Gluon Saturation at the Electron-Ion Collider

RHIC/AGS Users Meeting
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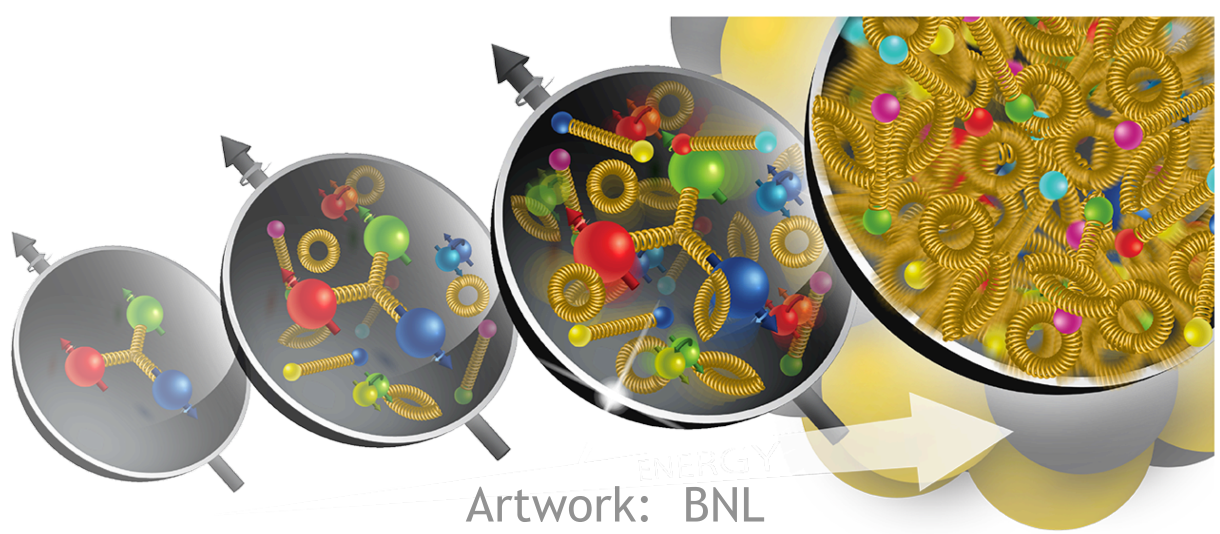


Artwork: BNL

Outline

- Gluon saturation and the CGC

- Measurements at the EIC

  Structure functions

  Diffractive processes

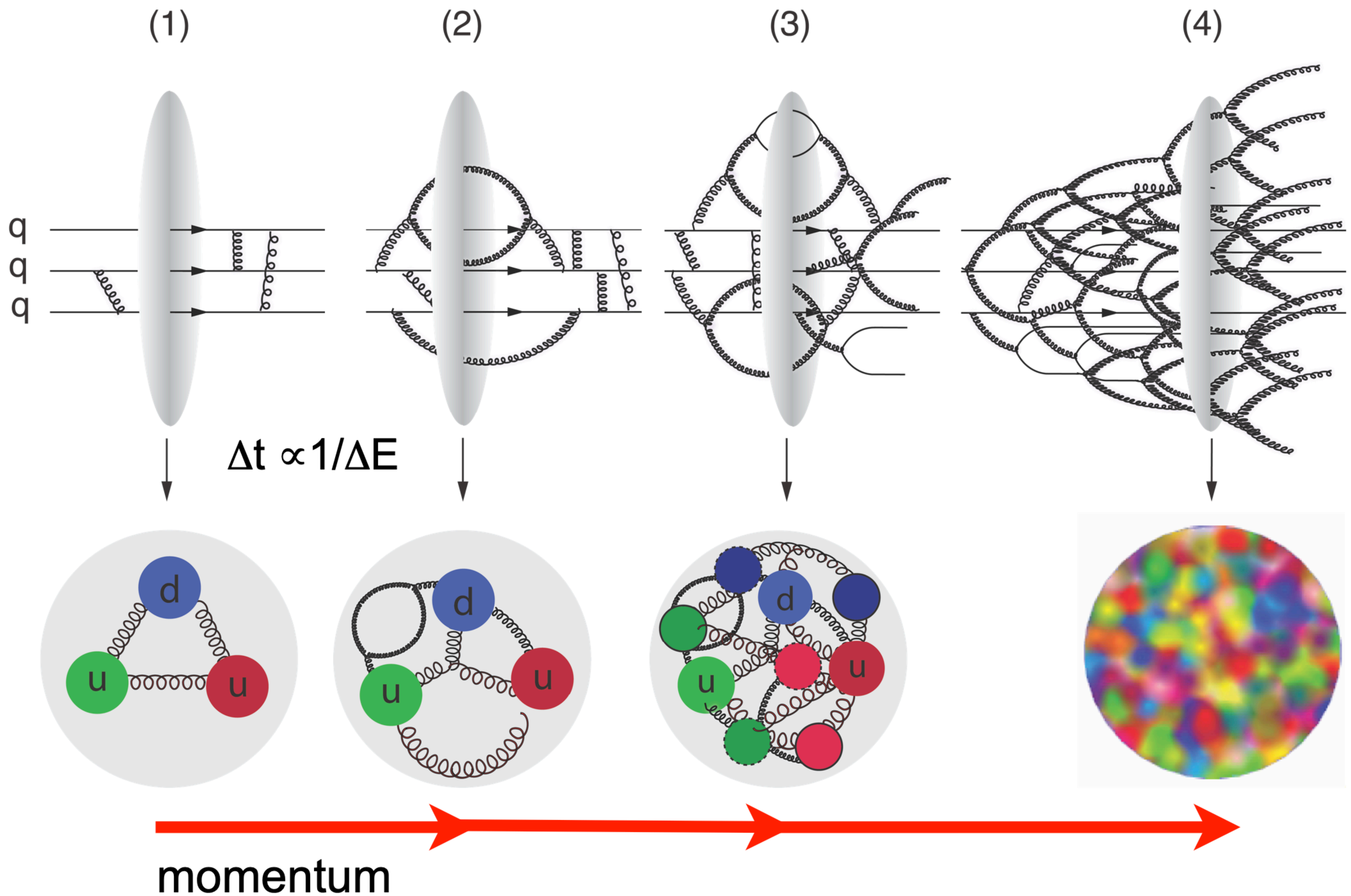
  Semi-inclusive measurements

- Some recent theoretical developments

  Matching CGC and TMD frameworks

  Next-to-leading order computations

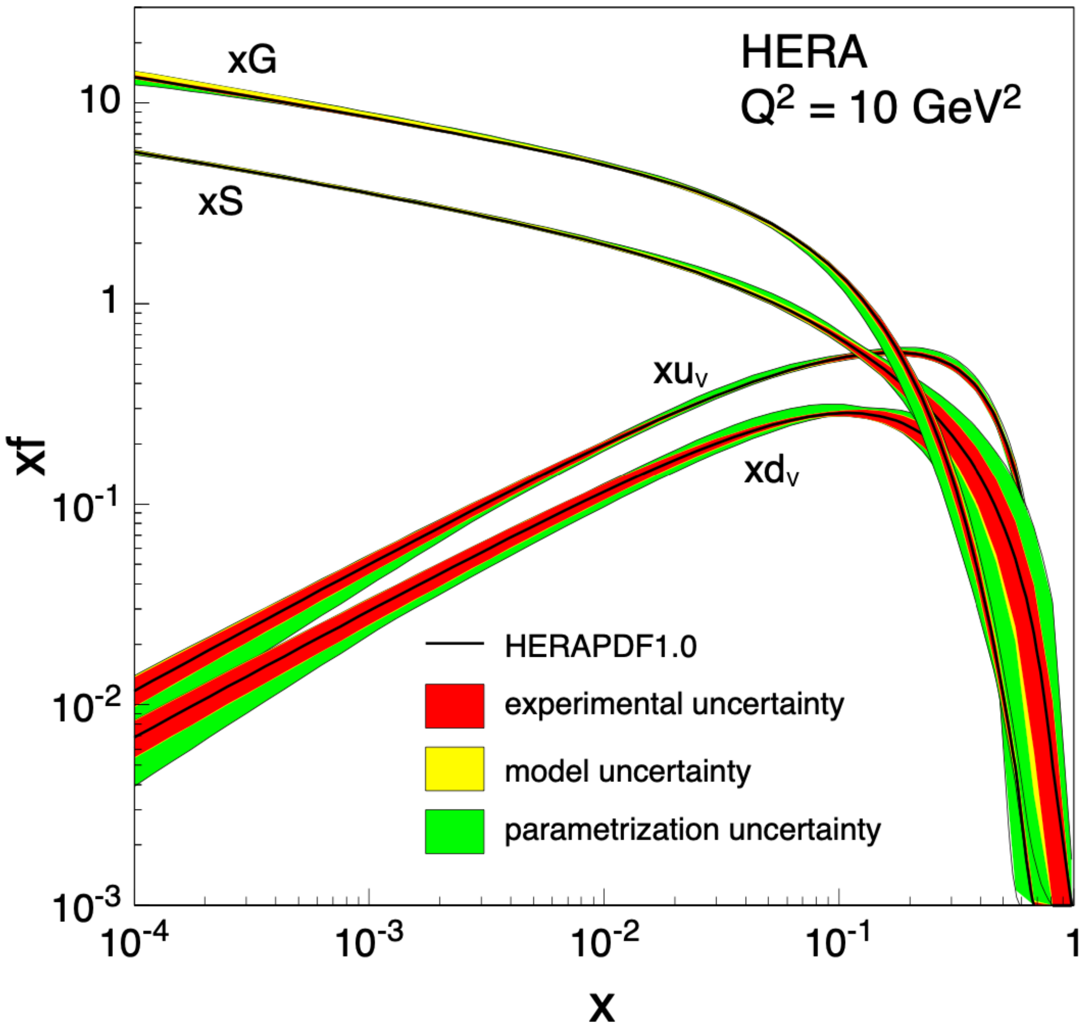
Gluon saturation

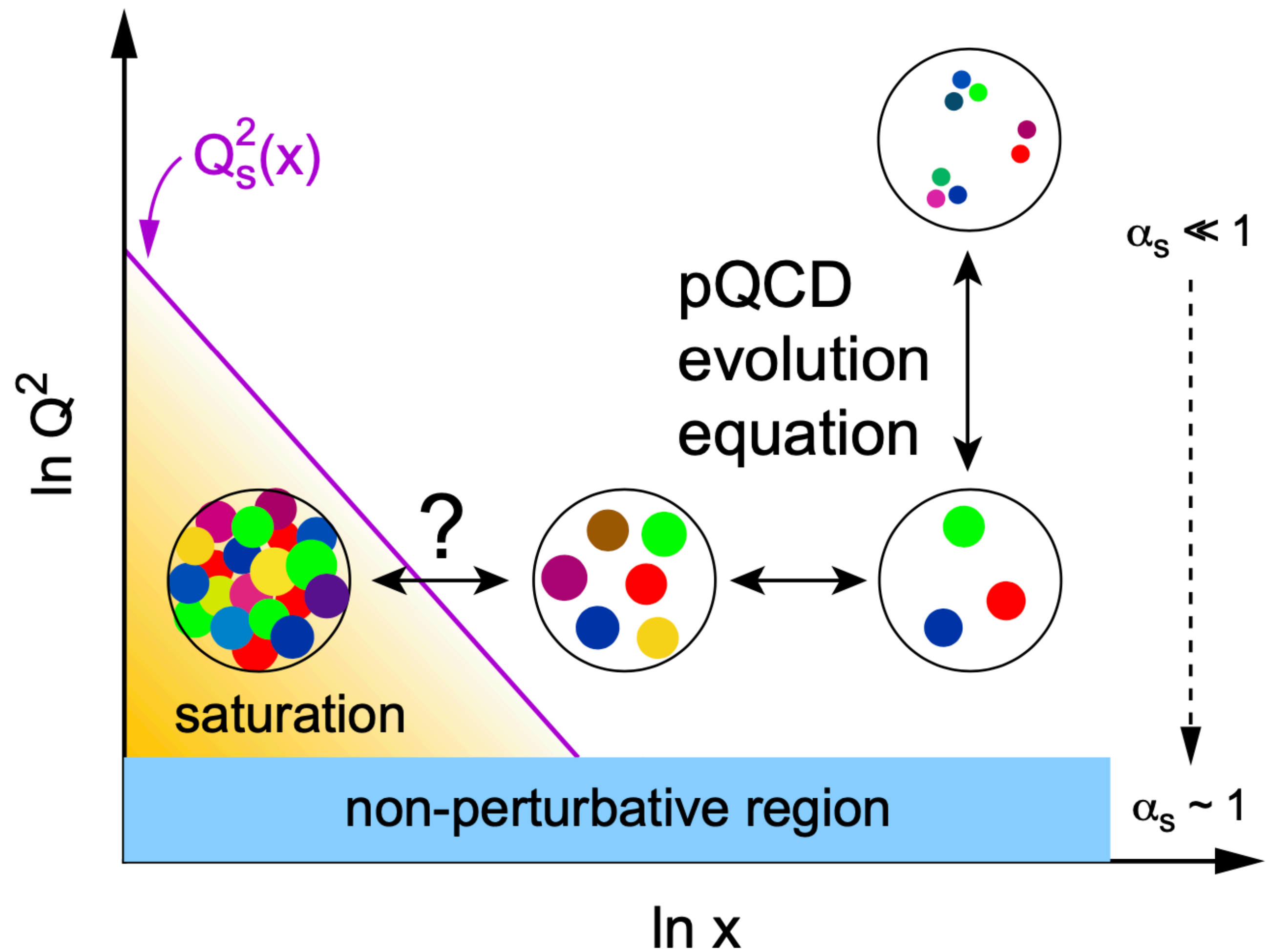


Artwork: T. Ullrich

Gluon Saturation

Rapid growth of gluon distributions at small x ⟶ Violate unitarity





Non-linear effects in QCD at sufficiently small x (e.g. gluon recombination) tame the growth ⟶

Gluon saturation

Characterized by a scale Q_s^2 (saturation scale)

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

Gluon Saturation

The Color Glass Condensate

McLerran, Venugopalan.
hep-ph/9309289, hep-ph/9311205

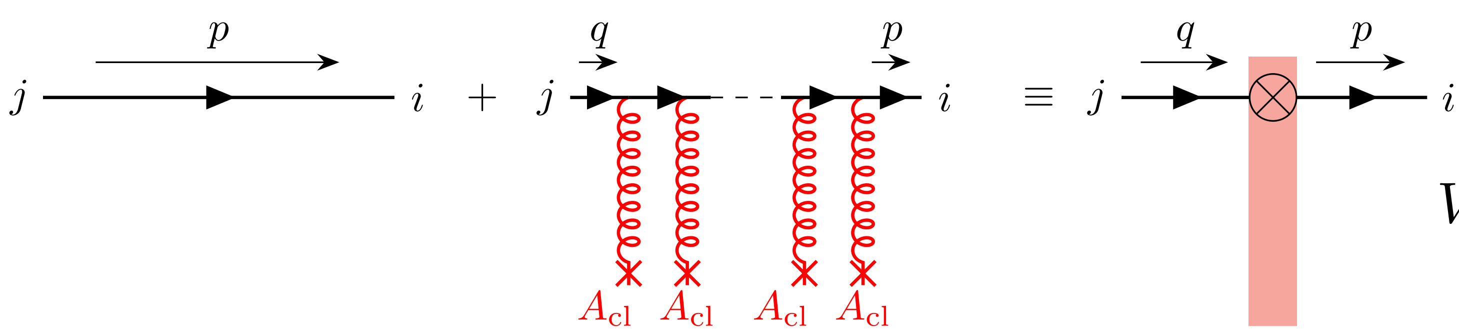
Large gluon densities at small x

$$xG \sim \frac{1}{\alpha_s}$$

Characterize small x gluon as a classical Yang-Mills field sourced by valence quarks

$$[D_\mu, F^{\mu\nu}] = J^\nu \longrightarrow A^\mu_{\rm cl}$$

Computations in QCD +QED in the presence of color back-ground field $A^\mu_{\rm cl}$



Effective eikonal quark vertex

Light-like Wilson line

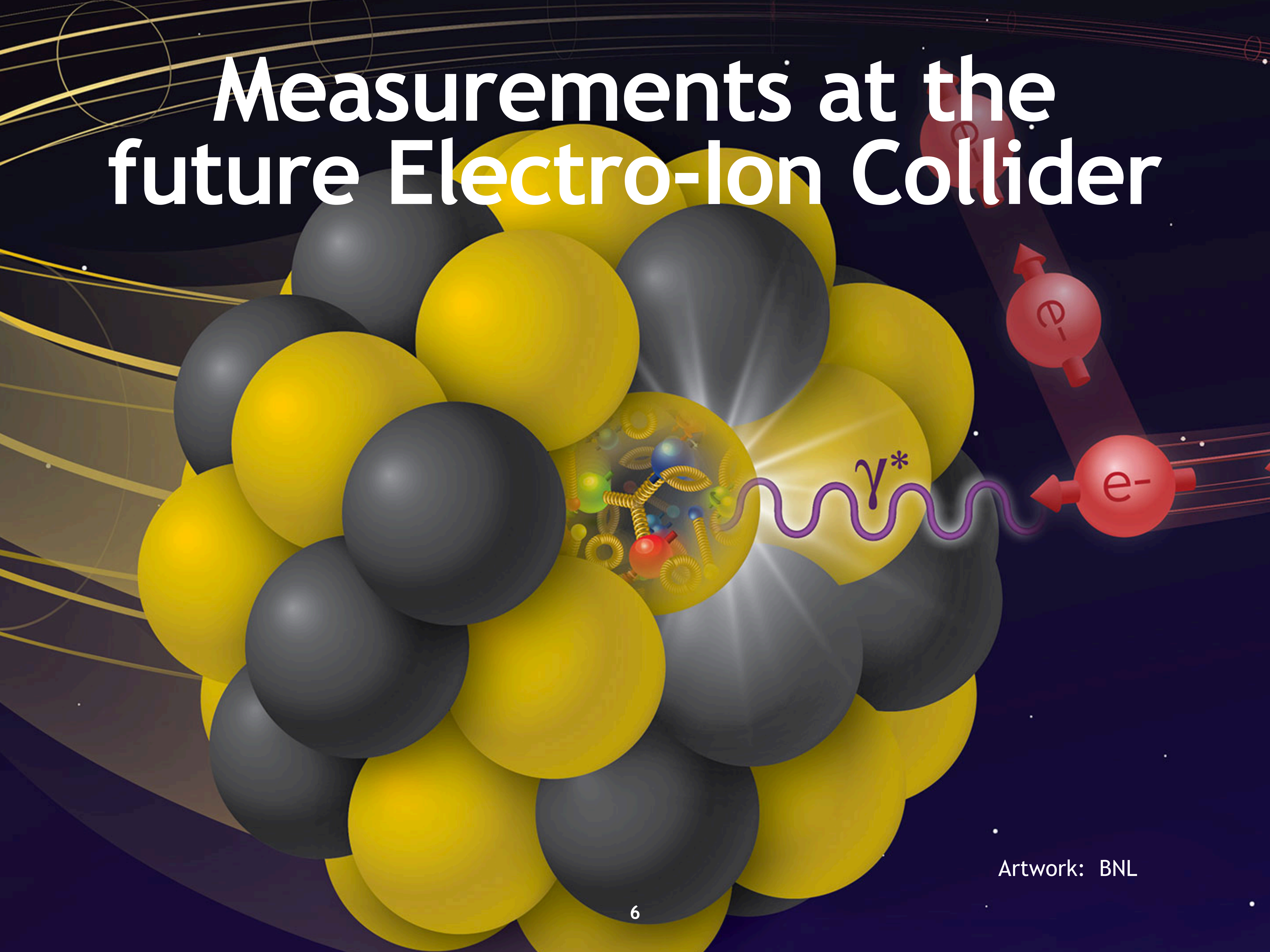
$$V_{ij}(\boldsymbol{x}) = P \exp\left\{ ig \int dx^- A^{+,a}_{cl}(\boldsymbol{x}, x^-) t^a \right\}$$

Observables depend on correlators of Wilson Lines

$$\frac{1}{N_c}\left\langle \mathrm{Tr}(V_{\boldsymbol{x_1}_\perp} V^\dagger_{\boldsymbol{x_2}_\perp})\right\rangle_Y \qquad \frac{1}{N_c}\left\langle \mathrm{Tr}(V_{\boldsymbol{x_1}_\perp} V^\dagger_{\boldsymbol{x_2}_\perp} V_{\bar{\boldsymbol{x}}_{\boldsymbol{2}\perp}} V^\dagger_{\bar{\boldsymbol{x}}_{\boldsymbol{1}\perp}})\right\rangle_Y$$

They obey RG equations (Balitsky-Kovchegov, JIMWLK) and depend implicitly on saturation scale Q_s^2

Measurements at the future Electro-Ion Collider

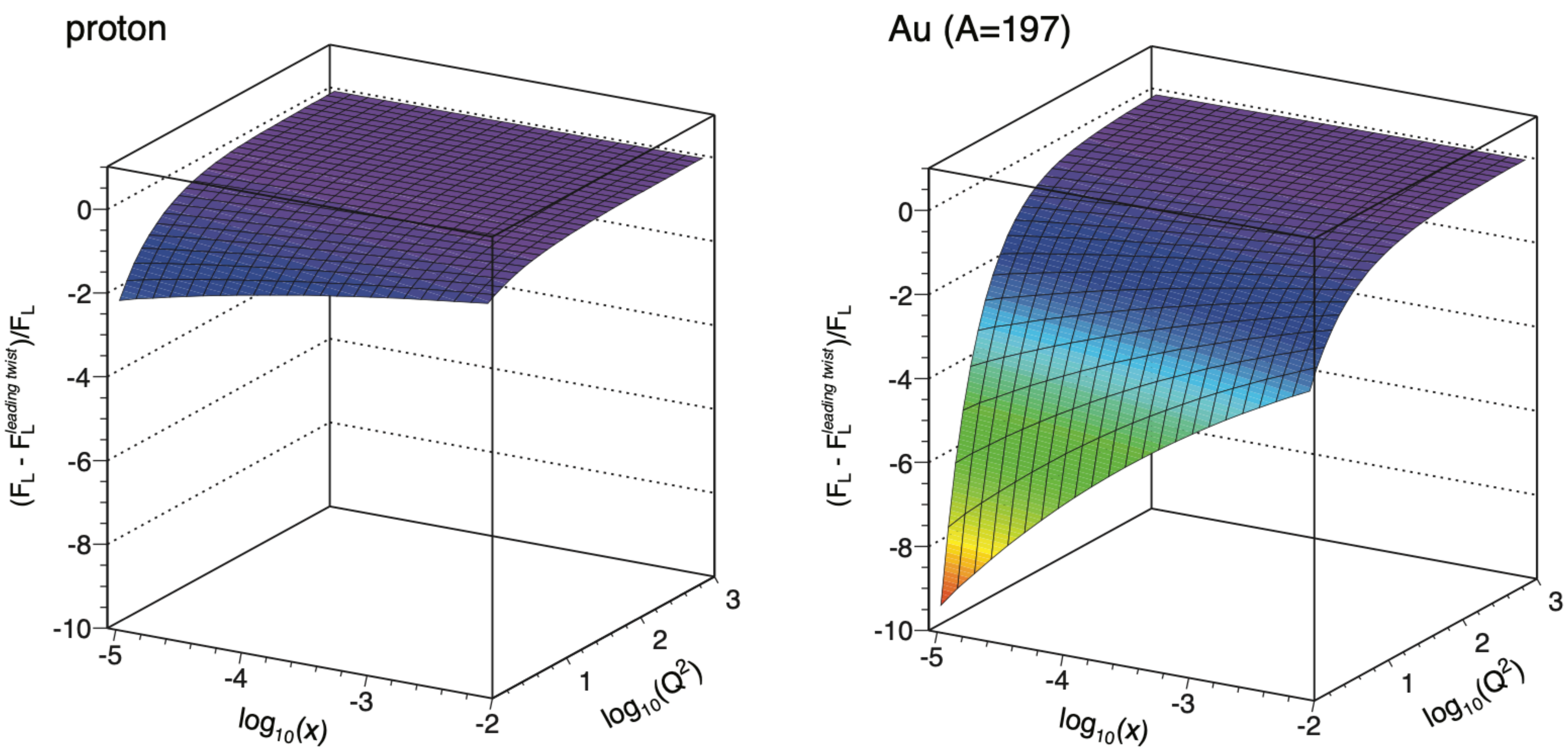


Artwork: BNL

Structure functions at small-x

F_L in the saturation framework vs leading twist

$$F_L(x, Q^2) = \frac{4\pi^2 \alpha_{em}}{Q^2} \sigma_L^{\gamma^* A}(x, Q^2)$$



Bartels, Golec-Biernat, Motyka. 0911.1935

F_L is affected by multiple gluon scatterings at all orders in twists ($1/Q^2$)

Enhanced for nuclear collisions and at smaller values of x

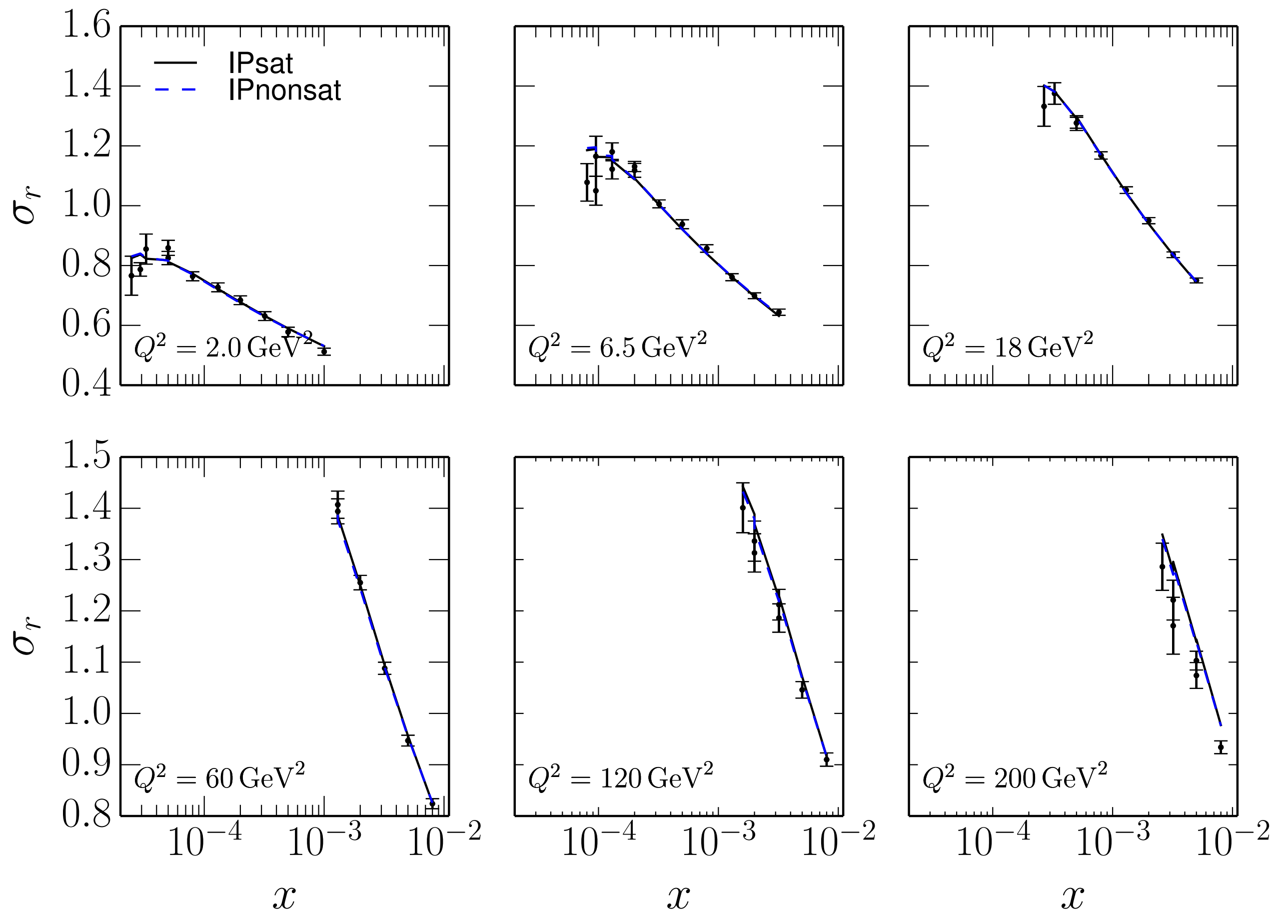
Will these differences manifest at colliders?

Structure functions at small-x

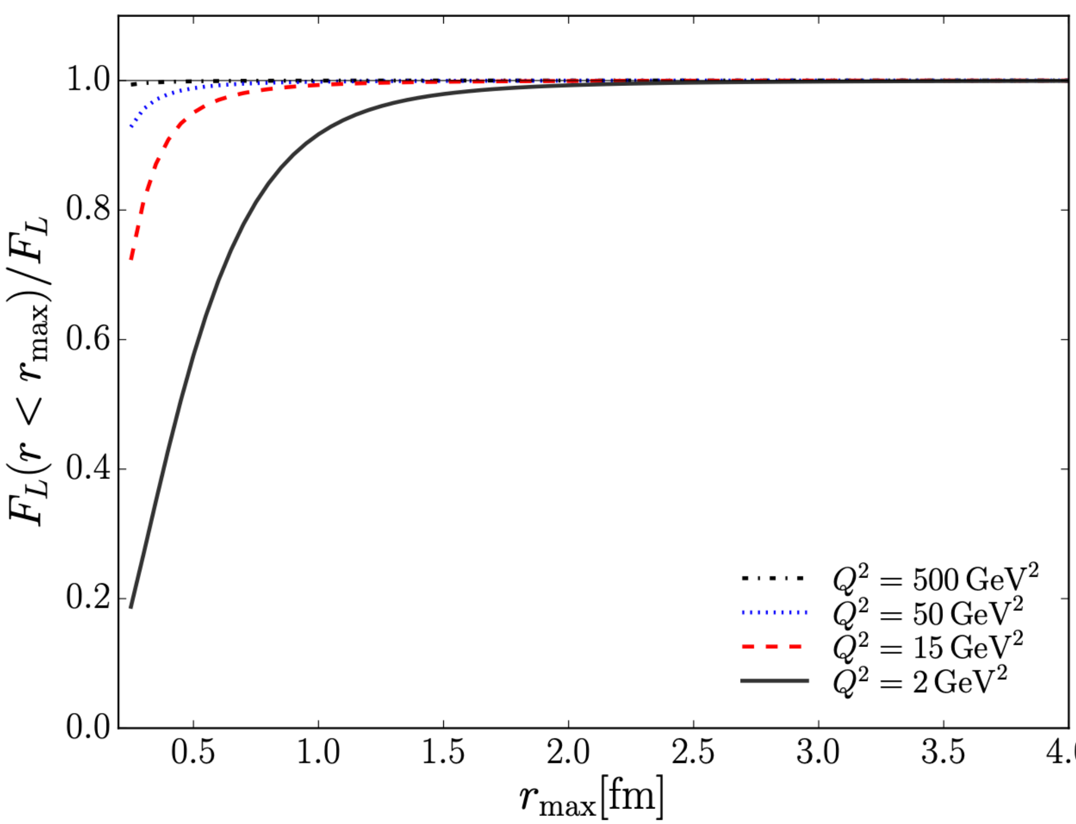
Reduced cross-section and F_L at HERA

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

IPsat & IPnonsat (lineralized IPsat)



Dipole size contributions to F_L



At HERA saturation searches are hindered by non-perturbative contributions

Independent fits using IPSAT and IPnonsat describe data equally well.

No clear evidence of gluon saturation at HERA

Mäntysaari, Zurita. 1804.05311

See also Mäntysaari, Schenke. 1806.06783

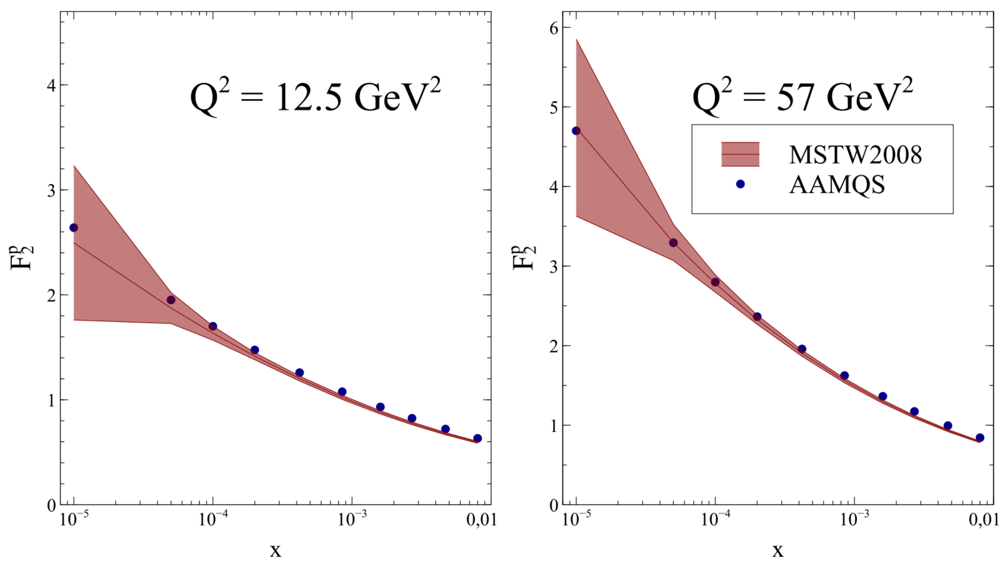
Structure functions at small-x

Nuclear PDFs vs saturation framework

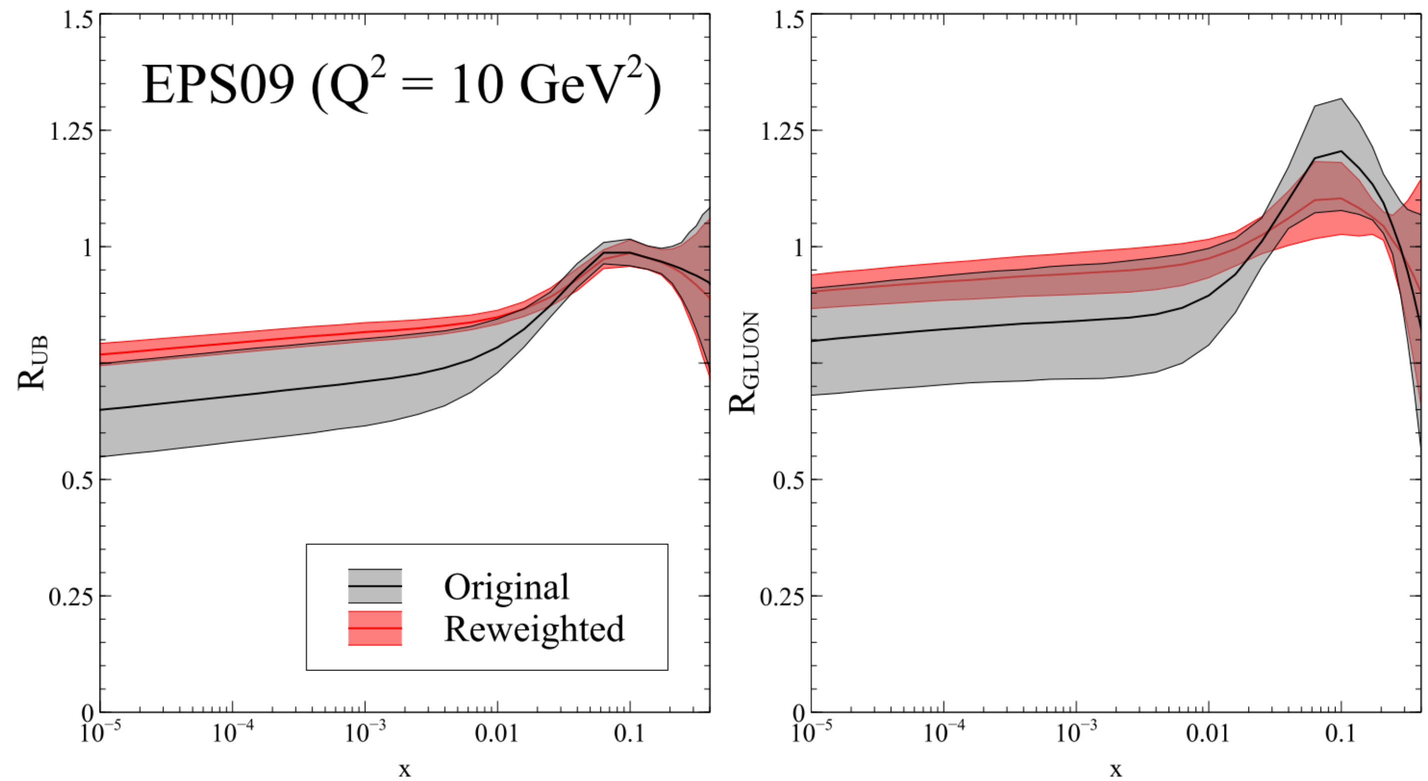
Saturation effects enhanced in nuclei

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

Less sensitivity to non-perturbative effects



Saturation vs collinear factorization for proton F_2

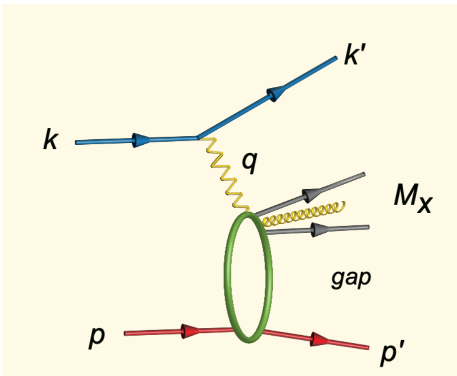


Sea quark and gluon distribution before and after Bayesian re-weighting

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

Marquet, Moldes, Zurita. 1702.00839

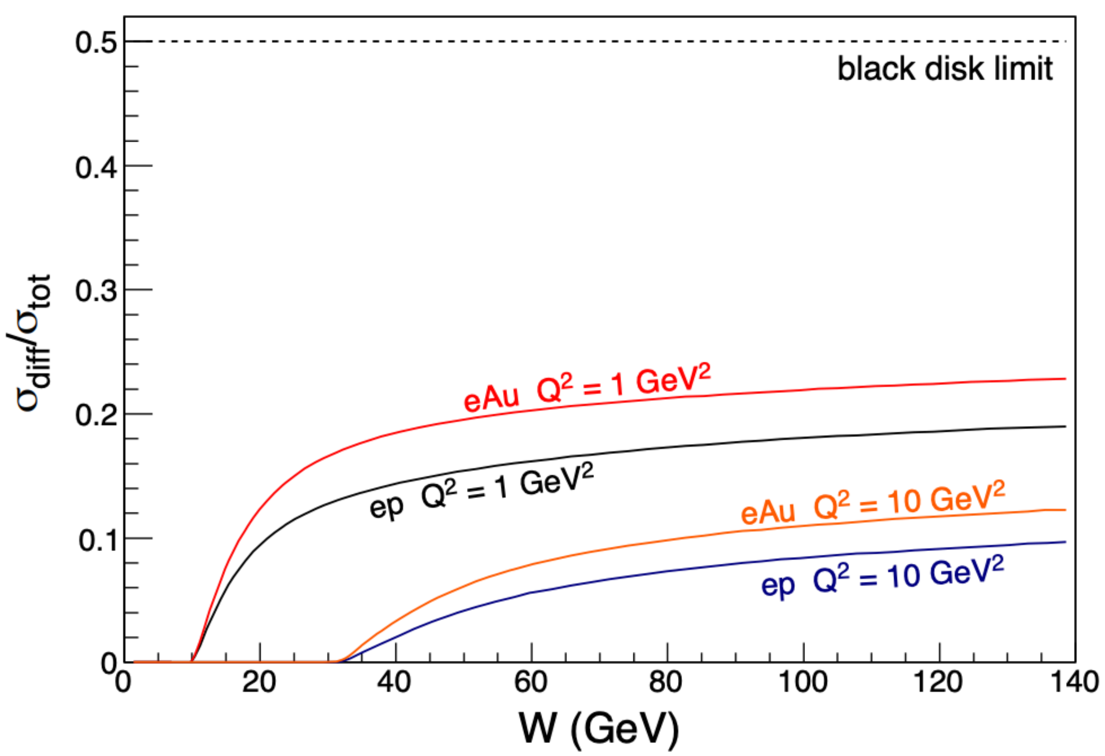
Diffractive processes



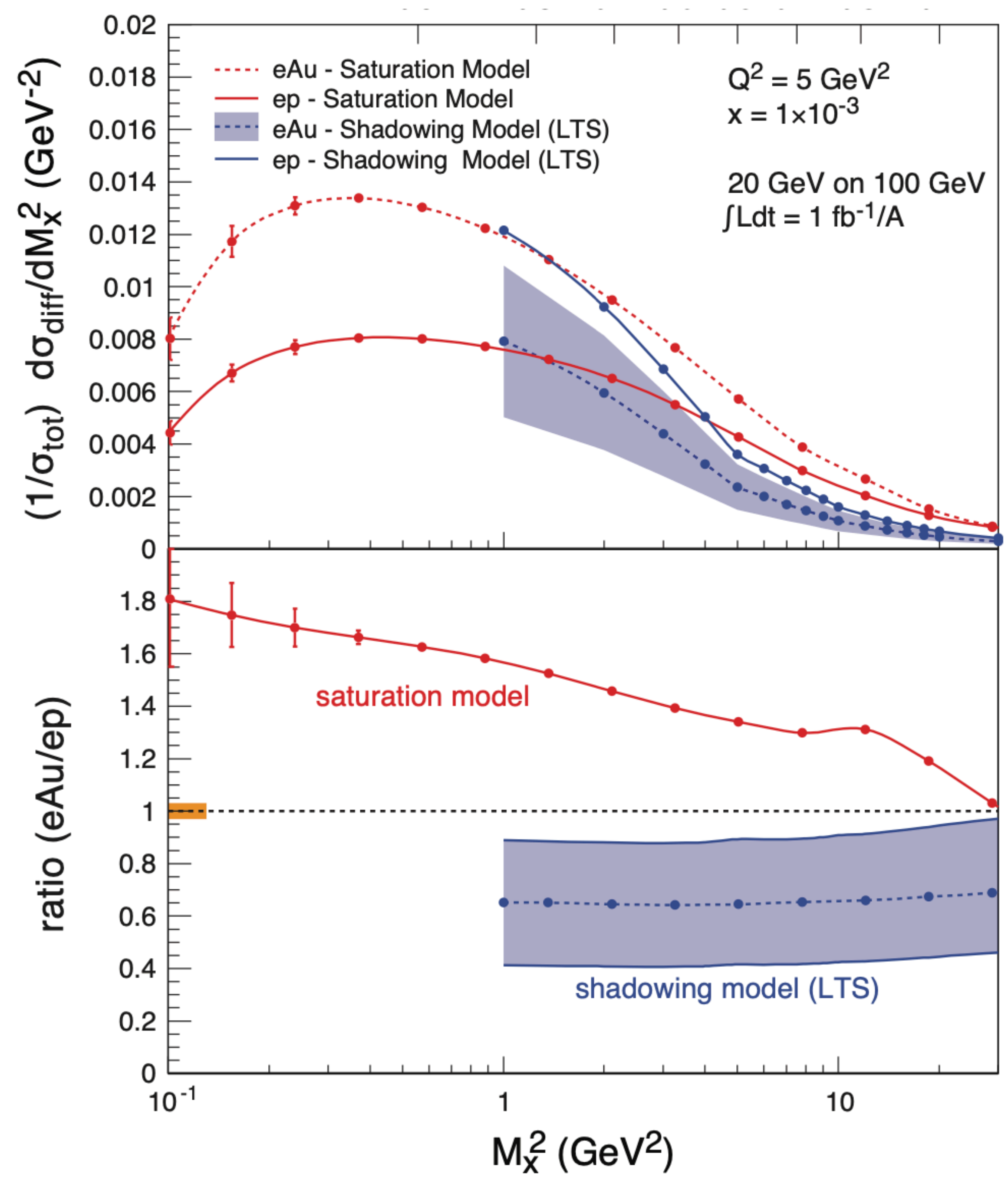
Diffractive events are characterized by rapidity gap

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

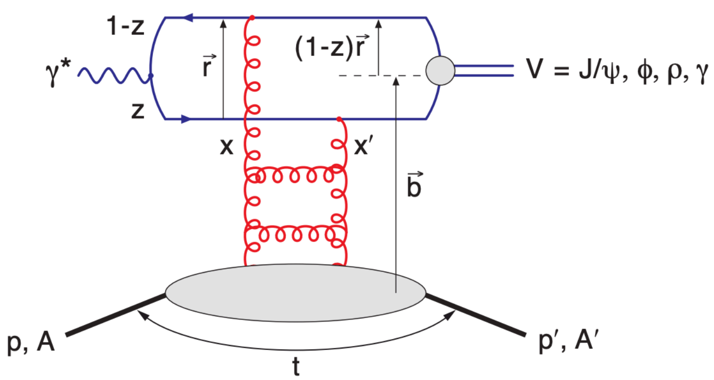


Clear difference between saturation models and leading twist shadowing (LTS)

EIC White paper. 1212.1701

Diffractive processes

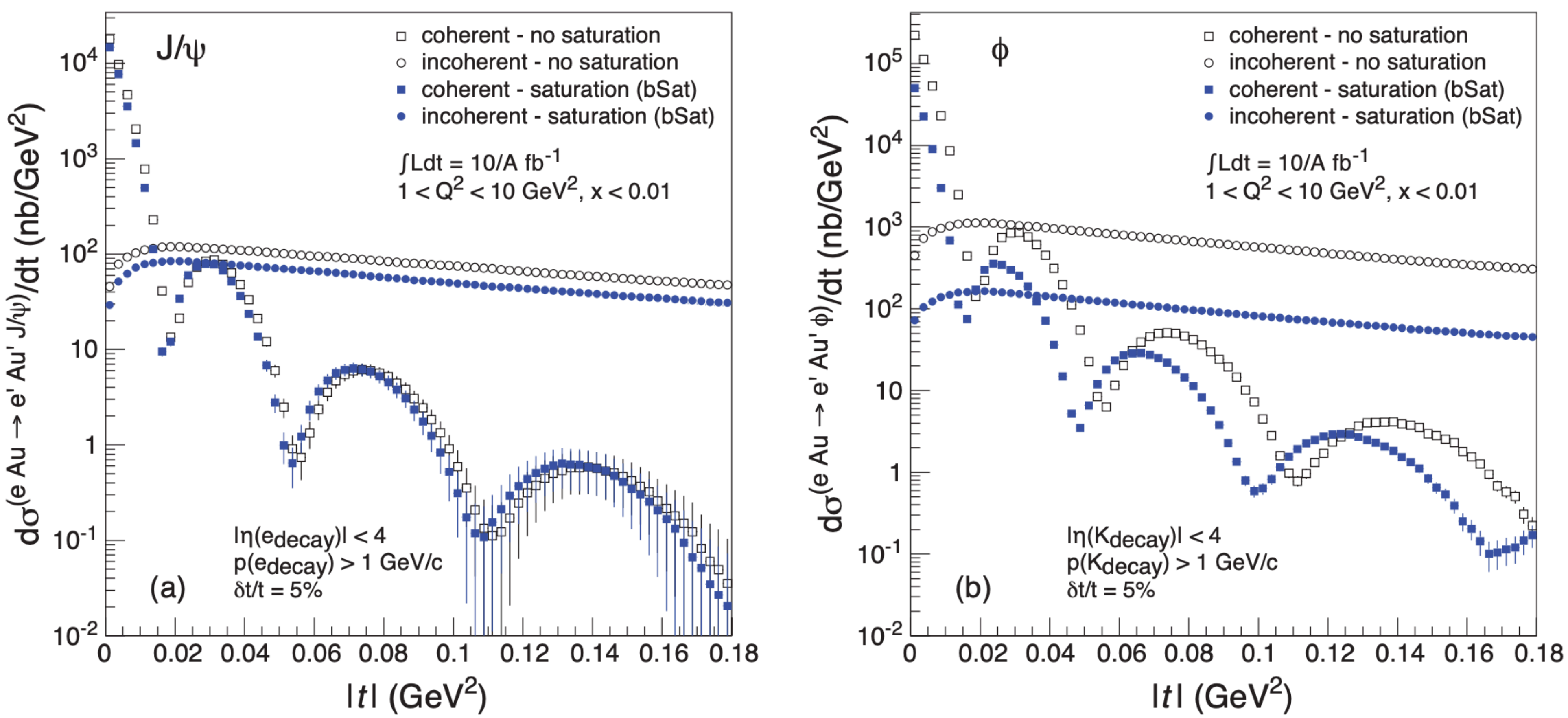
Exclusive nuclear electro-production of VM



Sensitive to spatial distribution (tomography)

$$t = -\boldsymbol{\Delta}_\perp^2$$

$$\boldsymbol{\Delta}_\perp \leftrightarrow \boldsymbol{b}_\perp$$



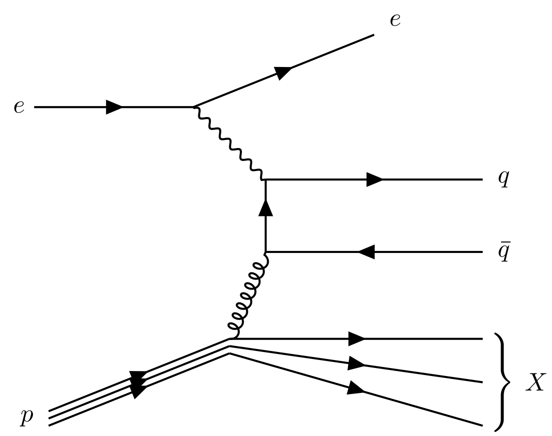
- Sartre event generator (bSat & bNonSat = linearized bSat)
- Large difference for φ less so for J/ψ

Toll, Ullrich. 1211.3048

Semi-inclusive measurements

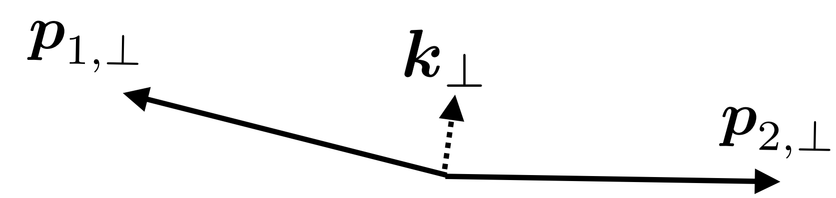
Back-to-back di-hadron suppression

Dominguez, Marquet, Xiao, Yuan. 1101.0715



TMD factorization at small-x Weizsäcker-Williams $xG_{WW}(x, k_\perp)$ gluon TMD

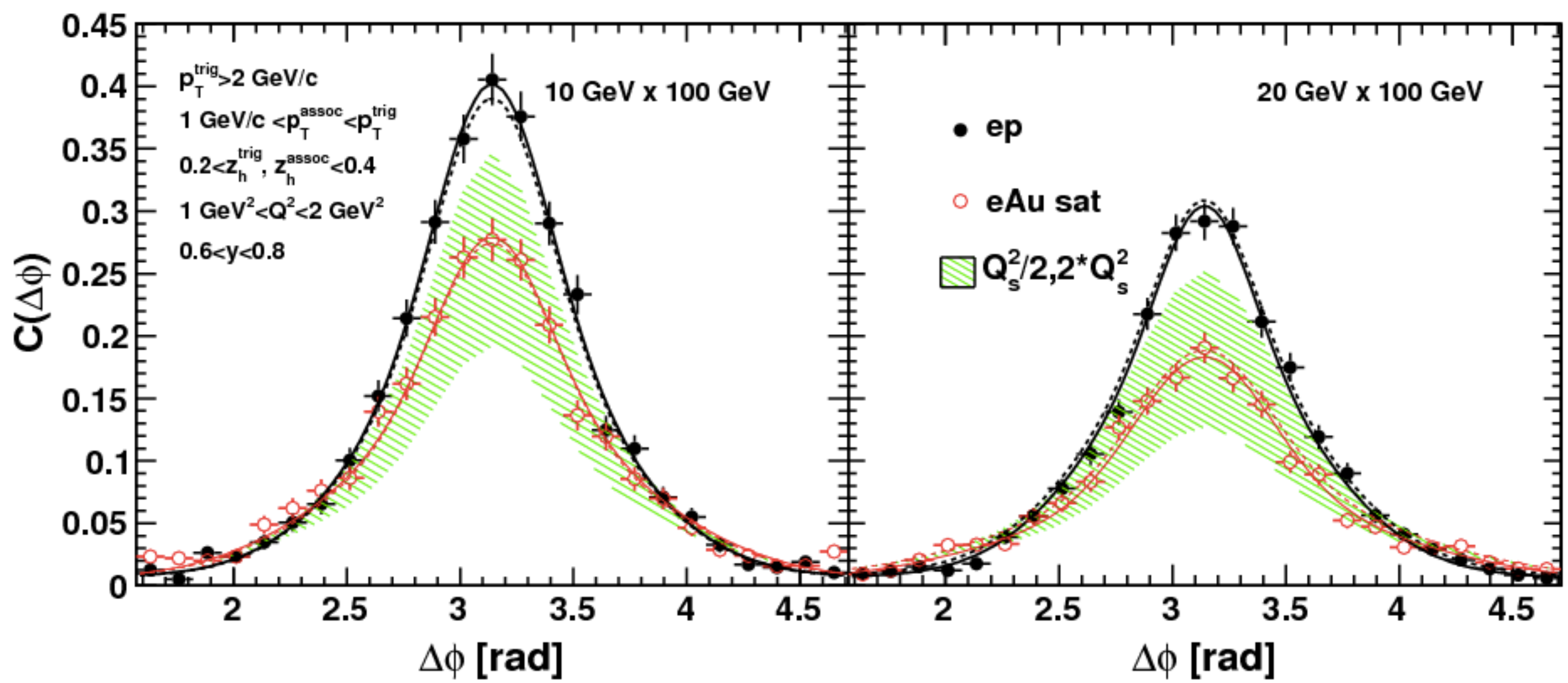
WW at small-x depends on sat scale Q_s



$\Delta\phi$ angle between $p_{1\perp}$ and $p_{2\perp}$

Typical momentum transfer from hadron/nucleus to

$$k_\perp \sim Q_s$$



Gluon saturation → **back-to-back suppression**

Zheng, Aschenauer, Lee, Xiao. 1403.2413

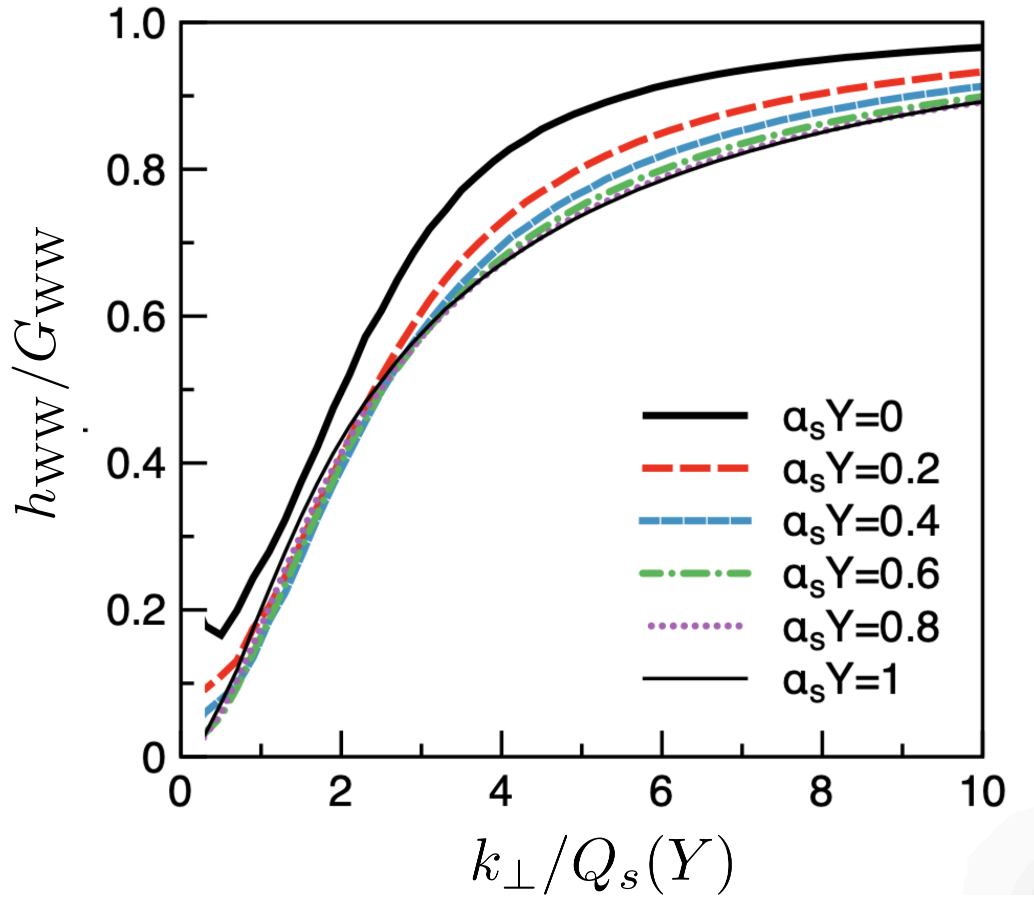
Sudakov factor included!

Semi-inclusive measurements

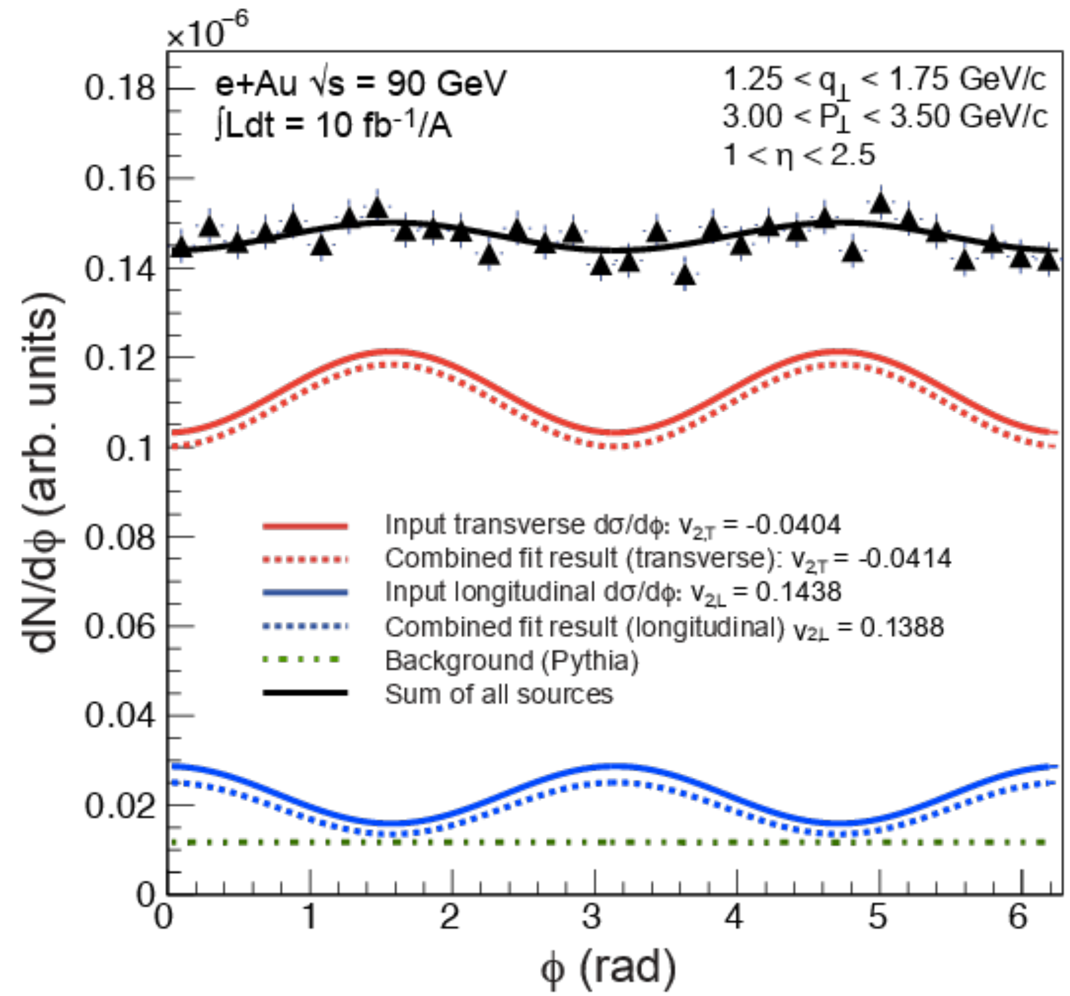
Azimuthal anisotropies of dijet momentum imbalance

Ratio linearly polarized to unpolarized WW gluon TMD in the CGC

WW gluon TMD (linearly polarized) → Dijet azimuthal asymmetries

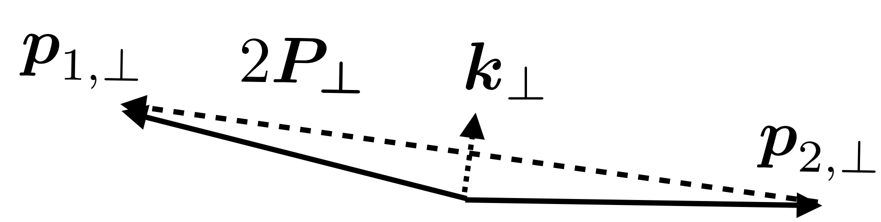


Dumitru, Lappi, Skokov. 1508.04438



Accessed in azimuthal asymmetry of momentum imbalance in dijet pairs

Dominguez, Qiu, Xiao, Yuan. 1109.6293



ϕ angle between $P_\perp$ and $k_\perp$

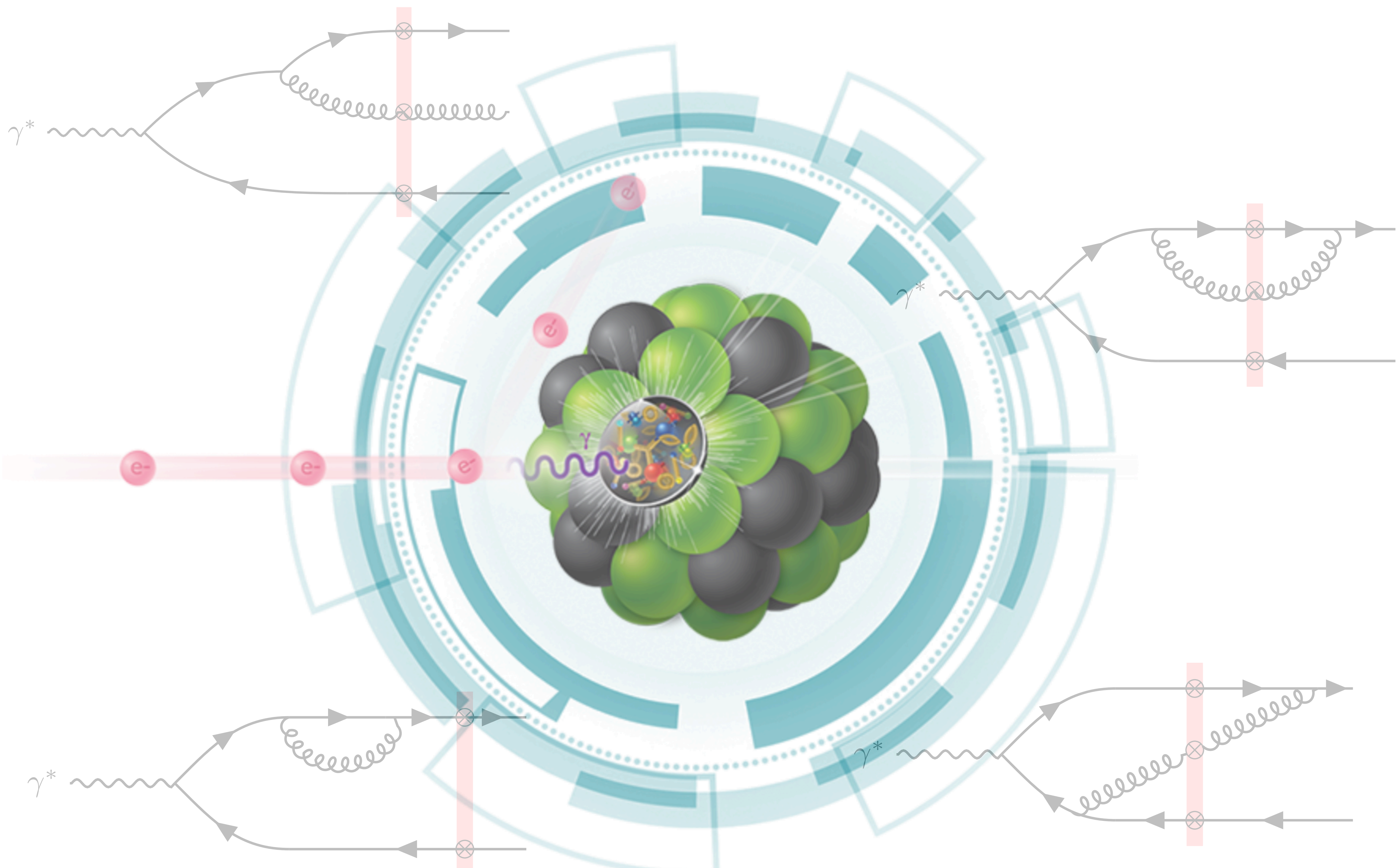
$$|v_2| \sim \frac{xh_{WW}}{xG_{WW}}$$

$$v_2 = \langle \cos(2\phi) \rangle$$

For effect of soft gluon final state radiation see Hatta, Xiao, Yuan, Zhou. 2010.10774

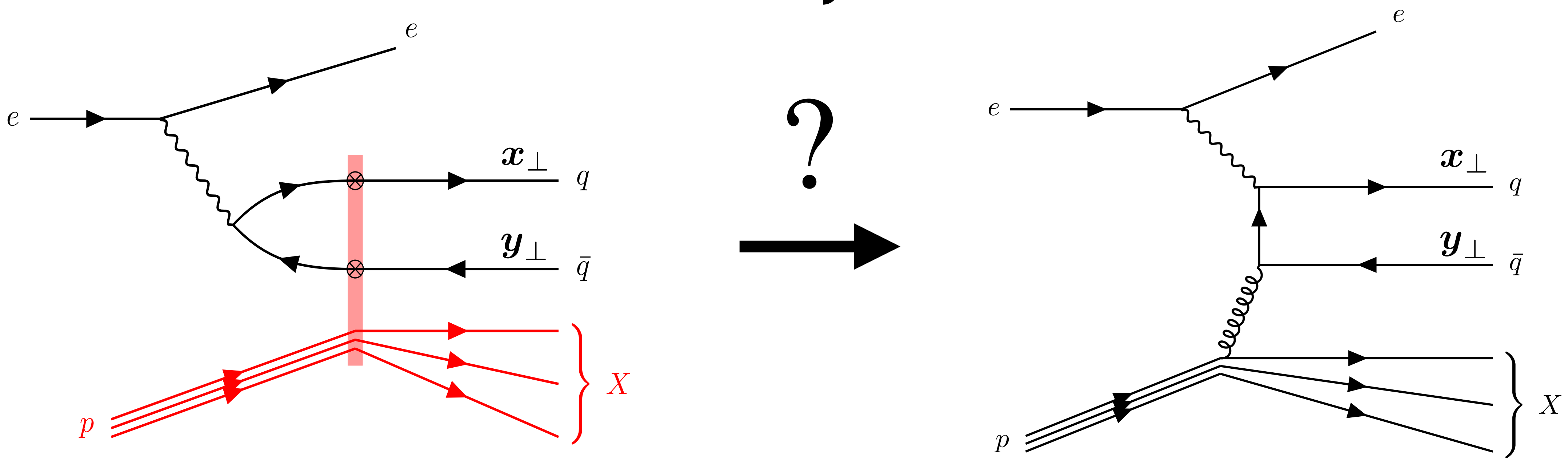
Dumitru, Skokov, Ullrich. 1809.02615

Recent theoretical developments



Matching TMD and CGC frameworks at small-x

From Wilson Lines to TMDs and beyond



Dominguez, Marquet, Xiao, Yuan. 1101.0715

Small dipole size expansion amplitude:

$$1 - V(\boldsymbol{x}_\perp)V^\dagger(\boldsymbol{y}_\perp) = \underbrace{ig\boldsymbol{r}_\perp^i \tilde{\boldsymbol{A}}_\perp^i}_{\text{TMD}} + \mathcal{O}(\boldsymbol{r}_\perp^2)$$

$$\boldsymbol{r}_\perp = \boldsymbol{x}_\perp - \boldsymbol{y}_\perp$$

Altinoluk, Boussarie. 1902.07930 Boussarie, Mehtar-Tani. 2001.06449

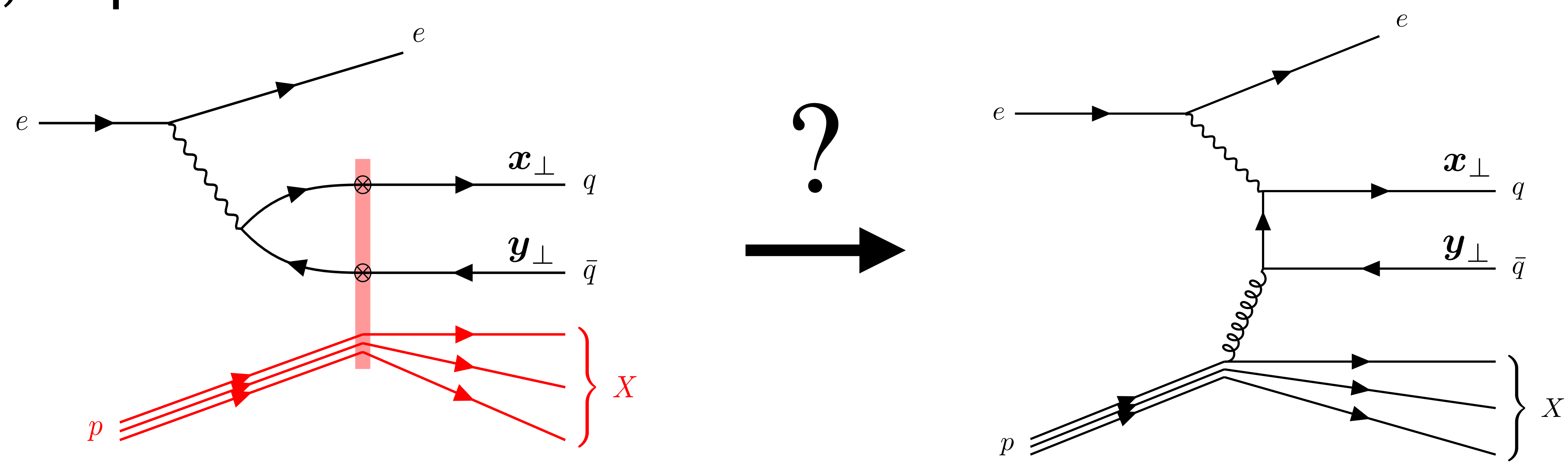
A gauge invariant expansion:

$$\mathbb{1} - V(\boldsymbol{x}_\perp)V^\dagger(\boldsymbol{y}_\perp) = \underbrace{ig\int_{\boldsymbol{y}_\perp}^{\boldsymbol{x}_\perp} \mathrm{d}\boldsymbol{z}_\perp^i \tilde{\boldsymbol{A}}_\perp^i(\boldsymbol{z}_\perp)}_{\text{ITMD}}$$

$$+ \underbrace{g^2 \int_{\boldsymbol{y}_\perp}^{\boldsymbol{x}_\perp} \mathrm{d}\boldsymbol{z}_{1\perp}^i \int_{\boldsymbol{y}_\perp}^{\boldsymbol{z}_{1\perp}} \mathrm{d}\boldsymbol{z}_{2\perp}^j \tilde{\boldsymbol{A}}_\perp^i(\boldsymbol{z}_{1\perp})V(\boldsymbol{z}_{1\perp})V^\dagger(\boldsymbol{z}_{2\perp})\tilde{\boldsymbol{A}}_\perp^j(\boldsymbol{z}_{2\perp})}_{\text{genuine higher twists (g.h.t.)}}$$

Matching TMD and CGC frameworks at small-x

CGC, improved TMD and TMD frameworks



Mäntysaari, Mueller, FS, Schenke. 1912.05586
Boussarie, Mäntysaari, FS, Schenke. 2106.XXXXX

$$\underbrace{d\sigma_{\rm CGC} = d\sigma_{\rm TMD} + \overbrace{\mathcal{O}\left(\frac{k_\perp}{Q_\perp}\right)}^{\rm kinematic}}_{d\sigma_{\rm ITMD}} + \overbrace{\mathcal{O}\left(\frac{Q_s}{Q_\perp}\right)}^{\rm genuine}$$

TMD valid $k_\perp, Q_s \ll Q_\perp$

back-to-back hadrons/jets
and transverse momenta larger than sat scale

Improved TMD valid $Q_s \ll Q_\perp$

transverse momenta larger than sat scale

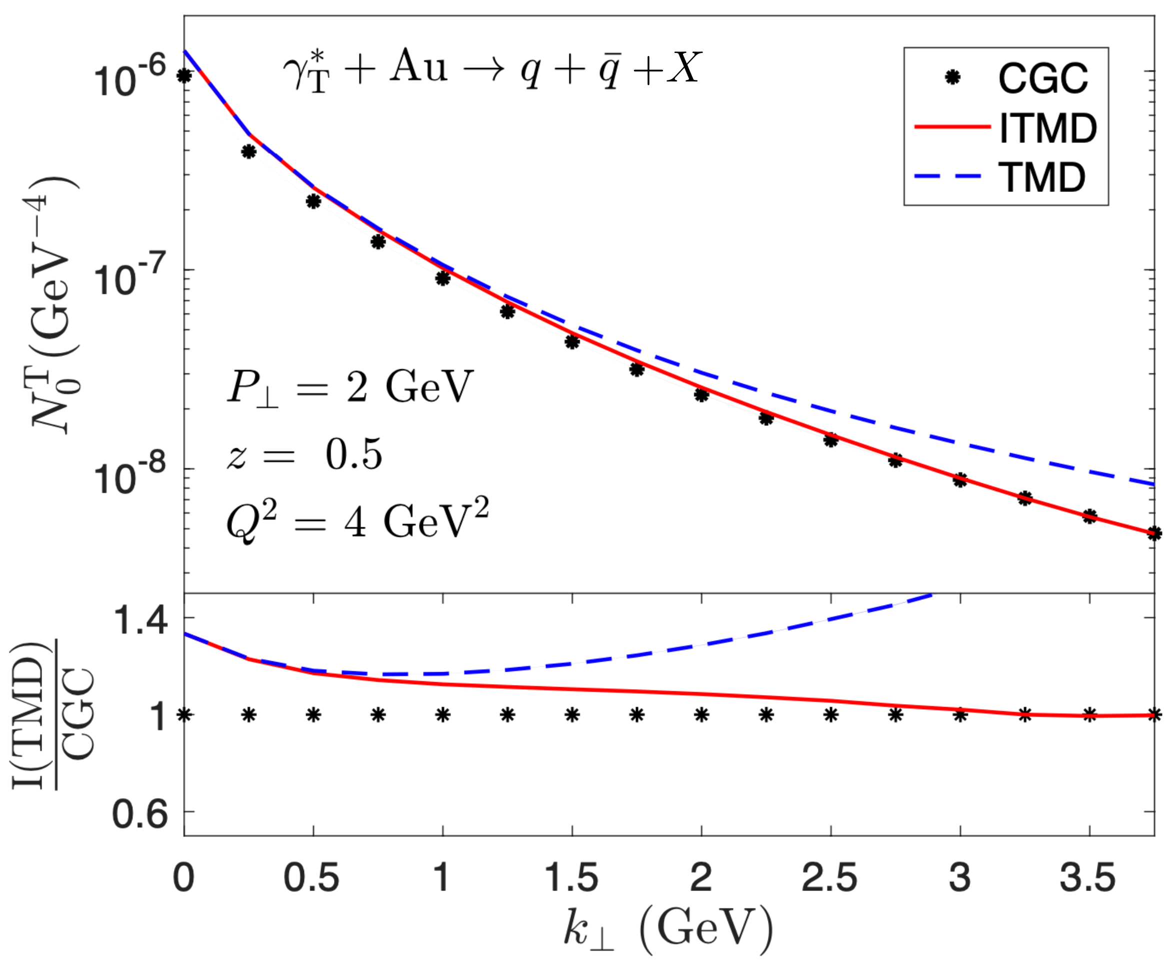
No need for back-to-back!

Matching TMD and CGC frameworks at small-x

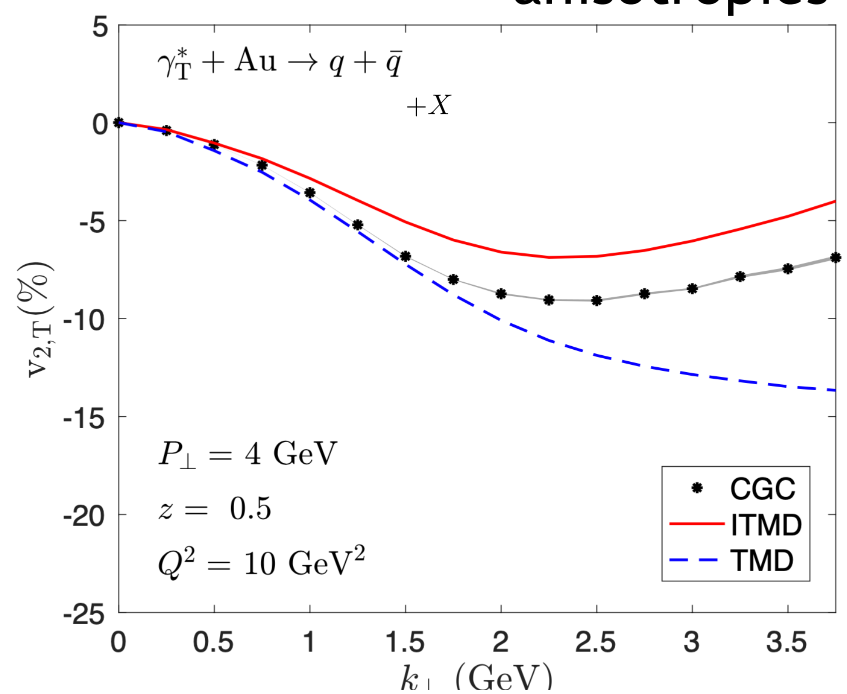
Kinematic and genuine higher saturation effects at the EIC

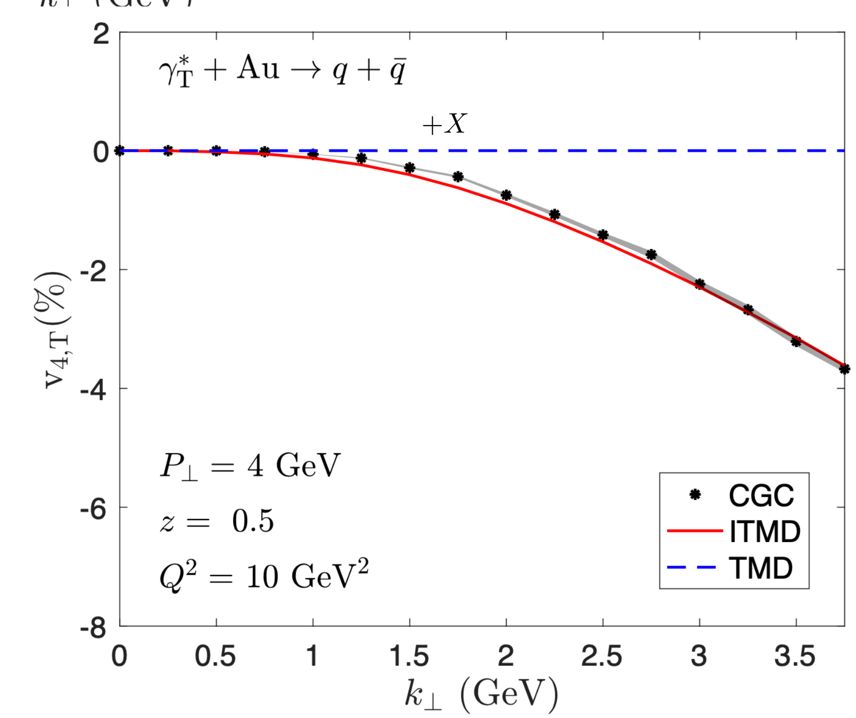
Boussarie, Mäntysaari, FS, Schenke. 2106.XXXXX

Differential yield

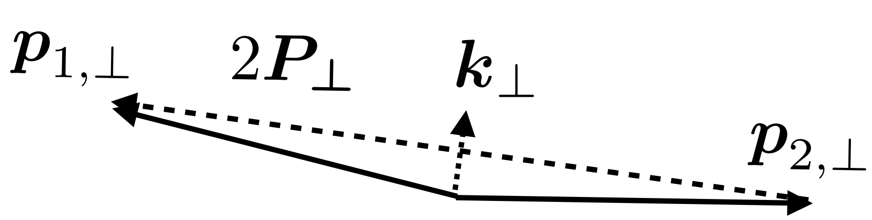


Momentum imbalance azimuthal anisotropies





CGC shows further suppression relative to TMD at back-to-back limit

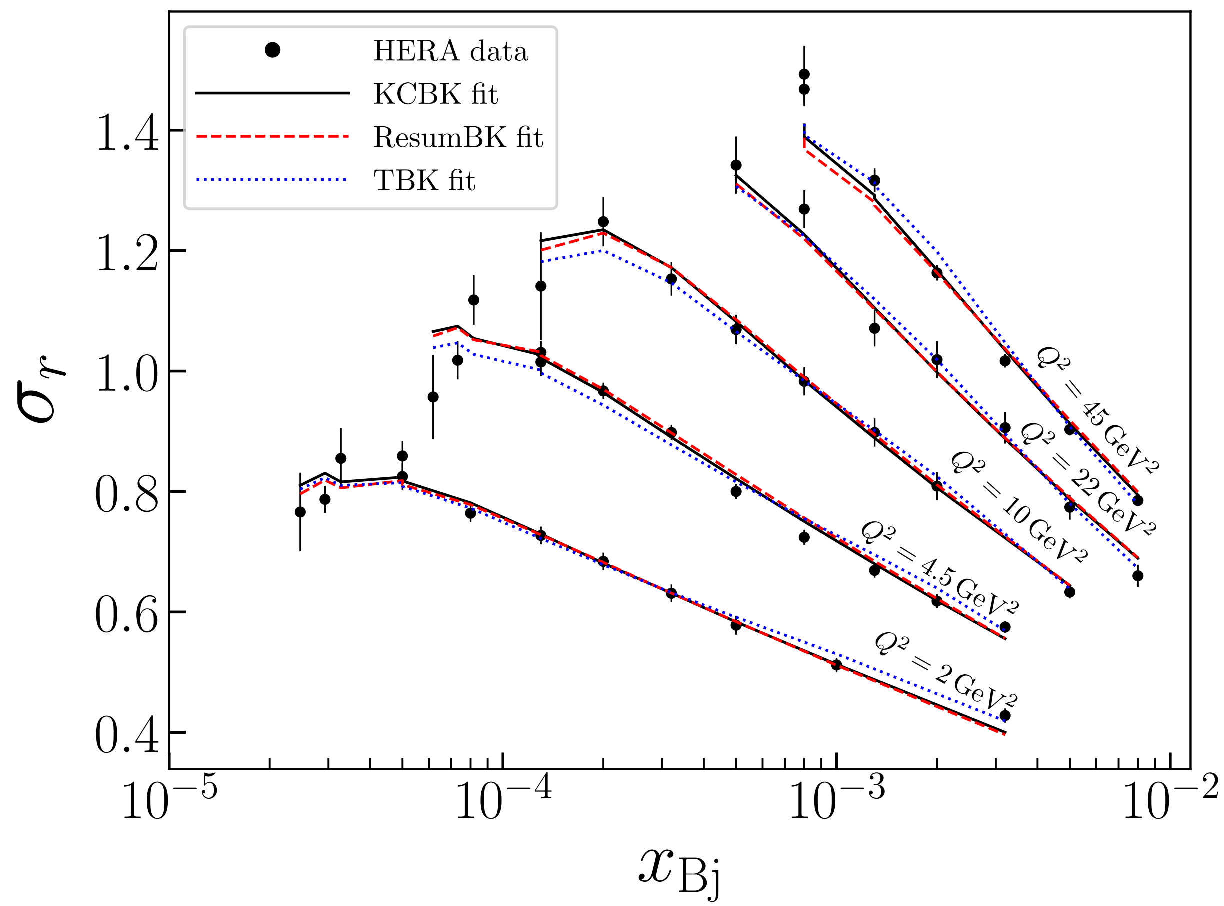


Anisotropies modified in ITMD and CGC

Next-to-leading order computations

Recent advances of NLO computations

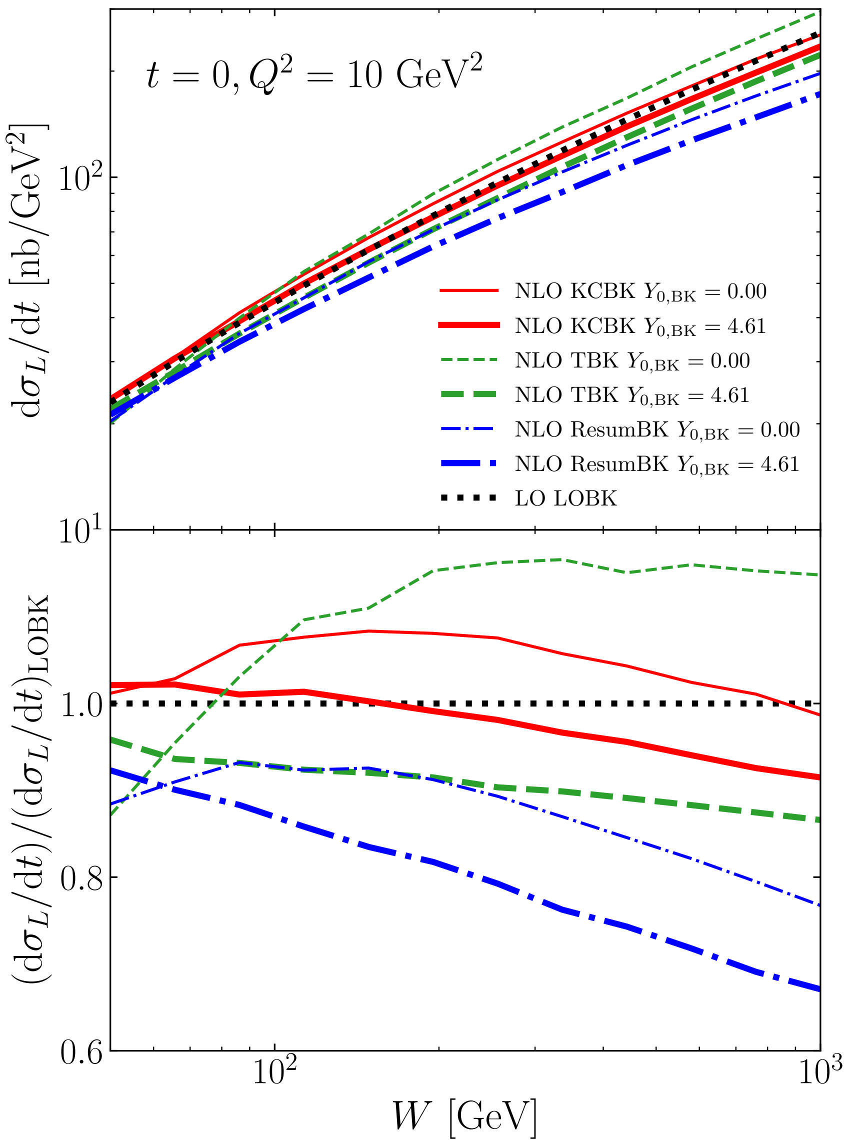
Reduced DIS cross-section fits with NLO BK + NLO impact factor*



Beuf, Lappi, Hänninen, Mäntysaari. 2007.01645

Should be extended to nuclear DIS for EIC predictions!

J/Ψ electron production (only L polarization) at NLO



Mäntysaari, Penttala. 2104.02349

Comparison with HERA data once T pol is theoretically available

* only light-quark contribution

Next-to-leading order computations

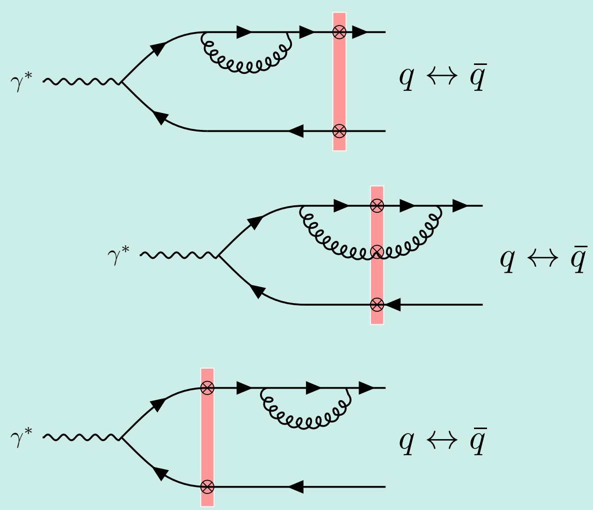
Dijet production at NLO

Caucal, FS, Venugopalan. 2107.XXXXX

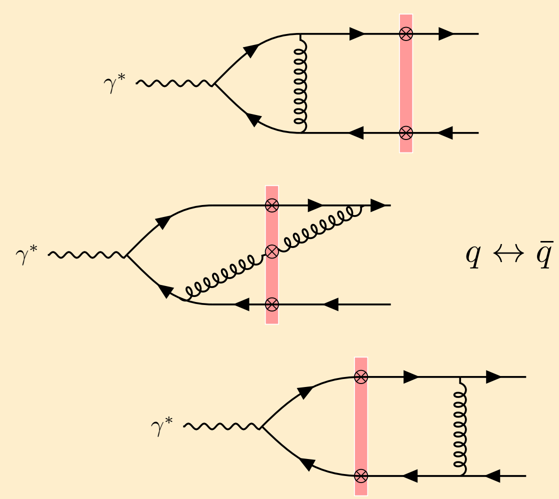
See also Roy, Venugopalan. 1911.04530 for photon+dijet

Computation of real and virtual contributions to dijet production

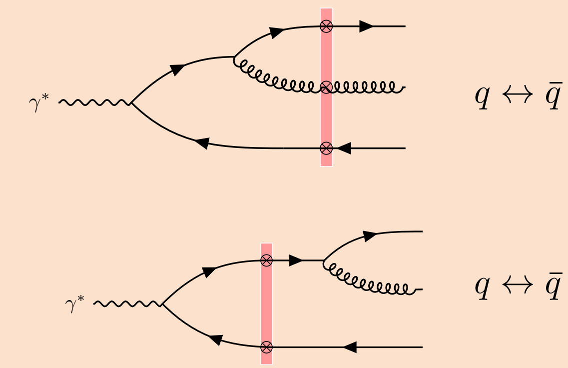
Self-energy contributions



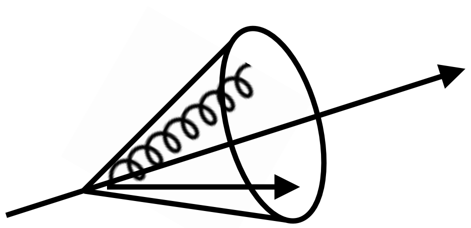
Vertex contributions



Real emission



Small-cone condition:



$$\mathcal{C}_{qg,\perp}^2 \leq \mathcal{C}_{qg,\perp}^2\big|_{\max} = R^2 \boldsymbol{p}_j^2 \min\left(\frac{z_g^2}{z_j^2}, \frac{(z_j - z_g)^2}{z_j^2}\right)$$

for proper jet definition

- *Cancellation of divergences:* *UV, soft and collinear*
- *Factorization of small-x:* *Leading Log JIMWLK evolution*
- *Numerically tractable expressions for impact factor*

Numerical results will be available in the near future!

Summary/Outlook

- Discovery of gluon saturation is one of the major goals of the future EIC

- The Color Glass Condensate is an EFT for this saturated regime that has been applied to calculate a variety of processes

- A wide variety of observables are available to search for gluon saturation:
  structure functions, diffractive processes and semi-inclusive measurements

- Recent advances in higher order computations and connections to TMD framework will allow to extend the robustness of theoretical predictions for the EIC

Other measurements at the EIC

- Exclusive dijet measurements and Wigner distribution

  Hatta, Xiao, Yuan. 1601.01585

  Mäntysaari, Mueller, Schenke. 1902.05087

- Incoherent diffraction and fluctuations

  Mäntysaari, Schenke. 1603.04349

  Mäntysaari, Roy, FS, Schenke. 2011.02464

- Single hadron/jet semi-inclusive production R_{eA} ratios

  Iancu, Mueller, Triantofyllopoulos, Wei. 2012.08562

- Inclusive quarkonia and WW gluon TMD

  Bacchetta, Boer, Pisano, Taels. 1809.02056

- Hadron+photon correlations

  Kolbé, Roy, FS, Schenke, Venugopalan. 2008.04372