Diffractive TMDs and their Evolution

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Bridging TMD Frameworks: Intersections, Tensions, and Applications
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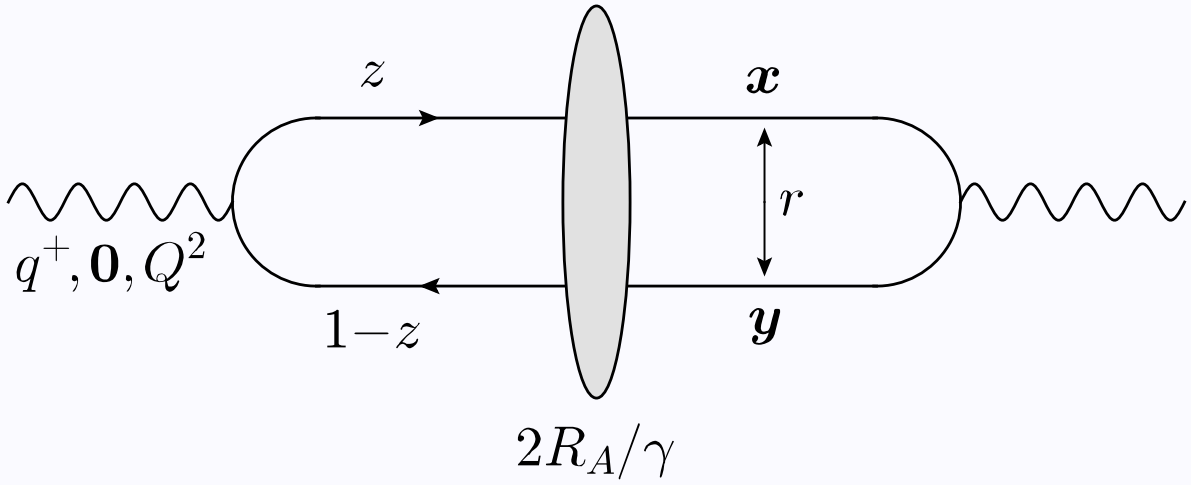
- S. Hauksson, E. Iancu, A.H. Mueller, DT, S.Y. Wei, F. Yuan: 2512.11730 (to appear in JHEP), 2402.14748 (JHEP), 2304.12401 (EPJC), 2207.06268 (JHEP), 2112.06353 (PRL)
- Hautmann, Hebecker, Soper, Golec-Biernat, Wüsthoff '97-'01
- Caucal, Iancu '24; Nefedov, Von Hameren '24

Content

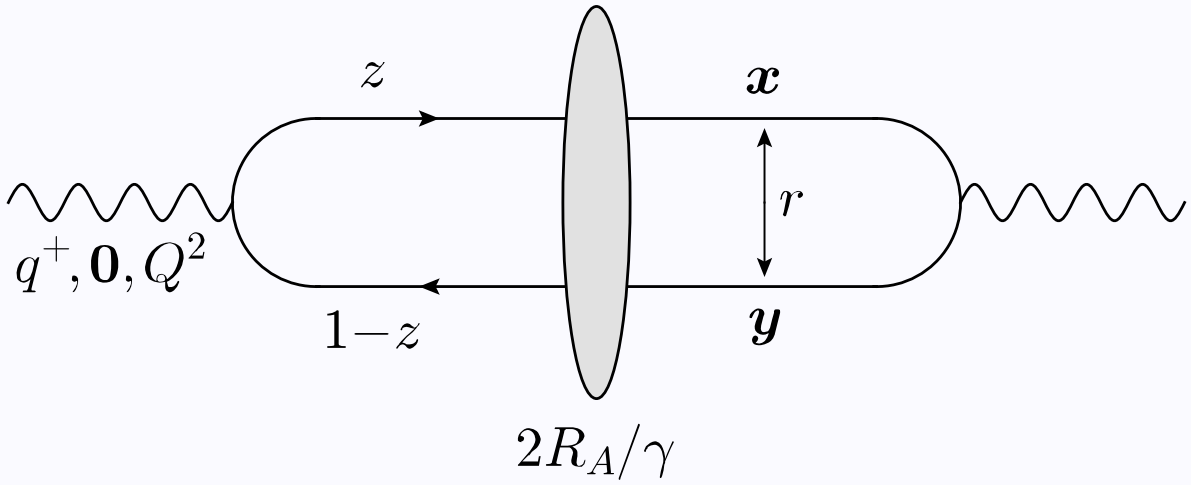
- Deep inelastic scattering in the dipole picture and time scales
- "2 + 1" jets in coherent diffraction as probes of saturation
- Factorization: Gluon diffractive TMDs
- Late time emissions
- Momentum space evolution
- Coordinate space evolution
- Analytical and numerical solutions

DIS at Small-x in Dipole Picture: Time Scales



- Right moving off-shell γ^*, $q^\mu = (q^+, \mathbf{0}, -Q^2/2q^+)$
- Left moving nucleus, $p^\mu = (M_N^2/2P_N^-, \mathbf{0}, P_N^-)$ per nucleon
- Projectile lifetime $\tau_\gamma \sim 2q^+/Q^2$
- Nucleus contracted length $L \sim 2R_A M_N/P_N^- \sim A^{1/3}/P_N^-$
- $L \ll \tau_\gamma \iff xA^{1/3} \ll 1$

DIS at Small-x in Dipole Picture: Factorization

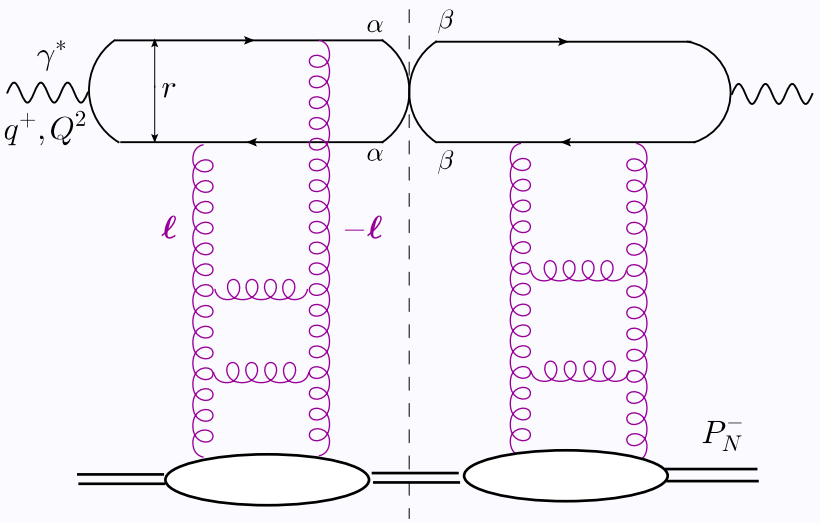


$$\sigma^{\gamma^* A}(x, Q^2) = \int \mathrm{d}^2\boldsymbol{r} \int_0^1 \mathrm{d}z \left|\Psi_{\gamma^* \to q\bar{q}}(Q^2; \boldsymbol{r}, z)\right|^2 2\pi R_A^2 T(r, x)$$

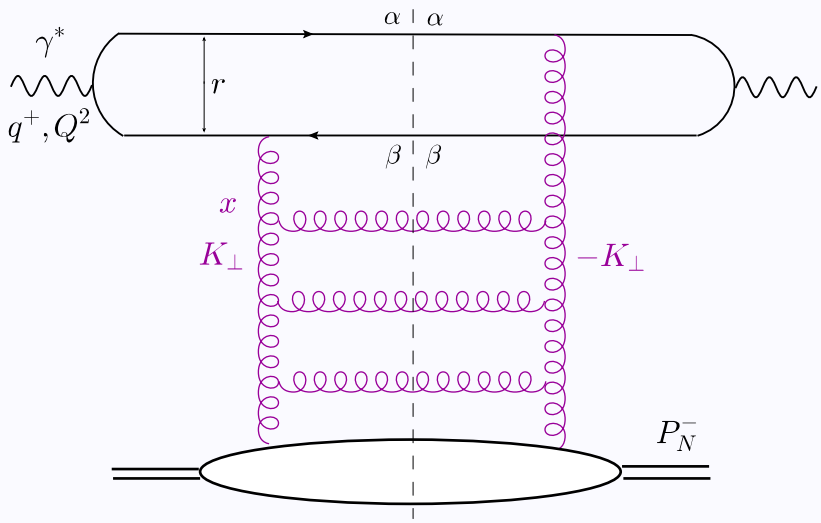
- All QCD dynamics in $T(r, x)$
- Virtuality limits large dipoles: $r \lesssim 1/\bar{Q}$, with $\bar{Q}^2 = z(1-z)Q^2$
- Saturation requires $r \gtrsim 1/Q_s$, hence $\bar{Q}^2 \lesssim Q_s^2$
- When $Q^2 \gg Q_s^2$ dominant contribution from weak scattering

Diffraction/Elastic Scattering

Elastic



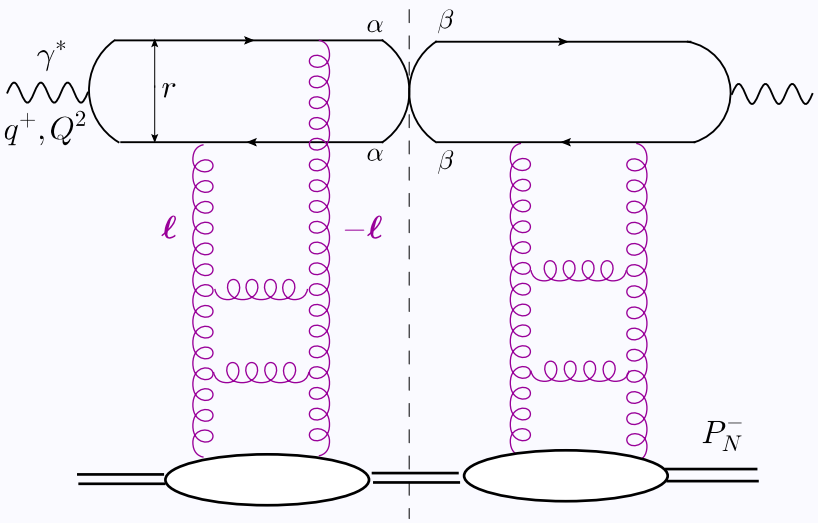
Total



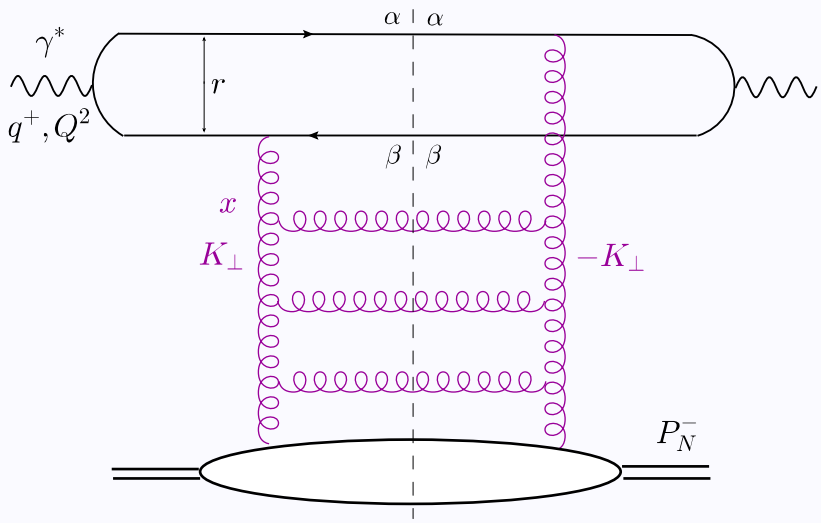
- Rapidity gap: wide angular region void of particles
- Elastic for projectile, no nuclear break-up (coherent reaction)
- Close color at amplitude level
- At least two gluons exchanged at amplitude

Large Dipoles in Diffraction

Elastic



Total



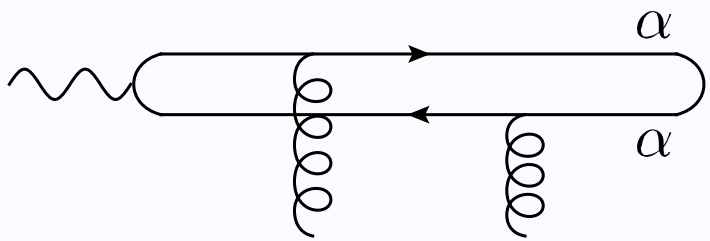
$$\sigma_{\mathrm{D}}^{\gamma^* A}(x, Q^2) = \int \mathrm{d}^2\boldsymbol{r} \int_0^1 \mathrm{d}z \left|\Psi_{\gamma^* \to q\bar{q}}(Q^2; \boldsymbol{r}, z)\right|^2 \pi R_A^2 [T(r, x)]^2$$

- T^2 : Diffractive cross section less sensitive to small dipoles
- Even for $Q^2 \gg Q_s^2$ dipoles with $r \gtrsim 1/Q_s$ and $z \sim Q_s^2/Q^2 \ll 1$ ("aligned jets") dominate diffractive cross section

- Eikonal multiple scattering of quark off target color field

$$V(\boldsymbol{x}) = \mathrm{T}\exp\left[ig\int \mathrm{d}x^+ t^a A_a^-(x^+, \boldsymbol{x})\right]$$

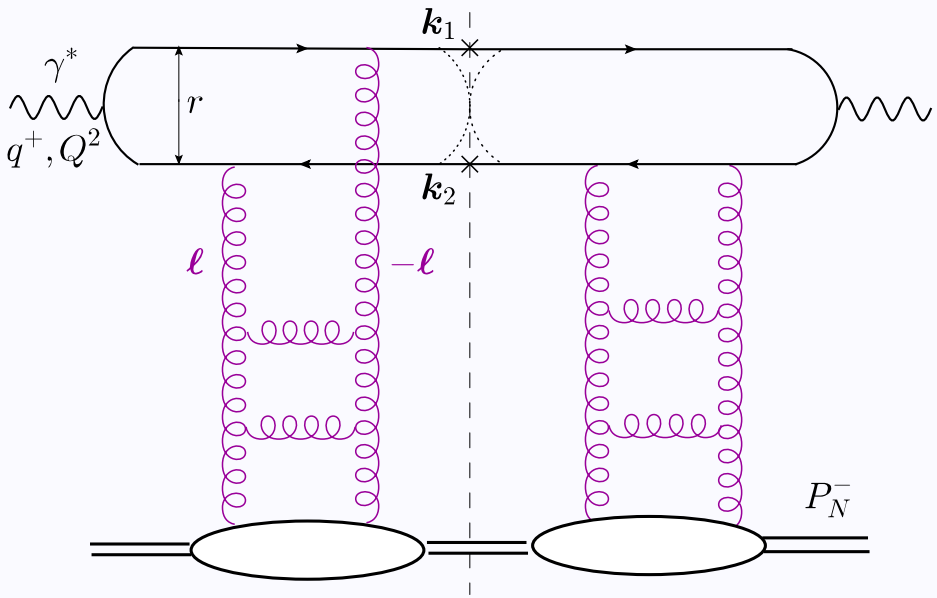
- Scattering of pair $q^\alpha \bar{q}^\beta$: $\left[V(\boldsymbol{x})V^\dagger(\boldsymbol{y}) - \mathbb{1}\right]_{\alpha\beta}$
- Diffractive projection: close color line in DA (and separately in CCA)



$$\left[V(\boldsymbol{x})V^\dagger(\boldsymbol{y}) - \mathbb{1}\right]_{\alpha\beta} \to \left\{\frac{1}{N_c}\,\mathrm{tr}\left[V(\boldsymbol{x})V^\dagger(\boldsymbol{y})\right] - 1\right\}\delta_{\alpha\beta} = -T(\boldsymbol{x},\boldsymbol{y})\,\delta_{\alpha\beta}$$

- CGC: Average color field, BK/JIMWLK evolution in gap $\ln 1/x_{\mathbb{P}}$

- More exclusive processes? Measured jets (or hadrons)?
- Hard scale sets dipole size $r \sim 1/P_\perp$, weak scattering
- Hard, symmetric, back to back $q\bar{q}$ pair:
  $k_{1\perp} \simeq k_{2\perp} \equiv P_\perp \sim Q \gg Q_s$, $z_{1,2} \sim 1/2$

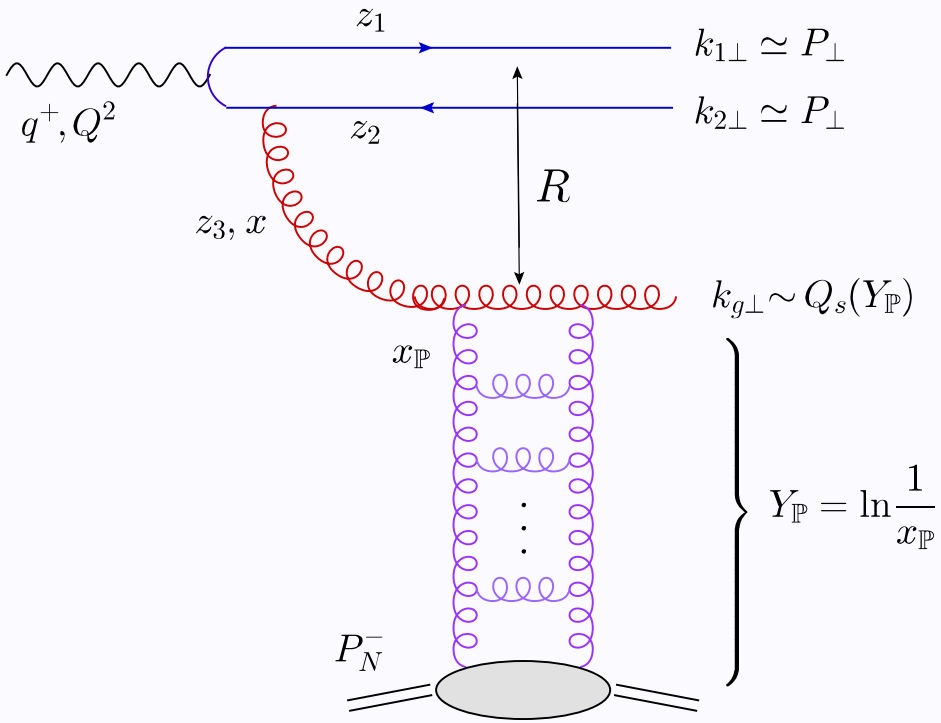


$$\frac{\mathrm{d}\sigma_{\mathrm{D}}^{\gamma^* A \to q\bar{q}A}}{\mathrm{d}z_1 \mathrm{d}^2\boldsymbol{P}} \propto \pi R_A^2 \underbrace{\frac{1}{Q^2}}_{\gamma^* q\bar{q}} \underbrace{\frac{Q_s^4}{P_\perp^4}}_{T^2(r)}$$

$$\sim \frac{1}{P_\perp^6} \text{ higher twist}$$

2+1 Jets in Diffraction

- Leading $1/P_\perp^4$? Two hard jets $P_\perp \gg Q_s$, semi-hard $k_{g\perp} \sim Q_s \ll P_\perp$
- Diffractive projection for $q^\alpha \bar{q}^\beta g^a$: $\mathcal{O}^a_{\alpha\beta} \equiv \frac{1}{C_F N_c} \mathrm{tr}\left[t^c \mathcal{O}^c\right] t^a_{\alpha\beta}$
- Semi-hard jet provides dijet imbalance

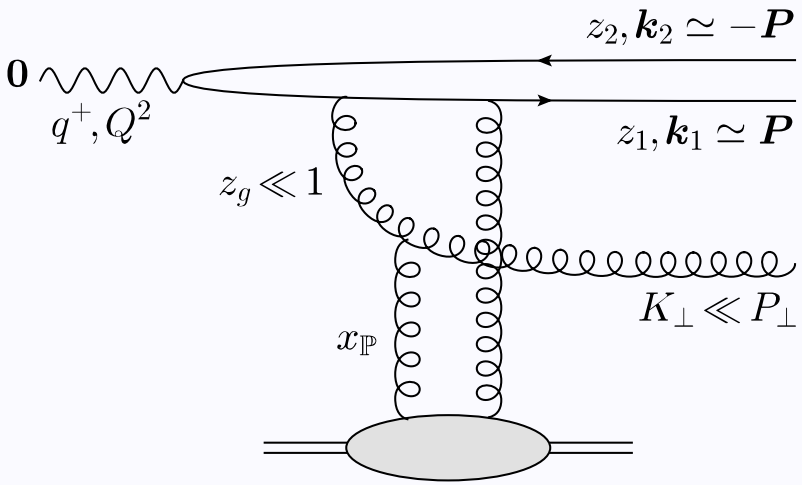


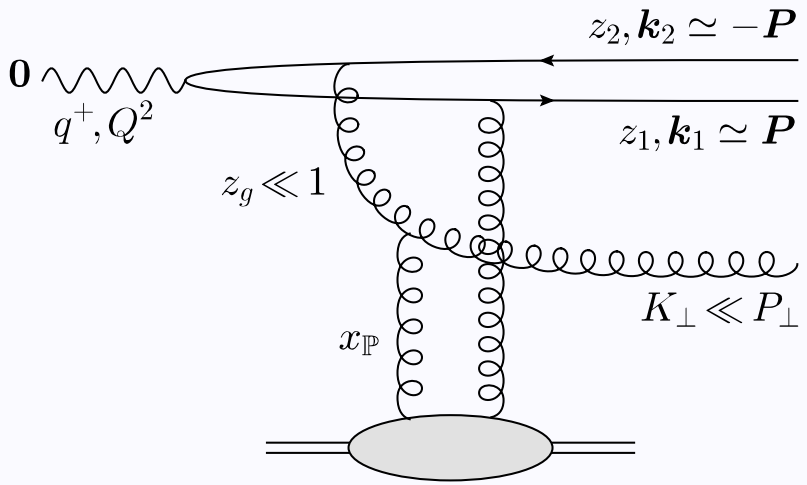
- $\mathcal{O}(\alpha_s)$ suppression
- $R \gg r$: gluon dipole
- $T_g(R, Y_\mathbb{P}) \simeq \mathcal{O}(1)$
- Hard factor

$$H \propto \underbrace{\frac{1}{Q^2}}_{\gamma^* q\bar{q}} \times \underbrace{r^2}_{\substack{\text{gluon} \\ \text{emission}}} \sim \frac{1}{P_\perp^4}$$

- "Energy" conservation: $x_\mathbb{P} \simeq \frac{1}{2q^+ P_N^-} \left(\frac{P_\perp^2}{z_1 z_2} + \frac{k_{g\perp}^2}{z_g} + Q^2 \right)$

Gluon Dipole Wavefunction



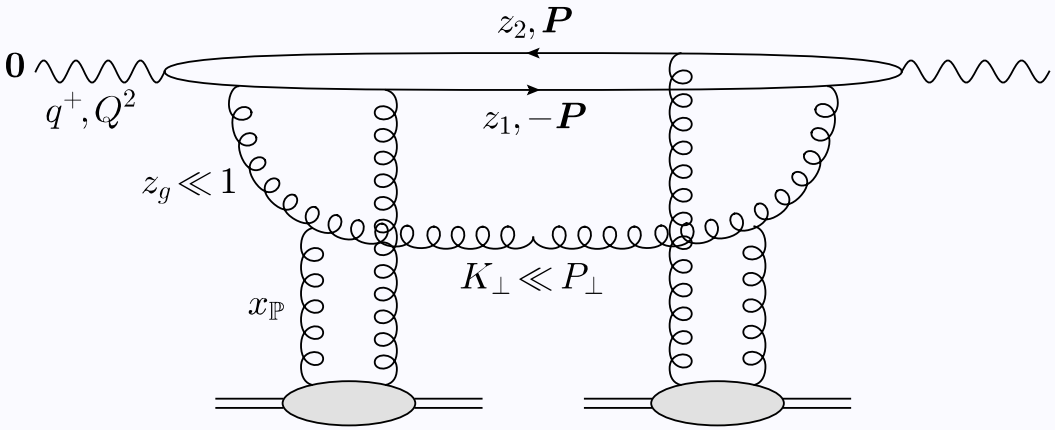


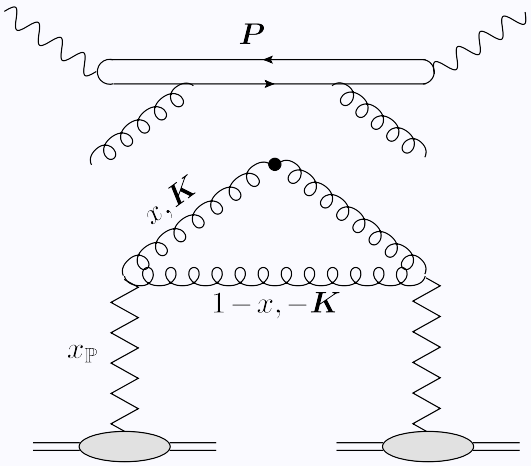
- Gluon formation time must be small enough:
  $k_g^+/k_{g\perp}^2 \lesssim q^+/Q^2 \rightsquigarrow z_g \lesssim k_{g\perp}^2/P_\perp^2 \ll 1$, gluon is soft
- Momentum space LCWF
  - Expand for $k_{g\perp} \ll P_\perp$ and $z_g \ll k_{g\perp}/P_\perp$ (no recoil)
  - Leading terms cancel $\rightsquigarrow$ Non-eikonal emission
  - Scattering is eikonal (Wilson lines), keep diffractive projection
  - Add instantaneous quark propagator graph

- Scales separation $\rightsquigarrow$ Factorization?
- View gluon as part of Pomeron. Variable change from ξ to x:

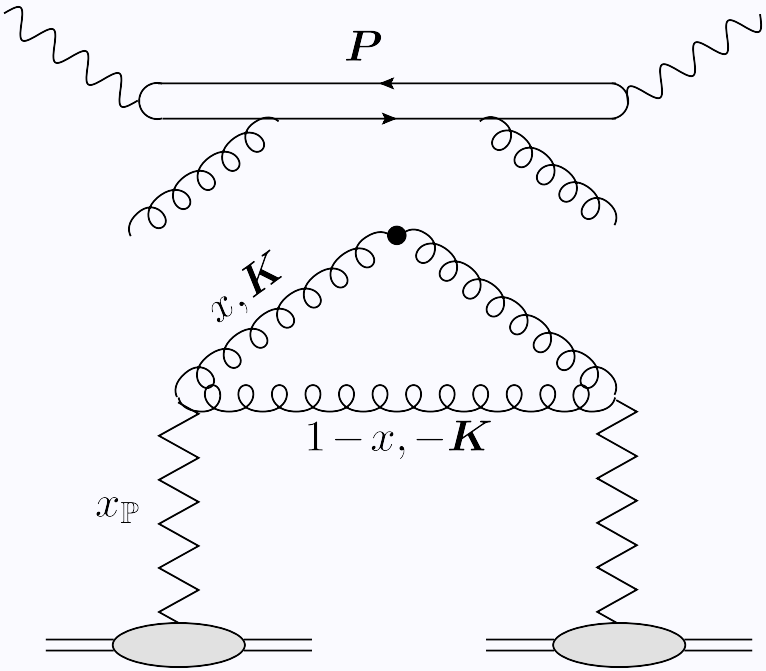
$$x = \frac{x_{q\bar{q}}}{x_{\mathbb{P}}} = \frac{\frac{P_\perp^2}{z_1 z_2} + Q^2}{\frac{P_\perp^2}{z_1 z_2} + \frac{k_{g\perp}^2}{z_g} + Q^2} \quad \text{or} \quad x = \beta \frac{x_{q\bar{q}}}{x_{\mathrm{Bj}}} \simeq \beta \frac{\bar{Q}^2 + P_\perp^2}{P_\perp^2}$$

- For given x_{Bj} and hard jets, only one of z_g, $x_{\mathbb{P}}$ and x is independent





TMD Factorization and Cross Section



$$\frac{\mathrm{d}\sigma_{\mathrm{D}}^{\gamma^*_{T,L}A\to q\bar{q}gA}}{\mathrm{d}z_1\mathrm{d}z_2\mathrm{d}^2\boldsymbol{P}\mathrm{d}^2\boldsymbol{K}\mathrm{d}Y_{\mathbb{P}}} = H_{T,L}(z_1,z_2,Q^2,P_\perp^2)\,\mathcal{F}_{\mathbb{P}}^{(0)}(x,x_{\mathbb{P}},K_\perp^2)$$

- Hard factor as in inclusive $q\bar{q}$ dijet cross section

$$H_T(z_1,z_2,Q^2,P_\perp^2) \equiv \alpha_{em}\alpha_s\Big(\sum e_f^2\Big)\,\delta_z\,\underbrace{(z_1^2+z_2^2)}_{2P_{q\gamma}(z_1)}\,\underbrace{\frac{P_\perp^4+\bar{Q}^4}{(P_\perp^2+\bar{Q}^2)^4}}_{\sim 1/P_\perp^4}$$

Semi-hard Factor: Gluon Diffractive TMD

- Gluon DTMD

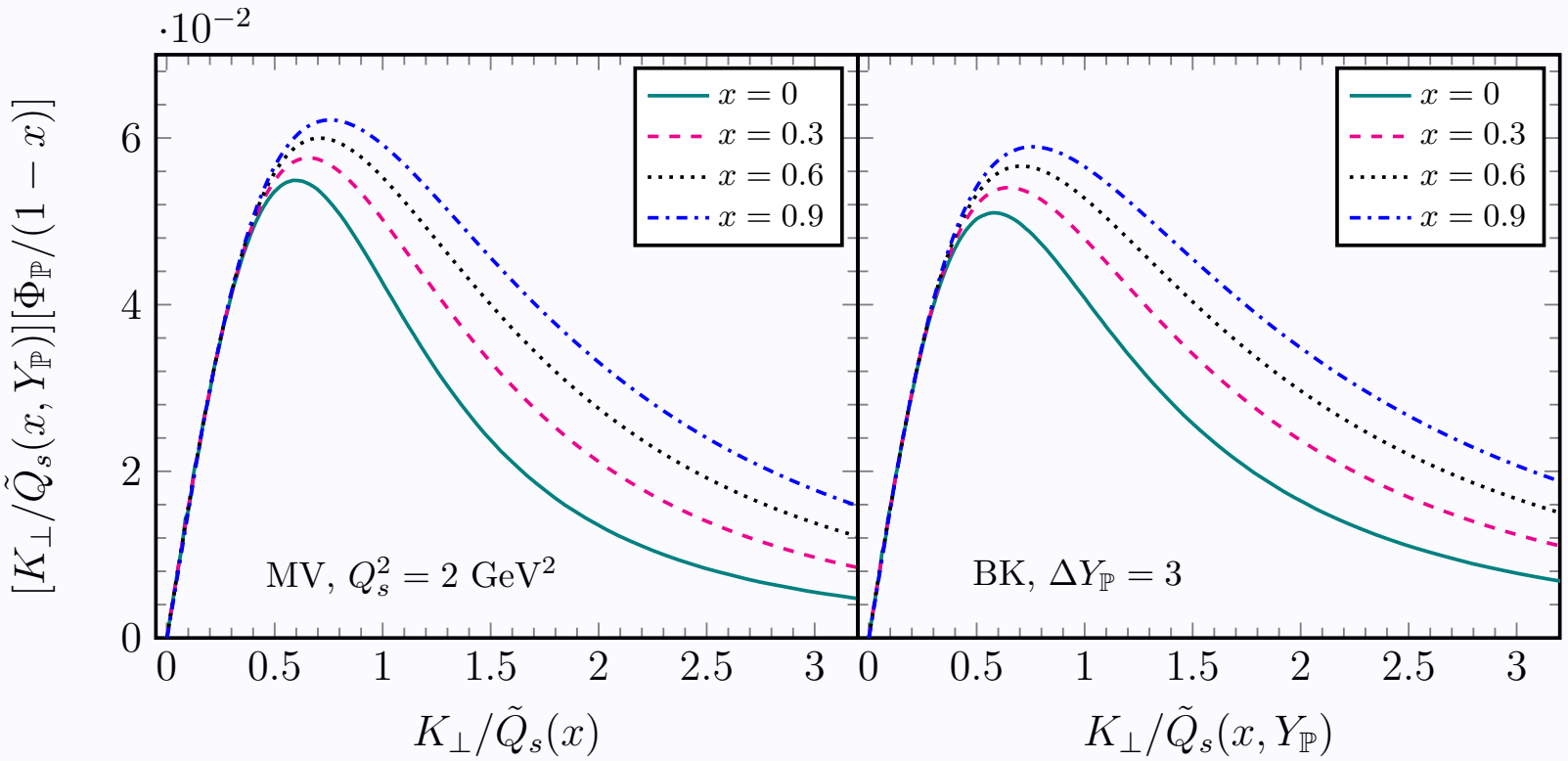
$$\mathcal{F}_{\mathbb{P}}^{(0)}(x, x_{\mathbb{P}}, K_\perp^2) = \underbrace{\frac{S_\perp (N_c^2 - 1)}{4\pi^3}}_{\text{d.o.f.}} \underbrace{\Phi_{\mathbb{P}}(x, x_{\mathbb{P}}, K_\perp^2)}_{\text{occupation number}}$$

- Explicit in terms of elastic amplitude
  (Bessel transform of $K_2(\sqrt{x/(1-x)}KR)\, T_g(R, x_{\mathbb{P}})$)

$$\Phi_{\mathbb{P}}(x, x_{\mathbb{P}}, K_\perp^2) \approx \frac{1-x}{2\pi} \begin{cases} 1 & \text{for} \quad K_\perp \ll \tilde{Q}_s(x) \\ \dfrac{\tilde{Q}_s^4(x, Y_{\mathbb{P}})}{K_\perp^4} & \text{for} \quad K_\perp \gg \tilde{Q}_s(x) \end{cases}$$

- Valid for large gaps: $x_{\mathbb{P}} \lesssim 10^{-2}$
- Effective saturation momentum $\tilde{Q}_s^2(x) \equiv (1-x) Q_s^2$
- Bulk of distribution at saturation $K_\perp \lesssim \tilde{Q}_s(x)$

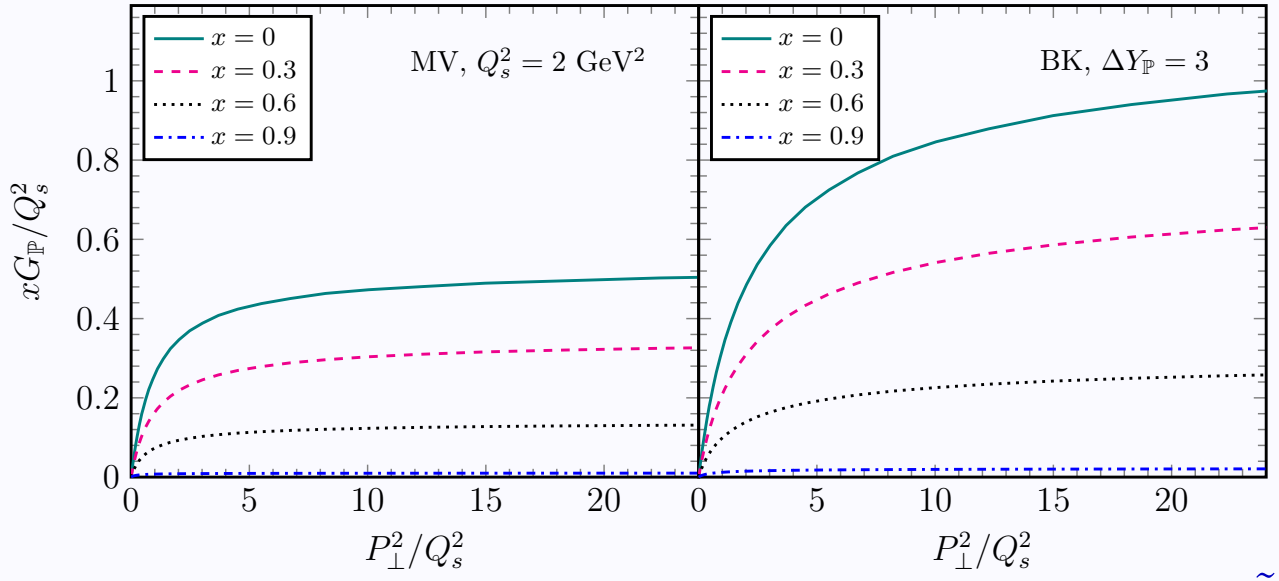
Gluon Diffractive TMD



$$\mathcal{T}_g(r) = 1 - \exp\left[-\frac{r^2 Q_A^2}{4}\ln\frac{4}{r^2\Lambda^2}\right] \text{ (left)} \qquad \text{plus BK (right)}$$

- Multiplied by $K_\perp$ (cf. measure $\mathrm{d}^2\boldsymbol{K}$)
- Pronounced maximum at $K_\perp \sim \tilde{Q}_s(x)$

Gluon Diffractive PDF and Collinear Factorization



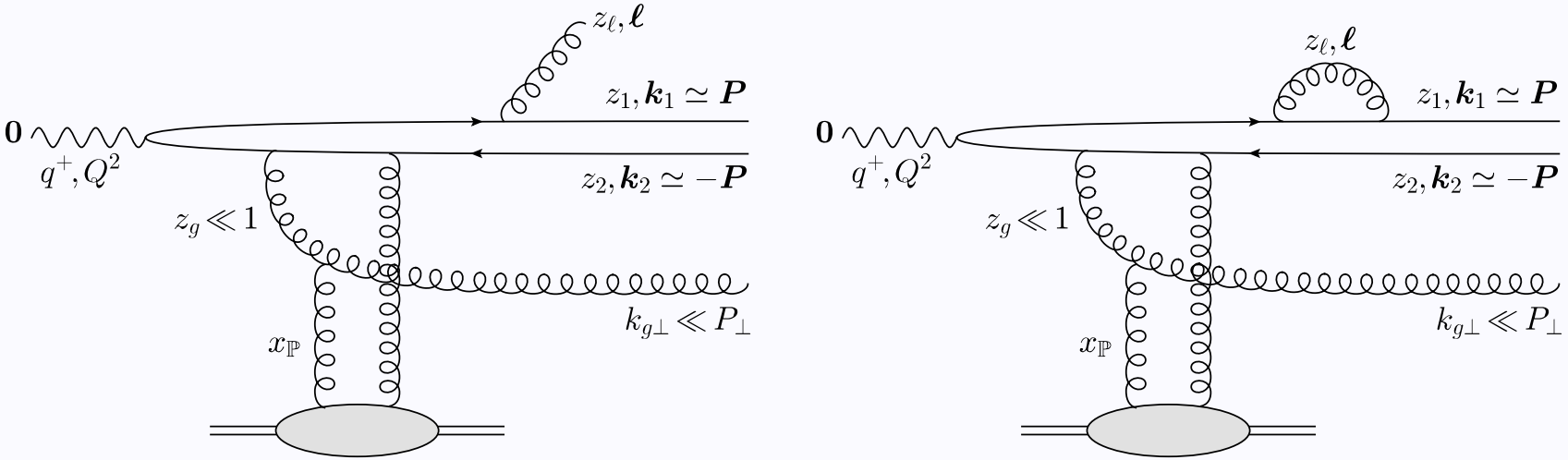
- Convergent integration, dominated by peak region $K_\perp \sim \tilde{Q}_s(x)$
- Familiar collinear factorization

$$\frac{\mathrm{d}\sigma_{\mathrm{D}}^{\gamma^* A \to q\bar{q}gA}}{\mathrm{d}z_1 \mathrm{d}z_2 \mathrm{d}^2\boldsymbol{P} \mathrm{d}Y_{\mathbb{P}}} = \underbrace{H(z_1, z_2, Q^2, P_\perp^2)}_{\sim 1/P_\perp^4} xG_{\mathbb{P}}^{(0)}(x, x_{\mathbb{P}}, P_\perp^2)$$

- Explicit result for gluon DPDF

$$xG_{\mathbb{P}}^{(0)}(x, x_{\mathbb{P}}, P_\perp^2) \propto \frac{S_\perp (N_c^2 - 1)}{4\pi^3} (1-x)^2 \, Q_s^2(x_{\mathbb{P}})$$

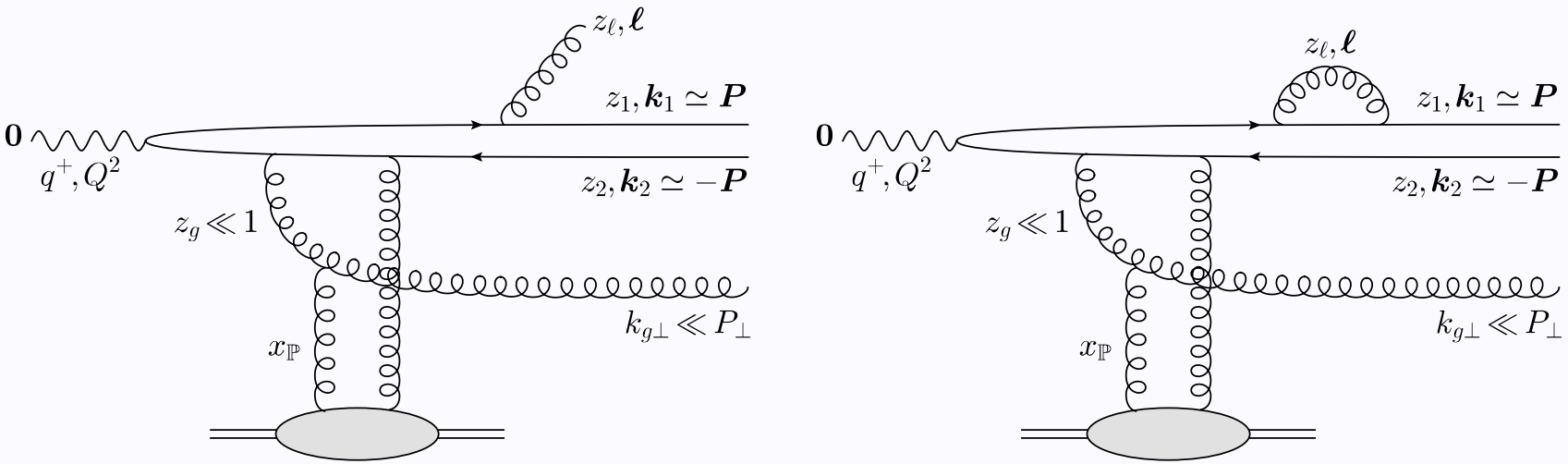
Additional late time emissions and CSS



- Gluons with $\tau_\ell \gg \tau_\gamma \to z_\ell \gg \ell_\perp^2/P_\perp^2$ do not interact
- Gluons going "out" at large angles: $\theta_\ell \gg \theta_q \to z_\ell \ll \ell_\perp/P_\perp$
- Induced change in the semi-hard factor (suppress $x, x_{\mathbb{P}}$):

$$\Delta\mathcal{F}_{\mathbb{P}}(\boldsymbol{K}) = \frac{\alpha_s N_c}{\pi^2}\int \frac{\mathrm{d}^2\boldsymbol{\ell}}{\boldsymbol{\ell}^2}\int_{\ell_\perp^2/P_\perp^2}^{\ell_\perp/P_\perp}\frac{\mathrm{d}z_\ell}{z_\ell}\left[\mathcal{F}_{\mathbb{P}}^{(0)}(\boldsymbol{K}+\boldsymbol{\ell}) - \Theta(P_\perp - \ell_\perp)\mathcal{F}_{\mathbb{P}}^{(0)}(\boldsymbol{K})\right]$$

Additional late time emissions and CSS



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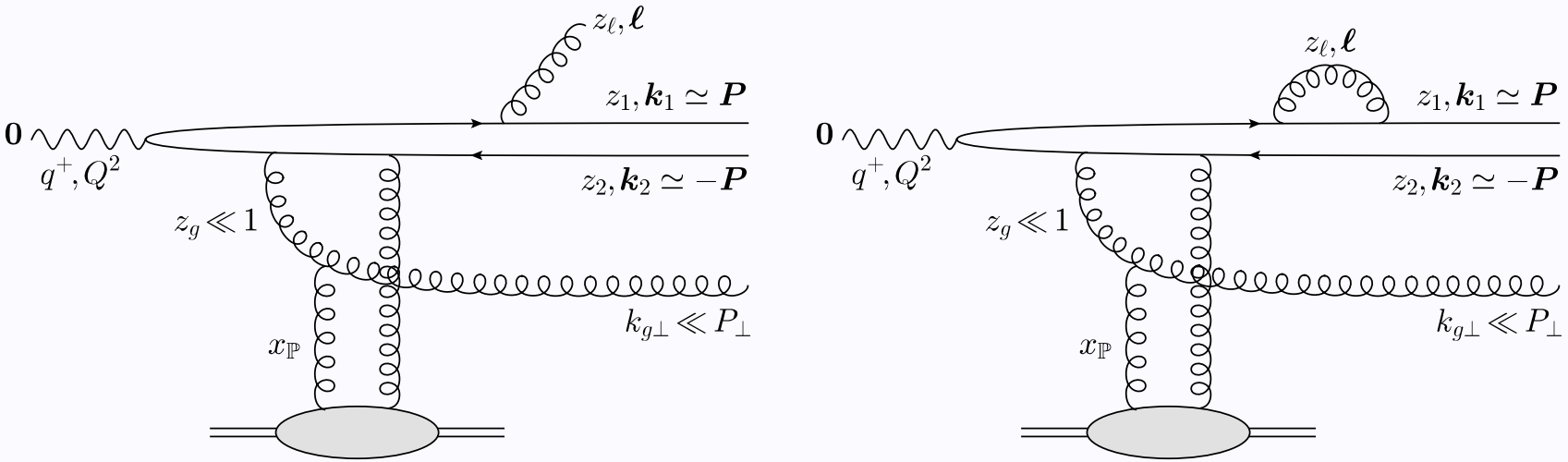
- Gluons going "out" at large angles: $\theta_\ell \gg \theta_q \to z_\ell \ll \ell_\perp/P_\perp$
- Do longitudinal integration

$$\Delta\mathcal{F}_{\mathbb{P}}(\boldsymbol{K}) = \frac{\alpha_s N_c}{2\pi^2}\int \frac{\mathrm{d}^2\boldsymbol{\ell}}{\boldsymbol{\ell}^2}\ln\frac{P_\perp^2}{\ell_\perp^2}\left[\mathcal{F}_{\mathbb{P}}^{(0)}(\boldsymbol{K}+\boldsymbol{\ell}) - \Theta(P_\perp-\ell_\perp)\mathcal{F}_{\mathbb{P}}^{(0)}(\boldsymbol{K})\right]$$

Additional late time emissions and CSS



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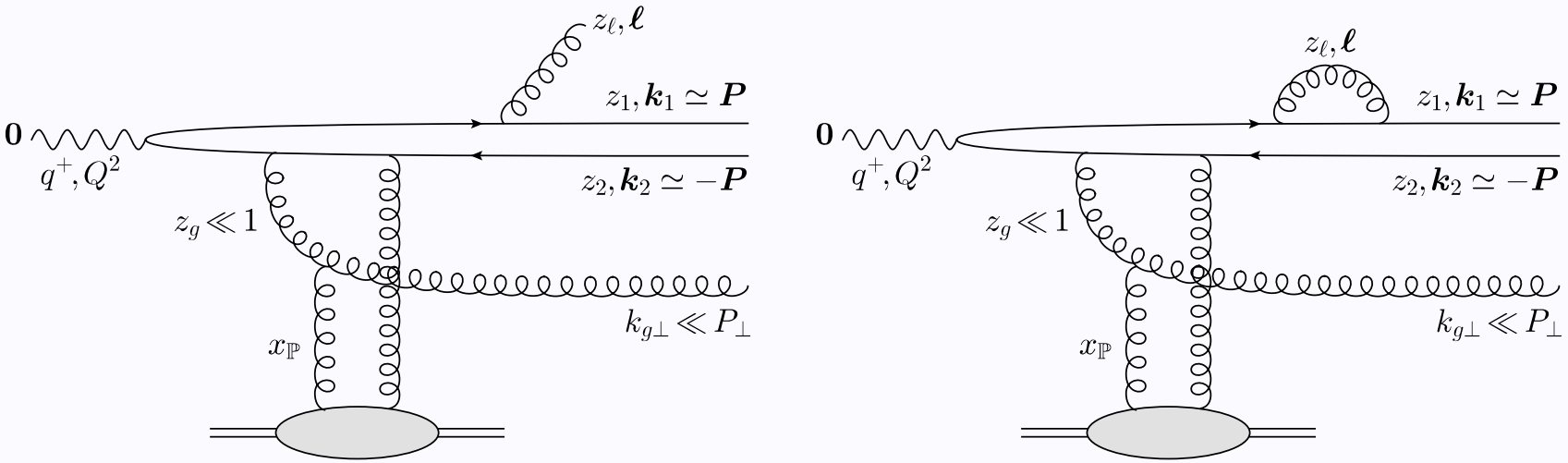
- Gluons going "out" at large angles: $\theta_\ell \gg \theta_q \to z_\ell \ll \ell_\perp/P_\perp$
- Promote to evolution

$$\frac{\mathrm{d}\mathcal{F}_{\mathbb{P}}(\boldsymbol{K}, P_\perp^2)}{\mathrm{d}\ln P_\perp^2} = \frac{\alpha_s N_c}{2\pi^2}\int \frac{\mathrm{d}^2\boldsymbol{\ell}}{\boldsymbol{\ell}^2}\left[\mathcal{F}_{\mathbb{P}}(\boldsymbol{K}+\boldsymbol{\ell}, P_\perp^2) - \Theta(P_\perp - \ell_\perp)\mathcal{F}_{\mathbb{P}}(\boldsymbol{K}, P_\perp^2)\right]$$

- Gluon DTMD depends on hard scale
- Finite both in UV and IR
- Saturation? Boundary condition: $\mathcal{F}_{\mathbb{P}}(\boldsymbol{K}, P_\perp^2 = K_\perp^2) = \mathcal{F}_{\mathbb{P}}^{(0)}(\boldsymbol{K})$

Additional late time emissions and CSS



- Gluons with $\tau_\ell \gg \tau_\gamma \to z_\ell \gg \ell_\perp^2/P_\perp^2$ do not interact
- Gluons going "out" at large angles: $\theta_\ell \gg \theta_q \to z_\ell \ll \ell_\perp/P_\perp$
- Fourier transform to coordinate space $\boldsymbol{K} \to \boldsymbol{b}$

$$\frac{\mathrm{d}\tilde{\mathcal{F}}_{\mathbb{P}}(b_\perp^2, P_\perp^2)}{\mathrm{d}\ln P_\perp^2} = -\frac{N_c}{2\pi}\int_{\mu_b^2}^{P_\perp^2} \frac{\mathrm{d}\ell_\perp^2}{\ell_\perp^2}\,\alpha_s(\ell_\perp^2)\tilde{\mathcal{F}}_{\mathbb{P}}(b_\perp^2, P_\perp^2), \qquad \mu_b^2 = 2e^{-\gamma_{\mathrm{E}}}/b_\perp^2$$

- Real term disappeared to give lower limit

Double Logarithmic Approximation

- Identify logarithmic regimes in transverse momenta

$$\frac{\partial \mathcal{F}_{\mathbb{P}}(K_\perp^2, P_\perp^2)}{\partial \ln P_\perp^2} = \frac{N_c}{2\pi}\left[\Theta(K_\perp, \mu_0)\,\frac{\alpha_s(K_\perp^2)}{K_\perp^2}\int_{\Lambda^2}^{K_\perp^2} \mathrm{d}k_{g_\perp}^2\,\mathcal{F}_{\mathbb{P}}(k_{g_\perp}^2, P_\perp^2) - \int_{K_\perp^2}^{P_\perp^2}\frac{\mathrm{d}\ell_\perp^2}{\ell_\perp^2}\,\Theta(\ell_\perp, \mu_0)\,\alpha_s(\ell_\perp^2)\mathcal{F}_{\mathbb{P}}(K_\perp^2, P_\perp^2)\right]$$

- $\mu_0 \sim Q_s$, step functions suppress not allowed emissions
- Real "gain" term: $k_{g_\perp} = |\boldsymbol{\ell} + \boldsymbol{K}| \ll K_\perp \simeq \ell_\perp$
- Virtual "loss" term: $\mu_0, K_\perp \ll \ell_\perp \ll P_\perp$
- Gluon DPDF "integral of motion"

$$\int_0^{P_\perp^2} \mathrm{d}^2\boldsymbol{K}\,\mathcal{F}_{\mathbb{P}}(K_\perp^2, P_\perp^2) = \int_0^{P_\perp^2} \mathrm{d}^2\boldsymbol{K}\,\mathcal{F}_{\mathbb{P}}^{(0)}(K_\perp^2, P_\perp^2) = xG_{\mathbb{P}}^{(0)}(P_\perp^2)$$

Exact DLA Solution

- Sudakov factor

$$\mathrm{S}(K_\perp^2, P_\perp^2) = \frac{N_c}{2\pi} \int_{K_\perp^2}^{P_\perp^2} \frac{\mathrm{d}\ell_\perp^2}{\ell_\perp^2}\, \Theta(\ell_\perp, \mu_0)\, \alpha_s(\ell_\perp^2) \ln \frac{P_\perp^2}{\ell_\perp^2}$$

- Exact solution

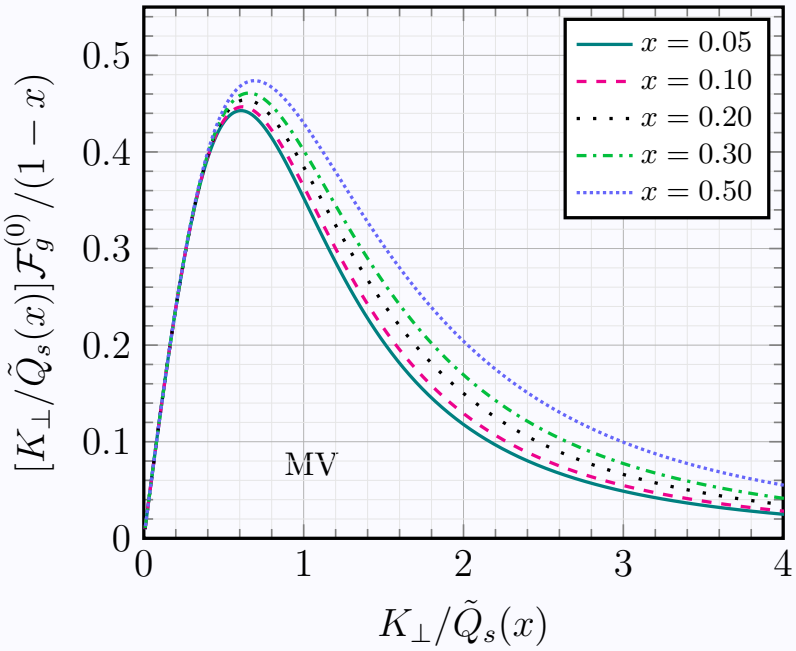
$$\mathcal{F}_{\mathbb{P}}(x, K_\perp^2, P_\perp^2) = \frac{1}{\pi} \frac{\partial x G_{\mathbb{P}}(x, K_\perp^2) \exp[-\mathrm{S}(K_\perp^2, P_\perp^2)]}{\partial K_\perp^2}$$

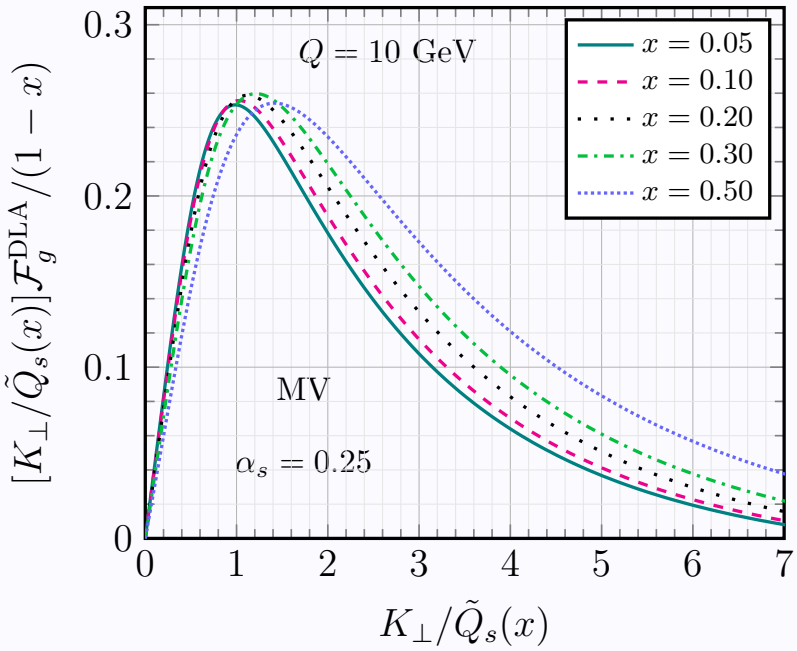
- More explicitly

$$\mathcal{F}_{\mathbb{P}}(x, K_\perp^2, P_\perp^2) = \Bigg[\mathcal{F}_{\mathbb{P}}^{(0)}(x, K_\perp^2) + \Theta(K_\perp, \mu_0) \times \frac{\alpha_s(K_\perp^2) N_c}{2\pi^2} \ln \frac{P_\perp^2}{K_\perp^2} \frac{x G_{\mathbb{P}}^{(0)}(x, K_\perp^2)}{K_\perp^2} \Bigg] \exp[-\mathrm{S}(K_\perp^2, P_\perp^2)]$$

- CSS tail $1/K_\perp^2$ created to be compared to tree tail $1/K_\perp^4$

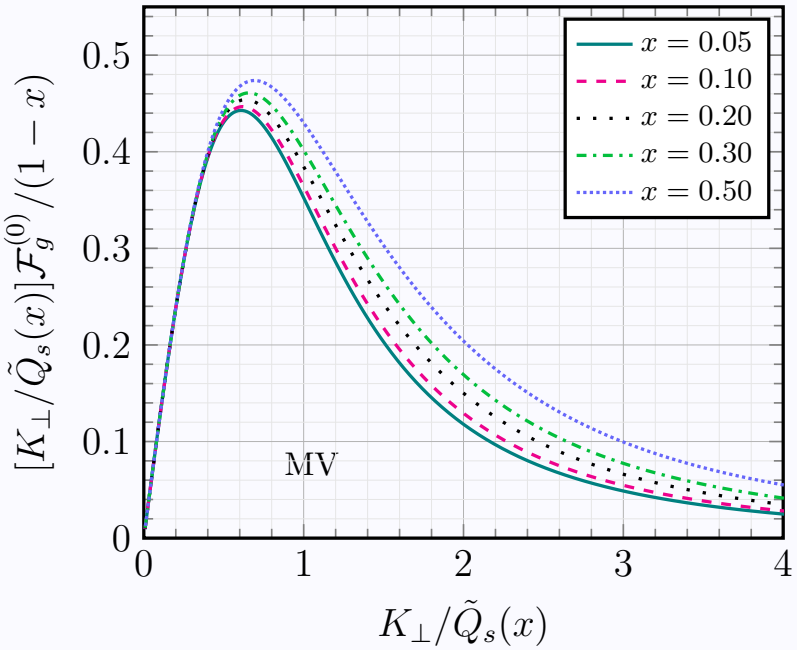
DLA Solutions

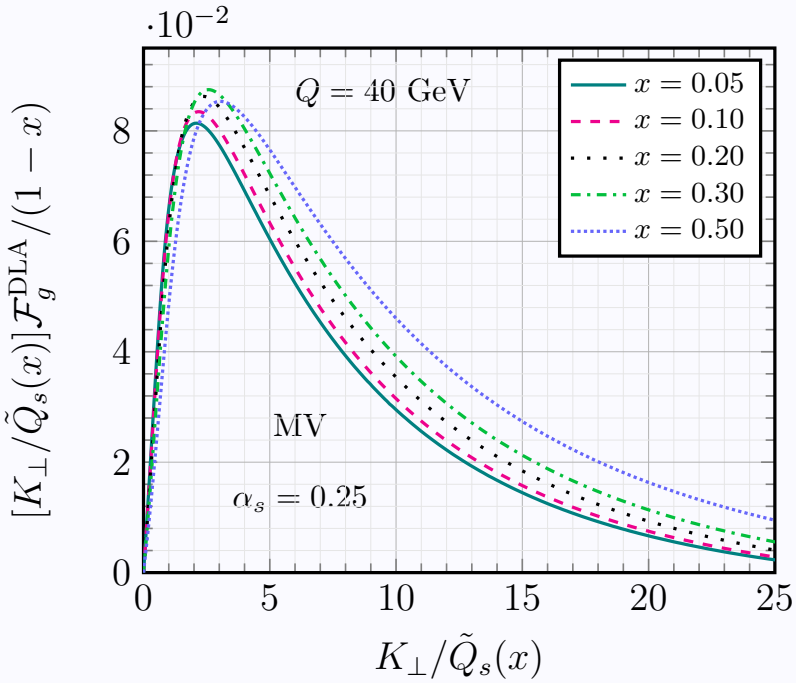




- Tree level : $K_{\perp\max} \sim \langle K_\perp \rangle \sim \tilde{Q}_s(x)$
- CSS : $K_{\perp\max} \simeq P_\perp e^{-1/(2\bar{\alpha}_s)}$ and $\langle K_\perp \rangle \simeq 2\bar{\alpha}_s P_\perp$
- Gluons pushed towards larger $K_\perp$

DLA Solutions





- Tree level : $K_{\perp\max} \sim \langle K_\perp \rangle \sim \tilde{Q}_s(x)$
- CSS : $K_{\perp\max} \simeq P_\perp e^{-1/(2\bar{\alpha}_s)}$ and $\langle K_\perp \rangle \simeq 2\bar{\alpha}_s P_\perp$
- Gluons pushed towards larger $K_\perp$

- Local equation in $b_\perp^2$

$$\frac{\mathrm{d}\tilde{\mathcal{F}}_{\mathbb{P}}(x,b_\perp^2,P_\perp^2)}{\mathrm{d}\ln P_\perp^2} = -\frac{N_c}{2\pi}\int_{\mu_b^2}^{P_\perp^2}\frac{\mathrm{d}\ell_\perp^2}{\ell_\perp^2}\,\alpha_s(\ell_\perp^2)\tilde{\mathcal{F}}_{\mathbb{P}}(x,b_\perp^2,P_\perp^2)$$

- Straightforward solution

$$\tilde{\mathcal{F}}_{\mathbb{P}}(x,b_\perp^2,P_\perp^2) = \tilde{\mathcal{F}}_{\mathbb{P}}^{(0)}(x,\mu_b^2)\exp\left[-\mathrm{S}(\mu_b^2,P_\perp^2)\right]$$

- But Sudakov is a bit different

$$\mathrm{S}(\mu_b^2,P_\perp^2) = \frac{N_c}{2\pi}\int_{\mu_b^2}^{P_\perp^2}\frac{\mathrm{d}\ell_\perp^2}{\ell_\perp^2}\,\cancel{\Theta(\ell_\perp,\mu_0)}\,\alpha_s(\ell_\perp^2)\ln\frac{P_\perp^2}{\ell_\perp^2}$$

- Boundary condition is FT of tree level DTMD : no Sudakov

$$\tilde{\mathcal{F}}_{\mathbb{P}}^{(0)}(x,\mu_b^2) = \tilde{\mathcal{F}}_{\mathbb{P}}(x,b_\perp^2,P_\perp^2=\mu_b^2) = \int\frac{\mathrm{d}^2\boldsymbol{K}}{(2\pi)^2}\,e^{i\boldsymbol{K}\cdot\boldsymbol{b}}\mathcal{F}_{\mathbb{P}}^{(0)}(x,K_\perp^2)$$

- Matching to $xG_{\mathbb{P}}^{(0)}(x,P_\perp^2)$ when $b_\perp\to 0$

Tree level BC in coordinate space

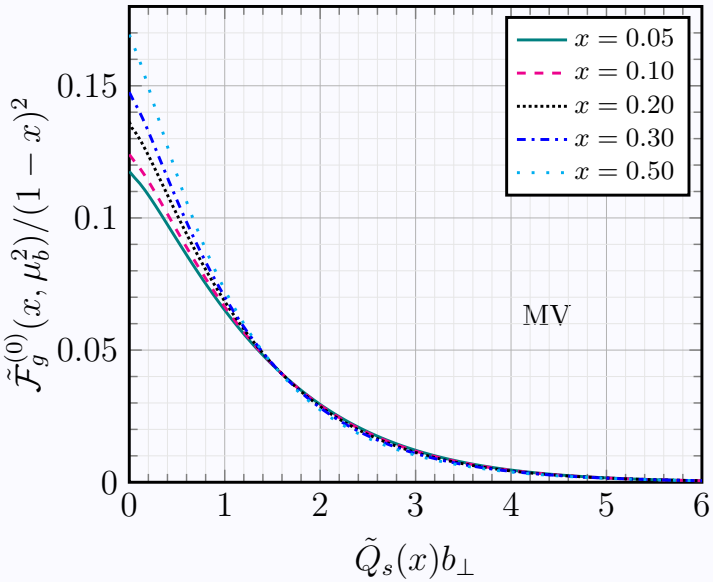
- Assume MV model. What is the large $b_\perp$ behavior? Need to distinguish two regimes $x = 0$ and $x \neq 0$:

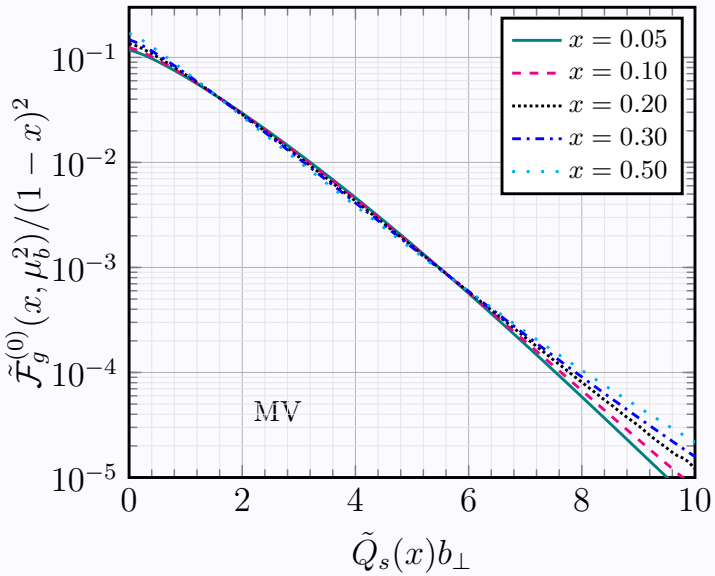
$$\tilde{\mathcal{F}}^{(0)}_{\mathbb{P}}(x = 0, \mu_b^2) \sim \frac{Q_s^2}{(b_\perp^2 Q_s^2/8)^2} \exp\left(-\frac{b_\perp^2 Q_s^2}{8}\right)$$

and

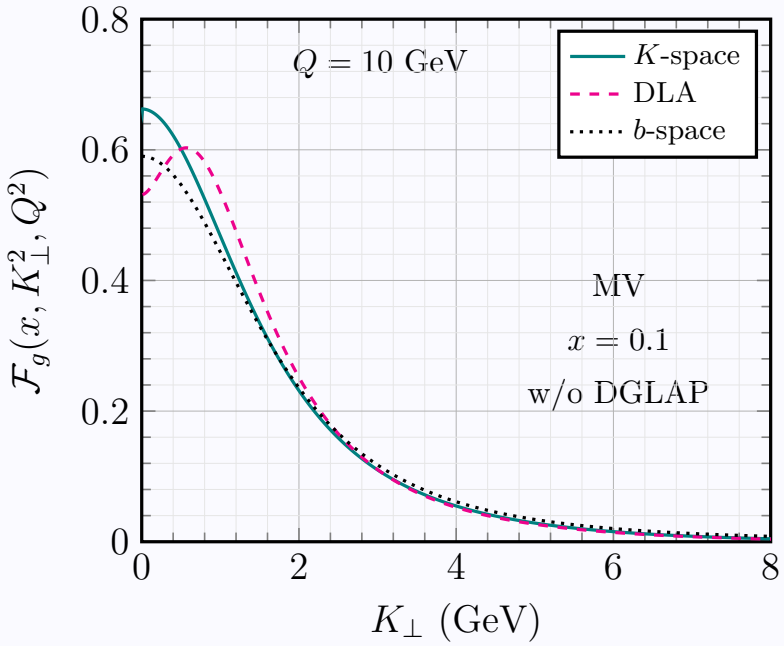
$$\tilde{\mathcal{F}}^{(0)}_{\mathbb{P}}(x, \mu_b^2) \sim \frac{x^2(1-x)\tilde{Q}_s^2}{(b_\perp^2 \tilde{Q}_s^2/8)^4}$$

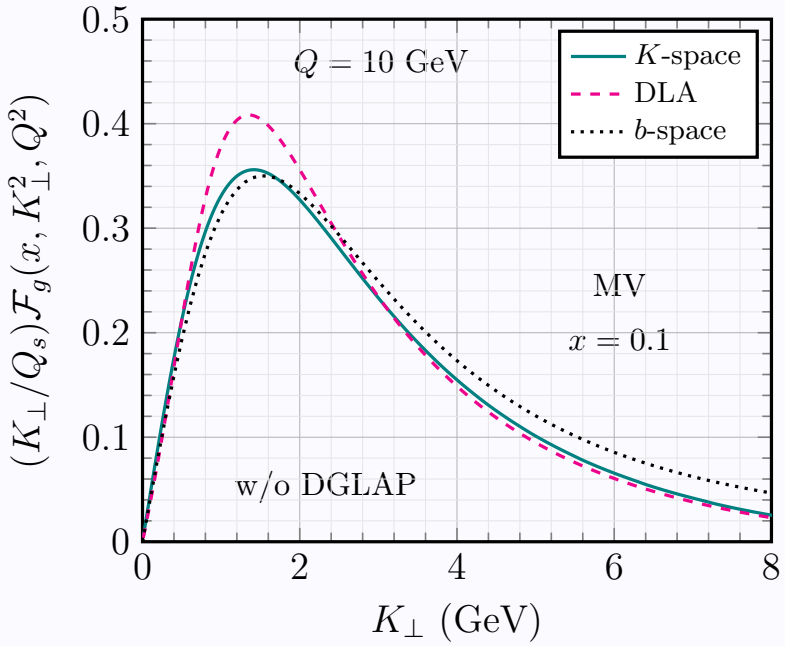
- Steep decay at large $b_\perp$ due to saturation, no need for NP Sudakov





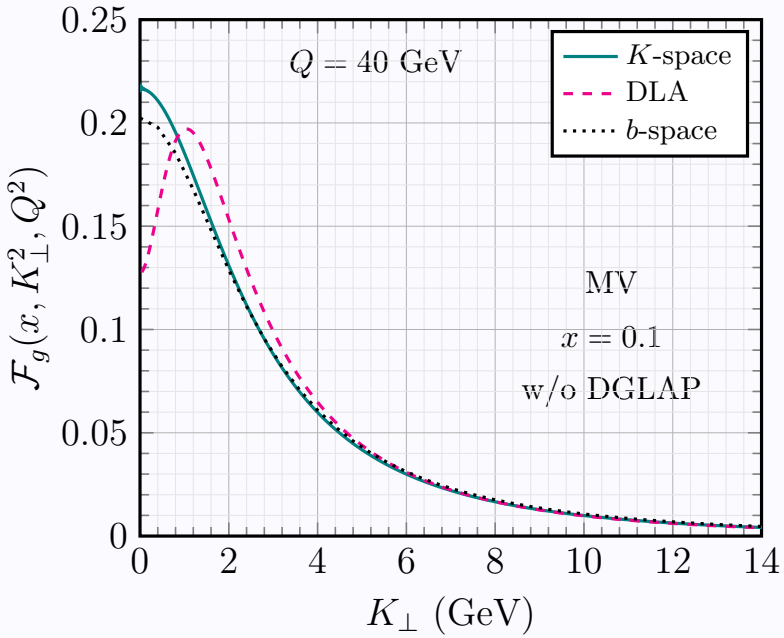
Solutions

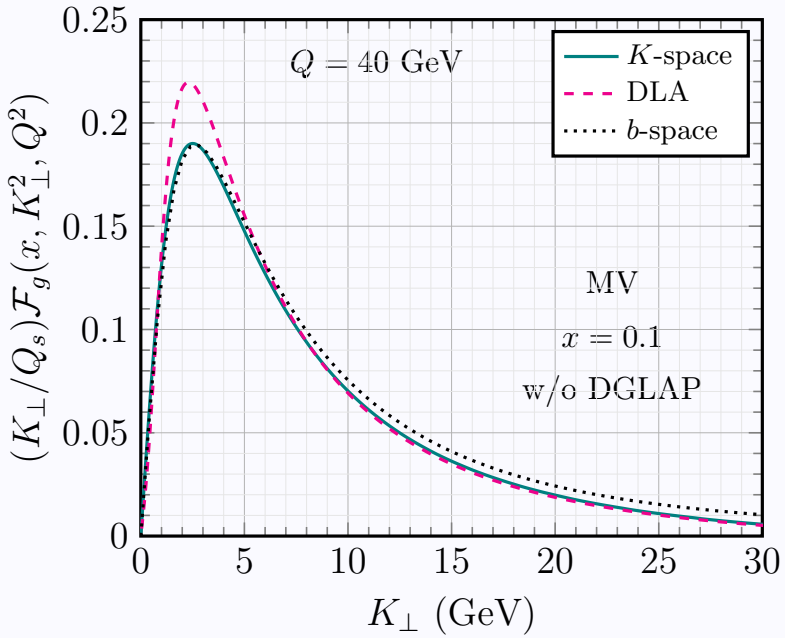




- Solutions not exactly equivalent due to
  - Boundary conditions
  - Running coupling
- Results of 3 equations match perturbatively to order $\bar{\alpha}_s$
  - Can choose the $K_\perp$-space BC to match results to order $\bar{\alpha}_s^2$
  - Cannot go beyond.

Solutions





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  - Cannot go beyond.

Adding DGLAP

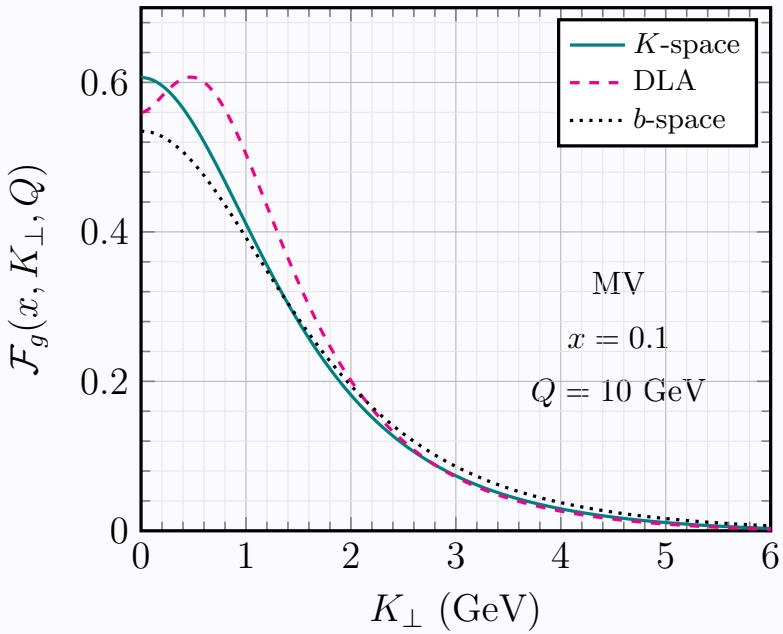
- If $\ln K_\perp^2/\mu_0^2$ gets significant one must DGLAP
- Exact DLA solution is still valid

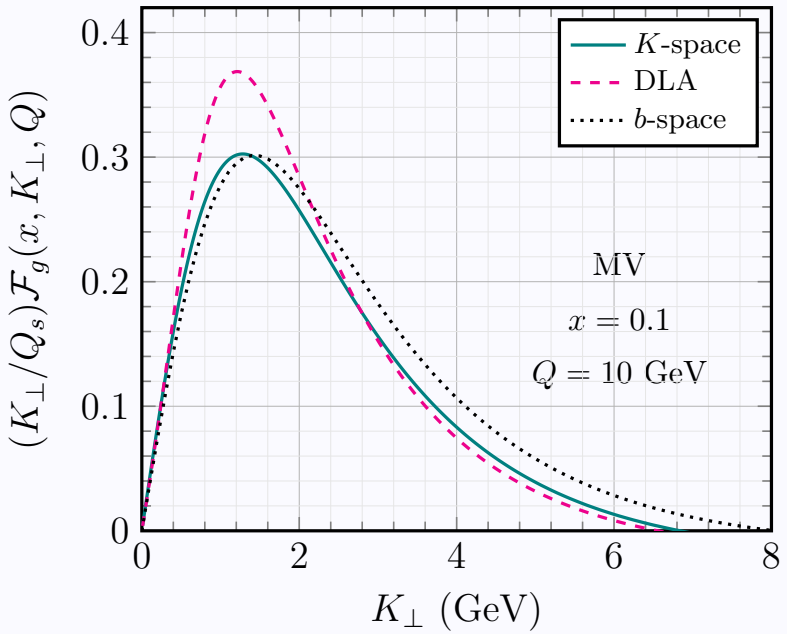
$$\mathcal{F}_{\mathbb{P}}(x, K_\perp^2, P_\perp^2) = \frac{1}{\pi} \frac{\partial x G_{\mathbb{P}}(x, K_\perp^2) \exp[-\mathrm{S}(K_\perp^2, P_\perp^2)]}{\partial K_\perp^2}$$

- $xG_{\mathbb{P}}(x, K_\perp^2)$ satisfies DGLAP evolution and modifies BC
- Sudakov also contains single logarithm $\propto \beta_0$
- Simple solution containing BK/JIMWLK, DGLAP and CSS
- $b_\perp$ space interpolating BC

$$\tilde{\mathcal{F}}_0(x, \mu_b^2) = \frac{xG_{\mathbb{P}}(x, \mu_b^2)}{xG_{\mathbb{P}}^{(0)}(x, \mu_b^2)} \tilde{\mathcal{F}}_{\mathbb{P}}^{(0)}(x, \mu_b^2)$$

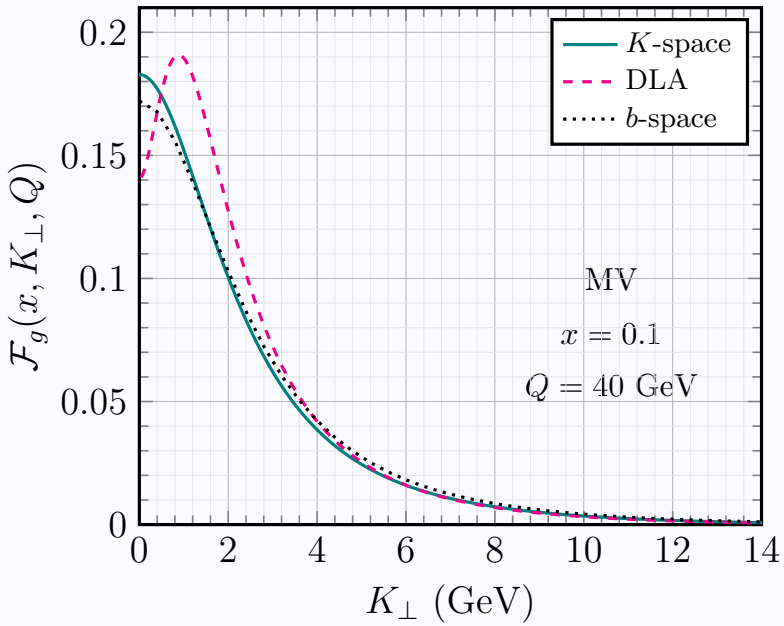
Solutions with DGLAP

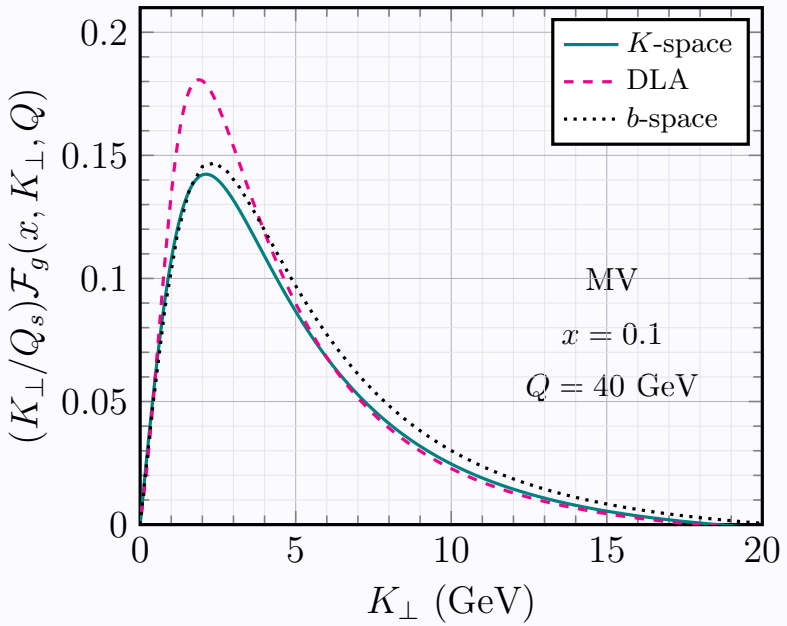




- DGLAP pushes peak to lower $K_\perp$
- Distribution negative above some $K_\perp$ for $x > 0$.
- Integral over $K_\perp$ still gives DPDF (exactly in DLA)
- Contribution from the negative region is not negligible

Solutions with DGLAP





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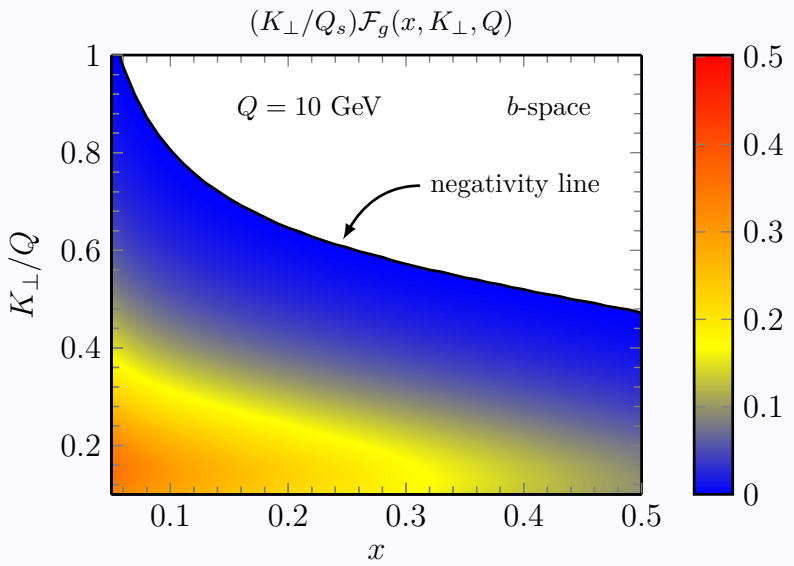
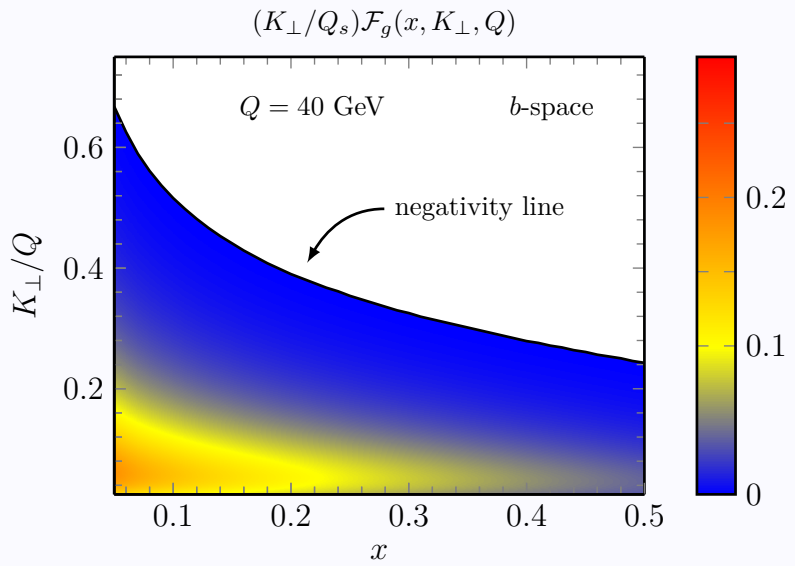
Solutions with DGLAP and negativity





- For harder $P_\perp$ the problem gets harder ...

Conclusion

- Diffraction at hard momenta in γA collisions in CGC
- Diffractive hard dijet cross sections dominated by 2+1 jets due to scattering near unitarity limit
- Factorization: Diffractive gluon TMD
- CSS evolution in momentum and coordinate space
- Large rapidity gaps and/or large nuclei: gluon DTMD calculated from "first principles", absence of NP Sudakov
- CGC, DGLAP and TMD evolution in the same formalism