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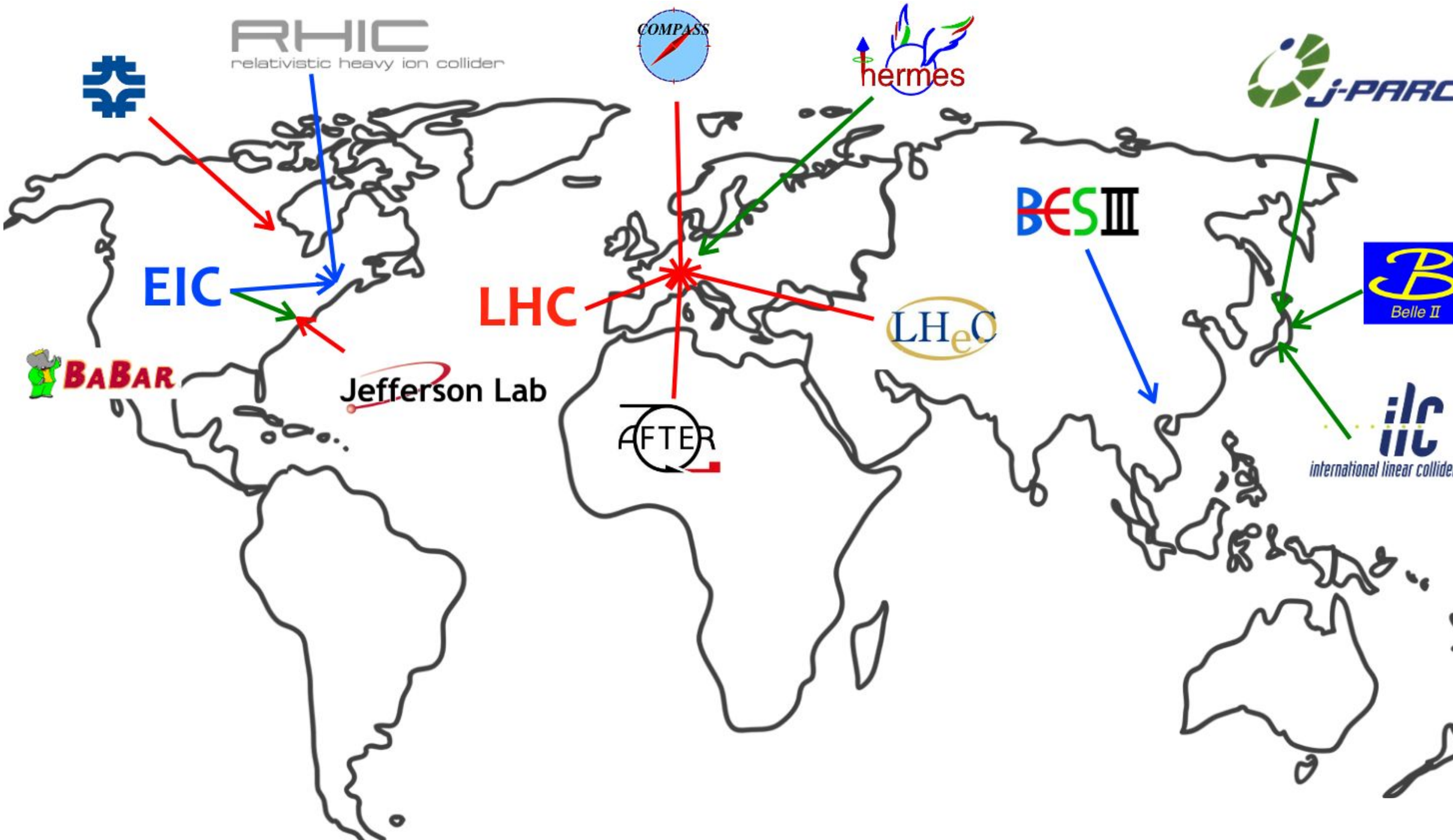
Opportunities for hadron structure studies at the EIC

EICUG Early Career workshop 2021

July 30, 2021

Outline

1. Introduction
2. Collinear PDFs
3. Unpolarized TMDs
4. Polarized TMDs


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

From the Yellow Report, p.17: https://inspirehep.net/literature/1851258

“EIC-based science is broad and diverse.

It runs the gamut from detailed investigation of hadronic structure with unprecedented precision to explorations of new regimes of strongly interacting matter.”

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.

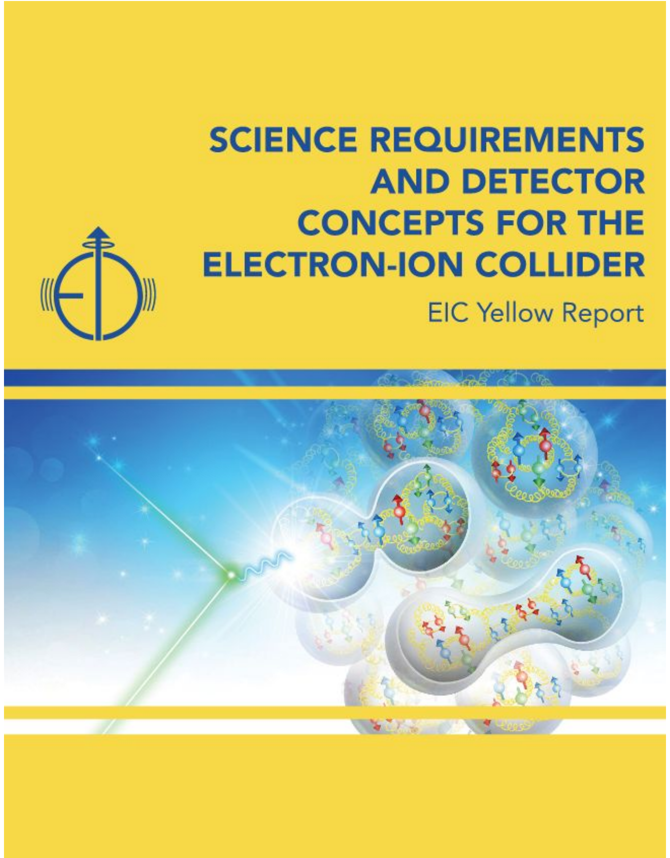
Quark and Gluon Confinement

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

The Yellow Report

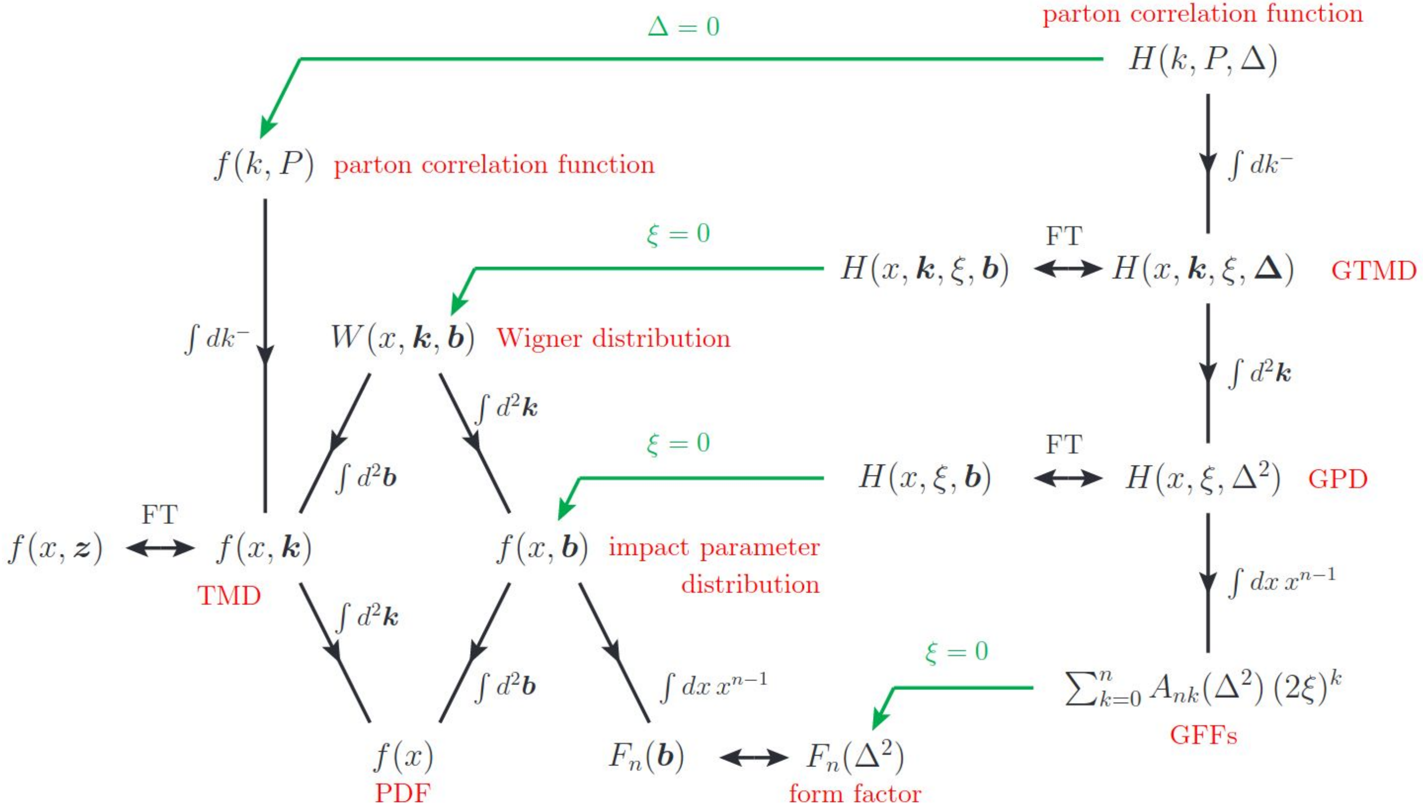


2021

The “EIC Yellow Report”
A community effort to line out the science requirements and detector concepts for the EIC

see also the EIC Users Group website:
http://eicug.org/

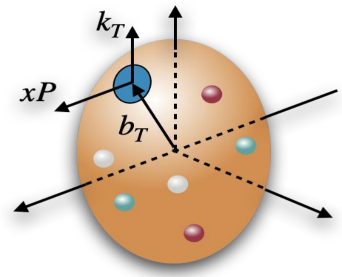
The hadron structure landscape



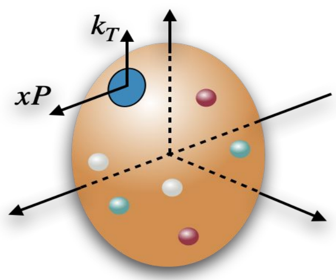
Credit picture: M. Diehl - [arXiv 1512.01328]

The hadron structure landscape

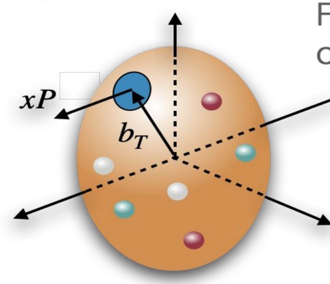
Wigner distributions (Fourier transform of GTMDs = Generalized Transverse Momentum Distributions)



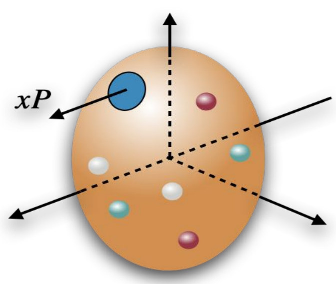
TMDs



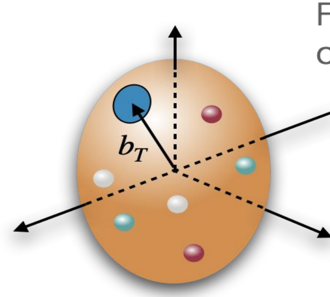
Fourier transform of GPDs



PDFs



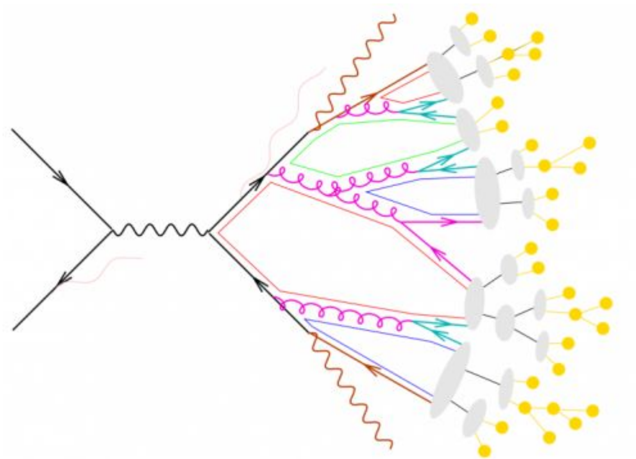
Fourier transform of Form Factors



see, e.g., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)

Fragmentation functions (FFs)

"Maps" of hadron *formation* in momentum space



$D_1^h(z)$	single-hadron collinear FF
$D_1^h(z, P_T^2)$	single-hadron TMD FF
$D_1^{h_1\,h_2}(z, \zeta)$	di-hadron FF
$J(s)$	inclusive jet FF
$\mathcal{G}^h(s, z)$	in-jet FF

Quark TMD PDFs (spin ½)

quark pol.

nucleon pol.	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

At leading twist: 8 TMD PDFs

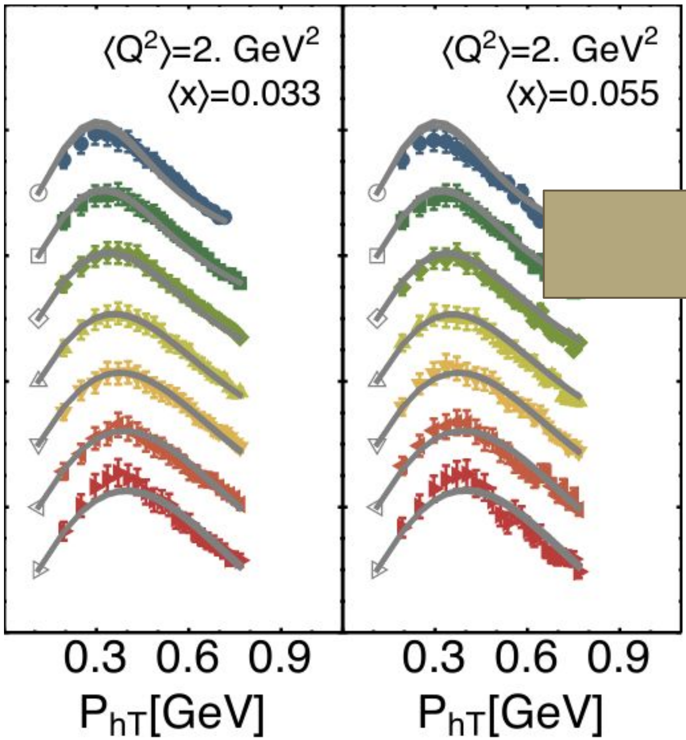
(similar classification for gluons)

The **symmetries of QCD** play a crucial role in this classification

- **Black**: time-reversal even AND collinear
- **Blue**: time-reversal even
- **Red**: time-reversal odd (*process dependence*)

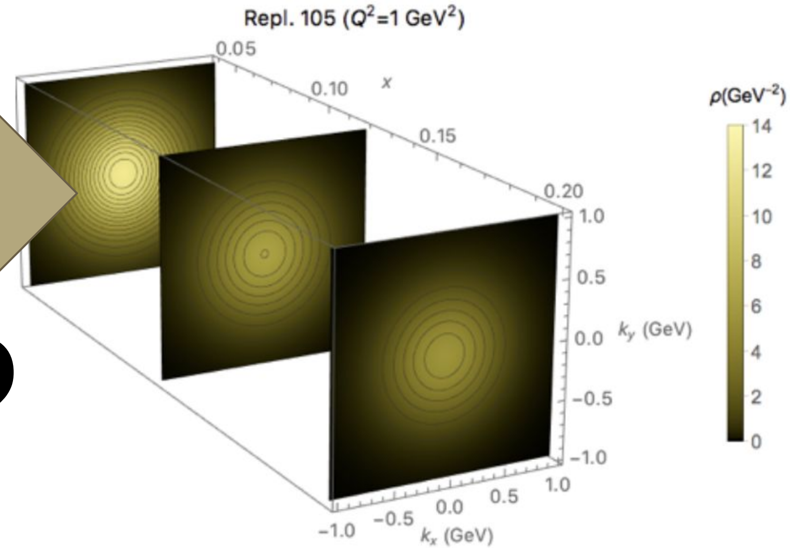
Quark inside spin ½ hadron

“Imaging”



⟨Q²⟩=2. GeV²
⟨x⟩=0.033
⟨Q²⟩=2. GeV²
⟨x⟩=0.055
0.3 0.6 0.9
P_hT[GeV]
0.3 0.6 0.9
P_hT[GeV]

?



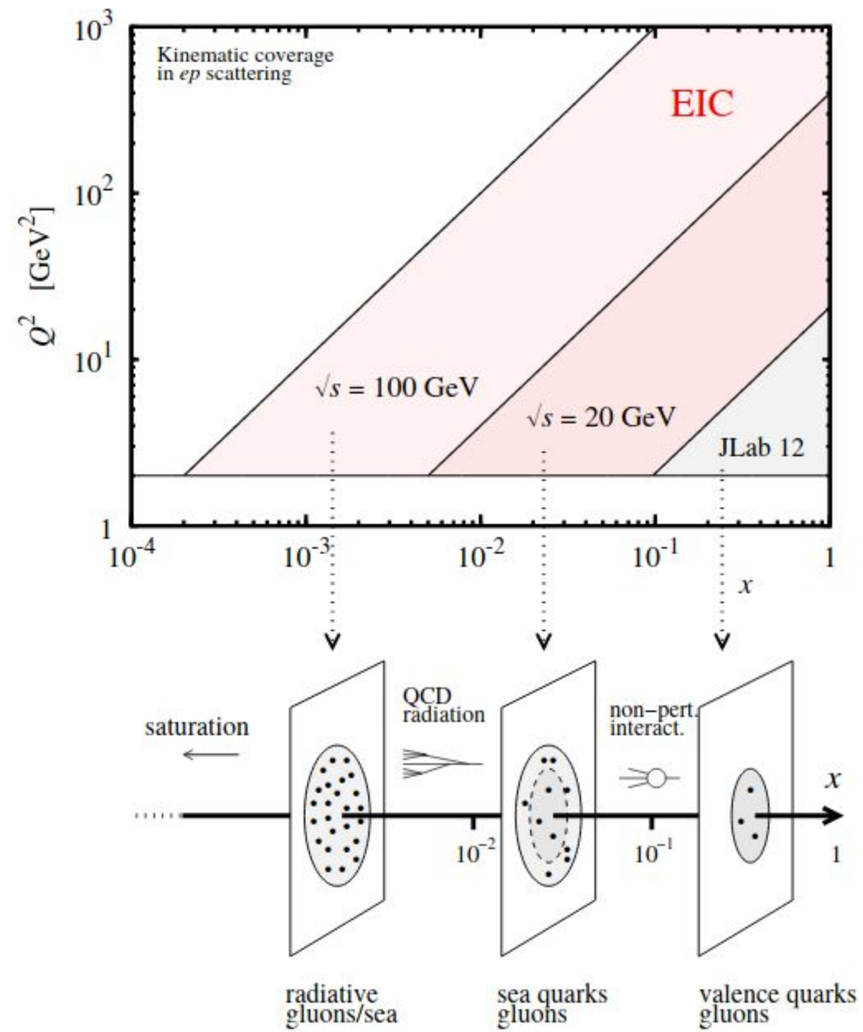
Repl. 105 (Q²=1 GeV²)
x
0.05
0.10
0.15
0.20
k_y (GeV)
k_x (GeV)
ρ(GeV⁻²)

"Imaging" from SIDIS

From JLab 12 GeV, Hermes, Compass
to the EIC:

zooming into hadron structure

Importance of "complementary" experiments!



Credit picture: C. Weiss

Collinear PDFs

PDFs: what do we know

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

2020 PDFLattice Report 5

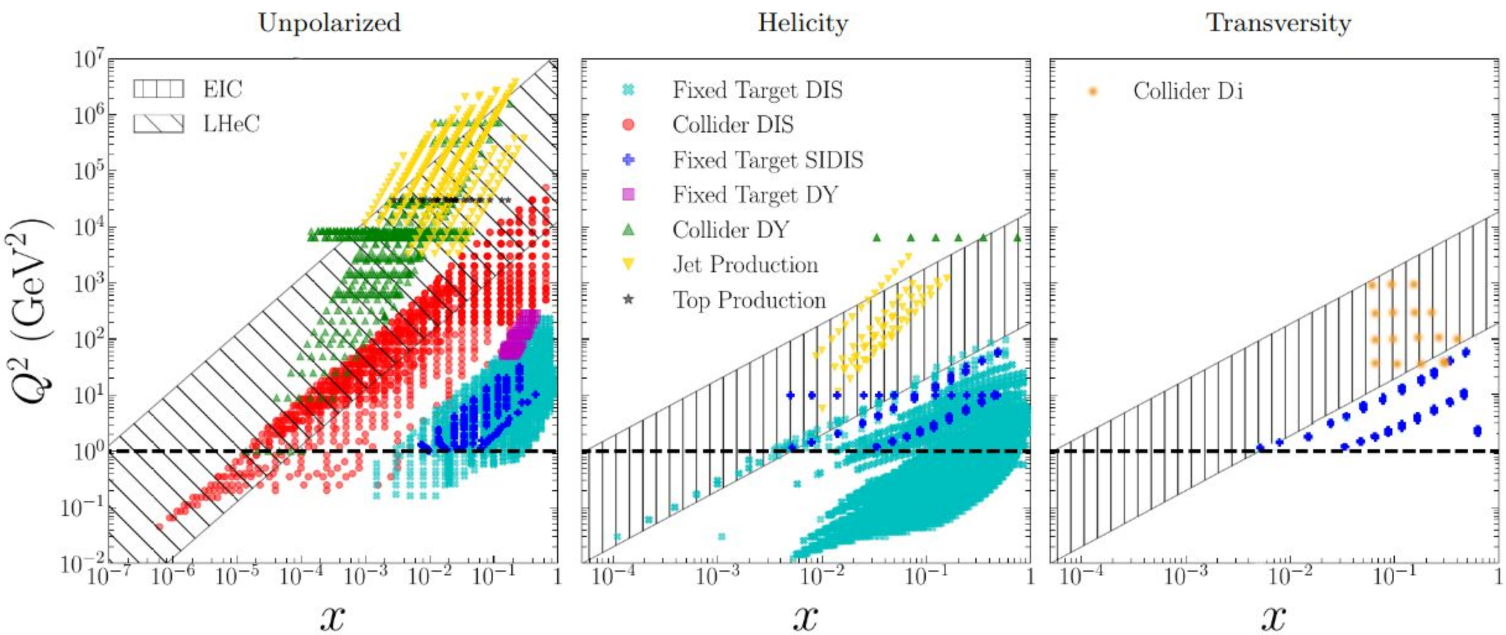


FIG. 1 The kinematic coverage in the (x, Q^2) plane of the hadronic cross-section data for the processes commonly included in global QCD analyses of collinear unpolarized, helicity, and transversity PDFs. The extended kinematic ranges attained by the LHeC and the EIC are also displayed. See Fig. 1 of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

PDFs: what do we know

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

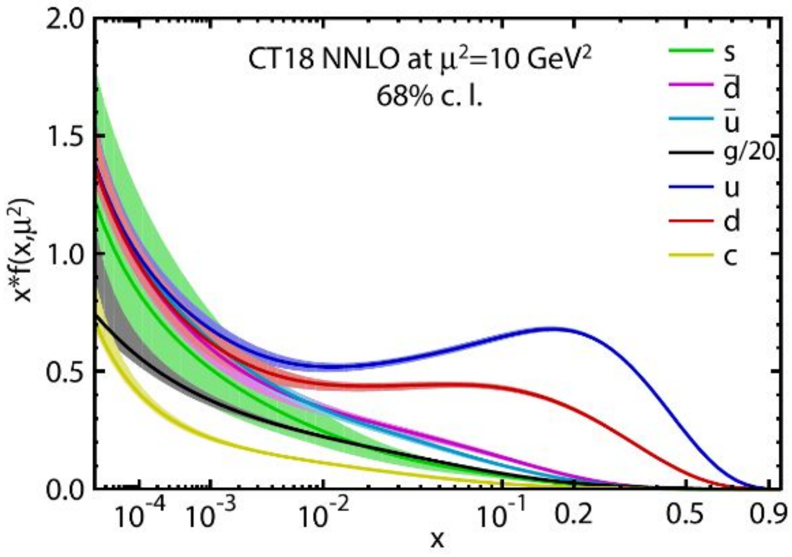


FIG. 2 The CT18 PDFs at $\mu^2 = 10$ GeV^2 for the xu, $x\bar{u}$, xd, $x\bar{d}$, $xs = x\bar{s}$, and xg PDFs. Error bands correspond to the 68% confidence level. Figure from (Kovařík *et al.*, 2019).

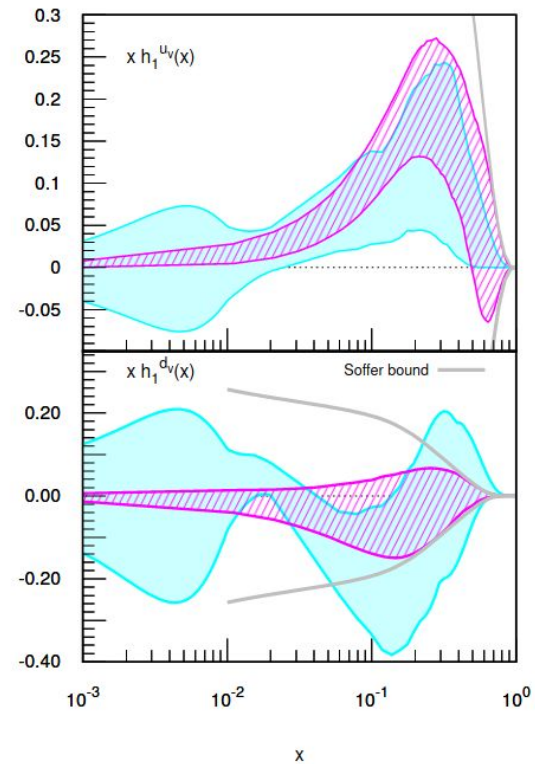


FIG. 6 The transversity $x\,h_1(x)$ at 90% CL. Upper (lower) plot for valence up (down) component. Gray lines represent the Soffer bound. Darker (pink) band for the PV18 global fit of (Radici and Bacchetta, 2018) at $Q^2 = 2.4$ GeV^2. Lighter (cyan) band for the MEX19 constrained analysis of (Benel *et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

Impact studies: helicity

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

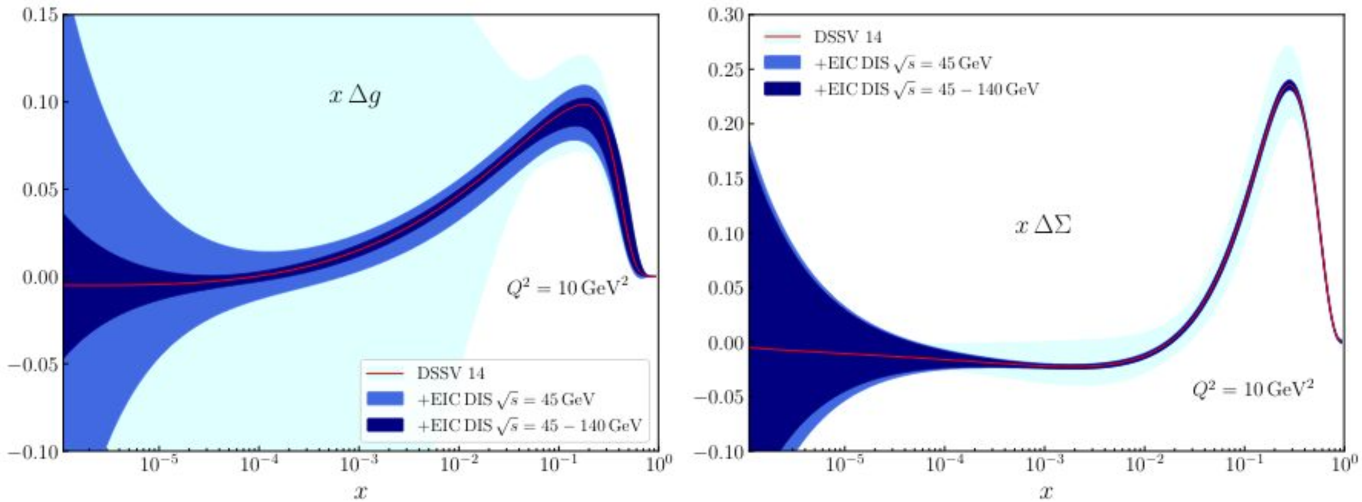


Figure 7.12: Impact of the projected EIC A_{LL} pseudoda on the gluon helicity (left panel) and quark singlet helicity (right panel) distributions as a function of x for $Q^2 = 10\,\mathrm{GeV}^2$. In addition to the DSSV14 estimate (light-blue), the uncertainty bands resulting from the fit including the $\sqrt{s} = 45$ GeV DIS pseudodata (blue) and, subsequently, the reweighting with $\sqrt{s} = 140$ GeV pseudodata (dark blue), are also shown.

Helicity PDF

Impact studies: helicity

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

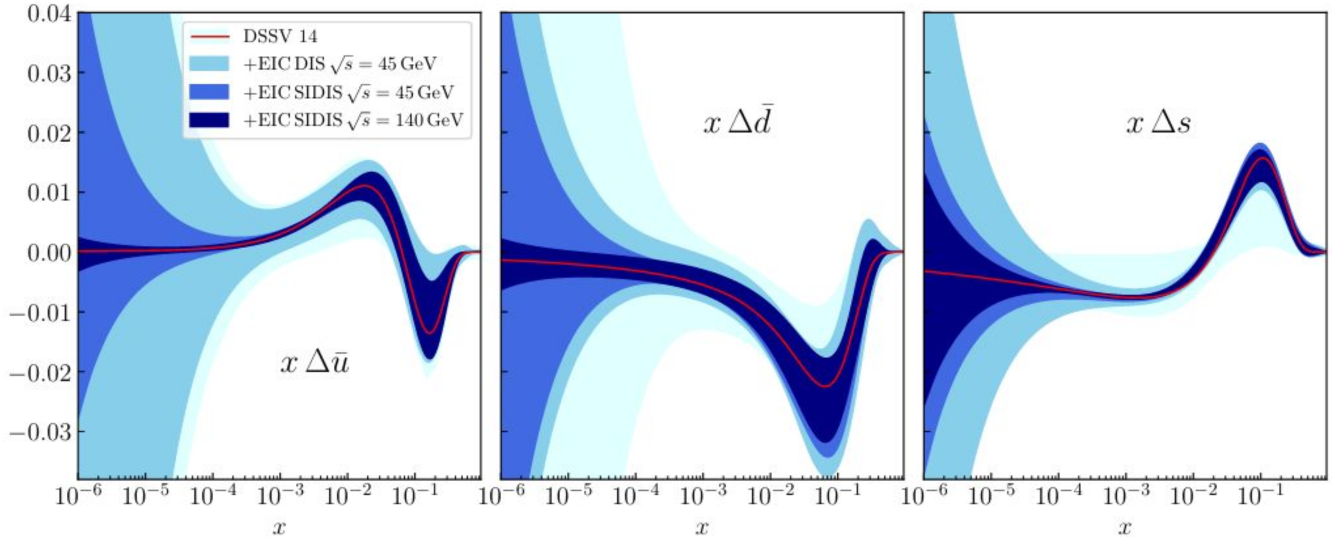
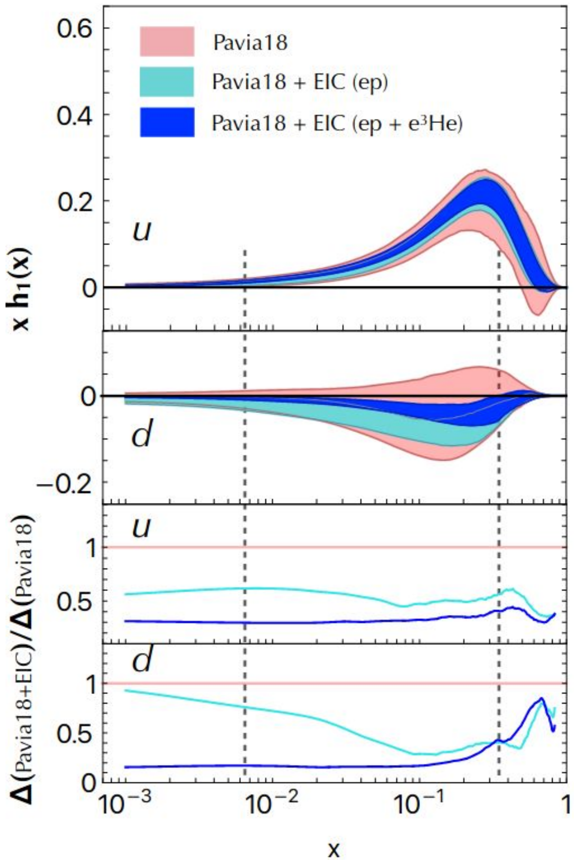


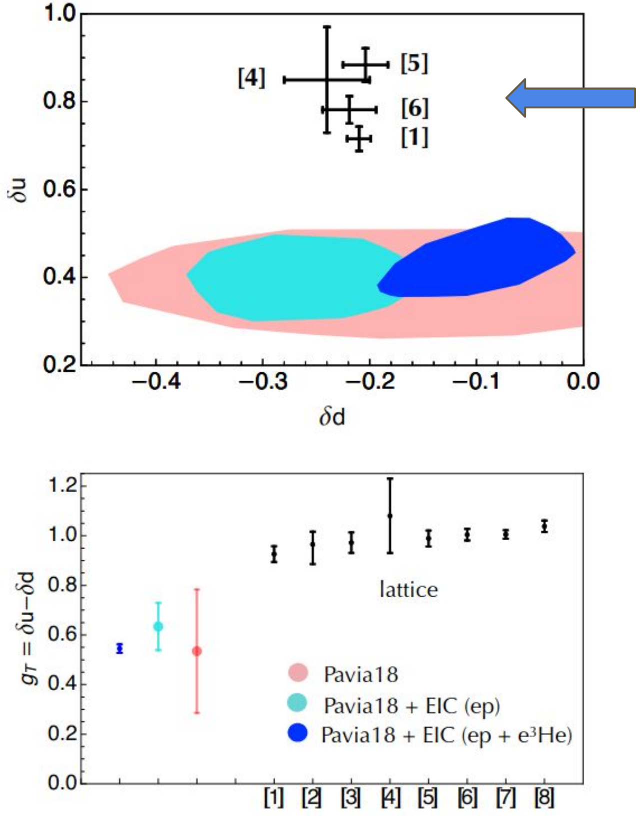
Figure 7.19: Impact of SIDIS measurements at the EIC on the sea quark helicities $x\Delta\bar{u}$, $x\Delta\bar{d}$ and $x\Delta s$ as a function of x at $Q^2 = 10\ \text{GeV}^2$.

Helicity PDF

Impact studies: transversity

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

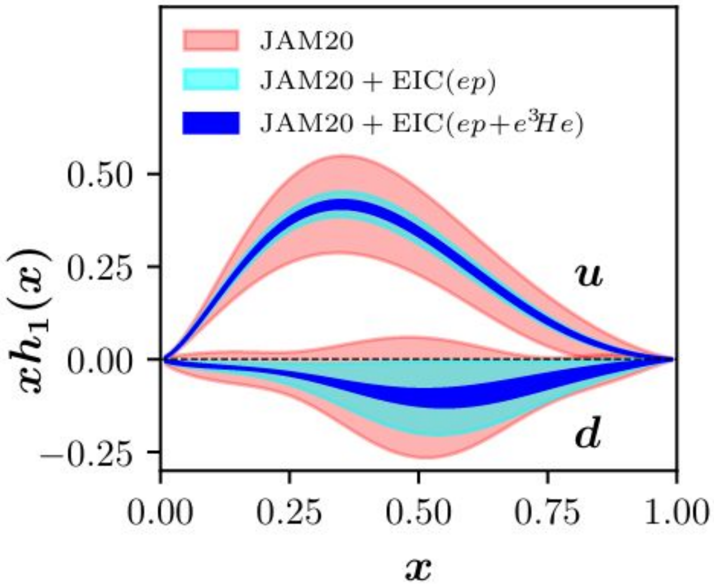


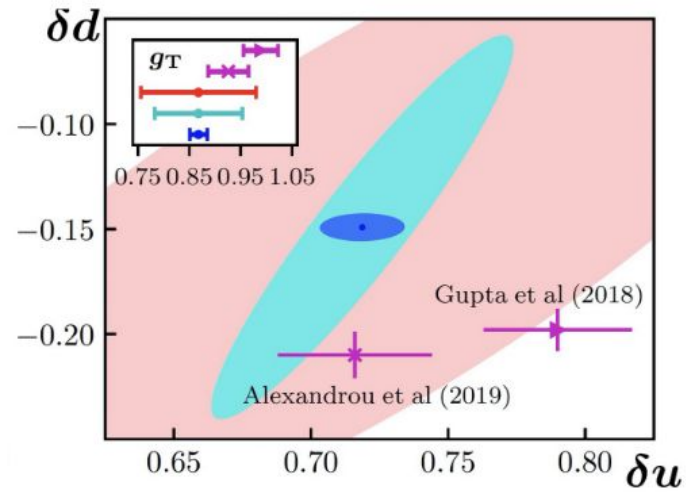


Transversity PDF and tensor charge: fit of EIC pseudo-data

Impact studies: transversity

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





Transversity PDF and tensor charge: fit of EIC pseudo-data

Impact studies: unpolarized

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

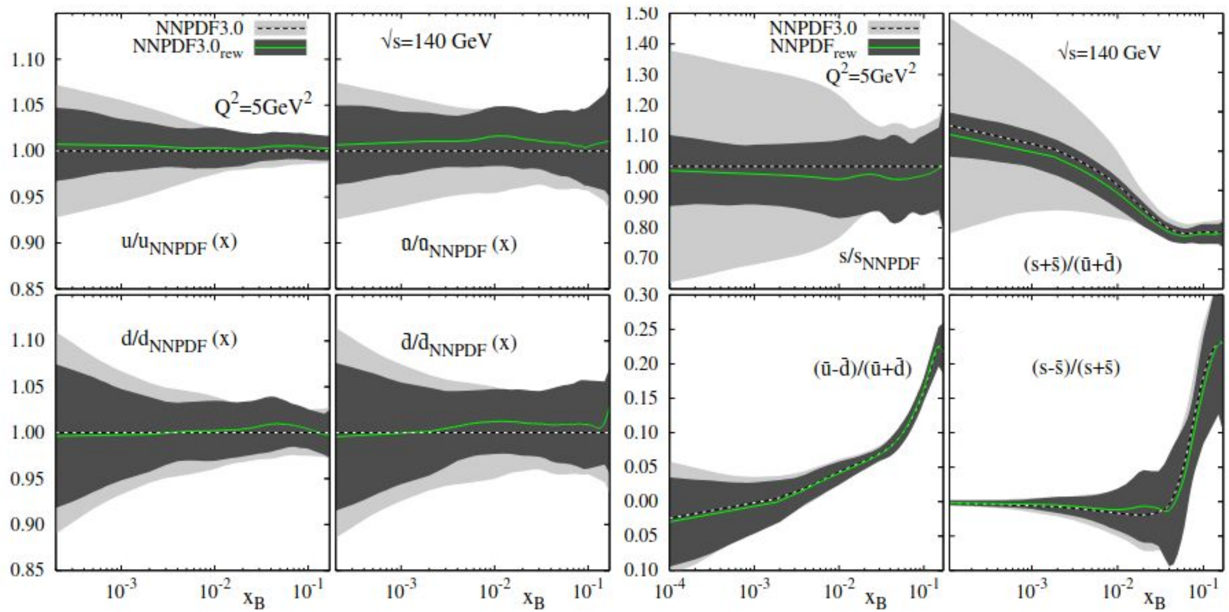


Figure 7.8: Expected impact on the unpolarized (sea) quark PDFs when adding SIDIS information from pions and kaons in *ep* collisions. The baseline NNPDFs were take from Ref. [79].

Reweighting technique: https://inspirehep.net/literature/1722245

Unpolarized TMDs

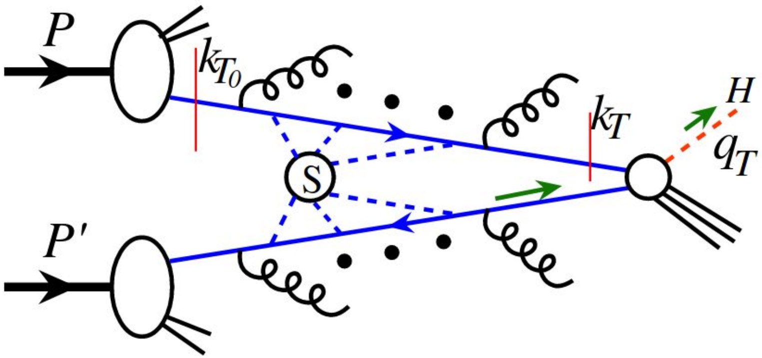
TMD factorization

$$pp \longrightarrow \gamma^{\cdot} \,/\, Z \longrightarrow l\,\bar{l} + X$$

$$\frac{d\sigma}{dq_T} \sim \mathcal{H}\, f_1(x_a, k_{T\,a}, Q, Q^2)\, f_1(x_b, k_{T\,b}, Q, Q^2)\, \delta^{(2)}(q_T - k_{T\,a} - k_{T\,b})$$

$$q_T \ll Q$$

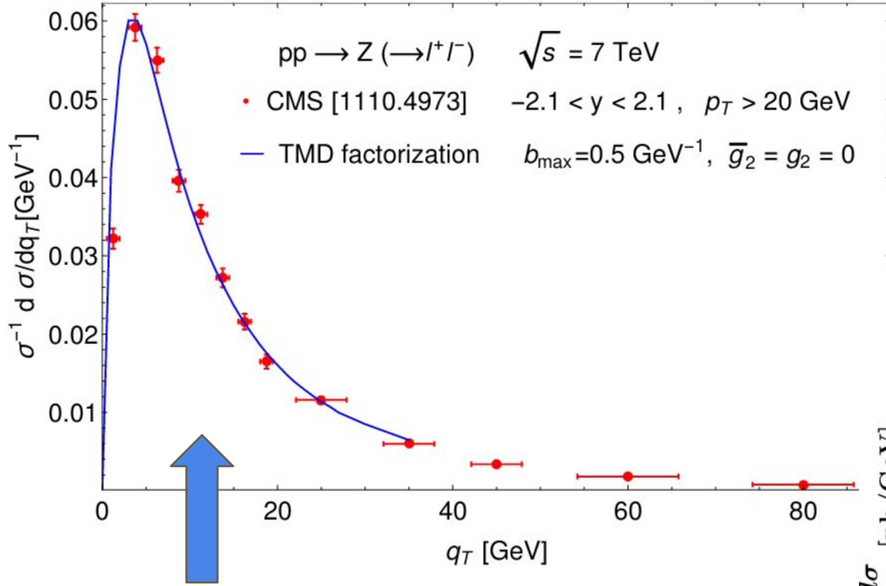
- The TMDs reproduce the structure of the **IR poles** in the cross section (same non-perturbative physics)
- The **observed transverse momentum** is accounted for by the transverse momenta of **quarks**
- The quark transverse momentum has **radiative** (perturbative) and **intrinsic** (non-perturbative) components
- Renormalization = **evolution** equations tell us how to distinguish between the two



TMD region: low transverse momentum

$q_T \ll Q$

https://inspirehep.net/literature/1785810

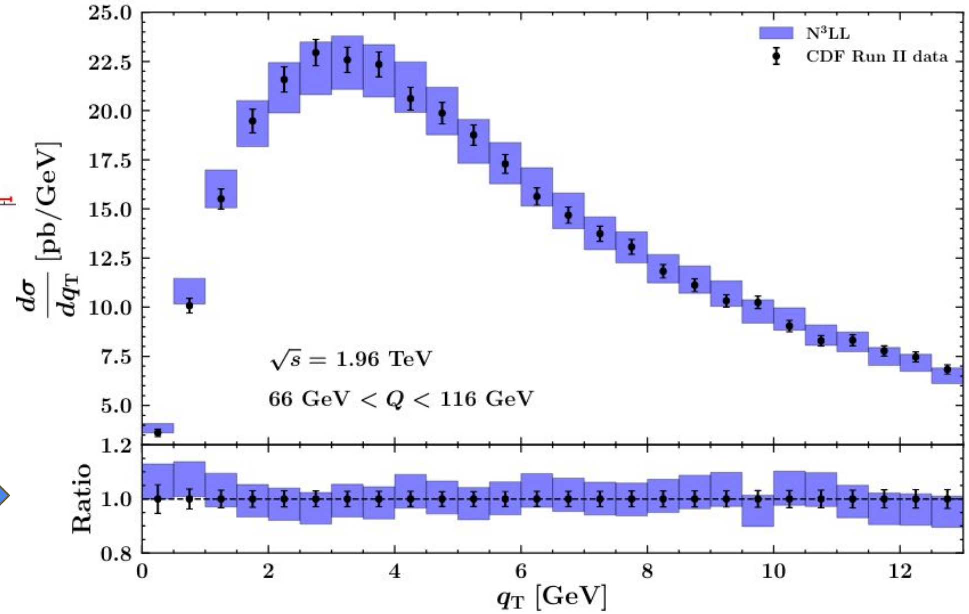


$$q_T \,/\, Q \;<\; 0.3$$

Hadronic collisions

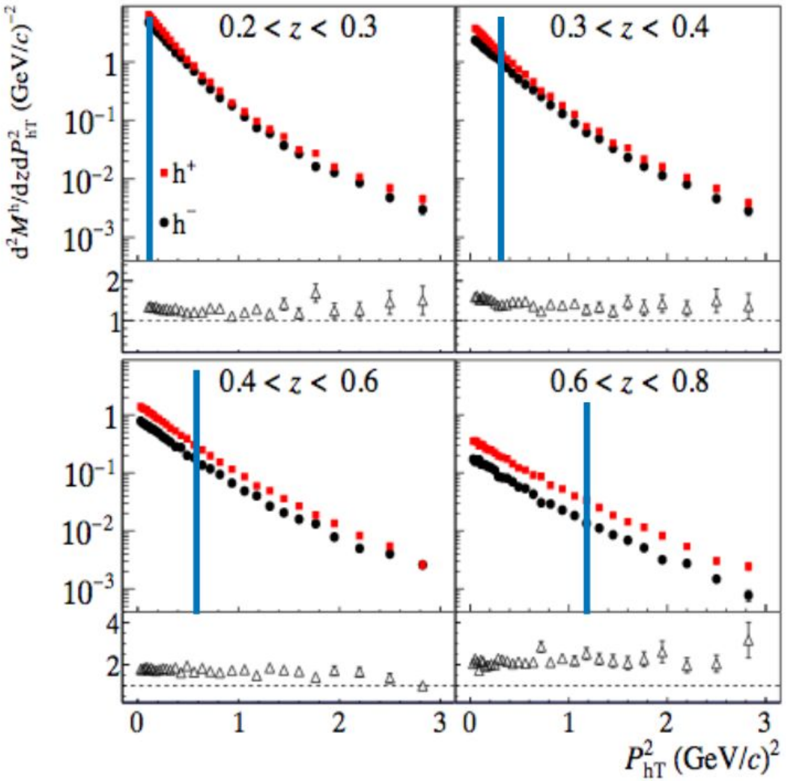
https://inspirehep.net/literature/1771006

$$q_T \,/\, Q \;<\; 0.2$$



TMD region: low transverse momentum

$q_T \ll Q$



SIDIS - TMD region

$P_{hT}^2/z^2 \ll Q^2$

Let's highlight

$P_{hT}^2/z^2 \sim 0.25\ Q^2$

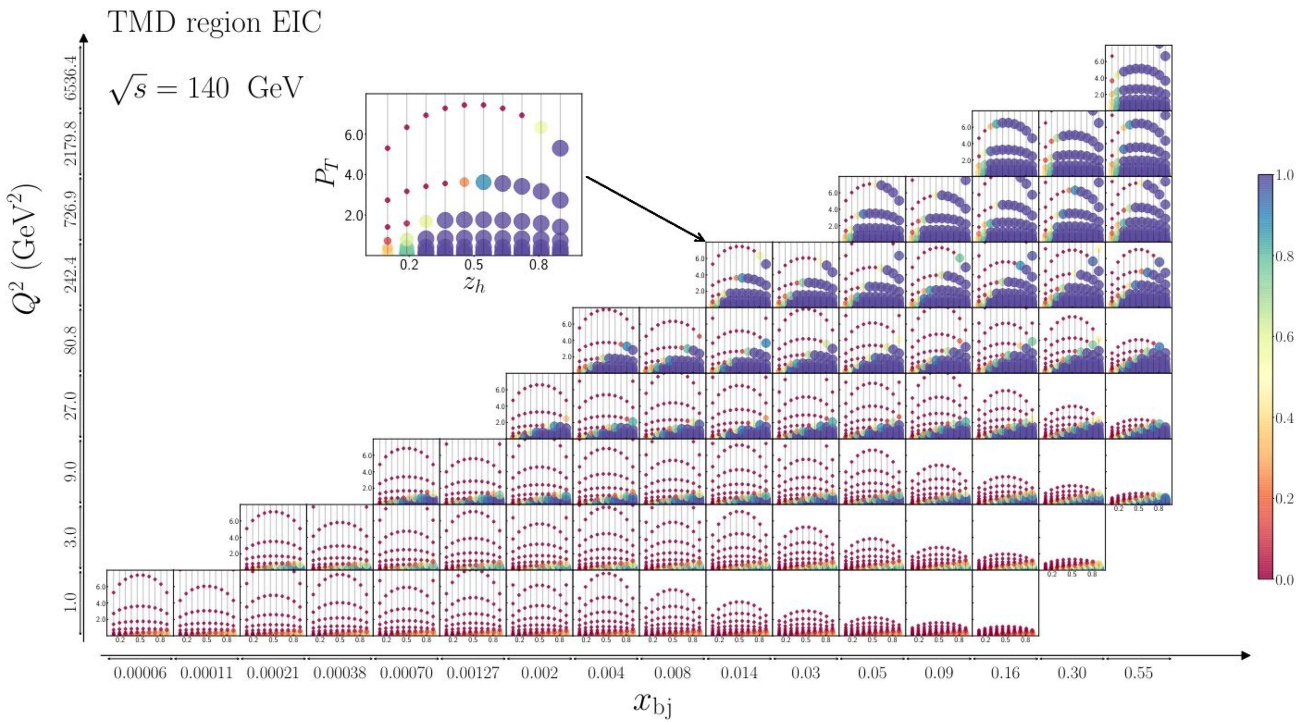
One of the bins with highest Q:

$$\langle Q^2 \rangle = 9.78\ \mathrm{GeV}^2$$
$$\langle x \rangle = 0.149$$

COMPASS unpolarized SIDIS multiplicities - arxiv 1709.07374

TMD region: low transverse momentum

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



"Affinity" with TMD region

Importance of EIC:

Extended kinematic ranges compared to existing facilities:
more data in the TMD region and **better separation of fragmentation regions**

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.)

A selection of recent fits

	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

Unpolarized TMDs: SV19

see https://inspirehep.net/literature/1770788

Extraction from **SIDIS** (Hermes, Compass) **and Drell-Yan** data (Phenix, fixed-target at Fermilab, CDF, DO, ATLAS, CMS, LHCb)

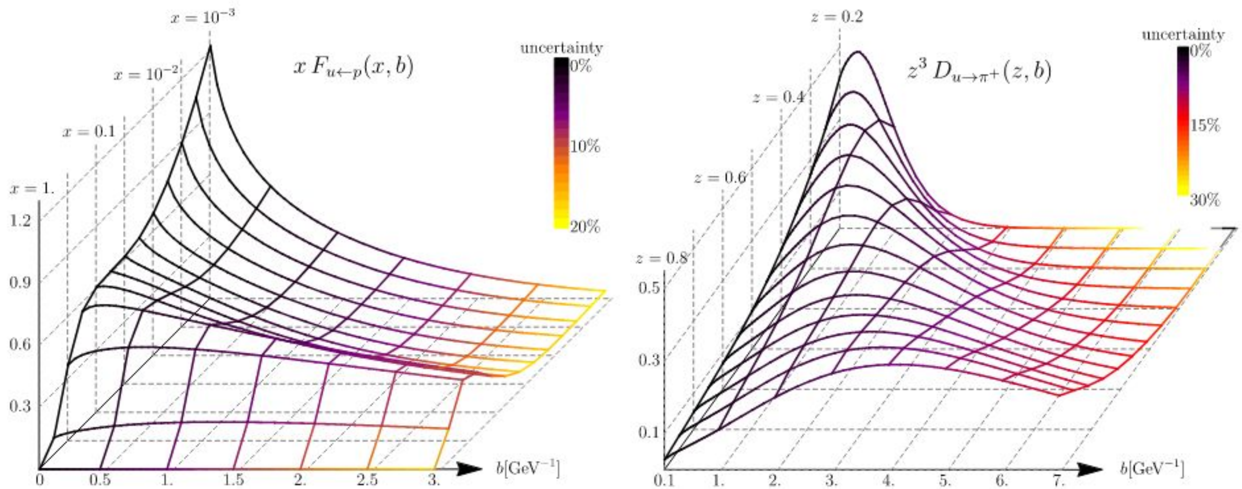


Figure 24. Example of extracted (optimal) unpolarized TMD distributions. The color indicates the relative size of the uncertainty band

TMD impact studies: SV19

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

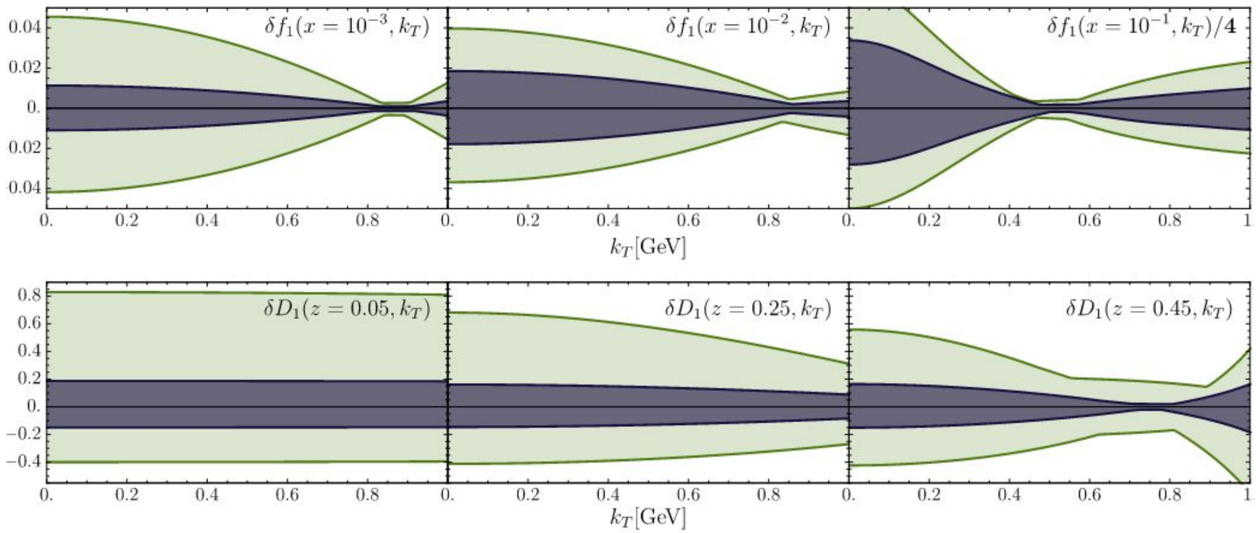


Figure 7.52: Comparison of relative uncertainty bands (i.e. uncertainties normalized by central value) for up-quark unpolarized TMD PDFs (upper panel) and $u \to \pi^+$ pion TMD FFs (lower panel), at different values of x and z as a function of k_T, for $\mu = 2$ GeV. Lighter band is the SV19 extraction, darker is SV19 with EIC pseudodata.

Up in proton
TMD PDF

Up to pion+
TMD FF

Fit with EIC pseudo-data

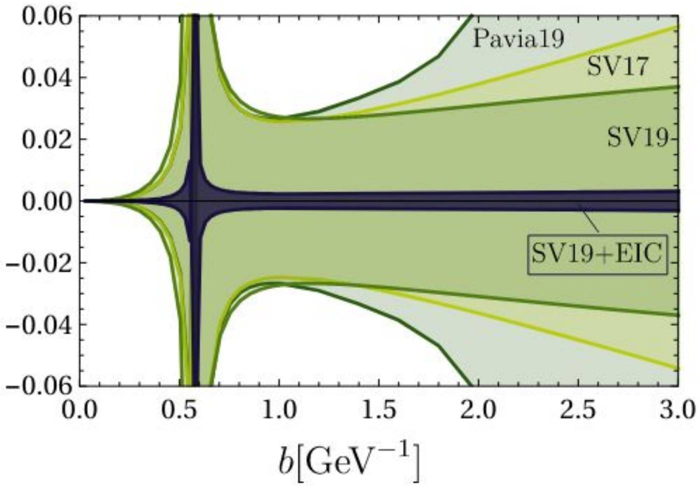
TMD impact studies: SV19

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

$$\left(\frac{\zeta}{\zeta_0}\right)^{-D(b_T\mu_0,\alpha_s(\mu_0))\,+\,g_K(b_T;\lambda)}$$

→ evolution in ζ

Non-pert. corrections (large bT)



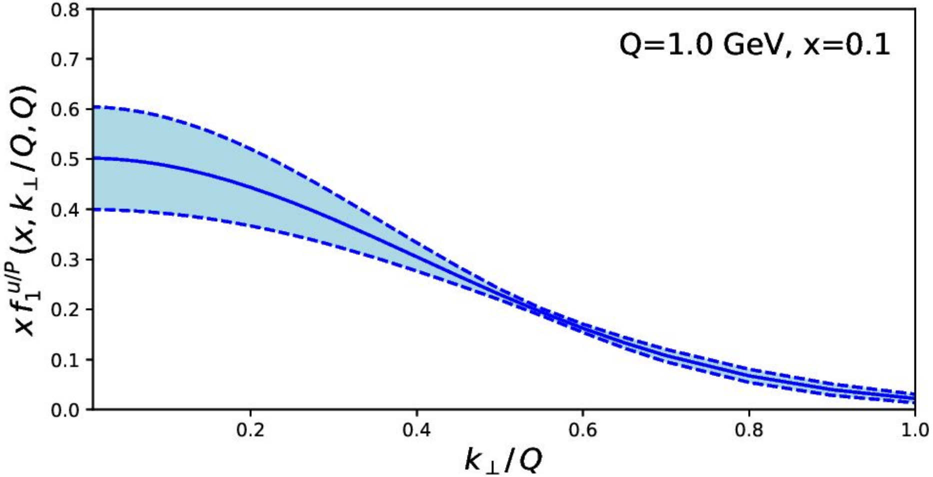
Typically a function of bT^2 with one or two parameters (with variations of course)

Huge impact of EIC SIDIS program on **non-perturbative TMD evolution**

Unpolarized TMDs: PV17

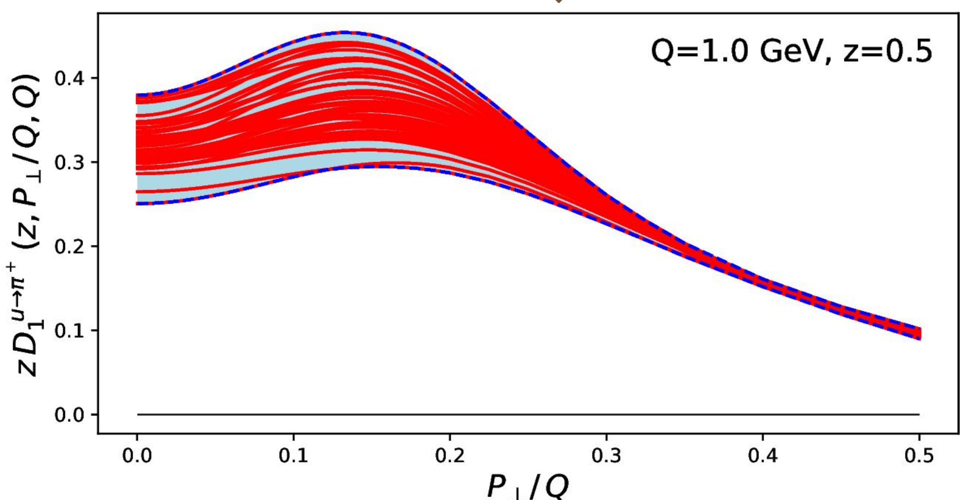
see https://inspirehep.net/literature/1520011

Imaging from **SIDIS** (Hermes and Compass) **and Drell-Yan** data (ixed-target at Fermilab, CDF, DO)



Unpolarized TMD PDF

Unpolarized TMD FF



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

See https://inspirehep.net/literature/1520011

TMD impact studies: PV17

200 replicas are compared with pseudodata

$$\chi_k^2 = \chi_{k,\mathrm{EIC}}^2 + \chi_{k,\mathrm{PV17}}^2$$

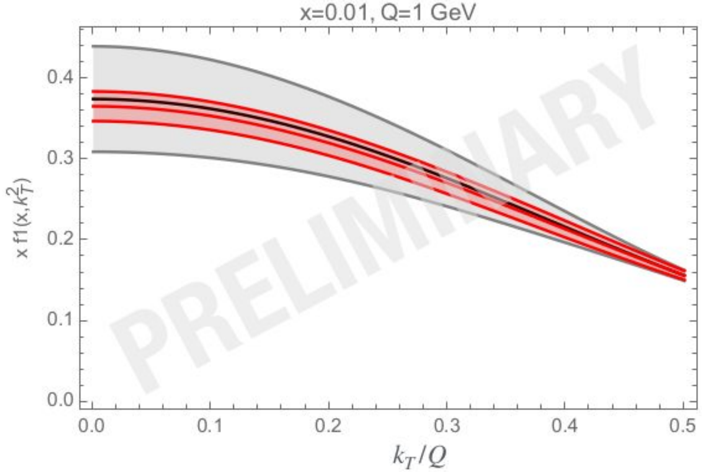
'original' χ^2 with respect to PV17 data

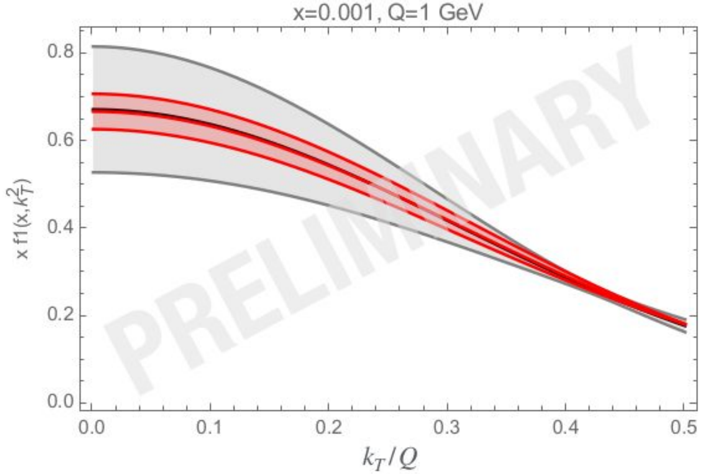
weights

$$w_k \propto \mathcal{P}(f_k|\chi_k) \propto \chi_k^{n-1} e^{-\frac{1}{2}\chi_k^2}$$

Reweighting technique (no fit of EIC pseudo-data)

(see C. Bissolotti's talk at DIS 2021)



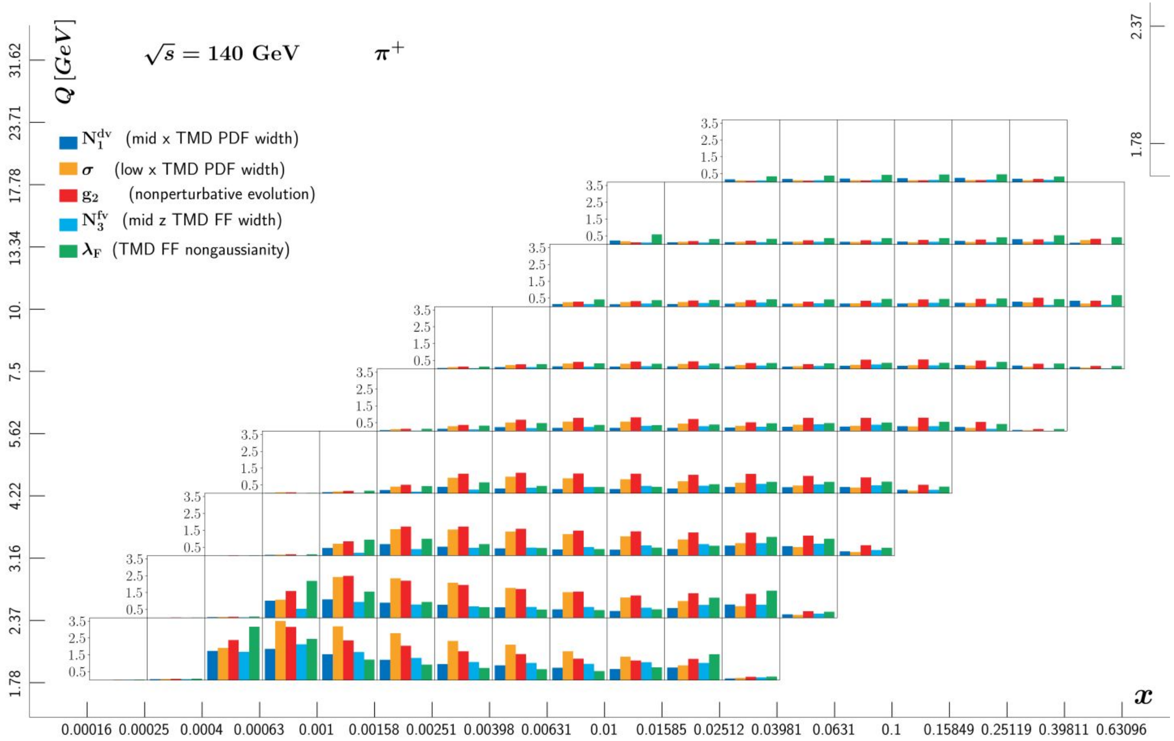


TMD impact studies: PV17

(see C. Bissolotti's talk at DIS 2021)

$$S[f_i,\mathcal{O}] = \frac{\langle \mathcal{O}\cdot f_i\rangle - \langle \mathcal{O}\rangle\langle f_i\rangle}{\delta\mathcal{O}\Delta f_i}$$

O: e.g. a SIDIS structure function
fi : the non-perturbative TMD parameters



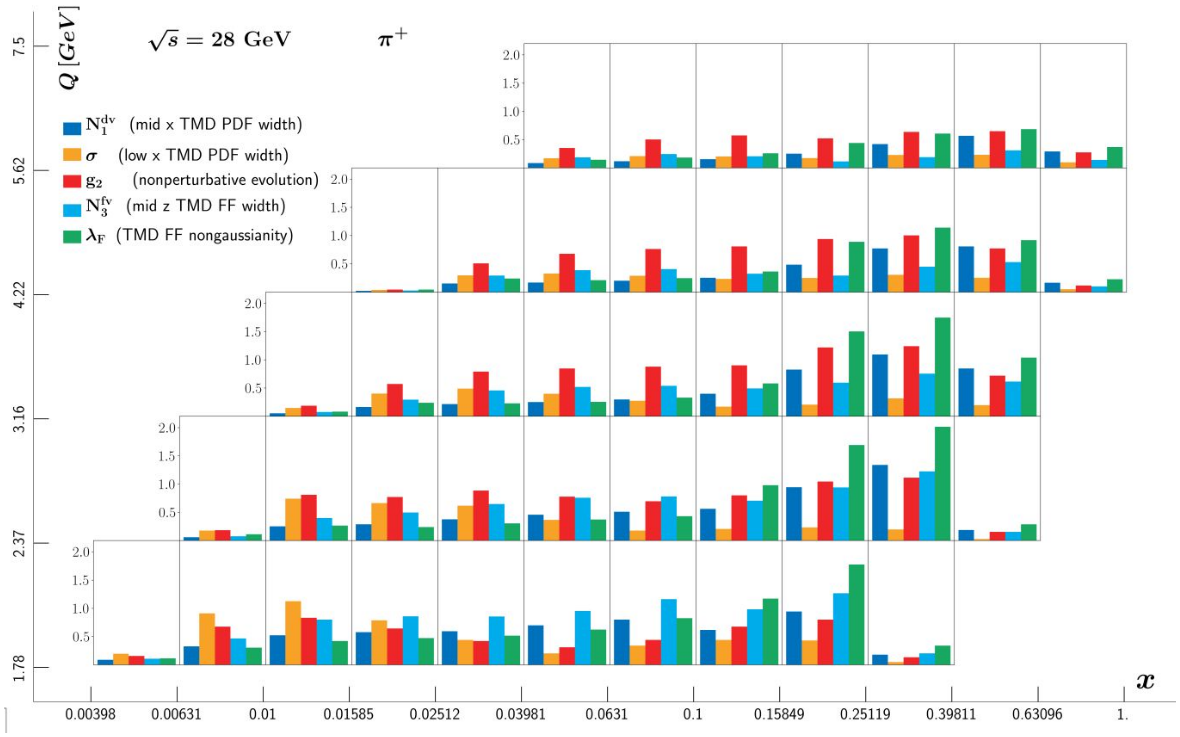
$\sqrt{s} = 140$ GeV

TMD impact studies: PV17

(see C. Bissolotti's talk at DIS 2021)

$$S[f_i, \mathcal{O}] = \frac{\langle \mathcal{O} \cdot f_i \rangle - \langle \mathcal{O} \rangle \langle f_i \rangle}{\delta \mathcal{O} \Delta f_i}$$

O: e.g. a SIDIS structure function
fi : the non-perturbative TMD parameters



$\sqrt{s} = 28$ GeV

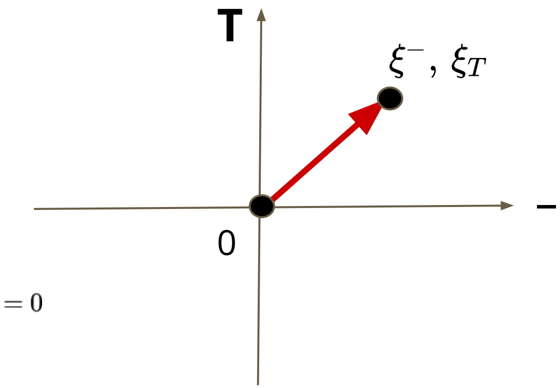
Stronger effect at lower energies

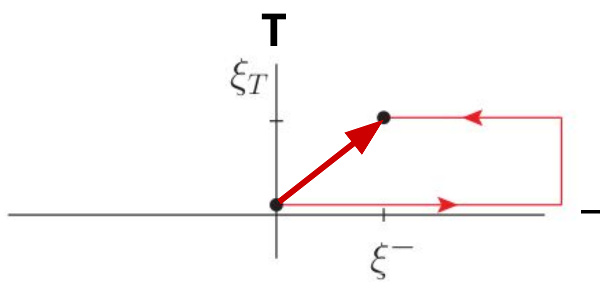
Polarized TMDs

Wilson lines for TMD PDFs

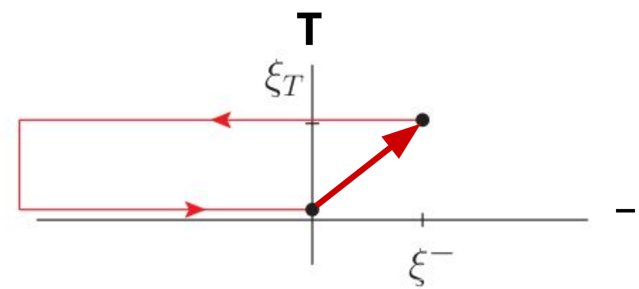
$$\Phi_{ij}^{[U]}(x,\, \mathbf{p}_T, S) \;=\; \int dp^+\, dp^-\, \delta\big(p^+ \;-xP^+\big)\,\Phi^{[U]}(p,P,S) =$$

$$= \int \frac{d\xi^-\, d^2\xi_T}{2\pi}\; e^{i\,p\cdot\xi}\, \langle PS \big|\, \overline{\psi}_j(0)\, U(0,\xi)\, \psi_i(\xi)\, \big| PS\rangle_{\,\xi^+=0}$$





$U^{[+]}$ Future pointing (SIDIS)

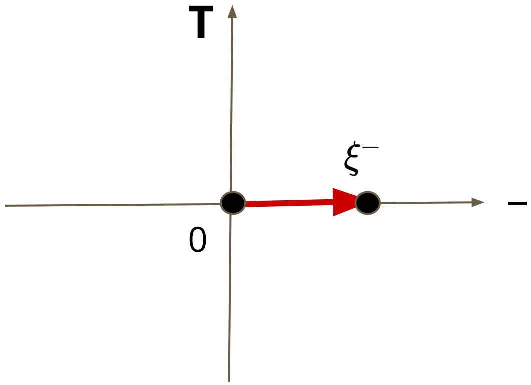


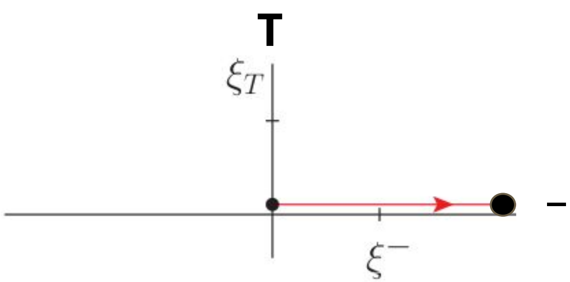
$U^{[-]}$ Past pointing (Drell-Yan)

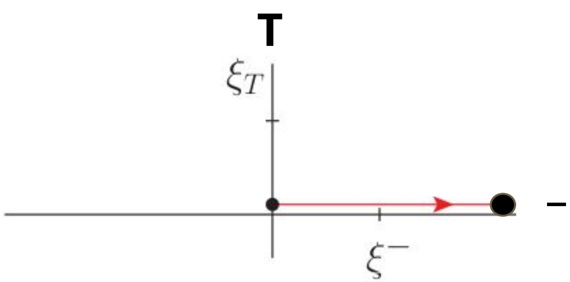
Wilson lines for collinear PDFs

$$\Phi_{ij}^{[U]}(x,S) = \int dk^+\,dk^-\,d^2\mathbf{k}_T\,\delta\big(k^+ - xP^+\big)\Phi^{[U]}(k,P,S) =$$

$$= \int \frac{d\xi^-}{2\pi}\, e^{i\,k\cdot\xi}\,\langle PS\big|\,\overline{\psi}_j(0)\,U(0,\xi)\,\psi_i(\xi)\,\big|PS\rangle_{\,\xi^+ = \,\xi_T\,=\,0}$$







In the collinear limit the two gauge links reduce to the same object

Jet SIDIS - Sivers asymmetry

$$e\,N^{\uparrow} \longrightarrow e\,jet\,X$$

Back-to-back electron-jet production at small imbalance qT

$$q_T = \left|p_T^e + p_T^{jet}\right| \ll p_T^e \sim p_T^{jet}$$

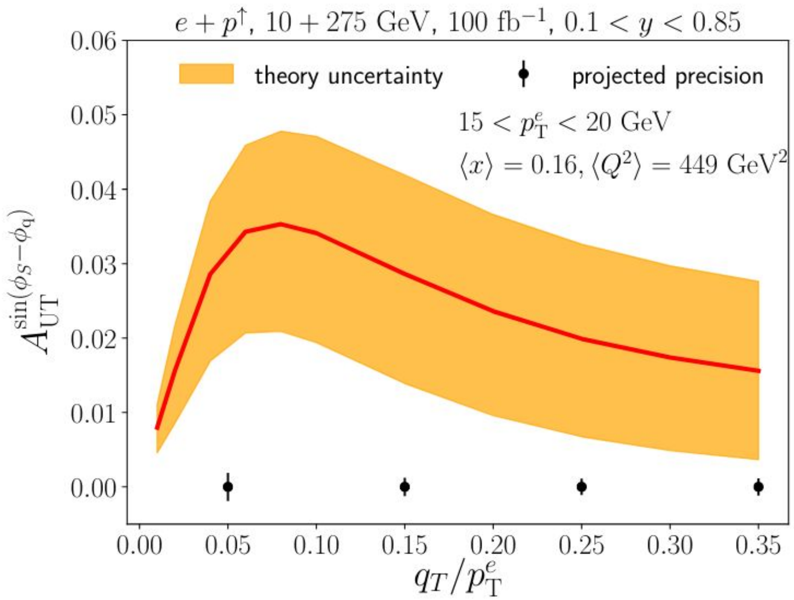
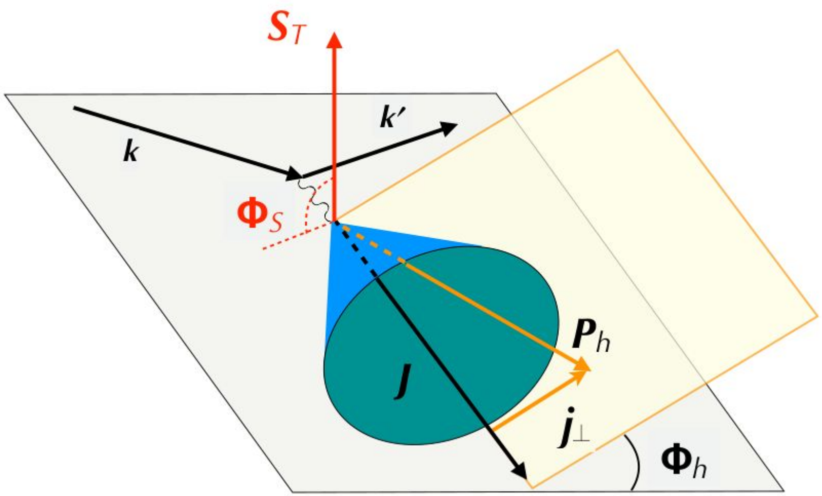


Figure 5. Theoretical result for the electron-jet asymmetry sensitive to the Sivers distribution (red). The uncertainty band (orange) displays the current uncertainty of the Sivers function of Ref. [64]. In addition, we show projections of statistical uncertainties for an EIC measurement (black error bars).

See https://inspirehep.net/literature/1806918

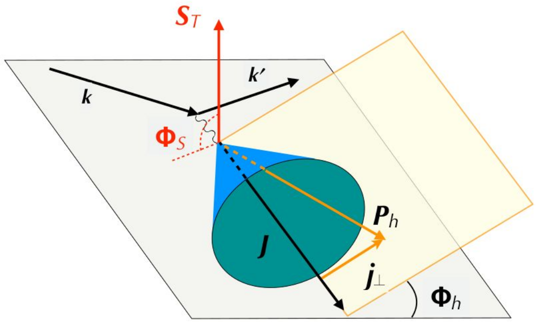
In-jet Collins TMD FF

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

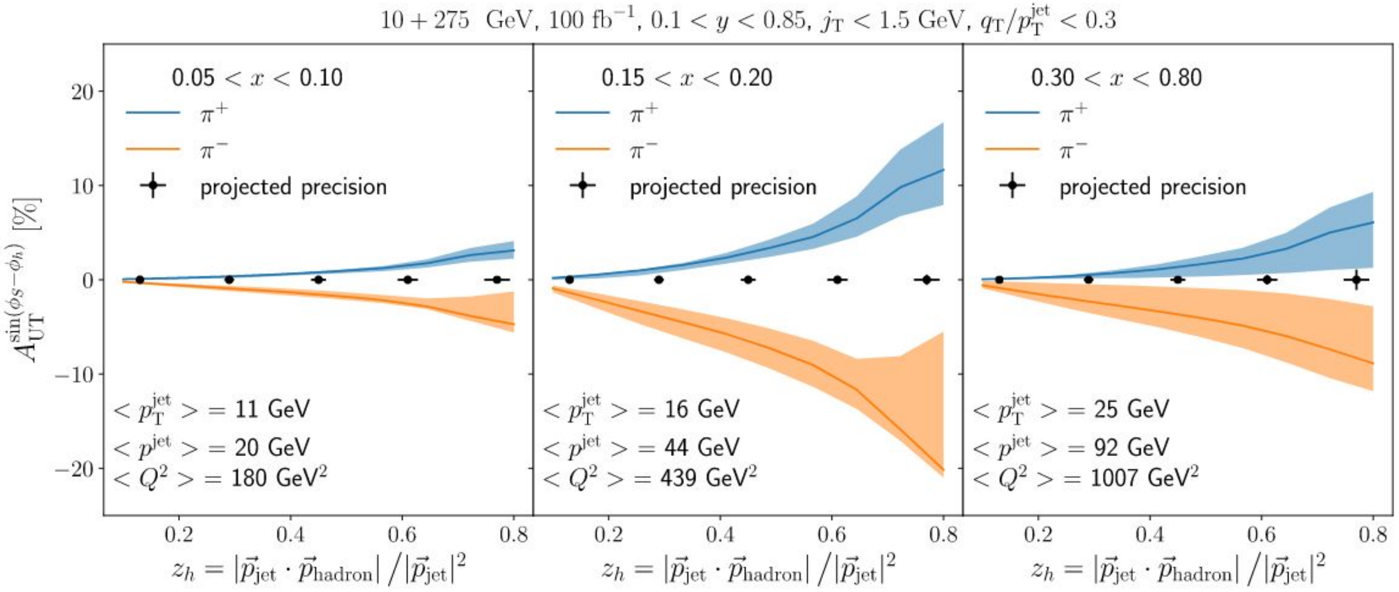


Credit picture: M. Radici

In-jet Collins TMD FF



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



See https://inspirehep.net/literature/1806918

Perspectives for the future

It's clear how the EIC will improve our understanding of (hadron) physics!

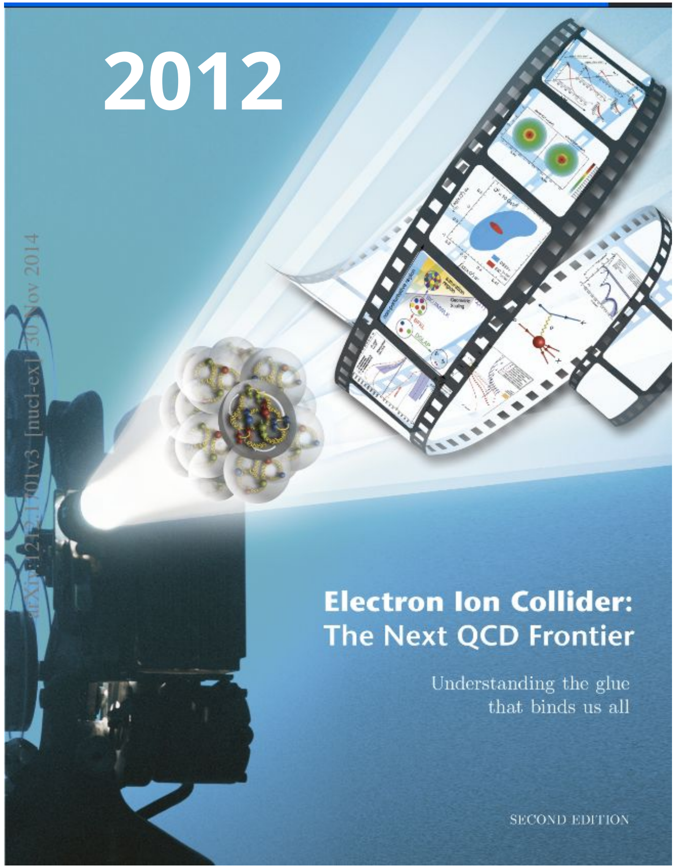
A non-exhaustive *personal* list of open questions:

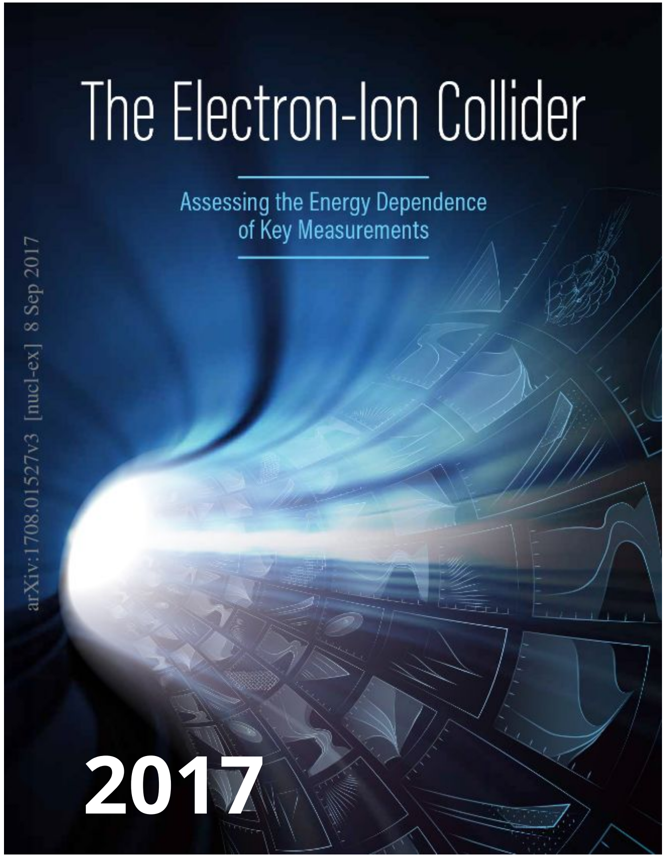
- experimental confirmation of **sign change** relation
- **Flavor** structure of TMDs
- **gluon** observables and **spin-1** effects
- what can **hadronization** teach us about **confinement**?
- interplay between **nuclear/hadron** and **high-energy** physics
  (BMS scenarios via large-x, transversity, flavor, etc.)
- ..

Backup

The Electron-Ion Collider (EIC)

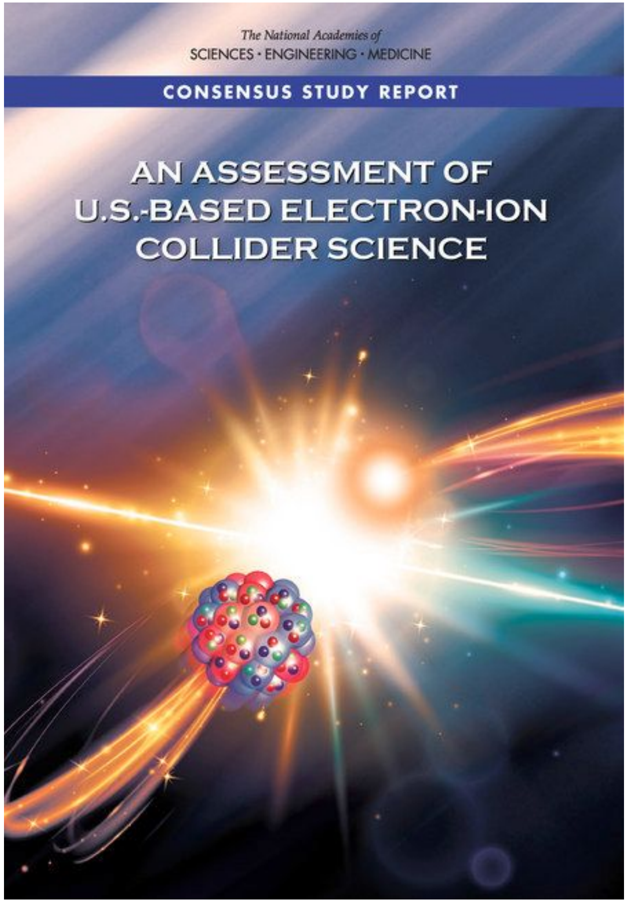
https://www.bnl.gov/eic/





The Electron-Ion Collider (EIC)

https://www.bnl.gov/eic/



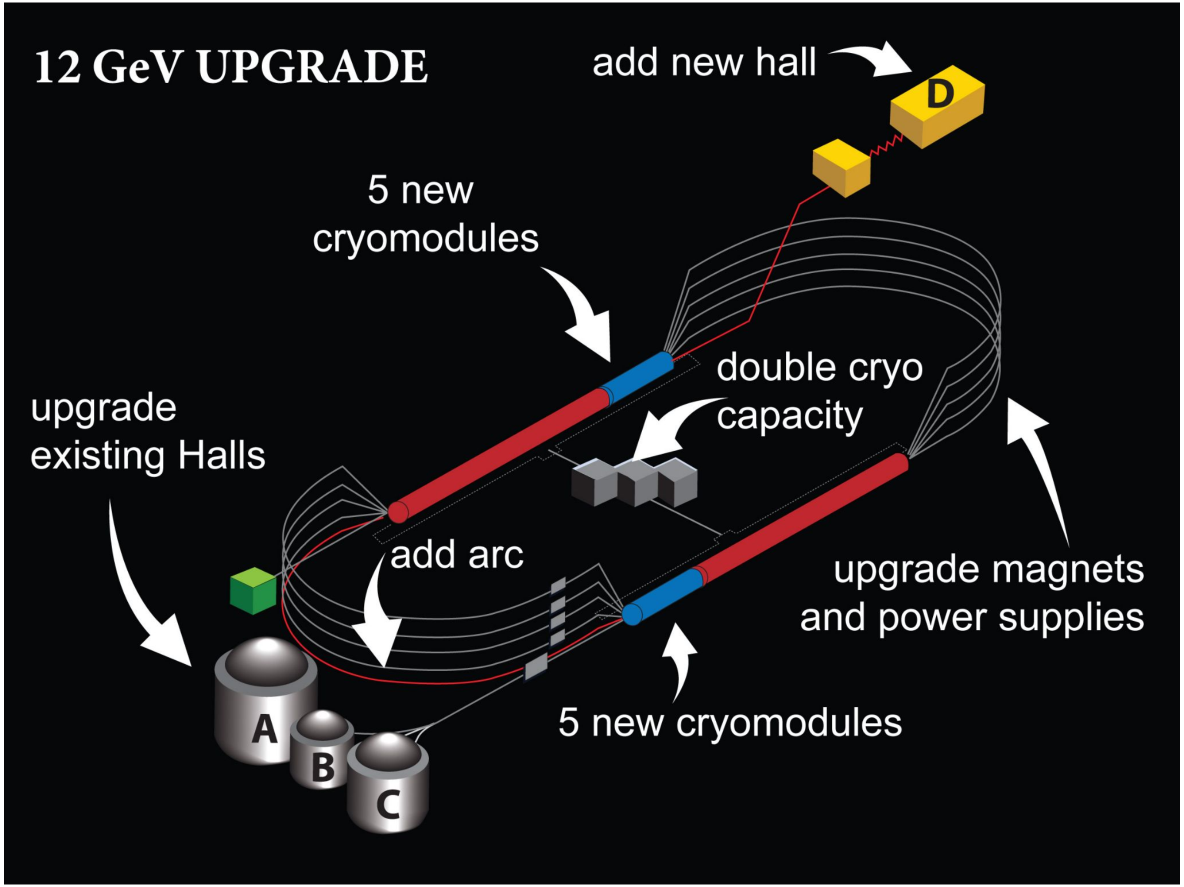
2018

2019: DoE critical decision 0

2020: site selection (BNL)

2021: DoE critical decision 1

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

Quark TMD PDFs (spin ½)

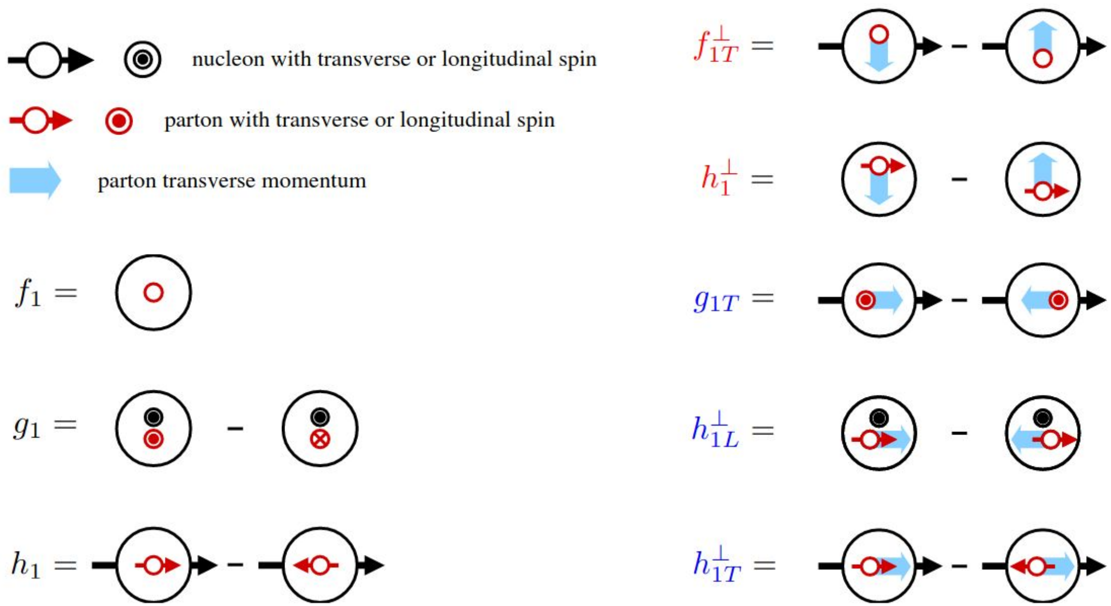
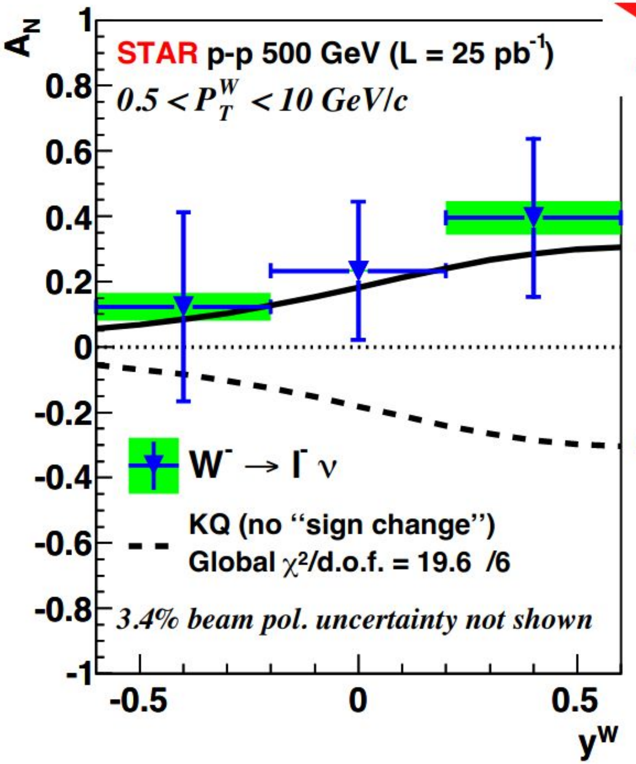


Figure 3.5: Probabilistic interpretation of twist-2 transverse-momentum-dependent distribution functions. To avoid ambiguities, it is necessary to indicate the directions of quark's transverse momemtum, target spin and quark spin, and specify that the proton is moving out of the page, or alternatively the photon is moving into the page.

From Bacchetta's "Trento" lecture notes

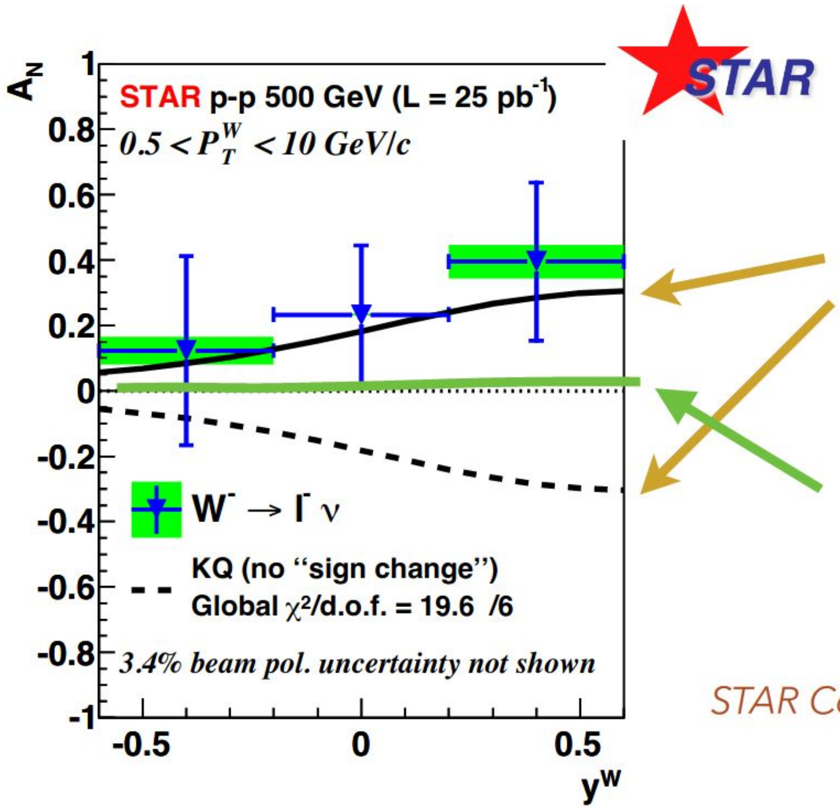
Sign-change for Sivers function



first evidence of sign change?

STAR Collab. arXiv:1511.06003

Sign-change for Sivers function

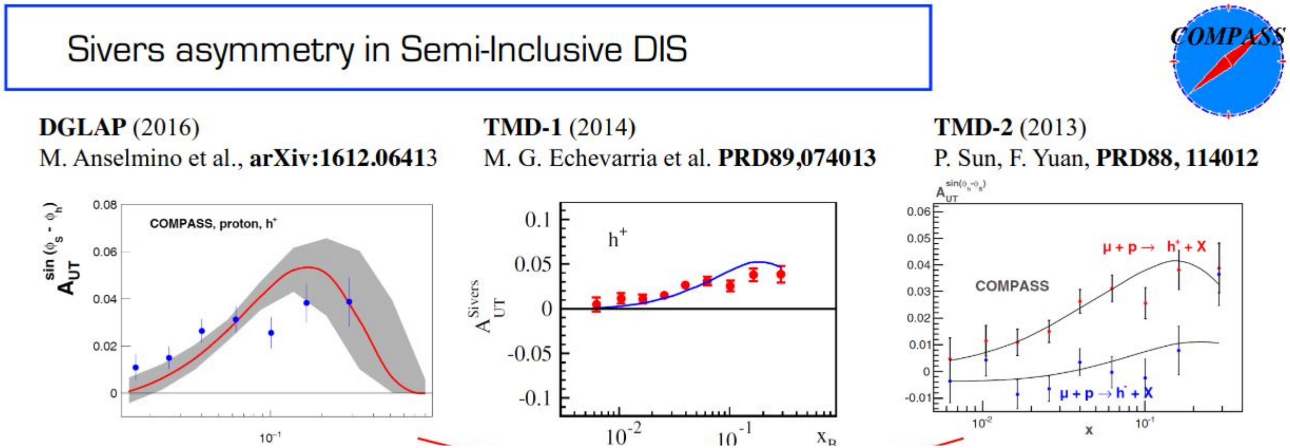


first evidence of sign change?

prediction with TMD evolution equations

STAR Collab. arXiv:1511.06003

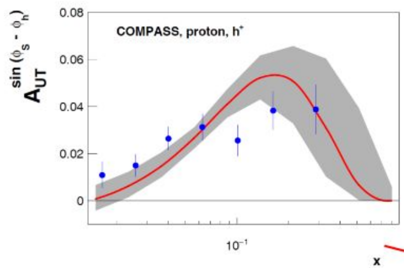
Sign-change for Sivers function



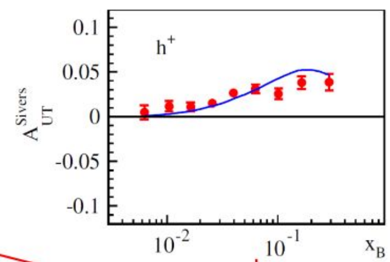
Sign-change for Sivers function

Sivers asymmetry in Semi-Inclusive DIS

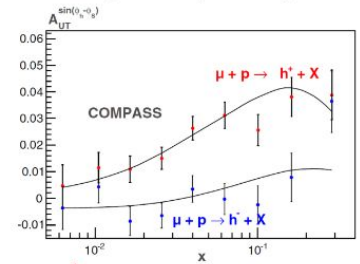
DGLAP (2016)
M. Anselmino et al., **arXiv:1612.06413**



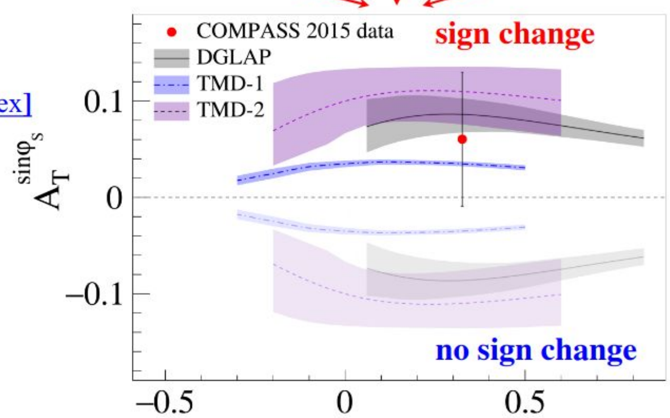
TMD-1 (2014)
M. G. Echevarria et al. **PRD89,074013**



TMD-2 (2013)
P. Sun, F. Yuan, **PRD88, 114012**



New! **03 April 2017**
COMPASS
[CERN-EP-2017-059]
[arXiv:1704.00488[hep-ex]]



Sivers asymmetry in Drell-Yan

courtesy B. Parsamyan

Higher twist

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

gT structure function in inclusive DIS (collinear twist 3 factorization)