U.S. DEPARTMENT OF ENERGY | Office of Science

SURGE COLLABORATION

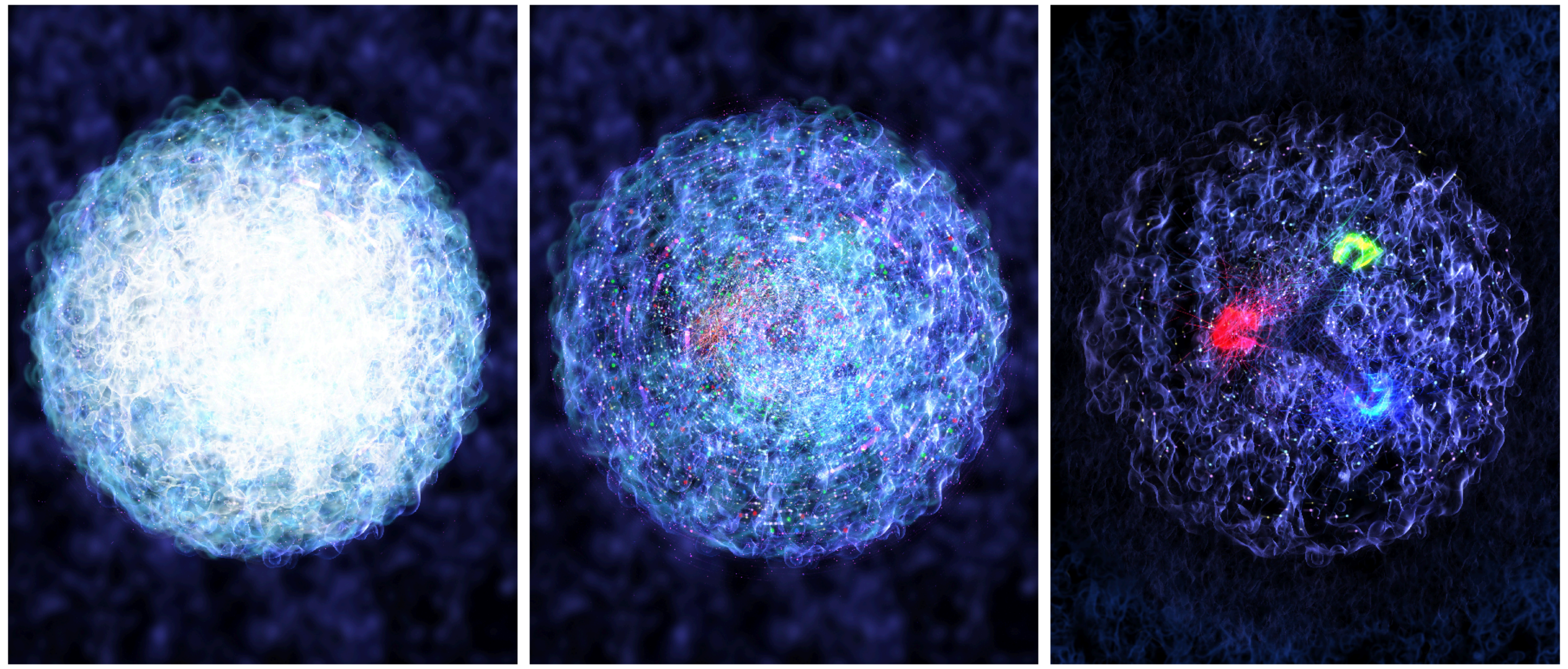
YEAR 1 PROGRESS

BJÖRN SCHENKE, BROOKHAVEN NATIONAL LABORATORY

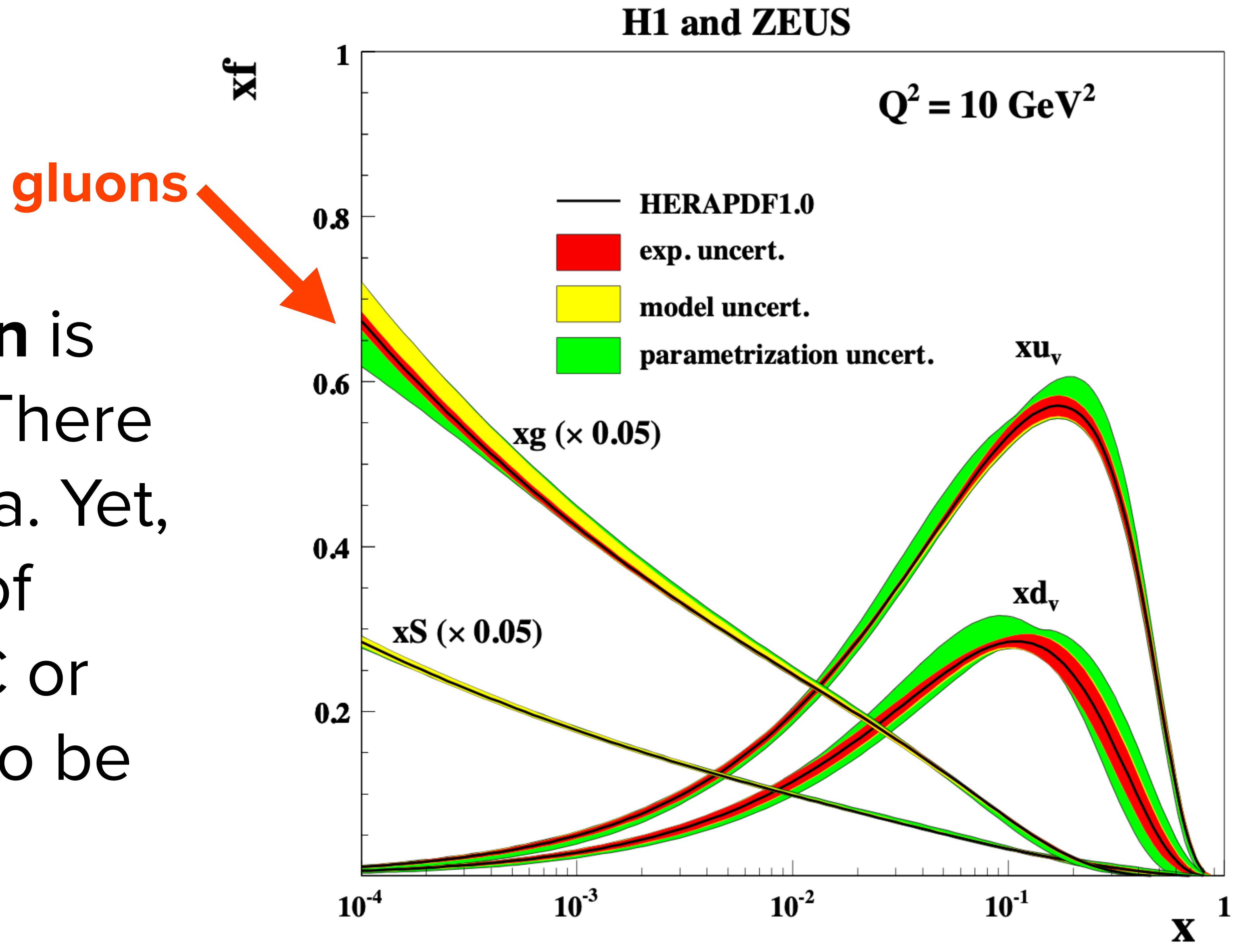
Topical Collaboration PI Meeting
Gaithersburg, MD
May 2, 2024

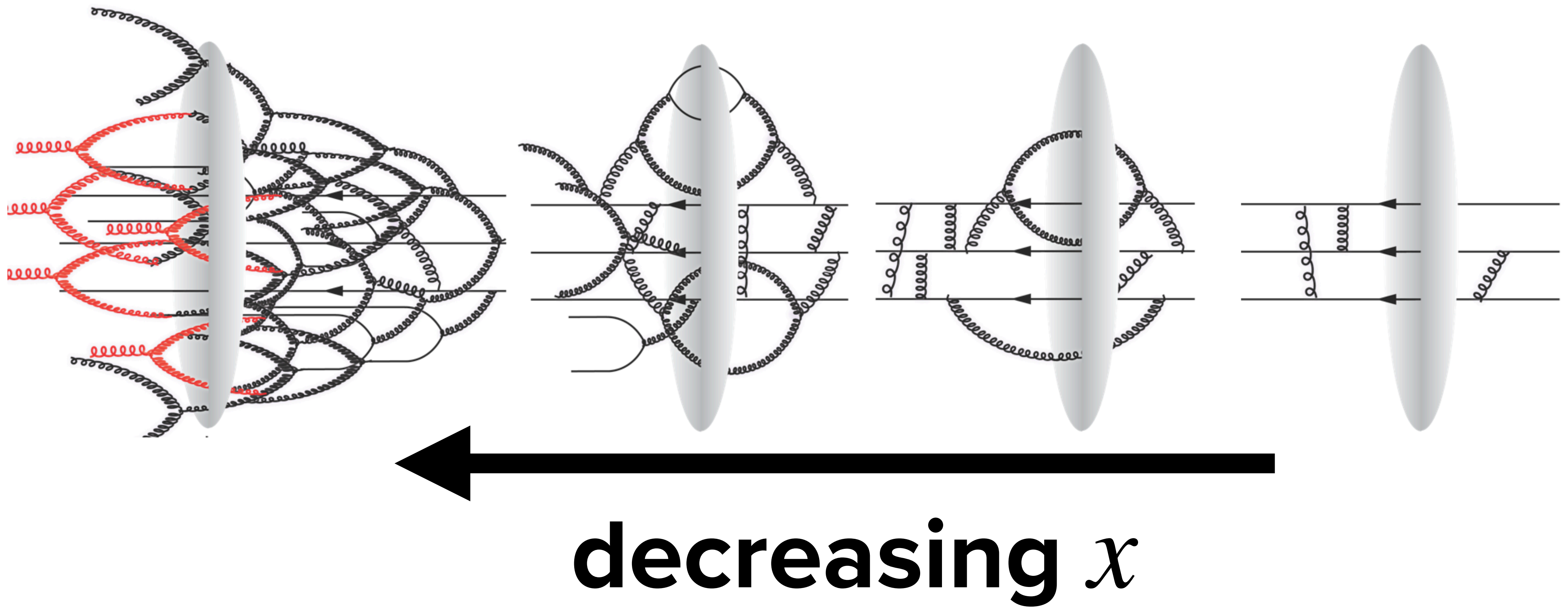
THE PROBLEM

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.





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

SURGE COLLABORATION

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MEMBERS

MEMBERS

Brookhaven National Laboratory
Y. Hatta, D. Kharzeev, Y. Mehtar-Tani, S. Mukherjee, P. Petreczky, B. Schenke *†, R. Venugopalan

Old Dominion University / JLab
I. Balitsky

McGill University
S. Caron-Huot

CUNY, Baruch College
A. Dumitru, J. Jalilian-Marian

University of California, Los Angeles
Z. Kang *

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Y. Kovchegov

University of Connecticut
A. Kovner

University of Illinois at Urbana Champaign
J. Noronha-Hostler *

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F. Olness

Lebanon Valley College
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New Mexico State University
M. Sievert *

North Carolina State University
V. Skokov

Penn State University
A. Stasto *†

University of California Berkeley / LBNL
X.-N. Wang

*=Steering Committee, †=co-spokesperson

SURGE WEBSITE

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

bnl.gov

Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

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

Bjoern Schenke
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SUMMARY OF PUBLICATIONS AND TALKS

SURGE COLLABORATION

- 57 papers on the arXiv (including 6 proceedings)
- 25 published refereed journal articles (including 5 letter publications)
- 83* talks at international conferences and workshops, seminars and student lectures

*as of December 2023

MEETINGS

- **Collaboration Meeting and SURGE Workshops:**
  - SURGE Collaboration Meeting and Workshop
    Brookhaven National Laboratory
    June 28-30, 2023
    35 talks, business meeting, breakout sessions
  - Workshop on Generalized Parton Distributions for Nucleon Tomography in the EIC Era
    Brookhaven National Laboratory
    January 17–19, 2024
  - From Quarks and Gluons to the Internal Dynamics of Hadrons
    Center for Frontiers in Nuclear Science, Stony Brook University
    May 15 – 17, 2024
- **Regular meetings of the individual working groups**
- **8 Meetings of Working Group Leaders and Steering Committee**

SUPPORT FOR STUDENTS, POSTDOCS, BRIDGE POSITION

- In Year 1 SURGE supported
  - Nicholas Baldonado (NMSU)
  - Jani Penttala (UCLA)
  - Shaswat Tiwari (NCSU)
  - Wenbin Zhao (UC Berkeley/LBNL)

- Year 2 we are and will be supporting
  - 3 postdocs (UCLA, Berkeley, UIUC)
  - 3 graduate students (OSU, NMSU, NCSU)

- Year 3-5 we will support a bridge position at UIUC

SURGE STRUCTURE

Initial State

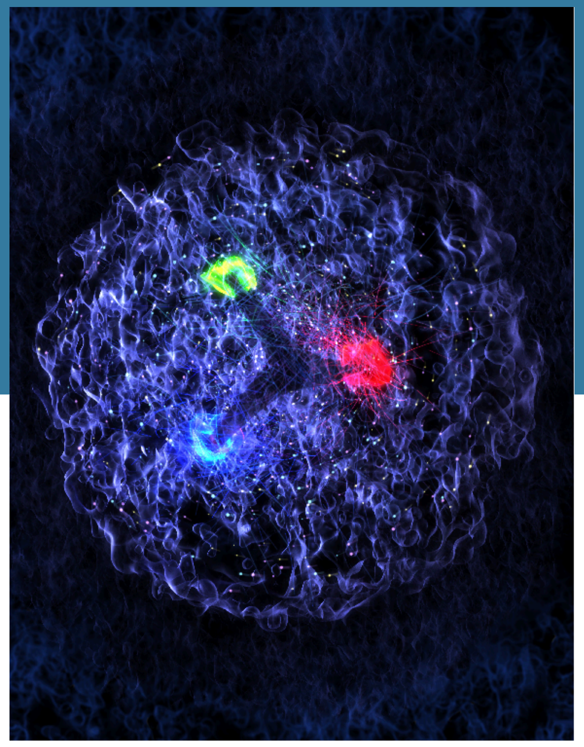
Evolution and parton level cross sections

NLO calculations

Final State

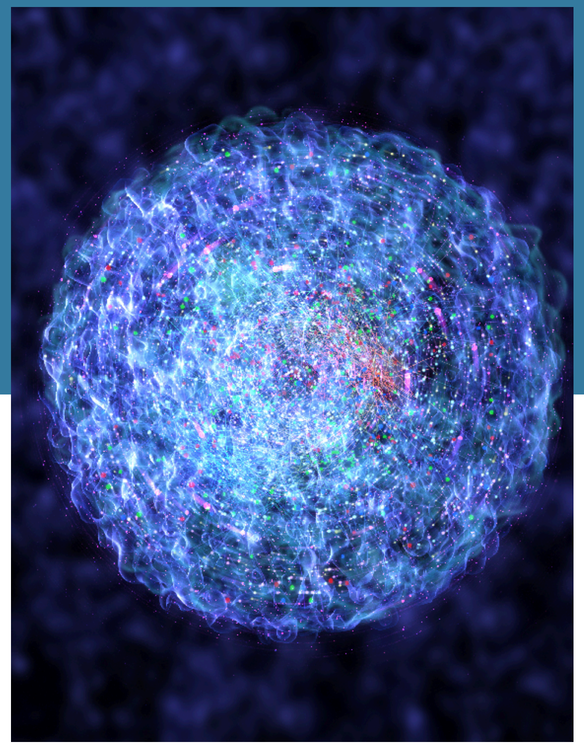
SURGE STRUCTURE

Initial State

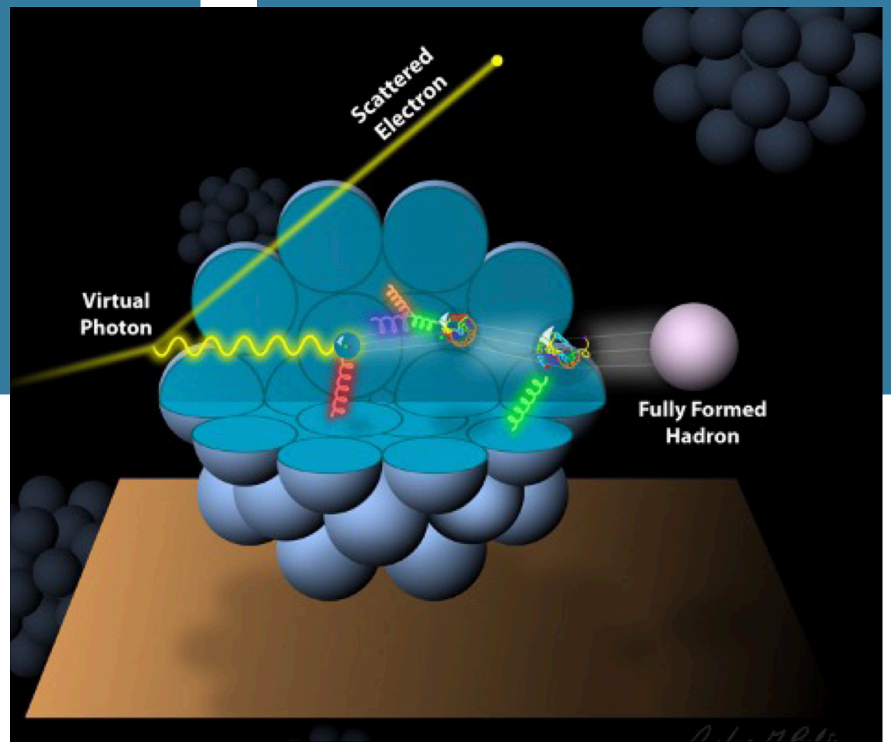


Evolution and parton level cross sections

NLO calculations

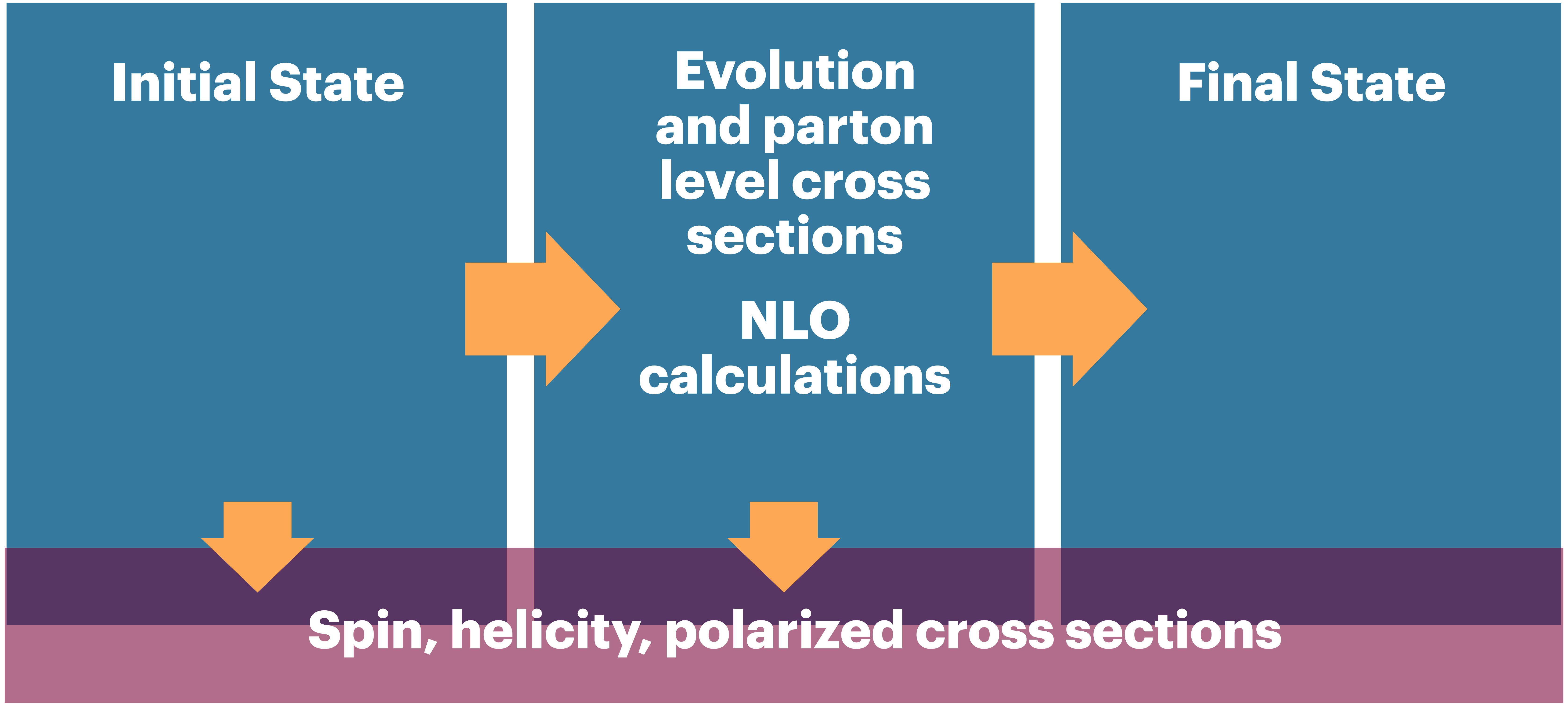


Final State

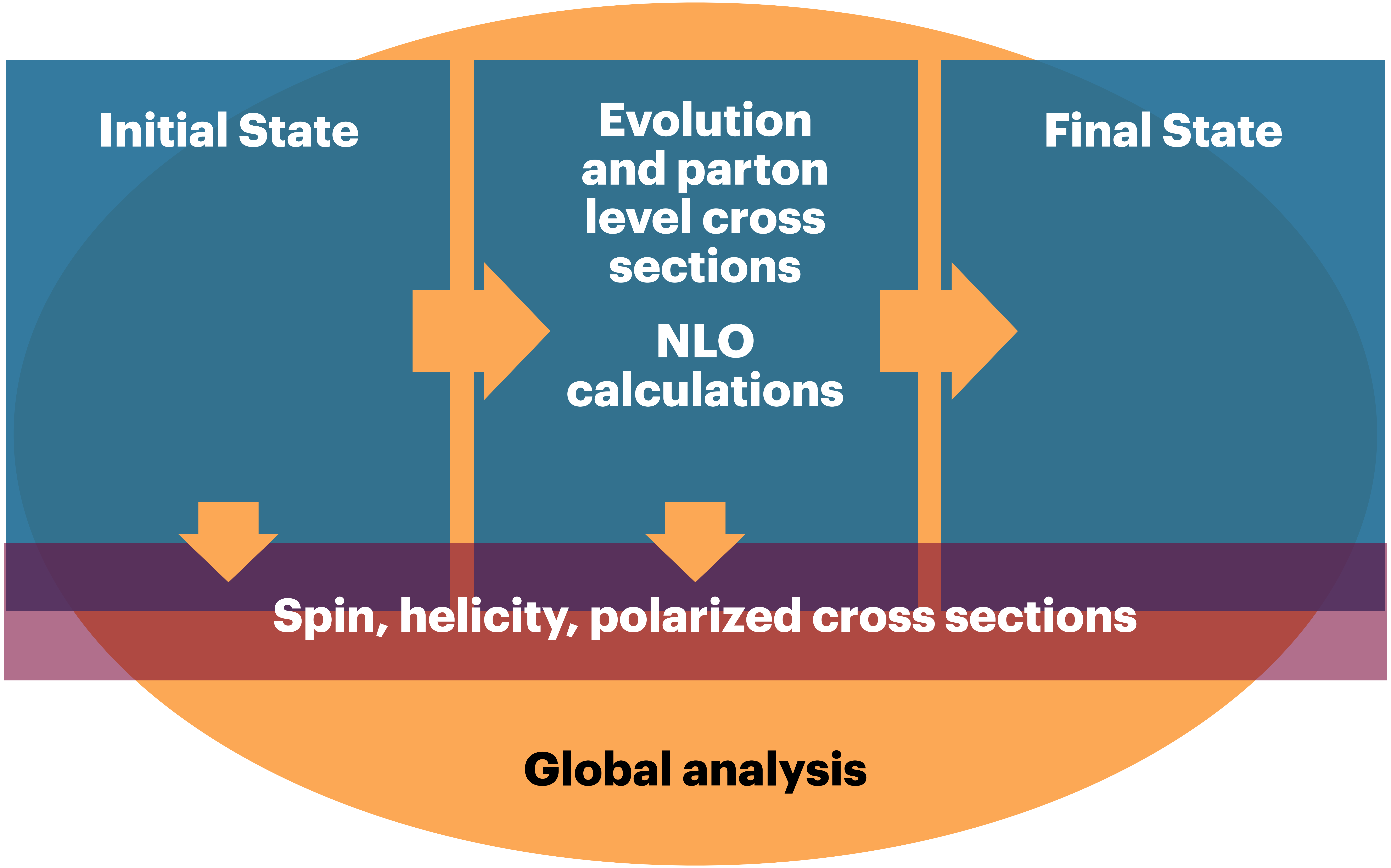


Images courtesy of James LaPlante, Sputnik Animation in collaboration with the MIT Center for Art, Science & Technology and Jefferson Lab.
and Joshua Rubin, University of Illinois Urbana-Champaign

SURGE STRUCTURE



SURGE STRUCTURE: 5 WORKING GROUPS



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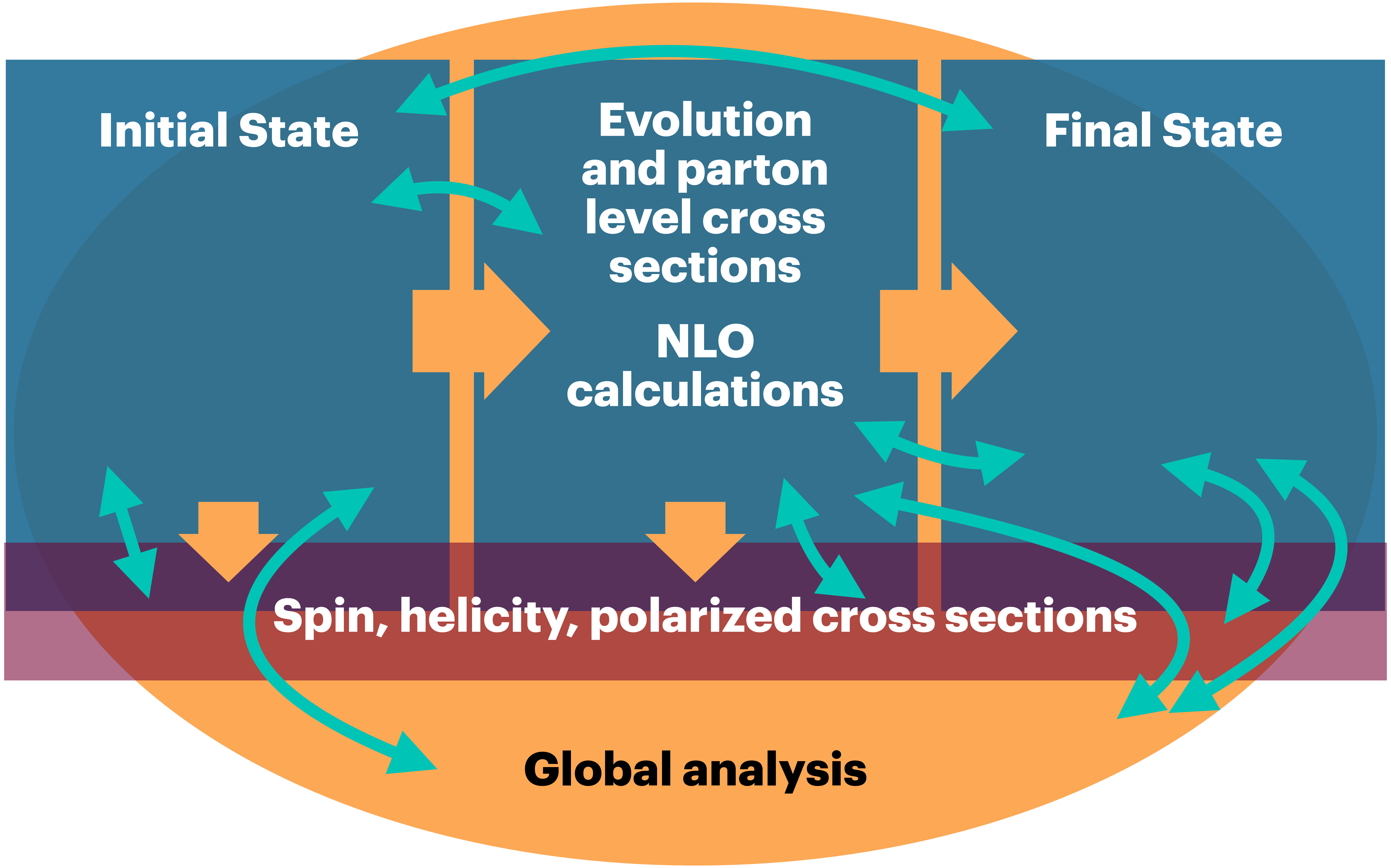


PROGRESS TOWARDS MILESTONES
A SELECTION OF TOPICS

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)

Drawbacks:

- No connection to underlying QCD dynamics, no explanation of the x0-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

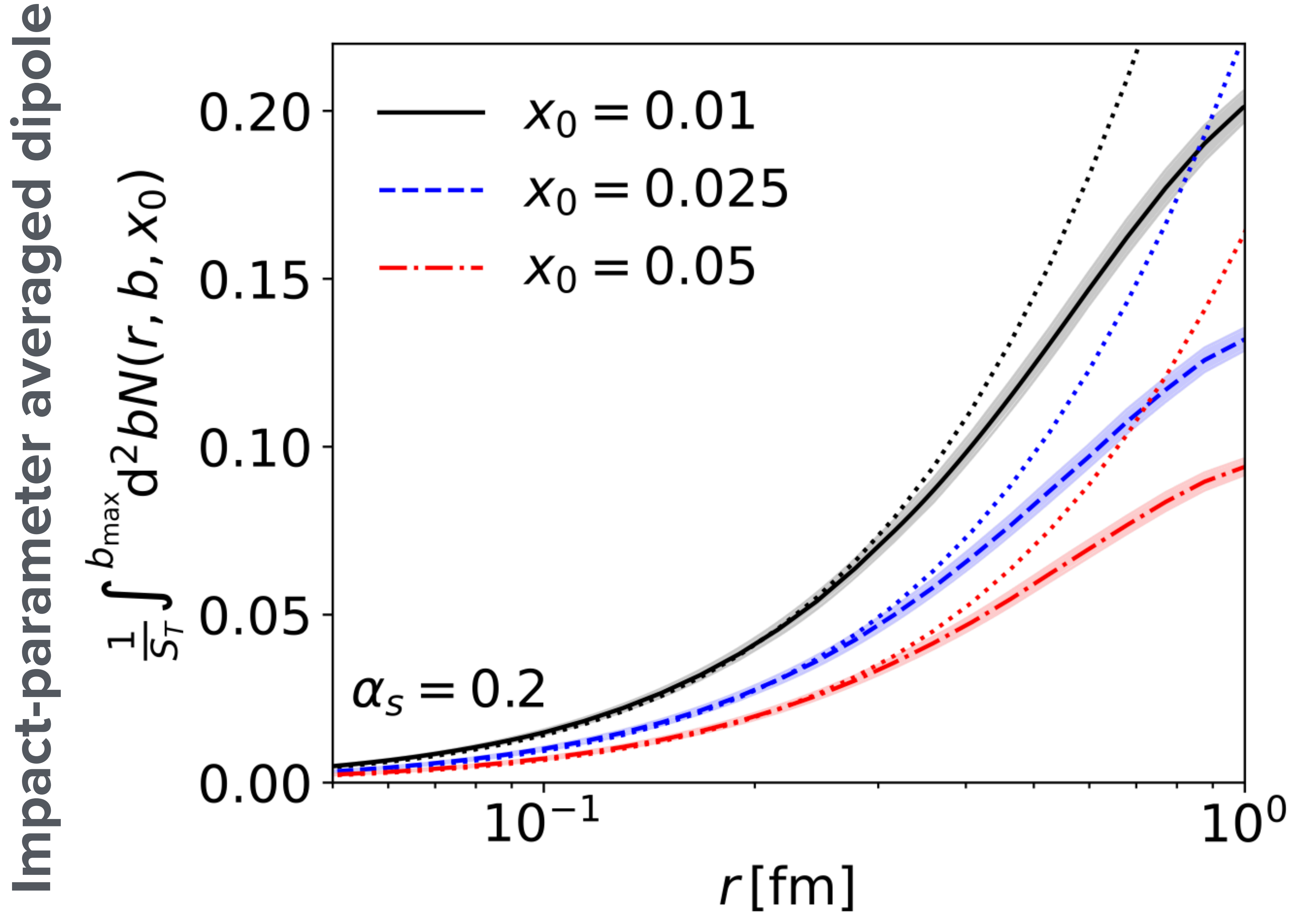
INITIAL STATE - MILESTONES

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 $N(x_0, r)$ (solid and dashed lines), compare to fit with modified MV model (which behaves differently for large dipoles (dotted lines), evolve with BK



INITIAL STATE - MILESTONES

Non-Gaussian corrections for large nuclei

MV model assumes Gaussian statistics

To improve on that:

- Account for quantum corrections enhanced by potentially large logarithm of the nucleus size
- First studied in the context of the transverse momentum broadening of a jet
- Resummation of the double logarithm leads to anomalous scaling and to non-Gaussian ICs

Status:

- First Analytical and numerical studies have been performed
- EIC observables sensitive to the non-Gaussian corrections were identified
- Publication is expected by the end of 2024 - on track

INITIAL STATE - MILESTONES

Model-independent first-principle based determination of ICs

Current status: partially delivered; novel TMD factorization for gluons was developed

See presentation by SURGE supported graduate student Shaswat Tiwari (NCSU)

S. Mukherjee, V. V. Skokov, A. Tarasov, S. Tiwari, Phys.Rev.D 109 (2024) 3, 034035
Unified description of DGLAP, CSS, and BFKL evolution: TMD factorization bridging large and small *x*

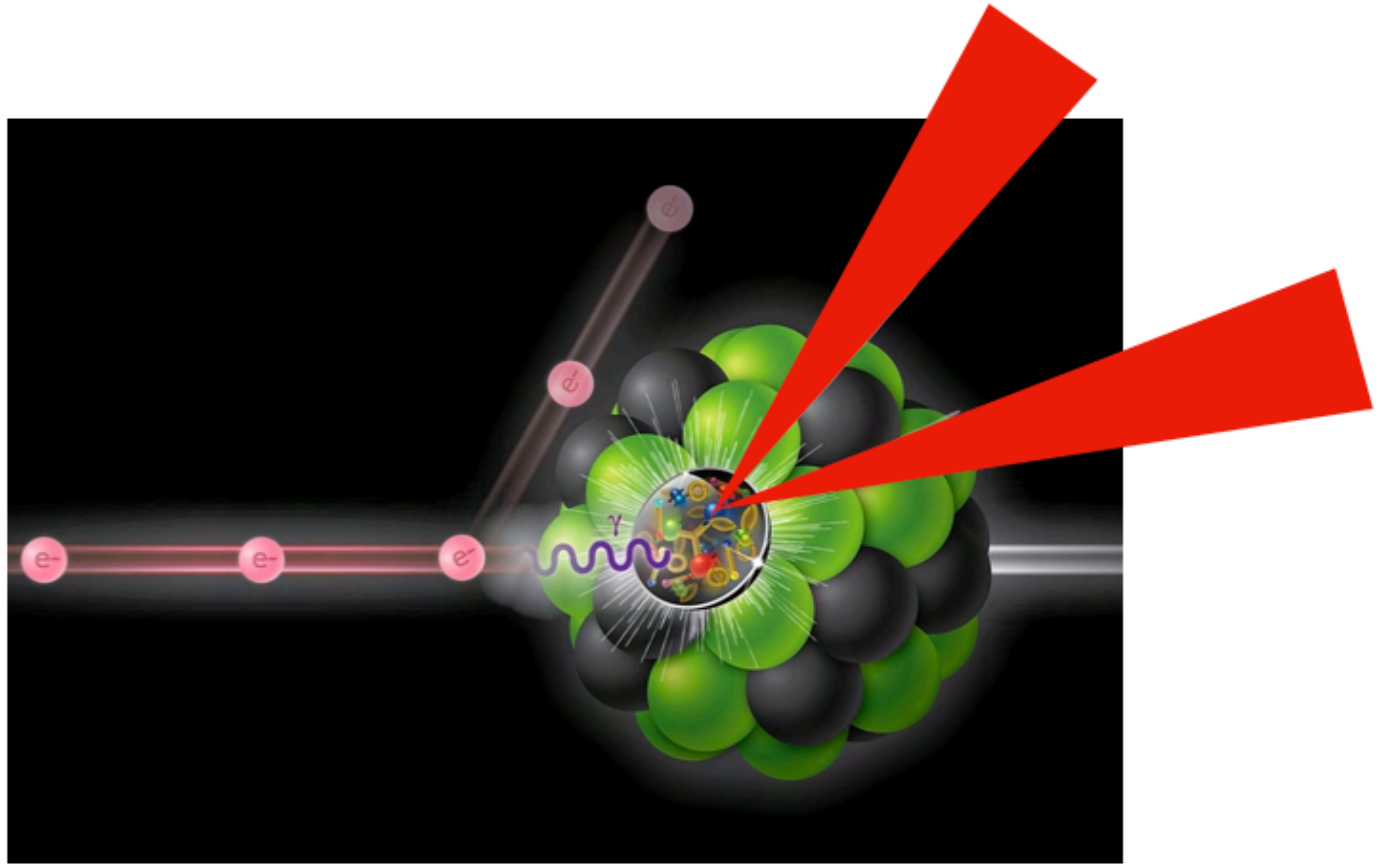
This lays the ground work to employ transverse momentum dependent parton distribution functions (TMDPDFs) computed from lattice QCD as initial condition for the small *x* evolution

MILESTONES - NLO AND EVOLUTION

- 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

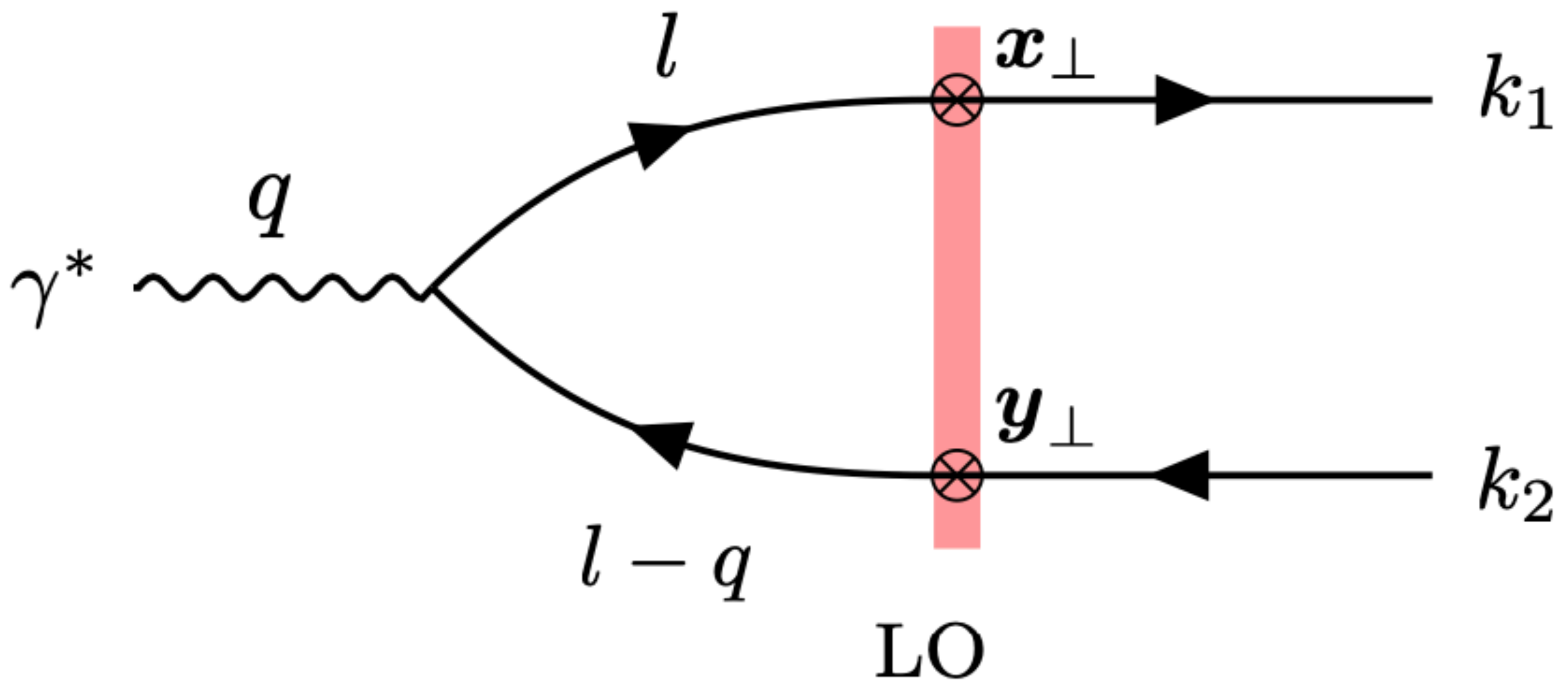
P. Caucal, F. Salazar, B. Schenke, T. Stebel, R. Venugopalan, JHEP 08 (2023) 062
Back-to-back inclusive dijets in DIS at small x: Gluon Weizsäcker-Williams distribution at NLO



Inclusive dijet production in e+A collisions:

Produce 2 jets + X

Work in the Color Glass Condensate (CGC) framework



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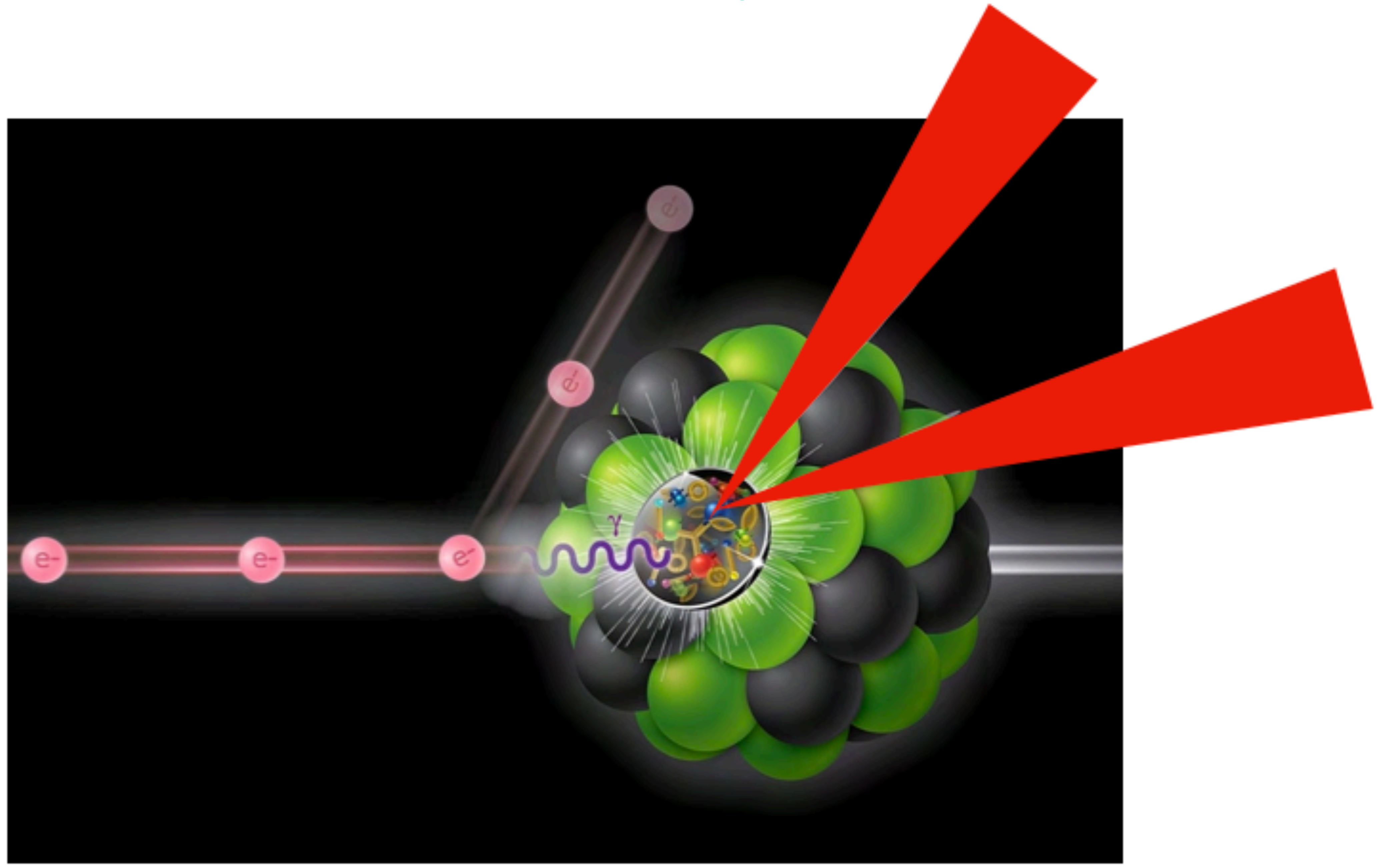
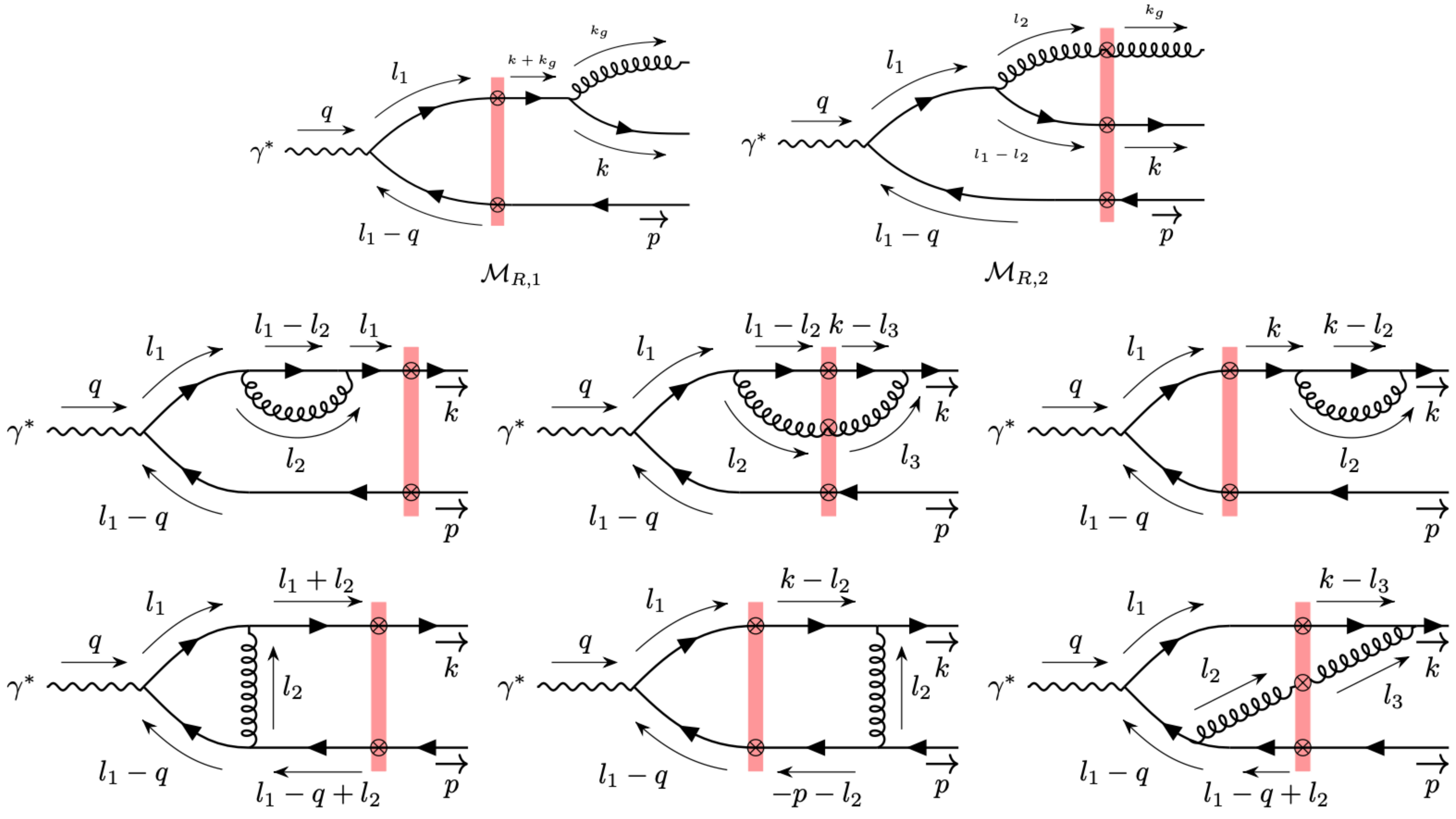


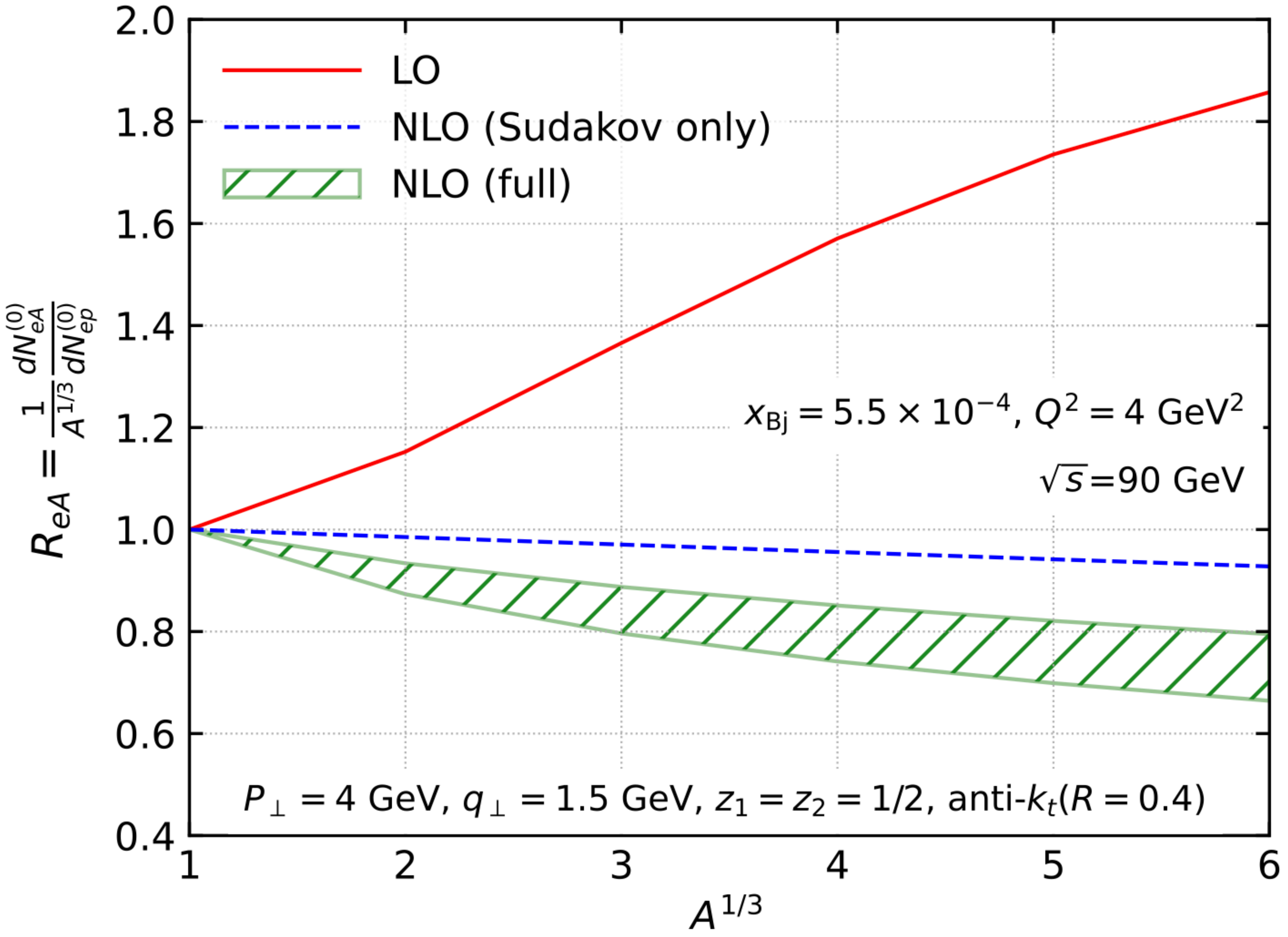


NLO

MILESTONES - NLO AND EVOLUTION

- 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

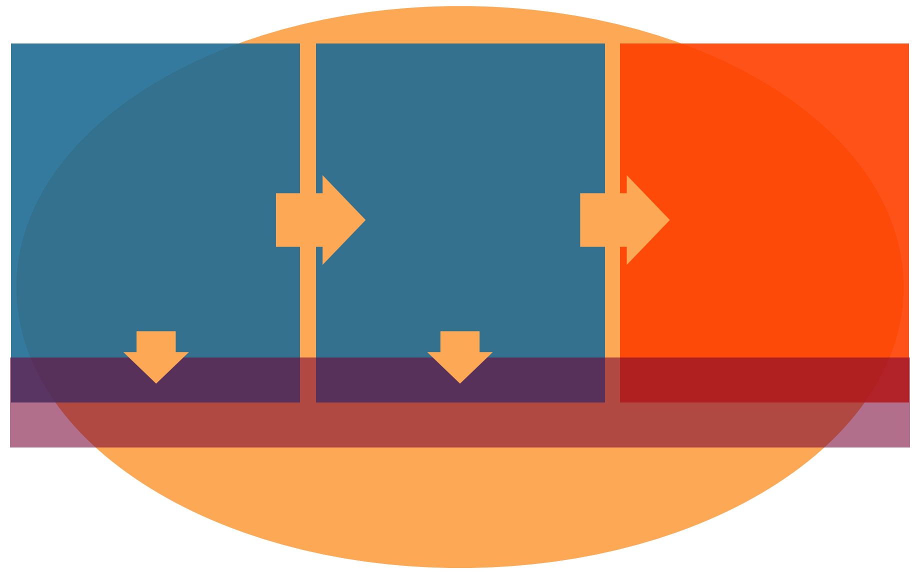
P. Caucal, F. Salazar, B. Schenke, T. Stebel, R. Venugopalan
Phys.Rev.Lett. 132 (2024) 8, 081902

MILESTONES - NLO AND EVOLUTION

- **Assess and formulate numerical implementation for NLLx BK (Year 3 milestone)**
  - Developed new Leading Logarithmic (LL) Balitsky-Kovchegov (BK) evolution code in julia
  - Code includes impact parameter dependence. Is ready for NLL evolution kernel to be implemented
  - On track to achieve milestone early
- **Perform NLO computations for dihadron production in e+A and assess status in p+A (Year 2-3)**
  - Ongoing transverse energy-energy correlator (TEEC) computation for dihadron production in e+A, similar to single hadron case **Z. Kang, J. Penttala, F. Zhao, Y. Zhou, e-Print: 2311.17142**

    See presentation by SURGE supported postdoc Jani Penttala (UCLA)
  - In back-to-back limit compare to NLO calculation by Bergabo and Jalilian-Marian (Phys.Rev.D 107 (2023) 5, 054036) Collaboration between Kang, Penttala, and Jalilian-Marian
  - Then numerical computations for dihadron in e+A, like the dijet in e+A above
  - On track to be finished in Year 2
  - Extension to p+A to follow

FINAL STATE



eHIJING: A Monte Carlo model for final-state interaction: HIJING

- Elastic scattering with saturated TMD distributions
- Induced gluon emission
- String hadronization

Year 1-2 Milestone ✓

W. Ke, Y.-Y. Zhang, H. Xing, X.-N. Wang, e-Print: 2304.10779 [hep-ph]
eHIJING: an Event Generator for Jet Tomography in Electron-Ion Collision

Projects in progress:

- Incorporate SMASH in eHIJING for final state hadronic rescattering
- Extension to small x:
  - Dipole approximation of multiple scattering
  - Initial state evolution: gluon saturation
  - LPM interference

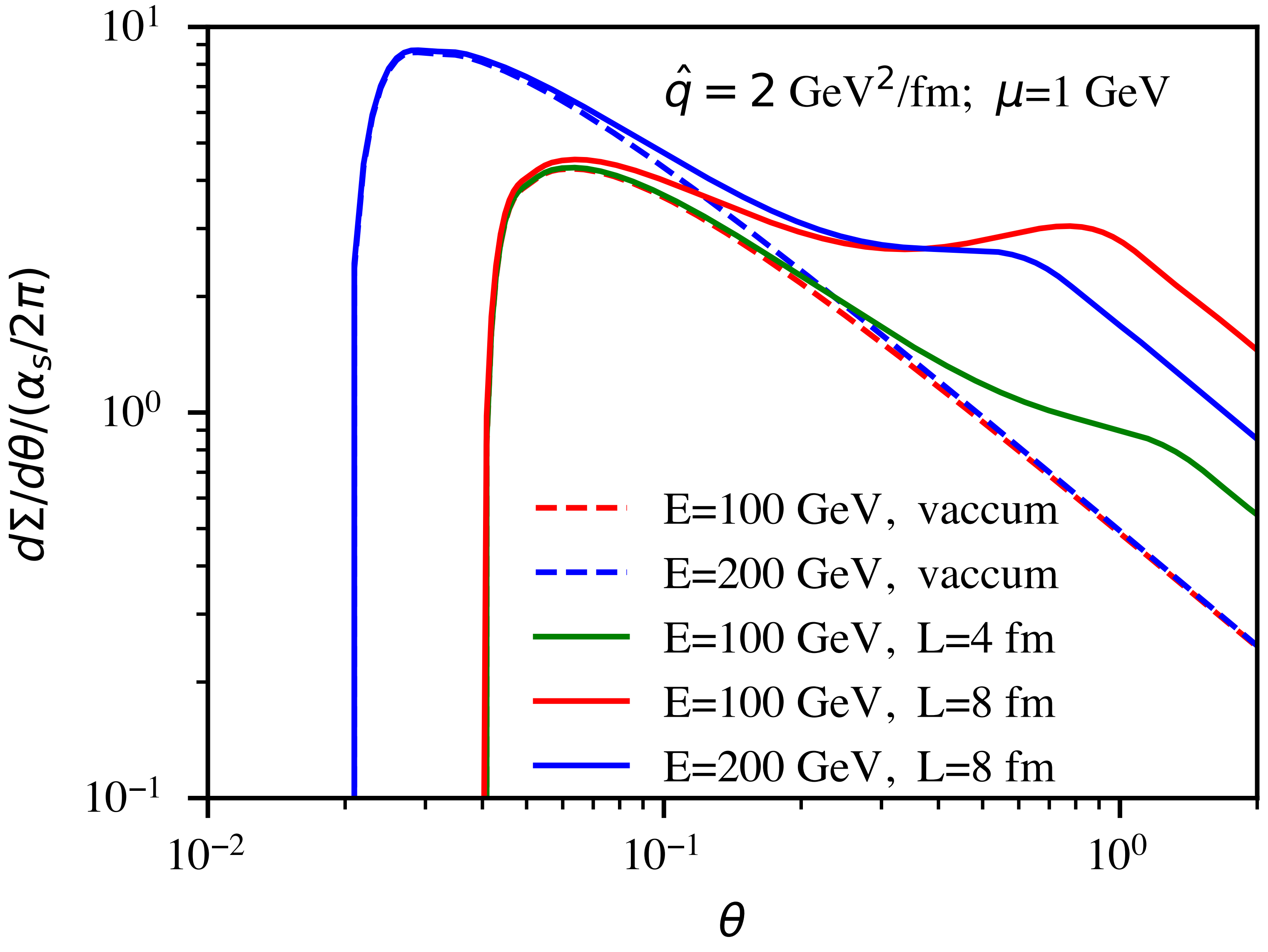
Year 2-3 Milestones

HIJING + smash

UIUC student Jordi Salinas will visit UC Berkeley with SURGE support to work on this

FINAL STATE

Z. Yang, Y. He, I. Moult, X.-N. Wang, Phys. Rev. Lett. 132, 011901 (2024)
Probing the Short-Distance Structure of the Quark-Gluon Plasma with Energy Correlators

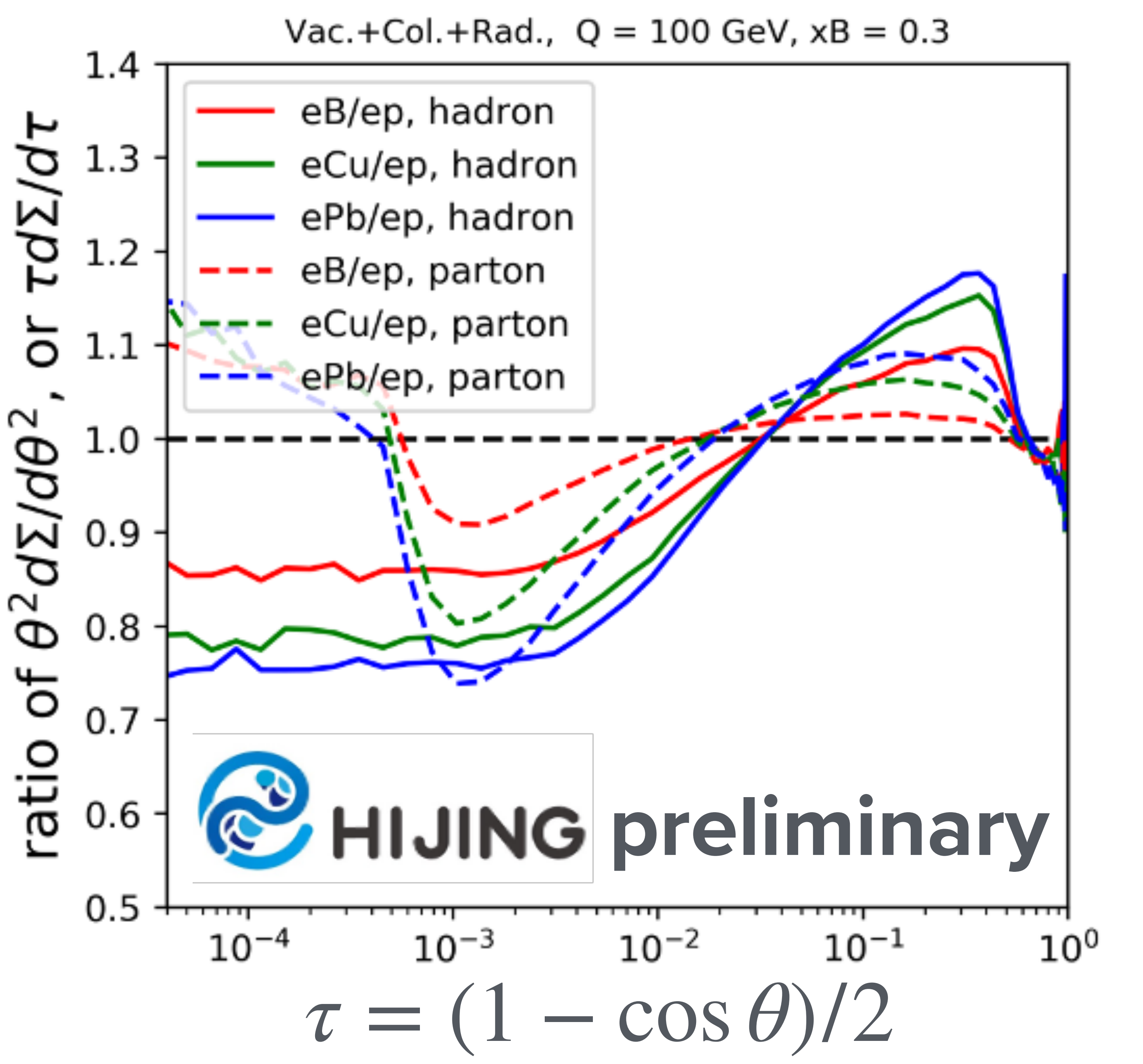


Enhancement of energy-energy correlator (EEC) at large angles due to medium induced gluon bremsstrahlung and medium response in A+A collisions

ongoing

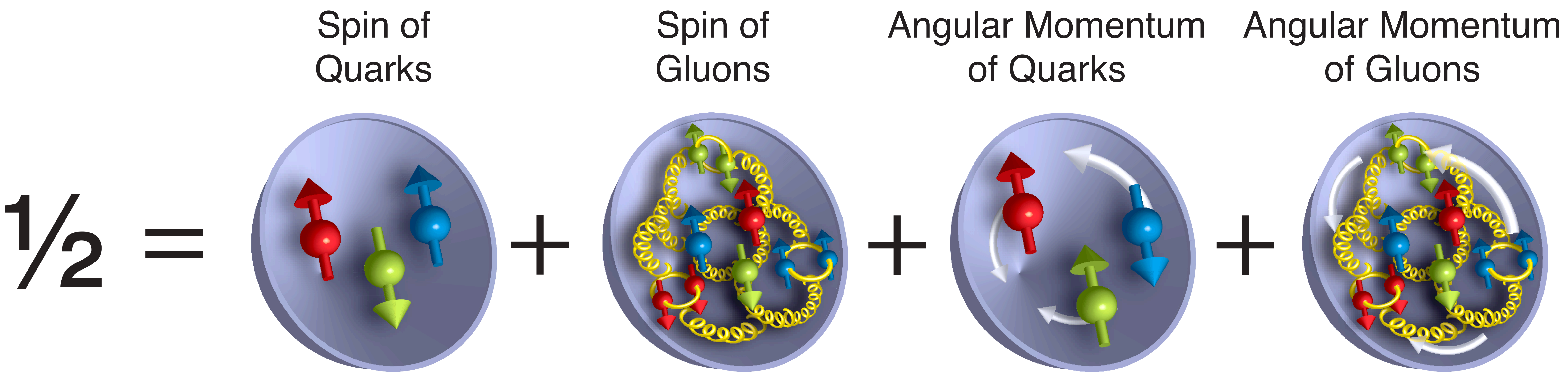
Modification of EEC at the EIC is mostly caused by transverse momentum broadening

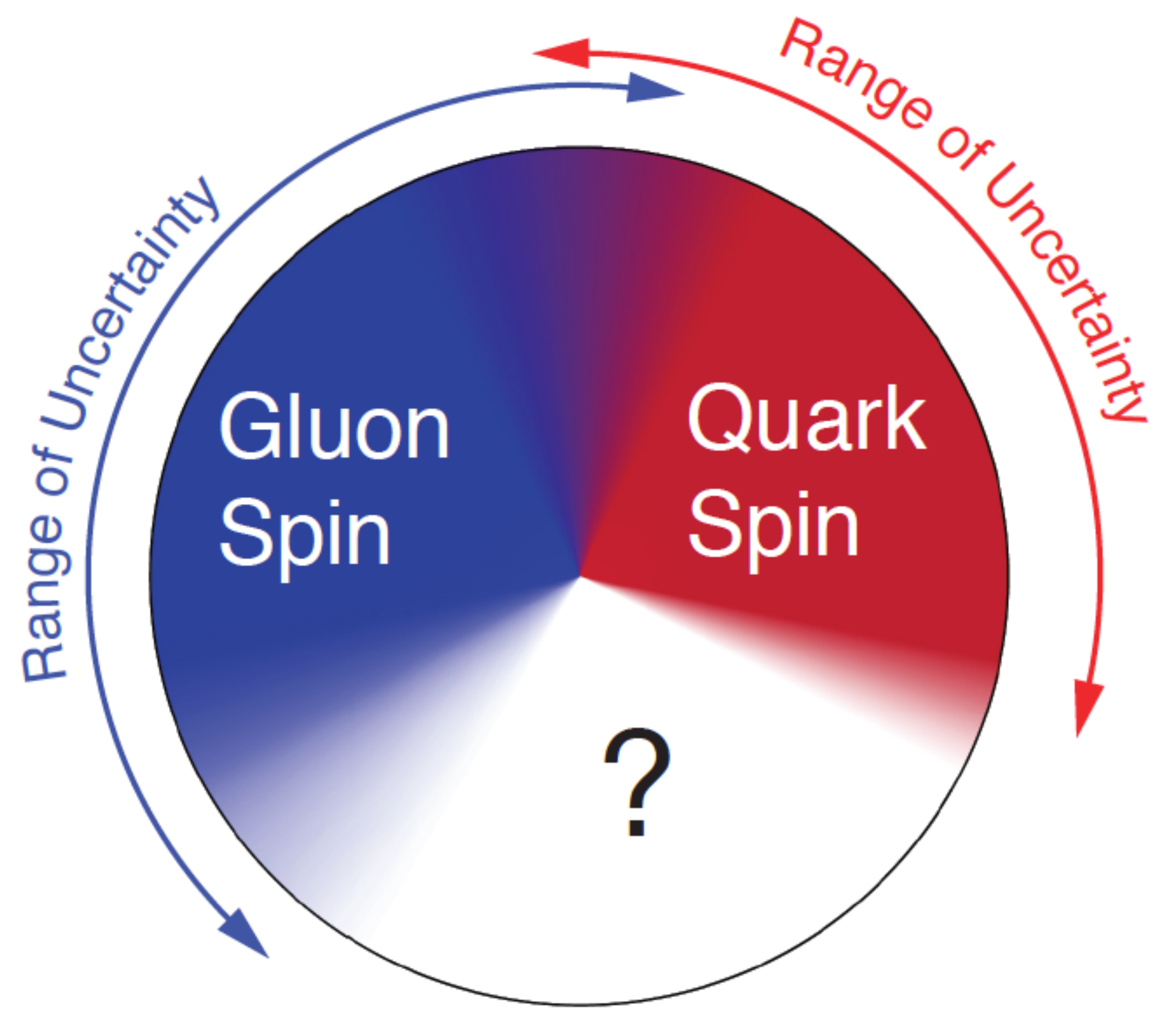
W. Ke, W. Zhao, X.-N. Wang to be published



SPIN AT SMALL X

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





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

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*
  (with SURGE supported OSU graduate student Brandon Manley - year 2 onward)

SPIN - MILESTONES

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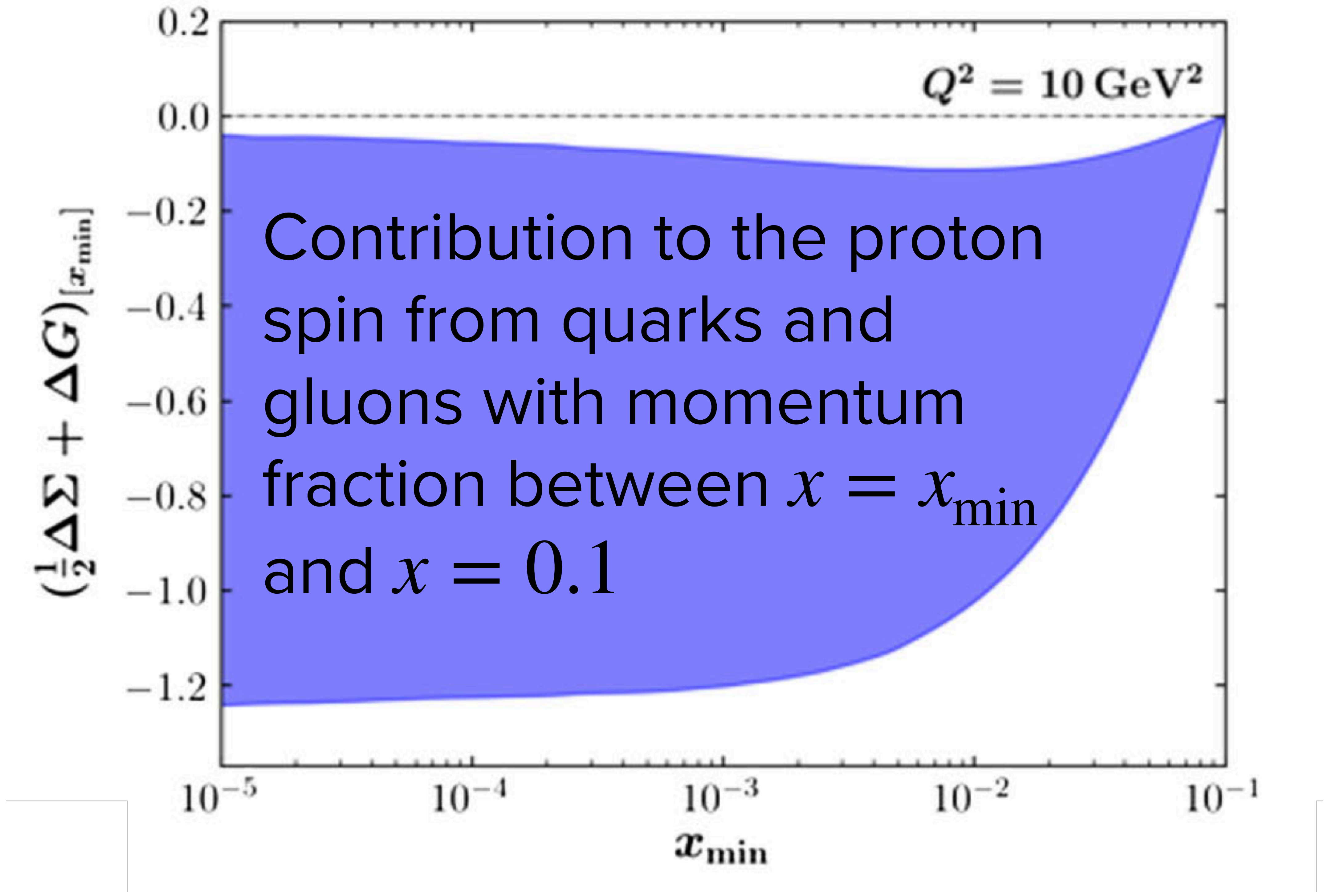
N. Sato, M. Sievert, A. Tarasov, Y. Tawabutr, Phys. Rev. D 108, 114007 (2023)
Global analysis of polarized DIS & SIDIS data with improved small-x helicity evolution

Helps answer the question: How much of the proton spin is at small *x*?

- Contribution from the net spin of small-*x* partons is negative
- This implies that a significant positive contribution from orbital angular momentum would be needed to obtain a total proton spin of $1/2$



See presentation by SURGE supported graduate student Nicholas Baldonado (NMSU)

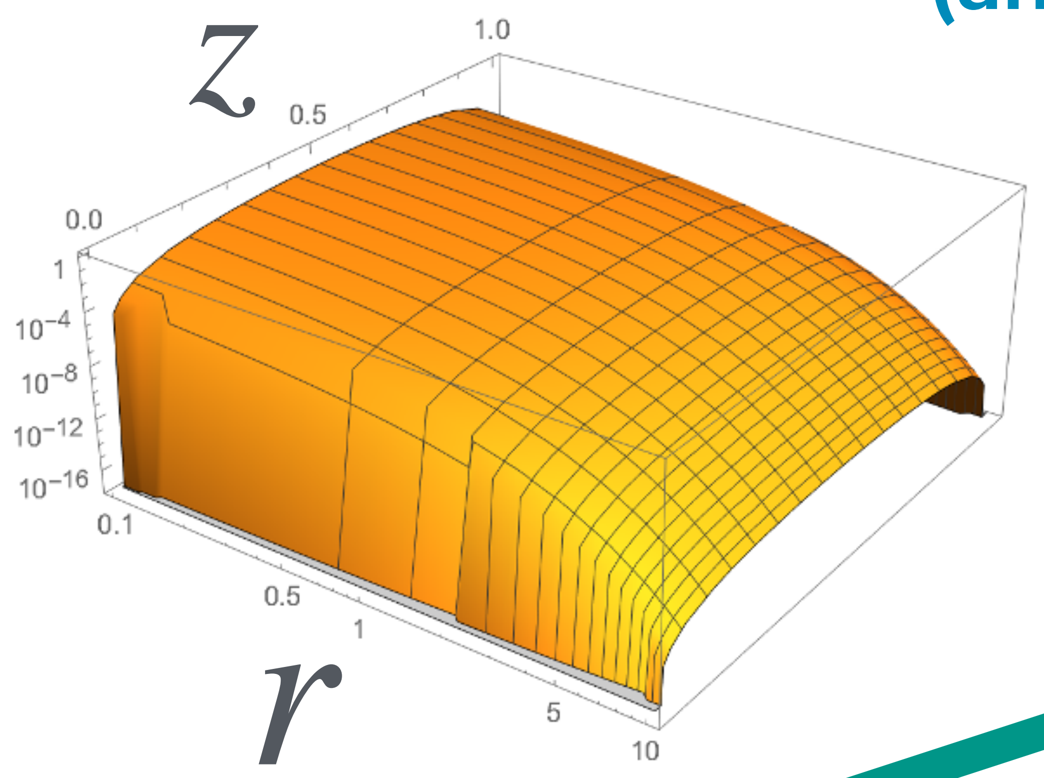
GLOBAL ANALYSIS

Develop a numerical framework with state of the art theory input

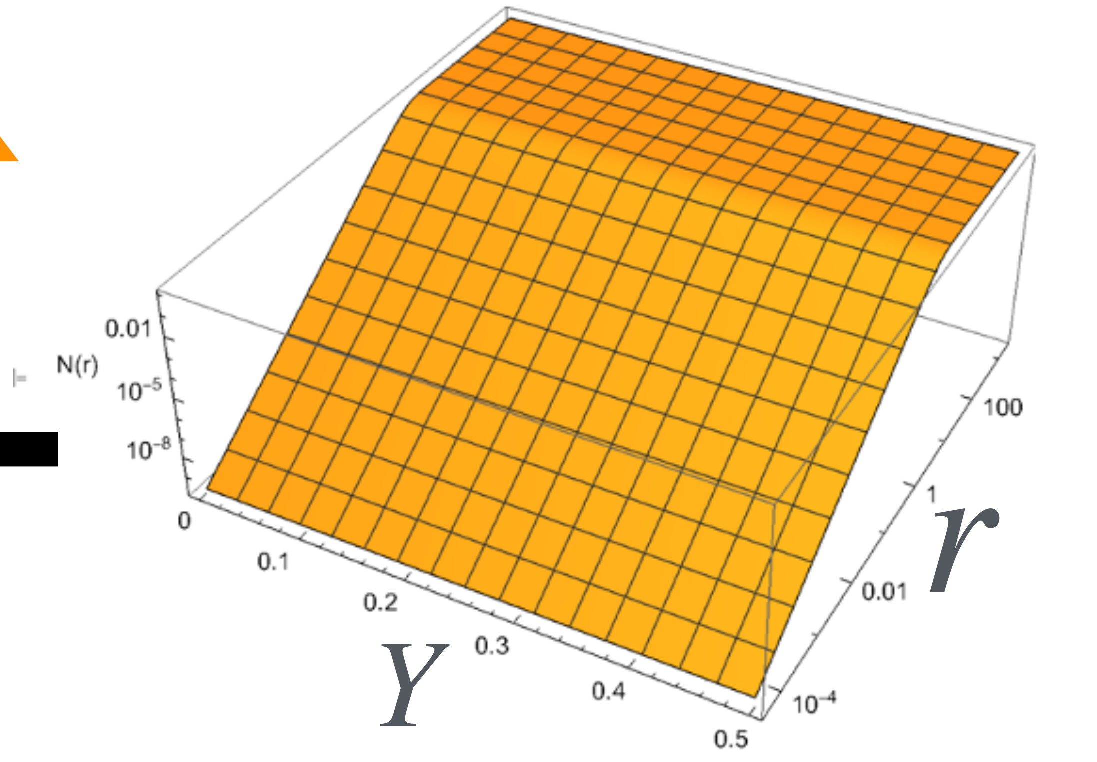
$$\sigma_{tot}^{\gamma^* A}(x, Q^2) = \int \frac{d^2 x_\perp}{4\pi} \int_0^1 \frac{dz}{z(1-z)} |\Psi^{\gamma^* \to q\bar{q}}(\vec{x}_\perp, z)|^2 \sigma_{tot}^{q\bar{q}A}(\vec{x}_\perp, Y).$$

photon wave function (analytic)

dipole cross section (grid)



Convolution



$$\sigma_{\text{tot}}^{\gamma^* A}(x, Q^2)$$
$$\ldots F_2, F_L$$

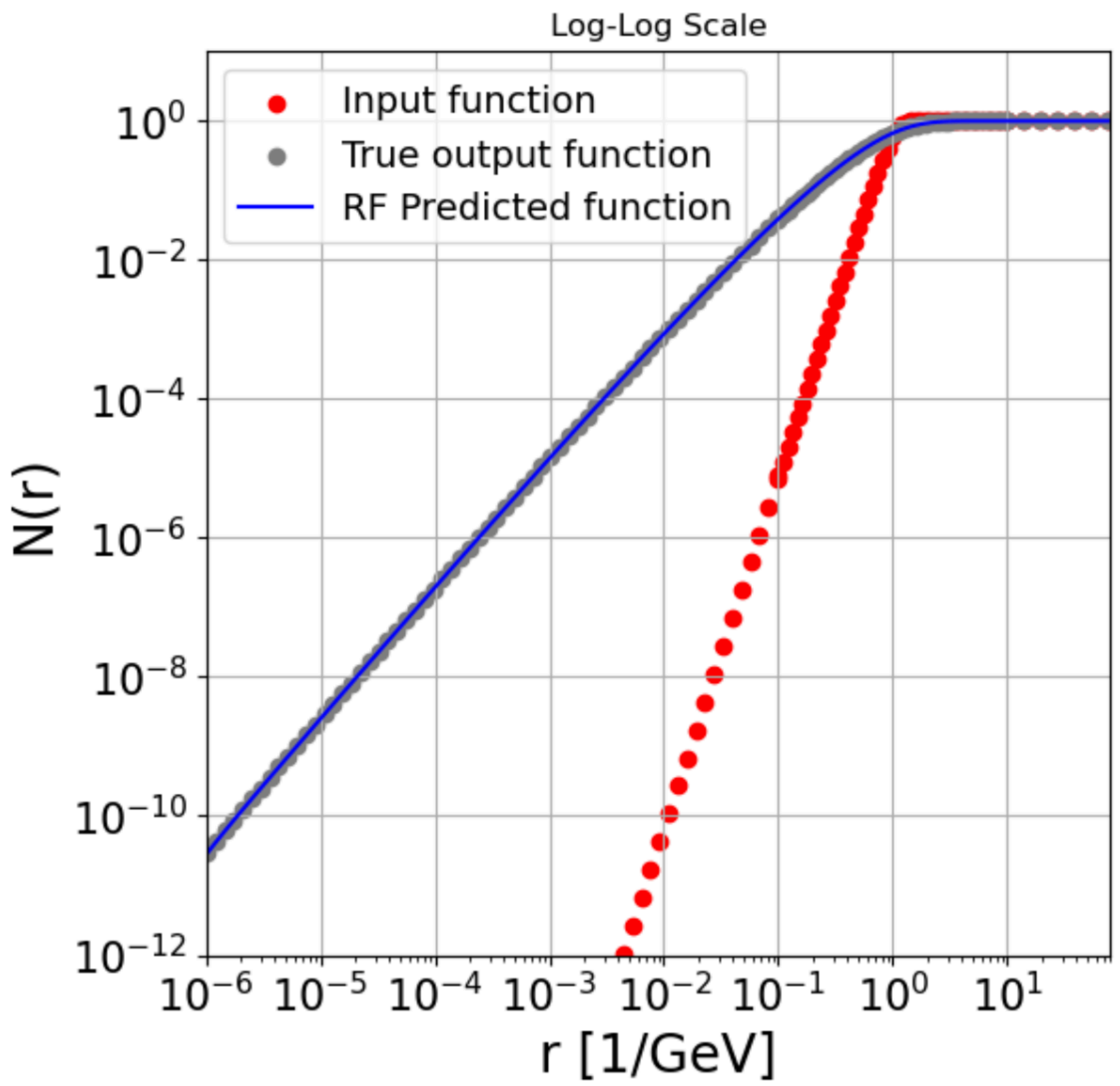
$$\chi^2 = \frac{(D-T)^2}{\sigma^2}$$

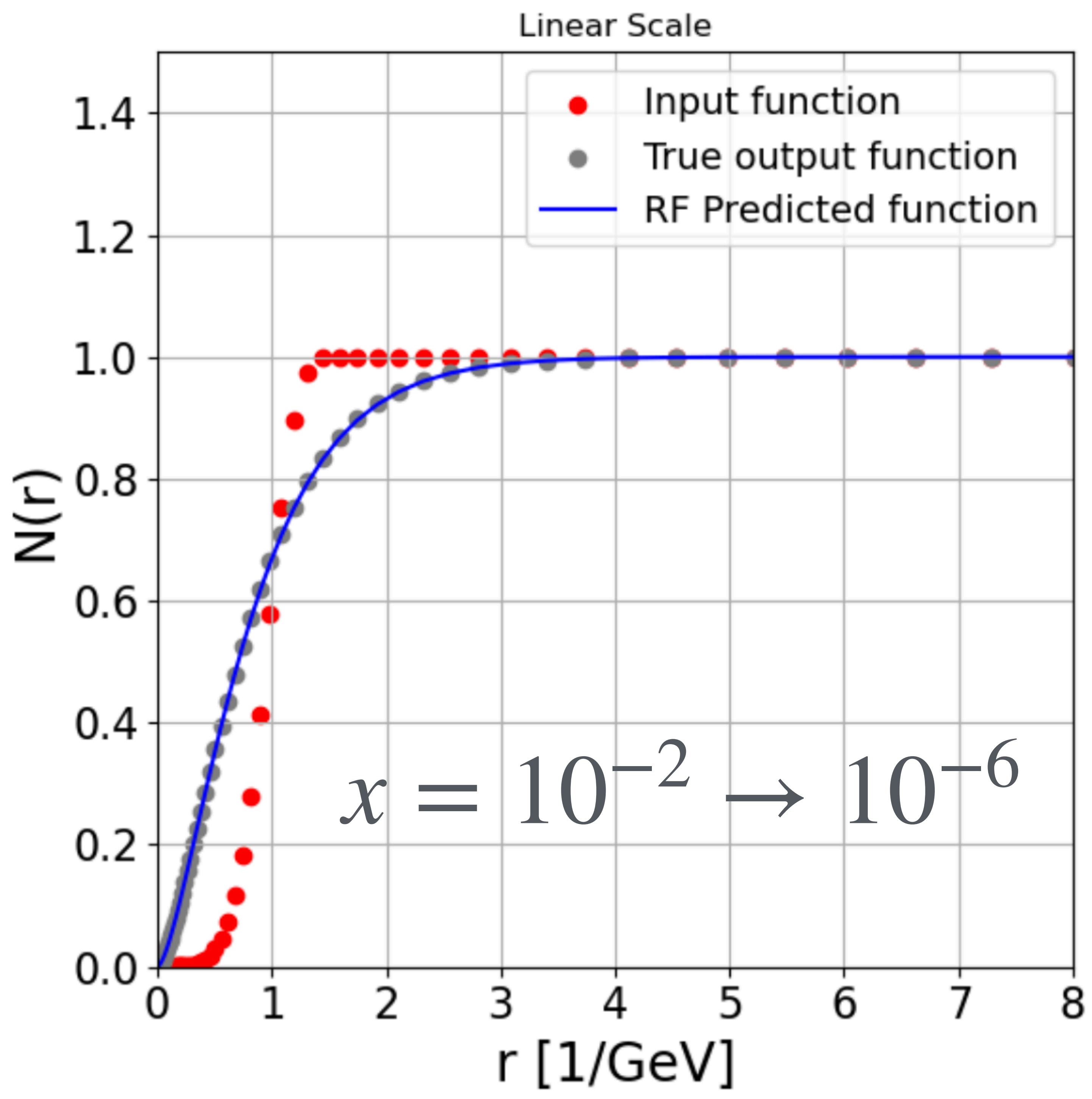
xFitter

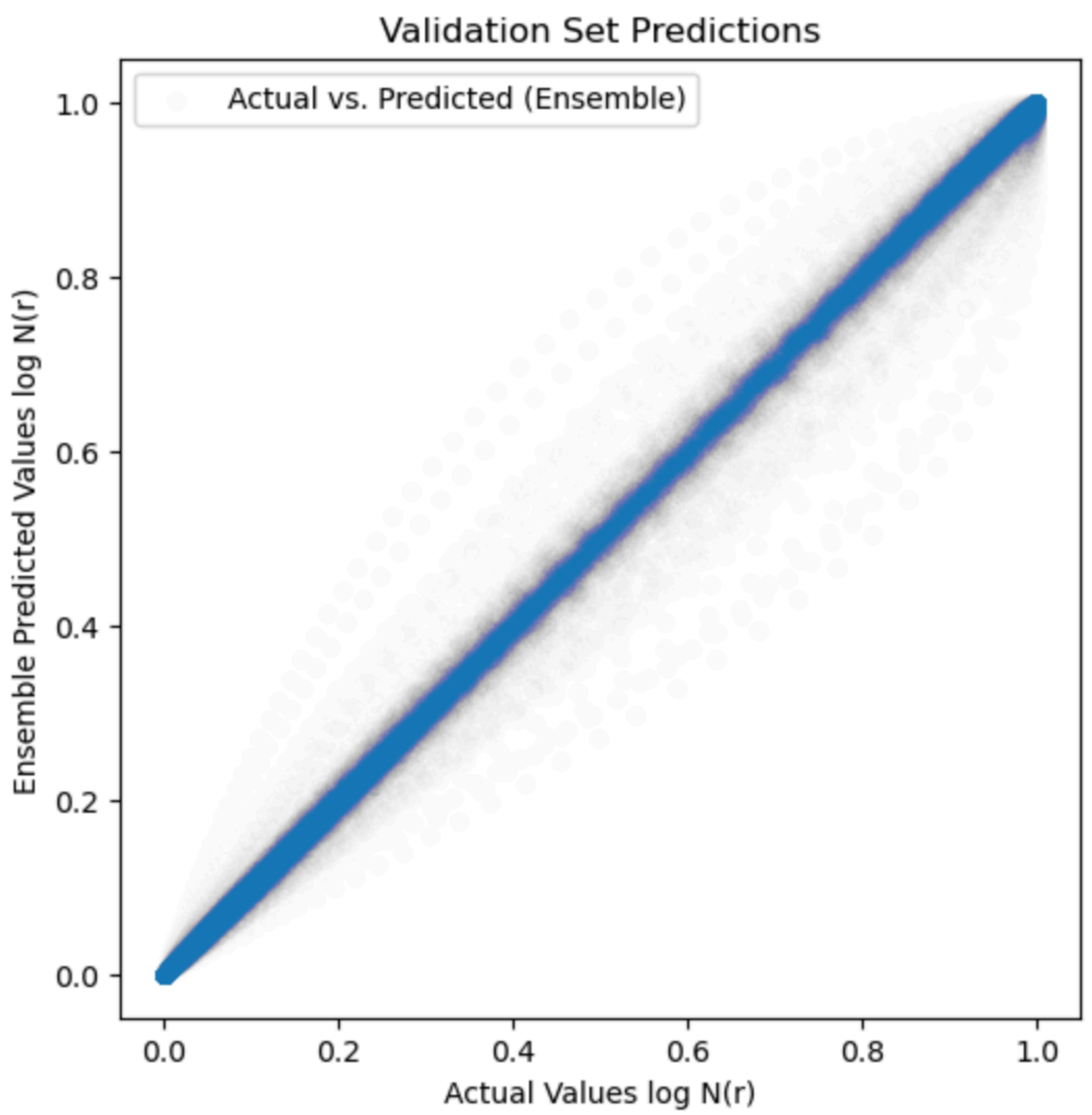
MACHINE LEARNING FOR SPEED

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) → module for many calculations, incl. with spin







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

SUMMARY

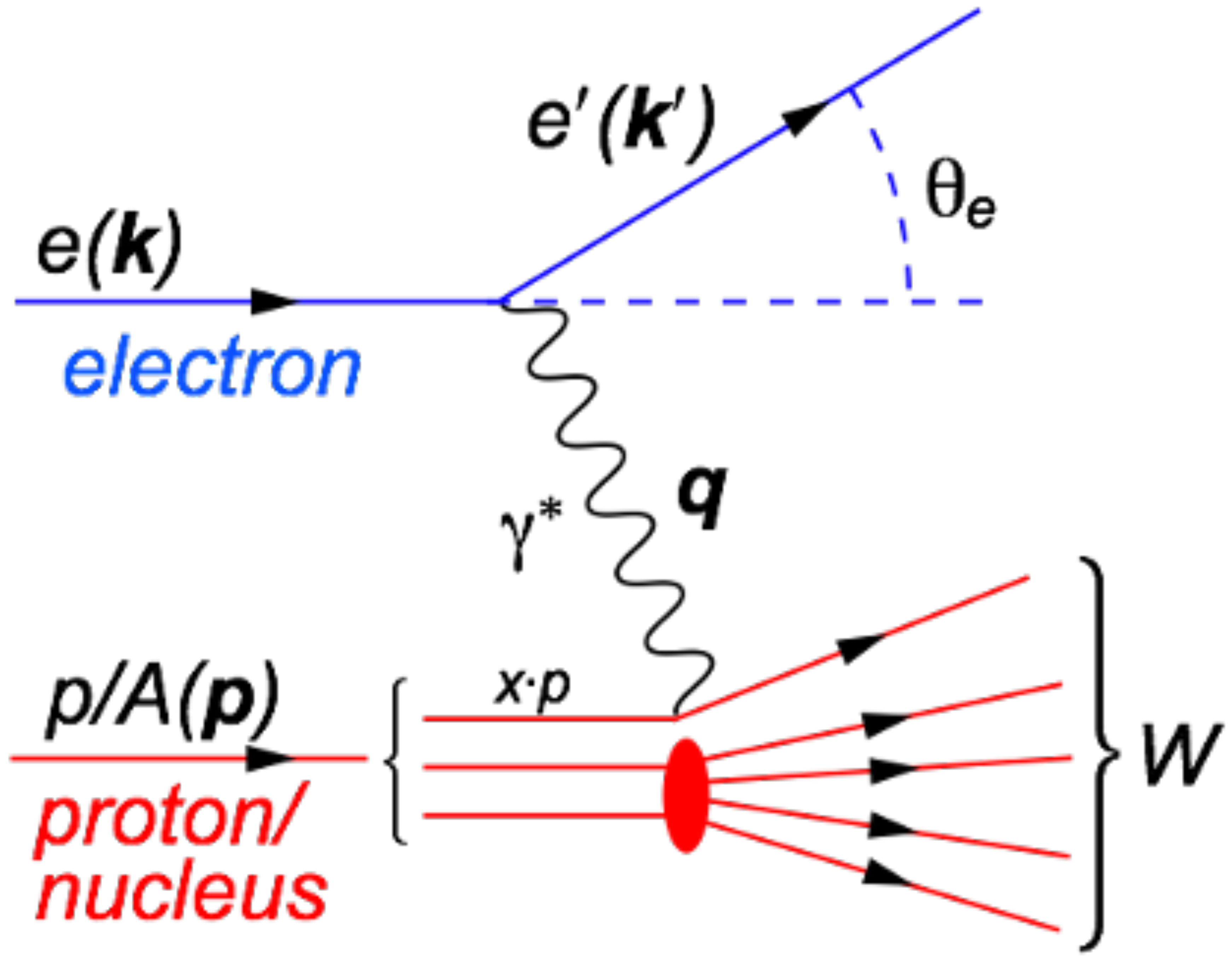
- Highly successful first year (16 months)
- Many achievements that would not have happened without the collaborative efforts in the TC
- Milestones achieved or on track to be achieved
- Output of 50+ papers on arXiv
- 25 refereed publications in high impact journals
- Support for students and postdocs
- Travel support for visits between institutions

BACKUP

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