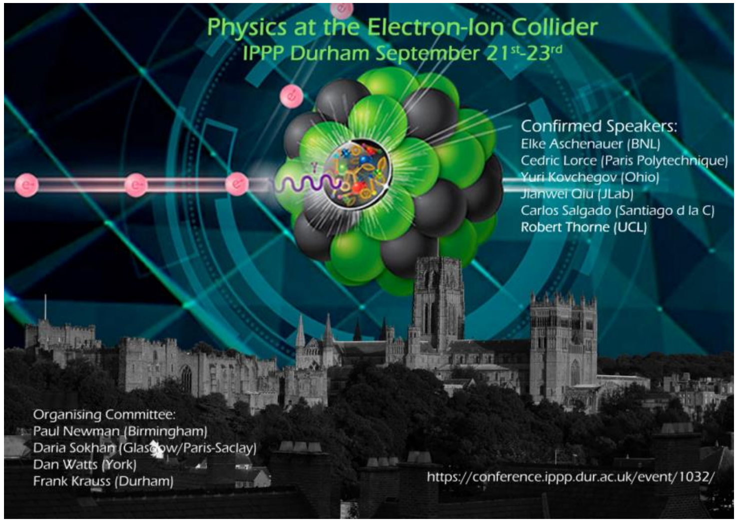
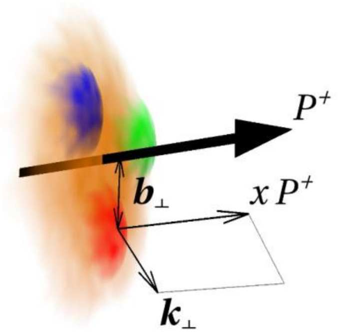


Physics at the Electron-Ion Collider
IPPP Durham September 21st-23rd

Confirmed Speakers:
Elke Aschenauer (BNL)
Cedric Lorce (Paris Polytechnique)
Yuri Kovchegov (Ohio)
Jianwei Qiu (JLab)
Carlos Salgado (Santiago d la C)
Robert Thorne (UCL)

Organising Committee:
Paul Newman (Birmingham)
Daria Sokhan (Glasgow/Paris-Saclay)
Dan Watts (York)
Frank Krauss (Durham)

https://conference.ippp.dur.ac.uk/event/1032/



TMDs and their friends

Cédric Lorcé

September 21

Outline

- Motivations
- Transverse-momentum dependent PDFs
- Generalized PDFs
- Wigner distributions

Nucleon structure

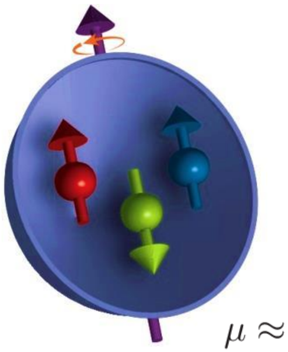
Non-relativistic picture

dominated by constituents

Mass

Spin

Spectroscopy



$\mu \approx \Lambda_{\mathrm{QCD}}$

$$M_N c^2 \sim \sum_Q M_Q c^2 + E_{\text{binding}}$$

~ 102 %   ~ - 2 %

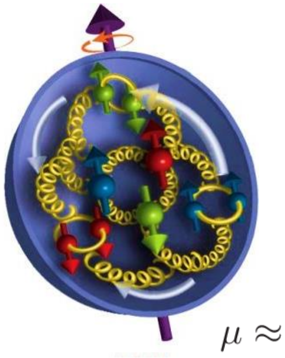
$$J_z^N \sim \sum_Q S_z^Q$$

~ 100 %

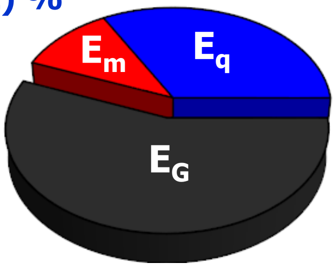
Relativistic picture

dominated by dynamics

High-energy scattering



$\mu \approx 2\,\mathrm{GeV}$



Quark mass & QCD condensate

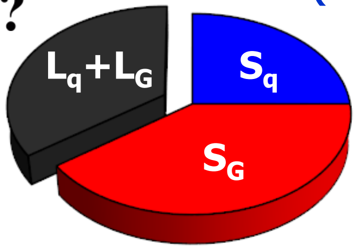
~ 11(2) %

Quark kinetic+potential energies

~ 33(2) %

?

Gluon kinetic+potential energies



Orbital angular momentum

?

Quark spin

~ 25(10) %

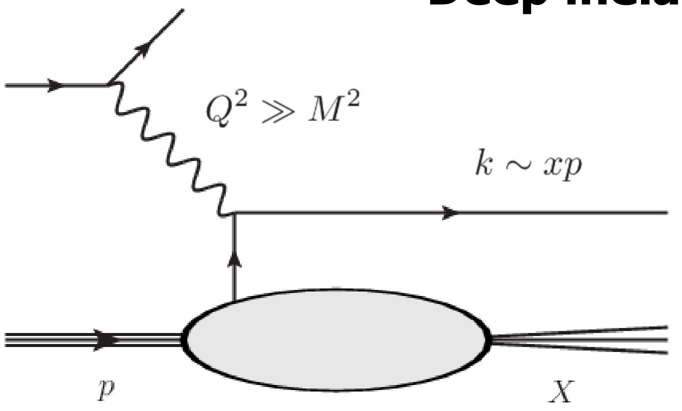
~ 40(?) %

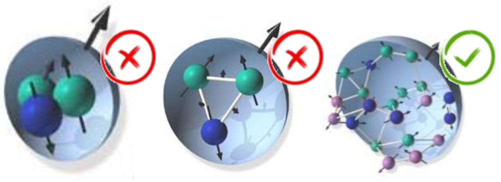
Gluon spin

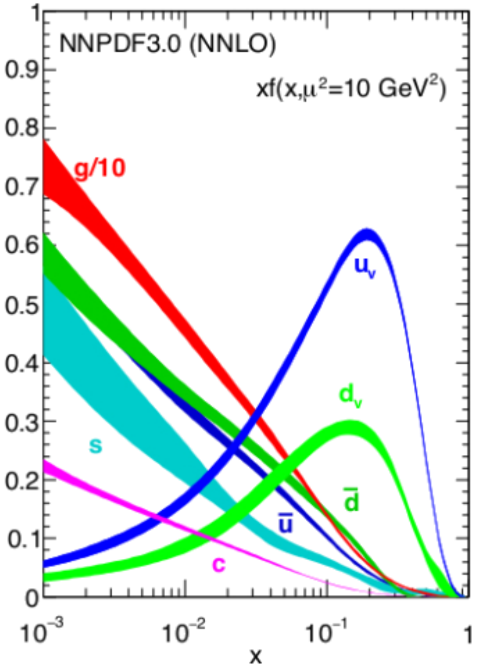
EIC !

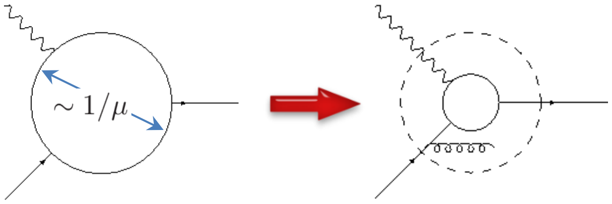
Parton distribution functions (PDFs)

Deep inelastic scattering (DIS)

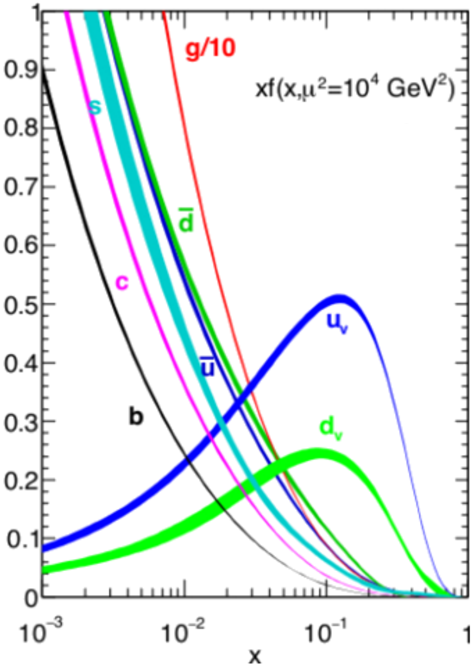






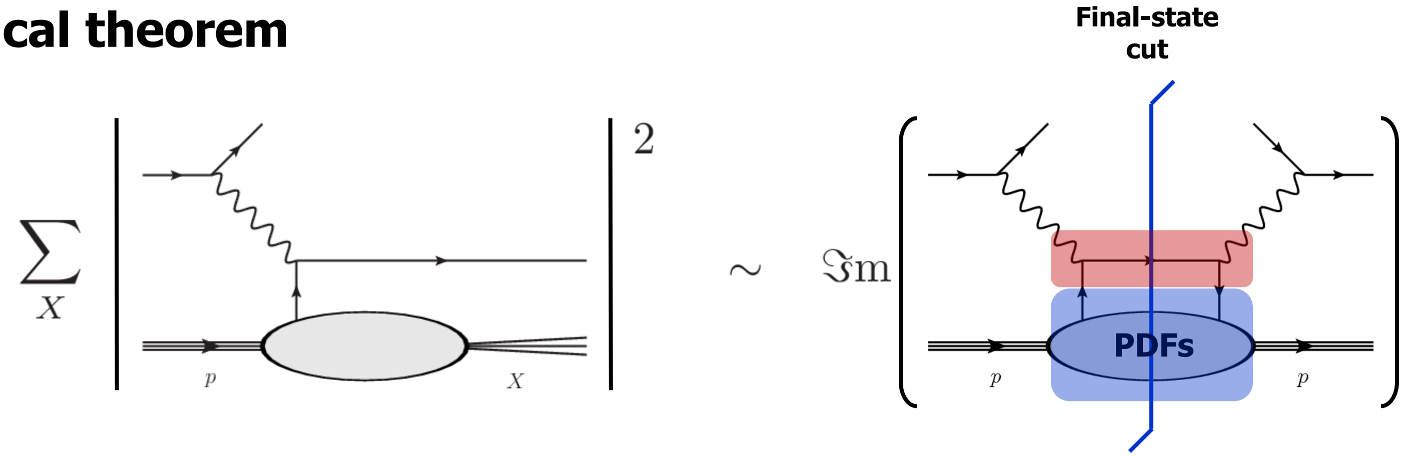


Perturbative QCD evolution (DGLAP)



Parton distribution functions (PDFs)

Optical theorem



$$\mathrm{d}\sigma^{lp\to lX} \sim \sum_i \int_x^1 \frac{\mathrm{d}y}{y} C_i\left(\frac{x}{y}, \frac{Q^2}{\mu_F^2}; \alpha_S(\mu_R)\right) f_i(y, \mu_F^2)$$

$$i = q_f, \bar{q}_f, g$$
$$\mu_F \approx \mu_R$$

Perturbative
Process-dependent

Non-perturbative
Process-independent

Parton density (in $A^+ = 0$ gauge)

$$a^\pm = \frac{1}{\sqrt{2}}(a^0 \pm a^3)$$

$$f(x) = \frac{1}{2}\int \frac{\mathrm{d}z^-}{2\pi} e^{ixP^+z^-} \langle P|\overline{\psi}(-\tfrac{z}{2})\gamma^+\psi(\tfrac{z}{2})|P\rangle\big|_{z^+=z_\perp=0}$$

$$k^+ = xP^+$$

$$\sim \frac{1}{2x(2\pi)}\sum_\lambda \int \frac{\mathrm{d}^2k_\perp}{(2\pi)^2} \frac{\langle P|b^\dagger_{k,\lambda}b_{k,\lambda}|P\rangle}{\langle P|P\rangle}$$

$$\langle p'|p\rangle = 2p^+(2\pi)^3\delta(p'^+ - p^+)\delta^{(2)}(\vec{p}'_\perp - \vec{p}_\perp)$$

Transverse-momentum dependent PDFs

Going beyond the collinear partonic picture

Quark Wigner operator (contour gauge)

$$j^\mu(r,k) = \int \frac{\mathrm{d}^4 z}{(2\pi)^4}\, e^{ik\cdot z}\, \overline{\psi}(r-\tfrac{z}{2})\gamma^\mu\psi(r+\tfrac{z}{2})$$

Non-local in both longitudinal and transverse directions !

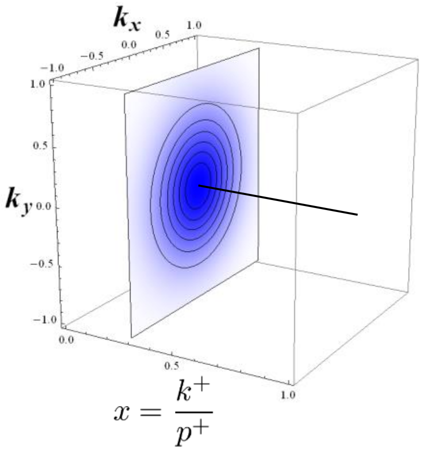
Charge current operator

$$j^\mu(r) = \int \mathrm{d}^4k\, j^\mu(r,k)$$

Unintegrated distributions

$$\mathrm{PDF}(x) \sim \frac{1}{2}\int \mathrm{d}k^-\, \mathrm{d}^2k_\perp\, \langle p|j^+(0,k)|p\rangle$$

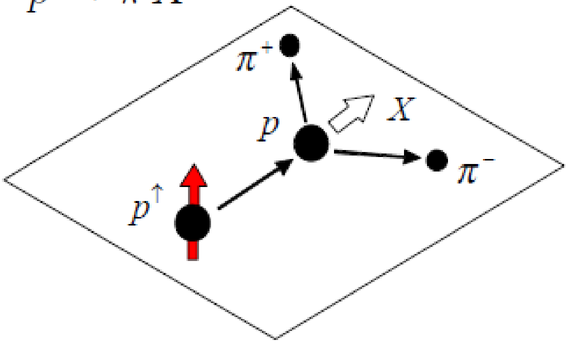
$$\mathrm{TMD}(x,\vec{k}_\perp) \sim \frac{1}{2}\int \mathrm{d}k^-\, \langle p|j^+(0,k)|p\rangle$$



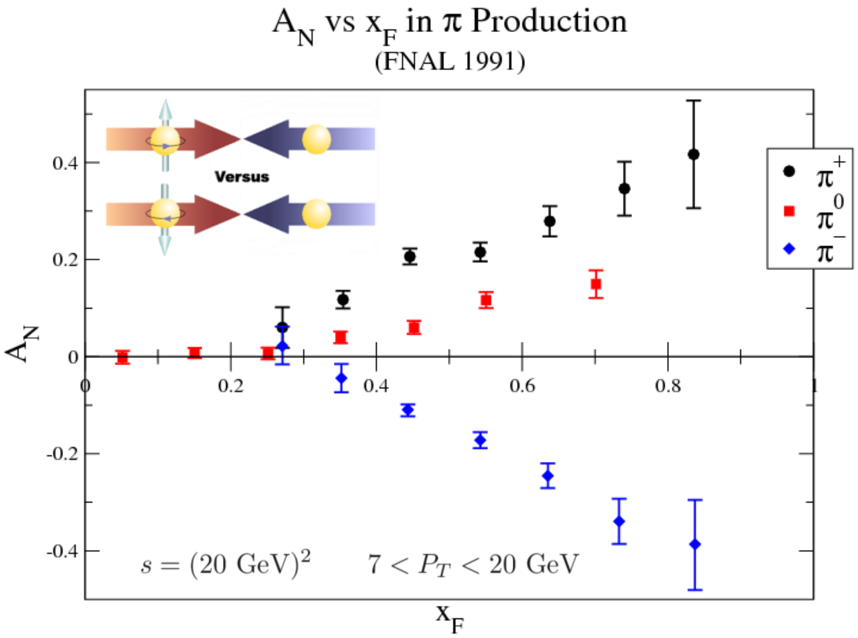
Transverse-momentum dependent PDFs

Single-spin asymmetries (SSA)

E.g. $p^{\uparrow}\, p \to \pi\, X$



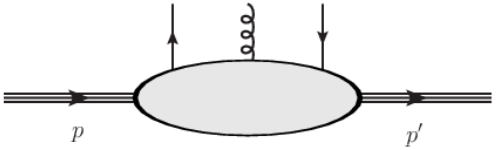
$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} \propto \vec{S}_N \cdot (\vec{p}_N \times \vec{P}_T)$$



Price for helicity flip

Collinear twist-2 ✗ $A_N \propto \frac{m_q}{E_q}\alpha$ → **Too small !** **[Kane, Pumplin, Repko (1978)]**

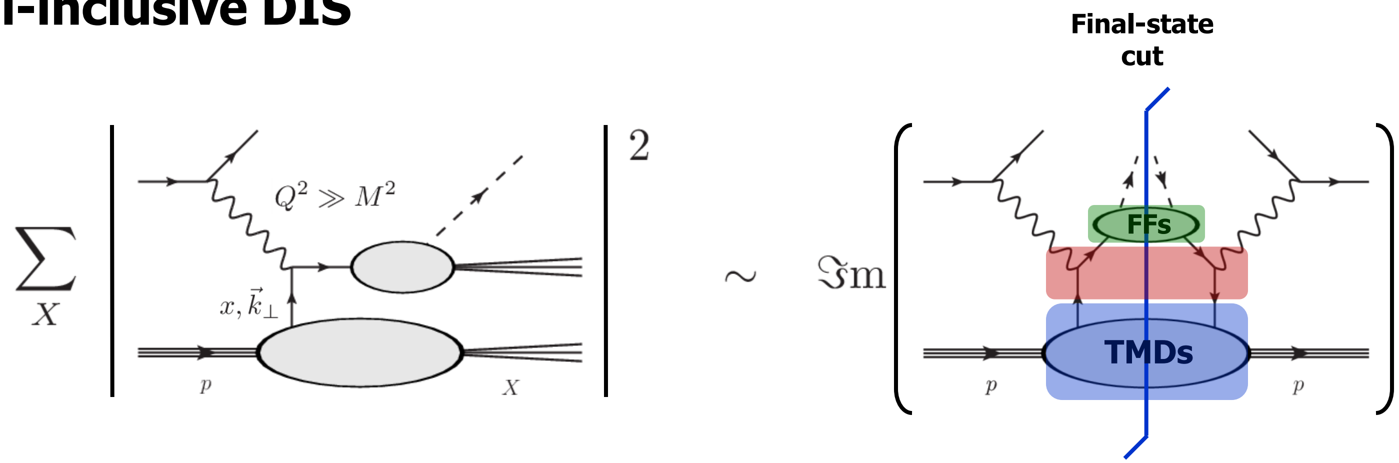
Collinear twist-3 ✓ $Q \sim P_T \gg \Lambda_{\rm QCD}$



Intrinsic k_T ✓ $Q \gg P_T \sim \Lambda_{\rm QCD}$

Transverse-momentum dependent PDFs

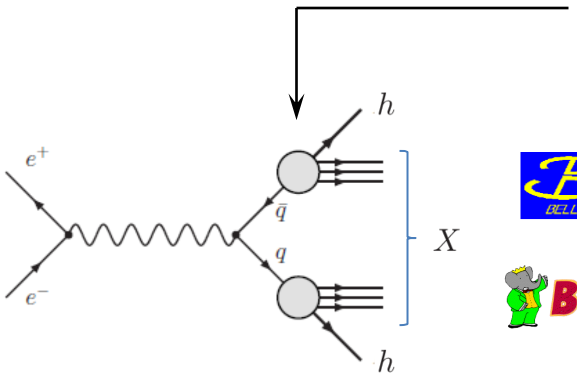
Semi-inclusive DIS



$$d\sigma \sim \sum \mathrm{TMD}(x,\vec{k}_\perp) \otimes d\hat{\sigma}_{hard} \otimes \mathrm{FF}(z,\vec{p}_\perp) + \mathcal{O}(\frac{P_T}{Q})$$

Fragmentation function

$e^+e^- \to hh'X$

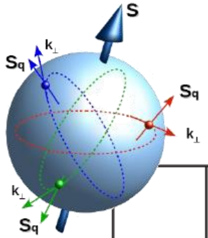


BELLE

BABAR

Transverse-momentum dependent PDFs

Rich spin structure (leading twist)



Quark polarization

Nucleon polarization

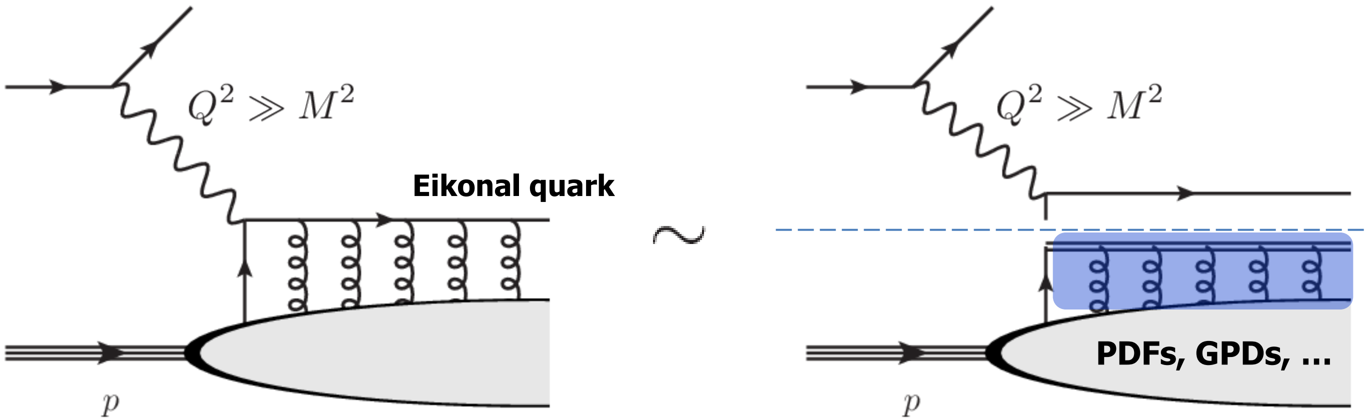
	γ^+	$i\sigma^{1+}\gamma_5$	$i\sigma^{2+}\gamma_5$	$\gamma^+\gamma_5$
	U	T_x	T_y	L
U	f_1	$\frac{k_y}{M}\, h_1^\perp$	$-\frac{k_x}{M}\, h_1^\perp$	
T_x	$\frac{k_y}{M}\, f_{1T}^\perp$	$h_1 + \frac{k_x^2 - k_y^2}{2M^2}\, h_{1T}^\perp$	$\frac{k_x k_y}{M^2}\, h_{1T}^\perp$	$\frac{k_x}{M}\, g_{1T}$
T_y	$-\frac{k_x}{M}\, f_{1T}^\perp$	$\frac{k_x k_y}{M^2}\, h_{1T}^\perp$	$h_1 - \frac{k_x^2 - k_y^2}{2M^2}\, h_{1T}^\perp$	$\frac{k_y}{M}\, g_{1T}$
L		$\frac{k_x}{M}\, h_{1L}^\perp$	$\frac{k_y}{M}\, h_{1L}^\perp$	g_{1L}

🟦 **Survives integration over transverse momentum**

Transverse-momentum dependent PDFs

Gauge symmetry

System **« Factorized » system**



Local **Non-local**

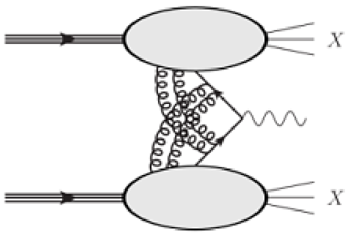
$$j^\mu(r,k) = \int \frac{\mathrm{d}^4 z}{(2\pi)^4}\, e^{ik\cdot z}\, \overline{\psi}(r - \tfrac{z}{2})\gamma^\mu \mathcal{W}(r - \tfrac{z}{2}, r + \tfrac{z}{2})\psi(r + \tfrac{z}{2})$$

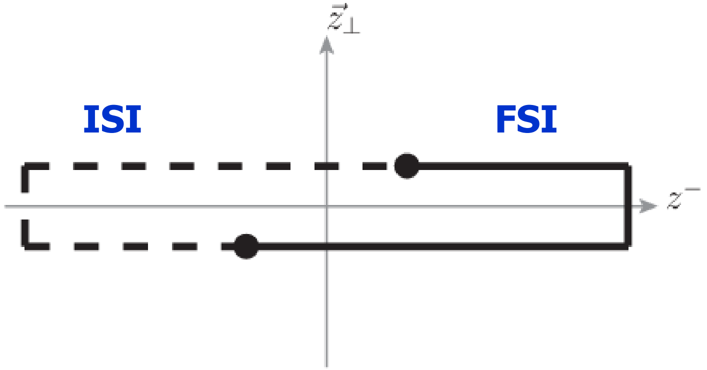
Wilson line $$\mathcal{W}(b,a) = \mathcal{P}\left[e^{ig\int_a^b A^\mu \,\mathrm{d}z_\mu}\right]$$

Transverse-momentum dependent PDFs

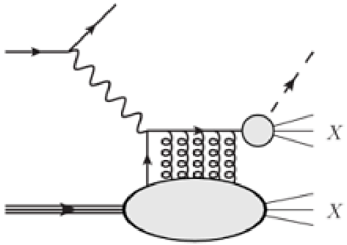
Process dependence

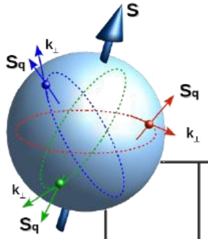
Drell-Yan





SIDIS



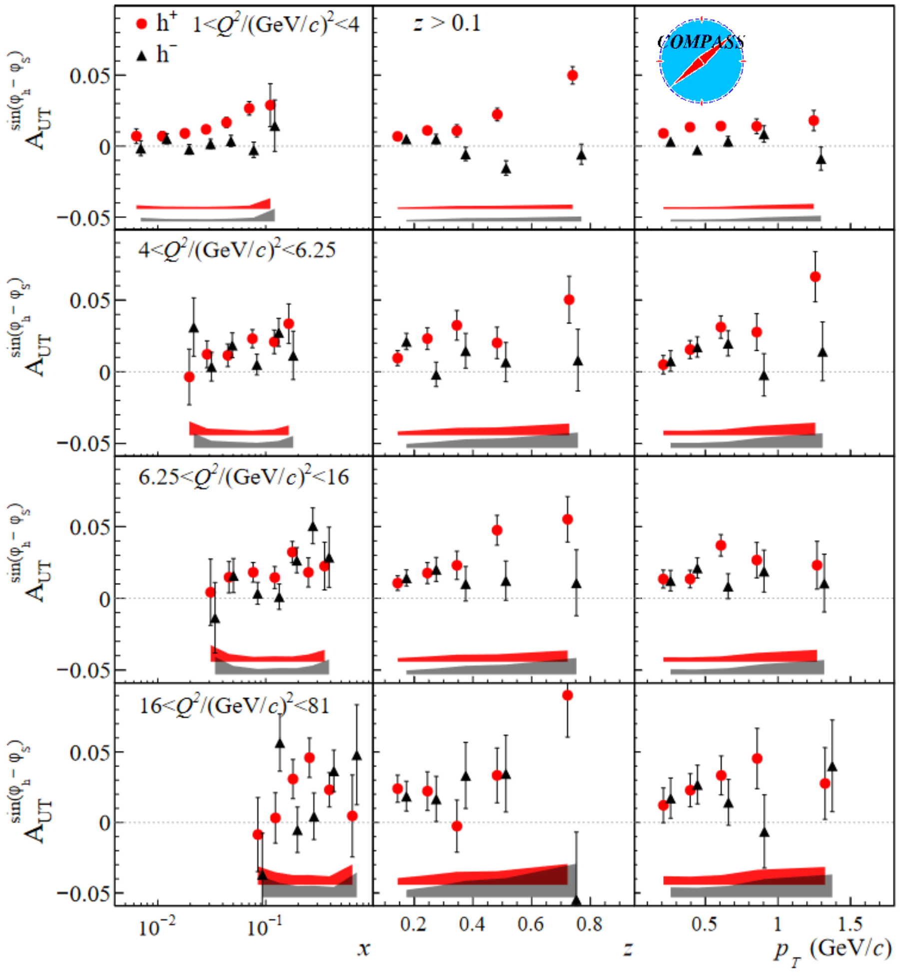


		Quark polarization			
		U	T_x	T_y	L
Nucleon polarization	U	f_1	🟥 $\frac{k_y}{M}\, h_1^\perp$	🟥 $-\frac{k_x}{M}\, h_1^\perp$	
	T_x	🟥 $\frac{k_y}{M}\, f_{1T}^\perp$	$h_1 + \frac{k_x^2 - k_y^2}{2M^2}\, h_{1T}^\perp$	$\frac{k_x k_y}{M^2}\, h_{1T}^\perp$	$\frac{k_x}{M}\, g_{1T}$
	T_y	🟥 $-\frac{k_x}{M}\, f_{1T}^\perp$	$\frac{k_x k_y}{M^2}\, h_{1T}^\perp$	$h_1 - \frac{k_x^2 - k_y^2}{2M^2}\, h_{1T}^\perp$	$\frac{k_y}{M}\, g_{1T}$
	L		$\frac{k_x}{M}\, h_{1L}^\perp$	$\frac{k_y}{M}\, h_{1L}^\perp$	g_{1L}

🟥 **Changes sign under ISI ↔ FSI (naive T-odd)**

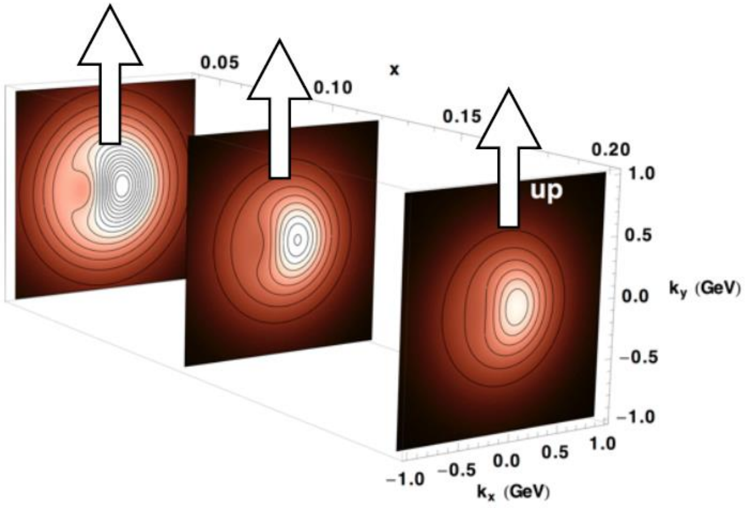
Transverse-momentum dependent PDFs

Clear SIDIS experimental signal



[Adolph *et al.*, PLB770 (2017) 138]

Transversely polarized proton



Courtesy of A. Bacchetta

Parton distribution zoo

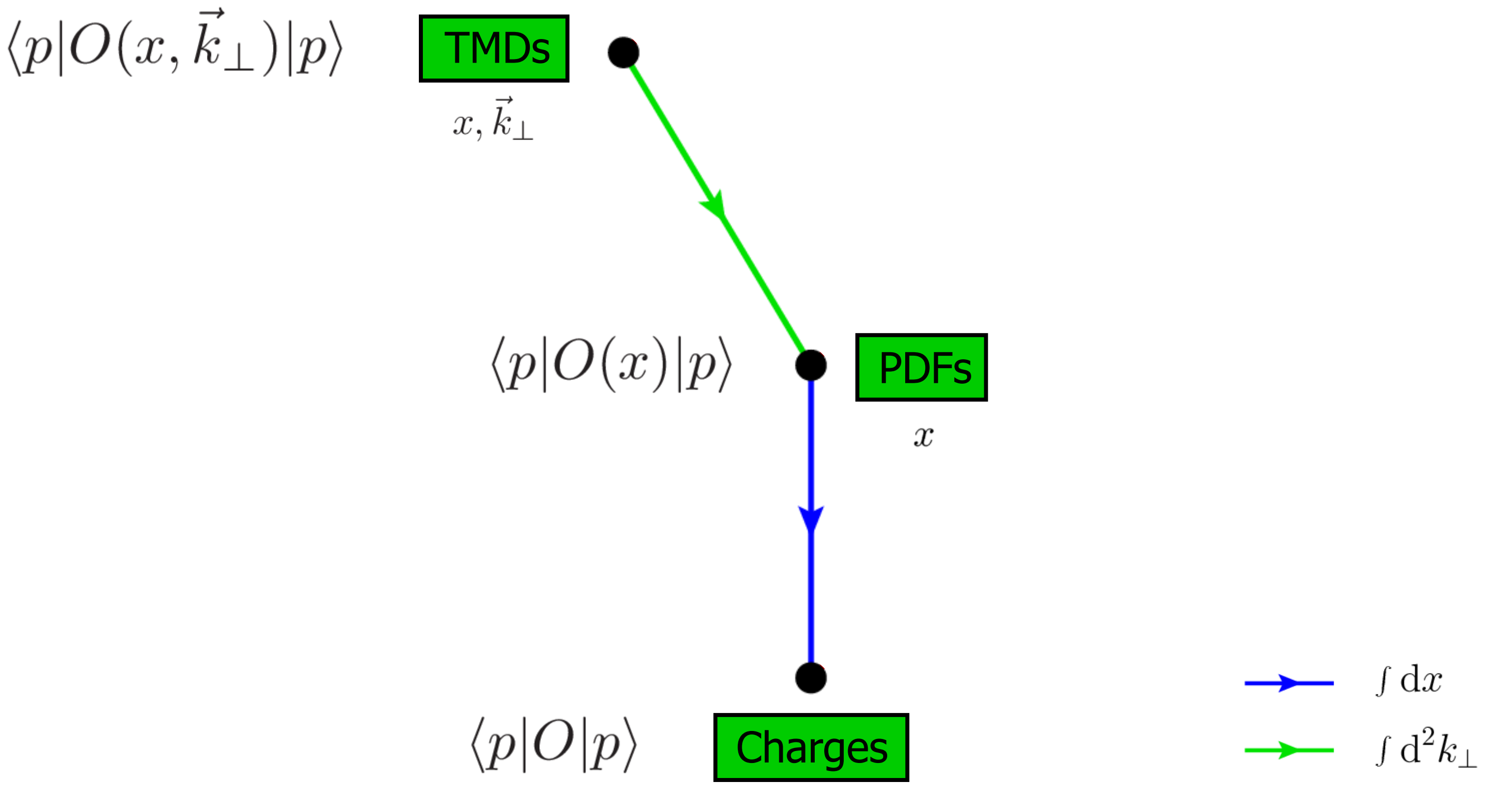
Nonlocal quark operator

$$\widetilde{O}(z) = \overline{\psi}(-\tfrac{z}{2})\Gamma\mathcal{W}(-\tfrac{z}{2},\tfrac{z}{2})\psi(\tfrac{z}{2}) \quad \Longrightarrow$$

$$O \sim \widetilde{O}(0)$$

$$O(x) \sim \int \frac{\mathrm{d}z^-}{2\pi}\, e^{ixP^+z^-}\, \widetilde{O}(z)\big|_{z^+=z_\perp=0}$$

$$O(x,\vec{k}_\perp) \sim \int \frac{\mathrm{d}z^-\,\mathrm{d}^2z_\perp}{(2\pi)^3}\, e^{ixP^+z^- - i\vec{k}_\perp\cdot\vec{z}_\perp}\, \widetilde{O}(z)\big|_{z^+=0}$$



$\langle p|O(x,\vec{k}_\perp)|p\rangle$ **TMDs** $x,\vec{k}_\perp$

$\langle p|O(x)|p\rangle$ **PDFs** x

$\langle p|O|p\rangle$ **Charges**

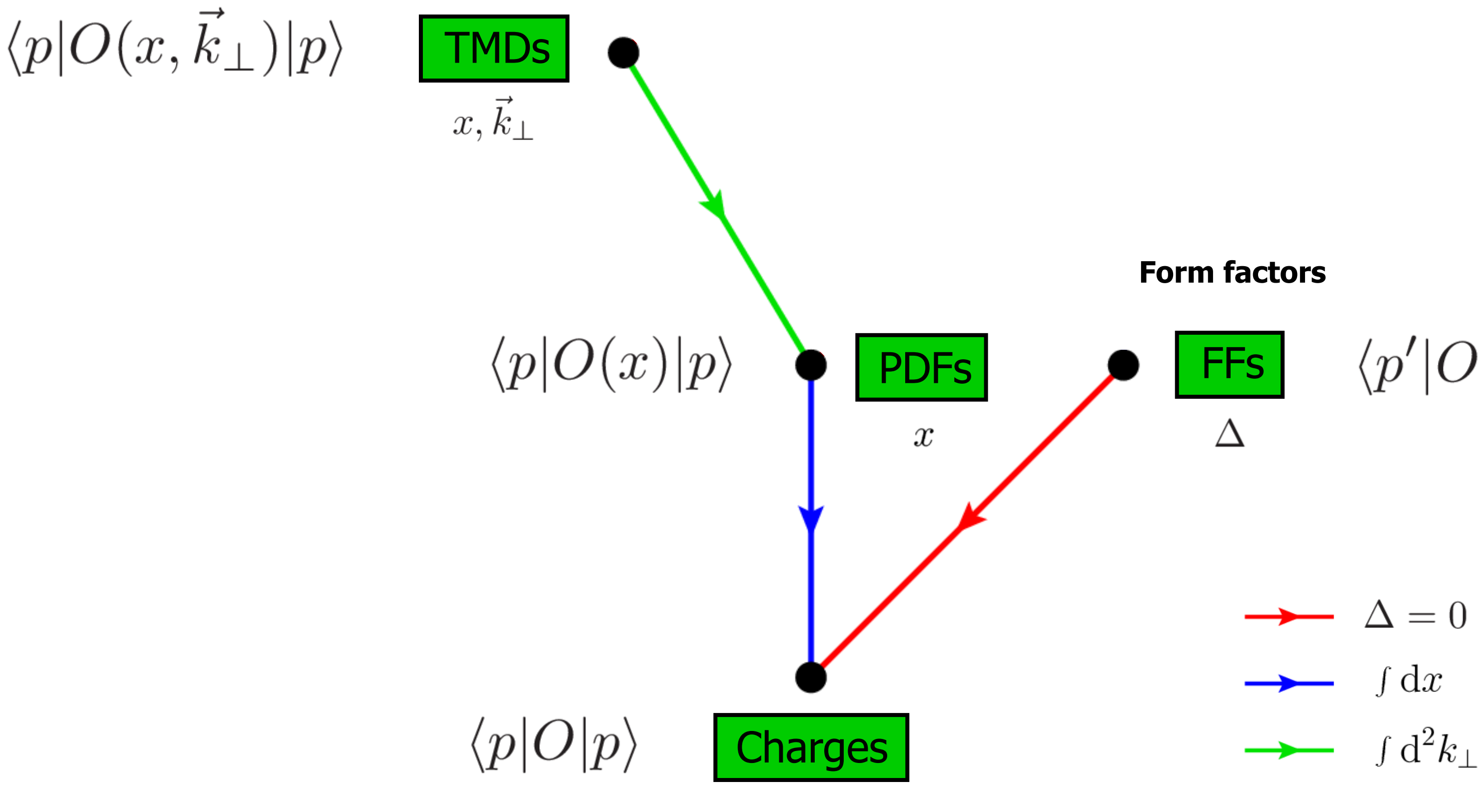
→ $\int \mathrm{d}x$

→ $\int \mathrm{d}^2k_\perp$

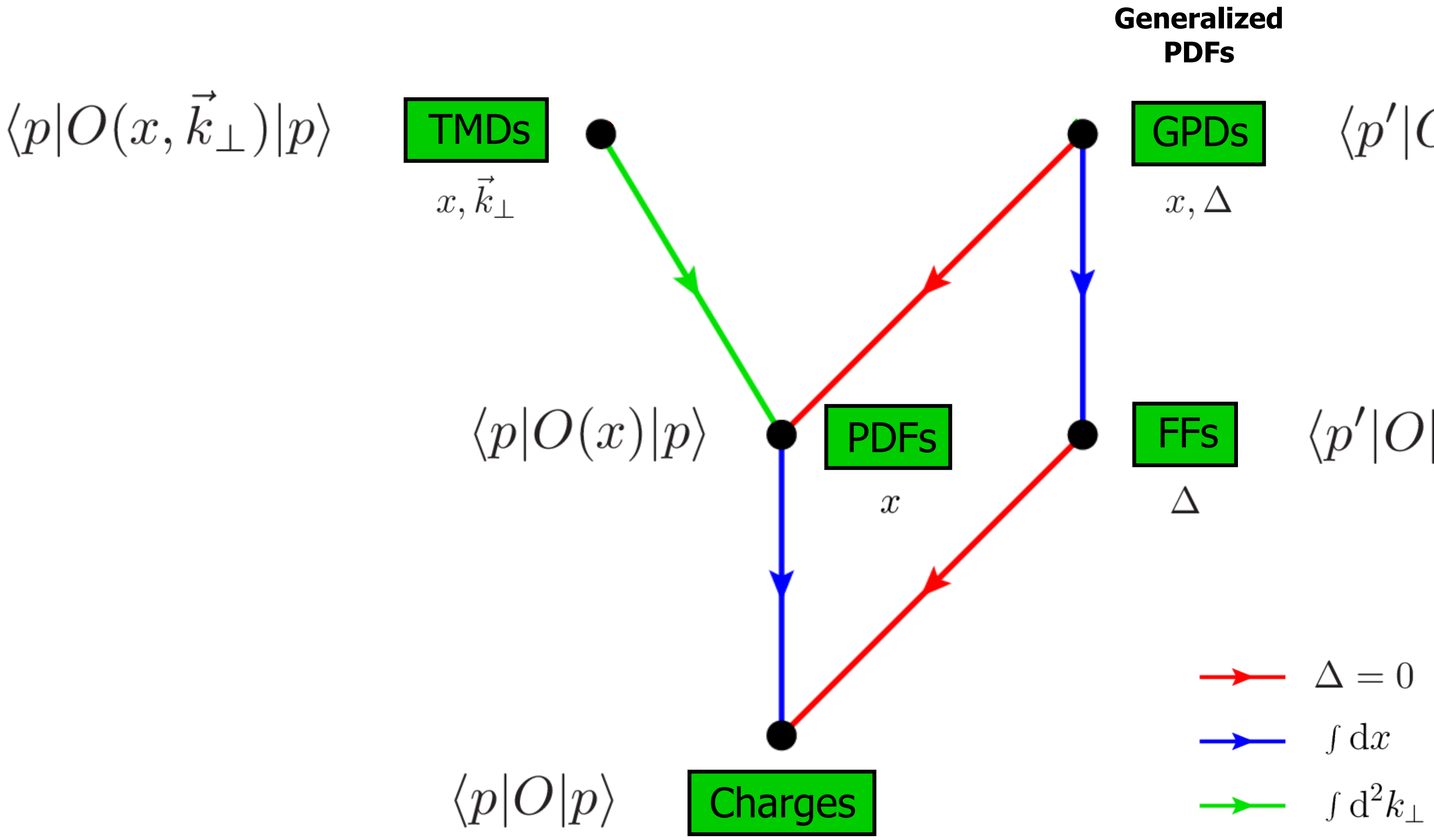
Parton distribution zoo

Off-forward amplitudes

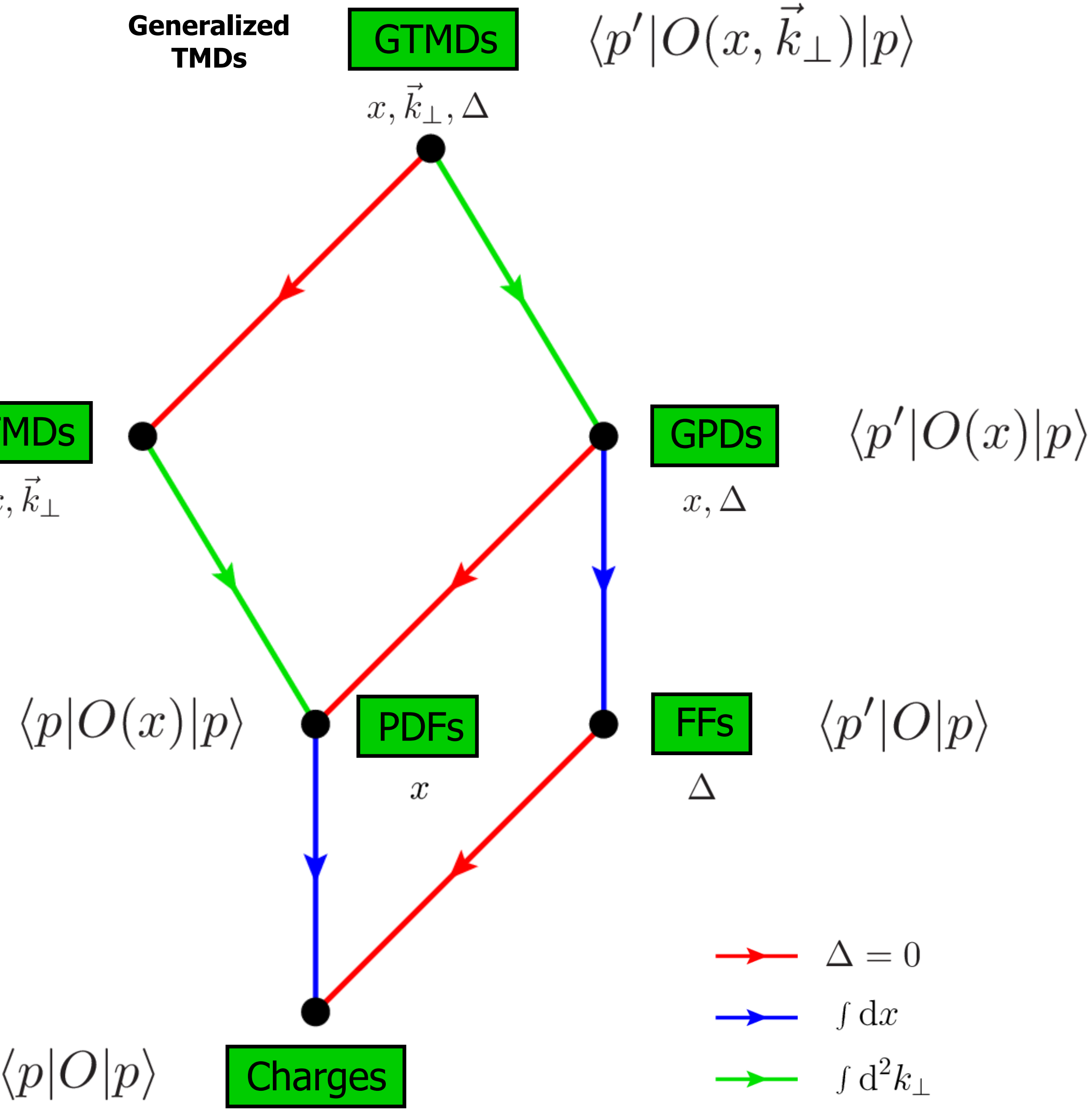
$$\langle p|\cdots|p\rangle \longrightarrow \langle p'|\cdots|p\rangle \qquad P=\tfrac{1}{2}(p'+p), \quad \Delta = p'-p$$



Parton distribution zoo



Parton distribution zoo



Generalized TMDs

GTMDs $\langle p'|O(x,\vec{k}_\perp)|p\rangle$

$x, \vec{k}_\perp, \Delta$

$\langle p|O(x,\vec{k}_\perp)|p\rangle$ TMDs

$x, \vec{k}_\perp$

GPDs $\langle p'|O(x)|p\rangle$

x, Δ

$\langle p|O(x)|p\rangle$ PDFs

x

FFs $\langle p'|O|p\rangle$

Δ

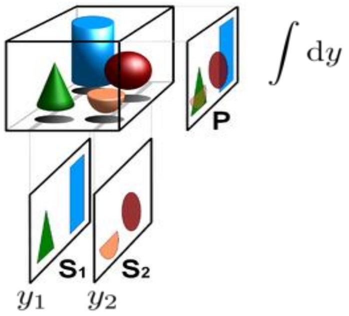
$\langle p|O|p\rangle$ Charges

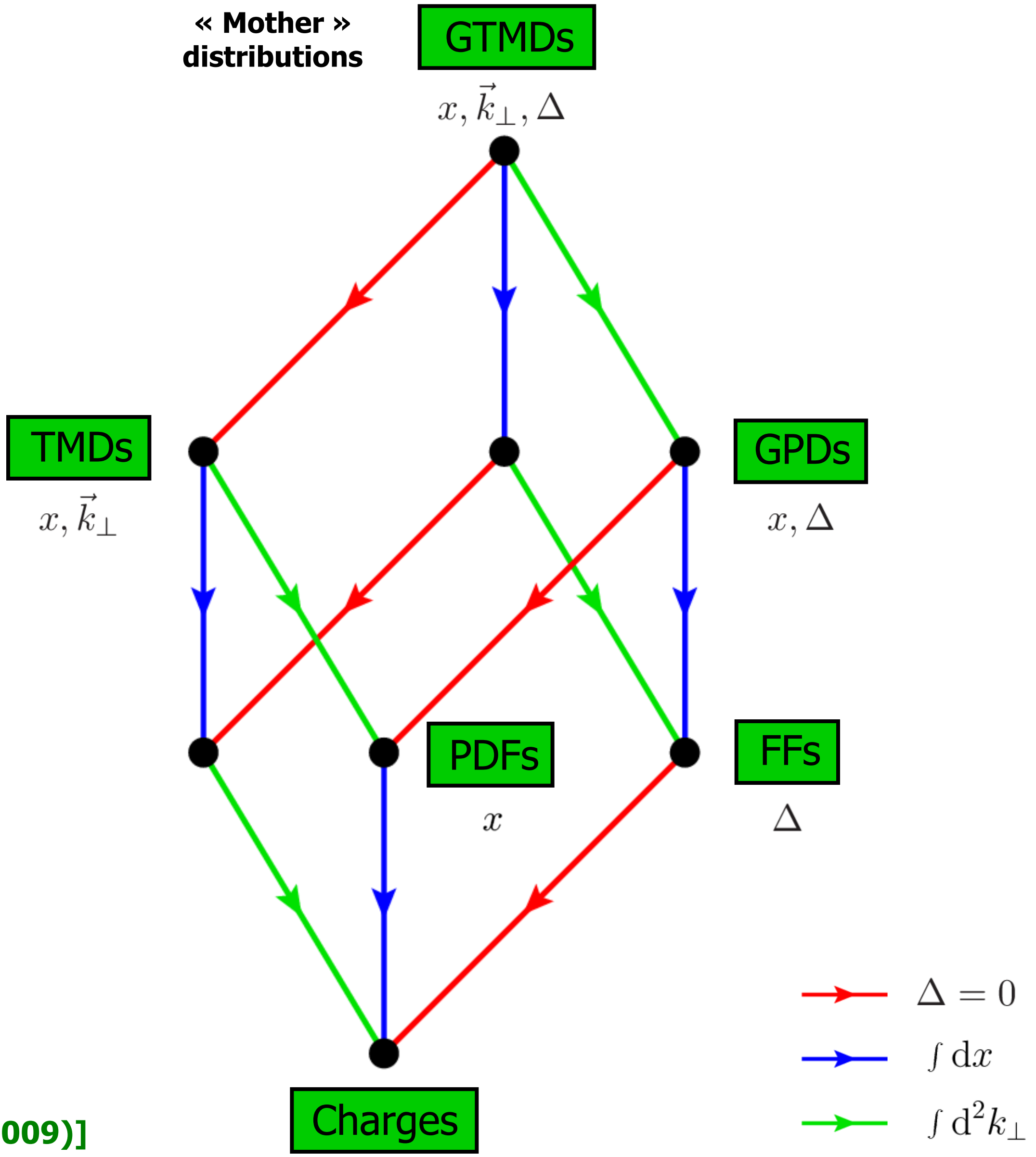
$\Delta = 0$

$\int \mathrm{d}x$

$\int \mathrm{d}^2 k_\perp$

Parton distribution zoo





« Mother » distributions

GTMDs

$x, \vec{k}_\perp, \Delta$

TMDs

$x, \vec{k}_\perp$

GPDs

x, Δ

PDFs

x

FFs

Δ

Charges

$\Delta = 0$

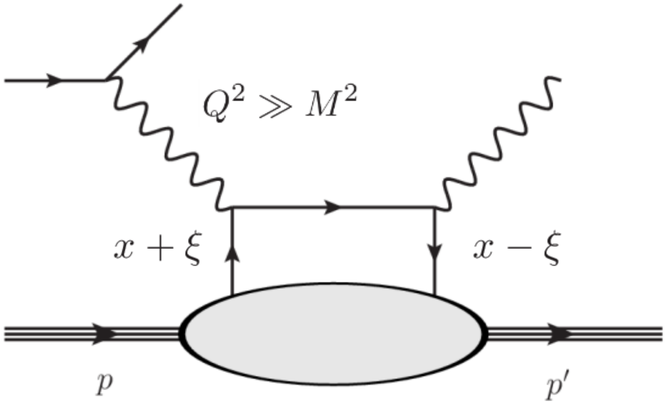
$\int \mathrm{d}x$

$\int \mathrm{d}^2 k_\perp$

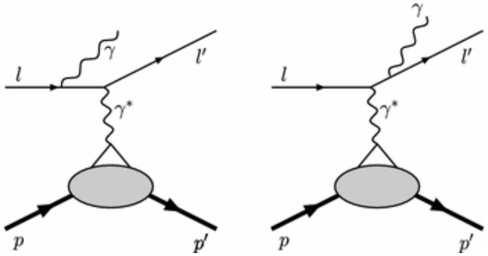
[Meissner, Metz, Schlegel (2009)]
[C.L., Pasquini, Vanderhaeghen (2011)]

Generalized PDFs

Deeply virtual Compton scattering (DVCS)



interferes with



Bethe-Heitler

Correlator (in $A^+ = 0$ gauge)

$$\frac{1}{2}\int \frac{\mathrm{d}z^-}{2\pi}\, e^{ixP^+z^-} \langle p'|\overline{\psi}(-\tfrac{z}{2})\gamma^+\psi(\tfrac{z}{2})|p\rangle\big|_{z^+=z_\perp=0}$$

$$= \frac{1}{2P^+}\,\overline{u}(p')\left[\gamma^+\,H(x,\xi,t) + \frac{i\sigma^{+\mu}\Delta_\mu}{2M}\,E(x,\xi,t)\right]u(p)$$

Momentum transfer variables

$$\xi = -\frac{\Delta^+}{2P^+} = \frac{p^+ - p'^+}{p^+ + p'^+}, \qquad t = \Delta^2 = (p'-p)^2$$

Generalized PDFs

Link with other non-perturbative functions

$$H(x,0,0) = f(x)$$

PDF

$$\int \mathrm{d}x\, H(x,\xi,t) = F_1(t)$$

$$\int \mathrm{d}x\, E(x,\xi,t) = F_2(t)$$

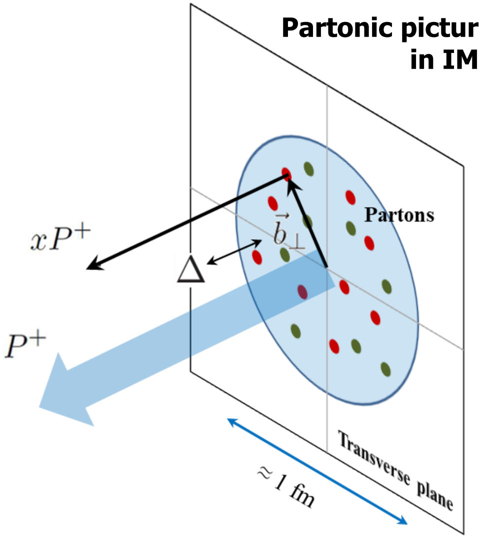
Electromagnetic form factors

2+1D imaging (in $A^+ = 0$ gauge)

$$\rho(x,\vec{b}_\perp) = P^+ \int \frac{\mathrm{d}^2\Delta_\perp}{(2\pi)^2}\, e^{-i\vec{\Delta}_\perp\cdot\vec{b}_\perp}\, \frac{\langle p'|j^+(xP^+)|p\rangle}{2P^+}\Big|_{\Delta^+=0}$$

$$j^\mu(k^+) = \int \frac{\mathrm{d}z^-}{2\pi}\, e^{ik^+z^-}\, \overline{\psi}(-\tfrac{z}{2})\gamma^\mu\psi(\tfrac{z}{2})\big|_{z^+=z_\perp=0}$$

Partonic picture in IMF



Generalized PDFs

Link with gravitational form factors

$$a^{\{\mu}b^{\nu\}} = \tfrac{1}{2}(a^\mu b^\nu + a^\nu b^\mu)$$
$$a^{[\mu}b^{\nu]} = \tfrac{1}{2}(a^\mu b^\nu - a^\nu b^\mu)$$

$$\langle p'|T^{\mu\nu}(0)|p\rangle = \overline{u}(p')\left[P^{\{\mu}\gamma^{\nu\}}A(t) + \frac{P^{\{\mu}i\sigma^{\nu\}\lambda}\Delta_\lambda}{2M}B(t) \right.$$
$$\left. + \frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{M}C(t) + Mg^{\mu\nu}\bar{C}(t) + \frac{P^{[\mu}i\sigma^{\nu]\lambda}\Delta_\lambda}{2M}D(t)\right]u(p)$$

$$T_q^{++}(0) = (\overline{\psi}\gamma^+ \tfrac{i}{2}\overset{\leftrightarrow}{D}{}^+\psi)(0)$$
$$= 2(P^+)^2 \int \mathrm{d}x\, x\, \frac{1}{2}\int \frac{\mathrm{d}z^-}{2\pi}\, e^{ixP^+z^-}\, \overline{\psi}(-\tfrac{z}{2})\gamma^+\psi(\tfrac{z}{2})\Big|_{z^+=z_\perp=0}$$

$$\Rightarrow \boxed{\begin{aligned}\int \mathrm{d}x\, x\, H(x,\xi,t) &= A(t) + 4\xi^2 C(t)\\ \int \mathrm{d}x\, x\, E(x,\xi,t) &= B(t) - 4\xi^2 C(t)\end{aligned}}$$

Generalized PDFs

Poincaré constraints

$$\sum_{a=q,g} A_a(0) = 1$$

$$\sum_{a=q,g} B_a(0) = 0$$

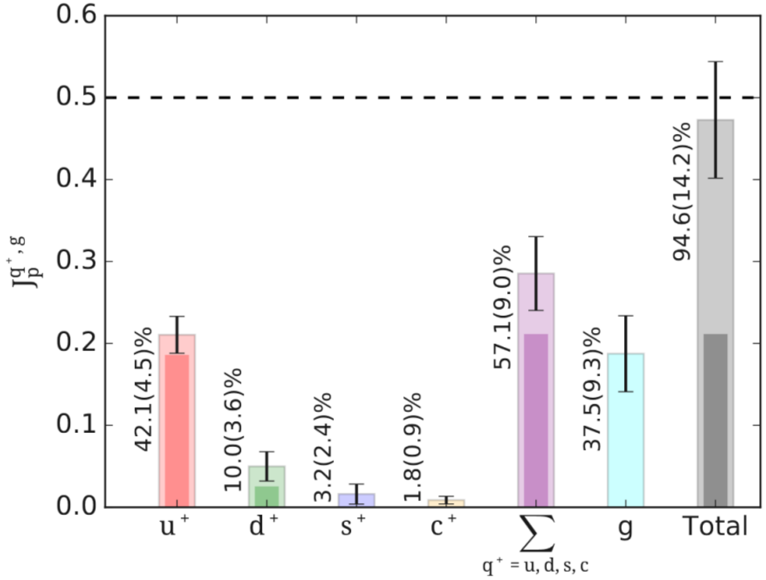
$$\sum_{a=q,g} \bar{C}_a(t) = 0$$

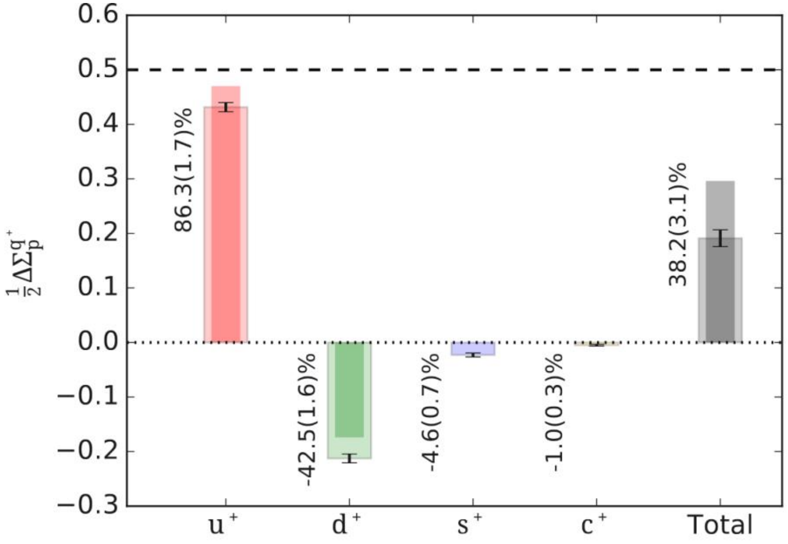
$$D_q(t) = -G_A(t)$$

Angular momentum

$$\langle J_q^z \rangle = \frac{A_q(0) + B_q(0)}{2}$$

$$\langle S_q^z \rangle = \frac{G_A(0)}{2} = \frac{\Delta\Sigma}{2}$$

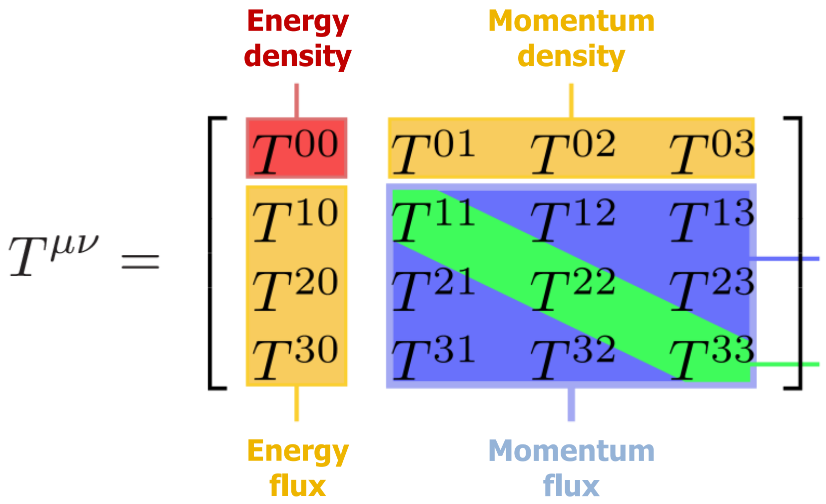




[Alexandrou *et al.*, PRD101 (2020) 094513]

Energy-momentum tensor

Instead of charge current, we can look at four-momentum current



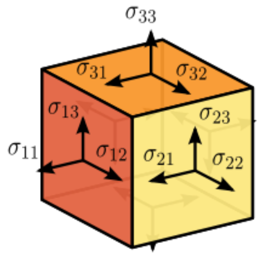
$$T^{\mu\nu} = \begin{bmatrix} T^{00} & T^{01} & T^{02} & T^{03} \\ T^{10} & T^{11} & T^{12} & T^{13} \\ T^{20} & T^{21} & T^{22} & T^{23} \\ T^{30} & T^{31} & T^{32} & T^{33} \end{bmatrix}$$

Energy density

Momentum density

Energy flux

Momentum flux



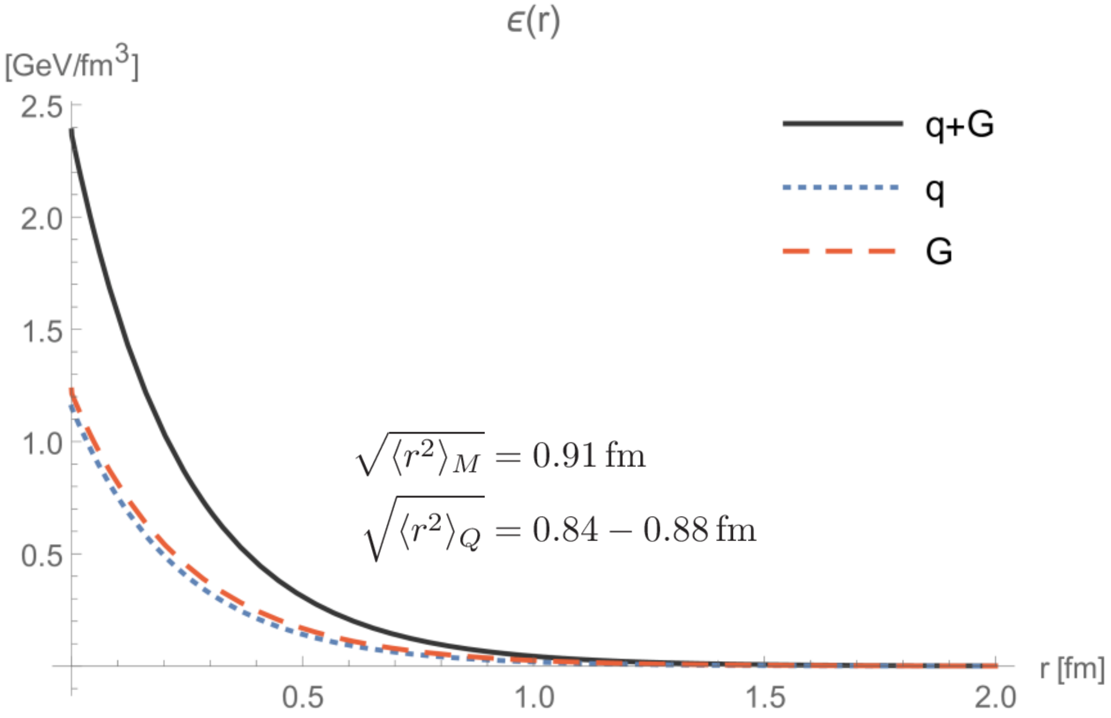
Shear stress

Normal stress **(pressure)**

Four-momentum operator $P^{\mu}_{a} = \int \mathrm{d}^3 r\, T^{0\mu}_{a}(r) \qquad a = q, g$

Energy distribution (3D Breit frame)

$$\langle T^{00}\rangle_{\vec{0},\vec{0}}(\vec{r}) = \int \frac{\mathrm{d}^3\Delta}{(2\pi)^3}\, e^{-i\vec{\Delta}\cdot\vec{r}}\langle \tfrac{\vec{\Delta}}{2}|T^{00}(0)| - \tfrac{\vec{\Delta}}{2}\rangle$$



$$\sqrt{\langle r^2\rangle_M} = 0.91\,\mathrm{fm}$$

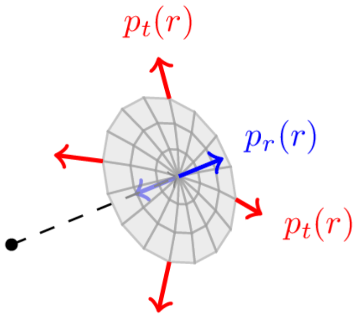
$$\sqrt{\langle r^2\rangle_Q} = 0.84 - 0.88\,\mathrm{fm}$$

Multipole model for the gravitational form factors

$$F(t) = \frac{F(0)}{(1+t/\Lambda^2)^n}$$

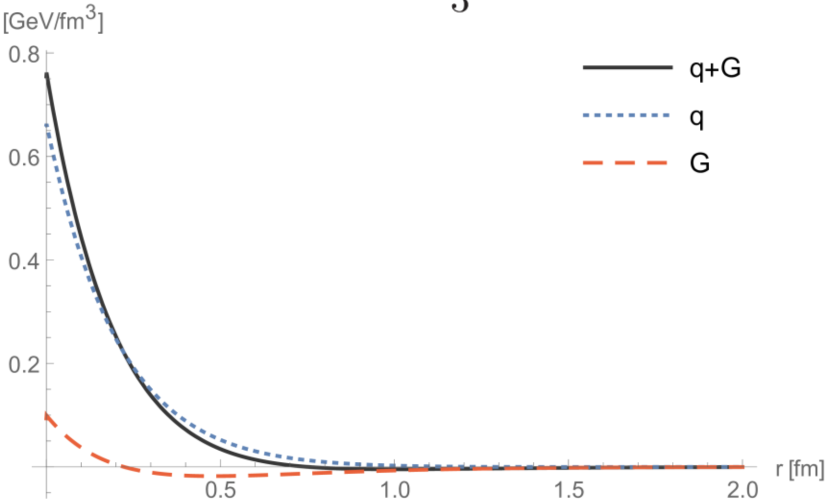
Pressure distributions (3D Breit frame)

$$\langle T^{ij}\rangle_{\vec{0},\vec{0}}(\vec{r}) = \int \frac{\mathrm{d}^3\Delta}{(2\pi)^3}\, e^{-i\vec{\Delta}\cdot\vec{r}}\langle \tfrac{\vec{\Delta}}{2}|T^{ij}(0)| -\tfrac{\vec{\Delta}}{2}\rangle$$



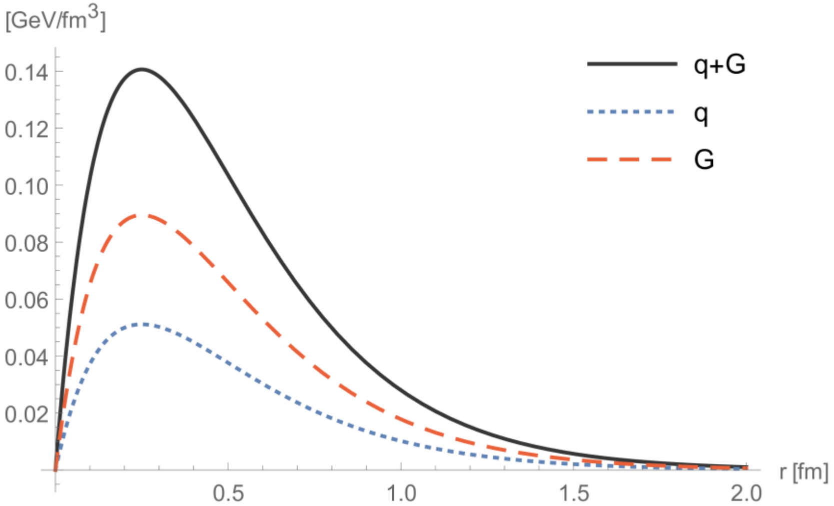
Isotropic pressure

$$p(r) = \frac{p_r(r) + 2p_t(r)}{3}$$



Pressure anisotropy

$$s(r) = p_r(r) - p_t(r)$$



Mechanical equilibrium

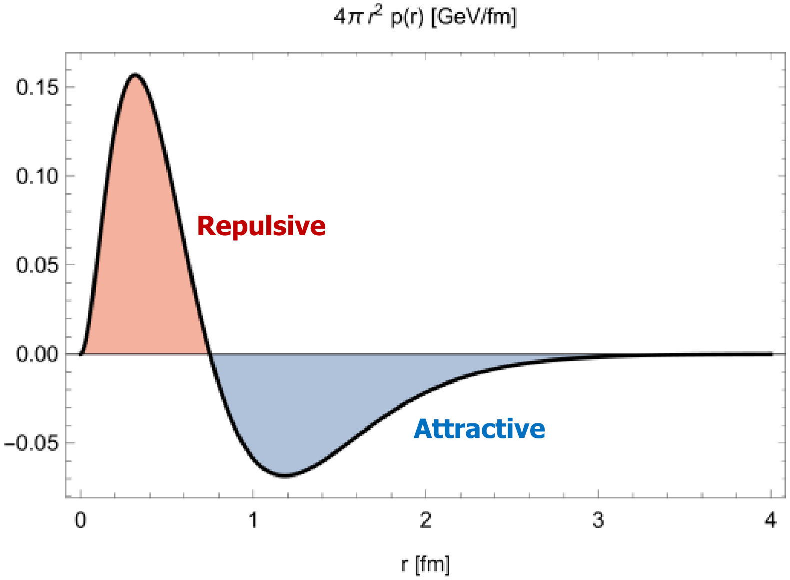
$$\nabla^i \langle T^{ij} \rangle_{\vec{0},\vec{0}}(\vec{r}) = 0 \quad \Rightarrow \quad \frac{\mathrm{d}p_r(r)}{\mathrm{d}r} = -\frac{2s(r)}{r}$$

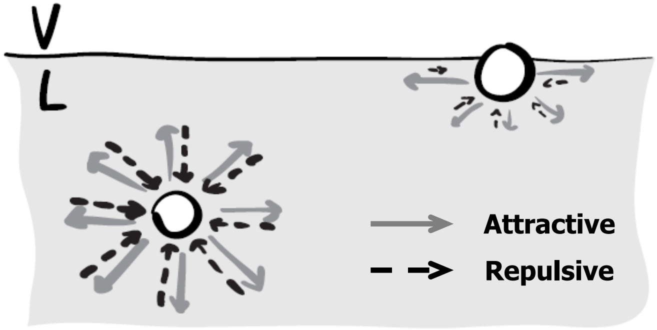
von Laue relation

$$\int_0^\infty \mathrm{d}r\, r^2\, p(r) = 0$$

Surface tension

$$\gamma = \int \mathrm{d}r\, s(r)$$





Angular momentum distributions

Orbital *vs* intrinsic

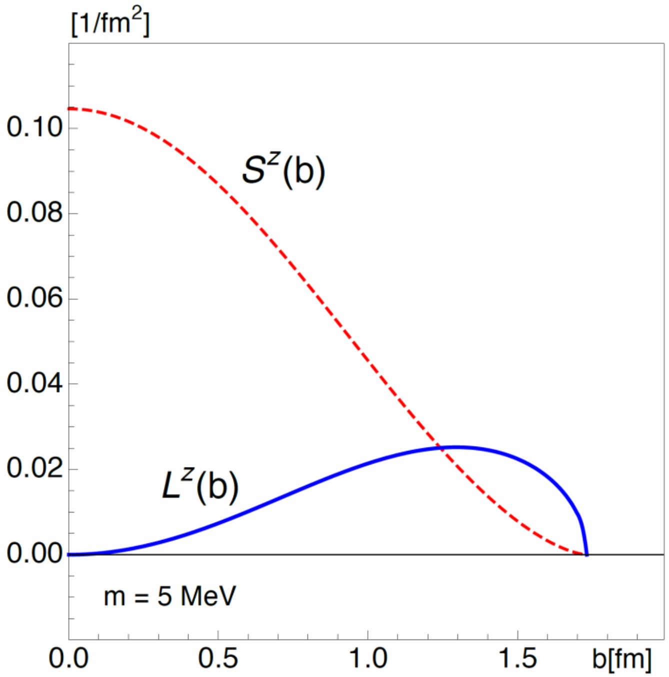
$$L^i(\vec{r}) = \epsilon^{ijk} r^j \langle T^{0k} \rangle_{\vec{0},\vec{0}}(\vec{r})$$

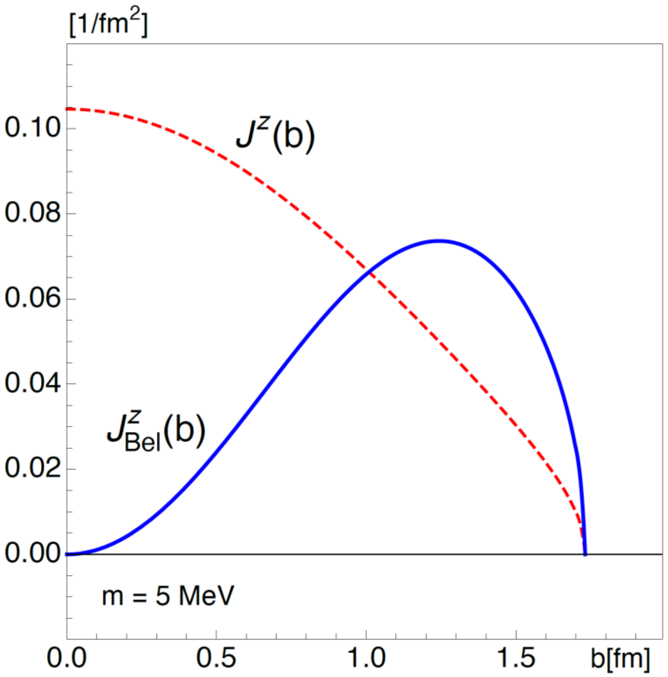
$$S^i(\vec{r}) = \langle \overline{\psi} \gamma^i \gamma_5 \psi \rangle_{\vec{0},\vec{0}}(\vec{r})$$

Kinetic *vs* Belinfante

$$J^i(\vec{r}) = L^i(\vec{r}) + S^i(\vec{r})$$

$$J^i_{\text{Bel}}(\vec{r}) = \epsilon^{ijk} r^j \langle \tfrac{1}{2}(T^{0k} + T^{k0}) \rangle_{\vec{0},\vec{0}}(\vec{r})$$





Large-N_c bag model

Generalized TMDs

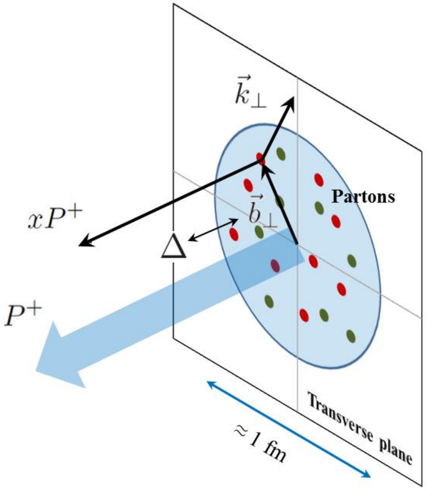
$$\mathrm{PDF}(x) \sim \frac{1}{2}\int \mathrm{d}k^-\,\mathrm{d}^2k_\perp\,\langle p|j^+(0,k)|p\rangle \qquad \mathrm{GPD}(x,\Delta) \sim \frac{1}{2}\int \mathrm{d}k^-\,\mathrm{d}^2k_\perp\,\langle p'|j^+(0,k)|p\rangle$$

$$\mathrm{TMD}(x,\vec{k}_\perp) \sim \frac{1}{2}\int \mathrm{d}k^-\,\langle p|j^+(0,k)|p\rangle \qquad \mathrm{GTMD}(x,\vec{k}_\perp,\Delta) \sim \frac{1}{2}\int \mathrm{d}k^-\,\langle p'|j^+(0,k)|p\rangle$$

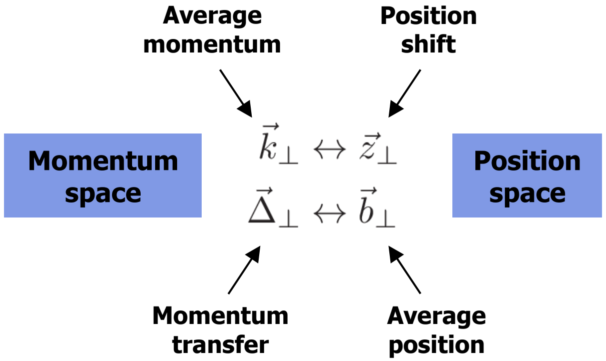
Quark Wigner operator

$$j^\mu(r,k) = \int \frac{\mathrm{d}^4z}{(2\pi)^4}\,e^{ik\cdot z}\,\overline{\psi}(r-\tfrac{z}{2})\gamma^\mu \mathcal{W}(r-\tfrac{z}{2},r+\tfrac{z}{2})\psi(r+\tfrac{z}{2})$$

Wigner (or phase-space) **distribution**



$$\mathrm{WD}(x,\vec{k}_\perp,\vec{b}_\perp) = \int \frac{\mathrm{d}^2\Delta_\perp}{(2\pi)^2}\,e^{-i\vec{\Delta}_\perp\cdot\vec{b}_\perp}\,\mathrm{GTMD}(x,\vec{k}_\perp,\Delta)\Big|_{\Delta^+=0}$$



Average momentum

Position shift

Momentum space

$\vec{k}_\perp \leftrightarrow \vec{z}_\perp$

$\vec{\Delta}_\perp \leftrightarrow \vec{b}_\perp$

Position space

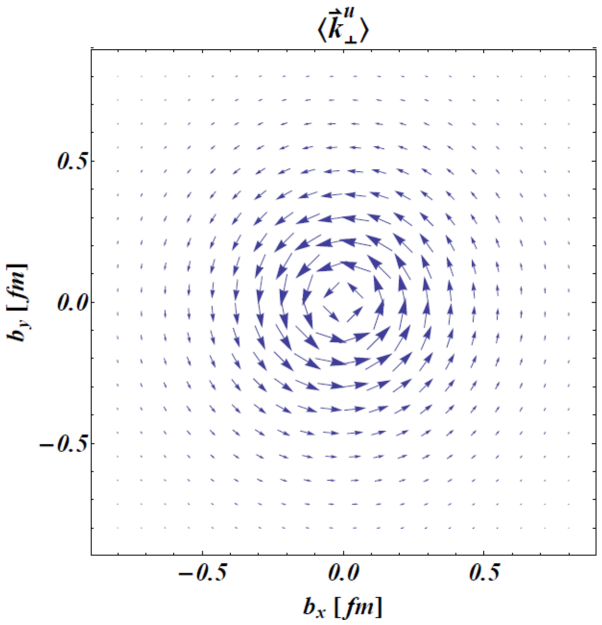
Momentum transfer

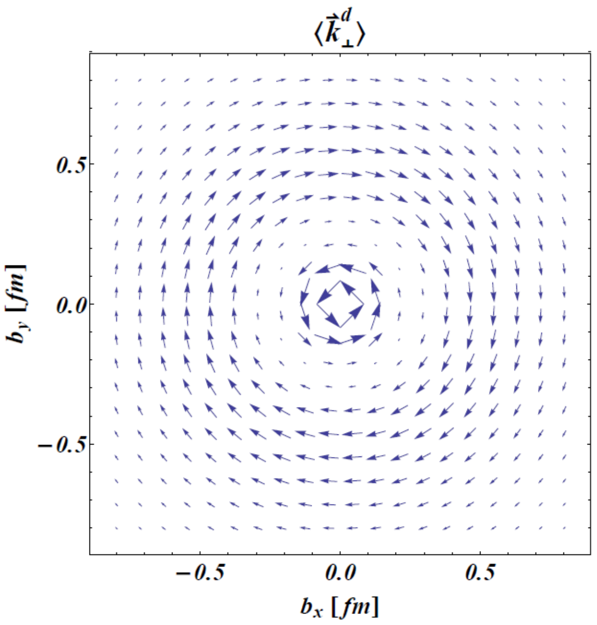
Average position

Generalized TMDs

Average transverse quark momentum

$$\langle \vec{k}_\perp \rangle (\vec{b}_\perp) = \int \mathrm{d}x \, \mathrm{d}^2 k_\perp \, \vec{k}_\perp \, \rho_{LU}(x, \vec{k}_\perp, \vec{b}_\perp)$$



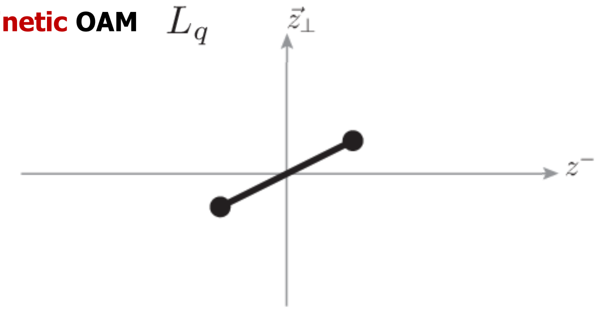


Generalized TMDs

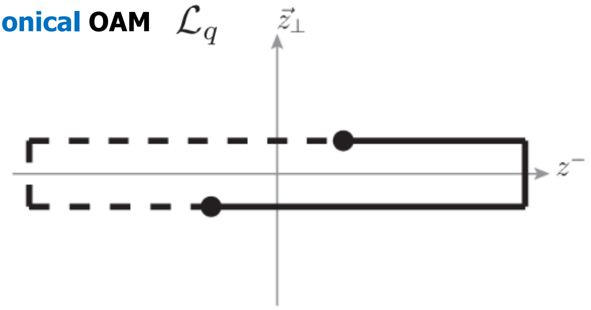
Orbital angular momentum

$$\ell_z = \int \mathrm{d}^2 b_\perp \, \vec{b}_\perp \times \langle \vec{k}_\perp \rangle (\vec{b}_\perp)$$

Kinetic OAM L_q

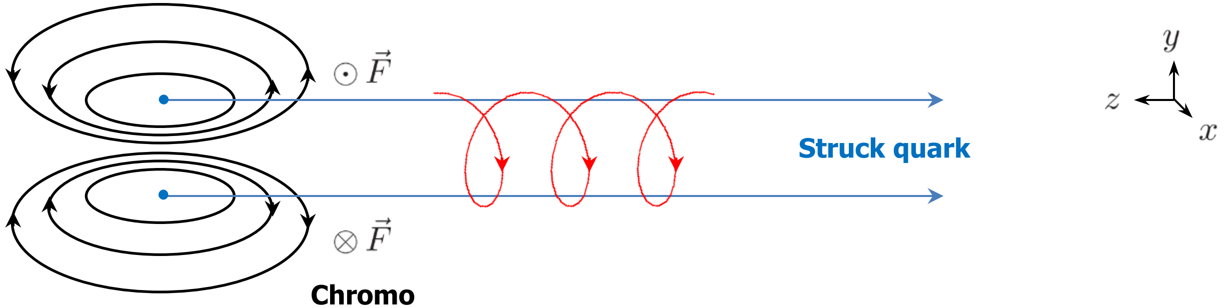


Canonical OAM $\mathcal{L}_q$



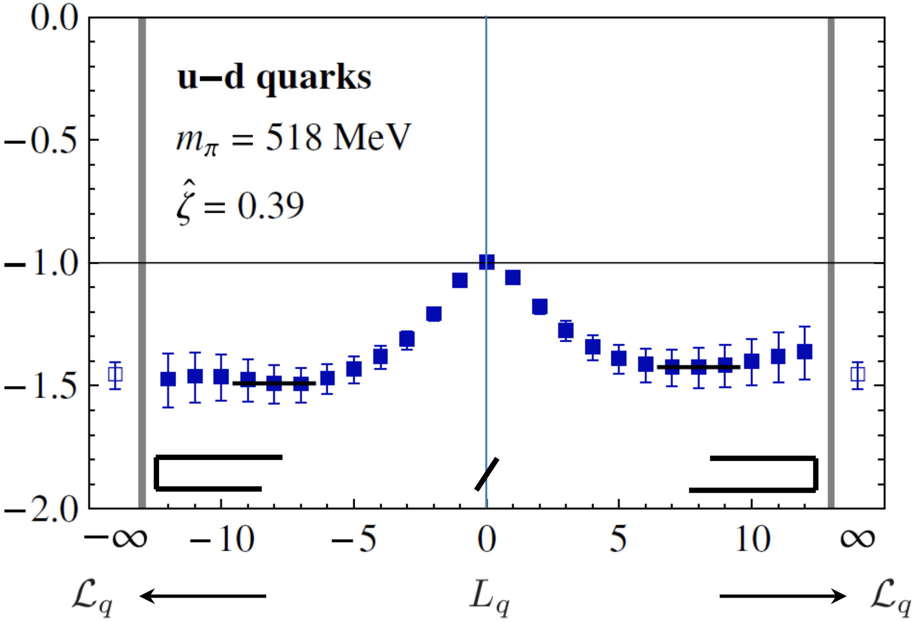
« Inside » the nucleon

« Outside » the nucleon



Chromo Lorentz force

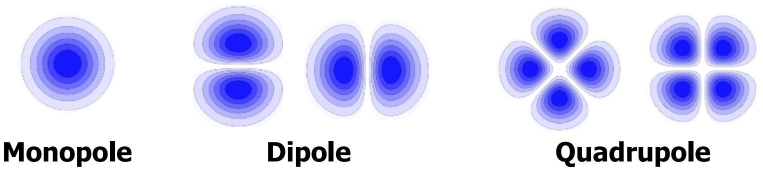
Generalized TMDs



[Engelhardt, PRD95 (2017) 094505]

Correlations

Twist-2



GTMDs

Quark polarization

Nucleon polarization

	U	T_x	T_y	L
U	F_{11}	$\frac{i}{M}\left(k_y H_{11} + \Delta_y H_{12}\right)$	$-\frac{i}{M}\left(k_x H_{11} + \Delta_x H_{12}\right)$	$\frac{i(\vec{\Delta}_\perp \times \vec{k}_\perp)_z}{M^2} G_{11}$
T_x	$\frac{i}{M}\left(k_y F_{12} + \Delta_y \bar{F}_{13}\right)$	$\cdots$	$\cdots$	$\frac{1}{M}\left(k_x \bar{G}_{12} + \Delta_x \bar{G}_{13}\right)$
T_y	$-\frac{i}{M}\left(k_x F_{12} + \Delta_x \bar{F}_{13}\right)$	$\cdots$	$\cdots$	$\frac{1}{M}\left(k_y \bar{G}_{12} + \Delta_y \bar{G}_{13}\right)$
L	$-\frac{i(\vec{\Delta}_\perp \times \vec{k}_\perp)_z}{M^2} F_{14}$	$\frac{1}{M}\left(k_x H_{17} + \Delta_x H_{18}\right)$	$\frac{1}{M}\left(k_y H_{17} + \Delta_y H_{18}\right)$	G_{14}

$\Delta = 0$

$\int \mathrm{d}^2 k_\perp$

$\vec{k}_\perp \leftrightarrow i\vec{\Delta}_\perp$

TMDs

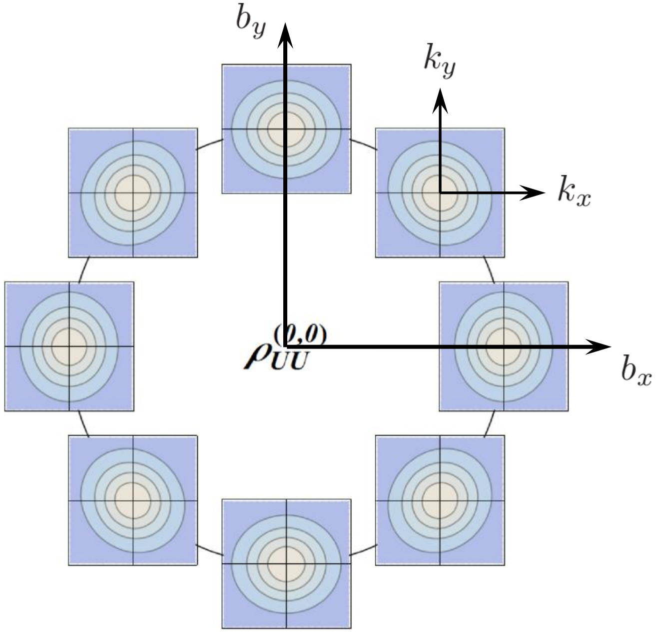
	U	T_x	T_y	L
U	f_1	$\frac{k_y}{M}\, h_1^\perp$	$-\frac{k_x}{M}\, h_1^\perp$	
T_x	$\frac{k_y}{M}\, f_{1T}^\perp$	$h_1 + \frac{k_x^2 - k_y^2}{2M^2}\, h_{1T}^\perp$	$\frac{k_x k_y}{M^2}\, h_{1T}^\perp$	$\frac{k_x}{M}\, g_{1T}$
T_y	$-\frac{k_x}{M}\, f_{1T}^\perp$	$\frac{k_x k_y}{M^2}\, h_{1T}^\perp$	$h_1 - \frac{k_x^2 - k_y^2}{2M^2}\, h_{1T}^\perp$	$\frac{k_y}{M}\, g_{1T}$
L		$\frac{k_x}{M}\, h_{1L}^\perp$	$\frac{k_y}{M}\, h_{1L}^\perp$	g_{1L}

GPDs

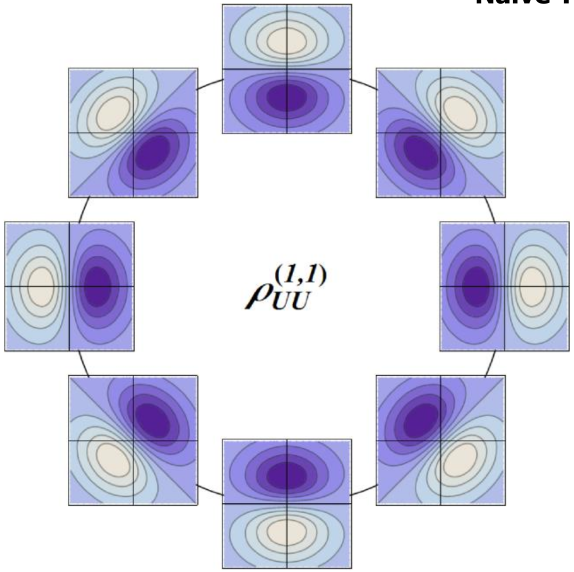
	U	T_x	T_y	L
U	$\mathcal{H}$	$i\,\frac{\Delta_y}{2M}\,\mathcal{E}_T$	$-i\,\frac{\Delta_x}{2M}\,\mathcal{E}_T$	
T_x	$i\,\frac{\Delta_y}{2M}\,\mathcal{E}$	$\mathcal{H}_T + \frac{\Delta_x^2 - \Delta_y^2}{2M^2}\,\tilde{\mathcal{H}}_T$	$\frac{\Delta_x \Delta_y}{M^2}\,\tilde{\mathcal{H}}_T$	$\frac{\Delta_x}{2M}\,\tilde{\mathcal{E}}$
T_y	$-i\,\frac{\Delta_x}{2M}\,\mathcal{E}$	$\frac{\Delta_x \Delta_y}{M^2}\,\tilde{\mathcal{H}}_T$	$\mathcal{H}_T - \frac{\Delta_x^2 - \Delta_y^2}{2M^2}\,\tilde{\mathcal{H}}_T$	$\frac{\Delta_y}{2M}\,\tilde{\mathcal{E}}$
L		$\frac{\Delta_x}{2M}\,\tilde{\mathcal{E}}_T$	$\frac{\Delta_y}{2M}\,\tilde{\mathcal{E}}_T$	$\tilde{\mathcal{H}}$

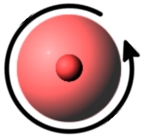
Phase-space representation

UU

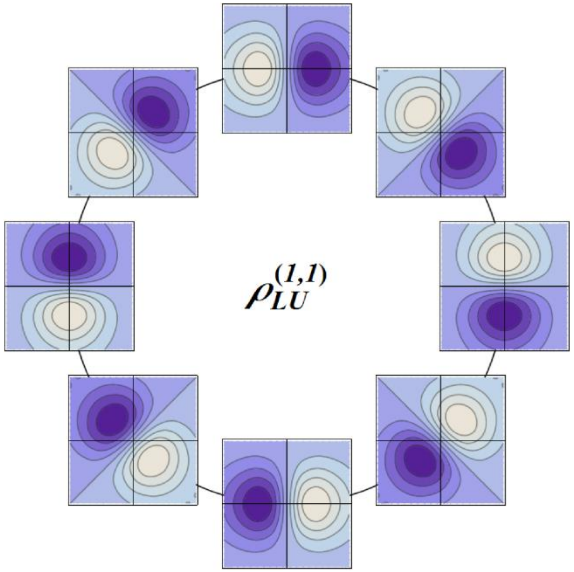


Naive T-odd

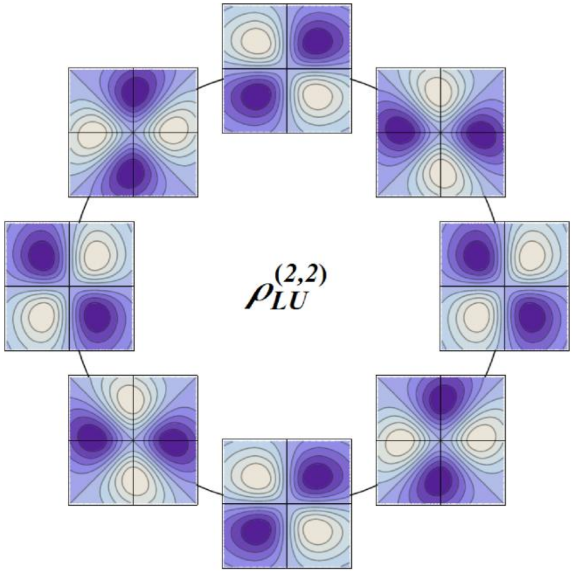




LU

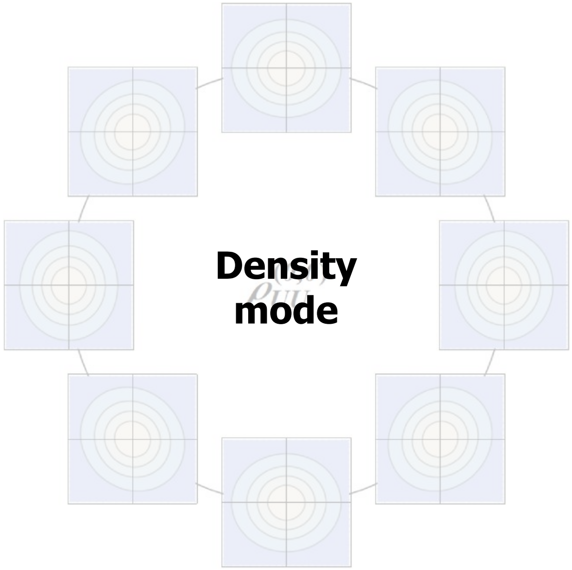


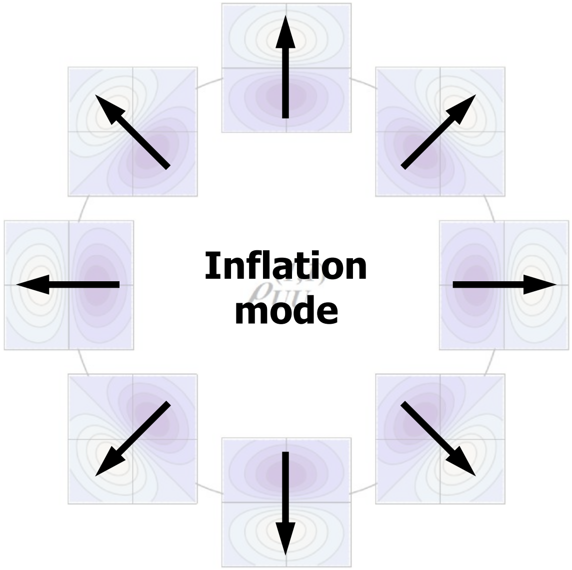
Naive T-odd

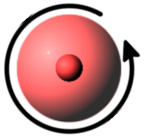


Phase-space representation

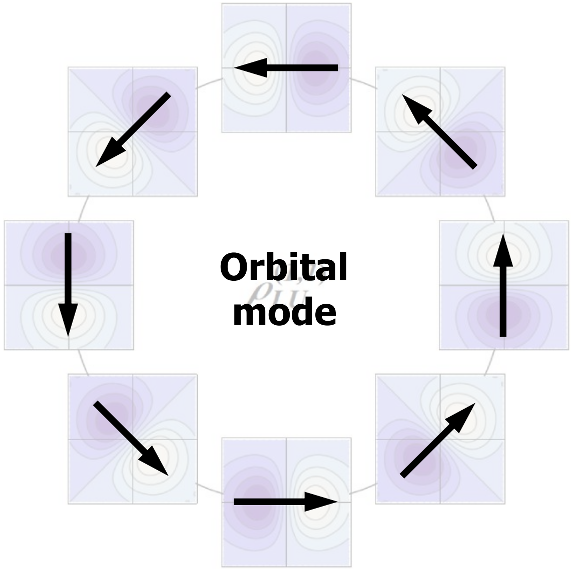
UU

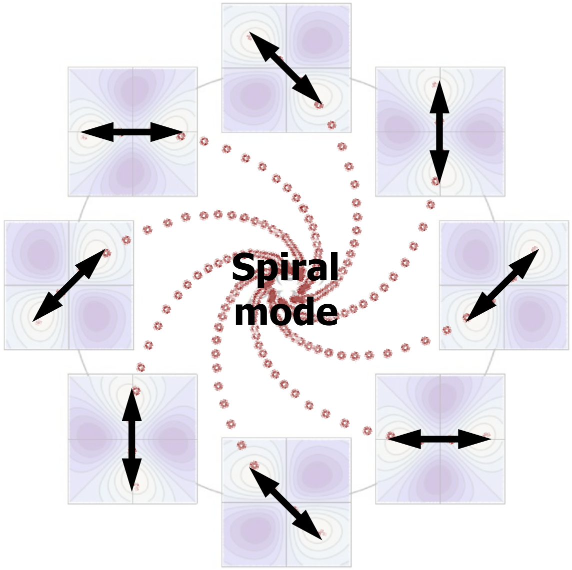






LU

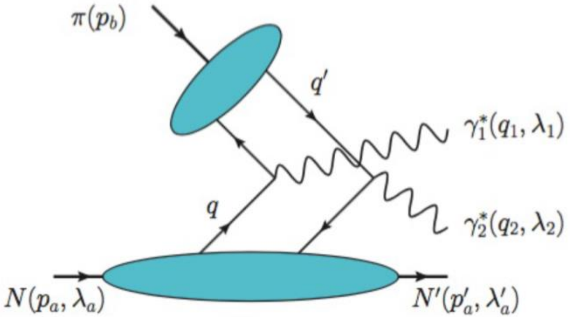


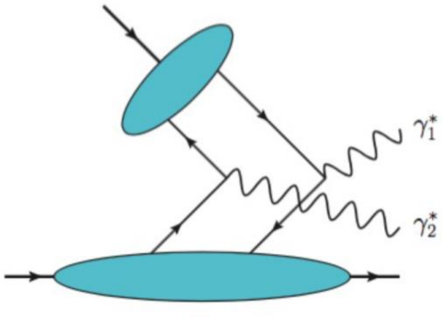


How to measure Wigner distributions

Many observables sensitive to GTMDs have recently been proposed

- **eA scattering**
  - **Dijet production** [Hatta, Xiao, Yuan (2016)]
  - **Longitudinal SSA** [Hatta, Nakagawa, Yuan, Zhao (2016)] [Ji, Yuan, Zhao (2016)]
- **pA scattering**
  - **Double parton scattering (DPS)** [Hagiwara, Hatta, Xiao, Yuan (2017)]
  - **Ultra-peripheral collisions (UPCs)** [Hagiwara *et al.* (2017)]
- **πN scattering**
  - **Exclusive double Drell-Yan** [Bhattacharya, Metz, Zhou (2017)]

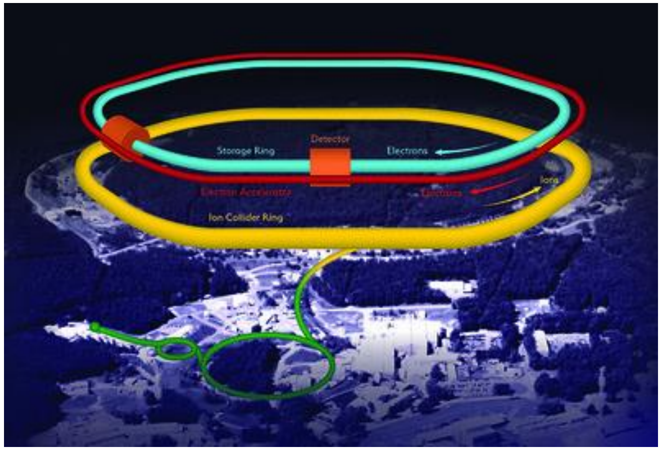




Typically complicated final state → very small cross sections !

Summary

- **Several generalizations of PDFs** (TMDs, GPDs, GTMDs, …)
- **Multidimensional imaging of nucleon structure**
- **Indirect access to energy-momentum tensor** (mass, spin, …)
- **Further extensions** (gluon distributions, higher spin, multiparton scattering, …)



So much to learn thanks to the EIC !