Shane Sweetman

Supervisor: Dr Ronan McNulty
Co-supervisors: Dr Valerio Bertone, Dr Francesco Bossu
Student No: 22308373

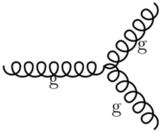
A TMD-oriented analysis of $\pi^+\pi^-$ pairs in e^+e^- collisions

QCD in one equation: the Lagrangian

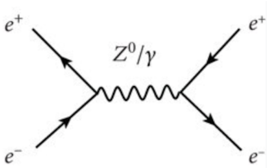
$$\mathcal{L}_{\mathrm{QCD}} = \underbrace{\bar{\psi}\, i\gamma^{\mu}\partial_{\mu}\psi}_{\text{kinetic}} + \underbrace{g_s\,\bar{\psi}\gamma^{\mu}t^{a}A^{a}_{\mu}\psi}_{\text{interaction}} - \underbrace{m_q\,\bar{\psi}\psi}_{\text{mass}} - \underbrace{\frac{1}{4}F^{a}_{\mu\nu}F^{a\,\mu\nu}}_{\text{gluon}} \qquad [4]$$

Non-Abelian $\Rightarrow$ gluon self-coupling.

[4]

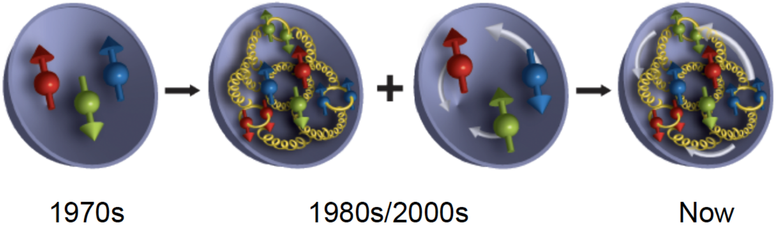


Proton model



Q sets resolution.

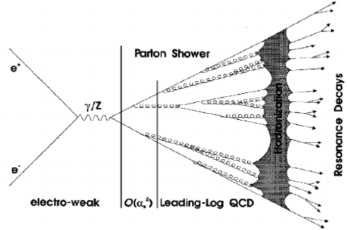
In e^+e^-: $Q = \sqrt{s}$ (typically γ^*/Z exchange).



QCD recap:

high $Q \Rightarrow \alpha_s$ small; low $Q \Rightarrow$ non-perturbative. [4]

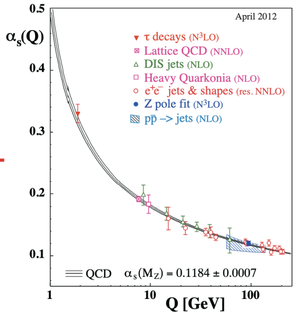
$$\alpha_s(Q^2) \sim \frac{1}{b_0 \ln\left(Q^2/\Lambda^2_{\mathrm{QCD}}\right)} \quad \Rightarrow \quad Q \to \Lambda_{\mathrm{QCD}} \quad \text{(Landau pole)}$$



Shower cutoff $Q_0 \sim \mathcal{O}(1\,\mathrm{GeV}) \Rightarrow$ hadronisation model. [4]

Landau Pole

& Confinement



Asymptotic Freedom

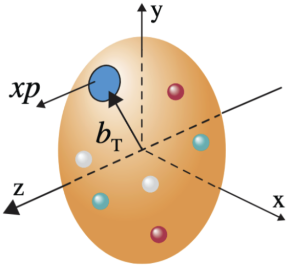
& Grand Unification?

PDFs

$f_i(x, Q)$

- **Initial state**: parton i inside a hadron.
- $x =$ longitudinal momentum fraction of the hadron.

[1,3,4]



FFs

$D_i^h(z, Q)$

- **Final state**: parton $i \to$ hadron h.
- $z =$ fraction of parton momentum carried by h.

[1,2,3]

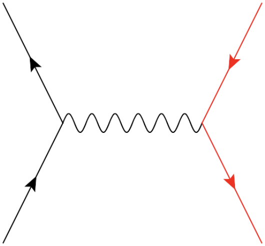
TMD

TMD PDFs/FFs add transverse momentum: $f_i(x, \boldsymbol{k}_T, Q)$, $D_i^h(z, \boldsymbol{k}_T, Q)$ ("3D": longitudinal + transverse). [3,5]

e^+e^- motivation (clean fragmentation)

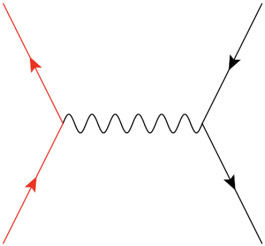
In e^+e^- there is **no hadronic initial state** $\Rightarrow$ no PDFs; focus is on the final-state fragmentation (FFs/TMD FFs). [1,2,3]

TMDs across reactions



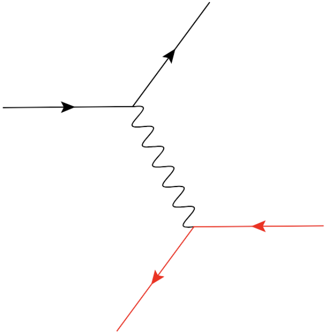
Hadronic Z decay

$e^-e^+ \to \gamma^*/Z^0 \to q\bar{q}$



Drell-Yan

$q\bar{q} \to \gamma^*/Z^0 \to \ell^+\ell^-$



DIS

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

When PDFs are enough vs when you need TMDs

Integrated over q_T (collinear)

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

Inclusive in q_T: PDFs capture the dominant structure. [5]

Small q_T (TMD-sensitive)

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

Differential in q_T: the *shape* probes transverse momentum. [5]

Often use Fourier/b_T space: $\tilde{f}(x,\boldsymbol{b}_T) = \int d^2\boldsymbol{k}_T\, e^{-i\boldsymbol{b}_T\cdot\boldsymbol{k}_T}\, f(x,\boldsymbol{k}_T)$ (convolutions $\rightarrow$ products). [5]

PYTHIA vs HERWIG (what is being tested)

How to extract? $\rightarrow$ need an observable **sensitive to TMDs**.

Plan (in this project)

- Use back-to-back jets in e^+e^- and study $\pi\pi$ pairs *within the two jets*. [3,5]
  - Define the pion in each jet either as: (i) **first/closest** to the parent parton, or (ii) **highest-momentum**. [2]

hadronisation is **non-perturbative** $\rightarrow$ need **phenomenological models**.

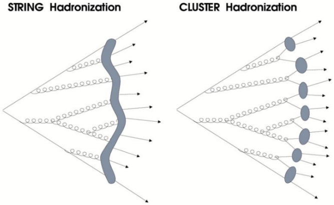
$$\textsc{Pythia} = \text{Lund/string} \qquad \textsc{Herwig} = \text{cluster}$$

[2,4]

PYTHIA vs HERWIG (hadronisation models)

PYTHIA

Lund/string: colour flux tube breaks $\rightarrow q\bar{q} \rightarrow$ hadrons. [2,4]



HERWIG

Cluster: colour-singlet clusters at shower cutoff $\rightarrow$ hadron decays. [2,4]

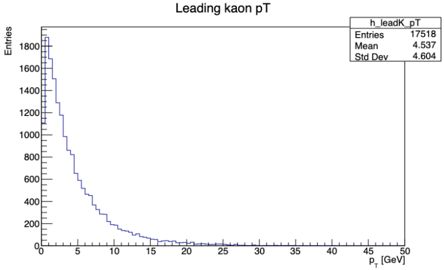
row	event	size	no	id	name	st	m1	m2	d1	d2	px	py	pz	E
0	3	134	0	90	system	-11	0	0	0	0	0.000	0.000	0.000	91.200
1	3	134	1	-11	e+	-12	0	0	3	0	0.000	0.000	45.600	45.600
2	3	134	2	11	e-	-12	0	0	4	0	0.000	0.000	-45.600	45.600
3	3	134	3	-11	e+	-21	1	0	5	0	0.000	0.000	45.600	45.600
4	3	134	4	11	e-	-21	2	0	5	0	0.000	0.000	-45.600	45.600
5	3	134	5	23	Z0	-22	3	4	6	7	0.000	0.000	0.000	91.200
6	3	134	6	1	d	-23	5	0	8	9	-44.829	7.850	2.821	45.600
7	3	134	7	-1	dbar	-23	5	0	10	10	44.829	-7.850	-2.821	45.600
8	3	134	8	1	d	-51	6	0	11	12	-41.505	0.505	4.102	41.711
9	3	134	9	21	g	-51	6	0	13	13	-0.289	6.813	-1.471	6.976

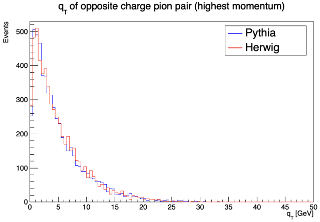
(showing rows 0 to 9 of 134 total)
More [Enter=+10, n=next event, q=quit]:

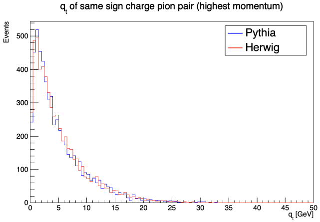
row	event	size	no	id	name	st	m1	m2	d1	d2	px	py	pz	E
80	3	134	80	-321	K-	83	57	73	0	0	-0.003	-0.112	-0.197	0.543
81	3	134	81	-3112	id-3112	-83	57	73	116	117	-3.258	0.221	-0.778	3.564
82	3	134	82	-211	pi-	83	57	73	0	0	-0.609	-0.776	0.336	1.051
83	3	134	83	211	pi+	83	57	73	0	0	-0.643	0.377	0.396	0.856
84	3	134	84	113	rho0	-84	57	73	97	98	0.230	0.721	-1.053	1.962
85	3	134	85	111	pi0	-84	57	73	118	119	0.908	0.129	-0.747	1.191
86	3	134	86	-213	rho-	-84	57	73	99	100	0.512	0.385	0.404	1.136
87	3	134	87	2212	p+	84	57	73	0	0	1.593	1.236	0.144	2.229
88	3	134	88	-211	pi-	84	57	73	0	0	0.647	-0.002	0.279	0.718
89	3	134	89	-2114	id-2114	-84	57	73	101	102	3.813	0.916	0.046	4.118

(showing rows 80 to 89 of 134 total)
More [Enter=+10, n=next event, q=quit]:

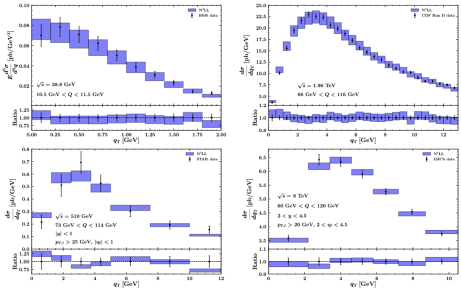
Current plots







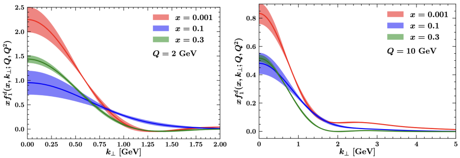
q_T spectra $\rightarrow$ TMD extraction (Drell–Yan example)



Low-q_T shape discriminates global fits. [6]

$\longrightarrow$

q_T data constrains TMD shape/parameters.



Target: summarise shapes with few parameters. [6]

Goal: use an analogous q_T-sensitive observable in e^+e^- to extract/compare TMD information. [6]

References I

1. O. Biebel, D. de Florian, D. Milstead, W. Vogelsang (PDG), *Fragmentation Functions in e^+e^-, ep, and pp Collisions (review)*, Prog. Theor. Exp. Phys. 2020, 083C01.
2. O. Biebel, P. Nason, B. R. Webber, *Jet fragmentation in e^+e^- annihilation*, arXiv:hep-ph/0109282v2 (2001).
3. A. Vossen, *Parton Fragmentation Functions*, arXiv:1702.01329 (2017).
4. P. Z. Skands, *Introduction to QCD*, arXiv:1207.2389 (2012).
5. R. Boussarie et al. (TMD Collaboration), *TMD Handbook*, arXiv:2304.03302 (2023).
6. A. Bacchetta et al., *Transverse-momentum-dependent parton distributions up to N^{3}LL from Drell-Yan data*, JHEP 07 (2020) 117, arXiv:1912.07550.