Experimental evidence for saturation — a mini-review

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Experimental evidence of saturation?

**Q^2 evolution: gluon density**

Gluon content of proton rises quickly with Q^2.

Something must ‘tame’ the gluons at low x non-linear evolution, gluon fusion?
Where do we expect saturation?

- Non-linear processes, gluon fusion expected to become important
  - At small $Q^2 < Q^2_s$
  - At small $x$, i.e. where $Q_s$ is large enough
  - Effect sets in earlier in nuclei than in protons
- Most studies to date: compare nuclei to protons/neutrons

\[ Q_s^2 \approx \frac{xG_A(x, Q^2)}{\pi R_A^2} \propto A^{1/3} x^{-\lambda} \]
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• Observables/measurements:
  • Inclusive production: forward, moderate to low $p_T$ probes small $x$
    • Forward open charm: reach to smallest $x$ in current LHC results
    • Direct photons: clean probe, but mostly measured at mid-rapidity, fairly high $p_T$
    • Electroweak bosons: both forward and mid-rapidity, large $Q^2$ —> Not discussed here
  • UPC $J/\psi$ production: very small $x$, small $Q^2$
  • Two-particle correlations: look for mono-jet topology, multi-gluon recoil

\[ Q_s^2 \approx \frac{xG_A(x, Q^2)}{\pi R_A^2} \propto A^{1/3} x^{-\lambda} \]
Evidence for saturation/shadowing from DIS: NMC data

DIS kinematics: small \( x \) is also small \( Q^2 \).

Small \( x \) reach depends on \( Q^2 \) cut-off.

Main evidence for shadowing/saturation from DIS concentrated at small \( Q^2 \).

**EPPS16 PDF fit**

- \( Q^2_{\text{min}} = 1.69 \text{ GeV}^2 \)

**nNNPDF fit**

- \( Q^2_{\text{min}} = 3.5 \text{ GeV}^2 \)

**Evidence for saturation/shadowing from DIS: NMC data**

NMC, Nucl. Phys. B441, 3

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nPDF gluon densities at small $x$

Suppression of gluon density ‘shadowing’ from global fit; small-$x$ driven by NMC data
Amount of suppression varies between fits
Large uncertainties over broad range $x < 10^{-2}$

EPPS16 gluon density in Pb nucleus

$n$PDF gluon densities at small $x$
Probing gluons with inclusive particle production
**2-parton kinematics**

**Both outgoing partons at mid-rapidity**

\[ x_2 \approx x_1 \approx \frac{2p_T}{\sqrt{s}} \]

**Both outgoing partons at forward rapidity**

\[ \hat{s} = x_1 x_2 s \approx (2p_T)^2 \]

\[ x_1 \approx \frac{p_T}{\sqrt{s}} e^{-y} \]

**One parton forward, one closer to mid-rap**

\[ \hat{s} = x_1 x_2 s \approx (2p_T)^2 \]

\[ Q^2 = \hat{s} > (2p_T)^2 \]

**Both incoming partons at moderate x**

\[ \hat{s} = x_1 x_2 s \approx (2p_T)^2 \]

**Boosted configuration:**

**One small-x, one large-x parton**

\[ x_1 \approx x_2 \approx \frac{2p_T}{\sqrt{s}} \]

**Large mass final state**

Note: 2 to 2 scattering is LO kinematics; NLO processes add additional freedom/smearing.

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RHIC forward particle suppression

- Nuclear modification factor $R_{dAu}$
  \[ R_{dAu} = \frac{dN/dp_T|_{dAu}}{Ad\sigma/dp_T|_{pp}} \]

- Yield suppression $R_{dAu} < 1$ seen at RHIC
  - Low $p_T$: expect also $N_{\text{part}}$ vs $N_{\text{coll}}$ scaling
  - $p_T > 2$ GeV, $R_{dAu} \sim 0.8$

  Probes $x \sim 10^{-3}$

First hint of saturation?  
⇒ Can we confirm this at LHC?

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STAR: charged hadrons, $\pi^0$

BRAHMS: charged hadrons

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RHIC and LHC for $x \sim 10^{-4}$

$x_2 \approx \frac{p_T}{\sqrt{s}} \left( e^{-y_3} + e^{-y_4} \right)$

Mid-rapidity at LHC $\approx$ forward rapidity at RHIC

No sign of suppression at high $p_T > 2$ GeV
$p_T < 2$ GeV expect soft effects; $N_{\text{part}}$ scaling

Enhancement for protons?
Open charm production vs rapidity at LHC

Backward rapidity: large x

Mid-rapidity

Forward rapidity: small x

\[ R_{p\text{Pb}} \sim 1 \text{ at backward and mid-rapidity; below 1 at forward rapidity} \]

Suppression mainly at small-x compatible with nuclear PDFs (shadowing) and CGC calculations

CGC: Decloue et al, PRD 91, 114005
Open charm production at backward and forward rapidity

ALICE: Heavy flavour decay muons

Forward muons (ALICE) show similar trend, different normalisation:

\( R_{pPb} \approx 1 \) at forward (small-\( x \)), but enhancement in backward direction

(Note: measured \( p_T \) is from decay muon)
Final state effects in p-Pb collisions: ‘radial and elliptic flow’?

$Q_{pPb}$ for charm, central and peripheral

ALICE Preliminary

p-Pb, $\sqrt{s_{NN}} = 5.02$ TeV

Prompt D mesons
Average $D^0$, $D^+$, $D^{**}$

-0.96 $< y_{cm} < 0.04$

$0$--$10\%$ ZN energy
$60$--$100\%$ ZN energy

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Final state effects in p-Pb collisions: ‘radial and elliptic flow’?

$Q_{pPb}$ for charm, central and peripheral

Ratio central/peripheral shows hint of flow-like ‘bump’

(Q$_{CP} > 1$ significance 1.5σ)

ALICE, PRL 122, 072301
Final state effects in p-Pb collisions: ‘radial and elliptic flow’?

$Q_{pPb}$ for charm, central and peripheral

$v_2$ for heavy flavour electrons and muons

Ratio central/peripheral shows hint of flow-like ‘bump’
($Q_{CP} > 1$ significance 1.5σ)

Clear $v_2$-like modulations for HF decay muons and electrons strength of modulation smaller than for charged particles in p-Pb

Interesting physics, but a ‘nuisance effect’ for parton density studies…
PDF reweighting with charm: full NLO charm calculation

Eskola, Helenius et al, JHEP 05 (2020) 037

EPPS16 reweighting

nCTEQ15 reweighting

Forward charm data brings significant constraints; prefer shadowing with

\[ R_g \sim 0.7 \text{ at } x < 5 \times 10^{-3} \ (Q^2 = 10 \text{ GeV}) \]
Q$^2$ dependence

Charm reweighted PDFs show strong dependence on Q$^2$

Probably a robust feature: DGLAP evolution

Can we test this experimentally? How low in Q$^2$ do we trust the formalism?
Probing the proton PDFs with UPC

\( \gamma + p \rightarrow J/\psi + p \)

parton level: \( \gamma g \rightarrow c \bar{c} \)

Probes proton structure at \( x < 10^{-4} \); potential to constrain PDFs at small-\( x \)
UPC J/ψ production: Pb-Pb

UPC Pb-Pb probes
gluon density in nucleus

Measured cross section below
free-nucleon ‘impulse approximation’

Indicates shadowing/saturation at Q ≈ 1/2 m_{J/ψ}
Summary so far

• Signs of suppression of inclusive particle production in small-\(x\) regime
  • RHIC: charged particle/light hadron suppression
  • LHC: \(D\) meson suppression at forward rapidity
• nPDF fits with forward \(D\) meson input: smaller gluon density in nuclei
• UPC results also indicate smaller gluon density in nuclei
• However, some open questions:
  • RHIC and LHC see effects at different \(x\)
    • Multiple interactions near kinematic limits?
  • Tension between ALICE forward muons and LHCb \(D\) mesons
  • Impact of flow-like effects? Final state scattering?

New/cleaner measurements (photons; maybe UPC?) and/or confirmation by multiple experiments very welcome!
Two-particle correlations: concept

QCD $2 \rightarrow 2$ scattering

Produces a back-to-back jet

CGC: recoil taken by multiple gluons

Soft gluon recoil

Recoil jet broadened/disappears

Attractive observable:
- Conceptually simple interpretation
- Probes multiple gluon interactions (CGC/saturation)
- Scan $x$ (and $Q^2$) by varying rapidity of both jets

Kharzeev et al, hep-ph/0403271
De-correlation of recoil yield for fwd-fwd correlations

- Consistent with CGC: coherent gluon field
- Very low $p_T$; other effects, e.g. multiple parton interactions might play a role
Di-hadron correlations at RHIC: PHENIX

Experimental review of saturation, Initial Stages 2021

Scan ‘x’ with $p_{T1}$ and forward, mid rapidity

Similar effects, trends as a function of $x$

Large suppression at ‘x’ $< 10^{-3}$ in central events
Di-hadron correlations at LHC

Multiplicity dependence of di-hadron correlations

Try to separate jet-like and flow-like correlations?
Near side long range amplitude 20-50 per cent of away side!
Di-hadron correlations at LHC

G Giacalone, C Marquet, NPA 982, 291 (QM2018)

Away-side peak after flow subtraction

Assumes pure $v_2$; near-away symmetry for long-range component

Yield suppression and mild broadening?

Comparison to CGC calculation

Theory calculations show narrow peak; add final state radiation/shower effects?
Summary

• Multiple indications of saturation/reduced gluon density at small $x$ in the data:
  • DIS on nuclei
  • Forward particle production at RHIC and LHC
  • UPC
  • Di-hadron correlations — so far not conclusive?
• However, not a ‘closed case’
  • Are RHIC and LHC consistent?
  • (Most) observed are at small $p_T$: theory uncertainties?
  • Di-hadron correlations not systematically explored
• Possible future directions
  • Other forward hadron production at LHC, e.g. charged (identified) particles in LHCb
  • Photons at fwd rapidity: ALICE FoCal, LHCb
  • Systematically explore forward correlations at LHC
  • EIC
Thank you for your attention!
**ALICE FoCal upgrade**

**FoCal-E**: high-granularity Si-W sampling calorimeter for photons and π⁰

**FoCal-H**: conventional metal-scintillator sampling calorimeter for photon isolation and jets

**Observables:**
- π⁰ (and other neutral mesons)
- **Isolated (direct) photons**
- Jets (and di-jets)
- J/ψ (ϒ) in UPC
- W, Z
- Event plane and centrality

Letter of Intent: LHCC-2020-009

Reweighted gluon PDFs

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R. A. Khalek et al, JHEP 09 (2020) 183
Hidden charm: forward/backward $J/\Psi$ production

ALICE, JHEP 07 (2018) 160

Caveat: $J/\Psi$ hadronisation and possible final state effects (e.g. co-movers) introduce sizeable uncertainties

Suppression at low $p_T < 6$ GeV qualitatively consistent with CGC expectations

nPDFs show less $p_T$ dependence

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**x-Dependence of PDF modification**

EPPS16, EPJC 77, 163

\[ R_i^A(x, Q^2) = \begin{cases} 
\frac{a_0 + a_1(x - x_a)^2}{b_0 + b_1 x^\alpha + b_2 x^{2\alpha} + b_3 x^{3\alpha}} & x \leq x_a \\
\frac{c_0 + (c_1 - c_2 x)(1 - x)^{-\beta}}{x_a \leq x \leq x_e} & x_e \leq x \leq 1 
\end{cases} \]

- parameterisation of \( R_A \)
- shape similar to EPS09
- at low \( x \) leads to “plateau” in \( \log(x) \)

- likely not sufficient
- more flexible PDF used for LHeC estimates

![Graph showing x-Dependence of PDF modification](image)
Constraining nPDFs with charm: reweighting

This reweighting procedure with a parametrised NLO calculation results in large shadowing; predict significant suppression at mid-rapidity; tension with data
Reweighting with charm, beauty


(a) $D$ RnPDFs

(b) $B \to J/\psi$ RnPDFs

(c) $J/\psi$ RnPDFs
Changing the total cross section?

Jyvaskyla group: ATLAS EW data suggest that effective total cross section is smaller in p-Pb than free nucleons.

PHENIX R_{dAu}: unexpected centrality dependence. Suggested interpretation: total cross section depends on x?
Forward di-jet correlations at LHC

Di-jets with $p_T$ 28-45 GeV

Some bins show difference, but no clear trend…

TMD framework calculation

TMD: expect ‘dip’ near $\Delta \phi = \pi$ for balancing jets

Physical origin?
Di-hadron correlations

Albacete, Giacalone, Marquet, Matas, PRD 99, 014002

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LHC prediction

- pA, 5 < \pT < 7 GeV
- pp, 5 < \pT < 7 GeV
- pA, 7 < \pT < 10 GeV
- pp, 7 < \pT < 10 GeV

\( R_{pA} \)

\( 3 < \eta < 4 \)

\( 4 < \eta < 5 \)

\( \sqrt{s} = 8.8 \text{ TeV} \)
Di-hadron correlation CGC theory: RHIC

Stasto, Wei, Xiao, Yuan, PLB 784, 301
Gluon Densities at small $x$

Even in the proton, limited information about gluons at $x < 10^{-4}$

Ratio Pb/p has large uncertainties over broad range $x < 10^{-2}$
**nPDFs with minimal constraints: nNNPDF**

nNNPDF use a more flexible parametrisation of PDFs at $Q_0$

R.A. Khalek et al, EPJ C 79, 6

**nNNPDF 2.0: include LHC electroweak data**

**DIS only vs DIS + LHC**

- DIS input only covers $x > 10^{-2}$
- LHC EW data reduce uncertainty at small $x$
  - prefer no shadowing, $R_g \approx 1$

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LHC vs RHIC

LHC: $x \approx 10^{-4} - 10^{-5}$ accessible, with $p_T \sim Q\sim 3-4$ GeV

RHIC forward: kinematic limit at $p_T \sim 5$ GeV

RHIC d+Au 200 GeV

RHIC fwd $x^2$

ALICE FoCal upgrade

kinematically excluded

saturation region

$y$
Proton structure: parton density functions

Low $Q^2$: valence structure

Valence quarks ($p = uud$)

$x \sim 1/3$

Soft gluons

$x$: momentum fraction carried by parton

$Q^2$ evolution (gluons)

Gluon content of proton rises quickly with $Q^2$

Something must ‘tame’ the gluons at low $x$

non-linear evolution, gluon fusion?
Saturation/Color Glass Condensate

Structure of a Nucleus

- Low x: large gluon density
- Low $Q^2$: large effective size of gluons

Strong fields, large occupation numbers

Large theoretical interest:
- Fundamentally new regime of QCD
- Theoretically calculable: Classical color fields; JIMWLK, etc

Experimental/phenomenological question:
Where/when is CGC dynamics relevant/dominant?

Non-linear evolution $\Leftrightarrow$ Reduced gluon density $\Leftrightarrow$ Suppression of yield
$1 + \text{many instead of } 2 \rightarrow 2 \Leftrightarrow$ Suppression of recoil jet (mono-jets?)
Multi-gluon emission and interference $\Leftrightarrow$ Azimuthal anisotropy (flow-like effects)
Probing the gluon density in a hadron collider

Direct photon production

Incoming partons: quark and gluon

direct-$\gamma$, Compton (LO)

Sensitive to **gluons at LO**

Photon momentum directly related to incoming partons

Charm production

Incoming partons: 2 gluons

Heavy hadron:
also directly sensitive
but fragmentation reduces
kinematic constraint

More processes contribute, e.g. gluon splitting