CGC for ultra-peripheral Pb+Pb collisions at the Large Hadron Collider

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Based on JHEP 12 (2022) 077, with Alex Kovner and Vladi Skokov

Intersection of nuclear structure and high-energy nuclear collisions
Institute for Nuclear Theory, 2023

Supported by DOE

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Ridge correlation in UPC

Two particle angular correlation observed in UPC measurement at LHC

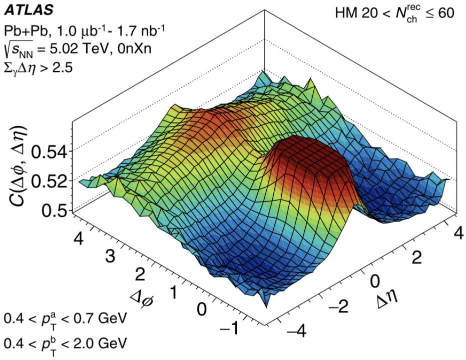

Figure: PHYSICAL REVIEW C 104, 014903 (2021), ATLAS

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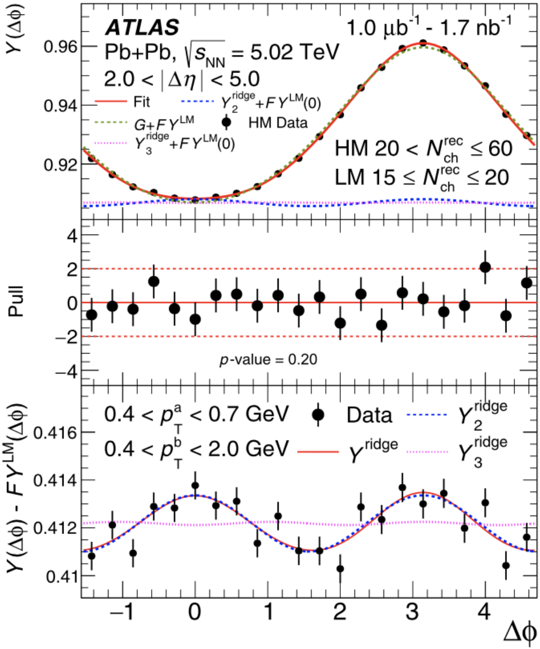
A demonstration of the signal and background



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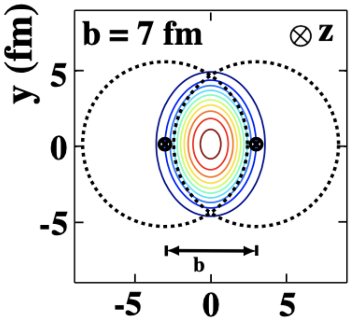
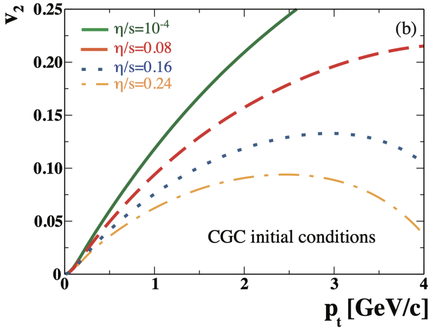
Elliptic flow



(a) Peripheral collision for AA



(b) $v_2 \to$ viscosity

Small viscosity η/s leads to higher v_2. (Figures from Raimond Snellings (2011))

$$\frac{dN}{dq_1^2 dq_2^2} \propto 1 + \sum_n 2v_n^2 \cos(n\Delta\theta)$$

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Ridge correlation in small systems ?

- If ridge correlation indicates fluid behavior, what is the smallest collision system to create QGP?
  - High multiplicity p+p (2010), p+Pb (2012) at LHC
  - p+Au, d+Au, ^{3}He+Au at RHIC (2013-2020)

- Is there additional origin of the ridge correlation?
  - Opportunities to probe novel effects

- The smallest projectile is DIS photon!

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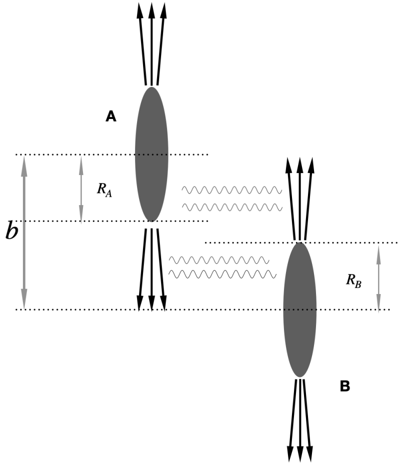
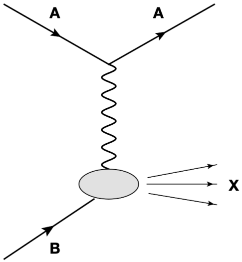
Ultra-peripheral collisions



- $b > R_A + R_B$
- Equivalent photon approximation
- Weizsäcker-Williams field
- Photon-nuclear interaction



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Non-perturbative photon

- Photon emitted by the nucleus coherently

- Resolution bounded by nucleus size

$$\frac{1}{Q} \gtrsim R_A$$

- For $A > 16$

$$Q^2 \lesssim (60Mev)^2$$

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Origins of the angular correlation in UPC

- Hydrodynamic

Collectivity in Ultra-Peripheral Pb+Pb Collisions at the Large Hadron Collider

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- Color domain effect in the target

Exploring the Collective Phenomenon at the Electron-Ion Collider

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- Quantum correlations (explored in our work)
  - Bose-Einstein correlation
  - HBT(Hanbury Brown and Twiss) effect
  - Dominated by the correlations in projectile

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Bose enhancement

Two particle correlator in a free boson gas,

$$D(\boldsymbol{x},\boldsymbol{y}) = \int_{\boldsymbol{p},\boldsymbol{p}',\boldsymbol{q},\boldsymbol{q}'} e^{-i\boldsymbol{x}\cdot(\boldsymbol{p}'-\boldsymbol{p})} e^{-i\boldsymbol{y}\cdot(\boldsymbol{q}'-\boldsymbol{q})} \langle \hat{a}^{\dagger}_a(\boldsymbol{p})\hat{a}^{\dagger}_b(\boldsymbol{q})\hat{a}_a(\boldsymbol{p}')\hat{a}_b(\boldsymbol{q}')\rangle$$

There are three different scenarios

- $\boldsymbol{p}=\boldsymbol{p}'$, $\boldsymbol{q}=\boldsymbol{q}'$: $\langle \hat{a}^{\dagger}_a(\boldsymbol{p})\hat{a}^{\dagger}_b(\boldsymbol{q})\hat{a}_a(\boldsymbol{p}')\hat{a}_b(\boldsymbol{q}')\rangle$, uncorrelated, $\mathcal{O}(1)$
- $\boldsymbol{p}=\boldsymbol{q}'$, $\boldsymbol{q}=\boldsymbol{p}'$: $\langle \hat{a}^{\dagger}_a(\boldsymbol{p})\hat{a}^{\dagger}_b(\boldsymbol{q})\hat{a}_a(\boldsymbol{p}')\hat{a}_b(\boldsymbol{q}')\rangle$, $\mathcal{O}(\frac{1}{N_c^2})$
- $\boldsymbol{p}=\boldsymbol{q}'=\boldsymbol{q}=\boldsymbol{p}'$, suppressed by $\frac{1}{N_c^2}$ and $\frac{1}{V}$

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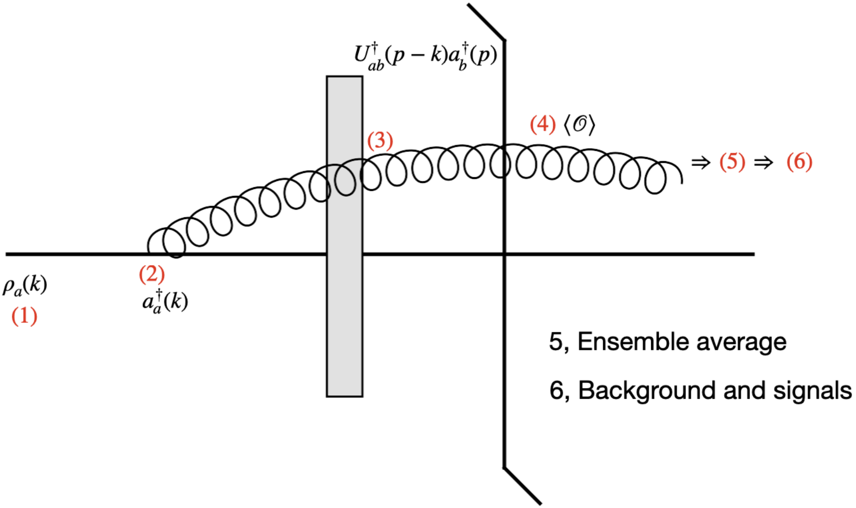
HBT

$$D_{\mathrm{HBT}}(\boldsymbol{k}_1, \boldsymbol{k}_2) = \sum_{a,b} \int_{\boldsymbol{x}_0, \boldsymbol{x}'_0, \boldsymbol{y}_0, \boldsymbol{y}'_0} \int_{\boldsymbol{x}_1, \boldsymbol{x}'_2, \boldsymbol{y}_3, \boldsymbol{y}'_4} e^{i\boldsymbol{k}_1 \cdot (\boldsymbol{x}'_0 - \boldsymbol{x}_0)} e^{i\boldsymbol{k}_2 \cdot (\boldsymbol{y}'_0 - \boldsymbol{y}_0)}$$
$$\times \langle \hat{a}^\dagger_a(\boldsymbol{x}_0) \hat{a}^\dagger_b(\boldsymbol{y}_0) \hat{a}_a(\boldsymbol{x}'_0) \hat{a}_b(\boldsymbol{y}'_0) \rangle$$
$$\times G(\boldsymbol{x}_0 - \boldsymbol{x}_1) G(\boldsymbol{y}_0 - \boldsymbol{y}_1) G(\boldsymbol{x}'_0 - \boldsymbol{x}'_1) G(\boldsymbol{y}'_0 - \boldsymbol{y}'_1)$$
$$\times \langle J_a(\boldsymbol{x}_1) J_b(\boldsymbol{y}_1) J_a(\boldsymbol{x}'_1) J_b(\boldsymbol{y}'_1) \rangle$$

- The "wrong" contraction is enforced by the ensemble average of the source correlator

$$\langle J_a(\boldsymbol{x}_1) J_b(\boldsymbol{y}_1) J_a(\boldsymbol{x}'_1) J_b(\boldsymbol{y}'_1) \rangle$$

Theoretical set-up



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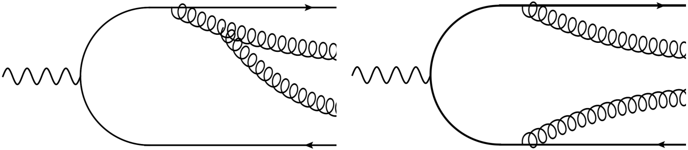
Dipole model ($|Q| < \Lambda_{QCD}$)



- Dipole model to approximate the photon
  Small Q^2 suppresses the longitudinal polarization

$$\Psi^T_\lambda(z,\boldsymbol{r},s_1) = -i\frac{2ee_f}{2\pi}\delta_{s_1,-s_2}(2z-1+2\lambda s_1)\sqrt{z(1-z)}\frac{\boldsymbol{r}\cdot\boldsymbol{\epsilon_\lambda}}{|r|}\varepsilon_f K_1(\varepsilon_f|r|)$$

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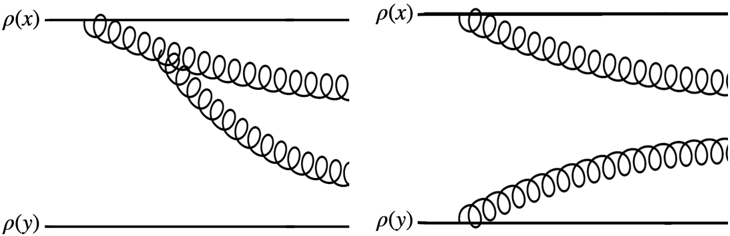
MV model



- Inspired by Vector Meson Dominance Model
- Due to the existence of the high energy fixed point, ρ-meson at asymptotically high energy $\equiv$ nucleus
- Valence degrees of freedom $\rho_a(\boldsymbol{x})$ follow the distribution defined by McLerran-Venugopalan (MV) model

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$$W(\rho_a) = \exp\left\{-\int_{\boldsymbol{x}} \frac{\rho_a(\boldsymbol{x})\rho_a(\boldsymbol{x})}{2\mu^2}\right\}$$

Gluon production

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Create gluons within initial states

One account for the emission of the gluons using coherent operators

$$C = \mathcal{P} e^{i\sqrt{2}\int d^2x d\xi\, \hat{b}^i_a(\xi,\boldsymbol{x})\left[a^\dagger_{i,a}(\xi,\boldsymbol{x}) + a_{i,a}(\xi,\boldsymbol{x})\right]}$$

with the background field

$$\hat{b}^i_a(\xi,\boldsymbol{x}) = \frac{g}{2\pi}\int d^2y \frac{(\boldsymbol{x}-\boldsymbol{y})^i}{|\boldsymbol{x}-\boldsymbol{y}|^2}\hat{\rho}^a_{\mathrm{P}}(\xi,\boldsymbol{y})$$

- MV model classical source ρ_a
- $\hat{\rho}^a_D(\boldsymbol{x}) = b^\dagger_{\alpha\sigma}(\boldsymbol{x_1})t^a_{\alpha\beta}b_{\beta\sigma}(\boldsymbol{x_1})\delta^{(2)}(\boldsymbol{x}-\boldsymbol{x_1}) - d^\dagger_{\alpha\sigma}(\boldsymbol{x_2})t^a_{\beta\alpha}d_{\beta\sigma}(\boldsymbol{x_2})\delta^{(2)}(\boldsymbol{x}-\boldsymbol{x_2})$
- $\hat{\rho}^a_g(\zeta,\boldsymbol{x}) = a^{i\dagger}_b(\eta,\boldsymbol{x})T^a_{bc}a_c(\eta,\boldsymbol{x})$

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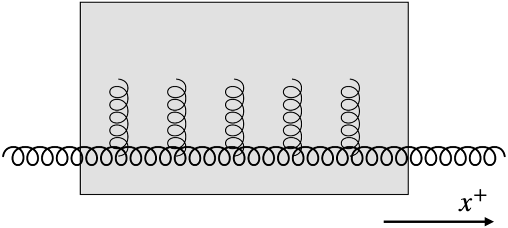
Eikonal scattering through the shock wave



$$U(\boldsymbol{x}) = \mathcal{P}\exp\left\{ig\int_{-\infty}^{\infty} dx^+ T^a A_a^-(x^+, \boldsymbol{x})\right\}$$

The strong gluon field $A_a^-(x^+, \boldsymbol{x})$ is a functional of the valance source in the target.

$$\frac{1}{N_c^2-1}\langle \mathrm{Tr}\Big(U^\dagger(r)U(0)\Big)\rangle_T = \exp\left[-\frac{1}{4}Q_s^2 r^2 \ln\left(\frac{1}{\Lambda^2 r^2}+e\right)\right].$$

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The cross section

$$\frac{d\mathcal{N}}{d\eta dq_1^2 d\xi dq_2^2} = \frac{1}{(2\pi)^4}\int d^2u_1 d^2u_2 d^2\bar{u}_1 d^2\bar{u}_2 e^{-i\boldsymbol{q}_1(\boldsymbol{u}_1-\bar{\boldsymbol{u}}_1)} e^{-i\boldsymbol{q}_2(\boldsymbol{u}_2-\bar{\boldsymbol{u}}_2)}\,\Sigma$$

and

$$\Sigma = \langle\gamma^*|C^\dagger\hat{S}^\dagger C a^\dagger_{i,a}(\eta,\boldsymbol{u}_1)a^\dagger_{j,b}(\xi,\boldsymbol{u}_2)a_{i,a}(\eta,\bar{\boldsymbol{u}}_1)a_{j,b}(\xi,\bar{\boldsymbol{u}}_2)C^\dagger\hat{S}C|\gamma^*\rangle$$

where $C = C_\xi C_\eta$, and $\eta \gg \xi$,

$$C_\eta \simeq 1 + i\sqrt{2}\int d^2v_1 \hat{b}^i_{Da}(\boldsymbol{v}_1)\left[a^{i\dagger}_a(\eta,\boldsymbol{v}_1) + a^i_a(\eta,\boldsymbol{v}_1)\right]$$

$$C_\xi \simeq 1 + i\sqrt{2}\int d^2v_2 \left(\hat{b}^j_{Db}(\boldsymbol{v}_2) + \delta\hat{b}^j_b(\eta,\boldsymbol{v}_2)\right)\left[a^{j\dagger}_b(\xi,\boldsymbol{v}_2) + a^j_b(\xi,\boldsymbol{v}_2)\right]$$

- $C|\gamma^*\rangle$ Initial state
- $\hat{S}$ S-matrix
- $Ca_{j,b}(\xi,\bar{\boldsymbol{u}}_2)C^\dagger$ dressed gluons in the final state

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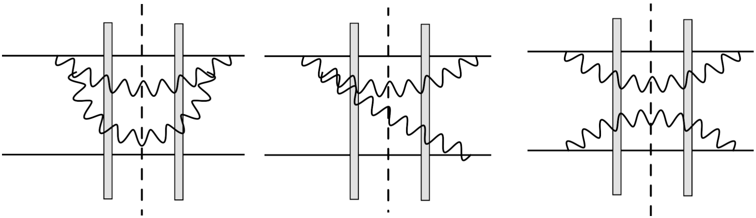
Organize the cross section

Organize the cross section Σ according to the order of ρ

$$\Sigma = \Sigma_2 + \Sigma_3 + \Sigma_4$$



(a) $\Sigma_2(\rho^2)$ (b) $\Sigma_3(\rho^3)$ (c) $\Sigma_4(\rho^4)$

Continue the calculation of Σ

Use Σ_2 as example, in coordinate space,

$$\Sigma_2 = 4\int d^2\boldsymbol{x}\int d^2\bar{\boldsymbol{x}} f^i(\bar{u}_1 - \boldsymbol{x}) f^i(u_1 - \bar{\boldsymbol{x}}) f^j(\bar{u}_2 - \bar{u}_1) f^j(u_2 - u_1) \langle \rho_{d'}(\bar{\boldsymbol{x}})\rho_d(\boldsymbol{x})\rangle_P$$
$$\left\langle \left[[U^\dagger(u_1)T^a U(u_1)][U^\dagger(u_2) - U^\dagger(u_1)][U(\bar{u}_2) - U(\bar{u}_1)][U^\dagger(\bar{u}_1)T^a U(\bar{u}_1)] \right]_{d'd} \right\rangle_T$$

where $f^i(\boldsymbol{x}) = \frac{g}{(2\pi)^2}\frac{x_i}{x^2}$.

- Kinematic factors (Eikonal emission vertices)
- Projectile (photon)
- Target (nucleus)

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Expectation values for projectile and target

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Dipole expectation values

- Expectation values for $q\bar{q}$

$$\langle q\bar{q}|\hat{\rho}_{d'}(\bar{\boldsymbol{x}})\hat{\rho}_d(\boldsymbol{x})|q\bar{q}\rangle = \frac{\delta^{dd'}}{2}\left(\delta^2(\bar{\boldsymbol{x}}-\boldsymbol{z}_1)-\delta^2(\bar{\boldsymbol{x}}-\boldsymbol{z}_2)\right)\left(\delta^2(\boldsymbol{x}-\boldsymbol{z}_1)-\delta^2(\boldsymbol{x}-\boldsymbol{z}_2)\right)$$

$$\begin{aligned}&\langle q\bar{q}|\hat{\rho}^a(\boldsymbol{x_1})\hat{\rho}^b(\boldsymbol{x_2})\hat{\rho}^c(\boldsymbol{x_3})|q\bar{q}\rangle\\ =&\frac{if_{abc}}{4}\left(\delta^{(2)}(\boldsymbol{x_2}-\boldsymbol{z_1})+\delta^{(2)}(\boldsymbol{x_2}-\boldsymbol{z_2})\right)\prod_{i=1,3}\left(\delta^{(2)}(\boldsymbol{x_i}-\boldsymbol{z_1})-\delta^{(2)}(\boldsymbol{x_i}-\boldsymbol{z_2})\right)\end{aligned}$$

$\boldsymbol{z}_1, \boldsymbol{z}_2$ are the transverse coordinates of quark and anti-quark.

- Average over different dipole size $\boldsymbol{r} = \boldsymbol{z}_1 - \boldsymbol{z}_2$

$$\langle \rho_{d'}(\bar{\boldsymbol{x}})\rho_d(\boldsymbol{x})\rangle_P \approx \sum_{s_1}\int_z\int d^2\boldsymbol{r}\Psi_\lambda^{T*}(z,r,s_1)\Psi_\lambda^T(z,r,s_1)\langle q\bar{q}|\rho_{d'}(\bar{\boldsymbol{x}})\rho_d(\boldsymbol{x})|q\bar{q}\rangle$$

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MV model projectile average

- MV model describes the distribution of classical color source not quantum operators.

$$W(\rho_a) = \exp\left\{-\int_{\boldsymbol{x}} \frac{\rho_a(\boldsymbol{x})\rho_a(\boldsymbol{x})}{2\mu^2}\right\}$$

-

$$\mu^2(\boldsymbol{x}) = \mathcal{N}\exp\left\{-\frac{\boldsymbol{x}^2}{R^2}\right\}.$$

- Two and three point correlators

$$\langle\hat{\rho}_a(\boldsymbol{x})\hat{\rho}_b(\boldsymbol{y})\rangle_{\mathrm{MV}} = \langle\rho_a(\boldsymbol{x})\rho_b(\boldsymbol{y})\rangle_{\mathrm{MV}} = \mu^2\delta^{(2)}(\boldsymbol{x}-\boldsymbol{y})\delta_{ab}$$
$$\langle\hat{\rho}_a(\boldsymbol{x})\hat{\rho}_b(\boldsymbol{y})\hat{\rho}_c(\boldsymbol{z})\rangle_{\mathrm{MV}} = -\frac{1}{2}\delta^{(2)}(\boldsymbol{x}-\boldsymbol{y})\delta^{(2)}(\boldsymbol{y}-\boldsymbol{z})T^a_{bc}\,\mu^2$$

- Symmetrization of $\hat{\rho}s$

$$\hat{\rho}_a(x)\hat{\rho}_b(y) = \frac{1}{2}\left\{\hat{\rho}_a(\boldsymbol{x}),\hat{\rho}_b(\boldsymbol{y})\right\} + \frac{1}{2}\left[\hat{\rho}_a(\boldsymbol{x}),\hat{\rho}_b(\boldsymbol{y})\right]$$
$$= \rho_a(\boldsymbol{x})\rho_b(\boldsymbol{y}) - \frac{1}{2}\delta^{(2)}(x-y)T^c_{ab}\rho_c(\boldsymbol{x})$$

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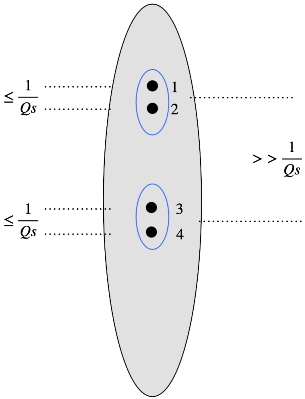
Target average(I)



- Factorized Dipole Approximation

  Phys. Rev. D 96, 074018, Kovner, Rezaeian

- Dense target $\rightarrow$ Saturated

- $\frac{1}{Q_s}$ serves the role of correlation length in transverse plane

- For the example configuration

  $\mathrm{Tr}\left[U(x_1)U^\dagger(x_2)U(x_3)U^\dagger(x_4)\right]$

  $\approx$

  $\frac{1}{N_c^2-1}\,\mathrm{Tr}\left[U(x_1)U^\dagger(x_2)\right]\,\mathrm{Tr}\left[U(x_3)U^\dagger(x_4)\right]+$

  ...

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Target average (II)

We only have one type of Wilson line correlator in momentum space

$$
\begin{aligned}
&\left\langle \mathrm{Tr}\left[U(k_1)T^a U^\dagger(k_2)U(k_3)T^a U^\dagger(k_4)\right]\right\rangle_T \\
=&T^a_{bc}T^a_{de}\left\langle\left[U^{fb}(k_1)U^{\dagger cg}(k_2)U^{gd}(k_3)U^{\dagger ef}(k_4)\right]\right\rangle_T \\
\approx&T^a_{bc}T^a_{de}(\frac{(2\pi)^2}{N_c^2-1})^2\Big\{(N_c^2-1)\delta^{bc}\delta^{de}\delta^{(2)}(k_1-k_2)D(k_1)\delta^{(2)}(k_3-k_4)D(k_3) \\
&+(N_c^2-1)\delta^{bd}\delta^{ce}\delta^{(2)}(k_1+k_3)D(k_1)\delta^{(2)}(k_2+k_4)D(-k_2) \\
&+(N_c^2-1)^2\delta^{be}\delta^{cd}\delta^{(2)}(k_1-k_4)D(k_1)\delta^{(2)}(k_2-k_3)D(-k_2)\Big\}
\end{aligned}
$$

here the dipole $D(p)$ is defined as

$$
D(p)=\frac{1}{N_c^2-1}\int dx^2 e^{ipx}\langle \mathrm{Tr}\Big(U^\dagger(x)U(0)\Big)\rangle_T
$$

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Isolating the signal

- Symmetrization of $\hat{\rho}s$ (MV model)

$$\hat{\rho}_a(\boldsymbol{x})\hat{\rho}_b(\boldsymbol{y}) = \frac{1}{2}\left\{\hat{\rho}_a(\boldsymbol{x}), \hat{\rho}_b(\boldsymbol{y})\right\} + \frac{1}{2}\left[\hat{\rho}_a(\boldsymbol{x}), \hat{\rho}_b(\boldsymbol{y})\right]$$
$$= \rho_a(\boldsymbol{x})\rho_b(\boldsymbol{y}) - \frac{1}{2}\delta^{(2)}(x-y)T^c_{ab}\rho_c(\boldsymbol{x})$$

- Symmetrization of color factors (Dipole model)

$$t^a t^b = \frac{1}{2}\left\{t^a, t^b\right\} + \frac{1}{2} i f^c_{ab} t^c$$

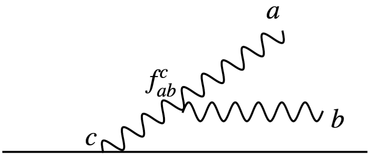

Figure: The color structure for the correction term

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Angular correlation from the cross section

From the cross section of the two gluon production

$$\Sigma = \frac{d\mathcal{N}}{d\eta dq_1^2 d\xi dq_2^2}$$

one can extract the angular correlation function

$$C(q,\theta) = \frac{\Sigma(q,\theta)}{\frac{1}{2\pi}\int_0^{2\pi}\Sigma(q,\theta)d\theta}$$

set $|q_1| = |q_2| = q$, and θ is the angle between the two particles

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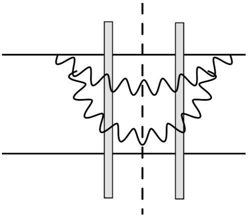
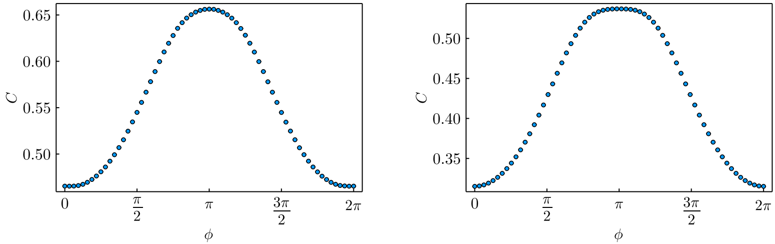
$\Sigma_2,\ q = Q_s$





(a) Dipole (b) MV

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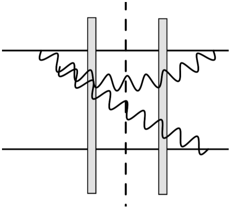
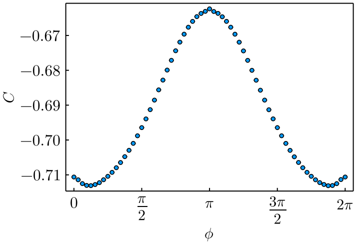
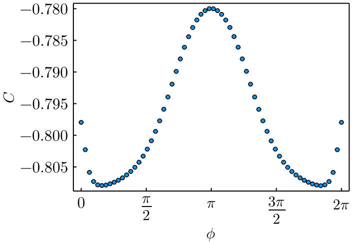
As expected, a strong back-to-back correlation.

$\Sigma_3,\ q = Q_s$





(a) Dipole



(b) MV

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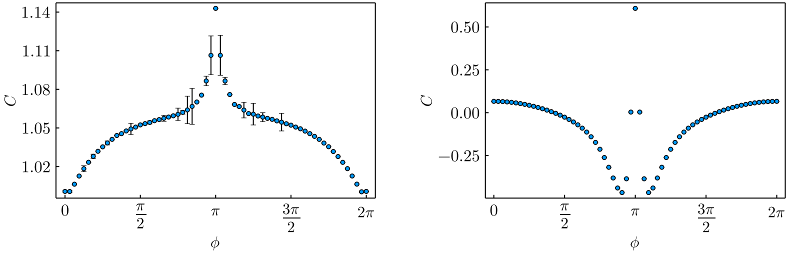
Back-to-back correlation

Σ_4^{nsym}, non-symmetric part, $q = Q_s$



(a) Dipole (b) MV

Also gives us back-to-back correlation. large error bar comes from the that monstrous dipole Σ_4^{nsym} is not Monte Carlo friendly.

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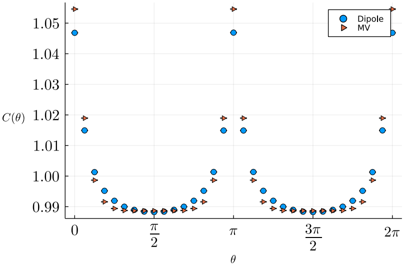
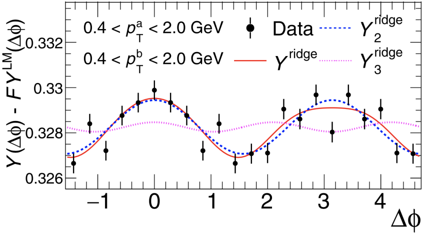
Σ_4^{sym}, symmetric part, $q = Q_s$





As what was done in experimental analysis, we subtract backgrounds and normalize the signal. The results show similar correlations in CGC calculation.

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v_2 and v_2^2

Recall,

$$\frac{dN}{d\boldsymbol{q}_1^2 d\boldsymbol{q}_2^2} \propto 1 + \sum_n 2v_n^2 \cos(n\Delta\theta)$$

One first define,

$$V_n(q_1) = \int d\theta_1 \int_0^{p_\perp^{\max}} d^2\boldsymbol{q}_2 \exp(in\Delta\theta) \frac{dN}{d\boldsymbol{q}_1^2 d\boldsymbol{q}_2^2 d\eta d\xi}$$

by definition,

$$v_2^{(2)}(p_\perp) = \sqrt{\frac{V_2(p_\perp)}{V_0(p_\perp)}}$$

assuming factorization,

$$v_2(p_\perp) = \frac{V_2(p_\perp)/V_0(p_\perp)}{\sqrt{V_2/V_0}} \, .$$

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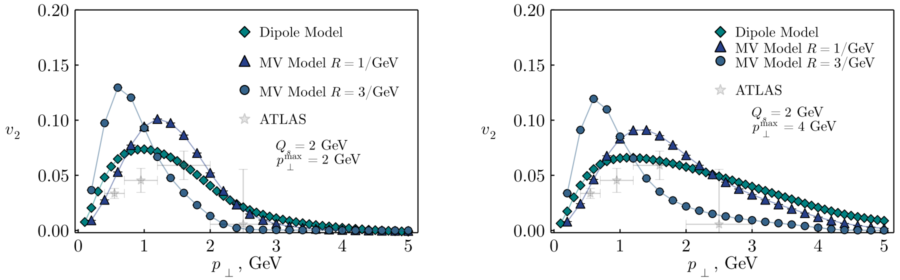
v_2 results



- Different behavior above $2\ Gev$ due to the lack of HBT contribution on the left.
- In the ATLAS analysis, $P_{\text{Max}} = 2\ Gev$

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Factorization test

Theoretical calculation

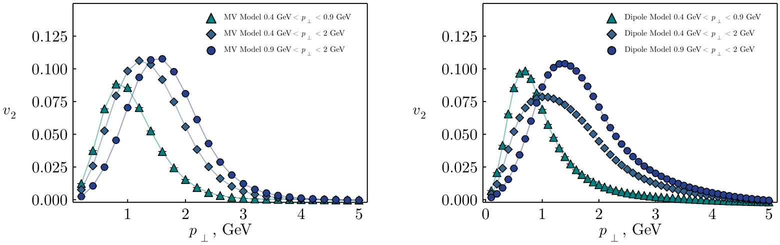

Figure: The elliptic flow v_2 for three different kinematic ranges of the trigger particle. Here as in the previous figure, $Q_s = 2$ GeV. The size of the projectile is set by $R = 1/\text{GeV}$.

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Average in momentum bins

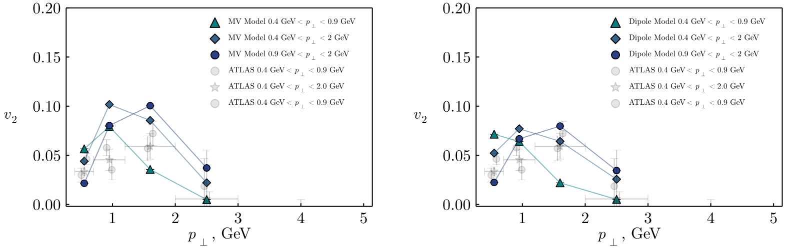

Figure: Parameters are the same as previous slides but binned with the same bin choice as the ATLAS analysis.

Binning the particles decreases the differences between the models.

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Summary and outlook

- We analytically derived inclusive two gluon production in UPC at mid-rapidity.
- To estimate systematic uncertainty originated from the poor knowledge of the real photon wave function, we studied two limiting cases.
- Both models result in qualitatively similar correlation. Quantitatively, the amplitude of azimuthal anisotropy for MV model is about two times the dipole model.
- Our results show similar correlation as experimental data.
- Further developments
  - Phenomenology
  - To extend to EIC physics (large Q^2, work in progress)
  - To incorporate rapidity dependence

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