Inclusive J/ψ production in forward proton-proton and proton-lead collisions at high energy

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arXiv:2409.01791 (2024)

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Outline

Based on *Gimeno-Estivill, Lappi, Mäntysaari (2024) arXiv:2409.01791*

- J/ψ production in Color Glass Condensate (CGC) + Non-relativistic QCD (NRQCD)

  $\rightarrow$ Correlators of Wilson Lines
  $\rightarrow$ Target parametrization constrained by DIS HERA data

- Predictions compared to LHCb and ALICE data + previous phenomenology

  $\rightarrow$ J/ψ cross section in p+p and p+Pb
  $\rightarrow$ Nuclear modification factor R_{pPb}

- Inclusive D^0 production in UPC (Work in progress)

Gluon saturation

- High-energy (small-x) regime $\rightarrow$ strong increase in gluon density

- Forward rapidity ($y \gg 1$) in pA and pp collisions

$$x_p \propto e^{y} \lesssim 1 \longrightarrow \text{dilute projectile}$$
$$x_A \propto e^{-y} \ll 1 \longrightarrow \text{dense gluon target}$$

- Massive quarks $c\bar{c}$: J/ψ

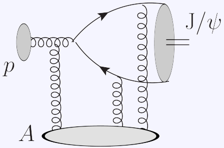
$M_{\mathrm{J}/\psi} \sim Q_{\mathrm{s}} \longrightarrow$ sensitive to gluon saturation
$v \ll 1,\ \alpha_{\mathrm{s}}(M_{\mathrm{J}/\psi}) \ll 1 \longrightarrow$ perturbative expansion in non-relativistic QCD

Inclusive J/ψ production

Color Glass Condensate (CGC) + Non-Relativistic QCD (NRQCD)

$$\frac{\mathrm{d}\sigma_{\mathrm{J}/\psi}}{\mathrm{d}^2\boldsymbol{p}\mathrm{d}y} = \sum_{\kappa} \frac{d\hat{\sigma}^{\kappa}_{c\bar{c}}}{\mathrm{d}^2\boldsymbol{p}\mathrm{d}y} \langle \mathcal{O}^{\mathrm{J}/\psi}_{\kappa} \rangle$$

short-distance cross sections $\times$ long-distance matrix elements (LDME)



LDME

- Values from cross section/polarization fit to Tevatron J/ψ data *Chao et al. (2012)*
- Ordered in powers of velocity

$$\langle \mathcal{O}^{\mathrm{J}/\psi}({}^3\mathrm{S}_1^{[1]}) \rangle \sim 1$$
$$\langle \mathcal{O}^{\mathrm{J}/\psi}({}^1\mathrm{S}_0^{[8]}) \rangle \sim v^3$$
$$\langle \mathcal{O}^{\mathrm{J}/\psi}({}^3\mathrm{S}_1^{[8]}) \rangle \sim v^4$$
$$\langle \mathcal{O}^{\mathrm{J}/\psi}({}^3\mathrm{P}_0^{[8]}) \rangle \sim v^4$$

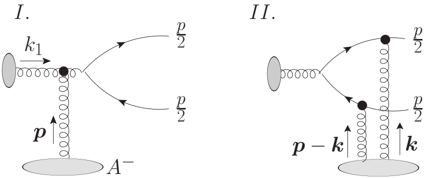
$$\kappa = {}^{2s+1}L_J^{[c]}$$

s: spin
L: orbital angular momentum
J: total angular momentum
c: color

Bodwin, Braaten, Lepage (1994)

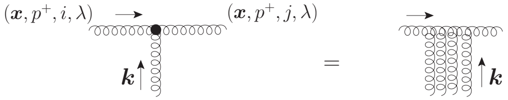
CGC

- Dilute-dense collision in the proton collinear limit ($\boldsymbol{k}_1 \to 0$)
- Target: classical gluon field A^-



Blaizot, Gelis, Venugopalan (2004)

- Eikonal interaction parton-nucleus: Wilson Line $V(\boldsymbol{x})$

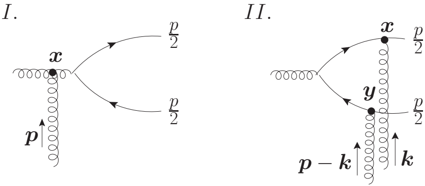


λ: polarization, i, j: color

Wilson Line

$$V_{\mathrm{F,A}}(\boldsymbol{x}) = \mathcal{P}\exp\left(-ig\int dx^+ A_a^-(x^+, \boldsymbol{x})t^a\right)$$

Short-distance coefficients in CGC



Color octet states: *I* & *II*

$$\frac{\mathrm{d}\hat{\sigma}^{\kappa}_{c\bar{c}}}{\mathrm{d}^2\boldsymbol{p}\,\mathrm{d}y} \propto \alpha_{\mathrm{s}} x_p f_{p/g}(x_p,\mu^2) \int_{\boldsymbol{b}} \int_{\boldsymbol{k}} \mathcal{N}(\boldsymbol{k})\mathcal{N}(\boldsymbol{p}-\boldsymbol{k})\tilde{\Gamma}^{\kappa}_{8}(p,k)$$

$\mathcal{N}(\boldsymbol{k}) = \int_{\boldsymbol{r}} e^{i\boldsymbol{k}\boldsymbol{r}} D_{\boldsymbol{r}}$

Color singlet states: *II*

$$\frac{\mathrm{d}\hat{\sigma}^{\kappa}_{c\bar{c}}}{\mathrm{d}^2\boldsymbol{p}\,\mathrm{d}y} \propto \alpha_{\mathrm{s}} x_p f_{p/g}(x_p,\mu^2) \int_{\boldsymbol{x},\boldsymbol{x}',\boldsymbol{y}',\boldsymbol{y}} e^{-i\boldsymbol{p}\boldsymbol{\Delta}}\Big(Q_{\boldsymbol{x},\boldsymbol{x}',\boldsymbol{y}',\boldsymbol{y}} - D_{\boldsymbol{r}}D_{\boldsymbol{r}'}\Big)\tilde{\Gamma}^{\kappa}_{1}(r,r')$$

$D_{\boldsymbol{r}} \sim \left\langle \mathrm{Tr}[V_{\mathrm{F}}(\boldsymbol{0})V^{\dagger}_{\mathrm{F}}(\boldsymbol{r})]\right\rangle$

$Q_{\boldsymbol{x},\boldsymbol{x}',\boldsymbol{y}',\boldsymbol{y}} \sim \left\langle \mathrm{Tr}\big[V_{\mathrm{F}}(\boldsymbol{x})V^{\dagger}_{\mathrm{F}}(\boldsymbol{x}')V_{\mathrm{F}}(\boldsymbol{y}')V^{\dagger}_{\mathrm{F}}(\boldsymbol{y})\big]\right\rangle$

Dipole size: $\boldsymbol{r} = \boldsymbol{x} - \boldsymbol{y}$ (conjugate amplitude: $\boldsymbol{r}' = \boldsymbol{x}' - \boldsymbol{y}'$)
Impact parameter: $\boldsymbol{b} = (\boldsymbol{x} + \boldsymbol{y})/2$
Shift center of dipoles: $\boldsymbol{\Delta} = (\boldsymbol{x}' + \boldsymbol{y}' - \boldsymbol{x} - \boldsymbol{y})/2$

Kang, Ma, Venugopalan (2014)

Color Structure

Dipole

$$D_{\boldsymbol{x}-\boldsymbol{y}} = \frac{1}{N_{\mathrm{c}}} \left\langle \mathrm{Tr}[V_{\mathrm{F}}(\boldsymbol{x}) V_{\mathrm{F}}^{\dagger}(\boldsymbol{y})] \right\rangle$$

- Proton target: rcBK with initial condition: MV model parametrization fit to HERA DIS data
- Nuclear target: $\boldsymbol{b}$-dependent initial condition from the optical Glauber model

Lappi, Mäntysaari (2014)

⟶ For nucleus target no free parameters besides Woods-Saxon nuclear density

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Quadrupole

$$Q_{\boldsymbol{x},\boldsymbol{x}',\boldsymbol{y}',\boldsymbol{y}} = \frac{1}{N_{\rm c}}\left\langle \mathrm{Tr}\left[V_{\rm F}(\boldsymbol{x})V_{\rm F}^{\dagger}(\boldsymbol{x}')V_{\rm F}(\boldsymbol{y}')V_{\rm F}^{\dagger}(\boldsymbol{y})\right]\right\rangle$$

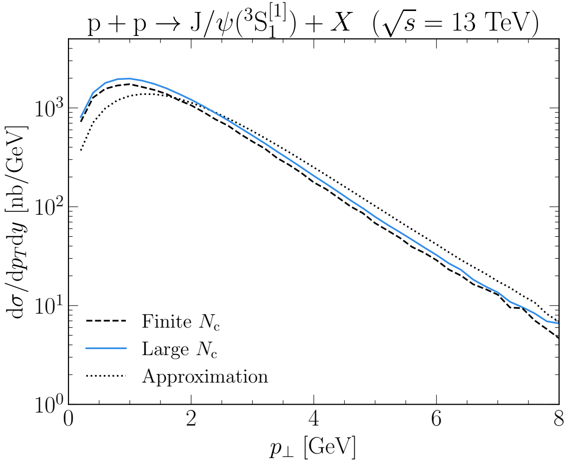
- Explicit expression in the Gaussian approximation for finite and large N_c

Dominguez, Marquet, Xiao, Yuan (2011)

⟶ Quantification of finite-$\mathrm{N_c}$ corrections + J/ψ phenomenology with explicit Q

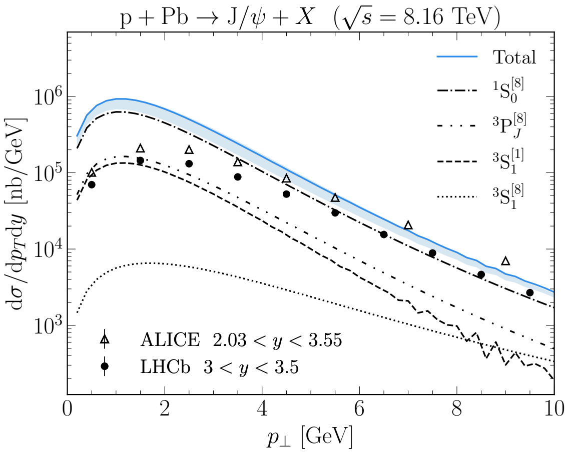
Results: finite-N_c corrections quadrupole

Color singlet state in proton-proton collisions at $y = 3.25$



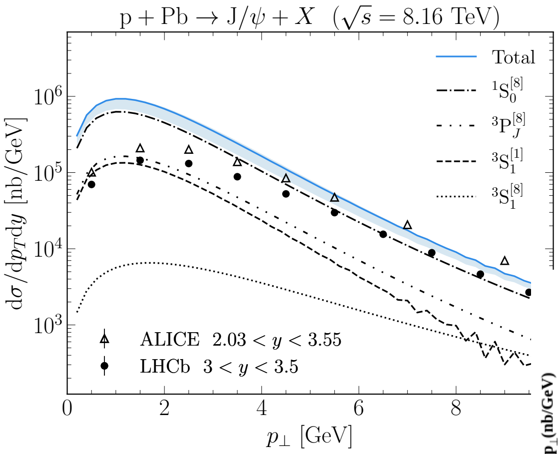
- Finite-N_c corrections are small $\mathcal{O}(1/N_c^2) \sim 12\%$
- Approximated quadrupole (*Ma, Venugopalan (2014/15)*) different by a factor of 2

J/ψ production in proton-nucleus collisions



- Correct description at high-$p_\perp$
- Low-$p_\perp$
  $\rightarrow$ Need Sudakov correction
- Dominant octet state ${}^1S_0^{[8]}$
- Color singlet state ${}^3S_1^{[1]} \sim 15\%$

J/ψ production in proton-nucleus collisions



Ma, Venugopalan, Zhang (2015)

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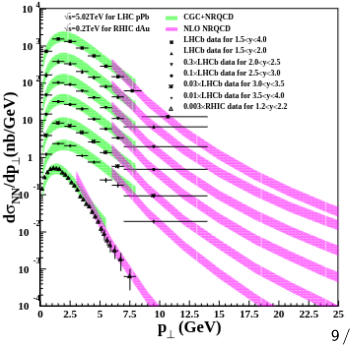
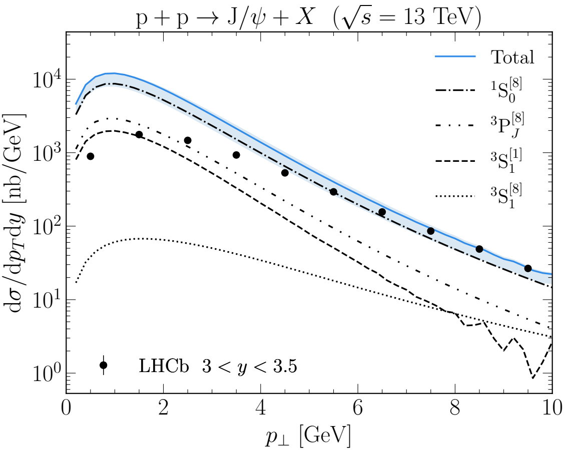


- Some parameters from interpolation between PDF and uGD

J/ψ production in proton-proton collisions



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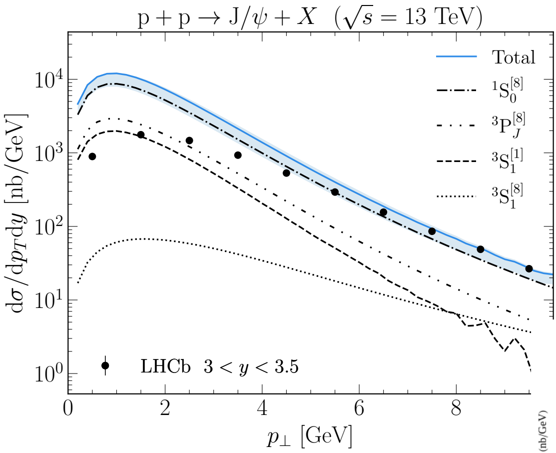

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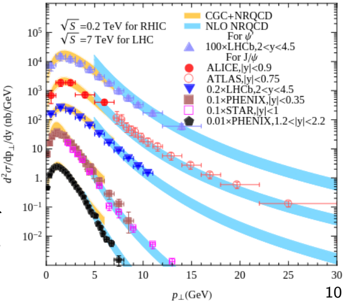

Ma, Venugopalan (2014)

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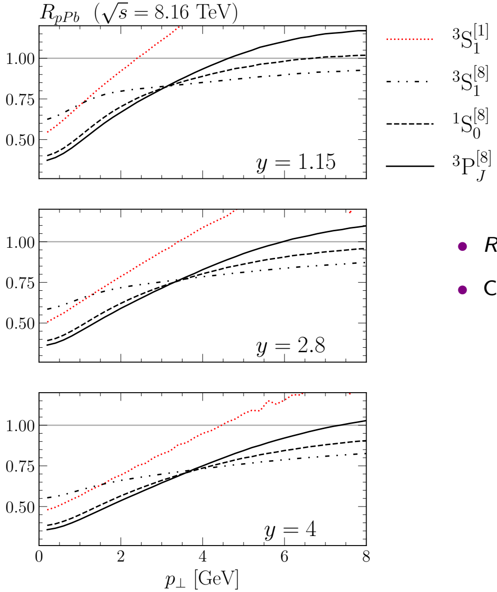
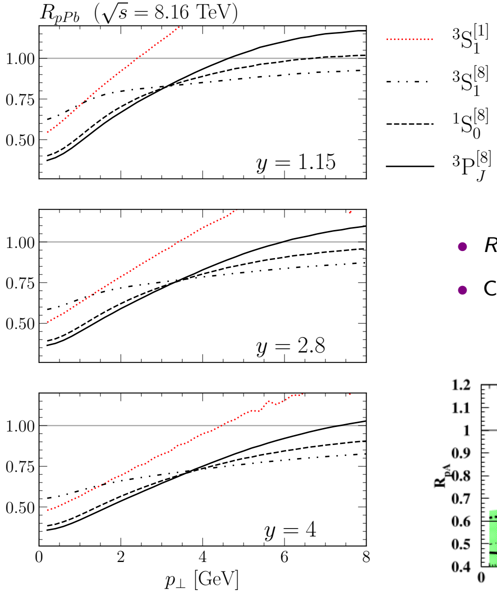
Nuclear modification ratio individual channels



$$R_{pPb} = \frac{d\sigma_{pPb}}{A d\sigma_{pp}}$$

- $R_{pPb} \to 1$ by construction at high-$p_\perp$
- Cronin enhancement color singlet $^3S_1^{[1]}$

Nuclear modification ratio individual channels



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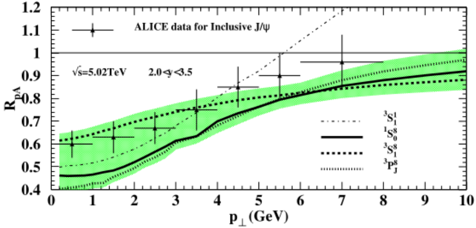
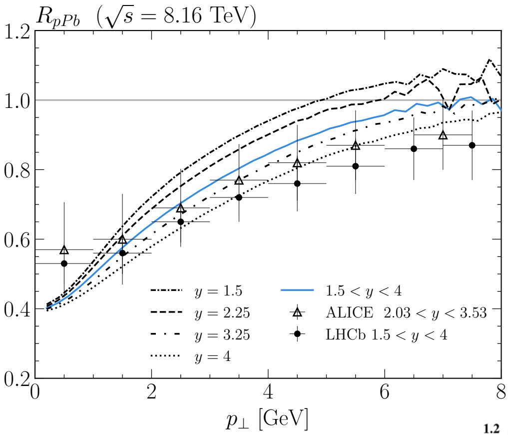
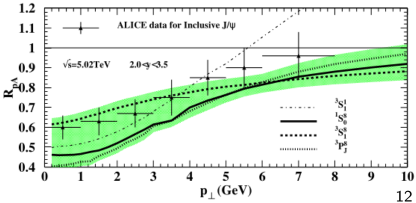
Ma, Venugopalan, Zhang (2015)



Nuclear modification ratio vs $p_\perp$



- Strong suppression at low $p_\perp$
- Steeper $p_\perp$-dependence
  → need NLO correction



Ma, Venugopalan, Zhang (2015)

Summary

- J/ψ production in forward p+p and p+A in CGC+NRQCD

  → Explicit expression of the quadrupole
  → Description of the dense target in CGC constrained by DIS HERA data

- R_{pPb} compatible with data, with a similar trend as the CGC+CEM calculation

  Ducloué, Lappi, Mäntysaari (2015)

- Possible improvements

  → Sudakov correction at NLO
  → Fit initial conditions for BK equation including heavy quarks

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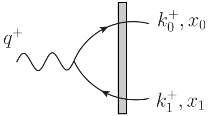
→ New CMS data on D^0 production in UPC

Inclusive D^0 production in UPC

LCPT for $\gamma_T^* + A \to q\bar{q}$ at LO and small-x



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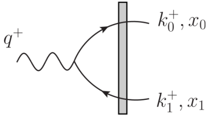

- Fock state expansion

$$\left|\gamma^*(q^+, \boldsymbol{q}; Q^2)\right\rangle_{\mathrm{D}} \propto \widetilde{\sum_{q\bar{q}}} \Psi^{\gamma^* \to q\bar{q}} |q\bar{q}\rangle_0 + \widetilde{\sum_{q\bar{q}g}} \Psi^{\gamma^* \to q\bar{q}g} |q\bar{q}g\rangle_0 + \dots$$

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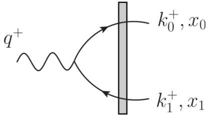

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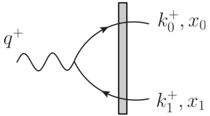
- Invariant amplitude from scattering matrix element

$$2q^+(2\pi)\delta(q^+ - k_0^+ - k_1^+) i\mathcal{M}(\boldsymbol{q} \to \boldsymbol{k}_0, \boldsymbol{k}_1) \equiv \left\langle q(\boldsymbol{k}_0, k_0^+)\bar{q}(\boldsymbol{k}_1, k_1^+)\right| \hat{S} - 1 \underbrace{\left|\gamma^*(q^+, \boldsymbol{q}; Q^2)\right\rangle}_{\text{F.T to mixed space}}$$

Inclusive D^0 production in UPC

LCPT for $\gamma^*_T + A \to q\bar{q}$ at LO and small-x



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$$\mathcal{M}_{\gamma^* \to q\bar{q}} = \int_{\boldsymbol{x}_0 \boldsymbol{x}_1} e^{i\boldsymbol{k}_0 \boldsymbol{x}_0} e^{i\boldsymbol{k}_1 \boldsymbol{x}_1} \left(\left[U_F(\boldsymbol{x}_0) U_F^\dagger(\boldsymbol{x}_1) \right]_{\beta_0 \beta_1} - \delta_{\beta_0 \beta_1} \right) \psi^{\gamma^* \to q_0 \bar{q}_1}$$

UPC: $Q^2 \to 0$

Inclusive D^0 production in UPC

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

Dominguez, Marquet, Xiao, Yuan (2011)

Inclusive D^0 production in UPC

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Dominguez, Marquet, Xiao, Yuan (2011)

- $D^0 = \bar{u}c \longrightarrow$ we integrate over the antiquark momentum $\boldsymbol{k}_1$

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

$$\left\langle \mathrm{Tr}\big(U(\boldsymbol{x}_0)U^\dagger(\boldsymbol{x}_1)U(\boldsymbol{x}_1')U^\dagger(\boldsymbol{x}_0')\big)\right\rangle - \left\langle \mathrm{Tr}\big(U(\boldsymbol{x}_0)U^\dagger(\boldsymbol{x}_1)\big)\right\rangle - \left\langle \mathrm{Tr}\big(U(\boldsymbol{x}_1')U^\dagger(\boldsymbol{x}_0')\big)\right\rangle + N_c$$

$$\underbrace{\int \frac{\mathrm{d}^2\boldsymbol{k}_1}{(2\pi)^2} e^{\boldsymbol{k}_1(\boldsymbol{x}_1-\boldsymbol{x}_1')}}_{\text{from P.S}} \longrightarrow \underbrace{\int \mathrm{d}^2\boldsymbol{x}_1'}_{\text{from F.T Fock state}} \quad \delta^{(2)}(\boldsymbol{x}_1-\boldsymbol{x}_1')$$

$$\downarrow$$

$$\left\langle \mathrm{Tr}\big(U(\boldsymbol{x}_0')U^\dagger(\boldsymbol{x}_0)\big)\right\rangle$$

Inclusive D^0 production in UPC

- Mixed space

$$\frac{\mathrm{d}\sigma^{\gamma^*+A\to c+X}}{\mathrm{d}^2\boldsymbol{k}_0\mathrm{d}y_0} \propto \int_{\boldsymbol{x}_0,\boldsymbol{x}_1,\boldsymbol{x}_0'} e^{i\boldsymbol{k}_0(\boldsymbol{x}_0-\boldsymbol{x}_0')}\left[D_{\boldsymbol{x}_0-\boldsymbol{x}_0'} - D_{\boldsymbol{x}_0-\boldsymbol{x}_1} - D_{\boldsymbol{x}_0'-\boldsymbol{x}_1} + 1\right]\psi(\boldsymbol{x}_0,\boldsymbol{x}_1)\psi^\dagger(\boldsymbol{x}_0',\boldsymbol{x}_1)$$

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- Momentum space

$$\frac{\mathrm{d}\sigma^{\gamma^*+A\to c+X}}{\mathrm{d}^2\boldsymbol{k}_0\mathrm{d}y_0} \propto \overbrace{\int \frac{\mathrm{d}^2\boldsymbol{\ell}}{(2\pi)^2}\ell^2 D(\ell)}^{UGD} X$$

$$X = \frac{2zm_c^2}{\ell^2}\left[\frac{1}{m_c^2+(\boldsymbol{k}_0-\boldsymbol{\ell})^2} - \frac{1}{m_c^2+\boldsymbol{k}_0^2}\right]^2 + \frac{4z}{\ell^2}\left(z^2+(1-z)^2\right)\left[\frac{\boldsymbol{k}_0-\boldsymbol{\ell}}{m_c^2+(\boldsymbol{k}_0-\boldsymbol{\ell})^2} - \frac{\boldsymbol{k}_0}{m_c^2+\boldsymbol{k}_0^2}\right]^2$$

- Soft scale: $l^2 \sim Q_\mathrm{S}^2$
- Quasi-real photon: $Q^2 \to 0$

Next: FF, photon flux, CMS data