

Complementarity: pA/eA/UPC

T. Lappi

University of Jyväskylä, Finland

Initial state 2016, Lisbon



Outline

1. A theorist's collision process: $pA, eA, \text{UPC} \approx qA, q\bar{q}A$
2. For initial state, need **theory** plus experimental constraints for
 - ▶ Counting color: nuclear pdf's
 - ▶ Small- x dynamics: dilute partons vs. dense color fields
 - ▶ Transverse geometry
 - ▶ Correlations

How to get these from pA, eA, UPC ?

Introduction

Probing small- x gluons

Counting color: nuclear PDF's

Small x dynamics

Transverse geometry

Parton correlations

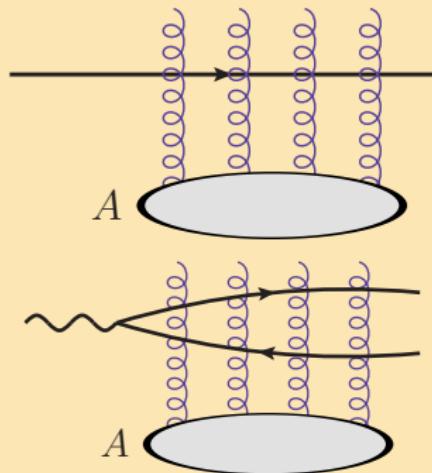
Dilute probes of small- x nucleus: theorists's view

At small x , the nucleus is a gluon field.
It can be probed with:

- ▶ Quark
 - ▶ Hard scale from p_T
- ▶ Photon $\rightarrow q\bar{q}$ dipole,
 - ▶ DIS $r \sim 1/Q \lesssim 1/\Lambda_{\text{QCD}}$
 - ▶ Heavy quarks $r \sim 1/M_Q \lesssim 1/\Lambda_{\text{QCD}}$
 \rightarrow also $Q^2 = 0$
- ▶ (Absolute value)² of quark is a dipole:
end up with same operator

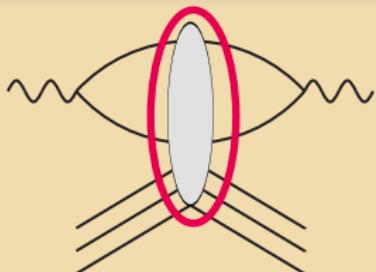
$$V = \mathbb{P} \exp \left\{ -ig \int dx^+ A^- \right\}$$

$$\mathcal{N}(\mathbf{x}_T - \mathbf{y}_T) = 1 - \frac{1}{N_c} \left\langle \text{Tr} V^\dagger(\mathbf{x}_T) V(\mathbf{y}_T) \right\rangle$$



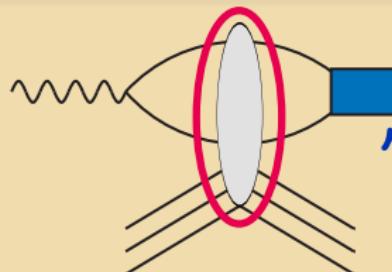
Dipole picture: exclusive and total related

Total cross section



$\sigma_{\text{tot}} \sim$ forward elastic $q\bar{q}$ -target amplitude (via optical theorem)

Diffractive DIS



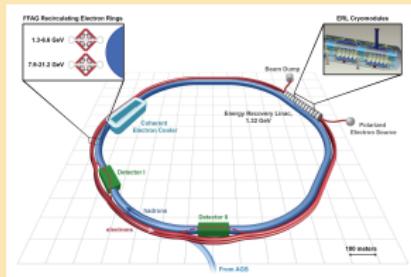
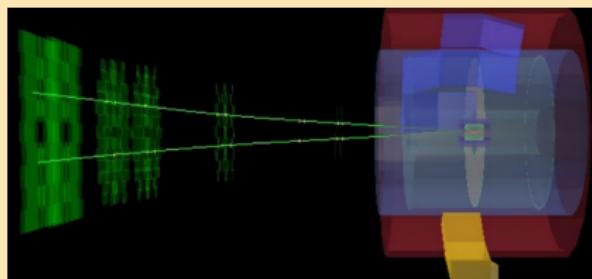
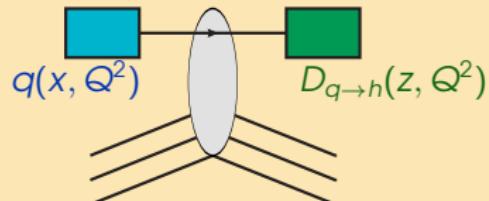
Diffractive cross section
 $\sim |\text{same amplitude}|^2$.

Same QCD-evolved amplitude describes both

- Unified description is a major advantage of the dipole picture
- No obvious inclusive-exclusive relation in collinear factorization
- Vector mesons: also need meson light cone wavefunction
- **Ultra-Peripheral Collision:** limit $Q^2 = 0$

Dilute probes of small- x nucleus: reality

- ▶ $q+A \rightarrow pA$
 - ▶ Parton distribution
 - ▶ Hadronization
- ▶ $\gamma A \rightarrow \text{UPC} @\text{LHC, RHIC}$
 - ▶ Trigger! \rightarrow exclusive only
 - ▶ Vector meson hadronization
- ▶ $\gamma^* A \rightarrow \text{DIS}$: clean, but machine \nexists yet



Initial state in AA from small-x glue

Need theory:

no way to directly measure initial state in AA

- ▶ Perturbative
 - ▶ parton distributions (integrated/unintegrated)
 - ▶ perturbative scatterings + IR cutoff
 - ▶ pdf's probed in eA , γA , pA , but how to constrain IR cutoff?
- ▶ **Classical Yang-Mills**
 - ▶ no cutoff needed
 - ▶ single nucleus CYM field constrained by scattering with dilute probe
- ▶ Strong coupling: strings, gauge/gravity duality ...
 - ▶ Constrain models by pp , pA (but eA , γA in same picture?)

This talk: not theory, but exp constraints from pA , eA , UPC

Introduction

Probing small- x gluons

Counting color: nuclear PDF's

Small x dynamics

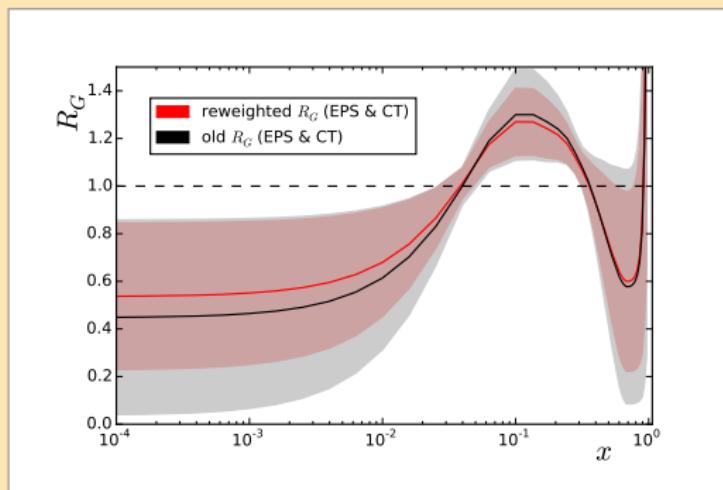
Transverse geometry

Parton correlations

Counting color: nuclear PDF constraints

Most rigorous weak coupling way to count partons in nucleus

- ▶ LHC pA data: basically conforms to what we already thought, but will allow relaxing constraints



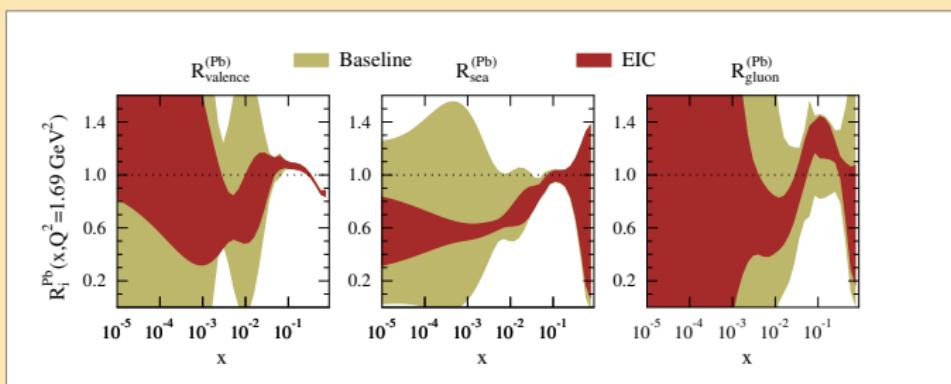
Adding LHC data to EPS: change in errors small

N. Armesto, H. Paukkunen, J. M. Penin, C. A. Salgado and P. Zurita, Eur. Phys. J. C **76** (2016) 218

Counting color: nuclear PDF constraints

Most rigorous weak coupling way to count partons in nucleus

- ▶ LHC pA data: basically conforms to what we already thought, but will allow relaxing constraints
- ▶ EIC will add constraints: more for valence than glue



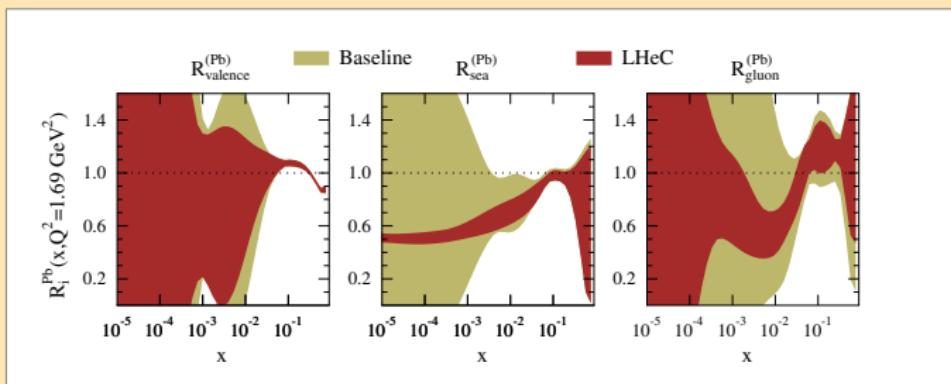
Effect of EIC on nPDF fits

Paukkunen et al, to appear

Counting color: nuclear PDF constraints

Most rigorous weak coupling way to count partons in nucleus

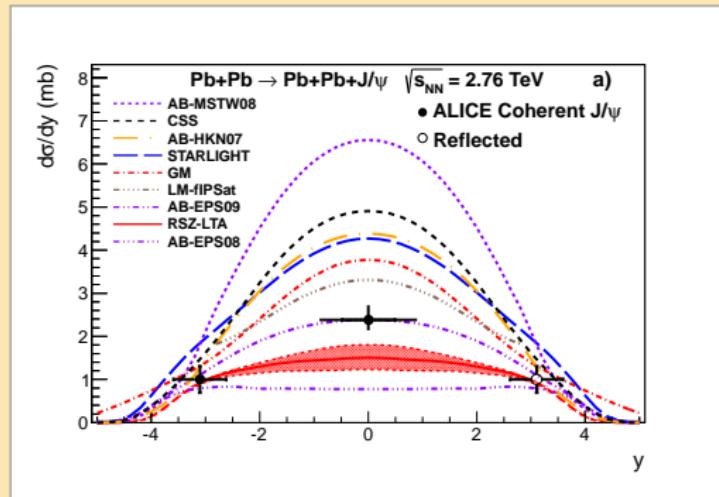
- ▶ LHC pA data: basically conforms to what we already thought, but will allow relaxing constraints
- ▶ EIC will add constraints: more for valence than glue
- ▶ LHeC would really make a difference



LHeC pseudodata

I. Helenius, H. Paukkunen and N. Armesto, PoS DIS **2015** (2015) 226 + to appear

Nuclear PDF's from UPC?



Certainly UPC's give a strong constraint on gluons at small x , **but** ...

- ▶ No factorization theorem for exclusive cross section $\sim xg(x, Q^2)^2$
- ▶ No full NLO calculation, pdf scheme, scale ... ?
- ▶ Normalization does not work that well:
additional factor fit to HERA (AB,RSZ) or separate pdf set (JMRT)
(Unlike for inclusive cross sections)

➡ UPC's cannot be included in **rigorous** pdf fit

Introduction

Probing small- x gluons

Counting color: nuclear PDF's

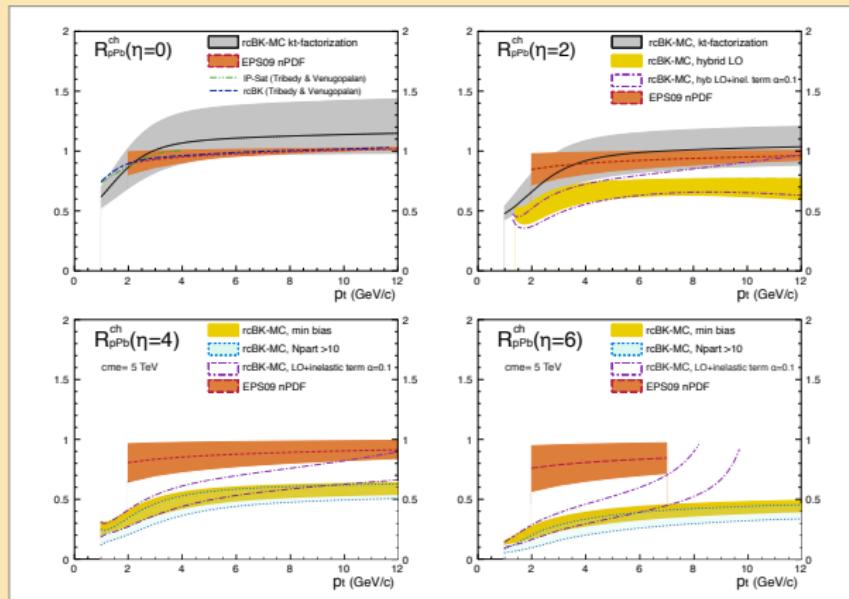
Small x dynamics

Transverse geometry

Parton correlations

What happens at the highest energy: small x dynamics in R_{pA} ?

- ▶ Unambiguous CGC/BFKL dynamics in inclusive scattering?
- ▶ LHC: highest \sqrt{s} for a long time $\implies R_{pA}$ at forward rapidity!

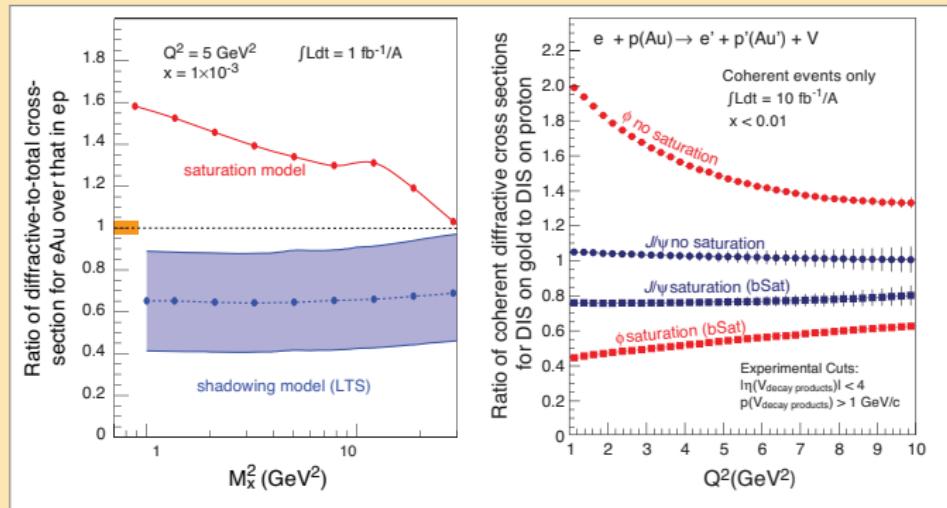


J. L. Albacete, A. Dumitru, H. Fujii and Y. Nara, Nucl. Phys. A **897** (2013) 1, (arXiv:1209.2001 (hep-ph)).

- ▶ Clear difference between **current** CGC calculations and EPS09
- ▶ **Caveat:** CGC here is LO; at NLO expect less BK effects at high p_T .

When does collinear factorization break down? Diffraction

Sat vs nonsat: differences much more drastic in diffractive DIS

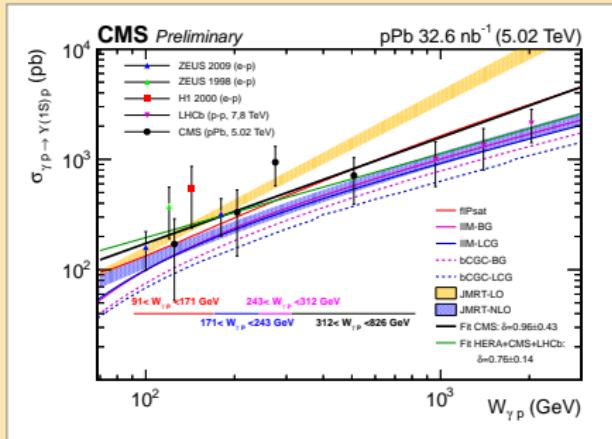


EIC white paper arXiv:1212.1701 : eA/ep ratios

- Generically: $\sigma_{\text{diff}}^{\gamma^* h} / \sigma_{\text{tot}}^{\gamma^* h}$ maximal at unitarity limit.
- **Lots of diffraction at high $Q^2 \implies$ saturation**
- IHMO: closest thing to “smoking gun”.
- Caveat: for collinear fact. no clean exclusive/inclusive relation: “nonsat” calculations easily unrealistic straw men.

(Terminology note: diffractive DIS = elastic γ^* -target)

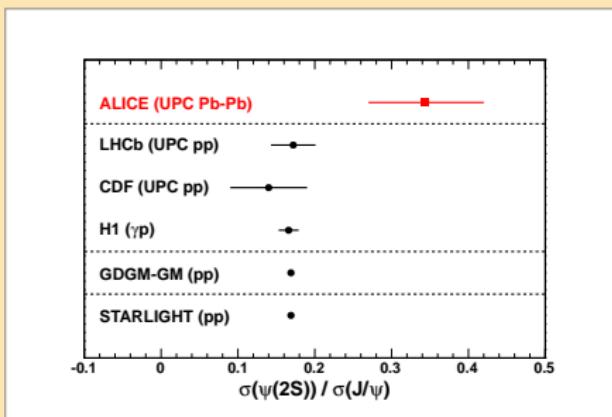
Small- x dynamics in UPC



CMS UPC $\gamma p \rightarrow \pi p$ CMS PAS FSQ-13-009

- UPC: highest energy γ -scattering data we have: very valuable!

- Still lot to do e.g. on VM species systematics
- Natural in dipole picture: but learn more about V.M. than about small x ?



ALICE Phys. Lett. B 751 (2015) 358,

Introduction

Probing small- x gluons

Counting color: nuclear PDF's

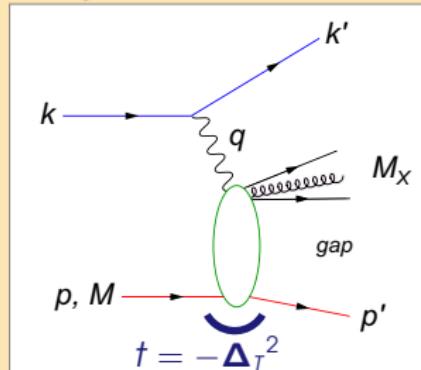
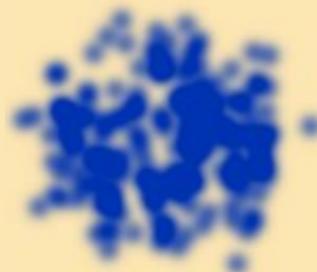
Small x dynamics

Transverse geometry

Parton correlations

How to measure transverse geometry of gluons

Diffractive DIS gives Fourier transform of gluon distribution



$$\mathcal{N}(\Delta_T) = \int d^2 \mathbf{b}_T e^{i \mathbf{b}_T \cdot \Delta_T} \mathcal{N}(\mathbf{b}_T)$$

Coherent target intact; measure average gluon distribution

Incoherent target breaks without color exchange: fluctuations

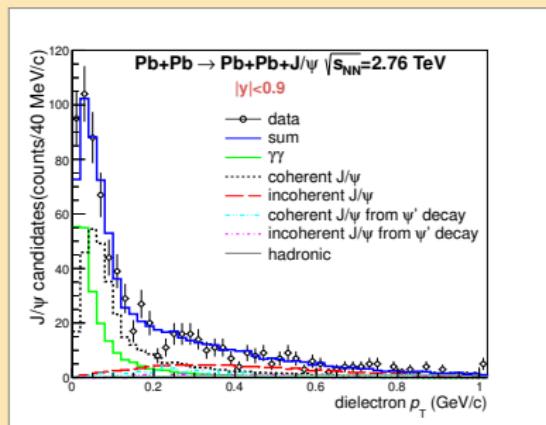
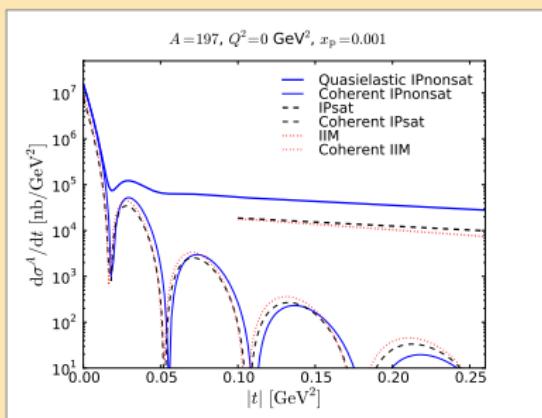
See parallel talk H. Mäntysaari: trasverse structure of proton

Coherent and incoherent: different target recoil

- ▶ Coherent $-t \sim \frac{1}{R_A^2} \sim 0.01 \text{ GeV}^2$
- ▶ Incoherent $-t \sim \frac{1}{R_P^2} \sim 1 \text{ GeV}^2$

For $Q^2 = 0$ $-t \approx p_{TJ/\psi}^2 = p_{TA}^2$:

for UPC experimentally separate by $p_{TJ/\psi}^2$



T.L., H. Mäntysaari, Phys. Rev. C **87** (2013), 032201

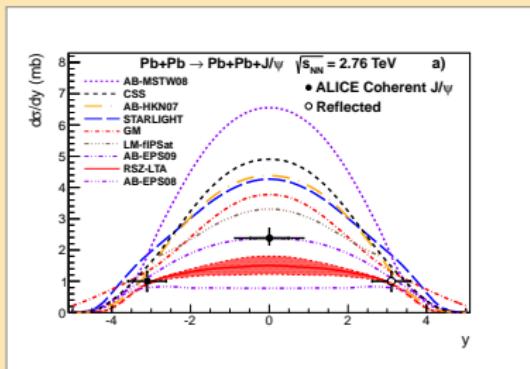
ALICE Eur. Phys. J. C **73** (2013) 2617

Reconstruct b from experimental t -distribution?

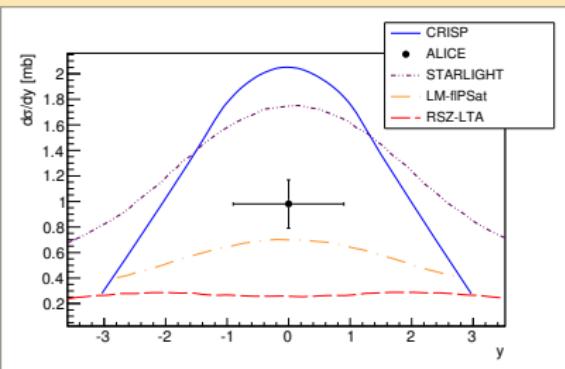
Not at LHC, challenge at EIC

Coherent and incoherent: need to compare models to both

For AA initial state: need average **and** fluctuations:
coherent **and** incoherent



ALICE Eur. Phys. J. C **73** (2013) 2617



E. Andrade-II, I. González, A. Deppman and
C. A. Bertulani, Phys. Rev. C **92** (2015) 064903

- ▶ J/ψ only at one scale: heavy quark mass.
- ▶ Q_s is p_T -scale: to study CGC dynamics need Q^2 -dependence: EIC

Introduction

Probing small- x gluons

Counting color: nuclear PDF's

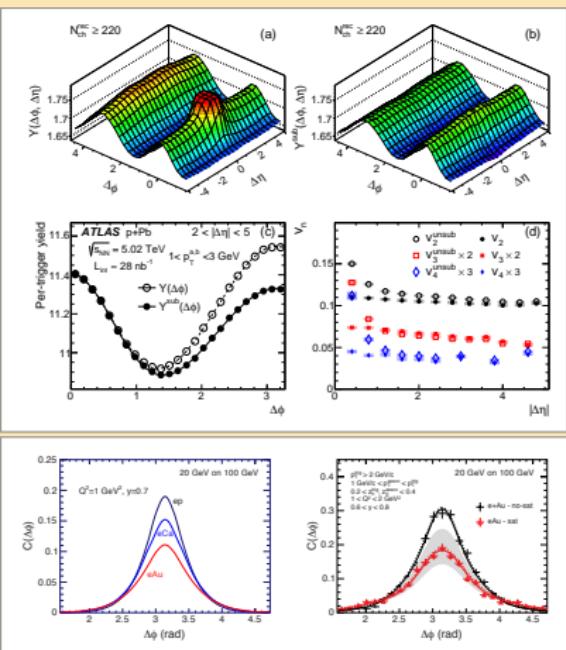
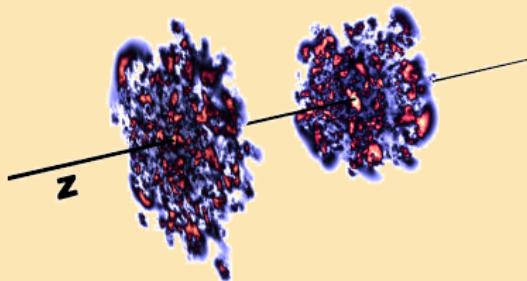
Small x dynamics

Transverse geometry

Parton correlations

Azimuthal correlations

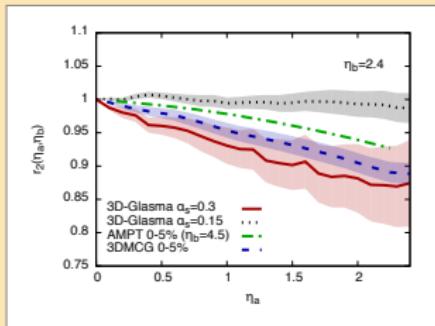
- ▶ Azimuthal correlations in pp, pA, interplay between:
 - ▶ Initial color fields
 - ▶ Hydrodynamical flow
- ▶ Az. correlations in eA:
 - ▶ Dilute limit: 2-particle “nonflow” only
 - ▶ In DIS: $v_2 \sim$ “linearly polarized gluon distribution”
A. Dumitru, T.L., V. Skokov
Phys. Rev. Lett. **115** (2015) 252301
 - ▶ Dense systems: p_T balance distributed among more particles: more flow-like



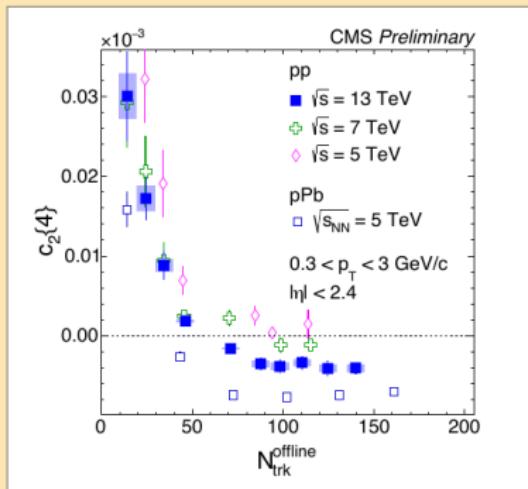
Approaching initial stage color fields from different directions

Things to do still

- ▶ Higher cumulants:
full set of $v_n\{m\}$'s
- ▶ Longitudinal correlations
 - ▶ Implemented in string models,
E.g. L. G. Pang, H. Petersen, G. Y. Qin,
V. Roy and X. N. Wang, Eur. Phys. J. A **52**
(2016), 97 ,
G. Denicol, A. Monnai and B. Schenke,
arXiv:1512.01538 (nucl-th).
- ▶ CGC contribution not yet fully understood



B. Schenke, S. Schlichting, arXiv:1605.07158



Conclusions

What can be learned? Depends on level of theory one is willing to live with.

Pure theory attitude: **calculate** initial stage of AA from QCD

- ▶ eA cleanest
- ▶ UPC covers part of EIC physics, but
 - ▶ Only exclusive
 - ▶ Cannot vary Q^2
- ▶ pA & pp is interesting but complicated! “Clean” only at large p_T , which is not where the interesting stuff happens

More phenomenological attitude:

build models of AA initial state, compare with AA data

- ▶ Want to benchmark to systems “close” to AA: pA & pp

UPC's and gluon pdf

Extra slides

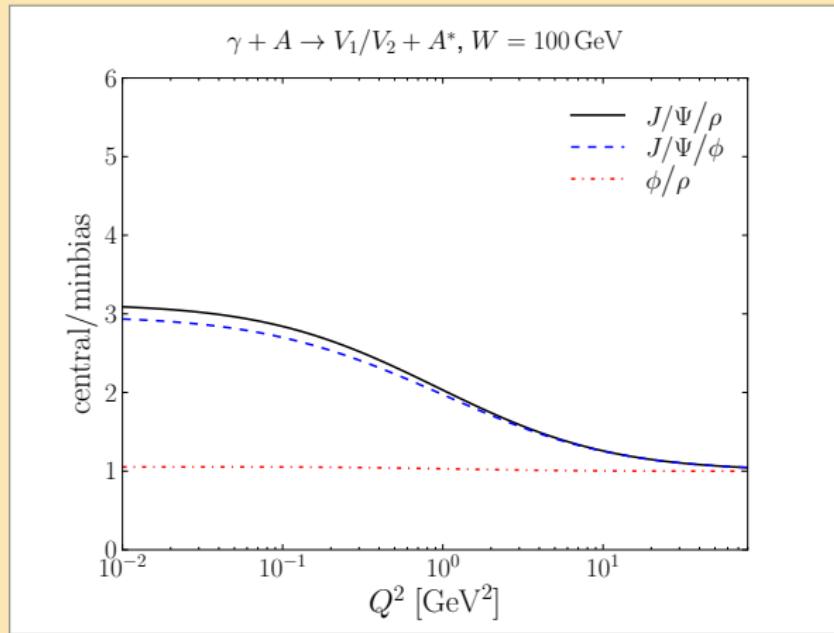
UPC's and gluon pdf

$$\frac{d\sigma^{\gamma^* H \rightarrow VH}}{dt} = \frac{16\pi^3 \alpha_s^2 \Gamma_{ee}}{3\alpha_{em} M_V^5} \left[xg(x, Q^2) \right]^2 \quad \text{this is a dipole model result!}$$

Use as constraint for gluon pdf ? Hesitations

- ▶ Not at the same level of pQCD rigor as inclusive cross sections: No “factorization theorem”
- ▶ Only LO, includes model of $Q\bar{Q}$ bound state
- ▶ Normalization does not work: either additional factor (AB, RSZ) or separate pdf (JMRT) additional fudge factors and corresponding theory uncertainty

Dependence on Q^2



T.L., H. Mäntysaari, R. Venugopalan PRL 2015

Central/minimum bias double ratio for vector mesons in incoherent diffractive nuclear DIS

Saturation turning off with increasing Q^2