Probing gluon saturation via diffractive jet production at the EIC

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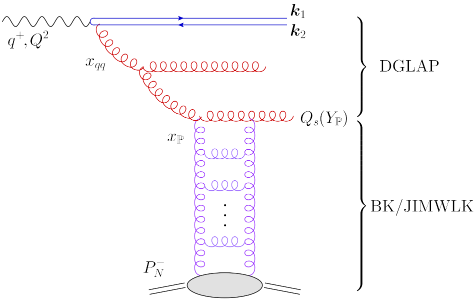
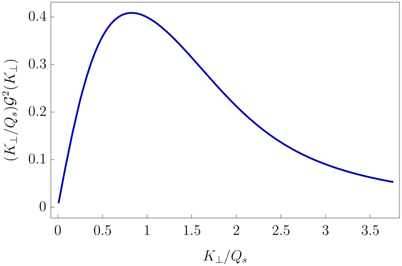
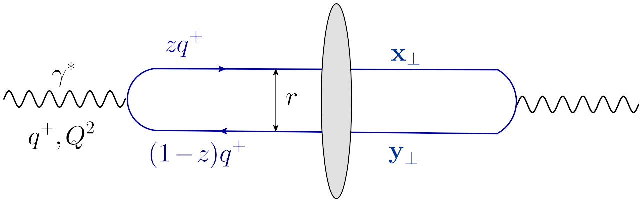
with A.H. Mueller and D.N. Triantafyllopoulos, arXiv:2112.06353





How to measure gluon saturation at the EIC ?

- Total $\gamma^* A$ cross-section at small $x_{\rm Bj} \equiv \frac{Q^2}{2P_N \cdot q}$ and not too high Q^2



- Excellent saturation/CGC fits at HERA: $x_{\rm Bj} \le 10^{-2}$, $Q^2 \le 50$ GeV^2
  - the pioneers: Golec-Biernat and Wüsthoff, 1999
  - Ducloué, E.I., Soyez and Triantafyllopoulos, 2019
  - Beuf, Hänninen, Lappi, Mäntysaari, 2020 ...
    (BK/JIMWLK, NLO effects, resummations) [talks by Anna, Tuomas]
- However, gluon saturation only marginally probed: $Q_s^2 \sim 1$ GeV^2
  - limited region in phase-space, non-perturbative contamination

How to measure gluon saturation at the EIC ?

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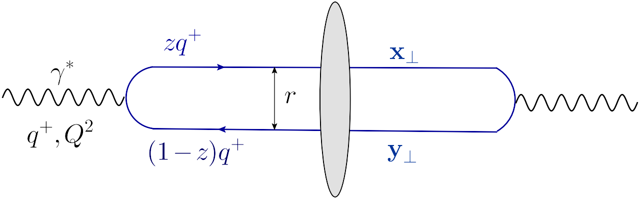

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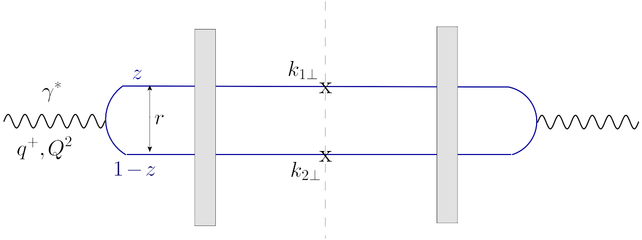
    (BK/JIMWLK, NLO effects, resummations) [talks by Anna, Tuomas]
- Can one measure saturation in hard DIS ? ($Q^2 \gg Q_s^2$)
- Consider more exclusive processes: correlations in particle production

Inclusive dijets in the correlation limit

- The $q\bar{q}$ fluctuation is put on shell by inelastic scattering off the nucleus



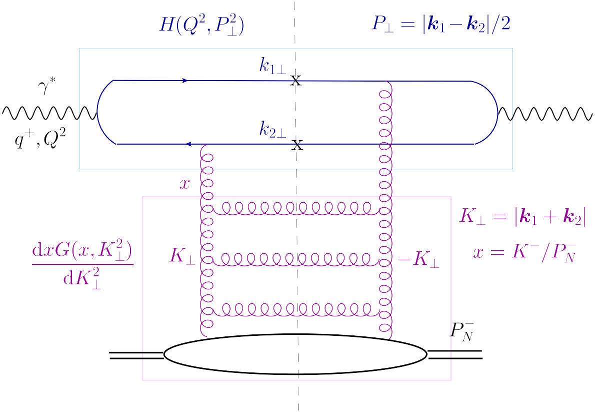
- Correlation limit : 2 hard jets which are nearly back-to-back

$$k_{1\perp} \simeq k_{2\perp} \sim Q \;\gg\; K_\perp \equiv |\boldsymbol{k}_{1\perp} + \boldsymbol{k}_{2\perp}| \sim Q_s$$

  - scattering is weak, by color transparency: small $q\bar{q}$ dipole: $r \sim 1/k_{i\perp}$
  - momentum imbalance fixed by scattering off the saturated gluons

- Measure saturation from azimuthal correlations ! *(Marquet, 2007)*
- TMD factorisation: hard impact factor $\times$ unintegrated gluon distribution *(Dominguez, Marquet, Xiao and Yuan, 2011)* [talk by Feng]

TMD factorisation for inclusive dijets

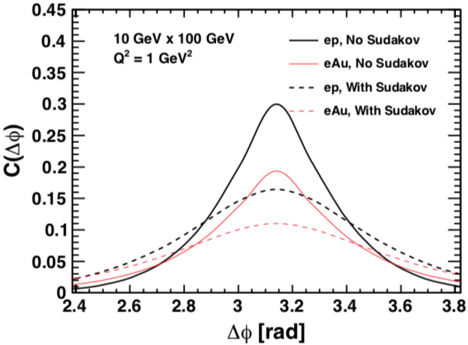


- For $Q^2 \gg Q_s^2$, one typically has $Q_s^2 \ll K_\perp^2 \ll Q^2$: saturation still marginal
    - the UGD decreases only like $1/K_\perp^2$ when $K_\perp \gg Q_s$
- Sudakov effect $\sim \alpha_s \ln^2(Q^2/Q_s^2)$ *(Mueller, Xiao and Yuan, 2013)*
    - strong additional broadening due to final-state radiation

Azimuthal correlations in dijets

(Zheng, Aschenauer, Lee, and Xiao, arXiv:1403.2413)

- Large competing effect due to final-state radiation ($Q \gg Q_s$): "Sudakov"



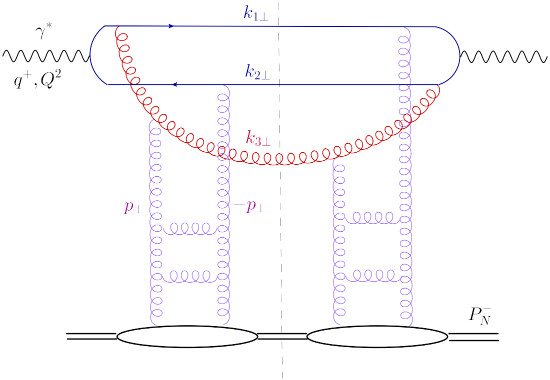
Metz, Zhou, 1105.1991; Dumitru, Lappi, Skokov, 1508.04438

Marquet, Petreska, Roiesnel, 1608.02577;

Dumitru, Skokov, Ullrich, 1809.02615; Mäntysaari et al, arXiv:1912:05586 ...

2+1 jets in hard DIS diffraction

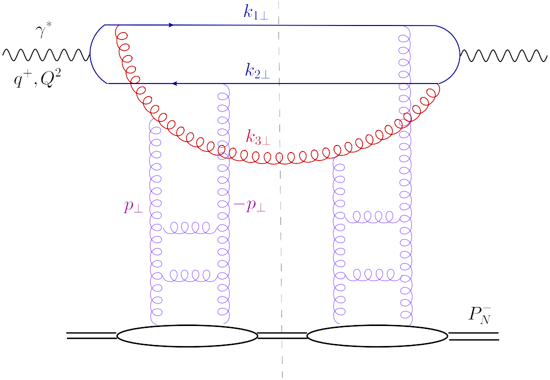
- 2 hard quark-antiquark jets + 1 softer gluon jet: $k_{1\perp}, k_{2\perp} \sim Q \gg k_{3\perp}$



- Coherent diffraction: elastic scattering, the target is not broken
  - colorless exchange (2-gluon ladder): "Pomeron"
  - rapidity gap $Y_{\mathbb{P}}$ between the 3 jets and the nucleus
  - the momentum transfer is negligible: $|\boldsymbol{k}_1 + \boldsymbol{k}_2 + \boldsymbol{k}_3| \sim \Lambda$

2+1 jets in hard DIS diffraction

- Hard dijet imbalance controlled by the gluon jet: $K_\perp \equiv |\boldsymbol{k}_1 + \boldsymbol{k}_2| \simeq k_{3\perp}$



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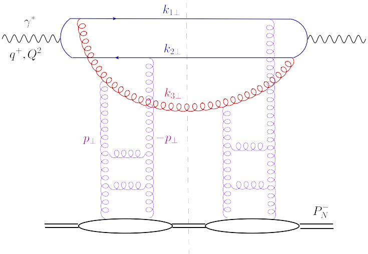
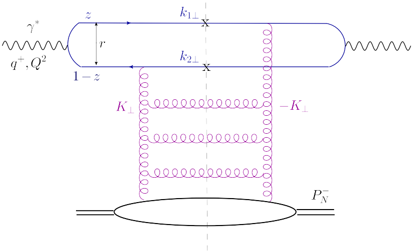
Why is this interesting ?

- Elastic scattering is more sensitive to gluon saturation [talk by Heikki]

$$\sigma_{el} \propto |\mathcal{A}_{el}|^2 \longleftrightarrow \sigma_{tot} \propto 2\,\mathrm{Im}\,\mathcal{A}_{el}$$



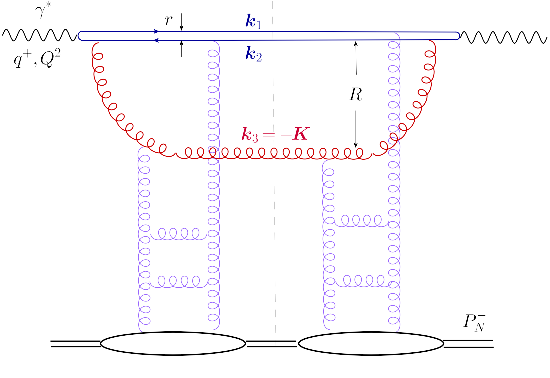


- At weak scattering $|\mathcal{A}_{el}| \ll 1$, elastic scattering is strongly suppressed
- Diffraction is controlled by strong scattering $|\mathcal{A}_{el}| \sim 1$: Black Disk Limit
- 2+1 jets: elastic scattering becomes strong when $k_{3\perp} \sim Q_s(Y_{\mathbb{P}})$
  - the gluon jet redistributes colour over a large transverse size $\sim 1/k_{3\perp}$

The gluon dipole

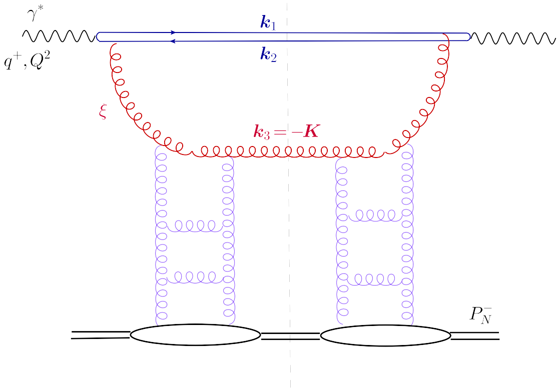
- The typical "hard dijet" events truly are 2+1 jets with $k_{3\perp} \sim Q_s(Y_{\mathbb{P}})$
  - dominate over exclusive dijets when $Q^2 \gg Q_s^2$
- A simpler, effective, picture for the colour flow *(Wüsthoff, 97)*

$R \sim 1/k_{3\perp} \sim 1/Q_s \gg r \sim 1/P_\perp \sim 1/Q \implies$ effective gg dipole



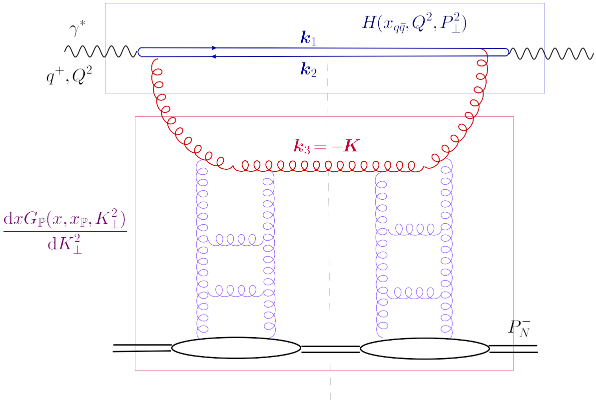
- 2+1 diffractive jets: an opportunity to measure the gluon dipole

TMD-like factorisation for diffractive dijets



- Gluon formation time $\tau_3 = \frac{2k_3^+}{k_{3\perp}^2} \lesssim$ photon coherence time $\tau_q = \frac{2q^+}{Q^2}$
- Soft gluon: $\xi \equiv \frac{k_3^+}{q^+} \lesssim \frac{k_{3\perp}^2}{Q^2} \ll 1 \implies$ eikonal approx $\implies$ factorisation

TMD-like factorisation for diffractive dijets



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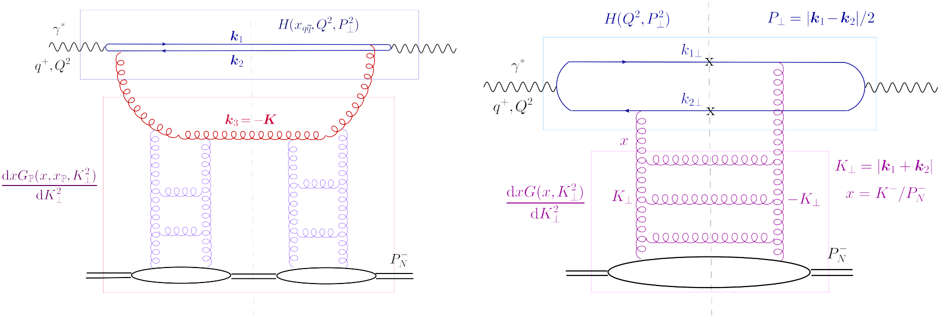
- Trijet cross-section $=$ Hard factor $\times$ UGD of the Pomeron

The hard impact factor

- Exactly the same for diffractive and inclusive dijets in the correlation limit

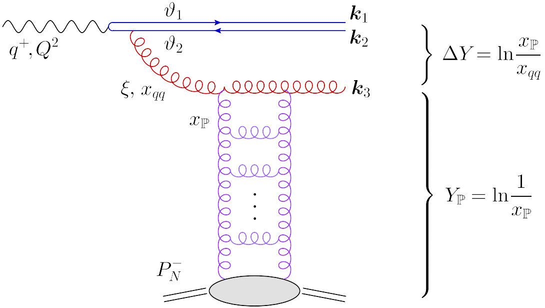


  - the decay of the virtual photon $\gamma^* \to q\bar{q}$
  - the scattering between a small $q\bar{q}$ pair and a gluon from the target

- What is different though is the actual source of this gluon
  - Pomeron (evolved to $x_{\mathbb{P}}$) vs. Hadronic target (evolved to $x_{q\bar{q}}$)

Rapidity scales

- $x_{\mathbb{P}}$: fraction of target longitudinal momentum P_N^- carried by the Pomeron
- $x_{q\bar{q}} \sim x_{\rm Bj}$: the corresponding quantity for the exchanged gluon
  - the exchanged gluon has $k^+ = \xi q^+$ and $k^- = x_{q\bar{q}} P_N^-$
- $x \equiv x_{q\bar{q}}/x_{\mathbb{P}}$: splitting fraction of the exchanged gluon w.r.t. the Pomeron



$$x \equiv \frac{x_{q\bar{q}}}{x_{\mathbb{P}}} = \frac{Q^2 + M_{q\bar{q}}^2}{Q^2 + M_{q\bar{q}g}^2}$$

$$M_{q\bar{q}}^2 = \frac{P_\perp^2}{\vartheta_1 \vartheta_2} \sim Q^2$$

$$M_{q\bar{q}g}^2 = M_{q\bar{q}}^2 + \frac{k_{3\perp}^2}{\xi}$$

- The eikonal approximation applies when $M_{q\bar{q}g}^2 \gg M_{q\bar{q}}^2$, or $x \ll 1$

The Pomeron unintegrated gluon distribution (1)

$$\frac{\mathrm{d}\, xG_{\mathbb{P}}(x, x_{\mathbb{P}}, K_\perp^2)}{\mathrm{d}^2\boldsymbol{K}\mathrm{d}^2\boldsymbol{b}} = \frac{N_c^2-1}{8\pi^4}\left[\mathcal{G}(K_\perp, Y_{\mathbb{P}})\right]^2$$

- $\mathcal{G}(K_\perp, Y_{\mathbb{P}})$: a Fourier transform of the gluon dipole scattering amplitude

$$\mathcal{G}(K_\perp, Y_{\mathbb{P}}) = 2\int_0^\infty \frac{\mathrm{d}R}{R}\,\mathrm{J}_2(K_\perp R)\mathcal{T}_g(R, Y_{\mathbb{P}})$$

  - integral controlled by dipole sizes $R \sim 1/K_\perp$

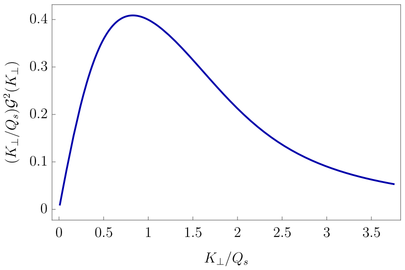
$$\mathcal{T}_g(R) \simeq \begin{cases} r^2 Q_s^2, & R \ll 1/Q_s \\ 1, & R \gg 1/Q_s \end{cases} \quad\Longrightarrow\quad \mathcal{G}(K_\perp) \simeq \begin{cases} Q_s^2/K_\perp^2, & K_\perp \gg Q_s \\ 1, & K_\perp \ll Q_s \end{cases}$$

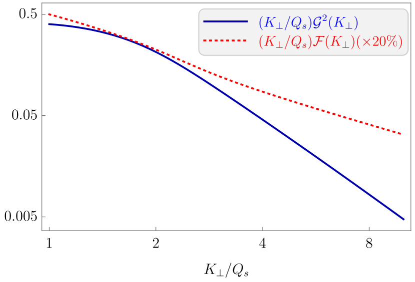
  - saturation scale is harder for a gluon dipole: $Q_s^2(gg) = (9/4)Q_s^2(q\bar{q})$

- Similar to the Weiszäcker-Williams gluon TMD from inclusive dijets ... except that the diffractive cross-section involves the square of $\mathcal{G}(K_\perp)$

The Pomeron unintegrated gluon distribution (2)

- At large $K_\perp \gg Q_s$, $\mathcal{G}^2(K_\perp) \propto 1/K_\perp^4$ decreases very fast.
  - the bulk of the diffractive cross-section lies at momenta $K_\perp \lesssim Q_s(Y_\mathbb{P})$





- Diffractive trijets are more sensitive to saturation than inclusive dijets
  - no need to explicitly measure (or even see) the third, softer, jet
  - study the distribution of the hard dijets in their momentum imbalance $K_\perp$, for various values of the rapidity gap $\Longrightarrow$ $Q_s(Y_\mathbb{P})$

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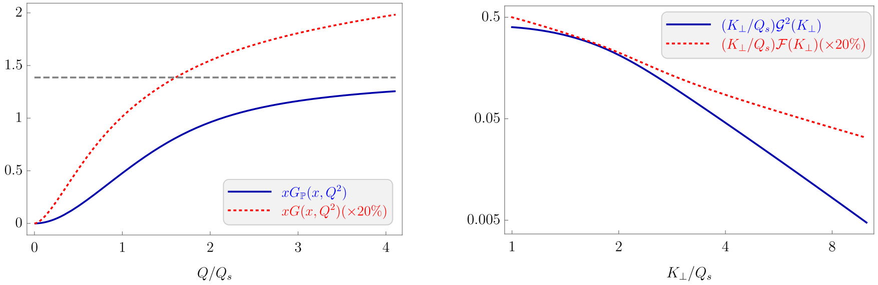
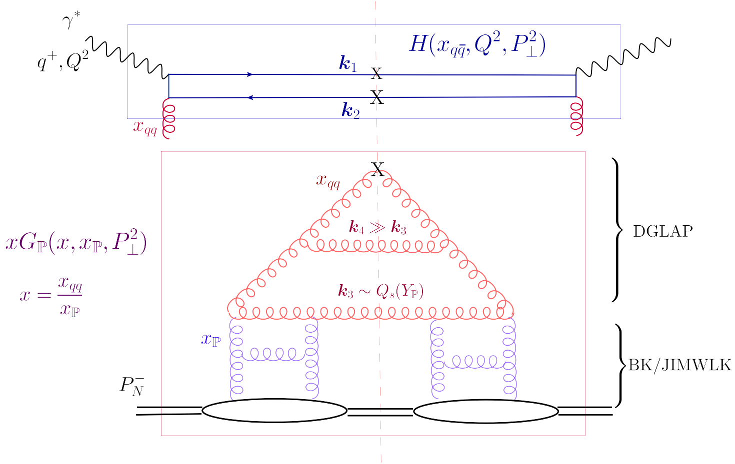


- This sensitivity persists after integrating out the $K_\perp$–distribution.
  - the integrated gluon distribution of the Pomeron $xG_\mathbb{P}(x, x_\mathbb{P}, Q^2)$

$$xG_\mathbb{P}(x, x_\mathbb{P}, Q^2) \propto Q_s^2(Y_\mathbb{P}) \qquad \text{vs.} \qquad xG(x, Q^2) \propto Q_0^2 \ln \frac{Q^2}{Q_0^2}$$

Collinear factorisation for diffractive dijets

- Measure the dijet distribution integrated over the imbalance $K_\perp$



$$\frac{d\sigma_D^{\gamma^* A \to q\bar{q}A' X}}{dy_1 dy_2 d^2\boldsymbol{P} dY_{\mathbb{P}}} = H(x_{q\bar{q}}, Q^2, P_\perp^2)\, xG_{\mathbb{P}}(x, x_{\mathbb{P}}, P_\perp^2)$$

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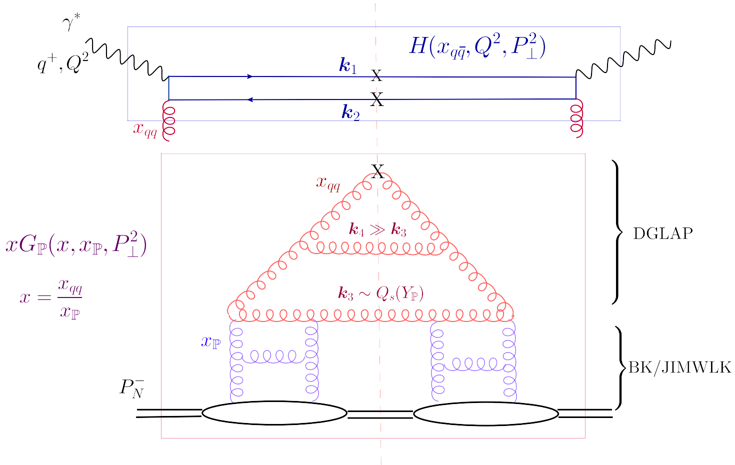
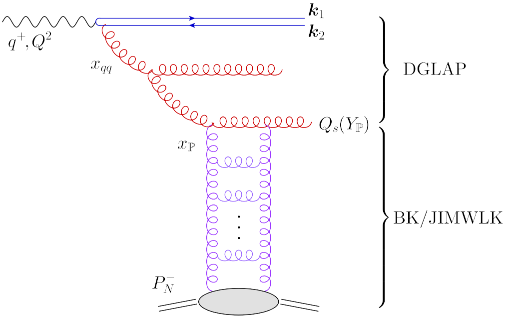


- eliminates the Sudakov effect $\sim \alpha_s \ln^2 \frac{P_\perp^2}{K_\perp^2}$ (final state radiation)
- Sudakov double logs replaced by the DGLAP single logs $\sim \alpha_s \ln \frac{P_\perp^2}{K_\perp^2}$

Collinear factorisation for diffractive dijets

- Gluon saturation provides the initial condition for the DGLAP evolution



- $xG_{\mathbb{P}}(x, x_{\mathbb{P}}, Q^2)$ for $Q^2 \sim Q_s^2(Y_{\mathbb{P}})$ and for any $x \leq 1$
- $x \equiv x_{q\bar{q}}/x_{\mathbb{P}}$: splitting fraction w.r.t. the Pomeron
- $x \sim 1$ is beyond eikonal approx.
- exploit black disk limit

$$xG_{\mathbb{P}}(x, x_{\mathbb{P}}, Q^2) = S_{\perp}(1-x)^2 \frac{N_c^2 - 1}{(2\pi)^3} \kappa \, Q_s^2(Y_{\mathbb{P}})$$

- A unique situation where DGLAP and BK/JIMWLK can be interconnected
- Diffraction matches the two evolutions at a fixed transverse scale $Q_s^2(Y_{\mathbb{P}})$

Collinear factorisation for diffractive dijets

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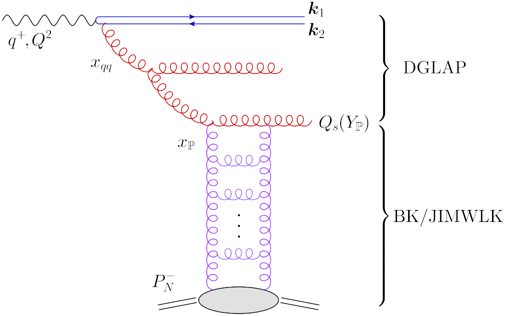

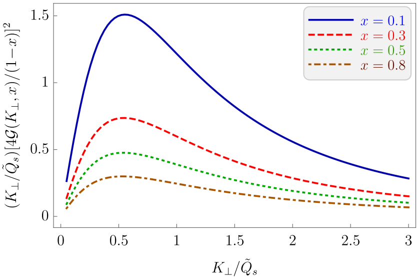

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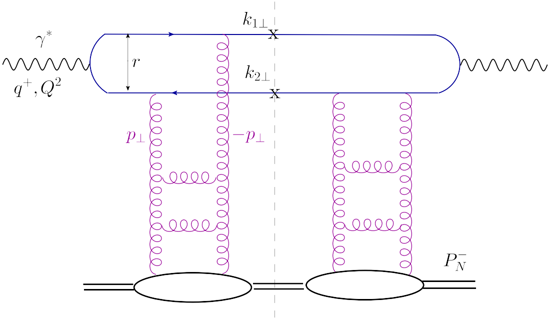
Conclusions

- A new, hard, process to study gluon saturation via final-state correlations
  - yet another avatar of "dijet production in the correlation limit"
- Especially sensitive to saturation since relying on elastic scattering
- Additional, comparatively soft, radiation plays an essential role:
  - use the 3rd jet to "open up the colour space" *(Bowen, via email)*
  - large-size (R), effective, gluon-gluon dipole
  - use elastic scattering as a filter to select $R \sim 1/Q_s$
- The actual measurement of the gg dipole would be a bonus !
- Saturation remains important if the dijet correlation is not measured
  - initial condition for DGLAP evolution emerging from first principles
- Similar processes might be interesting in ultraperipheral pA and AA

THANK YOU & STAY HEALTHY !

Back-up: Exclusive hard dijet production

- Elastic scattering off a small quark-antiquark dipole: $r \sim 1/P_\perp \ll 1/Q_s(Y)$
  - scattering is weak by colour transparency: $\mathcal{T}(r, Y) \simeq r^2 Q_s^2(Y) \ll 1$
  - cross-section: $\mathcal{T}^2(r, Y) \propto r^4$: strongly suppressed at high $P_\perp^2$



$$\sigma_{\rm el} \propto \frac{1}{P_\perp^6}\left[\frac{\alpha_s\, xG(x, P_\perp^2)}{S_\perp}\right]^2 \quad \longleftrightarrow \quad \sigma_{\rm diff} \propto \frac{\alpha_s}{P_\perp^4}\, Q_s^2(Y_{\mathbb{P}})$$