JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

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in Quark Matter

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INSTITUTE OF
PHYSICS

Inclusive D^0 photoproduction in UPCs

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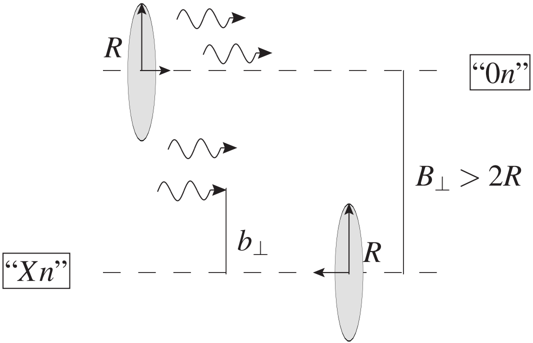
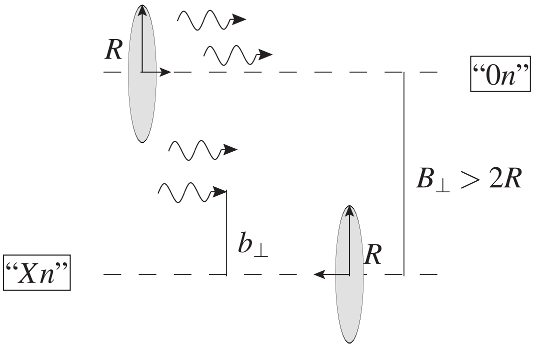
Outline

1. Inclusive D^0 in ultraperipheral collision (UPC)
    - Charm photoproduction in LCPT
    - Collinear limit
2. Comparison to CMS data

UPC

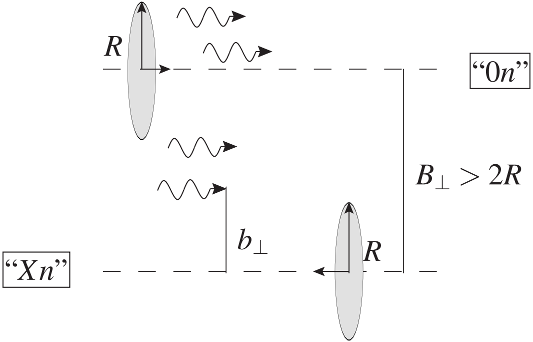


UPC



$$\frac{\mathrm{d}\sigma^{A+A\to \mathrm{D}^0+X}}{\mathrm{d}^2\boldsymbol{k}_{\mathrm{D}\perp}\mathrm{d}y_{\mathrm{D}}} = \int_\omega \int_{B_\perp} \mathrm{P}_{\text{“Xn0n”}}(B_\perp)\mathrm{PhotonFlux}(\omega, B_\perp) \int_{z_f} \frac{\mathrm{d}\sigma^{\gamma+A\to c+X}}{\mathrm{d}^2\boldsymbol{k}_{0\perp}\mathrm{d}y_0}\mathrm{Frag.Fun.}(z_f, m)$$

UPC



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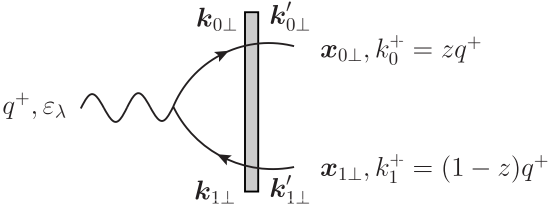
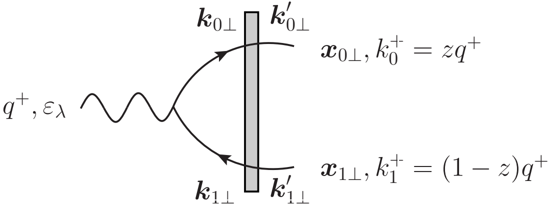
Charm photoproduction in LCPT

LO in α_s



Charm photoproduction in LCPT

LO in α_s



- Fock state expansion

$$\left|\gamma_\lambda(q^+, \mathbf{q}_\perp; Q^2)\right\rangle_{\mathrm{D}} \propto \sum_{q\bar{q}} \Psi^{\gamma_\lambda \to q\bar{q}} |q\bar{q}\rangle_0 + \sum_{q\bar{q}g} \Psi^{\gamma_\lambda \to q\bar{q}g} |q\bar{q}g\rangle_0 + \ldots$$

Beuf, Hänninen, Lappi, Mulian (2022)

Charm photoproduction in LCPT

- Invariant amplitude from scattering matrix element

$$\left\langle q(\boldsymbol{k}'_{0\perp}, k_0'^{+})\bar{q}(\boldsymbol{k}'_{1\perp}, k_1'^{+})\middle|\hat{S}-1\underbrace{\middle|\gamma^{*}(q^{+},\mathbf{q}_{\perp};Q^{2})\right\rangle}_{\text{F.T to mixed space}} \propto \mathcal{M}(\mathbf{q}_{\perp}\to\boldsymbol{k}'_{0\perp},\boldsymbol{k}'_{1\perp})$$

Charm photoproduction in LCPT

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$$\mathcal{M}_{\gamma^* \to q\bar{q}} = \int_{\boldsymbol{x}_{0\perp} \boldsymbol{x}_{1\perp}} e^{i\boldsymbol{k}_{0\perp}\boldsymbol{x}_{0\perp}} e^{i\boldsymbol{k}_{1\perp}\boldsymbol{x}_{1\perp}} \left(\left[U_F(\boldsymbol{x}_{0\perp}) U_F^\dagger(\boldsymbol{x}_{1\perp}) \right]_{\beta_0\beta_1} - \delta_{\beta_0\beta_1} \right) \psi^{\gamma^* \to q_0\bar{q}_1}$$

$$\mathrm{d}\sigma^{\gamma^* + A \to c\bar{c} + X} = \int \mathrm{d}[\mathrm{P.S}] \langle |\mathcal{M}|^2 \rangle$$

Dominguez, Marquet, Xiao, Yuan (2011)

Charm photoproduction in LCPT

- $D^0 = \bar{u}c \longrightarrow$ we integrate over the antiquark momentum $\boldsymbol{k}_{1\perp}$

Charm photoproduction in LCPT

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  Color structure in $\langle|\mathcal{M}|^2\rangle$:

  $$\left\langle \mathrm{Tr}\big(U(\boldsymbol{x}_{0\perp})U^\dagger(\boldsymbol{x}_{1\perp})U(\boldsymbol{x}'_{1\perp})U^\dagger(\boldsymbol{x}'_{0\perp})\big)\right\rangle - \left\langle \mathrm{Tr}\big(U(\boldsymbol{x}_{0\perp})U^\dagger(\boldsymbol{x}_{1\perp})\big)\right\rangle - \left\langle \mathrm{Tr}\big(U(\boldsymbol{x}'_{1\perp})U^\dagger(\boldsymbol{x}'_{0\perp})\big)\right\rangle + N_c$$

Charm photoproduction in LCPT

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$$\underbrace{\int \frac{\mathrm{d}^2\boldsymbol{k}_{1\perp}}{(2\pi)^2} e^{\boldsymbol{k}_{1\perp}(\boldsymbol{x}_{1\perp}-\boldsymbol{x}'_{1\perp})}}_{\text{from P.S}} \longrightarrow \underbrace{\int \mathrm{d}^2\boldsymbol{x}'_{1\perp}}_{\text{from F.T Fock state}} \qquad \delta^{(2)}(\boldsymbol{x}_{1\perp} - \boldsymbol{x}'_{1\perp})$$

$$\Big\langle \mathrm{Tr}\big(U(\boldsymbol{x}'_{0\perp})U^\dagger(\boldsymbol{x}_{0\perp})\big)\Big\rangle$$

Charm photoproduction in LCPT

- Mixed space

$$\frac{\mathrm{d}\sigma^{\gamma^*+A\to c+X}}{\mathrm{d}^2\boldsymbol{k}_{0\perp}\mathrm{d}y_0} \propto \int_{\substack{\boldsymbol{x}_{0\perp},\boldsymbol{x}_{1\perp},\\ \boldsymbol{x}'_{0\perp}}} e^{i\boldsymbol{k}_{0\perp}(\boldsymbol{x}_{0\perp}-\boldsymbol{x}'_{0\perp})}\left[D_{\boldsymbol{x}_{0\perp}-\boldsymbol{x}'_{0\perp}} - D_{\boldsymbol{x}_{0\perp}-\boldsymbol{x}_{1\perp}} - D_{\boldsymbol{x}'_{0\perp}-\boldsymbol{x}_{1\perp}} + 1\right]\psi(\boldsymbol{x}_{0\perp},\boldsymbol{x}_{1\perp})\psi^\dagger(\boldsymbol{x}'_{0\perp},\boldsymbol{x}_{1\perp})$$

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- Momentum space

$$\frac{\mathrm{d}\sigma^{\gamma^*+A\to c+X}}{\mathrm{d}^2\boldsymbol{k}_{0\perp}\mathrm{d}y_0} \propto \int \frac{\mathrm{d}^2\boldsymbol{\ell}_\perp}{(2\pi)^2} D(\boldsymbol{\ell}_\perp)\{\dots\}$$

$$\{\dots\} = 2zm^2\left[\frac{1}{m^2+(\boldsymbol{k}_{0\perp}-\boldsymbol{\ell}_\perp)^2} - \frac{1}{m^2+\boldsymbol{k}_{0\perp}^2}\right]^2 + 4z\left(z^2+(1-z)^2\right)\left[\frac{\boldsymbol{k}_{0\perp}-\boldsymbol{\ell}_\perp}{m^2+(\boldsymbol{k}_{0\perp}-\boldsymbol{\ell}_\perp)^2} - \frac{\boldsymbol{k}_{0\perp}}{m^2+\boldsymbol{k}_{0\perp}^2}\right]^2$$

– Soft scale: $\boldsymbol{\ell}_\perp^2 \sim Q_\mathrm{S}^2$
– Quasi-real photon: $Q^2 \to 0$

Collinear limit

Full expression: $\mathrm{I}_\ell = \int \frac{\mathrm{d}^2\boldsymbol{\ell}_\perp}{(2\pi)^2} D(\ell_\perp)\{\dots\}$

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$$D(\ell_\perp) \sim \begin{cases} \text{const.}, & \ell_\perp \ll Q_\mathrm{s} \\ 1/\ell_\perp^4, & \ell_\perp \gg Q_\mathrm{s} \end{cases}$$

McLerran, Venugopalan (1994) 🔗
Iancu, Venugopalan (2003) 🔗

Collinear limit

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Iancu, Venugopalan (2003)

$$\text{(A)} \quad \ell_\perp \ll Q_\mathrm{s} \ll k_{0\perp} : \int_0^{Q_\mathrm{s}} \mathrm{d}\ell_\perp \ell_\perp^3$$

$$\text{(B)} \quad Q_\mathrm{s} \ll \ell_\perp \ll k_{0\perp} : \int_{Q_\mathrm{s}}^{k_{0\perp}} \mathrm{d}\ell_\perp \frac{1}{\ell_\perp}$$

$$\text{(C)} \quad Q_\mathrm{s} \ll k_{0\perp} \ll \ell_\perp : \int_{k_{0\perp}}^{\infty} \mathrm{d}\ell_\perp \frac{1}{\ell_\perp^3}$$

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Collinear limit

- In the limit $\boldsymbol{\ell}_\perp \ll \boldsymbol{k}_{0\perp}$:

$$\mathrm{I}_{\ell_\perp}^{\text{collinear}} = \int^{\boldsymbol{k}_{0\perp}} \frac{\mathrm{d}^2\boldsymbol{\ell}_\perp}{(2\pi)^2} D(\ell_\perp)\boldsymbol{\ell}_\perp^2 \left\{ 2z \frac{2m^2 k_{0\perp}^2 + [z^2 + (1-z)^2](k_{0\perp}^2 + m^4)}{(k_{0\perp}^2 + m^2)^4} \right\}$$

Collinear limit

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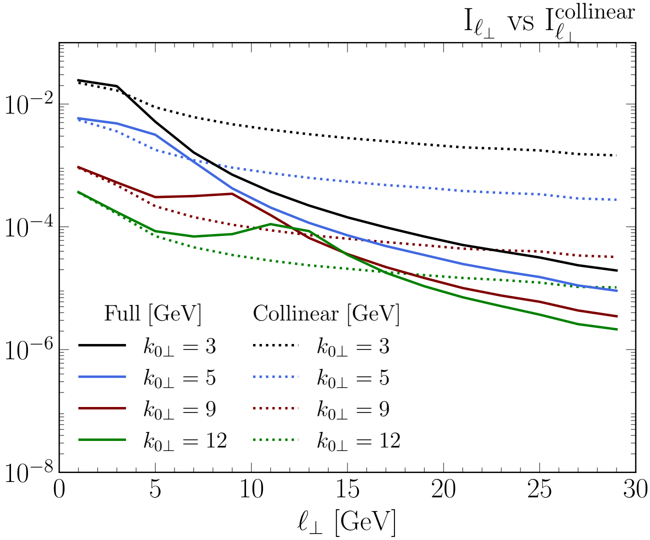
- Numerical comparison with the full expression

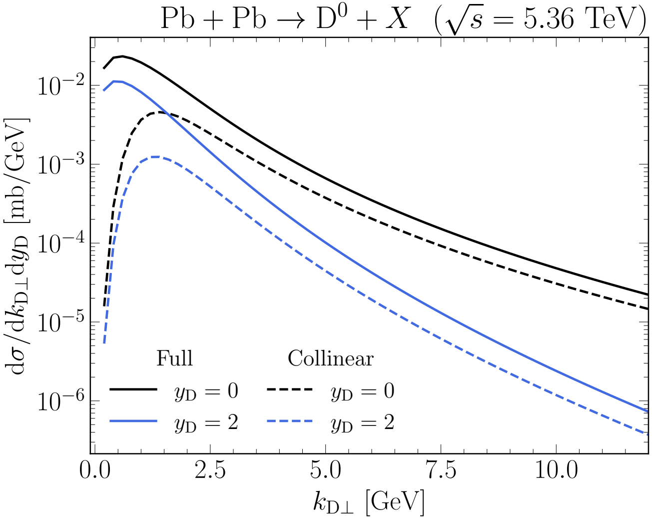
$$\mathrm{I}_\ell = \int \frac{\mathrm{d}^2\boldsymbol{\ell}_\perp}{(2\pi)^2} D(\ell_\perp)\{\ldots\}$$

Collinear limit, $\ell_\perp$-integrand



- Matching at small $\ell_\perp$, large $\boldsymbol{k}_{0\perp}$

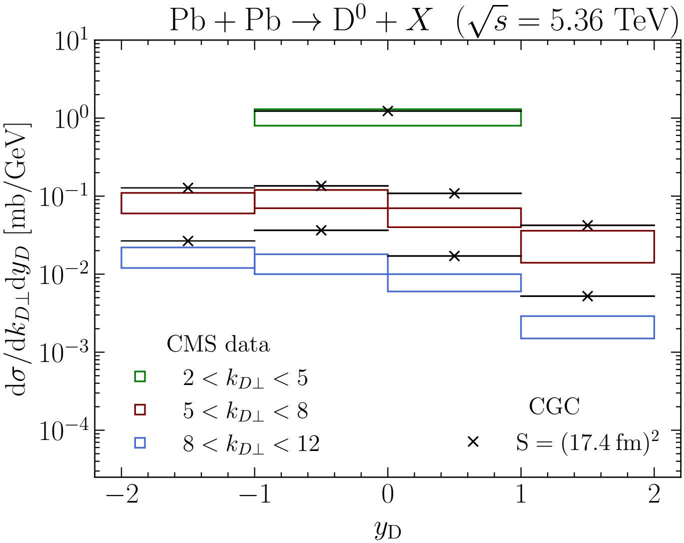
Collinear limit, cross section



- Small $k_{\mathrm{D}\perp}$: collinear result suppressed
- Large $k_{\mathrm{D}\perp}$: matching up to some normalization

Comparison to CMS data

Comparison to CMS data



- Small $k_{\mathrm{D}\perp}$: good agreement
- Large $k_{\mathrm{D}\perp}$: steeper data

Summary

- Rederived inclusive charm cross section for D^0 in UPC
- Collinear limit vs full expression: matching at large $k_{\mathrm{D}\perp}$
- Comparison to CMS data: good agreement at small $k_{\mathrm{D}\perp}$
- To improve: NLO, fit BK initial condition including massive quarks

Casuga, Karhunen, Mäntysaari (2024)