Gluons and low x in e+A collisions

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e+A Small-x Science Matrix

Primary new science deliverables	What we hope to fundamentally learn	Basic measurements	Typical required precision	Special requirements on accelerator/ detector	What can be done in phase I	Alternatives in absence of an EIC	Gain/Loss compared with other relevant facilities	Comments
integrated nuclear gluon distribution	The nuclear wave function throughout x-Q^2 plane	F_L, F_2, F_L^c, F_2^c	What HERA reached for F2 with combined data	displaced vertex detector for charm	stage 1: large-x & large-Q^2 need full EIC, for F_L and F_2^c	p+A at LHC (not as precise though) & LHeC	First experiment with good x, Q^2 & A range	This is fundamental input for A+A collisions
k_T dependence of gluon distribution and correlations	The non-linear QCD evolution - Qs	SIDIS & di-hadron correlations with light and heavy flavors		Need low-pt particle ID	SIDIS for sure TBD: saturation signal in di-hadron p_T imbalance	1) p+A at RHIC/LHC, although e+A needed to check univerality 2) LheC	Cleaner than p+A: reduced background	
b dependence of gluon distribution and correlations	Interplay between small-x evolution and confinement	Diffractive VM production and DVCS, coherent and incoherent parts	50 MeV resolution on momentum transfer	hermetic detector with 4pi coverage low-t: need to detect nuclear break-up	Moderate x with light and heavy nuclei	LHeC	Never been measured before	Initial conditions for HI collisions – eccentricity fluctuations

Integrated gluons

Inclusive structure functions

$F_2 \ , \ F_L \ , \ F_2^c$

this is fundamental knowledge about the nuclear wave function that is still lacking

the most basic observables from the theory side, they will be the first observables for which non-linear QCD evolution will be available at NLO

- F_2 measurement with the smallest x reach, but there is a cancelation of non-linear effects in F_2 (from summing F_T and F_L)

  this is presumably why the leading-twist approximation is able to describe F_2 down to 2 GeV^2 at HERA, if we had as precise F_L data, we might see the collinear approach fail already at 5-10 GeV^2

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- F_L better access to the gluon distribution, but can't reach x as small because of an energy scan is needed for the measurement
- F_2^c better access to the gluon distribution, but can't reach x as small because of the large charm quark mass

we should aim, for all of these, to get the same precision that was reached at HERA with the F_2 combined data

also, the heavy-ion program at the LHC would benefit a lot from a precise determination of nuclear pdfs over a large x-Q^2 range (similar to the impact of HERA on the p+p program)

The importance of saturation

- average strength of dipole scattering

Diehl and Lappi

$$\langle T_{q\bar{q}}\rangle_{2,L}(x,Q^2) = \frac{\int d^2r\ dz\ |\psi_{2,L}(z,\mathbf{r};Q^2)|^2 \int d^2b\ T^2_{q\bar{q}}(\mathbf{r},\mathbf{b};x)}{\int d^2r\ dz\ |\psi_{2,L}(z,\mathbf{r};Q^2)|^2 \int d^2b\ T_{q\bar{q}}(\mathbf{r},\mathbf{b};x)}$$

$T_{q\bar{q}} \ll 1 \ \Rightarrow$ linear dynamics $\qquad T_{q\bar{q}} \lesssim 1 \ \Rightarrow$ large gluon density, saturation

average dipole scattering amplitude $\langle T_{q\bar{q}}\rangle_{T,L} < 0.6 - 0.7$ and not 1 because of b int

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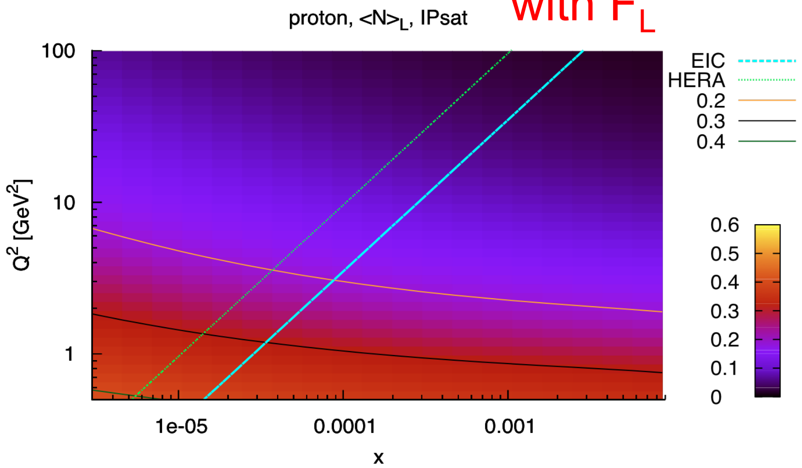
- off the proton

with F$_L$

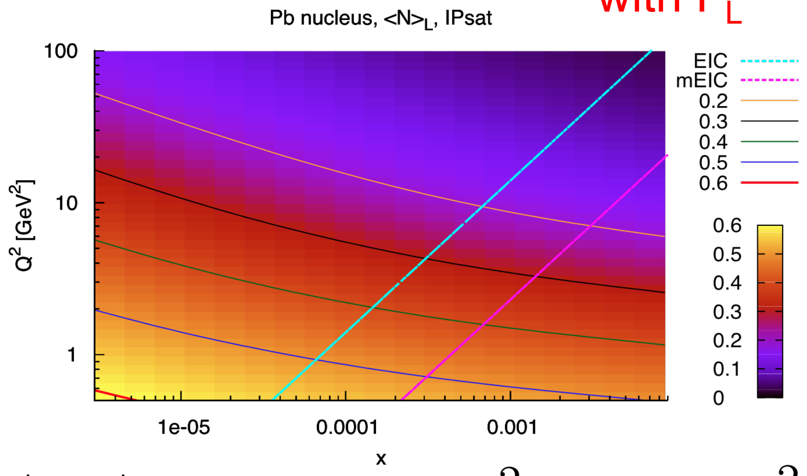


$$\langle T_{q\bar{q}}\rangle_{2,L} < 0.25 \text{ for } Q^2 > 2\ \text{GeV}^2$$

EIC comparable to HERA

- off the (Pb) nucleus

with F$_L$



$$\langle T_{q\bar{q}}\rangle_{L} \simeq 0.4 \text{ for } Q^2 = 2\ \text{GeV}^2$$

undoubtedly probing saturation/unitarity

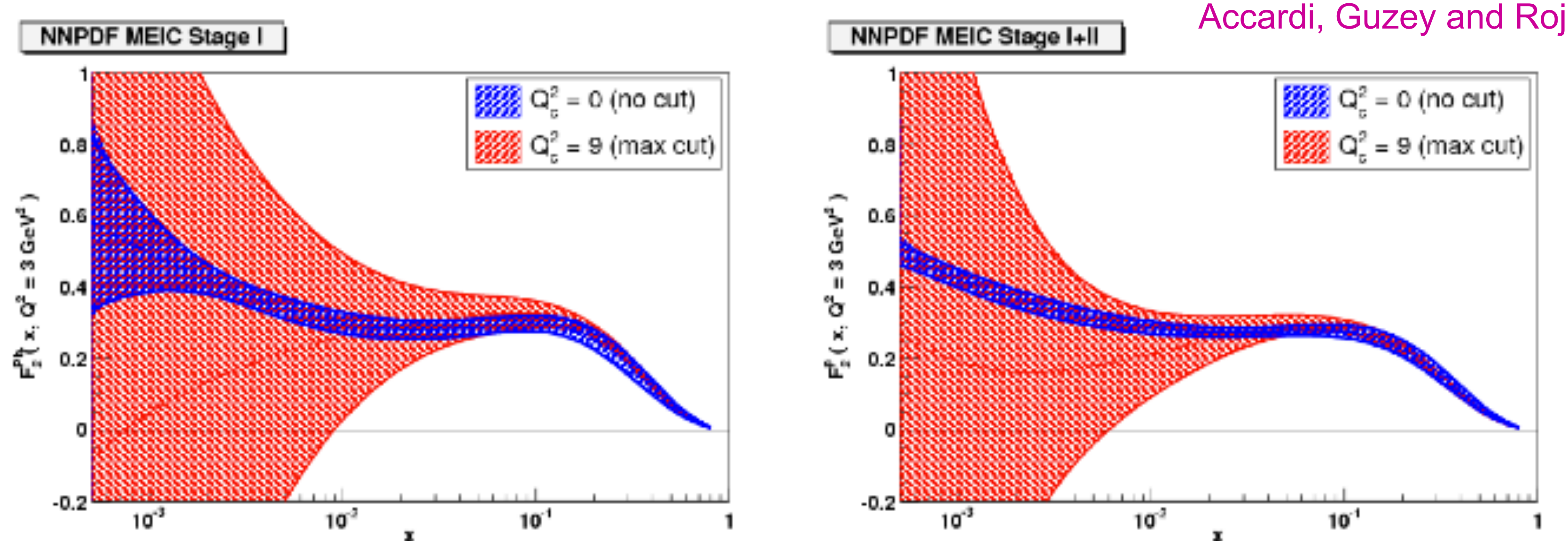
better to increase A that to decrease x

Detecting deviations from DGLAP

- Could DGLAP describe data in the saturation region:? no

- create small-x pseudo-data with non-linear QCD evolution
- perform a DGLAP fit only in the “safe region” large Q^2 region
- evolve into the “saturation” region using DGLAP
- compare to what a full DGLAP fit would have produced

Accardi, Guzey and Rojo

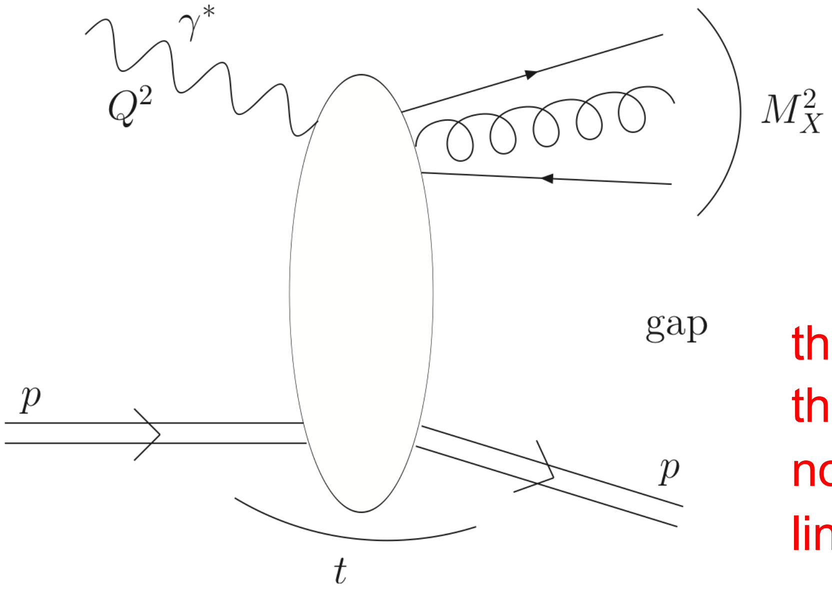


systematic downward shift: signal of deviations from DGLAP

for a Pb nucleus, deviations from DGLAP would be unambiguously identified within the x range of the full-energy EIC

Diffractive structure functions

they have never been measured in e+A



the sensitivity to saturation is better in diffraction, in fact many hints from saturation at HERA come from diffraction:

the constant ratio, with increasing energy, of the diffractive to inclusive cross section does not reflect the x dependence expected in the linear regime: $\sigma_{incl} \sim xg(x)$, $\sigma_{diff} \sim [xg(x)]^2$

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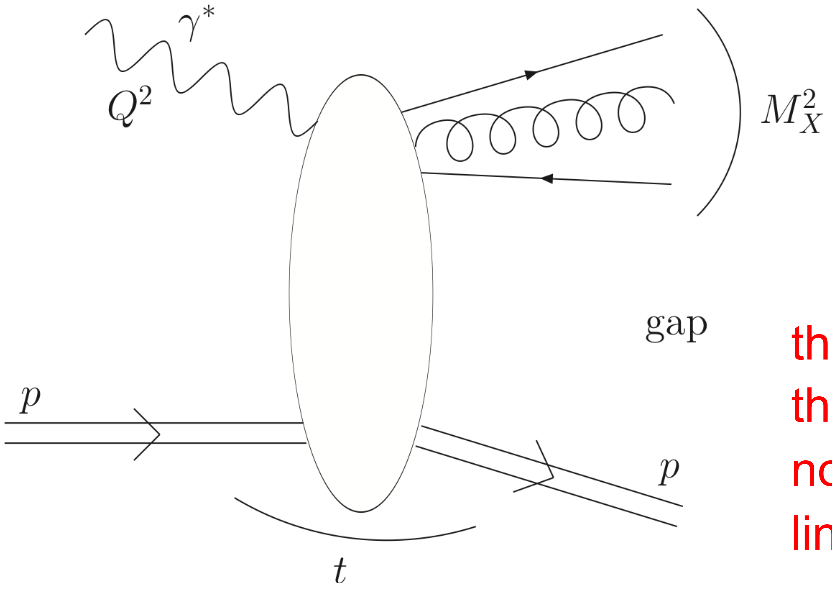

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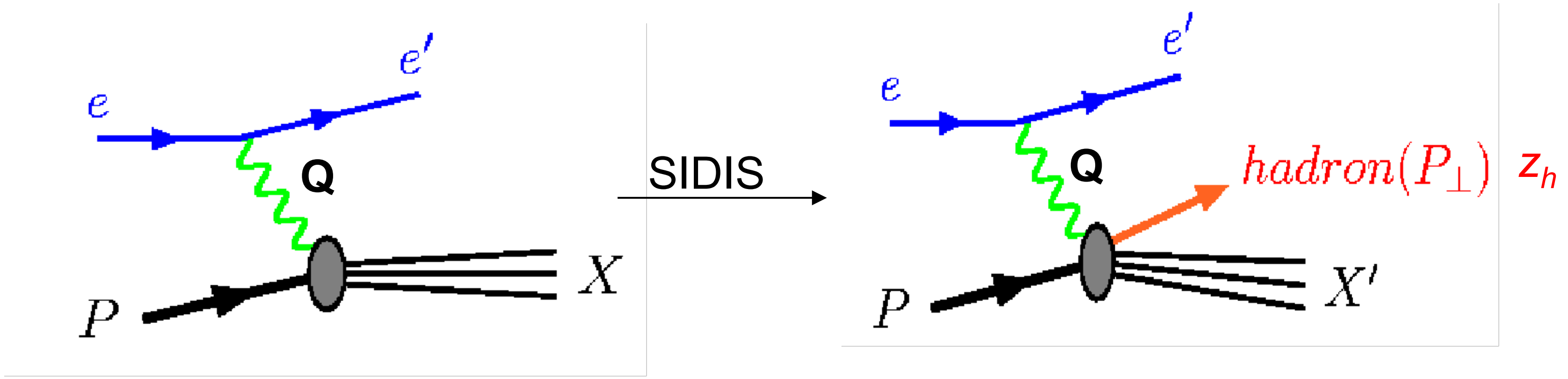
quantitatively, DGLAP fits for the inclusive structure function F_2 become problematic for Q^2 below 4 GeV^2 while for the diffractive structure function F_2^D they become problematic at a much higher Q^2 around 8 GeV^2

at HERA 10-15 % of events are diffractive, at an EIC we expect 30-35 %

k_T-dependent gluons - distributions and correlations

Semi-inclusive DIS



measured only at high x and for light nuclei

- at small x hadronization happens outside the nuclear matter

the k_T dependence of the gluon distribution can be extracted
from the P_T dependence of the SIDIS cross-section

for saturation physics the relevant regime is low P_T (~ Qs)

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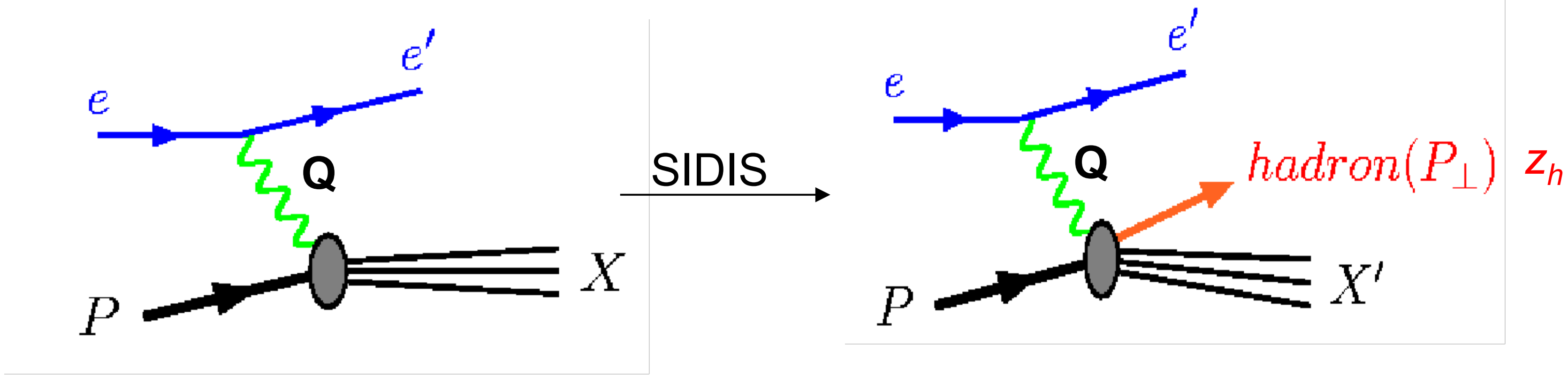

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- unique opportunity to study non-linear effects, while staying away from non-perturbative physics

CM, Xiao and Yuan (2009)

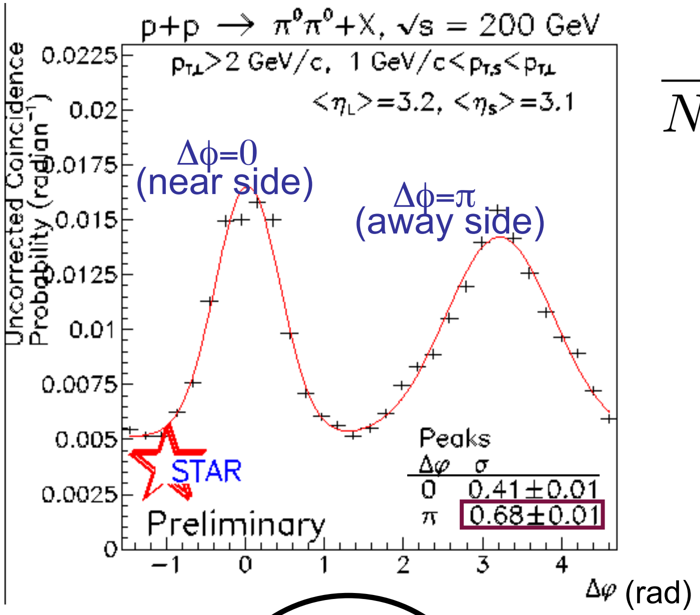
even if Q^2 is much bigger than Q_s^2, the saturation regime is important when $P_\perp^2 \sim Q_s^2$

in fact, thanks to the existence of Q_s, the limit $|P_\perp| \to 0$ is finite

Di-hadron angular correlations

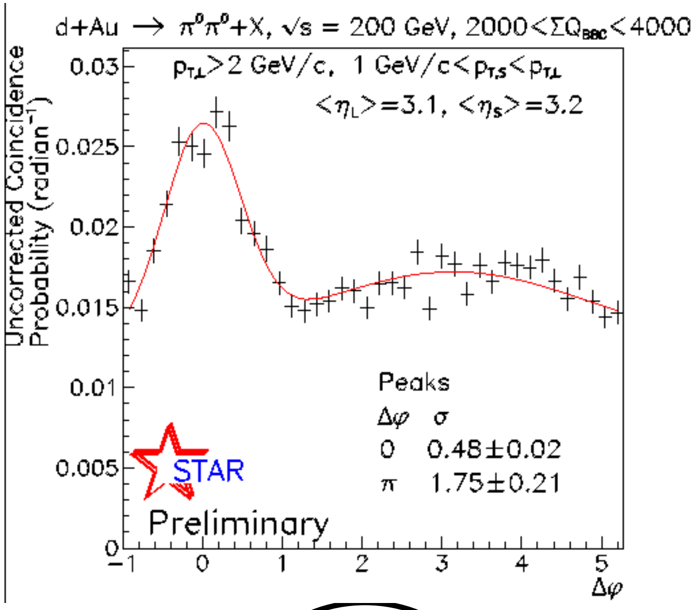
comparisons between d+Au → h_1 h_2 X (or p+Au → h_1 h_2 X) and p+p → h_1 h_2 X

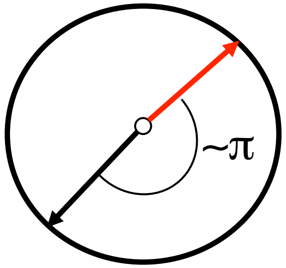
p+p collisions

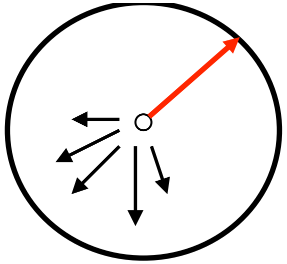


$$\frac{1}{N_{trig}}\frac{dN_{pair}}{d\Delta\varphi}$$

central d+Au collisions







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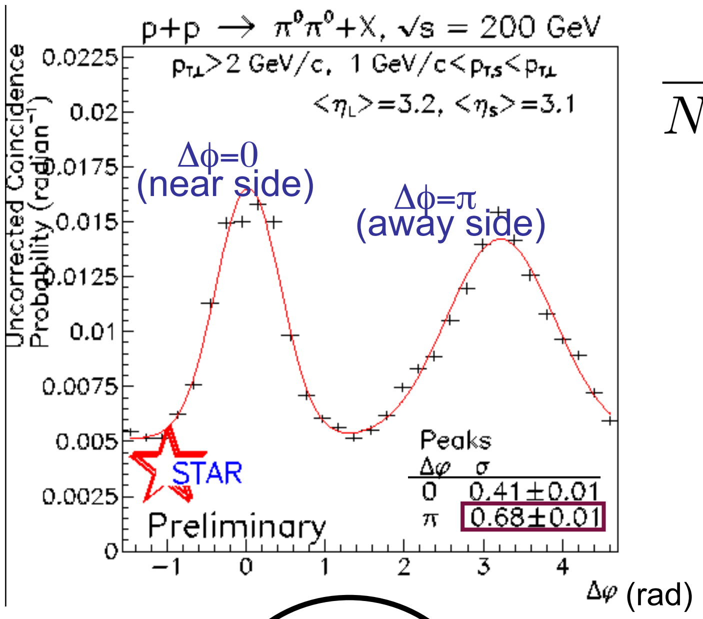

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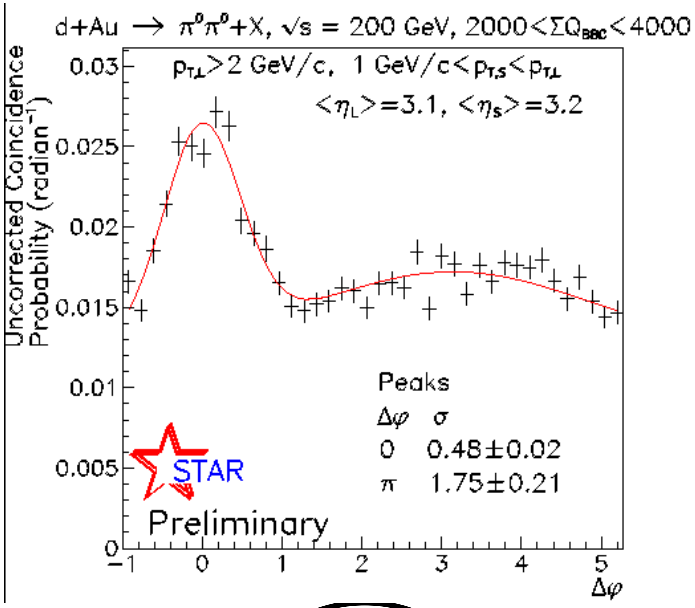
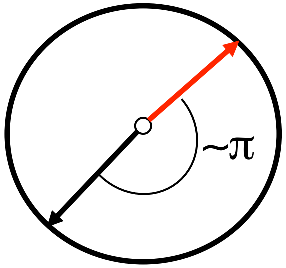
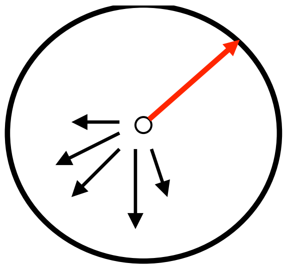




$$x_A = \frac{k_1\, e^{-y_1} + k_2\, e^{-y_2}}{\sqrt{s}} << 1$$

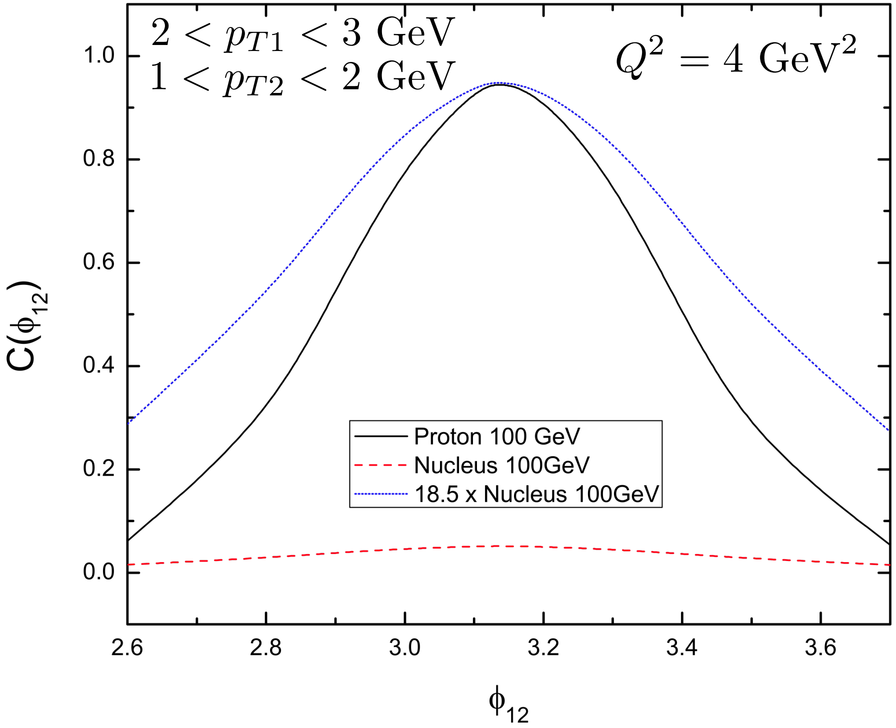


however, when $y_1 \sim y_2 \sim 0$ (and therefore $x_A \sim 0.03$),
the p+p and d+Au curves are almost identical

Di-hadron correlations in e+A

never been measured, we expect to see the same effect in e+A vs e+p

Dominguez, Xiao and Yuan (2010)



at small x, multi-gluon distributions are as important as single-gluon distributions, they contribute to such di-hadron correlations

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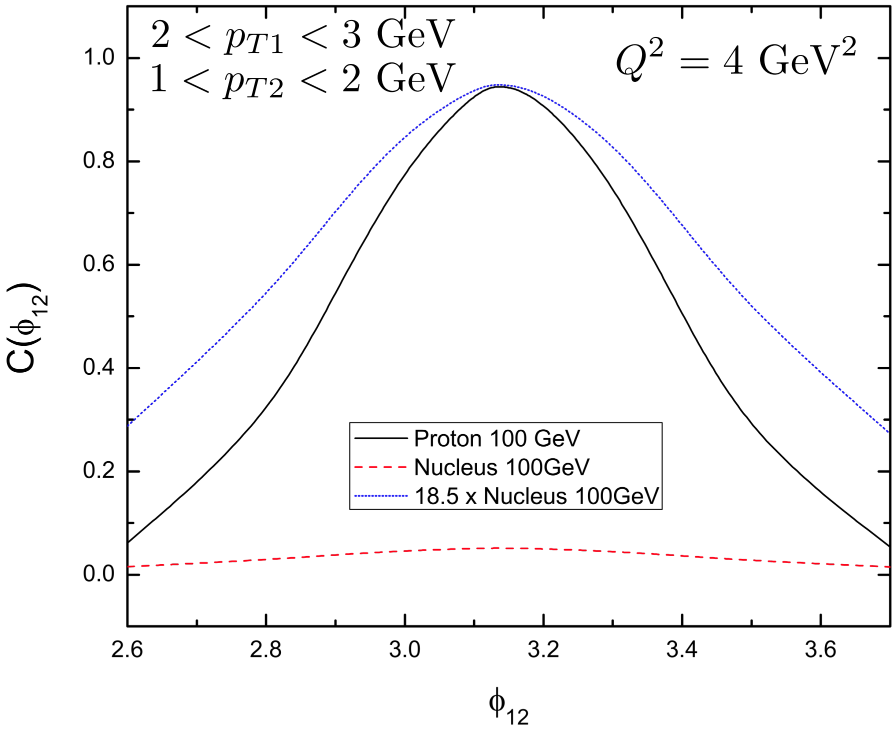

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the description of the RHIC data is therefore subject to uncertainties

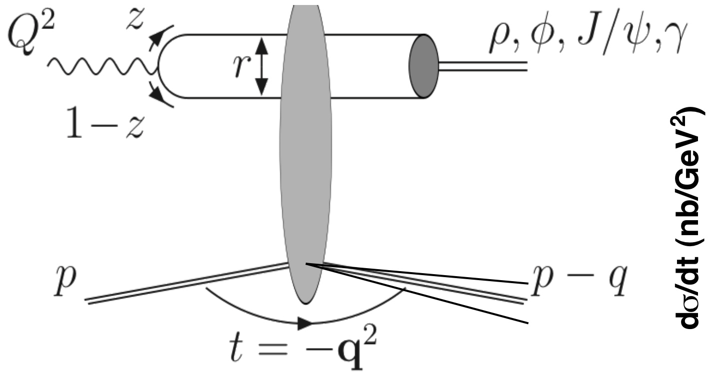
the same gluon correlations are involved in the d+Au case but the e+A measurement can constrain them better

the non-linear evolution of (k_T-dependent) multi-gluon distributions is different from that of the single-gluon distribution, and it is equally important to understand it

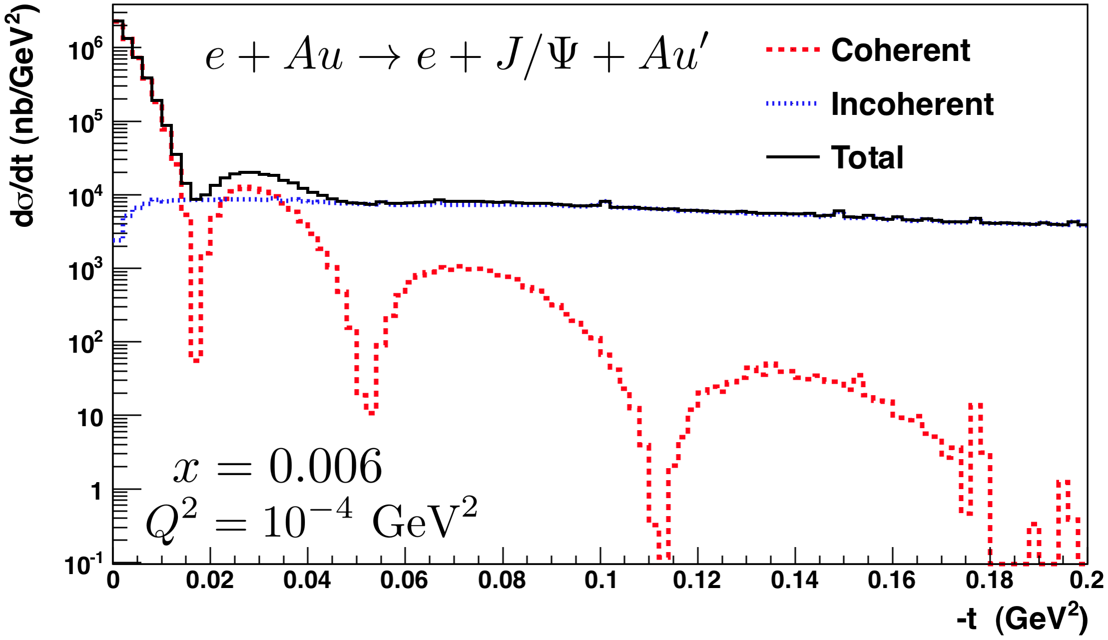
b-dependent gluons - distributions and correlations

Diffractive vector meson production

Stage 1: precise transverse imaging of the gluons, from light to heavy nuclei
Stage 2: how the small-x evolution modifies the transverse distribution of gluons



Toll and Ullrich (2011)



- as a function of t

exclusive production (coherent): the target undergoes elastic scattering, dominates at small |t|

→ steep exp. fall at small |t|

target dissociation (incoherent): the target undergoes inelastic scattering, dominates at large |t|

breakup into the nucleons
→ slower exp. fall at 0.02 < -t < 0.7 GeV^2

breakup of the nucleons
→ power-law tail at large |t|

Coherent vs incoherent

- coherent diffraction measured only at high x and for light nuclei

the b dependence of the gluon distribution is obtained from
the t dependence of the cross section by Fourier transformation

it is often assumed that gluons from different nucleons are
independent, the EIC allows to study how this changes
with the non-linear QCD evolution towards small x

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- incoherent diffraction has never been measured

gives access to gluon correlations in the transverse plane

the distribution and correlations of small-x gluons in the transverse
plane are poorly known, without this knowledge for instance one
cannot achieve a quantitative understanding of important RHIC results

the initial nuclear wave functions in relativistic heavy-ion collisions
are the source of large uncertainties, their descritption is based on
expectations which need to be checked and constrained with e+A data

e+A physics at higher-x

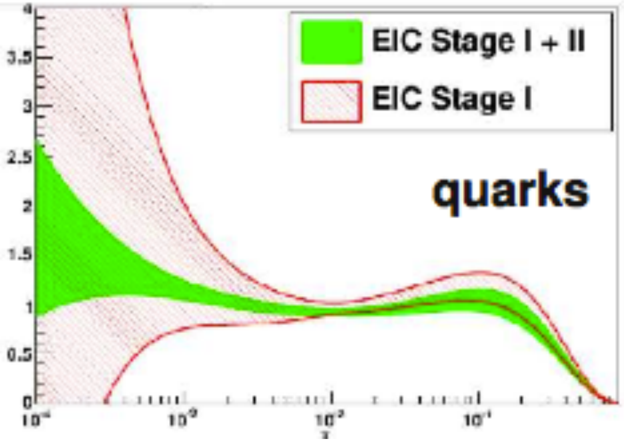
Nuclear quarks and gluons

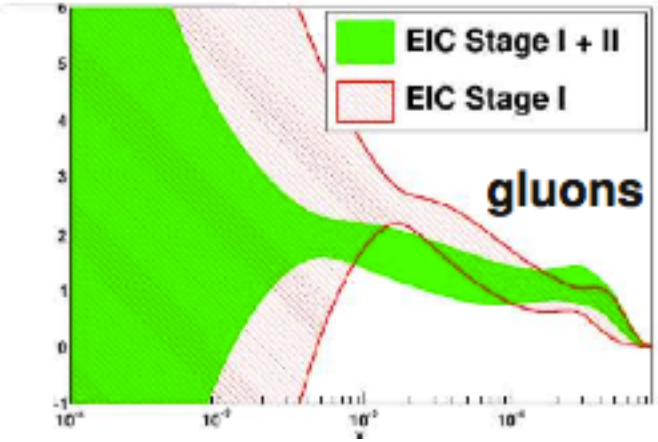
the EIC can reveal the nuclear structure throughout the (x,Q^2) plane, from gluon saturation at low x to the gluon EMC effect and its Q^2 evolution at high x

- QCD fits on e+A pseudo-data

with $\sqrt{s}$ = 12, 17, 24, 32, 44 GeV (medium energy EIC – stage I)
63, 88, 124 GeV (full energy EIC – stage I)

allows to estimate nuclear quark and gluon distributions and their uncertainties





the EIC has constraining power, it will be to nuclei what HERA is to the proton

- Nuclear GPDs, nuclear TMDs

In-medium fragmentation

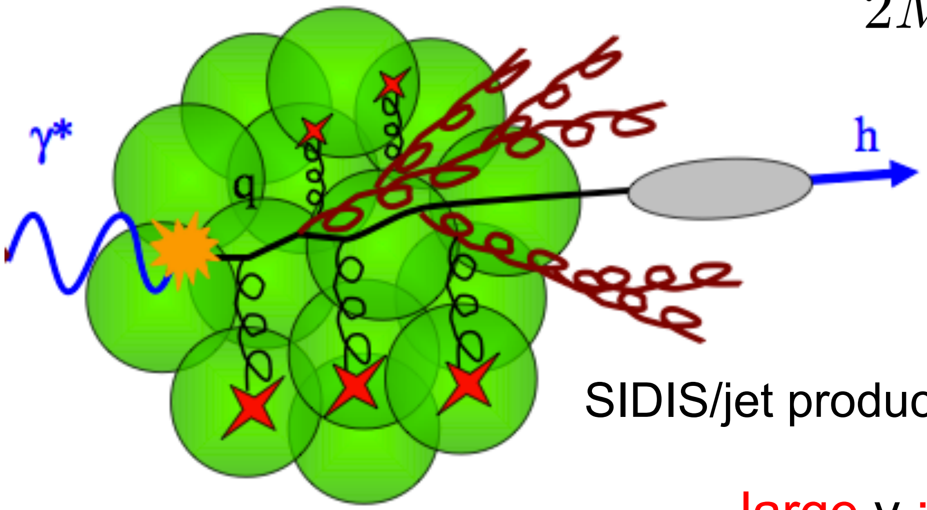
- unprecedented *v* range

$$\nu = \frac{Q^2}{2Mx}$$

small *v* :

in-medium hadronization

the EIC can study the dynamics of confinement: the stages of hadronization (parton, pre-hadron, hadron) and their time scales



SIDIS/jet production

large v : in-medium parton propagation

from the energy loss and p_T-broadening of leading partons as well as jet-shape modifications, the EIC can measure fundamental properties of cold nuclear matter: $\hat{e}$, $\hat{q}$, modifications of angular ordering

- heavy quarks

for the first time, the in-medium hadronization and propagation of heavy quarks can be studied, and the pQCD description of cold nuclear matter can be tested

Conclusions

- very little is known about the structure of nuclei at small x
  - only for inclusive structure functions we have data at moderate x
  - SIDIS and exclusive VM production data are at high x or for light nuclei
  - diffractive structure functions have never been measured

- crucial measurements at an EIC
  - inclusive and diffractive structure functions: integrated gluons
  - semi-inclusive DIS: the k_T dependence of the gluon distribution
  - di-hadron correlations: the k_T dependence of the gluon correlations
  - coherent diffraction: the impact-parameter dependence
  - incoherent diffraction: spatial correlations between small-x gluons

- in-medium fragmentation at an EIC
  - unprecedented ν range to study hadronization and parton propagation
  - unprecedented access to heavy quarks