Two Recent Developments in QCD Spectroscopy

Kamal K. Seth

Northwestern University, Evanston IL 60208, USA

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PREAMBLE

The quark-gluon model of hadrons was introduced by Gell-Mann in 1956 to explain the structure of quark-antiquark **mesons** and the three quark **baryons** which were the only hadrons known at that time. However, Gell-Mann suggested that other color-neutral hadrons containing larger number of quarks and antiquarks, as well as **hybrids** containing valence gluons and **glueballs** containing only gluons should exist. These predictions launched numerous searches for these conventional hadrons. Among the first of these was the search for six-quark **'dibaryons'.** Many were proposed, and numerous claims and counter-claims were published. Unfortunately, none survived, and I myself claim responsibility for the demise of many of them [1]. Similarly, despite many dedicated searches during the last twenty years most claims for glueballs have not survived either [2].

These failures did not stop the searches by stubborn physicists that we are. But, so far no dibaryons or glueballs have been convincingly identified, and I will not talk about them.

However, a silver lining has recently emerged. Several convincing citings of the unconventional hadrons have been reported [3]. I will only list them by reproducing the table from the compilation of *QWG*. Subsequent updates have been presented in this conference by Belle and LHCb on Thursday. With that said, I want to talk about only two developments in hadron spectroscopy in which I have been personally involved.

Table I: New Unconventional states in the $c\bar{c}$ and $b\bar{b}$ regions, ordered by mass[3].

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$X(3872)$	3871.52±0.20	1.3±0.6	$1^{++}/2^{-+}$	$B \to K(\pi^+\pi^- J/\psi)$	Belle [85, 86] (12.8), *BABAR* [87] (8.6)	2003	OK
		(<2.2)		$p\bar{p} \to (\pi^+\pi^- J/\psi) + ...$	CDF [88–90] (np), DØ [91] (5.2)		
				$B \to K(\omega J/\psi)$	Belle [92] (4.3), *BABAR* [93] (4.0)		
				$B \to K(D^{*0}\bar{D}^0)$	Belle [94, 95] (6.4), *BABAR* [96] (4.9)		
				$B \to K(\gamma J/\psi)$	Belle [92] (4.0), *BABAR* [97, 98] (3.6)		
				$B \to K(\gamma\psi(2S))$	*BABAR* [98] (3.5), Belle [99] (0.4)		
$X(3915)$	3915.6 ± 3.1	28±10	$0/2^{?+}$	$B \to K(\omega J/\psi)$	Belle [100] (8.1), *BABAR* [101] (19)	2004	OK
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [102] (7.7)		
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [103] (6.0)	2007	NC!
				$e^+e^- \to J/\psi\ (...)$	Belle [54] (5.0)		
$G(3900)$	3943 ± 21	52±11	1^{--}	$e^+e^- \to \gamma(D\bar{D})$	*BABAR* [27] (np), Belle [21] (np)	2007	OK
$Y(4008)$	4008^{+121}_{-49}	226±97	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	Belle [104] (7.4)	2007	NC!
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008	NC!
$Y(4140)$	4143.4 ± 3.0	15^{+11}_{-7}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [106, 107] (5.0)	2009	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [103] (5.5)	2007	NC!
$Z_2(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008	NC!
$Y(4260)$	4263 ± 5	108±14	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	*BABAR* [108, 109] (8.0)	2005	OK
					CLEO [110] (5.4)		
					Belle [104] (15)		
				$e^+e^- \to (\pi^+\pi^- J/\psi)$	CLEO [111] (11)		
				$e^+e^- \to (\pi^0\pi^0 J/\psi)$	CLEO [111] (5.1)		
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [107] (3.1)	2010	NC!
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0,2^{++}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle [112] (3.2)	2009	NC!
$Y(4360)$	4353 ± 11	96±42	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$	*BABAR* [113] (np), Belle [114] (8.0)	2007	OK
$Z(4430)^+$	4443^{+24}_{-18}	107^{+113}_{-71}	?	$B \to K(\pi^+\psi(2S))$	Belle [115, 116] (6.4)	2007	NC!
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$	Belle [25] (8.2)	2007	NC!
$Y(4660)$	4664±12	48±15	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$	Belle [114] (5.8)	2007	NC!
$Y_b(10888)$	10888.4±3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\pi^+\pi^-\Upsilon(nS))$	Belle [37, 117] (3.2)	2010	NC!

The major part of my talk is devoted to

HYPERONS

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

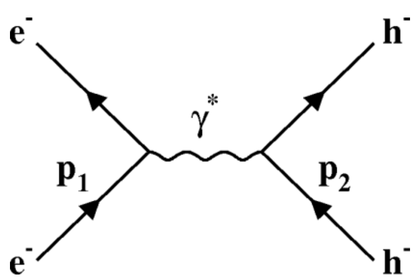
Hyperon	Quarks	Mass, M (MeV)	Mag.mom. (μ_N)	Main Decay
Proton, p	uud	938.272(<0.001)	2.793(<0.001)	stable
Λ^0	uds	1115.683(6)	-0.613(4)	$p\pi^-$ (64%)
Σ^0	uds	1192.642(24)	1.61(8)	$\Lambda^0\gamma$ (100%)
Σ^+	uus	1189.37(7)	2.458(10)	$p\pi^0$ (52%)
Σ^-	dds	1197.449(30)	-1.160(25)	$n\pi^-$ (99.8%)
Ξ^0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

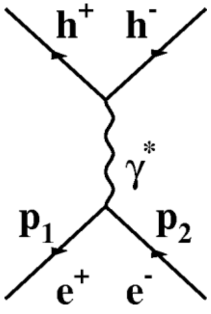
Most of our extensive knowledge of nucleon structure comes from lepton scattering by nucleon and nuclear targets [5]. Unfortunately, hyperons are not available as targets, and this is responsible in large part for the lack of our understanding of the structure of hyperons.

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

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

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





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

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

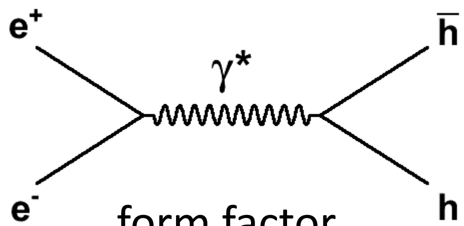
It took 30 years for the first measurement of the timelike form factors to be made by the DM2 Collaboration at Orsay [7], and seventeen more years by the BaBar Collaboration at SLAC [8] to report measurements of $G_M(|Q|^2)$ of Λ^0, Σ^0, and the Λ^0, Σ^0 transition form factors. Because both these measurements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

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

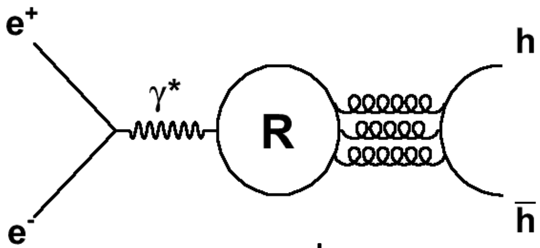
Hadronic decays at resonances proceed via gluons and have large yields. To measure electromagnetic form factors we require the decays to be electromagnetic, which have much smaller yields. To measure form factors we must measure e^+e^- annihilation at non-resonance energies, or at those resonances where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

Using the experimentally confirmed pQCD relation

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



form factor decay



resonance decay

We estimate resonance # of events:

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

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

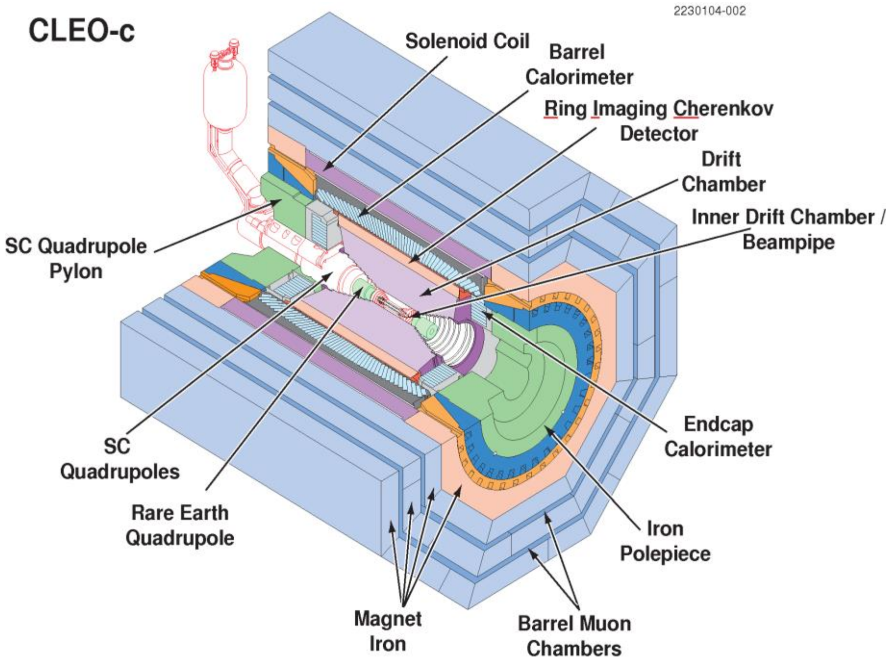
the observed hyperon yield is entirely electromagnetic.

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

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

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

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



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

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

The data consist of

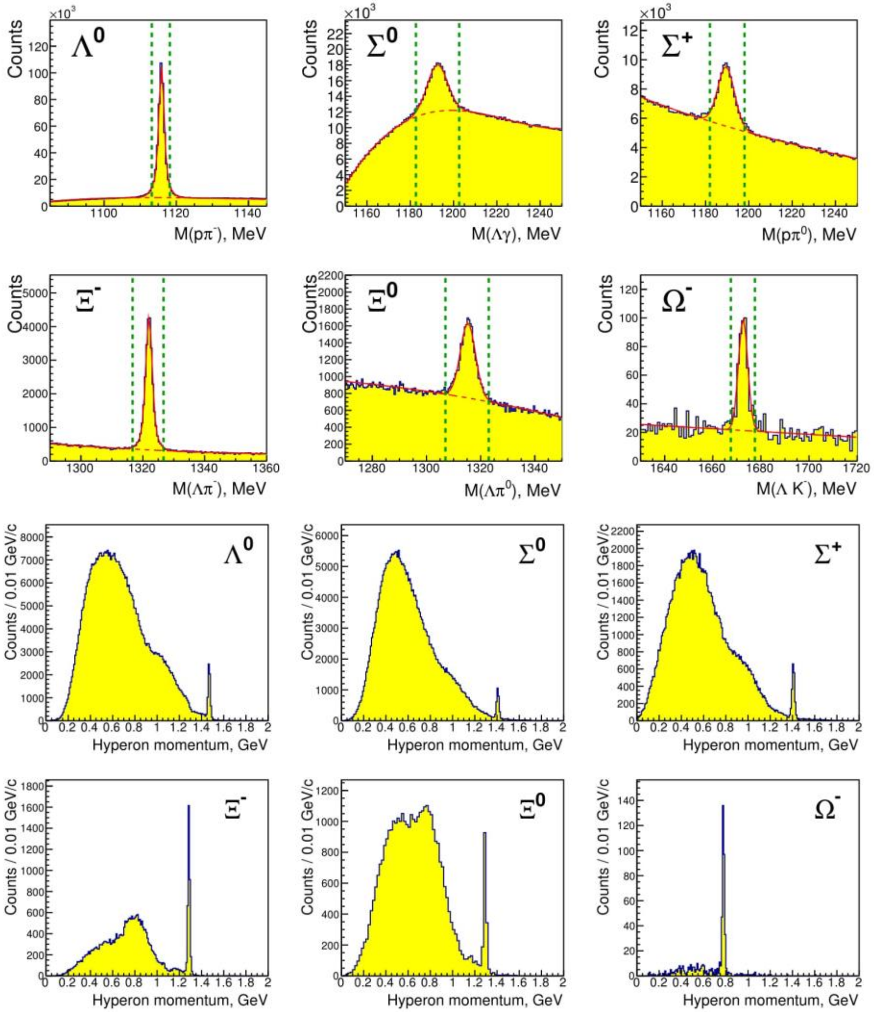
$\psi(2S)$, $\sqrt{s} = 3.69$ GeV, $|Q|^2$=13.59 GeV^2, $\mathcal{L}$= 48 pb^{-1},
$\psi(3770)$, $\sqrt{s} = 3.77$ GeV, $|Q|^2$=14.2 GeV^2, $\mathcal{L}$=805 pb^{-1},
$\psi(4160)$, $\sqrt{s} = 4.17$ GeV, $|Q|^2$=17.4 GeV^2, $\mathcal{L}$=586 pb^{-1}.

We identify the hyperons by detecting their major decay products,

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

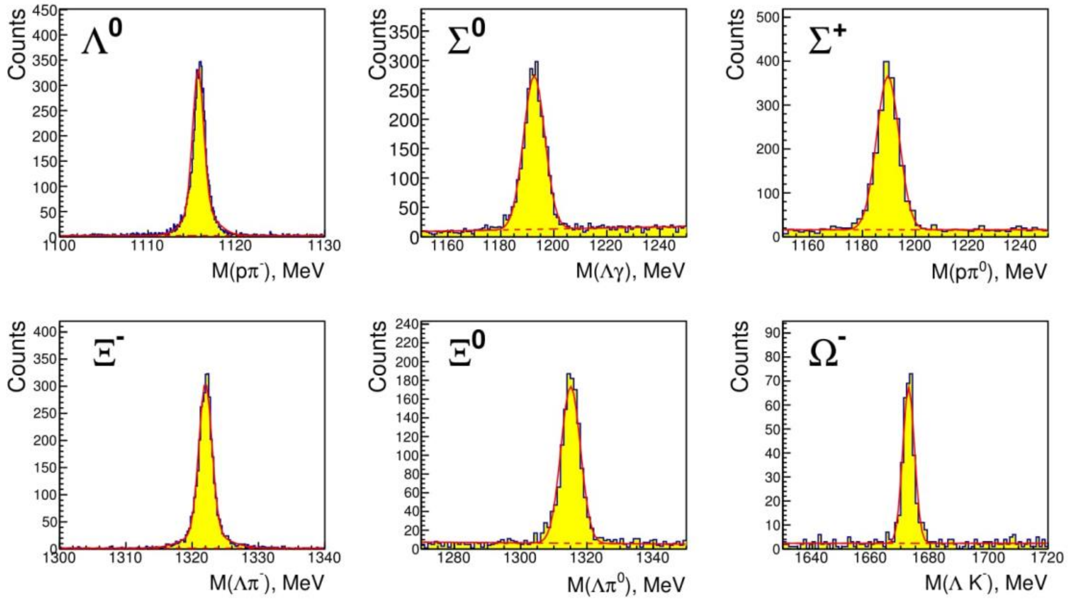
$\Xi^- \to \Lambda\pi^-$(100%) $\Xi^0 \to \Lambda\pi^0$ (100%) $\Omega^- \to \Lambda K^-$ (68%)

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



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

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

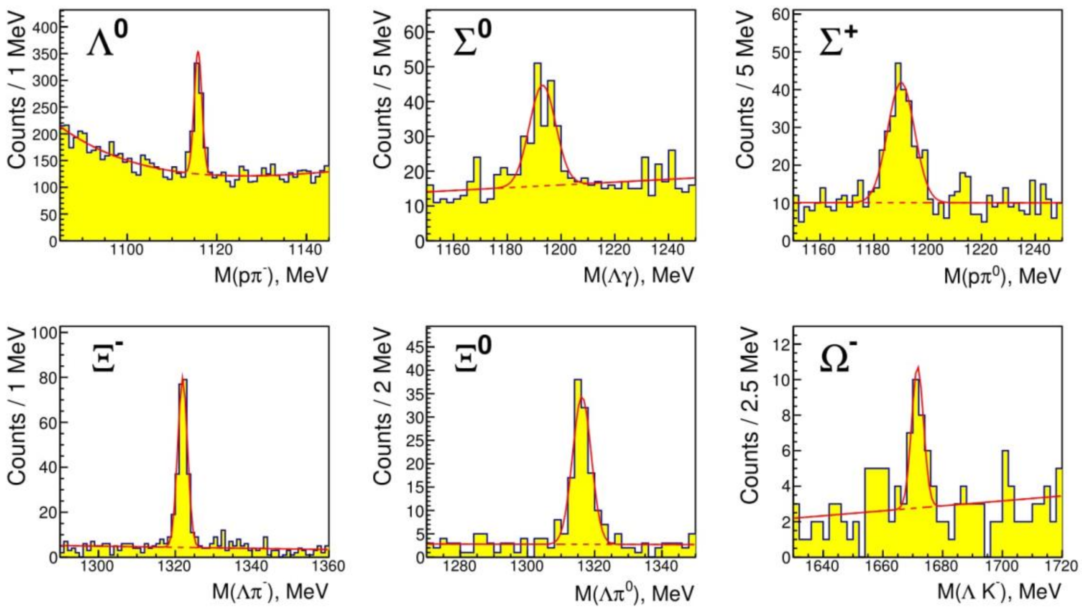


$\psi(2S)$ Pair Production

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

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

← Notice bountiful Ω^-



$\psi(3770)$ Pair Production

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

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

∗ Notice an order or more decrease than the resonance yield at $\psi(2S)$

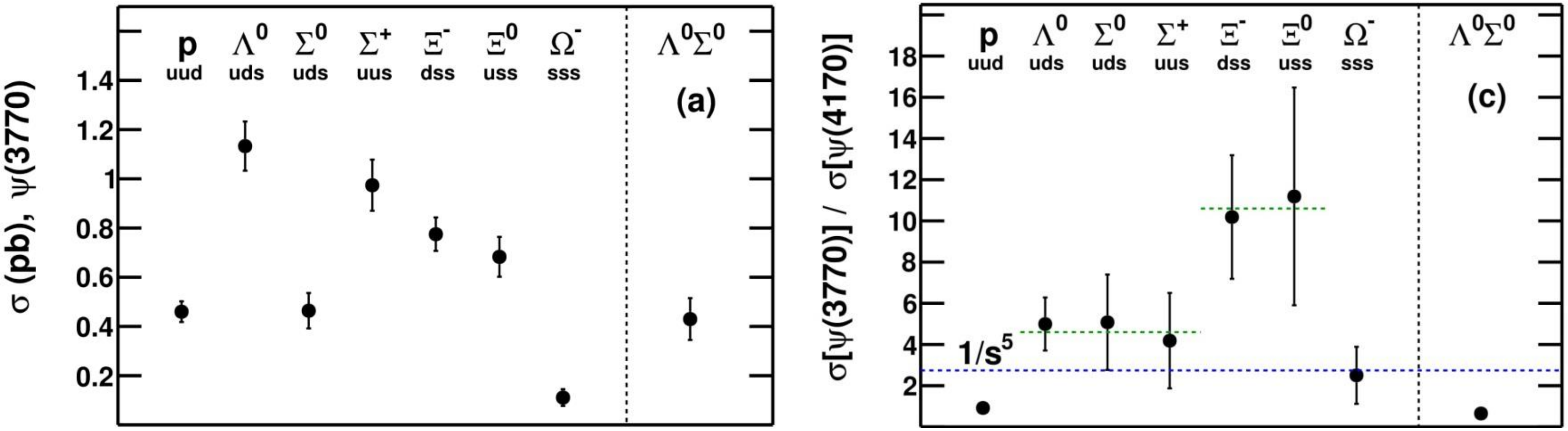
HYPERON PRODUCTION EXPERIMENTAL RESULTS

Pair Production Cross Sections (picobarns)

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

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

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



Notice steps with # of s-quarks

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

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

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

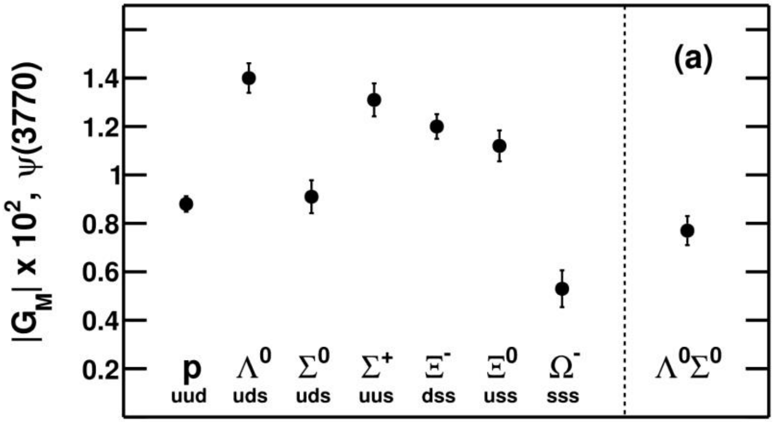
Because of small yield of hyperons from electromagnetic events, it is generally not possible to determine G_E and G_M, or G_E/G_M separately, and most experimental data are analyzed by assuming $G_E/G_M = 0$ or 1.

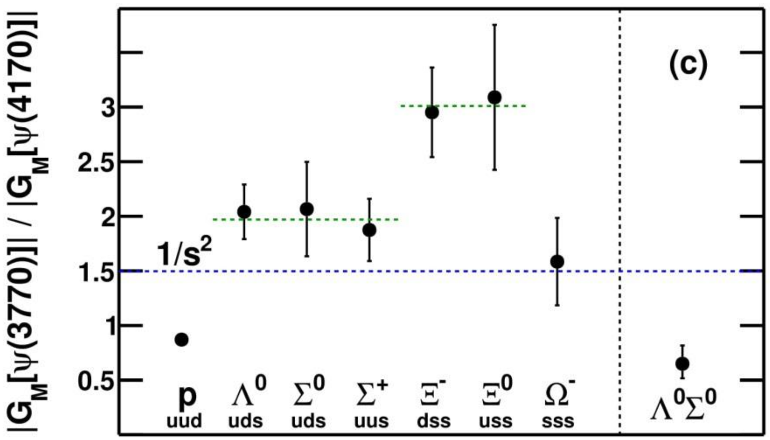
- BaBar has recently analyzed the angular distributions for their ISR based production of $\Lambda\bar{\Lambda}$ pairs in two $\sqrt{s}$ bins. They obtained two quite different values,
  $|G_E/G_M| = 1.73^{+0.99}_{-0.57}$ for the $\sqrt{s} = 2.23 - 2.40\ \mathrm{GeV/c^2}$ bin with 115 events, and
  $|G_E/G_M|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

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

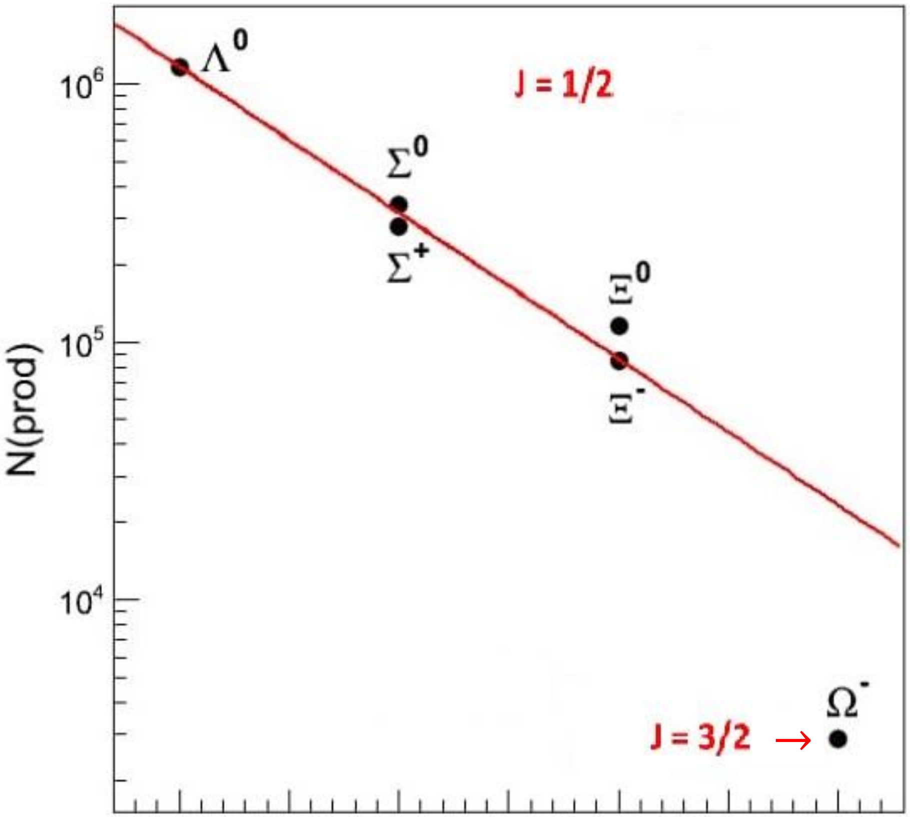
Timelike Form Factors for $|Q|^2 = 14.2\ GeV^2$

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





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



DISCUSSION OF EXPERIMENTAL RESULTS

Pair Production Cross Sections

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

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

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

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

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

DIQUARKS IN HYPERONS

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

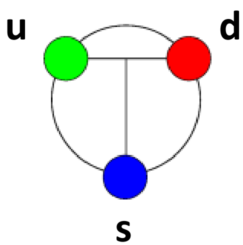
The importance of certain configurations of flavor, spin, and isospin of two quarks in the structure of hadrons has been recognized for a long time [12].

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

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

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

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



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

THRESHOLD PHOTOPRODUCTION OF J/ψ

The second part of my talk is not about a new subject like hyperons, but an old subject:

Threshold Photoproduction of J/ψ.

The discovery of J/ψ in $e^+e^- \rightarrow \gamma^* \rightarrow J/\psi$ launched the modern era in QCD spectroscopy. Despite the fact that all particle physics experiments cut their teeth on the detection of J/ψ , it remains true that J/ψ production mechanisms are not well understood. There are theoretical models to be sure, color singlet model, color evaporation model, factorization models, etc., but serious problems in quantitative understanding of J/ψ production remain.

Of particular interest is understanding photoprouction of J/ψ at energies near threshold, $E_\gamma \sim 8.5$ GeV, because at small momentum transfers coherent electro production of vector mesons like ϕ, J/ψ, etc. provides valuable insight into the

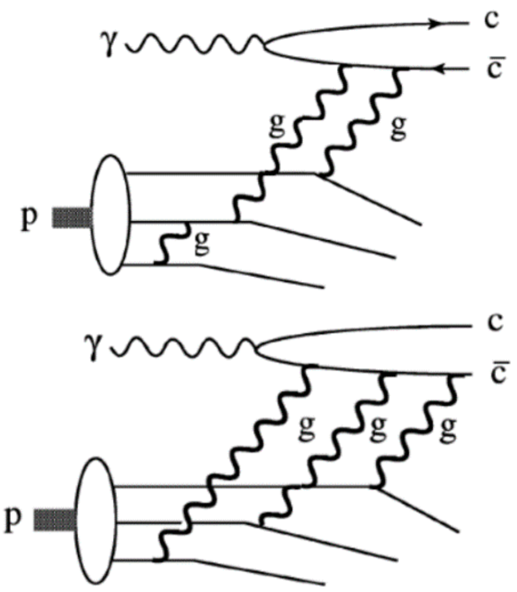
gluon structure function

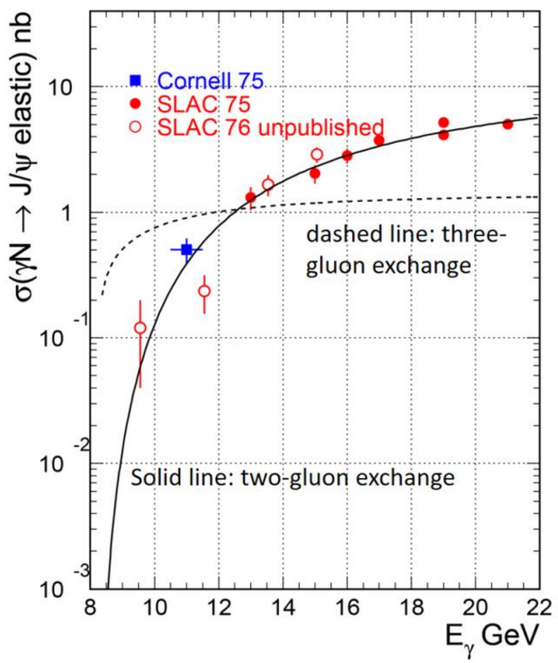
of the target [17].

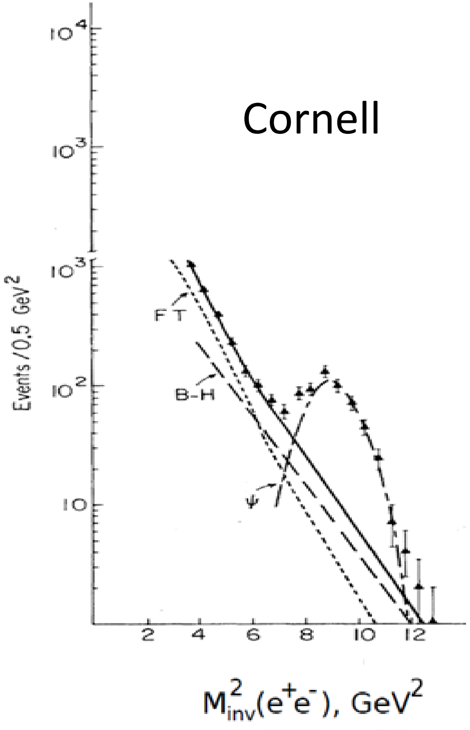
Gluon distribution functions at small x have been of interest in relation to studies of deconfinement in QGP, the phenomena of color transparency and others, and good precision data on J/ψ photo production near threshold energies has long been needed to distinguish between models of gluon structure functions.

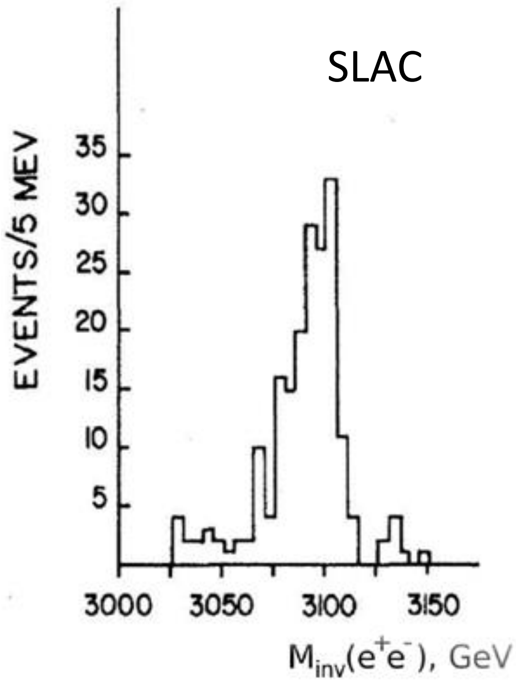
Brodsky et al. have made a more detailed study of J/ψ photoproduction and predicted that near threshold the J/ψ production cross sections have very different dependence on the momentum of photons depending on whether two or three gluons carry the targets momentum to the charm quarks [18].

The existing data consists of just two small statistics measurements by Cornell [19] and SLAC [20], and they are too sparse to distinguish between the two models.





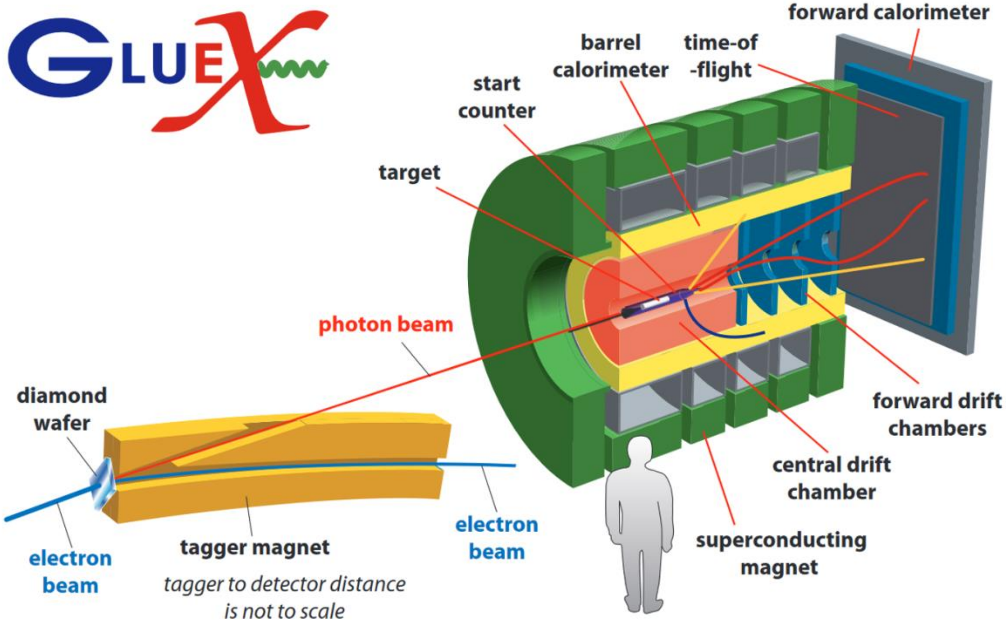




At the Jefferson lab we now have polarized and unpolarized electron beams of energies up to 12 GeV available, and a facility called **GlueX** has been constructed, dedicated to photo production experiments. This has made it possible to fill the gap in threshold measurements of J/ψ photo production. We have made the first such measurements of

$$\gamma + p \rightarrow p + J/\psi, \quad J/\psi \rightarrow e^+e^-,$$

and I want to present the first results of these measurements which we believe shed valuable light on the gluon content of protons and their role on J/ψ photo production.



The GlueX Detector

We have made the first successful measurements of

$$\gamma + p \rightarrow p + J/\psi, \quad J/\psi \rightarrow e^+e^-$$

with tagged photons of energies between 8 and 12 GeV at the GlueX facility at Jlab.

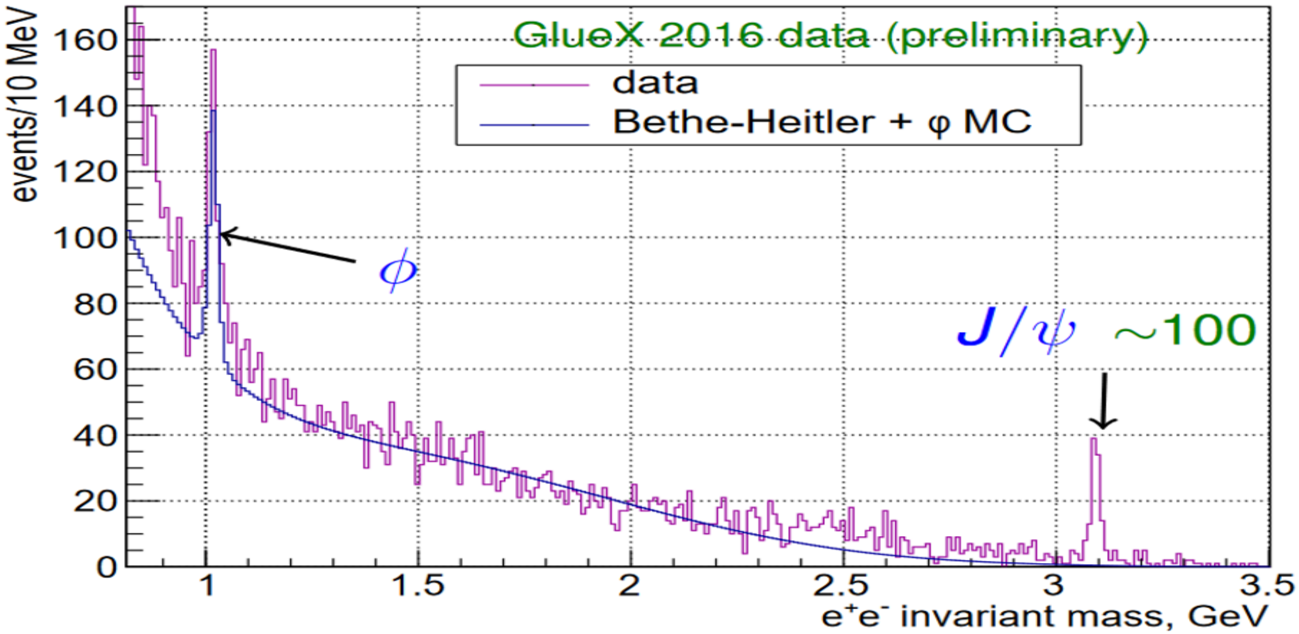
I will not bore you with the details of event selection for these, but here are a few details: the two important points.

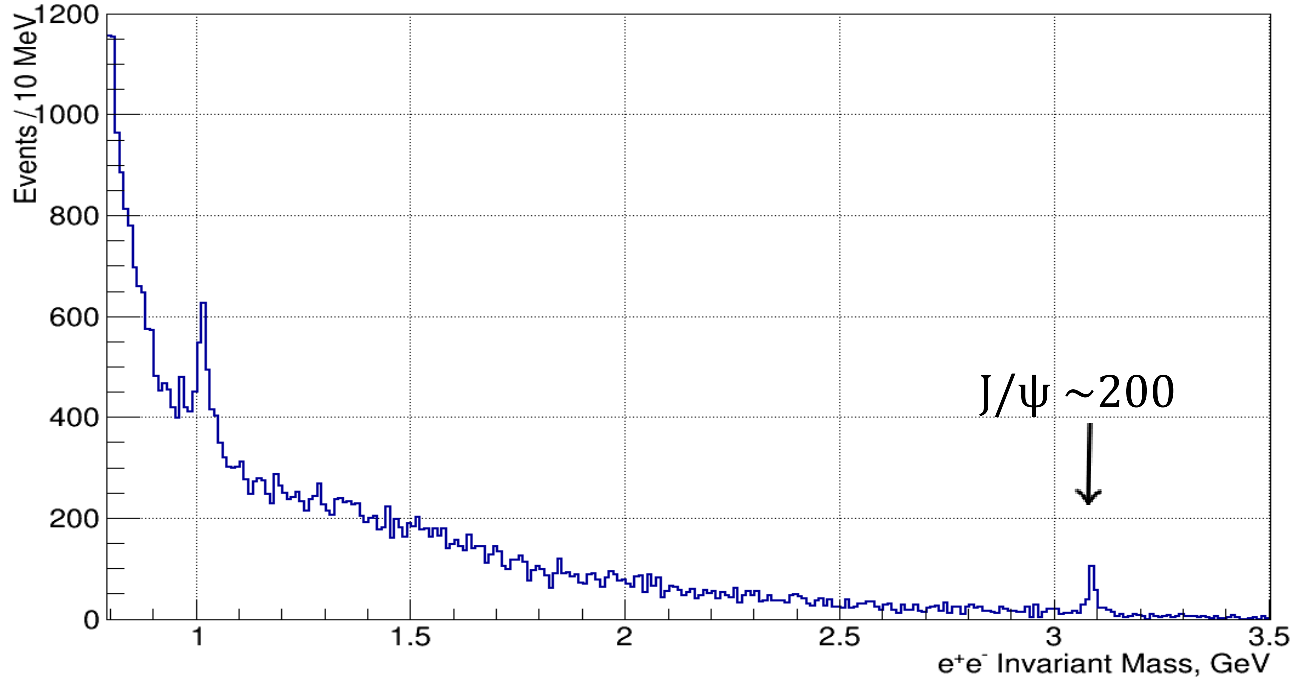
- At least 3 charged tracks are required in the event
- The yield of the e^+e^- decays are overwhelmed by more than three orders of magnitude larger production of the Bethe-Heitler production of $\pi^+\pi^-$ pairs

To reject the $\pi^+\pi^-$ BH background we use the quantity E/p, with E from em calorimeter and p from drift chambers.

$E/p \approx 1$ for electrons, and is much smaller for pions.

We require $E/p > 0.8$ for the selected events, which selects e^+e^- events very effectively, and provides very good rejection of the pion background.


GlueX 2016 data (preliminary)
data
Bethe-Heitler + φ MC
events/10 MeV
φ
J/ψ ~100
e+e- invariant mass, GeV


Events / 10 MeV
J/ψ ~200
e+e- Invariant Mass, GeV

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