T-odd angular coefficients for Drell-Yan process with Z neutral boson

A. S. Zhevlakov[1]
in collaboration with V. E. Lyubovitskij, W. Vogelsang and F. Wunder[2]

[1]Bogoliubov Laboratory of Theoretical Physics, JINR

[2]Institut fur Theoretische Physik, Universität Tübingen

DSPIN 2023, 5 September 2023
Efremov-90

Outline

Plan

1. Drell-Yan - theory part

2. Drell-Yan -from experiment

Drell-Yan process

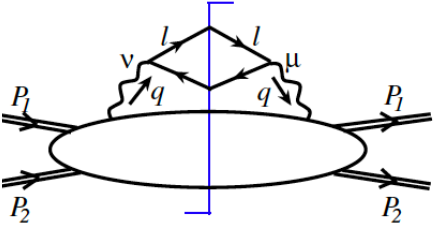


Figure: Diagrammatic representation of hadronic dilepton production via a virtual photon of four-momentum q.

Collins-Soper frame

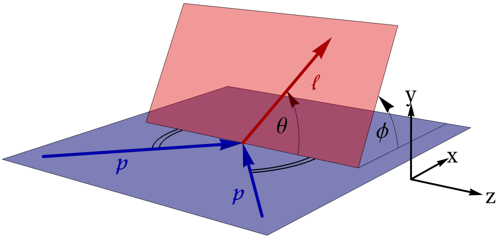


Figure: Definition of the polar and the azimuthal angles for the Drell-Yan process in the Collins-Soper frame.

Drell-Yan process $((\alpha_s)^0)$

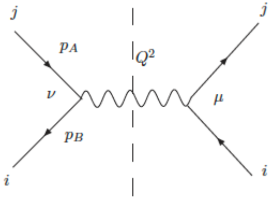


Figure: Born level

Drell-Yan process ($(\alpha_s)^0$)

In general the hadronic tensor for the DY reaction can be written in terms of the set of nine structure functions W_i and with the use of the basis of orthogonal unit vectors
$T^\mu = q^\mu/\sqrt{Q^2} = (1,0,0,0)$, $X^\mu = (0,1,0,0)$, $Z^\mu = (0,0,0,1)$,
$Y^\mu = \epsilon^{\mu\nu\alpha\beta} T_\nu Z_\alpha X_\beta = (0,0,1,0)$:

$$W^{\mu\nu} = (X^\mu X^\nu + Y^\mu Y^\nu) W_T \qquad (1)$$

Drell-Yan process $(\alpha_s)^1$

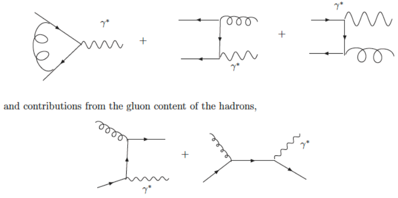


Figure: Diagram in parton level for Drell-Yan process $(\alpha_s)^1$

Drell-Yan process $(\alpha_s)^1$

In general the hadronic tensor for the DY reaction can be written in terms of the set of nine structure functions W_i and with the use of the basis of orthogonal unit vectors
$T^\mu = q^\mu/\sqrt{Q^2} = (1,0,0,0)$, $X^\mu = (0,1,0,0)$, $Z^\mu = (0,0,0,1)$,
$Y^\mu = \epsilon^{\mu\nu\alpha\beta} T_\nu Z_\alpha X_\beta = (0,0,1,0)$:

$$\begin{aligned} W^{\mu\nu} &= (X^\mu X^\nu + Y^\mu Y^\nu) W_T + Z^\mu Z^\nu W_L \\ &+ (Y^\mu Y^\nu - X^\mu X^\nu) W_{\Delta\Delta} - (X^\mu Z^\nu + Z^\mu X^\nu) W_\Delta \end{aligned} \tag{2}$$

Drell-Yan process $(\alpha_s)^1$ with Z

In general the hadronic tensor for the DY reaction can be written in terms of the set of nine structure functions W_i and with the use of the basis of orthogonal unit vectors
$T^\mu = q^\mu/\sqrt{Q^2} = (1,0,0,0)$, $X^\mu = (0,1,0,0)$, $Z^\mu = (0,0,0,1)$,
$Y^\mu = \epsilon^{\mu\nu\alpha\beta} T_\nu Z_\alpha X_\beta = (0,0,1,0)$:

with Z-boson

$$\begin{aligned} W^{\mu\nu} &= (X^\mu X^\nu + Y^\mu Y^\nu) W_T + i(X^\mu Y^\nu - Y^\mu X^\nu) W_{T_P} + Z^\mu Z^\nu W_L \\ &+ (Y^\mu Y^\nu - X^\mu X^\nu) W_{\Delta\Delta} - (X^\mu Z^\nu + Z^\mu X^\nu) W_\Delta + i(Y^\mu Z^\nu - Z^\mu Y^\nu) W_{\nabla_P}\,, \end{aligned} \quad (3)$$

Drell-Yan process with Z

In general the hadronic tensor for the DY reaction can be written in terms of the set of nine structure functions W_i and with the use of the basis of orthogonal unit vectors
$T^\mu = q^\mu/\sqrt{Q^2} = (1,0,0,0)$, $X^\mu = (0,1,0,0)$, $Z^\mu = (0,0,0,1)$,
$Y^\mu = \epsilon^{\mu\nu\alpha\beta} T_\nu Z_\alpha X_\beta = (0,0,1,0)$:
full structure is:

$$\begin{aligned} W^{\mu\nu} &= (X^\mu X^\nu + Y^\mu Y^\nu) W_T + i(X^\mu Y^\nu - Y^\mu X^\nu) W_{T_P} + Z^\mu Z^\nu W_L \\ &+ (Y^\mu Y^\nu - X^\mu X^\nu) W_{\Delta\Delta} - (X^\mu Y^\nu + Y^\mu X^\nu) W_{\Delta\Delta_P} \\ &- (X^\mu Z^\nu + Z^\mu X^\nu) W_\Delta - (Y^\mu Z^\nu + Z^\mu Y^\nu) W_{\Delta_P} \\ &+ i(Z^\mu X^\nu - X^\mu Z^\nu) W_\nabla + i(Y^\mu Z^\nu - Z^\mu Y^\nu) W_{\nabla_P} \end{aligned} \tag{4}$$

Lepton angular distributions $dN/d\Omega$ are expanded in terms of hadronic structure functions as

$$\frac{dN}{d\Omega} = \frac{3}{16\pi(2W_T + W_L)} \Big[g_T\, W_T + g_L\, W_L + g_\Delta\, W_\Delta + g_{\Delta\Delta}\, W_{\Delta\Delta} + g_{T_P}\, W_{T_P} + g_{\nabla_P}\, W_\nabla + g_\nabla\, W_\nabla + g_{\Delta\Delta_P}\, W_{\Delta\Delta_P} + g_{\Delta_P}\, W_{\Delta_P} \Big], \tag{5}$$

$$\frac{dN}{d\Omega} = \frac{3}{16\pi} \Big(1 + \cos^2\theta + \frac{A_0}{2}(1 - 3\cos^2\theta) + A_1 \sin 2\theta \cos\phi + \frac{A_2}{2}\sin^2\theta \cos 2\phi + A_3 \sin\theta\cos\phi + A_4\cos\theta + A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta\sin\phi \Big) \tag{6}$$

and

$$\frac{dN}{d\Omega} = \frac{3}{4\pi}\frac{1}{\lambda + 3} \Big(1 + \lambda\cos^2\theta + \mu \sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi + \tau \sin\theta\cos\phi + \eta\cos\theta + \xi\sin^2\theta\sin 2\phi + \zeta\sin 2\theta\sin\phi + \chi \sin\theta\sin\phi \Big). \tag{7}$$

Hadronic structure functions $W(x_1, x_2)$ relevant for the DY process with colliding of hadrons H_1 and H_2 are related to partonic-level structure functions $w^{ab}(x_1, x_2)$ in QCD by the collinear factorization formula

$$W(x_1, x_2) = \frac{1}{x_1 x_2} \sum_{a,b} \int_{x_1}^{1} dz_1 \int_{x_2}^{1} dz_2 \; w^{ab}(z_1, z_2) \, f_{a/H_1}\left(\frac{x_1}{z_1}\right) f_{b/H_2}\left(\frac{x_2}{z_2}\right) , \tag{8}$$

Feynman dyagram for T-odd Drell-Yan

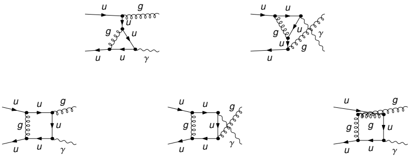


Figure: Diagrams describing NLO $u\bar{u} \to g\gamma$ subprocess at order $\mathcal{O}(\alpha_s^2)$.

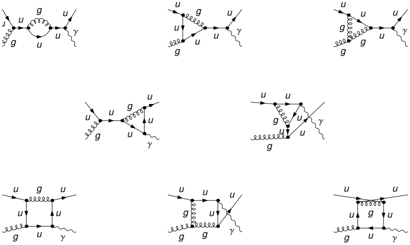


Figure: Diagrams describing NLO $ug \to u\gamma$ subprocess at order $\mathcal{O}(\alpha_s^2)$.

Calculation of T-odd helicity structures

In order to calculate the T-odd structure functions for convenience we use the orthogonal basis (P, R, K) [JHEP06(2021)066]:

$$
\begin{aligned}
P^\mu &= (p_1 + p_2)^\mu \,, \\
R^\mu &= (p_1 - p_2)^\mu \,, \\
K^\mu &= k_1^\mu - P^\mu \frac{P \cdot k_1}{P^2} - R^\mu \frac{R \cdot k_1}{R^2} = -q^\mu + P^\mu \frac{P \cdot q}{P^2} + R^\mu \frac{R \cdot q}{R^2}
\end{aligned}
\tag{9}
$$

obeying the conditions

$$
P^2 = -R^2 = \hat{s} \,, \quad K^2 = -\frac{\hat{u}\hat{t}}{\hat{s}} \,, \quad P \cdot R = P \cdot K = R \cdot K = 0 \,. \tag{10}
$$

Calculation of T-odd helicity structures

The (P, R, K) and (T, X, Y, Z) bases are related as:

$$\begin{aligned}
X^\mu &= \frac{T^\mu \sqrt{1+\rho^2}}{\rho} - \frac{P^\mu z_{12}^+ + R^\mu z_{12}^-}{2Q\rho\sqrt{1+\rho^2}} \\
&= \frac{\rho\left(P^\mu z_{12}^+ + R^\mu z_{12}^-\right)}{2Q\sqrt{1+\rho^2}} - \frac{K^\mu \sqrt{1+\rho^2}}{Q\rho}\,, \\
Z^\mu &= \frac{P^\mu z_{12}^- + R^\mu z_{12}^+}{2Q\sqrt{1+\rho^2}}\,, \\
Y^\mu &= -\,\epsilon^{\mu PRK}\frac{z_1 z_2}{Q^3\rho(1+\rho^2)}
\end{aligned} \tag{11}$$

where $z_{12}^\pm = z_1 \pm z_2$, $Q = \sqrt{Q^2}$, and $\epsilon^{\mu PRK} = \epsilon^{\mu\nu\alpha\beta} P_\nu R_\alpha K_\beta$. Here $z_i = x_i/\xi_i$ are the fraction parameters with $p_i = \xi_i P_i$, factors $x_{1,2} = e^{\pm y}\sqrt{(Q^2 + Q_T^2)/s}$ are the fractions of the longitudinal gauge boson momentum at finite Q_T. We also define the factors $x_{1,2}^0 = e^{\pm y}\, Q/\sqrt{s}$ at $Q_T^2 = 0$.

Calculation of T-odd helicity structures

Partonic-level T-odd structure functions are fixed as

$$
\begin{aligned}
w_{\Delta\Delta_P} &= -\frac{1}{2}(X^\mu Y^\nu + X^\nu Y^\mu)\, w_{\mu\nu} \\
&= -\frac{z_1 z_2}{4Q^4\rho^2(1+\rho^2)^{3/2}}\left[\epsilon^{\mu PRK}\left(P^\nu z_{12}^+ + R^\nu z_{12}^-\right) + \epsilon^{\nu PRK}\left(P^\mu z_{12}^+ + R^\mu z_{12}^-\right)\right] w_{\mu\nu}, \quad (12) \\
w_{\Delta_P} &= -\frac{1}{2}(Y^\mu Z^\nu + Y^\nu Z^\mu)\, w_{\mu\nu} \\
&= \frac{z_1 z_2}{4Q^4\rho(1+\rho^2)^{3/2}}\left[\epsilon^{\mu PRK}\left(P^\nu z_{12}^- + R^\nu z_{12}^+\right) + \epsilon^{\nu PRK}\left(P^\mu z_{12}^- + R^\mu z_{12}^+\right)\right] w_{\mu\nu}\,, \quad (13) \\
w_\nabla &= \frac{i}{2}(X^\mu Z^\nu - X^\nu Z^\mu)\, w_{\mu\nu} = \frac{i z_1 z_2}{2Q^2\rho(1+\rho^2)}\left(P^\nu R^\mu - P^\mu R^\nu\right) w_{\mu\nu}\,. \quad (14)
\end{aligned}
$$

Calculation of T-odd helicity structures

For $q\bar{q}$ annihilation we find

$$w^{q\bar{q}}_{\Delta\Delta_P} = \frac{g_{q\bar{q};1}}{2}\sqrt{\frac{Q^2\hat{s}}{(Q^2-\hat{u})(Q^2-\hat{t})}}\Bigg[-\frac{C_F}{2}\left(\frac{Q^2-\hat{t}}{Q^2-\hat{u}}+\frac{Q^2-\hat{u}}{Q^2-\hat{t}}\right)$$
$$+\; C_1\left(\frac{Q^2-\hat{t}}{\hat{t}}\left(1-\frac{\hat{s}}{\hat{t}}\log\frac{Q^2-\hat{u}}{\hat{s}}\right)+\frac{Q^2-\hat{u}}{\hat{u}}\left(1-\frac{\hat{s}}{\hat{u}}\log\frac{Q^2-\hat{t}}{\hat{s}}\right)\right)\Bigg], \quad (15)$$

$$w^{q\bar{q}}_{\Delta_P} = \frac{g_{q\bar{q};1}}{2}\frac{Q^2\hat{s}}{\sqrt{(Q^2-\hat{u})(Q^2-\hat{t})\hat{u}\hat{t}}}\Bigg[C_F\left(\frac{Q^2-\hat{t}}{Q^2-\hat{u}}-\frac{Q^2-\hat{u}}{Q^2-\hat{t}}\right)$$
$$+\; C_1\left(\frac{Q^2-\hat{u}}{\hat{u}}\log\frac{Q^2-\hat{t}}{\hat{s}}-\frac{Q^2-\hat{t}}{\hat{t}}\log\frac{Q^2-\hat{u}}{\hat{s}}\right)\Bigg], \quad (16)$$

$$w^{q\bar{q}}_{\nabla} = g_{q\bar{q};2}\sqrt{\frac{Q^2\hat{s}}{\hat{u}\hat{t}}}\Bigg[\frac{C_F}{2}\frac{(2Q^2\hat{s}+\hat{u}\hat{t})(Q^2+\hat{s})(\hat{u}-\hat{t})}{(Q^2-\hat{u})^2(Q^2-\hat{t})^2}$$
$$+\; C_1\left(-\frac{Q^2(\hat{u}-\hat{t})}{(Q^2-\hat{u})(Q^2-\hat{t})}+\frac{\hat{s}}{\hat{u}}\log\frac{Q^2-\hat{t}}{\hat{s}}-\frac{\hat{s}}{\hat{t}}\log\frac{Q^2-\hat{u}}{\hat{s}}\right)\Bigg]. \quad (17)$$

$$w^{q\bar{q}}_{\Delta\Delta_P} = -\frac{g_{q\bar{q};1}}{4z_1z_2}\frac{1}{\sqrt{1+\rho^2}}\left[\Big(C_F - C_1\Big)(z_1^2+z_2^2) + C_1\Big(z_1^2F_1(z_2)+z_2^2F_1(z_1)\Big)\right], \quad (18)$$

$$w^{q\bar{q}}_{\Delta_P} = -\frac{g_{q\bar{q};1}}{2z_1z_2}\frac{1}{\rho\sqrt{1+\rho^2}}\left[\Big(C_F - C_1\Big)(z_1^2-z_2^2) + C_1\Big(z_1^2F_2(z_2)-z_2^2F_2(z_1)\Big)\right], \quad (19)$$

$$w^{q\bar{q}}_{\nabla} = -\frac{g_{q\bar{q};2}}{z_1z_2}\frac{1}{\rho}\left[\Big(C_F\Big(1-\frac{\rho^2}{2(1+\rho^2)}\Big) - C_1\Big)(z_1^2-z_2^2) + C_1\Big(z_1F_2(z_2)-z_2F_2(z_1)\Big)\right] \quad (20)$$

Here, the functions F_1 and F_2 are defined as:

$$F_1(z) = \frac{1+z}{1-z} + \frac{2z\log(z)}{(1-z)^2} = 2\sum_{N=1}^{\infty}\frac{(1-z)^N}{(N+1)(N+2)} = \mathcal{O}(1-z)$$

$$, \quad F_2(z) = 1 + \frac{z\log(z)}{1-z} = \frac{1-z}{2}\Big(1+F_1(z)\Big) = \sum_{N=1}^{\infty}\frac{(1-z)^N}{N(N+1)} = \mathcal{O}(1-z)\,. \quad (21)$$

We have full agreement with results obtained in Refs. [Phys.Rev.Lett.52 Kaoru Hagiwara, Ken-ichi Hikasa,Naoyuki Kai and in Nucl.Phys.B 387 (1992) 3—85 E. Mirkes.]

ρ^2 – expansion

From the phase space

$$S(2\pi)^4\delta(p_1+p_2-q-p_4)\frac{d^3p_4}{(2\pi)^3 2E_4} = 2\pi S\delta(s+t+u-Q^2) \quad (22)$$

In the calculation of the phase space factor corresponding to the one-parton production we get the well-known delta function (see, e.g., in Ref. [D. Boer and P. J. Mulders PhysRevD.57.5780]) relevant for he DY process

$$\delta\Big((1-z_1)(1-z_2) - \frac{\rho^2}{1+\rho^2} z_1 z_2\Big)\, \varphi(z_1,z_2)\,. \quad (23)$$

ρ^2 – expansion

From Gelfand-Shilov:

$$\delta(xy - c) = -2\delta(x, y)\ln c + \left(\frac{\delta(y)}{x} + \frac{\delta(x)}{y}\right) + o(c).$$

$$\delta(G - c) = \delta(G) - c\delta'(G) + \frac{c^2}{2}\delta''(G) + \ldots + \frac{(-1)^k}{k!}\delta^{(k)}(G) + \ldots$$

ρ^2 – expansion

In $Q_T Q \to 0$ limit we can use famous expansion for delta-function which comes from phase space factor

$$\frac{S}{z_1 z_2}\delta(\hat{s}+\hat{t}+\hat{u}-Q^2) \Rightarrow \frac{1}{x_1 x_2}\left[\frac{\delta(1-z_2)}{(1-z_1)_+}+\frac{\delta(1-z_1)}{(1-z_2)_+} + \delta(1-z_1)\delta(1-z_2)\ln\frac{Q^2}{Q_\perp^2}\right]. \quad (23)$$

The standard definition of "+" distribution is

$$\int_x^1 dz \frac{f(z)}{(1-z)_+} = \int_x^1 dz \frac{f(z)-f(1)}{(1-z)} + f(1)\ln(1-x).$$

ρ^2 – expansion

$$
\begin{aligned}
W^{\mathrm{LO};q\bar q}_{\Delta\Delta_P}(x_1^0,x_2^0) &= -\frac{g_{q\bar q;1}}{4x_1^0x_2^0}\,(C_F - C_1)\,(2\log\rho^2+3)\,q_1(x_1^0)\,\bar q_2(x_2^0)\\
&- \frac{g_{q\bar q;1}}{4x_1^0x_2^0}\,\frac{C_F - C_1}{C_F}\left[\int_{x_2^0}^{1}\frac{dz_2}{z_2}\,P_{qq}(z_2)\,q_1(x_1^0)\,\bar q_2\left(\frac{x_2^0}{z_2}\right) + \int_{x_1^0}^{1}\frac{dz_1}{z_1}\,P_{qq}(z_1)\,q_1\left(\frac{x_1^0}{z_1}\right)\bar q_2(x_2^0)\right]\\
&- \frac{g_{q\bar q;1}}{4x_1^0x_2^0}\,C_1\left[\int_{x_2^0}^{1}\frac{dz_2}{z_2}\,f_1(z_2)\,q_1(x_1^0)\,\bar q_2\left(\frac{x_2^0}{z_2}\right) + \int_{x_1^0}^{1}\frac{dz_1}{z_1}\,f_1(z_1)\,q_1\left(\frac{x_1^0}{z_1}\right)\bar q_2(x_2^0)\right], \qquad (24)\\
W^{\mathrm{LO};q\bar q}_{\nabla}(x_1^0,x_2^0) &= 2\,\frac{g_{\mathrm{EW};1}}{g_{\mathrm{EW};2}}\,W^{\mathrm{LO};q\bar q}_{\Delta_P}(x_1^0,x_2^0)\\
&= -\frac{g_{q\bar q;1}}{\rho\,x_1^0x_2^0}\,\frac{C_F - C_1}{C_F}\left[\int_{x_2^0}^{1}\frac{dz_2}{z_2}\,\tilde P_{qq}(z_2)\,q_1(x_1^0)\,\bar q_2\left(\frac{x_2^0}{z_2}\right) - \int_{x_1^0}^{1}\frac{dz_1}{z_1}\,\tilde P_{qq}(z_1)\,q_1\left(\frac{x_1^0}{z_1}\right)\bar q_2(x_2^0)\right]\\
&- \frac{g_{q\bar q;1}}{\rho x_1^0x_2^0}\,C_1\left[\int_{x_2^0}^{1}\frac{dz_2}{z_2}\,f_2(z_2)\,q_1(x_1^0)\,\bar q_2\left(\frac{x_2^0}{z_2}\right) - \int_{x_1^0}^{1}\frac{dz_1}{z_1}\,f_2(z_1)\,q_1\left(\frac{x_1^0}{z_1}\right)\bar q_2(x_2^0)\right], \qquad (25)
\end{aligned}
$$

$$W^{\mathrm{LO};qg}_{\Delta\Delta_P}(x_1^0, x_2^0) = -\frac{g_{qg;1}}{4x_1^0 x_2^0} \int\limits_{x_2^0}^{1} \frac{dz_2}{z_2}\, P'_{qg}(z_2) q(x_1^0)\, g\left(\frac{x_2^0}{z_2}\right), \tag{26}$$

$$W^{\mathrm{LO};qg}_{\nabla}(x_1^0, x_2^0) = 2\,\frac{g_{\mathrm{EW};1}}{g_{\mathrm{EW};2}}\, W^{\mathrm{LO};qg}_{\Delta_P}(x_1^0, x_2^0) = \frac{g_{qg;1}}{\rho\, x_1^0 x_2^0} \int\limits_{x_2^0}^{1} \frac{dz_2}{z_2}\, P''_{qg}(z_2) q(x_1^0)\, g\left(\frac{x_2^0}{z_2}\right), \tag{27}$$

where

$$\begin{aligned}
P_{qq}(z) &= C_F\left[\frac{1+z^2}{(1-z)_+} + \frac{3}{2}\delta(1-z)\right], \\
\tilde{P}_{qq}(z) &= C_F(1+z), \\
P'_{qg}(z,\rho^2) &= C_F(1+2z) + C_1 z\,(2\log\rho^2 - z), \\
P''_{qg}(z,\rho^2) &= C_F(1-z) + C_1 z\,(\log\rho^2(1-z) + 1 - 2z).
\end{aligned} \tag{28}$$

Here

$$f_i(z) = \frac{F_i(z)}{1-z} \tag{29}$$

Sample frame title

For W_L and $W_{\Delta\Delta}$ we have Lam-Tung relation. This relation is work in LO and violate at high ρ^2 in NNLO (α_s^2) order. [Nucl.Phys.B 387 (1992) 3—85 E. Mirkes.; JHEP 11 (2017) 003 R. Gauld and etc.]

For T-odd structure helicity hadron fuctions of Drell-Yan process, we obtain new relation which exist at low ρ^2

Relation for T-odd

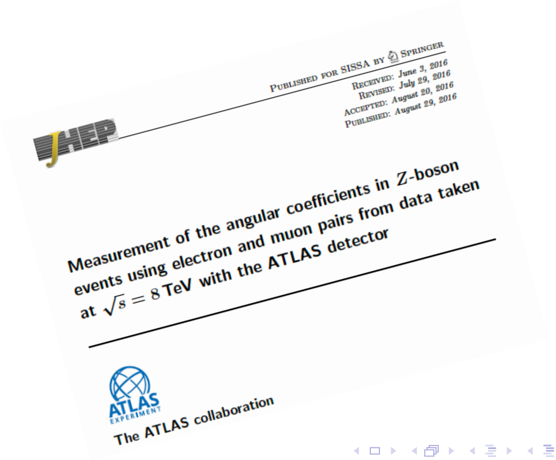
$$W_{\nabla}^{\mathrm{LO};ab}(x_1^0, x_2^0) = 2\,\frac{g_{\mathrm{EW};1}}{g_{\mathrm{EW};2}}\,W_{\Delta_P}^{\mathrm{LO};ab}(x_1^0, x_2^0) \tag{30}$$

at small $\rho^2 = Q_T^2/Q^2$.

Plan

Experiment measurents

Experimental measurements of T-odd $A_{5,6,7}$ angular coefficients were done in 2016.



JHEP
Published for SISSA by Springer
Received: June 3, 2016
Revised: July 29, 2016
Accepted: August 20, 2016
Published: August 29, 2016

Measurement of the angular coefficients in Z-boson events using electron and muon pairs from data taken at $\sqrt{s} = 8$ TeV with the ATLAS detector

ATLAS EXPERIMENT
The ATLAS collaboration

y^Z-binned A_5			
p_T^Z range [GeV]	$0 < \lvert y^Z \rvert < 1$	$1 < \lvert y^Z \rvert < 2$	$2 < \lvert y^Z \rvert < 3.5$
0.0–2.5	-0.002 ± 0.005 ± 0.003	0.000 ± 0.007 ± 0.004	-0.030 ± 0.072 ± 0.025
2.5–5.0	-0.003 ± 0.002 ± 0.001	-0.002 ± 0.003 ± 0.002	0.012 ± 0.026 ± 0.009
5.0–8.0	-0.003 ± 0.002 ± 0.001	-0.001 ± 0.002 ± 0.001	0.013 ± 0.015 ± 0.005
8.0–11.4	-0.002 ± 0.002 ± 0.001	0.000 ± 0.002 ± 0.001	0.006 ± 0.013 ± 0.005
11.4–14.9	0.000 ± 0.002 ± 0.001	0.003 ± 0.002 ± 0.001	0.004 ± 0.013 ± 0.005
14.9–18.5	0.000 ± 0.002 ± 0.001	0.004 ± 0.002 ± 0.001	0.000 ± 0.014 ± 0.005
18.5–22.0	0.002 ± 0.002 ± 0.001	0.005 ± 0.002 ± 0.001	0.004 ± 0.016 ± 0.005
22.0–25.5	0.003 ± 0.002 ± 0.001	0.005 ± 0.002 ± 0.001	0.013 ± 0.018 ± 0.006
25.5–29.0	0.003 ± 0.002 ± 0.001	0.004 ± 0.003 ± 0.001	0.012 ± 0.020 ± 0.006
29.0–32.6	0.004 ± 0.002 ± 0.001	0.003 ± 0.003 ± 0.001	0.025 ± 0.022 ± 0.007
32.6–36.4	0.004 ± 0.002 ± 0.001	0.002 ± 0.003 ± 0.001	0.026 ± 0.023 ± 0.008
36.4–40.4	0.003 ± 0.003 ± 0.001	0.001 ± 0.003 ± 0.002	0.041 ± 0.025 ± 0.008
40.4–44.9	0.002 ± 0.003 ± 0.002	0.001 ± 0.004 ± 0.002	0.030 ± 0.025 ± 0.008
44.9–50.2	0.002 ± 0.003 ± 0.002	0.002 ± 0.004 ± 0.002	0.025 ± 0.023 ± 0.009
50.2–56.4	0.001 ± 0.003 ± 0.002	0.004 ± 0.004 ± 0.002	0.002 ± 0.025 ± 0.010
56.4–63.9	0.001 ± 0.003 ± 0.002	0.006 ± 0.004 ± 0.002	-0.014 ± 0.026 ± 0.011
63.9–73.4	0.001 ± 0.004 ± 0.002	0.009 ± 0.005 ± 0.002	-0.010 ± 0.028 ± 0.012
73.4–85.4	0.003 ± 0.005 ± 0.002	0.011 ± 0.005 ± 0.003	-0.052 ± 0.032 ± 0.014
85.4–105	0.006 ± 0.005 ± 0.003	0.010 ± 0.006 ± 0.003	0.005 ± 0.049 ± 0.026
105–132	0.011 ± 0.006 ± 0.003	0.006 ± 0.007 ± 0.004	
132–173	0.018 ± 0.008 ± 0.004	-0.004 ± 0.010 ± 0.005	
173–253	0.030 ± 0.014 ± 0.007	-0.023 ± 0.017 ± 0.008	
253–600	0.045 ± 0.025 ± 0.012	-0.055 ± 0.031 ± 0.014	

Table 19. The angular coefficient $A_5 \pm \delta_{\text{stat}} \pm \delta_{\text{syst}}$ in bins of y^Z.

	$p_{\mathrm{T}}^{Z} = 5 - 8\,\mathrm{GeV}$		$p_{\mathrm{T}}^{Z} = 22 - 25.5\,\mathrm{GeV}$		$p_{\mathrm{T}}^{Z} = 132 - 173\,\mathrm{GeV}$	
	NLO	NNLO	NLO	NNLO	NLO	NNLO
A_0	$0.0115^{+0.0006}_{-0.0003}$	$0.0150^{+0.0006}_{-0.0008}$	$0.1583^{+0.0008}_{-0.0009}$	$0.1577^{+0.0041}_{-0.0018}$	$0.8655^{+0.0008}_{-0.0006}$	$0.8697^{+0.0017}_{-0.0023}$
A_2	$0.0113^{+0.0004}_{-0.0004}$	$0.0060^{+0.0010}_{-0.0017}$	$0.1588^{+0.0014}_{-0.0009}$	$0.1161^{+0.0092}_{-0.0028}$	$0.8632^{+0.0013}_{-0.0009}$	$0.8012^{+0.0073}_{-0.0215}$
$A_0 - A_2$	$0.0002^{+0.0007}_{-0.0005}$	$0.0090^{+0.0014}_{-0.0013}$	$-0.0005^{+0.0016}_{-0.0012}$	$0.0416^{+0.0036}_{-0.0067}$	$0.0023^{+0.0015}_{-0.0011}$	$0.0685^{+0.0200}_{-0.0082}$
A_1	$0.0052^{+0.0004}_{-0.0003}$	$0.0074^{+0.0020}_{-0.0008}$	$0.0301^{+0.0013}_{-0.0013}$	$0.0405^{+0.0014}_{-0.0038}$	$0.0600^{+0.0013}_{-0.0015}$	$0.0611^{+0.0018}_{-0.0023}$
A_3	$0.0004^{+0.0002}_{-0.0001}$	$0.0012^{+0.0003}_{-0.0006}$	$0.0066^{+0.0003}_{-0.0005}$	$0.0070^{+0.0017}_{-0.0020}$	$0.0545^{+0.0003}_{-0.0016}$	$0.0584^{+0.0018}_{-0.0047}$
A_4	$0.0729^{+0.0023}_{-0.0006}$	$0.0757^{+0.0021}_{-0.0025}$	$0.0659^{+0.0019}_{-0.0003}$	$0.0672^{+0.0018}_{-0.0050}$	$0.0253^{+0.0007}_{-0.0002}$	$0.0247^{+0.0024}_{-0.0018}$
A_5	$0.0001^{+0.0002}_{-0.0002}$	$0.0001^{+0.0007}_{-0.0007}$	< 0.0001	$0.0011^{+0.0013}_{-0.0030}$	$-0.0004^{+0.0005}_{-0.0005}$	$0.0044^{+0.0042}_{-0.0026}$
A_6	$-0.0002^{+0.0002}_{-0.0003}$	$0.0013^{+0.0006}_{-0.0005}$	$0.0004^{+0.0006}_{-0.0004}$	$0.0017^{+0.0043}_{-0.0015}$	$0.0003^{+0.0003}_{-0.0006}$	$0.0028^{+0.0017}_{-0.0018}$
A_7	< 0.0001	$0.0014^{+0.0007}_{-0.0004}$	$0.0002^{+0.0003}_{-0.0007}$	$0.0024^{+0.0013}_{-0.0013}$	$0.0003^{+0.0004}_{-0.0007}$	$0.0048^{+0.0027}_{-0.0012}$

Table 1. Summary of predictions from DYNNLO at NLO and NNLO for A_0, A_2, $A_0 - A_2$, A_1, A_3, A_4, A_5, A_6, and A_7 at low (5–8 GeV), mid (22–25.5 GeV), and high (132–173 GeV) p_{T}^{Z} for the y^{Z}-integrated configuration. The uncertainty represents the sum of statistical and systematic uncertainties.

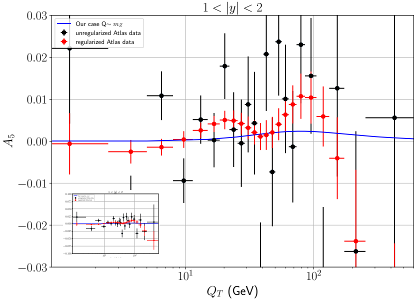


Figure: Comparison of analytical results for the A_5 coefficient at $Q \sim m_Z$ with ATLAS data [JHEP 08 (2016) 159]. Black and red experimental points denote data with statistical error and regularized points [JHEP 08 (2016) 159], respectively. Results for rapidity $1 < |y| < 2$. The scale of the y-axis is chosen to enhance visibility of the small predicted values of $A_{5,6,7}$. Some data points fall outside this range. Full set of data in small scale is shown in the left lower corner of Figure.

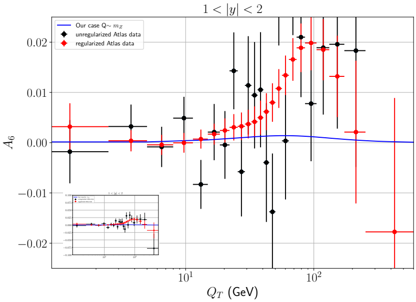


Figure: Comparison of analytical results for the A_6 angular coefficient at $Q \sim m_Z$ with ATLAS data [JHEP 08 (2016) 159] for rapidity $1 < |y| < 2$. Black and red experimental points denote data with statistical error and regularized points [JHEP 08 (2016) 159], respectively.

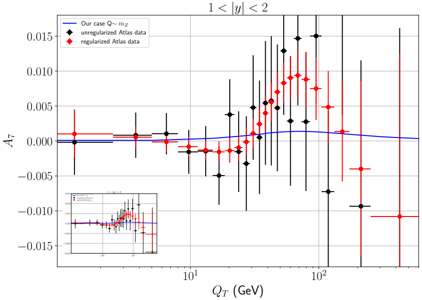


Figure: Comparison of analytical results for the A_7 coefficient at $Q \sim m_Z$ with ATLAS data [JHEP 08 (2016) 159]. Black and red experimental points denote data with statistical error and regularized points [JHEP 08 (2016) 159], respectively.

Summary

- T-odd helicity structure function for Drell-Yan process was obtained. In limit of small $\rho^2 = Q_T^2/Q^2$, we have new identity for W_∇ and W_{Δ_P}.
- We need additional experimental analysis of T-odd structures for Drell-Yan process with Z and W weak boson creation.