Unpolarized TMD fits

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Workshop
TMDs at JLab: present and future

Pavia, 19-20 December 2018

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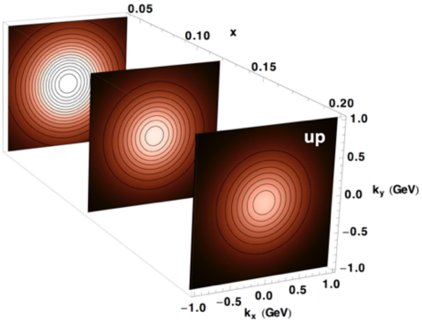
Motivation



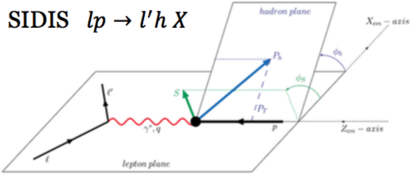
- Are unpolarized quark TMDs universal?
- Does TMD evolution allow for a description of the data at different Q^2?
- How wide is the transverse momentum distribution? Is it wider at low x?

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

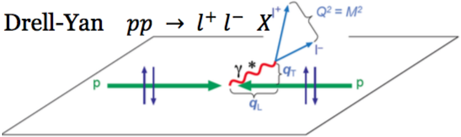
TMD factorization

Two scale processes $Q^2 \gg p_T^2$

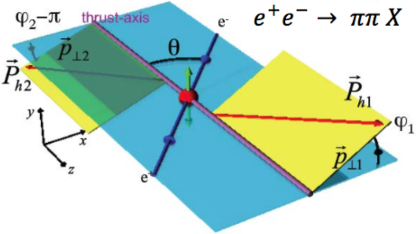
SIDIS $lp \to l'h\,X$



Drell-Yan $pp \to l^+ l^- X$

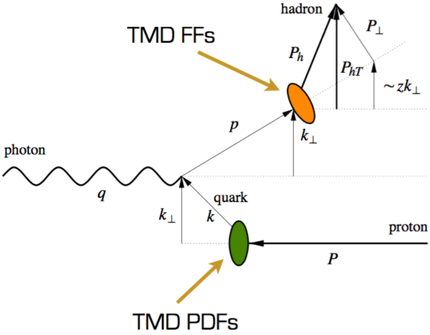


$e^+e^- \to \pi\pi\,X$

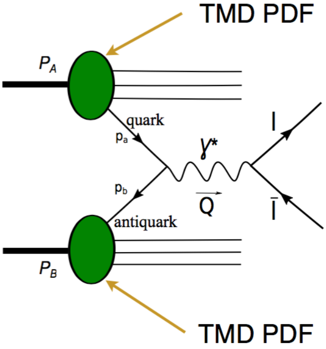


Factorization proven

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

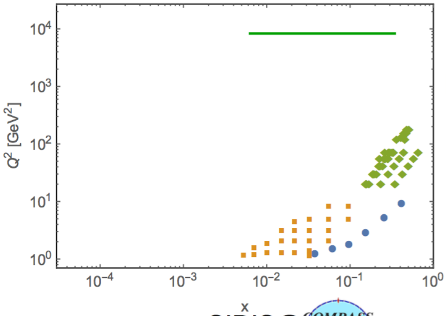


$$A + B \to \gamma^* \to l^+ l^-$$
$$A + B \to Z \to l^+ l^-$$



Electron-positron annihilation data are still missing

Experiments



Z production@ Fermilab

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

Drell-Yan@ Fermilab

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

SIDIS@ hermes

Airapetian et al., PRD87 (2013)

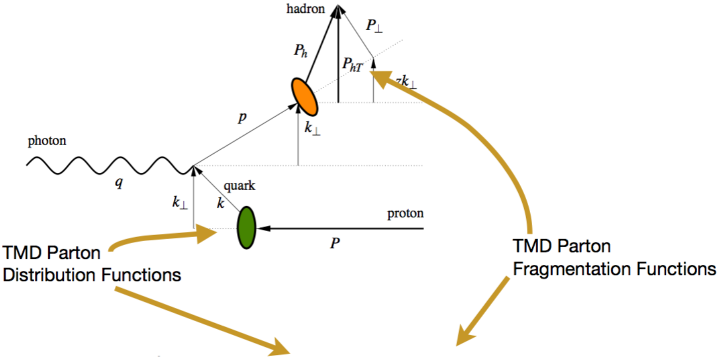
SIDIS@ COMPASS

Adolph et al., EPJ C73 (13)

	Framework	HERMES	COMPASS	DY	Z production	N of points
KN 2006 hep-ph/0506225	LO-NLL	✘	✘	✔	✔	98
Pavia 2013 (+Amsterdam, Bilbao) arXiv:1309.3507	No evo (QPM)	✔	✘	✘	✘	1538
Torino 2014 (+JLab) arXiv:1312.6261	No evo (QPM)	✔ (separately)	✔ (separately)	✘	✘	576 (H) 6284 (C)
DEMS 2014 arXiv:1407.3311	NLO-NNLL	✘	✘	✔	✔	223
EIKV 2014 arXiv:1401.5078	LO-NLL	1 (x,Q^2) bin	1 (x,Q^2) bin	✔	✔	500 (?)
Pavia 2017 arXiv:1703.10157	LO-NLL	✔	✔	✔	✔	8059
SV 2017 arXiv:1706.01473	NNLO-NNLL	✘	✘	✔	✔	309

courtesy of A. Bacchetta

SIDIS structure function



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

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

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

TMD evolution
Fourier transform

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

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

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

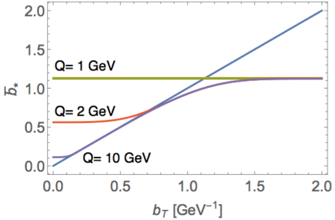
Collins, Soper, Sterman, NPB 250 (85)
Laenen, Sterman, Vogelsang, PRL 84 (00)
Echevarria, Idilbi, Schaefer, Scimemi, EPJ C73 (13)

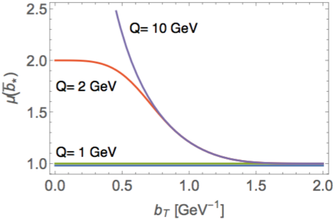
Assumption for nonperturbative evolution: $g_K = -g_2 \frac{b_T^2}{2}$

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

$$\bar{b}_\star \equiv b_{\max} \left(\frac{1 - e^{-b_T^4/b_{\max}^4}}{1 - e^{-b_T^4/b_{\min}^4}} \right)^{\frac{1}{4}} \qquad b_{\max} = 2e^{-\gamma_E} \qquad \mu_b = \frac{2e^{-\gamma_E}}{\bar{b}_\star}$$

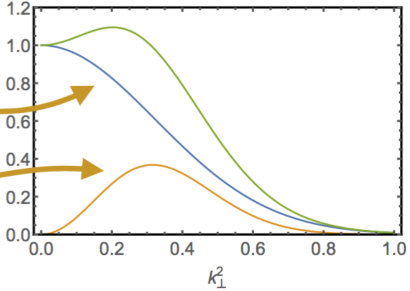
$$b_{\min} = \frac{2e^{-\gamma_E}}{Q}$$





- 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)

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



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)

$Q^2 > 1.4$ 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

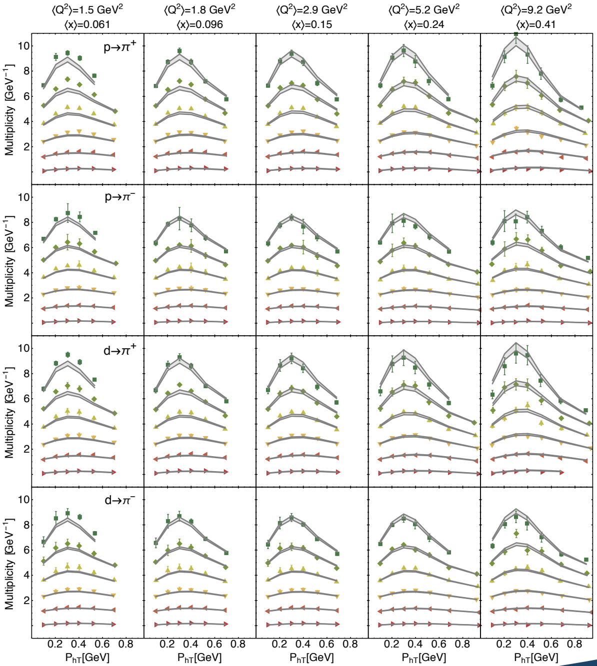
Total number of data points: 8059

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



- ⟨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)

χ^2/dof
4.83
2.47
3.46
2.00

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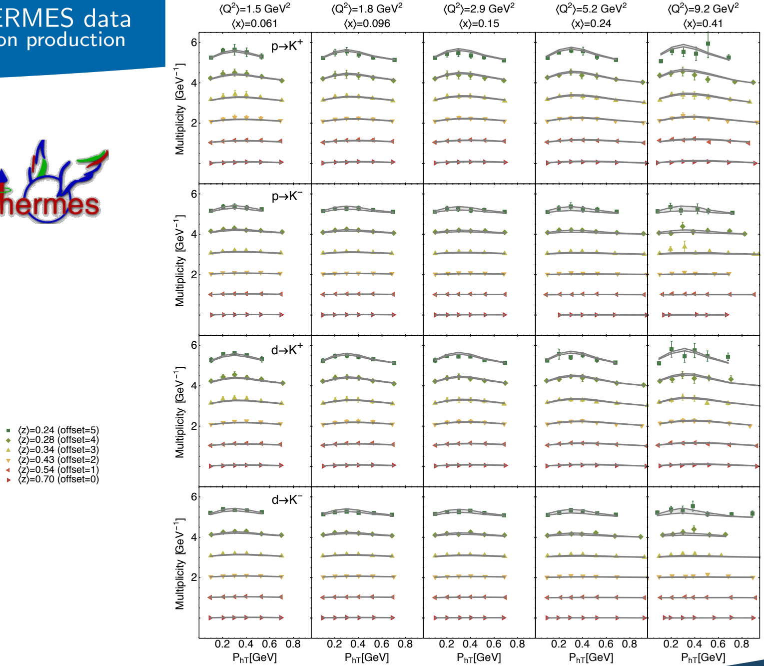
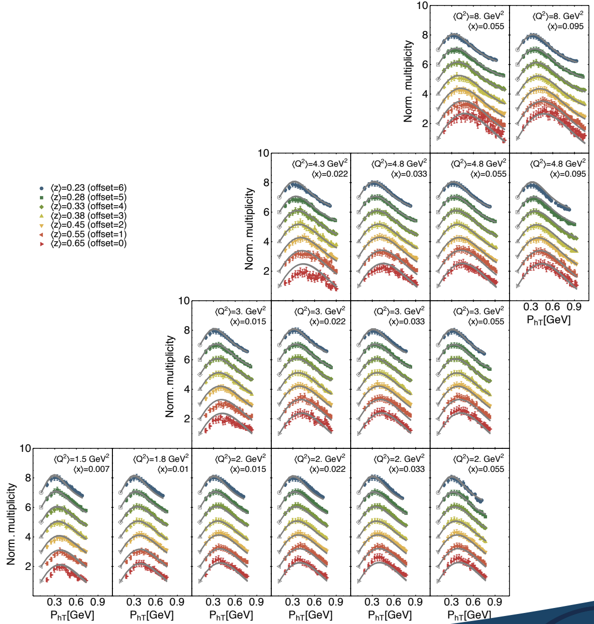
HERMES data
Kaon production



χ^2/dof
0.91
0.82
1.31
2.54

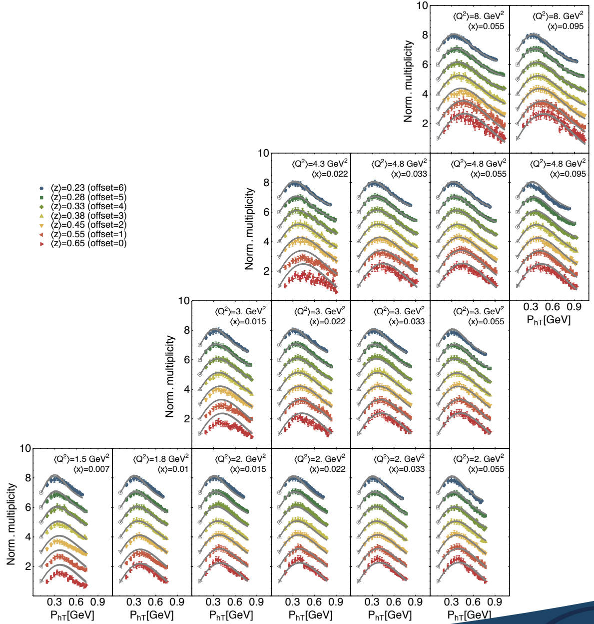
SIDIS h^+
COMPASS data

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

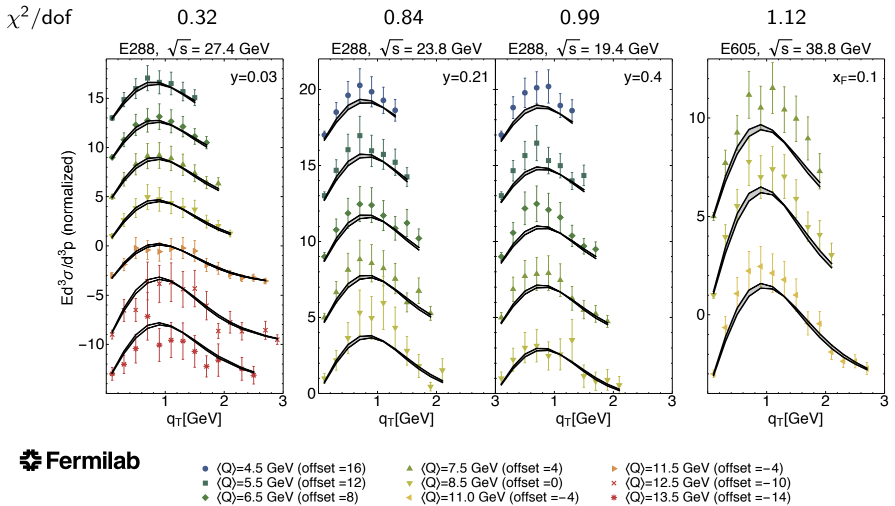


SIDIS h^-
COMPASS data

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



Drell-Yan data



Fermilab

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

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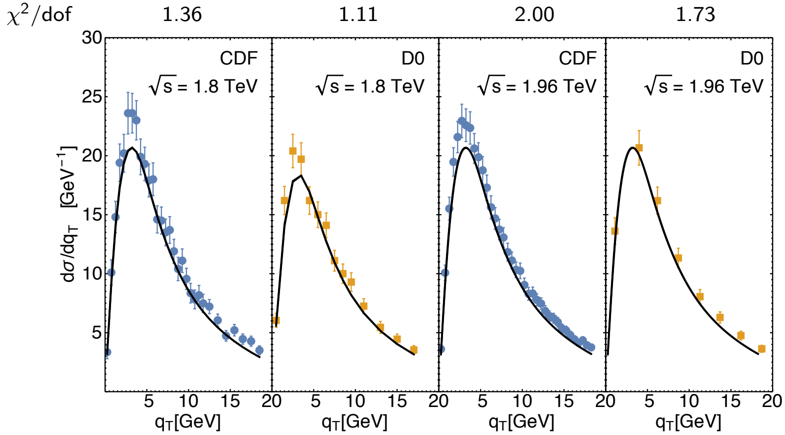
Z-boson production



- 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

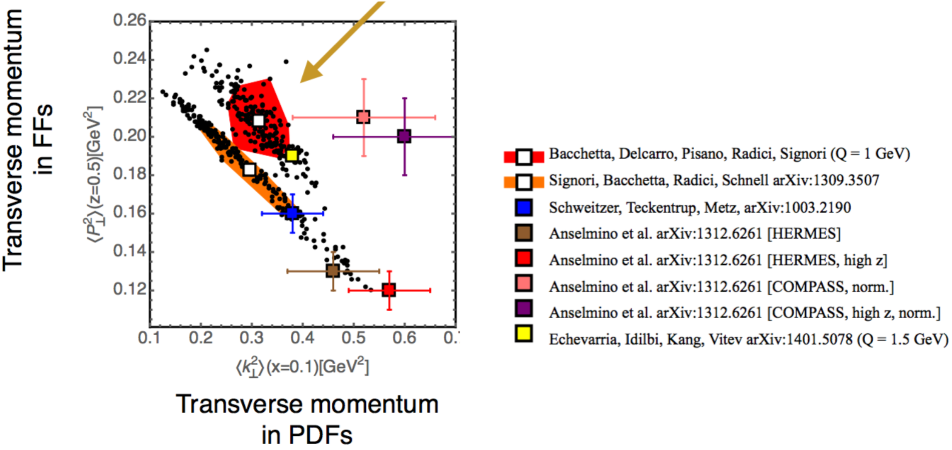
Nonperturbative input is needed to determine evolution precisely

	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

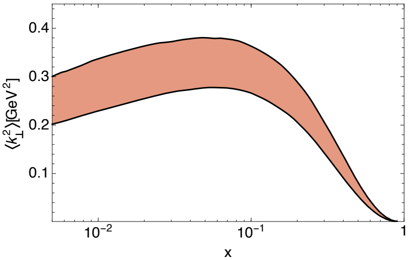
Slower evolution: the effect of gluon radiation is weaker

Pavia 2017 results

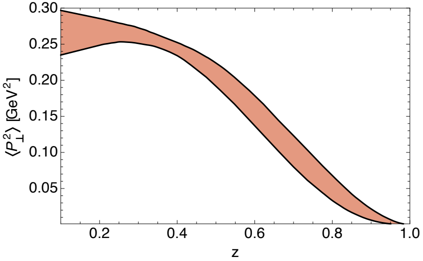


Anticorrelation between transverse momentum in TMD PDFs and in TMD FFs

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: $Q^2 > 1.5$ 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
- NLO+NLL calculation in progress, Y term still needs to be implemented