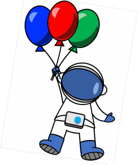

Theoretical developments on the initial state in relativistic particle collisions

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ACADEMY OF FINLAND

HELSINKI INSTITUTE OF PHYSICS

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

Heavy ion collisions: initial state ⇔ final state

- Extraction of QGP properties requires a precise knowledge of the initial state
- Interesting initial state physics can be accessed in heavy ion collisions as well!
  - QCD in the very high density region and gluon saturation
  - Nuclear modification to nucleon structure (density, shape, . . .)

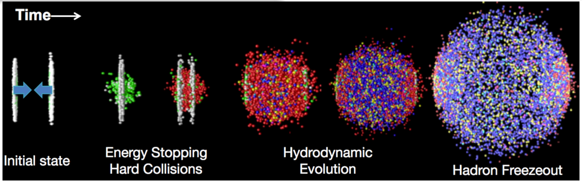
How to probe the initial state?

Probe a single nucleus (focus here)

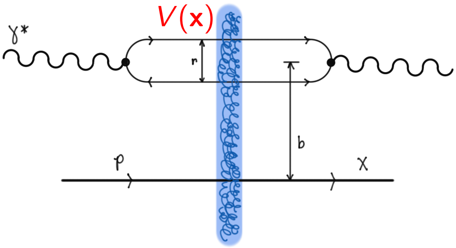
- e+p and e+A DIS (HERA, EIC)
- p+A collisions at the LHC

Infer the IS from A+A data

- Simulate the space-time evolution
- Constrain parameters of the IS model



Probing the initial state in Deep Inelastic Scattering and p+A collisions



Picture by C. Casuga

Other approaches not covered here (focus weak coupling & DIS/p+A):

- Angantyr
- HIJING
- EPOS
- TRENTo

etc... (see also Kanakubo Thu)

Color Glass Condensate approach (e.g. IP-Glasma)

- Target = dense color field
- Perturbative x (energy) evolution: BK/JIMWLK
- DIS, p+A, energy density in A+A expressed in terms of the same d.o.f (Wilson line $V(\mathbf{x})$)

Collinear factorization approach (EKRT)

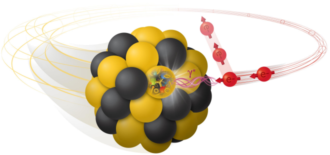
- Nuclear PDFs: global analyses (DIS, p+A) EPPS21, nCTEQ15, nNNPDF3.0
- Initial energy deposition in A+A: (NLO) pQCD + saturation criterion

Approach to equilibrium: Schlichting next

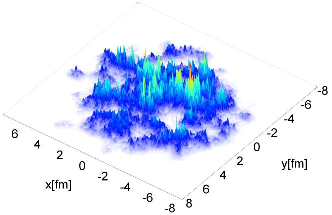
This talk

1. Nucleon and nuclear geometry from DIS
2. Gluon saturation at the precision level
3. Longitudinal dynamics in heavy ion collisions

Nuclear geometry from $\gamma + A$ scattering



BNL graphics



Schenke, Tribedy, Venugopalan 1206.6805

$\mathcal{F}$[Total momentum transfer] $\sim$ impact parameter

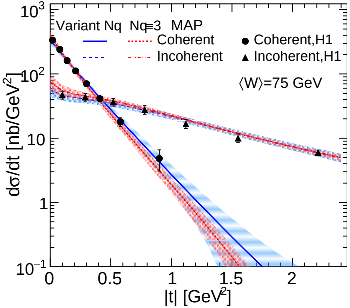
Coherent

- Target p/A remains on ground state
- Average geometry

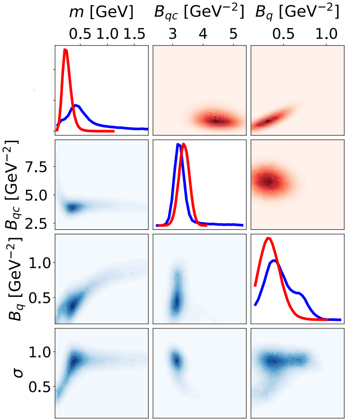
Incoherent:

- Target dissociates
- E-b-e fluctuations

Good, Walker, PRD120 1857, H.M, 2001.10705



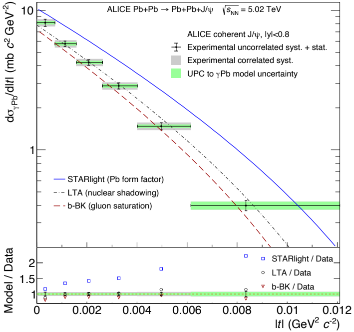
H.M, Schenke, Shen, Zhao, 2202.01998

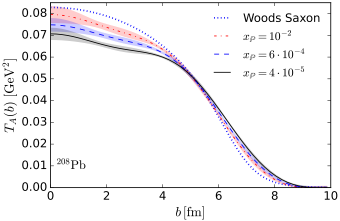


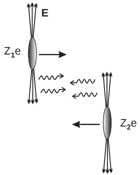
Possibility to propagate geometry uncertainties: HERA $\Rightarrow$ AA (computationally demanding)

Still missing from many IS models: energy dependent e-b-e geometry! Lappi Wed 11:40

Nuclear geometry from DIS: $\gamma + A \to J/\psi + A$







Probe *nuclear* structure down to $x \sim 10^{-5}$ using photons at RHIC and at the LHC!

- Nuclear-DIS before the EIC (Brandenburg after coffee, Stasto Sat 8:30))
- Significant nuclear suppression observed
  - Even stronger than saturation calculations typically predict
  - Compatible with nPDFs Guzey et al, 2008.10891
  - Potential to constrain nPDFs explored recently

    Eskola, Flett, Guzey, Löytäinen, Paukkunen, 2203.11613, 2210.16048, 2303.03007
- Steeper $t \approx p_T^2$ spectrum compared to the Pb form factor
  - Explanation: saturation modifying geometry

    H.M, Salazar, Schenke, 2207.03712, Bendova et al 2006.12980, Rezaeian et al, 1402.4831
  - Effect dynamically included e.g. in IP-Glasma

Matyja, Tue 15:30 Data: ALICE, 2101.04623

Nucleon substructure in nuclei

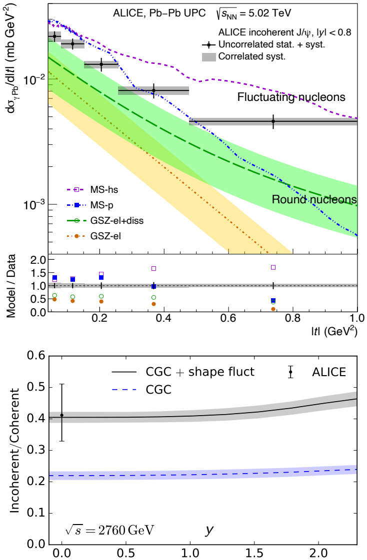
Matyja, Tue 15:30

Probe fluctuations at distance scale $\sim 1/|t|$

- Small $|t|$: nucleon positions fluctuate
- Large $|t|$: (potential) nucleon substructure

New data from ALICE and STAR: incoherent $\gamma + A \to \mathrm{J}/\psi + A^*$

- Nuclear modification to nucleon substructure not seen
- Models with substructure fluctuations preferred



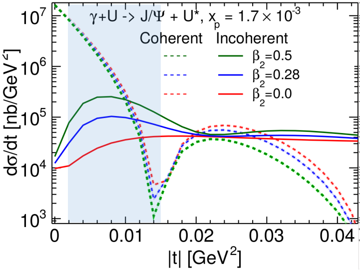
Recall: nucleon substructure crucial to explain flow in p+A

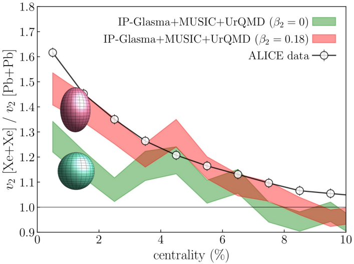
Schenke et al 1405.3605 H.M et al 1705.03177 Moreland et al 1808.02106, ...

ALICE, 2305.06169 STAR: Tu at DIS2023

CGC calculations: H.M, Schenke, Salazar, 2207.03712 H.M, Schenke, 1703.09256

Deformed nuclear geometry





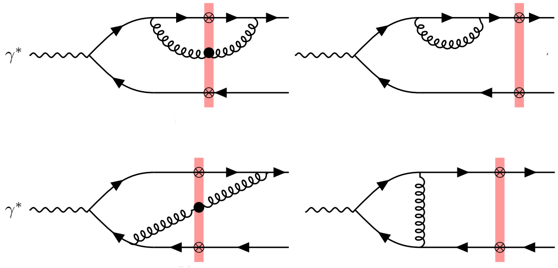
- Deformed ($\beta_n > 0$) nuclei (U, Xe) collided at RHIC & LHC
- Deformations modify initial density profile ⇒ flow, . . .
- Deformations also enhance e-b-e transverse density fluctuations probed in DIS
  - Enhanced incoherent $\gamma + A \to \mathrm{J}/\psi + A^*$ cross section
  - Momentum transfer conjugate to geometry ⇒ different $-t \approx p_T^2$ ranges probe different deformations
- EIC (or UPCs): clean access to deformations

H.M et al 2303.04866; Brandenburg et al, 2209.11042, Ryssens et al, 2302.13617

Talks by Zhao, Wed 15:40; Singh, Wed 16:50, Kanakubo Thu 9:30

Nuclear structure calculations not covered here, see Brandenburg et al, 2209.11042 for review

Precision frontier of CGC



Caucal, Salazar, Schenke, Venugopalan, 2208.13872

Color Glass Condensate at precision level

CGC calculations are now entering the NLO era ($\alpha_s \ln 1/x \sim \mathcal{O}(1)$, NLO $= \alpha_s^2 \ln 1/x$)

Factorization at small-x

$$\mathrm{d}\sigma \sim \text{Impact factor} \otimes \text{Wilson line correlator}$$

Building blocks for NLO accuracy

- Impact factors (hard coefficients)
- Small-x evolution for Wilson lines
- Non-perturbative input from fits

Precision probes of initial state

- RHIC&LHC p+A data
- Photonuclear processes in UPCs
- Future EIC

Look for gluon saturation & Impact on heavy ion phenomenology

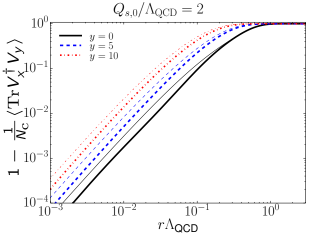
Properties of the initial state at precision level

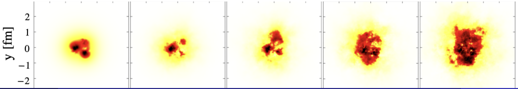
Additional direction potentially relevant for EIC: sub-eikonal corrections Altinoluk et al, 2212.10484; 2303.12691

Small-x energy evolution at NLO

Small-x evolution = energy dependence, NLO accuracy achieved already some time ago:

- Balitsky-Kovchegov (BK) for two-point function ($\langle \mathrm{Tr}\, V_x^\dagger V_y \rangle$) (Balitsky, Chirilli, 2007)
  - Resummation of transverse logs (Ducloué et al 2019, Iancu et al 2015, Beuf 2014)
  - Numerical solution (Lappi, H.M, 2016)





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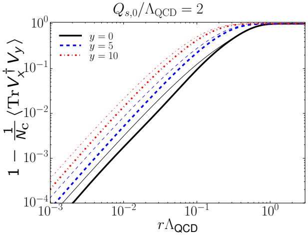
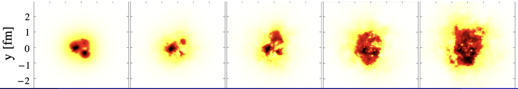
  - Resummation of transverse logs (Ducloué et al 2019, Iancu et al 2015, Beuf 2014)
  - Numerical solution (Lappi, H.M, 2016)
- JIMWLK (any Wilson line operator) (Balitksy, Chirilli, 2013, Kovner, Lublinsky, Mulian 2013)
  - Resummation of transverse logs (Hatta, Iancu, 2016)
  - No numerical solution yet



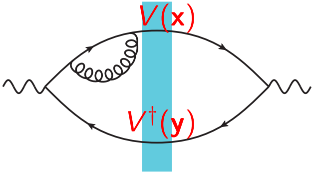
$$
\begin{aligned}
H^{NLO\ JIMWLK} &= \int_{x,y,z} K_{JSJ}(x,y;z)\,\left[J_L^a(x)\,J_L^a(y) + J_R^a(x)\,J_R^a(y) - 2\,J_L^a(x)\,S_A^{ab}(z)\,J_R^b(y)\right] + \\
&+ \int_{x\,y\,z\,z'} K_{JSSJ}(x,y;z,z')\left[f^{abc}\,f^{def}\,J_L^a(x)\,S_A^{be}(z)\,S_A^{cf}(z')\,J_R^d(y) - N_c\,J_L^a(x)\,S_A^{ab}(z)\,J_R^b(y)\right] + \\
&+ \int_{x,y,z,z'} K_{q\bar{q}}(x,y;z,z')\left[2\,J_L^a(x)\,tr[S^\dagger(z)\,T^a\,S(z')T^b]\,J_R^b(y) - J_L^a(x)\,S_A^{ab}(z)\,J_R^b(y)\right] + \\
&+ \int_{w,x,y,z,z'} K_{JJSSJ}(w;x,y;z,z') f^{acb}\left[J_L^d(x)\,J_L^e(y)\,S_A^{dc}(z)\,S_A^{eb}(z')\,J_R^a(w) - J_L^a(w)\,S_A^{cd}(z)\,S_A^{be}(z')\,J_R^d(x)\,J_R^e(y) + \right. \\
&\left. + \frac{1}{3}[\,J_L^c(x)\,J_L^b(y)\,J_L^a(w) - J_R^c(x)\,J_R^b(y)\,J_R^a(w)]\right] + \\
&+ \int_{w,x,y,z} K_{JJSJ}(w;x,y;z)\,f^{bde}\left[J_L^d(x)\,J_L^e(y)\,S_A^{ba}(z)\,J_R^a(w) - J_L^a(w)\,S_A^{ab}(z)\,J_R^d(x)\,J_R^e(y) + \right. \\
&\left. + \frac{1}{3}[\,J_L^d(x)\,J_L^e(y)\,J_L^b(w) - J_R^d(x)\,J_R^e(y)\,J_R^b(w)]\right] \qquad (
\end{aligned}
$$

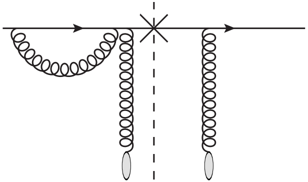


Hard factors at NLO

A lot of activity in recent years (too much for one slide)

- 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, 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 (partially) (Hänninen et al, 2022)



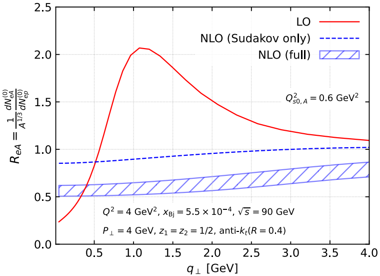


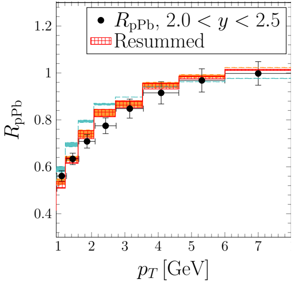
Huge global effort to enable precision level studies underway!

First phenomenological studies at NLO

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 $\mathrm{J}/\psi, \rho, \phi, \Upsilon$ (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)





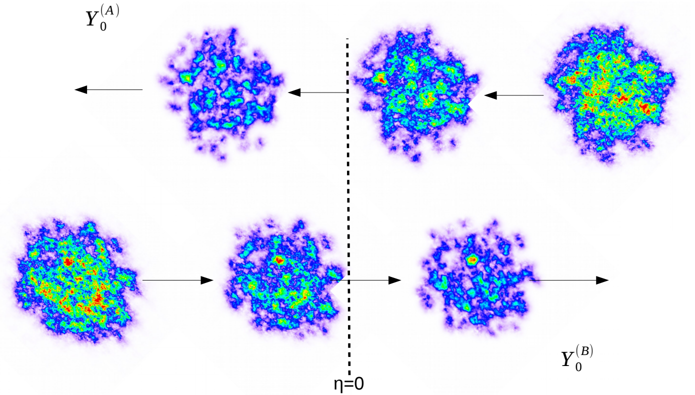
Next in the field

- 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

Shi Wed 17:30

Longitudinal dynamics



McDonald et al, 2306.04896

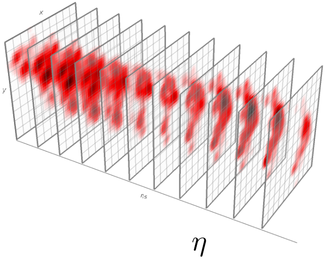
Moving away from midrapidity in $A + A$

QGP production in 3D

- Hydro and hadronic cascade already at 3+1D by default, initial state is the last missing ingredient
- Lots of dynamics away from midrapidity probing also the x-dependent nuclear structure

3D initial states from weak coupling

- CGC-based approaches
- pQCD-based EKRT now in 3D Poster by M. Kuha

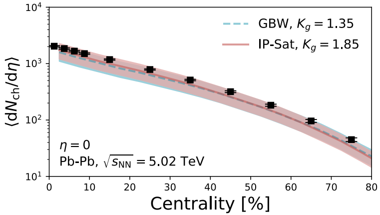


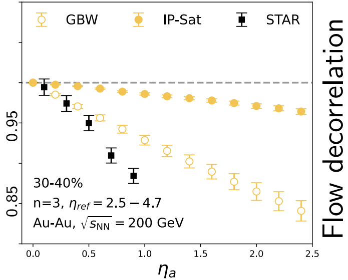
TRENTo-3D

Soeder et al, 2306.08665

Other 3D ICs not directly connected to eA/pA not covered here: TRENTo-3D, AMPT/HIJING, UrQMD, string deceleration, longitudinally extended nuclei&CYM, . . . (see also Kanakubo Thu)

CGC in 3D





McDipper, Garcia-Montero, Elfner, Schlichting, 2308.11713

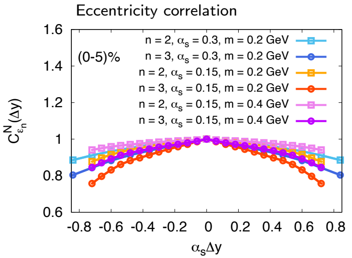
- Initial energy, charge and baryon density from CGC:
  - Gluon production: k_T factorization $\sim$ UGD^2
  - Quark production hybrid formalism $\sim$ PDF $\otimes$ UGD
- x dependence of UGD parametrized: IPsat/GBW fitting HERA DIS+vector meson data
- Currently LO
- NLO and perturbative evolution possible developments

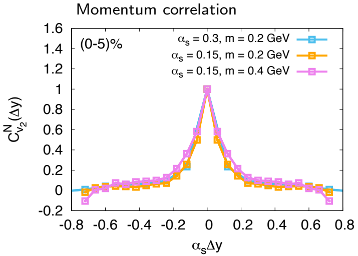
Lessons learnt

- Promising results (IS only, no time evolution)
- Additional fluctuations (valence q region?) required to explain flow decorrelation

Poster by Garcia-Montero, flow decorrelation exp: Seidlitz Tue 12:40

CGC in 3D: p+A with early time evolution





Schenke, Schlichting, Singh, 2201.08864:

- JIMWLK evolved p/A structure
- Early CYM evolution: independent 2D rapidity slices

Lessons learnt

- Momentum decorrelates much faster than geometry
- Initial momentum correlations have a small contribution to correlation measurements with rapidity gap
- ε_3 decorrelates faster than ε_2, compatible with HI data

Singh, Wed 16:50

First lessons from 3D: A+A

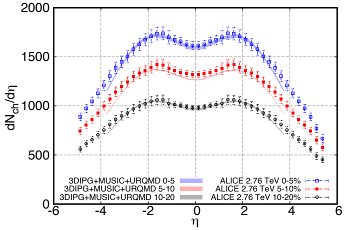
McDonald, Jeon, Gale, 2306.04896:

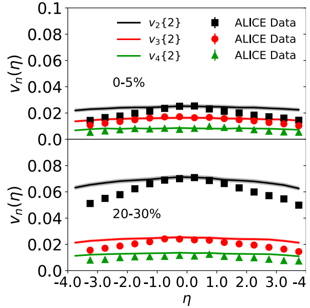
- JIMWLK evolved nuclei
- One possible implementation for early CYM dynamics in 3D
- Coupling to 3D hydro + UrQMD

Lessons learnt

- Full 3D simulations are possible
- Good description of spectra, $\langle p_T \rangle$, $v_n(\eta = 0)$ etc possible
- Not enough longitudinal decorrelation, need additional fluctuations?

Flow decorrelation exp: Seidlitz Tue 12:40, see also Kanakubo Thu 9:30





MC EKRT in 3D

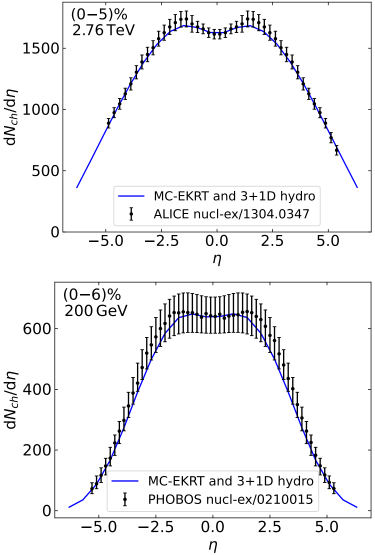
Initial state: minijet production from pQCD
+ saturation

Recent developments

- Minijet multiplicity fluctuations e-b-e (Poisson)
- Spatial nPDFs with e-b-e fluctuations
- Dynamical saturation, fluctuates e-b-e
- Energy conservation e-b-e
- Coupled to 3+1D viscous hydro

Good description of key observables

Poster by M. Kuha

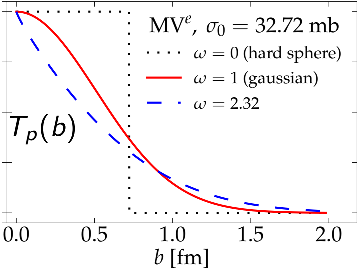


Conclusions

- Initial state of heavy ion collisions: interesting fundamental physics
  $+$ necessary input to QGP studies
- Proton, nucleon and nuclear event-by-event fluctuating geometries from DIS
- Color Glass Condensate calculations entering the precision NLO era
  - Extensive theoretical developments in recent years
  - First phenomenological applications
  - Saturation physics at precision level
  - Impact on initial state models expected in the coming years
- Longitudinal dynamics in A+A collisions: sensitivity to x-dependent nuclear structure
  - First consistent 3D simulations becoming feasible with weak coupling based initial conditions
- Next: global analyses with multiple DIS/pA/AA observables simultaneously

Backups

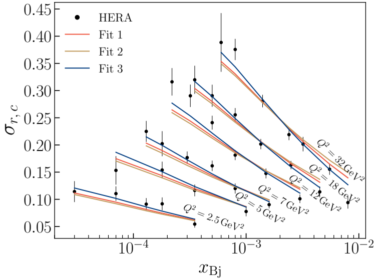
Stringent test for gluon saturation: global analyses at precision level



DIS and DDIS proton structure functions (LO)

- Steeper-than-Gaussian proton required

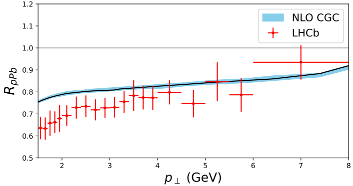
Lappi et al, 2307.16486



Heavy-q data in NLO DIS fits:

- Strong constraints for BK initial condition

Hänninen et al, 2211.03504



$p + \mathrm{Pb} \to \pi^0 + X$ consistently with NLO DIS

- Challenge to simultaneously describe HERA and LHC

Tawabutr et al, 2307.04831 + in preparation