Highlights, open questions and perspectives: nPDFs, saturation and electroweak probes

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11th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions

Aschaffenburg, Germany, 26-31 March 2023

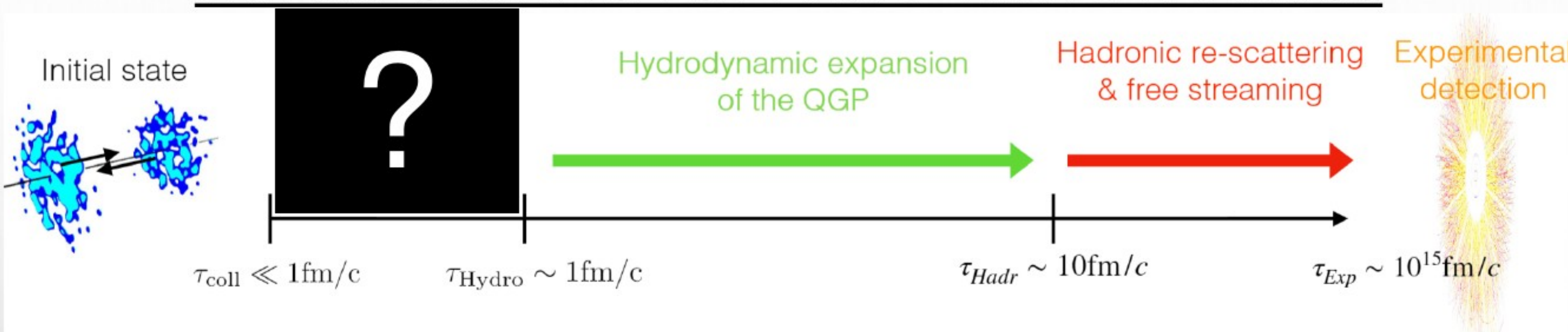
The charge:

"…..*we do not envisage a complete/comprehensive summary of the conference*, …., but rather a critical view on selected (and personal bias is understood here) aspects and a view on perspectives….."

High energy heavy ion collisions

slide from Travis Dore (Tues.)

THE IMPORTANCE OF EARLY TIME DYNAMICS



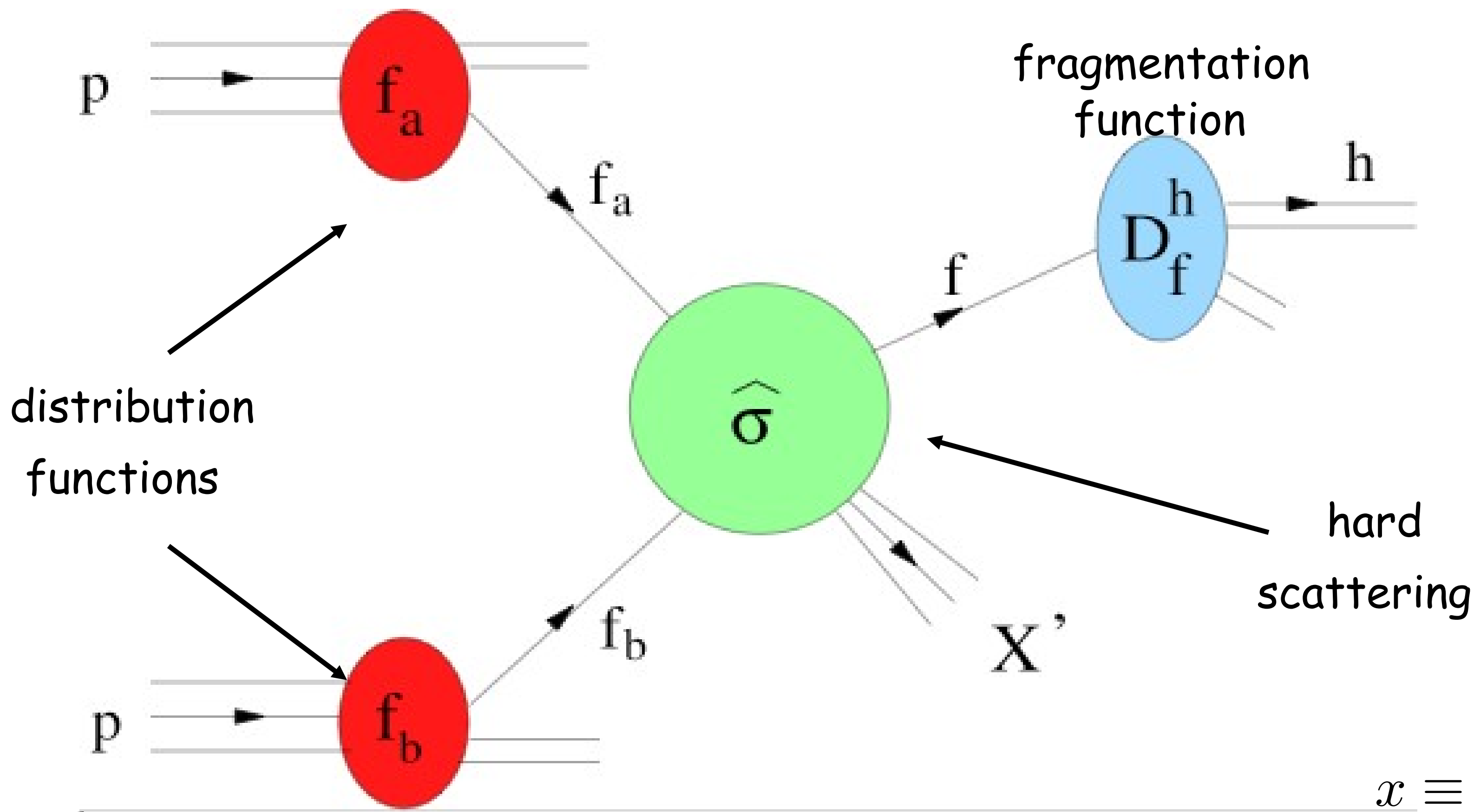
Far-from-equilibrium initial state ➡ Near thermal description at only slightly later times

- How to evolve from the non-equilibrium initial state to a hydrodynamic description?

start with simpler systems

High p_t particle production: pp collisions

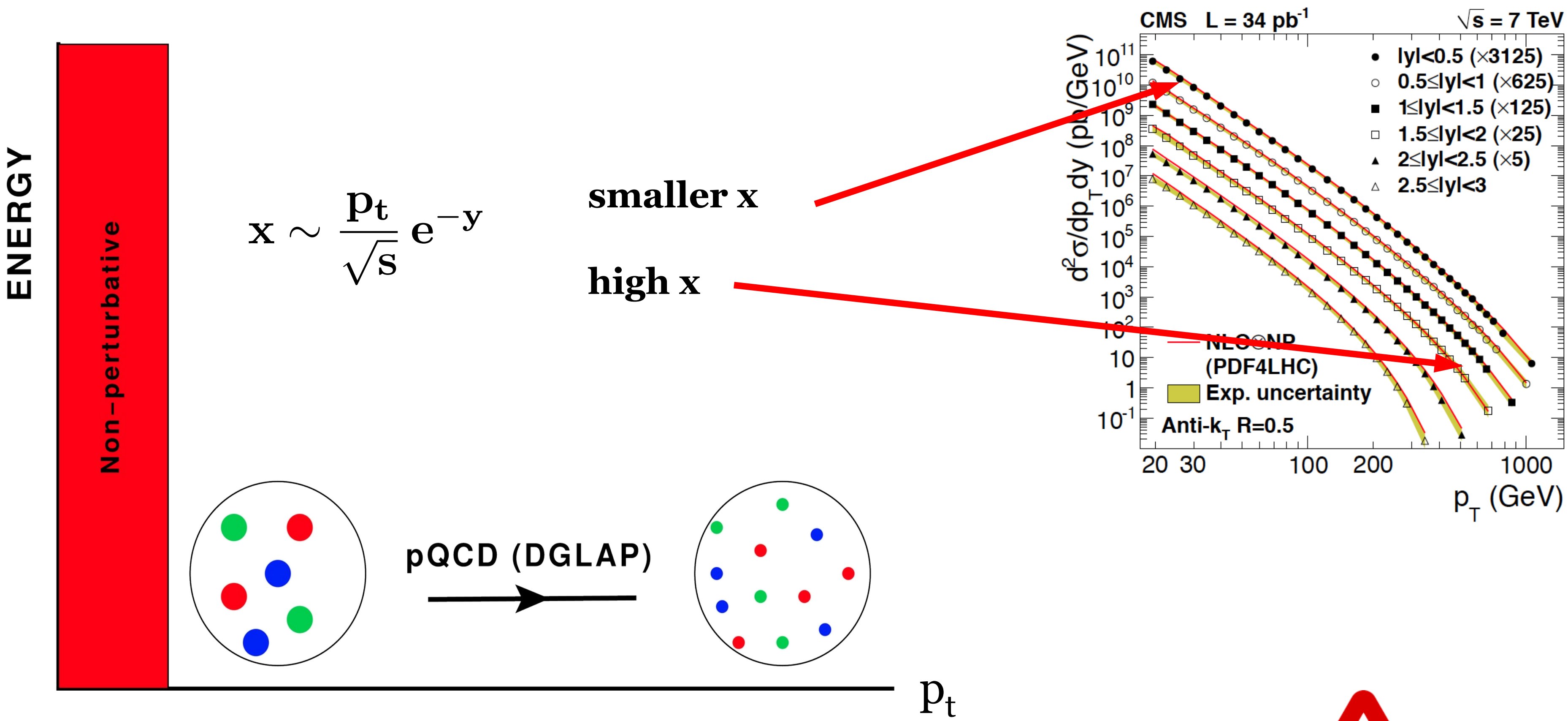
collinear factorization: separation of soft (long distance) and hard (short distance)



$$x \equiv \frac{p^+}{P^+}$$

$$\frac{d\sigma^{pp\to h\,X}}{d^2p_t\,dy} \sim f_a(x_1) \otimes f_b(x_2) \otimes \hat{\sigma} \otimes D_f^h(z) + \cdots\cdots$$

pQCD: the standard paradigm



bulk of QCD phenomena happens at low p_t (small x)

How about nuclear (pA) collisions?

universality ⟶ predictive power

$$\frac{d\sigma^{A_1 A_2 \to h\, X}}{d^2p_t\, dy} \; ? \; f_{A1}(x_1) \otimes f_{A2}(x_2) \otimes \hat{\sigma} \otimes D^h(z) + \cdots\cdots$$

power corrections

nPDFs:

shadowing, anti-shadowing,....

partonic cross section:

multiple scatterings from the target

Fragmentation functions:

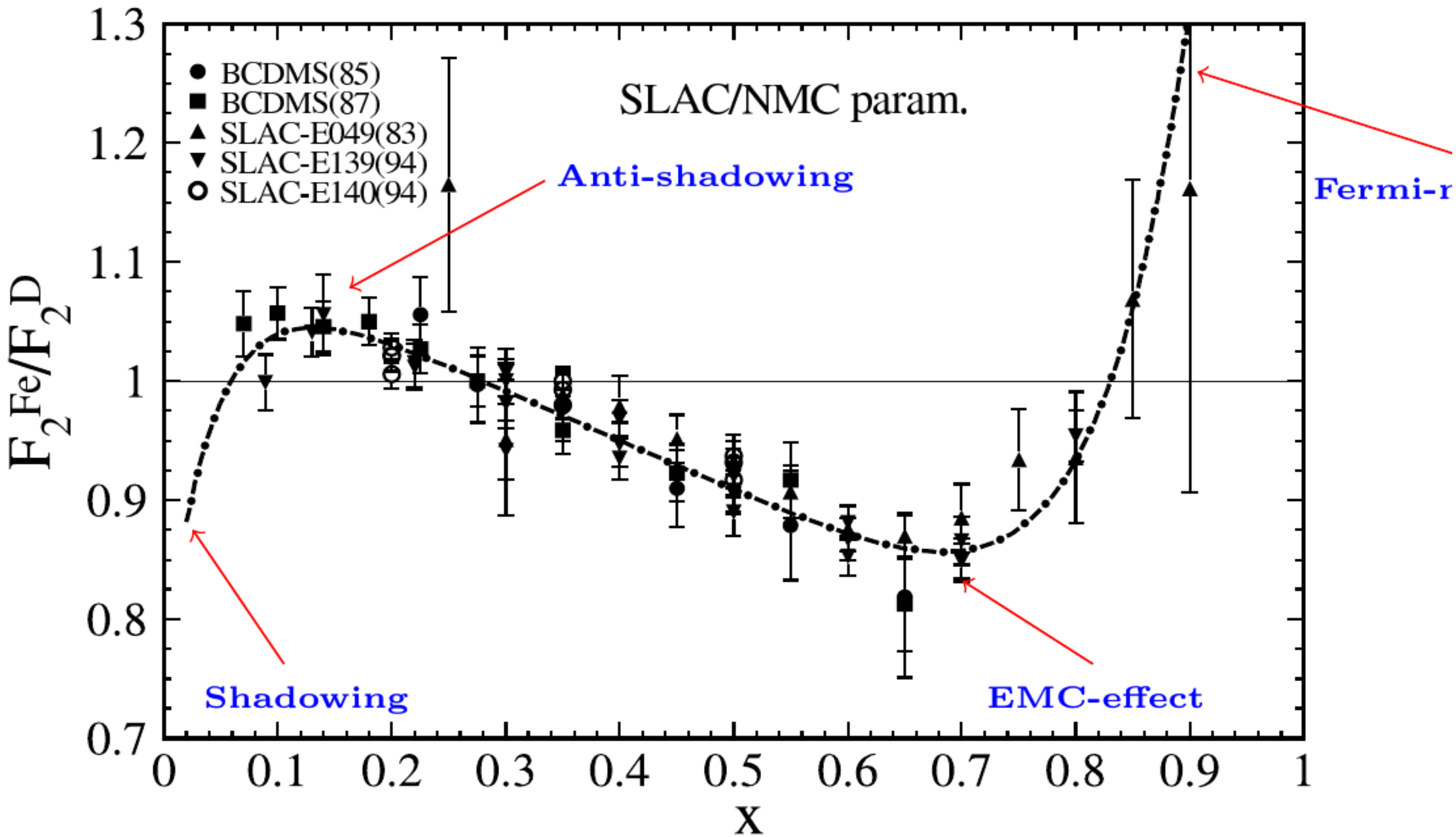
vacuum vs in-medium

Nuclear collision → nuclear PDFs

slide from Aleksander Kusina (Wed.)

- Cross-sections in nuclear collisions are modified

$$F_2^A(x) \neq Z F_2^p(x) + N F_2^n(x)$$

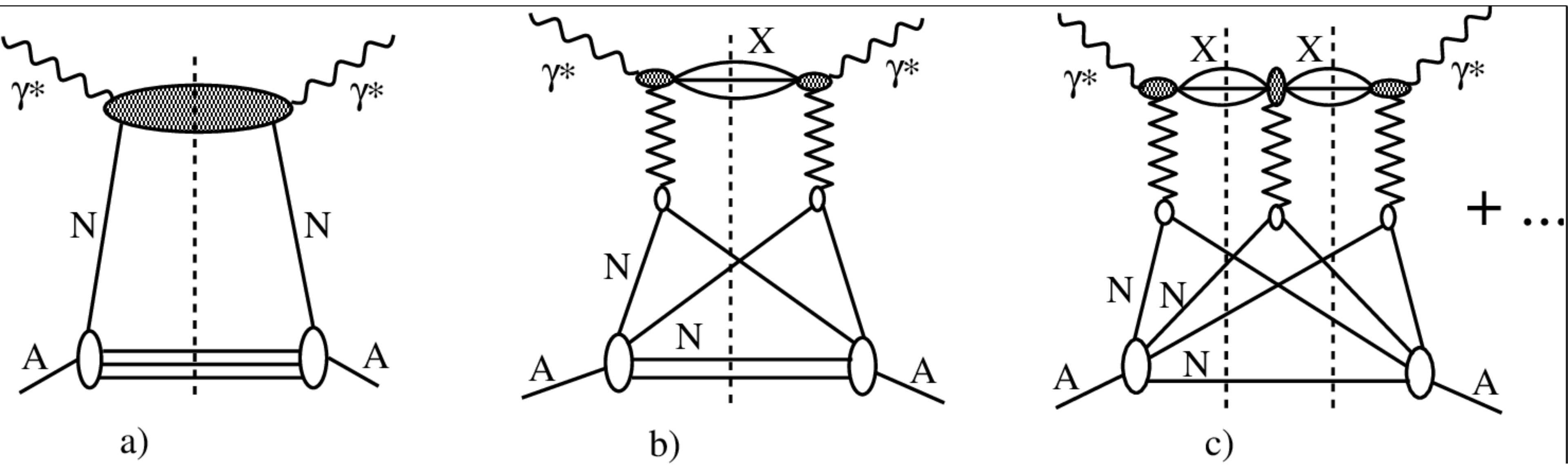


- Can we translate this modifications into **universal nuclear PDFs**?

$$\frac{d^2\sigma}{dx dQ^2} = \sum_{i=q,\bar{q},g} \int_x^1 \frac{dz}{z} f_i^A(z,\mu)\, d\hat{\sigma}_{il\to l' X}\left(\frac{x}{z}, \frac{Q}{\mu}\right) + \mathcal{O}\left(\frac{\Lambda_{QCD}^2}{Q^2}\right)$$

Gribov-Glauber model of nuclear shadowing: multiple hadronic scattering

talk by Vadim Guzey (Thurs.)



shadowing as destructive interference between multiple scattering amplitudes
nuclear parton distributions at initial scale Q_0
DGLAP evolution of distribution functions with hard scale Q^2

Frankfurt, Guzey, Strikman, Phys. Rep. 512 (2012) 255

nPDFs

slide from Tomas Jezo (Thurs.)

Global analyses of nPDFs

Recent

- **EPPS**
  - **EKS98:** hep-ph/9807297
  - **EKPS07:** hep-ph/0703104
  - **EPS08:** 0802.0139
  - **EPS09:** 0902.4154
  - **EPPS16:** 1612.05741
  - **EPPS21:** 2112.12462
- **nNNPDF**
  - **nNNPDF1.0:** 1904.00018
  - **nNNPDF2.0:** 2006.14629
  - **nNNPDF3.0:** 2201.12363
- **nCTEQ**
  - **nCTEQ09:** 0907.2357
  - **nCTEQ15:** 1509.00792
  - **nCTEQ15WZ:** 2007.09100
  - **nCTEQ15HiX:** 2012.11566
  - **nCTEQ15WZSIH:** 2105.09873
  - **nCTEQ15HQ:** 2204.09982
  - **nCTEQ15WZSIHdeut:** 2204.13157
  - **BaseDimuChorus:** 2204.13157
- **TUJU**
  - **TUJU19:** 1908.03355
  - **TUJU21:** 2112.11904
- **KA**
  - **KA15:** 1601.00939
  - **KSASG20:** 2010.00555

Outdated

- **nDS**
  - **nDS03:** hep-ph/0311227
  - **DSSZ12:** 1112.6324
- **HKM/HKN**
  - **HKM01:** hep-ph/0103208
  - **HKN04:** hep-ph/0404093
  - **HKN07:** 0709.3038

Adapted from a slide by I. Schienbein

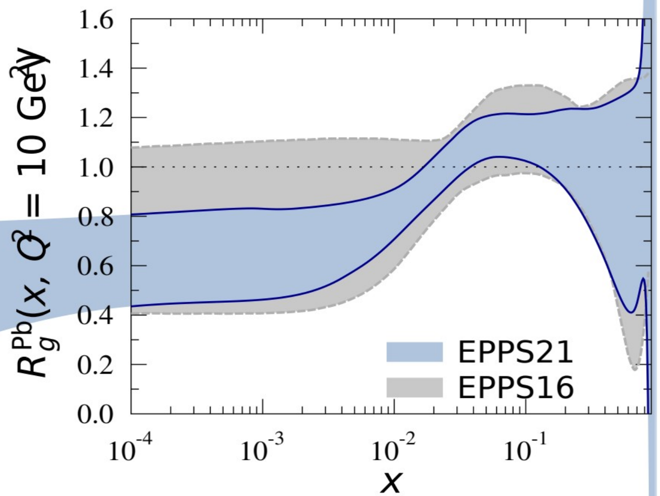
talk by Sara Sellam (Tues.)

nPDFs

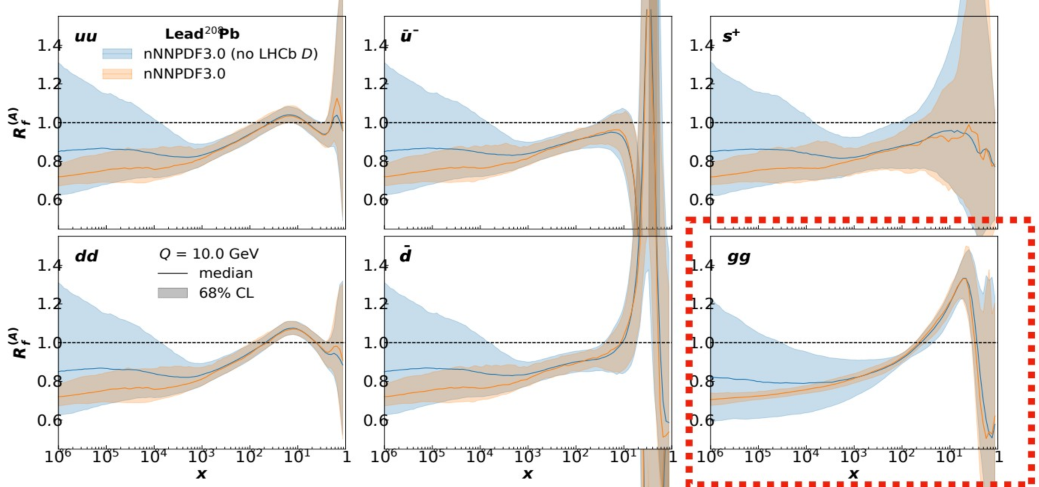
LHCb's impact on nPDF fits

LHCb measurements have a significant impact on nPDFs fits.

EPPS21 (EPJC 82 (2022) 5, 413)

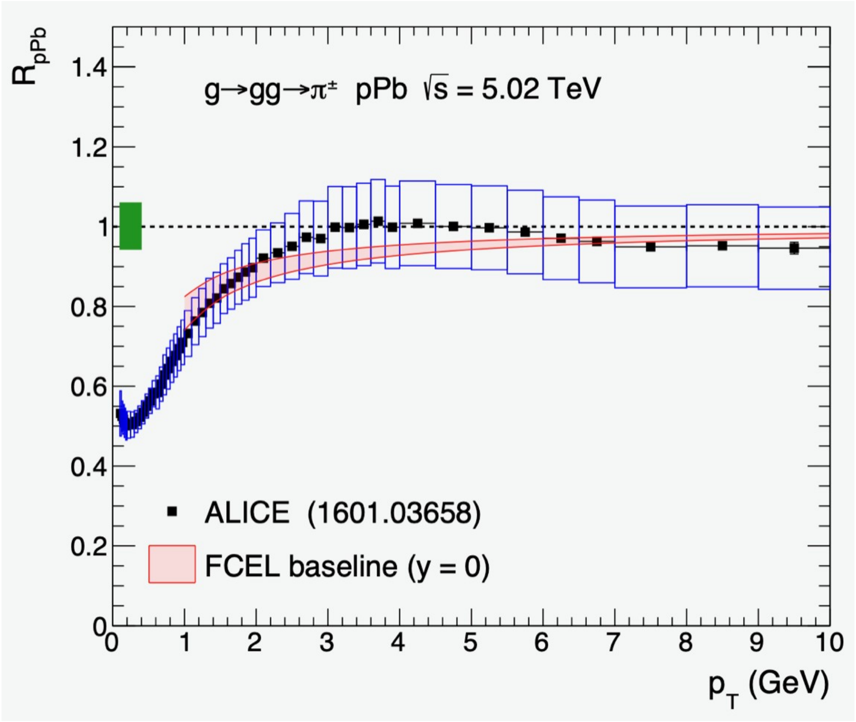


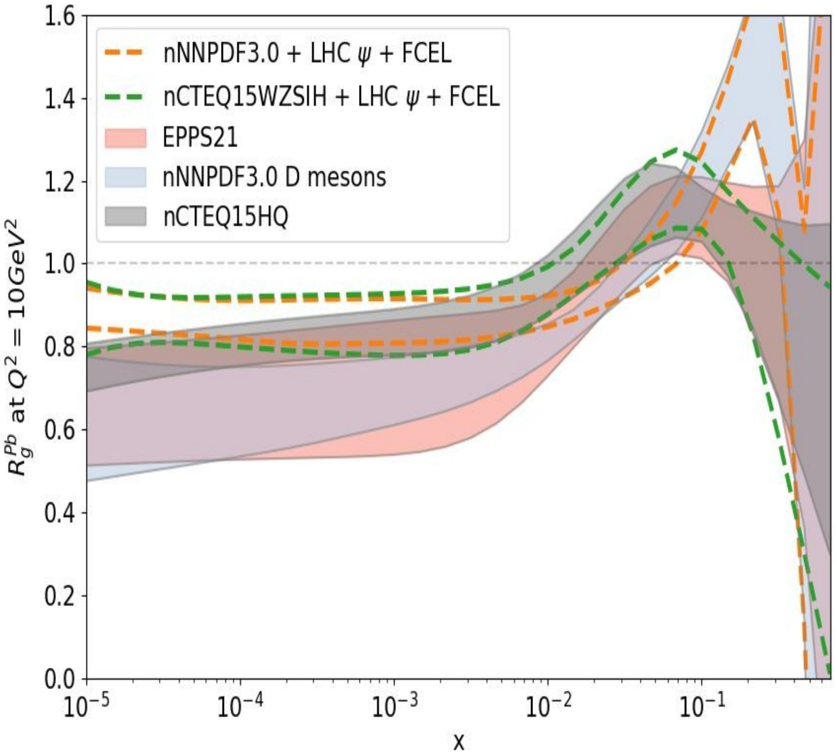
nNNPDF3.0 (EPJC 82 (2022) 6, 507)



LHCb D^0 meson production in pPb collisions at $\sqrt{s}$ = 5TeV: JHEP 1710 (2017) 090

nPDFs vs cold matter e-loss





arXiv:2003.06337, Arleo, Cougoulic, Peigne

talk by Tobie Avez (Wed.)

colorless initial/final states?

nPDFs

What's the QCD dynamics responsible for nuclear modification (shadowing)?

perturbative (parton d.o.f., linear/non-linear evolution in x)

non-perturbative (hadron d.o.f., Gribov-Galuber)

leading twist vs higher twist?

How far can we push collinear factorization here?

A-enhanced higher twist contributions?

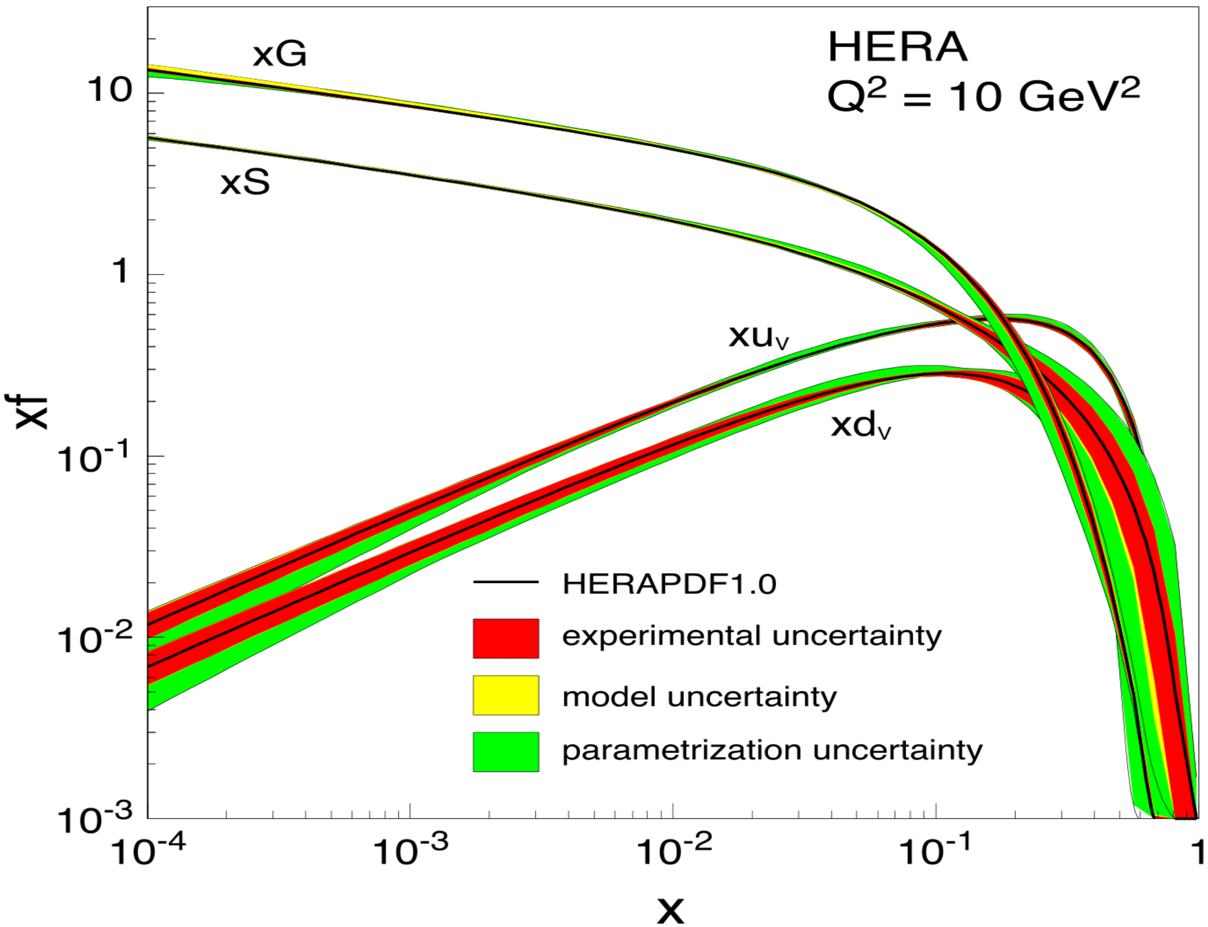
Can one calculate corrections systematically (twist-4 contributions)?

new parameters: can lattice, LaMET, ... help?

How about final state or initial-final state interference effects? cold matter eloss?....

Are we disregarding rich QCD dynamics by insisting on collinear factorization?

HERA: rise of the partons

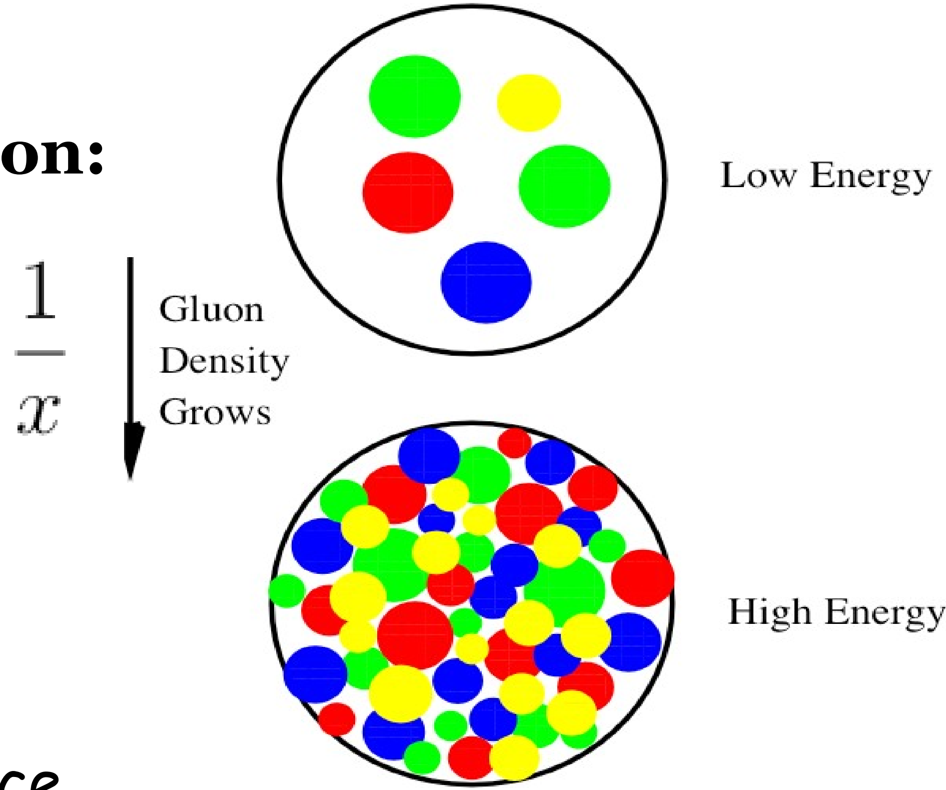


$$x = \frac{p^+}{P^+}$$

x *is the fraction of hadron energy carried by a parton*

Resolving the nucleus/hadron:

Regge-Gribov limit



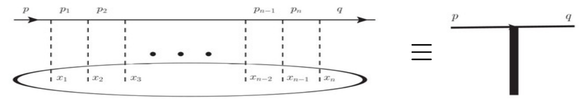
radiated gluons have the same size ($1/Q^2$) - the number of partons increase due to the increased longitudinal phase space

<u>hadron becomes a dense system of gluons: Feynman's concept of a quasi-free parton is not useful</u>

one can reach the same dense state in a <u>nucleus at not so small x</u>

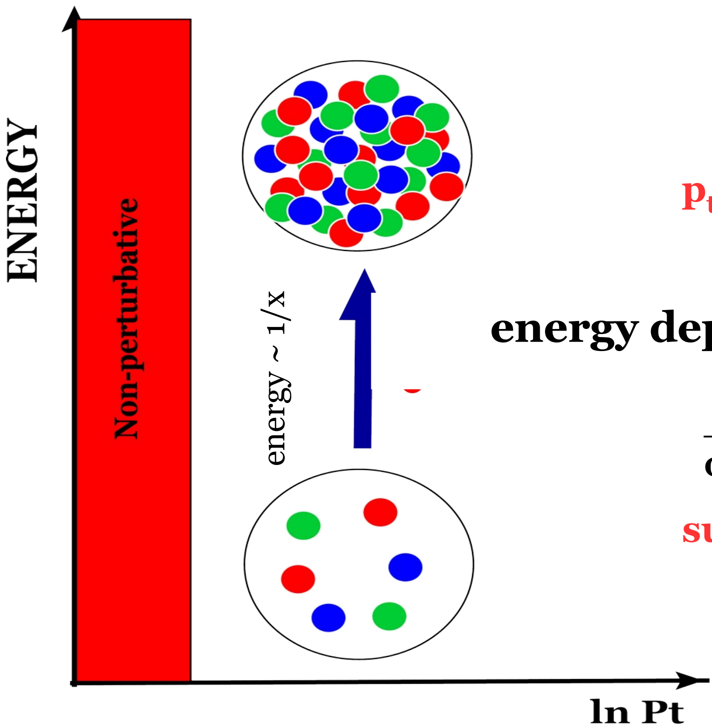
QCD at high energy/small x: gluon saturation

high gluon density: <u>Eikonal multiple scattering</u>



$$\equiv \mathbf{V}(\mathbf{x}_\perp)$$

p_t broadening (generic to multiple scattering)



energy dependence: <u>x-evolution via BK/JIMWLK</u>

$$\frac{\mathbf{d}}{\mathbf{dy}} < \mathbf{O} >_{\mathbf{y}} = \mathcal{H}_{\mathbf{JIMWLK}} < \mathbf{O} >_{\mathbf{y}}$$

suppression of spectra/away side peaks

$$\mathbf{Q_s^2(x, b_t, A) \sim A^{1/3}\, (\frac{1}{x})^{0.3}} \qquad \mathbf{Q_s^2(x = 3\times 10^{-4}) \sim 1\, GeV^2}$$

$$\mathbf{x \leq 0.01}$$

$$\alpha_s \ln{(x_v/x)} \sim 1$$

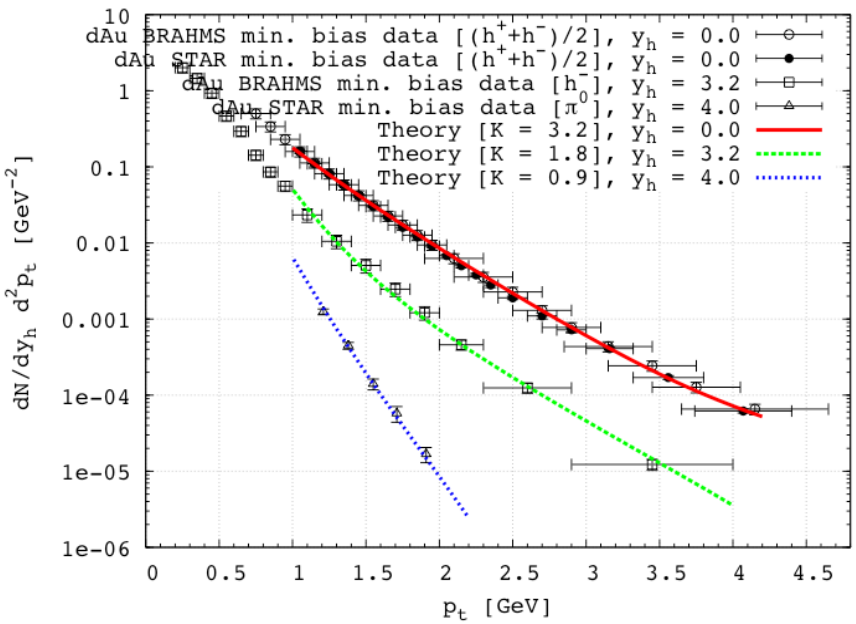
tremendous progress made toward precision

universal d.o.f.: dipole (Tr V V$^+$), quadrupole (Tr V V$^+$V V$^+$) in DIS, pA

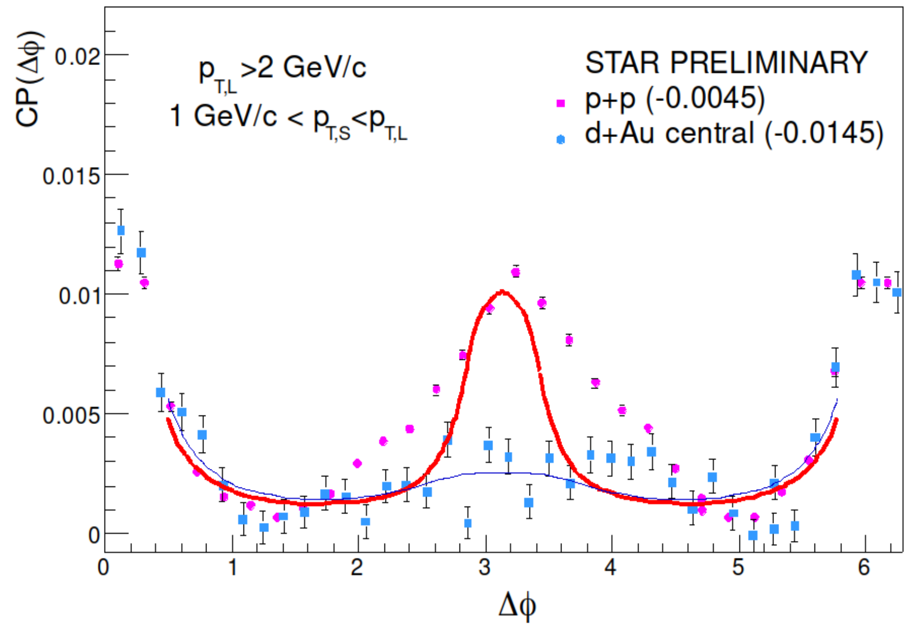
F. Domingues, C. Marquet, B. Xiao, F. Yuan, PRD83 (2011) 105005

CGC at RHIC

Single and double inclusive hadron production in dA collisions



Dumitru,Hayashigaki, JJM, NPA770 (2006) 57

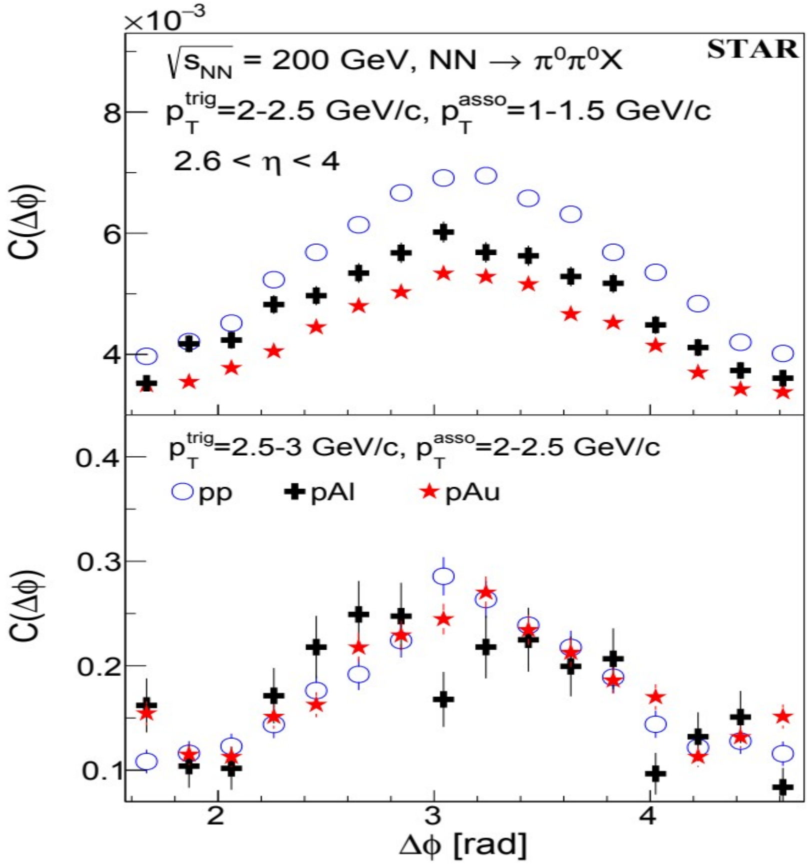


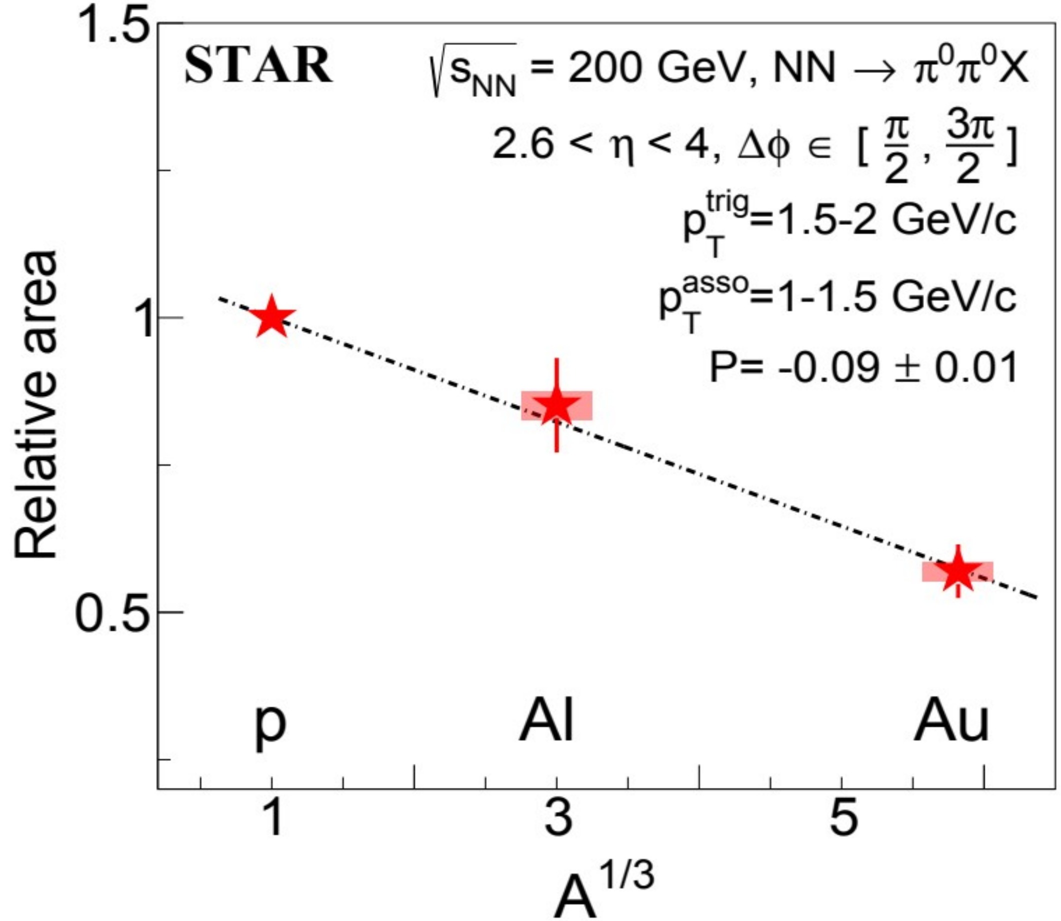
Albacete, Marquet, PRL105 (2010) 162301

related talk by Paul Caucal on Thursday

Back to back hadron production in pA collisions: forward rapidity

STAR collaboration(2021)
arXiv:2111.10396





A challenge for Gribov-Galuber model of shadowing!

CGC at NLO

slide from Paul Caucal (Thurs.)

Ingredients of N^{p}LO small-x calculation

Universal non linear N^{p}LL BK/JIMWLK evolution equation

- Process independent, resum $\alpha_s^{p+n} \ln^n(1/x_{\mathrm{Bj}})$ to all orders.
- Recents results on spin dependent small-x evolution, NLL JIMWLK with massive quarks.

  See Cougoulic, Kovchegov, Tarasov, Tawabutr, 2204.11898 and Dai, Lublinsky, 2203.13695

Process dependent N^p LO impact factors

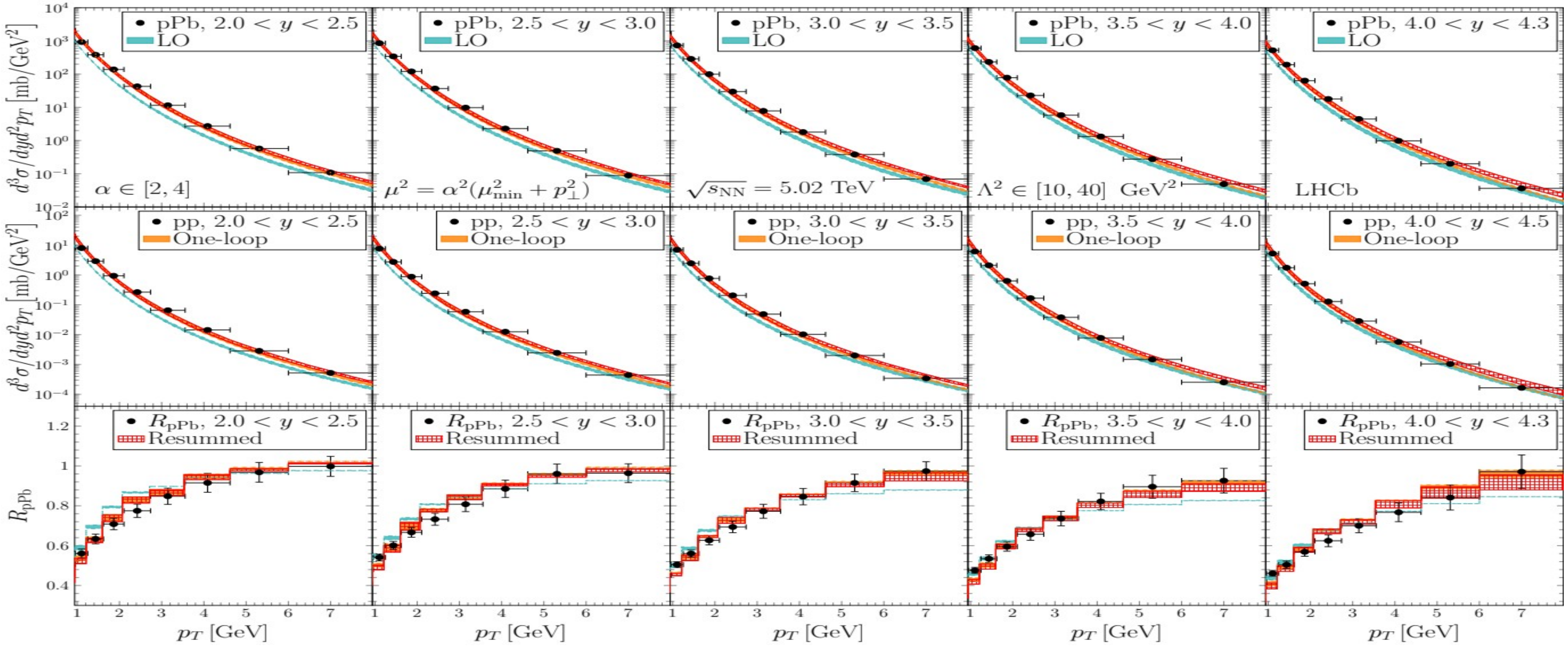
- **Non**-exhaustive list of recent NLO results in *eA* or *ep*
  - Dijet+photon in DIS Roy, Venugopalan, 1911.04530
  - Inclusive dijets PC, Salazar, Venugopalan, 2108.06347, inclusive dihadrons Bergabo, Jalilian-Marian, 2207.03606
  - Structure functions for massive quarks. Beuf, Lappi, Paatelainen, 2112.03158
  - Exclusive heavy-vector production. Mäntysaari, Penttala 2204.14031
  - Diffractive structure functions. Beuf, Hänninen, Lappi, Mulian, Mäntysaari, 2206.13161

- Topic not covered here: sub-eikonal corrections suppressed by powers of x_{Bj}.

  See e.g. Altinoluk, Beuf, Czajka, Tymowska, 2212.10484, Altinoluk, Armesto, Beuf, 2303.12691

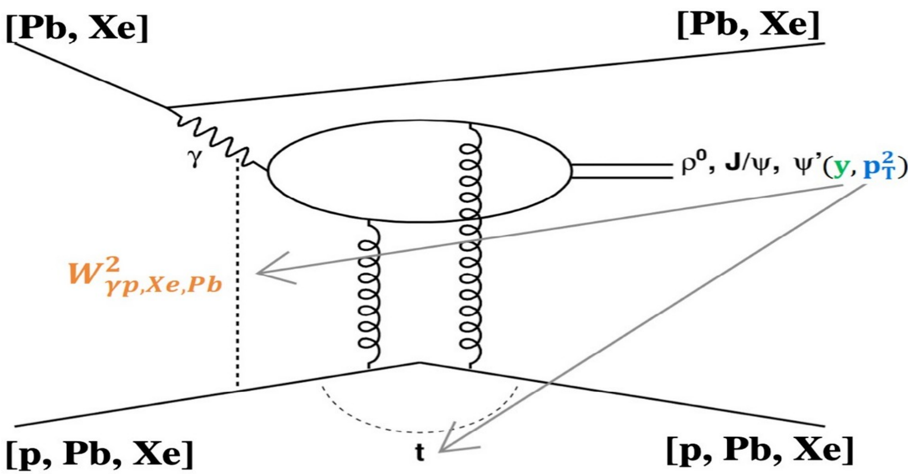
CGC at NLO

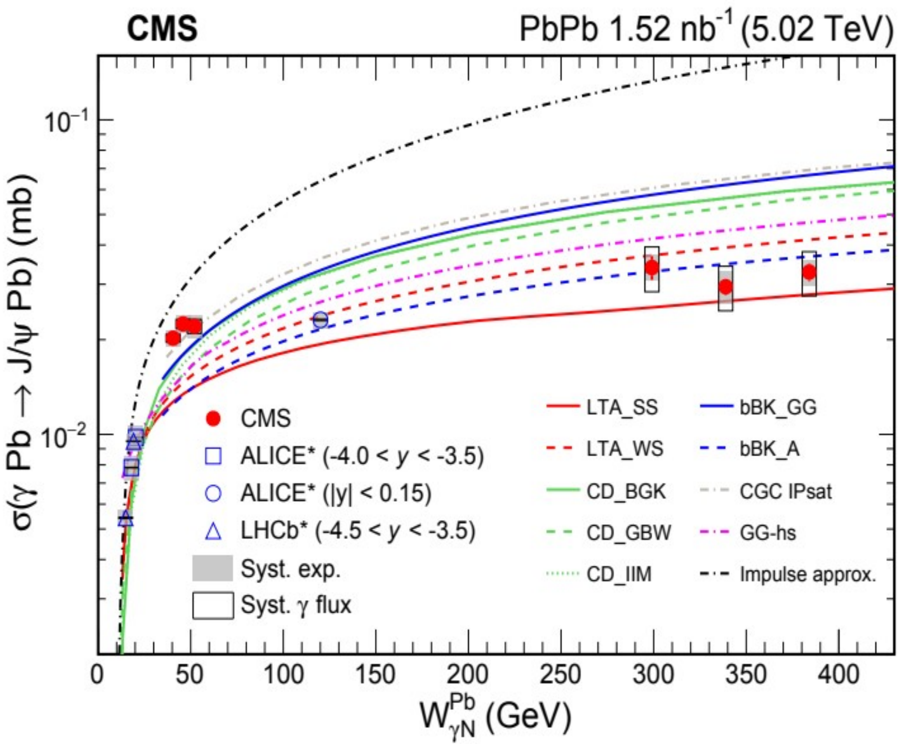
Single inclusive hadron production in pA collisions: LHCb



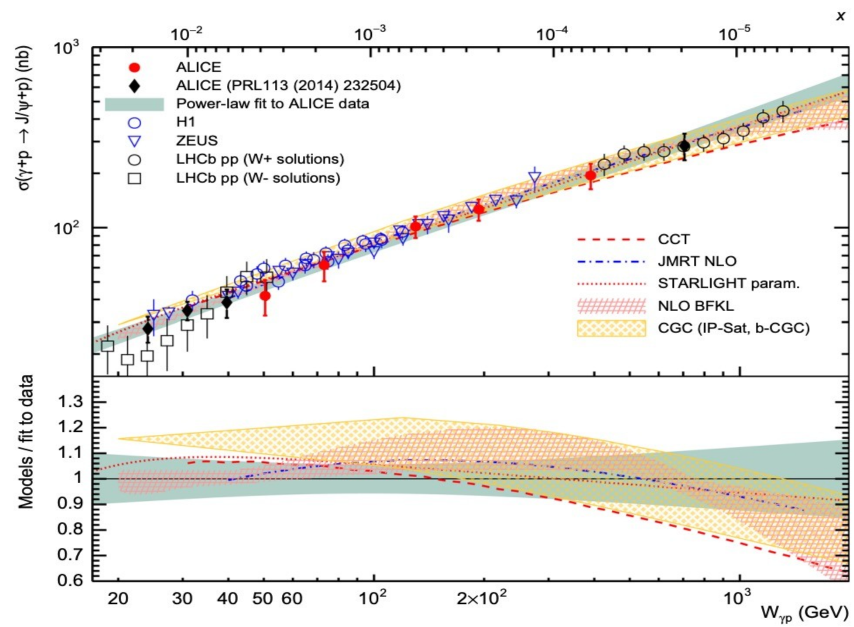
Shi, Wang, Wei and Xiao, arXiv:2112.06975

Ultra-peripheral collisions: coherent diffraction





figures from Wei Li (Wed.)



W dependence = evolution in x

initial condition (MV)

BK/JIMWLK evolution

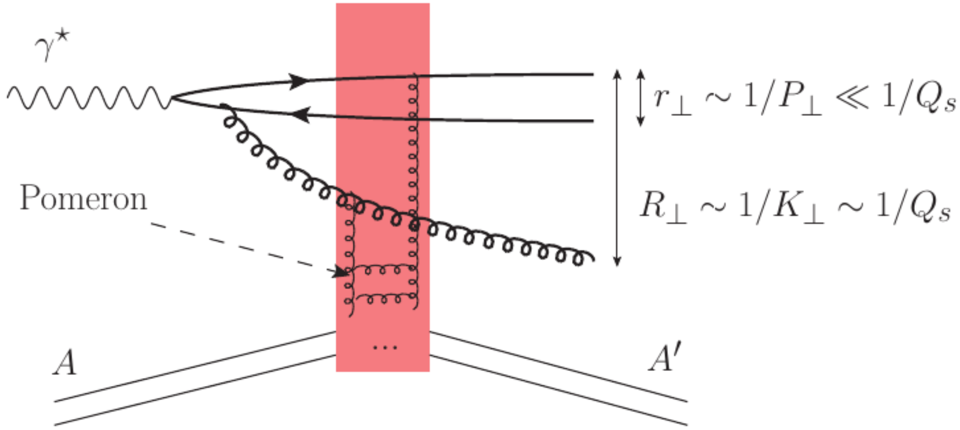
impact parameter diffusion!!

<u>cause for concern?</u>

CGC: promising signatures

2+1 diffractive jet production

- Hard $P_\perp \gg Q_s$ dijet + 1 semi-hard gluon jet $K_\perp \sim Q_s$ gives the dominant contribution to dijet diffractive events at large $P_\perp$.
- An $\mathcal{O}(\alpha_s)$ effect but leading twist!
- Strong sensitivity to saturation: effective gg dipole interacts strongly with the target.

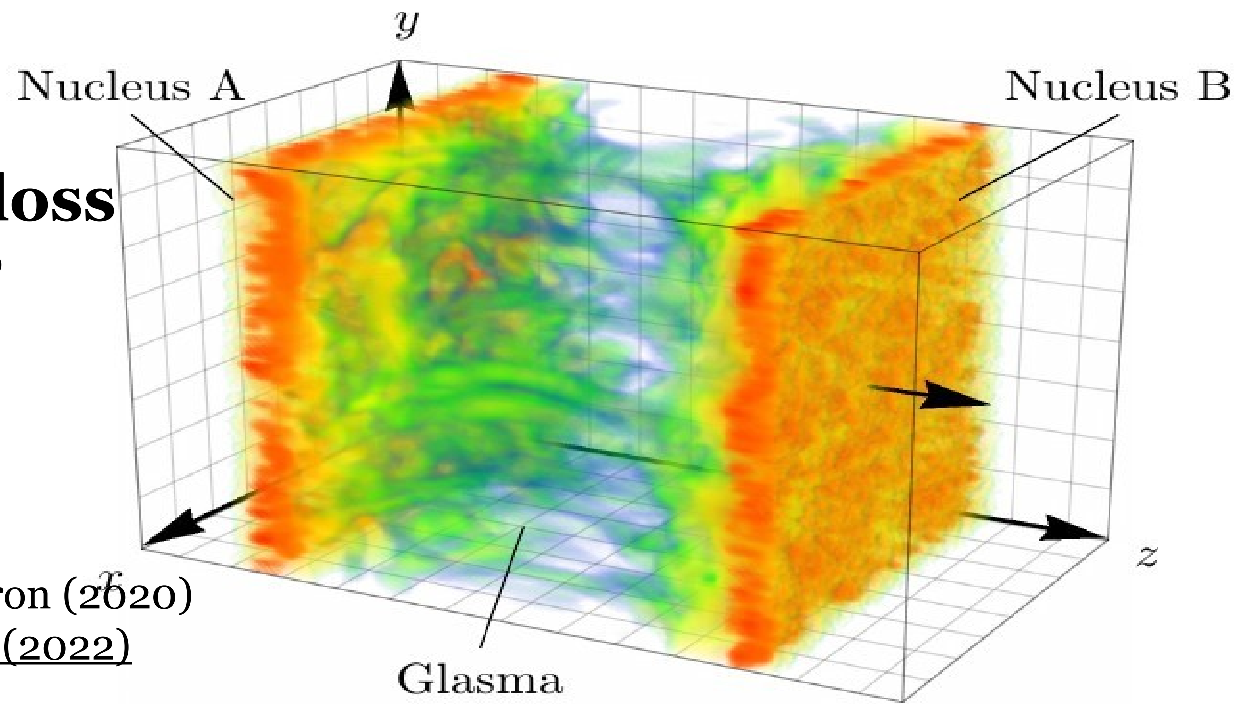


Iancu, Mueller, Triantafyllopoulos, 2112.06353

talk by Paul Caucal (Thurs.)

CGC: glasma

how important is eloss from glasma stage?



Ipp, Muller, Schuh (2020)
Boguslavski, Kurkela, Lappi, Peuron (2020)
Carrington, Czajka, Mrowczynski (2022)
……………………

Fig. by Ipp, Muller, arXiv:1703.00017

talk by Dana Avramescu (Tues.)

Overview talk by Kirill Boguslavski (Mon.)

need high p_t (large x) partons in CGC!

Not all is well!

cold matter eloss in forward rapidity region?

partially coherent, fully coherent,...

high density state but no (significant) evolution?

classical CGC?

small x is an extreme approximation

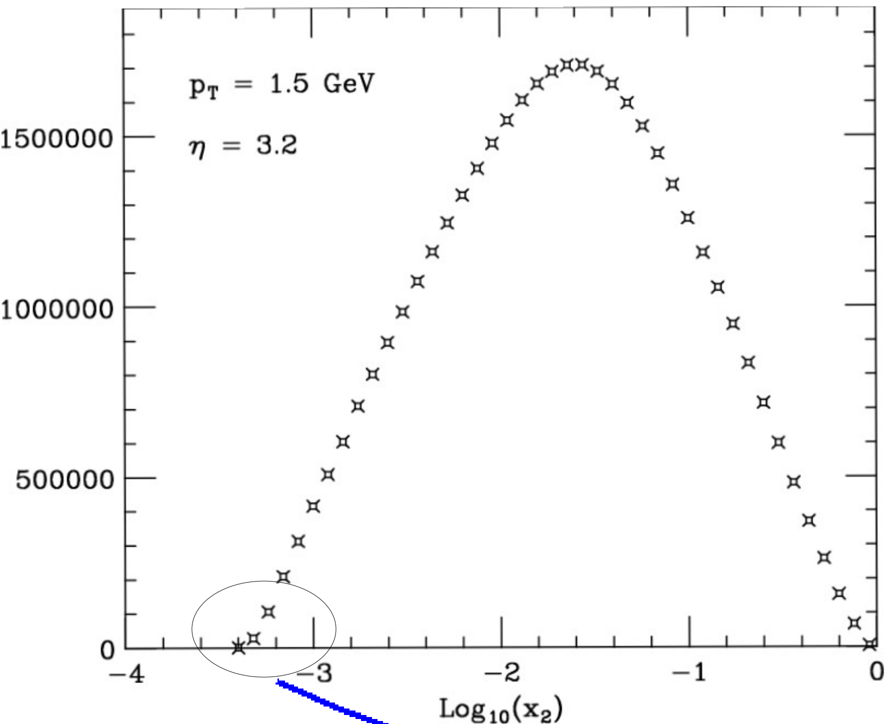
finite energy/large x corrections?

……

Single inclusive pion production in pp at RHIC

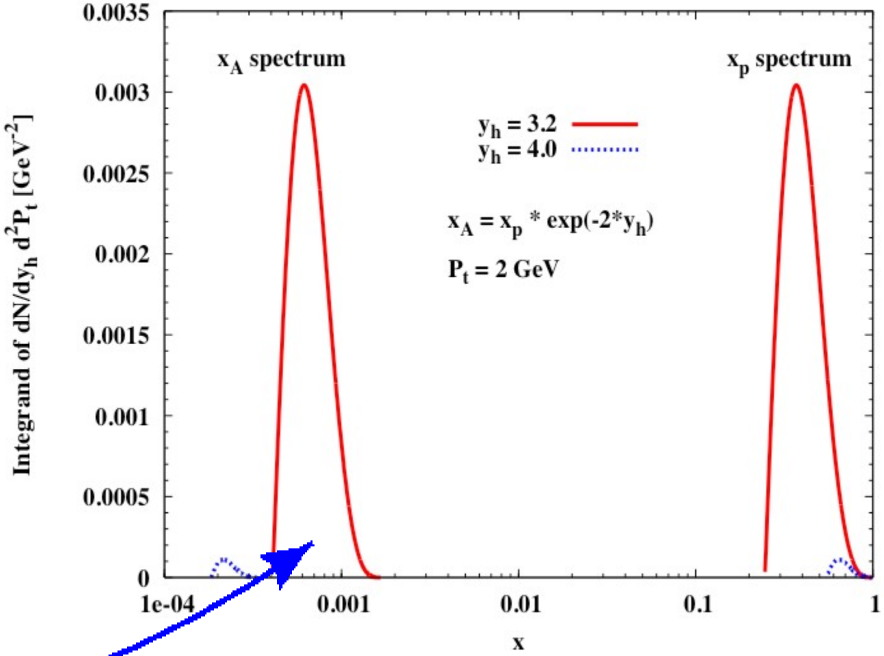
collinear factorization

GSV, PLB603 (2004) 173-183



CGC

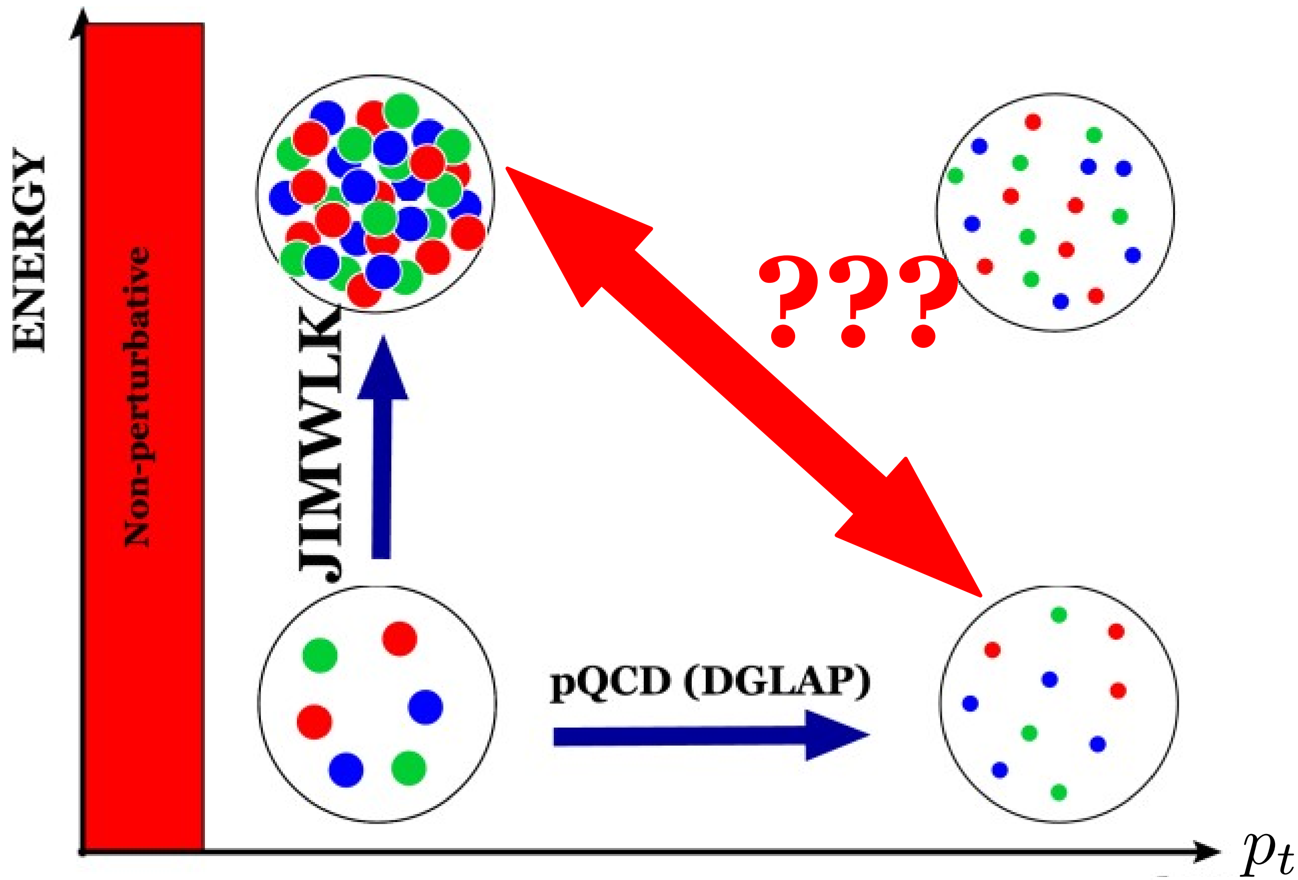
DHJ, NPA765 (2006) 57-70



$$\int_{x_{min}}^{1} dx\, xG(x, Q^2) \cdots\cdots \longrightarrow x_{min} G(x_{min}, Q^2) \cdots$$

which kinematics are we in?

QCD kinematic phase space

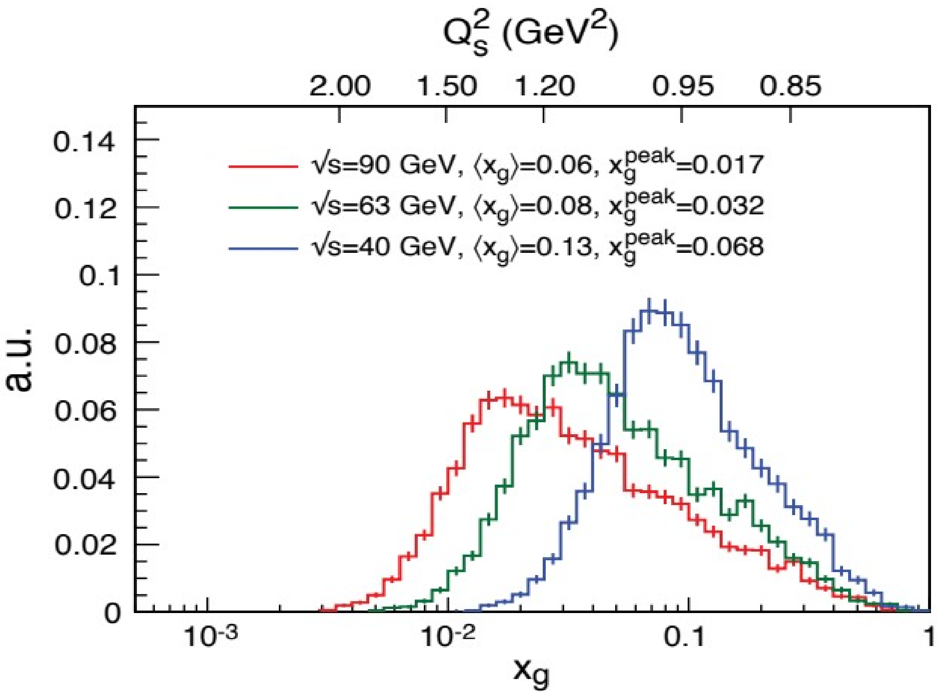


unifying saturation with high p_t (large x) physics?

kinematics of saturation: *where is saturation applicable?*
structure functions at all Q^2
high p_t particle production, forward-backward rapidity correlations
cold matter eloss, early time eloss in heavy ion collisions, spin asym. , ...

EIC

kinematics of double inclusive hadron production



Aschenauer et al. arXiv:1708.01527

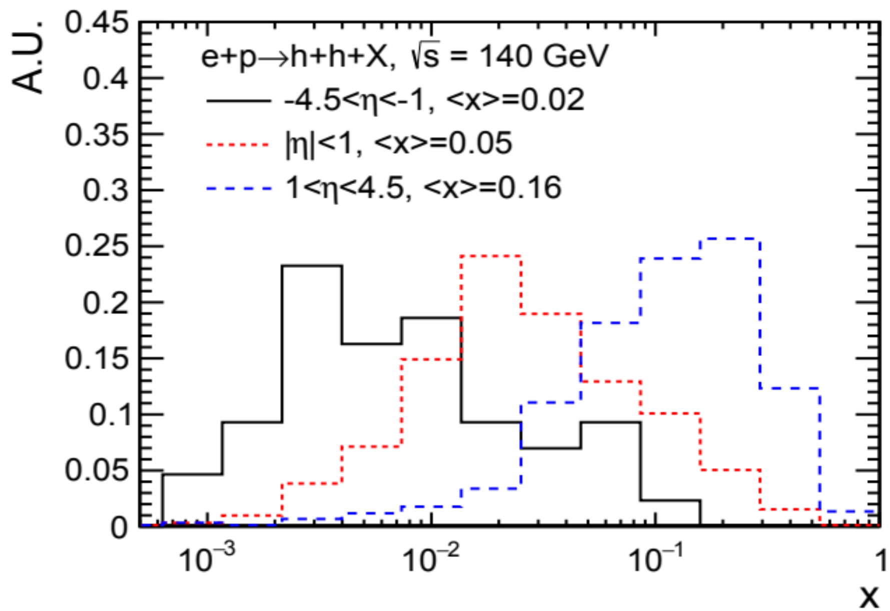
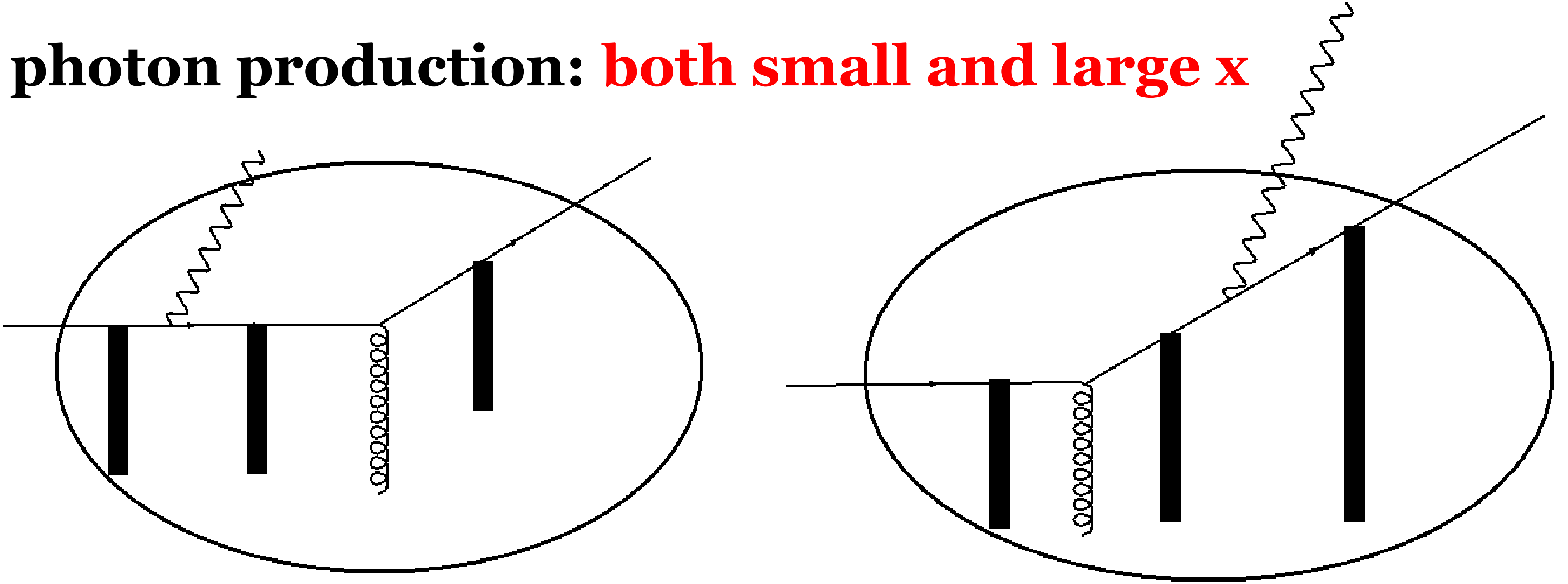
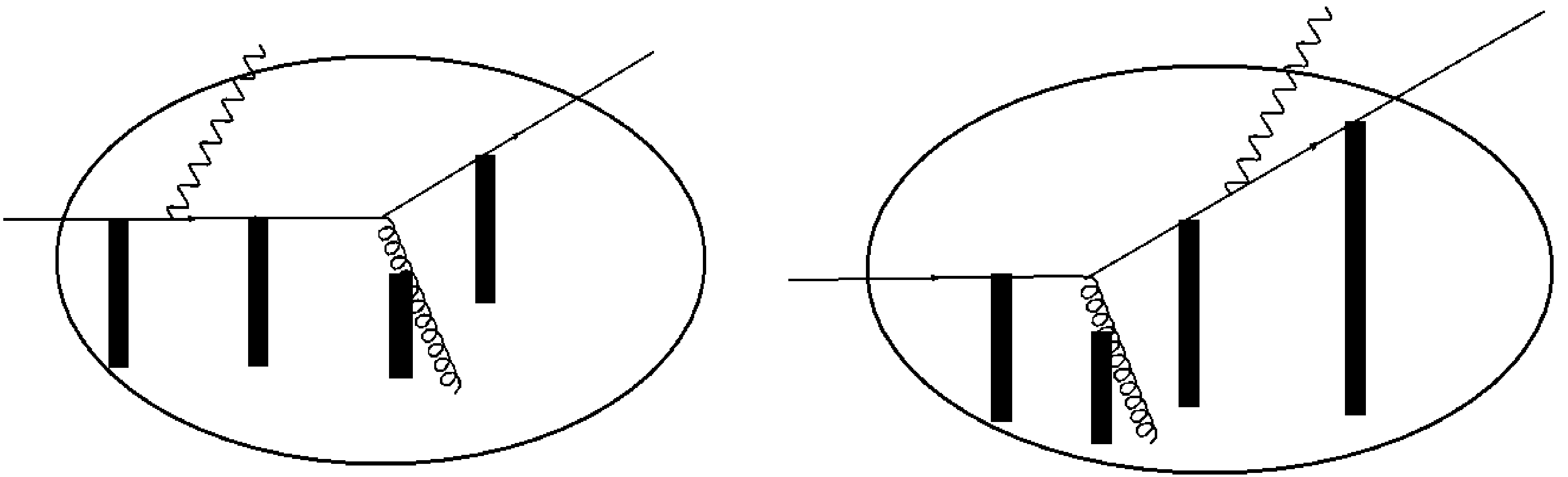


Fig. courtesy of Xiaoxuan Chu

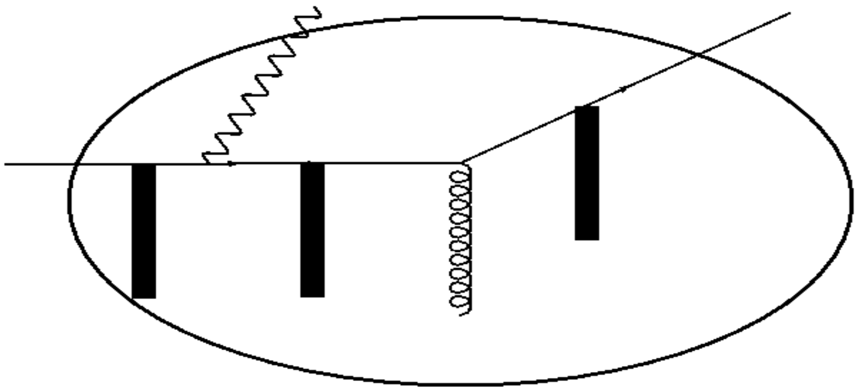
photon production: both small and large x

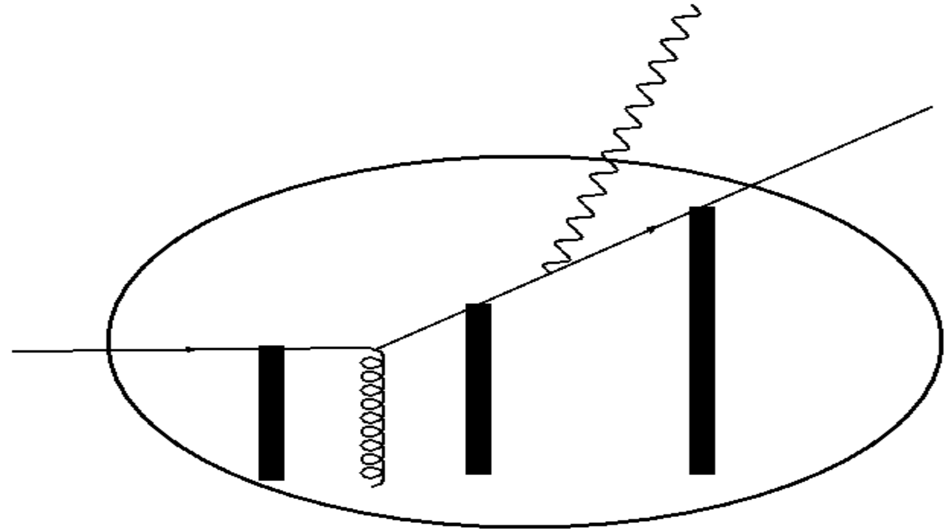


before hard scattering after hard scattering

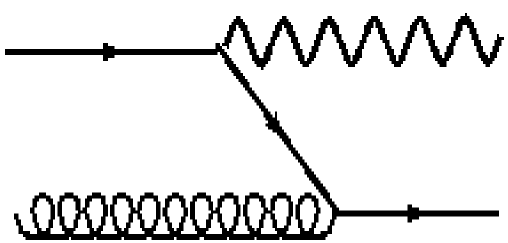


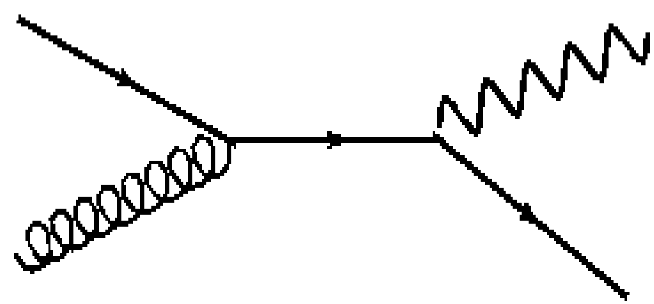
pQCD limit (large x: gluon PDF X partonic cross section):



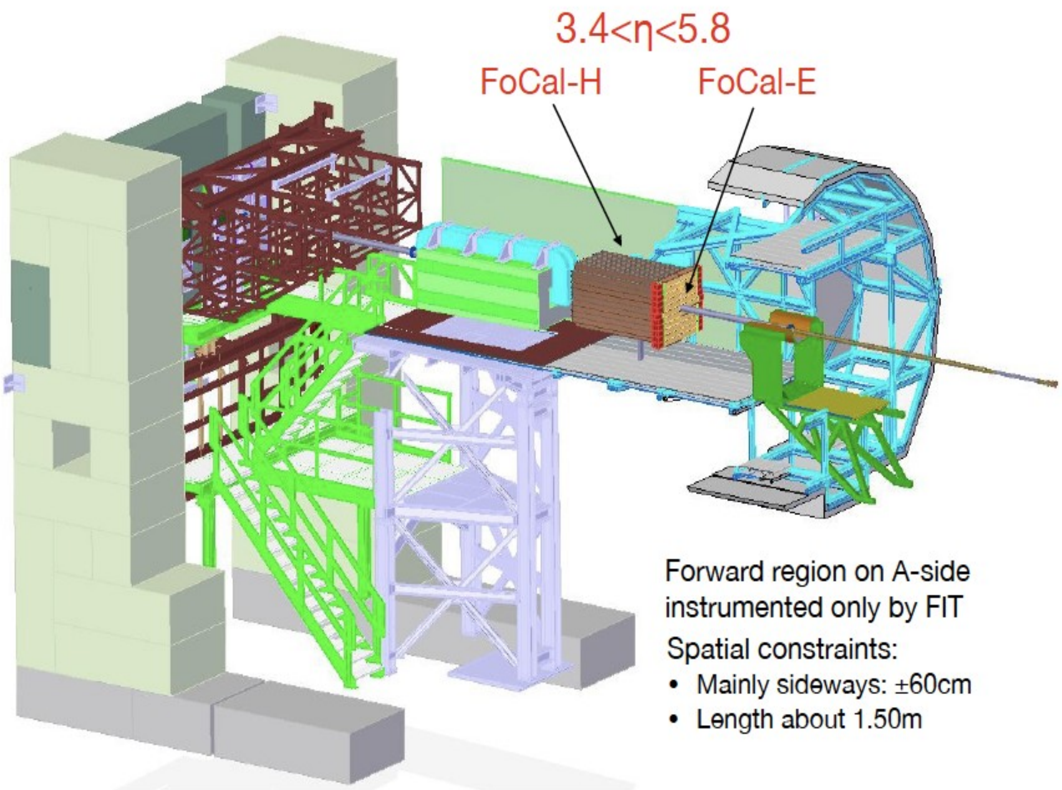


V = U = 1





The FoCal project



FoCal-E: high-granularity Si-W sampling sandwich calorimeter for photons and π^0

FoCal-H: conventional metal-scintillator sampling calorimeter for photon isolation and jets

Main physics goal:
Universal structure of matter at small-x

Observables
- π^0 and other neutral mesons
- Isolated (direct) photons
- Jets
- J/ψ, Υ (in UPC)
- Z, W
- Correlations

Letter-of-Intent: CERN-LHCC-2020-009

slide courtesy of P. Jacobs

SUMMARY

Exploring QCD dynamics via high energy collisions for 20+ years

pQCD: collinear factorization at asymptotically high p_t

CGC at asymptotically small x

each has its own advantages and shortcomings

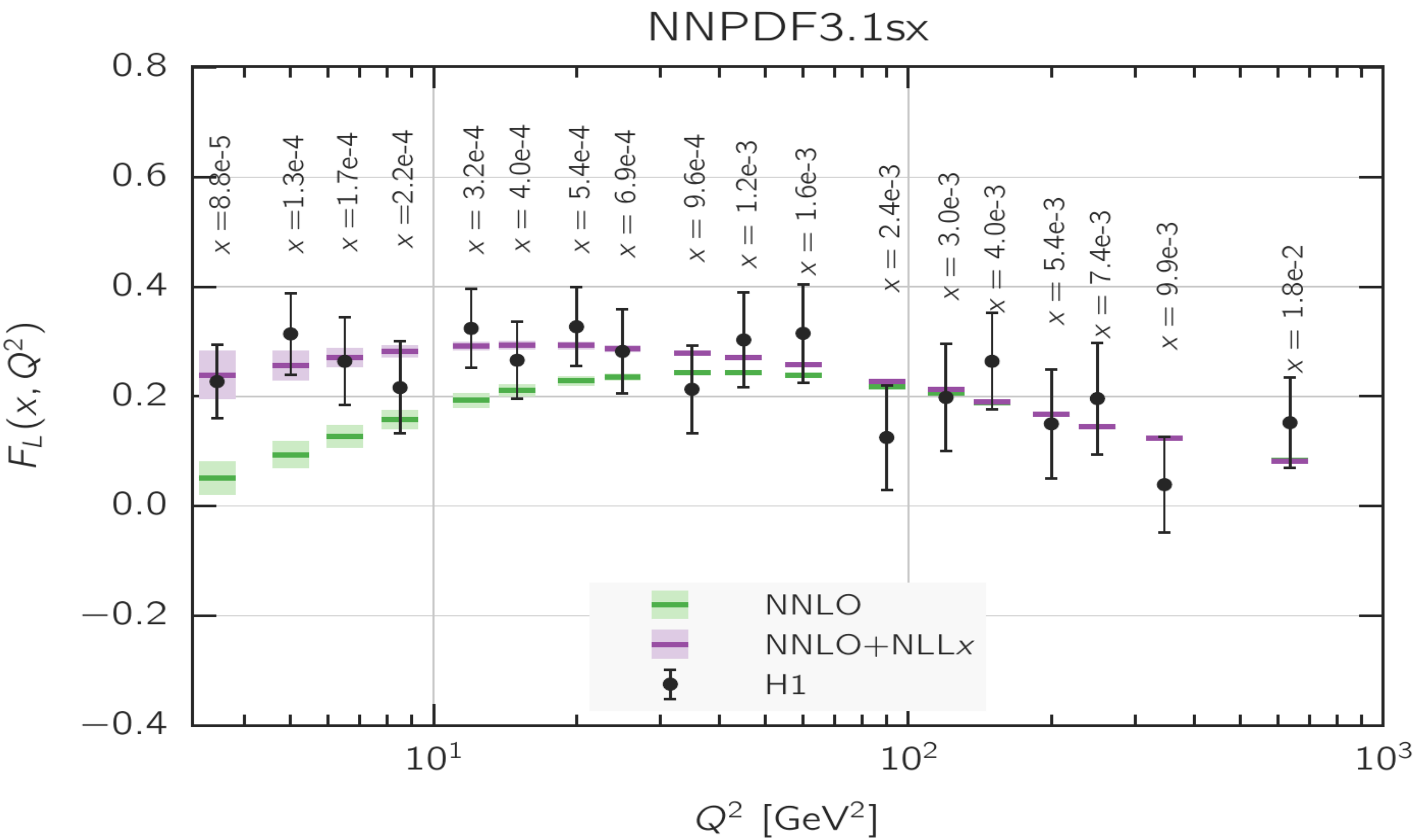
can they be unified?

New/upgraded detectors at RHIC

LHC will run for another ~20 years

Electron-Ion Collider is coming!

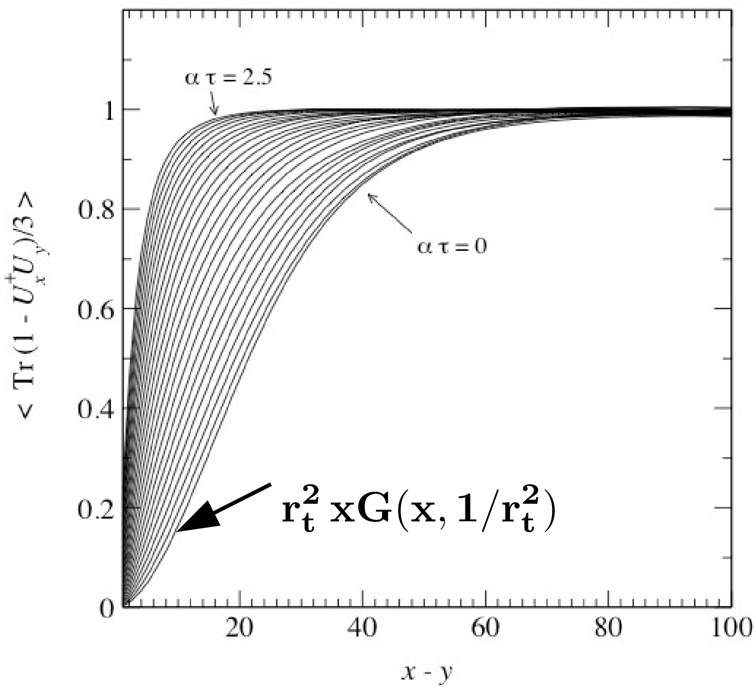
F_L at HERA, arXiv:1710.05935



Dipoles at large N_c : BK equation

$$\frac{d}{dy}T(x_t - y_t) = \frac{\bar{\alpha}_s}{2\pi}\int d^2z_t \frac{(x_t-y_t)^2}{(x_t-z_t)^2(y_t-z_t)^2}\left[T(x_t-z_t)+T(z_t-y_t)-T(x_t-y_t)-T(x_t-z_t)T(z_t-y_t)\right]$$

$$T(x_t, y_t) \equiv 1 - S(x_t, y_t) = \frac{1}{N_c}\mathrm{Tr}\left\langle 1 - V(x_t)V^\dagger(y_t)\right\rangle$$



$\tilde{T}(p_t) \to \log\left[\frac{Q_s^2}{p_t^2}\right]$ **saturation region**

$\tilde{T}(p_t) \to \frac{1}{p_t^2}\left[\frac{Q_s^2}{p_t^2}\right]^\gamma$ **extended scaling region**

$\tilde{T}(p_t) \to \frac{1}{p_t^2}\left[\frac{Q_s^2}{p_t^2}\right]$ **pQCD region**

Rummukainen-Weigert, NPA739 (2004) 183
NLO: Balitsky-Kovchegov-Weigert-Gardi-Chirilli (2007-2008)