Unique opportunities in p+A collisions at RHIC and LHC

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Phases of QCD Matter Town Meeting
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Outline

- Introduction
- RHIC vs LHC: complementarity and future
- pA vs eA: universality and dynamics
- Summary

The role of p+A collisions

- Started as a control experimental tool to calibrate the A+A measurements for a sounder interpretation
  - Benchmarking: Cold vs Hot nuclear matter effect

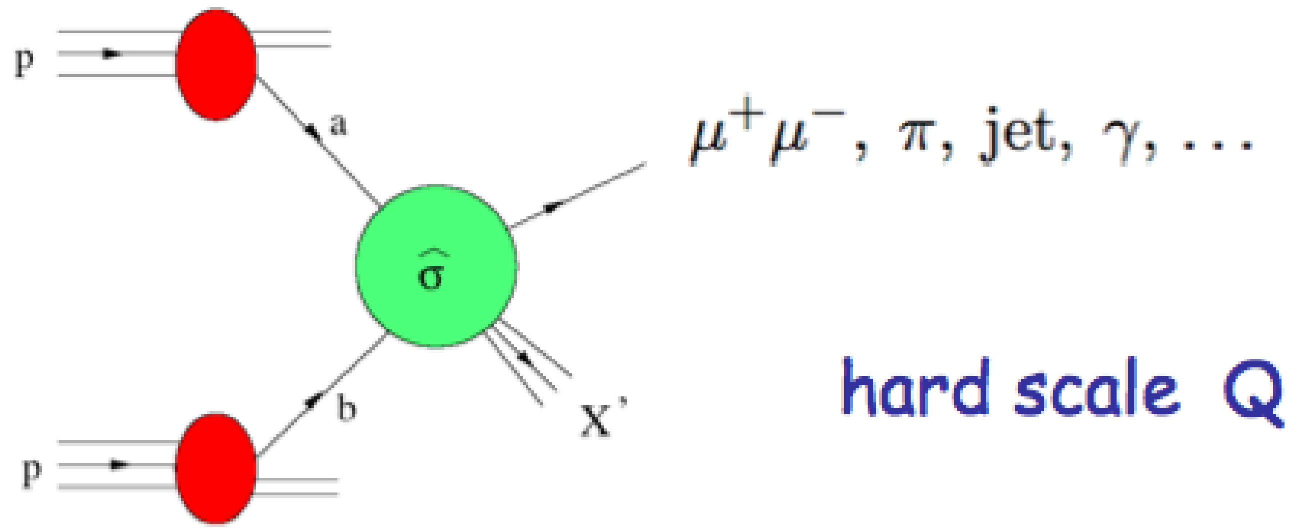
~~hot nuclear matter~~ hot nuclear matter

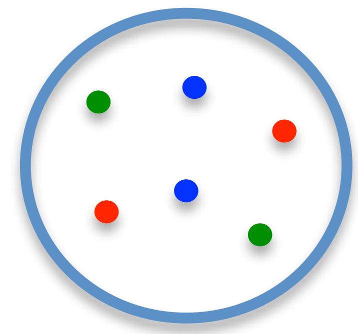
- It has evolved significantly in recent years, opening new windows to study
  - Novel QCD dynamics, such as gluon saturation, (in)coherent multiple scattering, nuclear PDFs, cold nuclear matter energy loss, ...
  - Nucleus: a laboratory for QCD
  - Even surprises: ridge, flow see B. Schenke's talk

Hard Probe

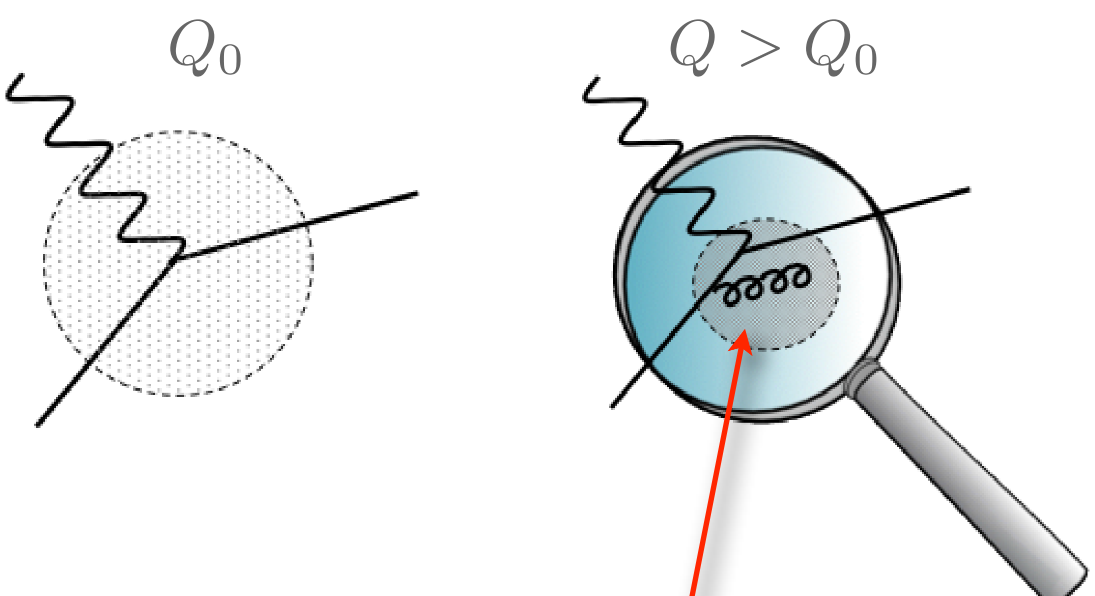
QCD collinear factorization

$$\sigma \propto \phi_p(x_a, Q^2) \otimes \phi_p(x_b, Q^2) \otimes \hat{\sigma}_{ab\to\gamma/\text{jet},\cdots}$$





- Main ingredients:
  - Protons are dilute systems of quarks and gluons, thus independent/incoherent single scattering
  - Collinear parton distribution is governed by a "linear" evolution equation

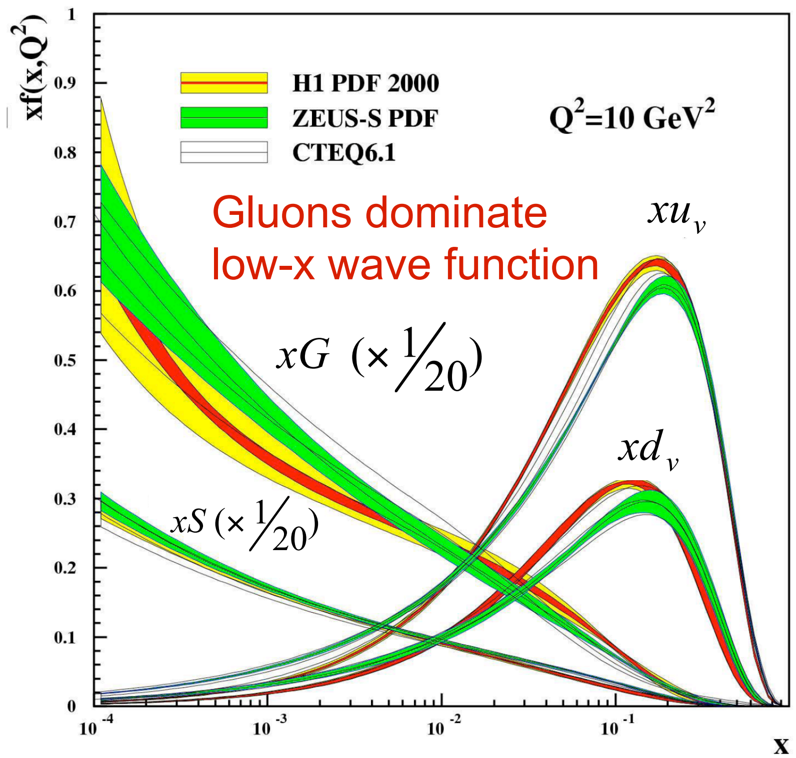


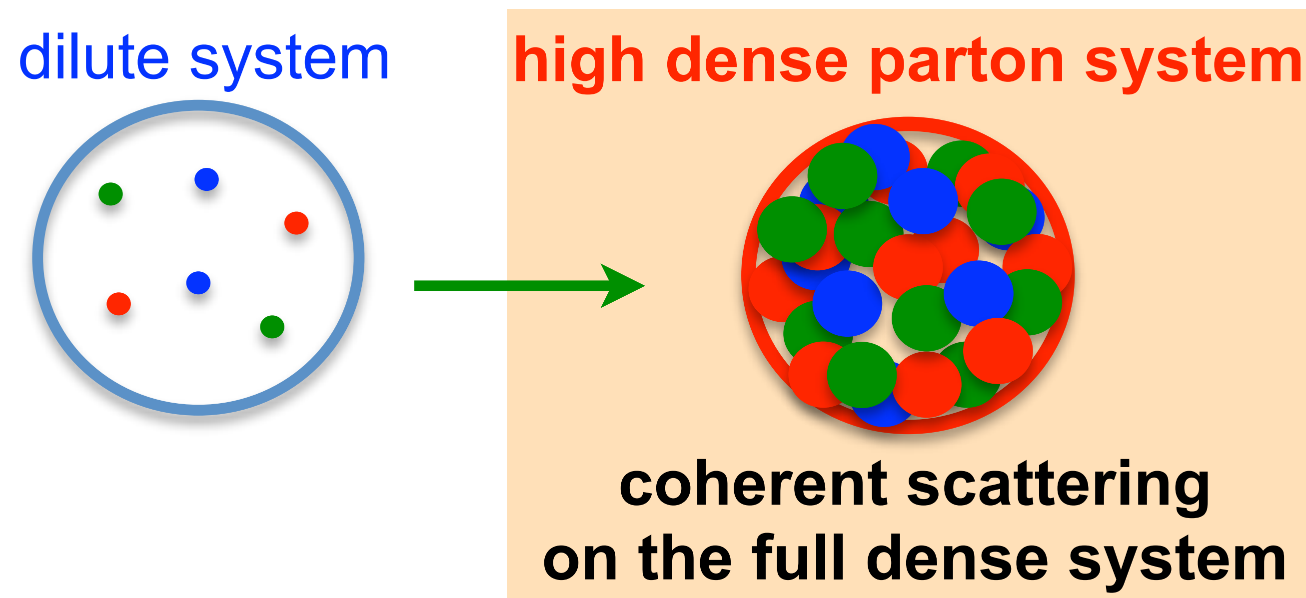
$$\frac{\partial \phi(x, Q^2)}{\partial \ln Q^2} = P_{\text{DGLAP}} \otimes \phi(x, Q^2)$$

parton radiation/splitting/branching

Parton distribution in small x

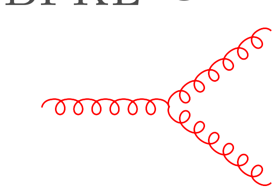
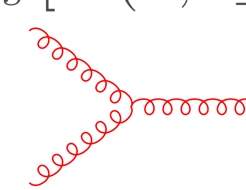
- Going to small x region, parton density (especially gluon density) grows dramatically





- Because it is so dense, the external probe will interact with the whole dense system "coherently"
  - When so many gluons are squeezed in a confined proton, besides the usual splitting, they also start to overlap and recombine
  - Nonlinear dynamics/evolution (BK eqn): saturation scale $Q_s(x)$ from the balance

$$\frac{\partial N(x,r_\perp)}{\partial \ln(1/x)} = \alpha_s K_{\mathrm{BFKL}} \otimes N(x,r_\perp) - \alpha_s \left[N(x,r_\perp)\right]^2$$

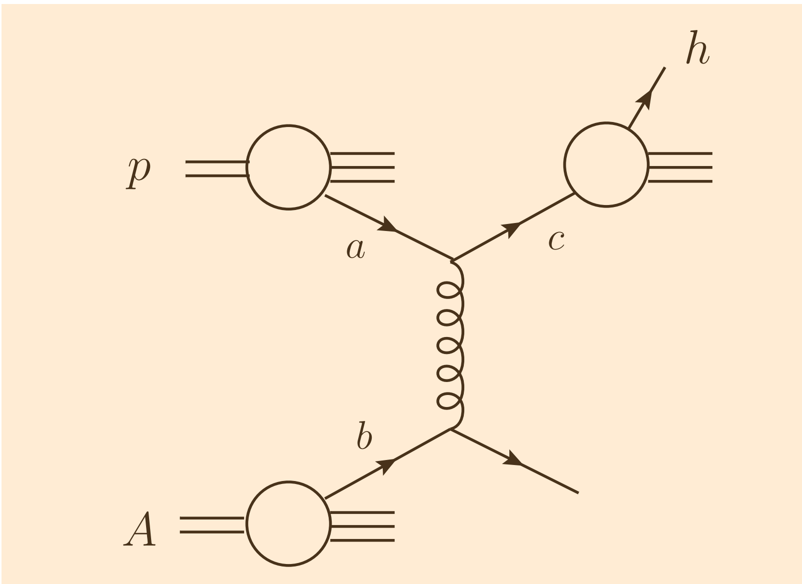
radiation   recombination

Search for gluon saturation

- Gluon saturation is an inevitable consequence of QCD dynamics at high energy (small x)
- Important questions:
  - Where does the transition happen?
  - What are the properties of this saturated regime?

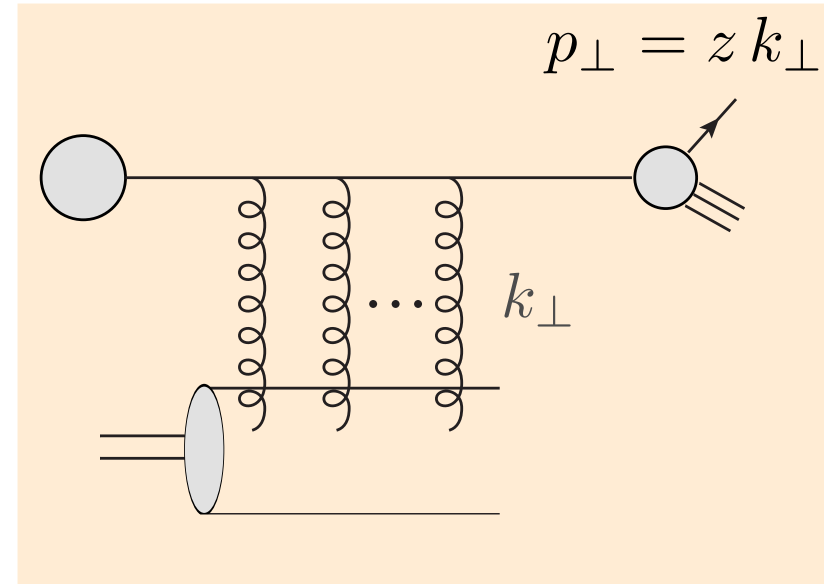
How does it work?

Collinear factorization



2→2 process, hard interaction

Color Glass Condensate



coherent multiple scattering

- Color Glass Condensate (CGC) approach

✓coherent multiple scattering encoded in $F(x, k_\perp) = \mathrm{F.T.}$ of $N(x, r_\perp)$

✓dipole gluon distribution: $N(x, r_\perp) = \langle U(0) U^\dagger(r_\perp) \rangle$

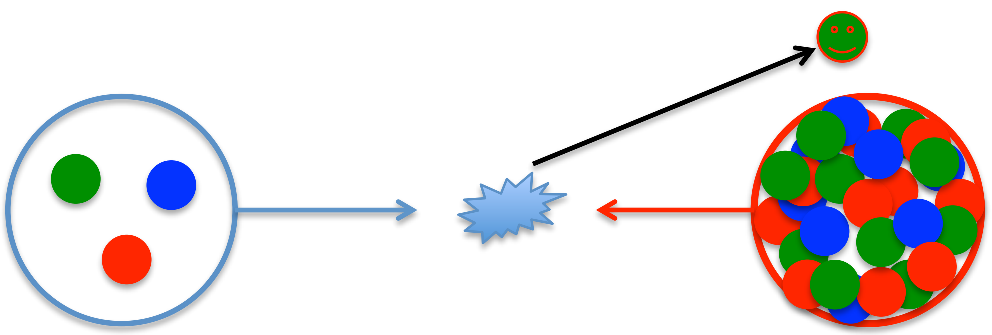
$$U(r_\perp) = P \exp\left(i g_s \int_{-\infty}^{+\infty} d\lambda^+ A^-(\lambda^+, r_\perp) \right)$$

- BK evolution equation for dipole gluon distribution

$$\frac{\partial N(x, r_\perp)}{\partial \ln(1/x)} = \alpha_s K_{\mathrm{BFKL}} \otimes N(x, r_\perp) - \alpha_s \left[N(x, r_\perp \right]^2$$

Study gluon saturation in p+A collisions

- Going to forward rapidities



$$\text{forward} \leftrightarrow y \gg 0$$

$$x_1 \sim \frac{p_\perp}{\sqrt{s}} e^{+y} \sim \mathcal{O}(1)$$

$$x_2 \sim \frac{p_\perp}{\sqrt{s}} e^{-y} \ll 1$$

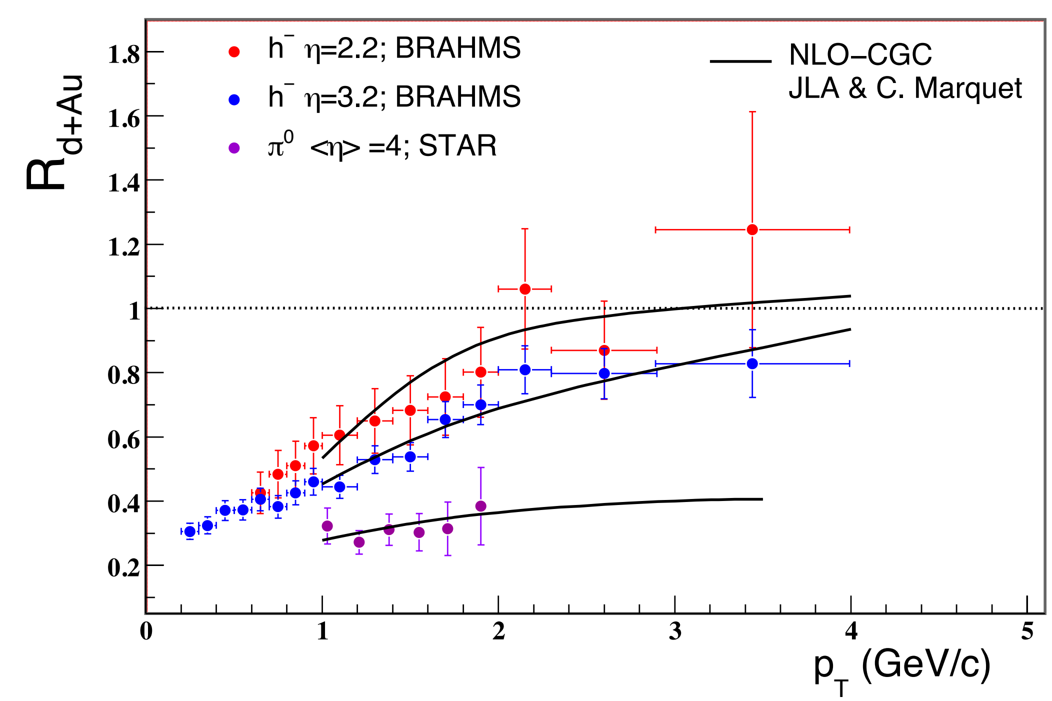
dilute on dense scattering

$$R_{pA} = \frac{1}{N_{\rm coll}} \frac{dN^{pA\to hX}/dyd^2p_\perp}{dN^{pp\to hX}/dyd^2p_\perp}$$

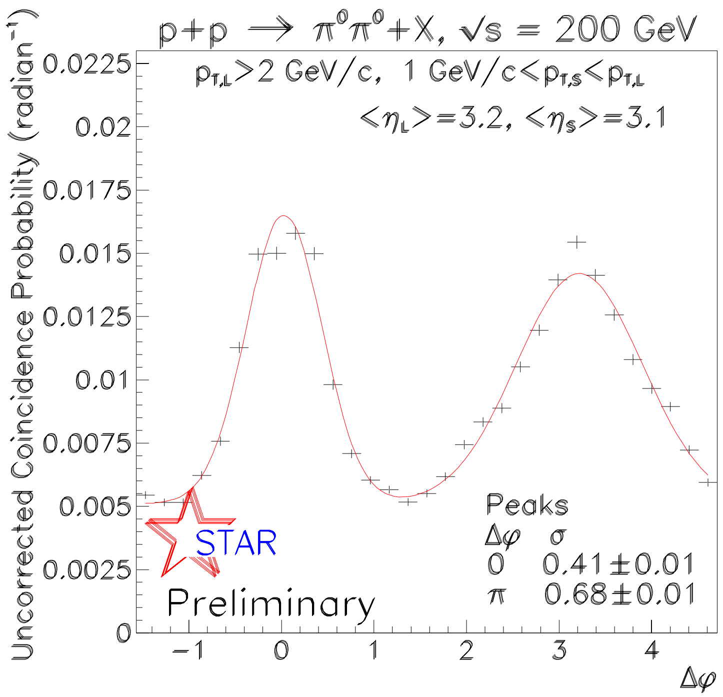
✓ $R_{pA} = 1$ in the absence of nuclear effects, i.e., if incoming parton interact with gluons in the nucleus incoherently as in A protons

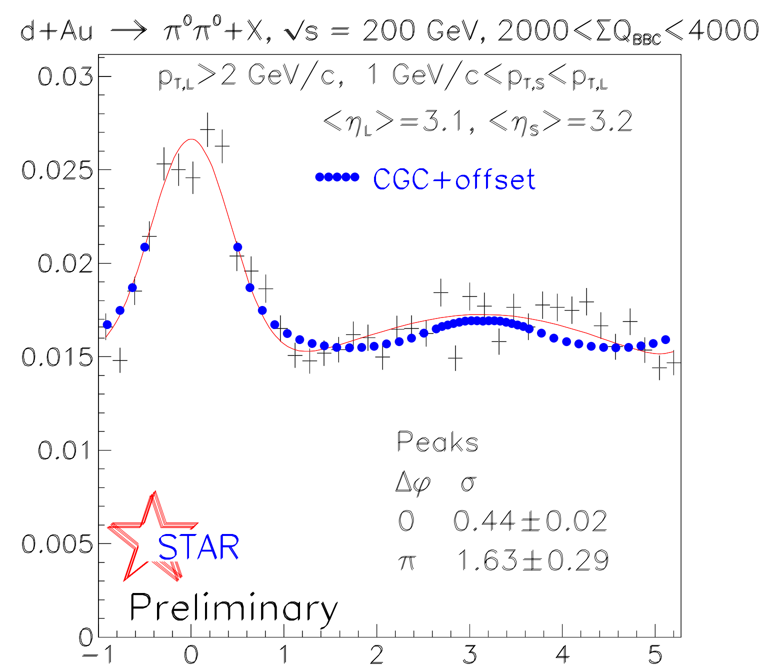
✓ The suppressed production was described in the CGC picture, along with the rapidity dependence

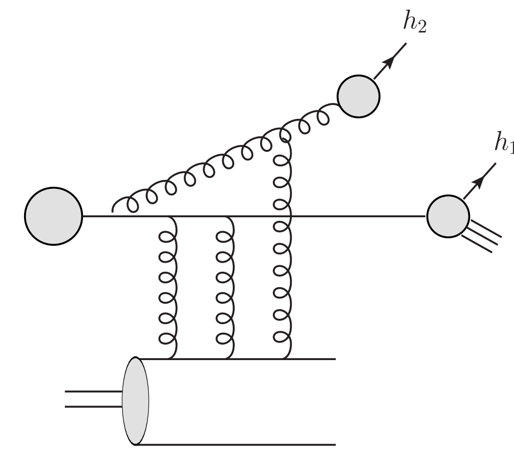
Albacete & Marquet 2010



- Forward-forward dihadron correlation







$$x_g = \frac{p_\perp}{\sqrt{s}}\left(e^{-y_1} + e^{-y_2}\right)$$

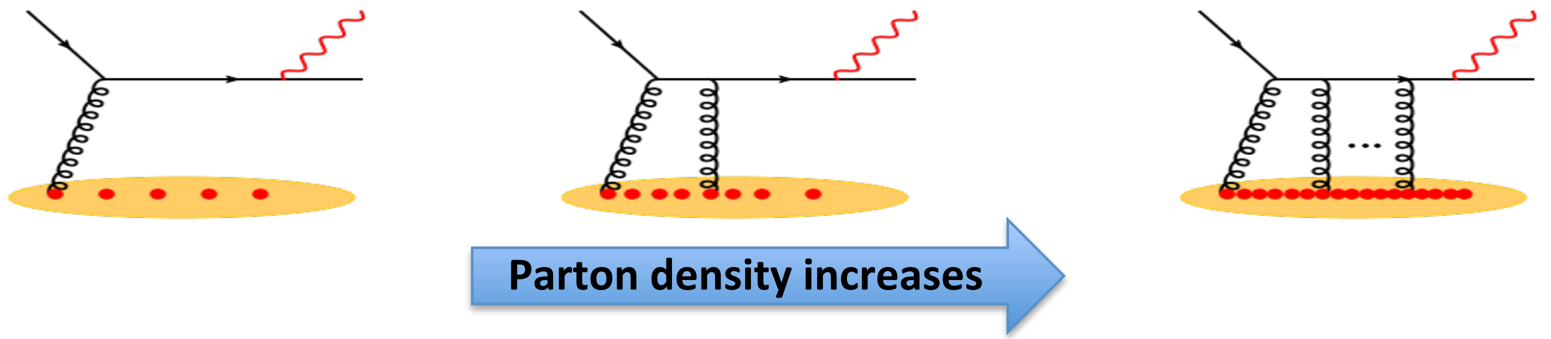
✓p+p: standard 2→2 process, momentum conservation ➡ back to back dihadron

✓p+A: both outgoing partons independently receives a coherent transverse momentum kick, which breaks the back-to-back correlation and thus depletes the angular correlation function around $\Delta\phi = \pi$

✓Experimental data seems to support such a CGC prediction ➡ smoking gun of gluon saturation?

Other approaches: high-twist/multiple scattering expansion

- Include additional scattering order by order through power correction



Qiu & Sterman 1992,
Qiu & Vitev, 03
X.N. Wang, X. Guo, 01
X.N. Wang, Z. Kang, I. Vitev,
H. Xing, 12, 13, 14

Cross section = single-scattering + double-scattering + ...

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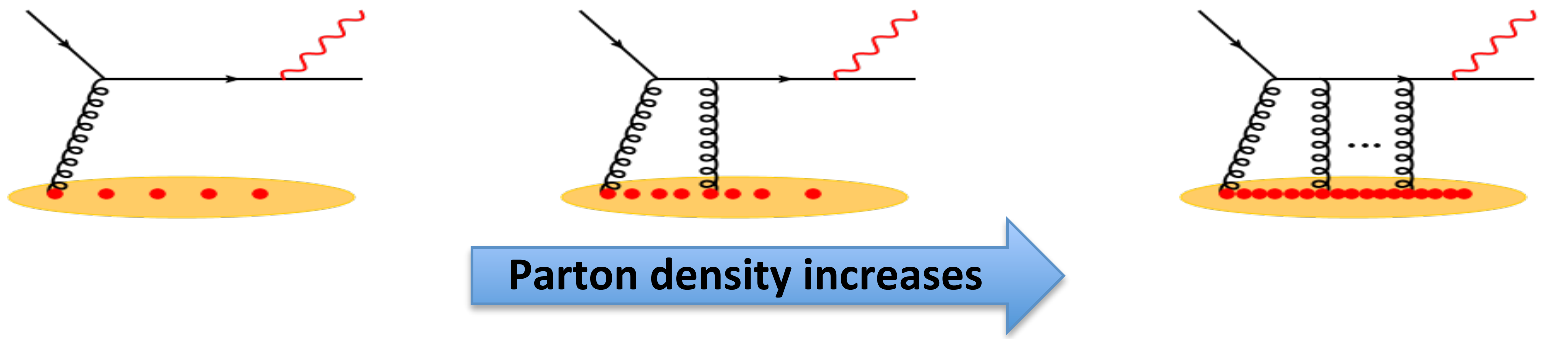

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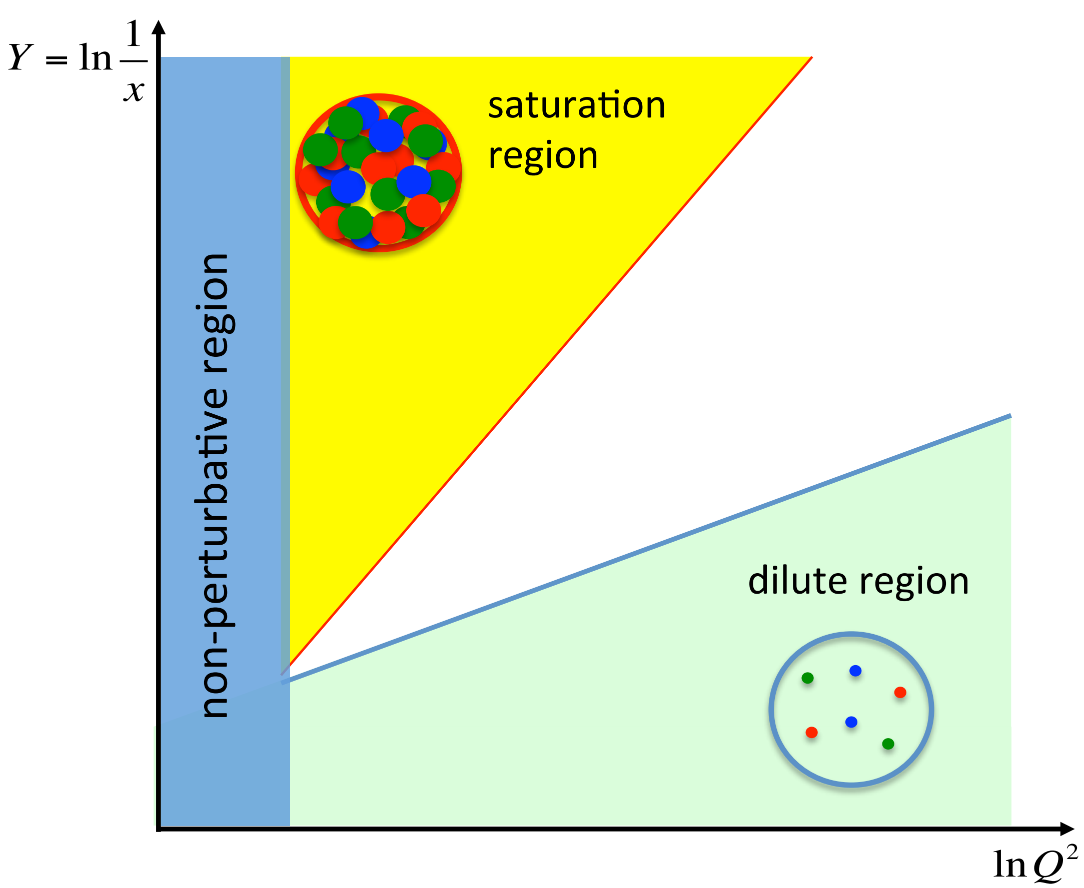
- Dense gluon phase diagram



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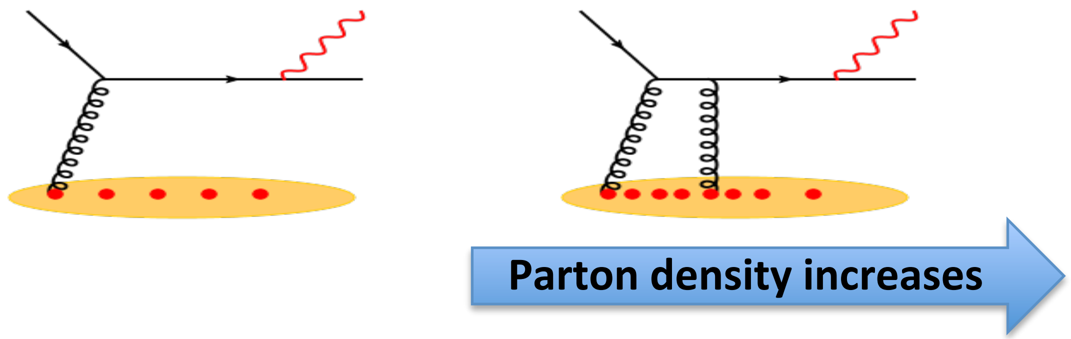

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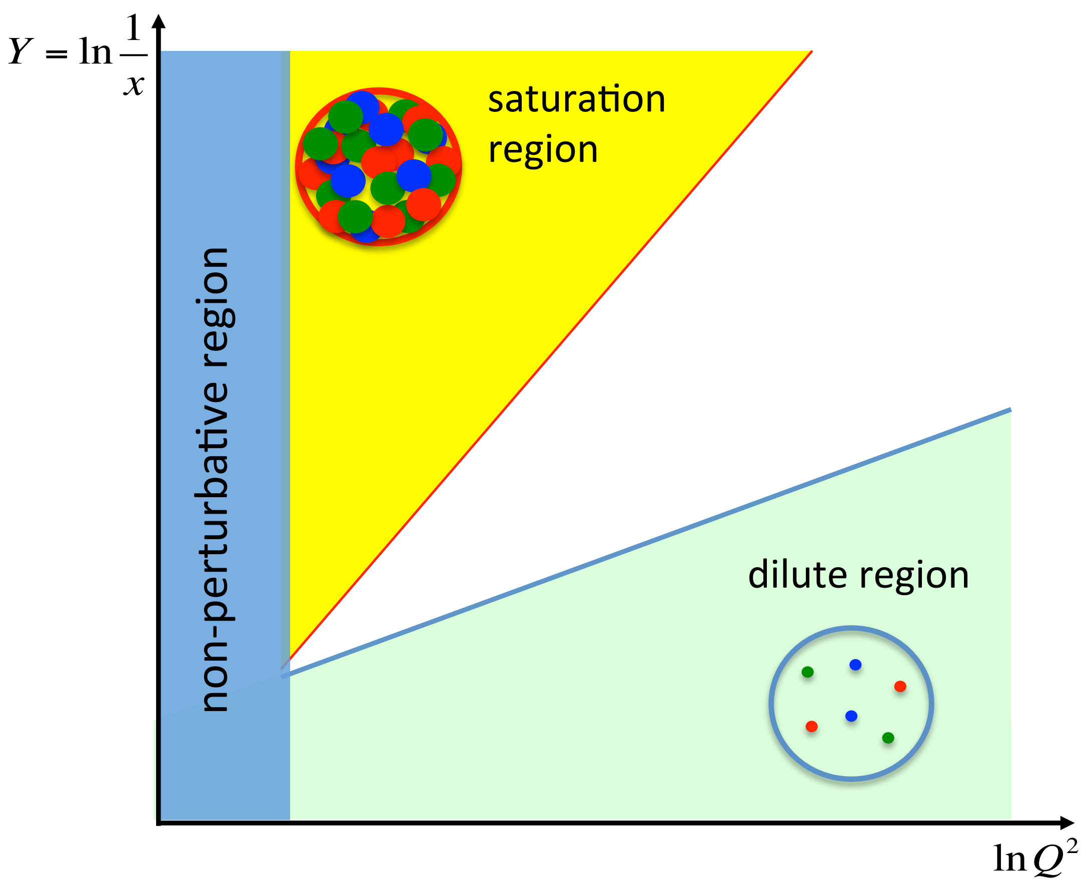

- Dilute: single scattering picture collinear factorization

- Saturation: all the coherent multiple scattering (MS) are equally important resumed to UGD $F(x_g, k_\perp)$ in CGC

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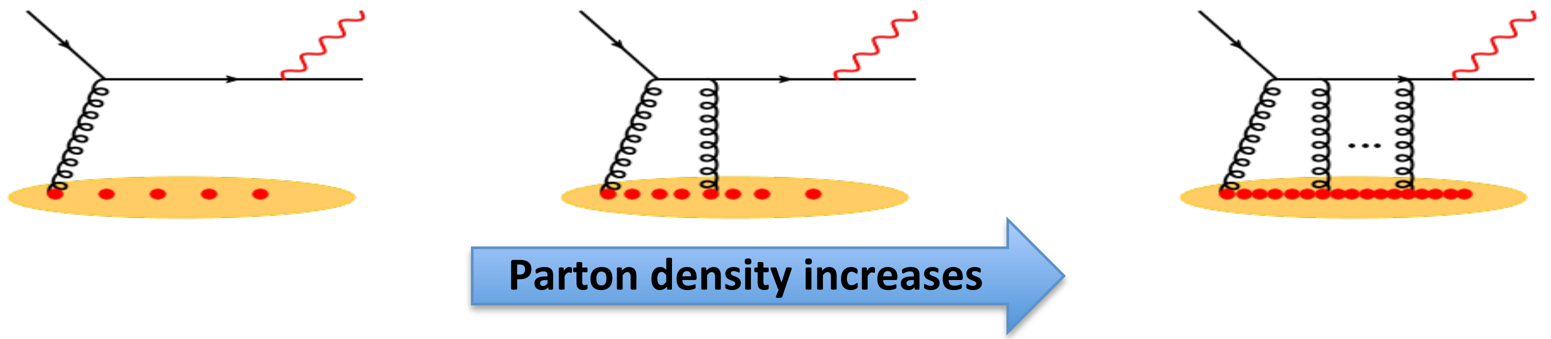

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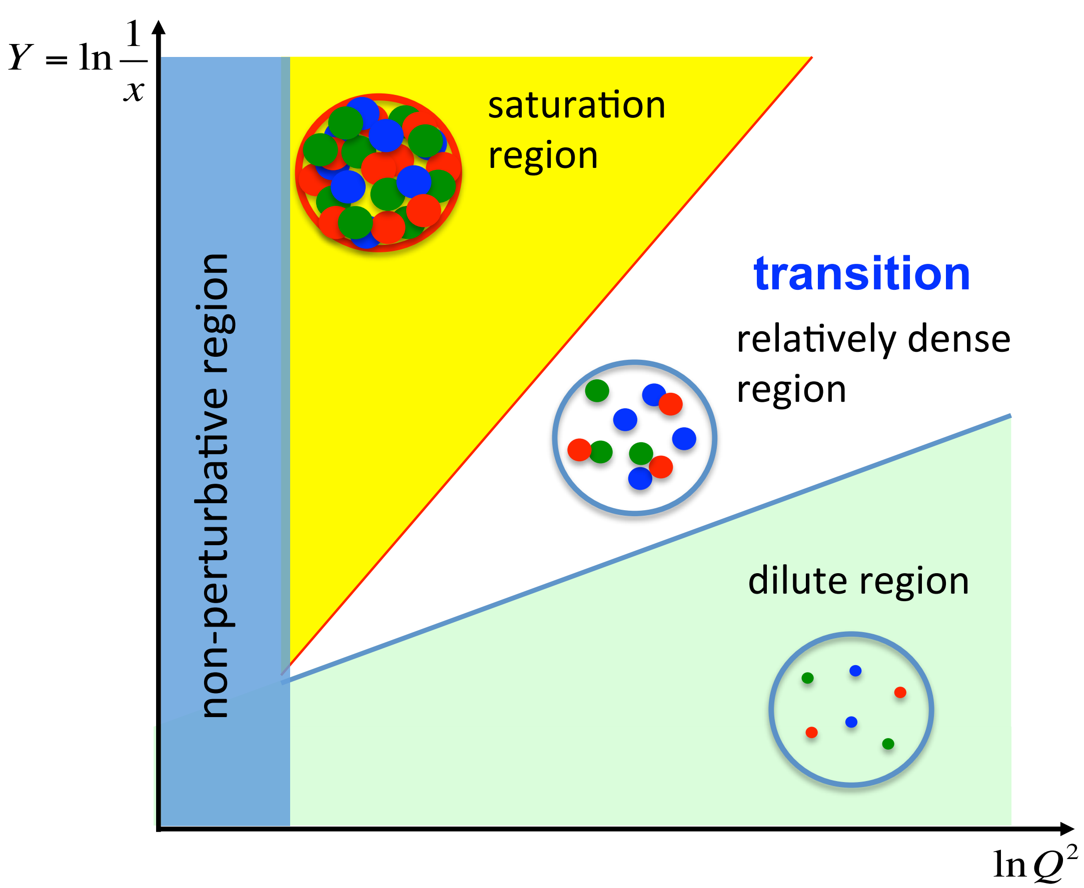

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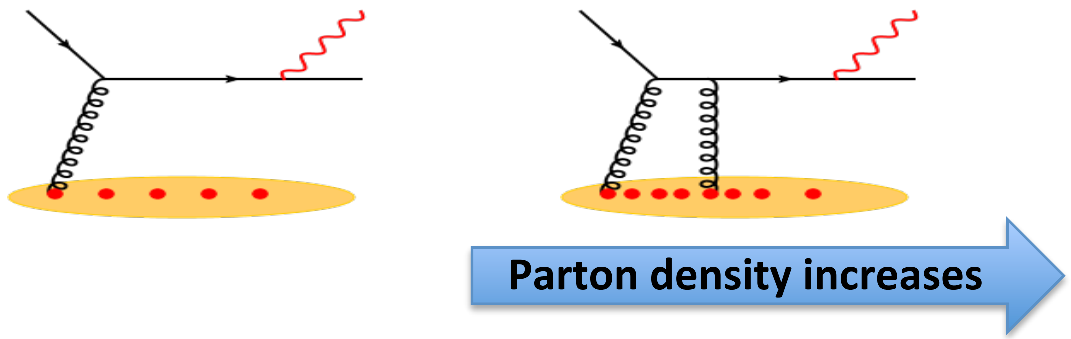

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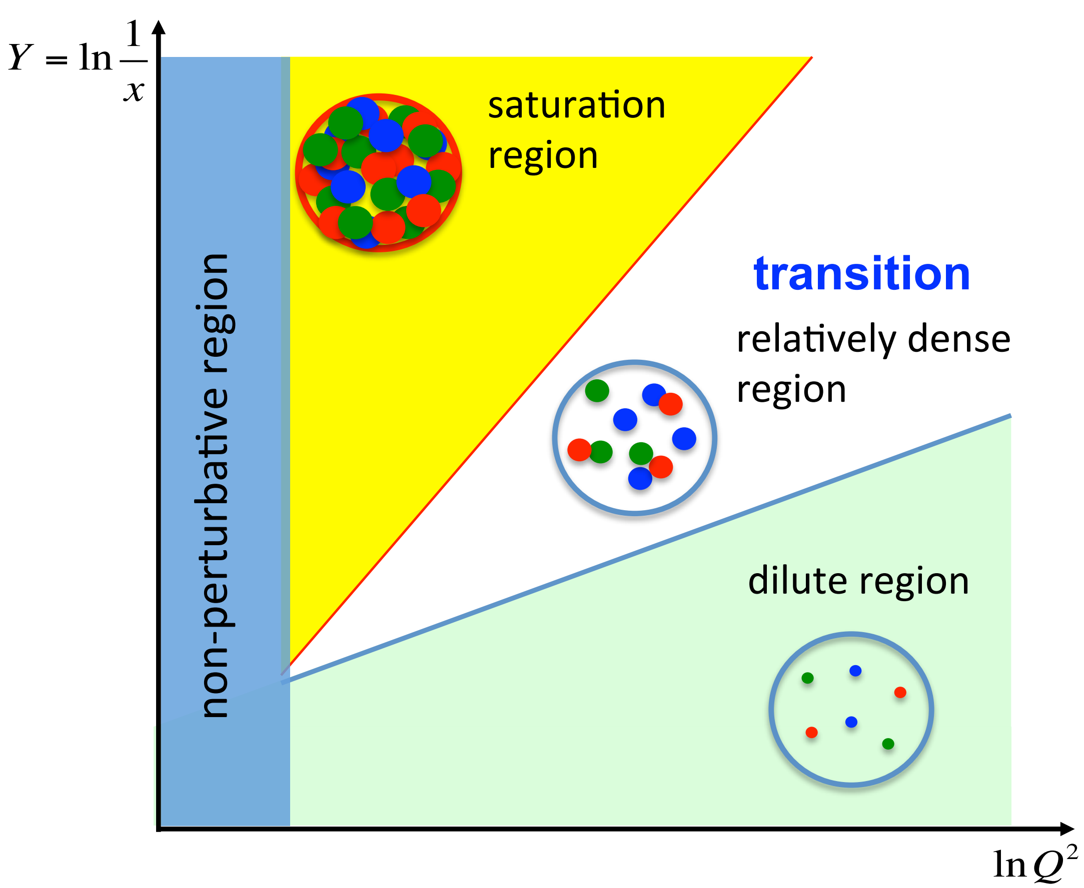


- Dilute: single scattering picture
  collinear factorization

- Saturation: all the coherent multiple scattering (MS) are equally important resumed to UGD $F(x_g, k_\perp)$ in CGC

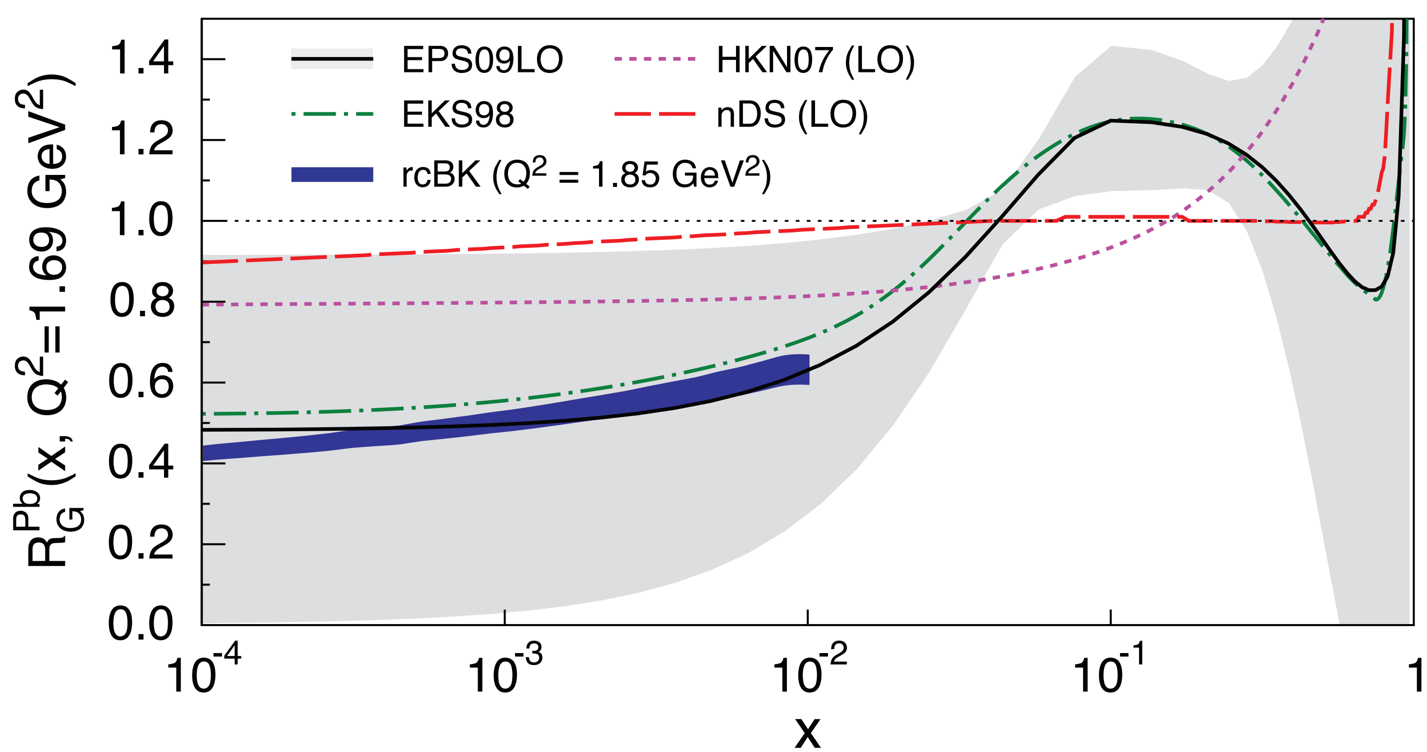
- Relatively dense: coherent MS starts to become important (high-twist)
  - ✓ works when each term is controllable
  - ✓ fails when all terms are equally important

Other approaches: nuclear PDFs

$$\sigma \propto \phi_p(x_a, Q^2) \otimes \phi_A(x_b, Q^2) \otimes \hat{\sigma}_{ab\to\gamma/\text{jet},\cdots}$$

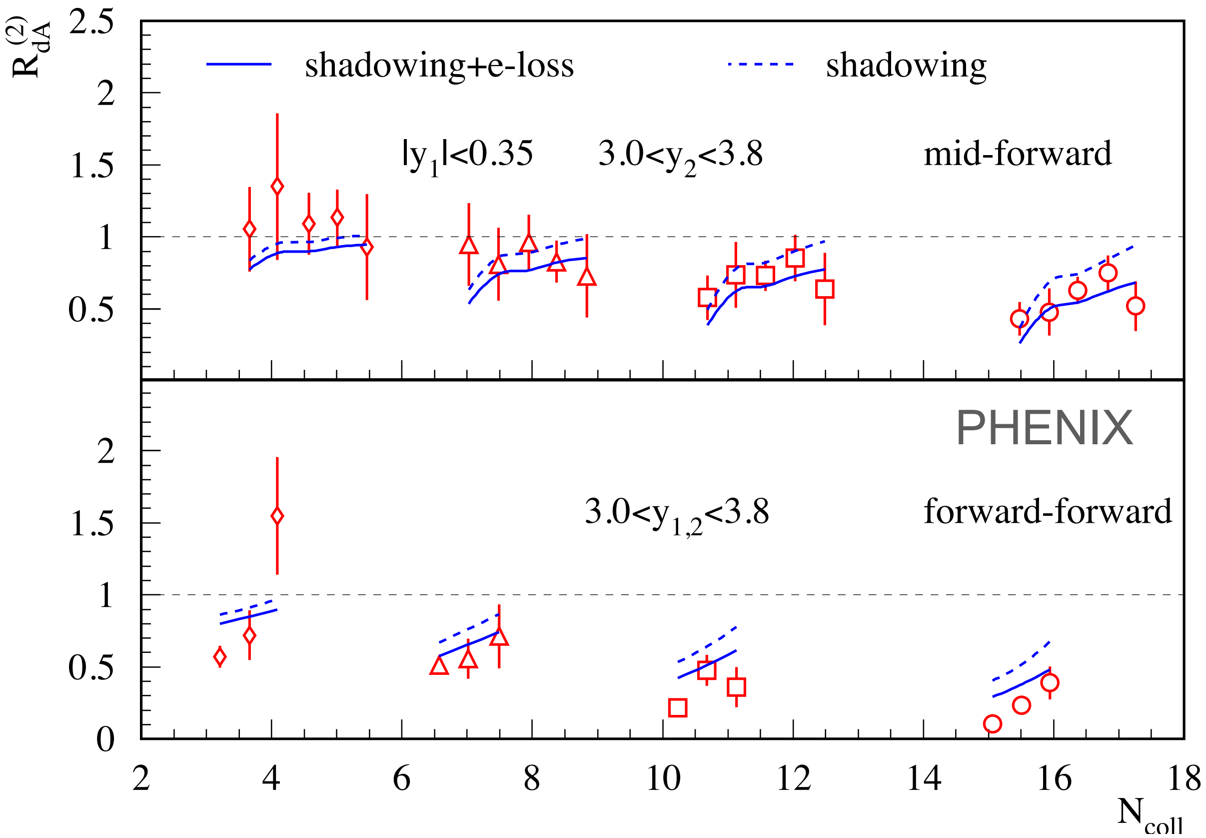
- Nuclear PDFs (nPDFs)
  - Include all the nuclear dependence within a universal nPDFs
  - Still the standard independent/incoherent single scattering
  - nPDFs follow the standard DGLAP linear evolution

Nuclear PDFs approach = Collinear factorization with a different boundary condition (for nPDFs)

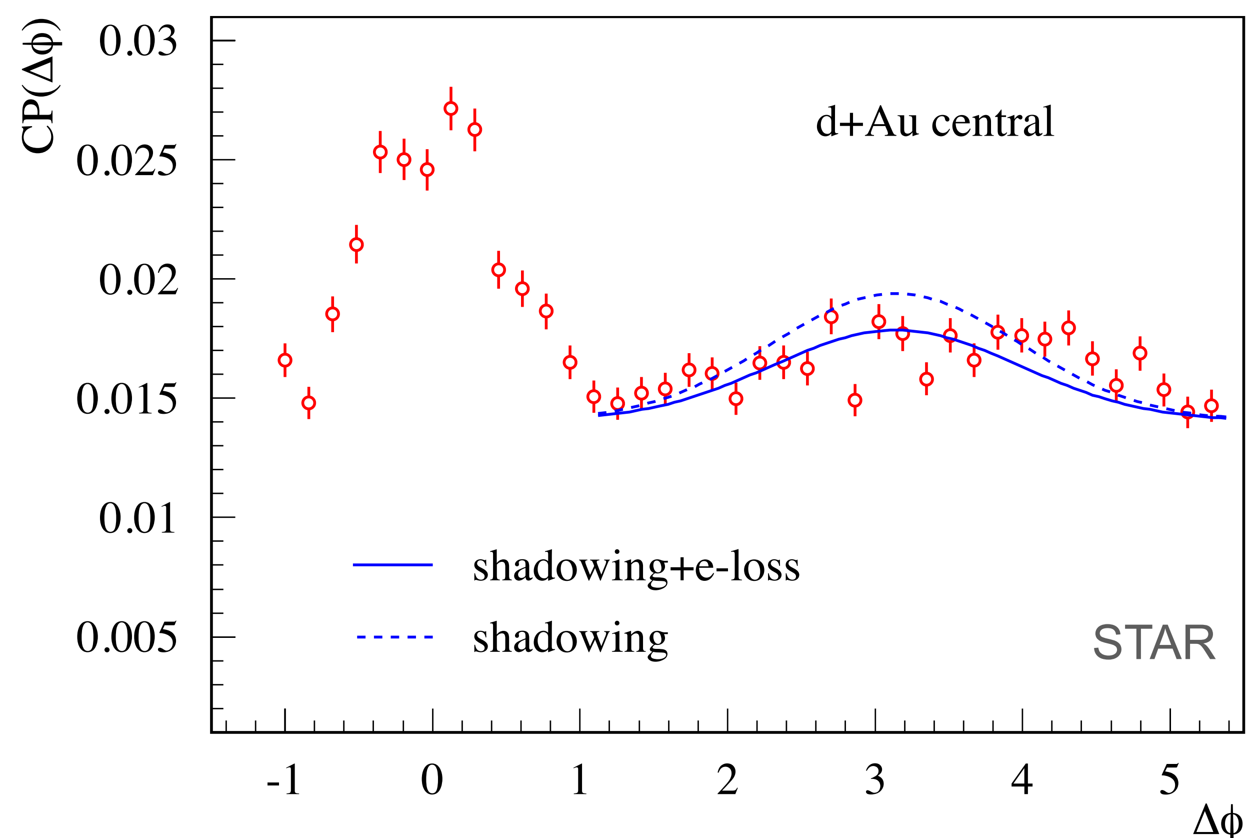


High-twist approach can describe forward suppression

suppression



decorelation

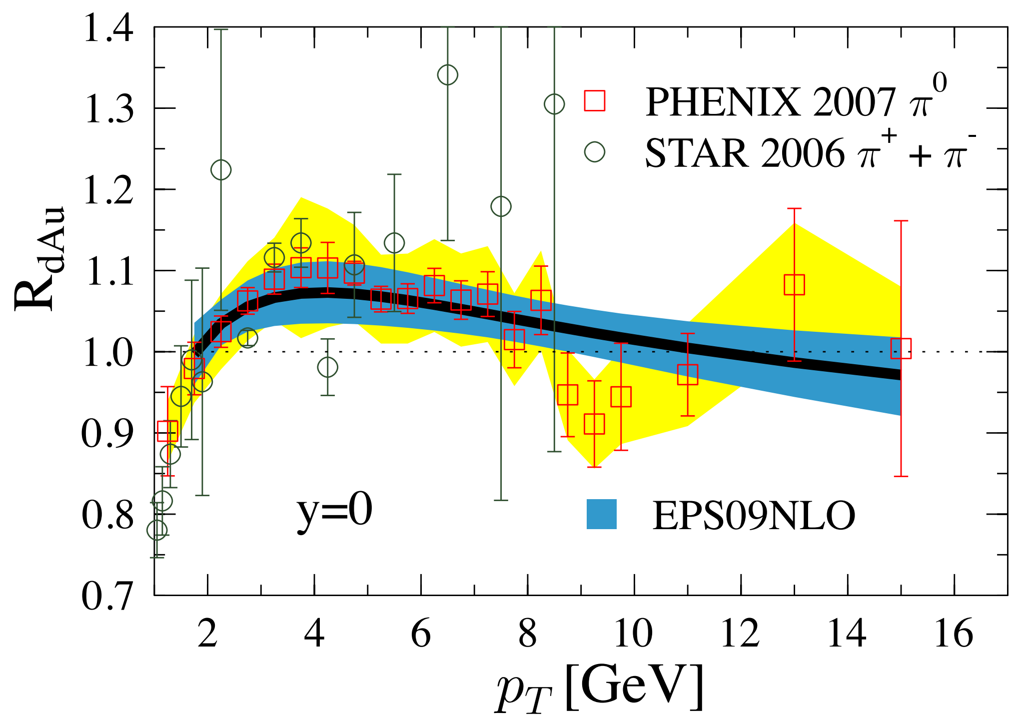


Kang, Vitev, & Xing, 1112.6021
Kang, Vitev & Xing, 1209.6030,
see also earlier Vitev & Qiu, 03, 06

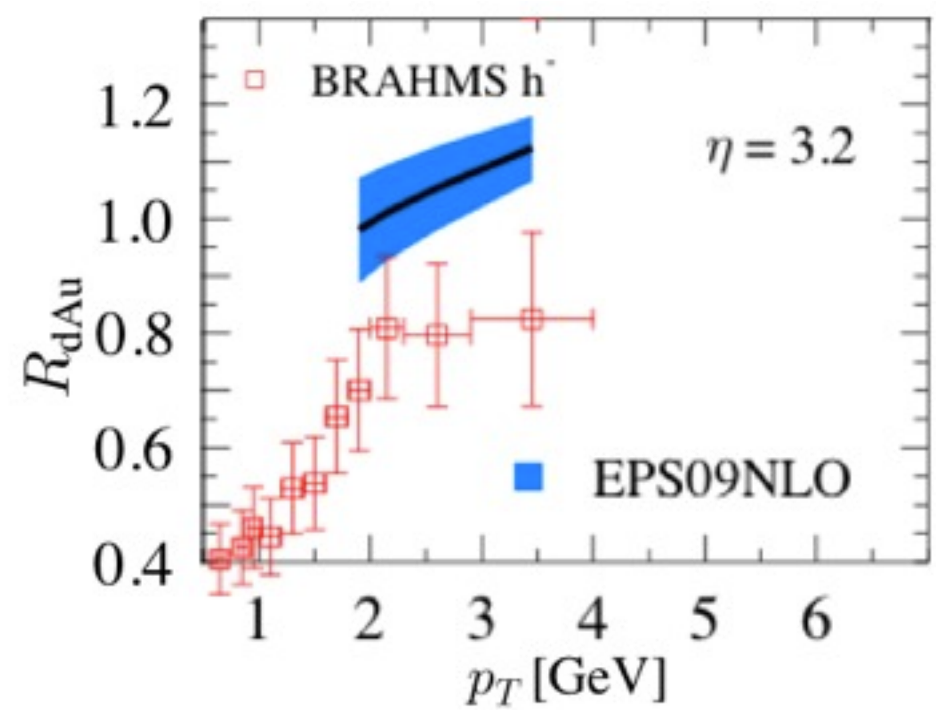
nPDFs: difficulty in describing the forward suppression

- nPDFs approach work rather well for central rapidity Eskola, et.al., 0902.4154

mid-rapidity



forward-rapidity



- A global fitting including the forward suppression data is possible, but resulting in a sizable tension with DIS data Salgado et.al., 1105.3919

Lesson learned:

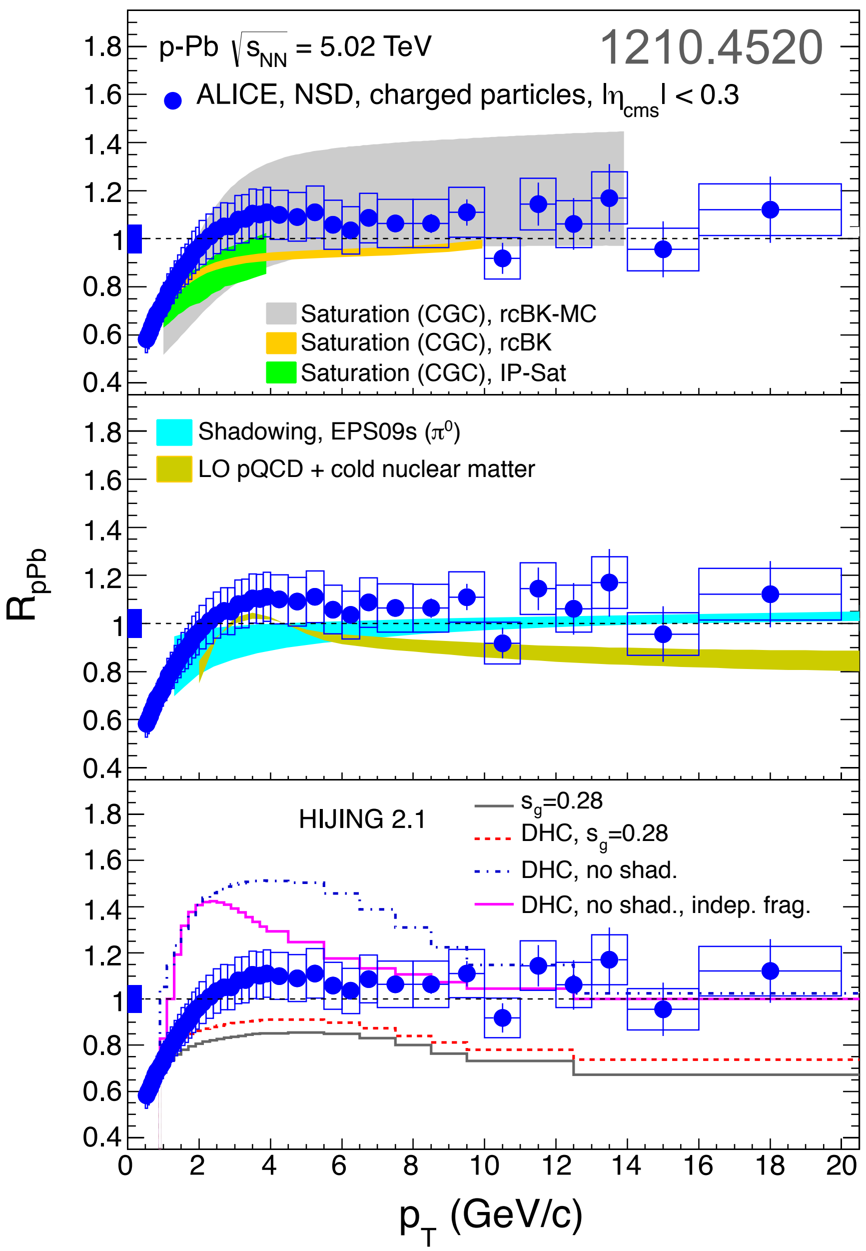
✓Coherent multiple scattering is crucial

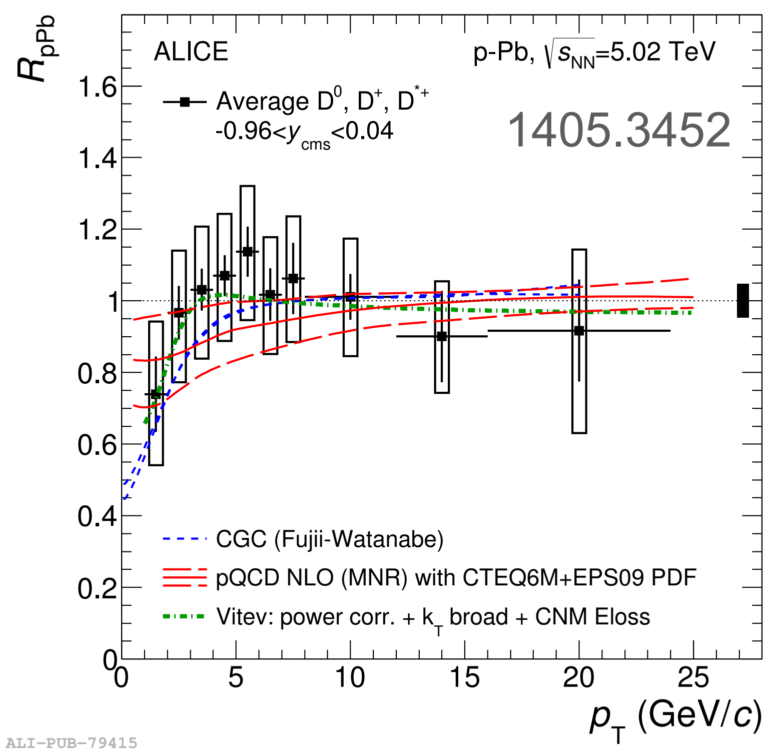
✓At current energy, power corrections are still controllable
➡ transition leading to saturation (onset of gluon saturation)

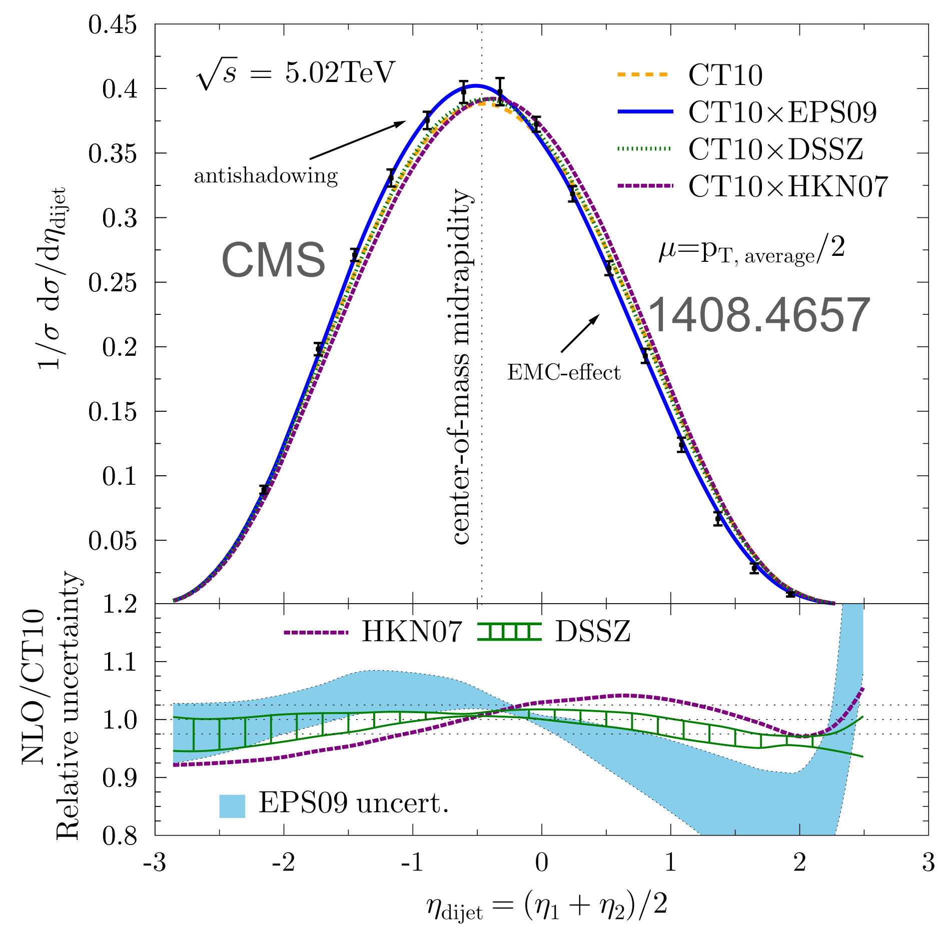
LHC data at mid-rapidity

- At the moment, seems no discriminate power between coherent scattering models and nPDF model

$$R_{pA} \approx 1$$







relevant x_g is not smaller than RHIC forward, looking forward to LHC at forward rapidity

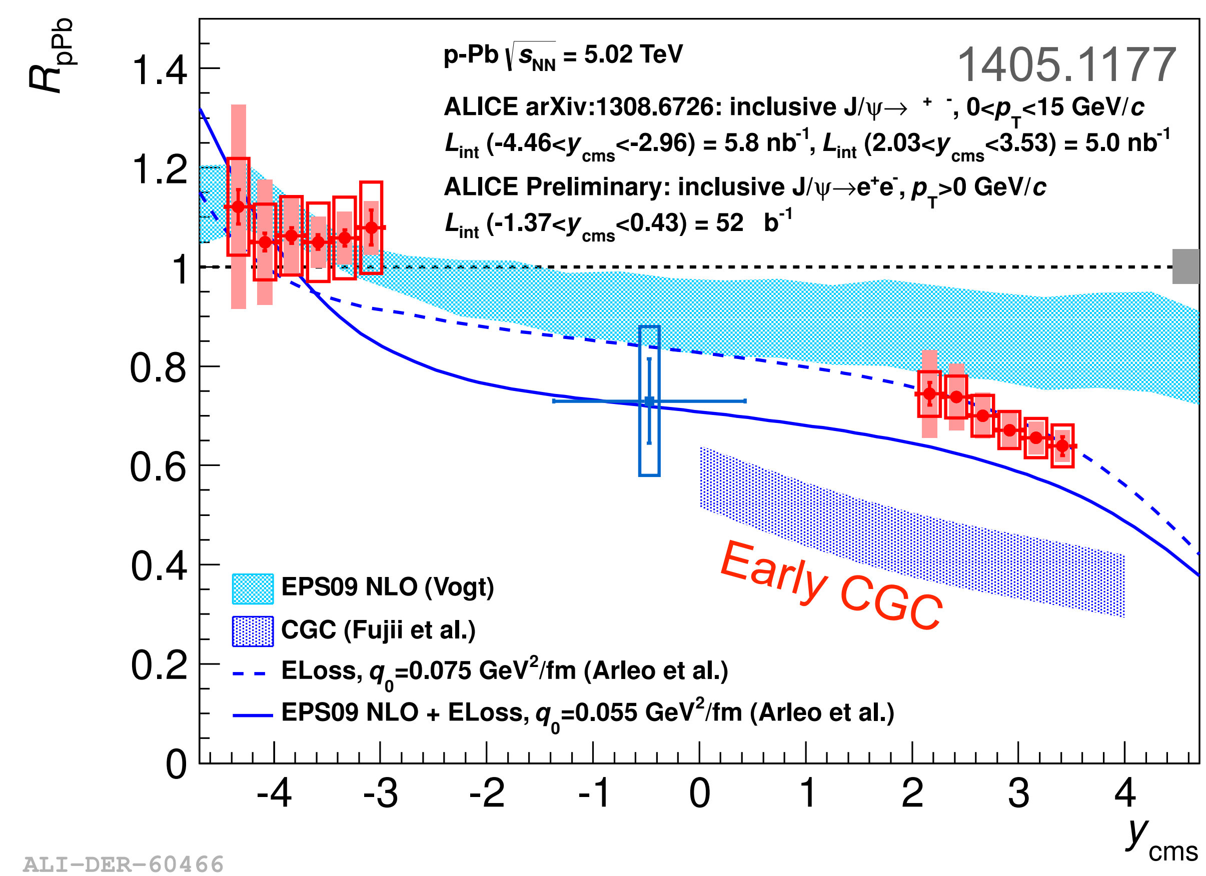
LHC p+Pb collisions at forward rapidity

- J/ψ production at forward rapidity at LHC: shows strong suppression

  ✓Earlier CGC model seems not to be working well: used color evaporation model

  ✓New CGC calculation has been developed recently: full small-x evolution + NRQCD

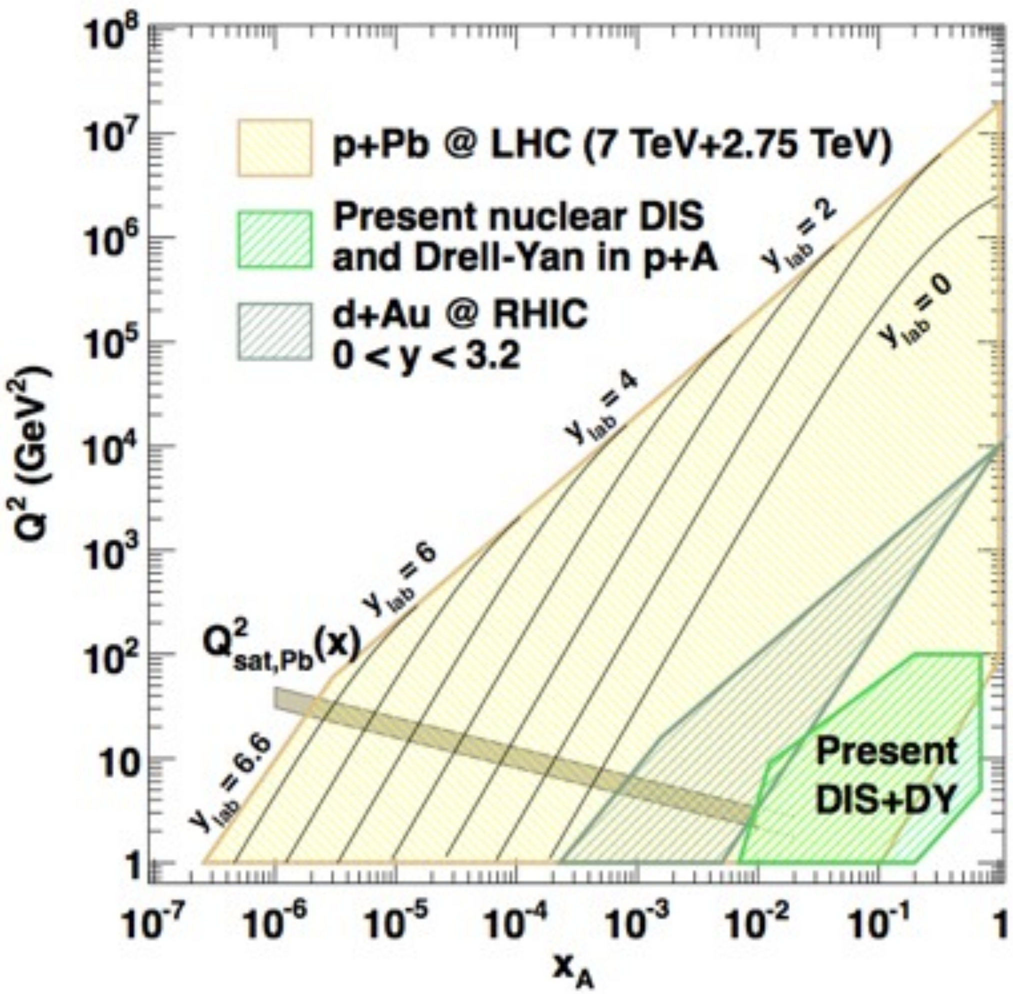
  Kang-Ma-Venugopalan, 1309.7337
  Qiu-Sun-Xiao-Yuan, 1310.2230



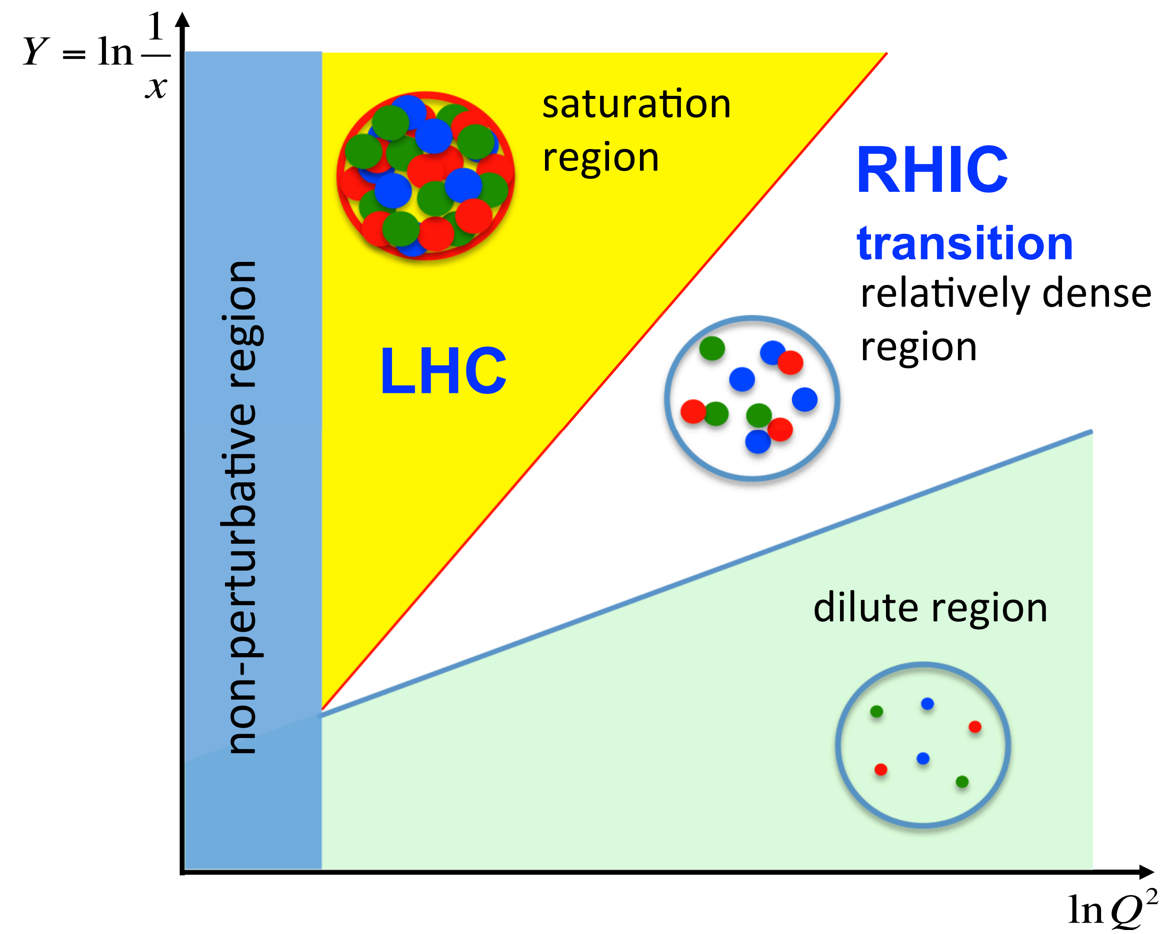
LHCb has similar forward rapidity result

- Inconsistency with model always provide new opportunities

RHIC and LHC: complementarity



Salgado, Hard Probe 2012

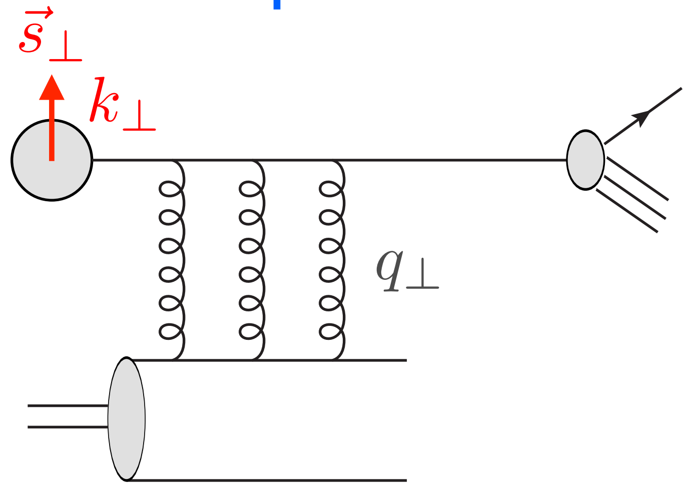


RHIC is sitting at the sweet spot ➡ sensitive to transition region
LHC at forward rapidity hopefully to be deep inside the saturation region

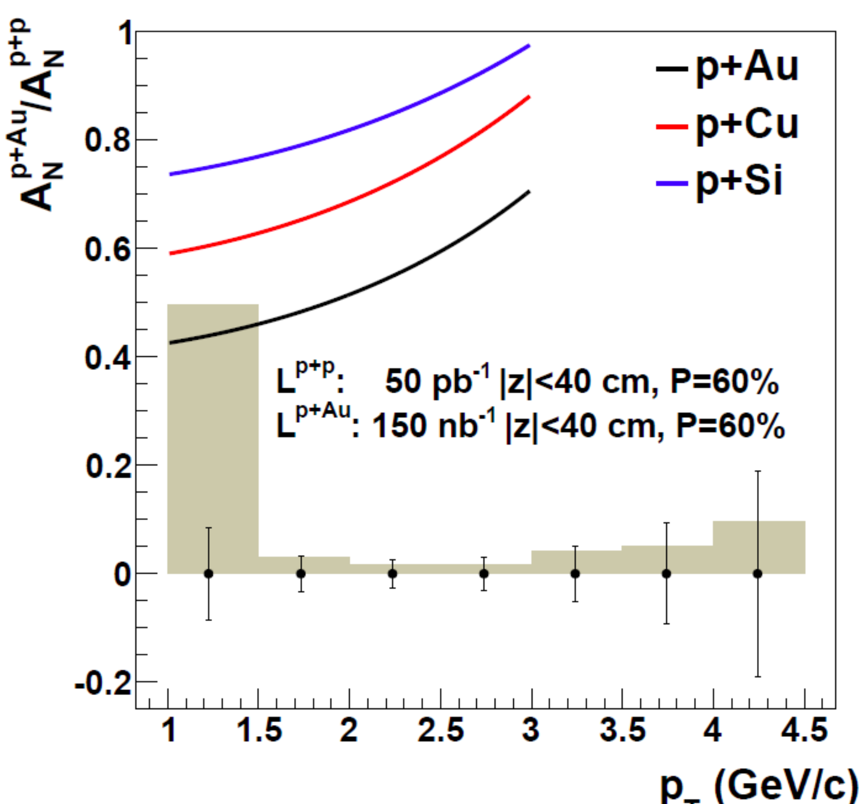
Other points: RHIC can study A-dependence, dilute-dense vs dense-dense ...

A unique new opportunity at RHIC

- Polarized p+A collisions



Kang & Yuan, 1106.1375
Kovchegov & Sievert, 1201.5890
Kang & Xiao, 1212.4809



✓Take advantage of large single spin asymmetry A_N in forward region

talk by E.C. Aschenauer

✓A_N is an azimuthal effect, spin-dependent function is $k_\perp$-odd function

✓Thus A_N will pick up the slope of the gluon distribution in momentum space, which is controlled by saturation scale

$$A_N \propto \frac{dF(x_g, q_\perp)}{dq_\perp} \sim 1/Q_s$$

$$\left.\frac{A_N^{pA\to h}}{A_N^{pp\to h}}\right|_{p_T^2 \lesssim Q_s^2} \approx \frac{Q_{s,p}^2}{Q_{s,A}^2} \qquad \left.\frac{A_N^{pA\to h}}{A_N^{pp\to h}}\right|_{p_T^2 \gg Q_s^2} = 1$$

Tremendous theoretical progress

- CGC/small-x formalism
  - NLO nonlinear evolution and solution

    NLO BK: Balitsky & Chirilli 08
    NLO BFKL solution: Chirilli & Kovchegov 13
    NLLx B-JIMWLK: Kovner, Lublinsky, Mulian 13, Caron-Huot, Balitsky, Chirilli
    Full B-JIMWLK solution: Dumitru, Jalilian-Marian, Lappi, Schenke & Venugopalan 11, Alvioli, Soyez & Triantafyllopoulos 13
  - NLO correction for production processes

    DIS: Balitsky & Chirilli 11, 13, G. Beuf 12, ...
    single hadron in pA: Chirilli, Xiao & Yuan 12, Altinoluk & Kovner 11, Kang, Vitev & Xing 14, ...
    nucleus-nucleus collisions: Gelis, Lappi & Venugopalan 08, ...
- High-twist/multiple scattering formalism
  - NLO correction for transverse momentum broadening at both e+A and p+A
  - DGLAP type evolution for the relevant multi-parton correlation functions

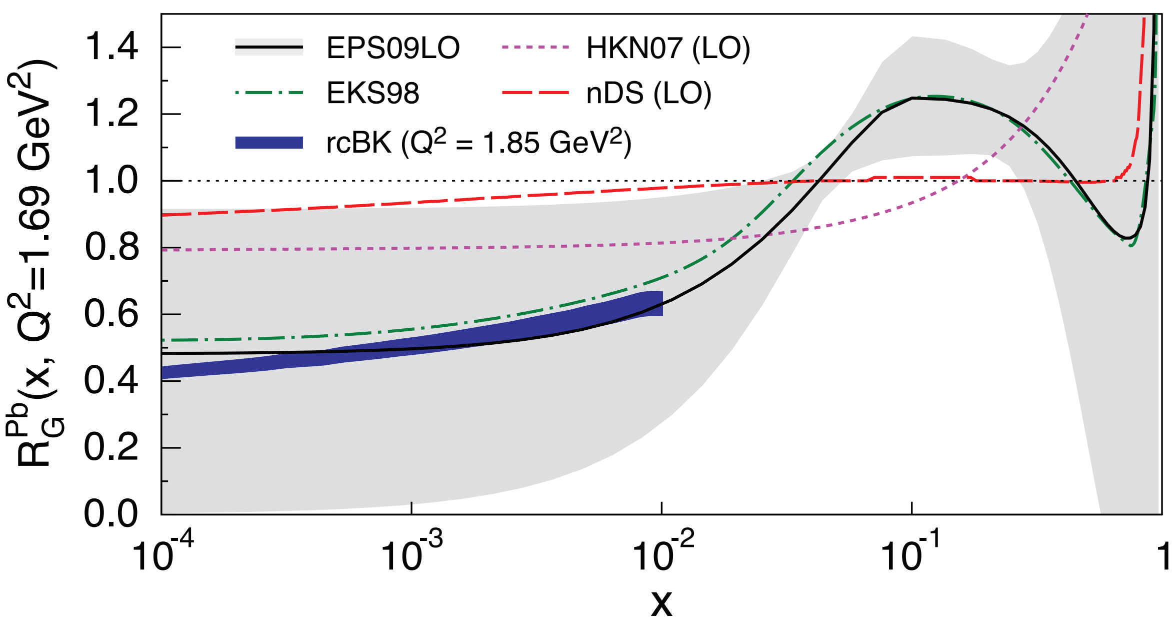
    Z. Kang, X.N. Wang, I. Vitev, E. Wang & H. Xing, 13, 14
- nPDFs approach
  - Full NLO global fitting

    Eskola, Paukkunen, Salgado, et.al., 09, 12
    de Florian, Sassot, Zurita & Stratmann 12
  - nPDFs with impact parameter dependence
- Connection between CGC, high-twist and collinear formalism

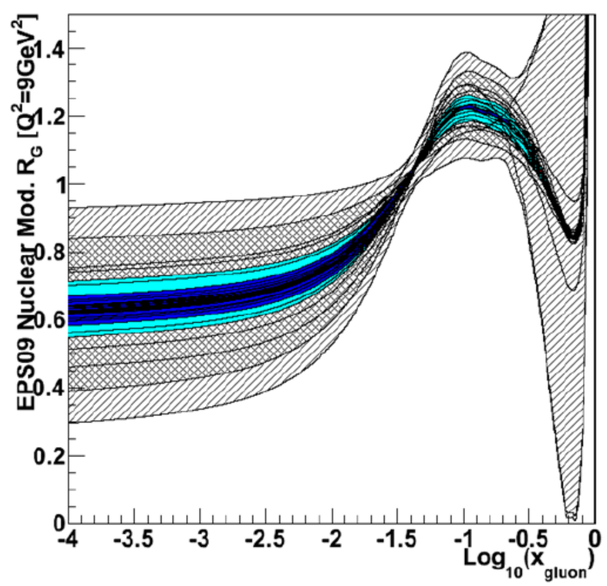
  Kang, Qiu & Xing 13, Ma & Venugopalan 14, Stasto, Xiao, Yuan & Zaslavsky 14

Looking into the future 1

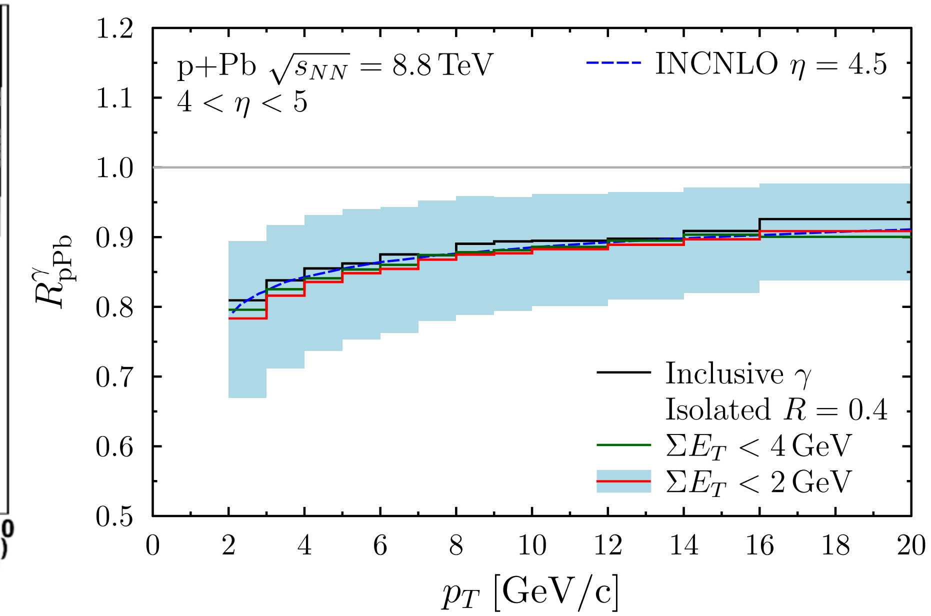
- Improve/constrain each model: hope to discriminate them and lead to the discovery of gluon saturation
- Global analysis of the most important ingredient in each formalism
  - nPDFs
  - CGC approach: dipole, quadrupole gluon correlator
- Nuclear PDFs

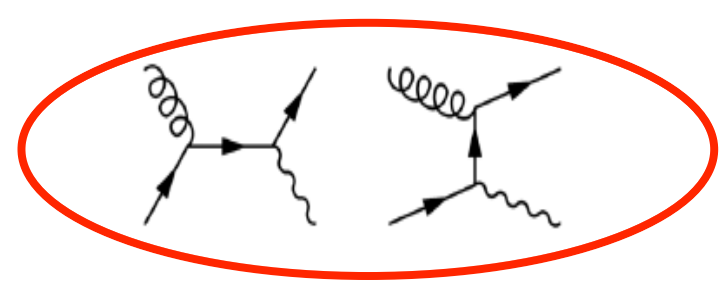


PHENIX, MPC-EX



Helenius, Eskola, Paukkunen, 1406.1689





Looking into the future 2

- Precision study for small-x dynamics: global analysis

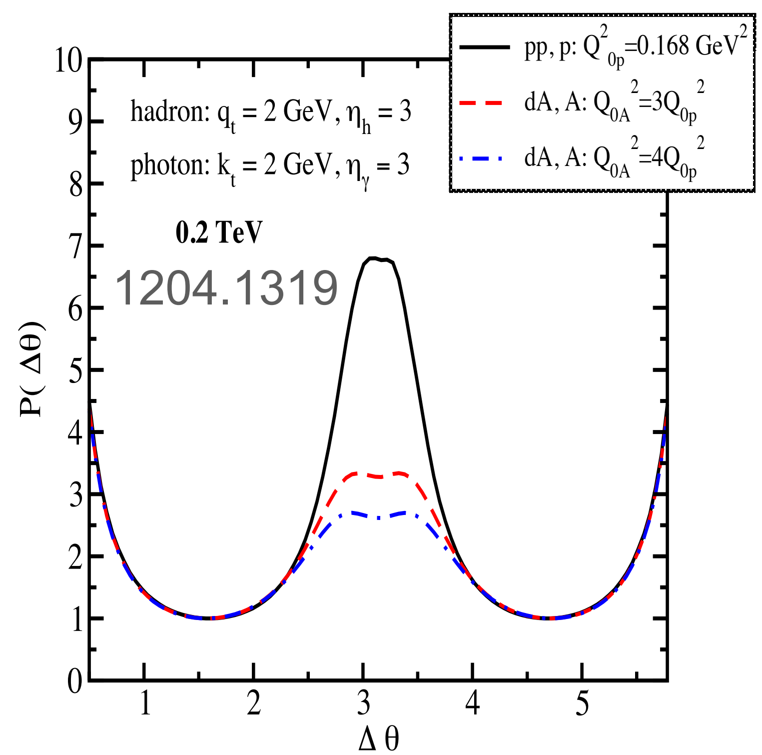
F(x, k_T) parameterization at initial $x=x_0$ → Evolution equation: *F(x, k_T)* at different x → Theory compare with experimental data → Fit parameters in *F(x, k_T)*: extraction of *F(x, k_T)*

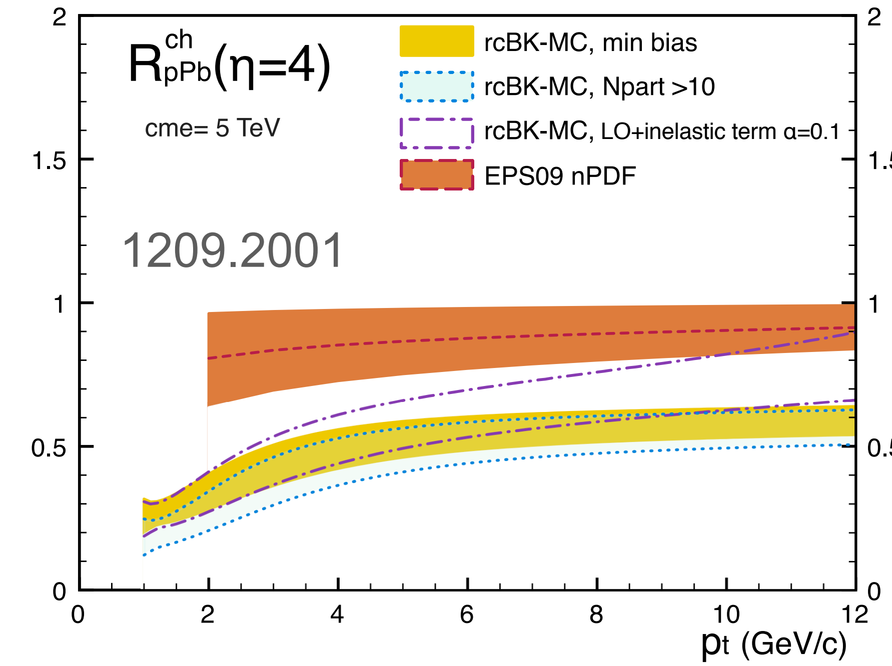
- What are needed?

Example prediction

dipole gluon distribution
✓Single hadron
✓Direct photon
✓photon + Jet (hadron)
✓Drell-Yan (DY)
✓DY + Jet (hadron)

dipole + quadrupole
✓dihadron
✓dijet, hadron + Jet
✓J/ψ, Υ





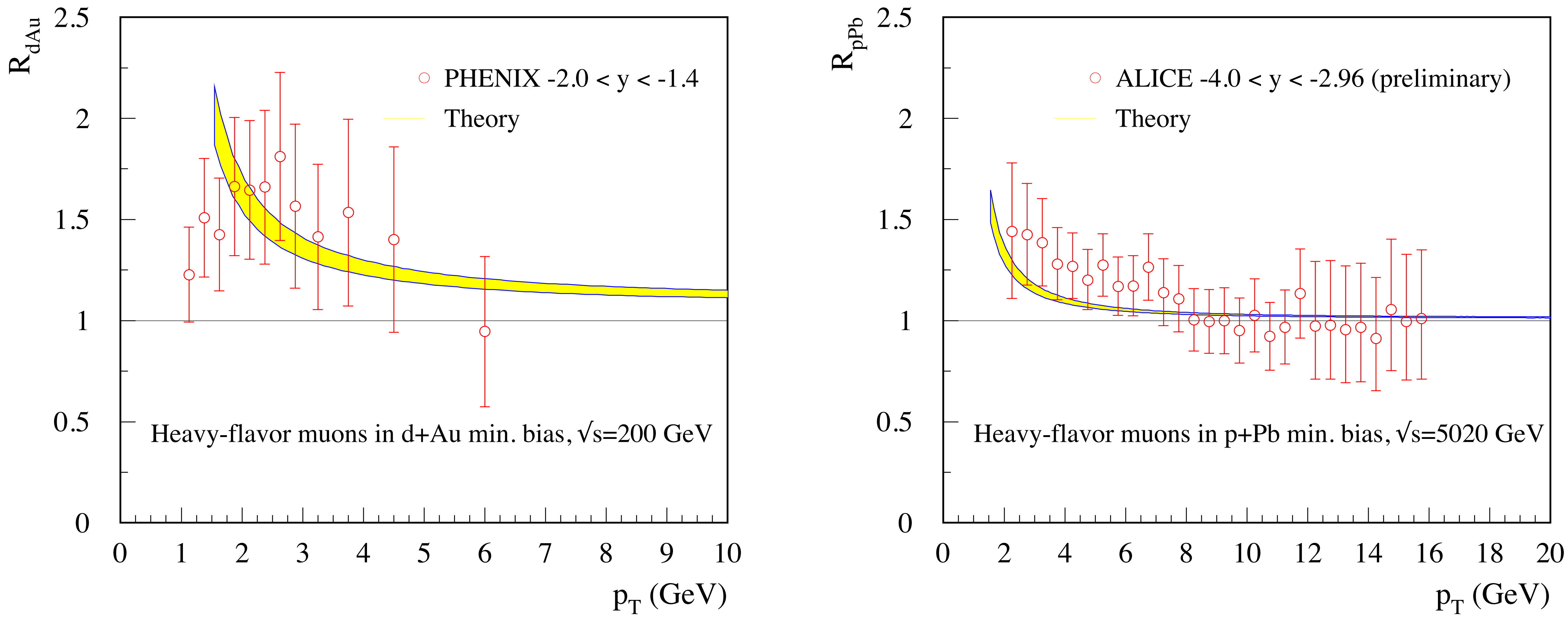
Other opportunities

- Backward rapidity region

  parton momentum fraction x is relatively large in the nucleus

  outside small x region: incoherent multiple scattering region

  Kang, Vitev, Xing, et.al., 1307.3557, 1409.2494

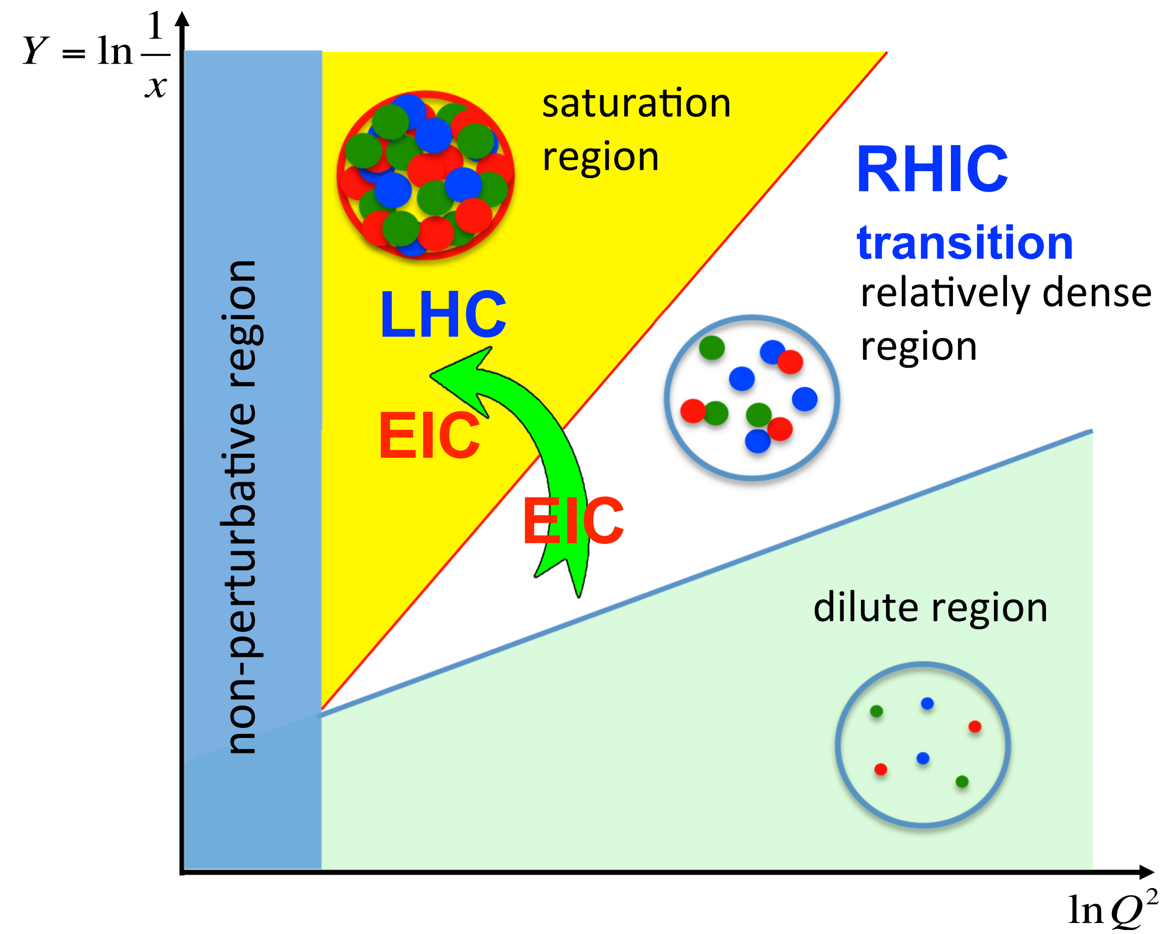


- Cold nuclear matter (CNM) energy loss talks by Y. Kovchegov and T. Ullrich

  radiation length, transport properties, ...

Future Electron Ion Collider (EIC)

- EIC: The Next QCD Frontier - understanding the glue that binds us all

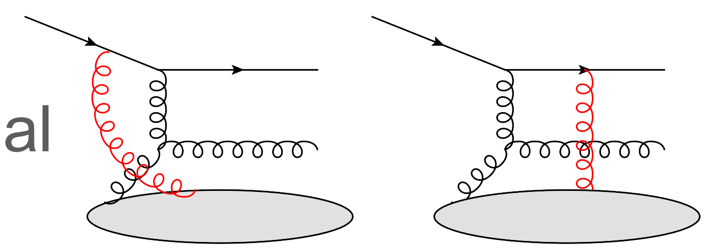


- The unambiguous ultimate proof of existence of saturation and its detailed properties can only come from EIC
  - Only DIS allows for the direct, model-independent, determination of the kinematics, such as x and Q^2
  - Electron: point like and structureless; Proton: also a complicated object

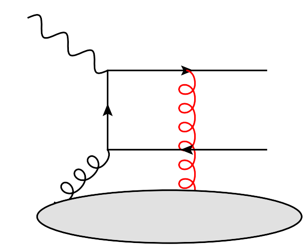
Each piece gives unique information

- Need both p+A and e+A for a full understanding of the QCD dynamics at high energy
  - Each process/observable has its own unique QCD dynamics - dynamics is process-dependent

pA: initial+final



DIS: final



  - If the theory of factorization is correct, the associated gluon distribution function (dipole and quadrupole) should be universal
  - It is important to test the process-dependence of the QCD dynamics and the universality of the gluon distribution (along with the detailed small-x evolution)

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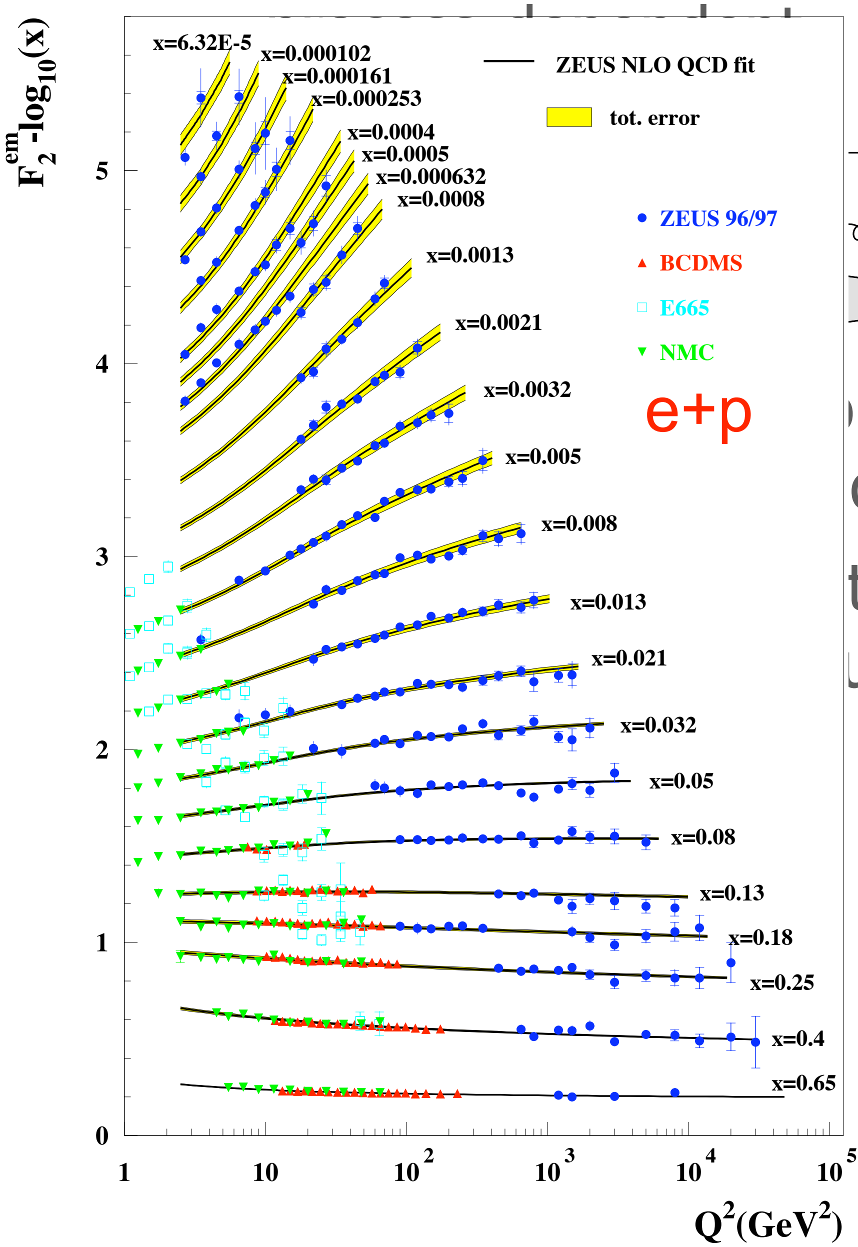

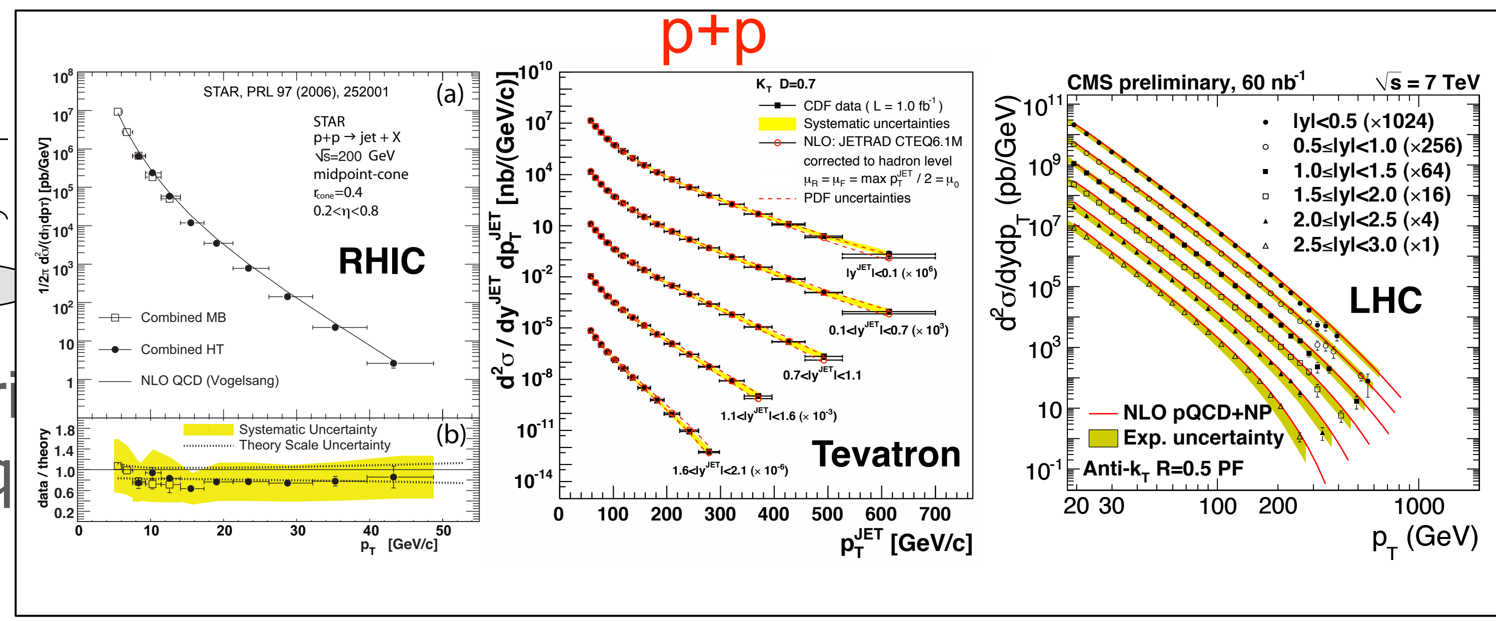

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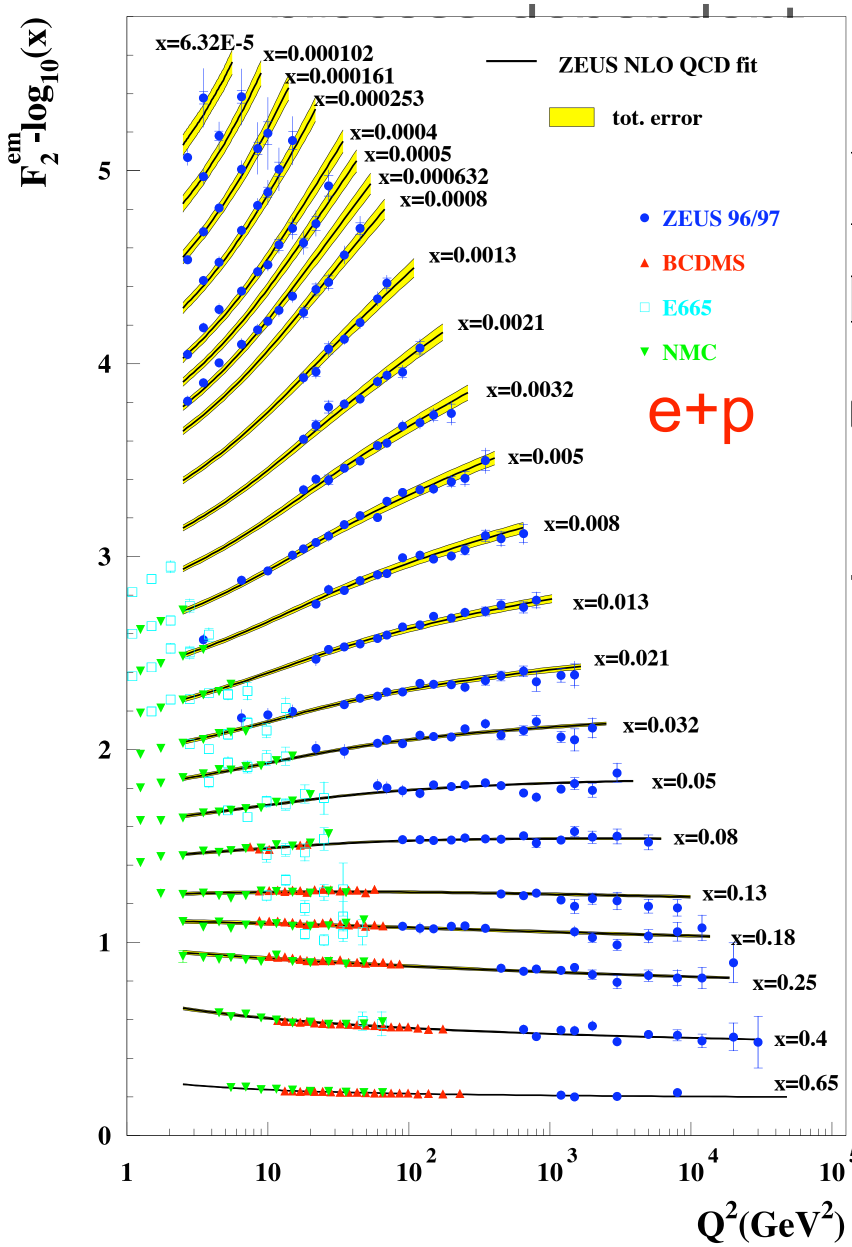
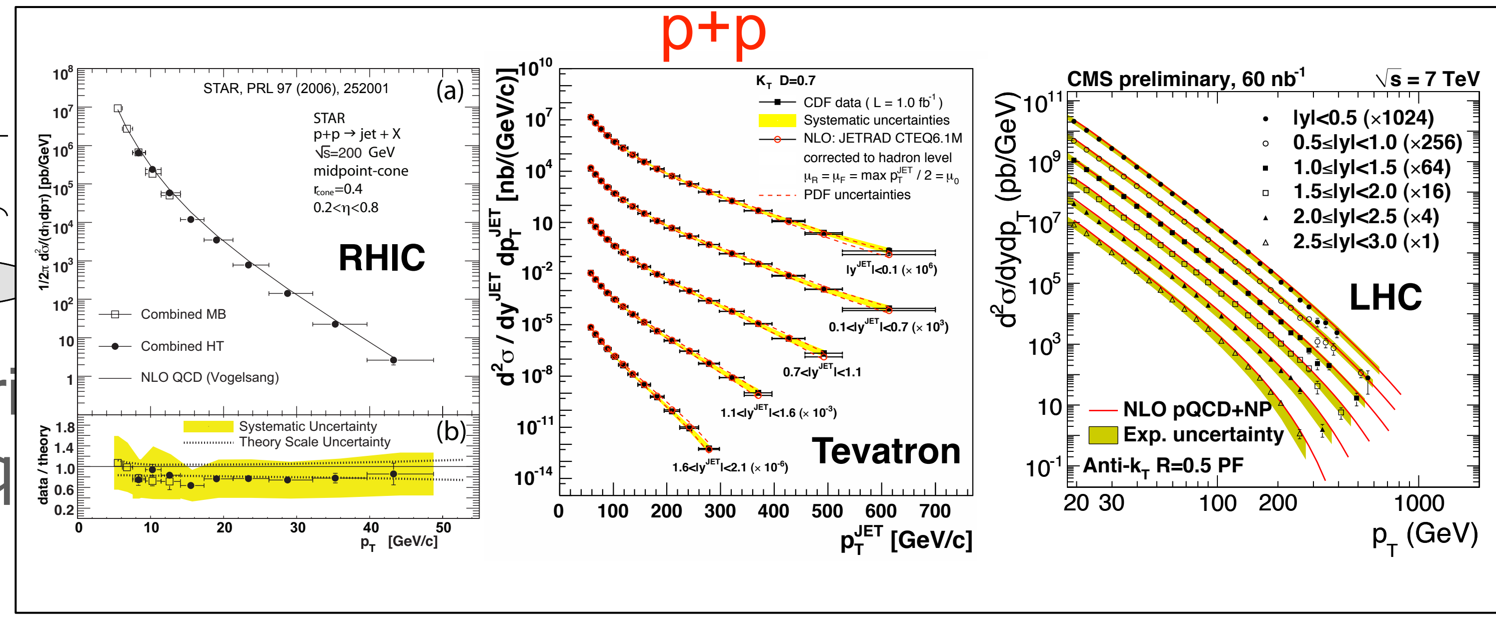
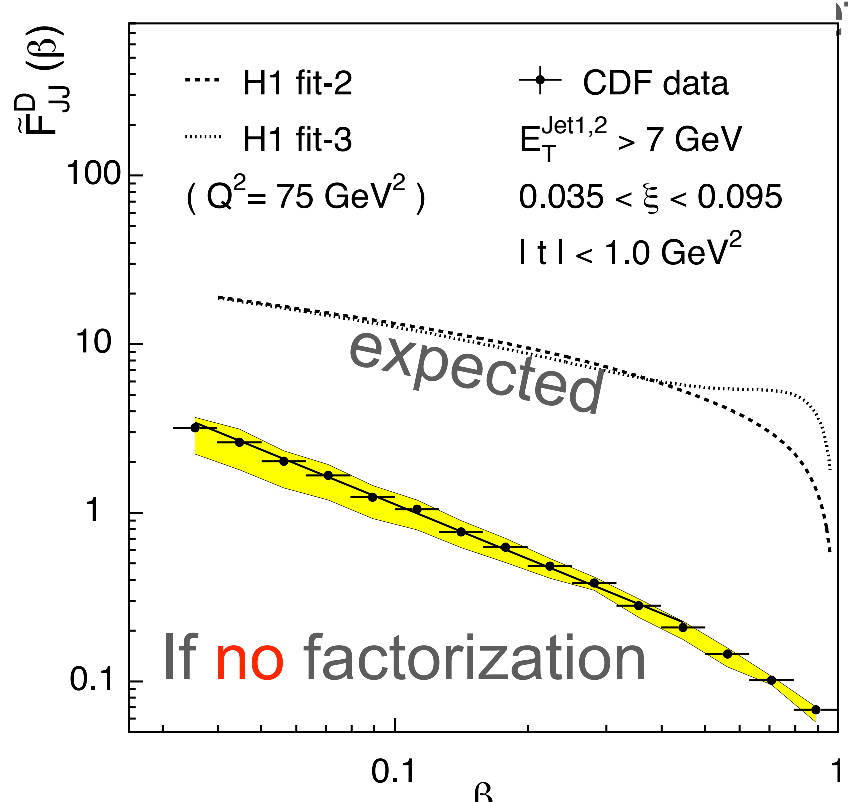




tailed small-x evolution)



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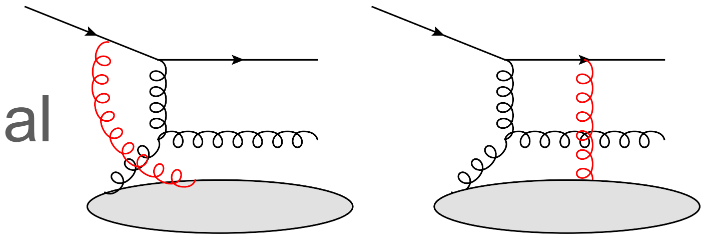

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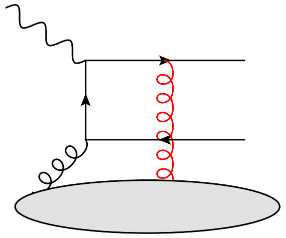

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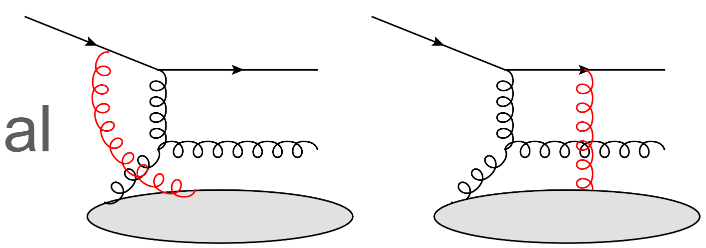

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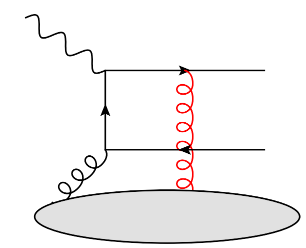

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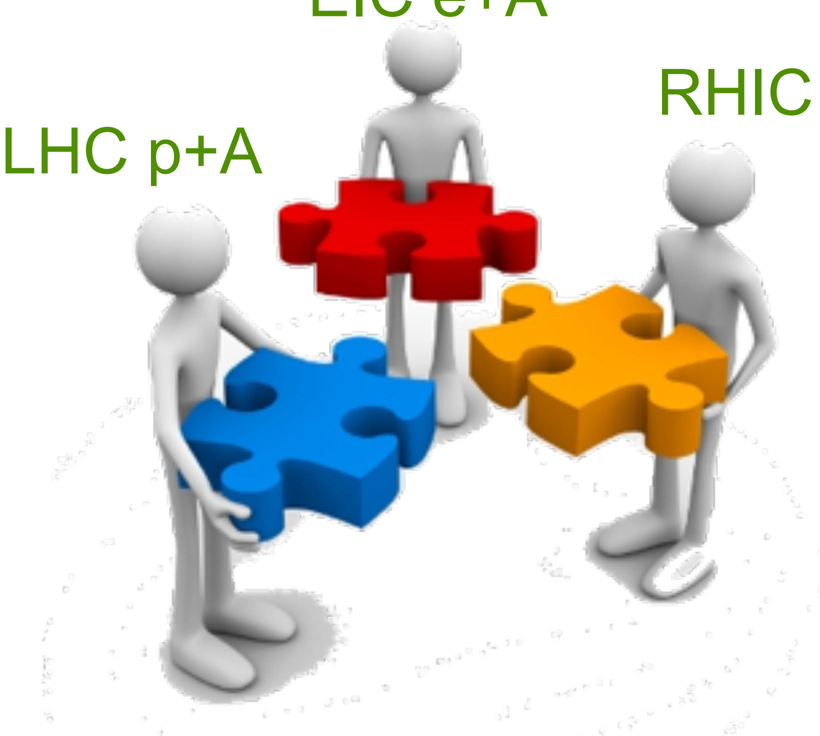
EIC e+A

LHC p+A

RHIC p+A



EIC e+A

EIC: seal the case for gluon saturation

Summary

- The study of p+A collisions on its own provides great opportunities
  - The transition from the dilute to dense parton system
  - The small-x gluon dynamics (coherent multiple scattering, small-x evolution) and gluon saturation
  - Incoherent multiple scattering, nuclear PDFs, CNM energy loss ...
- Tremendous progress has been made in promoting each formalism (CGC, high-twist/multiple scattering, nPDFs), and their connections
- RHIC p+A and LHC p+A has great potential
- Ultimately it will be the combination of strong p+A and e+A programs, each providing complementary measurements, that will enable us to obtain a full understanding of the gluon saturation
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Thank you