U.S. DEPARTMENT OF ENERGY | Office of Science

SURGE COLLABORATION

OVERVIEW

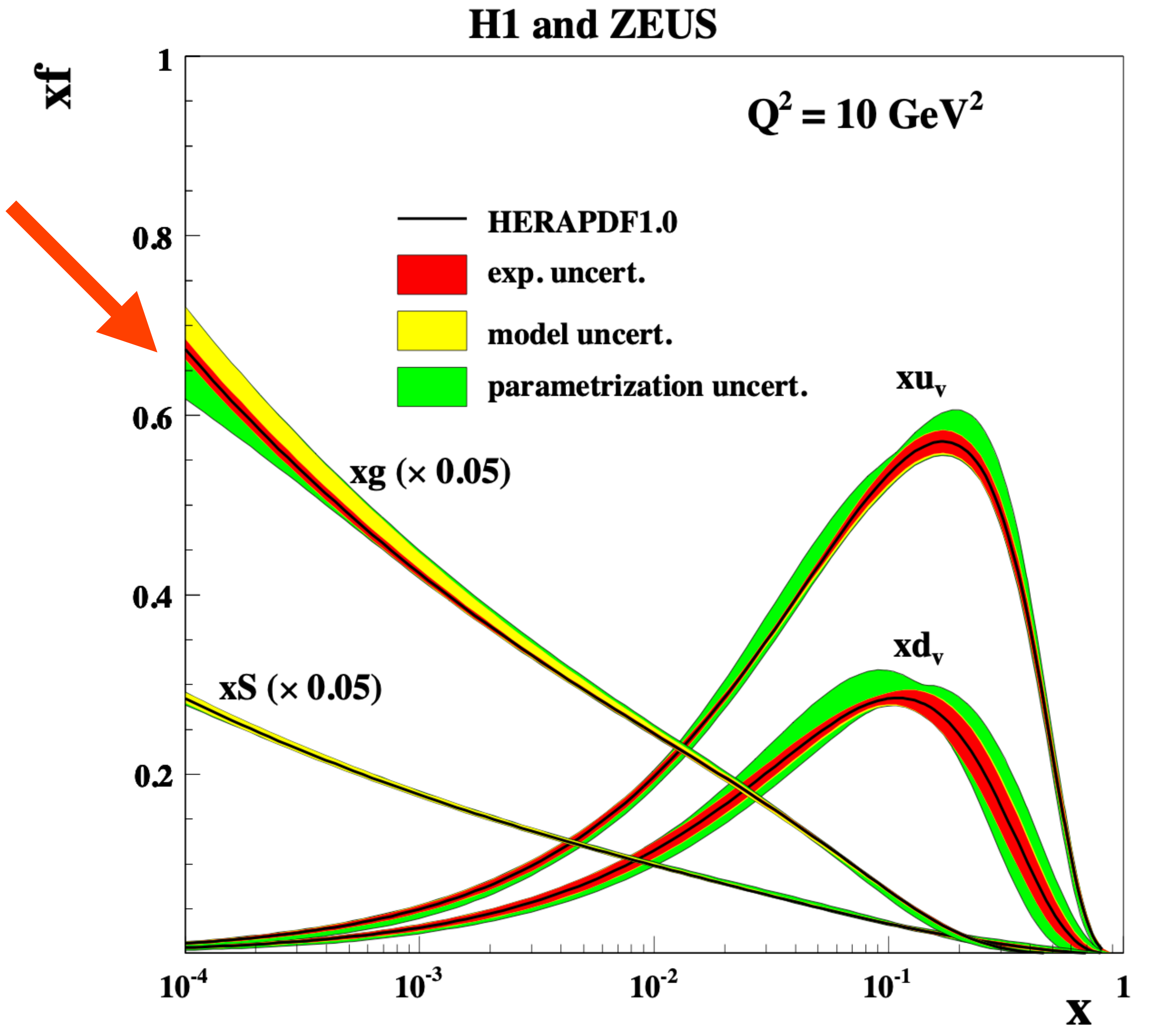
BJÖRN SCHENKE, BROOKHAVEN NATIONAL LABORATORY

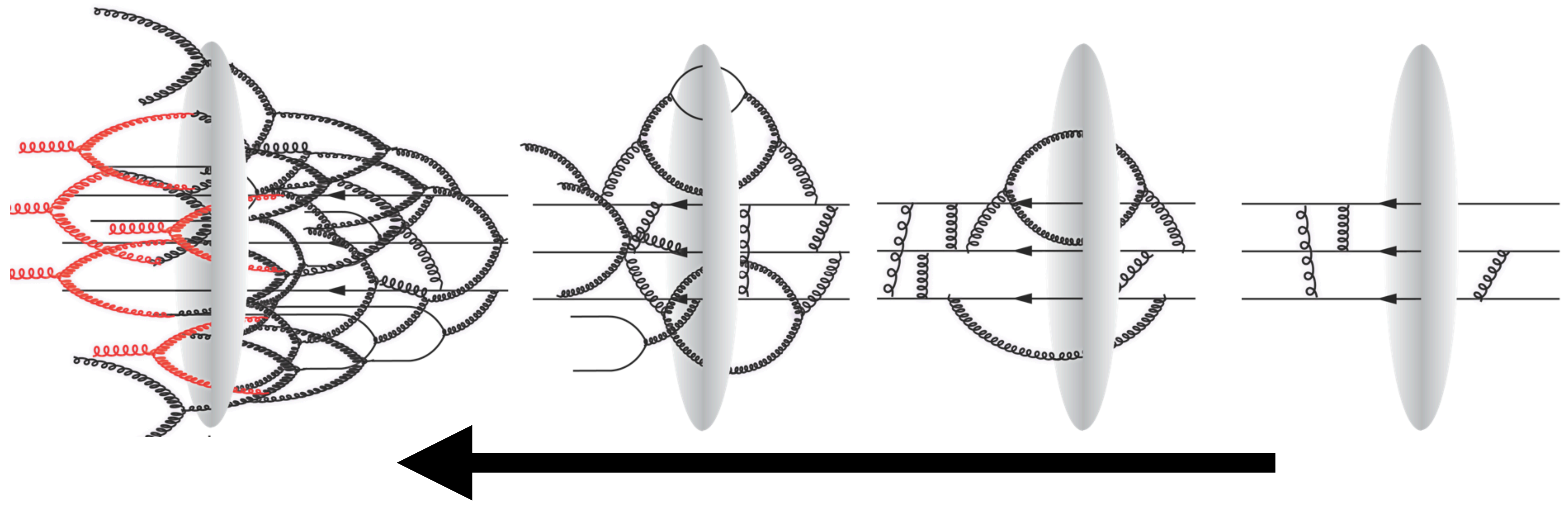
CFNS Summer School
CFNS, Stony Brook University
June 6, 2025

GLUON SATURATION

- At very small momentum fraction (x), the gluon density inside a proton grows so large that gluons begin to overlap
- Overlapping gluons recombine, balancing further splitting and “saturating” the density
- The saturation scale (Q_s) marks the momentum threshold below which the proton behaves as a dense, self-interacting gluon field

gluons

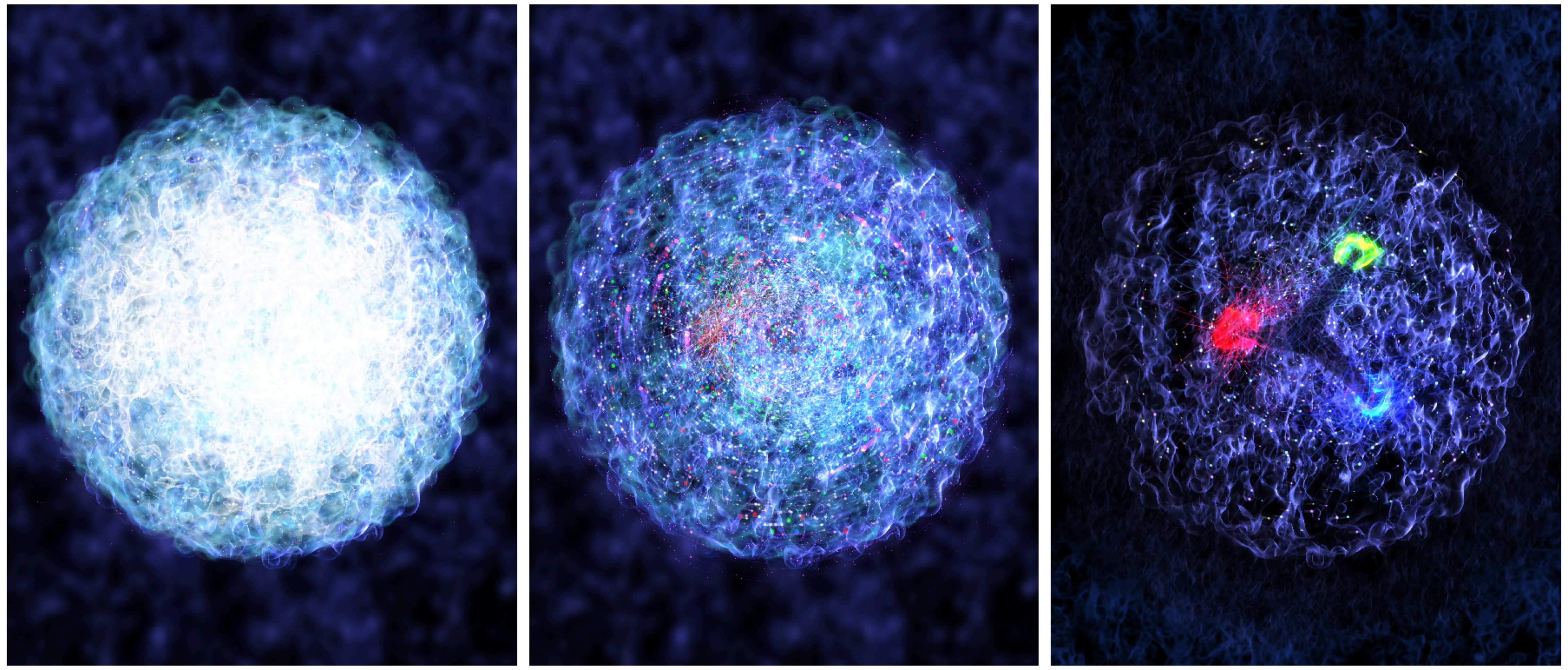




decreasing x

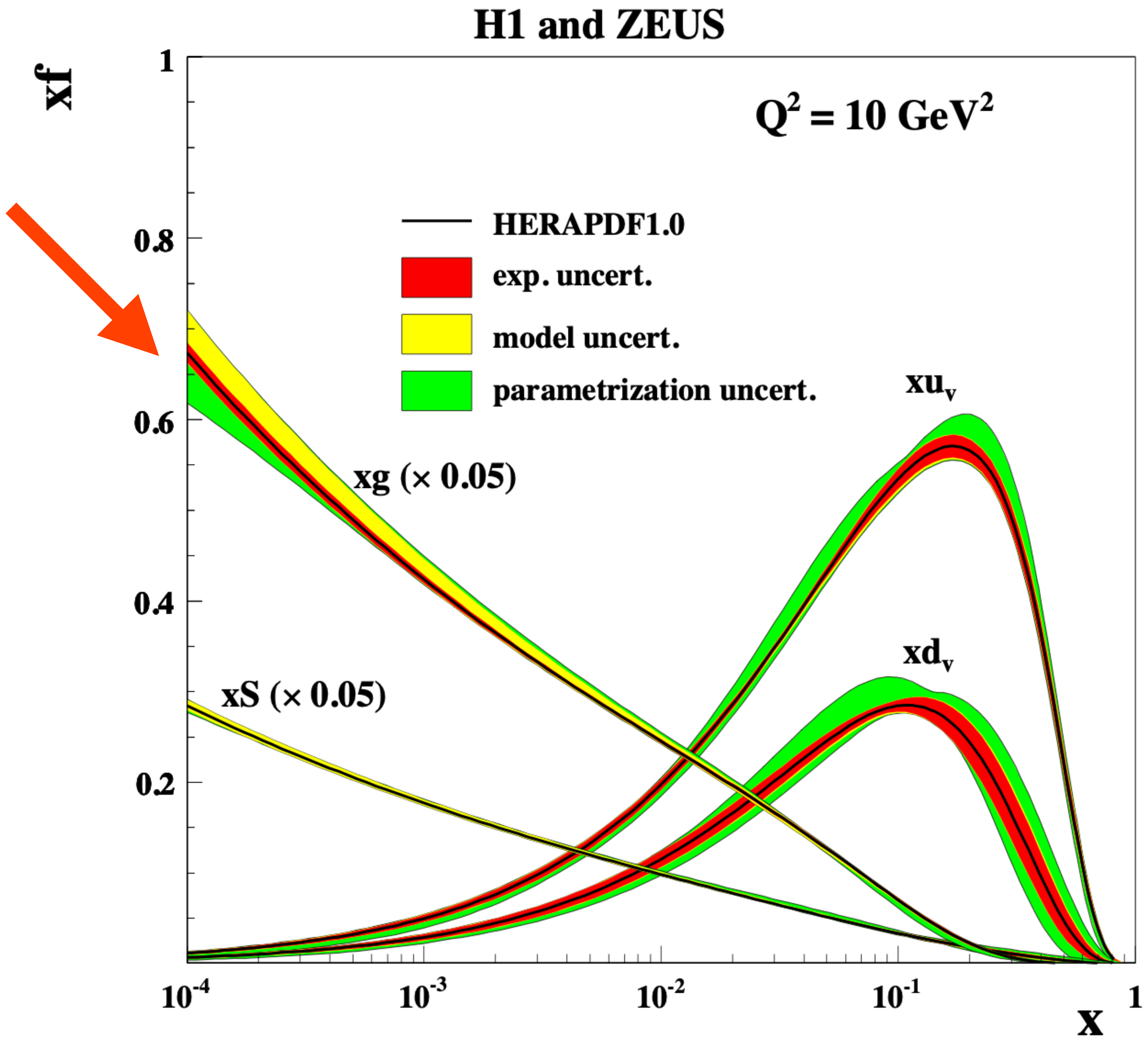
THE PROBLEM

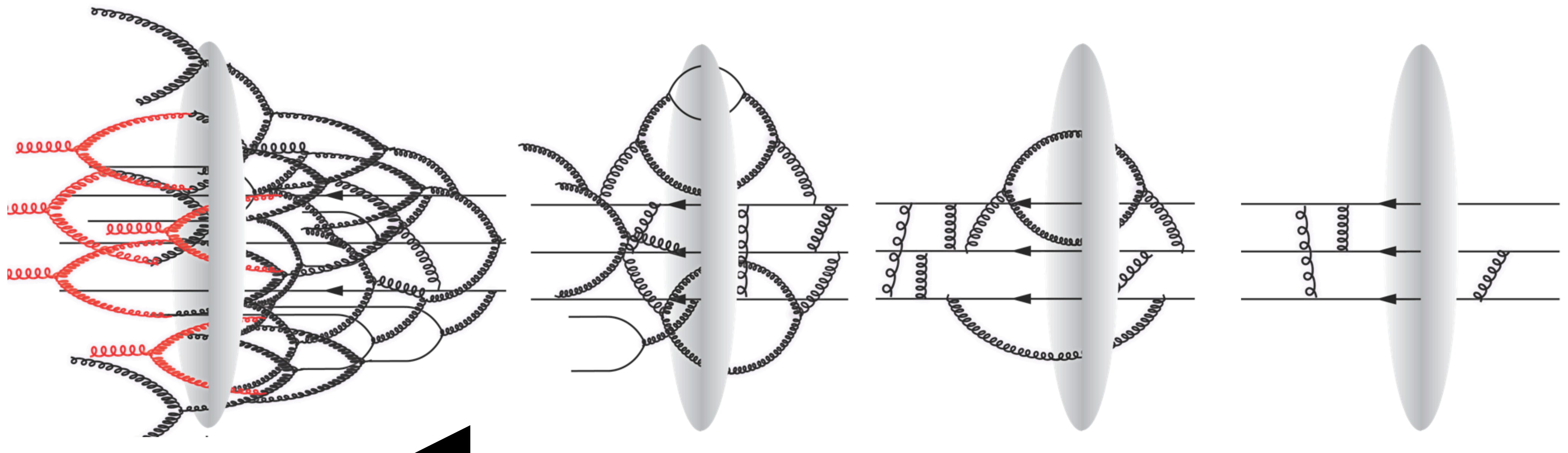
In nuclei at high energy, **gluon saturation** is expected on basic theoretical grounds. There are several hints in the experimental data. Yet, there has been no clear demonstration of saturation effects in observables at RHIC or LHC. Also, predictions for the EIC need to be made now, to maximize its impact.



Images courtesy of James LaPlante, Sputnik Animation in collaboration with the MIT Center for Art, Science & Technology and Jefferson Lab.

gluons





decreasing x

THE SOLUTION

A collaborative effort to identify the best observables, perform high precision calculations, and embed them in a comprehensive numerical framework that allows for direct comparison to experimental data and ultimately global analysis, to demonstrate the presence of gluon saturation effects

MEMBERS

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Lebanon Valley College
UIUC
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MEMBERS

SURGE COLLABORATION

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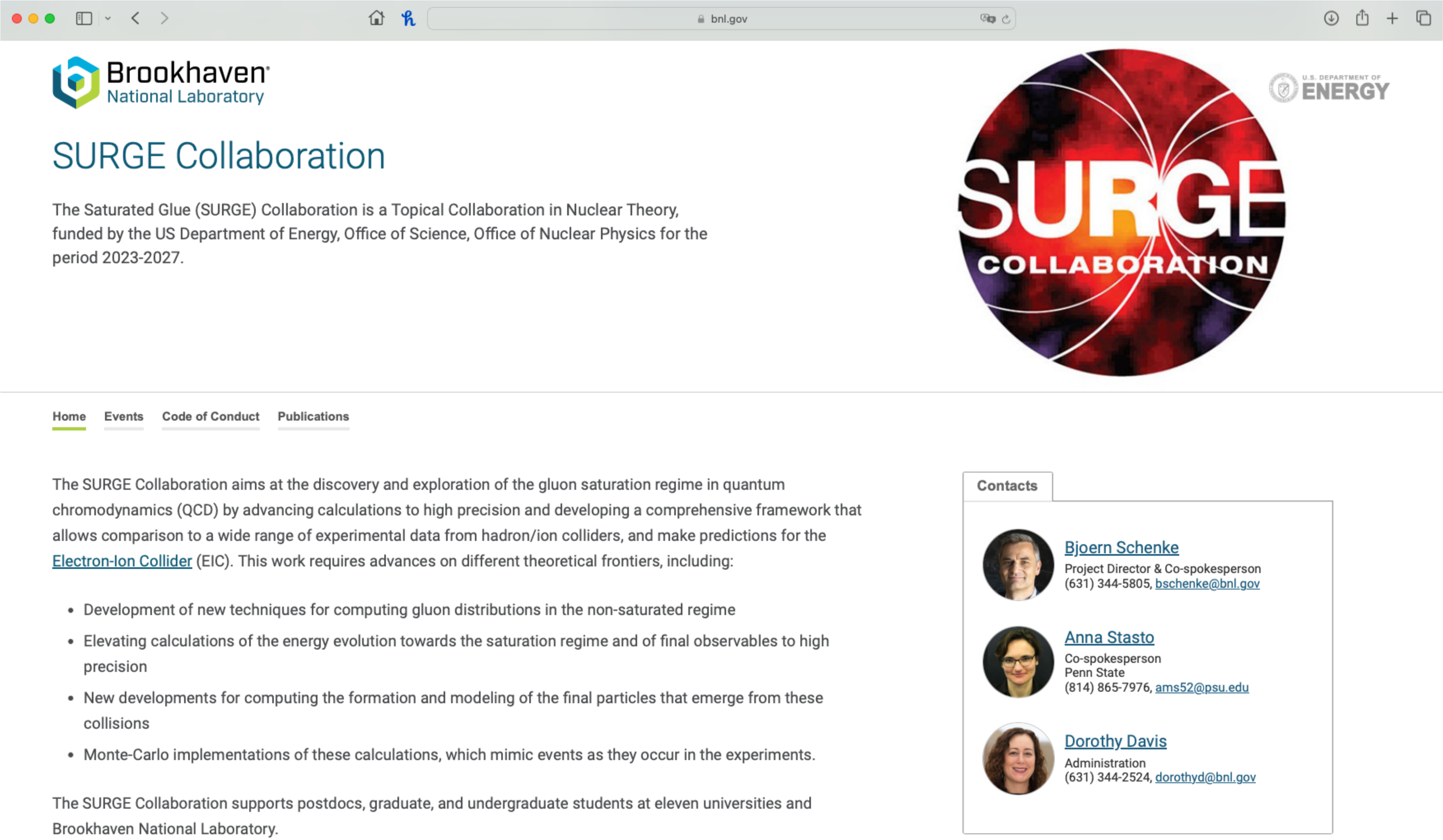
Penn State University
A. Stasto *†

*=Steering Committee, †=co-spokesperson

SURGE WEBSITE

HTTPS://WWW.BNL.GOV/PHYSICS/SURGE/



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SURGE Collaboration

The Saturated Glue (SURGE) Collaboration is a Topical Collaboration in Nuclear Theory, funded by the US Department of Energy, Office of Science, Office of Nuclear Physics for the period 2023-2027.

SURGE COLLABORATION

Home Events Code of Conduct Publications

The SURGE Collaboration aims at the discovery and exploration of the gluon saturation regime in quantum chromodynamics (QCD) by advancing calculations to high precision and developing a comprehensive framework that allows comparison to a wide range of experimental data from hadron/ion colliders, and make predictions for the Electron-Ion Collider (EIC). This work requires advances on different theoretical frontiers, including:

- Development of new techniques for computing gluon distributions in the non-saturated regime
- Elevating calculations of the energy evolution towards the saturation regime and of final observables to high precision
- New developments for computing the formation and modeling of the final particles that emerge from these collisions
- Monte-Carlo implementations of these calculations, which mimic events as they occur in the experiments.

The SURGE Collaboration supports postdocs, graduate, and undergraduate students at eleven universities and Brookhaven National Laboratory.

Contacts

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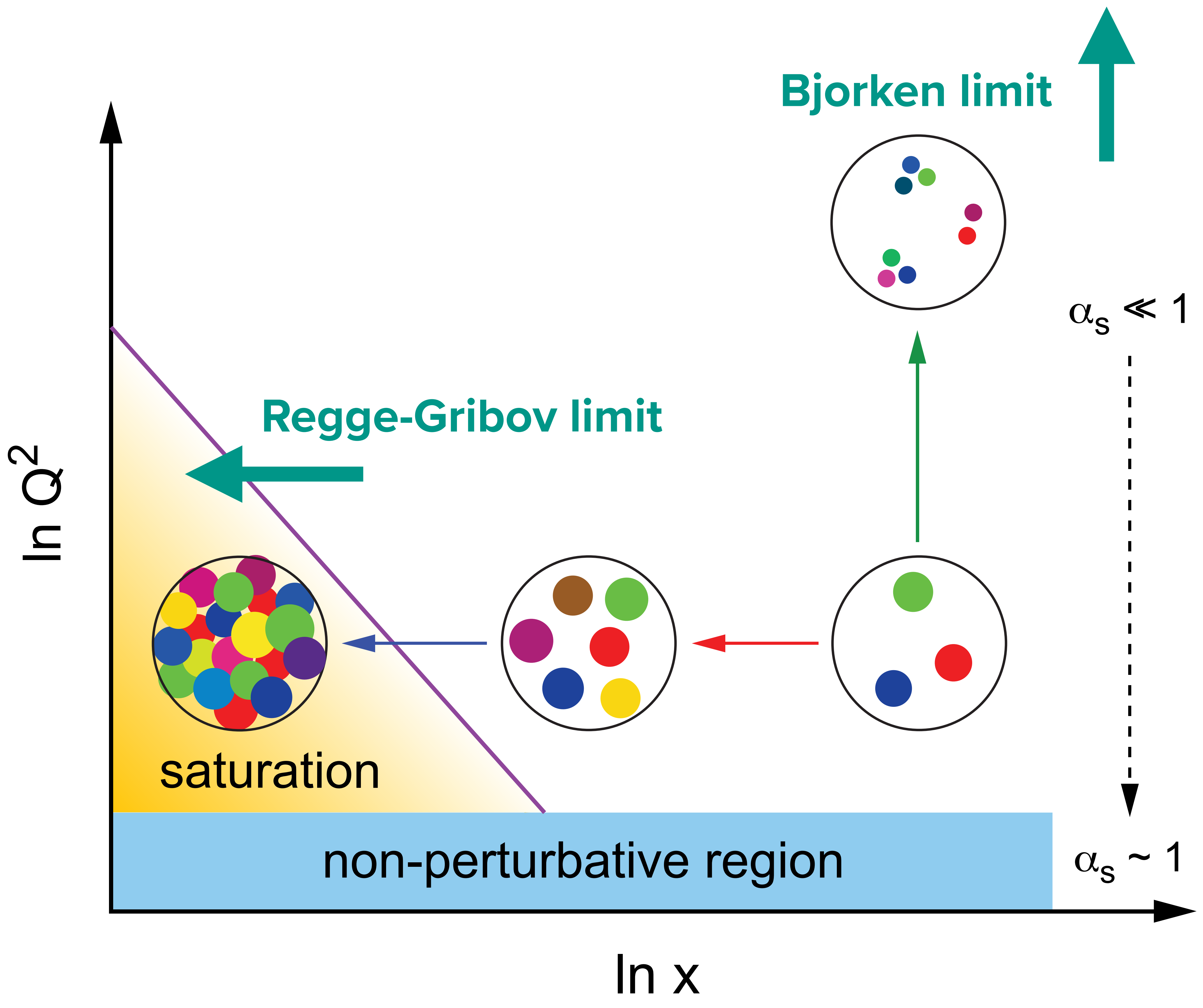
GOING TO HIGH ENERGY

Two high energy limits: $s \to \infty$ (center of mass energy goes to infinity, $s \propto Q^2/x$)

- Bjorken limit: fixed x, $Q^2 \to \infty$
- Regge-Gribov limit: fixed Q^2, $x \to 0$

- In the Regge-Gribov limit gluons overlap, leading to a maximal occupation number of $1/\alpha_s$
- This bound is saturated for gluons with transverse momenta $k_\perp \leq Q_s$
- $Q_s(x)$ is the "saturation scale"



COLOR GLASS CONDENSATE EFFECTIVE THEORY

McLerran, Venugopalan (PRD 1994 milestone)

The **Color Glass Condensate (CGC)** is the description of the properties of saturated gluons in the Regge-Gribov limit ($s \to \infty$, fixed Q^2, $x \to 0$)

Effective degrees of freedom: color sources ρ at large x and gauge fields at small x

- A probe will see large x degrees of freedom (modes with larger longitudinal momentum than the probe) as static and localized
- Small x degrees of freedom need to be treated dynamically

COLOR GLASS CONDENSATE EFFECTIVE THEORY

Leading order is purely classical and can be expressed by solutions of Yang-Mills equations (like Maxwell equations in electrodynamics):

$$[D_\mu, F^{\mu\nu}] = J^{\nu,a} t^a$$

field strength tensor containing dynamical gluon fields

current generated by moving sources

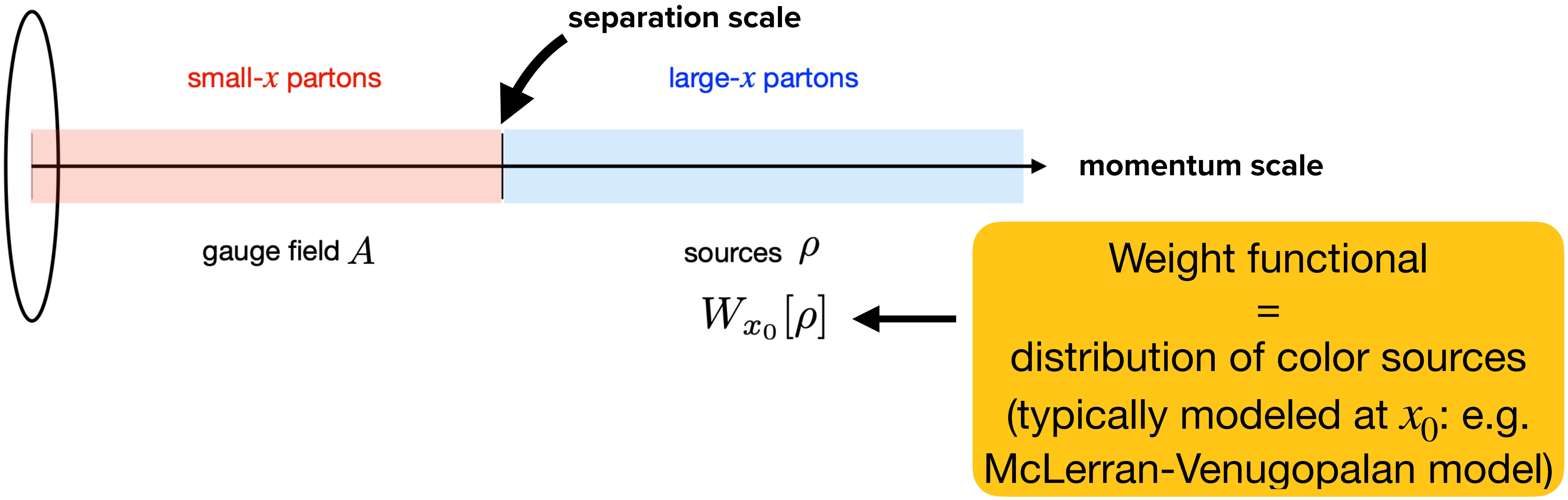
a is the color index of the gluon
the name "**color**" comes from this

These dynamical gluon fields are the small $x < x_0$ degrees of freedom

Gluon fields' occupation number is large $\langle AA \rangle \sim 1/\alpha_s$

name "**condensate**" comes from this scaling

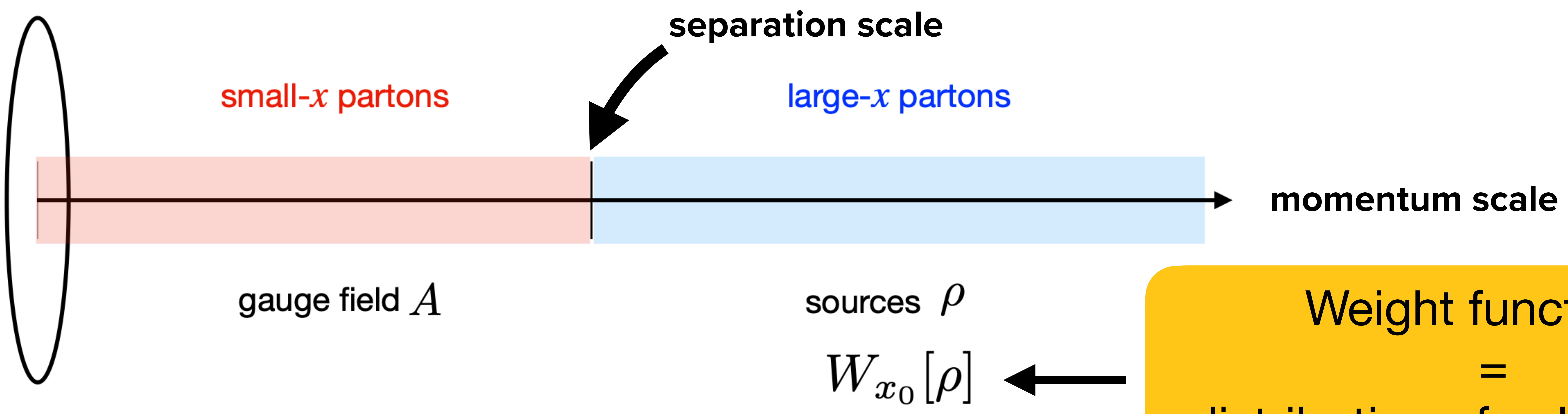
COLOR GLASS CONDENSATE EFFECTIVE THEORY



1) Sources ρ are frozen over the duration of a collision

2) But they fluctuate from “event to event”

COLOR GLASS CONDENSATE EFFECTIVE THEORY



Weight functional
=
distribution of color sources
(typically modeled at x_0: e.g. McLerran-Venugopalan model)

Two steps to compute expectation value of an observable $\mathcal{O}$:

1) Compute quantum expectation value $\mathcal{O}[\rho] = \langle \mathcal{O} \rangle_\rho$ for sources drawn from a given $W_{x_o}[\rho]$

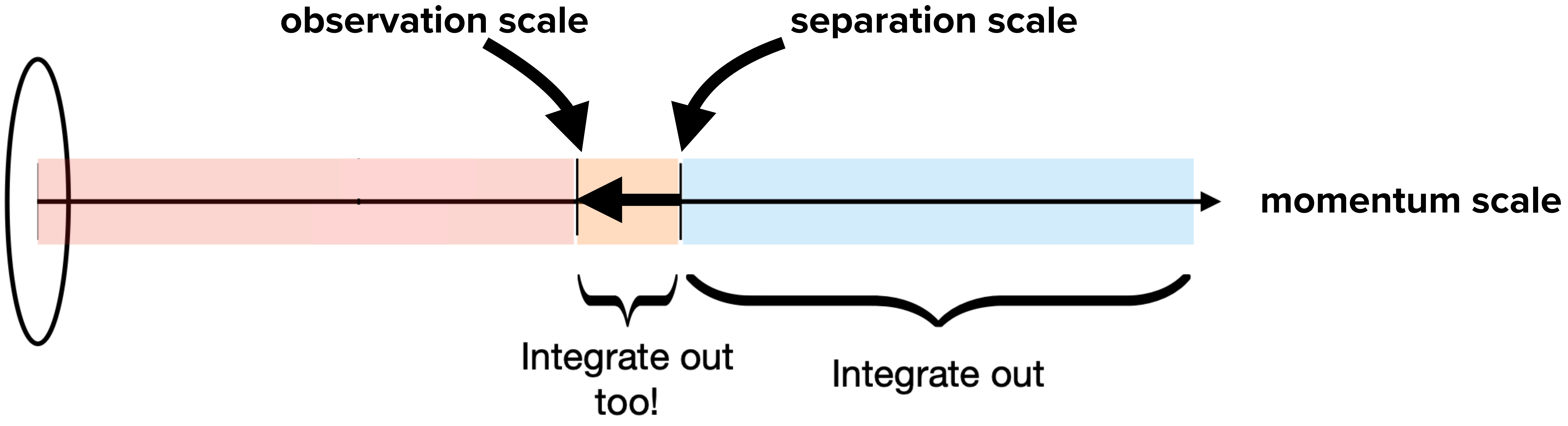
2) Average over all possible configurations given by the weight functional $W_{x_o}[\rho]$

this situation is similar to spin glasses - the name “**glass**” comes from this

COLOR GLASS CONDENSATE EFFECTIVE THEORY

A functional renormalization group equation (JIMWLK) describes how the statistical distribution $W[\rho]$ evolves with decreasing x

Jalilian-Marian, McLerran, Weigert, Leonidov, Kovner (1997-2001)



Weakly coupled fields integrated out at a given step in the evolution are interpreted as “induced color charges” that modify the statistical weight distribution $W_{x_0}[\rho] \to W_{x_1}[\rho]$

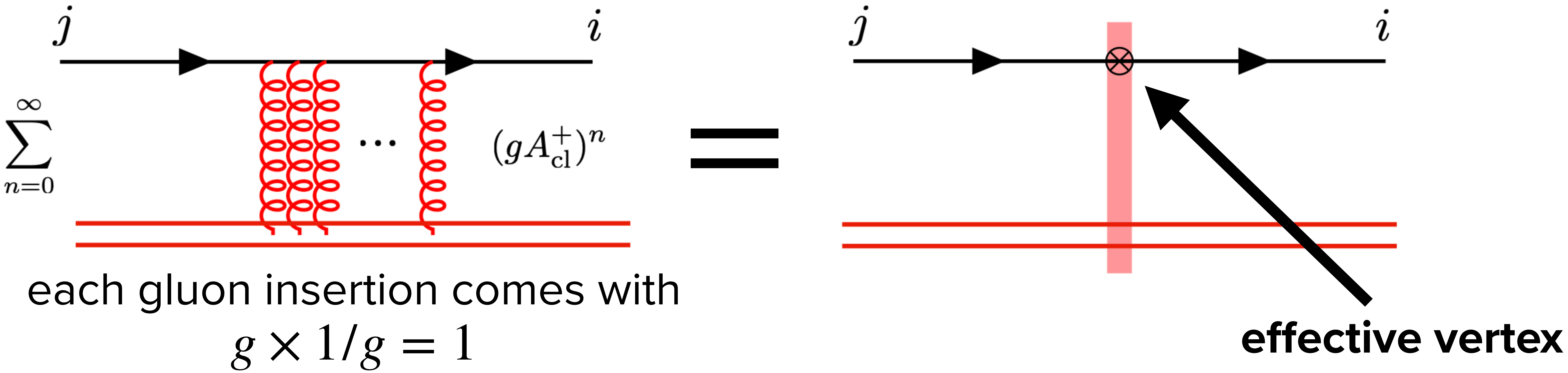
COLOR GLASS CONDENSATE EFFECTIVE THEORY

Interaction of high energy color-charged particle with a classical field of a nucleus can be described in the eikonal approximation:

The scattering rotates the color, but keeps longitudinal momentum, transverse position, and any other quantum numbers the same

MULTIPLE INTERACTIONS NEEDED TO BE RESUMMED, BECAUSE GLUON FIELDS ARE HIGHLY OCCUPIED

$$A \sim 1/g$$



each gluon insertion comes with

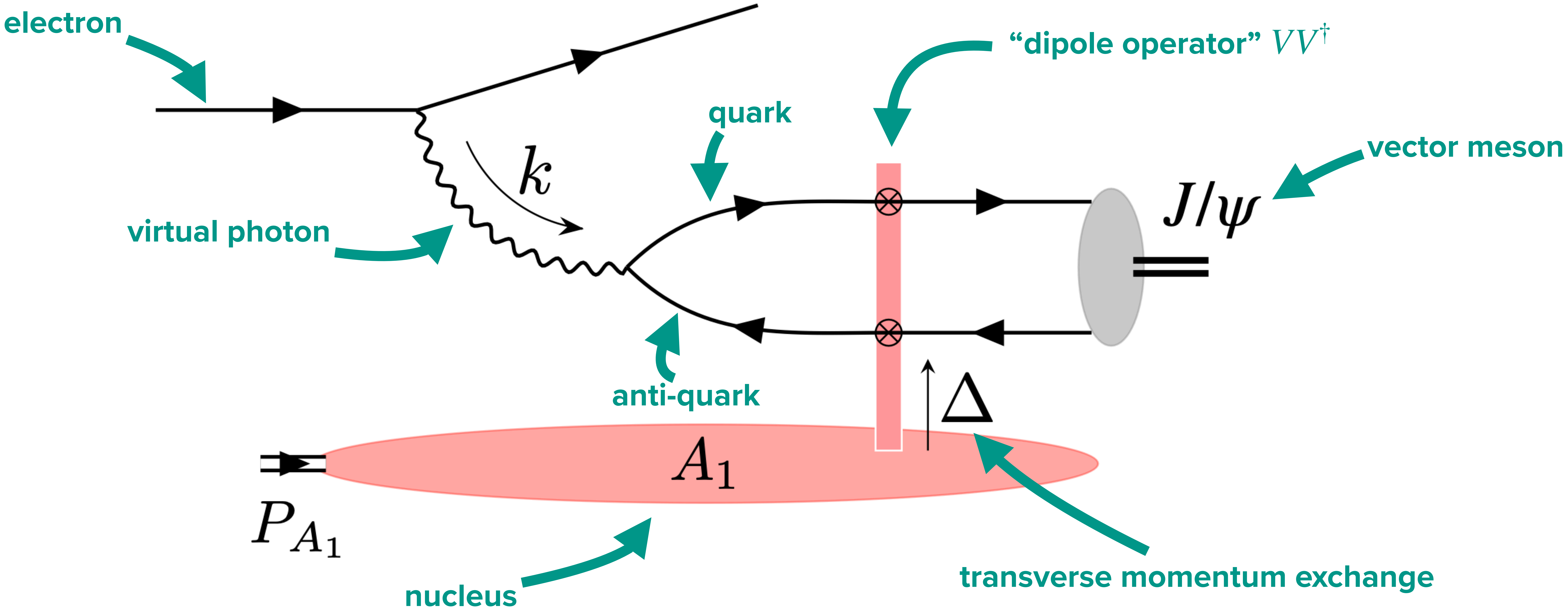
$$g \times 1/g = 1$$

The effective vertex is expressed by a *Wilson line* V:
Represents resummed multiple interaction with the gluon fields of the target

COMPUTING PHYSICAL PROCESSES

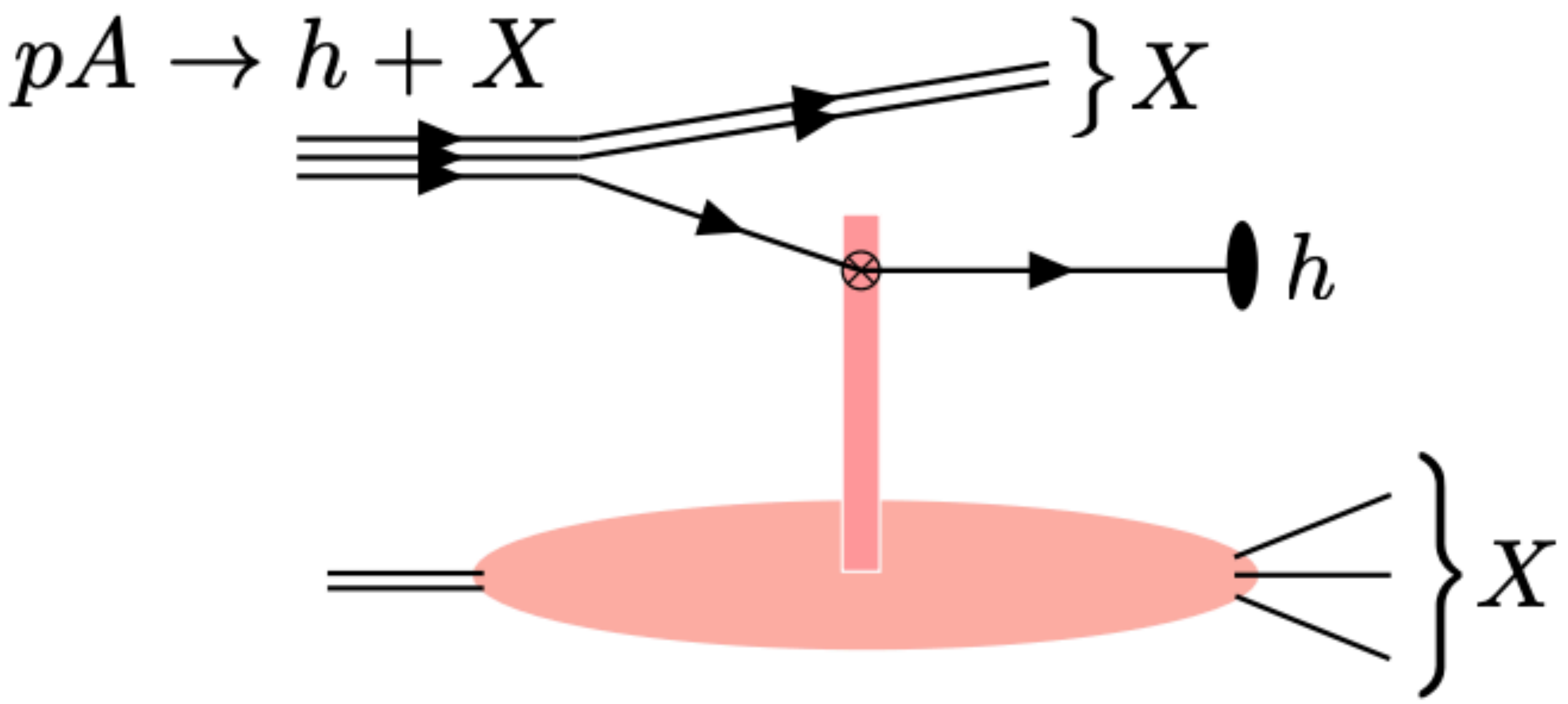
Interactions depend on operators consisting of the Wilson lines

For example: e + A → e + A + vector meson (**exclusive** vector meson production)

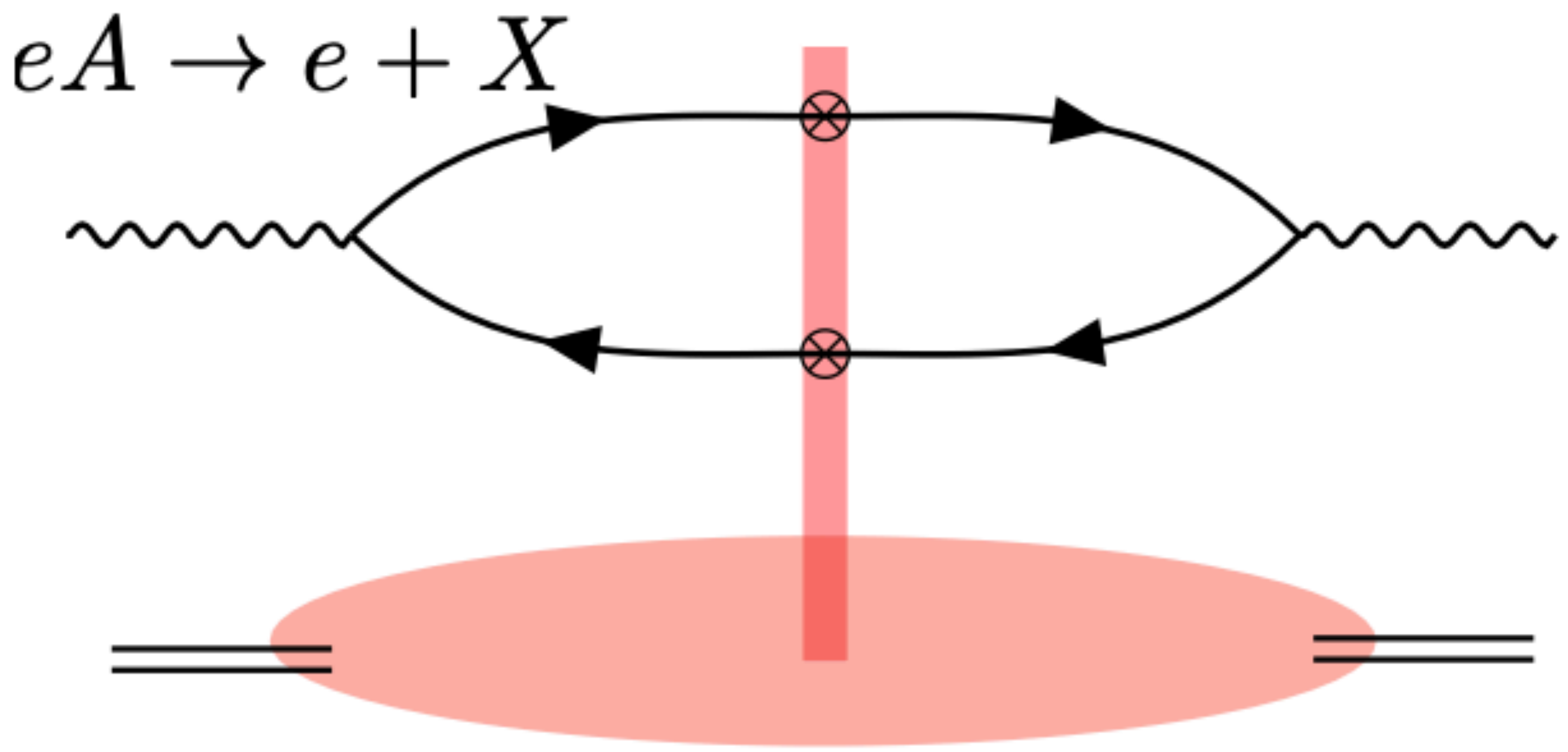


COMPUTING PHYSICAL PROCESSES

Can compute many other processes, for example:



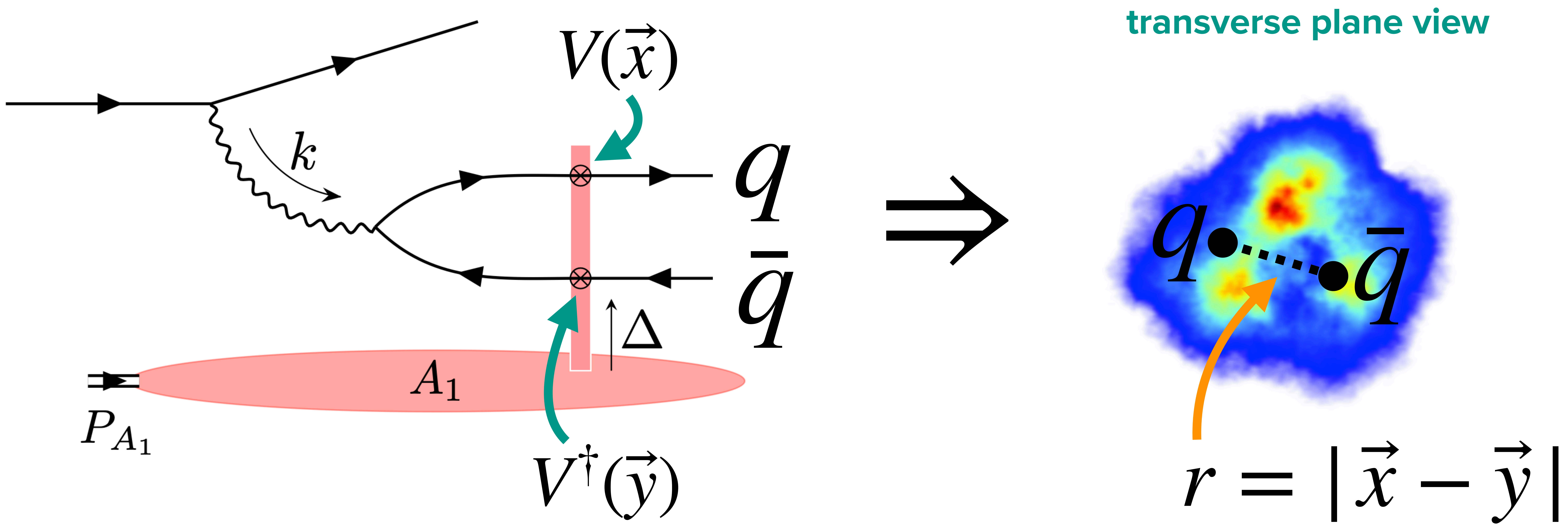
Hadron production in proton + nucleus collisions



Inclusive e+A scattering

Can even use the gluon fields of nuclei computed in the CGC
as initial state for heavy-ion collisions

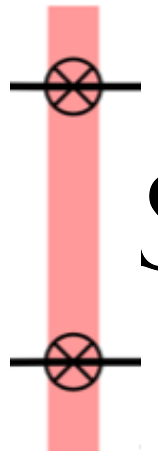
DIPOLE AMPLITUDE



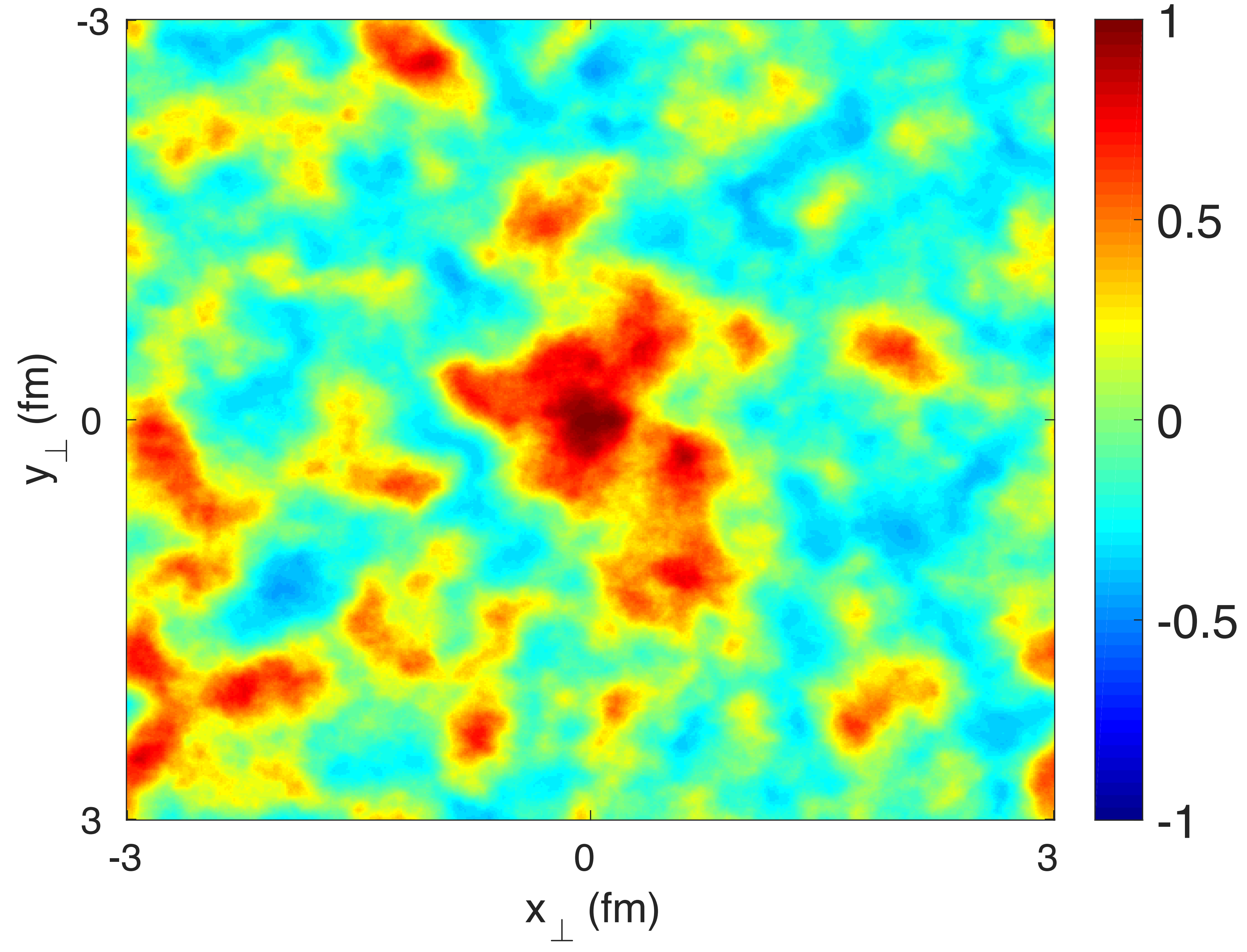
Is this one event we measure? No! We measure in momentum space.
Cross section in momentum space involves an average over all such configurations in coordinate space

DIPOLE AMPLITUDE

trace is over color (Wilson lines are color matrices)

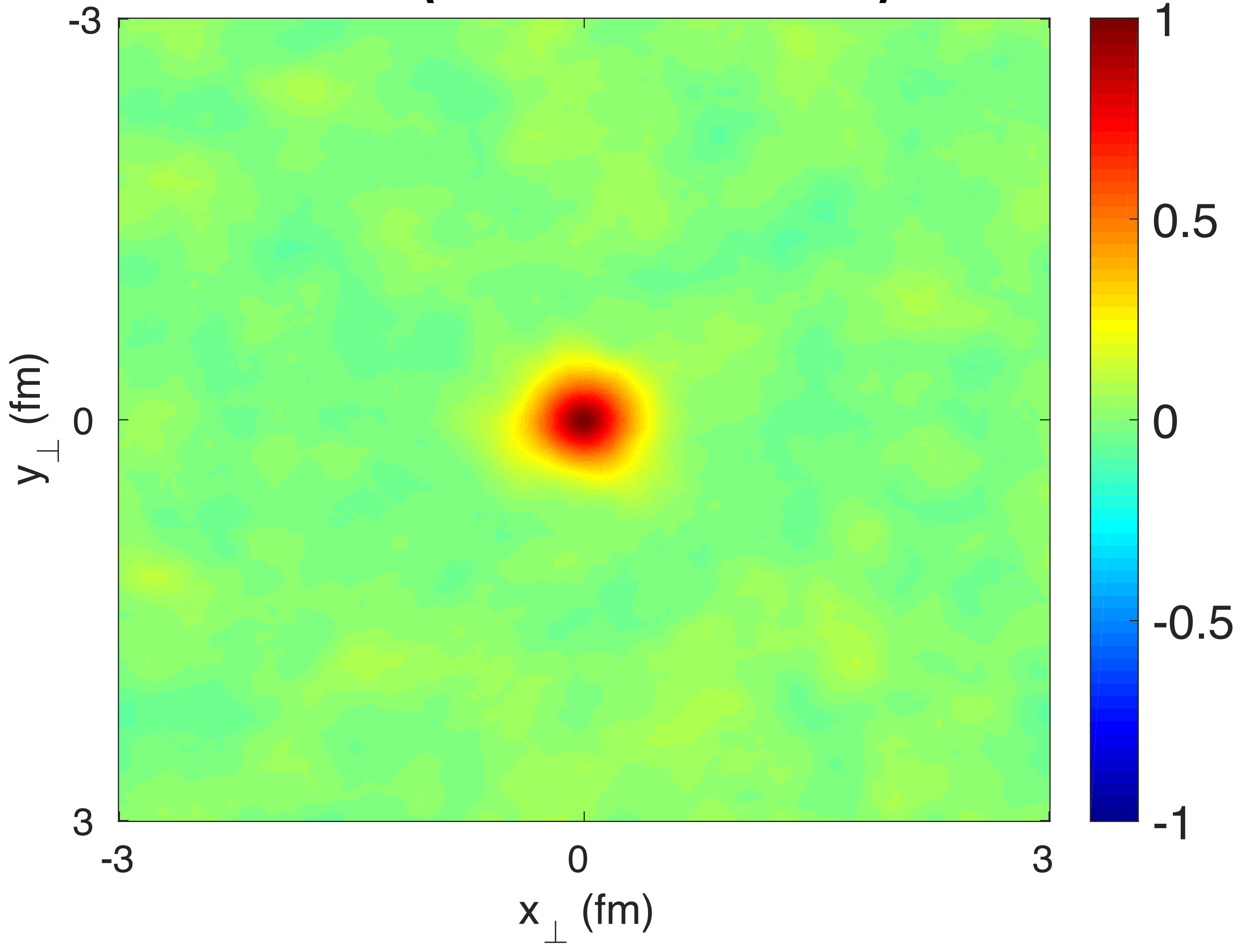
Dipole correlator  $S = \langle \mathrm{Tr}[V(\vec{x})V^\dagger(\vec{y})] \rangle / N_c$ appears in many scattering processes

$1/3\ tr\left(V(0)V^\dagger(r_\perp)\right)$



One color charge configuration

$1/3\left\langle tr\left(V(0)V^\dagger(r_\perp)\right)\right\rangle$

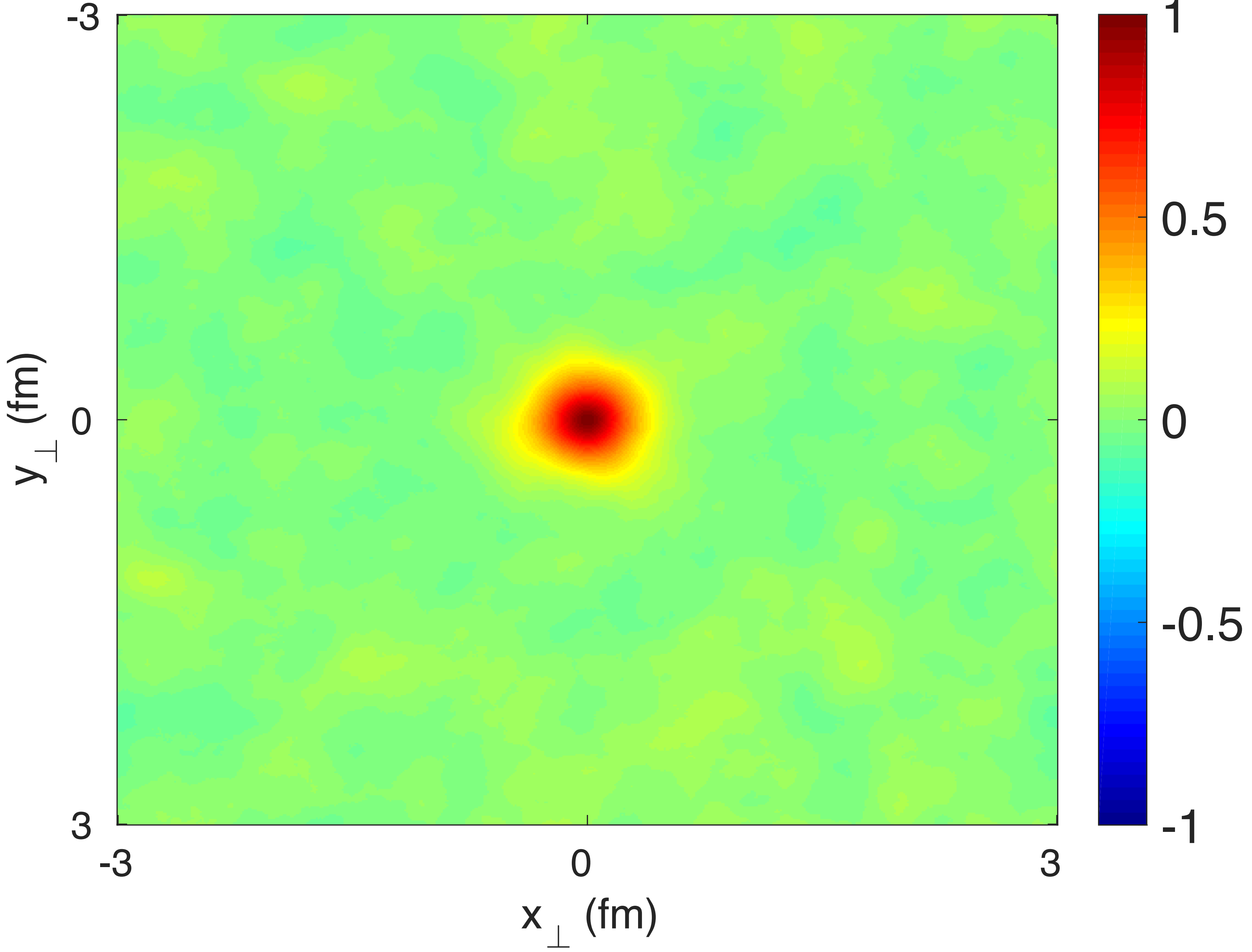


Averaged over 70 color charge configurations

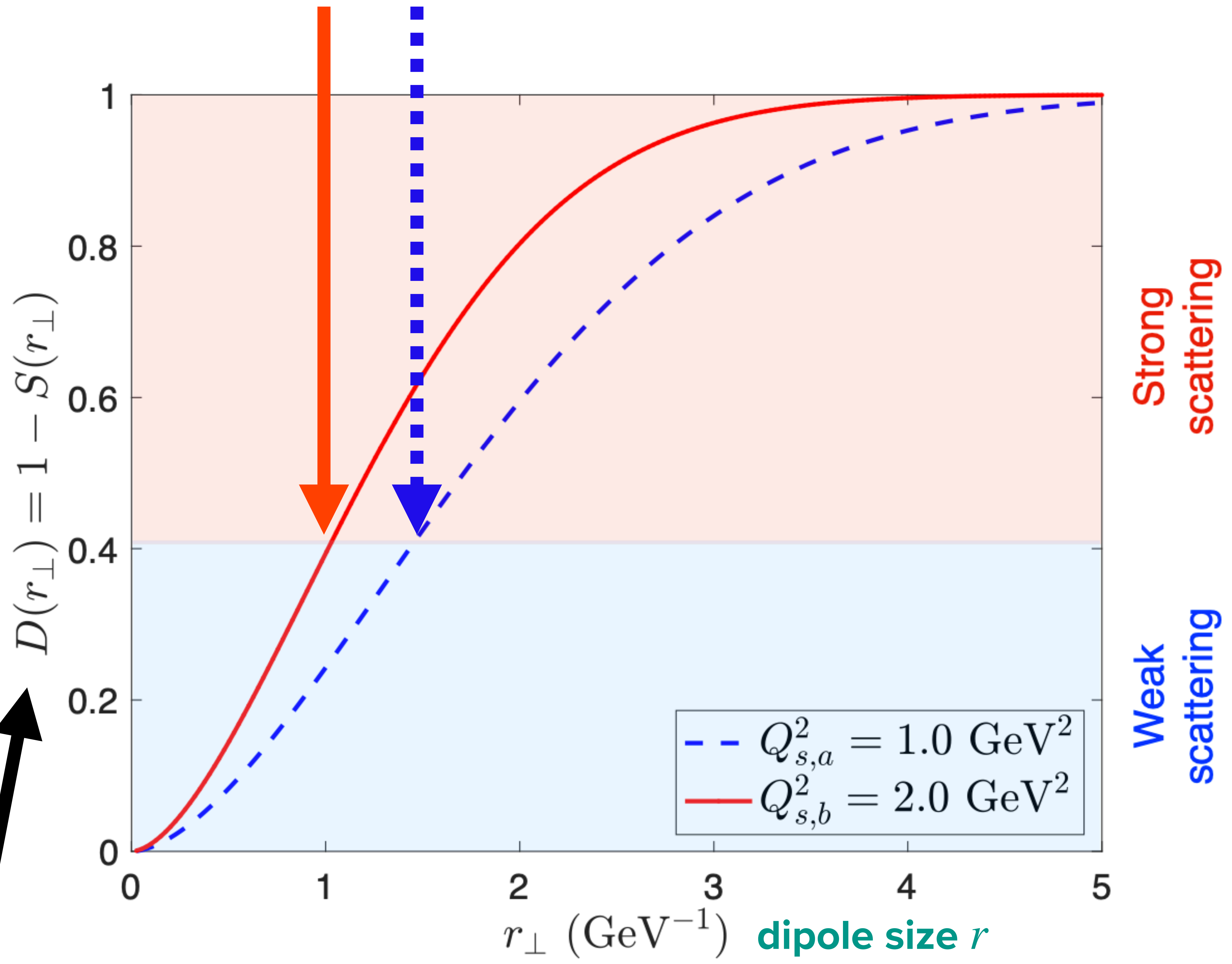
DIPOLE AMPLITUDE

defines Q_s (two examples)

$$1/3 \left\langle tr\left(V(0)V^\dagger(r_\perp)\right)\right\rangle$$



$\Rightarrow$

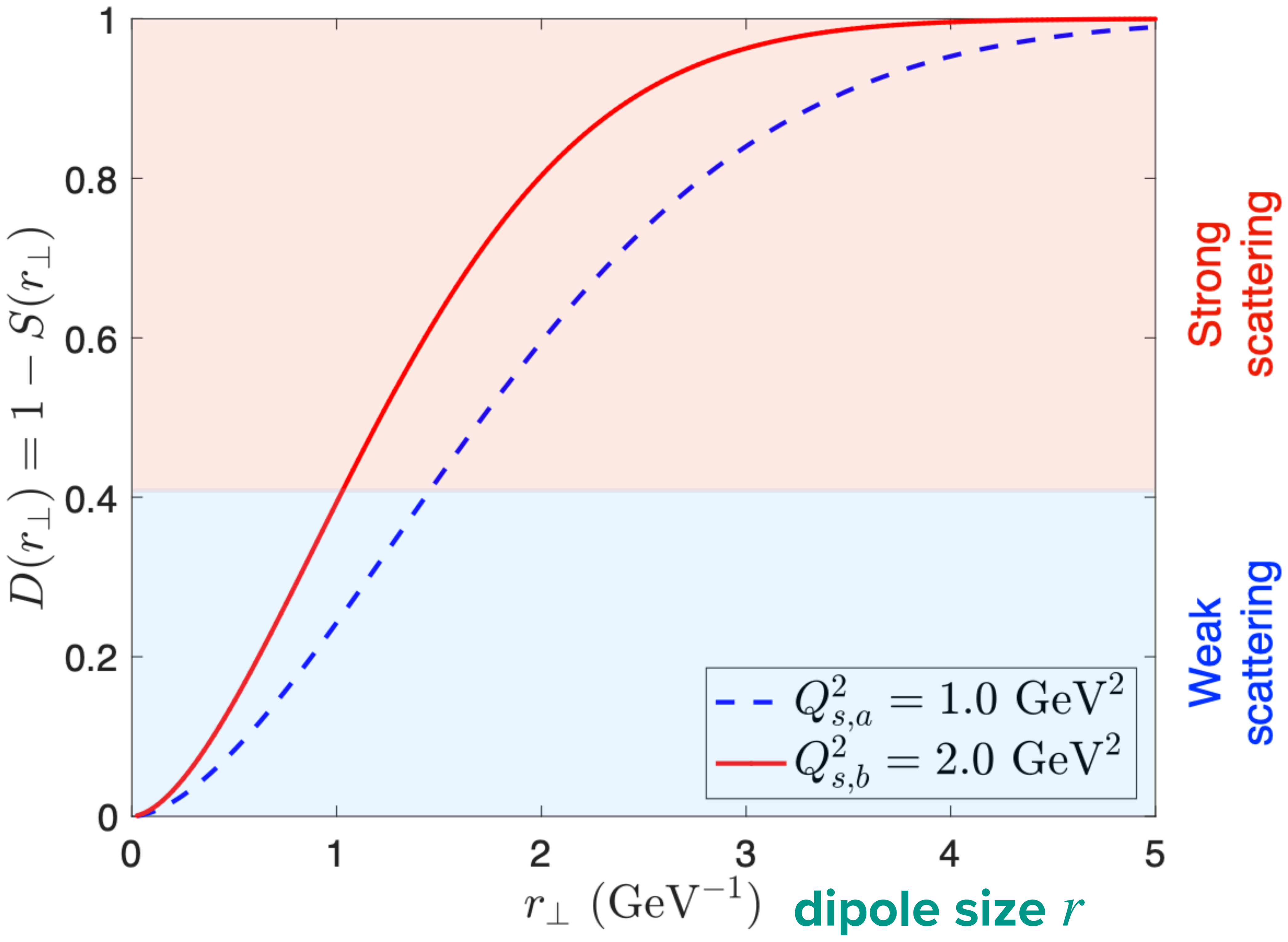


$\equiv S$

like a probability amplitude for no scattering

$$D = 1 - S$$

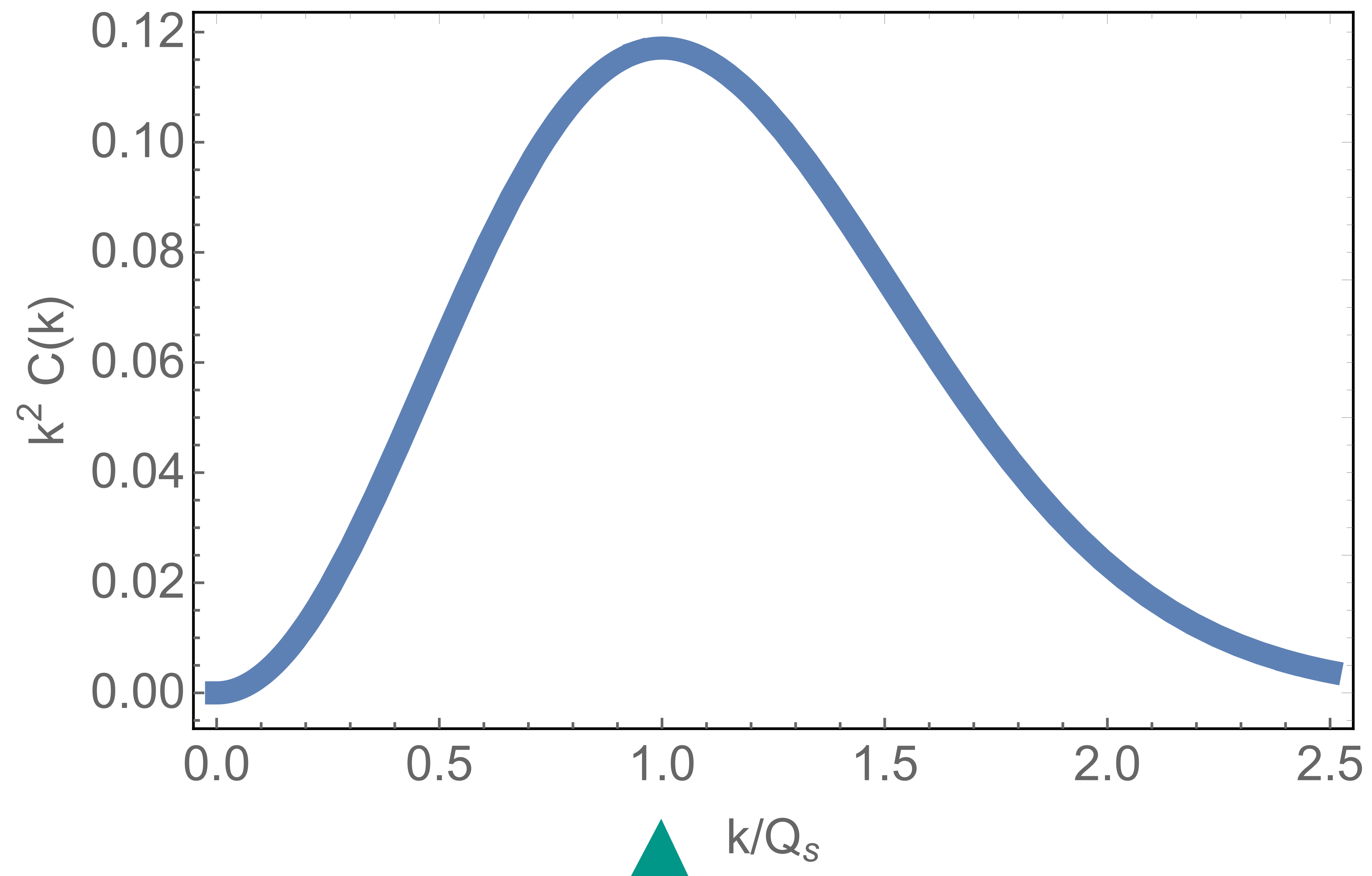
THE SATURATION SCALE



dipole size r

Fourier transform

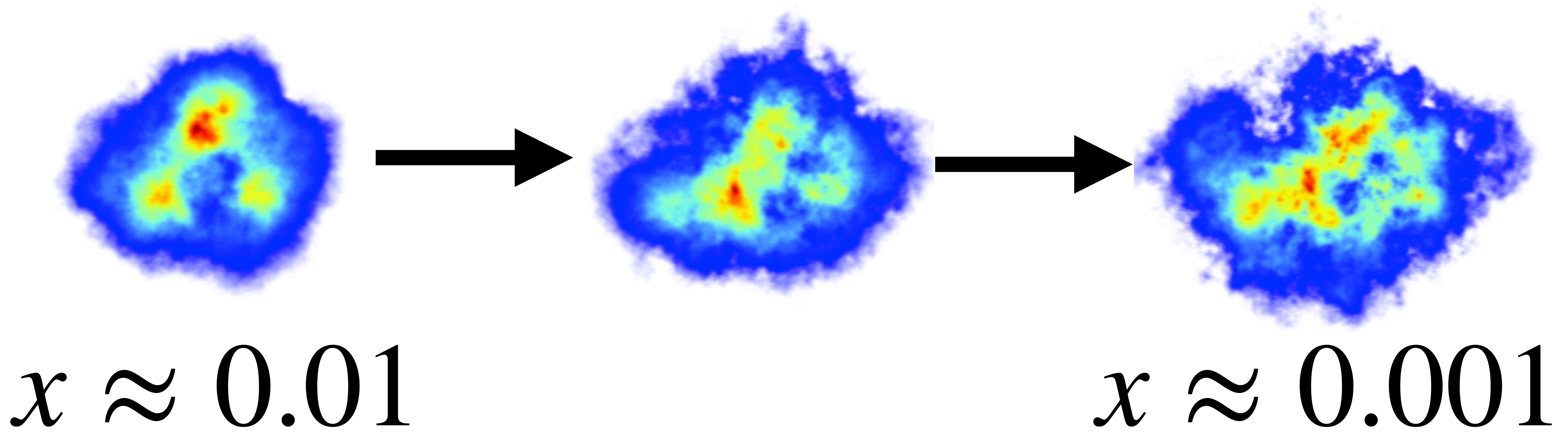
$\Rightarrow$

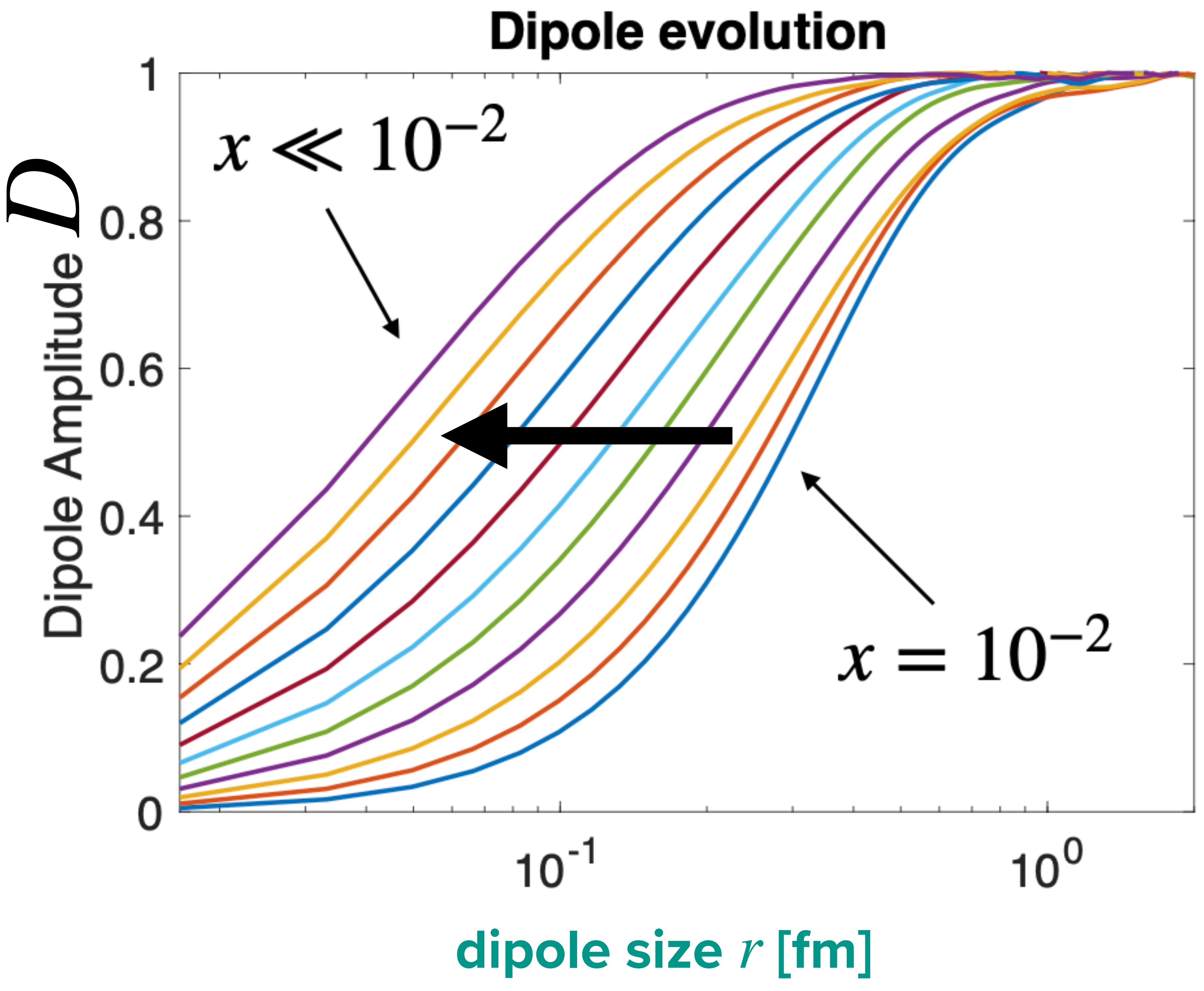


typical momentum $k = Q_s$

EVOLUTION TOWARDS SMALL x

JIMWLK evolution can be solved numerically. Langevin equation in color space:



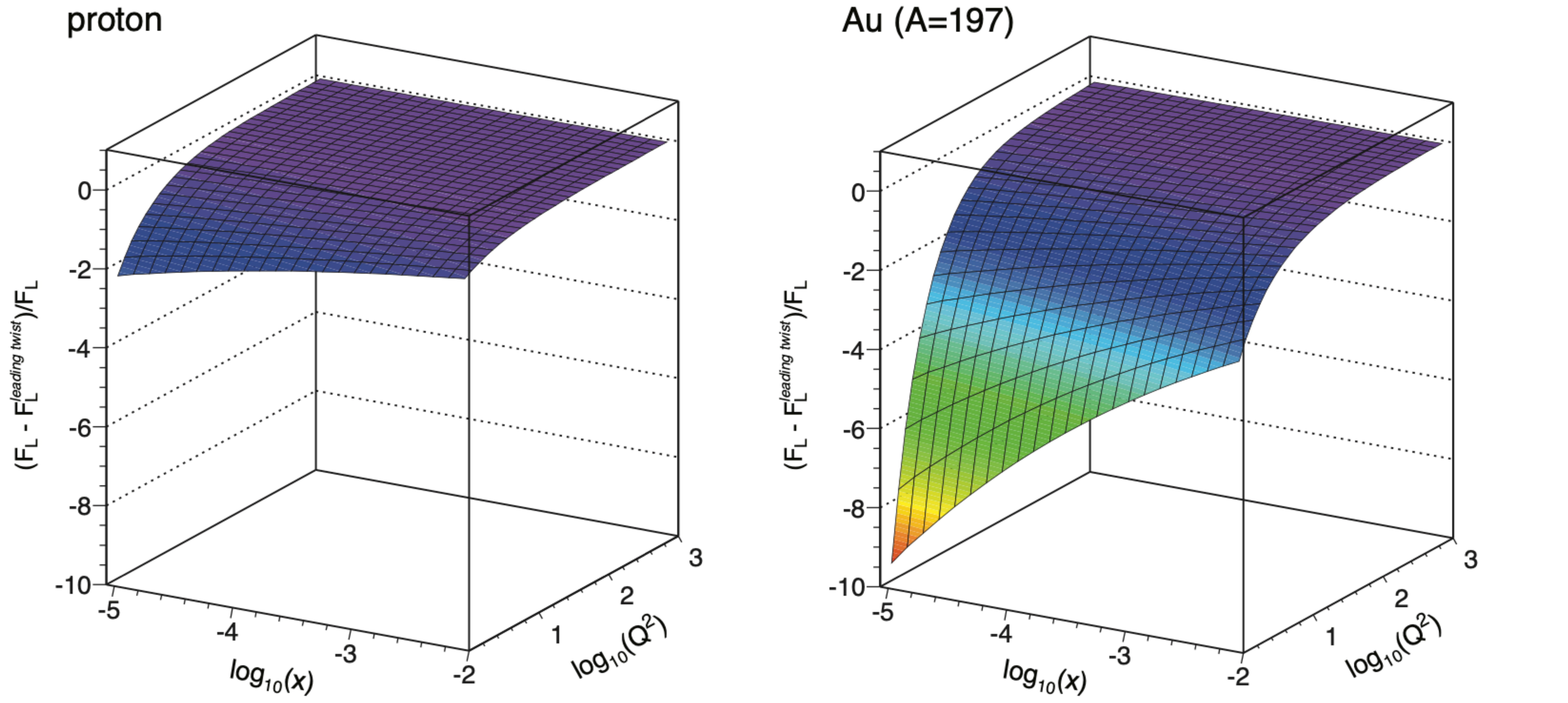


- Evolution leads to growth of typical transverse momentum scale $Q_s(x)$
- The typical correlation length in transverse space decreases $\sim 1/Q_s$
- Proton grows, gluon number increases

SATURATION EFFECTS ON OBSERVABLES

J. Bartels, K. Golec-Biernat, and L. Motyka, Phys. Rev. D81, 054017 (2010)

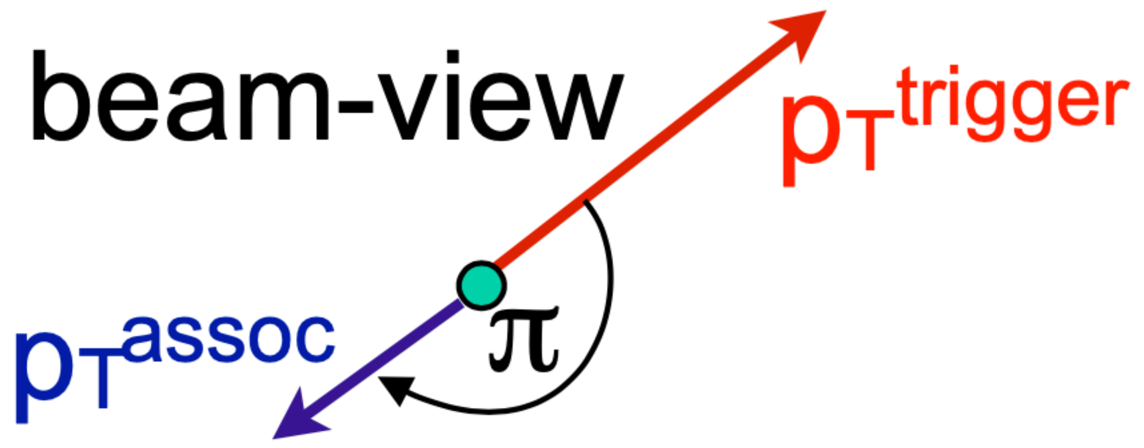
For nuclei at the EIC, saturation effects on structure functions should become prominent



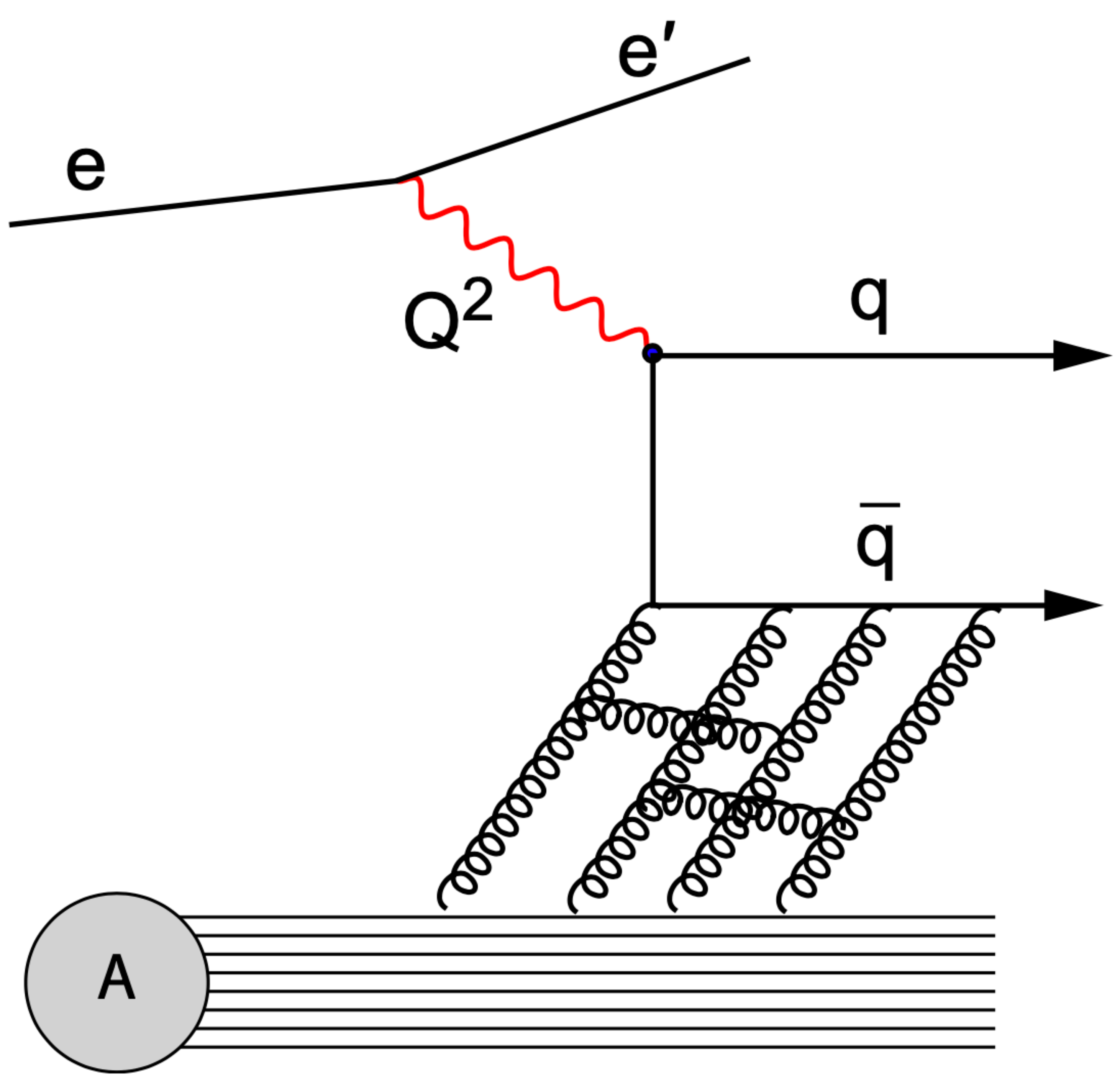
The multiple re-scatterings and gluon mergers contribute at all orders in twists (terms in a $1/Q^2$ expansion). Their effect increases with increasing A and decreases with increasing x

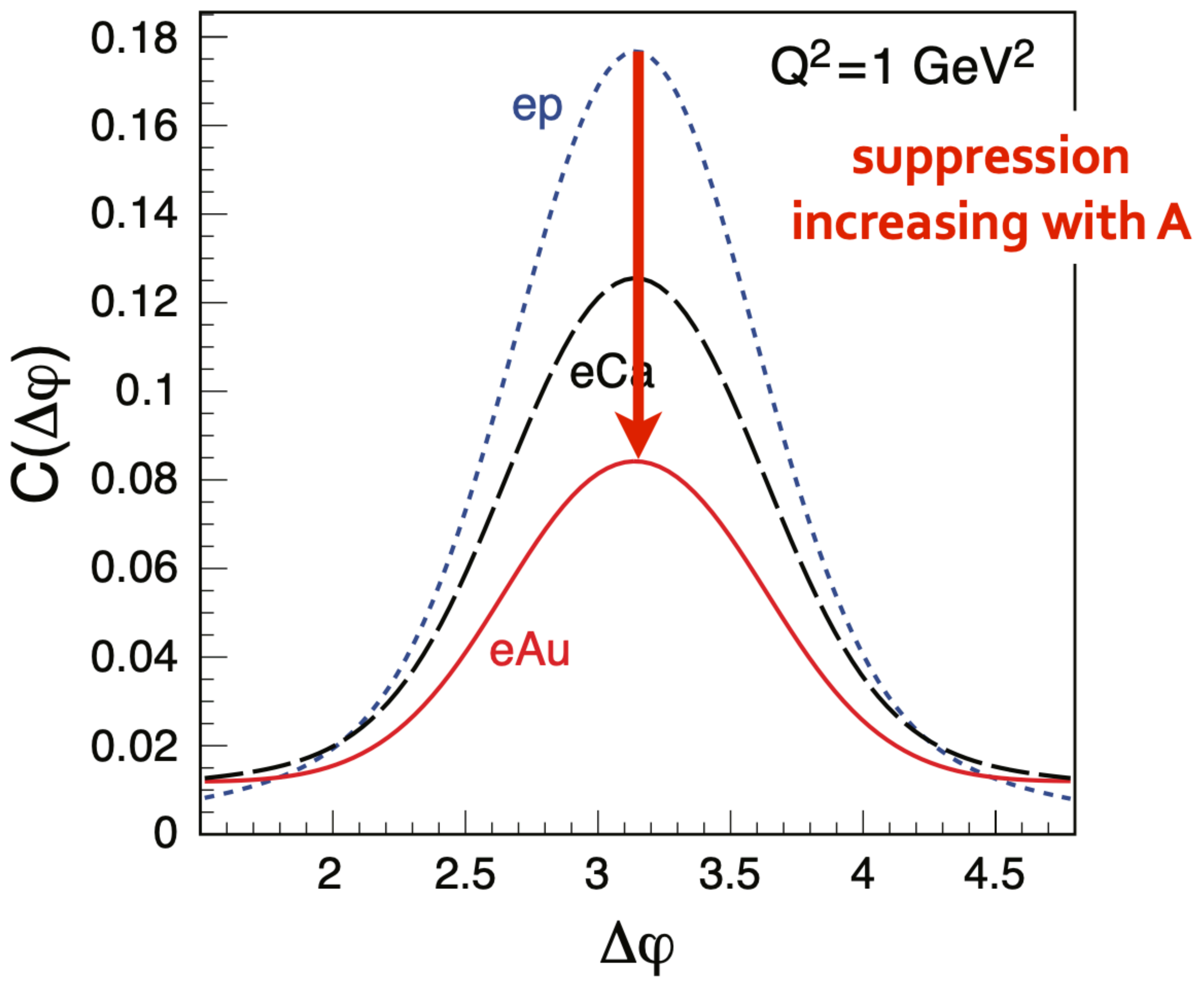
SATURATION EFFECTS ON OBSERVABLES

C. Marquet, B. -W. Xiao and F. Yuan, Phys. Lett. B 682 (2009) 207
L. Zheng, E.C. Aschenauer, J.H. Lee, Bo-Wen Xiao, Phys. Rev. D 89, 074037 (2014)



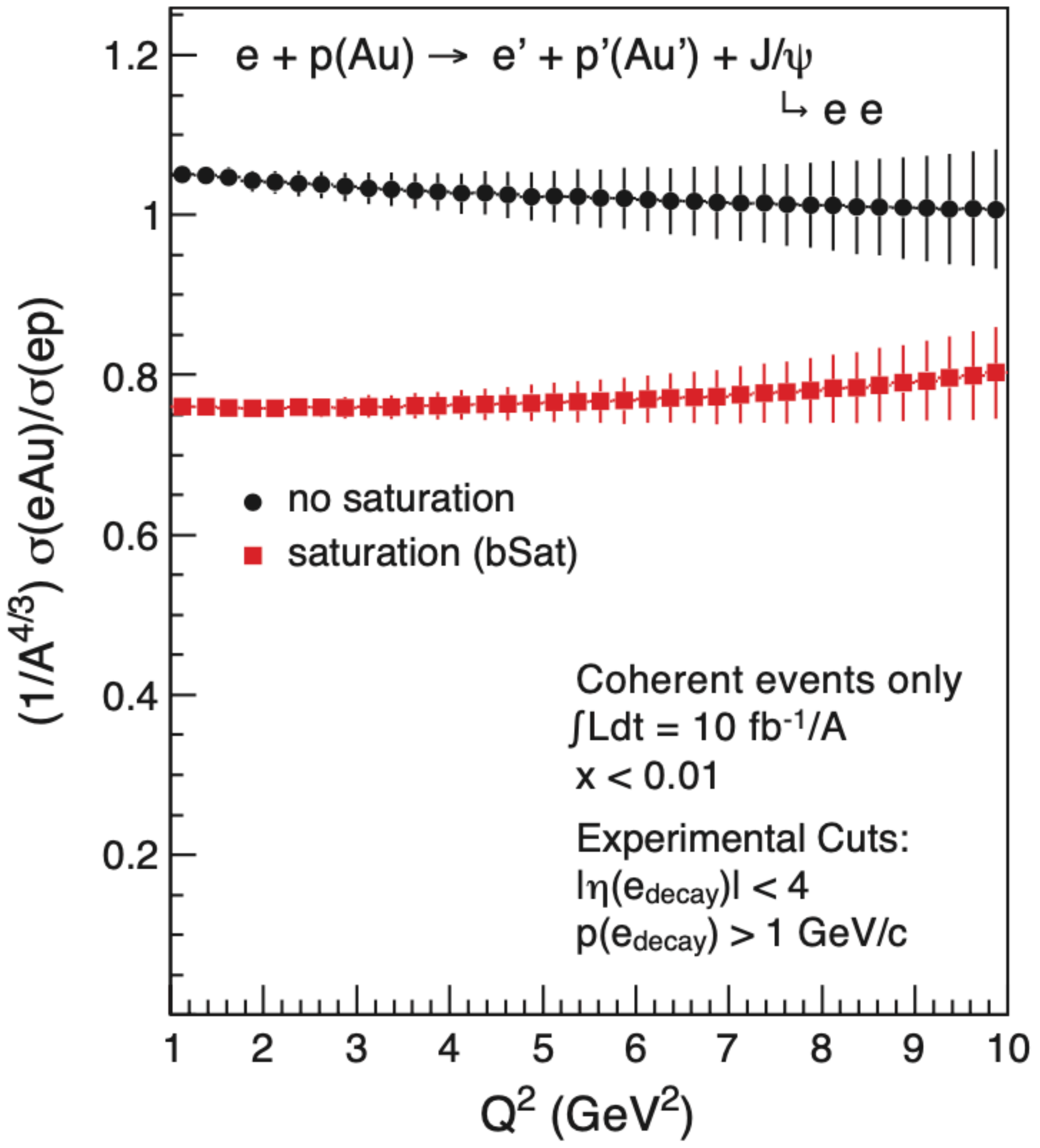
Double inclusive DIS:
Back-to-back peak suppressed more in larger nuclei as momentum imbalance $\sim Q_s$

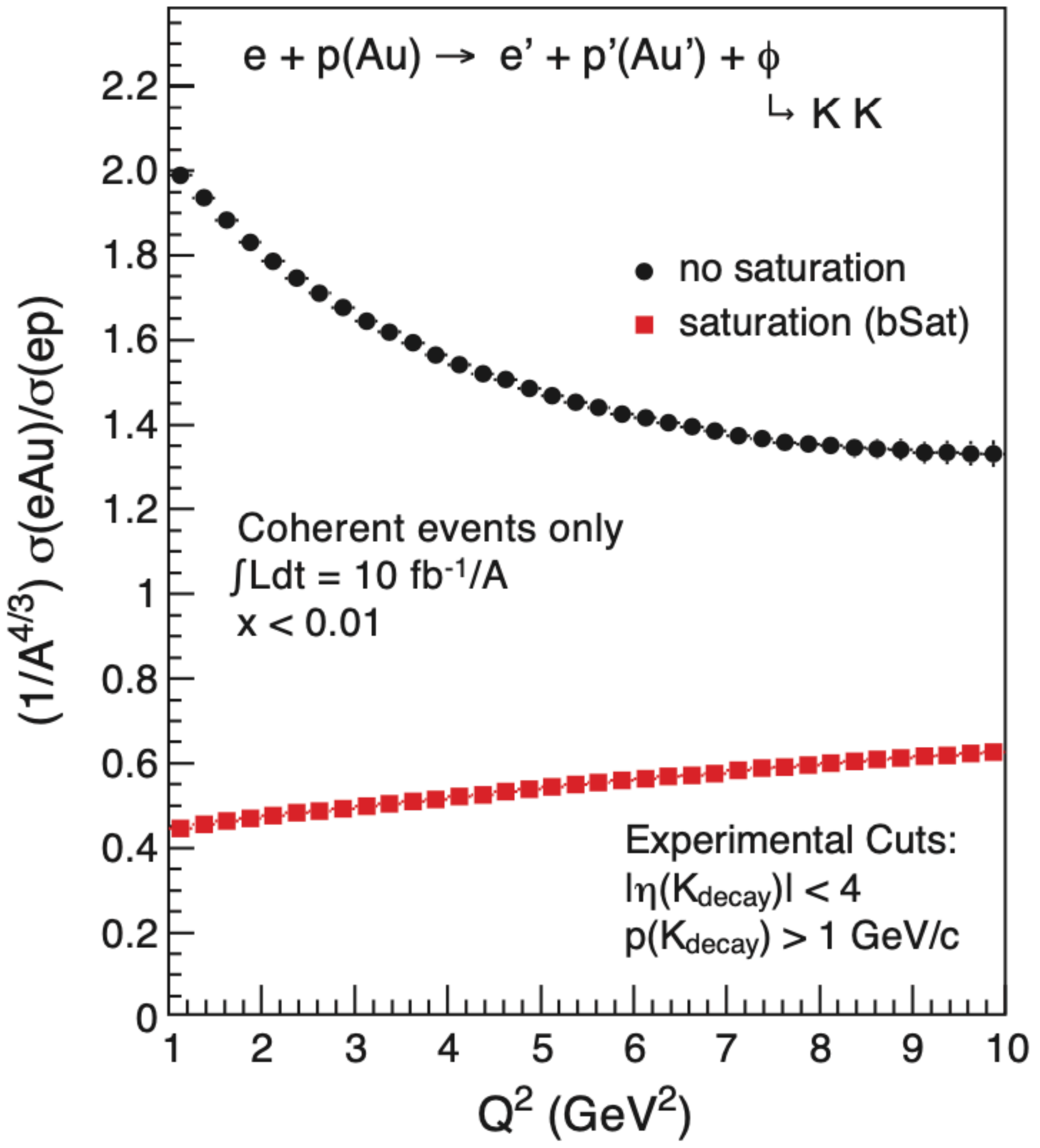




SATURATION EFFECTS ON OBSERVABLES

T. Toll, T. Ullrich, Phys.Rev.C 87 (2013) 2, 024913
A. Accardi et al., EIC White Paper, Eur.Phys.J.A 52 (2016) 9, 268



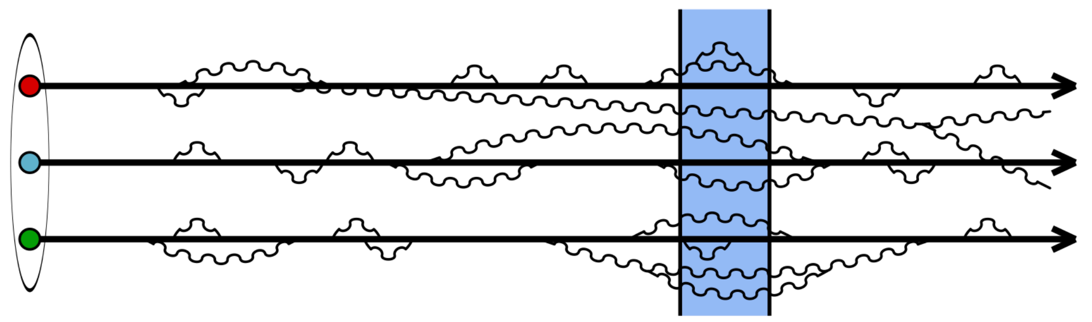


- Diffractive VM production: Sartre event generator (bSat & bNonSat = linearized bSat)
- Big difference for ϕ; less so for J/ψ (larger mass cuts off large dipoles)

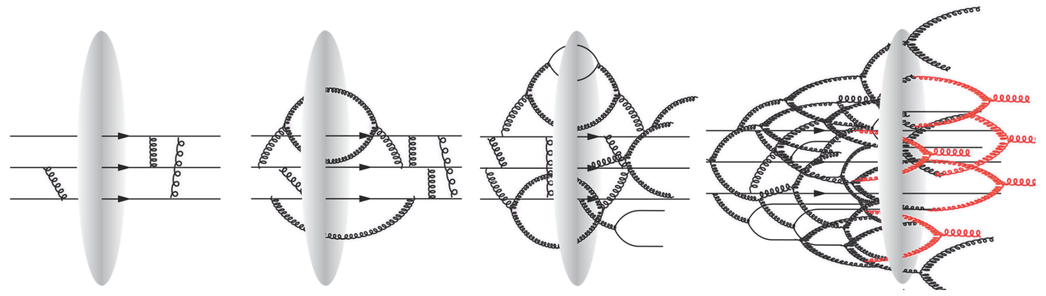
RECAP

- We study scattering in the limit $s \to \infty$ at fixed Q^2 and $x \to 0$

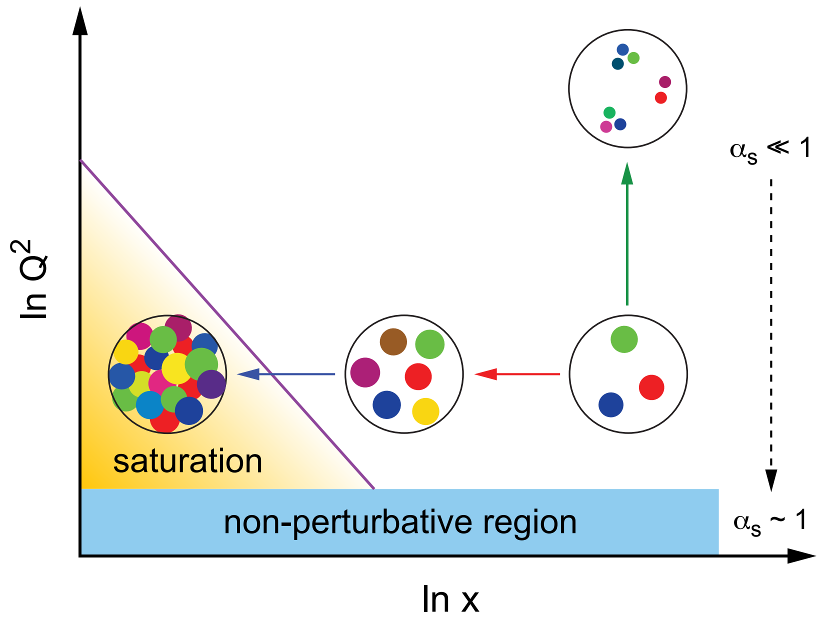
- A higher energy probe sees more partons in a nucleon/nucleus



- Growth cannot continue indefinitely and will be tamed by gluons merging

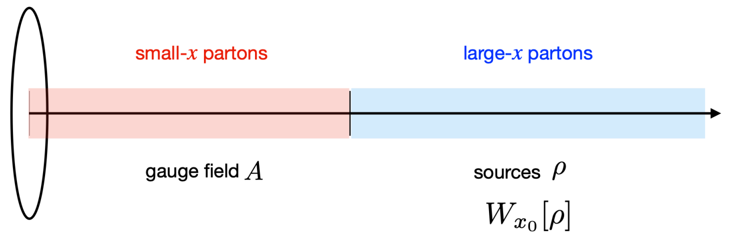


- When merging = splitting probability, gluons with $k_T \lesssim Q_s$ are saturated



- Effective degrees of freedom are static and localized large x color sources and dynamical gluon fields at small x

- A variety of observables should be sensitive to gluon saturation at high enough energy and large enough A



SURGE STRUCTURE

- Provide theory and tools to pin down gluon saturation from the data

Initial State

Evolution and parton level cross sections

NLO calculations

Final State

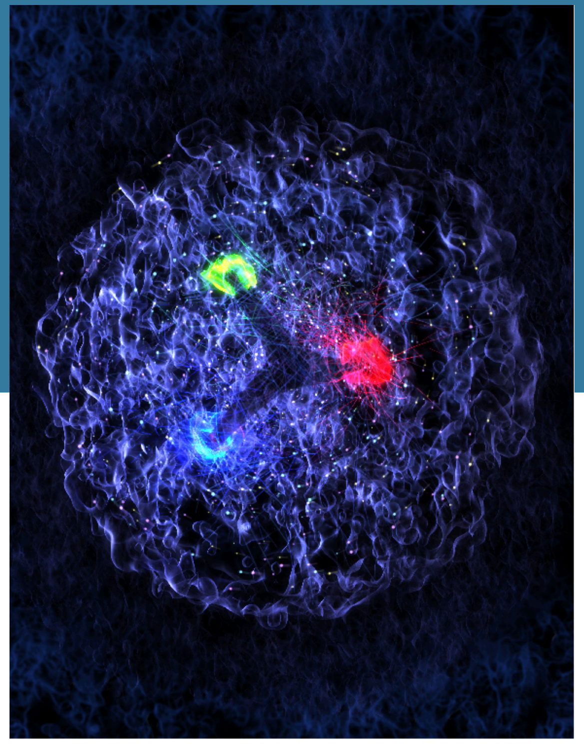
SURGE STRUCTURE

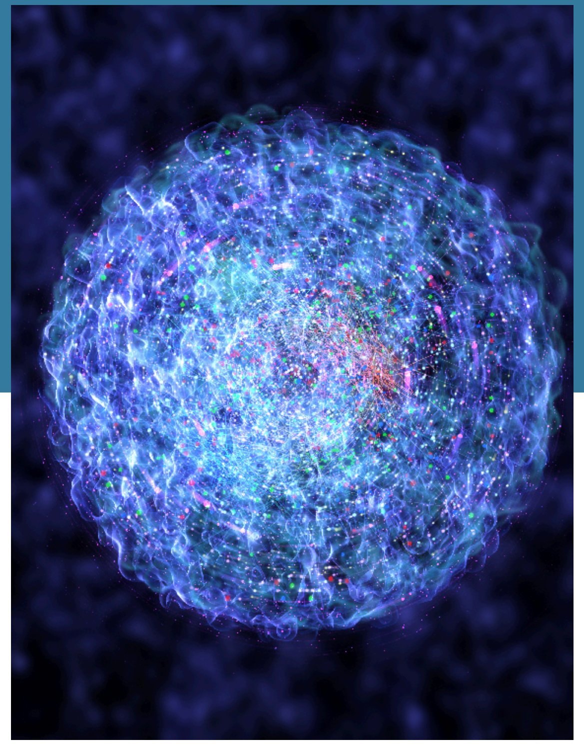
Initial State

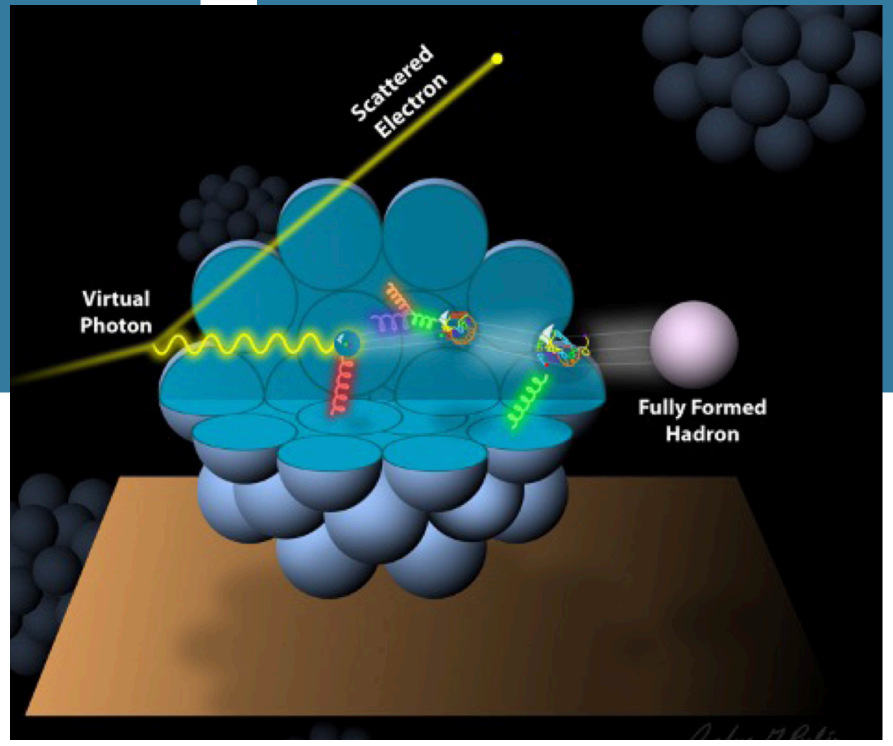
Evolution and parton level cross sections

NLO calculations

Final State

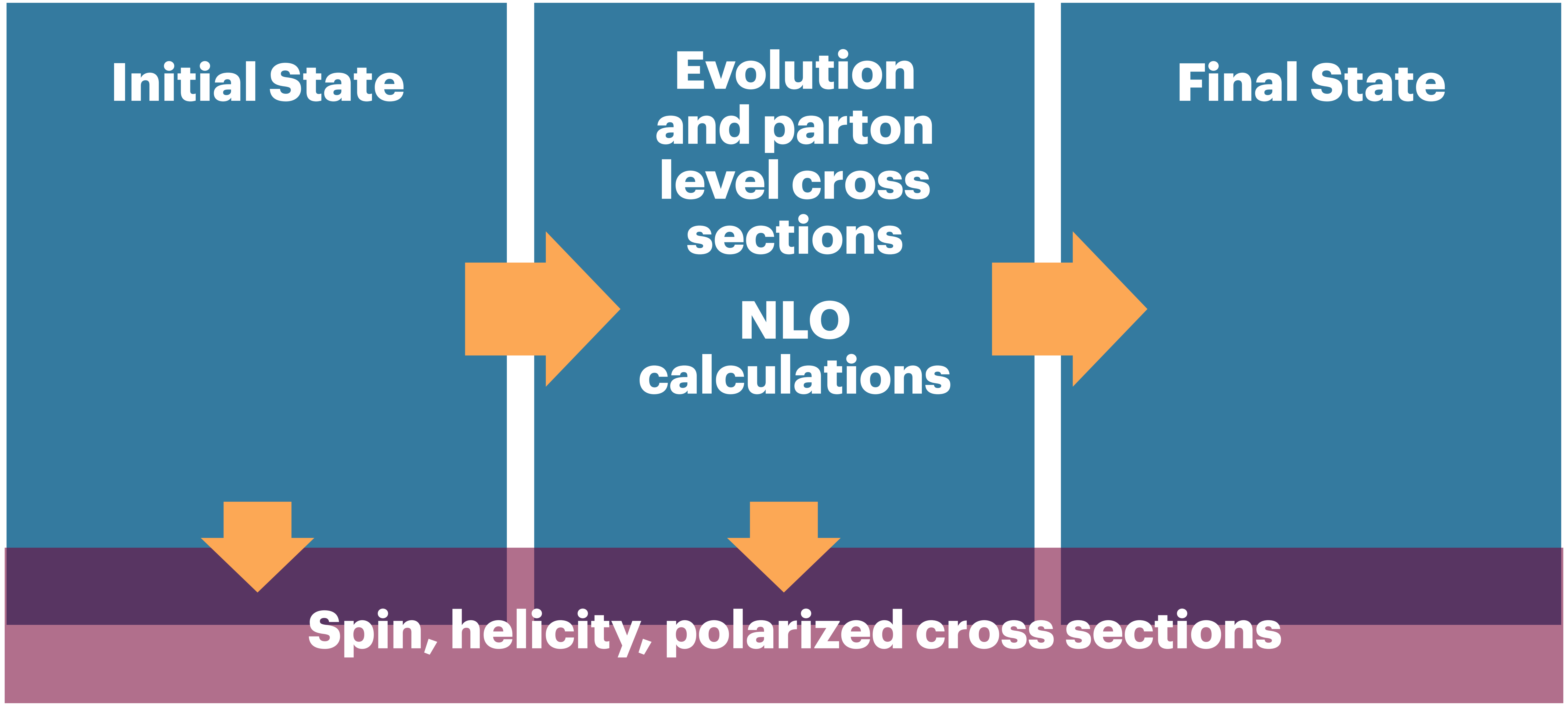




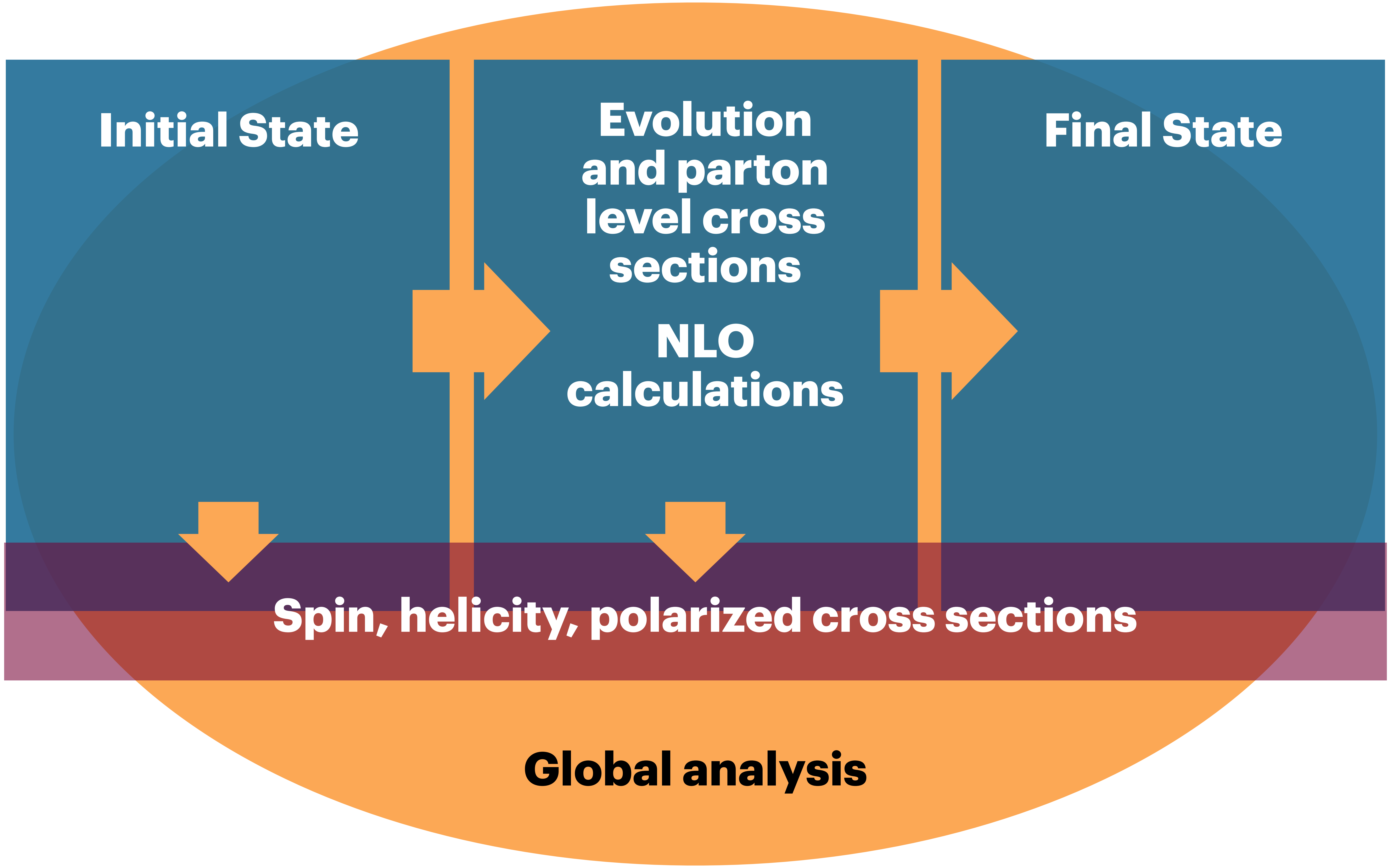


Images courtesy of James LaPlante, Sputnik Animation in collaboration with the MIT Center for Art, Science & Technology and Jefferson Lab.
and Joshua Rubin, University of Illinois Urbana-Champaign

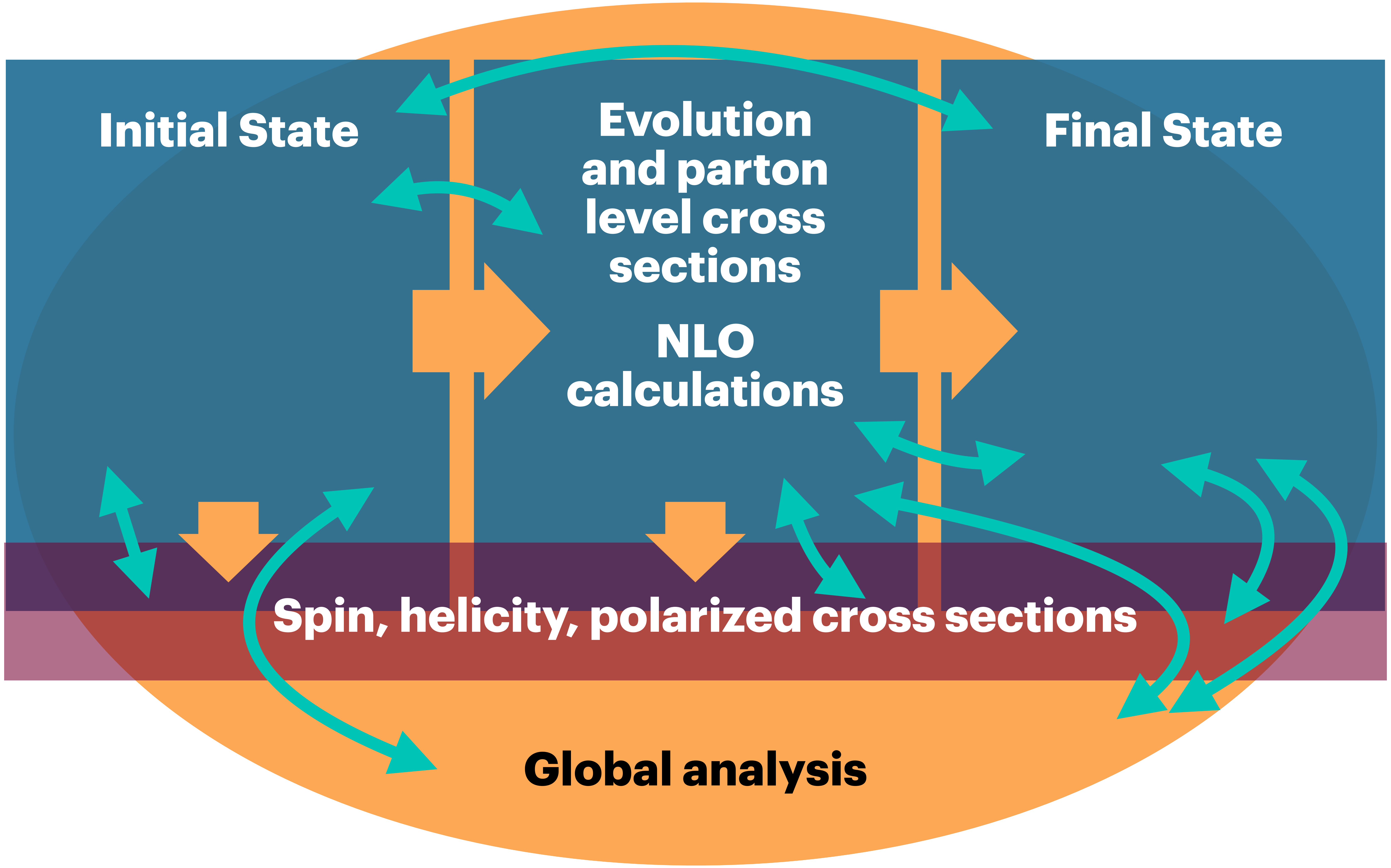
SURGE STRUCTURE



SURGE STRUCTURE: 5 WORKING GROUPS



SURGE STRUCTURE: 5 WORKING GROUPS



RECENT RESEARCH HIGHLIGHTS

INITIAL STATE

SURGE aims to improve the description of proton and nuclei at large *x*

to obtain more realistic initial conditions (IC) for the evolution towards smaller *x*

Previous approaches:

- Ad-hoc parametrization of ICs; adjusted to optimize fit to data
- Most ICs are modifications of McLerran-Venugopalan (MV) model

Drawbacks:

- No connection to underlying QCD dynamics, no explanation of the x_0-dependence, available ICs are most appropriate for large nuclei at high energy

SURGE pursues two directions:

- Improve models for initial conditions
- Construct model-independent first principles ICs

INITIAL STATE - MILESTONES

- Develop **improved initial conditions** for small-x evolution using lightcone perturbation theory

  A. Dumitru, H. Mäntysaari, R. Paatelainen, Phys. Rev. D107, 114024 (2023)
  High-energy dipole scattering amplitude from evolution of low-energy proton light-cone wave functions

Initial condition for proton: Start with nonperturbative three quark model wave function. Add $\mathcal{O}(g)$ corrections due to the emission of a gluon, and $\mathcal{O}(g^2)$ virtual corrections due to the exchange of a gluon, computed in light-cone perturbation theory with exact kinematics.

Provide dipole amplitude $N(x_0, r)$ - not easy to extend to nuclei (opposite approach to MV)

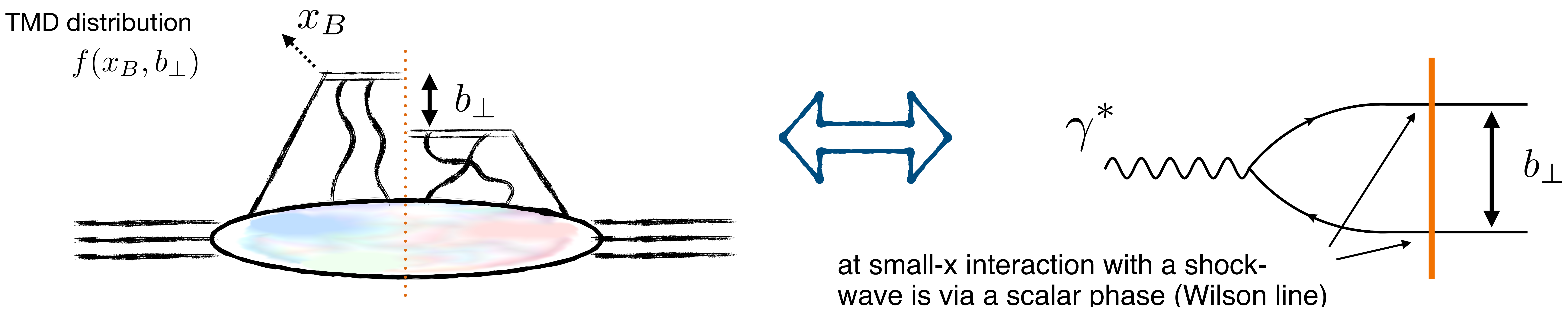
- **Non-Gaussian corrections for large nuclei**

  MV model assumes Gaussian statistics; working to improve on that

INITIAL STATE - TMDS - LATTICE QCD

Model-independent first-principle based determination of ICs

The relation between transverse momentum dependent parton distribution functions (TMDPDFs) and small-*x* dipoles can be observed already at the level of the corresponding operator definitions **Mukherjee, Skokov, Tarasov, Tiwari, arXiv:2502.15889**

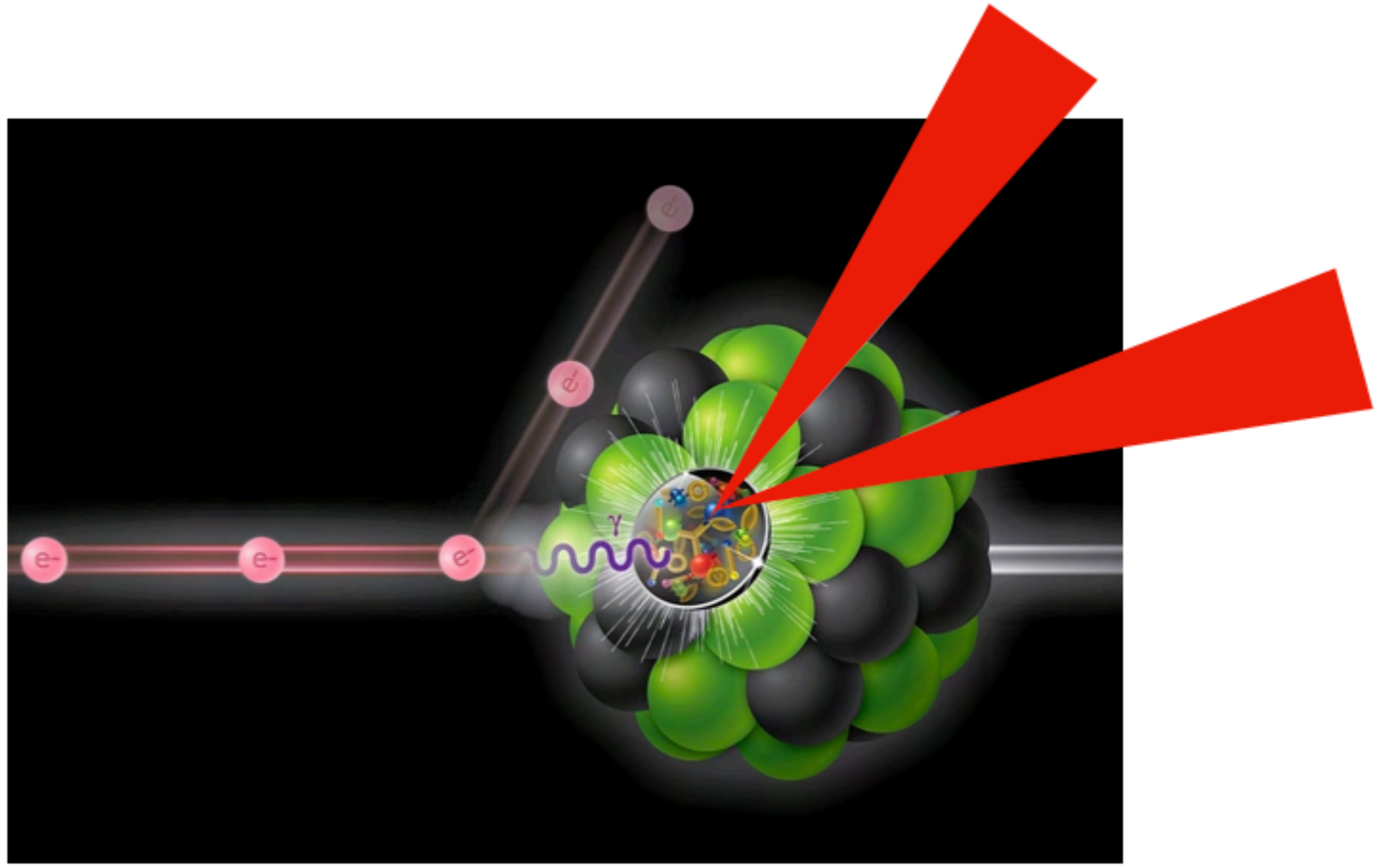


Established relation between the TMDPDFs and the small-x dipole amplitudes at **NLO**.
Lays the ground work to employ TMDPDFs computed from lattice QCD as initial condition for the small *x* evolution **S. Mukherjee, V. V. Skokov, A. Tarasov, S. Tiwari, Phys.Rev.D 109 (2024) 3, 034035**

NLO AND EVOLUTION - DIJETS AT NLO

- Improve precision by performing NLO calculations and NLL evolution
  P. Caucal, F. Salazar, B. Schenke, T. Stebel, R. Venugopalan
  Phys.Rev.Lett. 132 (2024) 8, 081902
  Back-to-back inclusive dijets in DIS at small x: Complete NLO results and predictions

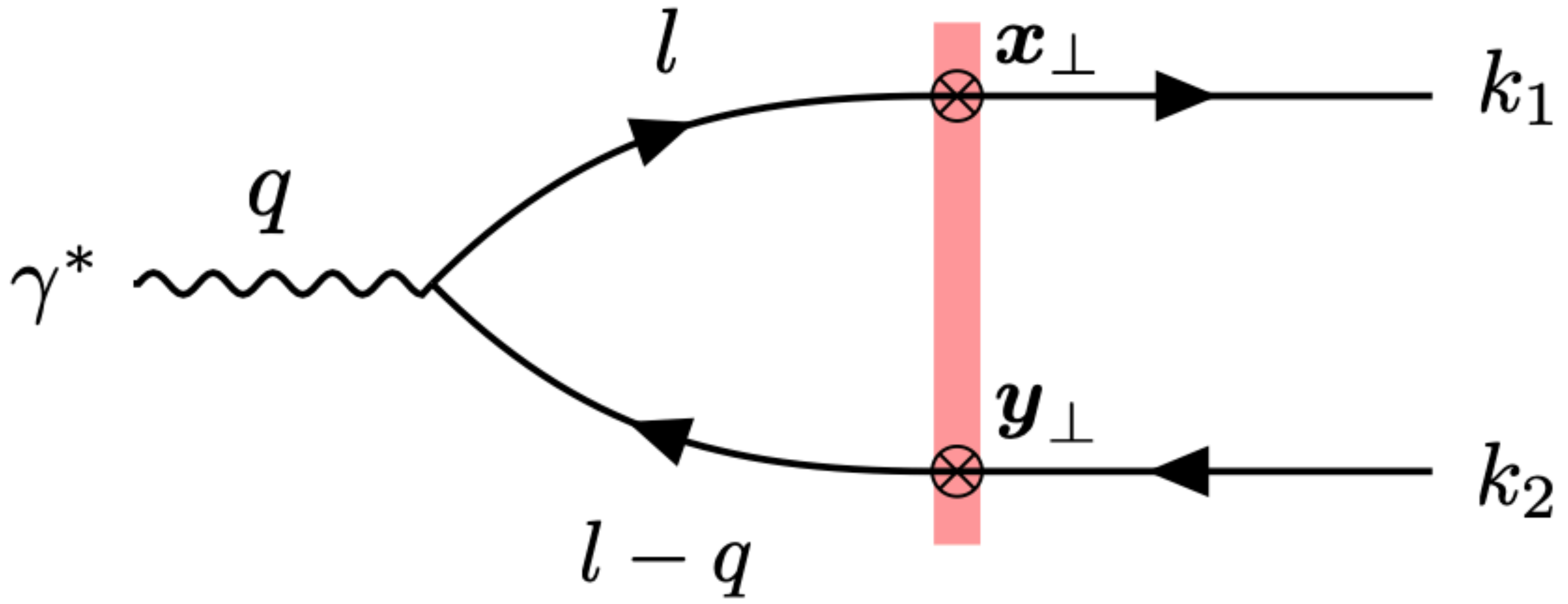
  P. Caucal, F. Salazar, B. Schenke, T. Stebel, R. Venugopalan, JHEP 08 (2023) 062
  Back-to-back inclusive dijets in DIS at small x: Gluon Weizsäcker-Williams distribution at NLO



Inclusive dijet production in e+A collisions:

Produce 2 jets + X

Work in the Color Glass Condensate (CGC) framework



LO

NLO AND EVOLUTION - DIJETS AT NLO

- Improve precision by performing NLO calculations and NLL evolution

  P. Caucal, F. Salazar, B. Schenke, T. Stebel, R. Venugopalan
  Phys.Rev.Lett. 132 (2024) 8, 081902
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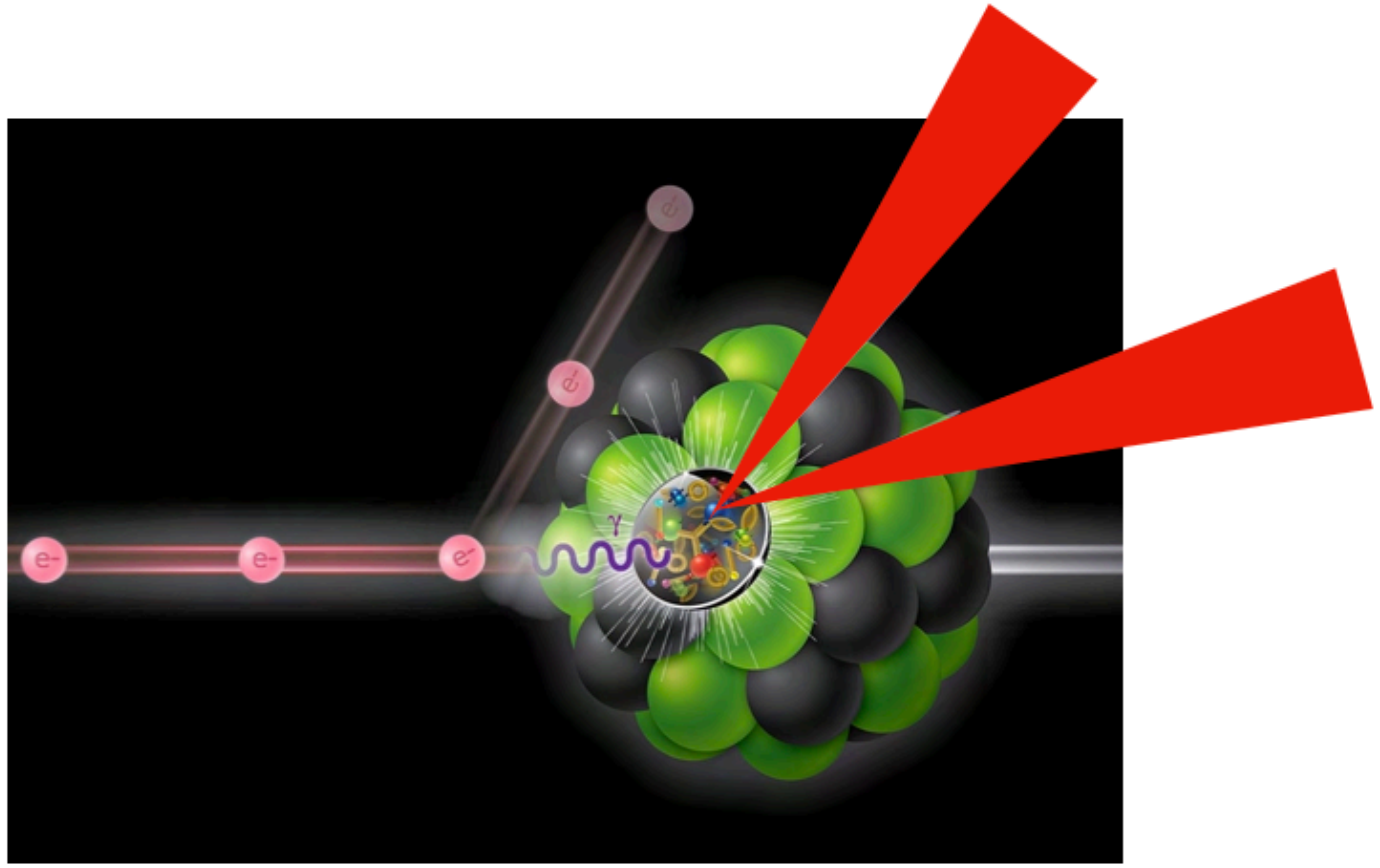
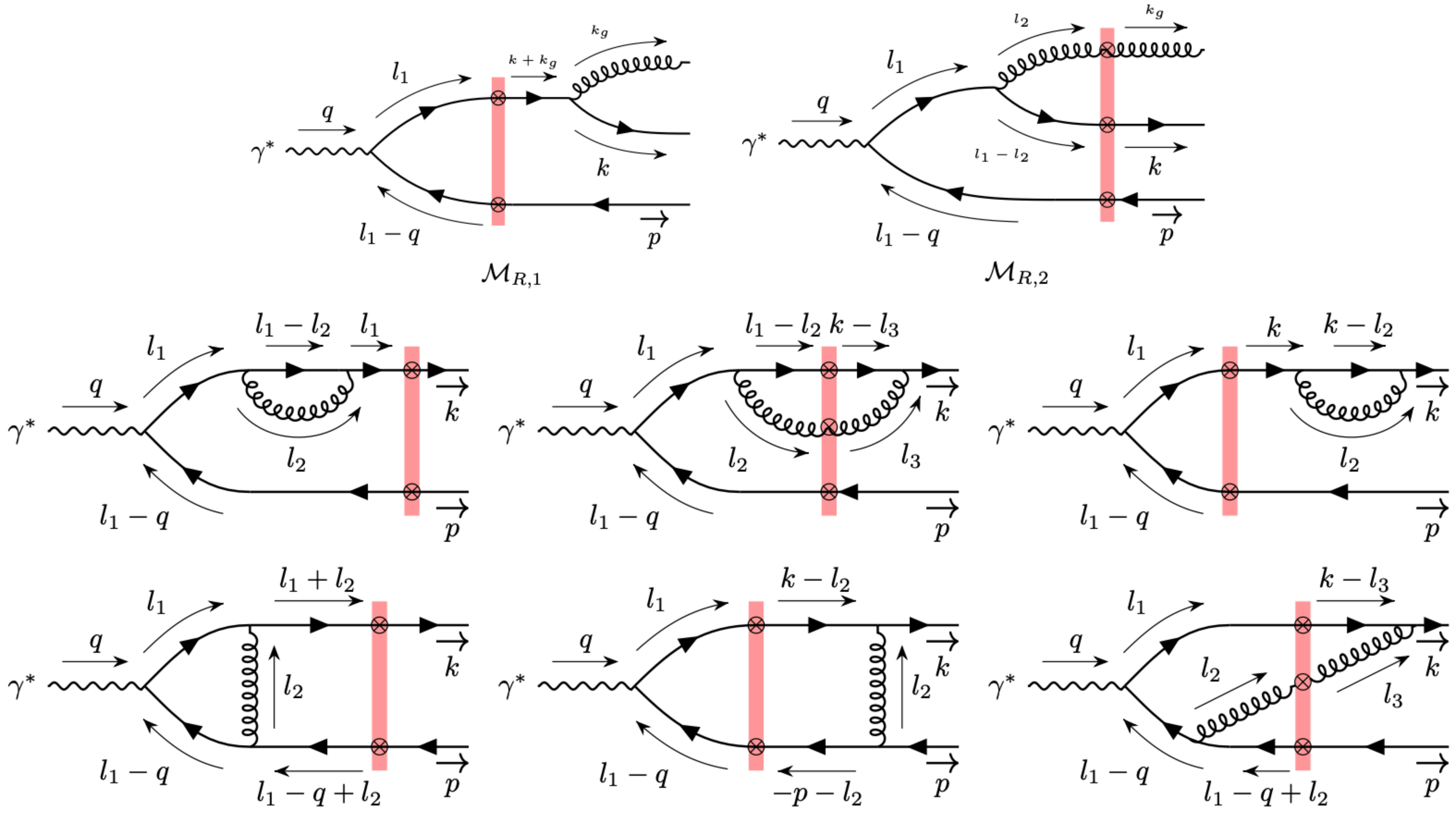


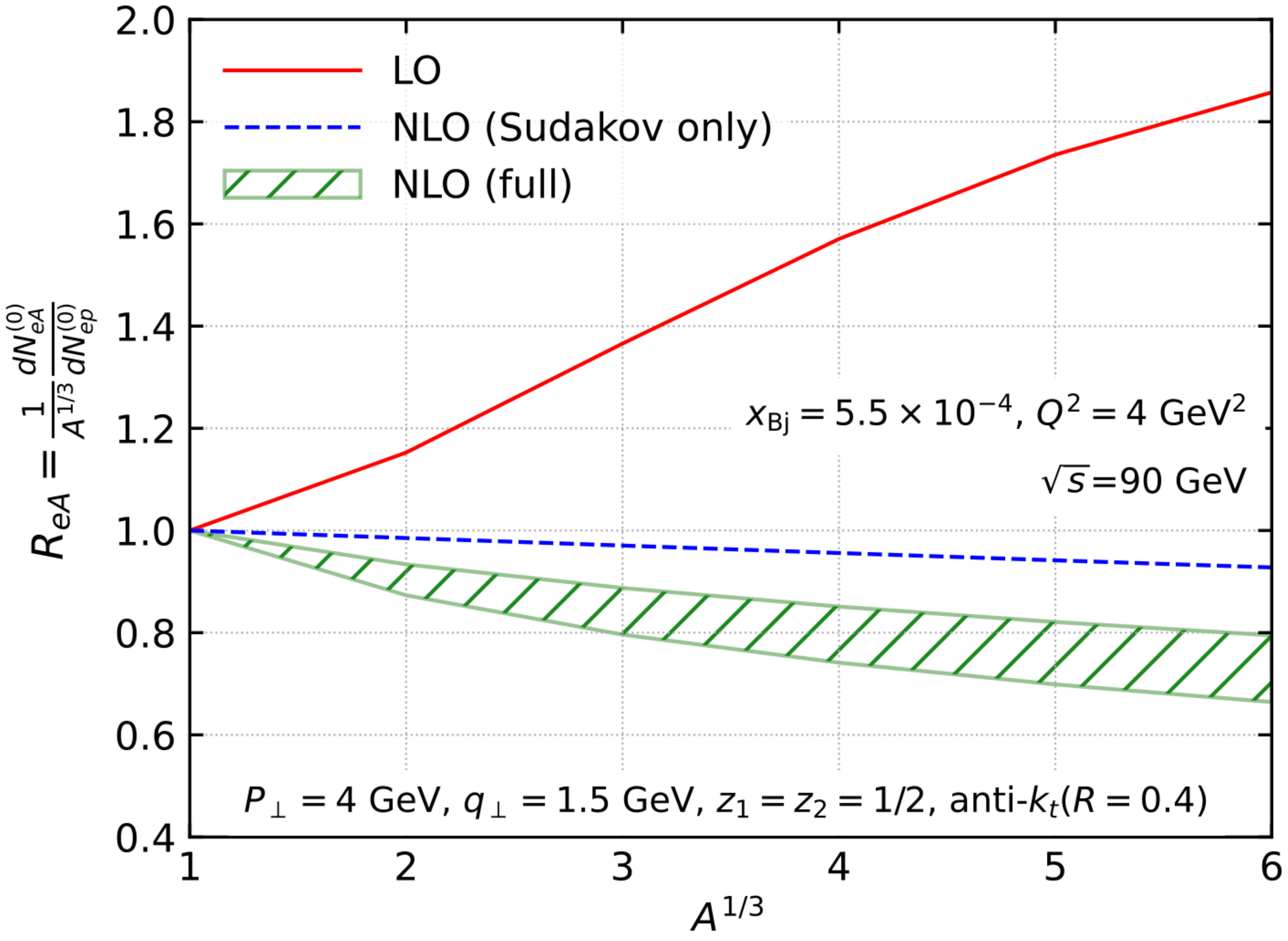


NLO

NLO AND EVOLUTION - DIJETS AT NLO

- Improve precision by performing NLO calculations and NLL evolution

Nuclear suppression e+A vs. e+p



Increasing nuclear mass →

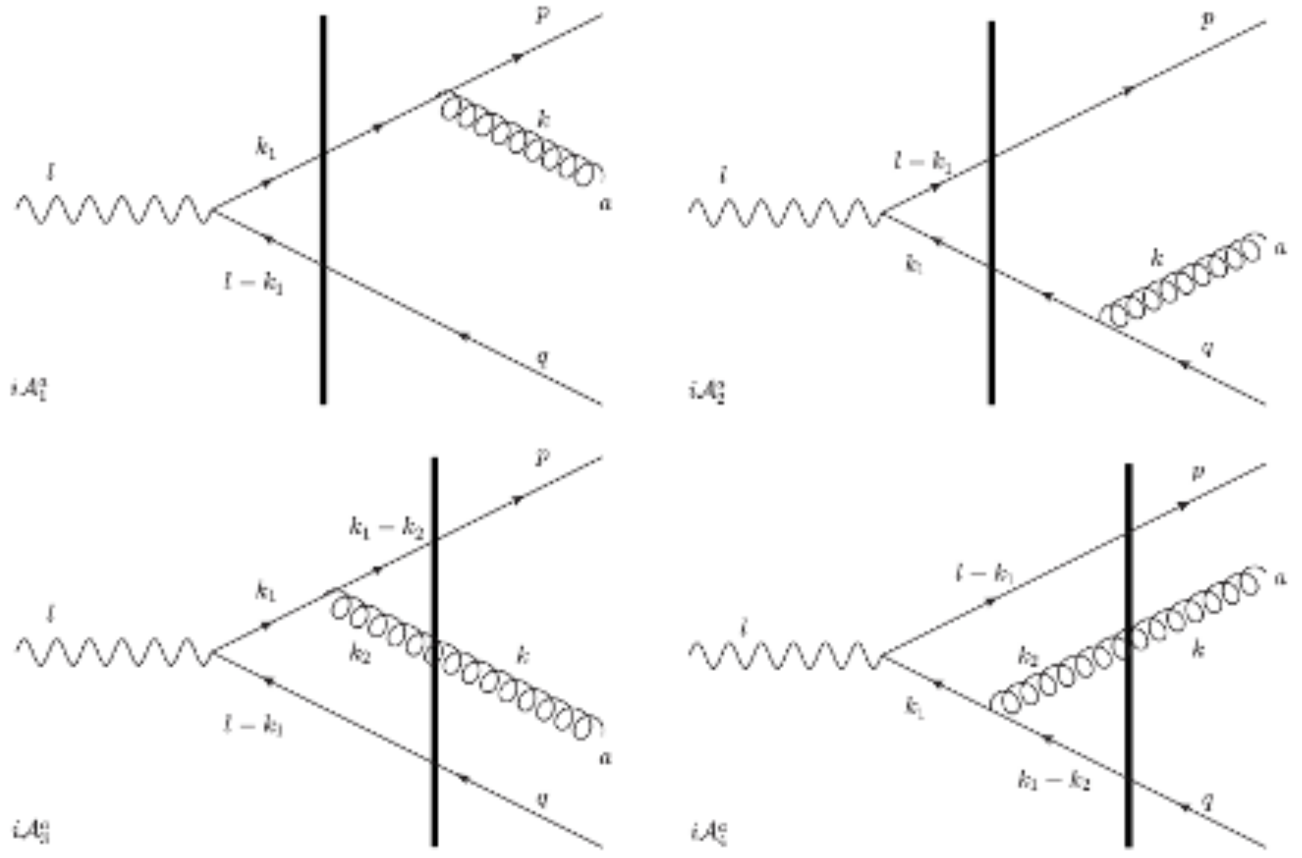
- Established factorization of the result at NLO
- Dramatic effect going from LO to NLO
- Quantified the effect of soft gluon radiation (Sudakov) compared to that of the renormalization group evolution of the gluon distribution
- Demonstrated necessity to go to NLO precision when looking for saturation effects in the gluon distribution

P. Caucal, F. Salazar, B. Schenke, T. Stebel, R. Venugopalan
Phys.Rev.Lett. 132 (2024) 8, 081902

NLO CALCULATIONS AND FACTORIZATION

- **Calculated the NLO corrections to single inclusive hadron production in DIS at small x regime**
  - UV and soft divergences cancel
  - Collinear divergences result in the scale evolution of quark-hadron fragmentation function
  - Rapidity divergence results in small-x evolution of dipole amplitude

Altinoluk, Bergabo, Jalilian-Marian, Marquet, Shi, 2505.04557

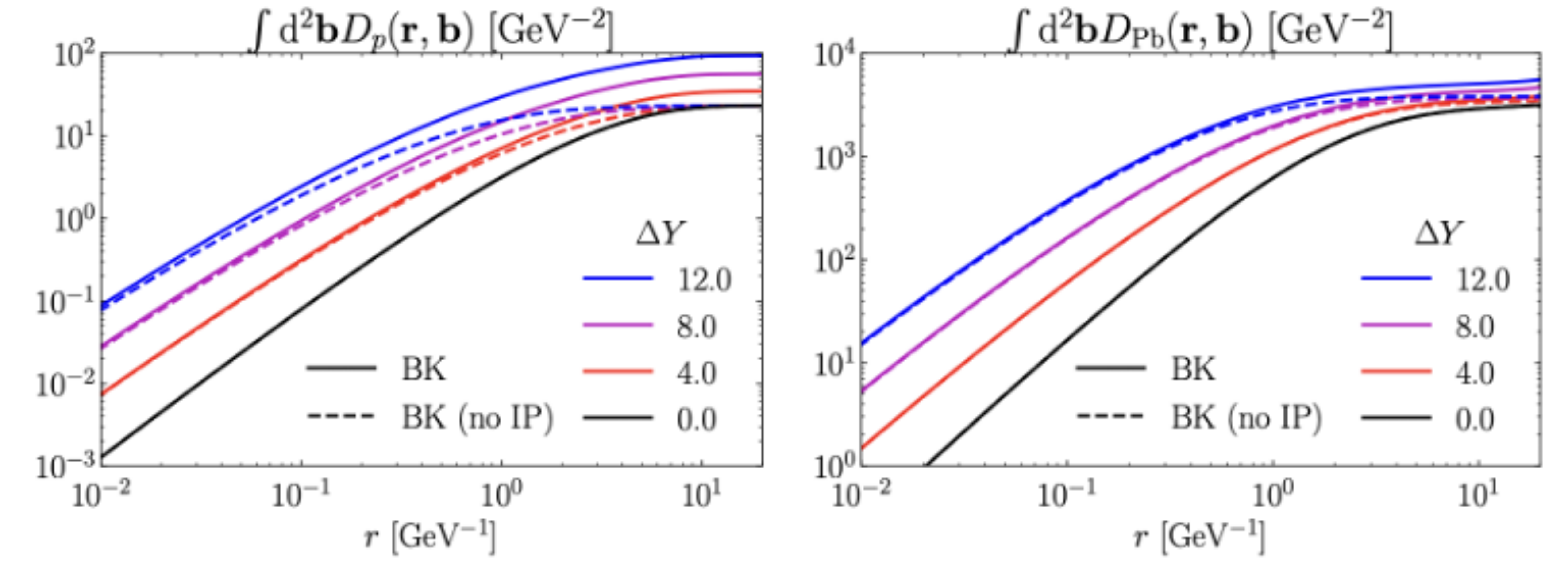


- **Properties of TMD factorization in the small x region have been studied for the following processes:**
  - Single inclusive particle production in the target fragmentation region in DIS: involving quark and gluon jet fracture functions
  - Two particle correlation: involving small-x sea quarks in the initial state

Caucal, Salazar, 2502.02634
Caucal, Guerrero, Iancu, Salazar, Yuan, 2503.16162

EFFECT OF IMPACT PARAMETER DEPENDENCE

- Developed julia-based solver for the BK evolution equation. Simplified syntax, performance comparable to C++ implementations
- Using this, considered the impact parameter dependence in the initial condition
  - Neglecting its dependence can result in overestimated saturation effects for protons, while it has little effect for heavy nuclei at the current experiments



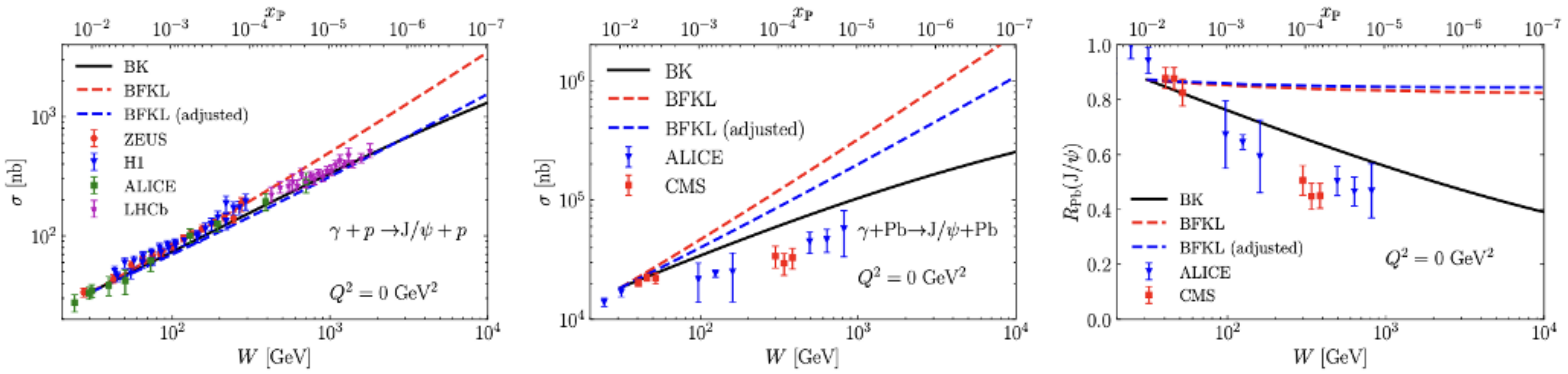
(a) Proton. (b) Lead.

Mantysaari, Penttala, Salazar, Schenke, PRD 2025

LINEAR VS. NON-LINEAR EVOLUTION

- Within the same framework, study exclusive J/psi and Upsilon photo-production for proton and Pb targets
- Energy dependence using linear BFKL and nonlinear BK equations
- No difference for proton target, preference for BK for Pb target in J/psi production

Penttala, Royon, PLB 2025

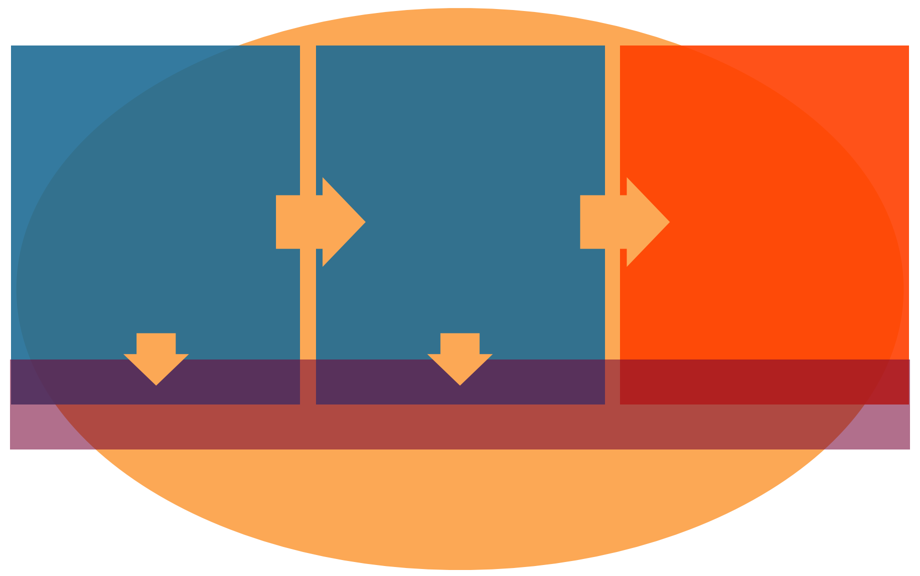


(a) Proton. (b) Lead. (c) Nuclear suppression factor.

FURTHER RESULTS FROM NLO+EVOLUTION

- **Transverse energy-energy correlator (TEEC)**
  - Transverse energy-energy correlator (TEEC) computation for dihadron production in e+A
    Z. Kang, J. Penttala, F. Zhao, Y. Zhou, PRD 2024
  - TEECs for polarized and unpolarized targets at the EIC Bhattacharya, Kang, Penttala, Padilla, 2504.10475
    - Sivers asymmetry for the TEEC can probe the C-odd odderon in the polarized proton
    - The flexibility of the BK solver allows to compute the evolution of the polarized odderon easily
- **Novel approach to QCD evolution using the sequential Born-Oppenheimer approximation**
  - This framework gradually incorporates higher and higher frequency modes as the evolution parameter increases, and provides a unified treatment of both high energy (small-x) evolution and evolution in transverse resolution scale Q^2
  - Derive evolution equations for both TMDs and PDFs, which include:
    - Linear term (e.g. CSS or DGLAP evolution)
    - Nonlinear contribution from stimulated gluon emission, reflecting the bosonic enhancement into already-occupied states Duan, Kovner, and Lublinsky, 2412.05085, 2412.05097

FINAL STATE



- Goals: **Create an event-genator** to be used at the EIC that allows us to probe saturation/small-x physics
  - Progress I: Developing wrappers to connect eHIJING+SMASH, model agnostic Gaussian Processes used to describe hadron formation time

    Jordi Salinas san Martin, Webin Zhao, Xin-Nian Wang, Jaki Noronha-Hostler

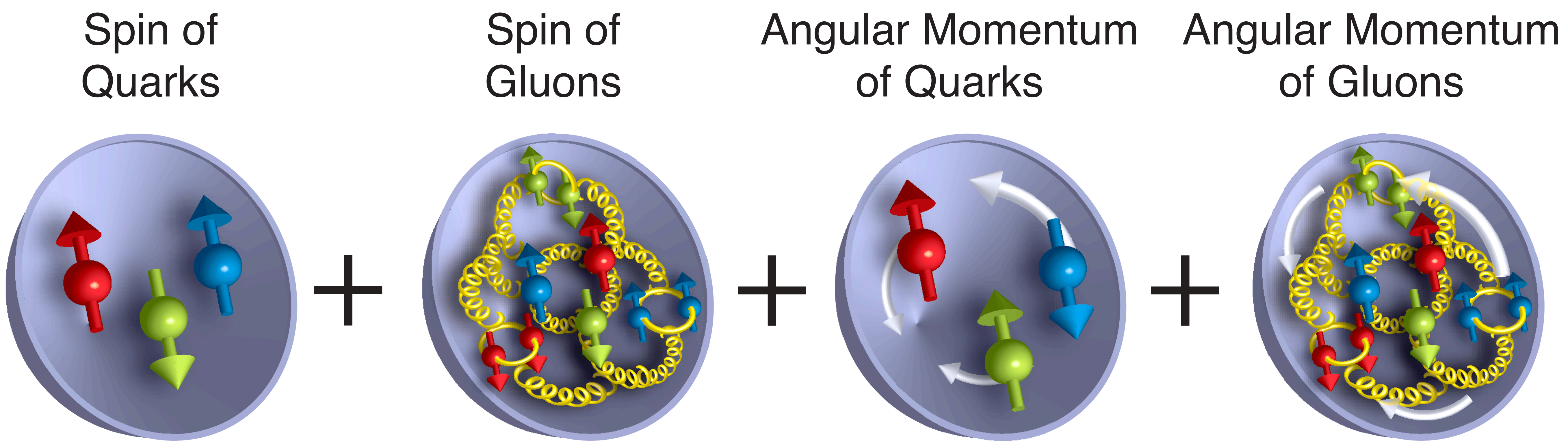
    HIJING + smash
  - Progress II: Sampler for CGC based cross sections and interface to PYTHIA to perform the fragmentation - currently studying dijets in p+A collisions

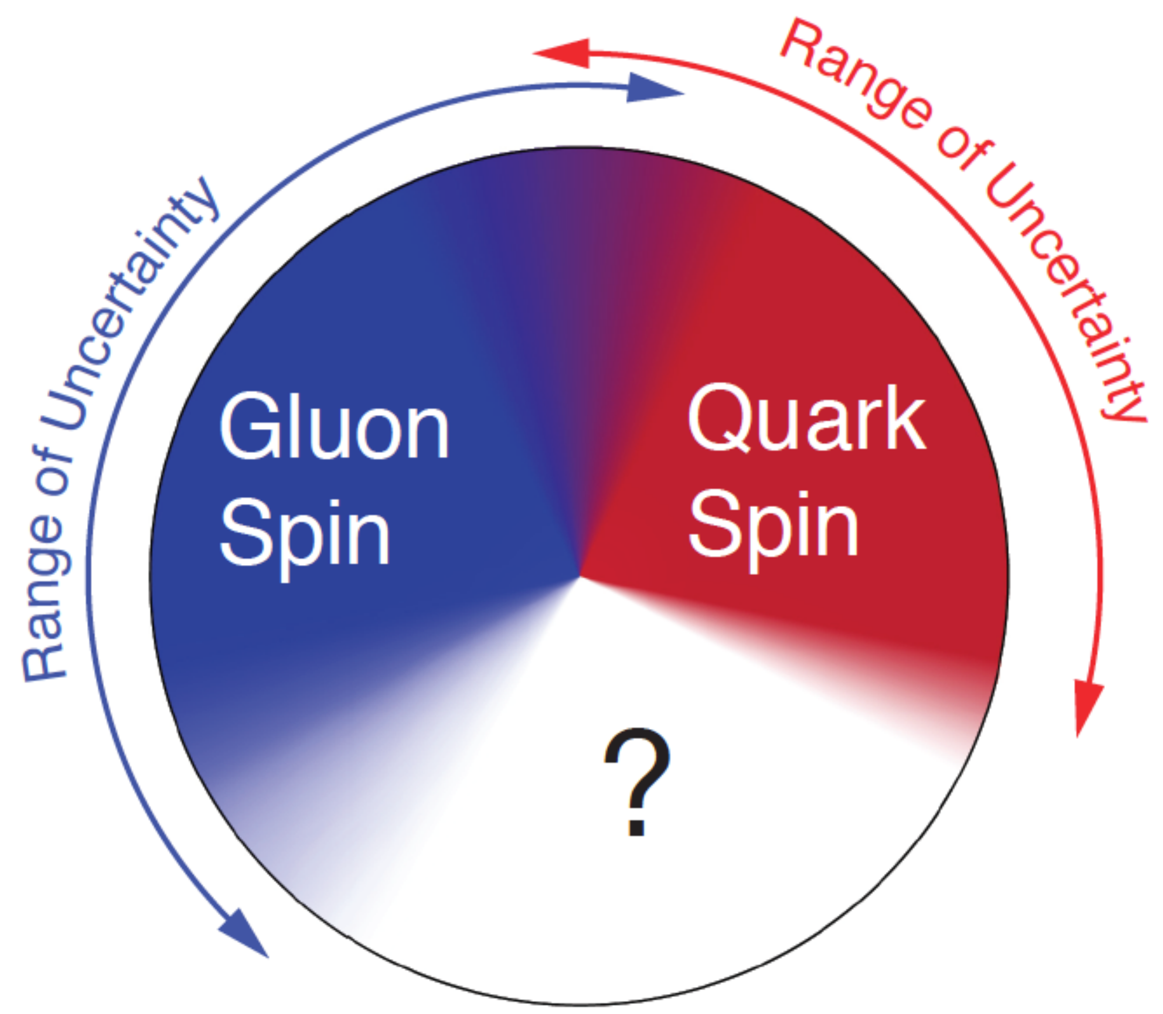
    Wenbin Zhao, F. Salazar, B. Schenke
- New **connections between the final state and gluon saturation**
  - Progress: Di-hadron production at small-x in DIS calculated within the CGC effective field theory at NLO (near back-to-back hadrons in the transverse plane). Identified the emergence of DGLAP and Sudakov logarithms in the final state which are absorbed into transverse-momentum-dependent fragmentation functions

    Caucal & Salazar JHEP 12 (2024) 130

SPIN AT SMALL x

How can we understand the spin of the proton within QCD?

$\frac{1}{2} =$ 

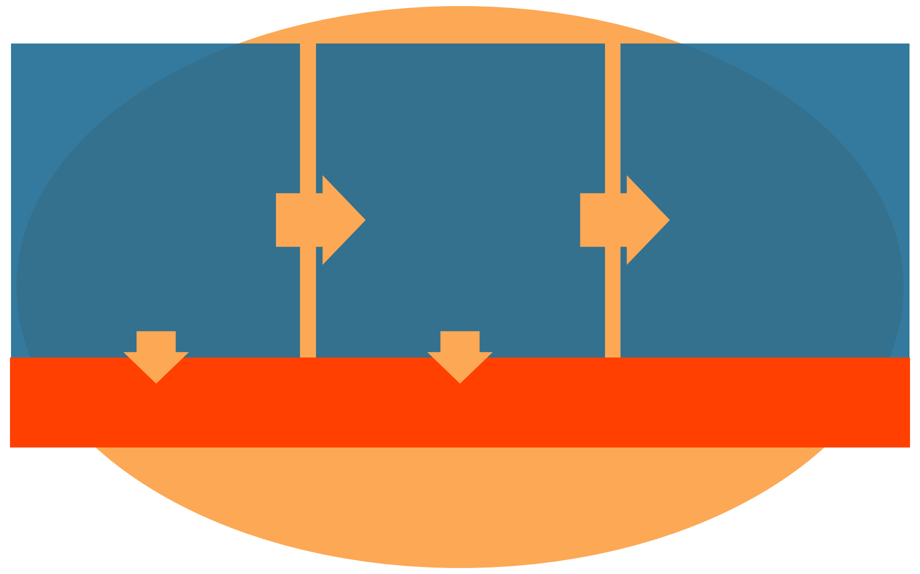


What we know:

- Quarks (valence and sea): ~30% of spin in limited x-range
- Gluons (latest RHIC data): ~40% of spin in limited x-range
- Where is the rest?
- SURGE focuses on the small x region

see Yoshitaka, Yuri and Martha's lectures

SPIN - MILESTONES



Provide improved helicity phenomenology framework at small x

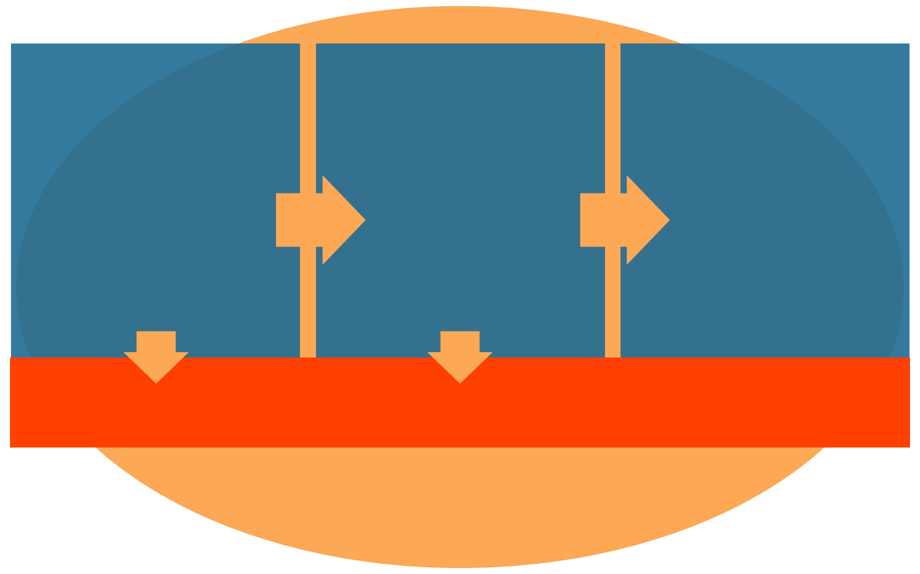
- Include running coupling corrections into large-N_c and N_f helicity evolution phenomenology

D. Adamiak, N. Baldonado, YK, W. Melnitchouk, D. Pitonyak,
N. Sato, M. Sievert, A. Tarasov, Y. Tawabutr, Phys. Rev. D 108, 114007 (2023)
Global analysis of polarized DIS & SIDIS data with improved small-x helicity evolution

- Bayesian Monte Carlo machinery (JAM Collaboration)
- Describe world polarized DIS and single inclusive DIS (SIDIS) data for $x < 0.1$.
- Improvement over the previous JAM-small-x analysis where only the DIS data was fitted

- Ongoing work to include polarized p+p data
- Ongoing work on orbital angular momentum at small *x*

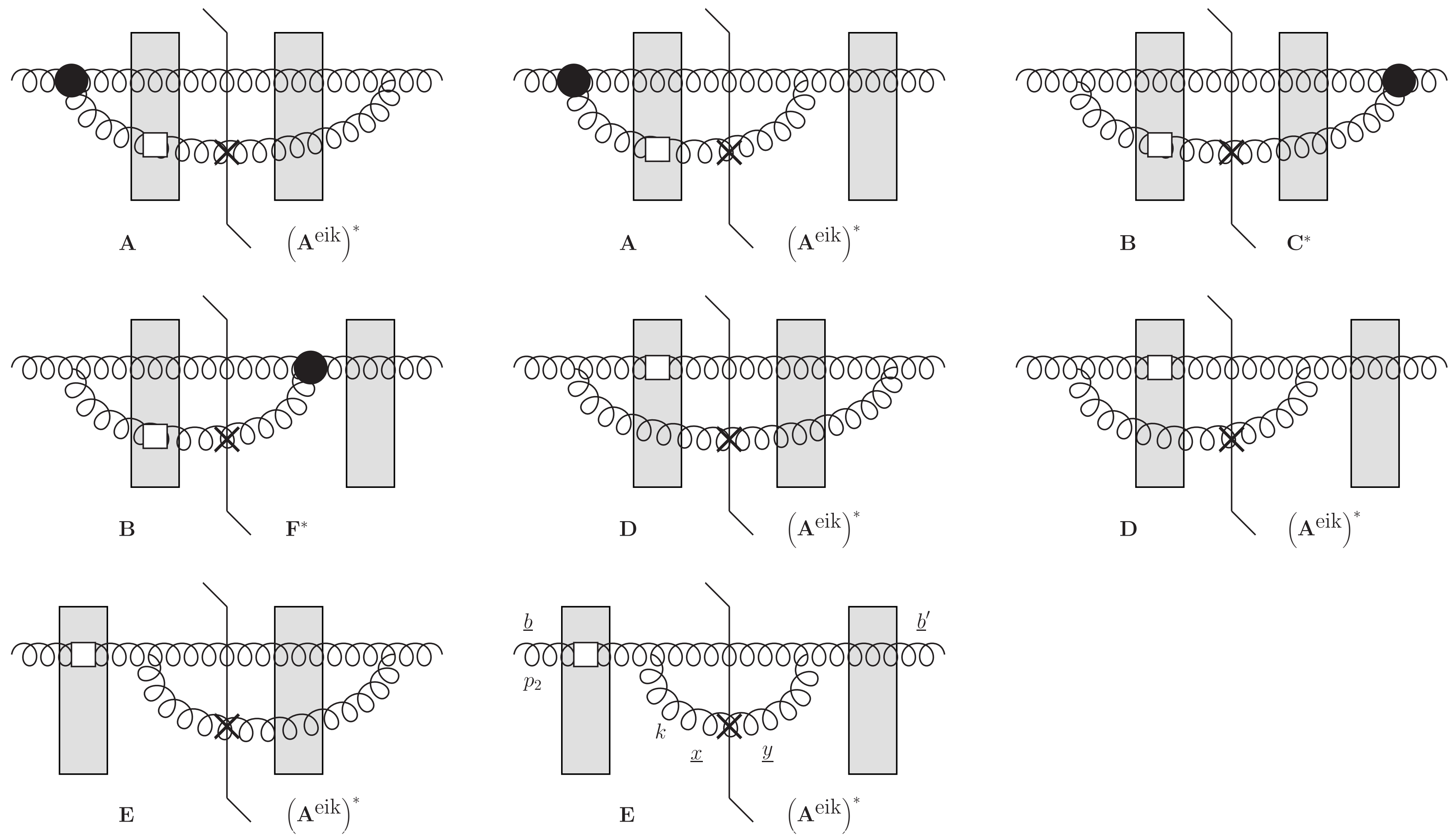
SPIN: PARTICLE PRODUCTION IN POLARIZED p+p



Y. Kovchegov, M. Li, JHEP 05 (2024) 177

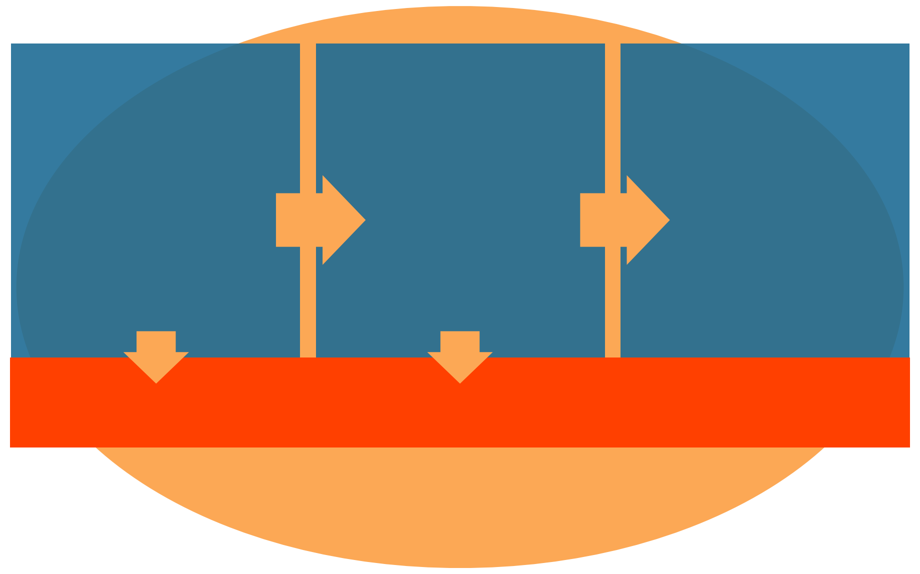
Goal: use polarized p+p data from RHIC to constrain the initial conditions for helicity evolution in *x*. This should lead to more precise predictions for spin-dependent observables at the EIC.

- Sum up all these diagrams
- Include small-*x* evolution on the projectile and target sides (symmetrize expression with respect to target–projectile interchange, to allow for including evolution on the projectile side)
- Results in cross section (at large N_c), where dipole amplitudes Q and G_2 evolve via evolution equations



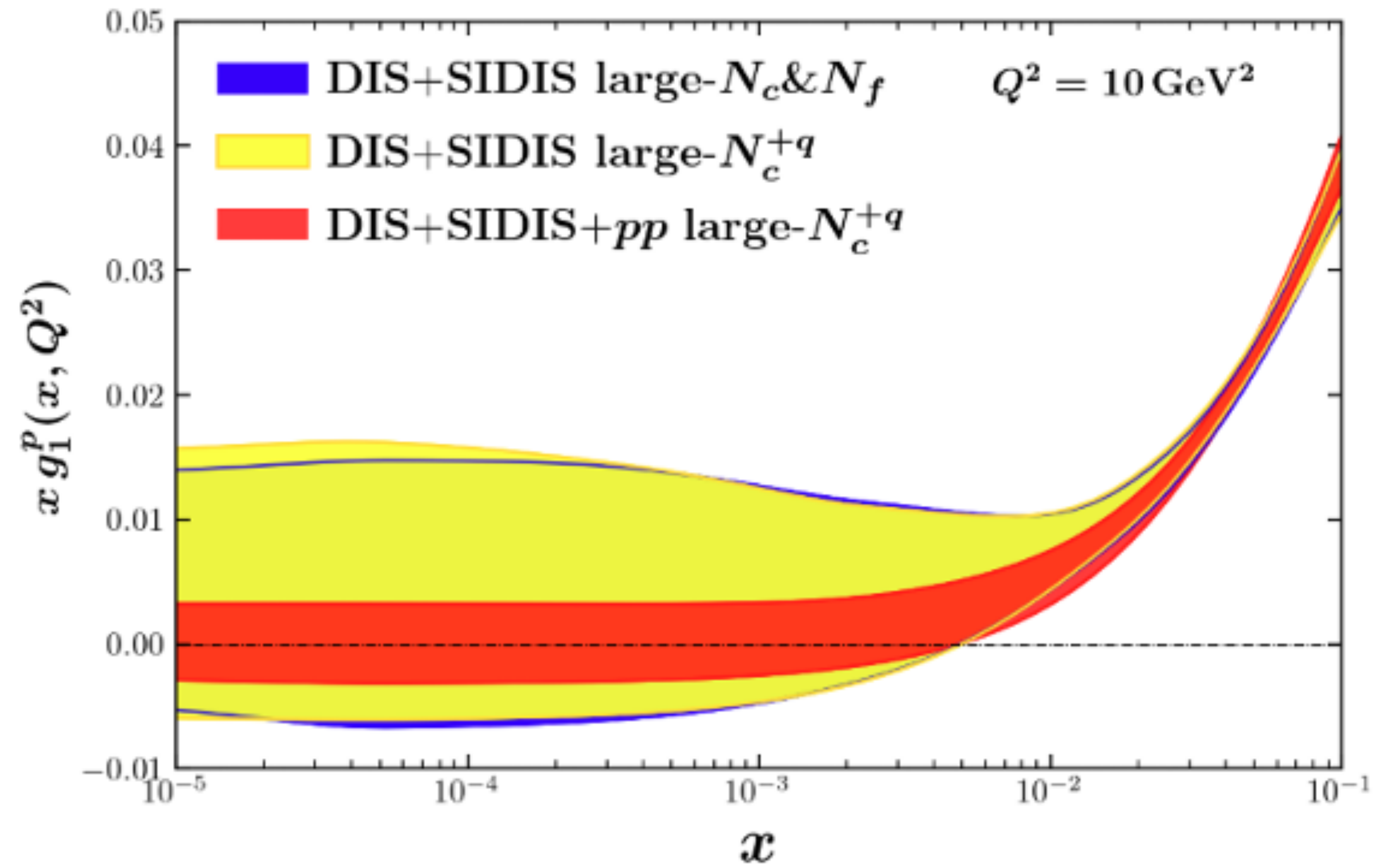
$$\frac{d\sigma}{d^2k_T\,dy} = \frac{C_F}{\alpha_s\,\pi^4}\,\frac{1}{s\,k_T^2}\int d^2x\, e^{-i\underline{k}\cdot\underline{x}}$$
$$\times\ \begin{pmatrix} 4\,Q_P & 2\,G_{2P}\end{pmatrix}(x_\perp^2, \sqrt{2}\,p_2^-\,k_T\,e^{-y}) \begin{pmatrix} \frac{1}{4}\overleftarrow{\nabla}_\perp\cdot\vec{\nabla}_\perp & \overleftarrow{\nabla}_\perp^{\,2} + \overleftarrow{\nabla}_\perp\cdot\vec{\nabla}_\perp \\ \vec{\nabla}_\perp^2 + \overleftarrow{\nabla}_\perp\cdot\vec{\nabla}_\perp & 0 \end{pmatrix} \begin{pmatrix} 4\,Q_T \\ 2\,G_{2T}\end{pmatrix}(x_\perp^2, \sqrt{2}\,p_1^+\,k_T\,e^{y}).$$

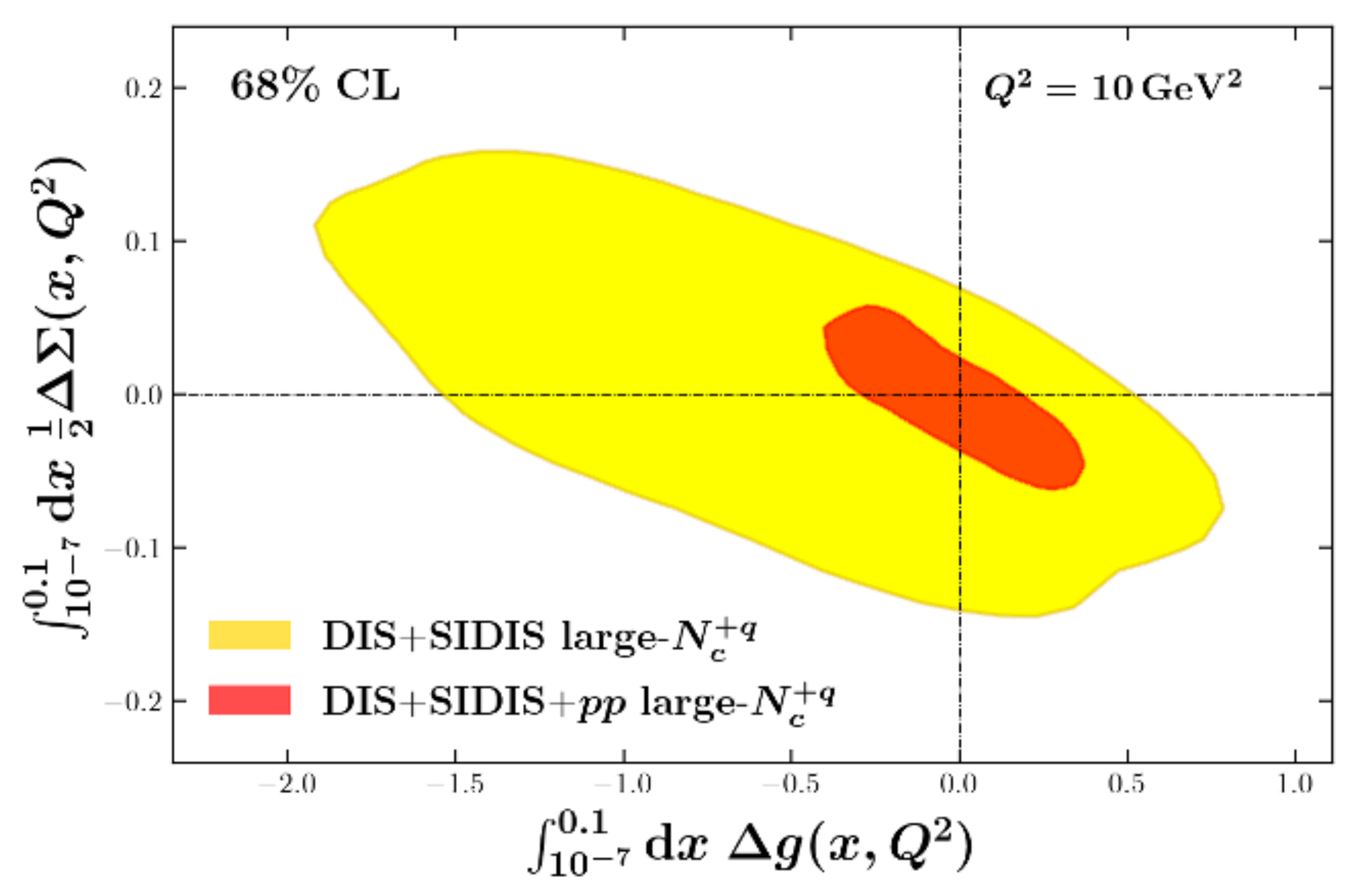
SPIN: PARTICLE PRODUCTION IN POLARIZED p+p



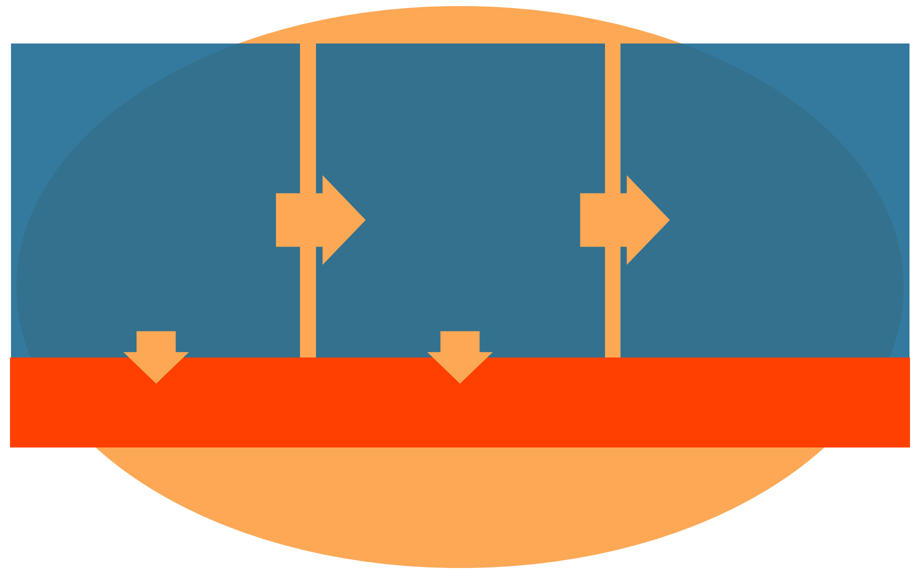
D. Adamiak, N. Baldonado, Y. V. Kovchegov, M. Li, W. Melnitchouk, D. Pitonyak, N. Sato, M. D. Sievert, A. Tarasov, Y. Tawabutr, arXiv:2503.21006 [hep-ph]

Polarized p+p can constrain proton g_1 structure function and estimates of spin at low *x*





SPIN: ORBITAL ANGULAR MOMENTUM AT SMALL x



Y. V. Kovchegov, B. Manley, Phys.Rev.D 111 (2025) 5, 054017

Goal: Establish a way to extract OAM distributions at small *x* from future EIC data

The OAM distributions have never been measured before at any *x*

$$L_z = \int \frac{d^2 b_\perp \, db^- \, d^2 k_\perp \, dk^+}{(2\pi)^3} \, (\underline{b} \times \underline{k})_z \, W(k, b) \longrightarrow$$

$$L_{q+\bar{q}}(x, Q^2) = -\frac{2\,N_f}{\alpha_s \pi^2} \, \widetilde{I} \left(x_{10}^2 = \frac{1}{Q^2}, s = \frac{Q^2}{x} \right),$$

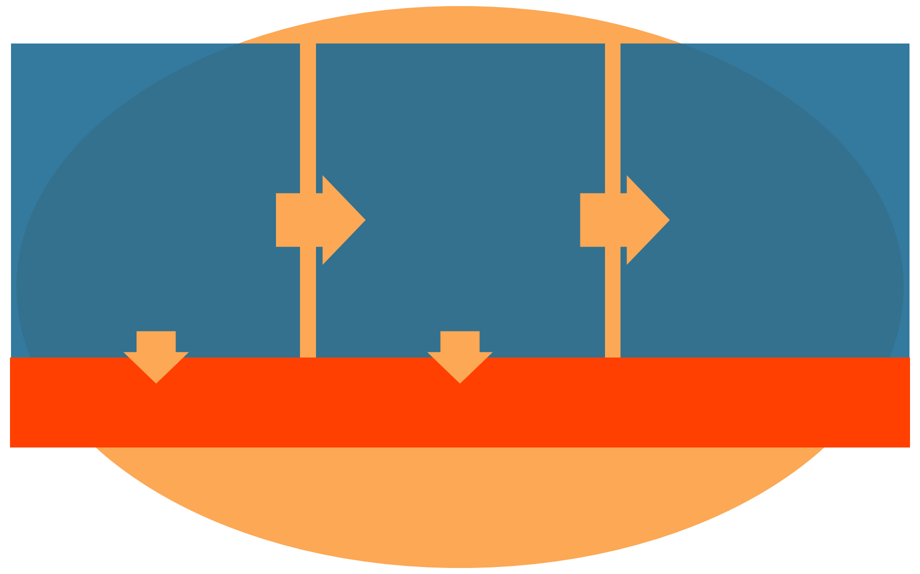
$$L_G(x, Q^2) = -\frac{2\,N_c}{\alpha_s \pi^2} \left[2\,I_4 + 3\,I_5 \right] \left(x_{10}^2 = \frac{1}{Q^2}, s = \frac{Q^2}{x} \right)$$

with impact parameter **moments of dipole amplitudes**, labeled I_3, I_4, I_5, and $\tilde{I}$

Evolution equations for the moment amplitudes in leading double-logarithmic approximation and at large N_c are derived in Y. Kovchegov, B. Manley, 2310.18404 (Y. Kovchegov, B. Manley, 2410.21260)

They can be solved numerically (same ref) and analytically (B. Manley, 2401.05508)

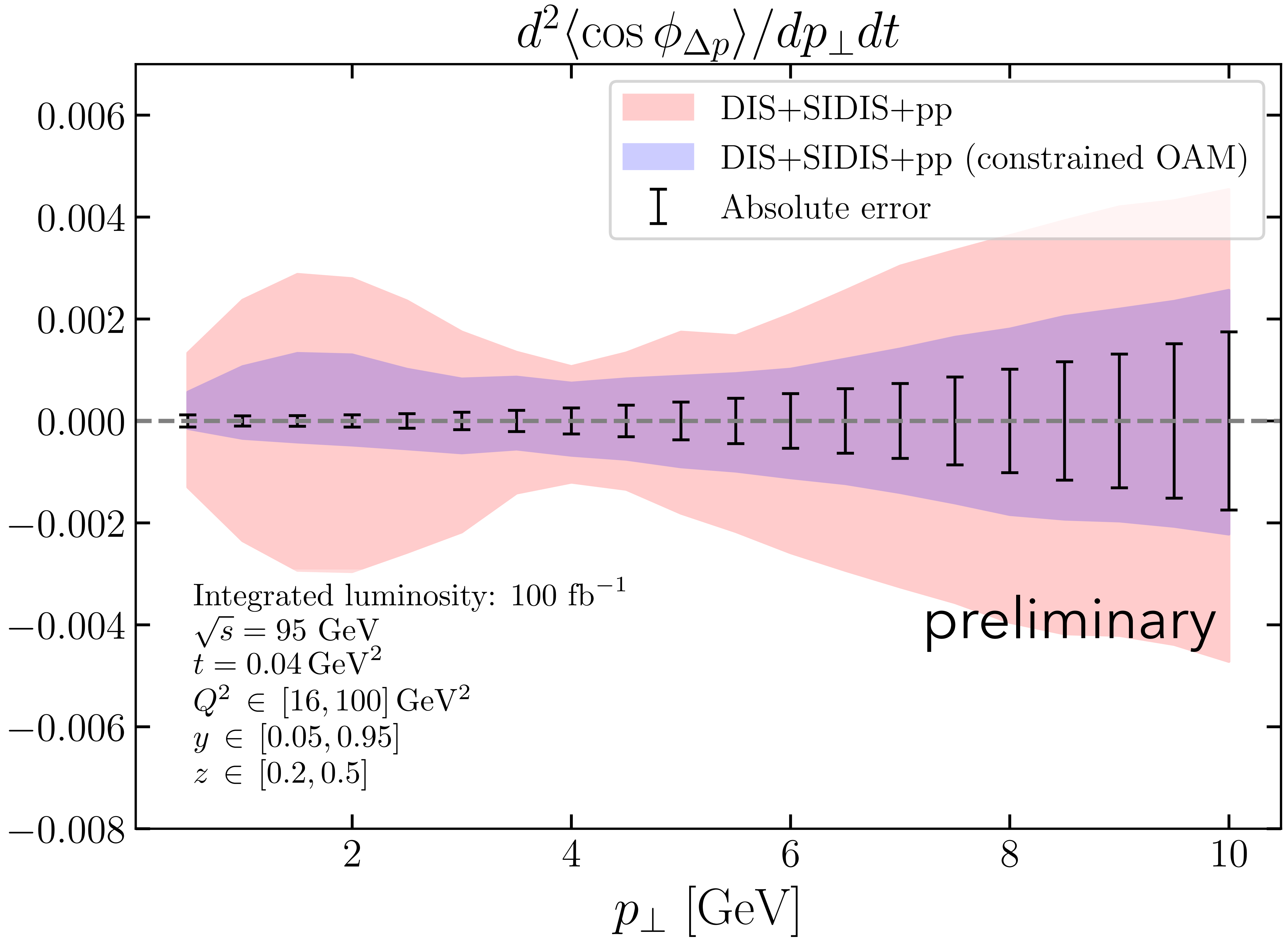
SPIN: ORBITAL ANGULAR MOMENTUM AT SMALL x



Y. V. Kovchegov, B. Manley, Phys.Rev.D 111 (2025) 5, 054017

Elastic dijet production in e+p collisions

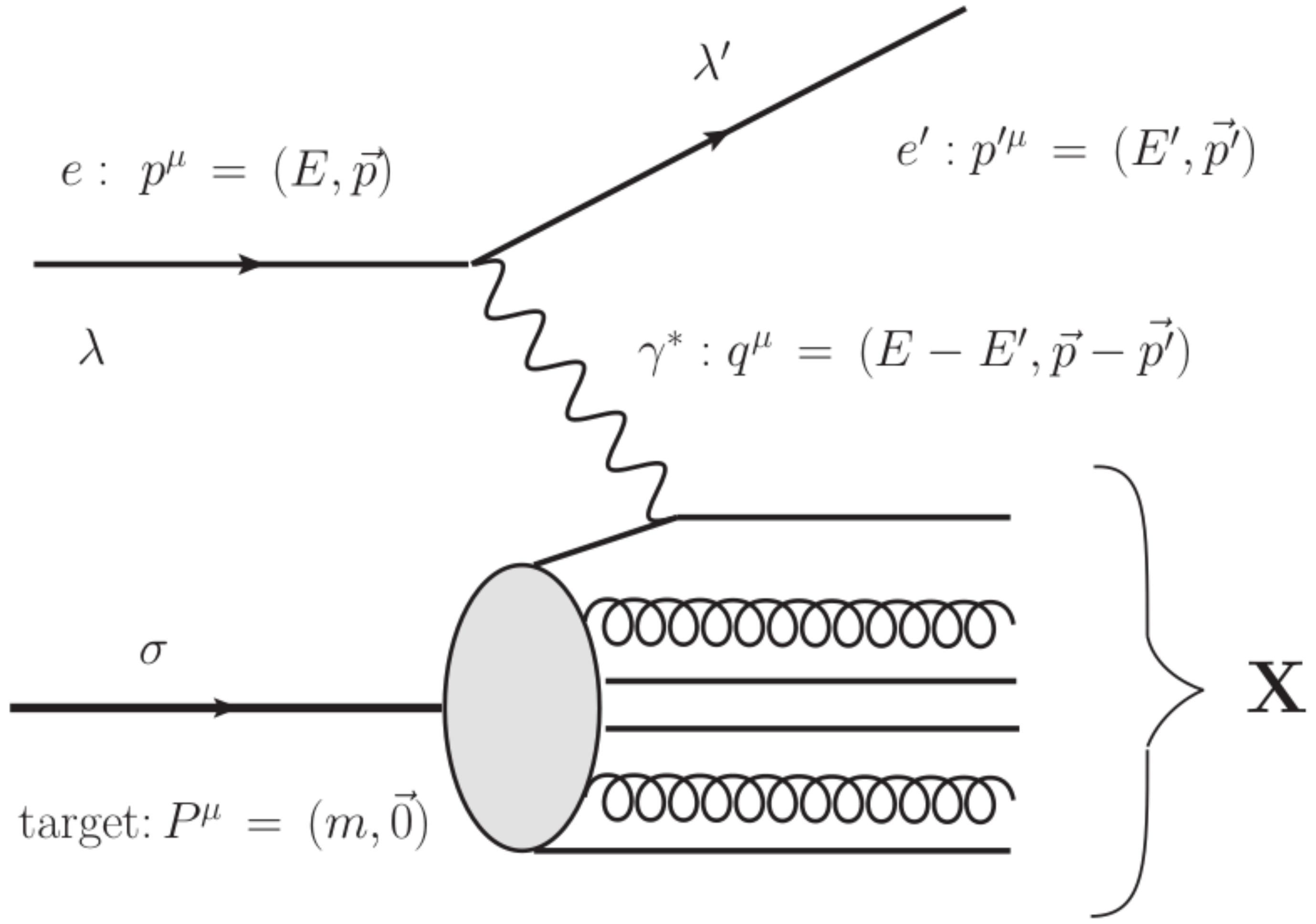
- In the small-t limit ($p_T, Q \gg \Lambda_{\text{QCD}} \gg \Delta_T$ with $t = -\Delta_T^2$) the elastic dijet double spin asymmetry measures moments of dipole amplitudes I_3, I_4, I_5, thus allowing (in principle) to **measure OAM distributions**!
- Feasibility study in progress (G.Z. Becker, J. Borden, B. Manley, Y. Kovchegov)



Hatta et al, 2016; S. Bhattacharya, R. Boussarie and Y. Hatta, 2022 & 2024; S. Bhattacharya, D. Zheng and J. Zhou, 2023; YK, B. Manley, 2410.21260 [hep-ph]

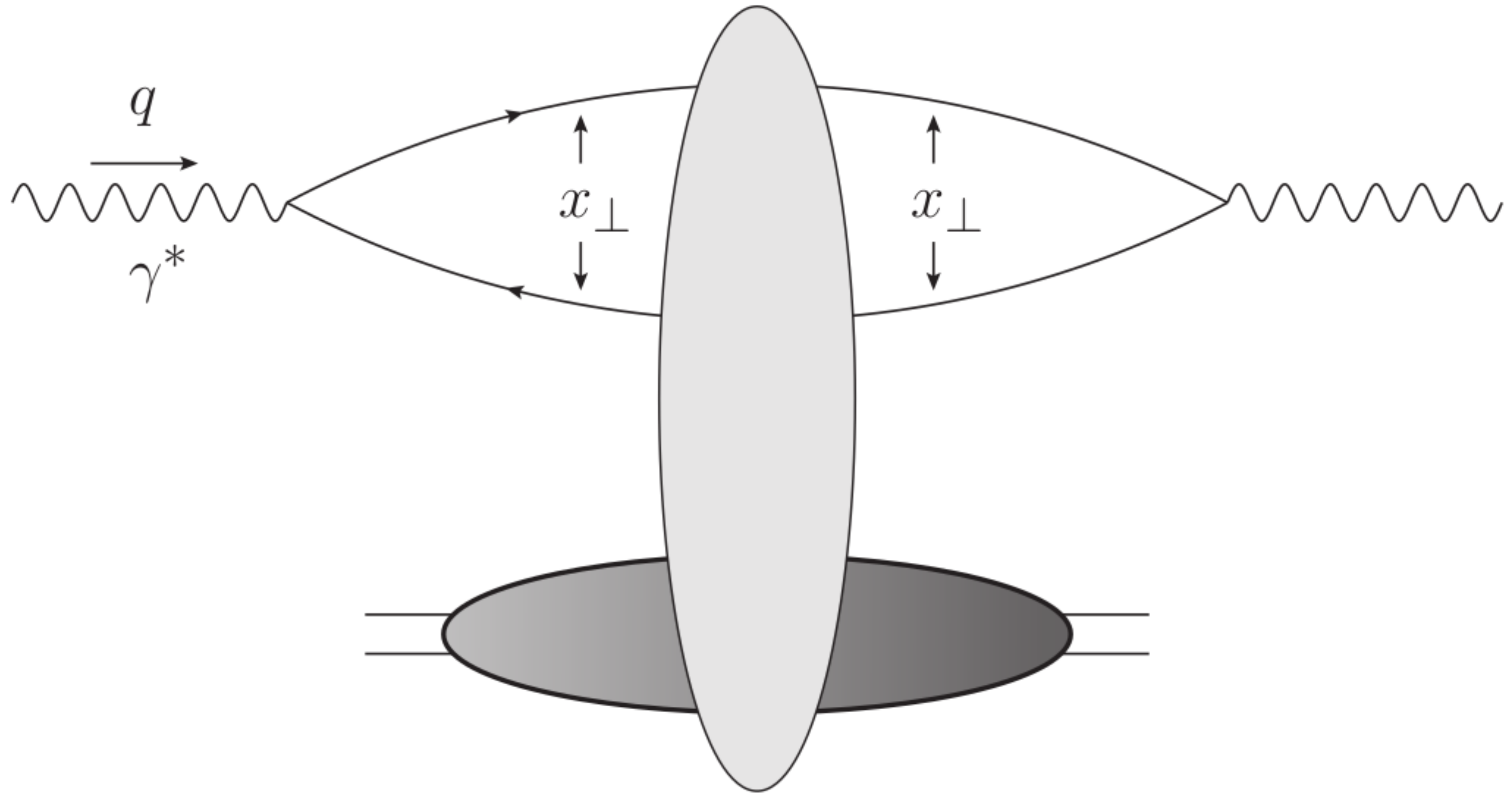
GLOBAL ANALYSIS

- Develop a numerical framework with state of the art theory input
- Compare the parton model (already in xFitter) and the dipole model (saturation model)



Parton model

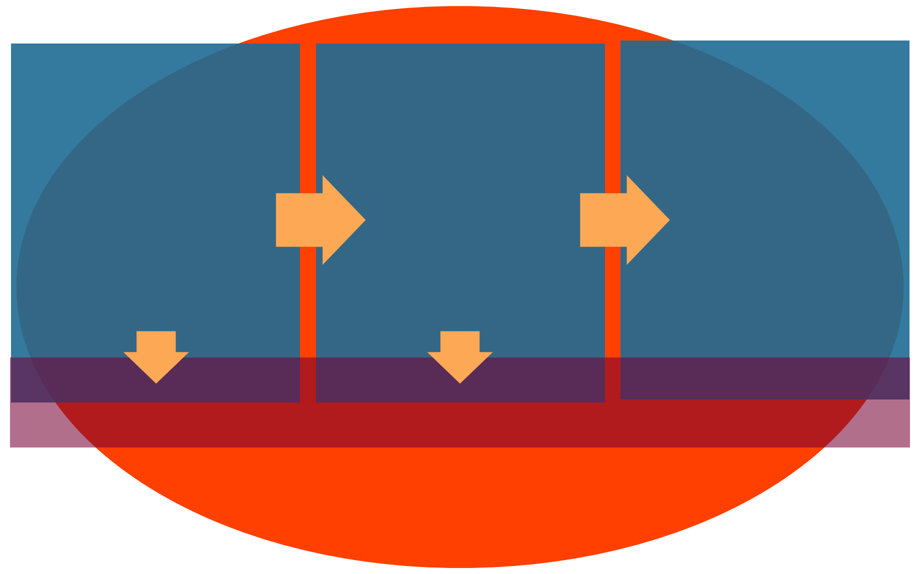
$$\sigma = f_{P\to a}(x, Q) \otimes \hat{\sigma}_{a\gamma\to X}(x, \hat{s})$$



Dipole model

$$\sigma_{tot}^{\gamma^* A}(x, Q^2) = \int \frac{d^2x_\perp}{4\pi} \int_0^1 \frac{dz}{z(1-z)} |\Psi^{\gamma^*\to q\bar{q}}(\vec{x}_\perp, z)|^2 \sigma_{tot}^{q\bar{q}A}(\vec{x}_\perp, Y).$$

GLOBAL ANALYSIS

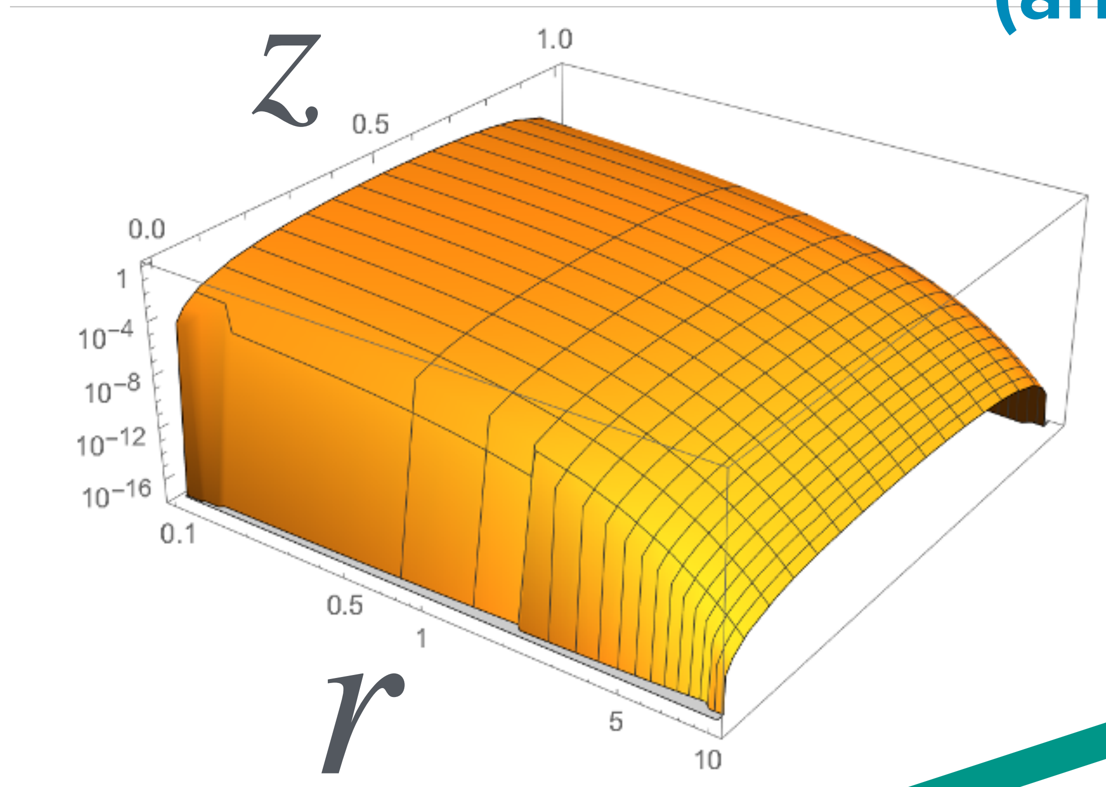


Develop a numerical framework implementing the dipole model

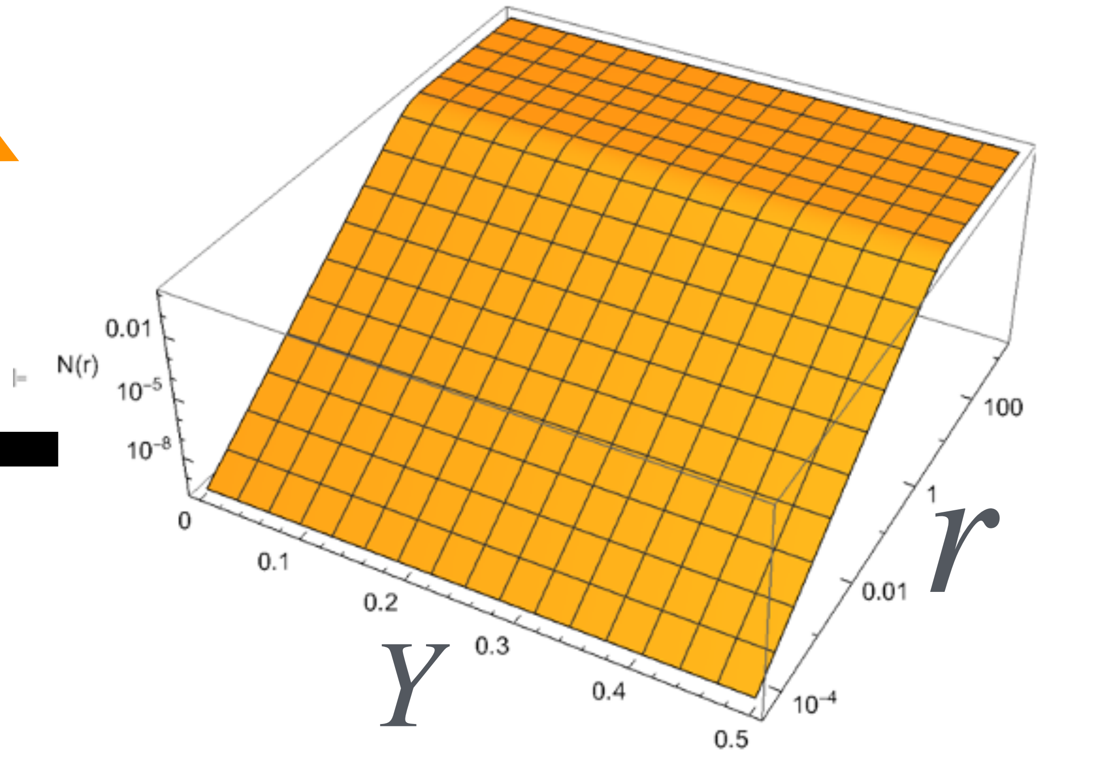
$$\sigma_{tot}^{\gamma^* A}(x, Q^2) = \int \frac{d^2 x_\perp}{4\pi} \int_0^1 \frac{dz}{z(1-z)} |\Psi^{\gamma^* \to q\bar{q}}(\vec{x}_\perp, z)|^2 \sigma_{tot}^{q\bar{q}A}(\vec{x}_\perp, Y).$$

photon wave function (analytic)

dipole cross section (grid)



Convolution



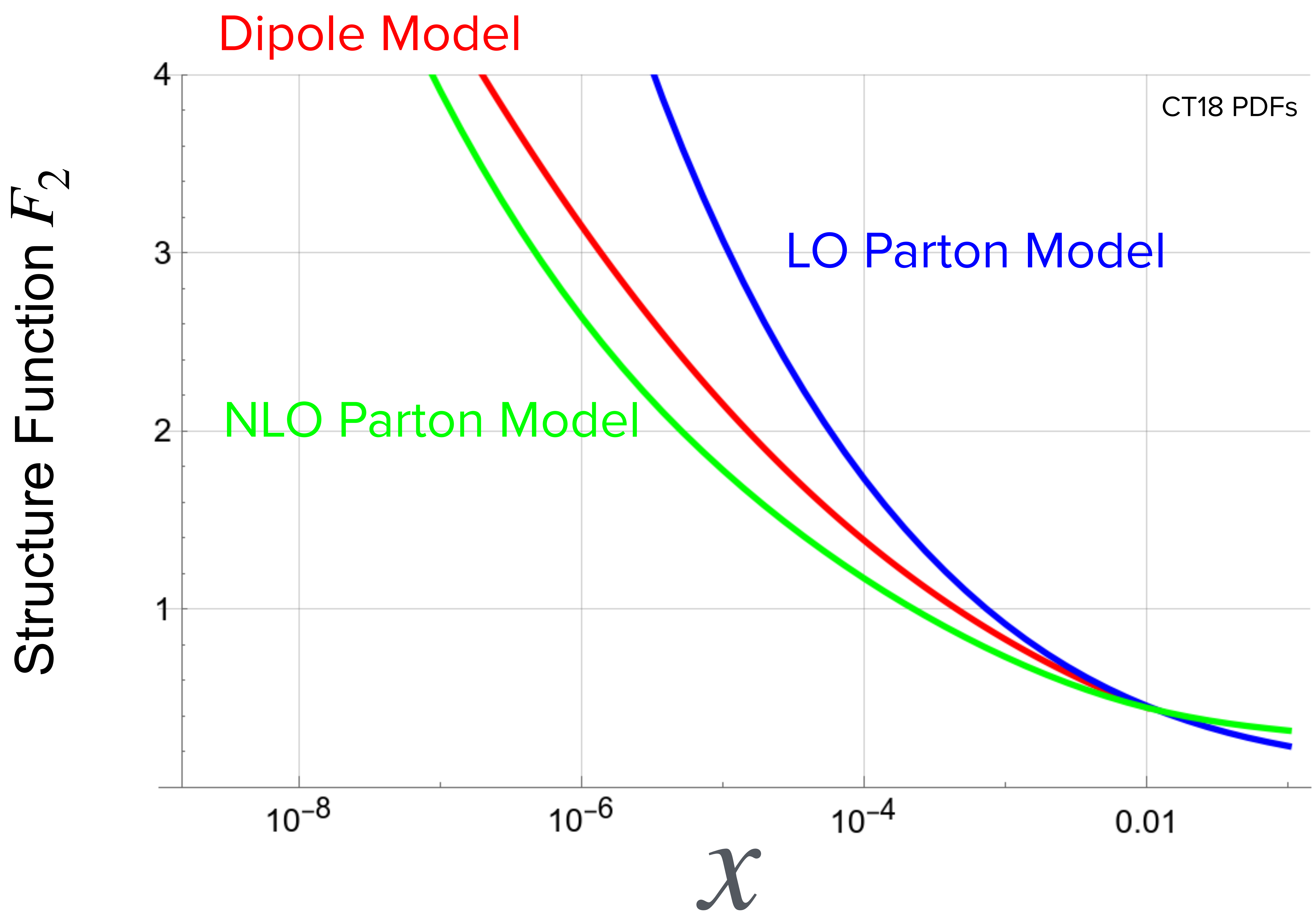
$$\sigma_{\text{tot}}^{\gamma^* A}(x, Q^2)$$

$$\ldots F_2, F_L$$

$$\chi^2 = \frac{(D-T)^2}{\sigma^2}$$

xFitter

F_2 STRUCTURE FUNCTION: COMPARE DIPOLE & PARTON MODEL



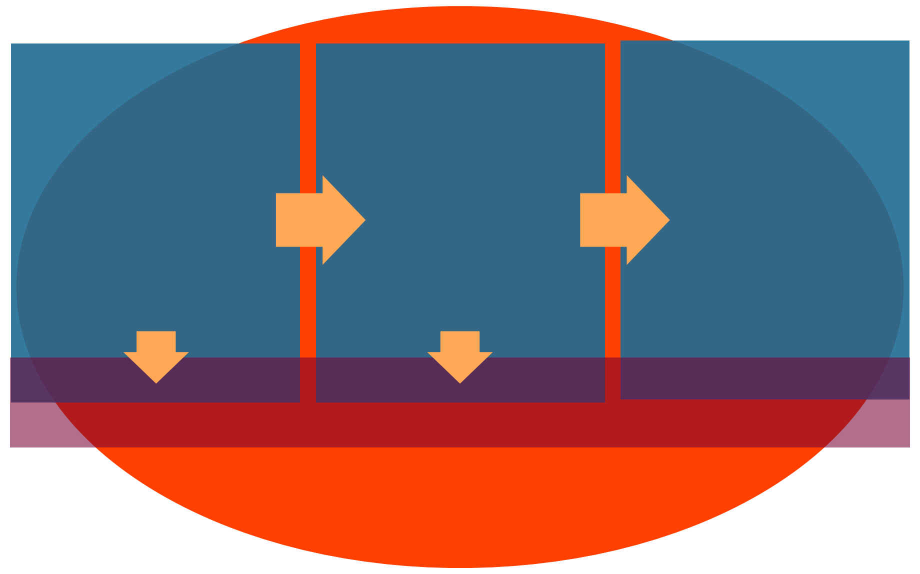
Compare x-dependence

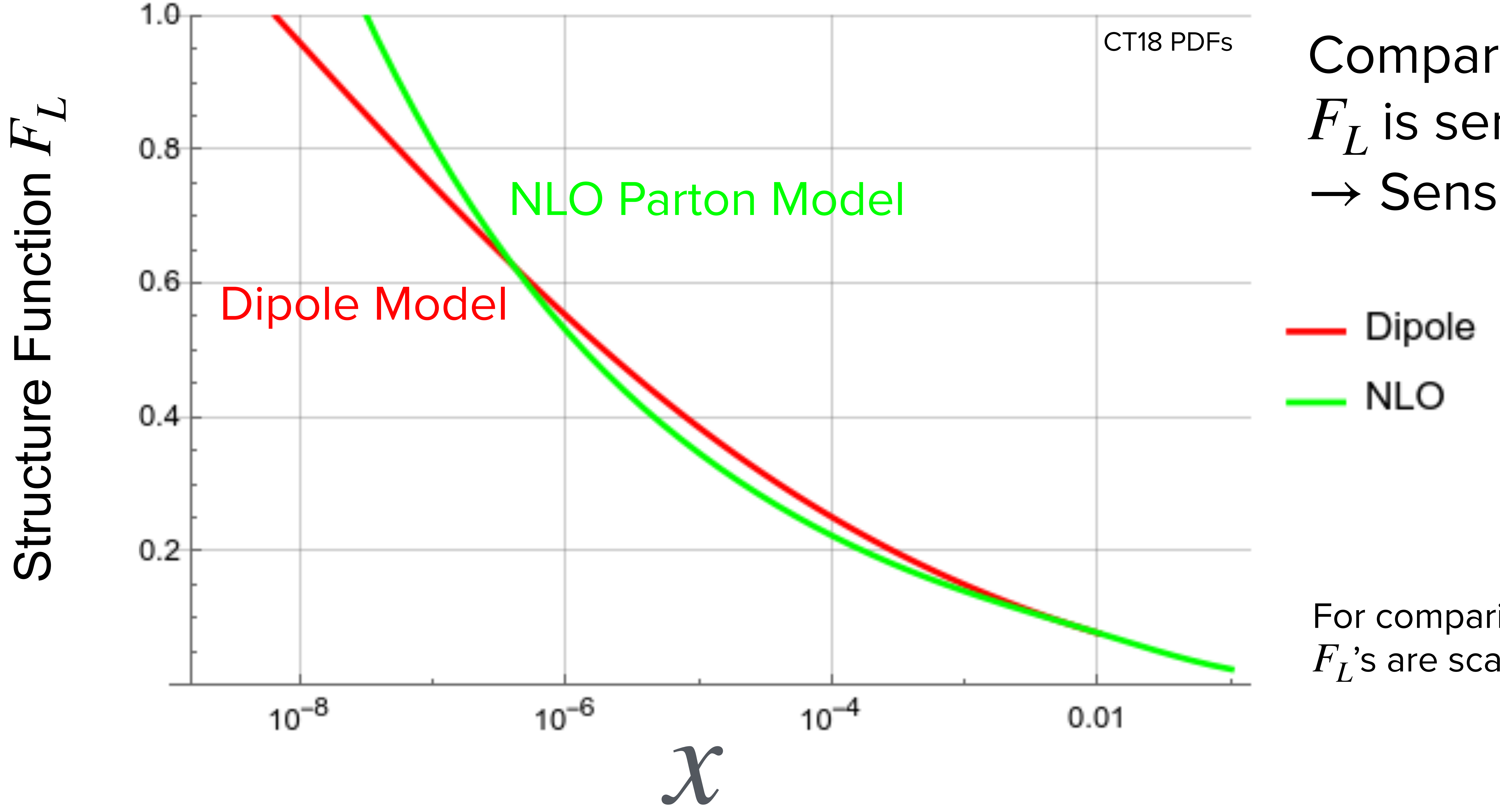
Dipole lies between LO and NLO

- Dipole
- LO
- NLO

For comparison of x-dependence, parton F_2's are scaled to coincide at 10^{-2}

F_L STRUCTURE FUNCTION: COMPARE DIPOLE & PARTON MODEL





Compare x-dependence

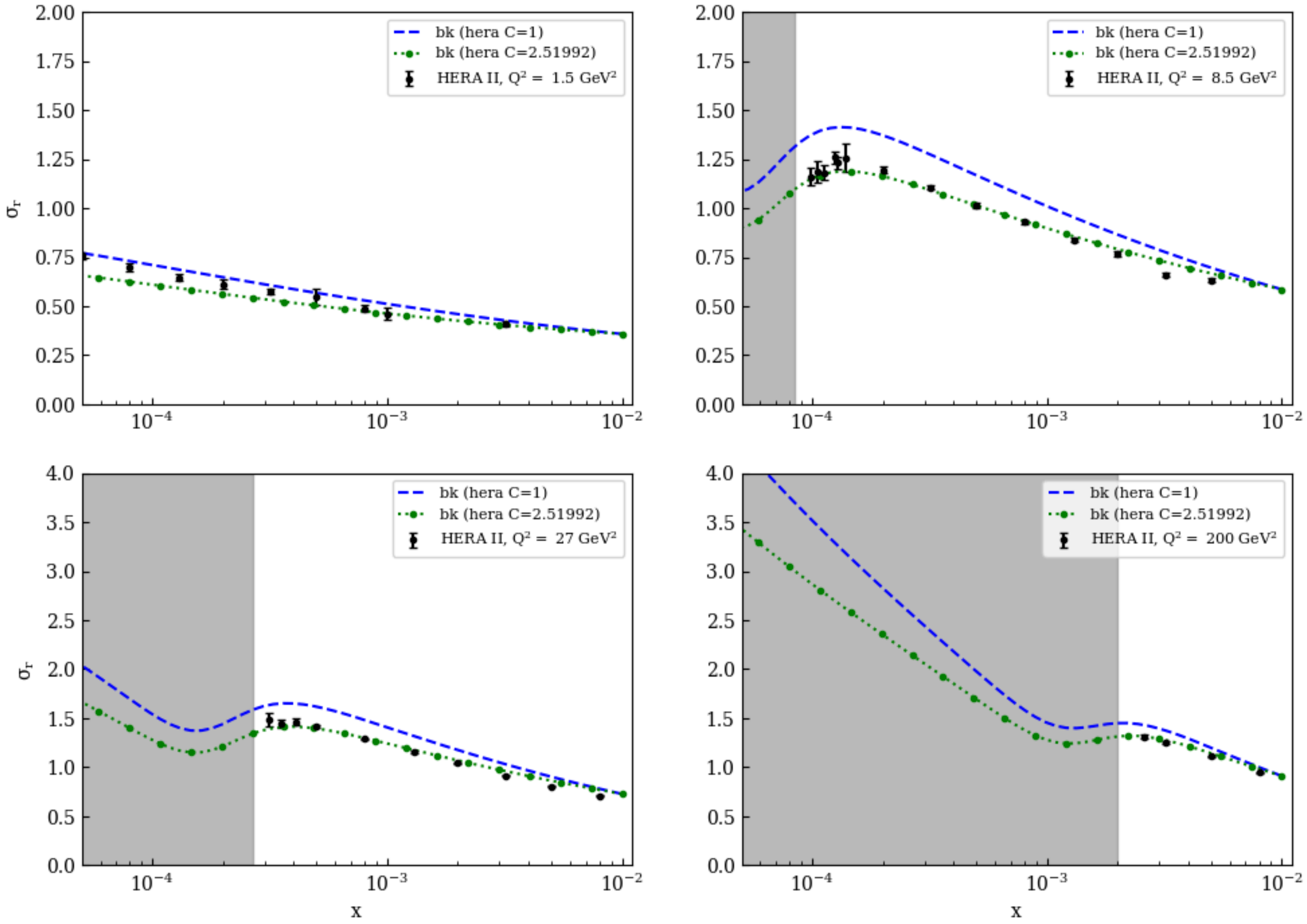
F_L is sensitive to gluon PDF

→ Sensitive to saturation

For comparison of x-dependence, parton F_L's are scaled to coincide at 10^{-2}

GLOBAL ANALYSIS

Comparison of Dipole Calculation to HERA Data



Comparison to HERA data for two values of the C parameter

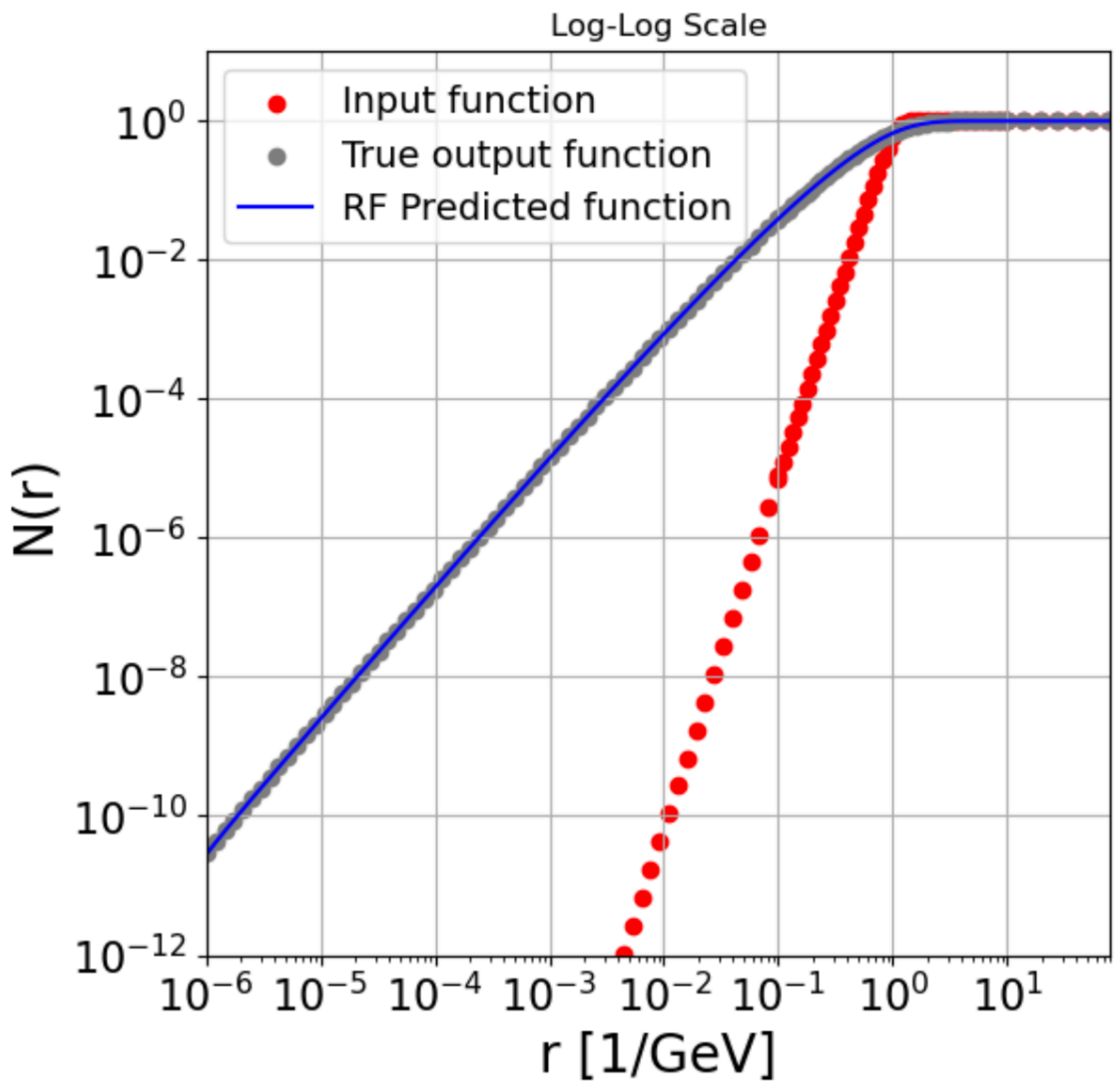
The gray regions are unphysical (no data there)

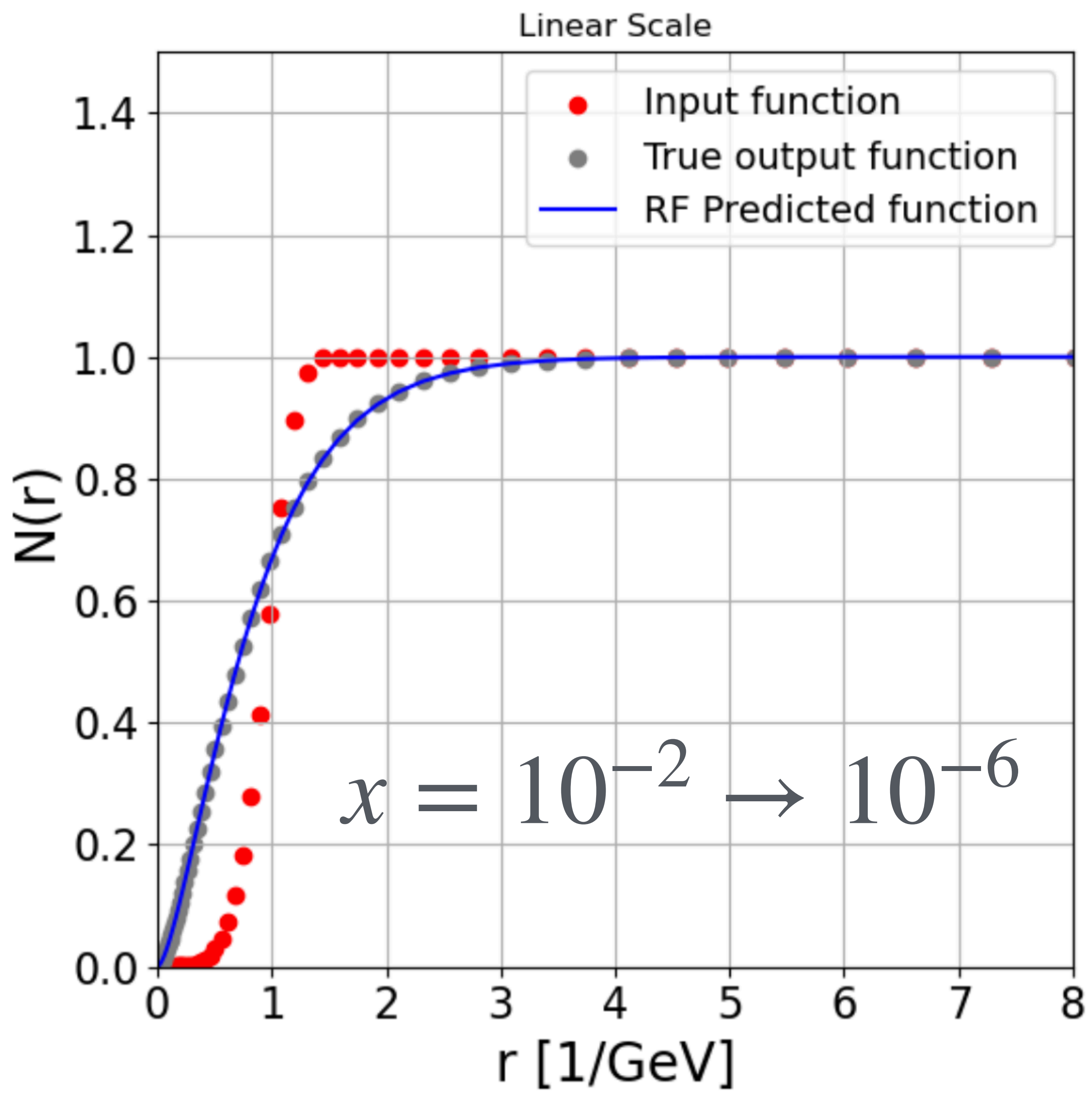
The quark masses are neglected for this sample calculation

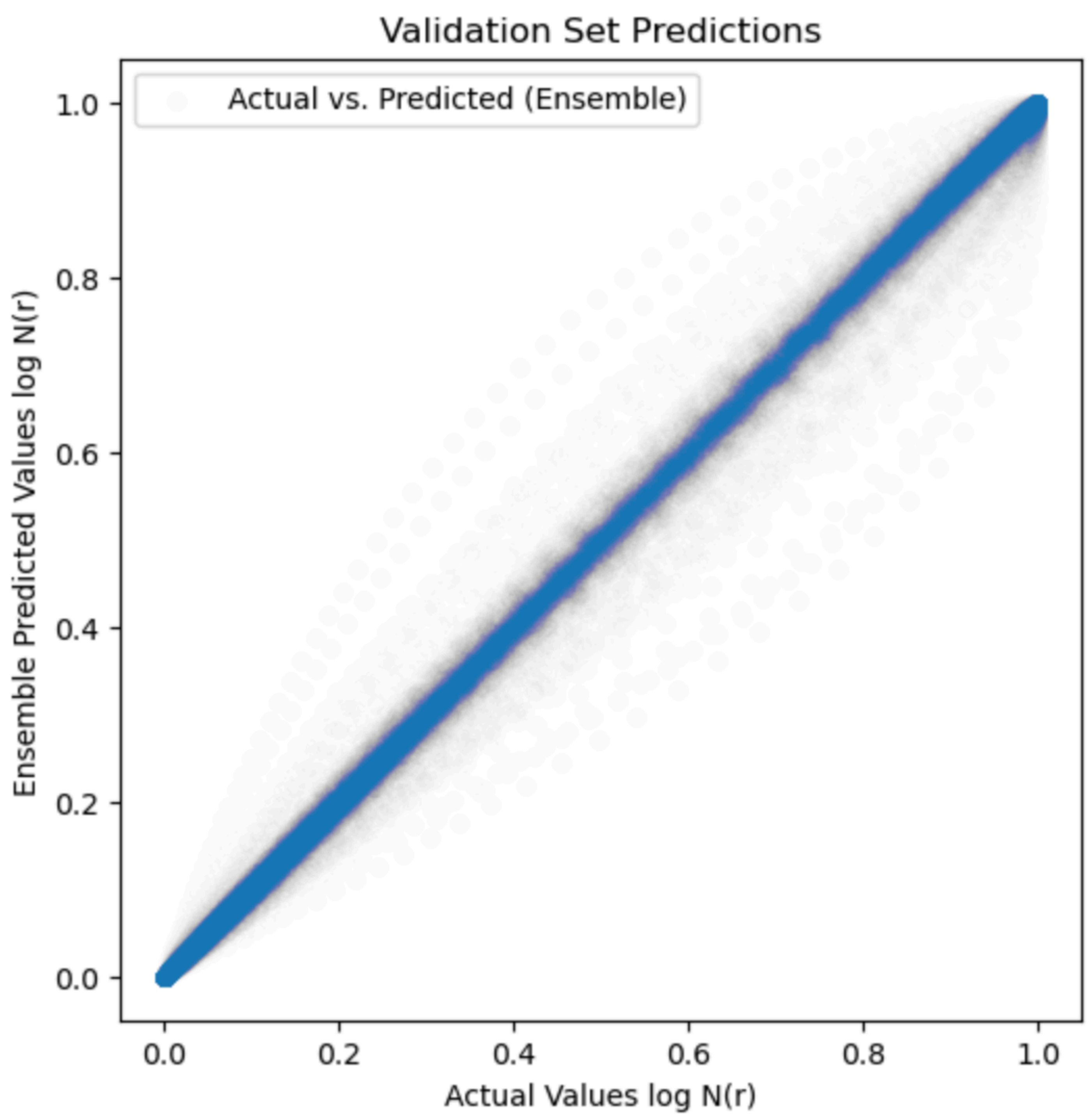
MACHINE LEARNING FOR SPEED

Need very fast small x evolution. Train ML model to predict evolved dipole amplitude

- Data: Wide variety of dipole amplitudes $N(x_0, r)$ (input) and BK evolved amplitudes $N(x, r)$ over range of x (so far leading log BK, implementing NLL now)
- Train Machine Learning Model (Random Forest) $\rightarrow$ module for many calculations, incl. with spin







SUMMARY

- Highly successful first 2 years
- Many achievements that would not have happened without the collaborative efforts in the TC
- Milestones achieved or on track to be achieved
- Output of 120+ papers on arXiv
- 70+ refereed publications in high impact journals
- Support for students and postdocs
- Travel support for visits between institutions
- Co-Sponsor of this CFNS-SURGE Summer School

BACKUP

OUTLOOK - GOALS FOR THE COMING YEAR

- Non-Gaussian initial conditions for large nuclei
- Extend factorization that bridges large and small-x regimes to lattice quantities
- Compare dihadron NLO calculations to TMD factorization calculations
- Perform numerical calculations for dihadron production in e+A collisions
- Go beyond eikonal approximation to understand power corrections of $1/Q^2$
- Study exclusive diffractive dijet production to access orbital angular momentum
- Include polarized p+p data into global analysis
- Develop phenomenology for orbital angular momentum distributions
- Incorporate the hadronic cascade SMASH into eHIJING
- Incorporate exclusive vector meson production into the EPIC event generator
- Continue development of modules for the global analysis framework - improve and develop more machine learning models

FINAL STATE

Jordi Salinas san Martin, Webin Zhao, Xin-Nian Wang, Jaki Noronha-Hostler, to appear

Introduce hadron formation time via scaling of hadron cross-sections using Gaussian Processes

smash

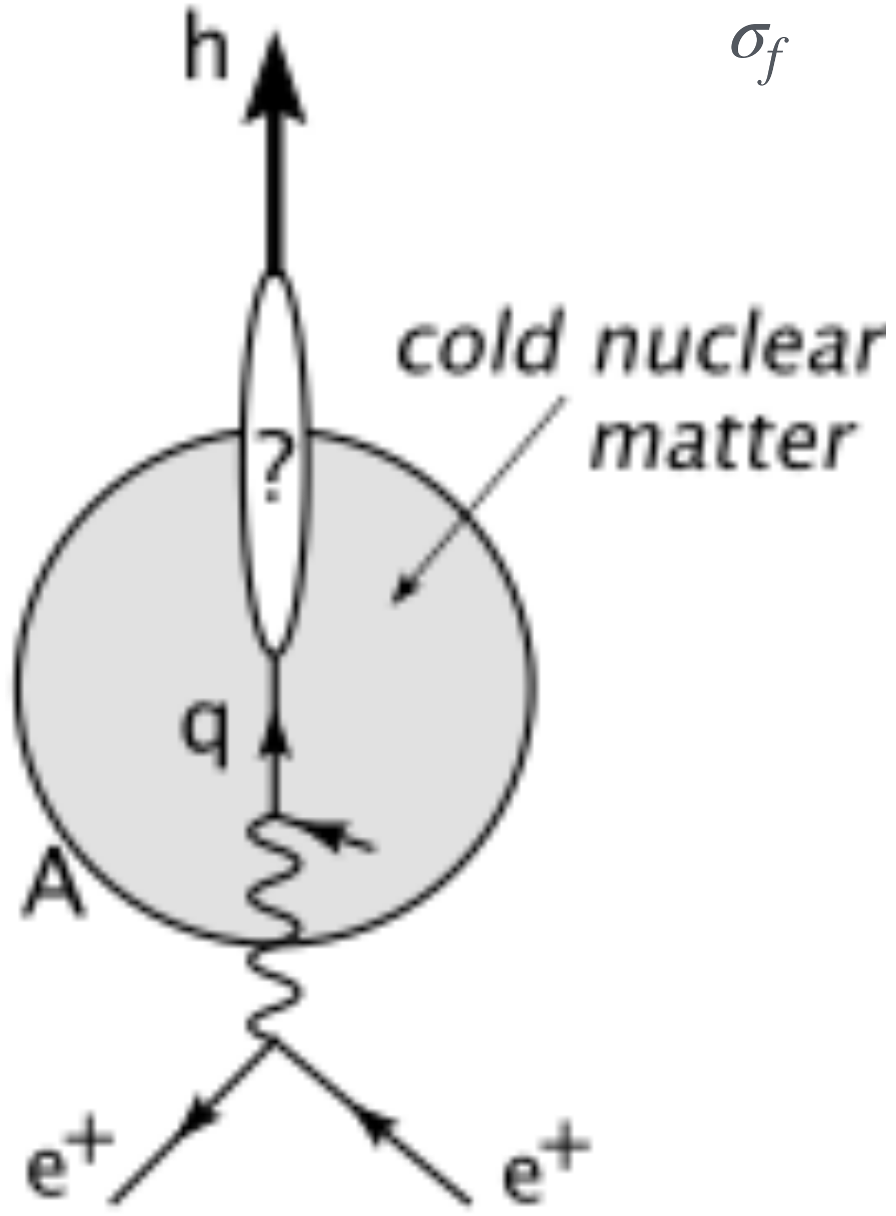
"soft"

Phys.Rev.C 94 (2016) 5, 054905

HIJING

"hard"

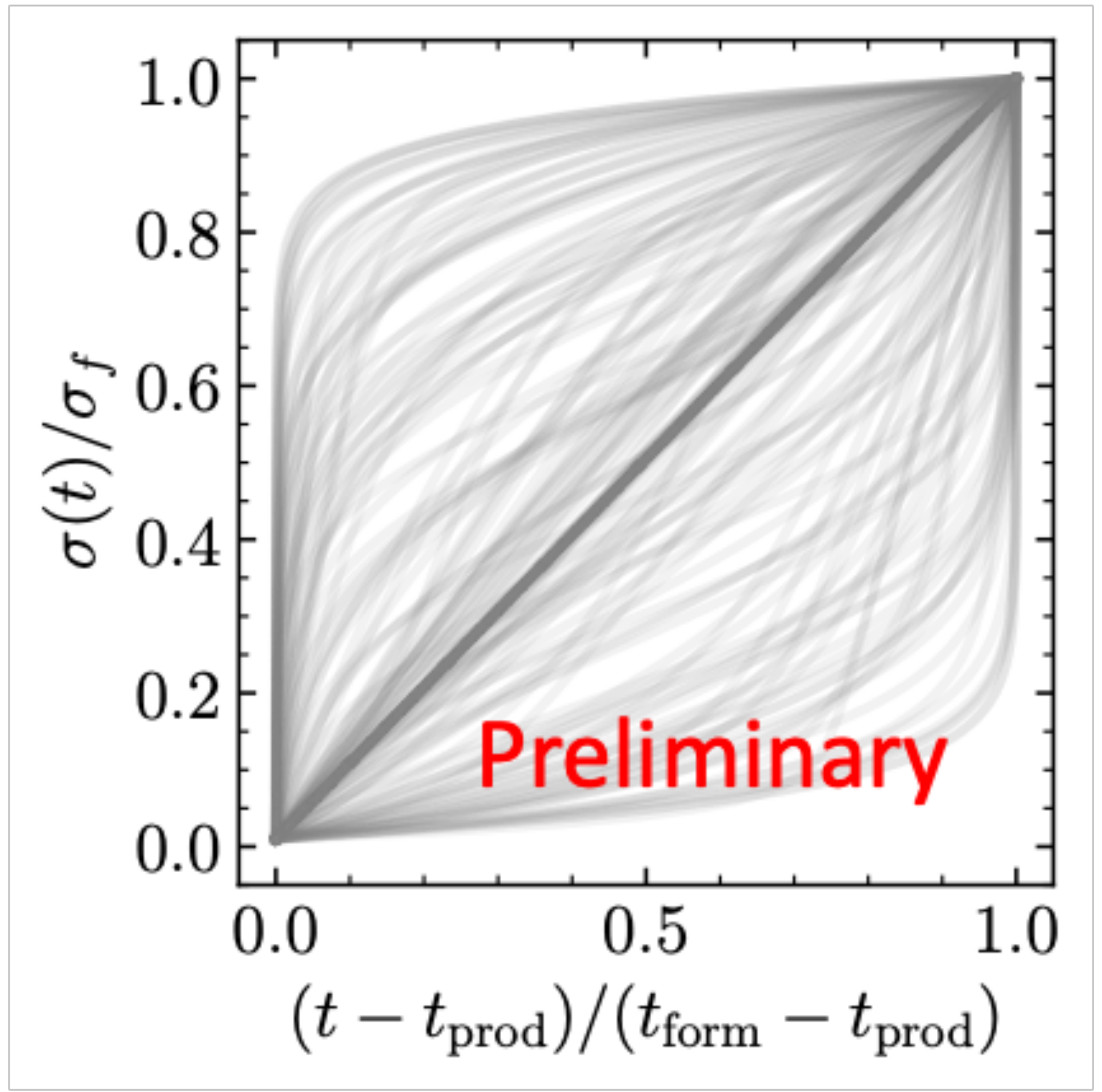
W. Ke et al, 2304.10779 (2023)

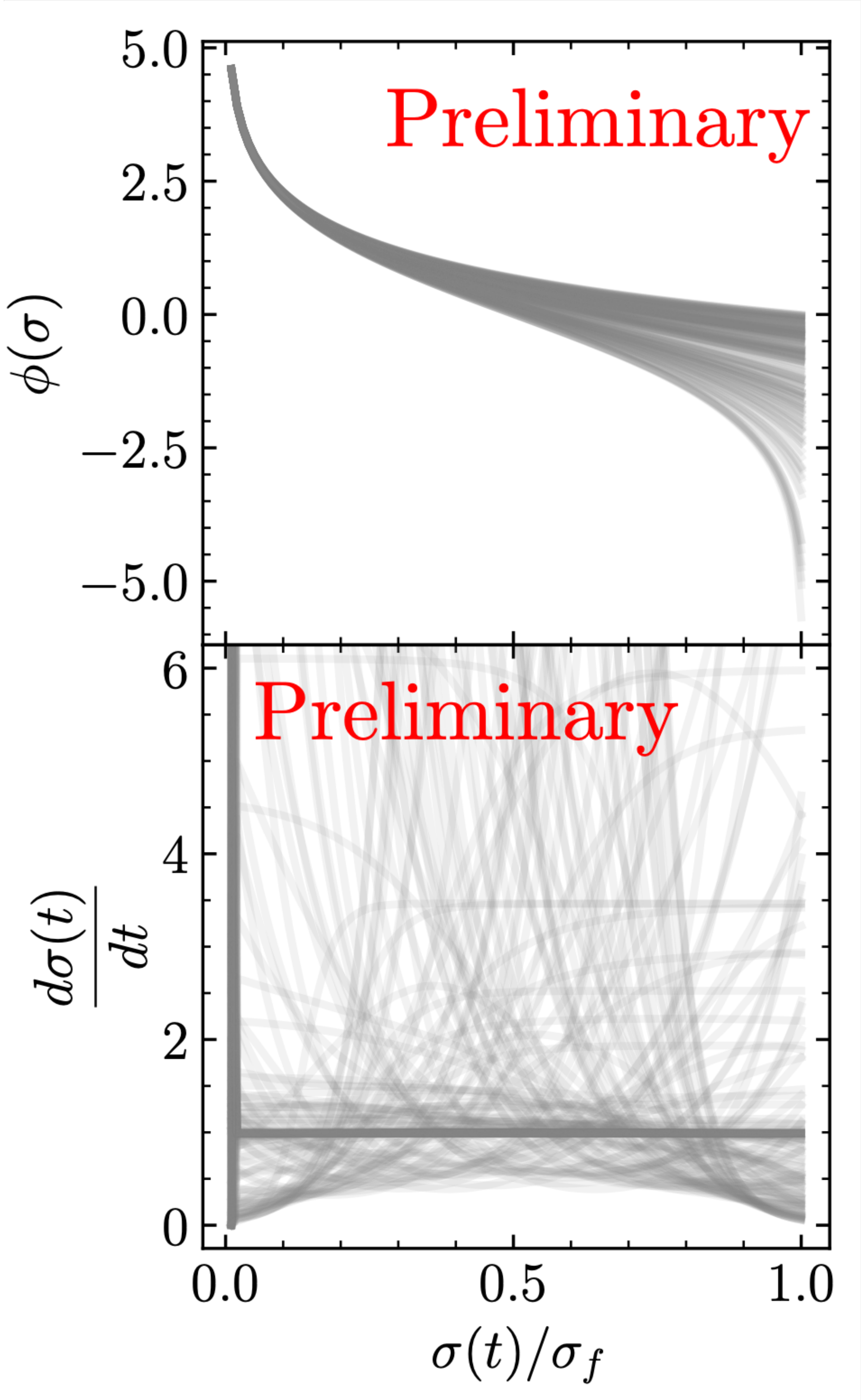


A. Accardi, nucl-th/0609010 (2006)

$$\frac{\sigma(t)}{\sigma_f} = \frac{1}{\mathscr{A}}\left(1-\frac{\sigma_0}{\sigma_f}\right)\left(\frac{t-t_{\rm prod}}{t_{\rm form}-t_{\rm prod}}\right)\frac{d\sigma(t)}{dt}+\frac{\sigma_0}{\sigma_f}$$

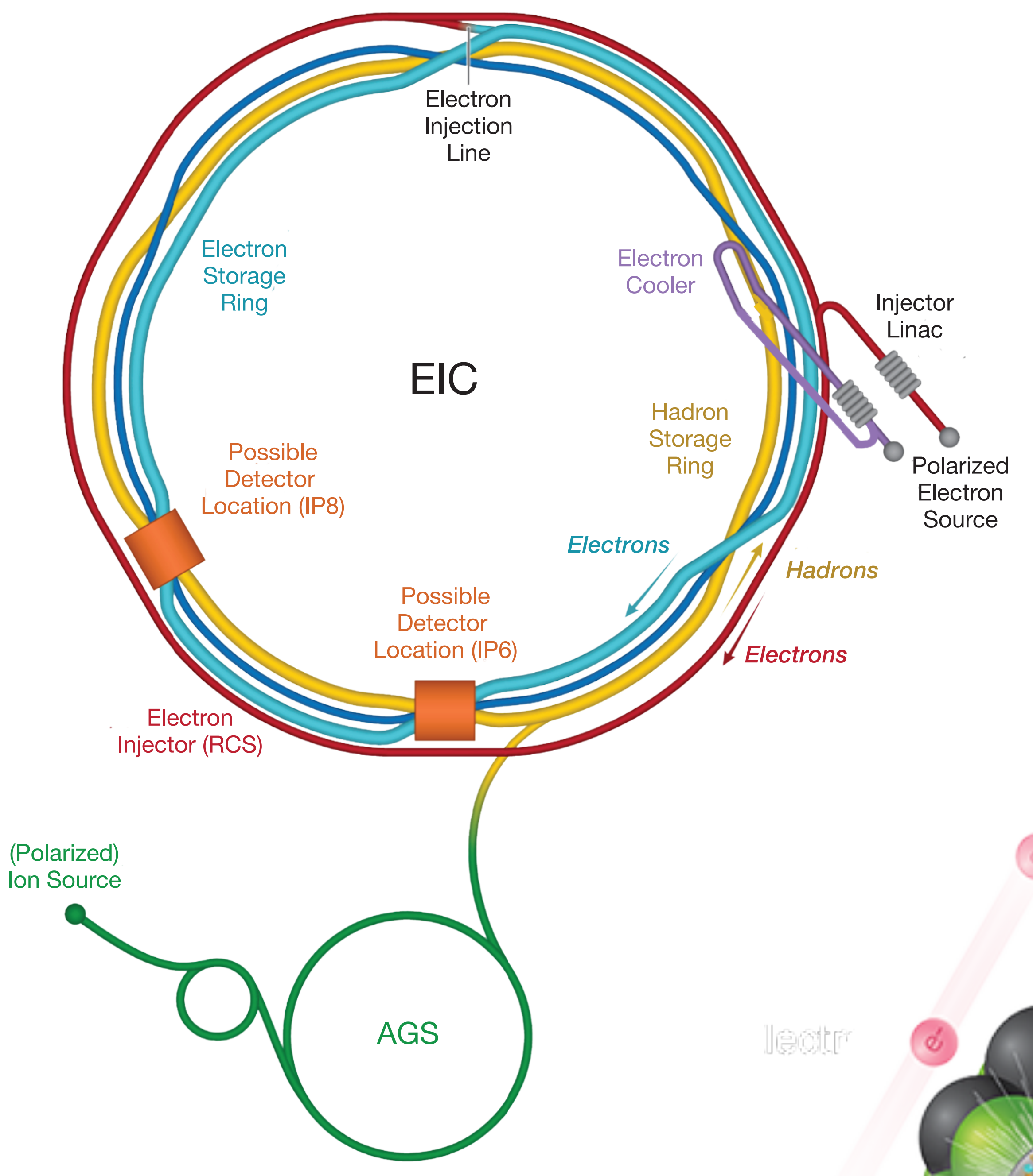
$$\phi[\sigma(t)] = \ln\left(\frac{\mathscr{A}}{d\sigma(t)/dt}-1\right)$$

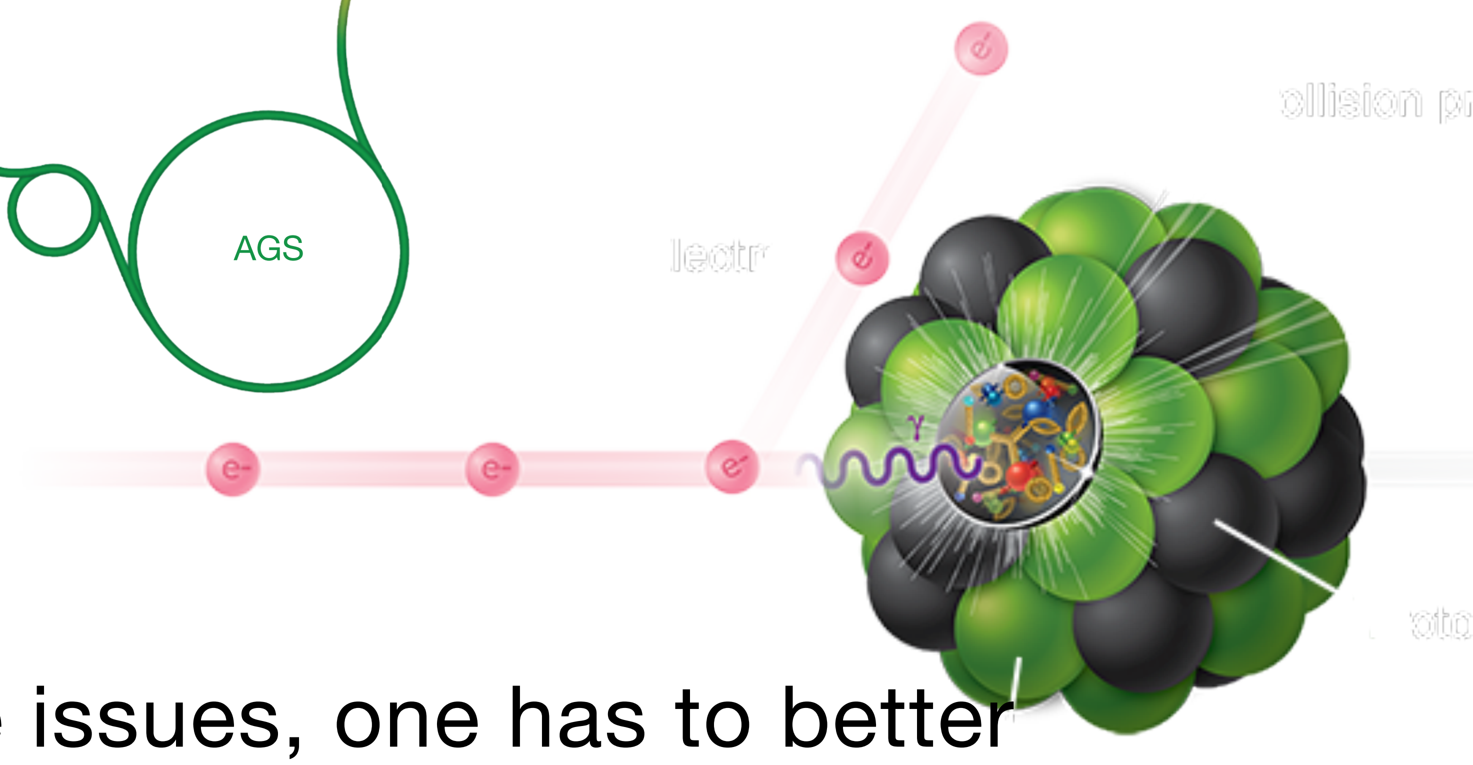


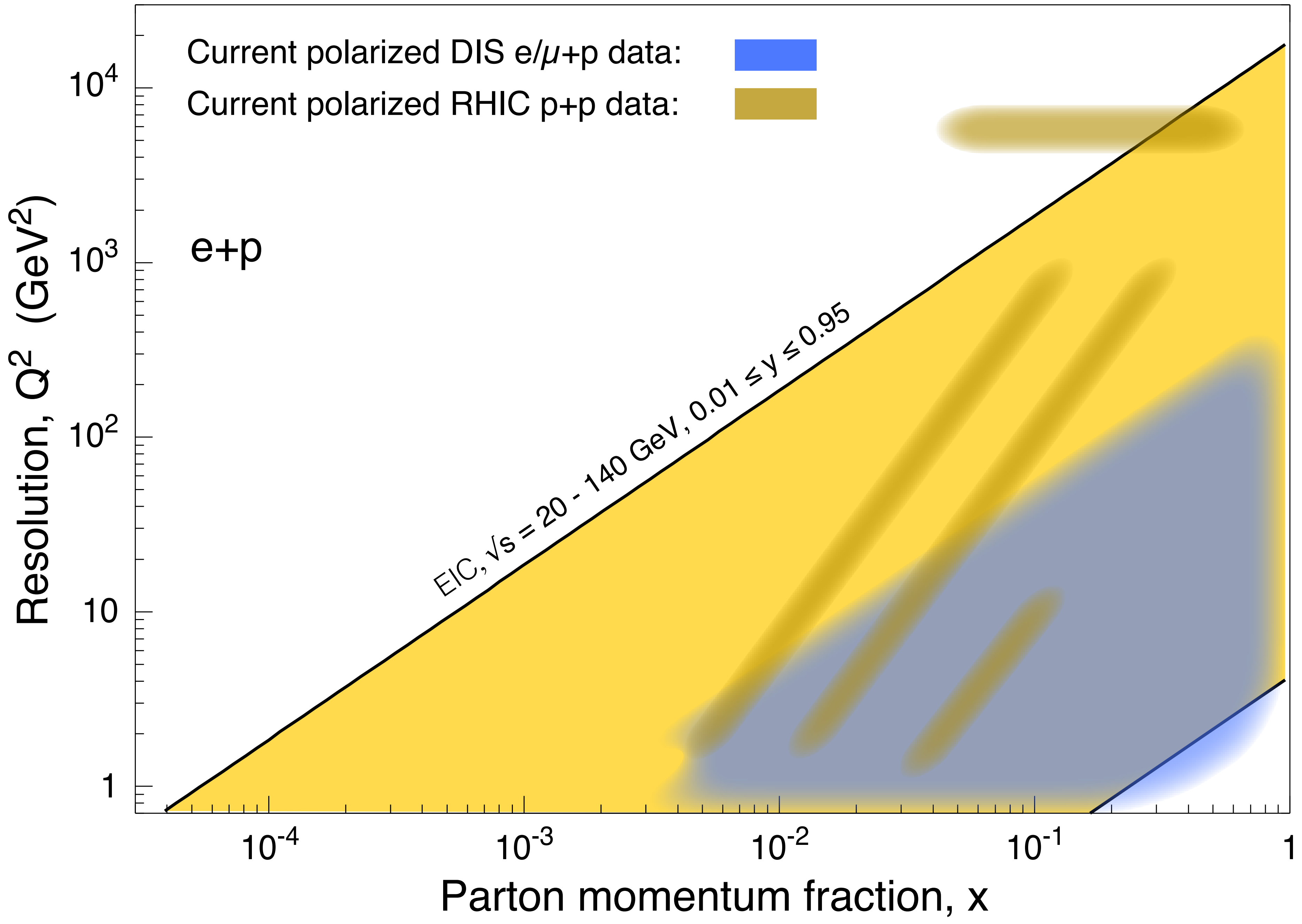


Saturation physics at the Electron-Ion collider (EIC)

- One of the main goals of the future Electron-Ion Collider is the search of the signatures of saturation
- However, EIC will be predominantly a moderate-x machine, covering the kinematic region of relatively large Bjorken-x
- For this reason the saturation effects will be diminished by a considerable contribution of the large-x dynamics
- One expects this to be reflected in large uncertainties of predictions for the region of small Bjorken-x due to either poorly constrained initial conditions for the small-x evolution defined at large vales of Bjorken-x or the limited predictive power of the small-x formalism due the significant large-x contribution

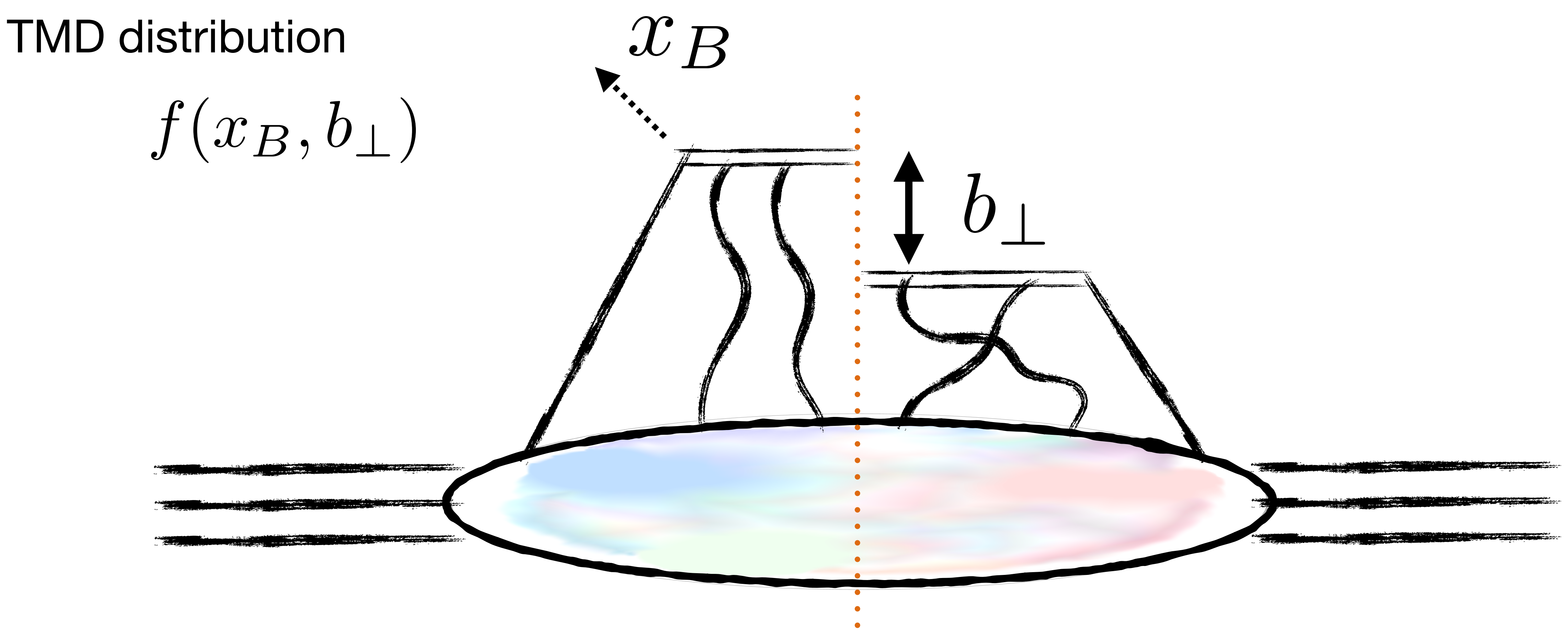


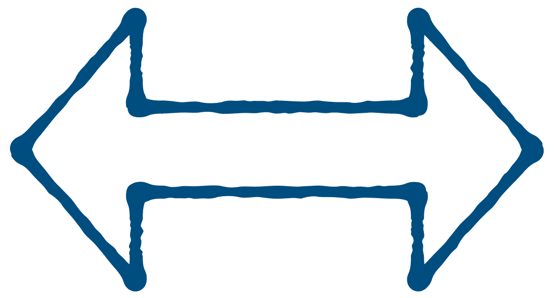


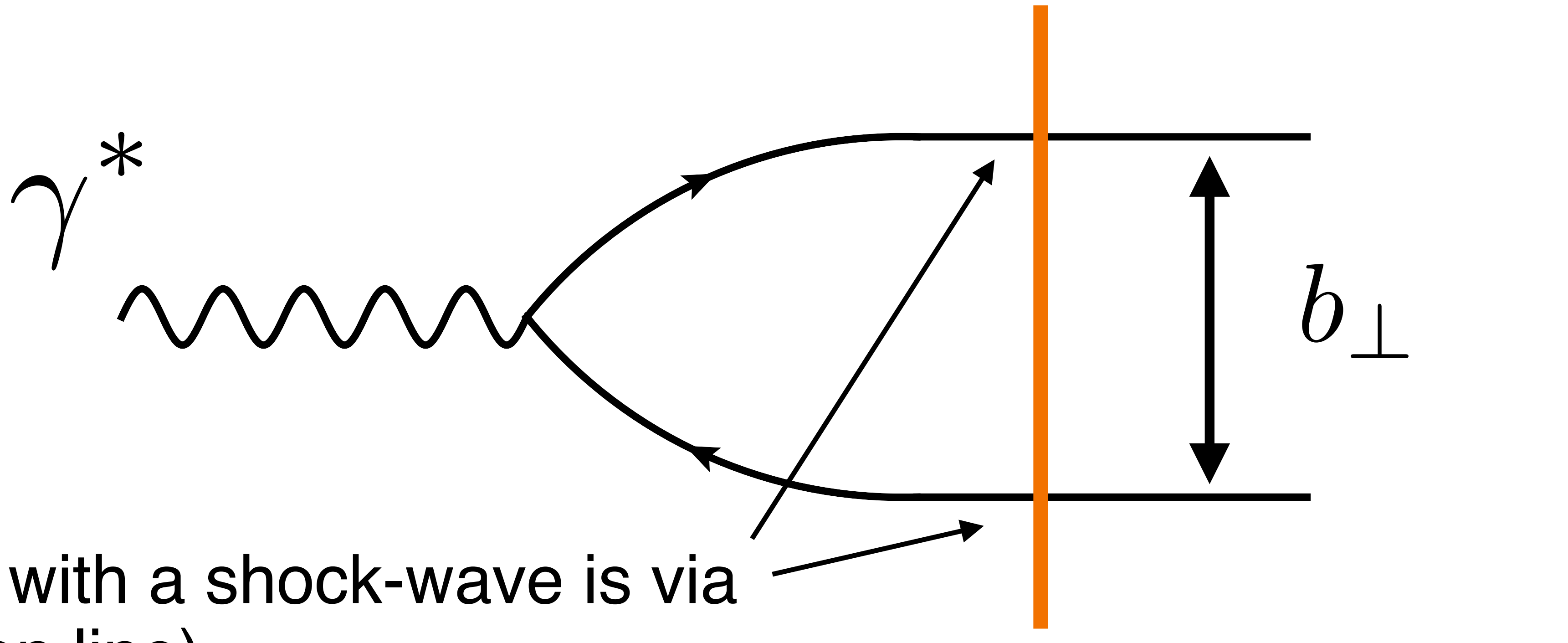


- To overcome both of these issues, one has to better understand the transition between different kinematic regimes and develop a formalism capable of describing physics in a wide kinematic range
- Aim is to develop such formalism based on the **transverse momentum dependent (TMD) factorization,** which can be matched to both collinear and high-energy rapidity factorization schemes designed to describe physics in the region of large and small Bjorken-x, correspondingly
- And eventually extract non-perturbative first-principle input for small-x initial conditions

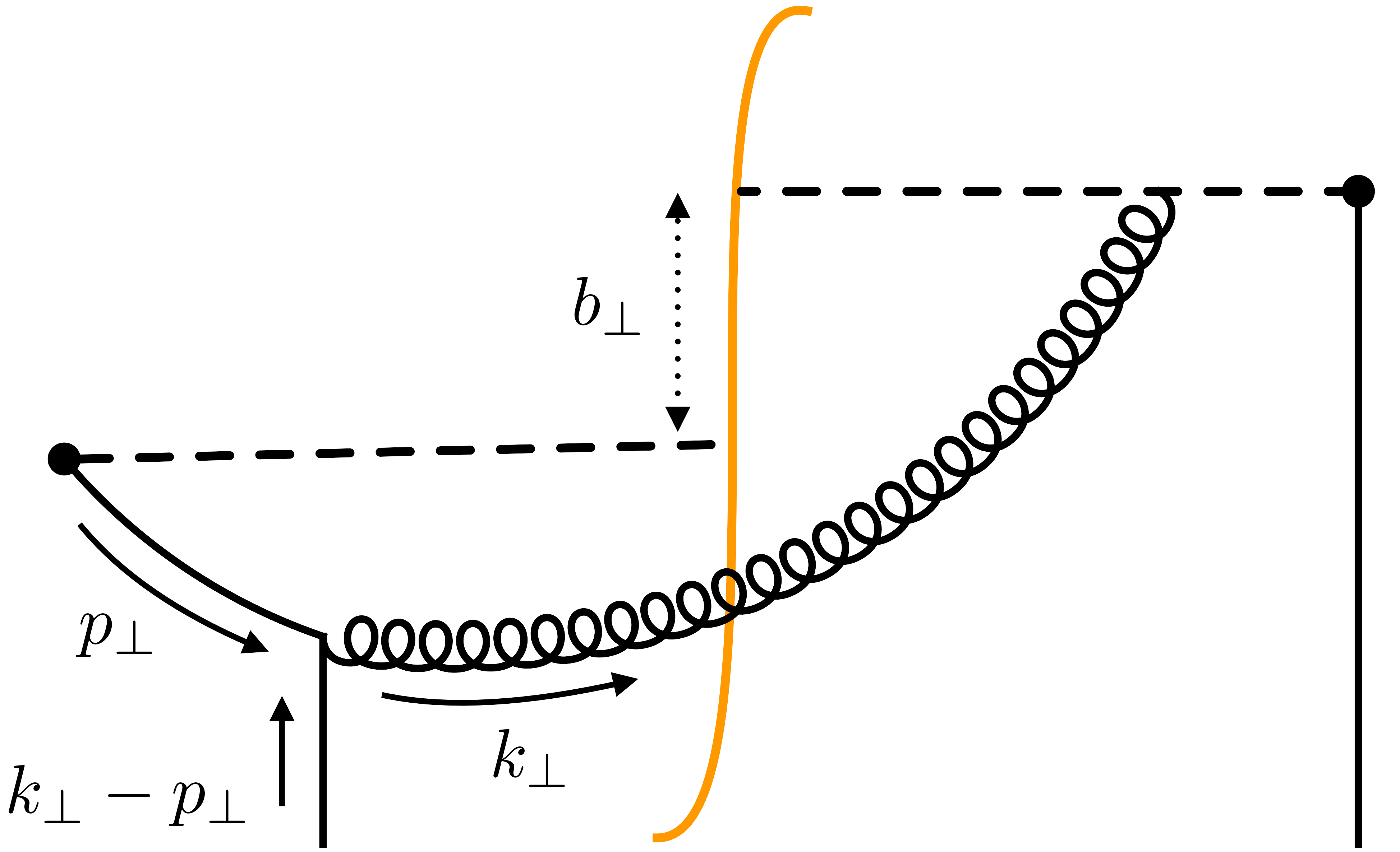
- The relation between TMDPDFs and small-x dipoles can be observed already at the level of the corresponding operator definitions
- both small-x dipoles and TMDPDFs contain Wilson lines separated in the transverse space $b_\perp$







- Investigated this relation at the NLO order by analyzing at the corresponding emission diagrams for gluon and quark TMDPDFs
- Special attention was paid to how different dynamic modes are separated from each other in a TMD factorization scheme
- Established relation between the TMDPDFs and the small-x dipole amplitudes at the NLO order
- This TMDPDFs can be used for constructing initial conditions for the small-x evolution which has potential for significant improving of the predictive power of the small-x formalism for the EIC phenomenology



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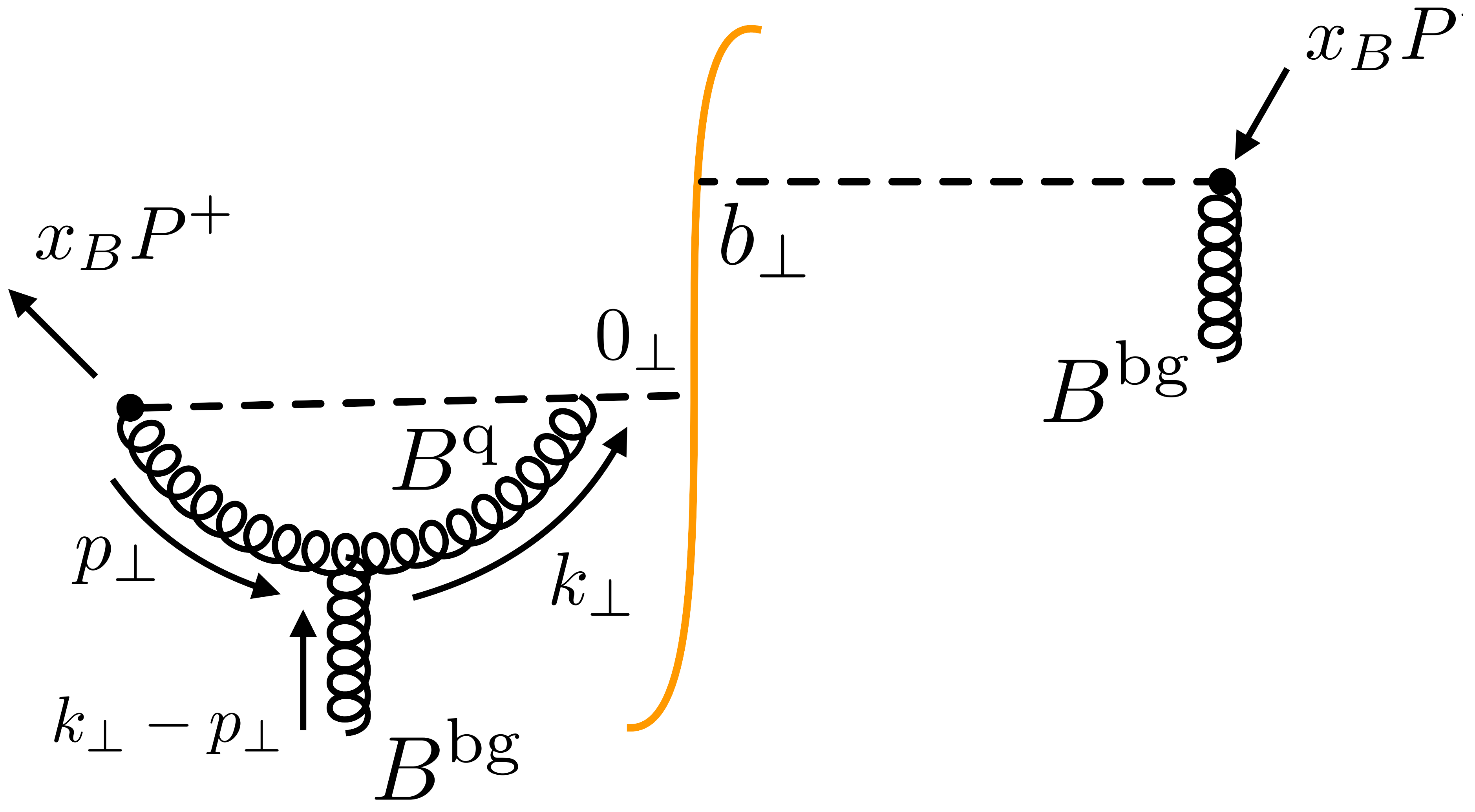
BFKL dynamics in TMDPDFs

- In particular, infrared rapidity singularity in the gluon TMDPDFs was observed

logarithmic dependence on ρ; "virtual" part of the BFKL evolution kernel

$$\mathcal{B}_{ij}^{\mathrm{q}(1)+\mathrm{bg;virt}}(x_B, b_\perp) = -\frac{\alpha_s N_c}{2\pi}\left(\frac{1}{\epsilon_{\mathrm{IR}}^2} + \frac{1}{\epsilon_{\mathrm{IR}}}\left(\frac{1}{\xi} + \ln\left(\frac{\rho}{x_B P^+}\right)\right) - \frac{\pi^2}{12}\right)$$
$$\times \int d^2 z_\perp \int \bar{d}^2 p_\perp e^{ip_\perp (b-z)_\perp}\left(\frac{\mu_{\mathrm{IR}}^2}{p_\perp^2}\right)^{\epsilon_{\mathrm{IR}}} \frac{g_{il}p_j p_m + p_i p_l g_{mj}}{p_\perp^2}\mathcal{B}_{lm}^{\mathrm{bg}}(x_B, z_\perp)$$

- This is due to the non-trivial structure of the virtual corrections that were originally found in the analysis
- The gluon TMDPDFs at **large** x_B contain logarithms of the BFKL type!
- To reveal this structure, one has to take into account the all-collinear twist content of the TMDPDFs in the region of large $b_\perp \lesssim \Lambda_{QCD}^{-1}$ using this approach
- This crucial observation allows the utilization of TMDPDFs for describing small-x dynamics. For example, to construct initial conditions for the small-x evolution at large x
- This can be done by using phenomenological extractions of the TMDPDFs performed within our approach or, potentially, from lattice calculations. Currently, the IC group continues the research in this direction

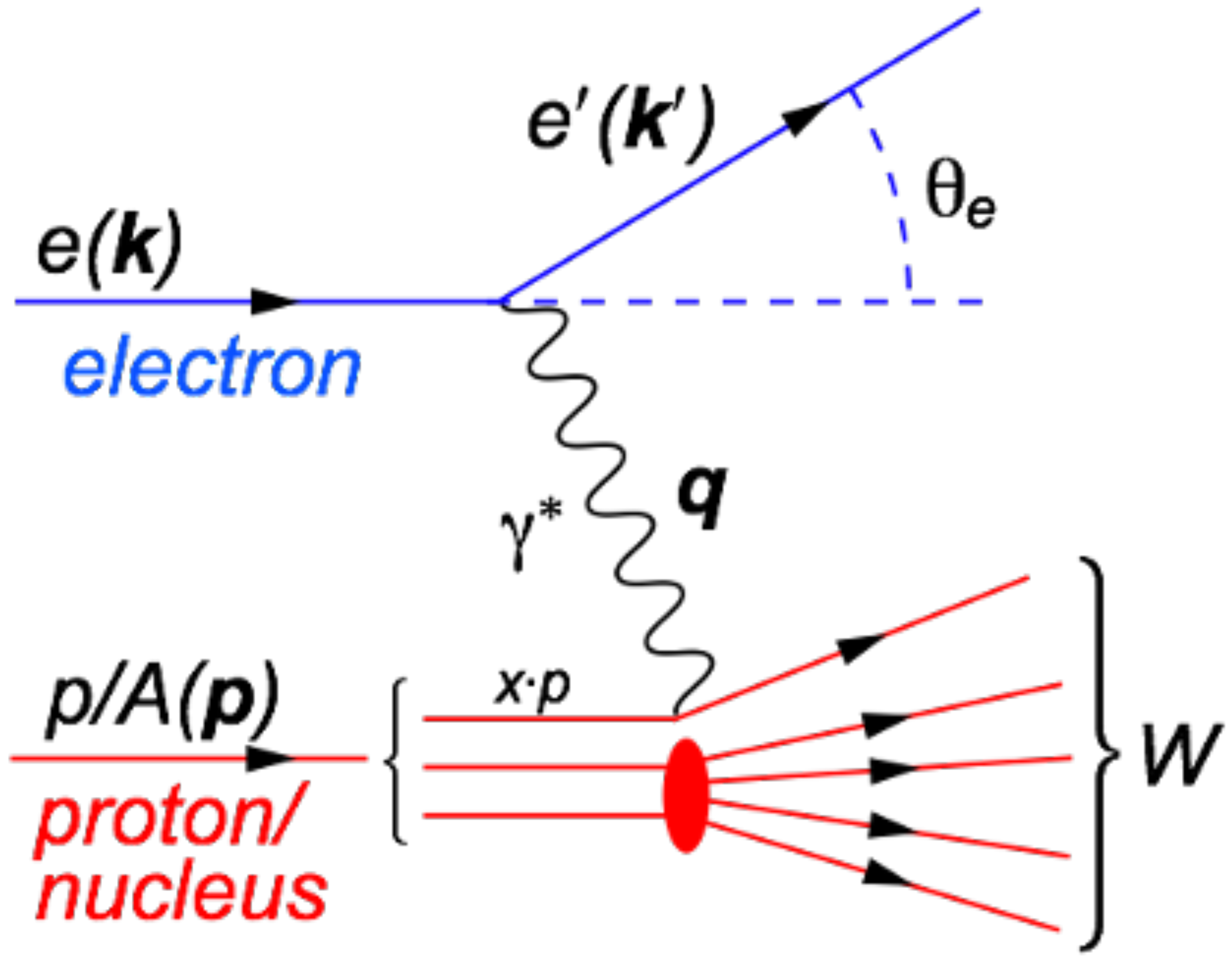


Mukherjee, Skokov, Tarasov, Tiwari, Phys. Rev. D 109 (2024) 3, 034035

SELECTION OF HIGHLIGHTS

- **Unified description of DGLAP, CSS, and BFKL evolution: TMD factorization bridging large and small *x***
  Swagato Mukherjee, Vladimir V. Skokov, Andrey Tarasov, *Shaswat Tiwari*
  e-Print: 2311.16402 [hep-ph], DOI: 10.1103/PhysRevD.109.034035
  Phys.Rev.D 109 (2024) 3, 034035
- **Global analysis of polarized DIS & SIDIS data with improved small-x helicity evolution**
  Daniel Adamiak, *Nicholas Baldonado*, Yuri V. Kovchegov, W. Melnitchouk, Daniel Pitonyak, Nobuo Sato, Matthew D. Sievert, Andrey Tarasov, Yossathorn Tawabutr
  e-Print: 2308.07461 [hep-ph], DOI: 10.1103/PhysRevD.108.114007
  Phys.Rev.D 108 (2023) 11, 11
- **Back-to-Back Inclusive Dijets in Deep Inelastic Scattering at Small x: Complete NLO Results and Predictions**
  Paul Caucal, Farid Salazar, Björn Schenke, Tomasz Stebel, Raju Venugopalan
  e-Print: 2308.00022 [hep-ph], DOI: 10.1103/PhysRevLett.132.081902
  Phys.Rev.Lett. 132 (2024) 8, 081902

DEEP INELASTIC SCATTERING



$s = (p + q)^2$ center of mass energy squared

$Q^2 = -\,q^2$ resolution power

$x = Q^2/(2p \cdot q)$ momentum fraction of the nucleon's momentum carried by the struck quark