

UCLA



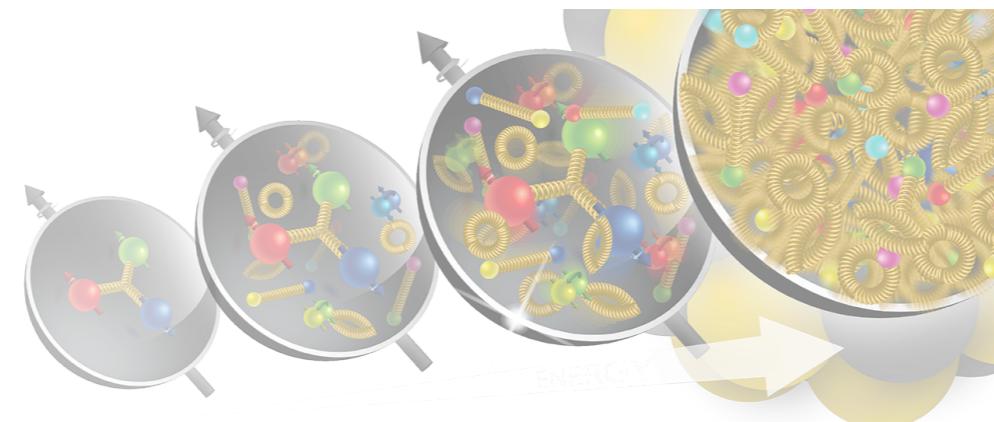
Berkeley
UNIVERSITY OF CALIFORNIA

Status of gluon saturation at colliders

The 9th International Conference on Quarks and Nuclear Physics

Florida State University
September 7th, 2022

Farid Salazar



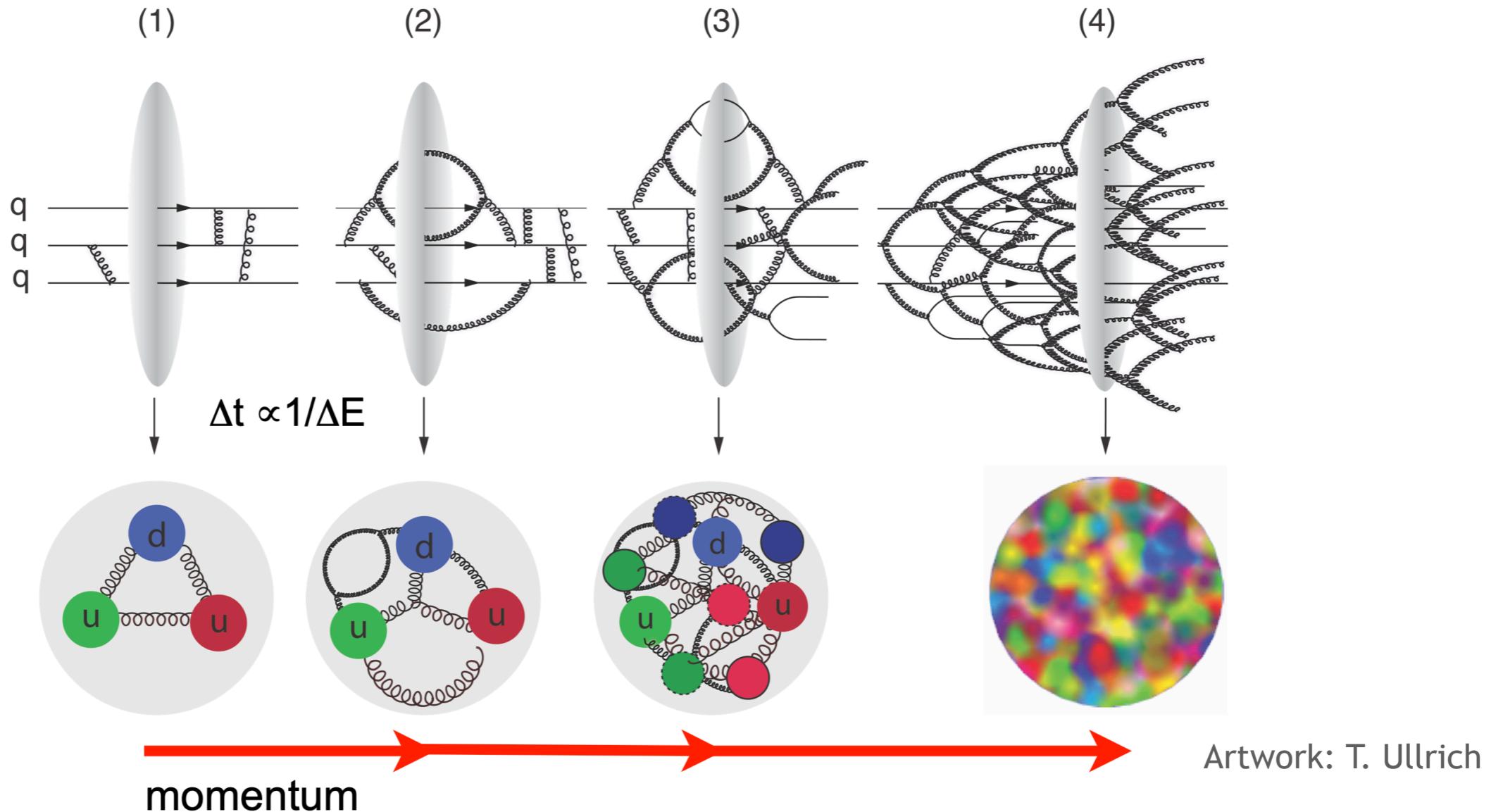
Talked based on “Mining Gluon Saturation at Colliders” Astrid Morreale, FS.
[2108.08254 \(Universe 7 \(2021\) 8, 312 \)](#)

Why gluon saturation?

- Search of gluon saturation is one of the major goals of the future EIC.
- The **Color Glass Condensate** is an EFT for this **gluon saturated regime**.
- A wide variety of observables are available to search for gluon saturation: **structure functions, diffractive processes, and semi-inclusive measurements**.
- Competing physical mechanisms might lead to similar signatures. Need sharper predictions (NLO era for gluon saturation).

Gluon saturation at small x

Anatomy of nuclear matter in the high energy limit

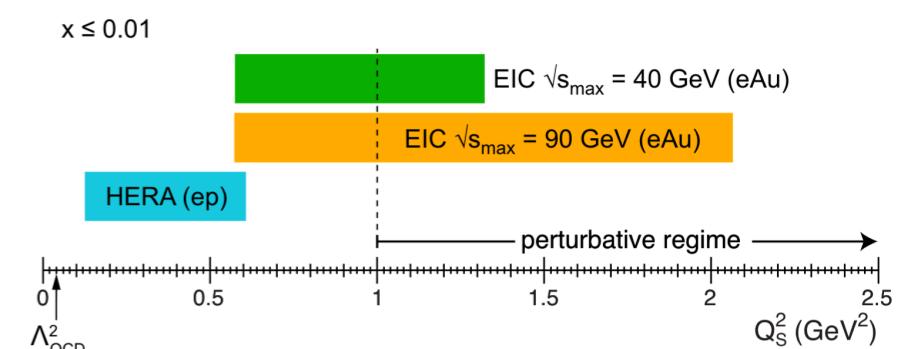


Emergence of an energy and nuclear specie dependent momentum scale (saturation scale) parametrizes importance of:

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

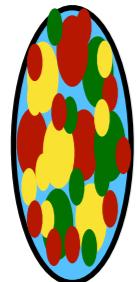
Multiple scattering (higher twist effects)

Non-linear evolution equations (BK/JIMWLK)



Gluon saturation at small x

Color Glass Condensate: sources, fields, multiple scattering

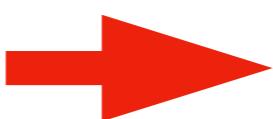
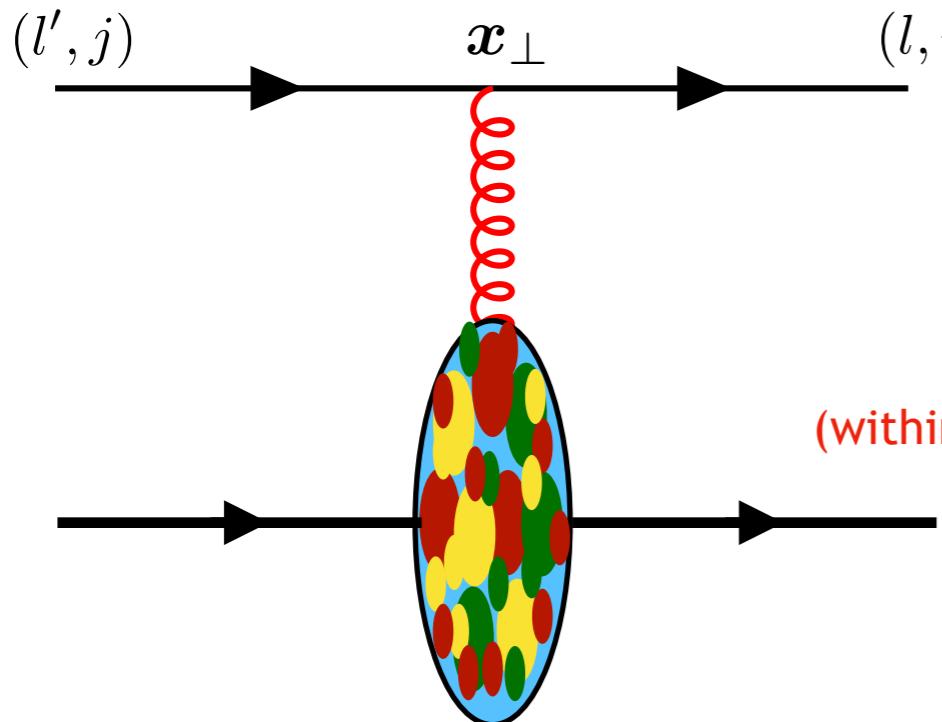


Large-x partons are effectively treated as a collection of recoilless localized and static random color sources

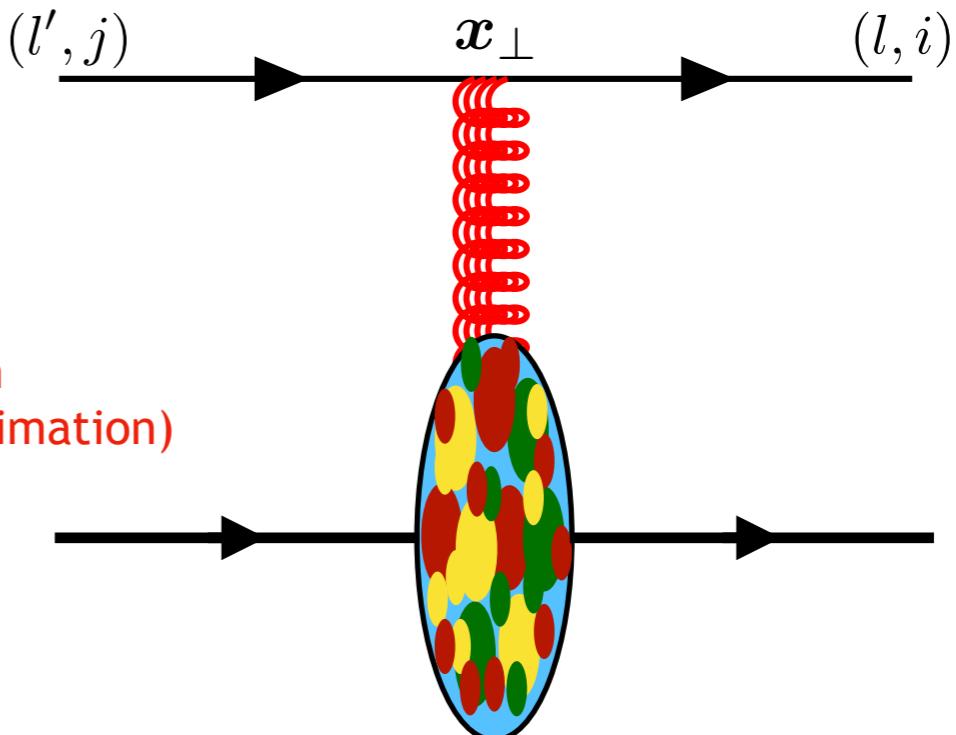
L. McLerran, R. Venugopalan (1993)

Source the back-ground field

$$A_{\text{cl}}^+(\mathbf{x}_\perp, x^-) \sim 1/g$$



Exponentiation
(within eikonal approximation)



A. Ayala, J. Jalilian-Marian,
L. McLerran, R. Venugopalan (1995)
I. Balitsky (1996)

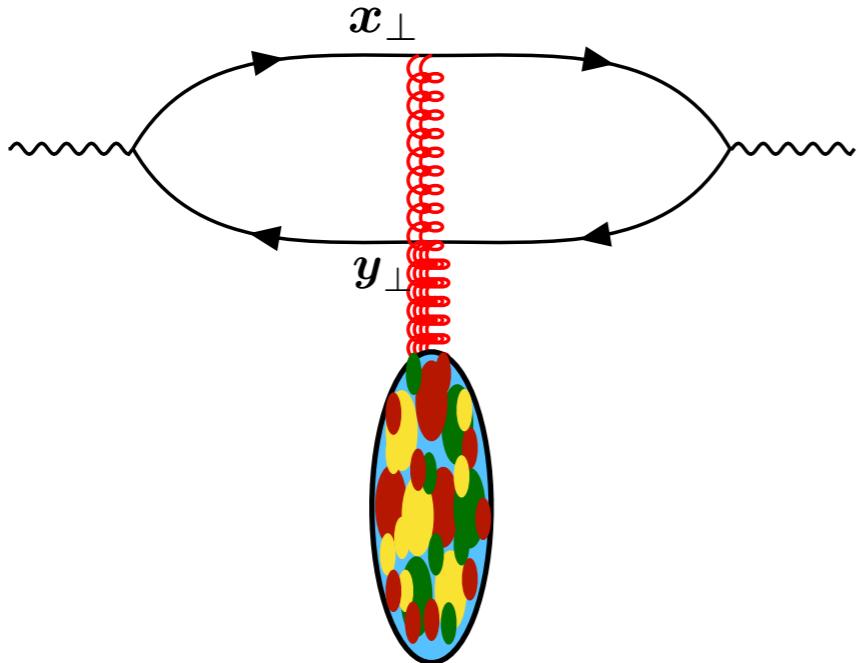
$$\mathcal{T}_{ij}^q(l, l') = (2\pi)\delta(l^- - l'^-) \gamma^- \text{sgn}(l^-) \int_{\mathbf{x}_\perp} e^{-i(\mathbf{l}_\perp - \mathbf{l}'_\perp) \cdot \mathbf{z}_\perp} V_{ij}(\mathbf{x}_\perp)$$

Light-like Wilson line

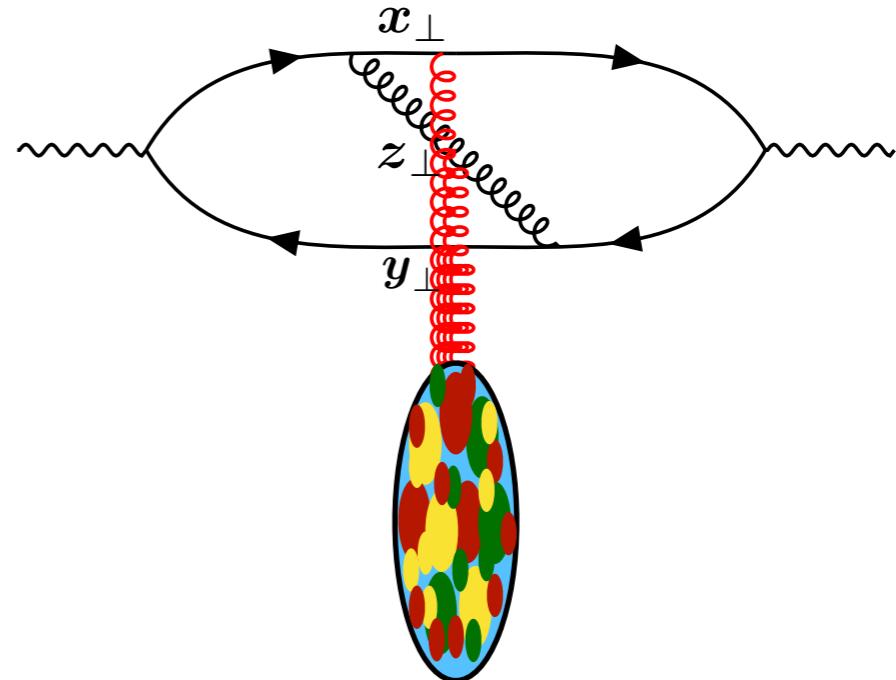
$$V_{ij}(\mathbf{x}) = P \exp \left\{ ig \int dx^- A_{\text{cl}}^{+,a}(\mathbf{x}, x^-) t^a \right\}$$

Gluon saturation at small x

Color Glass Condensate: non-linear evolution



$$\text{Tr} [V(\mathbf{x}_\perp) V^\dagger(\mathbf{y}_\perp)]$$



$$\text{Tr} [V(\mathbf{x}_\perp) t^a V^\dagger(\mathbf{y}_\perp) t^b] U_{ab}(z_\perp)$$

$$\text{Dipole: } S_Y^{(2)}(\mathbf{x}_\perp - \mathbf{y}_\perp) = \frac{1}{N_c} \langle \text{Tr} [V(\mathbf{x}_\perp) V^\dagger(\mathbf{y}_\perp)] \rangle_Y$$

Gluon emissions lead to evolution: BK and JIMWLK

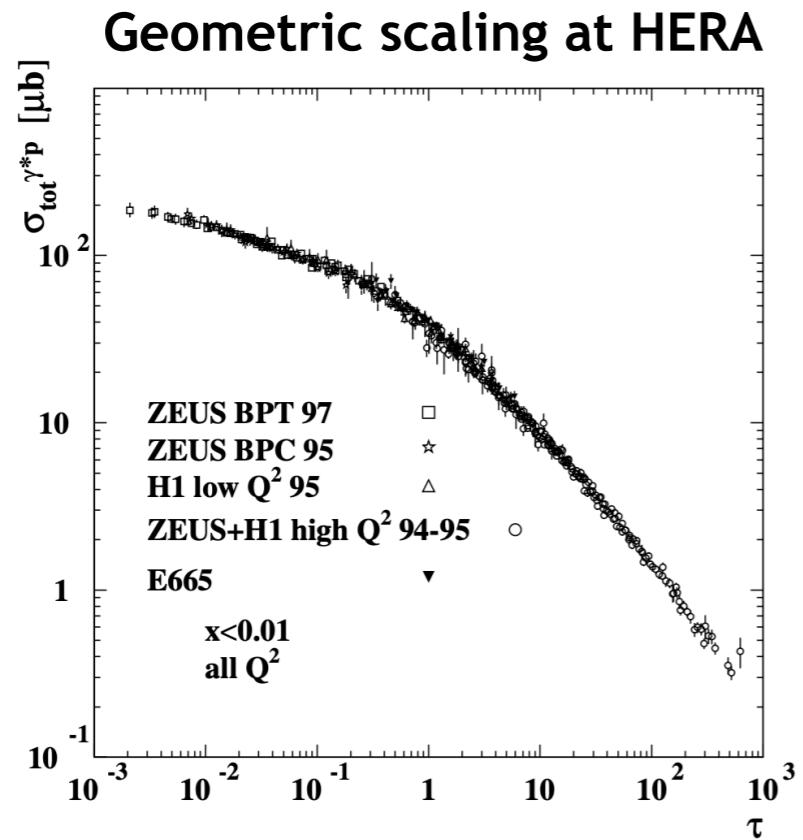
BK equation:

$$\frac{dS_Y^{(2)}(\mathbf{r}_\perp)}{dY} = \frac{\alpha_s N_c}{2\pi^2} \int d^2\mathbf{r}'_\perp \frac{\mathbf{r}_\perp^2}{\mathbf{r}'_\perp^2 (\mathbf{r}_\perp - \mathbf{r}'_\perp)^2} \left[S_Y^{(2)}(\mathbf{r}'_\perp) S_Y^{(2)}(\mathbf{r}_\perp - \mathbf{r}'_\perp) - S_Y^{(2)}(\mathbf{r}_\perp) \right]$$

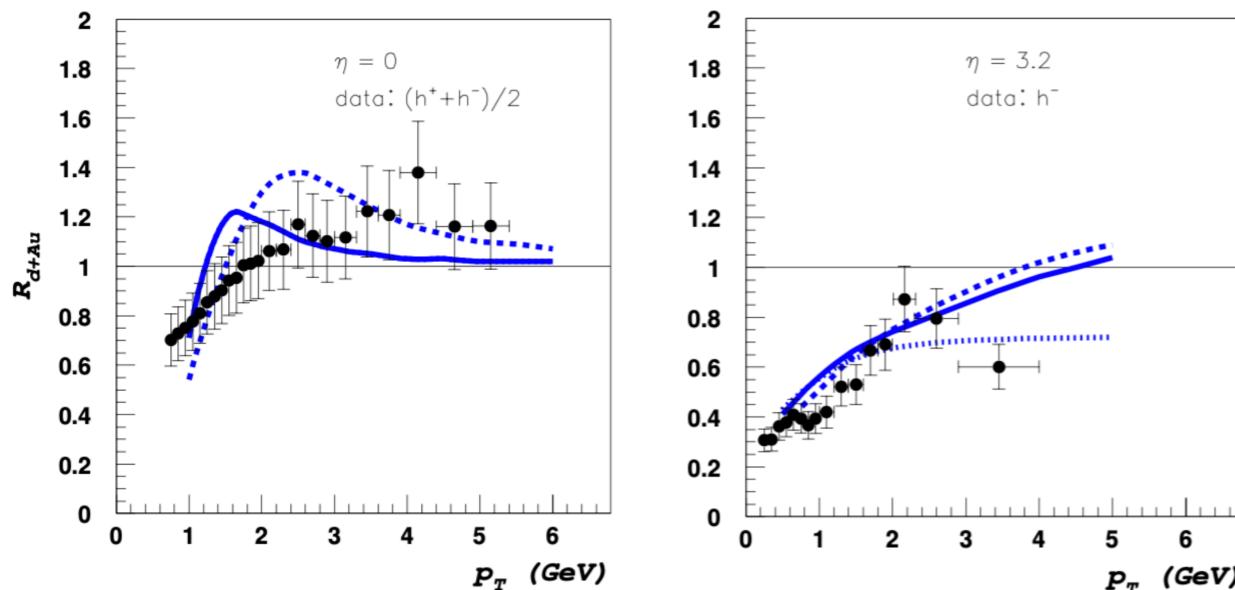
I. Balitsky (1995), Y. Kovchegov (1999)
J. Jalilian-Marian, E. Iancu, L. McLerran,
H. Weigert, A. Leonidov, A. Kovner (1996-2002)

Gluon saturation at colliders

From HERA to RHIC to LHC

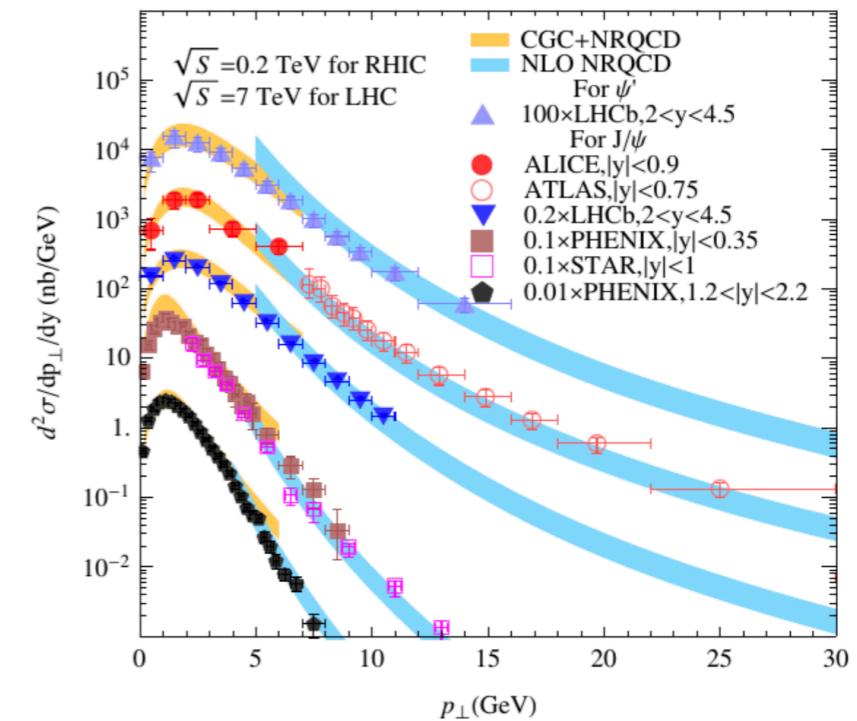


Nuclear modification factor at RHIC

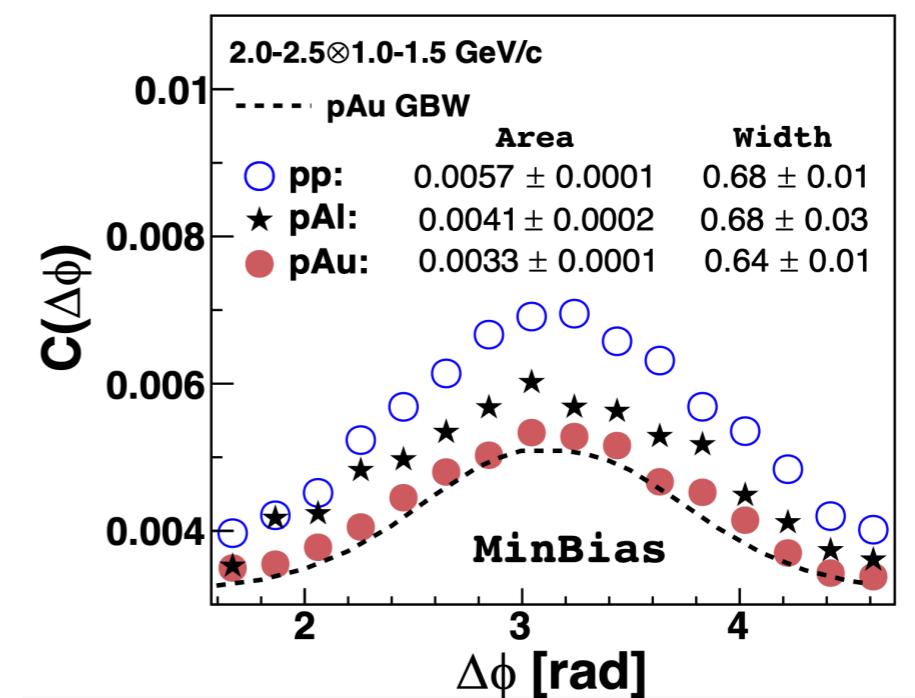


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Quarkonia production at RHIC and LHC



Dihadron suppression at RHIC



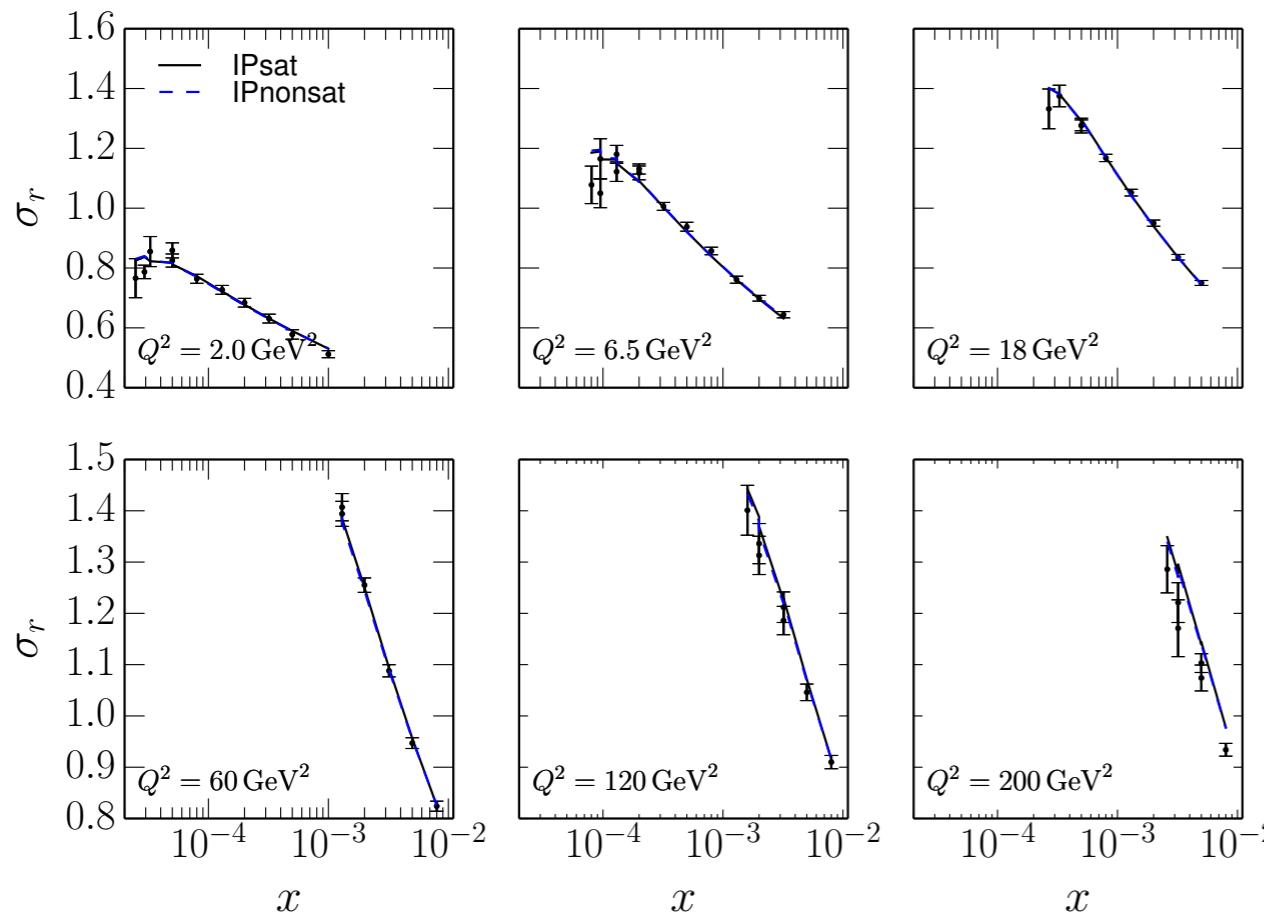
For references: see [2108.08254](#)

Structure functions

Reduced cross-section and F_L at HERA

$$\sigma_r(x, y, Q^2) = F_2(x, Q^2) - \frac{y^2}{1 + (1 - y)^2} F_L(x, Q^2)$$

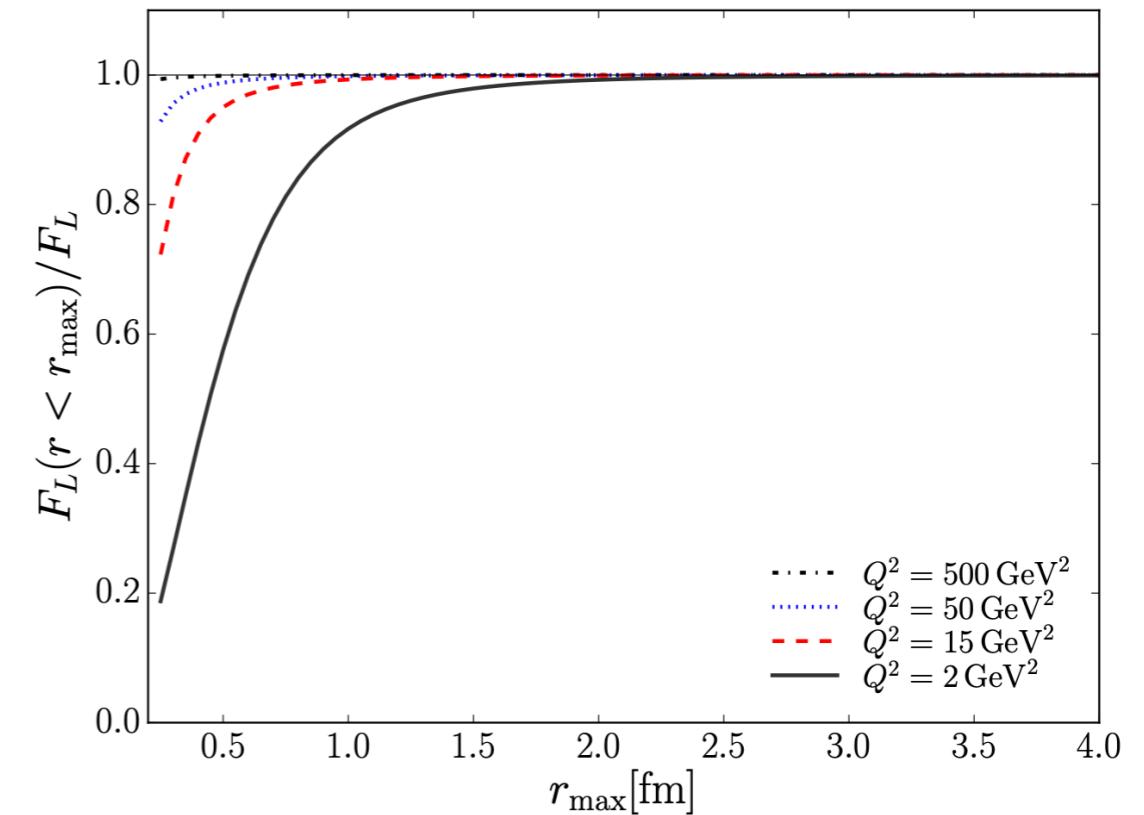
IPsat & IPnonsat (linearized IPsat)



Independent fits using IPSAT and IPnonsat describe data equally well.

No clear evidence of gluon saturation at HERA

Dipole size contributions to F_L



At HERA saturation searches are hindered by non-perturbative contributions

H. Mäntysaari, M.P. Zurita (2018)

See also H. Mäntysaari, B. Schenke (2018)

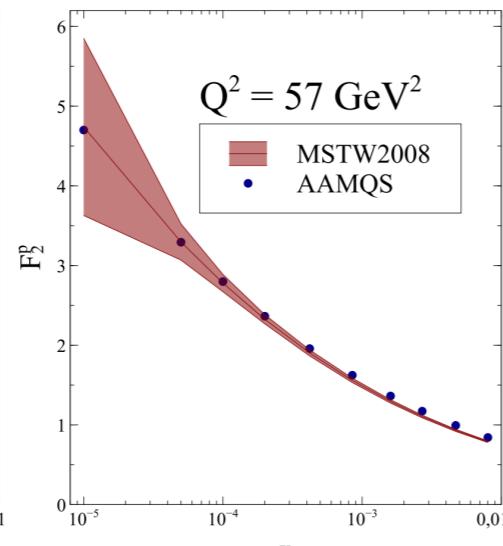
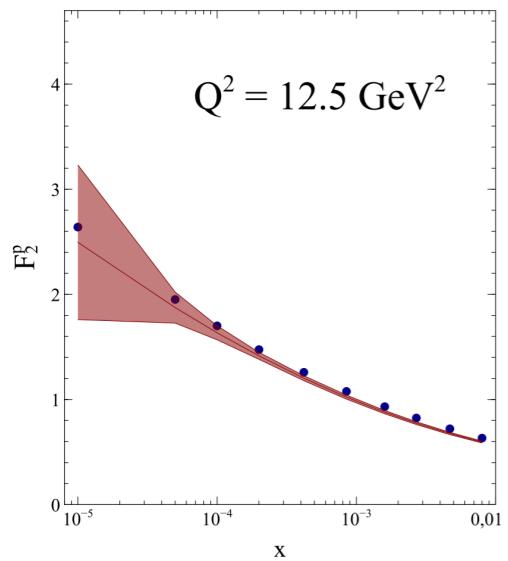
Structure functions

Nuclear PDFs vs saturation framework

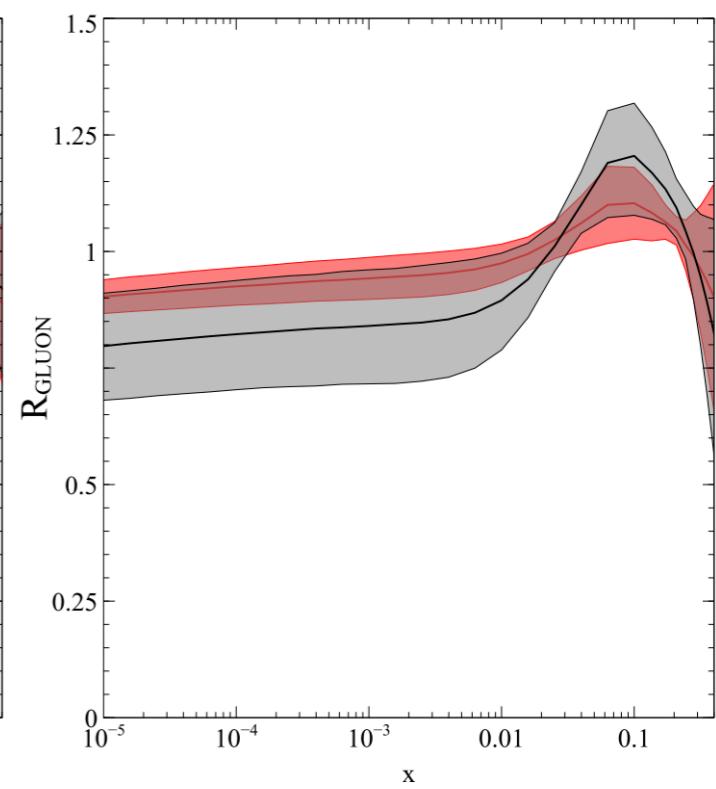
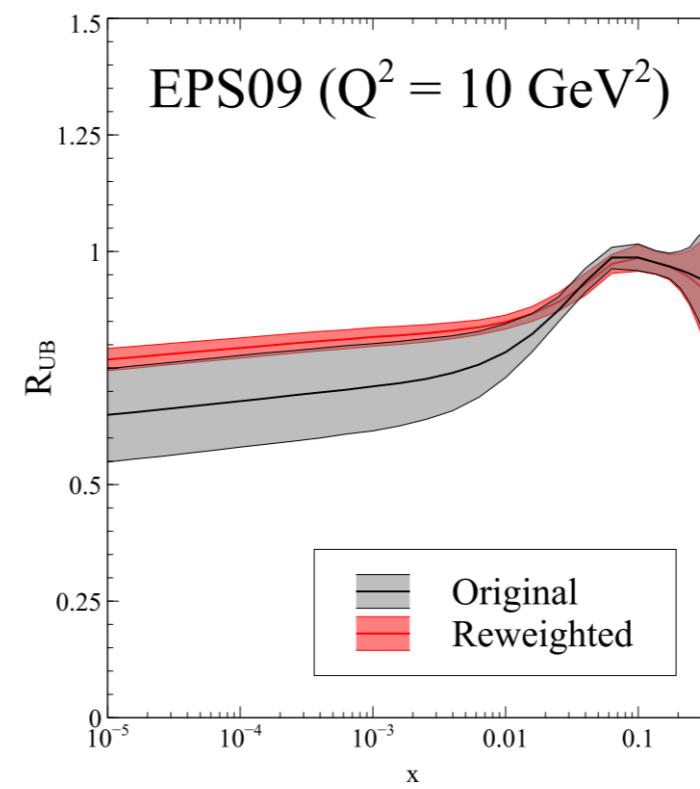
Saturation effects
enhanced in nuclei

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

Less sensitivity to
non-perturbative effects



Saturation vs collinear
factorization for proton F_2

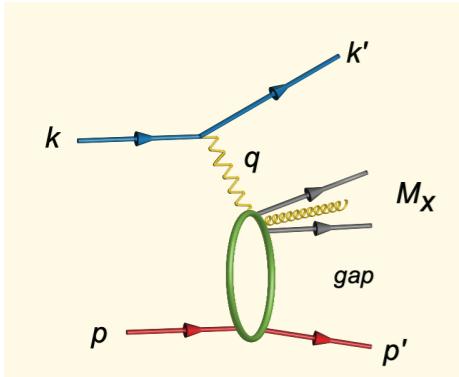


Sea quark and gluon distribution before
and after Bayesian re-weighting

At the EIC it might be possible to find tension between nuclear PDFs and saturation predictions

Diffractive processes

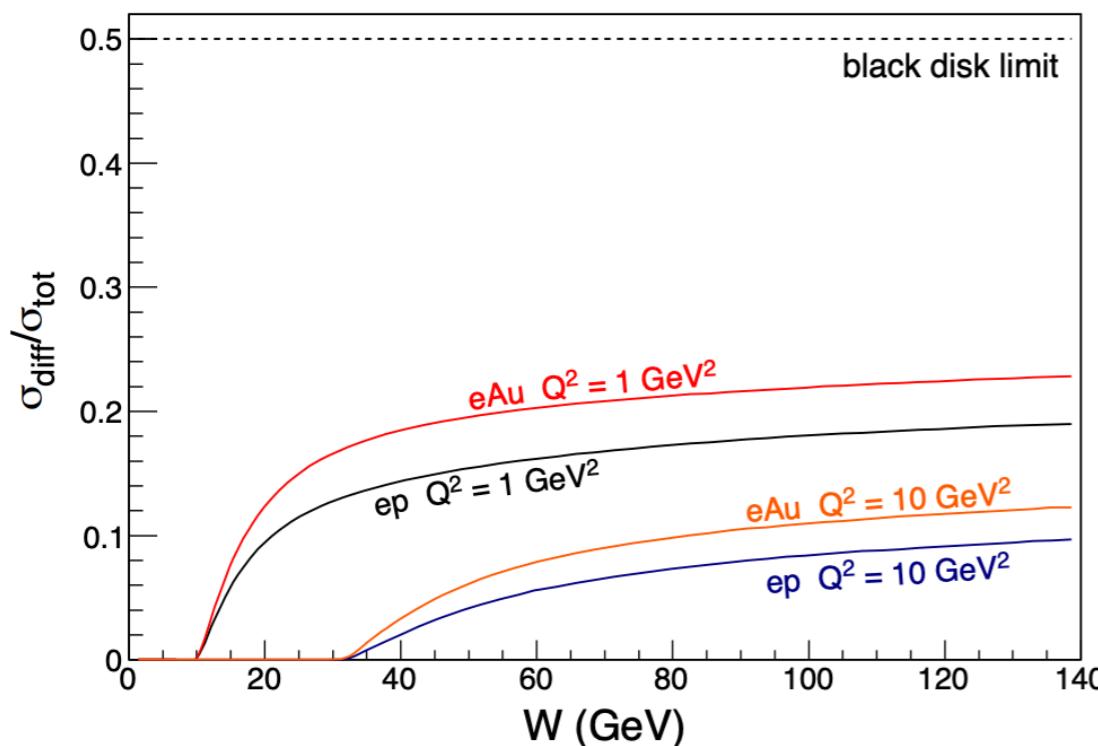
Diffractive structure functions



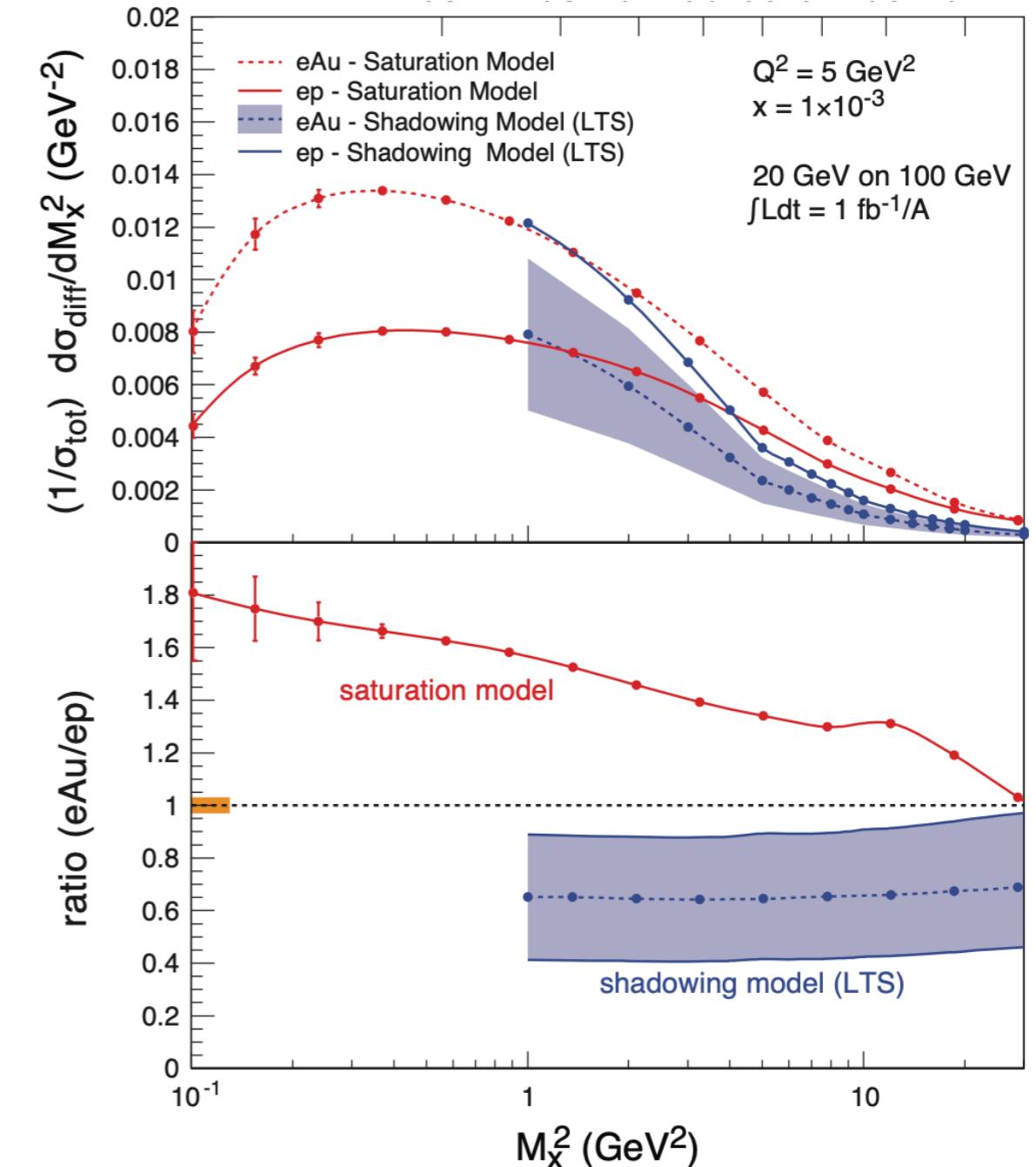
Diffractive events are characterized by rapidity gap

Neutral color exchange requires at least **two-gluons** (enhanced sensitivity to gluon sat)

Ratio of diffractive and total cross-section in ep and eAu collisions



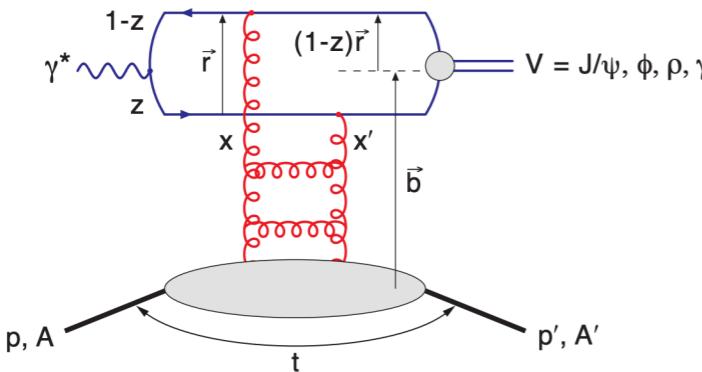
Diffractive events enhanced at lower Q^2 and have weak dependence on energy



Clear difference between saturation models and leading twist shadowing (LTS)

Diffractive processes

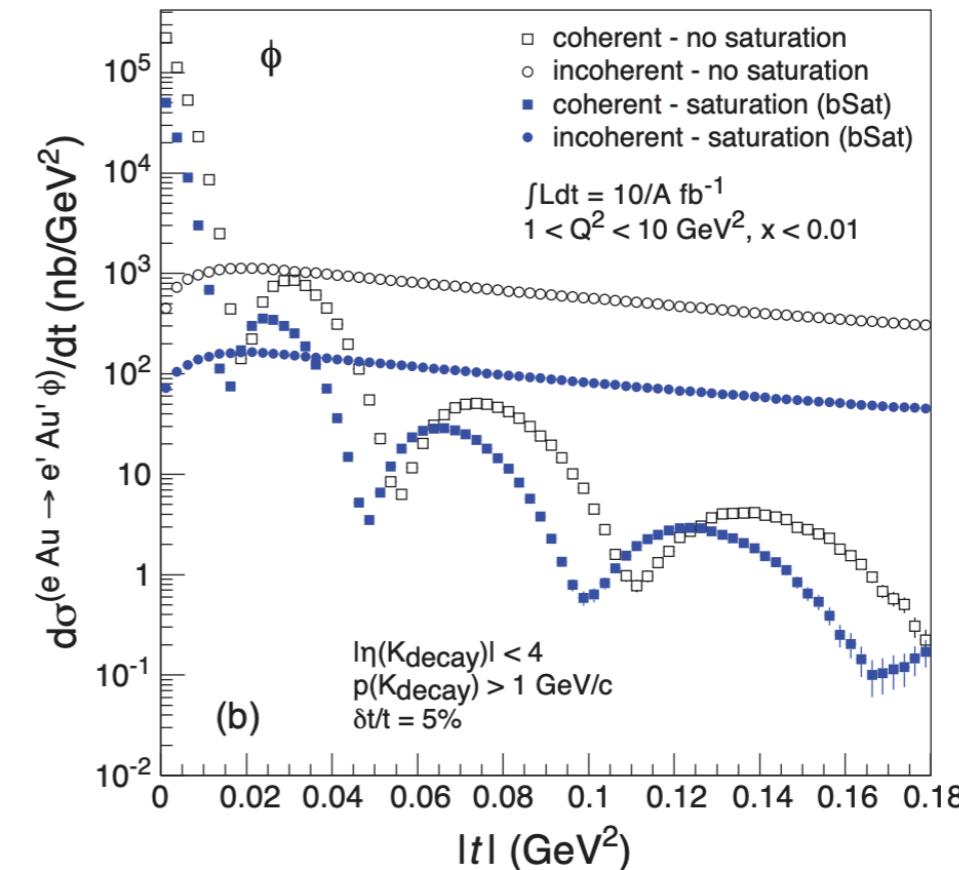
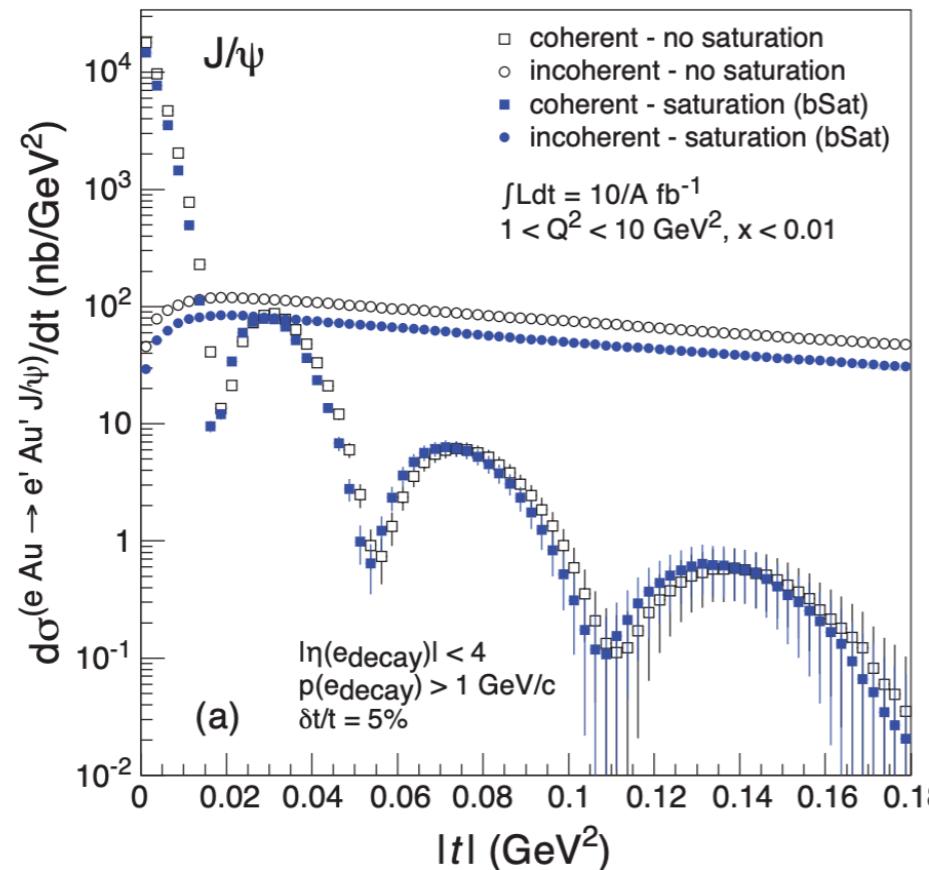
Exclusive nuclear electro-production of VM



*Sensitive to spatial distribution
(tomography)*

$$t = -\Delta_{\perp}^2$$

$$\Delta_{\perp} \leftrightarrow b_{\perp}$$

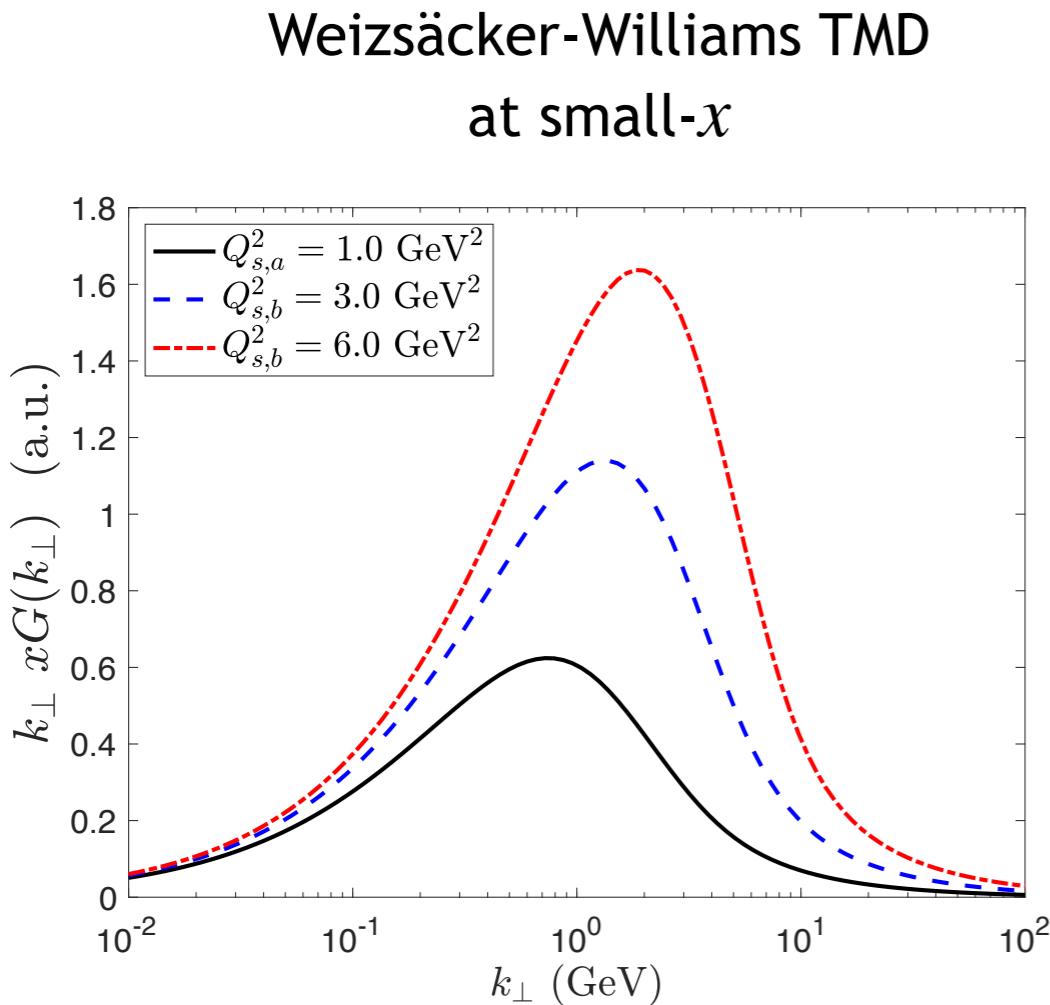


- Sartre event generator (bSat & bNonSat = linearized bSat)
- Large difference for ϕ less so for J/ψ

T. Toll, T. Ullrich (2012)

Semi-inclusive measurements

Suppression of back-to-back dihadrons

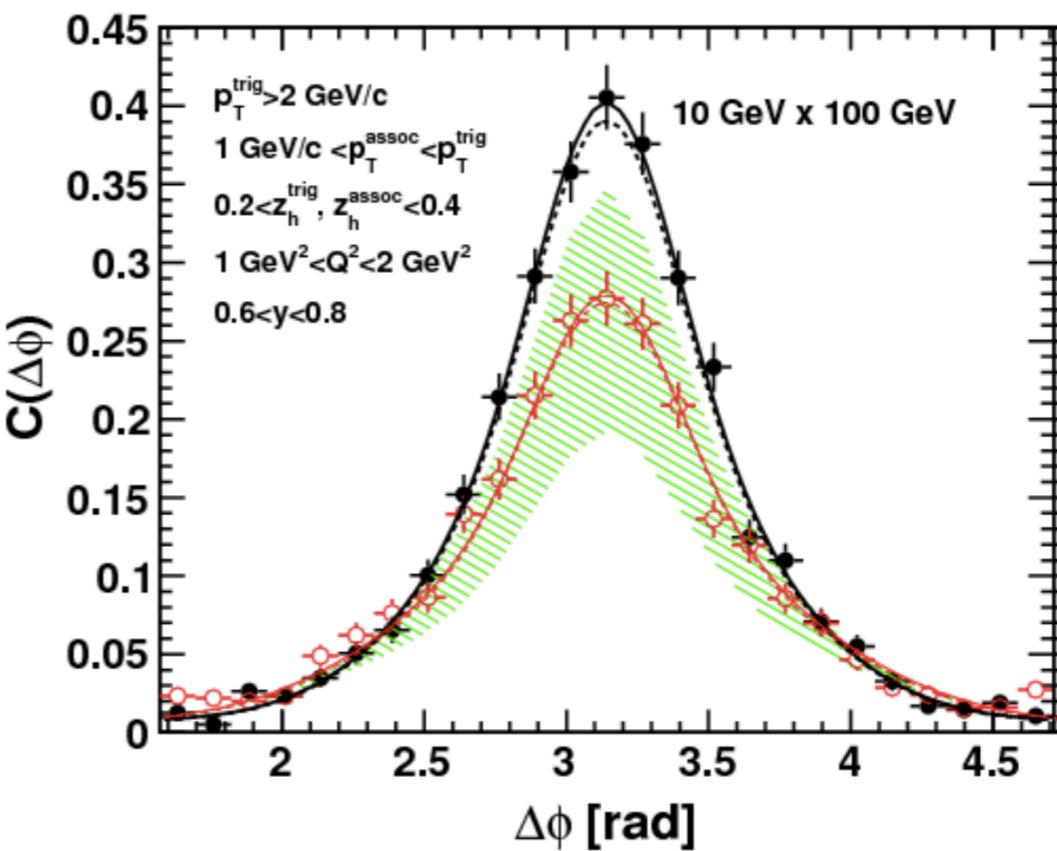


Typical momentum transfer from
hadron/nucleus to

Momentum imbalance $\rightarrow k_{\perp} \sim Q_s$ \leftarrow Saturation scale



Dihadron suppression
back-to-back peak

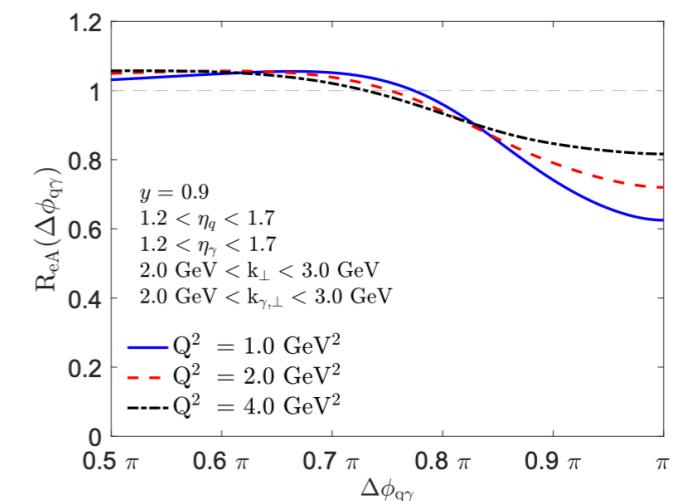
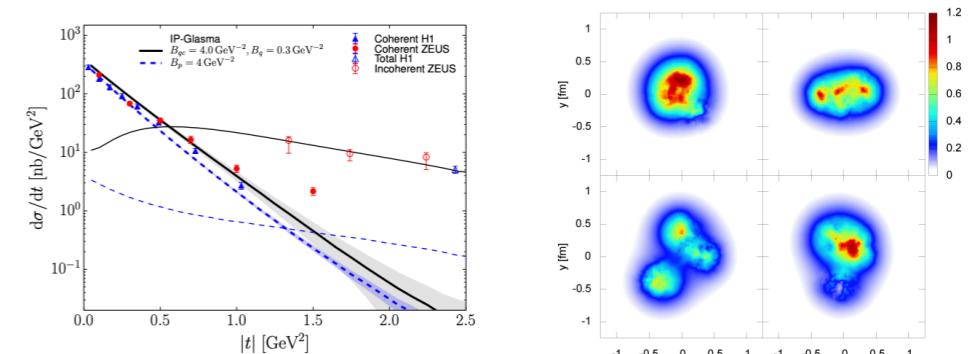
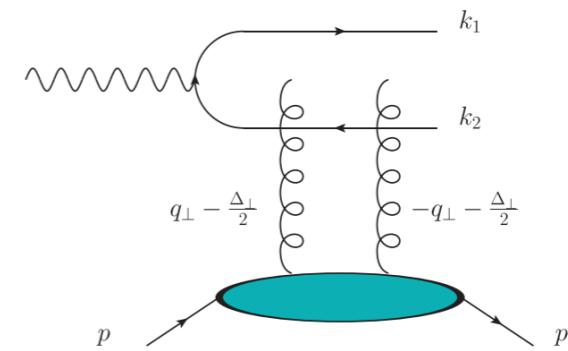


L. Zheng, E. Aschenauer, J.H. Lee, B.W Xiao (2014)

Soft gluon radiation (Sudakov) also leads
to suppression

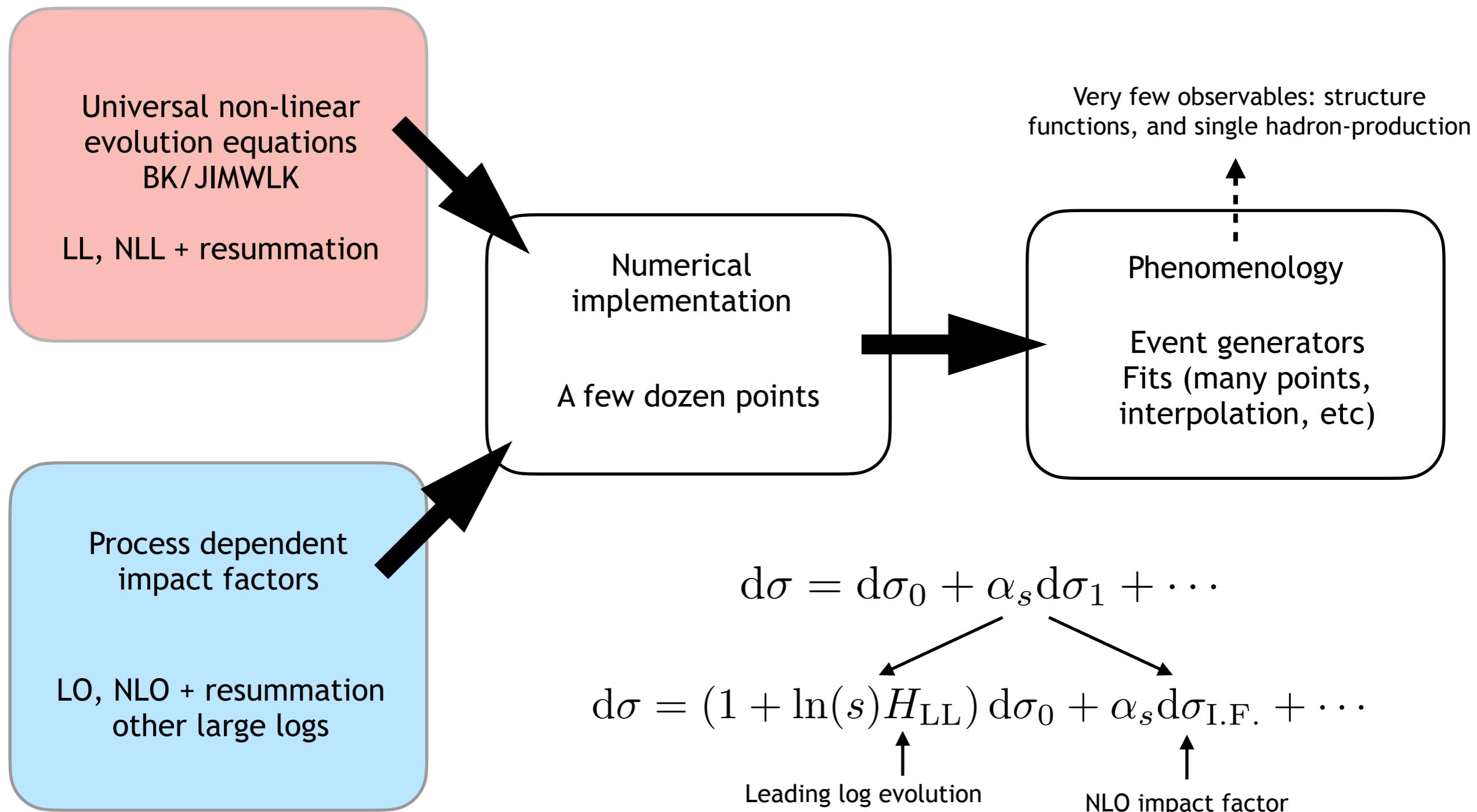
Other promising observables

- Diffractive dijet measurements
 - Y. Hatta, B.W. Xiao, F. Yuan (2016)
 - H. Mäntysaari, N. Mueller, B. Schenke (2019)
 - E. Iancu, A. Mueller, D. Triantafyllopoulos (2021)
- Incoherent diffraction and fluctuations
 - H. Mäntysaari, B. Schenke (2016)
 - H. Mäntysaari, K. Roy, FS, B. Schenke (2021)
- Single hadron/jet production
 - E. Iancu, A. Mueller, D. Triantafyllopoulos, S.Y. Wei (2020)
 - Y. Hatta, B.W. Xiao, F. Yuan (2022)
- Inclusive quarkonia and WW gluon TMD
 - A. Bacchetta, D. Boer, C. Pisano, P. Taels (2018)
 - V. Cheung, Z. Kang, FS, R. Vogt (in progress)
- Hadron+photon correlations
 - I. Kolb  , K. Roy, FS, B. Schenke, R. Venugopalan (2020)



Precision computations with saturation

Pipeline of NLO observables



Precision computations with saturation

Evolution equations at NLL accuracy

The evolution of the BK equation through the years

BK with running coupling

Y. Kovchegov, H. Weigert (2007)
I. Balitsky (2007)

BK at NLL

I. Balitsky, G. Chirilli (2008)

BK at NLL is unstable

T. Lappi, H. Mäntysaari (2015)

BK at NLL with resummation

B. Ducloue, E. Iancu, A. Mueller,
G. Soyez, D. Triantafyllopoulos
(2015)

BK at NLL with resummation is stable

T. Lappi, H. Mäntysaari (2016)

and the JIMWLK equation

JIMWLK running coupling

T. Lappi, H. Mäntysaari
(2013)

JIMWLK at NLL

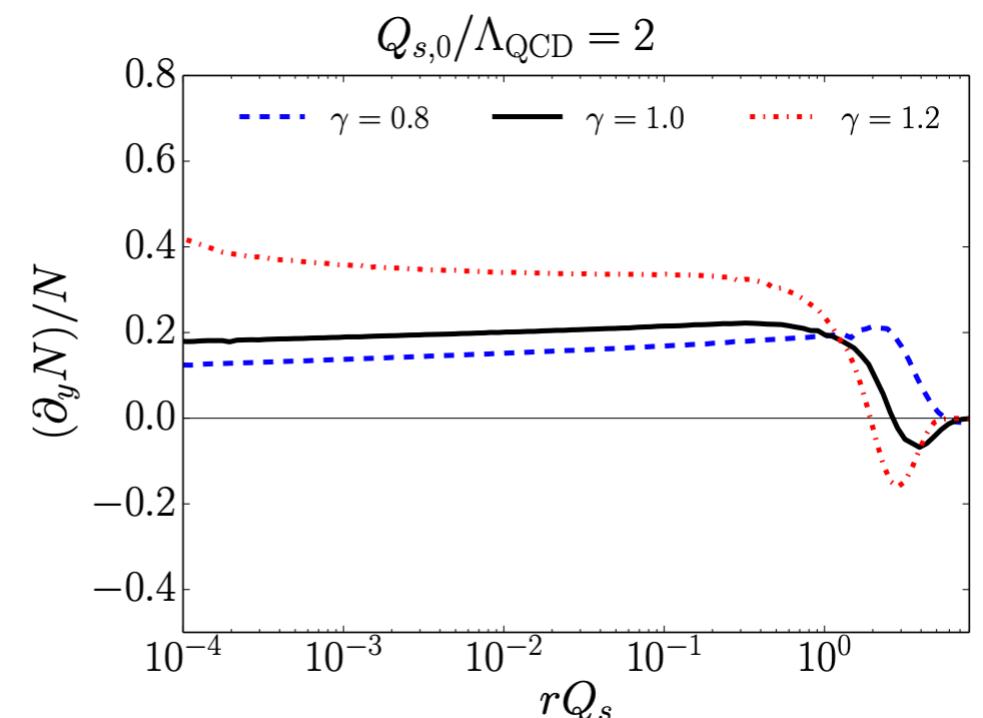
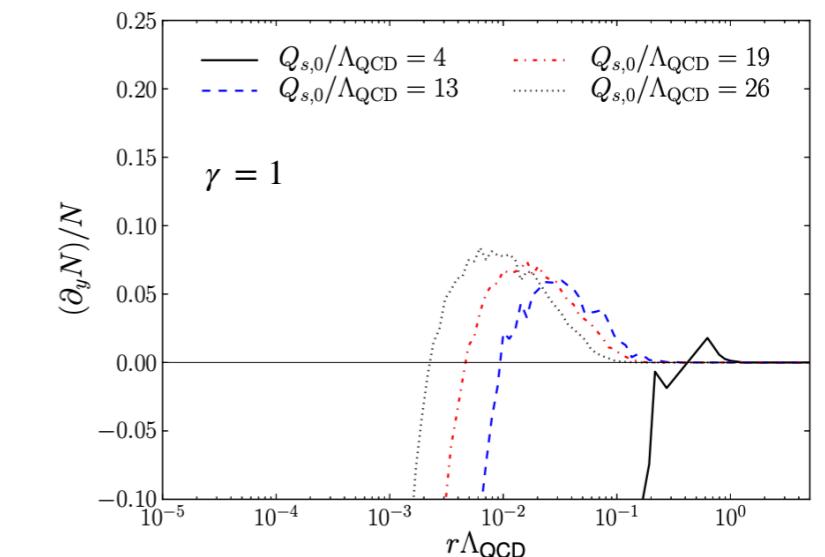
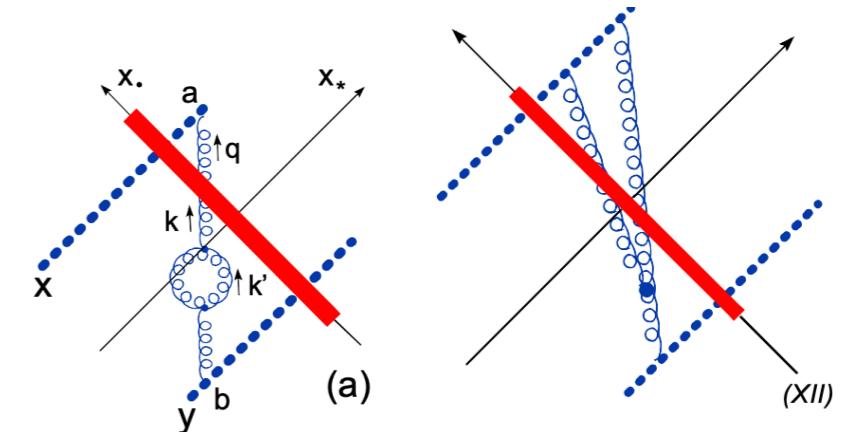
I. Balitsky, G. Chirilli (2013)
A. Kovner, M. Lublinsky, Y. Mulian (2014)

JIMWLK at NLL with resummation

Y. Hatta, E. Iancu (2016)

JIMWLK at NLL with massive quarks

L. Dai, M. Lublinsky (2022)



Precision computations with saturation

Impact factors at NLO

Structure functions

light quarks

I. Balitsky, G. Chirilli (2011)
G. Beuf (2017)
H. Hänninen, T. Lappi, R. Paatelainen (2017)

massive quarks

G. Beuf, T. Lappi, R. Paatelainen (2021)

Diffractive processes in DIS

dijets and light vector meson

R. Boussarie, A. Grabovsky, D. Ivanov,
L. Szymanowski, S. Wallon (2016)

vector meson

H. Mäntysaari, J. Penttala (2021, 2022)

Semi-inclusive processes in DIS

dijets

P. Caucal, FS, R. Venugopalan (2021, 2022)

dijets (photo-production limit)

P. Taels et al (2022)

dihadron

F. Bergabo, J. Jalilian-Marian (2022)

dijet+photon

K. Roy, R. Venugopalan (2019)

Semi-inclusive processes in pA

single hadron

G. Chirilli, B. Xiao, F. Yuan (2012)

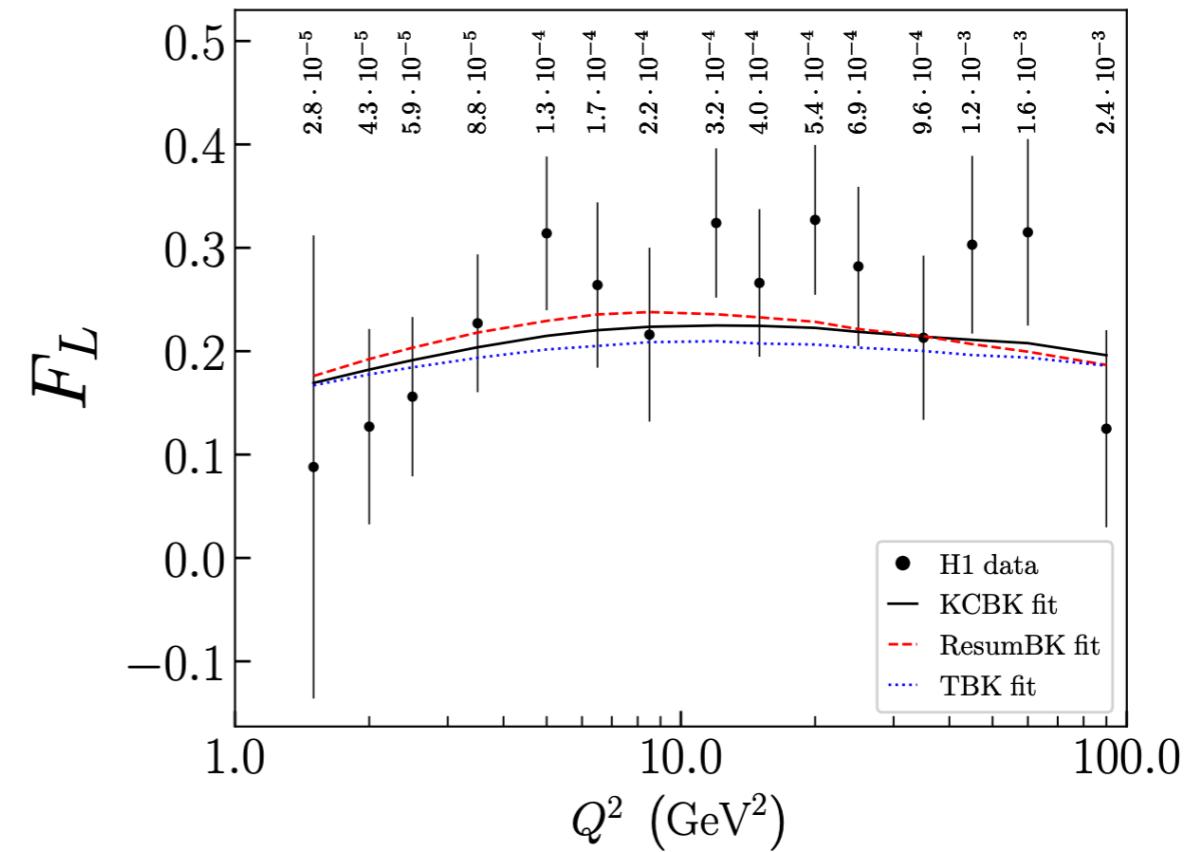
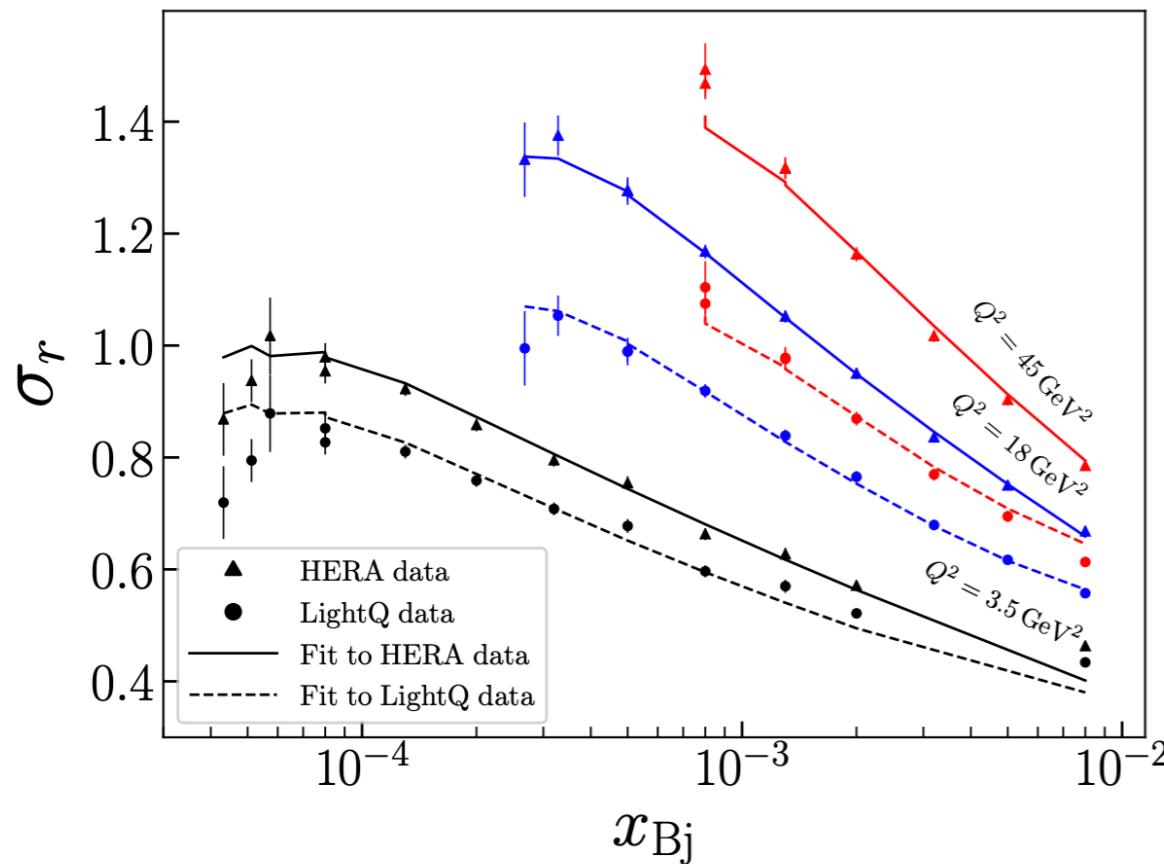
single jet

H.Y. Liu, K. Xie, Z. Kang, X. Liu (2022)

State-of-art phenomenology

Deep inelastic scattering structure functions

G. Beuf, T. Lappi, H. Hänninen, H. Mäntysaari (2020)



Theory curves based on CGC with NLO impact factor and (most of) NLL BK equation

Implementation of different schemes for the resummation of collinear double logs and DGLAP-like single logs

Comparison to HERA data and light-quark pseudo-data

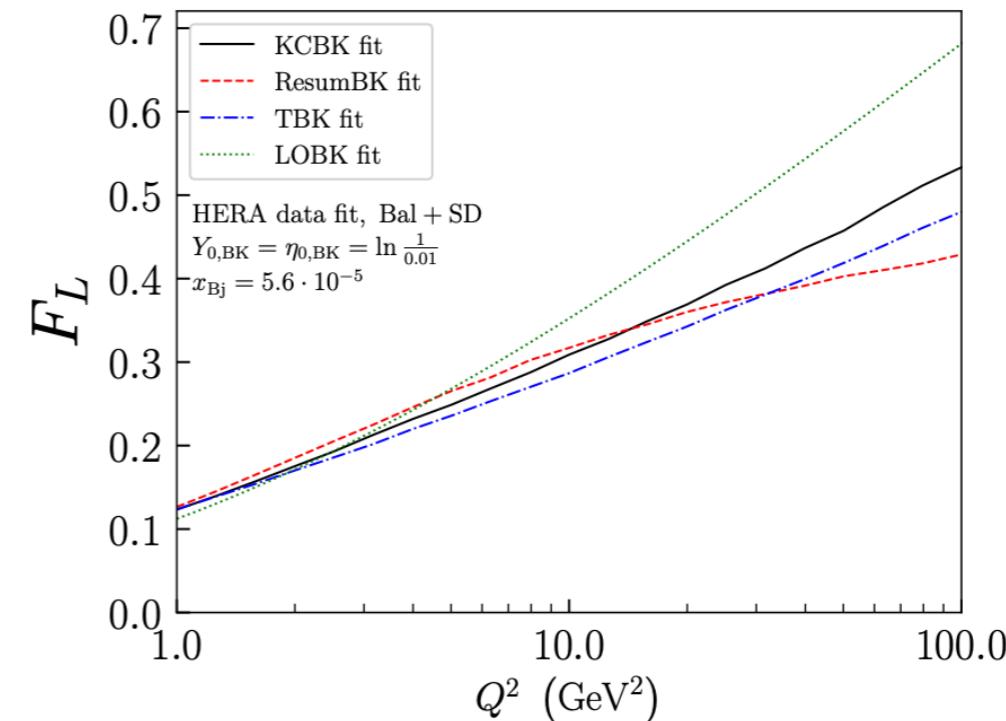
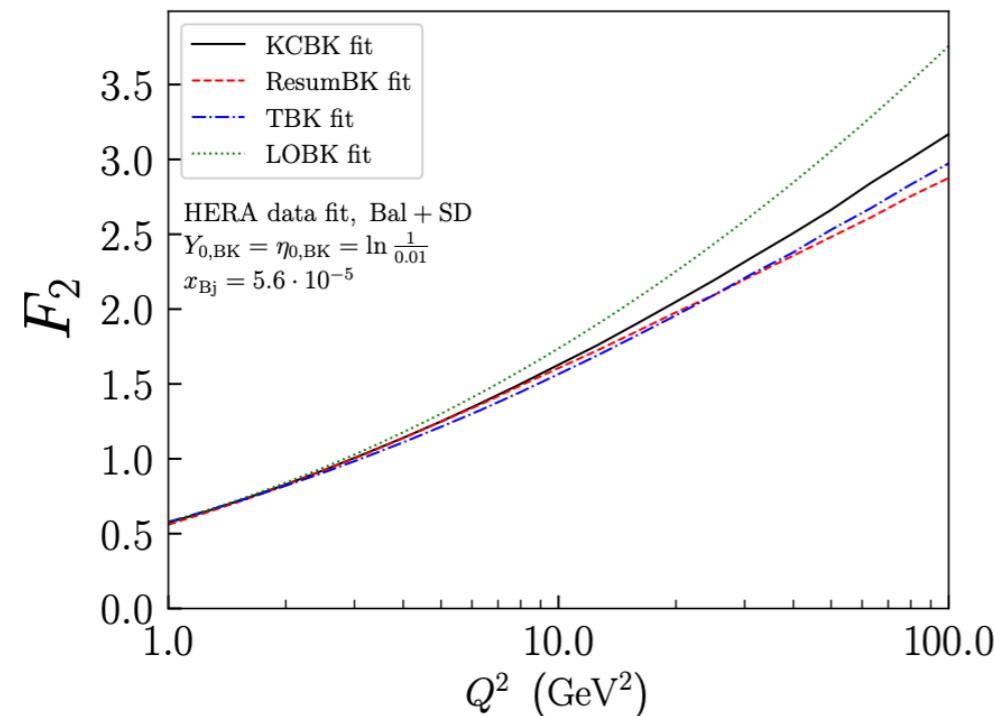
Light quarks are sensitive to large non-perturbative contributions

State-of-art phenomenology

Deep inelastic scattering structure functions

G. Beuf, T. Lappi, H. Hänninen, H. Mäntysaari (2020)

Predictions for F_2 and F_L at the LHeC



Outlook

Study charm structure functions (less non-perturbative contribution)

F_L can be much more precise at the EIC

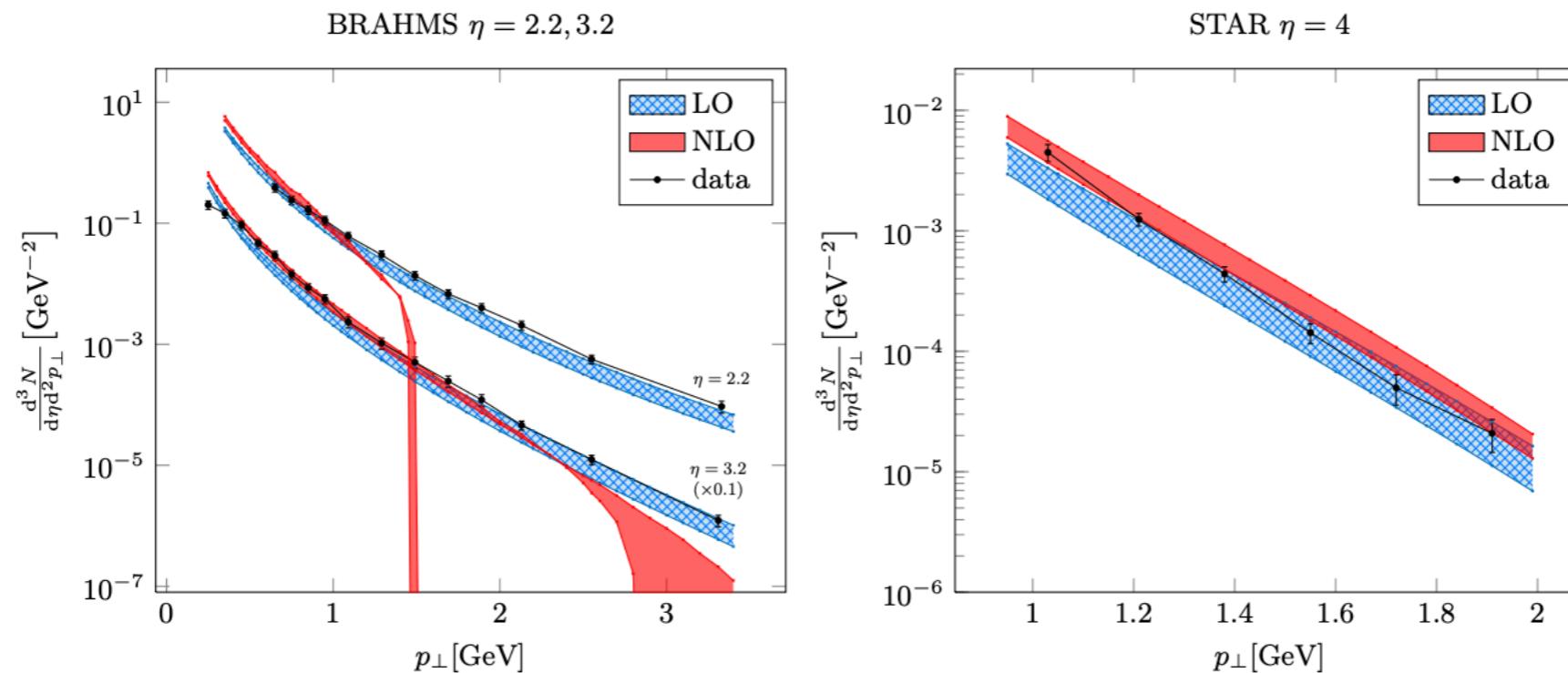
Predictions for nuclear structure functions at the EIC. Tension with DGLAP/BFKL based fits?

Structure functions as part of global analysis to other small- x observables

State-of-art phenomenology

Semi-inclusive single hadron production

A. Stasto, B. Xiao, D. Zaslavsky (2013)



First comparison of saturation framework at NLO to RHIC data showed NLO contribution can be large and negative!

Triggered lots of studies

Matching to collinear and small-x factorization

A. Stasto, B. Xiao, F. Yuan, D. Zaslavsky (2014)

Importance of kinematic constraints

T. Altinoluk, N. Armesto, G. Beuf, A. Kovner, M. Lublinsky (2014)

Rapidity factorization and NLL resummation

K. Watanabe, B. Xiao, F. Yuan, D. Zaslavsky (2015)

Rapidity factorization and threshold resummation

B. Ducloue, E. Iancu, T. Lappi ,A. Mueller, G. Soyez, D. Triantafyllopoulos, Y. Zhu (2018)

H. Liu, X. Liu, Z. Kang (2020)

Y. Shi, L. Wang, S. Wei, B. Xiao (2021)

State-of-art phenomenology

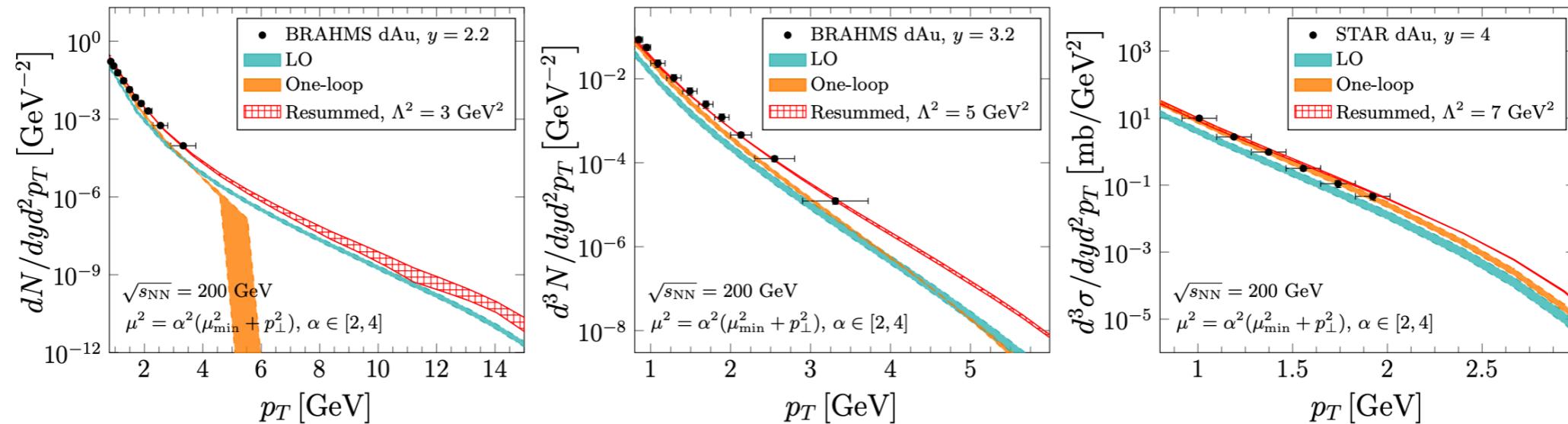
Semi-inclusive single hadron production

Most recent results:

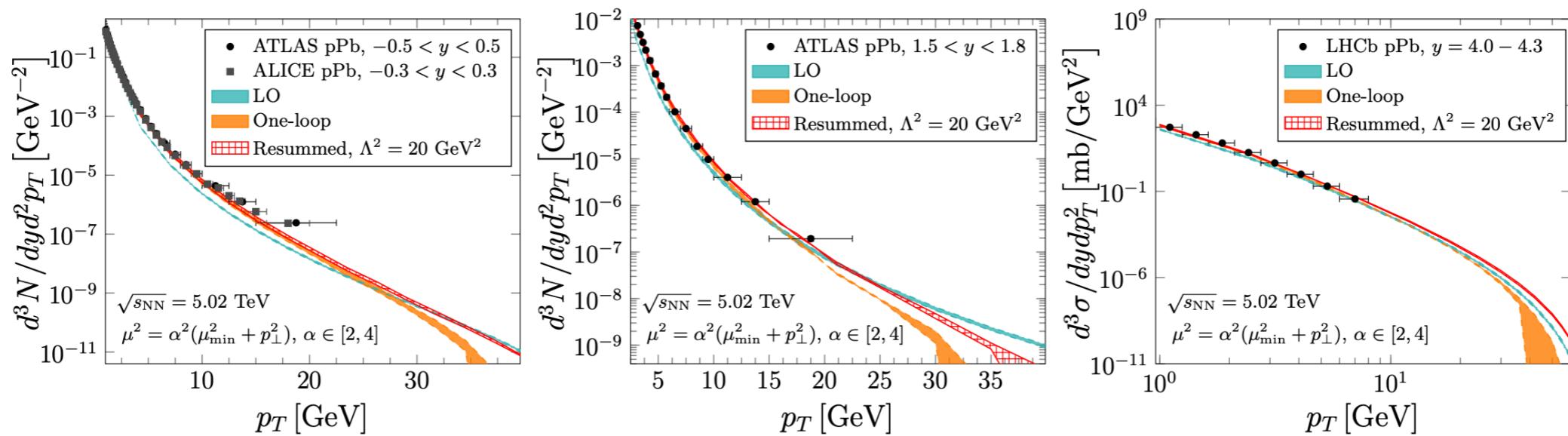
Theory curves based on CGC with NLO impact factor + rcBK evolution + threshold resummation

Comparison to RHIC data

Y. Shi, L. Wang, S. Wei, B. Xiao (2021)



Comparison to LHC data



See also H. Liu, X. Liu, Z. Kang (2020)

Summary

- Discovery of gluon saturation is one of the major goals of the future EIC.
- The Color Glass Condensate is an EFT for this gluon saturated regime of QCD.
- A wide variety of observables are available to search for gluon saturation: structure functions, diffractive processes, and semi-inclusive measurements.
- Promote saturation/CGC to a precision science
- Global analysis of CGC observables (e.g. ep, pA, UPCs,...)

Ongoing projects with undergrads at UCLA

- Global analysis of DIS and pp/pA data

with Amanda Wei and ZK (Miranda Li recently joined)*



- Isolated photon+hadron(jet) production

with Sky Shi and ZK*



- Leveraging the LHAPDF framework for efficient small-x computations

*with Jeisson Pulido** (Cal Bridge), ZK, and John Terry*



- Diffractive J/ ψ + photon production in DIS

*with Philip Velie** (U. Virginia) and ZK*



*graduated recently

**visiting students