Hyperons
Form Factors and Diquark Correlations

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Hyperons

- The universe is made of **baryons** containing three quarks.
- Prior to 1947 the world of baryons had just two members, the **protons** and **neutrons** with only two kind of known quarks, the **up** and the **down** quarks. In 1947, a cloud chamber picture showed the production of the first particles containing the new strange **quark**, $\pi^- + p \to \Lambda^0 + K^0, K^0 \to \pi^+\pi^-$. The first strange baryon, $\boldsymbol{\Lambda^0}$, was soon followed by others, **3 Sigmas** $\boldsymbol{\Sigma^{0,\pm}}$, **two Cascades** $\boldsymbol{\Xi^{0,-}}$, and finally in 1964 by the theoretically predicted $\boldsymbol{\Omega^-}$.
- Now we know six kinds of quarks, u,d,s,c,b,t, and 20 different species of baryons are possible, but in this talk I am only talking of the nine baryons possible with the u,d,s quarks, called hyperons. These nine **hyperons** are the subject of my talk. Their textbook properties are:

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)	$\Lambda^0 K^-$ (69%)

Hyperons

- The observation of hyperons led to great interest in their possible role in nuclear physics, ranging from strangeness containing dibaryons (in particular the object of perennial searches,
  the **H (uuddss) dibaryon**), nuclei containing hyperons (**hypernuclear physics**), and to even **strange matter** in **astrophysics**.
  I am now going to talk about any of these interesting objects, but only about the more fundamental objects, the **hyperons** themselves.
- Surprisingly, very little more than what is shown in Table I is known about the properties of the ground state hyperons. We have excellent information about the spatial distribution of charges and magnetic moments in nucleons because of extensive measurements of electron scattering from proton and deuteron targets for *spacelike momentum transfers* over a wide range, from $Q^2 \sim 0$ to $\sim$30 GeV^2 (for protons).
- Unfortunately, hyperon targets do not exist, and we do not have any such information about the structure of hyperons.
  So, how do we learn about the structure of hyperons?

Hyperons

- Quarks were only proposed in 1964, but by the end of 1950's many hyperons had been observed, and strangeness as a new attribute was accepted. It was natural to wonder

  how do baryons containing strangeness differ from the familiar nucleons?

  To address this question, in 1960-61 Cabibo and Gatto wrote two very prescient papers [6] pointing out that while it was not possible to measure form factors of hyperons for *spacelike momentum transfers*, electron-positron colliders were being proposed at SLAC and Frascati, and they were offered a unique new opportunity to learn about the structure of hyperons by measuring their electromagnetic form factors for *timelike momentum transfers* by means of the reaction,

  $\boldsymbol{e^+e^-} \rightarrow$ **hyperon-anti hyperon, or** $\boldsymbol{B\bar{B}}$.

- My talk will be largely devoted to the world's first precision measurements of the hyperon form factors at large momentum transfers, which we have made using our e^+e^- annihilation data taken at the CESR e^+e^- collider at Cornell with the CLEO-c detector.

- Before I go into form factor measurements, which requires measurements of the exclusive decays, $e^+e^- \rightarrow B\bar{B}$, let me describe results for the inclusive production of hyperons, i.e., $e^+e^- \rightarrow B(\bar{B}) + X$, where X contains light hadrons, mostly pions, kaons and etas.

Inclusive Hyperons

- We identify the hyperons by detecting their major decay products,

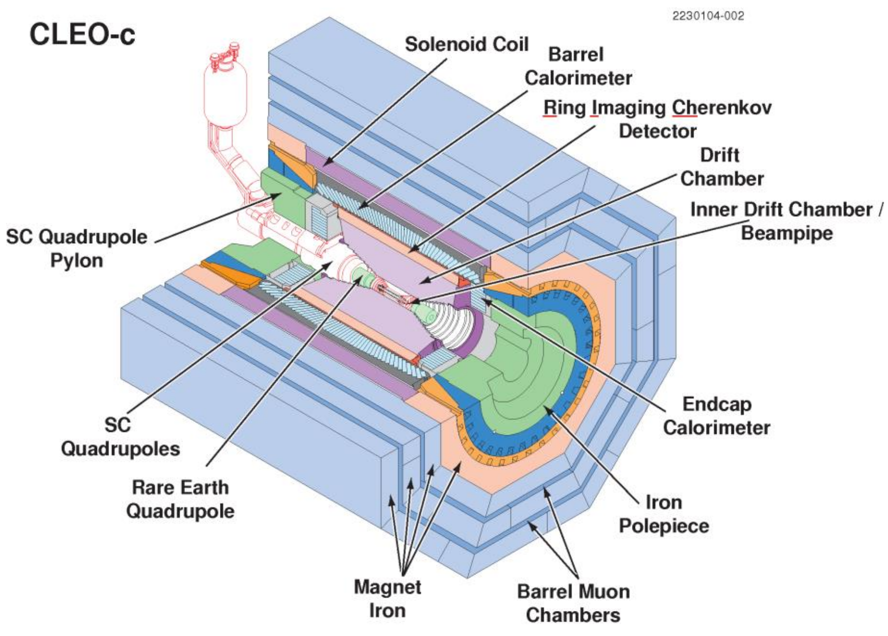
  $\Lambda^0 \to p\pi^-$ (64%) $\quad \Sigma^+ \to p\pi^0$ (52%) $\quad \Sigma^0 \to \Lambda\gamma$ (100%)

  $\Xi^- \to \Lambda\pi^-$(100%) $\quad \Xi^0 \to \Lambda\pi^0$ (100%) $\quad \Omega^- \to \Lambda K^-$ (68%)

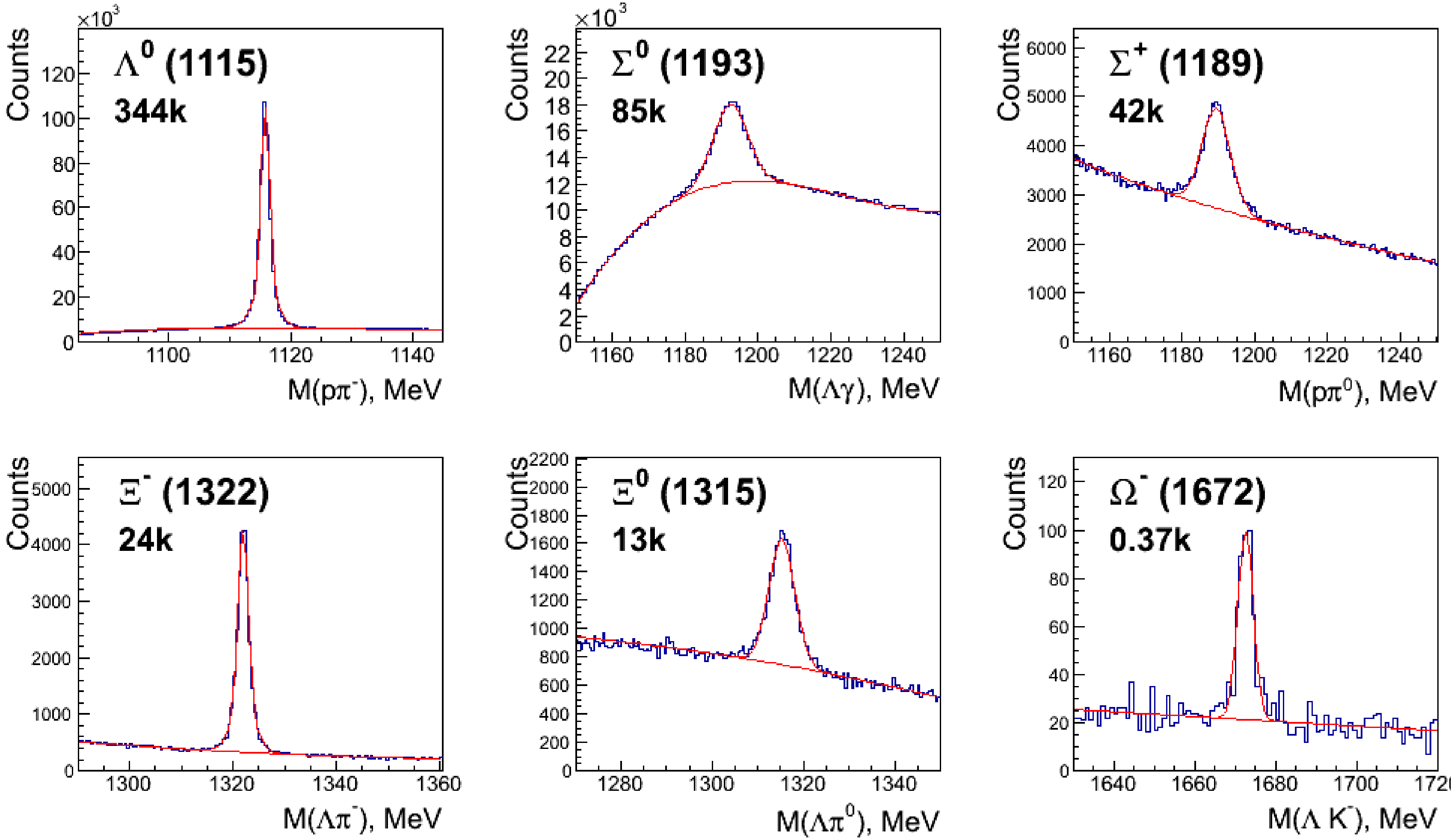
  in the near-4pi acceptance CLEO-c detector, which consists of a CsI electromagnetic calorimeter, drift chambers, and a RICH detector, all in a 1 Tesla solenoidal magnetic field.

  We use e^+e^- annihilation data of $\psi(2S)\ \sqrt{s} = 3686$ MeV: 48 pb^{-1}, $\psi(3770)\ \sqrt{s} = 3772$ MeV: 805 pb^{-1}, $\psi(4160)\ \sqrt{s} = 4170$ MeV: 586 pb^{-1}.

- The momenta of the inclusively produced hyperons, $\boldsymbol{e^+e^- \to B \text{ or } \bar{B} + X}$, where X consists mostly of pion and kaons, have a wide distribution, ending in small narrow peaks corresponding to exclusively produced $\boldsymbol{e^+e^- \to B\bar{B}}$ hyperons. Their distributions are shown in the next figure.



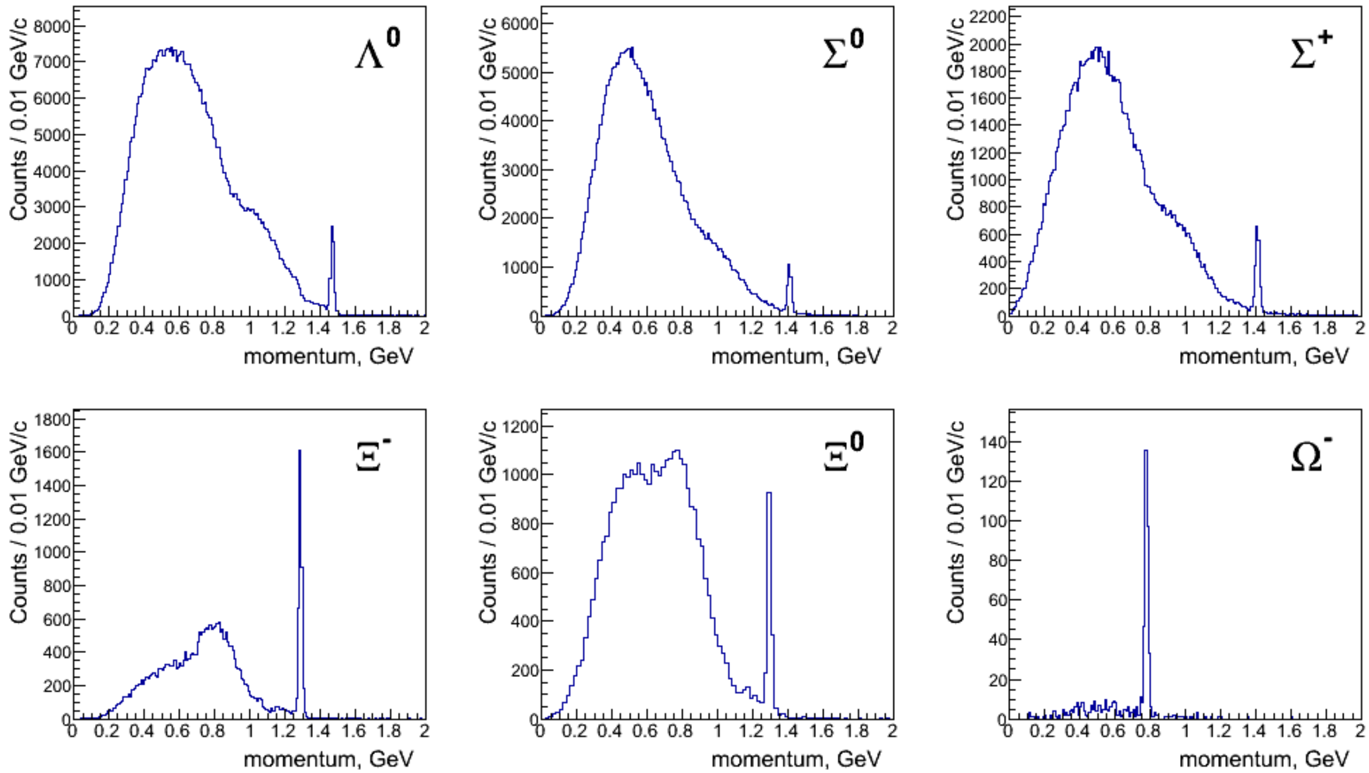
Inclusive Production of Hyperons from $\psi(2S)$
(number in 10^3 of single hyperons, B or $\bar{B}$ identified)



- **Notice the beautiful Ω^- peak with 370 Ω^- events.**

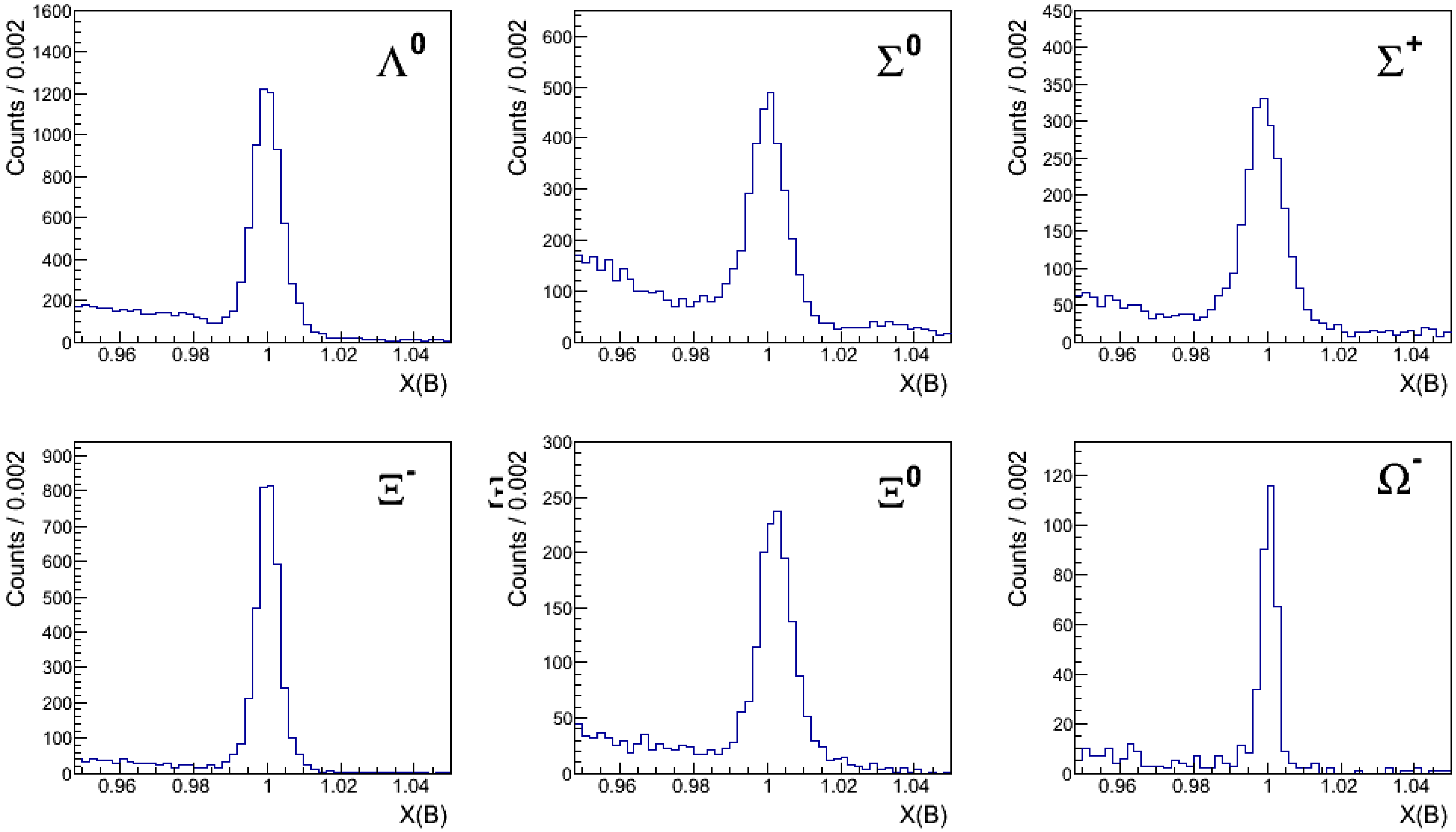
Inclusive Hyperons

(momentum distributions of inclusive hyperons)



- Note that the main yield of the hyperons is in $\psi(2S) \to B$ or $\bar{B} + X$ inclusive production. The narrow peaks at maximum momenta corresponding to exclusive pair production, $\psi(2S) \to B\bar{B}$. *For details about inclusive production, I refer you to the talk of S. Dobbs later in this session.*
- Detection efficiencies are momentum dependent, and are determined by generic Monte Carlo simulations in 10 slices of Δp.

Normalized Energy of Inclusive Hyperons
($X = [E(B)$ or $E(\bar{B})]/E_{\text{beam}}$)

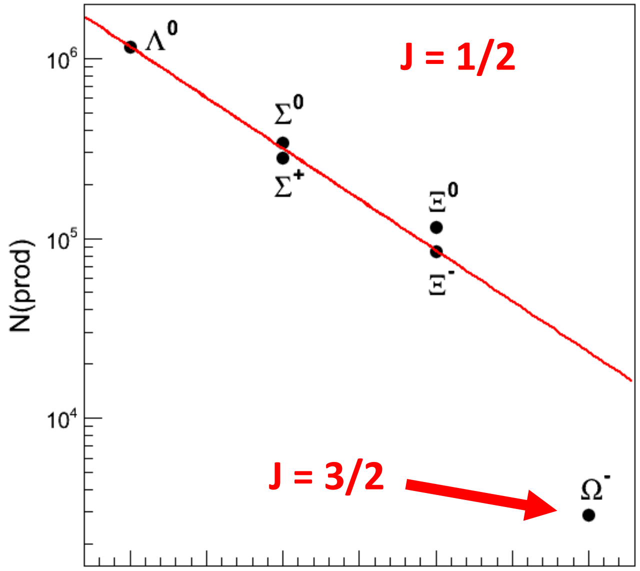


- Even though we reconstruct only one hyperon, B or $\bar{B}$, the $B\bar{B}$ peaks are very well defined, and the efficiency is much larger than for identifying both B **and** $\bar{B}$.

Inclusive Hyperon Production from $\psi(2S)$

$$\psi(2S) \to B(\bar{B}) + X \quad (\mathcal{L} = 48\ \text{pb}^{-1})$$

	N(obs) / 10^3	N(prod)=N_0/ϵ / 10^3	$\sigma = N_p/\mathcal{L}$ nb
Λ^0 (uds)	344.0(11)	1164.6(47)	24.3(1)
Σ^0 (uds)	84.8(13)	280.0(46)	5.83(10)
Σ^+ (uus)	41.8(5)	341.5(51)	7.11(11)
Ξ^0 (uss)	12.9(3)	115.9(28)	2.41(6)
Ξ^- (dss)	23.6(18)	84.2(8)	1.75(2)
Ω^- (sss)	0.37(2)	2.9(2)	0.060(4)



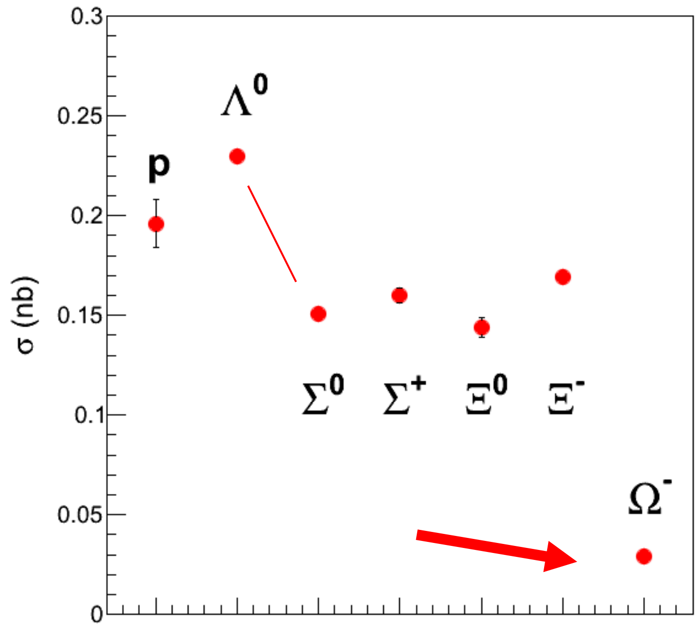
- **These inclusive cross sections are the first ever measured.**
- **Notice the factor four larger cross section for Λ^0 production compared to Σ^0 More about the physics implication of this later.**

Hyperon Pair Production from $\psi(2S)$

$$\psi(2S) \to B + \bar{B}$$

$\sigma(\text{pb}) = N(\text{obs})/[\varepsilon\mathcal{L}C]$, $\text{Br} = (N(\text{obs})/\varepsilon)/N(\psi(2S))$, $\mathcal{L} = 48\ \text{pb}^{-1}$, $C = 0.77$, $N(\psi(2S)) = 24.5 \times 10^6$

		N(obs) B or $\bar{B}$	ϵ %	σ nb	$\text{Br} \times 10^4$
p[7]	(uud)			0.196(12)	3.08(19)
Λ^0	(uds)	5762(78)	67.5	0.230(3)	3.49(5)
Σ^0	(uds)	2361(52)	41.9	0.151(3)	2.31(5)
Σ^+	(uus)	1520(42)	25.5	0.160(4)	2.44(7)
Ξ^0	(uss)	1108(36)	21.0	0.144(5)	2.16(7)
Ξ^-	(dss)	3089(57)	49.5	0.169(3)	2.55(5)
Ω^-	(sss)	171(14)	15.9	0.029(2)	0.44(4)



- These results represent improvement over those reported by us in Ref. [12]. Baryon identification efficiencies have been improved by nearly factor 3.
- **Notice that these exclusive σ are 50–100 times smaller than the inclusive σ, and that $\sigma(\Lambda^0)\ /\ \sigma(\Sigma^0) \approx 1.5$. All Br, except Ω^-, are nearly constant.**

Electromagnetic Form Factors

- It is interesting to measure the characteristics of the particles produced in a decay, their variety, their momentum distribution, and their branching fractions, and that is what I have been talking about the inclusive production of the different hyperons in e^+e^- annihilation.
- However, it is more interesting to probe their internal structure in terms of their constituents, the quarks and gluons. For nucleons this means study of the distributions of the up and down quarks, but for hyperons there is an added dimension to this study. Because hyperons come with one, two, or three strange quarks, we can study how baryon structure changes with the change in the *number of strange quarks*. This becomes possible with measuring the electromagnetic form factors of hyperons, and it is the primary objective which got us interested in the present measurements. The rest of my talk is devoted to measurement of hyperon form factors, and what they tell us about the nature of the quark distributions and correlations in the hyperons.

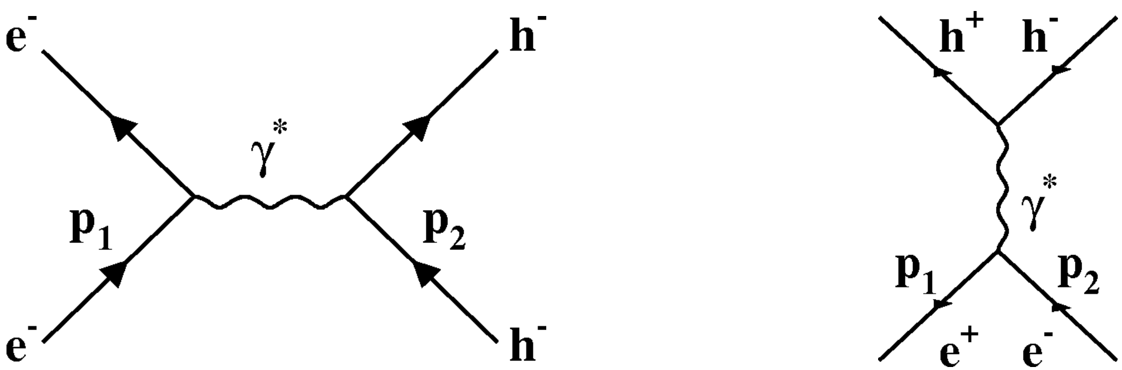
Form Factors

A few preliminaries about electromagnetic form factors are in order at this point.

- Form factors are analytic functions of four-momentum transfer, , which is defined as:

$$\mathrm{Q}(4\text{ mom.})^2 = q(3\text{ mom.})^2 - (\text{energy})^2 ,$$

and depending on whether momentum or energy is dominant in the transfer, the four-momentum transfer is called **spacelike**, or **timelike**, as illustrated below



There are three important things to note about form factors:

1. Because form factors are analytic functions of $|Q^2|$, it follows from Cauchy's theorem that $\mathbf{F(|Q^2|)spacelike = F(|Q^2|)timelike}$ for $|Q^2| = \infty$.

Form Factors

- The virtual photon which carries the momentum can do one of two things:
  a) It can directly produce a hadron-antihadron pair via *electromagnetic interaction*, providing us a measure of the electromagnetic form factor, or
  b) It can produce vector resonances like $\rho, \omega, J/\psi, \psi(2S)$, etc., which can decay by *strong interaction* into a hadron-antihadron pair. This resonance production has much larger cross section than the EM form factor production.
- Unfortunately, at e^+e^- colliders like CESR at Cornell, or BEPC at Beijing, most of the data are taken at energies $\sqrt{s} = M(J/\psi, \psi(2S), \psi(3770), \ldots)$, and form factor measurements have to be made with these data. It is then necessary to make sure that at the chosen energy the resonance contribution is negligibly small. This means that form factor measurements can not be made at J/ψ or $\psi(2S)$ where resonance yield is very large. Fortunately, at $\psi(3770)$, $\sqrt{s} = 3.77$ GeV, the resonance yield is expected to be very small, and we can hope to make good measurements of form factors. Sometime ago we took advantage of this to make successful measurements of proton, pion, and kaon form factors [7]. And we now do it for hyperons.

Form Factor Production of Hyperon Pairs

- A reliable estimate of the expected resonance yield of hyperon pairs at higher charmonium resonances, $\psi(n')$, is possible because of the pQCD prediction that the ratios of branching fractions of hadronic decays of two vector states, $\psi(n')$ and $\psi(n)$, is equal to the ratio of their decays to leptons, i.e.

$$\frac{\psi(n') \to ggg \to \text{hadrons}}{\psi(n) \to ggg \to \text{hadrons}} = \frac{\psi(n') \to \gamma^* \to \text{leptons}}{\psi(n) \to \gamma^* \to \text{leptons}}$$

This allows us to estimate yields of exclusive production of baryon pairs at at $\psi(3770)$, $\sqrt{s} = 3.77$ GeV, using the measured branching fractions for lepton and baryon pair production at J/ψ and $\psi(2S)$ and lepton branching fraction at $\psi(3770)$. The CLEO data we use consist of ~5 million $\psi(3770)$, and using expected detection efficiencies, the expected resonantly produced exclusive hyperon pair production events are:

$p\bar{p}$	$\Lambda\bar{\Lambda}$	$\Sigma^+\bar{\Sigma}^+$	$\Sigma^0\bar{\Sigma}^0$	$\Xi^-\bar{\Xi}^-$	$\Xi^0\bar{\Xi}^0$	$\Omega^-\bar{\Omega}^-$
1.3	**0.9**	**0.2**	**0.2**	**0.2**	**0.05**	**0.03**

These resonance yields are completely negligible, and we can therefore safely measure form factors at $\psi(3770)$, $\sqrt{s} = 3.77$ GeV.

- I describe these measurements in the following.

Hyperon Form Factors

- Let me first review what we knew about exclusive production of hyperon pairs before the measurements we have made.
- Cabibo and Gatto did not predict cross sections for the exclusive pair production of hyperons, or for the expected timelike form factors. The first, and so far the only theoretical prediction for all hyperon pairs, was made by Korner and Kuroda [8] in 1977 using what they called the modified vector dominance model (VDM). They predicted cross sections from thresholds up to $\sqrt{s} = 4.0$ GeV for all hyperon pairs.

  No data were available to provide experimental constrains for these calculations, and it is perhaps not surprising that these predictions were often orders of magnitude off from the eventually measured experimental cross sections.
- A few theoretical calculations exist in recent literature for spacelike form factors of Λ and Σ hyperons at small momentum transfers, but they have no relevance to our studies.

Hyperon Form Factors

- The experimental situation was not much better until very recently.
- The first experimental measurements for hyperon production were reported only thirty years after Cabibbo and Gatto's 1960/61 papers.
- In 1990, the **DM2 Collaboration** at Orsay [8] reported pair-production results for e^+e^- annihilation at $\sqrt{s} = 2.4$ GeV. They observed 4 $\Lambda^0\overline{\Lambda^0}$ events and failed to observe any $\Sigma^0\overline{\Sigma^0}$ or $\Lambda^0\overline{\Sigma^0}$ events.
- In 2005, the next measurement of $B\bar{B}$ production cross sections was made by the **CLEO Collaboration** at the $\psi(2S)$ resonance, $\sqrt{s} = 3.686$ GeV [10]. These measurements were dominated by large $\psi(2S) \to B\bar{B}$ resonance contributions, and the much smaller form factor contributions could not be separated from them to determine electromagnetic form factors. Only overall $\psi(2S) \to B\bar{B}$ branching fractions were reported.

Hyperon Form Factors

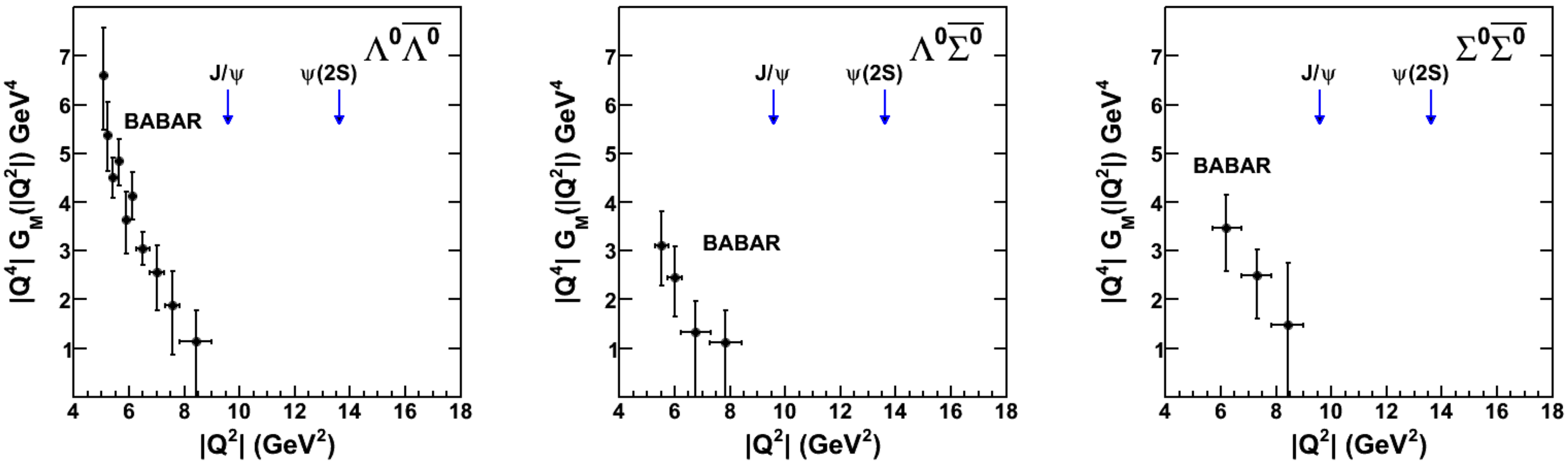
- In 2007 the **BaBar Collaboration** [11] reported near threshold measurements for $\Lambda^0\overline{\Lambda^0}$, $\Sigma^0\overline{\Sigma^0}$, and $\Lambda^0\overline{\Sigma^0}$ using the **initial state radiation (ISR) method**. The number of events observed at thresholds ($\sqrt{s} = 2.2 - 2.4$ GeV, in *small* bins of $\sqrt{s}$) were 22 $\Lambda^0\overline{\Lambda^0}$, 10 $\Sigma^0\overline{\Sigma^0}$, and 9 $\Lambda^0\overline{\Sigma^0}$, and dropped down to < 1 event by $\sqrt{s} = 3$ GeV. These data were analyzed for timelike form factors.
- For the spin-1/2 baryons, the proton and the hyperons, Λ, Σ, and Ξ, the well-known relation between the cross sections and the magnetic form factor $\left|G_M^B(s)\right|$, and the electric form factor $\left|G_M^E(s)\right|$ is

$$\boldsymbol{\sigma_0^B = \left(\frac{4\pi\alpha^2\beta_B}{3s}\right)\left[\left|G_M^B(s)\right|^2 + \tau/2\left|G_E^B(s)\right|^2\right]} \qquad (2)$$

  where α is the fine structure constant, β_B is the velocity of the baryon in the center-of-mass system, m_B is its mass, and $\tau = 4m_B^2/s$.
- The $G_M^B(s)$ and $G_E^B(s)$ form factors are related to the Dirac $F_1(s)$ and Pauli $F_2(s)$ form factors as $G_E = F_1 + F_2$ and $G_M = F_1 + \tau F_2$.
- Notice that $G_E = G_M$ implies $F_1 = G_M$, and $F_2 = 0$.

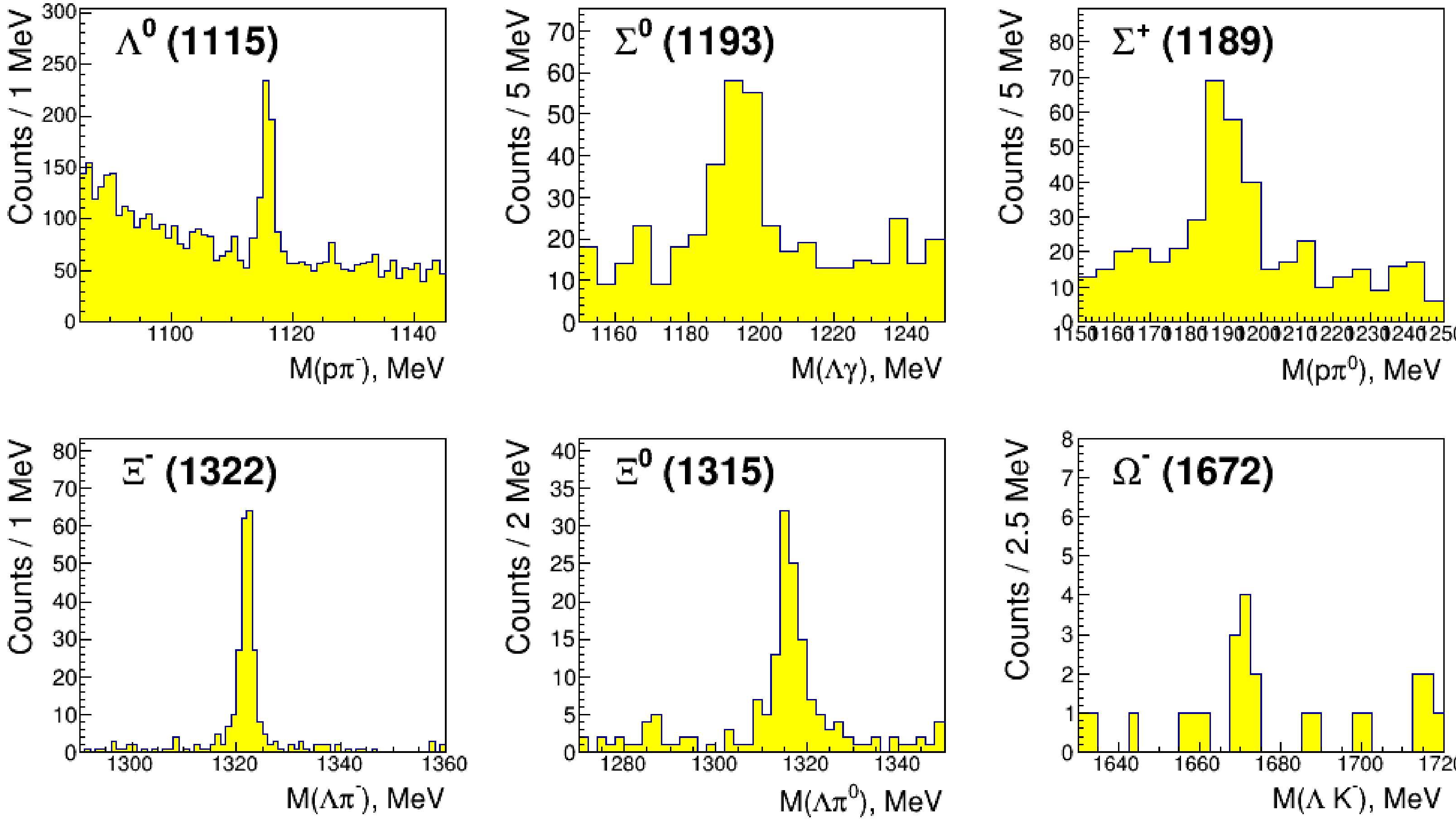
Hyperon Form Factors

- Eq. 1 is conventionally used to analyze the scattering data for spacelike momentum transfers, for which G_E and G_M are related via Fourier transforms to the spatial distributions of charge and magnetic moment in the baryon. It has become customary to also analyze the $B\bar{B}$ production data in terms of Eq. 1, although G_E and G_M relate in this case to the **helicity distributions** of the baryon pair produced.
- Perturbative QCD (pQCD) predicts that baryon form factors should decrease as Q^{-4}. Babar measurements have large errors, but as the figure shows they clearly disagree with the pQCD prediction of constancy of $\boldsymbol{Q^4 \times G_M(Q^2)}$ with $|Q^2|$.



$\psi(3770) \rightarrow B\bar{B}$ Event Distribution

- What is needed is good statistics measurements of hyperon form factors at large timelike momentum transfers. We have done so at Q^2 = 14.2 and 17.3 GeV^2.

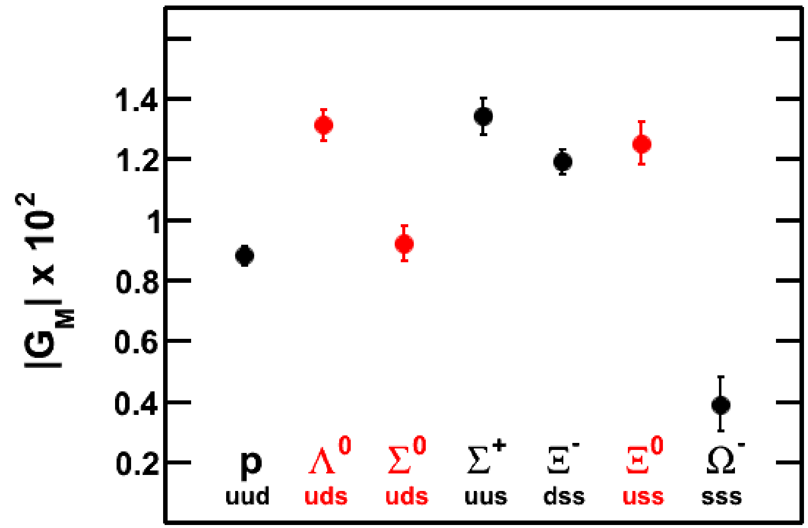


Hyperon Production from $\psi(3770)$

Exclusive: $\psi(3770) \rightarrow B + \bar{B}$

$\mathcal{L} = 805 \text{ pb}^{-1}, \quad C = 0.77$

	N(obs) B or $\bar{B}$	ϵ %	σ pb	$G_M \times 10^2$
p[7]	213(15)		0.46(4)	0.88(4)
Λ^0	405(28)	65.7	0.99(7)	1.31(5)
Σ^0	128(17)	43.2	0.48(6)	0.92(6)
Σ^+	166(16)	25.9	1.03(10)	1.34(6)
Ξ^0	107(12)	20.4	0.85(10)	1.25(7)
Ξ^-	228(16)	47.6	0.77(5)	1.19(4)
Ω^-	8(4)	20.3	0.06(3)	0.39(9)



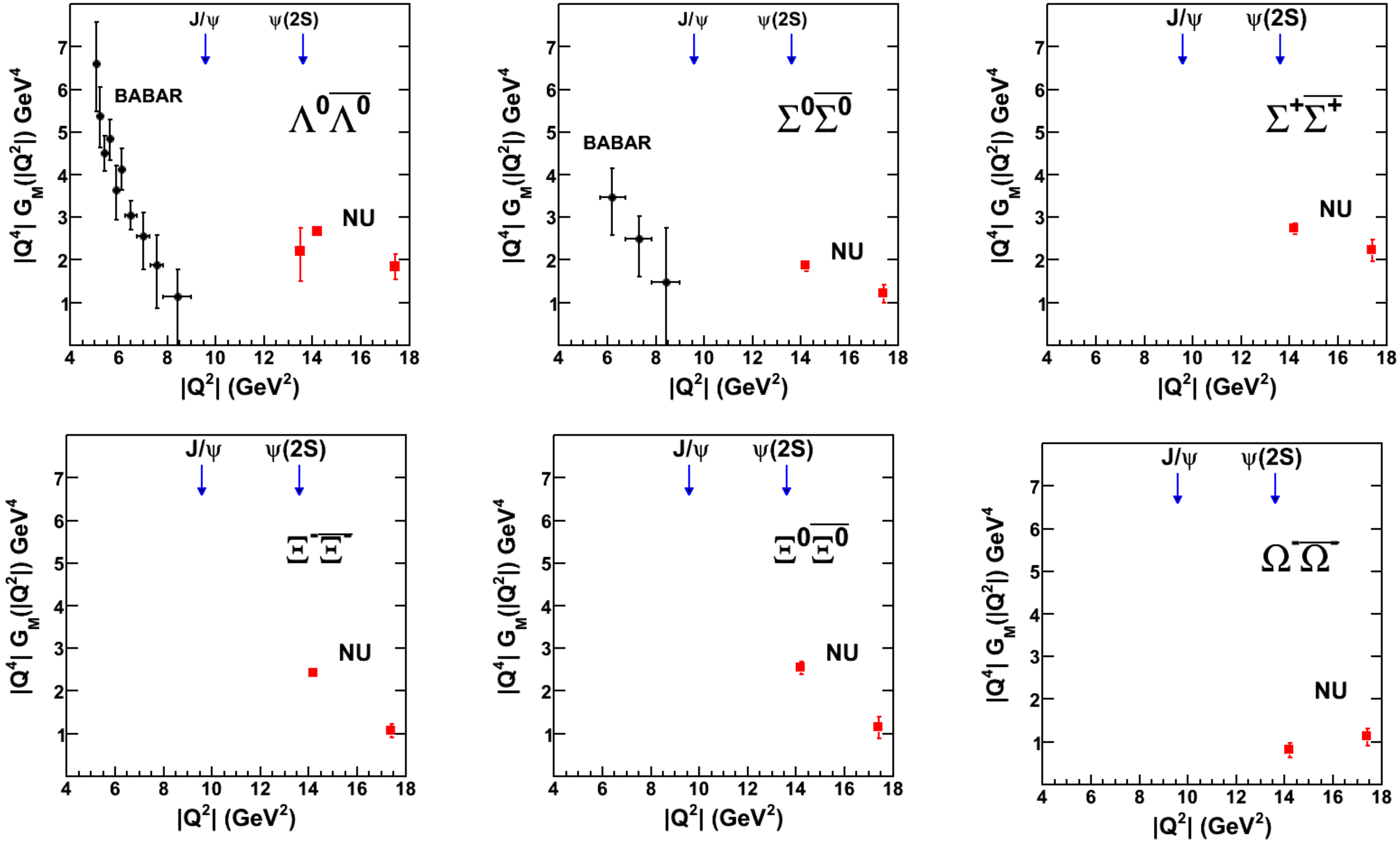
$\sigma(\text{pb}) = N(\text{obs})/[\varepsilon\mathcal{L}C]$, C = rad. corr.

$G_M^B(s) = \text{const} \times \sqrt{\sigma_0^B} \qquad \text{const} = [(4\pi\alpha^2\beta/3s)(1+\tau/2)]^{-2},$ for $G_M^B(s) = G_E^B(s)$

- **Notice that $G_M(\Lambda^0)\,/\,G_M(\Sigma^0) = 1.6(1)$. More about this later.**

HYPERON FORM FACTORS

Form factors fall as $|Q^{-4}|$, and our measurements at $|Q^2| = (4.17\ \text{GeV})^2 = 17.4\ \text{GeV}^2$ have very few counts and have not been very successful so far.



DIQUARKS

- It is good to make the world's first measurements of hyperon production and electromagnetic form factors for the largest timelike momentum transfer, and we are very proud of having done so. But measurements only give us numbers. The real important question is what they tell us about the underlying physics. And that is where the story of **DIQUARKS** comes in.
- **Diquarks** have a long history which was extensively reviewed by Anselmino et al. in a Review of Modern Physics article [13]. The first mention of "diquark" actually was by Gell-Mann [3] in his first paper proposing the existence of quarks.
- As the name would suggest, any assembly of two quarks considered together, having the quantum numbers of two quarks can be considered a **diquark**, but that is not what one means in the present context. One implies something more, some additional *correlation between two quarks* which distinguishes them from two isolated quarks. Such correlations can exist in quark-antiquark mesons and three quark baryons. In baryons, this gives rise to the existence of *diquark-quark structures*, and this is the subject of our interest with respect to hyperons.
- Actually, our first run-in with diquarks came with protons. In 1990, we made the first measurements of the form factors of the proton at large timelike momentum transfer, $|Q^2| = 9 - 13$ GeV^2, in our Fermilab $\boldsymbol{p\bar{p} \rightarrow e^+e^-}$ experiment, which is simply the reverse of $e^+e^- \rightarrow B\bar{B}$ measurements I have described for measuring the timelike form factors of hyperons.

DIQUARKS

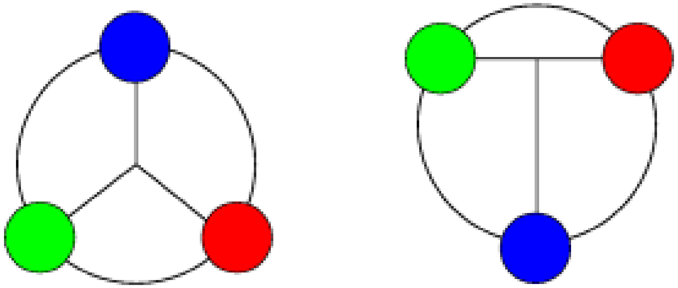
- We expected that with $|Q^2|$ as large as $\sim$13 GeV the magnetic timelike form factor $G_M(|Q^2|)$ should be equal to the spacelike form factor which had been measured at SLAC. To our great surprise, we found that

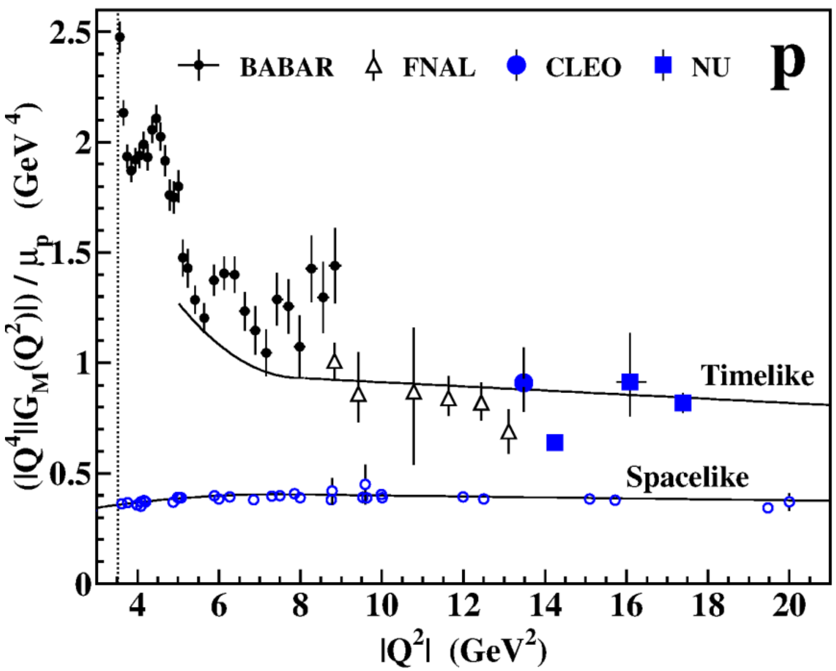
$$\boldsymbol{G_M(\textbf{timelike}) \approx 2 \times G_M(\textbf{spacelike}).}$$

- This was completely unexpected because of the QCD prediction that $G_M(\text{timelike}) = G_M(\text{spacelike})$ at $G_M(|Q2|) = \infty$.
- There were two possible explanations. Either $|Q^2| = 9 - 13\ \text{GeV}^2$ were not large enough to meet the $G_M(|Q2|) = \infty$ expectation, or there was some other, perhaps more exotic explanation.
- We extended the measurement to $\sim$18 GeV^2 at CLEO, but found that the factor 2 difference persisted.
- So, one is forced to the alternate explanation!
  The quark structure of the proton.

Timelike Form Factors of the Proton

- The conventional idea of proton structure has the three quarks playing identical roles, sharing momenta and spatial distribution identically in what has been called the **Mercedes Star** configuration. In this picture there was no explanation of the observation **G_M(timelike) ≈ 2 × G_M(spacelike).**
- It was therefore proposed that the proton has a quite different structure, a **diquark-quark construct**. With such a structure, Kroll et al. were able to explain the factor 2 difference, as shown by the curves in the figure.





DIQUARKS

- The diquark-quark explanation was treated with skepticism, but no alternate explanation has been forthcoming so far. So it is natural to see what the hyperons have to tell us about diquarks.
- Recently, the importance of diquarks was emphasized by Jaffe and Wilczek [14], and **Wilczek and colleagues** [15] have presented detailed discussion of the role of diquarks in baryons. To quote Wilczek:
  "It is plausible that several of the most profound aspects of low-energy QCD dynamics are connected to diquark correlations."
  Wilczek et al. point out that the requirement of antisymmetrization of the diquark under flavor, spin, and isospin gives rise to two different kinds of diquark correlations, giving rise to the scalar **"good" diquark**, and the vector **"bad" diquark**.
- The Λ^0 $(uds, I = 0)$ and Σ^0 $(uds, I = 1)$ hyperons both have the same quark content, but different isospin. In isoscalar, the u, d quarks make the "good" diquark with spin 0, whereas in the isovector Σ^0 they make the "bad" diquark.

DIQUARKS

- With this explanation, in e+e- annihilation, to quote Selem and Wilczek [16]

"the good diquark would be significantly more likely to be produced than the bad diquark. This would reflect itself in a large Λ/Σ ratio.

- This is exactly what we find. In the decay of the $\psi(2S)$ resonance, we find in inclusive decay $\sigma(\Lambda^0)/\sigma(\Sigma^0) = \mathbf{4.16(7)}$, and
  in the exclusive decay we find $\sigma(\Lambda^0)/\sigma(\Sigma^0) = \mathbf{1.50(3)}$.
- The same cross section ratio is obtained in the form factor decay of $\psi(3770)$. We obtain $\sigma(\Lambda^0)/\sigma(\Sigma^0) = \mathbf{2.06(30)}$, and $G_M(\Lambda^0)/G_M(\Sigma^0) = \mathbf{1.58(14)}$.
- We believe that these observations provide evidence for
  important diquark correlations in Λ^0/Σ^0 hyperons.

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