How do we obtain definitive evidence of gluon saturation and the CGC?

Heikki Mäntysaari

University of Jyväskylä
Centre of Excellence in Quark Matter
Finland

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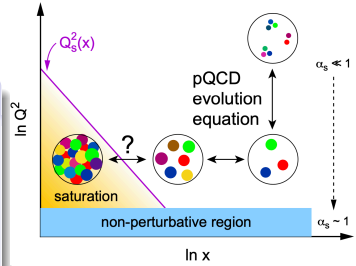
Gluon saturation at small x

More detailed introduction and connection to Heavy Ion initial state: Oscar Garcia-Montero (Mon 16:00)

- Very high occupation number $xg(x, Q^2)$
- Apparent gluon size $1/Q^2$



Non-linear dynamics important when

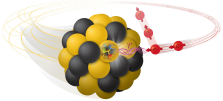
$$\pi R_p^2 = \alpha_s xg(x, Q^2) \frac{1}{Q^2}$$

Emergent saturation scale $Q^2 = Q_s^2 \gg \Lambda_{\text{QCD}}^2$
Characterizes the target wave function, weak coupling applicable

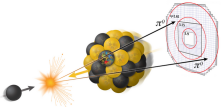
Color Glass Condensate

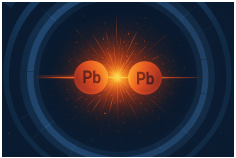
- Effective theory of QCD in the high energy limit
- $\alpha_s xg \sim 1$: need to resum multiple scattering effects, convenient to do in CGC framework
- Unitarity built in, relevant d.o.f. is dipole-target amplitude $N \leq 1$

Complementary probes of gluon saturation



BNL graphics





ChatGPT

- DIS: Clean dilute-dense environment, precision, limited $\sqrt{s}$, nuclei in UPCs (at $Q^2 = 0$)
- p+A: Dilute but complex probe, high $\sqrt{s}$, nuclei
- Heavy Ion Collisions: Complex dense-dense, complementary observables, high $\sqrt{s}$

Why nuclei (Oomph)

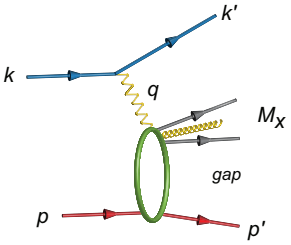
$$Q_s^2 \sim x^{-1/3} T_A(\mathbf{b}_\perp) \sim x^{-1/3} A^{1/3}$$

In practice more like $0.3 \ldots 0.5 x^{-1/3} A^{1/3}$

$\Rightarrow$ Going from $p \to \mathrm{Pb} \equiv$ increasing $\sqrt{s} \sim 1/x$ by a factor ~ 200 (but cheaper)

Most promising(?) "smoking gun" for saturation effects: diffractive DIS

If I have to pick one, although there may not be any



EIC WP

Why diffraction

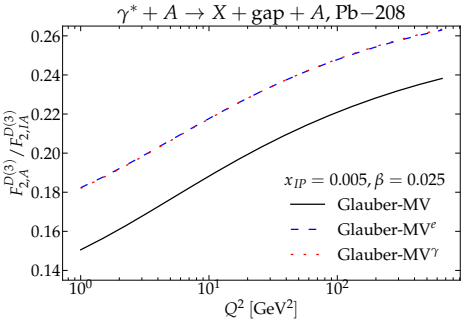
- No net color transfer ⇒ at least 2 gluons ⇒ sensitivity
- IR-safe, no dependence on e.g. jet algorithm or fragmentation function
- Genuine saturation prediction:

$$\frac{\sigma_{\text{diffractive}}}{\sigma_{\text{total}}} \to \frac{1}{2}$$

  for large Q_s^2, i.e. large A and/or small-x
- A and x dependencies dynamical, i.e. computable from CGC
- Same degrees of freedom as e.g. inclusive DIS

Most promising(?) "smoking gun" for saturation effects: diffractive DIS

If I have to pick one, although there may not be any



Dung Le, H.M, Lappi, 2307.16486

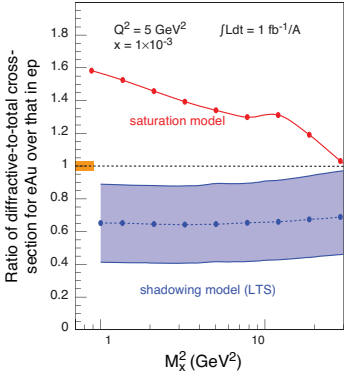
Very strong non-linear effect expected

- Diffractive structure function F_2^D
- Q^2 systematics measurable at the EIC
- Predicted nuclear modification factor $\sim \mathbf{0.2}$
- Impulse approximation $F_{2,IA}^D$:
  - $\gamma + p$ scaled to nuclei
  - Use nuclear form factor
  - Neglect saturation: $F_2^D = F_{2,IA}^D$

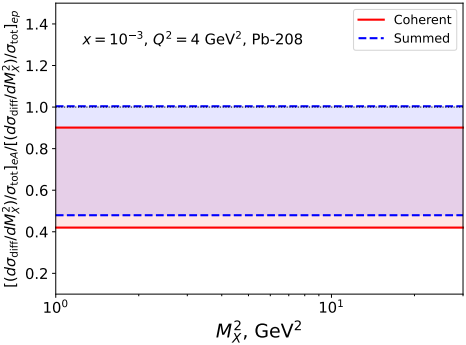
Most promising(?) "smoking gun" for saturation effects: diffractive DIS

If I have to pick one, although there may not be any

EIC White Paper (2012)



State-of-the-art LTS Guzey, Strikman, 2403.08342



Qualitative difference (suppression vs enhancement)

EIC: A, x, Q^2, M_X^2 dependence

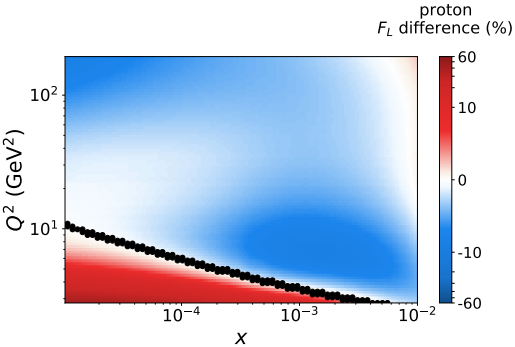
Note: Not a genuine DGLAP prediction, diffractive PDFs can fit data with enhancement!

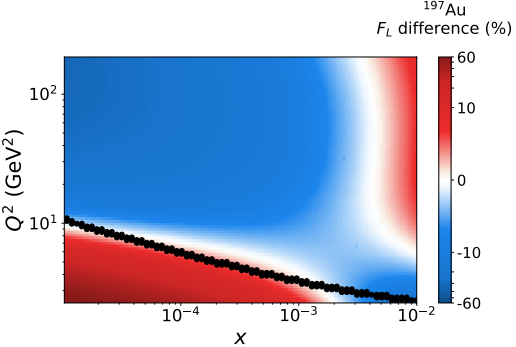
Baseline matters – look for deviations and tensions

Typically need non-perturbative input that can capture part of the saturation effects

Example: total DIS cross section, compare linear (DGLAP) and non-linear (BK) evolution

Tevio et al, 2203.05846: DGLAP and BK match at $Q^2 = 10Q_s(x)^2$ & quantify differences



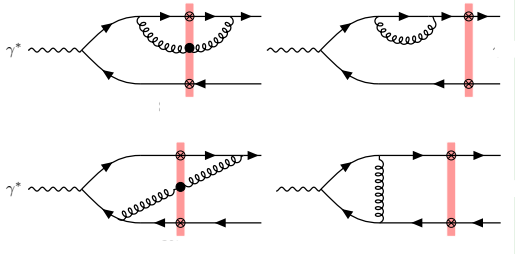


$\frac{\mathrm{BK-DGLAP}}{\mathrm{DGLAP}}$ for $F_{2,L}$ $\Rightarrow$ measurable differences especially for F_L and heavy-A

Also Marquet et al, 1702.00839

What if there is no smoking gun

Precision



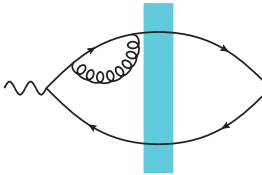
Global analyses

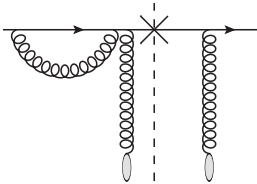
Path to precision: loop calculations (not a complete list; see Oscar's talk)

Needed to match EIC precision and to reliably extract systematic effects

Most phenomenology today is at LO ($\alpha_s \ln 1/x \sim 1$), NLO accuracy is coming

- Total DIS cross section (Hänninen et al, 2018, Beuf 2017)
- Quark mass LCPT renormalization + heavy quarks in DIS (Beuf, Lappi, Paatelainen 2022)
- VM in DIS (Boussarie et al 2017, 2025, Penttala, H.M, 2021, 2022)
- Inclusive and diffractive dihadrons/jets in DIS (Caucal et al 2023, Bergabo, Jalilian-Marian 2023, Taels et al 2022, Fucilla et al 2022)
- p+A (Chirilli et al, 2012, Stasto et al 2013, Ducloué et al 2016, 2017 Altinoluk et al, 2014, Watanabe et al, 2015, Iancu et al, 2016, . . .)
- Diffractive DIS (Penttala et al, 2024)
- SIDIS (Caucal et al, 2024, Altinoluk et al, 2025)
- Beyond infinite-E (Altinoluk, Beuf, . . . 2022–2025, poster by M. Bertilsson)





Path to precision: consistent NLO is getting possible

Necessary ingredients for precision CGC

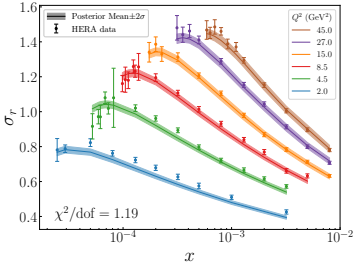
- Small-x evolution at NLO
  NLO BK + resummation of transverse logs
  NLO JIMWLK (no numerical solution yet)
- Initial condition fit to DIS at NLO
  - Uncertainties in non-perturbative input
    Reaching industry standards in PDF extraction

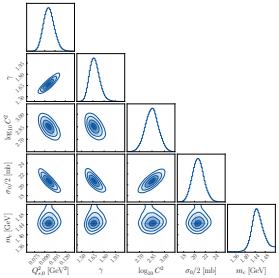
C. Casuga Wed 12:10

- Hard factors at NLO (previous slide)

Complementary probes of saturation available

With these ingredients we can go global



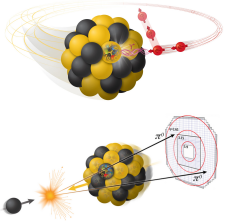


Casuga et al, 2506.00487

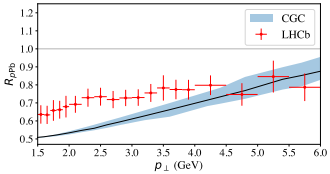
Global analyses in dilute-dense at NLO

DIS and LHC complementarity

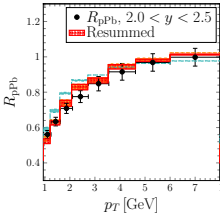
- Fix non-perturbative input to DIS data (typically F_2)
- Predict high-E: inclusive π^0, 2-particle correlations, exclusive $\mathrm{J}/\psi, \ldots$
  - More differential observables: potentially more powerful probse ...
  - ... but also other effeects (e.g. Sudakov in dihadron correaltions)



LHC $p + A \to \pi^0 + X$

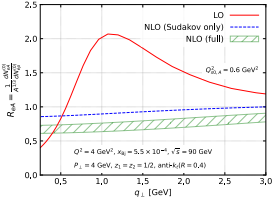


Tawabutr, H.M, 2310.06640



Shi et al, 2112.06975

$\gamma + A \to \mathrm{jet} + \mathrm{jet} + X$



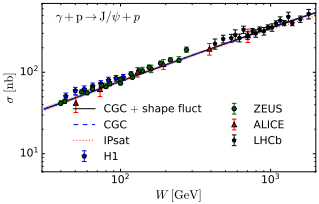
Caucal et al, 2308.00022

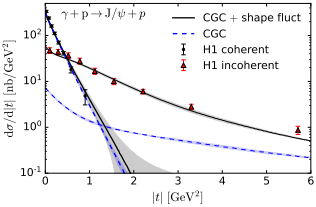
Future: global analyses confronting NLO calculations with different datasets where $\mu^2 \sim Q_s^2$

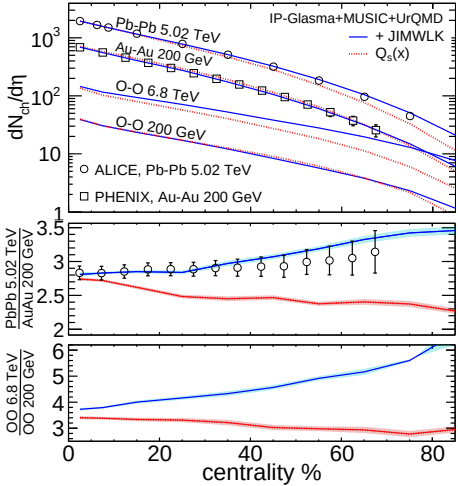
Global analyses including dense-dense: IP-Glasma, McDipper, . . .

See also Oscar Garcia-Montero Mon 16:00

Initial state: saturation + input from DIS ⇒ heavy ion $\sqrt{s}$ dependence: IP-Glasma+JIMWLK







- Extract QGP properties with better constrained IS
- Future: complementary constraints to IS from simultaneous global fits

H.M et al, 2502.05138, 2207.03712. Recent global J/ψ analysis: Roch et al 2507.14087

Conclusions

How to find definitive evidence of gluon saturation

- Probably the most powerful observable: diffractive structure function
- Get precision
- Go global

Lots of progress in this direction

- NLO calculations with phenomenological applications now possible
- Sophisticated statistical tools in use
- UPCs provide high-energy $\gamma + A$ data, EIC will bring A, Q^2 lever arm

Backups

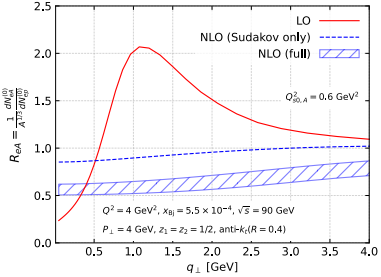
First phenomenological studies at NLO (not a complete list)

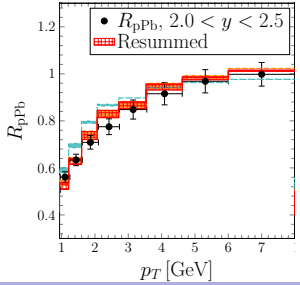
First phenomenological studies at NLO becoming available

- Initial condition for small-x evolution (Beuf et al, 2020)
- Heavy quark production (Hänninen et al, 2022)
- Exclusive J/ψ , ρ, ϕ, Υ (Penttala, H.M, 2021, 2022)
- Hadron production in pA (Shi et al, 2021, H.M, Tawabutr, 2023)
- Dihadron correlations in DIS (Caucal et al 2023)

Next in the field

- Global analyses probing saturation effects and constraining non-perturbative input
  $\Rightarrow$ Heavy ion initial state description at NLO





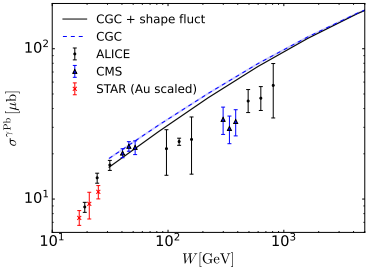
Plots: Caucal et al, 2308.00022, Shi et al, 2112.06975

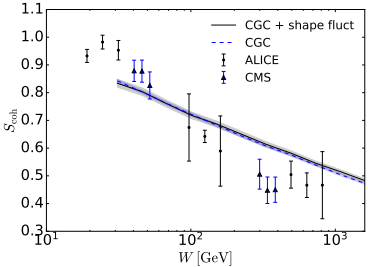
Need for global analyses

Why global

- Typically can adjust e.g. non-perturbative input to capture single dataset
- May not be possible to see statistically significant deviations from single observable alone
- Rigorous treatment of model uncertainties & uncertainty propagation
- Possibility to cancel model uncertainties
- Take correlated experimental uncertainties into account if available

Saturation in coherent production: $\gamma + \mathrm{Pb} \to \mathrm{J}/\psi + \mathrm{Pb}$





- Challenging to describe the W dependence of $\sigma^{\gamma\mathrm{Pb}}$
  - LHC data well reproduced at moderate $W \lesssim 100$ GeV
  - Energy dependence well reproduced at higher W, but overestimate overall cross section
- Nuclear suppression factor

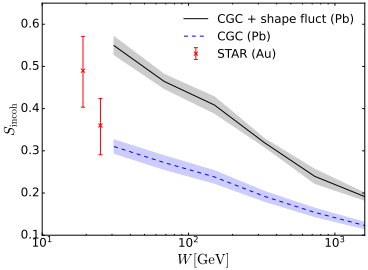
$$S_{\mathrm{coh}} = \sqrt{\frac{\sigma^{\gamma\mathrm{Pb}}}{\sigma_{\mathrm{IA}}}}, \quad \sigma_{\mathrm{IA}} = \left.\frac{\mathrm{d}\sigma^{\gamma p}}{\mathrm{d}t}\right|_{t=0} \int \mathrm{d}t\, |F(t)|^2$$

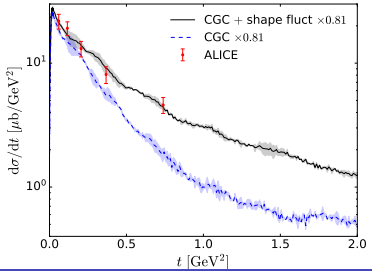
  - General trend captured...
  - ...but data would prefer a stronger W dependence

No free parameters when moving $p \to A$: genuine prediction (but J/ψ wave function does not completely cancel in S_{coh})

H.M, Salazar, Schenke, 2312.04194

Saturation in incoherent production: $\gamma + \mathrm{Pb} \to \mathrm{J}/\psi + \mathrm{Pb}^*$





- Proton e-b-e fluctuating geometry tuned to HERA data
- Smoother proton at small-x $\Rightarrow$ reduced fluctuations, incoherent cross section suppressed
- Lower-energy measurement from STAR for the suppression factor

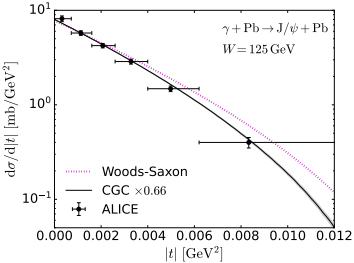
$$S_{\mathrm{incoh}} = \frac{\sigma^{\gamma+\mathrm{Pb}\to\mathrm{J}/\psi+\mathrm{Pb}^*}}{A(\sigma^{\gamma+p\to\mathrm{J}/\psi+p} + \sigma^{\gamma+p\to\mathrm{J}/\psi+p^*})}$$

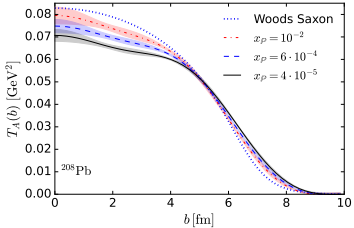
- LHC data can probe $x_{\mathbb{P}}$ dependent geometry fluctuations
- ALICE t spectra: compatible with no modification to nucleon substructure in nuclei at $x_{\mathbb{P}} \sim 10^{-3}$

H.M, Salazar, Schenke, 2312.04194

Saturation effect on nuclear geometry: $A + A \to A + A + \mathrm{J}/\psi$

$\gamma + \mathrm{Pb}$ at the LHC: very high density, saturation can modify the nuclear geometry





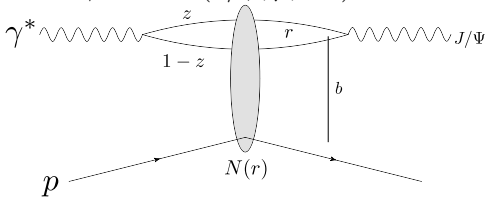
UPC data from LHC: $x = 6 \cdot 10^{-4}$

- Coherent $\gamma + \mathrm{Pb} \to \mathrm{J}/\psi + \mathrm{Pb}$
- No saturation: geometry = Woods-Saxon
  $\Rightarrow$ not compatible with ALICE data
- Saturation: nucleus $\approx$ black disc at the center
  $\Rightarrow$ modifies nuclear geometry
  $\Rightarrow$ J/ψ spectra compatible with ALICE measurements (shape, not normalization)

H.M, Schenke, Salazar, PRD106 (2022), ALICE: PLB817 (2021)

Powerful DIS probe: exclusive vector meson production

$$\gamma + A \to (\mathrm{J}/\psi, \rho, \dots) + A$$



Ω: target configuration
$\mathbf{\Delta}$: J/ψ transverse momentum
$\mathbf{r}_\perp$: $q\bar{q}$ transverse size
$\mathbf{b}_\perp$: $q\bar{q}$ center-of-mass
z: long. momentum fraction

At lowest order in perturbation theory:

$$\mathcal{A}_\Omega \sim i \int \mathrm{d}^2\mathbf{b}_\perp \, e^{-i\mathbf{b}_\perp \cdot \mathbf{\Delta}} \Psi^* \otimes N_\Omega \otimes \Psi_{\mathrm{J}/\psi}$$

1. $\gamma^* \to q\bar{q}$: photon wave function Ψ (QED)
2. qq-target interaction: dipole amplitude $N_\Omega = 1 - \frac{1}{N_c}\mathrm{Tr}\{V(\mathbf{x}_1)V^\dagger(\mathbf{x}_2)\}$
3. $q\bar{q} \to \mathrm{J}/\psi$: meson wave function $\Psi_{\mathrm{J}/\psi}$

Diffractive events

- $\mathbf{b}_\perp$ Fourier conjugate to $\mathbf{\Delta}_\perp$!
- Theory: no net color charge transfer
- Experimental signature: rapidity gap (empty detector) around J/ψ

High $E \Rightarrow$ transverse coordinates fixed

NLO: Penttala. H.M. 2204.14031