Probing the gluon Wigner distribution in nuclei

Lund U.

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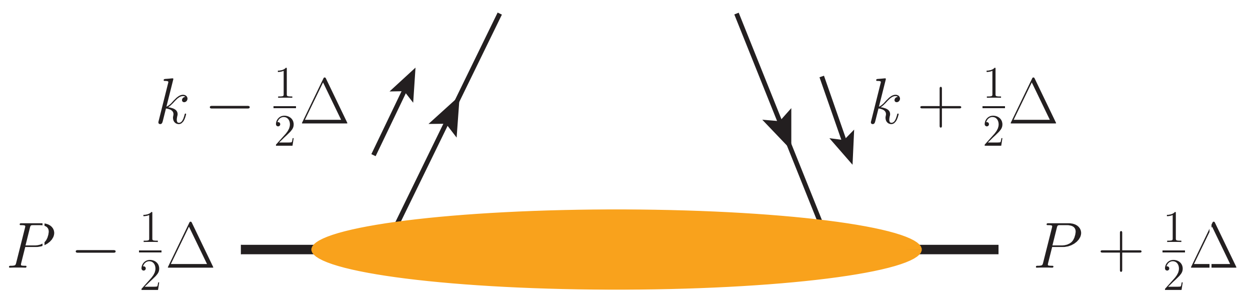
Y. Hagiwara, Y. Hatta, R. Pasechnik, M. Tasevsky , O. Teryaev, Phys. Rev. D96 (2017) 034009
arXiv:1706.01765

Nucleon tomography: phase space distributions

What do we know about the nucleon?



It is a complicated object!

$$H(k, P, \Delta) = (2\pi)^{-4} \int d^4z \, e^{izk} \times \langle p(P + \tfrac{1}{2}\Delta) | \bar{q}(-\tfrac{1}{2}z) \Gamma q(\tfrac{1}{2}z) | p(P - \tfrac{1}{2}\Delta) \rangle$$

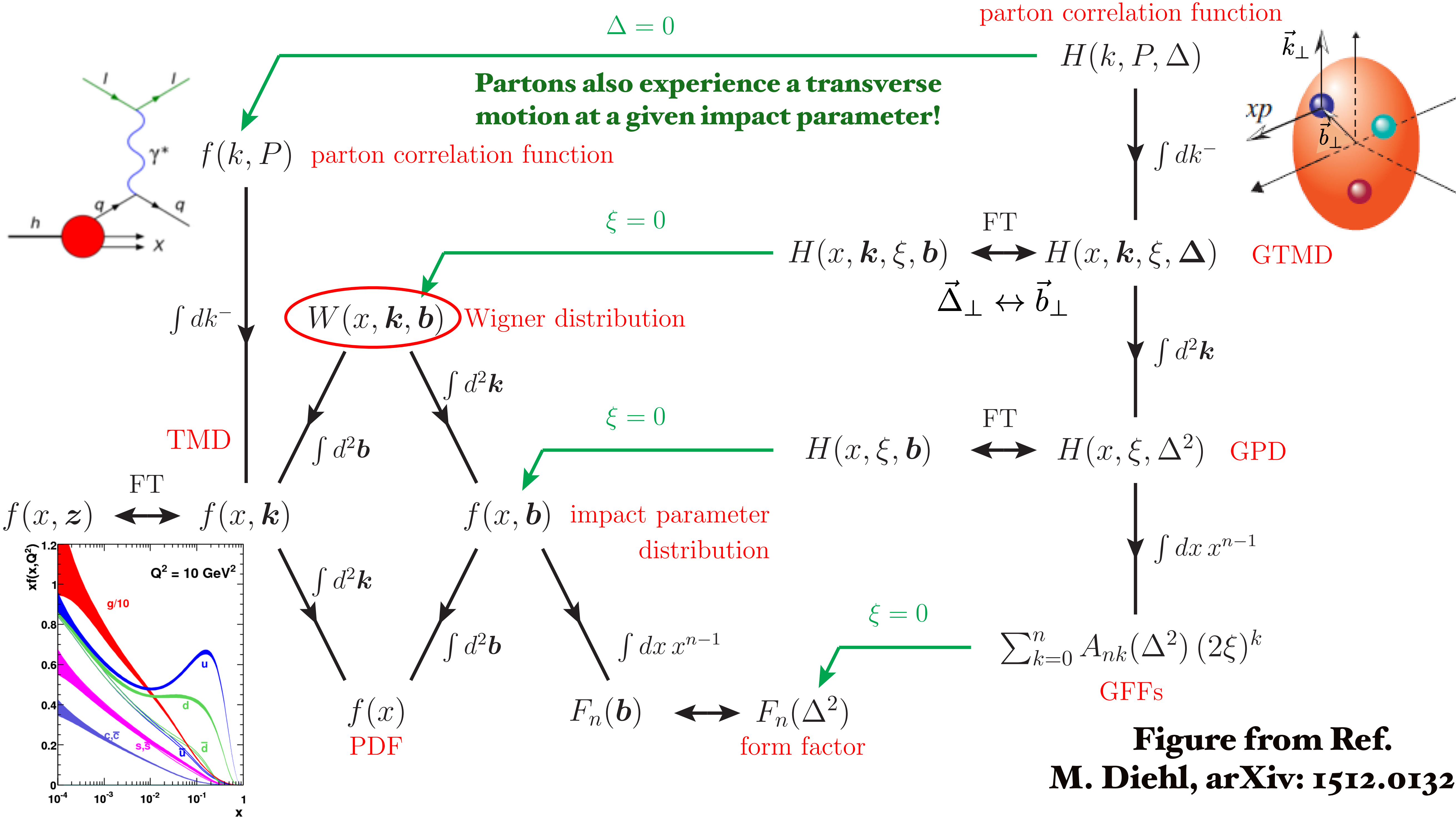


Figure from Ref.
M. Diehl, arXiv: 1512.01328

Nucleon 5D tomography: the "mother distribution"

✓ *5D tomography:* ***Generalised TMD (GTMD)*** — **Meissner, Metz, Schlegel (2009)…**

Husimi distribution — **Y. Hagiwara, Y. Hatta (2015)…**

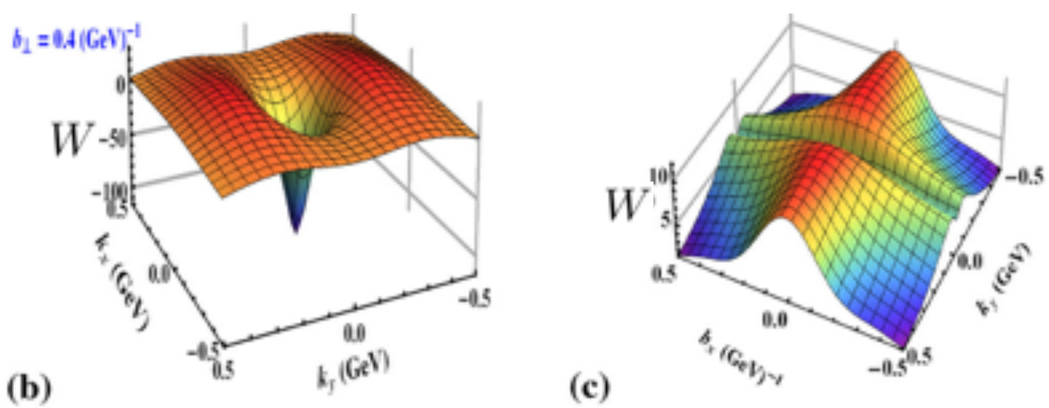
Wigner'1932 — ***Wigner distribution*** — **Belitsky, Ji, Yuan (2004); Ji (2003); Lorce, Pasquini (2011); Y. Hatta (2011)…**

+ many more studies…

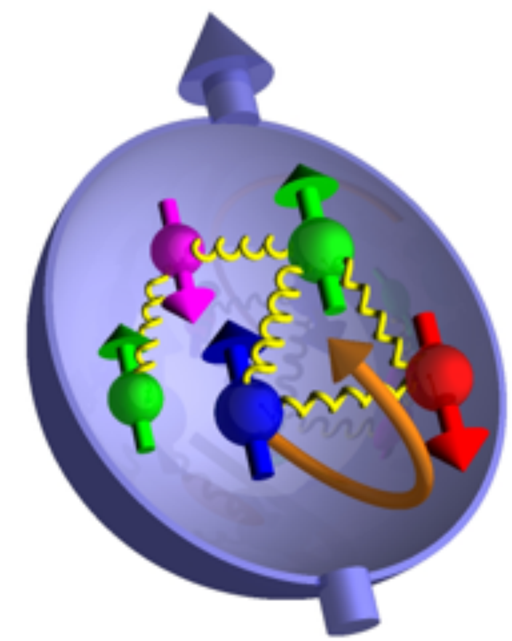
Example: leading-twist quark Wigner distribution

$$W(x,\vec{k}_\perp,\vec{b}_\perp) = \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{i\vec{b}_\perp\cdot\vec{\Delta}_\perp} \int \frac{dz^- d^2 z_\perp}{16\pi^3} e^{ixP^+z^- - i\vec{k}_\perp\cdot\vec{z}_\perp} \langle P-\frac{\Delta}{2}|\bar{q}(-z/2)\gamma^+ q(z/2)|P+\frac{\Delta}{2}\rangle$$

J. More et al, PRD'17



Non-trivial correlation between the transverse momentum and the impact parameter due to orbital angular momentum!



Spin decomposition of the nucleon: $$\frac{1}{2}\Delta\Sigma + \Delta G + L^q + L^g \equiv \frac{1}{2}$$

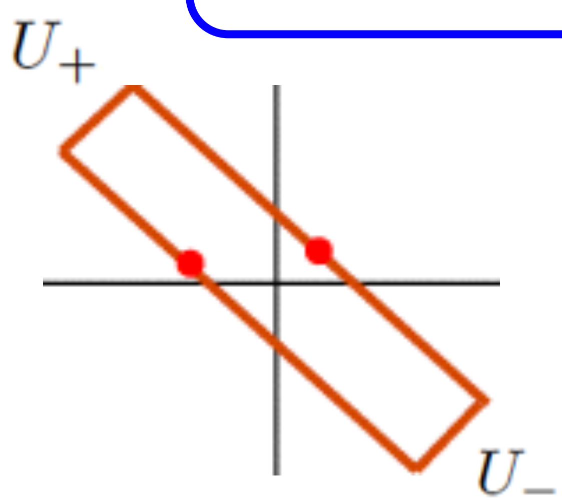
$$L = \int dx d^2b_\perp d^2k_\perp\, (\vec{b}_\perp \times \vec{k}_\perp)_z \cdot W(x,\vec{k}_\perp,\vec{b}_\perp)$$ **canonical orbital angular momentum**

Wigner/GTMD distributions provide the most complete information on partonic "image" of the nucleon!

The gluon Wigner distribution at small x: dipole picture

From quark to gluon: $\bar{\Psi}(\vec{r}-\xi/2)\Gamma\Psi(\vec{r}+\xi/2) \to F^{+\nu}(\vec{r}-\xi/2)F_{\nu}^{+}(\vec{r}+\xi/2)$

$$xW(x,\vec{q}_\perp,\vec{b}_\perp) = \frac{2}{P^+(2\pi)^3}\int dz^+ d^2\vec{z}_\perp \int \frac{d^2\vec{\Delta}_\perp}{(2\pi)^2} e^{i\vec{q}_\perp\cdot\vec{z}_\perp - ixP^- z^+} \times \left\langle P+\frac{\vec{\Delta}_\perp}{2}\right| \mathrm{Tr}\left[U_+ F_a^{+i}\left(\vec{b}_\perp+\frac{z}{2}\right)U_- F_a^{+i}\left(\vec{b}_\perp-\frac{z}{2}\right)\right]\left| P-\frac{\vec{\Delta}_\perp}{2}\right\rangle$$



Staple-shaped Wilson lines: $U_\pm \equiv U[0,\pm\infty;0]U[\pm\infty,z^+;\vec{z}_\perp]$

$$U[z_1^+,z_2^+;\vec{z}_\perp] \equiv \mathcal{P}\exp\left(ig\int_{z_1^+}^{z_2^+} dz^+ \hat{A}^-(z^+,\vec{z}_\perp)\right)$$

$x \ll 1 \qquad e^{-ixP^- z^+} \approx 1$

Y. Hatta, B. W. Xiao, F. Yuan, PRL 116, 202301 (2016)

$$xW_g(x,\mathbf{k},\mathbf{b}_\perp) = \frac{2N_c}{\alpha_S}\int \frac{d^2\mathbf{r}}{(2\pi)^2} e^{i\mathbf{k}\cdot\mathbf{r}}\left(\frac{1}{4}\nabla^2_{\mathbf{b}_\perp} - \nabla^2_{\mathbf{r}}\right) S_Y(\mathbf{r},\mathbf{b}_\perp) \qquad Y = \ln\frac{1}{x}$$

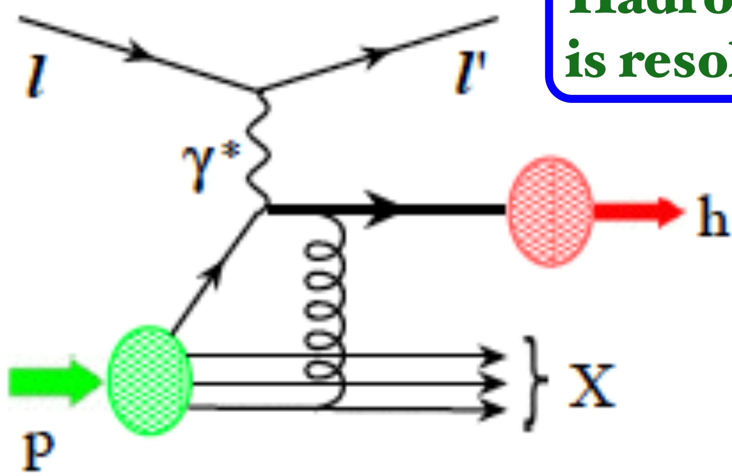
Dipole S-matrix: $S_Y(\vec{q}_\perp,\vec{\Delta}_\perp) = \int \frac{d^2\vec{r}_\perp d^2\vec{b}_\perp}{(2\pi)^4} e^{i\vec{\Delta}_\perp\cdot\vec{b}_\perp + i\vec{q}_\perp\cdot\vec{r}_\perp}\left\langle \frac{1}{N_c}\mathrm{Tr}\, U\left(\vec{b}_\perp+\frac{\vec{r}_\perp}{2}\right)U^\dagger\left(\vec{b}_\perp-\frac{\vec{r}_\perp}{2}\right)\right\rangle_Y$

Nucleon tomography: relevant processes

Combination of TMD and GPD provide a deep 3D picture of the quark and gluon content of the nucleon

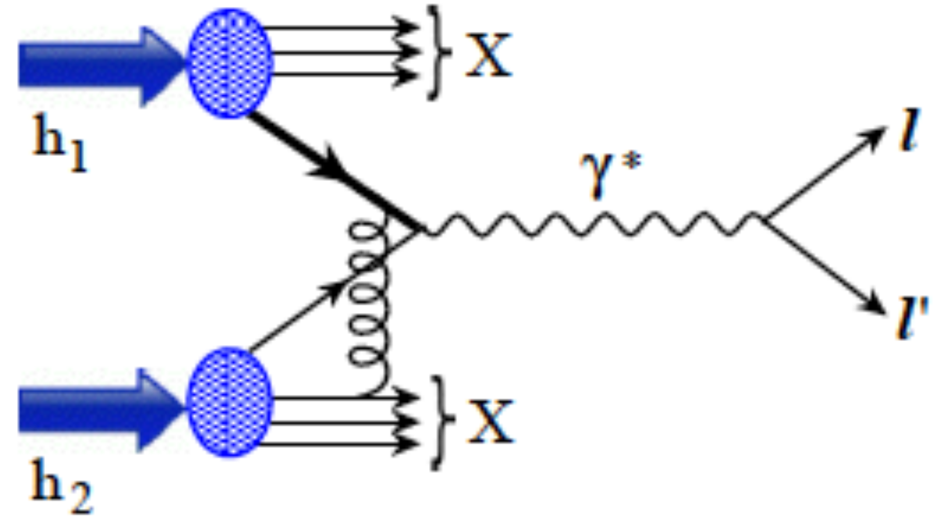
TMD

Semi-Inclusive DIS



Hadron pT is resolved!

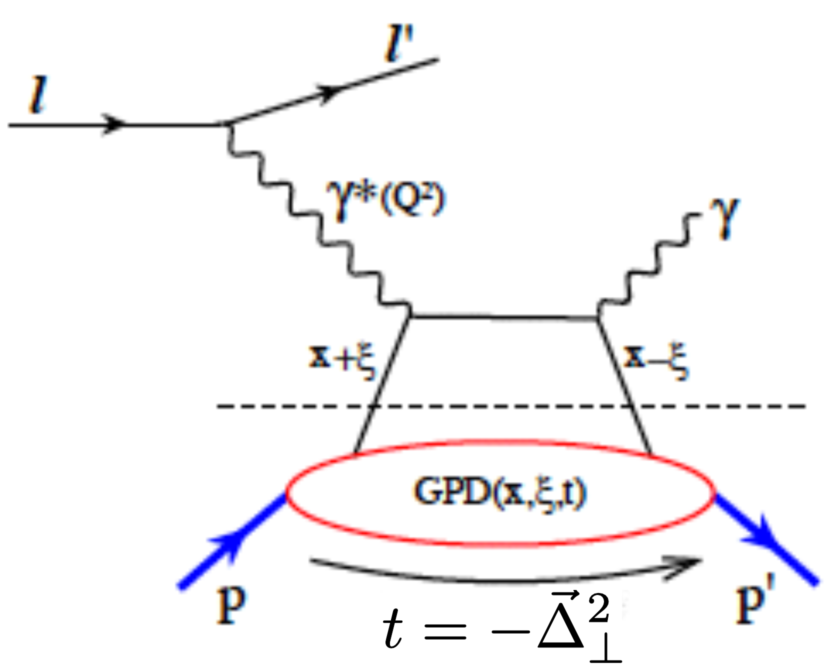
Drell-Yan

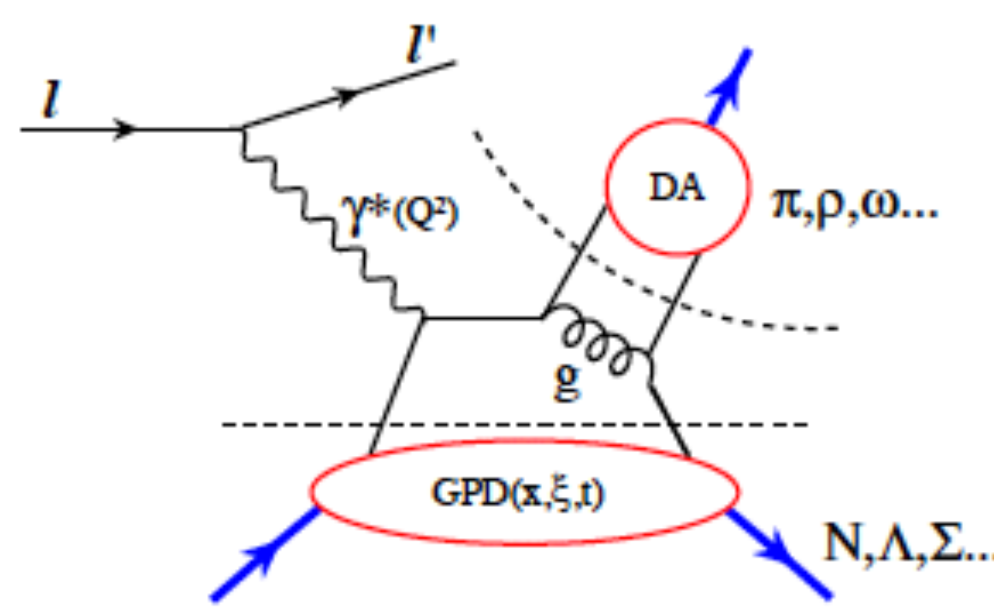


Review: e.g. N. Stefanis et al. arXiv: 1612.03077

Deeply-Virtual Compton Scattering

GPD

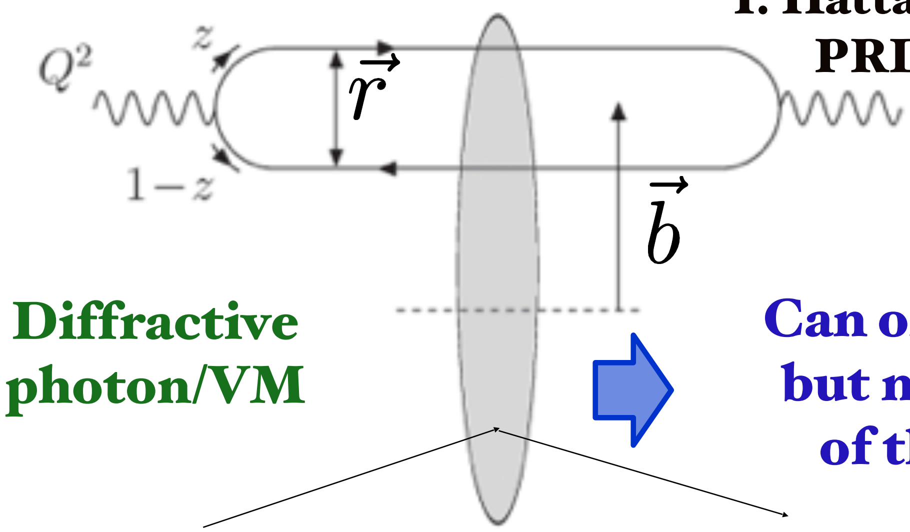




What about accessing the 5D Wigner/GTMD distributions?

Gluon Wigner from diffractive DIS processes

Y. Hatta, B. W. Xiao, F. Yuan, PRD95, 114026 (2017)

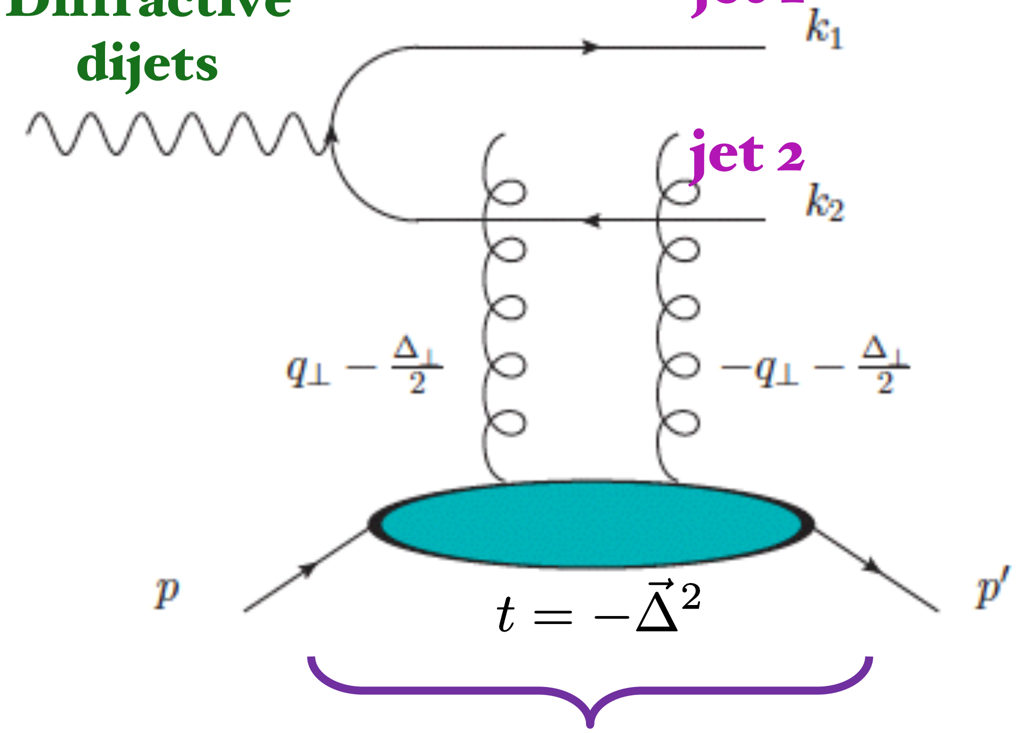


Diffractive photon/VM

Can only access b-profile but not kT-dependence of the gluon Wigner!

T. Altinoluk et al, PLB758, 373 (2016)

Diffractive dijets



Dijet observables:

Proton recoil momentum: $\vec{k}_{1\perp} + \vec{k}_{2\perp} = -\vec{\Delta}_\perp$

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

Y. Hatta, B. W. Xiao, F. Yuan, PRL 116, 202301 (2016)

$$\frac{d\sigma}{d\vec{P}_\perp d\vec{\Delta}_\perp} \propto |\vec{M}|^2, \qquad \vec{M}(\vec{P}_\perp, \vec{\Delta}_\perp) = \int \frac{d^2\vec{q}_\perp}{2\pi} \frac{\vec{P}_\perp - \vec{q}_\perp}{(\vec{P}_\perp - \vec{q}_\perp)^2 + \epsilon_f^2} S_Y(\vec{q}_\perp, \vec{\Delta}_\perp)$$

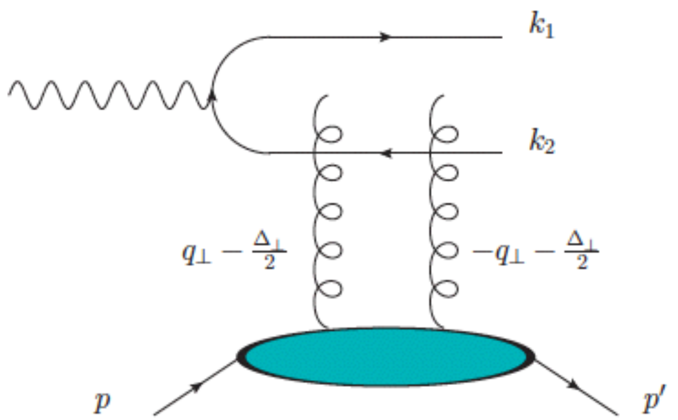
for small-Q^2 $\quad \vec{q}_\perp \sim \vec{P}_\perp$

Advantage!

$$\frac{d\sigma}{d\vec{P}_\perp d\vec{\Delta}_\perp} \propto \left(S_Y(\vec{P}_\perp, \vec{\Delta}_\perp)\right)^2$$

Fourier transform of the dipole S-matrix!

Elliptic Wigner distribution and dipole orientation



Y. Hatta, B. W. Xiao, F. Yuan, PRL 116, 202301 (2016)

Y. Hagiwara, Y. Hatta, T. Ueda, PRD 94, 094036 (2016)

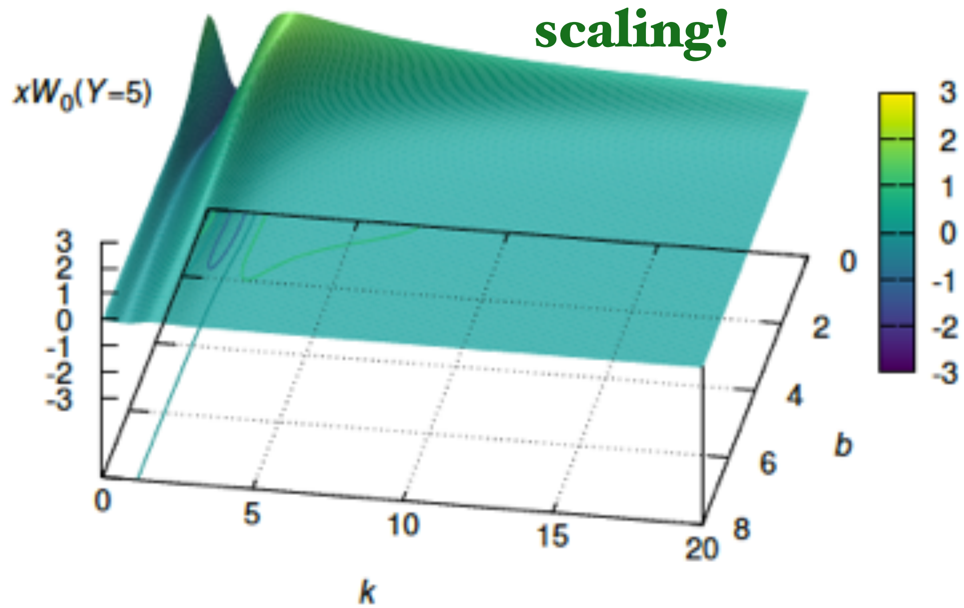
$$W(x,\boldsymbol{b},\boldsymbol{k}) = W_0(x,b,k) + 2\cos 2(\phi_k - \phi_b) W_1(x,b,k) + \cdots$$

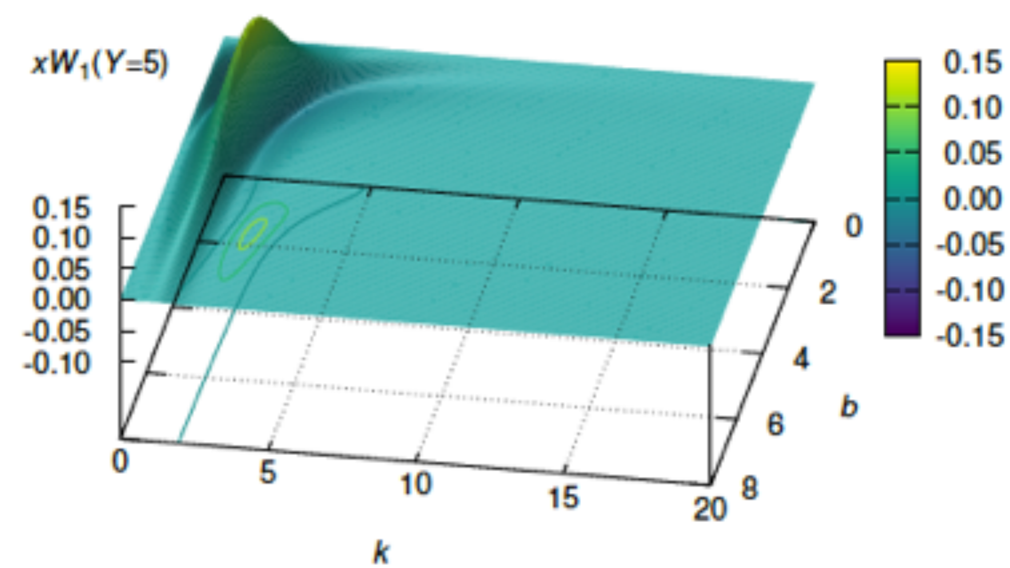
Geometric scaling!

"Elliptic" gluon Wigner

BK equation with SO(3) symmetry (CGC)

Gubser (2011)



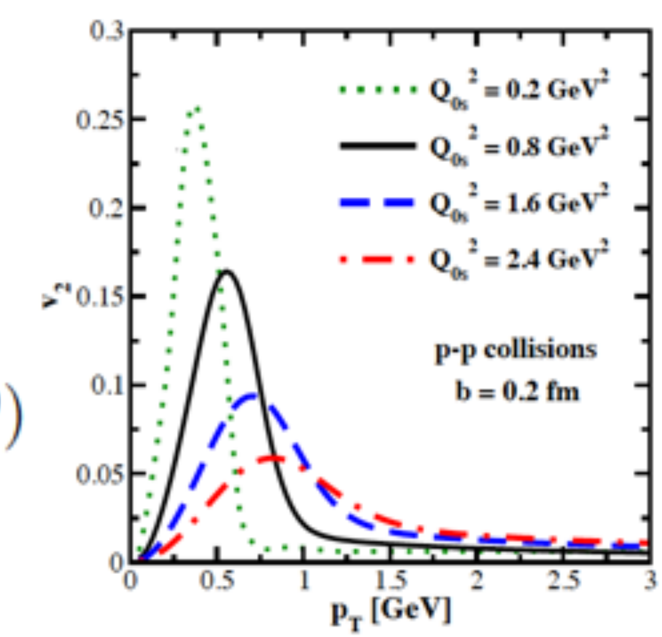


E. Iancu and A. Rezaeian, PRD95, 094003 (2017)

McLerran-Venugopalan model for the dipole S-matrix

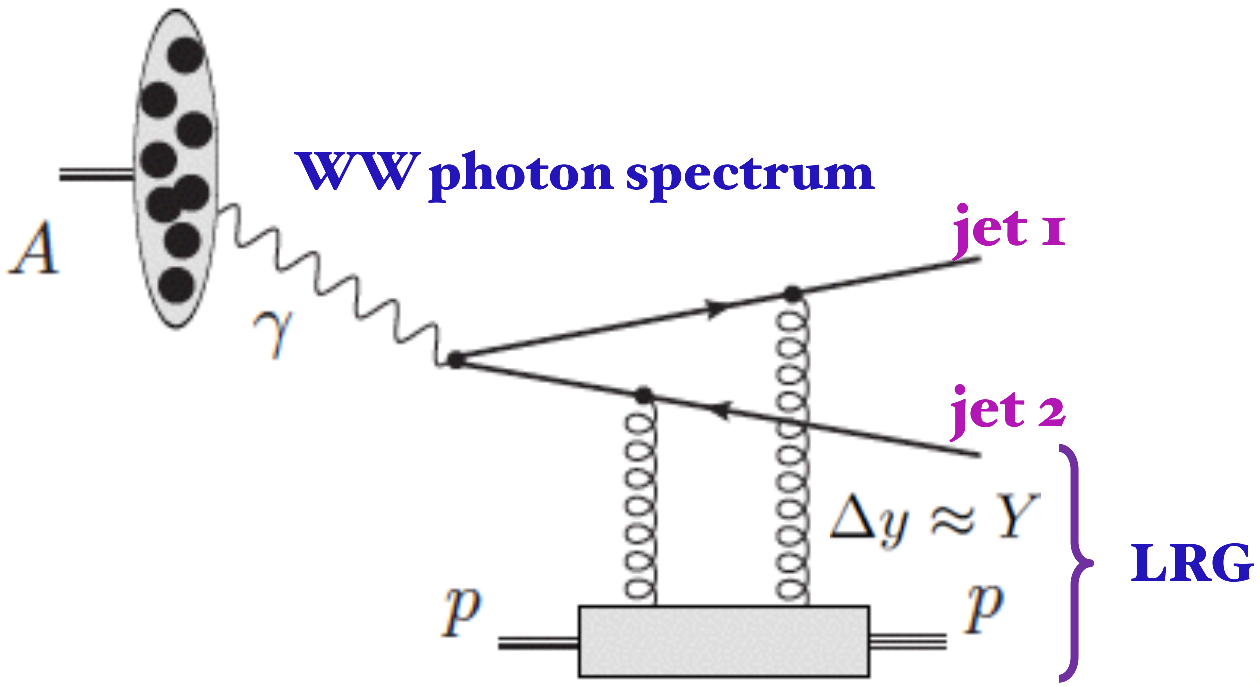
$$S(\boldsymbol{b},\boldsymbol{r}) = \exp\{-N_{2g}(\boldsymbol{b},\boldsymbol{r})\}$$

$$N_{2g}(b,r,\theta) = \mathcal{N}_0(b,r) + \mathcal{N}_\theta(b,r)\cos(2\theta)$$



Dipole orientation effects ⇒ Elliptic flow, gluon transversity, angular correlation in DVCS etc

Accessing the gluon Wigner from exclusive dijets in UPC



Y. Hagiwara, Y. Hatta, RP, M. Tasevsky, O. Teryaev, PRD 96, 034009 (2017)

photon-target diffractive amplitude

$$\vec{M}(\vec{P}_\perp, \vec{\Delta}_\perp) = \int \frac{d^2\vec{q}_\perp}{2\pi} \frac{\vec{P}_\perp - \vec{q}_\perp}{(\vec{P}_\perp - \vec{q}_\perp)^2} S(\vec{q}_\perp, \vec{\Delta}_\perp)$$

"Isotropic" "Elliptic"

$$S(\vec{q}_\perp, \vec{\Delta}_\perp) = S_0(q_\perp, \Delta_\perp) + 2\cos 2(\phi_q - \phi_\Delta)\tilde{S}(q_\perp, \Delta_\perp)$$

Photon-target cross section:

$$\frac{d\sigma^{p\gamma}}{dy_1 dy_2 d^2\vec{k}_{1\perp} d^2\vec{k}_{2\perp}} = N_c \alpha_{em}(2\pi)^2 q^+ \delta(k_1^+ + k_2^+ - q^+) \sum_f e_f^2 2z(1-z)(z^2 + (1-z)^2)|\vec{M}|^2 \qquad z = \frac{k_{1\perp}e^{y_1}}{k_{1\perp}e^{y_1} + k_{2\perp}e^{y_2}}$$

Nucleus-target cross section:

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

photon flux

$$S_0(P_\perp, \Delta_\perp) = -\frac{1}{P_\perp} \frac{\partial}{\partial P_\perp} A(P_\perp, \Delta_\perp)$$

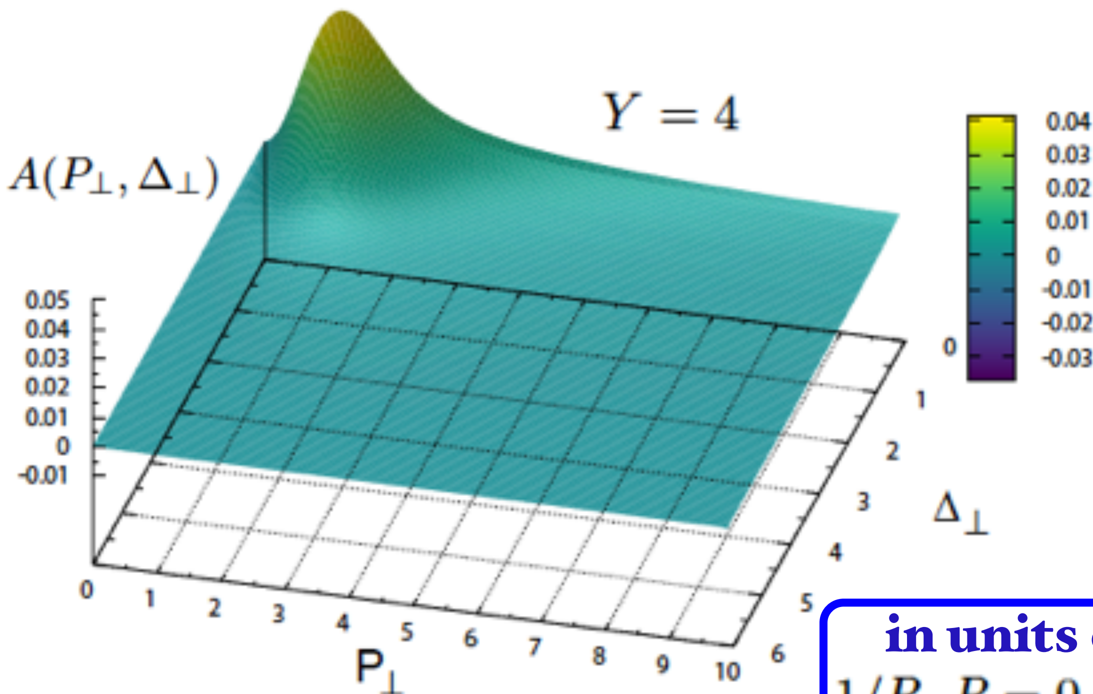
$$\tilde{S}(P_\perp, \Delta_\perp) = -\frac{\partial B(P_\perp, \Delta_\perp)}{\partial P_\perp^2} + \frac{2}{P_\perp^2} \int_0^{P_\perp^2} \frac{dP_\perp'^2}{P_\perp'^2} B(P_\perp', \Delta_\perp)$$

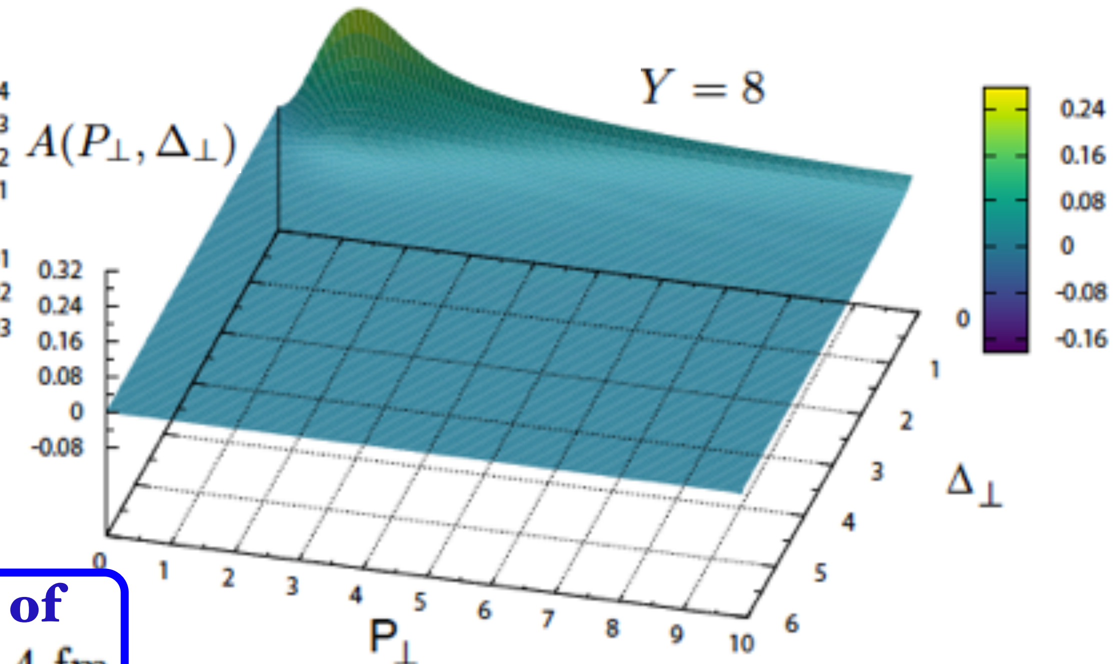
Separate measurements of A and B

full information about the gluon Wigner!

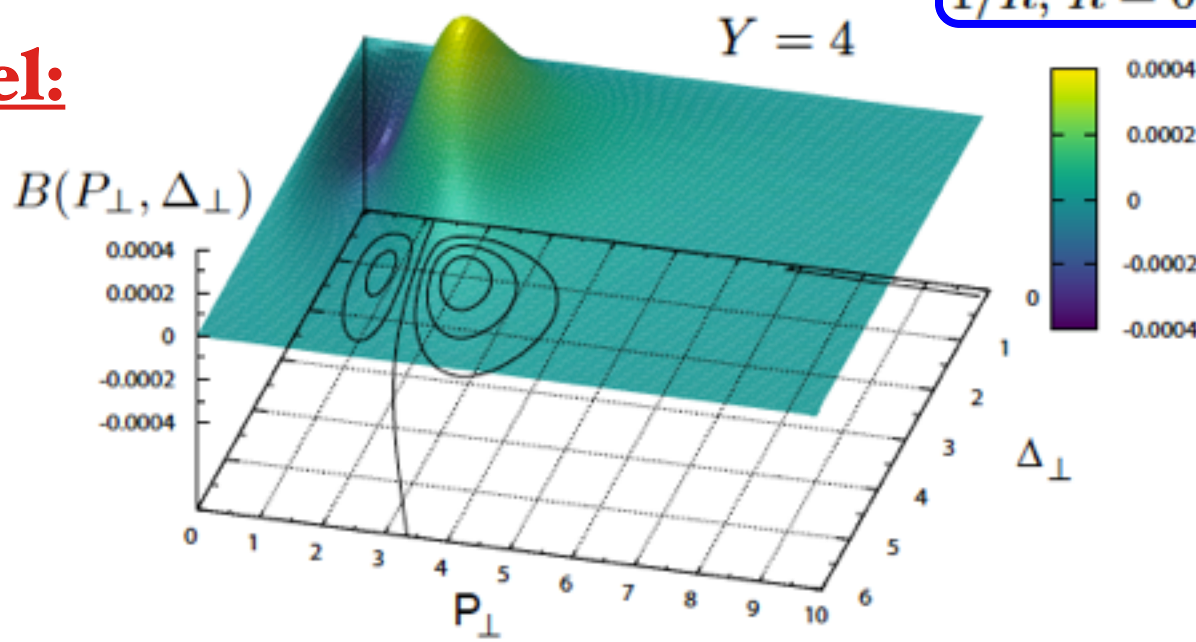
CGC results: BK vs MV

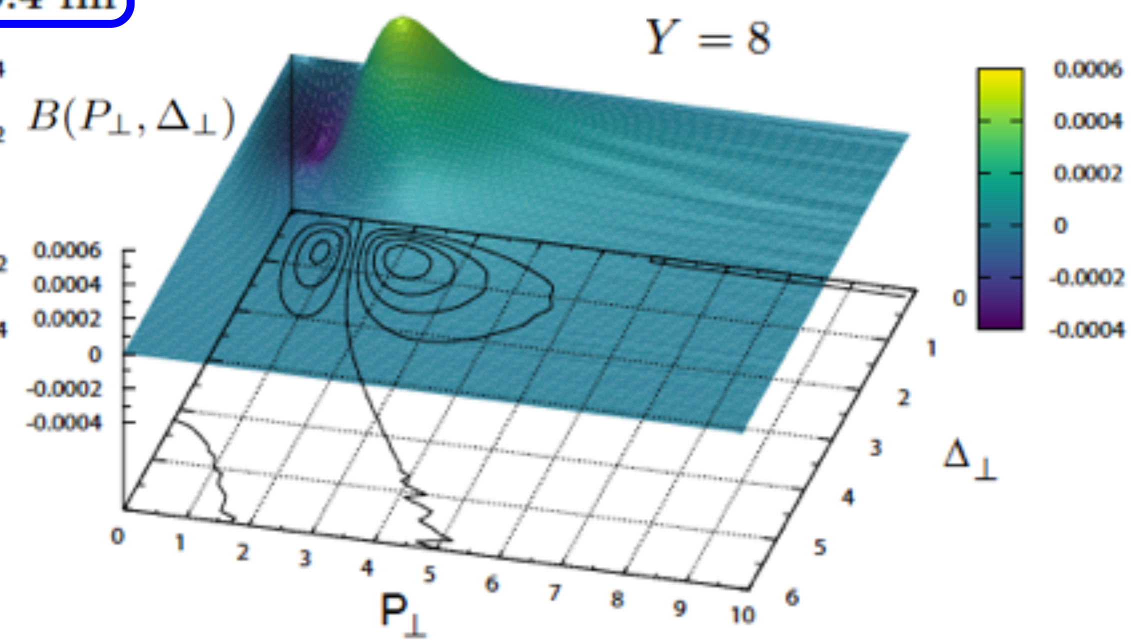
BK model:



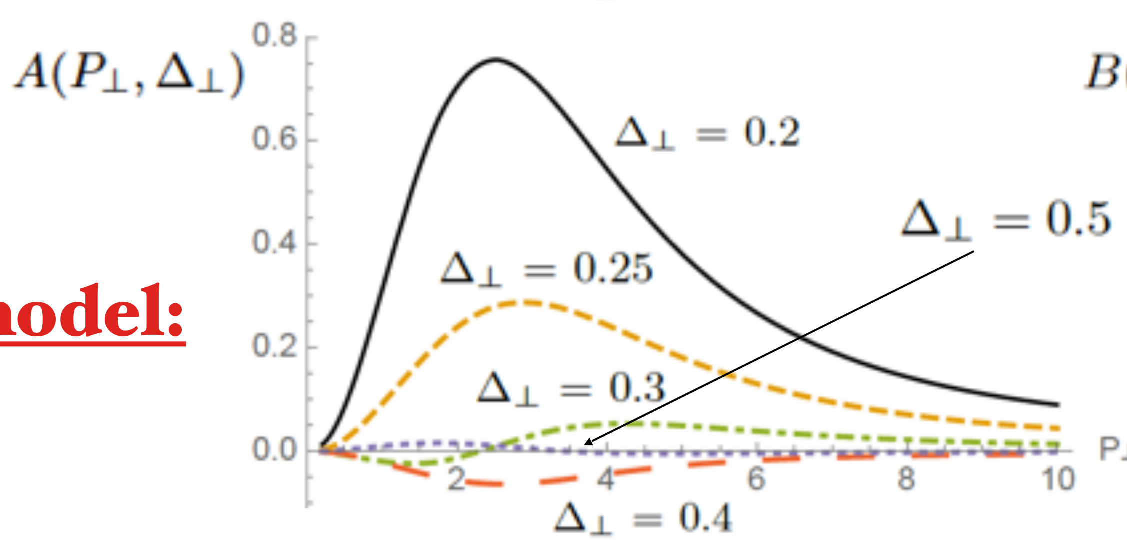


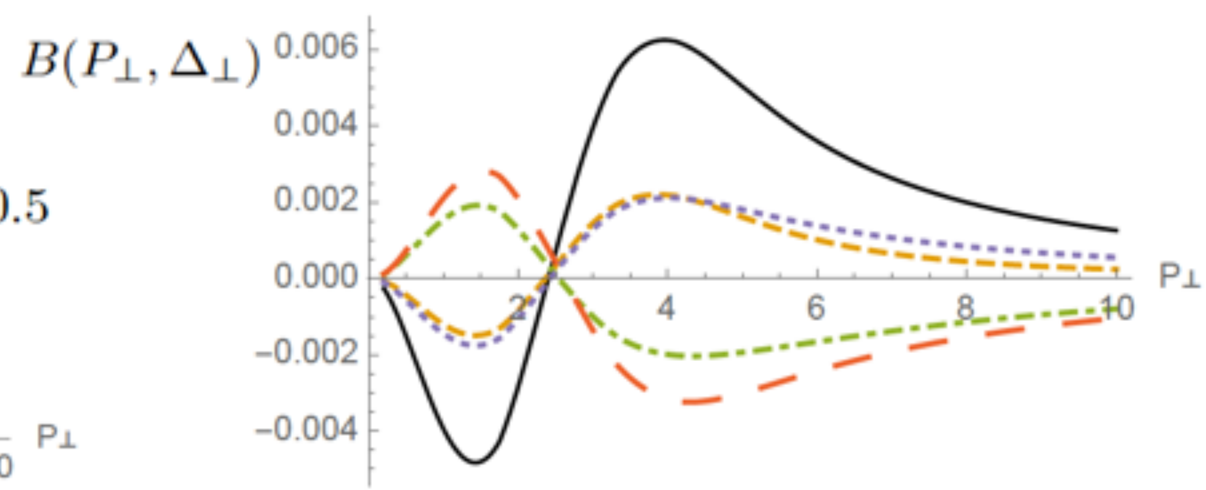
in units of
$1/R$, $R = 0.4$ fm





MV model:





Conclusions

- ✓ Quasi-probability (quark and gluon) Wigner distributions represent 5D snapshot of the hadronic structure and contain full information about it equivalent to knowing the exact wave functions of partons in the nucleon.

- ✓ The elliptic gluon Wigner distribution contains an important info on azimuthal angle correlation due to dipole orientation effects and is responsible e.g. for the elliptic flow and angular correction in exclusive dijet production.

- ✓ One of the most promising ways to access the gluon Wigner distribution is by measuring the differential cross section of exclusive dijet production in ultraperipheral pA/AA collisions. A dedicated analysis for a given experiment is necessary.