Topical Theory Collaboration for small x at the EIC

Define central goal: Identification and characterization of saturation

A Topical Theory Collaboration could be built around the goal of providing best possible calculations of a few "golden" observables sensitive to saturation

What does it take to do an end-to-end computation of such observables?

a) inclusive
b) diffractive/exclusive
c) spin-dependent observables

Including:

- initial conditions
- QCD evolution/resummation
- hadronization/fragmentation (in protons and nuclei)
- precision: NLO

Identify new observables

Topical Theory Collaboration for small x at the EIC

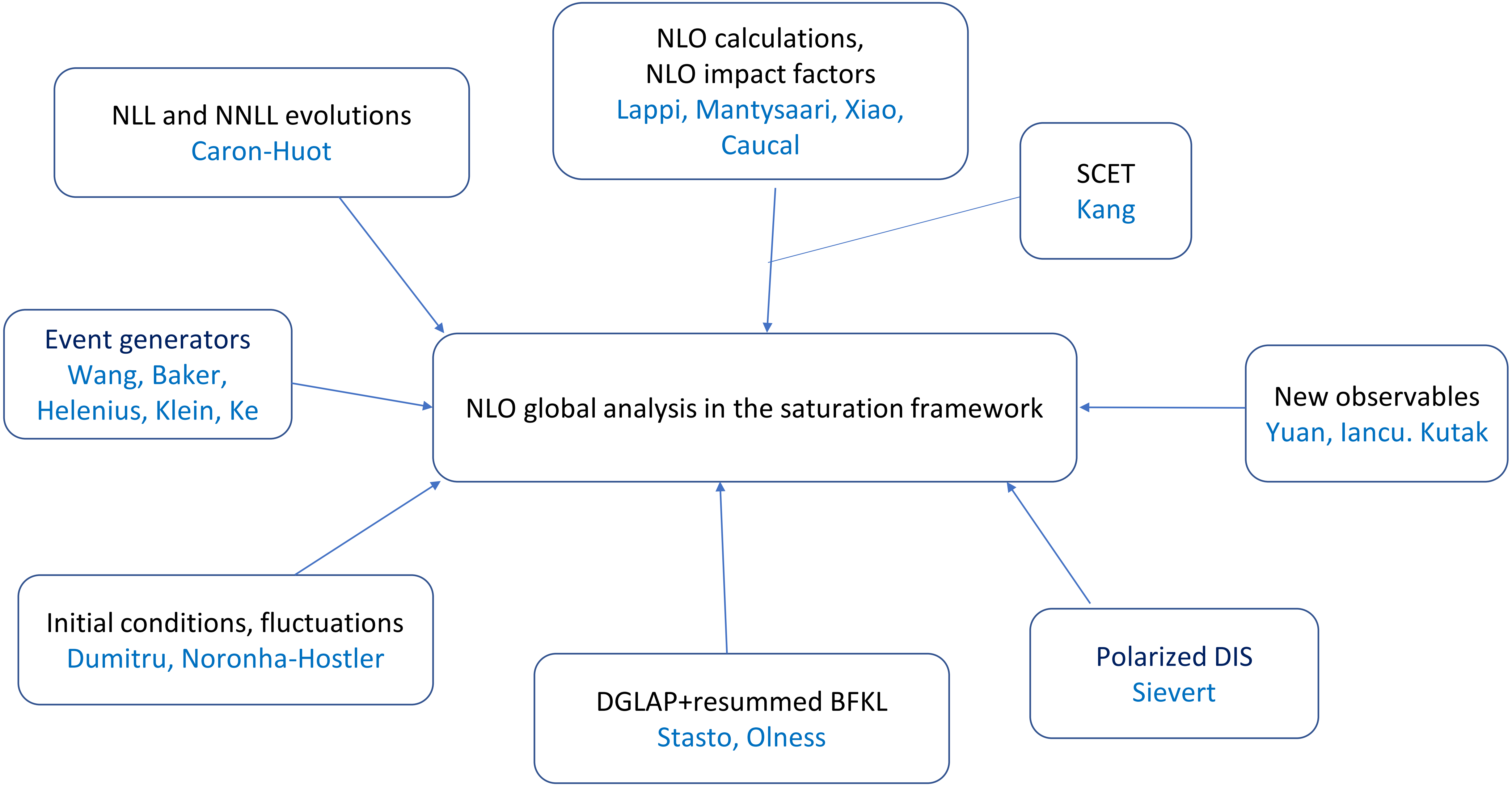
The collaboration should have different working groups, with focus on the various aspects of the problem: How to structure?

- Initial conditions
- QCD evolution/resummation
- hadronization/fragmentation (in protons and nuclei)
- numerical implementation / MC

- spin
- diffraction
- inclusive

First four can feed into calculation of all/most observables

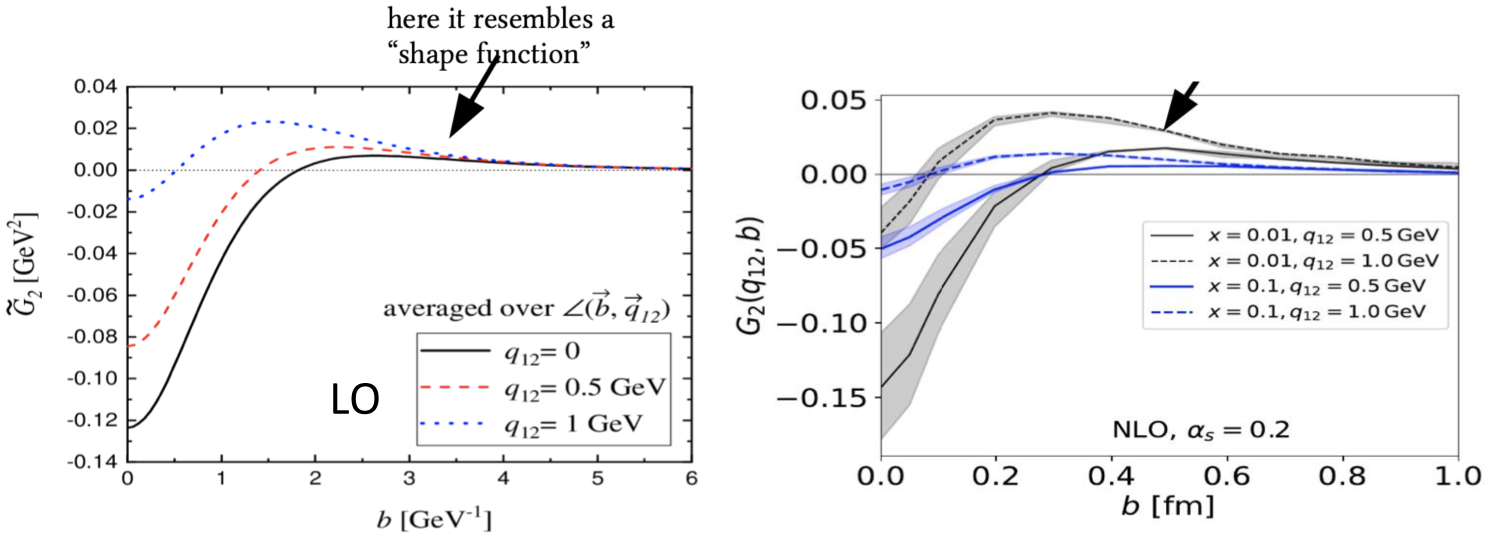
Other aspects to play a role: Entanglement, AI, connections to HICs


NLO calculations,
NLO impact factors
Lappi, Mantysaari, Xiao,
Caucal
NLL and NNLL evolutions
Caron-Huot
SCET
Kang
Event generators
Wang, Baker,
Helenius, Klein, Ke
NLO global analysis in the saturation framework
New observables
Yuan, Iancu. Kutak
Initial conditions, fluctuations
Dumitru, Noronha-Hostler
DGLAP+resummed BFKL
Stasto, Olness
Polarized DIS
Sievert

Initial conditions for small-x evolution

Dumitru: Use light cone perturbation theory (LCPT) to compute correlator of color charges (as opposed to e.g. MV)

Two- (and three-) body correlations in the proton LCwf at x ~ 0.1 – 0.01;
b-dependence, q_T dependence, angular dependence (!)



How to use this as initial state for JIMWLK; How to sample? Does it make sense for JIMWLK (dilute vs. dense)?

Mehtar-Tani: bridging low-x with high Q^2. factorization in xB/Q^2
(Evolution in p+ vs. frequency, not quite Born-Oppenheimer approximation, origin of large NLO corrections to BFKL, BK)
This introduces x dependence to gluon distribution; To do: small x evolution on top of that

Event generators for the EIC

Talks about:

eHIJING:

- Parton propagation inside nuclei in DIS (also possible hadronization in medium, hadron interaction with nucleus)
- Choose a model for the TMD, including saturation
- Generalized high twist approach: Induced gluon emission, LPM effect is important, String hadronization

BeAGLE:

- Hard interaction (DIS or diffractive, one or more nucleons); Intra-Nuclear Cascade; Excited nuclear remnant decay
- Forward (nuclear remnant) tagging is important for small x physics (remove e+skin collisions)
- BeAGLE needs more theory input: e.g. on dipole cross sections and nucleonic remnant
- Can use BeAGLE as afterburner

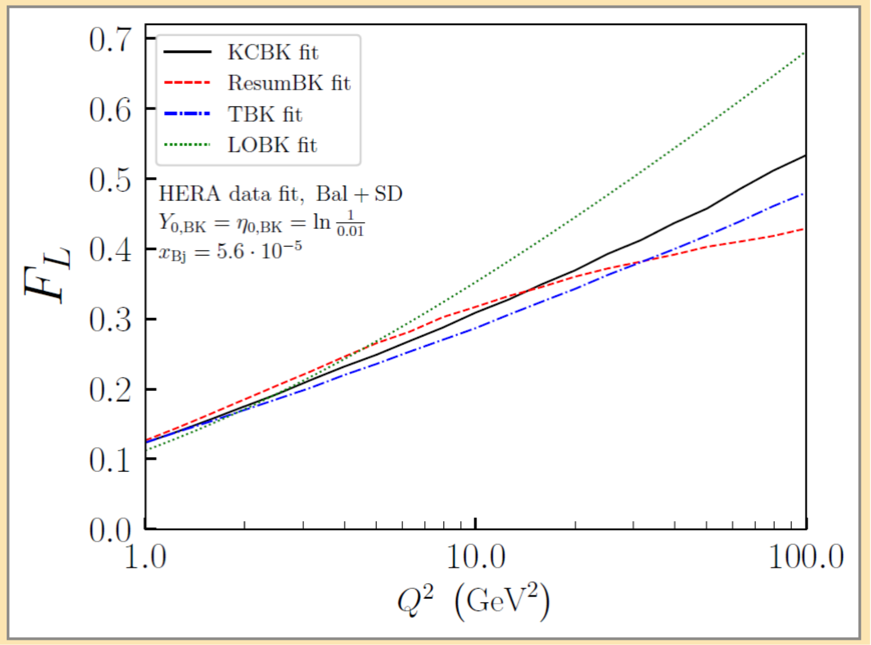
PYTHIA 8:

- Different beams, hard scattering, parton showers (FSR, ISR from hadron), (MPIs), string hadronization
- New showers for DIS: dipoleRecoil; DIRE: soft-gluon interference at lowest order, NLO corrections to collinear splittings
- Comparisons to HERA data and UPCs help to constrain model
- Solid theory for Q^2=0 and large Q^2, what about in between?

Also Sartre, Angantyr in the future with e+A?, DIPSY-like MC for e+A?
Role of a Topical Theory Collaboration in MC development?
Provide theory input? Develop components for specific processes? Including non-linear QCD effects in existing MCs?

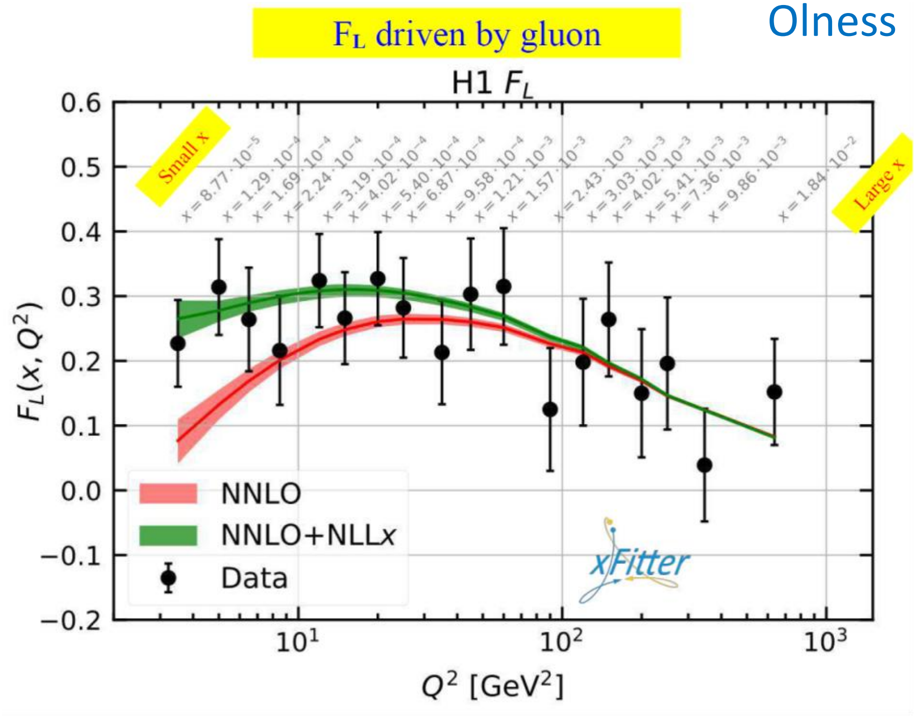
What are the unambiguous signatures of saturation?

Lappi



Different versions of resummed NLO BK give similar results…

Olness



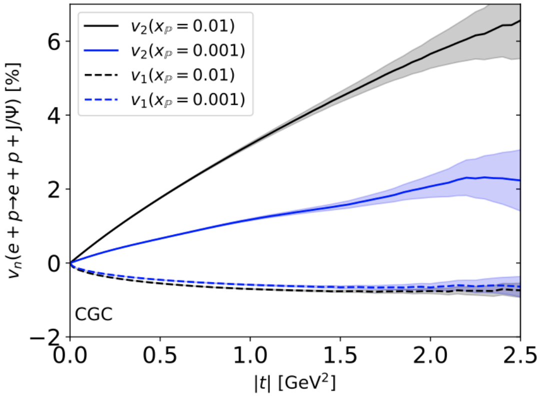
DGLAP + BFKL resummation can also fit FL

More exclusive observables…

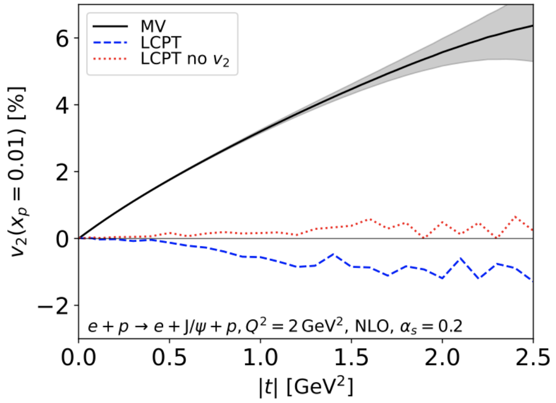
Diffractive vector meson, dijet

- Approximatively $d\sigma \sim \text{gluon}^2$
- Access to geometry (and event-by-event fluctuations)

Extract azimuthal modulations from cross sections: $v_n = \langle \cos(n\phi_{e\Delta}) \rangle$, $v_2 \sim \mathcal{M}_{\pm 1, \mp 1}$



H.M, Roy, Salazar, Schenke, 2011.02464



Dumitru *et al*, 2105.10144

At small-x Wigner=dipole Smatrix Yuan

$$xW_g^T(x, |\vec{q}_\perp|, |\vec{b}_\perp|) + 2\cos(2\phi) xW_g^\epsilon(x, |\vec{q}_\perp|, |\vec{b}_\perp|)$$

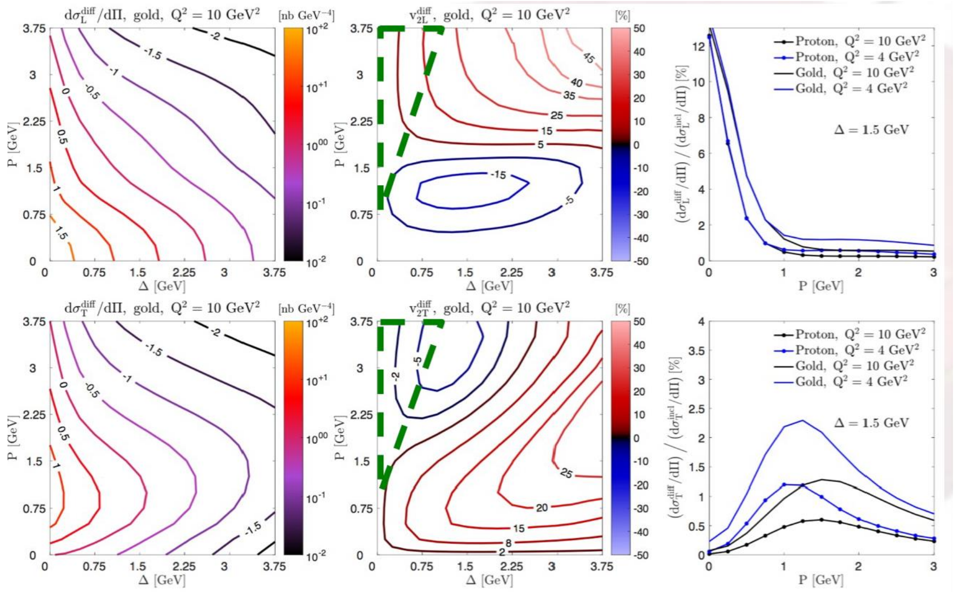
Anisotropy ~ few %

Exclusive heavy meson production at NLO

- Corrections $\sim \alpha_s$ and $\sim v^2$
  Both important in J/Ψ production
  Relativistic $\sim v^2$ correction negligible in Υ production
- L polarization published, T in preparation
- Codes for numerical evaluation

H.M, J. Penttala, 2104.02349 and in preparation; Lappi, H.M, Penttala, 2006.02830

Mäntysaari



Mäntysaari-Mueller-Salazar-Schenke, 1912.05586

What is needed for full EIC phenomenology

- Initial condition for small-x evolution:
  Fit to HERA F_2 data with quark masses at NLO
- Avoid problems with large dipoles in F_2??
- Geometry and perturbative small-x evolution??

Beware the final state soft gluon radiation that can affect angular-dependent observables.

NLO CGC calculations

- Photon wave function at NLO Beuf, Hänninen, Paatelainen, Lappi 2018-2021
- Heavy vector meson wave function at NLO Escobedo, Lappi, 2020
- Light meson at NLO Boussarie, Grabovsky, Ivanov, Szymanowski, Wallon, 2016
- Small-x evolution equations Balitsky 2008, Balitsky, Chirilli, 2013
- Initial condition fitted to F_2 data Beuf, Hänninen, Lappi, H.M, 2020
- NLO dijet $(+\gamma)$ in DIS Caucal, Salazar, Venugopalan, 2021; Roy, Venugopalan, 2020
- Particle production in pA Stasto, Xiao, Zaslavsky, 2013; Ducloue, Lappi, Zhu, 2017
- Proton color charge correlations Dumitru, H.M, Paatelainen, 2021

eavy meson production beyond LO, need

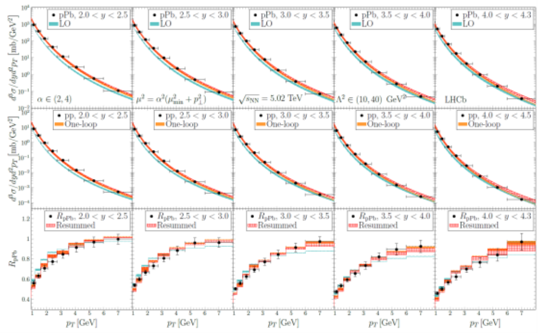
- Relativistic corrections $\sim v^2$ Lappi, H.M, Penttala, 2006.02830
- NLO $\sim \alpha_s$ corrections H.M, Penttala, 2104.02349

All these observables involve the dipole and quadrupole

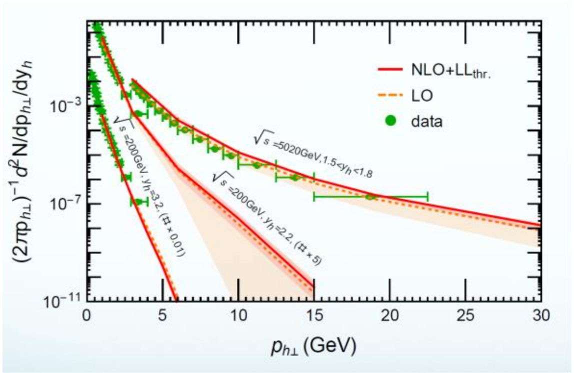
NLO single inclusive in pA

Benchmark NLO calculation in CGC.
There used to be the problem of negative cross section
Kinematic constraint + threshold resummation

Xiao 2112.06975



Kang

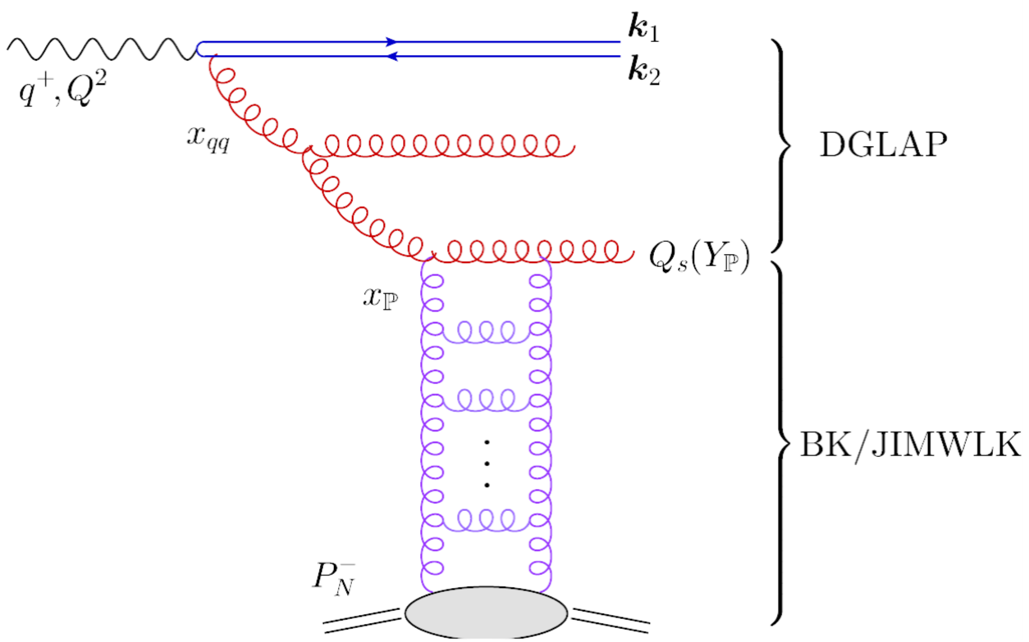


SCET approach to CGC

Systematic power-counting scheme, calculations made simpler? At NLO, agreement with the `standard' CGC approach. Paving the way for NNLO calculations? Could be emphasized for topical collaboration?

Probing saturation in high-pt jets

Iancu 2112.06353



Integrate over the (softer) third jets, dominated by $k_{3\perp} \sim Q_s(Y_{\mathbb{P}})$

Collinear factorization for an observable sensitive to saturation!

NNLO BK evolution

Caron-Huot

Schematic result:

explicit transverse functions

$$K^{(3)}U_{12} = \frac{11\pi^4}{45}K^{(1)}U_{12} + \int_{\beta_0,\beta_{0'}} \frac{\alpha_{12}}{\alpha_{10}\alpha_{00'}\alpha_{0'2}} K^{(3)}_{[1\,00'\,2]}(U_{10}U_{02}+U_{10'}U_{0'2}-2U_{10}U_{00'}U_{0'2})$$
$$+\int_{\beta_0,\beta_{0'},\beta_{0''}} \frac{\alpha_{12}}{\alpha_{10}\alpha_{00'}\alpha_{0'0''}\alpha_{0''2}} \Big[K^{(3)}_{[1\,00'0''\,2]}(2U_{10'}U_{0'2}-2U_{10}U_{00'}U_{0'0''}U_{0''2})$$
$$-(1+P)\left(K^{(3)c.t.}_{[1\,00'0''\,2]}(2U_{10'}U_{0'2}-2U_{10}U_{00'}U_{0'2})\right)\Big], \quad (4.34c)$$

(Planar) QCD: expect different functions, similar structure

the supersymmetric result could be independently tested

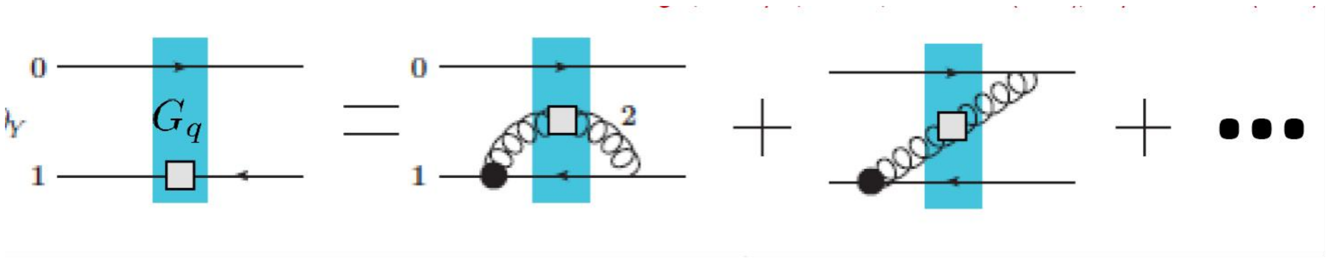
So far for N=4 SYM in the large-Nc limit. Challenging to derive in QCD.
Deep connection to amplitude calculations, integrability, spacelike-timelike correspondence.
Practical? Already NLO BK is tricky (instability, resummation,…)

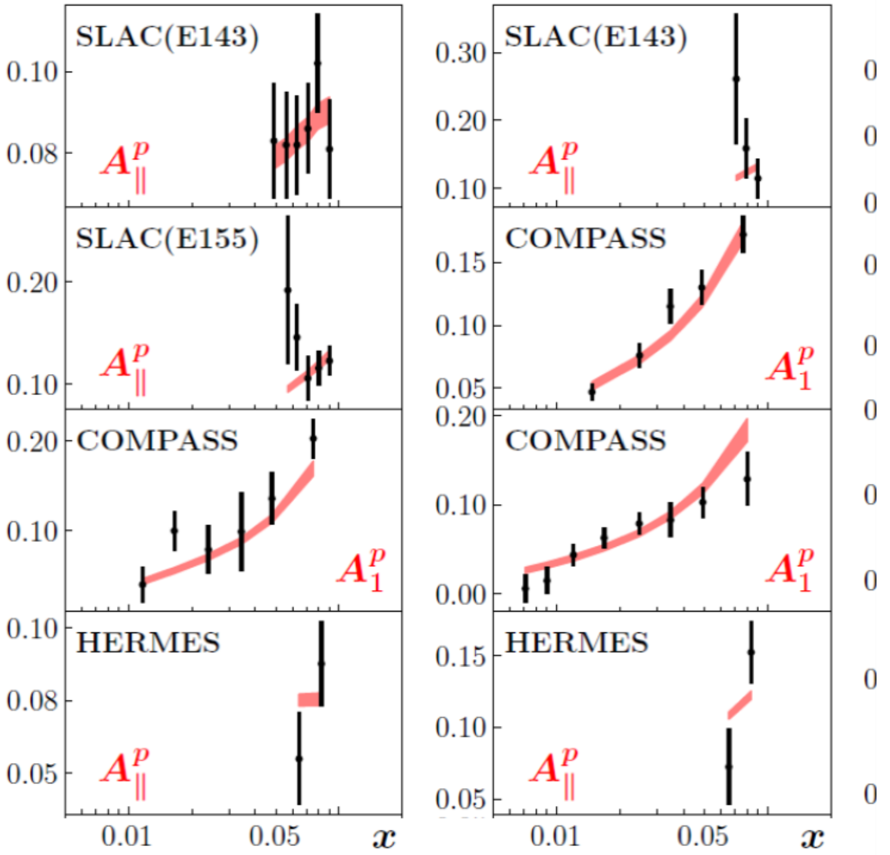
Spin at small-x

Sievert

Proton spin sum rule: another major goal of the EIC.

KPS approach to helicity distributions at small-x.





Global analysis of polarized dipole?
Coupling to BK at single log level.

Disagreements among the participants even at the conceptual level.

KPS/ BER(DGLAP)/chiral anomaly

There are also interesting developments on transverse spin at low-x (connection to odderon)

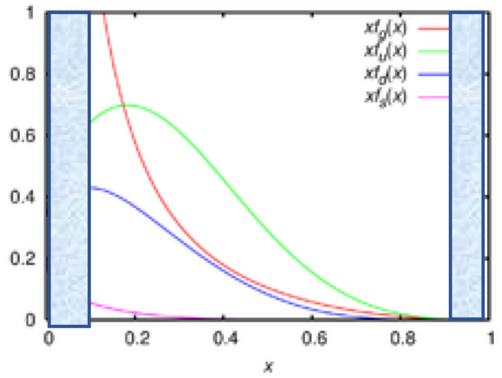
Lattice QCD approach to small-x

Ji

Revolution in 2014. Nowadays lattice QCD people are calculating PDF, TMD, GPD...
Small-x very challenging. Need very large lattices, very fine lattice spacings.
Not practical anytime soon.

$$xP_z \gg \Lambda_{QCD} \qquad \frac{1}{a} > P_z$$

For $P^z \sim 2-3\ GeV$, max x-range: 0.1-0.9



Hackett

Use machine learning to efficiently sample complicated probability distributions Great interest and progress in recent years, but still limited to low-dimensional models.

Instead of directly doing simulation at small-x, maybe one should consider some kind of RG equation

→ lattice BFKL, BK? Chirilli

Entanglement entropy

Kharzeev, Skokov, Kutak

Integrating out the `environment’ → entanglement entropy of partons

Different definitions of entropy. Even different x-dependencies $S \sim \ln \frac{1}{x}$ $S \sim \left(\frac{1}{x}\right)^{\alpha}$

Connection to observables? Precision?

Can this be a topic of topical collaboration?
US-based researchers actively involved.