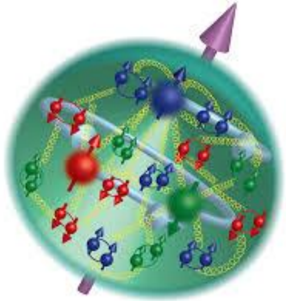

Spin Session

Introduction to 3D nucleon structure and spin physics

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B. Badelek Warsaw University

Diffraction and Low-x

8–14 Sept 2024
Hotel Tonnara Trabia,
Palermo, Sicily

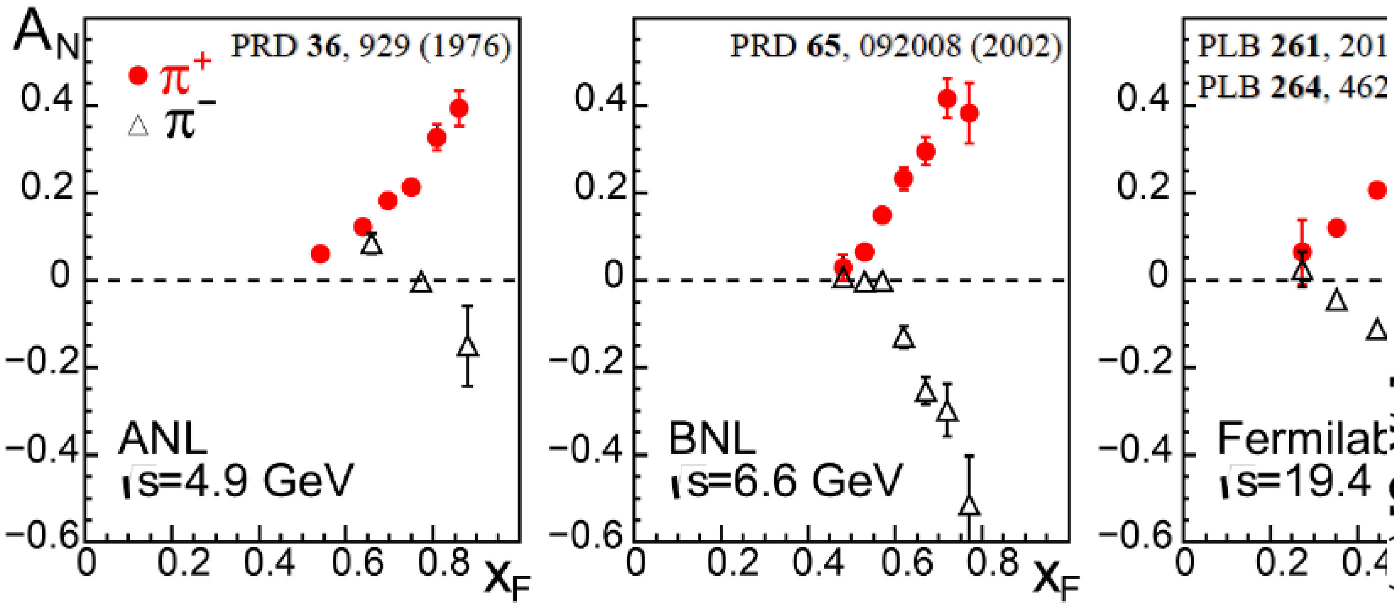
Diffraction and Low-x

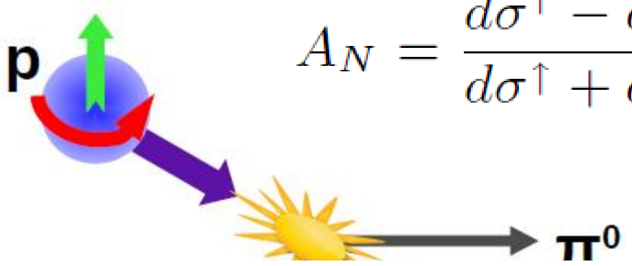
Outline

- Why spin, why 3D
- What
- How
- Where

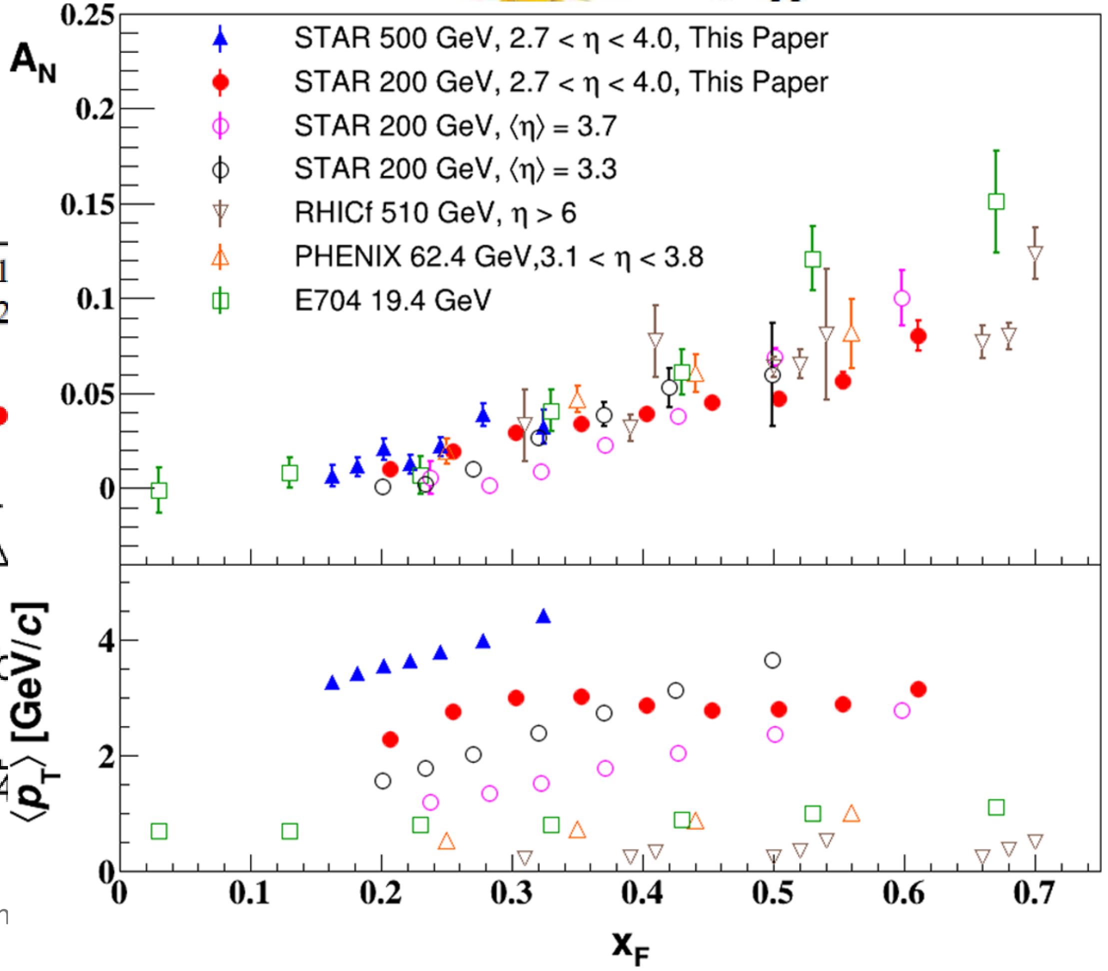
Why?

- Single spin asymmetries… puzzling in collinear pQCD at leading twist





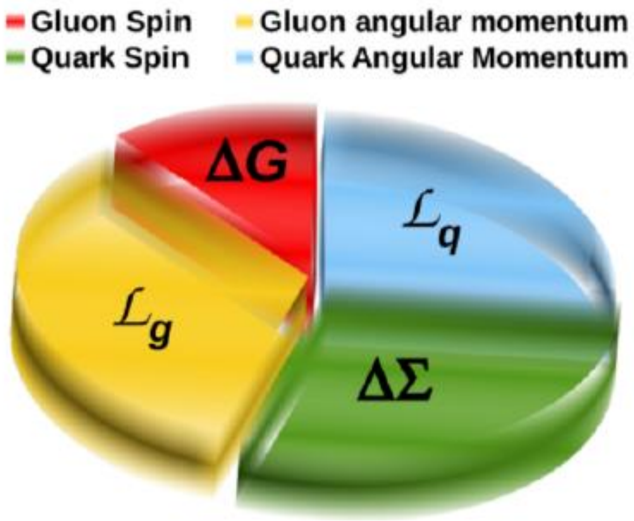
$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

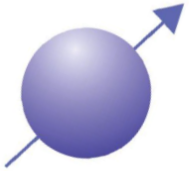


Why?

- Origin of the proton spin

How the constituents of the proton contribute to the proton spin?





$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L^q + L^g$$

Best known → **Quark helicity** $\sim 30\%$

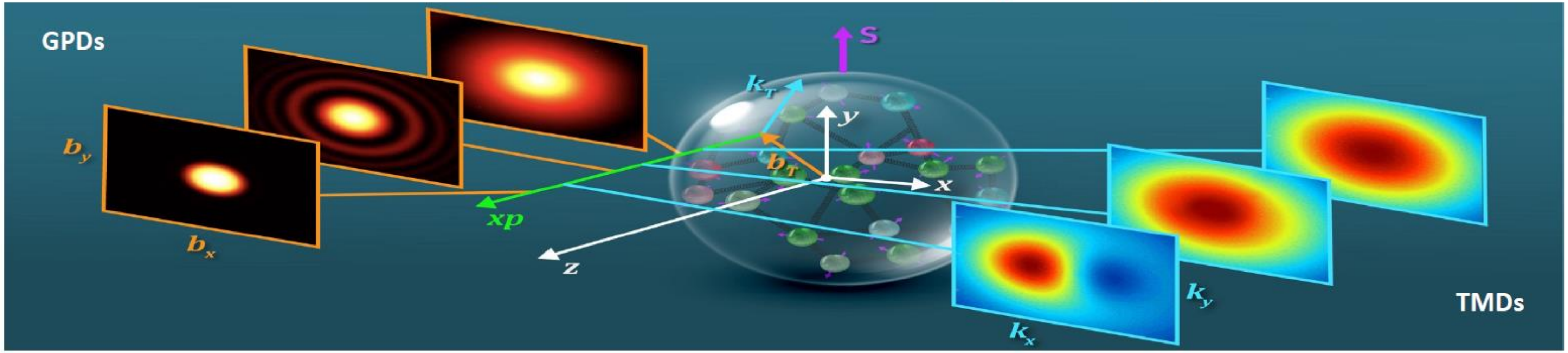
How well do we know? → **Gluon helicity** $\sim 40\%$

??????? → **OAM of quarks & gluons**

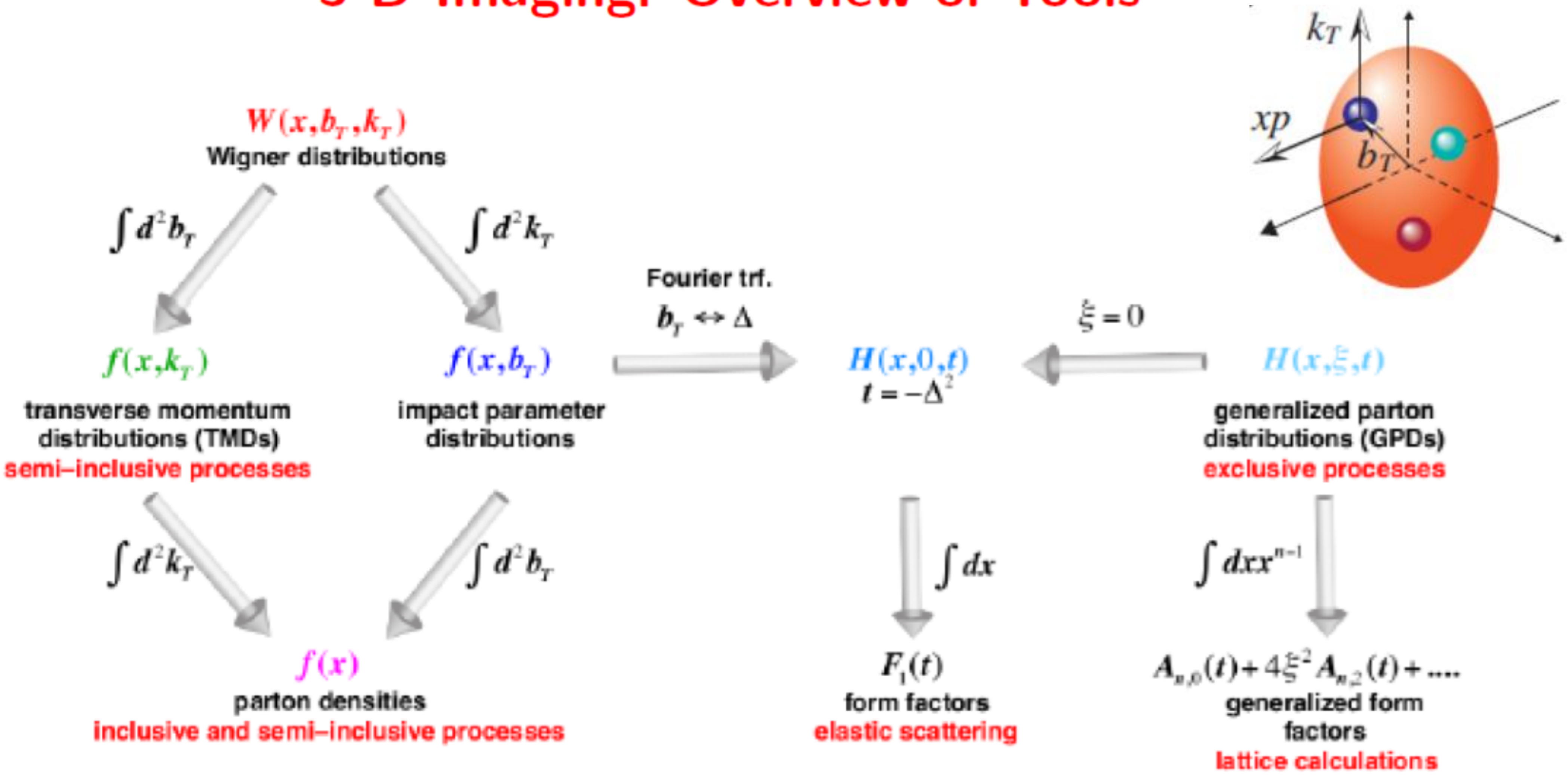
What: TMDs and GPDs

❑ **3D hadron structure:**

NO quarks and gluons can be seen in isolation!



3-D Imaging: Overview of Tools

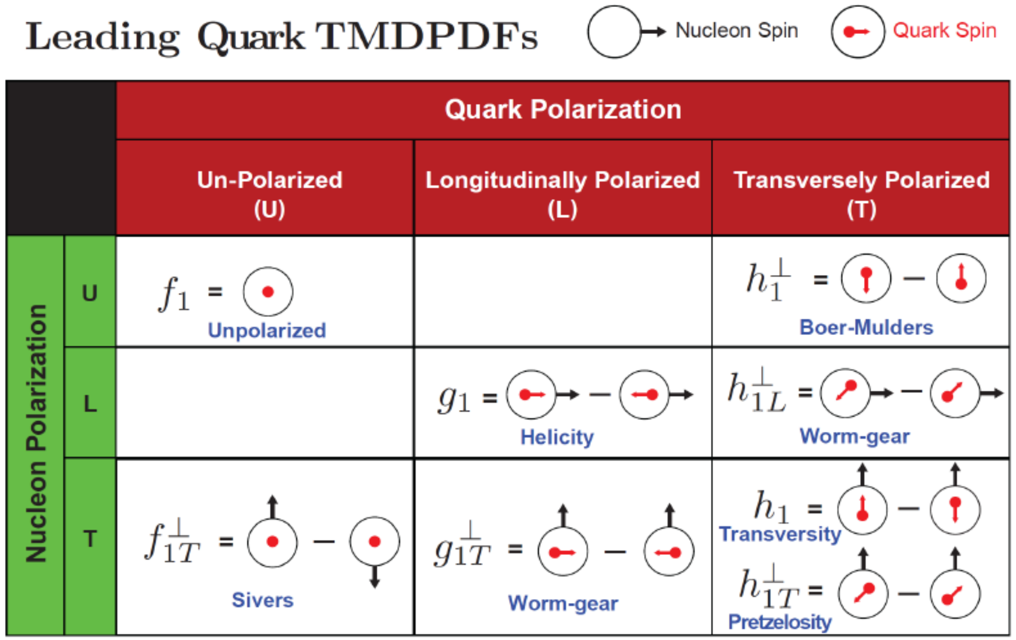


(from arXiv:1212.1701)

Wigner function: importance

$$L_z^{q,g} = \int dx \int d^2k_\perp d^2b_\perp (\vec{b}_\perp \times \vec{k}_\perp)_z \, W^{q,g} \; (x, \vec{b}_\perp, \vec{k}_\perp)$$

Spin-kT correlations: quark TMDs for spin-1/2 hadrons



T-odd

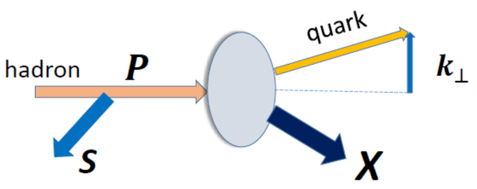
T-odd

- Unpol and Helicity: very good knowledge of x dep.
- Unpol: good knowledge of kT dep.
- Sivers (T-odd) and transversity (chiral odd): fair knowledge (mainly x dep.)
- Others: some hints
- Tensor charge: tension with lattice

8 TMD-PDFs

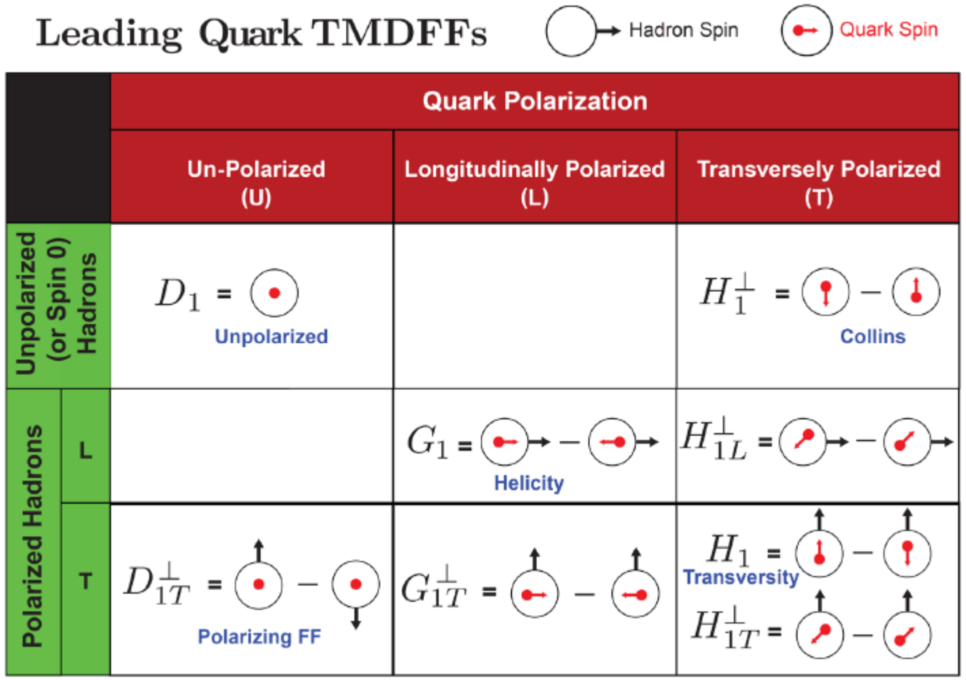
$$\delta q = \int_0^1 \left[h_1^q(x) - h_1^{\bar{q}}(x) \right] dx$$

Tensor charge



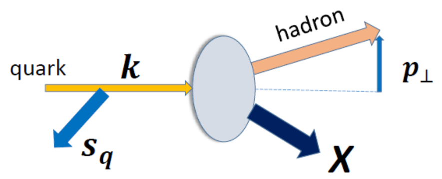
The Sivers function $f_{1T}^\perp$

Spin-kT correlations: quark TMDs for spin-1/2 hadrons



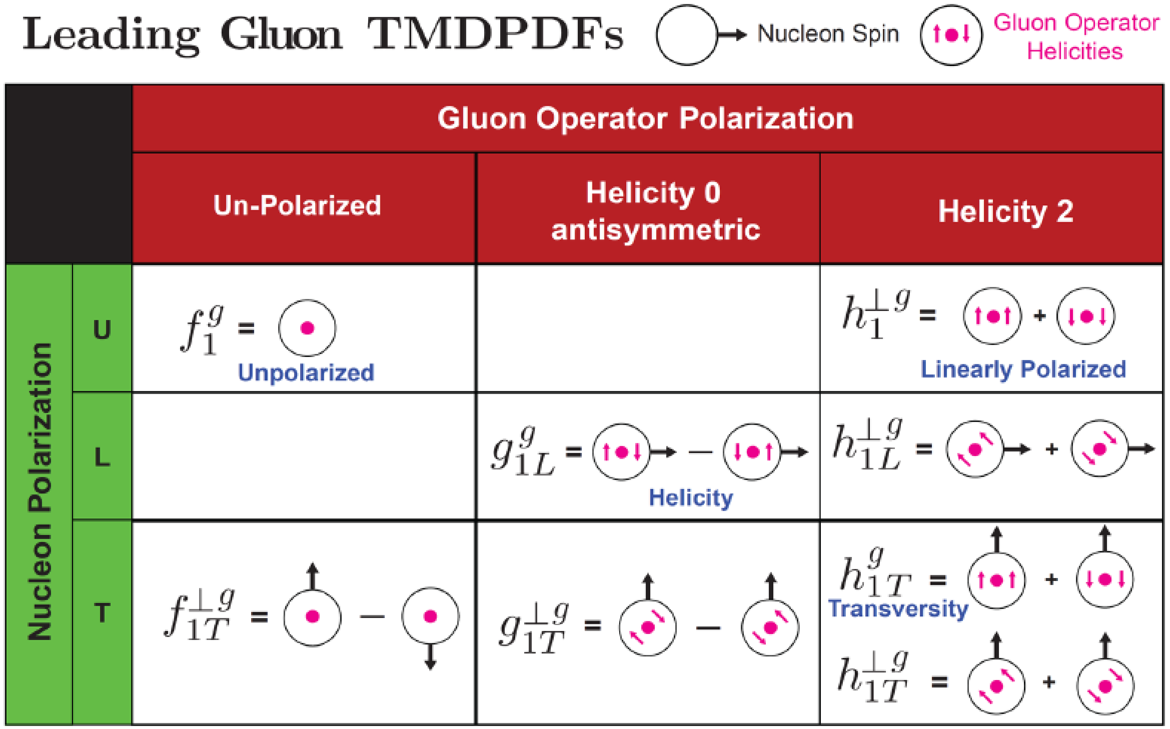
8 TMD-FFs

- Unpol and Helicity: good knowledge of x dep.
- Unpol: some knowledge of kT dep.
- Collins FF: fair knowledge (mainly z dep.)
- Polarizing FF: preliminary knowledge
- Others: Almost unknown



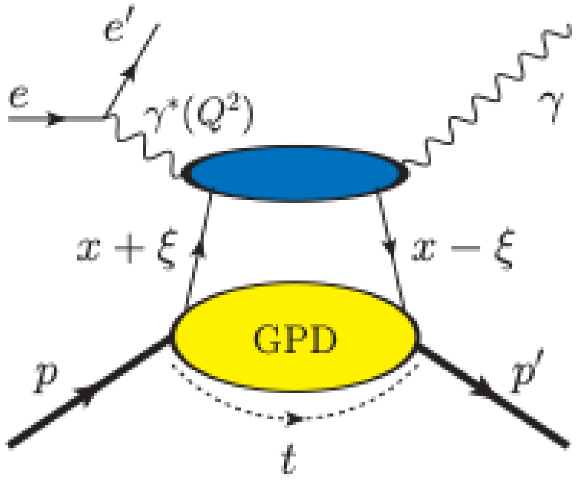
The Collins function $H_1^{\perp q}$

and gluon TMDs



- Unpol and Helicity: good knowledge of x dep.
- Unpol: some hints on kT dep.
- Others: almost unknown
- Modelling
- Theoretical and phenom. more challenging

Quark GPDs



		Quark Polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	H		$2\widetilde{H}_T + E_T$
	L		$\widetilde{H}$	$\widetilde{E}_T$
	T	E	$\widetilde{E}$	$H_T, \widetilde{H}_T$

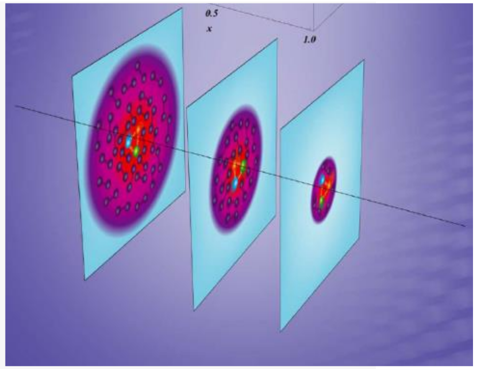
- GPDs encode correlations between parton longitudinal momentum and transverse position
- 8 GPDs: 4 chiral even and 4 chiral odd
- $H^q(x,0,0) = q(x), \quad \widetilde{H}^q(x,0,0) = \Delta q(x)$

E_T is related to the proton's anomalous tensor magnetic moment.

H_T is related to the proton's tensor charge.

$\int_{-1}^{1} dx H^q(x,\xi,t) = F_1^q(t)$ and $\int_{-1}^{1} dx E^q(x,\xi,t) = F_2^q(t)$.

What can we learn from GPDs?



- Tomography of the nucleon: the Fourier transform of the GPDs can be interpreted as a probability density:

$$H^q(x, b_\perp) = \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{-ib_\perp \Delta_\perp} H^q(x, 0, -\Delta_\perp^2)$$

- Understanding the spin composition of the nucleon (aka the "spin puzzle") using the Ji's sum rule:

$$\frac{1}{2} = J_Q + J_G \longrightarrow J_Q = \sum_q \frac{1}{2} \int_{-1}^{1} dx\ x(H^q(x,\xi,0) + E^q(x,\xi,0)) = \sum_q \frac{1}{2}(A^q(t) + B^q(t))$$

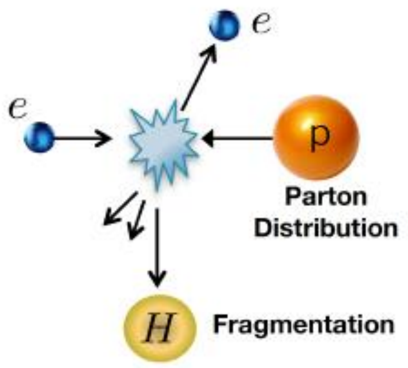
- Accessing Gravitational Form Factors by mimicking a spin-2 interaction:

$$\int_{-1}^{1} dx\ xH^q(x,\xi,t) = A^q(t) + \xi^2 D^q(t) \qquad \int_{-1}^{1} dx\ xE^q(x,\xi,t) = B^q(t) - \xi^2 D^q(t)$$

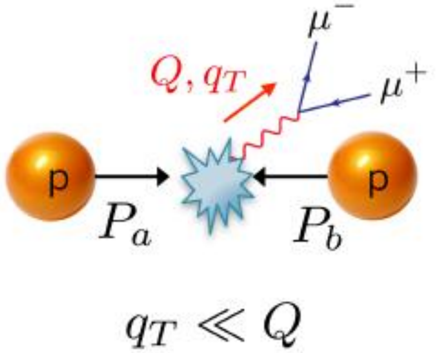
GFFs: information about internal distributions of mass, energy, pressure and shear

How can we acces TMDs?

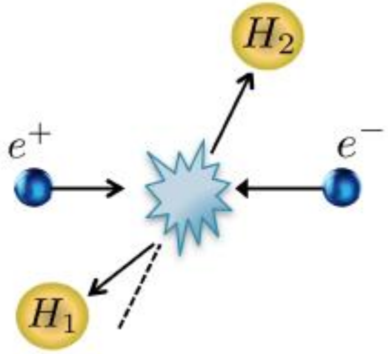
Semi-Inclusive DIS



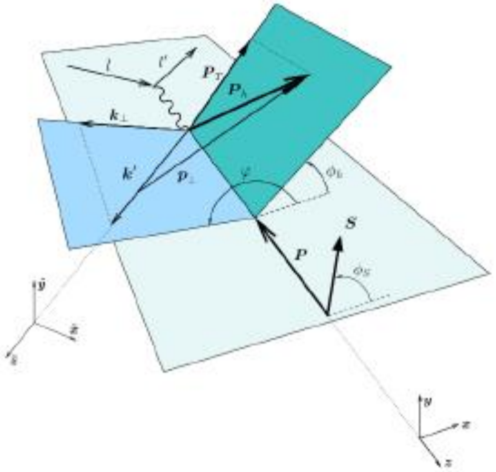
Drell-Yan

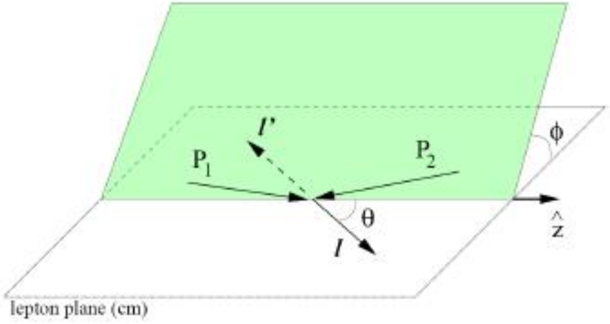


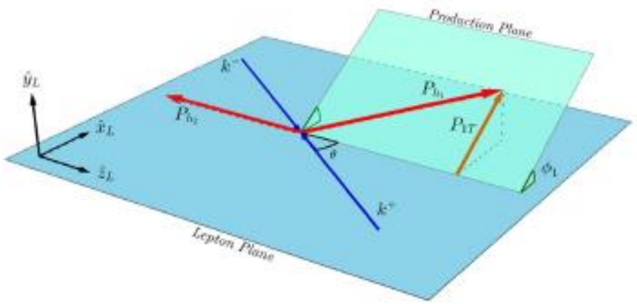
Dihadron in e+e-



Two-scale processes:
$Q^2 \gg p_T^2 \geq \Lambda_{QCD}^2$



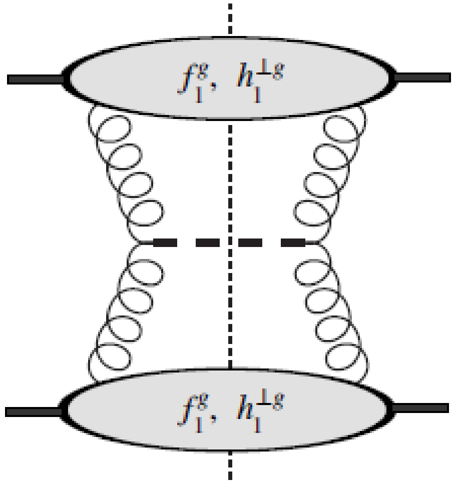




TMD factorization proven

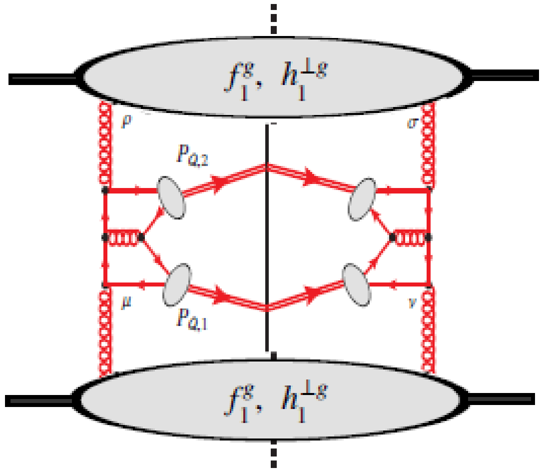
Access to gluon TMDs

$$pp \to H(\to \gamma\gamma) + X$$



Higgs production

[Gutierrez-Reyes, Leal-Gomez, Scimemi, Vladimirov, arXiv:1907.03780]



Quarkonium-pair production

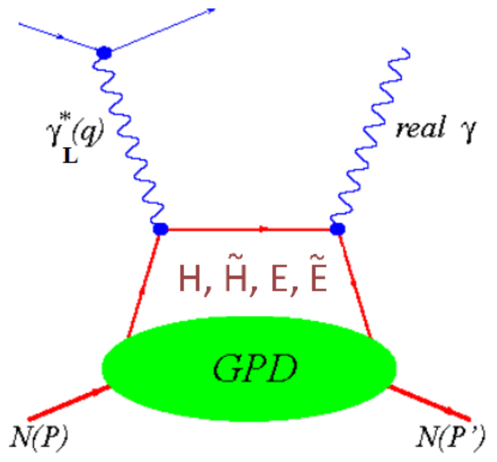
[Scarpa, Boer, Echevarria, Lansberg, Pisano, Schlegel, arXiv:1909.05769]

Other interesting processes

- $p^{\uparrow}\, p \to \mathrm{jet}\, \pi\, X$
- Jet-jet correlations
- $A(p_A)\, B(p_B) \to \mathrm{jet}(p_{\mathrm{j}})\, \Lambda^{\uparrow}(p_{\Lambda})\, X$
- Quarkonium production in *ep* and *pp* collisions
- SSAs in inclusive processes (twist-3…connection to TMDs)
- Connection to low-x physics and unintegrated PDFs (*C. Marquet*)

and GPDs? Exclusive reactions

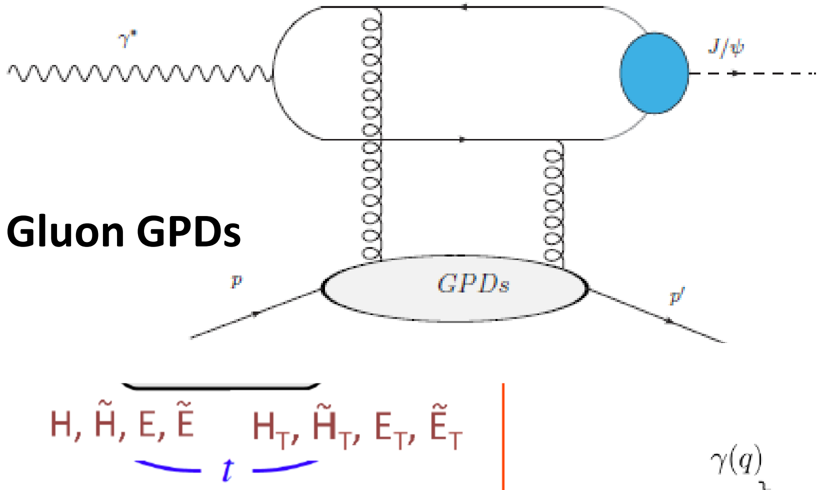
Deeply Virtual Compton Scattering (DVCS)



+ Clean process
- Only sensitive to chiral even GPDs

Deeply Virtual Meson Production (DVMP)

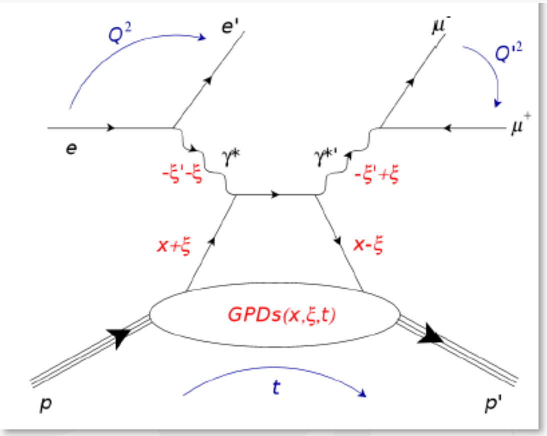
Gluon GPDs

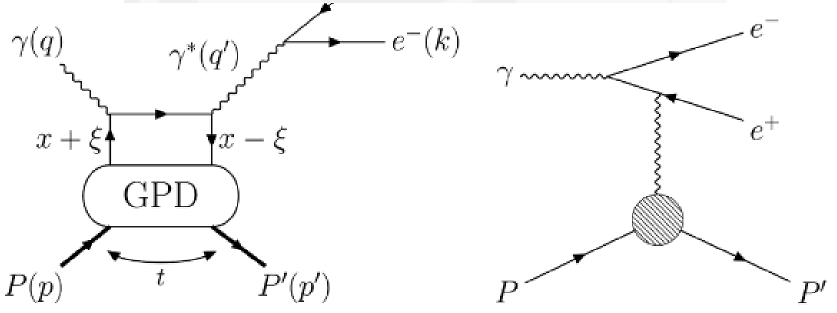


+ Access to transversity degrees of freedom described by chiral-odd GPDs
- Distribution Amplitude (DA) is involved as additional soft non pert. quantity

$$ep \to e'\mu^+\mu^- p$$

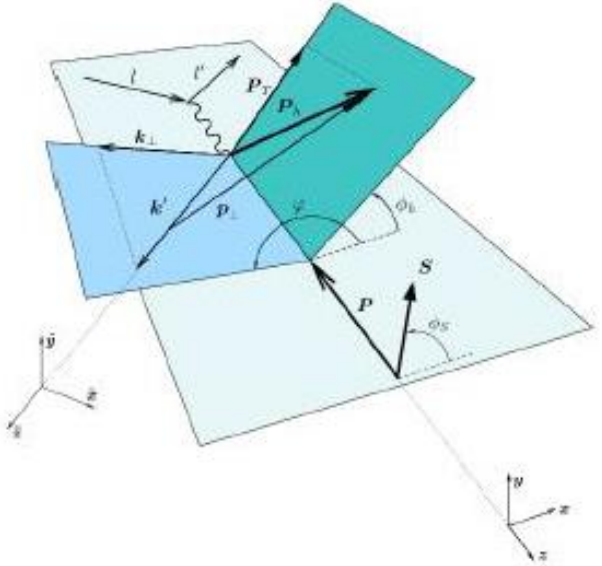
DDVCS





Timelike Compton Scattering

TMDs from SIDIS



$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$

$$\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h}$$

Boer-Mulders,Cahn,...

$$+\,\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}$$

$$+\,S_{\parallel}\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right]$$

Worm-gear $h_{1L}^{\perp}$

$$+\,S_{\parallel}\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right]$$

Sivers

$$+\,|\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\,\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big)$$

Collins

$$+\,\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}$$

Pretzelosity $h_{1T}^{\perp}$

$$+\,\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$

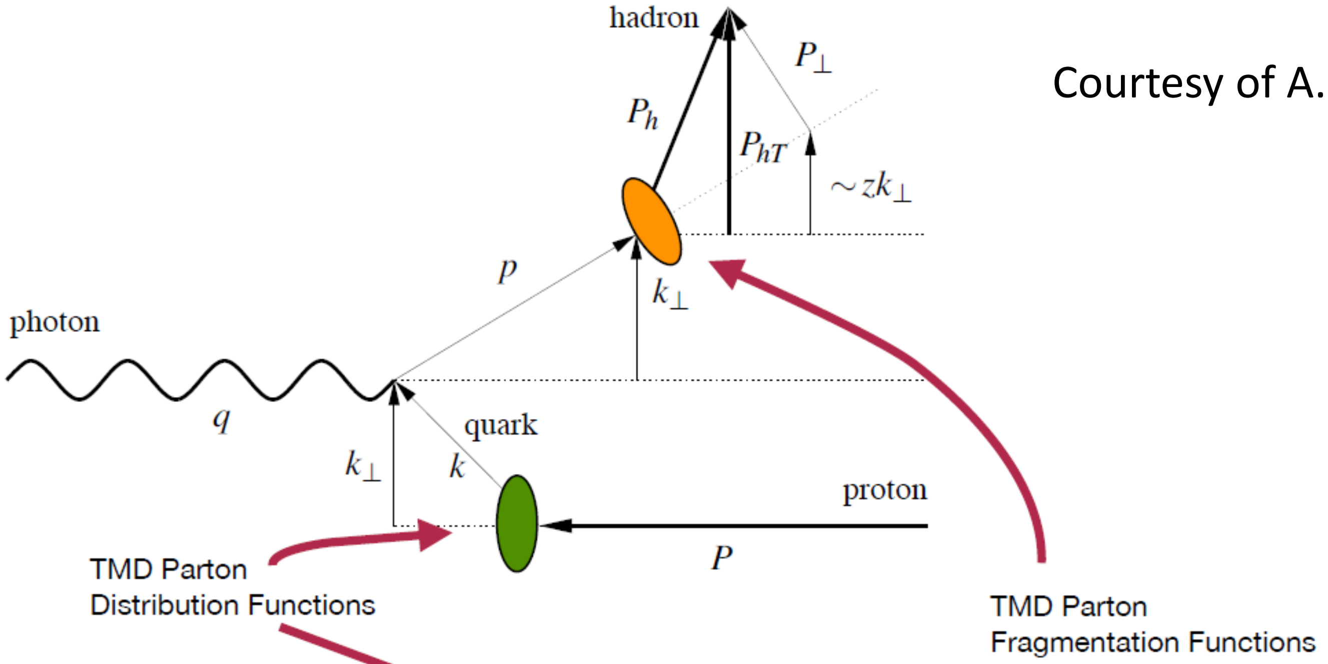
Worm-gear $g_{1T}^{\perp}$

$$+\,|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S}$$

$$+\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},$$

Bacchetta et al, JHEP 02 (2007) 093

TMD structure and factorization



Courtesy of A.Bacchetta

Each convolution….

$$F_{UU,T}(x,z,\boldsymbol{P}_{hT}^2,Q^2)$$
$$= x\sum_q \mathcal{H}^q_{UU,T}(Q^2,\mu^2)\int d^2\boldsymbol{k}_\perp\, d^2\boldsymbol{P}_\perp\, f_1^a(x,\boldsymbol{k}_\perp^2;\mu^2)\, D_1^{a\to h}(z,\boldsymbol{P}_\perp^2;\mu^2)\,\delta(z\boldsymbol{k}_\perp-\boldsymbol{P}_{hT}+\boldsymbol{P}_\perp)$$
$$= x\sum_a \mathcal{H}^q_{UU,T}(Q^2,\mu^2)\int db_T b_T J_0(b_T|\boldsymbol{P}_{h\perp}|)\hat{f}_1^q(x,z^2b_\perp^2;\mu^2)\,\hat{D}_1^{a\to h}(z,b_\perp^2;\mu^2)$$

Analysis in Fourier-transformed space….

Scale dependences: more complicate w.r.t. DGLAP....

$$\hat{f}_1^a(x, |\boldsymbol{b}_T|; \mu, \zeta) = \int d^2\boldsymbol{k}_\perp \, e^{i\boldsymbol{b}_T\cdot\boldsymbol{k}_\perp} \, f_1^a(x, \boldsymbol{k}_\perp^2; \mu, \zeta)$$

$$\hat{f}_1^a(x, b_T^2; \mu_f, \zeta_f) = [C \otimes f_1](x, \mu_{b_*}) \, e^{\int_{\mu_{b_*}}^{\mu_f} \frac{d\mu}{\mu} \left(\gamma_F - \gamma_K \ln \frac{\sqrt{\zeta_f}}{\mu}\right)} \left(\frac{\sqrt{\zeta_f}}{\mu_{b_*}}\right)^{K_{\rm resum} + g_K} f_{1\,NP}(x, b_T^2; \zeta_f, Q_0)$$

perturbative Sudakov form factor

matching coefficients (perturbative)

collinear PDF

Collins-Soper kernel (perturbative and nonperturbative)

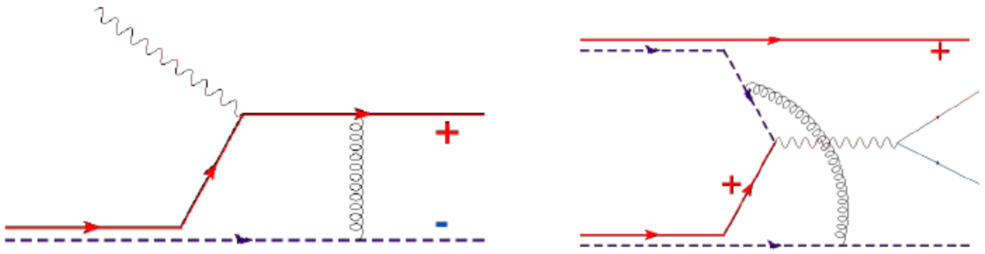
nonperturbative part of TMD

$$\mu_b = \frac{2e^{-\gamma_E}}{b_T}$$

CSS/SCET, Rapidity divergences and all that

Modified universality

Collinear PDFs: factorization → universality



$$f_{1T}^{\perp SIDIS} = -f_{1T}^{\perp DY}$$

Final state interactions in **SIDIS**
Initial state interactions in **DY**

T-odd TMDs: Sivers function

colored gluons at work ….

First experimental hints
at STAR, COMPASS

GPD..some more info

- Factorization fully proven for DVCS/TCS/Double-DVCS whereas partial proof for DVMP only at LO for longitunally polarized photon
- GPDs are universal
- TCS to test the universality of GPDs and to access the real part of the Compton FF

Status

- TMDs:
  - theory, phenom. and modelling (*M. Radici*)
  - global fits, towards a precision era

- Lattice: significant progress (*K. Cichy, S. Muckerjie*)

- GPDs: theory and modelling. still open issues but improving fast

Where

- Several experimental facilities/programmes:

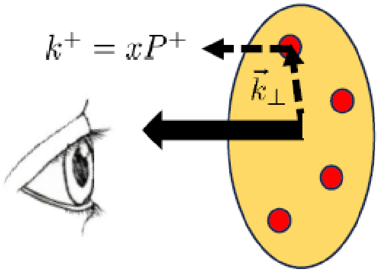
- HERMES,
- COMPASS (*B. Badelek, K. Lavickova*),
- JLab (*J.P. Chen*),
- BaBar, Belle, BESIII,
- RHIC (*R. Seidl*),
- LHCspin (*M. Santimaria*),
- EIC (*P. Nadel Turonski*)]

Enjoy the SPIN session

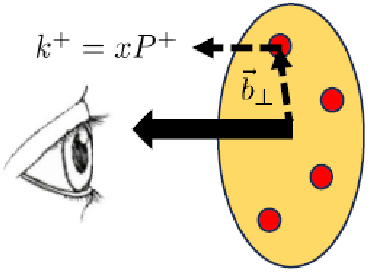
Backup slides

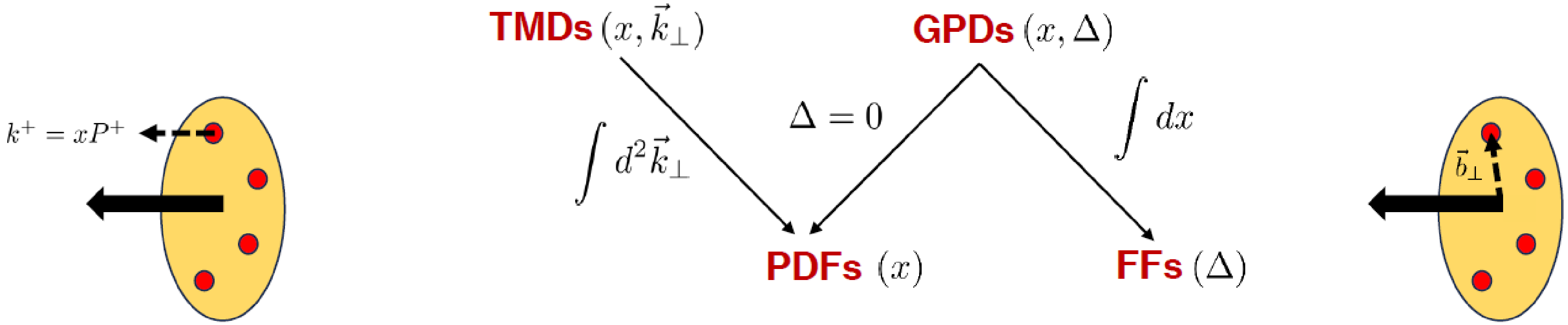
What: TMDs and GPDs

Transverse Momentum-dependent Distributions



Generalized Parton Distributions





Wigner function - The “mother function”