

# From RHIC to EIC: Connections between RHIC and EIC science

2026 RHIC/AGS ANNUAL USERS' MEETING  
AND RHIC SCIENCE SYMPOSIUM

## The Apex of RHIC Physics Resolving the Strong Force

May 11–15, 2026



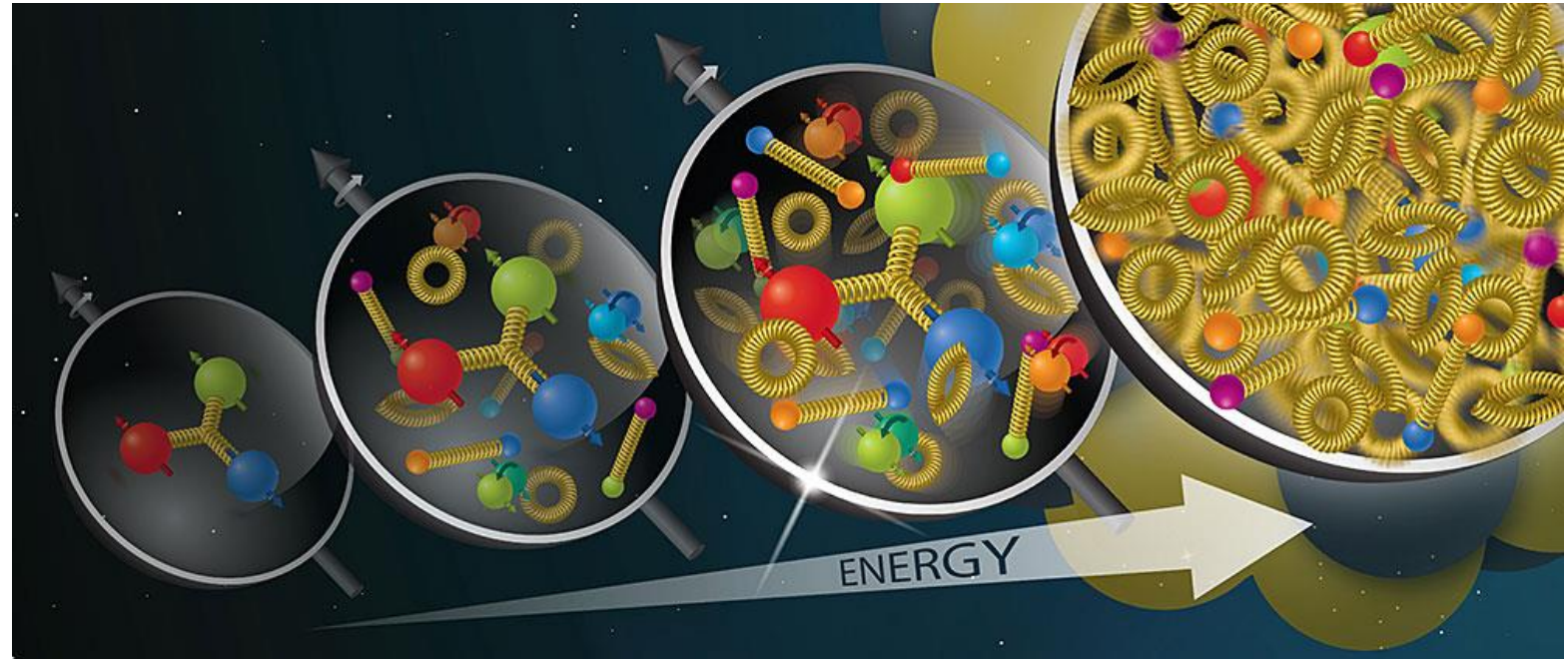
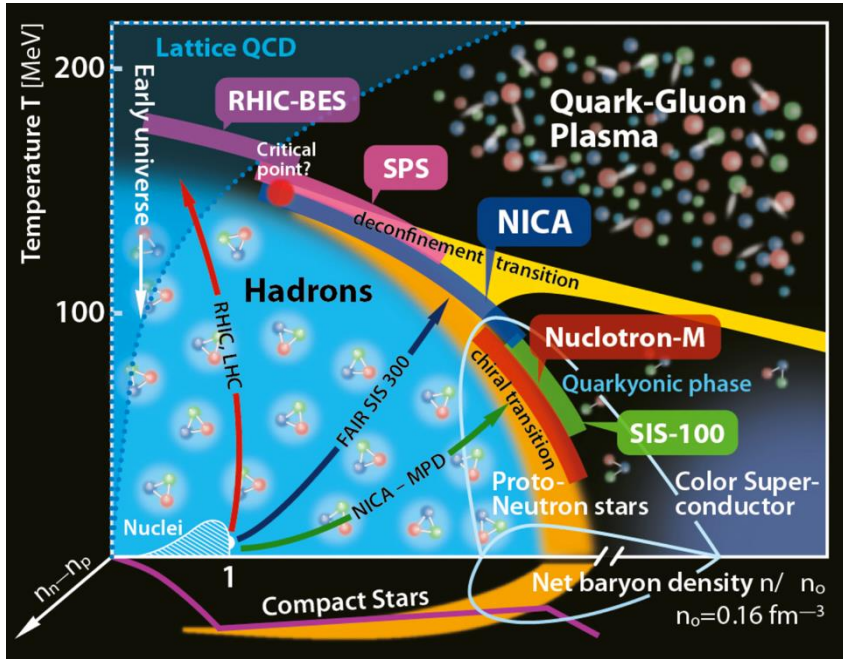
Rosi Reed  
Lehigh University



# Disclaimers

- I cannot cover all connections in one talk so I will attempt to focus on the big picture
- I am not speaking on behalf of the ePIC, sPHENIX or STAR
- Any errors are mine, anything correct was clearly obvious to everyone already 😊
- I assume everyone here knows what RHIC is and what the EIC will be

# The Big Picture from RHIC to the EIC



How do collective, many-body phenomena arise from QCD?

Rosi Reed - DNP 2023

How do collective, many-body phenomena arise from first-principles?



RHIC to the EIC...

# Outstanding Questions Heavy Ion Physics

## Completing the RHIC Science Mission

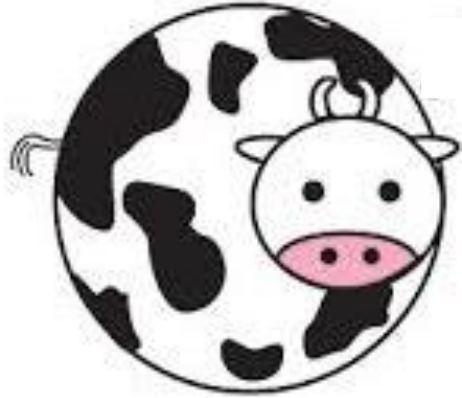
- What is the structure of nuclei at small- $x$ ? IC of HI collisions depend on the small- $x$  gluon structure
- How does the QGP thermalize so quickly? Hydrodynamic descriptions work very early ( $\sim 0.5 \text{ fm}/c$ )
- Why is the QGP such a perfect fluid? Measurements show very low viscosity ( $\eta/s \approx 0.1 - 0.2$ )
- What is the microscopic mechanism of jet quenching? Is  $E_{\text{loss}}$  dominated by radiative or collisional processes?
- What is the QCD phase diagram?
- How does hadronization occur in a QGP? Fragmentation? Recombination / coalescence?
- What are the relevant DOF in the QGP? Weakly interacting quasiparticles? Strongly coupled liquid?
- Why do small systems show collective flow? Hydrodynamic behavior? Initial-state correlations? Something else?
- What are the fluctuations inside nuclei?  $\rightarrow$  Many HI observables depend strongly on event-by-event fluctuations.
- How do EM and quantum effects influence HI collisions? CME, Vorticity + spin polarization, Quantum entanglement in UPCs

# Outstanding Questions Heavy Ion Physics

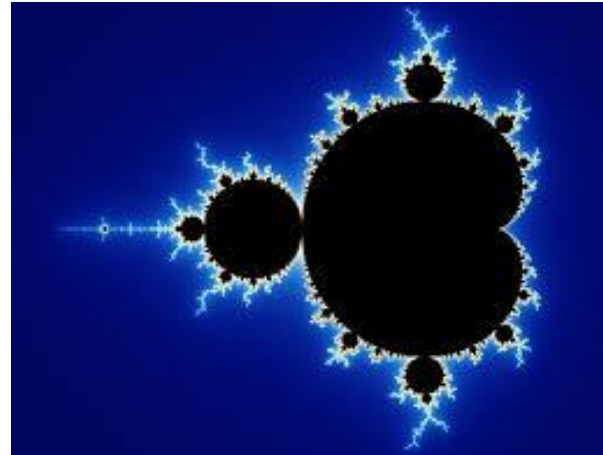
## EIC Direct Contributions EIC Indirect Contributions

- **What is the structure of nuclei at small-x? IC of HI collisions depend on the small-x gluon structure**
- How does the QGP thermalize so quickly? Hydrodynamic descriptions work very early ( $\sim 0.5 \text{ fm}/c$ )
- Why is the QGP such a perfect fluid? Measurements show very low viscosity ( $\eta/s \approx 0.1 - 0.2$ )
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# How do Physicists **Resolve** a Problem?



Simplify a complex system



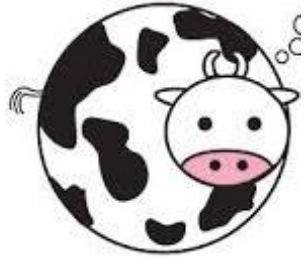
Assume scale invariance

$$f(x) \approx f(x_0) + (x - x_0)f'(x_0)$$

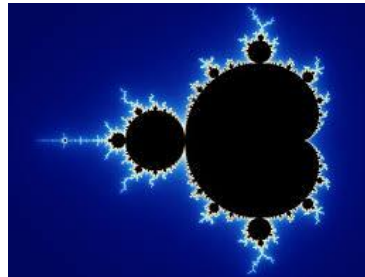
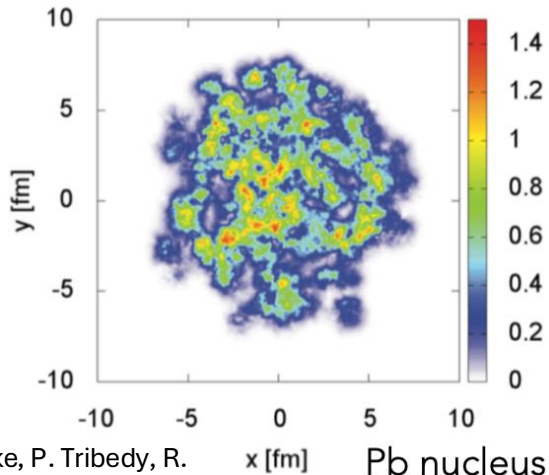
If the physics isn't linear, just Taylor expand until it is

**(Un) fortunately QCD refuses to cooperate with our usual tricks**

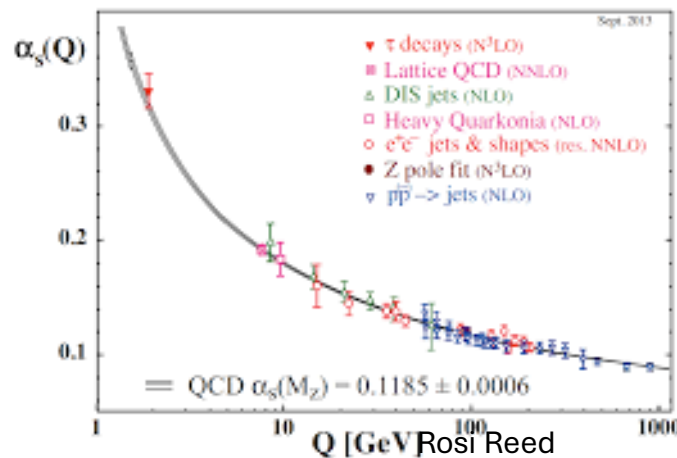
# How Physicists Approach a Problem



Simplify a complex system → A nucleus is a fluctuating many-body quantum system composed of correlated nucleons and gluon fields

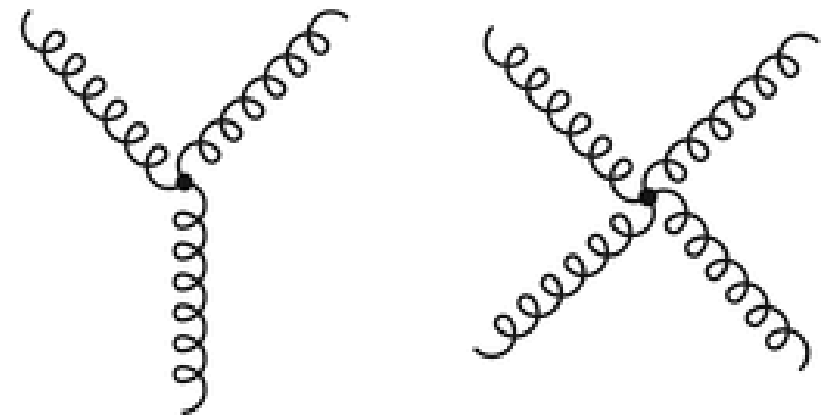


Assume scale invariance → Nature kindly breaks scale invariance for us through the running of the strong coupling



$$f(x) \approx f(x_0) + (x - x_0)f'(x_0)$$

If the physics isn't linear, just Taylor expand until it is → QCD is a Non-Abelian Gauge Theory

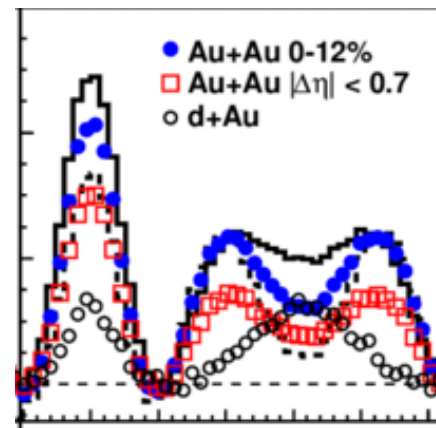
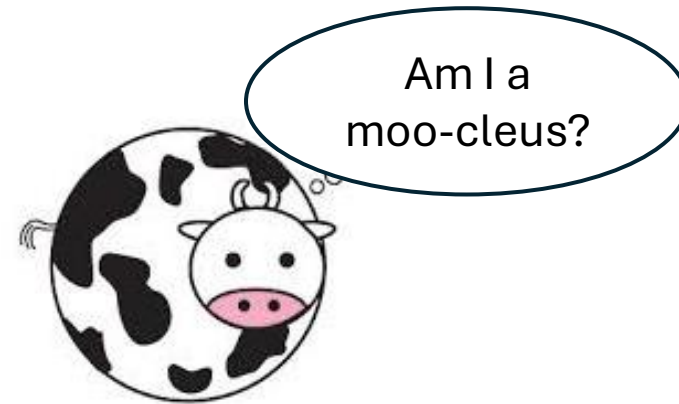
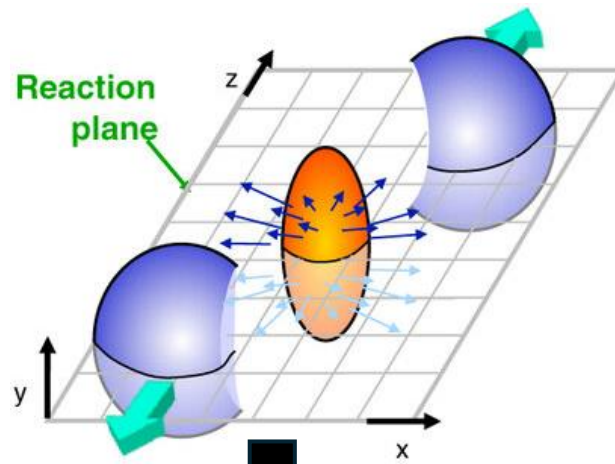


# Theory $\rightarrow$ Experiment $\rightarrow$ Theory

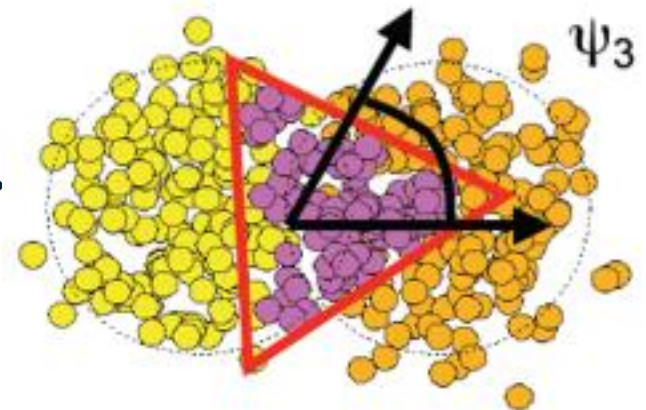
## Need to understand initial conditions

- Early RHIC pictures often showed collisions as 2 smooth spheres overlapping in a smooth almond-shaped region
  - Assumed  $v_3 = 0$ , as this would be true averaged over many events
  - $v_3$  arises from event-by-event fluctuations
- Early RHIC measurements showed double peaks in away-side correlations, which were interpreted as a Mach cone from a jet moving through the medium
- But later we realized that flow harmonics (especially  $v_3$  (reproduce the same pattern so the structure arises from collective flow fluctuations, not a Mach shock
- Assumptions about symmetry can hide important physics

Nucleus before  $\sim < 2010$



Phys. Rev. C **82**, 024912

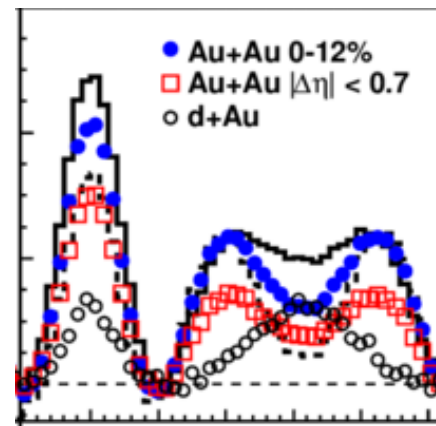
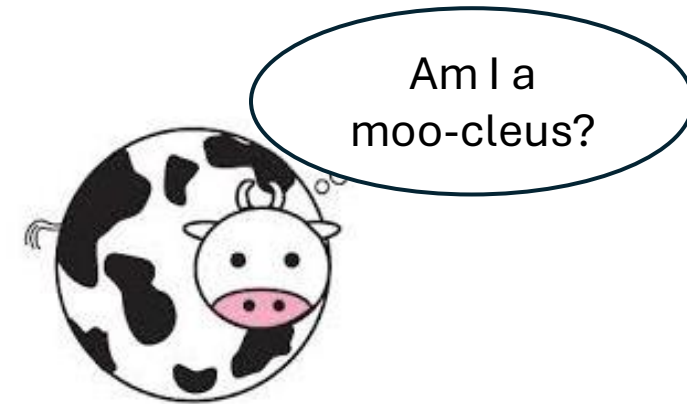
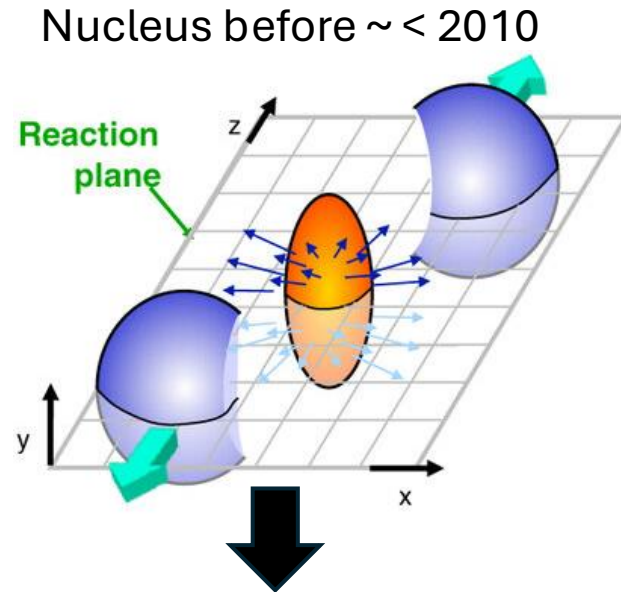


B. Alver and G.Roland, PRC 81 (2010) 054905

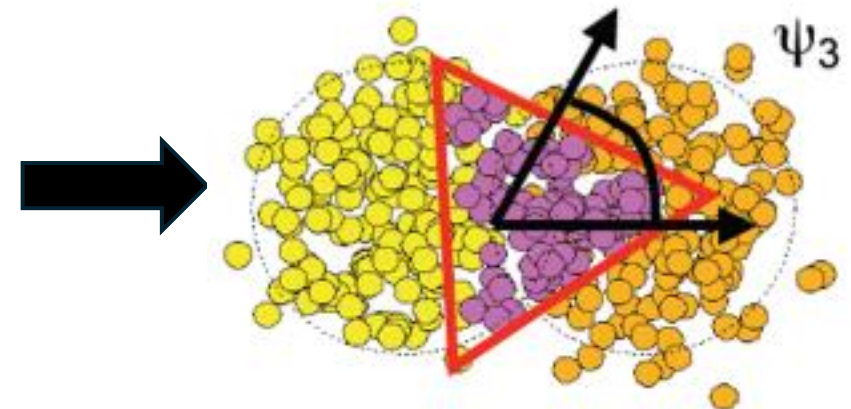
# Theory $\rightarrow$ Experiment $\rightarrow$ Theory

## Need to understand initial conditions

- Assumptions about symmetry can hide important physics
- To truly understand the QGP, we need to understand:
  - Initial conditions
  - Nuclear PDFs
- QCD is messy and factorization only can get us so far
- We need clean measurements in order to improve our models for the next stage in heavy ion physics
  - And to unironically say we are in an era of precision heavy ion physics



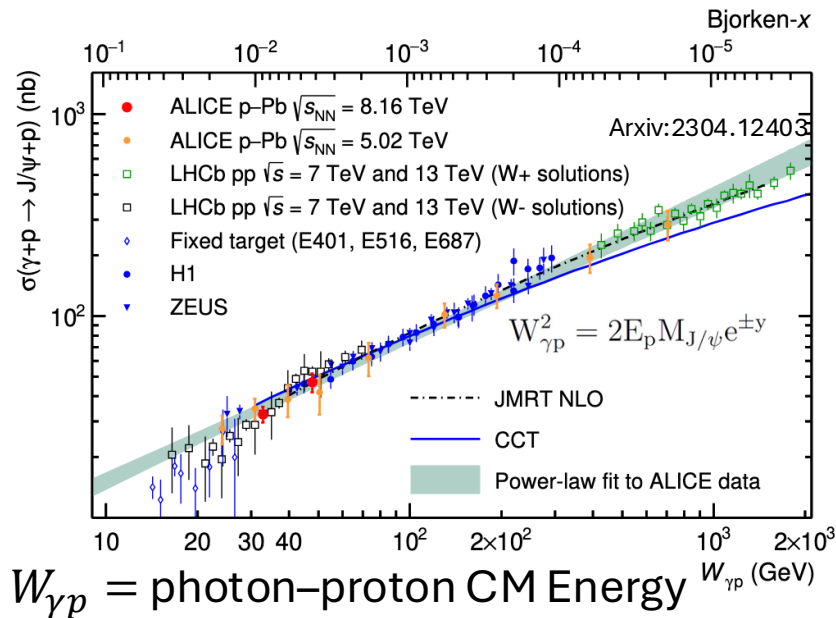
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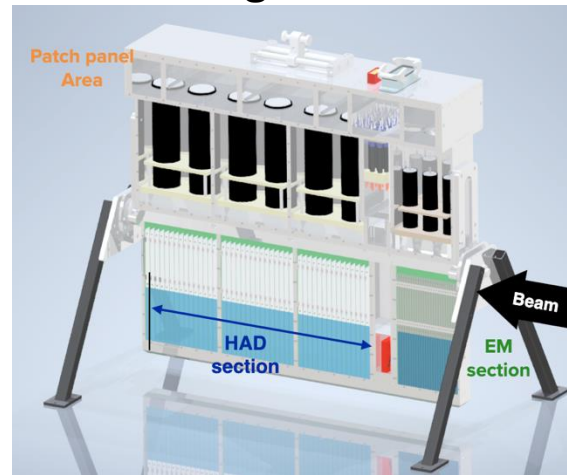
B. Alver and G.Roland, PRC 81 (2010) 054905

# What do UPCs teach us?

- I would be remiss if I did not mention UPCs
- Important to compare eA DIS with forward pA and UPC at the LHC/RHIC

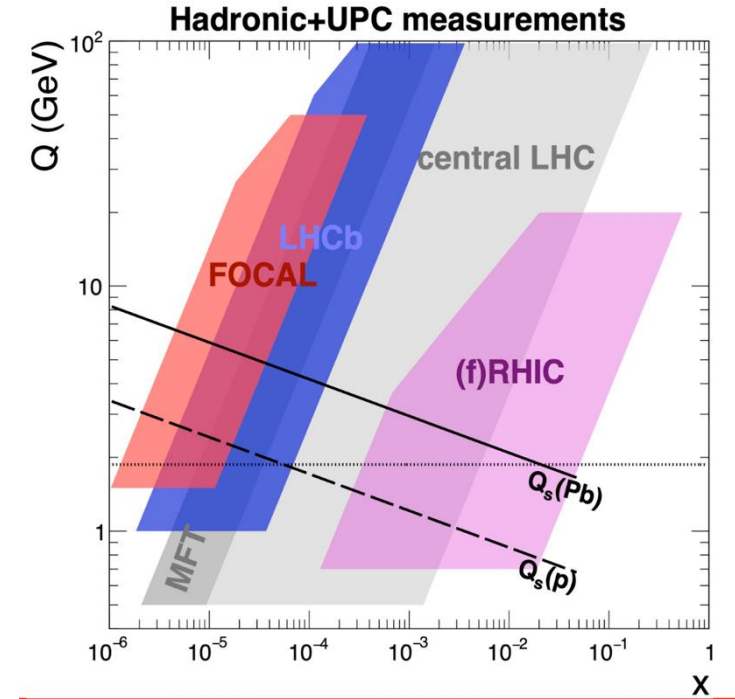


HL-ZDC design → Required for UPC Program



US institutions leading the first joint R&D project between the CMS & ATLAS!

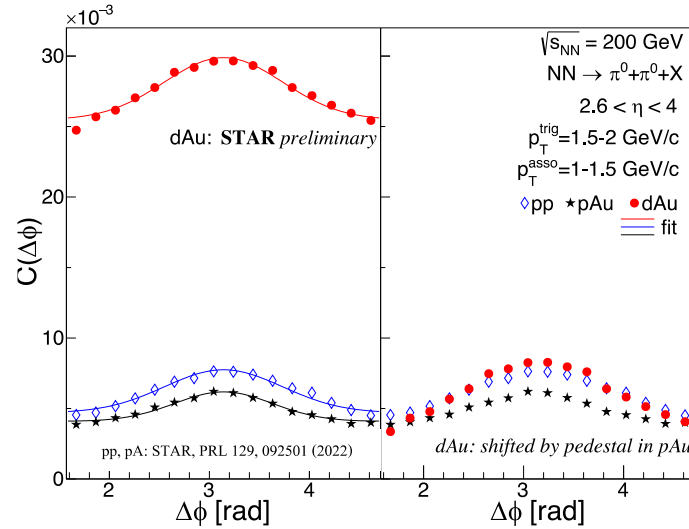
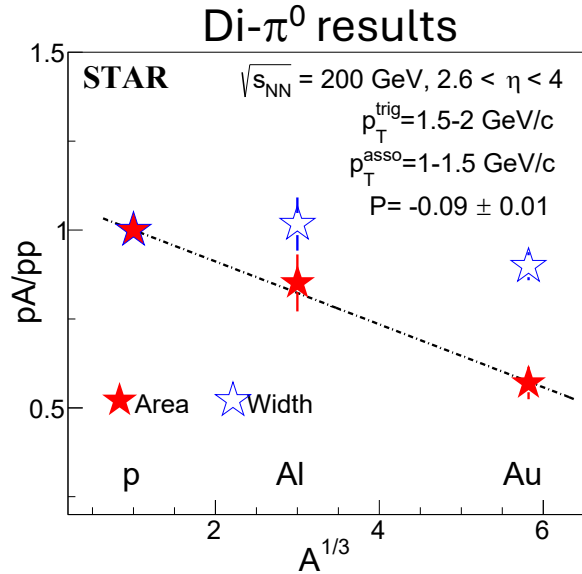
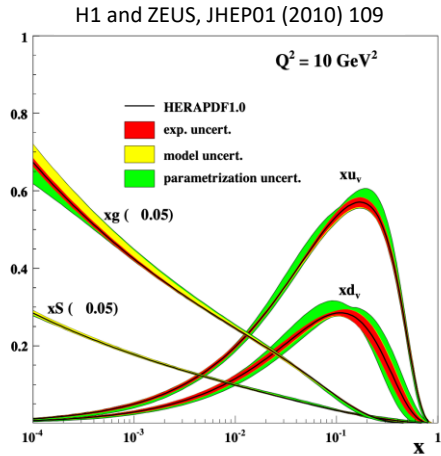
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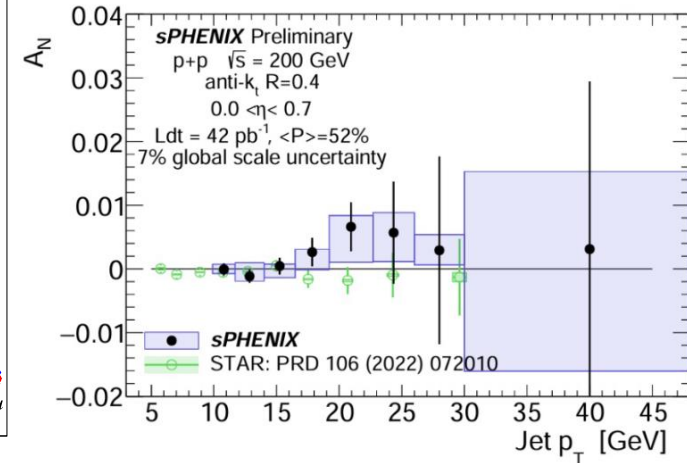
In UPCs the photon virtuality is essentially fixed ( $Q^2 \approx 0$ ), so UPCs probe photoproduction only

- Additional modeling uncertainties as the photon flux must be calculated from the electromagnetic field of the ion

# EIC-Type Physics Before the EIC



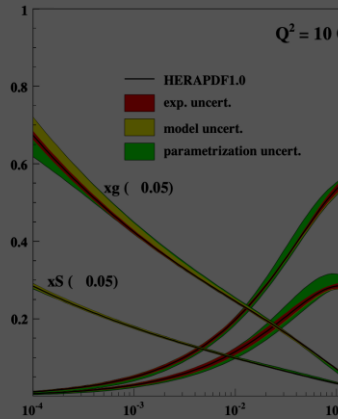
sPH-CONF-COLDQCD-2025-01



- Signatures of gluon saturation (from CGC) → broadening and suppression dependence on  $A$ , centrality,  $p_T$ , and rapidity predicted.
  - **Suppression dependence on  $A$ ,  $p_T$ , and rapidity observed**
  - Broadening not observed
- d+Au results at STAR → challenging to draw conclusions (background, PID)
- **Forward upgrade heavy ion results** will be very interesting!
  - Loss of pA data with the forward upgrade is unfortunate

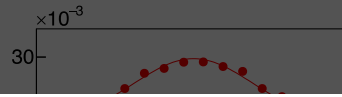
# EIC-Type Physics Before the EIC

H1 and ZEUS, JHEP01 (2010) 109



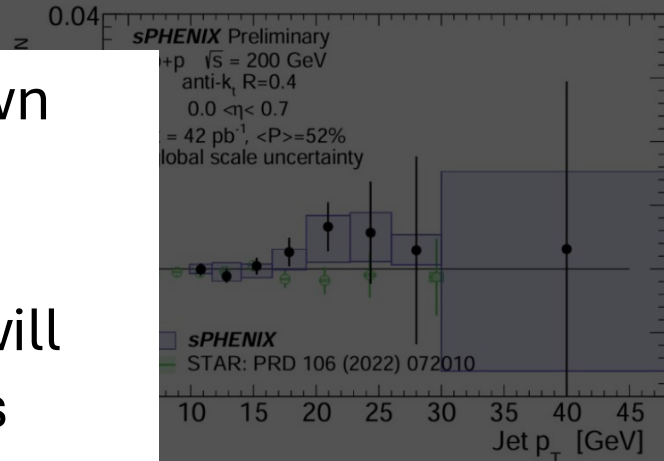
Di- $\pi^0$  results

STAR  $\sqrt{s_{NN}} = 200 \text{ GeV}, 2.6 < \eta < 4$   
 $p_{trig} = 1.5-2 \text{ GeV}/c$



$\sqrt{s_{NN}} = 200 \text{ GeV}$   
 $NN \rightarrow \pi^0 + \pi^0 + X$

sPH-CONF-COLDQCD-2025-01



Finishing the RHIC Science Mission is critical in its own right

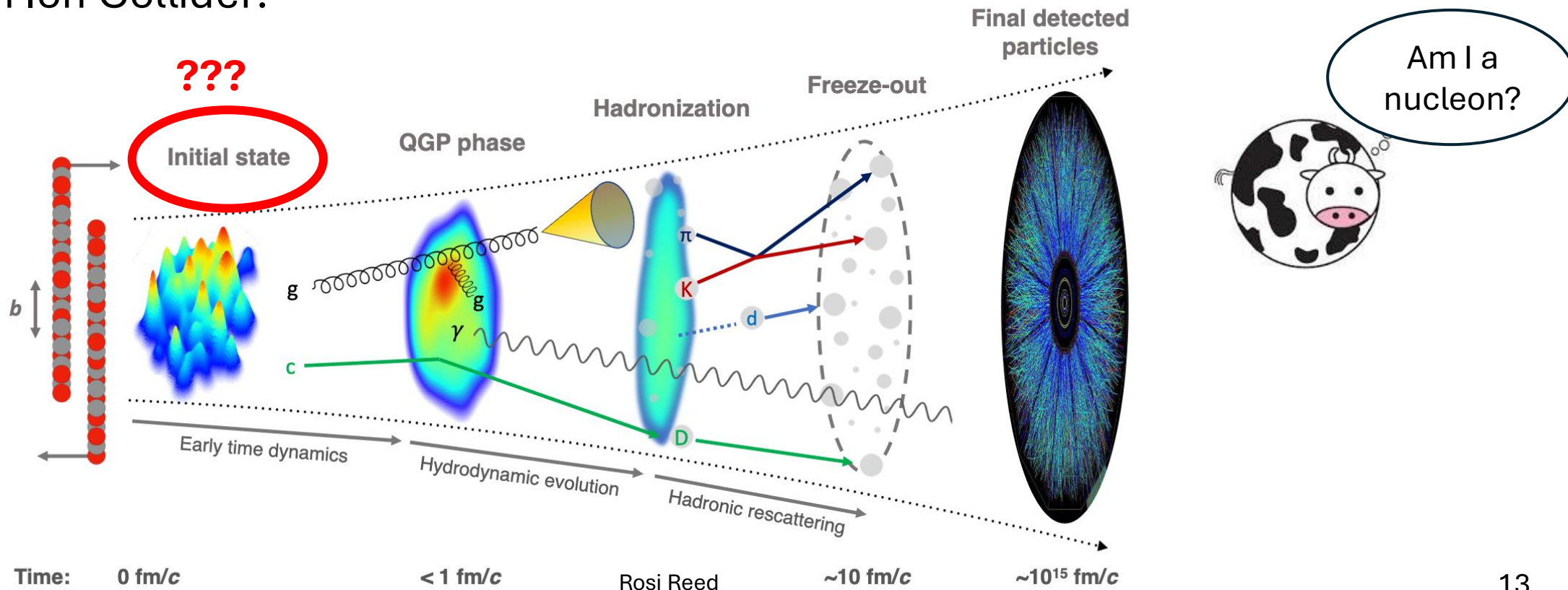
However, mining the RHIC data for EIC type physics will increase the impact of the future EIC result  $\rightarrow$  QCD is complicated and requires measurements over many scales

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- d+Au results at STAR  $\rightarrow$  challenging to draw conclusions (background, PID)
- **Forward upgrade and future data** will be very interesting!

# Heavy Ion Collision Evolution

There is considerable uncertainty in both the initial state and nuclear PDFs, that limit our ability to further interpret our results → Require clean measurements in order to further constrain models

- Electron Ion Collider!



# EIC Big Questions

- What happens to the **gluon density** in nucleons and nuclei at small  $x$ ?
- What is the **configuration and motion** of quarks and gluons located within nucleons?
- How do **quarks and gluons interact** with a nuclear medium?
- How do the **confined hadronic states** emerge from quarks and gluons?
- How do the **properties of the proton** such as **mass** and **spin** emerge from the sea of quarks, gluons, and their underlying interactions?

# EIC Big Questions for Heavy Ion Physicists

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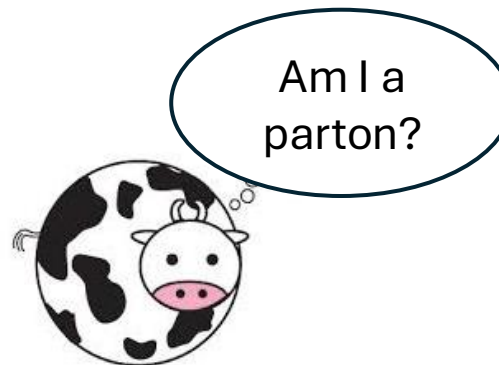
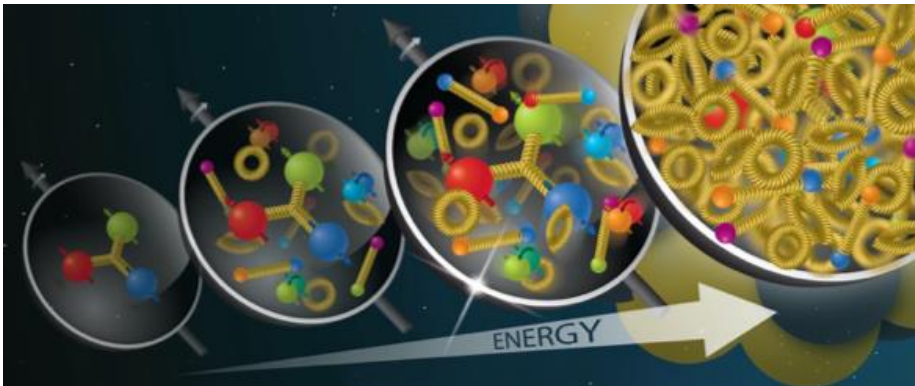
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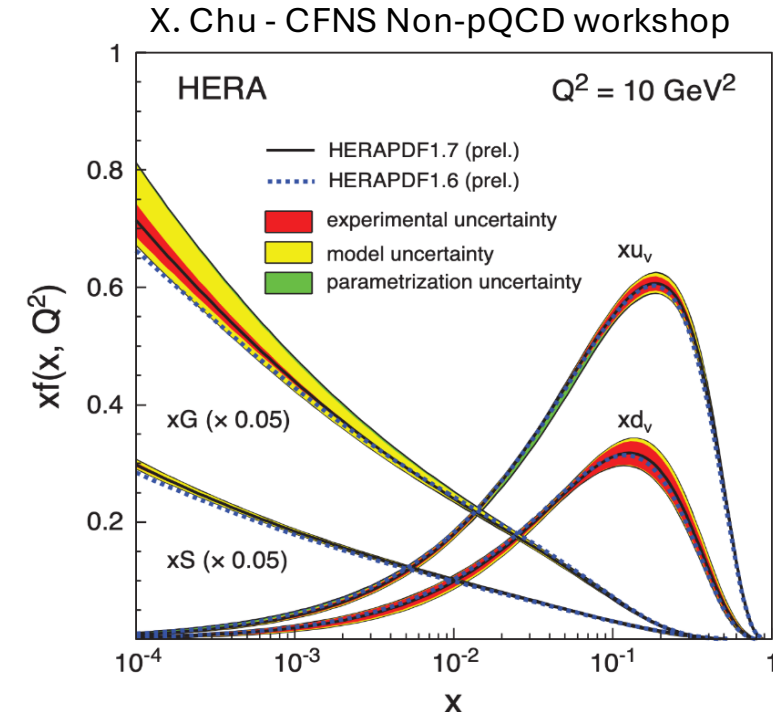
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# Gluon Saturation

- We assume the gluon density should saturate at some small value of  $x$ 
  - Momentum scale of  $Q_s$  (saturation scale)
    - Gluon splitting (linear) = Gluon recombination (non-linear)
    - Scale where the gluons overlap
    - $Q_s^2 \sim 1/x^{0.2-0.3}$
- In CGC / glasma pictures:  $p_T^{initial} \sim Q_s$
- Saturation should exist in nuclei too:  $Q_s^2 \propto A^{1/3}$



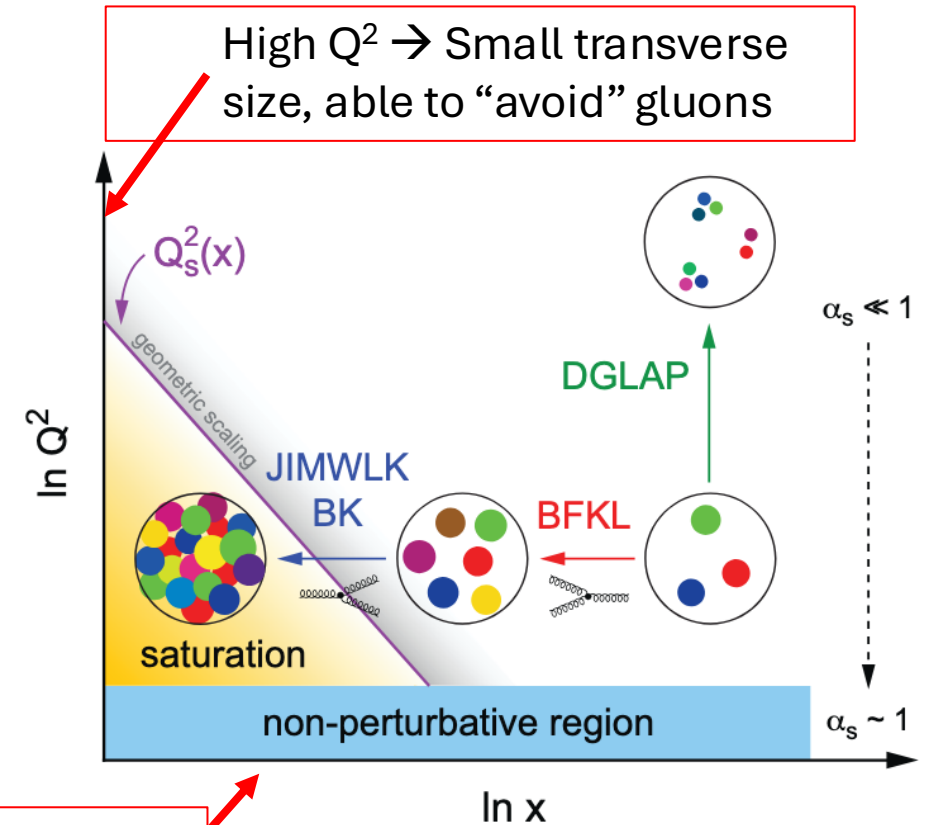
Rosi Reed



Understanding small- $x$  gluons directly constrains the **starting point of hydrodynamics**

# Gluon Saturation

- In CGC/Glasma pictures  $p_T^{initial} \sim Q_s$
- So  $Q_s$  sets
  - Initial gluon multiplicity
  - Energy density
  - Correlation length of glasma fields
  - Typical initial momentum scale
- How would we measure  $Q_s$  at the EIC?
  - Dijet/dihadron correlations



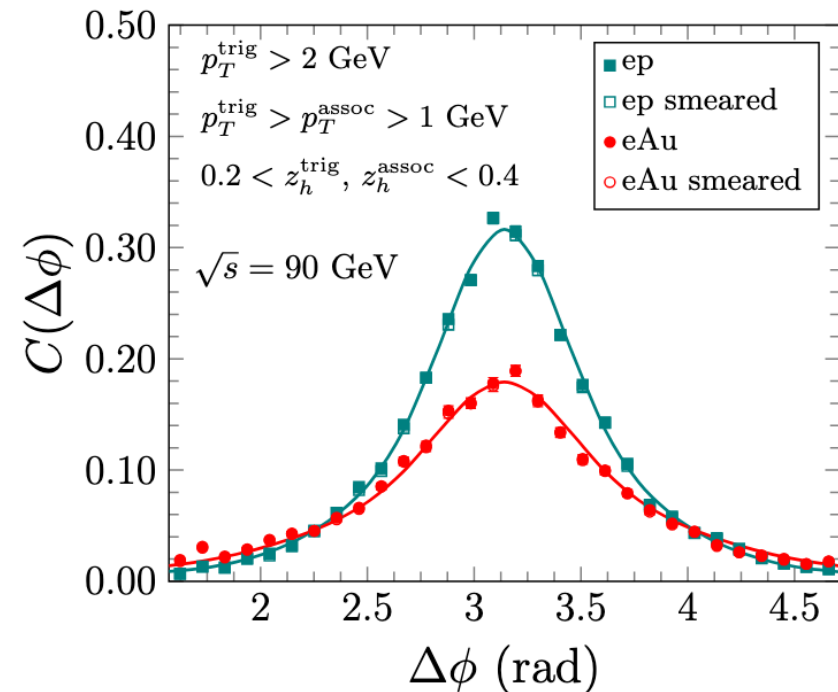
Some hints of saturation can be seen at:

- Photon-nucleus energy dependence of coherent  $J/\psi$  cross section in ultraperipheral PbPb collisions at 5.02 TeV with CMS (2022)
- M. S. Abdallah, et al., Evidence for Nonlinear Gluon Effects in QCD and Their Mass Number Dependence at STAR, Phys. Rev. Lett. 129 (9) (2022) 092501

# Dijet / dihadron correlations

## Saturation Probe


- Without saturation:
  - Jets/high  $p_T$  are strongly back-to-back
- With saturation:
  - Multiple scatterings in the dense gluon field broaden the correlation
  - $\Delta\phi \sim \pi \rightarrow$  broadened
- The broadening scale is roughly  $k_T \sim Q_s$
- Directly probe saturation momentum scale
- Easier to see in eA due as  $Q_s^2 \propto A^{1/3}$
- But it could be possible to explain results with conventional nPDF shadowing effects
  - PRC 111 (2025) 054901

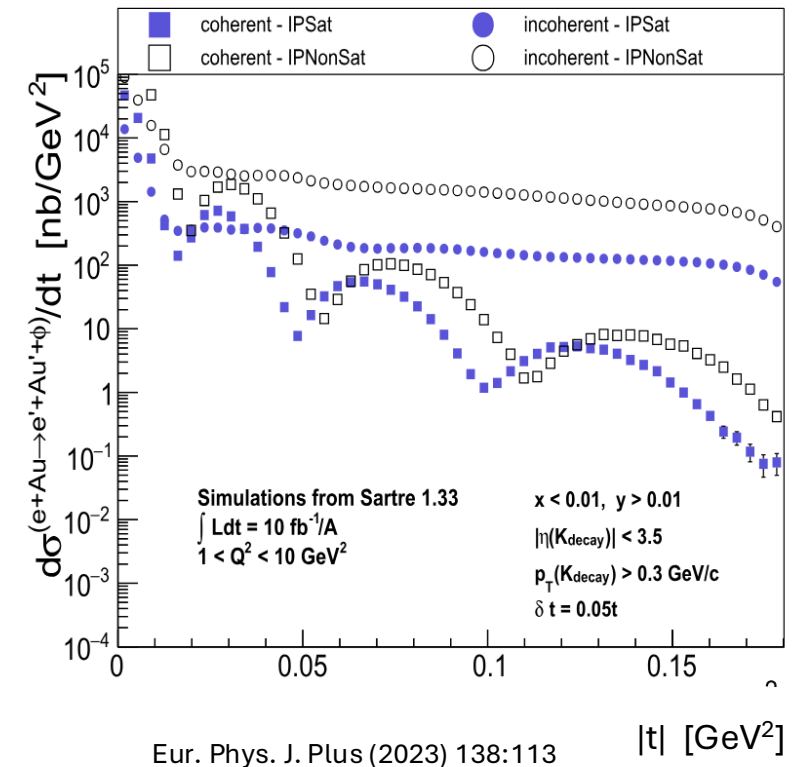


WP on the EIC in Preparation  
for the LRP

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

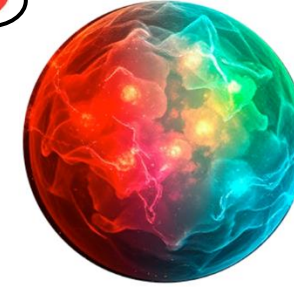
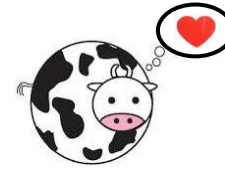
# Diffractive DIS

- Dijet/dihadron correlations  $\rightarrow$  transverse momentum scale  $Q_s$  
- Diffractive DIS  $\rightarrow$  nonlinear saturation dynamics
- Coherent diffractive vector-meson production provides direct sensitivity to the transverse spatial distribution of gluons in nuclei.
- $d\sigma/dt$  vs  $t$  shows diffractive pattern  $\rightarrow$  Fourier–Bessel transform is related to the gluon density as a function of impact parameter
  - An EIC early science measurement

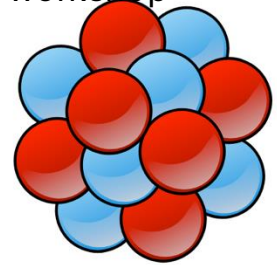


# Nuclear PDFs

- Is a nucleon inside of a nucleus the same as a free nucleon?
- Can we treat neutrons and protons the same?



≠



K. Greve – 2025 Light Ion workshop

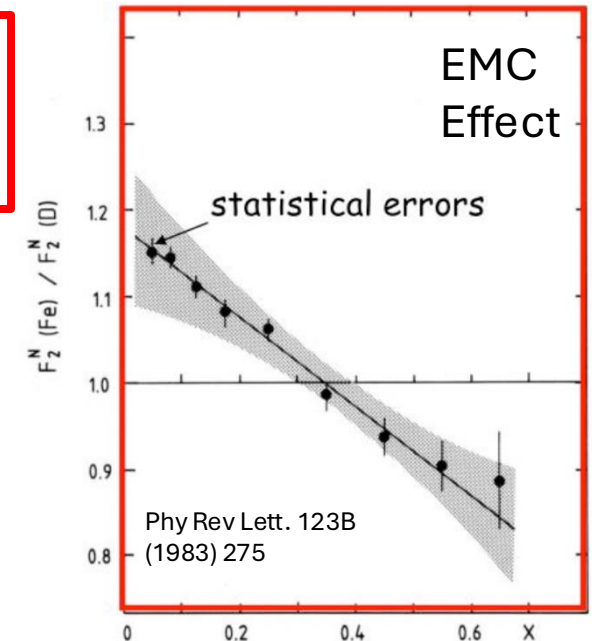
- Structure function  $F_2$

- At leading order in QCD:  $F_2(x, Q^2) = x \sum_q e_q^2 [q(x, Q^2) + \bar{q}(x, Q^2)]$
- $x$  = Bjorken  $x$
- $Q^2$  = photon virtuality
- $q(x, Q^2)$  = quark PDF
- $e_q$  = quark electric charge
- $F_2$  is essentially a charge-weighted sum of quark and antiquark PDFs

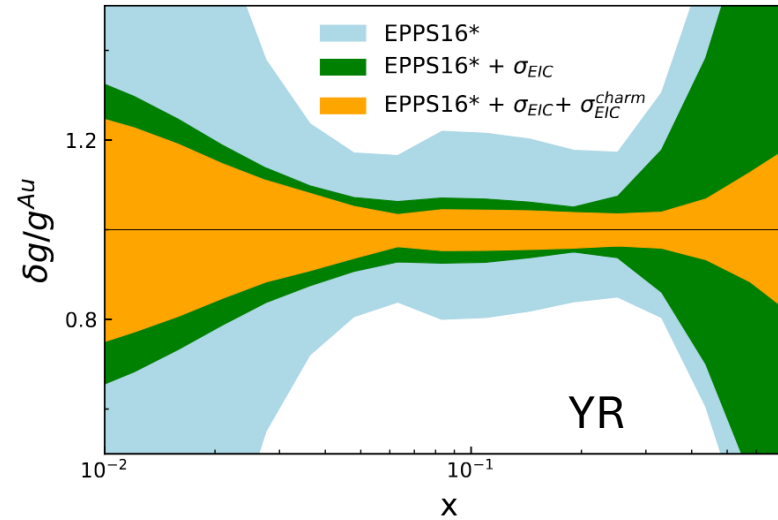
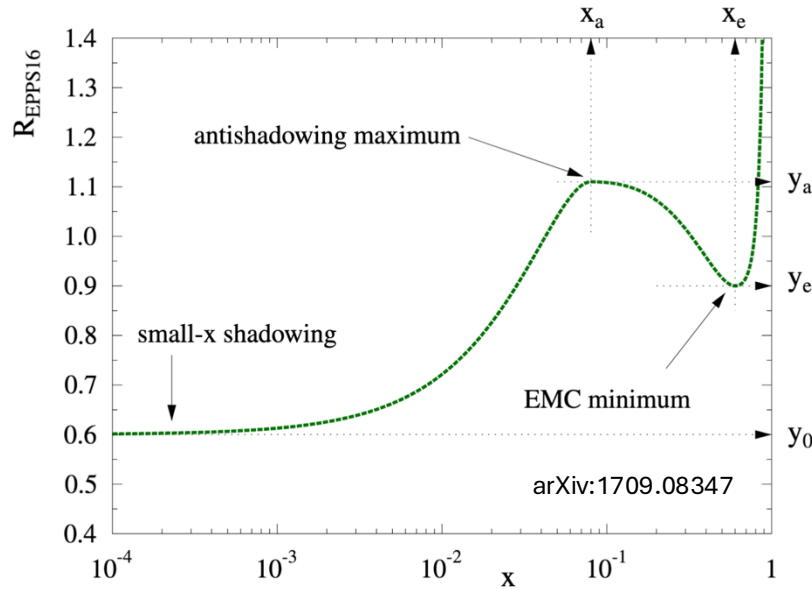
$$F_2^A \neq ZF_2^p + (A - Z)F_2^n$$

- $F_2$  measures quarks directly, but gluons only appear indirectly through QCD evolution
  - This is one reason why gluon nPDFs are poorly constrained

Nucleus in a nucleon is not the same!



# Nuclear PDFs



$\delta g(x, Q^2)$  = uncertainty from the global fit

$g^{\text{Au}}(x, Q^2)$  = gluon distribution in a gold nucleus

Early Science Paper from ePIC in progress with new impact studies!

$e + A \rightarrow e' + X$  Determine  $x, Q^2$  from  $e'$

Determine  $\frac{d^2\sigma}{dx dQ^2} = \frac{4\pi\alpha^2}{xQ^4} \left[ \left(1 - y + \frac{y^2}{2}\right) F_2(x, Q^2) - \frac{y^2}{2} F_L(x, Q^2) \right]$

nPDFs determine the expected yield of jets, photons, heavy flavor, etc,  $\rightarrow$  Need to fully understand hot QCD effects!



Most current constraints come from:

- fixed-target DIS
- Drell–Yan
- limited collider measurements.
- But gluon nPDFs are poorly constrained, especially at small  $x$

# EIC Big Questions for Heavy Ion Physicists

- What happens to the gluon density in nucleons and nuclei at small  $x$ ?
  - What is the **configuration and motion** of quarks and gluons located within nucleons?
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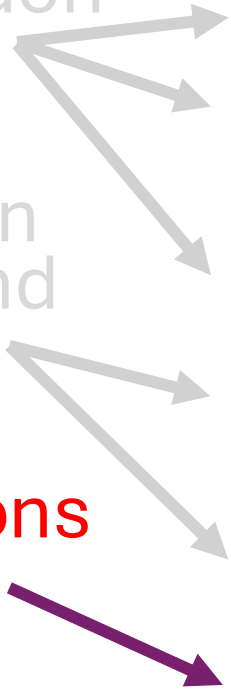
# Initial conditions

- For HI physics the best constraints of the initial state come from:
  - Dijet/dihadron correlations  $\rightarrow$  transverse momentum scale  $Q_s$  
  - Diffractive DIS  $\rightarrow$  nonlinear saturation dynamics 
  - Exclusive vector mesons  $\rightarrow$  transverse gluon geometry + fluctuations
  - Determine  $Q_s(x,A,b)$  and the structure of the gluon fields before the collision
- Heavy-ion observables depend on geometry
  - For example flow coefficients roughly follow  $v_n \sim \kappa_n \varepsilon_n$  where  $\varepsilon_n$  comes from the initial spatial distribution
  - Understanding event-by-event fluctuations
- EIC data in  $\sim 10$  years, what do we need to do in order to immediately take advantage of the increased precision on our IS knowledge?

# Initial conditions

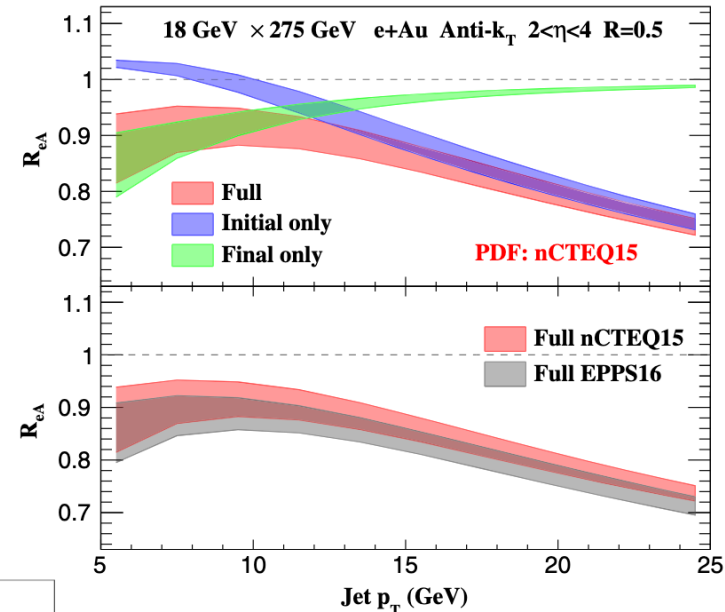
- For HI physics the best constraints of the initial state come from:
  - Build the analysis infrastructure now!
  - We desperately need the theory community
  - Create common heavy-ion/EIC observable definitions
  - Develop shared MC (beyond Pythia) and unfolding workflows
  - Benchmark measurements in RHIC/LHC data so that when EIC constrains the IS we can immediately translate that into reduced uncertainties QGP observables
  - Understanding event-by-event fluctuations
- Heavy-ion data in ~10 years, what do we need to do in order to immediately take advantage of the increased precision on our IS knowledge?

# EIC Big Questions for Heavy Ion Physicists

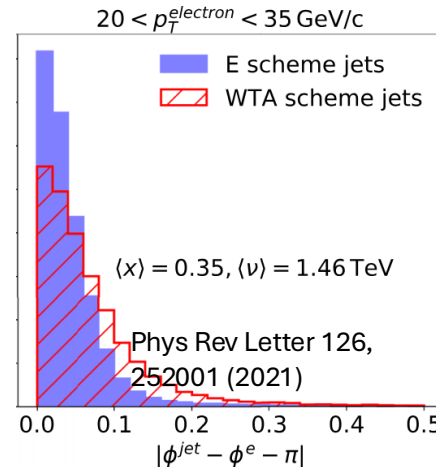
- What happens to the gluon density in nucleons and nuclei at small  $x$ ?
  - What is the configuration and motion of quarks and gluons located within nucleons?
  - How do **quarks and gluons interact** with a nuclear medium?
  - How do the confined hadronic states emerge from quarks and gluons?
  - What is the structure of nuclei at small- $x$ ?
  - How does the QGP thermalize so quickly?
  - Why is the QGP a perfect fluid?
  - Why do small systems show collective flow?
  - What are the fluctuations inside nuclei?
  - **What is the microscopic mechanism of jet quenching?**
  - How does hadronization occur in a QGP?
- 

# Cold Nuclear Matter Effects

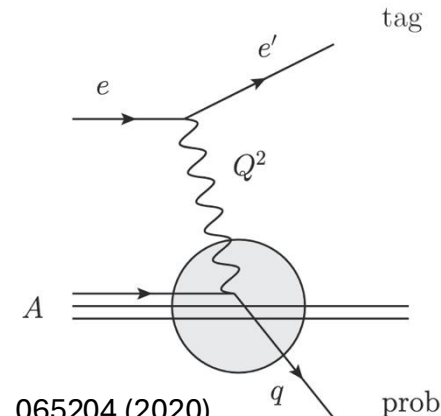
- Understanding CNM is critical for understanding jet quenching
  - pA systems are still messy (and there is the question of QGP formation in small systems)
- Comparisons of jet yields in ep vs eA will be informative and possible early in the EIC program
  - Ratio of  $R_{eA}(R = z) / R_{eA}(R = 1.0)$  will reduce nPDF impact
  - It will take time for nPDF determination
- Allows separation of initial and final state effects
- Dijets and  $\gamma$ -dijet correlations are useful probes of saturation and small-x dynamics
- Jets are defined by their algorithm, how do we save our HI data for comparison with EIC jets that may use different algorithms?



Phys Rev Letter 126, 252001 (2021)



Rosi Reed



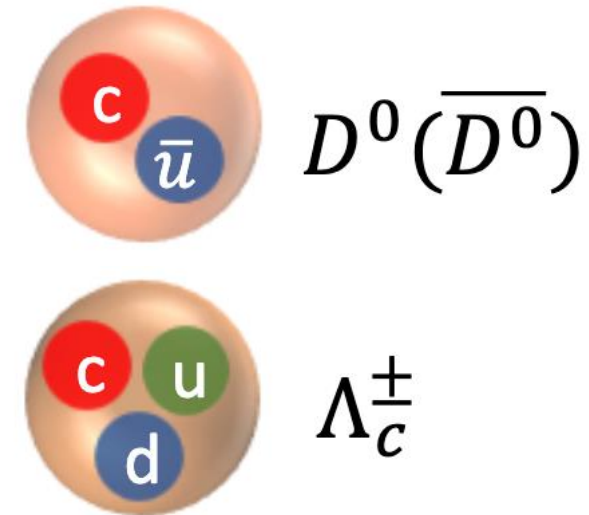
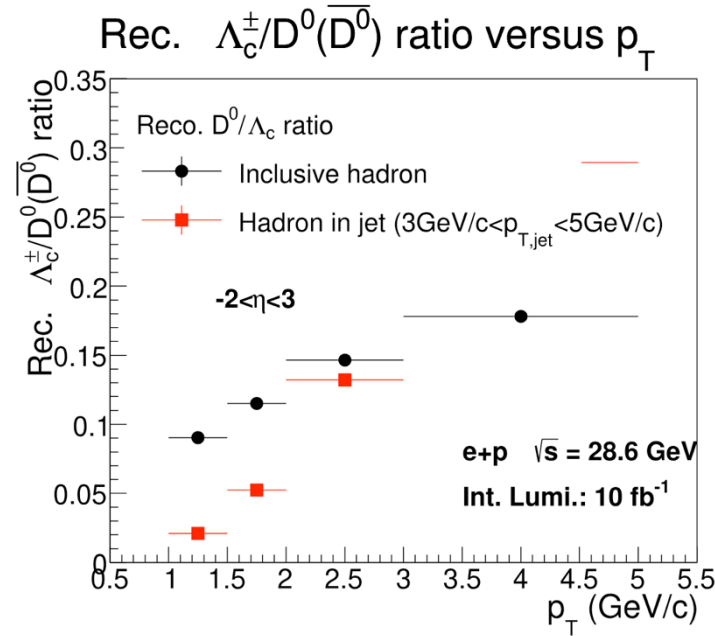
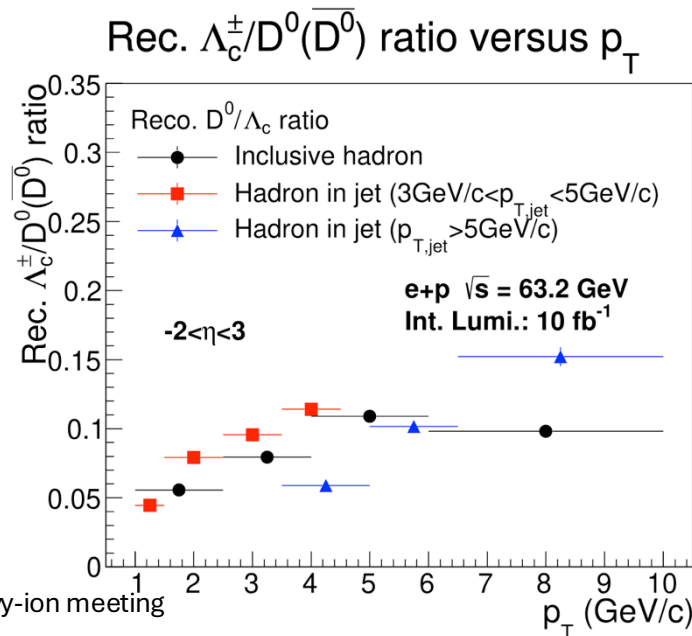
Phy Rev C 101, 065204 (2020)

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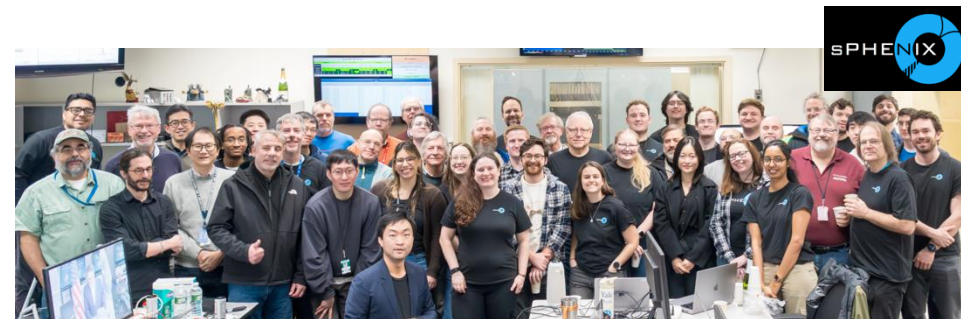
# Heavy Flavor Hadronization

- Charm production is predominantly via  $\gamma$ -g fusion, offering direct access to gluon densities  $\rightarrow \sigma_c$  is a complementary constraint on gluon PDFs
- Charm allows for a detailed study of hadronization mechanisms in both proton and nuclear environments
  - $\Lambda_c^+ / D^0 \rightarrow$  sensitive to fragmentation versus recombination mechanisms and possible baryon enhancement in nuclei
  - Probes confinement dynamics



# Conclusions/Discussion

- EIC data in ~10 years, what do we need to do in order to immediately take advantage of the increased precision on our IS knowledge?
  - Same for understanding CNM and jet quenching
- Do we know what precision we need from the EIC in order to sufficiently constrain both the initial state and hadronization to make progress in understanding the QGP?
- Data preservation → Are we making any ZYAM type mistakes?
  - What lessons can we take from the reanalysis of  $e^+e^-$  data from ALEPH, DELPHI?
  - Jets are defined by their algorithm, how do we save our HI data for comparison with EIC jets that may use different algorithms?
  - Would AI/ML help in this effort, we need to preserve calibrations and other details!



## Community preservation

- The EIC will be run by people who are graduate students/postdocs/assistant professors now!
- RHIC science mission is not complete until the data is analyzed and published!