SQUHADRON

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Opportunities for semi-inclusive studies at high energies

J-FUTURE - U. of Messina

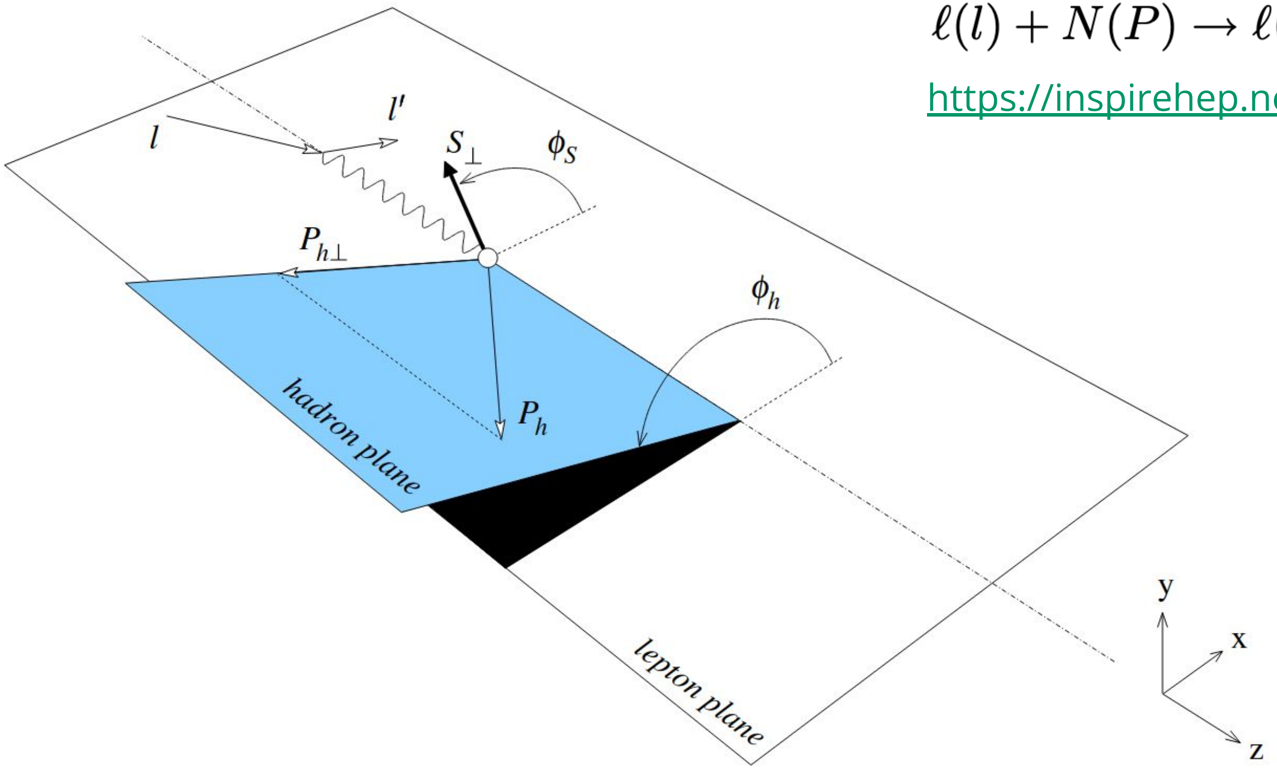
March 28, 2022

Outline

1. **SIDIS and TMD physics**
2. **Challenges and opportunities**
3. **Fits and impact studies**

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

https://inspirehep.net/literature/732275



SIDIS and TMD physics

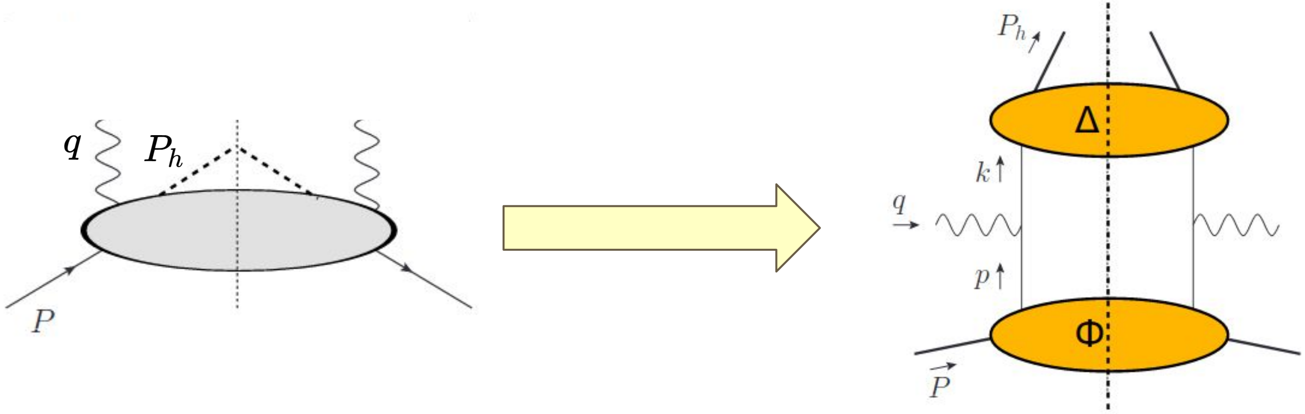
SIDIS cross section (polarized nucleon)

$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} \\
&= \frac{\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\biggl\{ F_{UU,T} + \varepsilon\,F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} \\
&\quad + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} + S_L\biggl[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\biggr] \\
&\quad + S_L\,\lambda_e\biggl[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\biggr] \\
&\quad + S_T\biggl[\sin(\phi_h-\phi_S)\,\Bigl(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\Bigr) + \varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} \\
&\qquad + \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} \\
&\qquad + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\biggr] + S_T\lambda_e\biggl[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} \\
&\qquad + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\biggr]\biggr\}
\end{aligned}
$$

18 structure functions
for polarized nucleon target

For more details see https://inspirehep.net/literature/732275

Partonic interpretation

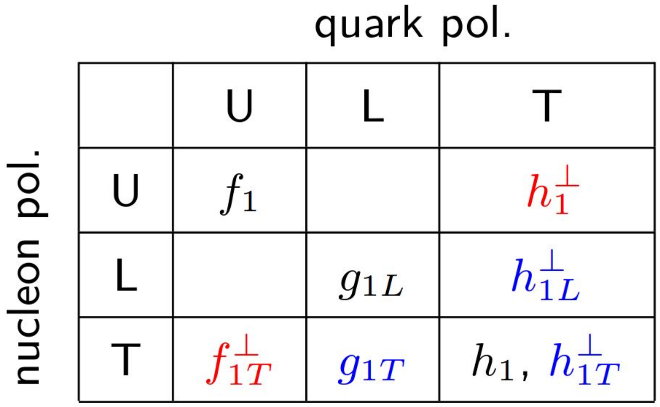


\+ higher twist (suppressed)

$$2MW^{\mu\nu}(q,P,S,P_h) = \frac{2z_h}{x_B}\,\mathcal{C}\Big[\mathrm{Tr}\big(\Phi(x_B,\boldsymbol{p}_T,S)\,\gamma^\mu\,\Delta(z_h,\boldsymbol{k}_T)\,\gamma^\nu\big)\Big]$$

$$\mathcal{C}\big[wfD\big] = \sum x e_a^2 \int d^2\boldsymbol{p}_T\, d^2\boldsymbol{k}_T\, \delta^{(2)}\big(\boldsymbol{p}_T-\boldsymbol{k}_T-\boldsymbol{P}_{h\perp}/z\big)\, w(\boldsymbol{p}_T,\boldsymbol{k}_T)\, f^a(x,p_T^2)\, D^a(z,k_T^2)$$

TMD PDFs and TMD FFs

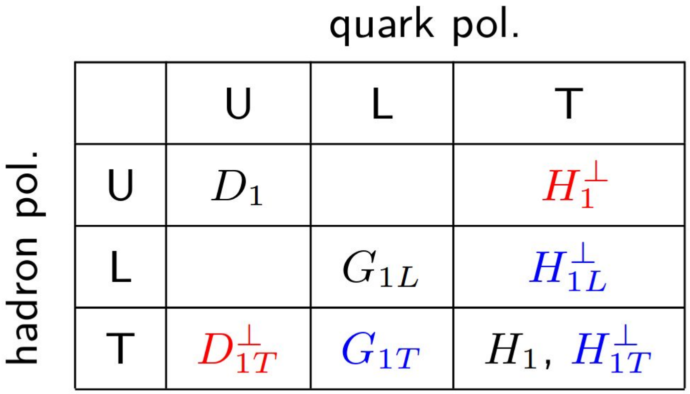


quark pol.

nucleon pol.

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

8 TMD PDFs at leading twist



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}	$H_1,\ H_{1T}^\perp$

8 TMD FFs at leading twist

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

SIDIS: structure functions and TMDs

Leading twist TMDs

$$F_{UU,T} = \mathcal{C}\boxed{\left[f_1 D_1\right]},$$

“Collins effect”

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

“Sivers effect”

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

Etc. ...

Higher twist TMDs

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

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

TMD factorization

$\boxed{q_T \ll Q}$

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

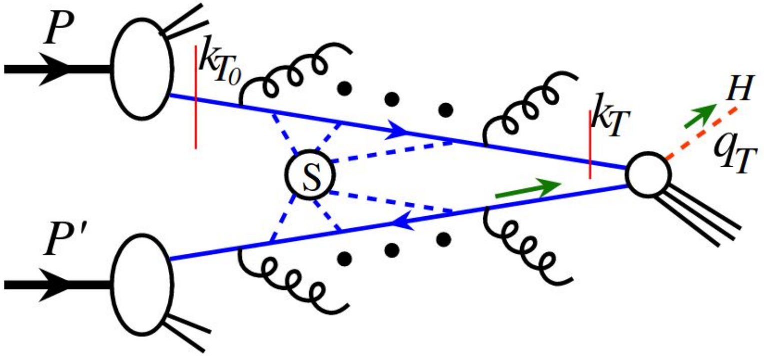
$$\frac{d\sigma}{dq_T} \sim \mathcal{H}\, f_1(x_a, k_{T\,a}, Q, Q^2)\, f_1(x_b, k_{T\,b}, Q, Q^2)\, \delta^{(2)}(q_T - k_{T\,a} - k_{T\,b}) \; + \mathcal{O}(q_T/Q) \, + \, \mathcal{O}(\Lambda/Q)$$

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

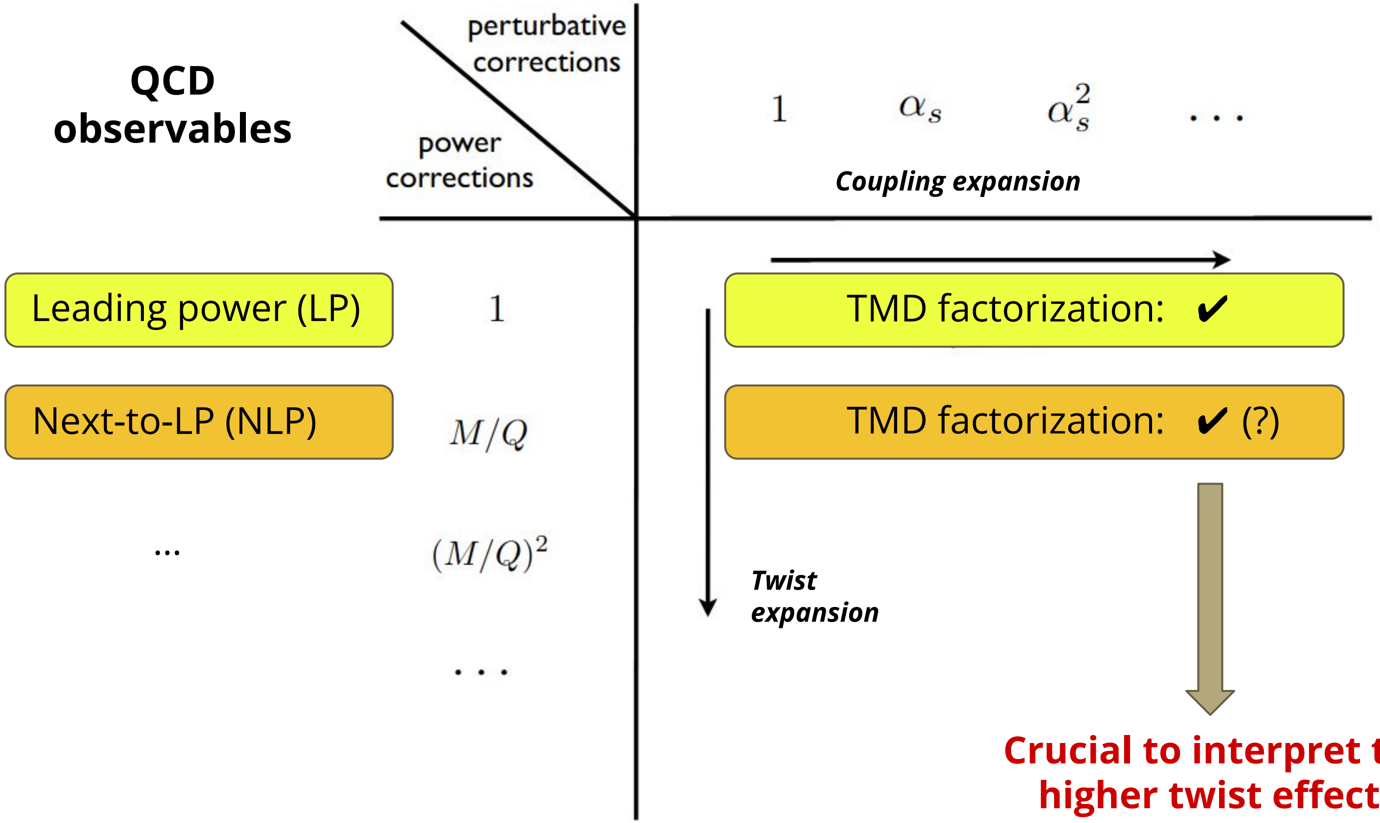
- **observed transverse momentum** :
  transverse momenta of **quarks**

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

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



Sub-leading power (twist)



QCD observables

Leading power (LP)

TMD factorization: ✔

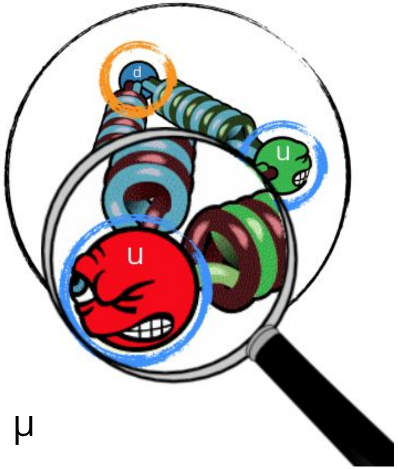
Next-to-LP (NLP)

TMD factorization: ✔ (?)

...

Crucial to interpret the higher twist effects

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 (?)

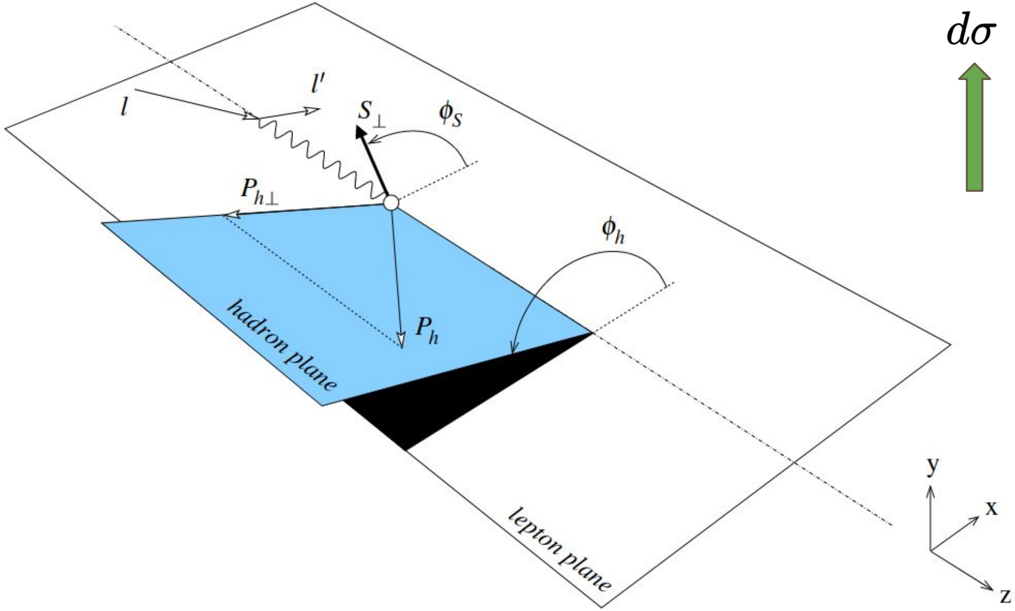
See e.g. https://inspirehep.net/literature/1785810 (but also JCC book and many other references)

Transverse momentum imaging

Calculable
in perturbation theory

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

The partonic “maps”, to be
extracted from data



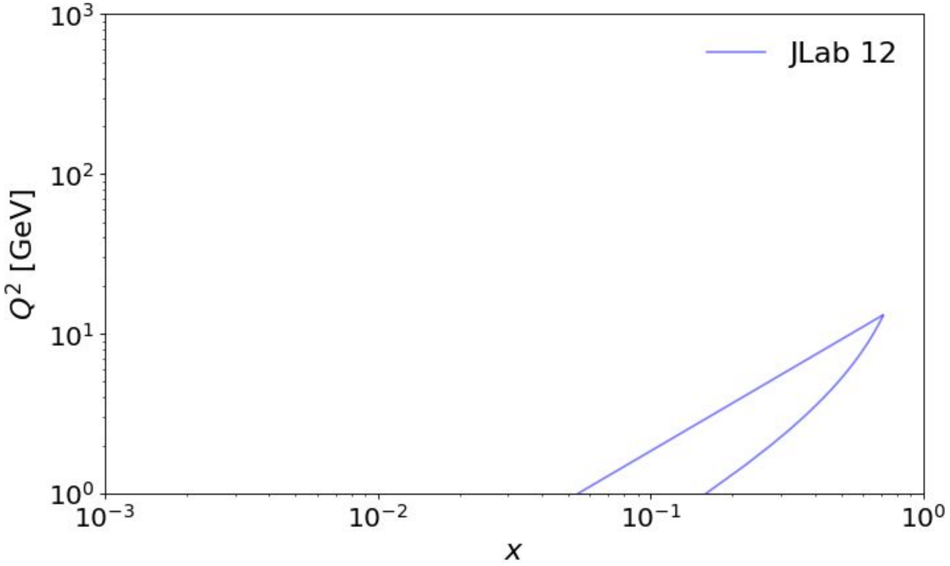
$$\ell(l) + N(P) \rightarrow \ell(l') + h(P_h) + X,$$

JLab, EIC, ...

Kinematics

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

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



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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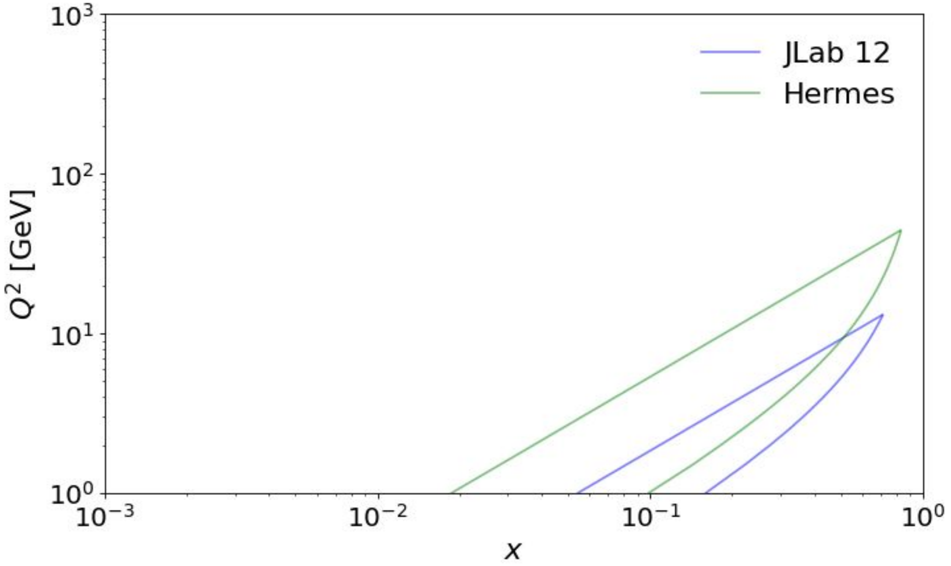

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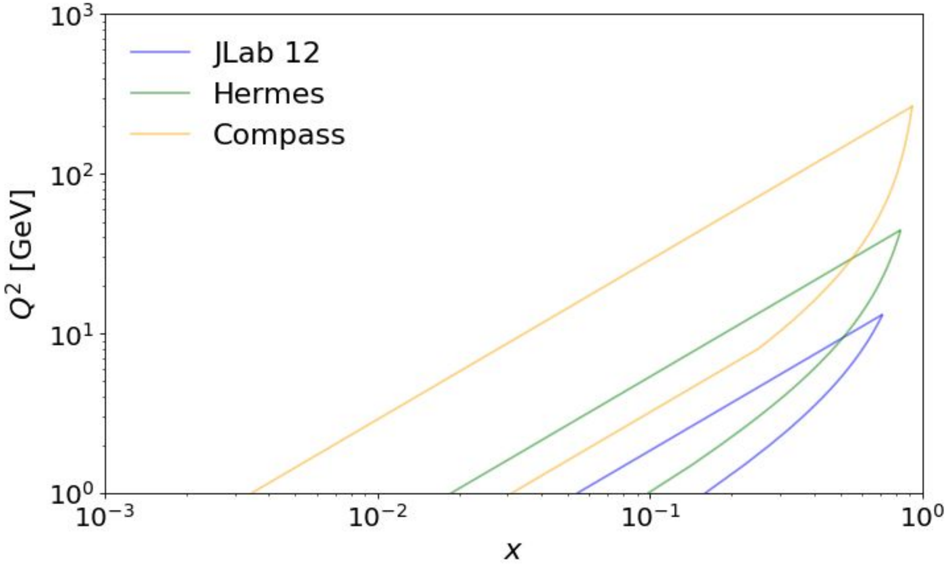
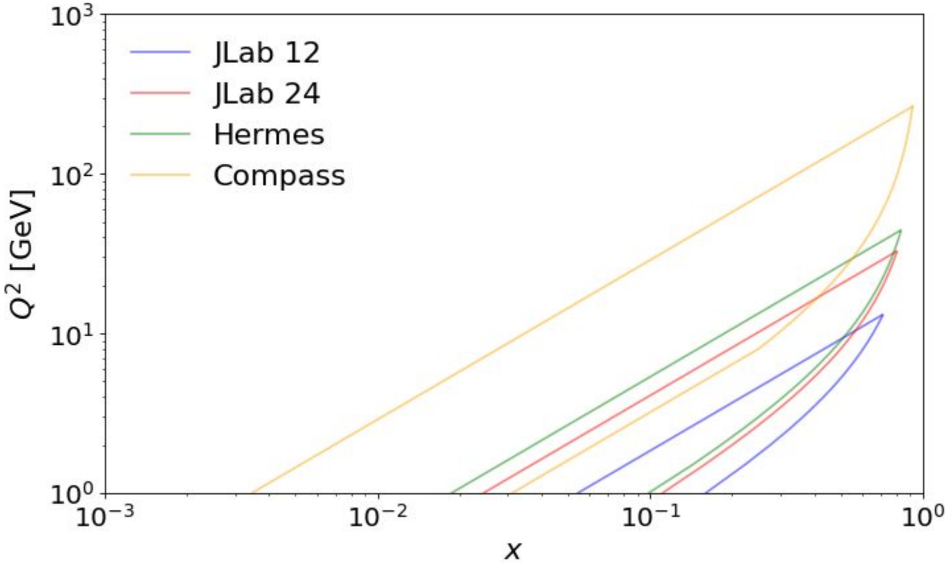


With the ***limited gain in Q*** from JLab 11 to Hermes and Compass we still experience the same "**problems**" related to the ***presence of power corrections to the TMD formalism***

Kinematics

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

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



The motivations for adding "**JLab 24**" should rely on the power of this data to *"**enrich**" the picture, but not to "**clean**" it* from the point of view of the formalism

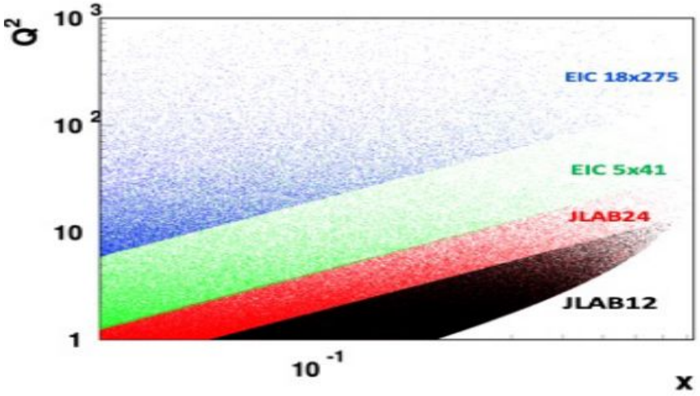
Fundamental insights into:
- non-pert. large x region
- polarization
- flavor separation
- collinear distributions (?)
- ...

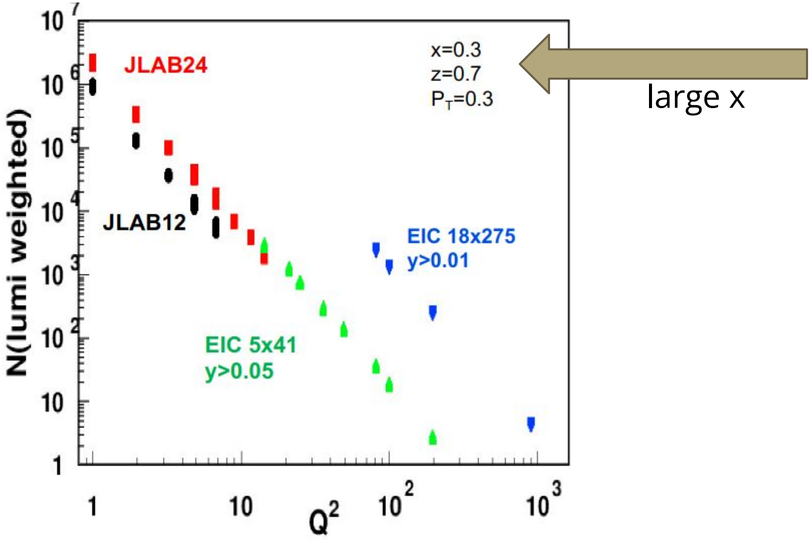
But same "complications" as the other fixed-target experiments

Kinematics and statistics

see Harut’s talk at CPHI 2022 (and next presentation)

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



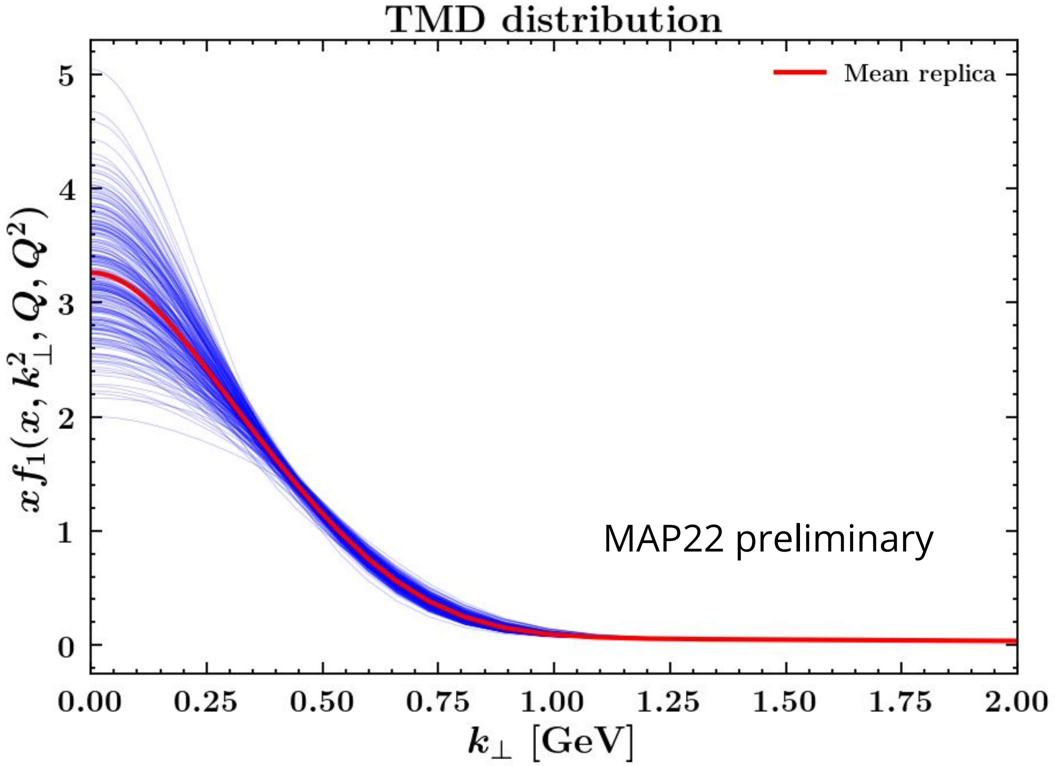


large x

NEED IMPACT STUDIES!

To get *more precise* information on TMDs ***should we aim at more statistics (JLab 24) or higher Q2 (EIC) ?***

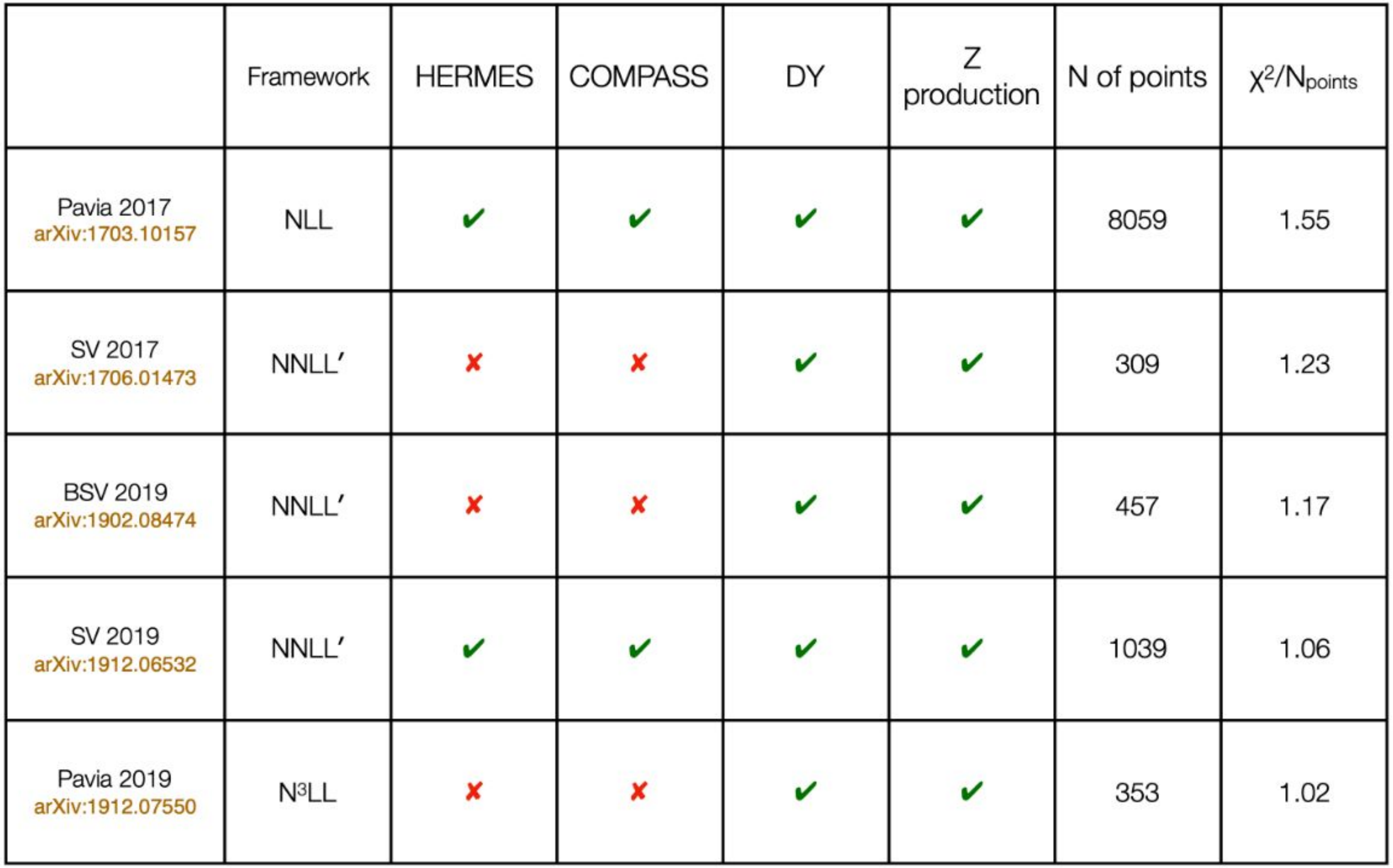
Recent fits and impact studies



MAP22 preliminary

TMD PDF of the u at Q = 2 GeV and x = 0.001

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^{3}LL	✘	✘	✔	✔	353	1.02

TMD impact studies: PV17

200 replicas are compared
with pseudodata

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

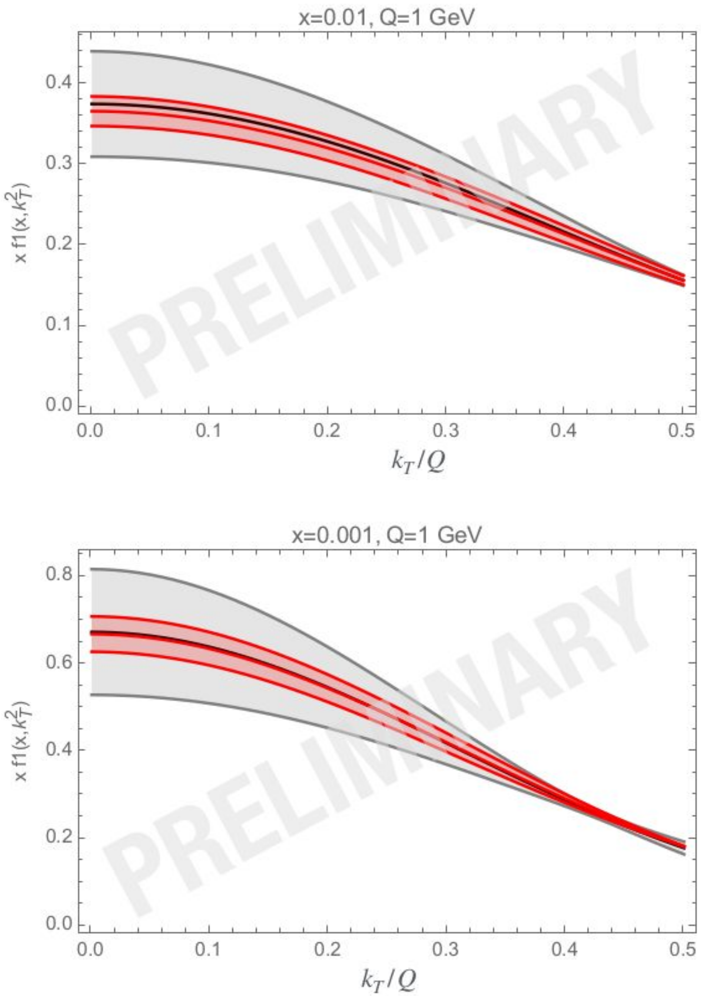
'original' χ^2
with respect to PV17 data

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)

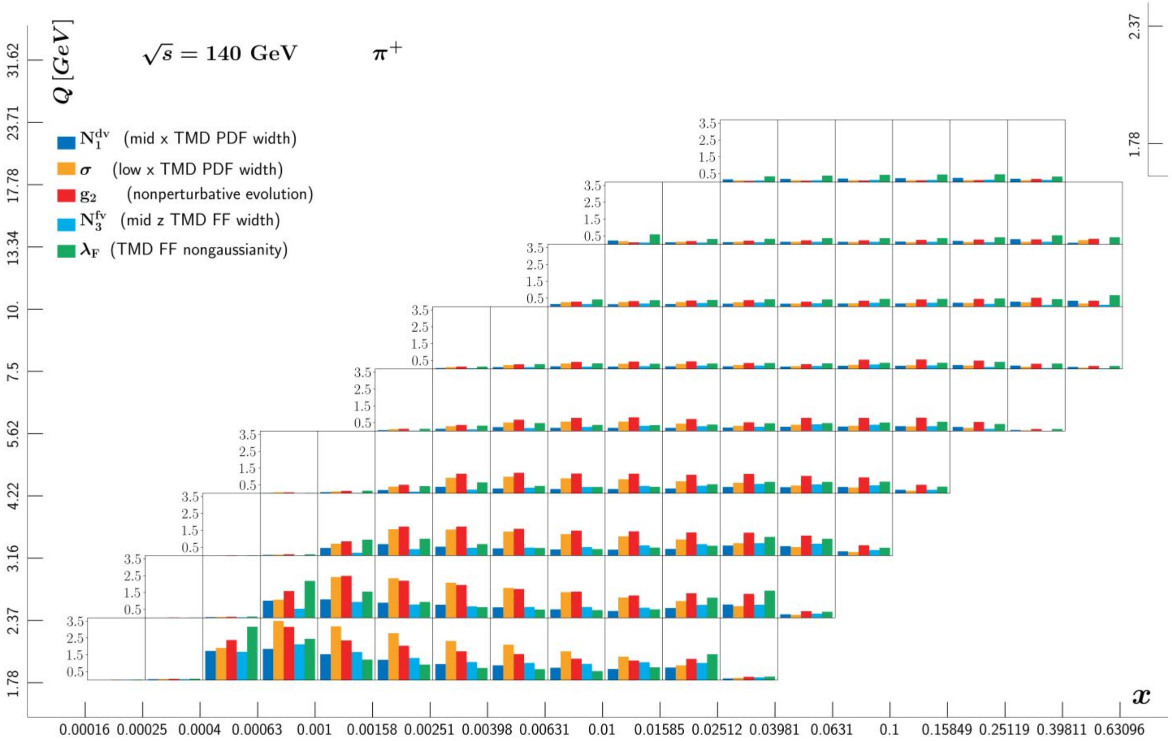


TMD impact studies: PV17

(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



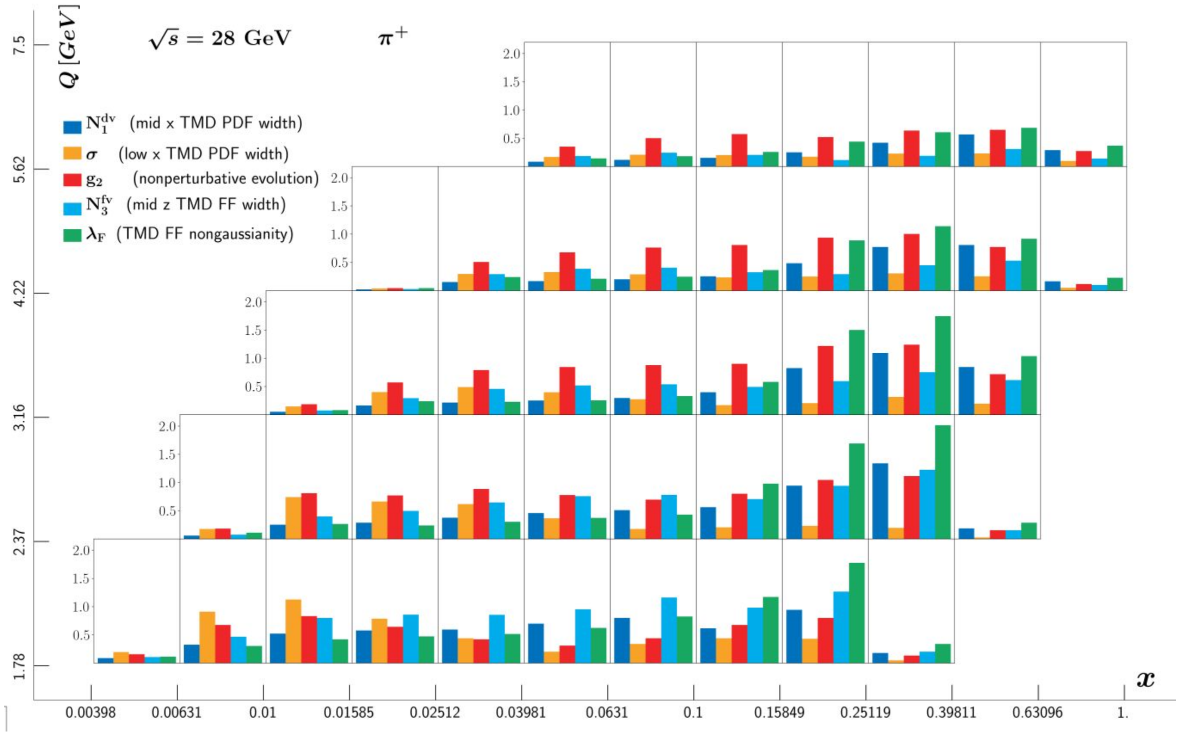
$$\sqrt{s} = 140 \;\; \text{GeV}$$

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



$\sqrt{s} = 28$ GeV

Complementary effects

TMD impact studies: SV19

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

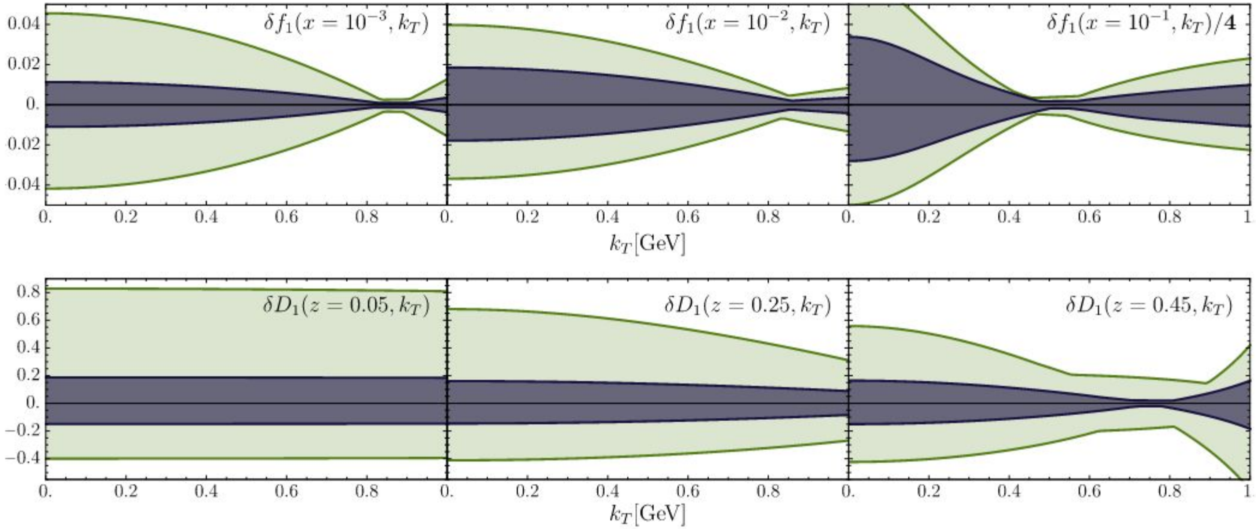


Figure 7.52: Comparison of relative uncertainty bands (i.e. uncertainties normalized by central value) for up-quark unpolarized TMD PDFs (upper panel) and $u \to \pi^+$ pion TMD FFs (lower panel), at different values of x and z as a function of k_T, for $\mu = 2$ GeV. Lighter band is the SV19 extraction,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

Up in proton
TMD PDF

Up to pion+
TMD FF

Fit with EIC
pseudo-data

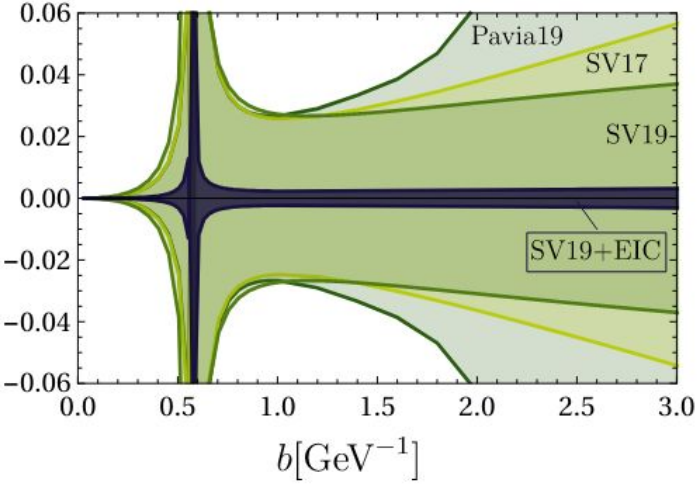
TMD impact studies: SV19

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

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

→ evolution in ζ

Non-pert. corrections (large bT)

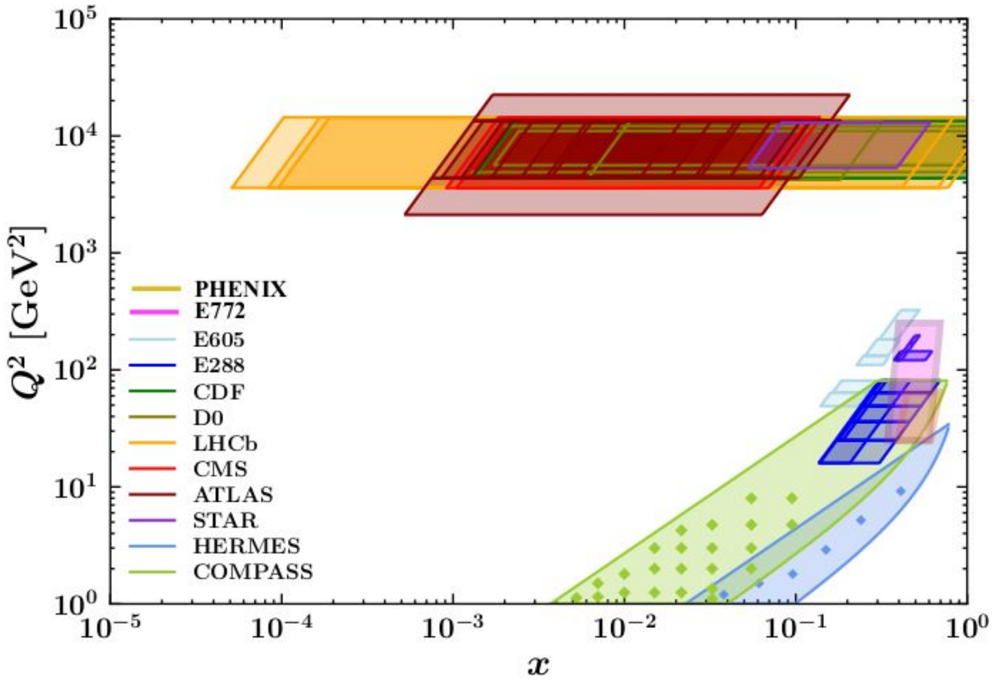


Typically a function of bT^2 with one or two parameters (with variations of course)

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

“MAP22” fit : kinematic coverage

In preparation



“***Global***” fit of ***unpolarized TMDs*** at ***N3LL*** accuracy

Drell-Yan/Z and **SIDIS** data

2031 data
21 parameters

Global chi2: 1.00

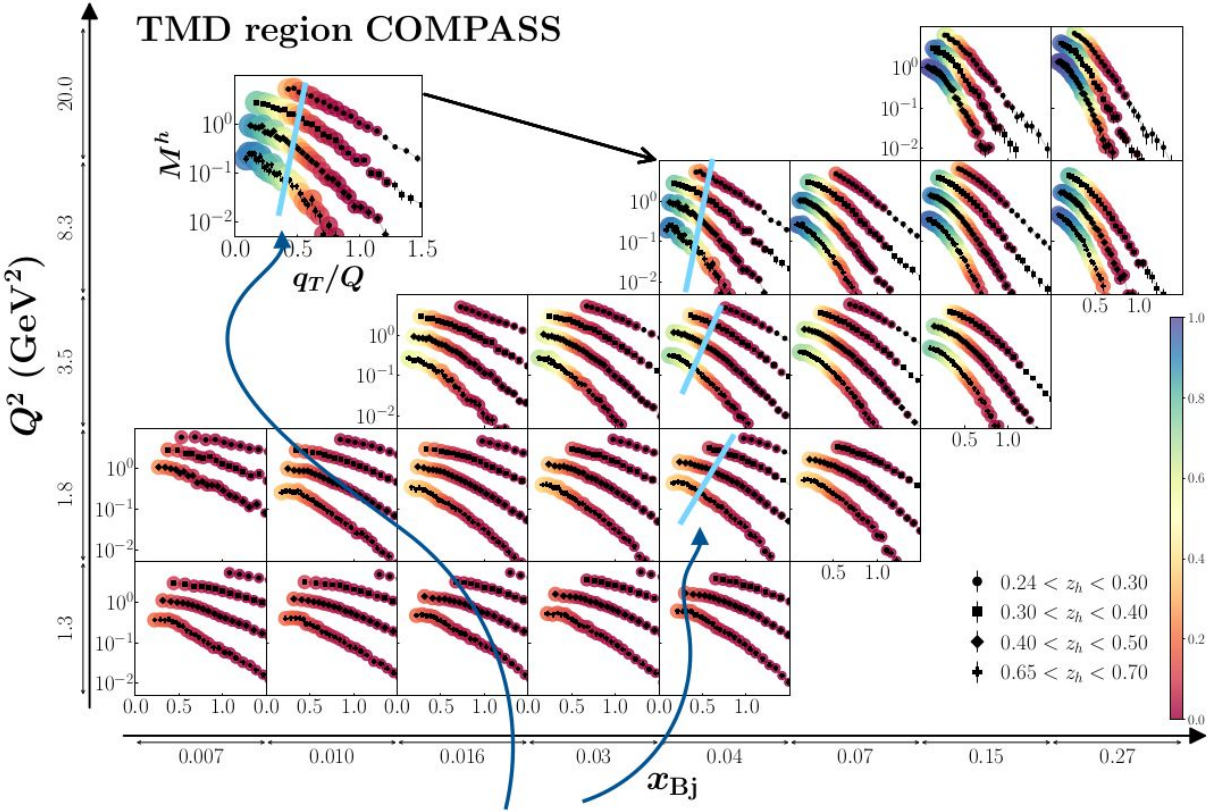
MAP22 : TMD region

https://inspirehep.net/literature/2021571

see A. Bacchetta, recent
“CLAS collaboration meeting”

MAP22 implementation
of TMD region for SIDIS:

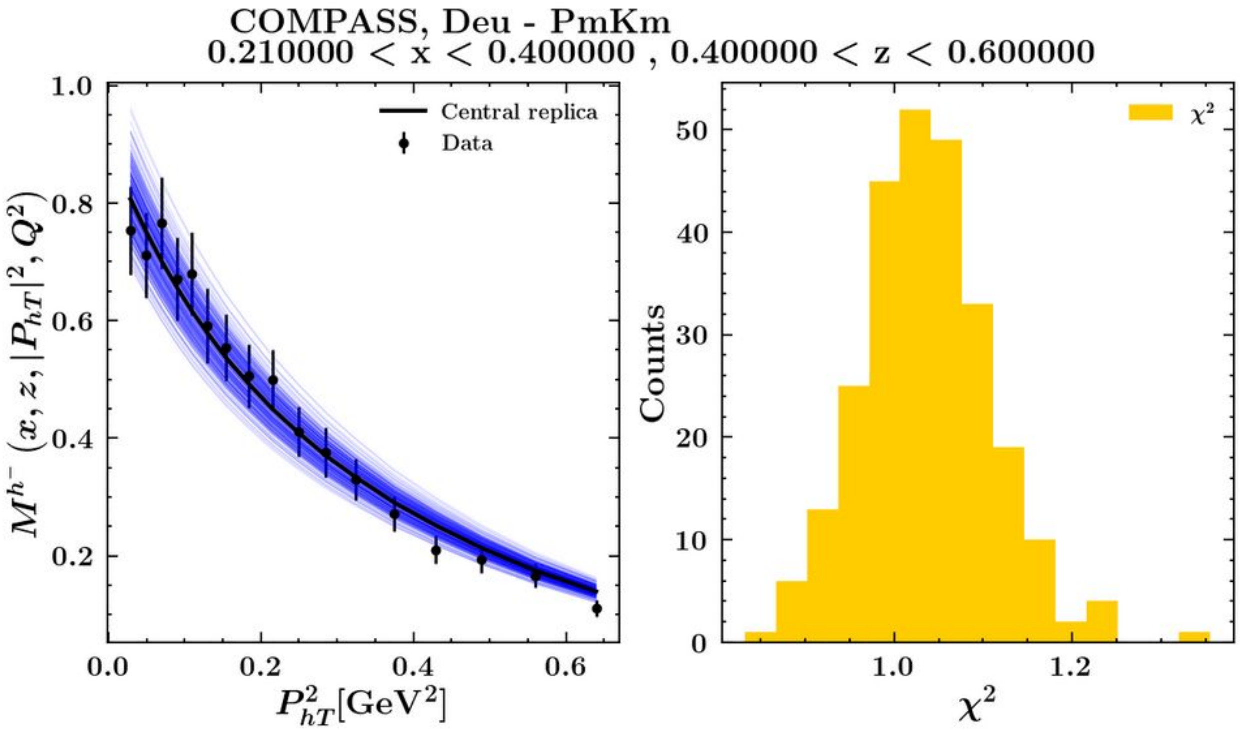
qT < Q at most



Approximate region included in MAP22 fit

MAP22 : comparison with data

In preparation



300 Monte Carlo
replicas
(bootstrap)

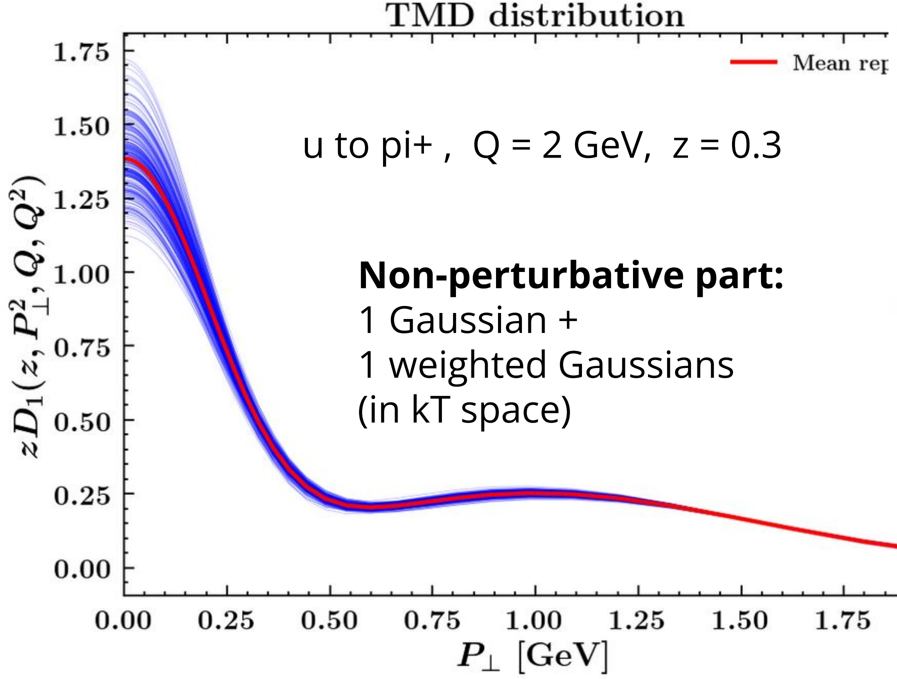
SIDIS data:
overall satisfactory

Drell-Yan data:
major problems with ATLAS data

The normalization coefficients play a crucial role
***BUT** they do **not** depend on q_T and the fit parameters*

MAP22 : TMDs

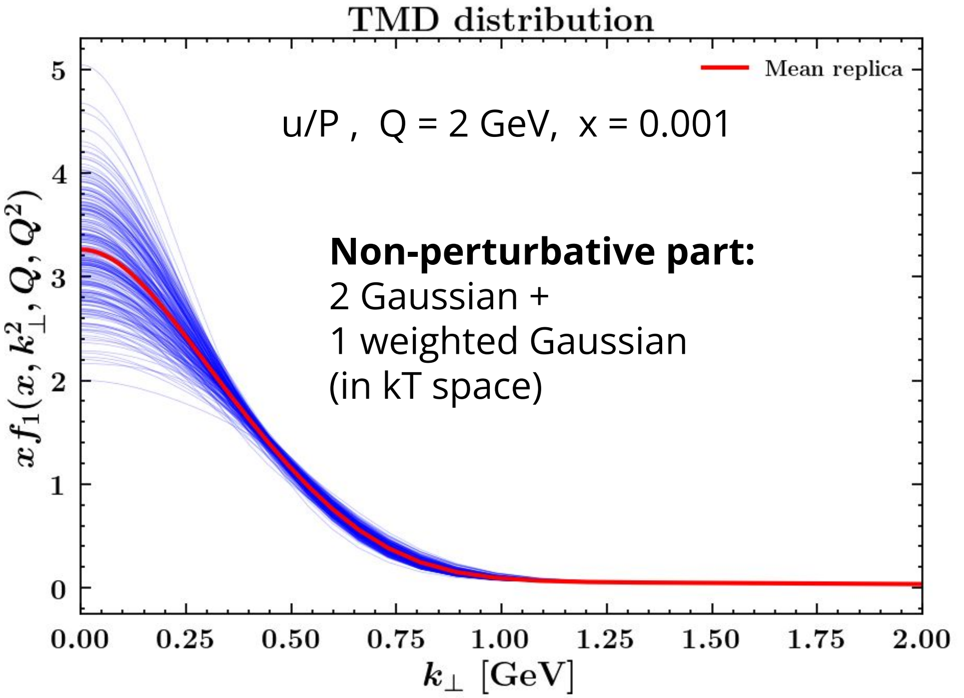
In preparation



u to pi+ , Q = 2 GeV, z = 0.3

Non-perturbative part:
1 Gaussian +
1 weighted Gaussians
(in kT space)

TMD FF of $u \to \pi^+$ *at* $Q = 2$ *GeV and* $z = 0.3$



u/P , Q = 2 GeV, x = 0.001

Non-perturbative part:
2 Gaussian +
1 weighted Gaussian
(in kT space)

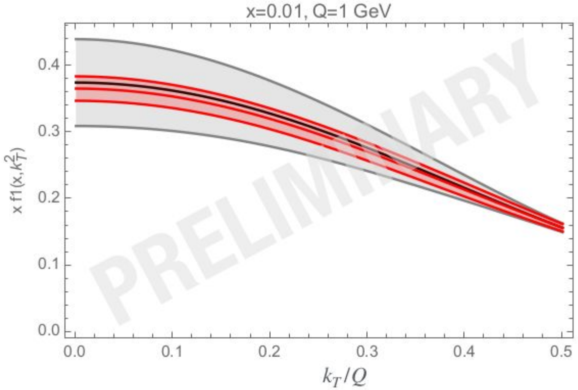
TMD PDF of the u *at* $Q = 2$ *GeV and* $x = 0.001$

No TMD flavor dependence yet

(computationally much
more demanding)

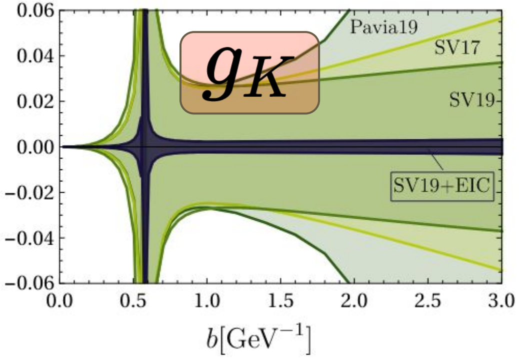
Possible *new* impact studies based on MAP22

Impact on TMD distributions

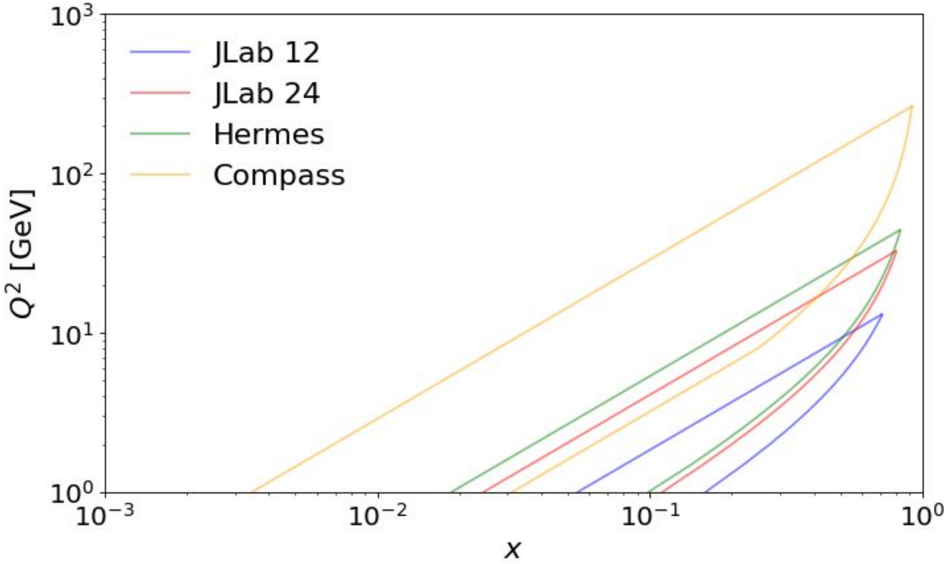


JLab 12 & 24
(pseudo-)data

Impact on TMD evolution



Conclusions and homework



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Fundamental insights into:
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- polarization
- flavor separation
- collinear distributions (?)
- …

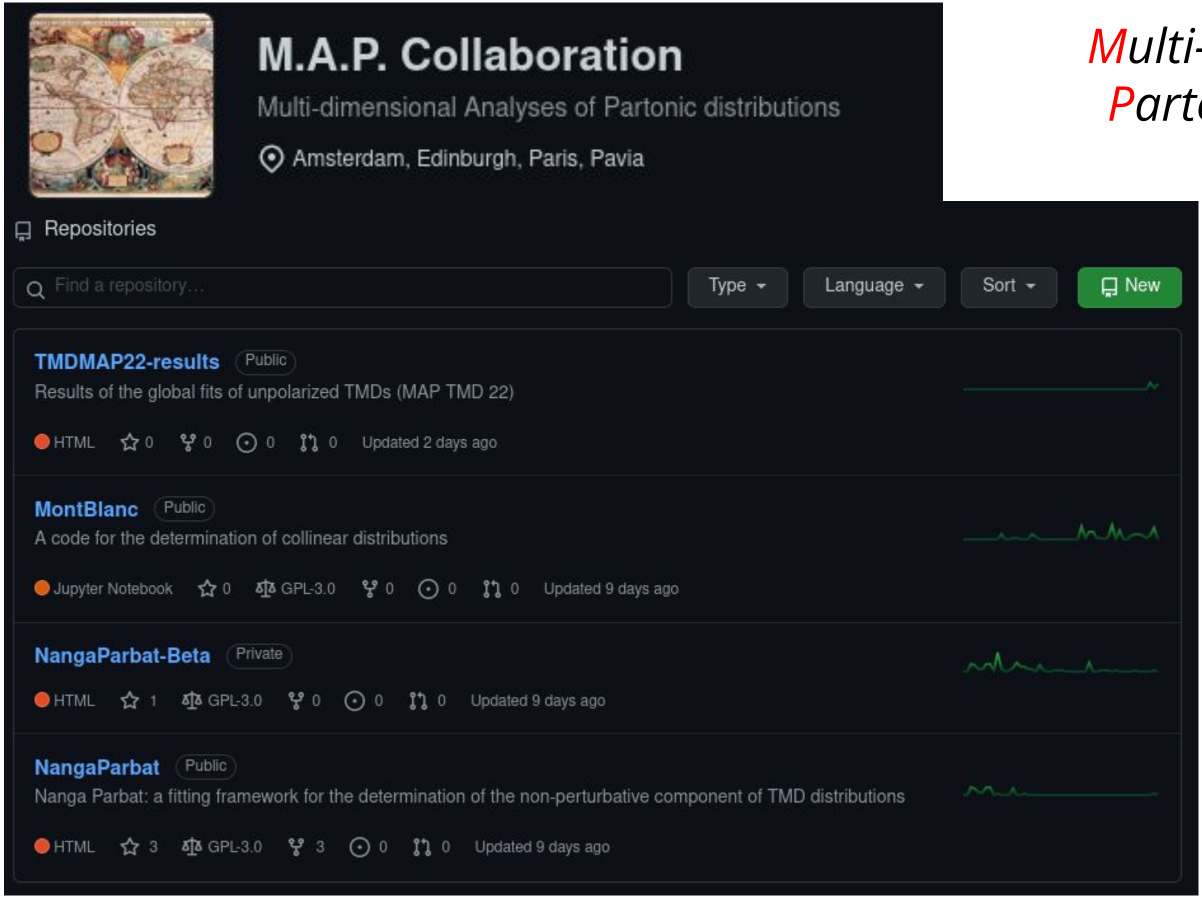
But same "complications" as the other fixed-target experiments

WE NEED IMPACT STUDIES!

Backup

MAP collaboration

https://github.com/MapCollaboration



M.A.P. Collaboration

Multi-dimensional Analyses of Partonic distributions

Amsterdam, Edinburgh, Paris, Pavia

TMDMAP22-results Public

Results of the global fits of unpolarized TMDs (MAP TMD 22)

HTML ☆ 0 0 0 0 Updated 2 days ago

MontBlanc Public

A code for the determination of collinear distributions

Jupyter Notebook ☆ 0 GPL-3.0 0 0 0 Updated 9 days ago

NangaParbat-Beta Private

HTML ☆ 1 GPL-3.0 0 0 0 Updated 9 days ago

NangaParbat Public

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

HTML ☆ 3 GPL-3.0 3 0 0 Updated 9 days ago

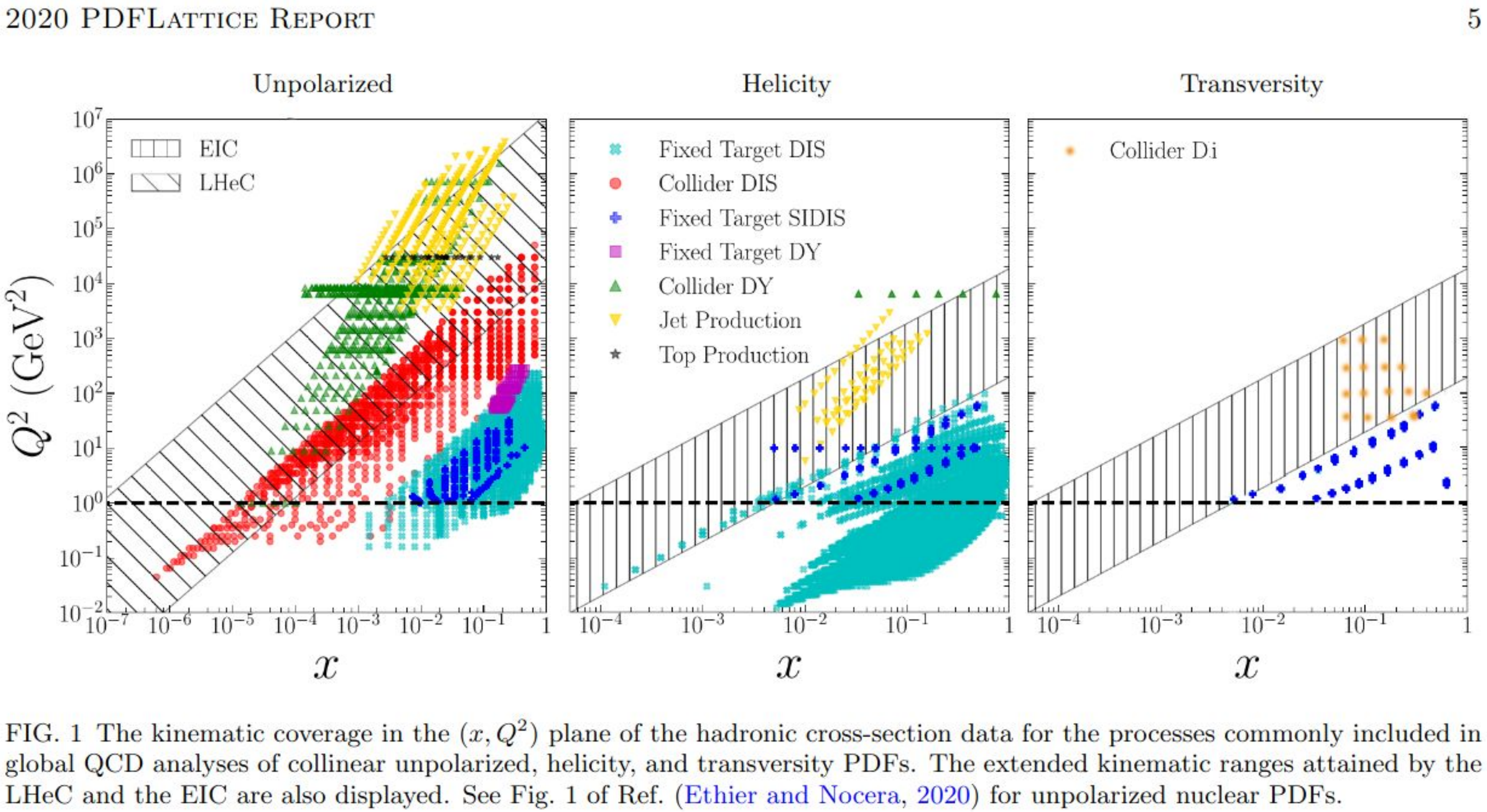
Multi-dimensional Analyses of Partonic distributions (MAP)

At the moment:
- Edinburgh
- JLab
- Paris
- Pavia

"A framework for discussion and for analyses of partonic distributions"

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.

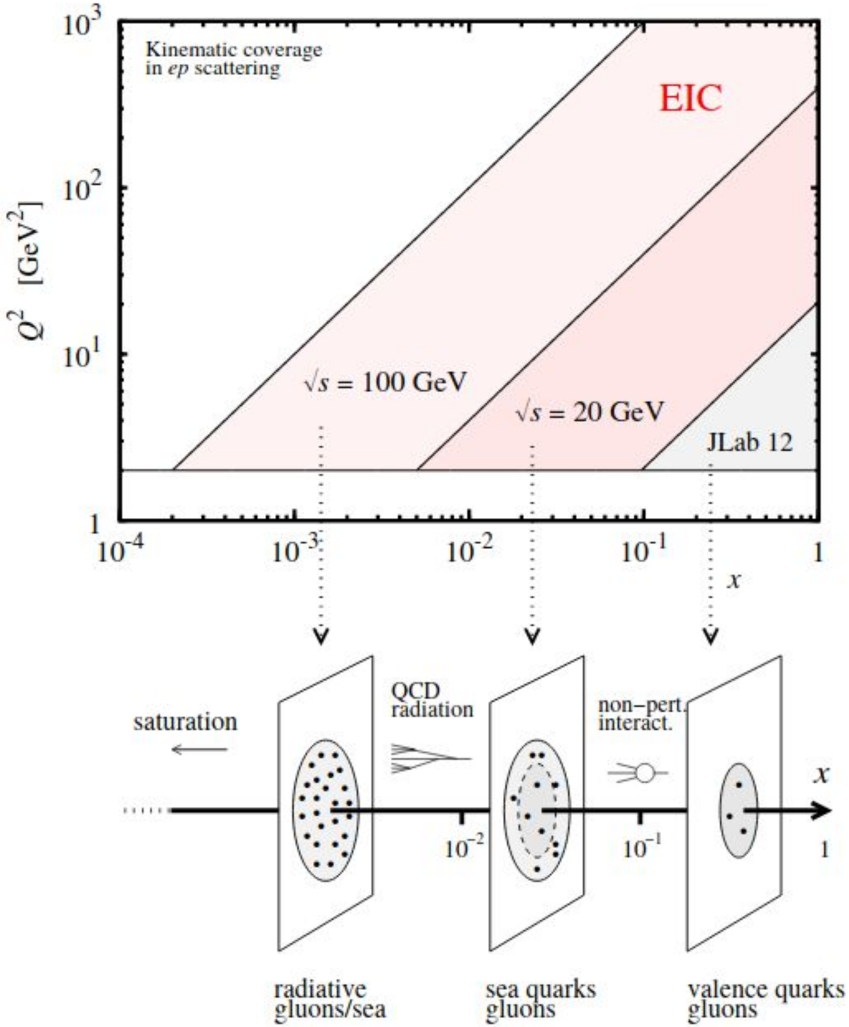
SIDIS coverage

Importance of
complementary experiments

from JLab 12 GeV, Hermes, Compass
to the EIC

zooming into hadron structure

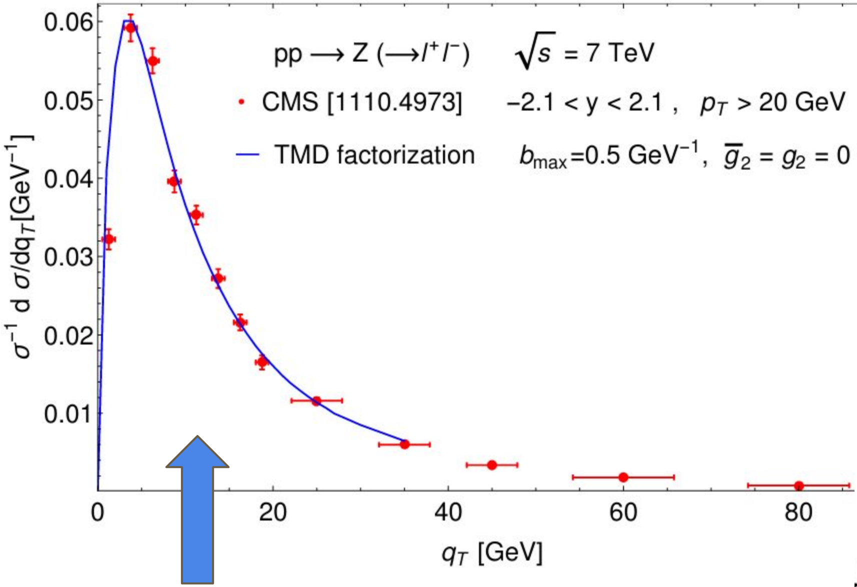
Credit picture: C. Weiss



TMD region: low transverse momentum

$q_T \ll Q$

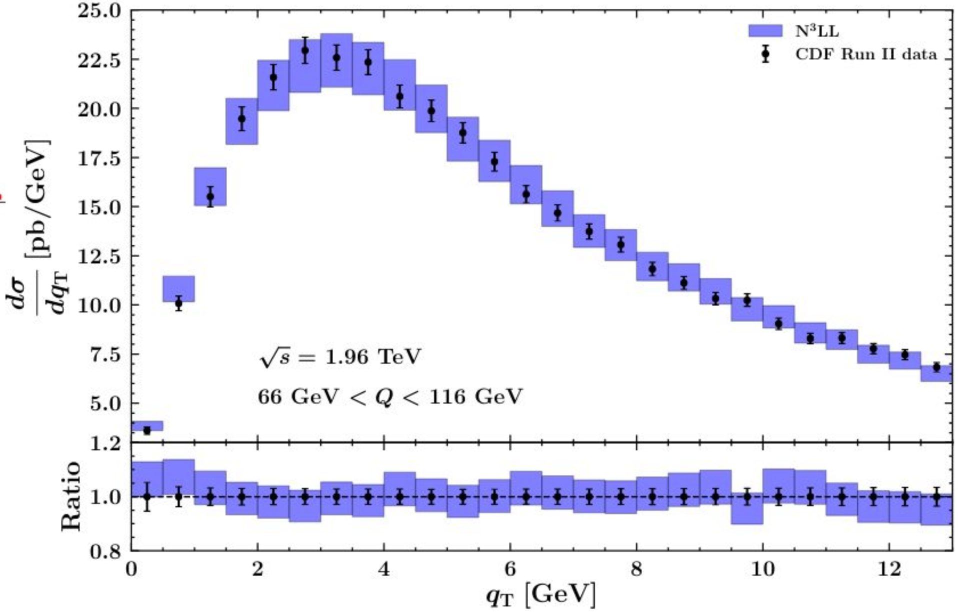
https://inspirehep.net/literature/1785810



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

Hadronic collisions

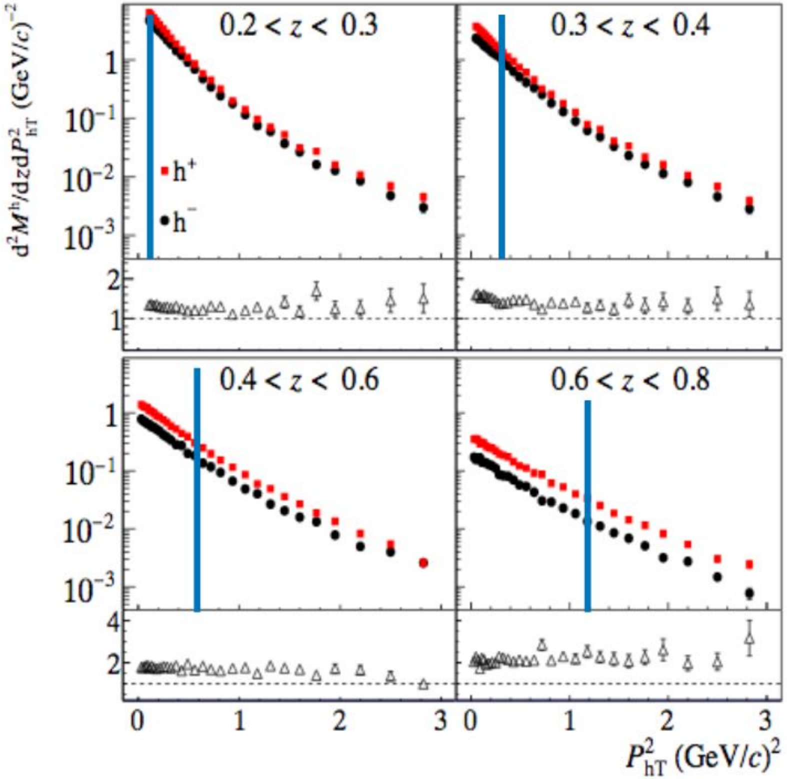
https://inspirehep.net/literature/1771006



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

TMD region: low transverse momentum

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



COMPASS unpolarized SIDIS multiplicities - arxiv 1709.07374

SIDIS - TMD region

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

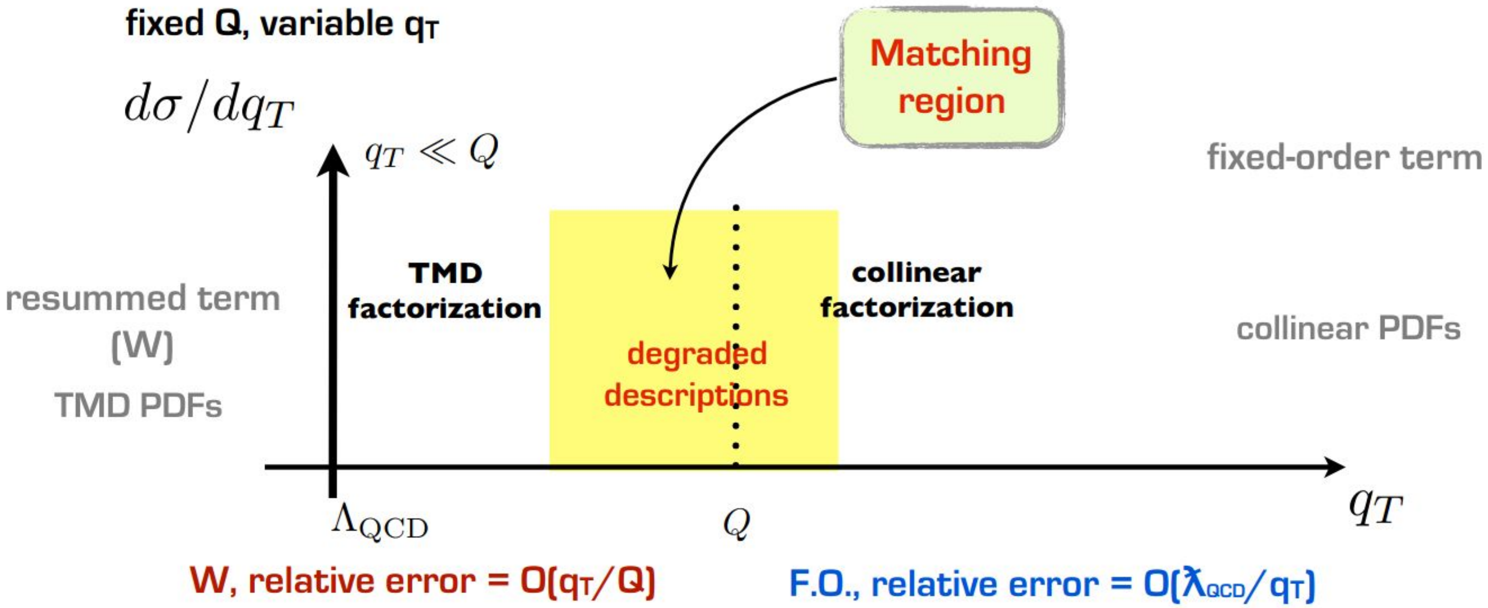
Let's highlight

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

One of the bins with highest Q:

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

Matching TMD and collinear factorization



fixed Q, variable q_T

$d\sigma/dq_T$

$q_T \ll Q$

Matching region

fixed-order term

resummed term (W)

TMD PDFs

TMD factorization

degraded descriptions

collinear factorization

collinear PDFs

Λ_{QCD}

Q

q_T

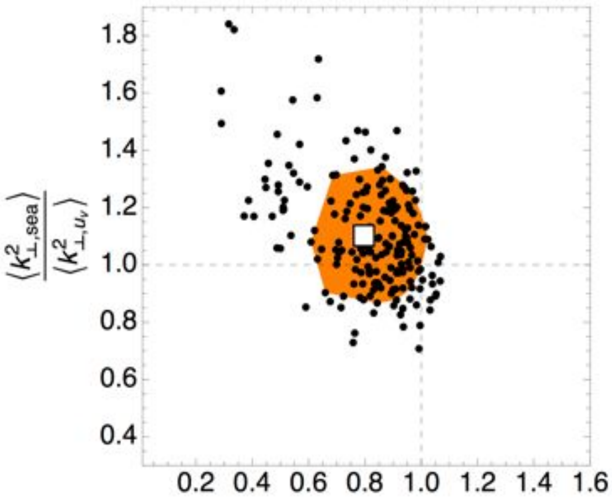
W, relative error = $O(q_T/Q)$

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

Flavor structure of TMDs (PV13)

Imaging from **SIDIS** data from Hermes experiment

Ratio of width of sea / width of up valence

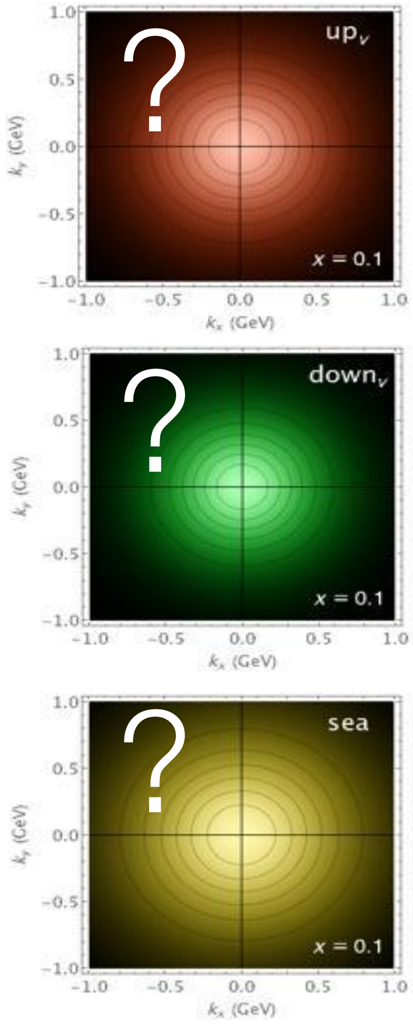


Ratio width of down valence/ width of up valence $\frac{\langle k^2_{\perp,d_v} \rangle}{\langle k^2_{\perp,u_v} \rangle}$

A lot of room for flavor-dependent distributions

NEWS: Recent analysis, Interplay with collinear PDFs

https://inspirehep.net/literature/2012944

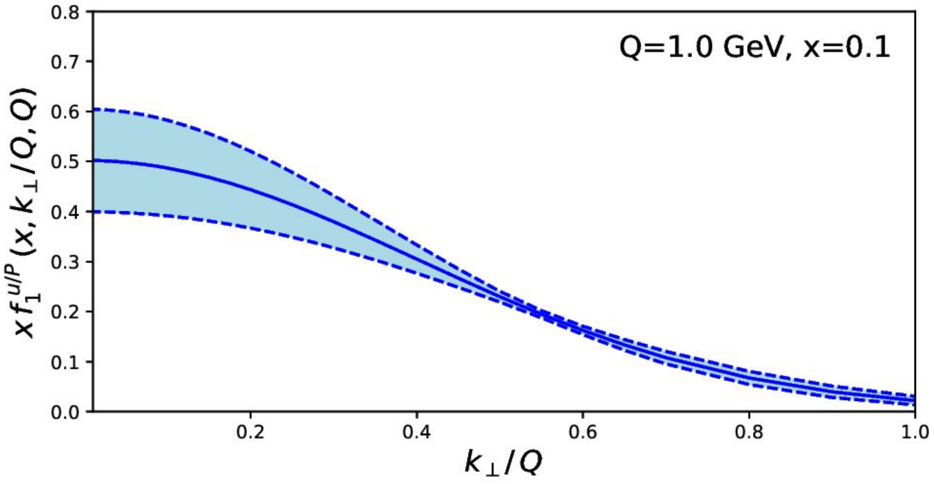


arXiv 1309.3507

Unpolarized TMDs: PV17

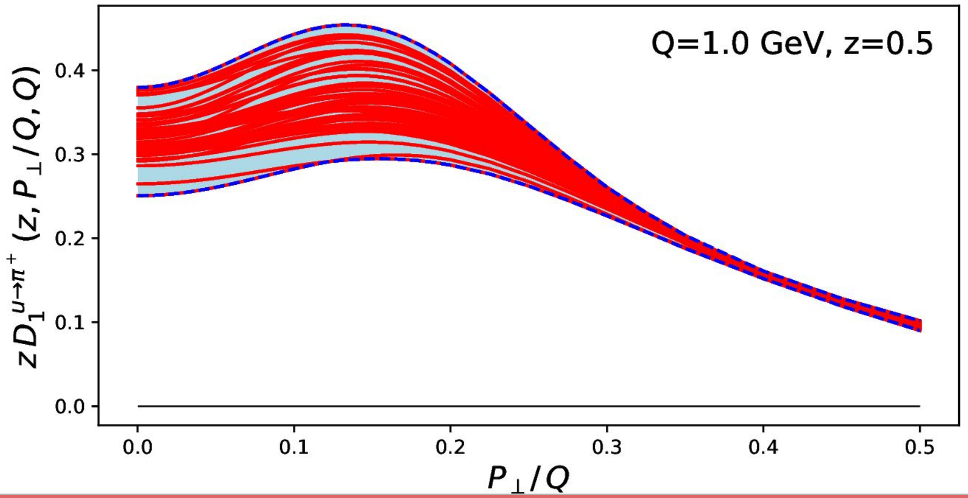
see https://inspirehep.net/literature/1520011

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

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)

No problems with normalization in SIDIS - several source of power corrections

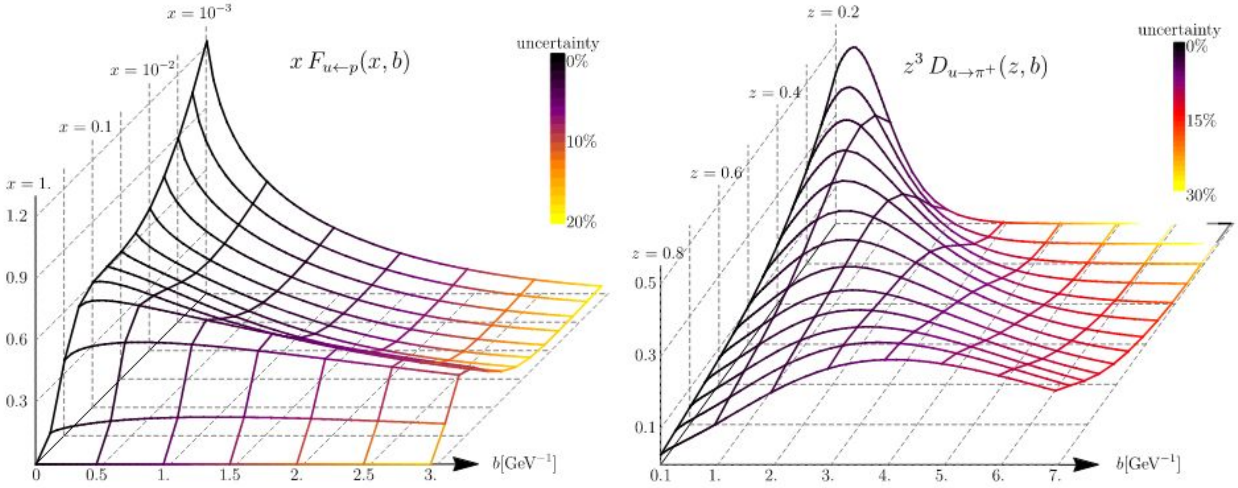
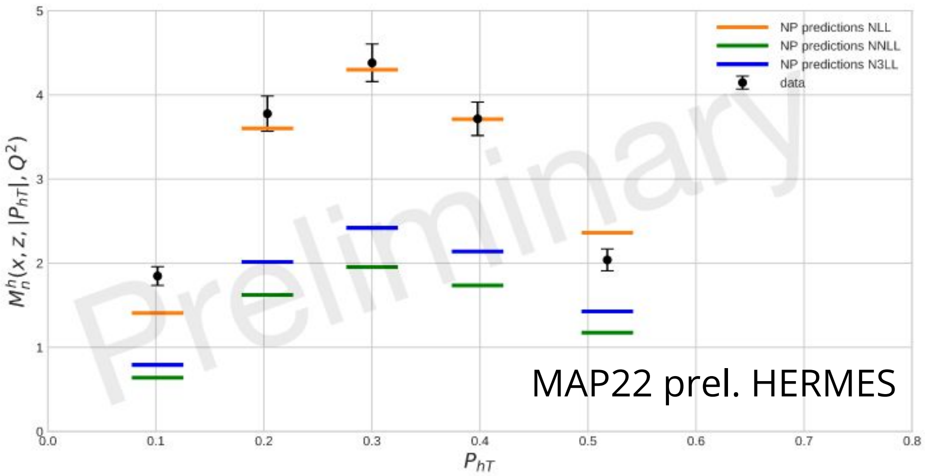


Figure 24. Example of extracted (optimal) unpolarized TMD distributions. The color indicates the relative size of the uncertainty band

Normalization issues

***Small** transverse momentum*



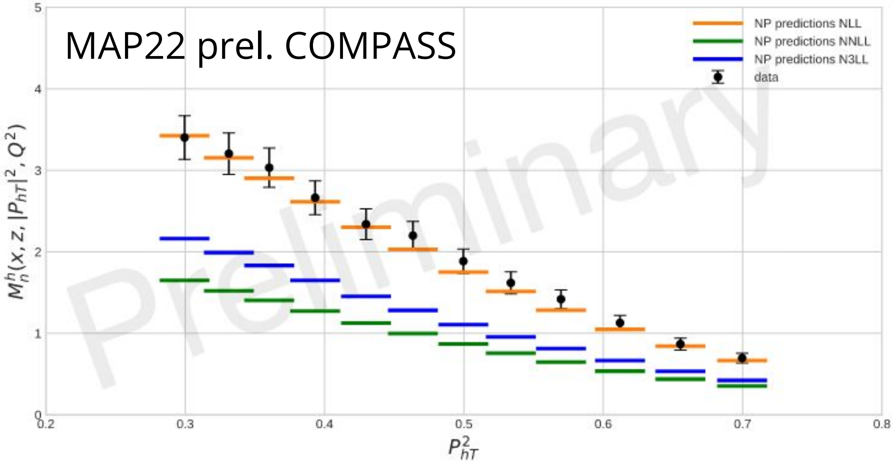
Beyond the NLL, the **theoretical** prediction is **way too low**

Who to blame:

- hard function (large coeffs.)
- low Q

But **no consensus** in literature, even about the problem

- **SV 19** : *not seen;* power corrections from the start?
- **MAP 22** : power corrections from pre-computed normalization coefficients



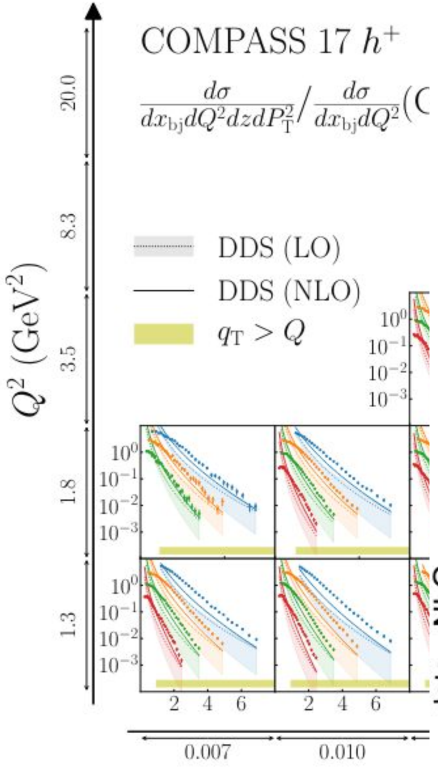
Normalization issues

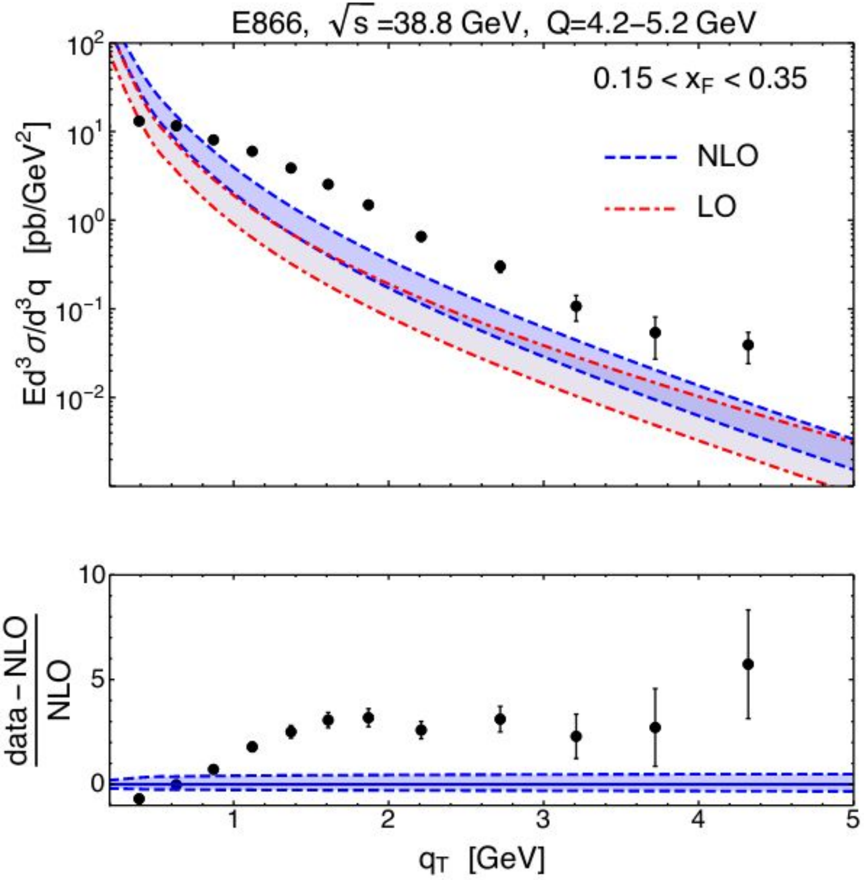
https://inspirehep.net/literature/1723777

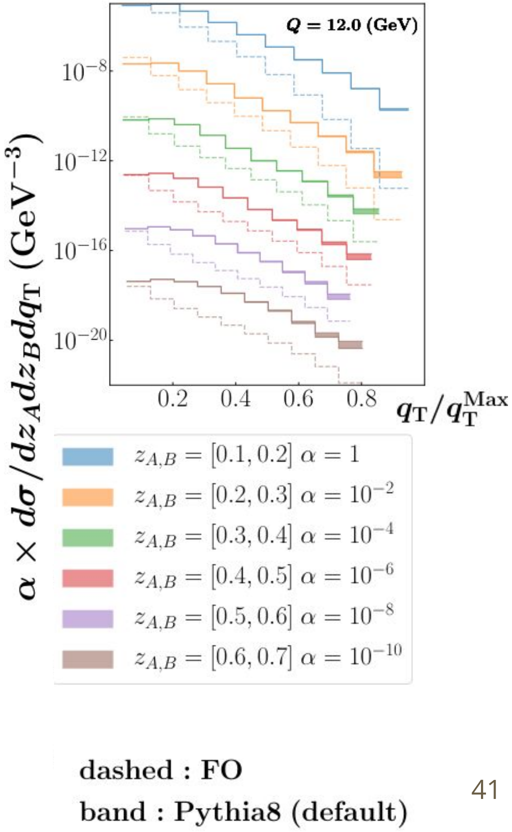
https://inspirehep.net/literature/1716140

***Large** transverse momentum*

https://inspirehep.net/literature/1752934

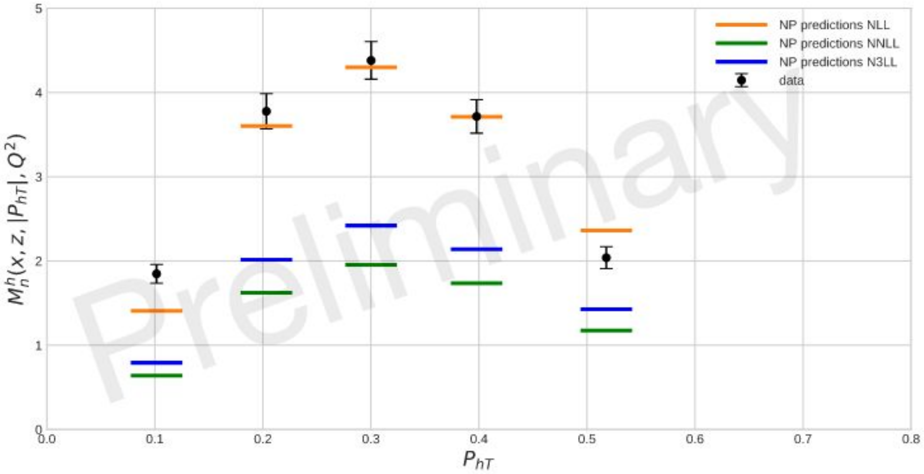






MAP22 : SIDIS normalization at low q_T

In preparation



$$\boxed{w(x, z, Q) = \frac{\frac{d\sigma^h}{dx\,dQ^2\,dz}}{\int \mathrm{W} d^2 \boldsymbol{q}_T}}$$

Beyond NLL:

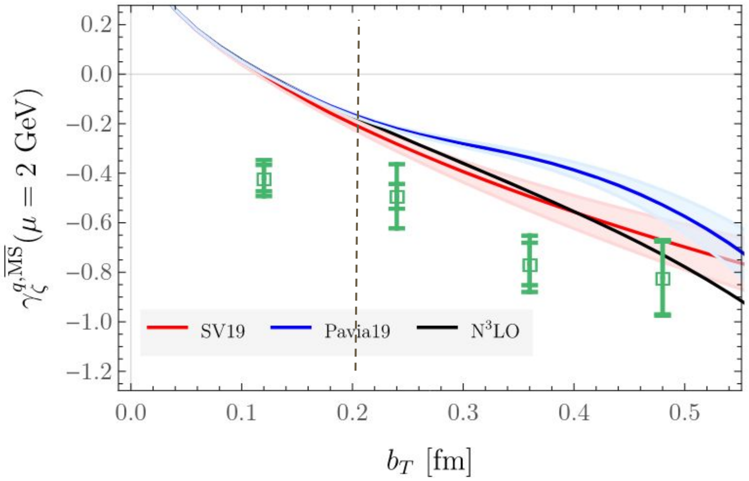
- The integral over qT of **SIDIS TMD** cross section **does not** yield the **collinear** cross section
- The hard part **heavily suppresses** the TMD cross section

We **enhance** the predictions with this factor that **restores** the correct normalization

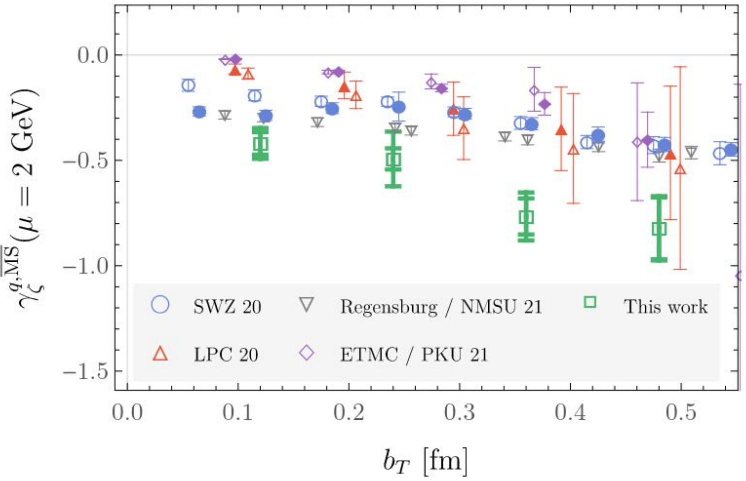
Effectively a ~1/Q correction & *no dependence on fit parameters*

Lattice input: non-perturbative evolution

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



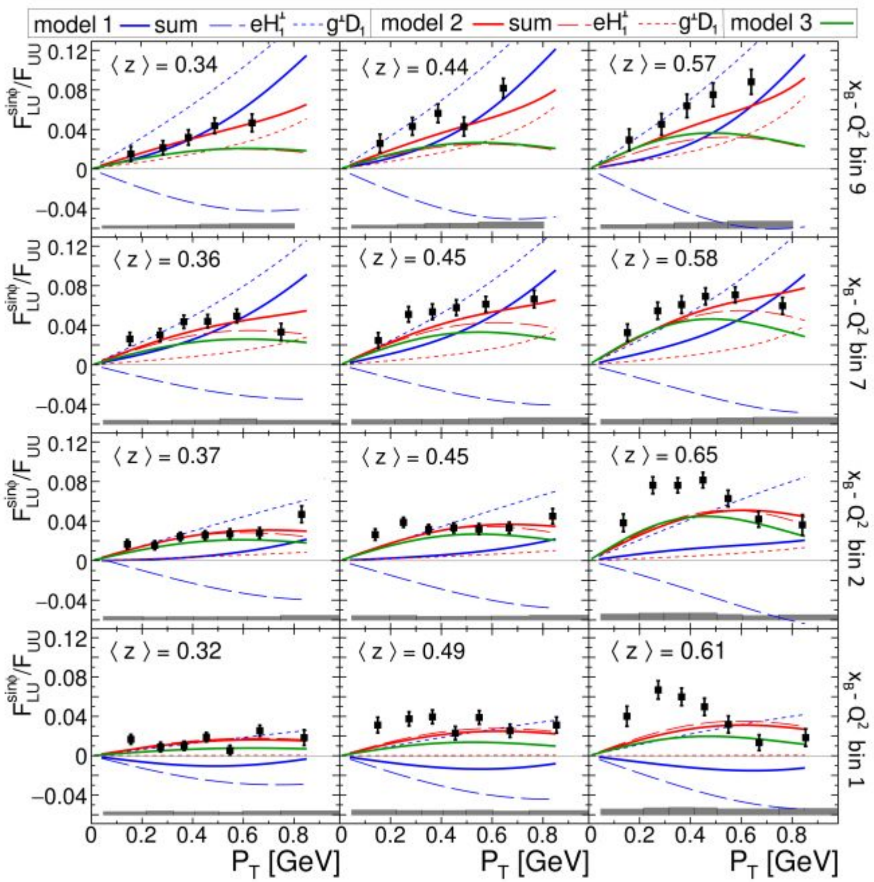
(a) Comparison with the SV19 [4] and Pavia19 [5] phenomenological parameterizations and the next-to-next-to-next-to-leading order (N^{3}LO) perturbative result [42, 43].



(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

Higher twist: beam-spin asymmetry @ CLAS12



Among the first CLAS12 publications

https://inspirehep.net/literature/1840207

Models can reproduce at least the size of the signal (not always the sign)

Higher twist: beam-spin asymmetry

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

Leading twist parts:

- f1, D1 : known with good precision from global anaylises
- Collins and Boer-Mulders : accessible and partially known

We can tackle the **higher twist** parts

TMD factorization at **NLP** (see the theory section)

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
- ..