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

ART23

Valentin Moos, Ignazio Scimemi, Alexey Vladimirov, Pia Zurita

based on: [2305.07473]

Outline

Technicalities and Theory

Main definitions

- TMD distributions and operators

$$\Phi^{[\Gamma]}_{q\leftarrow h}(x,b) = \int \frac{dz}{2\pi} e^{-ixzp_+} \langle P,S|\, \bar{q}\,[zn+b, \mp\infty+b]\,\Gamma\,[\mp\infty,0]\,q|P,S\rangle$$

- variables
  - x is Bjorken-x
  - b is the transverse (to scattering plane) distance $\sim p_T^{-1}$
  - n is a light-cone vector
    associated to the hadrons large momentum P
  - $\Gamma \in \left\{\gamma^+, \gamma^+\gamma_5, i\sigma_T^{\alpha+}\gamma_5\right\}$ the mainly contributing gamma structures
  - $[x,y]$ is a straight Wilson line
    Infinities depend on the Process: +/- in SIDIS/DY

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,
e.g. the unpolarized (f_1),
Sivers ($f_{1T}^\perp$)
pretzelosity $h_{1T}^\perp$ distribution.

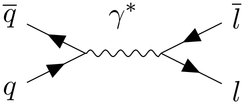
$$\Phi_{q\leftarrow h}^{[\gamma^+]}(x,b) = f_1(x,b) + i\epsilon_T^{\mu\nu} b_\mu s_{T\nu} M f_{1T}^\perp(x,b)$$

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

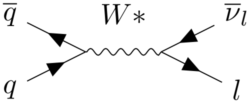
$$\Phi_{q\leftarrow h}^{[\sigma^{\alpha+}\gamma_5]}(x,b) = s_T^\alpha h_1(x,b) - i\lambda b^\alpha M h_{1L}^\perp(x,b) + i\epsilon_T^{\alpha\mu} b_\mu M h_1^\perp(x,b) - \frac{M^2 b^2}{2}\left(\frac{g_T^{\alpha\mu}}{2} - \frac{b^\alpha b^\mu}{b^2}\right) s_{T\mu} h_{1T}^\perp(x,b)$$

DY process

virtual photon

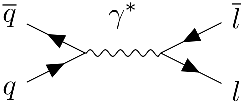


virtual W Boson

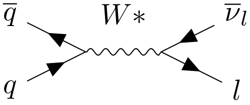


DY process

virtual photon



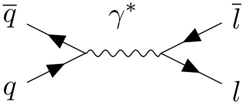
virtual W Boson



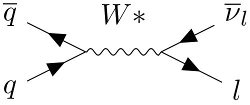
- unpolarized distribution f_1 enters for q, $\overline{q}$

DY process

virtual photon



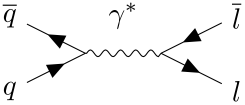
virtual W Boson



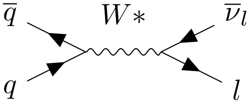
- unpolarized distribution f_1 enters for q, $\overline{q}$
- compute $\frac{d\sigma}{dydq_T^2}$ using artemide

DY process

virtual photon



virtual W Boson



- unpolarized distribution f_1 enters for q, $\overline{q}$
- compute $\frac{d\sigma}{dydq_T^2}$ using artemide
- comapare to data (fit!) to determine NP parameters

Our model: distribution's shape

Parametrization of TMDPDF:

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

depend on factorization scale $\mu_{OPE} = 2\,\mathrm{GeV} + \frac{2\exp^{-\gamma_E}}{b}$

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

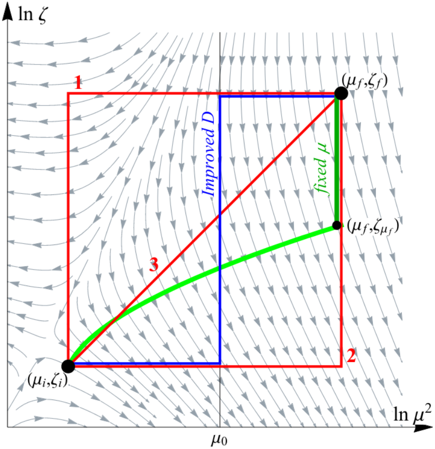
- $f \in \{u, \overline{u}, d, \overline{d}, sea\}$ $\to 2 \times 5$ independent parameters!
- $\lambda_{1,2}^f > 0$ imposed!

$$f_{1,f}(x,b) \equiv f_{1,f}(x,b,\mu,\zeta_\mu)$$

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

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)

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

In our fit, we truncate the series after the power(coefficient):

Γ_{cusp}	γ_V	β	$\mathcal{D}_{\text{small-b}}$	$C_{f\to f'}$	C_V	PDF
a_s^5 (Γ_4)	a_s^4 (γ_4)	a_s^5 (β_3)	a_s^4 $(d^{(4,0)})$	a_s^3 $(C^{[3]}_{f\to f'})$	a_s^4	NNLO

Our model: hard scale evolution

Parametrization of TMD Evolution:

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

Our model: hard scale evolution

Parametrization of TMD Evolution:

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

- Ansatz for NP part:

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

Our model: hard scale evolution

Parametrization of TMD Evolution:

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

- Ansatz for NP part:

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

- adds 3 parameters for TMDPDF scale evolution

Our model: hard scale evolution

Parametrization of TMD Evolution:

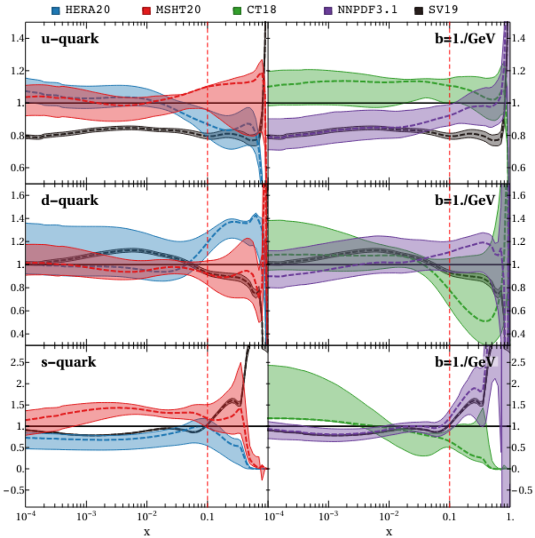
$$\mathcal{D}(b,\mu) = \mathcal{D}_{\text{small-b}}(b^*,\mu^*) + \int_{\mu^*}^{\mu} \frac{d\mu'}{\mu'}\Gamma_{\text{cusp}}(\mu') + \mathcal{D}_{\text{NP}}(b)$$

- Ansatz for NP part:

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

- adds 3 parameters for TMDPDF scale evolution
- 3 (NP CS kernel) $+\ 2\times 5\ (u,\overline{u},d,\overline{d},sea)$ $=13$ parameters to fit.

collinear PDF choice

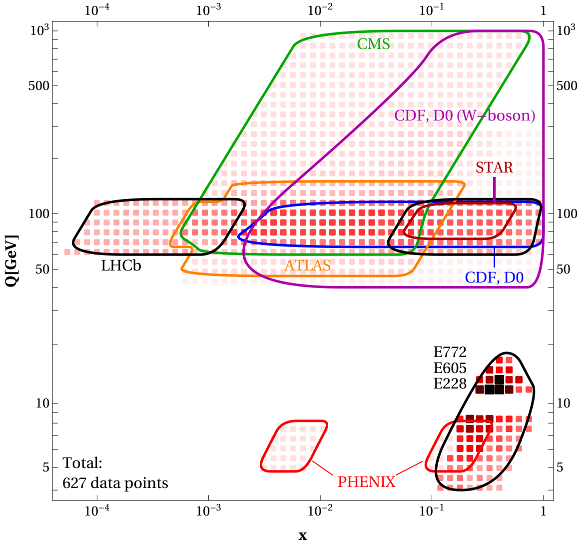


Param.	MSHT20	HERA2.0	NNPDF3.1	CT18
κ_1^u	0.12	0.11	0.28	0.05
κ_2^u	0.32	8.15	2.58	0.9

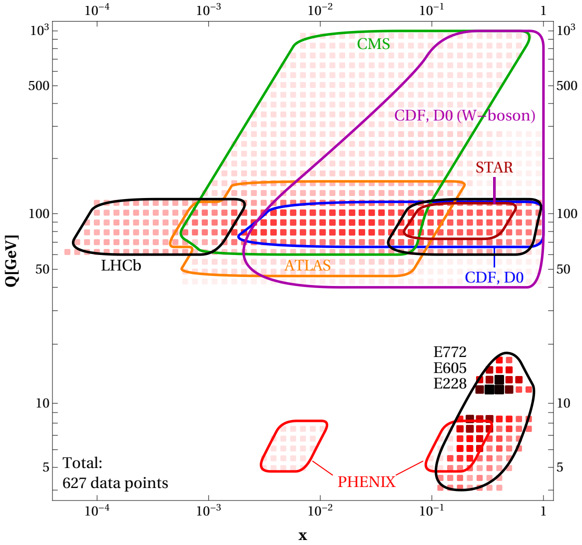
- obtained parameters stronly depend on PDF
- collinear PDF is base layer of TMDPDF
- we choose MSHT20 as the strongest candidate in JHEP 10 (2022) 118

included Data

Kinematic range of included data, Datasets

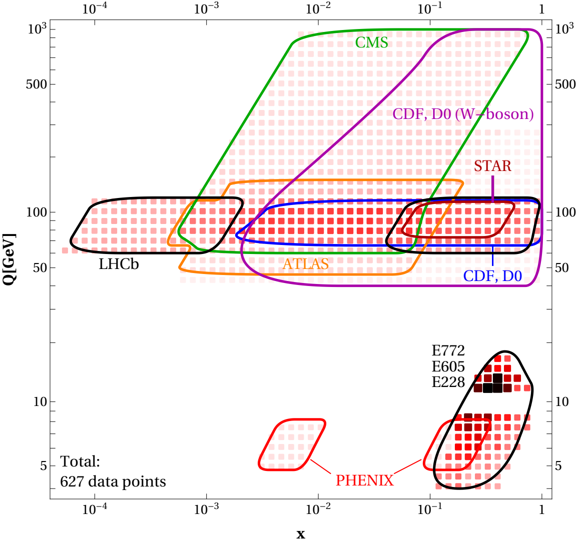


Kinematic range of included data, Datasets



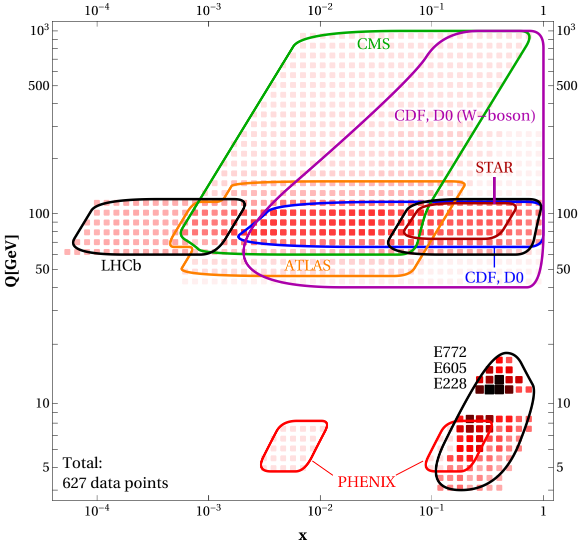
- high resolution scales up to 1 TeV

Kinematic range of included data, Datasets



- high resolution scales up to 1 TeV
- including W production in DY

Kinematic range of included data, Datasets



- high resolution scales up to 1 TeV
- including W production in DY
- 627 datapoints included
  457 (SV19),
  484 (MAP)

Cuts on datapoints

- q^μ: hard processes total momentum, $Q^2 = q^2$
- q_T: Its transverse component
- $\delta^2 = \frac{q_T^2}{Q^2}$
- σ: (uncorrelated.) Standard deviation (datapoint)

Cuts on datapoints

- q^μ: hard processes total momentum, $Q^2 = q^2$
- q_T: Its transverse component
- $\delta^2 = \frac{q_T^2}{Q^2}$
- σ: (uncorrelated.) Standard deviation (datapoint)

Criteria to include datapoint:

Cuts on datapoints

- q^μ: hard processes total momentum, $Q^2 = q^2$
- q_T: Its transverse component
- $\delta^2 = \frac{q_T^2}{Q^2}$
- σ: (uncorrelated.) Standard deviation (datapoint)

Criteria to include datapoint:

- $\delta < 0.25$

Cuts on datapoints

- q^μ: hard processes total momentum, $Q^2 = q^2$
- q_T: Its transverse component
- $\delta^2 = \frac{q_T^2}{Q^2}$
- σ: (uncorrelated.) Standard deviation (datapoint)

Criteria to include datapoint:

- $\delta < 0.25$
- at least **one** of the following:
  1. $q_T < 10\,GeV$
  2. $\delta^2/\sigma < 2$

Results

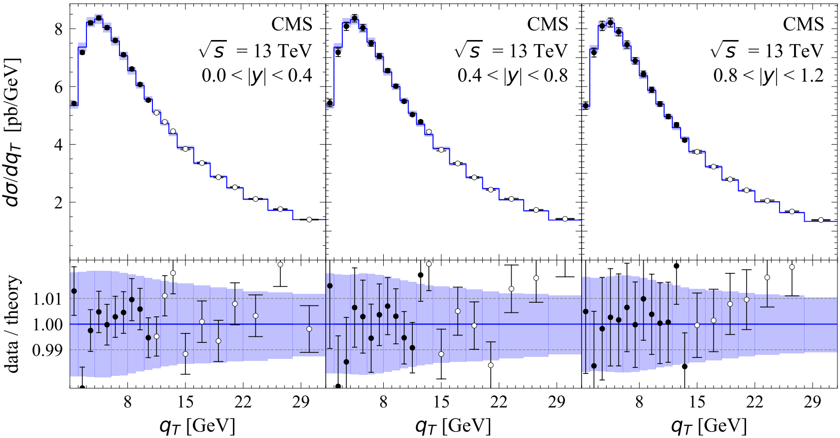
χ^2 results

dataset	N_{pt}	χ^2_D/N_{pt}	$\chi^2_\lambda/N_{\text{pt}}$	χ^2/N_{pt}	$\langle d/\sigma \rangle$
CDF (run1)	33	0.51	0.16	$0.67^{+0.05}_{-0.03}$	9.1%
CDF (run2)	45	1.58	0.11	$1.59^{+0.26}_{-0.14}$	4.0%
CDF (W-boson)	6	0.33	0.00	$0.33^{+0.01}_{-0.01}$	–
D0 (run1)	16	0.69	0.00	$0.69^{+0.08}_{-0.03}$	7.1%
D0 (run2)	13	2.16	0.16	$2.32^{+0.40}_{-0.32}$	–
D0 (W-boson)	7	2.39	0.00	$2.39^{+0.20}_{-0.18}$	–
ATLAS (8TeV, $Q \sim M_Z$)	30	1.60	0.49	$2.09^{+1.09}_{-0.35}$	4.1%
ATLAS (8TeV)	14	1.11	0.11	$1.22^{+0.47}_{-0.21}$	2.3%
ATLAS (13 TeV)	5	1.94	1.75	$3.70^{+16.5}_{-2.24}$	–
CMS (7TeV)	8	1.30	0.00	$1.30^{+0.03}_{-0.01}$	–
CMS (8TeV)	8	0.79	0.00	$0.78^{+0.02}_{-0.01}$	–
CMS (13 TeV, $Q \sim M_Z$)	64	0.63	0.24	$0.86^{+0.23}_{-0.11}$	4.3%
CMS (13 TeV, $Q > M_Z$)	33	0.73	0.12	$0.92^{+0.40}_{-0.15}$	1.0%

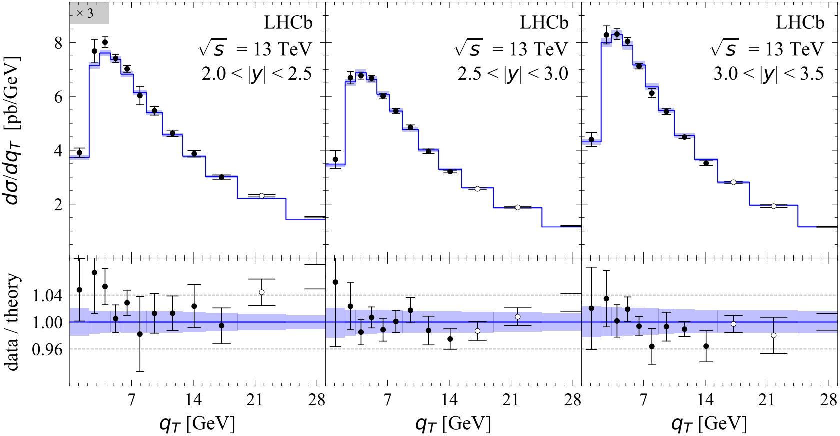
χ^2 results

dataset	N_{pt}	χ^2_D/N_{pt}	χ^2_λ/N_{pt}	χ^2/N_{pt}	$\langle d/\sigma \rangle$
LHCb (7 TeV)	10	1.21	0.56	$1.77^{+0.53}_{-0.31}$	5.0%
LHCb (8 TeV)	9	0.77	0.78	$1.55^{+0.94}_{-0.50}$	4.3%
LHCb (13 TeV)	49	1.07	0.10	$1.18^{+0.25}_{-0.01}$	4.5%
PHENIX	3	0.29	0.12	$0.42^{+0.15}_{-0.10}$	10.%
STAR	11	1.91	0.28	$2.19^{+0.51}_{-0.31}$	15.%
E288 (200)	43	0.31	0.07	$0.38^{+0.12}_{-0.05}$	44.%
E288 (300)	53	0.36	0.07	$0.43^{+0.08}_{-0.04}$	48.%
E288 (400)	79	0.37	0.05	$0.48^{+0.11}_{-0.03}$	48.%
E772	35	0.87	0.21	$1.08^{+0.08}_{-0.05}$	27.%
E605	53	0.18	0.21	$0.39^{+0.03}_{-0.00}$	49.%
Total	627	0.79	0.17	$0.96^{+0.09}_{-0.01}$	

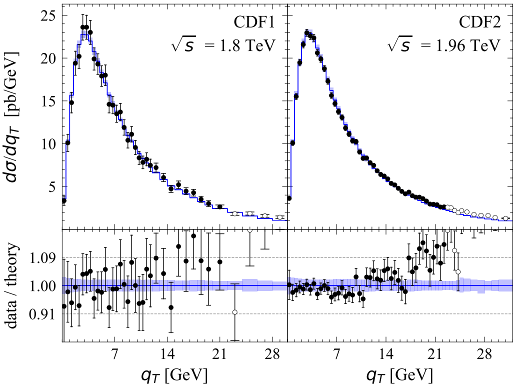
Data at $\sqrt{s} = 13$ TeV



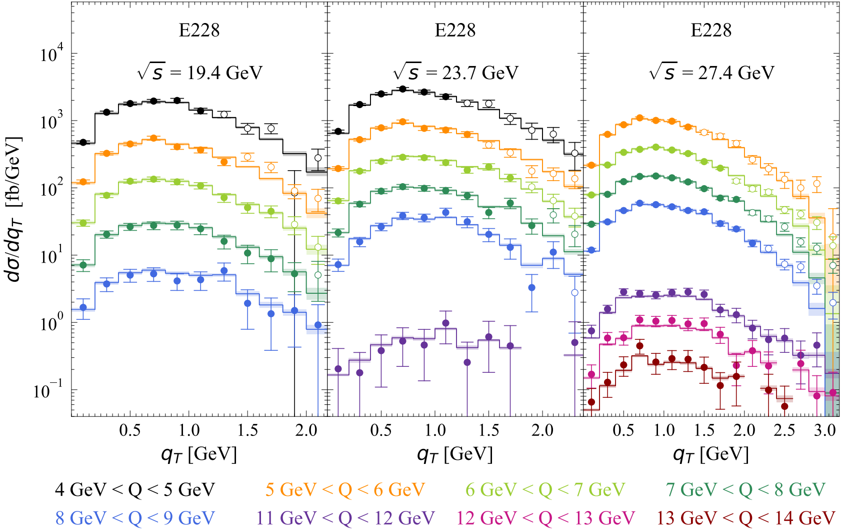
Data at $\sqrt{s} = 13$ TeV



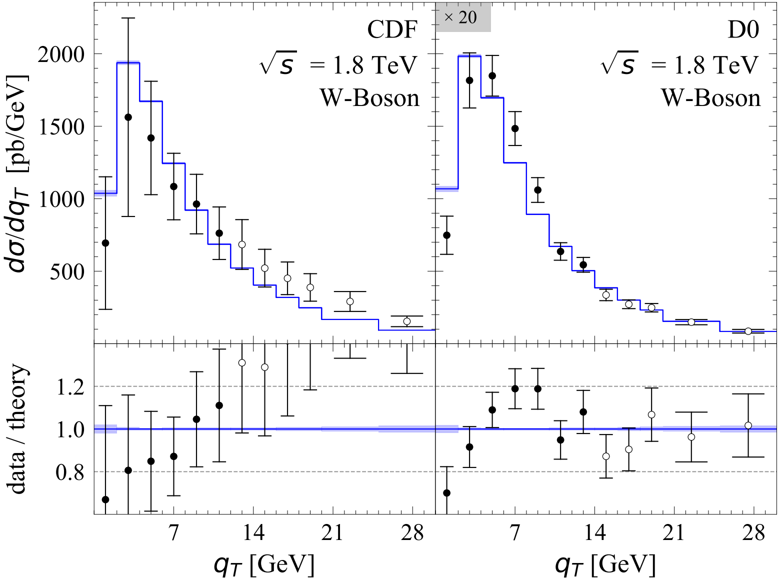
Data at $\sqrt{s} = 1.8$ TeV



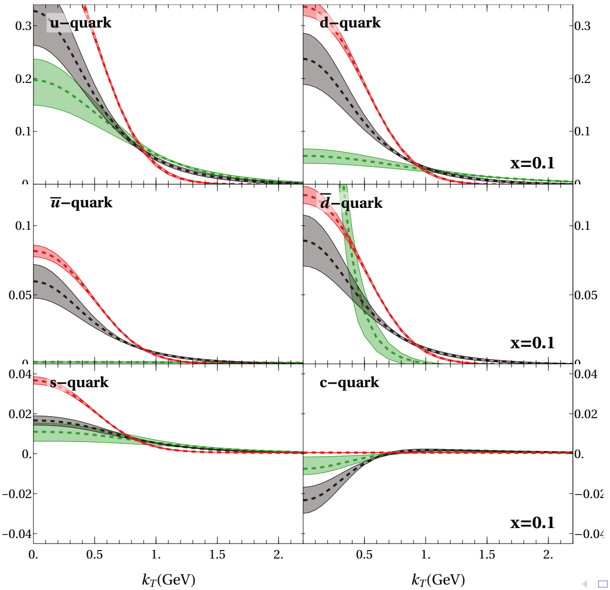
Data at $\sqrt{s} = 19, 23$ and 27 GeV



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

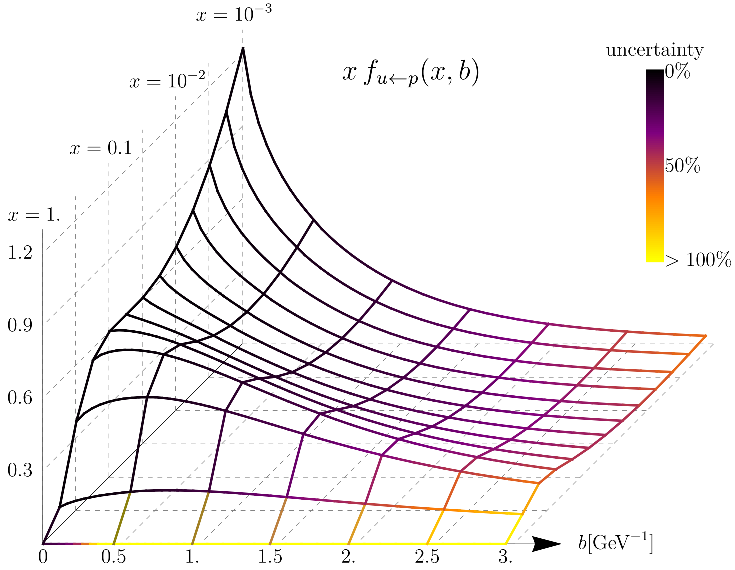


TMDPDF distributions visualized

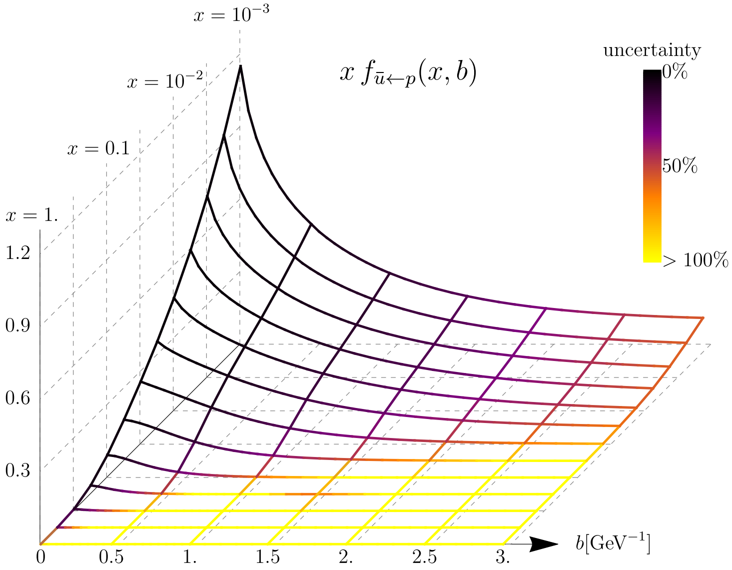


- MAP
  MMHT14
- ART23 (us)
  MSHT20
- SV19
  NNPDF3.1

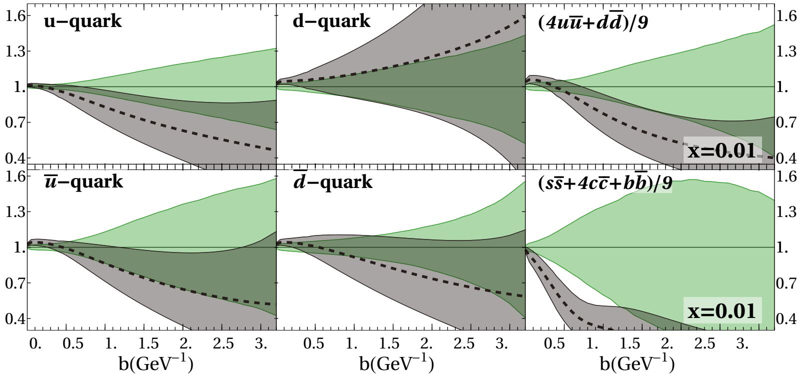
u TMDPDF vs. x and b



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

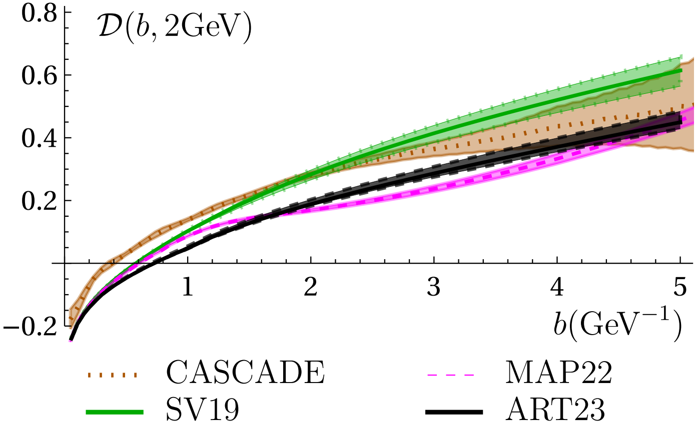


uncertainty Bands relative to central value



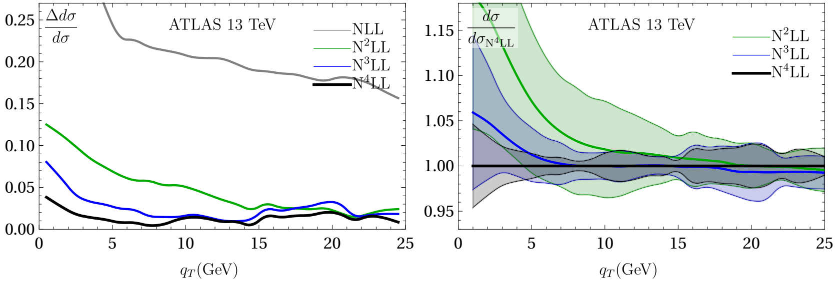
- MSHT20 extraction
- NNPDF3.1 extraction

Collins-Soper kernel



CS Kernels in comparison

Scale variation



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

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

- overall reducing (higher orders)
- minor oscillations

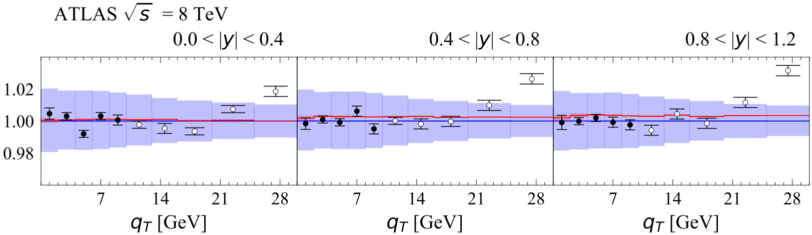
Recapitulation & Outlook

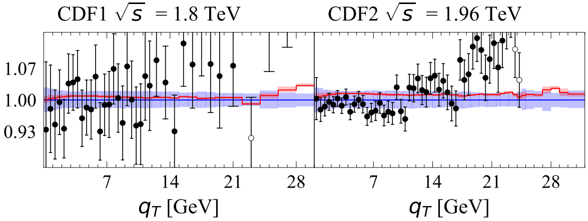
- A **first of a kind** N4LO extraction of TMDPDFs
- overall good prescription of data

Outlook:

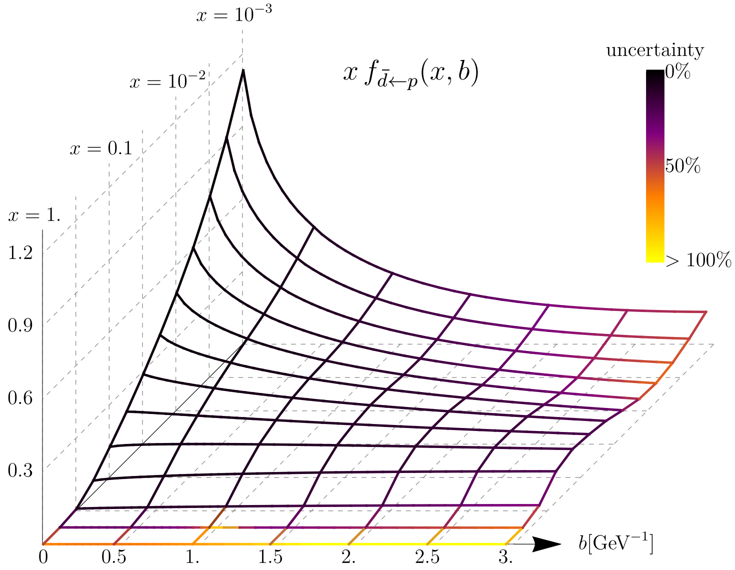
- Extension: DY+SIDIS fit
- Pion TMDPDF fit
- Impact Studies for EIC

PDF uncertainty impact

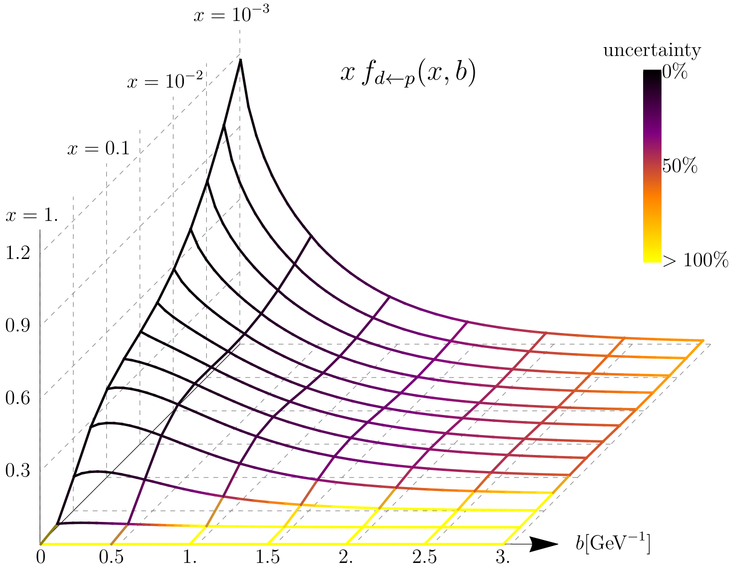




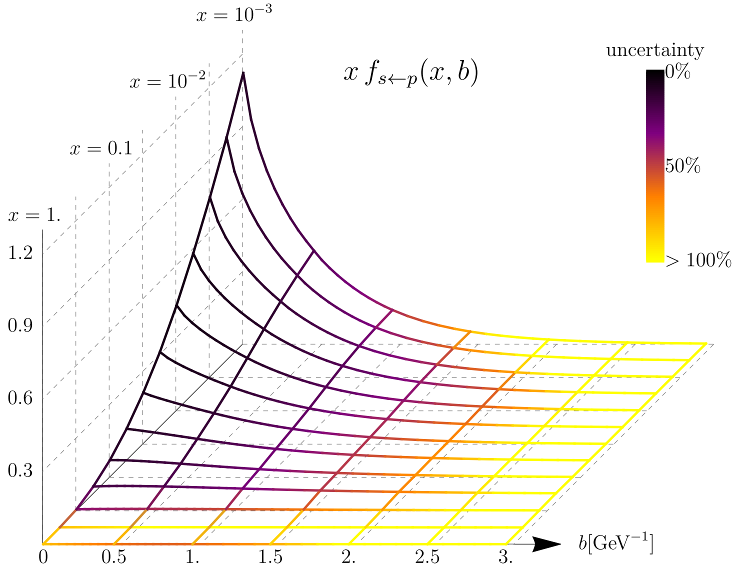
d TMDPDF vs. x and b



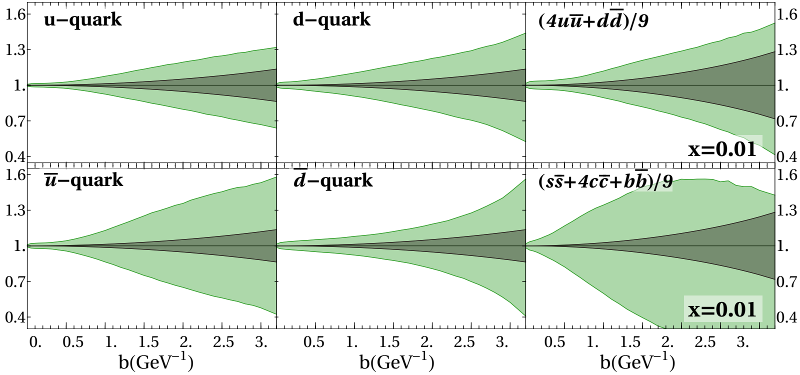
$\overline{d}$ TMDPDF vs. x and b



sea TMDPDF vs. x and b

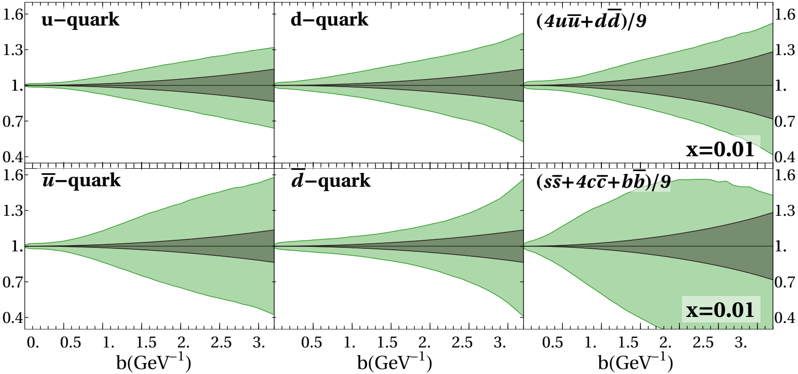


uncertainty Bands relative to central value



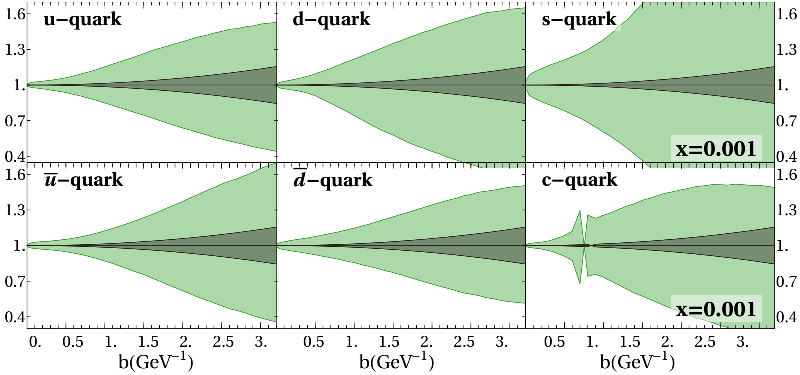
- ART23 (us)
- SV19

uncertainty Bands relative to central value



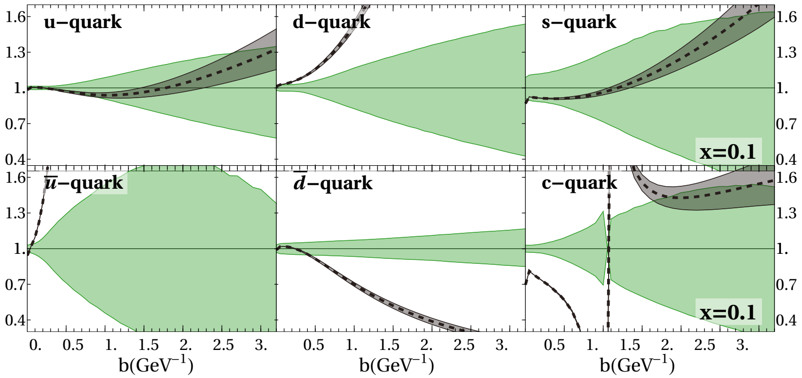
- ART23 (us)
- SV19

uncertainty Bands relative to central value



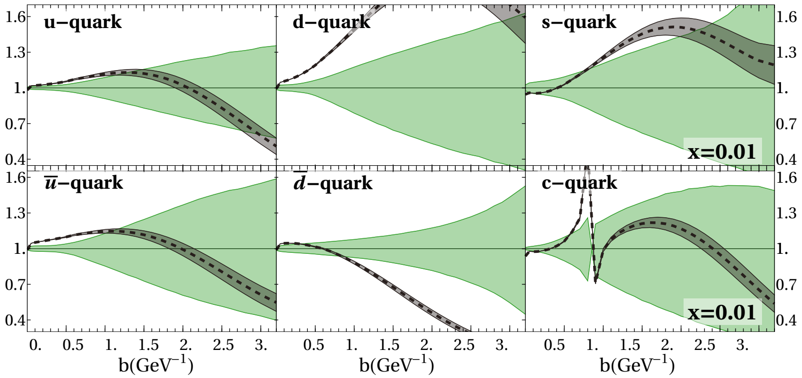
- ART23 (us)
- SV19

uncertainty Bands relative to central value



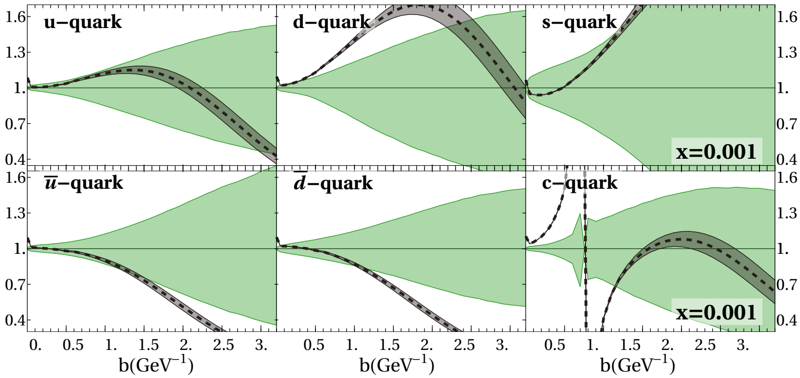
- ART23 (us)
- SV19

uncertainty Bands relative to central value



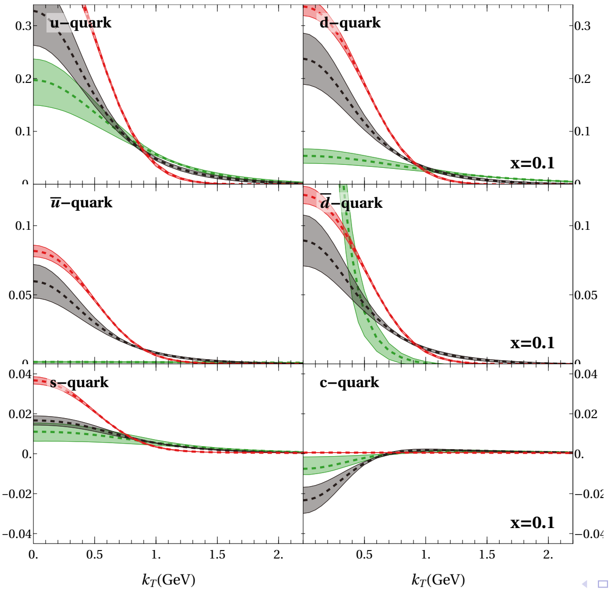
- ART23 (us)
- SV19

uncertainty Bands relative to central value



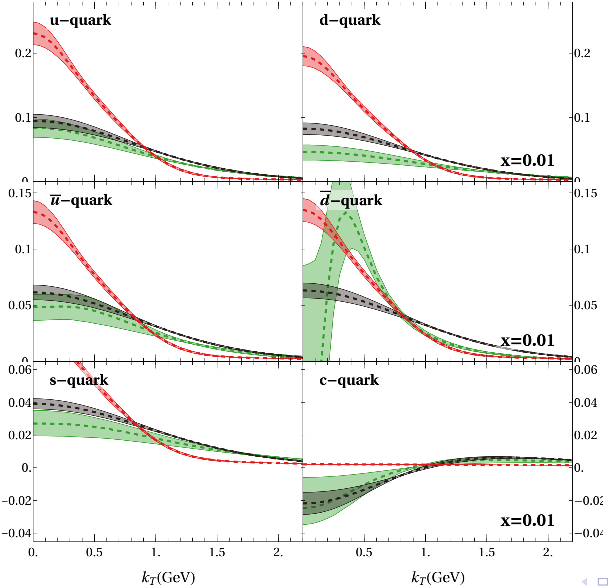
- ART23 (us)
- SV19

TMDPDF distributions visualized



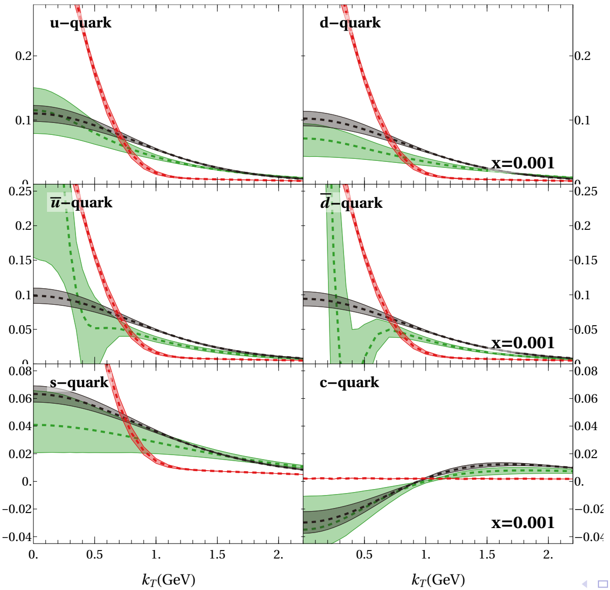
- MAP
  MMHT14
- ART23 (us)
  MSHT20
- SV19
  NNPDF31

TMDPDF distributions visualized



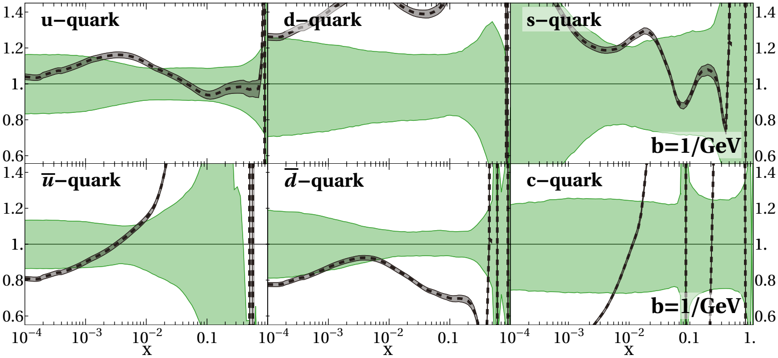
- MAP MMHT14
- ART23 (us) MSHT20
- SV19 NNPDF31

TMDPDF distributions visualized



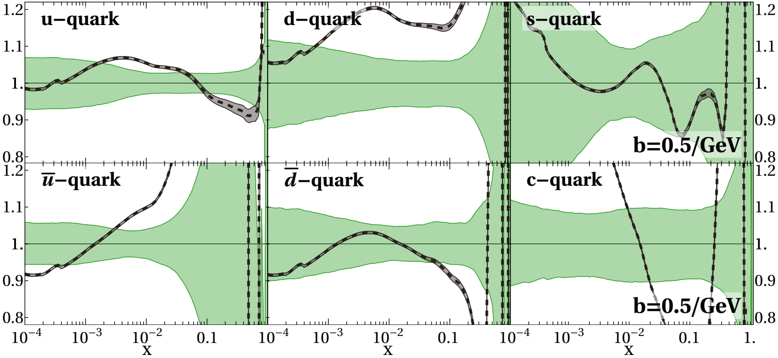
- MAP
  MMHT14
- ART23 (us)
  MSHT20
- SV19
  NNPDF31

uncertainty Bands relative to central value



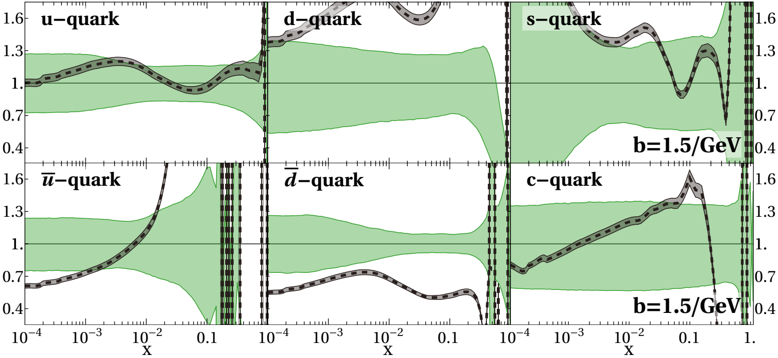
- ART23 (us)
- SV19

uncertainty Bands relative to central value



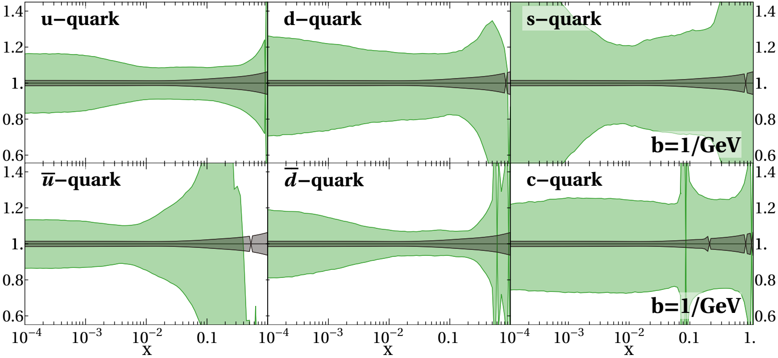
- ART23 (us)
- SV19

uncertainty Bands relative to central value



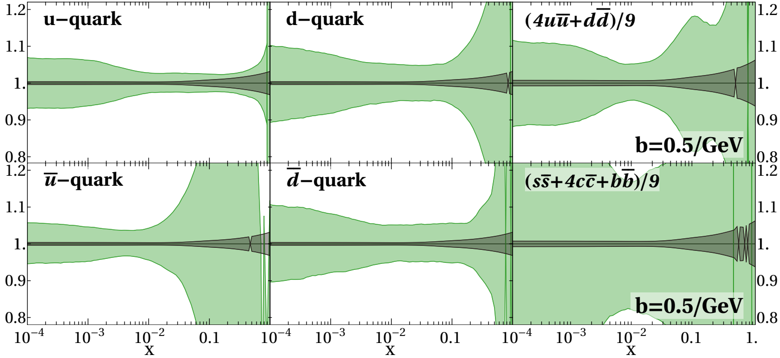
- ART23 (us)
- SV19

uncertainty Bands relative to central value



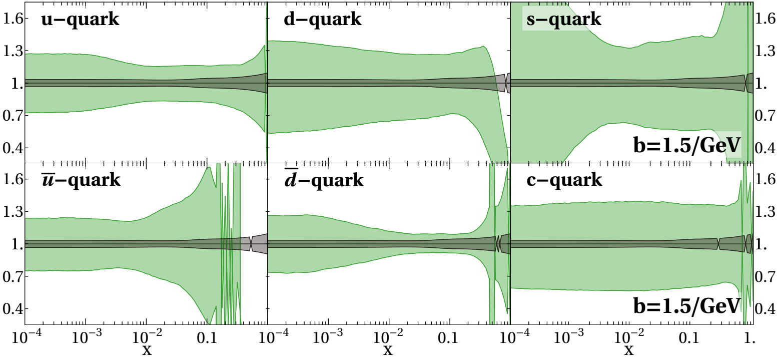
- ART23 (us)
- SV19

uncertainty Bands relative to central value



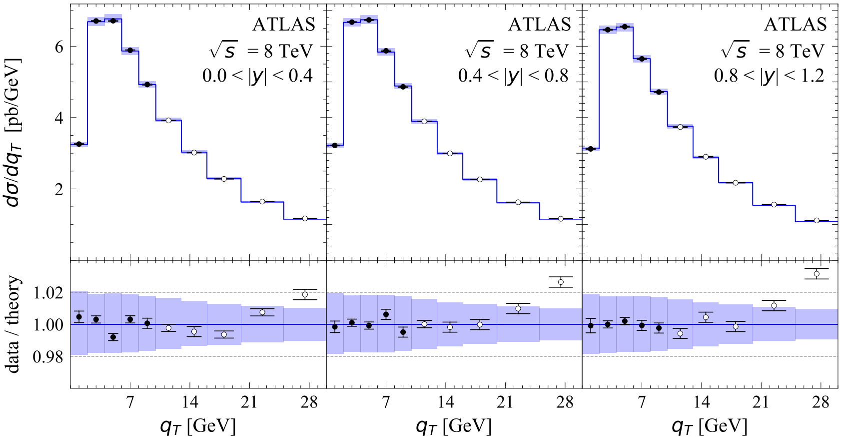
- ART23 (us)
- SV19

uncertainty Bands relative to central value

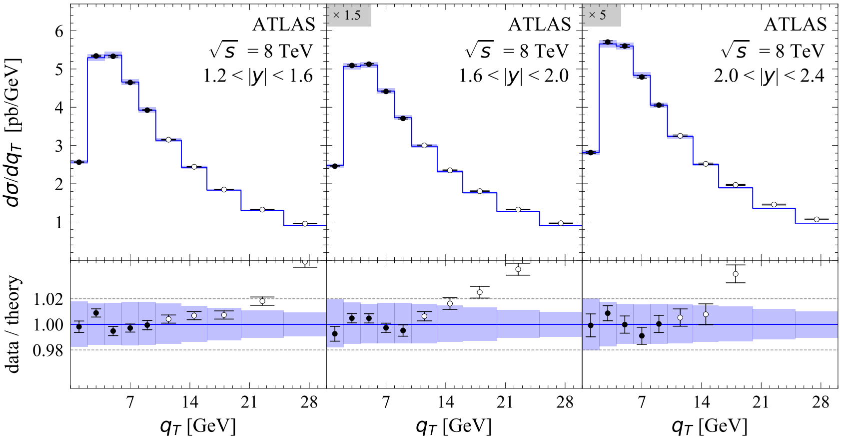


- ART23 (us)
- SV19

ATLAS

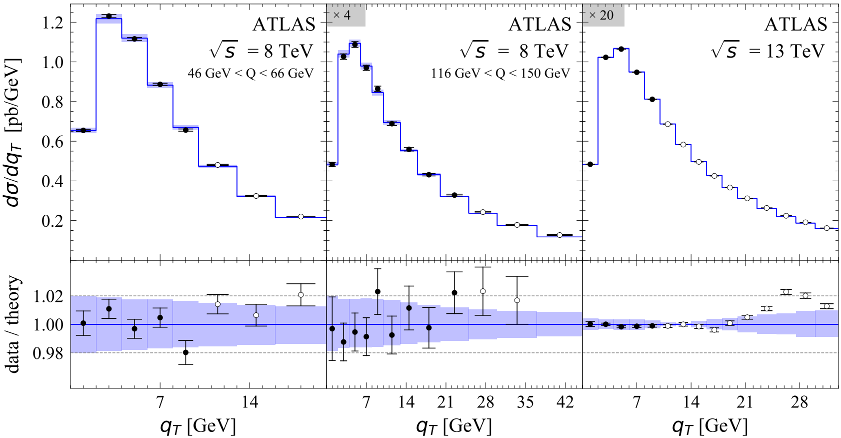

ATLAS
$\sqrt{s}$ = 8 TeV
0.0 < |y| < 0.4
0.4 < |y| < 0.8
0.8 < |y| < 1.2
$d\sigma/dq_T$ [pb/GeV]
data / theory
q_T [GeV]
2
4
6
0.98
1.00
1.02
7
14
21
28

ATLAS

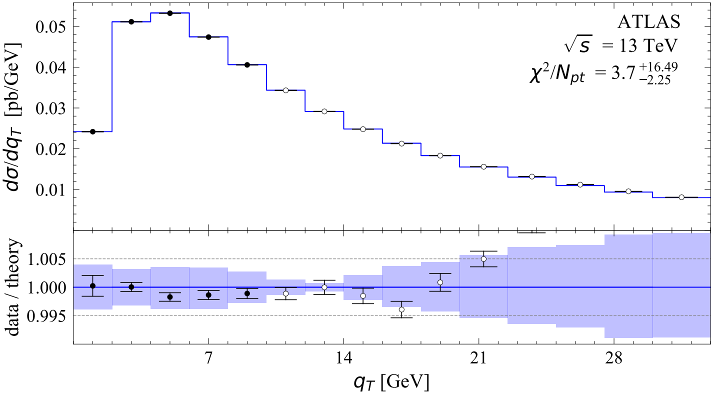


ATLAS
$\sqrt{s}$ = 8 TeV
1.2 < |y| < 1.6
× 1.5
ATLAS
$\sqrt{s}$ = 8 TeV
1.6 < |y| < 2.0
× 5
ATLAS
$\sqrt{s}$ = 8 TeV
2.0 < |y| < 2.4
$d\sigma/dq_T$ [pb/GeV]
data / theory
1.02
1.00
0.98
7
14
21
28
q_T [GeV]

ATLAS

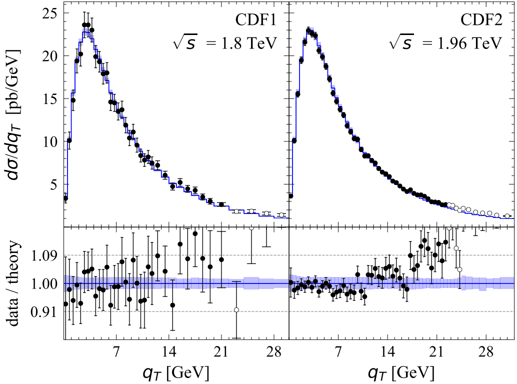

ATLAS
$\sqrt{s}$ = 8 TeV
46 GeV < Q < 66 GeV
× 4
ATLAS
$\sqrt{s}$ = 8 TeV
116 GeV < Q < 150 GeV
× 20
ATLAS
$\sqrt{s}$ = 13 TeV
$d\sigma/dq_T$ [pb/GeV]
data / theory
q_T [GeV]
q_T [GeV]
q_T [GeV]

ATLAS



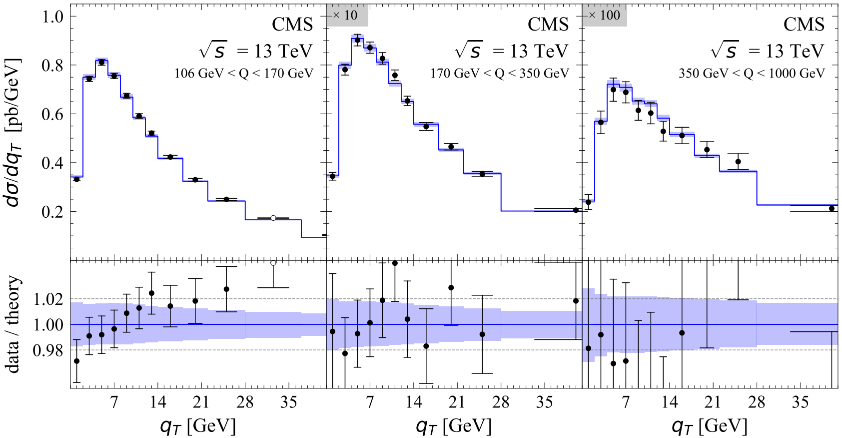
ATLAS
$\sqrt{s}$ = 13 TeV
$\chi^2/N_{pt} = 3.7^{+16.49}_{-2.25}$
$d\sigma/dq_T$ [pb/GeV]
0.05
0.04
0.03
0.02
0.01
data / theory
1.005
1.000
0.995
7
14
21
28
q_T [GeV]

CDF



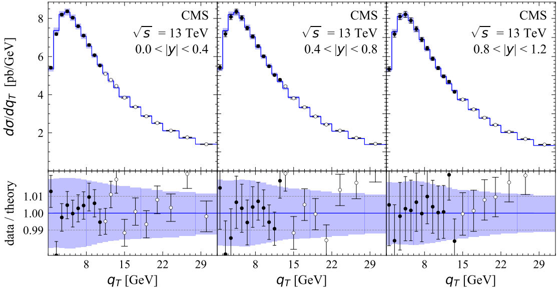
CDF1
$\sqrt{s}$ = 1.8 TeV
CDF2
$\sqrt{s}$ = 1.96 TeV
$d\sigma/dq_T$ [pb/GeV]
data / theory
q_T [GeV]
q_T [GeV]

CMS



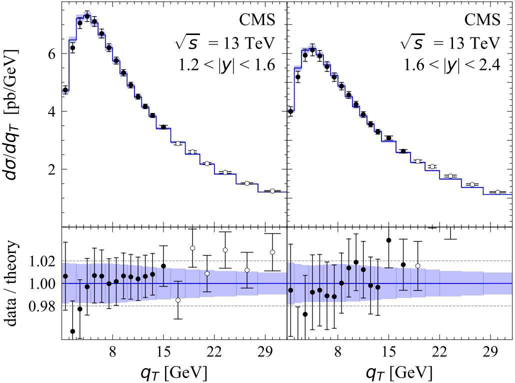
CMS
$\sqrt{s}$ = 13 TeV
106 GeV < Q < 170 GeV
170 GeV < Q < 350 GeV
350 GeV < Q < 1000 GeV
× 10
× 100
$d\sigma/dq_T$ [pb/GeV]
data / theory
q_T [GeV]

CMS

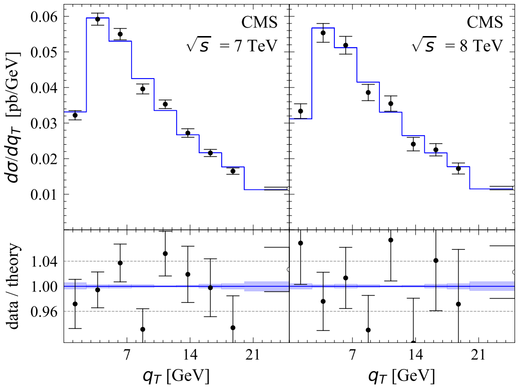


CMS
$\sqrt{s}$ = 13 TeV
0.0 < |y| < 0.4
CMS
$\sqrt{s}$ = 13 TeV
0.4 < |y| < 0.8
CMS
$\sqrt{s}$ = 13 TeV
0.8 < |y| < 1.2
$d\sigma/dq_T$ [pb/GeV]
data / theory
q_T [GeV]

CMS

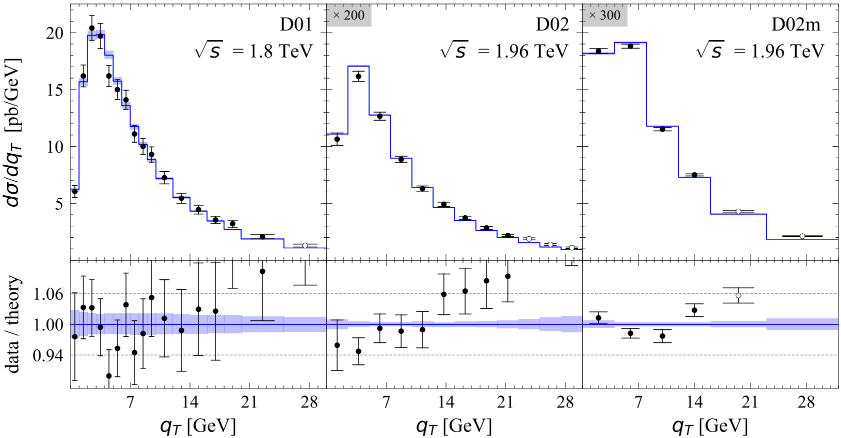

CMS
$\sqrt{s}$ = 13 TeV
1.2 < |y| < 1.6
CMS
$\sqrt{s}$ = 13 TeV
1.6 < |y| < 2.4
$d\sigma/dq_T$ [pb/GeV]
data / theory
q_T [GeV]
q_T [GeV]
6
4
2
1.02
1.00
0.98
8
15
22
29
8
15
22
29

CMS



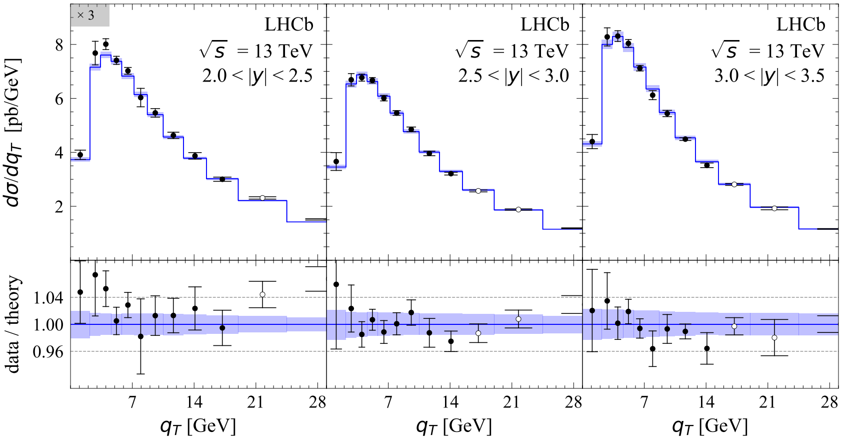
CMS
$\sqrt{s}$ = 7 TeV
CMS
$\sqrt{s}$ = 8 TeV
$d\sigma/dq_T$ [pb/GeV]
0.06
0.05
0.04
0.03
0.02
0.01
data / theory
1.04
1.00
0.96
7
14
21
q_T [GeV]

D0

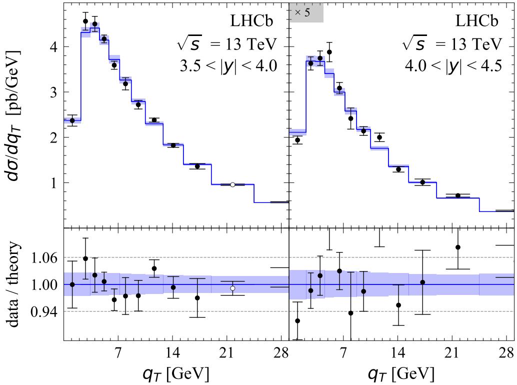


D01
$\sqrt{s}$ = 1.8 TeV
× 200
D02
$\sqrt{s}$ = 1.96 TeV
× 300
D02m
$\sqrt{s}$ = 1.96 TeV
$d\sigma/dq_T$ [pb/GeV]
20
15
10
5
data / theory
1.06
1.00
0.94
7
14
21
28
q_T [GeV]

LHCb

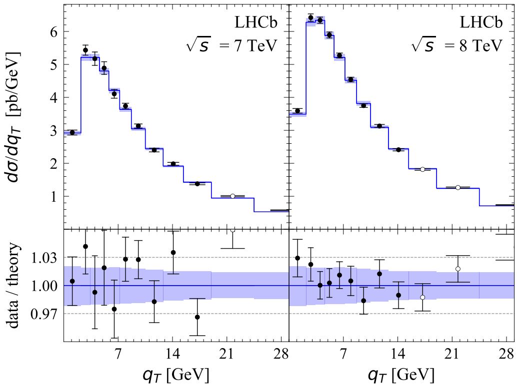

× 3
LHCb
$\sqrt{s}$ = 13 TeV
2.0 < |y| < 2.5
LHCb
$\sqrt{s}$ = 13 TeV
2.5 < |y| < 3.0
LHCb
$\sqrt{s}$ = 13 TeV
3.0 < |y| < 3.5
$d\sigma/dq_T$ [pb/GeV]
data / theory
8
6
4
2
1.04
1.00
0.96
7
14
21
28
q_T [GeV]

LHCb



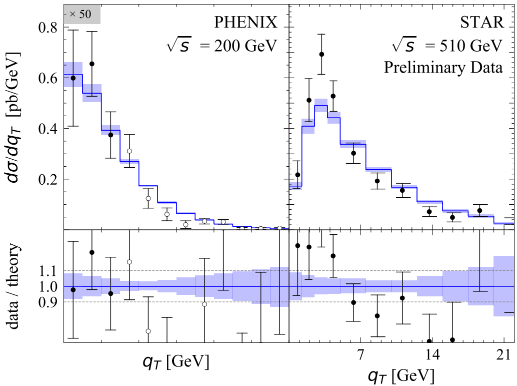
LHCb
$\sqrt{s}$ = 13 TeV
3.5 < |y| < 4.0
× 5
LHCb
$\sqrt{s}$ = 13 TeV
4.0 < |y| < 4.5
$d\sigma/dq_T$ [pb/GeV]
data / theory
q_T [GeV]
q_T [GeV]

LHCb

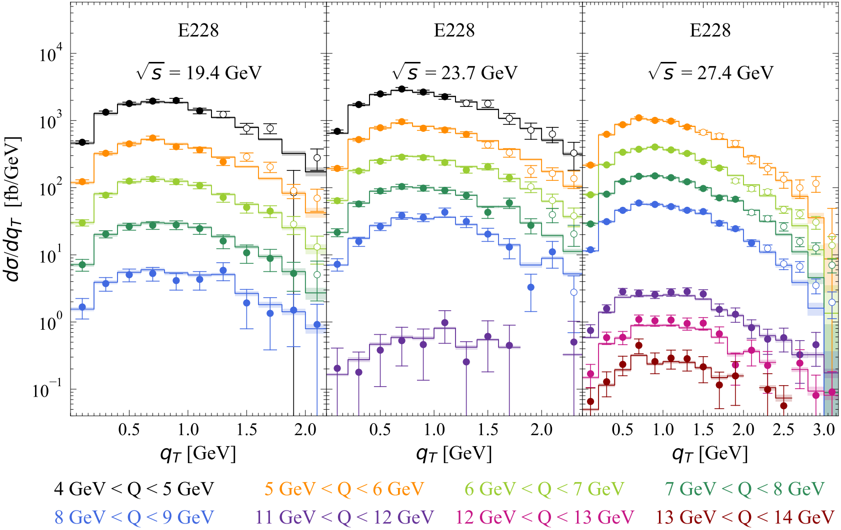


LHCb
$\sqrt{s}$ = 7 TeV
LHCb
$\sqrt{s}$ = 8 TeV
$d\sigma/dq_T$ [pb/GeV]
data / theory
q_T [GeV]
q_T [GeV]

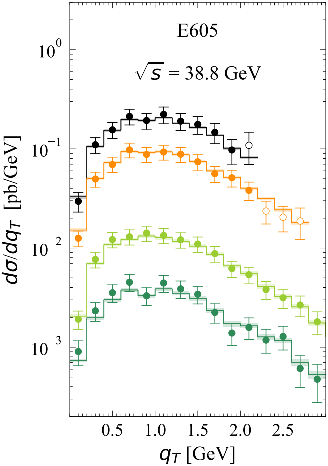
STAR and PHENIX

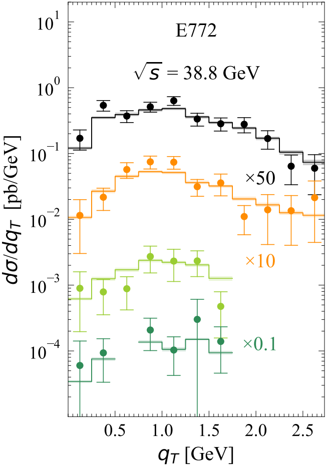


E228


E228
$\sqrt{s}$ = 19.4 GeV
E228
$\sqrt{s}$ = 23.7 GeV
E228
$\sqrt{s}$ = 27.4 GeV
$d\sigma/dq_T$ [fb/GeV]
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
11.5 GeV < Q < 13.5 GeV 13.5 GeV < Q < 18 GeV

11 GeV < Q < 12 GeV 12 GeV < Q < 13 GeV
13 GeV < Q < 14 GeV 14 GeV < Q < 15 GeV