

Early-Stage Jet Quenching

In collaboration with Tuomas Lappi

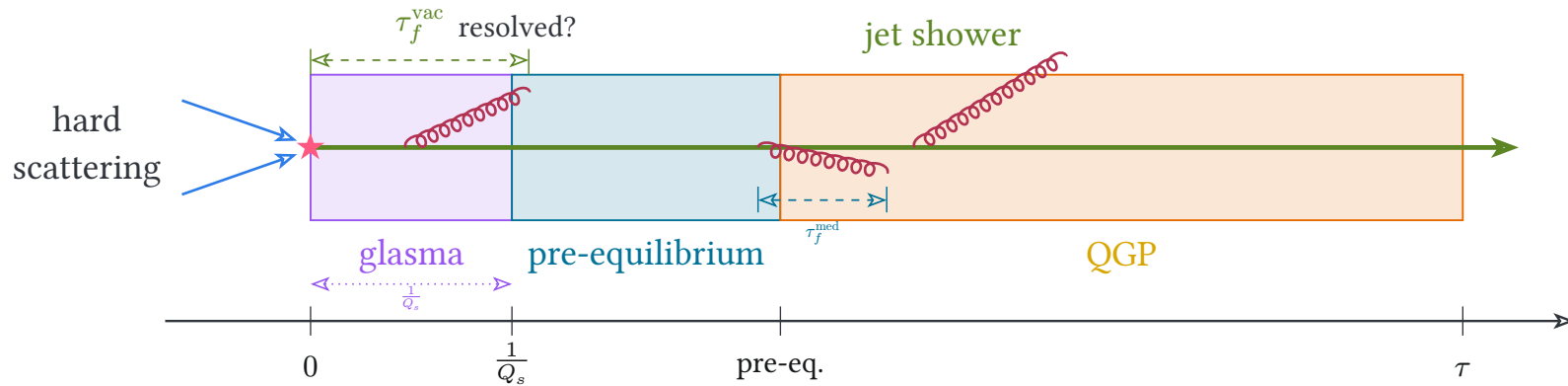
Ismail Soudi 

isma@physik.uni-bielefeld.de

Bielefeld University



Jets in heavy ion collisions



Medium

1. Initial Glasma Fields
2. Out-of-equilibrium evolution
2. Hydrodynamical QGP

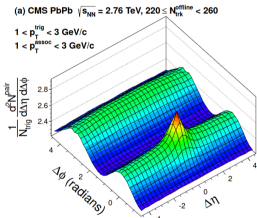
Jet

1. Hard production $\tau_{\text{hard}} \sim 1/p_T$
2. Vacuum-like shower
3. Jet-medium Shower

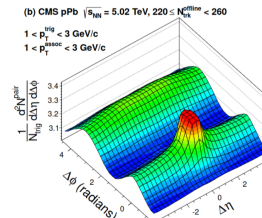
HIC vs Small Systems

Heavy-ion collisions

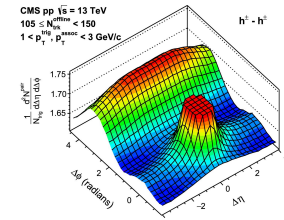
- ▶ Strong signals of collectivity
- ▶ Clear quenching observed
- ▶ QGP energy loss dominates



PbPb



pPb



high-mult. pp

System size

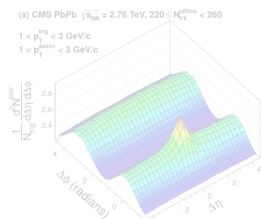
- ▶ Energy loss v.s. system size
- ▶ Early-time v.s. late-time energy loss

[Chatrchyan & others Phys. Lett. B 718, 795–814 2013; Chatrchyan & others Phys. Lett. B 724, 213–240 2013; Khachatryan & others Phys. Lett. B 765, 193–220 2017; Hayrapetyan & others Phys. Rev. Lett. 136, 162301 2026]

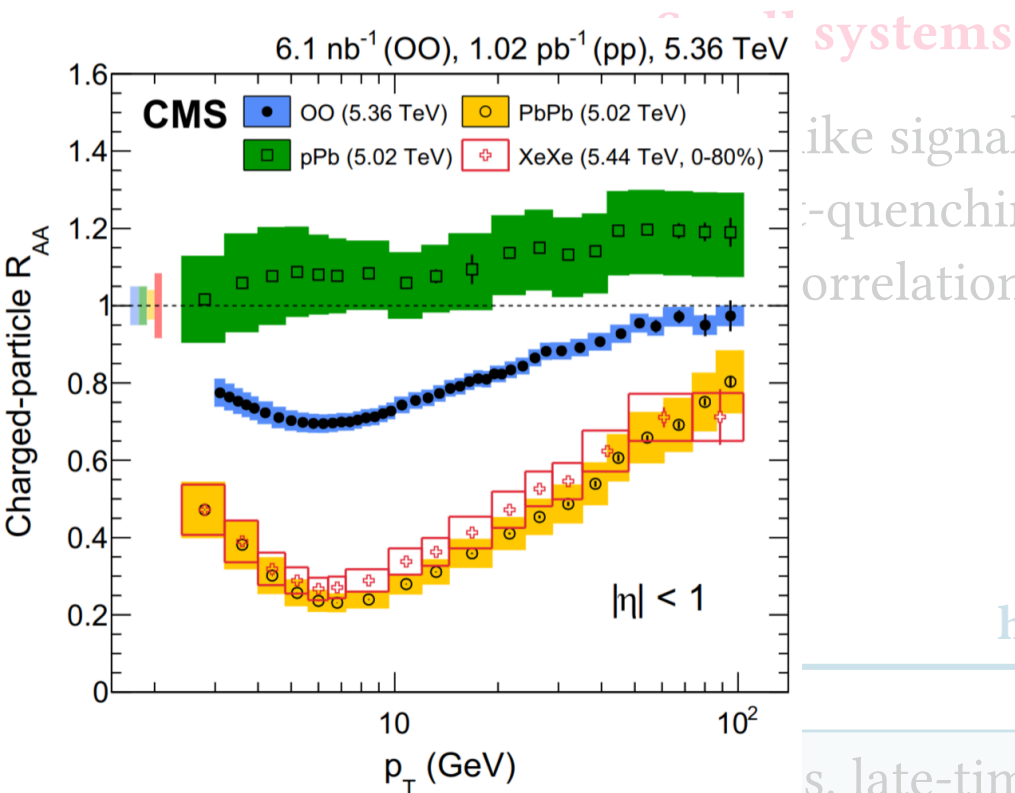
HIC vs Small Systems

Heavy-ion collisions

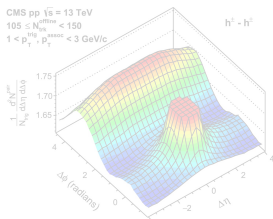
- ▶ Strong signals of collective flow
- ▶ Clear quenching observed
- ▶ QGP energy loss dominates



PbPb



like signals
 quenching signal
 correlations



high-mult. pp

s. late-time energy loss

▶ Energy loss v.s. syst

[Chatrchyan & others Phys. Lett. B 718, 795–814 2013; Chatrchyan & others Phys. Lett. B 724, 213–240 2013; Khachatryan & others Phys. Lett. B 765, 193–220 2017; Hayrapetyan & others Phys. Rev. Lett. 136, 162301 2026]

Momentum Broadening in Glasma

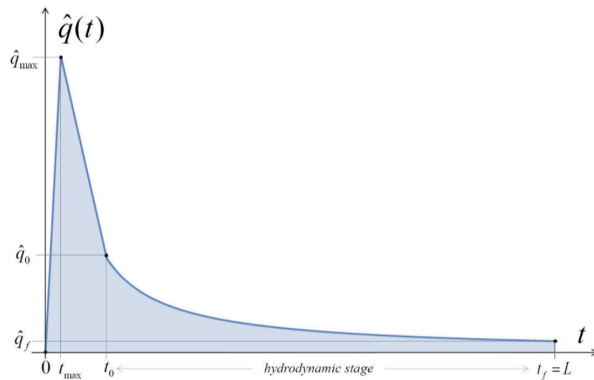
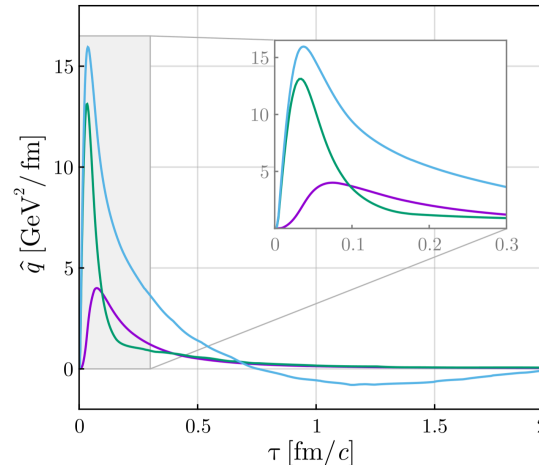
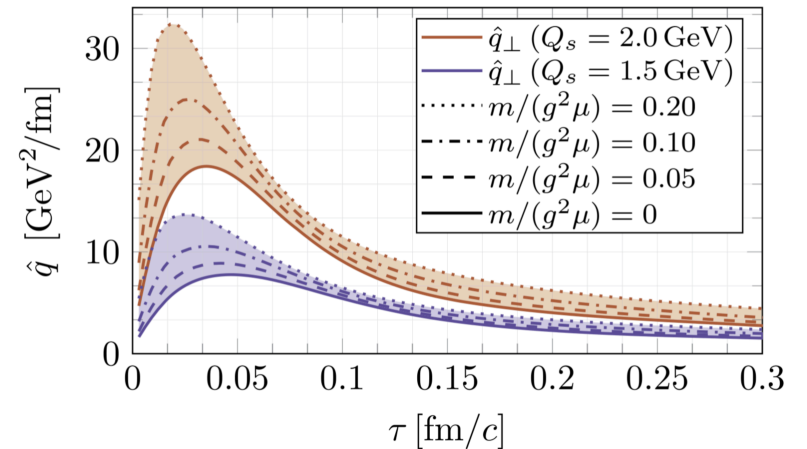


Figure 3: Schematic temporal evolution of $\hat{q}(t)$.

[Carrington et al. Phys. Lett. B 834, 137464 2022]



[Avramescu et al. Phys. Rev. D 107, 114021 2023]



[Ipp et al. Phys. Lett. B 810, 135810 2020]

► Large broadening $\hat{q}_{\text{glasma}} \gg \hat{q}_{\text{QGP}}$

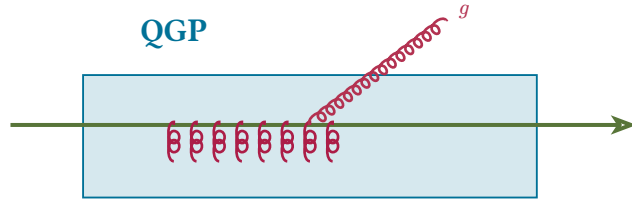
► Short lifetime

► BDMPS-Z Energy loss: $\Delta E \sim \hat{q} L^2$

[Baier et al. Nucl. Phys. B 483, 291–320 1997]

Medium-Induced Radiation

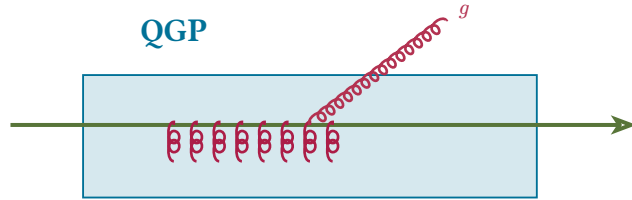
Standard picture



- ▶ Medium length $L \gg \tau_{\text{form}}$
- ▶ Multiple scatterings (LPM)
- ▶ Vacuum/medium separation
→ Jet resolved as on-shell

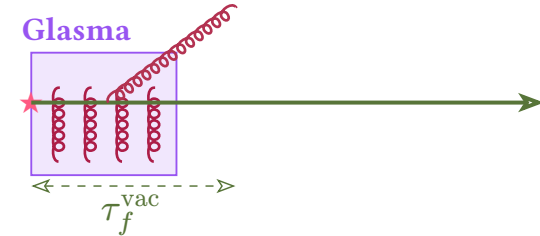
Medium-Induced Radiation

Standard picture



- ▶ Medium length $L \gg \tau_{\text{form}}$
- ▶ Multiple scatterings (LPM)
- ▶ Vacuum/medium separation
→ Jet resolved as on-shell

Early-time Plasma



- ▶ Short-lived glasma fields
- ▶ Highly virtual jet
- ▶ Vacuum-like splittings
→ Virtuality vs glasma resolution

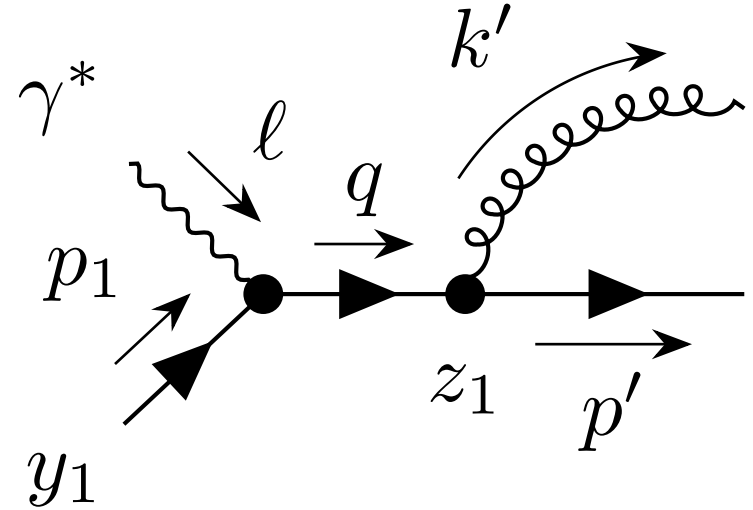
First emission: vacuum-like vs glasma modification

$$\tau_f^{\text{vac}} \Leftrightarrow 1/Q_s.$$

Modification of vacuum splitting

- ▶ Hard production: $\gamma^* q \rightarrow qg$
- ▶ Dense background at $x^+ = 0$
- ▶ Eikonal scattering: $\mathcal{U}_F, \mathcal{U}_A$
- ▶ Gluon momentum fraction

$$y = \frac{k'^+}{p'^+ + k'^+}$$



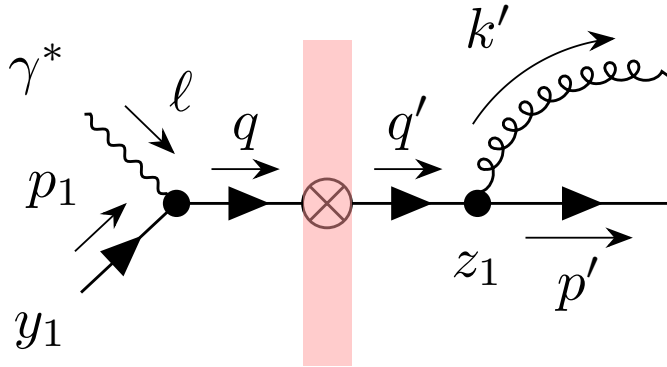
$Q^2 = -\ell^2$: photon virtuality

Finite virtuality: $M^2 = y(1 - y)(2\ell^+ p_1^- - Q^2)$

Three time orderings

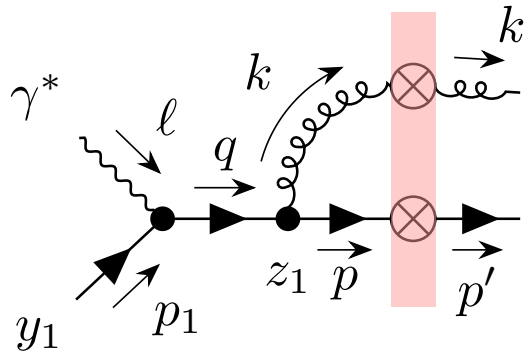
- **A:** emission **after** the shockwave

$$y_1^+ < 0 < z_1^+$$



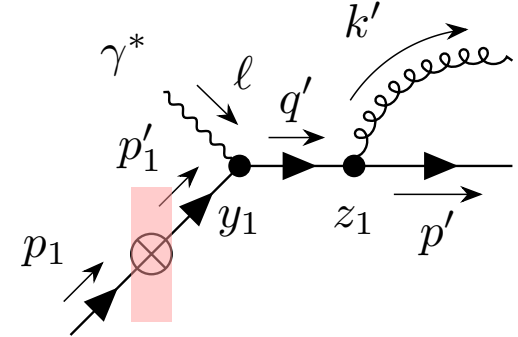
- **B:** emission **before** the shockwave

$$y_1^+ < z_1^+ < 0$$



- **C:** shockwave **before** the photon vertex

$$0 < y_1^+ < z_1^+$$



Total Amplitude

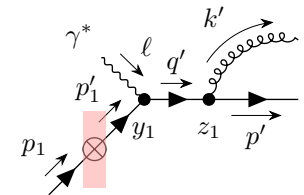
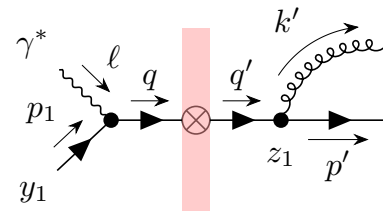
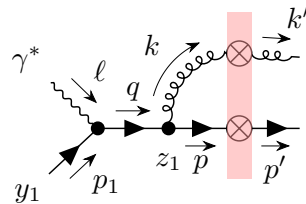
► Wave function:
$$\phi_0^\lambda(\mathbf{u}) = 2i\sqrt{1-y}\frac{\mathbf{u} \cdot \boldsymbol{\varepsilon}_\lambda^*}{2\pi\mathbf{u}^2} [\delta_{\lambda,s} + (1-y)\delta_{\lambda,-s}] \quad (1)$$

$$\phi_-^\lambda(\mathbf{u}) = \frac{-iM|\mathbf{u}|}{2} H_1^{(2)}(iM|\mathbf{u}|)\phi_0^\lambda(\mathbf{u})$$

► Total amplitude:

$$\mathcal{A}_{\text{total}} = 2eg \frac{\sqrt{p_1^- \ell^+}}{p_1^- + \ell^-} \int d^2\mathbf{u} d^2\mathbf{v} e^{-i\mathbf{v} \cdot (\mathbf{p}' + \mathbf{k}')} e^{-i\mathbf{u} \cdot ((1-y)\mathbf{k}' - y\mathbf{p}')} \quad (2)$$

$$\times \left[\underbrace{\phi_-^\lambda(\mathbf{u}) t^b \mathcal{U}_F(\mathbf{b})_{\beta\alpha} \mathcal{U}_A(\mathbf{r})^{ba}}_{\text{B}} - \underbrace{\phi_0^\lambda(\mathbf{u}) t^a \mathcal{U}_F(\mathbf{v})_{\beta\alpha}}_{\text{A}} + \underbrace{[\phi_0^\lambda(\mathbf{u}) - \phi_+^\lambda(\mathbf{u})] t^a \mathbf{1}_{\beta\alpha}}_{\text{C}} \right]$$



Square of the Amplitude

$$\begin{aligned} \langle |\mathcal{A}_{\text{med}}|^2 \rangle &= 4e^2 g^2 C_F N_c \frac{p_1^- \ell^+}{(p_1^- + \ell^-)^2} \int d^2 \boldsymbol{v} d^2 \bar{\boldsymbol{v}} d^2 \boldsymbol{u} d^2 \bar{\boldsymbol{u}} e^{-i(\boldsymbol{v} - \bar{\boldsymbol{v}}) \cdot (\boldsymbol{p}' + \boldsymbol{k}')} e^{-i(\boldsymbol{u} - \bar{\boldsymbol{u}}) \cdot ((1-y)\boldsymbol{k}' - y\boldsymbol{p}')} \\ &\times \left\{ \phi_0^\lambda(\boldsymbol{u}) \phi_0^{\lambda*}(\bar{\boldsymbol{u}}) [S^4(\boldsymbol{b}, \bar{\boldsymbol{b}}, \boldsymbol{r}, \bar{\boldsymbol{r}}) - S^3(\boldsymbol{b}, \boldsymbol{r}, \bar{\boldsymbol{v}}) - S^3(\bar{\boldsymbol{b}}, \bar{\boldsymbol{r}}, \boldsymbol{v}) + S^2(\boldsymbol{v}, \bar{\boldsymbol{v}})] \right\} \end{aligned} \quad (3)$$

Square of the Amplitude

$$\begin{aligned}
 \langle |\mathcal{A}_{\text{med}}|^2 \rangle &= 4e^2 g^2 C_F N_c \frac{p_1^- \ell^+}{(p_1^- + \ell^-)^2} \int d^2 v d^2 \bar{v} d^2 u d^2 \bar{u} e^{-i(v-\bar{v}) \cdot (p' + k')} e^{-i(u-\bar{u}) \cdot ((1-y)k' - y p')} \\
 &\times \left\{ \phi_0^\lambda(u) \phi_0^{\lambda*}(\bar{u}) [S^4(b, \bar{b}, r, \bar{r}) - S^3(b, r, \bar{v}) - S^3(\bar{b}, \bar{r}, v) + S^2(v, \bar{v})] \right. \\
 &\quad + [\phi_-^\lambda(u) - \phi_0^\lambda(u)] \phi_0^{\lambda*}(\bar{u}) [S^4(b, \bar{b}, r, \bar{r}) - S^3(b, r, \bar{v})] \\
 &\quad + \phi_0^\lambda(u) [\phi_-^{\lambda*}(\bar{u}) - \phi_0^{\lambda*}(\bar{u})] [S^4(b, \bar{b}, r, \bar{r}) - S^3(\bar{b}, \bar{r}, v)] \\
 &\quad \left. + [\phi_-^\lambda(u) - \phi_0^\lambda(u)] [\phi_-^{\lambda*}(\bar{u}) - \phi_0^{\lambda*}(\bar{u})] [S^4(b, \bar{b}, r, \bar{r}) + 1] \right\}. \tag{4}
 \end{aligned}$$

Square of the Amplitude

$$\begin{aligned}
 \langle |\mathcal{A}_{\text{med}}|^2 \rangle &= 4e^2 g^2 C_F N_c \frac{p_1^- \ell^+}{(p_1^- + \ell^-)^2} \int d^2 v d^2 \bar{v} d^2 u d^2 \bar{u} e^{-i(v-\bar{v}) \cdot (p' + k')} e^{-i(u-\bar{u}) \cdot ((1-y)k' - y p')} \\
 &\times \left\{ \phi_0^\lambda(u) \phi_0^{\lambda*}(\bar{u}) [S^4(b, \bar{b}, r, \bar{r}) - S^3(b, r, \bar{v}) - S^3(\bar{b}, \bar{r}, v) + S^2(v, \bar{v})] \right. \\
 &\quad + [\phi_-^\lambda(u) - \phi_0^\lambda(u)] \phi_0^{\lambda*}(\bar{u}) [S^4(b, \bar{b}, r, \bar{r}) - S^3(b, r, \bar{v})] \\
 &\quad + \phi_0^\lambda(u) [\phi_-^{\lambda*}(\bar{u}) - \phi_0^{\lambda*}(\bar{u})] [S^4(b, \bar{b}, r, \bar{r}) - S^3(\bar{b}, \bar{r}, v)] \\
 &\quad \left. + [\phi_-^\lambda(u) - \phi_0^\lambda(u)] [\phi_-^{\lambda*}(\bar{u}) - \phi_0^{\lambda*}(\bar{u})] [S^4(b, \bar{b}, r, \bar{r}) + 1] \right\}.
 \end{aligned} \tag{5}$$

► Setting $M \rightarrow 0$ gives $[\phi_-^\lambda(u) - \phi_0^\lambda(u)] \rightarrow 0$

→ recovering [Marquet Nucl. Phys. A 796, 41–60 2007]

Relevant Scales

- ▶ The wave function

$$\phi_{-}^{\lambda}(\mathbf{u}) \propto M[J_1(M|\mathbf{u}|) - iY_1(M|\mathbf{u}|)] \frac{\mathbf{u} \cdot \boldsymbol{\epsilon}_{\lambda}^{*}}{|\mathbf{u}|}, \quad (6)$$

→ Changes behavior for $M|\mathbf{u}| \approx 1$.

- ▶ Dipole correlator

$$S(u) \approx \exp\left(-Q_s^2 \frac{u^2}{4}\right). \quad (7)$$

→ Target resolution important $Q_s u \approx 1$.

Small Virtuality $M^2 \ll Q_s^2$

- ▶ Dipole correlators sets transverse size

$$u \approx 1/Q_s \quad \Rightarrow \quad Mu \ll 1. \quad (8)$$

- ▶ Small- M $|u|$ expansion:

$$J_1(M|u|) \approx 0, \quad Y_1(M|u|) \approx -\frac{2}{\pi M|u|}, \quad \Rightarrow \quad \phi_-^\lambda(\mathbf{u}) = \phi_0^\lambda(\mathbf{u}). \quad (9)$$

The splitting kernel approaches the usual on-shell limit.

$$\phi_0^\lambda(u) \phi_0^{\lambda*}(\bar{u}) [S^4(b, \bar{b}, r, \bar{r}) - S^3(b, r, \bar{v}) - S^3(\bar{b}, \bar{r}, v) + S^2(v, \bar{v})] \quad (10)$$

High Virtuality $M^2 \gg Q_s^2$

- ▶ Large- Mu Hankel phase:

$$H_1^{(2)}(M|u|) \sim \frac{e^{-iM|u|}}{\sqrt{M|u|}}, \quad M \gg Q_s \quad \Rightarrow \quad u \approx 1/M \ll 1/Q_s. \quad (11)$$

- ▶ Small dipole:

$$S(u) = \exp\left(-Q_s^2 \frac{u^2}{4}\right) \approx 1 - Q_s^2 \frac{u^2}{4}, \quad 1 - S(u) \approx Q_s^2/(4M^2). \quad (12)$$

- ▶ Medium correction:

$$\frac{|\mathcal{A}_{\text{med}}|^2}{|\mathcal{A}_{\text{vac}}|^2} \approx \mathcal{O}\left(\frac{Q_s^2}{M^2}\right). \quad (13)$$

- ▶ Vacuum-like radiation dominates;
→ Suppressed medium corrections.

Intermediate Virtuality $M^2 \approx Q_s^2$

- Two transverse scales

$$u \approx 1/Q_s \approx 1/M, \quad Mu \approx 1. \quad (14)$$

- Important contributions from all terms

$$\begin{aligned} & \phi_0^\lambda(u) \phi_0^{\lambda*}(\bar{u}) [S^4(b, \bar{b}, r, \bar{r}) - S^3(b, r, \bar{v}) - S^3(\bar{b}, \bar{r}, v) + S^2(v, \bar{v})] \\ & + [\phi_-^\lambda(u) - \phi_0^\lambda(u)] \phi_0^{\lambda*}(\bar{u}) [S^4(b, \bar{b}, r, \bar{r}) - S^3(b, r, \bar{v})] \\ & + \phi_0^\lambda(u) [\phi_-^{\lambda*}(\bar{u}) - \phi_0^{\lambda*}(\bar{u})] [S^4(b, \bar{b}, r, \bar{r}) - S^3(\bar{b}, \bar{r}, v)] \\ & + [\phi_-^\lambda(u) - \phi_0^\lambda(u)] [\phi_-^{\lambda*}(\bar{u}) - \phi_0^{\lambda*}(\bar{u})] [S^4(b, \bar{b}, r, \bar{r}) + 1]. \end{aligned} \quad (15)$$

- Interplay between Glasma scale Q_s and virtuality M .

Conclusions

Takeaways

- ▶ Off-shell radiation introduces a new scale M^2 competing with target resolution Q_s .
- ▶ The glasma resolves transverse sizes $u \approx 1/Q_s$:

$$M^2 \ll Q_s^2 \Rightarrow \text{on-shell limit}, \quad M^2 \gg Q_s^2 \Rightarrow \text{color transparency.} \quad (16)$$

- ▶ The glasma selects part of early shower with $M^2 \sim Q_s^2$.

Outlook

- ▶ Compute the medium-induced spectrum $\frac{dN}{dyd^2k'}$
→ Compare to on-shell results.

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