Small-x physics and gluon saturation

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UCLA

LPC Workshop on Physics Connections between the LHC and EIC
November 13 - 15, 2019

EIC on the horizon

Courtesy of A. Deshpande

Expected Soon (2019)

Technical feasibility (~2030)

PROJECT ACQUISITION PROCESS AND CRITICAL DECISIONS					
Project Planning Phase		Project Execution Phase			Mission
Preconceptual Planning	Conceptual Design	Preliminary Design	Final Design	Construction	Operations
CD-0 Approve Mission Need	CD-1 Approve Preliminary Baseline Range	CD-2 Approve Performance Baseline	CD-3 Approve Start of Construction	CD-4 Approve Start of Operations or Project Closeout	

CD-0	CD-1	CD-2	CD-3	
Actions Authorized by Critical Decision Approval				
• Proceed with conceptual design using program funds • Request PED funding	• Allow expenditure of PED funds for design	• Establish baseline budget for construction • Continue design • Request construction funding	• Approve expenditure of funds for construction	• Al op pr

DOE/CF-0154
Volume 4

Department of Energy
FY 2020 Congressional Budget Request

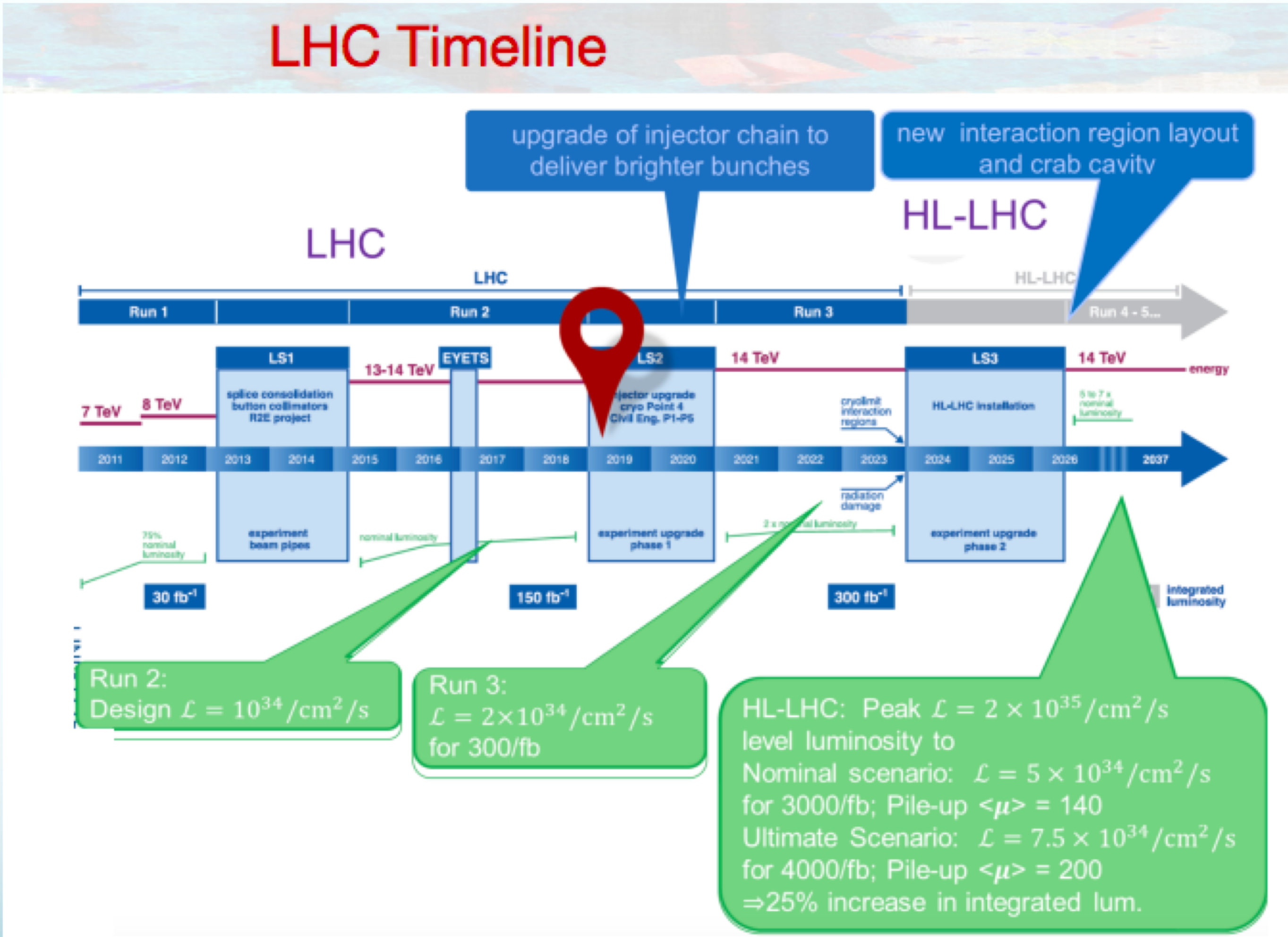
Science

Volume 4, Page 272:
"..(EIC)..Critical Decision-0, Approve Mission Need, is planned for FY 2019."

March 2019 Office of Chief Financial Officer Volume 4

HL-LHC will come in 2026

- LHC discovered Higgs, now the era of precision QCD?

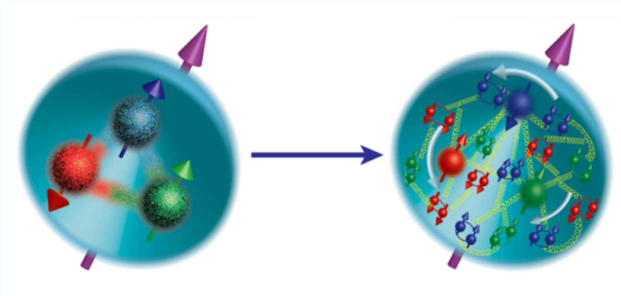


Courtesy of Sergo Jindariani

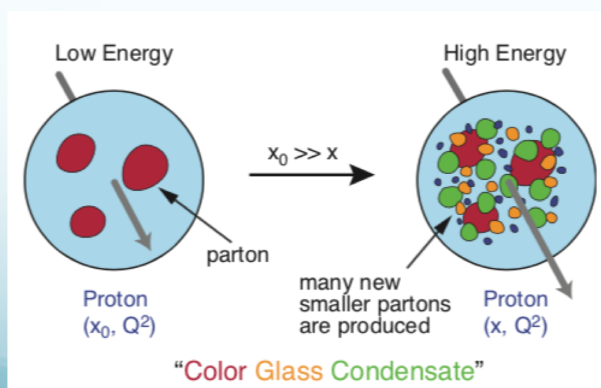
EIC Science Pillars: major ones

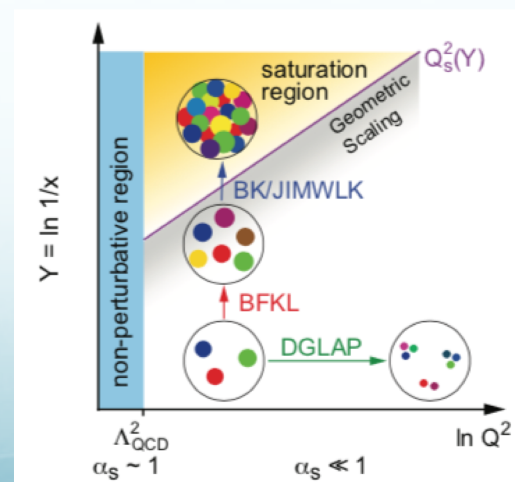
- Two major pillars
  - actively developed and developing at the moment (EIC white paper)

❖ Quantum Tomography of protons and nuclei: spin, TMDs, GPDs, Wigner distribution, all that



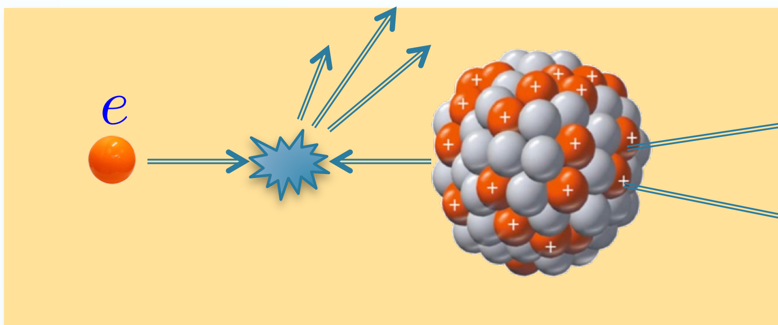
❖ A new form of matter - color glass condensate

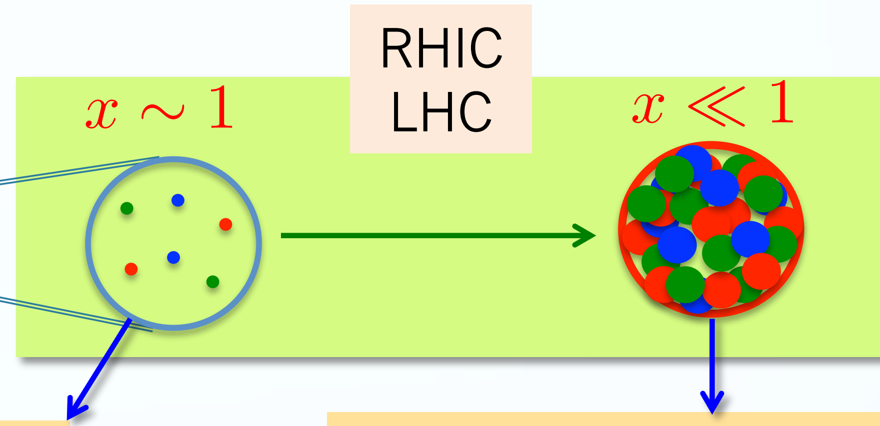




QCD structure of nucleons/nuclei revealed by high energy scattering

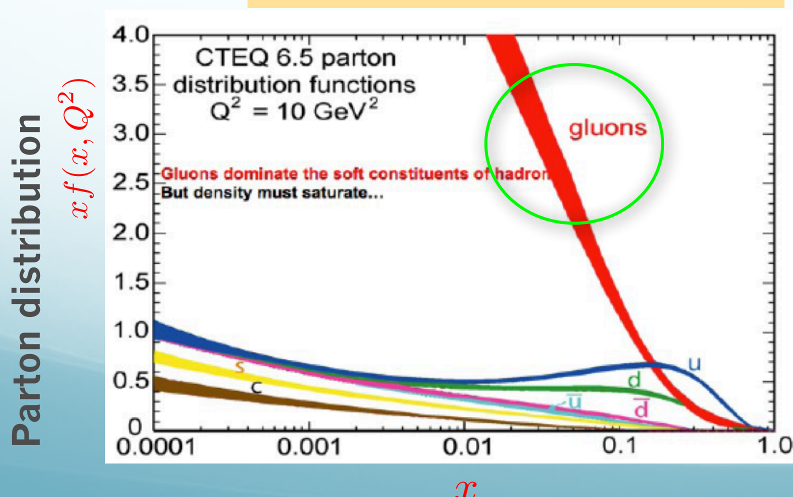
$$x = \frac{\text{parton (gluon) longitudinal momentum}}{\text{proton longitudinal momentum}}$$

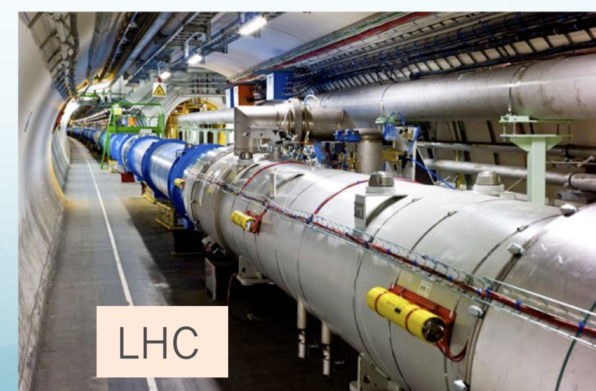




- A dilute system
- Probes interact independently

- A dense system
- Probes interact coherently



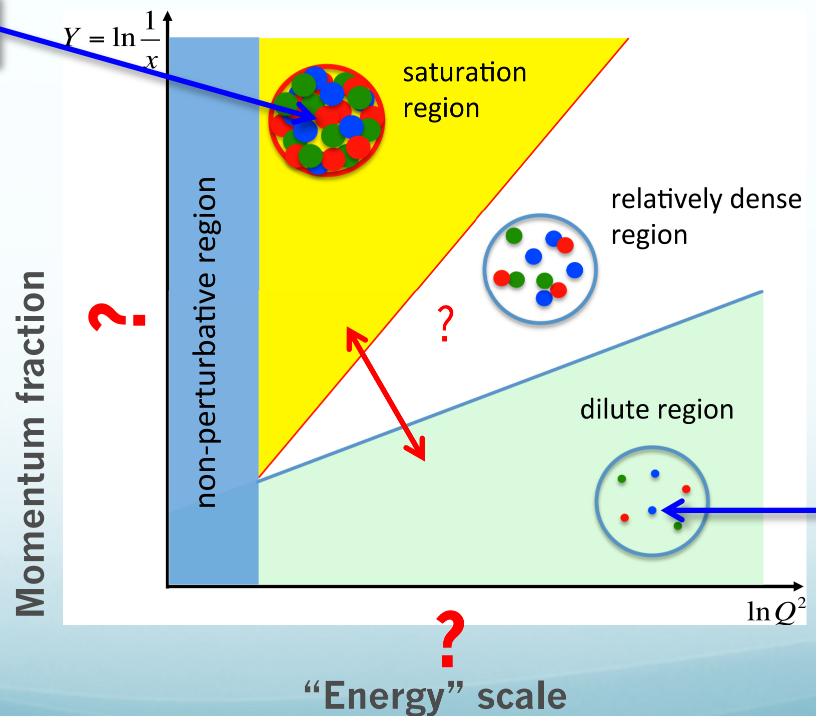


Key questions to be addressed?

QCD in this quantum coherent regime

- Where and how does the transition from a dilute parton system to a coherent dense gluon-dominated state occur?
- What are the properties of such a dense gluon regime?

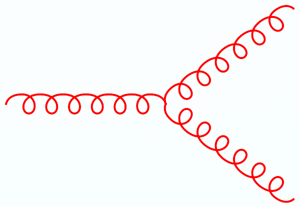
EIC would figure out

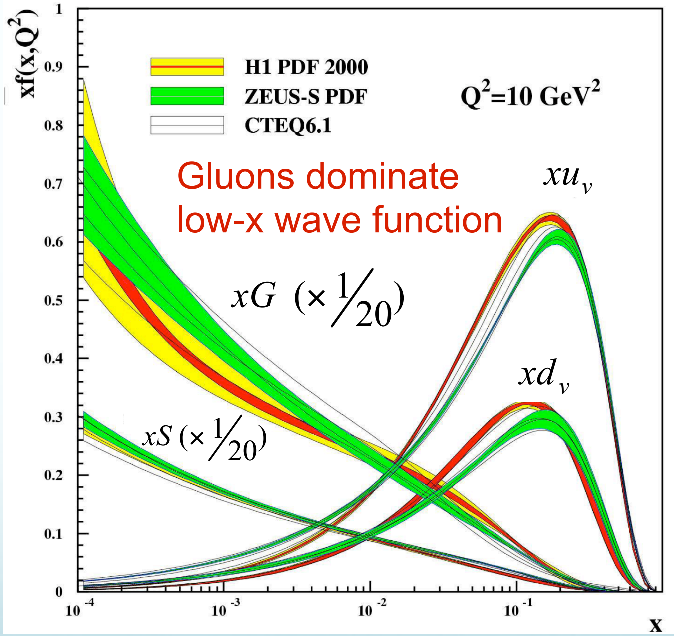


very successful, collinear factorization perturbative QCD

An unavoidable consequence of QCD

- Gluon saturation is an unavoidable consequence from first principle of QCD, and its discovery is mandatory
  - Its growth at small-x is governed by BFKL physics: g->gg splitting





An inevitable consequence of QCD at high energy

- However, when so many gluons are squeezed in a confined proton/nucleus, besides the usual splitting, they also start to overlap and recombine
  - Such recombination leads to non-linear dynamics

- Nonlinear dynamics/evolution (BK equation): saturation scale $Q_s(x)$ from the balance

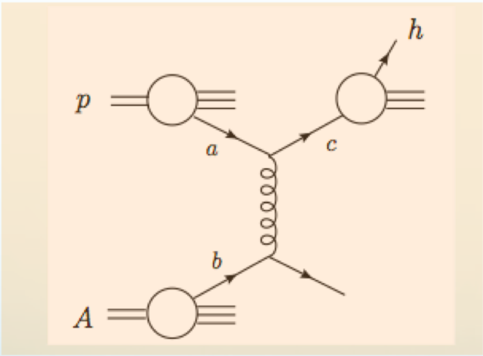
$$\frac{\partial N(x, r_\perp)}{\partial \ln(1/x)} = \alpha_s K_{\rm BFKL} \otimes N(x, r_\perp) - \alpha_s \left[N(x, r_\perp)\right]^2$$

radiation   recombination

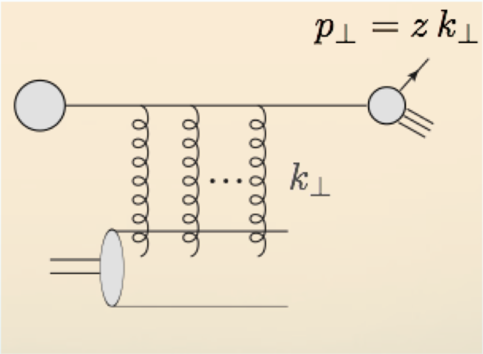
Two key ingredients

- How do you know if you have discovered gluon saturation?
  - After so many years of "smoking guns" and "not being able to convince people decisively", let's be realistic and define some criterions

- A two-ingredient criterion
  - The evolution of the system: the gluon system has to evolve via BK equation (note: **not BFKL**)
  - The interaction of the system: the gluon system has to interact with the external probe coherently = multiple scattering, instead of single scattering



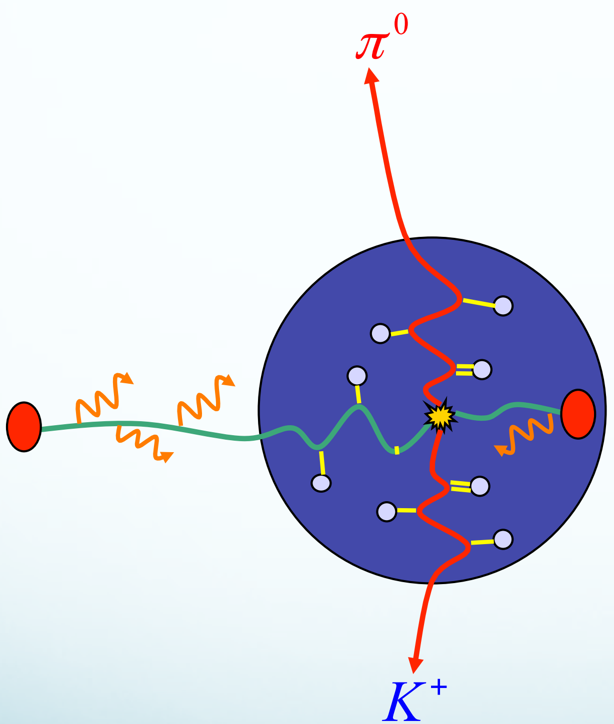
Single scattering
as in collinear factorization

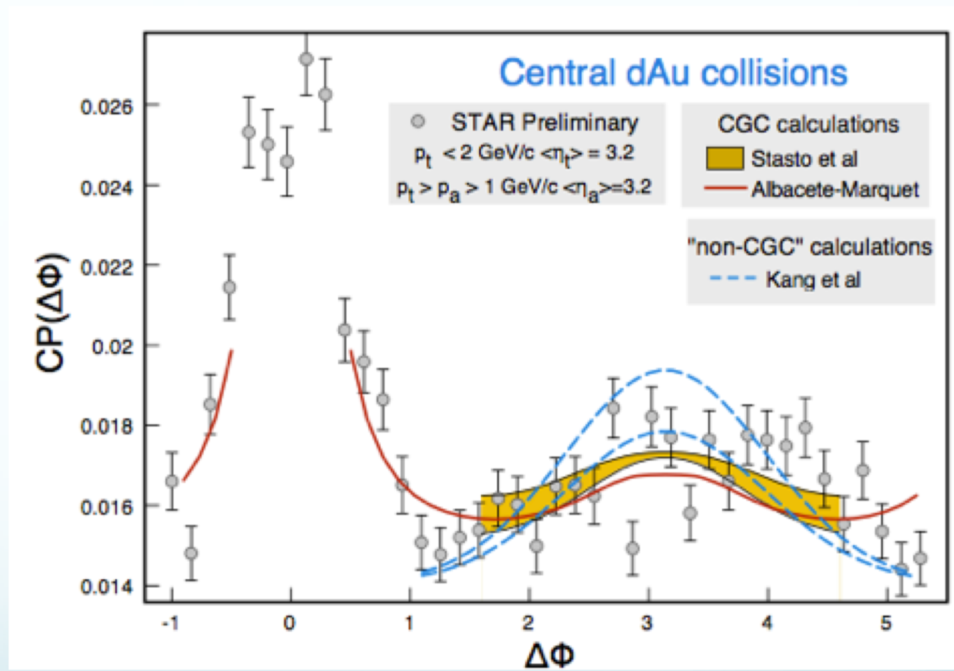


Coherent multiple scattering
as in small-x/CGC formalism

Early hints on gluon saturation

- Strong multiple scattering with the dense gluon system of the nucleus leads to broadening and suppression of away side
  - Different formalisms would lead to similar predictions



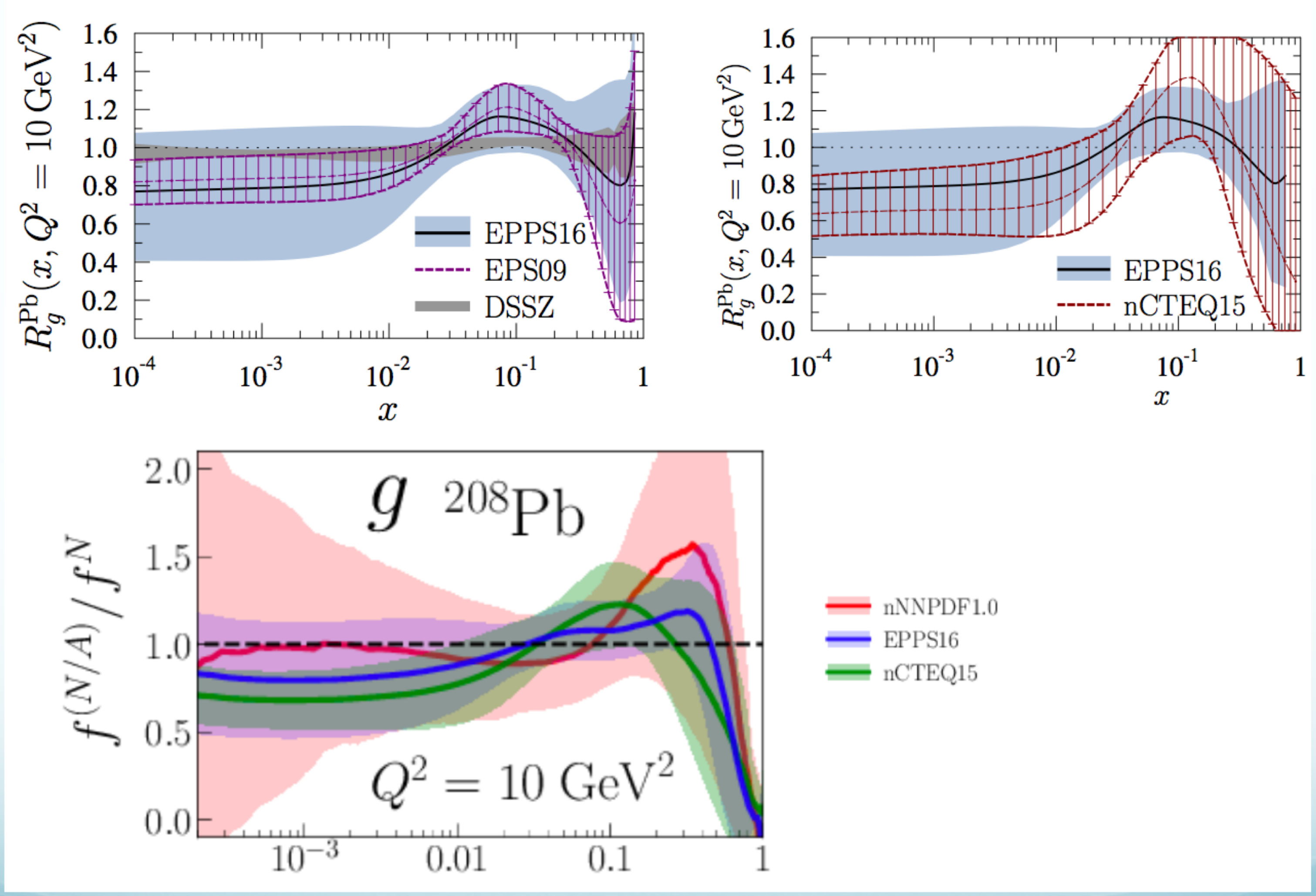


Why we are not convinced yet?

- CGC formalism uses: coherent multiple scattering + BK evolution
- Non-CGC formalism = high-twist formalism uses: coherent multiple scattering + DGLAP type evolution
- By our two-ingredient criterion, we have not discovered gluon saturation yet
- This dihadron correlation data cannot be described by models which **do not** contain multiple scattering

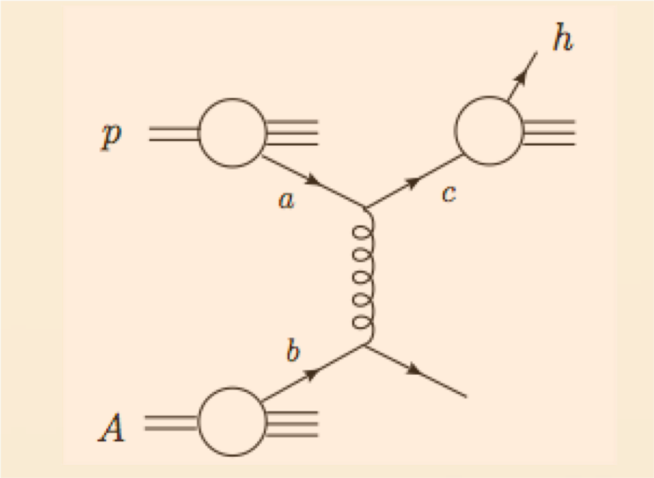
Other approach: nuclear PDFs

- Nuclear PDFs have been well-known in LHC community



Key points for nPDFs approach

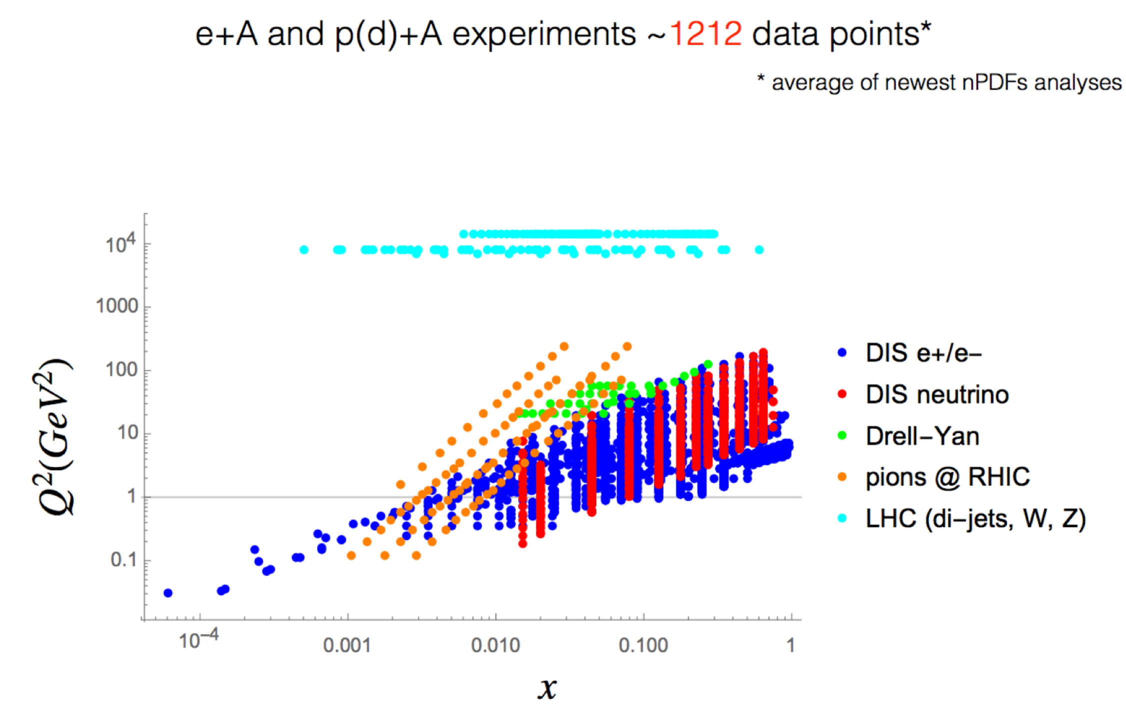
- Replacing proton PDFs by nuclear PDFs at an initial scale Q_0,
  - nPDFs: still follow DGLAP evolution
  - Dynamics: single scattering

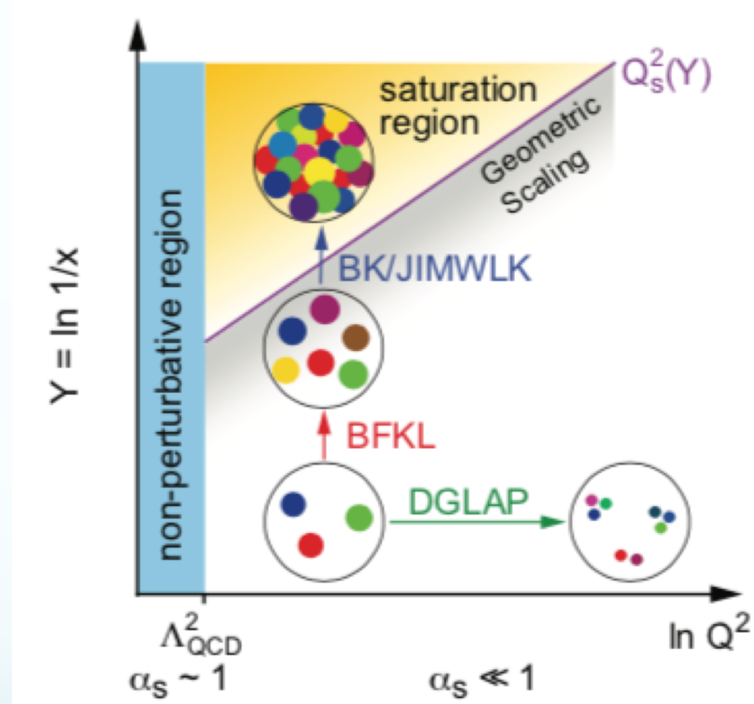


- According to our two-ingredient criterion, both are not satisfied. Completely different from gluon saturation
  - It's known that it cannot describe dihedron correlation data in p+A collisions

LHC can go really small-x though

- But your Q^2 is too high to discover gluon saturation
  - The larger Q^2 is, the even smaller x one has to go in order to probe saturation region





Courtesy of Pia Zurita at IS 2019 conference

- LHC and EIC complimentary: check (non)universality of gluon dynamics/distribution at small-x

Complimentary: LHC and EIC

- LHC and EIC complimentary: check (non)universality of gluon dynamics/distribution at small-x

A Tale of Two Gluon Distributions—-绝代双“胶”

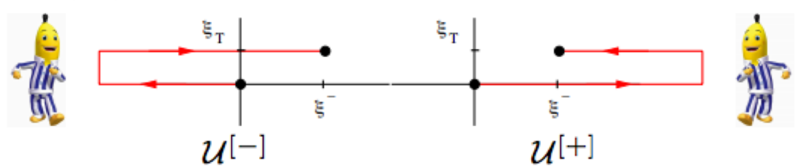
In terms of operators (TMD def. [Bomhof, Mulders and Pijlman, 06]), two gauge invariant gluon definitions: [Dominguez, Marquet, Xiao and Yuan, 11]

I. Weizsäcker Williams gluon distribution: conventional gluon distributions

$$xG_{WW}(x, k_\perp) = 2\int \frac{d\xi^- d\xi_\perp}{(2\pi)^3 P^+} e^{ixP^+\xi^- - ik_\perp\cdot\xi_\perp} \mathrm{Tr}\langle P|F^{+i}(\xi^-, \xi_\perp)\mathcal{U}^{[+]\dagger} F^{+i}(0)\mathcal{U}^{[+]}|P\rangle.$$

II. Color Dipole gluon distributions:

$$xG_{DP}(x, k_\perp) = 2\int \frac{d\xi^- d\xi_\perp}{(2\pi)^3 P^+} e^{ixP^+\xi^- - ik_\perp\cdot\xi_\perp} \mathrm{Tr}\langle P|F^{+i}(\xi^-, \xi_\perp)\mathcal{U}^{[-]\dagger} F^{+i}(0)\mathcal{U}^{[+]}|P\rangle.$$



- Modified Universality for Gluon Distributions:

	Inclusive	Single Inc	DIS dijet	γ +jet	dijet in pA
xG_{WW}	×	×	√	×	√
xG_{DP}	√	√	×	√	√

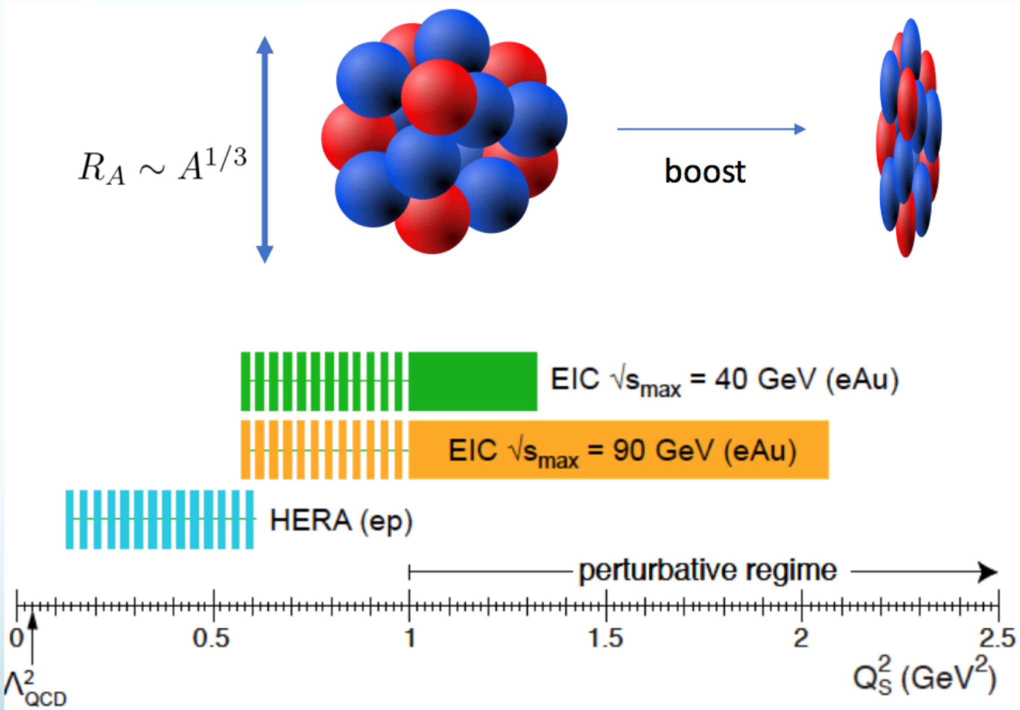
× ⇒ Do Not Appear. √ ⇒ Apppear.

- Measurements in pA collisions and at the EIC are tightly connected with complementary physics missions.

Courtesy of B.W. Xiao, 2018

EIC has nucleus target: vs HERA

- Nuclear enhancement of the saturation momentum (advantage over HERA)



$$Q_s^2 \propto A^{1/3}$$

At EIC, for heavy nuclei, Q_s becomes perturbative!
(It wasn't the case at HERA actually…)

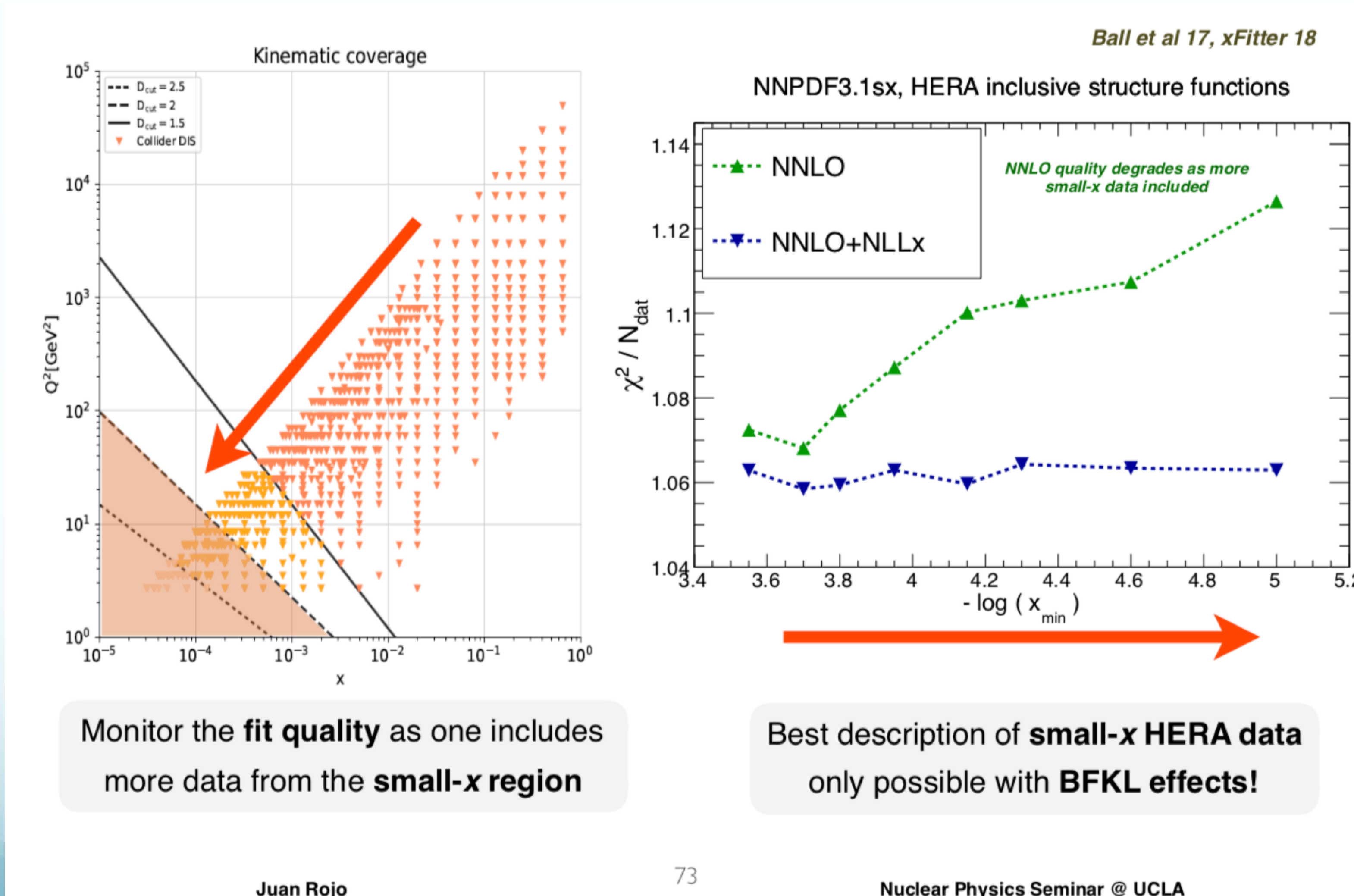
Courtesy of Y. Hatta at QM 2019 conference

What should we do?

- Establishing conclusively the discovery of gluon saturation is not going to be easy, even with EIC
  - Many people are not so easy to be convinced, e.g. J. Nagle (checked theorist's code to make sure, QM 2019 talk)
- Theory
  - Once saturation scale becomes really perturbative, we can turn small-x/gluon saturation physics into a precision physics, following the usual wisdom of LHC pQCD community
- Experiment
  - We need multi-channels/observables (instead of a single golden channel) for our study: establish gluon saturation in all of them
  - Of course golden channel is the one we will search first, e.g., dihadron correlation in e+A collisions, thanks to hard work of Elke Aschenauer and colleague's hard work on EIC simulations
- By carefully compare theory with experimental data, check our two-ingredient criterion, we should be able to make the final discovery of gluon saturation conclusively

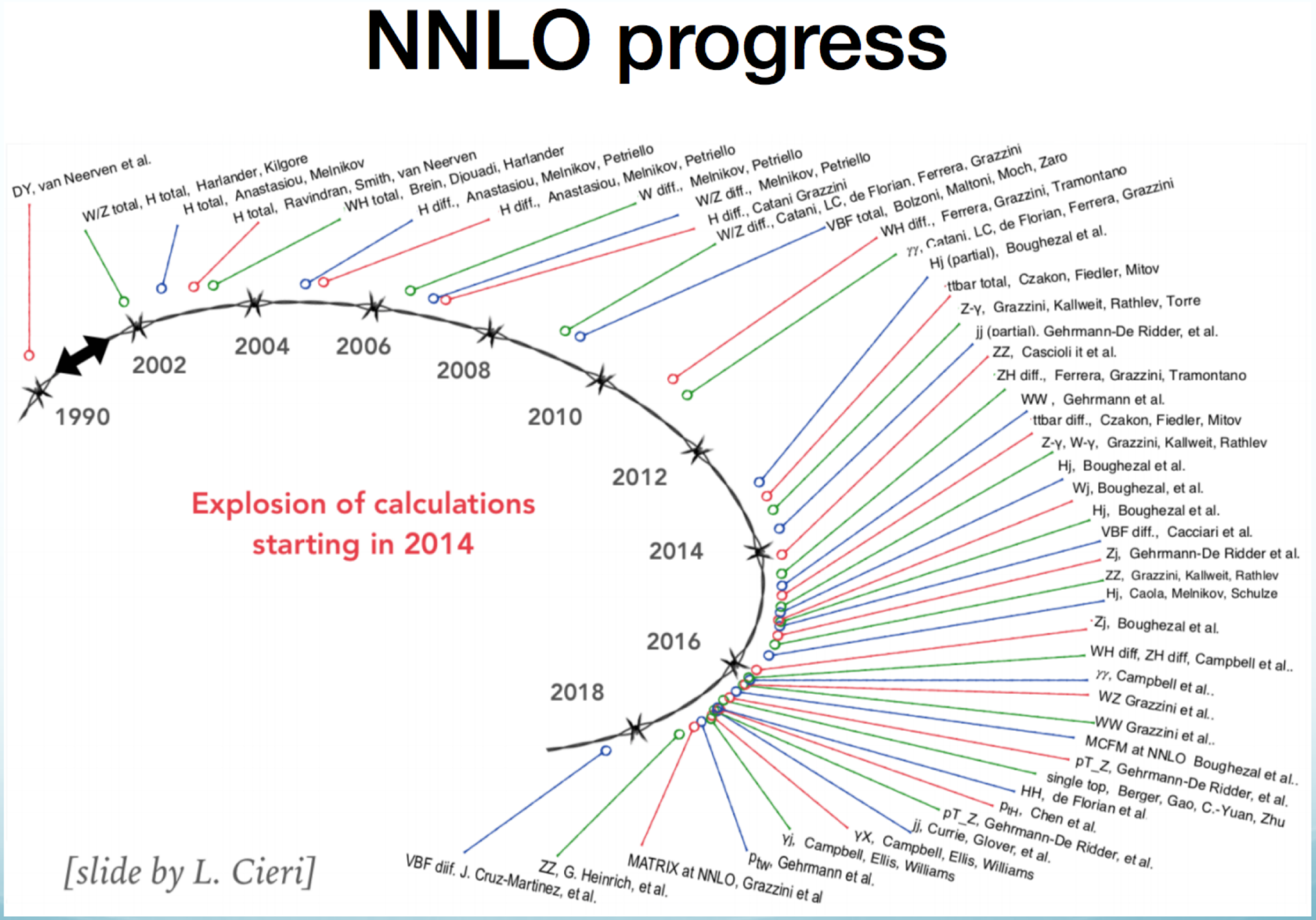
The recent lesson: hint of BFKL at small-x

- To discover hint of BFKL is already a long shot: HERA



Theory: go precision?

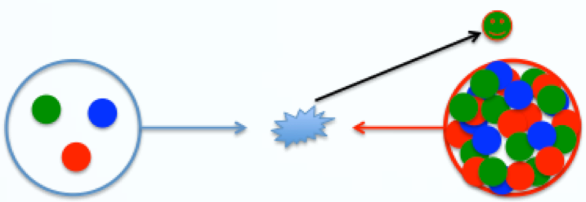
- LHC pQCD community: NLO is a solved problem since 1990s, now you are telling me “NLO at small-x physics” is not fully understood until recently?!



Courtesy of John Campbell

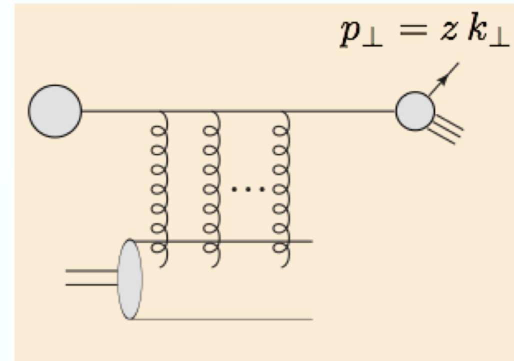
Theory at LO

- LO: a simple quark undergoes coherent multiple scattering, and then fragments into a hadron

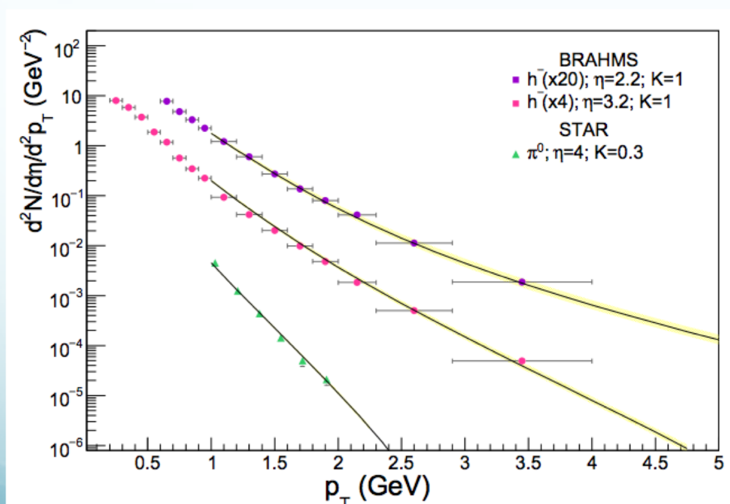


$$x_1 \sim \frac{p_\perp}{\sqrt{s}} e^{+y} \sim \mathcal{O}(1)$$

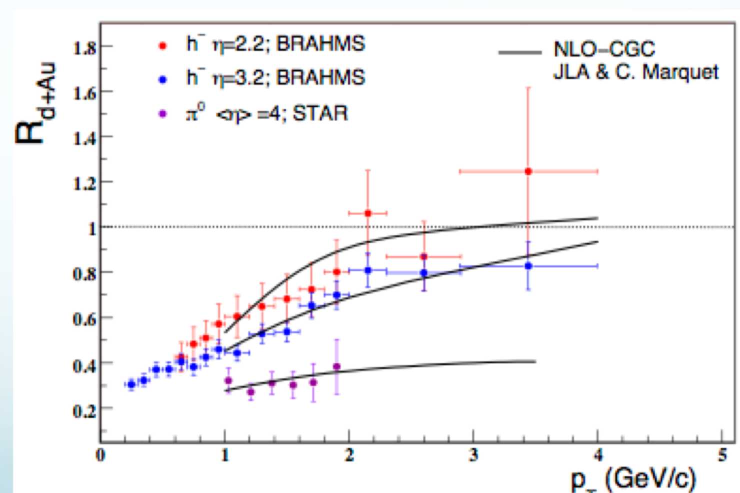
$$x_2 \sim \frac{p_\perp}{\sqrt{s}} e^{-y} \ll 1$$



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



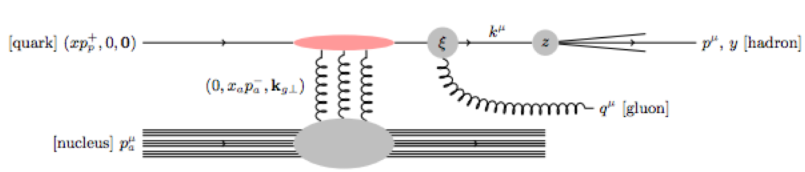
Albacete & Marquet 2010



Theory at NLO: negative cross section?

- One gluon radiation

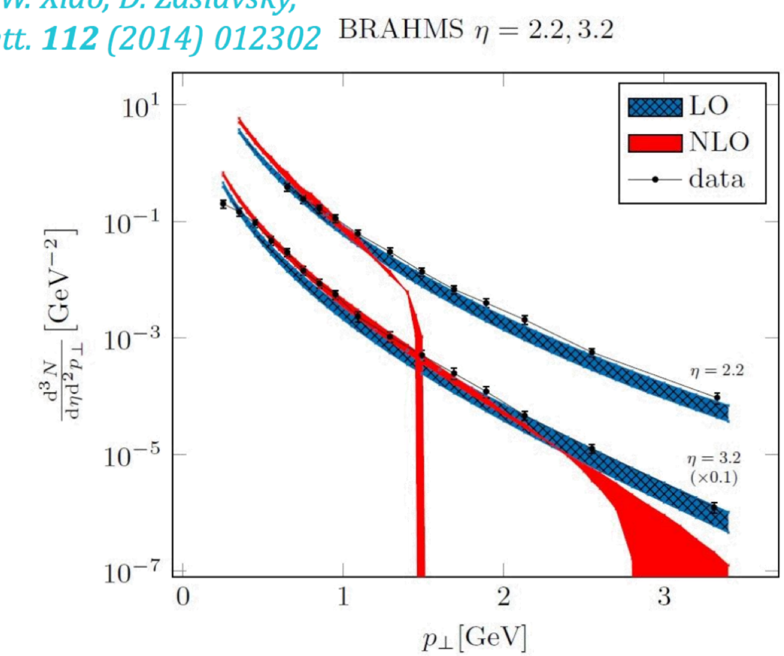
Dilute-Dense factorizations: large x proton or γ^* $\rightarrow$ as dilute probe:



$$x_p = \frac{k_\perp}{\sqrt{s}} e^{+y} \sim 1 \quad \text{dilute}$$

$$x_A = \frac{k_\perp}{\sqrt{s}} e^{-y} \ll 1 \quad \text{dense}$$

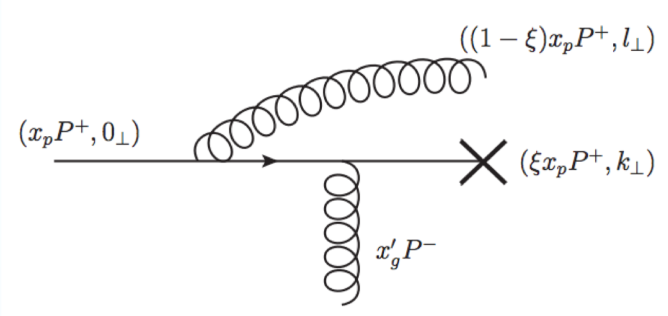
*A. Stasto, B.-W. Xiao, D. Zaslavsky, Phys. Rev. Lett. **112** (2014) 012302*



Many work to resolve this issue: Altinoluk, Armesto, Beuf, Kovner, Lublinsky, 14 Kang, Vitev, Xing, 14, Ducloue, Lappi, Zhu, 16/17, Iancu, Mueller, Triantafyllopoulos, 16, Liu, Ma, Chao, 19, Liu, X. Liu, Kang, 19, …

Ideas of kinematic constraints

- Follow exact kinematics of the gluon radiation

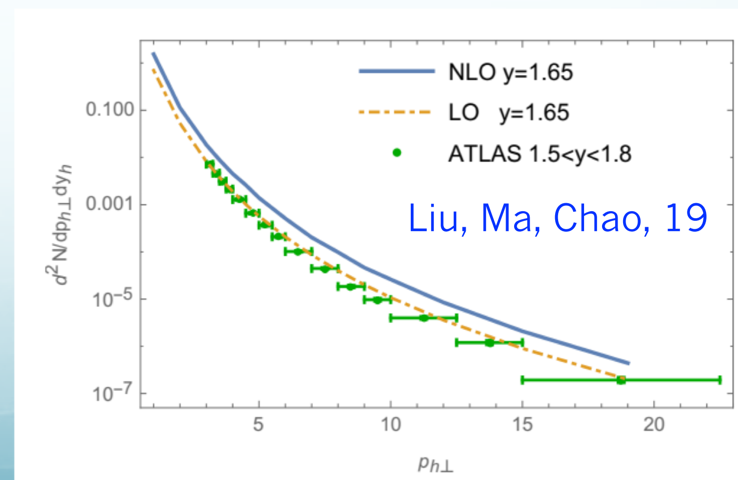


$$x'_gP^- = \frac{l_\perp^2}{2(1-\xi)x_pP^+} + \frac{k_\perp^2}{2\xi x_pP^+} \leq P^-$$

$$\xi \leq 1 - \frac{l_\perp^2}{x_ps}$$

  - Used mainly in event generators (LHC)
  - Leads to additional contributions
  - Further improve the instability of BK evolution equation, one can finally achieve much-better behaved NLO corrections
  - In LHC pQCD, you know very well why you favor DGLAP+NLLx method, instead of solving BFKL directly

- NLO is not agreeing with data
  - gluon distribution is fitted at LO



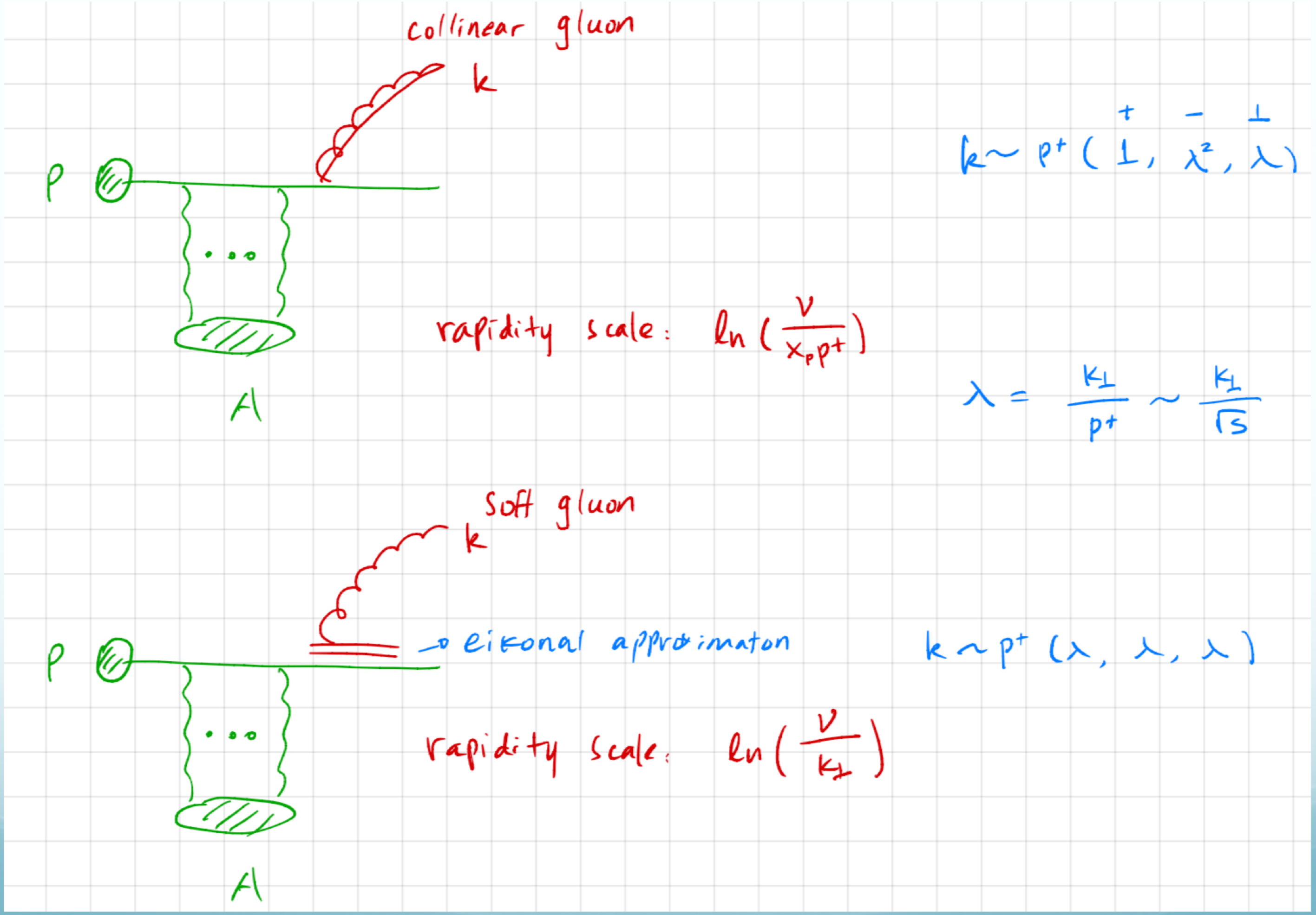
Theory at NLO

- Numerically this seems to be okay, however
  - So-called "exact kinematics" usually violates/mixes "power counting", thus it is not a systematic method in the standard pQCD factorization (though it is very useful in MC)
  - Another intrinsic problem: BK evolution of the gluons in the target nucleus evolves with x_g, or the rapidity of the gluon, such a scale should naturally come from your NLO computations, this is not achieved at the moment
  - This is in the same spirit of collinear factorization, renormalization mu scale for the PDF evolution naturally comes from the hard scale in your NLO computations
- A new systematic approach for small-x physics solving the above two problems

A new framework

- For semi-hard momentum region, both collinear and soft modes contribute

Kang, Liu, 1910.10166



Consistent with standard factorization

- Collinear has its natural rapidity scale as the incoming quark light-cone momentum
- Soft has its natural rapidity scale as the transverse momentum
- Now all are consistent

• add together ⇒ $\ln\left(\frac{\nu}{x_A P_A^-}\right)$

↳ rapidity scale for nucleus target

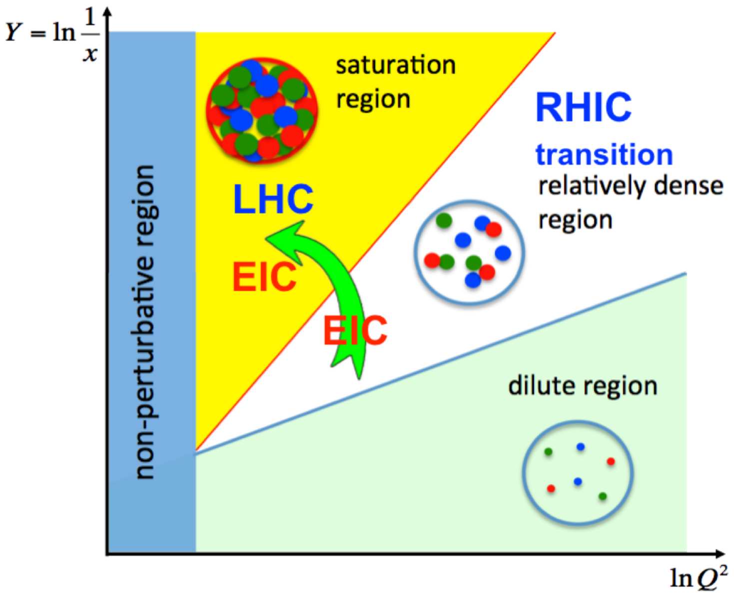
• soft gluon contribution ⇒ at NLO, reproduces "kinematic constrain" terms

beyond ⇒ systematic resummation and etc

- Earlier issue: DIS at NLO has even larger uncertainty than LO, can be fixed

Future 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

Summary

Electron Ion Collider (EIC) is the next QCD frontier

Exciting physics opportunities ahead of us

Thank you!