PRECISION FORM FACTORS OF PIONS, KAONS & PROTONS

at the highest timelike momentum transfers

&

FIRST MEASUREMENTS OF HYPERONS

Kamal K. Seth

Northwestern University, Evanston IL 60208, USA

(kseth@northwestern.edu)

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PREAMBLE

An **elementary** particle is defined, or should be defined, as one which is **not composite**. So, all we want to know about an elementary particle is its static properties, mass, charge, spin, etc. When, almost exactly 100 years ago, Rutherford discovered the **nucleus**, we had just two elementary particles, the **electron**, and the **proton**, and there was no question of their constituents. While the electron has remained elementary, we know today that **nucleons**, proton and neutron, are not. The **nucleons** are composite of three light, spin 1/2 ($m<10$ MeV each, charge +2/3 and -1/3) **up** and **down** quarks, which are bound by massless spin 1 gluons.

Hyperons are baryons like the nucleons, with one or more up/down quarks replaced by **strange** quarks, which are still rather light. Now that the nucleons and hyperons are composite, we have to find answers to a lot of questions. Among them, the important ones are:

a) How does one account for the ~1 GeV mass of light quark baryons, their spins and their spatial and momentum distributions?

b) How do the hyperons differ from nucleons?

c) What happens to the structure of a baryon when lots of momentum or energy is pumped into it from the outside?

PREAMBLE (contd.)

The questions are of fundamental importance, and they can only be answered by experimental measurements. The measurements in question are **form factor measurements**.

We are all familiar with how elastic scattering of electrons from nuclei and nucleons is related to **spacelike electric and magnetic form factors**, and they provide direct insight into the spatial distribution of charges and currents in the nuclei, and in the nucleon. Unfortunately, this can only be done for protons and nuclei which are available as targets. Other baryons and mesons are not available as targets, and so spacelike form factors of strange quark baryons (hyperons), charm- or beauty-baryons, and mesons like pions+kaons are not measurable by electron scattering. Fortunately, an equally important complementary measurement, measurement of **timelike form factors** can be made for any hadron, and that is what I am going to talk about.

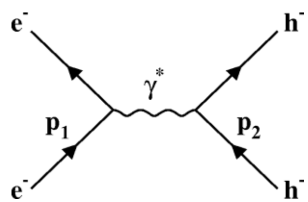
Since mesons contain only one quark and one antiquark, it is hoped that **meson** form factors may provide simpler and more direct insight into the questions posed for baryons. So I will also talk about meson form factors.

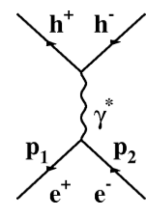
PRELIMINARIES

- Four momentum transfers defined as

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

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





- Form factors are analytic functions of momentum transfer, and therefore, a la Cauchy, for infinite momentum transfer

$$\mathbf{FF}(\mathbf{spacelike}, \boldsymbol{Q^2} = \infty) = \mathbf{FF}(\mathbf{timelike}, \boldsymbol{Q^2} = \infty)$$

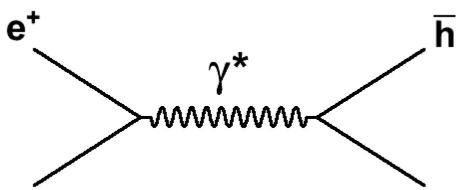
Because protons are available as targets, most of the early measurements were of **spacelike form factors of protons** via electron elastic scattering, $\boldsymbol{e + p \rightarrow e' + p}$

- In 1960, the first proposals for electron-positron colliders were being considered at **SLAC and Frascati**. In anticipation of these, **Cabibbo and Gatto** wrote two classic papers (PRL 4,313(1960), PRD 124,1577 (1961)) pointing out that these colliders would provide the unique opportunity to measure **timelike form factors of any hadrons**, mesons and baryons.

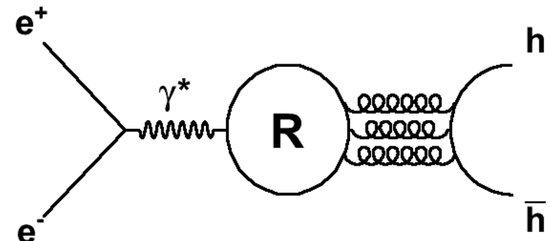
- We are now realizing the full promise of the vision of Cabibbo and Gatto!

A PROBLEM & ITS SOLUTION

There is a generic problem in making form factor measurements. Form factor decays are for producing $h\bar{h}$ via a **virtual photon**. The same $h\bar{h}$ final state is reached usually much more prolifically by strong $h\bar{h}$ decay of a hadronic resonance like J/ψ or $\psi(2S)$.



Form factor decay



Resonance decay

Since most collider physics is done for discovering and understanding resonances, one does not get the data at off-resonances needed for form factor studies.

Fortunately, there is a possible solution if it can be shown that a particular resonance decay is very weak compared to the form factor decay.

The bound vector states of charmonium, J/ψ and $\psi(2S)$ decay to $h\bar{h}$ states strongly, so one cannot measure form factors at them. But, the unbound vector $\psi(3770), \psi(4170)$, … decay almost entirely to $\mathrm{D\bar{D}}$ states, and very little to other $h\bar{h}$ pairs. So, hopefully one can measure ff at these resonances.

An important prediction of pQCD is that for the decays of vector resonances of charmonium, $\psi(n)$ and $\psi(n')$

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

We can use this relation to estimate hadronic decays of $\psi(n')$ knowing those of $\psi(n)$, if the leptonic decays of both are known.

With nearly 5 million ψ(3772) and ψ(4160) each, formed in the present measurements, and our detection efficiencies, we estimate resonance events

$\pi^+\pi^-$	K^+K^-	$p\overline{p}$	$\Lambda\overline{\Lambda}$	$\Sigma^+\overline{\Sigma}^+$	$\Sigma^0\overline{\Sigma}^0$	$\Xi^-\overline{\Xi}^-$	$\Xi^0\overline{\Xi}^0$	$\Omega^-\overline{\Omega}^-$
~0.04	0.4	1.3	0.9	0.2	0.2	0.2	0.05	0.03

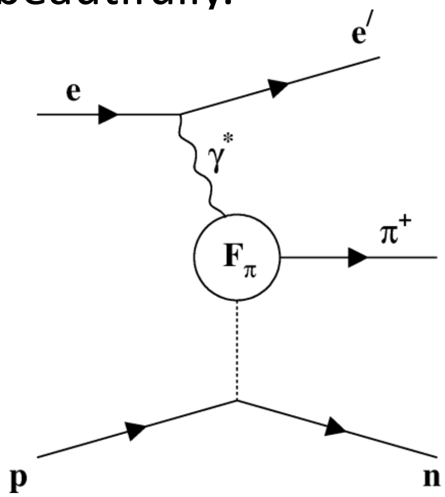
The observed counts for each form factor decay turn out to be about 100 times larger than these resonance contributions. Therefore,

all $e^+e^- \to \pi\pi, KK, p\bar{p}$, and hyperon yields we observe can be attributed to form factors.

FORM FACTORS OF PIONS AND KAONS

- Before going to the form factors for hyperons, let me describe briefly the results for the form factors of pions and kaons. Not only are they the world's first, but they show that the method works beautifully.

- Since meson targets do not exist, **spacelike form factors** for pions have to be determined by indirect means, like $e^{-}p \to e^{-}n\pi^{+}$. The measurements are difficult for large Q^2, and difficult to interpret because of the presence of strongly interacting particles in the final state.



The first thing to notice for measurements of **timelike form factors** is that for **spin zero pseudoscalars** like $\pi^{\pm}$, $K^{\pm}$ there is no magnetic form factor*, and there is just one form factor.

$$\sigma(e^{+}e^{-} \to \pi^{+}\pi^{-}, K^{+}K^{-}) = \frac{\pi\alpha^{2}\beta}{3s}|F_{\pi,K}(s)|^{2}$$

Before 1990, almost no experimental data with any precision existed for pion and kaon spacelike or timelike form factors for $|Q^2| > 5$ GeV^2.

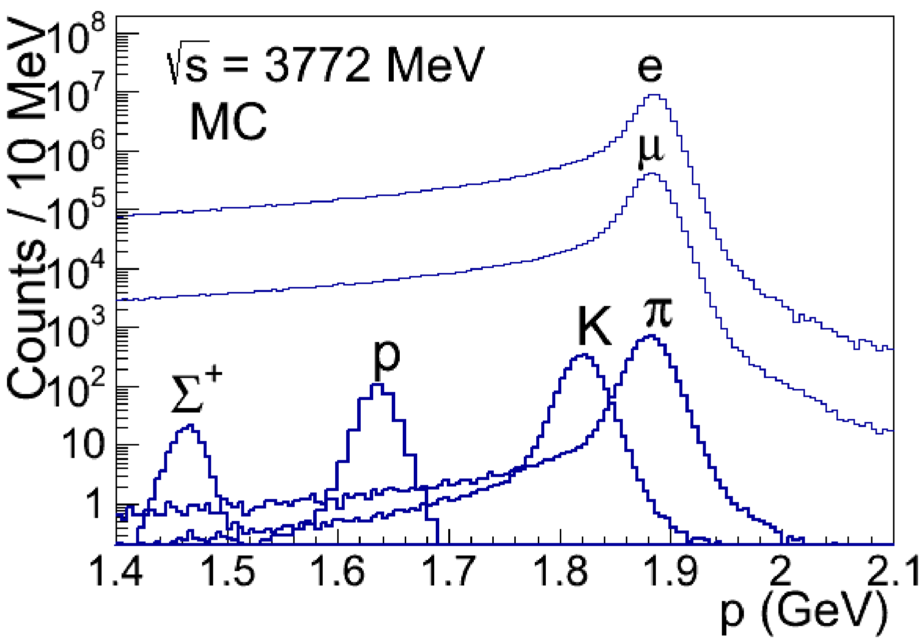
Measurements of Timelike Form Factors

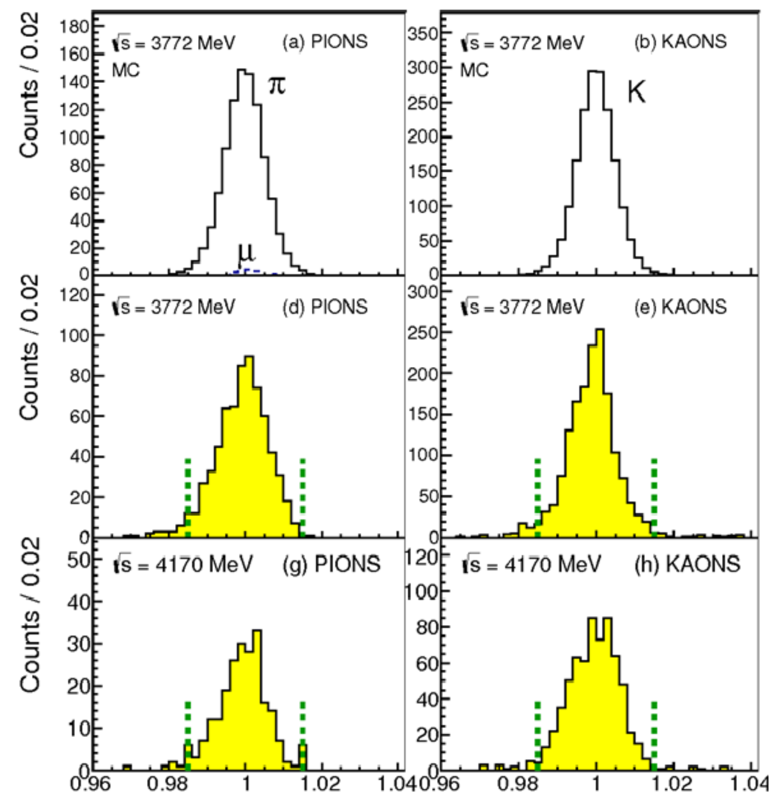
- Timelike form factors of any hadron can be determined by measuring

$$\sigma(e^+e^- \to h^+h^-), \qquad h = \pi, K, p, \text{hyperons,}$$

but one has to reject **3 to 4 orders of magnitude larger background of QED–produced e^+e^- and $\mu^+\mu^-$ pairs**, and substantial tails of lighter hadrons.

However, Using all components of our CLEO-c detector system we succeeded in identifying π, K and p very cleanly.





$$X_h \equiv [E(h^+) + E(h^-)]\ /\ \sqrt{s}$$

The CLEO-c detector is a cylindrical general purpose detector. The detector components important for the present measurements are the CsI electromagnetic calorimeter, the drift chamber for charged particle detection, and the RICH detector, all of which are located in a 1 Tesla solenoidal magnetic field. The acceptance for photons and charged particles in the central detector is $|\cos\theta| < 0.8$.

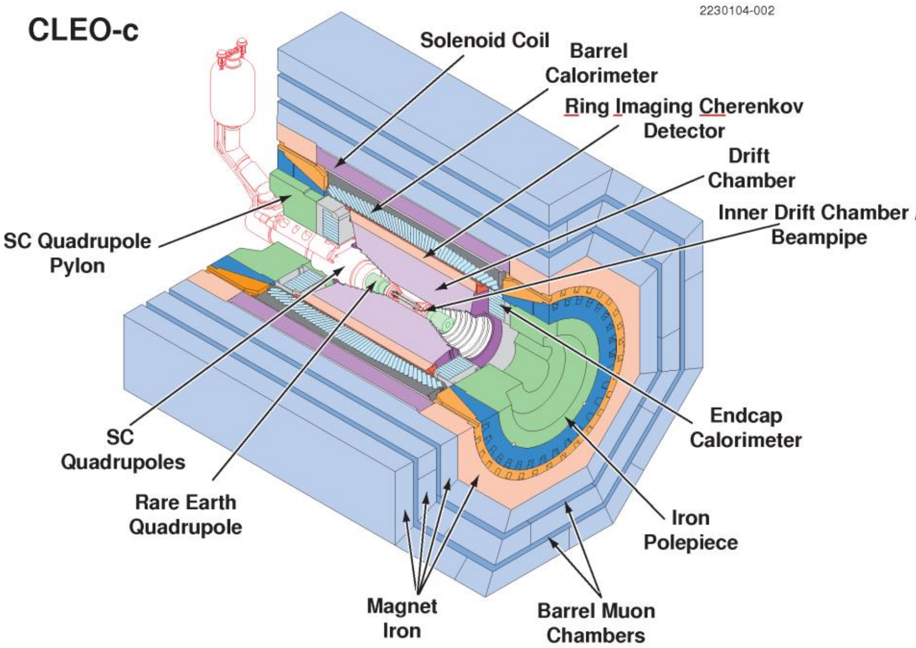
Charged particle resolution is

$\sigma_p/p = 0.6\%$ @ 1 GeV/c.

Photon resolution is

$\sigma_E/E = 2.2\%$ @1 GeV,

and 5% @ 100 MeV.



The data we use consists of

805 pb^{-1} at $\psi(3770)$, $|Q^2|$ = 14.2 GeV^2, and

586 pb^{-1} at $\psi(4170)$, $|Q^2|$ = 17.4 GeV^2.

Pion and Kaon Form Factors – Results

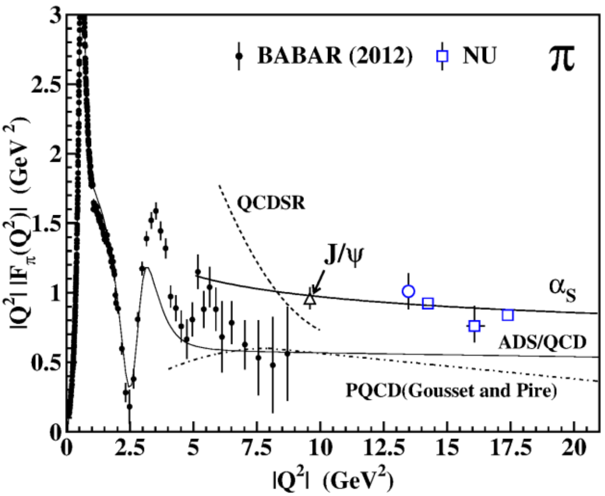
(PRL 95, 261803 (2005), PRL 110, 022002 (2013))

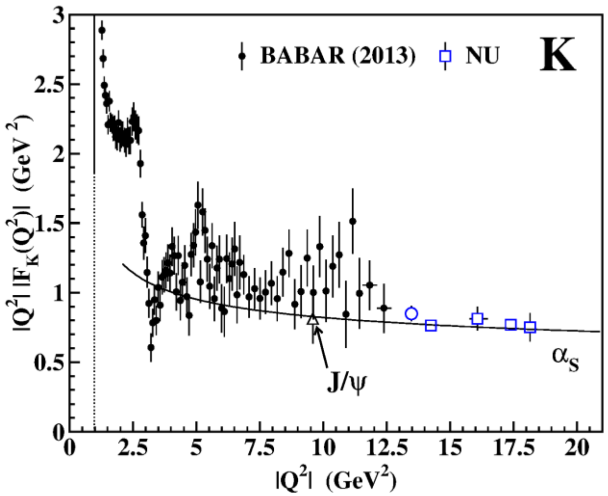
The numerical results are:

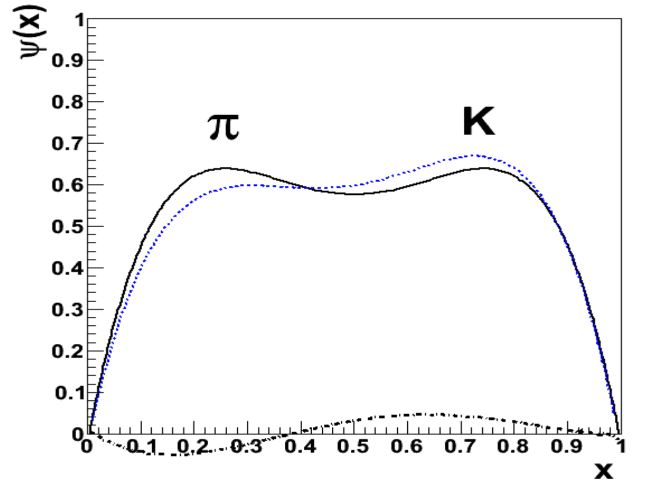
	Q^2 (GeV^2)	$N(\pi^+\pi^-)$	σ(Born), pb.	$F_\pi(\lvert Q^2\rvert) \times 10$	$Q^2 F_\pi(\lvert Q^2\rvert)$ (GeV^2)
CLEO(2005)	13.5	26 ± 5	9.0 ± 1.8	0.75 ± 0.09	1.02 ± 0.13
NU(2013)	14.2	661 ± 26	6.36 ± 0.25	0.65 ± 0.01	0.92 ± 0.04
NU(2013)	17.4	213 ± 12	2.89 ± 0.16	0.48 ± 0.01	0.84 ± 0.03
	Q^2 (GeV^2)	$N(K^+K^-)$	σ(Born), pb.	$F_K(\lvert Q^2\rvert) \times 10$	$Q^2 F_K(\lvert Q^2\rvert)$ (GeV^2)
CLEO(2005)	13.5	71 ± 9	5.7 ± 0.7	0.63 ± 0.04	0.91 ± 0.14
NU(2013)	14.2	1564 ± 40	3.95 ± 0.10	0.54 ± 0.01	0.76 ± 0.02
NU(2013)	17.4	644 ± 25	2.23 ± 0.09	0.44 ± 0.01	0.77 ± 0.03

Notice the order of magnitude improvement over our own 2005 results, and form factor measurements with a precision of about 1%!!

Pion and Kaon Form Factors







The important experimental results are:

1. There is a remarkable agreement of the form factors with the **dimensional counting rule prediction of QCD,** that $|Q^2|F_{\pi,K}$ are nearly constant.
2. The theoretical predictions for pions **underpredict** of $F_\pi(|Q^2|)$ by factors, ≥ 2.
3. We find: **$F_\pi / F_K = 1.21 \pm 0.03$ (at 14.2 GeV^2), $F_\pi / F_K = 1.09 \pm 0.04$ (at 17.4 GeV^2).**

Assuming identical wave functions for pion and kaon pQCD predicts **$F_\pi/F_K=(f_\pi/f_K)^2=0.67\pm0.01$.** Our experimental results suggest substantial differences between π and K wave functions as a result of the breaking of SU(3) symmetry. Lattice calculations, as well as recent calculations in Bethe-Salpeter light cone formulation appear to confirm this conclusion.

Timelike Form Factors for Protons and Hyperons

- **For baryons**, there are two form factors, the Pauli and Dirac form factors, or more familiarly, the magnetic $\boldsymbol{G_M^B(s)}$ and the electric $\boldsymbol{G_E^B(s)}$ form factors.
- For $\boldsymbol{e^+e^- \to p\bar{p}}$ the differential cross section is

$$\frac{d\sigma_0(s,\theta)_B}{d\Omega} = \frac{\alpha^2}{4s}\beta_B\left[\left|G_M^B(s)\right|^2\left(1+\cos^2\theta\right) + \tau/2\left|G_E^B(s)\right|^2\sin^2\theta\right]$$

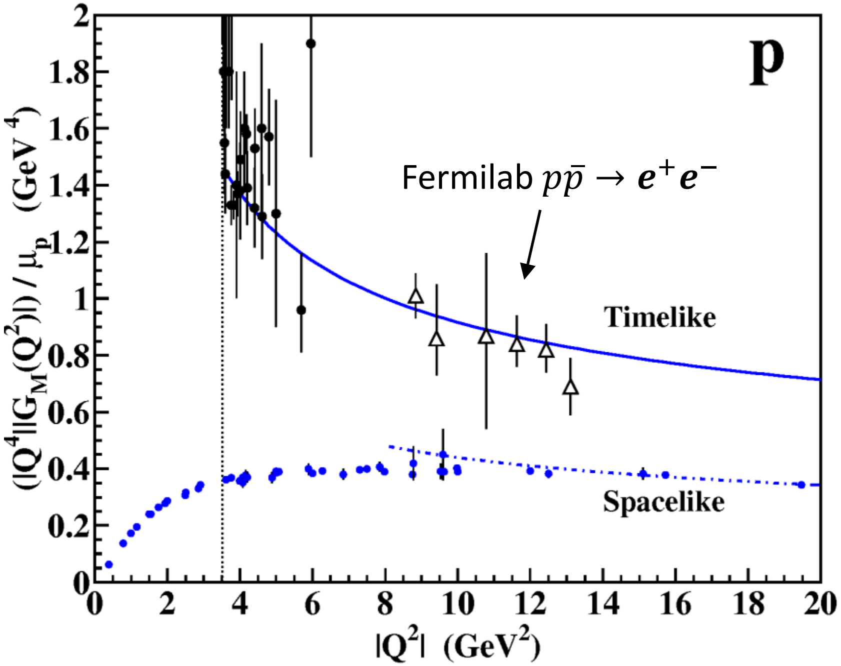
- At large squared momentum transfers, **s**, the quantity $\tau = 4m_p^2/s$ becomes small, the contribution of G_E^B becomes small, and it becomes difficult to determine it. So, we mostly talk about $G_M^B(s)$ only.
- The first baryon we want to talk about is proton. Hyperons follow!

Timelike Form Factors of the Proton

- **Spacelike form factors** of the proton have been measured since the 1980's, and precision measurements have existed for Q^2 up to 31 GeV^2.
- Prior to 1993, measurements of the **timelike form factors** of the proton by the reaction $e^+e^- \rightarrow p\bar{p}$ were sparse, had large errors, and were confined to $|Q^2| < 5.7$ GeV^2.
- In 1993, at **Fermilab** we measured $G_M(|Q^2|)$ by $p\bar{p} \rightarrow e^+e^-$ for $|Q^2| = 8.9$ to 13.11 GeV^2. While $Q^4 G_M(|Q^2|)$ was found to vary as α^2(strong) above 9 GeV^2, as predicted by QCD counting rules, a big surprise was discovered. It was found that

  $$G_M(\text{timelike}) \;/\; G_M(\text{spacelike}) \approx 2,$$

  in strong disagreement with the **pQCD expectation** of the two being equal at large momentum transfers.



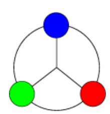
Timelike Form Factors of the Proton

- Two possible explanations of the unexpected observation

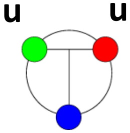
  $$G_M(\text{timelike}) \;/\; G_M(\text{spacelike}) \approx 2,$$

  at $|Q^2|$ = 8 – 13 GeV^2 were offered.

  1. The quark distribution in the proton is not like

     a Mercedes star 

     , with the three quarks having identical distributions

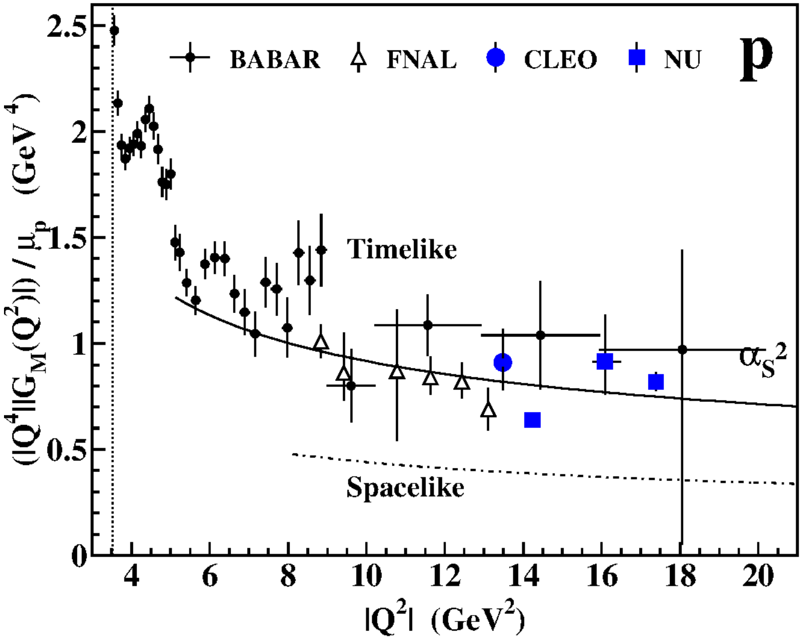
     but diquark-quark 

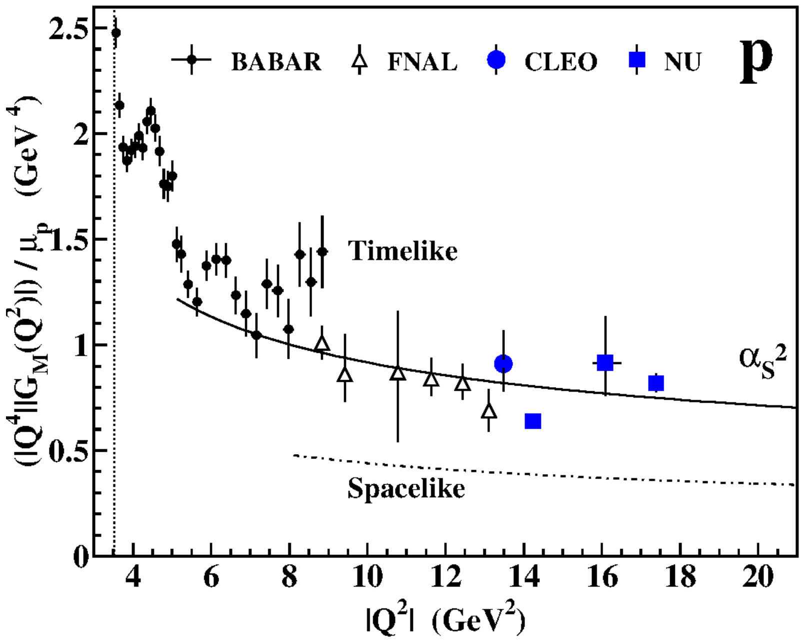
     , with a preferential pairing of the two identical u-quarks.

  2. $|Q^2|$ = 13 GeV^2 is not large enough for pQCD to be valid.

- Although no alternate explanations have been offered, the **diquark-quark** model did not acquire acceptance. **More about diquarks later.**

- To test the second possibility, the validity of pQCD at large $|Q^2|$, we have made high precision measurements of $G_M(p)$ to timelike **$|Q^2|$ = 14.2 and 17.4 GeV^2**. using data taken at the e^+e^- CESR collider at Cornell, and the detector CLEO-c.





	N_p	σ_B^p (pb)	$G_M^p \times 10^2$	$Q^4 G_M^p / \mu_p$
ψ(3770), $\lvert Q^2 \rvert = 14.2$ GeV^2	213(15)	0.46(4)	0.88(4)	**0.64(3)**
ψ(4170), $\lvert Q^2 \rvert = 17.4$ GeV^2	92(10)	0.29(4)	0.76(4)	**0.82(4)**

- The **QCD counting rule prediction** of $|Q^{-4}|$ variation of proton form factor continues even at 17.4 GeV^2.
- However, there is an **unexpected** dip, with **G_M(14.2 GeV^2) lower by (22 ± 4) %.**
- Despite > 300 observed counts, we are not able to determine G_E/G_M.
  We only **obtain** an upper limit of G_E/G_M < 1.02 at 90% CL.

Timelike Form Factors of Hyperons

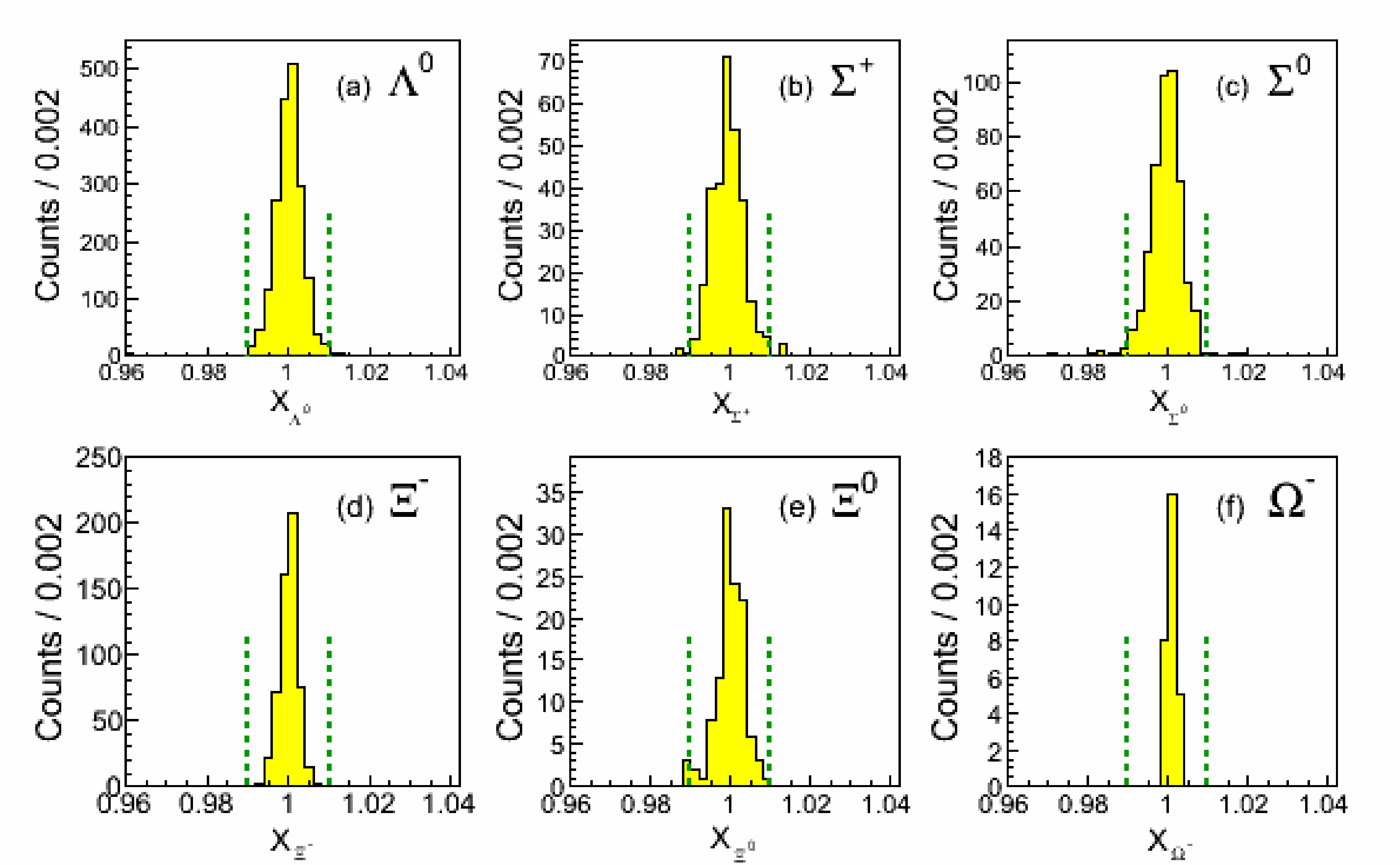
- We identify the hyperons by their dominant decays. These (and their branching fractions) are:

$$\Lambda^0 \to p\pi^- \text{ (64\%)} \quad \Sigma^+ \to p\pi^0 \text{ (52\%)} \quad \Sigma^0 \to \Lambda\gamma \text{ (100\%)}$$
$$\Xi^- \to \Lambda\pi^- \text{(100\%)} \quad \Xi^0 \to \Lambda\pi^0 \text{ (100\%)} \quad \Omega^- \to \Lambda K^- \text{ (68\%)}$$

  The final state charged particles, $p, \bar{p}, \pi^{\pm}$, and $K^{\pm}$, are detected and their momenta measured in the drift chambers, and π^0 are identified by their decay $\pi^0 \to 2\gamma$. Photons are detected and their energy measured in the CsI electromagnetic calorimeter. Track and shower detection algorithms are the standard ones for the CLEO-c detector.

- We identify the hyperon pairs with zero net charge, require that the total momentum of the hyperon pair be <50 MeV, and construct the variable $\boldsymbol{X = [E(B) + E(\bar{B})]/\sqrt{s}}$. We accept signal events in the region X = 0.99 – 1.01.
- We validate our analysis technique by using it to successfully measure branching fractions for $\psi(2S) \to B\bar{B}$.

$\psi(2S) \rightarrow$ Hyperon – Antihyperon pairs

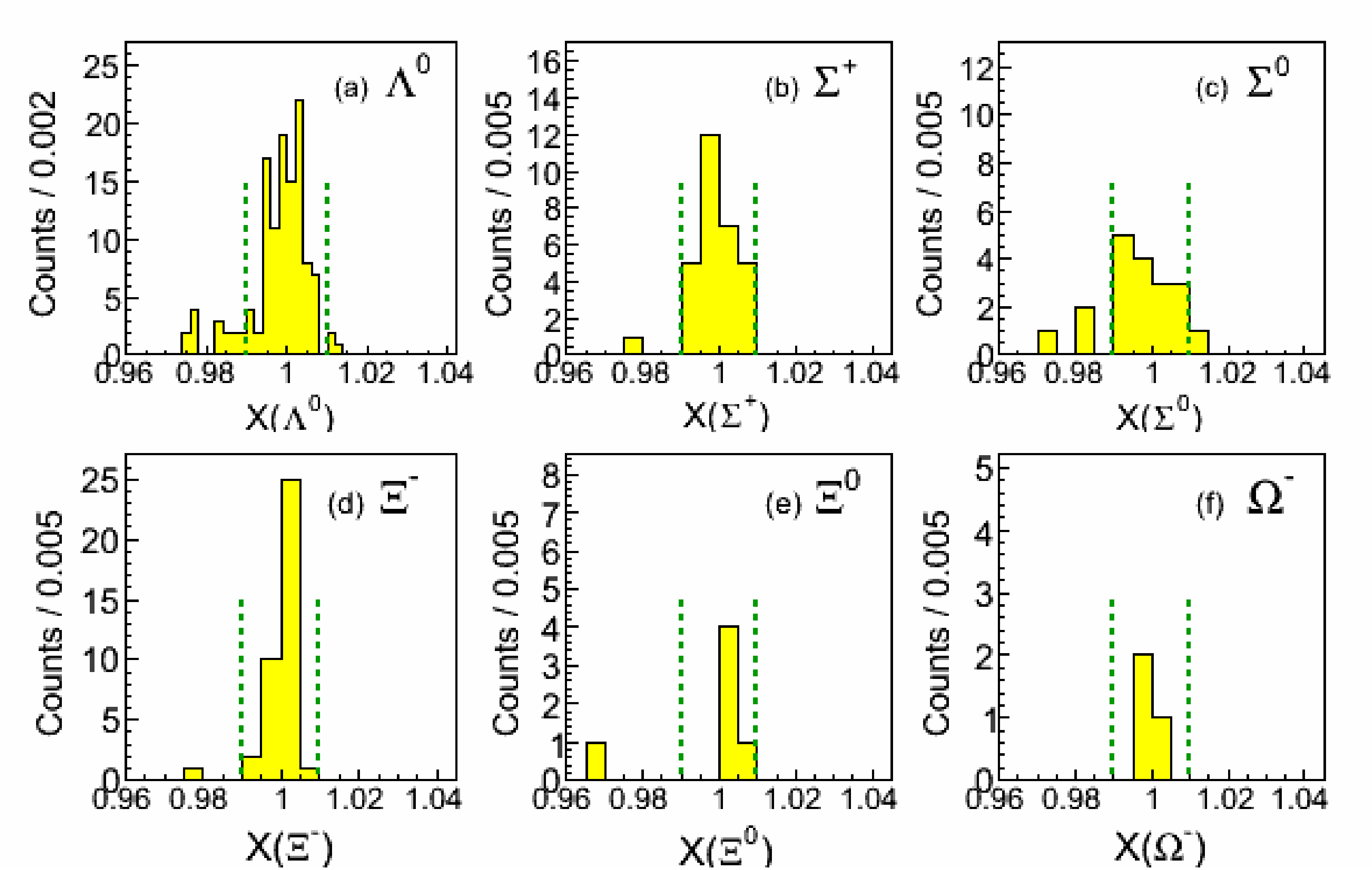


Hyperon Branching Fractions: $\mathcal{B}(\psi(2S) \to B\bar{B})$

		CLEO PRD 72, 051108 (2005)		Present		
		N	$\mathcal{B}$ $\times 10^4$	N	σ pb	$\mathcal{B}$ $\times 10^4$
p	(uud)	557(24)	2.87(19)	4475(78)	196(3)(12)	**3.08(19)**
Λ^0	(uds)	208(14)	3.28(34)	1901(44)	247(6)(15)	**3.75(25)**
Σ^0	(uds)	58(8)	2.63(41)	439(21)	148(7)(11)	**2.25(19)**
Σ^+	(uus)	35(6)	2.57(81)	281(17)	165(10)(11)	**2.51(22)**
Ξ^-	(dss)	63(8)	2.38(37)	548(23)	176(8)(13)	**2.66(23)**
Ξ^0	(uss)	19(4)	2.75(88)	112(11)	135(13)(10)	**2.02(24)**
Ω^-	(sss)	4(2)	$0.70^{+0.56}_{-0.34}$	27(5)	31(6)(3)	**0.47(10)**

Notice the large improvement of the present measurements.

Hyperon Form Factor Events
$\psi(3770) \rightarrow$ Hyperon – Antihyperon pairs



What Do We Expect to Learn from Hyperon Form Factors?

- As we go from protons to hyperons, serially replacing one, two, or three up/down quarks with strange quarks, what do we expect to learn at $|Q^2|$ = 14.2 GeV^2?
  Do we see SU(3) breaking effects?
  Do we see diquark correlation effects?
  Are $G_M(B)$ for hyperons proportional to μ_B, as for nucleons?
  Do neutral hyperons have finite $G_E(Q^2)$ as the neutron?
- **One strange quark** ($\Lambda^0\ (uds),\ \Sigma^0(uds),\ \Sigma^+\ (uus),\ \ \Sigma^-\ (dds)$), $J = 1/2$
  - Is there evidence for a SU(3)-breaking effects?
    Are there diquark effects related to isospin differences: Λ^0 (I=0) and Σ^0 (I=1)?
- **Two strange quarks** ($\Xi^-\ (dss)$, $\Xi^0\ (uss)$), $J = 1/2, I = 1/2$
  - Do the Cascades show any large differences from Sigmas?
    Is there evidence for diquark effects with two strange quarks in Cascades?
    Do the Cascades (I=1/2) resemble Nucleons (I=1/2)?
- **Three strange quarks** ($\Omega^-\ (sss)$) $J = 3/2, I = 0$
  - How does Ω^- with 3 s-quarks differ from proton with three u/d-quarks?

Obviously, not all these questions can be answered by the first measurements of hyperon form factors we report here, but they indicate the physics potential of such measurements.

Form Factors of Hyperons – Results

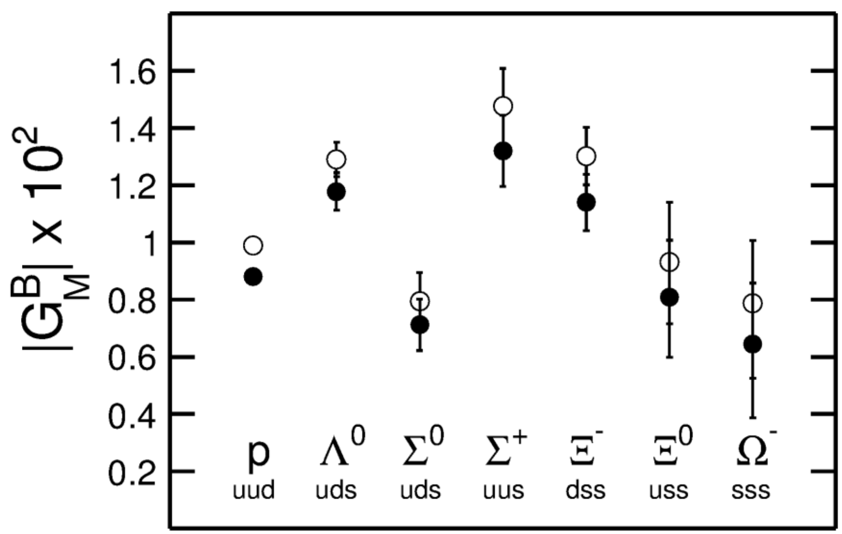
- The numbers of events $N(B\bar{B})$ in the signal region leads to the Born cross section $\sigma = N(B\bar{B})/(\epsilon\mathcal{L}C)$, where ε is the MC-determined efficiency, $\mathcal{L} = 802$ pb^{-1} is the e^+e^- luminosity, and C = 0.76 – 0.78 is the correction factor for initial state radiation. As is well known for protons, the cross sections are related to the form factors as

$$\boldsymbol{\sigma(s) = (4\pi\alpha^2\beta_B\,/3s)\left[|G_M(s)|^2 + \tau/2|G_E(s)|^2\right].}$$

- In the table we quote our results for $G_M(14.2\ \mathrm{GeV}^2)$ assuming $G_E(s) = G_M(s)$ for both charged and neutral hyperons, because at $s \equiv |Q^2| = 14.2\ \mathrm{GeV}^2$, finite values of $G_E(s)$ are possible even for the neutral hyperons.

		$N(B\bar{B})$	$\sigma(B\bar{B})$ pb	$G_M(B\bar{B})$ $\times 10^2$
p	(uud)	213(15)	0.46(3)(3)	0.88(3)(2)
Λ^0	(uds)	105(10)	0.80(8)(5)	**1.18(6)(4)**
Σ^0	(uds)	15(4)	0.29(7)(2)	**0.71(9)(3)**
Σ^+	(uus)	29(5)	0.99(18)(6)	1.32(13)(4)
Ξ^-	(dss)	38(6)	0.71(11)(5)	1.14(9)(4)
Ξ^0	(uss)	5^{+3}_{-2}	$0.35^{+0.20}_{-0.16}(3)$	0.81(21)(3)
Ω^-	(sss)	3^{+2}_{-1}	$0.16^{+0.13}_{-0.10}(2)$	$0.64^{+0.21}_{-0.25}(3)$

Note: $G_M(\Lambda^0) = 1.66(23)G_M(\Sigma^0)$

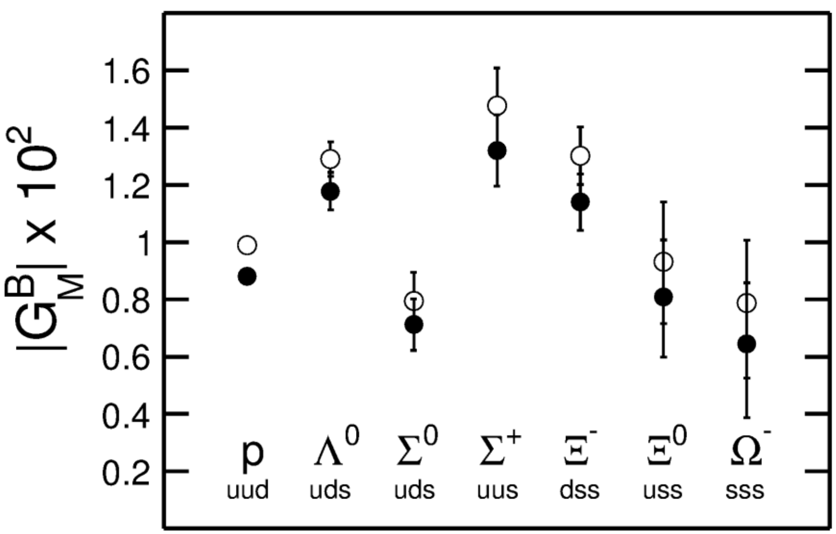


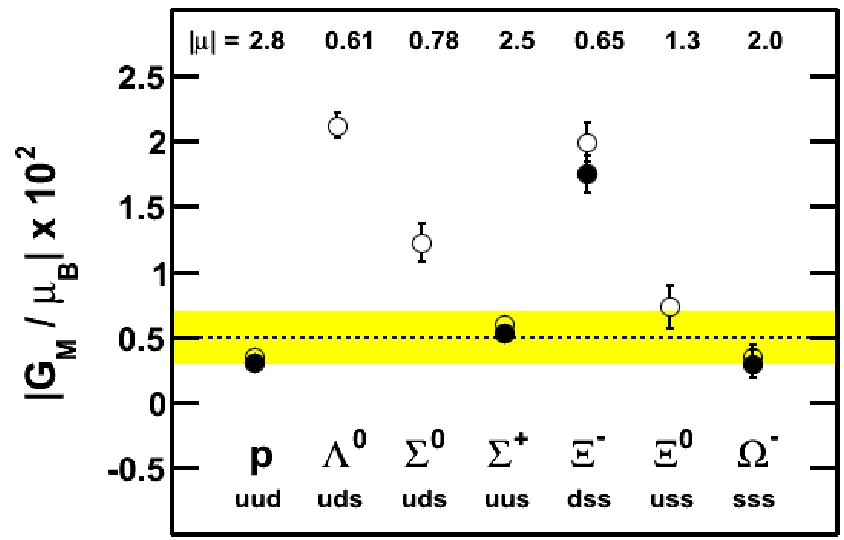
Closed circles : $G_E = G_M$, Open circles: $G_E = 0$

What do the Hyperon Form Factors Tell Us

- **No modern predictions of hyperon form factors for $|Q^2| > 1$ GeV^2 exist.** The old (1977) VDM-based predictions of $\sigma(e^+e^- \to B\bar{B})$ by Körner & Kuroda are **factor ~10 smaller** than what we measure. We can therefore only discuss **qualitative features** and patterns in our data.

1. No evidence is seen for G_M^B being proportional to μ_B . Actually, none is expected for timelike form factors.
2. G_M^B vary from 0.6×10^{-2} to 1.3×10^{-2} relatively smoothly, except for Σ^0.
3. There is a dramatic difference between $G_M(\Lambda^0)$ and $G_M(\Sigma^0)$. **Why?**





Closed circles : $G_E = G_M$, Open circles: $G_E = 0$

$G_M(\Lambda^0)$ and $G_M(\Sigma^0)$ and Diquark Correlations

There is a Dramatic Difference Between and . What does it imply?

- While both Λ^0 and Σ^0 have a $|uds>$ quark construct, $\mathrm{G_M}(\Lambda^0)$ **is ~70% larger than** $\mathrm{G_M}(\Sigma^0)$**. Why?**
- We note that the **isospins** of Λ^0 and Σ^0 are different:
  Since only the **u and d quarks carry isospin**, it is extremely suggestive that the observed difference in arises due to differences in the configurations of the **u and d quarks in Λ^0 and Σ^0.**
- The spins in isoscalar Λ^0 are coupled to **S=0**, and the spins in isovector Σ^0 are coupled to **S=1**. This leads to much stronger spatial correlation between the u and d quarks in Λ^0 compared to Σ^0.
  With large **$|Q^2|$ = 14.2 GeV^2** our measurements are sensitive to this difference in spatial correlation.
  We suggest that this gives rise to $\mathrm{G_M}(\Lambda^0)$ being much larger than $\mathrm{G_M}(\Sigma^0)$.
- What does this imply?

Diquark Correlations

Two-body (fermion) correlations are known to play an important role in many aspects of physics, ranging from Cooper pairs in **superconductivity**, to pairing interactions in **nuclear physics**. Diquark-quark models of nucleons have been proposed to explain many observations in hadron physics. Our own observation $G_M(\text{timelike}) \,/\, G_M(\text{spacelike}) \approx 2$ for the **proton** suggested it.

- Recently, Jaffe, Wilczek and colleagues have drawn attention to the fact that **"it is plausible that several of the most profound aspects of low-energy QCD dynamics are connected to diquark correlations."**
  Wilczek goes on to actually state that
  - **"The Λ is isosinglet, so it features the good diquark [ud], while Σ, being isotriplet, features the bad diquark (ud)."**
  - **"the good diquark would be significantly more likely to be produced than the bad diquark", and that "this would reflect in a large $\Lambda\,/\Sigma$ ratio."**
- We claim that this is exactly what we are observing with $G_M(\Lambda^0) \,/\, G_M(\Sigma^0) = 1.7 \pm 0.2$, **and** $\sigma(\Lambda^0) \,/\, \sigma(\Sigma^0) \approx 3.$
- **Our observations of hyperon form factors thus provide convincing evidence for diquark correlations.**