

A first determination of the unpolarized quark TMDs from a global analysis

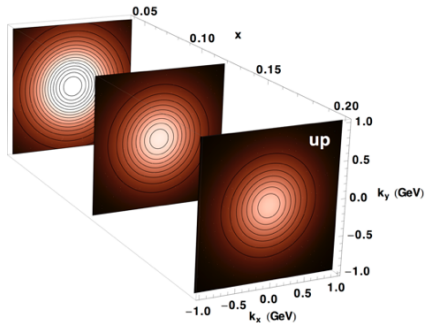
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QCD Evolution 2017

Thomas Jefferson National Accelerator Facility
Newport News, VA (USA)

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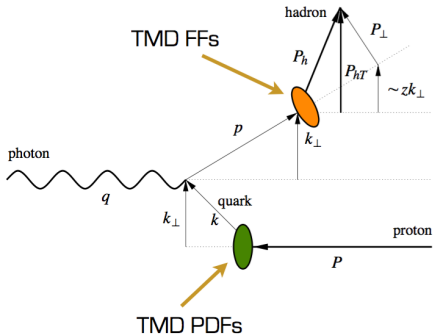
In collaboration with A. Bacchetta, F. Delcarro, M. Radici, A. Signori



- ▶ Are unpolarized quark TMDs universal?
- ▶ Does TMD evolution allow for a description of the data at different Q^2 ?
- ▶ How wide is the transverse momentum distribution? Is it wider at low x ?

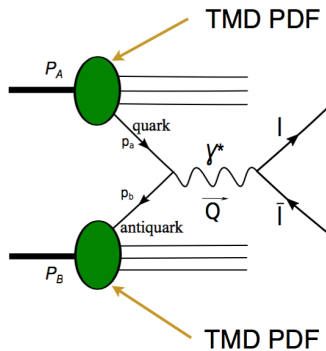
Bacchetta, Delcarro, CP, Radici, Signori (Pavia 2016)
ArXiv:1703.10157 [hep-ph]
Submitted to *JHEP*

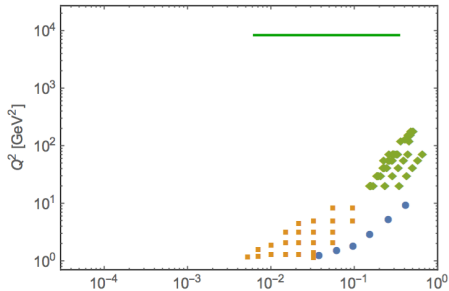
$$l(\ell) + N(\mathcal{P}) \rightarrow l(\ell') + h(\mathcal{P}_h) + X$$



$$A + B \rightarrow \gamma^* \rightarrow l^+ l^-$$

$$A + B \rightarrow Z \rightarrow l^+ l^-$$





Z production@



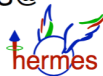
Abbot et al. hep-ex/9909020
Affolder et al. hep-ex/0001021
Abazov et al. arXiv:0712.0803

Drell-Yan@



Ito et al., PRD93 (81)
Moreno et al. PRD 43 (91)
Antreyan et al. PRL47 (81)

SIDIS@



Airapetian et al., PRD87 (2013)

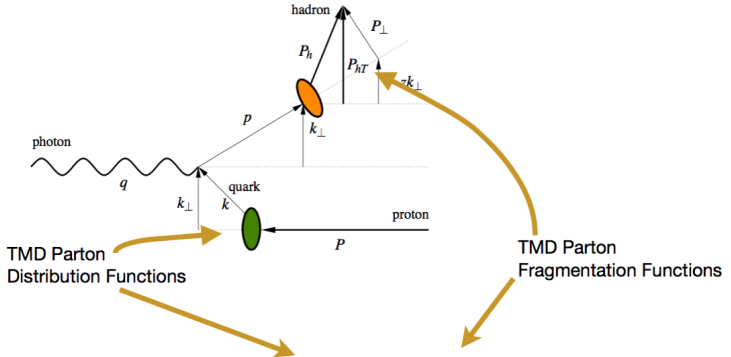


Adolph et al., EPJ C73 (13)

Extraction of unpolarized quark TMDs

State of the art

	Accuracy	HERMES	COMPASS	DY	Z production	N of points
KN 2006 <i>hep-ph/0506225</i>	NLL	✗	✗	✓	✓	98
Pavia 2013 (+Amsterdam,Bilbao) <i>arXiv:1309.3507</i>	No evo	✓	✗	✗	✗	1538
Torino 2014 (+JLab) <i>arXiv:1312.6261</i>	No evo	✓ (separately)	✓ (separately)	✗	✗	576 (H) 6284 (C)
DEMS 2014 <i>arXiv:1407.3311</i>	NNLL	✗	✗	✓	✓	223
EIKV 2014 <i>arXiv:1401.5078</i>	NLL	1 (x,Q ²) bin	1 (x,Q ²) bin	✓	✓	500 (?)
Pavia 2016	NLL	✓	✓	✓	✓	8059



$$F_{UU,T}(x, z, P_{hT}^2, Q^2) = \sum_a \mathcal{H}_{UU,T}^a(Q^2; \mu^2) \int d^2 k_T d^2 P_T f_1^a(x, k_T^2; \mu^2) D_1^{h/a}(z, P_T^2; \mu^2) \delta^2(zk_T - P_{hT} + P_T) + Y_{UU,T}(Q^2, P_{hT}^2) + \mathcal{O}(M^2/Q^2)$$

$$\mathcal{H}_{UU,T}^a \approx \mathcal{O}(\alpha_S^0), \quad Y_{UU,T}(Q^2, P_{hT}^2) \approx 0 \quad \text{in Pavia 2016}$$

$$\text{Multiplicities: } m_N^h(x, z, P_{hT}^2, Q^2) = \frac{d\sigma_N^h/dx dz dP_{hT}^2 dQ^2}{d\sigma_{\text{DIS}}/dx dQ^2} \approx \frac{2\pi |P_{hT}| F_{UU,T}(x, z, P_{hT}^2, Q^2)}{F_T(x, Q^2)}$$

$$f_1^a(x, k_\perp; \mu^2) = \frac{1}{2\pi} \int d^2 b_\perp e^{-i b_\perp \cdot k_\perp} \tilde{f}_1^a(x, b_\perp; \mu^2)$$

$$\tilde{f}_1^a(x, b_T; \mu^2) = \sum_i (\tilde{C}_{a/i} \otimes f_1^i)(x, b_*; \mu_b) e^{\tilde{S}(b_*; \mu_b, \mu)} e^{g_K(b_T) \ln \frac{\mu}{\mu_0}} \hat{f}_{\text{NP}}^a(x, b_T)$$

collinear PDF

pQCD

nonperturbative part of evolution

nonperturbative part of TMD

Rogers, Aybat, PRD 83 (11)

Collins, *Foundations of Perturbative QCD* (11)

Different schemes have been suggested

Collins, Soper, Sterman, NPB 250 (85)

Laenen, Sterman, Vogelsang, PRL 84 (00)

Echevarria, Idilbi, Schaefer, Scimemi, EPJ C73 (13)

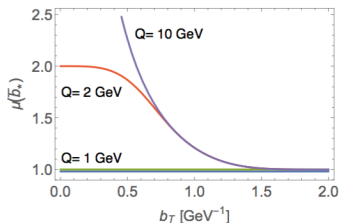
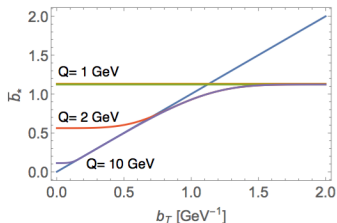
Assumption for nonperturbative evolution: $g_K = -g_2 \frac{b_T^2}{2}$

These choices are arbitrary: they should be checked/challenged in the future

$$\bar{b}_* \equiv b_{\max} \left(\frac{1 - e^{-b_T^4/b_{\max}^4}}{1 - e^{-b_T^4/b_{\min}^4}} \right)^{\frac{1}{4}}$$

$$b_{\max} = 2e^{-\gamma E} \quad \mu_b = \frac{2e^{-\gamma E}}{\bar{b}_*}$$

$$b_{\min} = \frac{2e^{-\gamma E}}{Q}$$

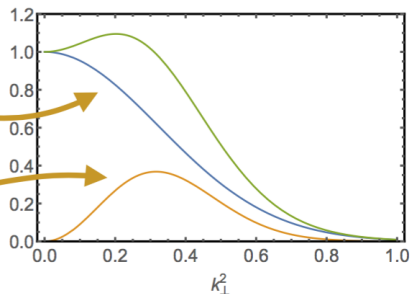


- ▶ Low b_T modification: integrated result is recovered (unitarity constraint)
- ▶ μ_b never bigger than Q now
- ▶ Large effect at low Q (inhibits gluon radiation)

Functional form of TMDs

Input distributions at $Q^2 = 1 \text{ GeV}^2$

$$\hat{f}_{\text{NP}}^a = \text{F.T. of } \left(e^{-\frac{k_T^2}{g_{1a}}} + \lambda k_T^2 e^{-\frac{k_T^2}{g_{1a}}} \right) \frac{1}{g_{1a} + \lambda g_{1a}^2}$$



x-dependent width:

$$g_1(x) = N_1 \frac{(1-x)^\alpha x^\sigma}{(1-\hat{x})^\alpha \hat{x}^\sigma}$$

where

$$N_1 \equiv g_1(\hat{x}) \quad \text{with} \quad \hat{x} = 0.1$$

$\alpha, \sigma, N_1, \lambda$: free parameters (4 for TMD PDFs, 6 for TMD FFs)

$$Q^2 > 1.4 \text{ GeV}^2$$

$$0.2 < z < 0.7$$

$$P_{hT}, q_T < \text{Min}[0.2Q, 0.7Qz] + 0.5 \text{ GeV}$$

Problems in separating the fragmentation regions in SIDIS at low Q^2

Boglione, Collins, Gamberg, Gonzalez-Hernandez, Rogers, Sato, PLB 766 (2017)

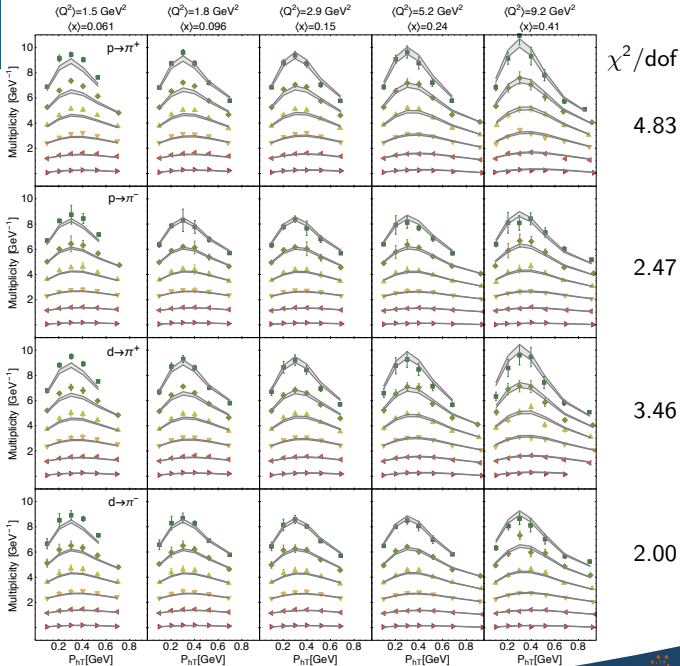
Fit of 200 replicas of the data

Total number of data points: 8059

Total number of free parameters: 11

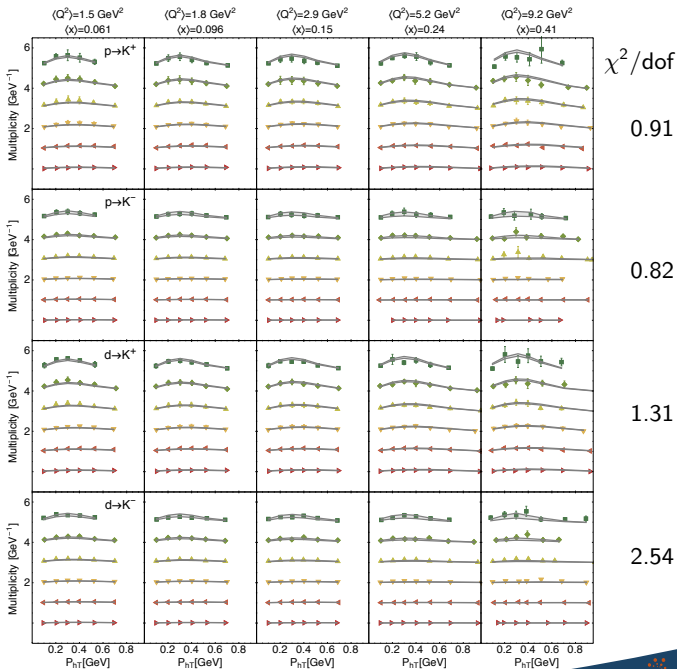
- ▶ 4 for TMD PDFs
- ▶ 6 for TMD FFs
- ▶ 1 for TMD evolution

Total $\chi^2/\text{dof} = 1.55 \pm 0.05$



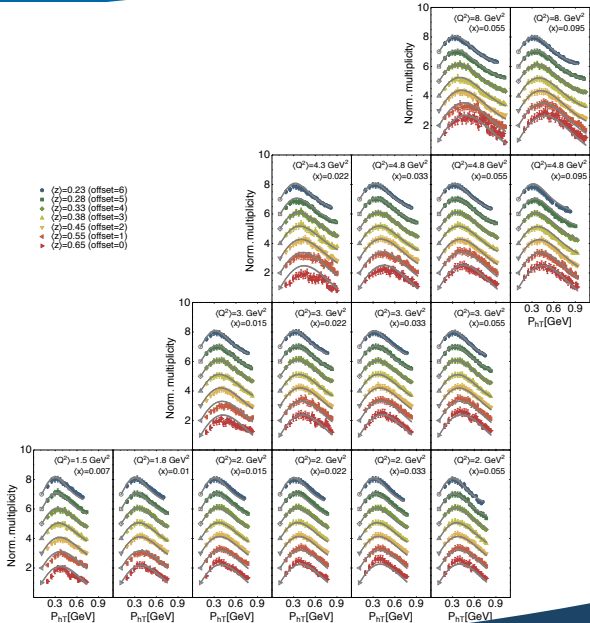


- (z)=0.24 (offset=5)
- (z)=0.28 (offset=4)
- ▲ (z)=0.34 (offset=3)
- ▼ (z)=0.43 (offset=2)
- ▲ (z)=0.54 (offset=1)
- ▼ (z)=0.70 (offset=0)



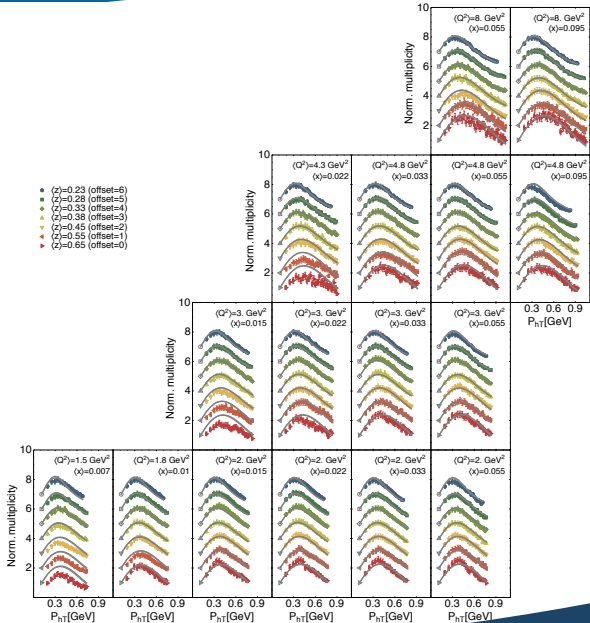


$\chi^2/\text{dof} = 1.01$

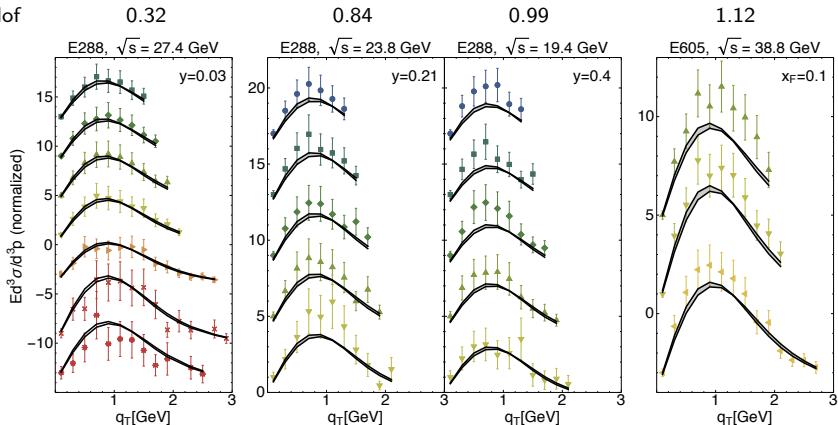




$\chi^2/\text{dof} = 1.61$

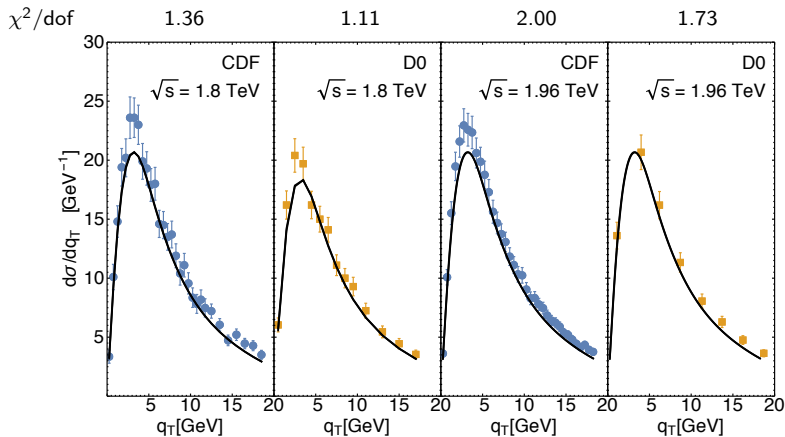


χ^2/dof



- (Q)=4.5 GeV (offset =16)
- ▲ (Q)=7.5 GeV (offset =4)
- ▶ (Q)=11.5 GeV (offset =-4)
- (Q)=5.5 GeV (offset =12)
- ▼ (Q)=8.5 GeV (offset =0)
- ✱ (Q)=12.5 GeV (offset =-10)
- ◆ (Q)=6.5 GeV (offset =8)
- ◃ (Q)=11.0 GeV (offset =-4)
- (Q)=13.5 GeV (offset =-14)

The peak is now at about 1 GeV, it was at 0.4 GeV



- ▶ The peak is now at 4 GeV
- ▶ Most of the χ^2 is due to normalization

TMD evolution is not uniquely determined by pQCD calculations

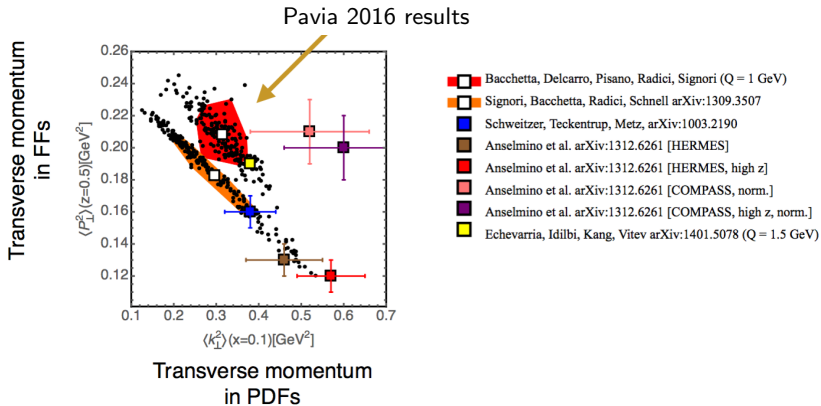
Different schemes may behave differently

Nonperturbative input is needed to determine evolution precisely

	g_2 (GeV ²)	b_{max} (GeV ⁻¹)
BLNY 2003	0.68 ± 0.02	0.5
KN 2006	0.184 ± 0.018	1.5
EIKV 2014	0.18	1.5
Pavia 2016	0.13 ± 0.01	1.123

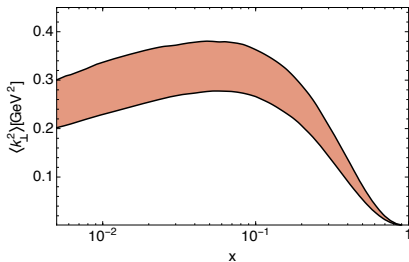
Faster evolution: transverse momentum increases faster due to gluon radiation

Slower evolution: the effect of gluon radiation is weaker

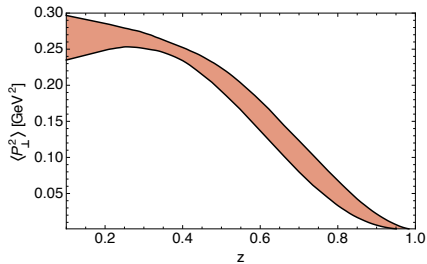


Anticorrelation between transverse momentum in TMD PDFs and in TMD FFs

In TMD distribution functions



In TMD fragmentation functions



How does the χ^2 of a single replica change if we modify our default choices?

Original $\chi^2/\text{dof} = 1.51$

- ▶ **Normalization** of HERMES data as done for COMPASS: $\chi^2/\text{dof} \rightarrow 1.27$
- ▶ **Parametrizations for collinear PDFs** (NLO GJR 2008 default choice):
NLO MSTW 2008 (1.84), NLO CJ12 (1.85)
- ▶ **More stringent cuts** (TMD factorization better under control) $\chi^2/\text{dof} \rightarrow 1$
Ex: $Q^2 > 1.5 \text{ GeV}^2$, $0.25 < z < 0.6$, $P_{hT} < 0.2Qz \implies \chi^2/\text{dof} = 1.02$ (477 bins)

- ▶ We demonstrated for the first time that it is possible to fit simultaneously SIDIS, DY, and Z boson production data
- ▶ We extracted unpolarized quark TMDs using more than eight thousand data points
- ▶ The TMD framework seems to work quite well
- ▶ Most of the discrepancies come from the normalizations
- ▶ The Y term still needs to be implemented