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BEAUTY, CHARM AND HYPERON PRODUCTION AT FIXED-TARGET EXPERIMENTS

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ABSTRACT

Over the years fixed-target experiments have performed numerous studies of particle production in strong interactions. The experiments have been performed with different types of beam particles of varying energies, and many different target materials. Since the physics of particle production is still not understood, ongoing research of phenomena that we observe as beauty, charm and strange-particle production is crucial if we are to gain an understanding of these fundamental processes. It is in this context that recent results from fixed-target experiments on beauty, charm, and hyperon production will be reviewed.

1 Introduction

Fixed-target experiments have a long history that covers a broad spectrum of physics research. One area of research that has received considerable attention for the past 50 years is particle production in strong interactions. In its infancy, the research was based on cosmic-ray data. Shortly thereafter fixed-target experiments began to study strange-particle production, followed by studies of charm and beauty production in later years. The research continues today, since an understanding of the underlying production mechanisms remains elusive.

Quantum chromodynamics (QCD) is widely accepted as the correct description of the strong interaction. The properties of strong interactions that involve hard processes, which are associated with large momentum transfer, can be calculated in QCD using perturbation theory. Perturbative QCD is applicable to beauty production in fixed-target experiments, however, the experiments are challenged by relatively low beauty production cross sections. Perturbative QCD is also applicable to charm production. Here theoretical calculations are plagued by larger uncertainties (compared to beauty production), while experiments have acquired large charm samples that have been, and continue to be, used to study different aspects of charm production. The studies often focus on effects that appear to fall outside the realm of perturbative QCD, thereby making theoretical interpretations more difficult. However, it is noteworthy that non-perturbative effects in charm production have remarkable similarities to effects observed in hyperon production. Perhaps the similarities and differences observed in studies of beauty, charm, and strange-particle production can be exploited more effectively to gain a better understanding of the underlying production mechansims.

2 Overview of Experiments and Results

Table 1 lists fixed-target experiments with results that are relevant for this conference. The table shows that the experiments cover a range of beam energies, use a variety of beam particles, and use many different target materials.

Results that are included for this conference are recent results that are unpublished or were published after the last *Heavy Quarks at Fixed Target* conference, held in Rio de Janeiro, 9-12 October 2000. The unpublished results are being prepared for publication. One of these results reports a possible observation of doubly-charmed baryons by SELEX. The SELEX result that was presented at this conference is based on an earlier analysis of SELEX data, while a new result from an updated analysis was presented a few days later at Fermilab. In this paper, the more recent SELEX result will be presented.

Table 1: *Overview of Fixed-Target Experiments*

Experiment	p_{beam} (GeV/c)	Beam	Target
HERA-B	920	p	C, Al, Ti, W
E690	800	p	LH_2
E771	800	p	Si
E866/NuSea E789 and E772	800	p	LH_2, LD_2, C, Ca, Fe, W, Ag, Au, and Cu dump
E769	250	$\pi^{\pm}$, $K^{\pm}$, p	Be, Al, Cu, and W
E781/SELEX	600 572	Σ^- and π^- p	C and Cu C and Cu
E791	500	π^-	C and Pt
E687	220	γ	Be
E831/FOCUS	170	γ	BeO and Si
E835	<8.9	$\overline{p}$	hydrogen gas jet
WA89	340 260	Σ^- and π^- n	C and Cu C and Cu

The measurements that are presented here are arranged by topic as follows:

- $\sigma(b\overline{b})$ cross section measurement
- bottomonium polarization
- kinematic correlations in charm-pair events
- observation of doubly-charmed baryons
- asymmetry measurements comparing particle/antiparticle production
- hyperon production (asymmetries, kinematic correlations, polarization)

Topics that have not been included are measurements of the A-dependence in heavy-quark production, charm production with neutrinos (see Pasquale Migliozzi's contribution to the conference), and a recent measurement [1] of the mass and width of the χ_{c0} from experiment E835 (see Matteo Negrini's contribution to the conference). Results that are presented in this paper are arranged by flavor starting with beauty, then charm, and ending with results on hyperon production.

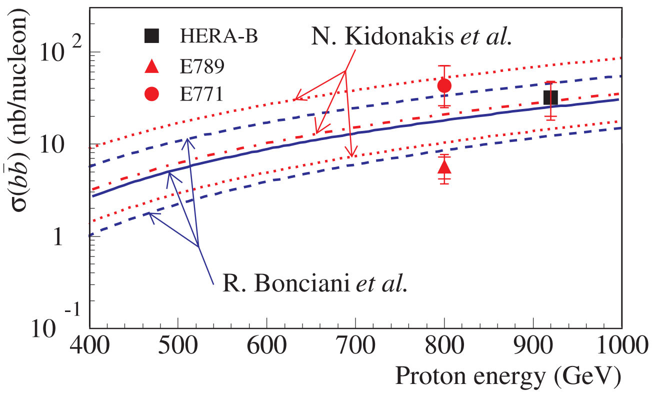
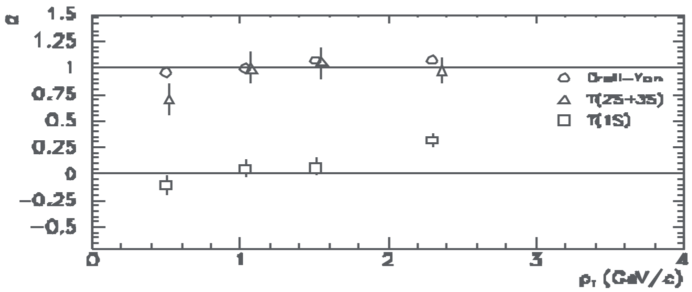


Figure 1: *HERA-B $\sigma(b\bar{b})$ measurement compared to measurements from E771 and E789, and theoretical predictions from R. Bonciani et al.* [5] *updated with the NNLL parton distribution function in* [7] *(solid line: central value, dashed lines: upper and lower bounds) and N. Kidonakis et al.* [6] *(dot-dashed line: central value, dotted lines: upper and lower bounds).*

3 Beauty Production

Measurements of beauty production continue to be a challenge for fixed-target experiments. Despite large theoretical and experimental uncertainties, the measurements are important in that they probe heavy quark production in a regime where perturbative QCD calculations are applicable. Results on beauty production from two experiments are presented here. The first is a preliminary measurement of the $b\bar{b}$ production cross section from HERA-B, the second is a published result on bottomonium polarization from NuSea.

Measuring $\sigma(b\bar{b})$ in a fixed-target experiment is a challenge. HERA-B measures the cross section for 920 GeV proton-nucleus interactions by placing wire targets in the halo of the HERA proton beam. For this measurement, HERA-B reconstructs $J/\psi \to \mu^+\mu^-$ and $J/\psi \to e^+e^-$ decay vertices. J/ψ's that satisfy detachment cuts with respect to the wire targets are used to determine the number of $b-$hadrons decaying to J/ψ, as distinguished from the large prompt J/ψ background. The background comes from J/ψ production in the targets, and HERA-B uses the background events to normalize $\sigma(b\bar{b})$ relative to prompt J/ψ production measurements from two fixed-target exper-



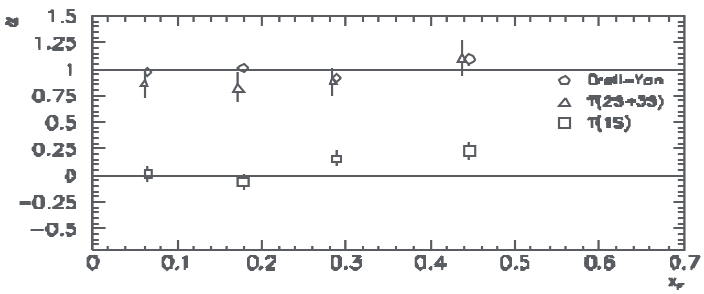


Figure 2: *NuSea data on bottomonium polarization. a)* α *versus* p_T *for Drell-Yan sidebands (8.1* $< m_{\mu^+\mu^-} <$ *8.45 GeV and 11.1* $< m_{\mu^+\mu^-} <$ *15.0 GeV),* Υ*(1S) (8.8* $< m_{\mu^+\mu^-} <$ *10.0 GeV), and* Υ*(2S+3S) (10.0* $< m_{\mu^+\mu^-} <$ *11.1 GeV). b)* α *versus* x_F *for the same mass regions. The error bars show statistical errors only. There is an additional systematic error (not shown) of 0.02 in* α *for Drell-Yan polarizations, and 0.06 in* α *for onium polarizations.*

iments [2), 3)]. A correction for the atomic number dependence of the target material is based on a measurement from NuSea [4)].

HERA-B obtains two samples of events, one with 2880 ± 60 $J/\psi \to \mu^+\mu^-$ decays and the other with 5710 ± 380(stat) $\pm$ 280(sys) $J/\psi \to e^+e^-$ decays. The number of events that satisfy detachment cuts are $1.9\,^{+2.2}_{-1.5}$ and $8.6\,^{+3.9}_{-3.2}$ for the $\mu^+\mu^-$ and e^+e^- channels, respectively. The two channels are combined in a simultaneous unbinned maximum likelihood fit that is used to obtain the measurement for $\sigma(b\bar{b})$. The result is $32\,^{+14}_{-12}\,(stat)\,^{+6}_{-7}\,(sys)$ nb/nucleon, which is shown in Fig. 1 along with the latest QCD calculations [5), 6)] beyond next-to-leading order (NLO). HERA-B has submitted this measurement for publication since the precision of the measurement is comparable to existing measurements from experiments E771 [8] and E789 [9] (also shown in Fig. 1). In an upcoming run, HERA-B expects to get significantly more data, which will be used to obtain a more precise determination of $\sigma(b\overline{b})$.

The second result on beauty production is a measurement of bottomonium polarization at $\sqrt{s} = 38.8$ GeV from NuSea [10]. The result is compared to predictions from Non-Relativistic Quantum Chromodynamics (NRQCD). This is important to help resolve the issue of color octet contributions to onium production. Fig. 2 shows the NuSea data points as a function of p_T and x_F. The data points for Drell-Yan dimuons are included to show that they are consistent with 100% transverse polarization, as expected for Drell-Yan virtual photons that are produced transversely polarized. The data for $\Upsilon(1S)$ show almost no polarization at small p_T and x_F, which disagrees with an NRQCD calculation [11] that predicts a value of 0.28 to 0.31 averaged over p_T and x_F. The data for $\Upsilon(2S)$ and $\Upsilon(3S)$ are combined in Fig. 2, since NuSea is unable to resolve the two states. The figure shows that the polarization of the cross-section-weighted average of the $2S + 3S$ states is much larger than the polarization of the $1S$ state for all values of p_T and x_F. This is different from polarization measurements in the charmonium system from CDF [12].

4 Charm Production

Studies of charm production benefit from the large data samples that have been collected by several fixed-target experiments. Four new results are presented in this paper. The results come from Fermilab experiments that acquired data during the 1991 fixed-target run, and a subsequent run in 1996-97. In the 1991 run the hadroproduction experiment E791 collected a large charm sample using a 500 GeV/c π^- beam, and a recent publication [13] presents their analysis of Λ_c production asymmetries. A study of Λ_c production asymmetries was also published recently [14] by SELEX, another hadroproduction experiment that ran in 1996-97 with π^-, Σ^-, and proton beams. In addition to studies of Λ_c asymmetries, SELEX may have observed doubly charmed baryons for the first time. The fourth charm production result, on $D\overline{D}$ correlations, comes from FOCUS, a photoproduction experiment that ran with a photon beam that had an average energy of 170 GeV.

FOCUS has extracted a large sample of 7066 ± 119 $D\overline{D}$ events from the data recorded in 1996-97. Each event has two D candidates. Both D candidates

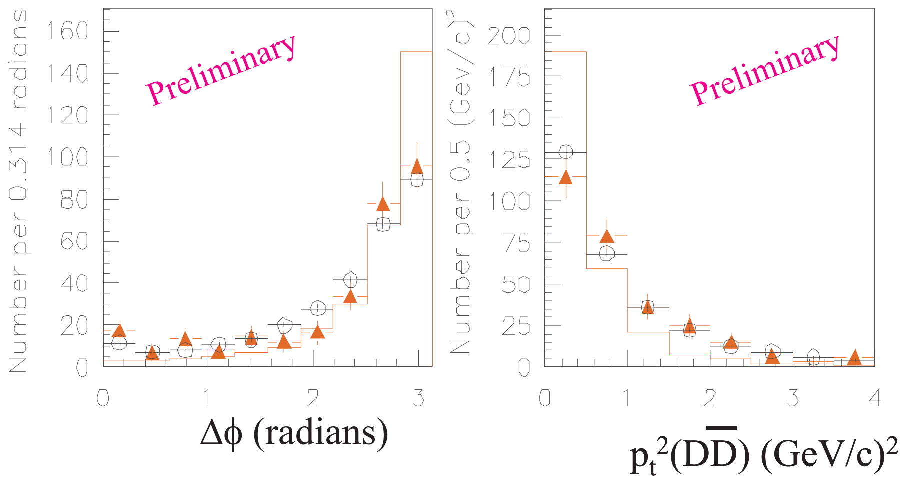


Figure 3: *$D\overline{D}$ correlations for FOCUS data (circles) and E687 data (triangles) compared to PYTHIA version 5.6 (solid line). The plot on the left shows the angle, $\Delta\phi$, between the D and $\overline{D}$ in the plane transverse to the beam, and the plot on the right shows the transverse momentum squared for the $D\overline{D}$ pair.*

are fully reconstructed. The decay modes that are considered for the analysis are $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $D^0 \to K^-\pi^+\pi^+\pi^-$, and charge conjugate modes. By reconstructing both the D and the $\overline{D}$ in an event, FOCUS is able to study $D\overline{D}$ correlations. Fig. 3 shows $\Delta\phi$, the angle between the D and $\overline{D}$ in the plane transverse to the beam, and the transverse momentum squared for the $D\overline{D}$ pair. These distributions are important with regard to heavy-quark production in QCD [15]. At leading order in QCD the c and $\overline{c}$ quarks are produced back-to-back with $\Delta\phi = 0$ and $p_T(c\overline{c}) = 0$. NLO corrections introduce a broadening of these distributions, but the data tend to disagree with NLO calculations and suggest significant contributions from non-perturbative effects.

Fig. 3 shows a comparison of FOCUS and E687 [16] data compared to PYTHIA version 5.6 [17] with default settings. The FOCUS data, which are preliminary, show good agreement with the published E687 data. Both the FOCUS data and E687 data show a significant discrepancy compared to PYTHIA 5.6, in that PYTHIA distributions are more sharply peaked compared to the data. In Fig. 4 the FOCUS data are compared to a more recent version

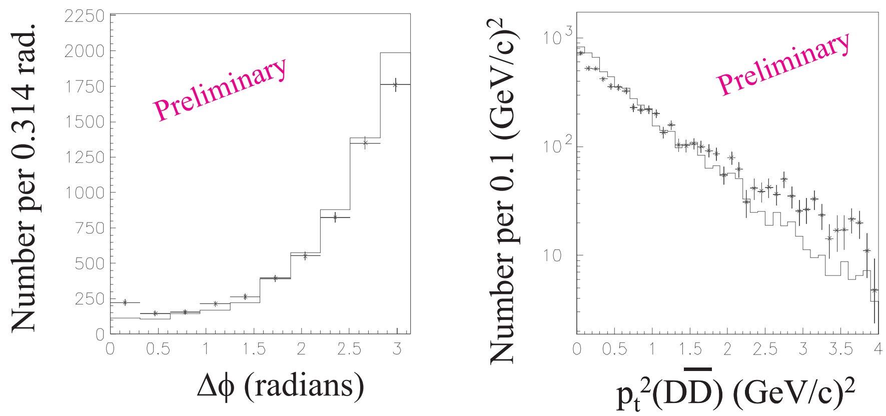


Figure 4: *FOCUS data (points with error bars) compared to PYTHIA version 6.203 (solid line).* $\Delta\phi$ *is the angle between the* D *and* $\overline{D}$ *in the plane transverse to the beam, and* p_t^2 *is the square of the transverse momentum of the* $D\overline{D}$ *pair.*

of PYTHIA (version 6.203) [18]. Here the agreement between data and the new version of PYTHIA has improved significantly. One of the reasons for the improvement is that the new version has a larger value for intrinsic k_T in the generator, which introduces a larger transverse momentum for initial partons. However, the new value for intrinsic k_T (PYTHIA 6.203 sets $< k_T^2 > = 1$ GeV^2) does not account for all of the improvement in these comparisons with data, and other changes in PYTHIA are believed to play a role. FOCUS is currently preparing these results for publication.

Another new result that is being prepared for publication is the possible observation of doubly charmed baryons by SELEX. SELEX observes three significant peaks (see Fig. 5) in $\Lambda_c^+ K^- \pi^+$ and $\Lambda_c^+ K^- \pi^+ \pi^+$ mass distributions. The three peaks are believed to be the ccd^+, ccu^{++}, and ccu^{*++} doubly-charmed baryons. One of the questions that has been raised by this analysis with regard to charm production concerns the number of reconstructed Λ_c^+ decays in the SELEX data. The data suggest that about half of all Λ_c^+'s come from the decay of these doubly-charmed baryons. This seems high. For comparison, FOCUS has looked for doubly-charmed baryons and sees no signal [19]. One possible explanation is the higher beam energy in SELEX compared to FOCUS, and another might be that the production of doubly-charmed baryons

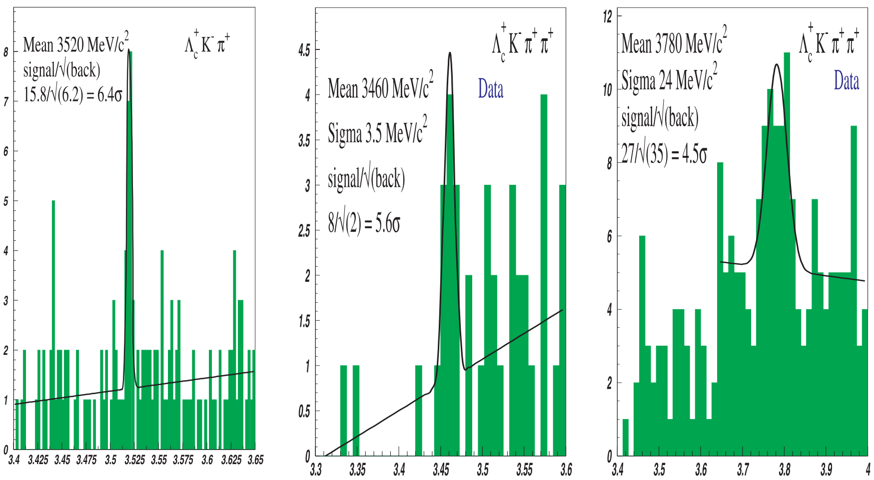


Figure 5: *SELEX invariant mass distributions for* $\Lambda_c^+ K^- \pi^+$ *in the range [3.4, 3.65] GeV (left),* $\Lambda_c^+ K^- \pi^+ \pi^+$ *in the range [3.3, 3.6] GeV (center), and* $\Lambda_c^+ K^- \pi^+ \pi^+$ *in the range [3.4, 4.0] GeV (right).*

is enhanced for a baryon beam, or more specifically a hyperon beam. In either case, if SELEX has observed doubly-charmed baryons, the implications for charm production are significant.

One of the most striking features observed in charm production is the *leading particle effect*. The effect is observed as an enhancement in the production rate of particles that have one or more valence quarks in common with an initial state hadron (either a beam hadron or a target hadron) compared to the corresponding antiparticle production rate. The effect is usually presented as an asymmetry distribution as a function of x_F and p_T^2. For each bin of x_F and p_T^2 the asymmetry parameter A is defined as

$$A \equiv \frac{N - \overline{N}/r}{N + \overline{N}/r}, \qquad r = \frac{\overline{\epsilon}}{\epsilon}, \tag{1}$$

where N ($\overline{N}$) is the number of particles (antiparticles) in the bin, and ϵ ($\overline{\epsilon}$) is an efficiency that accounts for geometrical acceptance, and trigger and reconstruction efficiencies. The leading particle effect is not limited to charm production, since it is also observed in light hadron production (see the next section on

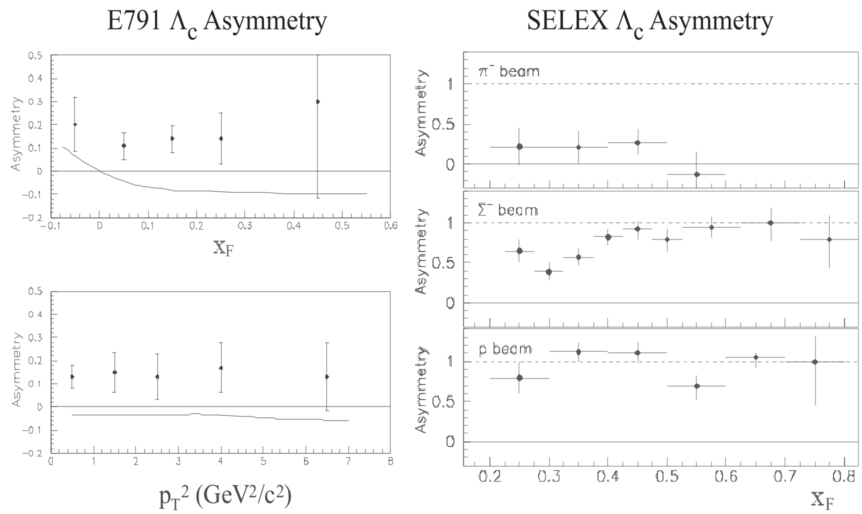


Figure 6: *a) E791 Λ_c asymmetry (data points with error bars) as a function of x_F (top left) and p_T^2 (bottom left) compared to PYTHIA 5.7 (solid lines). b) SELEX Λ_c asymmetry as a function of x_F (shown on the right) for three types of beam particles (top: π^- beam, middle: Σ^- beam, bottom: proton beam).*

hyperon production, for example). However, for charm production the data are compared to next-to-leading-order perturbative QCD calculations. Perturbative QCD predicts that particle/antiparticle asymmetries should be very small. The data, on the other hand, have indicated large asymmetries, which are usually attributed to non-perturbative QCD effects.

Two hadroproduction experiments, E791 and SELEX, have recently published results on Λ_c asymmetry measurements. Fig. 6 shows the E791 asymmetry measurement as a function of x_F and p_T^2 for a π^- beam on the left, and the SELEX measurements as a function of x_F for π^-, Σ^-, and proton beams on the right. The E791 results are compared to PYTHIA version 5.7. In PYTHIA there is an increase in the asymmetry for negative x_F as one would expect for the leading particle effect associated with the valence quarks in the target. In the forward x_F region, on the other hand, one does not expect an enhancement in the Λ_c asymmetry, since both particle and antiparticle share one valence quark with the incident pion beam, and PYTHIA distributions appear to be qualitatively correct. However, the E791 data have a positive asymmetry that differs from the PYTHIA predictions. This suggests that some effect that is not in PYTHIA or differs from the PYTHIA prediction may be involved, such as associated production of charmed mesons and baryons. Note that the energy threshold is higher for $\overline{\Lambda_c^+}$ production since an additional baryon-antibaryon pair must be produced to satisfy baryon number conservation. When the E791 results are compared to the SELEX asymmetry measurements, one observes the following. First, the SELEX data for the π^- beam are consistent with E791. Second, the asymmetry for baryon beams (both Σ^- and proton beams) is significantly higher. This is a good example of the leading particle effect, in that baryon beams tend to produce baryons, not antibaryons.

Although many of the recent results on charm production emphasize non-perturbative effects such as fragmentation, associated production, and the leading particle effect, there is recent work on a theoretical model that addresses the leading particle effect in the context of perturbative QCD. Recent papers [20), 21)] show that the leading particle effect can be described by a heavy-quark recombination mechanism for data that have been studied so far.

5 Hyperon Production

The same kinds of non-perturbative effects that are observed in charm production also appear in hyperon production data. Moreover, many results on hyperon production are still not represented adequately by models and Monte Carlo programs. Recent results are no exception.

E791 has published results on Λ, Ξ^-, and Ω^- production asymmetries [22)] that display discrepancies that are similar to the Λ_c asymmetries described in the previous section. Fig. 7 shows the asymmetries as a function of x_F and p_T^2 with comparisons to PYTHIA 5.7. The x_F distributions show evidence for the leading particle effect for Λ hyperons with $x_F < 0$, and for Ξ^- hyperons with $x_F < 0$ and $x_F > 0$ (the Ξ^- shares a valence quark with the π^- beam and with the target). Although PYTHIA describes some of the features of the data qualitatively, the model predicts smaller values of the asymmetries for x_F and p_T^2 ranges shown in Fig. 7. As was the case for charm production asymmetries, E791 suggests that the discrepancies in hyperon asymmetries could be due to associated production of strange baryons and mesons.

Experiment WA89 has two new results. They have published a thor-

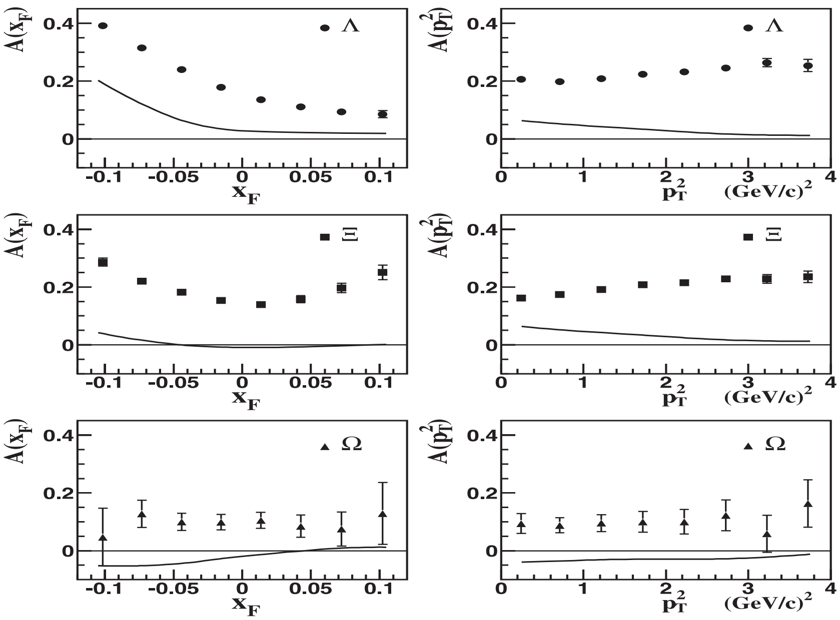


Figure 7: *E791 hyperon asymmetries (data points with error bars) as a function of* x_F *(left) and* p_T^2 *(right) compared to PYTHIA 5.7 (solid lines).*

ough investigation [23] of $\Sigma^{\pm}$, $\Sigma^{*\pm}$, and $\overline{\Sigma}^{-}_{1385}$ production with comparisons to PYTHIA and the quark-gluon-string model (QGSM) [25], and a study [24] of Λ and $\overline{\Lambda}$ correlations. The first publication presents numerous distributions and comparisons to models with some striking discrepancies between data and the models. The second publication presents an analysis of kinematic correlations for identical hyperons, showing how momentum-conservation constraints can affect x_F distributions for the hyperons.

The final result on hyperon production presented at this conference comes from a recent publication [26] on Λ polarization in fully reconstructed $pp \to p\Lambda K^+$ events from E690. E690 sees variations in Λ polarization that appear to be associated with structure in the invariant mass ($M_{\Lambda K}$) distribution for the ΛK^+ system. For small values of $M_{\Lambda K}$, E690 observes large positive polarization, which has not been seen by other experiments. For large values of $M_{\Lambda K}$ the E690 data agree with measurements from a previous experiment [27].

6 Concluding Remarks

Recent measurements from fixed-target experiments on beauty, charm, and hyperon production represent an ongoing effort to understand production mechanisms in strong interactions. Collectively, the measurements provide a wide range of QCD probes that include studies of perturbative QCD predictions and non-perturbative effects. Similarities and differences between heavy-quark and light-quark production characteristics should be exploited to improve our understanding of the underlying production mechanisms. Each quark flavor represents an opportunity to study production in strong interactions with an emphasis on its own physics regime.

7 Acknowledgements

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