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Colloquia: Transversity 2011

New COMPASS results on Collins and Sivers asymmetries

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Summary. — The study of transverse-spin and transverse-momentum effects is an important part of the scientific program of COMPASS, a fixed-target experiment at the CERN SPS. For these studies a 160 GeV/c momentum muon beam is scattered on a transversely polarized nucleon target, and the scattered muon and the forward going hadrons produced in DIS processes are reconstructed and identified in a magnetic spectrometer. The measurements have been performed on a deuteron target in 2002, 2003 and 2004, and on a proton target in 2007 and 2010. The results obtained for the Collins and Sivers asymmetries from the data collected in 2010 are here presented for the first time. They nicely confirm the findings of the 2007 run and allow for reduction of the errors by more than a factor of two.

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PACS 13.88.+e – Polarization in interactions and scattering.
PACS 14.65.Bt – Light quarks.

1. – Introduction

Transverse-spin phenomena in hard processes have been discovered and investigated theoretically for 40 years but the field was vigorously revisited in the 90s, when a general scheme [1] of all leading-twist and higher-twist parton distribution functions (PDFs) was worked out. To fully specify the quark structure of the nucleon at the twist-two level three parton distributions are necessary, the momentum distributions $q(x)$, the helicity distributions $\Delta q(x)$ and the transverse-spin distributions $\Delta_T q(x)$ (or $h_1^q(x)$), where x is the Bjorken variable. The latter distribution, known as transversity, is chiral-odd and thus not directly observable in deep inelastic lepton-nucleon scattering (DIS). In 1993 Collins suggested that transversity could be measured in semi-inclusive DIS (SIDIS) thanks to a mechanism involving in the hadronisation another chiral-odd function [2], known as the "Collins function" $\Delta_T^0 D_q^h$, *i.e.* a possible spin-dependent part of the usual fragmentation function D_q^h. The mechanism is expected to lead to an azimuthal transverse-spin asymmetry A_{Coll} (the "Collins asymmetry") in the distribution of the inclusively produced

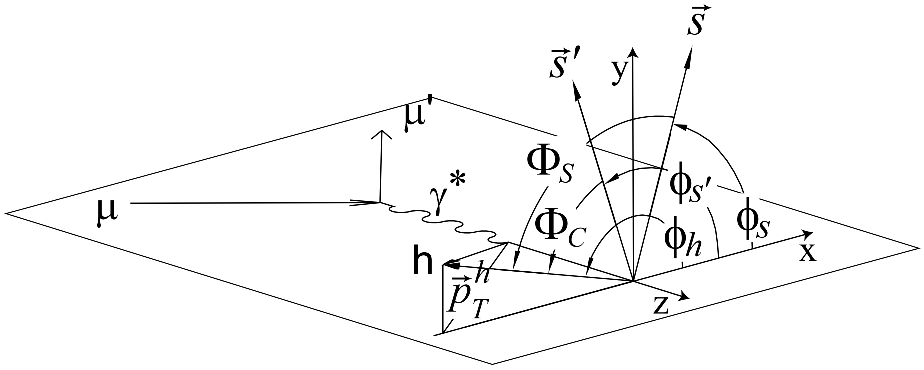

Fig. 1. – Definition of the Collins and Sivers angles. The vectors $\vec{p}_T^h$, $\vec{s}$ and $\vec{s'}$ are the hadron transverse momentum and the spin of the initial and struck quarks, respectively.

hadrons. At leading order this asymmetry can be written as

$$A_{Coll} = \frac{\sum_q e_q^2 \cdot \Delta_T q \cdot \Delta_T^0 D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h}, \tag{1}$$

and should show up as the amplitude of a $\sin \Phi_C$ modulation in the hadron azimuthal distribution. The Collins angle $\Phi_C = \phi_h + \phi_s - \pi$ is the sum of the azimuthal angles of the hadron transverse momentum $\vec{p}_T^h$ (ϕ_h) and of the spin direction of the target nucleon (ϕ_s) with respect to the lepton scattering plane, as measured in the Gamma-Nucleon System. Figure 1 illustrates the choice of the reference system and of the relevant angles. A non-zero Collins asymmetry for the proton was first observed by HERMES [3] implying that the Collins fragmentation and the transversity functions are both non-vanishing. Independent evidence of a non-zero and sizable Collins function came soon after from the measurements of a correlation between the azimuthal angles of the hadrons in the two jets resulting from the $e^+e^- \to hadrons$ annihilations into hadrons at high energy as measured by the Belle Collaboration [4].

If the quarks are assumed to be collinear with the parent nucleon (no intrinsic quark transverse momentum $\vec{k}_T$), or after integration over $\vec{k}_T$, the three distributions $q(x)$, $\Delta q(x)$ and $\Delta_T q(x)$ exhaust the information on the internal dynamics of the nucleon. However, admitting a finite $\vec{k}_T$, a total of eight transverse-momentum–dependent (TMD) distribution functions are needed for a full description of the nucleon [5]. All these functions lead to azimuthal asymmetries in the SIDIS cross-section and can be disentangled measuring their different angular modulations.

In between these TMD PDFs of particular interest is the Sivers function $\Delta_0^T q$ (or f_1^q) which arises from a correlation between the transverse momentum of an unpolarised quark in a transversely polarized nucleon and the nucleon polarization vector [6]. Neglecting the hadron transverse momentum with respect to the fragmenting quark, this $\vec{k}_T$ dependence could cause the "Sivers asymmetry"

$$A_{Siv} = \frac{\sum_q e_q^2 \cdot \Delta_0^T q \cdot D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h} \tag{2}$$

in the angular distribution of the hadrons resulting from the quark fragmentation. The Sivers asymmetry is the amplitude of a possible $\sin\Phi_S$ modulation in the number of produced hadrons, where $\Phi_S = \phi_h - \phi_s$ and ϕ_h and ϕ_s are the same azimuthal angles which enter in the definition of Φ_C. In SIDIS off a transversely polarized target the Collins and the Sivers effects can to be disentangled, as shown by the COMPASS and the HERMES experiments.

The Sivers function is of particular interest because it is odd under time reversal (T). Due to its T-odd nature and to the T-invariance property of the strong interaction soon after being proposed it was demonstrated that it had to be zero [2]. Ten years later, however, in an explicit calculation [7] it was proved that final-state interactions in SIDIS arising from gluon-exchange between the struck quark and the nucleon remnant, or initial-state interactions in Drell-Yan processes, can produce a non-zero Sivers asymmetry. Soon after it was understood [8] that taking correctly into account the gauge links in the TMD distributions, time reversal invariance does not imply a vanishing Sivers function but rather a sign difference between the Sivers function measured in SIDIS and the same distribution measured in Drell-Yan. Clearly the test of this pseudo-universality of the T-odd functions requires their measurement in Drell-Yan process and, first of all, a well-established non-zero signal in SIDIS.

Using a 160 GeV μ^+ beam COMPASS has measured SIDIS on a transversely polarized ^{6}LiD target in 2002, 2003 and 2004. In those data no appreciable asymmetries were observed within the accuracy of the measurements [9-11], a fact which is understood in terms of a cancellation between the u- and d-quark contributions. The COMPASS data are still today the only SIDIS data ever taken on a transversely polarized deuteron target, and provide important constraints to the contribution of the d-quark. Together with the HERMES data on a transversely polarized proton target and the $e^+e^- \to$ *hadrons* Belle data they allowed for the first global analysis and the first extraction of the transversity distributions and of the Sivers functions for the u- and d-quarks [12-14]. In 2007 COMPASS measured for the first time SIDIS on a transversely polarized proton (NH_3) target(1). The results [16] for the Collins asymmetry were in nice agreement with those of HERMES [17,18], while the Sivers asymmetry turned out to be somewhat smaller. Understanding the reasons for this difference was a strong motivation for a new proton run, and the entire 2010 data-taking period, from June to November, was dedicated to such a measurement. We have just recently finished the data analysis and I have the great pleasure to present here for the first time the new results.

2. – The COMPASS experiment

The COMPASS spectrometer [19] is in operation in the North Hall (Hall 888) of CERN since 2002. To ensure large angular acceptance and dynamical range it is a two-stage magnetic spectrometer, and to cope with the different requirements of location accuracy and rate capability at different angles it uses a variety of tracking detectors. Particle identification is provided by a large acceptance RICH detector, by calorimeters, and by muon filters.

In 2010 the spectrometer configuration was very similar to the one which was used in 2007. The main difference is the addition of a new triggering system for large-angle

(1) For a comprehensive review of recent experiments and theoretical developments see, *e.g.*, [15].

muons, based on two large-area scintillator counter hodoscopes with 32 horizontal bars each and a suitable coincidence matrix to provide target pointing in the non-bending vertical plane.

The polarized target consists of three cylindrical cells, 4 cm diameter: one central cell, 60 cm long, and two outer ones, each 30 cm long, separated by 5 cm. Neighboring cells are polarized in opposite directions, so that data from both spin directions are recorded at the same time.

To polarize the target material and to hold the polarization in the longitudinal mode the target is located along the axis of a solenoid which provides a field of 2.5 T with an excellent homogeneity of $\pm 2 \cdot 10^{-5}$ over the whole target volume. The magnet is also equipped with a set of saddle-shaped coils which can provide a 0.6 T vertical field, which is used either to rotate the target nucleon spin or to hold the polarization vertical for the transversity measurements. The target material (NH_3) is first longitudinally polarized in the solenoidal field with the method of dynamical nuclear polarization (DNP). The maximum polarization value achievable in the three cells ranges between 0.80 and 0.90, depending slightly on the sign of the polarization and on the cell location. About 48 hours are necessary to reach 95% of the maximal polarization. When the desired polarization value is reached, the radio frequency system is switched off, the target spins get frozen, the magnetic field is lowered to 0.6 T and adiabatically rotated to the vertical direction by suitably varing the solenoid and the dipole fields. In the frozen spin mode and with the holding field at its operational value the relaxation time of the polarization exceeds 3000 hours.

In 2010 data have been taken at a mean beam intensity of $2 \cdot 10^8\,\mu$/spill, for a spill length of ~ 10 s every 40 s. About $37 \cdot 10^9$ events, corresponding to 1.3 PB of data, have been collected, in twelve separate periods. In each period, after 4-5 days of data taking, a polarization reversal was performed by changing the microwave frequencies in the three cells, always keeping the central cell oppositely polarized with respect to the external ones.

In the data analysis, in order to ensure a DIS regime, only events with a photon virtuality $Q^2 > 1\,(\mathrm{GeV}/c)^2$, a fractional energy of the virtual photon $0.1 < y < 0.9$, and a mass of the hadronic final state system $W > 5\,\mathrm{GeV}/c^2$ are considered. The charged hadrons are required to have at least 0.1 GeV/c transverse momentum p_T^h with respect to the virtual photon direction and a fraction of the available energy $z > 0.2$. Within these cuts, we are left with about $16 \cdot 10^7$ DIS events, and $8 \cdot 10^7$ hadrons. Figure 2 shows at the left the distribution of the DIS events in the x-Q^2 plane, while the mean Q^2 values in the x-bins in which we give the results for the asymmetries are shown in the plot at the right.

The transverse spin asymmetries are obtained by comparing, cell by cell, the azimuthal distributions of the detected hadrons as measured in the first half of a period with the corresponding distributions of the second half. Since the two sets of data are taken typically one week apart, the stability of the apparatus is crucial and has been carefully checked. All the tests on the data quality and stability have not revealed any systematic effects, all the twelve periods give compatible results, and all of them have been used for the extraction of the final asymmetries.

3. – Results

The Collins and Sivers asymmetries have been evaluated for positive and negative hadrons in bins of the three kinematic variables x, z and p_T^h. The raw asymmetries have been extracted for each data taking period and have been divided by the dilution

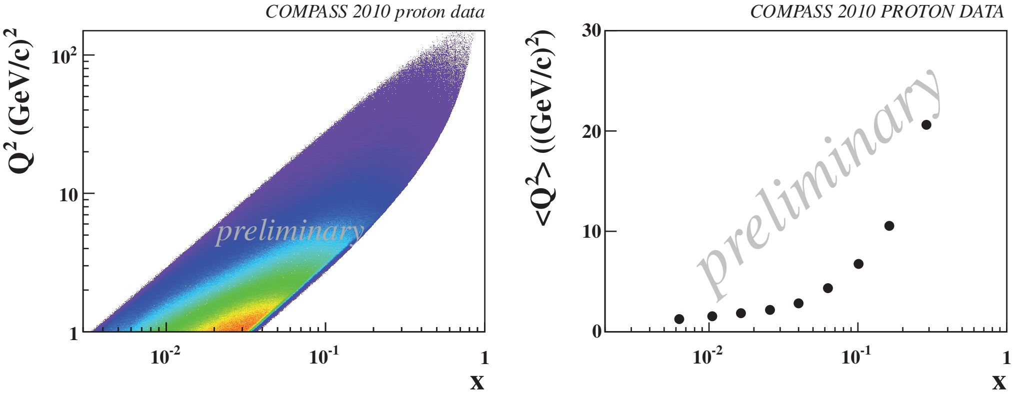

Fig. 2. – Left: distribution of the DIS events in the x-Q^2 plane. Right: mean Q^2 values in the different x-bins.

factor, the target polarization and, in the case of the Collins analysis, by the D_{NN} kinematical factor. The dilution factor of the ammonia target has been evaluated in each x bin; it increases with x from 0.14 to 0.17, and it has been assumed constant and equal to 0.15 in the z and p^h_T bins. The target polarization was measured individually for each cell and each period, with a 5% uncertainty. Finally, the weighted mean of the asymmetries measured in each period has been performed. The systematic errors have been evaluated as a fraction of the statistical error and are 0.5 for both the Collins and Sivers asymmetries.

The asymmetries are given as function of x, z, and p^h_T, for positive and negative hadrons, shown in figs. 3 and 4. The error bars are only statistical, while the bands indicate the size of the systematic errors. As is clear from fig. 3 the Collins asymmetry has a strong x-dependence. It is compatible with zero at small x and increases up to 0.10 in the valence region ($x > 0.1$). The values agree both in magnitude and in sign with our previous measurements [16], as well as with the measurements of HERMES [18], which

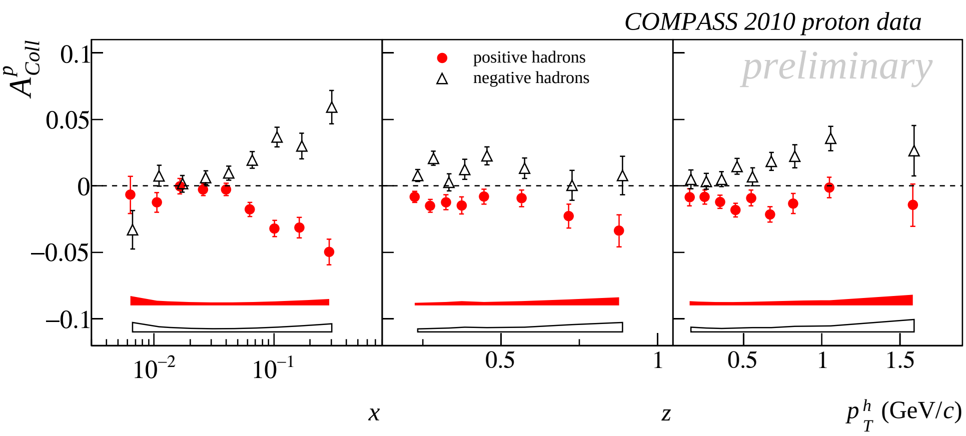

Fig. 3. – Collins asymmetry as a function of x, z, and p^h_T, for positive and negative hadrons.

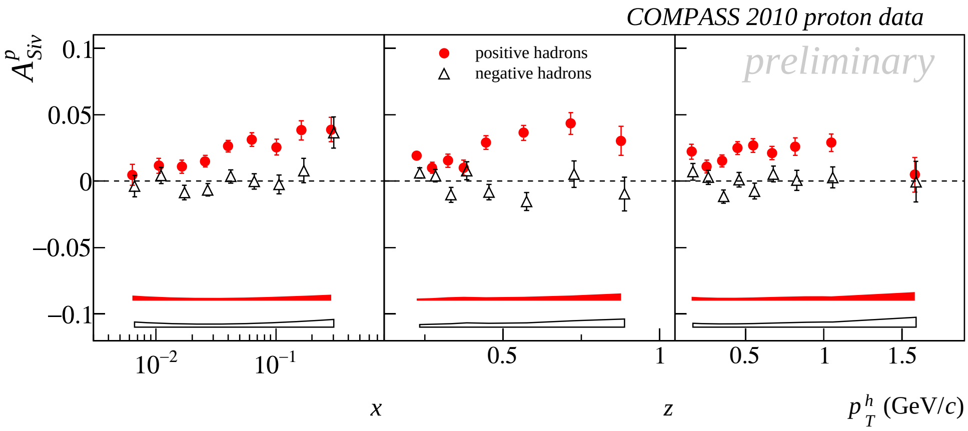

Fig. 4. – Sivers asymmetry as a function of x, z, and p_T^h, for positive and negative hadrons.

have been performed at a considerably lower electron beam energy.

Figure 4 shows our new results for the Sivers asymmetries. Again, there is an excellent agreement with our published results from the 2007 run, with a considerable reduction of the error bars (more than a factor of two). The asymmetry is definitely positive for positive hadrons and compatible with zero for negative hadrons. At variance with the Collins asymmetry, the Sivers asymmetry stays positive even for very small x-values, in the region of the sea. Moreover, very much as was the case for the 2007 data, the measured asymmetries are definitely smaller than the corresponding ones measured by HERMES. To understand the reason we have enlarged the kinematic domain, namely we have looked at the events with smaller y values (in the interval $0.05 < y < 0.1$) and at the hadrons with smaller z values ($0.1 < z < 0.2$).

Figure 5 shows the Sivers asymmetry for positive hadrons as function of x, z, and p_T^h for small y values ($0.05 < y < 0.1$) as compared with the "standard" sample ($0.1 < y <$

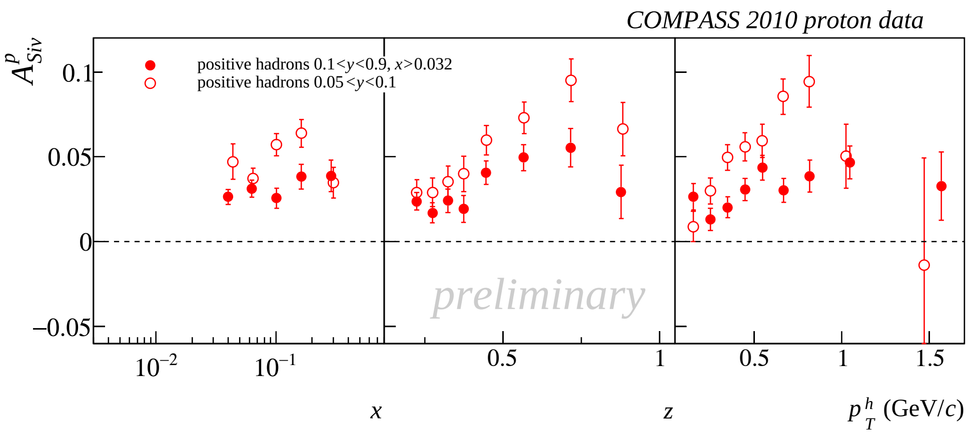

Fig. 5. – Sivers asymmetry for positive hadrons as a function of x, z, and p_T^h, for $x > 0.032$. The full points refer to the $0.1 < y < 0.9$ sample, the open points to the $0.05 < y < 0.1$ sample.

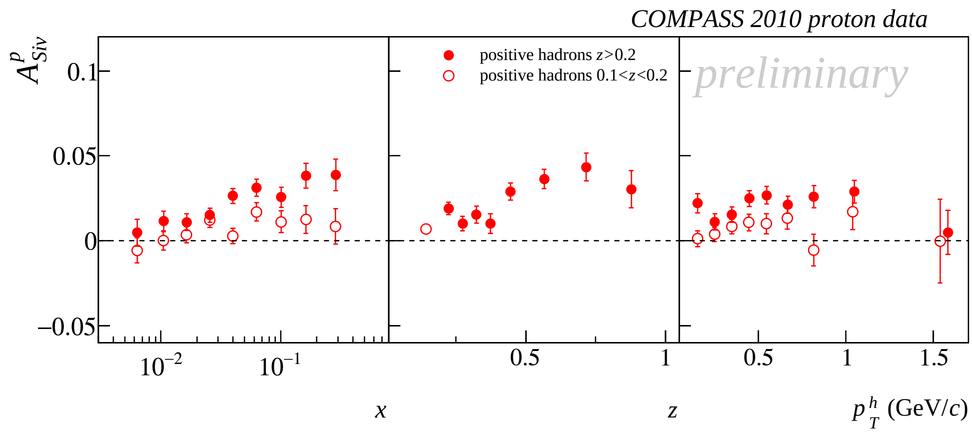

Fig. 6. – Sivers asymmetry for positive hadrons as a function of x, z, and p_T^h. The full points refer to the $z > 0.2$ sample, the open points to the $0.1 < z < 0.2$ sample.

0.9). Since at small y there are no low-x data, only data with $x > 0.032$ are plotted. A clear increase of the Sivers asymmetry is visible for the low-y data. This strong effect could be associated with the smaller values of Q^2 and/or with the smaller values of W, the invariant mass of the hadronic system. The "standard sample" ($y > 0.1$) corresponds to $W > 5\,\text{GeV}$, while in the range $0.05 < y < 0.1$ the W values are as low as $\sim 3\,\text{GeV}$. While a Q^2-dependence is expected and has been calculated [20], no dependence on y (nor on W) is foreseen. A similar correlation, statistically less significant, was already noticed in our published 2007 proton data. Clearly this point needs further investigation. No particular trend is observed for the case of the Sivers asymmetry of the negative hadrons, which are compatible with zero for the standard sample and stay compatible with zero at small y.

We have also investigated the trend of the Collins and Sivers asymmetries at low z. Our standard hadron selection requires $z > 0.2$, to stay well separated from the target hadronization. In the region $0.1 < z < 0.2$ the Collins asymmetries decrease only slightly in size, on the other hand the effect is again sizable for the Sivers asymmetry for the positive hadrons, and not visible for negative hadrons. Figure 6 compares the data in the "standard sample" ($z > 0.2$) with the events in the region ($0.1 < z < 0.2$) and the decrease of the Sivers asymmetry for positive hadrons is impressive. Also this effect looks quite interesting and will be further investigated.

4. – Conclusions

Transverse spin and transverse momentum effects in lepton nucleon scattering offer new tools to unveil the structure of the nucleon. COMPASS contributed its share by executing a first round of exploratory measurements scattering $160\,\text{GeV}/c$ muons on transversely polarized deuteron and proton targets. The proton data are particularly important because of the relatively large Collins and Sivers asymmetries which HERMES and COMPASS have observed for the first time. The COMPASS measurements are quite useful in assessing the leading twist nature of the effects since the asymmetries are non-zero mostly in the valence region, where the Q^2 values of the measurements are a factor of 3 to 4 larger than those of HERMES. By now, the amount of data which has been produced by HERMES, COMPASS and Belle is already impressive, and time has come for new phenomenological global analyses. Also, many more results are in the COMPASS pipe-line and should appear soon. The analysis of the Collins and Sivers asymmetries I have shown is essentially over, but work is still ongoing on the corresponding asymmetries for identified hadrons and on the kinematical dependence of the effect. Work is ongoing also to extract the other six transverse spin dependent asymmetries which are present in the expression of the SIDIS cross-section. Also in this case it is of interest to consider separately pions and kaons.

In the long term, the investigation of the spin structure of the nucleon in SIDIS will necessitate a major investment, to build a high luminosity electron-proton collider in which polarized electrons and polarized proton will collide at high energy. Projects are ongoing since some time at JLAB, at BNL, and, more recently, in Europe, where ideas to use the HESR antiproton storage ring of FAIR at GSI to store polarized protons are being put forward. The construction of a new polarized electron ring of suitable energy is not for free, but feasibility studies are ongoing. In the meantime, only JLAB and COMPASS can contribute to this field. JLAB experiments are unbeatable in statistical precision, but the interpretation of the data requires also measurements at high Q^2 which can only be performed using high energy beams. From this point of view, I think COMPASS should stay on the stage for several years, beyond the presently approved Drell-Yan [21] and DVCS [22] measurements, profit of the accelerator complex upgrade which is being carried on at CERN and thus increase its luminosity, and bridge the colleagues who are interested in this field across the time gap from now to the day the future collider will enter into operation.

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