Andrea Signori

University of Turin and INFN

EICUG Early Career workshop 2023
Warsaw, Poland - July 23

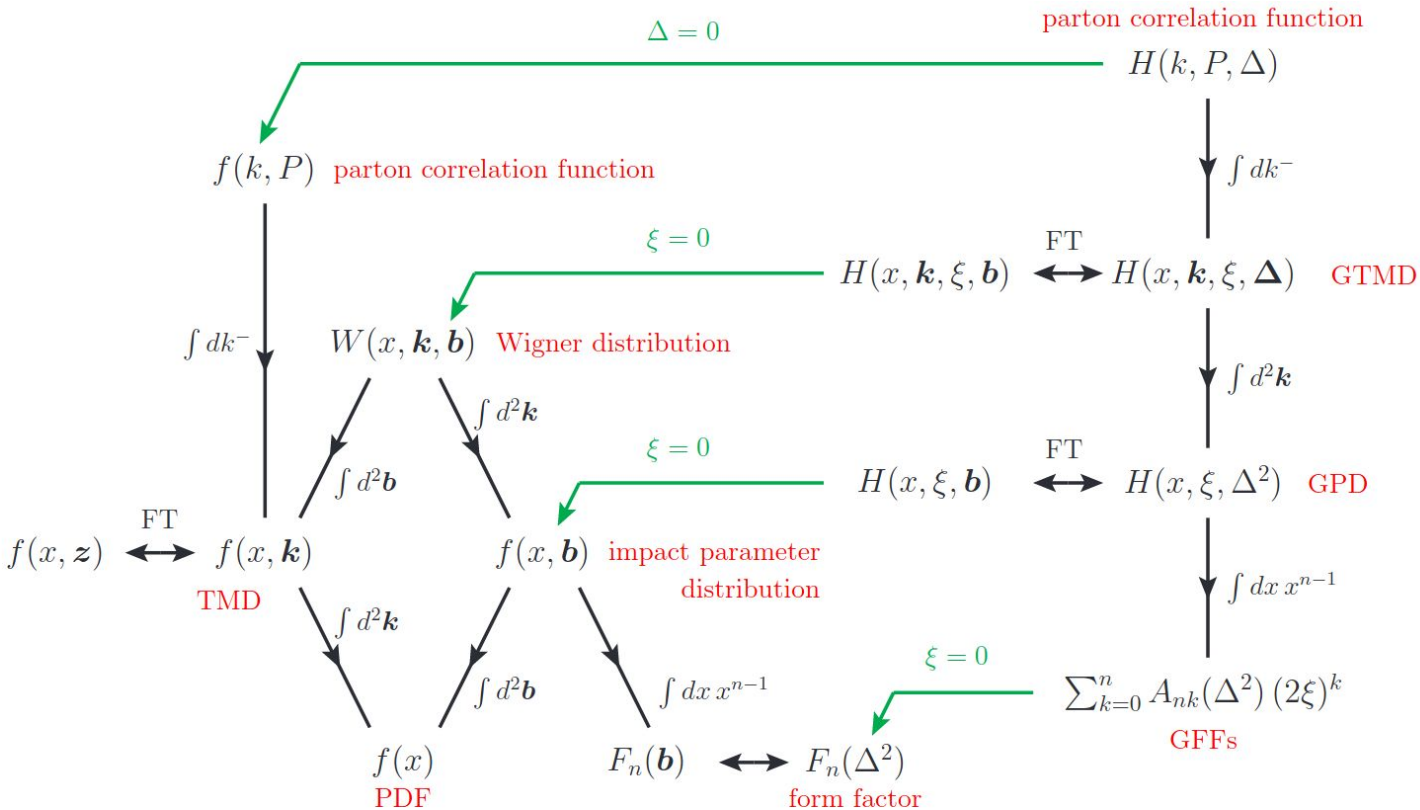
TMD phenomenology: status, future prospects, and the EIC

UNIVERSITÀ DI TORINO

INFN
Istituto Nazionale di Fisica Nucleare

Outline

1. **Theory**
2. **Experiments**
3. **Phenomenology and applications**

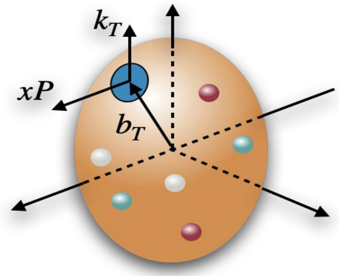


Theory

Credit picture: M. Diehl - [arXiv 1512.01328]

TMDs and GPDs

Wigner distributions

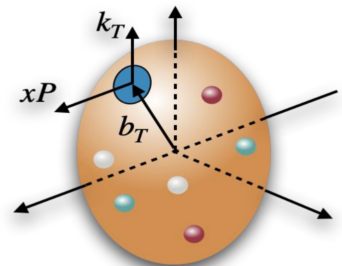


Position and momentum of partons

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

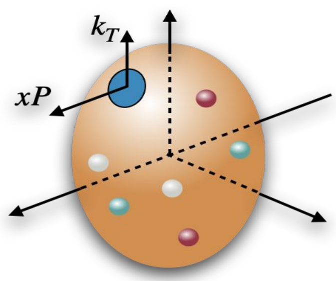
TMDs and GPDs

Wigner distributions



Position and momentum of partons

TMDs



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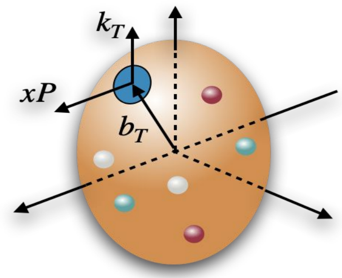

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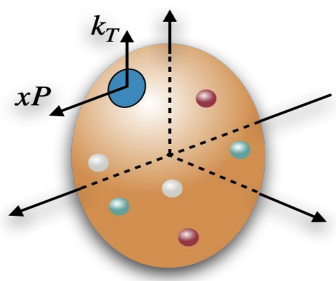
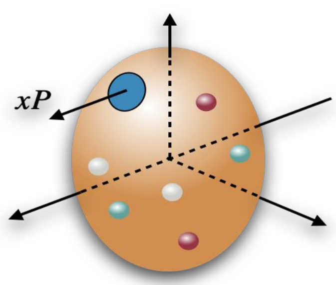


PDFs



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TMDs and GPDs

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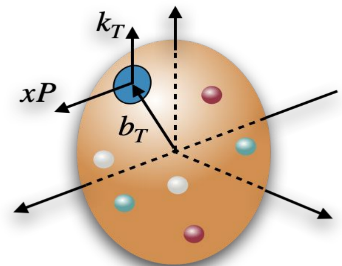
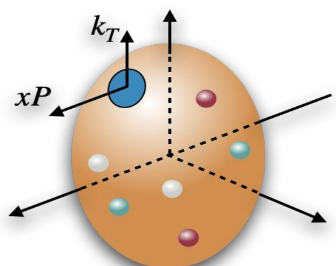
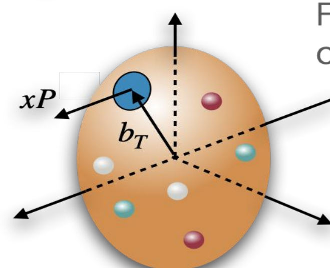


Position and momentum of partons

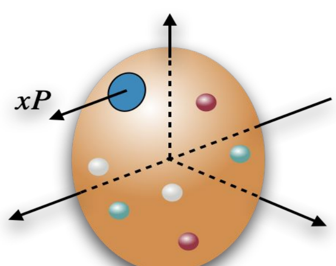
TMDs





Fourier transform of GPDs

PDFs

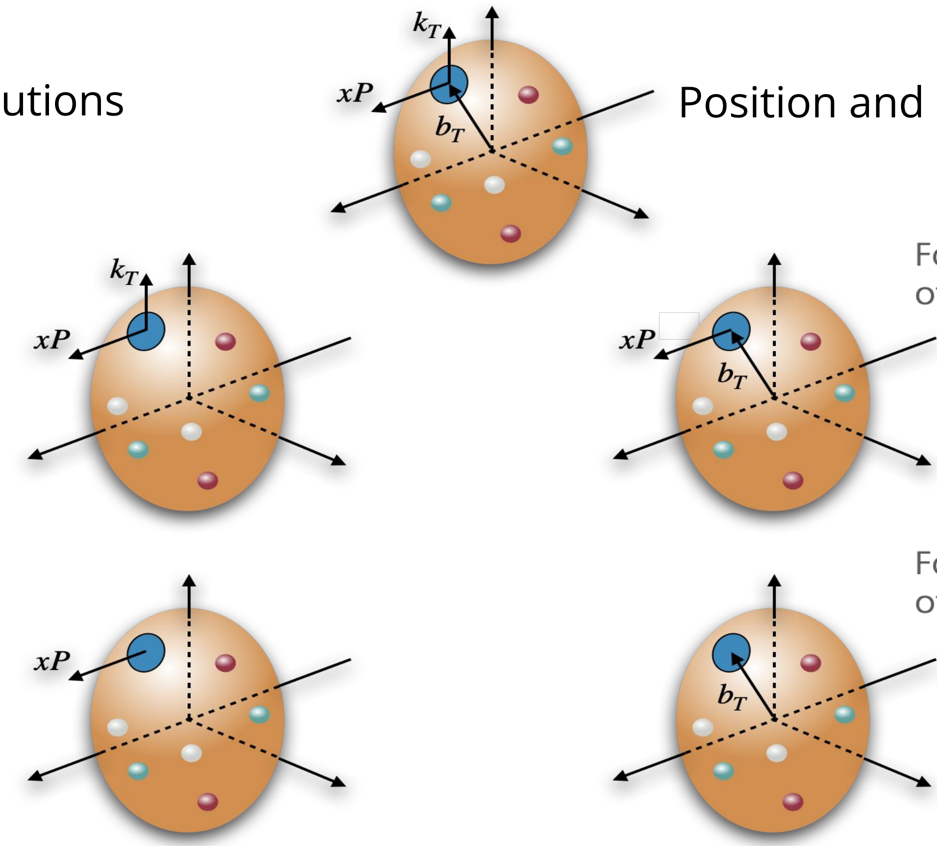


see, e.g., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)

TMDs and GPDs

Wigner distributions

Position and momentum of partons



TMDs

Fourier transform of GPDs

PDFs

Fourier transform of Form Factors

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

TMD PDFs for quarks in nucleon

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}	$h_1,\ h_{1T}^\perp$

$$\Phi_{ij}(k,P) \;=\; \mathrm{F.T.}\,\langle P|\,\overline{\psi}_j(0)\,U\,\psi_i(\xi)\,|P\rangle$$

At leading twist: 8 TMD PDFs

(similar classification for gluons and for FFs)

- **Black**: time-reversal even AND collinear (*S. Forte's talk*)
- **Blue**: time-reversal even
- **Red**: time-reversal odd (*process dependence*)

The **symmetries of QCD** play a crucial role in this classification (see the **gauge link U**)

TMD factorization

$q_T \ll Q$

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

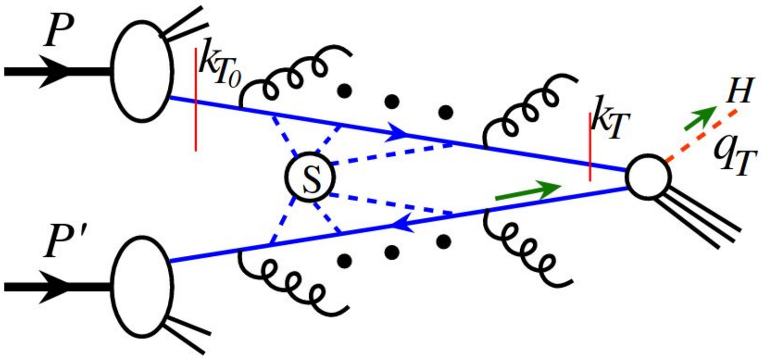
$$\frac{d\sigma}{dq_T} \sim \mathcal{H}\, f_1(x_a, k_{T\,a}, Q, Q^2)\, f_1(x_b, k_{T\,b}, Q, Q^2)\, \delta^{(2)}(q_T - k_{T\,a} - k_{T\,b}) \;+ \mathcal{O}(q_T/Q) \,+\, \mathcal{O}(\Lambda/Q)$$

- TMDs & partonic cross section:
  same **IR poles** = same non-perturbative physics

- **observed transverse momentum qT** :
  transverse momenta of **quarks**

- quark transverse momentum :
  radiative (perturbative) and **intrinsic** (non-perturbative) components

- Renormalization = **evolution** equations tell us how to distinguish between the two



Quarks

Drell-Yan / Z / W production (hh)

Semi-Inclusive DIS (eh)

2h-inclusive
e+e- annihilation

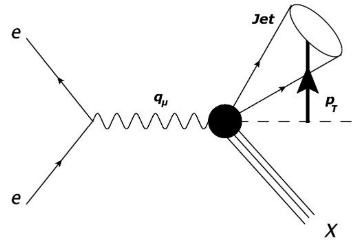
TMD factorization

Gluons

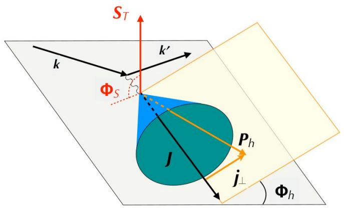
Higgs production
in hadronic collisions

Quarkonium production (e.g. $\eta_{b,c}$
in hadronic collisions)

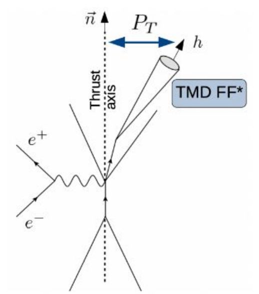
Jets:
(e.g. jet SIDIS,
di-jet SIDIS)



Hadron **"in jet"**:
(eh, hh, e+e-)



Y **"+ jet"**:
(e.g. Y = γ, h)



Quarks

Drell-Yan / Z / W production (hh)

Semi-Inclusive DIS (eh)

2h-inclusive
e+e- annihilation

Gluons

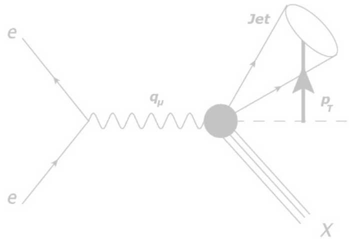
Higgs production
in hadronic collisions

Quarkonium production ($\eta_{b,c}$)
in hadronic collisions

Global fits (unpolarized)

**Not enough data
(or not at all)
for the other
processes**

Jets:
(e.g. jet SIDIS,
di-jet SIDIS)



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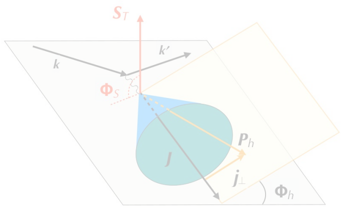

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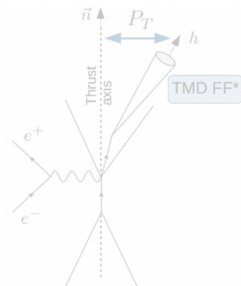
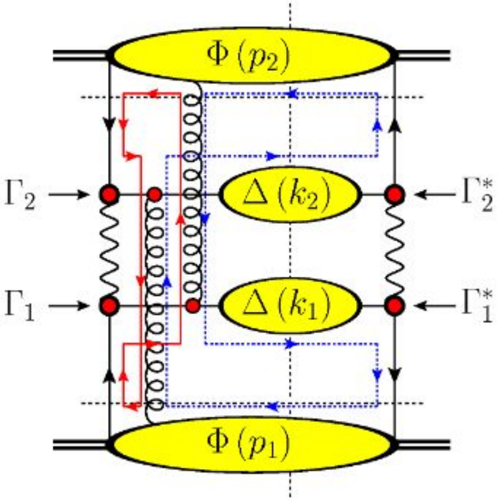


Non-TMD-factorizable processes



For **pp → h1 h2 X** TMD factorization is violated

See :

- Collins, Qiu (2007) : https://inspirehep.net/literature/750627
- Rogers, Mulders (2010) : https://inspirehep.net/literature/843028

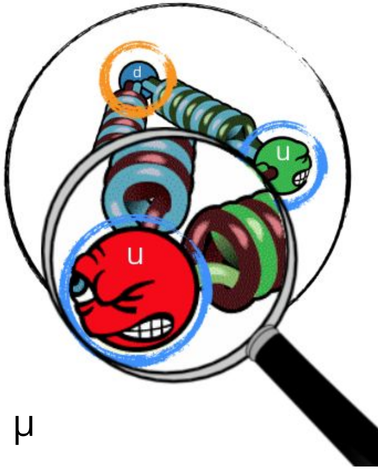
- Buffing (2016) : https://inspirehep.net/literature/1391461 (see figure)

This **endangers** also other processes such as **pp → h X (and similar)**

Quantify factorization breaking effects ? See e.g. :

- Buffing, Kang, Lee, Liu (2018) : https://inspirehep.net/literature/1709823
- Aidala (2019) : https://inspirehep.net/literature/1772224
- LHCb collaboration (2021) : https://inspirehep.net/literature/1901628

QCD evolution of a TMD PDF



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

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

Calculable in pQCD

x $$\left(\frac{\zeta}{\zeta_0}\right)^{-D(b_T\mu_0, \alpha_s(\mu_0)) + g_K(b_T; \lambda)}$$ → 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 J.C. Collins' book and many other references, e.g. https://inspirehep.net/literature/1393670

Non-perturbative TMD parts

$$F_a(x, b_T^2; \mu, \zeta) = F_a(x, b_T^2; \mu_0, \zeta_0)$$

$$\exp\left[\int_{\mu_0}^{\mu} \frac{d\mu'}{\mu'} \gamma_F\left(\alpha_s(\mu'), \frac{\zeta}{\mu'^2}\right)\right]$$

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

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Non-pert. corrections (large bT)

Intrinsic transverse momentum, potentially flavor dependent!

Sub-leading power (twist)

QCD observables

power corrections \ perturbative corrections	1	α_s	α_s^2	$\dots$
Leading power (LP) — 1	TMD factorization: ✔			
Next-to-LP (NLP) — M/Q	TMD factorization: ✔			
… — $(M/Q)^2$				
$\dots$				

Coupling expansion →

Twist expansion ↓

Possibility to go beyond a parton model interpretation

Sub-leading power (twist)

Recent developments :

- Ebert, Gao, Stewart (2022) : https://inspirehep.net/literature/1991138
(factorization of **azimuthal asymmetries in SIDIS** at NLP)

- Gamberg, Kang, Shao, Terry, Zhao (2022) : https://inspirehep.net/literature/2514090
(factorization of **semi-inclusive DIS and Drell-Yan cross sections** at NLP)

- Rodini, Vladimirov (2023) : https://inspirehep.net/literature/2669575
(factorization of **semi-inclusive DIS cross section** at NLP)

SIDIS: structure functions and TMDs

Leading twist TMDs

$$F_{UU,T} = \mathcal{C}\big[f_1 D_1\big],$$

"Collins effect"

$$F_{UU}^{\cos 2\phi_h} = \mathcal{C}\left[-\frac{2\,(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T)\,(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T) - \boldsymbol{k}_T\cdot\boldsymbol{p}_T}{M M_h}\, h_1^{\perp} H_1^{\perp}\right]$$

"Sivers effect"

$$F_{UT,T}^{\sin(\phi_h-\phi_S)} = \mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\, f_{1T}^{\perp} D_1\right],$$

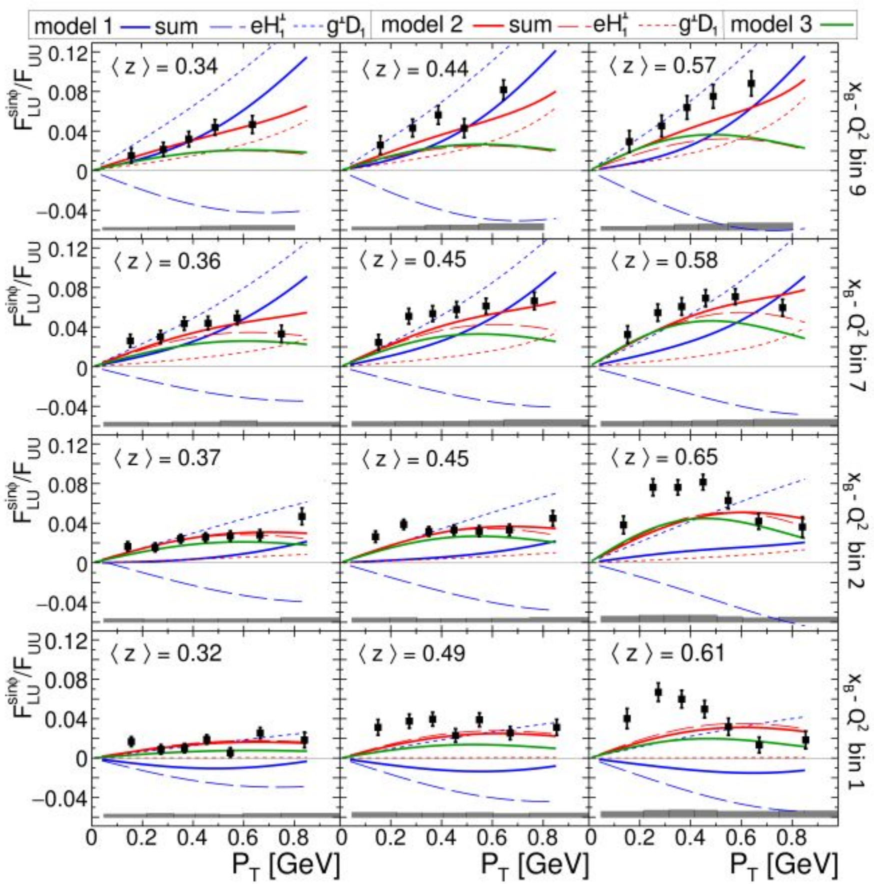
Etc. ...

Higher twist TMDs

$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(x e H_1^{\perp} + \frac{M_h}{M}\, f_1 \frac{\tilde{G}^{\perp}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(x g^{\perp} D_1 + \frac{M_h}{M}\, h_1^{\perp} \frac{\tilde{E}}{z}\right)\right]$$

For a summary see https://inspirehep.net/literature/732275

Higher twist: beam-spin asymmetry @ CLAS12



Among the first CLAS12 publications

https://inspirehep.net/literature/1840207

Further theory developments

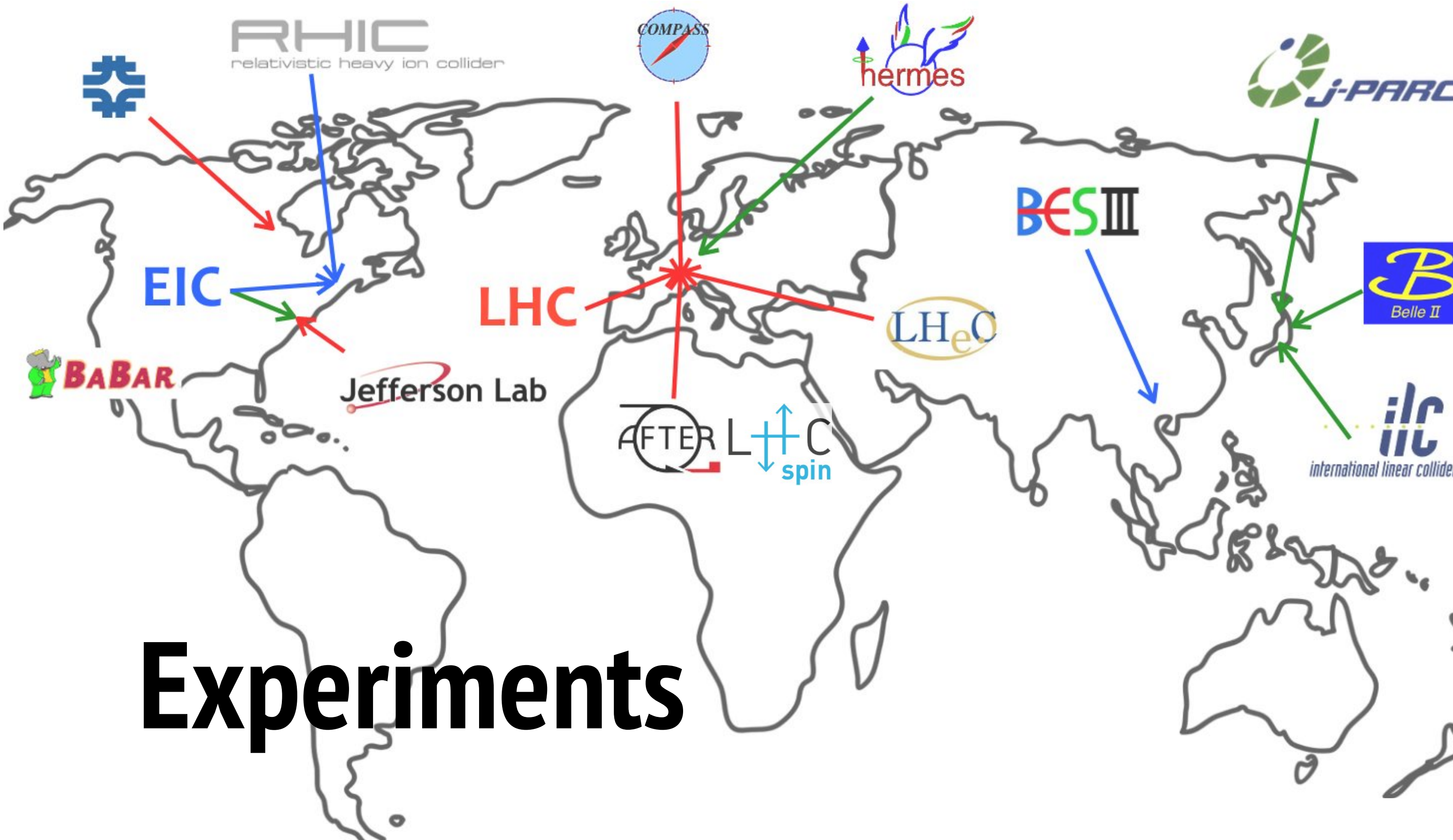
- Better angle on TMDs at EIC (MIT) :
  https://inspirehep.net/literature/2155131

- Hadron structure oriented approach (ODU/JLab):
  https://inspirehep.net/literature/2640018

- Parton branching TMDs and their relation with Collins-Soper-Sterman formalism (PB group):
  https://inspirehep.net/literature/2676615

- …

Experiments



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."

00 home
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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

arXiv > nucl-ex > arXiv:2211.15746

Nuclear Experiment

[Submitted on 28 Nov 2022 (v1), last revised 10 Feb 2023 (this version, v3)]

Precision Studies of QCD in the Low Energy Domain of the EIC

CONCEPTS FOR THE

arXiv > hep-ph > arXiv:2305.14572

High Energy Physics - Phenomenology

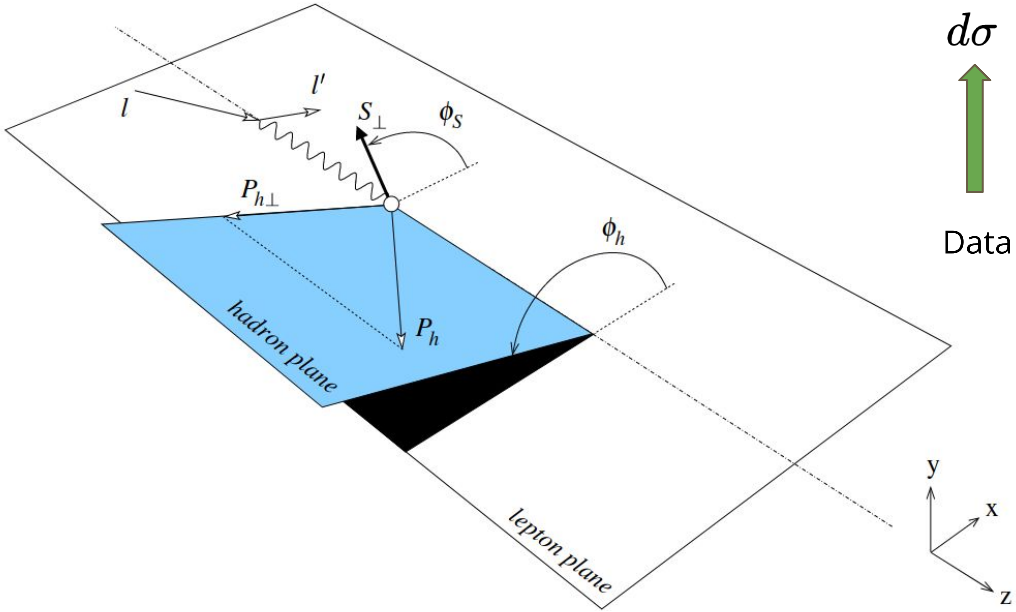
[Submitted on 23 May 2023]

The case for an EIC Theory Alliance: Theoretical Challenges of the EIC

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

See R. Ent's talk

Hadronic "imaging" from SIDIS



$$\ell(l) + N(P) \to \ell(l') + h(P_h) + X,$$

Calculable in perturbation theory

$$d\sigma \sim \mathcal{H} \; \boxed{\text{TMD PDF} \otimes \text{TMD FF}}$$

Data

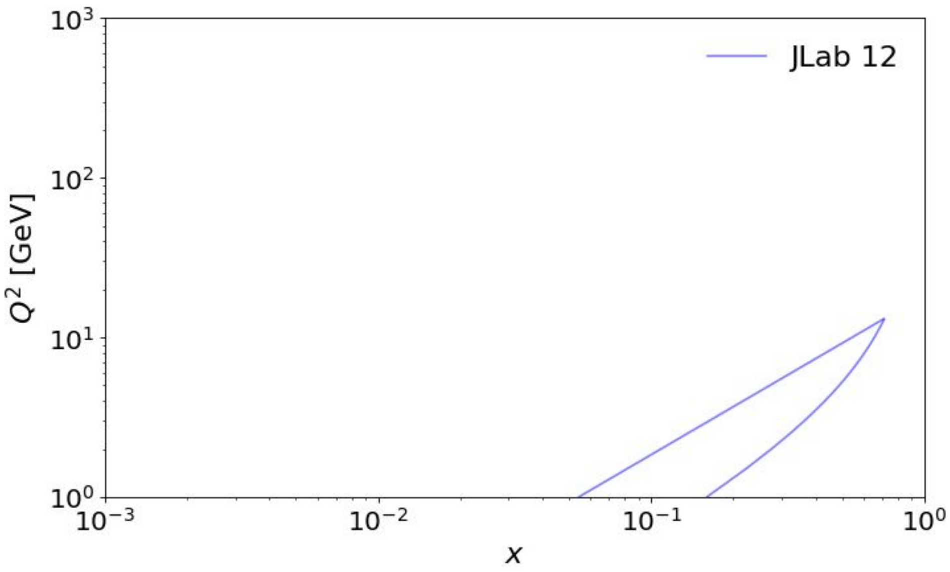
The partonic "maps", to be extracted from data

hermes COMPASS JLab, EIC, ...

SIDIS kinematics: current experiments

"inelasticity": $y = \dfrac{P \cdot q}{P \cdot l} = \dfrac{E_\gamma}{E_\ell}$ $\qquad y_{\min} < y < y_{\max}$

Invariant mass hadronic final states: $W^2 = (P+q)^2 = M^2 + y\, s\,(1-x)$ $\qquad W^2 > W^2_{cut}$



PROs

- Rich territory for non-perturbative effects

- sensitivity to higher twist

- valence region (focus for flavor, spin, etc.)

CONs

- Low Q: applicability of collinear and TMD formalism ?

- Low Q: separation of fragmentation regions?

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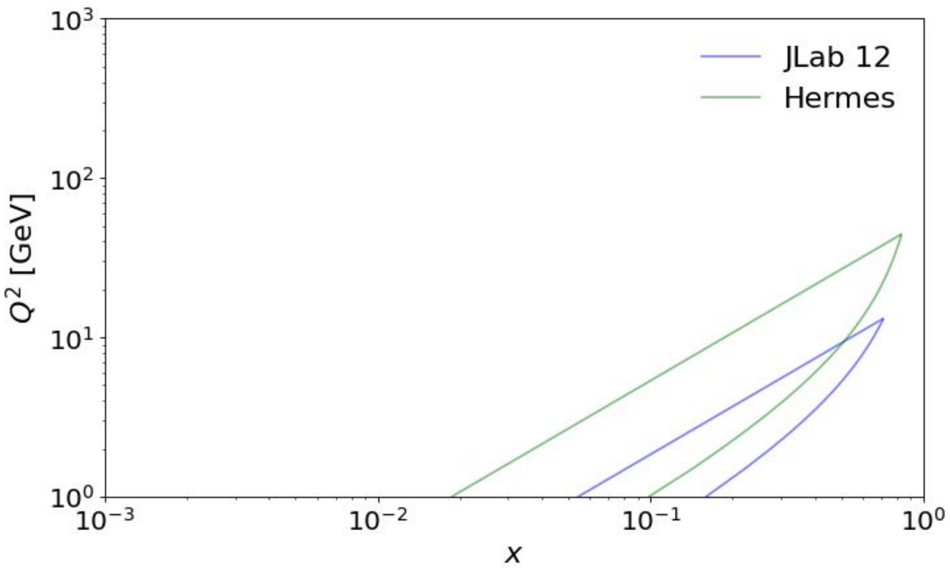

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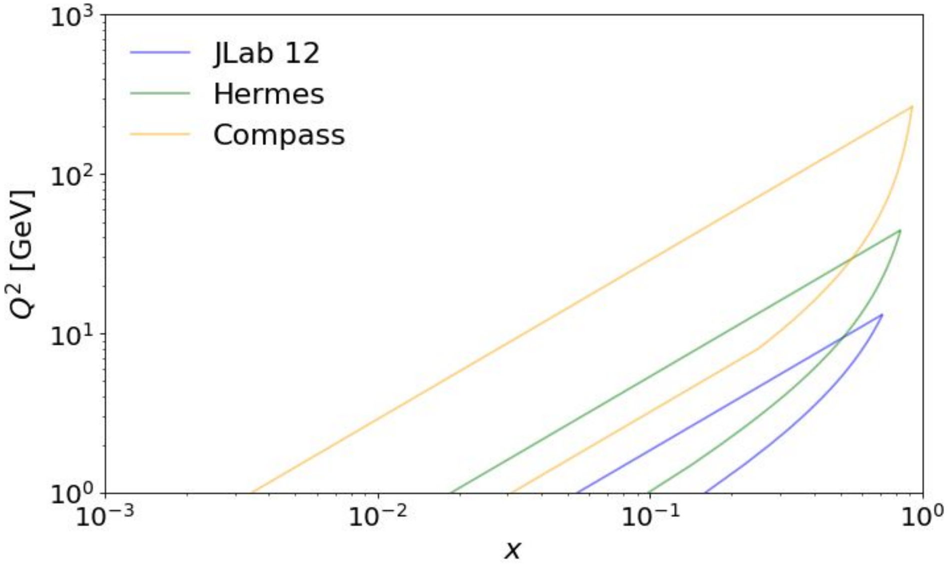


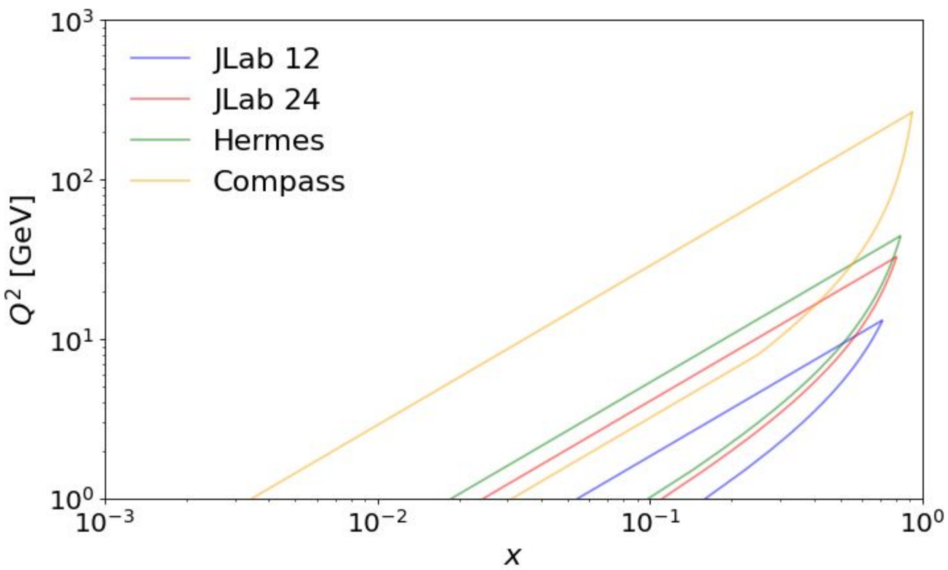
With the ***limited gain in Q*** from JLab 11 to Hermes and Compass we still experience the same "**problems**" related to the ***presence of power corrections to the TMD formalism*** arXiv > nucl-ex > arXiv:2306.09360

Nuclear Experiment

[Submitted on 13 Jun 2023]

Strong Interaction Physics at the Luminosity Frontier with 22 GeV Electrons at Jefferson Lab

Invariant mass hadronic final states: $W^2 = (P+q)^2 = M^2 + y\,s\,(1-x)$ $\qquad W^2 > W^2_{cut}$



An upgrade of the CEBAF (**JLab 22**) relies on the power of its data to *"**enrich**" the picture, but not to "**clean**" it* from the point of view of the formalism

Fundamental insights into:
- non-pert. large x region
- polarization
- flavor separation
- collinear distributions (?)
- higher twists, etc. …

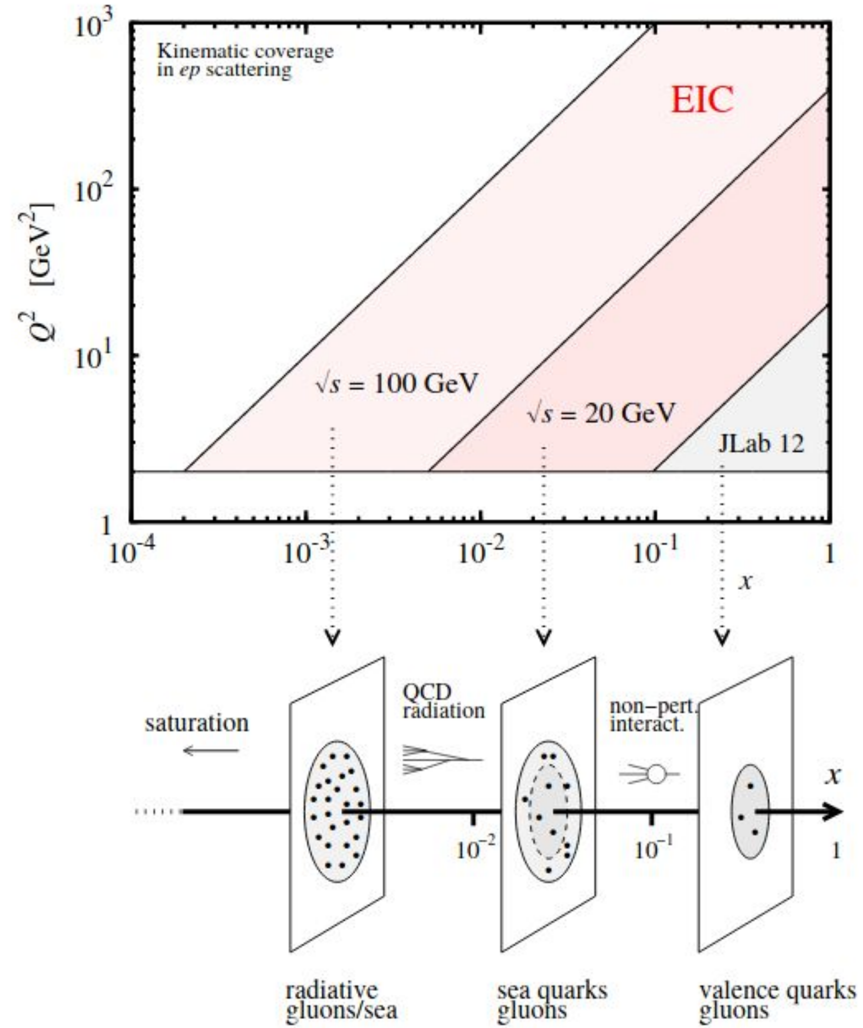
But same "complications" as the other fixed-target experiments

SIDIS kinematics: EIC

Importance of complementary experiments

EIC: zooming into hadron structure

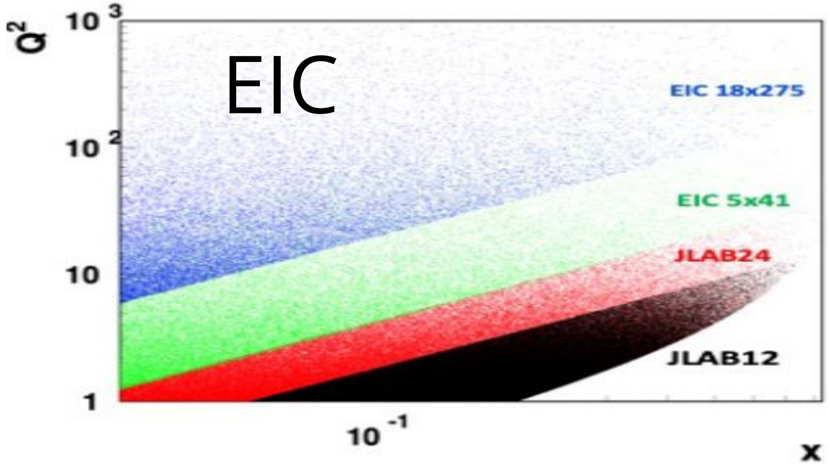
Credit picture: C. Weiss

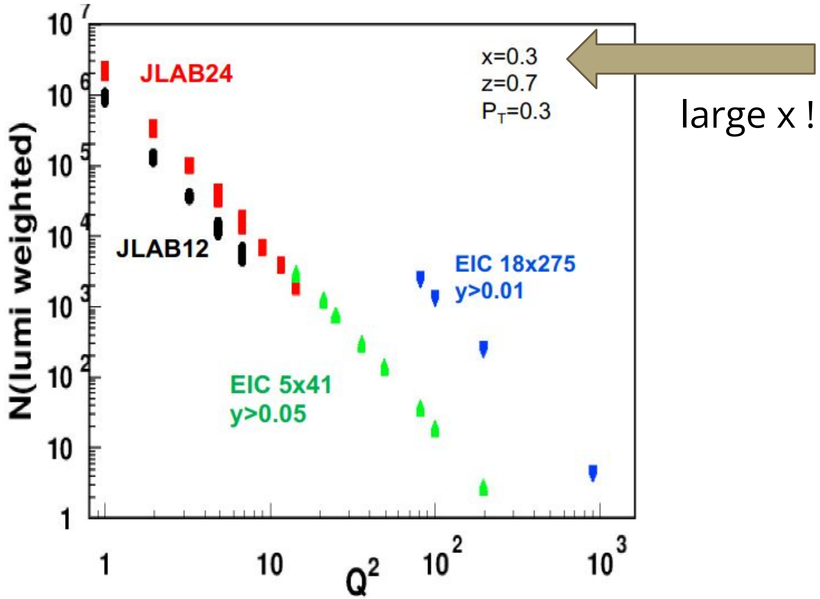


SIDIS kinematics and statistics

see H. Avakian's talk at CPHI 2022

A crucial role is played by the available **statistics** *within* the kinematic coverage



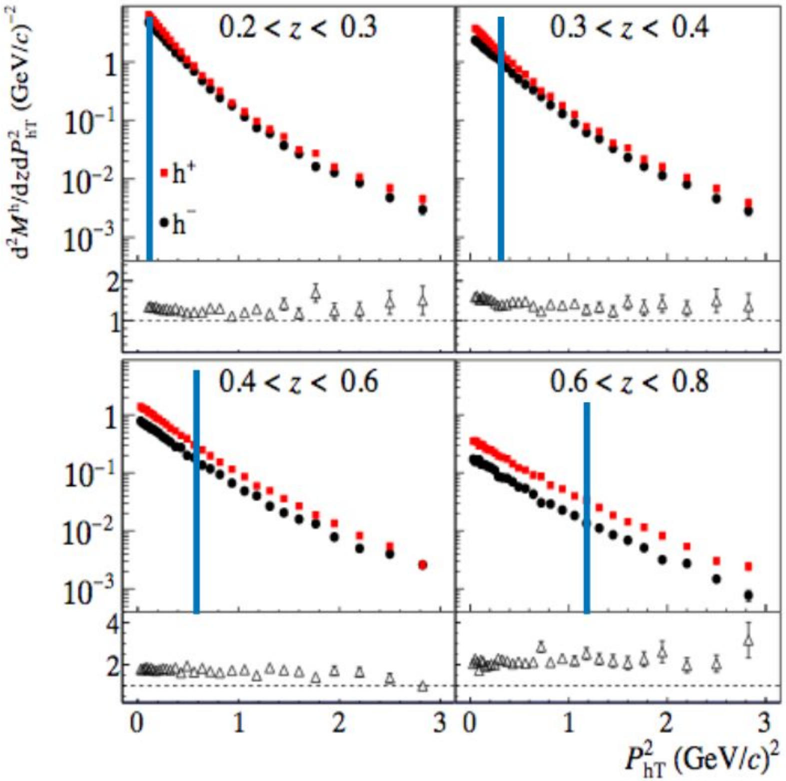


large x !

broader (x,Q) coverage (EIC) ⟷ ***higher statistics (JLab 22)***

TMD region: low transverse momentum

$q_T \ll Q$



SIDIS - TMD region

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

Let's highlight

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

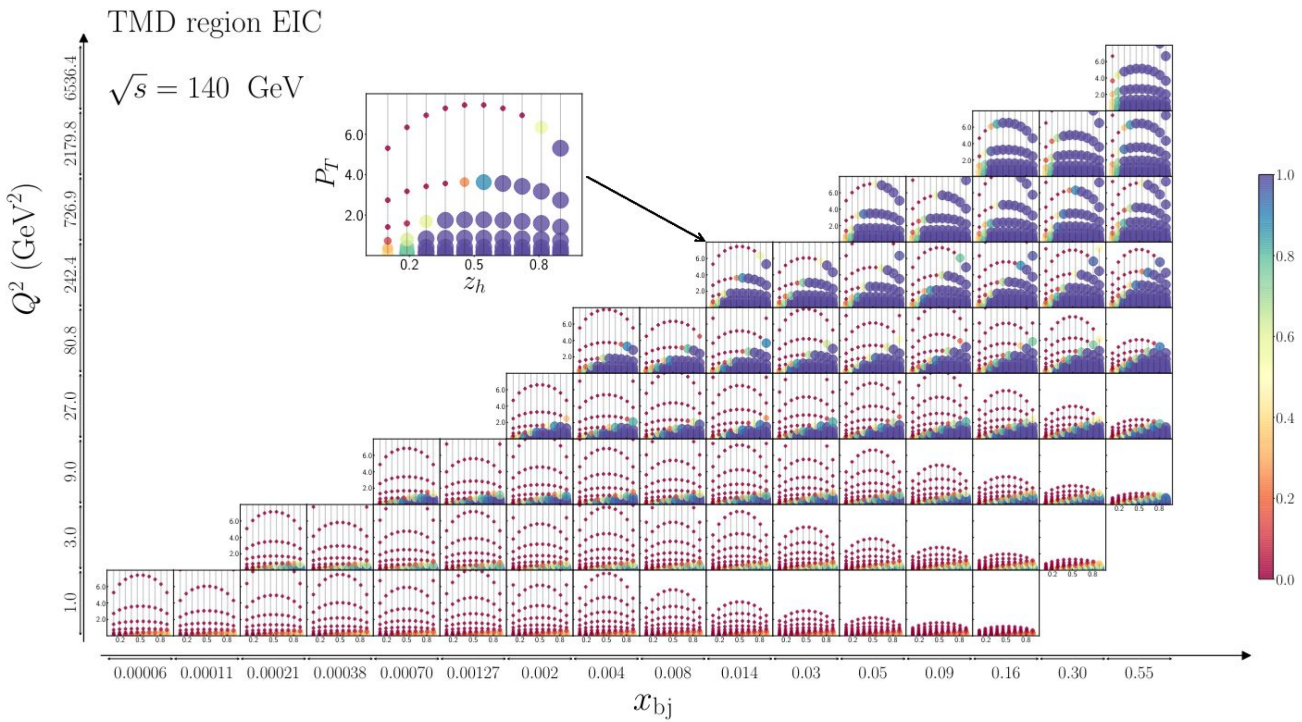
One of the bins with highest Q:

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

COMPASS unpolarized SIDIS multiplicities - arxiv 1709.07374

Current fragmentation region

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**

A fixed-target program at the LHC

Contents lists available at ScienceDirect

ELSEVIER

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

High-x partonic content of nucleons and nuclei

Spin structure of (un)polarized nucleons

Heavy-Ion collisions at large rapidities

A fi… pro… d astroparticle studies

Check for updates

C. Hadjidakis [1,a], D. K…
M.G. Echevarria [3,4,b], …
A. Signori [11,3,12,b], B. …
F. Donato [18], E.G. Ferreiro [19,20], I. Hrivnacova [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

Hadronization studies at Belle II

Opportunities for precision QCD physics in hadronization at Belle II – a Snowmass whitepaper

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https://inspirehep.net/literature/2063309

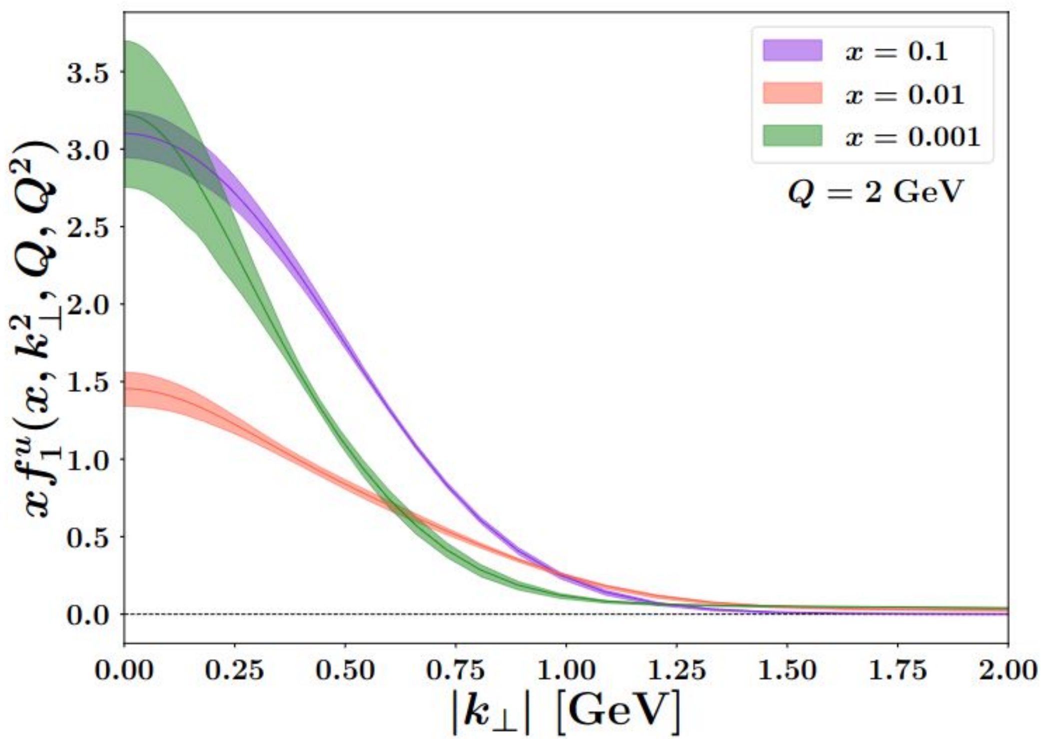
https://inspirehep.net/literature/2087635

Snowmass 2021 White Paper
Upgrading SuperKEKB with a Polarized Electron Beam: Discovery Potential and Proposed Implementation

April 13, 2022

US Belle II Group [1]
and
Belle II/SuperKEKB e- Polarization Upgrade Working Group [2]

TMD phenomenology



MAPTMD22 extraction : https://inspirehep.net/literature/2096333

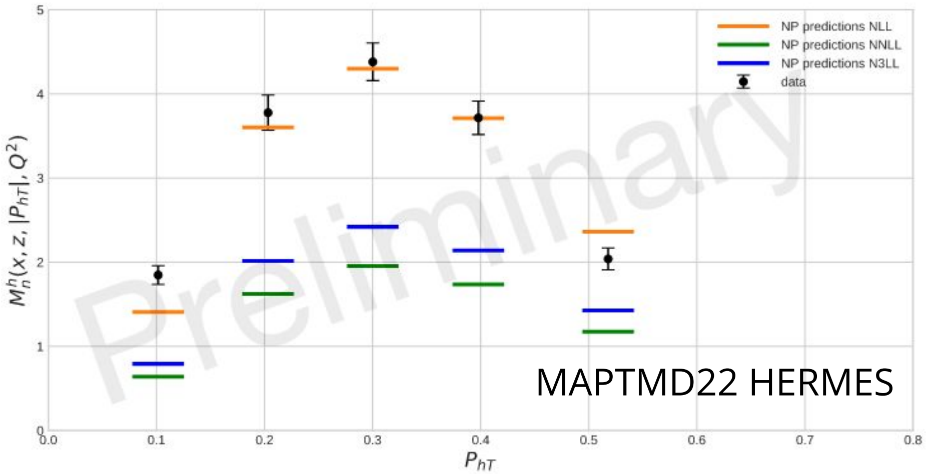
Available global fits of unpolarized TMDs

	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

Normalization issues: SIDIS

***Small** transverse momentum*



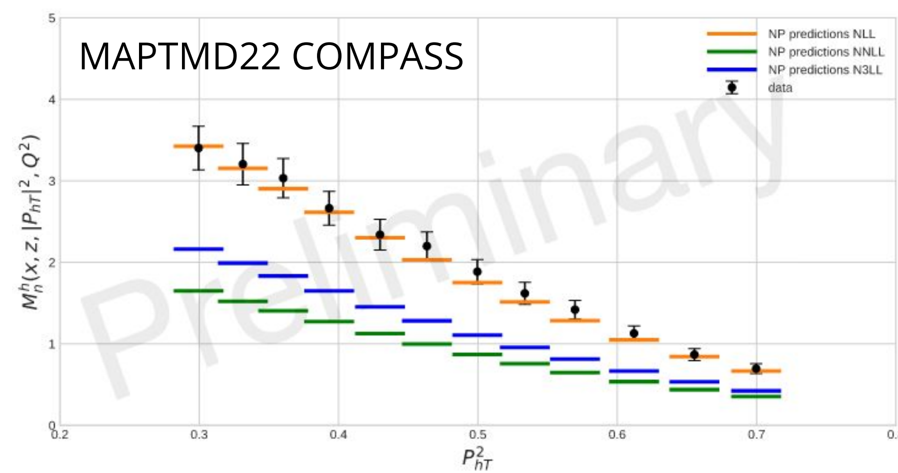
Beyond the NLL, the **theoretical** prediction for **SIDIS** is **way too low**

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



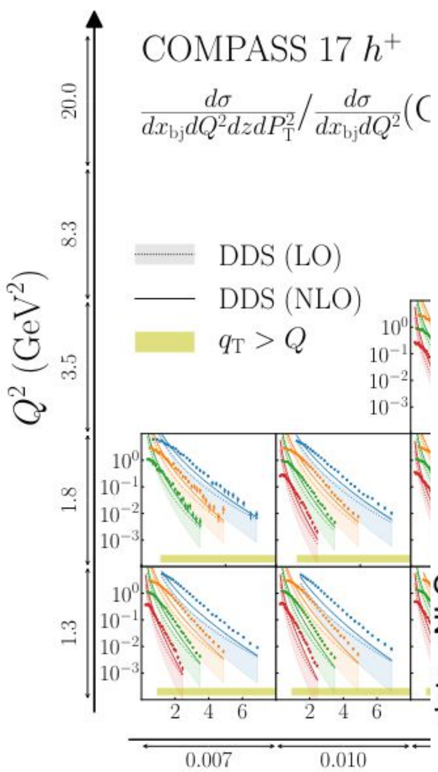
Normalization issues

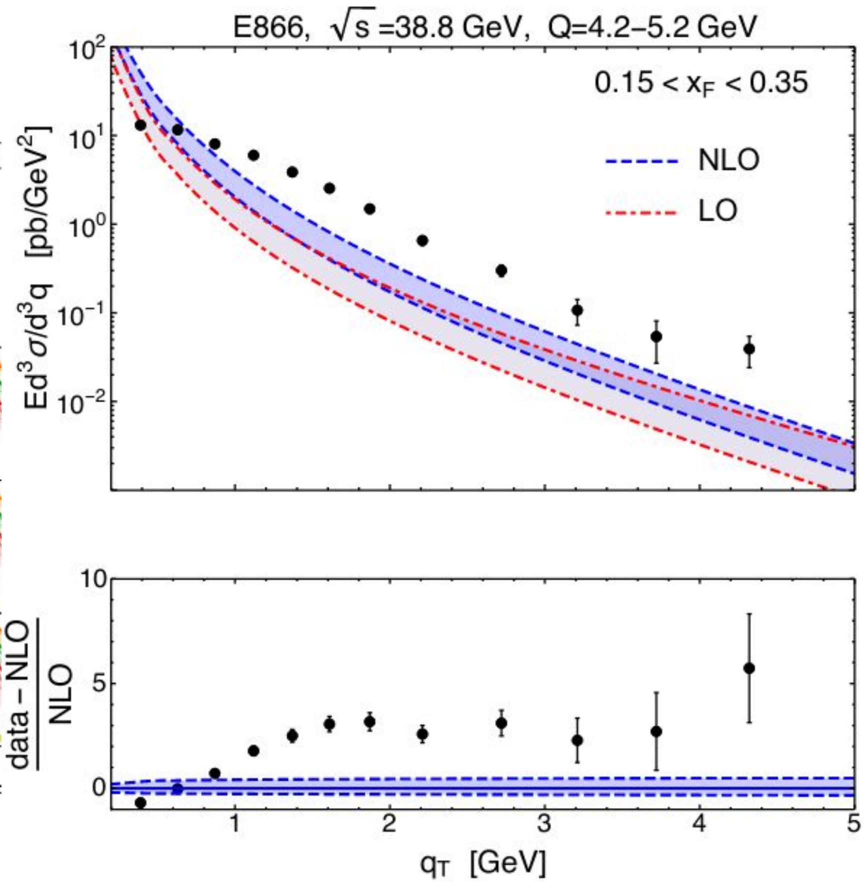
https://inspirehep.net/literature/1723777

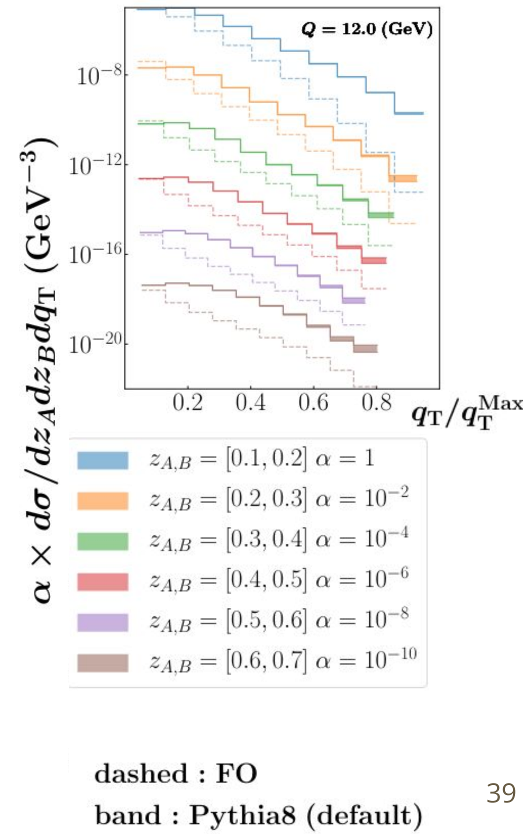
https://inspirehep.net/literature/1716140

https://inspirehep.net/literature/1752934

Large *transverse momentum (no TMDs)*







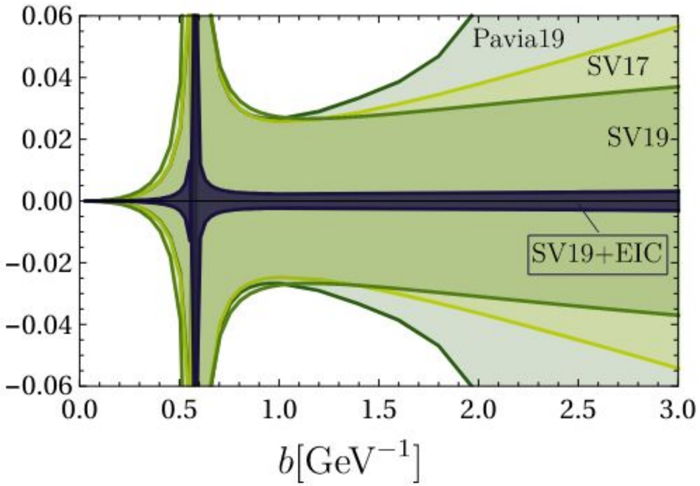
Non-perturbative evolution: impact of EIC

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

→ evolution in ζ

Non-pert. corrections (large bT)

EIC YR: https://inspirehep.net/literature/1851258

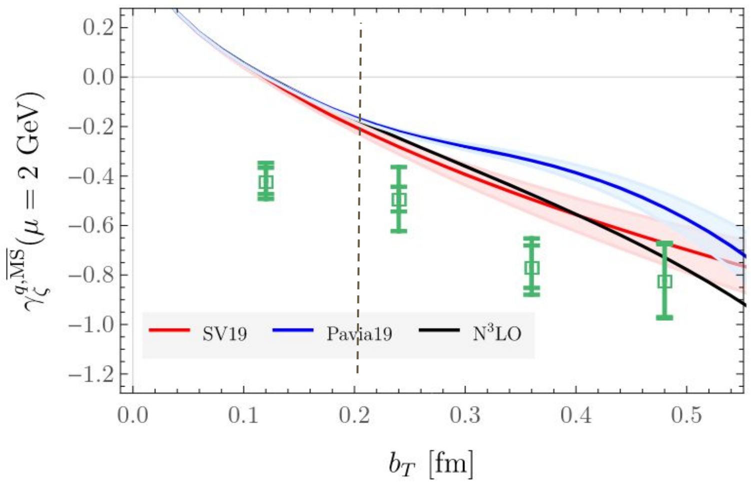


Huge impact of **EIC** SIDIS program on **non-perturbative TMD evolution**

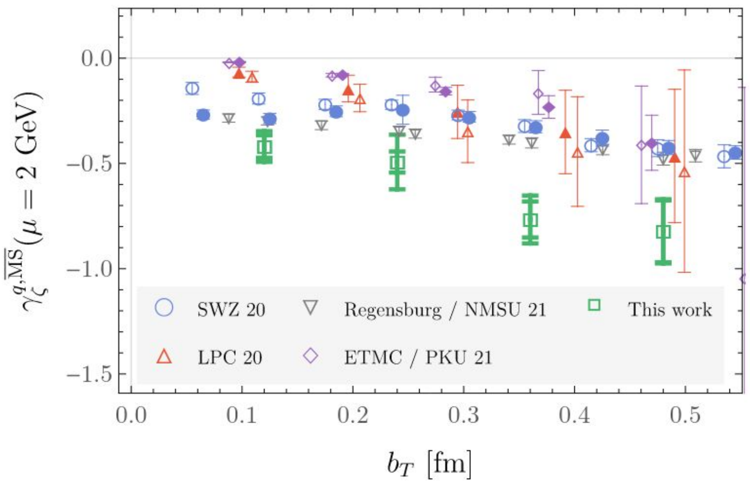
SV19 extraction: https://inspirehep.net/literature/1770788

Non-perturbative evolution: input from lattice

Lattice QCD can also calculate some of the quantities that we are trying to extract from experimental data: e.g. **gK**



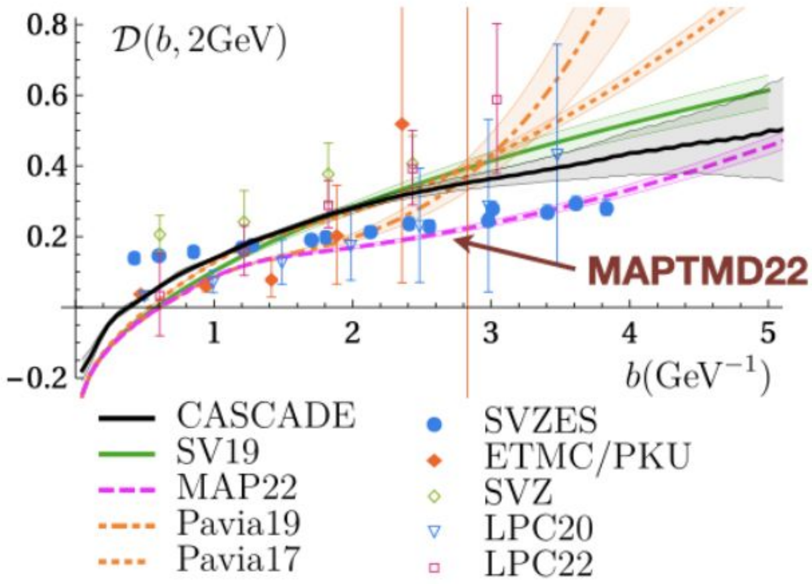
(a) Comparison with the SV19 [4] and Pavia19 [5] phenomenological parameterizations and the next-to-next-to-next-to-leading order (N^{3}LO) perturbative result [42, 43].



(b) Comparison with quenched results of Ref. [19] (SWZ), as well as results from the LPC [20], Regensburg/NMSU [21], and ETMC/PKU [22] collaborations. Different sets of points with the same color show different sets of results from the same collaboration.

https://inspirehep.net/literature/1892223

Non-perturbative evolution: extractions and lattice



Martinez, Vladimirov *Phys.Rev.D* 106 (2022) 9

TMDs (SV19): impact of EIC

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

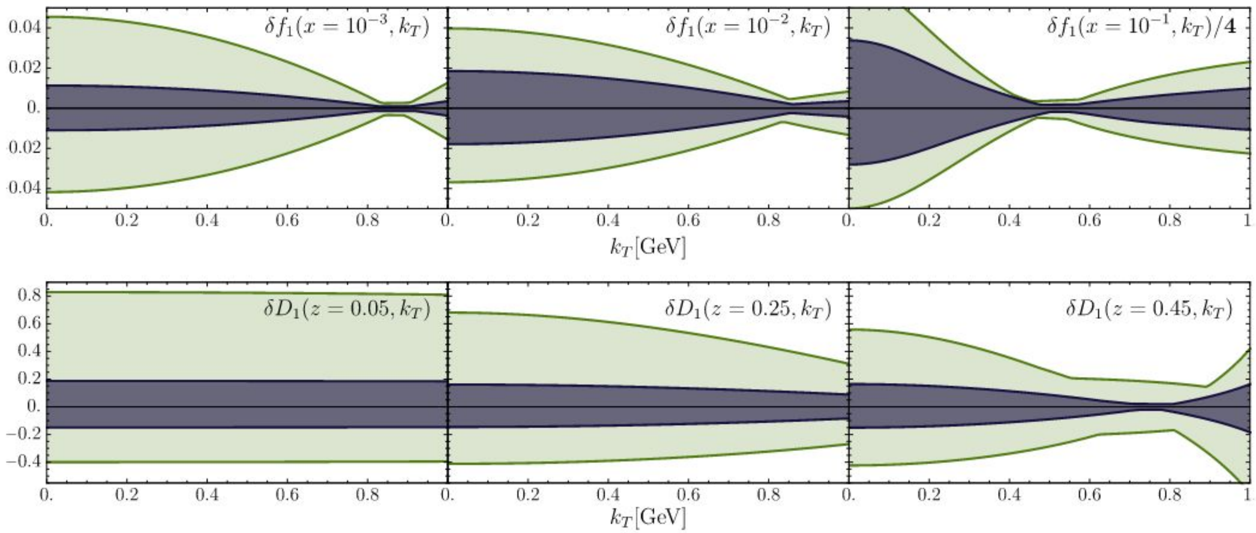


Figure 7.52: Comparison of relative uncertainty bands (i.e. uncertainties normalized by central value) for up-quark unpolarized TMD PDFs (upper panel) and $u \to \pi^+$ pion TMD FFs (lower panel), at different values of x and z as a function of k_T, for $\mu = 2$ GeV. Lighter band is the SV19 extraction,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

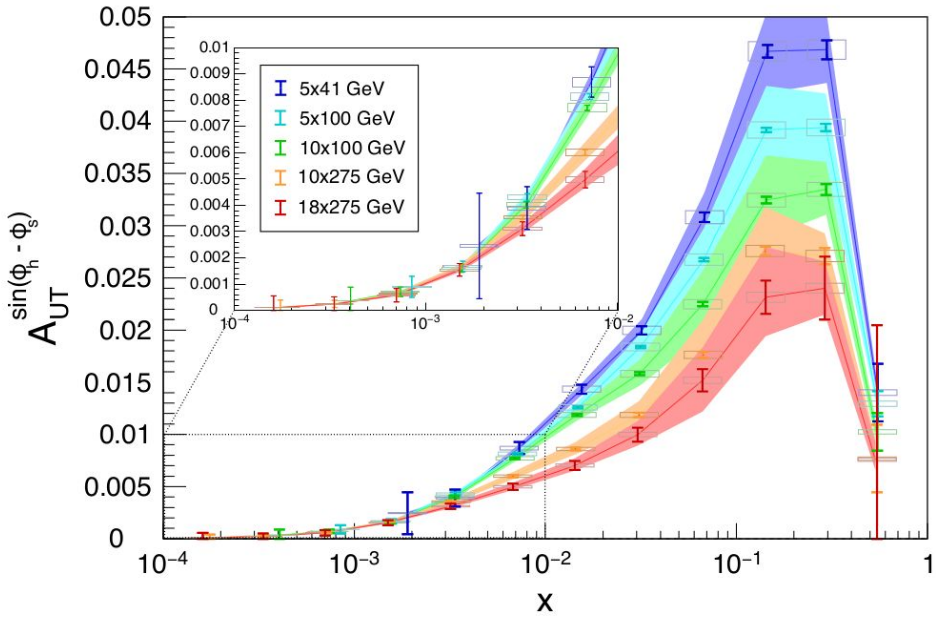
Up in proton
TMD PDF

Up to pion+
TMD FF

Fit with EIC
pseudo-data

Sivers asymmetry (PV20): impact of EIC

Projected uncertainties for **Sivers asymmetry in SIDIS**



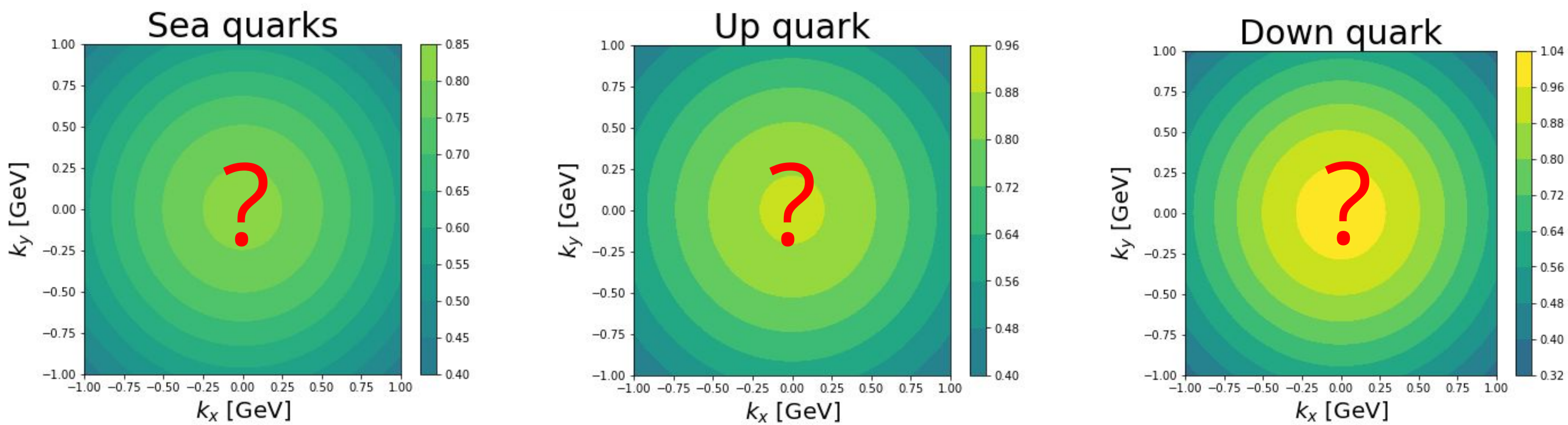
Bands: uncertainty from PV20 extraction of Sivers TMD PDF

Points: projected experimental uncertainty on ATHENA pseudo-data

PV20 extraction: https://inspirehep.net/literature/1793441

(from ATHENA detector proposal)

Flavor dependent TMD PDFs

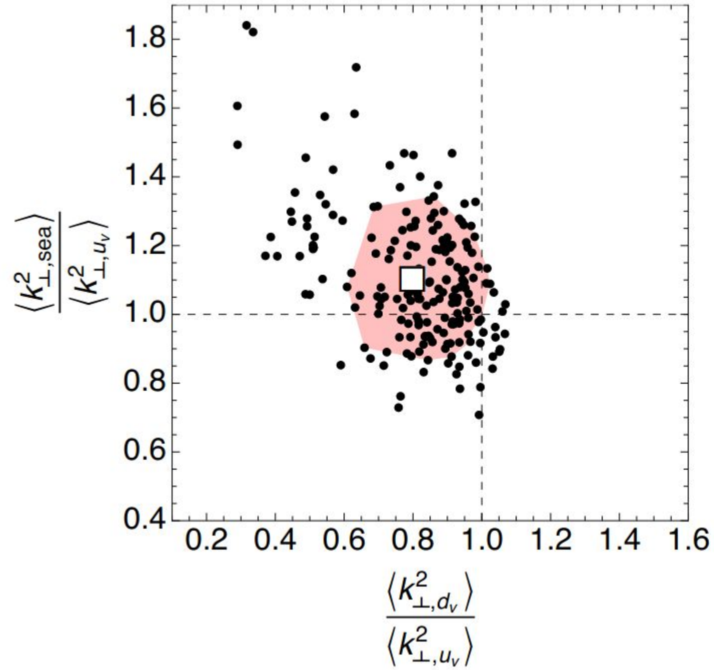


Are there **differences** among the quark **flavors** in the

intrinsic transverse momentum distributions?

Flavor dependent TMD PDFs

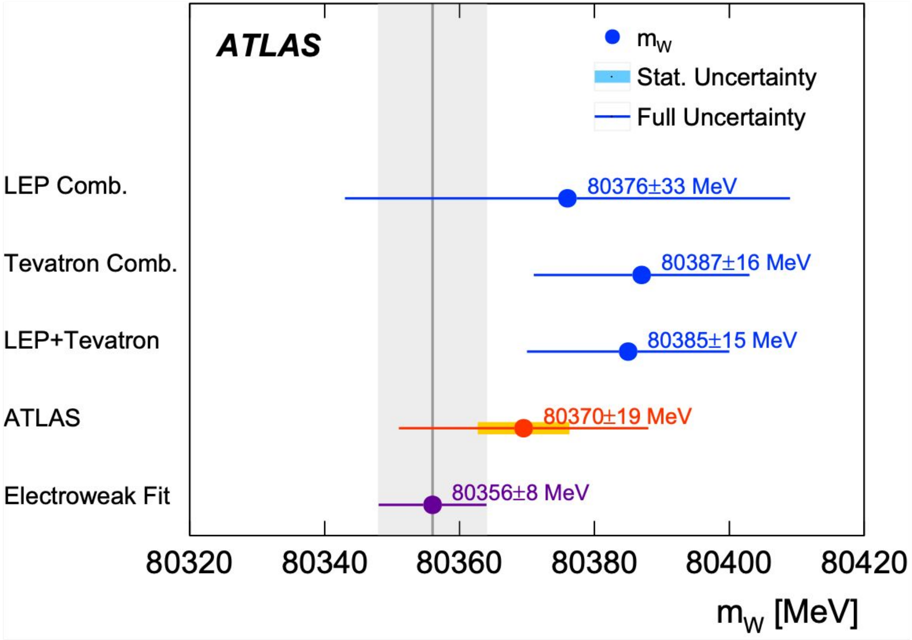
- Signori et al. (SIDIS, 2013) : https://inspirehep.net/literature/1254070
- Bury et al. (DY, 2022) : https://inspirehep.net/literature/2012944
- Moos et al. (DY, 2023) : https://inspirehep.net/literature/2659271



$$\langle k^2_{\perp,\text{sea}} \rangle \vee \langle k^2_{\perp,\text{u}_v} \rangle \vee \langle k^2_{\perp,\text{d}_v} \rangle$$

Mw: ATLAS determination

https://inspirehep.net/literature/1510564

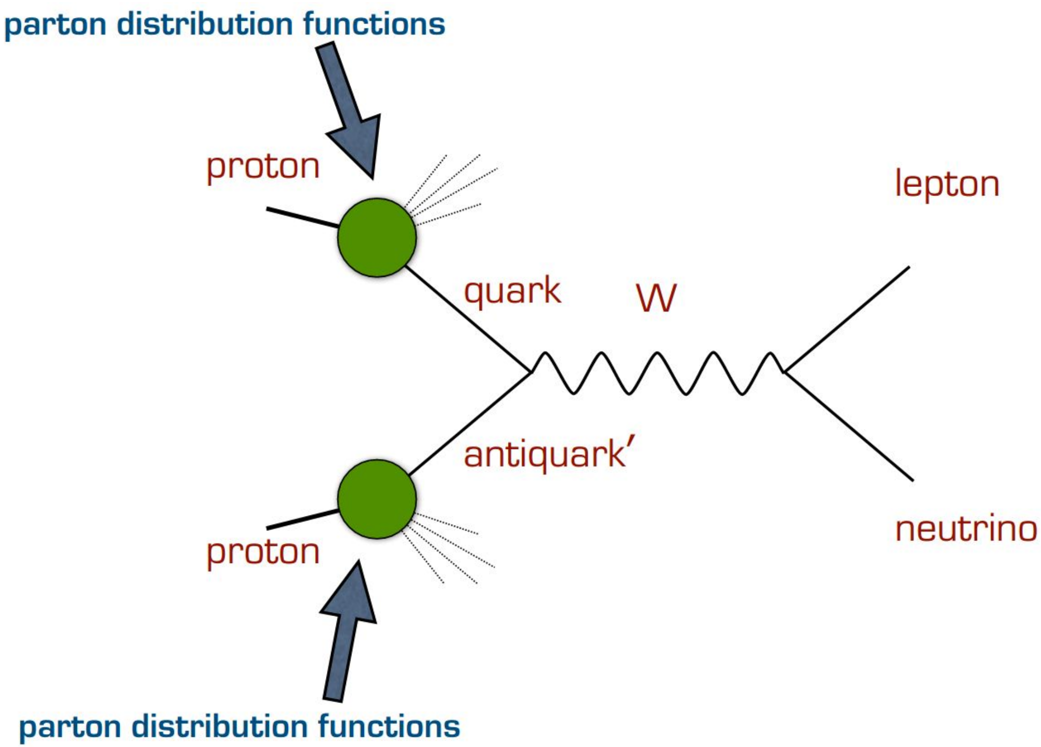


Possibly underestimated ?

$$m_W = 80370 \pm 7\,(\text{stat.}) \pm 11\,(\text{exp. syst.}) \pm 14\,(\text{mod. syst.})\ \text{MeV}$$
$$= 80370 \pm 19\ \text{MeV},$$

$$m_{W^+} - m_{W^-} = -29 \pm 28\ \text{MeV}.$$

W vs Z boson production



Usual procedure:

1. **Fit** non-perturbative TMD effects on **Z production** data

2. **Use** the results to predict the cross section **for W production**

The fact that **Z and W** productions are **initiated by different flavor configurations** is neglected!

Impact of TMD flavor

https://inspirehep.net/literature/1681006

ATLAS 7 TeV

$$-6 \leq M_{W^+} \leq 9 \text{ MeV}$$

$$-4 \leq M_{W^-} \leq 3 \text{ MeV}$$

Statistical uncertainty: ±2.5 MeV

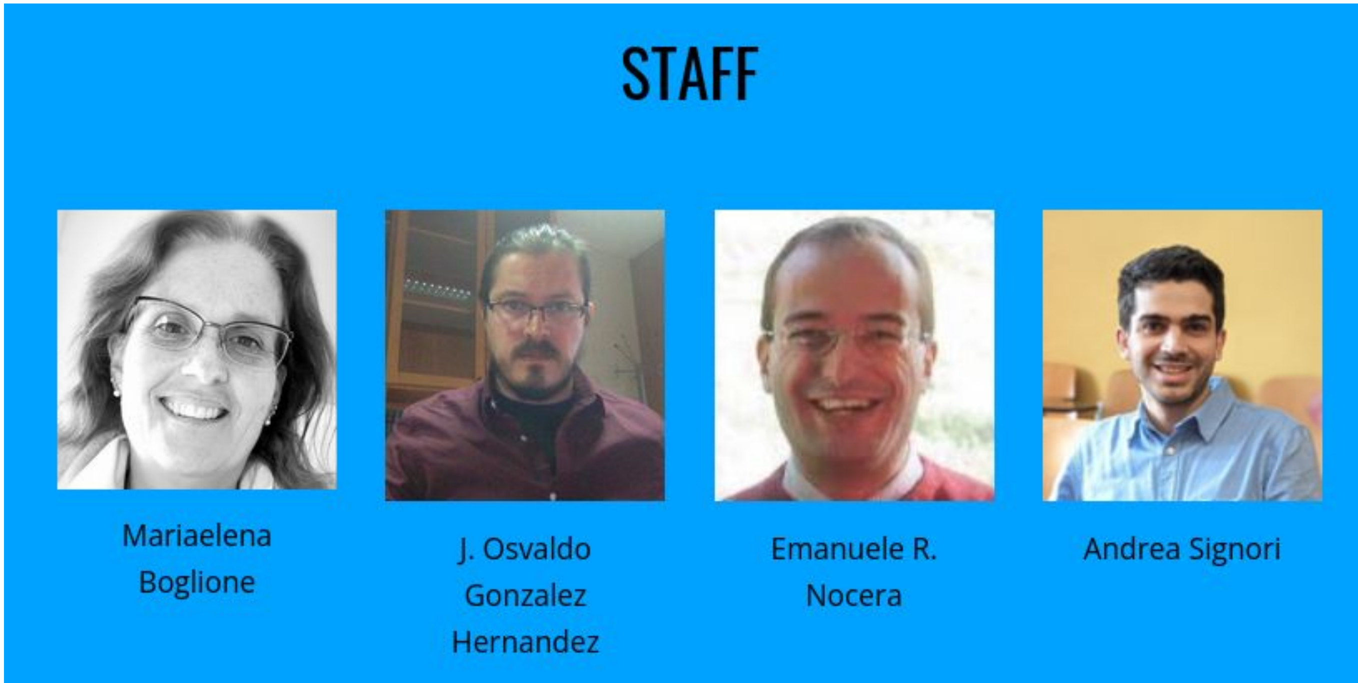
The fact that **quark intrinsic transverse momentum** can be **flavor dependent** leads to an **additional uncertainty** on mW, not considered so far

We believe the theory systematics are underestimated

- the four-loop QCD corrections generates a shift of -2.2 MeV
- The expectation from missing higher orders is 4 MeV

Eur.Phys.J. C74 (2014) 3046 ("Global EW fit at NNLO")

Our group in Turin



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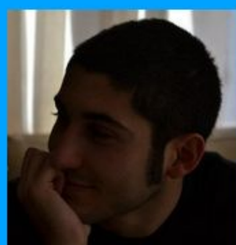

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GRADUATE STUDENTS

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