PRECISION FORM FACTORS OF PIONS, KAONS (& BARYONS)

at the highest timelike momentum transfers

Kamal K. Seth

Northwestern University, Evanston IL 60208, USA

(kseth@northwestern.edu)

Seminar at Frascati, Italy
July 3, 2013

PREAMBLE

- No talk on form factors can ignore protons.

  Despite the obvious bias of DeBeers for diamonds,

  ONLY PROTONS ARE FOREVER

  And nucleons do make up nearly all of the Universe!
  So, I will talk about protons briefly.
  However, the emphasis in my talk will be on
  PIONS AND KAONS.

- **And there are good reasons for it.**
  Pions and Kaons, with only two quarks and no spin and only one form factor, should be a hell-of-a lot **simpler** to understand **than baryons** with three quarks!

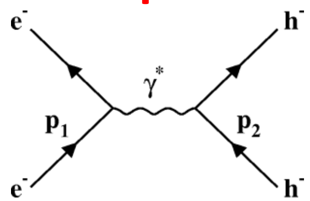
  And easier wins over harder, anytime!

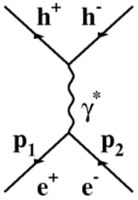
PRELIMINARIES

- Four momentum transfers defined as

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

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

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

Because protons have the unique distinction of being 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!

Timelike Momentum Transfers – Preliminary

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

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

- At large momentum transfer, $\tau = 4m_p^2/s$ becomes small, the contribution of G_E^p becomes small, and it becomes difficult to determine it.
- According to the **dimensional counting rule of QCD**, the above cross section decreases as **s^{-5}**, making it extremely difficult, if not impossible, to measure form factors for $|Q^2| \equiv s > 20$.
- **For pseudoscalar mesons, π and K**, with zero spin, there is only one form factor, $F_m(s)$, and the differential cross section is

$$\frac{d\sigma_0(s,\theta)_p}{d\Omega} = \frac{\alpha^2}{4s}\beta_p|F_m(s)|^2\sin^2\theta$$

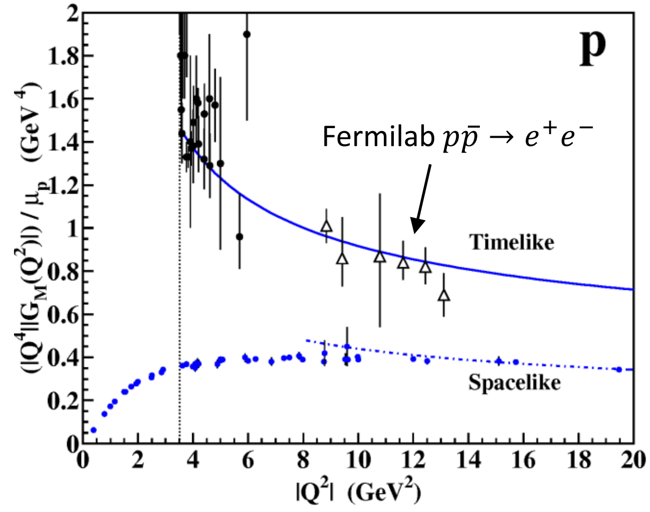
  Further, the cross sections decrease only as **s^{-3}**, making life at large $|Q^2|$ easier!

Timelike Form Factors of the Proton

- **Spacelike form factors** of the proton have been measured since the 1980's, and precision measurements have exited 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 $Q^4G_M(|Q^2|)$ 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.



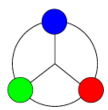
Timelike Form Factors of the Proton

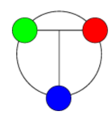
- Two possible explanations of the unexpected observation

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

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

  1. The quark distribution in the proton is not like

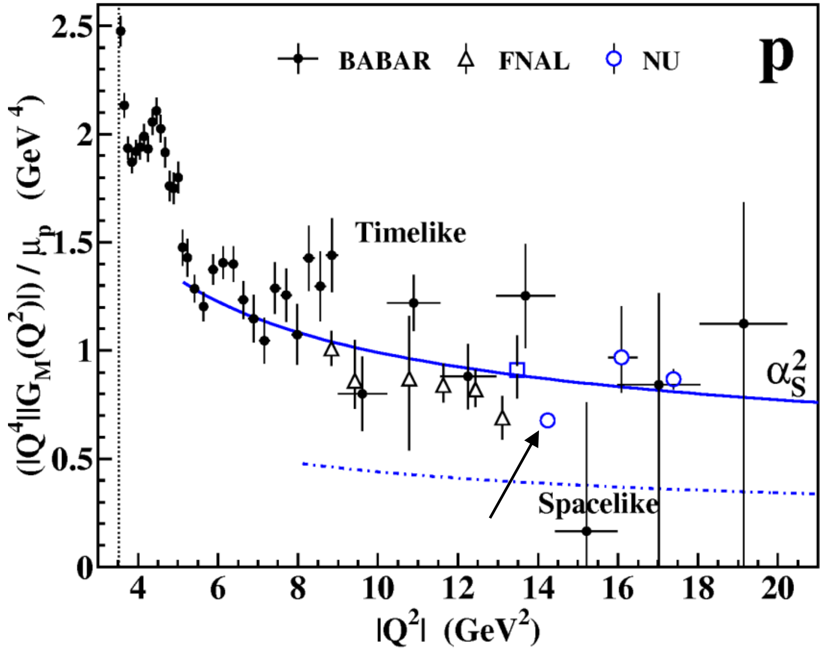
     a Mercedes star 

     but diquark-quark. 

  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 has failed to acquire acceptance. So, we have attempted to examine the second possibility, the validity of pQCD at large $|Q^2|$.

- We have now extended measurements of $G_M(p)$ to timelike $|Q^2|$ of **14.2 and 17.4 GeV^2** with high precision.



Things to note:

1. The ISR-based measurements of BaBar run out of statistics for $|Q^2| \gtrsim 5\ \mathrm{GeV}^2$. For example, for $|Q^2|$ = 15.2 GeV^2 only **1±4 counts** are observed, leading to 100% error in G_M. In contrast, even for $|Q^2|$ = 17.4 GeV^2, we observe **92±10 counts** which lead to G_M with ±5% error.
2. The **QCD counting rule prediction** of $|Q^{-4}|$ variation of $G_M^p|Q^2|$ continues. However, there is an **unexpected** dip, with **G_M(14.2 GeV^2) lower by (22 ± 4) %.**
3. The **G_M(timelike) / G_M(spacelike) ≈ 2** persists, and so does the lack of explanation.
4. Despite > 300 observed counts, we are not able to determine G_E / G_M. We **obtain $G_E / G_M = 0.8^{+0.9}_{-0.7}$**.

FORM FACTORS OF PIONS AND KAONS

I now turn to the main part of my talk: form factors of pions and kaons

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

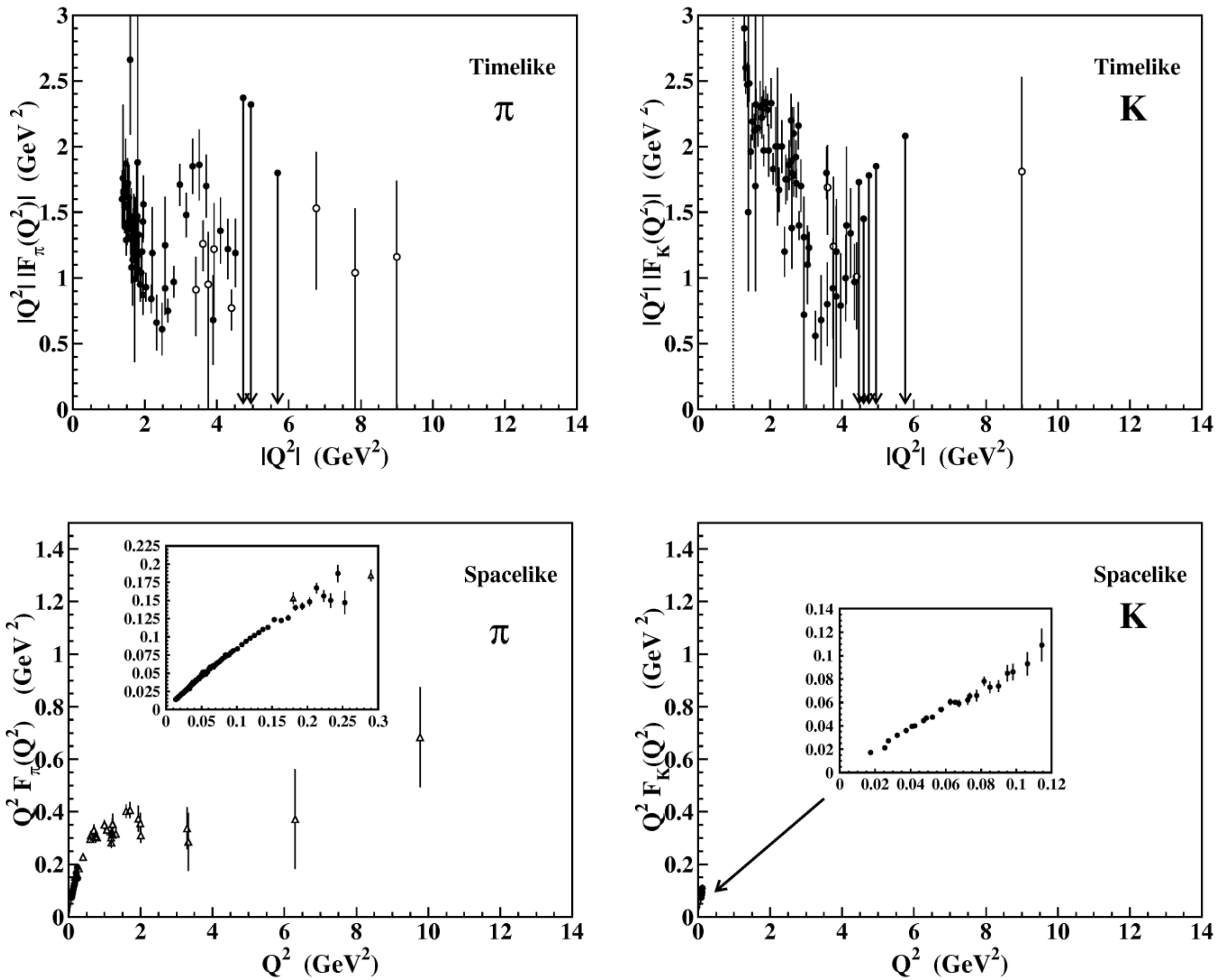
   $$\sigma(e^+e^- \to \pi^+\pi^-, K^+K^-) = \frac{\pi\alpha^2\beta}{3s}|F_{\pi,K}(s)|^2$$

   Note that the above implies that, with $F_{\pi,K}(s)$ varying as s^{-1}, the cross sections decrease rapidly as $s^{-3}(\equiv |Q^{-6}|)$

2. Almost no experimental data with any precision exists for pion and kaon spacelike or timelike form factors for $|Q^2| > 5$ GeV^2.

3. **Historical note:** Recall the famous Brodsky versus Isgur/Llwellyn-Smith debate (1984—1989) on **when the momentum transfer is large enough for perturbative QCD to be valid**. At that time, the discussion could only use the small amount of small Q^2 data for F_π with larger errors which was available then.

Form Factors of Pions and Kaons (pre-1990)



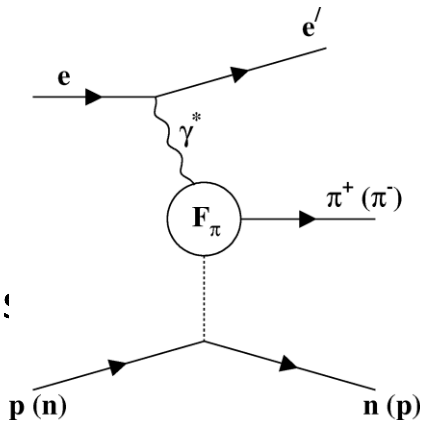
For $|Q^2| > 5$ GeV^2
Up to ±100% errors

Data limited to
$Q^2 < 2.5$ GeV^2 for π
$Q^2 < 0.12$ GeV^2 for K

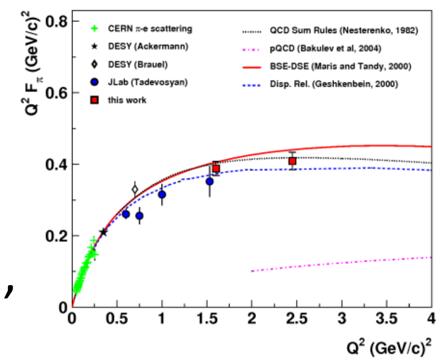
Spacelike Form Factors of Pions and Kaons

- Spacelike form factors of mesons are **very difficult** to measure, because meson targets do not exist. Two different methods have been used.

1. **F_π and F_K from Elastic Scattering** of pions/kaons off atomic electrons, $\pi(K)e^- \rightarrow \pi(K)e^-$. Unfortunately, in this approach the momentum transfer is very small. At CERN for 200 GeV pions, $Q^2(\pi) \leq 0.25$ GeV^2 and $Q^2(K) \leq 0.11$ GeV^2 were realized.



2. **F_π from Electroproduction of pions**, $e^-p \rightarrow e^-\pi^-p$ $(e^-\pi^+n)$, has serious theoretical problems and uncertainties. The good precision data are confined to $Q^2 < 2.45$ GeV^2 (JLab).
   F_K from Electroproduction of kaons — No data exist.



- As you will see, excellent timelike form factor data for π and K at large Q^2 now exist. It is a pity that the corresponding spacelike data do not exist to allow us to determine if the ratio of **timelike/spacelike** form factors for mesons is also ≈ 2, as it is for protons.

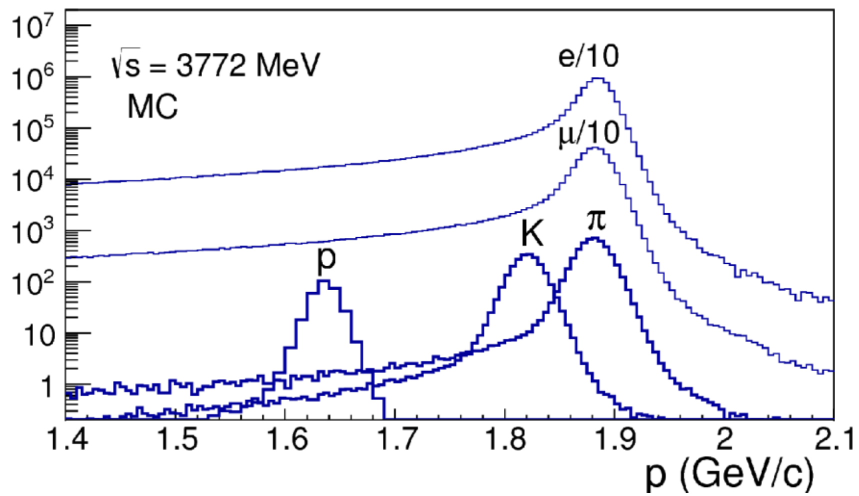
Measurements of Pion and Kaon Timelike Form Factors

- Timelike form factors are determined by measuring the cross sections for

$$e^+e^- \to h^+h^-, \qquad h = \pi, K, p, \text{etc.}$$

They have the great advantage of being able to determine form factors of any hadron, but they have the great problem of detecting the desired hadron pair in presence of **several orders of magnitude larger background of QED–produced e^+e^- and $\mu^+\mu^-$ pairs**.

- The MC–generated figure shows that for $\sqrt{s} = 3.77$ GeV, the expected peak counts for π, K, and p range from 500 to 100 counts, whereas the peak counts for electrons and muons are 10^7 and $\sim 10^6$,
i.e., **lepton rejection at 3 to 4 orders of magnitude is required.**



- Cabibo anecdote!

PREJUDICES & OBSTACLES

- In trying to measure form factors at a collider like CESR at Cornell, one has to overcome two big obstacles.

1. The first is the prejudice that only **weak interaction** flavor physics is important, the rest has little priority. It is an uphill battle to get the required beam time allocated for form factor measurements.
2. The second obstacle is more generic. Everybody loves resonances, and they want to love to **run on resonances**.

- Unfortunately, hadron form factors are not **weak interaction** physics and you do not want to measure on the peaks of vector resonances which directly decay into e^+e^-.
- Unless, of course, you can show that the resonances do not decay into the hadron pairs of your interest, i.e., $\sigma(R) \not\to h^+h^-$.
  Our measurements are based on just this fact, so that we are able to use data taken at $\psi(3770)$ and $\psi(4160)$ to measure form factors.

- An important pQCD prediction, which has been verified for many hadronic decays of charmonium resonances is that since both leptonic and hadronic decays depend on wave functions at the origin, the ratios of their branching fractions are identical,

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

- This simple prediction allows us to estimate branching fractions for a specific hadronic decay of a resonance ψ(n') if that same decay has been measured at another resonance ψ(n), and measurement of the leptonic decays of both resonances exist. The known ratios are

$$\mathcal{B}(\psi(3770) \to e^+e^-) \,/\, \mathcal{B}(\psi(3686) \to e^+e^-) = 0.36 \times 10^{-3}$$
$$\mathcal{B}(\psi(4170) \to e^+e^-) \,/\, \mathcal{B}(\psi(3686) \to e^+e^-) = 1.04 \times 10^{-3}$$

- This implies that the branching fractions for the hadronic decays of ψ(3770) and ψ(4160) are more than **three orders of magnitude smaller** than the corresponding measured decays of ψ(3686).

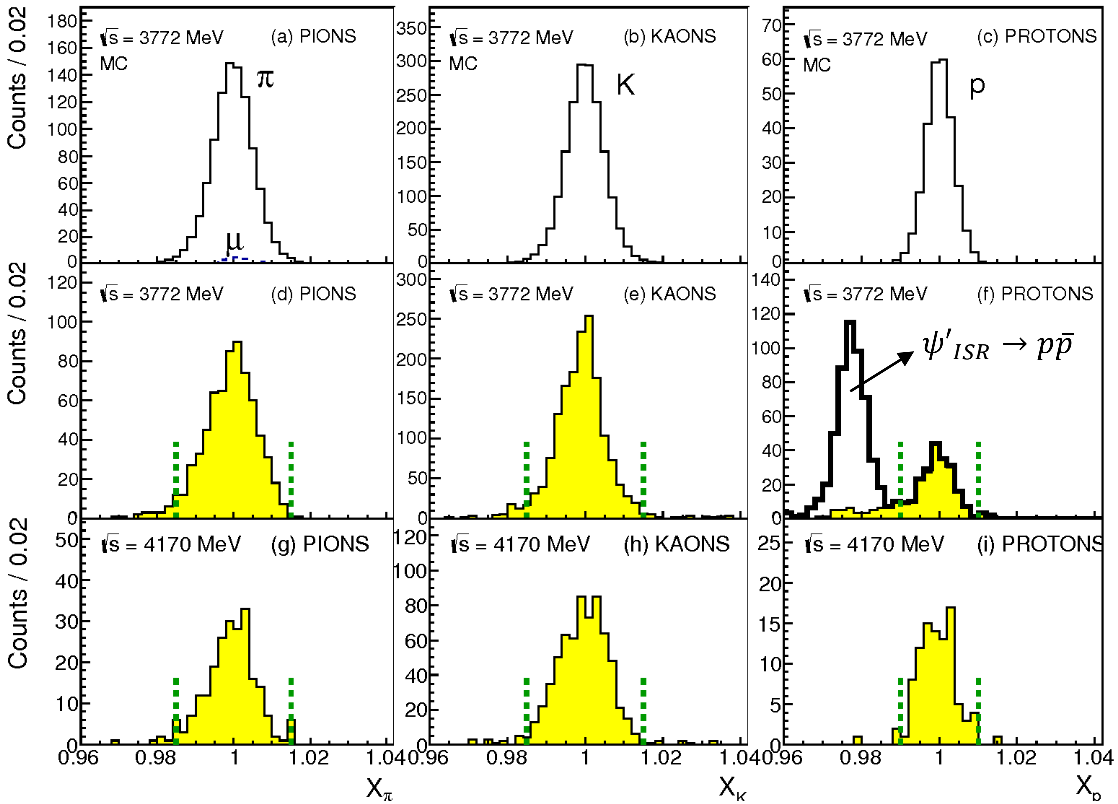
- With nearly 5 million ψ(3772) and ψ(4160) each, formed in the present measurements, and our detection efficiencies, we estimate resonance yields of ~0.04 $\pi^+\pi^-$, 0.4 K^+K^-, and 1.8 $p\bar{p}$, i.e.,

  all observed yields can be attributed to form factors.

- This is the basis of all pion, kaon, proton, and hyperon form factors I am reporting (PRL 110, 022002 (2013), and to be submitted).

Measurements of Pion and Kaon Form Factors

- I will not bore you with the nitty-gritty of how using all the detector components of CLEO-c, the drift chambers, the central calorimeter, the RICH detector, and muon detector, we were able to identify π, K, and p cleanly, in presence of the monstrous backgrounds of electrons and muons. Here is how clean!



3.77 GeV – MC

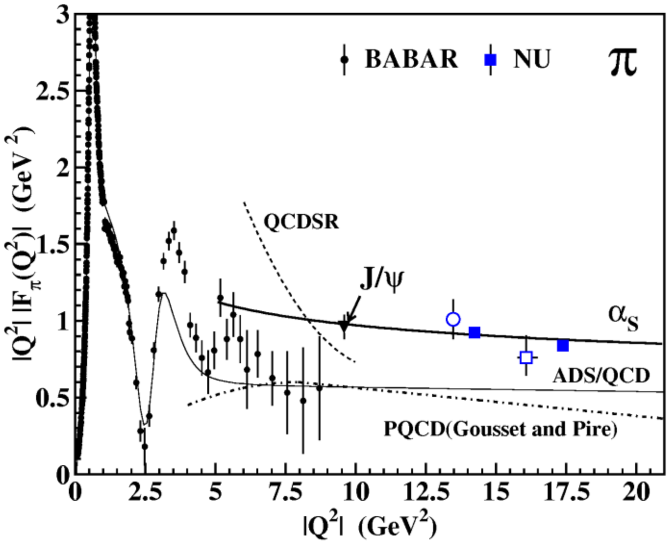
3.77 GeV – Data

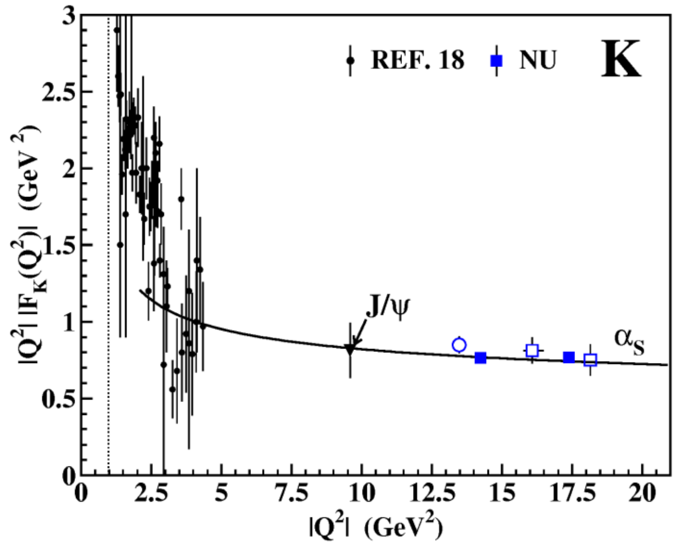
4.17 GeV – Data

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

Pion and Kaon Form Factors – Results

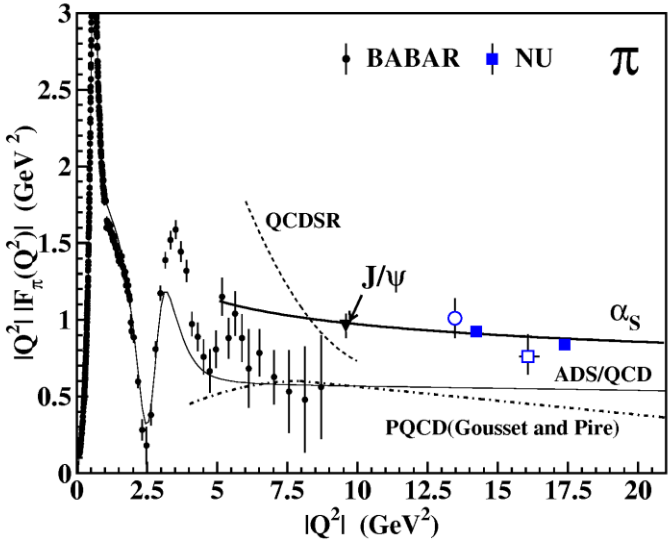
(PRL 95, 261803 (2005), PRL 110, 022002 (2013))

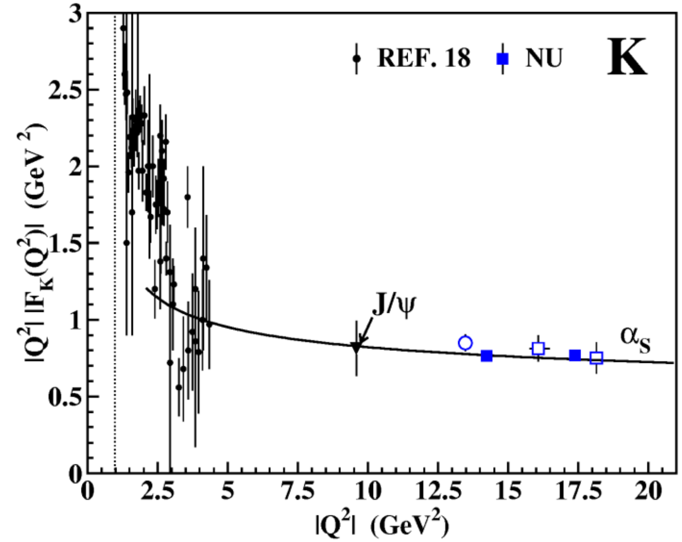




	Q^2 (GeV^2)	$N(\pi^+\pi^-)$	σ(Born), pb.	$F_\pi(\|Q^2\|) \times 10$	$Q^2 F_\pi(\|Q^2\|)$ (GeV^2)
CLEO(2005)	13.5	26 ± 5	9.0 ± 1.8	0.75 ± 0.09	1.02 ± 0.13
(2013)	14.2	661 ± 26	6.36 ± 0.25	0.65 ± 0.01	0.92 ± 0.04
(2013)	17.4	213 ± 12	2.89 ± 0.16	0.48 ± 0.01	0.84 ± 0.03
	Q^2 (GeV^2)	$N(K^+K^-)$	σ(Born),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

Pion and Kaon Form Factors



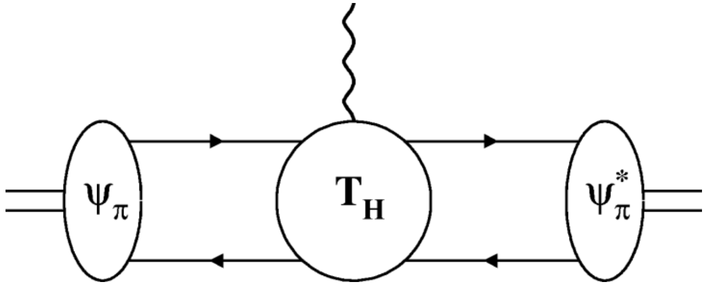


The important experimental results are:

1. There is a remarkable agreement of the form factors for both pions and kaons with the **dimensional counting rule prediction of QCD,** that $|Q^2|F_{\pi,K}$ are nearly constant, varying with $|Q^2|$ only weakly as $\alpha_S(|Q^2|)$.
2. The existing theoretical predictions **underpredict the magnitude** of $F_\pi(|Q^2|)$ at large $|Q^2|$ by large factors, ≥ 2. More about this later.
3. The big surprise is that while pQCD predicts that **$F_\pi/F_K=(f_\pi/f_K)^2=0.67\pm0.01$,** we find: **$F_\pi(14.2\ \text{GeV}^2) / F_K(14.2\ \text{GeV}^2) = 1.21 \pm 0.03$,**
   $F_\pi(17.4\ \text{GeV}^2) / F_K(17.4\ \text{GeV}^2) = 1.09 \pm 0.04$.
   More about this later.

Theoretical Implications

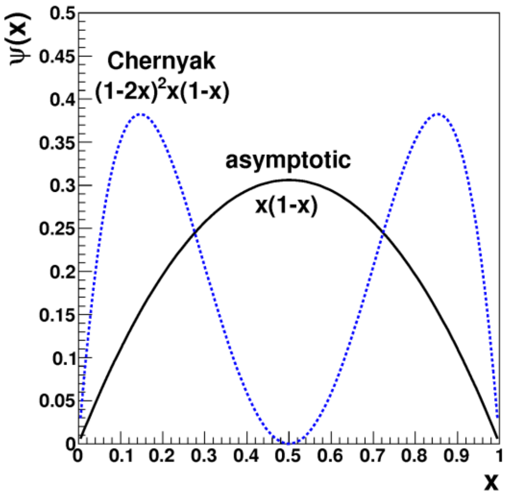
- Lattice lives in **Euclidean time**, and is not capable of addressing timelike form factors. So we expect no lattice-based predictions for form factors, and have to live with predictions based on **QCD–based models** for timelike form factor predictions.
- The starting point of the existing calculations is **factorization**, with



$$F(Q^2) = \psi_{\text{in}} \times T_H \times \psi_{\text{out}}$$

  The meson wave functions $\psi_{\text{in,out}}$ represent soft components, not calculable perturbatively. $\mathbf{T_H}$ represents the hard interaction, "**hopefully calculable in perturbative QCD**."

- Since **ab initio** the quark wave functions are not known, various empirical wave functions have been used.
  Lepage and Brodsky used the asymptotic wave function $\phi(x)_{as} \propto f_\pi\, x(1-x)$ where the q and $\bar{q}$ share momenta equally.
  Chernyak and Zhitnitsky used the QCD sum-rule-inspired wave function $\phi(x)_{CZ} \propto (1-2x^2)\,\phi(x)_{as}$ which produces a two humped distribution.



Theoretical Implications (cont'd)

- **For pions**, Lepage and Brodsky obtained
  $|Q^2|F_\pi(|Q^2|) = 16\pi\alpha_S|Q^2| \times f_\pi^2 = \mathbf{0.21\ GeV^2}, \qquad |Q^2| = 17.4\ \mathrm{GeV}^2$
  with the pion decay constant f_π = 130.41 MeV.
  This is a factor 4 smaller than what we measure.

- **For kaons**, with f_K = 156.1 MeV replacing f_π, and assuming wave function for kaons identical to that for pions the Lepage-Brodsky prediction is
  $|Q^2|F_K(|Q^2|) = 16\pi\alpha_S|Q^2| \times f_K^2 = \mathbf{0.31\ GeV^2}, \qquad |Q^2| = 17.4\ \mathrm{GeV}^2$
  This is a factor 2.6 smaller than what we measure.

- This leads to the **serious problem** that the ratio, which is supposed to remove the dependence on the assumed identity of pion and kaon wave functions, is predicted to be
  $$F_\pi(17.4\ \mathrm{GeV}^2)\ /\ F_K(17.4\ \mathrm{GeV}^2) = f_\pi^2\ /\ f_K^2 = 0.67 \pm 0.01$$
  This is (36±1)% smaller than our measured value of 1.09 ± 0.04.

- With our precision measurements now available, it is quite obvious that something is very wrong.

Could it be the wave functions?

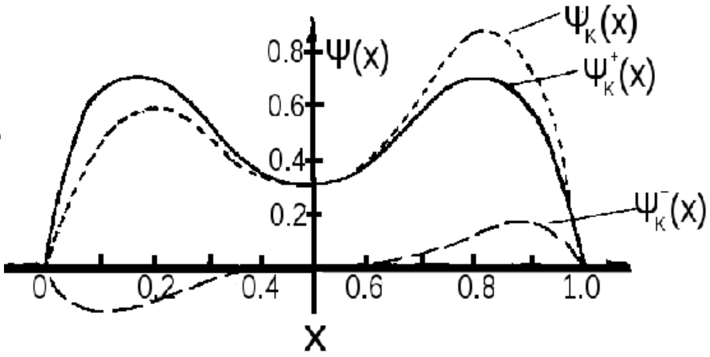
Theoretical Implications (cont'd)

- Since the relation

$$F_\pi(|Q^2|) \;/\; F_\pi(|Q^2|) = \; f_\pi^2 \;/\; f_K^2$$

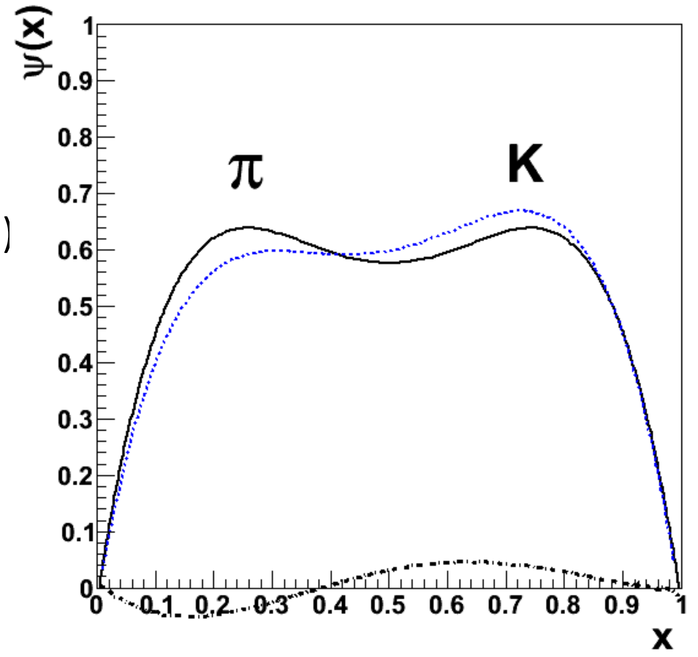
  is based on assuming identical wave functions for pions and kaons, **Lepage and Brodsky (1980)** conjectured that because the **s-quark** in the kaon is $\sim$27 times heavier than the $\langle u, d\rangle$ quarks in the pion, and the SU(3) **flavor symmetry is broken**, the kaon wave function may differ from the pion wave function by acquiring an **asymmetric component**, and account for the observed violation of the above relation.

- As a matter of fact, **Chernyak and Zhitnitsky (1984)** were able to explain the experimental observation in terms of their two–humped wave function, and a rather **large effect of SU(3) breaking in the kaon**.

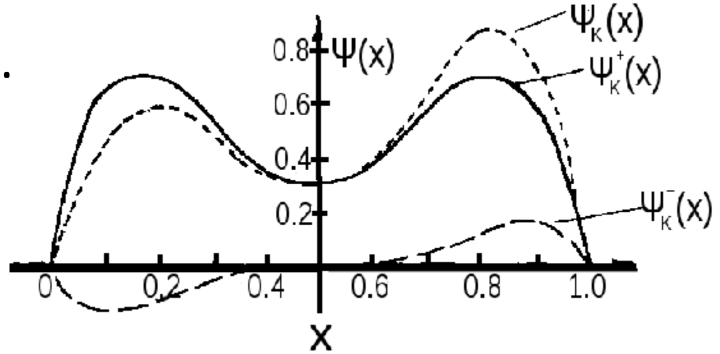


- Unfortunately, the CZ wave functions, and the conclusions drawn from them, "have largely been discredited" (Brown et al. 2006), and we have to look elsewhere for the explanation.

- Recently some **quenched lattice calculations** (Braun et al., PRD 74, 074501 (2006)), and **AdS/CFT** light–front QCD model calculations (Brodsky and de Teremond, arXiv:0802.0514[hep-ph] (2008)) have addressed the question of pion and kaon wave functions. Both obtain a much smaller asymmetric component in the kaon wave function, and a much smaller effect of SU(3) breaking than CZ proposed.

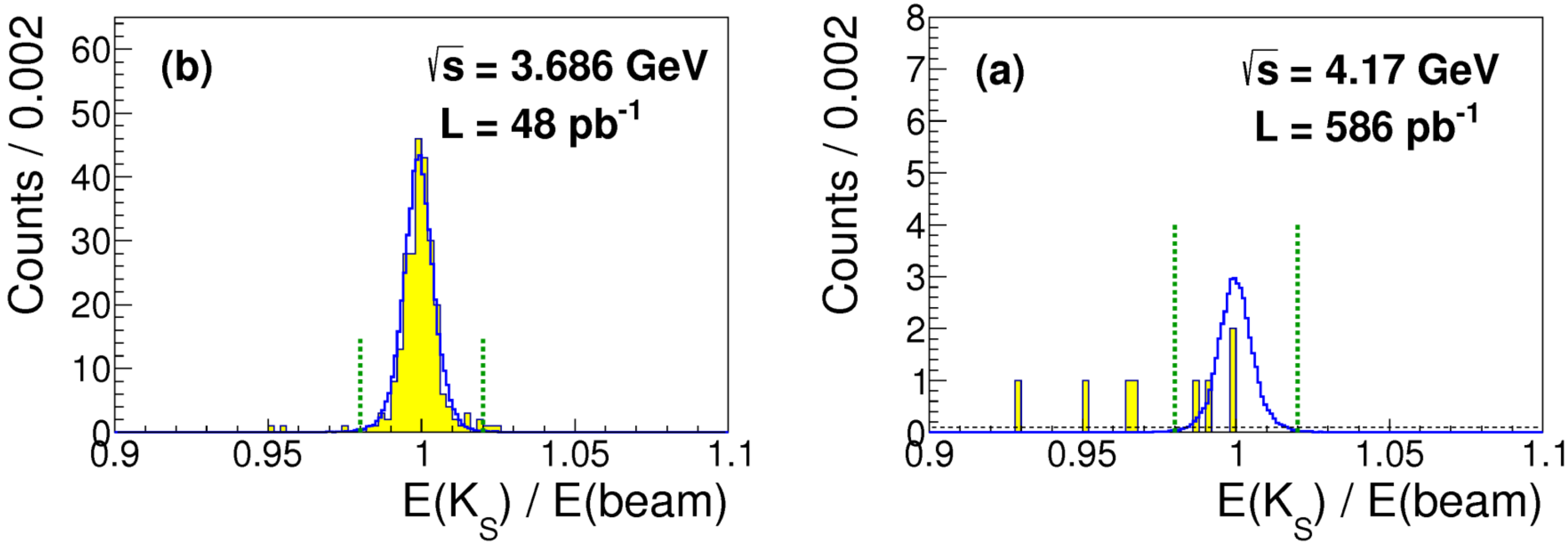


- What is needed to resolve theoretical differences is an **experimental measure of the effect of SU(3) breaking in the kaon**.
- We have now made the first such measurement.



Estimating SU(3) Breaking in the Kaon

- **Lepage and Brodsky (1980)** suggested that a large violation of the $F_{\pi}/F_K \;=\; f_{\pi}^2/f_K^2$ identity can arise if there is a substantial SU(3) breaking effect in the kaon wave function. They predicted that a large SU(3) breaking effect would lead to a large form factor for the neutral kaon, and $\boldsymbol{F_{K_S K_L}}$ / $\boldsymbol{F_{K^+K^-}}$ **of the order one,** and suggested that $F_{K_S K_L}$ should be measured.
- Following this suggestion, we have made the first ever measurement of the form factor $\boldsymbol{F_{K_S K_L}(|Q^2|)}$ **at |Q²| = 17.4 GeV².**
- Since the cross section for $e^+e^- \to K_S K_L$ is expected to be small, and we do not attempt to detect $K_{L=}$, careful criteria for event identification had to be developed, and their efficacy tested. We have done so by measuring $\psi(2S) \to K_S K_L$ for $|Q^2|$ = 13.6 GeV^2 using the same event selection criteria as for $|Q^2|$ = 17.4 GeV^2, and confirmed that we obtain $\mathcal{B}(\psi(2S) \to K_S K_L)$ in agreement with its known value.



- For $e^+e^- \to K_S K_L$ at $\sqrt{s} = 4.17$ GeV, we obtain 4 events in the signal region, and a Monte Carlo background estimate of 2 counts. This leads for $|Q^2| = 17.4$ GeV^2 to:
  $\boldsymbol{F_{K_S K_L}(|Q^2|) = 3.9 \times 10^{-3}}$, **90% CL of** $\boldsymbol{(0 - 7.0) \times 10^{-3}}$
  $\boldsymbol{F_{K_S K_L}(|Q^2|) \,/\, F_{K^+K^-}(|Q^2|) = 0.09}$, **90% CL of** $\boldsymbol{0 - 0.16}$.
- In other words, the **SU(3) breaking effect on the ratio is found to be small, certainly much less than of "the order of one".**
- To come back to the original problem of $F_\pi / F_K(\text{expt.}) \neq f_\pi^2 \,/\, f_K^2$, it is now apparent that it can not be attributed to SU(3) breaking alone.
  The problem remains unresolved.
- Here is **a challenge** worthy of the best theoretical attempts.

Form Factors of Hyperons

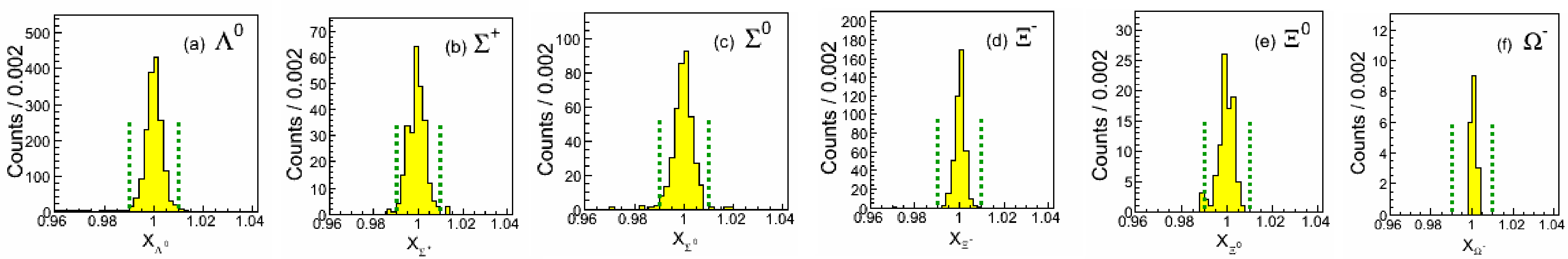
- I can not resist the temptation of telling you about our latest form factor measurements, **form factors of hyperons**, which are even more unique than those of pions and kaons.
- I already told you that in 1960, before quarks were even proposed, but strangeness and strange baryons, the hyperons, were known, **Cabibbo and Gatto** wrote the classic papers on the measurement of timelike form factors **by $e^+e^- \to$ hadron–antihadron**. They discussed the proton and neutron, and pion and kaon, and went on to say that it would be very interesting to measure **hyperon form factors**. But they noted that the cross sections are likely to be very small, and despaired whether they could be measured.
- And now we have measured them, and with good precision.

Actually, this is not quite true, in 1988 DM2 tried to measure $\sigma(e^+e^- \to \Lambda\overline{\Lambda})$ near threshold (@ 2.386 GeV), observed 2 events, and reported $\sigma(e^+e^- \to \Lambda\overline{\Lambda}) = 100^{+60}_{-35}$ pb. [D. Bisello et al. (DM2 Collaboration), Z. Phys C 48, 23 (1990)]. Also, recently BaBar [PRD 76, 092006 (2007)] reported form factor measurements for $\Lambda\overline{\Lambda}$ and $\Sigma^0\overline{\Sigma^0}$ from threshold to about 6 GeV with better than ±10% errors. Above 6 GeV their errors become large rapidly.

Hyperon Branching Fractions

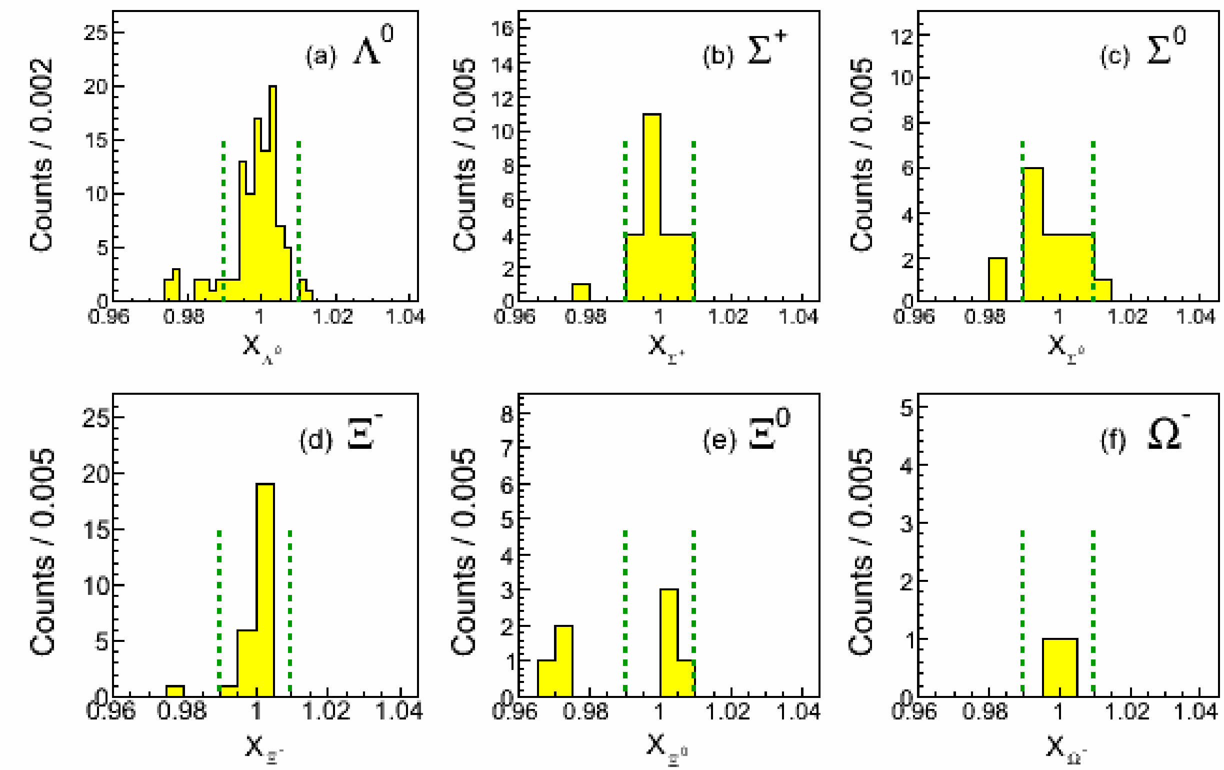
- Actually, our measurement of hyperon form factors follow naturally from our published and updated measurements of hyperon decays of the charmonium resonance ψ(2S), $\sqrt{s} = 3.686$ GeV.
- The figure shows the distribution of the events as function of the variable $\boldsymbol{X \equiv (E(B) + E(\bar{B}))/\sqrt{s}}$. There is essentially no background in any case.
- The table shows the results. Our updated results have less than ±5% errors. The result for $\Omega^-\overline{\Omega^-}$ is the first ever.

		M_B GeV	BaBar PRD 76, 092006 (2007) N	BaBar $\mathcal{B}$ $\times 10^4$	CLEO PRD 72, 051108 (2005) N	CLEO $\mathcal{B}$ $\times 10^4$	Present N	Present σ pb	Present $\mathcal{B}$ $\times 10^4$
p	(uud)	0.938			557(24)	2.87(19)	5514(78)	201(3)	3.16(5)
Λ^0	(uds)	1.115	17(4)	6.0(15)	208(14)	3.28(34)	1606(40)	238(6)	3.61(9)
Σ^+	(uus)	1.189			35(6)	2.57(81)	253(16)	173(11)	2.63(17)
Σ^0	(uds)	1.192	2	—	58(8)	2.63(41)	364(19)	132(7)	2.08(11)
Ξ^-	(dss)	1.322			63(8)	2.38(37)	431(21)	165(8)	2.50(12)
Ξ^0	(uss)	1.315			19(4)	2.75(88)	88(10)	114(12)	1.71(18)
Ω^-	(sss)	1.672			4(2)	$0.70^{+0.56}_{-0.34}$	18(4)	26(6)	0.40(10)



Form Factors of Hyperons

- We now turn to the form factor measurements with 5.2 million e^+e^- annihilations at $\sqrt{s} = 3.772$ GeV, or $|Q^2| = 14.2$ GeV^2.
  The figure shows that, as anticipated by Cabibbo and Gatto, the yields of form factor events are smaller by nearly an order of magnitude compared to the ψ(2S) event yields. The X distributions have, however, very small backgrounds, which arise from decays of ψ(2S) formed by ISR.



Form Factors of Hyperons (cont'd)

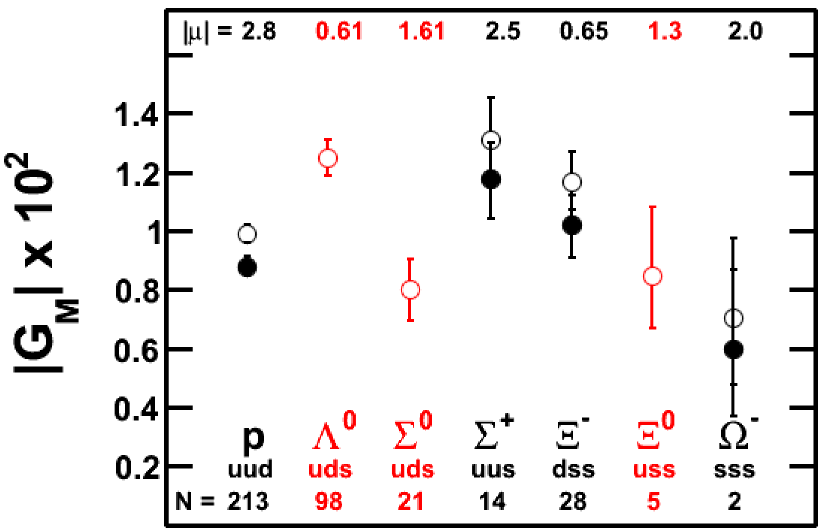
- The numbers of events $N(B\bar{B})$ in the peak region, defined as $X = 0.99 - 1.01$, leads to $\sigma_{\text{Born}} = N(B\bar{B})/(\epsilon\mathcal{L}C)$ where ε is the MC-determined efficiency, $\mathcal{L} = 802$ pb^{-1} is the e^+e^- luminosity, and C = 0.76 – 0.78 is the correction factor for initial state radiation. The cross section is related to the form factors as $\boldsymbol{\sigma(s) = (4\pi\alpha^2\beta_p\,/3s)\left[|G_M(s)|^2 + \tau/2|G_E(s)|^2\right]}$.
We set $G_E(s) = 0$ for the neutral hyperons, Λ^0, Σ^0, Ξ^0, although at $s \equiv |Q^2| = 14.2\ \text{GeV}^2$, small, non-zero values are possible. For the charged hyperons, Σ^+, Ξ^-, and Ω^-, we quote $G_M(s)$ assuming $G_E(s) = G_M(s)$.

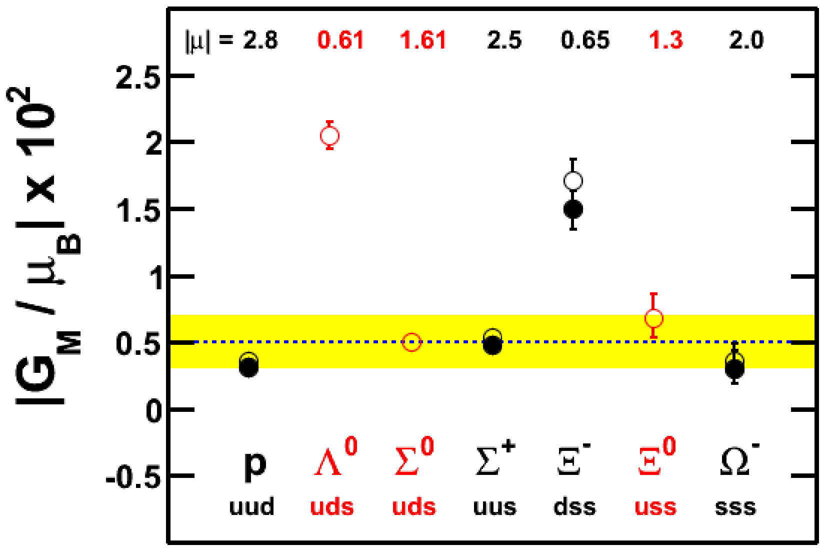
		M_B GeV	N	σ pb	G_M $\times 10^2$	$\lvert\mu_B\rvert$	$\lvert G_M/\mu_B\rvert$ $\times 10^2$
p	(uud)	0.938	213(15)	0.46(3)	0.88(3)	2.79	0.31(1)
Λ^0	(uds)	1.115	90(9)	0.77(8)	1.25(6)	0.61	**2.28(10)**
Σ^+	(uus)	1.189	21(5)	0.79(17)	1.40(13)	2.46	0.57(5)
Σ^0	(uds)	1.192	14(4)	0.30(8)	0.80(10)	1.61	0.53(6)
Ξ^-	(dss)	1.322	26(5)	0.56(11)	1.26(10)	0.68	**1.94(15)**
Ξ^0	(uss)	1.315	4^{+3}_{-2}	$0.32^{+0.22}_{-0.13}$	$0.85^{+0.23}_{-0.18}$	1.25	$0.68^{+0.18}_{-0.14}$
Ω^-	(sss)	1.672	2^{+2}_{-1}	$0.14^{+0.16}_{-0.09}$	$0.60^{+0.27}_{-0.23}$	2.02	$0.30^{+0.14}_{-0.12}$

Note: BaBar [PRD 76, 092006 (2007)] has reported ISR-based measurements of $\Lambda\bar{\Lambda}$ and $\Sigma^0\overline{\Sigma^0}$ form factors. They observe < 4.6 $\Lambda\bar{\Lambda}$ events and < 2.3 events in the region |Q^2| = 10.2 – 13 GeV^2, and are only able to establish upper limits of $G_M(\Lambda\bar{\Lambda}) < 1.7 \times 10^{-2}$ and $G_M(\Sigma^0\overline{\Sigma^0}) < 1.9 \times 10^{-2}$.

Form Factors of Hyperons (cont'd)

- In the lowest order, $G_M(s)$ of a hyperon should be proportional to its magnetic moment μ_B, and these are predicted by the simple quark model to better than 10%. In the figure we show plots both for $G_M(s)$ and $G_M(s) / \mu_B$.
- We note that for four out of six hyperons, $G_M(s) / \mu_B \approx 0.5 \pm 0.2$, and this agrees with that for protons. **There are two very dramatic disagreements** from this, **$G_M(s) / \mu_B$ for Λ^0 and Ξ^- are an astonishing factor ~4 larger**.
- This was unexpected, to say the least, and no simple explanation comes to mind! We do note that Λ^0 and Ξ^- magnetic moments are ~factor 2–3 smaller than the rest.





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

The Theoretical Landscape for Hyperons

- **Well, there is essentially none!**
  This is understandable in absence of any experimental data until now.
- Actually, two old predictions, both based on “generalized vector dominance model” (VDM) exist.
- **In a 1977 paper, Körner and Kuroda** (PRD 7, 2165 (1977)) predicted cross sections for all hyperon–antihyperon pairs, which are generally about factors ≈100 smaller than what we measure.
- **In a 1990 report, Biagini et al.** (Dubna E2-90-396, unpublished) predicted $e^+e^- \to \Lambda\overline{\Lambda}$ form factors from threshold to $|Q^2| = 10$ GeV^2. They anchored their prediction on the 1988 DM2 measurement based on 2 observed counts, and their prediction can not be taken seriously.

So, all in all, the theoretical landscape is empty.

Hopefully, our measurements will catalyze some new theoretical activity.