# Shining Light on Saturated Gluons

## GlueSatLight

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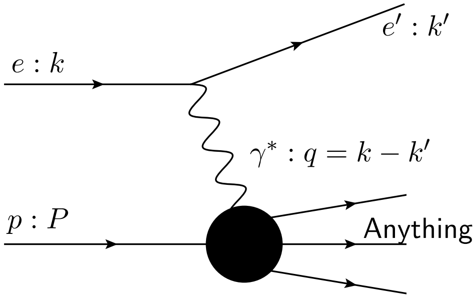
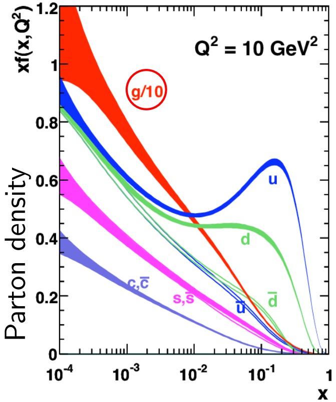
Particle Physics Days, Nov 28, 2024

# Outline

# Proton structure at high energy

Experiments at HERA $e + p$ collider (92–07):
Deep Inelastic Scattering $e + p \to e + X$




$Q^2 = -q^2$: photon virtuality $\sim 1/$length scale

Observation: proton is full of gluons!

$x = Q^2/(2P \cdot q)$: fraction of the proton momentum carried by the quark or gluon

# QCD at high energies

## QCD is non-abelian ⇒ non-linear

$$\mathcal{L} = -\frac{1}{2}\underbrace{F^{\mu\nu}F_{\mu\nu}}_{\sim(A^\mu)^3,\,(A^\mu)^4} + \overline{\psi}(\underbrace{i\not{D}}_{\sim A^\mu} - m)\psi$$

- Gluons ($\sim A^\mu$) have self-couplings: $g \to gg$ increases density at low $x$
- Non-linear when $g$ density large: $gg \to g$ balances $g \to gg$
- Effective theory at high energy: Color Glass Condensate (CGC)

## When is non-linear QCD visible?

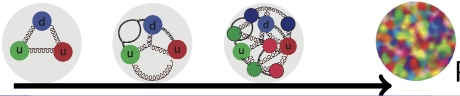
- Transverse size probed $\sim 1/Q^2$
- Number of gluons $xg(x,Q^2)$
- Proton transverse area $\pi R_p^2$
- QCD coupling strength $\alpha_s$

Non-linearities important when

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

Pronounced in nuclei: $xg(x,Q^2)/\pi R_p^2 \sim A^{1/3}$

High-$x$/small-$E$




Small-$x$/high-$E$

Perturbative evolution

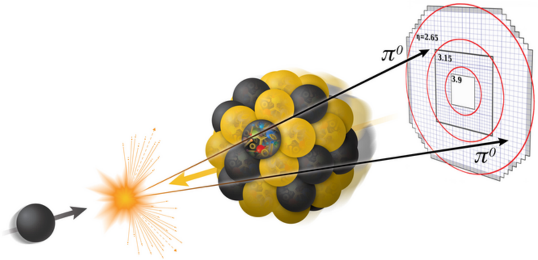
# Outline

# "Standard" experimental access to high-density QCD at the LHC

No unambiguous signal of non-linearities seen so far. Look for densest possible systems!

**p+A collisions**

- Probe: proton (complex substructure)
- Target: heavy (dense) nucleus




Particle production in the *forward* (proton-going) direction

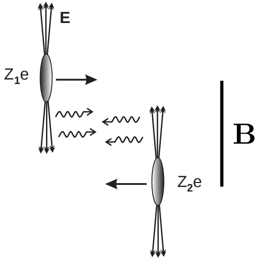
- Proton: $x_p \sim 1$
- Nucleus: $x_A \ll 1$

Access to small-$x_A$, but messy

# Light in GlueSatLight

## Ultra Peripheral Collisions

- Impact parameter $|\mathbf{B}| > 2R_A$: Hadronic interaction suppressed
- Probe: photon (elementary particle)
- Target: heavy (dense) nucleus




## GlueSatLight

- $\gamma + A$ scattering at $W_{\gamma N} \sim \mathcal{O}(\mathrm{TeV})$: Clean probe of gluon saturation & geometry at small-$x$ and large-$A$
- Focus: exclusive vector meson production

EM field of the fast nucleus
$\sim$ quasi-real photon flux

# Light in 2030s: Electron-Ion Collider (EIC)

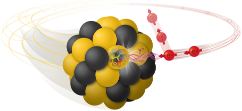
## Electron Ion Collider (EIC)

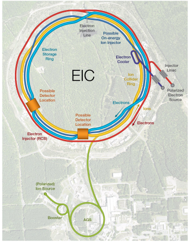
- Approved by the US DOE, data $\sim 2032$
- First $e + A$ collider
- Polarized protons (and light nuclei)
- High luminosity $\mathcal{L} \sim 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

## EIC physics program & requirements

- 3D imaging (luminosity) ERC
- Proton spin (polarized beam)
- Saturation (large $E$ and $A$) ERC

CoE QM theory groups involved



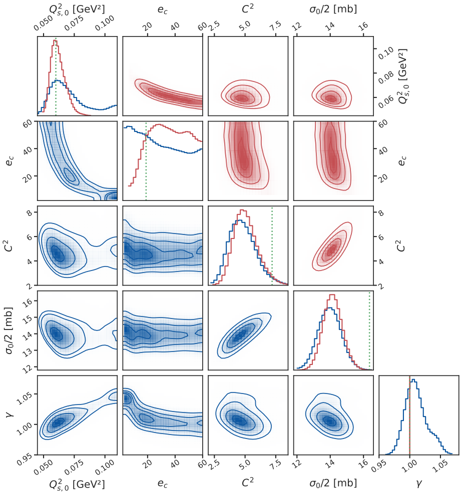



Interaction via virtual photon exchange

- Kinematics known (measure $e$)
- Access different length scales $\sim$ photon virtualities $Q^2$

# Outline

# Non-perturbative input from structure function measurements

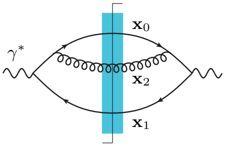


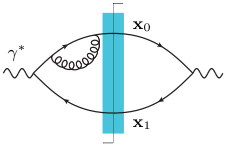

C. Casuga, M. Karhunen, H. Mäntysaari, PRD 2024

- Perturbative $\sqrt{s}$ evolution: BK/JIMWLK
  Requires a non-perturbative input with uncertainties
- Necessary ingredient for all CGC calculations
- Cleanest observable: total $\gamma^* p \to X$ cross section

## GlueSatLight

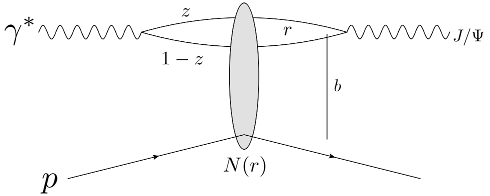
- Precision: NLO, finite-$\sqrt{s}$ corrections
- Global analyses: include diffraction, $p + \mathrm{A}, \ldots$
- Impact of future EIC data



# Exclusive vector meson production at the EIC and in UPCs

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




$\Omega$: target configuration
$\boldsymbol{\Delta}$: $\mathrm{J}/\psi$ transverse momentum
$\mathbf{r}$: $q\bar{q}$ transverse size
$\mathbf{b}$: $q\bar{q}$ center-of-mass
$z$: long. momentum fraction

## Lowest order in perturbation theory:

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

1. $\gamma^* \to q\bar{q}$: photon wave function $\Psi$ (QED)
2. $qq$-target interaction: dipole amplitude $N_\Omega$
3. $q\bar{q} \to \mathrm{J}/\psi$: meson wave function $\Psi_{\mathrm{J}/\psi}$

Calculation of $F_2$, $F_{2,D}$ similar

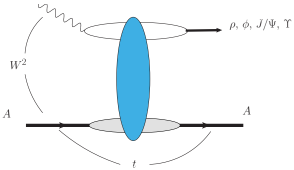
## Diffractive scattering

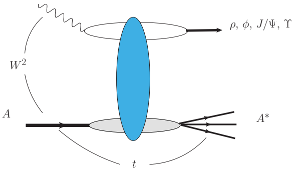
- Theory: no net color charge transfer
- Experimental signature: rapidity gap (empty detector) around $\mathrm{J}/\psi$

$\mathbf{b}$ and $\Delta$ Fourier conjugates:
access to geometry!

# Coherent and incoherent vector meson production

Coherent




Incoherent

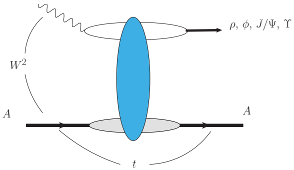
Coherent: target remains intact, initial state $|i\rangle$ = final state $|f\rangle$

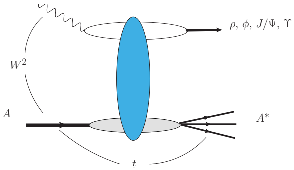
Good, Walker, Phys. Rev. 1960: $\frac{d\sigma}{d\mathbf{\Delta}^2} \sim |\langle \mathcal{A} \rangle_\Omega|^2$

$\Rightarrow$ Probe average interaction $\Rightarrow$ average geometry

# Coherent and incoherent vector meson production

Coherent

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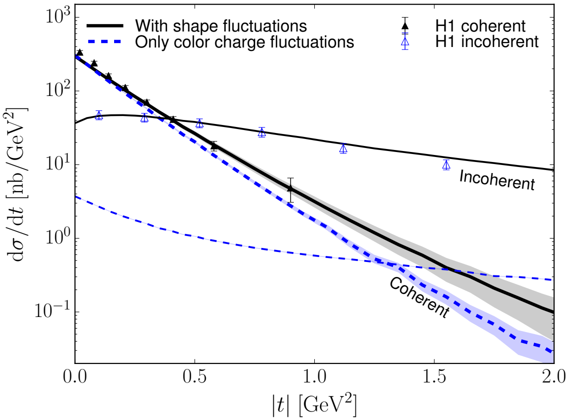
$\Rightarrow$ Probe average interaction $\Rightarrow$ average geometry

Incoherent: $|i\rangle \neq |f\rangle$, target breaks up: $\frac{d\sigma}{d\mathbf{\Delta}^2} \sim \left\langle |\mathcal{A}|^2 \right\rangle_\Omega - \left|\left\langle \mathcal{A} \right\rangle_\Omega\right|^2$

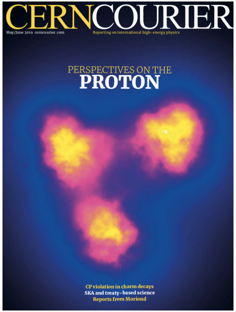
Variance $\Rightarrow$ access to event-by-event fluctuations in the target structure

# Proton shape from: $\gamma + p \to J/\psi + p$

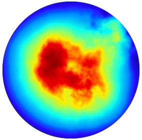



Parametrize e-b-e fluctuating geometry, fit data

Fluctuations




Round

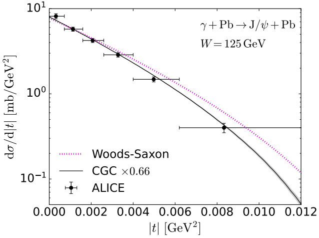


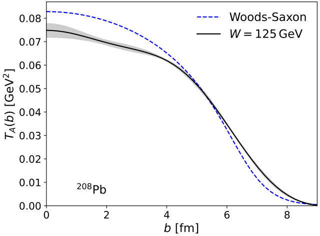
HERA data can be described with large event-by-event fluctuations in the proton geometry

H.M, B. Schenke, PRL 117, 052301 (2016), PRD 94, 034042, H1: EPJC73, 2466, later many papers by different groups

# Nuclear density profile from $\mathrm{Pb}+\mathrm{Pb} \to \mathrm{Pb}+\mathrm{Pb}+\mathrm{J}/\psi$

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




UPC data from LHC ($x=6\cdot10^{-4}$, $W_{\gamma N}=125$ GeV)

- Coherent $\gamma+\mathrm{Pb}\to\mathrm{J}/\psi+\mathrm{Pb}$
- Saturation effects modify nuclear goemetry
  $\Rightarrow$ Supported by the ALICE data
- Saturation: nucleus $\approx$ black disc at the center

## GlueSatLight

- Nucleon&nuclear (fluctuating) $x$-dependent geometry
- Nuclear modification to nucleon substructure fluctuations
- DIS + LHC $\mathrm{J}/\psi$ data: probe saturation in global analyses
- Promote phenomenology to NLO accuracy

# Outline

# Gluon saturation at precision level

This talk so far: LO (but $\alpha_s \ln 1/x \sim \mathcal{O}(1)$ resummed to all orders)

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-$x$

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

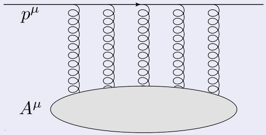
## Building blocks for NLO accuracy

Perturbative calculations at NLO accuracy need

- Impact factors (perturbative calculation)
- Perturbative energy evolution for Wilson lines
- Non-perturbative input from fits

Probe QCD in the high-density domain at precision level

## Wilson line $V(x)$




Quark propagating through the target, include multiple scattering (as density $\sim 1/$coupling)

# Progress towards the NLO accuracy – our contributions so far

Significant contributions from the CoE QM, for example

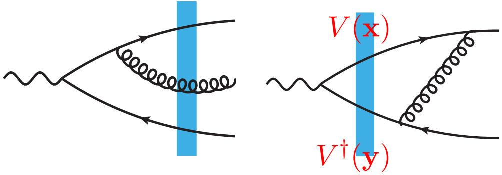
## Impact factors at NLO

- Total cross section in $\gamma^* + A$
  Beuf, Lappi, Paatelainen, Hänninen, 2017–2022
- Exclusive $\gamma^* + A \to V + A$ $(V = \rho, \mathrm{J}/\psi, \Upsilon)$
  H.M, Penttala, 2021–2022
- Total diffractive $\gamma^* + A$ cross section
  Beuf, Lappi, H.M, Paatelainen, Penttala, 2024

## Evolution equations at NLO

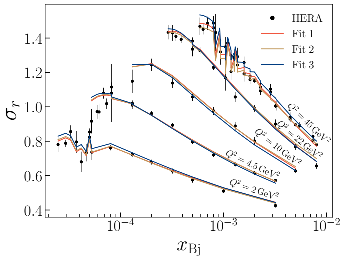
- First numerical solution Lappi, H.M, 2015
- Initial condition from $e + p$ data:
  Hänninen, H.M, Paatelainen, Penttala 2023

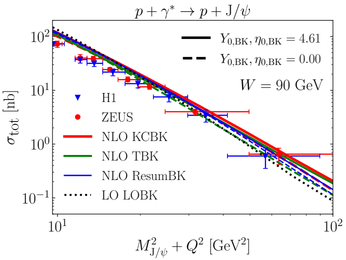
Diagrammatic calculations using Light Cone Perturbation Theory

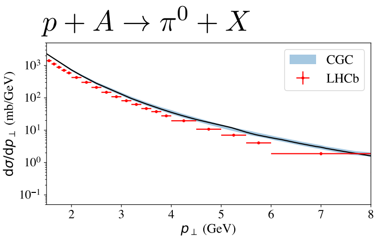



Examples for $q\bar{q}$ and $q\bar{q}g$ production

# Towards NLO phenomenology




- First NLO calculations applied to HERA&LHC phenomenology (our speciality): Total $\gamma + p$ cross section, exclusive ${\rm J}/\psi$ production, forward particle production in p+A

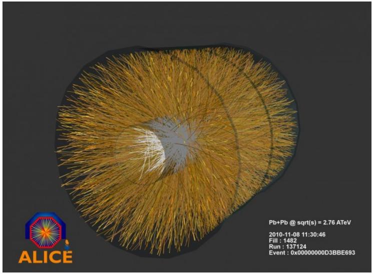
## ERC project GlueSatLight

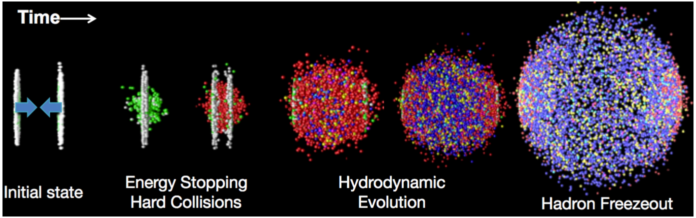
No single "smoking gun" for gluon saturation expected

- Probe gluon saturation by performing global analyses at NLO accuracy
- Apply these results to heavy ion phenomenology

# Outline

# Heavy ion collisions



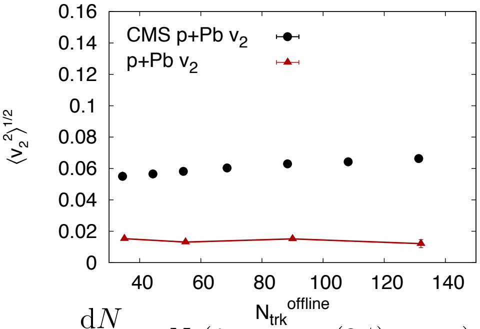

- High-$E$ Pb+Pb collisions
- Goal: determine properties of the deconfined QCD matter
  Quark Gluon Plasma

- Multi-stage process
- Describing all stages + measurements:
  CoE in Quark Matter
- ERC project: $0^{\text{th}}$ stage
  = dense saturated nuclei before collision
  $\Rightarrow$ input to simulations

# Initial state description from e+p in heavy ion collisions

## LHC surprise

- Initially p+Pb considered as a baseline, too small system for collectively evolving QGP
- However, a large flow was observed, comparable to Pb+Pb measurements




$$\frac{\mathrm{d}N}{\mathrm{d}\phi} \sim N_0(1 + v_2 \cos(2\phi) + \dots)$$

Same hydro framework failed with p+Pb...

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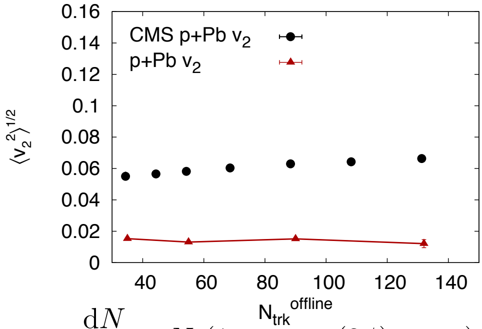



$$\frac{\mathrm{d}N}{\mathrm{d}\phi} \sim N_0(1 + v_2 \cos(2\phi) + \dots)$$

Same hydro framework failed with p+Pb. . .


. . . However, a round proton was assumed, and nature is quantum mechanical (more complicated)

# Initial state description from e+p in heavy ion collisions

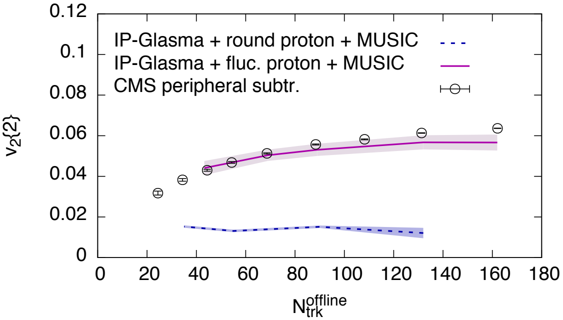
## Geometry from DIS

Can use $e + p$ / $e + A$ to constrain the proton/nuclear fluctuating geometry

## GlueSatLight

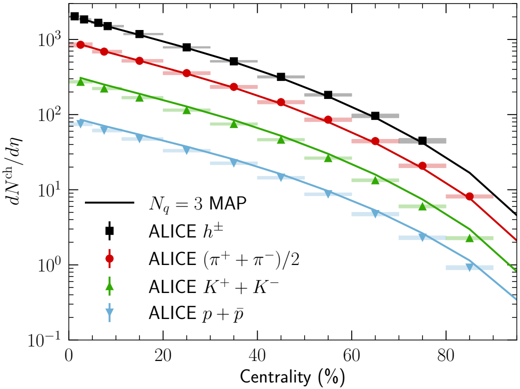
- JIMWLK evolution in IP-Glasma
- Input from DIS/global analyses
- Nucleon substructure in [deformed] nuclei
- Effect on the extraction of QGP properties

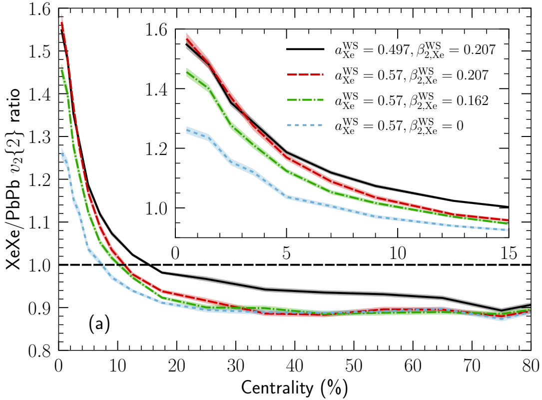
Proton geometry from HERA
$\Rightarrow$ LHC flow measurements ✓




H.M, Schenke, Shen, Tribedy, PLB 2017

# Example of recent developments




## Recent development

arXiv:2409.19064 [hep-ph]: initial state with (approximative) JIMWLK evolution in IP-Glasma, show that LHC Xe+Xe measurements are sensitive to deformed Xe geometry at small-$x$

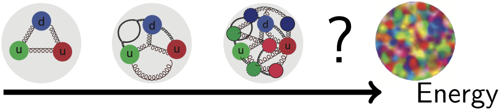
# Conclusions: GlueSatLight

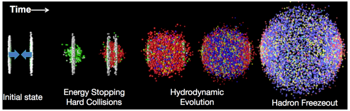
## Background: path to gluon saturation

- Soft gluon emission is favored in QCD $\Rightarrow$ protons and nuclei dense at high energy
- Eventually $g \to gg$ and $gg \to g$ balance: new state of matter with non-linear dynamics

## Open questions answered in this project

- Is non-linear QCD dynamics visible in current collider energies? (discover)
- How do these saturation effects modify the nuclear high-energy structure? (quantify)
- What is the effect on the extraction of the Quark Gluon Plasma properties? (apply)



# Backups

# Saturation effects: coherent $\gamma + A \to \mathrm{J}/\psi + A$

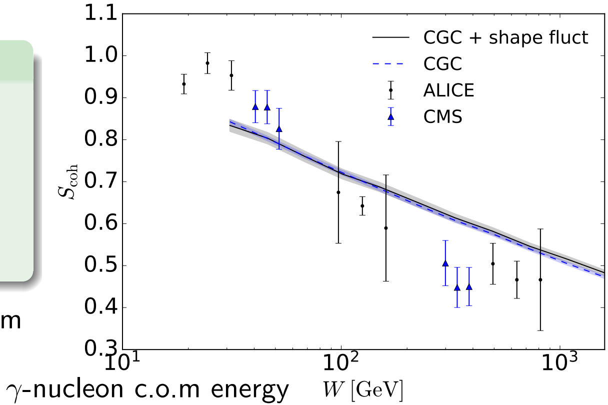
## Power of exclusive processes

- Can measure total momentum transfer
  $\Rightarrow$ geometry
- No net color charge transfer
  $\Rightarrow$ need to exchange at least 2 gluons
  $\Rightarrow$ sensitivity

Extract $\gamma + \mathrm{Pb} \to \mathrm{J}/\psi + \mathrm{Pb}$ cross section from ultra-peripheral Pb+Pb data

Nuclear modification:

$$S_{\mathrm{coh}} = \sqrt{\frac{\sigma^{\gamma \mathrm{Pb}}}{\text{Scaled } \sigma^{\gamma p}}}$$

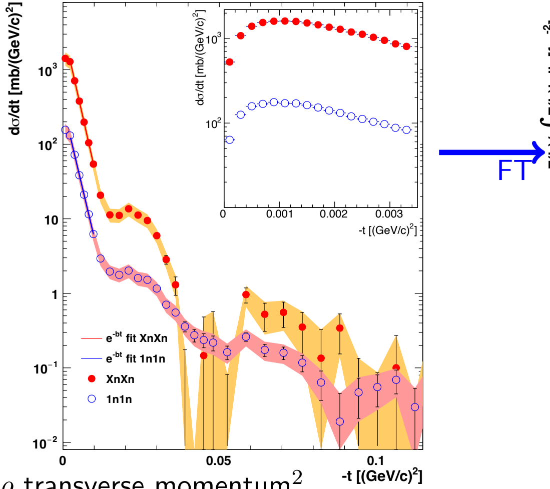



Very strong suppression observed and predicted

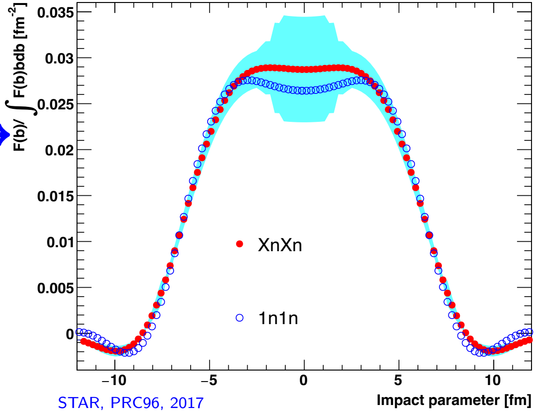
H.M, Salazar, Schenke, arXiv:2312.04194

# Geometry from exclusive scattering: $\mathrm{Au} + \mathrm{Au} \to \mathrm{Au} + \mathrm{Au} + \rho^0$

Total transverse momentum transfer: conjugate to distance ⇒ access to geometry




$\rho$ transverse momentum$^2$




Extract geometry at high $E$/small-$x$!