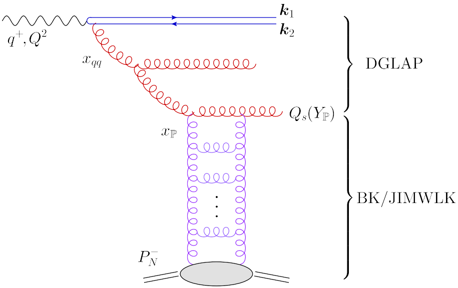
Probing gluon saturation via diffractive jets in ultra-peripheral nucleus-nucleus collisions

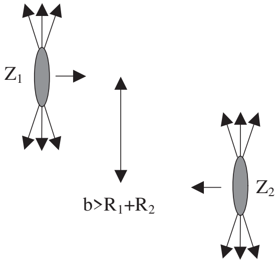
Edmond Iancu

IPhT, Université Paris-Saclay

with A.H. Mueller, D.N. Triantafyllopoulos, and S.-Y. Wei

arXiv:2304.12401

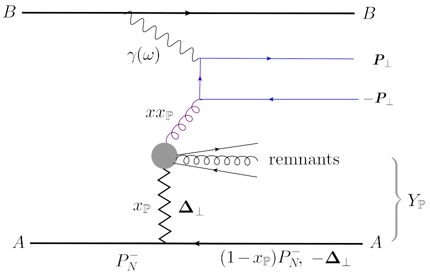




Outline

- 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: this talk
- 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

- Coherent diffraction: target nucleus does not break $\Delta_\perp \sim 1/R_A \sim 30$ MeV
- Elastic scattering $\Rightarrow$ "Pomeron" exchange $\Rightarrow$ rapidity gap: $Y_{\mathbb{P}} = \ln \frac{1}{x_{\mathbb{P}}}$
  - $x_{\mathbb{P}} \ll 1$: longitudinal momentum fraction taken by the Pomeron
- Quark-antiquark dijet produced via photon-gluon fusion
  - gluon produced by the Pomeron, together with remnants (color octet)

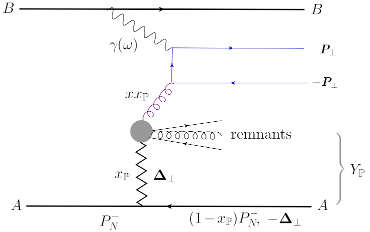


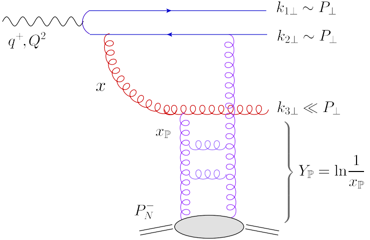
- x: gluon splitting fraction
- $xG_{\mathbb{P}}^A(x, x_{\mathbb{P}}, P_\perp^2)$: gluon distribution of the Pomeron
- ... a.k.a. the gluon diffractive PDF
- "non-perturbative" in collinear fact.

- Cross-section: Photon energy flux $\times$ Hard factor $\times$ $xG_{\mathbb{P}}^A(x, x_{\mathbb{P}}, P_\perp^2)$

Colour dipole picture

- For small $x_{\mathbb{P}} \lesssim 10^{-2}$ and large $A \sim 200$, $xG_{\mathbb{P}}(x, x_{\mathbb{P}}, P_\perp^2)$ can be computed from first principles: CGC & colour dipole picture
- Work in the "dipole frame" (the photon has a large q^+): $\frac{2q^+}{P_\perp^2} \gg R_A$
  - quark, antiquark and gluon now belong to the photon wavefunction

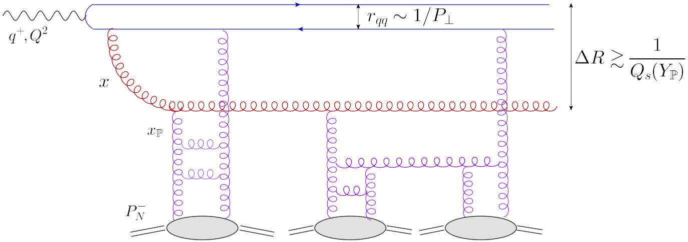




- Their elastic scattering: an explicit realisation of the Pomeron
  - 2 or more gluon exchanges + high energy evolution (BK/JIMWLK)
  - $Y_{\mathbb{P}}$: the rapidity phase-space for high-energy evolution: $Q_s(A, Y_{\mathbb{P}})$

Colour dipole picture

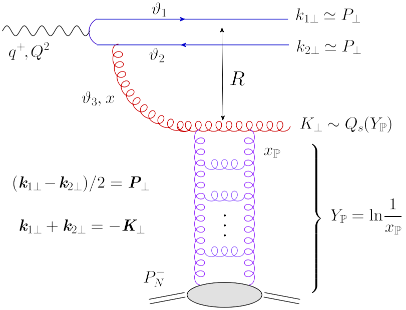
- For small $x_{\mathbb{P}} \lesssim 10^{-2}$ and large $A \sim 200$, $xG_{\mathbb{P}}(x, x_{\mathbb{P}}, P_\perp^2)$ can be computed from first principles: CGC & colour dipole picture
- Work in the "dipole frame" (the photon has a large q^+): $\frac{2q^+}{P_\perp^2} \gg R_A$
  - quark, antiquark and gluon now belong to the photon wavefunction



- Gluon saturation at $k_\perp \lesssim Q_s \Longrightarrow$ Strong scattering $T_{q\bar{q}g} \sim 1$
  - this requires a sufficiently large partonic projectile: $\Delta R \sim 1/Q_s$
  - by itself, the $q\bar{q}$ pair is much smaller: $r \sim 1/P_\perp$ with $P_\perp \gg Q_s$

2+1 diffractive jets

- Pb+Pb UPCs at the LHC (ATLAS, CMS): $P_\perp \gtrsim 15\,\text{GeV} \gg Q_s \sim 1 \div 2\,\text{GeV}$
- A leading twist contribution requires strong scattering: $T_{q\bar{q}g} \sim 1$
  - $\sigma_{\rm el} \propto |T_{q\bar{q}g}|^2$ is strongly suppressed for weak scattering ($T_{q\bar{q}g} \ll 1$)
- Strong scattering requires the gluon to be semi-hard: $K_\perp \sim Q_s$



- Large separation between g and $q\bar{q}$:

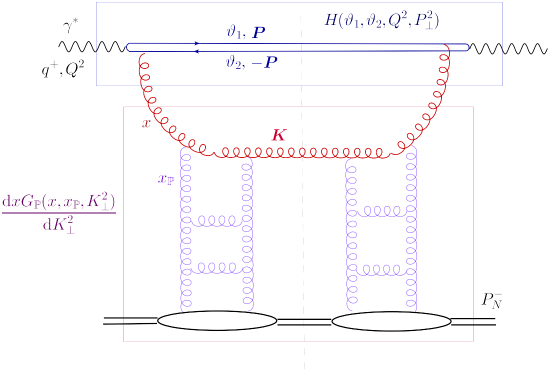
$$R \sim \frac{1}{Q_s} \gg r \sim \frac{1}{P_\perp}$$

- Effective gluon-gluon dipole
- Strong scattering: $T_{gg}(R, Y_{\mathbb{P}}) \sim 1$
- Leading twist: $\sim Q_s^2/P_\perp^4$

TMD factorisation for diffractive 2+1 jets

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

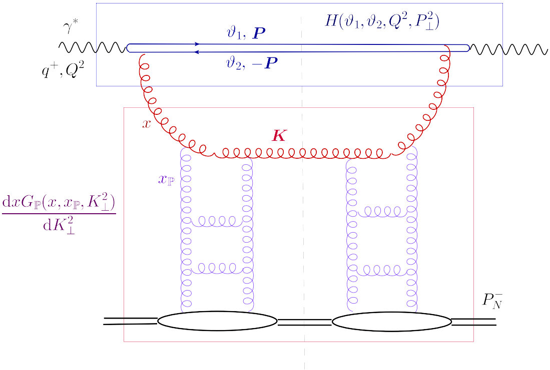
- At high $P_\perp \gg Q_s$, collinear factorisation emerges from the dipole picture
  - the gluon can alternatively be seen as a part of the Pomeron



- Explicit result for the gluon diffractive TMD
  - the unintegrated gluon distribution of the Pomeron

TMD factorisation for diffractive 2+1 jets

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



- The hard factor: the same as for inclusive dijets *(cf. talk by C. Marquet)*

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

The Pomeron UGD

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

- Explicitly computed in terms of the gluon-gluon dipole amplitude $T_{gg}(R, Y_{\mathbb{P}})$
- Operatorial definition clarified by *Hatta, Xiao, and Yuan (2205.08060)*
- Effective (x-dependent) saturation momentum: $\tilde{Q}_s^2(x, Y_{\mathbb{P}}) = (1-x)Q_s^2(Y_{\mathbb{P}})$

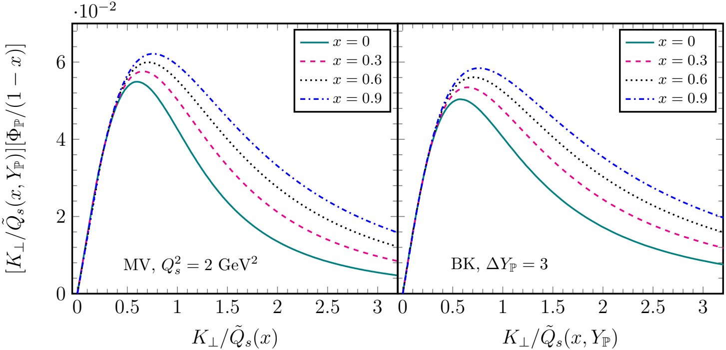
$$\Phi_{\mathbb{P}}(x, x_{\mathbb{P}}, K_\perp) \simeq (1-x) \begin{cases} 1, & K_\perp \lesssim \tilde{Q}_s(x) \\ \dfrac{\tilde{Q}_s^4(x)}{K_\perp^4}, & K_\perp \gg \tilde{Q}_s(x) \end{cases}$$

- Very fast decrease $\sim 1/K_\perp^4$ at large gluon momenta $K_\perp \gg \tilde{Q}_s(x)$
  - bulk of the distribution lies in the saturation domain at $K_\perp \lesssim \tilde{Q}_s(x)$
- Diffractive production of 2 hard jets is controlled by gluon saturation

Numerical results

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

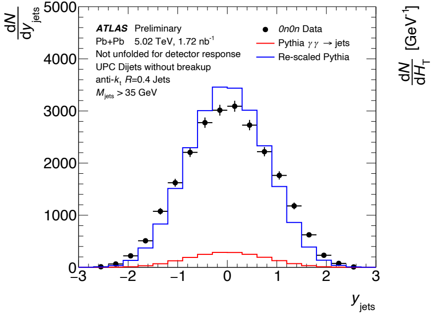
- Occupation number Φ multiplied by $K_\perp/\tilde{Q}_s$ and divided by $1-x$
- Pronounced peak at $K_\perp \simeq \tilde{Q}_s$: diffraction is controlled by saturation

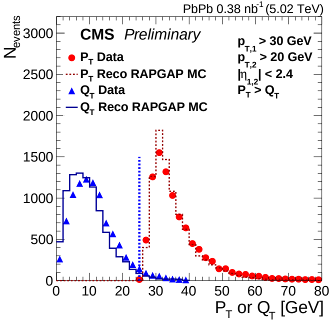


- BK evolution of $T_{gg}(R, Y_\mathbb{P})$ with increasing $Y_\mathbb{P} = \ln \frac{1}{x_\mathbb{P}}$
  - $Q_s(Y_\mathbb{P})$ is rising but the shape is unchanged ("geometric scaling")

Diffractive jets in Pb+Pb UPCs at the LHC

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



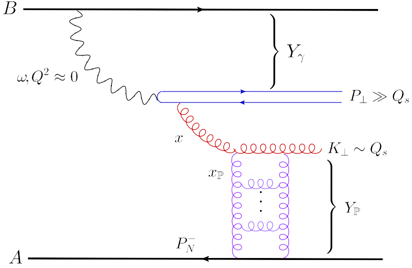


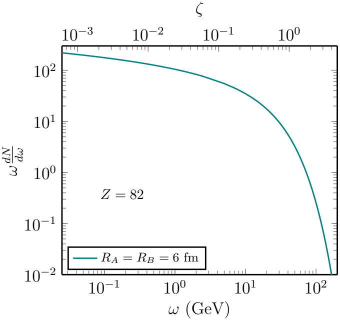
- Several thousands of candidate-events for coherent diffraction
  - no just $\gamma\gamma$ scattering: cross-section would be 10 times smaller
- Most likely: 2+1 jets ... but not that easy to experimentally check
  - the experimental set-up is not ideal for observing the 3rd jet

2+1 diffractive dijets in AA UPCs

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

- Rapidity gaps on both sides: photon gap + diffractive gap
  - how to distinguish the photon emitter from the nuclear target ?
- Energy is not that high: $\sqrt{s_{NN}} = 5$TeV, yet $\sqrt{s_{\gamma N}} = \sqrt{4\omega_{\max}E_N} \simeq 650$GeV

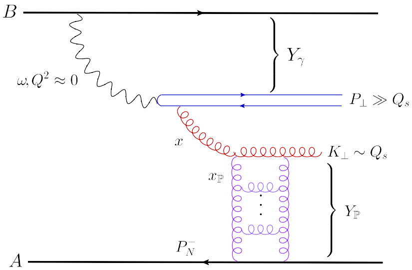




- upper energy cutoff: $b \sim \frac{1}{Q} > 2R_A \;\Rightarrow \omega < \frac{\gamma}{2R_A} \equiv \omega_{\max} \simeq 40$ GeV

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

- Rapidity gaps on both sides: photon gap + diffractive gap
  - how to distinguish the photon emitter from the nuclear target ?
- Energy is not that high: $\sqrt{s_{NN}} = 5$TeV, yet $\sqrt{s_{\gamma N}} = \sqrt{4\omega_{\max} E_N} \simeq 650$GeV



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

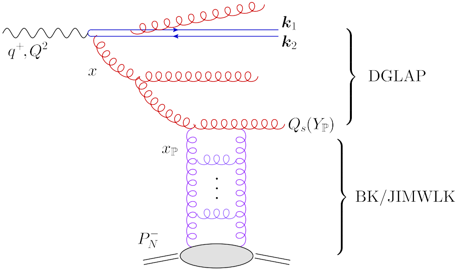
$$\omega = P_\perp e^y$$

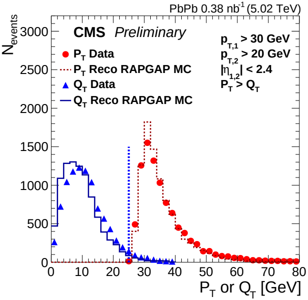
$$P_\perp \sim \omega_{\max} \Rightarrow y \lesssim 1$$

- Hard dijets $P_\perp \geq 15$ GeV $\Rightarrow x_{\mathbb{P}}$ is not that small: $x_{\mathbb{P}} \gtrsim 5 \times 10^{-3}$

DGLAP evolution & Final state radiation

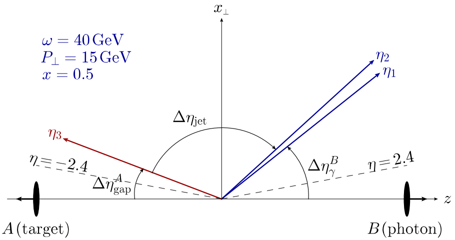
- When $x_{\mathbb{P}} \gtrsim 5 \times 10^{-3}$, gluon saturation is only marginally probed
  - one cannot probe the high energy evolution of the Pomeron
- Large $P_\perp \Rightarrow$ large phase-space for DGLAP evolution
  - additional gluons with transverse momenta $Q_s \ll k_\perp \ll P_\perp$





- 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

- Can one directly measure the third jet ?
  - $K_\perp \sim Q_s \sim 1 \div 2\,$GeV: too soft to qualify as a jet!
  - it could be measured as a hadron... depending upon its rapidity
- It always propagates towards the nuclear target: lift the ambiguity
- Assume the photon to be a right mover: it was emitted by nucleus B

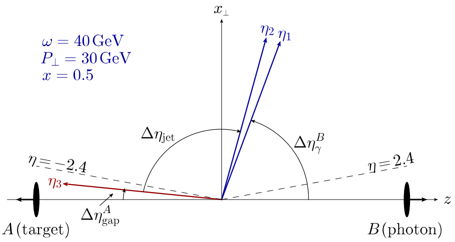


- large $\omega = 40$GeV, low $P_\perp = 15$GeV
- $\eta_{1,2} \simeq 1,\ \Delta\eta_{\rm jet} = 2.7,\ x_{\mathbb{P}} \simeq 0.004$

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

- The 3rd "jet" could have been seen as a hadron by CMS: $|\eta_3| < |\eta_{\rm max}| = 2.4$

- Can one directly measure the third jet ?
  - $K_\perp \sim Q_s \sim 1 \div 2$ GeV: too soft to qualify as a jet!
  - it could be measured as a hadron... depending upon its rapidity
- It always propagates towards the nuclear target: lift the ambiguity
- Assume the photon to be a right mover: it was emitted by nucleus B

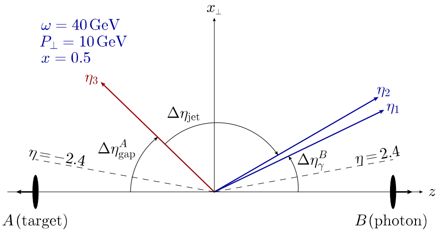


- large $\omega = 40$GeV, large $P_\perp = 30$GeV
- $\eta_{1,2} \simeq 0.3, \;\; \Delta\eta_{\rm jet} = 3.4, \;\; x_{\mathbb{P}} \simeq 0.02$

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

- Yet, CMS measured $P_\perp = 30$ GeV... so they missed it! *(arXiv:2205.00045)*

- Can one directly measure the third jet ?
  - $K_\perp \sim Q_s \sim 1 \div 2\,$GeV: too soft to qualify as a jet!
  - it could be measured as a hadron... depending upon its rapidity
- It always propagates towards the nuclear target: lift the ambiguity
- Assume the photon to be a right mover: it was emitted by nucleus B



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

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

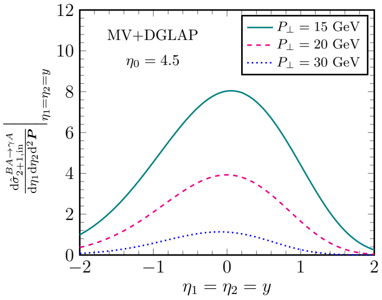
- The situation would greatly improve by decreasing $P_\perp$ *(ALICE ?)*
- Rapidity separation $\Delta\eta_{\rm jet}$: a direct measure of the saturation momentum Q_s

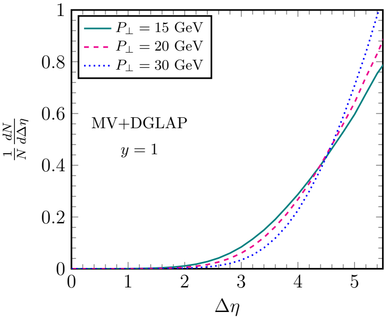
Conclusions

- 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 $P_\perp \leq 10\,\mathrm{GeV}$
- Use hadronic detectors at larger rapidities

Rapidity distributions

- Left: y distribution of the hard dijets (after integrating out the 3rd jet)
  - roughly symmetric around $y = 0$
  - rapidly decreasing when increasing $P_\perp$





- Right: rapidity separation $\Delta\eta_{\text{jet}}$ between the 3rd jet and the hard dijets

$$\Delta\eta_{\text{jet}} = \eta_{1,2} - \eta_3 = \ln\frac{1-x}{x} + \ln\frac{2P_\perp}{K_\perp} \gtrsim \ln\frac{2P_\perp}{Q_s} \simeq 2 \div 3$$

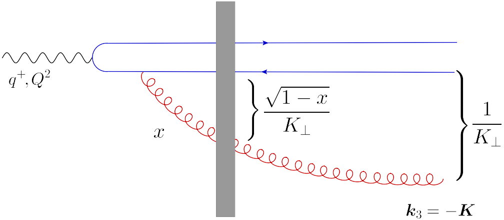
The Pomeron UGD: a diffractive TMD

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

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

$$\mathcal{G} = \mathcal{M}^2\int_0^\infty \mathrm{d}R\,R\,\mathrm{J}_2(K_\perp R)\mathrm{K}_2(\mathcal{M}R)\mathcal{T}_{gg}(R,Y_{\mathbb{P}}) \quad \text{with} \quad \mathcal{M}^2 \equiv \frac{x}{1-x}K_\perp^2$$

  - the gluon dipole size R is limited by the virtuality: $R \lesssim 1/\mathcal{M}$

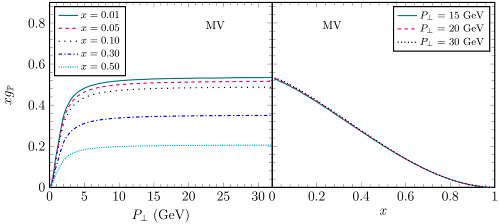


The gluon diffractive PDF

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

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

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

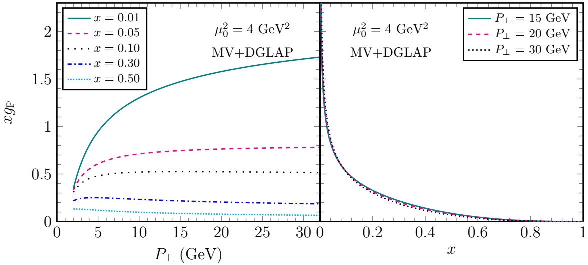


The gluon diffractive PDF

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

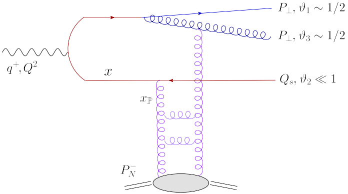
$$xG_{\mathbb{P}}(x, x_{\mathbb{P}}, P_\perp^2) \equiv \int^{P_\perp} \mathrm{d}^2\boldsymbol{K}\, \frac{\mathrm{d}xG_{\mathbb{P}}^A(x, x_{\mathbb{P}}, K_\perp^2)}{\mathrm{d}^2\boldsymbol{K}} \propto (1-x)^2\, Q_s^2(A, Y_{\mathbb{P}})$$

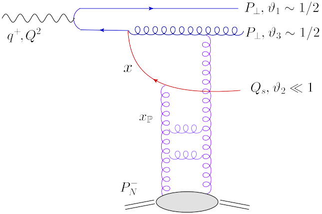
- ... but with an explicit result for the gluon diffractive PDF.
- The integral is rapidly converging and effectively cut off at $K_\perp \sim \tilde{Q}_s(x)$
- The $(1-x)^2$ vanishing at the end point is a hallmark of saturation



2+1 jets with a hard gluon

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





- TMD factorisation: quark unintegrated distribution of the Pomeron