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Azimuthal asymmetries in lepton and heavy-quark pair production in UPCs

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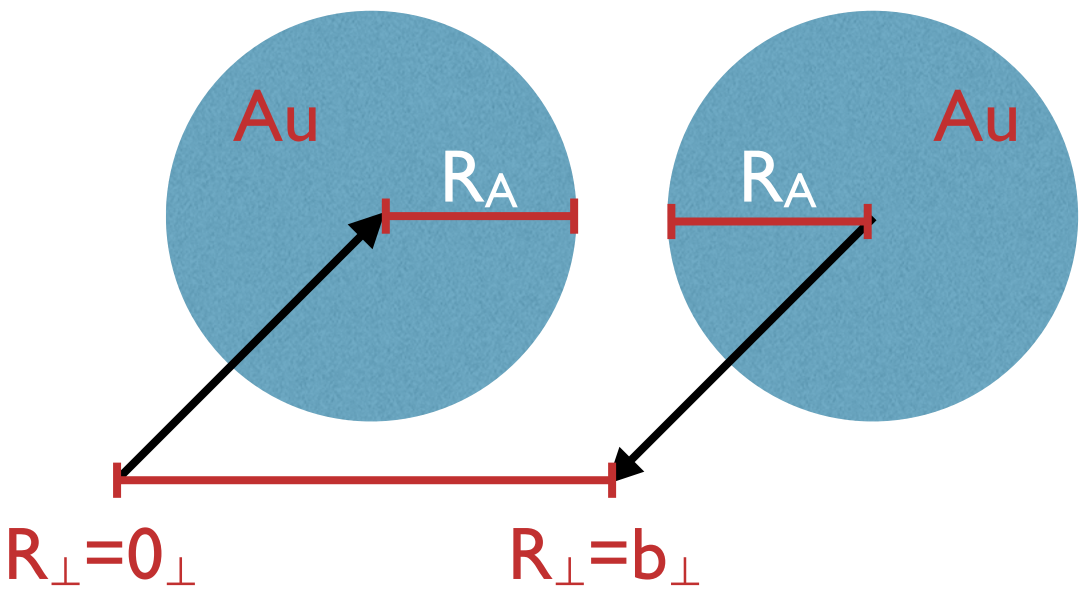


QCD evolution 2026, El Escorial, May 14, 2026

Photon-photon scattering in UPCs

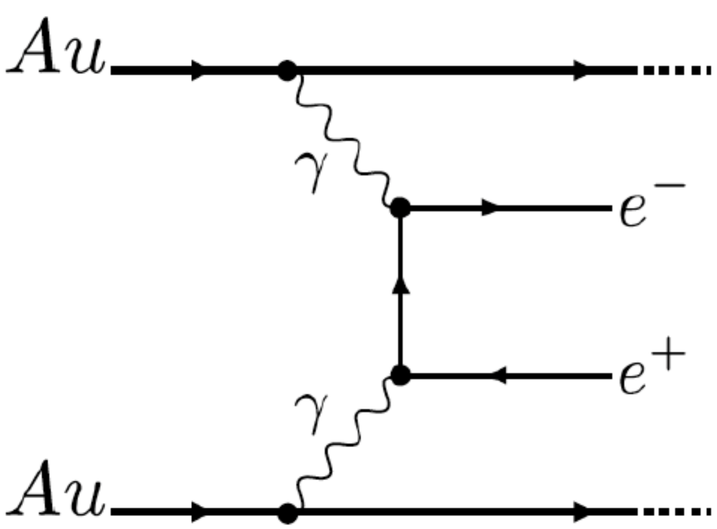
In Ultra-Peripheral Collisions of two highly charged relativistic ions, the ions themselves do not collide but rather their electromagnetic fields

The photons are nearly real ($Q^2 < 1/R_A^2 \sim 10^{-3}$ GeV^2) → light-by-light scattering

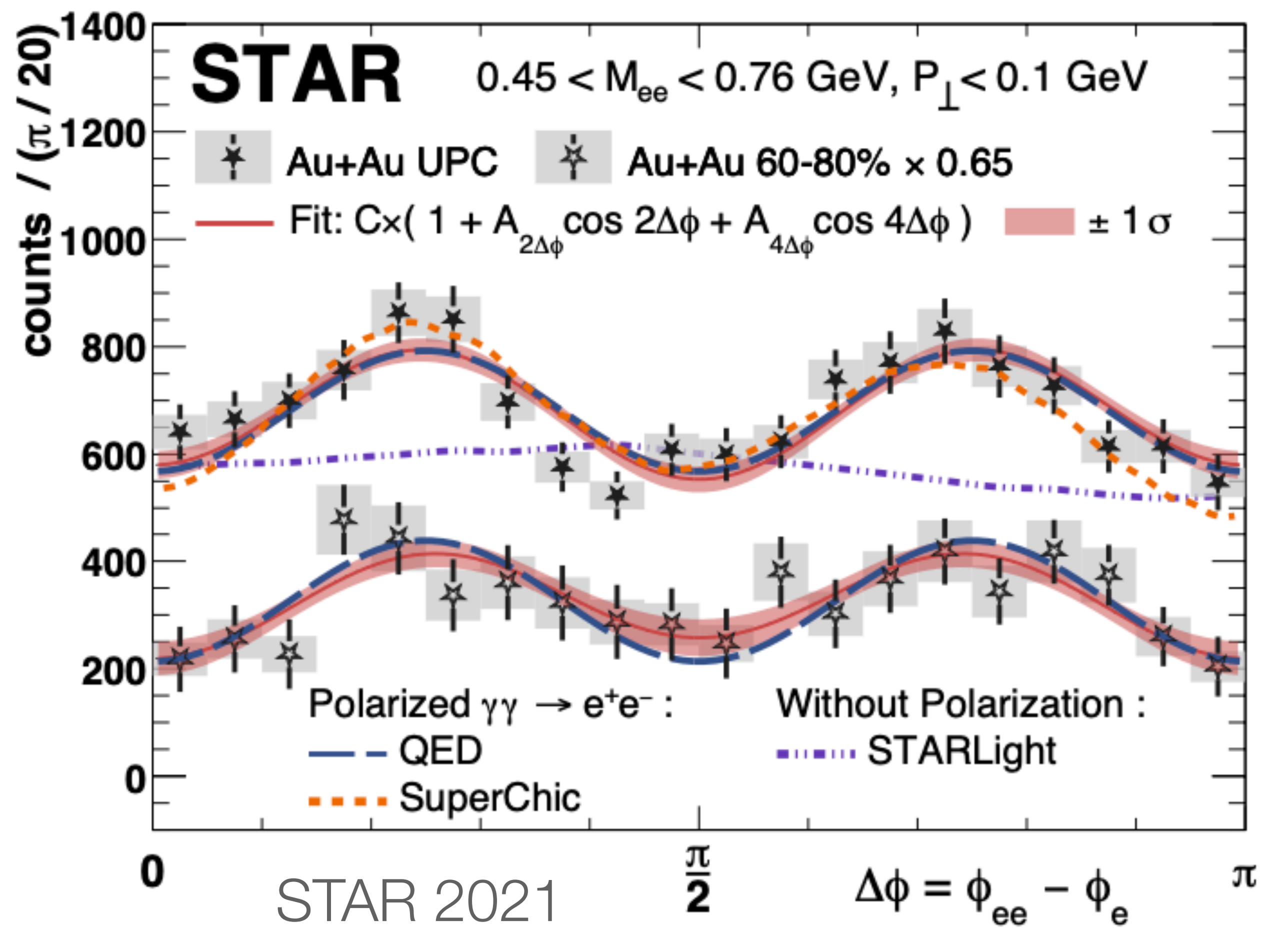
A mostly QED topic, but it is instructive to compare it to the small-x gluon case

In the photon-photon collision e^+e^- pairs can be produced, but due to the high center of mass energy also muon & heavy quark pairs

Breit-Wheeler process



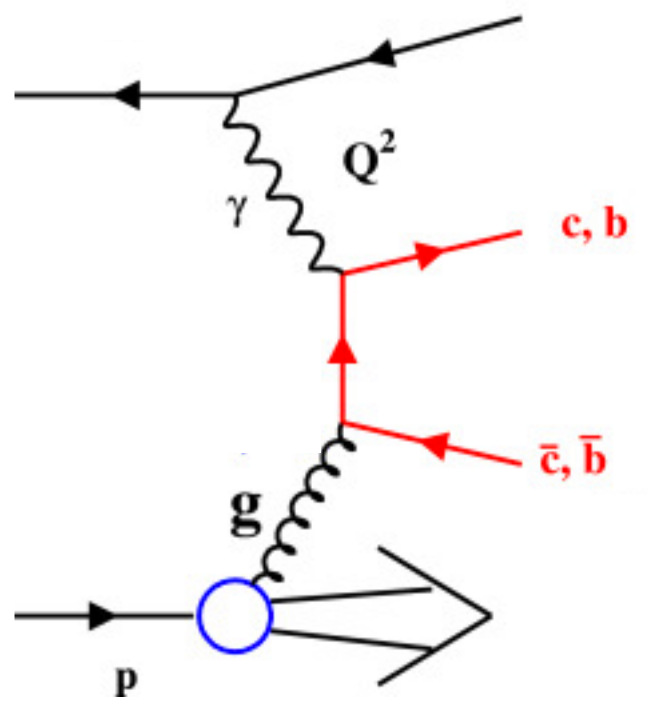
RHIC data shows a 17±3 % $\cos 4\phi$ asymmetry in e^+e^- pair production



Angles

Which angle enters in this $\cos 4\phi$?

Recall open heavy quark electroproduction



The heavy quarks will not be exactly back-to-back in the transverse plane:

$$K_\perp = (K_{Q\perp} - K_{\bar{Q}\perp})/2$$

$$q_T = K_{Q\perp} + K_{\bar{Q}\perp}$$

$$|q_T| \ll |K_\perp|$$

ϕ_q, ϕ_K are the angles of q_T, $K_\perp$

Linear gluon polarization ($h_1^{\perp g}$) shows up as a $\cos 2\phi_{qK}$ distribution

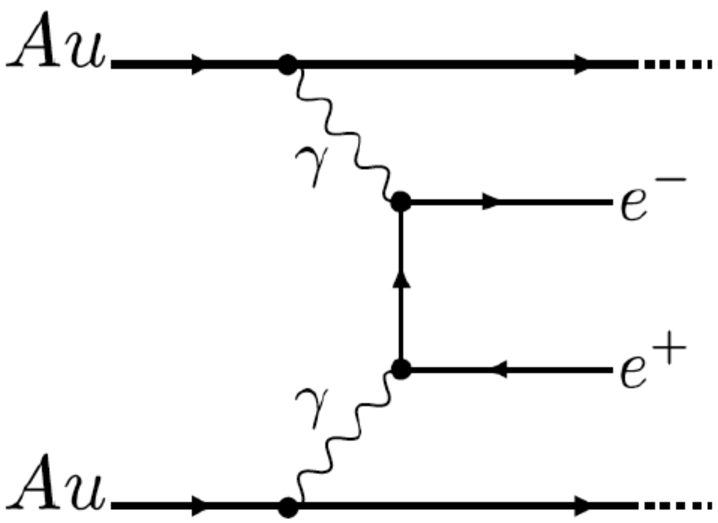
DB, Brodsky, Mulders & Pisano, 2010

Similarly, linear photon polarization will lead to such asymmetries in UPCs

For helicity flip on both heavy ion sides: $\cos 4\phi_{qK} \rightarrow$ STAR data

Angles

In this process there are actually 3 angles, besides the ones of the sum and the difference of the lepton transverse momenta: q_T and $K_\perp$



$$|q_T| \ll |K_\perp|$$

ϕ_q , ϕ_K are the angles of q_T, $K_\perp$

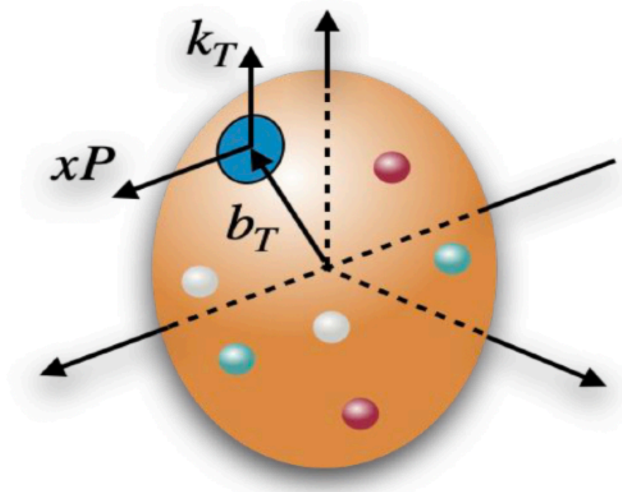
There is also the orientation of the impact parameter b_T (in analogy to the lepton plane for electroproduction)

There will be angular modulations in ϕ_{qK} , ϕ_{bK}, ϕ_{qb}

Shi, Chen, Wei & Xiao, 2025; DB, Maxia & Pisano, 2025

The differential cross section can be expressed in terms of Generalized Transverse Momentum Dependent (GTMD) photon distributions

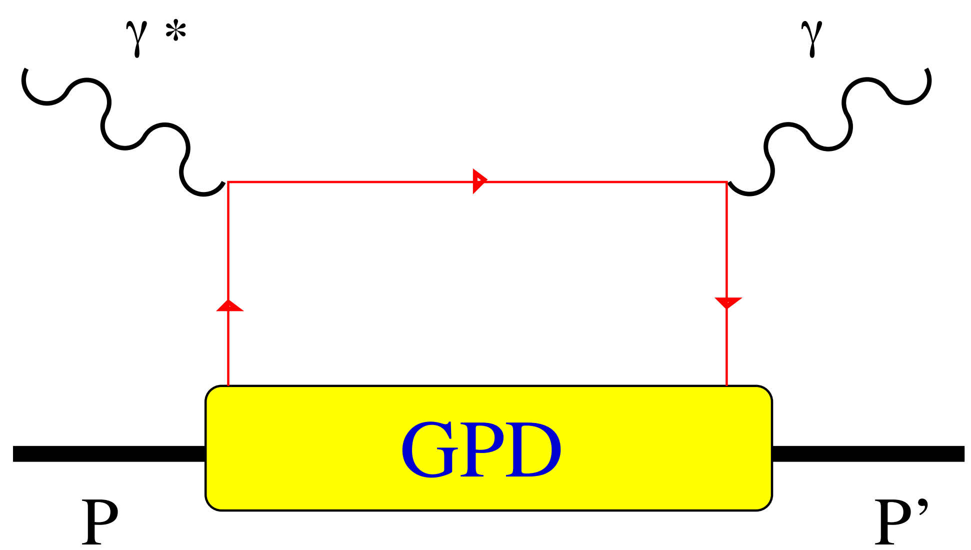
Correlators



One probes the photon distribution f(x,k_T,b_T)

This is the TMD generalization of the impact parameter dependent GPD f(x,b_T), which is a Fourier transform of an off-forward distribution (P’ ≠ P)

DVCS



GPDs provide information about the spatial distribution of partons inside nucleons

b_T is *not* the Fourier conjugate of k_T

$b_\perp$ = transverse spatial distance w.r.t. the “center” of the nucleon

The transverse center of longitudinal momentum:

$$\mathbf{R}_\perp^{CM} = \sum_i x_i \mathbf{r}_{\perp i}$$

[Soper, 1977; Burkardt, 2000]

Impact parameter dependent GPDs

Impact parameter dependent quark GPD [Burkardt, 2000]

$$q(x, \boldsymbol{b}_\perp) = \int \frac{d\lambda}{2\pi P^+} \, e^{i\lambda x} \, \langle P^+, \boldsymbol{R}_\perp = 0 | \, \overline{\psi}(-\frac{\lambda}{2}n + \boldsymbol{b}_\perp) \, \gamma^+ \, \mathcal{L} \, \psi(\frac{\lambda}{2}n + \boldsymbol{b}_\perp) \, | P^+, \boldsymbol{R}_\perp = 0 \rangle$$

Normalized proton state localized in the spatial $\perp$ direction for some wave packet Φ

$$|P^+, \boldsymbol{R}_\perp = 0\rangle = \mathcal{N} \int \frac{d^2 \boldsymbol{P}_\perp}{(2\pi)^2} \Phi(\boldsymbol{P}_\perp) |P^+, \boldsymbol{P}_\perp\rangle$$

The wave packet must be sufficiently localized in transverse position space, in order to be viewed as the FT of a GPD:

$$q(x, \boldsymbol{b}_\perp) \approx \int \frac{d^2 \boldsymbol{\Delta}_\perp}{(2\pi)^2} \, e^{-i\boldsymbol{b}_\perp \cdot \boldsymbol{\Delta}_\perp} \, H(x, 0, -\boldsymbol{\Delta}_\perp^2)$$

↑

$\Phi(\boldsymbol{P}_\perp + \boldsymbol{\Delta}_\perp) \approx \Phi(\boldsymbol{P}_\perp)$

[Burkardt, 2000; Diehl, 2002]

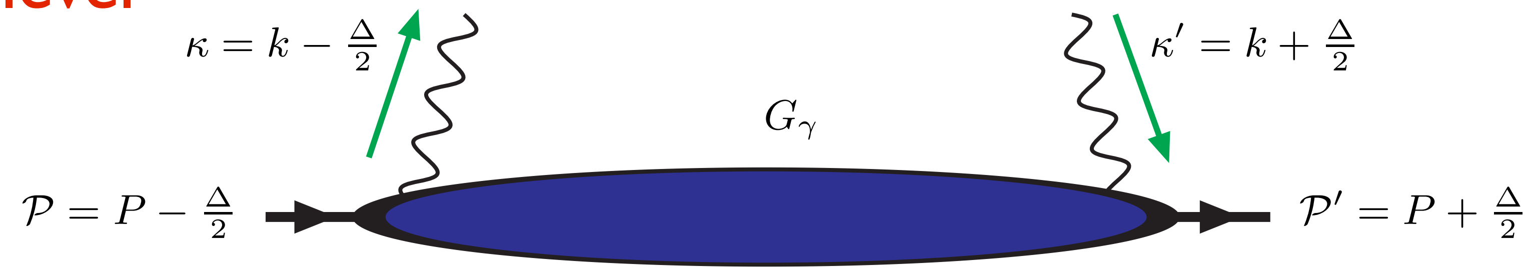
Ensured in the $P^+ \rightarrow \infty$ (IMF) limit

For ξ=0 one has a density interpretation [Burkardt 2000]

Crucial point here: not diagonal in transverse momentum space

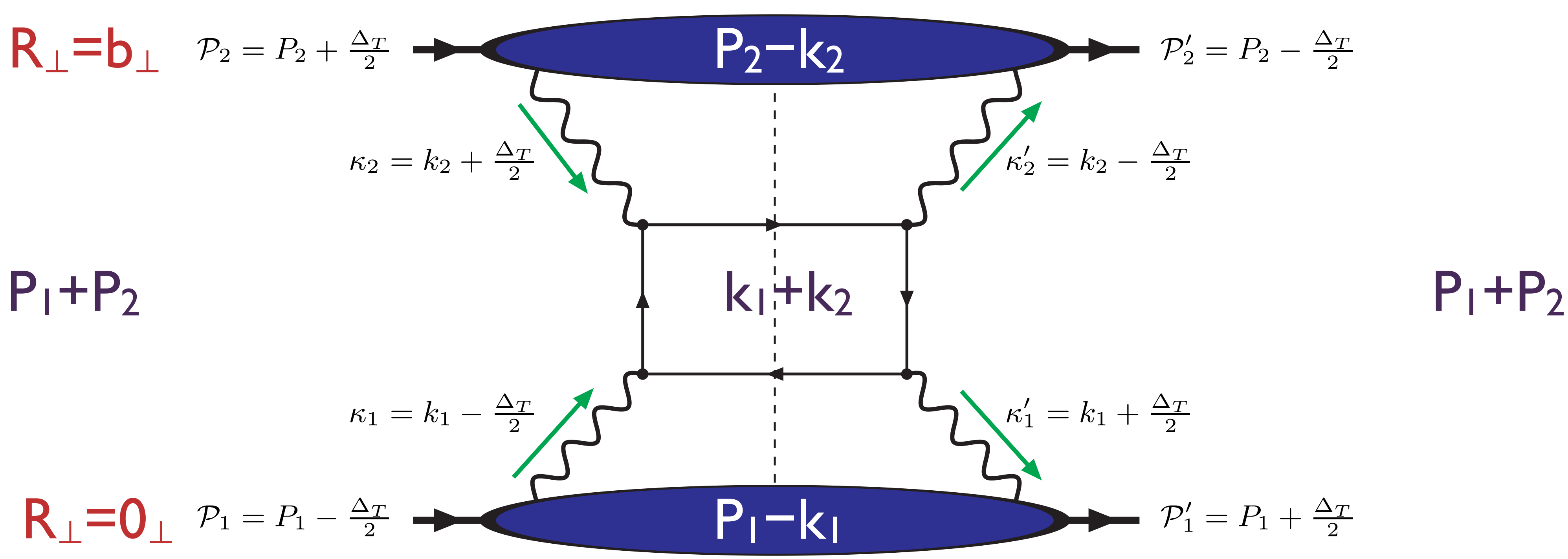
Correlators

Like in DVCS we consider off-forward matrix elements in UPCs, but unlike DVCS this is not on the amplitude level



The correlator is not a matrix element of transverse momentum eigenstates, as a consequence there is interference between states with different transverse momenta and unlike QCD processes there are no constraints from the color flow

The cross section -rather than the amplitude- now contains two GTMDs:



$\xi=0$ necessarily though (they *are* eigenstates of P^+)

GTMD description

This description is a TMD extension of the one in terms of photon distributions $n(\omega, b_\perp)$ by Vidovic, M. Greiner, Best & Soff, 1993

The description of $d\sigma_{AA}/db_T$ in terms of impact parameter photon GPD $f_{\gamma/A}(x, b_T)$ or $\omega\, n(\omega, b_T) = x\, f_{\gamma/A}(x, b_T)$, was considered in several studies

Vidovic, M. Greiner, Best & Soff, 1993; Hencken, Trautmann & Baur, 1995; Zha *et al*, 2018

Recently the extension with transverse momentum dependence (GTMDs with ξ=0) received quite some attention

Li, J. Zhou & Y.-J. Zhou, 2020; Xiao, F. Yuan & J. Zhou, 2020; Wang, Pu, Wang, 2021;
Mazurek, Kłusek-Gawenda & Szczurek, 2022; Shao, Zhang, J. Zhou & Y.-J. Zhou, 2023

Full angular dependence was considered by Shi, Chen, Wei & Xiao 2025;
DB, Maxia & Pisano, 2025

The forward limit $\gamma\gamma \to Q\bar{Q}$ and $\ell^+\ell^-$ was considered by Pisano *et al*, 2013

Photon GTMDs

The helicity states of the ions (whatever their spin) is summed over

In that case there are only 4 GTMDs, like for gluons

Lorcé, Pasquini, 2013; More, Mukherjee, Nair, 2018; DB, van Daal, Mulders, Petreska, 2018

$$G_\gamma^{ij}(x,\boldsymbol{k}_T,\boldsymbol{\Delta}_T) = \frac{1}{2x}\left(\delta_T^{ij}\,\mathcal{F}_1^\gamma + \frac{k_T^{ij}}{M^2}\,\mathcal{F}_2^\gamma + \frac{\Delta_T^{ij}}{M^2}\,\mathcal{F}_3^\gamma + \frac{k_T^{[i}\Delta_T^{j]}}{M^2}\,\mathcal{F}_4^\gamma\right)$$

$$a_T^{ij} \equiv a_T^i a_T^j - \frac{1}{2}a_T^2\delta_T^{ij}$$

Each photon GTMD $\mathcal{F}_i^\gamma(x,k_T,\Delta_T)$ can have a $k_T \cdot \Delta_T$ dependence, related to OAM

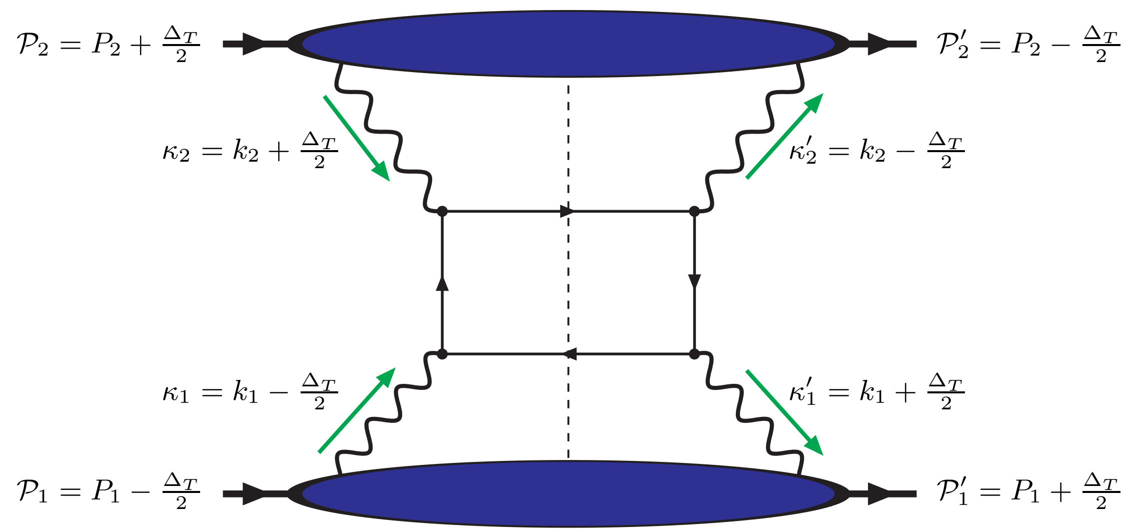
The effect of gauge links for this QED case will be ignored, such that the GTMDs will be strictly real and for $\xi=0$ they can only depend on **even** powers of $k_T \cdot \Delta_T$

$$\mathcal{F}_i^\gamma(x,\boldsymbol{k}_T^2,\boldsymbol{\Delta}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{\Delta}_T) = \sum_{m=0}^{\infty} F_i^{\gamma\,(2m)}\,\cos^{2m}\phi_{k\Delta}$$

Fourier transform of $m=1$ part is referred to as elliptic Wigner distribution

Differential cross sections

$d^2\sigma/d^2\Delta_T$



The expression for $d^2\sigma/d^2\Delta_T$ in terms of GTMDs is quite compact:

$$\frac{\mathrm{d}\sigma}{\mathrm{dPS}\,\mathrm{d}^2\boldsymbol{\Delta}_T} = \frac{\alpha^2}{s_{NN}M_T^2}\Big[F^0 + F^{\cos 2\phi_{q\Delta}}\cos 2\phi_{q\Delta} + F^{\sin 2\phi_{q\Delta}}\sin 2\phi_{q\Delta}$$
$$+ F^{\cos 2\phi_{qK}}\cos 2\phi_{qK} + F^{\sin 2\phi_{qK}}\sin 2\phi_{qK} + F^{\cos 2\phi_{\Delta K}}\cos 2\phi_{\Delta K}$$
$$+ F^{\cos 4\phi_{qK}}\cos 4\phi_{qK} + F^{\sin 4\phi_{qK}}\sin 4\phi_{qK} + F^{\cos 4\phi_{\Delta K}}\cos 4\phi_{\Delta K}$$
$$+ F^{\cos 2(\phi_{qK}+\phi_{\Delta K})}\cos 2(\phi_{qK}+\phi_{\Delta K}) + F^{\sin 2(\phi_{qK}+\phi_{\Delta K})}\sin 2(\phi_{qK}+\phi_{\Delta K})\Big]$$

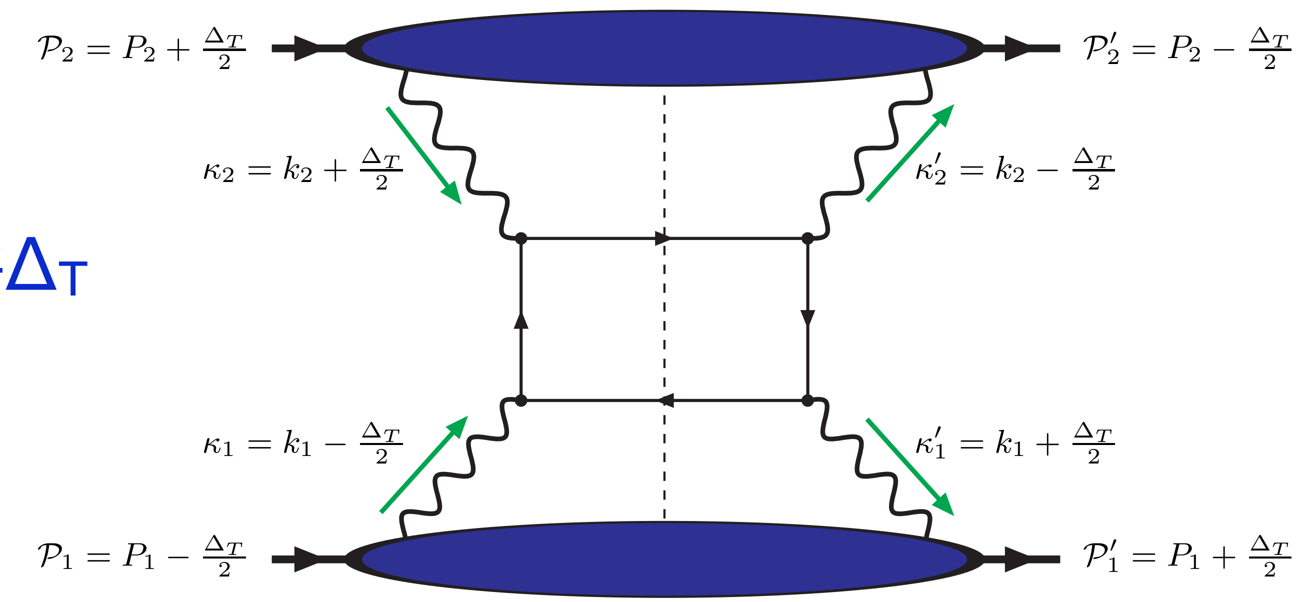
Here the structure functions are transverse momentum convolutions of $\mathcal{F}_i(x_1,k_{1T},\Delta_T)\mathcal{F}_j(x_2,k_{2T},-\Delta_T)$

The sine modulations are only present if the GTMDs have an imaginary part

Differential cross sections

However, the measured differential cross section is not as a function of off-forwardness Δ_T, since the recoil momenta of the ions are not measured

$d^2\sigma/d^2b_T$ = Fourier transform of $d^2\sigma/d^2\Delta_T$



One needs to consider $d^2\sigma/d^2b_T$, but this comes with two complications:

- UPCs require $b_T > 2\ R_A$ (for gold nuclei $R_A \approx 6.4$ fm)
- b_T is also not accessible directly; instead the number of participants is used as a proxy and bins of centrality are considered (UPCs have > 90%)

Therefore, we consider $\int d^2b_T\ d^2\sigma/d^2b_T$ under the condition $b_T > 2\ R_A$

Differential cross sections

$d^2\sigma/d^2\Delta_T$	$d^2\sigma/d^2b_T$
not measured	measured to some extent
harmonics up to $4\phi_\Delta$	harmonics in all $n\phi_b$

What causes this difference?

The GTMD $\mathcal{F}(x,k_T,\Delta_T)$ can have a $k_T \cdot \Delta_T$ dependence, which removes the one-to-one correspondence between harmonics in ϕ_Δ and ϕ_b

The sine modulations only appear when there are odd powers of $k_T \cdot \Delta_T$

Differential cross sections

Since the photon GTMDs are real and ξ=0, there is only dependence on even powers of $k_T \cdot \Delta_T$:

$$\mathcal{F}_i^\gamma(x, \boldsymbol{k}_T^2, \boldsymbol{\Delta}_T^2, \boldsymbol{k}_T \cdot \boldsymbol{\Delta}_T) = \sum_{m=0}^{\infty} F_i^{\gamma\,(2m)} \cos^{2m}\phi_{k\Delta}$$

Due to the $m \neq 0$ terms one loses the one-to-one correspondence between harmonics in ϕ_Δ and ϕ_b, for example:

$$\frac{\mathrm{d}\sigma}{\mathrm{dPS}\,\mathrm{d}^2\boldsymbol{\Delta}_T} = \frac{\alpha^2}{s_{NN} M_T^2}\left[F^0 + F^{\cos 2\phi_{q\Delta}}\cos 2\phi_{q\Delta} + \ldots\right]$$

For example for $m=1$, the angular integral for $\cos 2\phi_{\Delta q}$ gives:

$$\int_0^{2\pi} \mathrm{d}\phi_\Delta\, \mathrm{e}^{ib_T\Delta_T\cos\phi_{\Delta b}}\,\cos 2\phi_{\Delta q}\,\cos^2\phi_{\Delta q}$$
$$= \pi\left(\frac{1}{2}J_0(b_T\,\Delta_T) - J_2(b_T\,\Delta_T)\cos 2\phi_{bq} + \frac{1}{2}J_4(b_T\,\Delta_T)\cos 4\phi_{bq}\right)$$

$m \neq 0$ terms feed into higher *and* lower harmonics

DB, Maxia & Pisano, 2025

Differential cross sections

For m=0 and neglecting lepton masses one obtains

$$\frac{\mathrm{d}\sigma}{\mathrm{dPS}\,\mathrm{d}^2\boldsymbol{b}_T} \approx \frac{\alpha^2}{s_{NN}M_T^2}\int\frac{\mathrm{d}\boldsymbol{\Delta}_T^2}{4\pi}\Big\{J_0(b_T\,\Delta_T)\Big[F^0 + F^{\cos 2\phi_{qK}}\cos 2\phi_{qK} + F^{\cos 4\phi_{qK}}\cos 4\phi_{qK}\Big] - J_2(b_T\,\Delta_T)\Big[F^{\cos 2\phi_{\Delta K}}\cos 2\phi_{bK} + F^{\cos 2\phi_{q\Delta}}\cos 2\phi_{qb} + F^{\cos 2(\phi_{qK}+\phi_{\Delta K})}\cos 2(\phi_{qK}+\phi_{bK})\Big] + J_4(b_T\,\Delta_T)\,F^{\cos 4\phi_{\Delta K}}\cos 4\phi_{bK}\Big\}\,.$$

Including $m \neq 0$ the angular independent term in $d^2\sigma/d^2b_T$ will receive contributions from angular dependent terms in $d^2\sigma/d^2\Delta_T$

$$\widetilde{F}^0 = \int\frac{\mathrm{d}^2\boldsymbol{\Delta}_T}{8\pi}\frac{\mathrm{d}^2\boldsymbol{b}_T}{2\pi}\,\mathrm{d}\overline{\mathrm{PS}}\,\mathrm{e}^{-i\boldsymbol{b}_T\cdot\boldsymbol{\Delta}_T}\Big[F^0 + F^{\cos 2\phi_{q\Delta}}\cos 2\phi_{q\Delta} + F^{\sin 2\phi_{q\Delta}}\sin 2\phi_{q\Delta}\Big]$$

$$\mathrm{d}\overline{\mathrm{PS}} = \mathrm{d}y_1\,\mathrm{d}y_2\,\mathrm{d}K_T^2\,\mathrm{d}q_T^2\,\mathrm{d}\phi_q$$

Restricting to just the angular independent terms leads to an incomplete result

DB, Maxia & Pisano, 2025

Differential cross sections

Circular polarization ($\mathcal{F}_4$) enters in:

$$
\begin{aligned}
F^0 &= 2\left[z^2 + (1-z)^2 + 4z\,(1-z)\,\frac{M_\ell^2}{M_T^2}\left(1-\frac{M_\ell^2}{M_T^2}\right)\right]\mathcal{C}[\mathcal{F}_1^\gamma\,\mathcal{F}_1^\gamma] \\
&\quad - z\,(1-z)\frac{M_\ell^4}{M_T^4}\left(\mathcal{C}[w_0^{22}\,\mathcal{F}_2^\gamma\,\mathcal{F}_2^\gamma] + \frac{\mathbf{\Delta}_T^4}{M_N^4}\mathcal{C}[\mathcal{F}_3^\gamma\,\mathcal{F}_3^\gamma]\right) \\
&\quad + \left[z^2 + (1-z)^2\right]\left(1 - 2\frac{M_\ell^2}{M_T^2}\right)\frac{\mathbf{\Delta}_T^2}{M_N^2}\,\mathcal{C}[w_0^{44}\,\mathcal{F}_4^\gamma\,\mathcal{F}_4^\gamma]\,, \\
F^{\cos 2\phi_{q\Delta}} &= -\frac{\mathbf{\Delta}_T^2}{M_N^2}\bigg\{\left[z^2 + (1-z)^2\right]\left(1 - 2\frac{M_\ell^2}{M_T^2}\right)\mathcal{C}[w_{c2}^{44}\mathcal{F}_4^\gamma\mathcal{F}_4^\gamma] \\
&\qquad + z\,(1-z)\,\frac{M_\ell^4}{M_T^4}\,\mathcal{C}[w_{c2}^{23}\,\mathcal{F}_2^\gamma\,\mathcal{F}_3^\gamma + w_{c2}^{32}\,\mathcal{F}_3^\gamma\,\mathcal{F}_2^\gamma]\bigg\}\,, \\
F^{\sin 2\phi_{q\Delta}} &= -\frac{\mathbf{\Delta}_T^2}{M_N^2}\bigg\{\left[z^2 + (1-z)^2\right]\left(1 - 2\frac{M_\ell^2}{M_T^2}\right)\mathcal{C}[w_{s2}^{44}\mathcal{F}_4^\gamma\mathcal{F}_4^\gamma] \\
&\qquad + z\,(1-z)\,\frac{M_\ell^4}{M_T^4}\,\mathcal{C}[w_{s2}^{23}\,\mathcal{F}_2^\gamma\,\mathcal{F}_3^\gamma + w_{s2}^{32}\,\mathcal{F}_3^\gamma\,\mathcal{F}_2^\gamma]\bigg\}\,,
\end{aligned}
$$

$$
\widetilde{F}^0 = \int \frac{\mathrm{d}^2\mathbf{\Delta}_T}{8\pi}\,\frac{\mathrm{d}^2\boldsymbol{b}_T}{2\pi}\,\mathrm{d}\overline{\mathrm{PS}}\,\mathrm{e}^{-i\boldsymbol{b}_T\cdot\mathbf{\Delta}_T}\left[F^0 + F^{\cos 2\phi_{q\Delta}}\cos 2\phi_{q\Delta} + F^{\sin 2\phi_{q\Delta}}\sin 2\phi_{q\Delta}\right]
$$

DB, Maxia & Pisano, 2025

Model & predictions

Model

To arrive at predictions we consider an equivalent photon approximation (EPA) model (plane polarized photons) for the photon GTMD:

$$G_\gamma^{\mu\nu}(x, \boldsymbol{k}_T, 0, \boldsymbol{\Delta}_T) = \frac{\kappa_T^\mu \, \kappa_T'^\nu}{\boldsymbol{\kappa}_T \cdot \boldsymbol{\kappa}_T'} \, \frac{f_{\gamma/A}(x, \boldsymbol{k}_T, \boldsymbol{\Delta}_T)}{x}$$

$$\kappa_T^\mu = k_T^\mu - \frac{\Delta_T^\mu}{2}$$

$$\kappa_T'^\mu = k_T^\mu + \frac{\Delta_T^\mu}{2}$$

$$\kappa_T^\mu \, \kappa_T'^\nu = -\frac{1}{2}\left(\boldsymbol{k}_T^2 - \frac{1}{4}\boldsymbol{\Delta}_T^2\right) g_T^{\mu\nu} + k_T^{\mu\nu} - \frac{1}{4}\Delta_T^{\mu\nu} + \frac{1}{2} k_T^{[\mu}\Delta_T^{\nu]}$$

This implies relations among the 4 GTMDs:

$$\mathcal{F}_1^\gamma = \frac{\boldsymbol{k}_T^2 - \frac{1}{4}\boldsymbol{\Delta}_T^2}{2M_N^2}\mathcal{F}_2^\gamma = -2\frac{\boldsymbol{k}_T^2 - \frac{1}{4}\boldsymbol{\Delta}_T^2}{M_N^2}\mathcal{F}_3^\gamma = \frac{\boldsymbol{k}_T^2 - \frac{1}{4}\boldsymbol{\Delta}_T^2}{M_N^2}\mathcal{F}_4^\gamma$$

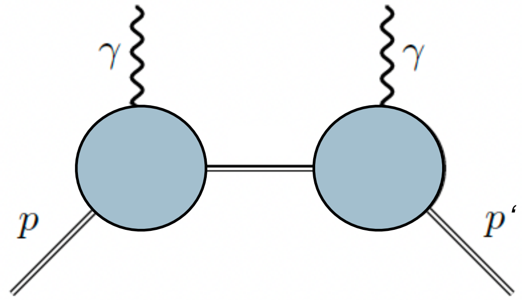
$$\mathcal{F}_1^\gamma(x, \boldsymbol{k}_T, \boldsymbol{\Delta}_T) = f_{\gamma/A}(x, \boldsymbol{k}_T, \boldsymbol{\Delta}_T)$$

This is analogous to the small-x gluon GTMD case for the dipole gauge link

Unlike in the forward limit (TMD case) one cannot say that the photons are 100% linearly polarized, since they also have circular polarization now

Model

Next we consider a model for the photon GTMD:



$$x f_{\gamma/A}(x, \boldsymbol{k}_T, \boldsymbol{\Delta}_T) = \frac{Z^2\alpha}{\pi^2} \frac{\boldsymbol{\kappa}_T \cdot \boldsymbol{\kappa}'_T}{M(x, \kappa_T, \varepsilon) M(x, \kappa'_T, \varepsilon)} F_A(\boldsymbol{\kappa}_T^2 + x^2 M_N^2) F_A^*(\boldsymbol{\kappa}'^2_T + x^2 M_N^2)$$

$F_A(k^2)$ = nuclear form factor, describes the photon source

We have introduced a parameter ε to investigate the effect of the angular dependence of the GTMD:

$$M(x, \kappa_T, \varepsilon) = \boldsymbol{\kappa}_T^2 + (1-\varepsilon)\, \boldsymbol{k}_T \cdot \boldsymbol{\Delta}_T + x^2 M_N^2$$

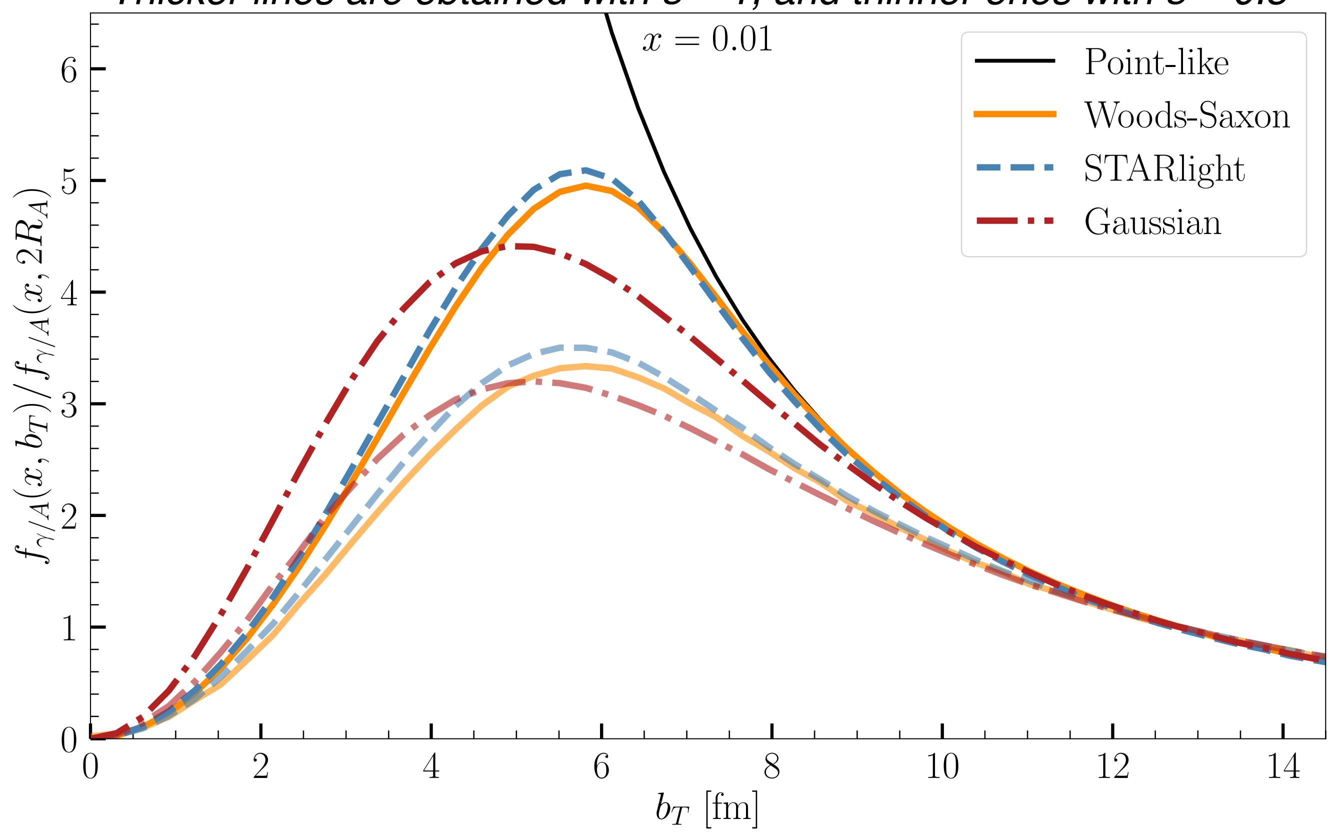
For ε=1 it is the model for $f(x,k_T,b_T)$ employed by Klein, Mueller, Xiao & F. Yuan, 2020

ε regulates the strength of the feed-in of harmonics of a given order into harmonics of a different order (ε = 0.5 already strongly suppresses that)

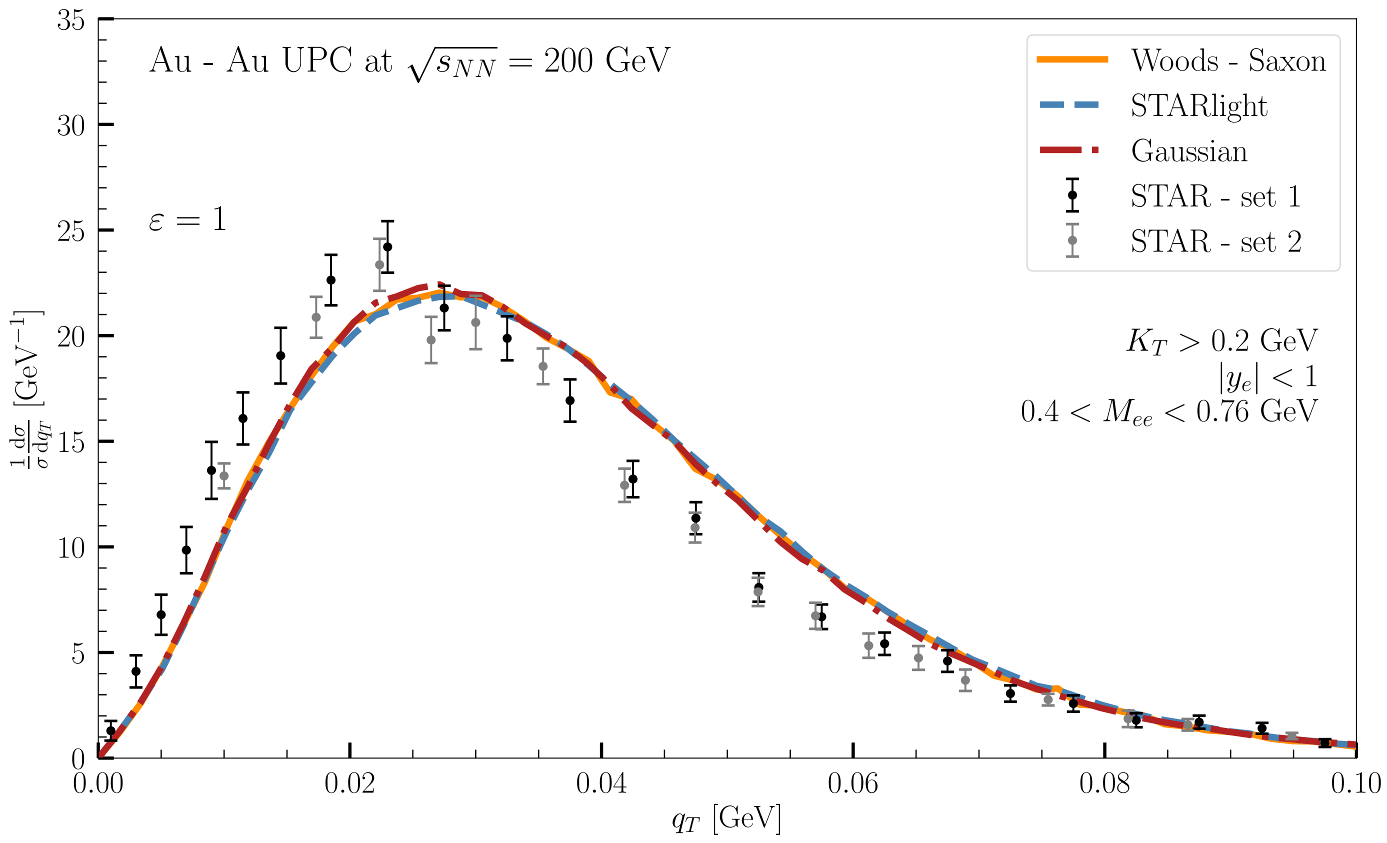
DB, Maxia & Pisano, 2025

Form factor

Thicker lines are obtained with ε = 1, and thinner ones with ε = 0.5



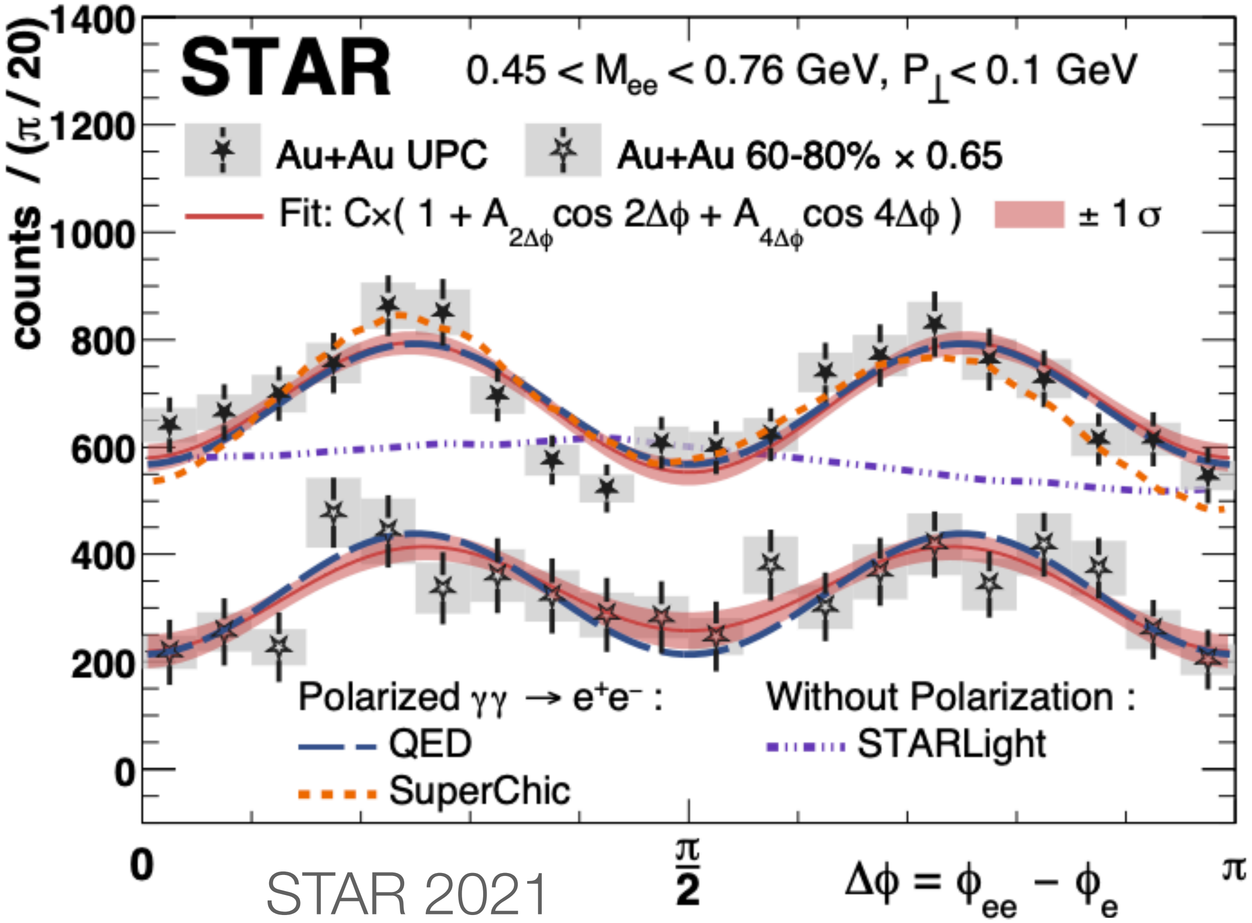
For $2R_A \approx 13$ fm, the various photon source distributions all approximately yield the same distribution

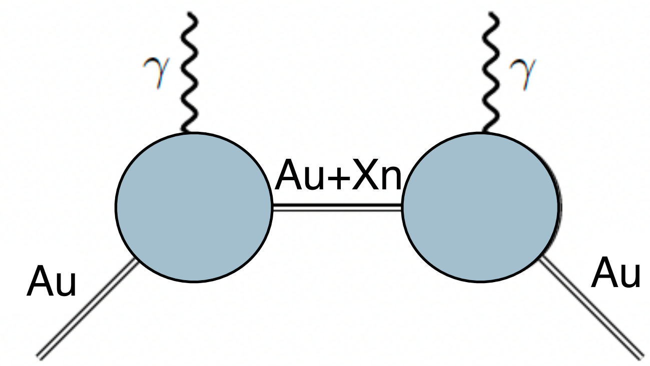


They all lead to the same qualitative description of the q_T distribution, which for the angular distribution is integrated over: $|q_T| \leq 0.1$ GeV

DB, Maxia & Pisano, 2025

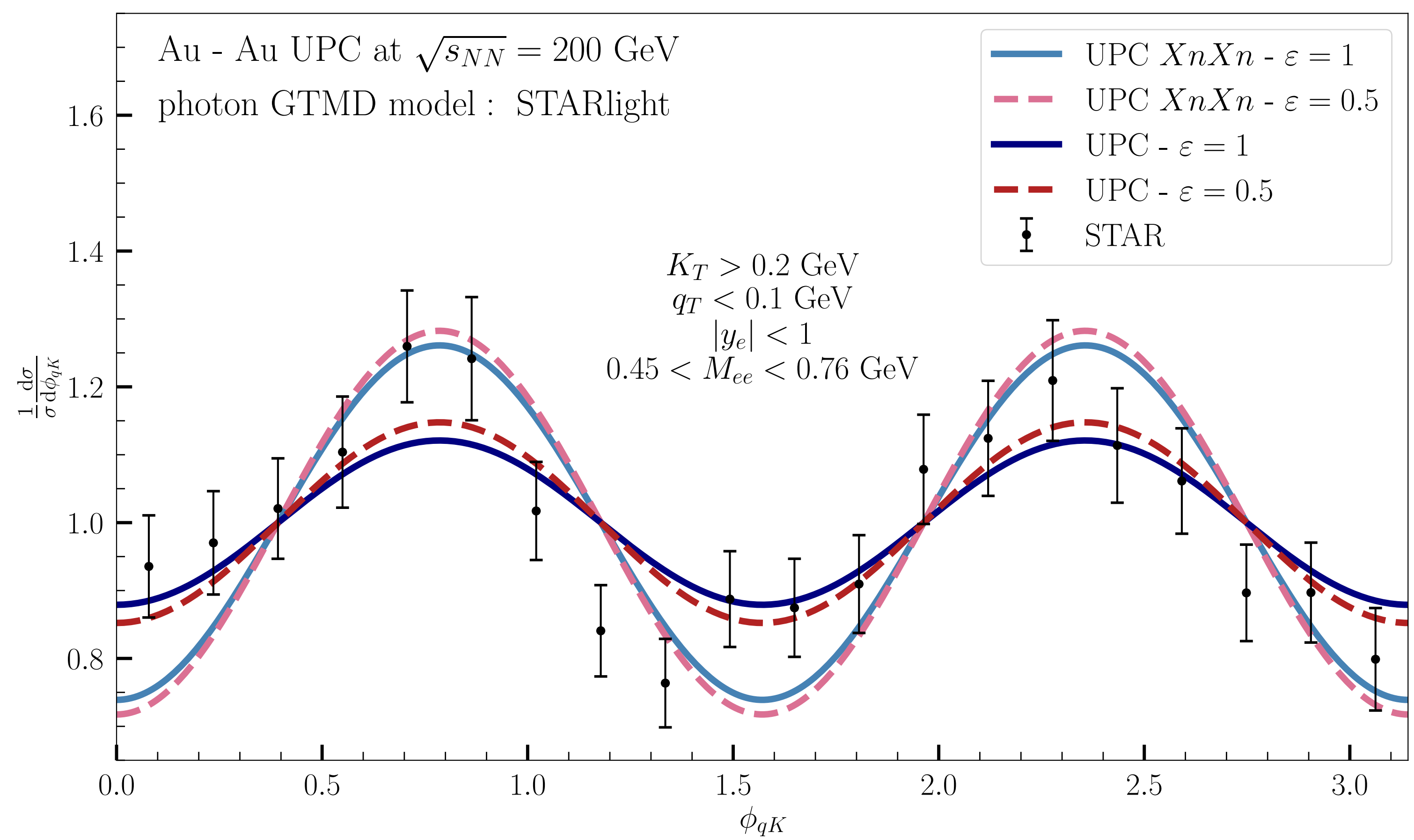
Angular distributions





Xn corresponds to "one or more neutrons" detected

DB, Maxia & Pisano, 2025



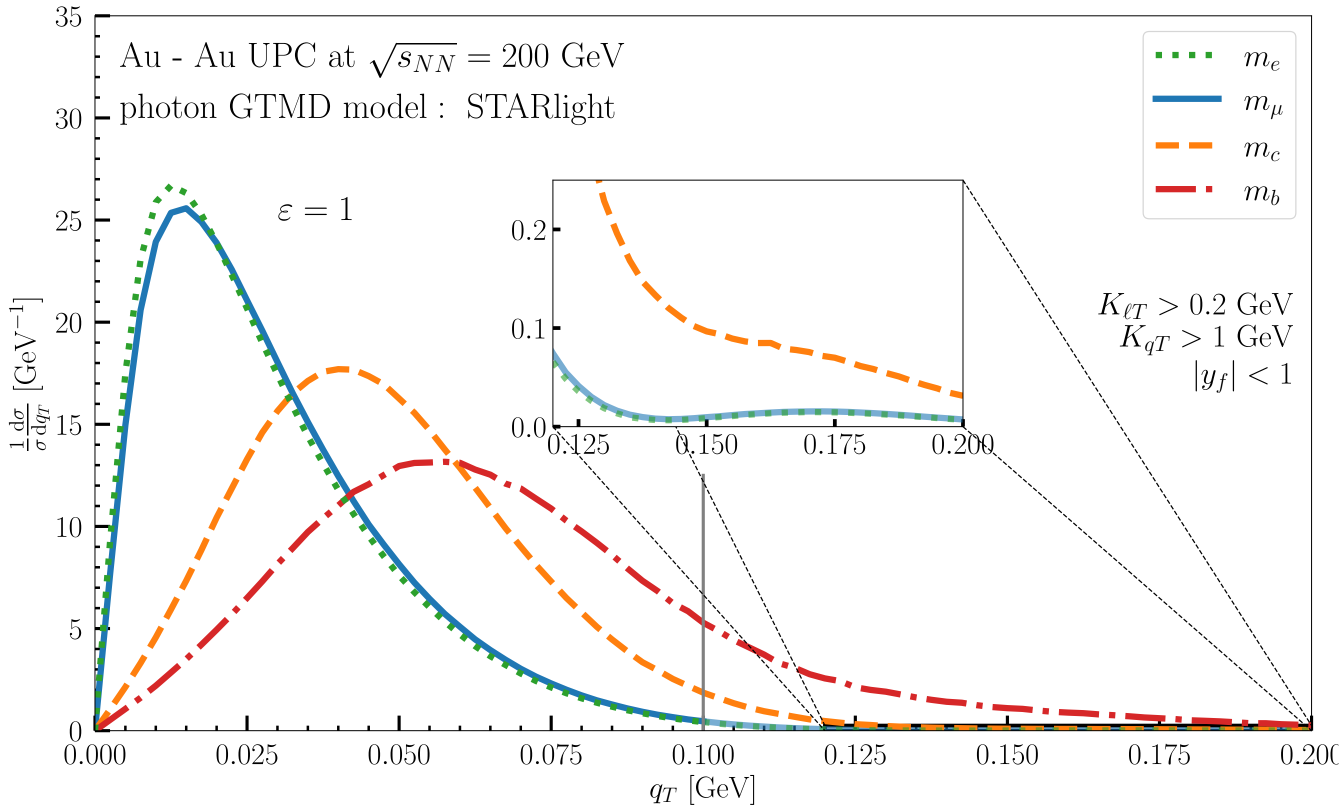
STAR (2021) for e^+e^-:

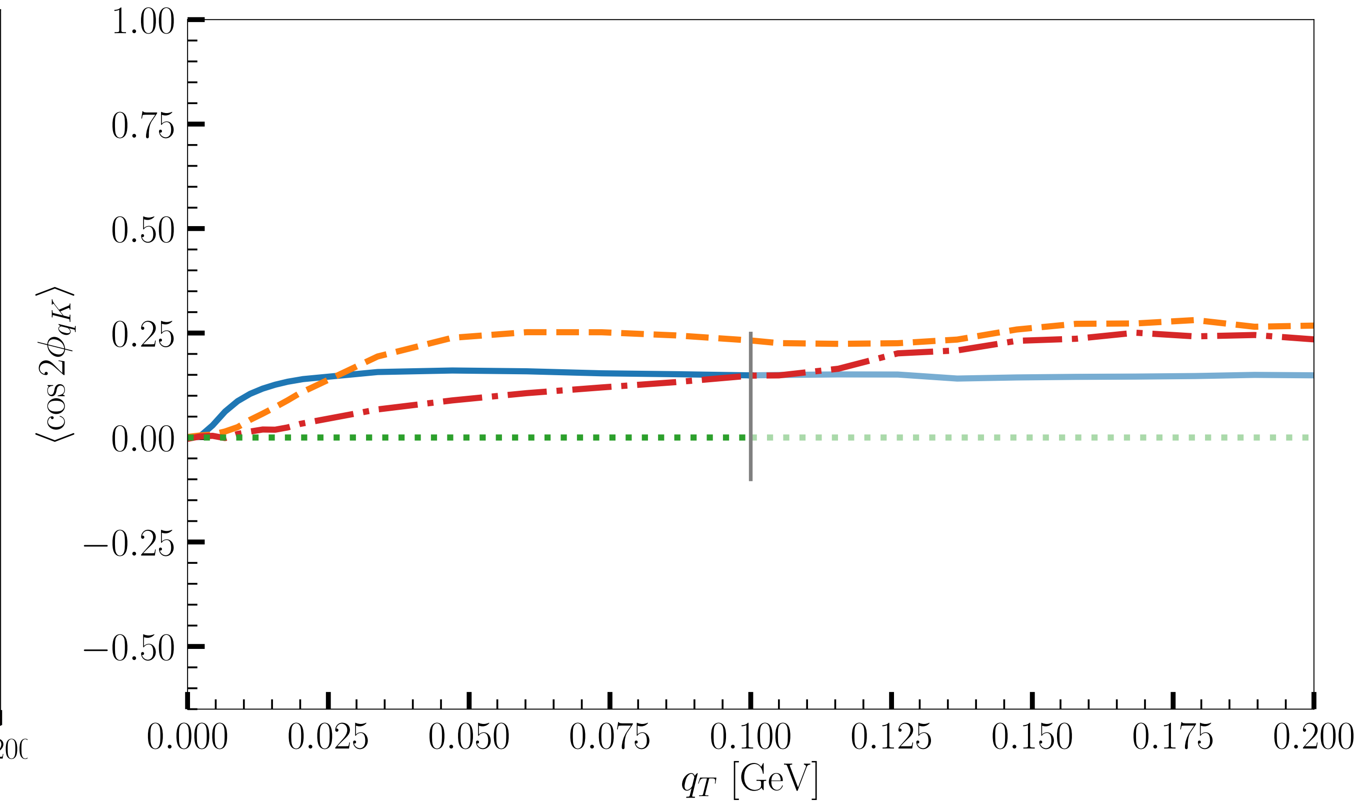
$\langle \cos 2\phi_{qK} \rangle$ = 2.0 ± 2.4 %

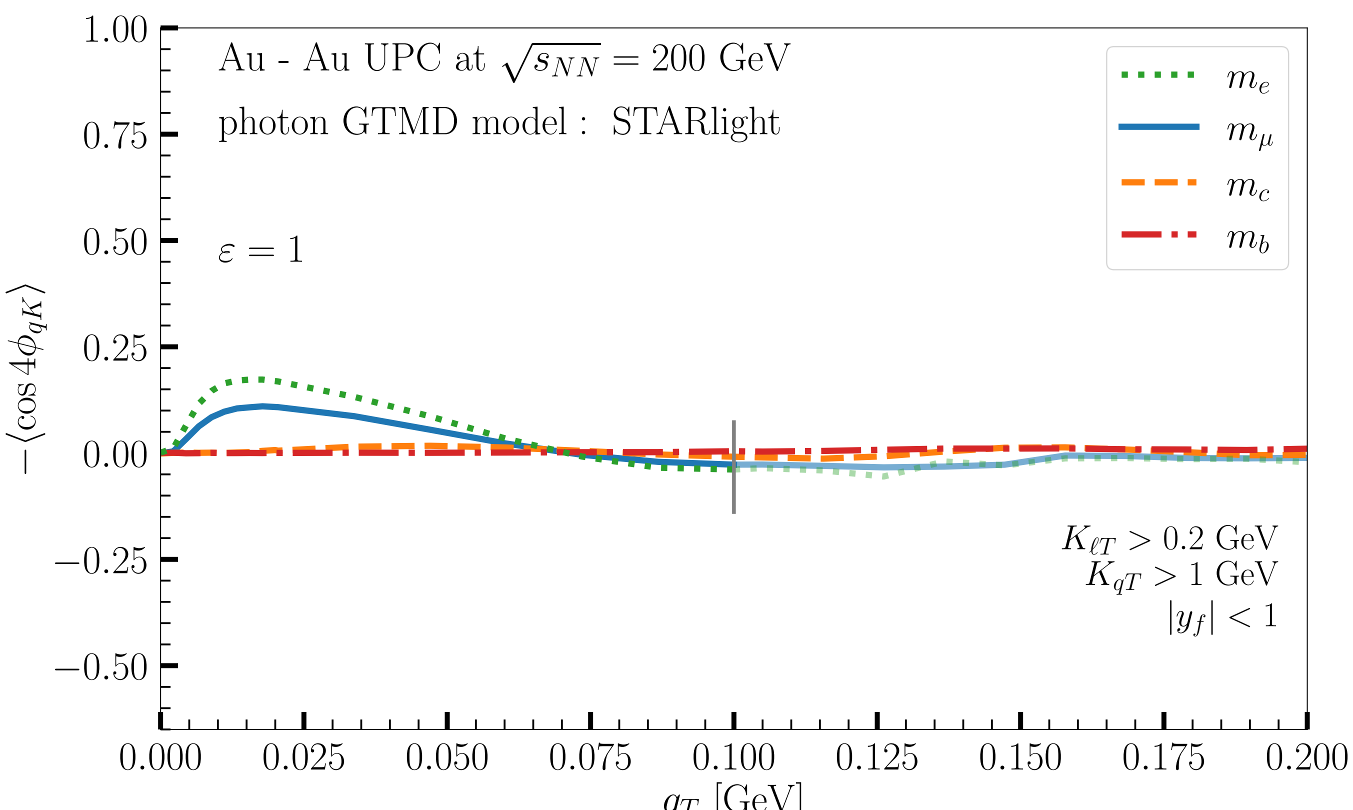
$\langle \cos 4\phi_{qK} \rangle$ = 16.8 ± 2.5 %

Mass dependence

$$\langle \cos\phi \rangle = 2\, \frac{\int \mathrm{d}\phi\, \mathrm{dPS}'\, \mathrm{d}\sigma\, \cos\phi}{\int \mathrm{d}\phi\, \mathrm{dPS}'\, \mathrm{d}\sigma}$$







model:

$\langle \cos 2\phi_{qK} \rangle$ small for ***e***, large for $\boldsymbol{\mu}$

$\langle \cos 4\phi_{qK} \rangle$ large for ***e***, large for $\boldsymbol{\mu}$

STAR (2021) for e^+e^-:

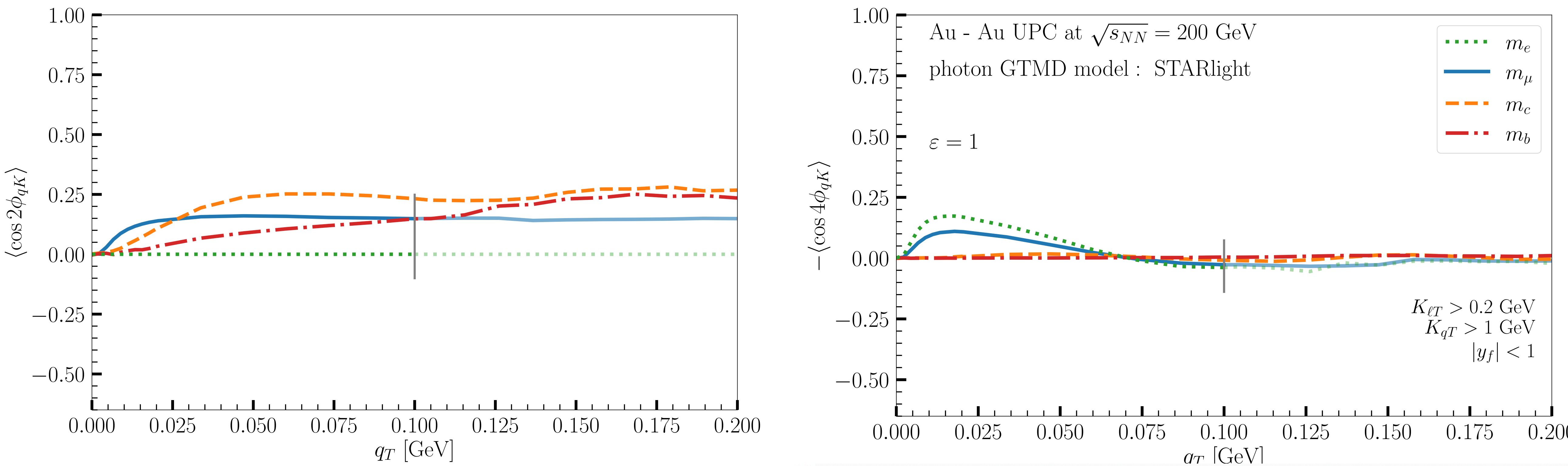
$\langle \cos 2\phi_{qK} \rangle = 2.0 \pm 2.4$ %

$\langle \cos 4\phi_{qK} \rangle = 16.8 \pm 2.5$ %

DB, Maxia & Pisano, 2025

Mass dependence

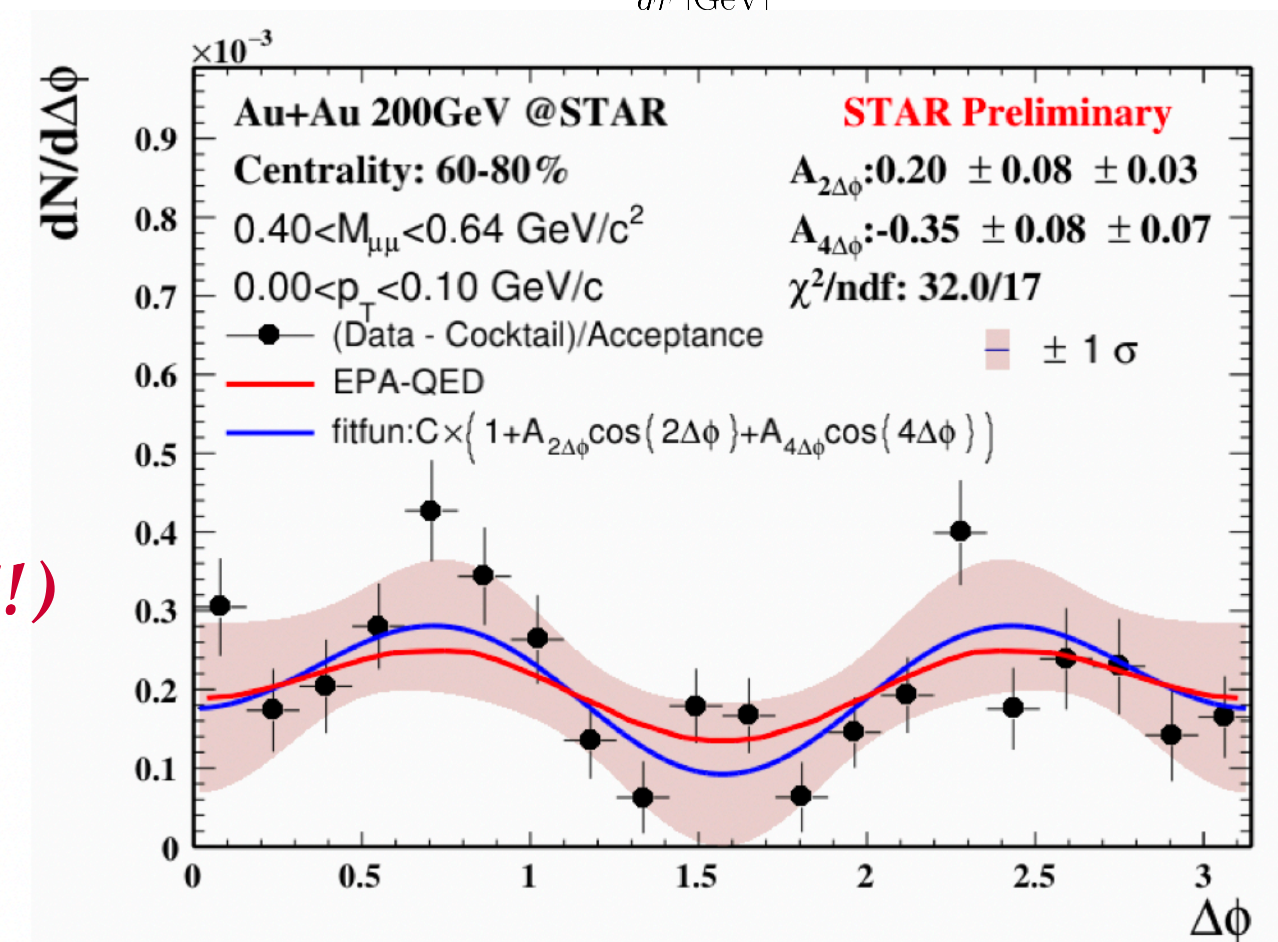
DB, Maxia & Pisano, 2025



model:

$\langle \cos 2\phi_{qK} \rangle$ small for ***e***, large for $\boldsymbol{\mu}$

$\langle \cos 4\phi_{qK} \rangle$ large for ***e***, large for $\boldsymbol{\mu}$



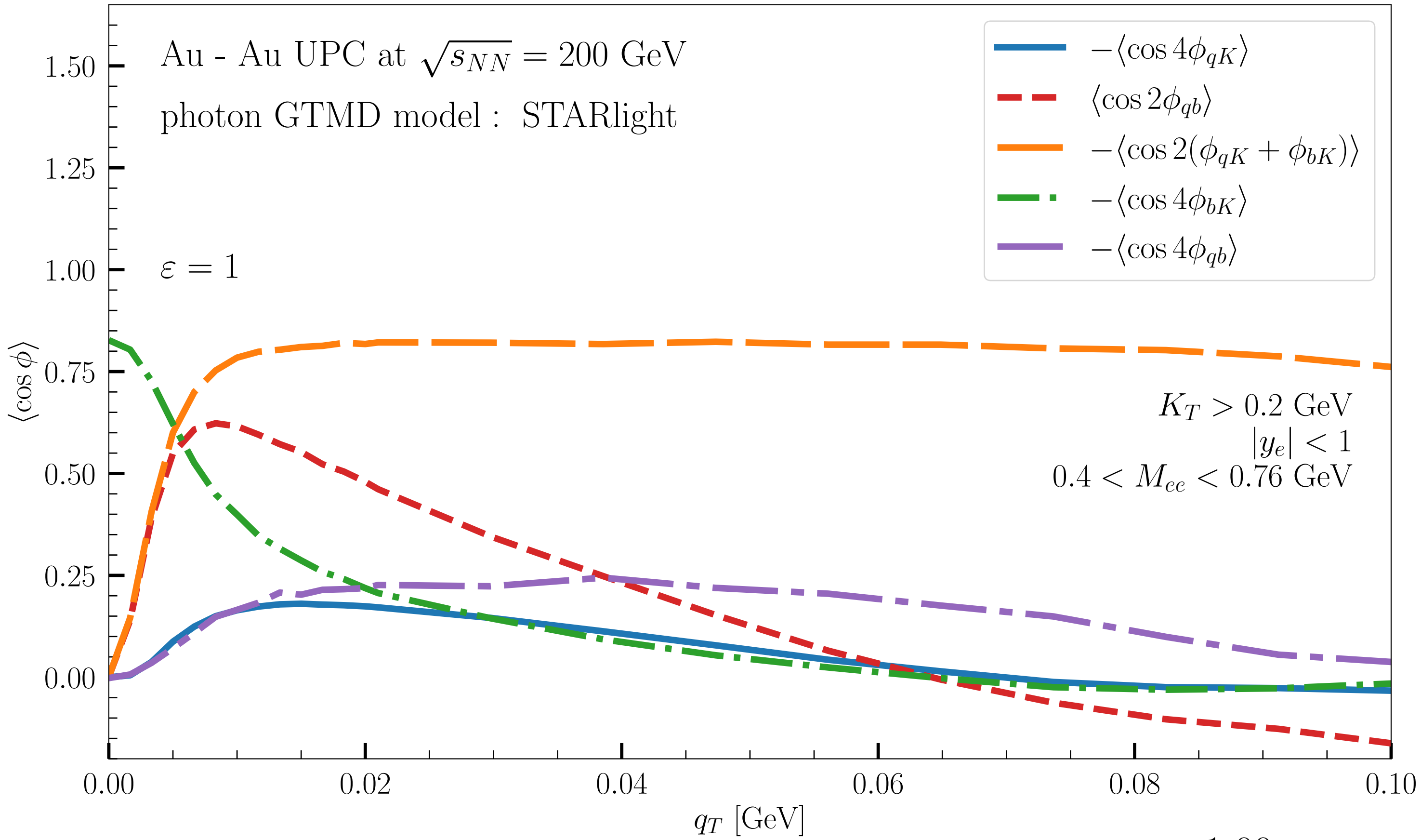
STAR (2022, preliminary, not yet UPC!)

for $\mu^+\mu^-$: $\langle \cos 2\phi_{qK} \rangle = 20 \pm 8 \pm 3$ %

$\langle \cos 4\phi_{qK} \rangle = -35 \pm 8 \pm 7$ %

Jian Zhou (for STAR), 2022

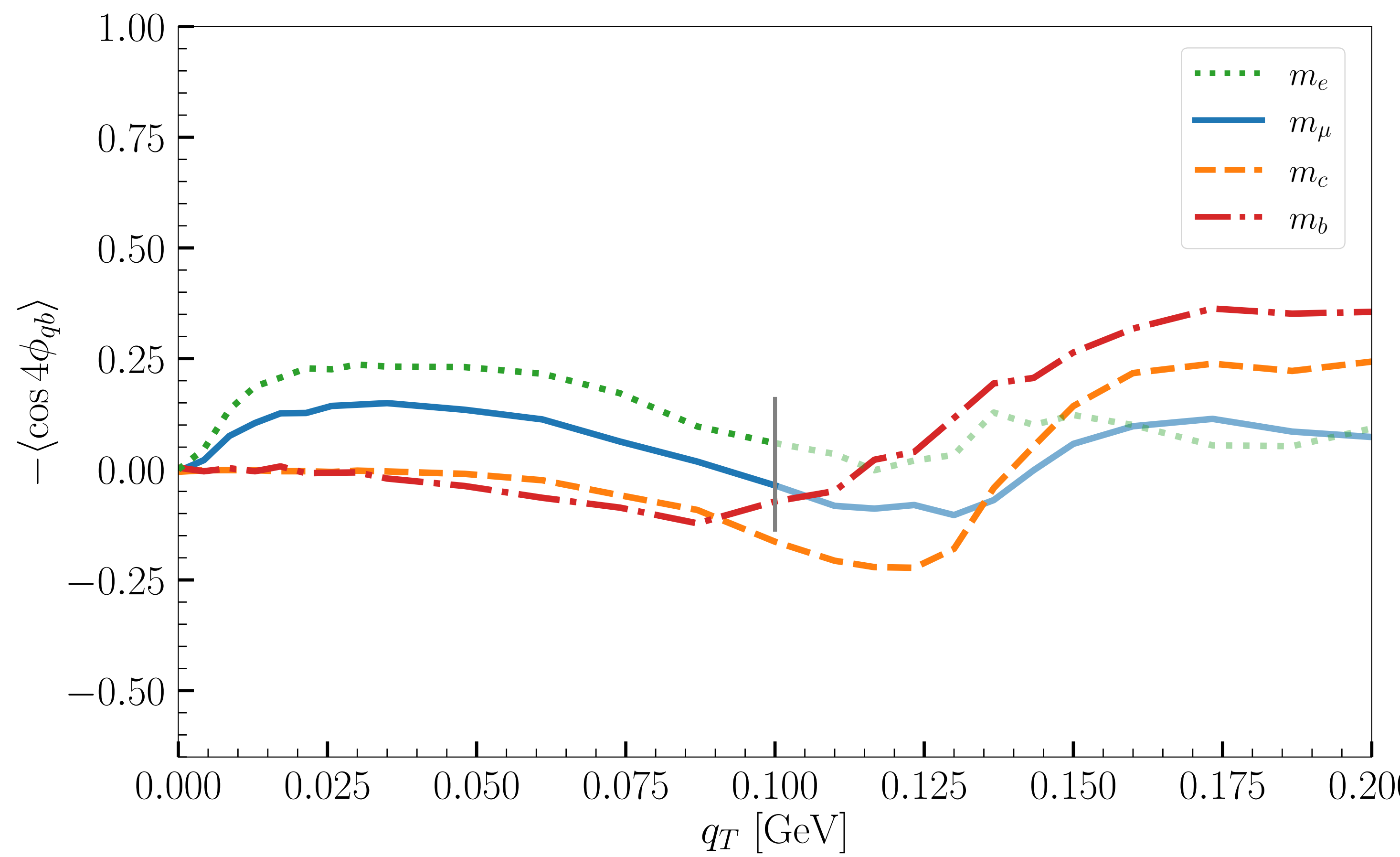
Feed-in



Besides cos $2\phi_{qK}$ & cos $4\phi_{qK}$ some modulations in ϕ_{qb} and ϕ_{bK} can be quite large

A cos $4\phi_{qb}$ will only appear from feed-in contributions, as there is no cos $4\phi_{q\Delta}$ term

This does not mean it is small



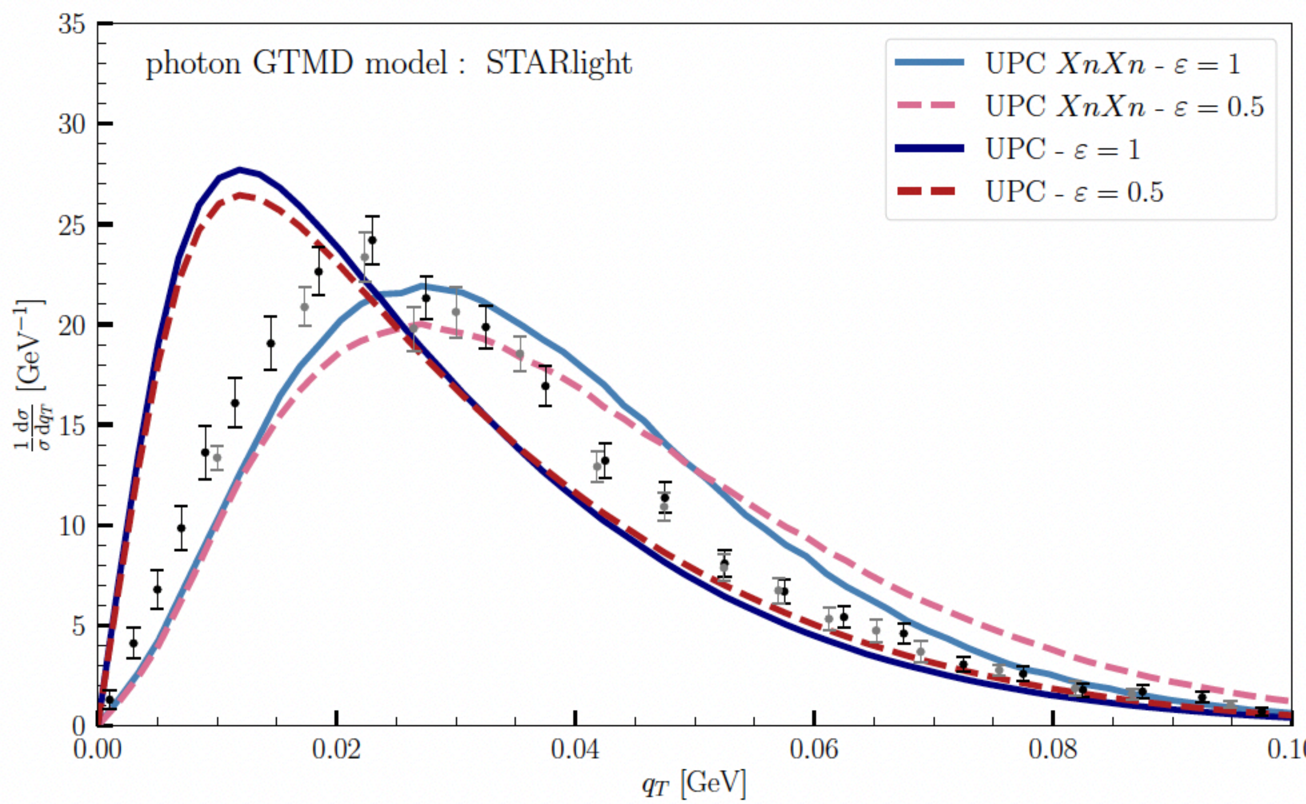
DB, Maxia & Pisano, 2025

Differential cross sections

Also the angular independent term in $d^2\sigma/d^2b_T$ will receive contributions from angular dependent terms in $d^2\sigma/d^2\Delta_T$ due to the feed-in from anisotropic GTMDs

$$\widetilde{F}^0 = \int \frac{\mathrm{d}^2\boldsymbol{\Delta}_T}{8\pi}\frac{\mathrm{d}^2\boldsymbol{b}_T}{2\pi}\mathrm{d}\overline{\mathrm{PS}}\mathrm{e}^{-i\boldsymbol{b}_T\cdot\boldsymbol{\Delta}_T}\left[F^0 + F^{\cos 2\phi_{q\Delta}}\cos 2\phi_{q\Delta} + F^{\sin 2\phi_{q\Delta}}\sin 2\phi_{q\Delta}\right]$$

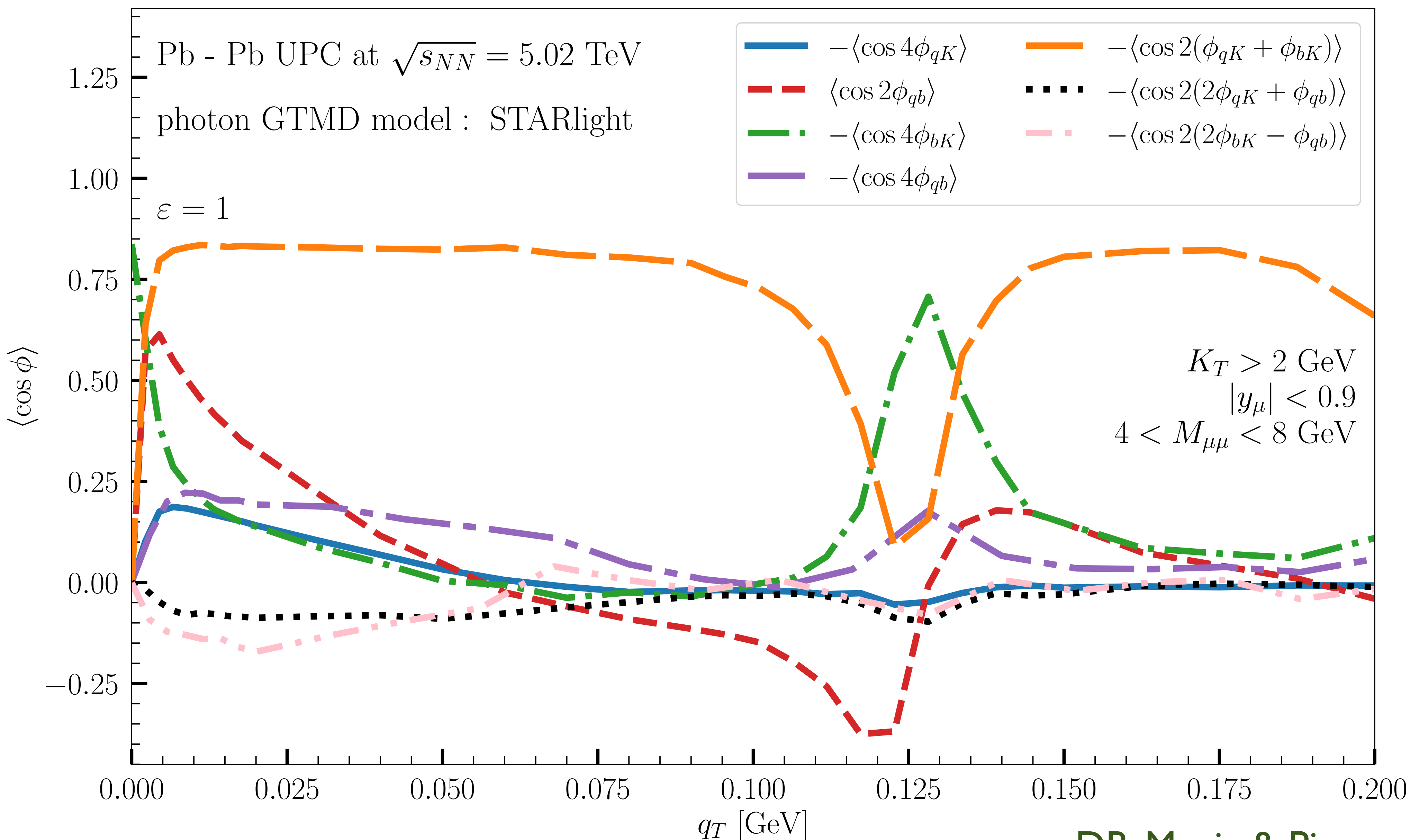
Therefore, sticking to just the angular independent terms leads to an incomplete result, but the effect is not very large:



This does not mean that feed-in effects are small in general, as we have seen

DB, Maxia & Pisano, 2025

UPCs at LHC

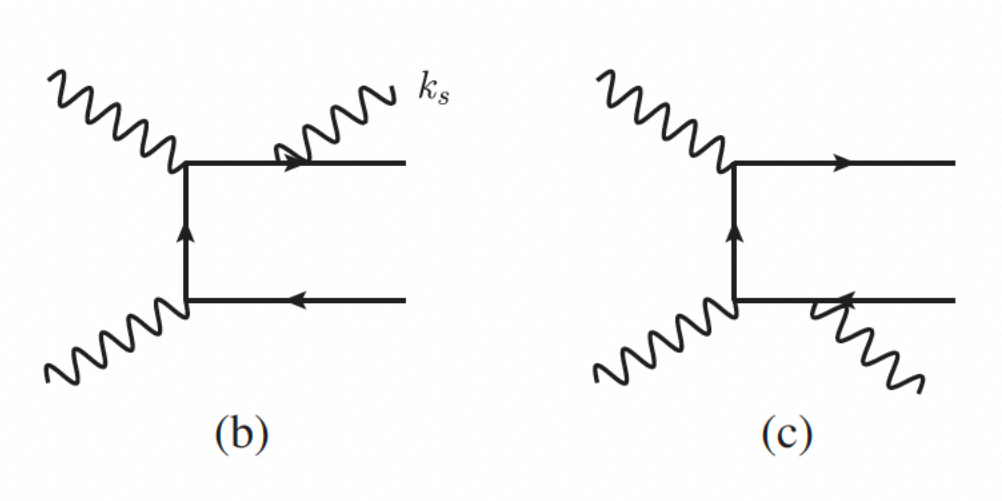


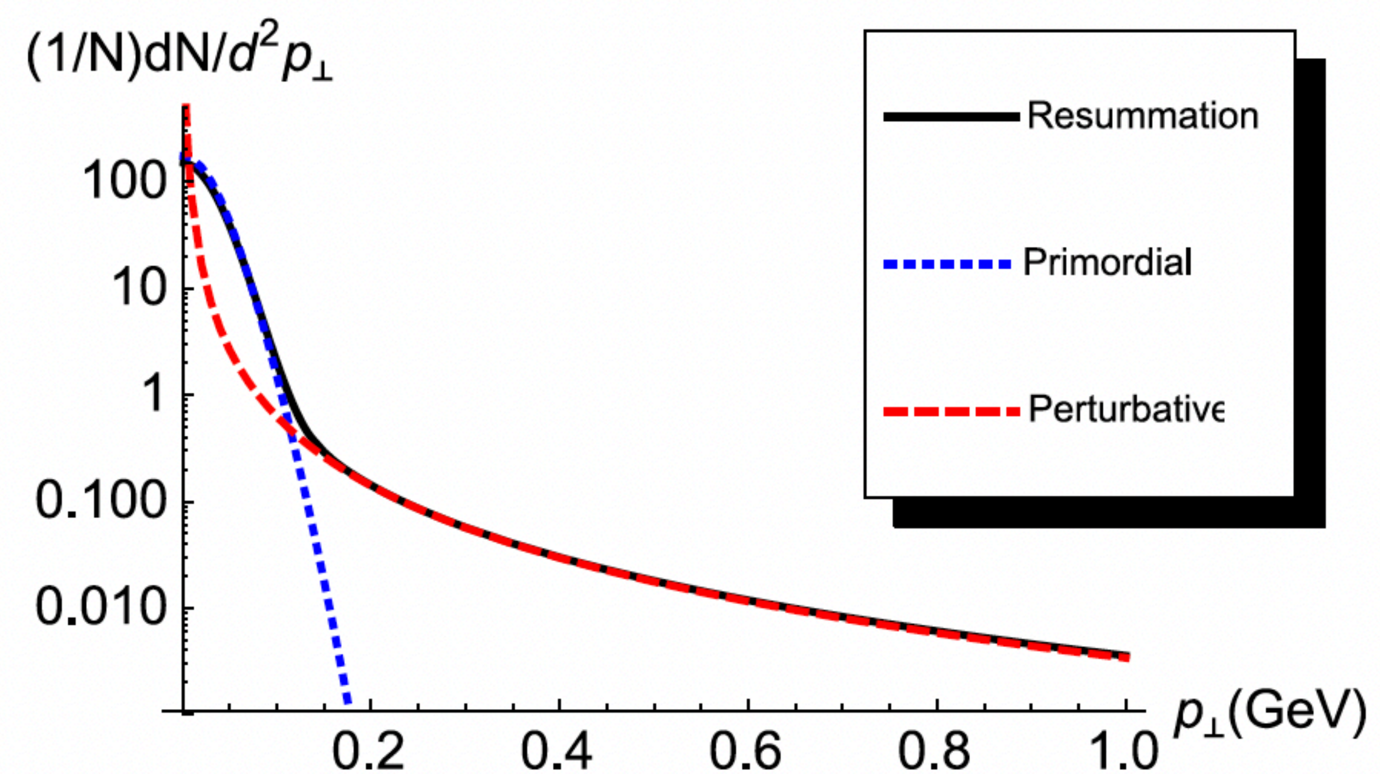
DB, Maxia & Pisano, 2025

While the cross section does not depend much on the rapidity region, for the asymmetries the mid-rapidity region is a better choice to measure the asymmetries

In the forward rapidity region most of these asymmetries become negligible, with solely $\langle \cos 2(\phi_{qK} + \phi_{bK}) \rangle$, $\langle \cos 4\phi_{bK} \rangle$, and $\langle \cos 2\phi_{bq} \rangle$ remaining above 10%

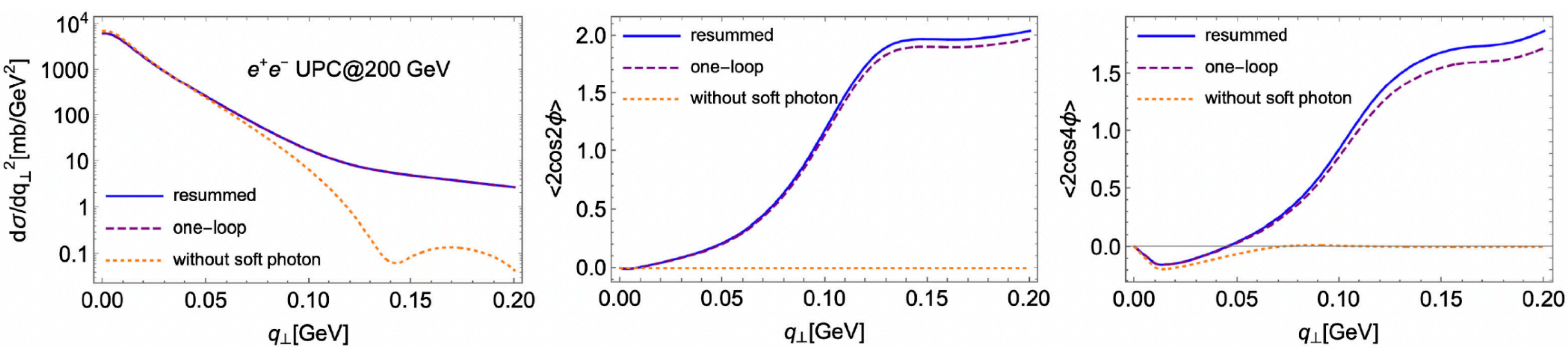
Perturbative corrections





Klein, Mueller, Xiao & F. Yuan, 2020

Below ~ 0.1 GeV the soft-photon resummed result does not differ much from the Gaussian model considered at leading order



Shao, Zhang, J. Zhou & Y.-J. Zhou, 2023

Conclusions

Conclusions

- Electron-positron pair production in UPCs can be described by photon-photon collisions and in terms of photon GTMDs
- In a model based on the EPA and nuclear form factors the photon distribution in UPCs can be described rather robustly (different choices yield the same result)
- The STAR data for both the normalized cross section as function of q_T and the dependence on ϕ_{qK} can be described reasonably well in this way
- The photon distribution is linearly polarized as expected for ultrarelativistically moving charges, but off-forward there is also a circular polarization component
- Upon Fourier transforming from Δ to b the anisotropic angular dependences of the GTMDs break the 1-1 correspondence between harmonics. There is feed-in to both higher *and* lower order harmonics, which can lead to sizable effects
- A cos $4\phi_{qb}$ will solely appear from feed-in contributions (there is no cos $4\phi_{q\Delta}$), and can be as large as 25%, such modulations are not considered yet in the small-x gluon case for which anisotropies are generally claimed to be small

Back-up slides

Dipole gluon GTMD

In the $x \to 0$ the dipole gluon GTMD becomes a correlator of a single Wilson loop:

$$G^{[+,-]\,ij}(\boldsymbol{k},\boldsymbol{\Delta}) = \frac{2N_c}{\alpha_s}\left[\frac{1}{2}\left(\boldsymbol{k}^2 - \frac{\boldsymbol{\Delta}^2}{4}\right)\delta_T^{ij} + k_T^{ij} - \frac{\Delta_T^{ij}}{4} - \frac{k_T^{[i}\Delta_T^{j]}}{2}\right] G^{[\Box]}(\boldsymbol{k},\boldsymbol{\Delta})$$

$$G^{[\Box]}(\boldsymbol{k},\boldsymbol{\Delta}) \equiv \int \frac{d^2\boldsymbol{x}\, d^2\boldsymbol{y}}{(2\pi)^4}\, e^{-i\boldsymbol{k}\cdot(\boldsymbol{x}-\boldsymbol{y})+i\boldsymbol{\Delta}\cdot\frac{\boldsymbol{x}+\boldsymbol{y}}{2}}\, \frac{\langle p'|\, S^{[\Box]}(\boldsymbol{x},\boldsymbol{y})\,|p\rangle\big|_{\text{LF}}}{\langle P|P\rangle},$$

All gluon polarization states (linear & circular) and their GTMDs become related:

$$\lim_{x,\xi\to 0} x\mathcal{F}_1 = \lim_{x,\xi\to 0} x\mathcal{F}_2^{(1)} = -4\lim_{x,\xi\to 0} x\mathcal{F}_3^{(1)} = -2\lim_{x,\xi\to 0} x\mathcal{F}_4^{(1)} = \mathcal{E}^{(1)}$$

$$\mathcal{F}_i^{(n)} \equiv \left[(\boldsymbol{k}^2 - \boldsymbol{\Delta}^2/4)/(2M^2)\right]^n \mathcal{F}_i$$

DB, van Daal, Mulders, Petreska, 2018

Not expected to hold for the WW GTMD, except at large $k_\perp$

Real part of $G^{[\Box]}(k,\Delta)$ only depends on k^2, Δ^2 and $(k\cdot\Delta)^2$

It means that also the δ_T^{ij} term can be anisotropic now

Elliptic Wigner distributions

$$xW(x, \boldsymbol{b}, \boldsymbol{k}) = x\mathcal{W}_0(x, \boldsymbol{b}^2, \boldsymbol{k}^2) + 2\cos(\phi_b - \phi_k)\, x\mathcal{W}_1(x, \boldsymbol{b}^2, \boldsymbol{k}^2)$$
$$+ 2\cos 2(\phi_b - \phi_k)\, x\mathcal{W}_2(x, \boldsymbol{b}^2, \boldsymbol{k}^2) + \ldots$$

The $cos\ 2(\phi_b\text{-}\phi_k)$ part is called "the" elliptic Wigner distribution

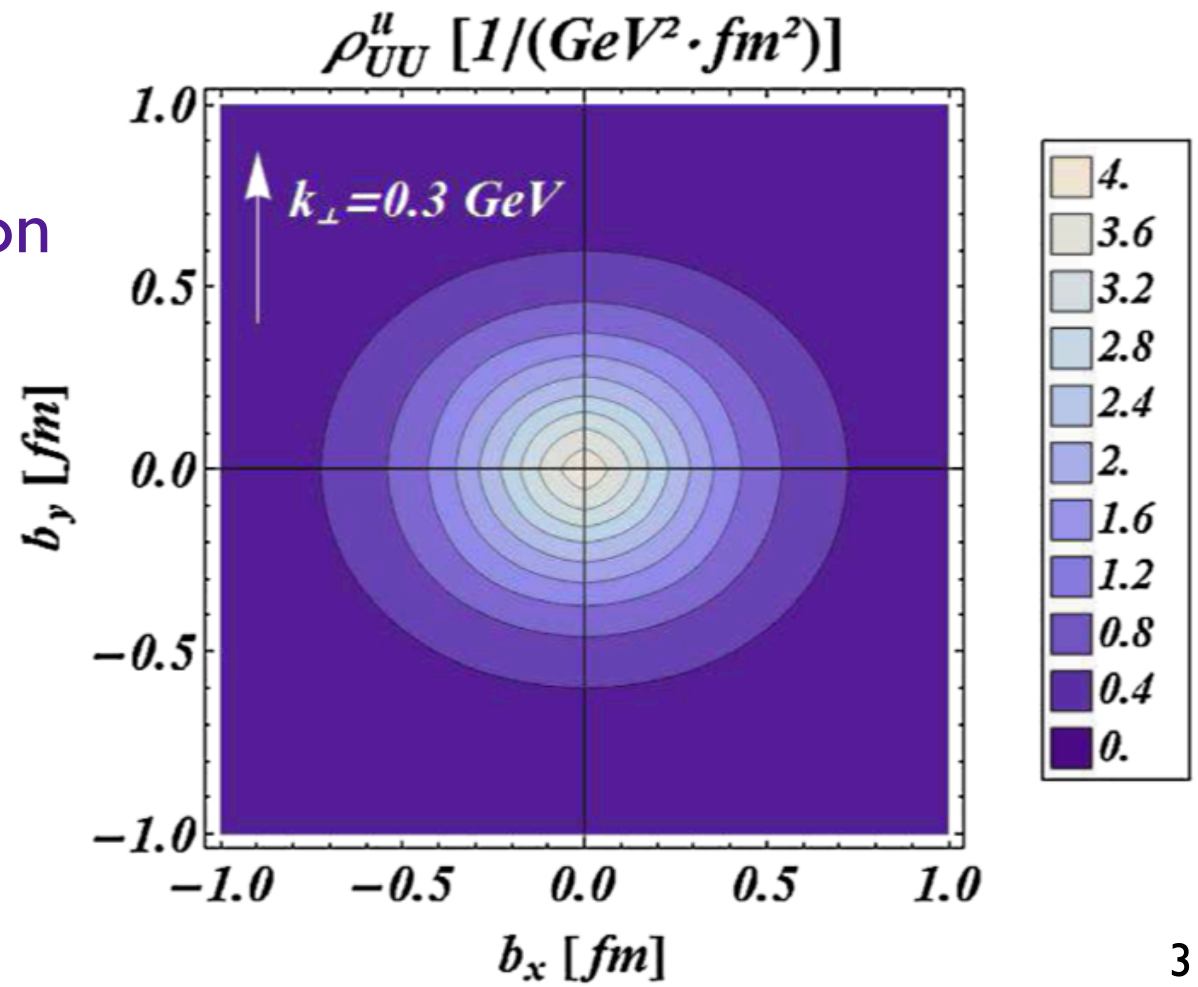
Hatta, Xiao, Yuan, 2016; J. Zhou, 2016; Mäntysaari, Mueller, Schenke, 2019; Salazar, Schenke, 2019

There can be such an elliptic piece in each Wigner distribution

Hence 4 different ones for unpolarized protons, reducing to 1 in the small-x limit

A nonzero elliptic quark Wigner distribution in the lightcone constituent quark model:

Lorcé, Pasquini, 2011



Due to quark orbital angular momentum

Lorcé, Pasquini, 2011; Hatta, 2011

Odderon GTMDs

Hermiticity and PT constraints imply:

$$G^{[\Box]*}(\boldsymbol{k},\boldsymbol{\Delta}) = G^{[\Box]}(\boldsymbol{k},-\boldsymbol{\Delta}) \qquad G^{[\Box]*}(\boldsymbol{k},\boldsymbol{\Delta}) = G^{[\Box^\dagger]}(-\boldsymbol{k},-\boldsymbol{\Delta})$$

$$G^{[\Box]}(\boldsymbol{k},\boldsymbol{\Delta}) - G^{[\Box^\dagger]}(\boldsymbol{k},\boldsymbol{\Delta}) \text{ only depends on odd powers of } \boldsymbol{k}\cdot\boldsymbol{\Delta}$$

Odderon (for $\xi = 0$) involves only odd harmonics $\cos[(2n+1)(\phi_k - \phi_\Delta)]$

$$xW(x,\boldsymbol{b},\boldsymbol{k}) = x\mathcal{W}_0(x,\boldsymbol{b}^2,\boldsymbol{k}^2) + 2\cos(\phi_b-\phi_k)\,x\mathcal{W}_1(x,\boldsymbol{b}^2,\boldsymbol{k}^2)$$
$$+\,2\cos 2(\phi_b-\phi_k)\,x\mathcal{W}_2(x,\boldsymbol{b}^2,\boldsymbol{k}^2) + \ldots$$

$\mathcal{W}_1$ leads to odd harmonics in forward dihadron production through double parton scattering in pA collisions (not exclusive in this case)

DB, van Daal, Mulders, Petreska, 2018

Lappi, Schenke, Schlichting, Venugopalan, 2016

For $\xi \neq 0$ odd powers of $k \cdot \Delta$ can appear in the real parts as well