Probing gluon saturation via diffractive jets in photon-nucleus interactions

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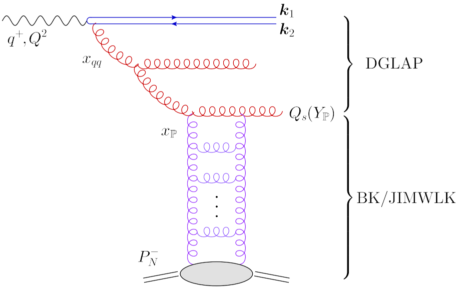
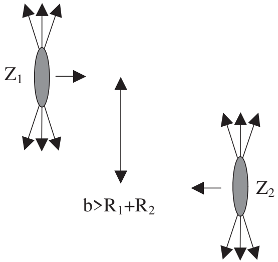
arXiv:2112.06353 (PRL) & 2207.06268 & 2304.12401



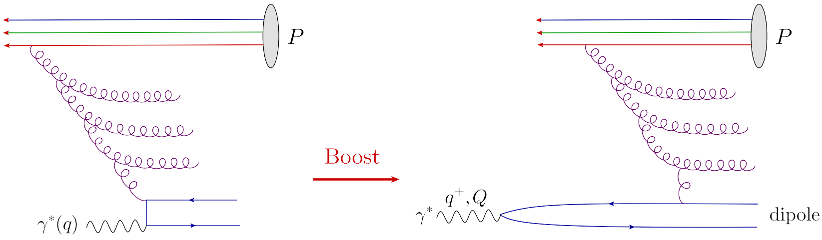


Outline

- Diffractive dijet production in photon-nucleus interactions at high energy: a golden channel to study saturation
  - electron-nucleus DIS at the future EIC (LHeC ?)
  - nucleus-nucleus UPCs at the LHC
- Why diffraction ?
  - elastic scattering $\Rightarrow$ controlled by strong scattering ("black disk limit")
  - particularly sensitive to high parton densities/gluon saturation
- Diffractive jets: a unique example of a hard process ($P_\perp \gg Q_s \sim 1$ GeV) which is controlled by the physics of saturation
  - hard processes are easy to measure
  - a priori, well described by the collinear factorisation
  - saturation hidden in the diffractive PDFs ("non-perturbative")
- The CGC allows one to compute diffractive dijets from first principles
  - collinear (actually, TMD) factorisation emerges from the CGC

Dipole picture for DIS at high energy

- Small Bjorken $x_{\rm Bj} = \frac{Q^2}{2q\cdot P} \ll 1$: convenient to work in the dipole frame
  - Lorentz boost to a frame where the dipole is energetic: large q^+

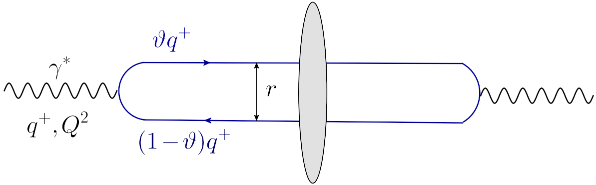


$$x_{\rm Bj} = \frac{Q^2}{2P^- q^+} \ll 1 \iff \Delta x^+ \simeq \frac{2q^+}{Q^2} \gg \frac{1}{P^-}$$

- the virtual photon fluctuates into a $q\bar{q}$ pair long before the scattering
- the $q\bar{q}$ color dipole acts as a probe of the gluon distribution
- the dipole transverse size r is preserved by the scattering

Dipole factorisation for inclusive DIS

- Photon wavefunction ($\gamma^* \to q\bar{q}$) times dipole scattering (known to NLO)

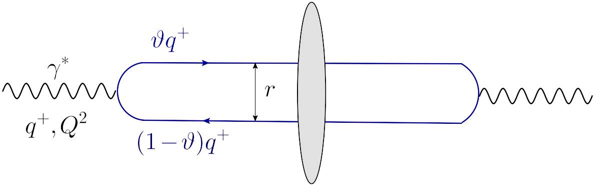


$$\sigma_{\gamma^* A}(Q^2, x) = \int \mathrm{d}^2 r \int_0^1 \mathrm{d}\vartheta \left|\Psi_{\gamma^* \to q\bar{q}}(r, z; Q^2)\right|^2 \underbrace{\sigma_{\text{dipole}}(r, A, x)}_{2\pi R_A^2\, T_A(r,x)}$$

- Dipole amplitude $T_A(r, x)$: solution to BK/JIMWLK equations (to NLO)

$$T_A(r,x) \simeq \begin{cases} r^2 Q_s^2(A,x) & \text{for } rQ_s \ll 1 \text{ (color transparency)} \\ 1 & \text{for } rQ_s \gtrsim 1 \text{ (black disk/saturation)} \end{cases}$$

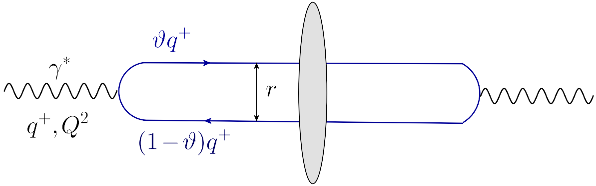
- Saturation momentum: $Q_s^2(A, x) \sim A^{1/3}/x^{\lambda_s}$ with $\lambda_s \sim 0.3$



$$\sigma_{\gamma^* A}(Q^2, x) = \int \mathrm{d}^2 r \int_0^1 \mathrm{d}\vartheta \left|\Psi_{\gamma^* \to q\bar{q}}(r, z; Q^2)\right|^2 \underbrace{\sigma_{\text{dipole}}(r, A, x)}_{2\pi R_A^2\, T_A(r,x)}$$

- Dipole size limited by virtuality: $r^2 \lesssim 1/\bar{Q}^2$ with $\bar{Q}^2 \equiv \vartheta(1-\vartheta)Q^2$
- To probe saturation, one needs $r \gtrsim 1/Q_s$, hence $\bar{Q}^2 \lesssim Q_s^2$
- A priori, two interesting situations:
  - symmetric jets $\vartheta \sim 1/2$, but semi-hard photon: $Q^2 \sim Q_s^2$
  - hard photon $Q^2 \gg Q_s^2$, but asymmetric jets (“aligned”): $\vartheta(1-\vartheta) \ll 1$

Inclusive DIS in the dipole picture



$$\sigma_{\gamma^* A}(Q^2, x) = \int \mathrm{d}^2 r \int_0^1 \mathrm{d}\vartheta \left|\Psi_{\gamma^* \to q\bar{q}}(r, z; Q^2)\right|^2 \underbrace{\sigma_{\text{dipole}}(r, A, x)}_{2\pi R_A^2\, T_A(r,x)}$$

- Excellent fits to ep data (F_2, F_L, F_{2c}) at HERA: $x \leq 10^{-2}$, $Q^2 \leq 50$ GeV^2
- However, inclusive DIS probes (quasi)symmetric $q\bar{q}$ configurations

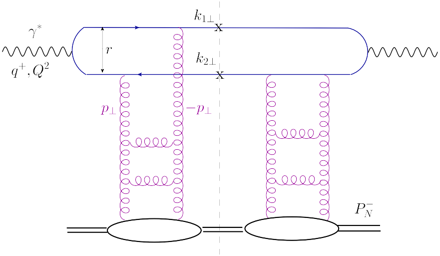
  $\Rightarrow$ gluon saturation probed only for low $Q^2 \sim Q_s^2 \lesssim 1$ GeV^2

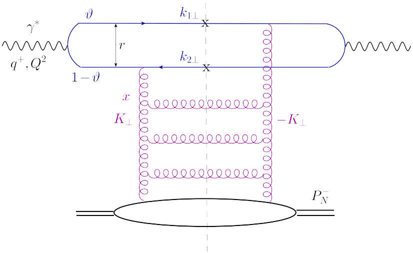
  - limited region in phase-space, non-perturbative contamination ☹
- Can one measure saturation directly at high Q^2 ?

Diffraction: F_{2D}

- Elastic scattering/diffraction is more sensitive to strong scattering

$$\sigma_{el} \propto |T|^2 \longleftrightarrow \sigma_{tot} \propto 2\text{Im}\,T$$





- Colourless exchange: 2-gluon ladder, (BFKL) Pomeron, rapidity gap $Y_{\mathbb{P}}$
- F_{2D} controlled by the black disk limit $(T \sim 1)$ even when $Q^2 \gg Q_s^2$
  - asymmetric $q\bar{q}$ pairs, $\vartheta(1-\vartheta) \ll 1$, with large size $r \sim 1/Q_s$
  - would be non-perturbative, $r \sim 1/\Lambda$, in absence of saturation

One vs two Pomerons... at HERA

- Naively (2-gluon exchange): $\sigma_{\rm diff}$ rises with $\frac{1}{x}$ or with A like two Pomerons

$$T^2 \simeq \left(r^2 Q_s^2(A,x)\right)^2 \propto \frac{A^{2/3}}{x^{2\lambda_s}} \qquad \text{vs.} \qquad T \simeq r^2 Q_s^2(A,x) \propto \frac{A^{1/3}}{x^{\lambda_s}}$$

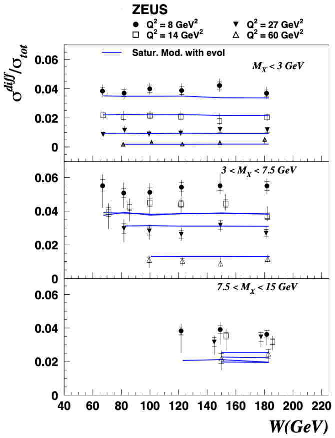


Figure 9: The ratio of $\sigma_{diff}/\sigma_{tot}$ versus the $\gamma^* p$ energy W. The data is from ZEUS and the solid

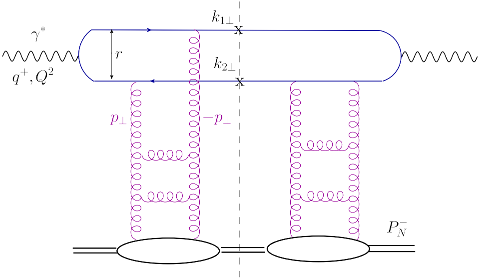
- But it doesn't! Diffraction is controlled by $T \sim 1$, or $r \sim 1/Q_s$
- Almost the same scaling as σ_{tot}:

$$\frac{\sigma_{el}}{\sigma_{tot}} \sim \frac{1}{\ln\left(Q^2/Q_s^2\right)}$$

- Weak x-dependence confirmed by HERA *(Bartels, Golec-Biernat, Kowalski, 2002)*
- Would be interesting to also check the A-dependence at the EIC

Exclusive dijets is higher twist

- What would be a jet measurement analogous to F_{2D} ?
- Elastic scattering can also produce exclusive dijets:
  - a $q\bar{q}$ pair which is hard: $k_{1\perp} \simeq k_{2\perp} \equiv P_\perp \gg Q_s$ & symmetric: $\vartheta \sim 1/2$
- ... but these are rare events ("higher twist"), insensitive to saturation:
  - $\sigma_{\rm el} \sim |T_{q\bar{q}}(r, Y_{\mathbb{P}})|^2$ with $r \sim 1/P_\perp$
  - $P_\perp \gg Q_s(Y_{\mathbb{P}})$: small dipole $\Longrightarrow$ weak scattering



- rapidity gap $Y_{\mathbb{P}} = \ln \frac{1}{x_{\mathbb{P}}}$

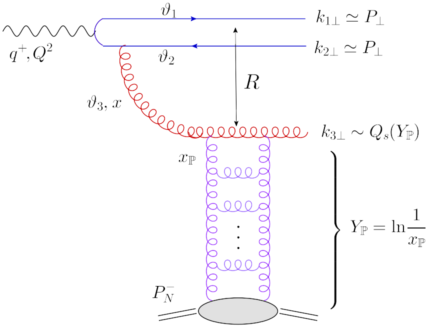
$$\frac{{\rm d}\sigma_{\rm el}^{\gamma A \to q\bar{q}A}}{{\rm d}\vartheta_1 {\rm d}\vartheta_2 {\rm d}^2\boldsymbol{P}} \propto \frac{1}{P_\perp^6}$$

$$Q_s^2 \equiv Q_s^2(A, Y_{\mathbb{P}}) \sim A^{1/3}\, {\rm e}^{0.3 Y_{\mathbb{P}}}$$

Diffractive 2+1 jets

(E.I., A.H. Mueller, D.N. Triantafyllopoulos, Phys.Rev.Lett. 128 (2022) 20)

- Can one have diffractive dijets at leading twist ? $(\sim 1/P_\perp^4)$
- Yes ... provided one allows for strong scattering !
- 2+1 jets: 2 hard $(P_\perp \gg Q_s)$ and 1 semi-hard $(k_{3\perp} \sim Q_s)$



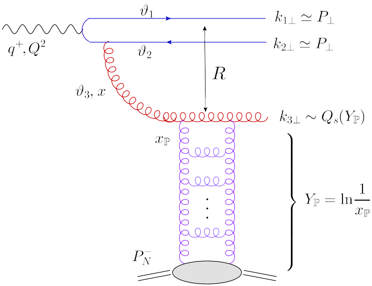
$$R \sim \frac{1}{Q_s} \gg r \sim \frac{1}{P_\perp}$$

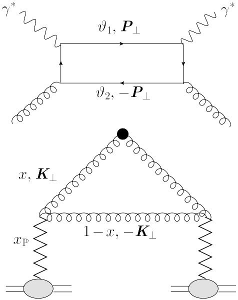
- Effective gluon-gluon dipole
- Strong scattering: $T_{gg}(R, Y_{\mathbb{P}}) \sim 1$
- Semi-inclusive dijet production
- $\mathcal{O}(\alpha_s)$, but leading-twist

- 3rd jet controls the hard dijet imbalance: $K_\perp \equiv |\boldsymbol{k}_1 + \boldsymbol{k}_2| = k_{3\perp} \ll P_\perp$

TMD factorisation for diffractive 2+1 jets

- The third jet is relatively soft: $k_3^+ = \vartheta_3 q^+$ with $\vartheta_3 \sim \frac{Q_s^2}{Q^2} \ll 1$
  - gluon formation time must be small enough to scatter: $\frac{k_3^+}{k_{3\perp}^2} \lesssim \frac{q^+}{Q^2}$
- It can alternatively be seen as a part of the Pomeron wavefunction
  - boost back to target infinite momentum frame & change gauge

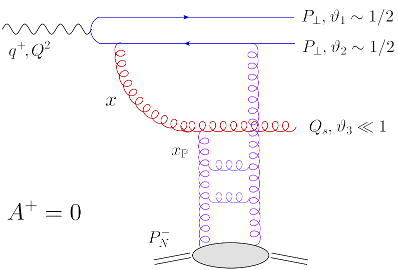


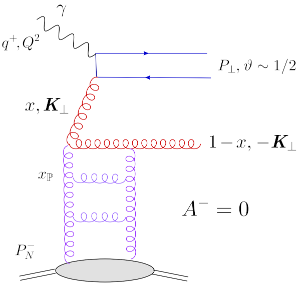


- x: energy fraction of the exchanged gluon with respect to the Pomeron

TMD factorisation for diffractive 2+1 jets (2)

- The strong ordering in both $k_\perp$ and k^+ is essential for factorisation
- The dipole picture holds in the projectile light cone gauge $A^+ = 0$
  - right moving partons couple to the A^- component of the target field

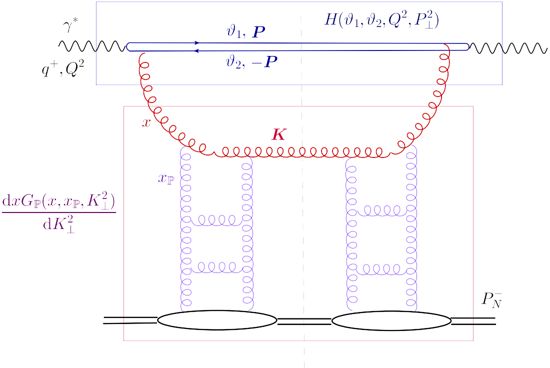




- The TMD picture holds in the target light cone gauge $A^- = 0$
  - only the soft gluon couples to the target field: $v^i A^i$ with $v^i = k^i / k^+$

TMD factorisation for diffractive 2+1 jets (3)

$$\frac{\mathrm{d}\sigma_{2+1}^{\gamma_{T,L}^* A\to q\bar{q}gA}}{\mathrm{d}\vartheta_1\mathrm{d}\vartheta_2\mathrm{d}^2\boldsymbol{P}\mathrm{d}^2\boldsymbol{K}\,\mathrm{d}Y_{\mathbb{P}}} = H_{T,L}(\vartheta_1,\vartheta_2,Q^2,P_\perp^2)\,\frac{\mathrm{d}xG_{\mathbb{P}}(x,x_{\mathbb{P}},K_\perp^2)}{\mathrm{d}^2\boldsymbol{K}}$$

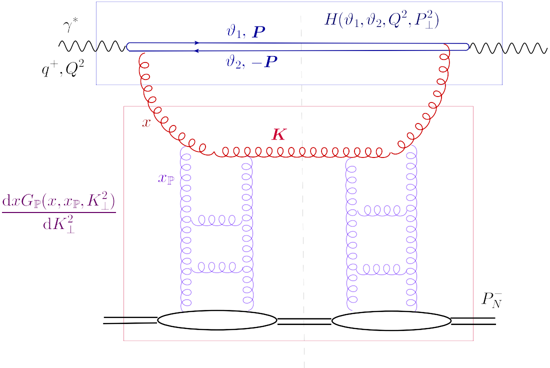


- The hard factor: $\gamma^* \to q\bar{q}$ decay & the gluon emission

$$H_T = \alpha_{\rm em}\alpha_s\left(\sum e_f^2\right)\vartheta_1\vartheta_2(\vartheta_1^2+\vartheta_2^2)\,\frac{1}{P_\perp^4}\quad \text{when } Q^2 \ll P_\perp^2$$

TMD factorisation for diffractive 2+1 jets (3)

$$\frac{\mathrm{d}\sigma_{2+1}^{\gamma_{T,L}^{*}A\to q\bar{q}gA}}{\mathrm{d}\vartheta_1\mathrm{d}\vartheta_2\mathrm{d}^2\boldsymbol{P}\mathrm{d}^2\boldsymbol{K}\mathrm{d}Y_{\mathbb{P}}} = H_{T,L}(\vartheta_1,\vartheta_2,Q^2,P_\perp^2)\,\frac{\mathrm{d}xG_{\mathbb{P}}(x,x_{\mathbb{P}},K_\perp^2)}{\mathrm{d}^2\boldsymbol{K}}$$



- The unintegrated gluon distribution of the Pomeron: a diffractive TMD
- Implicit in early studies of inclusive diffraction
  (Hebecker, Golec-Biernat, Wüsthoff, Hautmann, Soper ... 97-01)

The Pomeron UGD

$$\frac{\mathrm{d}xG_{\mathbb{P}}(x, x_{\mathbb{P}}, K_\perp^2)}{\mathrm{d}^2\boldsymbol{K}} = \frac{S_\perp(N_c^2-1)}{4\pi^3} \underbrace{\Phi_g(x, x_{\mathbb{P}}, K_\perp^2)}_{\text{occupation number}}$$

- Explicitly computed in terms of the gluon-gluon dipole amplitude $T_{gg}(R, Y_{\mathbb{P}})$

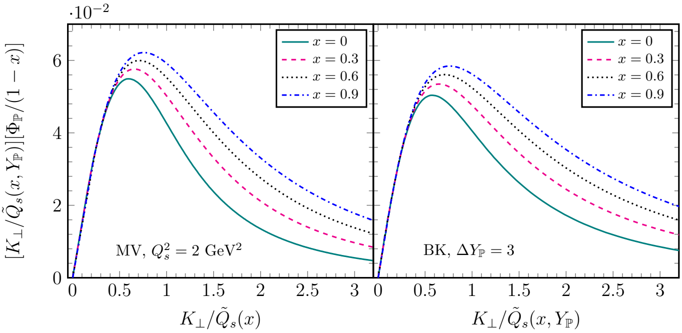
$$\Phi_g(x, x_{\mathbb{P}}, K_\perp^2) \simeq (1-x)\begin{cases} 1, & K_\perp \lesssim \tilde{Q}_s(x) \\ \dfrac{\tilde{Q}_s^4(x)}{K_\perp^4}, & K_\perp \gg \tilde{Q}_s(x) \end{cases}$$

- Valid for small $x_{\mathbb{P}} \lesssim 10^{-2}$ but any $x \le 1$
  - effective saturation momentum: $\tilde{Q}_s^2(x, Y_{\mathbb{P}}) = (1-x)Q_s^2(Y_{\mathbb{P}})$
- Very fast decrease $\sim 1/K_\perp^4$ at large gluon momenta $K_\perp \gg \tilde{Q}_s(x)$
- The bulk of the distribution lies at saturation: $K_\perp \lesssim \tilde{Q}_s(x)$

Numerical results

(E.I., A.H. Mueller, D.N. Triantafyllopoulos, S.-Y. Wei, arXiv:2207.06268)

- Left: McLerran-Venugopalan model. Right: adding high-energy evolution
- Pronounced peak at $K_\perp \simeq \tilde{Q}_s$: diffraction is controlled by saturation



- BK evolution of $T_{gg}(R, Y_\mathbb{P})$: evolution of $\Phi_\mathbb{P}(x, x_\mathbb{P}, K_\perp)$ in $x_\mathbb{P}$ and $K_\perp$
  - increasing $Q_s^2(Y_\mathbb{P})$, but the shape remains the same (geometric scaling)

The gluon diffractive PDF

- By integrating the gluon momentum $K_\perp$: the usual collinear factorisation

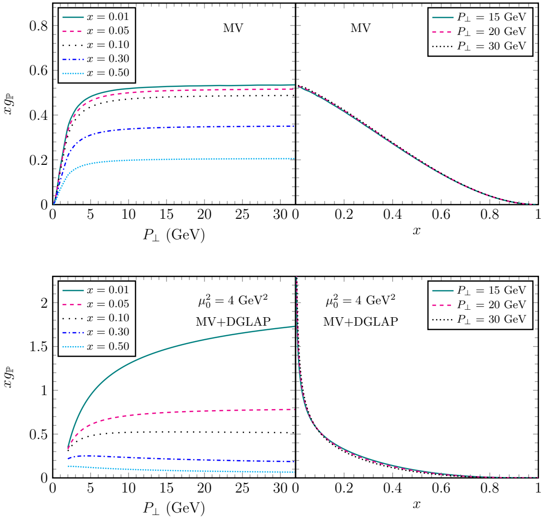
$$\frac{d\sigma_{2+1}^{\gamma A\to q\bar{q}gA}}{d\vartheta_1 d\vartheta_2 d^2\boldsymbol{P} dY_{\mathbb{P}}} = H(\vartheta_1,\vartheta_2,Q^2,P_\perp^2)\, xG_{\mathbb{P}}(x,x_{\mathbb{P}},P_\perp^2)$$

- ... but with an explicit result for the gluon diffractive PDF:

$$xG_{\mathbb{P}}(x,x_{\mathbb{P}},P_\perp^2) \equiv \int^{P_\perp} d^2\boldsymbol{K}\, \frac{dxG_{\mathbb{P}}(x,x_{\mathbb{P}},K_\perp^2)}{d^2\boldsymbol{K}} \,\propto\, (1-x)^2\, Q_s^2(A,Y_{\mathbb{P}})$$

- The integral is rapidly converging and effectively cut off at $K_\perp \sim \tilde{Q}_s(x)$
- The $(1-x)^2$ vanishing at the end point is a hallmark of saturation
- DGLAP evolution with increasing $P_\perp^2$
- Initial condition for DGLAP determined by saturation (MV+BK)

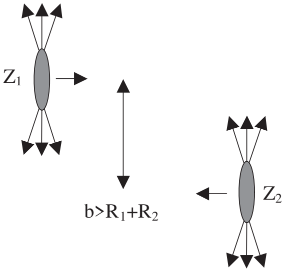
The gluon diffractive PDF: numerical results

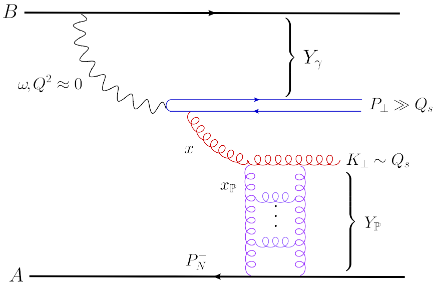


- DGLAP: increase for very small $x \le 0.01$, slight decrease for $x > 0.05$
- When $x \to 1$, the distribution vanishes even faster

2+1 diffractive dijets in AA UPCs

- Large impact parameter $b > R_A + R_B \implies$ photon-mediated interactions
  - one nucleus acts as a photon emitter, the other one as a hadronic target
- Quasi-real photon: virtuality $Q^2 = (\omega/\gamma)^2$ with $\gamma =$ Lorentz factor





$$\frac{d\sigma_{2+1}^{AB\to q\bar{q}gAB}}{d\eta_1 d\eta_2 d^2\boldsymbol{P} d^2\boldsymbol{K} dY_{\mathbb{P}}} = \omega\frac{dN_B}{d\omega} H(\eta_1, \eta_2, P_\perp^2) \frac{dxG_{\mathbb{P}}^A(x, x_{\mathbb{P}}, K_\perp^2)}{d^2\boldsymbol{K}} + (A \leftrightarrow B)$$

- Energy flux $\times$ Hard factor $\times$ Gluon diffractive TMD

2+1 diffractive dijets in AA UPCs

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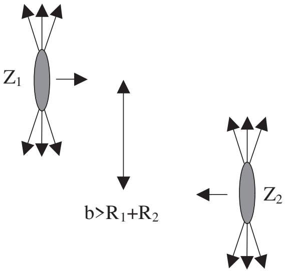
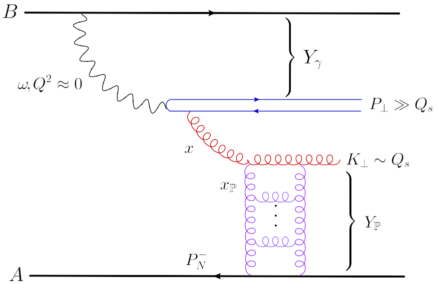
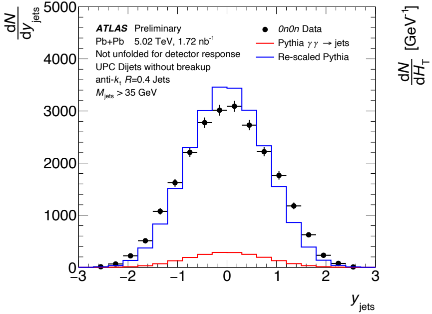


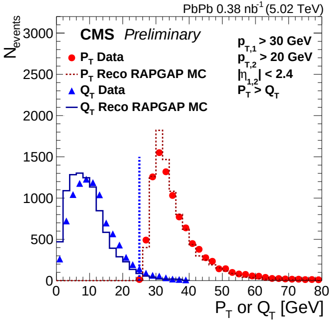


- Coherent diffraction: target nucleus does not break
  - rapidity gaps on both sides: photon gap + diffractive gap
  - how to distinguish the photon emitter from the nuclear target ?

Diffractive jets in Pb+Pb UPCs at the LHC

- Recent measurements: *ATLAS-CONF-2022-021* and *CMS arXiv:2205.00045*

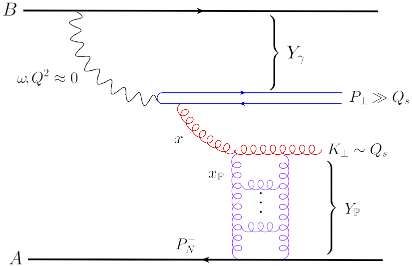


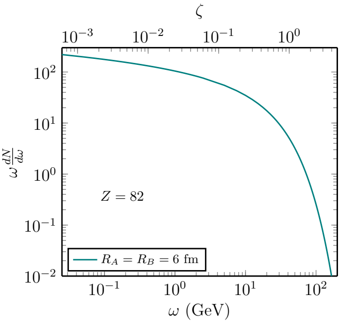


- Several thousands of candidate-events for coherent diffraction
  - no just $\gamma\gamma$ scattering: cross-section would be 10 times smaller
- Most likely: 2+1 jets ... but not that easy to experimentally check
  - the experimental set-up is not ideal for observing the 3rd jet

Energy cutoff

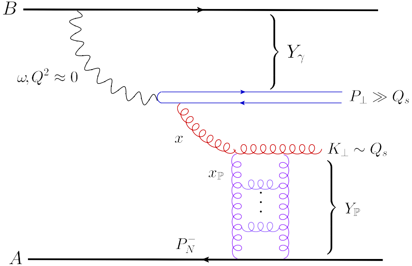
- Energy is not that high:
  - LHC: $\sqrt{s_{NN}} = 2E_N = 5\,\text{TeV}$, yet $\sqrt{s_{\gamma N}} = \sqrt{4\omega_{\max} E_N} \simeq 650\text{GeV}$
  - upper energy cutoff: $b \sim \frac{1}{Q} > 2R_A \;\Rightarrow \omega < \frac{\gamma}{2R_A} \equiv \omega_{\max} \simeq 40\,\text{GeV}$
  - exponential suppression for $\omega > \omega_{\max}$





$x_{\mathbb{P}}$ is not that small

- Limited energy and relatively hard dijets $P_\perp \geq 15\,\text{GeV}$
  - relatively large $x_{\mathbb{P}}$: $x_{\mathbb{P}} \gtrsim 5 \times 10^{-3}$
  - one cannot probe the high energy evolution of the Pomeron



$$\eta_1 \simeq \eta_2 \equiv y$$

$$x_{\mathbb{P},\,\text{min}} = \frac{P_\perp}{E_N}\, e^{-y}$$

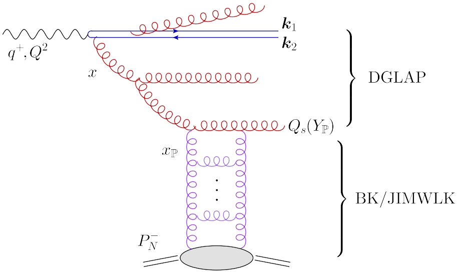
$$\omega = P_\perp\, e^{y}$$

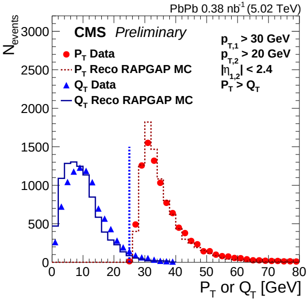
$$P_\perp \sim \omega_{\text{max}} \;\Rightarrow\; y \lesssim 1$$

- Not the ideal "small–$x_{\mathbb{P}}$" set-up! Similar in that sense to the EIC
- Decreasing $P_\perp$ would greatly help !

The 3rd jet is not easy to observe

- $K_\perp \sim Q_s \sim 1 \div 2$ GeV: not really a jet! could be measured as a hadron
- Large $P_\perp \Rightarrow$ large phase-space for DGLAP evolution
  - additional gluons with transverse momenta $Q_s \ll k_\perp \ll P_\perp$

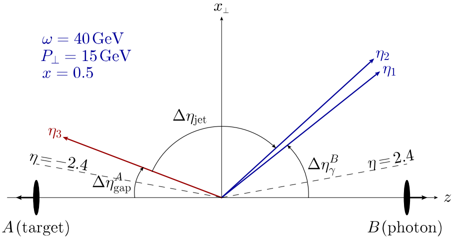




- Large dijet imbalance $Q_T = |\boldsymbol{k}_1 + \boldsymbol{k}_2| \sim 10\,\text{GeV} \gg Q_s$ (seen at the LHC)
  - consistent with final state radiation *(Hatta et al, 2010.10774)*
  - insensitive to the 3rd jet

How to measure the 3rd jet ?

- Observing the 3rd jet would be extremely useful
  - it propagates towards the nuclear target: lift the A vs. B ambiguity
  - measure the diffractive rapidity gap and thus infer $x_{\mathbb{P}}$
- E.g.: assume the photon to be a right mover: it was emitted by nucleus B



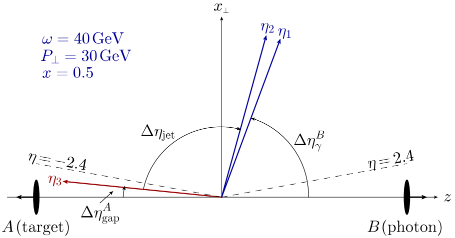
$$\Delta\eta_{\text{jet}} \gtrsim \ln\frac{2P_\perp}{Q_s} \simeq 2 \div 3$$

- large $\omega = 40$GeV, $P_\perp = 15$GeV
- $\eta_{1,2} \simeq 1,\ \Delta\eta_{\text{jet}} = 2.7,\ x_{\mathbb{P}} \simeq 0.004$

- Rapidity separation $\Delta\eta_{\text{jet}}$: a direct measure of the saturation momentum Q_s
- The 3rd "jet" could have been seen as a hadron by CMS: $|\eta_3| < |\eta_{\max}| = 2.4$

How to measure the 3rd jet ?

- Observing the 3rd jet would be extremely useful
  - it propagates towards the nuclear target: lift the A vs. B ambiguity
  - measure the diffractive rapidity gap and thus infer $x_{\mathbb{P}}$
- E.g.: assume the photon to be a right mover: it was emitted by nucleus B



$$\Delta\eta_{\text{jet}} \gtrsim \ln\frac{2P_\perp}{Q_s} \simeq 2 \div 3$$

- large $\omega = 40$GeV, larger $P_\perp = 30$GeV
- $\eta_{1,2} \simeq 0.3, \;\; \Delta\eta_{\text{jet}} = 3.4, \;\; x_{\mathbb{P}} \simeq 0.02$

- Rapidity separation $\Delta\eta_{\text{jet}}$: a direct measure of the saturation momentum Q_s
- Yet, CMS measured $P_\perp = 30$ GeV... so they missed it! *(arXiv:2205.00045)*

How to measure the 3rd jet ?

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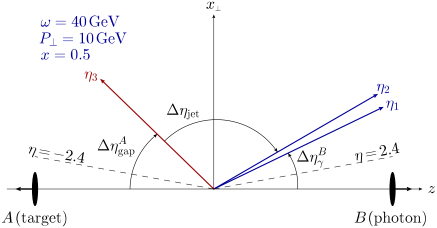


$$\Delta\eta_{\rm jet} \gtrsim \ln\frac{2P_\perp}{Q_s} \simeq 2 \div 3$$

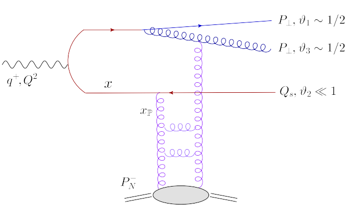
- large $\omega = 40$GeV, lower $P_\perp = 10$GeV
- $\eta_{1,2} \simeq 1.4,\ \Delta\eta_{\rm jet} = 2.3,\ x_{\mathbb{P}} \simeq 0.002$

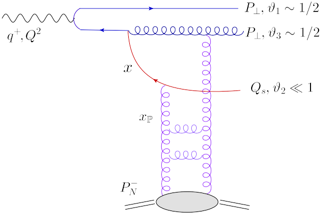
- Rapidity separation $\Delta\eta_{\rm jet}$: a direct measure of the saturation momentum Q_s
- The situation would greatly improve by decreasing $P_\perp$ *(ALICE ?)*

Conclusions

- Diffraction in γA (EIC, UPC): the best laboratory to study gluon saturation
- For sufficiently small $x_{\mathbb{P}} \lesssim 10^{-2}$ and/or large $A \sim 200$, diffractive TMDs and PDFs can be computed from first principles
- Due to saturation, diffractive dijets are dominated by (2+1)–jet events
- Experimentally observing the semi-hard, 3rd, jet appears to be tough, but it would be highly beneficial
  - distinguish the photon emitter from the target nucleus
  - confirm the overall physical picture and its predictions
- Measure dijets (or dihadrons) with lower $P_\perp \leq 10\,\text{GeV}$
- Use hadronic detectors at larger rapidities

- The third (semi-hard) jet can also be a quark: same-order





- TMD factorisation: quark unintegrated distribution of the Pomeron