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

ART23

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# Outline

# Technicalities and Theory

# 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 $\mu_{OPE} = 2\,\mathrm{GeV} + \frac{2\exp^{-\gamma_E}}{b}$

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

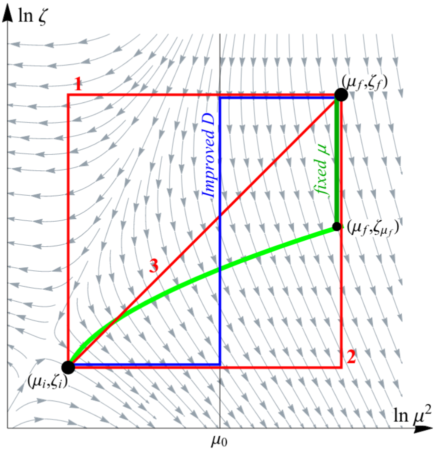
- $f \in \{u, \overline{u}, d, \overline{d}, sea\}$ $\rightarrow 2 \times 5$ independent parameters!
- $\lambda_{1,2}^f > 0$ imposed!

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

# 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 |
|---|---|---|---|---|---|---|
| $a_s^5$ $(\Gamma_4)$ | $a_s^4$ $(\gamma_4)$ | $a_s^5$ $(\beta_3)$ | $a_s^4$ $(d^{(4,0)})$ | $a_s^3$ $(C^{[3]}_{f\to f'})$ | $a_s^4$ | 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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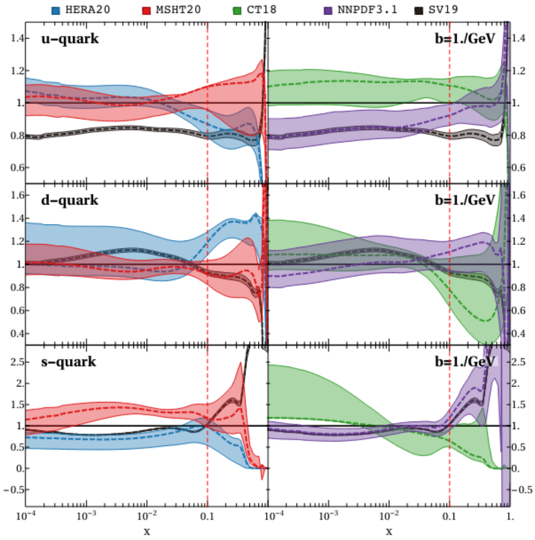
- adds 3 parameters for TMDPDF scale evolution
- 3 (NP CS kernel) $+\, 2 \times 5\ (u, \overline{u}, d, \overline{d}, sea)$ $= 13$ parameters to fit.

# collinear PDF choice

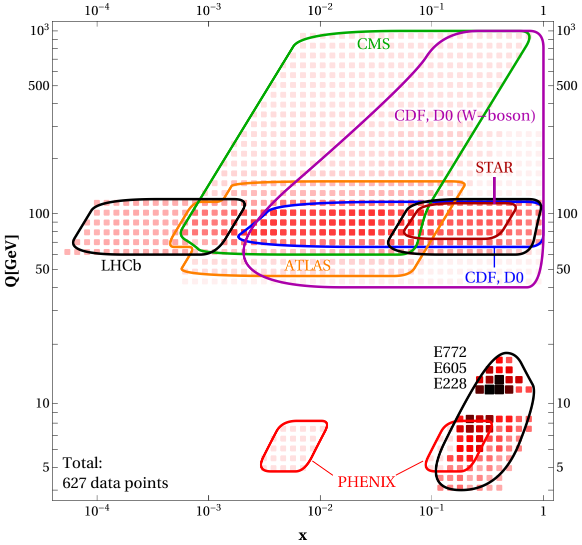



| Param. | MSHT20 | HERA2.0 | NNPDF3.1 | CT18 |
|---|---|---|---|---|
| $\kappa_1^u$ | 0.12 | 0.11 | 0.28 | 0.05 |
| $\kappa_2^u$ | 0.32 | 8.15 | 2.58 | 0.9 |

- 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



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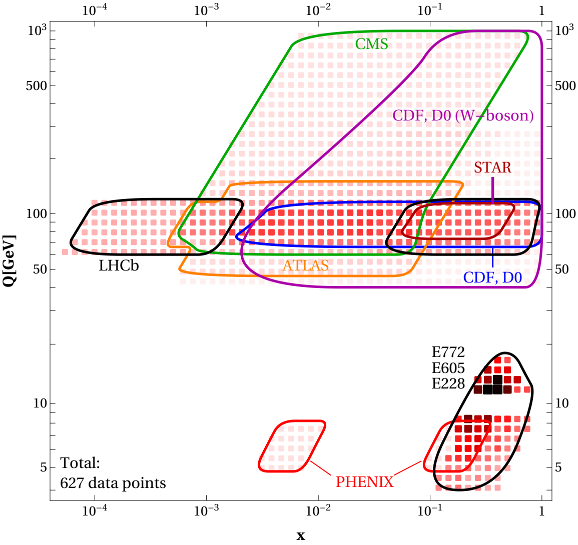


- high resolution scales up to 1 TeV

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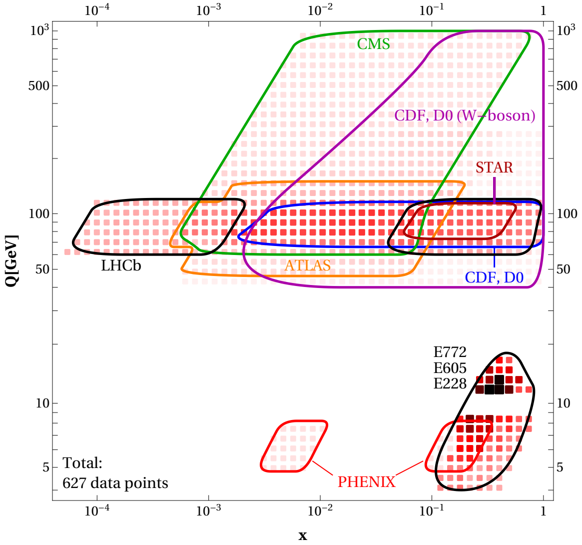


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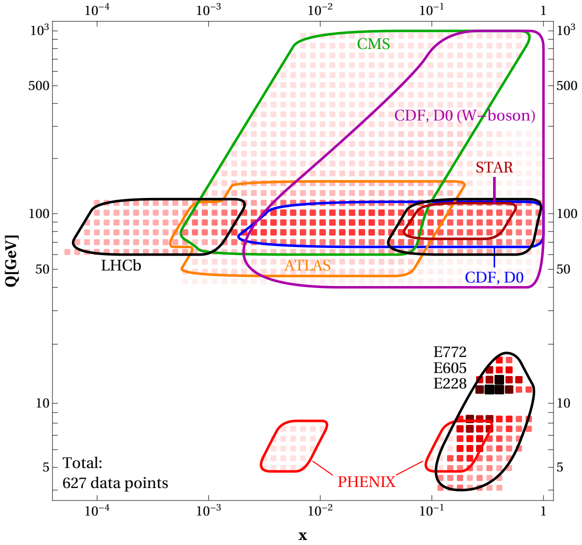


- high resolution scales up to 1 TeV
- including $W$ production in DY
- 627 datapoints included
  457 (SV19),
  484 (MAP)

# Additional cuts on the data

- $Q^\mu$: Hard process' total momentum
- $q_T$: Its transverse component
- $\sigma$: (uncorrelated.) Standard deviation (datapoint)

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**Criteria to include datapoint:**

- $\delta < 0.25$

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- $\sigma$: (uncorrelated.) Standard deviation (datapoint)
- $\delta^2 = \frac{q_T^2}{Q^2}$

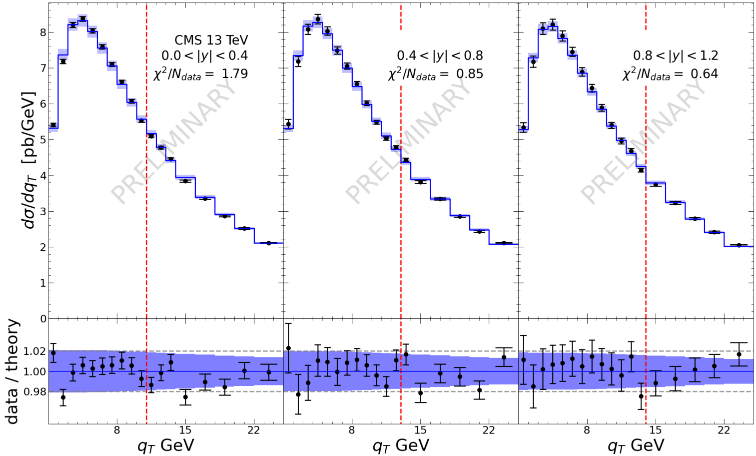
**Criteria to include datapoint:**

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

PRELIMINARY

# Results

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



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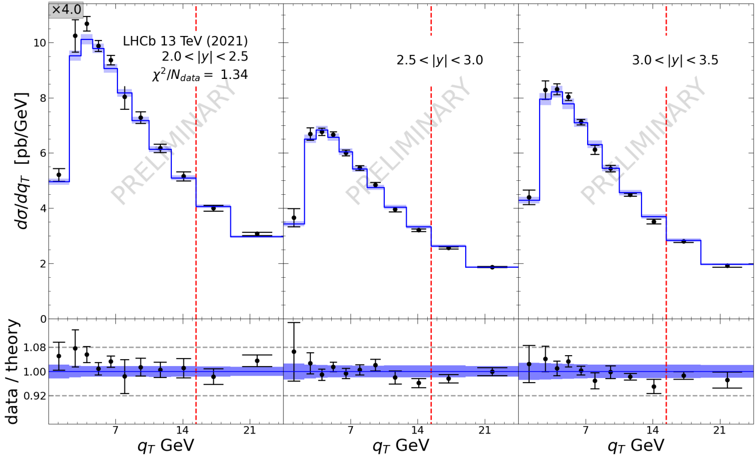
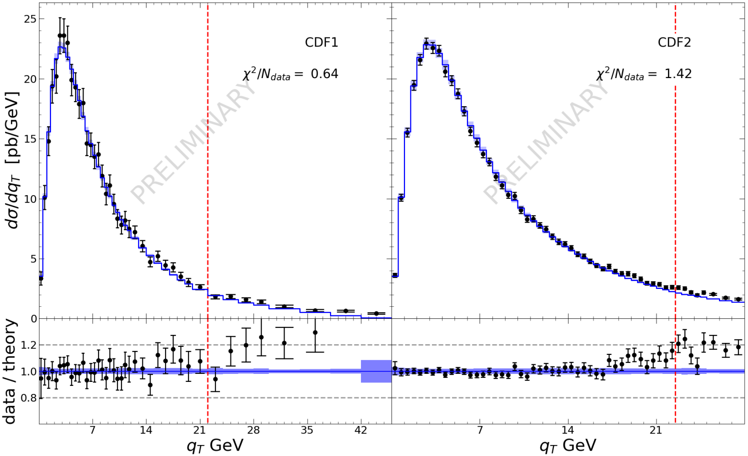
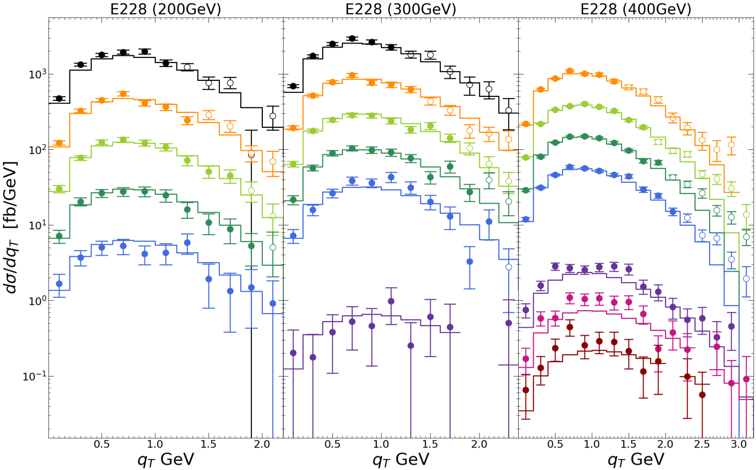


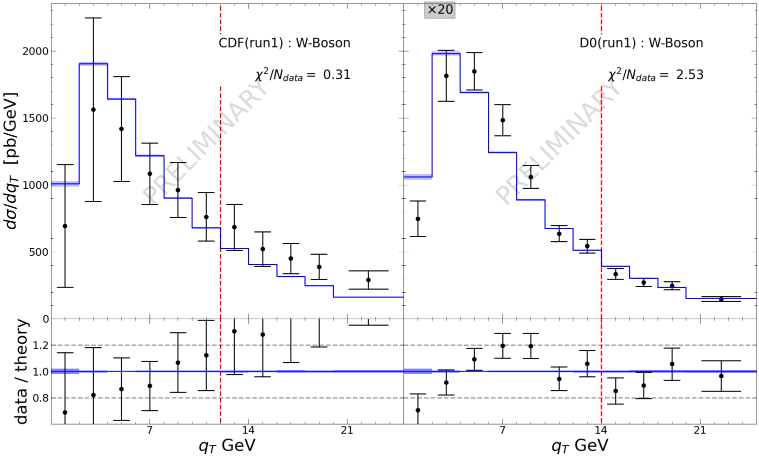
# Data at $\sqrt{s} = 1.8$ TeV



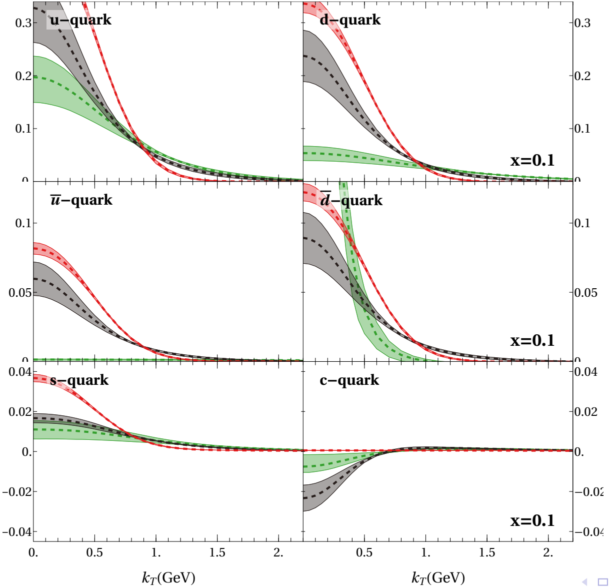
# Data at $\sqrt{s} = 19$, 23 and 27 GeV



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

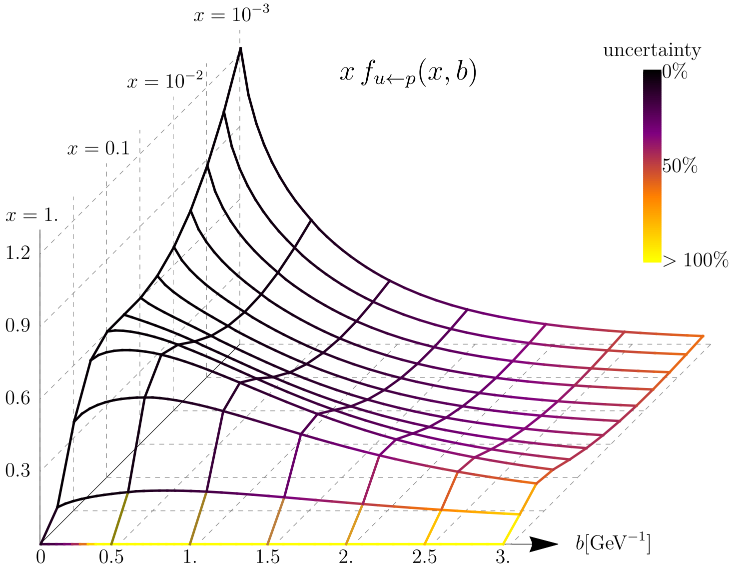


# TMDPDF distributions visualized

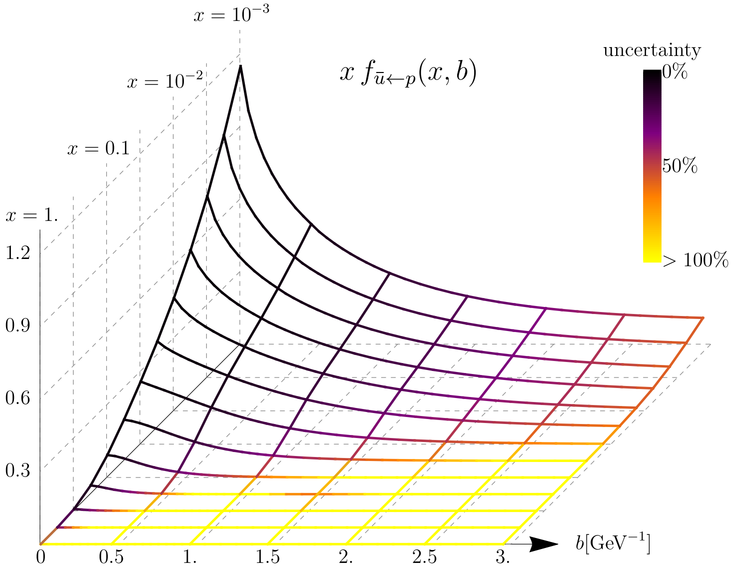



- MAP
  MMHT14
- ART23 (us)
  MSHT20
- SV19
  NNPDF3.1

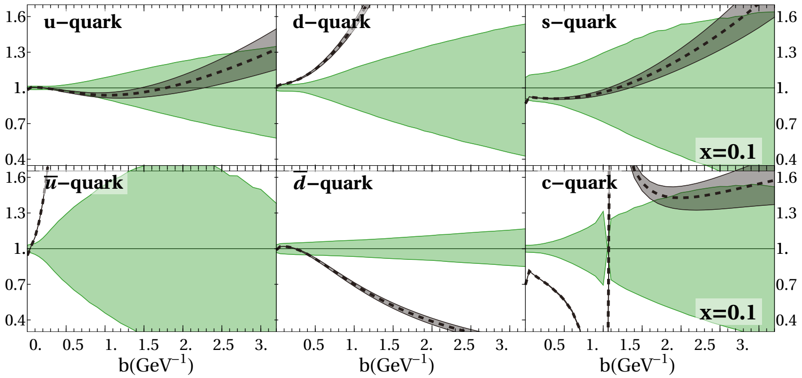
# $u$ TMDPDF vs. x and b



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



# uncertainty Bands relative to central value




- ART23 (us)
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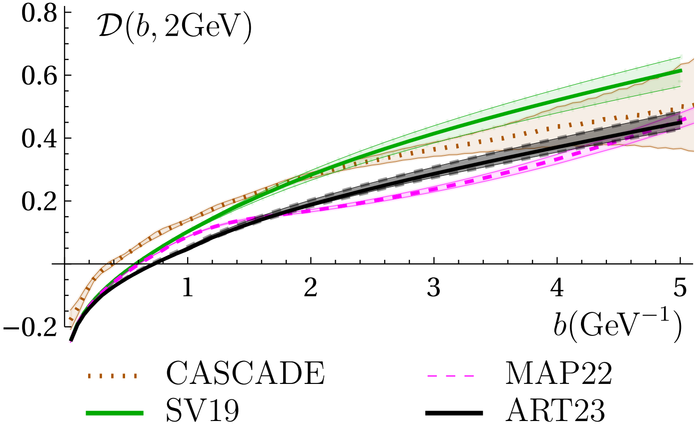
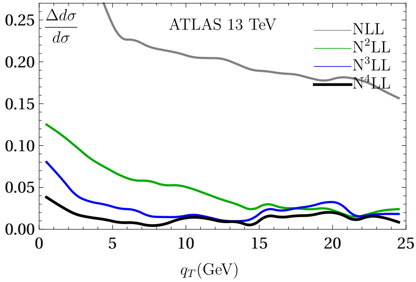
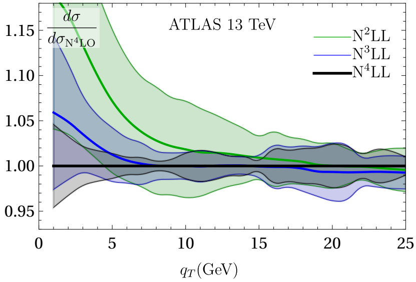
# Collins-Soper kernel




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

- We work on
  a **first of a kind** N4LO extraction of TMDPDFs

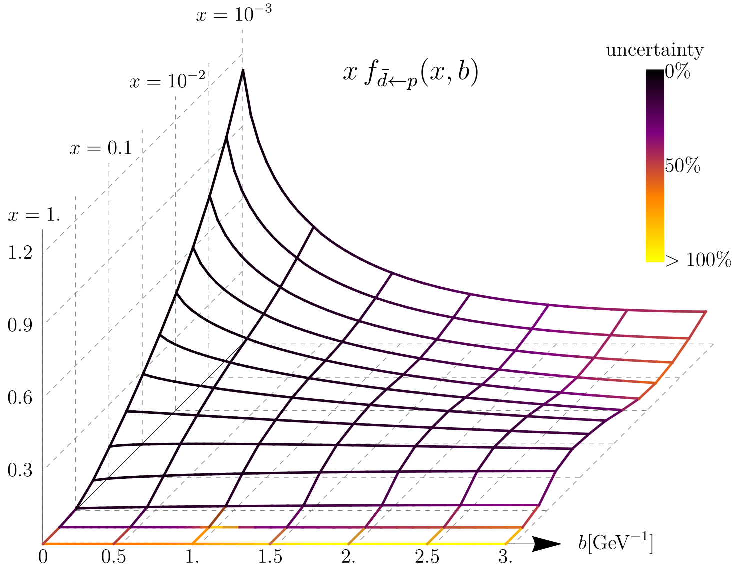
- overall good prescription of data

Outlook:

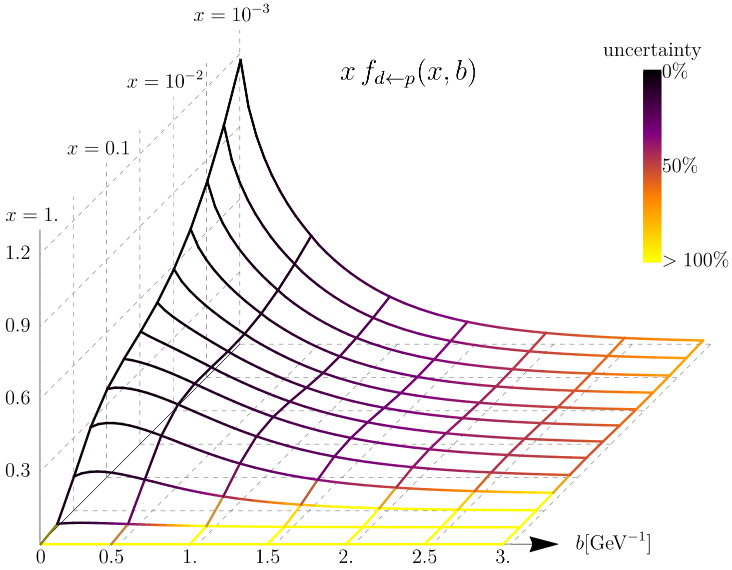
- Upcoming: DY+SIDIS fit

- Impact Studies for EIC

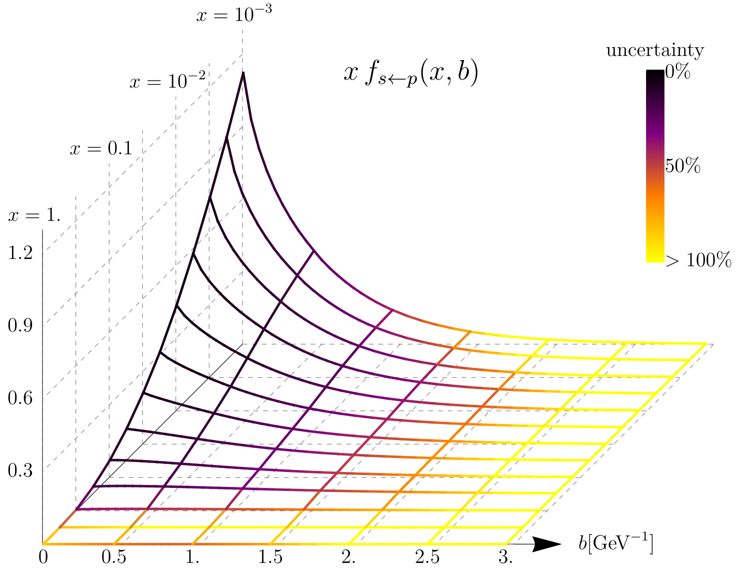
# $d$ TMDPDF vs. x and b



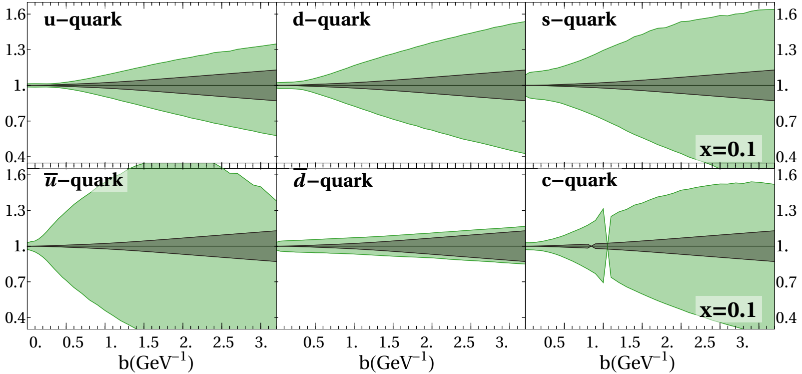
# $\overline{d}$ TMDPDF vs. x and b



# sea TMDPDF vs. x and b



# uncertainty Bands relative to central value




- ART23 (us)
- SV19

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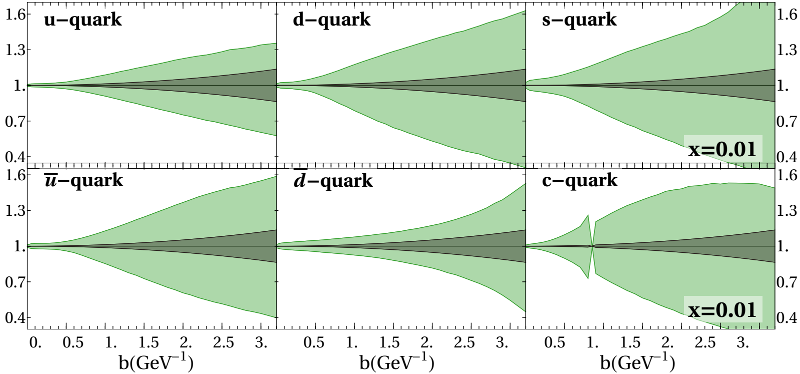


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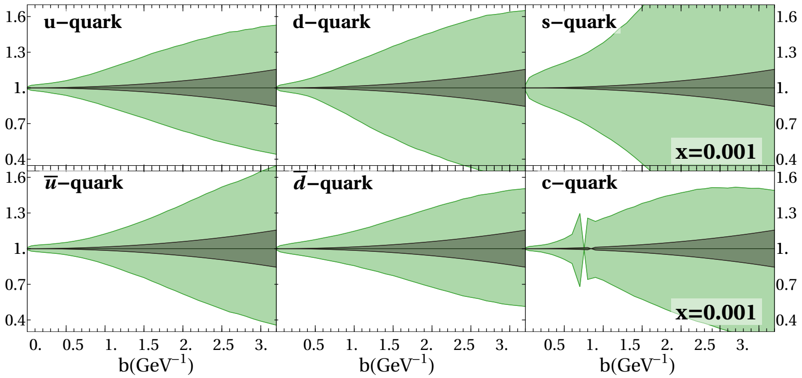


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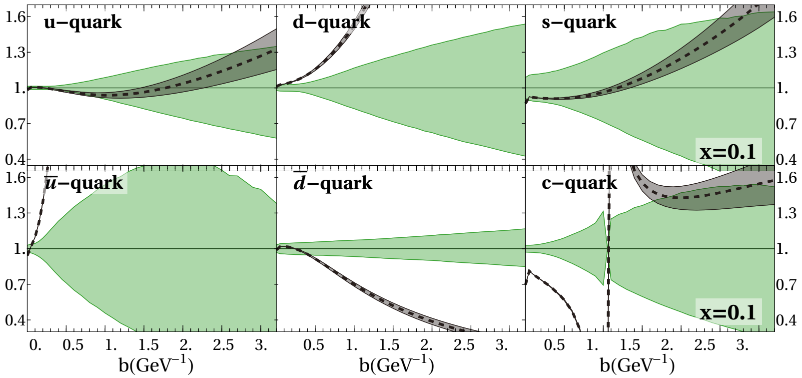


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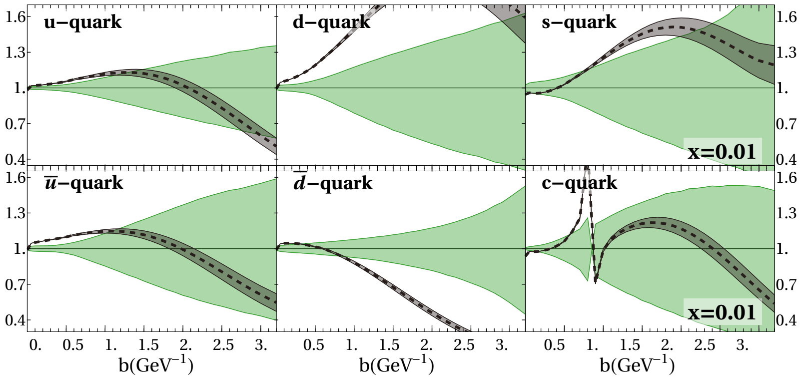


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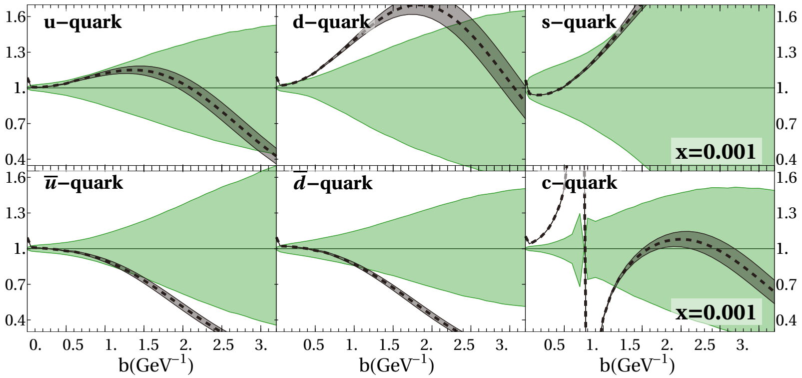


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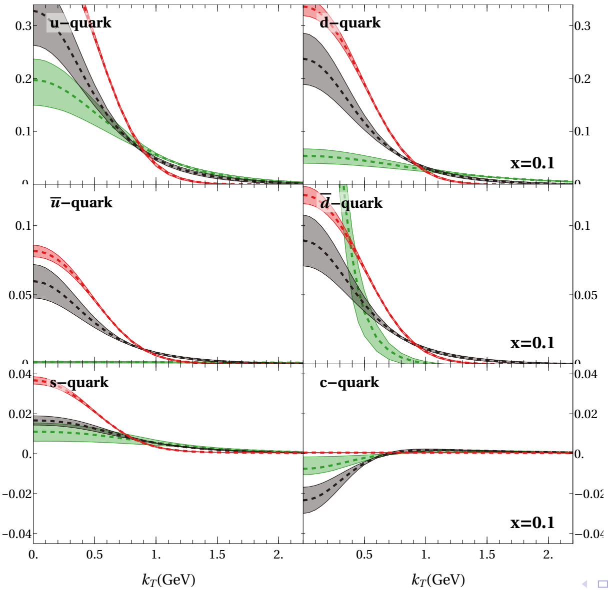


- MAP MMHT14
- ART23 (us) MSHT20
- SV19 NNPDF31

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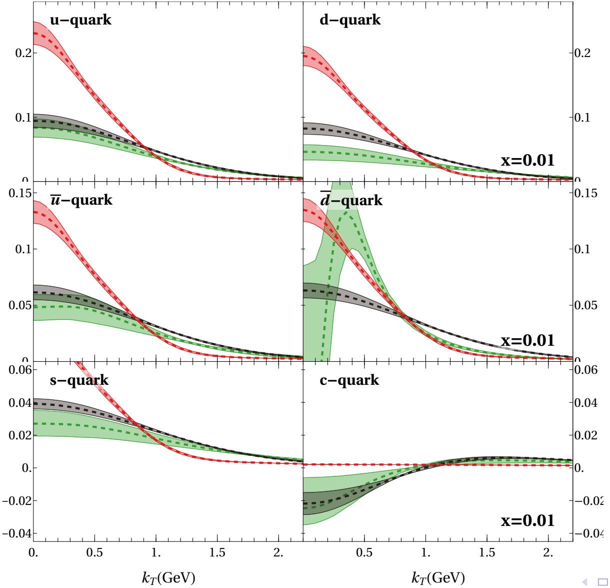


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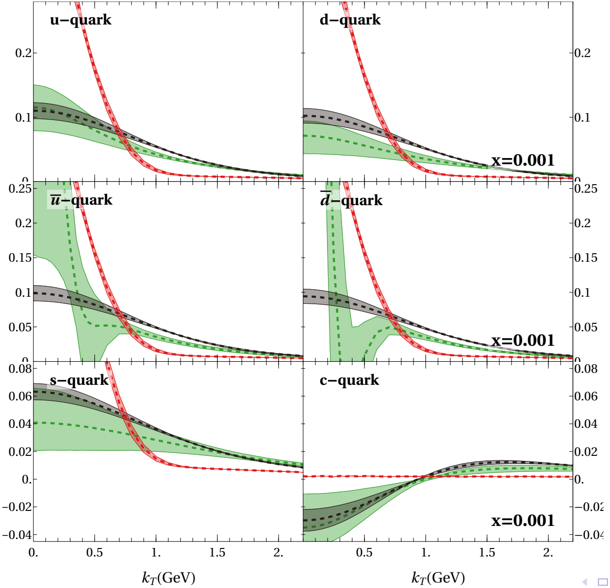


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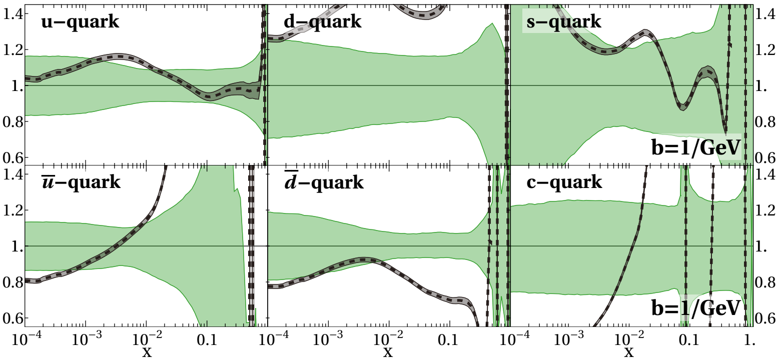


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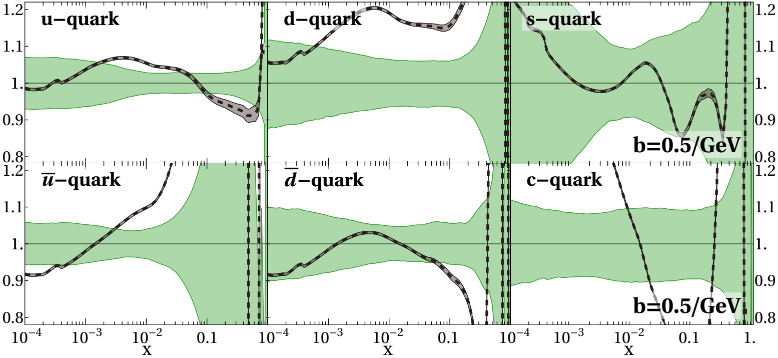


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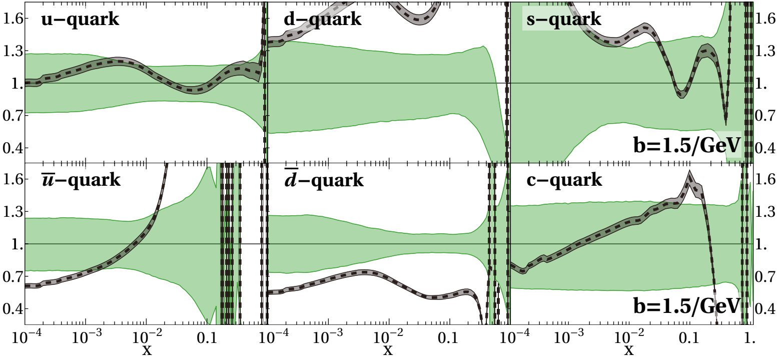


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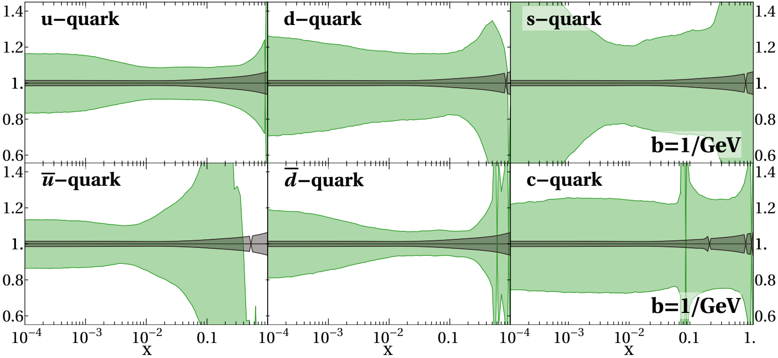


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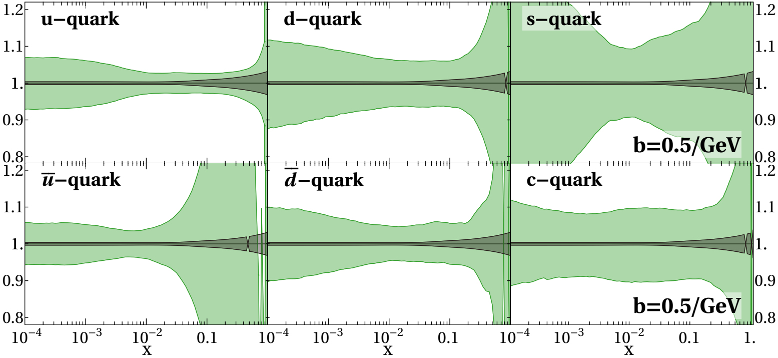


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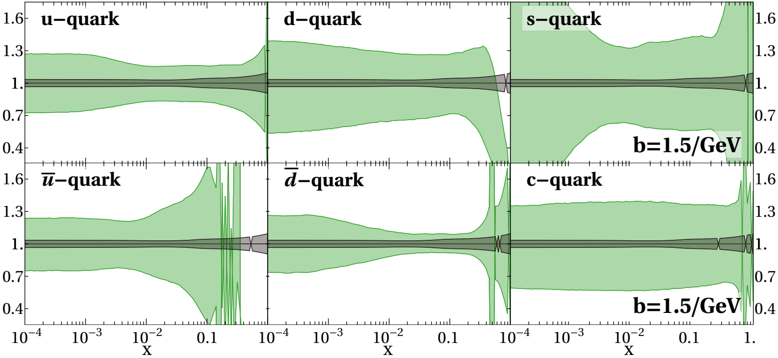
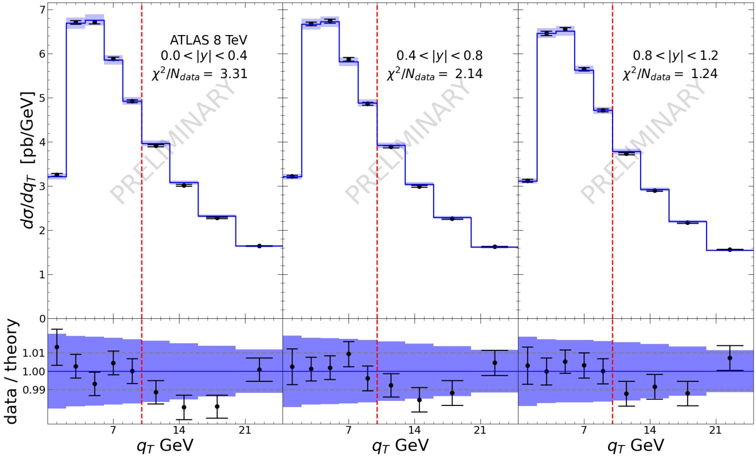


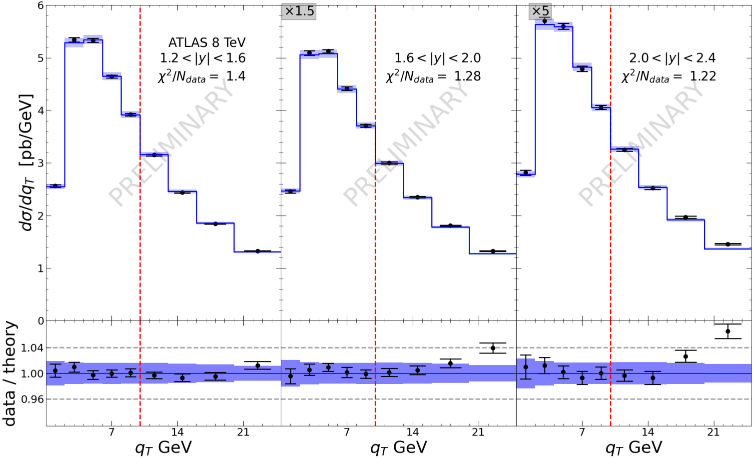

- ART23 (us)
- SV19

# ATLAS

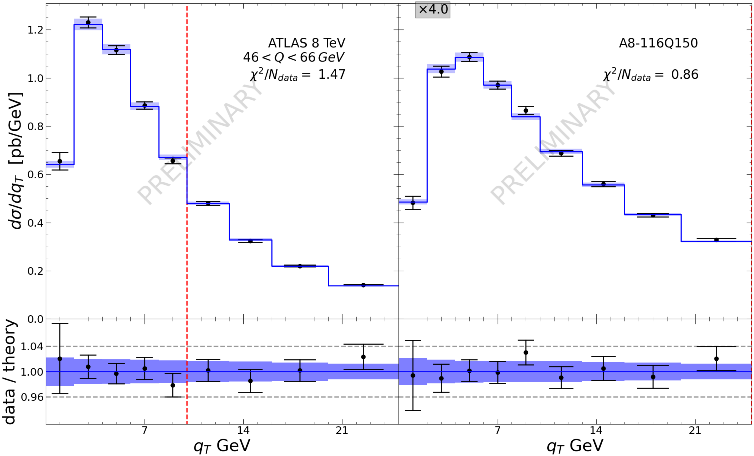


ATLAS 8 TeV
$0.0 < |y| < 0.4$
$\chi^2/N_{data} = 3.31$
$0.4 < |y| < 0.8$
$\chi^2/N_{data} = 2.14$
$0.8 < |y| < 1.2$
$\chi^2/N_{data} = 1.24$
PRELIMINARY
$d\sigma/dq_T$ [pb/GeV]
data / theory
$q_T$ GeV

# ATLAS

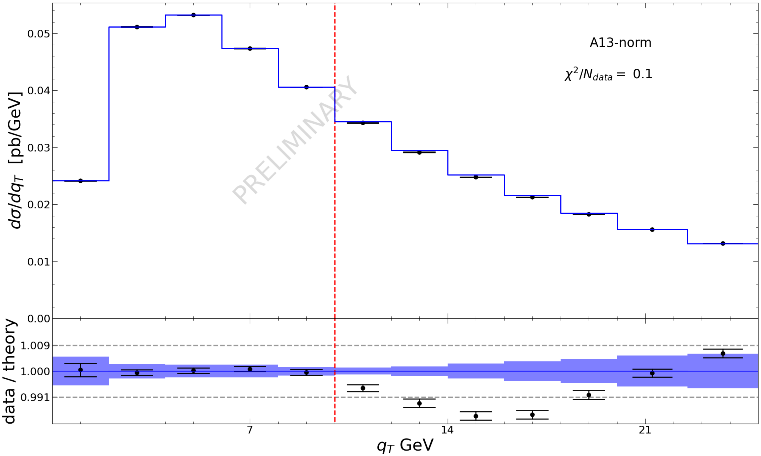

×1.5
×5
ATLAS 8 TeV
$1.2 < |y| < 1.6$
$\chi^2/N_{data} = 1.4$
$1.6 < |y| < 2.0$
$\chi^2/N_{data} = 1.28$
$2.0 < |y| < 2.4$
$\chi^2/N_{data} = 1.22$
PRELIMINARY
$d\sigma/dq_T$ [pb/GeV]
data / theory
$q_T$ GeV
0
1
2
3
4
5
6
1.04
1.00
0.96
7
14
21

# ATLAS



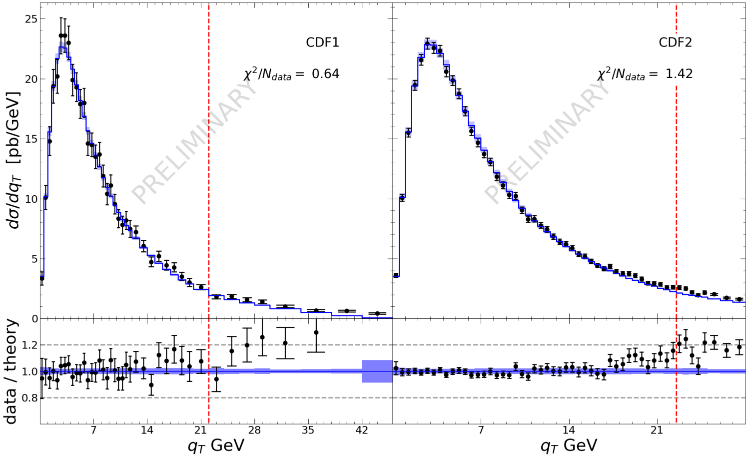
ATLAS 8 TeV
$46 < Q < 66\,GeV$
$\chi^2/N_{data} = 1.47$
×4.0
A8-116Q150
$\chi^2/N_{data} = 0.86$
PRELIMINARY
PRELIMINARY
$d\sigma/dq_T$ [pb/GeV]
data / theory
$q_T$ GeV
$q_T$ GeV

# ATLAS



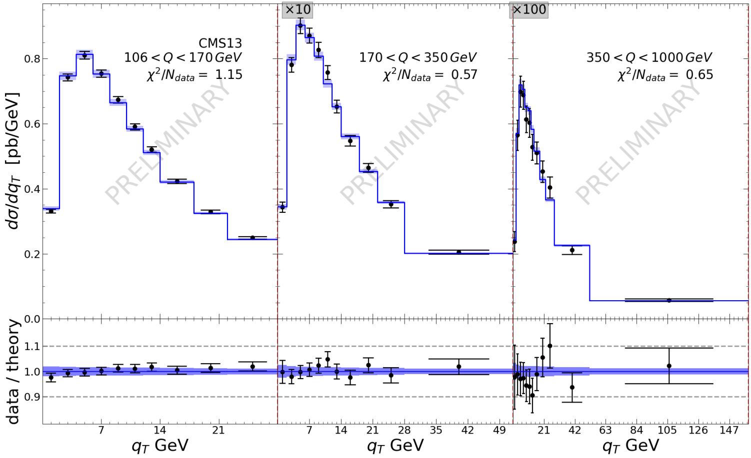
A13-norm
$\chi^2/N_{data} = 0.1$
PRELIMINARY
$d\sigma/dq_T$ [pb/GeV]
0.00
0.01
0.02
0.03
0.04
0.05
data / theory
1.009
1.000
0.991
7
14
21
$q_T$ GeV

# CDF



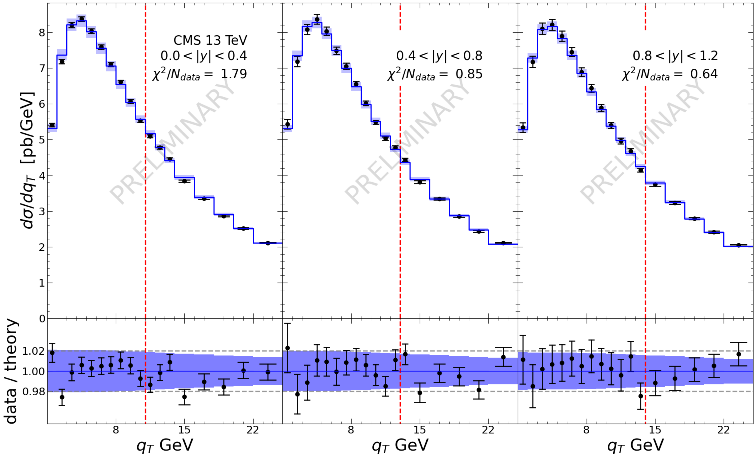
CDF1
$\chi^2/N_{data} = 0.64$
CDF2
$\chi^2/N_{data} = 1.42$
PRELIMINARY
$d\sigma/dq_T$ [pb/GeV]
data / theory
$q_T$ GeV

# CMS



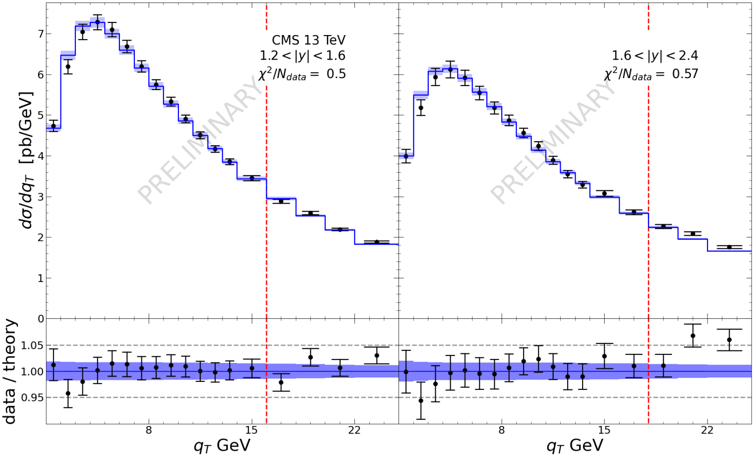
CMS13
106 < Q < 170 GeV
$\chi^2/N_{data}$ = 1.15
170 < Q < 350 GeV
$\chi^2/N_{data}$ = 0.57
350 < Q < 1000 GeV
$\chi^2/N_{data}$ = 0.65
×10
×100
PRELIMINARY
$d\sigma/dq_T$ [pb/GeV]
data / theory
$q_T$ GeV

# CMS



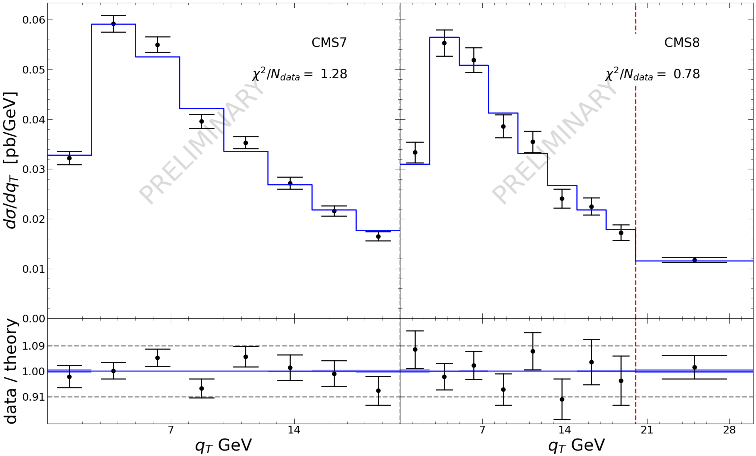
CMS 13 TeV
$0.0 < |y| < 0.4$
$\chi^2/N_{data} = 1.79$
$0.4 < |y| < 0.8$
$\chi^2/N_{data} = 0.85$
$0.8 < |y| < 1.2$
$\chi^2/N_{data} = 0.64$
PRELIMINARY
$d\sigma/dq_T$ [pb/GeV]
data / theory
$q_T$ GeV

# CMS



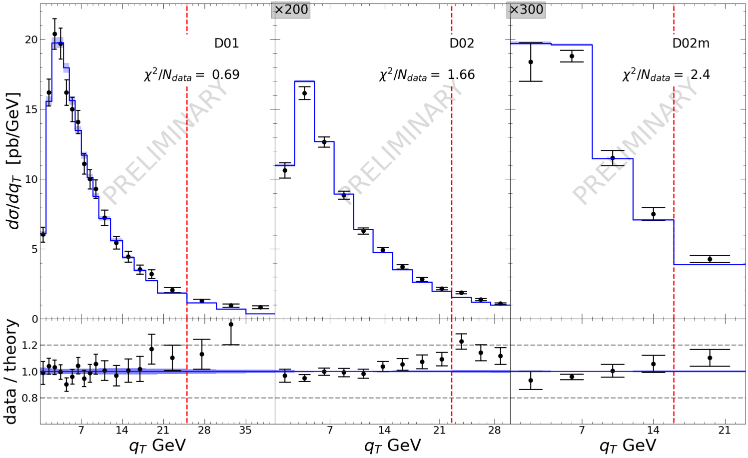
CMS 13 TeV
$1.2 < |y| < 1.6$
$\chi^2/N_{data} = 0.5$
$1.6 < |y| < 2.4$
$\chi^2/N_{data} = 0.57$
PRELIMINARY
PRELIMINARY
$d\sigma/dq_T$ [pb/GeV]
data / theory
$q_T$ GeV
$q_T$ GeV

# CMS



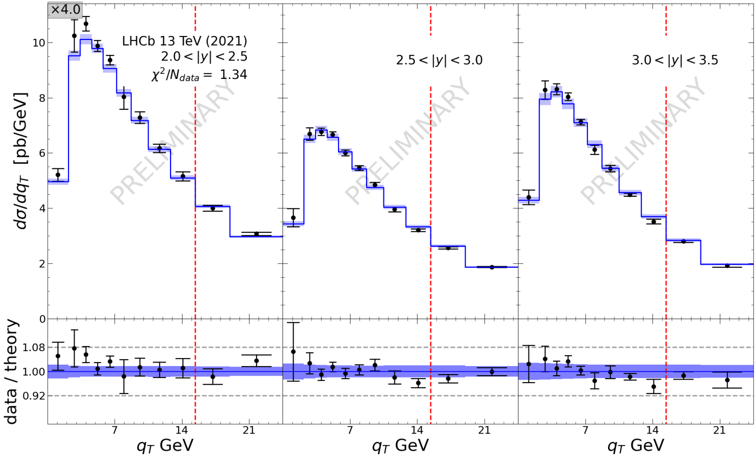
CMS7
$\chi^2/N_{data} =$ 1.28
CMS8
$\chi^2/N_{data} =$ 0.78
PRELIMINARY
PRELIMINARY
$d\sigma/dq_T$ [pb/GeV]
data / theory
$q_T$ GeV
$q_T$ GeV
0.06
0.05
0.04
0.03
0.02
0.01
0.00
1.09
1.00
0.91
7
14
7
14
21
28

# D0

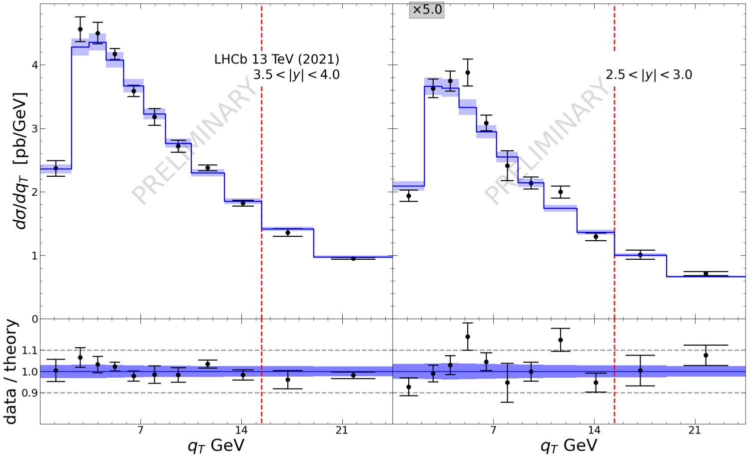


×200
×300
D01
$\chi^2/N_{data}$ = 0.69
D02
$\chi^2/N_{data}$ = 1.66
D02m
$\chi^2/N_{data}$ = 2.4
PRELIMINARY
PRELIMINARY
PRELIMINARY
$d\sigma/dq_T$ [pb/GeV]
data / theory
$q_T$ GeV
$q_T$ GeV
$q_T$ GeV

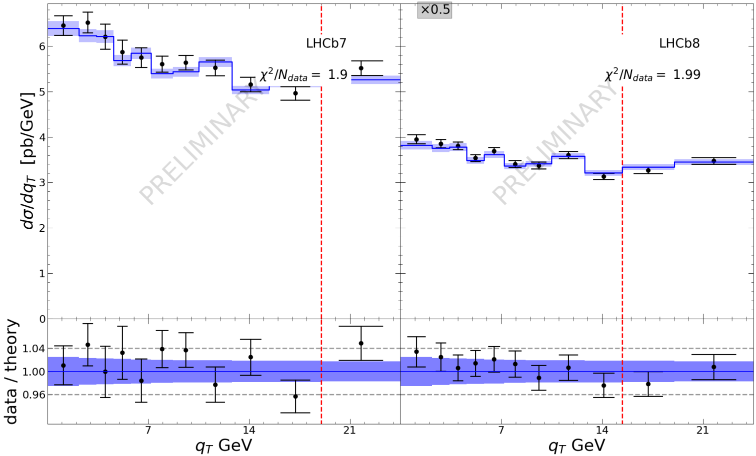
# LHCb


×4.0
LHCb 13 TeV (2021)
2.0 < |y| < 2.5
χ²/N_data = 1.34
2.5 < |y| < 3.0
3.0 < |y| < 3.5
PRELIMINARY
dσ/dq_T [pb/GeV]
data / theory
q_T GeV

# LHCb

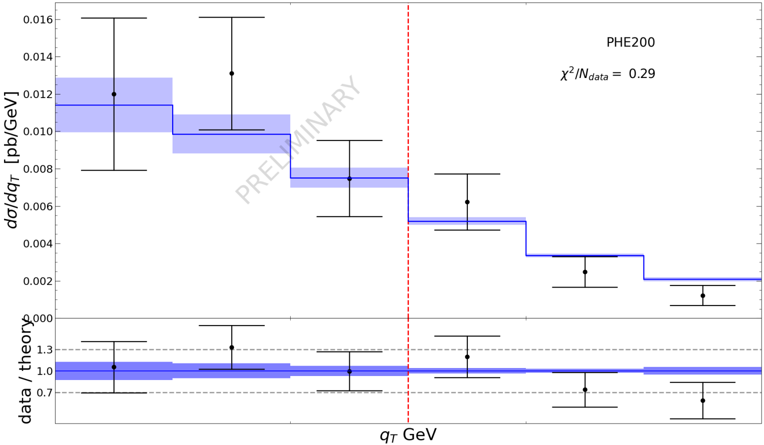

×5.0
LHCb 13 TeV (2021)
3.5 < |y| < 4.0
2.5 < |y| < 3.0
PRELIMINARY
PRELIMINARY
dσ/dq_T [pb/GeV]
data / theory
q_T GeV
q_T GeV

# LHCb

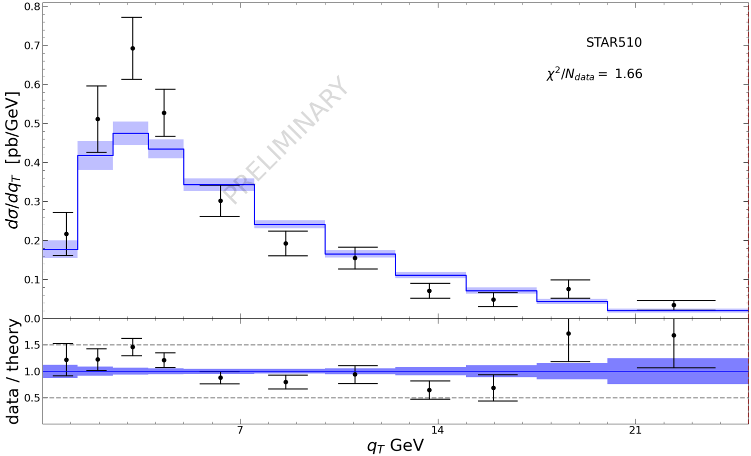


×0.5
LHCb7
$\chi^2/N_{data} = 1.9$
LHCb8
$\chi^2/N_{data} = 1.99$
PRELIMINARY
PRELIMINARY
$d\sigma/dq_T$ [pb/GeV]
data / theory
$q_T$ GeV
$q_T$ GeV

# PHENIX

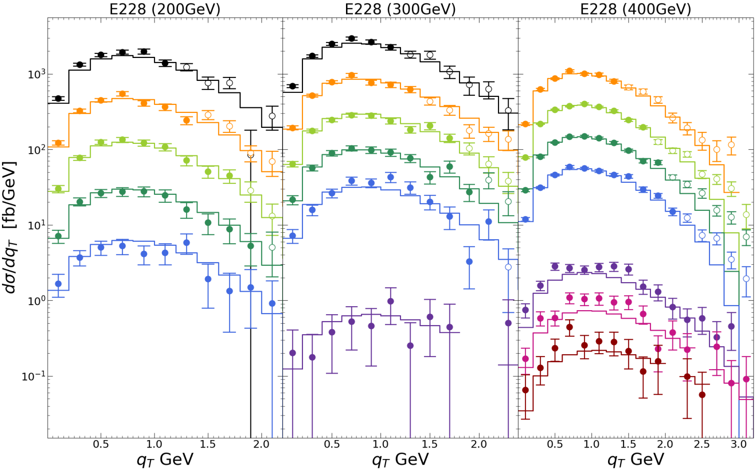

PHE200
$\chi^2/N_{data} =$ 0.29
PRELIMINARY
$d\sigma/dq_T$ [pb/GeV]
0.016
0.014
0.012
0.010
0.008
0.006
0.004
0.002
0.000
data / theory
1.3
1.0
0.7
$q_T$ GeV

# STAR



STAR510
$\chi^2/N_{data} = 1.66$
PRELIMINARY
$d\sigma/dq_T$ [pb/GeV]
data / theory
$q_T$ GeV
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.5
1.0
1.5
7
14
21

# E228


E228 (200GeV)
E228 (300GeV)
E228 (400GeV)
$d\sigma/dq_T$ [fb/GeV]
$10^3$
$10^2$
$10^1$
$10^0$
$10^{-1}$
0.5
1.0
1.5
2.0
2.5
3.0
$q_T$ GeV

# E772 + E605