Phenomenology of TMDs

ART23

Extraction of unpolarized TMDPDF from global fit of Drell-Yan data at N4LL

V. Moos, I. Scimemi, A. Vladimirov, P. Zurita

based on: [arXive:2305.07473]

Paphos, Cyprus 31.10.2023

Outline

1. TMDs
2. Experimental Data
3. Consistency and Limitations

TMDs

8 TMD distributions

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

The parametrized forms of the TMD distributions include 8 functions.

In this work we extract the unpolarized distribution (f_1).

$$\Phi_{q\leftarrow h}^{[\gamma^+]}(x,b) = f_1(x,b) + i\epsilon_T^{\mu\nu} b_\mu s_{T\nu} M f_{1T}^\perp(x,b)$$

$$\Phi_{q\leftarrow h}^{[\gamma^+\gamma_5]}(x,b) = \lambda g_{1L}(x,b) + i b_\mu s_T^\mu M g_{1T}(x,b)$$

$$\Phi_{q\leftarrow h}^{[\sigma^{\alpha+}\gamma_5]}(x,b) = s_T^\alpha h_1(x,b) - i\lambda b^\alpha M h_{1L}^\perp(x,b) + i\epsilon_T^{\alpha\mu} b_\mu M h_1^\perp(x,b)$$
$$- \frac{M^2 b^2}{2}\left(\frac{g_T^{\alpha\mu}}{2} - \frac{b^\alpha b^\mu}{b^2}\right) s_{T\mu} h_{1T}^\perp(x,b)$$

Our model: distribution's shape

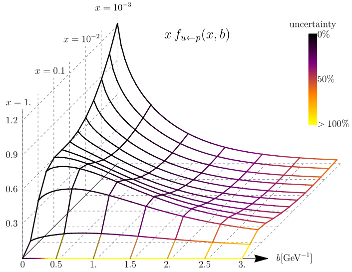
Parametrization of TMDPDF:

$$f_{1,f}(x,b) = \int_x^1 \frac{dy}{y} \sum_{f'} C_{f\to f'}(y,\mathbf{L},a_s) q_{f'}\left(\frac{x}{y}\right) f_{\text{NP}}^f(x,b)$$

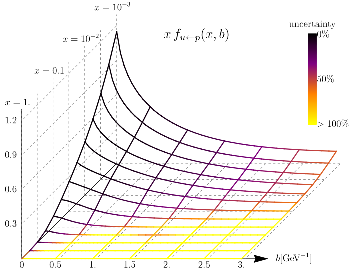
$$f_{\text{NP}}^f(x,b) = \frac{1}{\cosh\left(\left(\lambda_1^f(1-x)+\lambda_2^f x\right) b\right)}$$

- $f \in \{u, \bar{u}, d, \bar{d}, sea\}$ $\rightarrow 2\times 5$ independent parameters!
- flavour dependent ansatz! **(=NEW feature!)**

TMDPDF distributions visualized: two dimensional picture



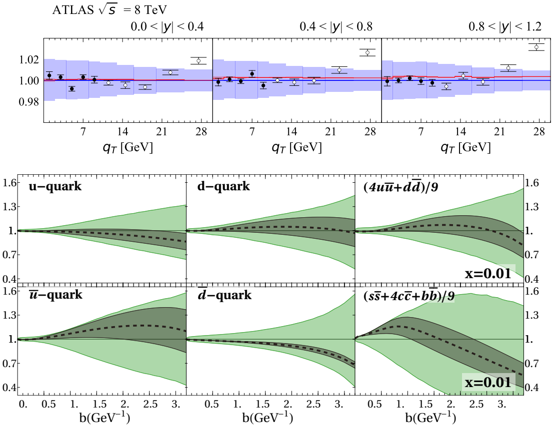
u quark TMD distribution



$\overline{u}$ quark TMD distribution

Collinear PDF can be understood as projection to $b = 0$ plane.

Impact of PDF uncertainty on prediction



- Uncertainty to a large amount effect of PDF.
- Uncertainty in general is quite **large** for the extracted TMDPDF.

Data normalised to Theory. Extraction with and without taking into account PDF uncertainties.

Our model: hard scale evolution

Parametrization of TMD Evolution:

$$\mathcal{D}(b,\mu) = \mathcal{D}_{\text{small-b}}(b^*,\mu^*) + \int_{\mu^*}^{\mu} \frac{d\mu'}{\mu'} \Gamma_{\text{cusp}}(\mu') + \mathcal{D}_{\text{NP}}(b)$$

- perturbative series(a_s, L_μ) in α_s
- non perturbative (model)

$$\mathcal{D}_{\text{small-b}} = \sum_{n,k=0}^{\infty,n} a_s^n \mathbf{L}_\mu^k d^{(n,k)} \quad \Gamma_{\text{cusp}}(\mu) = \sum_{n=0}^{\infty} a_s^{n+1} \Gamma_n \quad \gamma_V(\mu) = \sum_{n=1}^{\infty} a_s^n \gamma_n$$

Γ_{cusp}	γ_V	$\mathcal{D}_{\text{small-b}}$	$C_{f\to f'}$	C_V	PDF
a_s^5 (Γ_4)	a_s^4 (γ_4)	a_s^4 $(d^{(4,0)})$	a_s^3 $(C_{f\to f'}^{[3]})$	a_s^4	NNLO

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- Ansatz for NP part:

$$\mathcal{D}_{\text{NP}}(b) = c_0 b b^* + c_1 b b^* \ln\left(\frac{b^*}{B_{\text{NP}}}\right)$$

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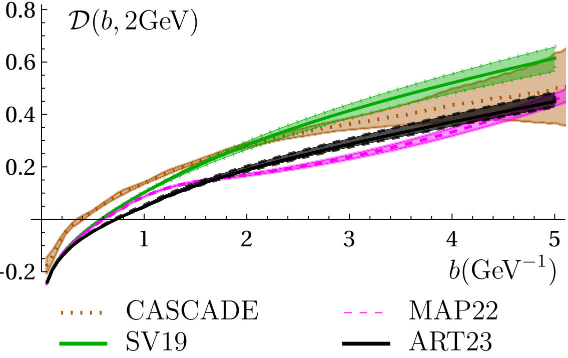
- 3 parameters for TMDPDF scale evolution
- log term brings sensitivity to moderate b region, determined by high energy DY data!

Collins-Soper kernel: Various extractions

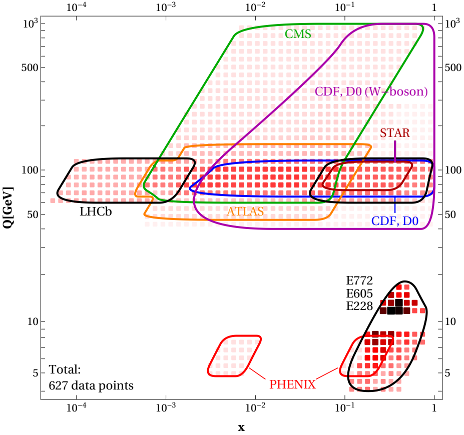


- small uncertainty!
- sensitive to moderate $b \approx 1/\text{GeV}$ region
- steady grow, no inflection point

$$\mathcal{D}(b,\mu) = a_s^n \mathbf{L}_\mu^k d^{n,k} + \int_{\mu^*}^{\mu} \frac{d\mu'}{\mu'} a_s^{n+1}\Gamma_n + c_0 b b^* + c_1 b b^* \ln\left(\frac{b^*}{B_{\text{NP}}}\right)$$

Experimental Data

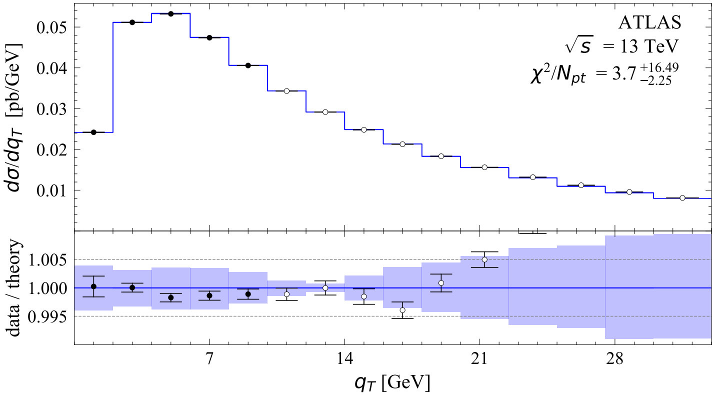
Kinematic range of included data, datasets



Features:

- large range of resolution scale: 4 GeV $\rightarrow$ 1 TeV
- including DY W production
- $\frac{q_T}{Q} < 0.25$ (TMD region!)
- 627 datapoints included in fit vs. 457 (SV19), vs. 484 (MAP22)

Most precise data from ATLAS

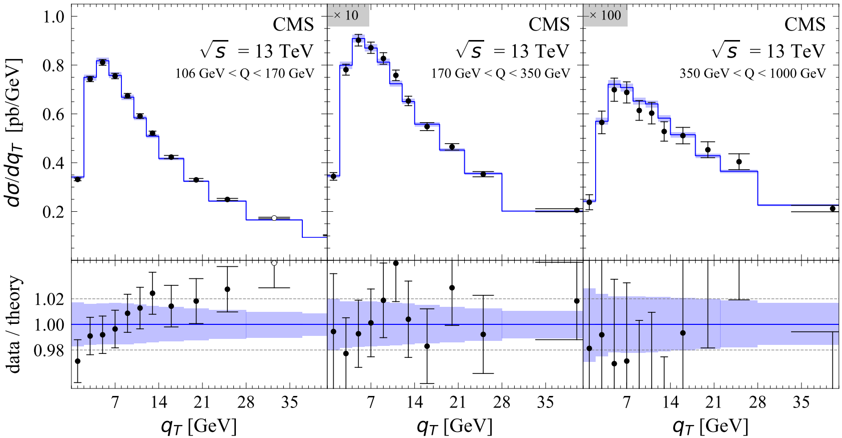


We can describe this VERY precise data!

$$\text{overall } \chi^2/N_{pt} = 0.96^{+0.09}_{-0.01}$$

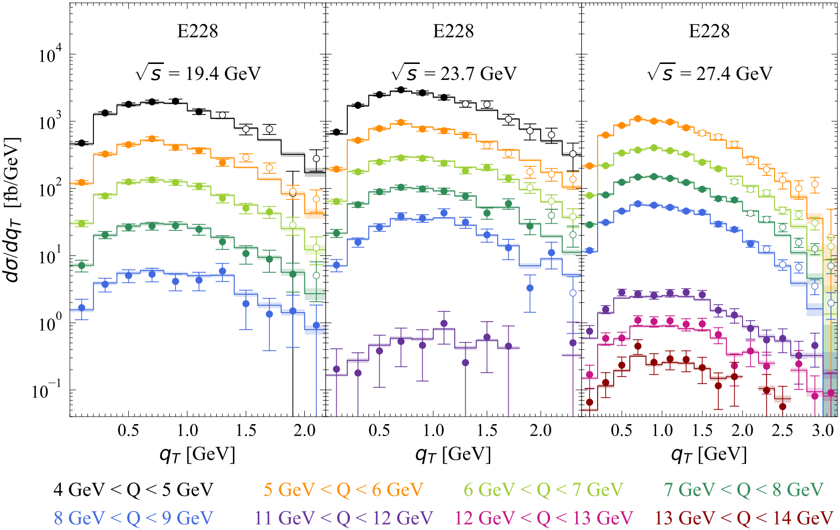
Data at $\sqrt{s} = 13$ @ LHCb

We have good data description above the Z pole up to 1 TeV...



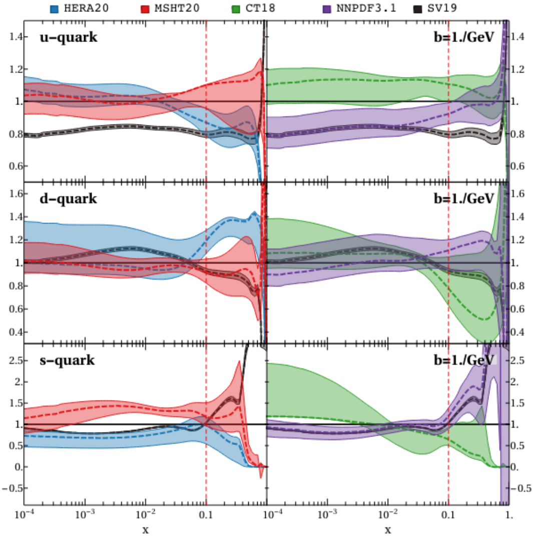
Data at $\sqrt{s} = 19, 23$ and 27 GeV

...and also at very low Q for fixed target experiments.



Problems

collinear PDF choice

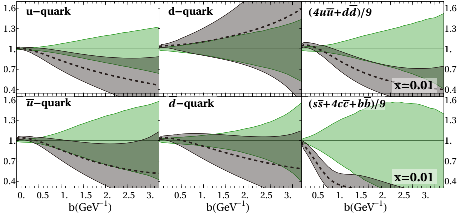


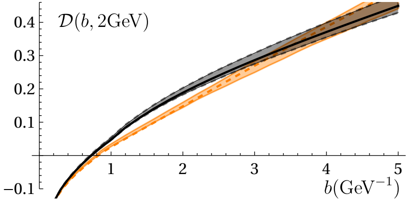
Param.	MSHT20	HERA2.0	NNPDF3.1	CT18
κ_1^u	0.12	0.11	0.28	0.05
κ_2^u	0.32	8.15	2.58	0.9

- obtained parameters stronly depend on PDF
- collinear PDF is base layer of TMDPDF
- we choose MSHT20 as the strongest candidate in JHEP 10 (2022) 118

Consistency and Limitations

Effect of collinear PDF on the extraction:





- impact of PDF is significant!
- even CS kernel is affected at moderate b

Extractions using MSHT20 and NNPDF3.1

Consistency and Limitations

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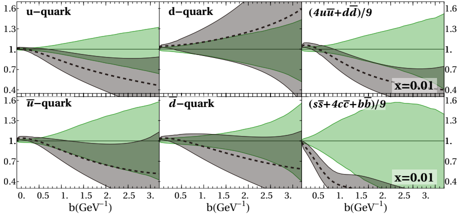

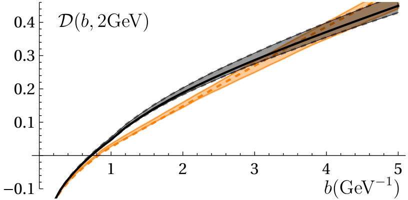

- impact of PDF is significant!
- even CS kernel is affected at moderate b
- additional, systematic uncertainty: estimate?

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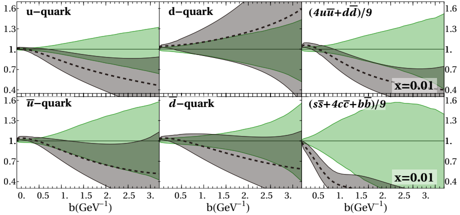

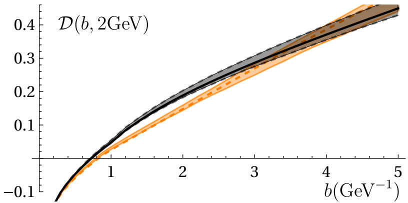

Extractions using MSHT20 and NNPDF3.1

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- Solution(?): independent TMDPDF fit w.o. constraint due to PDF

Consistency and Limitations

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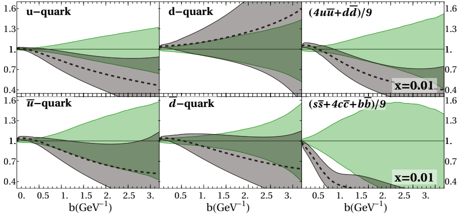
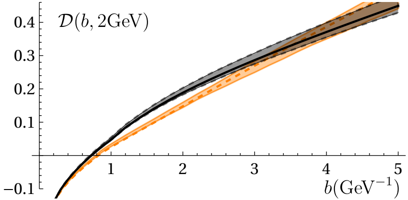




- impact of PDF is significant!
- even CS kernel is affected at moderate b
- additional, systematic uncertainty: estimate?
- Solution(?): independent TMDPDF fit w.o. constraint due to PDF
- at this precision core hours become a problem.

Extractions using MSHT20 and NNPDF3.1

Recapitulation & Outlook

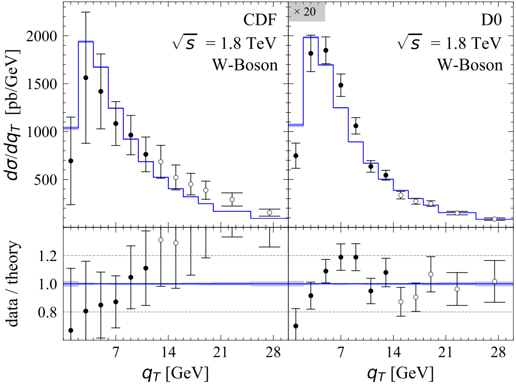
What has been done:

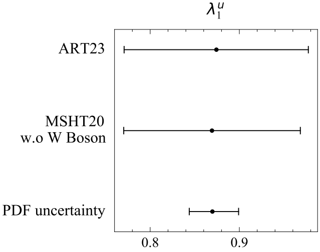
- A **first of a kind** N4LO extraction of TMDPDFs including determination of CS kernel
- good quality of fit ($\chi^2/N_{pt} = 0.96^{+0.09}_{-0.01}$)
- various checks have been done (e.g. PDF uncertainty, PDF choice)

Work in progress:

- a SIDIS fit for TMD fragmentation functions
- a Pion TMDPDF fit
- impact Studies for EIC once TMDFFs are determined.

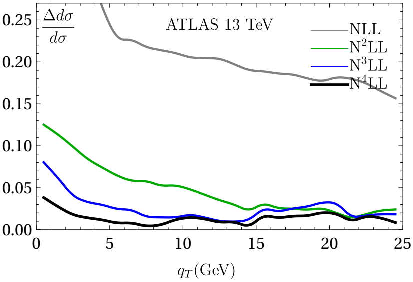
W Boson ($\sqrt{s} = 1.8$ TeV)

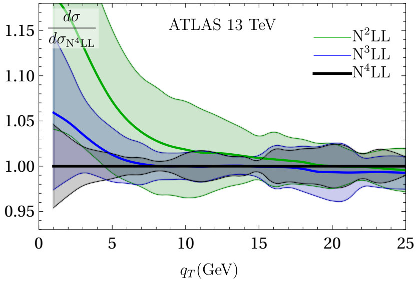




- large exp. uncertainties
- small impact on extraction

Scale variation





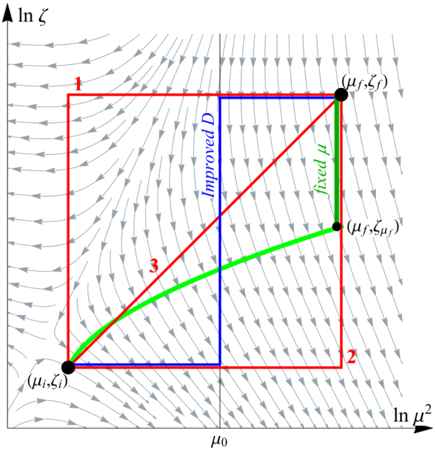
Variation of the 3 scales μ, μ^*, μ_{OPE} with factors $\frac{1}{2}$, 1, 2

$$\Delta d\sigma = \max_i \left(|d\sigma_i - d\sigma| \right)$$

Our model: hard scale evolution

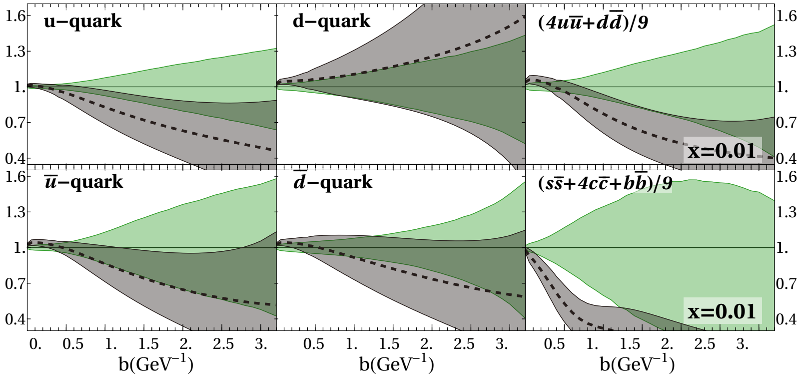
Evolution equation:

$$F(x,b;\mu_f,\zeta_f) = \exp\left[\int_P \left(\gamma_F \frac{d\mu}{\mu} - \mathcal{D}(\mu,b)\frac{d\zeta}{\zeta}\right)\right] F(x,b;\mu_i,\zeta_i)$$



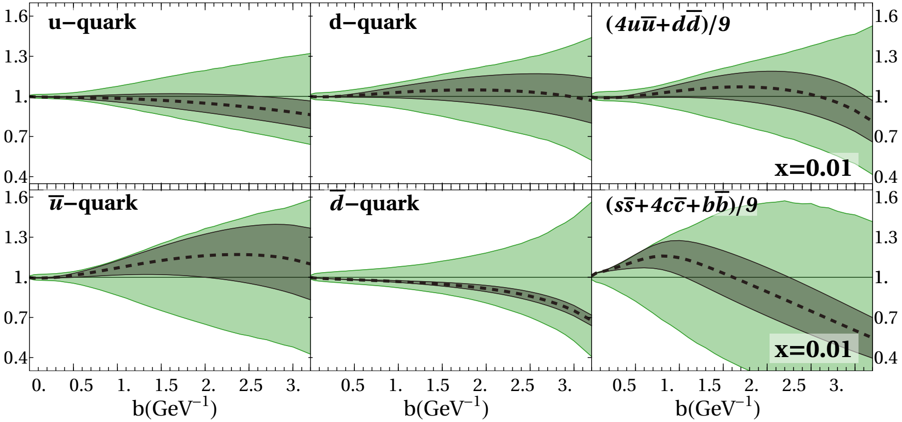
- $\gamma_F = \Gamma_{cusp} \ln\left(\frac{\mu^2}{\zeta}\right) - \gamma_V$
- $\mathcal{D}$ denotes CS kernel
- ***Path*** dependent due to truncation of series
- use evolution along no evolution curve JHEP 08 (2018) 003

Impact of choice collinear PDF



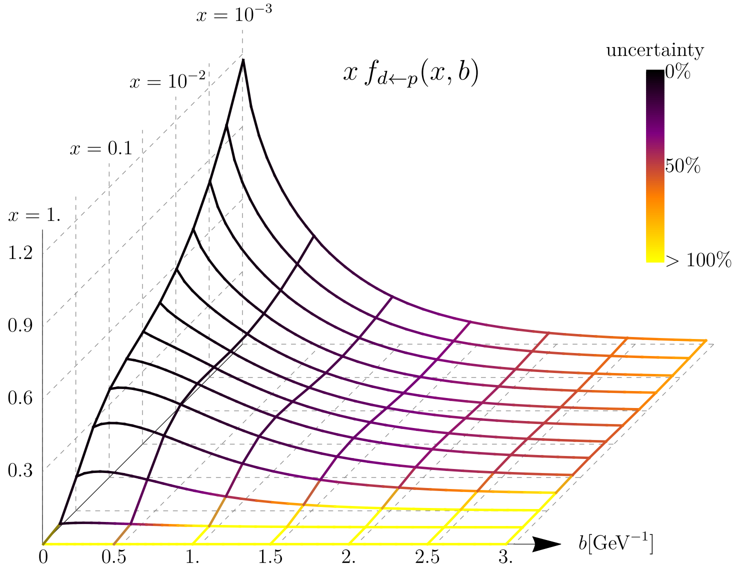
- MSHT20 extraction
- NNPDF3.1 extraction

Impact of PDF uncertainty on TMDPDF

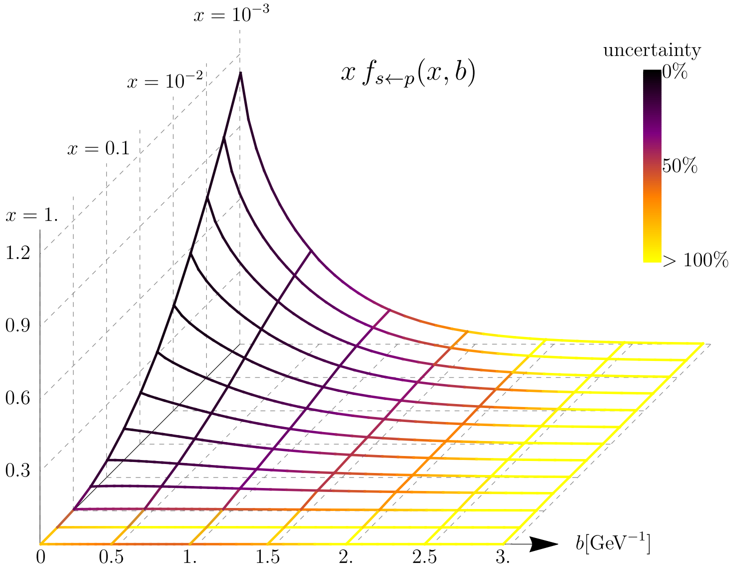


Normalised TMDPDFs. Extraction with and without taking into account PDF uncertainties.

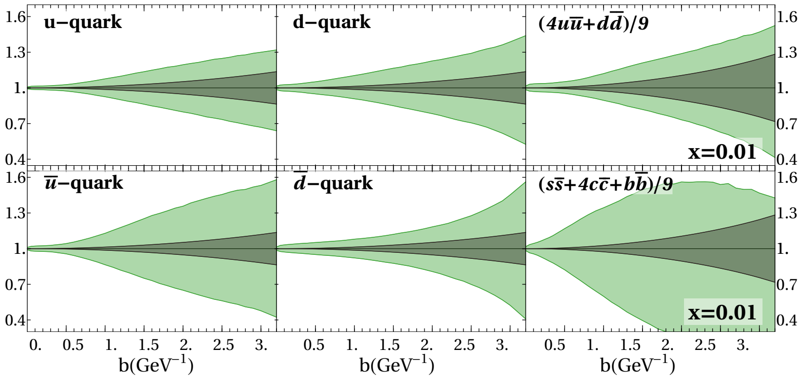
$\overline{d}$ TMDPDF vs. x and b



sea TMDPDF vs. x and b



uncertainty Bands relative to central value



- ART23 (us)
- SV19

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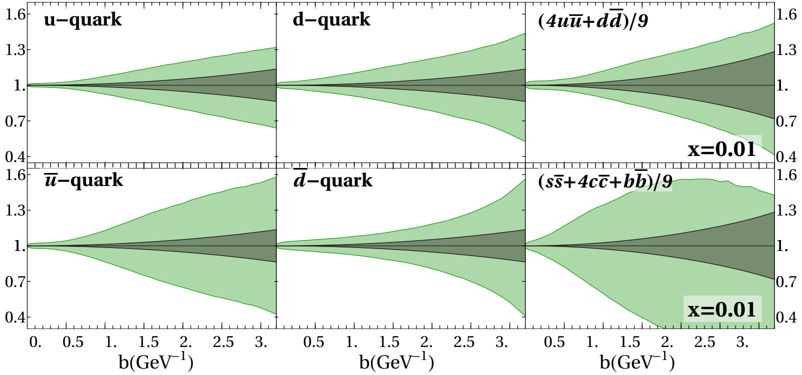

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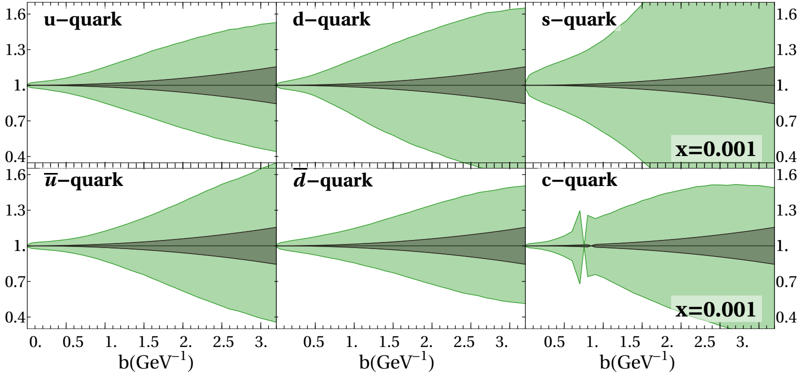

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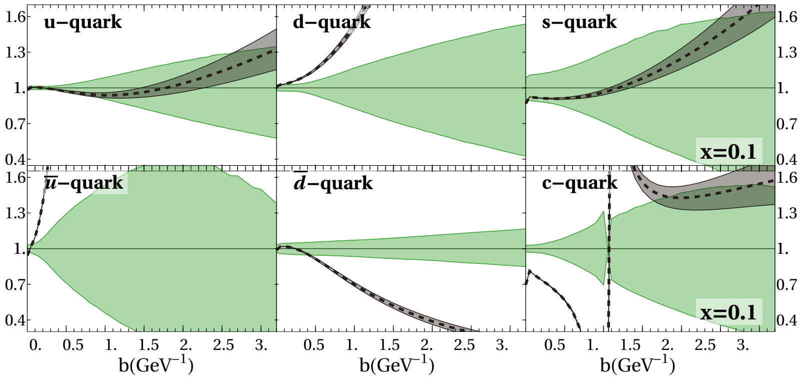

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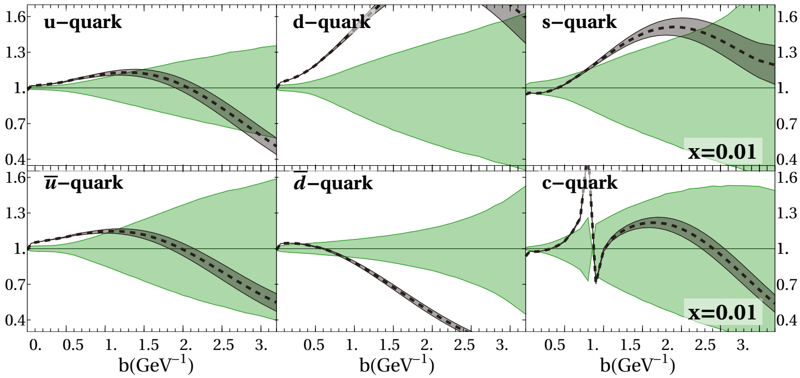

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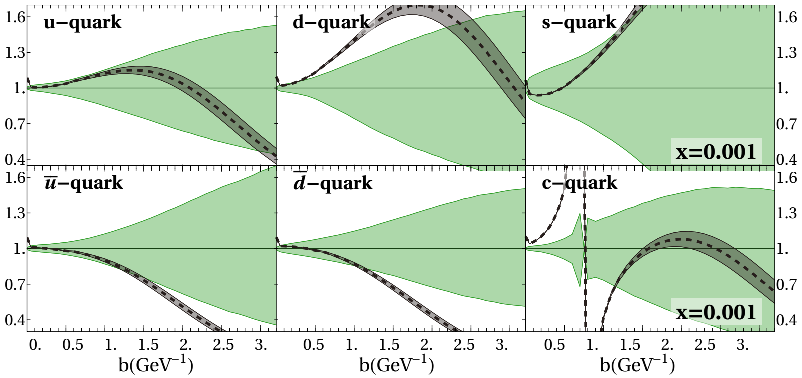

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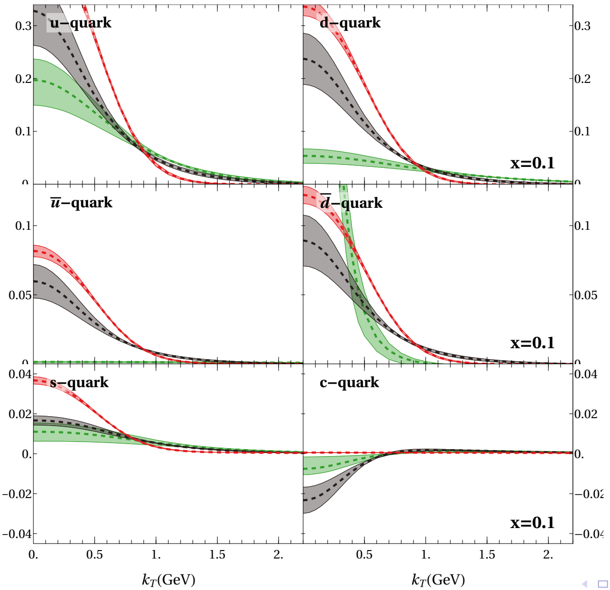
TMDPDF distributions visualized



- MAP
  MMHT14
- ART23 (us)
  MSHT20
- SV19
  NNPDF31

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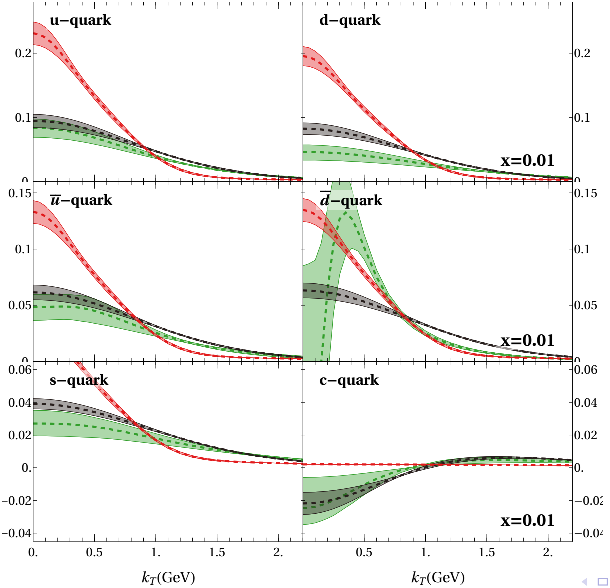

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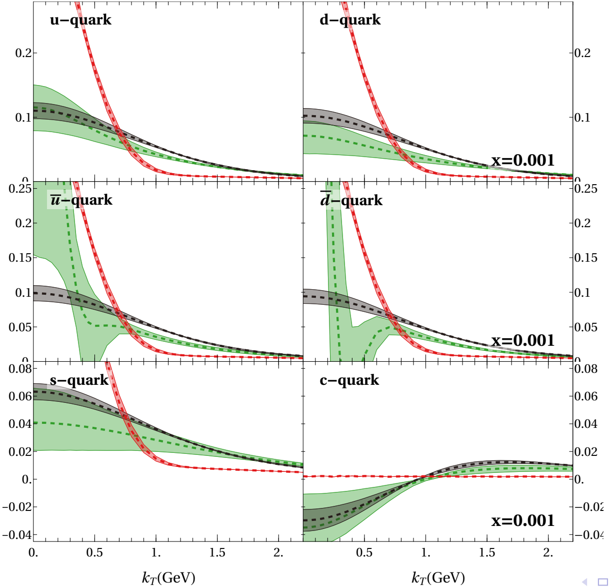

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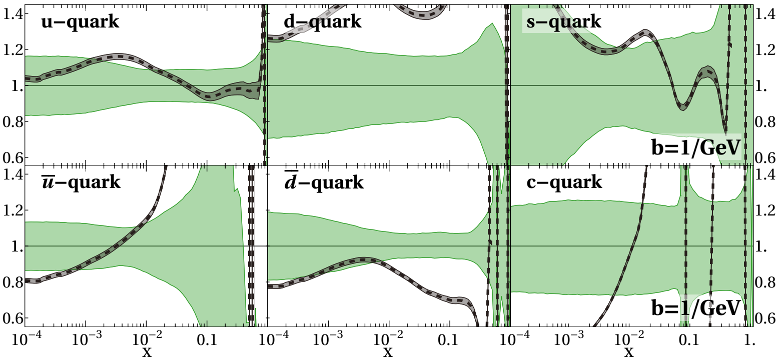

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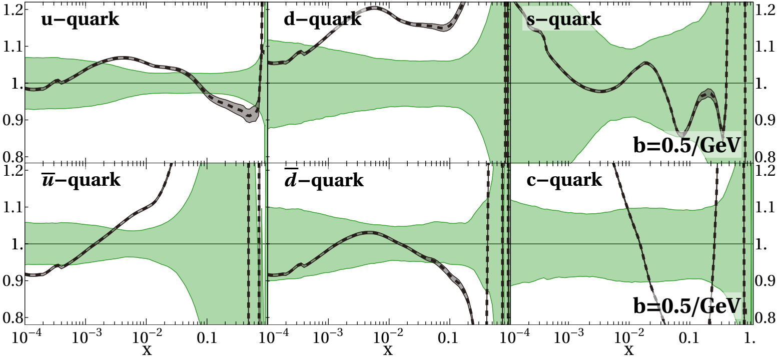

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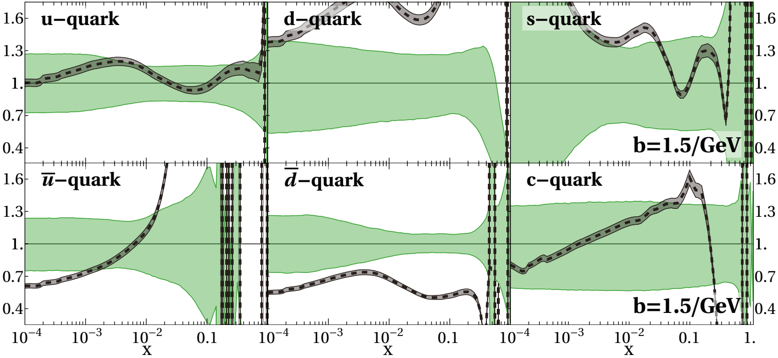

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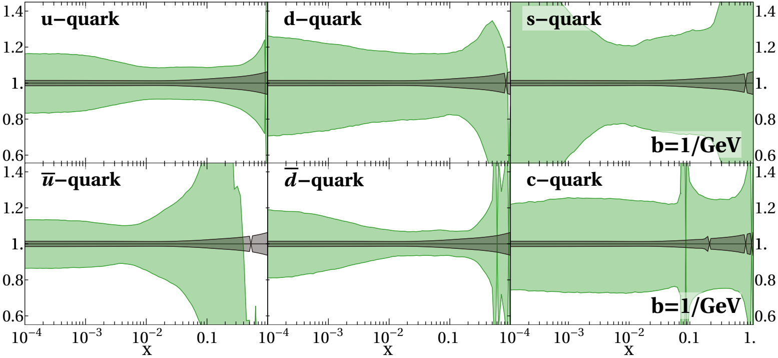

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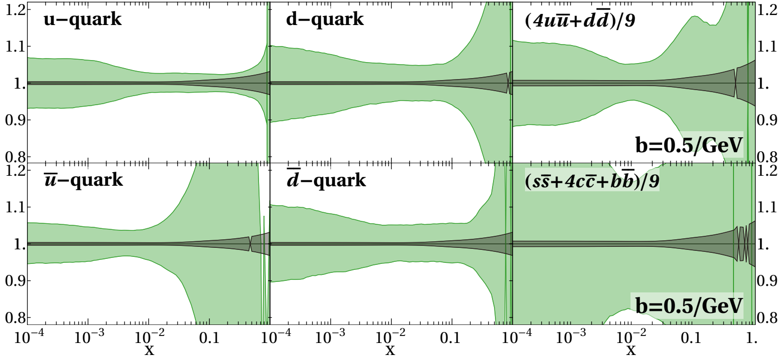

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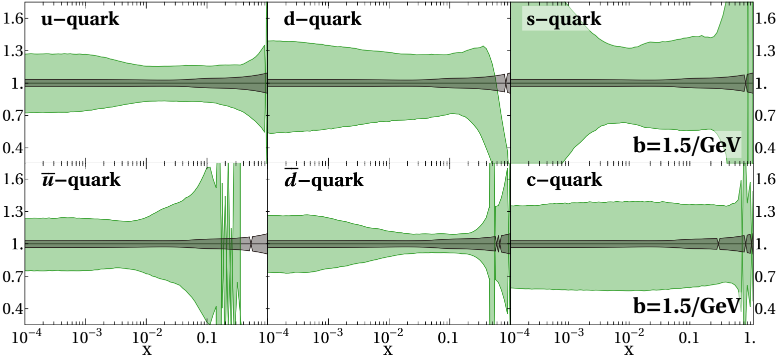

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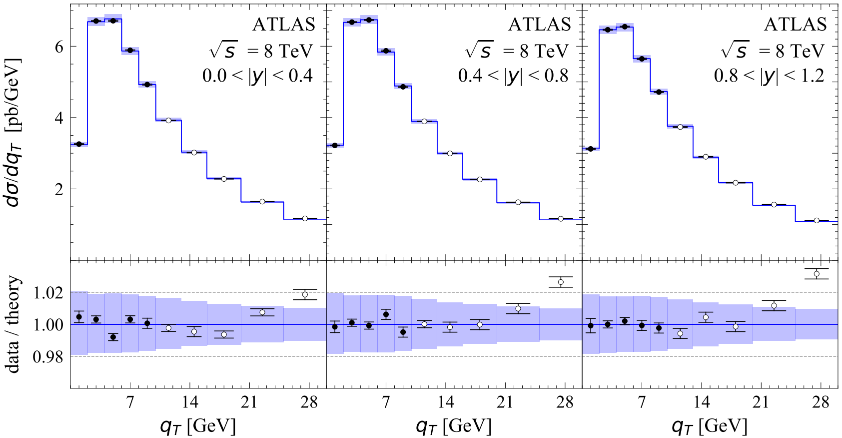
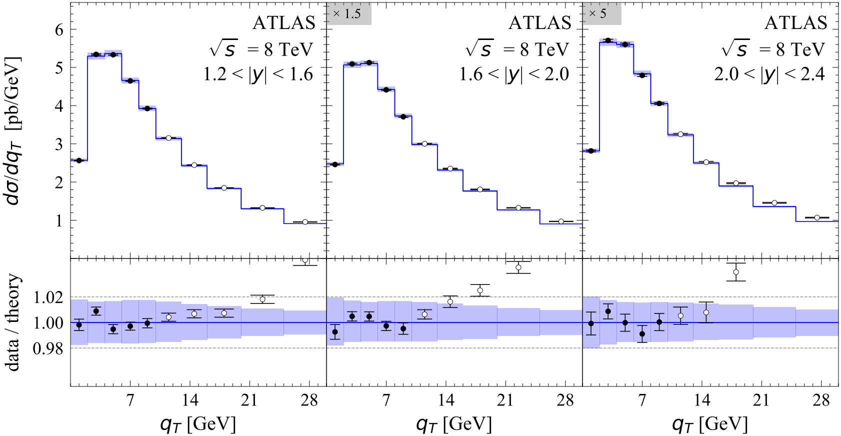
ATLAS



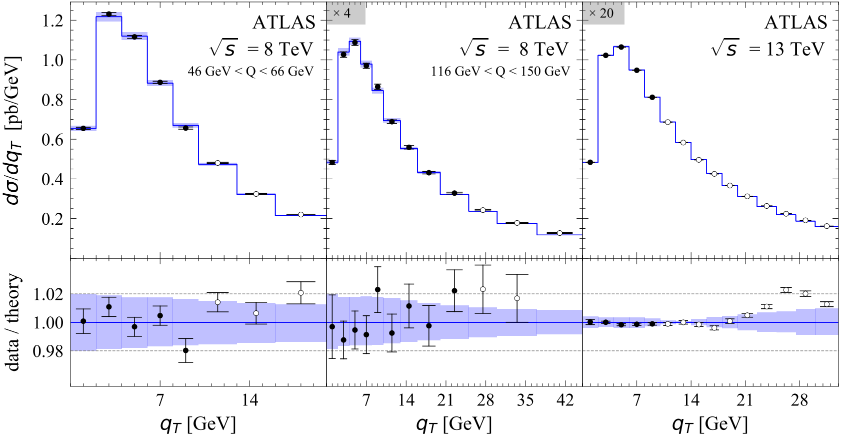
ATLAS
$\sqrt{s}$ = 8 TeV
0.0 < |y| < 0.4
ATLAS
$\sqrt{s}$ = 8 TeV
0.4 < |y| < 0.8
ATLAS
$\sqrt{s}$ = 8 TeV
0.8 < |y| < 1.2
$d\sigma/dq_T$ [pb/GeV]
data / theory
q_T [GeV]

ATLAS



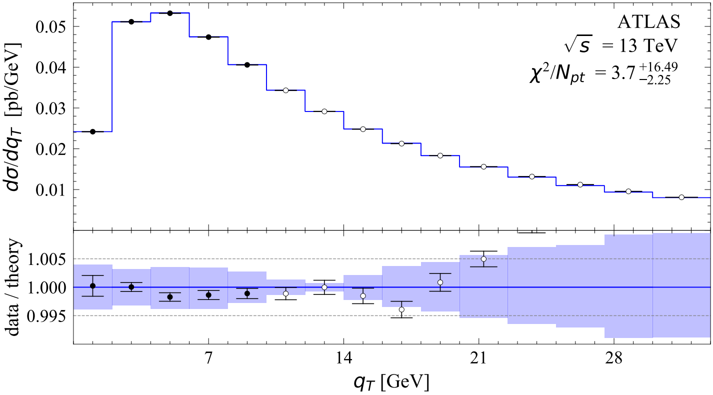
ATLAS
$\sqrt{s}$ = 8 TeV
1.2 < |y| < 1.6
× 1.5
1.6 < |y| < 2.0
× 5
2.0 < |y| < 2.4
$d\sigma/dq_T$ [pb/GeV]
data / theory
q_T [GeV]

ATLAS

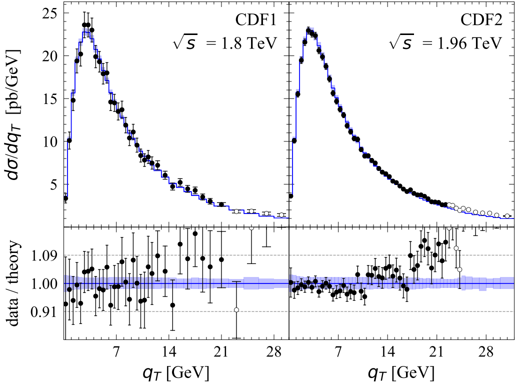


ATLAS
$\sqrt{s}$ = 8 TeV
46 GeV < Q < 66 GeV
× 4
ATLAS
$\sqrt{s}$ = 8 TeV
116 GeV < Q < 150 GeV
× 20
ATLAS
$\sqrt{s}$ = 13 TeV
$d\sigma/dq_T$ [pb/GeV]
data / theory
q_T [GeV]
q_T [GeV]
q_T [GeV]

ATLAS

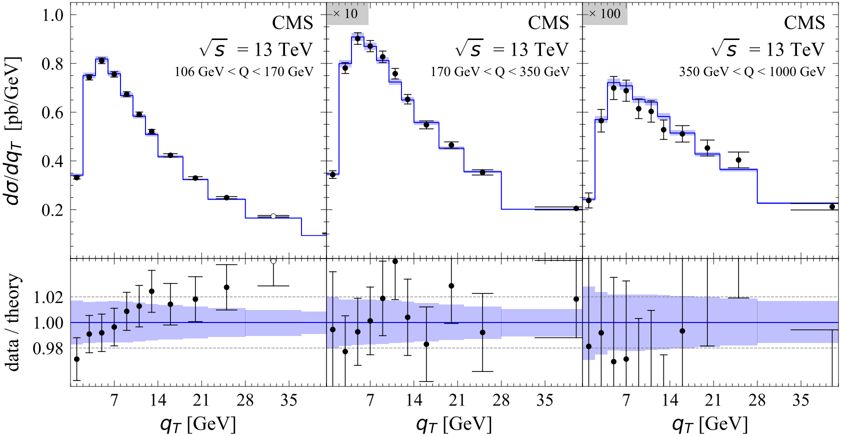

ATLAS
$\sqrt{s}$ = 13 TeV
$\chi^2/N_{pt} = 3.7^{+16.49}_{-2.25}$
$d\sigma/dq_T$ [pb/GeV]
0.05
0.04
0.03
0.02
0.01
data / theory
1.005
1.000
0.995
7
14
21
28
q_T [GeV]

CDF

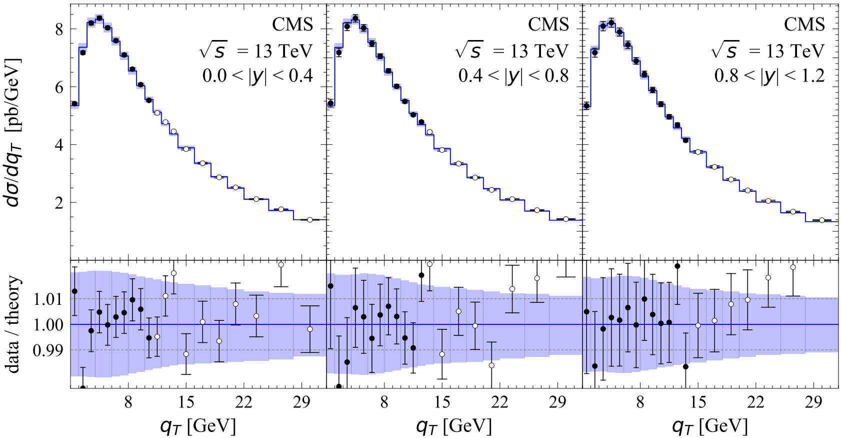


CDF1
$\sqrt{s}$ = 1.8 TeV
CDF2
$\sqrt{s}$ = 1.96 TeV
$d\sigma/dq_T$ [pb/GeV]
data / theory
q_T [GeV]
q_T [GeV]

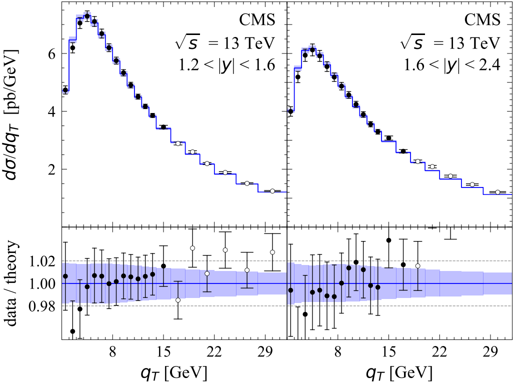
CMS


× 10
× 100
CMS
$\sqrt{s}$ = 13 TeV
106 GeV < Q < 170 GeV
170 GeV < Q < 350 GeV
350 GeV < Q < 1000 GeV
$d\sigma/dq_T$ [pb/GeV]
data / theory
q_T [GeV]
1.0
0.8
0.6
0.4
0.2
1.02
1.00
0.98
7
14
21
28
35

CMS

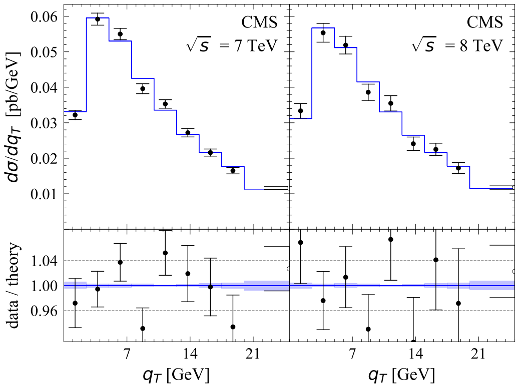

CMS
$\sqrt{s}$ = 13 TeV
0.0 < |y| < 0.4
CMS
$\sqrt{s}$ = 13 TeV
0.4 < |y| < 0.8
CMS
$\sqrt{s}$ = 13 TeV
0.8 < |y| < 1.2
$d\sigma/dq_T$ [pb/GeV]
data / theory
q_T [GeV]
q_T [GeV]
q_T [GeV]
8
6
4
2
1.01
1.00
0.99
8
15
22
29

CMS

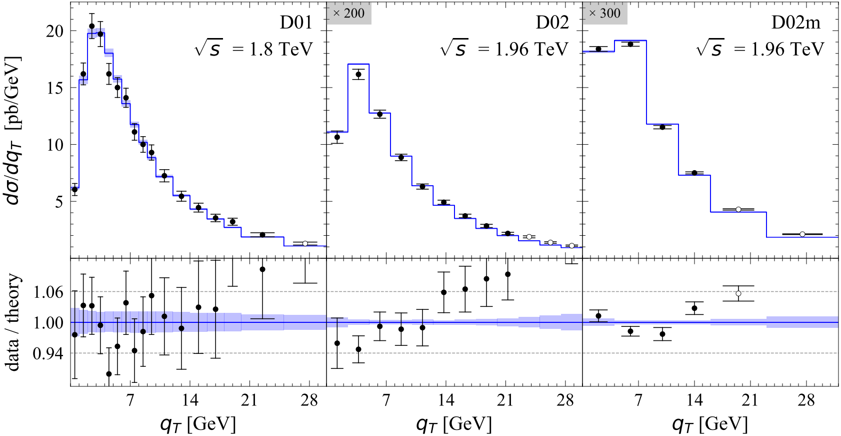


CMS
$\sqrt{s}$ = 13 TeV
1.2 < |y| < 1.6
CMS
$\sqrt{s}$ = 13 TeV
1.6 < |y| < 2.4
$d\sigma/dq_T$ [pb/GeV]
data / theory
q_T [GeV]
q_T [GeV]

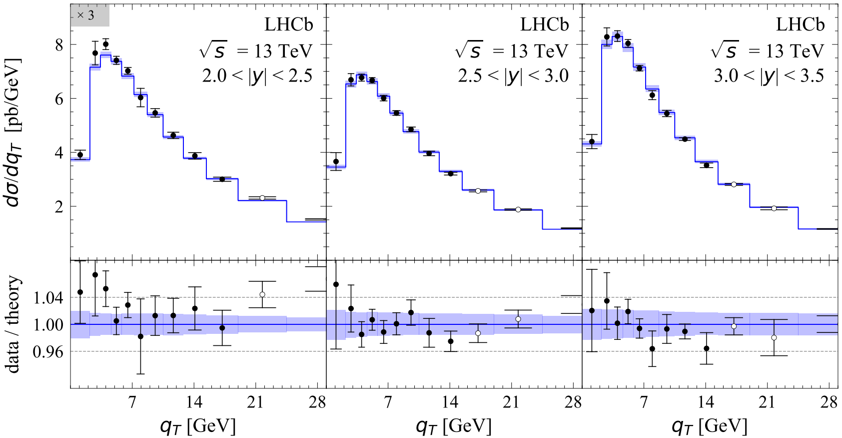
CMS


CMS
$\sqrt{s}$ = 7 TeV
CMS
$\sqrt{s}$ = 8 TeV
$d\sigma/dq_T$ [pb/GeV]
0.06
0.05
0.04
0.03
0.02
0.01
data / theory
1.04
1.00
0.96
7
14
21
q_T [GeV]

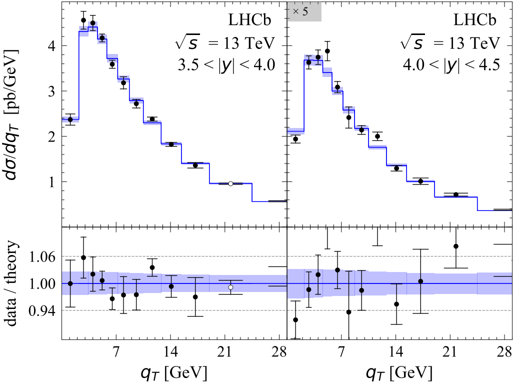
D0


D01
$\sqrt{s}$ = 1.8 TeV
× 200
D02
$\sqrt{s}$ = 1.96 TeV
× 300
D02m
$\sqrt{s}$ = 1.96 TeV
$d\sigma/dq_T$ [pb/GeV]
data / theory
q_T [GeV]

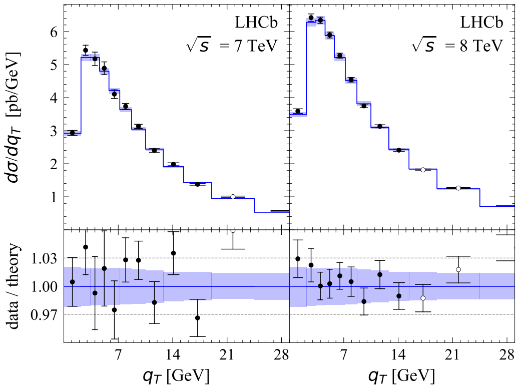
LHCb


× 3
LHCb
$\sqrt{s}$ = 13 TeV
2.0 < |y| < 2.5
2.5 < |y| < 3.0
3.0 < |y| < 3.5
$d\sigma/dq_T$ [pb/GeV]
data / theory
8
6
4
2
1.04
1.00
0.96
7
14
21
28
q_T [GeV]

LHCb

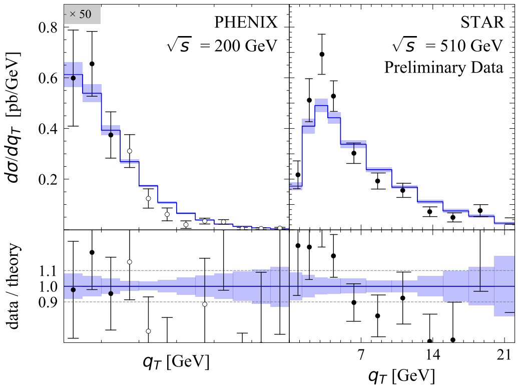

LHCb
$\sqrt{s}$ = 13 TeV
3.5 < |y| < 4.0
LHCb
$\sqrt{s}$ = 13 TeV
4.0 < |y| < 4.5
× 5
dσ/dq_T [pb/GeV]
data / theory
1.06
1.00
0.94
1
2
3
4
7
14
21
28
q_T [GeV]

LHCb

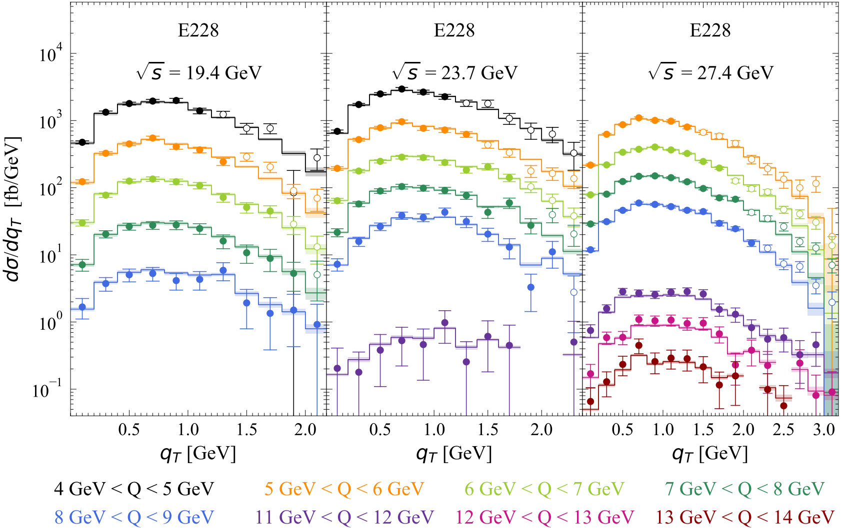


LHCb
$\sqrt{s}$ = 7 TeV
LHCb
$\sqrt{s}$ = 8 TeV
$d\sigma/dq_T$ [pb/GeV]
data / theory
q_T [GeV]
q_T [GeV]

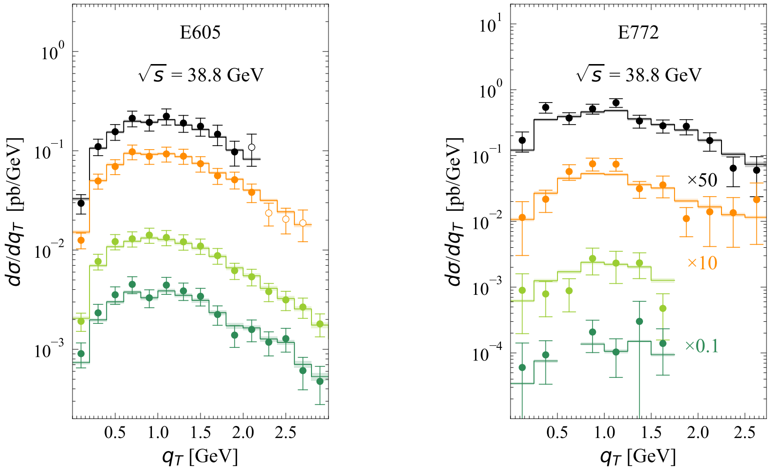
STAR and PHENIX



E228


E228
$\sqrt{s}$ = 19.4 GeV
E228
$\sqrt{s}$ = 23.7 GeV
E228
$\sqrt{s}$ = 27.4 GeV
$d\sigma/dq_T$ [fb/GeV]
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
0.5
1.0
1.5
2.0
2.5
3.0
q_T [GeV]
4 GeV < Q < 5 GeV
5 GeV < Q < 6 GeV
6 GeV < Q < 7 GeV
7 GeV < Q < 8 GeV
8 GeV < Q < 9 GeV
11 GeV < Q < 12 GeV
12 GeV < Q < 13 GeV
13 GeV < Q < 14 GeV

E772 + E605



7 GeV < Q < 8 GeV   8 GeV < Q < 9 GeV   11 GeV < Q < 12 GeV   12 GeV < Q < 13 GeV

11.5 GeV < Q < 13.5 GeV   13.5 GeV < Q < 18 GeV   13 GeV < Q < 14 GeV   14 GeV < Q < 15 GeV