The Curious Story of the Photon

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- S. Klein, A. Mueller, BX, F. Yuan, 1811.05519; 2003.02947;
- Y. Shi, L. Wang, S. Y. Wei, BX, L. Zheng, 2008.03569

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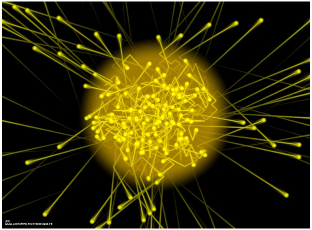
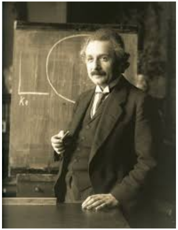
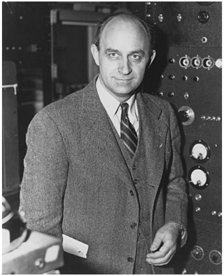
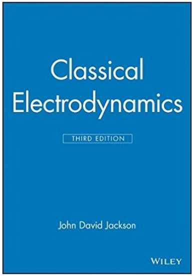
Early History of the Photon

- Photons are quanta of EM radiation and represent the particle nature of light.
- A. Einstein was awarded the Nobel Prize in Physics (1921)
  "for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect."
- This led us into the quantum world and the concept of Wave-Particle duality.

Classical Electrodynamics and Virtual Quanta

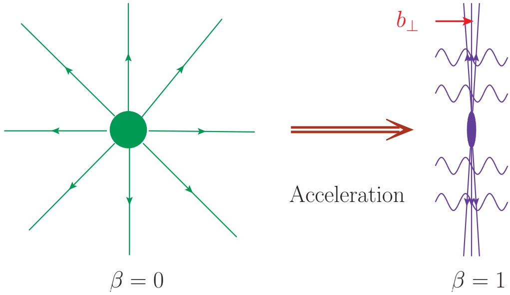




- Following Fermi[24], Weizsäcker [34] and Williams [35] discovered that the EM fields of a relativistically moving charged particle are almost transverse.
- This is equivalent to say that the charged particle carries a cloud of quasi-real photons, which are ready to be radiated if perturbed.
- Weizsäcker-Williams method of virtual quanta (Equivalent Photon Approximation).
- Application in QCD: WW gluon distribution. [McLerran, Venugopalan, 94; Kovchegov, 96; Jalilian-Marian, Kovner, McLerran and Weigert, 97]

EPA and Weizsäcker-Williams Photon Distribution

Boost the static potential to the infinite momentum frame ($\gamma \to \infty$):
[Jackiw, Kabat and Ortiz, 92] and HW problem (P11.18) in [Jackson]

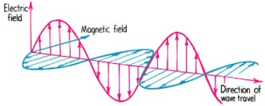


$$A^+_{Cov} = -\frac{q}{\pi}\ln(\lambda b_\perp)\delta(t-z),$$

$$\vec{E} = \frac{q}{2\pi}\frac{\vec{b}_\perp}{b^2_\perp}\delta(t-z),$$

$$\vec{B} = \frac{q}{2\pi}\frac{\hat{v}\times\vec{b}_\perp}{b^2_\perp}\delta(t-z),$$

$$\vec{A}^{LC}_\perp = -\frac{q}{2\pi}[\vec{\nabla}_\perp \ln(\lambda b_\perp)]\theta(t-z).$$



Static electric fields $\Rightarrow$ Electro-Magnetic Wave
$\Rightarrow$ The EM pulses are equivalent to a lot of photons

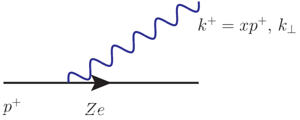
- The gauge potentials A_μ in Covariant gauge and LC gauge are related by a gauge transformation. λ is an irrelevant parameter setting the scale.
- Classical EM: transverse EM fields $\Leftrightarrow$ QM: Co-moving Quasi-real photons.

Transverse Momentum Dependent (TMD) Photon Distribution

The photon distribution (flux) for a point particle can be computed from $\vec{A}_\perp^{LC}$

$$xf_\gamma(x,b_\perp) = \frac{Z^2\alpha}{\pi^2}x^2m^2K_1^2(xm\,b_\perp) = \left.\frac{Z^2\alpha}{\pi^2 b_\perp^2}\right|_{m\to 0} \quad \text{with} \quad q = Ze.$$

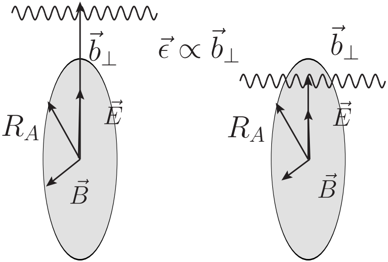
The photon distribution in the transverse momentum space



$$\begin{aligned} xf_\gamma(x,\vec{k}_\perp) &= \int \frac{d\xi^- d^2\xi_\perp}{(2\pi)^3} e^{-ixP^+\xi^- - ik_\perp\cdot\xi_\perp} \left\langle A \left| F^{+i}\left(\frac{\xi}{2}\right) F^{+i}\left(-\frac{\xi}{2}\right) \right| A \right\rangle \\ &\simeq \frac{Z^2\alpha}{\pi^2} \frac{k_\perp^2}{(k_\perp^2 + x^2M^2)^2} F_A^2(k^2). \end{aligned}$$

- $F_A(k^2)$ is the charge form factor with $k^2 = k_\perp^2 + x^2M^2$. $F_A = 1$ for point charge.
- Wood-Saxon or Gaussian models for realistic nuclei.
- Typical transverse momentum of the photon is $1/R_A$, which is 30MeV for Pb.

Linearly Polarized Photon



- E is linearly polarized along the impact parameter $b_\perp$ direction;
- $\vec{B} \perp \vec{E}$;
- The LC gauge potential $A_\perp \propto \vec{b}_\perp$;
- Polarization vector $\vec{\epsilon}_\perp = \vec{b}_\perp / b_\perp$.
- Similar case in momentum space.

- WW photon distribution is maximumly polarized, since $xf_\gamma = xh_\gamma$.

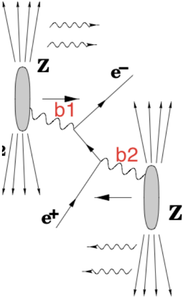
$$xf_\gamma^{ij}(x; b_\perp) = \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{i\Delta_\perp \cdot b_\perp} \langle A, -\frac{\Delta_\perp}{2} | F^{+i} F^{+j} | A, \frac{\Delta_\perp}{2} \rangle ,$$

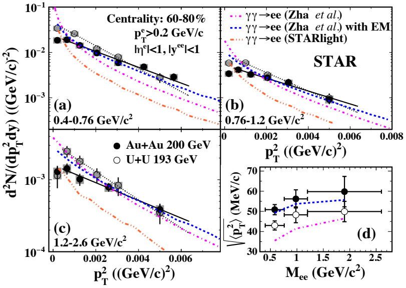
$$xf_\gamma^{ij}(x; b_\perp) = \frac{\delta^{ij}}{2} xf_\gamma(x; b_\perp) + \left(\frac{b_\perp^i b_\perp^j}{b_\perp^2} - \frac{\delta^{ij}}{2} \right) xh_\gamma(x; b_\perp) = \frac{b_\perp^i b_\perp^j}{b_\perp^2} xf_\gamma ,$$

$$xh_\gamma(x, b_\perp) = xf_\gamma(x, b_\perp) = 4Z^2\alpha \left| \int \frac{d^2k_\perp}{(2\pi)^2} e^{ik_\perp \cdot b_\perp} \frac{\vec{k}_\perp}{k^2} F_A(k^2) \right|^2$$

The Need of Photon Wigner Distribution from Experiments

STAR[1806.02295], ATLAS ([CONF-2019-051]) and CMS[PAS-HIN-19-014] collaborations observe $\gamma\gamma \to l^+ l^-$ azimuthal angular correlations in AA collisions with different impact parameter $b_\perp = b_{1\perp} - b_{2\perp}$

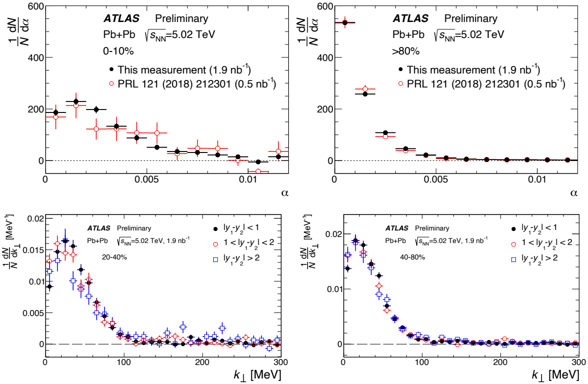




- Need the incoming photon $k_\perp$ distribution at fixed impact parameter $b_\perp$.
- [Vidovic, *et al*, 93; Hencken, *et al*, 94; Zha, *et al*, 18; Li, Zhou, Zhou, 19; etc]
- STAR: “This level of broadening is measurable and may indicate the possible existence of high magnetic fields (trapped in a con- ducting QGP)". ???

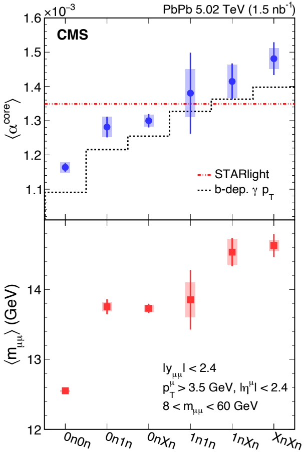
The Need of Photon Wigner Distribution from Experiments

ATLAS ([CONF-2019-051; 2206.12594]) measures the acoplanarity $\alpha \equiv 1 - |\Delta\phi|/\pi$ ($\Delta\phi = \phi_{l+} - \phi_{l-}$) and the total momentum imbalance $k_\perp$ of the muon pair in *PbPb* collisions with different centralities (impact parameter $b_\perp$)



- Need the incoming photon $k_\perp$ distribution at fixed impact parameter $b_\perp$.
- Mysterious and interesting displaced peaks (dips) in central collisions.

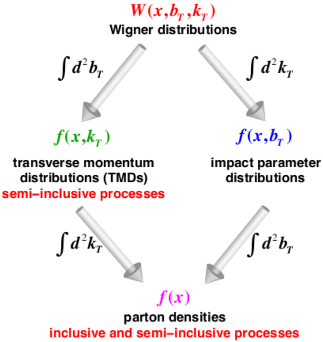
CMS Results

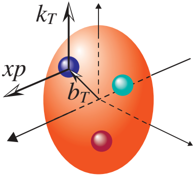


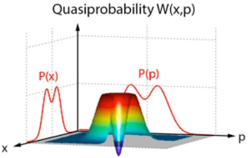
- CMS[PAS-HIN-19-014] measures the number of neutrons in the very forward region in UPC.
- Higher neutron multiplicity corresponds to smaller $\langle b \rangle$ on average, and vice versa.
- This measurement demonstrates the transverse momentum imbalance and energy of photons (invariant mass of the dilepton) emitted from relativistic ions have impact parameter dependence.
- Great way to select events with $\langle b \rangle$. Even measure various asymmetries.

Wigner distribution

Wigner distributions [Ji, 03; Belitsky, Ji, Yuan, 2004] ingeniously encode all quantum information of how partons are distributed inside hadrons.







- Quasi-probability distribution; Not positive definite.
- Need to smear over k_T and $b_\perp$ $\rightarrow$ Husimi distribution. [Hagiwara, Hatta, 14]

Photon Wigner Distribution and Generalized TMD

Def. of Wigner distribution:

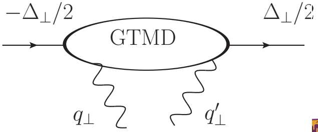
$$xf_\gamma(x,\vec{k}_\perp;\vec{b}_\perp) = \int \frac{d\xi^- d^2\xi_\perp}{(2\pi)^3 P^+} \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{-ixP^+\xi^- - ik_\perp\cdot\xi_\perp}$$
$$\times \quad \left\langle A, +\frac{\Delta_\perp}{2} \middle| F^{+i}\left(\vec{b}_\perp + \frac{\xi}{2}\right) F^{+i}\left(\vec{b}_\perp - \frac{\xi}{2}\right) \middle| A, -\frac{\Delta_\perp}{2} \right\rangle ,$$

Def. of GTMD

$$xf_\gamma(x,k_\perp,\Delta_\perp) \equiv \int d^2 b_\perp e^{-i\Delta\cdot b_\perp} xf_\gamma(x,\vec{k}_\perp;\vec{b}_\perp).$$

- For a heavy nucleus with charge Ze, the GTMD reads

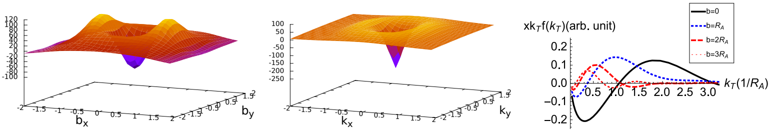
$$xf_\gamma(x,k_\perp;\Delta_\perp) = xh_\gamma(x,k_\perp;\Delta_\perp)$$
$$= \frac{4Z^2\alpha}{(2\pi)^2}\frac{q_\perp\cdot q'_\perp}{q^2 q'^2} F_A(q^2)F_A(q'^2) ,$$
$$q_\perp = k_\perp - \frac{\Delta_\perp}{2}, \quad \text{and} \quad q'_\perp = k_\perp + \frac{\Delta_\perp}{2}$$



- $\int d^2b_\perp xf_\gamma(x,k_\perp,b_\perp) \Rightarrow TMD$; $\int d^2k_\perp xf_\gamma(x,k_\perp,b_\perp) \Rightarrow b_\perp$ distribution.
- EPA $\rightarrow$ Generalized EPA.

The Oscillating Behavior of Wigner Distributions

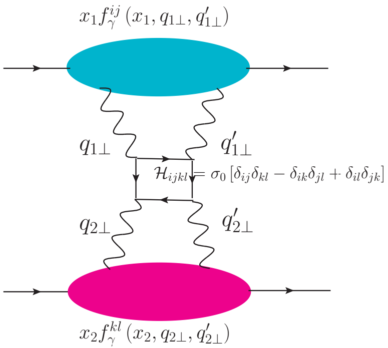
Models of Wigner[Lorcé, Pasquini, 11; Lorcé, Pasquini, Xiong, Yuan, 11] [Hagiwara, Hatta, 14] [S. Klein, A. Mueller, BX, F. Yuan, 20]



- Due to the uncertainty principle, Wigner distributions often has the oscillating behavior when one tries to measure $b_\perp$ and $k_\perp$ simultaneously.
- Will the negative region of the Wigner distribution cause a serious problem?
- Two observations: diffractive dijets in DIS and $\gamma\gamma \to l^+ l^-$ in $PbPb$ collisions.
- Opinion: No, it seems that the LO cross-sections are always positive-definite. (It will be interesting if one can prove this conjecture.)

The Factorization of Wigner distribution in the lepton pair production

The GEPA factorization at LO, and compute the hard factor $\mathcal{H}$



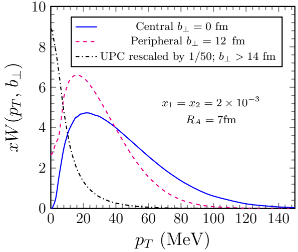
$$\frac{d\sigma(AB[\gamma\gamma] \to \mu^+\mu^-)}{dy_1 dy_2 d^2p_{1T} d^2p_{2T} d^2b_\perp}$$
$$= \int d^2k_{1T} d^2k_{2T} \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{-i\Delta_\perp \cdot b_\perp}$$
$$\times x f_\gamma^{ij}(k_{1T}; \Delta_\perp) x_2 f_\gamma^{kl}(k_{2T}; \Delta_\perp) H_{ijkl}$$
$$\times \delta^{(2)}(p_T - k_{1T} - k_{2T})$$
$$\propto \int d^2b_{1\perp} d^2b_{2\perp} \delta^{(2)}(b_\perp - b_{1\perp} + b_{2\perp})$$
$$\times x f_\gamma^{ij}(k_{1T}; b_{1\perp}) x_2 f_\gamma^{kl}(k_{2T}; b_{2\perp}) H_{ijkl}$$

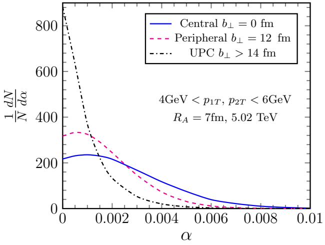
- Notations for the momenta: $q_\perp = k_T - \frac{\Delta_\perp}{2}$, and $q'_\perp = k_T + \frac{\Delta_\perp}{2}$.
- Need the off-diagonal momenta $\Delta_\perp$ to access impact parameter $b_\perp$.
- Will negative region of Wigner Dist $x f_\gamma^{ij}(k_T; b_\perp)$ ever be catastrophic?

Results of GEPA

If we define $G^{ik} = \int \frac{d^2k_{1T}}{(2\pi)} e^{ik_{1T}\cdot b_\perp} k^i_{1T} k^k_{2T} \frac{F(k_1^2)}{k_1^2} \frac{F(k_2^2)}{k_2^2}$, and note $k_{1T} + k_{2T} = p_T$

$$\frac{d\sigma}{dy_1 dy_2 d^2p_{1T} d^2p_{2T} d^2b_\perp} = \sigma_0 \left[(G^{11} - G^{22})(G^{11*} - G^{22*}) + (G^{12} + G^{21})(G^{12*} + G^{21*}) \right] \geq 0$$

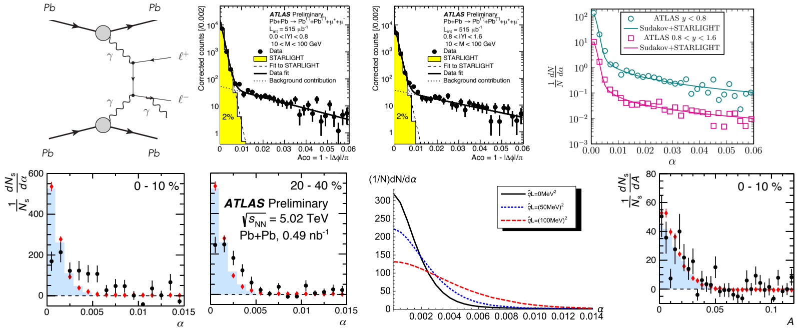




- The cross section $= 0$ when $b_\perp = 0$ and $p_T = 0$ ($G11 = G_{22}$ and $G_{12} = -G_{21}$)
- Explains the dip (displaced peak, ATLAS) in central AA. $\sigma \sim xW(p_T, b_\perp)$
- However, the dip becomes much less significant after averaging over momenta.
- Qualitatively explains recent ATLAS CONF-2019-51 data. Still a bit puzzling.

Dilepton productions in AA collisions

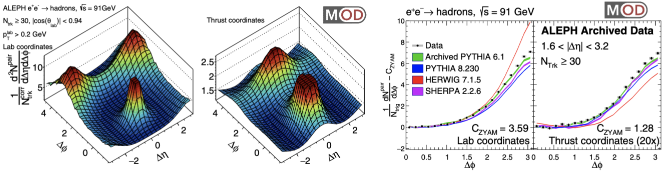
[ATLAS, 1806.08708; 2019 Conf-51]; [Klein, Mueller, Xiao, Yuan, 18; 20]



- Acoplanarity $\alpha \equiv 1 - \Delta\phi/\pi$ and asymmetry $A \equiv ||p_T^+| - |p_T^-||/||p_T^+| + |p_T^-||$.
- Initial photon $k_\perp$ distribution plus photon radiation describes the background.
- p_T broadening $\hat{q}_{\rm QED}L \sim (50{\rm MeV})^2 \sim \frac{\alpha_{em}^2}{\alpha_s^2}\hat{q}_{\rm QCD}$ but QED energy loss is weak.
- Independent final state medium broadening, since the typical distance between l^+ and l^- in QGP is much larger than the coherence length $1/P_T$.

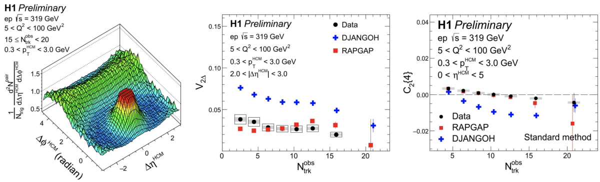
Search for collectivity in e^+e^- collisions at LEP and in DIS at HERA

Two-Particle Correlations in e^+e^- with ALEPH data[Badea *et al*, 19] ▸ Link



- No significant enhancement of long-range correlations is observed.

Search for collectivity at HERA [Chuan Sun For H1 Collaboration, IS2021] ▸ Link



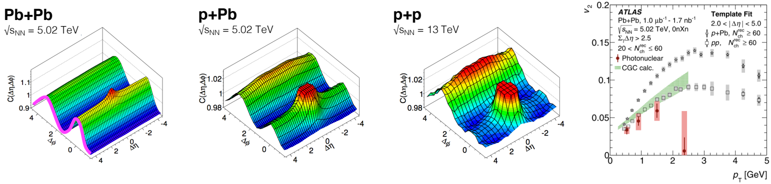
- No collectivity observed at HERA. Data agree with RAPGAP.

Collectivity (correlation, flow) is everywhere!

In high multiplicity events, large azimuthal angle correlations are observed:

$$C_n\{2\} \equiv \{e^{in(\phi_1-\phi_2)}\} = \frac{\int d\phi_1 d\phi_2 e^{in(\phi_1-\phi_2)} \frac{dN}{d\phi_1}\frac{dN}{d\phi_2}}{\int d\phi_1 d\phi_2 \frac{dN}{d\phi_1}\frac{dN}{d\phi_1}}$$

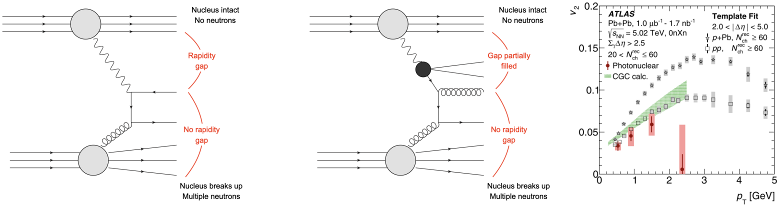
$$= \{e^{in(\phi_1-\phi_{RP})}\}\{e^{in(\phi_{RP}-\phi_2)}\} = v_n^2\{2\}.$$



- Collectivity is used to describe the particle correlation. It is observed in both large and small systems and for light and heavy hadrons!
- New exciting results for UPC in PbPb collisions.

Collectivity at EIC?

Two-particle correlations in photonuclear (Pb+Pb) UPC by ATLAS ▸ Link

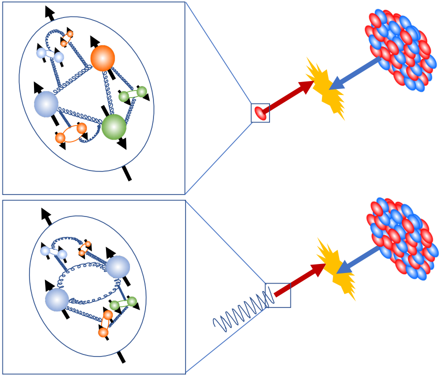


- New exciting results for UPC in PbPb collisions. (Mini-EIC)
- WW equivalent photon approximation: Small virtuality, like a plane wave.
- Photons with energy up to 80 GeV at the LHC + the high-energy nuclei.
- What about predictions for the collectivity at the EIC on the horizon?

The Structure of Photons

Photons can have a very rich QCD structure

$$|\gamma\rangle = |\gamma_0\rangle + \sum_{m,n} |m\, q\bar{q} + n\, g\rangle + \sum_{\rho,\omega,\cdots} |V\rangle + \cdots ,$$



- Point like (high Q^2)
- Partonic
- VMD [Sakurai, 60]

Strong similarity between $\gamma^* A$ and pA collisions when γ^* has a long lifetime.

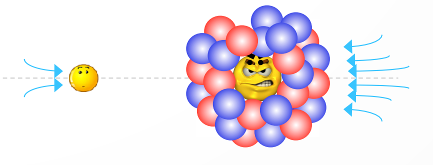
$$t_{\text{lifetime}} \sim \frac{1}{q^-} = \frac{q^+}{Q^2} \gg \frac{m_p}{P^-} R \quad \Rightarrow \quad x_B \ll \frac{1}{m_p R}$$

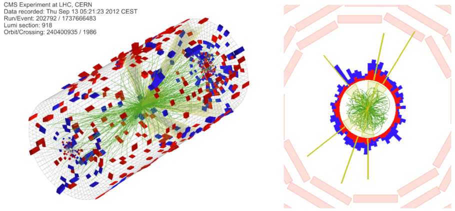
Opinion: collectivity in $\gamma^* A$ collisions regardless the underlying interpretation.

Collectivity in high multiplicity events in pA collisions

Qualitative understanding of high multiplicity events and correlation.

- Many active partons
  $|P\rangle = |qqq\rangle + |qqq\,ng\rangle + \cdots$
- Fluctuation in parton density
  Stronger Q_s in nuclei.
- Correlated multiple scatterings
  Non-trivial color correlation.
- Possible stronger parton shower.
  Shower produce soft particles due to hard collisions.



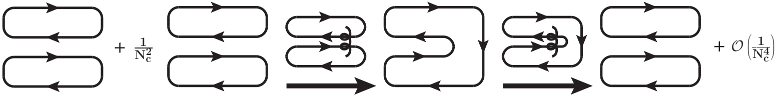


A CGC model for correlation based on the above three pillar in Red.

- Let us pick two initially uncorrelated collinear partons (say $q + q$) from proton, and consider their interactions with the target nucleus.
- Correlation can be generated between them due to multiple interaction.
- Due to Unitarity, the un-observed partons do not affect the correlation of the system.

Correlations in CGC

Correlations between uncorrelated incoming quarks (gluons) are generated due to quadrupole as N_c corrections. [Lappi, 15; Lappi, Schenke, Schlichting, Venugopalan, 16; Dusling, Mace, Venugopalan, 17; Davy, Marquet, Shi, Xiao, Zhang, 18]



$$\frac{d^2N}{d^2k_{1\perp}d^2k_{2\perp}} = \int d^2r_{1\perp}d^2r_{2\perp}e^{-ik_{1\perp}\cdot r_{1\perp}}e^{-ik_{2\perp}\cdot r_{2\perp}} \times \frac{1}{N_c^2}\left\langle \mathrm{tr}\left[V(x_1)V(x_2)^\dagger\right]\mathrm{tr}\left[V(x_3)V(x_4)^\dagger\right]\right\rangle$$

where

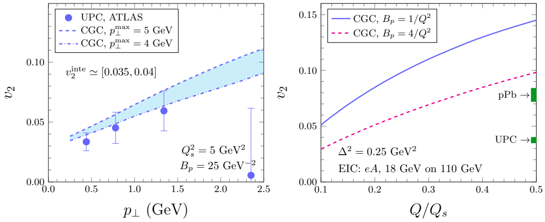
$$\frac{1}{N_c^2}\left\langle \mathrm{tr}\left[V(x_1)V(x_2)^\dagger\right]\mathrm{tr}\left[V(x_3)V(x_4)^\dagger\right]\right\rangle \neq \frac{1}{N_c^2}\left\langle \mathrm{tr}\left[V(x_1)V(x_2)^\dagger\right]\right\rangle\left\langle \mathrm{tr}\left[V(x_3)V(x_4)^\dagger\right]\right\rangle$$

$$= e^{-\frac{Q_s^2}{4}(r_1^2+r_2^2)}\left[1+\frac{(\frac{Q_s^2}{2}\boldsymbol{r}_1\cdot\boldsymbol{r}_2)^2}{N_c^2}\int_0^1 d\xi\int_0^\xi d\eta e^{\frac{\eta Q_s^2}{8}[(\boldsymbol{r}_1-\boldsymbol{r}_2)^2-4(\boldsymbol{b}_1-\boldsymbol{b}_2)^2]}\right]$$

- At leading N_c, $\frac{d^2N}{d^2k_{1\perp}d^2k_{2\perp}} = \left(\frac{dN}{d^2k_{1\perp}}\right)\left(\frac{dN}{d^2k_{2\perp}}\right)$, there are no correlations.
- The correlations only come in as higher order N_c corrections as shown above.

v_2 Predictions in γA collisions from CGC

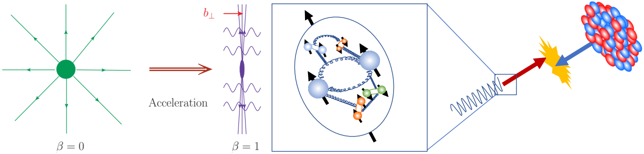
[Shi, Wang, Wei, Xiao, Zheng, Phys. Rev. D **103**, 054017 (2021)] Link



- New results from UPC in PbPb collisions at LHC. (Mini-EIC)
- Photons can have a rich QCD structure due to fluctuation.
- Consider the photon-resolved (hadron like) processes in CGC. ⇒ similar v_2
- Selecting different Q^2 and y bins ⇒ handles to change system size and energy.
- Comment on ep collisions at HERA: saturation effect may not be sufficient, and the number of high multiplicity events is also a limiting factor. ($\sim$ 20 trks)
- It will be interesting to compare the future EIC data with HERA data.

Summary

Several curious and interesting aspects of the photon



- Wigner distribution $\Rightarrow$ Interesting measurements and theoretical issue.
- Linear polarization $\Rightarrow$ Non-trivial correlations in dilepton. (See Zhou's talk)
- Rich partonic structure $\Rightarrow$ Collectivity at the future EIC.

Backup: PhD student recruitment

2023年博士项目夏令营

报名方式

线上报名，扫描二维码可以进入申请界面。

https://apply.cuhk.edu.cn/matrix-base/tsc/login

面向群体

2024年毕业的本科生或硕士研究生，应具有理工相关教育背景。
*就读于教育部认可的大学或机构，截止申报前成绩不低于二级荣誉或不低于 “B”或平均分80分以上
（评审委员会将对申请者的教育背景进行评估与筛选）

活动安排

Day 0:7月6日 注册报到、入住校园；
Day 1:7月7日 集体开营仪式、理工学院博士项目介绍、导师科研项目分享；
Day 2:7月8日 导师见面会、数学项目笔试、博士项目面试；
Day 3:7月9日 博士项目面试。

申请流程

申请者需在报名界面选择希望参加的博士项目，并上传系统所述的相关材料。
报名截止时间为2023年6月20日下午16:00。
入选者将在6月30日前收到邮件通知；未入选者，将不另行通知。