Pion-induced Drell-Yan and pion TMD distribution

Alexey Vladimirov

Regensburg University

Workshop on Pion and Kaon Structure Functions at the EIC

Introduction

I present the analysis of q_T-spectrum of pion-induced DY
within TMD factorization
JHEP 10 (2019) 090 [1907.10356]

Main aim: Preparation for COMPASS πDY

Plan of talk

- Reminder TMD factorization
- πDY data TMD data
- Problems with normalization of fixed target DY
- TMDs for pion!

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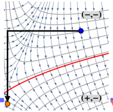
TMD factorization formula for DY with TMD evolution

$$\frac{d\sigma}{dxdzdQ^2d^2\mathbf{q}_T} = \sum_{ff'} H_{ff'}\Big(\frac{Q}{\mu}\Big) \int d^2b\, e^{i(\mathbf{b}\cdot\mathbf{q}_T)}\, F_{f\leftarrow p}(x_1,b,\mu,\zeta) F_{f'\leftarrow\pi}(x_2,b,\mu,\zeta)$$

TMD evolution (usual solution)



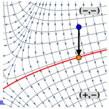
$$\frac{d\sigma}{dxdzdQ^2d^2\mathbf{q}_T} = \sum_{ff'} H_{ff'}\Big(\frac{Q}{\mu}\Big) \int \ldots e^{\int_{\mu_0}^{Q}\gamma_V - \mathcal{D}\ln(\frac{\zeta}{\zeta_0})} F_{f\leftarrow p}(x_1,b,\mu_0,\zeta_0) F_{f'\leftarrow\pi}(x_2,b,\mu_0,\zeta_0)$$

$$e^{\int_{\mu_0}^{Q}\gamma_V - \mathcal{D}\ln(\frac{\zeta}{\zeta_0})} = \exp\left(\int_{\mu_0}^{\mu}\frac{d\mu'}{\mu'}\left(\Gamma_{cusp}(\mu')\ln\left(\frac{\mu^2}{\sqrt{\zeta}}\right) - \gamma_V(\mu')\right) - D(b,\mu_0)\ln\left(\frac{\zeta}{\zeta_0}\right)\right)$$

TMD factorization formula for DY with TMD evolution

$$\frac{d\sigma}{dxdzdQ^2d^2\mathbf{q}_T} = \sum_{ff'} H_{ff'}\left(\frac{Q}{\mu}\right) \int d^2b\, e^{i(\mathbf{b}\cdot\mathbf{q}_T)}\, F_{f\leftarrow p}(x_1,b,\mu,\zeta)F_{f'\leftarrow\pi}(x_2,b,\mu,\zeta)$$

TMD evolution (optimal solution)
"ζ-prescription"



$$\frac{d\sigma}{dxdzdQ^2d^2\mathbf{q}_T} = \sum_{ff'} H_{ff'}\left(\frac{Q}{\mu}\right) \int d^2b\, e^{i(\mathbf{b}\cdot\mathbf{q}_T)} \left(\frac{Q^2}{\zeta_\mu[\mathcal{D}]}\right)^{-2\mathcal{D}(b,\mu)} F_{f\leftarrow p}(x_1,b)F_{f'\leftarrow\pi}(x_2,b)$$

- Clean separation of TMDs from non-perturbative evolution (TMDs are defined at the point with $\mathcal{D}=0$)
- Solution is made in terms of non-perturbative $\mathcal{D}$
- Simple and fast expression for TMD evolution factor (just an algebraic function)
- Simpler expression for perturbative matching for TMDs

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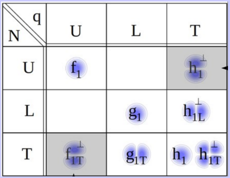
TMD factorization formula (in ζ-prescription)

Rapidity anomalous dimension
$\mathcal{D} \sim \langle 0|F_{+b}[\text{staple link}]|0\rangle$
[AV,2003.02288]



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 $h_{1T}^{\perp}$

$F \sim \langle P|\bar{q}[\text{staple link}]q|0\rangle$

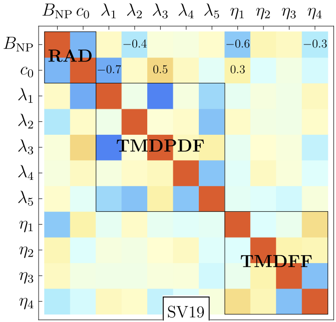
$$\frac{d\sigma}{dxdzdQ^2d^2\mathbf{q}_T} = \sum_{ff'} H_{ff'}\left(\frac{Q}{\mu}\right)\int d^2b\, e^{i(\mathbf{b}\cdot\mathbf{q}_T)}\left(\frac{Q^2}{\zeta_\mu[\mathcal{D}]}\right)^{-2\mathcal{D}(b,\mu)} F_{f\leftarrow p}(x_1,b)F_{f'\leftarrow\pi}(x_2,b)$$

- Each data-point is a product (convolution) of **three independent non-perturbative** functions
- Functions do not “cross-talk” and could be modeled independently
- Each function is responsible for a separate kinematic variable
  - Rapidity AD: $\mathcal{D}$ $\rightarrow$ Q and b
  - TMD N1: F_1 $\rightarrow$ x_1 and b
  - TMD N2: F_2 $\rightarrow$ x_2 and b

Universality of TMDs

Global fit SV19
unpolarized DY + SIDIS
[1912.06532]

- DY: LHC, Tevatron, FermiLab, RHIC
- SIDIS: HERMES, COMPASS
- Large energy coverage (2<Q<150 GeV) = decorrelation of RAD and TMDs
- NNLO matching + N^{3}LO evolution



TMD evolution and proton TMD PDF is known

To describe πDY one needs only πTMD PDF

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Model for πTMD PDF

$$F_{q\leftarrow\pi}(x,b)=\sum_f\int_x^1\frac{dy}{y}C_{q\leftarrow f}(y,\mathbf{L}_\mu)f_{1,f\to\pi}\left(\frac{x}{y},\mu\right)f_{\rm NP}(x,b)$$

- NNLO matching to collinear distributions
- Collinear PDF is `JAM18pionPDFnlo`
- NP-part can be Gauss/Exponent, with three parameters $a_{1,2,3}$

$$f_{\rm NP}(x,b)=\exp\left(-\frac{(a_1+(1-x)^2a_2)b^2}{\sqrt{1+a_3b^2}}\right)$$

πDY q_T-data
not too much...

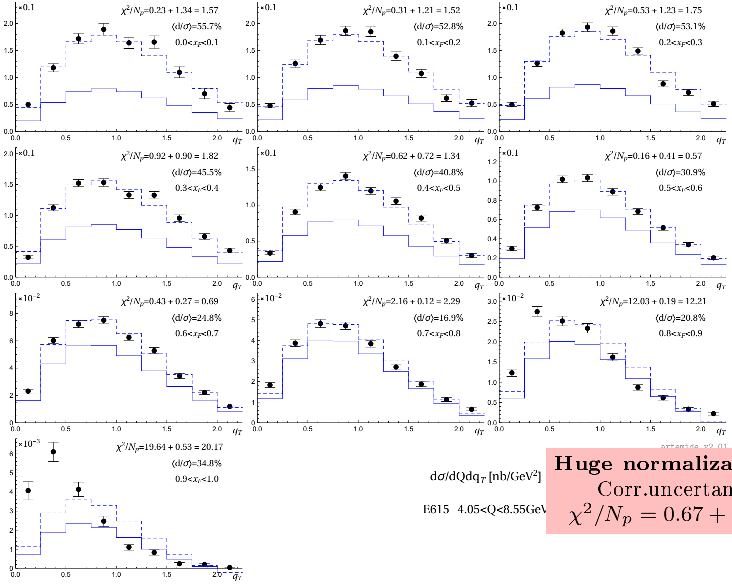
Experiment	$\sqrt{s}$[GeV]	Q[GeV]	x_F	N_{pt}	corr.err.	Typical stat.err.
E537 (Q-diff.)	15.3	$4.0 < Q < 9.0$ in 10 bins	$-0.1 < x_F < 1.0$	60/146	8%	$\sim 20\%$
E537 (x_F-diff.)	15.3	$4.0 < Q < 9.0$	$-0.1 < x_F < 1.0$ in 11 bins	110/165	8%	$\sim 20\%$
E615 (Q-diff.)	21.8	$4.05 < Q < 13.05$ in 10(8) bins	$0.0 < x_F < 1.0$	51/155	16%	$\sim 5\%$
E615 (x_F-diff.)	21.8	$4.05 < Q < 8.55$	$0.0 < x_F < 1.0$ in 10 bins	90/159	16%	$\sim 5\%$
NA3	16.8 , 19.4 22.9	$4.1 < Q < 8.5$ $4.1 < Q < 4.7$	$y > 0(?)$ $0 < y < 0.4$	–	15%	–

The usual TMD cut ($q_T/Q < 0.25$)

Data selected for fit

reason:

- E537 has too large uncertainties
- NA3 is available only as a plot
- It is better to use x-differential data, since Q-dependence is known.



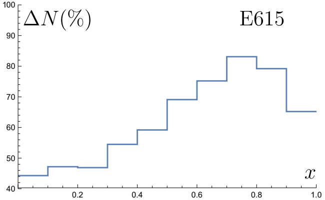
Huge normalization deficit

Corr.uncertanty=16%

$\chi^2/N_p = 0.67 + 0.77 = 1.44$

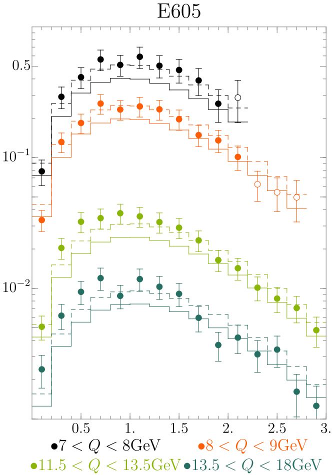
Possible sources of discrepancy

- Nuclear effects: multiplication by $R(x)$ could give $\sim 10\%$ effect (not enough+x-dependence)
- Effect of πPDF uncertainty: significant at a point (up to 20%) but only 2-3% in normalization
- Threshold logarithms: could be but the main disagreement is at $x \sim 0.2$ and decreases to $x \sim 0.7$
- Power corrections: unknown (but I would not expect more than 5%)
- Model bias: ?? (I don't think so)
- Resonance contamination: The bins go down to $3-4$GeV, they could be contaminated by J/ψ or ψ' resonances. However, typically, in this case theory overshoot the data.

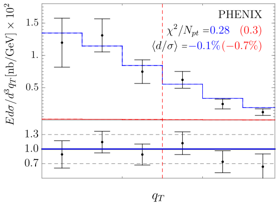


Conclusion:
I do not see theory sources that would cover 50% normalization gap.

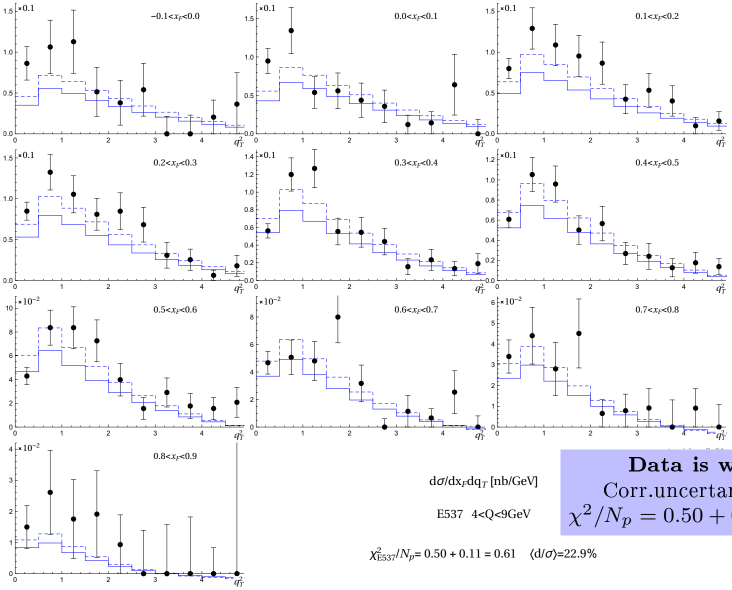
The deficit in normalization is typical for TMD description of fixed-target experiments
However, it is usually 10-20% (not 50%)



- Such problem does not exists for collider experiments



$4.8 < Q < 8.2$



Data is worse

Corr.uncertanty=8%

$\chi^2/N_p = 0.50 + 0.11 = 0.61$

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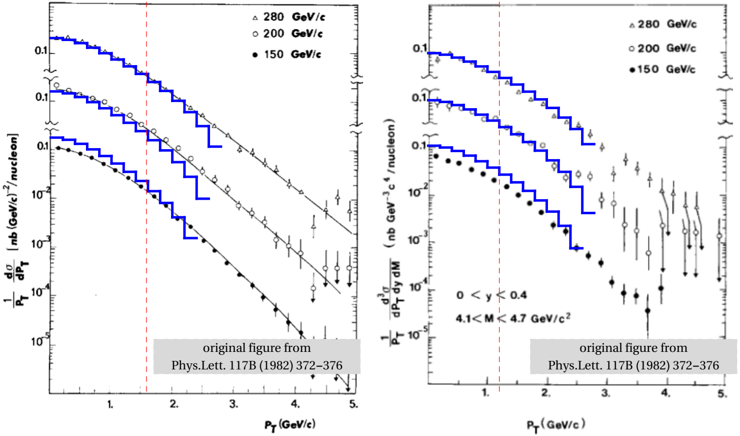
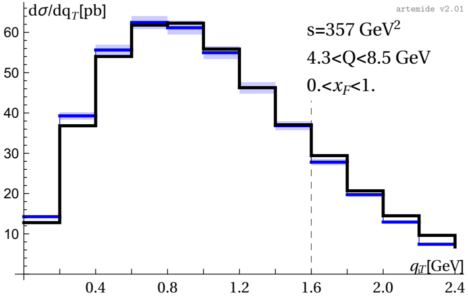


πDY-data from NA3 abd E537 does not show such anomalous behavior

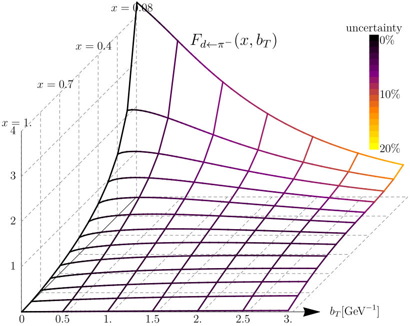
Comparison with COMPASS preliminary [Phys.Rev.Lett. **119** (2017)]



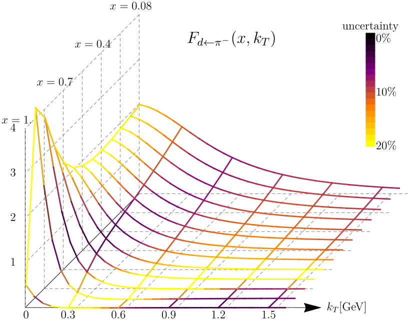
Normalization by theory

$$a_1 = 0.17 \pm 0.11 \pm 0.03, \qquad a_2 = 0.48 \pm 0.34 \pm 0.06, \qquad a_3 = 2.15 \pm 3.25 \pm 0.32.$$

Position-space



Momentum-space



Only statistical uncertainties are shown

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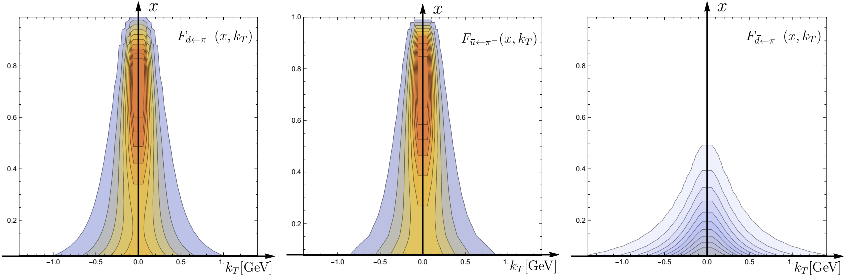
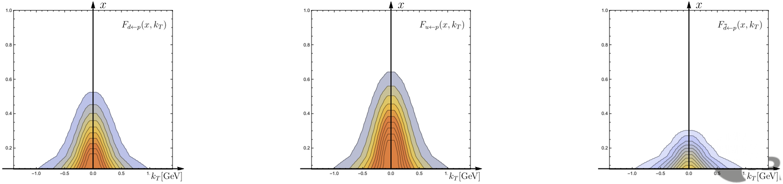


Pion is “narrower” in the momentum space.



Conclusion

- The analysis of πDY is made within the best available TMD-framework
  - NNLO matching, N^3LO evolution
  - Other components (proton TMD, NP TMD evolution) are from the global analysis SV19
  - Numerics is done by `artemide`
- Pion TMDs are extracted from the existing data
  - Normalization problem of q_T-dependent E615-data
  - Rest available data (lower quality) have no problem with normalization
- The extraction `Vpion19` is available as a part of default `artemide` distribution

  `github.com/VladimirovAlexey/artemide-public`

Prospects

- The road to consistent global analysis (πDY angular modulations by COMPASS)
- Looking forward for COMPASS unpolarized πDY
- ...

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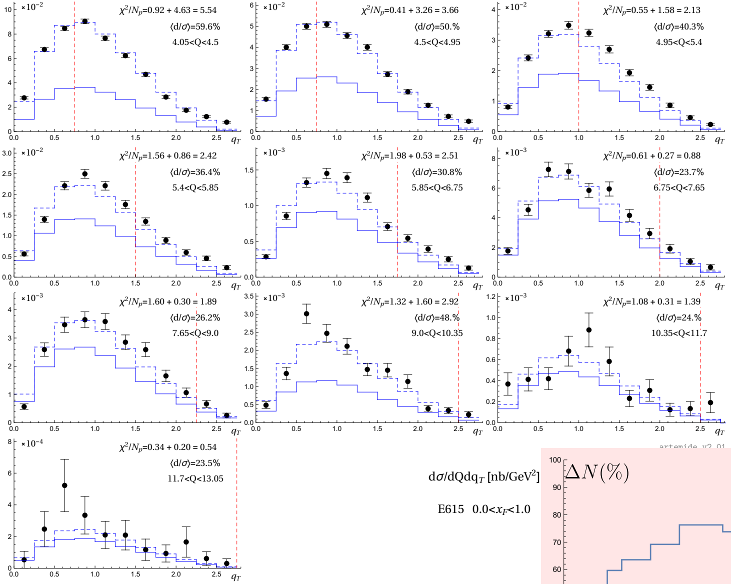
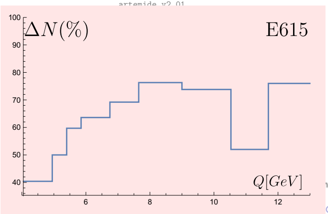
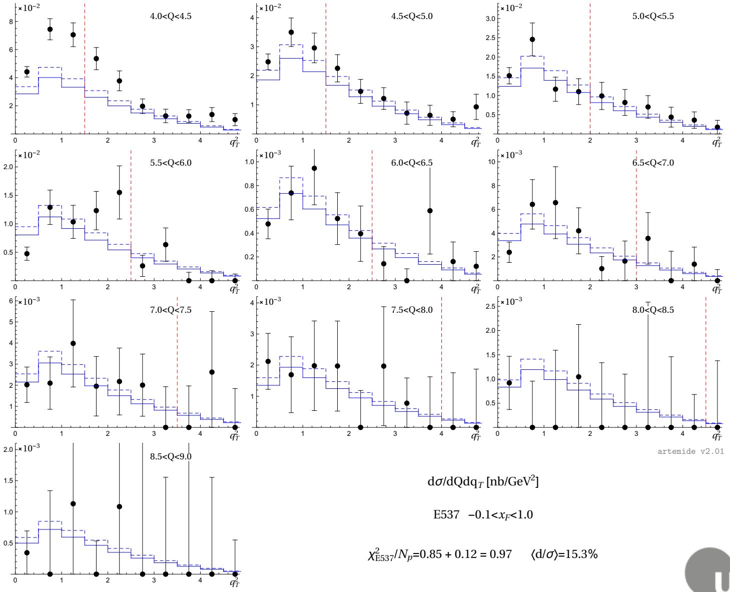
Backup slides



$d\sigma/dQdq_T$ [nb/GeV^2]

E615 $0.0<x_F<1.0$





$d\sigma/dQdq_T$ [nb/GeV^2]

E537 $-0.1<x_F<1.0$

χ^2_{E537}/N_p=0.85 + 0.12 = 0.97 ⟨d/σ⟩=15.3%