Istituto Nazionale di Fisica Nucleare
MARIE CURIE ACTIONS
SQUHADRON

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Opportunities for unpolarized and polarized hadron structure

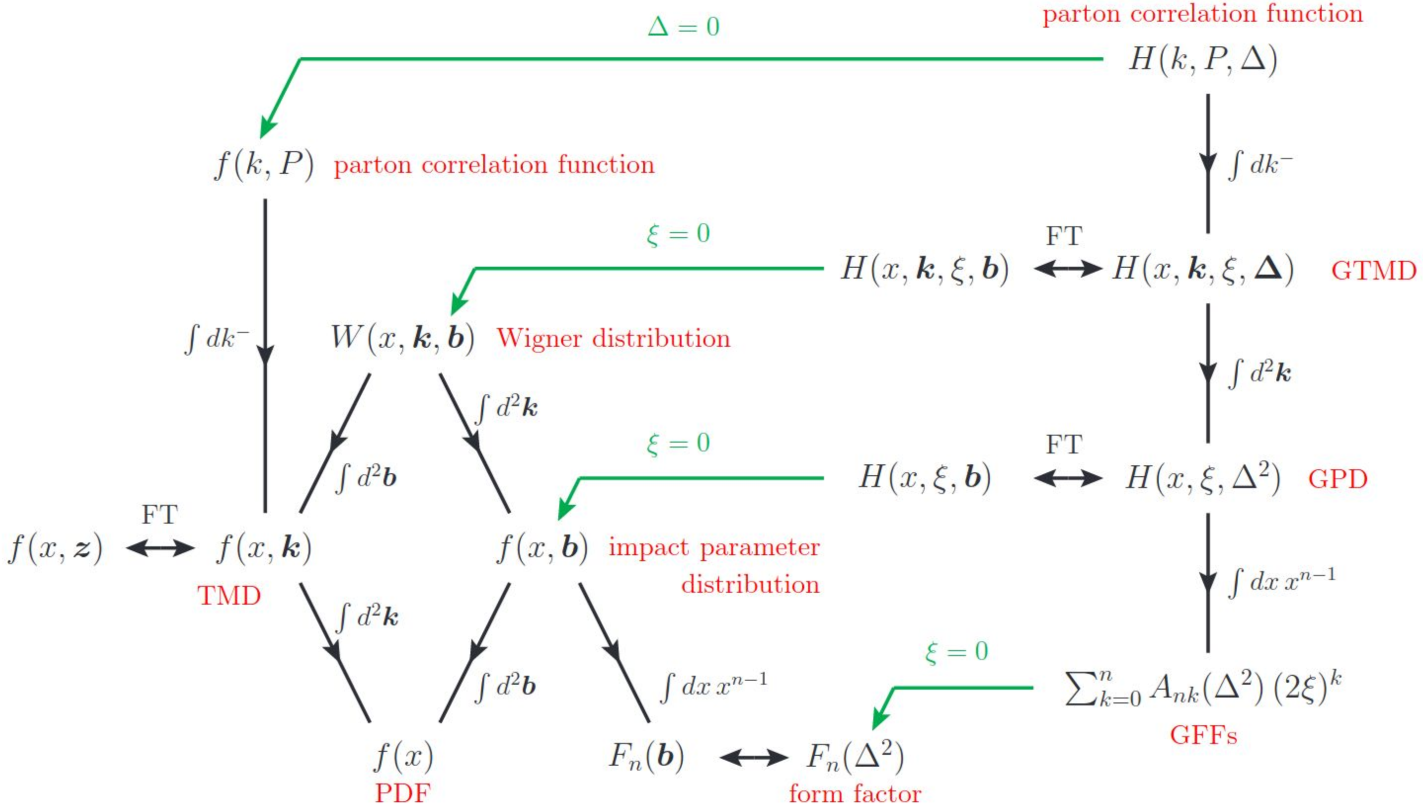
Fixed-target experiments at LHC - CERN

June 22, 2022

Outline

1. **Introduction and motivation**
2. **Structure of TMDs and its interplay with data**
3. **Opportunities with a fixed-target at the LHC (short selection!)**

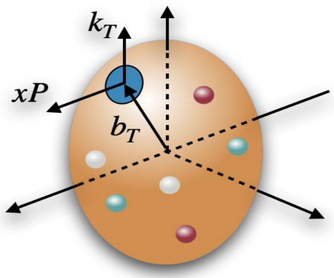
The hadron structure landscape



Credit picture: M. Diehl - [arXiv 1512.01328]

TMDs and GPDs

Wigner distributions

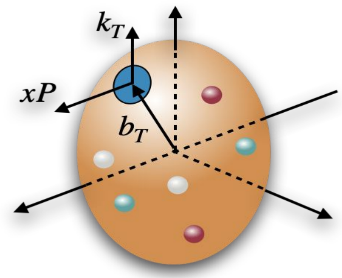


Position and momentum of partons

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

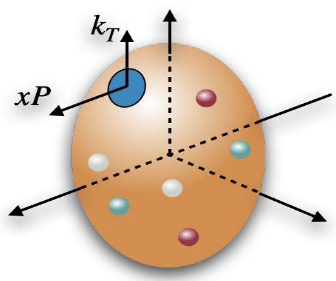
TMDs and GPDs

Wigner distributions



Position and momentum of partons

TMDs



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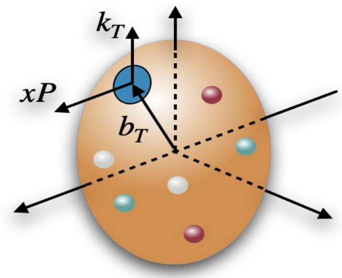
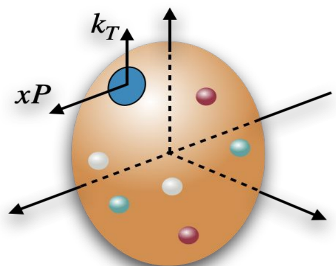
TMDs and GPDs

Wigner distributions

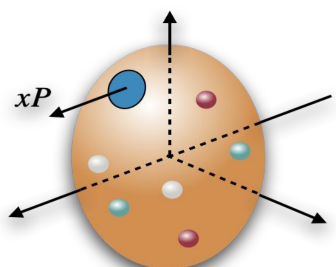


Position and momentum of partons

TMDs



PDFs

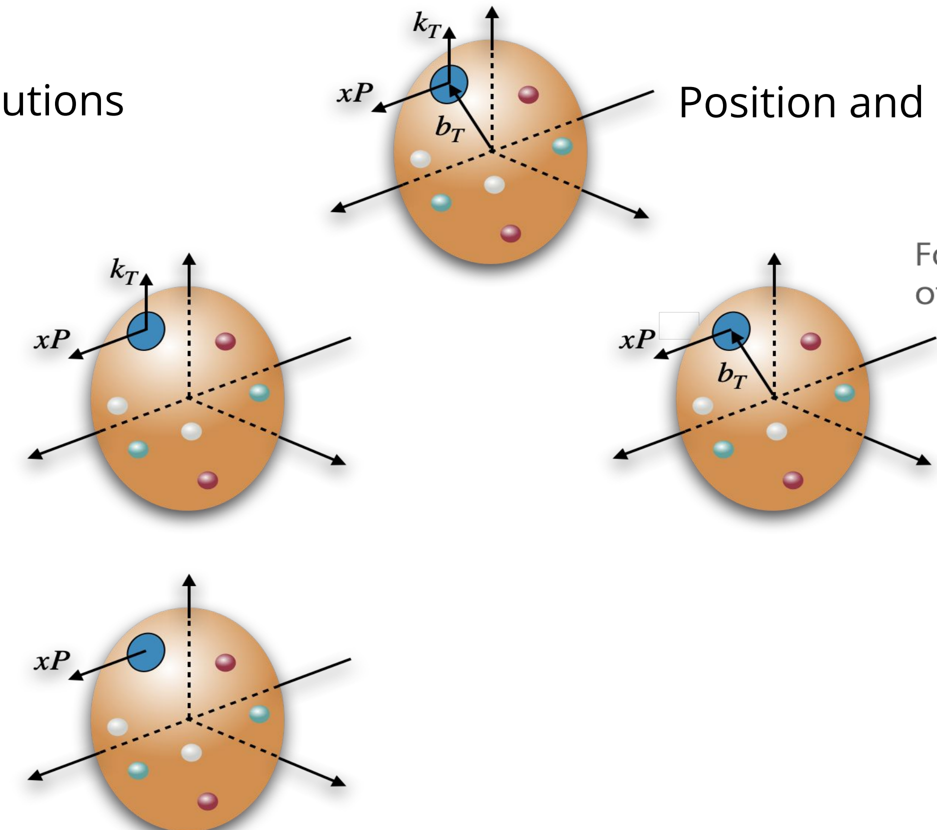


see, e.g., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)

TMDs and GPDs

Wigner distributions

Position and momentum of partons



TMDs

Fourier transform of GPDs

PDFs

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

TMDs and GPDs

Wigner distributions

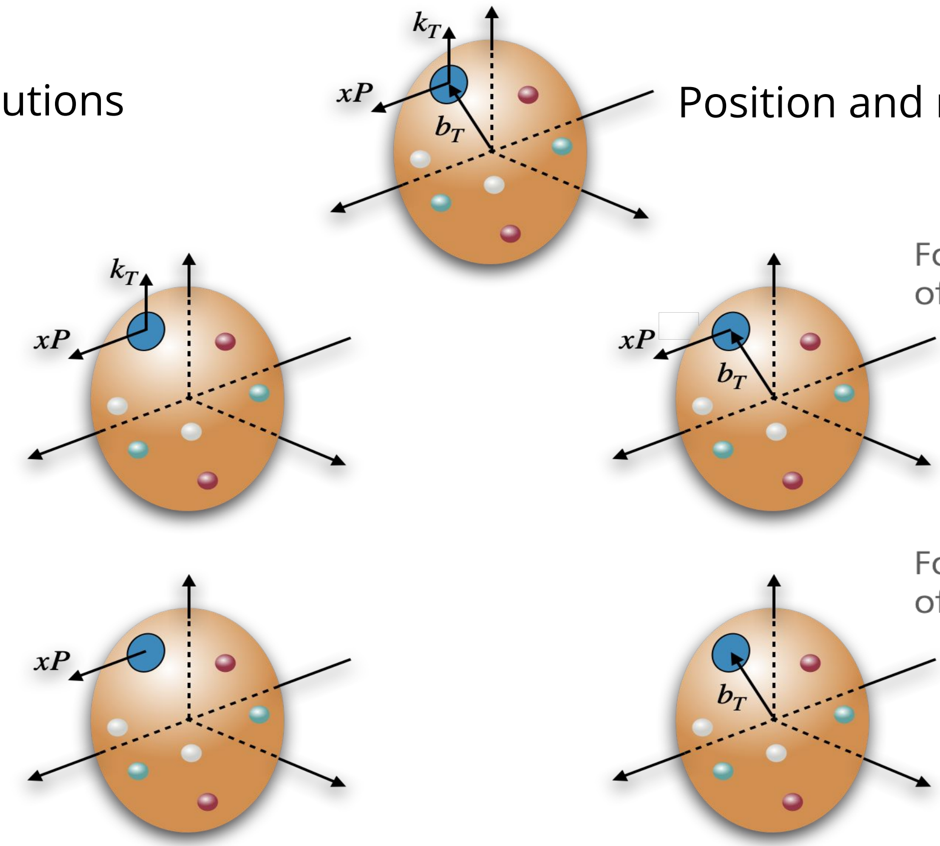
Position and momentum of partons

TMDs

Fourier transform of GPDs

PDFs

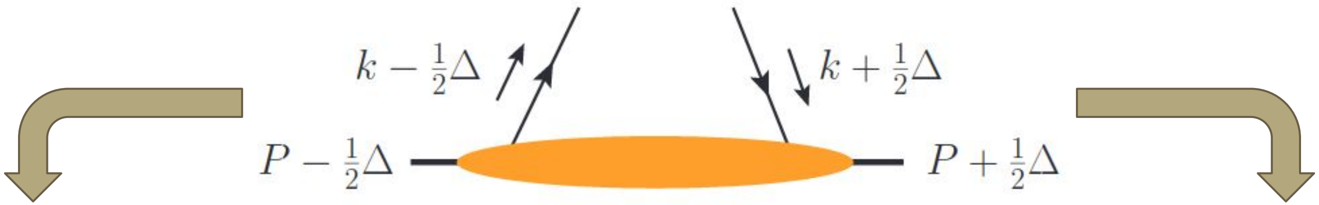
Fourier transform of Form Factors



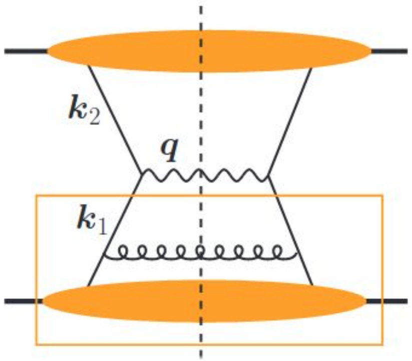
see, e.g., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)

Correlation functions: which processes ?

$$H(k,P,\Delta) = (2\pi)^{-4} \int d^4z\, e^{izk} \langle p(P+\tfrac{1}{2}\Delta)|\bar{q}(-\tfrac{1}{2}z)\,\Gamma\, q(\tfrac{1}{2}z)|p(P-\tfrac{1}{2}\Delta)\rangle$$



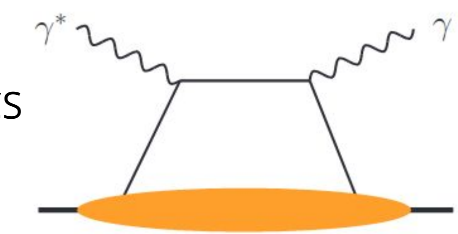
Δ = 0 (forward case):
(semi-)inclusive processes



Drell-Yan

Δ ≠ 0 (non-forward case)
Exclusive processes

DVCS



TMD PDFs for quarks in nucleon

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

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

At leading twist: 8 TMD PDFs

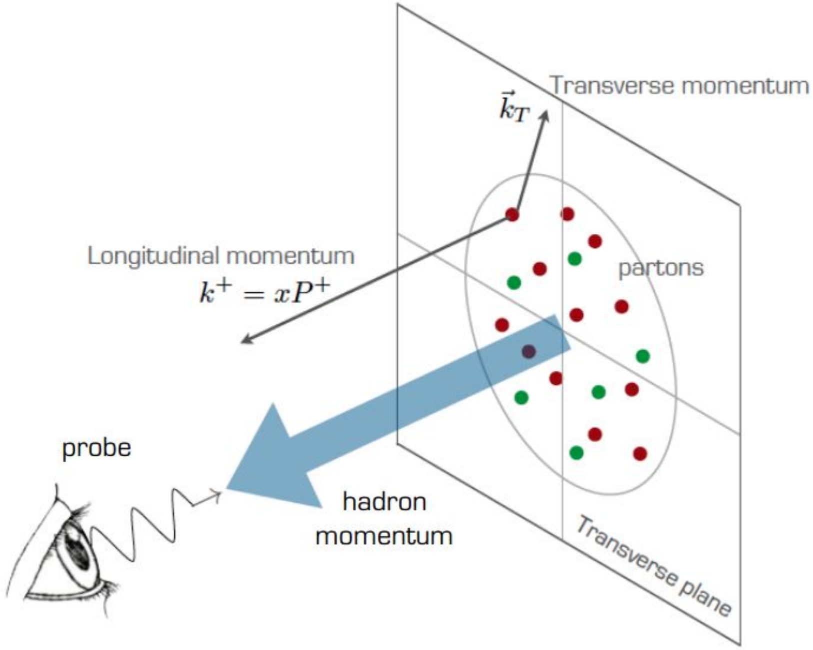
(similar classification for gluons
and for fragmentation functions
... and for GPDs too)

- **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

Parton distribution functions

“Maps” of hadron structure in momentum space



$f_1(x)$

1D structure
in momentum space
(“collinear”)

$f_1(x, k_T^2)$

3D structure
in momentum space
(“transverse momentum dependent” - **TMD PDFs**)

Credit picture: A. Bacchetta

GPDs for quarks in nucleon

		Quark Polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	H		$\bar{E}_T = 2\tilde{H}_T + E_T$
	L		$\tilde{H}$	$\tilde{E}_T$
	T	E	$\tilde{E}$	H_T, $\tilde{H}_T$

N. d'Hose, Transversity 2022 - https://agenda.infn.it/event/19219/

Why studying this maps?

f_1

- Test **factorization** and **universality**
- *Precise* knowledge: impact on **HEP**, e.g. **mW** determination

h_1

- Tensor charge of the nucleon: **CP** violation and access to **BSM** physics

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

- Test the **symmetries** of QCD

e

- Quark-gluon correlations and quark contribution to hadron **mass**

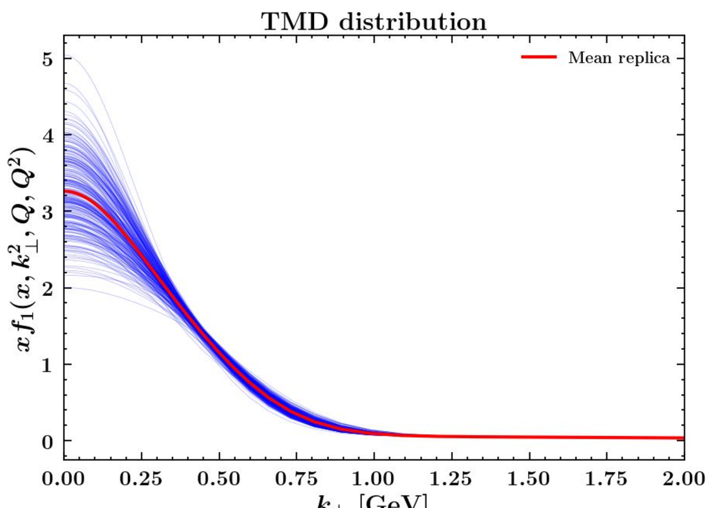
E

- Quark-gluon correlations and **dynamical** generation of quark mass

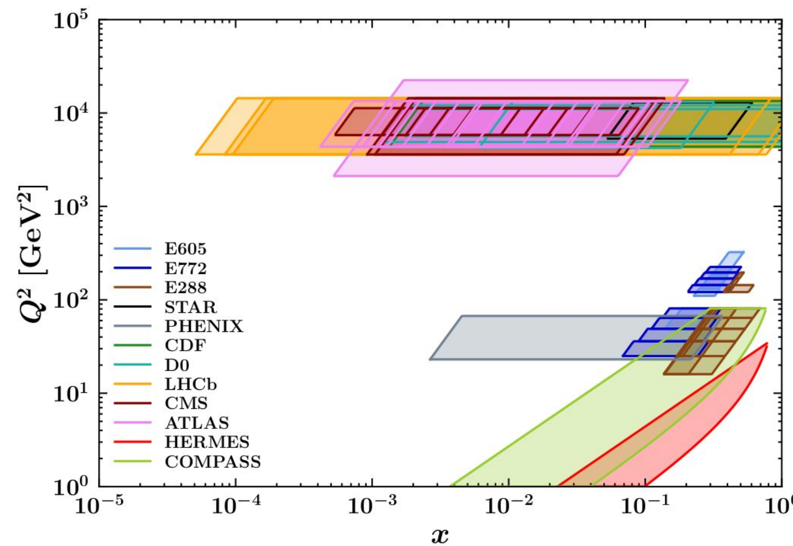
Structure of TMDs

&

interplay with data



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



TMD factorization

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

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

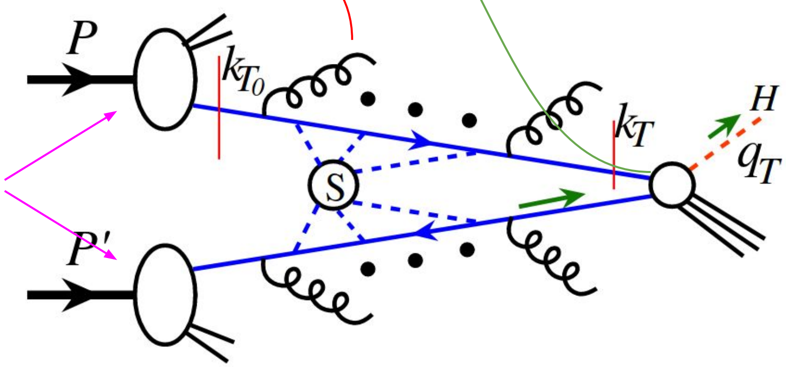
Experimental measurements

Perturbative contributions

Large qT corrections

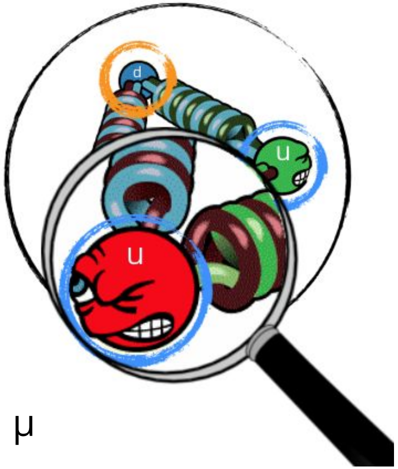
Low Q corrections

Non-perturbative parts



$$q_T \ll Q$$

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

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

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

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

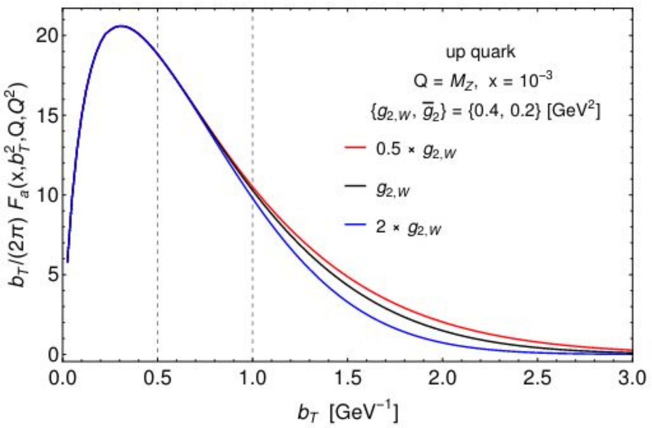
Non-pert. corrections (large bT)

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

Intrinsic transverse momentum, potentially flavor dependent!

Predictive power - quark TMDs

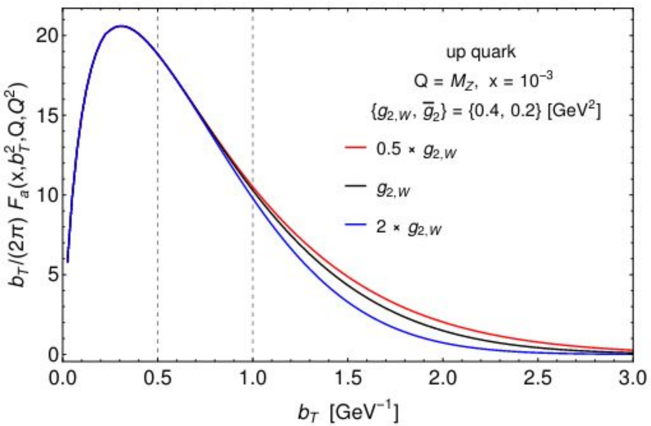
Large Q
Small x



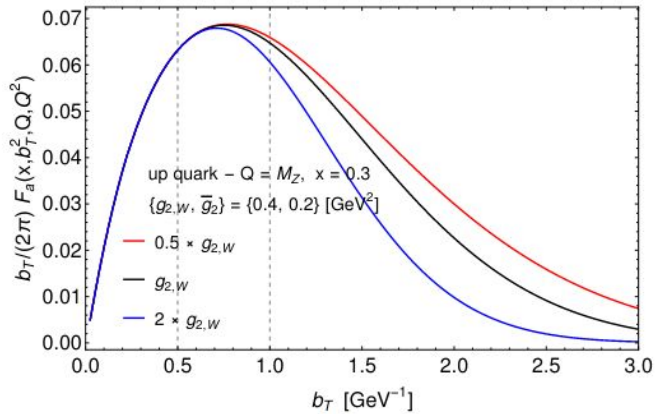
(a)

Predictive power - quark TMDs

Large Q
Small x



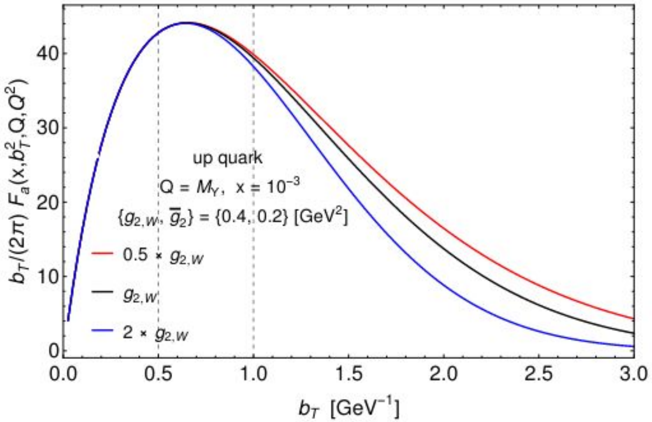
(a)



(b)

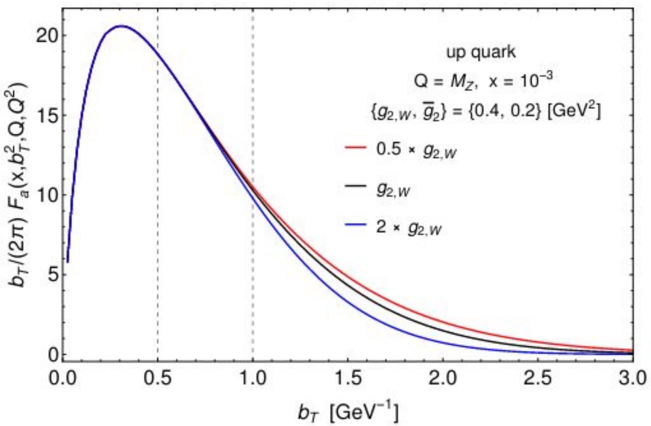
Large Q
Large x

Mid Q
Small x



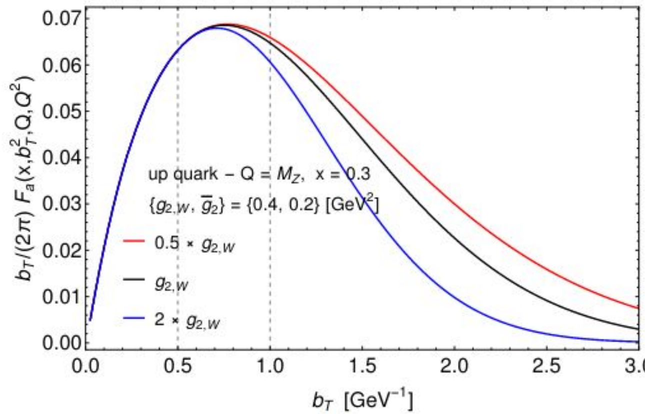
Predictive power - quark TMDs

Large Q
Small x



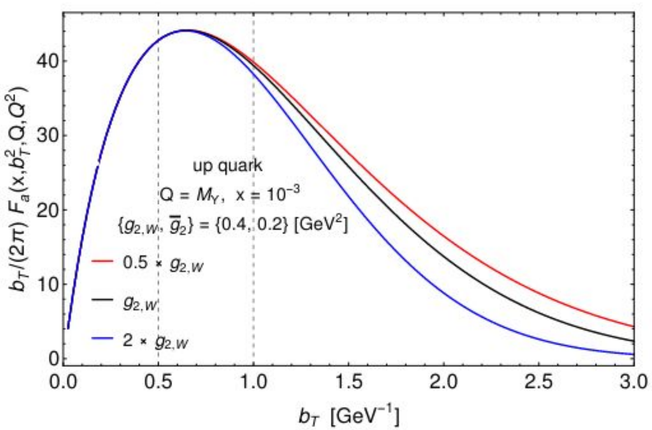
(a)

Large Q
Large x

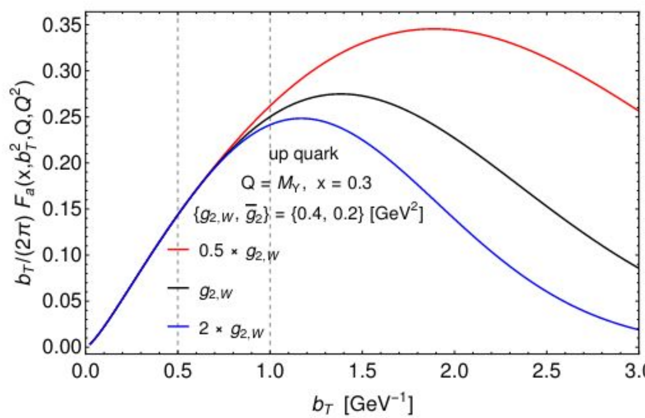


(b)

Mid Q
Small x

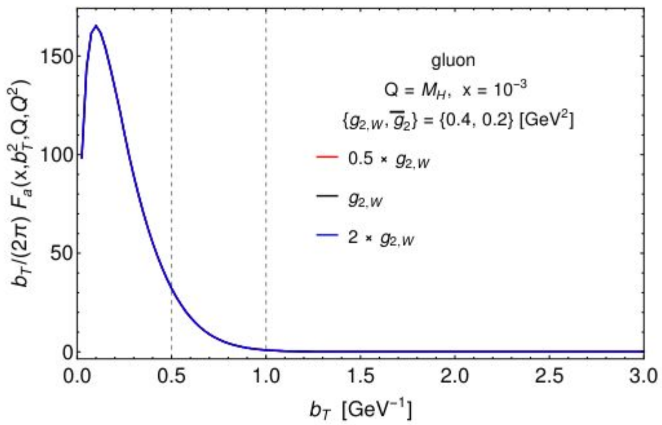


Mid Q
Large x



Predictive power - gluon TMDs

Large Q
Small x

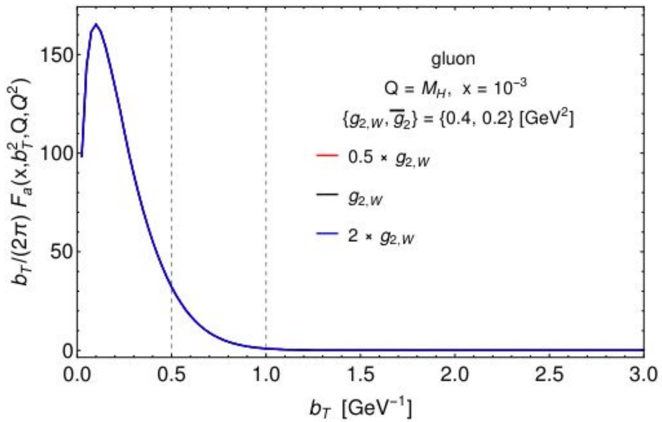


(a)

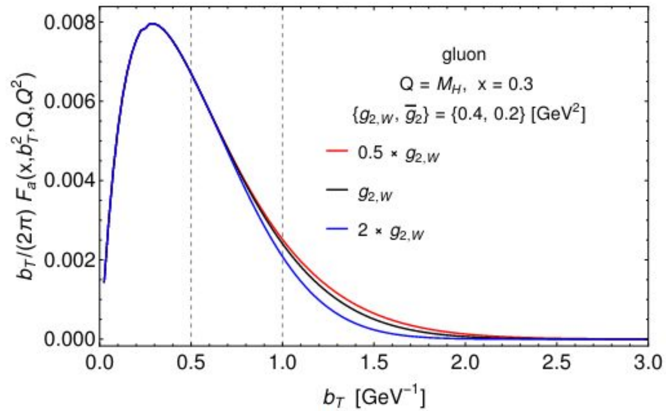
b_T [GeV]

Predictive power - gluon TMDs

Large Q
Small x



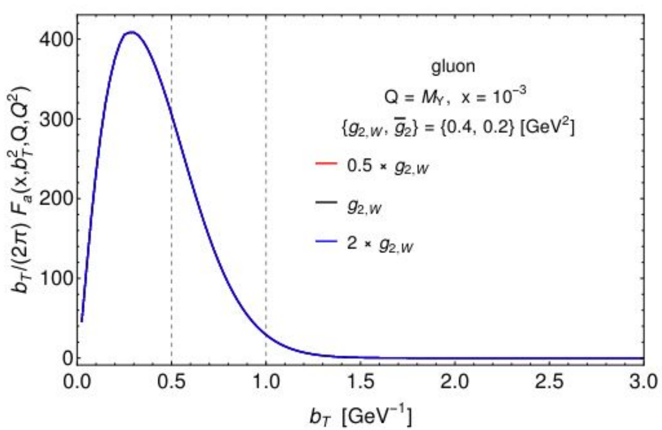
(a)



(b)

Large Q
Large x

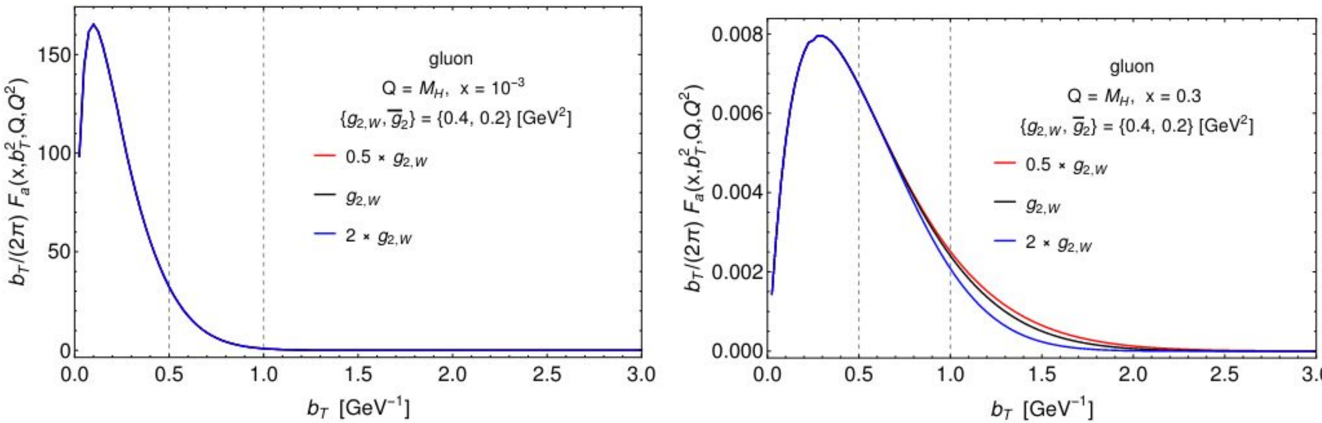
Mid Q
Small x



Predictive power - gluon TMDs

Large Q
Small x

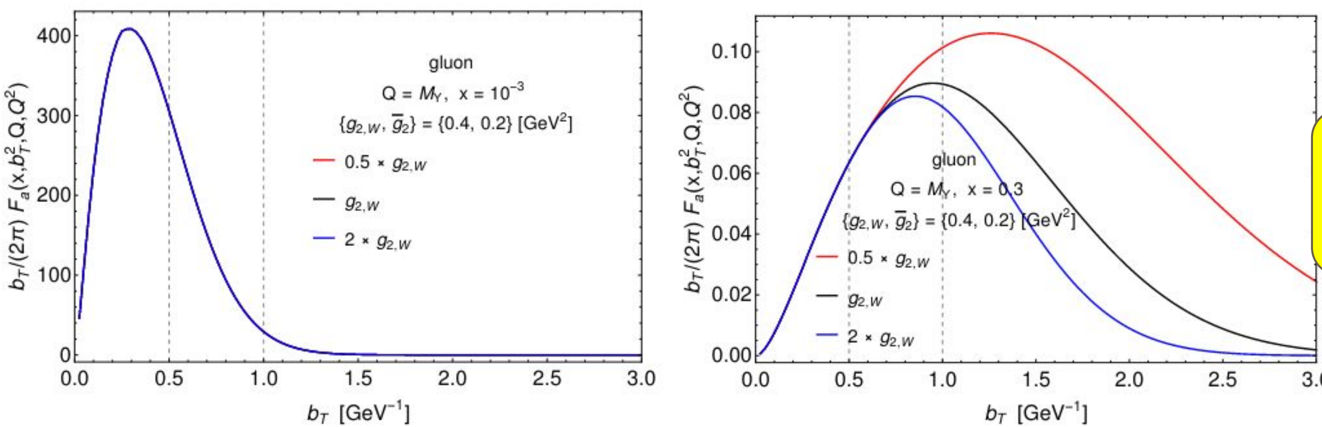
Large Q
Large x



(a) (b)

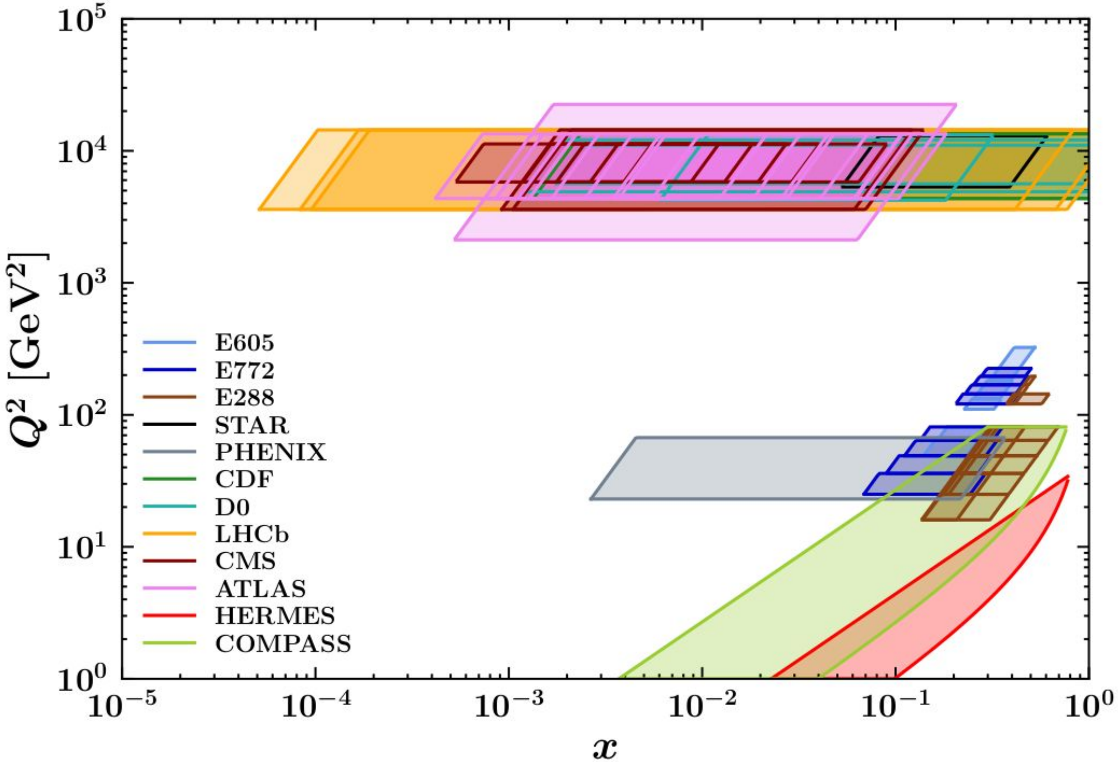
Mid Q
Small x

Mid Q
Large x



Data for unpolarized TMDs

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



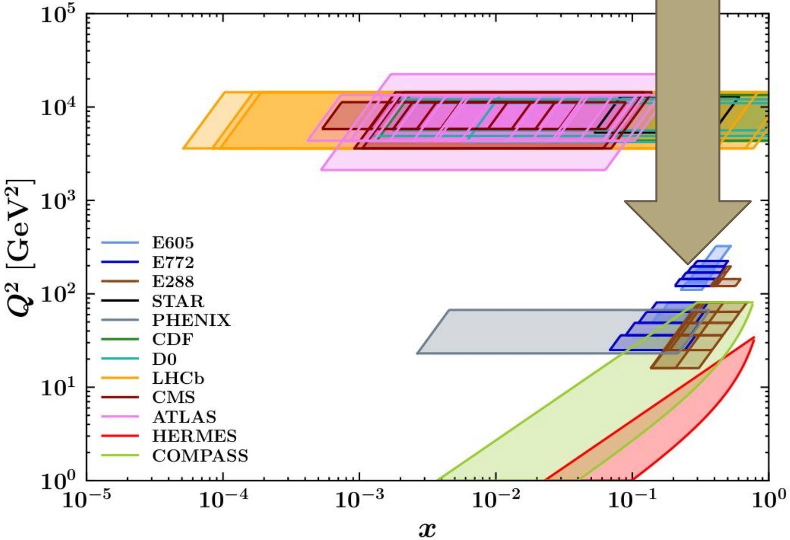
Drell-Yan collider

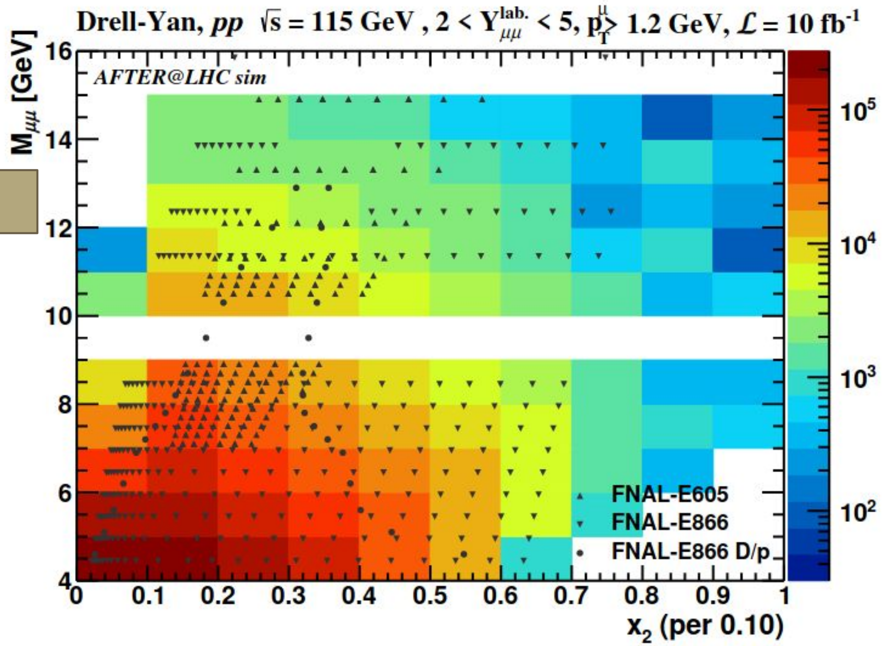
Drell-Yan fixed-target

SIDIS fixed-target

Data for unpolarized TMDs + DY from FT@LHC

Provides data in a **very interesting region** (see predictive power), where now the error bars are large





Impact on collinear PDFs

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

2020 PDFLattice Report 5

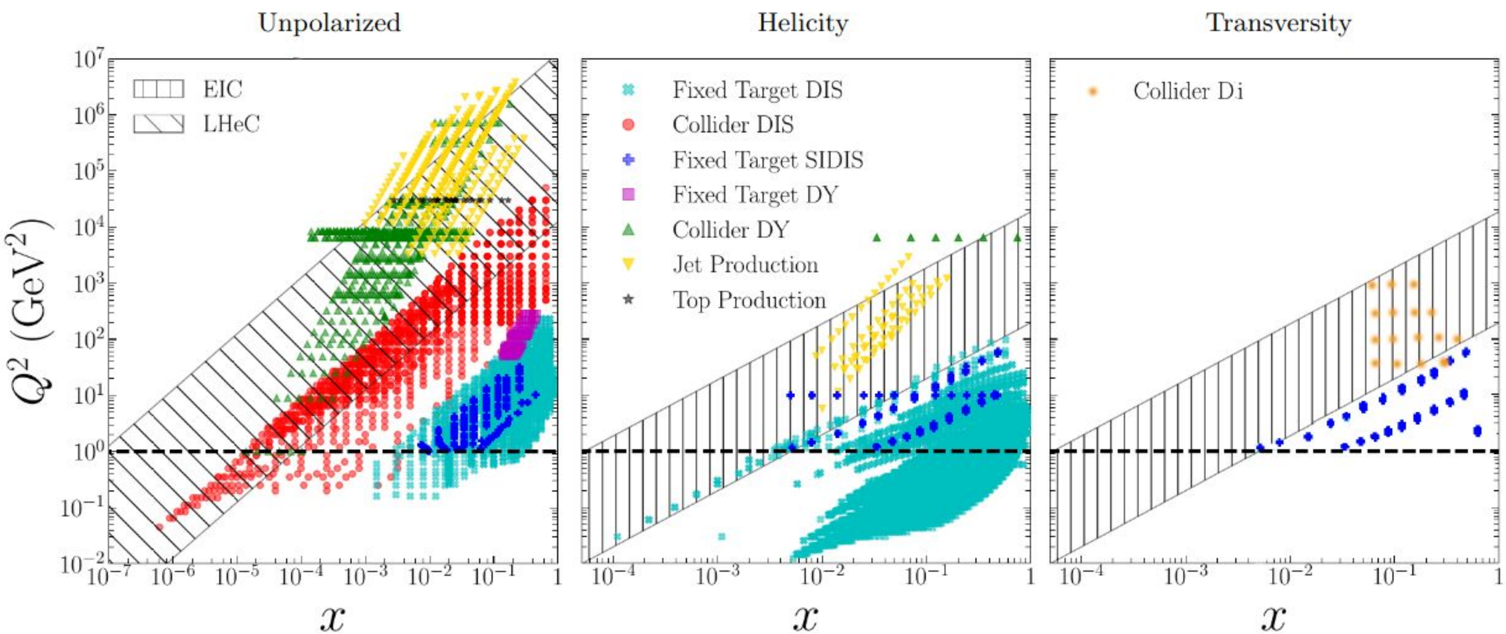


FIG. 1 The kinematic coverage in the (x, Q^2) plane of the hadronic cross-section data for the processes commonly included in global QCD analyses of collinear unpolarized, helicity, and transversity PDFs. The extended kinematic ranges attained by the LHeC and the EIC are also displayed. See Fig. 1 of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

Kinematics for FT @ LHC

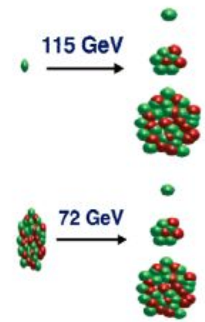
Energy range similar to RHIC

7 TeV proton beam on a fixed target

c.m.s. energy:	$\sqrt{s} = \sqrt{2m_N E_p} \approx 115\,\mathrm{GeV}$	**Rapidity shift:** $y_{c.m.s.} = 0 \rightarrow y_{lab} = 4.8$
Boost:	$\gamma = \sqrt{s}/(2m_N) \approx 60$	

2.76 TeV Pb beam on a fixed target

c.m.s. energy:	$\sqrt{s_{NN}} = \sqrt{2m_N E_{Pb}} \approx 72\,\mathrm{GeV}$	**Rapidity shift:** $y_{c.m.s.} = 0 \rightarrow y_{lab} = 4.3$
Boost:	$\gamma \approx 40$	

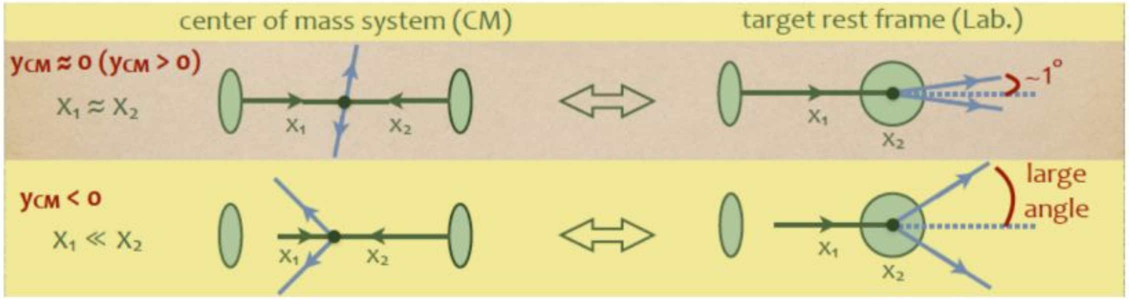


Hadjidakis et al.: https://inspirehep.net/literature/1680452

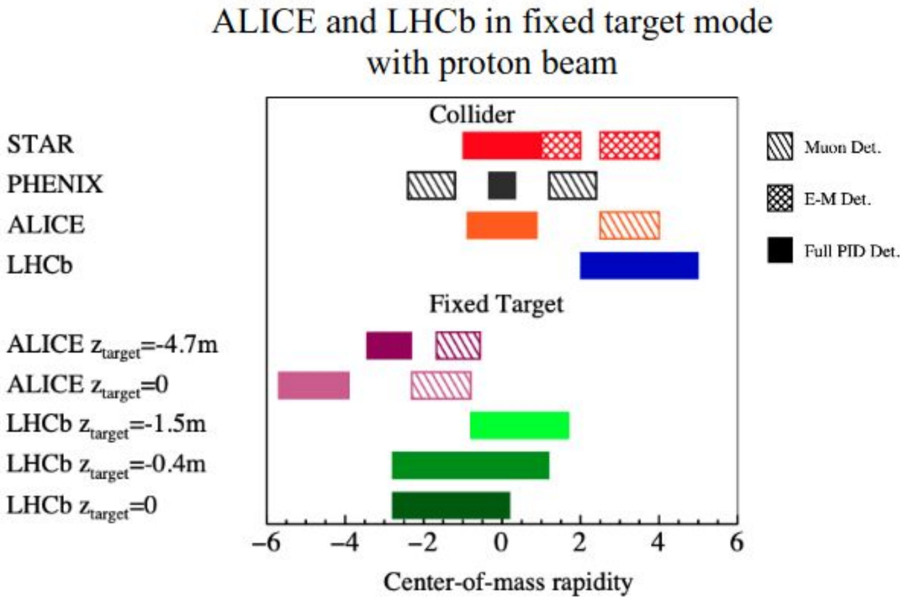
C. Hadjidakis at
“Synergies LHC/EIC workshop”
https://indico.ph.tum.de/event/7014/

Rapidity range

- Entire center-of-mass forward hemisphere ($y_{CM} > 0$) within 1 degree
- Easy access to (very) large backward rapidity range ($y_{CM} < 0$) and large parton momentum fraction in the target (x_2)



C. Hadjidakis et al.:
https://inspirehep.net/literature/1680452



Advantages for FT @ LHC

Accessing **high-x** frontier (→ **nonperturbative** effects)

Achieving **high luminosity** (→ **precise** information)

Varying **atomic mass number** of the target (→ explore **nuclear** effects)

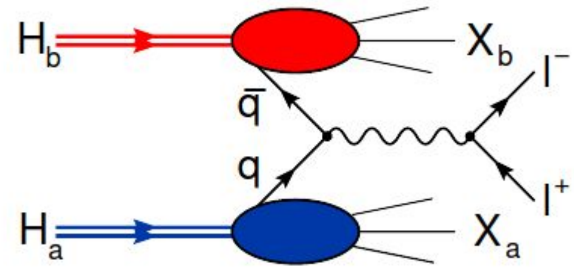
Polarizing the target (→ explore **spin-momentum** correlations)

This can be realised at LHC in a **parasitic** mode

Probes for q&g TMDs
&
projections

C. Hadjidakis et al.: https://inspirehep.net/literature/1680452

Unpolarized Drell-Yan



unpolarized

$$F_{UU}^{1} = \mathcal{C}[f_1 \bar{f}_1],$$

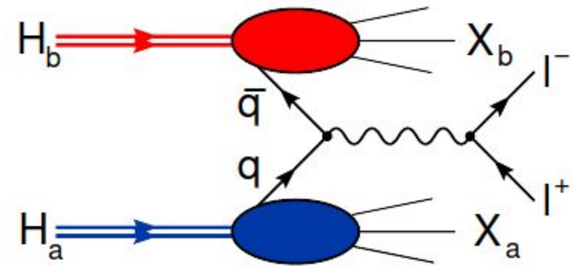
Unpolarized (TMD) PDF

$$F_{UU}^{\cos 2\phi} = \mathcal{C}\left[\frac{2(\vec{h}\cdot\vec{k}_{aT})(\vec{h}\cdot\vec{k}_{bT}) - \vec{k}_{aT}\cdot\vec{k}_{bT}}{M_a M_b} h_1^{\perp} \bar{h}_1^{\perp}\right],$$

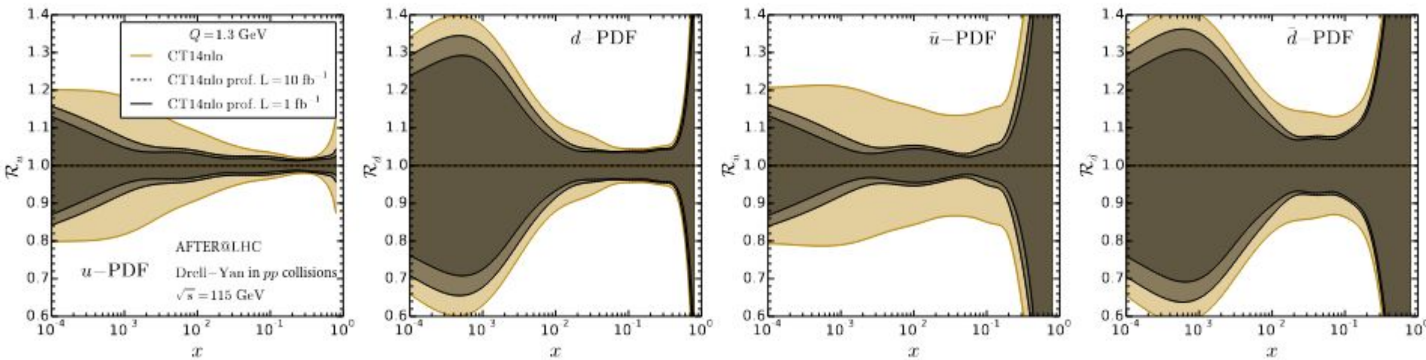
Boer-Mulders TMD PDF

No sub-leading twist in literature ..! Important for FT configuration

Unpolarized Drell-Yan



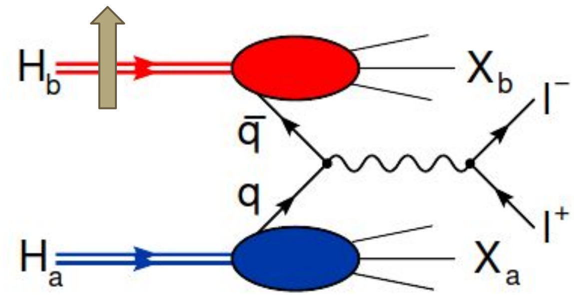
Impact on extraction of unpolarized collinear PDF f1



(a) u PDF (b) d PDF (c) $\bar{u}$ PDF (d) $\bar{d}$ PDF

Figure 17: Impact of the DY lepton pair production in pp collisions at $\sqrt{s} = 115$ GeV on the PDF uncertainties. The $u, d, \bar{u}$ and $\bar{d}$ PDFs from CT14 [5] are plotted as a function of x at a scale $Q = 1.3$ GeV before and after including AFTER@LHCb pseudo-data in the global analysis using the profiling method [193, 194]. Two scenarios with different integrated luminosities were considered: inner band: $\mathcal{L}_{pp} = 10$ fb^{-1}, middle band: $\mathcal{L}_{pp} = 1$ fb^{-1} (the outer band represents current PDF uncertainties).

Polarized Drell-Yan



Longitudinally polarized

$$F_{UL}^{\sin 2\phi} = -\mathcal{C}\left[\frac{2(\vec{h}\cdot\vec{k}_{aT})(\vec{h}\cdot\vec{k}_{bT}) - \vec{k}_{aT}\cdot\vec{k}_{bT}}{M_a M_b} h_1^{\perp}\bar{h}_{1L}^{\perp}\right],$$

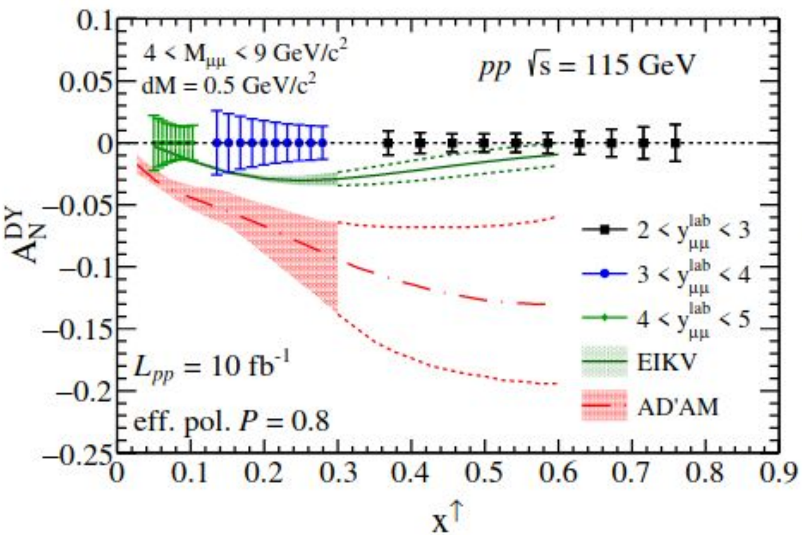
Transversally polarized

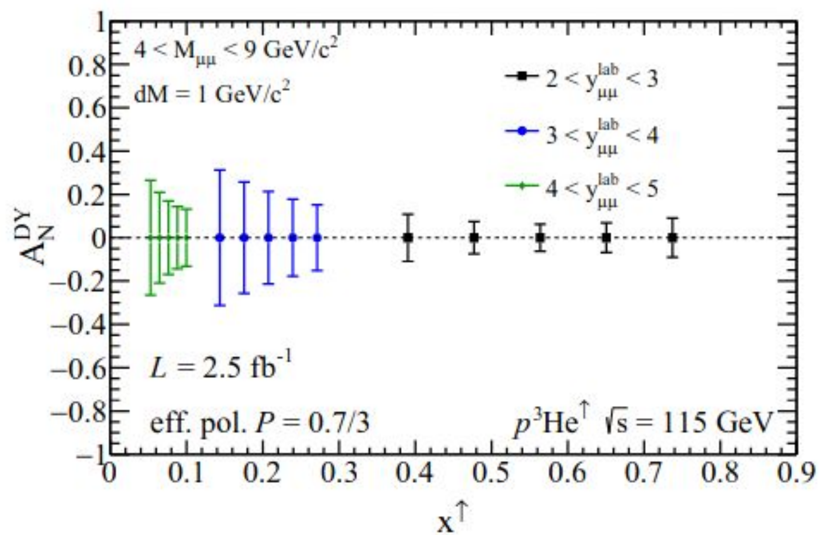
$$F_{UT}^{1} = \mathcal{C}\left[\frac{\vec{h}\cdot\vec{k}_{bT}}{M_b} f_1 \bar{f}_{1T}^{\perp}\right],$$

$$F_{UT}^{\sin(2\phi-\phi_b)} = -\mathcal{C}\left[\frac{\vec{h}\cdot\vec{k}_{aT}}{M_a} h_1^{\perp}\bar{h}_1\right],$$

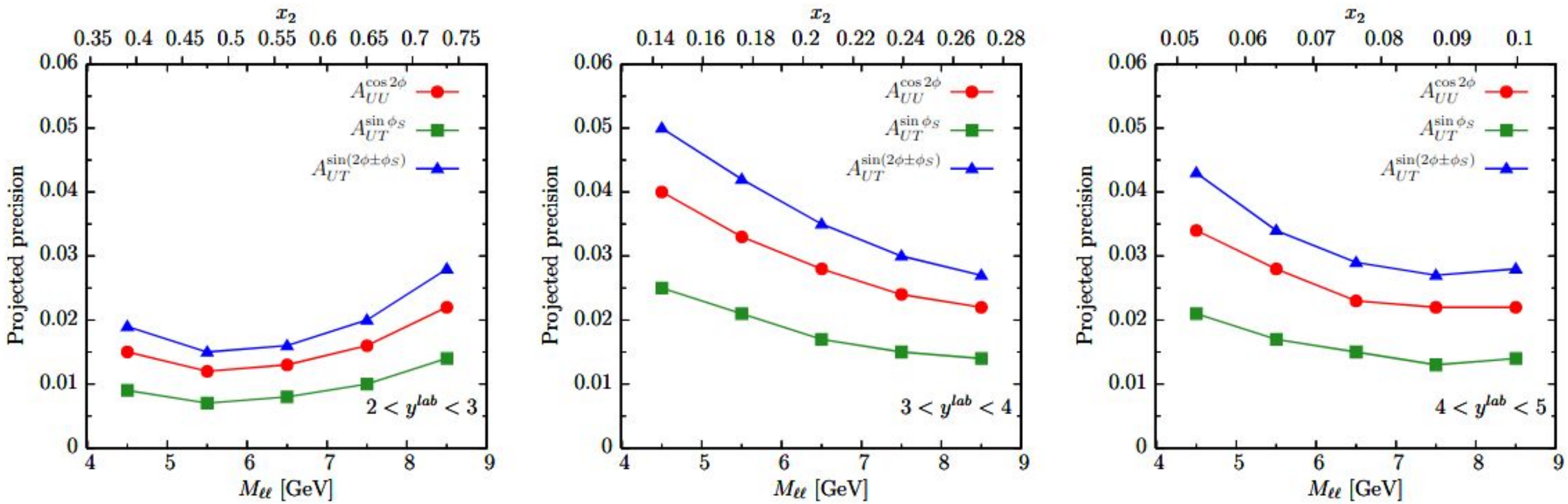
$$F_{UT}^{\sin(2\phi+\phi_b)} = -\mathcal{C}\left[\frac{2(\vec{h}\cdot\vec{k}_{bT})[2(\vec{h}\cdot\vec{k}_{aT})(\vec{h}\cdot\vec{k}_{bT}) - \vec{k}_{aT}\cdot\vec{k}_{bT}] - \vec{k}_{bT}^{2}(\vec{h}\cdot\vec{k}_{aT})}{2M_a M_b^2} h_1^{\perp}\bar{h}_{1T}^{\perp}\right],$$

Sivers asymmetry





More asymmetries



$$A_{UU}^{cos2\phi} \sim \frac{h_1^{\perp q} \otimes h_1^{\perp q}}{f_1^q \otimes f_1^q}$$

$$A_{UT}^{sin\phi_S} \sim \frac{f_1^q \otimes f_{1T}^{\perp q}}{f_1^q \otimes f_1^q}$$

$$A_{UT}^{sin(2\phi+\phi_S)} \sim \frac{h_1^{\perp q} \otimes h_{1T}^{\perp q}}{f_1^q \otimes f_1^q}$$

$$A_{UT}^{sin(2\phi-\phi_S)} \sim \frac{h_1^{\perp q} \otimes h_1^q}{f_1^q \otimes f_1^q}$$

One example for gluon TMDs: eta b,c production

unpolarized

$$\frac{d\sigma_{UU}(\eta_Q)}{dy\, d^2\boldsymbol{q}_T} = \frac{2}{9}\frac{\pi^3\alpha_s^2}{M_h^3\, s}\langle 0|\mathcal{O}_1^{\eta_Q}({}^1S_0)|0\rangle \left\{\mathcal{C}\left[f_1^g\, f_1^g\right] - \mathcal{C}\left[w_{UU}\, h_1^{\perp\, g}\, h_1^{\perp\, g}\right]\right\}$$

Transversally polarized

$$\frac{d\sigma_{UT}(\eta_b)}{dy d^2\boldsymbol{q}_T} = \frac{2}{9}\frac{\pi^3\alpha_s^2}{M_h^3\, s}\langle 0|\mathcal{O}_1^{\eta_b}({}^1S_0)|0\rangle\, |\boldsymbol{S}_{TB}|\sin\phi_S\, \times$$
$$\left\{\mathcal{C}\left[w_{UT}^{(A)}\, f_1^g\, f_{1T}^{\perp g}\right] - \mathcal{C}\left[w_{UT}^{(B)}\, h_1^{\perp g}\, h_1^g\right] - \mathcal{C}\left[w_{UT}^{(C)}\, h_1^{\perp g}\, h_{1T}^{\perp g}\right]\right\}$$

Longitudinally polarized

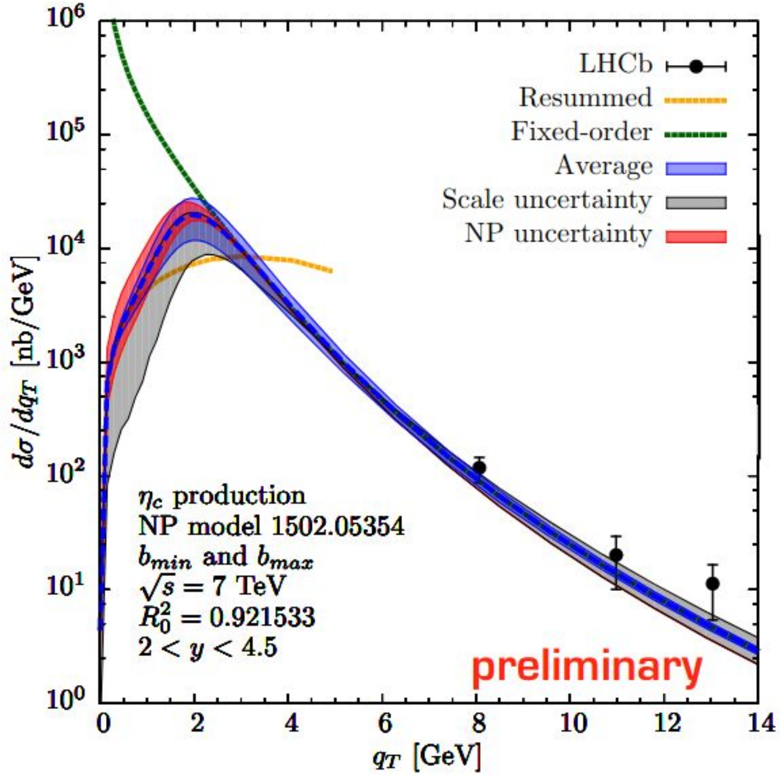
$$\frac{d\sigma_{UL}}{dy d^2\boldsymbol{q}_T} = 0$$

→ non-zero signal..? Twist 3 gluon TMDs

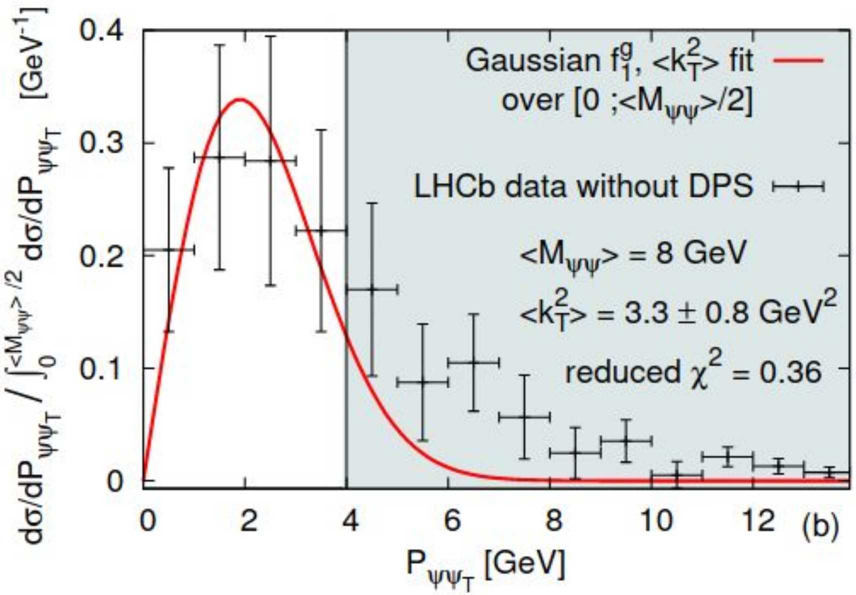
Eta c at LHCb

Lansberg et al. - ongoing work

full transverse momentum spectrum:
low qT matched with high qT region



Di-J/Psi at LHCb

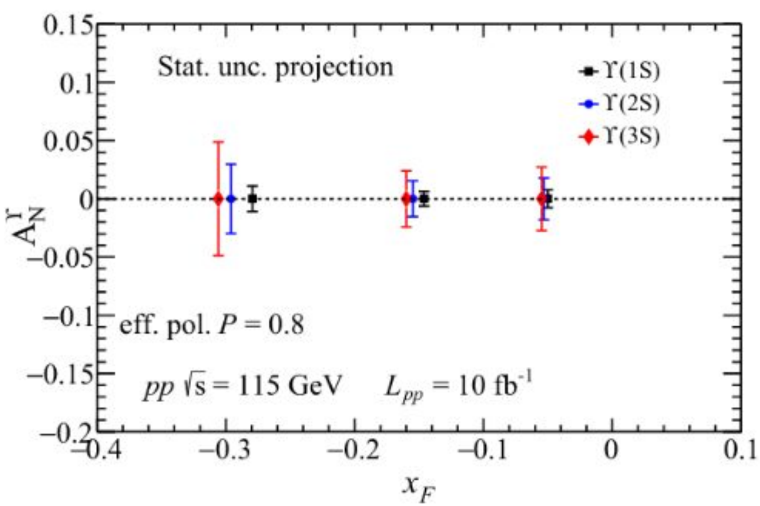


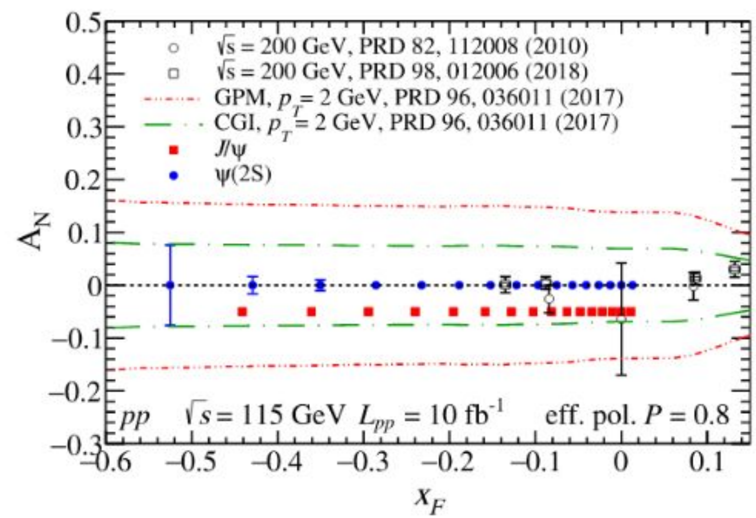
First “extraction” of unpolarized gluon TMD PDF

Lansberg at al. : https://inspirehep.net/literature/1628653

C. Hadjidakis *et al.*, 1807.00603; D. Kikola *et al.* Few Body Syst. 58 (2017) 139

- A_N for all quarkonia (J/ψ, ψ', χ_c, $\Upsilon(nS)$, χ_b & η_c) can be measured [So far, only J/ψ by PHENIX with larger uncertainties]
- Also access to polarised neutron ($^3\mathrm{He}^\uparrow$) at the per cent level for J/ψ
- Completely new perspectives to study the gluon Sivers effect
- Di-J/ψ allow one to study the k_T dependence of the gluon Sivers function for the very first time





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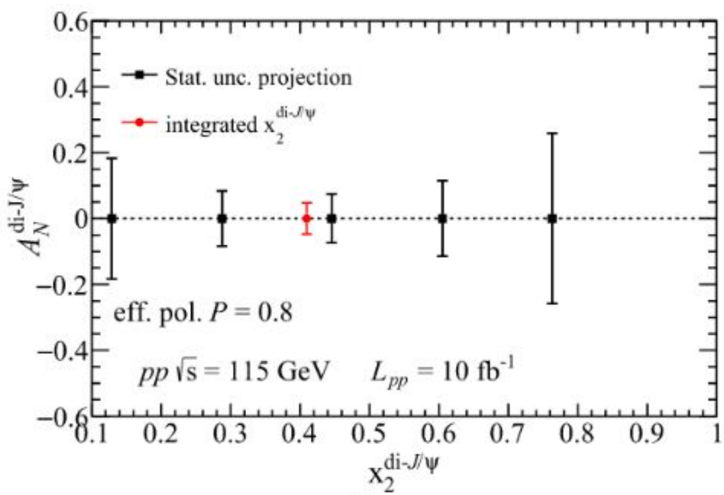
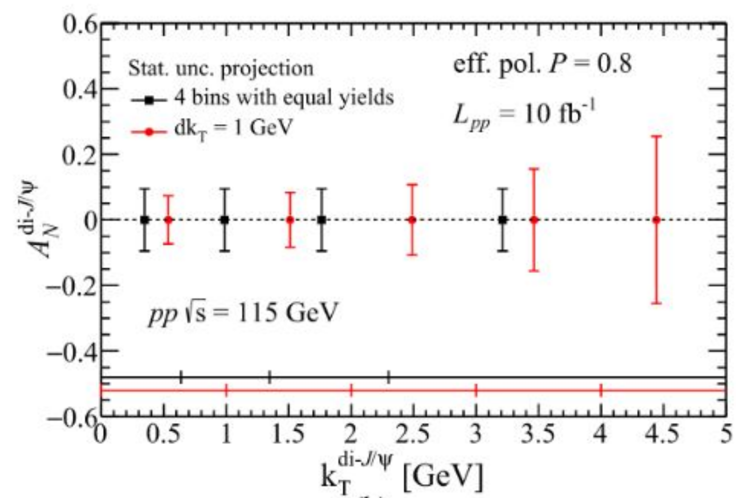




Conclusions and outlook

Spin and transverse dynamics

High x frontier

Heavy Ion collisions

Astroparticle physics

The physics reach of the LHC complex can greatly be extended at a very limited cost with the adjunction of an ambitious and long term research program using the LHC beams in the fixed-target mode.

Different possible technical implementations:
see next talks

Backup

TMD factorization

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

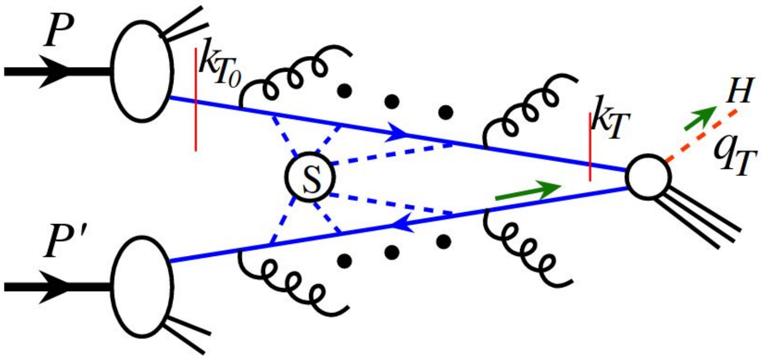
$$\frac{d\sigma}{dq_T} \sim \mathcal{H}\, f_1(x_a, k_{T\,a}, Q, Q^2)\, f_1(x_b, k_{T\,b}, Q, Q^2)\, \delta^{(2)}(q_T - k_{T\,a} - k_{T\,b}) \; + \mathcal{O}(q_T/Q) \, + \, \mathcal{O}(\Lambda/Q)$$

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

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

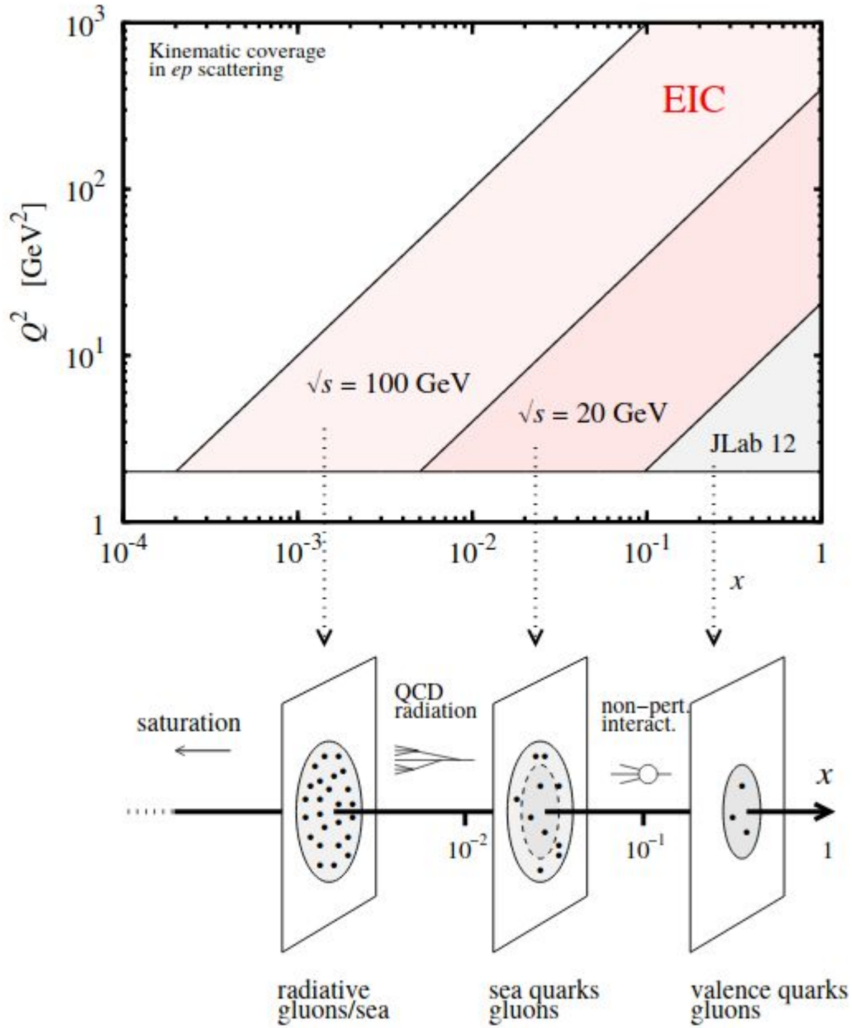
- quark transverse momentum :
  radiative (perturbative) and **intrinsic** (non-perturbative) components

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



SIDIS coverage

Importance of complementary experiments

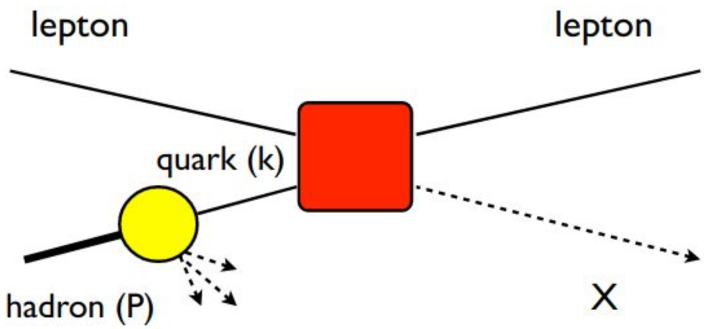


from JLab 12 GeV, Hermes, Compass
to the EIC

zooming into hadron structure

Credit picture: C. Weiss

PDFs: operator definition

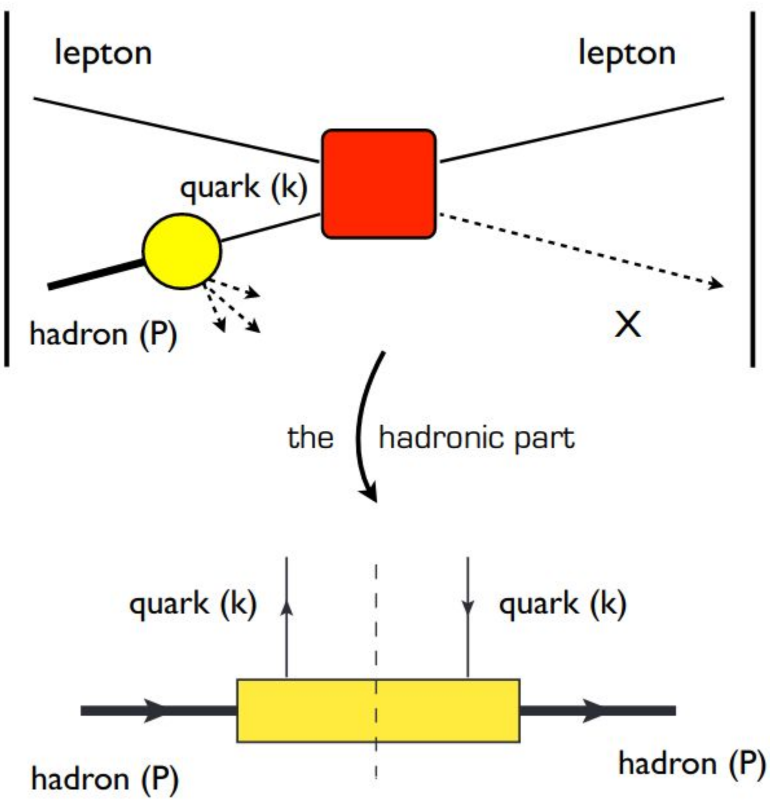


Scattering process with hadron in initial state :
(e.g. Deep Inelastic Scattering - DIS)

need a “hadron → parton” transition

(Parton Distribution Function)

PDFs: operator definition



PDFs defined as traces of Φ :

$$F^{[U]}(x, k_T^2) \sim \mathrm{Tr}\,[\Phi\,\Gamma]\;,\;\; \Gamma = \gamma^+\,,\ldots$$

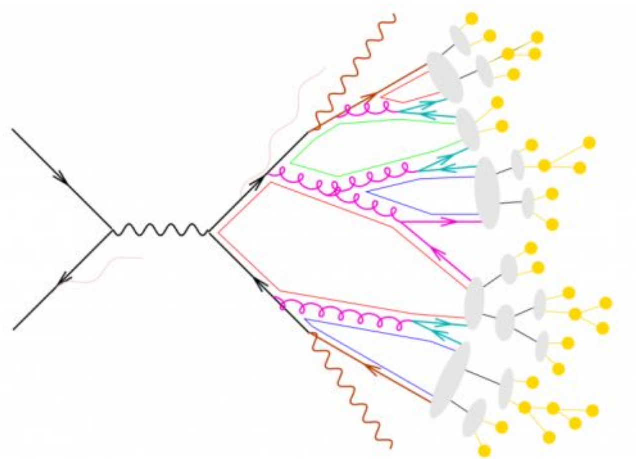
(***8 functions*** that depend on parton kinematics and gauge link U)

Hadronic part described as a ***universal*** "quark-quark correlation function" in space-time

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

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

Different frameworks, same observable

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

$$\mathcal{H} = HC_1C_2$$

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

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

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/

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 (MAPTMD22 analysis)
[https://github.com/MapCollaboration/NangaParbat]

Parton branching

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

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

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/

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]
- ...