Lepton pair production in UPCs:

from probing the linear polarization of photons to the test of the resummation formalism

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PLB 795 (2019) 576-580, PRD101, 034015 (2020), and arXiv:2306.02337

Dec 15, UPC 2023, Playa del Carmen

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1. The story of linearly polarized photons

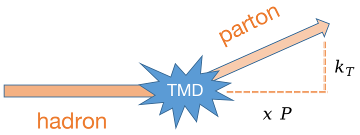
2. Probing the linear polarization of photons

3. Toward the precision test of the resummation formalism

4. Summary

Gluon TMDs

Process involving hadron states:



Cross section= Hard part * PDFs/PFFs/TMDs

TMDs: Transverse momentum dependent functions.

e.g. gluon correlator

$$\Gamma^{[U,U']\mu\nu;\rho\sigma}(x,\boldsymbol{k}_T;P,n) \equiv \int \frac{d\xi\cdot P\, d^2\xi_T}{(2\pi)^3} e^{ik\cdot\xi} \langle P|\, F^{\mu\nu}(0) U_{[0,\xi]} F^{\rho\sigma}(\xi) U'_{[\xi,0]}\, |P\rangle\Big|_{\xi\cdot n=0}$$

Gluons	$-g_T^{ij}$	$i\epsilon_T^{ij}$	$k_T^i,\ k_T^{ij}$, etc.
U	f_1^g		$h_1^{\perp g}$
L		g_1^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	$h_1^g,\ h_{1T}^{\perp g}$

Mulders, Rodrigues, PRD63(01)

how to probe?

linearly polarized gluon TMD

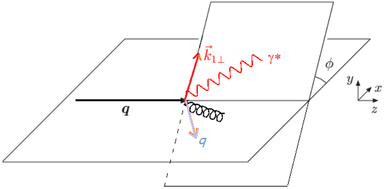
how to probe: azimuthal asymmetry

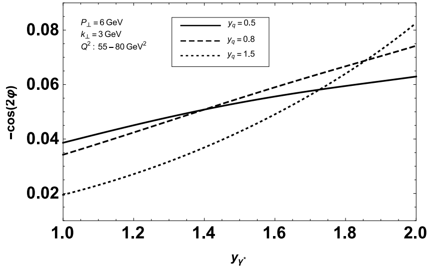
see e.g., Boer, Mulders, Pisano, PRD 80 (2009) 094017

CGC gluons are highly linearly polarized. [A. Metz and J. Zhou, 2011]

e.g., γ^*-jet production in pA collisions (cleanest way to measure $xh_1^\perp$):

$$\frac{\sigma^{pA\to\gamma^*\, q\, X}}{dP.S} = \sum_q x_p\, f_1^q(x_p)\Big\{x\, f_{1,DP}^g(x,k_\perp)\; H_{Born} + \boxed{\cos(2\phi)}\;\boxed{x\, h_{1,DP}^{\perp g}(x,k_\perp)}\; H_{Born}^{\cos(2\phi)}\Big\}$$





D. Boer, P. Mulders, J. Zhou and YZ, 2017

Ultraperipheral collisions (UPCs)

relativistically moving ions will introduce electromagnetic field.

UPC:
Two nuclei physically miss each other, interact (only) electromagnetically

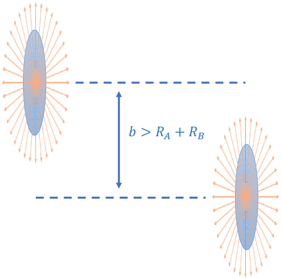
Equivalent photon approximation(EPA)
1924, Fermi;
Weizäscker and Williams, 1930's;

$$xf_1^{\gamma}(x,k_\perp^2) = \frac{Z^2\alpha_e}{\pi^2}k_\perp^2\left[\frac{F(k_\perp^2+x^2M_p^2)}{(k_\perp^2+x^2M_p^2)}\right]^2$$

Woods-Saxon form factor,

$$F(\vec{k}^2) = \int d^3re^{i\vec{k}\cdot\vec{r}}\frac{\rho^0}{1+\exp\left[(r-R_{WS})/d\right]}$$

But! strong interaction dominant in center collisions

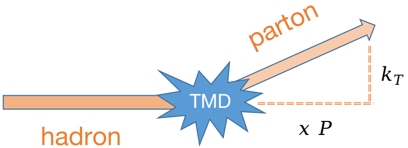


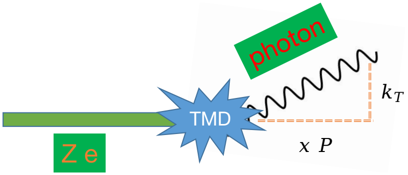
clean background

Transverse momentum dependent photons

The UPC photons are coherent photons with small x and transverse momentum.

similar to gluon TMDs, photon also have TMDs





gluon/photon TMD

gluon/photon TMD factorization:

$$\int \frac{2dy^- d^2y_\perp}{xP^+(2\pi)^3} e^{ik\cdot y} \langle P|F_+^\mu(0)F_+^\nu(y)|P\rangle\Big|_{y^+=0}$$
$$= \delta_\perp^{\mu\nu} f_1(x,k_\perp^2) + \left(\frac{2k_\perp^\mu k_\perp^\nu}{k_\perp^2} - \delta_\perp^{\mu\nu}\right) h_1^\perp(x,k_\perp^2),$$

Mulders, Rodrigues, PRD63(2001)

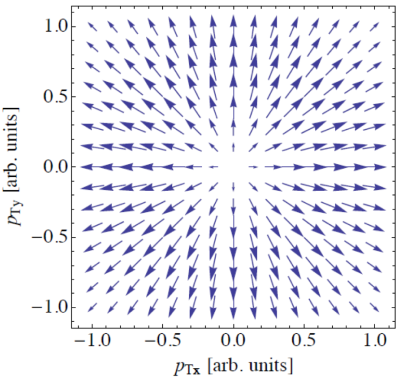
A nucleus moves along P^+, A^+ dominant, $F_+^\mu \propto k_\perp^\mu A^+$, so $F_+^\mu F_+^\nu \propto k_\perp^\mu k_\perp^\nu A^+ A^+$ implies

$$\boxed{f_1(x,k_\perp^2) = h_1^\perp(x,k_\perp^2)}$$

small-x photons/gluons are linearly polarized

A. Metz and J. Zhou, 2011, C. Li, J. Zhou and YZ, 2019

EM field in $k_\perp$ space,
beam view



$\epsilon_\perp \; // \; k_\perp$

Dilepton production in UPCs

$$\gamma(x_1 P + k_{1\perp}) + \gamma(x_2 \bar{P} + k_{2\perp}) \to l^+(p_1) + l^-(p_2)$$

leptons almost back to back in azimuthal:
$P_\perp \equiv (p_{1\perp} - p_{2\perp})/2 \simeq p_{1\perp} \simeq -p_{2\perp}$

$q_\perp \equiv p_{1\perp} + p_{2\perp} = k_{1\perp} + k_{2\perp}$

correlation limit: $P_\perp \gg q_\perp$

$\phi = P_\perp \wedge q_\perp$

Observables:

azimuthal asymmetries

$$\langle \cos(2\phi) \rangle = \frac{\int \frac{d\sigma}{d\mathcal{P}.\mathcal{S}.} \cos(2\phi) d\mathcal{P}.\mathcal{S}.}{\int \frac{d\sigma}{d\mathcal{P}.\mathcal{S}.} \, d\mathcal{P}.\mathcal{S}.}$$

$$\langle \cos(4\phi) \rangle = \frac{\int \frac{d\sigma}{d\mathcal{P}.\mathcal{S}.} \cos(4\phi) \, d\mathcal{P}.\mathcal{S}.}{\int \frac{d\sigma}{d\mathcal{P}.\mathcal{S}.} d\mathcal{P}.\mathcal{S}.}$$

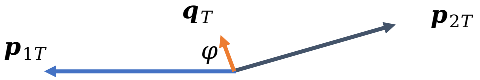
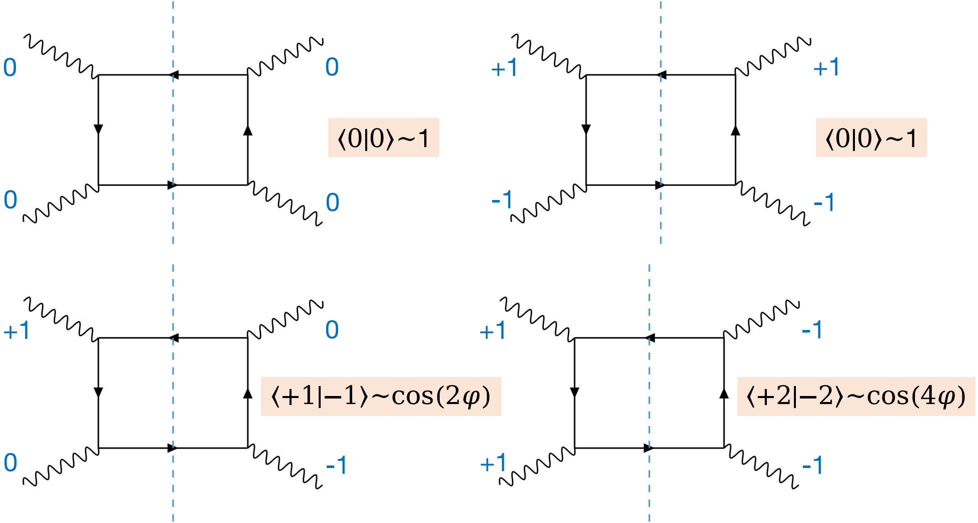


illustration diagrams



cross section: in the framework of EPA

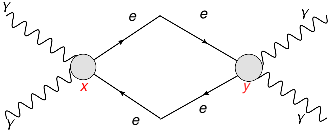
cross section at the lowest order QED:

$$\frac{d\sigma}{d^2p_{1\perp}d^2p_{2\perp}dy_1dy_2} = \frac{2\alpha_e^2}{Q^4}\left[\mathcal{A} + \mathcal{B}\cos 2\phi + \mathcal{C}\cos 4\phi\right]$$

$$\begin{aligned}
\mathcal{A} &= \frac{(Q^2-2m^2)m^2+(Q^2-2P_\perp^2)P_\perp^2}{(m^2+P_\perp^2)^2}x_1x_2\int d^2k_{1\perp}d^2k_{2\perp}\delta^2(q_\perp-k_{1\perp}-k_{2\perp})f_1^\gamma(x_1,k_{1\perp}^2)f_1^\gamma(x_2,k_{2\perp}^2) \\
&+\frac{m^4}{(m^2+P_\perp^2)^2}x_1x_2\int d^2k_{1\perp}d^2k_{2\perp}\delta^2(q_\perp-k_{1\perp}-k_{2\perp})\left[2(\hat{k}_{1\perp}\cdot\hat{k}_{2\perp})^2-1\right]h_1^{\perp\gamma}(x_1,k_{1\perp}^2)h_1^{\perp\gamma}(x_2,k_{2\perp}^2) \\
\mathcal{B} &= \boxed{\frac{4m^2P_\perp^2}{(m^2+P_\perp^2)^2}}x_1x_2\int d^2k_{1\perp}d^2k_{2\perp}\delta^2(q_\perp-k_{1\perp}-k_{2\perp}) \\
&\times\left\{\left[2(\hat{k}_{2\perp}\cdot\hat{q}_\perp)^2-1\right]f_1^\gamma(x_1,k_{1\perp}^2)\boxed{h_1^{\perp\gamma}(x_2,k_{2\perp}^2)}+\left[2(\hat{k}_{1\perp}\cdot\hat{q}_\perp)^2-1\right]\boxed{h_1^{\perp\gamma}(x_1,k_{1\perp}^2)}f_1^\gamma(x_2,k_{2\perp}^2)\right\} \\
\mathcal{C} &= \frac{-2P_\perp^4}{(m^2+P_\perp^2)^2}x_1x_2\int d^2k_{1\perp}d^2k_{2\perp}\delta^2(q_\perp-k_{1\perp}-k_{2\perp}) \\
&\times\left[2\left(2(\hat{k}_{2\perp}\cdot\hat{q}_\perp)(\hat{k}_{1\perp}\cdot\hat{q}_\perp)-\hat{k}_{1\perp}\cdot\hat{k}_{2\perp}\right)^2-1\right]\boxed{h_1^{\perp\gamma}(x_1,k_{1\perp}^2)}\;\boxed{h_1^{\perp\gamma}(x_2,k_{2\perp}^2)}
\end{aligned}$$

impact parameter dependence

Various centrality classes and UPC measurements in experiments.
Take into account $b_\perp$ dependence in theoretical calculations.



$$\gamma(x_1 P + k_{1\perp}) + \gamma(x_2 \bar{P} + k_{2\perp}) \to l^+(p_1) + l^-(p_2)$$

$$|\mathcal{M}|^2 \propto \int d^4x\, d^4y \,\langle \mathcal{P}|\, \bar\psi(x)\Gamma^{\mu\nu}\psi(x)A_\mu(x)A_\nu\,(x+b_\perp)\,\bar\psi(y)\Gamma^{\mu'\nu'}\psi(y)A_{\mu'}(y)A_{\nu'}\,(y+b_\perp)\,|\mathcal{P}\rangle$$

$$\propto \int d^4x\, e^{-ik_1\cdot x}e^{-ik_2\cdot(x+b_\perp)}e^{ip_1\cdot x}e^{ip_2\cdot x}\int d^4y\, e^{ik_1'\cdot y}e^{ik_2'\cdot(y+b_\perp)}e^{-ip_1\cdot y}e^{-ip_2\cdot y}$$

$$\propto \delta^4(k_1+k_2-p_1-p_2)\,\delta^4(k_1'+k_2'-p_1-p_2)e^{-ik_{2\perp}\cdot b_\perp}e^{ik_{2\perp}'\cdot b_\perp}$$

$$\propto \delta^2(k_{1\perp}+k_{2\perp}-p_{1\perp}-p_{2\perp})\,\delta^2(k_{1\perp}'+k_{2\perp}'-p_{1\perp}-p_{2\perp})e^{i(k_{2\perp}'-k_{2\perp})\cdot b_\perp}$$

M. Vidovic, M. Greiner, C. Best and G. Soff; 93

Successfully describes dilepton k_t broadening

cross section

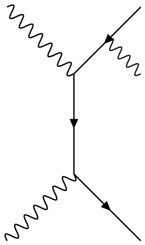
$$\frac{d\sigma_0}{d^2p_{1\perp}d^2p_{2\perp}dy_1dy_2d^2b_\perp} = \frac{2\alpha_e^2}{Q^4}\frac{1}{(2\pi)^2}\left[\mathcal{A} + \mathcal{C}\cos 4\phi\right]$$

$$\mathcal{A} = \frac{Q^2 - 2P_\perp^2}{P_\perp^2}\frac{Z^4\alpha_e^2}{\pi^4}\int d^2k_{1\perp}d^2k_{2\perp}d^2\Delta_\perp\delta^2\left(q_\perp - k_{1\perp} - k_{2\perp}\right)e^{i\Delta_\perp\cdot b_\perp}$$
$$\times\left[\left(k_{1\perp}\cdot k'_{1\perp}\right)\left(k_{2\perp}\cdot k'_{2\perp}\right) + \left(k_{1\perp}\cdot k_{2\perp}\right)\Delta_\perp^2 - \left(k_{1\perp}\cdot\Delta_\perp\right)\left(k_{2\perp}\cdot\Delta_\perp\right)\right]$$
$$\times\mathcal{F}\left(x_1, k_{1\perp}^2\right)\mathcal{F}^*\left(x_1, k_{1\perp}'^2\right)\mathcal{F}\left(x_2, k_{2\perp}^2\right)\mathcal{F}^*\left(x_2, k_{2\perp}'^2\right)$$

$$\mathcal{C} = -2\frac{Z^4\alpha_e^2}{\pi^4}\int d^2k_{1\perp}d^2k_{2\perp}d^2\Delta_\perp\delta^2\left(q_\perp - k_{1\perp} - k_{2\perp}\right)e^{i\Delta_\perp\cdot b_\perp}$$
$$\times\left\{2\left[2\left(k_{2\perp}\cdot\hat{q}_\perp\right)\left(k_{1\perp}\cdot\hat{q}_\perp\right) - k_{1\perp}\cdot k_{2\perp}\right]\left[2\left(k'_{2\perp}\cdot\hat{q}_\perp\right)\left(k'_{1\perp}\cdot\hat{q}_\perp\right) - k'_{1\perp}\cdot k'_{2\perp}\right]\right.$$
$$\left.-\left[\left(k_{1\perp}\cdot k'_{1\perp}\right)\left(k_{2\perp}\cdot k'_{2\perp}\right) + \left(k_{1\perp}\cdot k_{2\perp}\right)\Delta_\perp^2 - \left(k_{1\perp}\cdot\Delta_\perp\right)\left(k_{2\perp}\cdot\Delta_\perp\right)\right]\right\}$$
$$\times\mathcal{F}\left(x_1, k_{1\perp}^2\right)\mathcal{F}^*\left(x_1, k_{1\perp}'^2\right)\mathcal{F}\left(x_2, k_{2\perp}^2\right)\mathcal{F}^*\left(x_2, k_{2\perp}'^2\right)$$

where $\mathcal{F}\left(x, k_\perp^2\right) = \frac{F\left(k_\perp^2 + x^2M_p^2\right)}{\left(k_\perp^2 + x^2M_p^2\right)}$, $\Delta_\perp = k_{1\perp} - k'_{1\perp} = k'_{2\perp} - k_{2\perp}$

soft photon radiation



considering high order QED effects, large logarithms $\alpha_e^n \ln^{2n}\frac{Q^2}{m^2}$ will appear, which can be resummed using Collin-Soper-Sterman (CSS) formalism, result in Sudakov factor in exponential in the impact parameter space.

At one-loop order [Klein, Mueller, Xiao, Yuan, PRL122 (2019)],

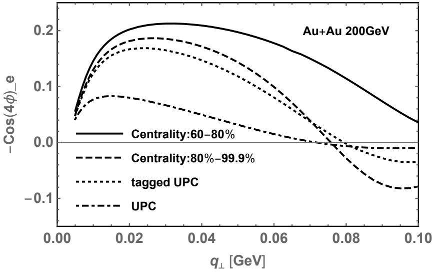
$$\mathrm{Sud}_{1-\mathrm{loop}}(r_\perp) = \frac{\alpha_e}{\pi}\ln\frac{Q^2}{m^2}\ln\frac{P_\perp^2}{\mu_r^2}, \quad \text{with } \mu_r = 2e^{-\gamma_E}/r_\perp$$

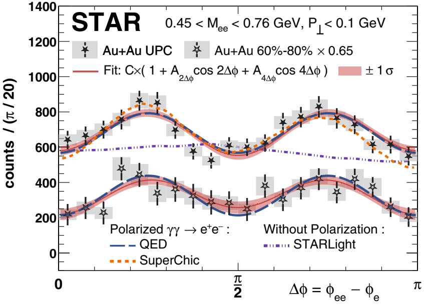
cross section:

$$\frac{d\sigma}{d^2p_{1\perp}d^2p_{2\perp}dy_1dy_2d^2b_\perp} = \int \frac{d^2r_\perp}{(2\pi)^2} e^{ir_\perp\cdot(q_\perp - k_{1\perp} - k_{2\perp})} e^{-S(Q,r_\perp)} \frac{d\sigma_0}{d^2p_{1\perp}d^2p_{2\perp}dy_1dy_2d^2b_\perp}$$

Linearly polarized photon verified by STAR collaboration

numerical calculation: linearly polarized photon, impact parameter dependence, Sudakov resummation





	Measured $|A_4|$	QED calculation A_4
Tagged UPC	16.8%±2.5%	-16.5%
60%-80%	27%±6%	-34.5%

see also Wolfgang's talk Tuesday

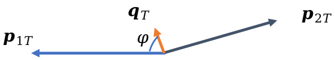
STAR collaboration, PRL127, 052302 (2021)

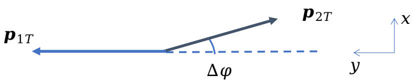
C. Li, J. Zhou and YZ, 2020

VERIFIED!

Revisiting, aim to test the resummation formalism

Observables: Azimuthal asymmetry, Acoplanarity





$$\langle\cos(n\varphi)\rangle = \frac{\int \frac{d\sigma}{d\mathcal{P}.\mathcal{S}.} \cos(n\varphi) d\mathcal{P}.\mathcal{S}.}{\int \frac{d\sigma}{d\mathcal{P}.\mathcal{S}.} d\mathcal{P}.\mathcal{S}.}$$

$$\alpha = \frac{|\Delta\varphi|}{\pi} \simeq \frac{q_x}{\pi P_\perp}$$

What we already knew: two-dimensional $q_\perp$ resummation at leading logarithm

What we do [arxiv:2306.02337]:

- Derive the resummation formula for acoplanarity, which is one dimensional,
- All order resummation up to single logarithm accuracy.

Soft photon radiation

~100MeV

Coherent photon

Soft photon radiation

~1/R~30MeV

$$\mathrm{Sud}_{1-\mathrm{loop}}(r_\perp) = \frac{\alpha_e}{\pi} ln\frac{Q^2}{m^2} ln\frac{P_\perp^2}{\mu_r^2}$$

the recoiled momentum of the lepton
also induce azimuthal anisotropy

Soft photon radiation

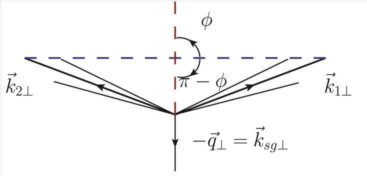
- to azimuthal asymmetry:

cross section with soft photon radiation

$$\frac{d\sigma(q_\perp)}{d\mathcal{P}.\mathcal{S}.} = \int d^2q'_\perp \frac{d\sigma_0(q'_\perp)}{d\mathcal{P}.\mathcal{S}.} S(q_\perp - q'_\perp)$$

soft factor at leading order:

$$S(l_\perp) = \delta(l_\perp) + \frac{\alpha_e}{\pi^2 l_\perp^2}\left\{c_0 + 2c_2 \boxed{\cos 2\phi} + 2c_4 \boxed{\cos 4\phi} + ...\right\}$$



Y. Hatta, B.W. Xiao, F. Yuan and J. Zhou, PRL(2021) and PRD(2021)

- to acoplanarity:
  deviate from the back-to-back configuration

Leading logarithm resummation

- Cross section with the final state photon resumed:

$$\frac{d\sigma}{d^2p_{1\perp}d^2p_{2\perp}dy_1dy_2d^2b_\perp} = \int \frac{d^2r_\perp}{(2\pi)^2} e^{ir_\perp\cdot q_\perp} e^{-\mathrm{Sud}(r_\perp)} \int d^2q'_\perp e^{-ir_\perp\cdot q'_\perp} \frac{d\sigma_0(q'_\perp)}{d\mathcal{P}.\mathcal{S}.},$$

leading logarithm:

$$\mathrm{Sud}(r_\perp) = \frac{\alpha_e}{\pi}\ln\frac{M^2}{m^2}\ln\frac{P_\perp^2}{\mu_r^2},$$

- The q_x dependent cross section

$$\frac{d\sigma}{dq_xd^2P_\perp dy_1dy_2d^2b_\perp} = \int \frac{dr_x}{2\pi} e^{ir_xq_x} e^{-\mathrm{Sud_a}(r_x,r_y=0)} \int dq'_xdq'_y\, e^{-ir_xq'_x} \frac{d\sigma_0(q'_\perp)}{d\mathcal{P}.\mathcal{S}.}.$$

leading logarithm

$$\mathrm{Sud_a}(r_x) = \frac{\alpha_e}{2\pi}\left[\ln^2\frac{M^2}{\mu_{rx}^2} - \ln^2\frac{m^2}{\mu_{rx}^2}\theta(m-\mu_{rx})\right]$$

Mass factorization and resummation in SCET: at low $\mathbf{q}_\perp$

massless hard function

collinear jet function

$$\frac{d\sigma(q_\perp)}{d\mathcal{P}.\mathcal{S}.} = H(M,\mu)J^2(m,\mu)\int d^2\boldsymbol{l}_\perp d^2\boldsymbol{k}_{1\perp} d^2\boldsymbol{k}_{2\perp}\frac{d\sigma_0(|\boldsymbol{q}_\perp - \boldsymbol{l}_\perp - \boldsymbol{k}_{1\perp} - \boldsymbol{k}_{2\perp}|)}{d\mathcal{P}.\mathcal{S}.}$$
$$\times S(l_\perp, \Delta y, \mu)C_1(k_{1\perp}, P_\perp, y_1, m, \mu)C_2(k_{2\perp}, P_\perp, y_2, m, \mu),$$

massless soft function

collinear-soft functions

$$\mathrm{Sud}(r_\perp) = \int_{\mu_r}^{M}\frac{d\mu}{\mu}\Gamma_H + 2\int_{\mu_r}^{m}\frac{d\mu}{\mu}\Gamma_J + \int_{\mu_r}^{\mu_r m/(2P_\perp)}\frac{d\mu}{\mu}\Gamma_{C_1} + \int_{\mu_r}^{\mu_r m/(2P_\perp)}\frac{d\mu}{\mu}\Gamma_{C_2},$$

anomalous dimension:

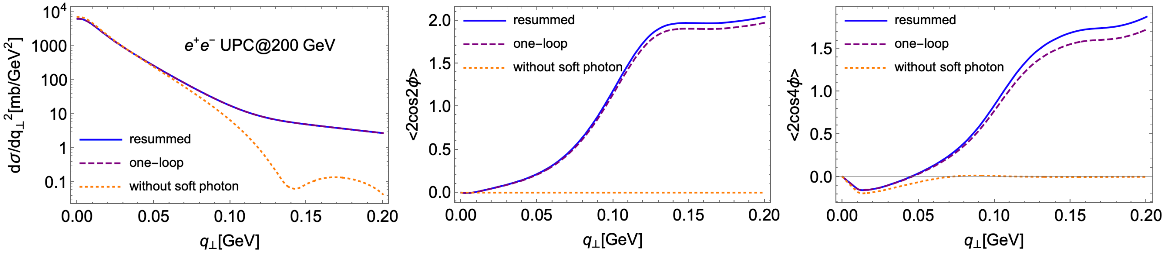
$$\Gamma_H = \frac{\alpha_e}{4\pi}\left(8\ln\frac{M^2}{\mu^2} - 12\right), \quad \Gamma_S = \frac{\alpha_e}{4\pi}\left(8\ln\frac{\mu^2 r_\perp^2}{b_0^2} + 8\ln\cos^2\phi_r - 8\ln\frac{1+\cosh\Delta y}{2}\right),$$
$$\Gamma_J = \frac{\alpha_e}{4\pi}\left(4\ln\frac{\mu^2}{m^2} + 2\right), \quad \Gamma_{C_{1,2}} = \frac{\alpha_e}{4\pi}\left(-4\ln\frac{4P_\perp^2\mu^2 r_\perp^2}{b_0^2 m^2} + 4 - 4\ln\cos^2\phi_r \pm 4i\pi\right).$$

Numerical results: azimuthal asymmetry

$$\frac{d\sigma}{d^2p_{1\perp}d^2p_{2\perp}dy_1dy_2d^2b_\perp} = \int \frac{d^2r_\perp}{(2\pi)^2} e^{ir_\perp\cdot q_\perp} e^{-\text{Sud}(r_\perp)} \int d^2q'_\perp e^{-ir_\perp\cdot q'_\perp} \frac{d\sigma_0(q'_\perp)}{d\mathcal{P.S.}},$$

Born cross section: $\frac{d\sigma_0}{d^2p_{1\perp}d^2p_{2\perp}dy_1dy_2d^2b_\perp} = \frac{2\alpha_e^2}{Q^4}\left[\mathcal{A} + \mathcal{B}\cos 2\phi + \mathcal{C}\cos 4\phi\right]$

with all order Sudakov factor, ..., $\left[\text{Sud}(r_\perp)\Big|_{\text{DL},\Delta y=0} = \frac{\alpha_e}{\pi}\ln\frac{M^2}{m^2}\ln\frac{P_\perp^2}{\mu_r^2} + \frac{\alpha_e}{\pi}\ln\frac{M^2}{m^2}\ln 4\cos^2\phi_r\right]$



Mass factorization and resummation in SCET: at low q_x

massless hard function

collinear jet function

$$\frac{d\sigma(\alpha)}{d\mathcal{P}.\mathcal{S}.} = 2P_\perp H(M,\mu) J^2(m,\mu) \int dl_x dk_{1,x} dk_{2,x} \frac{d\sigma_0(q_x - l_x - k_{1x} - k_{2x})}{d\mathcal{P}.\mathcal{S}.}$$
$$\times S(l_x, \Delta y, \mu, \nu) C_1(k_{1x}, P_\perp, y_1, m, \mu, \nu) C_2(k_{2x}, P_\perp, y_2, m, \mu, \nu),$$

massless soft function

collinear-soft functions

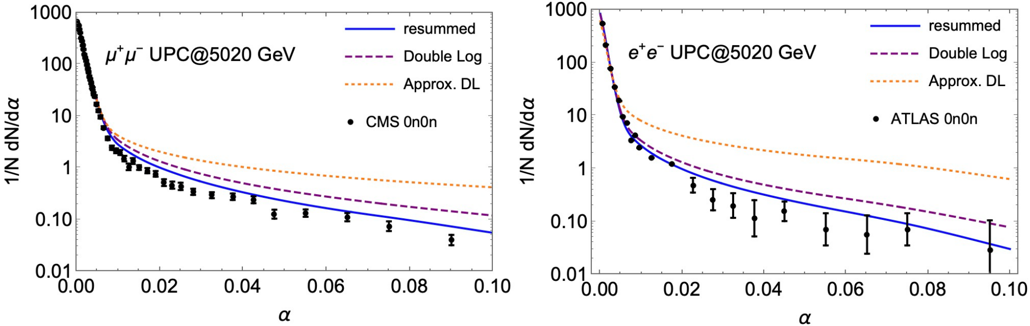
$$\mathrm{Sud}_a(r_x) = \int_{\mu_{rx}}^{M} \frac{d\mu}{\mu}\Gamma_H + 2\int_{\mu_{rx}}^{m} \frac{d\mu}{\mu}\Gamma_J \theta(m-\mu_{rx}) = \frac{\alpha_e}{2\pi}\left[\left(\ln^2\frac{M^2}{\mu_{rx}^2} - 3\ln\frac{M^2}{\mu_{rx}^2}\right) - \left(\ln^2\frac{m^2}{\mu_{rx}^2} - \ln\frac{m^2}{\mu_{rx}^2}\right)\theta(m-\mu_{rx})\right]$$

Numerical results: acoplanarity

$$\frac{d\sigma}{dq_x d^2P_\perp dy_1 dy_2 d^2b_\perp} = \int \frac{dr_x}{2\pi} e^{ir_x q_x} e^{-\mathrm{Sud_a}(r_x, r_y=0)} \int dq'_x dq'_y \, e^{-ir_x q'_x} \frac{d\sigma_0(q'_\perp)}{d\mathcal{P.S.}}.$$

Born cross section: $\frac{d\sigma_0}{d^2p_{1\perp} d^2p_{2\perp} dy_1 dy_2 d^2b_\perp} = \frac{2\alpha_e^2}{Q^4}\mathcal{A}$

with all order Sudakov factor, $\mathrm{Sud}_a(r_x) = \frac{\alpha_e}{2\pi}\left[\left(\ln^2\frac{M^2}{\mu_{rx}^2} - 3\ln\frac{M^2}{\mu_{rx}^2}\right) - \left(\ln^2\frac{m^2}{\mu_{rx}^2} - \ln\frac{m^2}{\mu_{rx}^2}\right)\theta(m-\mu_{rx})\right]$



data from CMS Collaboration, PRL 127, 122001 (2021) ATLAS collaboration,JHEP 2306 (2023) 182

Summary

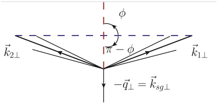
- Anology to gluon, the photon is linealy polarized, which induce azimuthal asymmetries in UPCs and have been verified by STAR.
- At relative high $q_\perp$ soft photon radiation effect dominant, and will change the azimuthal asymmetry shapes significantly, particularly, will induce large $\cos 2\phi$ asymmetry which is absent at leading order due to the neglegible electron mass.
- All order one-dimensional resummation is necessary to describe the acoplanarity data from ATLAS and CMS.

Thanks!

Back ups

di-muon production in UPCs: $Q \sim m$

at relatively high $q_\perp$, soft photon radiation dominant



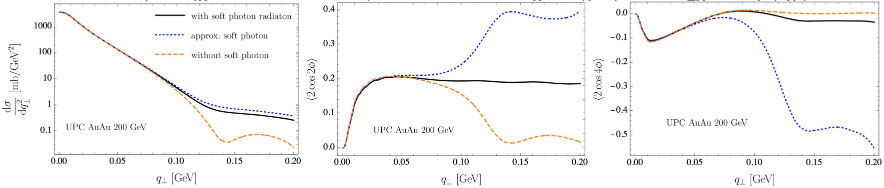
$$\mathrm{Sud}_{1-\mathrm{loop}}(r_\perp) = \frac{\alpha_e}{\pi} \ln\frac{Q^2}{m^2} \ln\frac{P_\perp^2}{\mu_r^2}$$

Y. Hatta, B.W. Xiao, F. Yuan and J. Zhou, PRL(2021) and PRD(2021)

double-logarithmic approximation, $\frac{d\sigma(q_\perp)}{d\mathcal{P}.\mathcal{S}.} = \int \frac{d^2 r_\perp}{(2\pi)^2} \left[1 - \frac{2\alpha_e c_2}{\pi} \cos 2\phi_r + \frac{\alpha_e c_4}{\pi} \cos 4\phi_r\right] e^{i r_\perp \cdot q_\perp} e^{-\mathrm{Sud}(r_\perp)} \int d^2 q'_\perp e^{i r_\perp \cdot q'_\perp} \frac{d\sigma_0(q'_\perp)}{d\mathcal{P}.\mathcal{S}.}$.

all order resummation, (D.Y. Shao, C. Zhang, J. Zhou, YZ, PRD (2023))

$$e^{-\mathrm{Sud}(r_\perp)} \left[1 + \frac{\alpha_e}{4\pi}(s_{11} + s_{22} + 2s_{12})\right], \mathrm{Sud}_{1-\mathrm{loop}}(r_\perp) = \frac{\alpha_e}{\pi} \ln\frac{P_\perp^2}{\mu^2} \left(-1 - \frac{1+\beta^2}{2\beta} \ln\frac{1-\beta}{1+\beta}\right),$$



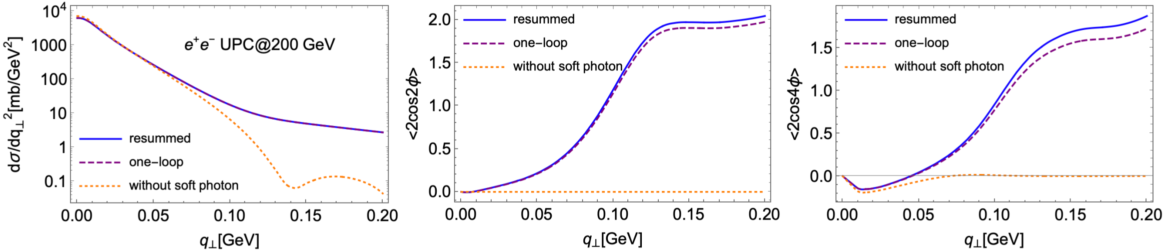


Figure: Di-electron production in unrestricted UPCs in Au+Au collisions at RHIC energy. The following kinematic cuts are imposed: the electrons' rapidities $|y_{1,2}| < 1$, transverse momentum $P_\perp > 200$ MeV, and the invariant mass of the electron pair 450 MeV $< M < 760$ MeV. The blue solid lines stand for the fully resummed results from Eq.24, and the purple dashed lines represent the results with the azimuthal dependent part being treated at the one loop order. The results without soft photon radiation effect are shown with the dotted orange lines. Left panel: azimuthal averaged differential cross sections; middle panel: $\langle\cos(2\phi)\rangle$ azimuthal asymmetry; right panel: $\langle\cos(4\phi)\rangle$ azimuthal asymmetry.

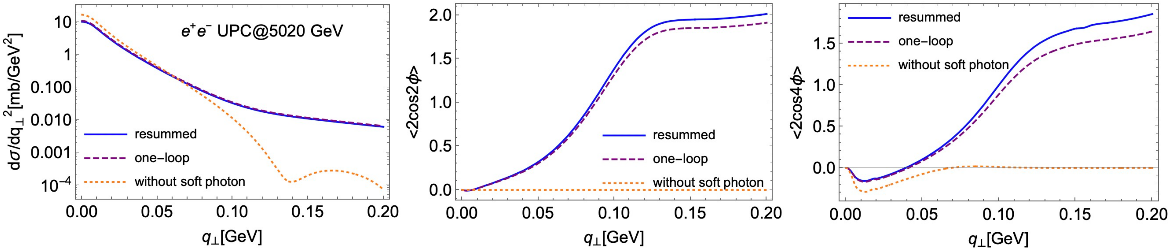


Figure: Di-electron production in unrestricted UPCs in Pb+Pb collisions at LHC energy. The following kinematic cuts are imposed: the electrons' rapidities $|y_{1,2}| < 0.8$ and the invariant mass of the di-electron 10 GeV $< M < 20$ GeV. The blue solid lines stand for the fully resummed results from Eq.24, and the purple dashed lines represent the results with the azimuthal dependent part being treated at the one loop order. The results without soft photon radiation effect is shown with the dotted orange lines. Left panel: azimuthal averaged differential cross sections; middle panel: $\langle\cos(2\phi)\rangle$ azimuthal asymmetry; right panel: $\langle\cos(4\phi)\rangle$ azimuthal asymmetry.

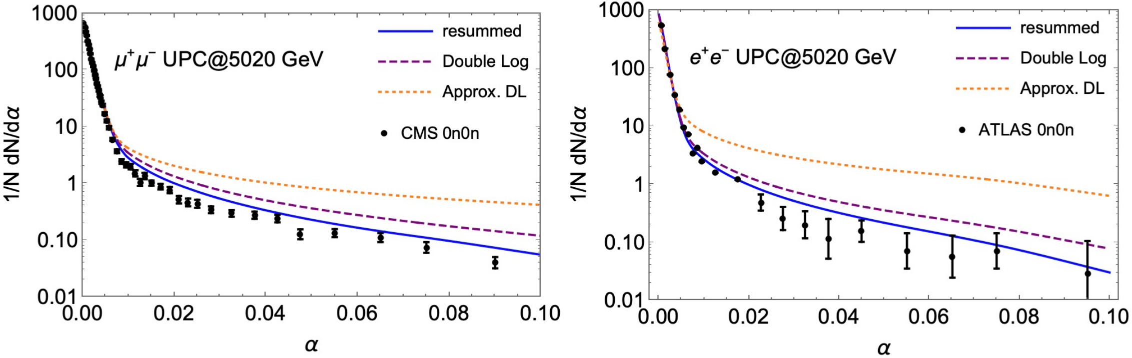


Figure: The normalized cross sections of di-lepton production are plotted as the function of α (color online). Left panel: di-muon production in Pb+Pb collisions for the 0n0n case, with the kinematic cutoff: leptons' rapidities $|y_{1,2}| < 2.4$, transverse momentum $P_\perp > 3.5$ GeV, and the invariant mass of the di-muon 8 GeV $< M < 60$ GeV. The CMS data displayed in the figure is taken from [1]. Right panel: di-electron production in Pb+Pb collisions for the 0n0n case, with the kinematic cutoff: leptons' rapidities $|y_{1,2}| < 0.8$ and the invariant mass of the di-electron 10 GeV $< M < 20$ GeV. The ATLAS data shown in the figure is taken from [2] The blue solid lines stand for the fully resummed results from Eq.(**??**), the purple dashed lines represent the leading double logarithm resummed results obtained using Eq.(**??**). The acoplanarity distribution reconstructed from the resummed $q_\perp$ distribution given by Eq. (1) and Eq. (1) is shown with the dotted orange lines.