SQUHADRON

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TMD PDFs and FFs pheno & tools

MC4EIC - Monte Carlo event simulations for the EIC

November 19, 2021

Outline

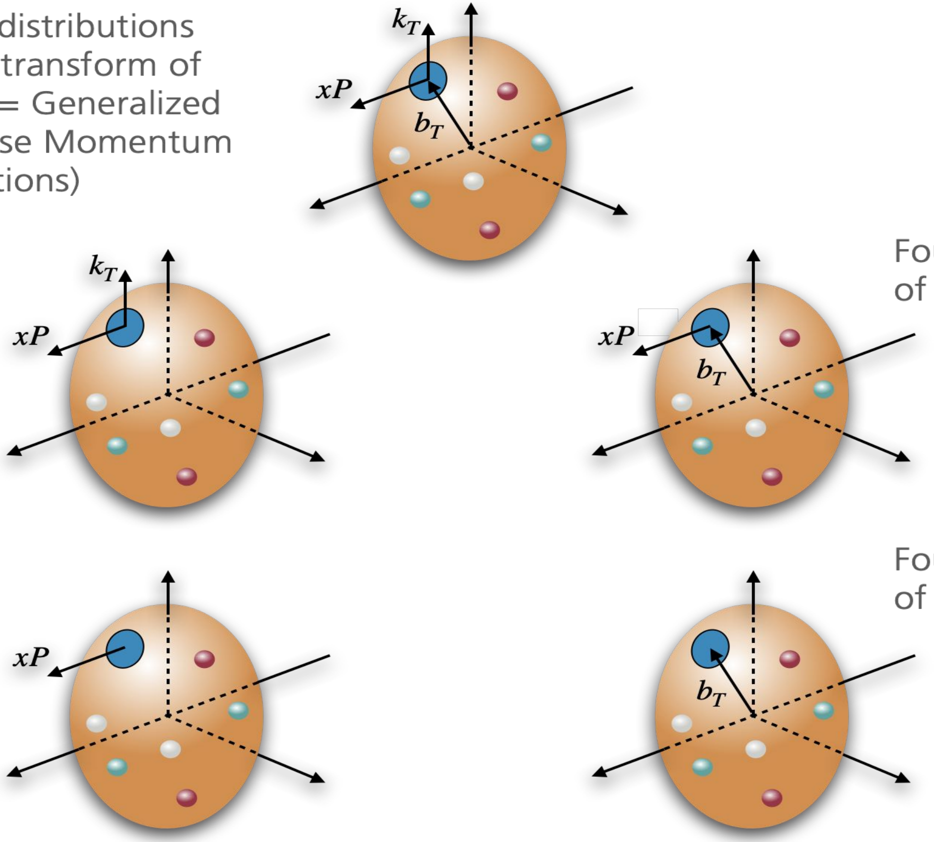
1. **Introduction**
2. **Experimental information**
3. **TMDs: recent phenomenology**
4. **TMDs: tools**

The hadron structure landscape

$$\begin{tikzcd}
 & & & & & & \overset{\text{parton correlation function}}{H(k,P,\Delta)} \arrow[lllll, d, "\Delta = 0"'] \arrow[dd, "\int dk^-"] \\
 & f(k,P)\ \text{parton correlation function} \arrow[dddd, "\int dk^-"'] & & & & & \\
 & & & & & H(x,\boldsymbol{k},\xi,\boldsymbol{b}) \arrow[r, leftrightarrow, "\text{FT}"] \arrow[lll, d, "\xi = 0"'] & H(x,\boldsymbol{k},\xi,\boldsymbol{\Delta})\ \text{GTMD} \arrow[dd, "\int d^2\boldsymbol{k}"] \\
 & & W(x,\boldsymbol{k},\boldsymbol{b})\ \text{Wigner distribution} \arrow[ddl, "\int d^2\boldsymbol{b}"] \arrow[ddr, "\int d^2\boldsymbol{k}"] & & & & \\
 & & & & & H(x,\xi,\boldsymbol{b}) \arrow[r, leftrightarrow, "\text{FT}"] \arrow[ll, d, "\xi = 0"'] & H(x,\xi,\Delta^2)\ \text{GPD} \arrow[dd, "\int dx\, x^{n-1}"] \\
f(x,\boldsymbol{z}) \arrow[r, leftrightarrow, "\text{FT}"] & \underset{\text{TMD}}{f(x,\boldsymbol{k})} \arrow[ddr, "\int d^2\boldsymbol{k}"] & & f(x,\boldsymbol{b})\ \text{impact parameter distribution} \arrow[ddl, "\int d^2\boldsymbol{b}"] \arrow[ddr, "\int dx\, x^{n-1}"] & & & \\
 & & & & & & \underset{\text{GFFs}}{\sum_{k=0}^{n} A_{nk}(\Delta^2)\,(2\xi)^k} \arrow[dl, "\xi = 0"'] \\
 & & \underset{\text{PDF}}{f(x)} & & F_n(\boldsymbol{b}) \arrow[r, leftrightarrow] & \underset{\text{form factor}}{F_n(\Delta^2)} &
\end{tikzcd}$$

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

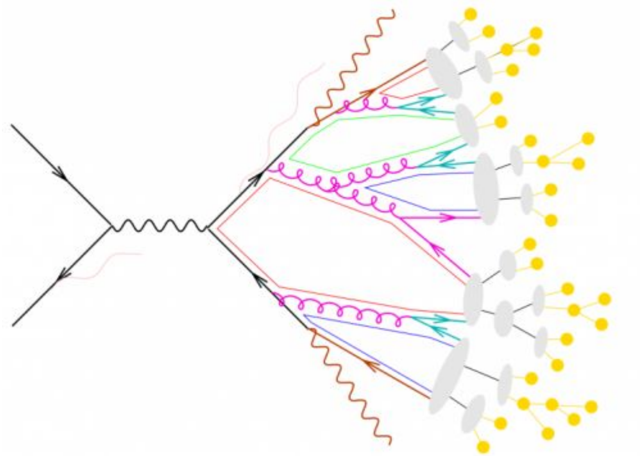
PDFs

Fourier transform
of Form Factors

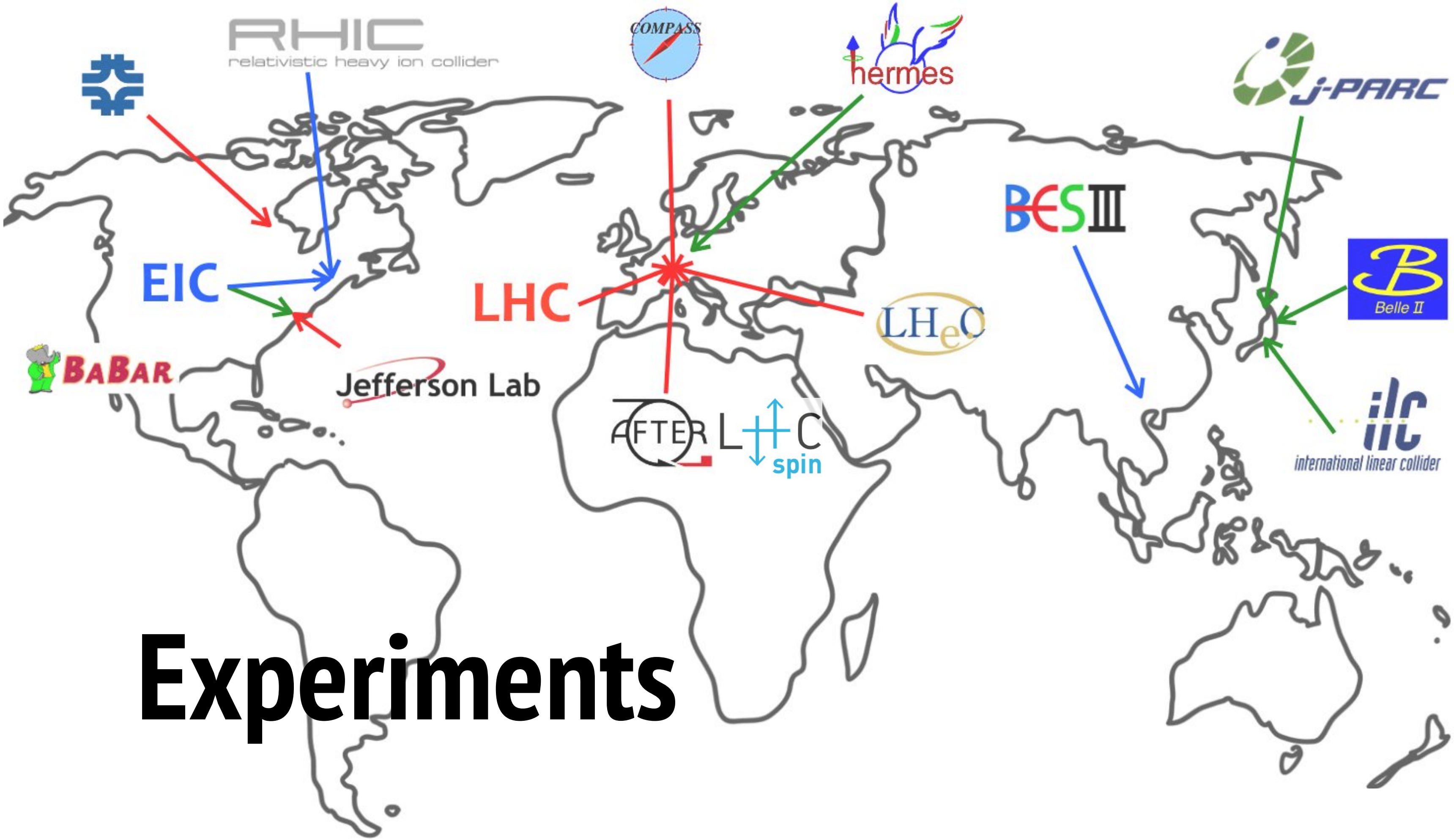
see, e.g., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)

Hadronization and fragmentation functions (FFs)

“Maps” of hadron formation in momentum space



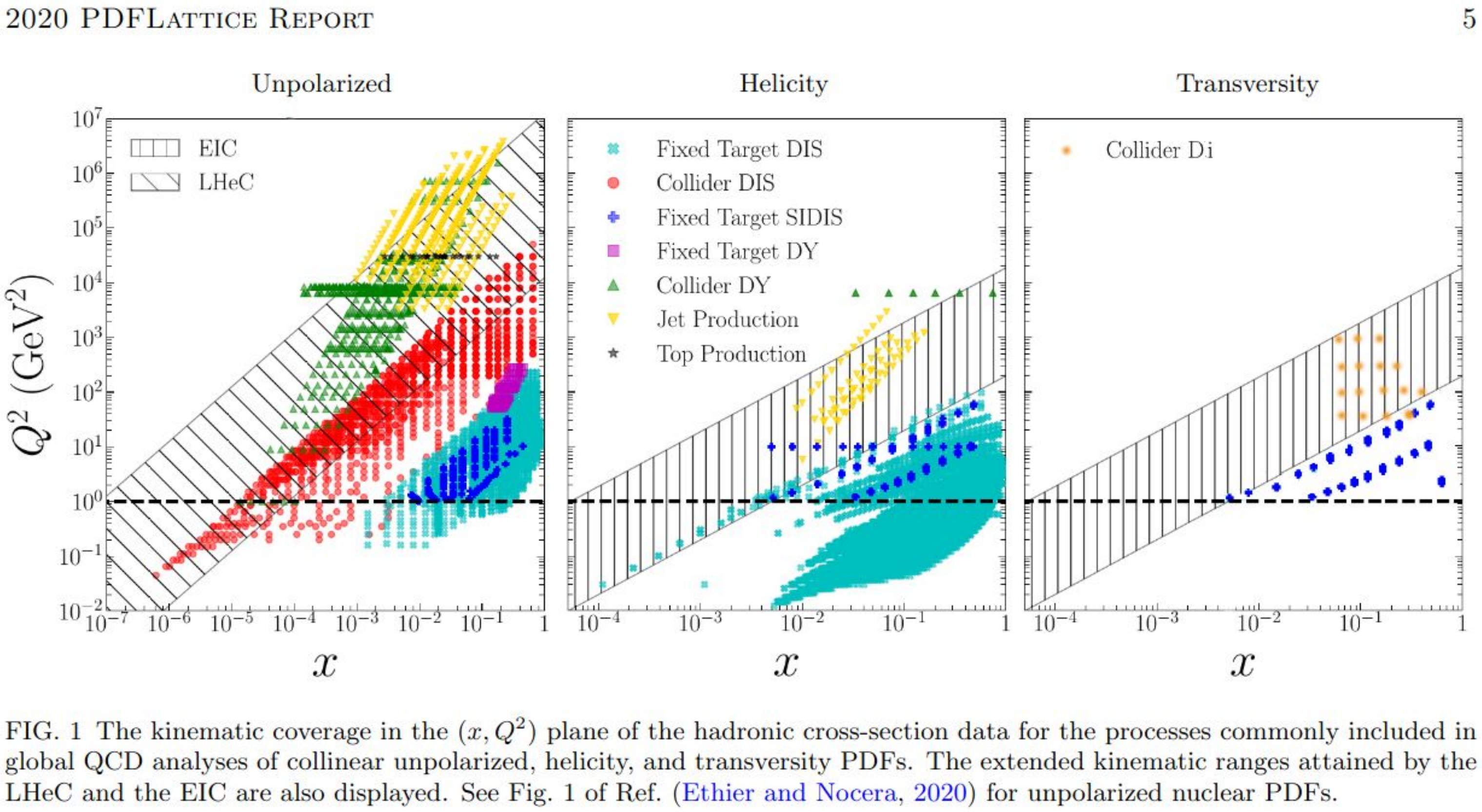
$D_1^h(z)$	single-hadron collinear FF
$D_1^h(z, P_T^2)$	single-hadron TMD FF
$D_1^{h_1\,h_2}(z, \zeta)$	di-hadron FF
$J(s)$	inclusive jet FF
$\mathcal{G}^h(s, z)$	in-jet FF



Experiments

Enough data ..?

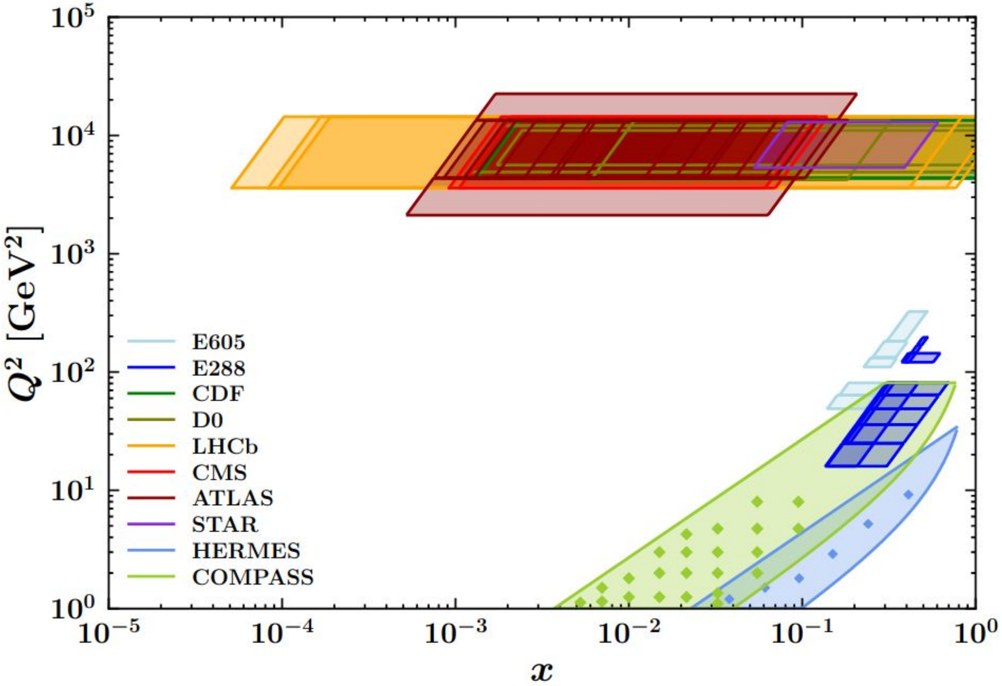
See https://inspirehep.net/literature/1801417



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.

Enough data ..?



Experimental data for unpolarized TMDs

From Pavia analysis
(work in progress)

Semi-Inclusive DIS,
Drell-Yan, Z-production

Need more multidimensional data!

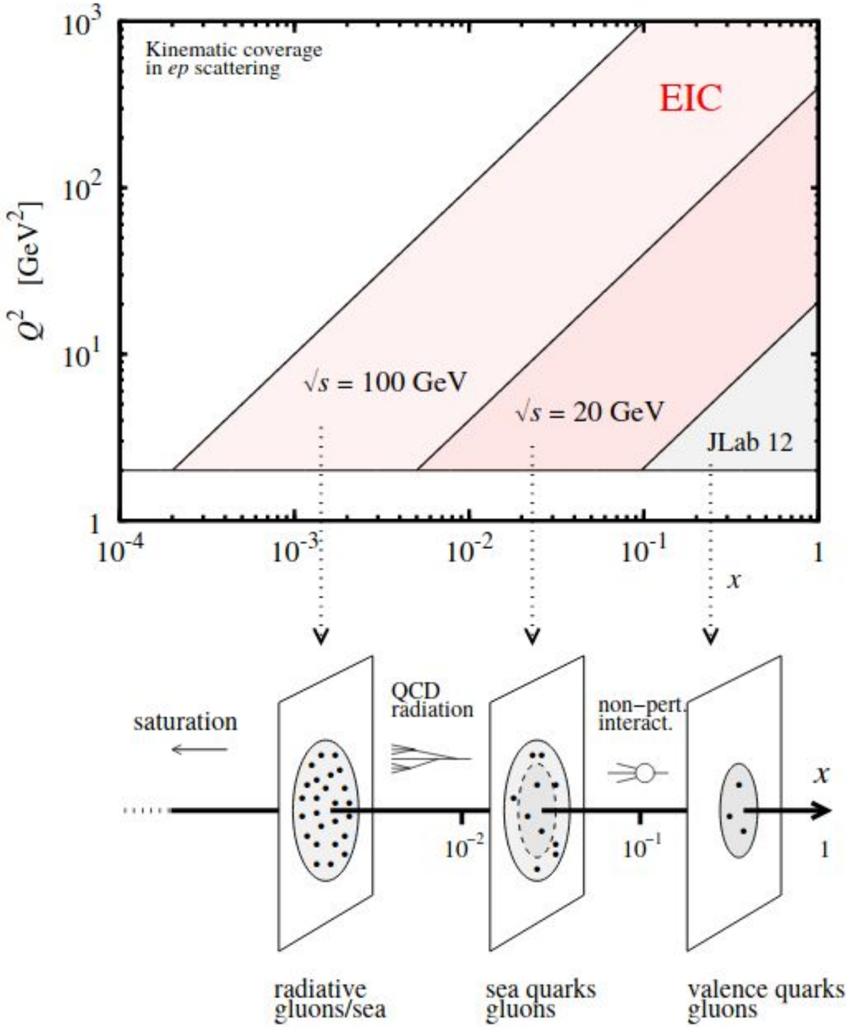
SIDIS coverage

Importance of
complementary experiments

from JLab 12 GeV, Hermes, Compass
to the EIC

zooming into hadron structure

Credit picture: C. Weiss



TMDs and recent phenomenology

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

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

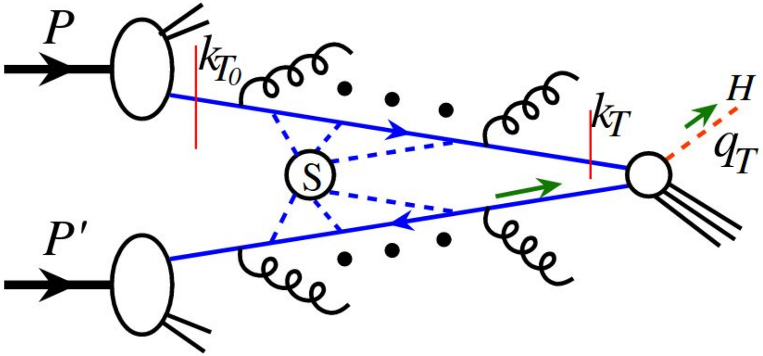
TMD factorization

$$\boxed{q_T \ll Q}$$

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

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

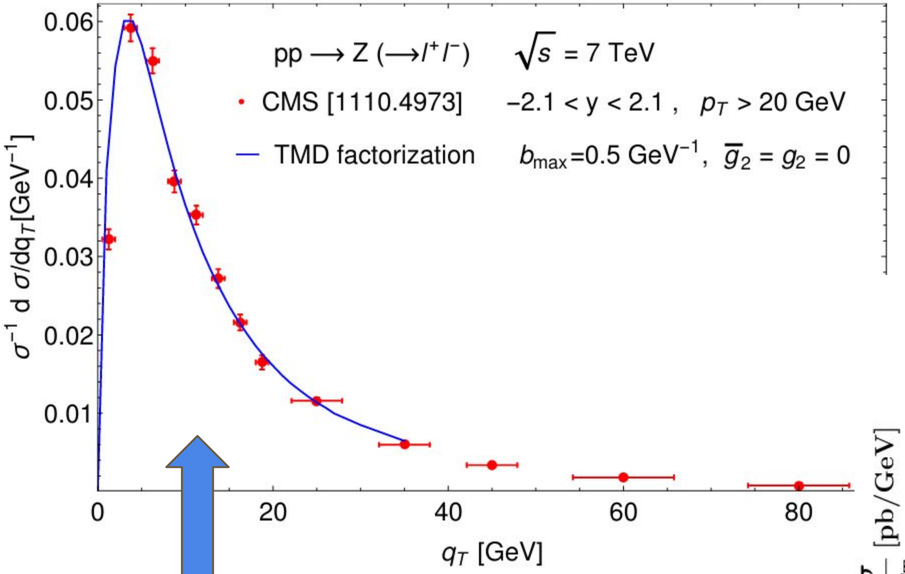
- The TMDs reproduce the structure of the **IR poles** in the cross section (same non-perturbative physics)
- The **observed transverse momentum** is accounted for by the transverse momenta of **quarks**
- The quark transverse momentum has **radiative** (perturbative) and **intrinsic** (non-perturbative)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



TMD region: low transverse momentum

$q_T \ll Q$

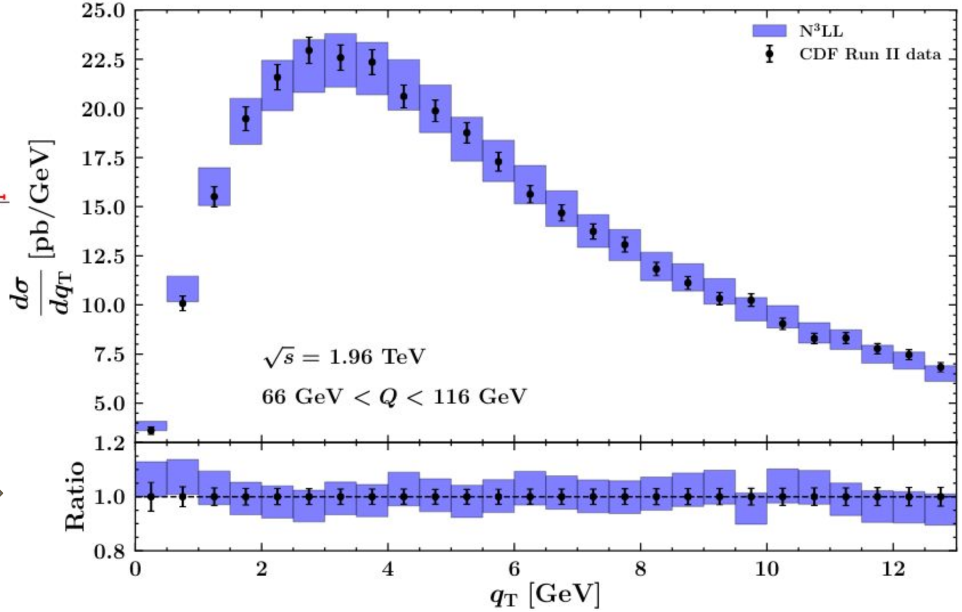
https://inspirehep.net/literature/1785810



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

Hadronic collisions

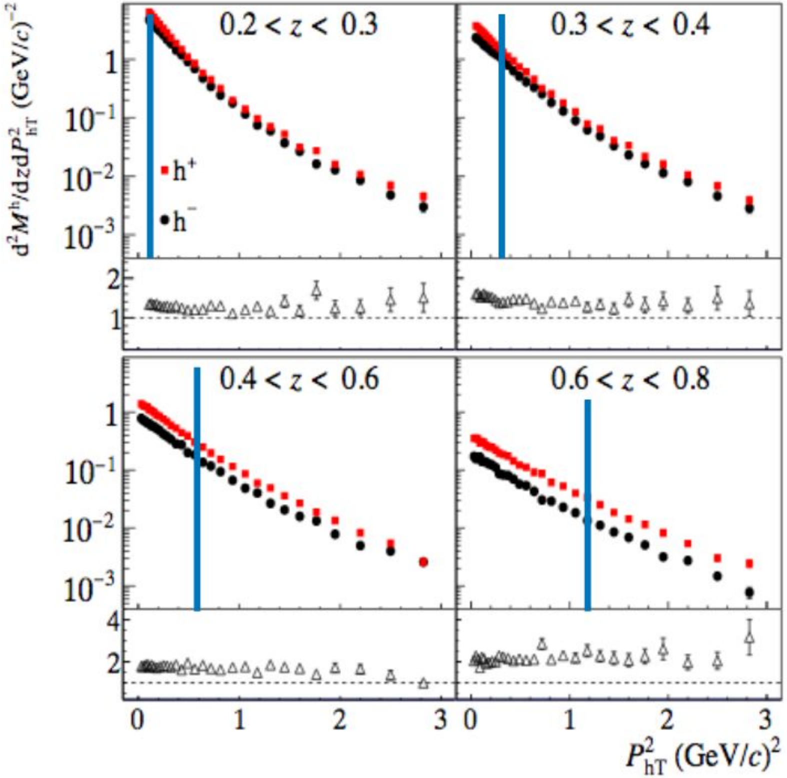
https://inspirehep.net/literature/1771006



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

TMD region: low transverse momentum

$$\boxed{q_T \ll Q}$$



COMPASS unpolarized SIDIS multiplicities - arxiv 1709.07374

SIDIS - TMD region

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

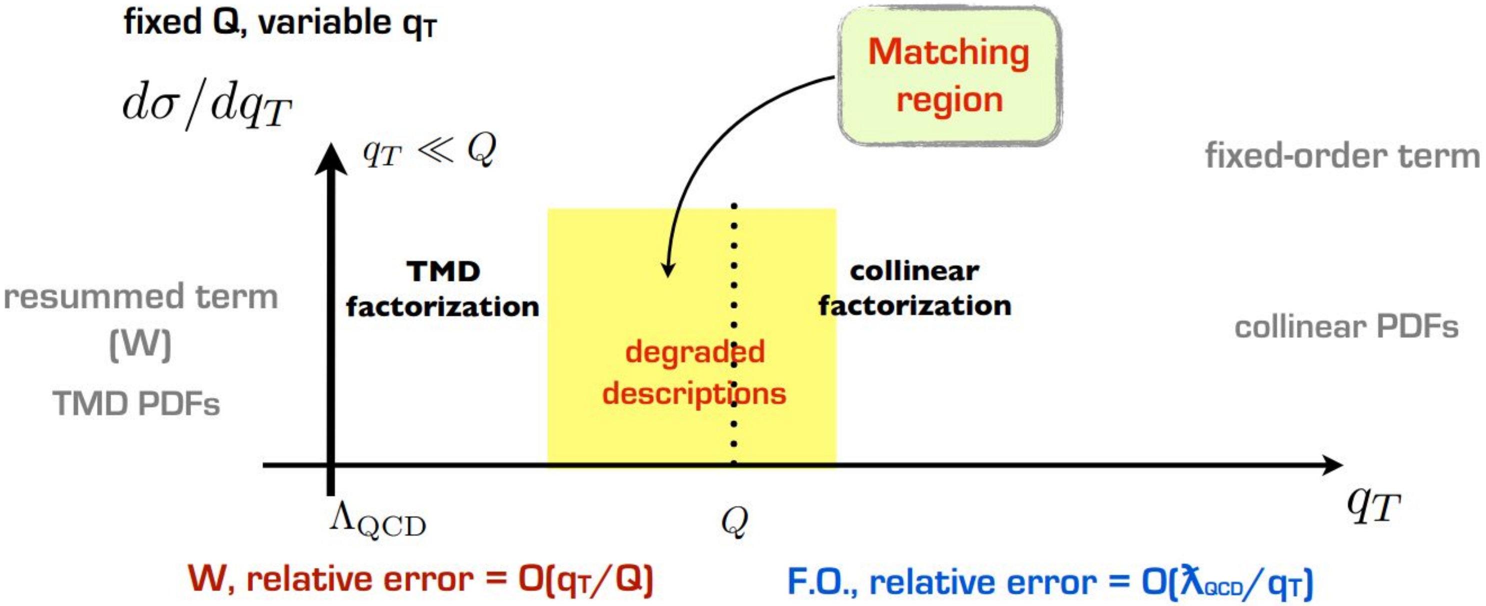
Let's highlight

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

One of the bins with highest Q:

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

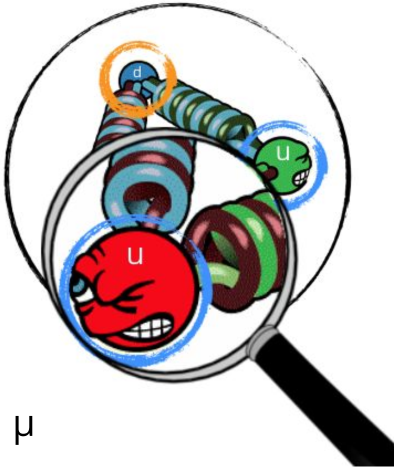
Matching TMD and collinear factorization



W, relative error = $O(q_T/Q)$

F.O., relative error = $O(\Lambda_{\text{QCD}}/q_T)$

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

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

→ evolution in μ

Calculable in pQCD

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

→ evolution in ζ

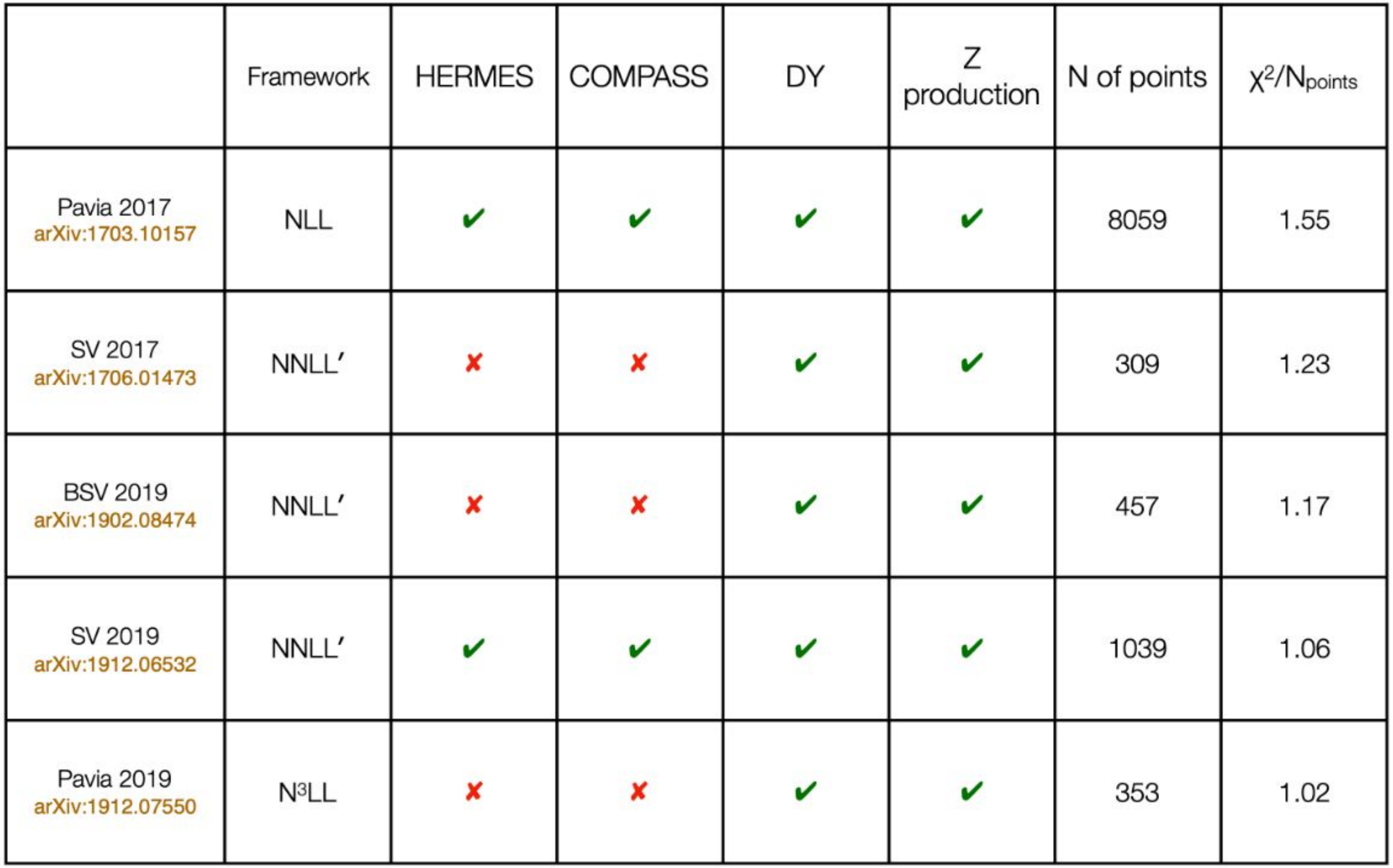
Non-pert. corrections (large bT)

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

Prior knowledge assumed (?)

See e.g. https://inspirehep.net/literature/1785810 (but also JCC book and his talk later today)

A selection of recent fits

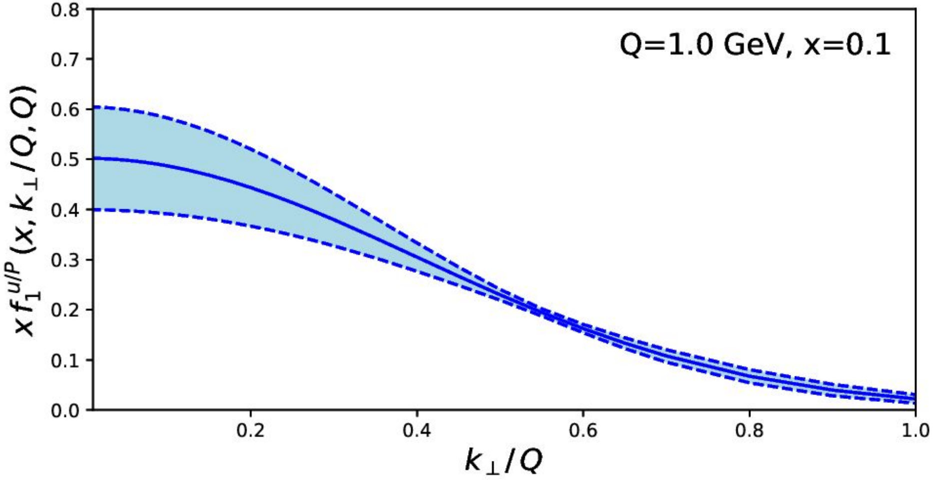


	Framework	HERMES	COMPASS	DY	Z production	N of points	χ^2/N_{points}
Pavia 2017 arXiv:1703.10157	NLL	✓	✓	✓	✓	8059	1.55
SV 2017 arXiv:1706.01473	NNLL′	✗	✗	✓	✓	309	1.23
BSV 2019 arXiv:1902.08474	NNLL′	✗	✗	✓	✓	457	1.17
SV 2019 arXiv:1912.06532	NNLL′	✓	✓	✓	✓	1039	1.06
Pavia 2019 arXiv:1912.07550	N^3LL	✗	✗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

Unpolarized TMDs: PV17

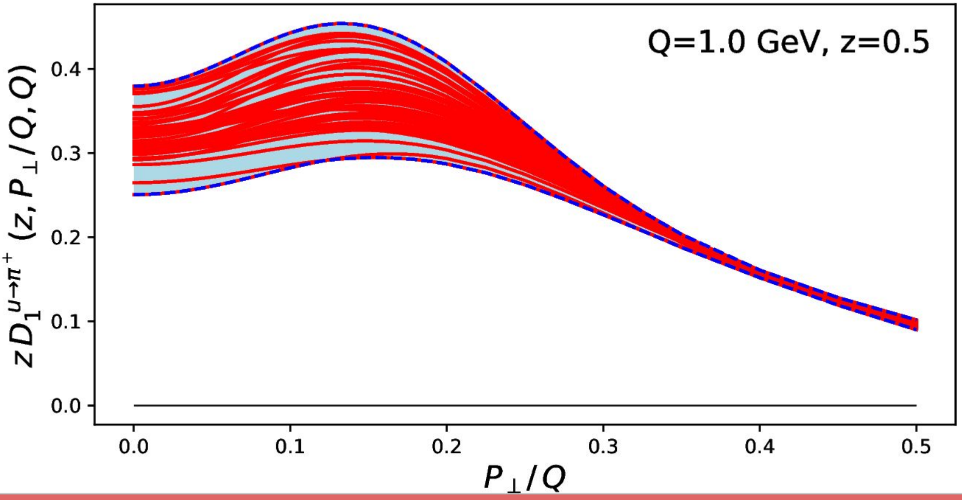
see https://inspirehep.net/literature/1520011

Imaging from **SIDIS** data (Hermes and Compass)
and **Drell-Yan** data (fixed-target & Z production @ Fermilab)



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

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

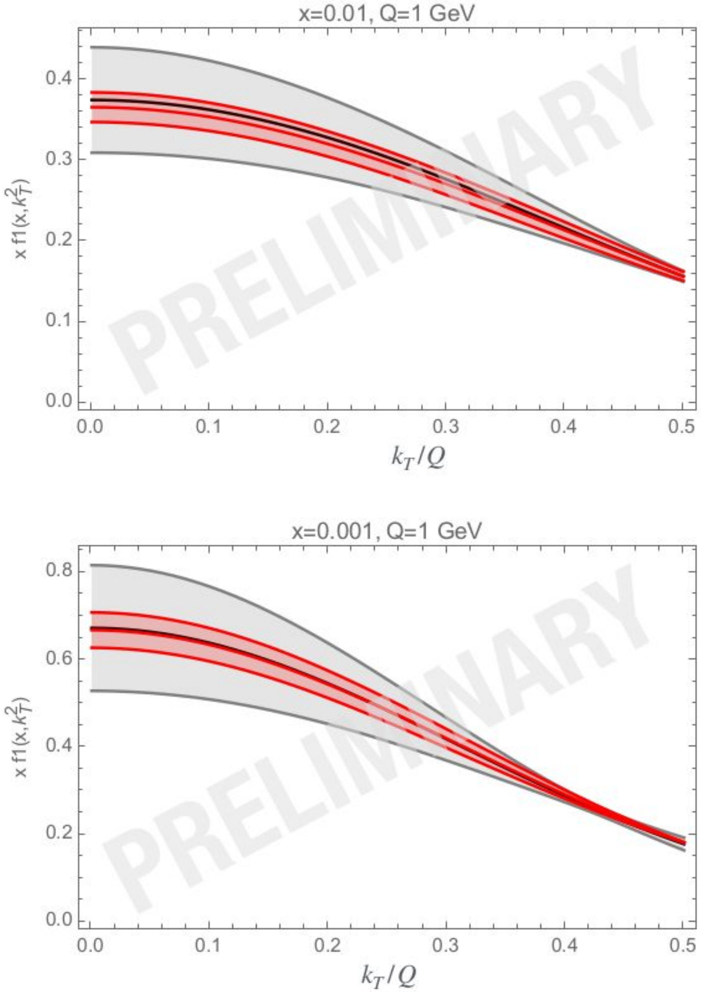
'original' χ^2
with respect to PV17 data

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)



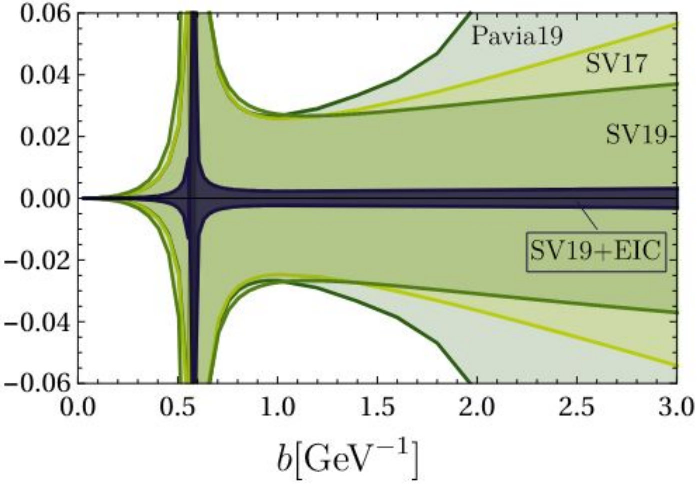
TMD impact studies: SV19

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

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

→ evolution in ζ

Non-pert. corrections (large bT)



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

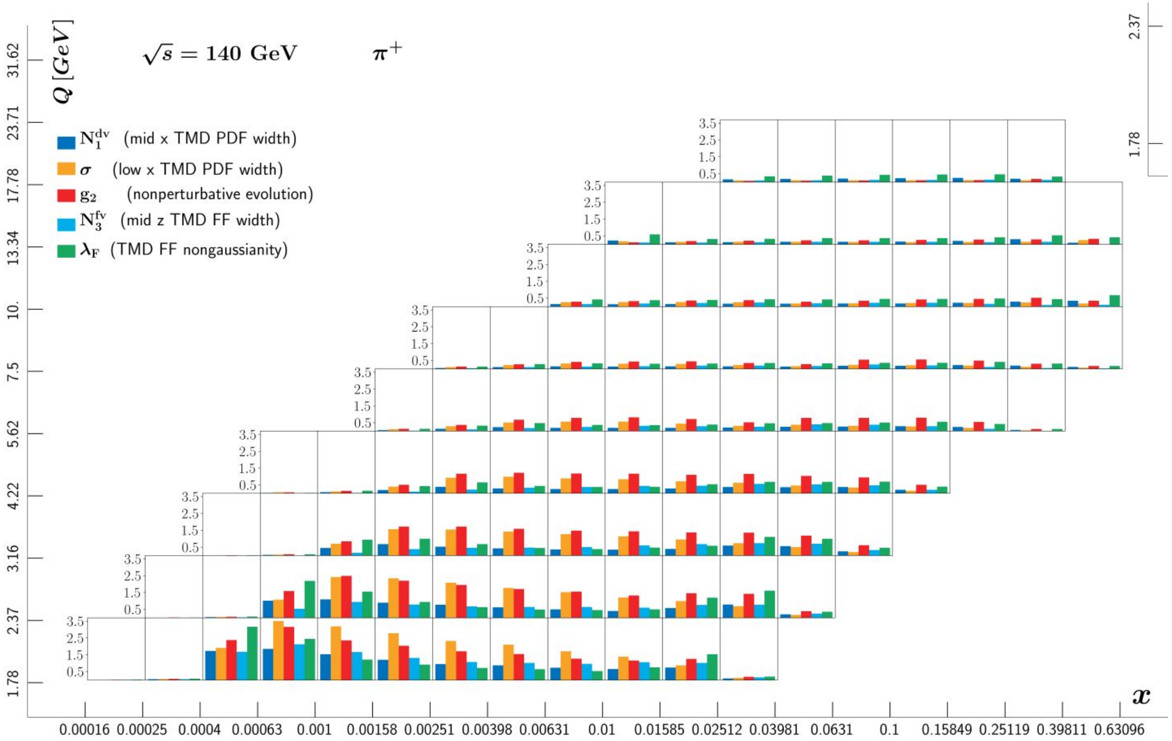
Huge impact of EIC SIDIS program on **non-perturbative TMD evolution**

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



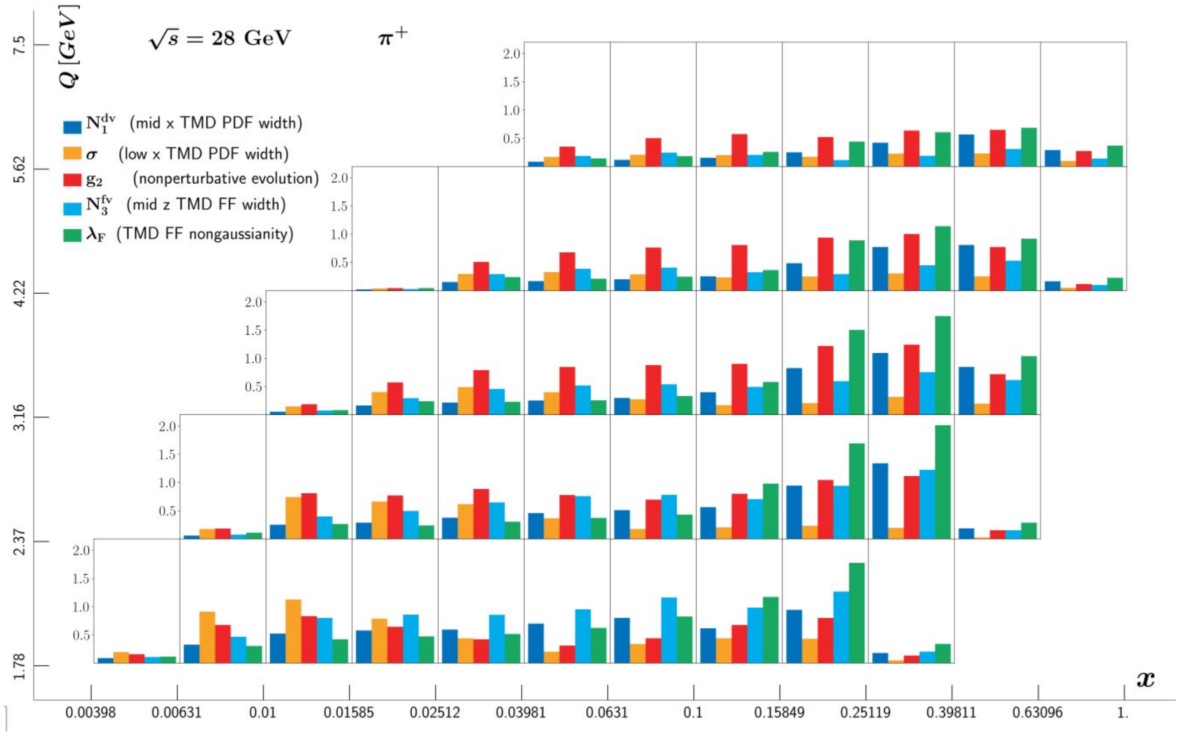
$$\sqrt{s} = 140 \ \text{GeV}$$

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



$$\sqrt{s} = 28 \text{ GeV}$$

Stronger effect at
lower energies

Different frameworks, same observable

$$\left(\frac{d\sigma}{dq_T}\right)_{\text{res.}} \begin{array}{ll} \overset{q_T-\text{res.}}{\underset{\text{PB}}{\propto}} & e^{2S}\,[f_1\otimes\mathcal{H}\otimes f_2] \\ \overset{\text{TMD}}{\propto} & H\times F_1\times F_2 \\ \overset{\text{SCET}}{\propto} & H\times B_1\times B_2\times S \end{array} + \mathcal{O}\left[\left(\frac{q_T}{Q}\right)^m\right]$$

$$\mathcal{H} = HC_1C_2$$

$$F_i = e^S C_i \otimes f_i$$

$$F_i = \sqrt{S}\times B_i$$

Dictionary to compare different factorization frameworks

“equivalent” to the extent of describing TMD physics

G. Bozzi at SarWors 2021 - https://agenda.infn.it/event/27742/

Tools for TMD physics

Codes

SCETlib
[https://confluence.desy.de/display/scetlib]

CuTe
[https://cute.hepforge.org/]

SCET

DYRes/DYTurbo, DYqT, etc.
[https://gitlab.cern.ch/DYdevel/DYTURBO]

ReSolve
[https://github.com/fkhorad/reSolve]

ResBos
[https://resbos.hepforge.org/]

qT resummation

TMD factorization

arTeMiDe
[https://teorica.fis.ucm.es/artemide/]

Nanga Parbat
[https://github.com/MapCollaboration/NangaParbat]

Parton branching

RadISH
[https://arxiv.org/pdf/1705.09127.pdf]

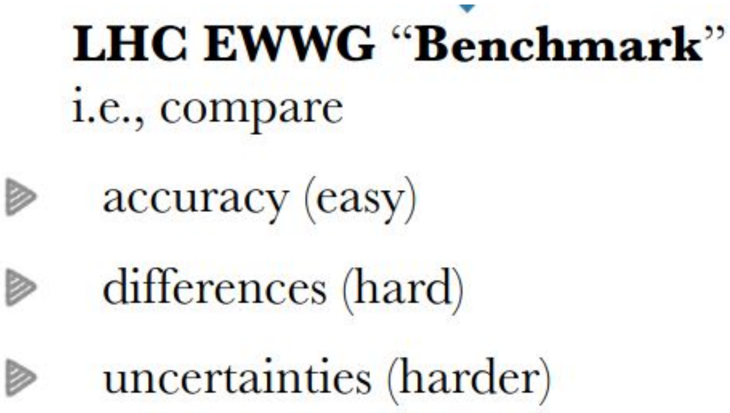
PB-TMDs
[https://arxiv.org/pdf/1906.00919.pdf]

G. Bozzi at SarWors 2021 - https://agenda.infn.it/event/27742/

Codes

Excellent accuracy **BUT** *only unpolarized and leading twist*!

Basic ingredients **common** to all codes



LHC EWWG "Benchmark"
i.e., compare

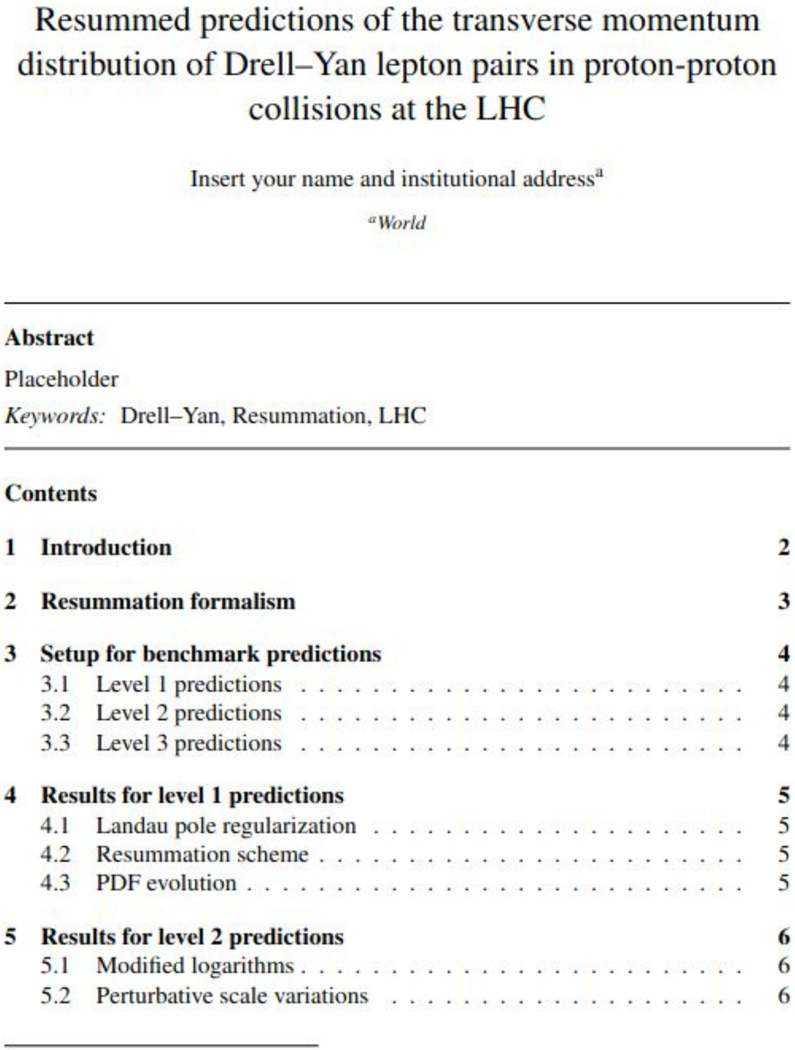
- accuracy (easy)
- differences (hard)
- uncertainties (harder)

Main **differences**:

- "Space": position vs momentum space
- Perturbative QCD: PDF evolution, scale variation, matching with fixed-order
- Non-perturbative QCD: treatment of Landau pole, intrinsic-kT

G. Bozzi at SarWors 2021 - https://agenda.infn.it/event/27742/

LHC EWWG "yellow report"



Resummed predictions of the transverse momentum distribution of Drell–Yan lepton pairs in proton-proton collisions at the LHC

Insert your name and institutional address[a]

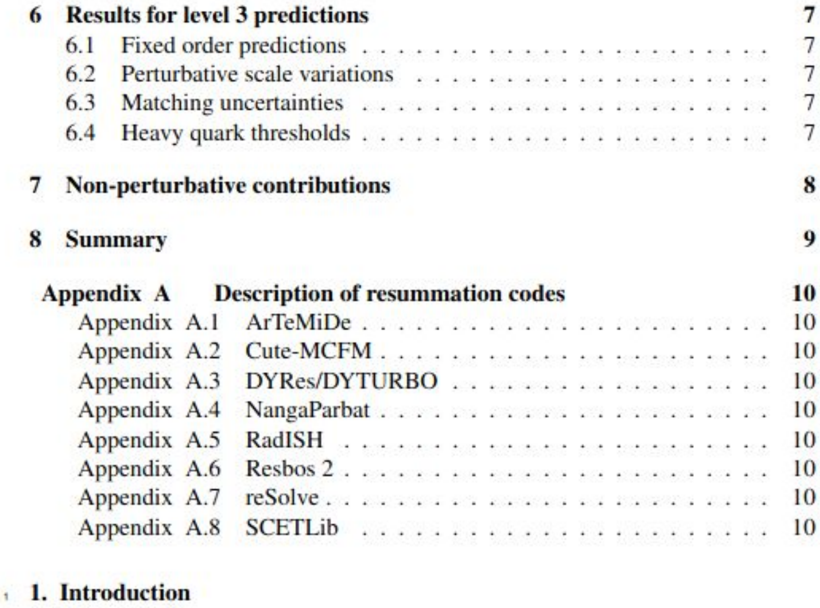
[a]*World*

Abstract

Placeholder

Keywords: Drell–Yan, Resummation, LHC

Contents



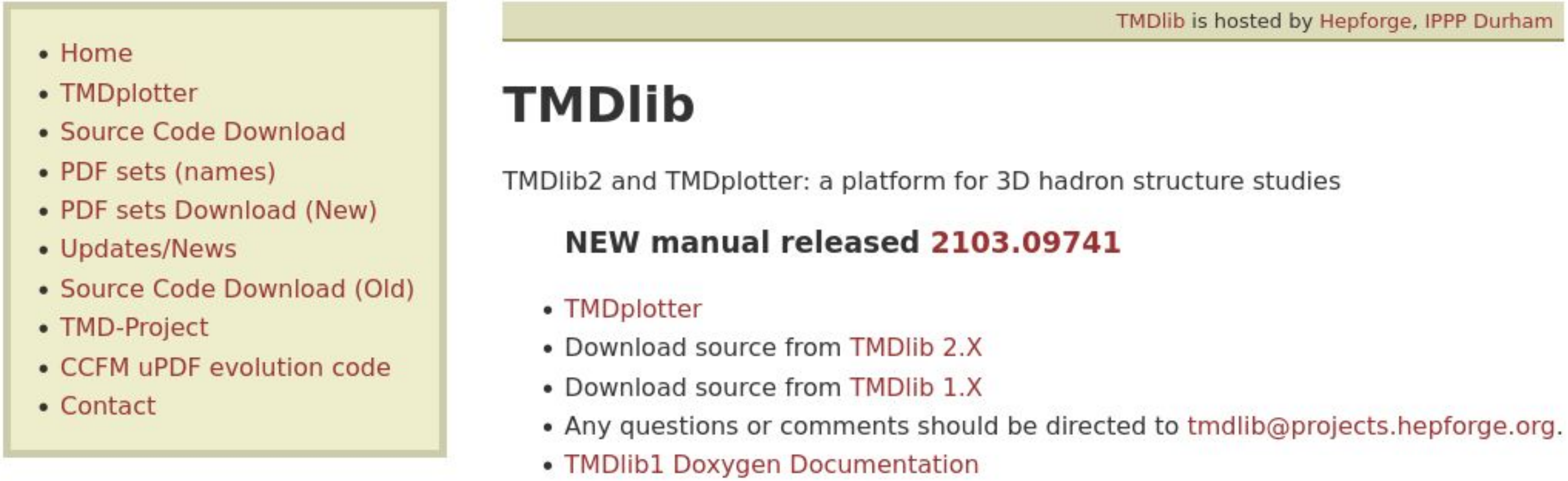
1. Introduction

G. Bozzi at SarWors 2021 - https://agenda.infn.it/event/27742/

TMDlib

https://inspirehep.net/literature/1852038

https://tmdlib.hepforge.org/



- Home
- TMDplotter
- Source Code Download
- PDF sets (names)
- PDF sets Download (New)
- Updates/News
- Source Code Download (Old)
- TMD-Project
- CCFM uPDF evolution code
- Contact

TMDlib is hosted by Hepforge, IPPP Durham

TMDlib

TMDlib2 and TMDplotter: a platform for 3D hadron structure studies

NEW manual released 2103.09741

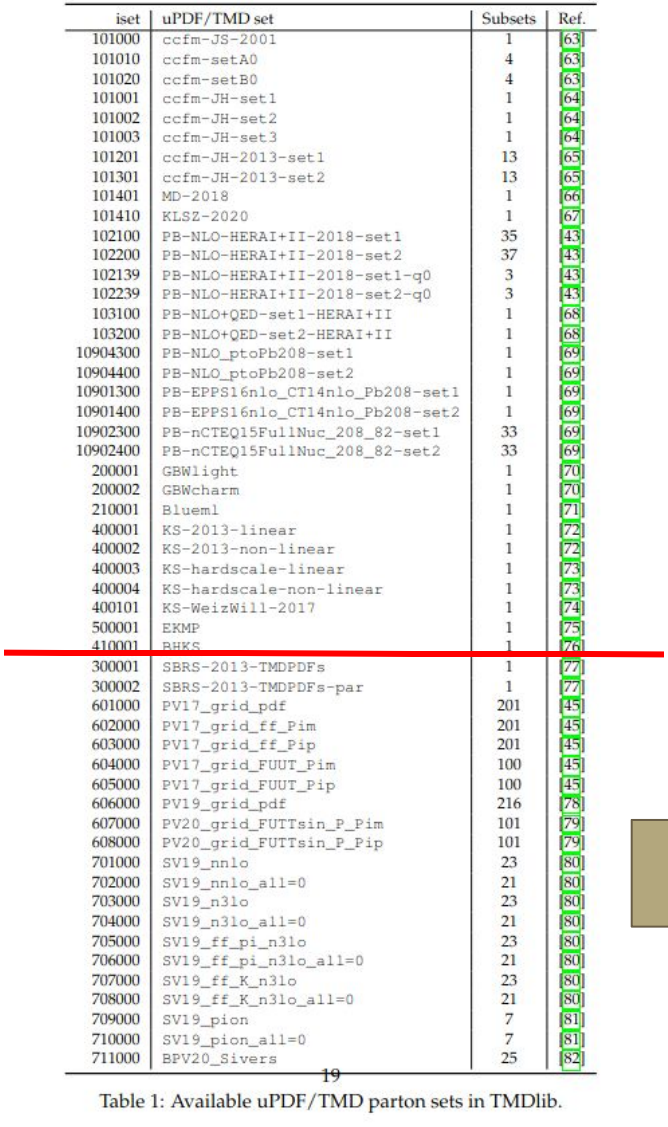
- TMDplotter
- Download source from TMDlib 2.X
- Download source from TMDlib 1.X
- Any questions or comments should be directed to tmdlib@projects.hepforge.org.
- TMDlib1 Doxygen Documentation

TMDlib

PB TMDs, etc

https://inspirehep.net/literature/1852038

https://tmdlib.hepforge.org/



iset	uPDF/TMD set	Subsets	Ref.
101000	ccfm-JS-2001	1	[63]
101010	ccfm-setA0	4	[63]
101020	ccfm-setB0	4	[63]
101001	ccfm-JH-set1	1	[64]
101002	ccfm-JH-set2	1	[64]
101003	ccfm-JH-set3	1	[64]
101201	ccfm-JH-2013-set1	13	[65]
101301	ccfm-JH-2013-set2	13	[65]
101401	MD-2018	1	[66]
101410	KLSZ-2020	1	[67]
102100	PB-NLO-HERAI+II-2018-set1	35	[43]
102200	PB-NLO-HERAI+II-2018-set2	37	[43]
102139	PB-NLO-HERAI+II-2018-set1-q0	3	[43]
102239	PB-NLO-HERAI+II-2018-set2-q0	3	[43]
103100	PB-NLO+QED-set1-HERAI+II	1	[68]
103200	PB-NLO+QED-set2-HERAI+II	1	[68]
10904300	PB-NLO_ptoPb208-set1	1	[69]
10904400	PB-NLO_ptoPb208-set2	1	[69]
10901300	PB-EPPS16nlo_CT14nlo_Pb208-set1	1	[69]
10901400	PB-EPPS16nlo_CT14nlo_Pb208-set2	1	[69]
10902300	PB-nCTEQ15FullNuc_208_82-set1	33	[69]
10902400	PB-nCTEQ15FullNuc_208_82-set2	33	[69]
200001	GBWlight	1	[70]
200002	GBWcharm	1	[70]
210001	Blueml	1	[71]
400001	KS-2013-linear	1	[72]
400002	KS-2013-non-linear	1	[72]
400003	KS-hardscale-linear	1	[73]
400004	KS-hardscale-non-linear	1	[73]
400101	KS-WeizWill-2017	1	[74]
500001	EKMP	1	[75]
410001	BHKS	1	[76]
300001	SBRS-2013-TMDPDFs	1	[77]
300002	SBRS-2013-TMDPDFs-par	1	[77]
601000	PV17_grid_pdf	201	[45]
602000	PV17_grid_ff_Pim	201	[45]
603000	PV17_grid_ff_Pip	201	[45]
604000	PV17_grid_FUUT_Pim	100	[45]
605000	PV17_grid_FUUT_Pip	100	[45]
606000	PV19_grid_pdf	216	[78]
607000	PV20_grid_FUTTsin_P_Pim	101	[79]
608000	PV20_grid_FUTTsin_P_Pip	101	[79]
701000	SV19_nnlo	23	[80]
702000	SV19_nnlo_all=0	21	[80]
703000	SV19_n3lo	23	[80]
704000	SV19_n3lo_all=0	21	[80]
705000	SV19_ff_pi_n3lo	23	[80]
706000	SV19_ff_pi_n3lo_all=0	21	[80]
707000	SV19_ff_K_n3lo	23	[80]
708000	SV19_ff_K_n3lo_all=0	21	[80]
709000	SV19_pion	7	[81]
710000	SV19_pion_all=0	7	[81]
711000	BPV20_Sivers	25	[82]

Table 1: Available uPDF/TMD parton sets in TMDlib.

TMD factorization:

Unpolarized TMDs (PV13, PV17, SV19)
Sivers TMD PDF (PV20, BPV20)

SIDIS structure functions (PV17, PV20)

Event generators

Based on TMDs:

- Cascade (PB TMDs)
  [https://cascade.hepforge.org/]

- gmctrans/TMDgen
  - parton model level TMDs
  - includes polarization and higher twist, but no evolution: too primitive for EIC?
  - semi-inclusive
  [https://wiki.bnl.gov/eic/index.php/Gmc_trans
  Hermes collaboration + independent work]

Exclusive generators with transverse momentum effects

- Pythia [https://pythia.org/]
- Herwig [https://herwig.hepforge.org/]
- Geneva [https://stash.desy.de/projects/GENEVA]
- ...

Conclusions and outlook

1. We are working hard to build “**maps**” of hadron structure and formation: **parton distribution and fragmentation functions** and the like, connected to fundamental properties of QCD

2. **Crucial input** is provided by **experiments**.
The **Electron-Ion Collider** is the next experimental frontier of QCD and will provide us with a wealth of information: **we have to be ready for that!**

3. Which **tools for TMD physics** are most needed?
How can **theorists** and **experimentalists work together** to develop these tools?

4. Can we define **“best practices”** for these tools? Standard formats, availability, etc.?

Backup

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)

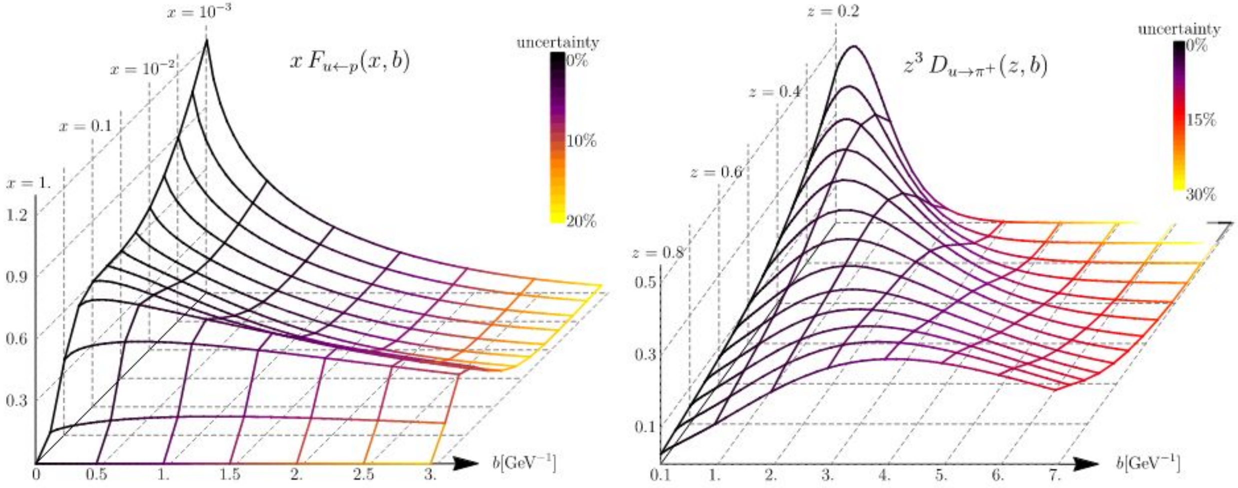


Figure 24. Example of extracted (optimal) unpolarized TMD distributions. The color indicates the relative size of the uncertainty band

TMD impact studies: SV19

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

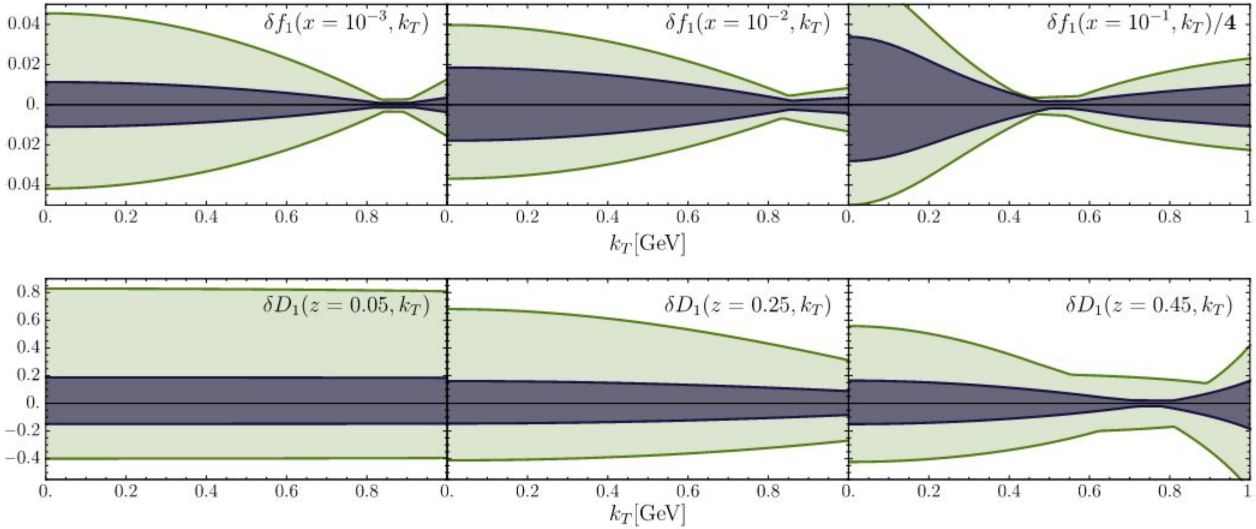


Figure 7.52: Comparison of relative uncertainty bands (i.e. uncertainties normalized by central value) for up-quark unpolarized TMD PDFs (upper panel) and $u \to \pi^+$ pion TMD FFs (lower panel), at different values of x and z as a function of k_T, for $\mu = 2$ GeV. Lighter band is the SV19 extraction,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

Up in proton
TMD PDF

Up to pion+
TMD FF

Fit with EIC
pseudo-data

Quark TMD PDFs (spin ½)

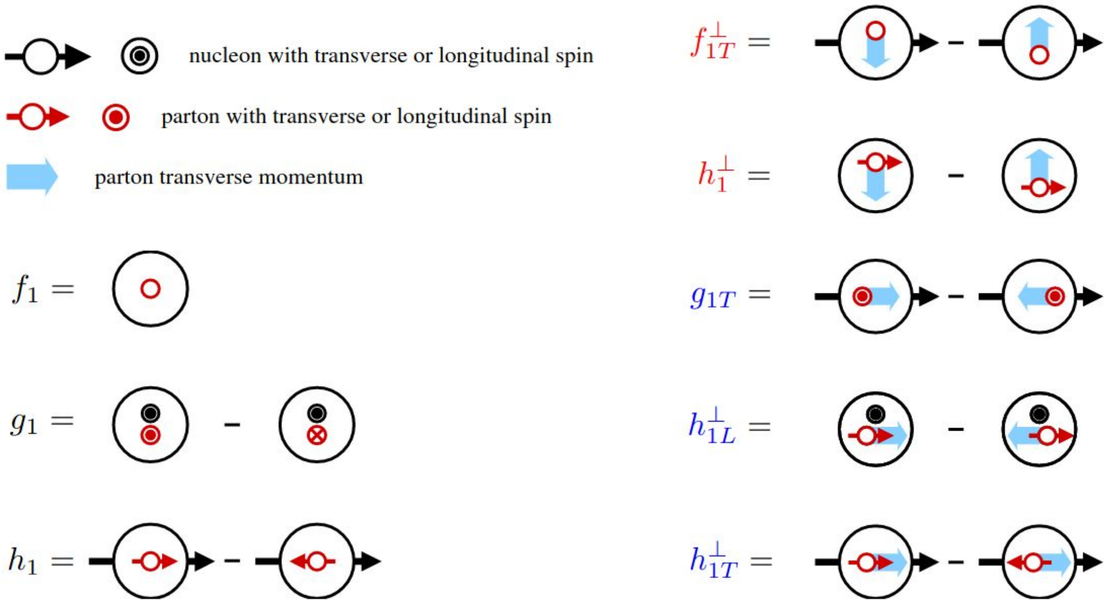


Figure 3.5: Probabilistic interpretation of twist-2 transverse-momentum-dependent distribution functions. To avoid ambiguities, it is necessary to indicate the directions of quark's transverse momemtum, target spin and quark spin, and specify that the proton is moving out of the page, or alternatively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

From Bacchetta's "Trento" lecture notes

Matching schemes

- **“Subtraction” schemes :**

  cross section = **W + (FO - ASY)** = **W + Y**

  cross section = W * FO / ASY

At low Q (e.g. SIDIS) these cancellations do not work well as expected

- **“Average” scheme :**

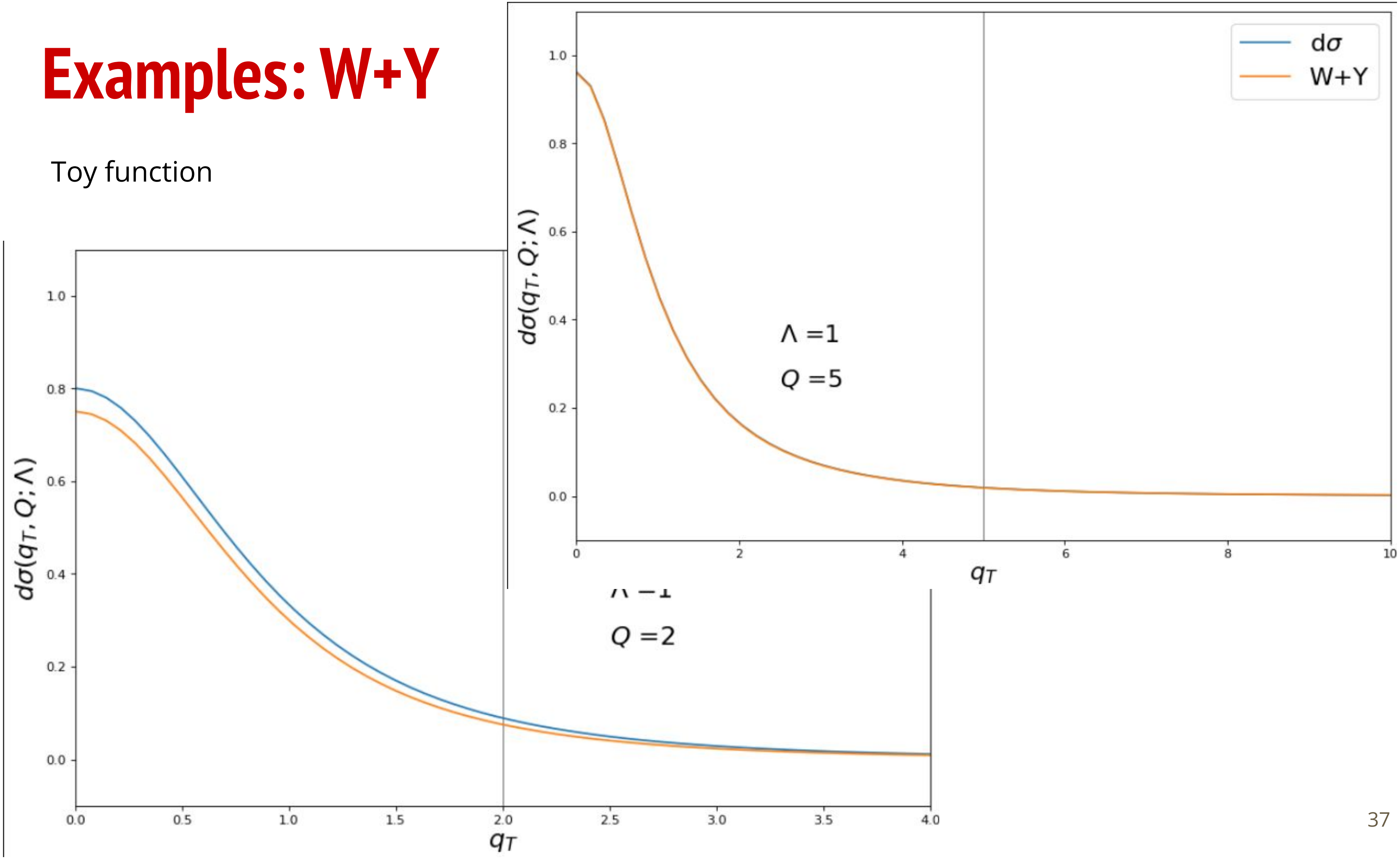
  Cross section = **a W + b FO**
  a, b : weights related to *power corrections to factorization theorems*

  (weighted average scheme: model-dependence better under control)

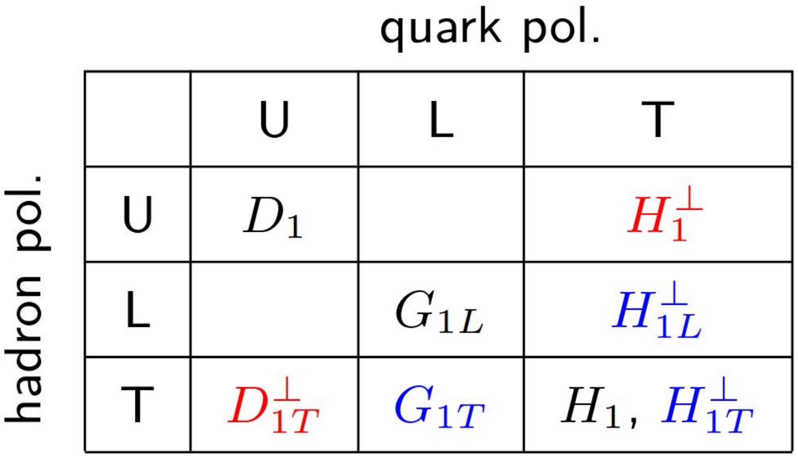
AS et al. https://inspirehep.net/literature/1646273

Examples: W+Y

Toy function



Collinear and TMD single-hadron FFs



quark pol.

hadron pol.

	U	L	T
U	D_1		$H_1^\perp$
L		G_{1L}	$H_{1L}^\perp$
T	$D_{1T}^\perp$	G_{1T}	$H_1,\ H_{1T}^\perp$

At leading twist:
8 TMD FFs and
3 collinear FFs (diagonal)

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

Universality..!

Transversity

Distribution of transversely polarized quarks in a transversely polarized nucleon

Chiral-odd function - needs a chiral odd partner in the cross section

Potential to access new physics in high-precision low-energy experiments

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

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

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

Otherwise gluon “absorption” instead of “emission”

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

Separating small and large bT

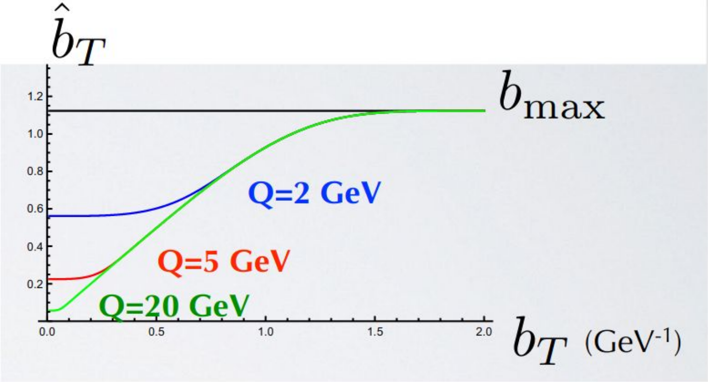
One needs to “separate” the small (perturbative) bT region from the large (non-perturbative) bT region:

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

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

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

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



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

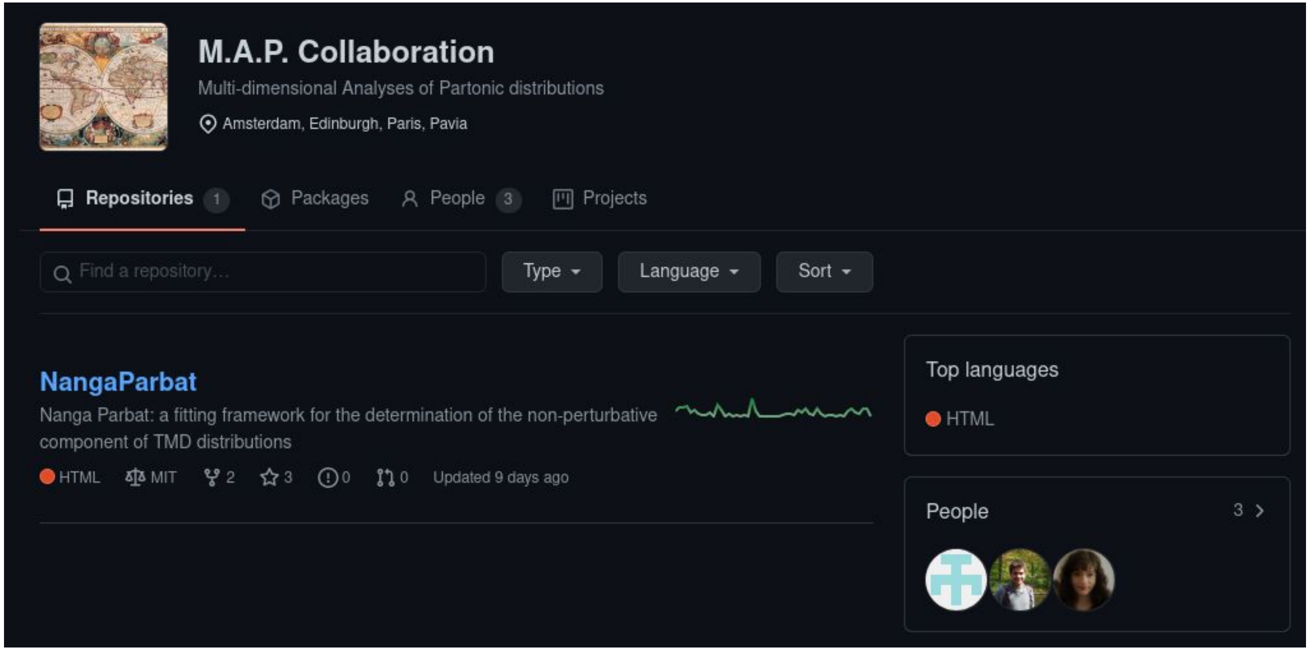
Some open questions

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
- ..

The M.A.P. collaboration

https://github.com/MapCollaboration



M.A.P. Collaboration

Multi-dimensional Analyses of Partonic distributions

Amsterdam, Edinburgh, Paris, Pavia

NangaParbat

Nanga Parbat: a fitting framework for the determination of the non-perturbative component of TMD distributions

● HTML MIT 2 3 0 0 Updated 9 days ago

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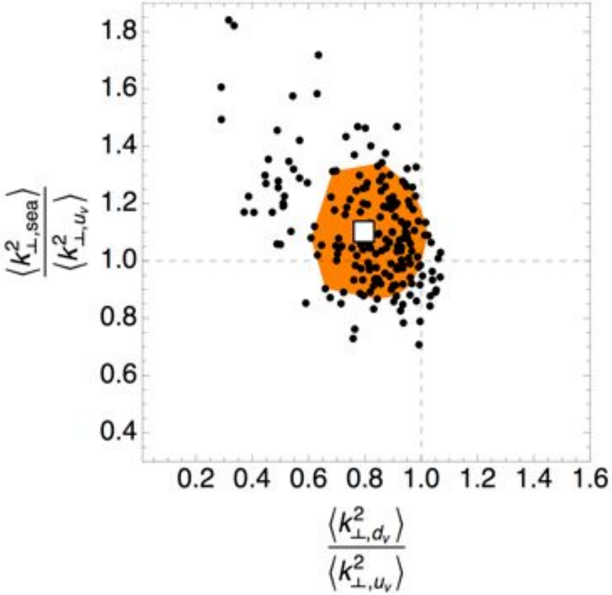
People 3

Multi-dimensional analyses of partonic distributions (MAP)
Amsterdam / Edinburgh / Paris / Pavia

Flavor structure of TMDs (PV13)

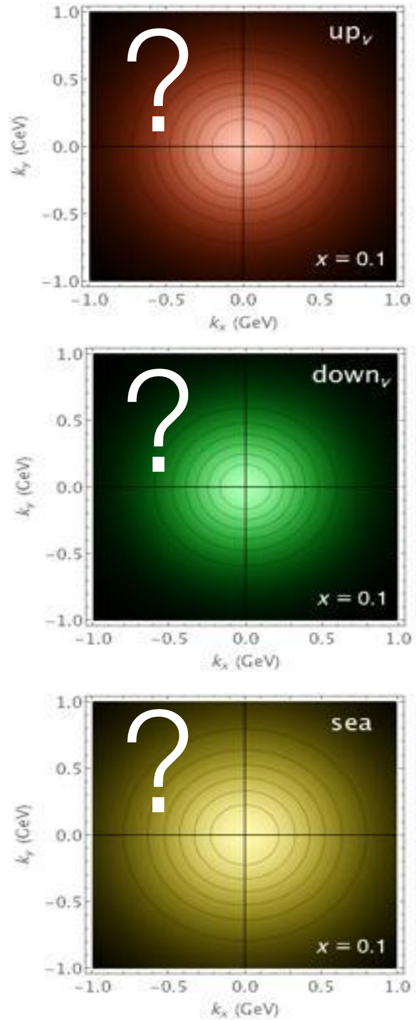
Imaging from **SIDIS** data from Hermes experiment



Ratio of width of sea / width of up valence

Ratio width of down valence/ width of up valence

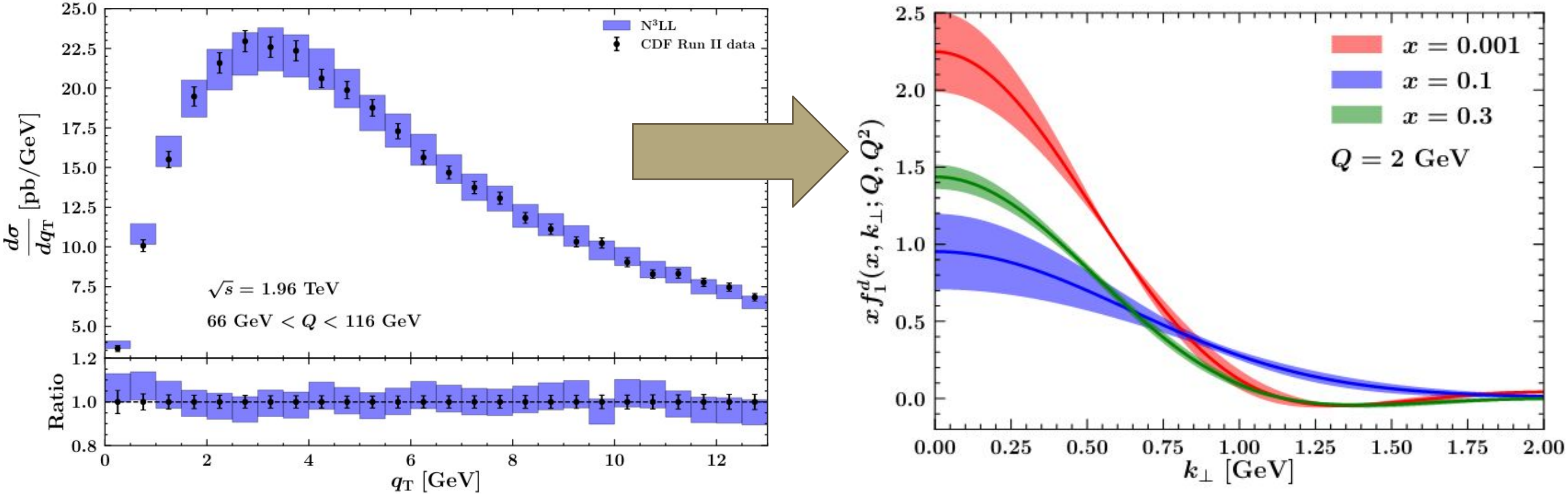
A lot of room
for flavor-dependent distributions



arXiv 1309.3507

Precise extraction of TMDs (PV19)

Imaging from **Drell-Yan** data (Fermilab, low energy and Z + LHC)



State of the art accuracy in perturbation theory (N3LL)

arXiv 1912.07550