

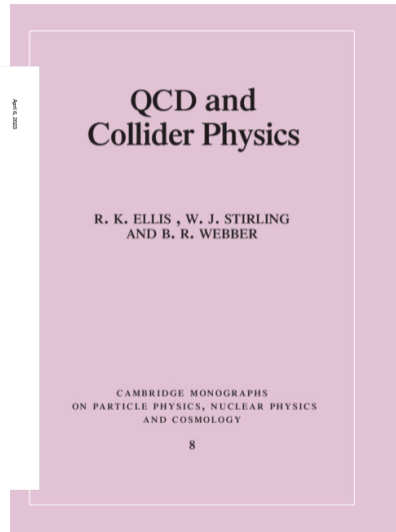
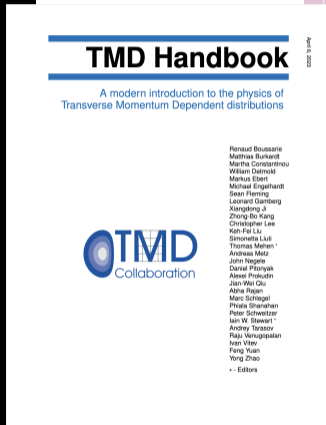
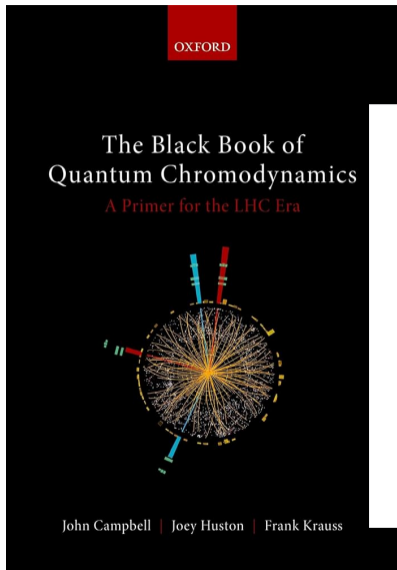



Shane Sweetman

Project update meeting

Student No: 22308373

A TMD-oriented analysis of $\pi^+\pi^-$ pairs in e^+e^- collisions



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Literature Review Notes: Fragmentation, Jets, and TMD Motivation

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SCOPE

These notes collect short summaries of the state references I am using for my thesis on transverse-momentum-sensitive observables in hadron-hadron collisions. Each paper title links to the associated PDF stored in my Google repository.

PAPERS

19. Fragmentation Functions in e^+e^- , ep , and pp Collisions

19. Fragmentation Functions in e^+e^- , ep , and pp Collisions

Revised August 2019 by O. Behr (Ludwig-Maximilians U.), D. de Florian (ICAS and ICFE, UNSAM), D. Mladon (Stockholm U.) and W. Vogelsang (Tübingen U.).

19.1 Introduction to Fragmentation

Quarks and gluons produced in hard-scattering reactions will ultimately give rise to the colorless hadronic bound states that may be observed in the detector. The associated hadronization process is described by fragmentation functions $D_i^h(x, \mu^2)$ ($i = q, \bar{q}, g$) which are universal functions representing, in the simplest picture, a measure of the probability density that an outgoing parton produces a hadron h . Thus, x is the fraction of the parton's momentum transferred to the hadron, and μ is a 'resolution' scale known as factorization scale. The $D_i^h(x, \mu^2)$ may be viewed as the final-state analogs of the initial-state parton distribution functions (PDFs) addressed in Section 18 of this Review. They are also sometimes referred to as timelike distributions since they are primarily accessed in e^+e^- annihilation via a timelike intermediate boson. (See Refs. [3, 2] for introductory reviews, and Refs. [3–6] for summaries of experimental and theoretical research in this field).

The clearest laboratory for the study of fragmentation functions is provided by semi-inclusive electro-positron annihilation, $e^+e^- \rightarrow \gamma/Z \rightarrow h + X$. The cross section for this reaction may be expressed in terms of fragmentation structure functions $F_{1,2,h}$ that are directly related to the fragmentation functions. At center-of-mass (CM) energy $\sqrt{s} = q^2$ we have

$$\frac{1}{s_0} \frac{d^2\sigma}{dx d\cos\theta} = \frac{1}{s_0} (1 + \cos^2\theta) F_1^h(x, q^2) + \frac{2}{s_0} \sin^2\theta F_2^h(x, q^2) + \frac{8}{s_0} \cos\theta F_3^h(x, q^2), \quad (19.1)$$

Here, q is the four-momentum of the intermediate photon or Z -boson, with $q^2 > 0$, and $s = 2E_1 E_2/q^2$ with the hadron's four-momentum P_h is the fragmentation counterpart of the familiar DIS Bjorken variable. (Note that $s = 2E_1 E_2/q^2 \leq 1$ in terms of the energy E_h of the produced hadron in the CM frame of the electron-positron pair.) Furthermore, in the same frame, θ is the hadron's angle relative to the electron beam direction. Eq. (19.1) is the most general form for unpolarized inclusive single-particle production via vector bosons [8]. The fragmentation structure functions F_1 and F_2 represent the contributions from γ/Z polarizations transverse or longitudinal with respect to the direction of motion of the hadron. The parity-violating term with the asymmetric fragmentation function F_3 arises from the interference between vector and axial-vector contributions. Various normalization factors s_0 are used in the literature, ranging from the total cross section σ_{tot} for $e^+e^- \rightarrow$ hadrons, including all weak and QCD contributions, to $s_0 = 4\pi\alpha^2 N_c / (3s)$ with $N_c = 3$, the lowest-order QED cross section for $e^+e^- \rightarrow \mu^+\mu^-$ times the number of colors N_c . LEPI measurements of the three fragmentation structure functions are shown in Fig. 19.1.

Integration of Eq. (19.1) over all θ yields the total fragmentation structure function $F^h \equiv F_1^h + F_2^h$

$$\frac{1}{s_0} \frac{d\sigma}{dx} = F^h(x, q^2) = \sum_{i=q,\bar{q},g} \sum_{h=p,\pi,K,\dots} C_i^h \left(\frac{z_i \alpha_s(\mu^2)}{4\pi} \right) D_i^h \left(\frac{x}{z_i}, \mu^2 \right) \quad (19.2)$$

On the right we have written the factorized expression for the structure function in terms of a sum over convolutions of the fragmentation functions D_i^h for partons $i = u, \bar{u}, d, \bar{d}, \dots, g$ with perturbative coefficient functions C_i^h . Since photons and Z bosons do not distinguish between quarks and antiquarks, e^+e^- annihilation primarily constrains the combinations $D_i^+ + D_i^-$. Given fragmentation contributions only at higher order in perturbation theory or by scaling violations. Corrections to the factorized expression in Eq. (19.2) are suppressed by higher powers of q^2 . They

Recap

- › Successfully graphed the pion p_T distributions for:
 - ›› the pion closest to the $q\bar{q}$ pair,
 - ›› the highest-momentum pion.
- › Did not differentiate between same-sign and opposite-sign pairs (OS/SS combined).

Aim(s)

- › Fragmentation in e^+e^- as a clean environment (final-state analogue of PDFs). [1,2,4]
- › Understand the hadronisation pictures used in event generators:
 - ›› Lund / string model (PYTHIA). [2,4]
 - ›› Cluster model (HERWIG). [2,4]
- › Recreate the same plots in HERWIG and compare shapes against PYTHIA. [2,4]

- Fragmentation functions $D_i^h(z, Q)$ encode how an outgoing parton turns into a hadron carrying longitudinal momentum fraction z at scale Q (final-state analogue of PDFs). [1,2,3]
- Here Q is the hard (factorisation/renormalisation) scale that sets the resolution of the probe, e.g. $Q \simeq \sqrt{s}$ in e^+e^- or $Q \sim M_Z$ at the Z pole. [1,2,3]
- Parton distribution functions (PDFs) $f_i(x, Q)$ describe the *initial-state* partonic content of an incoming hadron: the probability density to find a parton of flavour i carrying momentum fraction x when probed at scale Q . [1,2,3]
- In short: PDFs describe the *start* of the event (inside the incoming hadron), while FFs describe the *end* of the event (hadronisation of outgoing partons). [1,2,3]

Why phenomenology is unavoidable: Λ_{QCD} / Landau pole

From perturbative QCD to hadronisation

- ▶ Λ_{QCD} is the characteristic QCD scale (\sim a few 100 MeV) where the coupling becomes strong and confinement/non-perturbative physics sets the boundary between perturbative and hadronic descriptions. [4]

- ▶ The running coupling grows at low scales:

$$\alpha_s(Q^2) \sim \frac{1}{b_0 \ln(Q^2/\Lambda_{\text{QCD}}^2)} \quad \Rightarrow \quad Q \rightarrow \Lambda_{\text{QCD}} \text{ (Landau pole / breakdown of fixed-order pQCD)}$$

- ▶ In showers, evolution proceeds down to a cutoff $Q_0 \sim \mathcal{O}(1 \text{ GeV})$, where confinement dominates and hadrons must be modelled (not computed) \Rightarrow *phenomenological hadronisation models*. [4]

What the model is doing

- After showering to a hadronisation scale, colour flow is represented as a string/flux tube with roughly linear confinement potential, so energy grows as partons separate. [2,4]
- String breaking produces $q\bar{q}$ pairs iteratively, giving a chain of primary hadrons along the colour connection (then decays). [2,4]
- Pair creation at a string break is modelled as quantum tunnelling, giving a Schwinger-like suppression for transverse mass:

$$P \propto \exp\left(-\frac{\pi m_{\perp}^2}{\kappa}\right), \quad m_{\perp}^2 = m_q^2 + p_{\perp}^2$$

[2,4]

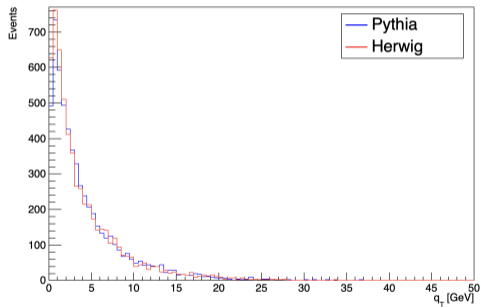
- Non-perturbative transverse momentum arises from the pair-creation (“string break”) step, with a characteristic transverse width feeding into hadron-level p_T observables. [2,4]

Cluster hadronisation: what is happening

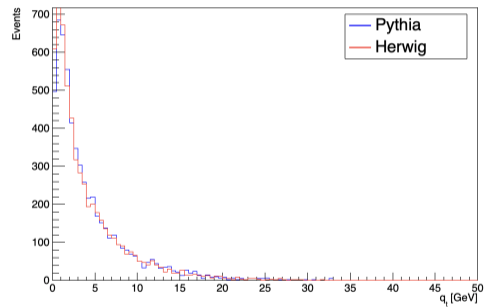
- The cluster model uses preconfinement: colour-connected partons at the shower cutoff form colour-singlet clusters with masses \sim hadronic scale. [2]
- At cutoff, remaining gluons are split $g \rightarrow q\bar{q}$, then colour-connected q and \bar{q} are paired into clusters. [2]
- Clusters decay into hadrons; overly massive clusters undergo fission (extra $q\bar{q}$ creation) before decaying. [2]

PYTHIA vs HERWIG: closest-to-quark selection

Opposite-sign ($\pi^+\pi^-$)
 q_T of opposite charge pion pair (closest to quark)

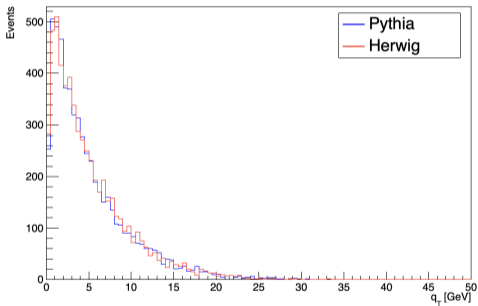


Same-sign ($\pi^\pm\pi^\pm$)
 q_l of same sign charge pion pair (closest to quark)

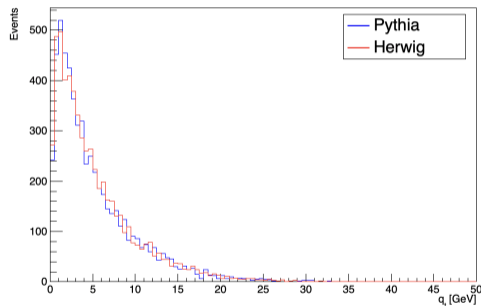


PYTHIA vs HERWIG: highest-momentum selection

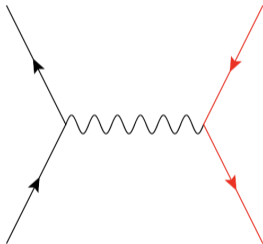
Opposite-sign ($\pi^+\pi^-$)
 q_T of opposite charge pion pair (highest momentum)



Same-sign ($\pi^\pm\pi^\pm$)
 q_l of same sign charge pion pair (highest momentum)

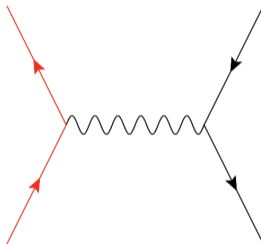


- Typical TMD “triad”: SIDIS, Drell–Yan, and back-to-back hadrons/jets in e^+e^- . [5]



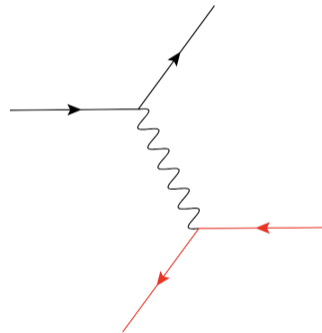
Hadronic Z decay

$$e^-e^+ \rightarrow \gamma^*/Z^0 \rightarrow q\bar{q} \\ \propto N_C$$



Drell-Yan

$$q\bar{q} \rightarrow \gamma^*/Z^0 \rightarrow \ell^+\ell^- \\ \propto 1/N_C$$



DIS

$$\ell\bar{q} \xrightarrow{\gamma^*/Z^0} \ell\bar{q} \\ \propto 1$$

For inclusive Drell–Yan, integrated over the full transverse-momentum range, collinear factorization gives

$$\frac{d\sigma}{dQ^2 dY} = \sum_{i,j} \int \frac{d\xi_a}{\xi_a} \frac{d\xi_b}{\xi_b} f_{i/H_a}(\xi_a) f_{j/H_b}(\xi_b) \frac{d\hat{\sigma}_{ij}(\xi_a, \xi_b)}{dQ^2 dY} \left[1 + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}^2}{Q^2}\right) \right].$$

(TMDH Eq. 2.2)

Here $Q^2 = q^2$ is the dilepton invariant mass, Y is the dilepton rapidity, and

$$x_a = \frac{Qe^{+Y}}{\sqrt{s}}, \quad x_b = \frac{Qe^{-Y}}{\sqrt{s}}.$$

(TMDH Eq. 2.3)

Key point (why PDFs can be enough here): because the observable is averaged over a large allowed range of dilepton transverse momentum, the detailed partonic transverse-momentum dependence is not numerically important; the collinear PDFs $f_{i/H}(\xi)$ (depending only on longitudinal fractions) capture the dominant structure. [5]

When PDFs are not enough: (TMDH p. 27)

Small transverse momentum ($\Lambda_{\text{QCD}} \lesssim q_T \ll Q$): the cross section becomes sensitive to intrinsic transverse momentum in the incoming hadrons \Rightarrow *TMD PDFs*,

$$\frac{d\sigma}{d^4q} = \frac{1}{s} \sum_{i \in \text{flavors}} \hat{\sigma}_{i\bar{i}}^{\text{TMD}}(Q) \int d^2\mathbf{k}_T f_{i/H_a}(x_a, \mathbf{k}_T) f_{\bar{i}/H_b}(x_b, \mathbf{q}_T - \mathbf{k}_T) \left[1 + \mathcal{O}\left(\frac{q_T^2}{Q^2}, \frac{\Lambda_{\text{QCD}}^2}{Q^2}\right) \right].$$

(TMDH Eq. 2.6)

Main point: momentum conservation forces \mathbf{k}_T to add up to \mathbf{q}_T , so the distribution is directly sensitive to transverse structure.

Why Fourier space is used: one often works with the b_T -space TMD,

$$\tilde{f}_{i/H}(x, \mathbf{b}_T) = \int d^2\mathbf{k}_T e^{-i\mathbf{b}_T \cdot \mathbf{k}_T} f_{i/H}(x, \mathbf{k}_T),$$

(TMDH Eq. 2.7)

which turns transverse-momentum convolutions into products and is convenient for resummation.

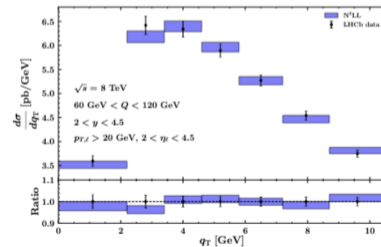
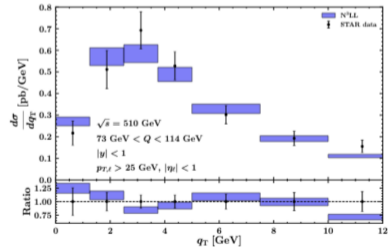
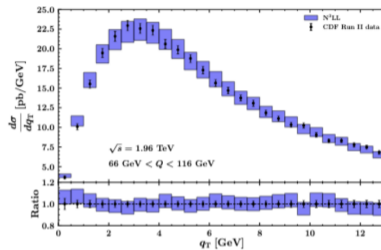
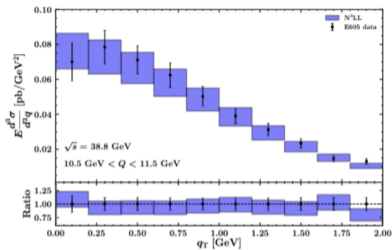
[5]

- ▶ In the notation of Bacchetta & Bertone et al. (Eq. 3.2), the fitted observable is the bin-averaged spectrum:

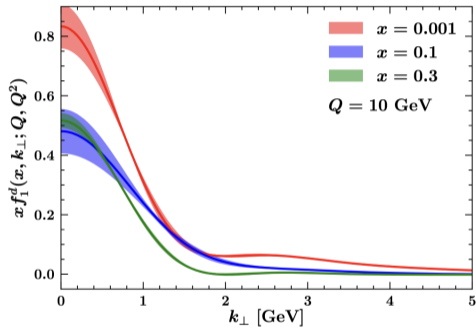
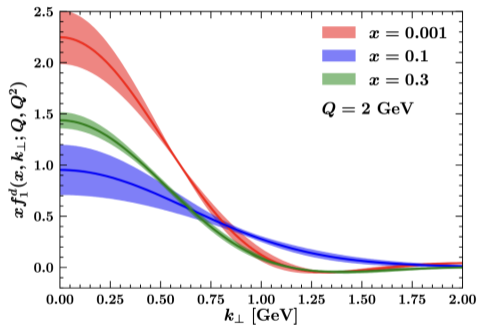
$$\left. \frac{d\sigma}{dq_T} \right|_{\text{bin}} = \frac{1}{q_{T,\text{max}} - q_{T,\text{min}}} \int_{y_{\text{min}}}^{y_{\text{max}}} dy \int_{Q_{\text{min}}}^{Q_{\text{max}}} dQ \int_{q_{T,\text{min}}}^{q_{T,\text{max}}} dq_T \frac{d\sigma}{dQ dy dq_T}.$$

- ▶ The kernel $\frac{d\sigma}{dQ dy dq_T}$ is computed with TMD resummation (up to N³LL) plus a fitted non-perturbative component, so the measured q_T shape directly constrains the unpolarised TMD PDFs. [6]

Global fit quality across experiments (q_T spectra) [6]



Example result: fit quality on q_T spectra [6]



Plan for thesis?

Physics / TMD background

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- 4 P. Z. Skands, *Introduction to QCD*, arXiv:1207.2389 (2012).
- 5 R. Boussarie et al. (TMD Collaboration), *TMD Handbook: A modern introduction to the physics of transverse momentum dependent distributions*, arXiv:2304.03302 (2023).
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Software / Herwig setup

- 7 J. Bellm et al., *Herwig 7.0 / Herwig++ 3.0 Release Note*, Eur. Phys. J. C76 (2016) 196, arXiv:1512.01178.
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