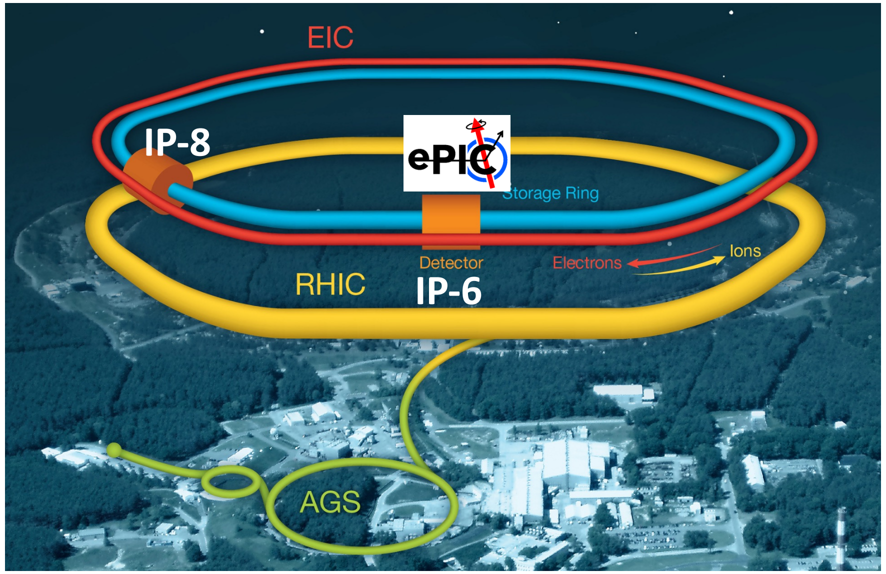
Physics at the EIC

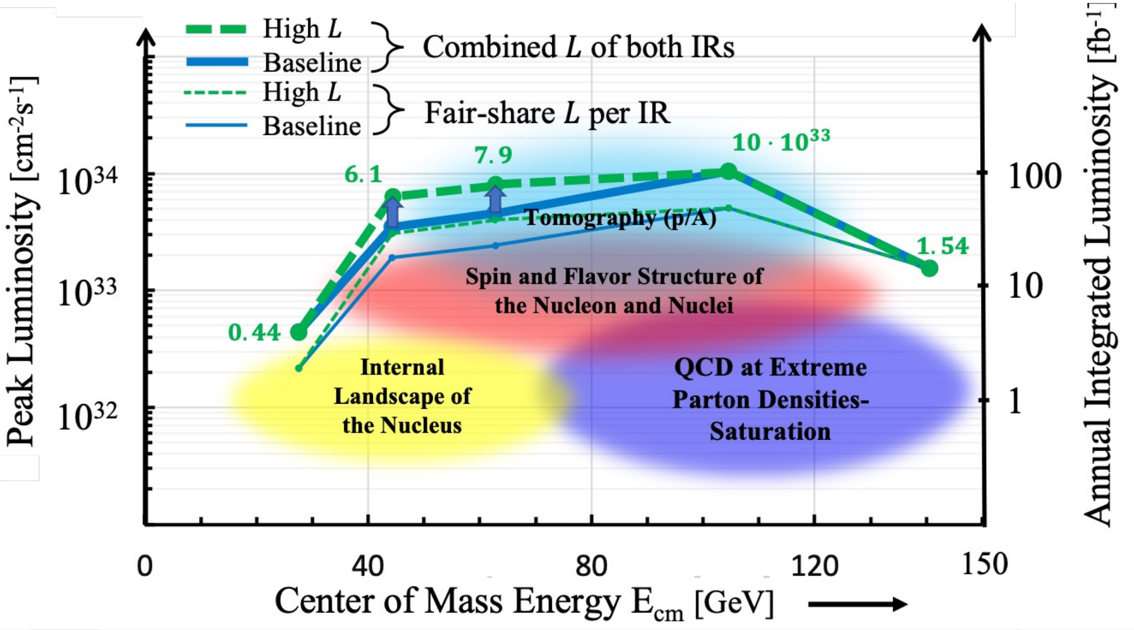
and the connections to the RHIC Cold QCD Program

Xiaoxuan Chu, BNL

JETSCAPE Online Summer School
July 28th 2023

The EIC facility





What is the EIC:

A high luminosity ($10^{33} – 10^{34}$ cm^{-2}s^{-1}) polarized electron proton / ion collider with $\sqrt{s_{ep}}$ = 28 – 140 GeV

What is included in the EIC Project:

collider & 1 interaction region and 1 general purpose detector

What can the EIC Facility support:

> 2 decades increase in kinematic coverage in x and Q^2

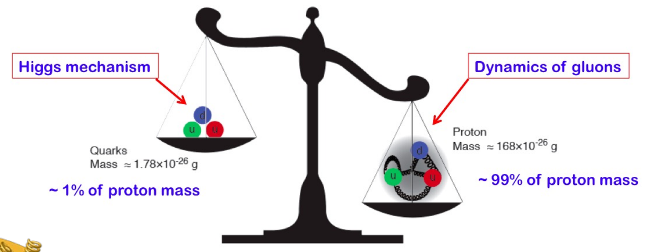
Beam set up:

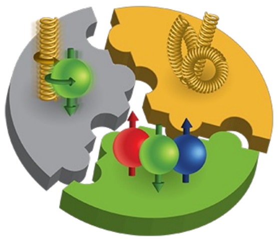
- Leptons: 5, 10, 18 GeV
- Protons: 41 GeV, 100 – 275 GeV
- d, A: 41 GeV, 100 – 110 GeV
- He-3: 41 GeV, 100 – 166 GeV
- transverse and longitudinally polarized p, He-3 and later d
- longitudinally polarized electrons

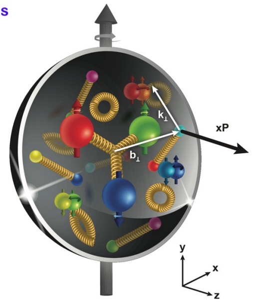
The EIC physics

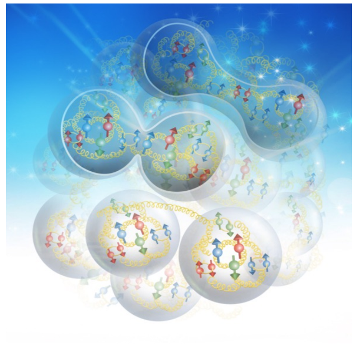
How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?

How do the nucleon properties emerge from them and their interactions?



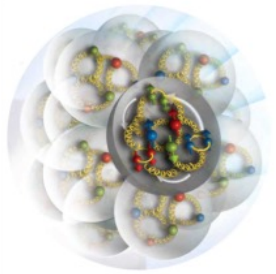






How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?
How do the confined hadronic states emerge from these quarks and gluons?
How do the quark-gluon interactions create nuclear binding?

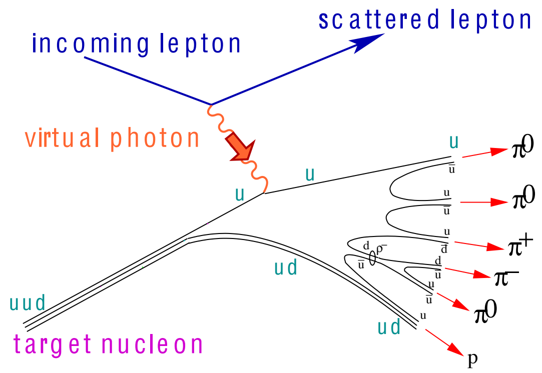
How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?



What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?

How to access partons in DIS

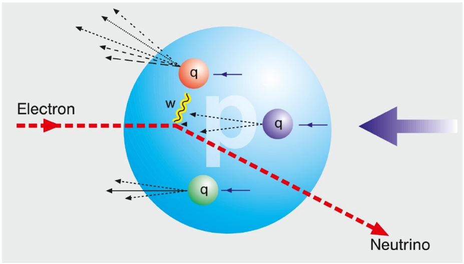
SIDIS:



Detect scattered lepton (DIS) in coincidence with identified hadrons (SIDIS)

- → one can measure the correlation between different hadrons as fct. of p_t, z, h
- → needs fragmentation functions to correlate hadron type with parton
- → Detector: PID over a wide range of η and p

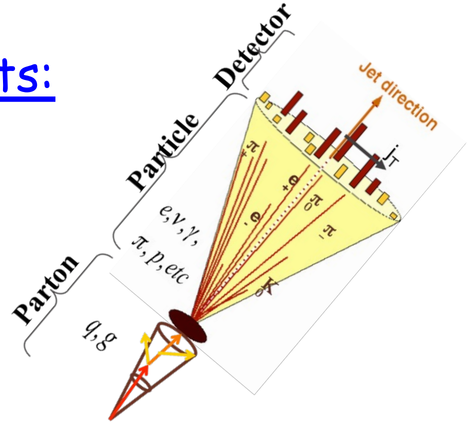
Charge Current:



W-exchange: direct access to the quark flavor; no FF – complementary to SIDIS

- → Kinematics reconstruction through the detection of hadronic state
- → Detector: large rapidity coverage and large √s

Jets:

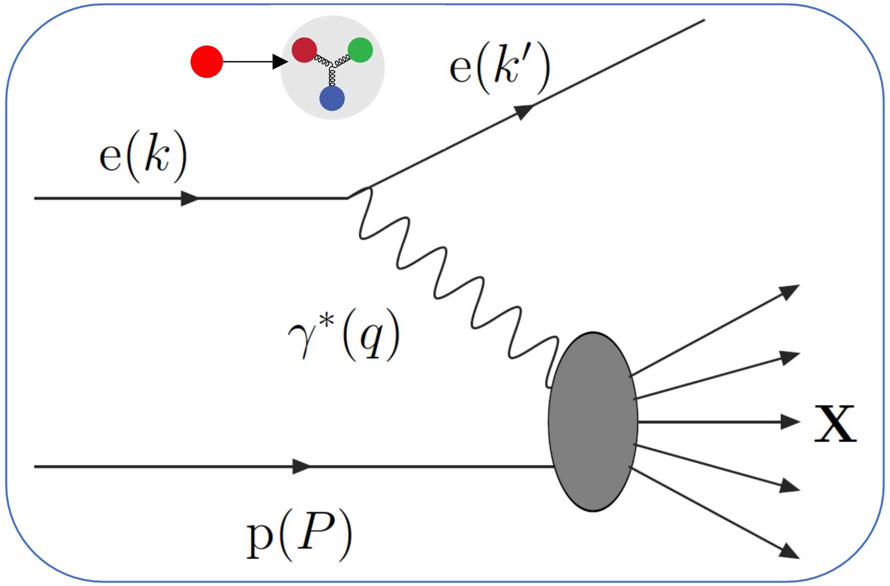


Best observable to access parton kinematics tag partons through the sub-processes and jet substructure

- → di-jets: relative p_t → correlated to k_t
- → tag on PGF: charm production
- → Detector: large rapidity coverage and PID

What is needed to address the EIC physics

DIS: deep inelastic scattering



- Electron beams provide unmatched precision of the electromagnetic interaction
- Direct, model independent determination of parton kinematics of physics processes

Important kinematics

$$\boldsymbol{Q^2 = s \cdot x \cdot y}$$

$$Q^2 = -q^2 = -(k - k')^2$$

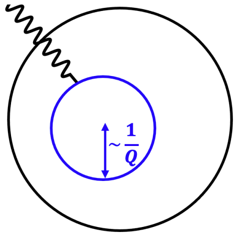
$$x = \frac{Q^2}{2P \cdot q}$$

Q^2: resolution power; y: inelasticity

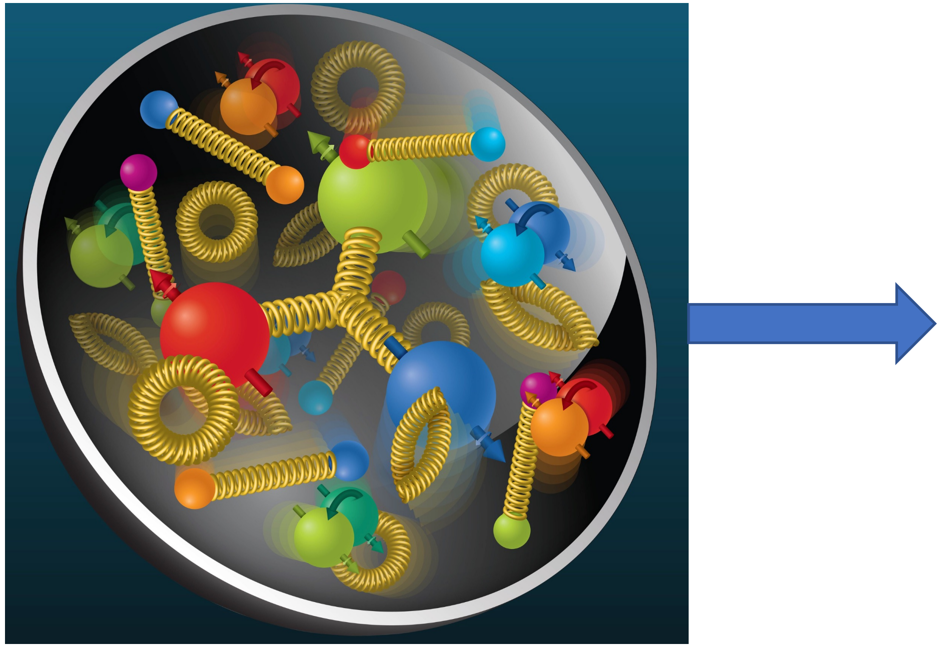
x: momentum fraction of the struck quark from the nucleon

Transverse resolution $\Delta r \sim \frac{1}{Q}$

$Q = 100\ GeV, \Delta r = 0.002 fm$

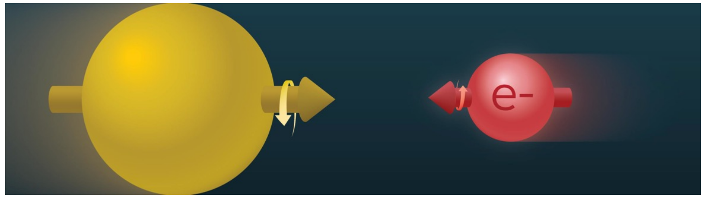


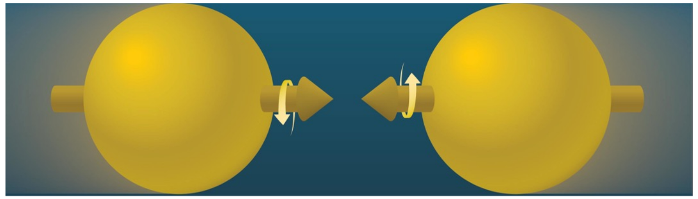
Collinear parton distribution functions (PDFs)

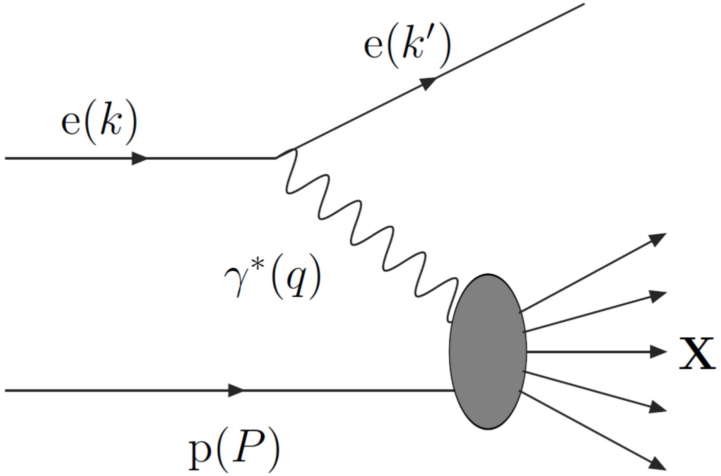


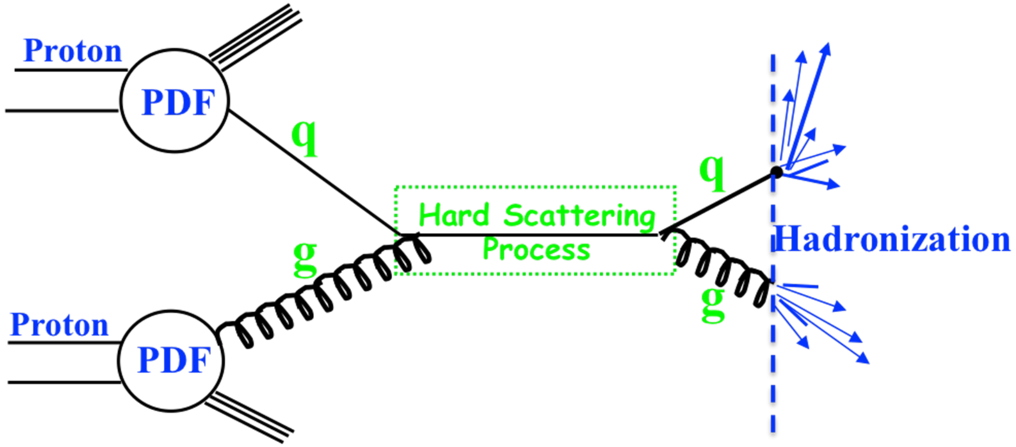
momentum direction of the beam,
or longitudinal direction,
or z

1D partonic structure









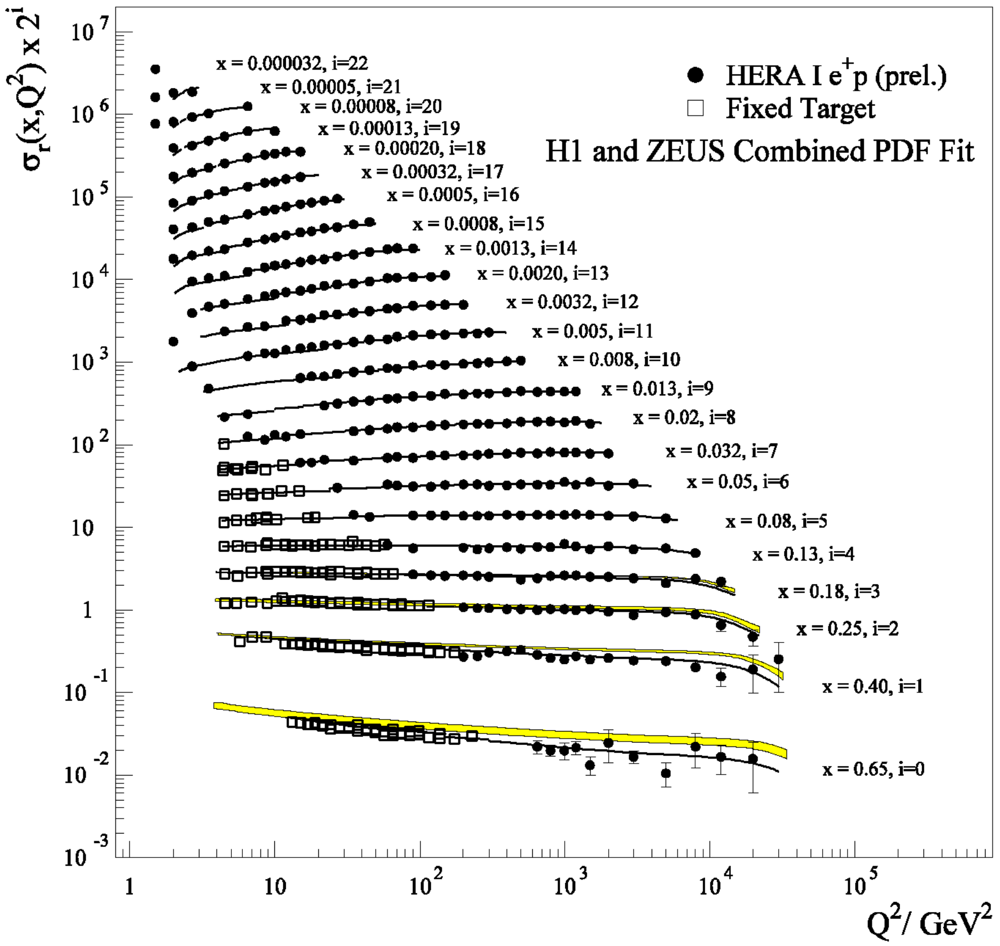
$$\frac{d^2\sigma}{dxdQ^2} = \gamma_{flux} \otimes f(x,Q^2) \otimes \sigma_{ij} \otimes \text{hadronization}$$

$$\frac{d^2\sigma}{dxdQ^2} = f_q(x,Q^2) \otimes f_g(x,Q^2) \otimes \sigma_{ij} \otimes \text{hadronization}$$

Factorization

$f(x,Q^2)$ from p+p and e+p: complementarity and universality

What we’ve learnt from HERA



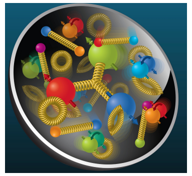
Increasing Q^2

Decreasing x

Low x, soft gluons emerge

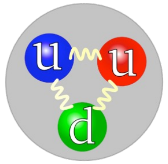
- Bjorken scaling violated: strong rise of cross section with Q^2

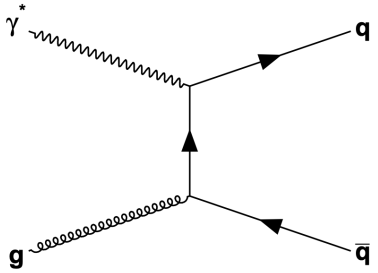
→ Gluon Distribution: $\frac{d^2\sigma(x,Q^2)}{dlnQ^2}$



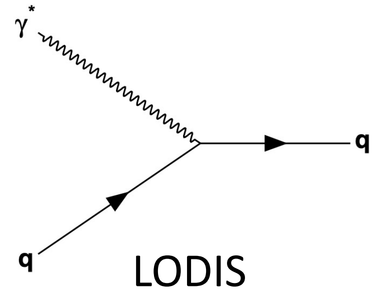
High x, three valence quarks dominant

- Bjorken scaling: cross section depends only on x



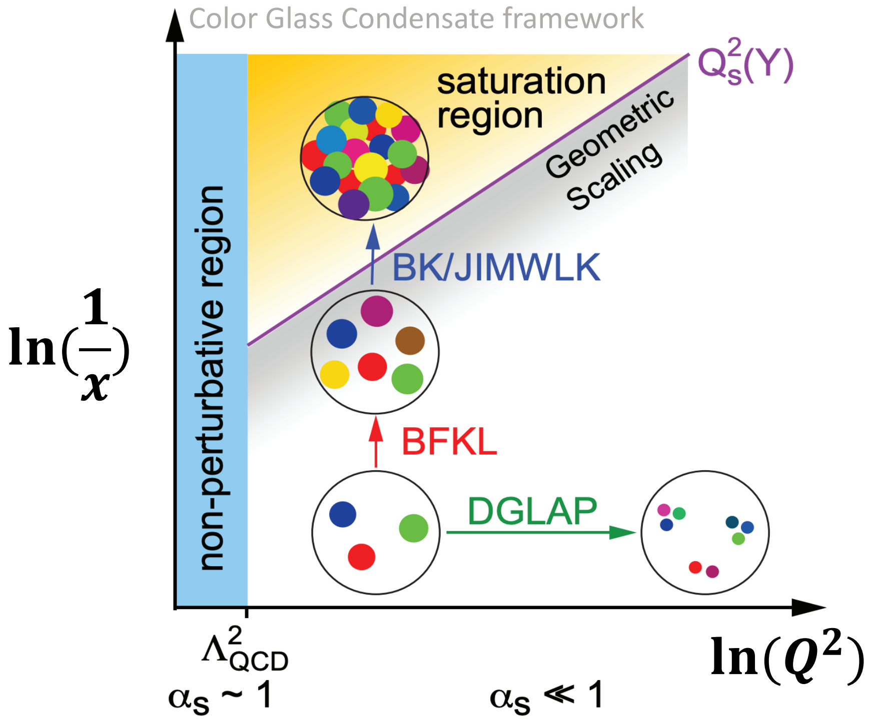


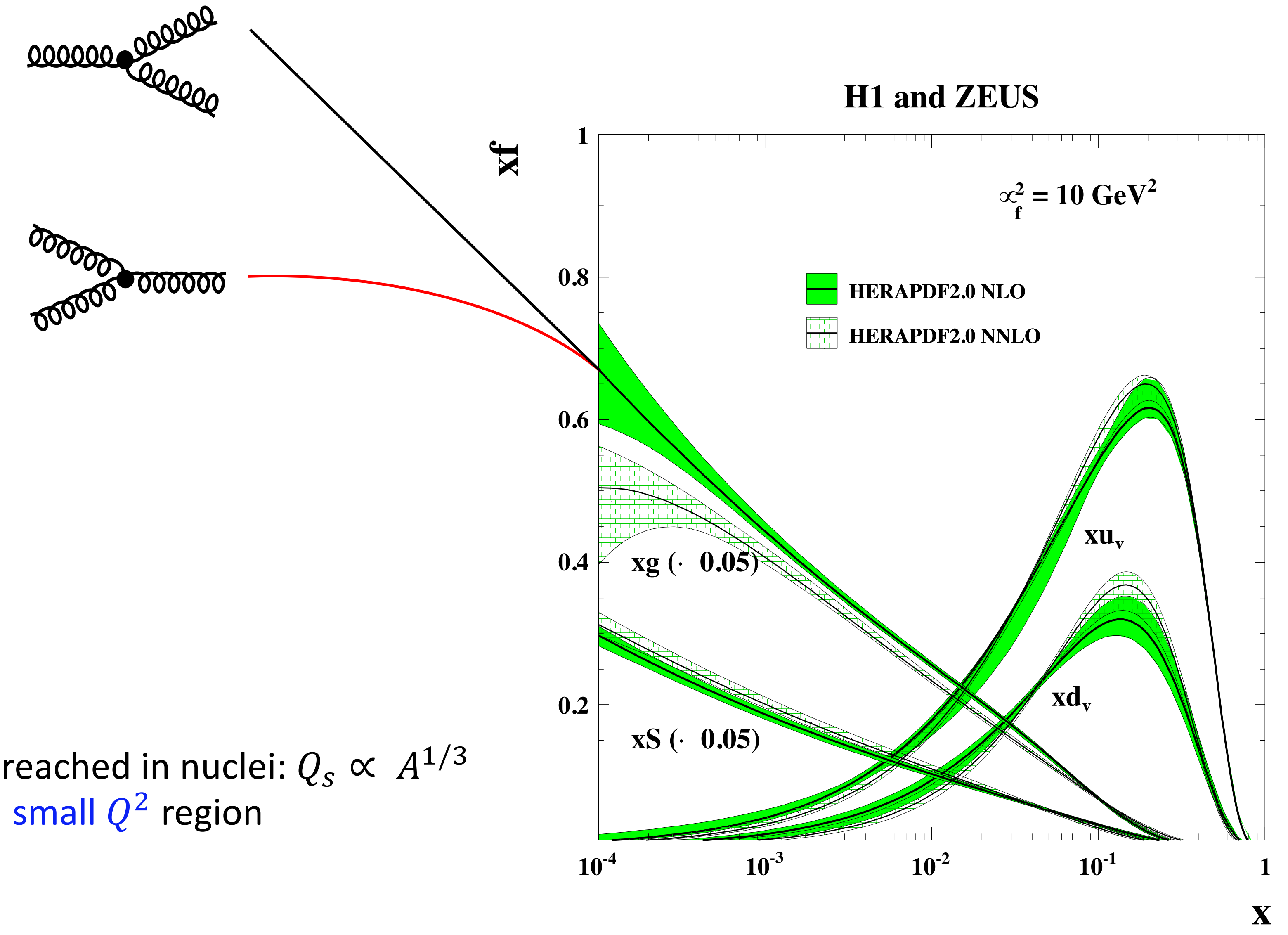
PGF



LODIS

Unpolarized parton distribution functions





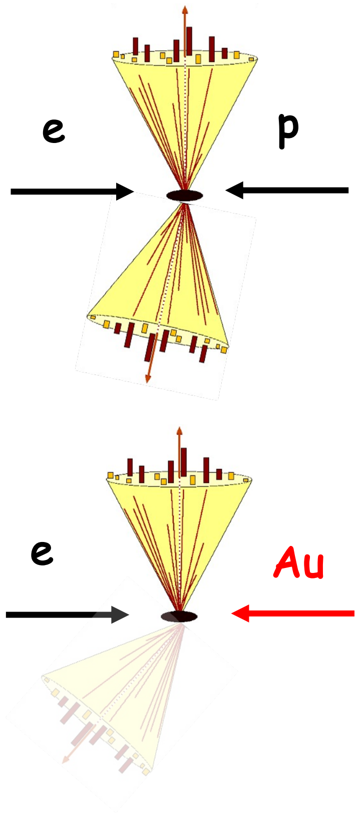
Gluon saturation ($Q^2 < Q_s^2$) is easier to be reached in nuclei: $Q_s \propto A^{1/3}$

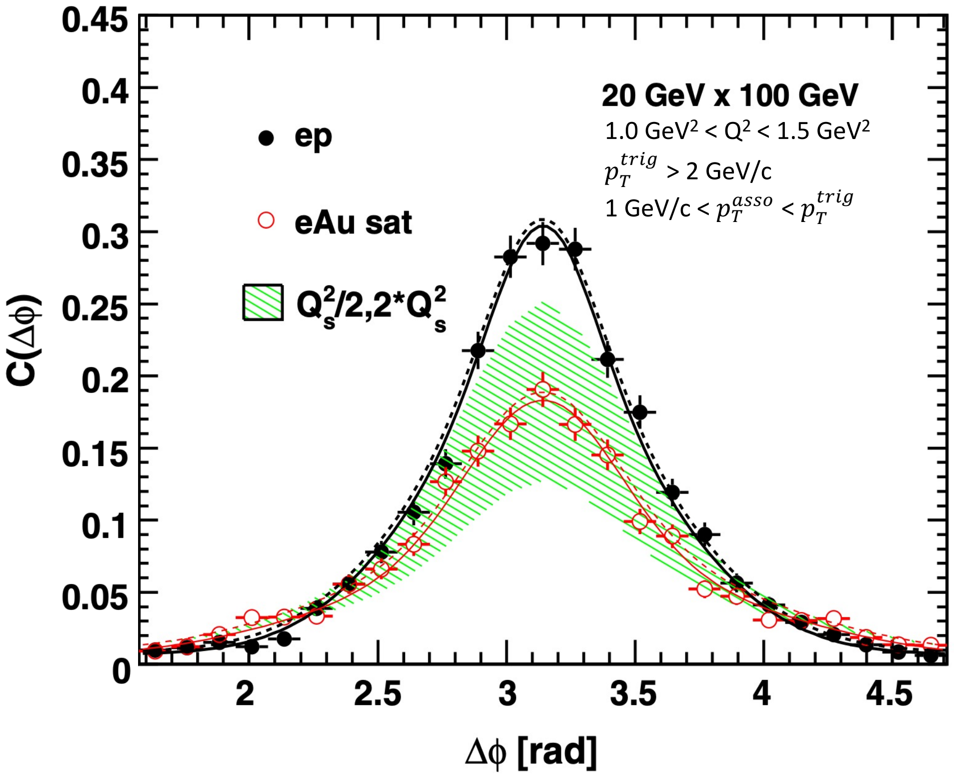
Saturation region: small x and small Q^2 region

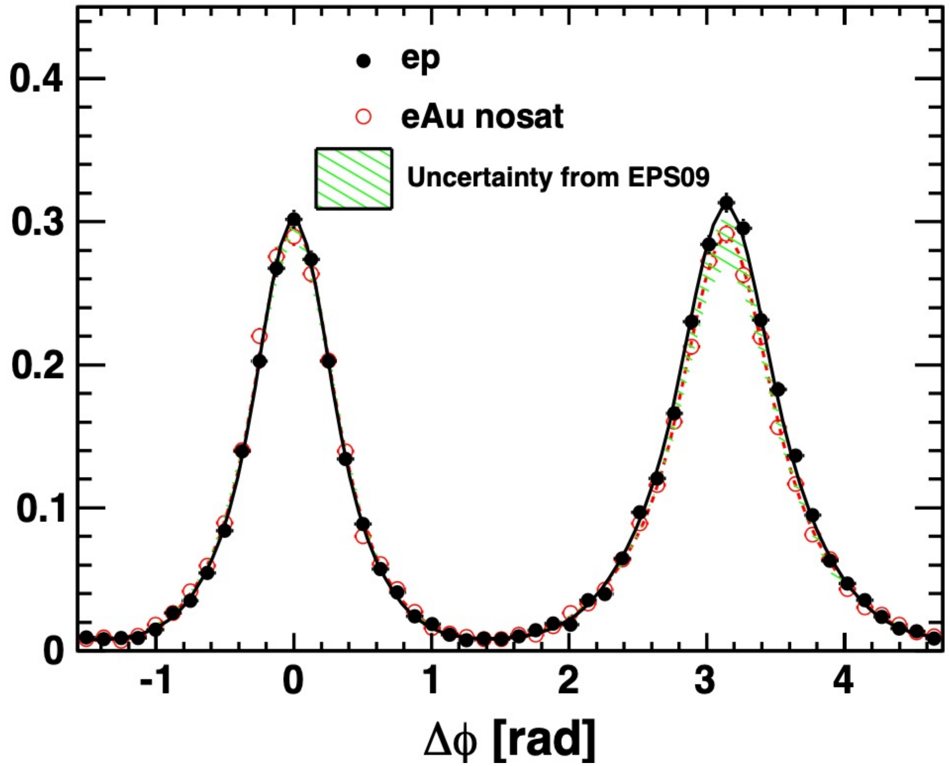
Gluon saturation at the EIC

L. Zheng et al., PRD 89 (2014) 074037

Observable: $C(\Delta\phi) = \frac{N_{pair}(\Delta\phi)}{N_{trig} \times \Delta\phi_{bin}}$







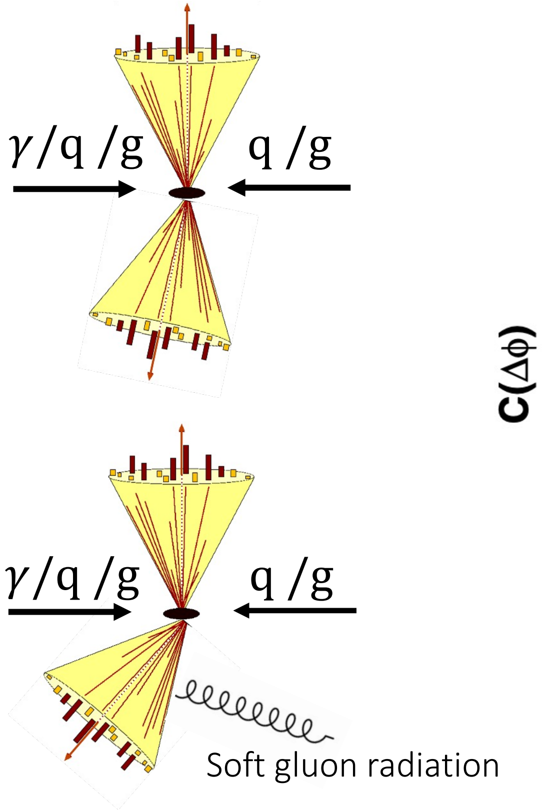
CGC predicts the back-to-back suppression and a broadening phenomena from gluon saturation

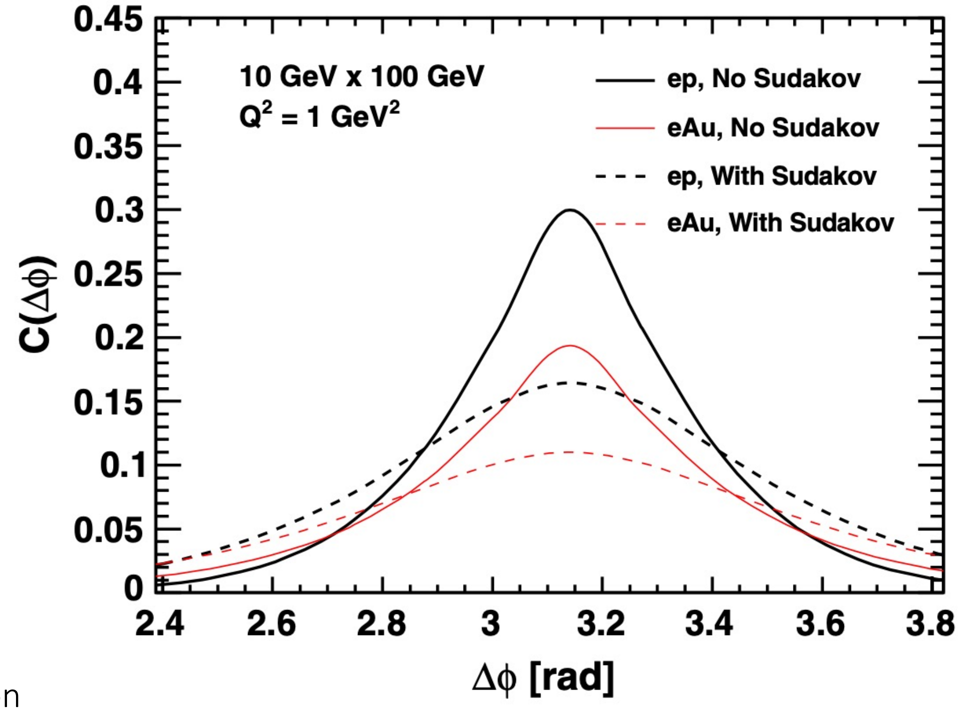
EIC simulation: Constrain sat. and nosat. models with limited statistics of 1 fb^{-1}

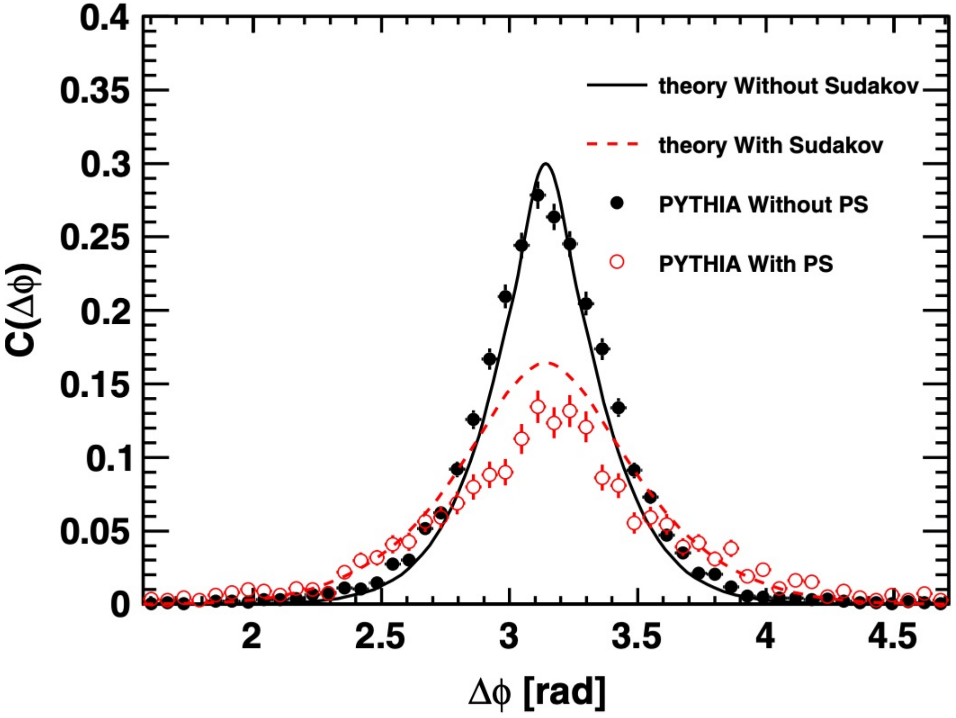
- Strong suppression is reproduced by sat. model, not by nosat. model (EPS09 nPDF) including energy loss

L. Zheng et al., PRD 89 (2014) 074037

Sudakov effects in ep and eA



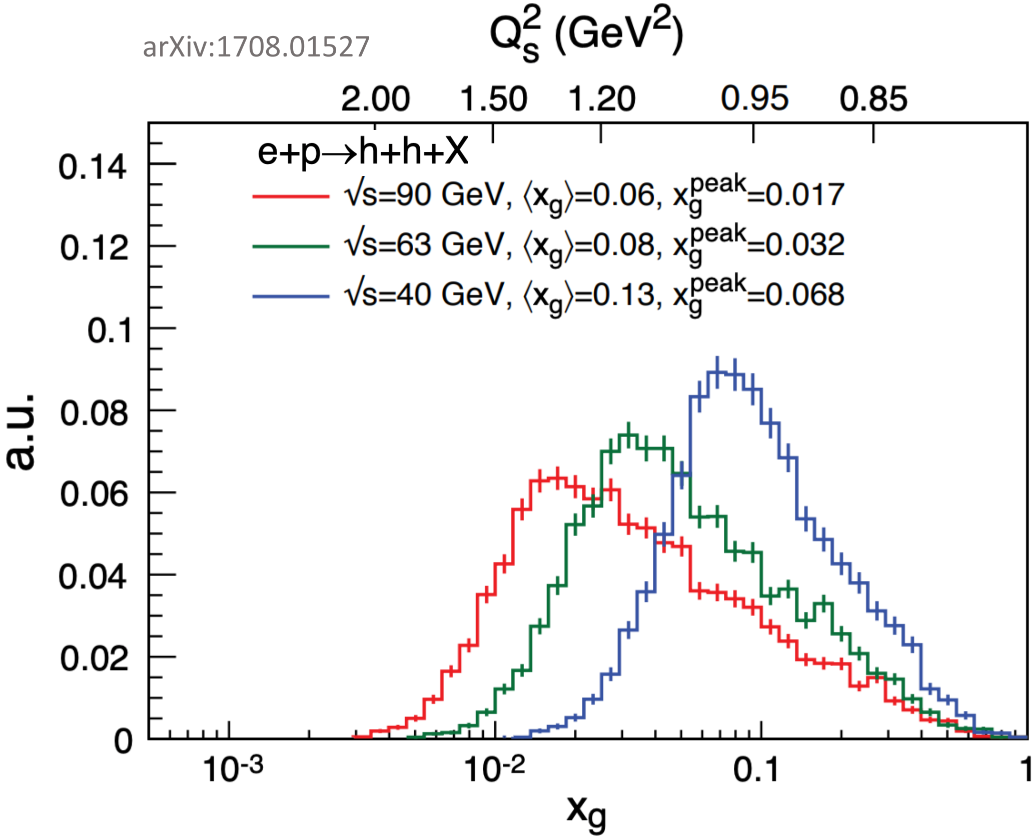


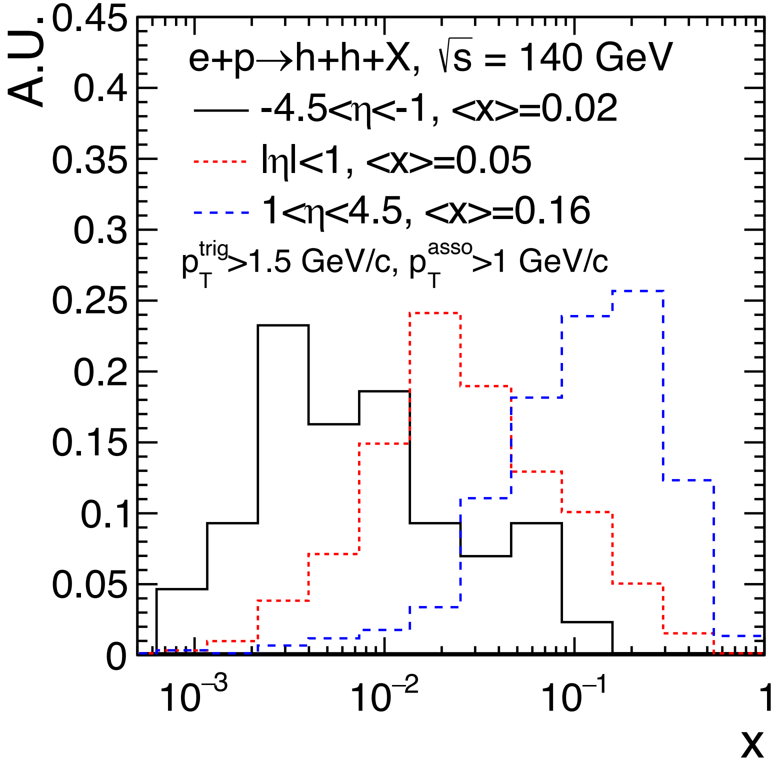


- Sudakov effect can also cause the the broadening phenomena but not suppression, it exits in all collision systems
- Agreement between Sudakov effects and parton shower in ep collisions

Scanning x-Q^2 phase at the EIC

arXiv:1708.01527



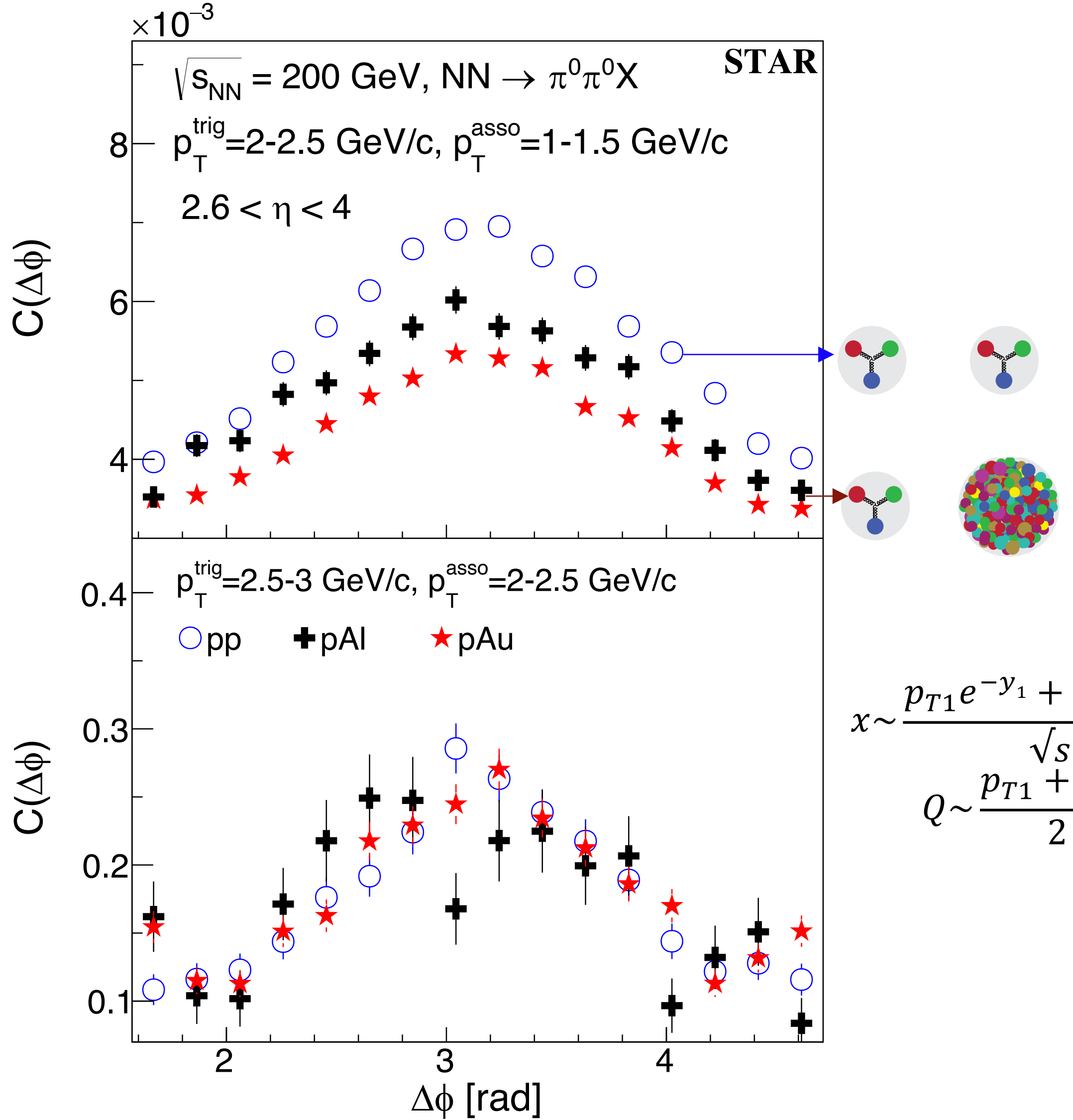


$$x \sim \frac{p_{T1}e^{-y_1} + p_{T2}e^{-y_2}}{\sqrt{s}}\,; Q \sim \frac{p_{T1} + p_{T2}}{2}$$

By increasing the center-of-mass energy and detecting forward production, one can access small x region

Current knowledge of saturation

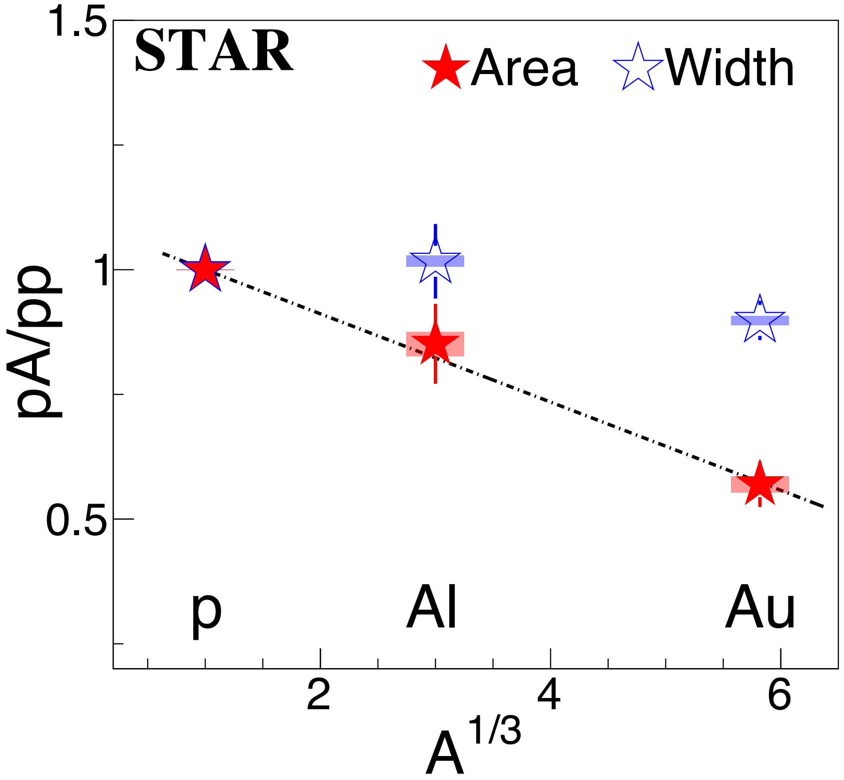
STAR, PRL 129, 092501 (2022)



Gaussian (Area and width) at $\Delta\phi = \pi$ + pedestal

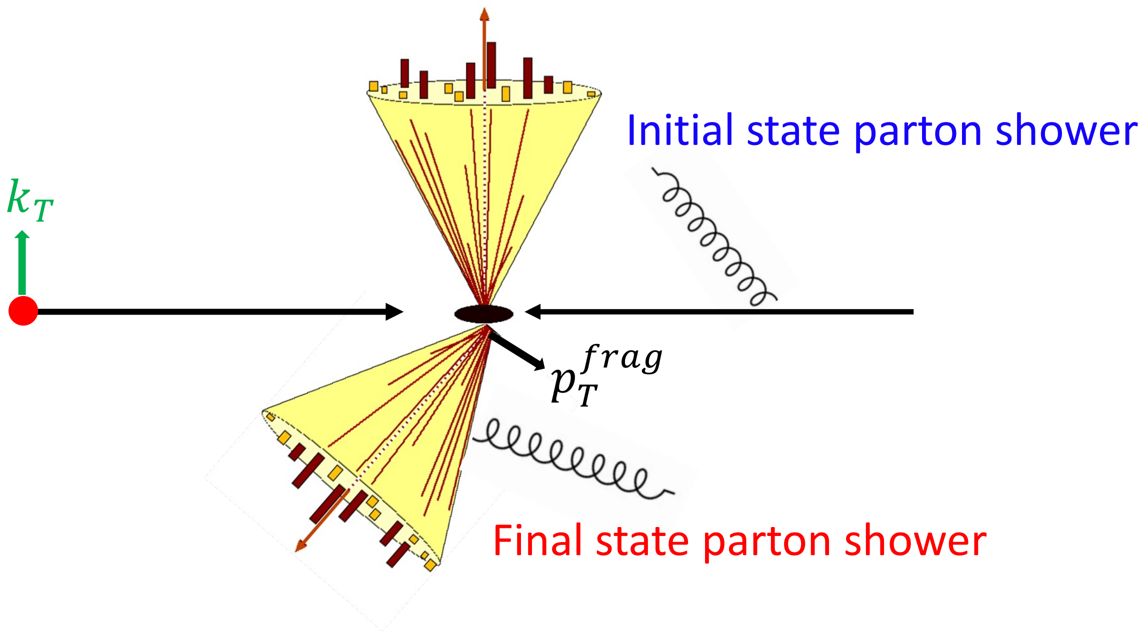
$$x \sim \frac{p_{T1}e^{-y_1} + p_{T2}e^{-y_2}}{\sqrt{s}}$$

$$Q \sim \frac{p_{T1} + p_{T2}}{2}$$



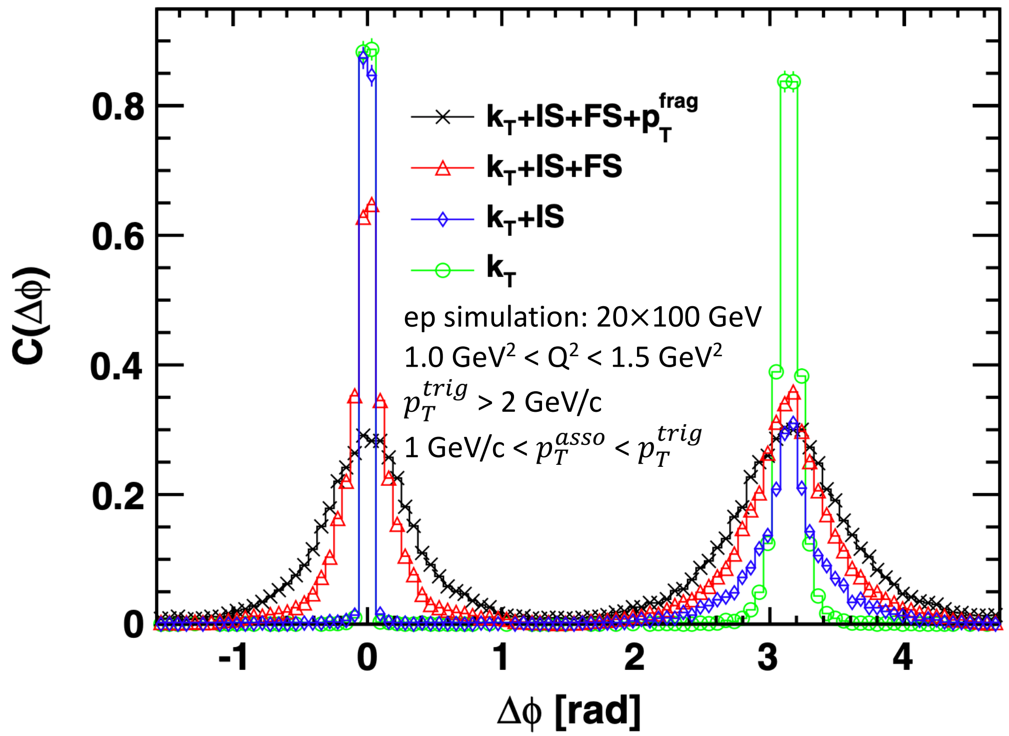
- Suppression at low p_T not high p_T
- No broadening is observed, why?
- In fixed $x - Q^2$ phase space, suppression is dominantly affected by various A:
  - Suppression linearly depends on $A^{1/3}$

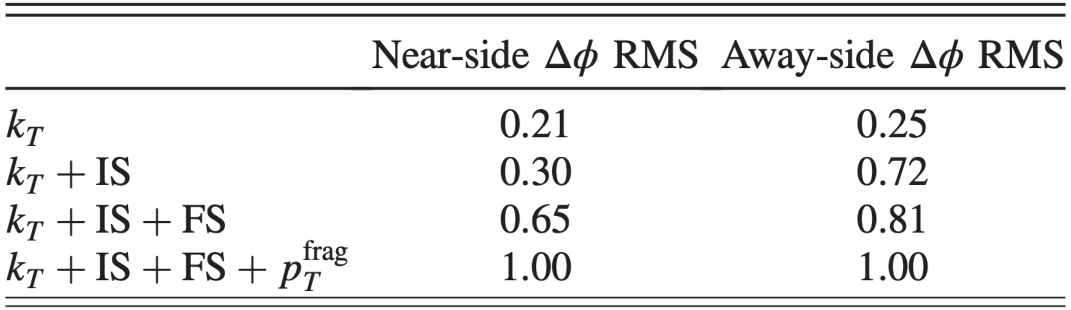
How about broadening?



- IS: the dominate effect leading to a broad away-side peak
- Considering intrinsic k_T, PS, p_T^{frag}, and detector smearing, challenging to observe broadening phenomena
- Future measurement at the EIC with di-charged hadron: near-side peak used to calibrate

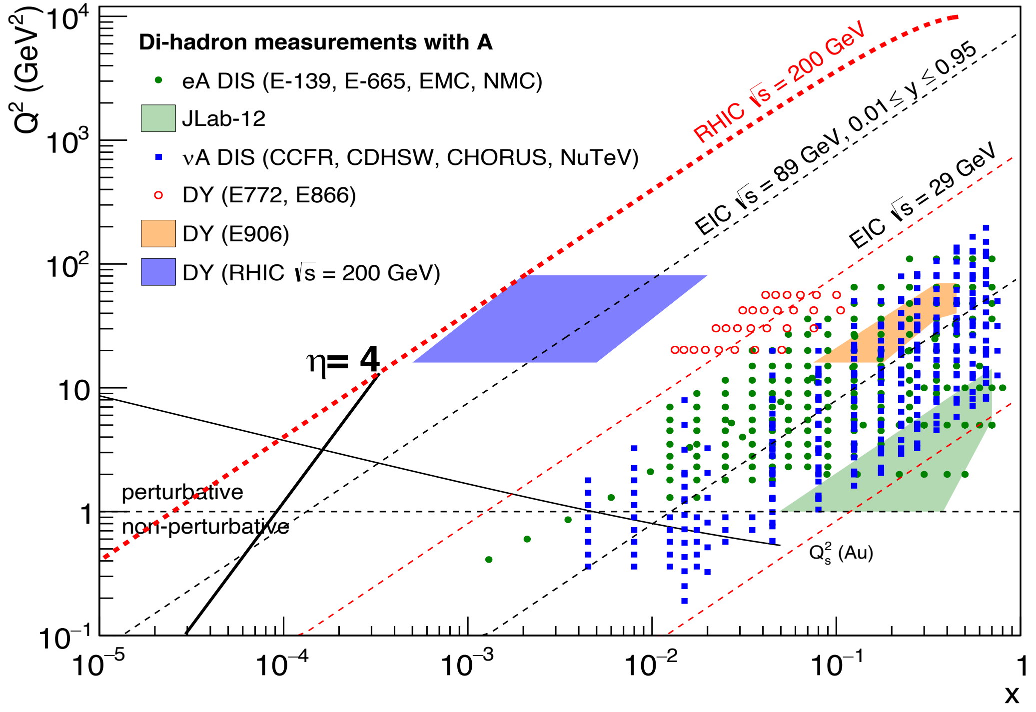
PRD 89, 074037 (2014)

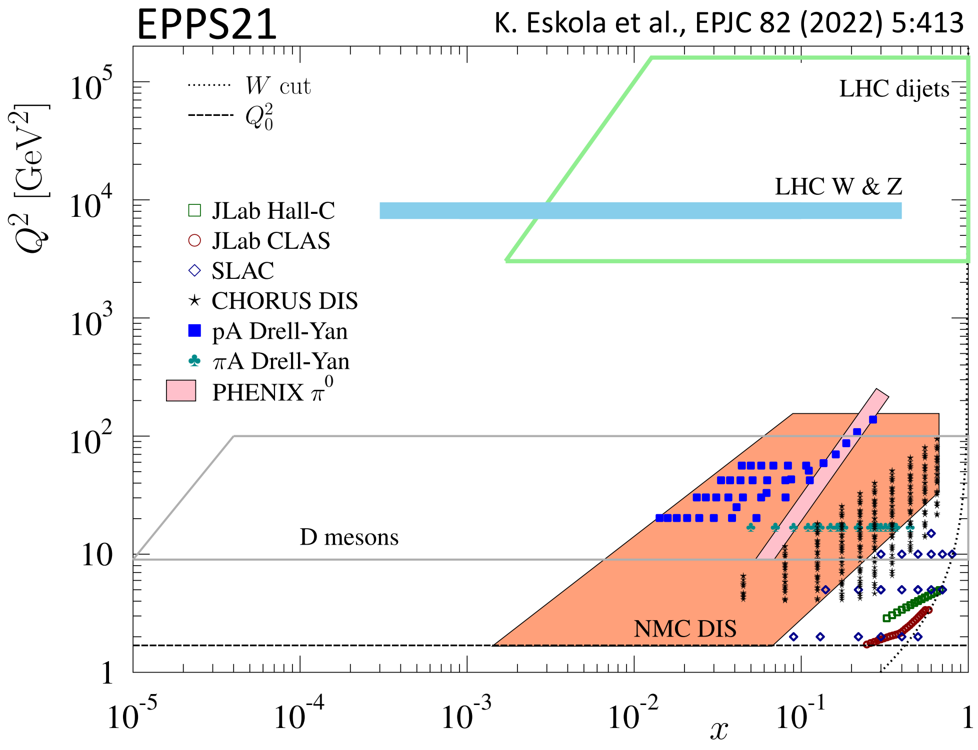




	Near-side $\Delta\phi$ RMS	Away-side $\Delta\phi$ RMS
k_T	0.21	0.25
$k_T + \mathrm{IS}$	0.30	0.72
$k_T + \mathrm{IS} + \mathrm{FS}$	0.65	0.81
$k_T + \mathrm{IS} + \mathrm{FS} + p_T^{\mathrm{frag}}$	1.00	1.00

Full phase space with RHIC, the LHC and EIC





EPPS21

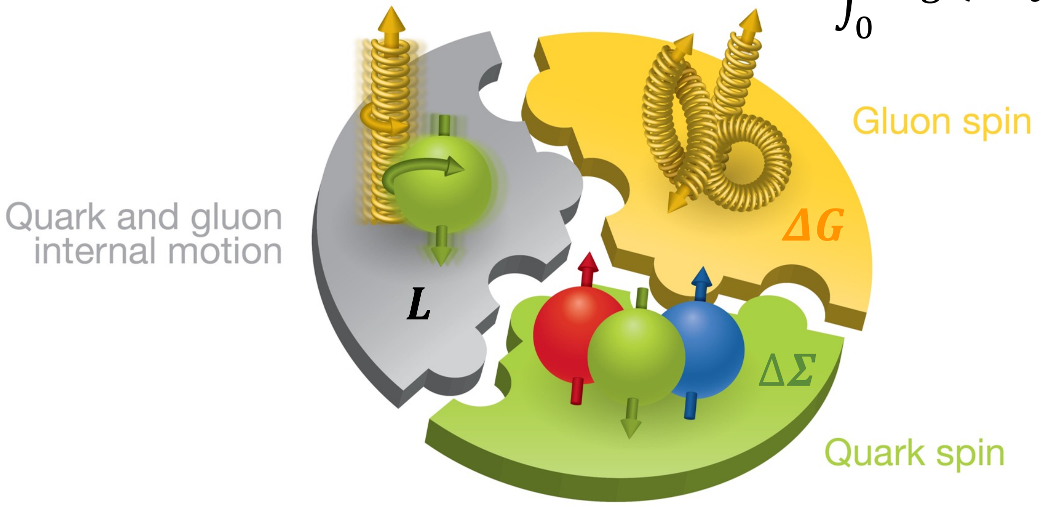
K. Eskola et al., EPJC 82 (2022) 5:413

- RHIC result is an important basis for very similar measurements at the future EIC
  - Nonlinear effects seen with different complementary probes (eA and pA), one can claim a discovery of saturation effects and their universality
- Data from the EIC+ RHIC + the LHC access the full phase space: *LHC data → low x at high Q^2; EIC and RHIC data → low/moderate Q^2

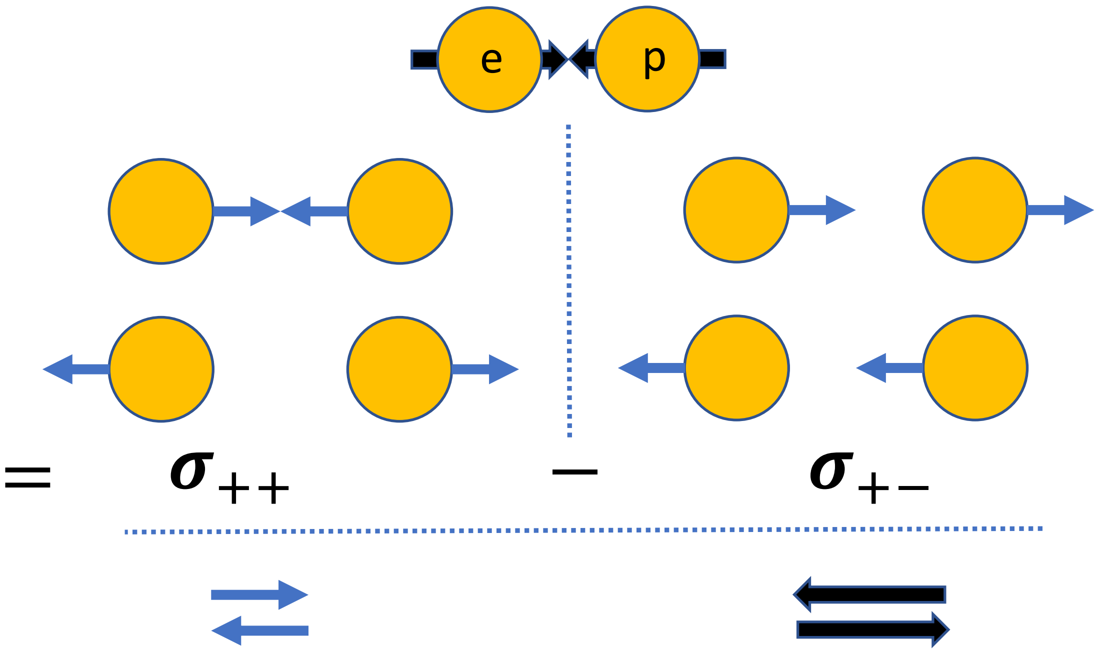
*ALICE FoCal and LHCb pushing the small-x program at LHC

How about the 1D polarized structure?

$$\Delta G = \int_0^1 \Delta g(x, Q^2)dx$$



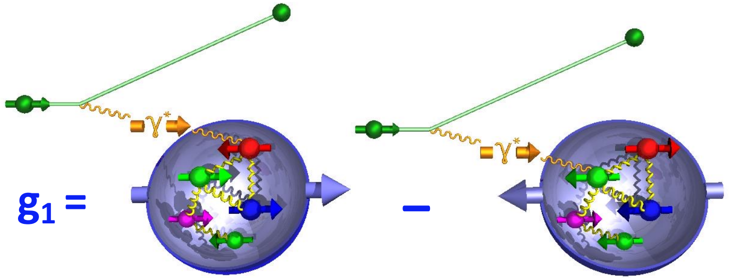
Proton Spin $S = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$



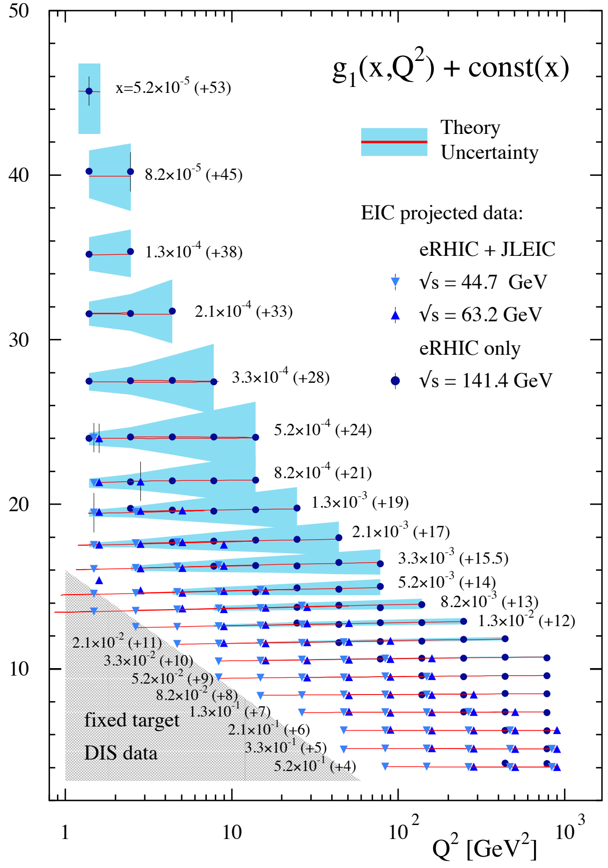
$$\boldsymbol{\Delta\sigma = \sigma_{++} - \sigma_{+-}}$$

$$\underbrace{A_{LL} = \frac{\Delta\sigma}{\sigma} \propto \frac{\Delta f \otimes \hat{\sigma}\widehat{a_{LL}} \otimes D}{f \otimes \hat{\sigma} \otimes D}}_{\textit{Factorization}} \xrightarrow{\text{Global fit}} \Delta f(x, Q^2)$$

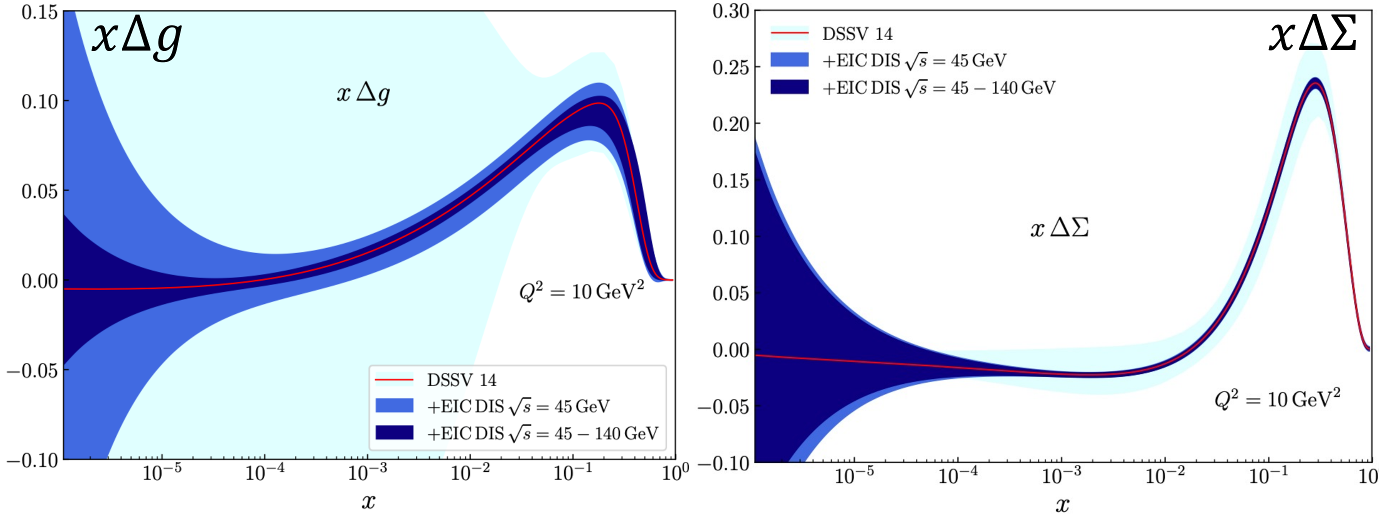
How to decompose the spin of the proton

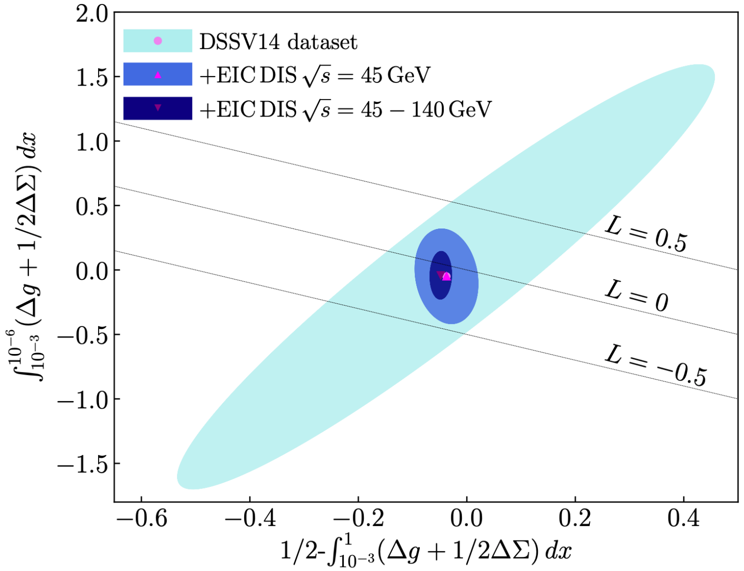


arXiv:1708.01527



arXiv:2007.08300





Cross-section difference $g_1 \rightarrow \Delta f(x, Q^2)$:

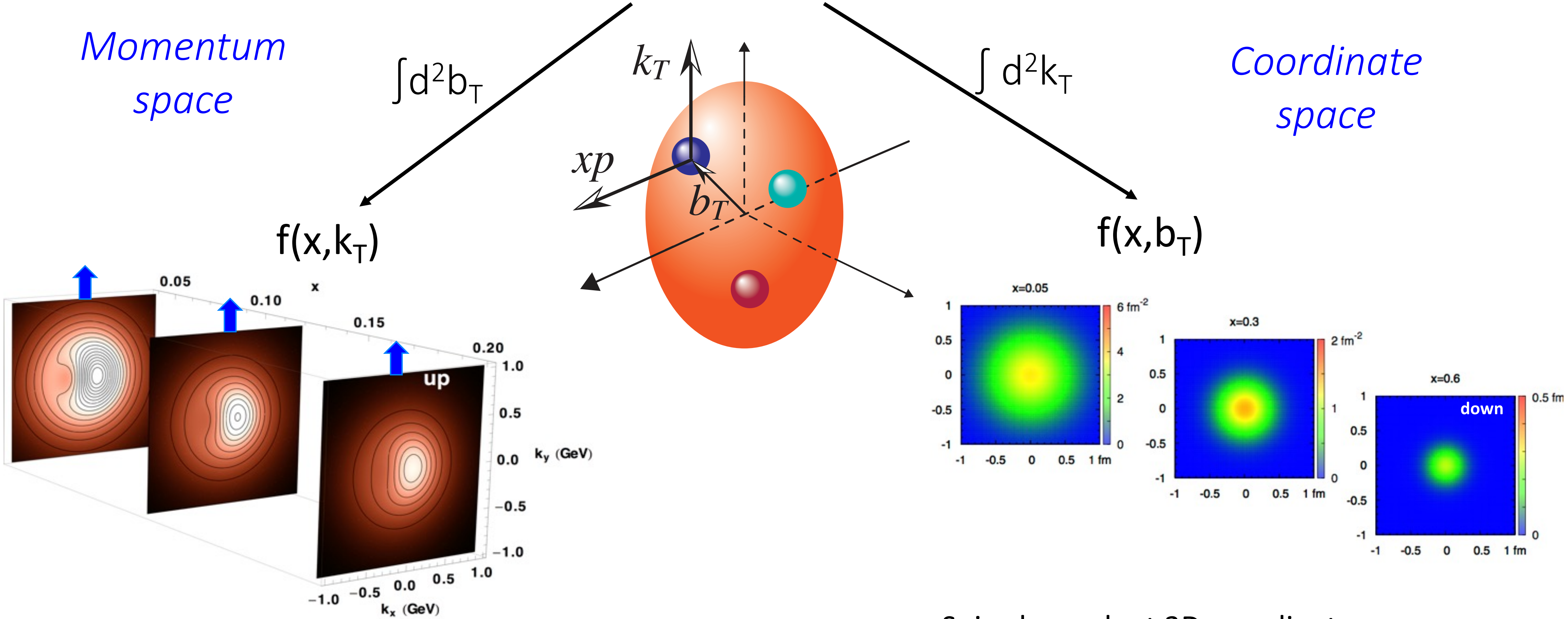
- Δq: the integral of g_1 over x from 0 to 1
- $\Delta g \rightarrow dg_1(x,Q^2)/dlnQ^2$

Significant impact from EIC pseudo data:

- Constrain $\Delta g(x, Q^2)$ and $\Delta q(x, Q^2)$
- Predict the room left for L

3D structure of the nucleon

Wigner function: $W(x,b_T,k_T)$ → QCD genetic map



Momentum space

$f(x,k_T)$

Coordinate space

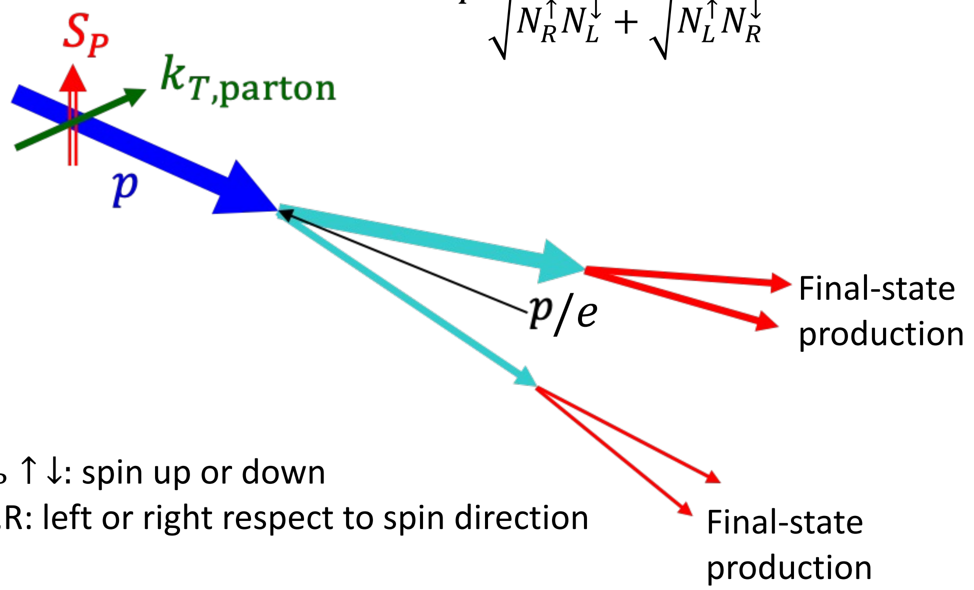
$f(x,b_T)$

Spin-dependent 3D momentum space images from semi-inclusive scattering

Spin-dependent 3D coordinate space images from exclusive scattering

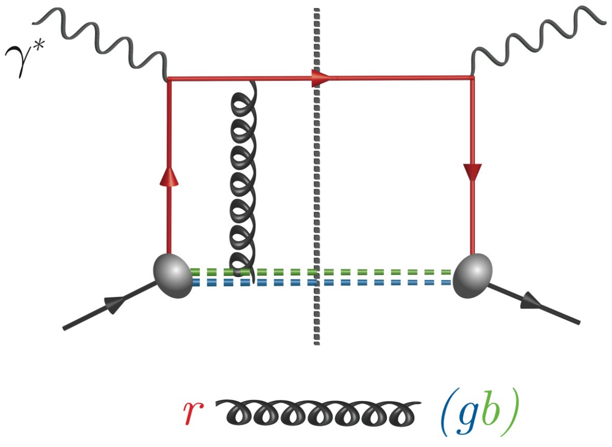
Sivers function

$$A_N cos\theta = \frac{1}{P}\frac{\sqrt{N_R^{\uparrow}N_L^{\downarrow}}-\sqrt{N_L^{\uparrow}N_R^{\downarrow}}}{\sqrt{N_R^{\uparrow}N_L^{\downarrow}}+\sqrt{N_L^{\uparrow}N_R^{\downarrow}}}$$

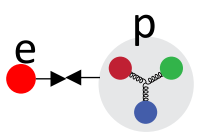


*S_P ↑↓: spin up or down
* L,R: left or right respect to spin direction

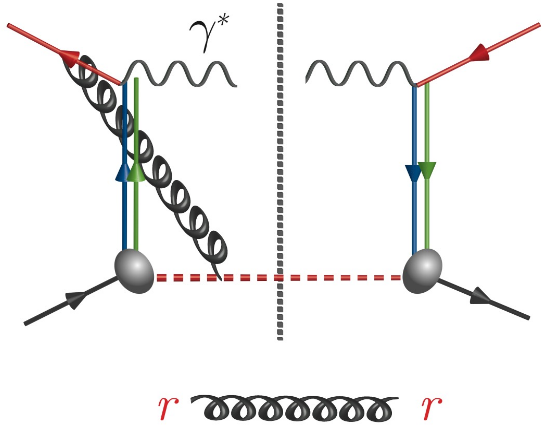
SIDIS



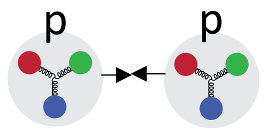
Color attractive



DY, W, Z^0



Color repulsive



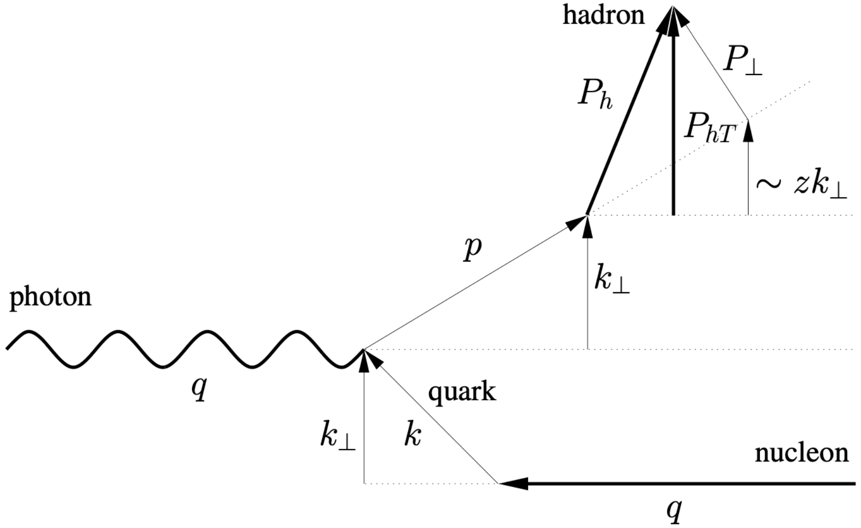
- Sivers function is one of the eight leading twist transverse momentum dependent parton distribution functions (TMDs)
- Sivers function can be constraint from both ep and pp collisions with proton beam transversely polarized
- EIC and RHIC data: used to test the fundamental prediction of the sign change of the Sivers asymmetry

Results from the EIC and other colliders

SIDIS: f($x, k_\perp, Q^2$)

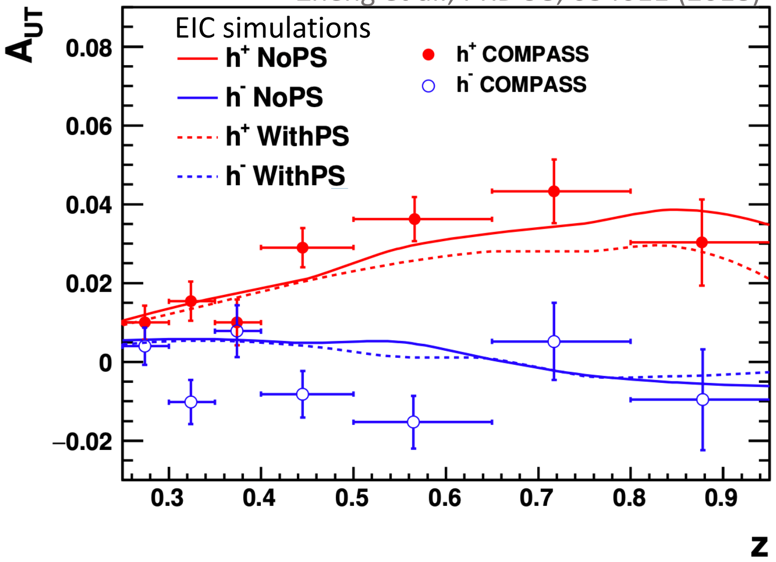
- Q is the 4-momentum of the exchange photon
- Require $p_T^h \ll Q$

EIC simulation validated



COMPASS, PLB717, 383 (2012)

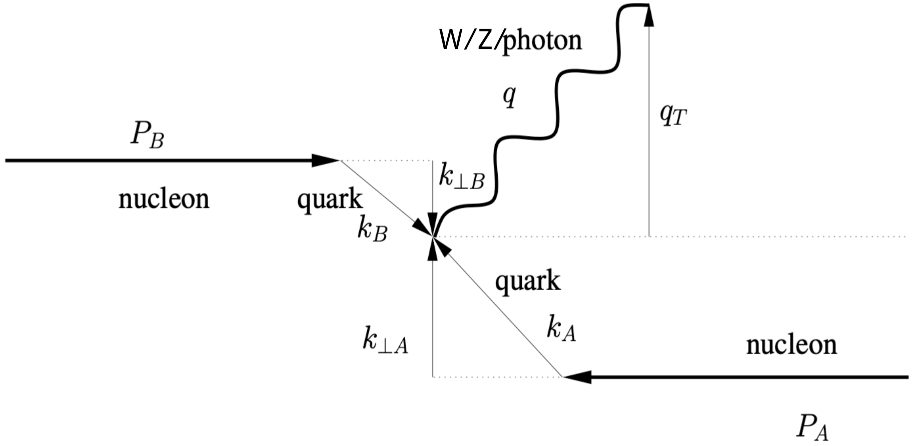
Zheng et al., PRD 98, 034011 (2018)



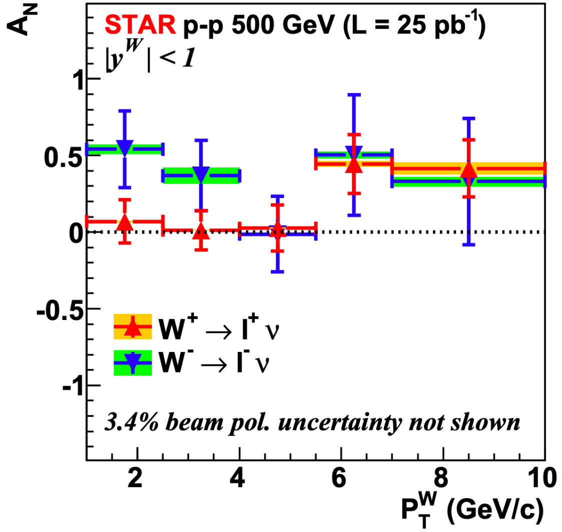
W/Z from pp collisions: f($x, k_\perp, Q^2$)

- Q is the mass of W/Z
- Require $q_T^{W/Z} \ll Q \sim \frac{90\ GeV}{c^2}$

STAR data not yet concluded

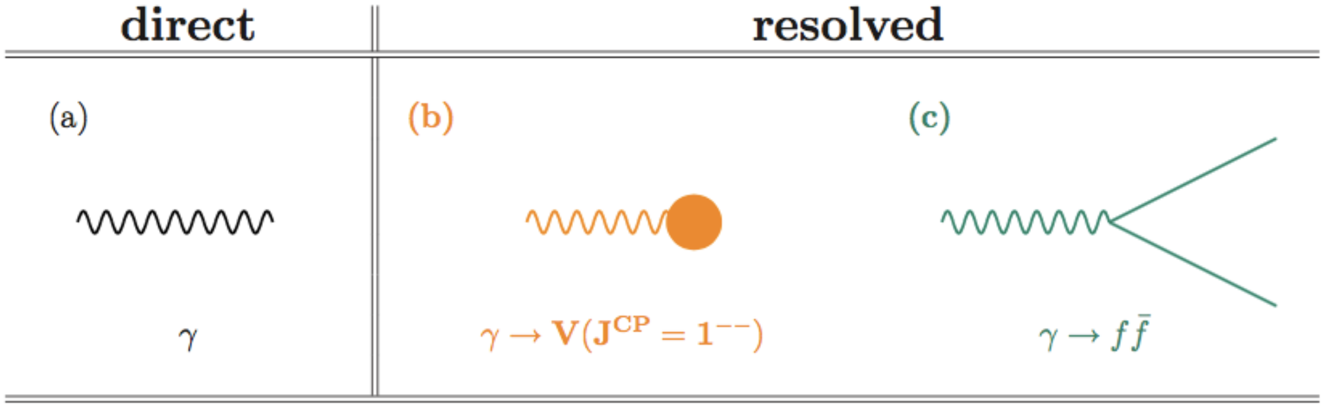


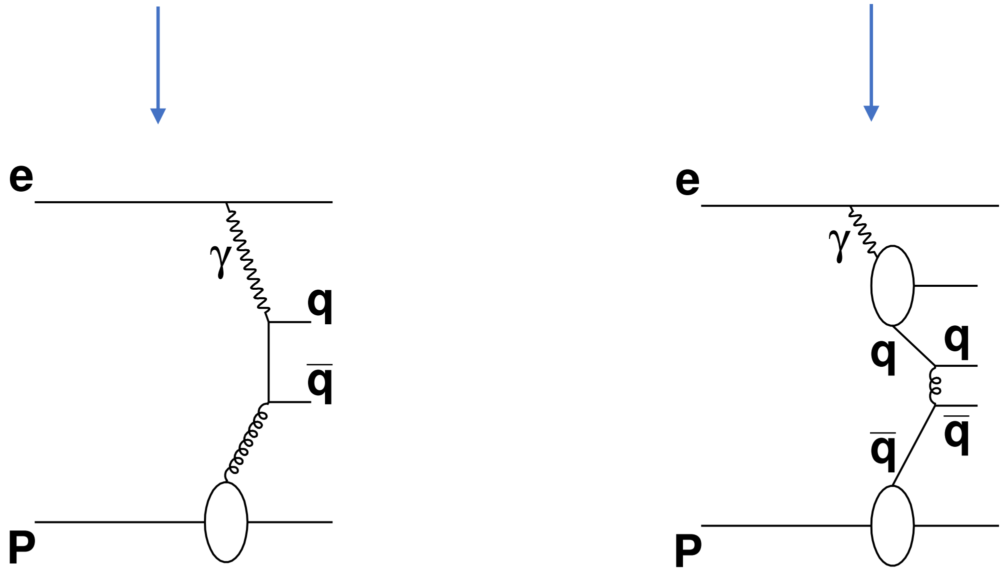
STAR, PRL 116 (2016), 132301



z: energy fraction of a hadron with respect to virtual photon in the target rest frame

Jets at the EIC: to study the PDFs of the photon



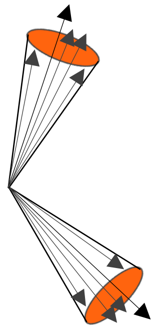


direct resolved

Photon PDFs rarely known:

- Unpolarized: extracted from PLUTO, AMY, etc.
- Polarized: zero knowledge
- Critical input for EIC

Dijet reconstructed from PYTHIA ep:



- $x_\gamma^{rec} = \frac{1}{2E_e y}(p_{T1}e^{-\eta 1} + p_{T2}e^{-\eta 2})$
- Resolved $x_\gamma < 1$
- Direct $x_\gamma = 1$

Unpol. PDFs: measuring resolved dijet cross section

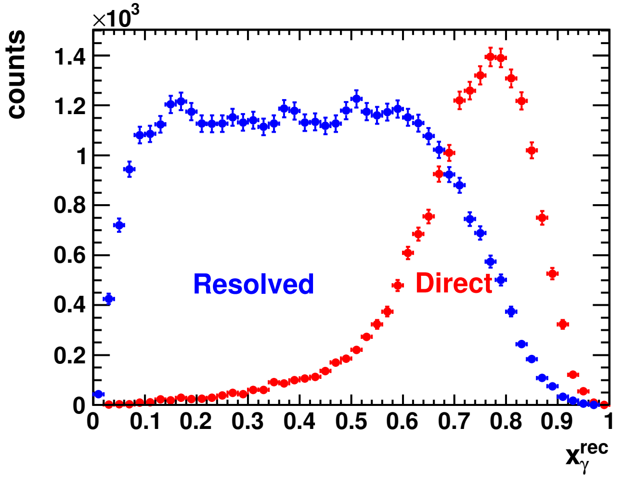
- $\frac{d^2\sigma}{dxdp_T} = f_\gamma \otimes f_p \otimes \sigma_{ij}$

Pol. PDFs:

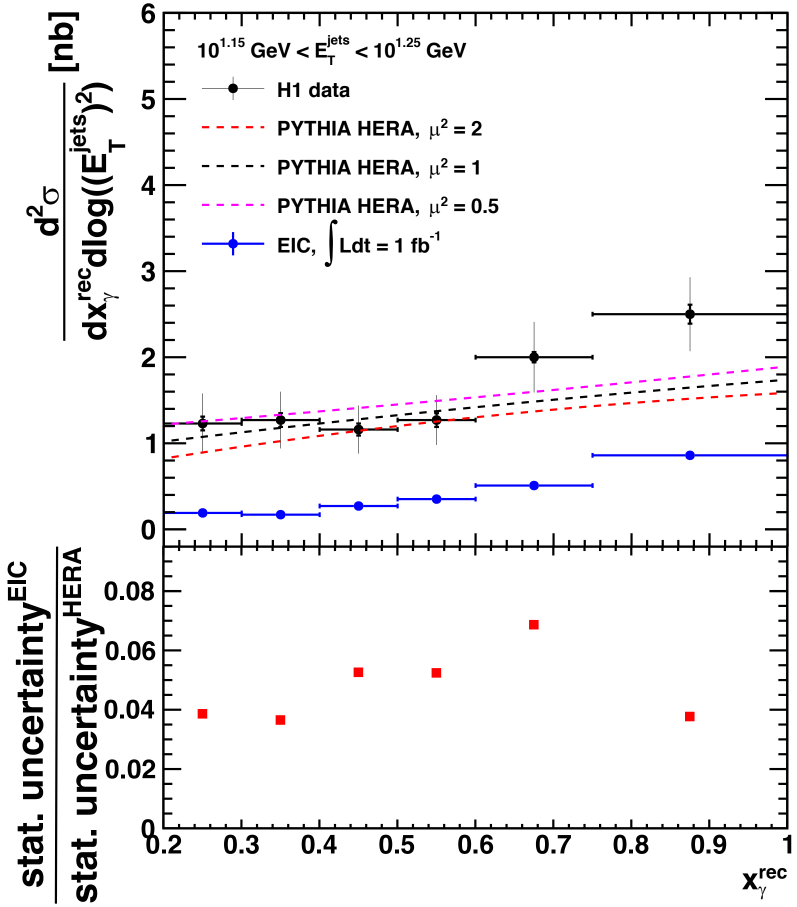
- $A_{LL} = \frac{\Delta\sigma}{\sigma}, \frac{d^2\Delta\sigma}{dxdp_T} = \Delta f_\gamma \otimes \Delta f_p \otimes \sigma_{ij}$

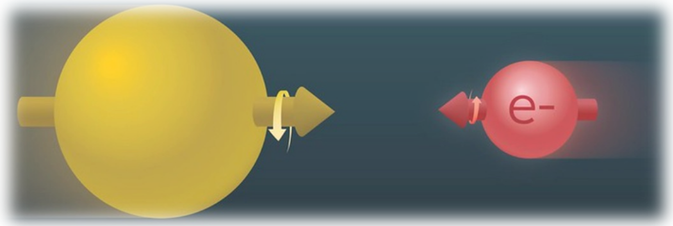
Resolved photon at EIC

X.Chu et al., PRD 96, 074035 (2017)

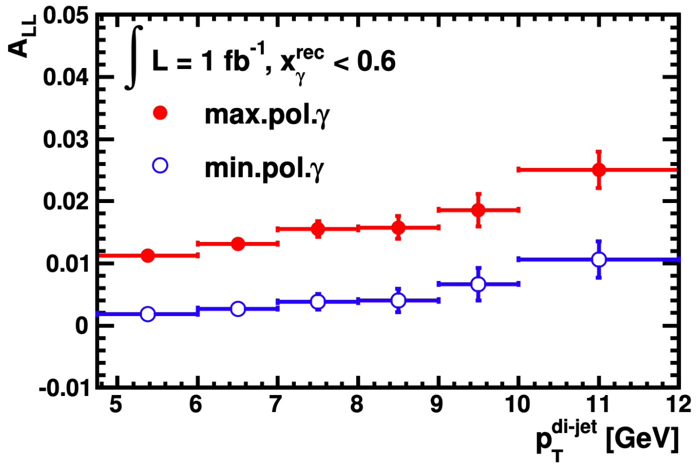


- Low x_γ^{rec} helps to select resolved photon channels
- Validated with HERA data





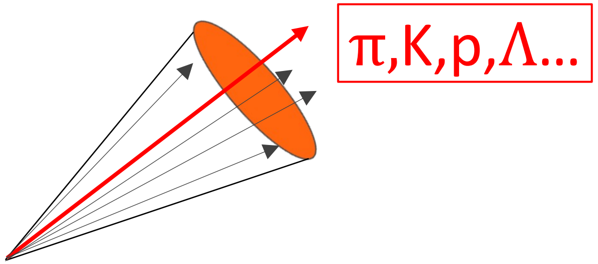
$$A_{LL} = \frac{\Delta\sigma}{\sigma}, \Delta\sigma = \Delta f_\gamma \otimes \Delta f_p \otimes \Delta\sigma_{ij}$$

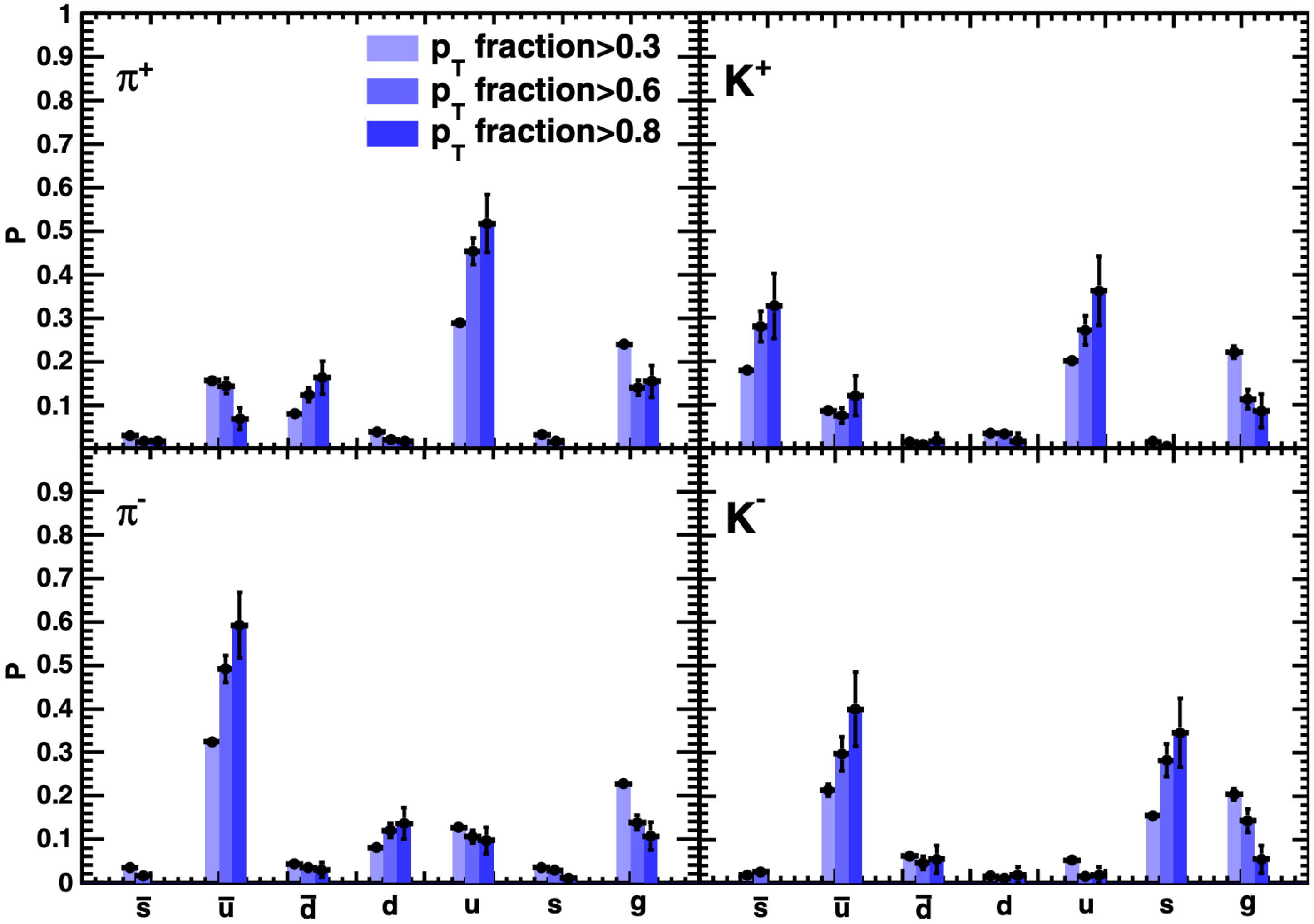


$1\ fb^{-1}$ statistic at EIC provides high precision constraining unpol. photon PDFs; first measurement of pol. photon PDFs simulated at the EIC

X.Chu et al., PRD 96, 074035 (2017)

Flavor tagging with jets at the EIC





Fragmentation functions: flavor tagging→ advantage of PID at EIC; test universality with the results from other colliders:

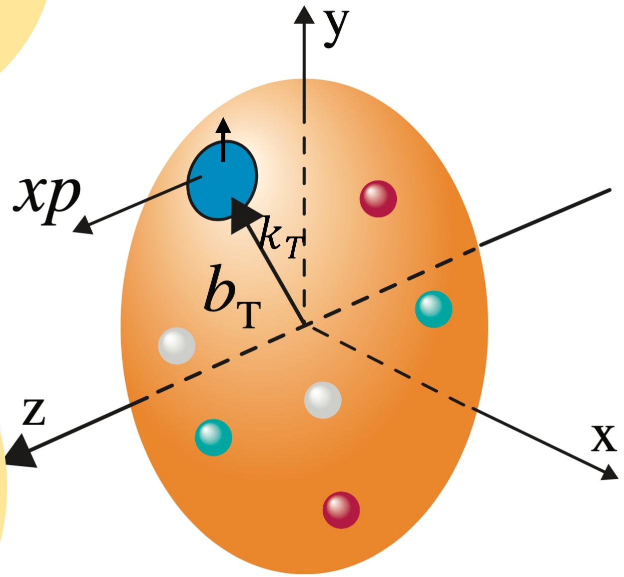
- Probe the flavor of the originating parton by the particle specie of the leading hadron
- This method can be performed in different collision systems

Summary

1D-structure in Z direction:

- Collinear parton distribution $f(x, Q^2)$
- Longitudinally polarized distribution $\Delta f(x, Q^2)$

- Gluon saturation: EIC data is essential to understand the nonlinear QCD dynamics of the gluon
- EIC data will provide large impact of constraining quark and gluon helicity, and orbital angular momentum



1+2D-structure in $Z + XY$ direction:

- Transverse momentum dependent parton distribution, TMDs, $f(x, k_T, Q^2)$
- Polarized TMDs → Sivers function

Applications of jets at the EIC:

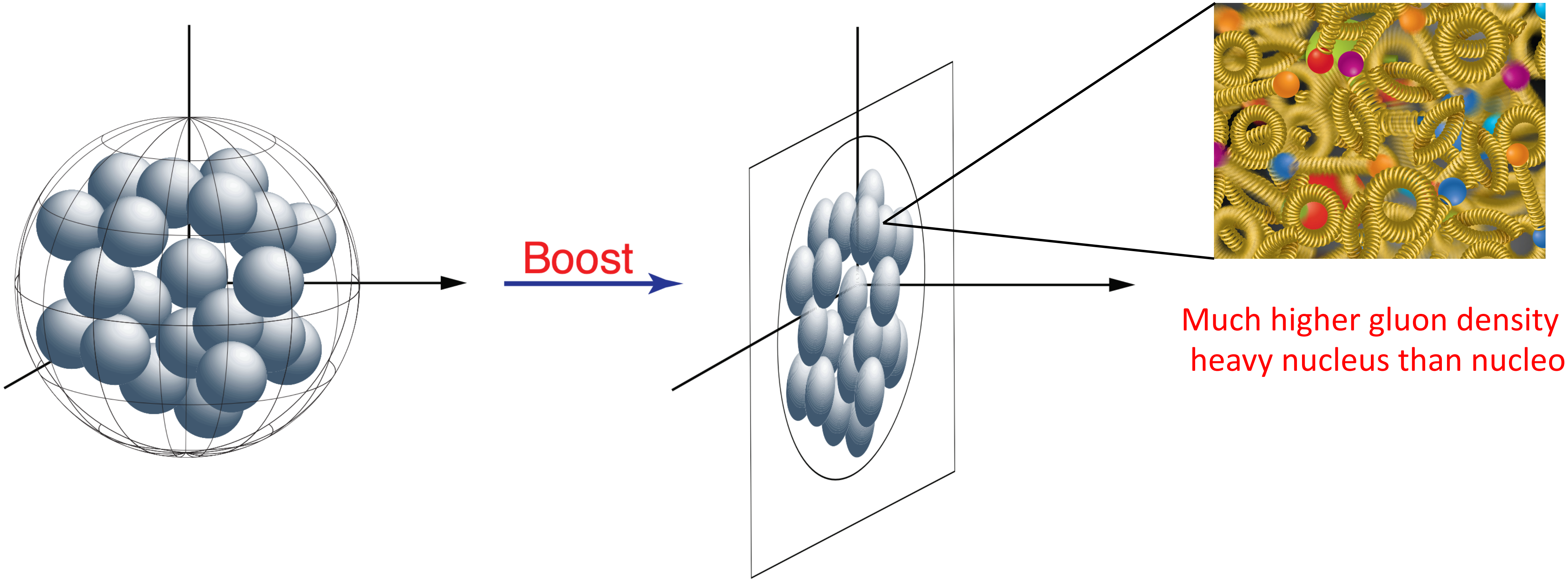
- Dijet photoproduction used to constrain unpol. and pol. photon PDFs
- Particles within jets: flavor tagged fragmentation functions

Thanks for your attention!

Back up

EIC Double Ring Design Based on Existing RHIC Facilities	
Hadron Storage Ring: 40, 100 - 275 GeV	Electron Storage Ring: 5 - 18 GeV
RHIC Ring and Injector Complex: p to Pb	9 MW Synchrotron Radiation
1A Beam Current	Large Beam Current - 2.5 A
1160 bunches → 9 ns bunch spacing	
Light ion beams (p, d, ^{3}He) polarized (L,T)	Polarized electron beams
Nuclear beams: d to U	Electron Rapid Cycling Synchrotron
Requires Strong Cooling: new concept →CEC	Spin Transparent Due to High Periodicity
High Luminosity Interaction Region – one on project – 2nd one possible	
25 mrad Crossing Angle with Crab Cavities	

Easy to be observed in heavy nucleus

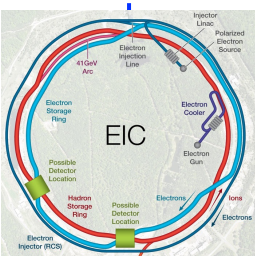


Much higher gluon density in heavy nucleus than nucleon

Total transverse gluon density by a factor of $A^{1/3}$ for a nucleus with mass number A

It’s easier to access saturation in heavy nuclei, how?

Complementarity for 1st-IR & 2nd-IR



	1st IR (IP-6)	2nd IR (IP-8)
Globally:	same accelerator highlights and challenges	
Geometry:	ring inside to outside	ring outside to inside
Crossing Angle:	25 mrad	35 mrad → more difficult to get acceptance at high η
	different blind spots different far-forward detector acceptances	
Luminosity:	same luminosity at both IRs same center-of-mass energy coverage	
IR-Design:	0.2 GeV < p_T < 1.3 GeV	2nd focus → improved low p_T acceptance at far-forward Roman Pots x_L ~1 → p_T ~0
Experiment:	complementarity through different subdetector technologies	