# 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.

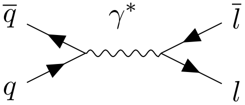
$$\Phi_{q\leftarrow h}^{[\gamma^+]}(x,b) = f_1(x,b) + i\epsilon_T^{\mu\nu} b_\mu s_{T\nu} M f_{1T}^\perp(x,b)$$

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

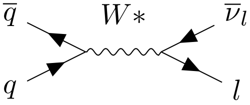
$$\Phi_{q\leftarrow h}^{[\sigma^{\alpha+}\gamma_5]}(x,b) = s_T^\alpha h_1(x,b) - i\lambda b^\alpha M h_{1L}^\perp(x,b) + i\epsilon_T^{\alpha\mu} b_\mu M h_1^\perp(x,b) - \frac{M^2 b^2}{2}\left(\frac{g_T^{\alpha\mu}}{2} - \frac{b^\alpha b^\mu}{b^2}\right) s_{T\mu} h_{1T}^\perp(x,b)$$

# DY process

virtual photon




virtual W Boson



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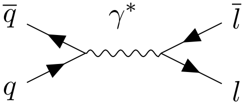


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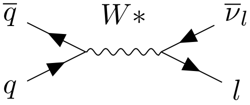


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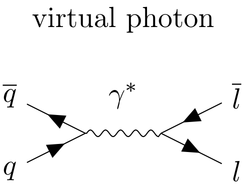


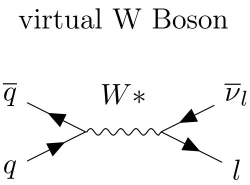


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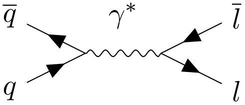


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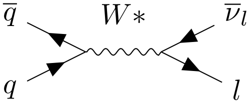



- unpolarized distribution $f_1$ enters for $q$, $\overline{q}$
- compute $\frac{d\sigma}{dydq_T^2}$ using artemide
- comapare to data (fit!) to determine NP parameters

# Our model: distribution's shape

Parametrization of TMDPDF:

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

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

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

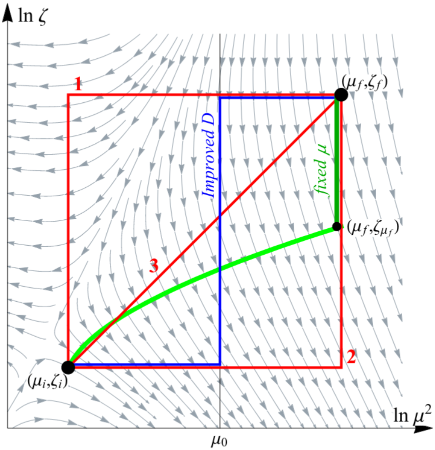
- $f \in \{u, \overline{u}, d, \overline{d}, sea\}$ $\rightarrow 2 \times 5$ independent parameters!
- $\lambda_{1,2}^f > 0$ imposed!

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

# 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$(a_s, L_\mu)$

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

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

| $\Gamma_{\text{cusp}}$ | $\gamma_V$ | $\beta$ | $\mathcal{D}_{\text{small-b}}$ | $C_{f\to f'}$ | $C_V$ | PDF |
|---|---|---|---|---|---|---|
| $a_s^5$ $(\Gamma_4)$ | $a_s^4$ $(\gamma_4)$ | $a_s^5$ $(\beta_3)$ | $a_s^4$ $(d^{(4,0)})$ | $a_s^3$ $(C_{f\to f'}^{[3]})$ | $a_s^4$ | 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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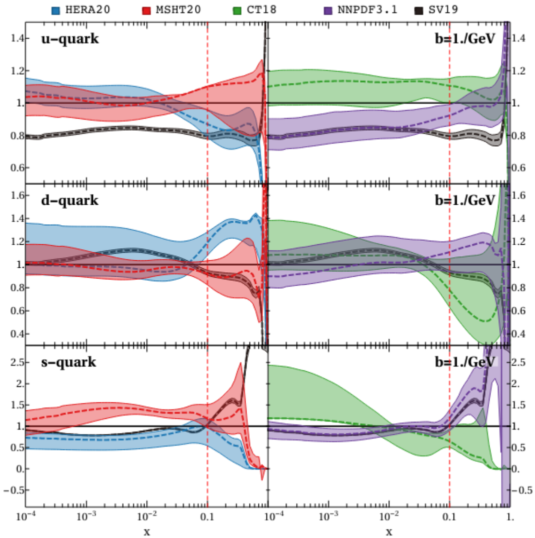
- adds 3 parameters for TMDPDF scale evolution
- 3 (NP CS kernel) $+ 2 \times 5$ $(u, \overline{u}, d, \overline{d}, sea)$ $= 13$ parameters to fit.

# collinear PDF choice

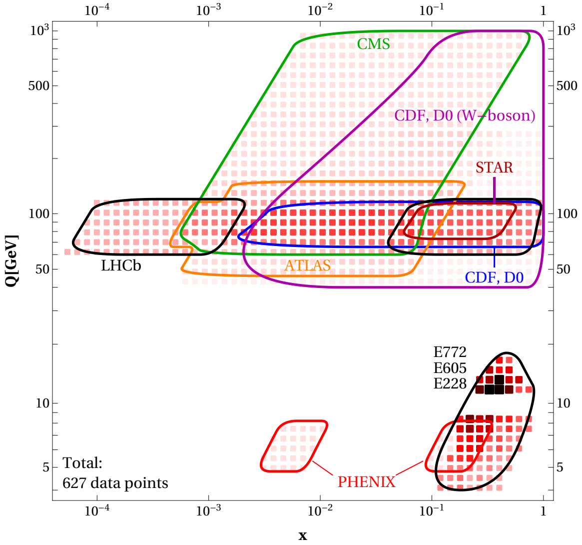



| Param. | MSHT20 | HERA2.0 | NNPDF3.1 | CT18 |
|---|---|---|---|---|
| $\kappa_1^u$ | 0.12 | 0.11 | 0.28 | 0.05 |
| $\kappa_2^u$ | 0.32 | 8.15 | 2.58 | 0.9 |

- 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



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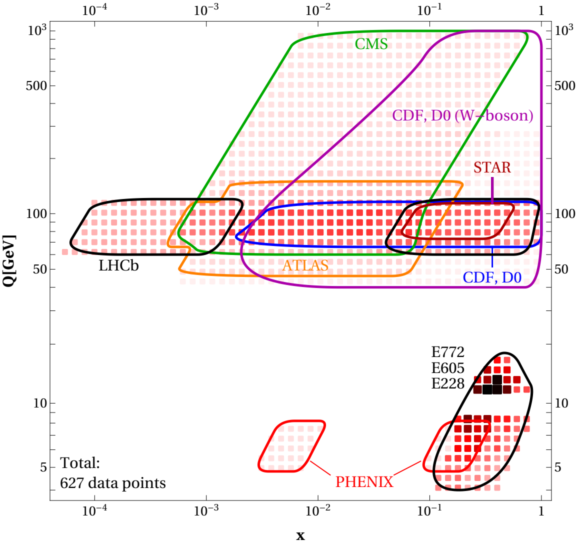


- high resolution scales up to 1 TeV

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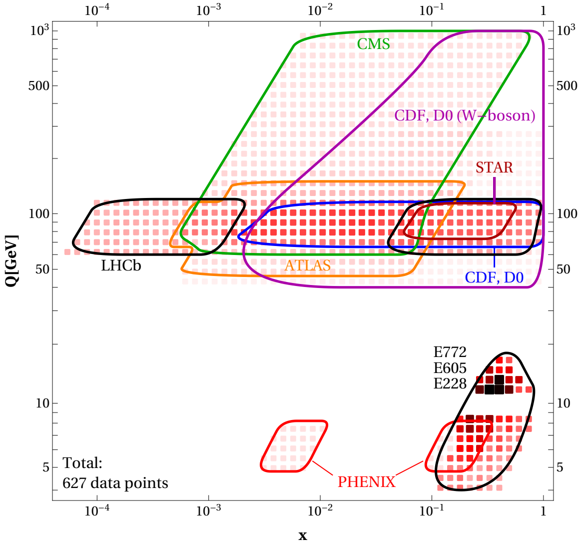


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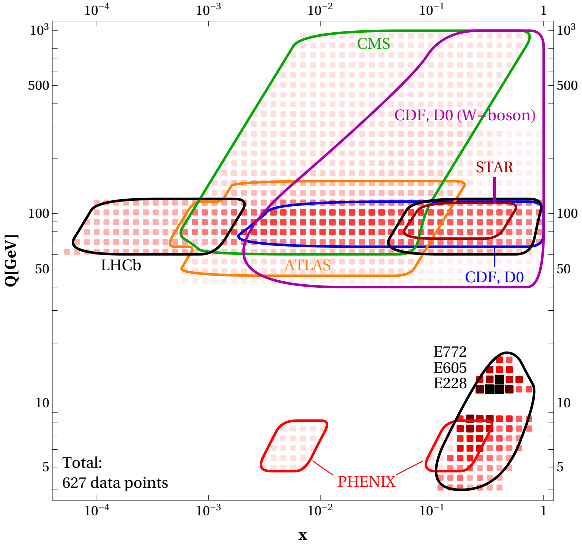


- high resolution scales up to 1 TeV
- including $W$ production in DY
- 627 datapoints included
  457 (SV19),
  484 (MAP)

# Cuts on datapoints

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

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**Criteria to include datapoint:**

- $\delta < 0.25$

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- $q_T$: Its transverse component
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- $\delta^2 = \frac{q_T^2}{Q^2}$

**Criteria to include datapoint:**

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

# Results

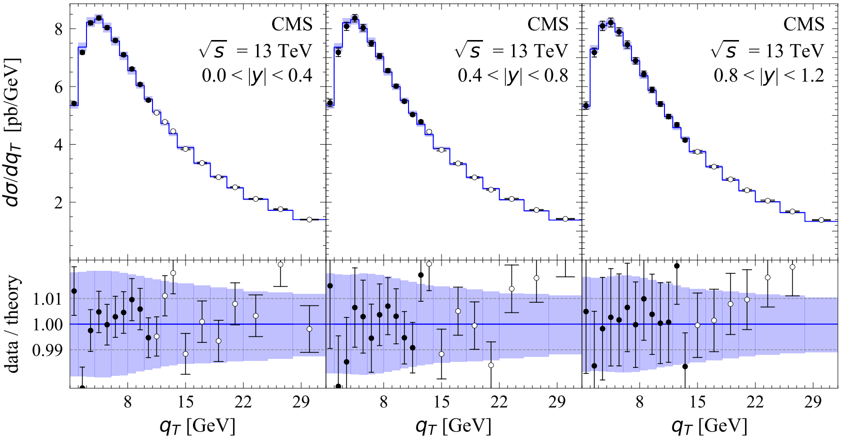
# $\chi^2$ results

| dataset | $N_{\text{pt}}$ | $\chi^2_D/N_{\text{pt}}$ | $\chi^2_\lambda/N_{\text{pt}}$ | $\chi^2/N_{\text{pt}}$ | $\langle d/\sigma \rangle$ |
|---|---|---|---|---|---|
| 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% |

# $\chi^2$ results

| dataset | $N_{pt}$ | $\chi^2_D/N_{pt}$ | $\chi^2_\lambda/N_{pt}$ | $\chi^2/N_{pt}$ | $\langle d/\sigma \rangle$ |
|---|---|---|---|---|---|
| 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



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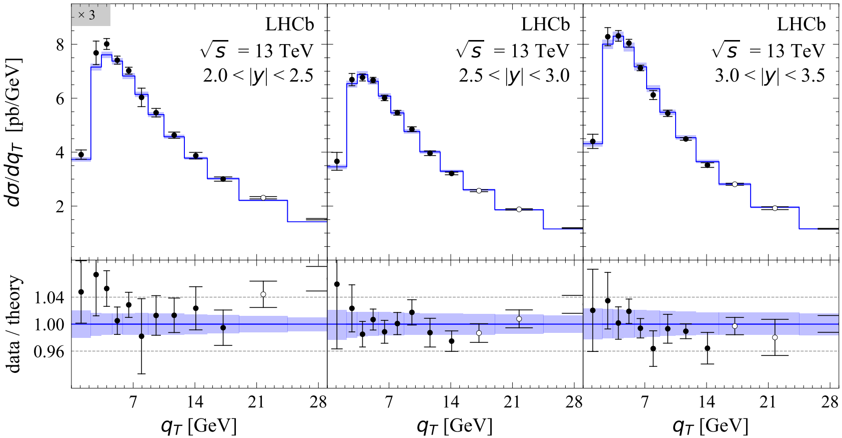
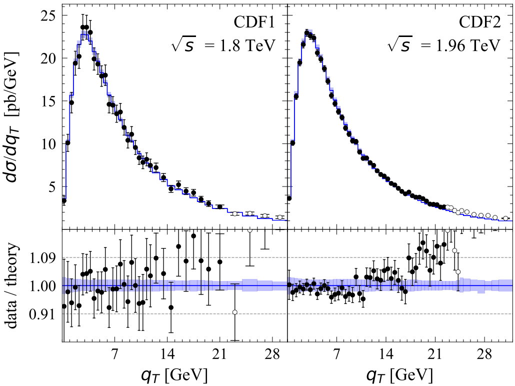
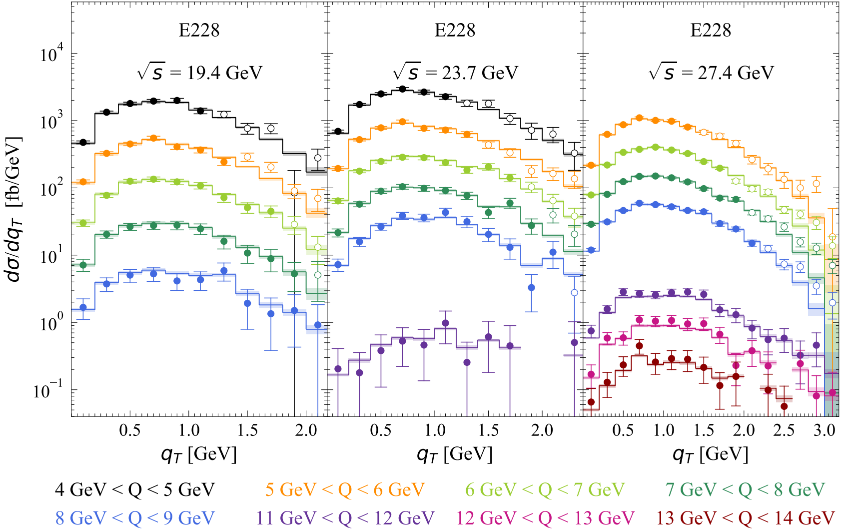


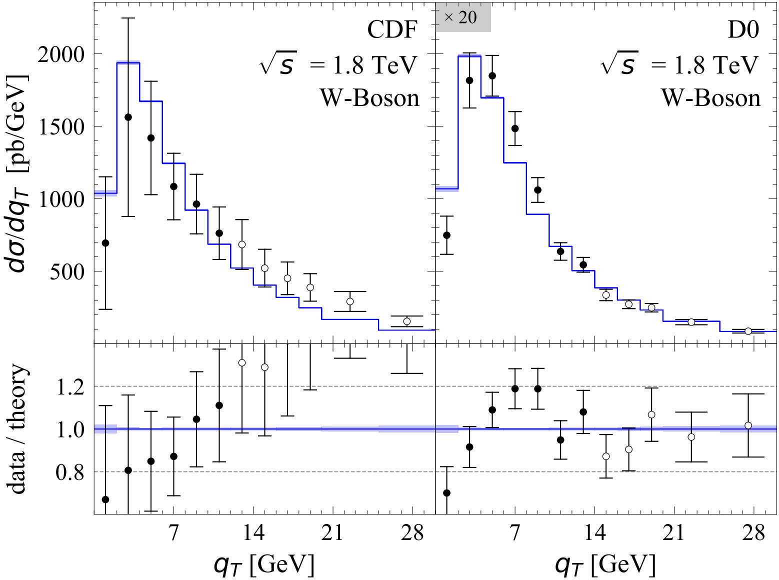
# Data at $\sqrt{s} = 1.8$ TeV



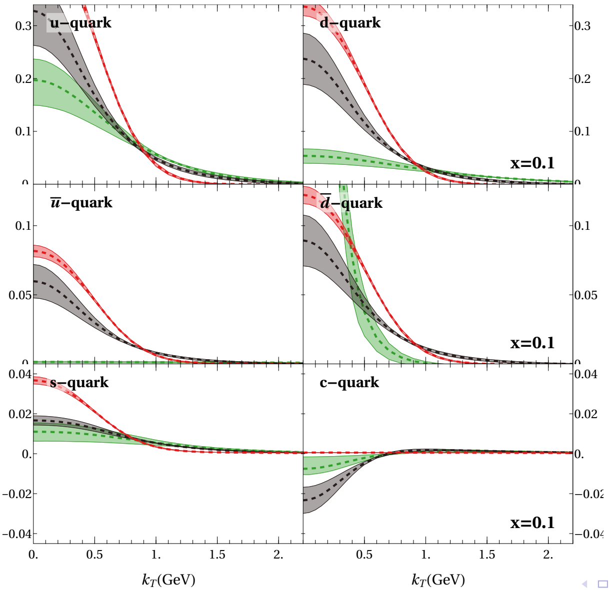
# Data at $\sqrt{s} = 19, 23$ and $27$ GeV



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

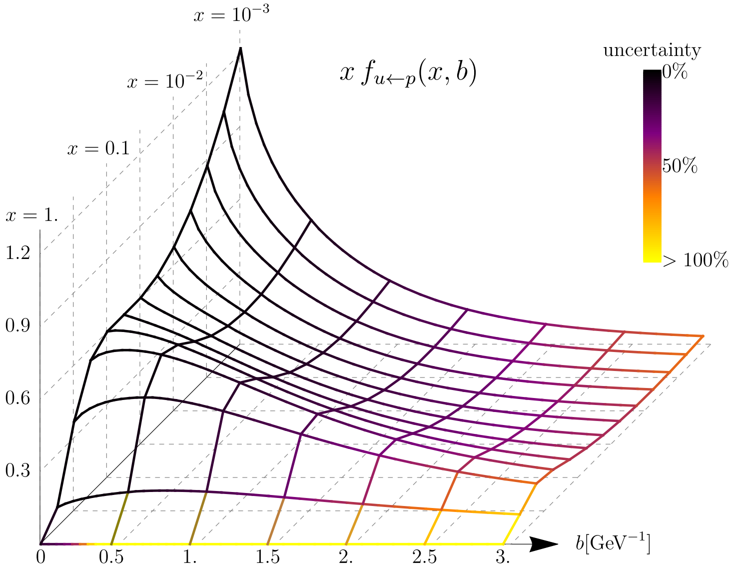


# TMDPDF distributions visualized




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

# $u$ TMDPDF vs. x and b



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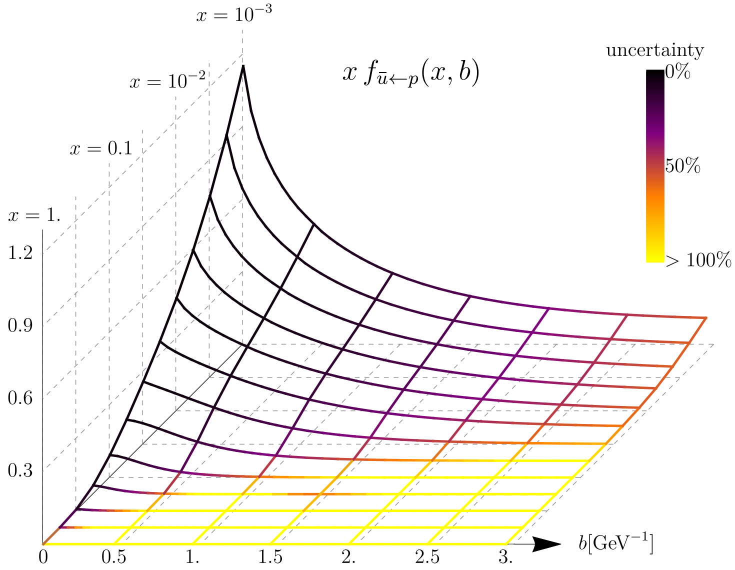
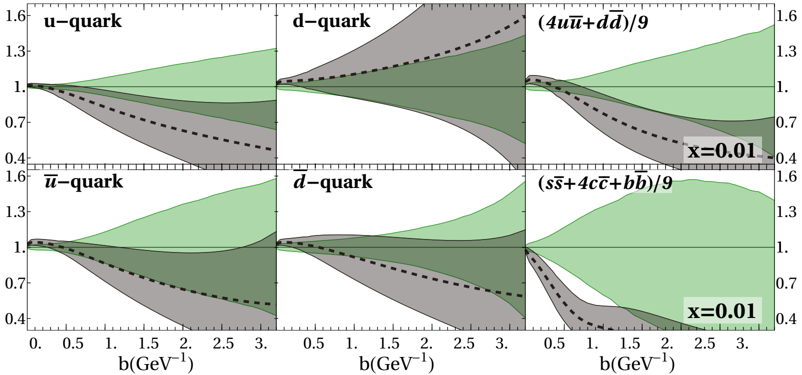
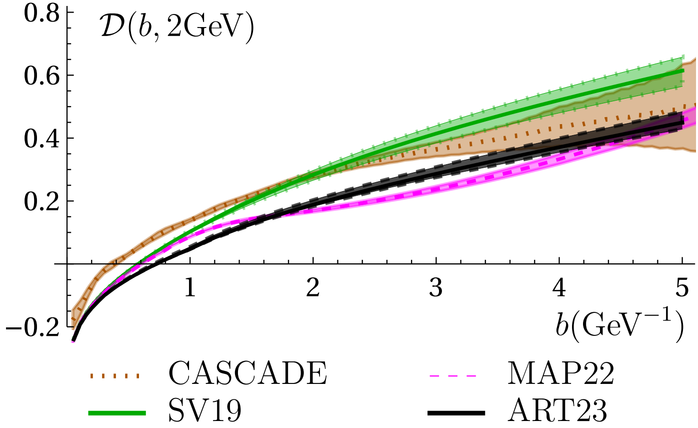


# uncertainty Bands relative to central value



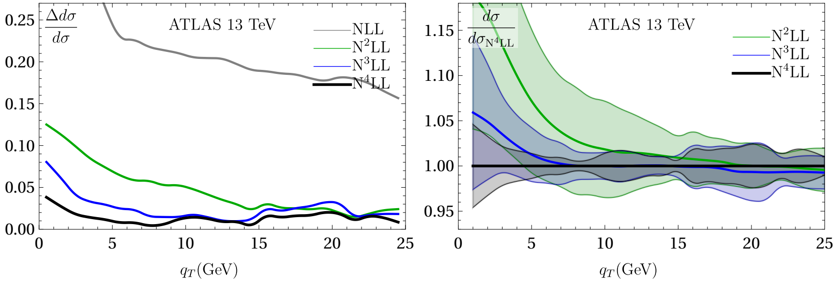

- MSHT20 extraction
- NNPDF3.1 extraction

# Collins-Soper kernel




CS Kernels in comparison

# Scale variation




Variation of the 3 scales $\mu, \mu^*, \mu_{OPE}$ 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

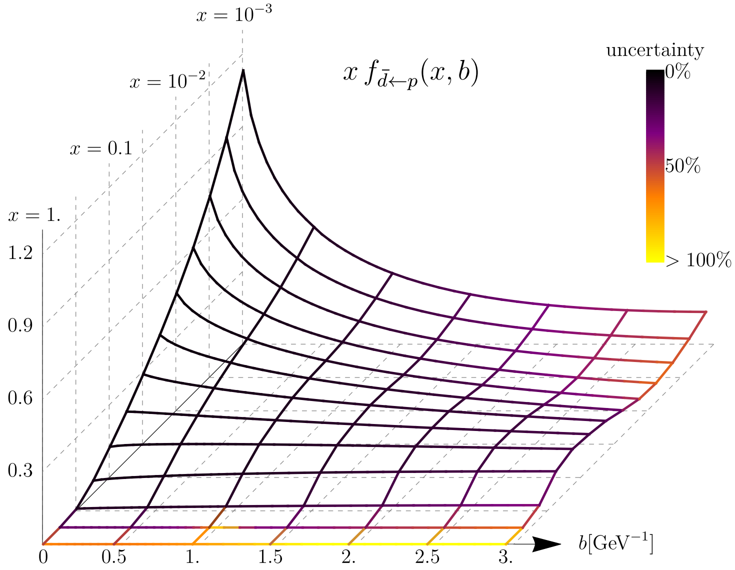
# Recapitulation & Outlook

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

Outlook:

- Upcoming: DY+SIDIS fit
- Impact Studies for EIC

# $d$ TMDPDF vs. x and b



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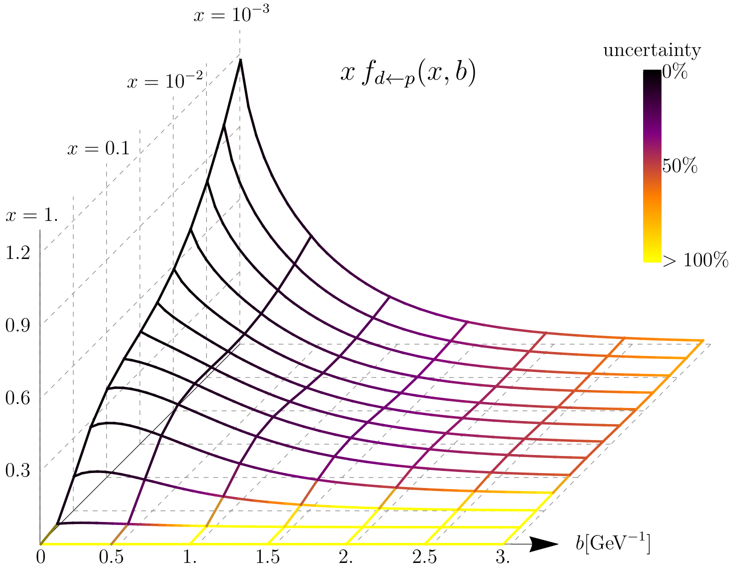
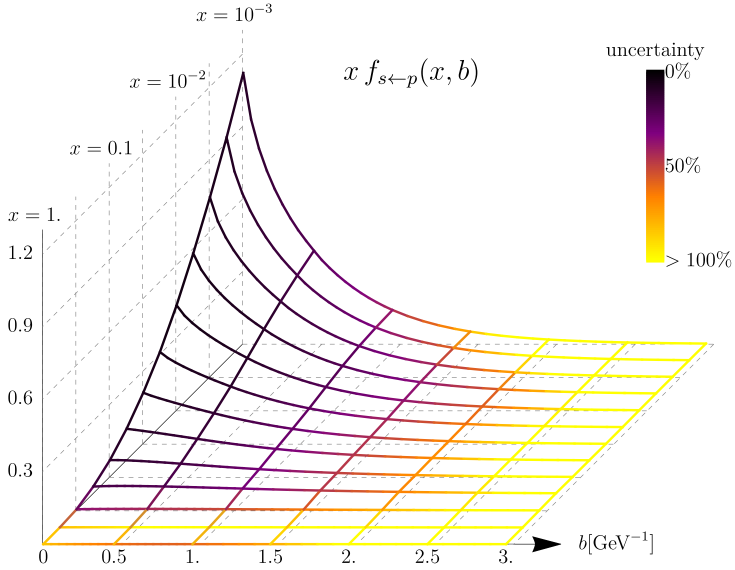


# sea TMDPDF vs. x and b



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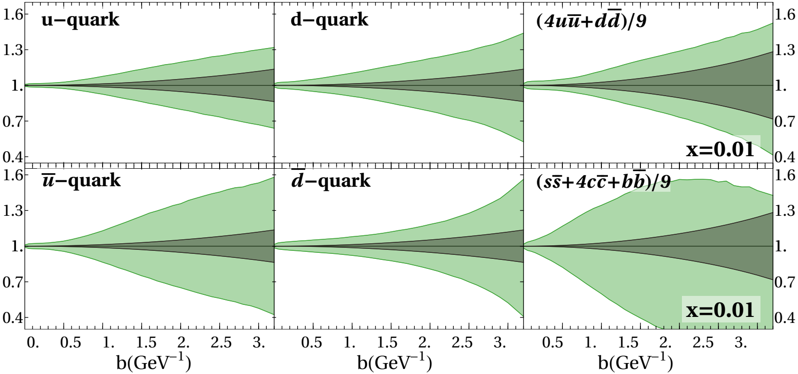


- ART23 (us)
- SV19

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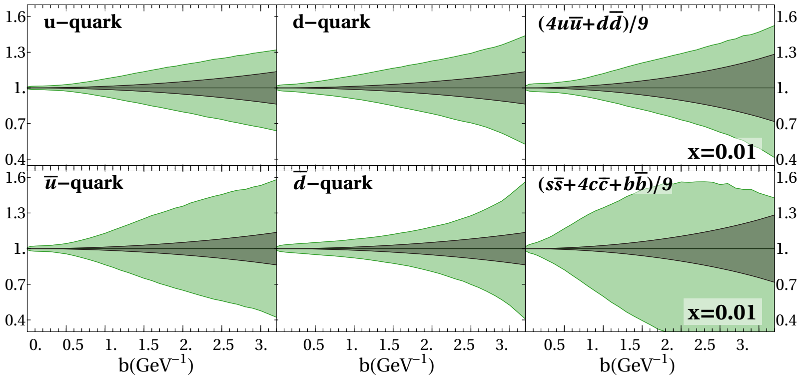


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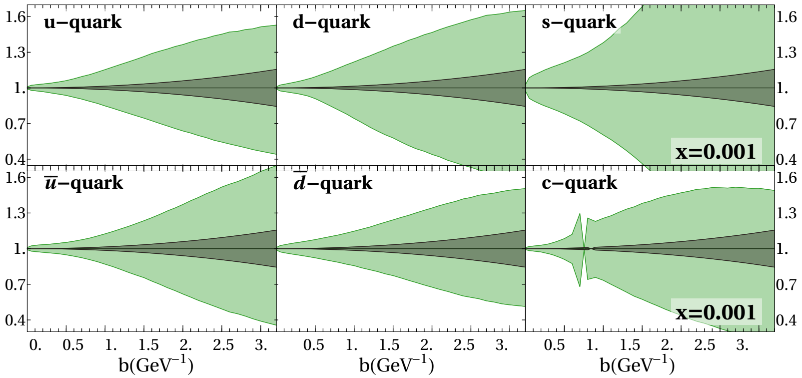


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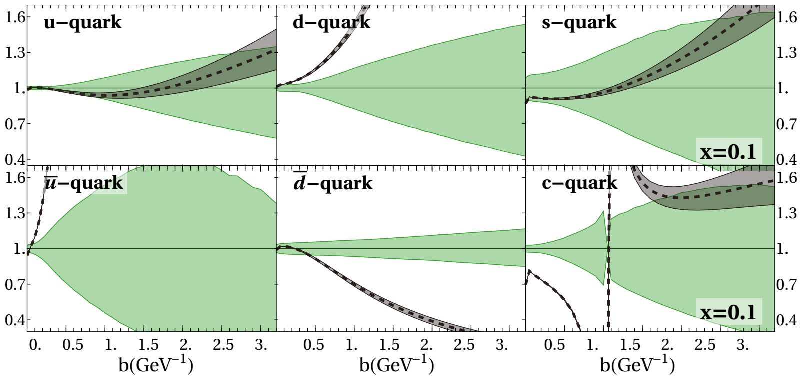


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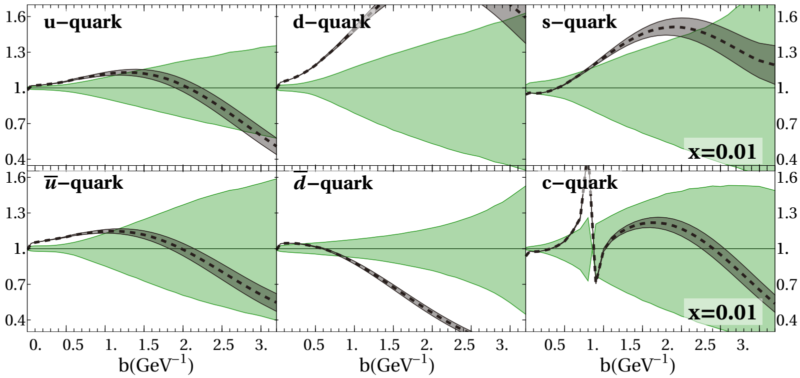


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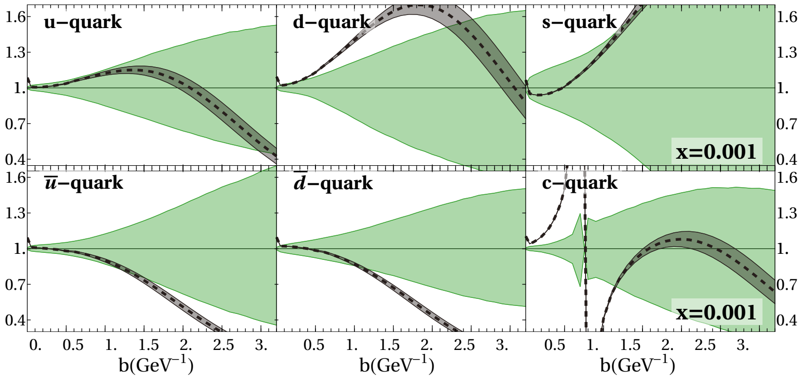


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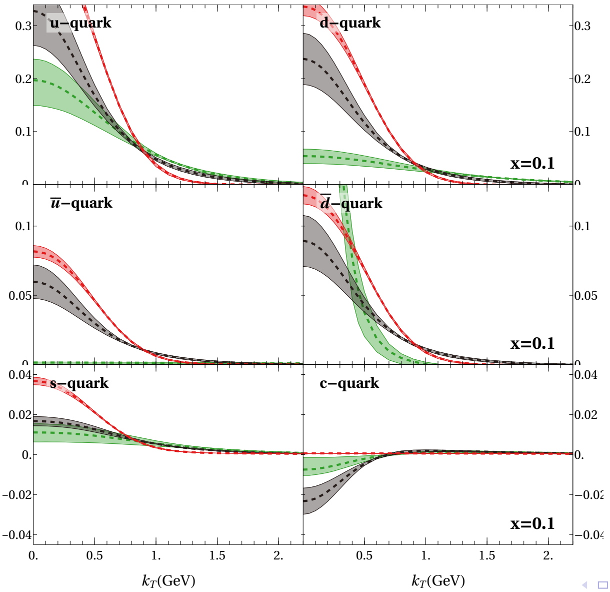
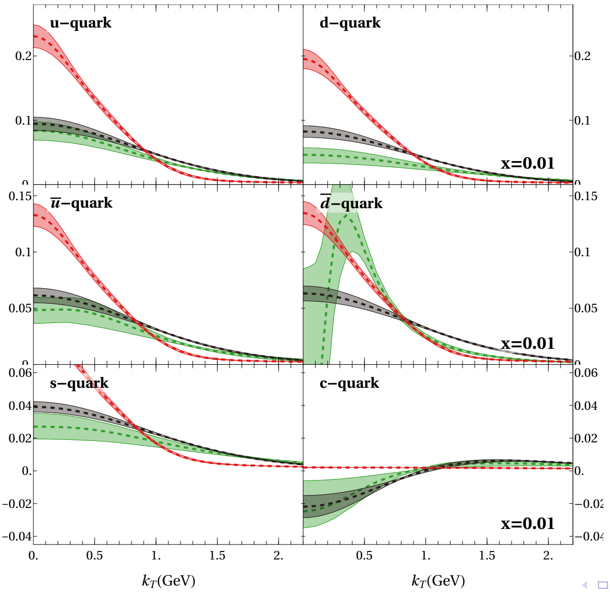


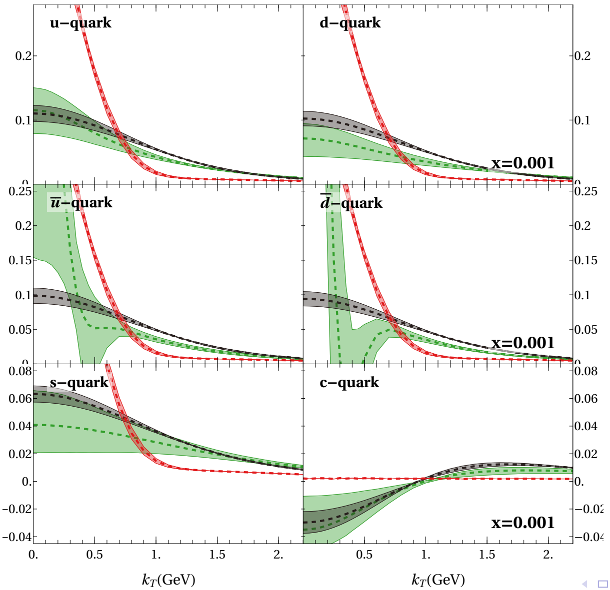

- MAP
  MMHT14
- ART23 (us)
  MSHT20
- SV19
  NNPDF31

# TMDPDF distributions visualized



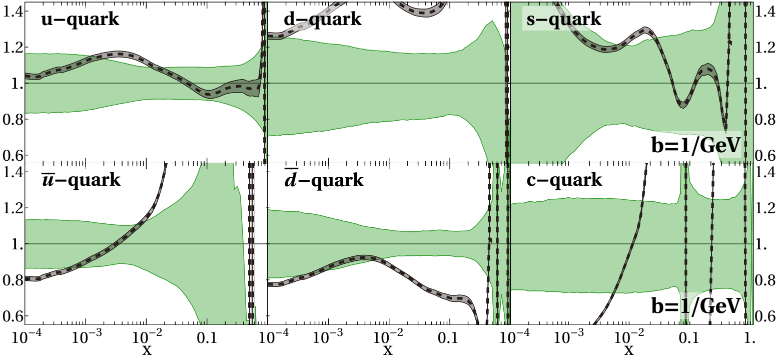

- MAP
  MMHT14
- ART23 (us)
  MSHT20
- SV19
  NNPDF31

# TMDPDF distributions visualized



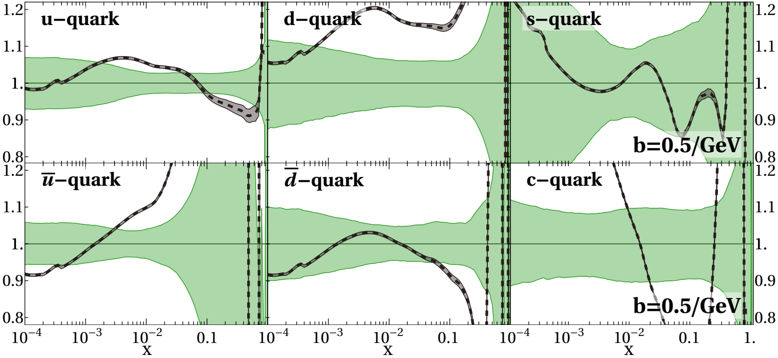

- MAP
  MMHT14
- ART23 (us)
  MSHT20
- SV19
  NNPDF31

# uncertainty Bands relative to central value



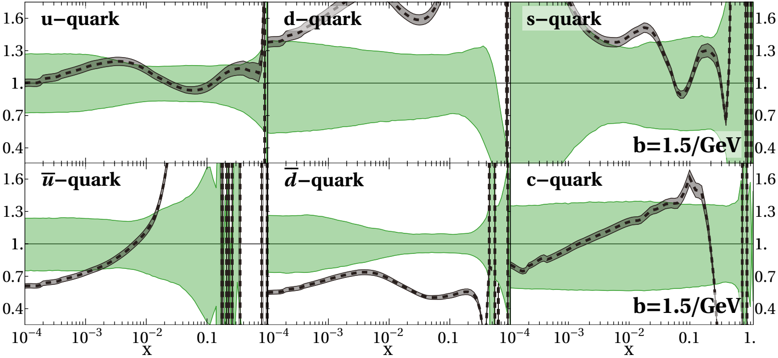

- ART23 (us)
- SV19

# uncertainty Bands relative to central value



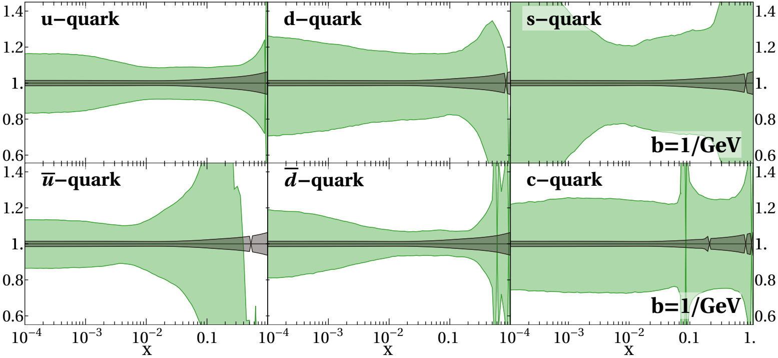

- ART23 (us)
- SV19

# uncertainty Bands relative to central value



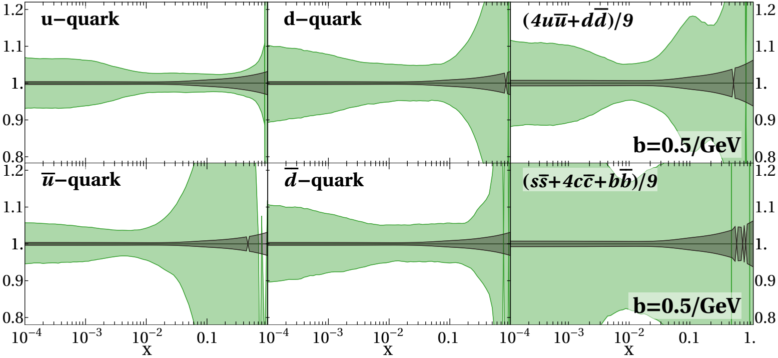

- ART23 (us)
- SV19

# uncertainty Bands relative to central value



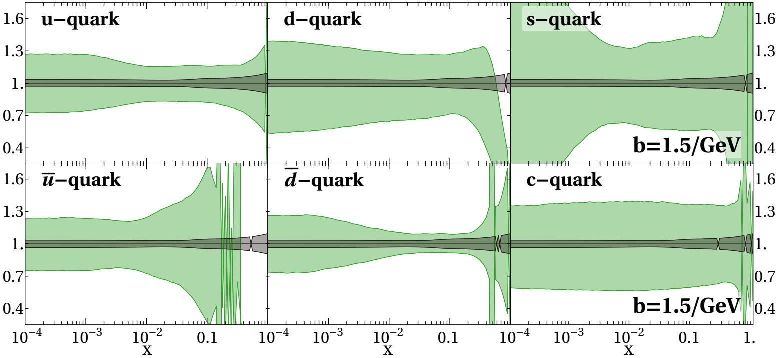

- ART23 (us)
- SV19

# uncertainty Bands relative to central value



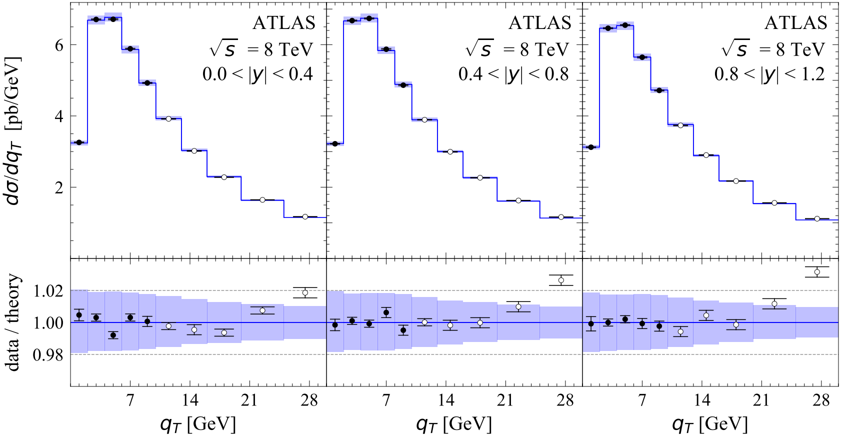

- ART23 (us)
- SV19

# uncertainty Bands relative to central value



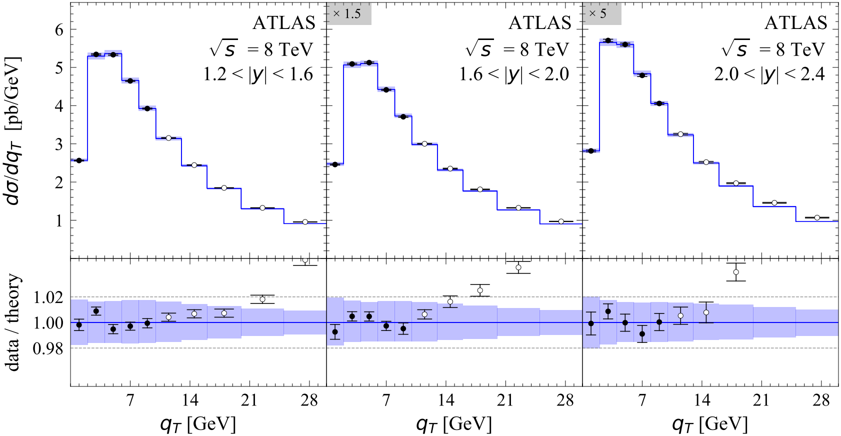

- ART23 (us)
- SV19

# ATLAS



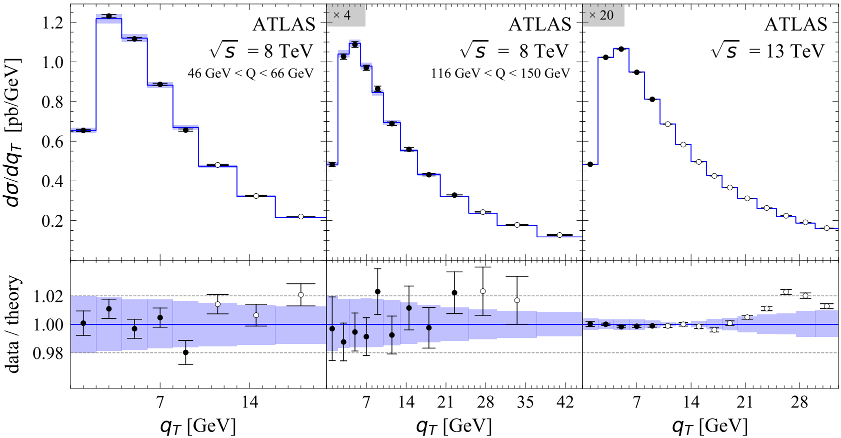
ATLAS
$\sqrt{s}$ = 8 TeV
0.0 < |y| < 0.4
ATLAS
$\sqrt{s}$ = 8 TeV
0.4 < |y| < 0.8
ATLAS
$\sqrt{s}$ = 8 TeV
0.8 < |y| < 1.2
$d\sigma/dq_T$ [pb/GeV]
data / theory
6
4
2
1.02
1.00
0.98
7
14
21
28
$q_T$ [GeV]

# ATLAS



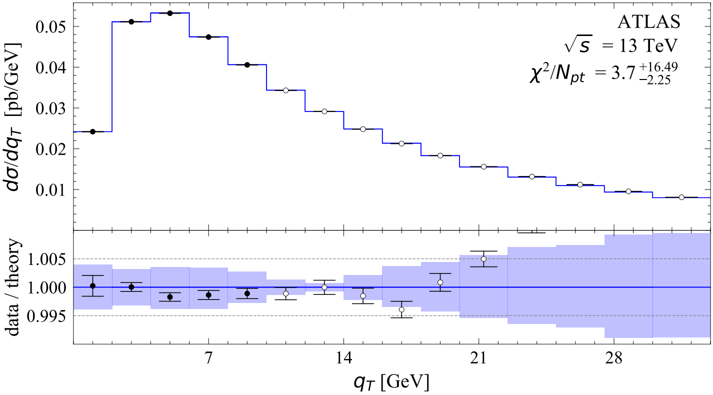
ATLAS
$\sqrt{s}$ = 8 TeV
1.2 < |y| < 1.6
× 1.5
ATLAS
$\sqrt{s}$ = 8 TeV
1.6 < |y| < 2.0
× 5
ATLAS
$\sqrt{s}$ = 8 TeV
2.0 < |y| < 2.4
$d\sigma/dq_T$ [pb/GeV]
data / theory
$q_T$ [GeV]

# ATLAS



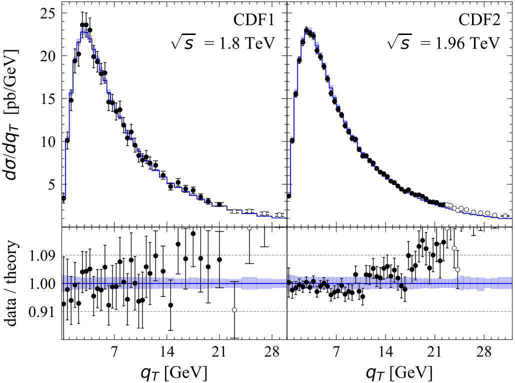
ATLAS
$\sqrt{s}$ = 8 TeV
46 GeV < Q < 66 GeV
× 4
ATLAS
$\sqrt{s}$ = 8 TeV
116 GeV < Q < 150 GeV
× 20
ATLAS
$\sqrt{s}$ = 13 TeV
$d\sigma/dq_T$ [pb/GeV]
data / theory
$q_T$ [GeV]
$q_T$ [GeV]
$q_T$ [GeV]

# ATLAS



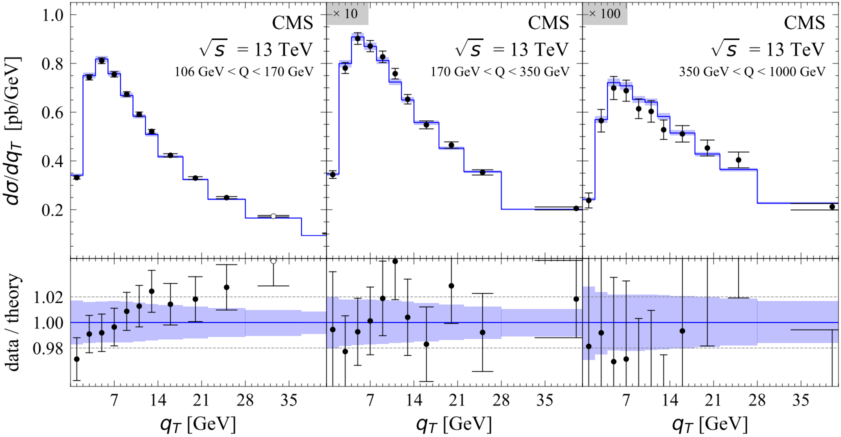
ATLAS
$\sqrt{s}$ = 13 TeV
$\chi^2/N_{pt} = 3.7^{+16.49}_{-2.25}$
$d\sigma/dq_T$ [pb/GeV]
0.05
0.04
0.03
0.02
0.01
data / theory
1.005
1.000
0.995
7
14
21
28
$q_T$ [GeV]

# CDF

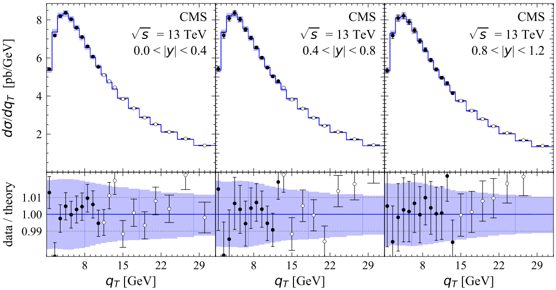


CDF1
$\sqrt{s}$ = 1.8 TeV
CDF2
$\sqrt{s}$ = 1.96 TeV
$d\sigma/dq_T$ [pb/GeV]
data / theory
$q_T$ [GeV]
$q_T$ [GeV]

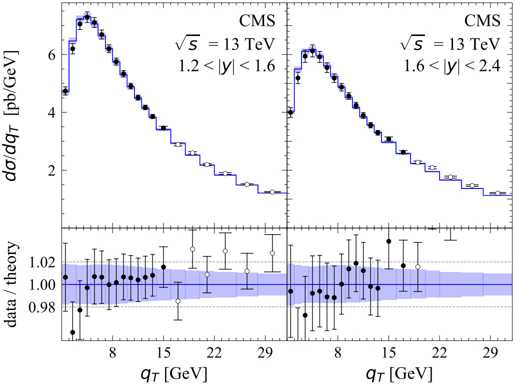
# CMS


CMS
$\sqrt{s}$ = 13 TeV
106 GeV < Q < 170 GeV
× 10
170 GeV < Q < 350 GeV
× 100
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

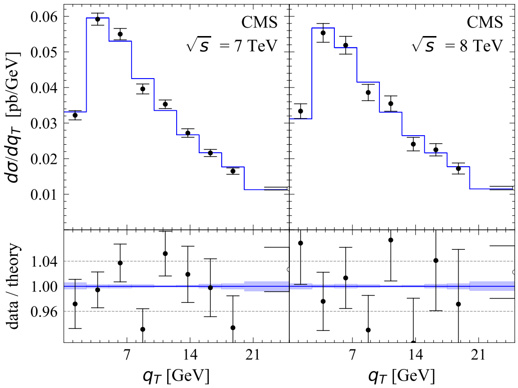

CMS
$\sqrt{s}$ = 13 TeV
0.0 < |y| < 0.4
0.4 < |y| < 0.8
0.8 < |y| < 1.2
$d\sigma/dq_T$ [pb/GeV]
data / theory
$q_T$ [GeV]
2
4
6
8
1.01
1.00
0.99
8
15
22
29

# CMS

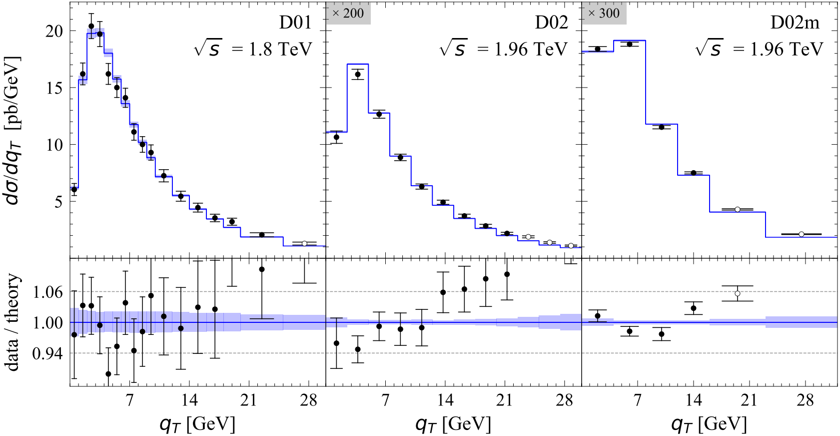


CMS
$\sqrt{s}$ = 13 TeV
1.2 < |y| < 1.6
CMS
$\sqrt{s}$ = 13 TeV
1.6 < |y| < 2.4
$d\sigma/dq_T$ [pb/GeV]
data / theory
$q_T$ [GeV]
$q_T$ [GeV]

# CMS

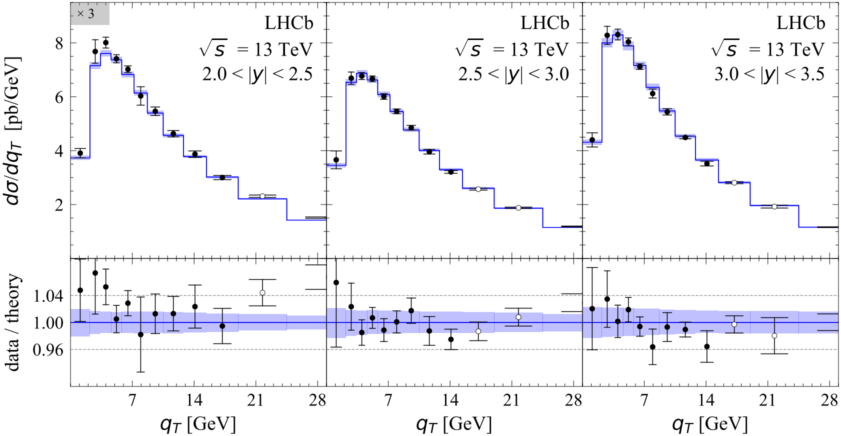

CMS
$\sqrt{s}$ = 7 TeV
CMS
$\sqrt{s}$ = 8 TeV
$d\sigma/dq_T$ [pb/GeV]
0.06
0.05
0.04
0.03
0.02
0.01
data / theory
1.04
1.00
0.96
7
14
21
$q_T$ [GeV]
$q_T$ [GeV]

# D0

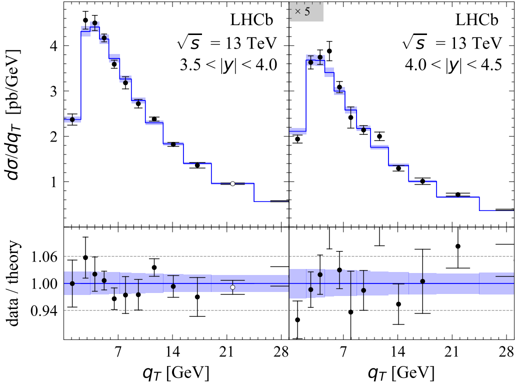


D01
$\sqrt{s}$ = 1.8 TeV
× 200
D02
$\sqrt{s}$ = 1.96 TeV
× 300
D02m
$\sqrt{s}$ = 1.96 TeV
$d\sigma/dq_T$ [pb/GeV]
data / theory
20
15
10
5
1.06
1.00
0.94
7
14
21
28
$q_T$ [GeV]

# LHCb

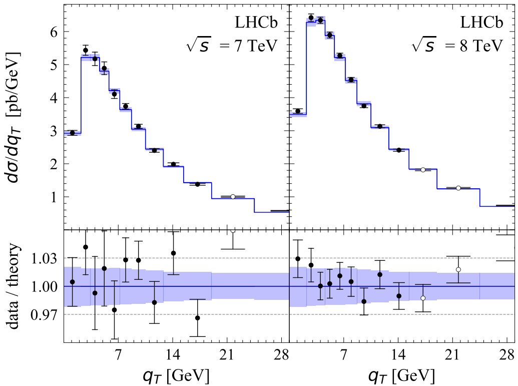

× 3
LHCb
$\sqrt{s}$ = 13 TeV
2.0 < |y| < 2.5
LHCb
$\sqrt{s}$ = 13 TeV
2.5 < |y| < 3.0
LHCb
$\sqrt{s}$ = 13 TeV
3.0 < |y| < 3.5
$d\sigma/dq_T$ [pb/GeV]
data / theory
$q_T$ [GeV]
2
4
6
8
1.04
1.00
0.96
7
14
21
28

# LHCb

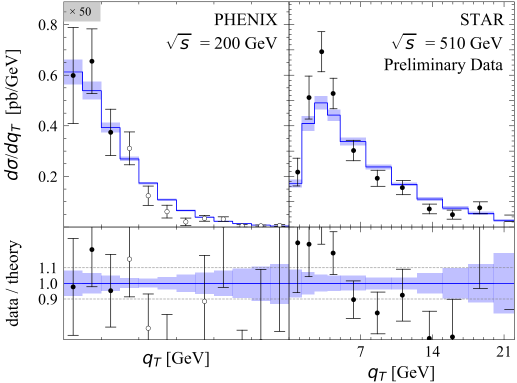


LHCb
$\sqrt{s}$ = 13 TeV
3.5 < |y| < 4.0
× 5
LHCb
$\sqrt{s}$ = 13 TeV
4.0 < |y| < 4.5
$d\sigma/dq_T$ [pb/GeV]
data / theory
1.06
1.00
0.94
1
2
3
4
7
14
21
28
$q_T$ [GeV]

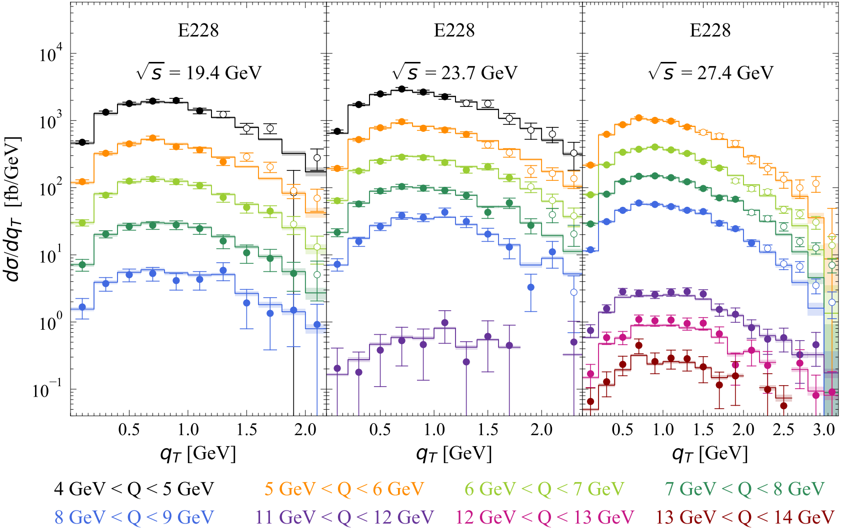
# LHCb


LHCb
$\sqrt{s}$ = 7 TeV
LHCb
$\sqrt{s}$ = 8 TeV
$d\sigma/dq_T$ [pb/GeV]
data / theory
6
5
4
3
2
1
1.03
1.00
0.97
7
14
21
28
$q_T$ [GeV]

# STAR and PHENIX

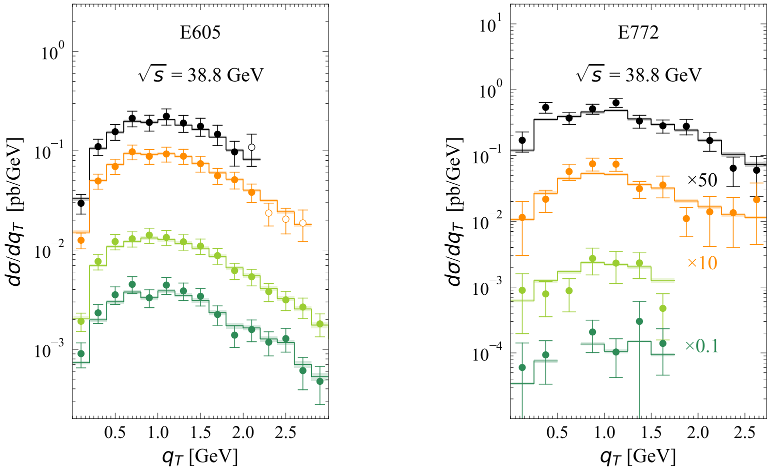


# E228



E228
$\sqrt{s}$ = 19.4 GeV
E228
$\sqrt{s}$ = 23.7 GeV
E228
$\sqrt{s}$ = 27.4 GeV
$d\sigma/dq_T$ [fb/GeV]
$10^4$
$10^3$
$10^2$
$10^1$
$10^0$
$10^{-1}$
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

11.5 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