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University of Turin and INFN

LHCb implications workshop

CERN - October 25, 2023

A fixed-target configuration at the LHC -theoretical aspects-

UNIVERSITÀ DI TORINO

INFN Istituto Nazionale di Fisica Nucleare

Outline

1. **Describing hadron structure**
2. **The role of experimental data**
3. **Opportunities with a fixed target at the LHC (very short selection)**

Phys. Rept. 2021 - fixed-target program at LHC

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Contents lists available at ScienceDirect

Physics Reports

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

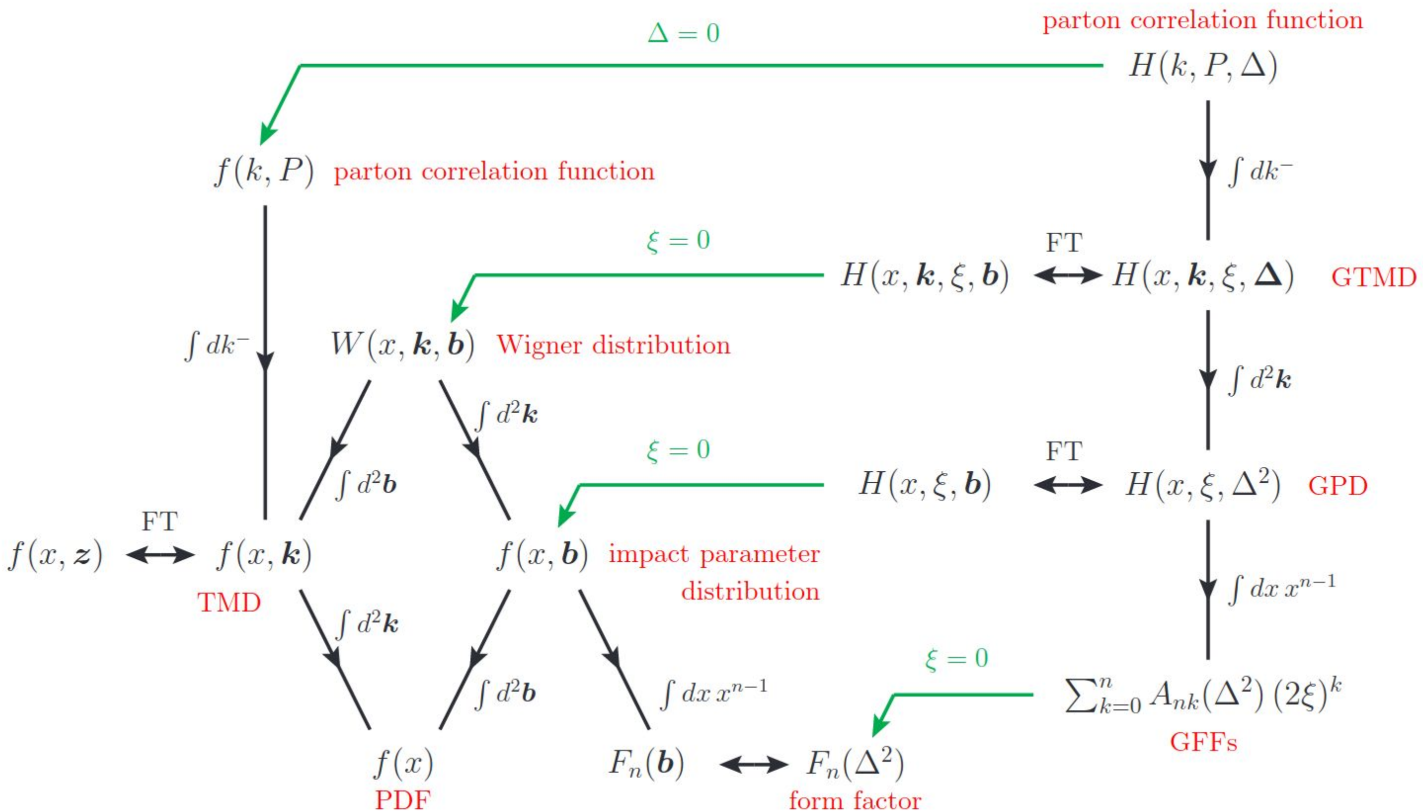
Check for updates

A fixed-target programme at the LHC: Physics case and projected performances for heavy-ion, hadron, spin and astroparticle studies

C. Hadjidakis [1,a], D. Kikoła [2,a], J.P. Lansberg [1,*,a], L. Massacrier [1,a], M.G. Echevarria [3,4,b], A. Kusina [5,b], I. Schienbein [6,b], J. Seixas [7,8,9,b], H.S. Shao [10,b], A. Signori [11,3,12,b], B. Trzeciak [13,14,b], S.J. Brodsky [15], G. Cavoto [16], C. Da Silva [17], F. Donato [18], E.G. Ferreiro [19,20], I. Hřivnáčová [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]

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

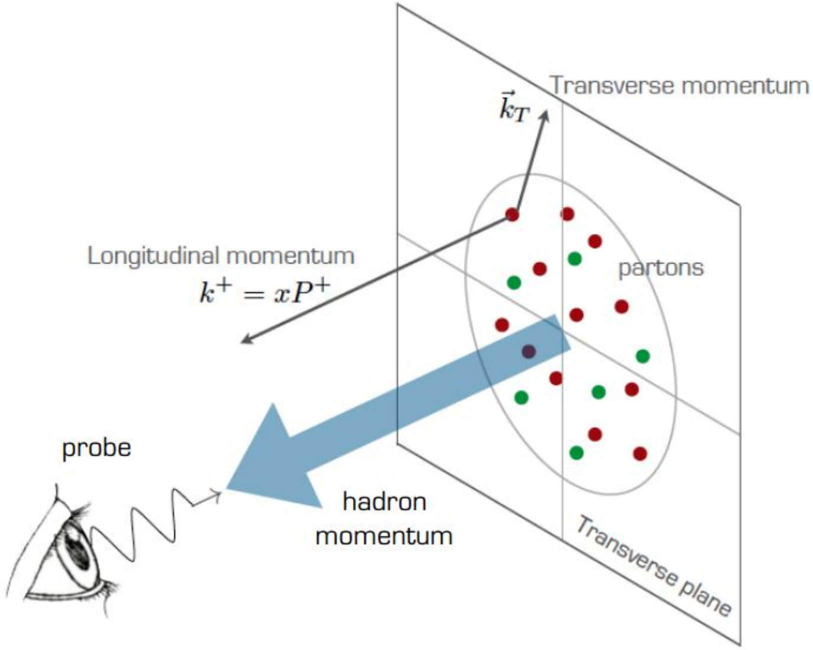
PDFs, TMDs, GPDs, etc.



Credit picture: M. Diehl - [arXiv 1512.01328]

PDFs, TMDs

"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

PDFs, TMDs - 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, $h_{1T}^\perp$

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

At leading twist: 8 TMD PDFs

(similar classification for gluons and for fragmentation functions)

- **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

Why studying these 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

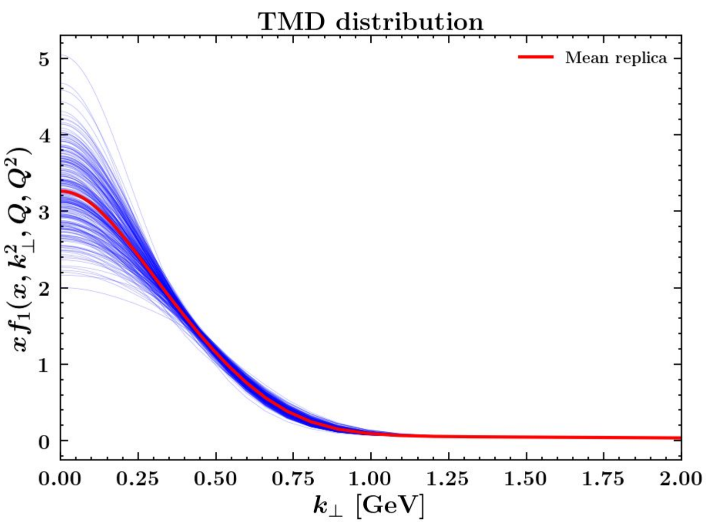
e

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

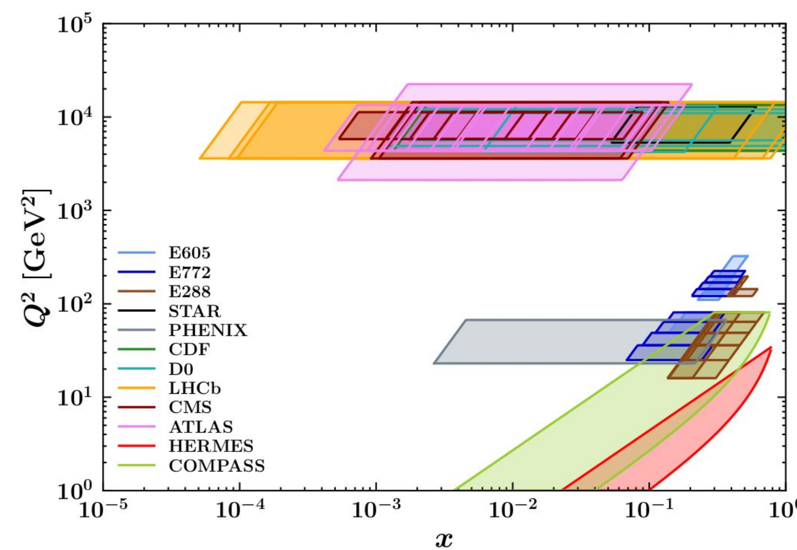
E

- 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

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

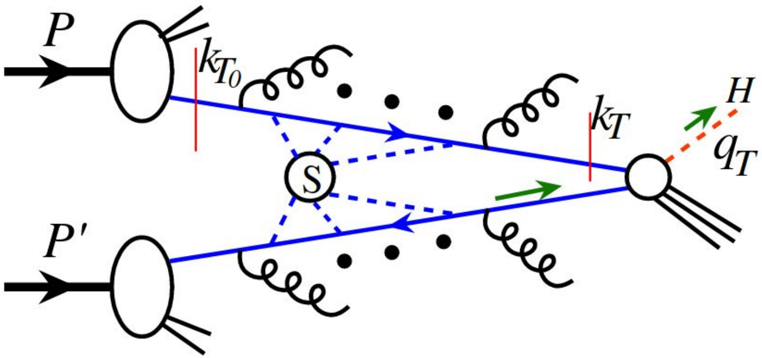
$$\frac{d\sigma}{dq_T} \sim \mathcal{H}\, f_1(x_a, k_{T\,a}, Q, Q^2)\, f_1(x_b, k_{T\,b}, Q, Q^2)\, \delta^{(2)}(q_T - k_{T\,a} - k_{T\,b}) \; + \mathcal{O}(q_T/Q) \; + \; \mathcal{O}(\Lambda/Q)$$

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

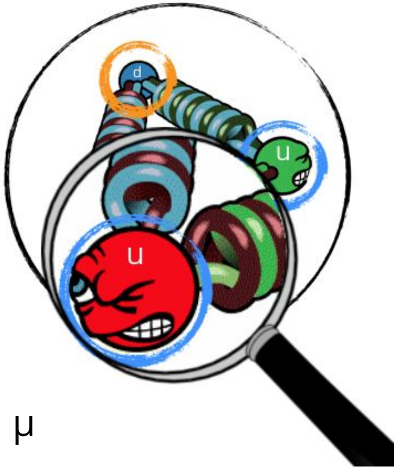
- **observed transverse momentum** :
  handle on transverse momenta of **quarks**

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

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



"Structure" of TMD PDFs



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

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

Calculable in pQCD

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

TMD PDFs: non-perturbative content

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

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

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

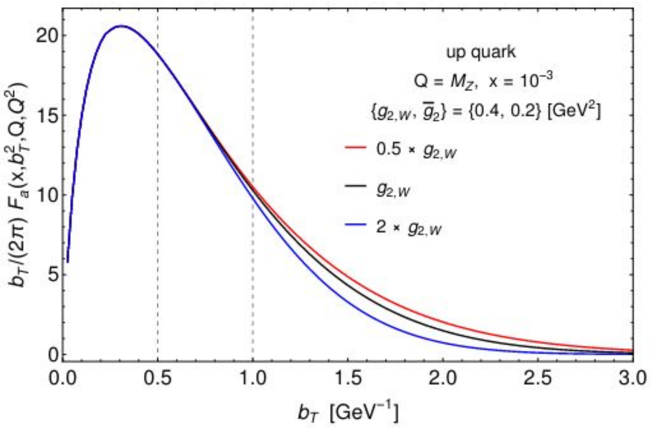
$$F_a(x, b_T^2; \mu_0, \zeta_0) = \sum_b C_{a/b}(x, b_T^2, \mu_0, \zeta_0) \otimes f_b(x, \mu_0) \boxed{F_{NP}(b_T; \lambda)}$$

Non-pert. corrections (large bT)

Intrinsic transverse momentum, potentially flavor dependent!

Dominance of non-perturbative effects

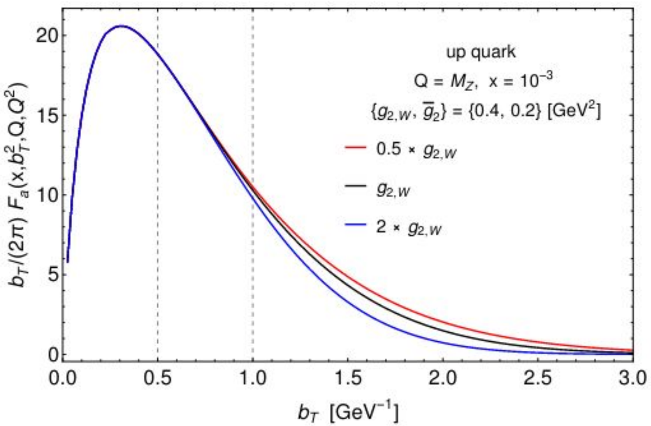
Large Q
Small x



(a)

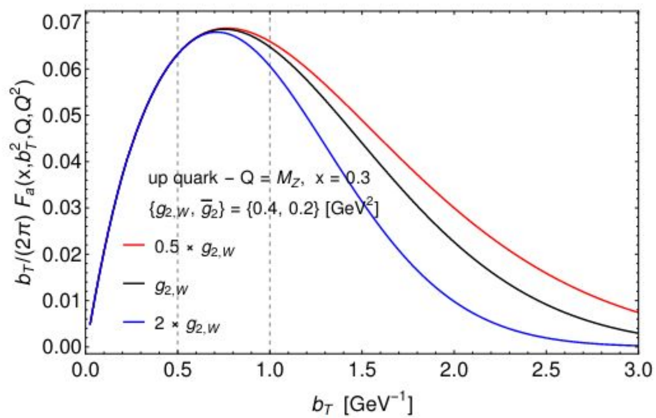
Dominance of non-perturbative effects

Large Q
Small x



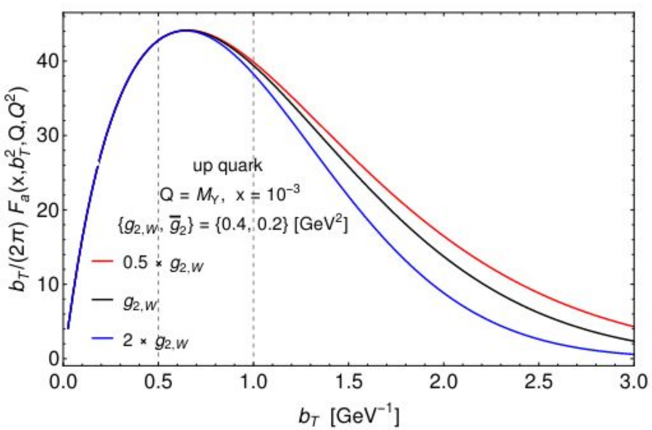
(a)

Large Q
Large x



(b)

Mid Q
Small x



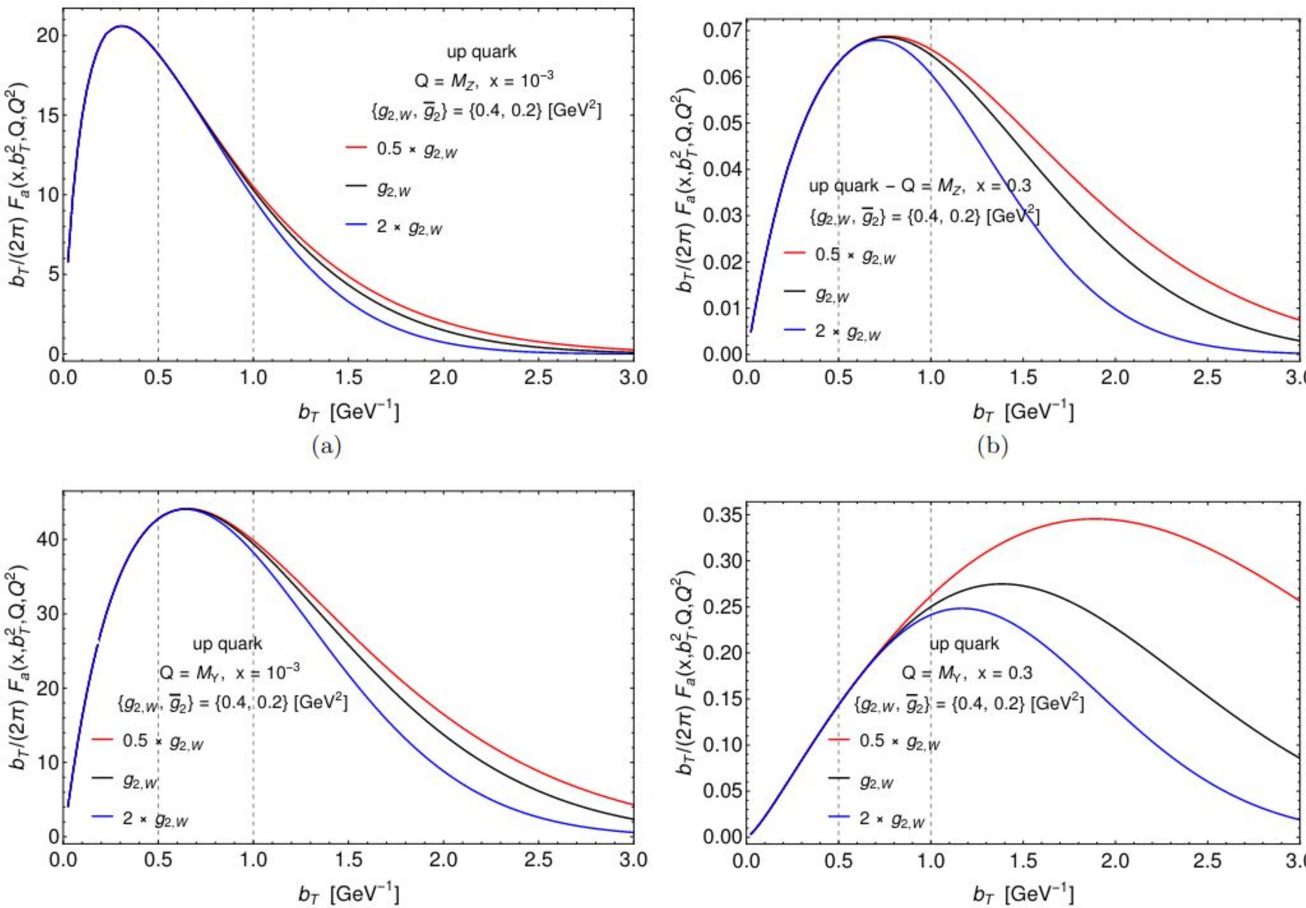
Dominance of non-perturbative effects

Large Q
Small x

Large Q
Large x

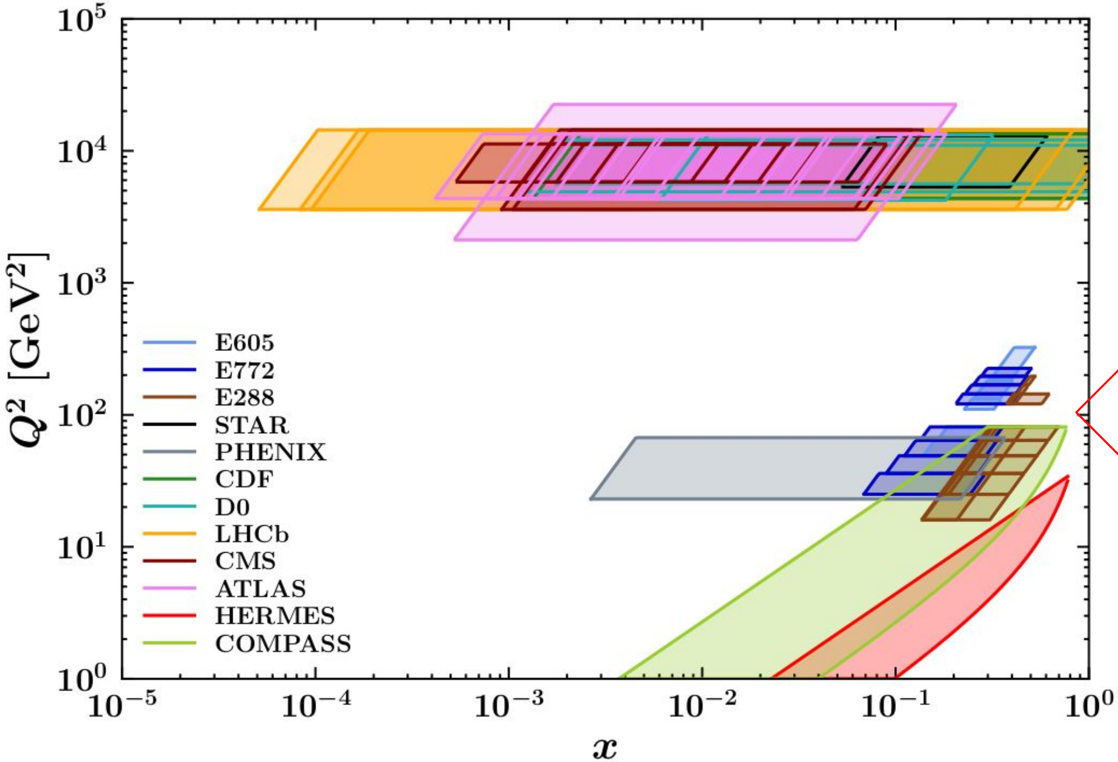
Mid Q
Small x

Mid Q
Large x



Data for unpolarized TMDs

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



Drell-Yan collider

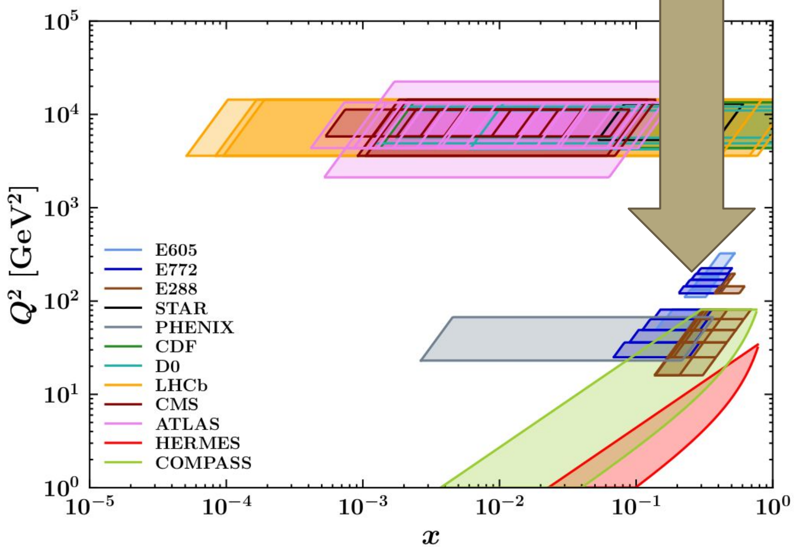
Sweet spot for hadron structure studies

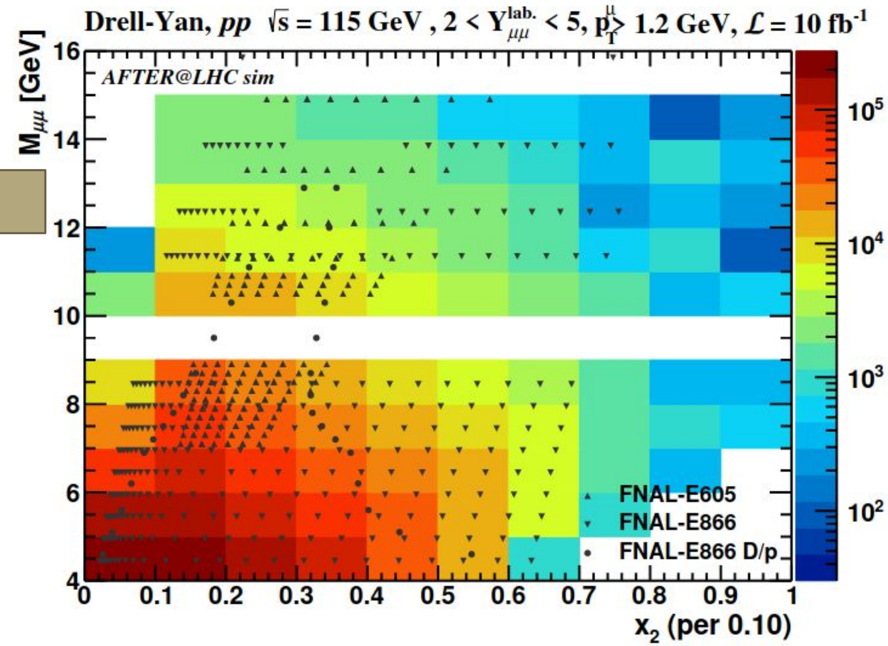
Drell-Yan fixed-target

SIDIS fixed-target

Drell-Yan coverage - FT configuration at LHC

Provides **precise** data in a **very interesting region**, where the **current data is not precise** (old data from Fermilab)

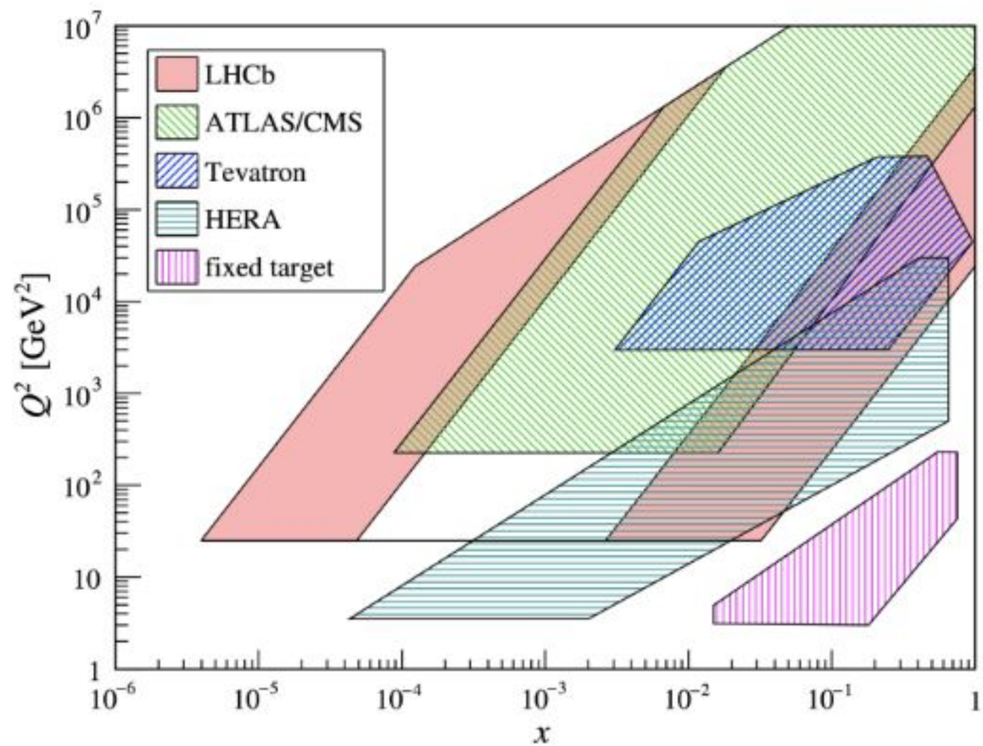




Hadjidakis et al.:
https://inspirehep.net/literature/1680452
(Physics Reports, 2022)

Drell-Yan coverage - FT configuration at LHCb

Slide from opening talk by
M. Pepe-Altarelli



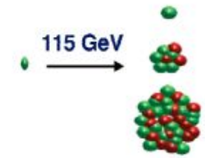
See also **next talk** by **K. Mattioli**

Drell-Yan kinematics - FT configuration at LHC

Energy range similar to RHIC

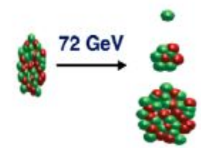
7 TeV proton beam on a fixed target

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



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

See **next talk** by **K. Mattioli** for more up-to-date numbers (LHCb)

Advantages - FT configuration @ LHC

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

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

Varying **atomic mass number** of the target (→ explore **nuclear** effects
See talks by **I. Schienbein** and **S. Sellam**)

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

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

Opportunities for hadron structure studies

(a very short selection)

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

Collinear PDFs

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

The only DY FT data. Polarization of both hadrons needed to access polarized PDFs

(or look at h1(x) via pp to dihadrons)

2020 PDFLattice Report 5

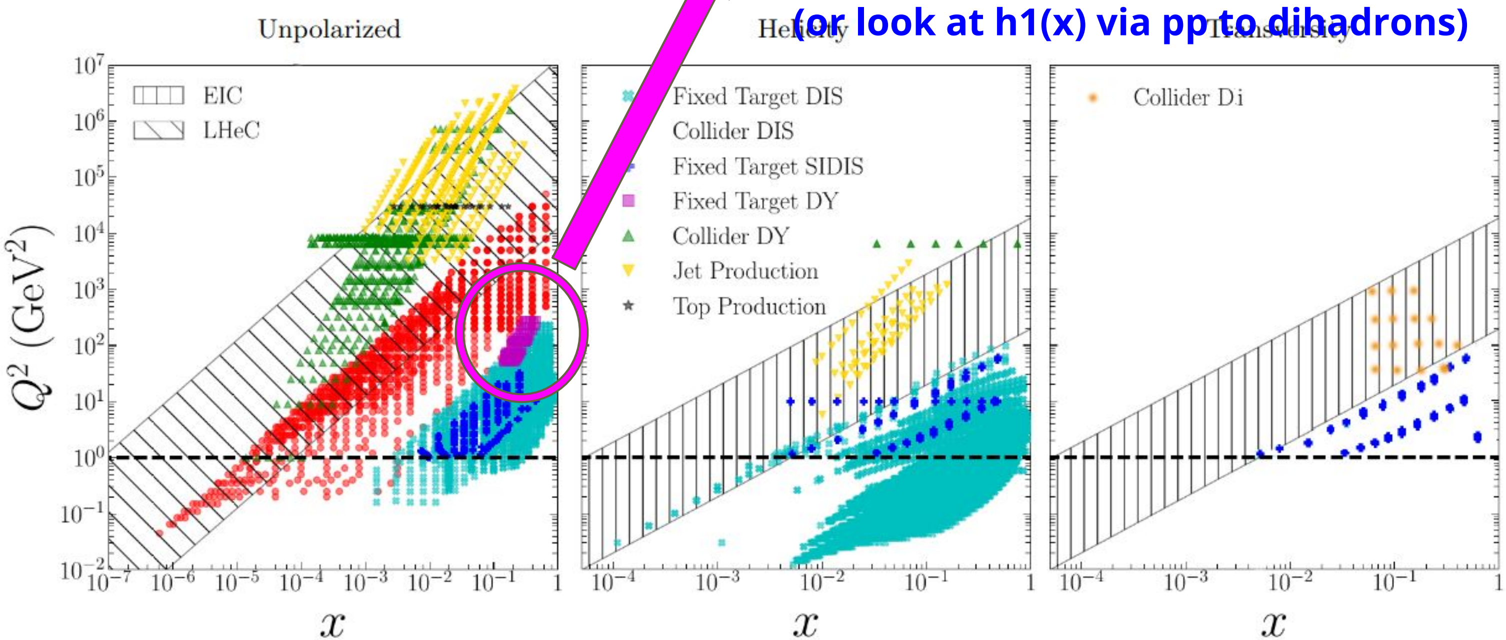
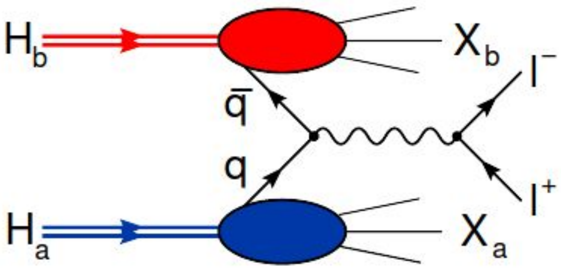


FIG. 1 The kinematic coverage in the (x, Q^2) plane of the hadronic cross-section data for the processes commonly included in global QCD analyses of collinear unpolarized, helicity, and transversity PDFs. The extended kinematic ranges attained by the LHeC and the EIC are also displayed. See Fig. 1 of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

Unpolarized Drell-Yan (TMDs)



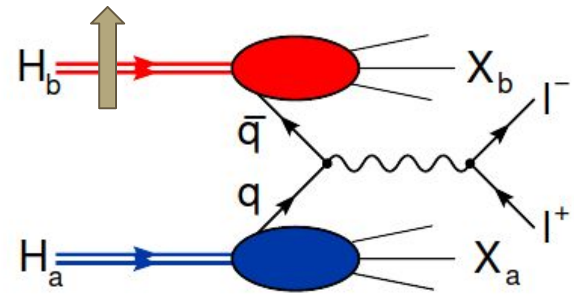
Unpolarized (TMD) PDF

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

Boer-Mulders TMD PDF

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

Polarized Drell-Yan (TMDs)



Longitudinally polarized

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

Transversally polarized

Sivers TMD PDF: **sign change** measurement! **Extremely important**

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

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

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

eta b,c production : access to gluon TMD PDFs

unpolarized

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

Transversally polarized

$$\frac{d\sigma_{UT}(\eta_b)}{dy d^2\boldsymbol{q}_T} = \frac{2}{9}\frac{\pi^3\alpha_s^2}{M_h^3\, s}\langle 0|\mathcal{O}_1^{\eta_b}({}^1S_0)|0\rangle\, |\boldsymbol{S}_{TB}|\sin\phi_S\ \times$$

$$\left\{\mathcal{C}\left[w_{UT}^{(A)}\ \underline{f_1^g\ f_{1T}^{\perp g}}\right] - \mathcal{C}\left[w_{UT}^{(B)}\ \underline{h_1^{\perp g}\, h_1^g}\right] - \mathcal{C}\left[w_{UT}^{(C)}\ \underline{h_1^{\perp g}\, h_{1T}^{\perp g}}\right]\right\}$$

Unpolarized gluons

Longitudinally polarized gluons

Sivers gluon TMD PDF

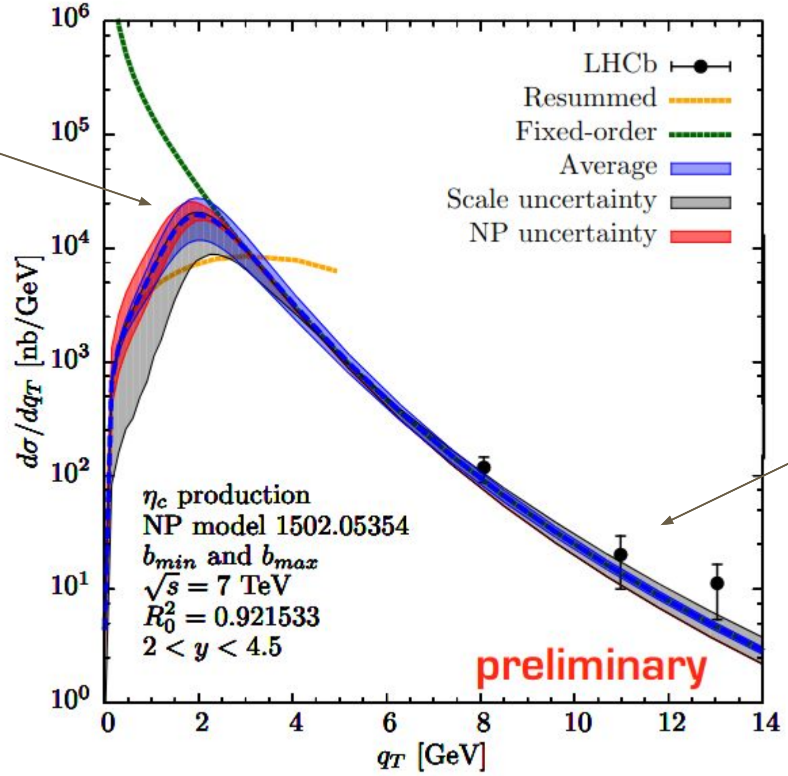
Longitudinally polarized

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

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

eta b,c production : access to gluon TMD PDFs

The **low transverse momentum** region gives access to gluon TMD PDFs



LHCb measurement at **large transverse momentum**: collinear gluon PDFs

Lansberg et al. - ongoing work

Conclusions and outlook

Spin and transverse dynamics

High x frontier

Astroparticle physics

Heavy Ion collisions

In particular, a fixed-target configuration at the LHC will open new windows on:

- the **non-perturbative structure** of unpolarized collinear and TMD PDFs
- also **gluon** TMD PDFs
- **spin-dependent** observables (e.g. sign change for the **Sivers** function)
- **nuclear** effects
- nuclear dependence of spin-momentum correlations
- ...

Fixed-target implementation in LHCb: see next talk(s)

Backup

TMD factorization

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

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

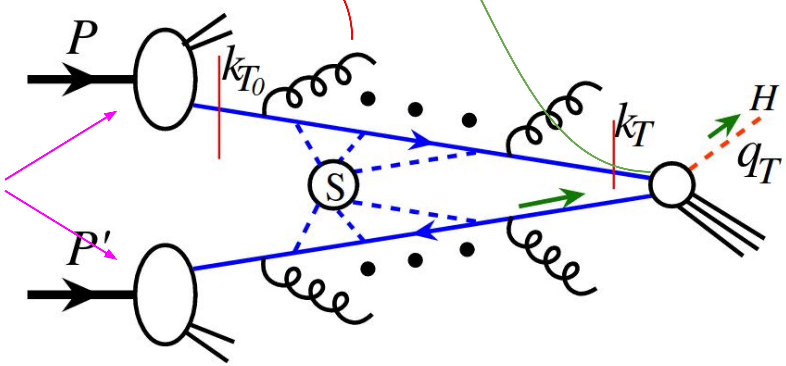
Experimental measurements

Perturbative contributions

Large qT corrections

Low Q corrections

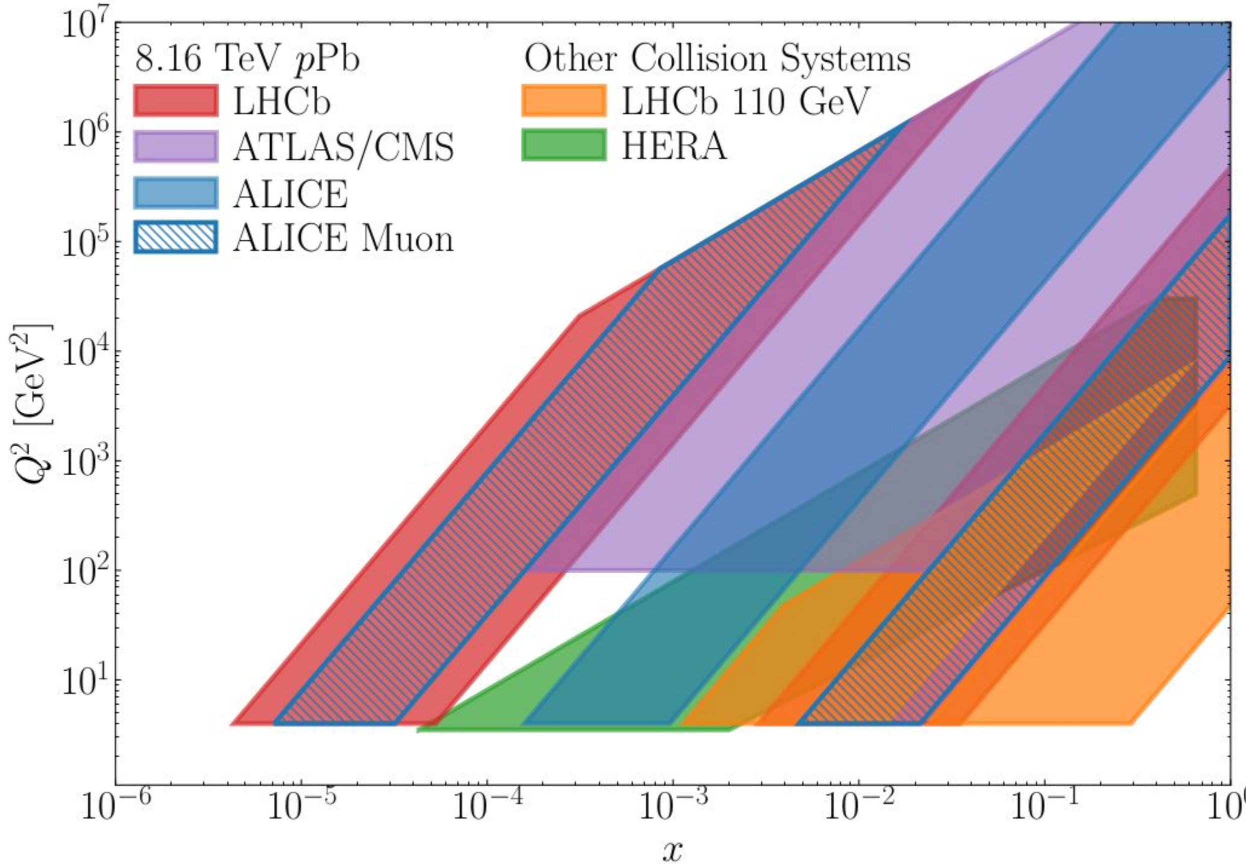
Non-perturbative parts



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

DY from FT@LHC

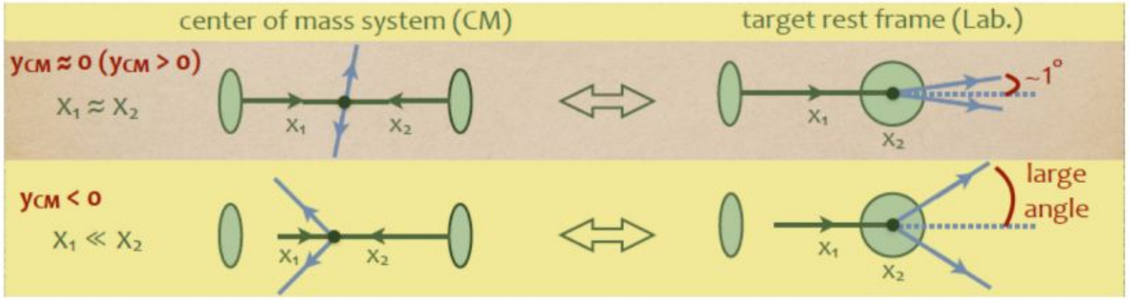
From Kara Mattioli's talk



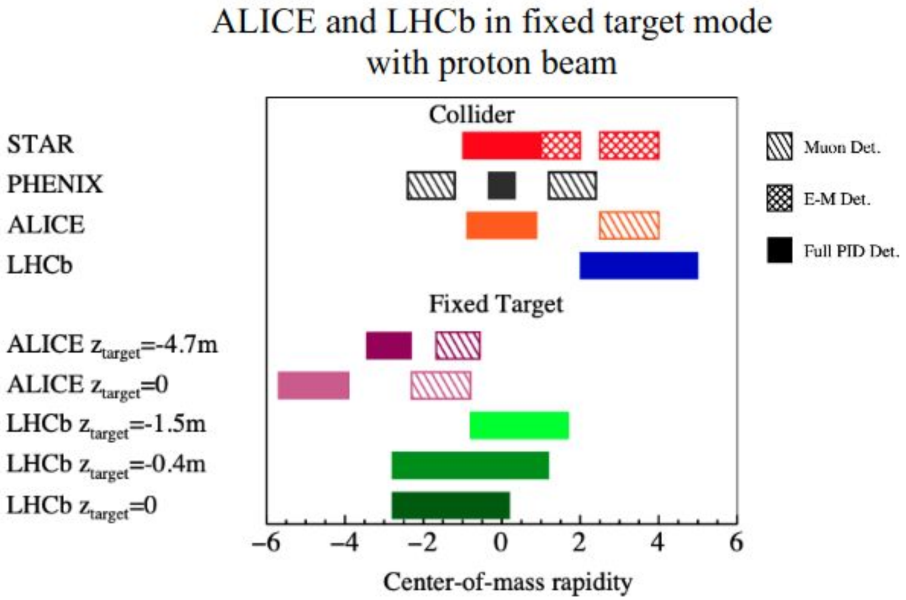
C. Hadjidakis at
"Synergies LHC/EIC workshop"
https://indico.ph.tum.de/event/7014/

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



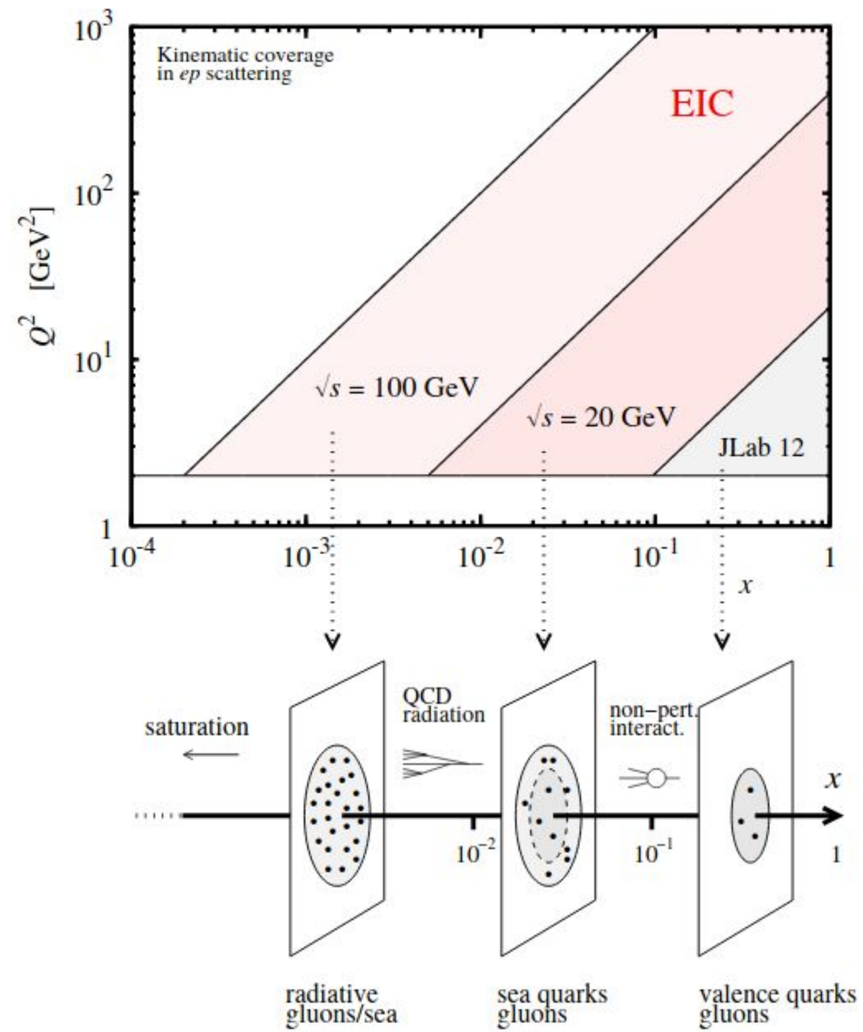
SIDIS coverage

Importance of complementary experiments

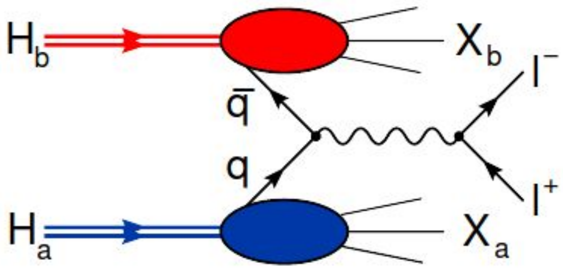
from JLab 12 GeV, Hermes, Compass
to the EIC

zooming into hadron structure

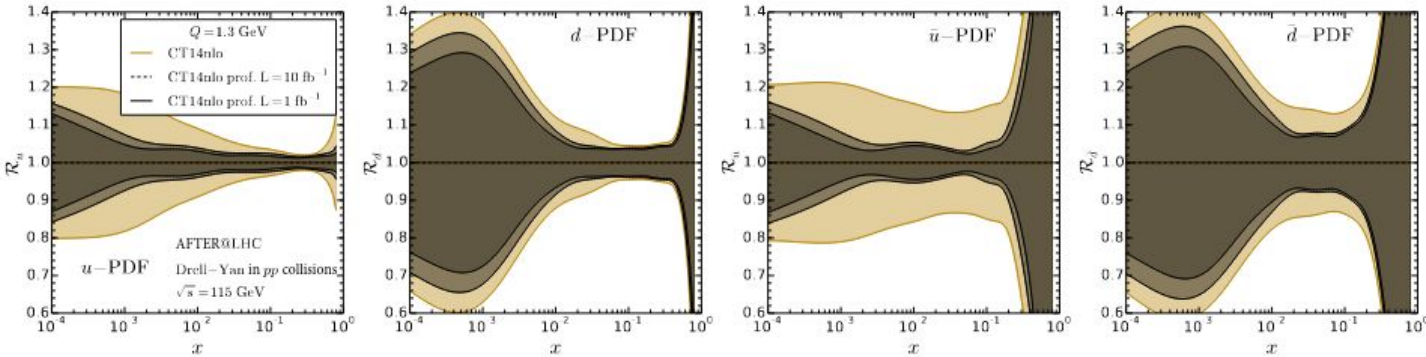
Credit picture: C. Weiss



Unpolarized Drell-Yan



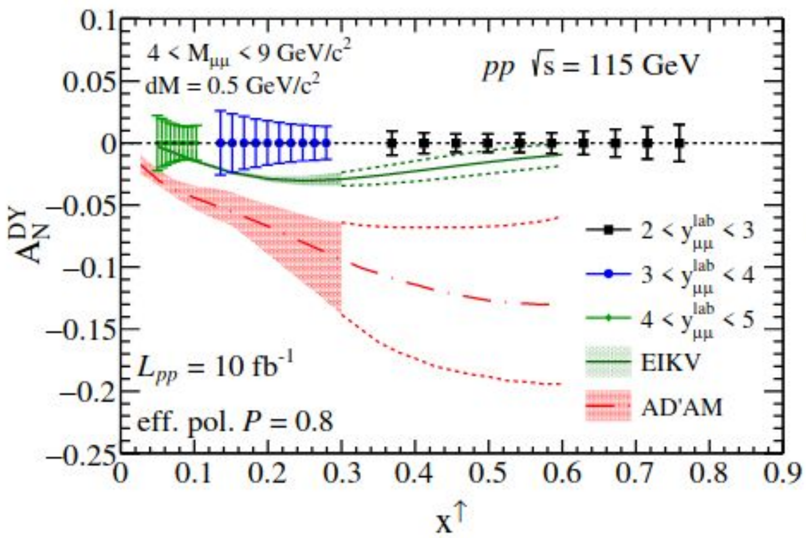
Impact on extraction of unpolarized collinear PDF f1

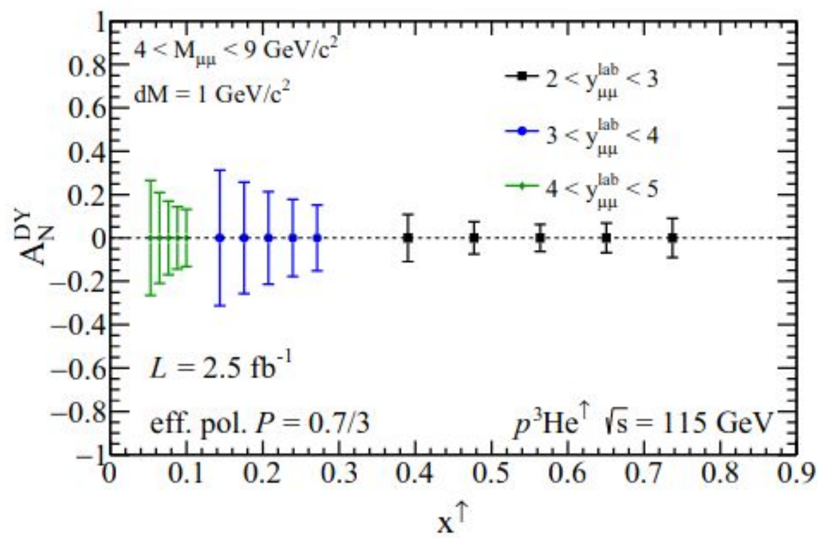


(a) u PDF (b) d PDF (c) $\bar{u}$ PDF (d) $\bar{d}$ PDF

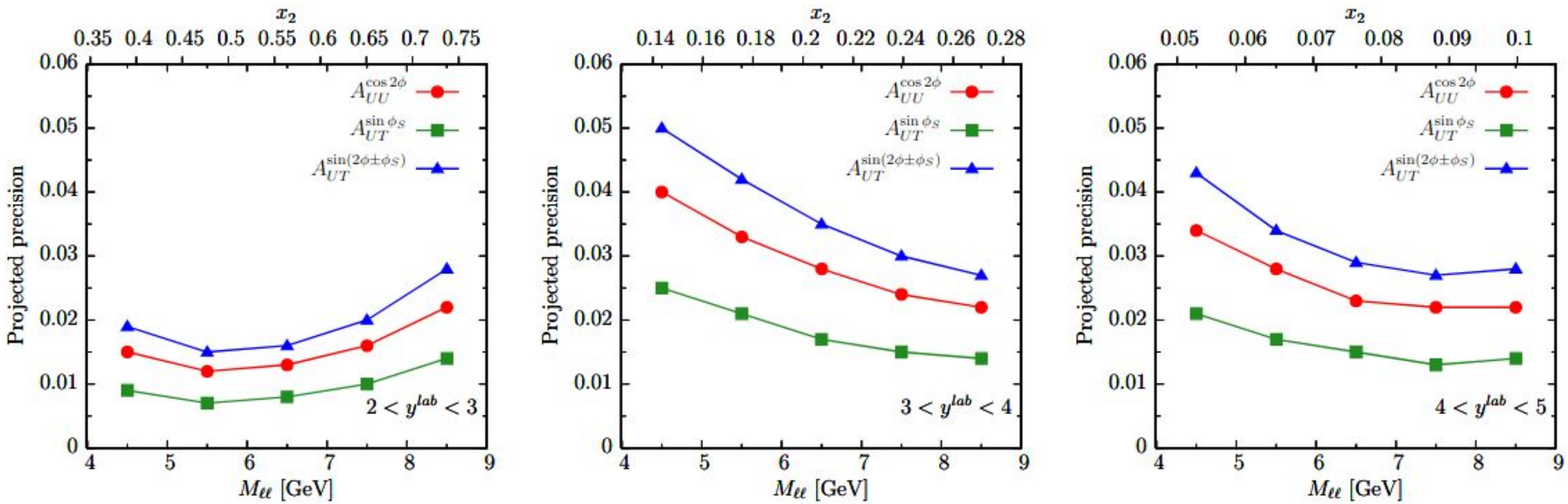
Figure 17: Impact of the DY lepton pair production in pp collisions at $\sqrt{s} = 115$ GeV on the PDF uncertainties. The $u, d, \bar{u}$ and $\bar{d}$ PDFs from CT14 [5] are plotted as a function of x at a scale $Q = 1.3$ GeV before and after including AFTER@LHCb pseudo-data in the global analysis using 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).

Sivers asymmetry





More asymmetries



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

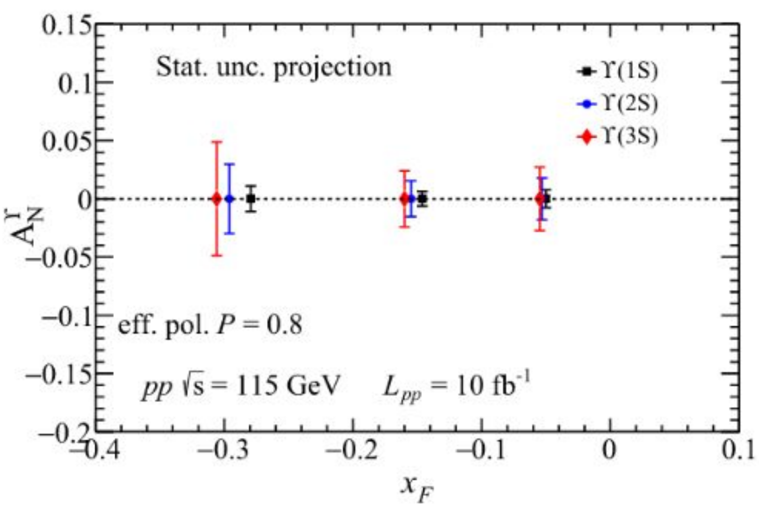
$$A_{UT}^{sin\phi_S} \sim \frac{f_1^q \otimes f_{1T}^{\perp q}}{f_1^q \otimes f_1^q}$$

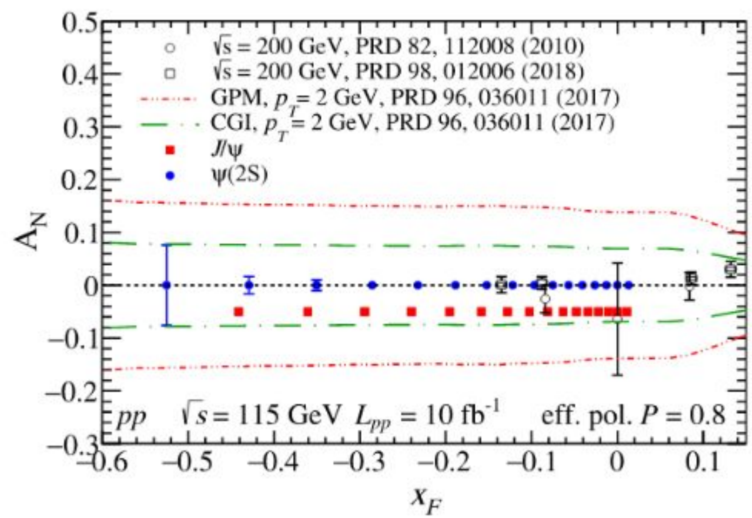
$$A_{UT}^{sin(2\phi+\phi_S)} \sim \frac{h_1^{\perp q} \otimes h_{1T}^{\perp q}}{f_1^q \otimes f_1^q}$$

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

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

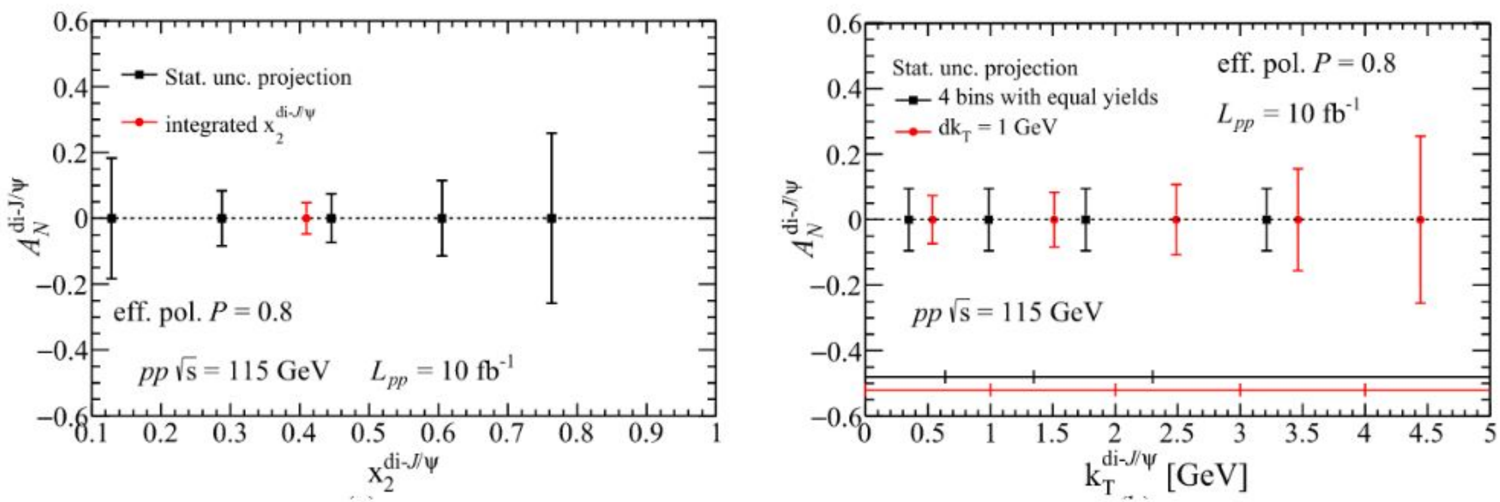
- A_N for all quarkonia (J/ψ, ψ', χ_c, $\Upsilon(nS)$, χ_b & η_c) can be measured [So far, only J/ψ by PHENIX with larger uncertainties]
- Also access to polarised neutron ($^3\mathrm{He}^\uparrow$) at the per cent level for J/ψ
- Completely new perspectives to study the gluon Sivers effect
- Di-J/ψ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



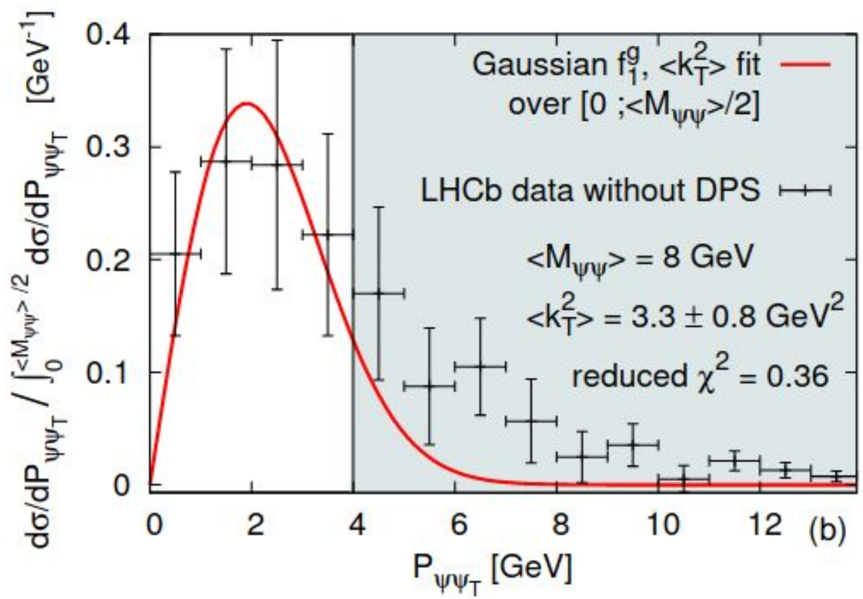


C. Hadjidakis *et al.*, 1807.00603; D. Kikola *et al.* Few Body Syst. 58 (2017) 139

- 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}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



di-J/Psi at LHCb

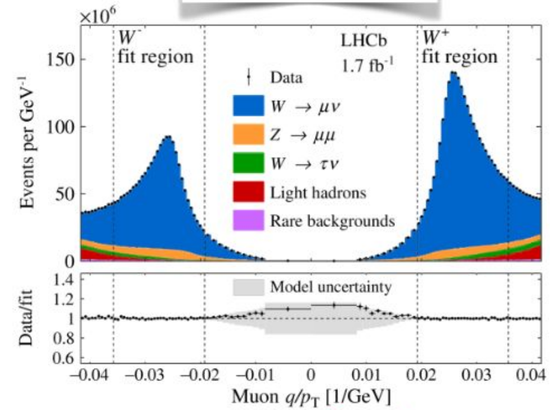


First “extraction” of unpolarized gluon TMD PDF

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

W mass @ LHCb

[JHEP01 (2022) 036]



- Measurement based on shape of p_T distribution of muons from W decay
- Simultaneous fit of q/p_T of muons from W and of ϕ^* of $Z \to \mu\mu$

  Proxy of p_T^Z

$$m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}} \text{ MeV}$$

~32 MeV total (~20 MeV with all data)

- Result based on 1.7 fb^{-1} (3x more data on tape); efforts are now being made to improve the modelling and reduce the systematic uncertainties
- Important because LHCb probes an acceptance region complementary to that of ATLAS/CMS
- Exploit anticorrelation of PDF uncertainties to partially cancel out uncertainties in M_W combination