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

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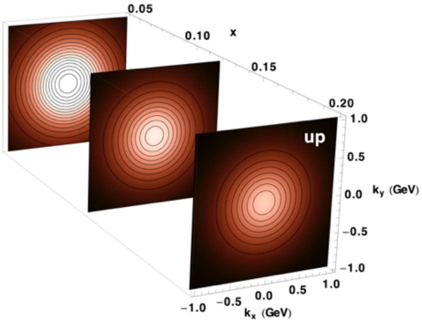
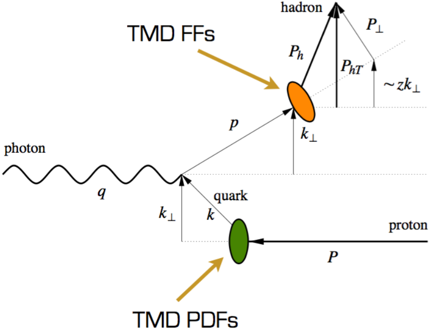


- Are unpolarized quark TMDs universal?
- Does TMD evolution allow for a description of the data at different Q^2?
- How wide is the transverse momentum distribution? Is it wider at low x?

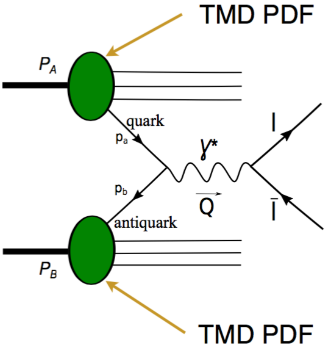
Bacchetta, Delcarro, CP, Radici, Signori, JHEP 1706 (2017)

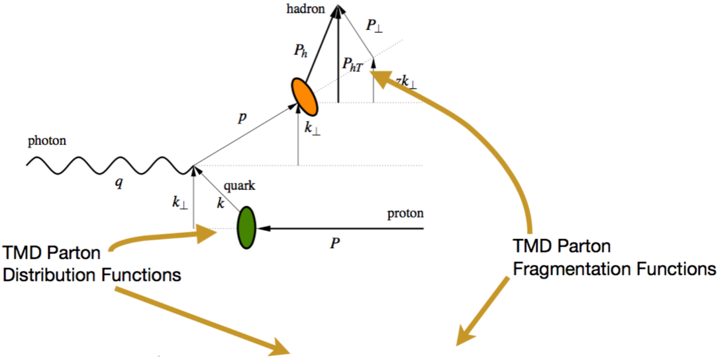
Semi-inclusive DIS vs DY

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



$$A + B \to \gamma^* \to l^+ l^-$$
$$A + B \to Z \to l^+ l^-$$





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

$\mathcal{H}^a_{UU,T} \approx \mathcal{O}(\alpha_S^0)$, $Y_{UU,T}(Q^2,\boldsymbol{P}_{hT}^2) \approx 0$ in Pavia 2016

Multiplicities: $m_N^h(x,z,\boldsymbol{P}_{hT}^2,Q^2) = \dfrac{d\sigma_N^h/dx\,dz\,d\boldsymbol{P}_{hT}^2\,dQ^2}{d\sigma_{\mathrm{DIS}}/dx\,dQ^2} \approx \dfrac{2\pi|\boldsymbol{P}_{hT}|F_{UU,T}(x,z,\boldsymbol{P}_{hT}^2,Q^2)}{F_T(x,Q^2)}$

TMD evolution
Fourier transform

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

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

collinear PDF

pQCD

nonperturbative part of evolution

nonperturbative part of TMD

Rogers, Aybat, PRD 83 (11)
Collins, *Foundations of Perturbative QCD* (11)

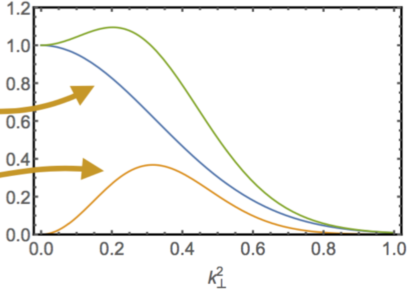
Different schemes have been suggested

Collins, Soper, Sterman, NPB 250 (85)
Laenen, Sterman, Vogelsang, PRL 84 (00)
Echevarria, Idilbi, Schaefer, Scimemi, EPJ C73 (13)

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

Functional form of TMDs
Input distributions at $Q^2 = 1\ \mathrm{GeV}^2$

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



x-dependent width:

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

where

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

α, σ, N_1, λ: free parameters (4 for TMD PDFs, 6 for TMD FFs)

Data selection and analysis

$Q^2 > 1.4$ GeV^2

$0.2 < z < 0.7$

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

Summary of the results

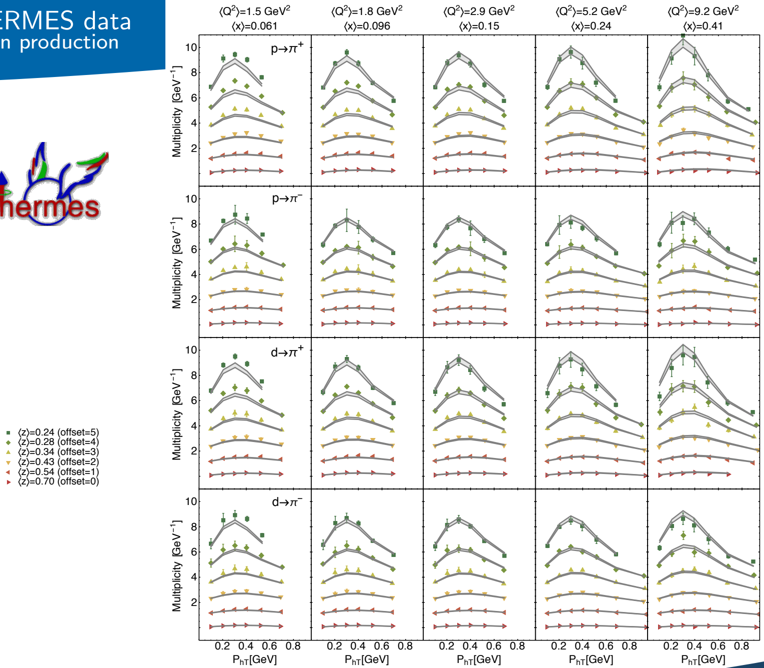
Total number of data points: 8059

Total number of free parameters: 11

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

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

HERMES data
Pion production



χ^2/dof

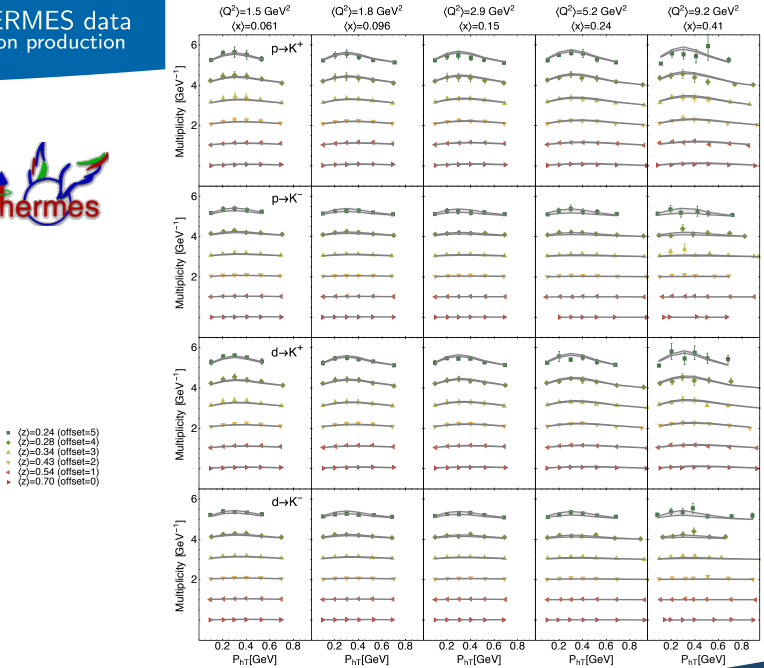
4.83

2.47

3.46

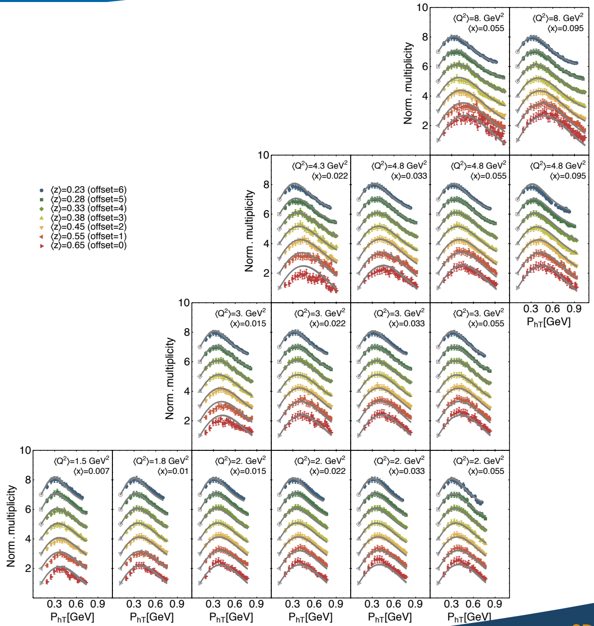
2.00

HERMES data
Kaon production



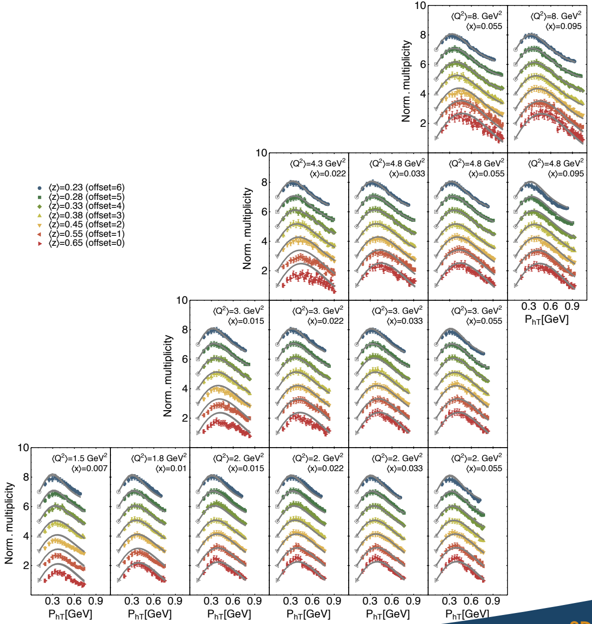
χ^2/dof
0.91
0.82
1.31
2.54

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

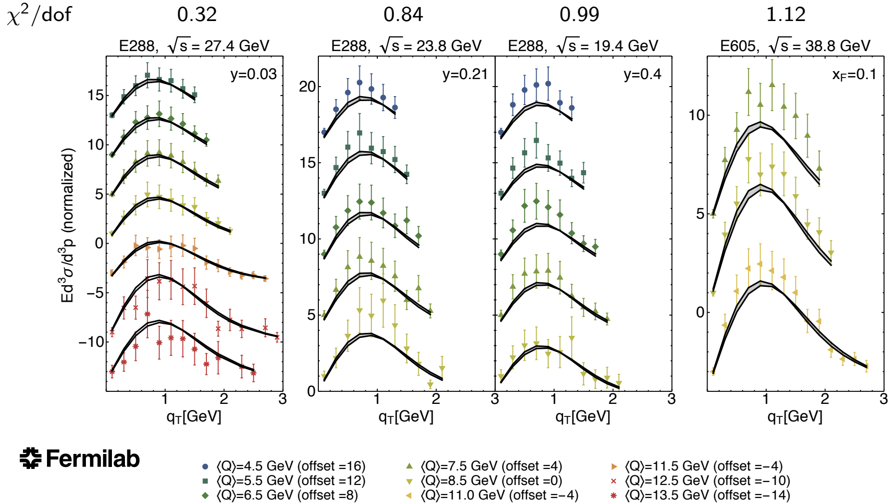


SIDIS h^-
COMPASS data

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

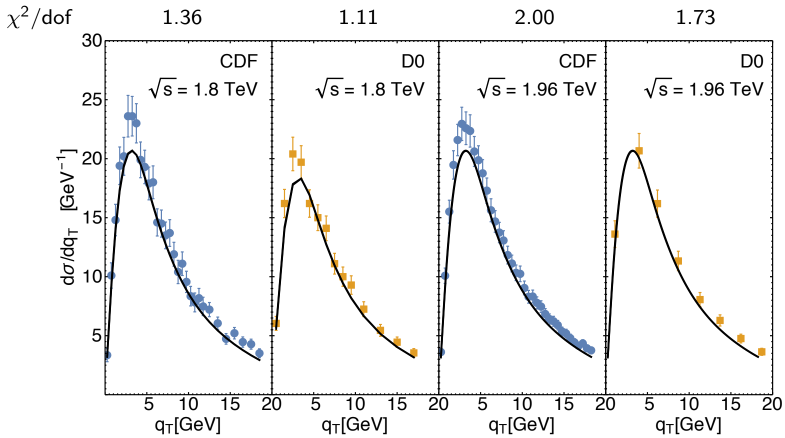


Drell-Yan data



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

Z-boson production



- 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

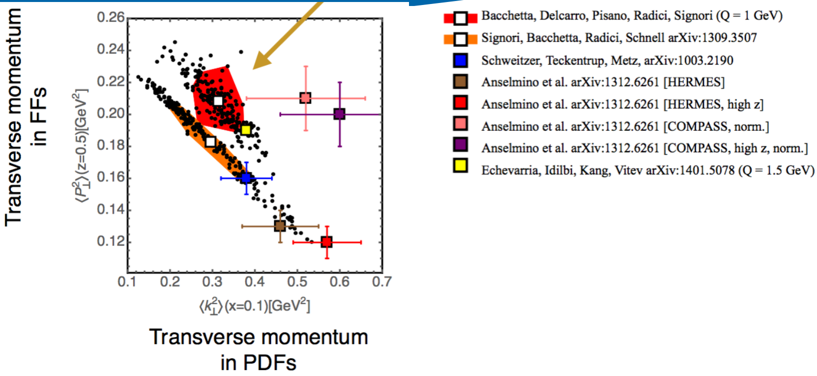
Different schemes may behave differently

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

Very recent extraction of unpolarized TMDs at NNLO+NNLL from DY

Scimemi, Vladimirov, arXiv:1706.01473

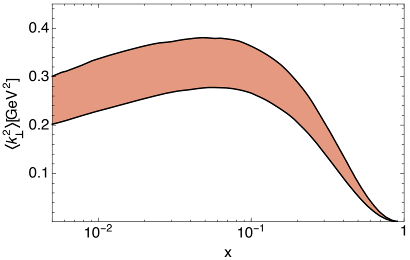
Talk by A. Vladimirov

Unpolarized quark TMDs inside the pion at NLO+NLL from πp DY data

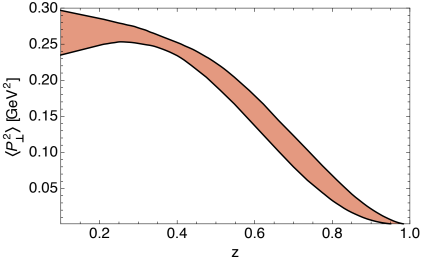
Wang, Lu, Schmidt, arXiv:1707.05207

Mean transverse momentum
$Q^2 = 1\ \text{GeV}^2$

In TMD distribution functions



In TMD fragmentation functions



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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: $\chi^2/\text{dof} \to 1.27$
- 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) $\chi^2/\text{dof} \to 1$

  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)

Conclusions

- 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
- NLO+NLL calculation in progress, Y term still needs to be implemented