Soft gluon resummation in dijet production

Yoshitaka Hatta

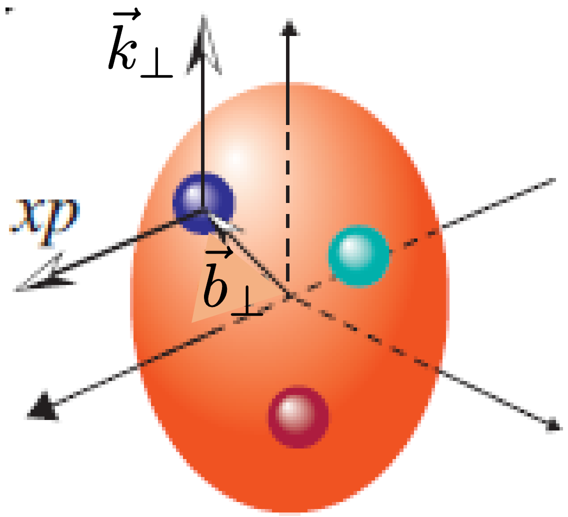
BNL & RIKEN BNL

in collaboration with Bowen Xiao, Feng Yuan, Jian Zhou

2010.10774 (PRL)
2106.05307 (PRD)

QCD@LHC, Orsay Nov.28-Dec.2, 2022

Multi-dimensional tomography



$$u(x) = \int \frac{dz^-}{4\pi} \langle P|\bar{u}(0)\gamma^+ u(z^-)|P\rangle \; e^{ixP^+z^-}$$

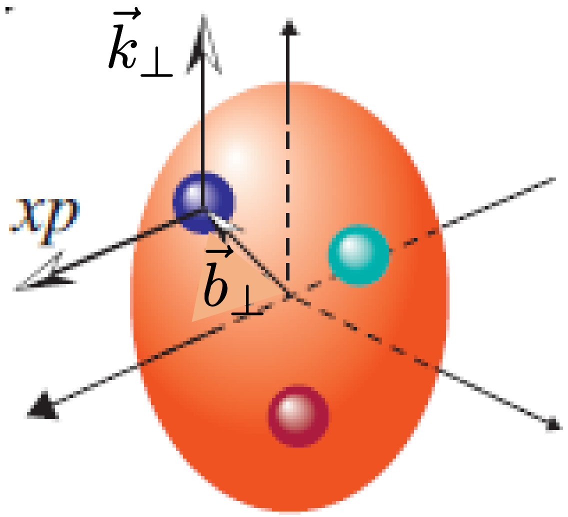
Ordinary parton distribution functions (PDF) can be viewed as the 1D tomographic image of the nucleon

The nucleon is much more complicated!
Partons also have transverse momentum $\vec{k}_\perp$
and are spread in impact parameter space $\vec{b}_\perp$

$u(x)$ →

- $u(x, \vec{k}_\perp)$ — Transverse momentum dependent distribution (TMD) — 3D tomography
- $u(x, \vec{b}_\perp)$ — Generalized parton distribution (GPD) — 3D tomography
- $u(x, \vec{k}_\perp, \vec{b}_\perp)$ — Wigner distribution —Fourier→ GTMD $u(x, \vec{k}_\perp, \vec{\Delta}_\perp)$ — 5D tomography

Angular correlations



Rich angular correlations between impact parameter $\vec{b}_\perp$
and transverse momentum $\vec{k}_\perp$

$$W(x, \vec{b}_\perp, \vec{k}_\perp)$$
$$= W_0 + \cos 2(\phi_{b_\perp} - \phi_{k_\perp}) W_2 + \cos(\phi_{b_\perp} - \phi_{k_\perp}) W_O + \sin(\phi_{b_\perp} - \phi_{k_\perp}) W_{OAM} + \cdots$$

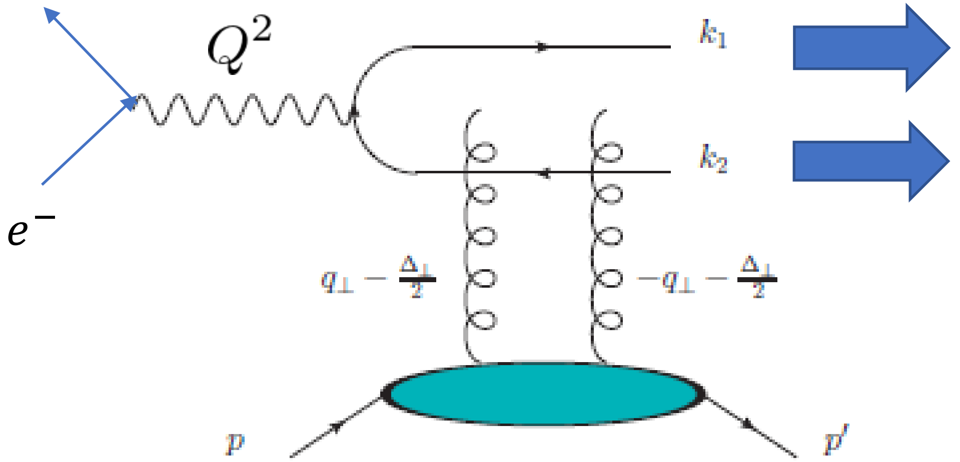
Elliptic Wigner — Odderon — Orbital angular momentum

Fourier transform → GTMD

$$W(x, \vec{\Delta}_\perp, \vec{k}_\perp) = W_0 + \cos 2(\phi_{\Delta_\perp} - \phi_{k_\perp}) W_2 + \cdots$$

Probing gluon Wigner in exclusive dijet production in DIS

YH, Xiao, Yuan (2016)



$$\Delta^\mu = p'^\mu - p^\mu$$ proton recoil

$$\vec{q}_\perp = \vec{k}_{1\perp} + \vec{k}_{2\perp}$$ dijet total

$$\vec{P}_\perp = \frac{1}{2}(\vec{k}_{2\perp} - \vec{k}_{1\perp})$$ dijet relative

$$\frac{d\sigma}{dy_1 dy_2 d^2\vec{\Delta}_\perp d^2\vec{P}_\perp} \propto z(1-z)[z^2+(1-z)^2]\int d^2q_\perp d^2q'_\perp S(q_\perp,\Delta_\perp)S(q'_\perp,\Delta_\perp)$$
$$\times \left[\frac{\vec{P}_\perp}{P_\perp^2+\epsilon^2} - \frac{\vec{P}_\perp - \vec{q}_\perp}{(P_\perp - q_\perp)^2+\epsilon^2}\right] \cdot \left[\frac{\vec{P}_\perp}{P_\perp^2+\epsilon^2} - \frac{\vec{P}_\perp - \vec{q}'_\perp}{(P_\perp - q'_\perp)^2+\epsilon^2}\right]$$

$$\epsilon^2 = z(1-z)Q^2$$

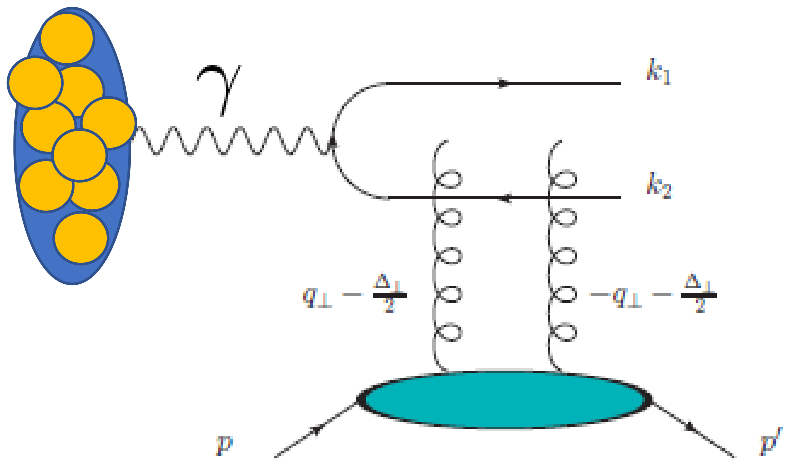
Color dipole S-matrix ≈ GTMD

$$\sim d\sigma_0 + 2\cos 2(\phi_P - \phi_\Delta)d\tilde{\sigma}$$

\`elliptic flow', expected to be a few percent effect

Exclusive dijet in UPC

Hagiwara, YH, Pasechnik, Tasevsky, Teryaev (2017)



UPC: where the heavy-ion and EIC communities can meet

$$\frac{d\sigma^{pA}}{dy_1 dy_2 d^2\vec{k}_{1\perp} d^2\vec{k}_{2\perp}} = \omega\frac{dN}{d\omega}\frac{N_c\alpha_{em}(2\pi)^4}{P_\perp^2}\sum_f e_f^2 2z(1-z)(z^2+(1-z)^2)\left(A^2 + 2\cos 2(\phi_P - \phi_\Delta)AB\right)$$

photon flux $\propto Z^2$

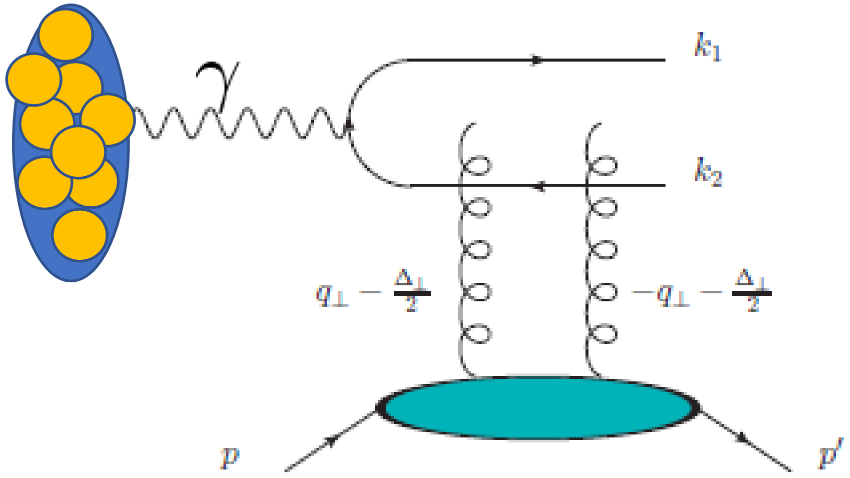
When $Q^2 \approx 0$, simple analytical relations at leading order $S(\vec{q}_\perp, \vec{\Delta}_\perp) = S_0(q_\perp, \Delta_\perp) + 2\cos 2(\phi_q - \phi_\Delta)\tilde{S}(q_\perp, \Delta_\perp)$

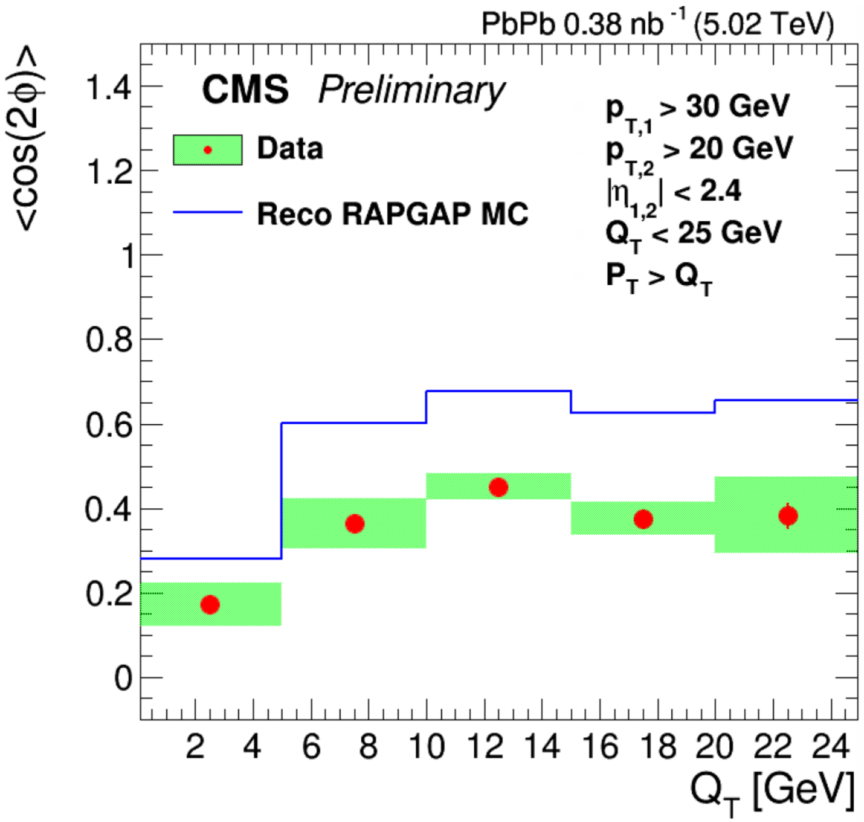
$$S_0(P_\perp, \Delta_\perp) = \frac{1}{P_\perp}\frac{\partial}{\partial P_\perp}A(P_\perp, \Delta_\perp). \quad S_1(P_\perp, \Delta_\perp) = \frac{\partial B(P_\perp, \Delta_\perp)}{\partial P_\perp^2} - \frac{2}{P_\perp^2}\int^{P_\perp^2}\frac{dP_\perp'^2}{P_\perp'^2}B(P_\perp', \Delta_\perp)$$

CMS dijet measurements

dijet angular correlation in PbPb UPC

CMS-PAS-HIN-18-011





Use $\vec{q}_\perp = \vec{k}_{1\perp} + \vec{k}_{2\perp}$ as a proxy for $\vec{\Delta}_\perp$

$\vec{\Delta}_\perp = -\vec{q}_\perp$ to leading order

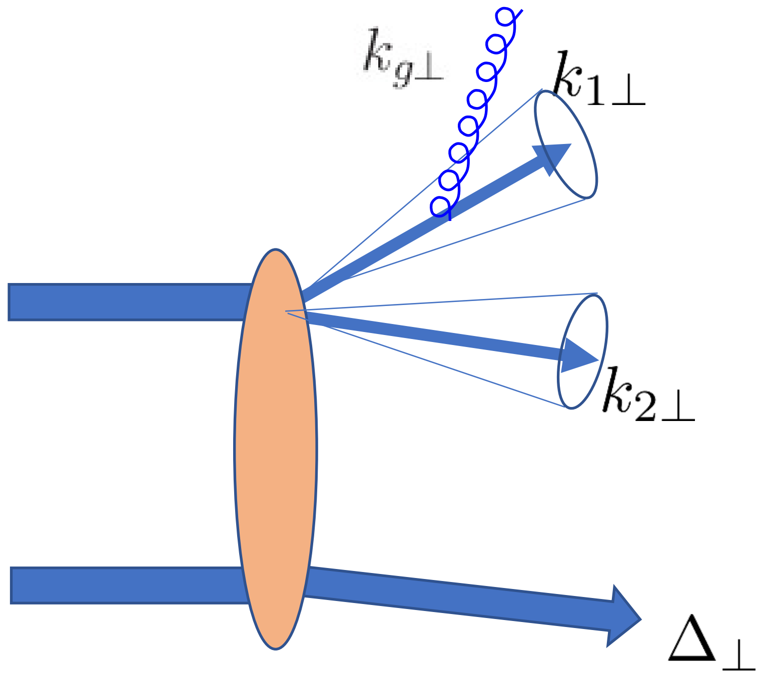
Measured the $\cos 2\phi$ correlation between $q_\perp$ and $P_\perp$, instead of that between $\vec{\Delta}_\perp$ and $P_\perp$

Very large asymmetry!
Anything to do with the elliptic Wigner?

Dijet with soft gluons: general consideration

To leading order, dijet total momentum
is equal to the proton recoil momentum

$$q_\perp = k_{1\perp} + k_{2\perp} = -\Delta_\perp \qquad \frac{d\sigma}{d^2q_\perp} = \frac{d\sigma}{d^2\Delta_\perp}$$



With soft radiation, this becomes

$$\vec{q}_\perp = -\vec{\Delta}_\perp - \sum_i \vec{k}^i_{g\perp}$$

$k_{g\perp}$ tend to be along jet directions → $q_\perp$ tends to be along jet directions → $\cos 2\phi$

$$\frac{d\sigma}{d^2P_\perp d^2q_\perp} = \int d^2q'_\perp \frac{d\sigma_0}{d^2P_\perp d^2q'_\perp} S_J(q_\perp - q'_\perp),$$

measured primordial Soft factor

One-loop analytical result

$$g^2 \int \frac{d^3 k_g}{(2\pi)^3 2E_{k_g}} \delta^{(2)}(q_\perp + k_{g\perp}) C_F S_g(k_1, k_2)$$
$$= \frac{C_F \alpha_s}{\pi^2 q_\perp^2} [c_0^{\rm diff}(q_\perp^2) + 2\cos(2\phi) c_2^{\rm diff}(q_\perp^2) + \cdots].$$

all even harmonics $\cos 2n(\phi_{q_\perp} - \phi_{P_\perp})$

$$c_n(q_\perp) = c_n(0) + \mathcal{O}(q_\perp^a / P_\perp^a)$$

power corrections

$$c_0^{\rm diff}(0) = \ln \frac{a_0}{R^2}, \qquad a_0 = 2 + 2\cosh(\Delta y_{12})$$

$$c_2^{\rm diff}(0) = \ln \frac{a_2}{R^2}. \qquad \ln a_2 = \Delta y_{12} \sinh \Delta y_{12} - \cosh \Delta y_{12} \ln [2(1 + \cosh \Delta y_{12})]$$

$$\frac{d\sigma}{d\phi} \sim \alpha_s \cos 2\phi \int \frac{dq_\perp^2}{q_\perp^2} = \infty$$

Angular dependent cross section divergent at fixed order.

Resummation

Catani, Grazzini, Torre, (2014), Catani, Grazzini, Sargsyan (2017)
YH, Yuan, Xiao, Zhou (2020~)

Fourier transform $q_\perp \to b_\perp$

Angular-independent part

$$\int \frac{d\vec{q}_\perp}{(2\pi)^2} e^{i\vec{b}_\perp\cdot\vec{q}_\perp} \left[\frac{1}{q_\perp^2}\right]_+ = -\frac{1}{4\pi} \ln \frac{b_\perp^2 P_\perp^2}{c_0^2}$$

IR divergent
→ regularized by the plus prescription

$$\Rightarrow \quad \exp\left(-\frac{2C_F c_0}{\pi}\int_{\mu_b}^{P_\perp} \frac{d\mu}{\mu}\alpha_s(\mu)\right)$$

Angular-dependent

$$\int \frac{d\vec{q}_\perp}{(2\pi)^2} e^{i\vec{b}_\perp\cdot\vec{q}_\perp} \frac{\cos 2\phi_{q_\perp}}{q_\perp^2} = -\frac{\cos 2\phi_{b_\perp}}{2\pi} \underbrace{\int_0^\infty \frac{dq_\perp}{q_\perp} J_2(b_\perp q_\perp)}_{=\frac{1}{2}}$$

No plus-prescription, but finite!

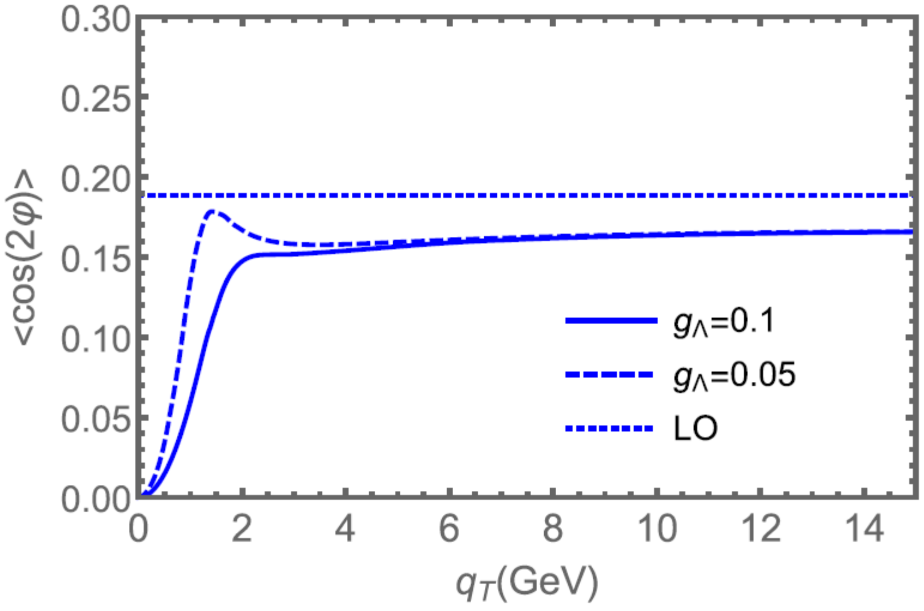
Before $\langle \cos n\phi \rangle \sim \frac{1}{q_\perp^2}$ $\Rightarrow$ After $\langle \cos(n\phi)\rangle \propto q_\perp^n$

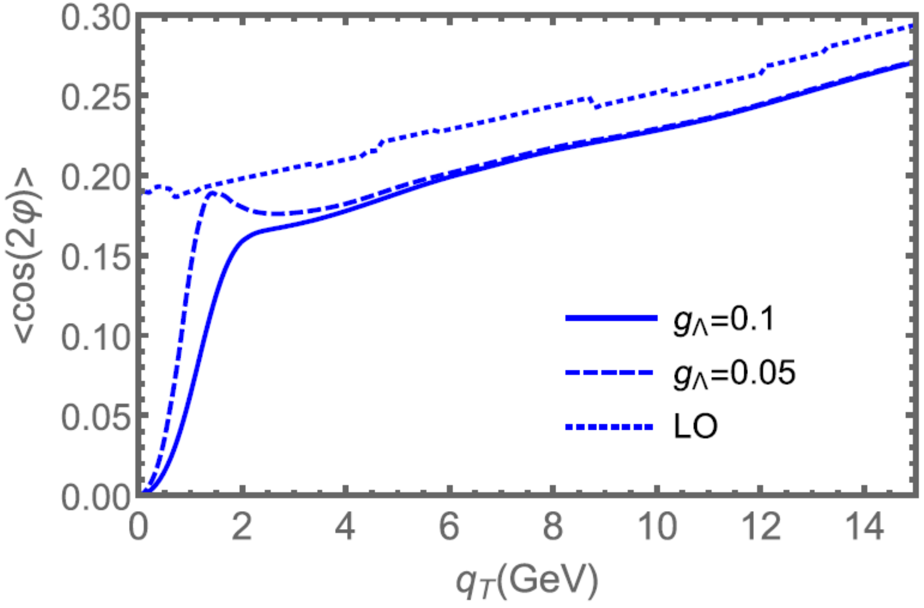
Resummation by the same Sudakov factor

Towards explaining the CMS data

2010.10774
2106.05307

UPC at the LHC, $P_\perp = 35\text{GeV}$ $R = 0.4$





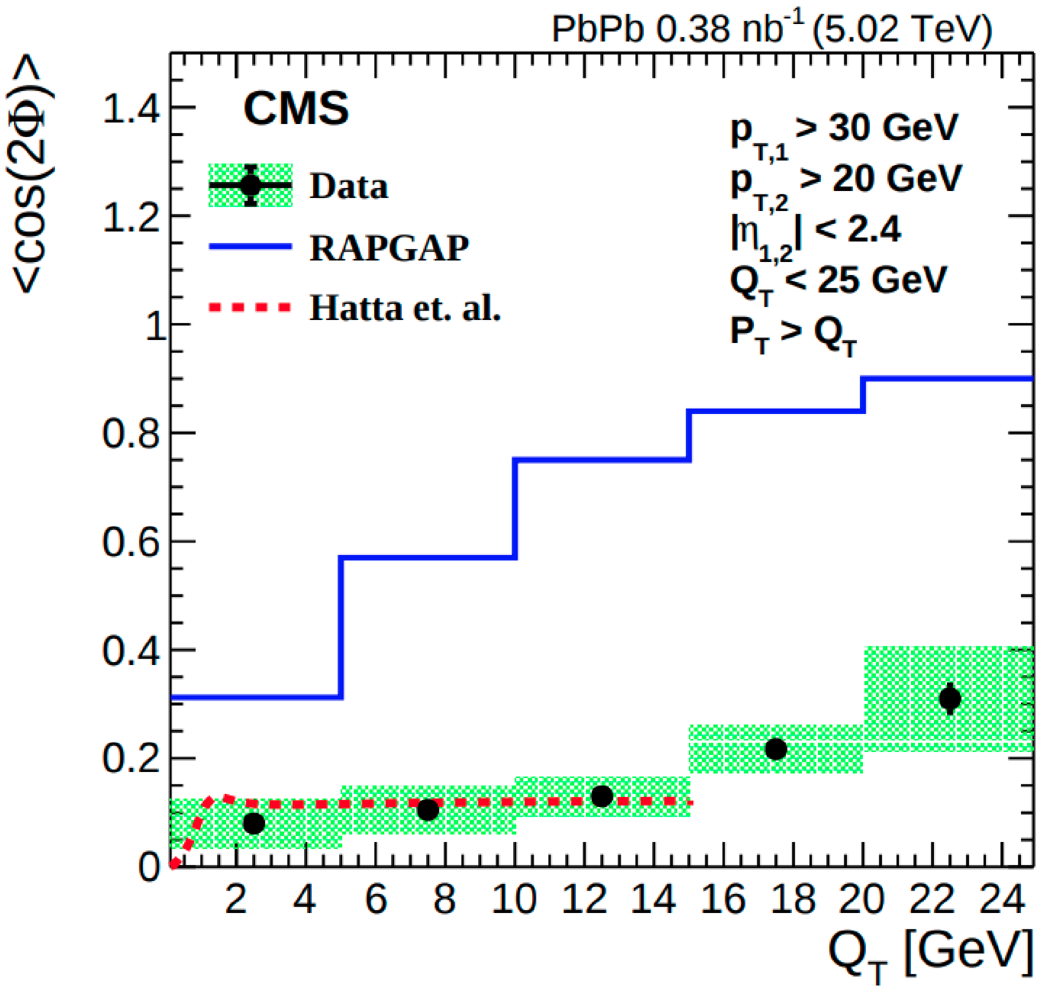
Part of power corrections included
→ monotonically rising behavior

Lesson learned:

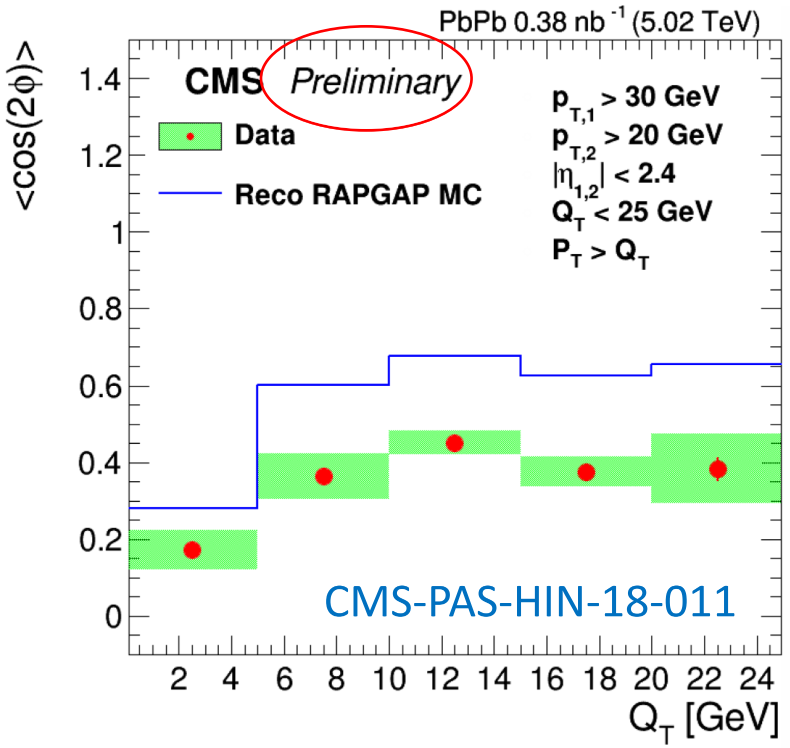
$\vec{q}_\perp = \vec{k}_{1\perp} + \vec{k}_{2\perp}$ cannot be a proxy for $\vec{\Delta}_\perp$.

CMS update

CMS-PAS-HIN-18-011
2205.00045 (updated plots)

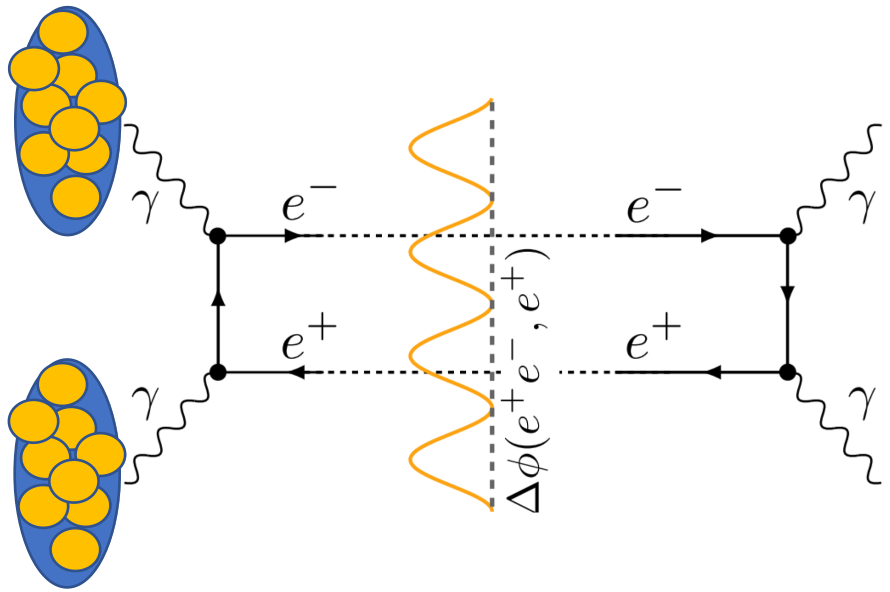


unfolding



Ultraperipheral AA collisions (UPC) at RHIC and LHC

A large nucleus—copious source of linearly polarized photons



$$f(\Delta\phi) = C(1 + A_{2\Delta\phi}\cos 2\Delta\phi + A_{4\Delta\phi}\cos 4\Delta\phi)$$

Li, Zhou, Zhou (2019)

PHYSICAL REVIEW LETTERS **127,** 052302 (2021)

Measurement of e^+e^- Momentum and Angular Distributions from Linearly Polarized Photon Collisions

(STAR Collaboration)

Dielectron production at midrapidity at low transverse momentum in peripheral and semi-peripheral Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV

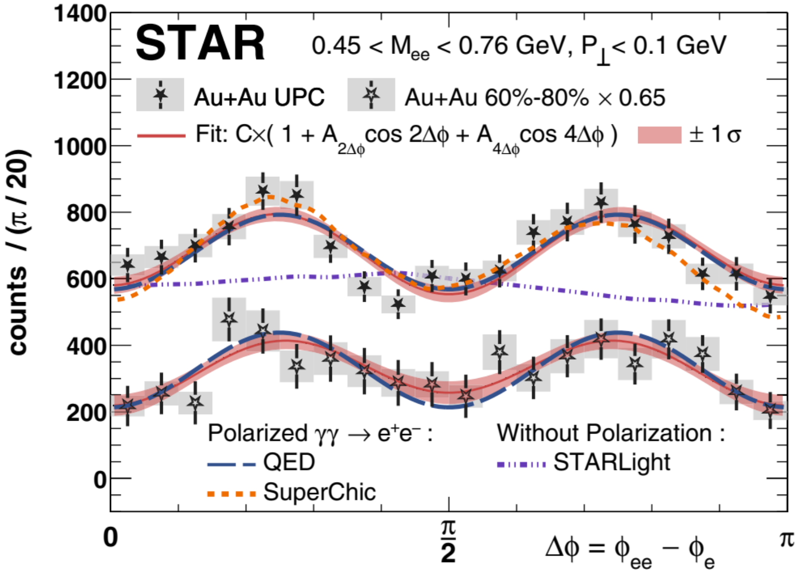
ALICE Collaboration

PHYSICAL REVIEW LETTERS **121,** 212301 (2018)

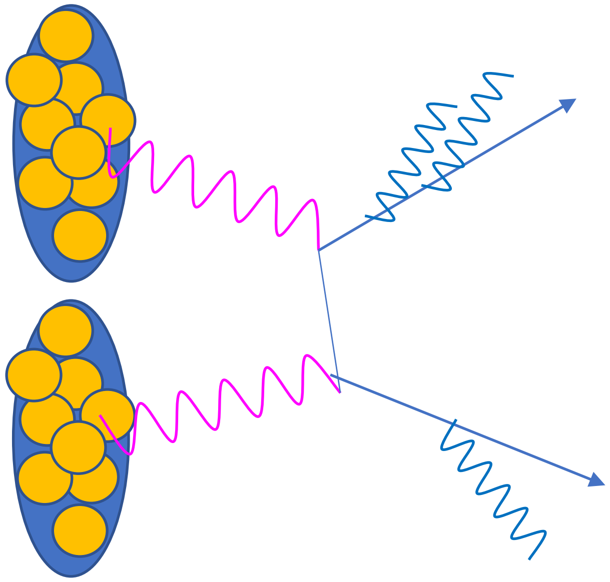
Observation of Centrality-Dependent Acoplanarity for Muon Pairs Produced via Two-Photon Scattering in Pb + Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS Detector

M. Aaboud *et al.**

(ATLAS Collaboration)



Soft photon resummation in UPC

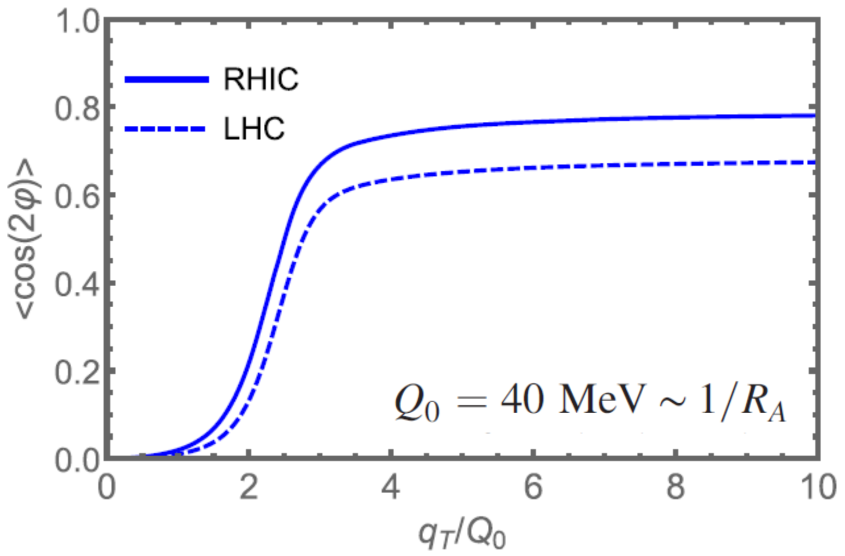


Linearly polarized photon→ $\cos 2\phi$ correlation in lepton pairs

Background from QED soft photon radiation

Large anisotropy $\frac{c_2}{c_0} = \frac{\ln \frac{k_\perp}{2m}}{\ln \frac{2k_\perp}{m}} \sim \mathcal{O}(1)$ $\quad R \leftrightarrow m/k_\perp$

Resummation Klein, Mueller, Xiao, Yuan (2020);
YH, Xiao, Yuan, Zhou (2021)



linearly polarized photon distribution dominates when

$$q_\perp < 100\,\mathrm{MeV}$$

At larger momentum, the final state radiation dominates.

Conclusions

- Multi-dimensional tomography (TMD, GPD, Wigner) important theme at the EIC, preview at LHC via UPC
- New distributions often probed in jet angular correlations.
- Things took an interesting turn after the CMS measurement. Soft gluon radiations can overwhelm the signal. Interesting in its own right.
- Dijet total momentum $\vec{q}_\perp = \vec{k}_{1\perp} + \vec{k}_{2\perp}$ very sensitive to higher order corrections, cannot be a proxy for $\vec{\Delta}_\perp$