Precision small-x physics at the Electron-Ion Collider

Correlations in Hadronic and Partonic Interactions
March 8th, 2022

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Outline

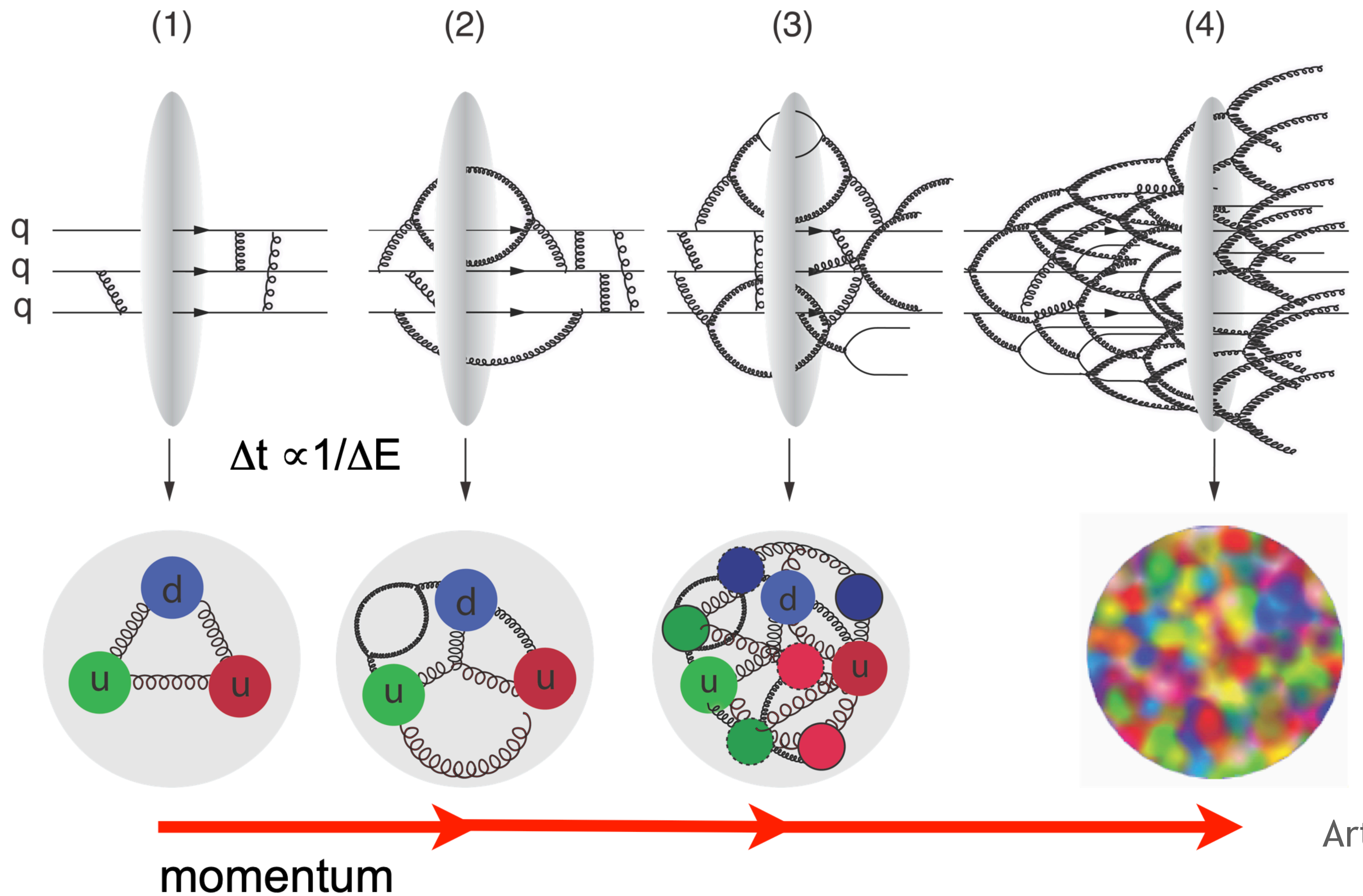
- Review: Gluon saturation at small x

- Precision computations with saturation

- State-of-art phenomenology

Gluon saturation at small x

Anatomy of nuclear matter in the high energy limit



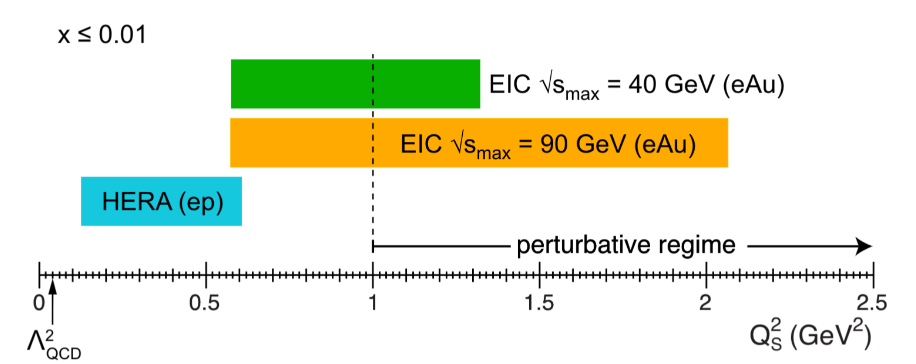
Artwork: T. Ullrich

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)

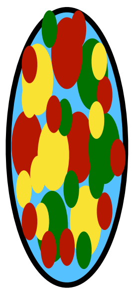
Non-linear evolution equations (BK/JIMWLK)



Review of gluon sat. A. Morreale, FS (2021)

Gluon saturation at small x

Color Glass Condensate: sources, fields, multiple scattering

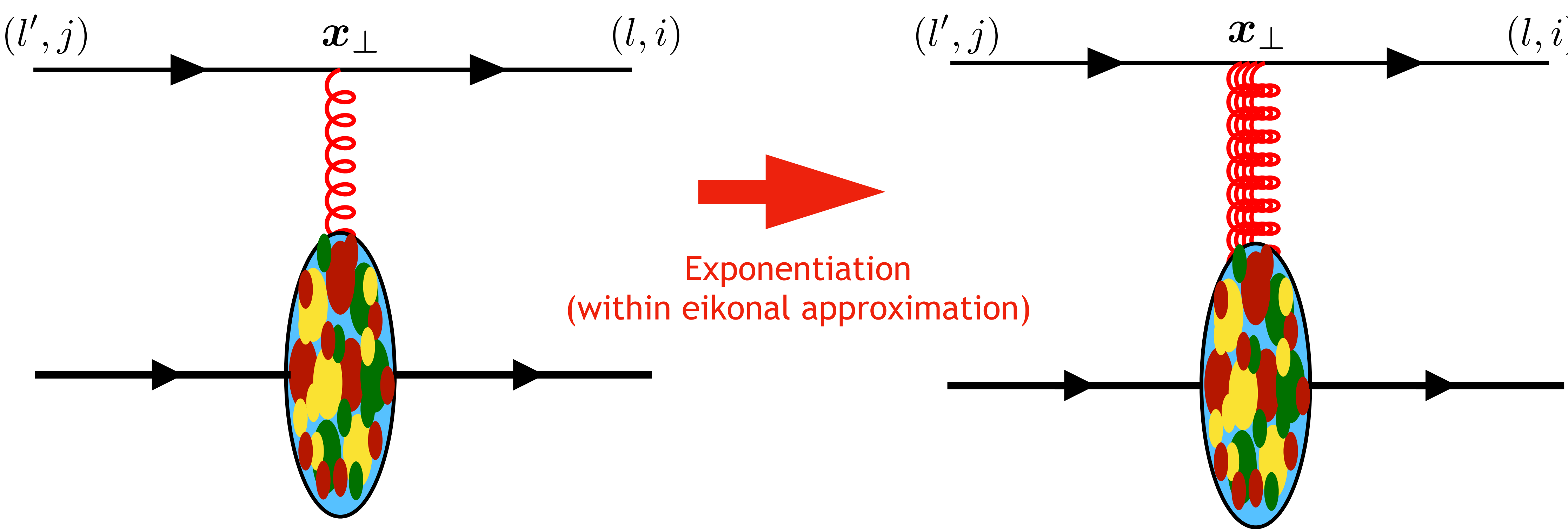


Large-x partons are effectively treated as a collection of recoilless localized and static random color sources

L. McLerran, R. Venugopalan (1993)

Source the back-ground field

$$A^{+}_{\rm cl}(\boldsymbol{x}_\perp, x^-) \sim 1/g$$



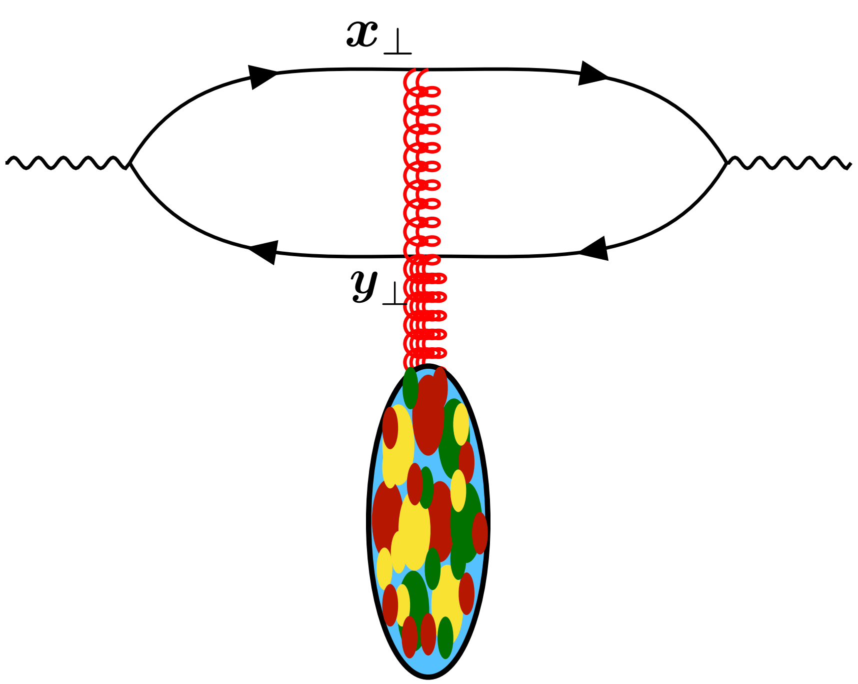
Ayala, Jalilian-Marian,
McLerran, Venugopalan (1995)
Balistky (1996)

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

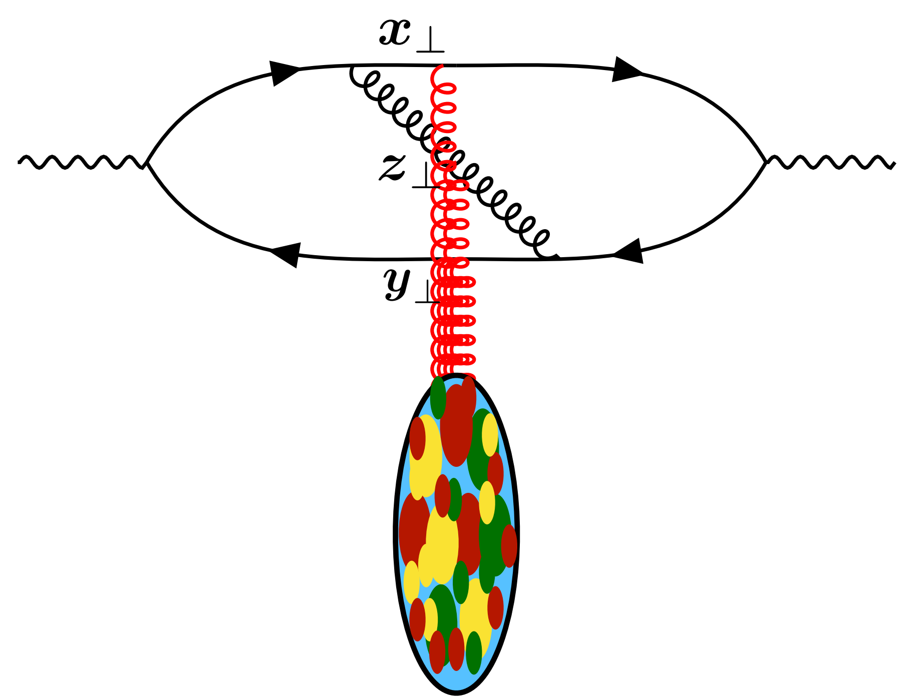
Light-like Wilson line $\quad V_{ij}(\boldsymbol{x}) = P \exp\left\{ ig \int dx^- A^{+,a}_{cl}(\boldsymbol{x}, x^-) t^a \right\}$

Gluon saturation at small x

Color Glass Condensate: non-linear evolution



$$\mathrm{Tr}\left[V(\boldsymbol{x}_\perp)V^\dagger(\boldsymbol{y}_\perp)\right]$$



$$\mathrm{Tr}\left[V(\boldsymbol{x}_\perp)t^a V^\dagger(\boldsymbol{y}_\perp)t^b\right]U_{ab}(\boldsymbol{z}_\perp)$$

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

Gluon emissions lead to evolution: BK and JIMWLK

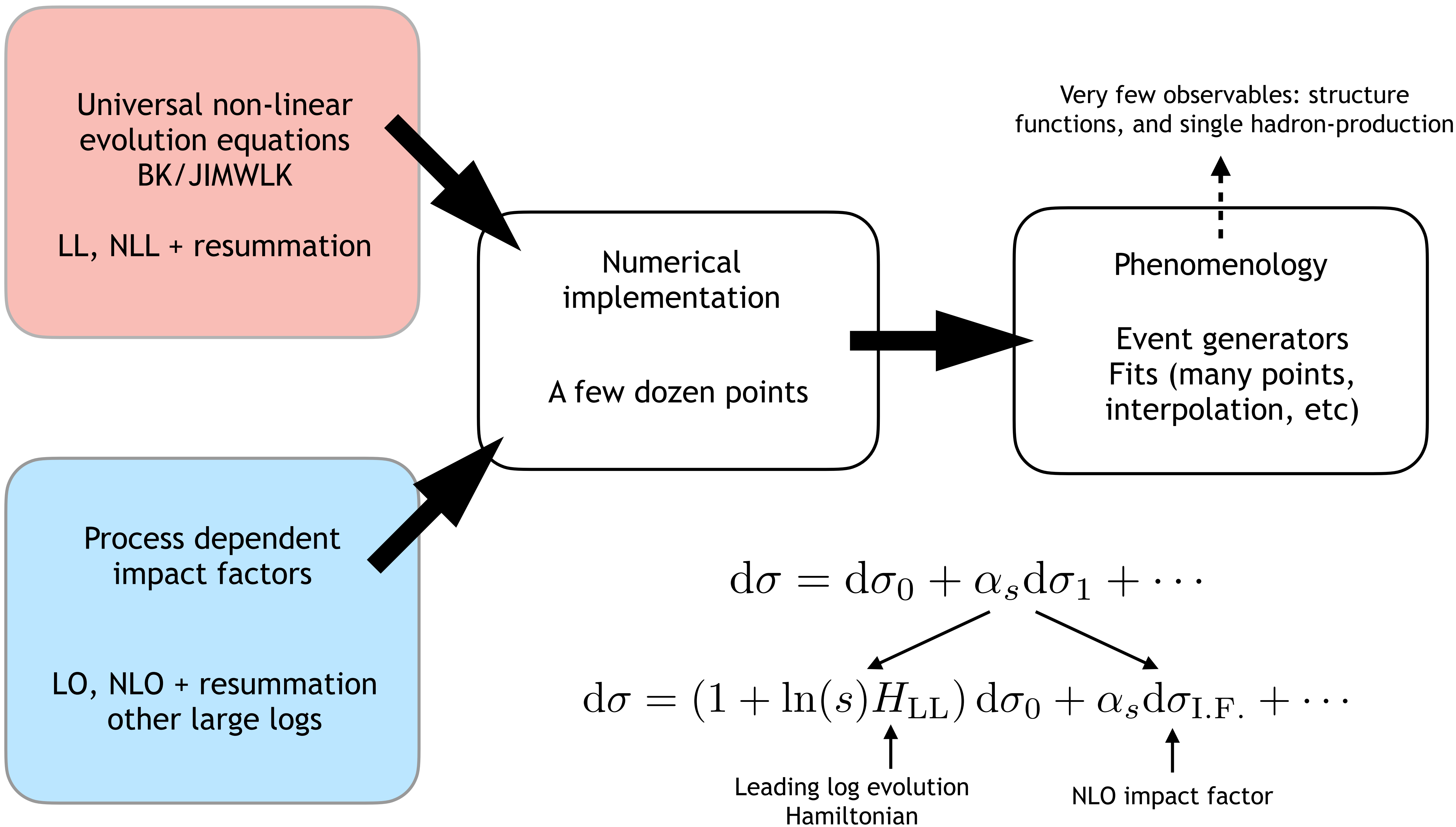
I. Balistky (1995), Y. Kovchegov (1999)
J. Jalilian-Marian, E. Iancu, L. McLerran,
H. Weigert, A. Leonidov, A. Kovner (1996-2002)

BK equation:

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

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

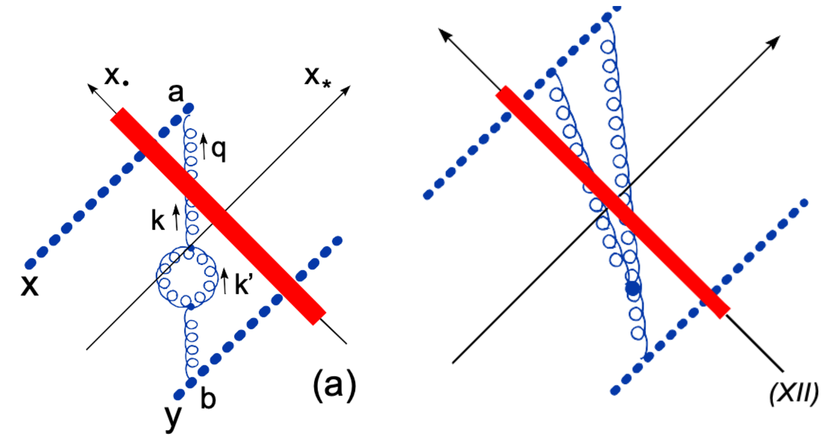
BK with running coupling	Y. Kovchegov, H. Weigert (2007) I. Balistky (2007)
BK at NLL	I. Balistky, G. Chirilli (2008)
BK at NLL is unstable	T. Lappi, H. Mäntysaari (2015)
BK at NLL with resummation	B. Ducloue, E. Iancu, A. Mueller, G. Soyez, D. Triantafyllopoulos (2015)
BK at NLL with resummation is stable	T. Lappi, H. Mäntysaari (2016)

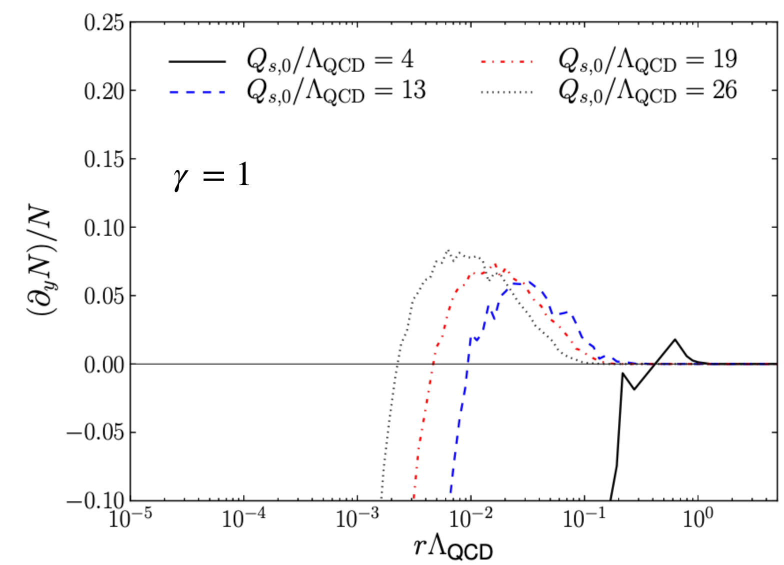
and the JIMWLK equation

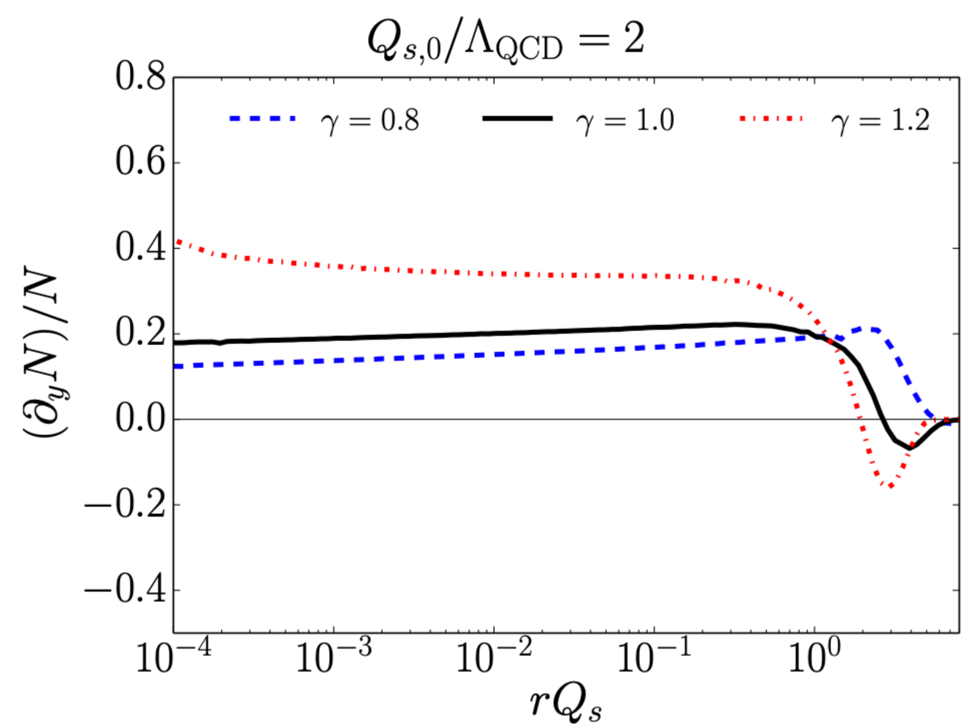
JIMWLK running coupling	T. Lappi, H. Mäntysaari (2013)
JIMWLK at NLL	I. Balistky, G. Chirilli (2013) A. Kovner, M. Lublinky, Y. Mulian (2014)
JIMWLK at NLL with resummation	Y. Hatta, E. Iancu (2016)

Numerical results for JIMWLK at NLL still missing!

Instead use Gaussian approximation for evolution of higher-point correlators?







Precision computations with saturation

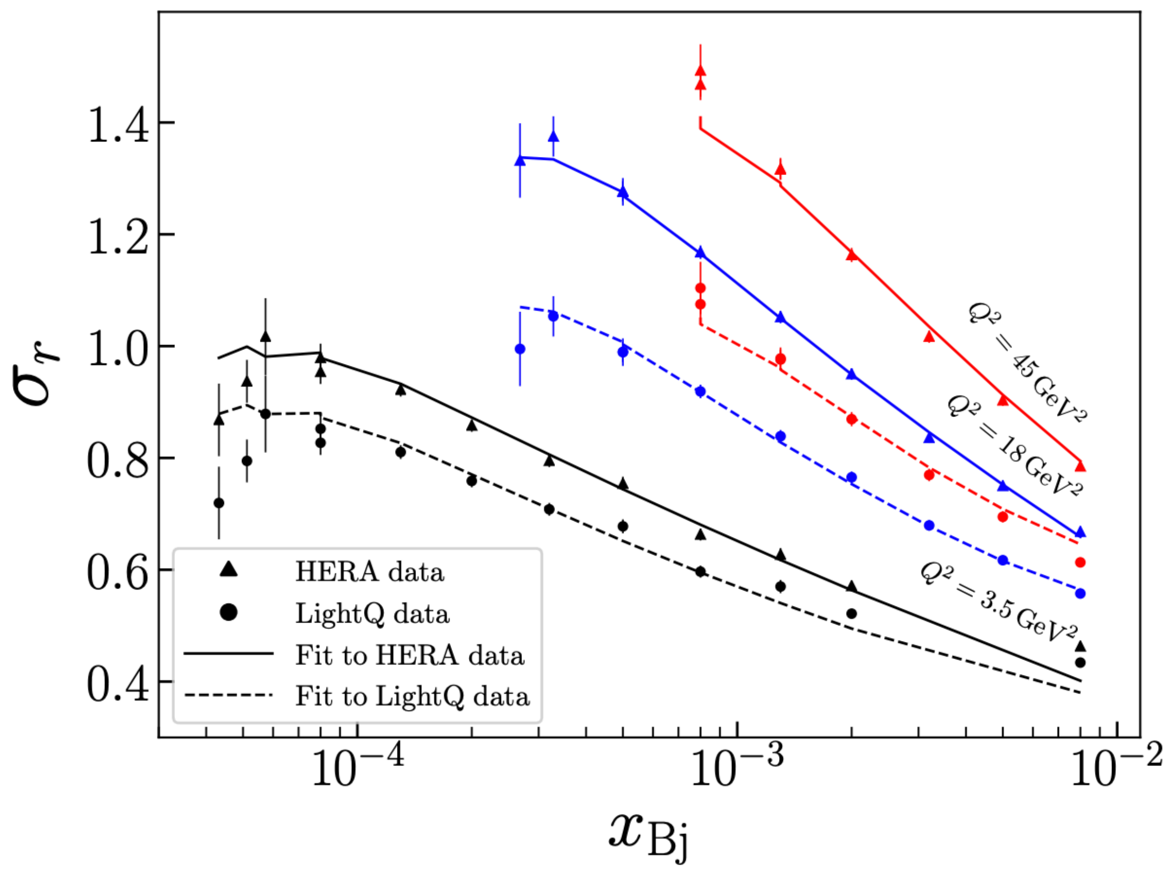
Impact factors at NLO

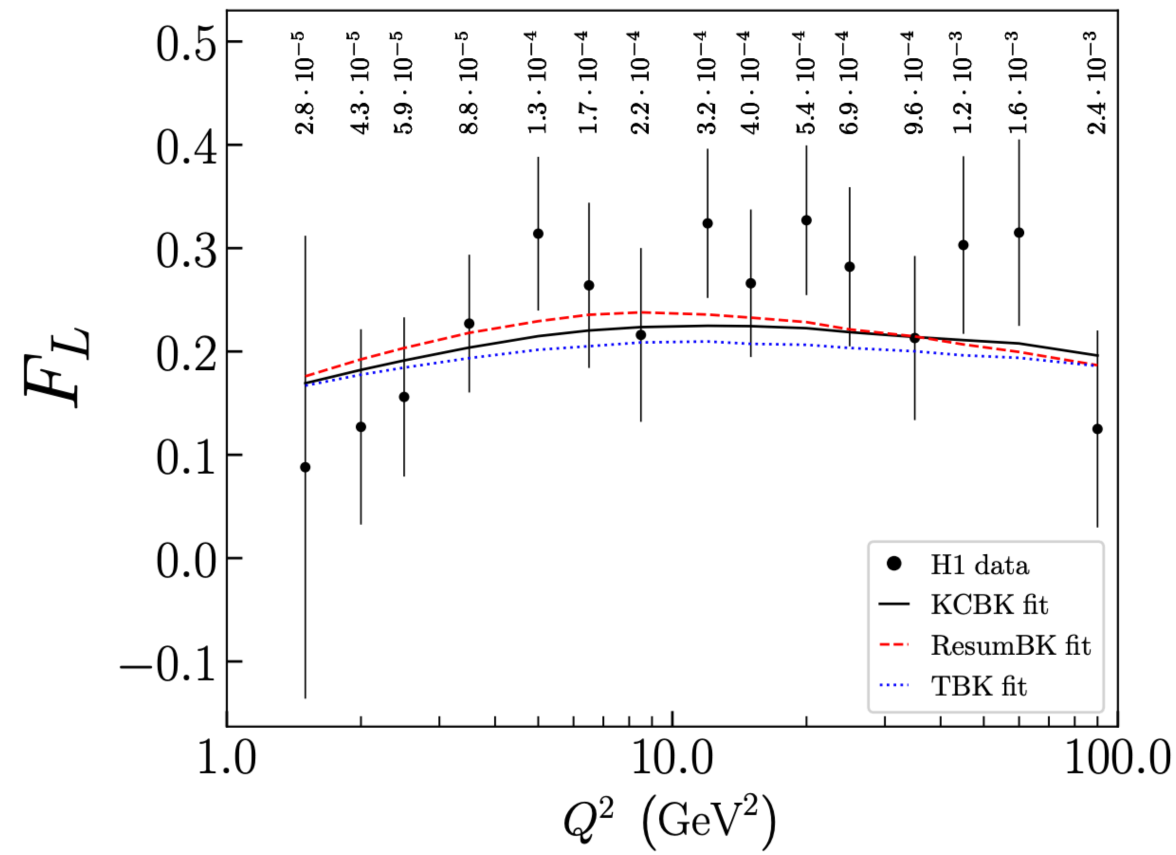
Structure functions	
light quarks	I. Balitsky, G. Chirilli (2011) G. Beuf (2017) H. Hänninen, T. Lappi, R. Paatelainen (2017)
massive quarks	G. Beuf, T. Lappi, R. Paatelainen (2021)
Diffractive processes in DIS	
dijets and light vector meson	R. Boussarie. A. Grabovsky, D. Ivanov, L. Szymanowski, S. Wallon (2016)
heavy vector meson	H. Mäntysaari, J. Penttala (2021)
Semi-inclusive processes	
Single hadron in pA	G. Chirilli, B. Xiao, F. Yuan (2012)
Dijet in DIS	P. Caucal, FS, R. Venugopalan (2021)
Dijet+photon in DIS	K. Roy, R. Venugopalan (2019)
Dijet+photon in pA (real emission)	E. Iancu, Y. Mulian (2021)

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

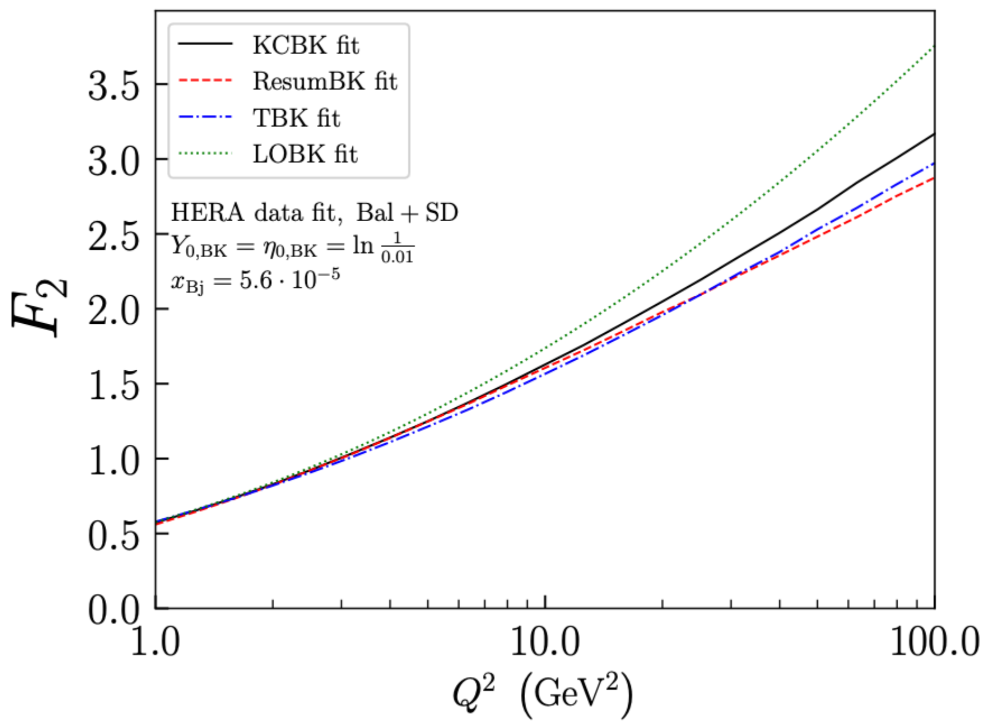
Light quarks are sensitive to large non-perturbative contributions

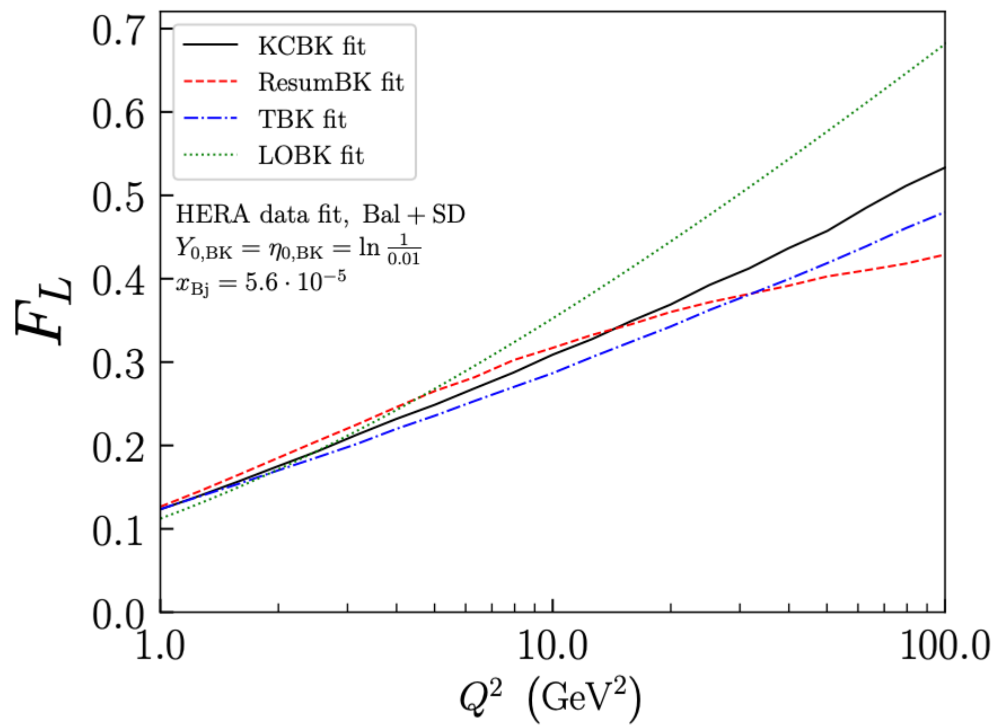
State-of-art phenomenology

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

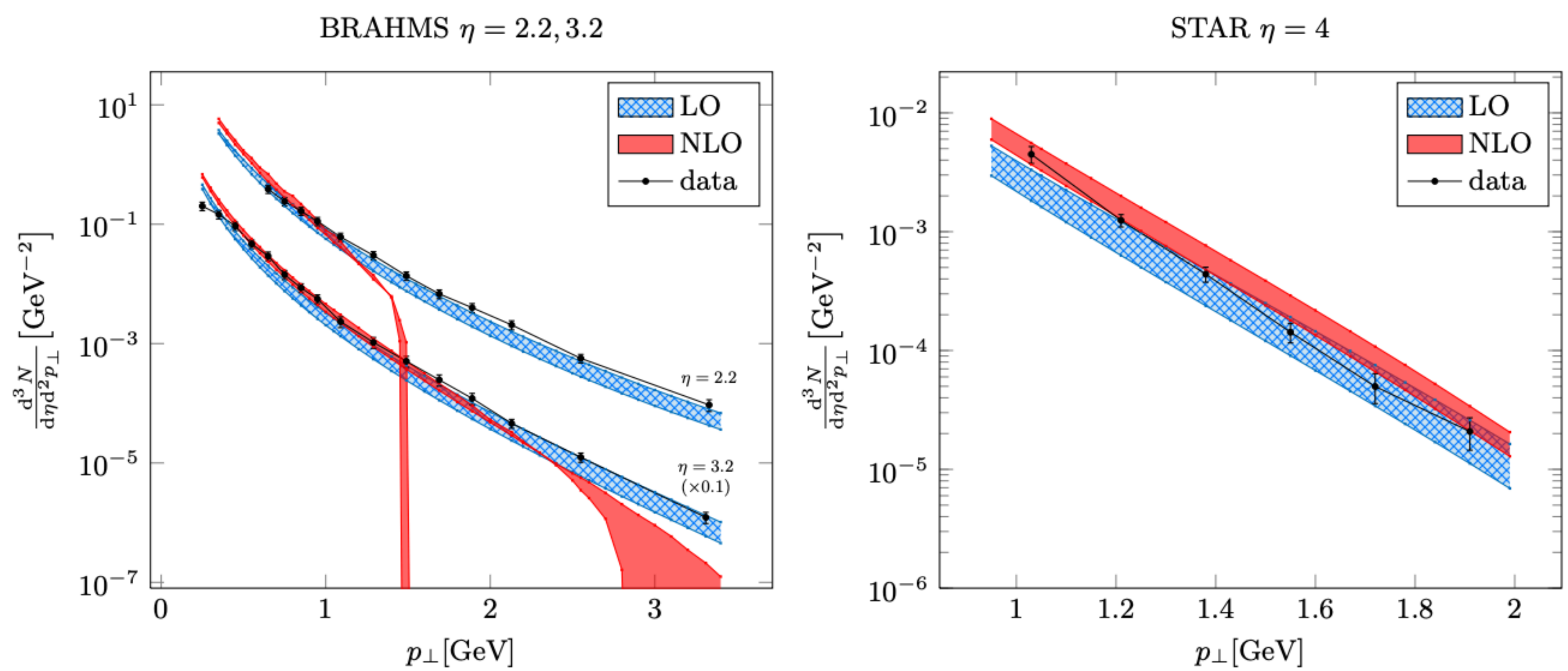
Predictions for nuclear structure functions at the EIC. Tension with DGLAP/BFKL based fits?

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

Rapidity factorization and NLL resummation — B. Ducloue, E. Iancu, A. Mueller, G. Soyez, D. Triantafyllopoulos, Y. Zhu (2018)

Rapidity factorization and threshold resummation — H. Liu, X. Liu, Z. Kang (2020); Y. Shi, L. Wang, S. Wei, B. Xiao (2021)

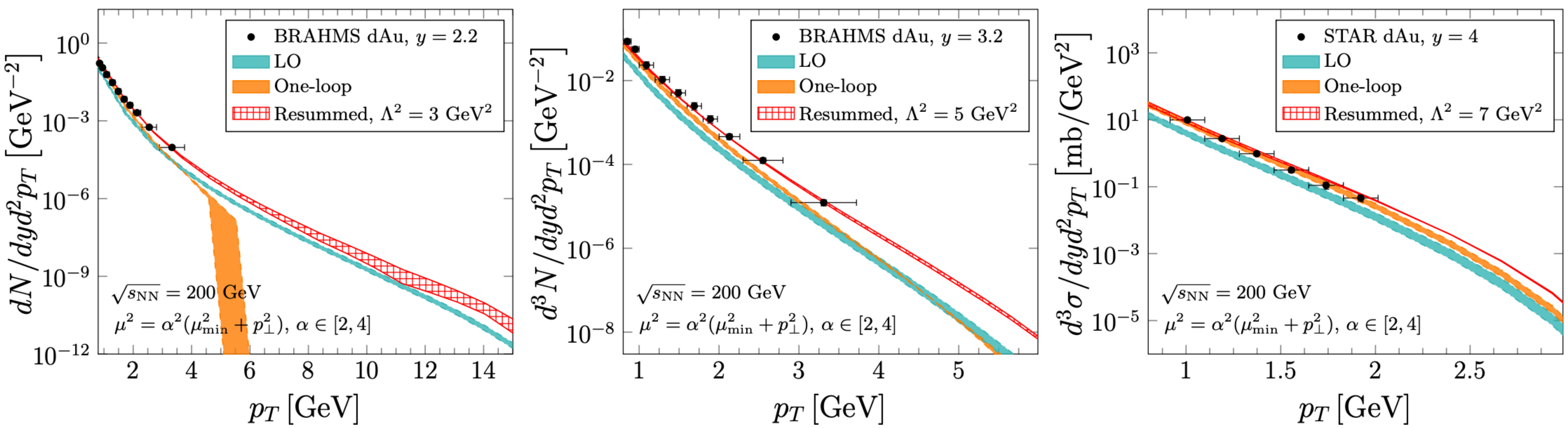
State-of-art phenomenology

Semi-inclusive single hadron production

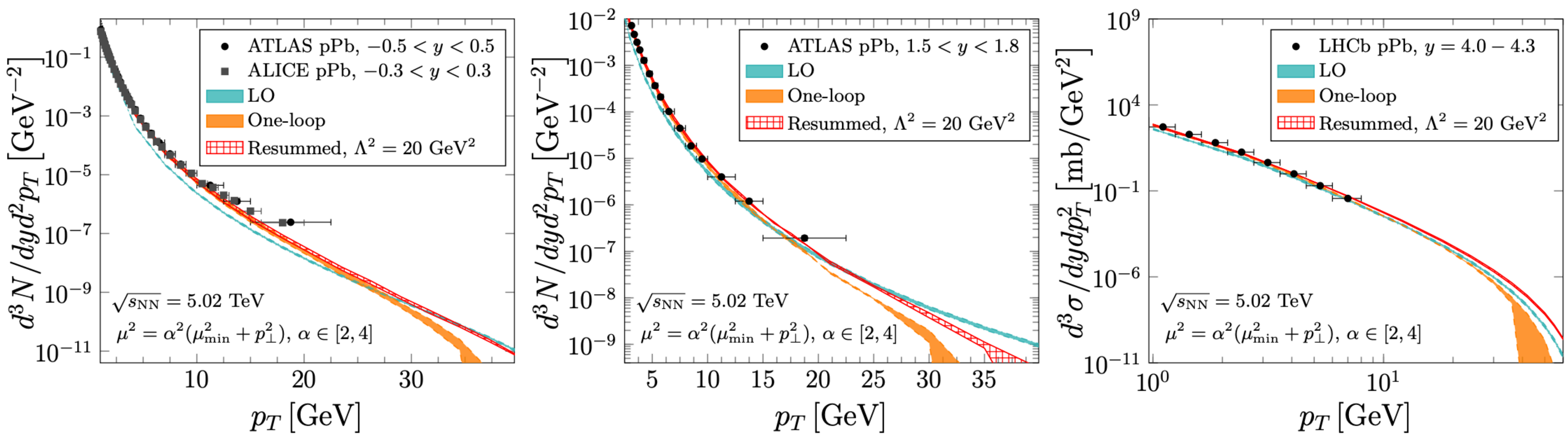
Most recent results:
Theory curves based on CGC with NLO impact factor + rcBK evolution + threshold resummation

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)

How to efficiently do higher-order loop computations?

Two-ideas:

- SCET + CGC

  Kinematic constraints can be reproduced by soft mode

  Efficient resummation of threshold logarithms in single hadron production

  X. Liu, Z. Kang (2019) H. Liu, X. Liu, Z. Kang (2020)

Apply to other processes (e.g. dijets in DIS and pA)

- Timelike-spacelike correspondence

  Perfect map between BMS equation (soft-wide angle radiation) and BK equation (high-energy evolution of dipole)

  H. Weigert (2004) Y. Hatta (2008) A. Mueller (2018)

  Used to evaluate NNLL BFKL and NNLL BK equation in $\mathcal{N} = 4$ SYM

  S. Caron-Huot (2015) S. Caron-Huot, M. Herranen (2016)

QCD non-linear evolution equations at NNLL? Impact factors at NNLO?

Summary

- Saturation physics is gearing up for the precision era
- Resummation plays a critical role to attain predictive power
- Structure functions in DIS and single hadron production at NLO compare well to data
- Many more observables to come in the next couple of years (e.g. charm structure functions, vector meson/DVCS in DIS, dihadrons/dijets in DIS and pA)
- Exciting possibilities by employing SCET techniques and correspondence with jet-physics could boost the field towards higher-order loop computations