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Introduction to transverse momentum imaging

lecture 5

International school on probing hadron structure at the EIC

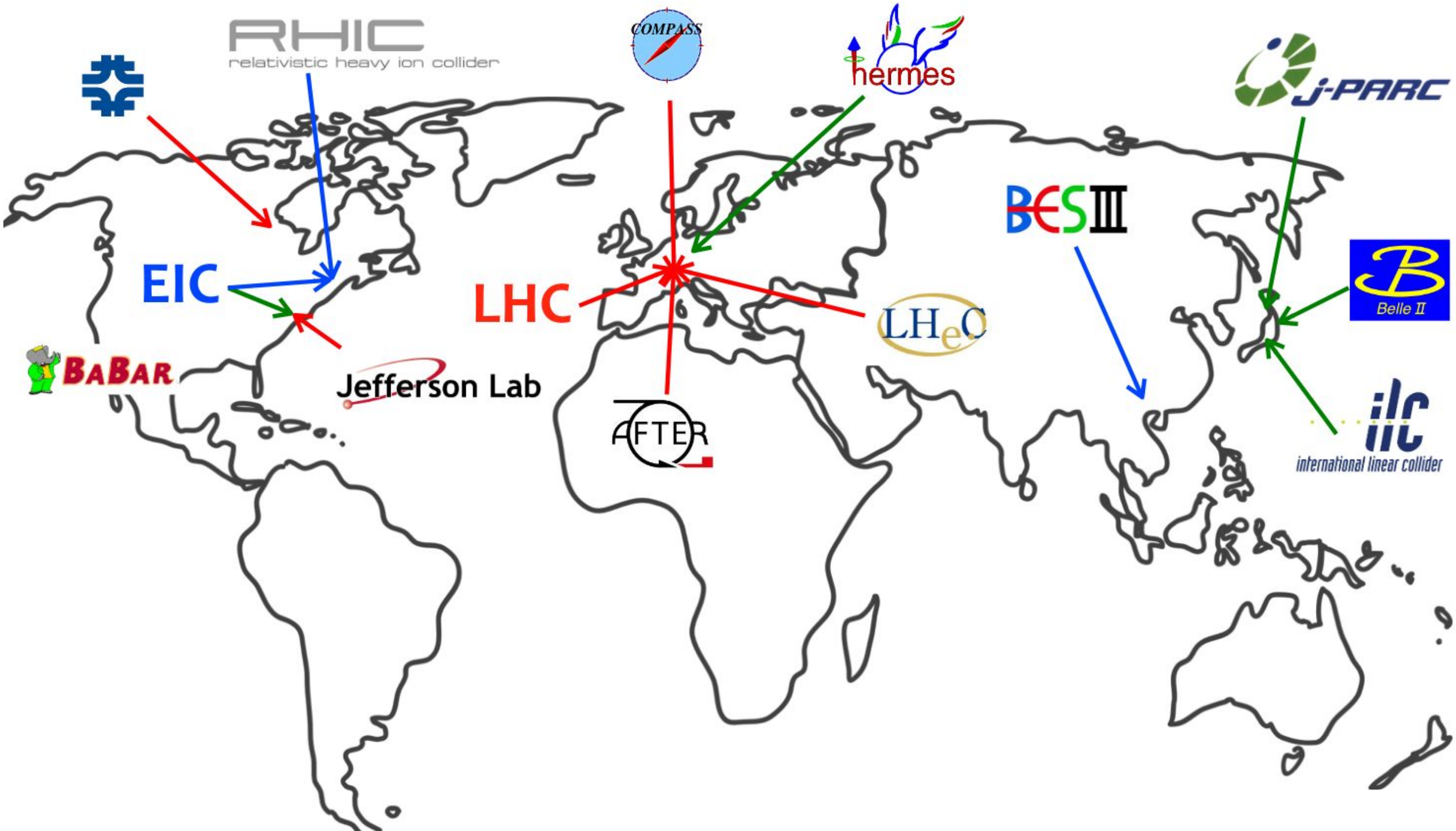
ICTS, Bangalore
February 1, 2024

Plan of these lectures

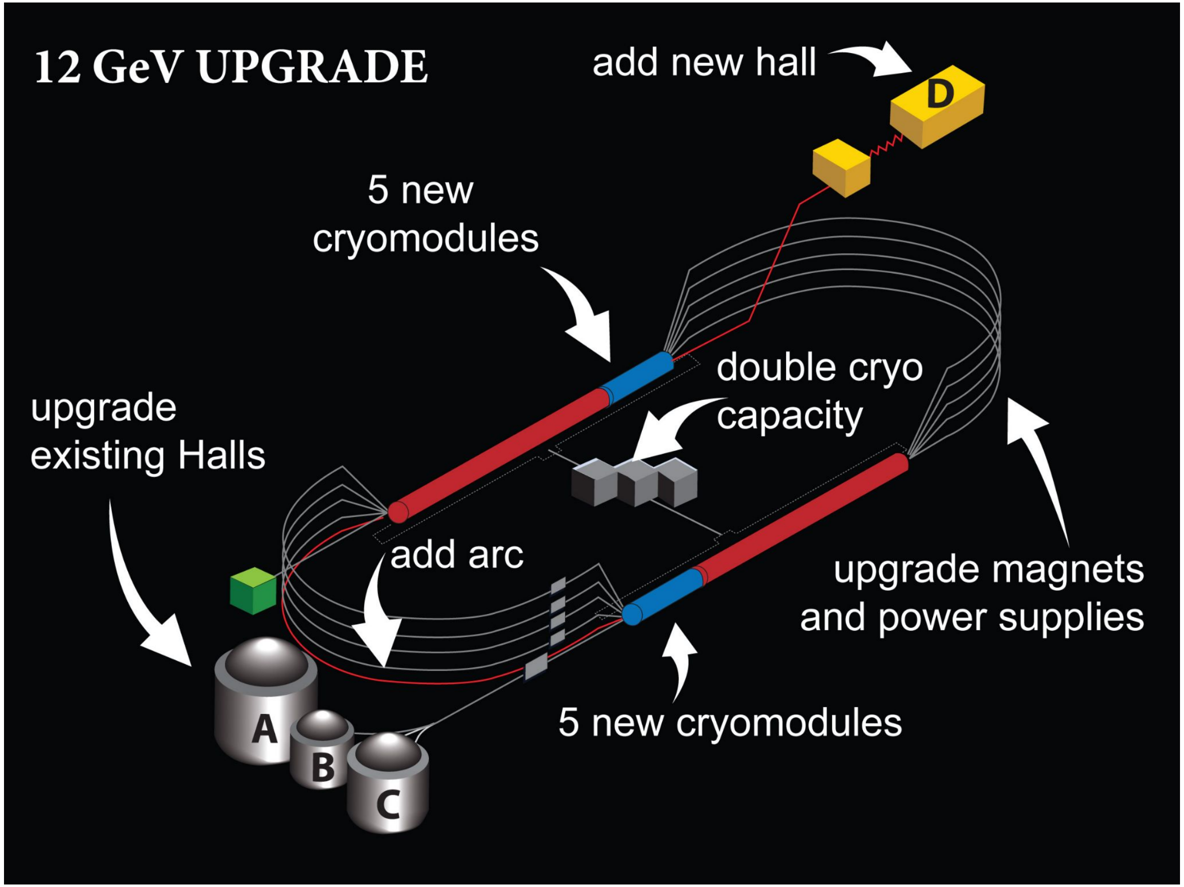
1. **Breaking hadrons**
2. **Non-collinear partons**
3. **Symmetries & spin**
4. **Factorization, evolution, matching**
5. **Phenomenology**

5.1 Experiments

(a short selection)


RHIC
relativistic heavy ion collider
COMPASS
hermes
J-PARC
EIC
LHC
BESIII
Belle II
LHeC
BABAR
Jefferson Lab
AFTER
ilc
international linear collider

CEBAF at Jefferson Lab



CEBAF:

Continuous Electron
Beam
Accelerator Facility

Built in 1984,
recently completed a
major upgrade
from 6 GeV to 12 GeV
+ one new hall

- Hall A & C: hadron structure, high luminosity
- Hall B: hadron structure, 4π coverage
- Hall D: hadron spectroscopy

The Electron-Ion Collider

00 home
01 about
02 goals
03 design
04 benefits
05 status
06 news

about | benefits
goals | status
design | news

The Electron-Ion Collider is a proposed machine for delving deeper than ever before into the building blocks of matter, so that we may better understand the matter within us and its role in the universe around us..

https://www.jlab.org/eic

Precision 3D imaging of protons and nuclei

An Electron-Ion Collider will take three-dimensional precision snapshots of the internal structure of protons and atomic nuclei.

Solving the Mystery of Proton Spin

An EIC would reveal how the teeming quarks and gluons inside the proton combine their spins to generate the proton's overall spin.

Search for Saturation

A unique form of matter, the color glass condensate, may be produced for study for the first time by an EIC, providing deeper insight into gluons and their interactions.

Quark and Gluon Confinement

Experiments at an EIC would cast fresh light on the mystery of why quarks or gluons can never be observed in isolation but must remain confined within protons and nuclei.

https://www.jlab.org/eic

more

A fixed-target program at the LHC

Contents lists available at ScienceDirect

Physics Reports

journal homepage: www.elsevier.com/locate/physrep

A fixed-target programme at the LHC: Physics case and projected performances for heavy-ion, hadron, spin and astroparticle studies

C. Hadjidakis [1,a], D. Kikoła [2,a], J.P. Lansberg [1,*,a], L. Massacrier [1,a], M.G. Echevarria [3,4,b], A. Kusina [5,b], I. Schienbein [6,b], J. Seixas [7,8,9,b], H.S. Shao [10,b], A. Signori [11,3,12,b], B. Trzeciak [13,14,b], S.J. Brodsky [15], G. Cavoto [16], C. Da Silva [17], F. Donato [18], E.G. Ferreiro [19,20], I. Hřivnáčová [1], A. Klein [17], A. Kurepin [21], C. Lorcé [22], F. Lyonnet [23], Y. Makdisi [24], S. Porteboeuf Houssais [25], C. Quintans [8], A. Rakotozafindrabe [26], P. Robbe [1], W. Scandale [27], N. Topilskaya [21], A. Uras [28], J. Wagner [29], N. Yamanaka [1,32,30,31], Z. Yang [33], A. Zelenski [24]

https://doi.org/10.1016/j.physrep.2021.01.002

5.2 Collinear PDFs

PDFs: what do we know

See https://inspirehep.net/literature/1801417

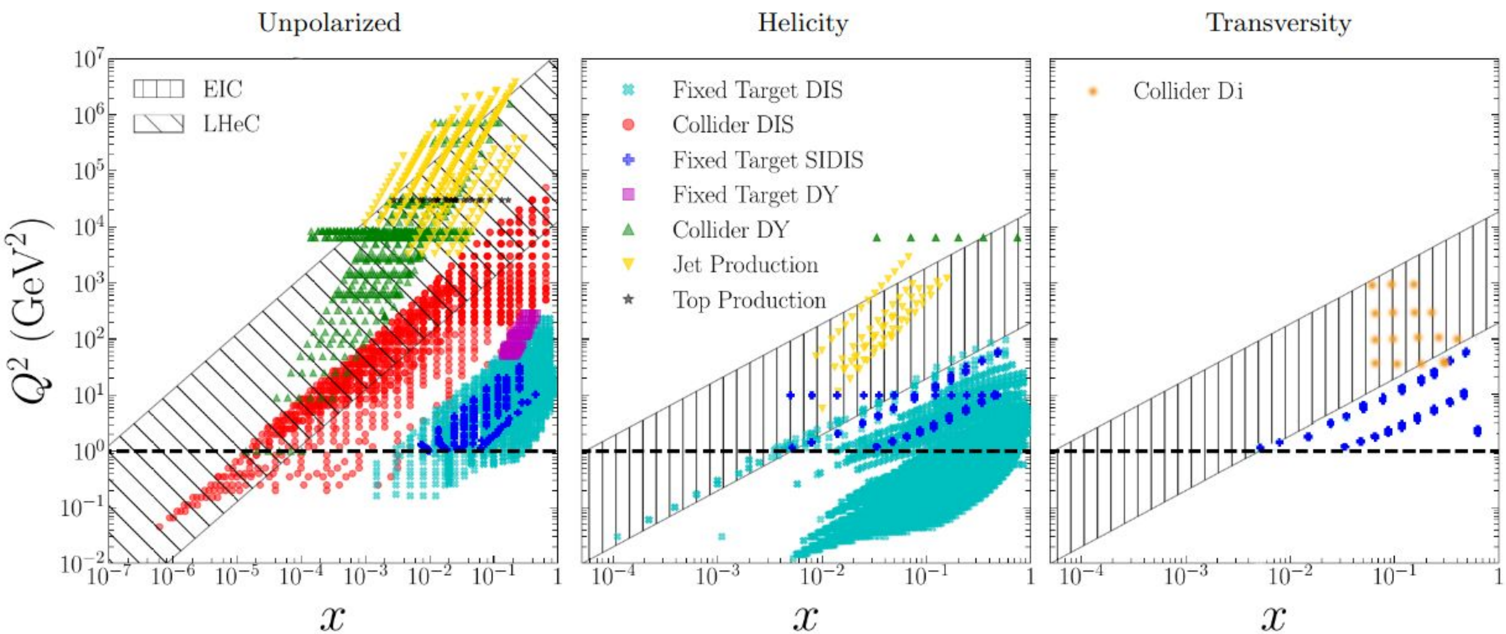


FIG. 1 The kinematic coverage in the (x, Q^2) plane of the hadronic cross-section data for the processes commonly included in global QCD analyses of collinear unpolarized, helicity, and transversity PDFs. The extended kinematic ranges attained by the LHeC and the EIC are also displayed. See Fig. 1 of Ref. (Ethier and Nocera, 2020) for unpolarized nuclear PDFs.

PDFs: unpolarized

See https://inspirehep.net/literature/1801417

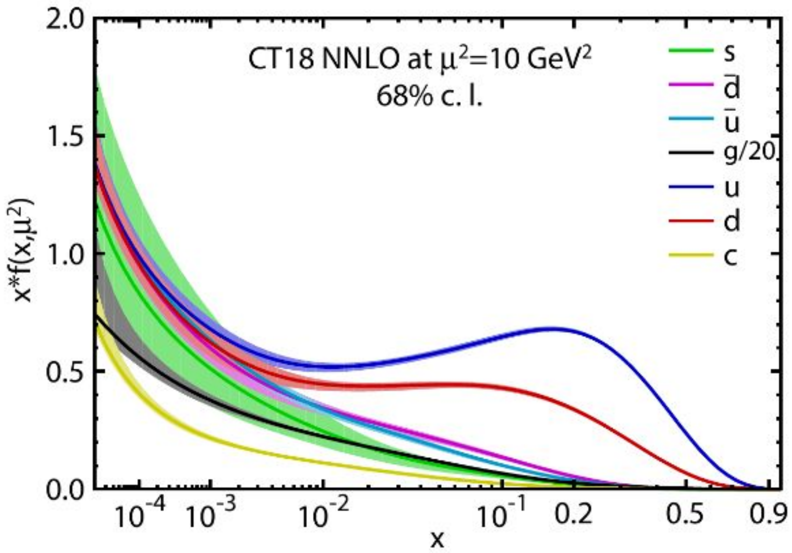


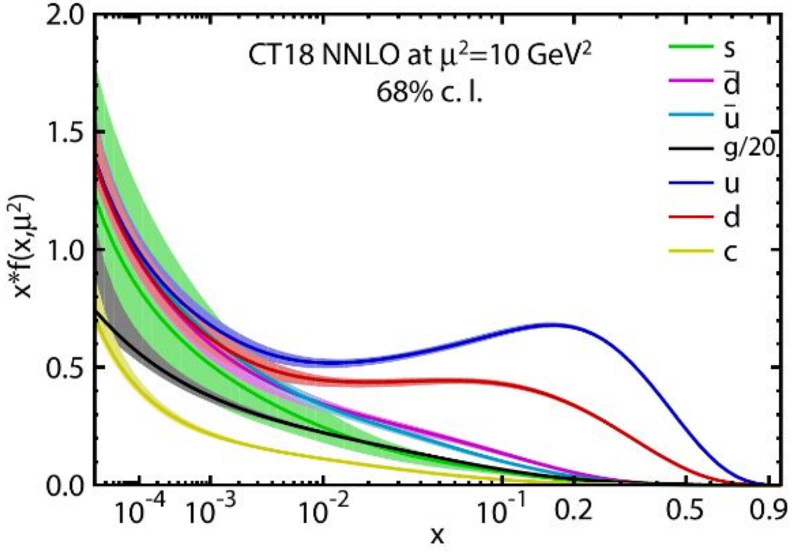
FIG. 2 The CT18 PDFs at $\mu^2 = 10$ GeV^2 for the xu, $x\bar{u}$, xd, $x\bar{d}$, $xs = x\bar{s}$, and xg PDFs. Error bands correspond to the 68% confidence level. Figure from (Kovařík *et al.*, 2019).

Many extractions available
See e.g. the LHAPDF library
https://lhapdf.hepforge.org/

A similar repository exists for TMDs:
https://tmdlib.hepforge.org/

PDFs: helicity

See https://inspirehep.net/literature/1801417



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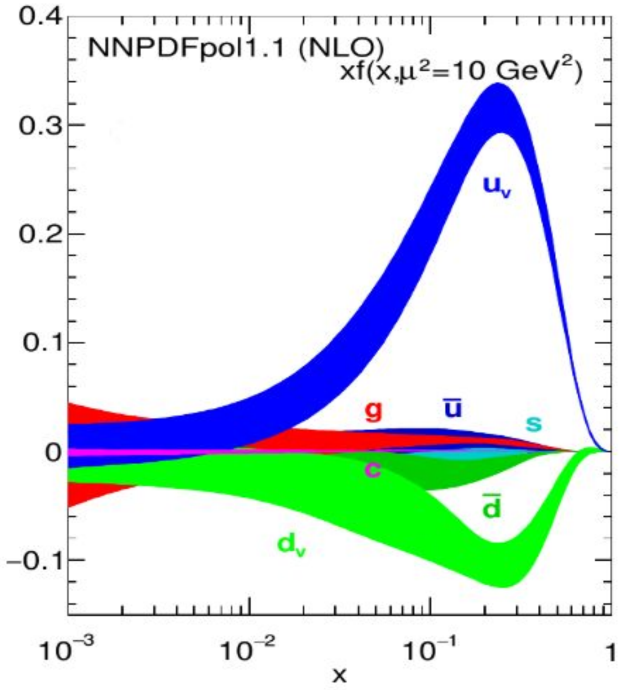


FIG. 5 The helicity PDFs from the NNPDFpol1.1 parton set at $\mu^2 = 10$ GeV^2. Figure from (Tanabashi *et al.*, 2018).

PDFs: transversity

See https://inspirehep.net/literature/1801417

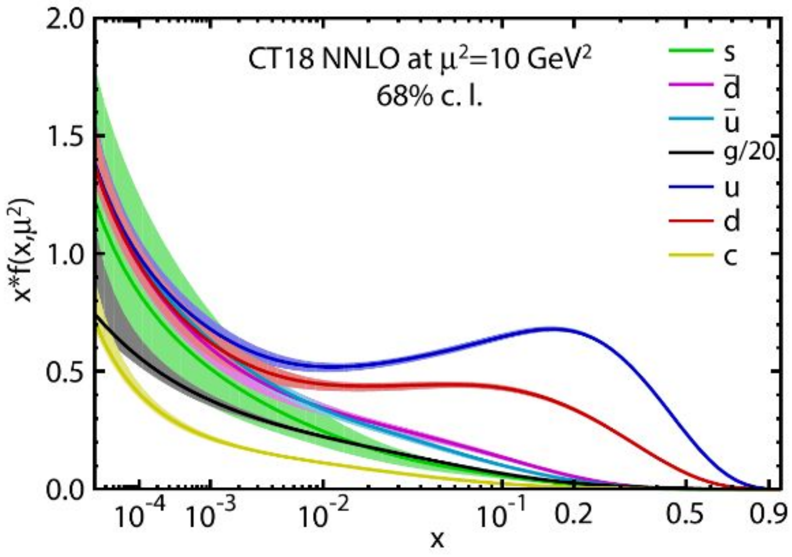


FIG. 2 The CT18 PDFs at $\mu^2 = 10$ GeV^2 for the xu, $x\bar{u}$, xd, $x\bar{d}$, $xs = x\bar{s}$, and xg PDFs. Error bands correspond to the 68% confidence level. Figure from (Kovařík *et al.*, 2019).

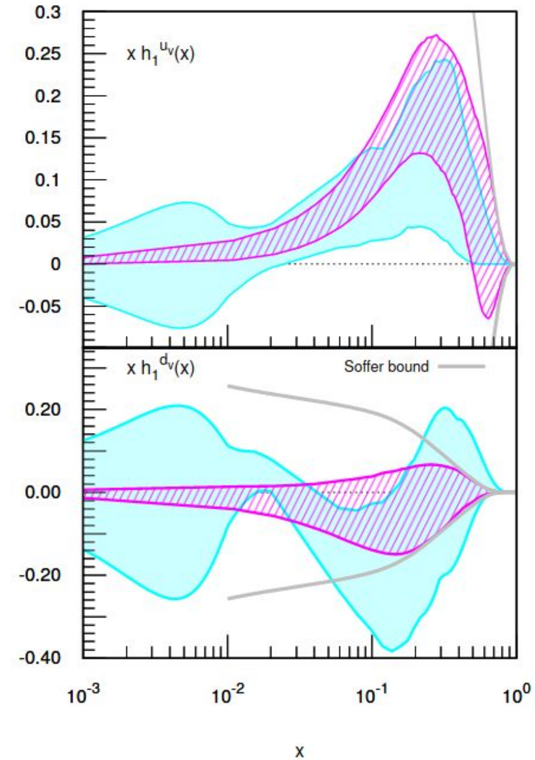


FIG. 6 The transversity $x\,h_1(x)$ at 90% CL. Upper (lower) plot for valence up (down) component. Gray lines represent the Soffer bound. Darker (pink) band for the PV18 global fit of (Radici and Bacchetta, 2018) at $Q^2 = 2.4$ GeV^2. Lighter (cyan) band for the MEX19 constrained analysis of (Benel *et al.*, 2020) at the average scale of the data.

Impact studies

See https://inspirehep.net/literature/1851258

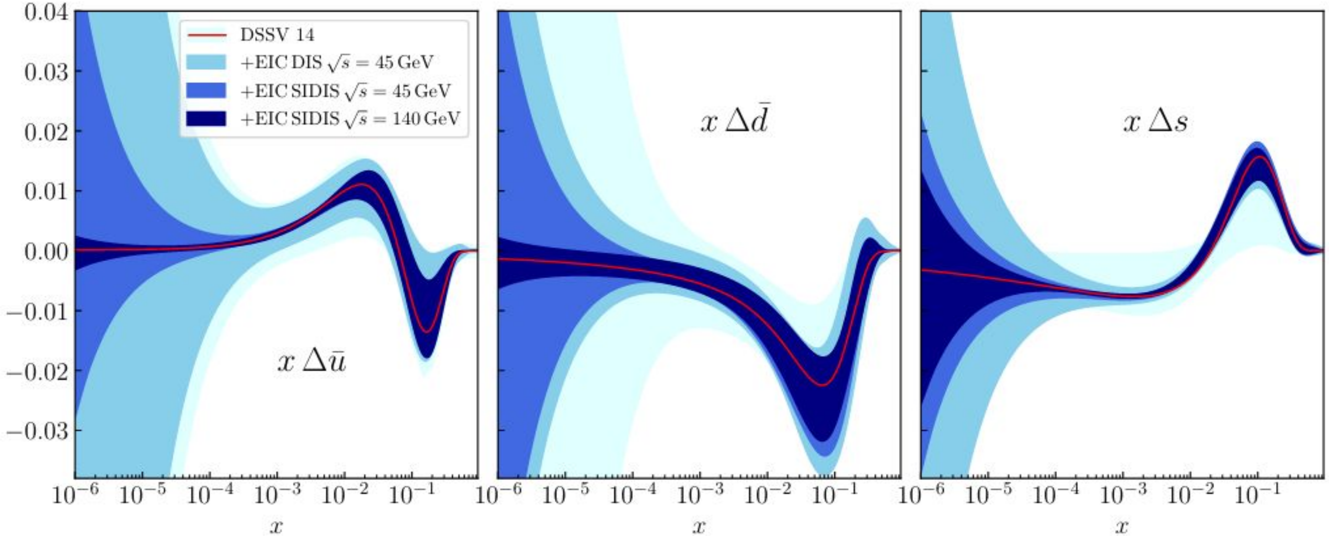
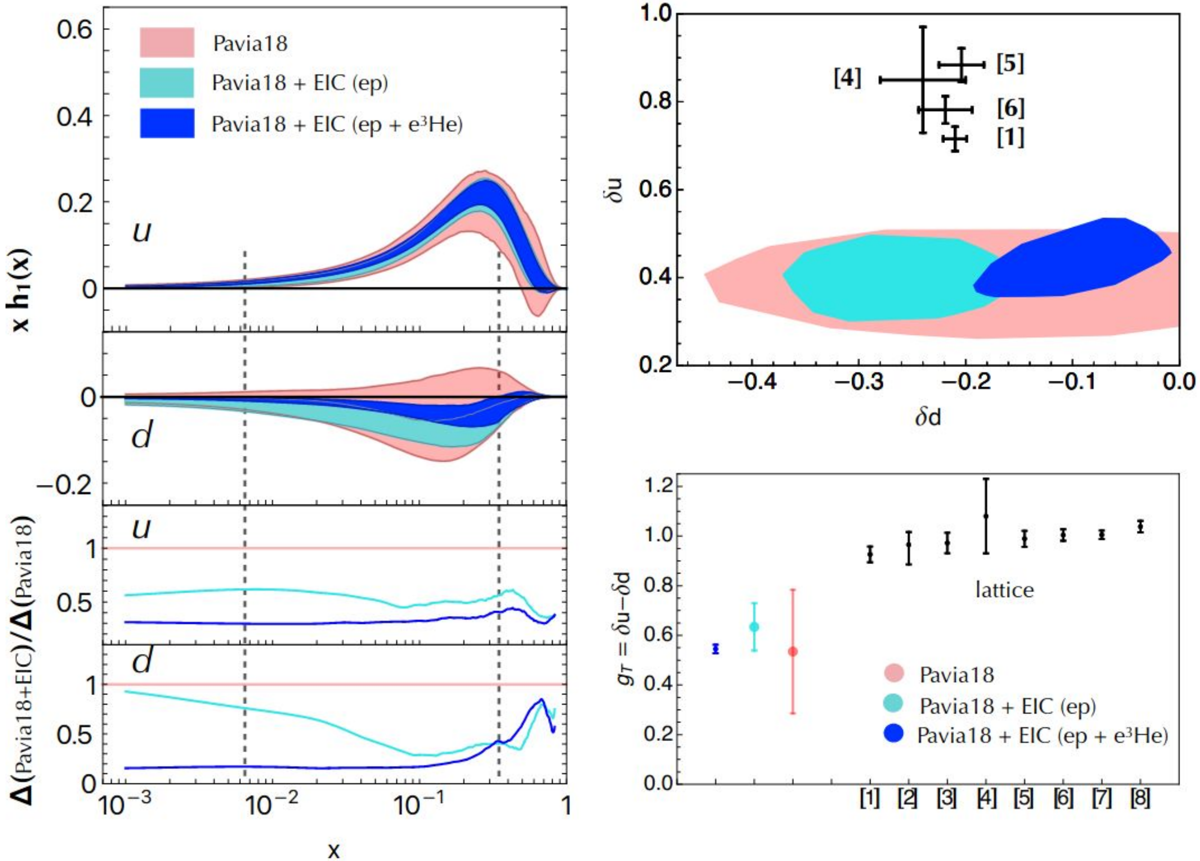


Figure 7.19: Impact of SIDIS measurements at the EIC on the sea quark helicities $x\Delta\bar{u}$, $x\Delta\bar{d}$ and $x\Delta s$ as a function of x at $Q^2 = 10$ GeV^2.

Helicity PDF

Impact studies

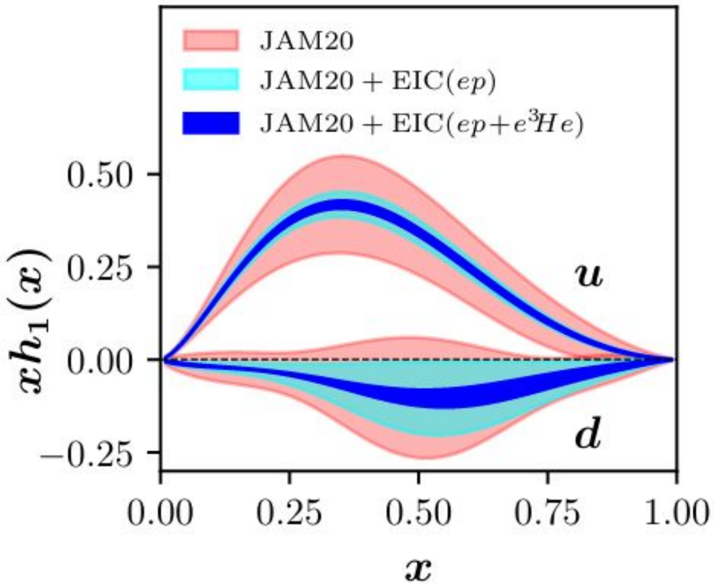
See https://inspirehep.net/literature/1851258

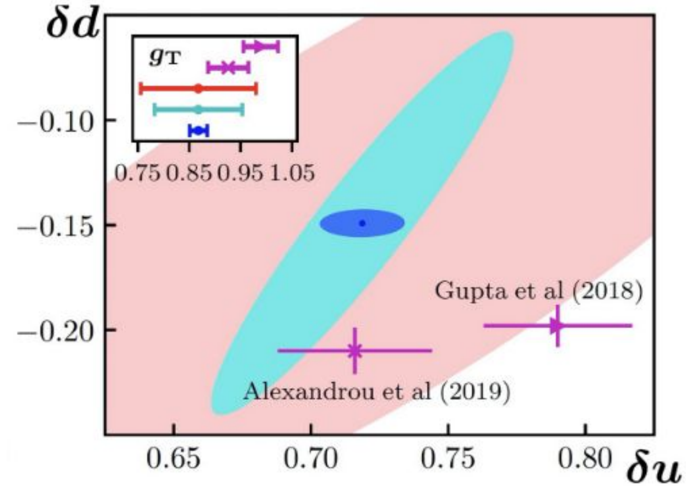


Transversity PDF and tensor charge

Impact studies

See https://inspirehep.net/literature/1851258

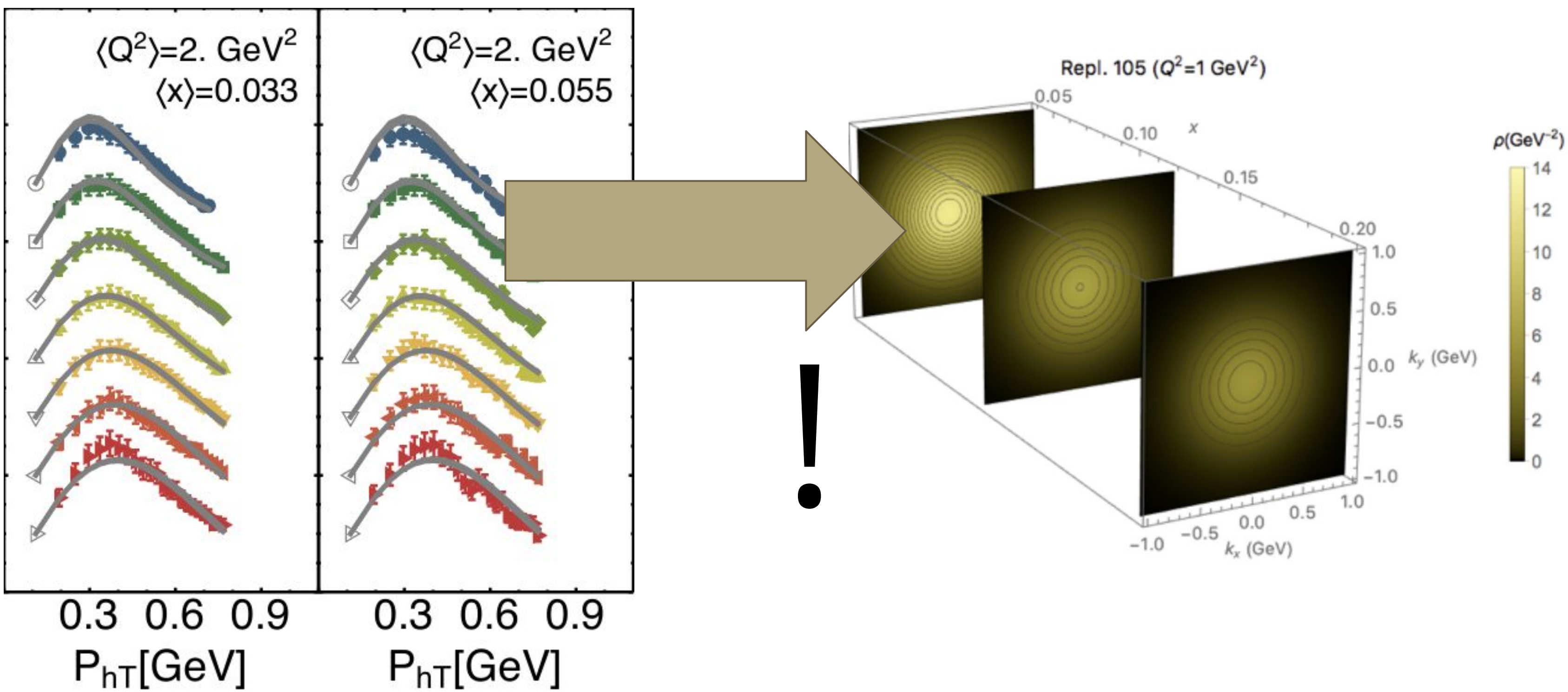




Transversity PDF and tensor charge

5.3 Unpolarized TMDs

Transverse momentum imaging



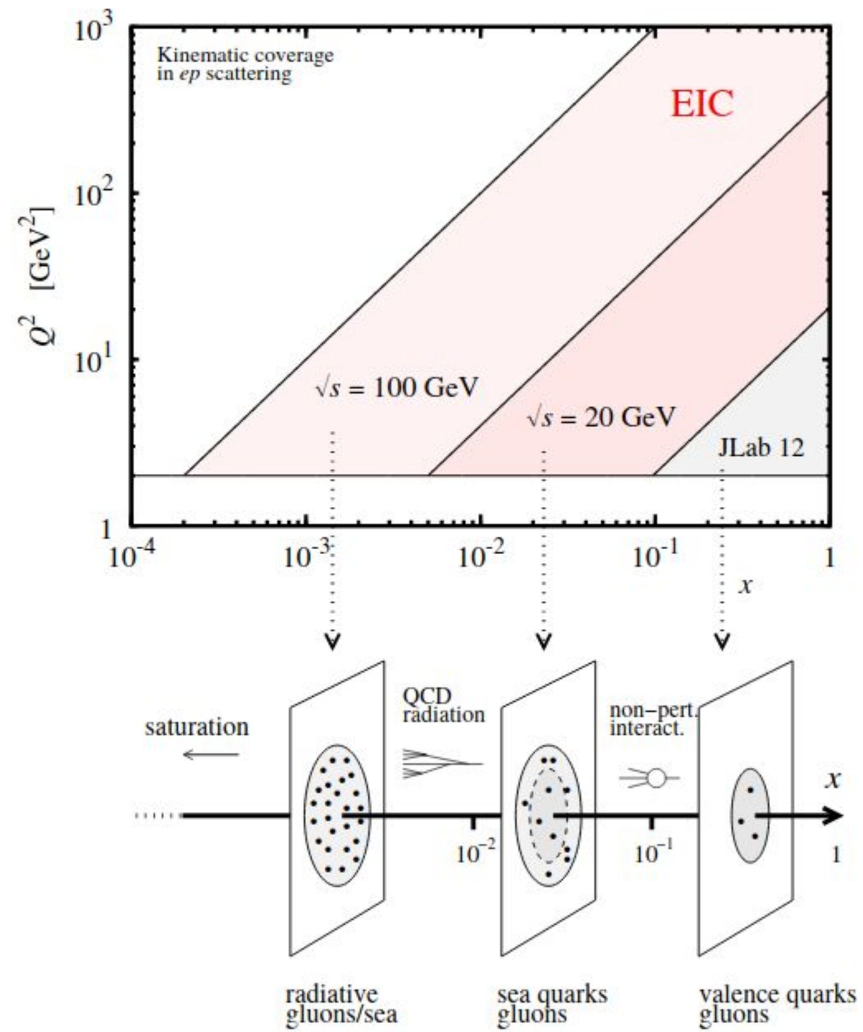
Imaging from SIDIS

Importance of complementary experiments

from JLab 12 GeV, Hermes, Compass
to the EIC

zooming into hadron structure

Credit picture: C. Weiss



Available global fits of unpolarized TMDs

	Accuracy	SIDIS	DY	Z production	N of points	χ^2/N_{data}
Pavia 2017 arXiv:1703.10157	NLL	✔	✔	✔	8059	1.55
SV 2019 arXiv:1912.06532	N^3LL	✔	✔	✔	1039	1.06
MAPTMD22	***N^3LL^-***	✔	✔	✔	***2031***	***1.06***

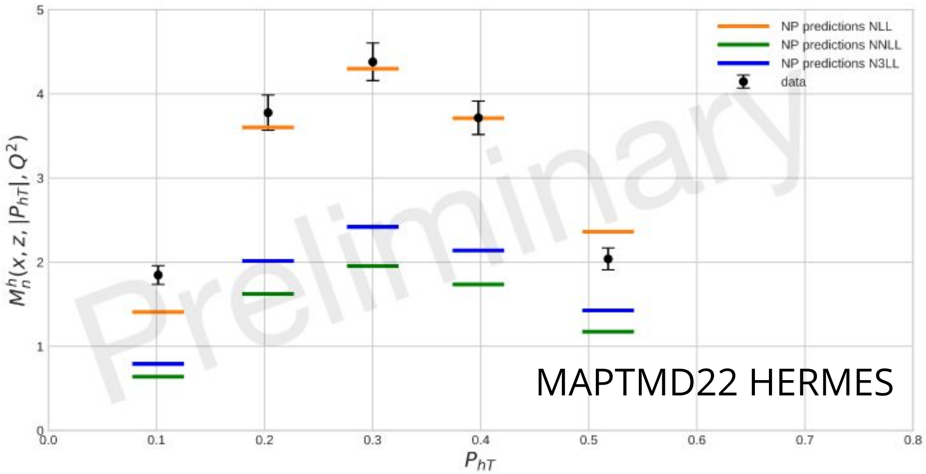
MAP collaboration : https://github.com/MapCollaboration

Other fits of unpolarized TMDs

	Framework	HERMES	COMPASS	DY	Z production	N of points	χ^2/N_{points}
Pavia 2017 arXiv:1703.10157	NLL	✔	✔	✔	✔	8059	1.55
SV 2017 arXiv:1706.01473	NNLL′	✘	✘	✔	✔	309	1.23
BSV 2019 arXiv:1902.08474	NNLL′	✘	✘	✔	✔	457	1.17
SV 2019 arXiv:1912.06532	NNLL′	✔	✔	✔	✔	1039	1.06
Pavia 2019 arXiv:1912.07550	N^3LL	✘	✘	✔	✔	353	1.02

Normalization issues: SIDIS

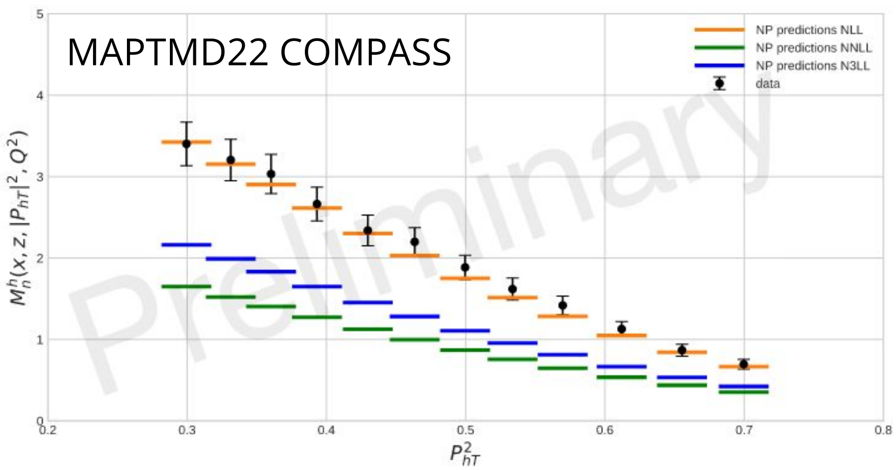
***Small** transverse momentum*



Beyond the NLL,
the **theoretical** prediction for **SIDIS undershoots the data**

Who to blame:

- hard function (large coeffs.)
- low Q



But **partial consensus** in literature, about the problem

- **SV 19** : *not seen;* power corrections from the start?
- **MAPTMD22** : power corrections from pre-computed normalization coefficients

Non perturbative components

$$F_a(x, b_T^2; \mu, \zeta) = F_a(x, b_T^2; \mu_0, \zeta_0)$$ → TMD distribution at initial scales

$$\times \quad \exp\left[\int_{\mu_0}^{\mu} \frac{d\mu'}{\mu'} \gamma_F\left(\alpha_s(\mu'), \frac{\zeta}{\mu'^2}\right)\right]$$ → evolution in μ

Calculable in pQCD

$$\times \quad \left(\frac{\zeta}{\zeta_0}\right)^{-D(b_T \mu_0, \alpha_s(\mu_0)) + g_K(b_T; \lambda)}$$ → evolution in ζ

Non-pert. corrections (large bT)

$$F_a(x, b_T^2; \mu_0, \zeta_0) = \sum_b C_{a/b}(x, b_T^2, \mu_0, \zeta_0) \otimes f_b(x, \mu_0) F_{NP}(b_T; \lambda)$$

Prior knowledge assumed (?)

See e.g. https://inspirehep.net/literature/1785810 for more details (but also JCC book, etc.)

Separating small and large bT

One needs to “separate” the small (perturbative) bT region from the large (non-perturbative) bT region:

$$\alpha_s(\mu = \mu_b \sim 1/b_T) \;\longrightarrow\; b_T < b_{max}$$

Avoid the Landau pole of QCD

$$\int_{\mu_b \sim 1/b}^{Q} \gamma_F \;, \;\; \mu_b < Q \;\longrightarrow\; b_T > b_{\min}$$

Otherwise gluon “absorption” instead of “emission”

For more details see https://inspirehep.net/literature/1520011

Separating small and large bT

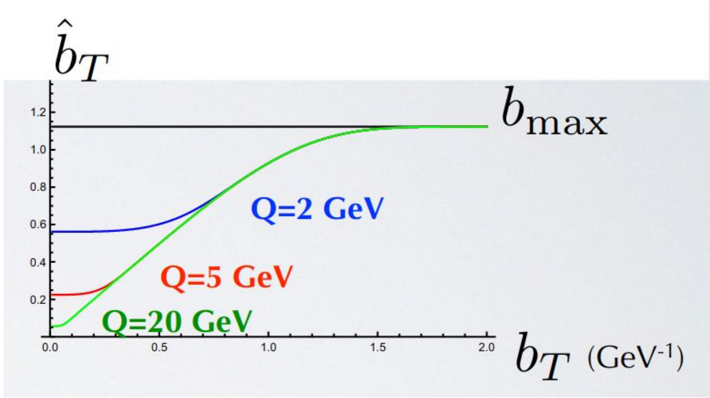
One needs to "separate" the small (perturbative) bT region from the large (non-perturbative) bT region:

$$\hat{b}(b_T; b_{\min}, b_{\max}) = b_{\max} \left(\frac{1 - e^{-b_T^4/b_{\max}^4}}{1 - e^{-b_T^4/b_{\min}^4}} \right) \begin{cases} \nearrow b_{\max}\,, & b_T \to +\infty \\ \searrow b_{\min}\,, & b_T \to 0 \end{cases}$$

$$b_{\max} = 2e^{-\gamma_E}$$

$$b_{\min} = 2e^{-\gamma_E}/Q$$

These choices guarantee that for Q=1 GeV the TMD coincides with the NP model

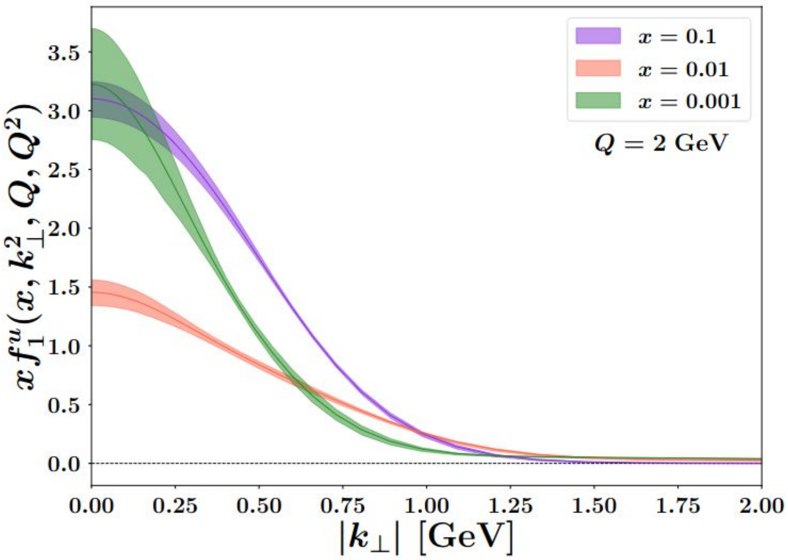


For more details see https://inspirehep.net/literature/1520011

MAP extraction

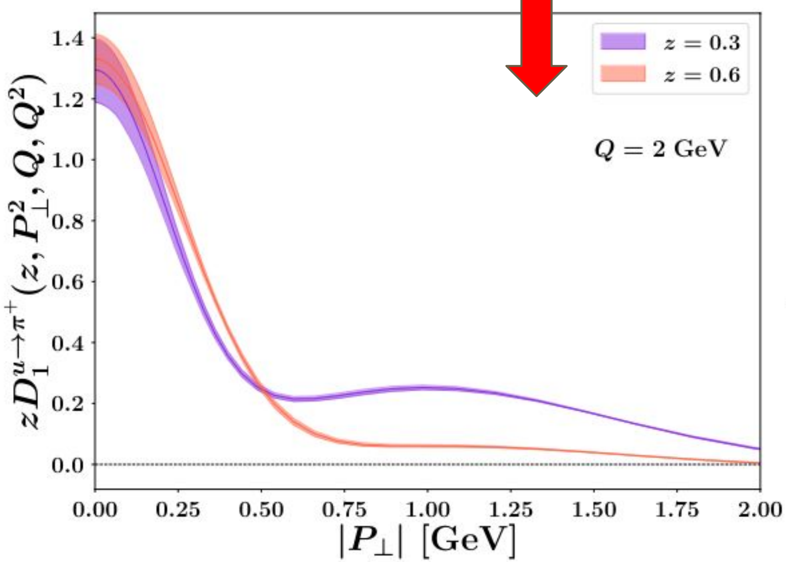
See : https://inspirehep.net/literature/2096333

Imaging from **SIDIS** data (Hermes and Compass) **and Drell-Yan** data (low and high energy)



Unpolarized TMD PDF

Unpolarized TMD FF



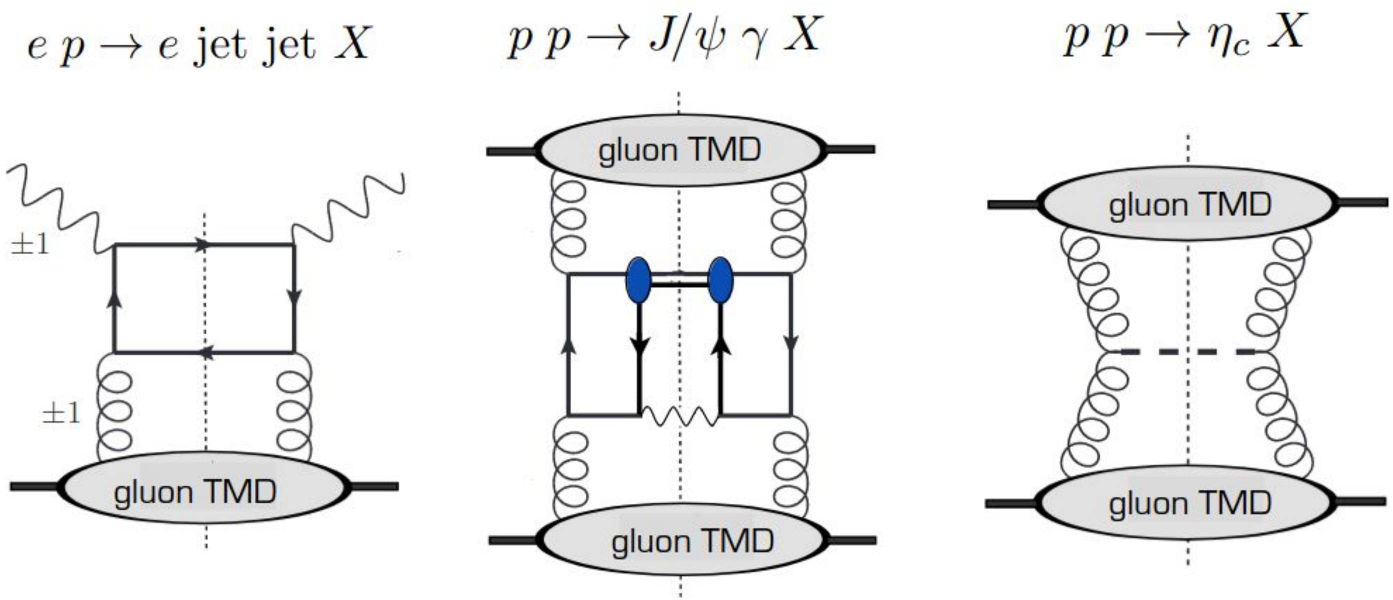
Combining SIDIS and Drell-Yan:
Possibility to disentangle
hadron structure and formation

Some open questions

A non-exhaustive *personal* list of open questions:

- deepen our understanding of **sea** quarks
- **flavor structure** of TMDs
- experimental confirmation of **sign change** relation
- **gluon** observables and **spin-1** effects
- what can **hadronization** teach us about **confinement**?
- interplay between **nuclear/hadron** and **high-energy** physics (e.g. **W mass**)
- ..

Access to gluon distributions



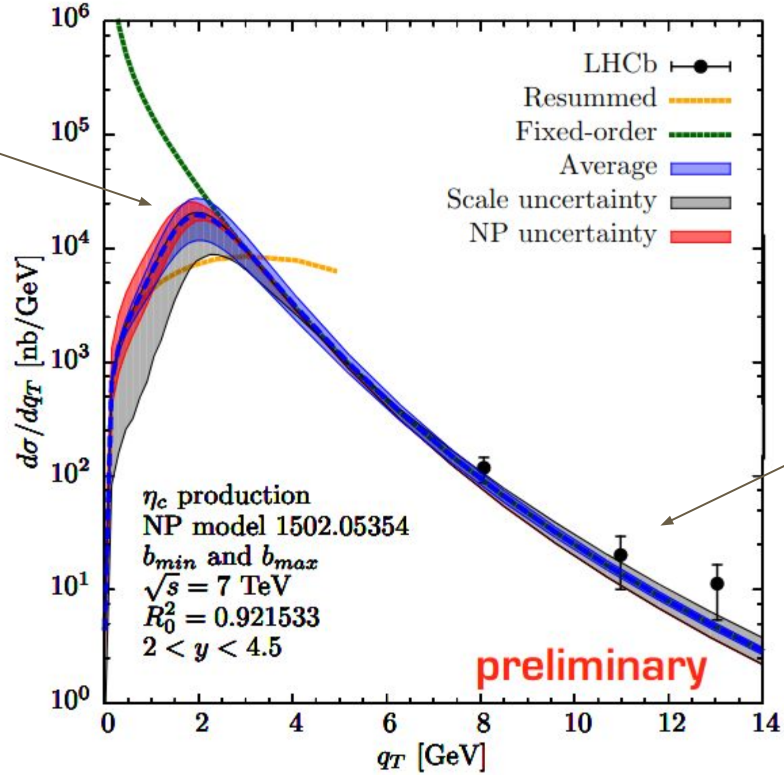
...

See e.g.:
- https://inspirehep.net/literature/1962932 (di-jet case)
- https://inspirehep.net/literature/1279490 (ccbar-photon case)

This is going to be discussed also next week during the workshop.

eta b,c production : access to gluon TMD PDFs

The **low transverse momentum** region gives access to gluon TMD PDFs



LHCb measurement at **large transverse momentum**: collinear gluon PDFs

Lansberg et al. - ongoing work

5.4 Polarized TMDs

Spin asymmetries

$$A_{UT} \sim \frac{d\sigma(\uparrow) - d\sigma(\downarrow)}{d\sigma(\uparrow) + d\sigma(\downarrow)}$$

→ Polarized structure functions / unpolarized one

↓

$$f_1 \otimes D_1$$

Asymmetries in general have the benefits to :

- Single out **specific structure functions** (using Fourier analysis too)
- **Reduce** the effect of **systematic uncertainties** common to denominator and numerator (e.g. acceptance effects)
- But … **knowledge** of the **unpolarized** cross section (denominator) is required in order to study the numerator

Sivers from SIDIS

see https://inspirehep.net/literature/1806922

Sivers TMD PDF

$$\frac{f_{1T}^{\perp} \otimes D_1}{f_1 \otimes D_1}$$

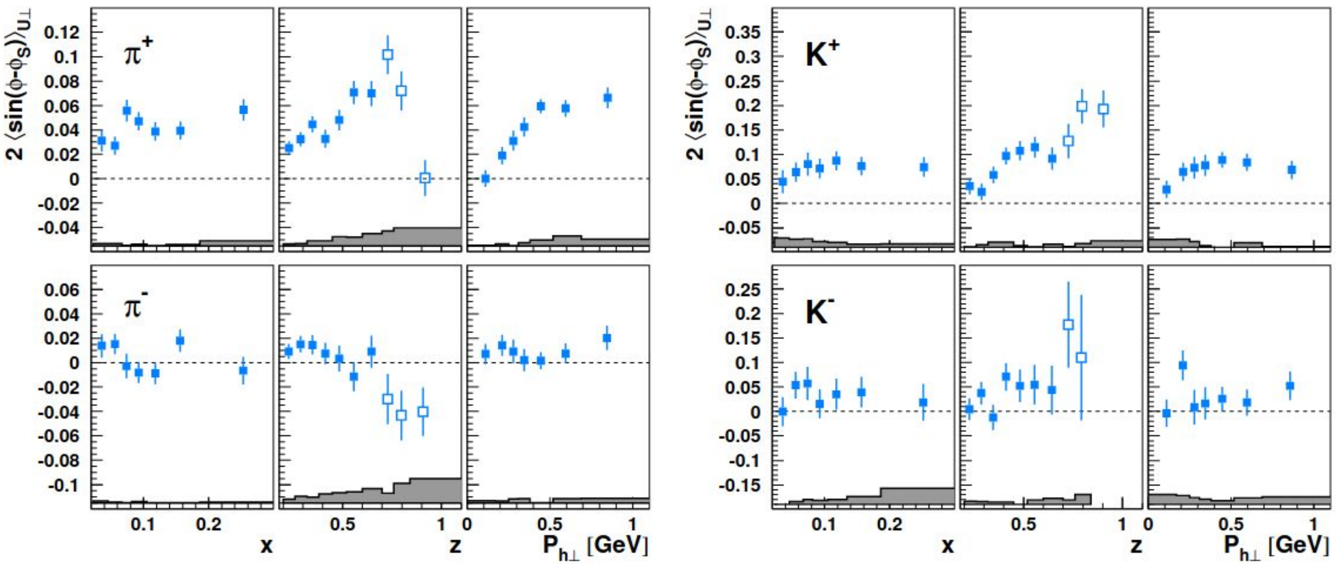


Figure 12. Sivers SFA for charged mesons (left: pions; right: kaons) presented either in bins of x, z, or $P_{h\perp}$. Data at large values of z, marked by open points in the z projection, are not included in the other projections. Systematic uncertainties are given as bands, not including the additional scale uncertainty of 7.3% due to the precision of the target-polarization determination.

hermes

Chiral-odd structures

spin-1/2 hadron (Nucleon)

$\Gamma = \gamma^+ \rightarrow$

$\Gamma = \gamma^+ \gamma_5 \rightarrow$

$\Gamma = i\sigma^{i+}\gamma_5 \rightarrow$

quark polarization

N polarization	U ●	L →	T ↑	
U ○	f_1		$h_1^\perp$	unpolarized PDF
L →		g_{1L}	$h_{1L}^\perp$	helicity PDF
T ↑	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$	transversity PDF

$\Gamma = \gamma^+ \rightarrow \bar{\psi}\gamma^+\psi \rightarrow R^\dagger R + L^\dagger L$ sum of right-handed / left-handed quark densities $f_1 =$ 

$\Gamma = \gamma^+\gamma_5 \rightarrow \bar{\psi}\gamma^+\gamma_5\psi \rightarrow R^\dagger R - L^\dagger L$ difference " " " $g_1 =$ 

$\Gamma = i\sigma^{i+}\gamma_5 \rightarrow \bar{\psi}\, i\sigma^{i+}\gamma_5\psi \rightarrow L^\dagger\gamma_i R - R^\dagger\gamma_i L$ not diagonal on helicity basis "chiral-odd" structure $h_1 =$ 

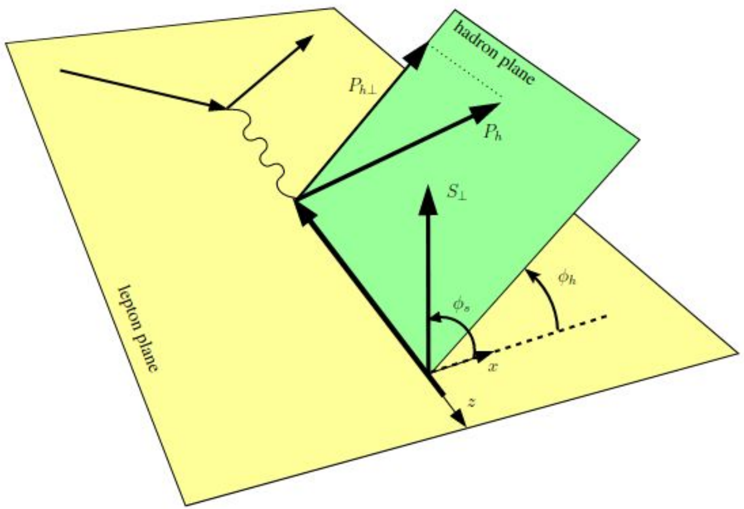
Slide from M. Radici's lectures

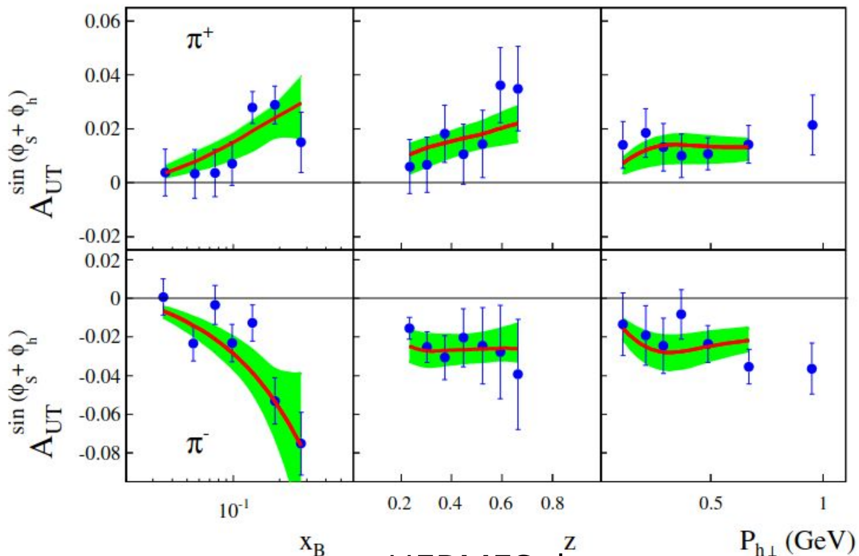
Transversity and Collins

One possible "partnership" between chiral-odd structures

$$d\sigma^{\,l\,N \to l\,h\,X} \sim h_1(x, k_T^2) \otimes H_1^\perp(z, P_T^2)$$

See https://inspirehep.net/literature/1372084





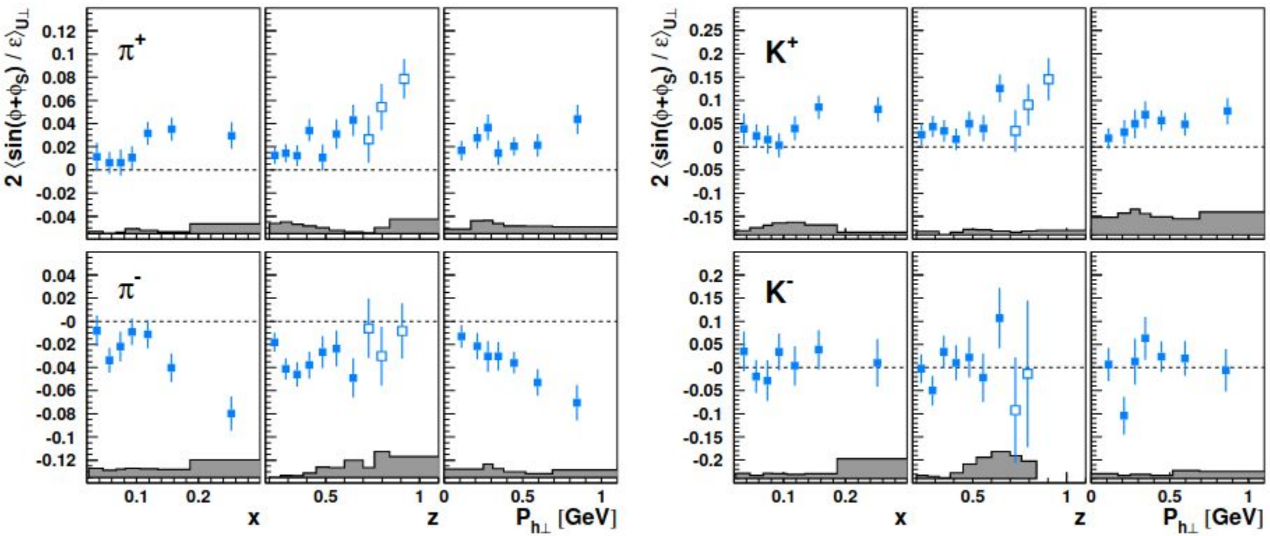
HERMES data

Correlation between **transverse spin** of the quark and **transverse momentum** of the quark (similar to spin-orbit effect!)

Other TMDs from SIDIS

see https://inspirehep.net/literature/1806922

Transversity TMD PDF & Collins TMD FF



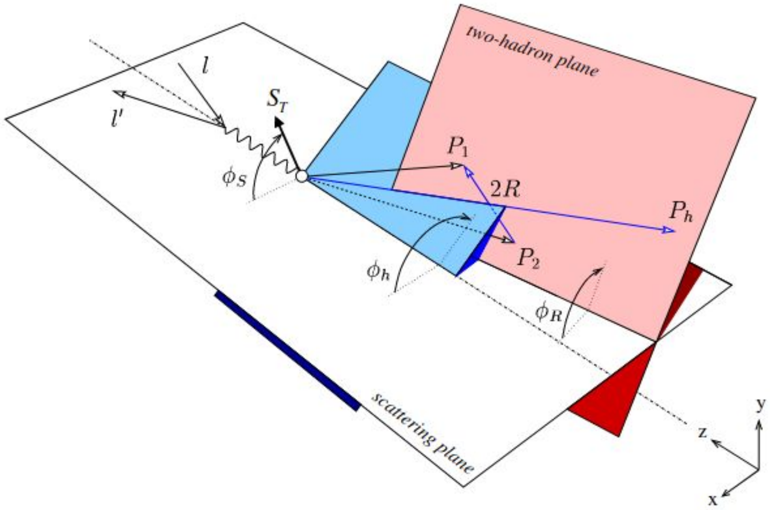
$$\frac{h_1 \otimes H_1^{\perp}}{f_1 \otimes D_1}$$

Figure 8. Collins SFA for charged mesons (left: pions; right: kaons) presented either in bins of x, z, or $P_{h\perp}$. Data at large values of z, marked by open points in the z projection, are not included in the other projections. Systematic uncertainties are given as bands, not including the additional scale uncertainty of 7.3% due to the precision of the target-polarization determination.

hermes

2h interference FF

$$d\sigma^{l\,N \to l\,h_1\,h_2\,X} \sim h_1(x) \otimes H_1^{\triangleleft}(z)$$

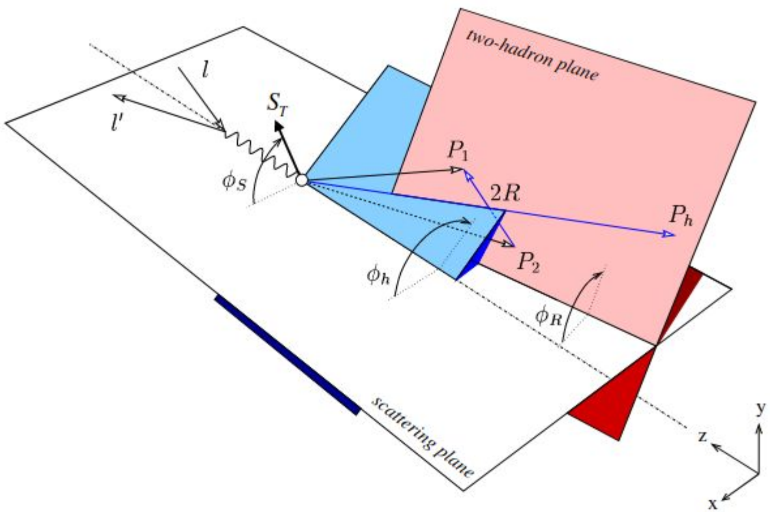


hep-ph/0311173 - Bacchetta et al.

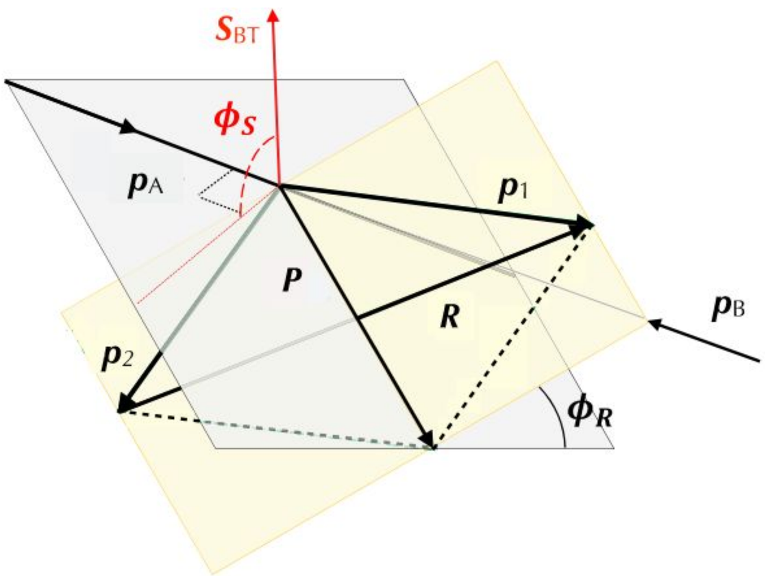
2h interference FF

$$d\sigma^{\,l\,N \to l\,h_1\,h_2\,X} \sim h_1(x) \otimes H_1^{\sphericalangle}(z)$$

$$d\sigma^{\,p\,p \to h_1\,h_2\,X} \sim f_1(x_a)\,h_1(x_b)\,H_1^{\sphericalangle}(z)$$



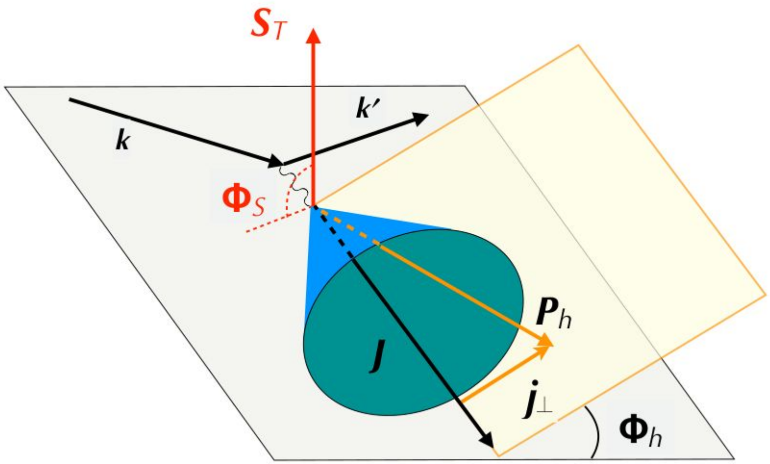
hep-ph/0311173 - Bacchetta et al.



arXiv 1604.06585 - Radici et al.

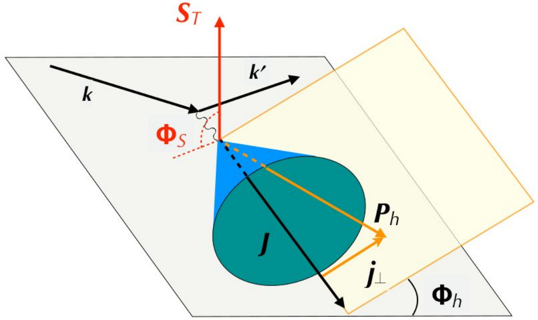
In-jet Collins TMD FF

$$d\sigma^{\,l\,N \to l\,jet(h)\,X} \sim h_1\big(x, k_T^2\big) \otimes H_1^{\perp}\big(z_h, j_T^2\big)$$

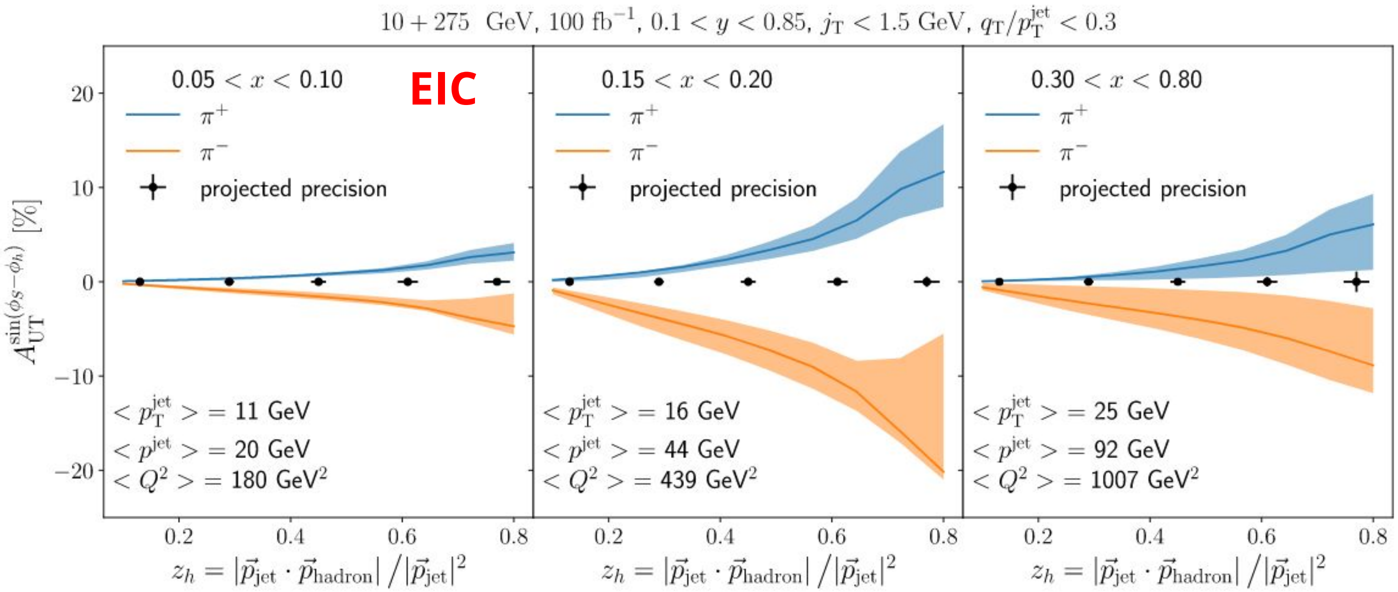


Credit picture: M. Radici

In-jet Collins TMD FF



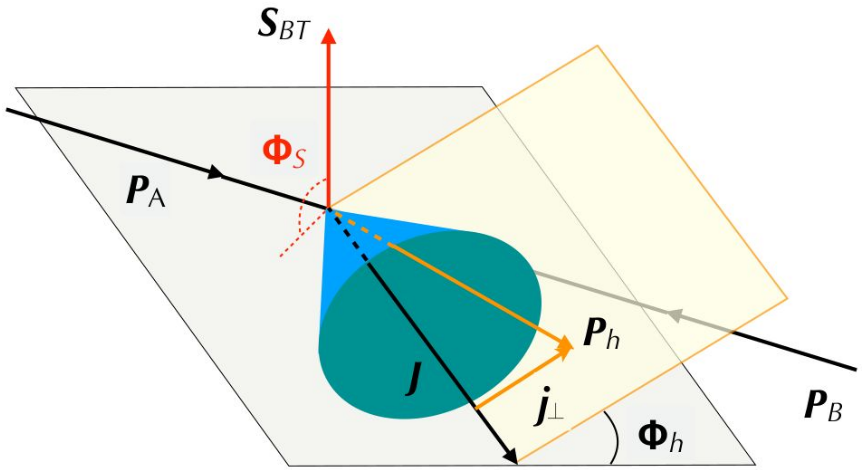
$$d\sigma^{\,l\,N \to l\; jet(h)\; X} \sim h_1(x, k_T^2) \otimes H_1^{\perp}(z_h, j_T^2)$$



arXiv 2007.07281 - Arratia et al.

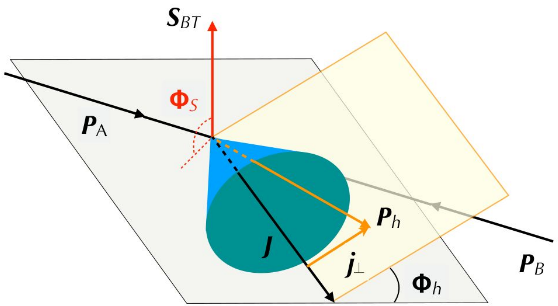
In-jet Collins TMD FF

$$d\sigma^{\,p\,p \to jet(h)\,X} \sim f_1(x_a) \otimes h_1(x_b) \otimes H_1^{\perp}(z_h, j_T^2)$$

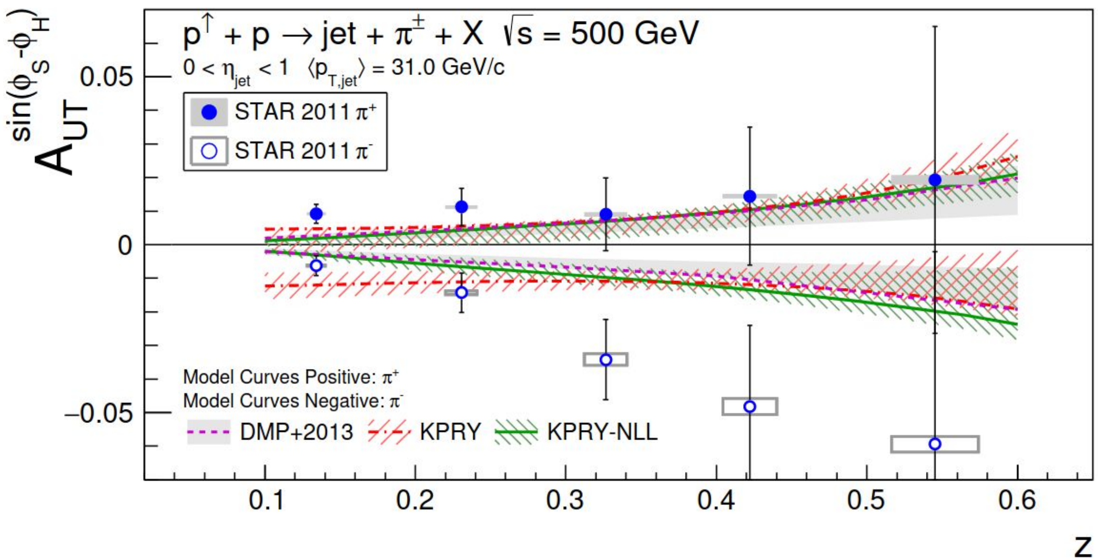


Credit picture: M. Radici

In-jet Collins TMD FF



$$d\sigma^{\,p\,p\,\rightarrow\,jet(h)\,X} \sim f_1(x_a) \otimes h_1(x_b) \otimes H_1^\perp(z_h, j_T^2)$$

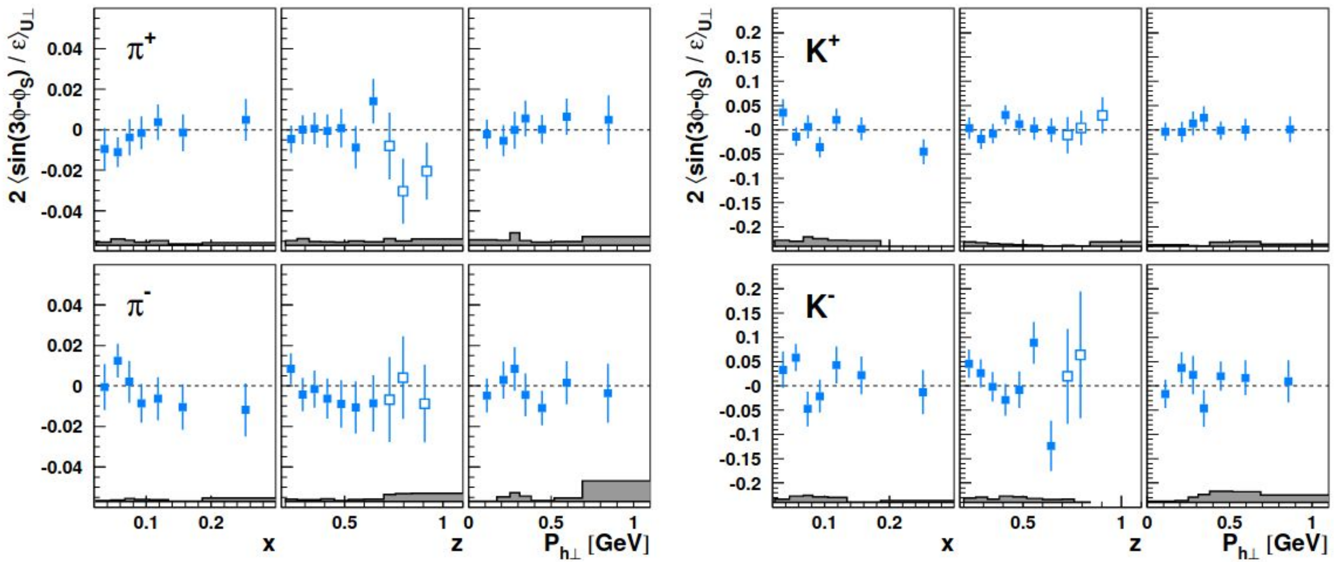


arXiv 1708.07080 - STAR coll.

Other TMDs from SIDIS

see https://inspirehep.net/literature/1806922

Pretzelosity TMD PDF & Collins TMD FF (*vanishing signal ..?*)



$$\frac{h_{1T}^{\perp} \otimes H_1^{\perp}}{f_1 \otimes D_1}$$

Figure 19. Pretzelosity SFA for charged mesons (left: pions; right: kaons) presented either in bins of x, z, or $P_{h\perp}$. Data at large values of z, marked by open points in the z projection, are not included in the other projections. Systematic uncertainties are given as bands, not including the additional scale uncertainty of 7.3% due to the precision of the target-polarization determination.

hermes

Other TMDs from SIDIS

see https://inspirehep.net/literature/1806922

Worm-gear TMD PDF

$$\frac{g_{1T} \otimes D_1}{f_1 \otimes D_1}$$

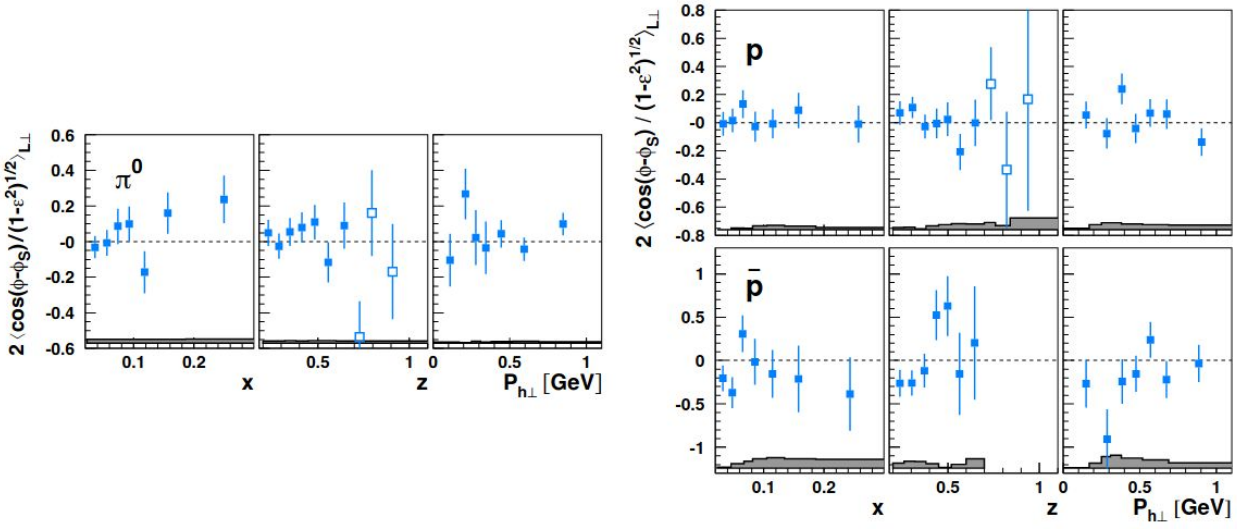


Figure 22. The $2\langle\cos(\phi-\phi_S)/\sqrt{1-\epsilon^2}\,\rangle^h_{L\perp}$ amplitudes for π^0 (left), protons, and antiprotons (right) presented either in bins of x, z, or $P_{h\perp}$. Data at large values of z, marked by open points in the z projection, are not included in the other projections (no such high-z points are available for antiprotons due to a lack of precision). Systematic uncertainties are given as bands, not including the additional scale uncertainty of 8.0% due to the precision in the determination of the target and beam polarizations.

Other TMDs from SIDIS

see https://inspirehep.net/literature/1806922

Twist 3 TMD PDFs and TMD FFs

$$\frac{f_T \otimes D_1}{f_1 \otimes D_1} \quad \frac{h_1 \otimes \tilde{H}}{f_1 \otimes D_1} \quad \frac{h_T \otimes H_1^\perp}{f_1 \otimes D_1}$$

$$\frac{g_{1T} \otimes \tilde{G}^\perp}{f_1 \otimes D_1}$$

$$\frac{h_T^\perp \otimes H_1^\perp}{f_1 \otimes D_1}$$

$$\frac{f_{1T}^\perp \otimes \tilde{D}^\perp}{f_1 \otimes D_1}$$

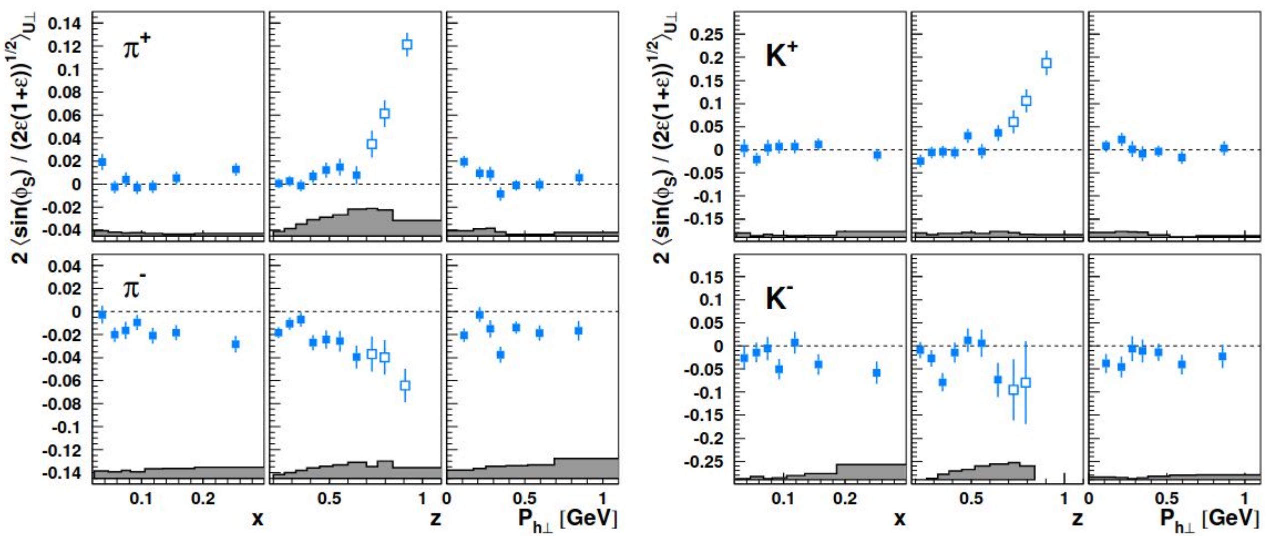


Figure 25. The $2\langle \sin(\phi_S)/\sqrt{2\epsilon(1+\epsilon)}\rangle^h_{\mathrm{U}\perp}$ amplitudes for charged mesons (left: pions; right: kaons) presented either in bins of x, z, or $P_{h\perp}$. Data at large values of z, marked by open points in the z projection, are not included in the other projections. Systematic uncertainties are given as bands, not including the additional scale uncertainty of 7.3% due to the precision of the target-polarization determination.