Recent Developments in Hyperon Spectroscopy

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My talk is devoted to

HYPERONS

The universe is built of baryons. Before 1947 only two baryons, the proton and neutron, made of **up** and **down** quarks, were known. The 1947 discovery of the first strange particles, the **kaon** and the **Lambda**, and consequently, of the **strange** quark enriched the field of baryons immensely. By 1960, when the theoretically predicted $\Omega^-$was discovered, all eight light baryons, containing strange quarks, $\Lambda^0, \Sigma^0, \Sigma^+, \Sigma^-, \Xi^0$, Ξ^- and Ω^-, known as **hyperons**, were known. However, even more than 50 years after their discovery very little more than the static properties of their ground states is known [4]. We do not know their quark-gluon structure, their form factors, their response to momentum transfer, and how their structure evolves as one, two, and three up/down quarks in the nucleons are replaced by strange quarks.

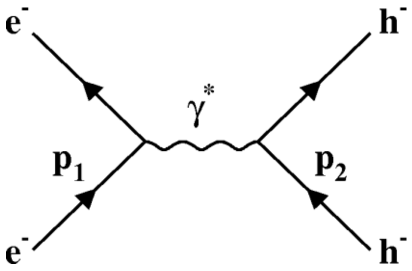
Hyperon	Quarks	Mass, M (MeV)	Mag.mom. ($\boldsymbol{\mu_N}$)	Main Decay
Proton, p	uud	938.272(<0.001)	2.793(<0.001)	stable
Λ^0	uds	1115.683(6)	-0.613(4)	$p\pi^-$ (64%)
Σ^0	uds	1192.642(24)	1.61(8)	$\Lambda^0\gamma$ (100%)
Σ^+	uus	1189.37(7)	2.458(10)	$p\pi^0$ (52%)
Σ^-	dds	1197.449(30)	-1.160(25)	$n\pi^-$ (99.8%)
Ξ^0	uss	1314.86(20)	-1.250(14)	$\Lambda^0\pi^0$ (99.5%)
Ξ^-	dss	1321.71(7)	-0.6507(25)	$\Lambda^0\pi^-$ (99.9%)
Ω^-	sss	1672.45(29)	-2.02(5)	Λ^0K^- (69%)

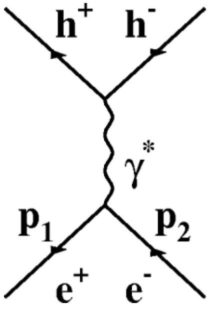
Most of our extensive knowledge of nucleon structure comes from lepton scattering by nucleon and nuclear targets [5]. Unfortunately, hyperons are not available as targets, and this is responsible in large part for the lack of our understanding of the structure of hyperons.

In 1960 **Cabibo and Gatto** [6] pointed out that electron-positron colliders were being planned at various laboratories, and they offered opportunity of overcoming the lack of target disadvantage of hyperons; one could measure **timelike form factors** of hyperons in $e^+e^- \to B\overline{B}$ $(B \equiv$ hyperon$)$ measurements. To put this opportunity in perspective, we note that four momentum transfers is defined as

$$Q(4\text{ mom.})^2 = q(3\text{ mom.})^2_{\text{space}} - (\text{energy})^2_{\text{time}}.$$

It can be **positive and spacelike**, or **negative and timelike.**





Form factors are analytic functions of momentum transfer $|\mathrm{Q}|^2$, and $\mathrm{B\overline{B}}$ pair production experiments can be analyzed in the same formalism as the scattering experiments, i.e., in terms of **the Dirac form factor, $\mathbf{F_1(|Q|^2)}$, and the Pauli form factor, $\mathbf{F_2(|Q|^2)}$,** or equivalently, in terms of the electric and magnetic form factors,

$$\mathrm{G_E(|Q|^2) = F_1(|Q|^2) + (s/m^2)F_2(|Q|^2)}, \quad \text{and } \mathrm{G_M(|Q|^2) = F_1(|Q|^2) + F_2(|Q|^2)}.$$

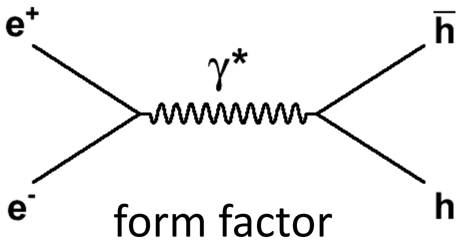
It took 30 years for the first measurement of the timelike form factors to be made by the DM2 Collaboration at Orsay [7], and seventeen more years by the BaBar Collaboration at SLAC [8] to report measurements of $\mathrm{G_M(|Q|^2)}$ of Λ^0, Σ^0, and the Λ^0, Σ^0 transition form factors. Because both these measurements were made near threshold energies, and only a few events were observed, they were not suitable for QCD based analyses. No further progress in hyperon production studies was made until at CLEO in 2005 we made measurements of pair production of hyperons at $\psi(2\mathrm{S})$ resonance,
$\sqrt{s} = 3.69$ GeV, $|\mathrm{Q}|^2$=13.59 GeV^2 [9].

We must remember, however, that unlike for spacelike form factors, $\mathrm{G_E}$ and $\mathrm{G_M}$ do not relate to spatial distributions of charge and magnetic moment. Instead they relate to the helicity correlations between the particle antiparticle pair produced. $\mathrm{F_2(|Q|^2)}$ denotes photon coupling to parallel spins and $\mathrm{F_1}$ to antiparallel spins of the pair.

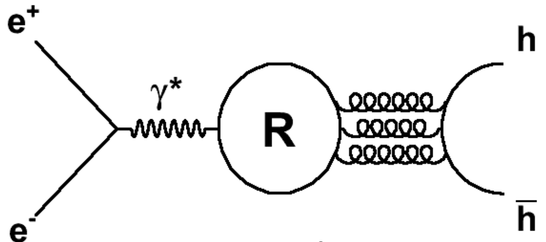
Hadronic decays at resonances proceed via gluons and have large yields. To measure electromagnetic form factors we require the decays to be electromagnetic, which have much smaller yields. To measure form factors we must measure e^+e^- annihilation at non-resonance energies, or at those resonances where it can be demonstrated that resonance yields are negligibly small, as $\psi(3770)$ and $\psi(4170)$ which mainly decay to $D\overline{D}$.

Using the experimentally confirmed pQCD relation

$$\mathcal{B}(\psi(n'))\ /\ \mathcal{B}(\psi(n))\ \text{to hadrons} = \mathcal{B}(\psi(n'))\ /\ \mathcal{B}(\psi(n))\ \text{to leptons}$$



form factor decay



resonance decay

We estimate resonance # of events:

	$\Lambda\overline{\Lambda}$	$\Sigma^+\overline{\Sigma}^+$	$\Sigma^0\overline{\Sigma}^0$	$\Xi^-\overline{\Xi}^-$	$\Xi^0\overline{\Xi}^0$	$\Omega^-\overline{\Omega}^-$
$\psi(3770)$:	3.0	1.4	1.2	1.2	0.6	0.3
$\psi(4170)$:	2.0	1.0	0.9	0.9	0.4	0.2

i.e., resonance contribution is indeed negligible for all hyperons, and

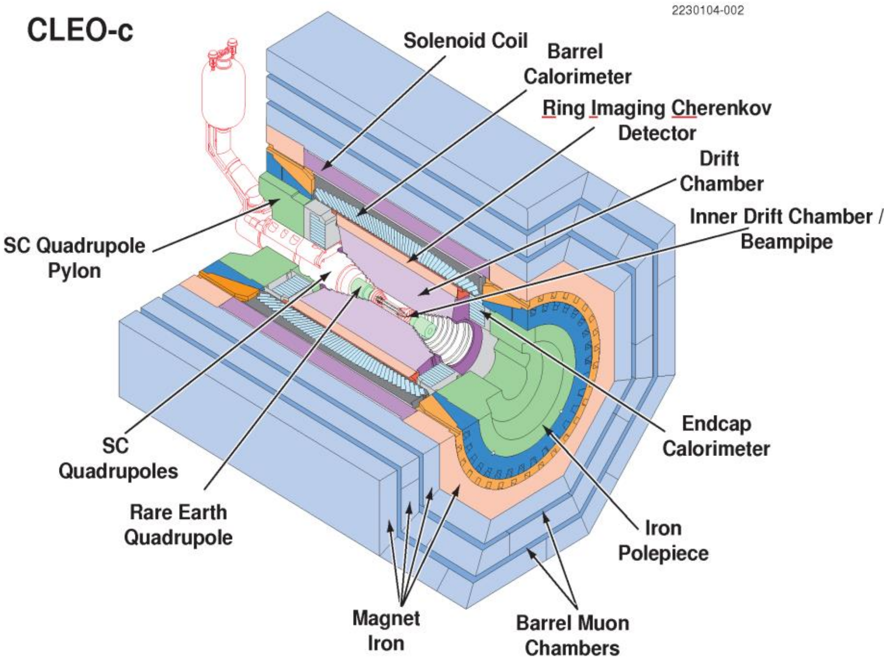
the observed hyperon yield is entirely electromagnetic.

We have now made the world’s first measurements of the

pair production of Λ^0, Σ^0, Σ^+, Ξ^0, Ξ^- and Ω^- hyperons

at large momentum transfers of 14.2 GeV^2 and 17.4 GeV^2 ,and with good statistics.

These measurements provide insight into the systematics of pair production of hyperons, their dependence of their cross section on their s-quark content, evidence for diquark correlations, and their timelike form factors.



We use e^+e^- annihilation data taken at the CESR collider using the CLEO-c detector.

The near-4pi acceptance CLEO-c detector of cylindrical geometry consists of a CsI electromagnetic calorimeter, drift chambers, and a RICH detector, all in a 1 Tesla solenoidal magnetic field.

The data consist of

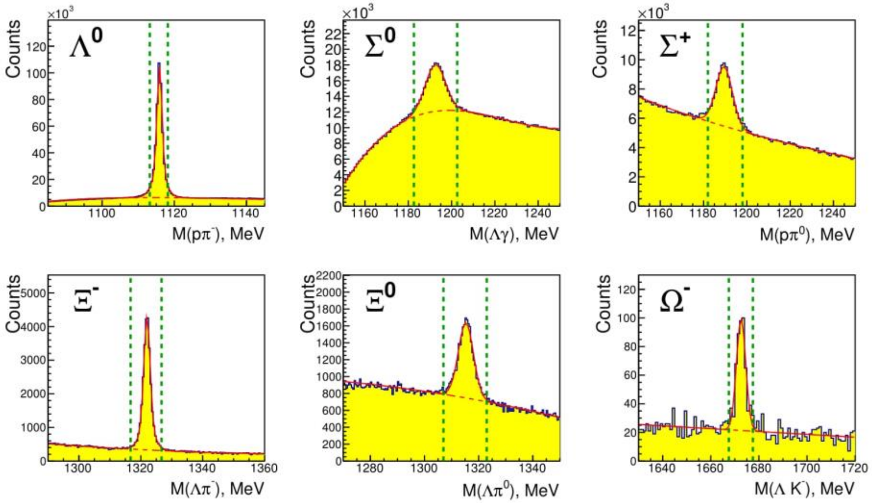
$\psi(2S)$, $\sqrt{s} = 3.69$ GeV, $|Q|^2$=13.59 GeV^2, $\mathcal{L}$= 48 pb^{-1},
$\psi(3770)$, $\sqrt{s} = 3.77$ GeV, $|Q|^2$=14.2 GeV^2, $\mathcal{L}$=805 pb^{-1},
$\psi(4160)$, $\sqrt{s} = 4.17$ GeV, $|Q|^2$=17.4 GeV^2, $\mathcal{L}$=586 pb^{-1}.

We identify the hyperons by detecting their major decay products,

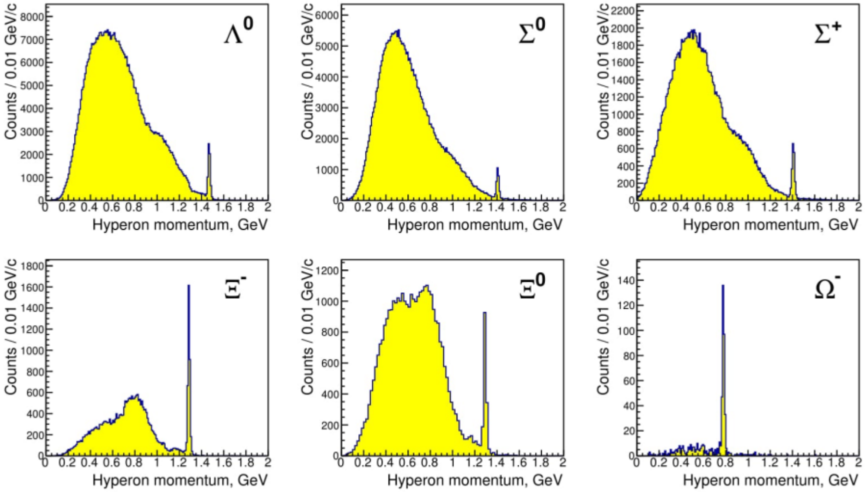
$$\Lambda^0 \rightarrow p\pi^- \ (64\%) \qquad \Sigma^+ \rightarrow p\pi^0 \ (52\%) \qquad \Sigma^0 \rightarrow \Lambda\gamma \ (100\%)$$

$$\Xi^- \rightarrow \Lambda\pi^- (100\%) \qquad \Xi^0 \rightarrow \Lambda\pi^0 \ (100\%) \qquad \Omega^- \rightarrow \Lambda K^- \ (68\%)$$

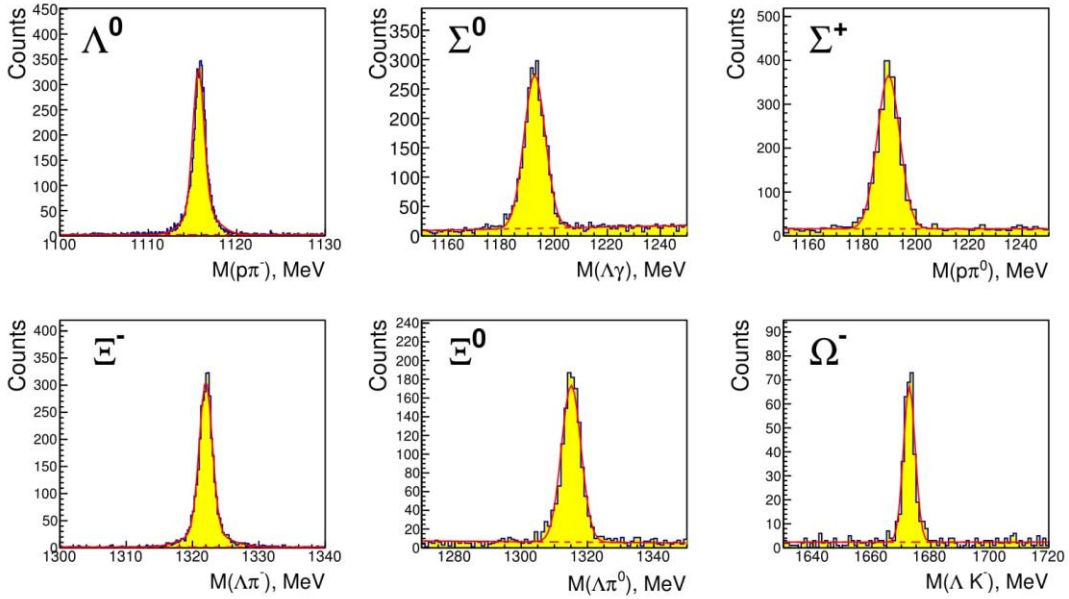
The $\psi(2S)$ resonance decay into hyperons has a prolific yield, and although it is not the subject of my talk, it illustrates the steps in hyperon identification very effectively.



Raw Invariant mass distribution for $\psi(2S)$ data.



Momentum distribution for $\psi(2S)$ data.

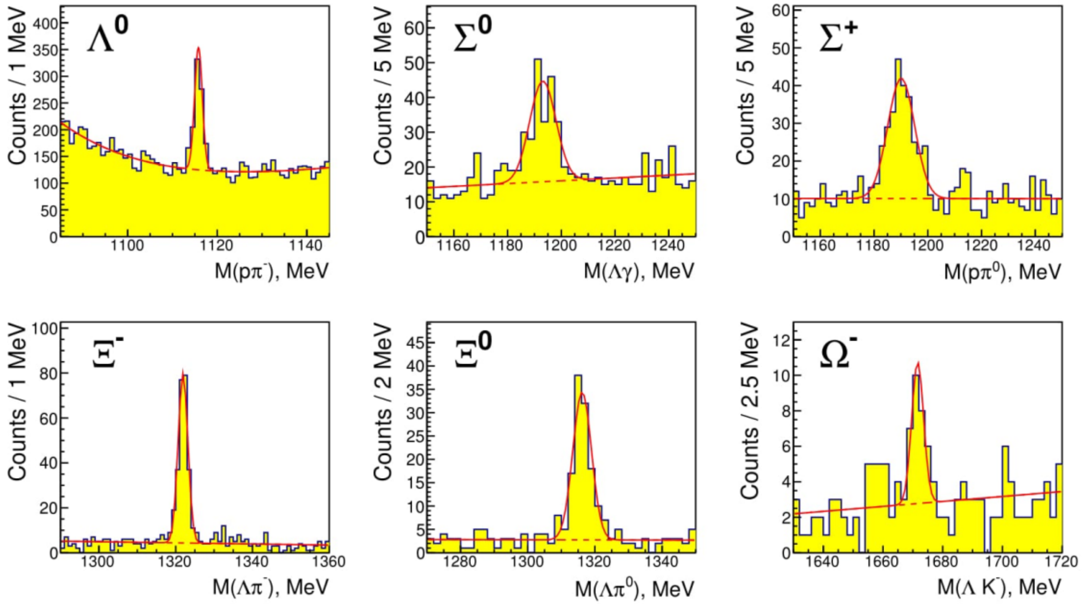


ψ(2S) Pair Production

$N(\Lambda,\ \Sigma^0, \Sigma^+) = 6531,\ 2645,\ 1874$

$N(\Xi^-,\ \Xi^0, \Omega) = 3580,\ 1242,\ 326$

← Notice bountiful Ω^-



ψ(3770) Pair Production

$N(\Lambda,\ \Sigma^0, \Sigma^+) = 498,\ 142,\ 200$

$N(\Xi^-,\ \Xi^0, \Omega) = 240,\ 111,\ 20$

$*$ Notice an order or more decrease than the resonance yield at ψ(2S)

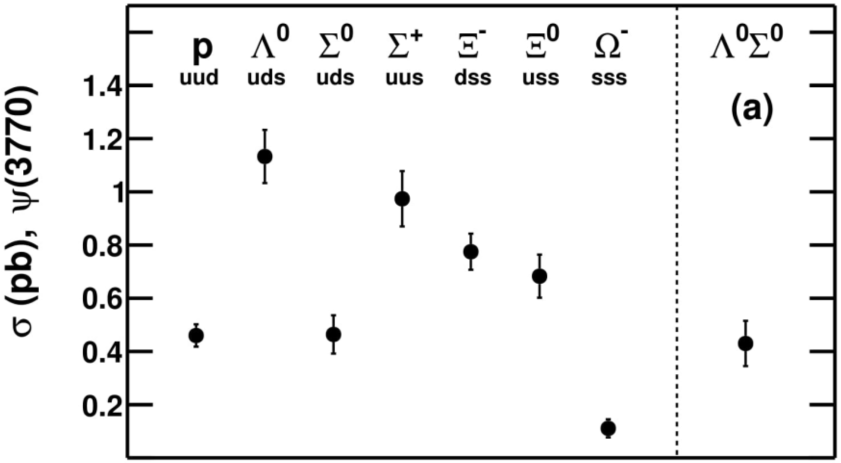
HYPERON PRODUCTION EXPERIMENTAL RESULTS

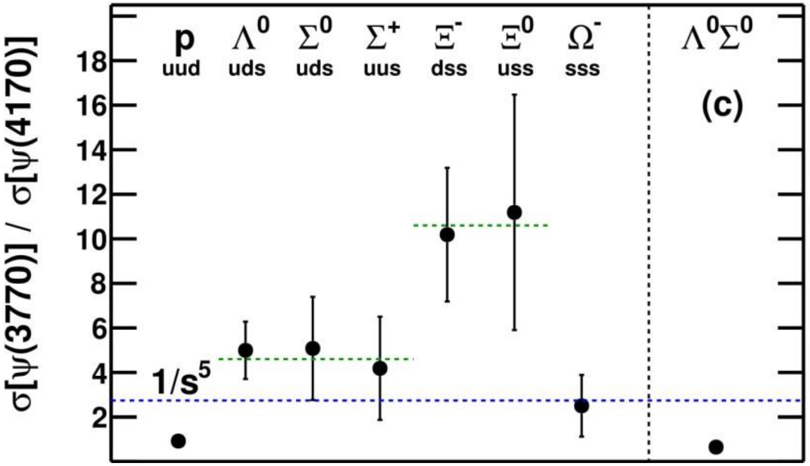
Pair Production Cross Sections (picobarns)

	p	Λ^0	Σ^0	Σ^+	Ξ^-	Ξ^0	Ω^-	$\Lambda^0\Sigma^0$
$\psi(2S)$	196(12)	244.7(106)	145.6(77)	151.4(74)	199.9(100)	131.6(82)	33.7(28)	8.1(16)
$\psi(3770)$	0.46(4)	1.13(10)	0.46(8)	0.97(10)	0.78(7)	0.68(9)	0.11(3)	0.43(9)
VDM Theory $\psi(3770)$ [10]	0.069	0.010		0.081	0.064	0.014	0.006	0.042

- Note that σ for electromagnetic production at $\psi(3770)$ are smaller by factors ≥ 200 than for the resonance production at $\psi(2S)$.
- Note that the GVDM theoretical predictions of Körner and Kuroda [10] for $\psi(3770)$ are smaller by orders of magnitude than the measured values.

$* *$ Note that $\sigma(\Sigma^0)$ is much smaller than the general trend of the data for $J = 1/2$ hyperons. More about this very important observation later.





Notice steps with # of s-quarks

Measurements of Timelike Form Factors for $|Q|^2 > 6\ \mathrm{GeV}^2$

As for nucleons, the timelike form factors are related to cross sections in terms of form factors G_E and G_M, which now refer to correlations between the helicities of the baryon and antibaryon

$$\sigma_{B\bar{B}} = \left(\frac{4\pi\alpha^2\beta_B}{3s}\right)\left[\left|G_M^B(s)\right|^2 + (2m_B^2/s)\left|G_E^B(s)\right|^2\right]$$

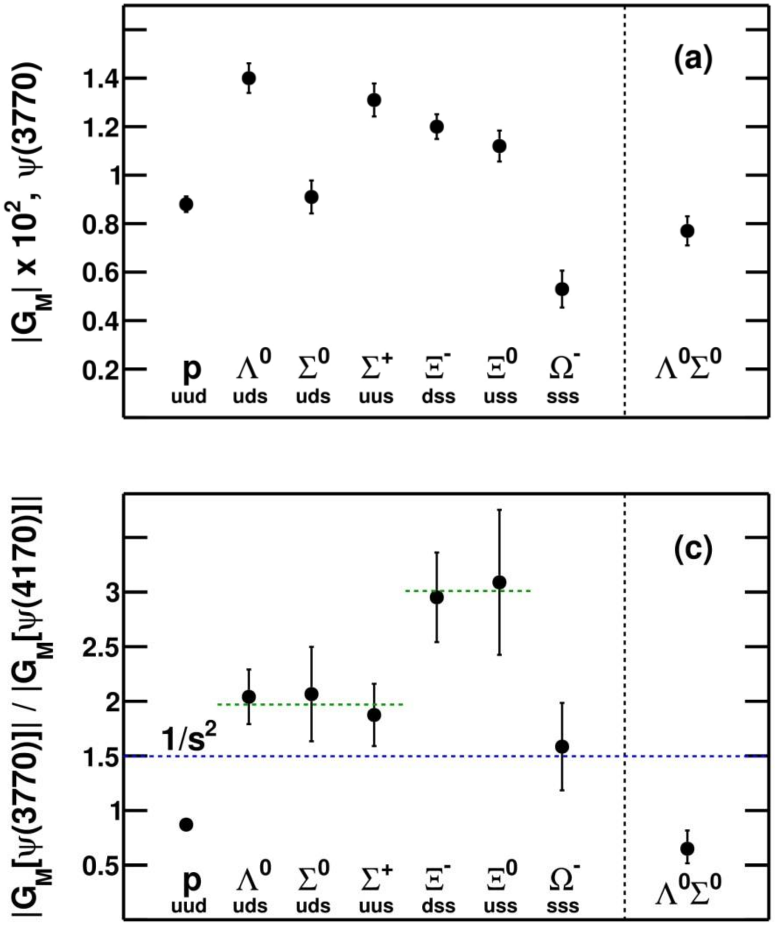
Because of small yield of hyperons from electromagnetic events, it is generally not possible to determine G_E and G_M, or G_E/G_M separately, and most experimental data are analyzed by assuming $G_E/G_M = 0$ or 1.

- BaBar has recently analyzed the angular distributions for their ISR based production of $\Lambda\bar{\Lambda}$ pairs in two $\sqrt{s}$ bins. They obtained two quite different values,
  $|G_E/G_M| = 1.73^{+0.99}_{-0.57}$ for the $\sqrt{s} = 2.23 - 2.40\ \mathrm{GeV/c^2}$ bin with 115 events, and
  $|G_E/G_M| = 0.71^{+0.66}_{-0.71}$ for the $\sqrt{s} = 2.40 - 2.80\ \mathrm{GeV/c^2}$ bin with 61 events.
  They considered both of them as consistent with $G_E/G_M = 1$, and analyzed their data with that assumption.

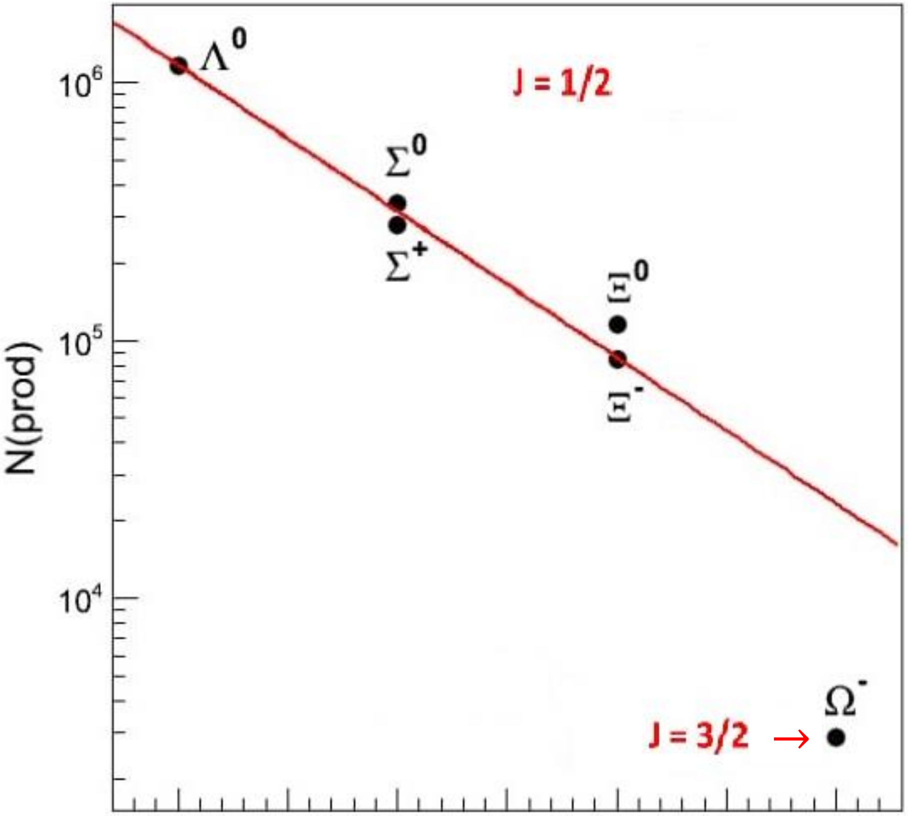
- We have analyzed our data for Λ^0, Ξ^0, Ξ^- production, and obtained $G_E/G_M = 0$ in all three cases, with 90% confidence limits: $\Lambda^0 < 0.17$, $\Xi^0 < 0.32$, $\Xi^- < 0.29$.
  Unexpected as this result is, it is consistent with the recent Jlab observation, $G_E = 0$ at $|Q|^2 \approx 8\ \mathrm{GeV}^2$ for proton. We have analyzed our data for $|Q|^2 = 14.2$ and $17.4\ \mathrm{GeV}^2$ assuming $G_E = 0$. Unfortunately, unlike for the proton there are no measurements of spacelike form factors to compare with.

Timelike Form Factors for $|Q|^2 = 14.2\ \mathrm{GeV}^2$

	p	Λ^0	Σ^0	Σ^+	Ξ^-	Ξ^0	Ω^-	$\Lambda^0\Sigma^0$
$G_M(3770)$	0.88(4)	1.40(6)	0.91(7)	1.31(7)	1.20(5)	1.12(6)	0.53(8)	0.77(8)



An Interesting Trend for Inclusive Events Produced with $\mathcal{L}$= 48 pb^{-1} at $\psi(2S)$



DISCUSSION OF EXPERIMENTAL RESULTS

Pair Production Cross Sections

- No pQCD or lattice-based predictions for hyperon pair production or inclusive hyperon production cross sections or timelike form factors exist. Two predictions based on the vector dominance (VDM) model exist:
  - The 1977 prediction of Körner and Kuroda [10] for pair production cross sections of all hyperons for $|Q|^2$ = threshold to $s = 16$ GeV^2,
  - The recent (1991) VDM calculation by Dubnickova *et al.* [11] for the spacelike and timelike form factors of Λ from threshold to $s = 10$ GeV^2 was normalized to DM2 measurement at 5.7 GeV^2, and they do not make predictions.
- No experimental data were available to Korner and Kuroda in 1977 to constrain the parameters of their calculation, and their predicted cross sections at $\psi(3770)$ are found to be generally more than an order of magnitude smaller than our measured cross sections.
- Perturbative QCD predicts that baryon form factors should be proportional to $1/Q^4$ or $1/s^2$, or σ should be proportional to $1/s^5$.

There are no predictions about the variability of these predictions with the strange quark content of the baryon.

However, we observe that cross sections, and timelike form factors show clear dependence on the number $n_s = 0$, 1, or 2 of the strange quarks in the hyperon.

We find the ratio $R \equiv \sigma(\text{observed})/\sigma(\text{pQCD})$,

$R(n_s = 0,\ \text{proton}) = 0.5$, $R(n_s = 1,\ \Lambda^0, \Sigma^0, \Sigma^+) \approx 2$, and $R(n_s = 2, \Xi^-, \Xi^0) \approx 3$.

DIQUARKS IN HYPERONS

Our most important result concerns the evidence for diquark corelations in hyperon pair production.

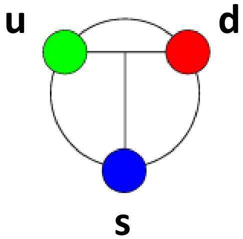
The importance of certain configurations of flavor, spin, and isospin of two quarks in the structure of hadrons has been recognized for a long time [12].

One dramatic example of the role of diquarks was provided by the Fermilab observation that the timelike form factor of protons was twice as large as the spacelike form factor at the same large momentum transfer $|Q|^2$ [13], and its successful explanation by Kroll *et al.* [14] in terms of the **diquark-quark structure of the proton**.

Recently Wilczek and colleagues [15] have emphasized the role of diquarks in QCD in terms of **isoscalar "good", and isovector "bad" diquarks**. They predicted that the "good" diquark in Λ^0 with isospin 0 compared to the "bad" diquark in Σ^0 with isospin 1, would lead to enhancement of Λ^0 over Σ^0 in production experiments. They cited the observation of $\Lambda^0/\Sigma^0 = 3.5 \pm 1.7$ in the LEP experiment in support of this prediction.

Our measurements provide strong independent support for the role of diquarks in Λ^0/Σ^0 hyperon production. We observe

$\sigma(\Lambda^0)/\sigma(\Sigma^0) = 2.46 \pm 0.46$ at $|Q|^2 = 14.2\ \mathrm{GeV}^2$ (in exclusive pair production),
$= 2.56 \pm 1.40$ at $|Q|^2 = 17.4\ \mathrm{GeV}^2$ (in exclusive pair production),
$= 4.1 \pm 0.6$ at $|Q|^2 = 13.6\ \mathrm{GeV}^2$ (in inclusive production).

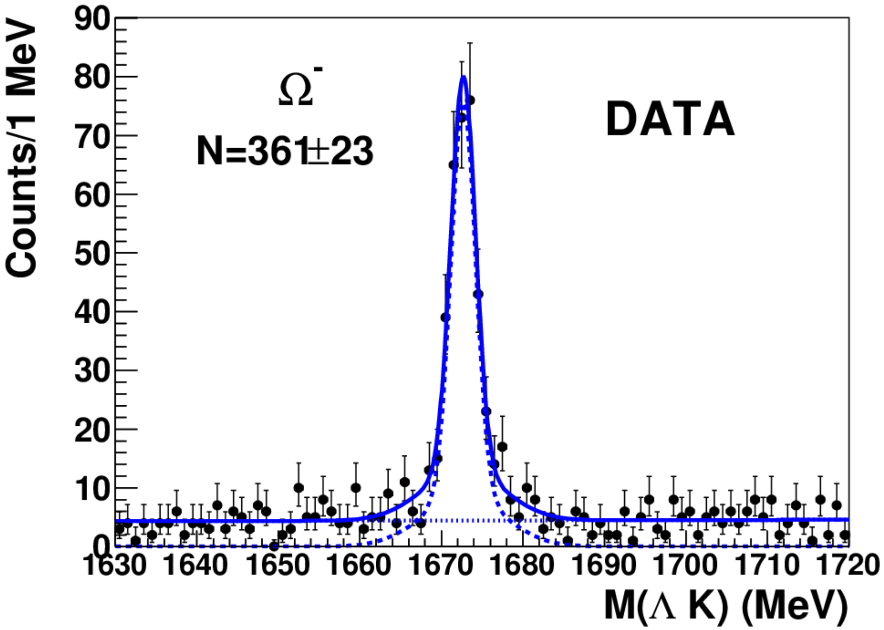


Our data provide the opportunity to consider diquark pairs other than the up/down diquarks, and we expect that they will lead to a deeper understanding of diquark correlations [16].

Omega minus Decay Branching Fractions

- The second part of my talk concerns specifically one particular hyperon out of the eight hyperons I have talked about.
  It is the Omega minus, Ω^-.
- Among the three quark baryons those which carry all three quarks of the same flavor hold a special place. Only two such are known: The charge 2 $\Delta^{++}(uuu)$, and the charge minus $\Omega^-(sss)$.
- In principle the negatively charged |bbb> and the 2 ++ charge |ccc> baryons should exist, but neither has been observed. So Ω^- remains unique in its type.
- Also, only one measurement of branching fractions for the decay of Ω^- has ever been reported [17]. It is based on 1954 report of 16,000 Ω^- identified by magnetic analysis of the hyperon beam produced at the CERN SPS with 240 GeV/c protons incident on a 32~cm BeO target. The branching fractions reported for the dominant strong decays were: $\Omega^- \to \Lambda^0 \mathrm{K}^- = 67.8 \pm 0.7\%$, $\Omega^- \to \Xi^0 \pi^- = 23.6 \pm 0.7\%$, and $\Omega^- \to \Xi^- \pi^0 = 8.6 \pm 0.4\%$. No estimates of systematic errors were reported.
- In the first part of this presentation [18] I have reported the first measurements ofΛ, Σ^{+0}, Ξ^{+0}, and Ω^- hyperons in their production in e+e- annihilation at CLEO. Although compared to the hyperon beam measurement of CERN we have identified far fewer Ω^- $(N = 326 \pm 19)$, since no other measurements of the branching fractions of Ω^- have been reported since [1], we consider it important to report the results of our independent measurements of the branching fractions of Ω^-decays to $\Lambda^0 K^-$and $\Xi^0 \pi^-$ made by using different method for Ω^-production. Also, because both are two-body decays our analyses require only the measurement of K^- and π^- momenta to measure the branching fractions.

- All event selection criteria are the same as described earlier, except that for kaons from the decay $\Omega^- \rightarrow \Lambda^0 K^-$, a looser cut of $\Delta\mathcal{L}_{K,\pi} < -9$ and $\Delta\mathcal{L}_{K,p} < -9$ is used.
- The invariant mass distributions for Ω^- candidate in $\psi(2S)$ data in the pair-production region given by E(B)/E(beam)=0.99-1.01 is shown below. A Gaussian signal and a constant background is used to fit the spectrum. The number of Ω^- from the fit is $N_\Omega = N_{fit} - N_{ff} = (361 \pm 23) - (1 \pm 1) = 360 \pm 23.$



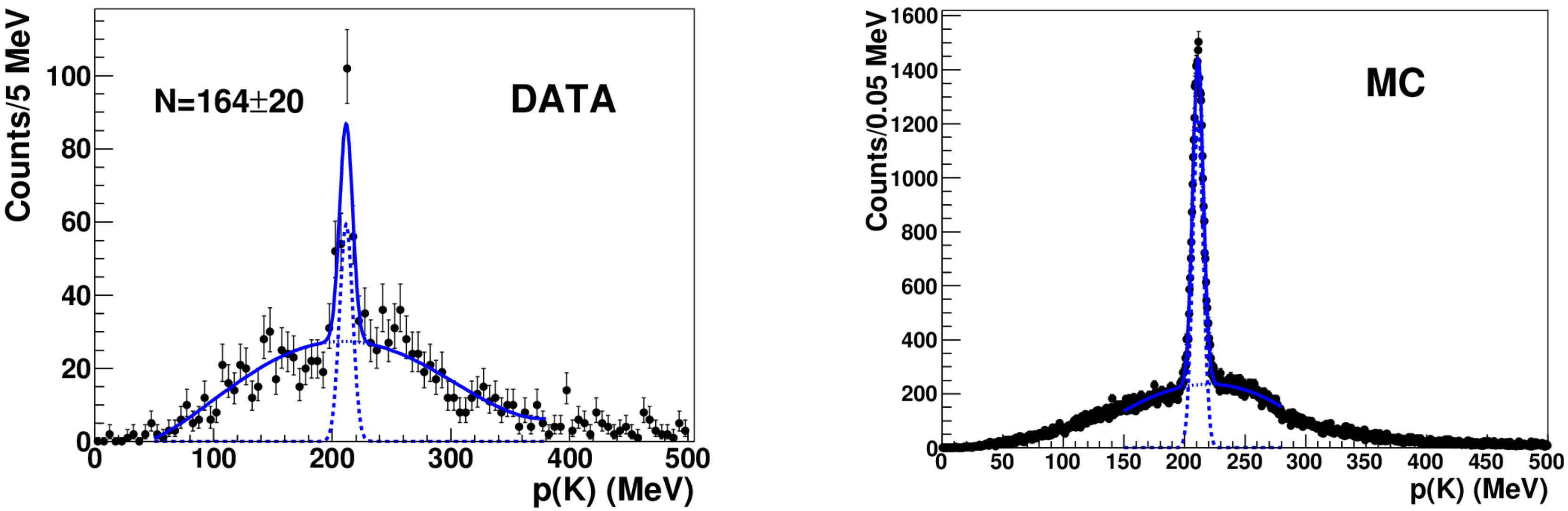
Invariant mass distributions for Ω^- candidate in $\psi(2S)$ data in the pair-production region, E(B)/E(beam)=0.99-1.01

- To determine reconstruction efficiencies 10,000 MC events were generated for each decay (charge conjugate decay modes are included):
  1. $\psi(2S) \to \Omega^-\overline{\Omega}^+, \Omega^- \to \Lambda^0 K^-, \overline{\Omega}^+ \to \overline{\Lambda}^0 K^+$
  2. $\psi(2S) \to \Omega^-\overline{\Omega}^+, \Omega^- \to \Lambda^0 K^-, \overline{\Omega}^+ \to \overline{\Xi}^0 \pi^+$
- One Ω^-hyperon is reconstructed by combining a Λ^0 candidate with a charged track identified as K^-. The rest of the tracks must meet the following requirements:

  (1). The track should be more like a pion or a kaon than a proton, i.e., $\Delta\mathcal{L}_{\pi,p} < 0$ and $\Delta\mathcal{L}_{K,p} < 0$;

  (2). It is required that the track should not form a Λ^0 by combining with another track. As before we identify by kinematically fitting two oppositely charged tracks, assuming that one is a $\pi^-/\pi^+$and the other is a $p/\bar{p}$, to its nominal mass, $M(\Lambda^0) = 1115.683$ MeV [3] within 5σ. The decay vertex of Λ^0 is further required to be displaced from the interaction point by 2σ.

- The figure shows the momentum distribution of the tracks in the rest frame of Ω^-, assuming they are kaons. It is fitted with a Gaussian signal and a 3rd order polynomial background. The number of kaons from the fit to the momentum distribution is $N_K = 164 \pm 20$.



The figure shows the momentum distribution of tracks from Ω^- decays in the ψ(2S) data (left) and MC (right), assuming they are kaons.

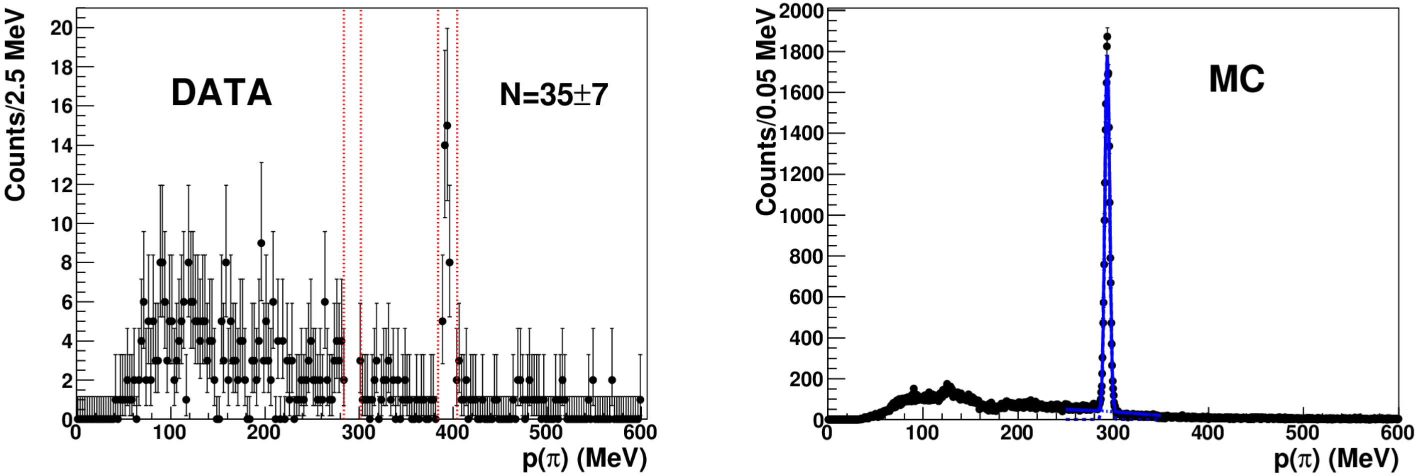
- The branching fraction for $\Omega^- \to \Lambda^0 K^-$ is calculated as

$$B(\Omega^- \to \Lambda^0 K^-) = \frac{N_K}{\epsilon_K N_K},$$

where $\epsilon_K = 66.1\%$ is the MC-determined efficiency.

Thus, $B(\Omega^- \to \Lambda^0 K^-) = \frac{164 \pm 20}{0.661 \times (360 \pm 23)} = (68.9 \pm 9.5)\%$.

- To measure the branching fraction for the channel $\Omega^- \to \Xi^0\pi^-$, we reject the tracks that lie in the range of 195 to 230 MeV as shown in figure from page 17. The momentum distribution of the remaining tracks in the rest frame of Ω^-, assuming they are pions, is shown in figure below. We fit the momentum spectrum with a Gaussian signal and a 3rd order polynomial background. Even though there is a big background in the low momentum region, the fit is able to identify the peak very well. The result from the fit gives $N_\pi = 35 \pm 7$.



The figure shows the momentum distribution of tracks from Ω^- decays in the $\psi(2S)$ data (left) and MC (right), assuming they are pions. For the sake of clarity the $p(\pi)$ peak is shown at $p(\pi) \approx 400$ MeV/c rather than its actual position at $p(\pi) \approx 294$ MeV/c.

- MC-determined efficiency for pion detection, $\epsilon_\pi = 51.1\%$.This leads to

$$B(\Omega^- \to \Xi^0\pi^-) = \frac{35\pm7}{0.511\times(360\pm23)} = (19.0 \pm 4.0)\%.$$

Omega minus Decay Branching Fractions

- In summary, we have measured Ω^- decay branching fractions using CLEO e+e- annihilation data. The results are:
  $B(\Omega^- \to \Lambda^0 K^-) = (68.9 \pm 9.5)\%$, $B(\Omega^- \to \Xi^0 \pi^-) = (19.0 \pm 4.0)\%$.
- These results can be compared with the PDG results [4]:
  $B(\Omega^- \to \Lambda^0 K^-) = (67.8 \pm 0.7)\%$, $B(\Omega^- \to \Xi^0 \pi^-) = (23.6 \pm 0.7)\%$, obtained by the CERN SPS measurement.

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