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Constraints on the Collins Function from New $e^+e^- \to h_1h_2X$ Measurements in a Leading Order Analysis

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New data from the BaBar Collaborations, on azimuthal correlations measured for pairs of pions produced in e^+e^- annihilations, are analysed together with analogous, previous data from the BELLE Collaboration and with Semi-Inclusive Deep Inelastic scattering (SIDIS) data, for a simultaneous extraction of transversity and the Collins function. Special attention is devoted to the $p_\perp$ dependence of the Collins favoured and disfavoured functions. A comparison with BESIII new measurements allows a preliminary study on the sensitivity of azimuthal asymmetries on TMD evolution effects.

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1. Introduction

The Collins fragmentation function can be studied in Semi-Inclusive Deep Inelastic Scattering (SIDIS) experiments, where it appears convoluted with the transversity distribution, and where, being dependent on the hadronic intrinsic transverse momentum, it induces a typical azimuthal modulation, the Collins asymmetry. Clear signals of a non-zero Collins asymmetry in SIDIS processes were detected at HERMES [1] and COMPASS [2, 3]. The Collins fragmentation functions also induce azimuthal angular correlations between hadrons produced in opposite jets in e^+e^- annihilations: here two of such functions, corresponding to the two final hadrons, appear convoluted. Consequently, a simultaneous analysis of SIDIS and e^+e^- data allows the combined extraction of the transversity Parton Distribution Function (PDF) and the Collins Fragmentation Function (FF) [4, 5, 6].

Recently, new data on the $e^+e^- \to h_1\, h_2\, X$ process have been published by the BaBar Collaboration, focusing on their z and $p_\perp$ dependence [7]. It is the first direct measurement of the transverse momentum dependence of an asymmetry, in e^+e^- processes, related to transverse momentum dependent (TMD) functions. In particular, BaBar measures the A_0 asymmetry as a function of P_{1T}, the transverse momentum of the final hadron h_1 with respect to the plane which contains both the e^+e^- pair and the other final hadron, h_2, in the e^+e^- c.m. frame. These measurements will be the focus of this talk. Indeed, information on the transverse momentum dependence of the asymmetries thus allows a first glance at the dependence of the Collins FFs on the transverse momentum, $p_\perp$.

The explicit dependence of the TMDs on their corresponding momentum fractions x or z is relatively easy to access, as most measured observables (cross sections, multiplicities, asymmetries) are given as functions of x_B or z_h, although in a limited range. Notice that $x = x_B$ and $z = z_h$ at leading order. Instead, gathering information on the transverse momentum dependence is a much more involved task, as $k_\perp$ and $p_\perp$ are never observed directly but only through convolutions. Asymmetries alone are not sufficient for a complete study of the Collins transverse momentum dependence, as they require the knowledge of the unpolarised TMD fragmentation functions, which appear in the denominator of the asymmetry.

The study presented here, entirely based on Ref. [8], cannot deliver an absolute determination of the Collins function. However, our analysis of the new BaBar measurements allows to obtain the relative TMD behaviour of the Collins function with respect to that of the unpolarised TMD–FF. In this paper we adopt a phenomenological model for TMD–PDFs and FFs in a scheme where the cross section is written as the convolution of two TMDs with the corresponding partonic cross section. Moreover, we assume that the TMD longitudinal and transverse degrees of freedom factorize. The z-dependent part of our TMDs evolves in Q^2 while the transverse momentum dependent part, assumed to be a Gaussian, is Q^2 independent.

Newest results from the BESIII Collaboration [9], at much lower Q^2 values with respect to Belle and BaBar data, confirm the need of having non vanishing Collins functions. We do not include them in our fitting procedure, but rather we will compare our determination of the Collins functions with these new results, and explore the sensitivity of these azimuthal correlations on Q^2 dependent effects.

2. Formalism

In SIDIS processes, at $\mathcal{O}(k_\perp/Q)$, the $\sin(\phi_h+\phi_S)$ moment of the measured spin asymmetry A_{UT} [10], is proportional to the spin dependent part of the fragmentation function of a transversely polarised quark, encoded in the Collins function, $\Delta^N D_{h/q^\uparrow}(z,p_\perp)$, convoluted with the TMD transversity distribution $\Delta_T q(x,k_\perp)$ [4]. As mentioned above, we adopt a Gaussian and factorized parameterisation for the TMDs. For the unpolarised parton distribution and fragmentation functions we assume:

$$f_{q/p}(x,k_\perp) = f_{q/p}(x)\,\frac{e^{-k_\perp^2/\langle k_\perp^2\rangle}}{\pi\langle k_\perp^2\rangle}\,, \qquad D_{h/q}(z,p_\perp) = D_{h/q}(z)\,\frac{e^{-p_\perp^2/\langle p_\perp^2\rangle}}{\pi\langle p_\perp^2\rangle}\,, \tag{2.1}$$

with fixed Gaussian widths $\langle k_\perp^2\rangle = 0.57\,\mathrm{GeV}^2$ and $\langle p_\perp^2\rangle = 0.12\,\mathrm{GeV}^2$, as found in Ref. [11]. For the transversity distribution, $\Delta_T q(x,k_\perp)$, and the Collins FF, $\Delta^N D_{h/q^\uparrow}(z,p_\perp)$, we adopt the following factorized shapes [4]:

$$\Delta_T q(x,k_\perp;Q^2) \;=\; \Delta_T q(x,Q^2)\,\frac{e^{-k_\perp^2/\langle k_\perp^2\rangle_T}}{\pi\langle k_\perp^2\rangle_T}\,, \tag{2.2}$$

$$\Delta^N D_{h/q^\uparrow}(z,p_\perp;Q^2) \;=\; \tilde{\Delta}^N D_{h/q^\uparrow}(z,Q^2)\,h(p_\perp)\,\frac{e^{-p_\perp^2/\langle p_\perp^2\rangle}}{\pi\langle p_\perp^2\rangle}\,, \tag{2.3}$$

where $\Delta_T q(x)$ is the integrated transversity distribution and $\tilde{\Delta}^N D_{h/q^\uparrow}(z)$ is the z-dependent part of the Collins function. In order to easily implement the proper bounds, these functions are written, at the initial scale Q_0^2, as [4]

$$\Delta_T q(x,Q_0^2) = \mathcal{N}_q^T(x,Q_0^2)\,\frac{1}{2}\,[f_{q/p}(x,Q_0^2)+\Delta q(x,Q_0^2)] \tag{2.4}$$

$$\tilde{\Delta}^N D_{h/q^\uparrow}(z,Q_0^2) = 2\,\mathcal{N}_q^C(z,Q_0^2)\,D_{h/q}(z,Q_0^2)\,. \tag{2.5}$$

They are then evolved up to the proper value of Q^2. Here Δq is the helicity collinear distribution function. For $\Delta_T q(x,Q^2)$ we employ a transversity DGLAP kernel and the evolution is performed by an appropriately modified Hoppet code [12]. For the Collins function, we assume that the only scale dependence is contained in $D(z,Q^2)$, which is evolved with an unpolarised DGLAP kernel, while $\mathcal{N}_q^C$ does not evolve with Q^2. This is equivalent to assuming that the ratio $\tilde{\Delta}^N D(z,Q^2)/D(z,Q^2)$ is constant in Q^2. Throughout the paper, we will refer to this choice as the "standard" evolution scheme. The function $h(p_\perp)$, defined as [4]

$$h(p_\perp) = \sqrt{2e}\,\frac{p_\perp}{M_C}\,e^{-p_\perp^2/M_C^2}\,, \tag{2.6}$$

allows for a possible modification of the $p_\perp$ Gaussian width of the Collins function with respect to the unpolarised FF; for the TMD transversity distribution, instead, we assume the same Gaussian width as for the unpolarised TMD, $\langle k_\perp^2\rangle_T = \langle k_\perp^2\rangle$. In this analysis, we use a simplified model which implies no Q^2 dependence in the $p_\perp$ distribution. We parameterise $\mathcal{N}_q^T(x)$, for valence quarks as

$$\mathcal{N}_q^T(x) = N_q^T\,x^\alpha(1-x)^\beta\,\frac{(\alpha+\beta)^{\alpha+\beta}}{\alpha^\alpha\beta^\beta} \qquad (q=u_v,d_v) \tag{2.7}$$

where $-1 \le N_q^T \le +1$, α and β are free parameters of the fit. Thus, the transversity distributions depend on a total of 4 parameters ($N^T_{u_v}, N^T_{d_v}, \alpha, \beta$). For the Collins function, we distinguish between favoured and disfavoured fragmentation, parameterised as

$$\mathcal{N}^C_{\rm fav}(z) = N^C_{\rm fav}\, z^\gamma (1-z)^\delta\, \frac{(\gamma+\delta)^{\gamma+\delta}}{\gamma^\gamma \delta^\delta}, \qquad \mathcal{N}^C_{\rm dis}(z) = N^C_{\rm dis}\,. \tag{2.8}$$

where $-1 \le N^C_{\rm fav/dis} \le +1$, γ and δ are free parameters of the fit. Thus, we have a total of five free parameters for the Collins functions ($M_C, N^C_{\rm fav}, N^C_{\rm dis}, \gamma, \delta$). Notice that, although present data are still unable to tightly constrain the disfavoured Collins function, it clearly turns out that choosing independent parameterisations for $\mathcal{N}^C_{\rm fav}(z)$ and $\mathcal{N}^C_{\rm dis}(z)$ definitely improves the quality of the fit.

Finally, the expression for $A_{UT}^{\sin(\phi_h+\phi_S)}$ is the following:

$$A_{UT}^{\sin(\phi_h+\phi_S)} = \frac{\sqrt{2e}\,\dfrac{P_T}{M_C}\,\dfrac{\langle p_\perp^2\rangle_C^2}{\langle p_\perp^2\rangle}\,\dfrac{e^{-P_T^2/\langle P_T^2\rangle_C}}{\langle P_T^2\rangle_C^2}\,\dfrac{1-y}{sxy^2}\,\sum_q e_q^2\,\Delta_T q(x)\,\tilde{\Delta}^N D_{h/q^\uparrow}(z)}{\dfrac{e^{-P_T^2/\langle P_T^2\rangle}}{\langle P_T^2\rangle}\,\dfrac{[1+(1-y)^2]}{sxy^2}\,\sum_q e_q^2\, f_{q/p}(x)\, D_{h/q}(z)}\,, \tag{2.9}$$

with

$$\langle p_\perp^2\rangle_C = \frac{M_C^2\,\langle p_\perp^2\rangle}{M_C^2 + \langle p_\perp^2\rangle} \qquad\qquad \langle P_T^2\rangle_{(C)} = \langle p_\perp^2\rangle_{(C)} + z^2\langle k_\perp^2\rangle\,. \tag{2.10}$$

Independent information on the Collins functions can be obtained in unpolarised e^+e^- processes, by looking at the azimuthal correlations of hadrons produced in opposite jets. The Belle Collaboration [13, 14] and, more recently, the BaBar Collaboration [7] have measured azimuthal hadron-hadron correlations for inclusive charged pion production in $e^+e^- \to \pi\pi X$ processes, which, involving the convolution of two Collins functions, can be interpreted as a direct measure of the Collins effect.

Two methods have been adopted in the experimental analysis of the Belle and BaBar data [13, 7]:

1. In the "thrust-axis method" the jet thrust axis, in the e^+e^- c.m. frame, fixes the $\hat{z}$ direction and the $e^+e^- \to q\bar{q}$ scattering defines the $\widehat{xz}$ plane; φ_1 and φ_2 are the azimuthal angles of the two hadrons around the thrust axis, while θ is the angle between the lepton direction and the thrust axis. In this reference frame, the cross section normalized to its azimuthally averaged counterpart $\langle d\sigma\rangle$ reads [4]:

$$\begin{aligned} R_{12}(z_1,z_2,p_{\perp 1},p_{\perp 2},\theta,\varphi_1+\varphi_2) &\equiv \frac{1}{\langle d\sigma\rangle}\,\frac{d\sigma^{e^+e^-\to h_1h_2X}}{dz_1\,dz_2\,p_{\perp 1}\,dp_{\perp 1}\,p_{\perp 2}\,dp_{\perp 2}\,d\cos\theta\,d(\varphi_1+\varphi_2)} \\ &= 1 + \frac{1}{4}\,\frac{\sin^2\theta}{1+\cos^2\theta}\,\cos(\varphi_1+\varphi_2) \\ &\times \frac{\sum_q e_q^2\,\Delta^N D_{h_1/q^\uparrow}(z_1,p_{\perp 1})\,\Delta^N D_{h_2/\bar{q}^\uparrow}(z_2,p_{\perp 2})}{\sum_q e_q^2 D_{h_1/q}(z_1,p_{\perp 1})\,D_{h_2/\bar{q}}(z_2,p_{\perp 2})}\,. \end{aligned} \tag{2.11}$$

To eliminate false asymmetries, the Belle and BaBar Collaborations consider the ratio of unlike-sign ($\pi^+\pi^-$ + $\pi^-\pi^+$) to like-sign ($\pi^+\pi^+$ + $\pi^-\pi^-$) or charged ($\pi^+\pi^+$ + $\pi^+\pi^-$ +

$\pi^-\pi^+ + \pi^-\pi^-$) pion pair production, denoted respectively with indices U, L and C:

$$\frac{R_{12}^U}{R_{12}^{L(C)}} = 1 + \cos(\varphi_1 + \varphi_2)\, A_{12}^{UL(C)}(z_1, z_2, p_{\perp 1}, p_{\perp 2}, \theta)\,, \tag{2.12}$$

with A_{12}^{UL} and A_{12}^{UC}, defined in Ref. [8], directly related to the Collins functions through the combinations $\sum_q e_q^2 \Delta^N D_{h_1/q^\uparrow}(z_1, p_{\perp 1})\, \Delta^N D_{h_2/\bar{q}^\uparrow}(z_2, p_{\perp 2})$.

2. In the "hadronic-plane method", one of the produced hadrons (h_2 in our case) identifies the $\hat{z}$ direction and the $\widehat{xz}$ plane is determined by the lepton and the h_2 directions; the other relevant plane is determined by $\hat{z}$ and the direction of the other observed hadron, h_1, at an angle ϕ_1 with respect to the $\widehat{xz}$ plane. Here θ_2 is the angle between h_2 and the e^+e^- direction.

   In this reference frame, the elementary process $e^+e^- \to q\bar{q}$ does not occur in the $\widehat{xz}$ plane, and thus the helicity scattering amplitudes involve an azimuthal phase φ_2. As in the previous case, we can build ratios of unlike/like and unlike/charged asymmetries:

$$\frac{R_0^U}{R_0^{L(C)}} = 1 + \cos(2\phi_1)\, A_0^{UL(C)}\,, \tag{2.13}$$

   which can then be directly compared to the experimental measurements. All details and definitions of R^U, R^L, R^C and A_0^{UL}, A_0^{UC} can be found in Ref. [8]

3. Best fitting and results

We can now perform a best fit of the data on $A_{UT}^{\sin(\phi_h+\phi_S)}$ from HERMES and COMPASS and of the data on $A_0^{UL,C}$, from the Belle and BaBar Collaborations. As anticipated above, we will not exploit the $A_{12}^{UL,C}$ data. In our fit – we shall refer to it as the "reference" fit – these asymmetries, given in Eqs. (2.9) and (2.13), are expressed in terms of the transversity and the Collins functions, parameterised as in Section 2, and evolved according to the "standard" evolution scheme.

The transversity and the Collins functions depend on the free parameters $\alpha, \beta, \gamma, \delta, N_q^T, N_q^C$ and M_C. Following Ref. [4] we assume the exponents α, β and the mass scale M_C to be flavour independent. Here we consider the transversity distributions only for u and d valence quarks (with the two free parameters $N_{u_v}^T$ and $N_{d_v}^T$). The favoured Collins function is fixed by the flavour independent exponents γ and δ, and by $N_{\rm fav}^C$, while the disfavoured Collins function is determined by the sole parameter $N_{\rm dis}^C$ (see comments before Eq. (2.8)). This makes a total of 9 parameters, to be fixed with a best fit procedure.

The total χ^2 of this fit is $\chi^2_{\rm d.o.f.} = 0.84$, while the χ^2 contributions corresponding to SIDIS and e^+e^- experiments separately amount to $\chi^2_{\rm points} = 0.89$ and $\chi^2_{\rm points} = 0.71$ respectively. As one can see, this is a fit of excellent quality, and all data sets are very well reproduced.

In this contribution we focus on the new BaBar measurements of A_0^{UL} and A_0^{UC} asymmetries as functions of P_{1T} (p_{t0} in the notation used by the BaBar Collaboration). These data offer the first direct insight of the dependence of the Collins function on the parton intrinsic transverse momentum: in fact, our global fit now delivers a more precise determination of the Gaussian width of the Collins function (through the M_C parameter), which in our previous fits was affected by a

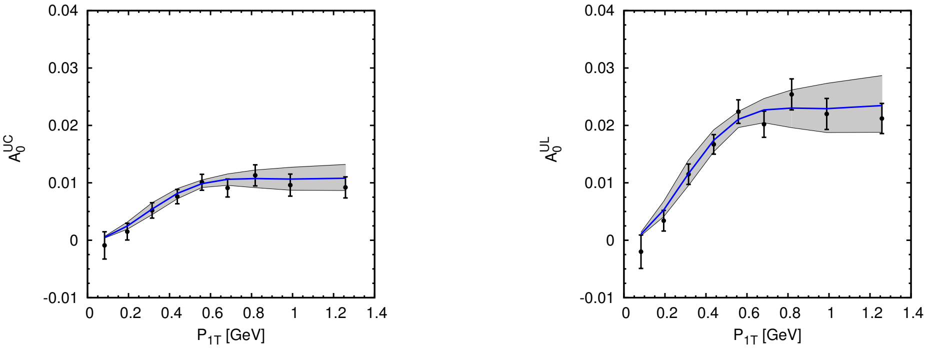

Figure 1: The experimental data on the azimuthal correlations A_0^{UC} (left panel) and A_0^{UL} (right panel) as functions of P_{1T} in unpolarised $e^+e^- \to h_1\,h_2X$ processes, as measured by the BaBar Collaboration [7], are compared to the curves obtained from our global reference fit (solid lines). The shaded areas represent the statistical uncertainty from the fit, corresponding to 95.45confidence level.

very large uncertainty. Fig. 1 shows our best fit of the BaBar A_0^{UL} and A_0^{UC} asymmetries as functions of P_{1T}. In Fig. 2 we show the valence quark transversity distributions and the lowest $p_\perp$-moment of the favoured and disfavoured Collins functions, as extracted from our reference fit, compared with those extracted in our previous analysis [6]. From Fig. 2 we can see that only the Collins functions differ significantly; this is due to the different choice of parameterisation. In fact, in the 2013 fit, we imposed that the favoured and disfavoured $\mathcal{N}^C(z)$ functions had the same z-dependence and could differ only by a normalisation constant, while here they are left uncorrelated, with the disfavoured function being simply a constant multiplied by the unpolarised fragmentation function, see Eq. (2.8). The u_v and d_v transversity functions, instead, are well compatible with their u and d counterparts extracted in 2013. Notice that the present data actually allow the extraction of the sole u_v transversity function, due to the strong u dominance in the SIDIS data.

For the best fit presented above we have adopted a simple phenomenological Q^2 evolution for the Collins function: we assumed the ratio $\tilde{\Delta}^N D(z,Q^2)/D(z,Q^2)$ to be constant in Q^2, with the unpolarised fragmentation function $D(z,Q^2)$ evolving with a DGLAP kernel. However, the Collins function can be shown to be related to the collinear $H_{h/q}^{(3)}$ twist-three fragmentation function, the diagonal part of which evolves with a transversity kernel as the transversity function. Therefore, it is interesting to apply this kind of evolution to the Collins function and study the consequences of such an evolution on our best fit.

To this purpose, we assume the z-dependent part of the Collins distribution, $\tilde{\Delta}^N D_{h/q^\uparrow}$, to evolve with a transversity kernel, similarly to what is done for the transversity function. The results we obtain show a slight deterioration of the fit quality, with a global $\chi^2_{\rm d.o.f.}$ increasing from 0.84 to 1.20. Although this is still an acceptable result, one may wonder whether this is a genuine effect of the chosen evolution model or, rather, a byproduct of the functional form adopted for the Collins function parameterisation.

We have therefore exploited a different parameterisation based on a first order polynomial form, which has the added advantage of depending on the same number of free parameters as the standard parameterisation of Eq. (2.8). We consider generic combinations of fixed order Bern-

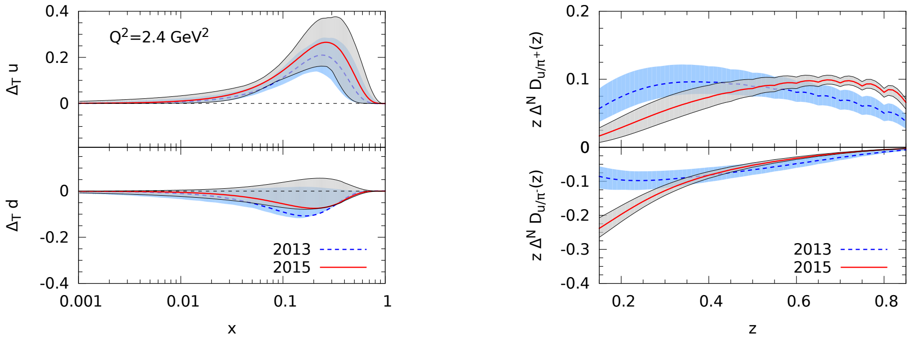

Figure 2: Comparison of our reference best fit results (red, solid lines) for the valence u and d quark transversity distributions (left panel) and for the lowest $p_\perp$ moment of the favoured and disfavoured Collins functions (right panel), at $Q^2 = 2.4$ GeV^2, with those from our previous analysis [6] (blue, dashed lines).

stein polynomials as they offer a relatively straightforward way to keep track of the appropriate normalisation:

$$\mathcal{N}_i^C(z) = a_i P_{01}(z) + b_i P_{11}(z) \qquad i = \text{fav, dis} \tag{3.1}$$

where $P_{01}(z) = (1-z)$ and $P_{11}(z) = z$ are Bernstein polynomials of order one. Notice that by constraining the four free parameters in such a way that $-1 \le a_i \le +1$ and $-1 \le b_i \le +1$, the Collins function automatically fulfils its positivity bounds, as in the standard parameterisation. The Collins function will be globally modelled as shown in Eqs. (2.3) and (2.5), with $\mathcal{N}_{\rm fav}^C(z)$ and $\mathcal{N}_{\rm dis}^C(z)$ as given in Eq. (3.1).

It turns out that with a transversity-like Q^2 evolution of the Collins function coupled to this polynomial parameterisation, we can obtain best fit results of similar quality as we found for our reference fit, with $\chi^2_{\rm d.o.f.} = 1.00$. Since these two fits involve very different evolution schemes, their equivalence suggests that the observables considered exhibit very mild Q^2 dependence. In fact, we have checked that a similar $\chi^2_{\rm d.o.f.}$ can be obtained by not including any Q^2 dependence at all in the PDFs and FFs. One of the reasons our model works well is that it allows for an approximate cancellation of the Q^2-dependence in the asymmetries. See section IV of Ref. [8] for a more detailed discussion.

4. BESIII azimuthal correlations

Quite recently, the BESIII Collaboration have released their measurements of the azimuthal Collins correlations in e^+e^- annihilations into pion pairs, completely analogous to those of BaBar and Belle, but at the lower energy $\sqrt{s} = Q = 3.65$ GeV [9]. Their low Q^2 values, as compared with Belle and BaBar experiments, might help in assessing the importance of TMD evolution effects. It is therefore interesting to check how our model can describe these new sets of measurements.

In Fig. 3 the solid, black circles represent the A_0^{UC} and A_0^{UL} asymmetries measured by the BESIII Collaboration at $Q^2 = 13$ GeV^2, in bins of (z_1, z_2), while the solid blue circles (with their relative bands) correspond to the predictions obtained by using the results of our alternative fit, based on a transversity evolution kernel for the Collins function combined with a polynomial parameterisation. These asymmetries are well reproduced at small z_1 and z_2, where we expect our model to work, while they are underestimated at very large values of either z_1 or z_2, or both. Notice that the values of z_1, z_2 in the last bins are very large for an experiment with $\sqrt{s} = 3.65$ GeV: such data points might be contaminated by exclusive production contributions, and other effects which cannot be reproduced by a TMD model.

Fig. 4 shows the same asymmetries, plotted as functions of P_{1T}. The A_0^{UC} asymmetry is described reasonably well by our model, while A_0^{UL} is slightly underestimated, especially at large P_{1T} where the effects of the experimental cuts, namely the opening angle, become more important.

At this stage, it is quite difficult to draw any clear-cut conclusion. The predictions of our approach, which does not include TMD evolution, seems to be quite satisfactory. On the other hand, the TMD evolution approach of Ref. [15] gives very good results. Despite the sizable difference in Q^2 among the different sets of e^+e^- data, the measured asymmetries do not show any sensitivity to evolution effects in Q^2.

One should also add that, at the moderate energies of BESIII experiment, with the difficulties to isolate opposite jet hadrons, some corrections to the TMD factorised approach might still be relevant, like the appropriate insertion of kinematical cuts, of higher-twist contributions and of threshold effects.

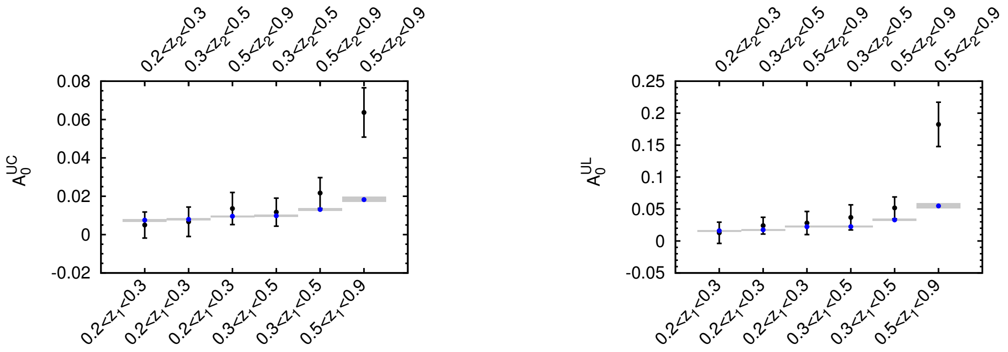

Figure 3: The solid, black circles represent the A_0^{UC} (left panel) and A_0^{UL} (right panel) asymmetries measured by the BESIII Collaboration [9] at $Q^2 = 13$ GeV^2, in bins of (z_1, z_2), while the solid blue circles (with their relative bands) correspond to the predictions obtained by using the Collins functions from our alternative fit.

5. Comments and conclusions

We have performed a new global analysis of SIDIS and e^+e^- azimuthal asymmetries, motivated by the recent release of BaBar data, with high statistics and precision, which offer new insights on the $p_\perp$ dependence of the Collins azimuthal correlations A_0 and A_{12}. We have extracted the Collins functions and the transversity distributions by adopting a simple phenomenological model for these TMD–PDFs and FFs, such that their x or z-dependent parts evolve with Q^2 while the transverse momentum dependent part is assumed to be Q^2 independent.

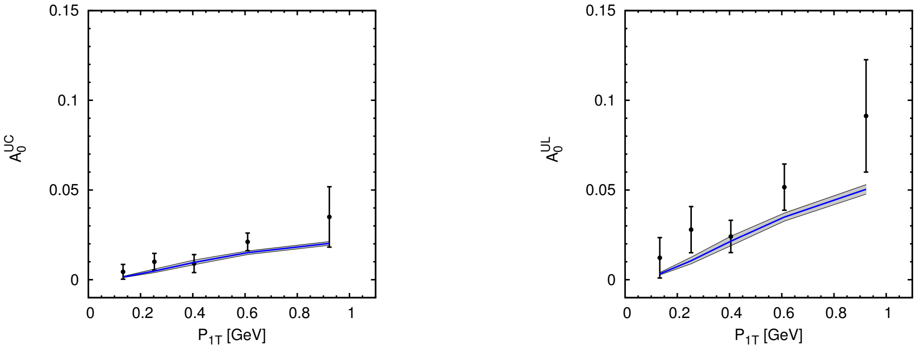

Figure 4: The predictions obtained by using the Collins functions from our alternative fit, (solid, blue lines) are compared to the A_0^{UC} (left panel) and A_0^{UL} (right panel) asymmetries measured by the BESIII Collaboration [9] at $Q^2 = 13$ GeV^2, as functions of P_{1T} (black circles). The shaded areas represent the statistical uncertainty from the fit, corresponding to 95.45confidence level.

The u and d quark transversity functions obtained by best fitting SIDIS results and the new e^+e^- data simultaneously are compatible with the previous extractions [4, 5, 6]; while the u valence transversity distribution has a clear trend, the d valence transversity still shows large uncertainties.

Instead, our newly extracted Collins functions look different from those obtained in our previous analyses. This is mainly due to the fact that we have exploited a different parametrisation for the disfavoured Collins function. Our study indicates that the actual shape of the disfavoured Collins function is still largely unconstrained by data.

About the $p_\perp$ dependence of the Collins function, we observe that its Gaussian width can now be determined with remarkable precision. However, our extraction is still subject to a number of initial assumptions: a Gaussian shape for the TMDs, a complete separation between transverse and longitudinal degrees of freedom, a Gaussian width of the unpolarised TMD–FFs fixed solely by SIDIS data. Hopefully, higher statistics and higher precision multidimensional data, for asymmetries and unpolarised multiplicities, will help clarifying the picture.

We have also made an attempt to understand the Q^2 dependence of these experimental data. We see that our model provides a very satisfactory description of the data and, although it relies on a Q^2 independent $p_\perp$ distribution, the quality of our best fit is similar to that obtained by using TMD evolution [15]. This can be an indication that there might be cancellations of the Q^2 dependence of the TMDs in these azimuthal asymmetries, which are ratios or even double ratios of cross sections.

One can study these Q^2 evolution effects by directly comparing the same azimuthal correlations measured at very different Q^2 values by BaBar–Belle and BESIII Collaborations. Our model predicts almost identical asymmetries for different Q^2. Differences among BESIII and BaBar-Belle asymmetries could be explained by the different kinematical configurations and cuts. Our predictions are in qualitatively good agreement with the present BESIII measurements, indicating that the data themselves do not show any strong sensitivity to the Q^2 dependence in the transverse momentum distribution.

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