Azimuthal asymmetries in photon induced dijet & dilepton productions in UPCs

Cheng Zhang 2023.5.28

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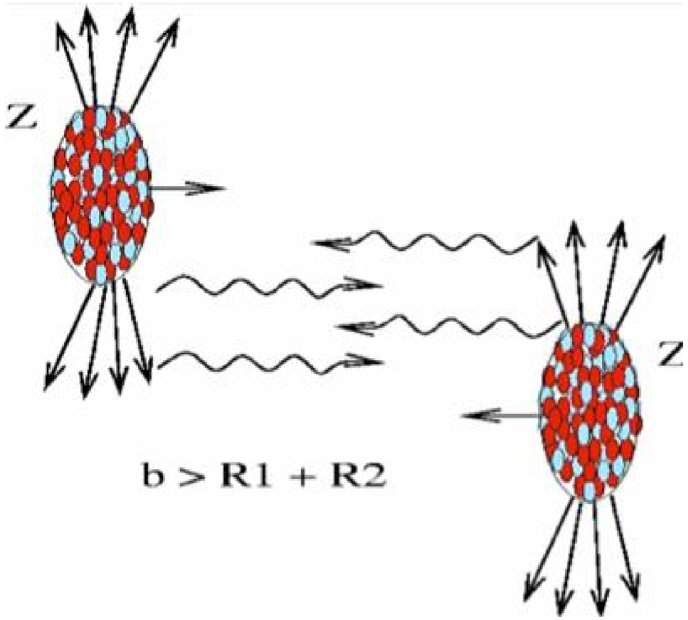
JHEP02(2023)002 Phys.Rev.D107,036020(2023)

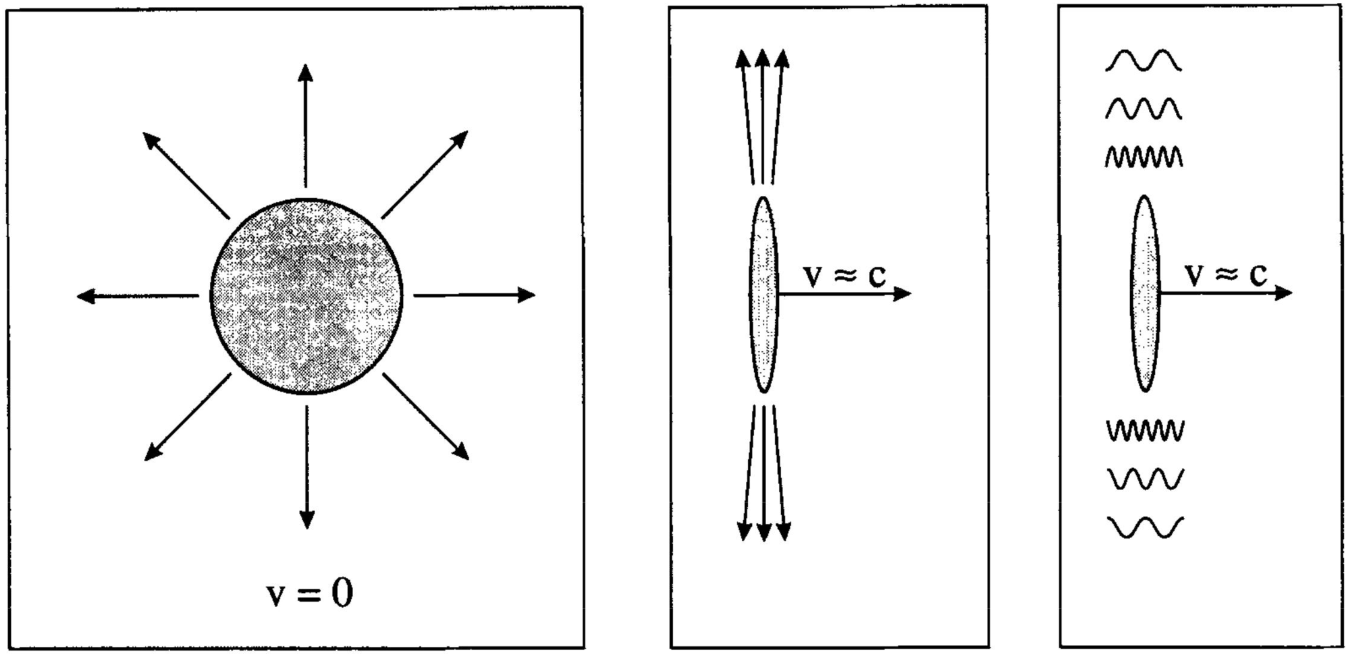
Outline

- Ultraperipheral collisions (UPCs)
- Acoplanarity (azimuthal decorrelation) of dijet productions from photon-photon fusions JHEP02(2023)002
- Acoplanarity & cos2φ, cos4φ azimuthal asymmetries in di-lepton (e^+e^- & $\mu^+\mu^-$) productions Phys.Rev.D107,036020(2023)
- Summary and outlook

Ultraperipheral collisions (UPCs)

Two nuclei miss each other, interact electromagnetically





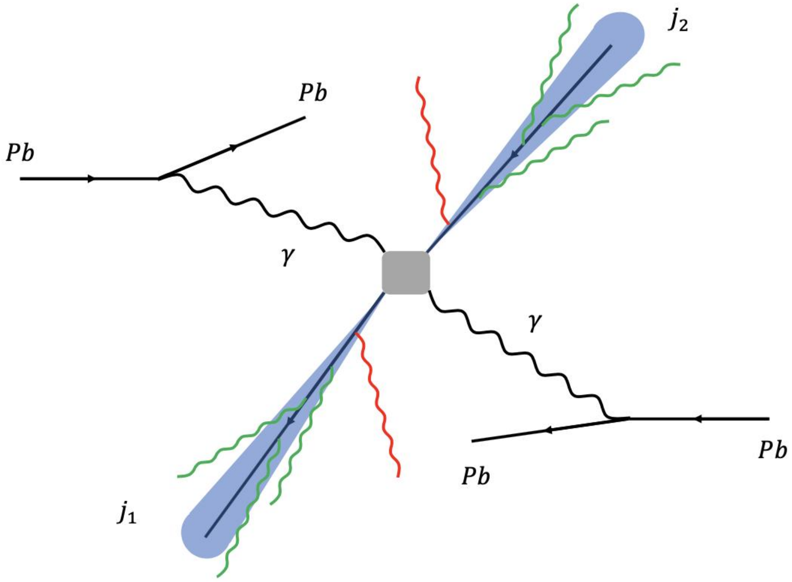
Fast moving nucleus, highly boosted and almost transverse electromagnetic fields

Different types: γ-γ, γ-A

Initial state coherent photons & gluons

Final state soft radiations & resummations

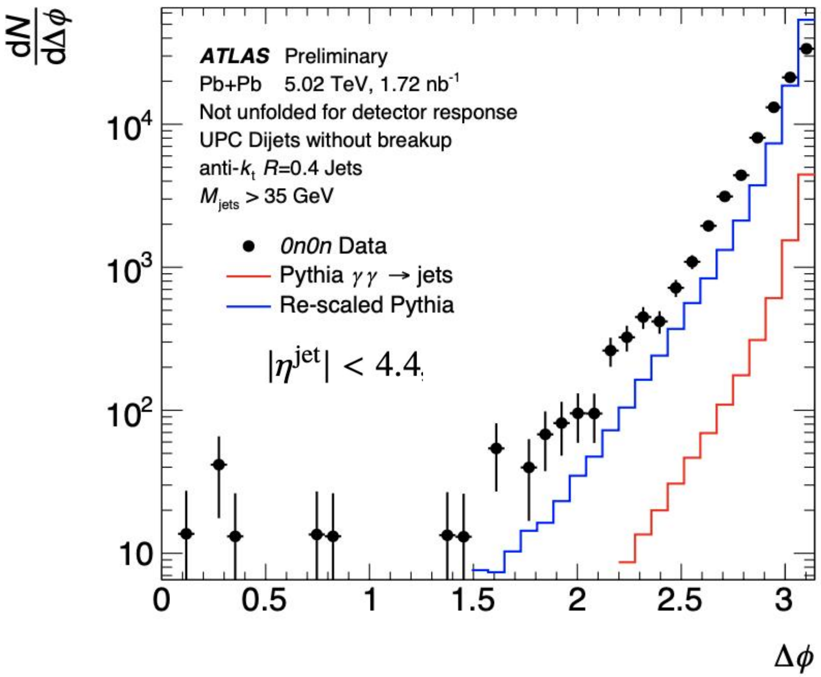
$$\gamma(\omega_1, \boldsymbol{k}_{1T}) + \gamma(\omega_2, \boldsymbol{k}_{2T}) \to q(y_1, \boldsymbol{p}_{1T}) + \bar{q}(y_2, \boldsymbol{p}_{2T})$$



Born cross section of A(γ)A(γ) → qq:

$$\frac{\mathrm{d}^5\sigma_0}{\mathrm{d}^2\boldsymbol{q}_T \mathrm{d}p_T \mathrm{d}y_1 \mathrm{d}y_2} = N_c \sum_q e_q^4 \frac{4Z^4\alpha_{\mathrm{em}}^4}{\pi^5 M^4} p_T \int \mathrm{d}^2\boldsymbol{b}_T \mathrm{d}^2\boldsymbol{k}_{1T} \mathrm{d}^2\boldsymbol{k}_{2T} \mathrm{d}^2\boldsymbol{k}'_{1T} \mathrm{d}^2\boldsymbol{k}'_{2T}$$
$$\times \delta^{(2)}(\boldsymbol{k}_{1T} + \boldsymbol{k}_{2T} - \boldsymbol{q}_T)\, \delta^{(2)}(\boldsymbol{k}'_{1T} + \boldsymbol{k}'_{2T} - \boldsymbol{q}_T)\, e^{i(\boldsymbol{k}_{1T} - \boldsymbol{k}'_{1T})\cdot \boldsymbol{b}_T}$$
$$\times k_{1T} \frac{F(-k_1^2)}{-k_1^2} k_{2T} \frac{F(-k_2^2)}{-k_2^2} k'_{1T} \frac{F(-k_1'^2)}{-k_1'^2} k'_{2T} \frac{F(-k_2'^2)}{-k_2'^2} \frac{M^2 - 2p_T^2}{p_T^2}$$
$$\times \cos\left(\phi_{\boldsymbol{k}_{1T}} - \phi_{\boldsymbol{k}'_{1T}} + \phi_{\boldsymbol{k}_{2T}} - \phi_{\boldsymbol{k}'_{2T}}\right),$$

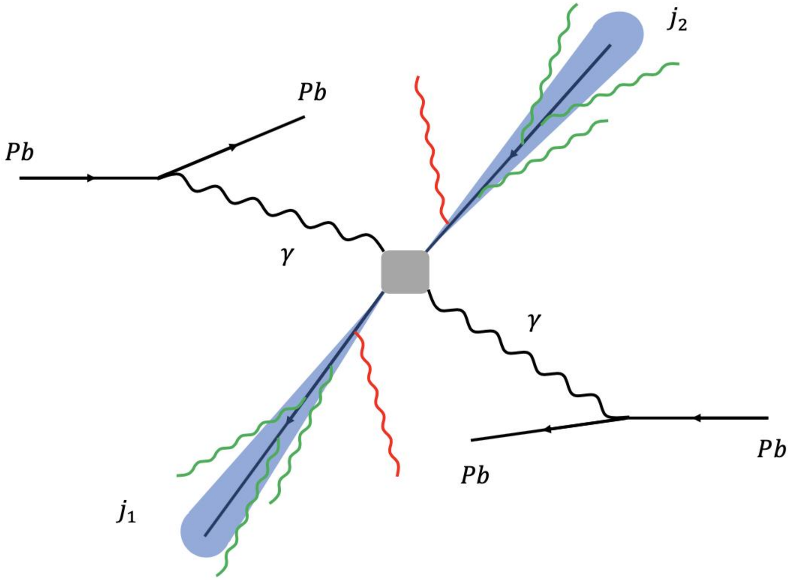
$$B(k_x, p_T, y_1, y_2) = \int \mathrm{d}k_y \frac{\mathrm{d}^5\sigma_0}{\mathrm{d}^2\boldsymbol{k}_T \mathrm{d}p_T \mathrm{d}y_1 \mathrm{d}y_2}$$



QM2022, ATLAS-CONF-2022-021

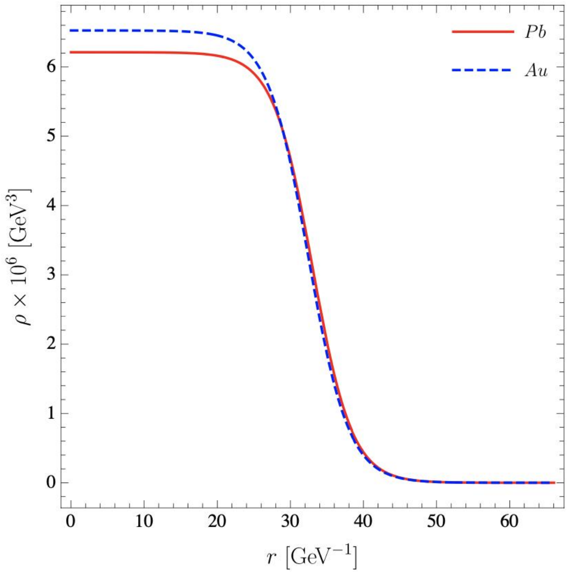
acoplanarity

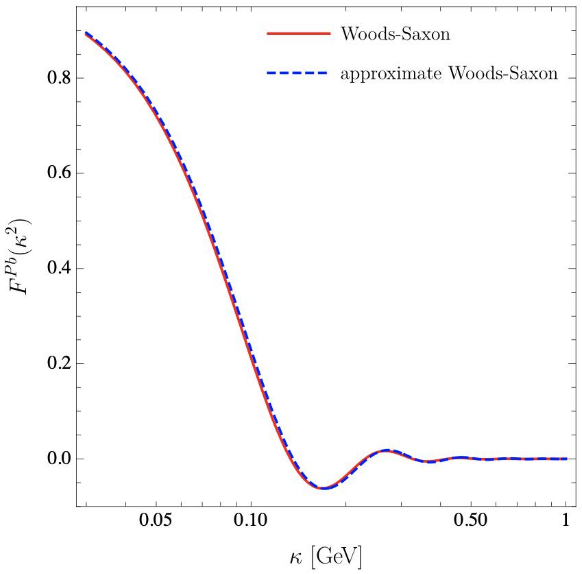
$$\gamma(\omega_1, \boldsymbol{k}_{1T}) + \gamma(\omega_2, \boldsymbol{k}_{2T}) \to q(y_1, \boldsymbol{p}_{1T}) + \bar{q}(y_2, \boldsymbol{p}_{2T})$$



$$\frac{\mathrm{d}^5\sigma_0}{\mathrm{d}^2\boldsymbol{q}_T \mathrm{d}p_T \mathrm{d}y_1 \mathrm{d}y_2} = N_c \sum_q e_q^4 \frac{4Z^4\alpha_{\mathrm{em}}^4}{\pi^5 M^4} p_T \int \mathrm{d}^2\boldsymbol{b}_T \mathrm{d}^2\boldsymbol{k}_{1T} \mathrm{d}^2\boldsymbol{k}_{2T} \mathrm{d}^2\boldsymbol{k}'_{1T} \mathrm{d}^2\boldsymbol{k}'_{2T}$$
$$\times\, \delta^{(2)}(\boldsymbol{k}_{1T} + \boldsymbol{k}_{2T} - \boldsymbol{q}_T)\, \delta^{(2)}(\boldsymbol{k}'_{1T} + \boldsymbol{k}'_{2T} - \boldsymbol{q}_T)\, e^{i\,(\boldsymbol{k}_{1T} - \boldsymbol{k}'_{1T})\cdot \boldsymbol{b}_T}$$
$$\times\, k_{1T} \frac{F(-k_1^2)}{-k_1^2} k_{2T} \frac{F(-k_2^2)}{-k_2^2} k'_{1T} \frac{F(-k_1'^2)}{-k_1'^2} k'_{2T} \frac{F(-k_2'^2)}{-k_2'^2} \frac{M^2 - 2p_T^2}{p_T^2}$$
$$\times\, \cos\left(\phi_{\boldsymbol{k}_{1T}} - \phi_{\boldsymbol{k}'_{1T}} + \phi_{\boldsymbol{k}_{2T}} - \phi_{\boldsymbol{k}'_{2T}}\right),$$

$$\sigma^{WW}_{A_1A_2 \to A_1A_2X} = \iint d\omega_1 d\omega_2 n_{A_1}(\omega_1)\, n_{A_2}(\omega_2)\, \sigma_{\gamma\gamma\to X}(\omega_1, \omega_2)$$



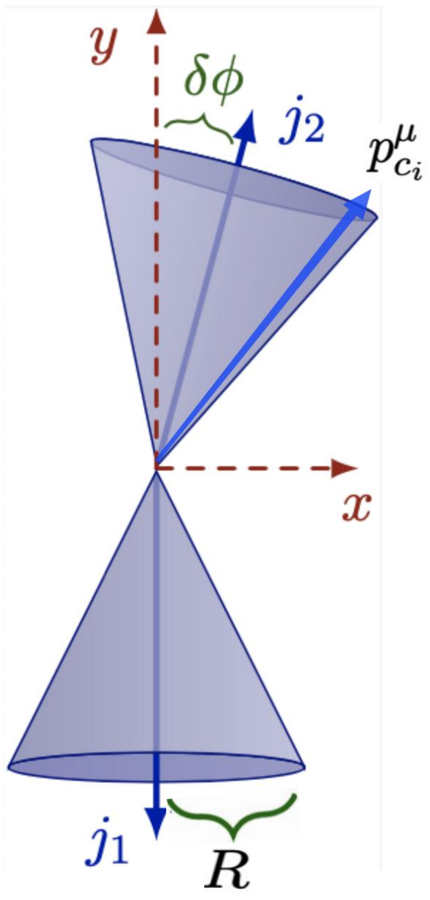


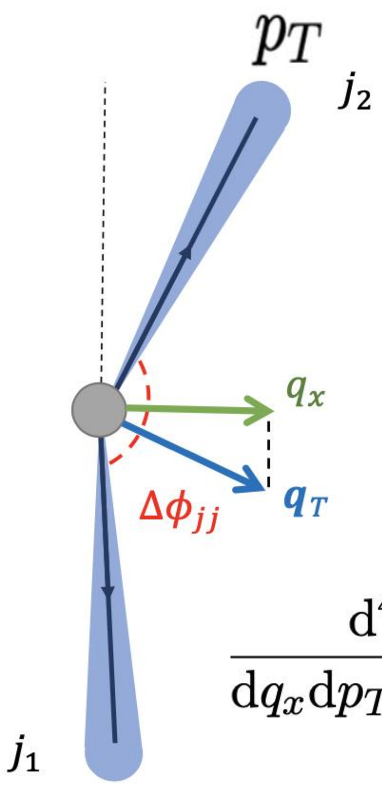
Equivalent photon approximation(EPA):

$$n(\omega) = \frac{4Z^2\alpha}{\omega} \int \frac{\mathrm{d}^2k_\perp}{(2\pi)^2} \left(\frac{F\left(\mathbf{k}_\perp^2 + \omega^2/\gamma^2\right)}{\mathbf{k}_\perp^2 + \omega^2/\gamma^2} \right)^2 |\mathbf{k}_\perp|^2$$

Woods-Saxon nuclear charge form factor:

$$F(\boldsymbol{k}_\perp) = \int d^3\boldsymbol{x} e^{i\boldsymbol{k}\cdot\boldsymbol{x}} \frac{\rho}{1 + \exp[(r - R_{WS})/d]}$$





Energy modes in the factorized expression

$$n_i \text{ collinear}: \quad p^\mu_{c_i} \sim p_T\,(R^2, 1, R)_{n_i\bar{n}_i},$$

$$n_i \text{ collinear-soft}: \quad p^\mu_{cs_i} \sim \frac{p_T\,\delta\phi}{R}(R^2, 1, R)_{n_i\bar{n}_i}$$

$$\text{soft}: \quad p^\mu_s \sim p_T\,(\delta\phi, \delta\phi, \delta\phi),$$

Factorization and Resummation formalism in Soft-Collinear Effective Theory (SCET):

$$\frac{\mathrm{d}^4\sigma}{\mathrm{d}q_x \mathrm{d}p_T \mathrm{d}y_1 \mathrm{d}y_2} = \int \mathrm{d}k_x\,\mathrm{d}\lambda_x\,\mathrm{d}l_{1,x}\,\mathrm{d}l_{2,x}\delta(k_x + \lambda_x + l_{1,x} + l_{2,x} - q_x)B(k_x, p_T, y_1, y_2)$$

hard function

jet function

$$\times H(p_T, \Delta y, \mu) S(\lambda_x, y_1, y_2, \mu, \nu) U_1(l_{1,x}, R, y_1, \mu, \nu) J_1(p_T, R, \mu)$$

$$\times U_2(l_{2,x}, R, y_2, \mu, \nu) J_2(p_T, R, \mu),$$

acoplanarity

$$|q_x| \equiv p_T \sin(\pi - \Delta\phi_{jj}) = p_T \sin \delta\phi$$

RG equation of the hard function

$$\frac{\mathrm{d}}{\mathrm{d}\ln\mu}H(p_T,\Delta y,\mu)=\underbrace{\left[-2C_F\gamma_{\mathrm{cusp}}(\alpha_s)\ln\frac{\mu^2}{M^2}+4\gamma_q(\alpha_s)\right]}_{\equiv\Gamma_H(\alpha_s)}H(p_T,\Delta y,\mu)$$

RG equation of the hard function

$$\frac{\mathrm{d}}{\mathrm{d}\ln\mu}J_i(p_T,R,\mu)=\underbrace{\left[-C_F\gamma_{\mathrm{cusp}}(\alpha_s)\ln\frac{p_T^2R^2}{\mu^2}-2\gamma_q(\alpha_s)\right]}_{\equiv\Gamma_J(\alpha_s)}J_i(p_T,R,\mu)$$

RG consistency relations

$$\frac{\mathrm{d}}{\mathrm{d}\ln\mu}\left[SU_1U_2\,H(p_T,\Delta y,\mu)J_1(p_T,R,\mu)J_2(p_T,R,\mu)\right]=0$$

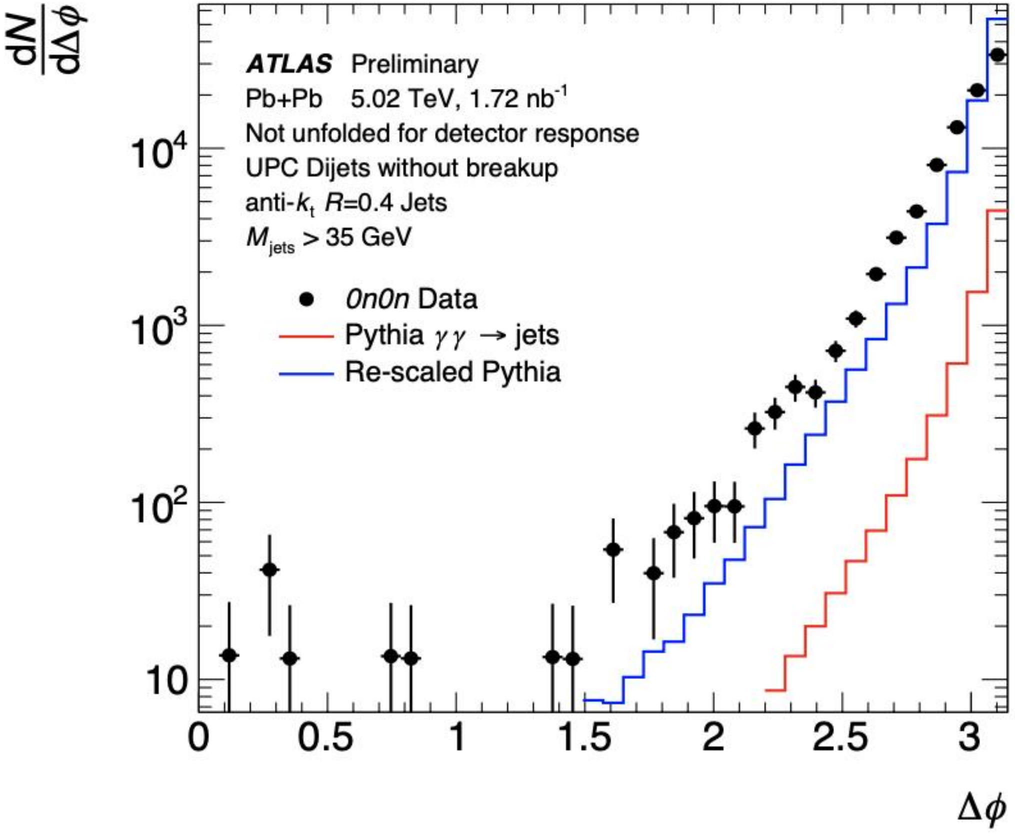
Evolve the hard and jet function at NLL accuracy

$$\frac{\mathrm{d}^4\sigma^{\mathrm{NLL}}}{\mathrm{d}q_x\mathrm{d}p_T\mathrm{d}y_1\mathrm{d}y_2}=\int_0^\infty\frac{\mathrm{d}b_x}{\pi}\cos(q_xb_x)\tilde{B}(b_x,p_T,y_1,y_2)$$
$$\times\exp\left[\int_{\mu_h}^{\mu_b}\frac{\mathrm{d}\mu}{\mu}\Gamma_H(\alpha_s)+2\int_{\mu_j}^{\mu_b}\frac{\mathrm{d}\mu}{\mu}\Gamma_J(\alpha_s)\right]$$

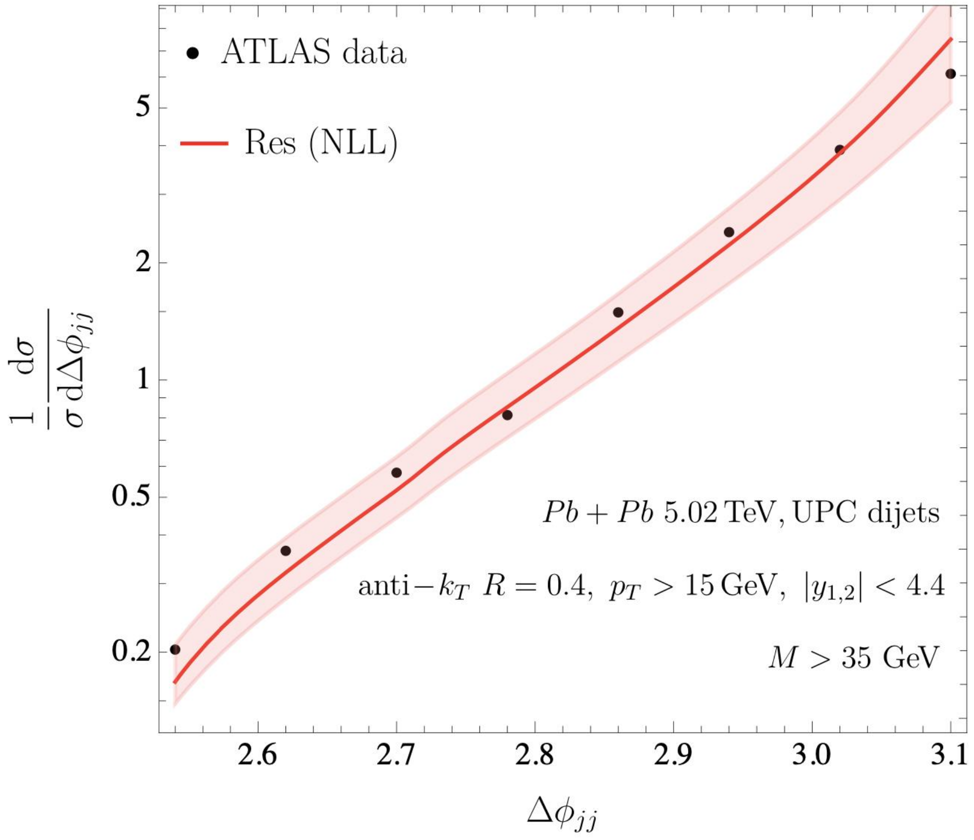
Acoplanarity

for $\gamma\gamma$ processes. Also, the data fall off more steeply with increasing H_T than the PYTHIA 8 and the measured $\Delta\phi$ distribution is noticeably wider than that in the PYTHIA 8 MC.

QM2022, ATLAS-CONF-2022-021



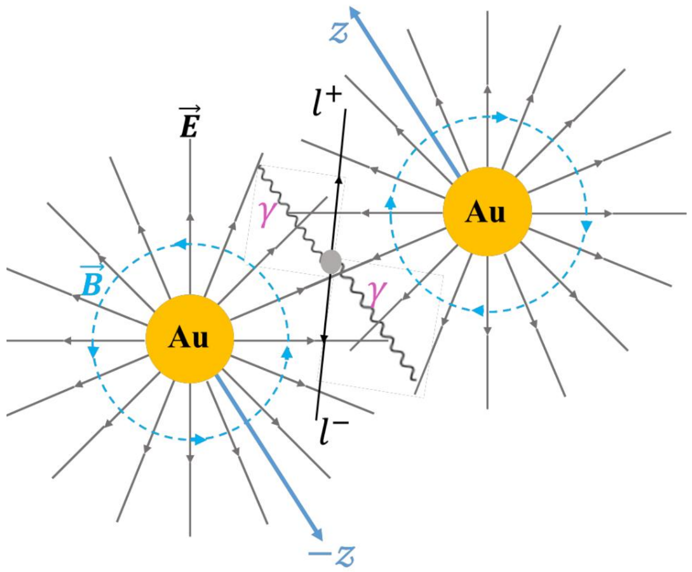
C.Z., Q.S. Dai and D.Y. Shao, JHEP02(2023)

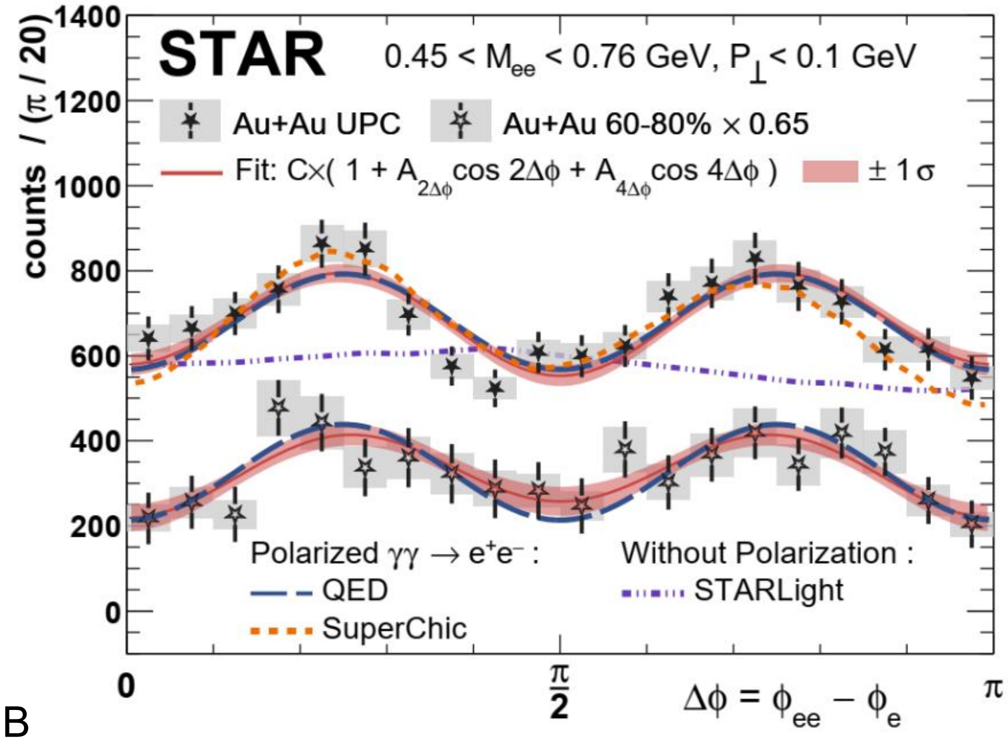


Di-lepton (e^+e^-) production

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

J.Adam et al. (STAR) 2021 Phys. Rev. Lett. 127 52302.





C. Li, J. Zhou and Y. Zhou, 2020

W. Zha, L. Ruan, Z. Tang, Z. Xu, S. Yang, 2018 Phys. Lett.B

BW. Xiao, and F. Yuan, J. Zhou, 2020 Phys.Rev.Lett

RJ. Wang, Shi Pu, and Qun Wang, 2021 Phys.Rev.D

Azimuthal asymmetry

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

$$\phi=\phi_{ee}-\phi_e$$

e^+e^- production in UPCs $\quad M \gg q_\perp \gtrsim m$

Resummation formula that includes lepton mass resummation

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

Anomalous dimension

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

RG consistency relations $\quad \Gamma_H + \Gamma_S + 2\Gamma_J + \Gamma_{C_1} + \Gamma_{C_2} = 0.$

Sudakov factor

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

$$\mathrm{Sud}(r_\perp)\Big|_{\mathrm{DL},\Delta y=0} = \boxed{\frac{\alpha_e}{\pi}\ln\frac{M^2}{m^2}\ln\frac{P_\perp^2}{\mu_r^2}} + \frac{\alpha_e}{\pi}\ln\frac{M^2}{m^2}\ln 4\cos^2\phi_r$$

Y. Hatta, BW. Xiao, F. Yuan, and J. Zhou, 2021 Phys. Rev. Lett

Soft photon resummed cross section

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

$$\mathrm{Sud}(r_\perp)\Big|_{\mathrm{DL},\Delta y=0} = \frac{\alpha_e}{\pi}\ln\frac{M^2}{m^2}\ln\frac{P_\perp^2}{\mu_r^2} + \frac{\alpha_e}{\pi}\ln\frac{M^2}{m^2}\ln 4\cos^2\phi_r$$

Born cross section of dilepton

$$\frac{d\sigma_0}{d^2q_\perp d^2P_\perp dy_1dy_2d^2b_\perp} = A_0 + A_2\cos2\phi + A_4\cos4\phi$$

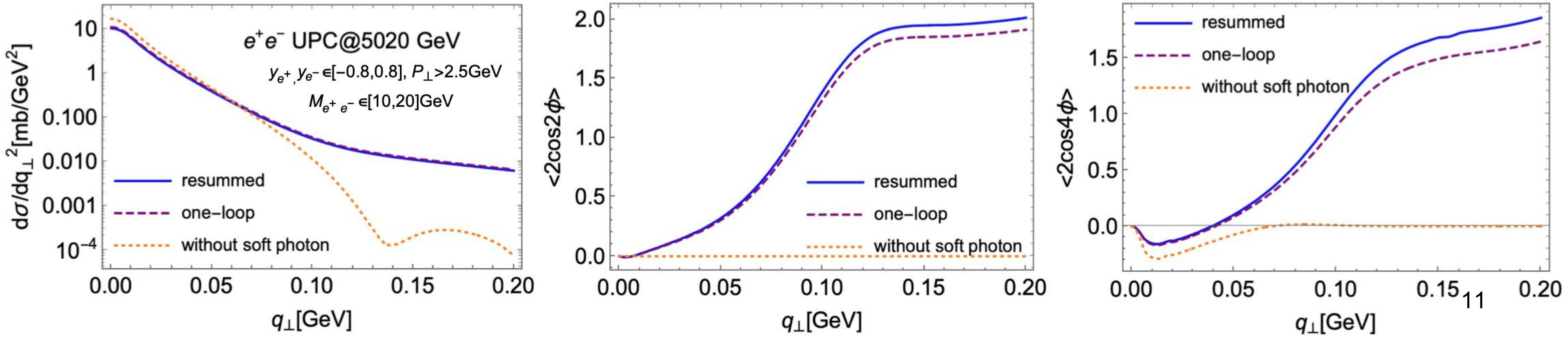
Born cross section

$$A_0 = \int [d\mathcal{K}_\perp] \frac{1}{(P_\perp^2+m^2)^2}\Big[-2m^4\cos\left(\phi_{k_{1\perp}}+\phi_{k'_{1\perp}}-\phi_{k_{2\perp}}-\phi_{k'_{2\perp}}\right) + P_\perp^2\left(M^2-2P_\perp^2\right)\cos\left(\phi_{k_{1\perp}}-\phi_{k'_{1\perp}}+\phi_{k_{2\perp}}-\phi_{k'_{2\perp}}\right)\Big],$$

$$A_2 = \int [d\mathcal{K}_\perp] \frac{8m^2P_\perp^2}{(P_\perp^2+m^2)^2}\cos\left(\phi_{k_{1\perp}}-\phi_{k_{2\perp}}\right)\cos\left(\phi_{k'_{1\perp}}+\phi_{k'_{2\perp}}-2\phi\right)$$

$$A_4 = \int [d\mathcal{K}_\perp] \frac{-2P_\perp^4}{(P_\perp^2+m^2)^2}\cos\left(\phi_{k_{1\perp}}+\phi_{k'_{1\perp}}+\phi_{k_{2\perp}}+\phi_{k'_{2\perp}}-4\phi\right).$$

Azimuthal asymmetry



Factorization formula at low α

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

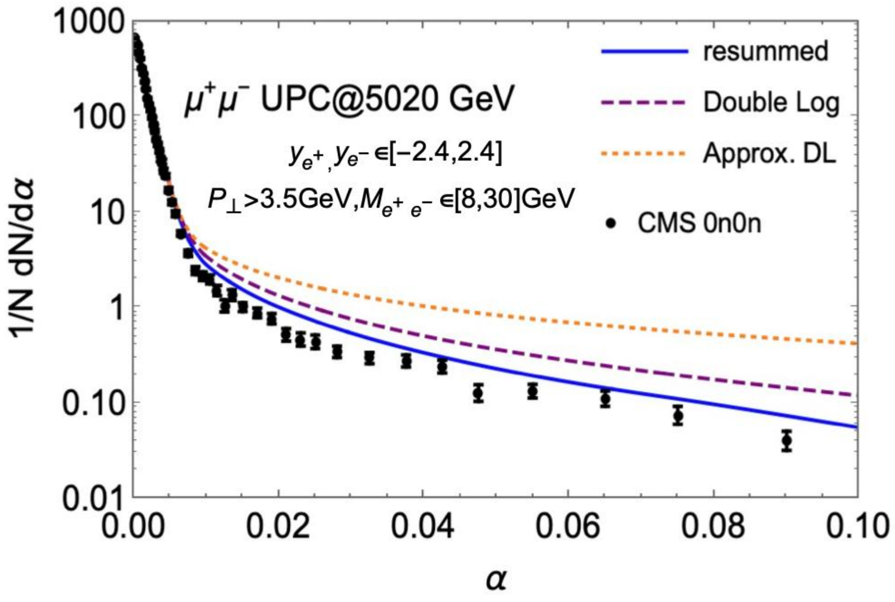
Sudakov factor for α distribution

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

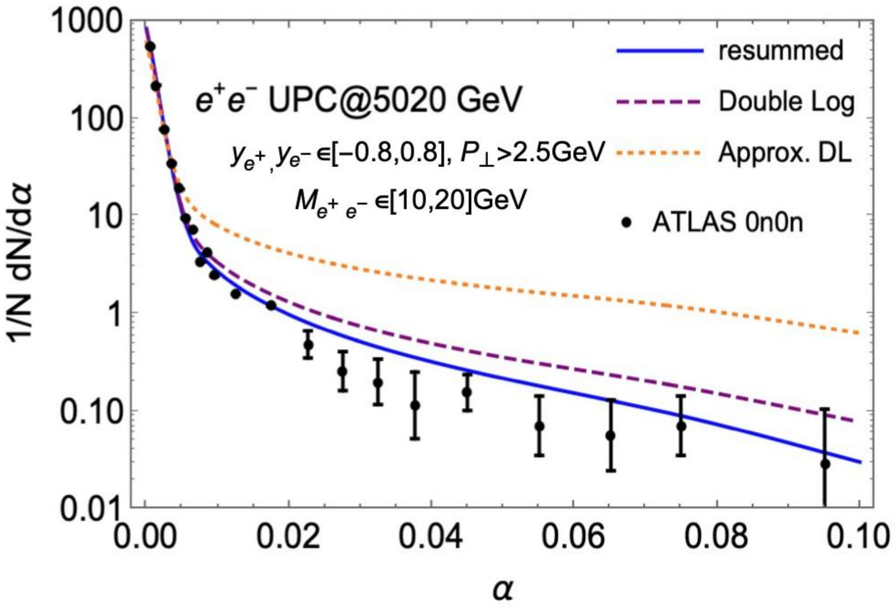
$$|q_x| \equiv p_T \sin(\pi - \Delta\phi_{jj}) = p_T \sin \alpha$$

Acoplanarity

CMS, 2021 Phys.Rev.Lett.



ATLAS, 2207.12781

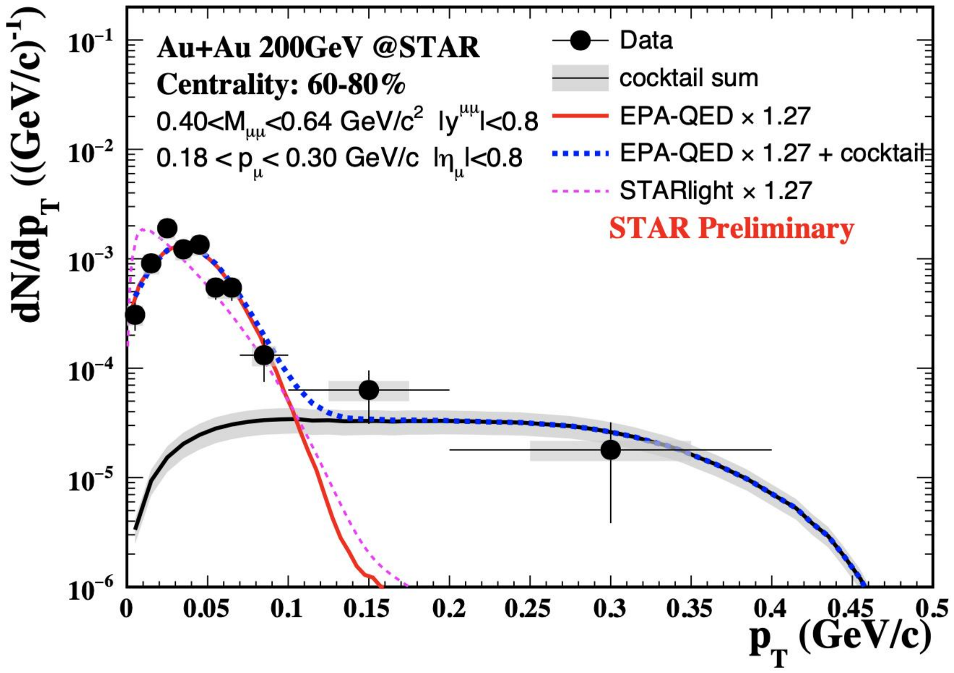


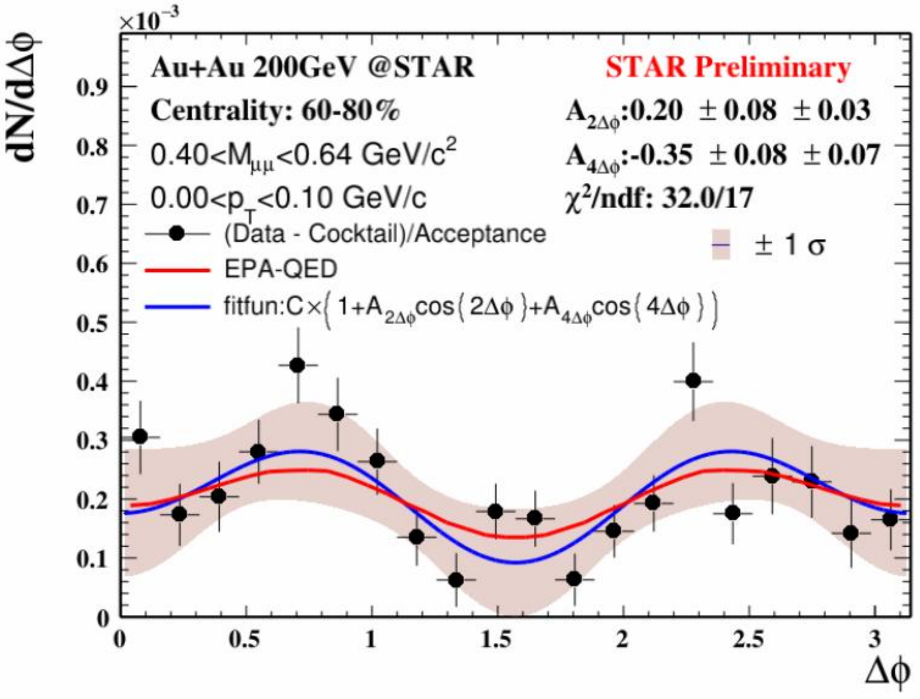
Di-lepton ($\mu^+\mu^-$) production

$$M \sim m \gg q_\perp$$

$\mu^+\mu^-$ pairs

STAR QM 2022





Azimuthal asymmetry

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

$$\phi = \phi_{\mu\mu} - \phi_{\mu}$$

Azimuthal asymmetries of μ⁺μ⁻ production $M \sim m \gg q_\perp$

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

$$\frac{d\sigma_0}{d^2q_\perp d^2P_\perp dy_1 dy_2 d^2b_\perp} = A_0 + A_2\cos 2\phi + A_4 \cos 4\phi, \qquad \frac{d\sigma(q_\perp)}{d\mathcal{P}.\mathcal{S}.} = \int d^2 l_\perp \frac{d\sigma_0(q_\perp - l_\perp)}{d\mathcal{P}.\mathcal{S}.} S(l_\perp)$$

Born cross section

$$A_0 = \int [d\mathcal{K}_\perp] \frac{1}{\left(P_\perp^2 + m^2\right)^2}\Big[-2m^4 \cos\left(\phi_{k_{1\perp}} + \phi_{k'_{1\perp}} - \phi_{k_{2\perp}} - \phi_{k'_{2\perp}}\right) + m^2\left(M^2 - 2m^2\right)\cos\left(\phi_{k_{1\perp}} - \phi_{k'_{1\perp}} - \phi_{k_{2\perp}} + \phi_{k'_{2\perp}}\right)$$
$$+ P_\perp^2\left(M^2 - 2P_\perp^2\right)\cos\left(\phi_{k_{1\perp}} - \phi_{k'_{1\perp}} + \phi_{k_{2\perp}} - \phi_{k'_{2\perp}}\right)\Big], \tag{3}$$

$$A_2 = \int [d\mathcal{K}_\perp] \frac{8m^2P_\perp^2}{\left(P_\perp^2 + m^2\right)^2}\cos\left(\phi_{k_{1\perp}} - \phi_{k_{2\perp}}\right)\cos\left(\phi_{k'_{1\perp}} + \phi_{k'_{2\perp}} - 2\phi\right), \tag{4}$$

$$A_4 = \int [d\mathcal{K}_\perp] \frac{-2P_\perp^4}{\left(P_\perp^2 + m^2\right)^2}\cos\left(\phi_{k_{1\perp}} + \phi_{k'_{1\perp}} + \phi_{k_{2\perp}} + \phi_{k'_{2\perp}} - 4\phi\right). \tag{5}$$

Resummed cross section

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

Soft function

$$S(l_\perp, m, M) = \sum_{i,j} \int \frac{d^d k}{(2\pi)^{d-1}} \delta(k^2)\theta(k^0) \frac{e^2 v_i \cdot v_j}{v_i \cdot k\, v_j \cdot k} \times \delta^{(2)}(l_\perp - k_\perp)$$

Massless limit $M \gg m$

$$S(l_\perp) = \delta(l_\perp) + \frac{\alpha_e}{\pi^2 l_\perp^2}\{c_0 + 2c_2 \cos 2\phi_l + 2c_4 \cos 4\phi_l + \ldots\}$$

$$c_0 \approx \ln\frac{M^2}{m^2},\ c_2 \approx \ln\frac{M^2}{m^2} - 4\ln 2 \text{ and } c_4 \approx \ln\frac{M^2}{m^2} - 4$$

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

Y. Hatta, BW. Xiao, F. Yuan, and J. Zhou, 2021 Phys. Rev. Lett

Massive soft function $M \sim m$

S. Catani, M. Grazzini, A. Torre, 2014 Nucl.Phys. B

$$e^{-\mathrm{Sud}(r_\perp)}\left[1 + \frac{\alpha_e}{4\pi}(s_{11} + s_{22} + 2s_{12})\right]$$

ere the one-loop Sudakov factor is given by

$$\mathrm{Sud}(r_\perp) = \frac{\alpha_e}{\pi}\ln\frac{P_\perp^2}{\mu_r^2}\left(1 - \frac{1+\beta^2}{2\beta}\ln\frac{1-\beta}{1+\beta}\right)$$

$$s_{11} = s_{22} = -\frac{4c_r}{\sqrt{c_r^2+1}}\ln\left(\sqrt{c_r^2+1} + c_r\right), \qquad (13)$$

$$s_{12} = -\frac{1+\beta^2}{2\beta}\,\mathrm{sign}(c_r)\left[L_\zeta\left[\zeta(c_r, \alpha_r), \alpha_r\right] - L_\zeta\left[\zeta(-c_r, \alpha_r), \alpha_r\right]\right], \qquad (14)$$

with

$$c_r = \cos\phi_r P_\perp/m, \quad \beta = \sqrt{1 - 4m^2/M^2},$$

$$\alpha_r = \frac{2P_\perp^2 \cos^2\phi_r}{-m^2 + P_\perp^2 + (m^2 + P_\perp^2)\cosh(y_1 - y_2)},$$

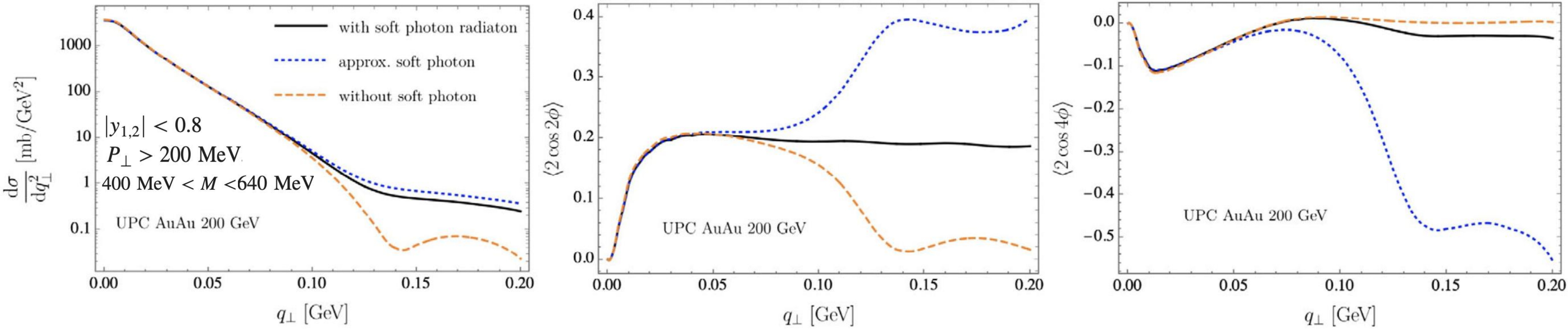
$$\zeta(a,b) = \left(a + \sqrt{1+a^2}\right)\left(a + \sqrt{a^2+b}\right),$$

$$L_\zeta(a,b) = 2\left[-\mathrm{Li}_2\left(\frac{a+b}{b-1}\right) + \mathrm{Li}_2(-a) + \ln(a+b)\ln(1-b)\right] - \ln^2\left(\frac{a}{a+b}\right) + \frac{1}{2}\ln^2\left[\frac{a(a+1)}{a+b}\right].$$

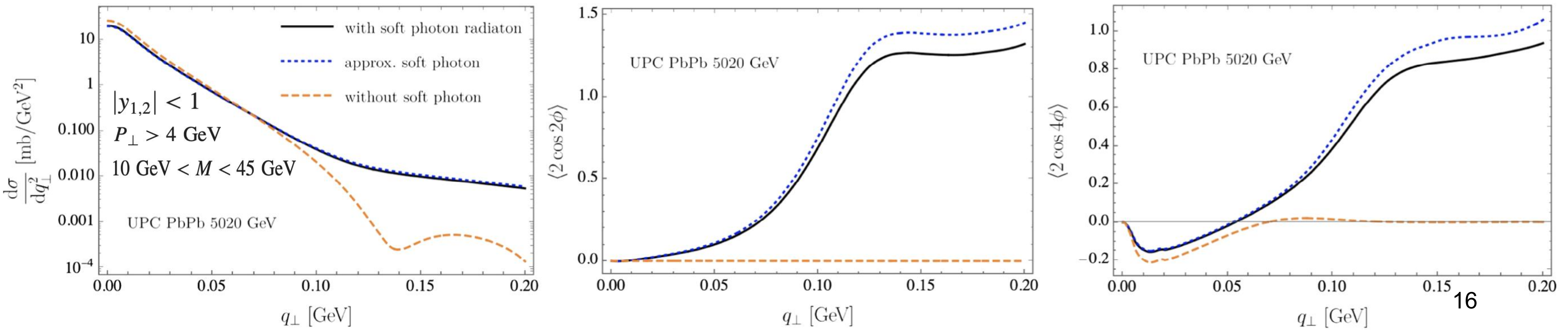
Azimuthal asymmetry

RHIC

D.Y. Shao, C.Z., J. Zhou, Y.j. Zhou, Phys.Rev.D(2023)



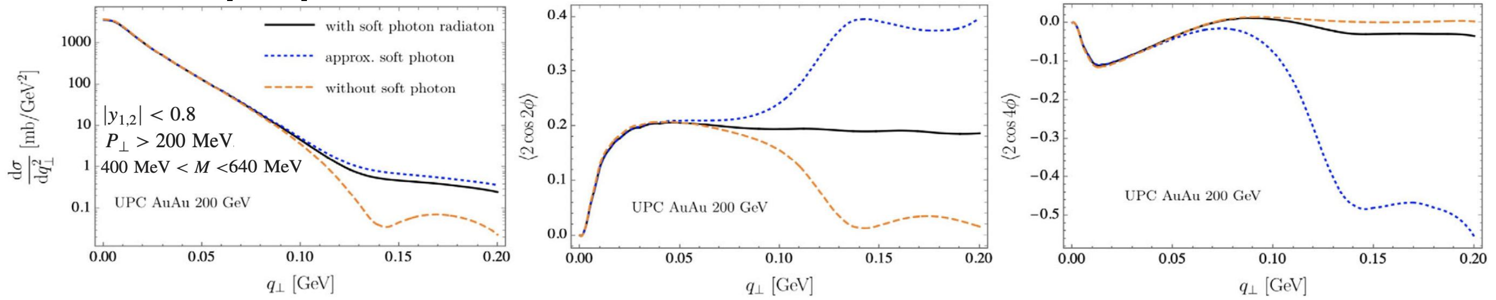
LHC



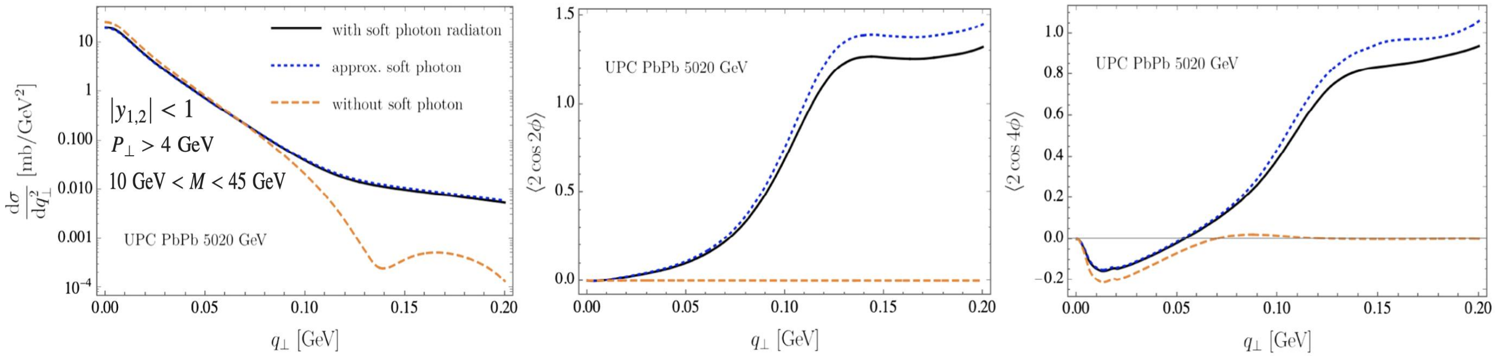
Azimuthal asymmetry

D.Y. Shao, C.Z., J. Zhou, Y.j. Zhou, Phys.Rev.D(2023)

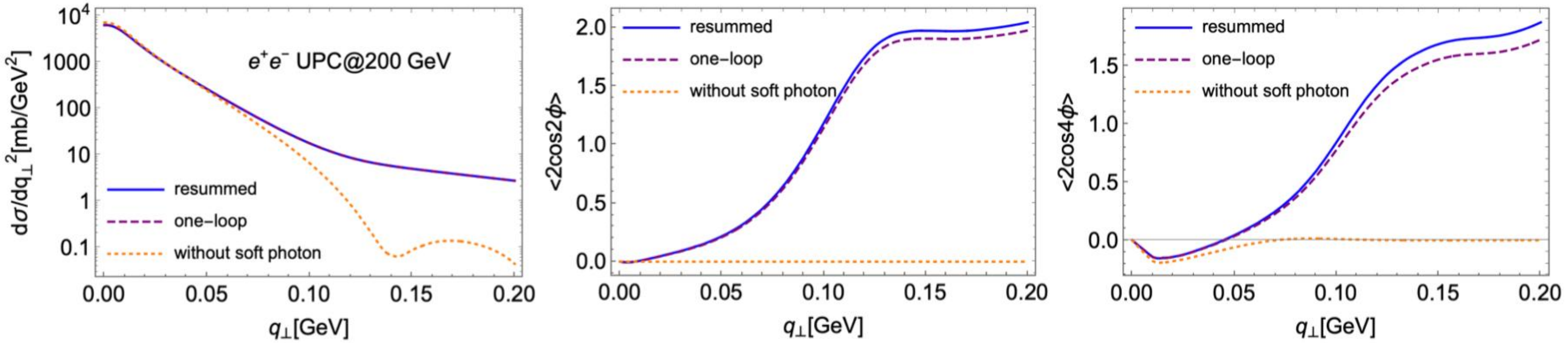
RHIC μ+μ-



LHC μ+μ-



RHIC e+e-



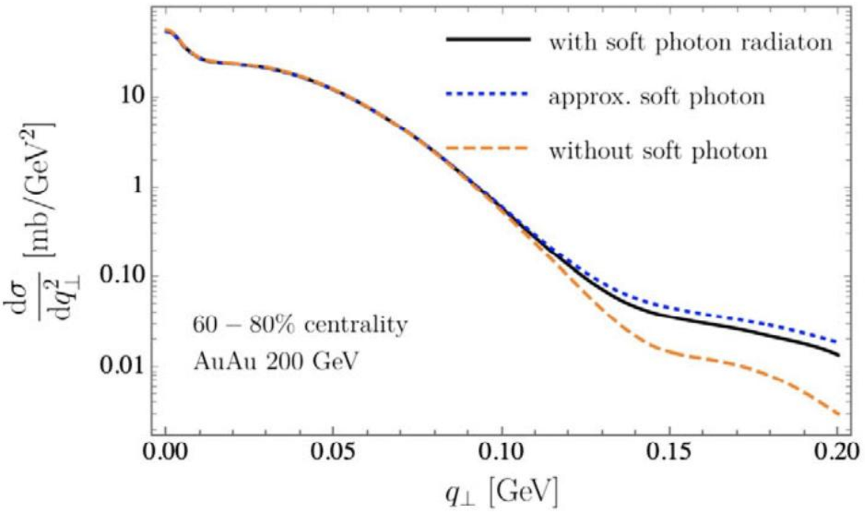
$$\mathrm{Sud}(r_\perp) = \frac{\alpha_e}{\pi}\ln\frac{M^2}{m^2}\ln\frac{P_\perp^2}{\mu_r^2}$$

Summary

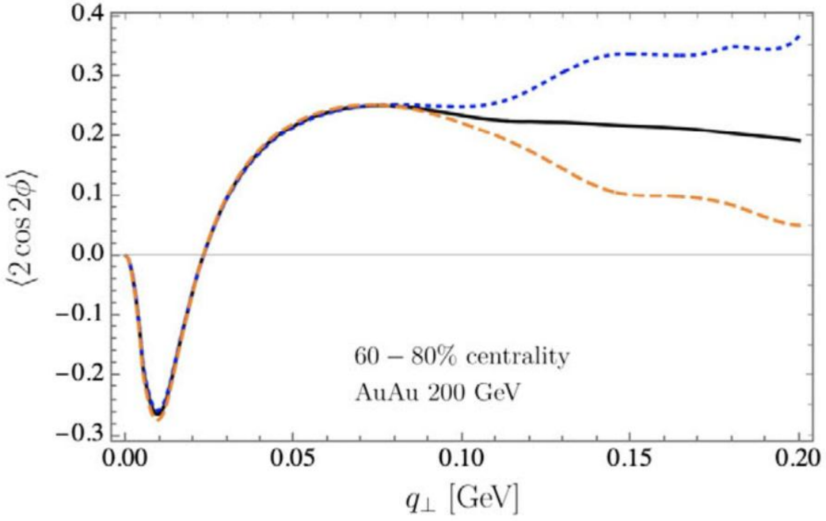
- Dijet productions in UPCs: initial EPA photon & final QCD radiations leads to the factorization and resummation formula at NLL accuracy in SCET. Good agreement with the ATLAS acoplanarity, wider than Pythia8.
- e^+e^- productions: single logarithm accuracy of resummation formula is essential to describe the acoplanarity data from ATLAS and CMS.
- $\mu^+\mu^-$ productions: muon mass corrections to the asymmetries is quite sizable at large $q_\perp$. At low $q_\perp$, the asymmetries are mainly induced by the linearly-polarized coherent photons.

Thanks!

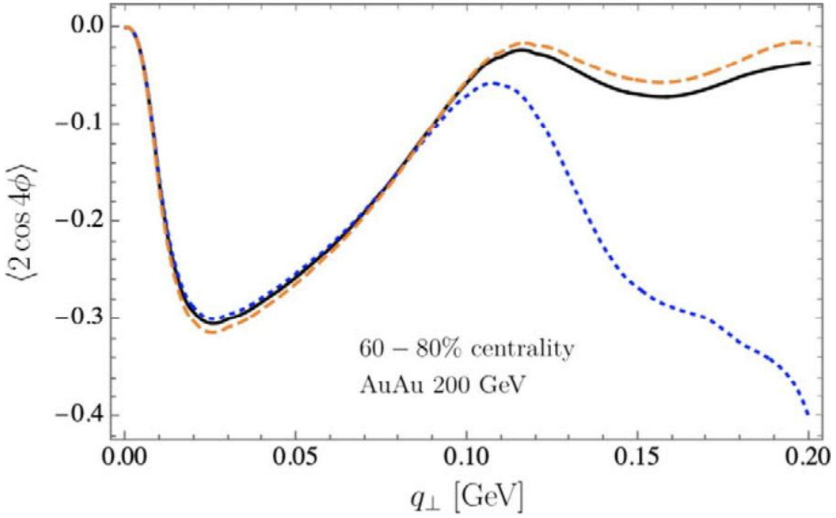
RHIC μ+μ-



with soft photon radiaton
approx. soft photon
without soft photon
60 − 80% centrality
AuAu 200 GeV
$\frac{d\sigma}{dq_\perp^2}$ [mb/GeV^2]
$q_\perp$ [GeV]



60 − 80% centrality
AuAu 200 GeV
$\langle 2\cos 2\phi \rangle$
$q_\perp$ [GeV]



60 − 80% centrality
AuAu 200 GeV
$\langle 2\cos 4\phi \rangle$
$q_\perp$ [GeV]

$$
\begin{aligned}
\tilde{S}(b_x, y_1, y_2, \mu, \nu) &= 1 + 2\, C_F g_s^2 \tilde{\mu}^{2\epsilon} \int \frac{\mathrm{d}^d k}{(2\pi)^{d-1}} \delta(k^2)\theta(k^0) \left(\frac{\nu}{2k^0}\right)^{\eta} \frac{n_1 \cdot n_2}{n_1 \cdot k\, k \cdot n_2} e^{-i b_x k_x} \\
&= 1 + \frac{\alpha_s}{4\pi} C_F \left[-\left(\frac{2}{\eta} + \ln \frac{\nu^2 n_1 \cdot n_2}{2\mu^2}\right)\left(\frac{4}{\epsilon} + 4 \ln \frac{\mu^2 b_x^2}{b_0^2}\right) + \frac{4}{\epsilon^2} - 2 \ln^2 \frac{\mu^2 b_x^2}{b_0^2} - \frac{\pi^2}{3}\right],
\end{aligned}
$$

with $\tilde{\mu}^2 = \mu^2 e^{\gamma_E}/(4\pi)$ and $b_0 = 2e^{-\gamma_E}$. Here the rapidity regulator is given in (3.9).

$$
\begin{aligned}
\tilde{U}_i(b_\perp, y_i, \mu, \nu) &= 1 + 2\, C_F g_s^2 \tilde{\mu}^{2\epsilon} \int \frac{\mathrm{d}^d k}{(2\pi)^{d-1}} \delta(k^2)\theta(k^0) \left(\frac{\nu}{\bar{n}_i \cdot k}\right)^{\eta} \frac{n_i \cdot \bar{n}_i}{n_i \cdot k\, k \cdot \bar{n}_i} \\
&\times \left\{ e^{-i \boldsymbol{b}_\perp \cdot \boldsymbol{k}_\perp} \theta\left[\frac{n_i \cdot k}{\bar{n}_i \cdot k} - \left(\frac{R}{2\cosh y_i}\right)^2\right] + \theta\left[\left(\frac{R}{2\cosh y_i}\right)^2 - \frac{n_i \cdot k}{\bar{n}_i \cdot k}\right]\right\} \\
&= 1 + \frac{\alpha_s}{4\pi} C_F \left[\left(\frac{2}{\eta} + \ln \frac{\nu^2 R^2}{4\mu^2 \cosh^2 y_i}\right)\left(\frac{2}{\epsilon} + 2 \ln \frac{\mu^2 b_\perp^2}{b_0^2}\right) - \frac{2}{\epsilon^2} + \ln^2 \frac{\mu^2 b_\perp^2}{b_0^2} + \frac{\pi^2}{6}\right]
\end{aligned}
$$

$$
\begin{aligned}
&\tilde{S}(b_x, y_1, y_2, \mu, \nu)\tilde{U}_1(b_x, y_1, \mu, \nu)\tilde{U}_2(b_x, y_2, \mu, \nu) \\
&\qquad = 1 + C_F \frac{\alpha_s}{\pi}\left[\ln R^2 - \ln(2 + 2\cosh \Delta y)\right]\left(\frac{1}{\epsilon} + \ln \frac{b_x^2 \mu^2}{b_0^2}\right) + \mathcal{O}(\alpha_s^2)
\end{aligned}
$$

$$J^{\rm NLO}(m,\mu) = 1 + \frac{\alpha_e}{4\pi}\left[\frac{2}{\epsilon^2} + \frac{1}{\epsilon}\left(1 + 2\ln\frac{\mu^2}{m^2}\right) + \left(1 + \ln\frac{\mu^2}{m^2}\right)\ln\frac{\mu^2}{m^2} + 4 + \frac{\pi^2}{6}\right]$$

anomalous dimension associated with this jet function is given by

$$\Gamma_J = \frac{\alpha_e}{4\pi}\left(4\ln\frac{\mu^2}{m^2} + 2\right).$$

$$S_{n_i}(x) = \exp\left[-ie\int_{-\infty}^{0} ds n_i\cdot A\,(x + sn_i)\right],$$

ibe a point-like source traveling along the path $x^\mu + sn_i^\mu$ with the light-like vect
soft function

$$\tilde{S}(r_\perp,\Delta y) = \langle 0|\bar{\rm T}\left[S_{n_1}^\dagger(r_\perp)S_{n_2}(r_\perp)\right]{\rm T}\left[S_{n_2}^\dagger(0)S_{n_1}(0)\right]|0\rangle,$$

denote the directions of finial-state leptons. Expanding the Wilson line in the co
ft function is obtained as

$$\tilde{S}^{\rm NLO}(r_\perp,\Delta y) = 1 + e_0^2\int\frac{d^dk}{(2\pi)^{d-1}}\delta(k^2)\theta(k^0)\frac{2n_1\cdot n_2}{n_1\cdot k\,k\cdot n_2}e^{ik_\perp\cdot r_\perp},$$

the bare electric charge, and k is the momentum of the final-state photon. N
momentum with the beam directions which is different from the direction of
integral, we obtain

$$\tilde{S}^{\rm NLO}(r_\perp,\Delta y) = 1 + \frac{\alpha_e}{4\pi}\left[\frac{4}{\epsilon^2} + \frac{4}{\epsilon}\ln\frac{\mu^2 r_\perp^2}{b_0^2 A_r} + 2\ln^2\frac{\mu^2 r_\perp^2}{b_0^2 A_r} + \pi^2 - 4\ln A_r\ln(1-A_r)\right.$$

$$A_r = M^2/(4P_\perp^2\cos^2\phi_r)$$

$$\Gamma_S = \frac{\alpha_e}{4\pi}\left(8\ln\frac{\mu^2 r_\perp^2}{b_0^2} + 8\ln\cos^2\phi_r - 8\ln\frac{1+\cosh\Delta y}{2}\right)$$

$$\tilde{C}_i(r_\perp,P_\perp,y_i,m) = \langle 0|\bar{\rm T}[S_{v_i}^\dagger(r_\perp)S_{\bar{n}_i}(r_\perp)]{\rm T}[S_{\bar{n}_i}^\dagger(0)S_{v_i}(0)]|0\rangle,$$

the soft Wilson line S_{v_i} is defined in analogy with S_{n_i} in Eq. (13), but with the lig
he time-like vector v_i, which is

$$v_i^\mu = \frac{\omega_i}{m}\frac{n_i^\mu}{2} + \frac{m}{\omega_i}\frac{\bar{n}_i^\mu}{2},\quad \text{with } \omega_i = 2P_\perp\cosh y_i.$$

loop, the perturbative expansion of colliear-soft function gives us

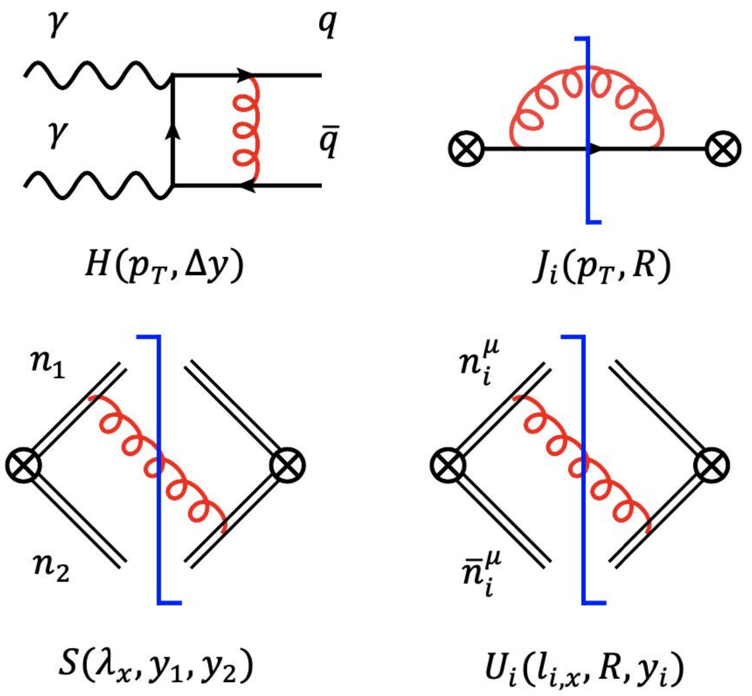
$$\tilde{C}_i^{\rm NLO}(r_\perp,P_\perp,y_i,m) = 1 + e_0^2\int\frac{d^dk}{(2\pi)^{d-1}}\delta(k^2)\theta(k^0)\left(\frac{2v_i\cdot\bar{n}_i}{v_i\cdot k\,k\cdot\bar{n}_i} - \frac{v_i\cdot v_i}{v_i\cdot k\,k\cdot v_i}\right)$$

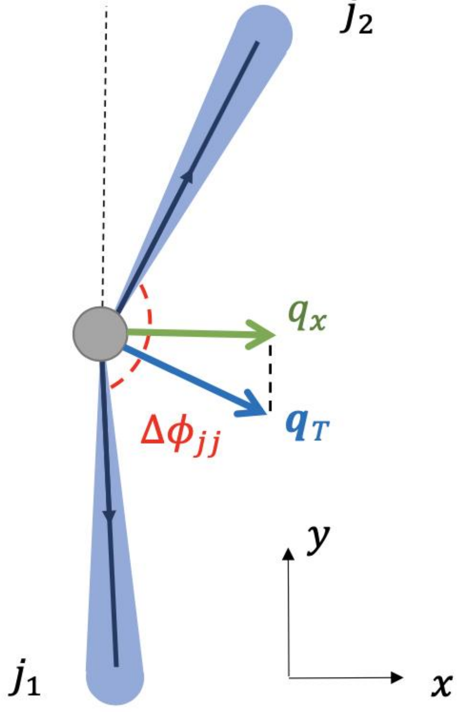
e obtain

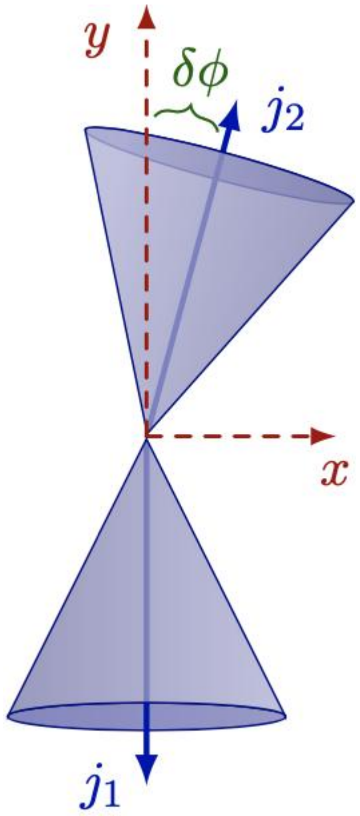
$$\tilde{C}_i^{\rm NLO}(r_\perp,P_\perp,y_i,m) = 1 + \frac{\alpha_e}{4\pi}\left[-\frac{2}{\epsilon^2} + \frac{2}{\epsilon}(1 - 2\ln\mu R) - 4\ln^2\mu R + 4\ln\mu R\right.$$

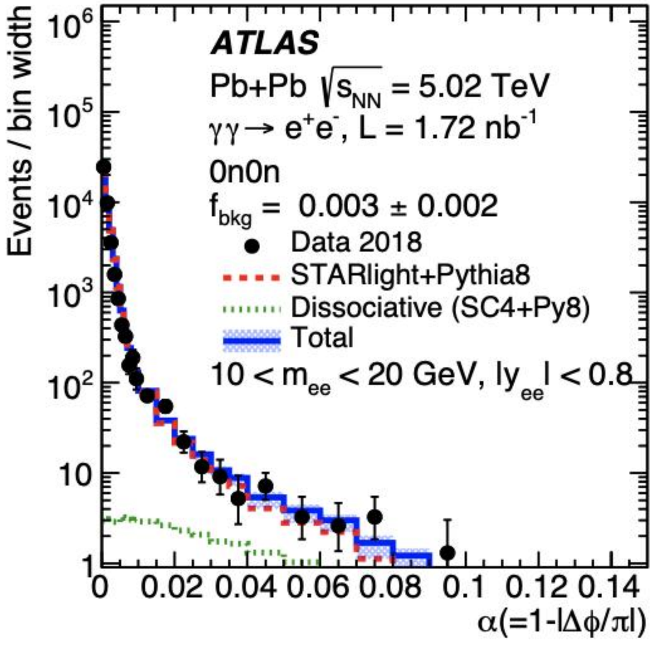
$R = -iP_\perp e^{\gamma_E}n_i\cdot r_\perp/(m\,r_\perp)$, and the anomalous dimension is

$$\Gamma_{C_{1,2}} = \frac{\alpha_e}{4\pi}\left(-4\ln\frac{4P_\perp^2\mu^2 r_\perp^2}{b_0^2 m^2} + 4 - 4\ln\cos^2\phi_r \pm 4i\pi\right).$$


γ
q
γ
q̄
H(p_T, Δy)
J_i(p_T, R)
n_1
n_2
S(λ_x, y_1, y_2)
n_i^μ
n̄_i^μ
U_i(l_{i,x}, R, y_i)


j_2
q_x
Δφ_jj
q_T
y
x
j_1


y
δφ
j_2
x
j_1


ATLAS
Pb+Pb √s_NN = 5.02 TeV
γγ→ e⁺e⁻, L = 1.72 nb⁻¹
0n0n
f_bkg = 0.003 ± 0.002
Data 2018
STARlight+Pythia8
Dissociative (SC4+Py8)
Total
10 < m_ee < 20 GeV, |y_ee| < 0.8
Events / bin width
α(=1-|Δφ/π|)

$$\frac{d\sigma}{d^2k_{1\perp}d^2k_{2\perp}dy_1dy_2d^2\tilde{b}_\perp} = \frac{2N_c\alpha_e e_q^2}{(2\pi)^2}\int d^2\Delta_\perp d^2k_\perp d^2k'_\perp \delta^2(k_\perp + \Delta_\perp - l_\perp)\int d^2q_\perp d^2q'_\perp$$
$$\times 2z(1-z)[z^2+(1-z)^2]\left[\left(\frac{\vec{P}_\perp}{P_\perp^2+e_f^2} - \frac{\vec{P}_\perp - \vec{q}_\perp}{(P_\perp - q_\perp)^2 + e_f^2}\right)\cdot \hat{k}_\perp\right]\cdot\left[\left(\frac{\vec{P}_\perp}{P_\perp^2+e_f^2} - \frac{\vec{P}_\perp - \vec{q}'_\perp}{(P_\perp - q'_\perp)^2 + e_f^2}\right)\cdot \hat{k}'_\perp\right]$$
$$\left\{\left[e^{i\tilde{b}_\perp\cdot(k'_\perp - k_\perp)}G(Y,q_\perp,\Delta_\perp)G(Y,q'_\perp,\Delta'_\perp)\mathcal{F}(Y,k_\perp)\mathcal{F}(Y,k'_\perp)\right]\right.$$
$$+\left[e^{i\tilde{b}_\perp\cdot(\Delta'_\perp - \Delta_\perp)}G(-Y,q_\perp,\Delta_\perp)G(-Y,q'_\perp,\Delta'_\perp)\mathcal{F}(-Y,k_\perp)\mathcal{F}(-Y,k'_\perp)\right]$$
$$+\left[e^{i\tilde{b}_\perp\cdot(\Delta'_\perp - k_\perp)}G(Y,q_\perp,\Delta_\perp)G(-Y,q'_\perp,\Delta'_\perp)\mathcal{F}(Y,k_\perp)\mathcal{F}(-Y,k'_\perp)\right]$$
$$\left.+\left[e^{i\tilde{b}_\perp\cdot(k'_\perp - \Delta_\perp)}G(-Y,q_\perp,\Delta_\perp)G(Y,q_\perp,\Delta'_\perp)\mathcal{F}(-Y,k_\perp)\mathcal{F}(Y,k'_\perp)\right]\right\},$$

The gluon distribution is given by,

$$G(q_\perp,\Delta_\perp) = \int \frac{d^2r_\perp}{(2\pi)^2}\frac{d^2b_\perp}{(2\pi)^2}e^{-iq_\perp\cdot r_\perp - i\Delta_\perp\cdot b_\perp}\frac{1}{N_c}\mathrm{Tr}\left[U(b_\perp + \frac{r_\perp}{2})U^\dagger(b_\perp - \frac{r_\perp}{2})\right]$$

Spencer Klein, A. H. Mueller, Bo-Wen Xiao, and Feng Yuan, 2019 Phys.Rev.Lett