Probing gluon saturation via diffractive jets in nucleus-nucleus UPCs

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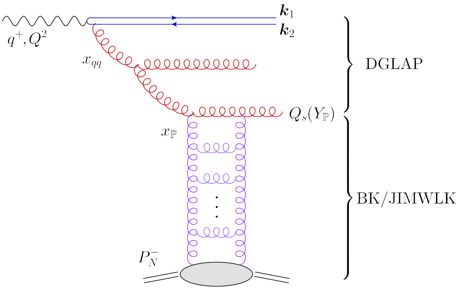
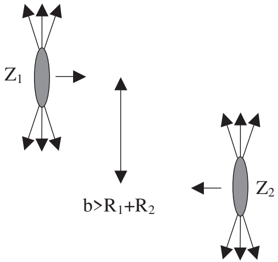


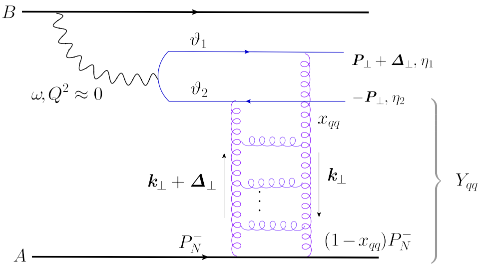


Outline

- 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 ?
    - since controlled by strong scattering in the black disk limit
    - it lives at the hardest scale where scattering is still strong
    - if saturation exists ($Q_s \gg \Lambda$), this scale is Q_s
- Why jets (hard jets/hadrons with $P_\perp \gg Q_s$) ?
    - easy to measure; a priori well described by collinear factorisation
- Why should saturation be relevant for hard jets/hadrons ?
    - to have strong scattering, the hard dijets must be accompanied by semi-hard radiation (at least, one additional gluon with $K_\perp \sim Q_s$)
    - such a 2+1 event can be computed in the CGC
- Collinear (actually, TMD) factorisation emerges from the CGC

Exclusive dijets in AA UPCs

- Colour dipole picture: $q\bar{q}$ dipole undergoing elastic scattering
- Coherent process: target nucleus does not break: $\Delta_\perp \sim 1/R_A \sim 30$ GeV
- Hard dijets: $P_\perp \gg Q_s \ggg \Delta_\perp$, $\vartheta_1 \sim \vartheta_2 \sim 1/2$



$$\omega = \frac{P_\perp}{2}\left(e^{\eta_1} + e^{\eta_2}\right)$$

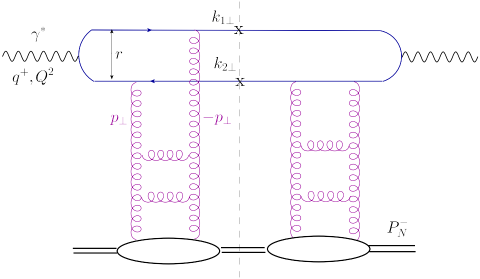
$$x_{q\bar{q}} P_N^- = \frac{P_\perp}{\sqrt{2}}\left(e^{-\eta_1} + e^{-\eta_2}\right)$$

$\eta_1 \simeq \eta_2$: can have any sign

- Pomeron rapidity gap: $Y_{q\bar{q}} = \ln \frac{1}{x_{q\bar{q}}}$: phase-space for target evolution
- Pseudo-rapidity gap: $\Delta\eta_{q\bar{q}} = \eta_{1,2} - \eta_A = \ln \frac{2}{x_{q\bar{q}}} + \ln \frac{P_\perp}{M_N}$: measurable

Exclusive dijets is higher twist

- Elastic scattering: $\sigma_{\rm el}(P_\perp) \propto |T_{q\bar q}(r)|^2$ with $r \sim 1/P_\perp \ll 1/Q_s$
- Small dipole $\Longrightarrow$ weak scattering ("colour transparency")



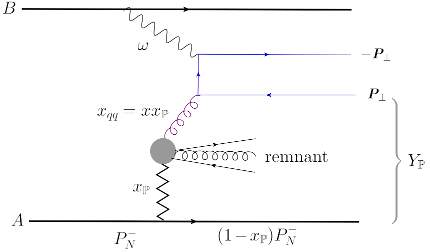
$$T_{q\bar q}(r) \simeq \begin{cases} r^2 Q_s^2, & \text{for } rQ_s \ll 1 \\ 1, & \text{for } rQ_s \gtrsim 1 \end{cases}$$

$$\sigma_{\rm el}(P_\perp) \propto \frac{Q_s^4}{P_\perp^6}$$

- "Higher twist": strongly suppressed at large $P_\perp \gg Q_s$
- For comparison: inclusive dijet cross-section: $\sigma_{\rm incl}(P_\perp) \propto \frac{Q_s^2}{P_\perp^4}$
- Exclusive dijets are truly rare events: ignored in the collinear factorisation

Collinear factorisation: leading twist

- The $q\bar{q}$ dipole does not directly couple to the Pomeron
  - it rather couples to a gluon component of the Pomeron
- The final state also contains a set of "remnants" with overall gluon quantum numbers and $k_\perp \ll P_\perp$: semi-inclusive diffractive dijets



- The gluon carries a fraction $x = \frac{x_{q\bar{q}}}{x_{\mathbb{P}}}$
- Pomeron rapidity gap $Y_{\mathbb{P}} = \ln \frac{1}{x_{\mathbb{P}}}$
- Distribution in $x \leq 1$ & in $Y_{\mathbb{P}} \leq Y_{q\bar{q}}$
- DGLAP evolution for the remnants

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

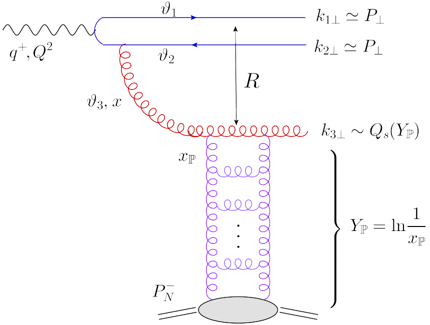
- Energy flux × Hard factor × Gluon distribution of the Pomeron (diff PDF)

Colour dipole picture: 2+1 jets

- In collinear factorisation, $xG_{\mathbb{P}}(x, x_{\mathbb{P}}, P_\perp^2)$ is a "black box"
  - for a proton target: determined via fits to HERA
  - for a nuclear target: resort on models (Pomeron flux, shadowing ...)
- For small $x_{\mathbb{P}} \lesssim 10^{-2}$ and $A = 200$, one has $Q_s(A, Y_{\mathbb{P}}) \gtrsim 1$ GeV

$\Longrightarrow xG_{\mathbb{P}}(x, x_{\mathbb{P}}, P_\perp^2)$ can be computed from first principles: CGC

- Leading order: 2 hard $(P_\perp \gg Q_s)$ and 1 semi-hard $(K_\perp \sim Q_s)$ jets



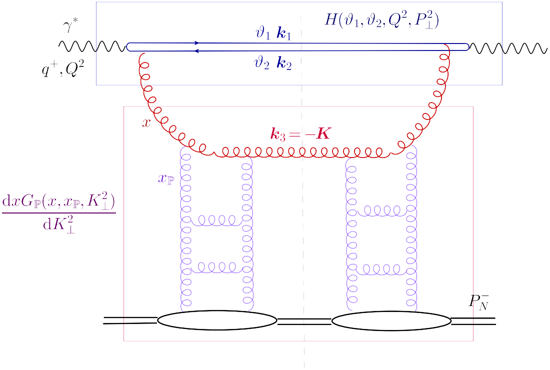
$$R \sim \frac{1}{Q_s} \gg r \sim \frac{1}{P_\perp}$$

- 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)

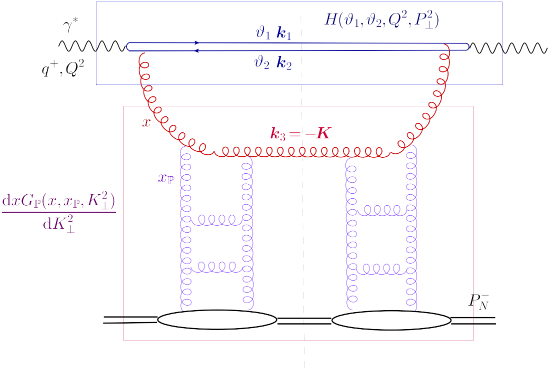
- At high $P_\perp \gg Q_s$, collinear factorisation emerges from the dipole picture
  - the gluon can alternatively be seen as a part of the Pomeron
  - essential condition: the gluon is relatively soft $\vartheta_3 \sim \frac{Q_s^2}{Q^2} \ll 1$



- Actually: the "unintegrated" (TMD) version of collinear factorisation

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 (same physics)

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

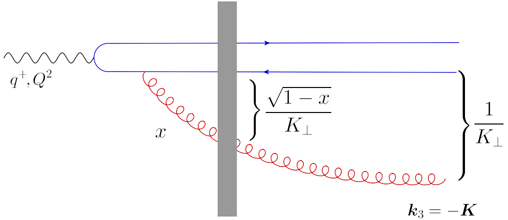
The Pomeron UGD: a diffractive TMD

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

- 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: $R \lesssim 1/\mathcal{M}$



- Operatorial definition clarified by *Hatta, Xiao, and Yuan (2205.08060)*

The Pomeron UGD (2)

- Strong scattering: $R \gtrsim \frac{1}{Q_s}$, but $R \lesssim \frac{\sqrt{1-x}}{K_\perp} \Longrightarrow K_\perp^2 \lesssim (1-x)Q_s^2$
- Effective saturation momentum: $\tilde{Q}_s^2(x, Y_{\mathbb{P}}) = (1-x)Q_s^2(Y_{\mathbb{P}})$

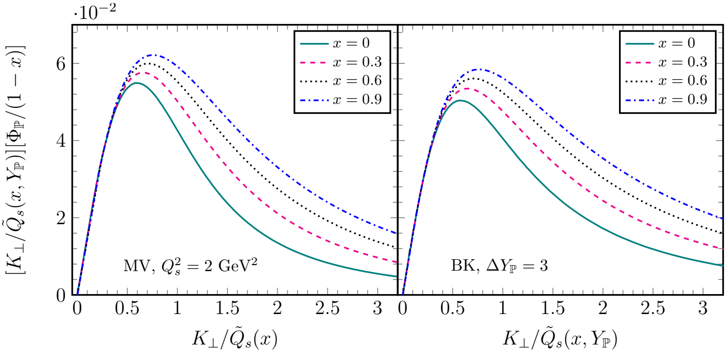
$$\Phi(x, x_{\mathbb{P}}, K_\perp^2) \simeq (1-x) \begin{cases} 1, & K_\perp \lesssim \tilde{Q}_s(x) \\ \dfrac{\tilde{Q}_s^4(x)}{K_\perp^4}, & K_\perp \gg \tilde{Q}_s(x) \end{cases}$$

- 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 $K_\perp \lesssim \tilde{Q}_s(x)$
- Contrast with the WW UGD (inclusive dijets): $\Phi_{WW} \sim Q_s^2/K_\perp^2$ at high $K_\perp$
- Suppression when $x \to 1$: endpoint of the phase-space for gluon emission
- Geometric scaling after dividing through $1-x$: a function of $K_\perp/\tilde{Q}_s(x)$

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



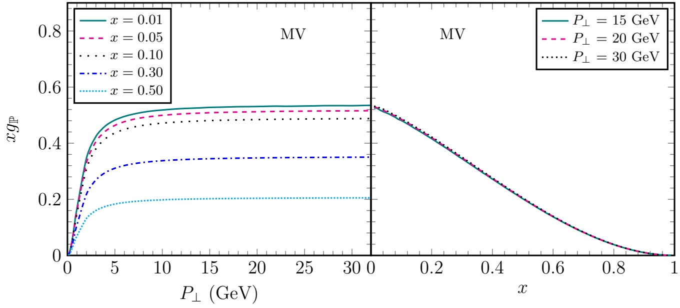
- BK evolution of $T_{gg}(R,Y_\mathbb{P})$: evolution of $\Phi_\mathbb{P}(x,x_\mathbb{P},K_\perp)$ in $x_\mathbb{P}$ and $K_\perp$
  - increasing $Q_s^2(Y_\mathbb{P})$ & approximate geometric scaling

The gluon diffractive PDF

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

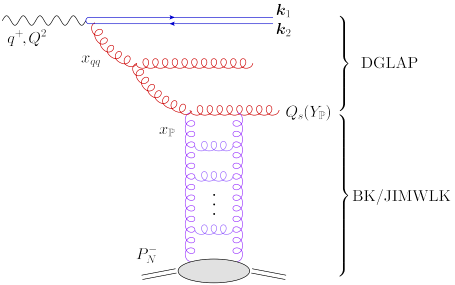
$$xG_{\mathbb{P}}(x, x_{\mathbb{P}}, P_\perp^2) \equiv \int^{P_\perp} \mathrm{d}^2\boldsymbol{K}\, \frac{\mathrm{d}xG_{\mathbb{P}}^A(x, x_{\mathbb{P}}, K_\perp^2)}{\mathrm{d}^2\boldsymbol{K}} \propto (1-x)^2\, Q_s^2(A, Y_{\mathbb{P}})$$

- ... 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



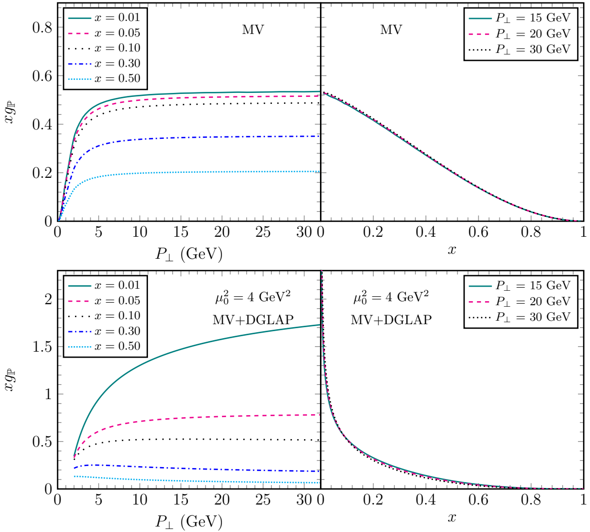
The quantum evolution of the Pomeron

- The unintegrated distrib. (the gluon diff TMD) undergoes BK/JIMWLK
  - the evolution of the internal structure of the Pomeron (colour sources)
  - this affects the dependencies upon $x_{\mathbb{P}}$ and $K_\perp$, but not upon x
- The integrated distribution (the gluon diff PDF) obeys DGLAP
  - the evolution of the partons emitted by the Pomeron
  - this affects the dependencies upon x and $P_\perp$, but not upon $x_{\mathbb{P}}$



- additional DGLAP gluons
- intermediate transverse momenta $Q_s \ll k_\perp \ll P_\perp$

- The solution to BK acts as a source in the DGLAP equation

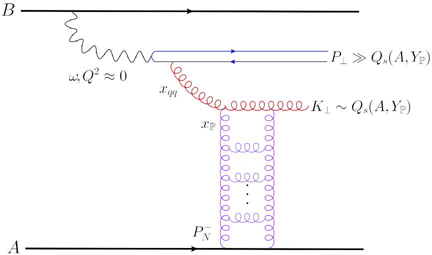


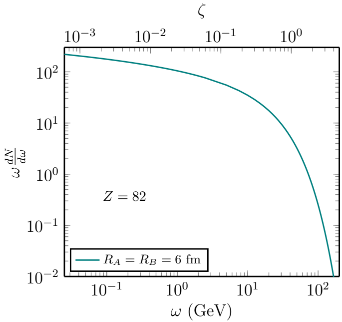
- increase for very small $x \leq 0.01$, slight decrease for $x > 0.05$
- when $x \to 1$, the distribution vanishes even faster

Back to AA UPCs (1)

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

- LHC: $\sqrt{s_{NN}} = 2E_N = 5$ TeV, yet $\sqrt{s_{\gamma N}} = \sqrt{4\omega_{\max}E_N} \simeq 650$ GeV



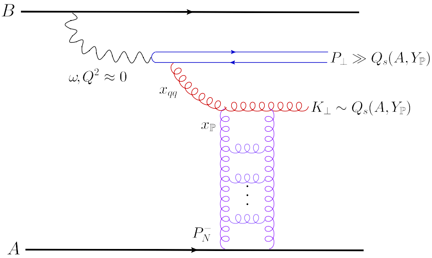


- quasi-real photon: virtuality $Q^2 = (\omega/\gamma)^2$ with $\gamma =$ Lorentz factor
- upper energy cutoff: $b \sim \frac{1}{Q} > 2R_A \;\Rightarrow \omega < \frac{\gamma}{2R_A} \equiv \omega_{\max} \simeq 40$ GeV

Back to AA UPCs (2)

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

- LHC: Very hard dijets $P_\perp \geq 15\,\text{GeV} \Rightarrow$ non-forward physics: $x_{q\bar{q}} \gtrsim 0.005$



$$\omega = P_\perp\,(e^{\eta_1}+e^{\eta_2})/2$$

$$x_{q\bar{q}}E_N = P_\perp(e^{-\eta_1}+e^{-\eta_2})/2$$

$$P_\perp \sim \omega_{\max} \;\Rightarrow\; |\eta_{1,2}| \lesssim 1$$

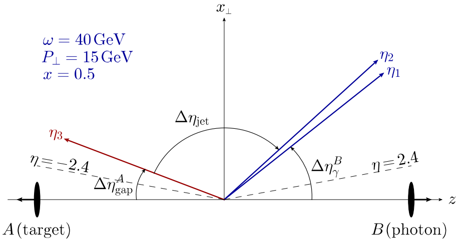
$$x_{\mathbb{P}} = \frac{x_{q\bar{q}}}{x}$$ is even larger

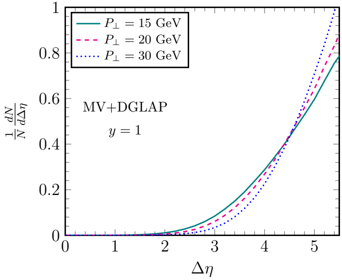
- Not the ideal small $x_{\mathbb{P}}$ set-up! Decreasing $P_\perp$ would greatly help!
- $K_\perp \sim Q_s \sim 1 \div 2\,\text{GeV}$: not really a jet! Could be measured as a hadron
- Hard dijet imbalance $|\boldsymbol{k}_1+\boldsymbol{k}_2| \gg K_\perp$ controlled by final-state radiation

A high-energy event

- Assume the photon to be a right mover: it has been emitted by nucleus B
- Optimal conditions: highest $\omega = 40\,\text{GeV}$, lowest $P_\perp = 15\,\text{GeV}$, large $x = 0.5$

$$x_{\mathbb{P}} = 2x_{q\bar{q}} \simeq 4 \times 10^{-3}, \quad Y_{\mathbb{P}} = 5.4, \quad \eta_{1,2} \simeq 1, \quad \Delta\eta_{\rm jet} = 2.7$$





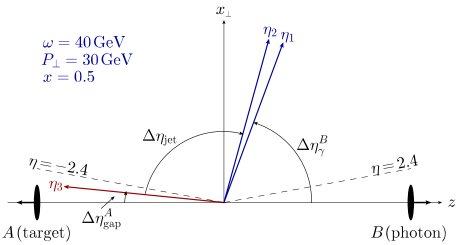
$$\Delta\eta_{\rm jet} = \eta_{1,2} - \eta_3 = \ln\frac{2(1-x)}{x} + \ln\frac{P_\perp}{K_\perp} \gtrsim \ln\frac{2P_\perp}{Q_s} \simeq 2 \div 3$$

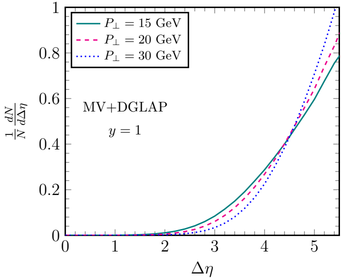
- The 3rd "jet" could have been seen as a hadron by CMS: $|\eta_3| < |\eta_{\rm max}| = 2.4$

A high-energy event

- Assume the photon to be a right mover: it has been emitted by nucleus B
- Optimal conditions: highest $\omega = 40$ GeV, lowest $P_\perp = 15$ GeV, large $x = 0.5$

$$x_{\mathbb{P}} = 2x_{q\bar{q}} \simeq 0.02, \quad Y_{\mathbb{P}} = 4, \quad \eta_{1,2} \simeq 0.3, \quad \Delta\eta_{\text{jet}} = 3.4$$





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

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

A more inclusive observable

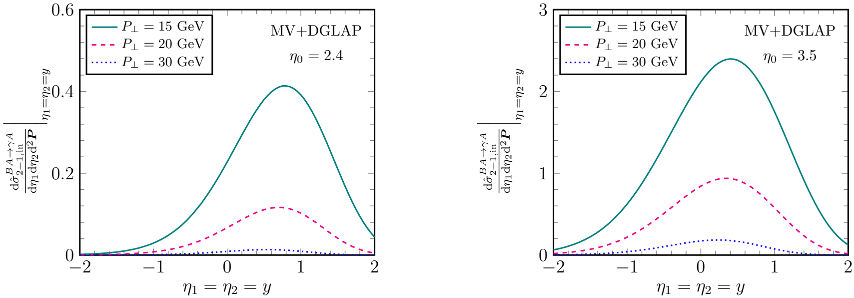
- What is the cross-section to observe the 3rd jet in a hadronic tracker with rapidity acceptance η_0 (with any $K_\perp$) ? (e.g. $\eta_0 = 2.4$ at CMS)
  - integrate the 3rd jet over $K_\perp$ up to $P_\perp$
  - any $|\eta_3| < \eta_0 \Longrightarrow$ integrate over $x > x_0$
  - assume $\eta_1 = \eta_2 \equiv y$ for simplicity

$$\left.\frac{\mathrm{d}\hat{\sigma}_{2+1,\mathrm{in}}^{BA\to\gamma A}}{\mathrm{d}\eta_1\mathrm{d}\eta_2\mathrm{d}^2\boldsymbol{P}}\right|_{\eta_0} = \omega\frac{\mathrm{d}N_B}{\mathrm{d}\omega}\int_{x_0}^{1}\frac{\mathrm{d}x}{x}\,xG_{\mathbb{P}}^{A}(x, x_{\mathbb{P}}, P_\perp^2)\,, \qquad x_0 = \frac{1}{1+\frac{Q_s}{2P_\perp}\,e^{y+\eta_0}}$$

- "Reduced cross-section": we removed the trivial hard factor $H \propto 1/P_\perp^4$.
- Plot as a function of y for various values of $P_\perp$ and η_0
- As before, we assume the photon to be a right mover

The cross-section for seeing the 3rd jet

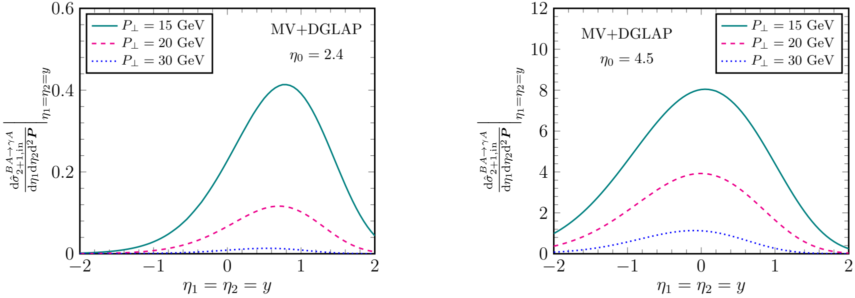
$$\left.\frac{\mathrm{d}\hat{\sigma}^{BA\to\gamma A}_{2+1,\mathrm{in}}}{\mathrm{d}\eta_1 \mathrm{d}\eta_2 \mathrm{d}^2\boldsymbol{P}}\right|_{\eta_0} = \omega\frac{\mathrm{d}N_B}{\mathrm{d}\omega}\int_{x_0}^{1}\frac{\mathrm{d}x}{x}\, xG^A_{\mathbb{P}}(x, x_{\mathbb{P}}, P_\perp^2)\,, \qquad x_0 = \frac{1}{1+\frac{Q_s}{2P_\perp}\, e^{y+\eta_0}}$$



- Suppression at large positive y due to the energy cutoff in the photon flux
- Suppression at large negative y and also at large $P_\perp$ because
  - x_0 increases when y decreases and/or $P_\perp$ increases
  - $xG^A_{\mathbb{P}}(x, x_{\mathbb{P}}, P_\perp^2)$ vanishes like $(1-x)^2$ when $x \to 1$

The cross-section for seeing the 3rd jet

$$\left.\frac{\mathrm{d}\hat{\sigma}^{BA\to\gamma A}_{2+1,\mathrm{in}}}{\mathrm{d}\eta_1\mathrm{d}\eta_2\mathrm{d}^2\boldsymbol{P}}\right|_{\eta_0} = \omega\frac{\mathrm{d}N_B}{\mathrm{d}\omega}\int_{x_0}^{1}\frac{\mathrm{d}x}{x}\,xG^{A}_{\mathbb{P}}(x, x_{\mathbb{P}}, P_\perp^2)\,, \qquad x_0 = \frac{1}{1+\frac{Q_s}{2P_\perp}\,e^{y+\eta_0}}$$

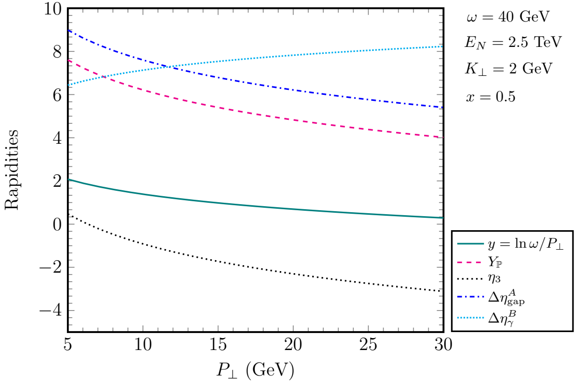


- Slight bias in favour of positive y (dijets in the direction of the photon)
- ... which however decreases when increasing $P_\perp$ and/or η_0
- By observing the hard dijets alone, one cannot decide the photon direction

Why is the 3rd jet so useful

- Experimentally observing the semi-hard, 3rd jet would be highly beneficial
- Distinguish the nucleus which emitted the photon from the target nucleus
  - the third jet propagates opposite to the photon
  - one could deduce the photon energy ω, hence the value of $x_{q\bar{q}}$
- Confirm the physical picture expected in pQCD/CGC
  - a semi-hard transverse momentum $K_\perp \sim Q_s \sim 1 \div 2\,\text{GeV}$
  - a large pseudo-rapidity separation $\Delta\eta_{\text{jet}} \gtrsim 2 \div 3$ from the hard dijets
- ... hence the phenomenon of gluon saturation
- It would allow one to deduce the Pomeron gap: $Y_{\mathbb{P}} = \ln \frac{1}{x_{q\bar{q}}} - \ln \frac{1}{x}$
- ... hence the importance of high energy evolution

Can one measure jets with lower $P_\perp$?



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

$$x_{q\bar{q}} E_N = P_\perp \, e^{-y}$$

$$Y_{\mathbb{P}} = \ln \frac{1}{x_{q\bar{q}}} - \ln \frac{1}{x}$$

$$y - \eta_3 = \ln \frac{2(1-x)}{x} + \ln \frac{P_\perp}{K_\perp}$$

- Reducing $P_\perp$ increases the chances to detect the 3rd jet & improves the case for saturation
  - increases $\eta_{1,2} \equiv y$, decreases $\Delta\eta = y - \eta_3$, increases $Y_{\mathbb{P}}$
- For $P_\perp \leq 10$ GeV, the 3rd jet would propagate at nearly central rapidities !