TMD and unintegrated PDFs: QCD factorization at the LHC

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3D Parton Distributions: Path to the LHC
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The TMD and the $\mathbf{k}_\perp$-dependent factorization frameworks and their application to high-energy physics phenomenology are discussed, emphasising the role played by the transverse momentum dependent (TMD) and the unintegrated parton densities (uPDF), respectively. Several processes and observables relevant for the LHC are identified in two main regimes: transverse momentum spectra of Higgs and vector bosons in the low-q_T region, and behaviour of the structure functions at small-x.

Outline

- A guided tour to the 70ths; two sources of transverse momentum; early 'TMDs' and 'uPDFs': first evolution equation for TMDs
- Modern era: again two sources of transverse momentum, now with more data; processes and observables relevant for the LHC
- TMD evolution, edition 2010ths: how much the things changed
- Experimental prospects and outlook

Parton Distributions and High-Energy Processes

Inclusive processes $\to$ **collinear factorization**: one or less hadron detected; e.g., DIS, electron-positron annihilation to hadrons

Semi-inclusive processes $\to$ **TMD** or $k_\perp$**-dependent** factorization: two or more hadrons in the initial or final state detected; e.g., Drell-Yan, SIDIS, hadron-hadron to jets, Higgs and heavy-flavour production

Collinear factorization: longitudinal momenta of the patrons are intrinsic, transverse momenta can be created by perturbative radiation effects (parton showers) $\to$ **collinear (integrated) pdfs**

TMD factorization and $k_\perp$**-dependent factorization:** a unifying QCD-based framework with both mechanisms of the transverse-momentum creation taken into account–intrinsic (essentially non-perturbative) and perturbative radiation $\to$ **transverse-momentum dependent / unintegrated /** $3D$**) pdfs**

TMD and uPDF: A Bit of History

How to define an intrinsically transverse momentum dependent parton density in a renormalizable field theory?

[Soper: PRD 15 (1977) 1141]

[Soper: PRL 43 (1979) 1847]

[Collins: PRD 21 (1980) 2962]

First-ever (to the best of my knowledge) operator definition of TMD pdf: bilocal operator by Soper-Collins; scalar theory in the ω-dimensional space-time

$$\mathcal{P}(k^+, \mathbf{k}_\perp) = \int dy^- d^{\omega-2}y_\perp \mathrm{e}^{-ik^+y^- + ik_\perp y_\perp} \; \phi_R(y)\phi_R(0)|_{y^+=0}$$

$$\phi_R = Z^{-1/2}\phi$$

$$\mathcal{P}(k^+, \mathbf{k}_\perp) \to P(x; \mathbf{k}_\perp)$$

TMD and uPDF: A Bit of History

How to define an intrinsically transverse momentum dependent parton density in a renormalizable field theory?

[Soper: PRD 15 (1977) 1141; PRL 43 (1979) 1847]

[Collins: PRD 21 (1980) 2962]

Collinear limit is trivial (sic!):

$$\mathcal{F}(k^+) = \int d^{\omega-2}k_\perp \ \mathcal{P}(k^+, \mathbf{k}_\perp)$$

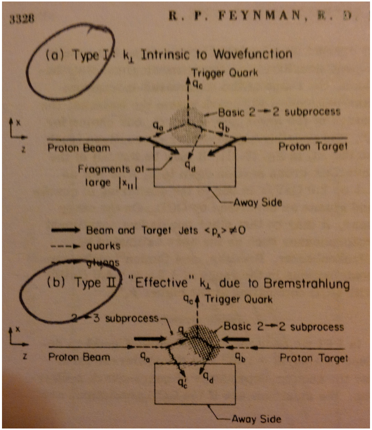
$$= \int dy^- \mathrm{e}^{-ik^+y^-} \ \phi_R(y)\phi_R(0)|_{y^+, y_\perp = 0} \to f(x)$$

Renormalization and evolution is also trivial (sic!): *'although the RG equation for the $f(x)$ is an integro-differential equation, the one for $P(x, k_\perp)$ is just a differential equation and $P(x, k_\perp)$ changes multiplicatively under the RG according to the anomalous dimension of the parton field'* (Collins, 1980)

$$\mu \frac{d}{d\mu} P(x, k_\perp; \mu) = 2\gamma_\phi P(x, k_\perp; \mu)$$

Old ‘uPDFs’ and ‘TMDs’: Two Sources of Transverse Momentum

[Feynman, Field, Fox: PRD 18 (1978) 3320]



Old 'uPDFs' and 'TMDs': Two Sources of Transverse Momentum

[Feynman, Field, Fox: PRD 18 (1978) 3320]

i Nonperturbative component of the transverse momentum of a quark within proton is intrinsic to the proton's wave function. This transverse momentum is balanced by the remaining constituents of the proton = /source of the **type I**/

ii Perturbative component of the transverse momentum of a quark is due to the Bremstrahlung of a gluon before the basic $2 \to 2$ subprocess occurs. This transverse momentum is balanced by the gluon and quark jets = /source of the **type II**/

How much of the dimuon transverse momentum spectra is due to the wave function **type I** and how much can be explained perturbatively **type II**?

Parton Distributions: Evolution Methods

1. **Fully inclusive processes:** collinear ($\mathbf{k}_\perp$-integrated) PDFs
   - DGLAP:
     - strong ordering in the transverse momenta of emitted patrons;
     - hard matrix elements are on-shell
     - sums up $\ln \mu^2/\Lambda^2$ logs

2. **Semi-Inclusive processes:**
   - BFKL
   - CCFM
   - SCET
   - TMD

Parton Distributions: Evolution Methods

1. **Fully inclusive processes:** collinear ($\mathbf{k}_\perp$-integrated) PDFs
   - DGLAP

2. **Semi-Inclusive processes:**
   - BFKL:
     - high energy $=$ small-x domain;
     - ordering in the rapidities of emitted partons;
     - hard matrix elements are off-shell
     - sums up $\ln 1/x$ logs
     - nonlinear extensions
   - CCFM
   - SCET
   - TMD

Parton Distributions: Evolution Methods

1. **Fully inclusive processes:** collinear ($\mathbf{k}_\perp$-integrated) PDFs
   - DGLAP
2. **Semi-Inclusive processes:**
   - BFKL
   - CCFM
     - angular ordering of the emitted patrons;
     - hard matrix elements are off-shell;
     - dependence on extra scale (maximal angle);
     - valid for low as well as for high x
     - sums up $\ln 1/x$ a well as $\ln 1/(1-x)$ logs
   - SCET
   - TMD

Parton Distributions: Evolution Methods

1. **Fully inclusive processes:** collinear ($\mathbf{k}_\perp$-integrated) PDFs
   - DGLAP
2. **Semi-Inclusive processes:**
   - BFKL
   - CCFM
   - SCET:
     - scale separation and effective Lagrangian
     - finally equivalent to the TMD approach /theoretically/
   - TMD

Parton Distributions: Evolution Methods

1. **Fully inclusive processes:** collinear ($\mathbf{k}_\perp$-integrated) PDFs
   - DGLAP

2. **Semi-Inclusive processes:**
   - BFKL
   - CCFM
   - SCET
   - TMD:
     - direct generalisation of the collinear picture;
     - valid (formally?) in the whole range of x;
     - extra rapidity scale;
     - combined evolution

Modern Time: Intrinsic or Perturbative?

[REF Workshop: APPB 46 (2015) 2501]

TMD- or uPDF-related regimes:

i Heavy particle spectra at the low-q_T and fixed invariant mass: vector boson, Higgs, heavy flavours

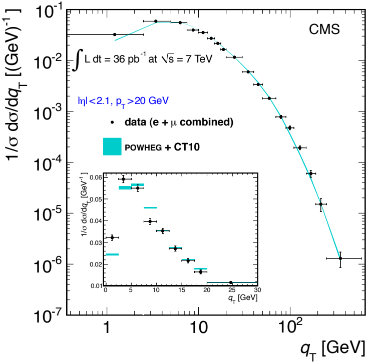
ii High-energy limit: $s \to \infty$ for fixed momentum transfer t

Modern Time: Intrinsic or Perturbative?

DY hadroproduction of EW bosons

[CMS: PRD 85 (2012) 032002]

[REF Workshop: APPB 46 (2015) 2501]



low-q_T DY: $d\sigma^{Z*}_{\mathrm{DY}}(q_T)$;

lepton pair's inv. mass: $60\ GeV < M < 120\ GeV$

Modern Time: Intrinsic or Perturbative?

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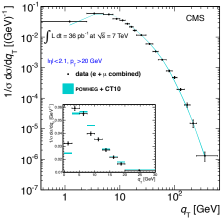

i high-q_T region $\sim 10^2$ GeV: finite-order pQCD + collinear pdfs $\to$ works well

ii 'peak' region ~ 10 GeV: multiparton radiation becomes important $\to$ resummation of arbitrary many parton emissions needed

iii low-q_T region ~ 1 GeV finite-order pQCD + collinear pdfs$\to$ $d\sigma_{\rm DY}^{Z*}(q_T)$ diverges at small q_T

Modern Time: Intrinsic or Perturbative?

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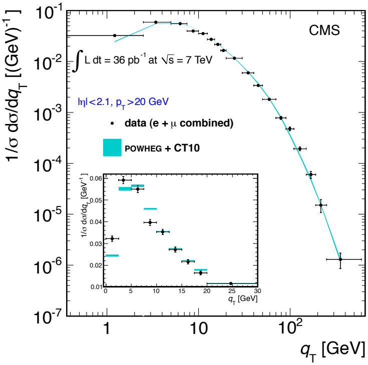


'peak' and low-q_T regions: TMD factorization allows to resum $\ln M/q_T$ contributions → good agreement with the data

Modern Time: Intrinsic or Perturbative?

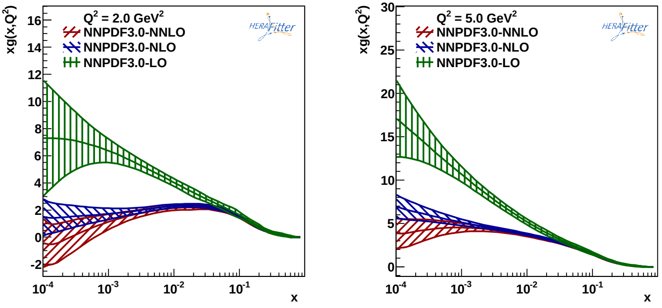
Structure Functions at small-x

[Ball et al.: JHEP 1504 (2015) 040]

[Alekhin et al.: EPJC 75 (2015) 304]

[REF Workshop: APPB 46 (2015) 2501]

Longitudinal fraction x decreases $\rightarrow$ transverse components become increasingly important



Modern Time: Intrinsic or Perturbative?

Structure Functions at small-x

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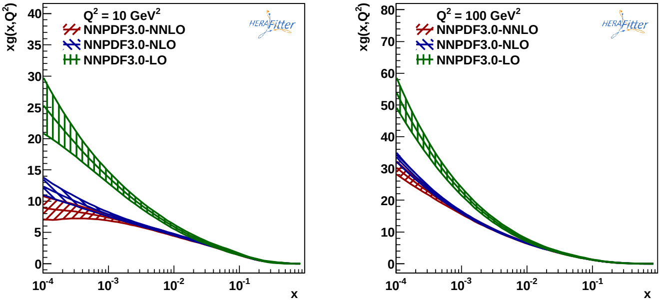
Higher-order perturbative corrections are large $\rightarrow$ uncertainty of the gluon pdfs increases



Modern Time: Intrinsic or Perturbative?

Structure Functions at small-x

[Catani, Hautmann: PLB 315 (1993) 157]

[Catani, Hautmann: NPB 427 (1994) 475]

[Catani, Ciafaloni, Hautmann: NPB 366 (1991) 135]

[REF Workshop: APPB 46 (2015) 2501]

- Longitudinal fraction x decreases $\rightarrow$ transverse components become increasingly important
- Higher-order perturbative corrections are large $\rightarrow$ uncertainty of the gluon pdfs increases
- Resummation of unordered multi-gluon emission $\rightarrow$ high-energy factorization + uPDFs
- $\ln \sqrt{s}/Q$ are resumed in all orders

Intrinsic Transverse Momentum: TMD Evolution

Good old time:

$$P(x, \mathbf{k}_\perp) = \int dz^- d^2 z_\perp \mathrm{e}^{-ik^+ z^- + ik_\perp z_\perp} \ \langle \psi_R(z) \gamma^+ \psi_R(0) \rangle |_{y^+=0}$$

$$\mu \frac{d}{d\mu} P(x, k_\perp; \mu) = 2\gamma_q P(x, k_\perp; \mu)$$

Modern view:

$$P_{\mathrm{unsubtr.}}(x, \mathbf{b}_\perp, n_B(y_b)) = \ldots$$

Intrinsic Transverse Momentum: TMD Evolution

Modern view:

[Collins: *Foundations of pQCD* **(2011)]**

[Rogers: EPJA 52 (2016) 153]

$$P_{\mathrm{unsubtr.}}(x, \mathbf{b}_\perp, n_B(y_b)) = \int dz^- \mathrm{e}^{-ik^+ z^-}$$

$$\times \langle \psi_R(z) \mathcal{W}^\dagger(z, \infty, n_B(y_b)) \gamma^+ \mathcal{W}(0, \infty, n_B(y_b)) \psi_R(0) \rangle |_{y^+=0}$$

Soft factor

$$P(x, \mathbf{b}_\perp, n_B(y_b)) = P_{\mathrm{unsubtr.}}(x, \mathbf{b}_\perp, n_B(y_b))$$

$$\times \sqrt{\frac{S_0(b_\perp; y_s, y_b)}{S_0(b_\perp, y_a, y_s) S_0(b_\perp, y_a, y_b)}}$$

Key Processes for TMD/uPDF Approaches at the LHC

[REF Workshop: APPB 46 (2015) 2501]

i DY (+ jets) lepton pair

ii Higgs (+ jets)

iii Heavy flavour

iv Quarkonium