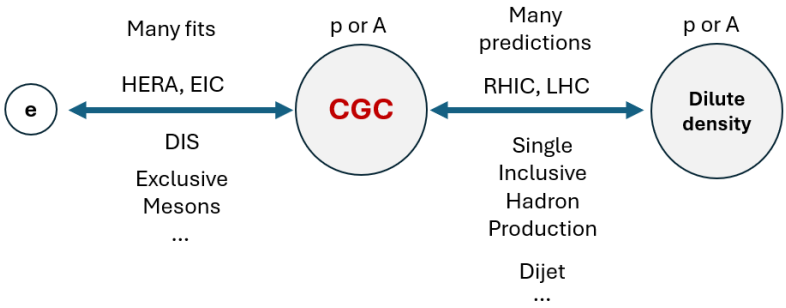
where $Y = \ln 1/x$.

Question: What is the value of initial $\mathcal{N}(r,x_0)$? $\rightarrow$ Fitting.

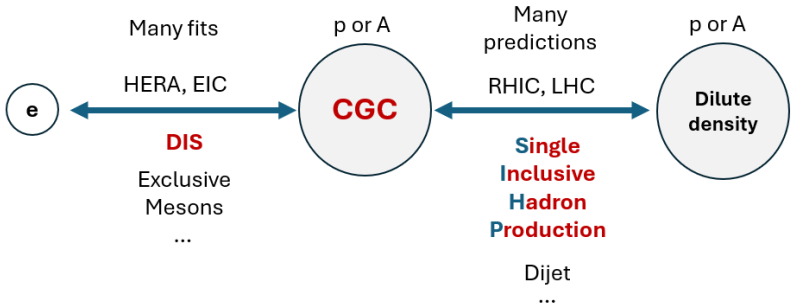
Initial dipole amplitude ansatz: MV$^\gamma$ [McLerran and Venugopalan, 1998]

$$\mathcal{N}(r_T,x_0) = 1-\exp\left[-\frac{(r_T^2 Q_{s0}^2)^\gamma}{4}\ln\left(\frac{1}{|r_T|\Lambda_{\rm QCD}}+e\right)\right] \quad (2)$$

Which observables ?

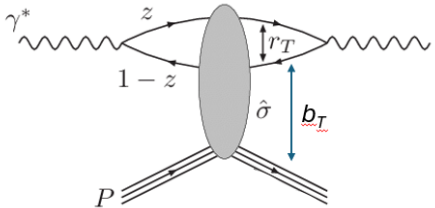


Which observables ?



Goal: Show universal property of CGC by performing a global fit.

DIS in dipole formalism



Reduce cross-section:

$$\sigma_{T,L}^{\gamma^* p}(x,Q^2) = 2\frac{\sigma_0}{2}\sum_f \int dz \int d^2\boldsymbol{r_T} \underbrace{\left|\psi_{T,L}^{\gamma^*\to f\bar{f}}(z,r_T,Q^2)\right|^2}_{\gamma^*\to q\bar{q}} \underbrace{\mathcal{N}(r_T,x)}_{q\bar{q}+\mathrm{CGC}}, \tag{3}$$

where $\left|\psi_{T,L}^{\gamma^*\to f\bar{f}}\right|$ is computed in QED.
$\sigma_0/2$ is the effective proton transverse area.

Data source: HERA [Abramowicz et al., 2015]

The invariant yield cross-section: [Chirilli et al., 2012, Rezaeian, 2013]

$$\frac{dN_h}{dy_h d^2\boldsymbol{p}_T} = \frac{K}{(2\pi)^2}\frac{\sigma_0/2}{\sigma_{inel}}\int_{x_F}^1 \frac{dz}{z^2}\Big[\sum_q x_1 f_{q/p}(x_1,\mu^2)\widetilde{\mathcal{N}}_F(x_2,\frac{p_T}{z})D_{h/q}(z,\mu^2) + x_1 f_{g/p}(x_1,\mu^2)\widetilde{\mathcal{N}}_A(x_2,\frac{p_T}{z})D_{h/g}(z,\mu^2)\Big]. \quad (4)$$

where $x_1 = \frac{p_T}{z\sqrt{s}}e^{y_h} \gg x_0$, $\quad x_2 = \frac{p_T}{z\sqrt{s}}e^{-y_h} \ll x_0$ and $x_F = \frac{p_T}{\sqrt{s}}e^{y_h}$.
$\widetilde{\mathcal{N}}_{F(A)}(k,x) = \int d^2\boldsymbol{r}e^{-i\boldsymbol{r}\cdot\boldsymbol{k}}\left[1-\mathcal{N}_{F(A)}(r,x)\right]$, $\quad \mathcal{N}_A = 2\mathcal{N}_F - \mathcal{N}_F^2$.

Data source:
BRAHMS, STAR (RHIC) [Arsene et al., 2004, Adams et al., 2006]
LHCb 5,02 TeV and 13 TeV [Aaij et al., 2022a, Aaij et al., 2022b].

Set up

1. Initial dipole model: MV$^\gamma$.
2. BK evolution: rcBK and kcBK [Beuf, 2014]
3. Strong coupling: [Beuf et al., 2020]

$$\alpha_S(r^2) = \frac{4\pi}{\beta_0 \left[\left(\frac{\mu_0^2}{\Lambda_{QCD}^2} \right)^{1/c} + \left(\frac{4C^2}{r^2 \Lambda_{QCD}^2} \right)^{1/c} \right]^c} \tag{5}$$

4. Factorization scale for PDF and FF:

$$\mu^2 = (p_T/z)^2 + Q_s^2, \quad Q_s^2 = Q_0^2 \left(\frac{x_0}{x} \right)^\lambda.$$

5. Parameters:

$$Q_{s0}^2, \quad \sigma_0, \quad C, \quad \gamma, \quad K_{\text{RHIC}}, \quad K_{\text{LHCb}}.$$

6. Uncertainties:
   Experimental + Theoretical (FF + Scale variation from $[\mu^2/2, 2\mu^2]$)

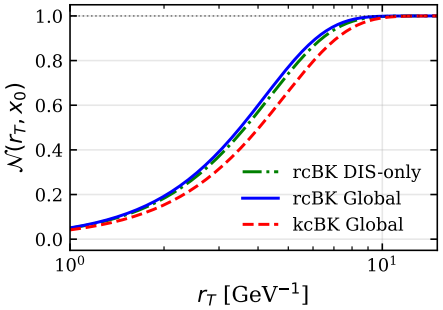
Numerical set up

- PDF: CTEQ NLO [Stump et al., 2003],
  FF: NNFF1.0 [Bertone et al., 2017]
- 3 light flavor quarks
- $x_0 = 0.015, \quad \Lambda_{QCD} = 0.241$ GeV, $\quad m_q = 0.14$ GeV,
  $\sigma_{inel} = 41$ mb.
- Freeze strong coupling to ≈ 0.75.
- Data:
  DIS: cut-off $Q^2 < 45\text{GeV}^2$, $\quad$ SIHP: cut-off $p_T > 1$ GeV.

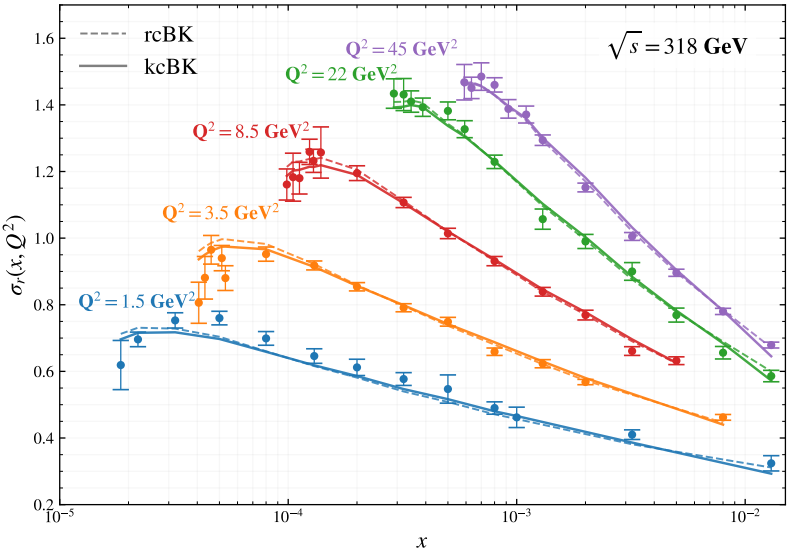
Results

Table 1: Best-fit parameters for DIS-only fit and global fit. (dof = dof' + # parameters)

Scheme	Q_{s0}^2 (GeV^2)	γ	C^2	$\sigma_0/2$ (mb)	$\chi^2_{\rm DIS}/dof'$	$\chi^2_{\rm RHIC}/dof'$	$\chi^2_{\rm LHCb}/dof'$	$\chi^2_{\rm tot}/dof$
rcBK	0.141	1.152	10.296	17.263	0.97	—	—	0.98
rcBK	0.149	1.17	8.6	16.766	0.98	0.22	1.04	0.97
K-factors	—	—	—	—	—	5.42	2.66	—
kcBK	0.118	1.138	1.11	18.82	1.15	0.21	1.47	1.18
K-factors	—	—	—	—	—	5.88	2.83	—

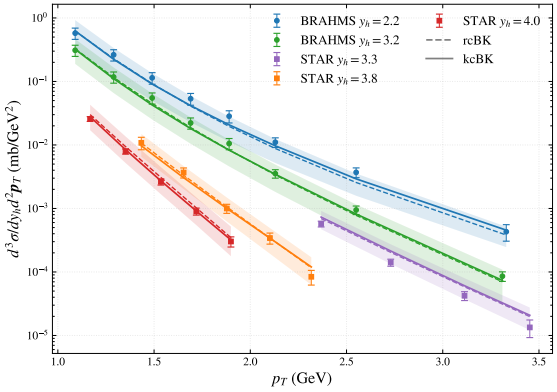


DIS Observable

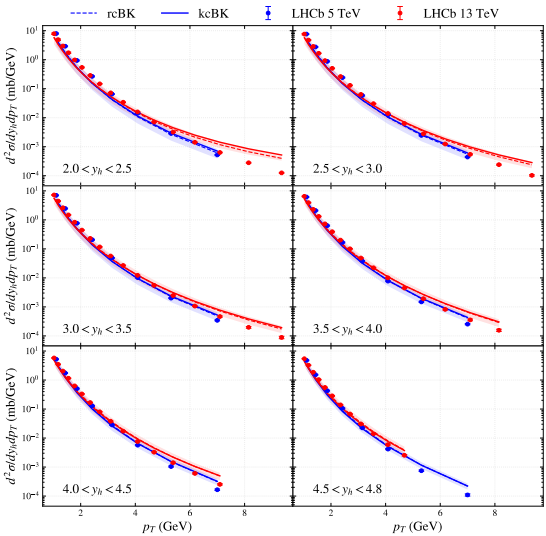


SIHP Observables

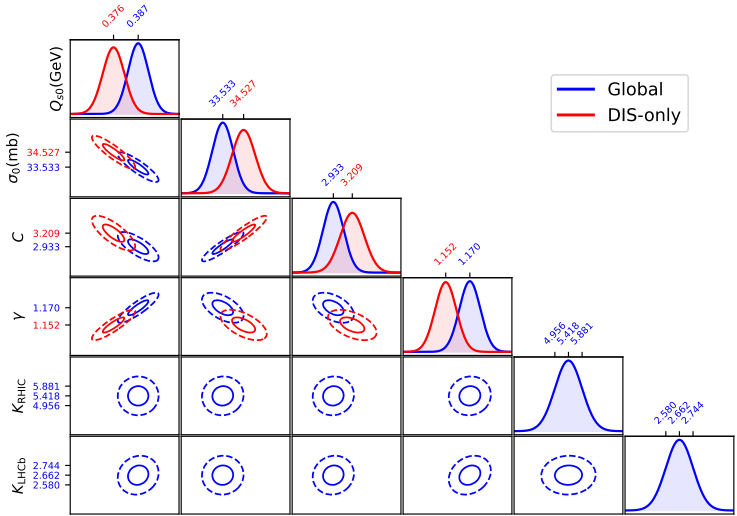
(a) RHIC results



(b) LHCb results



Correlation Matrices



Conclusions

1. Show the applicability of CGC framework to explain different processes $\rightarrow$ universal property.
2. Need to improve: Higher-order effect, resummation for large p_t.
3. Future: Apply for p+A processes, different obsevables, NLO BK evolution.

Thank you for listening!

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Figure 2: Integrand

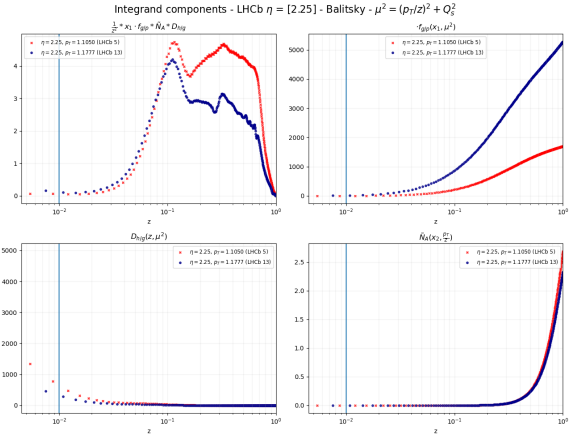


Figure 3: Comparision of 2 different factorization scales choices

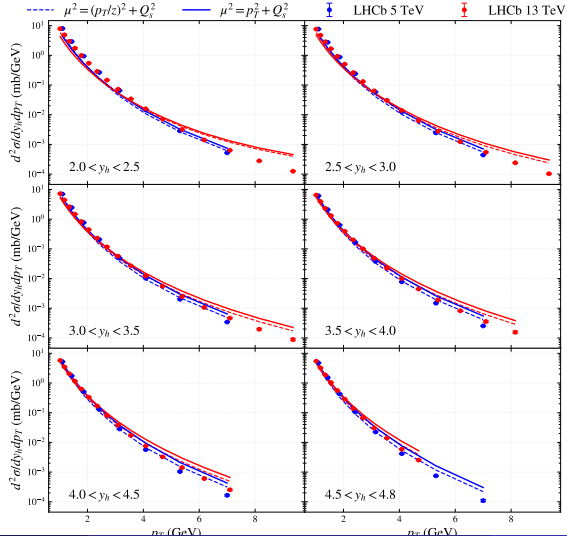
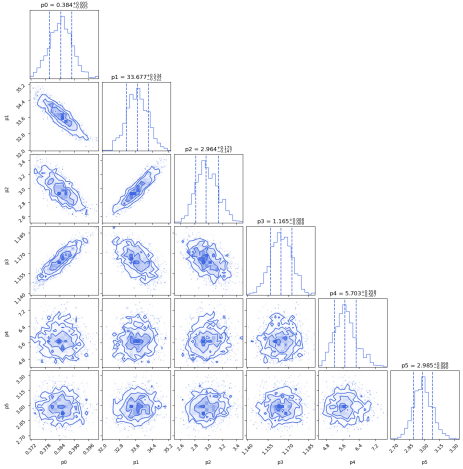


Table 2: Results for different choice of FF sets

Data	Scheme	Q_{s0}(GeV)	σ_0 (mb)	C	e_c	γ	K_{brahms} / χ^2_{brahms}	K_{star} / χ^2_{star}	K_{lhcb5} / χ^2_{lhcb5}	K_{lhcb13} / χ^2_{lhcb13}	DIS χ^2_{DIS}	$\chi^2/d.o.f$	# data
DIS SIHP	Balit all errs	0.3865699	33.53254	2.932521	1.0	1.169583	5.418338		2.66203		0.978	0.967	704
							0.224	0.211	1.076	1.024			
DIS SIHP MSTW+JAM	Balit all errs	0.4251642	29.91363	2.082021	1.0	1.2243	8.279709		4.22993		1.15	1.73	704
							0.467	0.111	3.235	4.551			
DIS SIHP CTEQ+NPC23	Balit all errs	0.4535374	28.46309	1.747888	1.0	1.28959	6.043932		5.857884		1.42	3.22	704
							9.62	1.82	9.66	9.04			
DIS SIHP MSTW+NPC23	Balit $p_T < 6$	0.3967832	32.79983	2.782417	1.0	1.187585	13.96747	4.867839	6.262937		1.0	1.89	681
							0.27	0.56	7.76	5.2			

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