# Challenges in Hadron Physics

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# CHALLENGES

- It is a privilege to be asked to give this closing talk of HADRON07.
- I was encouraged to make this closing talk different from the usual summary talk, and not attempt to repeat bits and pieces you have heard in 36 plenary talks and as many of the 146 parallel talks as you could attend.
- So, I will talk about the challenges our field presents. My choices will be necessarily subjective – I will talk about things which I know something about, and avoid subjects about which I know that I do not known much.
- HADRON V (1991) defined our charter as

**“hadron spectroscopy and some areas of related hadron structure”**

So strong interactions and QCD is what I will talk about, referring to interesting results, both those which were presented at this conference, and those which were not.

We go first with

# BARYONS

Two quarks are easier than three, but we live in a world of baryons, not mesons.

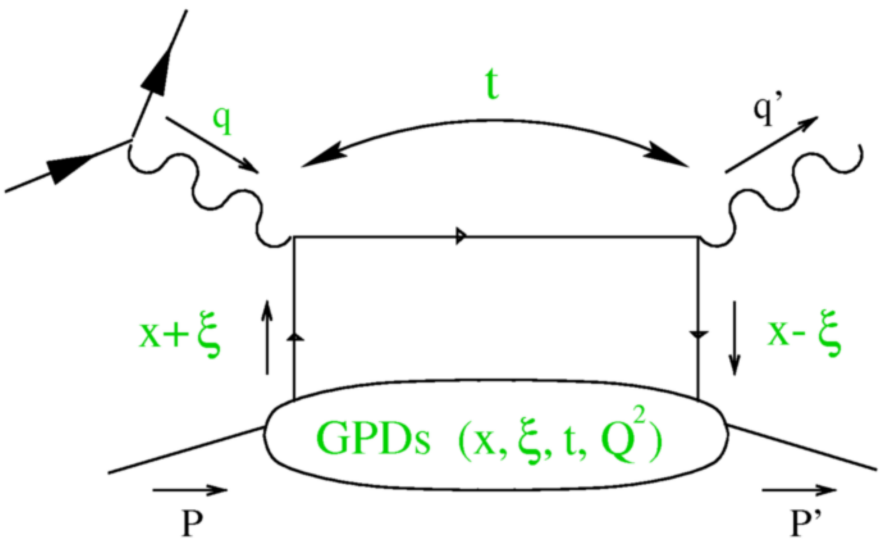
# The Nucleons

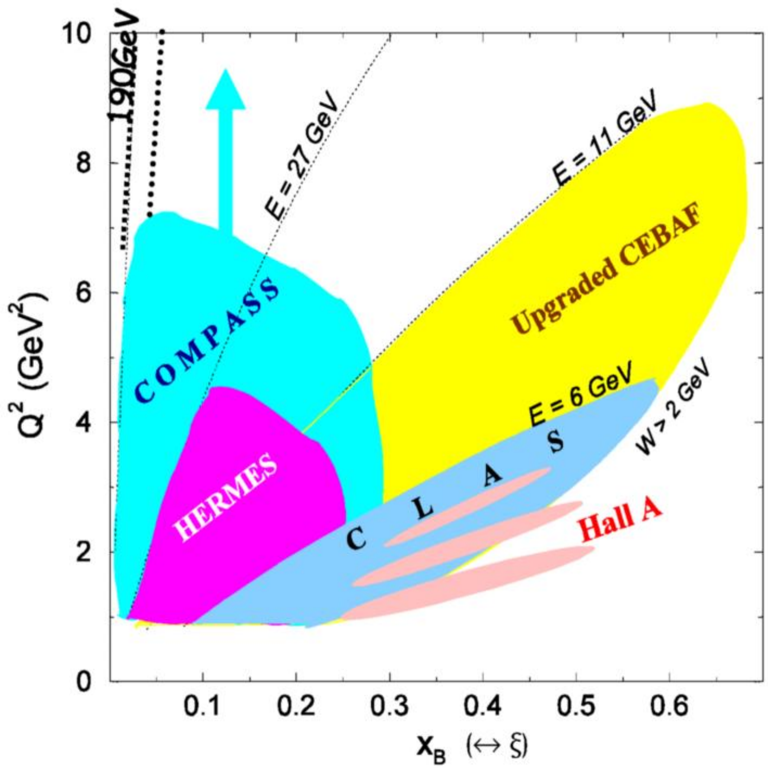
- **Not too much to ask:** What do nucleons look like? How do their static properties, mass, charge, spin, and structure arise. We are told **GPD's** will tell us all.
  (Beware, they also told us that **GDP** contains all that you wish to know about a country).

- GPD's are determined by Deeply Virtual Compton Scattering (**DVCS**), and Deeply Virtual Meson Production (**DVMP**), and all the labs in the world are busy measuring them.

**but**

the GPD observables are integrals over x (fractional quark momenta), which must be deconvoluted to get anything transparent out.

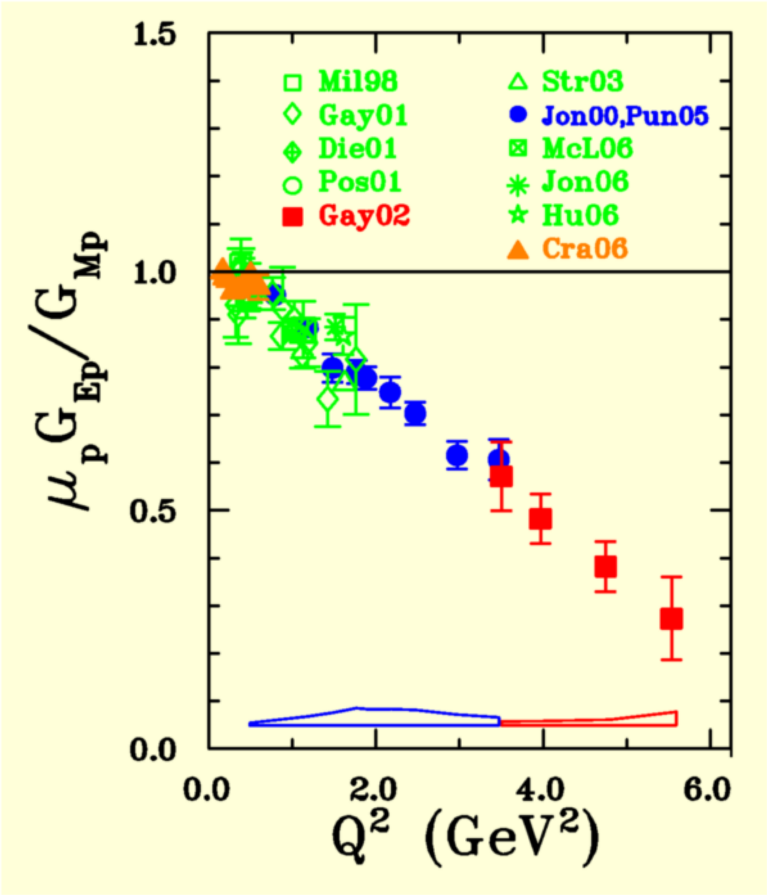


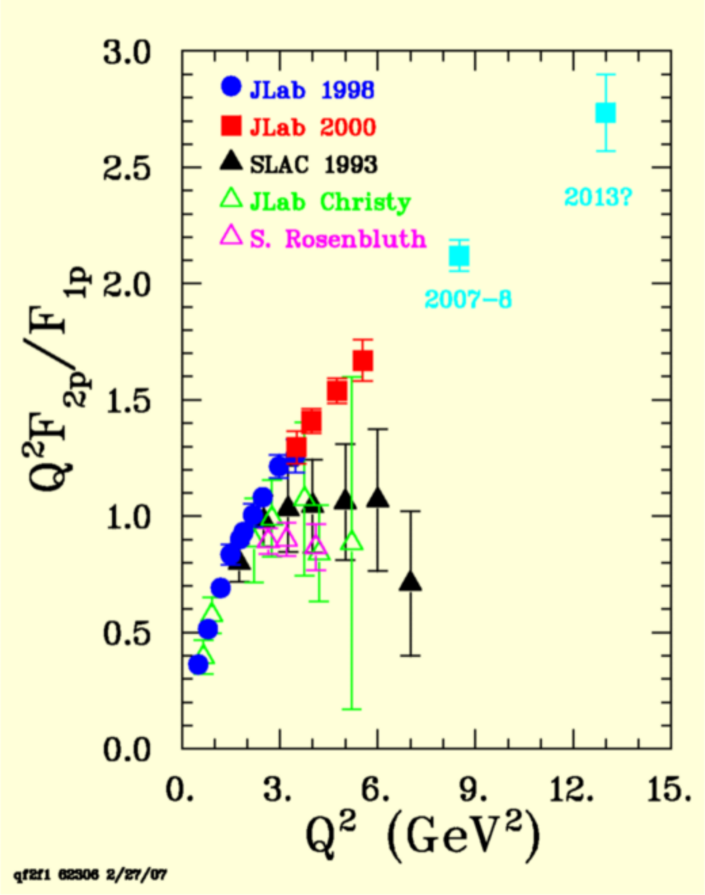




So, for the present, we will stay with the old-fashioned way of measuring form factors, deep inelastic scattering, etc…

# The Challenge of $G_E$(proton) for Spacelike Momentum Transfers

- Jlab polarization measurements tell us that $G_E(p)$ is falling like a rock!



- If this keeps on going, we reach $G_E(p) = 0$ at $Q^2$(spacelike) = 8.6 GeV$^2$.

- What does $G_E(p)=0$ mean?
Go a bit further, and $G_E(p)$ becomes negative? What would this mean?

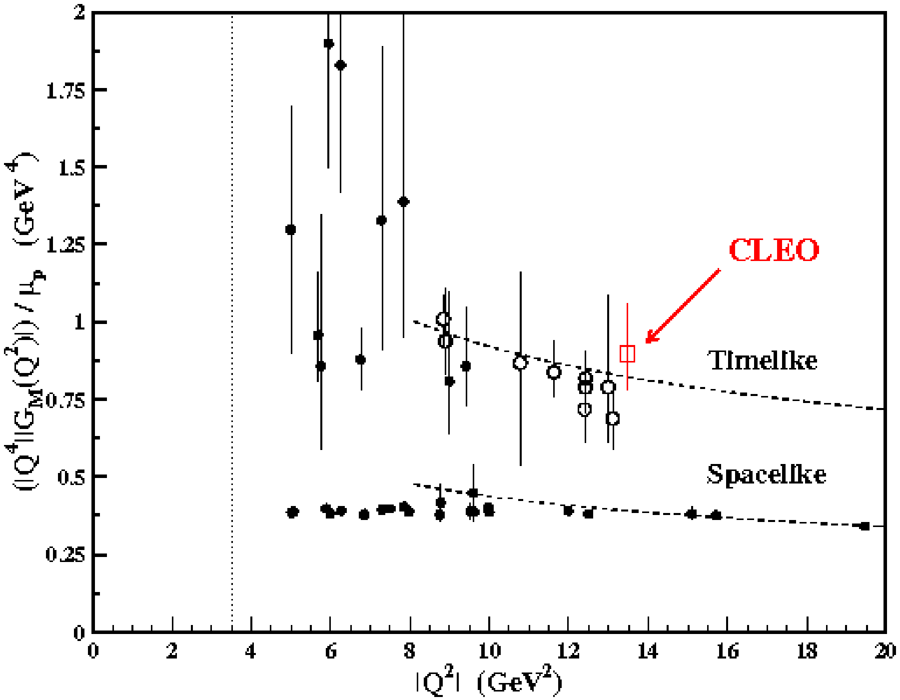
- And what does this imply for timelike momentum transfers?

**Is this a challenge or what?**

- Incidentally, we now have beautiful measurements of $G_M(n)$ for $Q^2$=0.1–4.8 GeV$^2$ from JLab. No surprises there. The form factors agree with the dipole variation, as for $G_M(p)$.

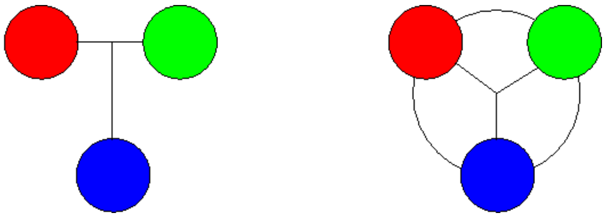
# The Challenge of Timelike $|Q^2|$

- Perturbative QCD (actually Cauchy's theorem for an analytic function, tells us that at large $Q^2$, the timelike and spacelike form factors should become equal. Fermilab measurements, now confirmed by measurements by Babar, CLEO, and BES, tell us that this is not so, at least up to $Q^2 = 15$ $GeV^2$. **The $G_M$(timelike) ≈ $2G_M$(spacelike).** What is going on?



- So it is a confirmed result that **$G_M$(timelike) ≈ 2$G_M$(spacelike).** How to explain that is a challenge!

- Of the theoretical ideas offered, the only one that appears to work is that the proton look like a diquark-quark like a T, and not a Mercedes star Y.



But many distinguished theorists do not like it. The only other explanation possible is to say $Q^2$=15 $GeV^2$ is not large enough.

- That poses the challenge for PANDA to extend the measurement to ~$Q^2$=25 $GeV^2$, where the pp $\to e^+e^-$ cross section, decreasing as $s^{-5}$, will be < 50 fb! And to try and measure $G_E$, as well!

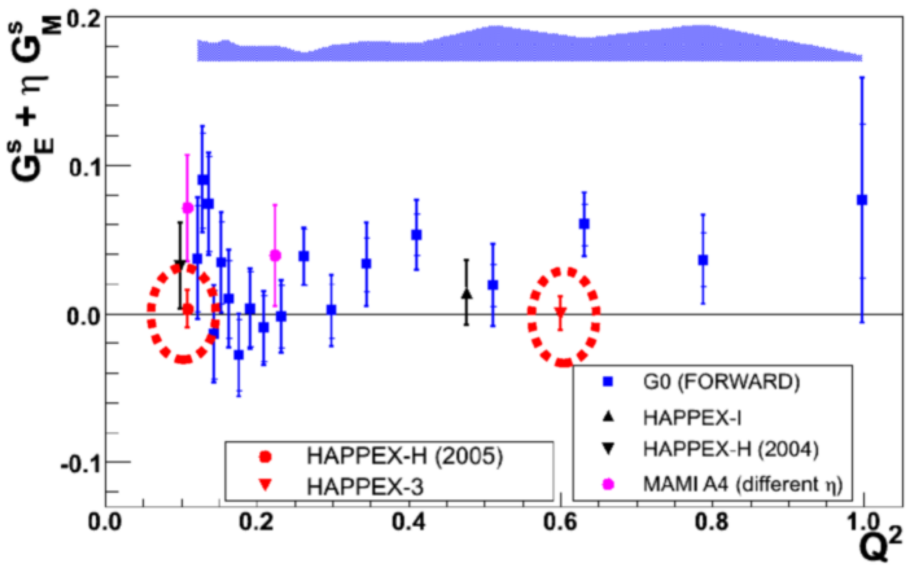
# The Challenge of the Strange Quarks

- There has always been the nagging question about what role the strange quarks, present in the sea, play in a nucleon. Several labs, notably JLab, have tried to answer this by measuring the strange quark form factors **$G_E^s(p)$** and **$G_M^s(p)$** by making the very demanding measurements of parity-violating electron scattering.

Results of an analysis of the global data for $Q^2 \leq 0.48$ GeV$^2$ is that

$$G_E^s(p) = -0.008(16)$$
$$G_M^s(p) = 0.29(21)$$

i.e., both are consistent with zero. The challenge here is for JLab to extend the measurements to larger $Q^2$ and to improve their precision, which they plan to do.



# The Challenge of the Nucleon Spin

- We all know what this is about. The quarks just don't add up to spin 1/2. So what accounts for the rest?

  Proton spin = 1/2 = $1/2\, \Delta\Sigma + \Delta G + L_z$

  where $\Delta\Sigma = \Delta u + \Delta d + \Delta s$, $\Delta q = (q_+ - q_-) + (\bar{q}_+ - \bar{q}_-)$

- The latest results are

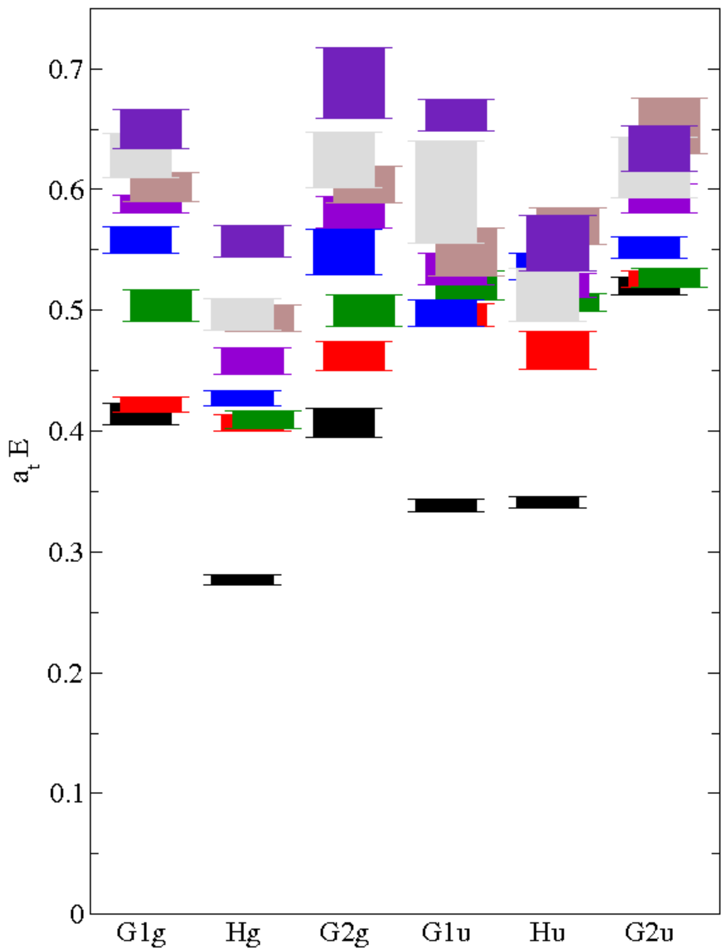
  $\Delta\Sigma = 0.35 \pm 0.06$ (COMPASS), $0.33 \pm 0.04$ (HERMES)

- Attempts have been made to measure $\Delta G$ via DIS, polarized semi-inclusive DIS, polarized pp collisions, and all results are consistent with $|\Delta G| \leq 0.3$.

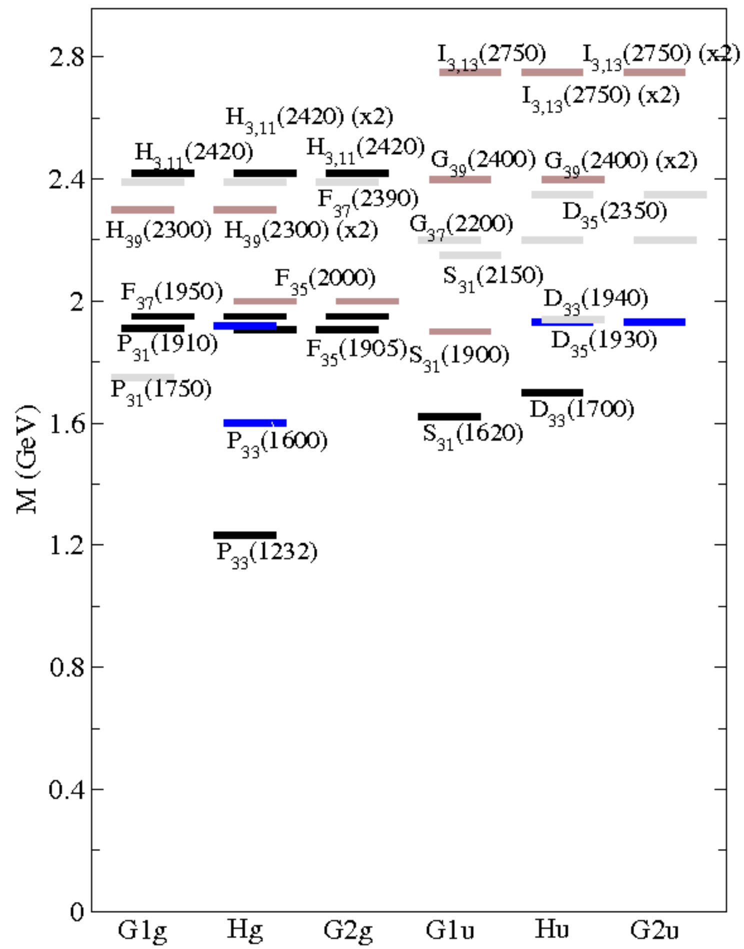
- The sign of $\Delta G$ is so far undetermined. If $\Delta G$ is positive, $L_z$ is small. If $\Delta G$ is negative, one will need large $L_z$ from quarks and gluons. So the spin crisis remains unresolved after 20 years of experiments.

# The Challenge of N* and Δ Resonances

- Many N* and Δ are predicted by both lattice and quark model calculations, but few have ever been identified.




Lattice




Quark Model

- As far as  the star rating of N* and $\Delta$ states by PDG is concerned, nothing has changed since 1996.  For example, for M > 2000 MeV, 15 resonances remain stuck with the same one star * or two stars **, meaning doubtful.

- All old identifications come from measurements with pion beams.   They always had the limitation that pions can not be polarized. Now there is one more. There are no new pion beams.

- The only hope is in photo- and electro-production, and in decays into $\eta$, $\eta'$, and $\omega$ final states, but as Capstick and Roberts have warned, these amplitudes are expected to be small, and progress is going to be tough.  But as we have heard, MAMI, ELSA, and Jlab are trying.

- A further limitation is that of PWA analysis, which is often not unambiguous.

# $\Delta$, $\Sigma$, and $\Xi$ Resonances

- The situation here is also quite bleak. PDG07 summarizes it as follows:
  - $\Delta$ and $\Sigma$: "The field remains at a standstill and will only be revived if a kaon factory is built."
  - $\Xi$ : "Nothing of significance on $\Xi$ resonances has been added since our 1998 review."
- What can we expect in the near future? The only kaon factory on the horizon is JPARC and hopefully they will put high priority on $\Delta$ and $\Sigma$ **formation** experiments.
- Other than with kaon beams, we have only production experiments possible, in pp collisions at COSY and photoproduction experiments at JLab. In fact, some low-lying $\Delta$ and $\Sigma$ are being currently studied in photoproduction experiments at JLab with polarized photons. Also, an ambitious program of $\Xi$ spectroscopy has been proposed at JLab. Unfortunately, we do not have any finished results so far.

# Charm and Bottom Baryons

- Here, progress is more encouraging. Adding charm quarks to the SU(3) octet and decuplet of u,d,s quarks gives 18 baryons with one c-quark, 6 baryons with two c-quarks and one baryon $\Omega_{ccc}^{++}$ with three c-quarks.
- The B factories have weighed in in the charm baryon sector, and CDF and D∅ are making numerous discoveries with the data from Run II.
  - BaBar: $\Lambda_c(2940)$, $\Omega_{cc}(2770)$
  - Belle: $\Sigma_c\,(2800)$, $\Sigma_c\,(2980)$, $\Xi_c\,(3080)$ with $\Gamma$ = 6.2 MeV!
  - The double charm $\Xi_{cc}^{+}\,(3519)$ of SELEX has never been confirmed.
  - The holy grail, triple-charm $\Omega_{ccc}^{++}$ remains unclaimed.
- Before 2006, only one bottom baryon $\Lambda_b^0$ was known. Now, from CDF and D∅ we have $\Sigma_b^{\pm}$, $\Sigma_b^{*}$, and $\Xi_b$.
  - These are extremely challenging measurements, resolving states at ~6 GeV separated by ~20 MeV, e.g.,

$$m(\Sigma_b^{\pm}) - m(\Sigma_b^{*}) = 21.2 \pm 0.2 \text{ MeV.}$$

# Threshold States of Two Baryons

- In prehistory, there were dibaryons. Many were claimed, none survived.
- Then there was baryonium, a bound state of p and $\bar{p}$. After many, many experiments at BNL, CERN, and Fermilab, it was pronounced dead. It has now risen from the dead!
- BES has claimed it as a $p\underline{p}$ state bound by ~20 MeV, giving rise to an enhancement near pp threshold in $J/\psi \to \gamma\, p\bar{p}$. There are problems. There is no evidence for it in $J/\psi \to \pi^0 p\bar{p}$, or in $\psi(2S) \to (\gamma, \pi^0)\, p\bar{p}$.
  Notwithstanding these problem, BES has claimed threshold enhancements in $J/\psi$ radiative decays to $p\bar{\Lambda}$, $\Lambda\bar{\Lambda}$ and $\omega\phi$.
- My personal prejudice is that while there is no denying the enhancements, their interpretation as due to bound states is highly questionable. They are most likely due to final state interactions between two baryons with very small relative momenta.

# MESONS

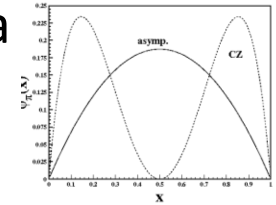
While there has been little progress in the baryon sector, between 2004 and 2006 the PDG records 70 pages of new information on mesons.  90% of the increase comes from heavy mesons, with most from the charmonium region.

# Challenge of the Meson Form Factors

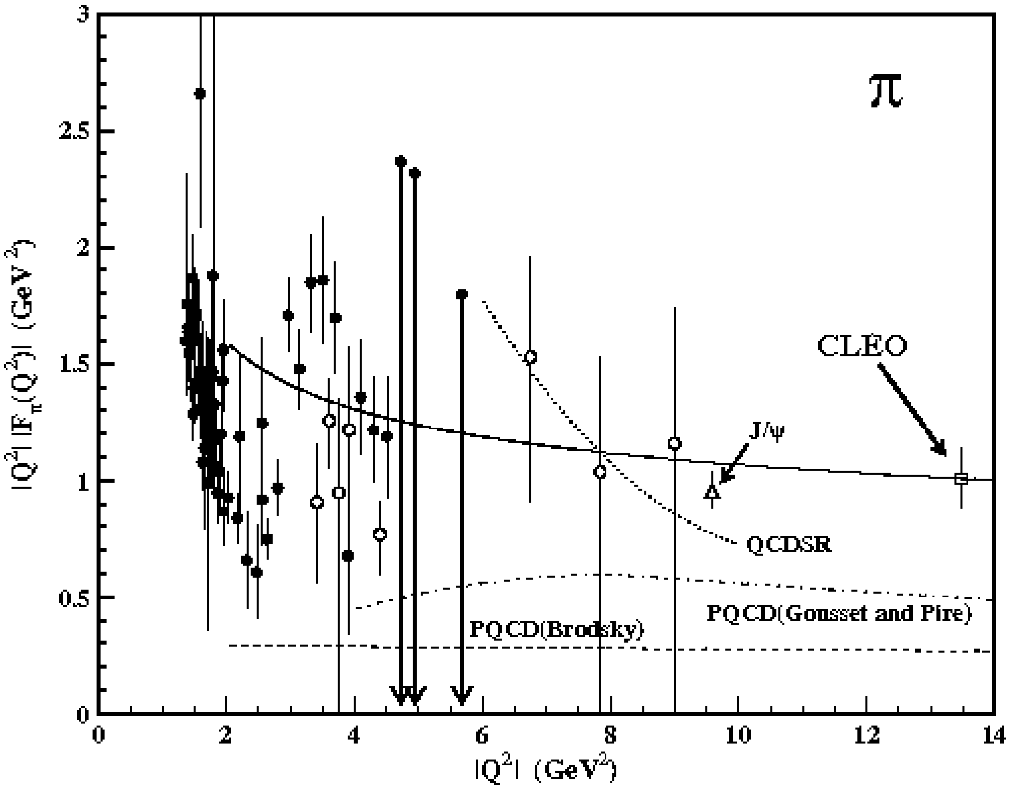
- Earlier, I asked, "Is it too much to ask what the proton looks like?" Now, I ask the easier (?) question, "What does a meson look like?"

- The essential data needed to answer this question is form factors. Meson form factors, until recently, were almost non-existent at large momentum transfers.

- The famous debate about the momentum transfer at which pQCD becomes valid which took place between Brodsky and colleagues ($Q^2 > 10$ GeV$^2$) and Isgur and Llwellyn-Smith ($Q^2 >$ 100's GeV$^2$) had only poor data for pion form factors for $Q^2 \leq 4$ GeV$^2$ available. No wonder one couldn't decide whether a meson looks like a dumbbell or a bell!




- Now we have precision data from CLEO for pion and kaon form factors at ~ 14 GeV$^2$. They pose challenge to both theorists and experimentalists.




# Pion Form Factors For timelike $Q^2$

- For pion form factors, none of the theoretical predictions, pQCD or QCD sum rules works.
- Challenge to the theorists: Poor predictions were perhaps excusable without precision data. Now there is no excuse. Give us some good postdictions now.
- Challenge to the experimentalists (mostly BES III): Give high priority to precision measurements of meson form factors via $e^+ e^- \to m\bar{m}$ in the whole range $Q^2 = 4 - 20$ GeV$^2$.

# Light Quark Scalar Mesons

- Perhaps this is the hottest topic in light quark physics, particularly because it intersects with the question of the lowest mass $0^{++}$ glueball, and with the very concept of what constitutes a resonance.
- A recent review devotes more than 60 pages to the topic. It offers several provocative suggestions, with many of which I do not agree, but then the authors admit, with remarkable candor, that they have "offered a series of clear statements with little reasoning or justification."
- The essential problem with the scalars is that in the quark model with three light quarks you expect three scalars, two isospin zero $f_0$'s and one isospin one $a_0$. But we have an embarrassment of riches. We have at least five $f_0$'s: $f_0$ (600) or $\sigma$(600), $f_0$(980), $f_0$(1370), $f_0$(1500), and $f_0$(1710). So, we have to disqualify three of these as $q\bar{q}$ mesons.

# The Challenge of the $\sigma$ and the $\kappa$

- **The $\sigma$**: All evidence now says that the $\sigma$ is a real Breit-Wigner resonance with a proper pole structure, and

  $$M(\sigma) \approx 480 \text{ MeV}, \qquad \Gamma(\sigma) \approx 570 \text{ MeV}$$

  But, what is $\sigma$ ? The debate is wide open. Is it a $q\bar{q}$ meson, or a glueball, or a 4-quark state, or what? Any new ideas?

- **The $\kappa$**: The reality of $\kappa$ is still questionable although it is claimed in $K\pi$ scattering, decays of D mesons, and radiative decays of $J/\psi$. Different analyses give very different masses and widths.

  $$M(\kappa) \approx 658\text{-}841 \text{ MeV}, \qquad \Gamma(\kappa) \approx 410\text{-}840 \text{ MeV}$$

# The $f_0(980)$, $a_0(980)$, and the $K\bar{K}$ Molecules

- Does the proximity of the masses of these states to the sum of two kaon masses, and the fact that they have healthy decays to $K\bar{K}$, make them $K\bar{K}$ molecules?
- I do not believe so.
- The canonical potential model calculation by Godfrey–Isgur, predicts the lowest $q\bar{q}$ scalar to have a mass of about 1090 MeV.
- I have no trouble accepting that the mass shifts to 980 MeV due to admixtures of 4-quark configurations of either $|qq.\bar{q}\bar{q}\rangle$, or $|q\bar{q}.q\bar{q}\rangle$ type.

  On the other hand, I have great trouble accepting the PDG suggestion of exactly inverted $L \cdot S$ splitting with $f_0(1370)$, $f_1(1285)$, $f_2(1270)$. The $f_0(980)$ and $a_0(980)$ fully deserve to be counted as $q\bar{q}$ states.

# The $f_0(1370)$, $f_0(1500)$, $f_0(1710)$ and the Glueballs

- It is now agreed that all three exist, and have spin $0^{++}$.
- The presumed challenge is which one is more glueball than the others. Since all of the above three, and perhaps the other two can mix, the search for the uniquely identifiable $0^{++}$ scalar glueball makes no sense.
- The $2^{++}$ tensor glueball is likely to have the same fate as the $0^{++}$ scalar because at least six tensor $q\bar{q}$ states are predicted in its neighborhood, and claims have been made for twelve $2^{++}$ states. The old claims for $\zeta(2230)$ have almost died, anyway.
- Then there is a long awaited report of $(14 \pm 4)\%$ gluonium admixture in $\eta'$ by KLOE. Congratulations!

# The Challenge of the Open Flavor Mesons

- The $Q\bar{q}$ mesons with $J = j_q + S_Q$ have been very successfully studied in the HQET, but there are surprises and challenges.
- **The Open Charm, or D mesons:** In 2003 BaBar and CLEO discovered that the $D^*_s$ ($c\bar{s}$) $J = 0^+$ and $1^+$ mesons were unexpectedly below the DK and DK* thresholds, and hence very narrow. This has given rise to several theoretical explanations, displaced by mixing, DK molecules, tetraquarks, etc., but there is no consensus.
- The analogues D* $0^+$ and $1^+$ expected to be wide and with ~100 MeV smaller masses, have not been firmly identified.
- BaBar reports two new $D_s$ with $M/\Gamma$=2857/48, 2688/112 MeV, but Belle does not find $D_s$(2857). Are these radials?

# The Challenge of the Open Flavor Mesons

- **The Open Beauty, or B Mesons**: This is the domain of CDF and D0 contributions from the Tevatron, and they have made many measurements of B-mesons, ($B^0_1$, $B^0_{s1}$), and ($B^{*0}_2$, $B^{*0}_{s2}$). Their latest triumph is the $B_c$ meson with $M(B_c) = 6274.1 \pm 4.1$ MeV. It is rather remarkable that the s-quark B mesons are always almost exactly 100 MeV heavier, just as in the case of D mesons.

- Of course, the main thrust of the study of open flavor B and D mesons at the Tevatron , CLEO, or the B-factories is weak interactions, decay constants, form factors, and the CKM matrix elements which shall lead them to the promised land of "Beyond the Standard Model". But I will confine myself to strong interactions.

# The Challenges of the Hidden Flavor Mesons

- The SU(3) mesons have such similar masses that no states of $q\bar{q}$ of one flavor exist (the $\phi$ comes close). However, pure $c\bar{c}$ and $b\bar{b}$ quarkonium states do exist. By far the greatest activity has occurred in the charmonium energy region, which I define as ~3 - 5 GeV.
- In the region of bound states, $M < 3.7$ GeV, the major contributions in **charmonium** spectroscopy have come from BES and CLEO.
- In the region above the $D\bar{D}$ breakup threshold at 3.73 GeV, the major contributions about the spectroscopy of what are now called **charmonium-like** states have come from CLEO, Belle and BaBar.

# The Challenge of the Charmonium Singlets

- The spin-triplet states of charmonium have been known and well studied for a long time. The spin singlets have not, and this means that the $q\bar{q}$ spin-spin hyperfine interaction, which produces the splitting of singlet and triplet states, is not well studied.
- The spin-spin interaction is all important. Recall the text book exercises for constructing ground state masses of baryons and mesons. Only the spin-spin interaction between quarks survives.
- Until a couple of years ago the only singlet state of any quarkonia that was known was $\eta_c$, from which one obtained

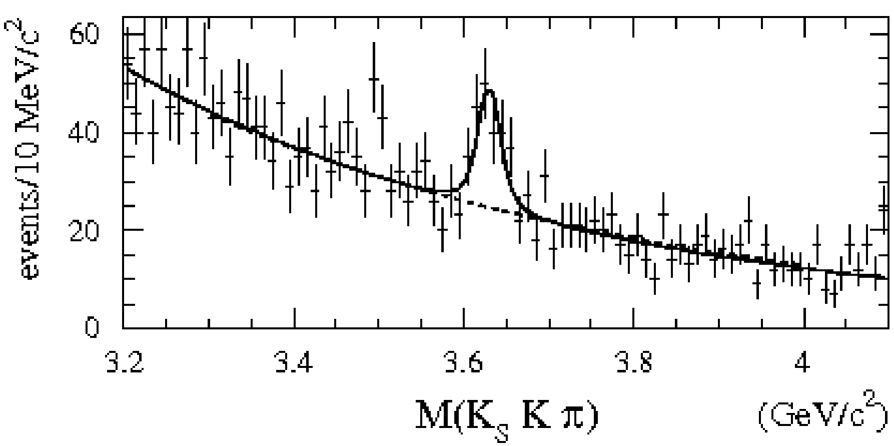
  $\Delta M_{hf}(1S) = 172$ MeV.
- One did not know how $\Delta M_{hf}$ varies for the radials or for the P-wave states. The new measurements answer both these questions.

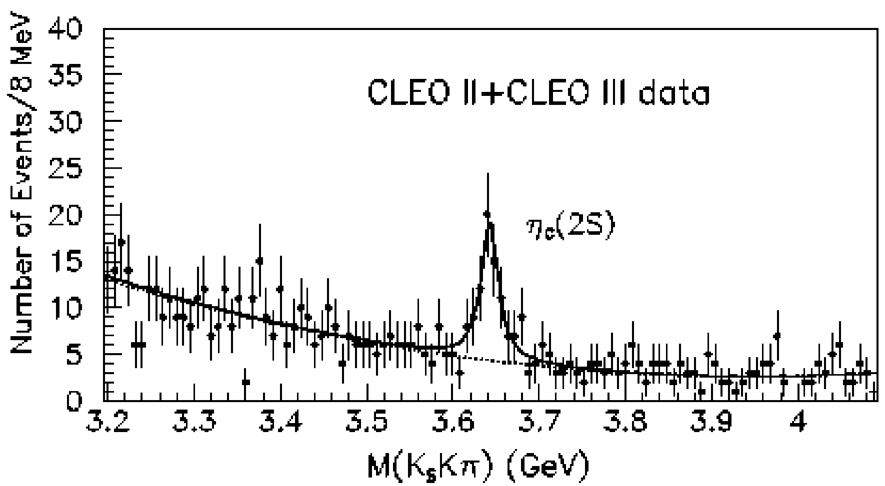
# The Charmonium Singlets $\eta_c'$ and $h_c$

- In 2003, Belle, CLEO and BaBar firmly identified $\eta_c'$. This led to the unexpected result that $\Delta M_{hf}(2S) = 48$ MeV, nearly factor 2.5 smaller than $\Delta M_{hf}(1S) = 172$ MeV, signaling that there are perhaps other surprises in store for other hyperfine splittings.

BaBar: $\gamma\gamma \to K_S K\pi$ ( L = 86 fb$^{-1}$ )

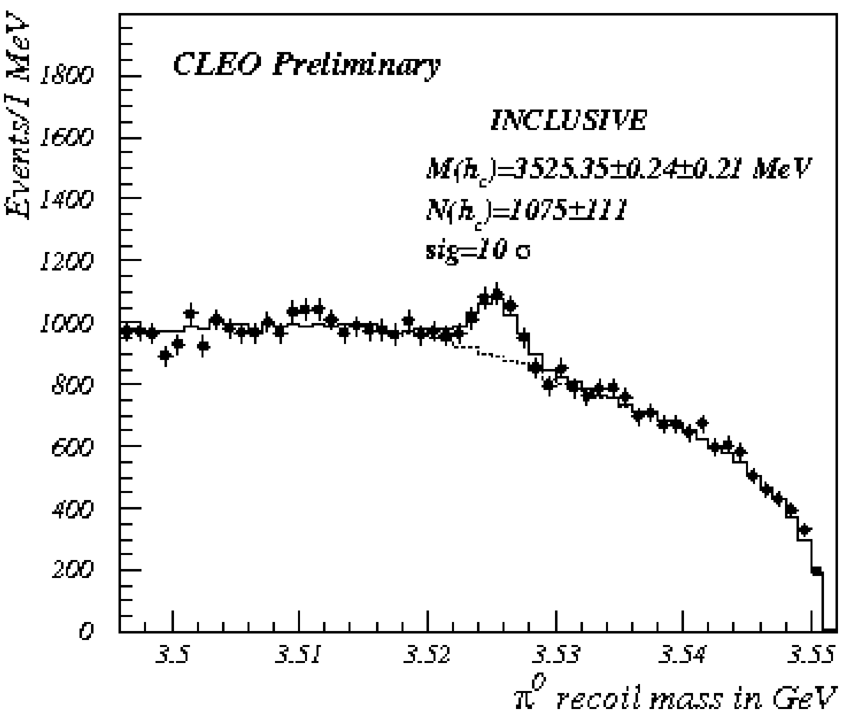
CLEO: $\gamma\gamma \to K_S K\pi$ ( L = 27 fb$^{-1}$ )

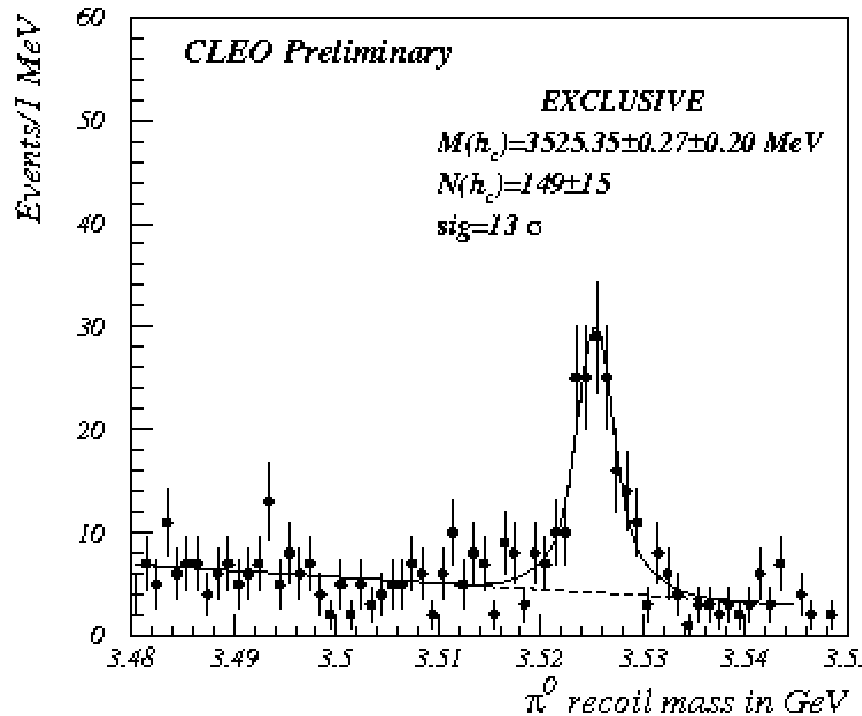


- In 2005, CLEO announced the discovery of $h_c$, the singlet P-wave state of charmonium which had eluded many previous searches. The precision of the measured mass was limited. Now CLEO has measured it with nearly ten times larger luminosity ( $L = 24.5\ pb^{-1}$ ), with a precision result,

$$\Delta M_{hf}(1P) = M(<^3P_J>) - M(^1P_1) = -\,0.04 \pm 0.19 \pm 0.15\ \mathrm{MeV}$$



# The Challenge of $h_c(^1P_1)$

- What challenge does the result, $\Delta M_{hf}(1P) = 0$ offer?
- The "naïve" prediction of pQCD is that the hyperfine interaction which arises from the one photon exchange Coulombic potential is a contact interaction, and therefore zero for all but S-wave states, and the confinement interaction is scalar and makes no long-range contribution to the hyperfine interaction. Therefore, $\Delta M_{hf}(1P) = 0$.
It would therefore appear that our experimental result confirms this prediction. Actually, this is not so.
- It has been pointed out that it is not correct to obtain $M(^3P)$ as $[5M(^3P_2)+3M(^3P_1)+M(^3P_0)]/9$ which is only true for perturbatively small $L \cdot S$ splitting. When $M(^3P)$ is determined by turning $L \cdot S$ and Tensor interaction off, one typically obtains $\Delta M_{hf}(1P) = 9$ MeV. So, what is the true $\Delta M_{hf}(1P)$ ?

# Summarizing the Challenge of Singlet States

- With both $\eta_c'$ and $h_c$ identified, the spectrum of the bound states of **charmonium** is complete. But we are far from understanding the true nature of the $q\bar{q}$ hyperfine interaction.
- We do not really know if there is an intrinsic long range hyperfine interaction. And if there is, what is its origin?
  Is there a vector component in the confinement part of the potential?
- We do not know how to improve on the lowest order Breit-Fermi reduction of the spin dependent interaction which makes the spin-spin a contact interaction.
- We do not know the hyperfine splitting in the **bottomonium** system, **because $\eta_b$ is still not identified.**

# The Challenge of the Unexpected States above the $D\overline{D}$ threshold

- Three years ago, all that was known above $D\overline{D}$ was four vector states ψ(3770, 4040, 4160, and 4415) observed as enhancements in the ratio, $R = \sigma(h\overline{h}) / \sigma(\mu^+\mu^-)$.

- There has been a great amount of work by CLEO, Belle and BaBar about the properties of D and $D_s$ mesons produced at these resonances.

- However, the great excitement , often called the **renaissance** in hadron spectroscopy, has come from the discovery of a whole host of unexpected states by the meson factory detectors, Belle and BaBar. The alphabet soup is getting thick with X(3872), X,Y,Z (~3940), Y(4260), and more recently X', X", X'". Let me go over them one by one.

# The Challenge of X(3872)

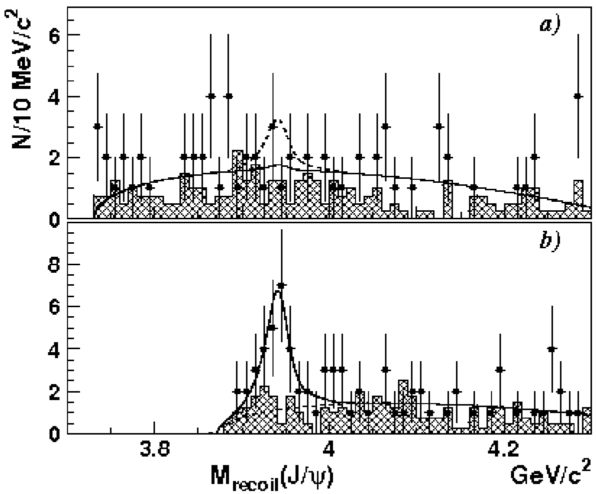
- This narrow state with M(X) = 3871.4 ± 0.6 MeV, and $\Gamma$(X) <2.3 MeV, has been observed by Belle, BaBar, CDF, D0, and it definitely exists.
- CDF angular correlation studies show that its $J^{PC} = 1^{++}$,or $2^{-+}$.
- X(3872) does not easily fit in the charmonium spectrum. Since its mass is very close to M(D)+M(D*), the most popular conjecture is that it is weakly **bound molecule** of D and D*. If so, a recent precision measurement of $D^0$ mass gives its binding energy as 0.6 ± 0.6 MeV. For this small a binding energy the branching fraction for the molecule's breakup into $D\bar{D}\pi$ Is predicted to be factor 400 smaller than observed.
- To avoid this big trouble it is speculated that there is another resonance nearby. There are no convincing observations of it so far. So what is X(3872) ?
- We need higher precision M(X) and M($D^0$), and B($X \to D^0 D^0 \pi^0$).

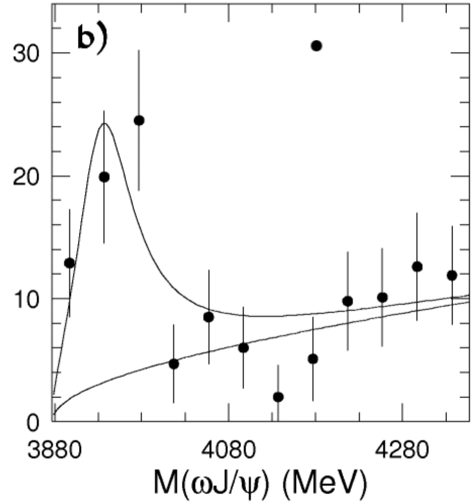
# The Challenge of Y(4260)

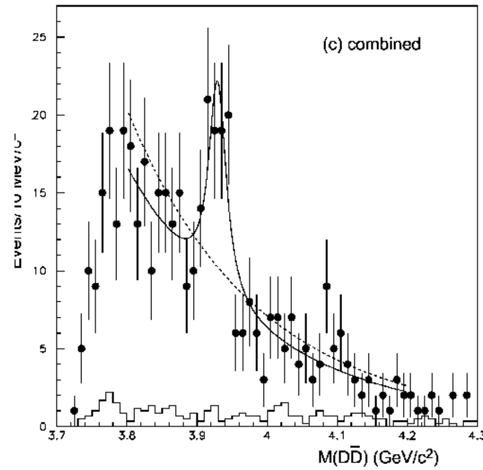
- The Y(4260) has been observed in ISR production by BaBar, CLEO and Belle, and in direct production by CLEO. It is clearly a vector, but a very strange one, since it sits at a very deep minimum in R. So it is not likely to be a charmonium vector, which are all spoken for, anyway. So what is Y(4260) ?
- It is suggested that Y(4260) is a $c\bar{c}g$ charmonium hybrid. If so, there ought to be $0^{-+}$ and $1^{-+}$ hybrids nearby. The exciting challenge for experimentalists is to find them.
- There are new problems. Belle has revived the question whether there is actually one resonance or two. Further, Belle reports that M(Y) in $Y \to J/\psi\pi\pi$ and $Y \to \psi'\pi\pi$ is different by almost 120 MeV .
- It is a real experimental challenge to clarify this situation before taking any theoretical conjecture seriously.

# The Challenge of X,Y,Z (~3940)

- These three states, reported so far by Belle only, all have same masses within ±7 MeV. All decay into states which contain a c and a $\bar{c}$ quark; hence the designation **charmonium-like**. Each is produced in a different formation channel and each decays into a different decay channel. Even with $e^+e^-$ luminosities of up to ~700 $fb^{-1}$ thrown at them none has more than 75 counts in their favorite decay. If all that makes you slightly skeptical you are not alone. I summarize them in a table.
- The X(3943) is produced in $e^+e^- \to$ double charmonium, and since only J=0 states, $\eta_c$, $\chi_{c0}$, and $\eta_c'$ appear to be produced in the same spectrum, it is conjectured that its spin is also J=0, and it is most likely $\eta_c''(3\,^1S_0)$.
- The Z(3929) is produced in $\gamma\gamma$ fusion and decays to $D\bar{D}$. Its angular distribution suggests J=2, and it is conjectured to be $\chi_{c2}'(2\,^3P_2)$.
- The Y(3943) is produced in $B \to KY$ and decays to $\omega J/\psi$. It is speculated that it might be a hybrid. It appears least convincing of the three.

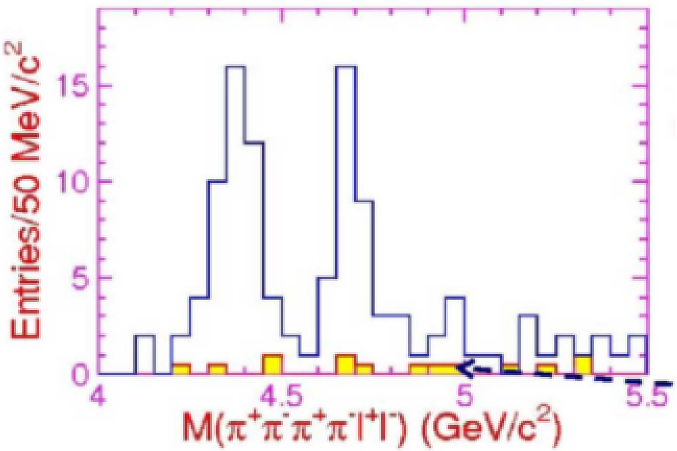


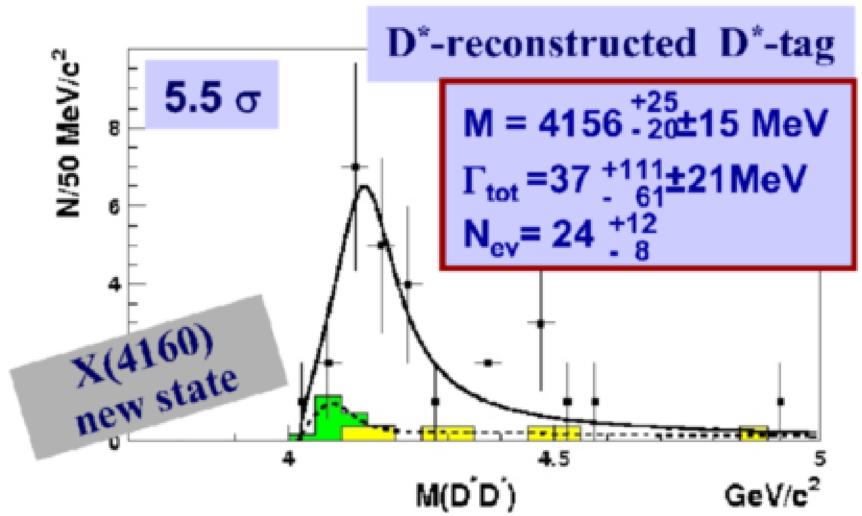




| | **X(3943)** | **Y(3943)** | **Z(3929)** |
|---|---|---|---|
| | N(X) = 24.5 ± 6.9 | N(Y) = 58 ± 11 | N(Z) = 64 ± 18 |
| | M(X) = 3943 ± 10 MeV | M(Y) = 3943 ± 17 MeV | M(Z) = 3929 ± 5 MeV |
| | $\Gamma$(X) = 15.4 ± 10.1 MeV | $\Gamma$(Y) = 87 ± 26 MeV | $\Gamma$(Z) = 20 ± 8 MeV |
| **Production:** | Double Charmonium | $B \rightarrow K\,Y$ | $\gamma\gamma$ fusion ( J = 2 ) |
| **Decay:** | $X \rightarrow D^*D \geq 45\%$ | $Y \rightarrow \omega\, J/\psi$ | $Z \rightarrow D\bar{D}$ |
| | $X \not\rightarrow DD \leq 41\%$ | $Y \not\rightarrow D\bar{D}$ | |
| | $X \not\rightarrow \omega\, J/\psi < 26\%$ | | |
| **Best Guess:** | $\eta_c''(3^1S_0)$ | Hybrid?? | $\chi_{c2}'(2^3P_2)$ |
| **Challenge:** | Search for X in $\gamma\gamma$ fusion | Search for $Y \rightarrow D\bar{D}$, $D^*\bar{D}$ | Search for $Z \rightarrow D^*\bar{D}$ |

# Three New States from Belle




| | Source | Mass (MeV) | Width (MeV) | Events | Reaction |
|---|---|---|---|---|---|
| X′ | Belle | 4160 | $139(^{113}_{65})$ | $24(^{12}_{8})$ | $e^+e^- \to J/\psi + D^* D^*$ |
| X″ | BaBar | 4324 | 172(33) | 65(10) | $e^+e^- \to \psi(2S)\pi^+\pi^-$ |
| | Belle | 4360 | 74(18) | $\sim 50$ | $e^+e^- \to \psi(2S)\pi^+\pi^-$ |
| X‴ | Belle | 4660 | 48(15) | $\sim 36$ | $e^+e^- \to \psi(2S)\pi^+\pi^-$ |

# Challenges in Bottomonium Spectroscopy

- In principle, bottomonium is a much better place to get insights into onium spectroscopy because $\alpha$(strong) is smaller (~0.2), and the relativistic problems are much less severe than for charmonium. However, $b\bar{b}$ cross sections are expected to be ~5000 times smaller, and the states are denser packed,
- The Upsilon (1S,2S,3S) and $\chi_b$ and $\chi_b'$ states have been long known. We have precision determinations of the leptonic branching ratios of the Upsilons, and the $\pi\pi$ transitions between them, one hadronic transition, and little else. Compare this to charmonium and you will be shocked. Even the ground state of the entire bottomonium family, $\eta_b$ has never been identified.
- So it is a big challenge. CLEO can do very little more with its old data. Unless Belle and BaBar run at Upsilon(1S,2S,3S) energies directly we are not likely to improve the situation much. Further, there are no prospects of bringing $p\bar{p}$ production into the game. That would require 50 GeV antiproton beams on a fixed target, or ~6 GeV $p\bar{p}$ colliding beams. In principle, Fermilab could tackle either approach, but that does not get it any closer to the Higgs!!

# Mesons in the Nuclear Medium

- It has been conjectured for a long time that in the nuclear medium meson masses and widths should change by as much as 20%, and meson-nucleon cross sections should also change (color transparency). We are now beginning to have some answers, though not unambiguous ones.
- There are contradictory reports for mass and width changes of the $\rho$ meson from JLab and CERN.
- It is claimed that at Fermilab energies Color Transparency has been observed. At lower energies, in the JLab and BNL experiments, the answer is not so clear.
- The tell-tale signal of QGP was $J/\psi$ attenuation in heavy ion collisions. Its proper interpretation requires knowledge of $J/\psi$ - nucleon cross section in the nuclear medium. Hopefully, It can be measured at PANDA with $J/\psi$ production in $p\bar{p}$ annihilation with a nuclear proton.

# To Summarize

- Beautiful high precision experiments in hadron spectroscopy are being done at laboratories around the world. But many extremely interesting questions remain unanswered.
  They pose challenges for both experimentalists and theorists.
  There is great hope that the upcoming facilities, PANDA at GSI, JPARC at KEK, and the 12 GeV upgrade at JLab will augment the presently available experimental arsenal, and we will see great progress in the near future.
- Of course, we will keep pushing the theorists to device new theoretical tools to keep pace with the experimental ones.
- Good luck to us all!

# FINALLY

As the last speaker at the conference let me take the opportunity, on behalf of all the participants, to thank all the organizers of the conference for a very successful conference, and especially Stefano Bianco for their wonderful hospitality, and even for the beautiful weather.

GRAZIE TUTTI !!