First Measurements of Hyperon Timelike Form Factors at Large Q^2 and Evidence of Diquark Correlations

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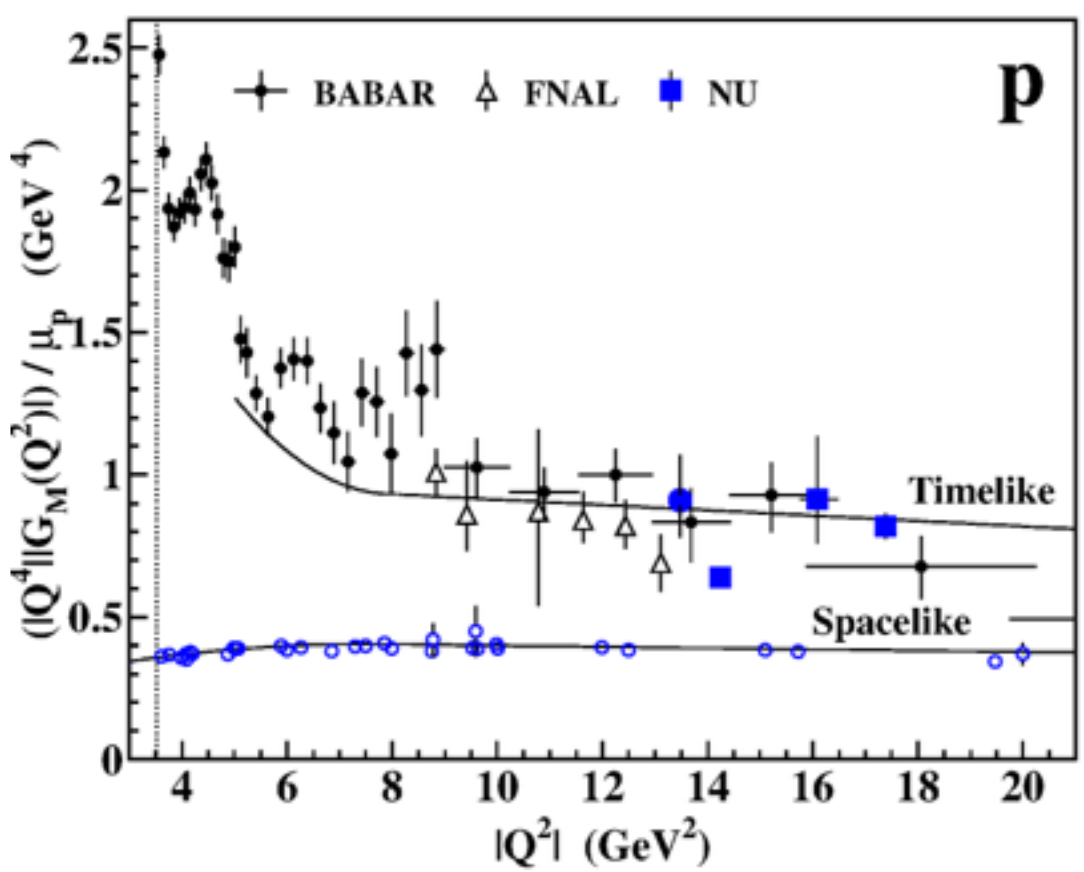
Introduction

- Electromagnetic form factors of hadrons give some of the most transparent insight into their structure.
- *Timelike* ($Q^2 < 0$) form factors are analytic continuations of *spacelike* ($Q^2 > 0$) form factors and give complementary information. Comparing the two can lead to unexpected questions.
- Example: Why are measurements of proton timelike form factors at large $|Q^2|$ are factor ~2 larger than corresponding spacelike form factors?
  - SL and TL FF expected to be equal in asymptotic limit ($Q^2 \rightarrow \infty$).
  - Are measured Q^2 not high enough?
  - Models with diquarks can also explain this discrepancy [e.g. Kroll et al.].
- Studying timelike FFs of hyperons gives us another window to look for potential effects of diquarks, and how FFs vary with differing quark composition.



Data Sets & Hyperon Reconstruction

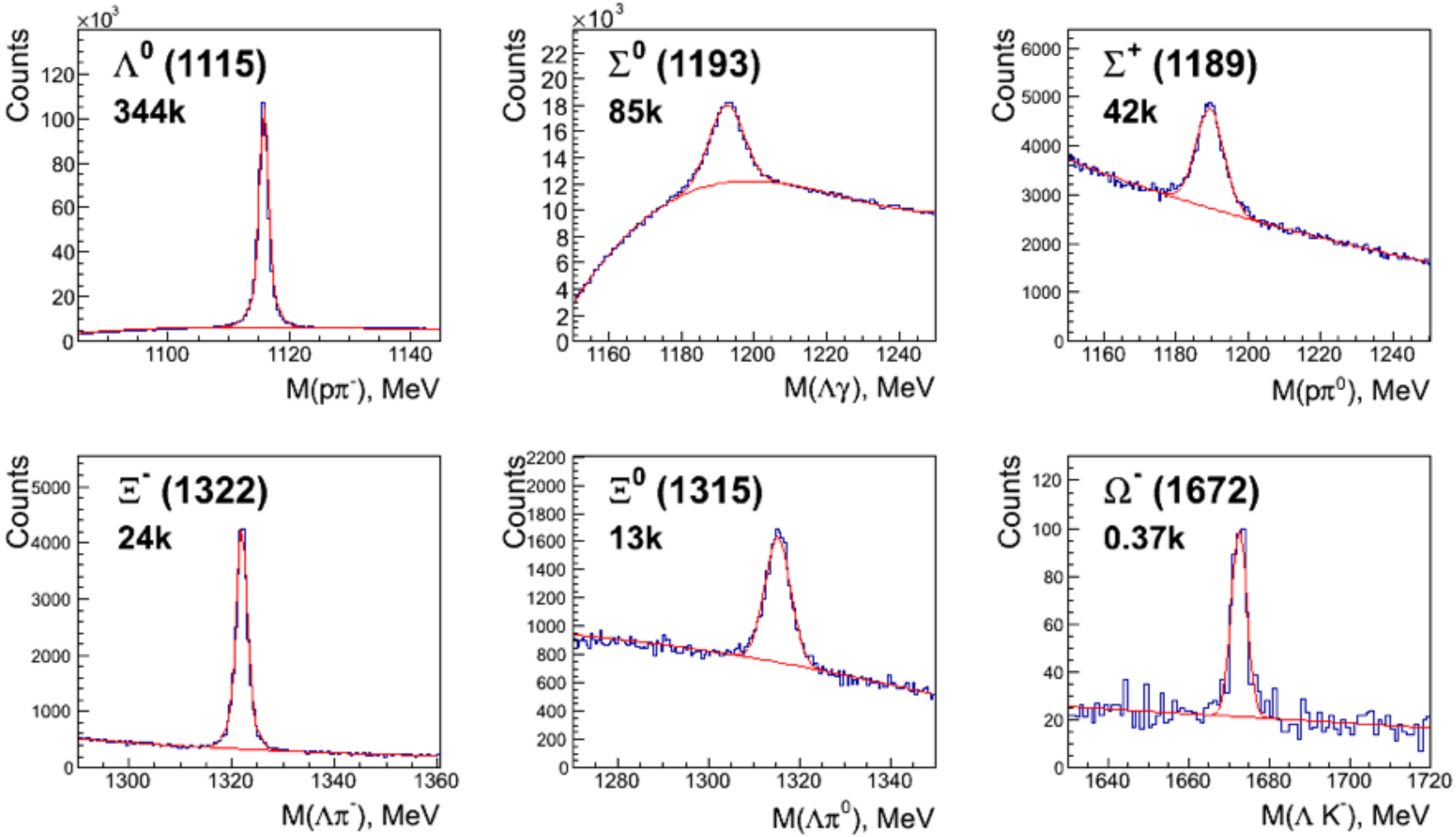
- We use e^+e^- annihilation data taken with the CLEO-c detector at
  - **$\psi(2S)$** [$\sqrt{s}$ = 3686 MeV]: 48 pb^{-1}, 25 M $\psi(2S)$
  - **$\psi(3770)$** [$\sqrt{s}$ = 3772 MeV]: 805 pb^{-1}
  - **$\sqrt{s}$ = 4170 MeV**: 586 pb^{-1}

- We identify the hyperons by their dominant decays:

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

- There are two methods we can use to reconstruct **$e^+e^- \to B\bar{B}$** events
  - Full reconstruction — small backgrounds, low efficiency
  - Partial reconstruction — high efficiency, larger backgrounds

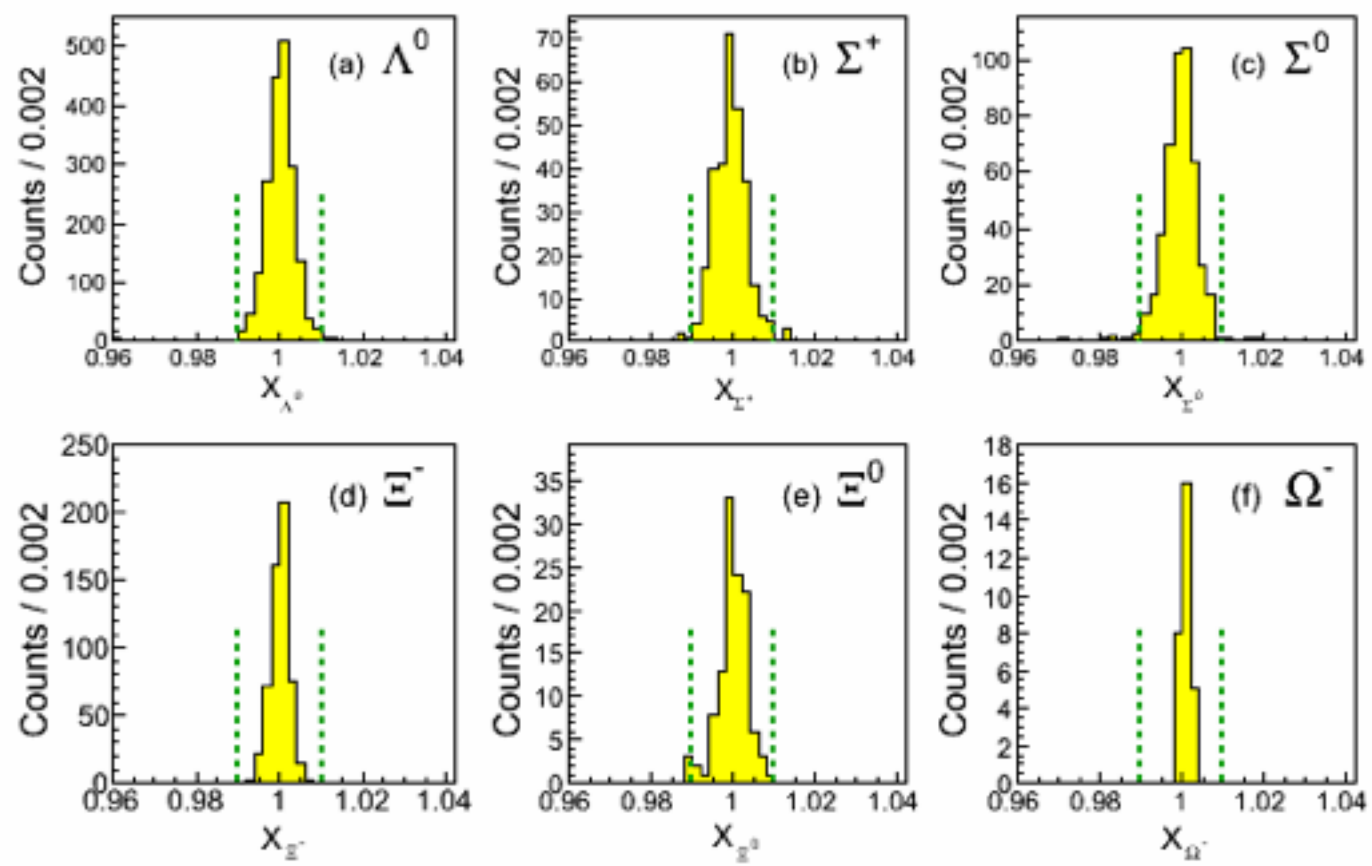
Inclusive Hyperon Mass Spectra From ψ(2S)



- Well reconstructed particles with a vertex displaced from the e^+e^- IP are selected. Strong peaks are seen in each channel.

Fully Reconstructed ψ(2S) → Hyperon + Antihyperon

[N(ψ(2S)) = 24.5M, published in PLB 739, 90 (2014)]



$X_B = [E(B) + E(\bar{B})] / \sqrt{s}$

ψ(2S) → B$\bar{\text{B}}$ Branching Fractions

$\mathcal{B}$	N_{data}	ϵ_B (%)	σ_B (pb)	$\mathcal{B} \times 10^4$
p	4475(78)	63.1	196(3)(12)	3.08(5)(18)
Λ^0	1901(44)	20.7	247(6)(15)	3.75(9)(23)
Σ^0	439(21)	7.96	148(7)(11)	2.25(11)(16)
Σ^+	281(17)	4.54	165(10)(11)	2.51(15)(16)
Ξ^-	548(23)	8.37	176(8)(13)	2.66(12)(20)
Ξ^0	112(11)	2.26	135(13)(10)	2.02(19)(15)
Ω^-	**27(5)**	**2.32**	**31(6)(3)**	**0.47(9)(5)**

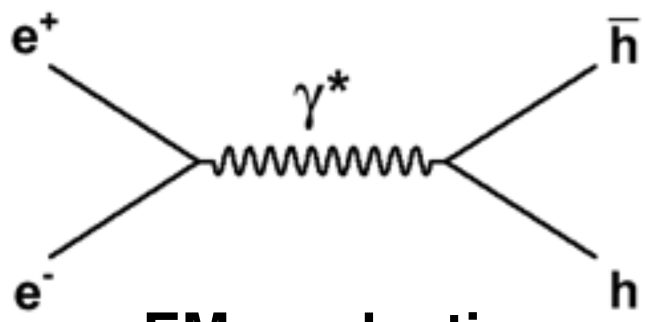
- **B$\bar{\text{B}}$** pairs with total momentum consistent with zero are selected.
- Branching fraction results obtained are consistent with previous measurements, with 3 times smaller uncertainties.
- First significant observation of ψ(2S) → $\Omega^- \bar{\Omega}^-$

Timelike Form Factor Measurements

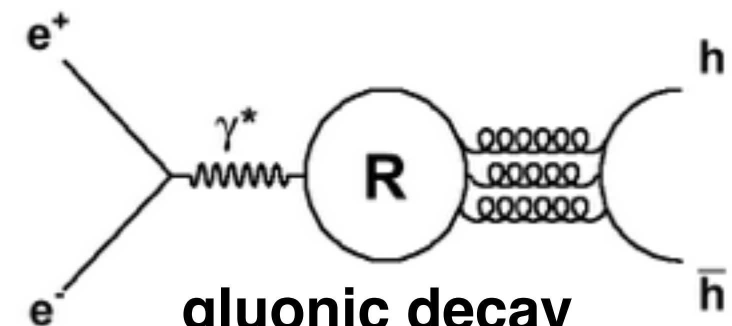
- EM form factors are determined from e^+e^- annihilation through

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

- Baryon pair production in e^+e^- annihilation can proceed through two primary processes:



EM production



gluonic decay of resonance

- To estimate the contribution from gluonic decays of higher resonances (e.g. ψ(3770)), we can use the pQCD prediction:

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

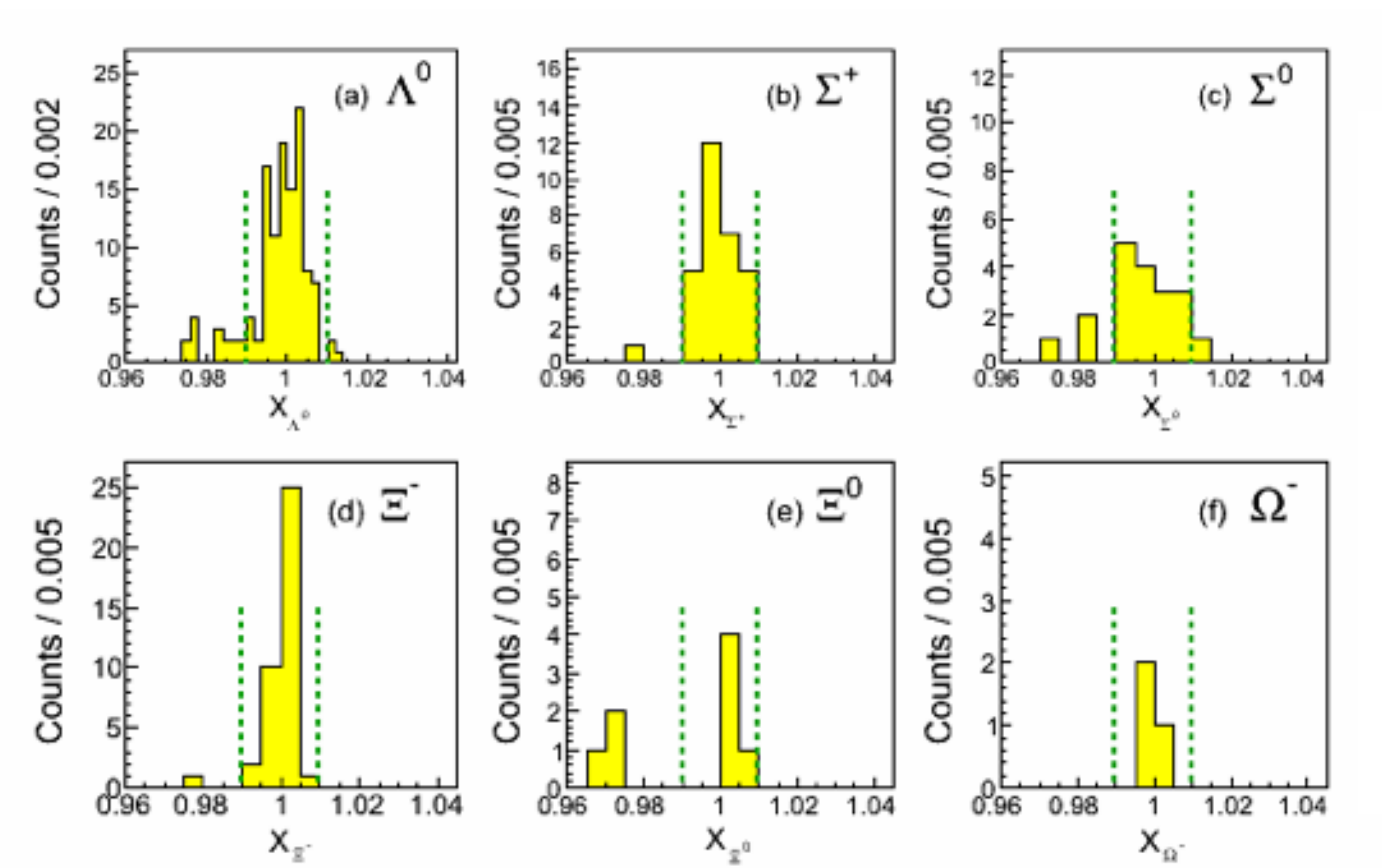
- Thus we obtain, for example, the following yields for fully reconstructed hyperon pair production from ψ(3770):

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

- The expected yields are minimal, and we can use these data for form factor measurements.

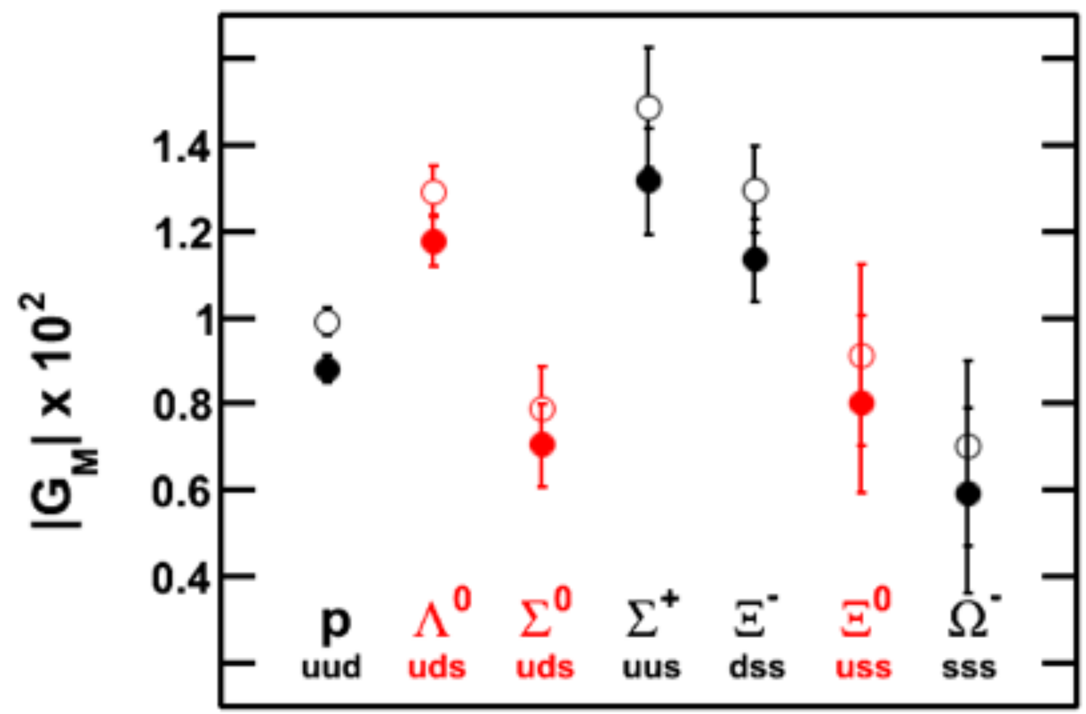
Fully Reconstructed ψ(3770) → Hyperon + Antihyperon

[$\mathscr{L}$(3770) = 805 pb^{-1}, published in PLB 739, 90 (2014)]



$X_B = [E(B) + E(\bar{B})] / \sqrt{s}$

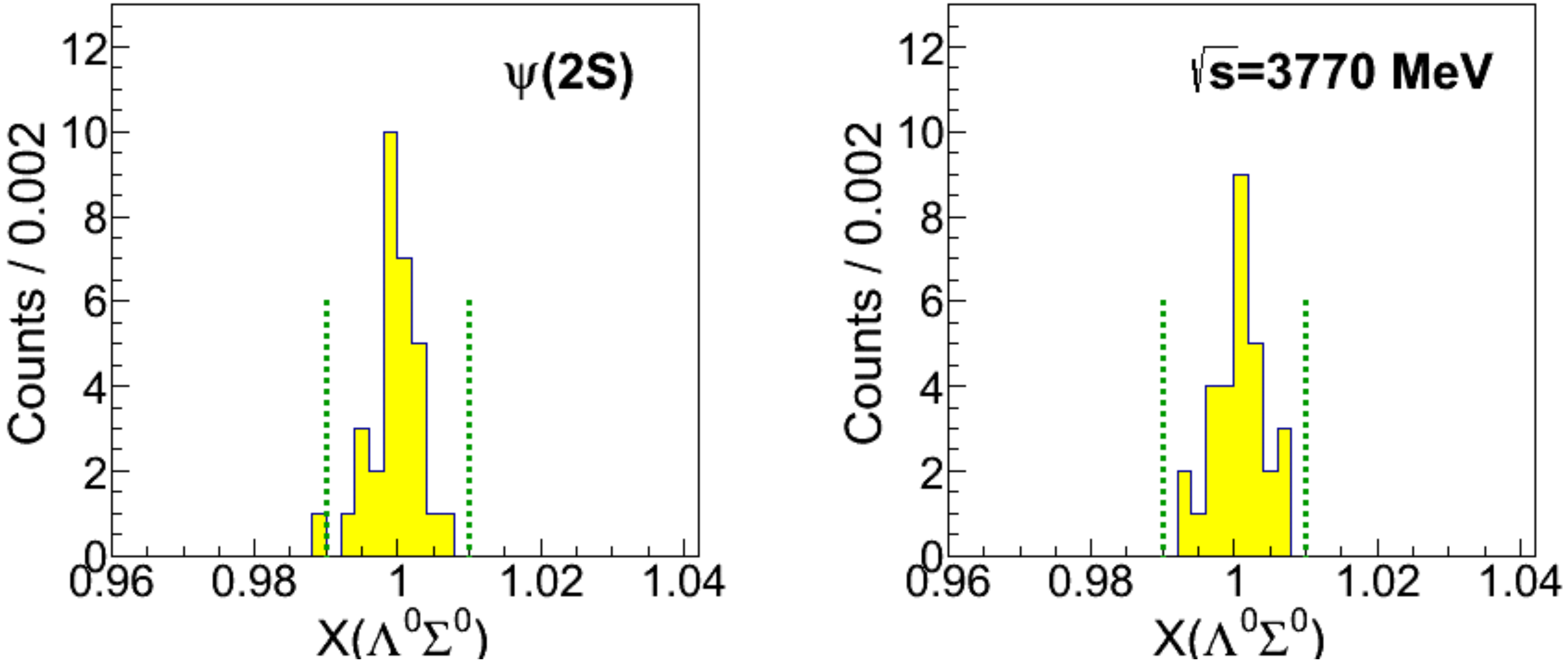
Hyperon EM Form Factors for $|Q^2|$ = 14.2 GeV^2



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

- Event yields and cross sections are ~1 and ~2 orders of magnitude smaller than from ψ(2S), respectively.
- **First** measurements of hyperon EM form factors at large momentum transfer.

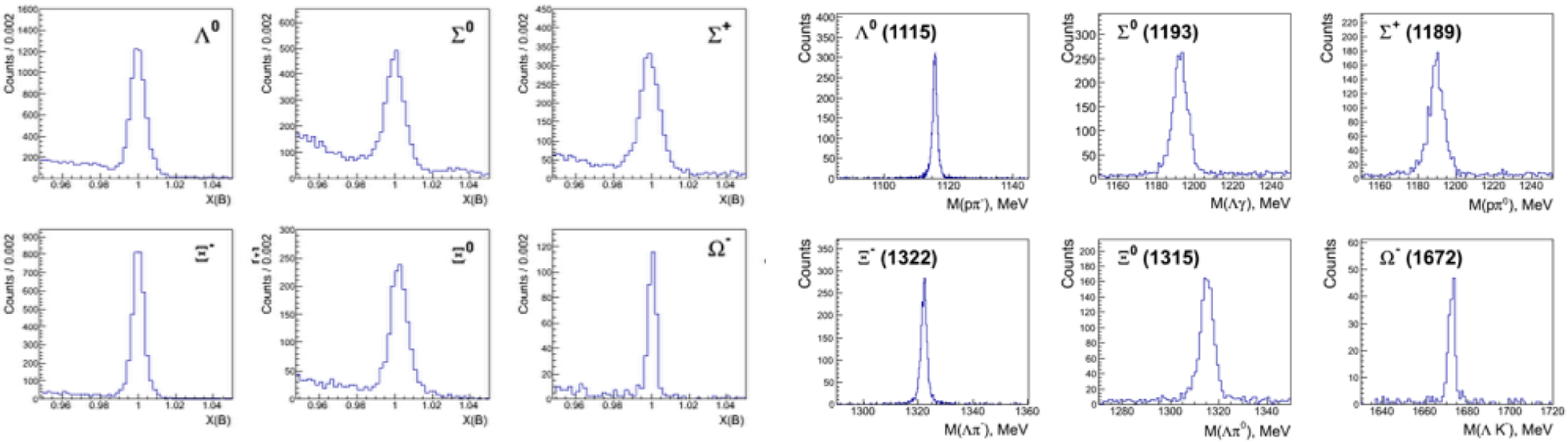
Unequal Baryons — Form Factors of $\Lambda^0 \Sigma^0$



- $\psi(2S)$: **N = 30 ± 5**, **Br = (0.12 ± 0.02(stat)) x 10^{-4}**
  This is **20 – 30** times smaller than Br($\psi(2S) \to \Lambda^0 \Lambda^0, \Sigma^0 \Sigma^0$)
- Form factor @ $|Q^2|$ = 14.2 GeV^2:
  N = 30 ± 5, **$G_M(\Lambda^0 \Sigma^0)$ = (0.79 ± 0.07(stat)) x 10^{-2}**
  This is consistent with $G_M(\Sigma^0)$ = (0.79 ± 0.07) x 10^{-2}

Partially Reconstructed ψ(2S) → Hyperon + Antihyperon

[N(ψ(2S)) = 24.5M, preliminary]

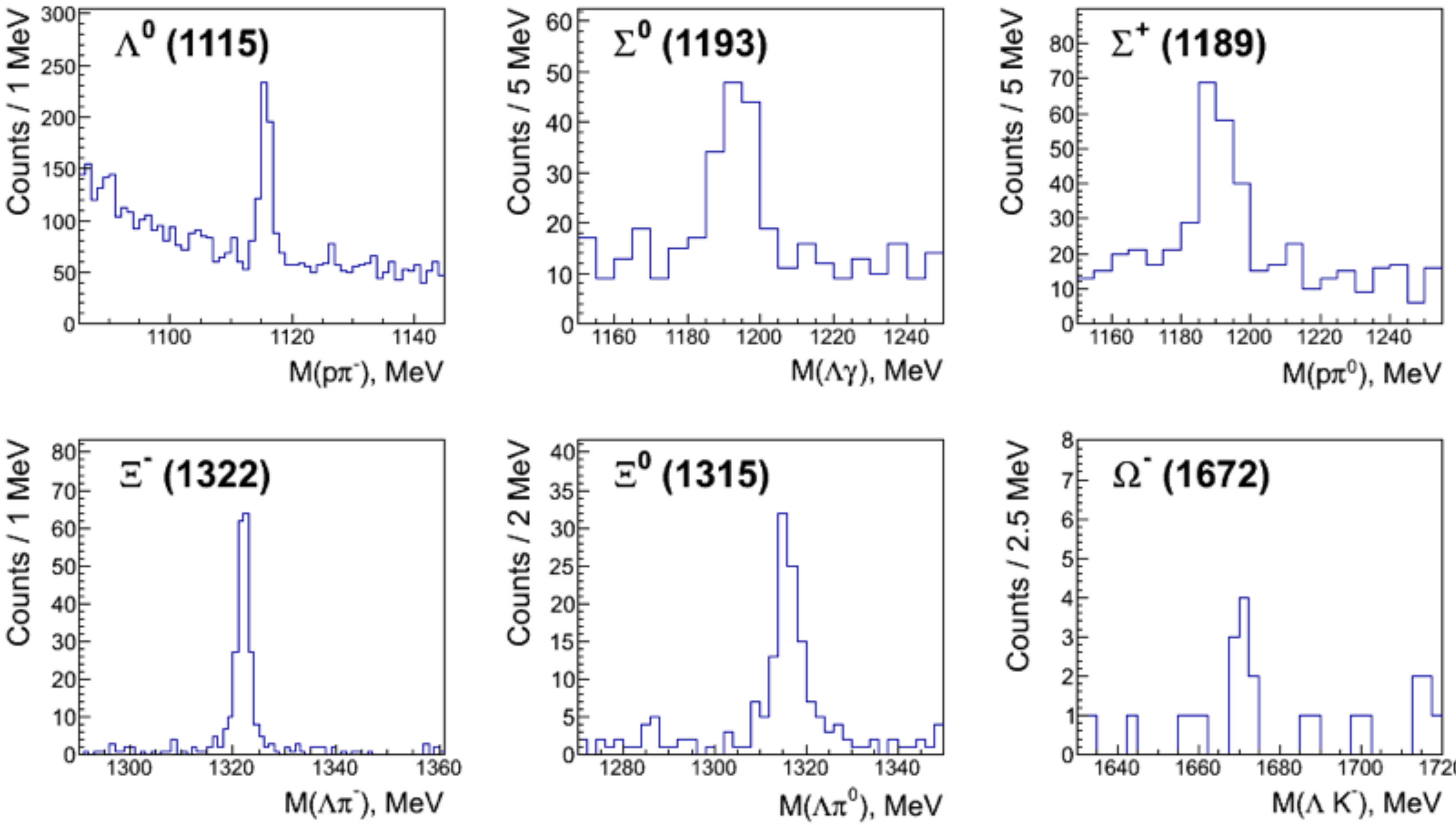


X_B = [E(B) or E($\bar{B}$)] / E(beam) **X_B = 0.99 — 1.01**

- Next step: try to improve form factor results using partial reconstruction.
- Clear peaks due to pair production are seen in the ψ(2S) hyperon energy spectrum.
- Select hyperon candidates with **X_B = 0.99 — 1.01**.
- Branching fraction results obtained are consistent with those obtained from fully reconstructed events, with efficiencies ~3-5 times larger.

Partially Reconstructed ψ(3770) → Hyperon + Antihyperon

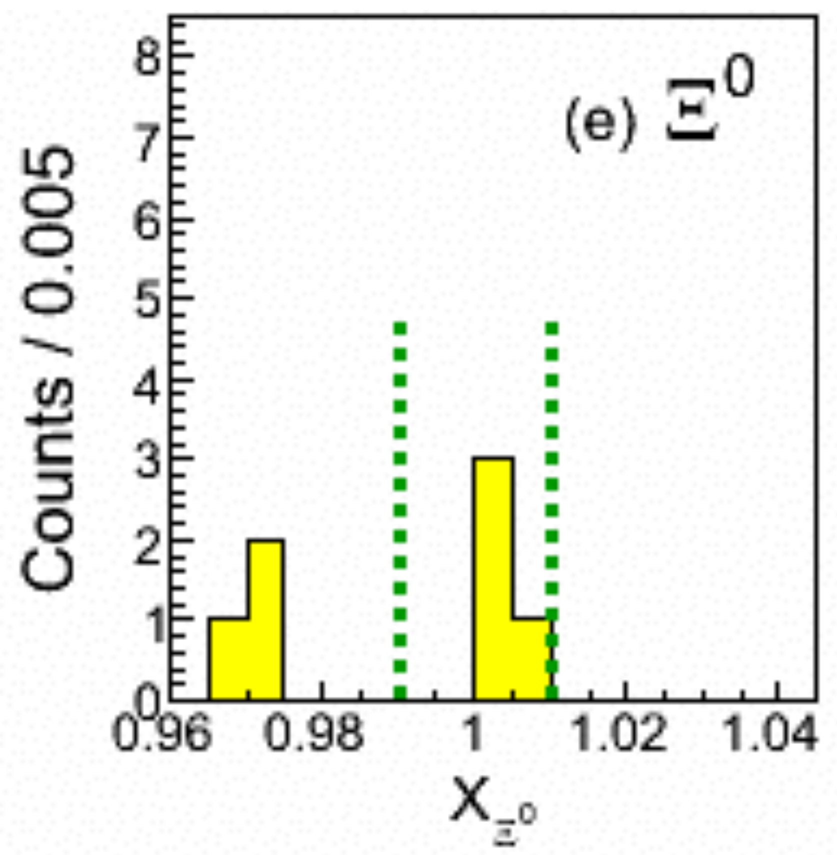
[$\mathscr{L}$(3770) = 805 pb^{-1}, preliminary]

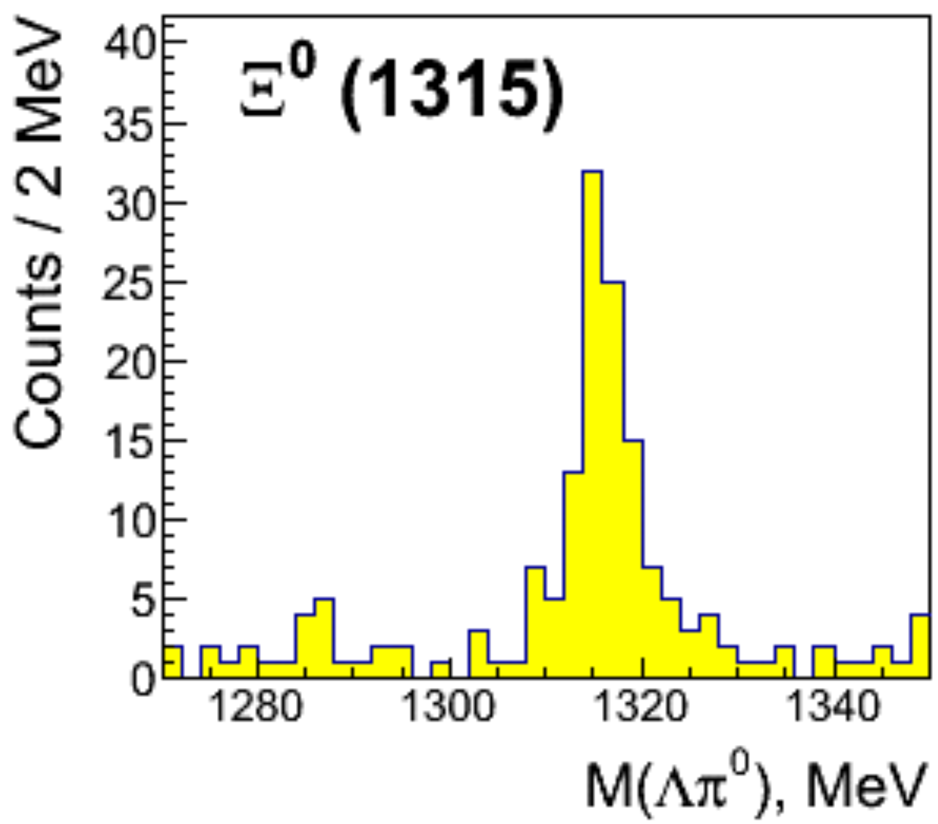


E(B or B̄)/E(beam) = 0.99 — 1.01

- Mass spectra show peaks in all decays with larger statistics than with fully reconstructed events.

Comparison of Fully and Partially Reconstructed Decays





$X_B = [E(B) + E(\bar{B})] / \sqrt{s}$

$E(B \text{ or } \bar{B})/E(\text{beam}) = 0.99 — 1.01$

Fully Reconstructed

Partially Reconstructed

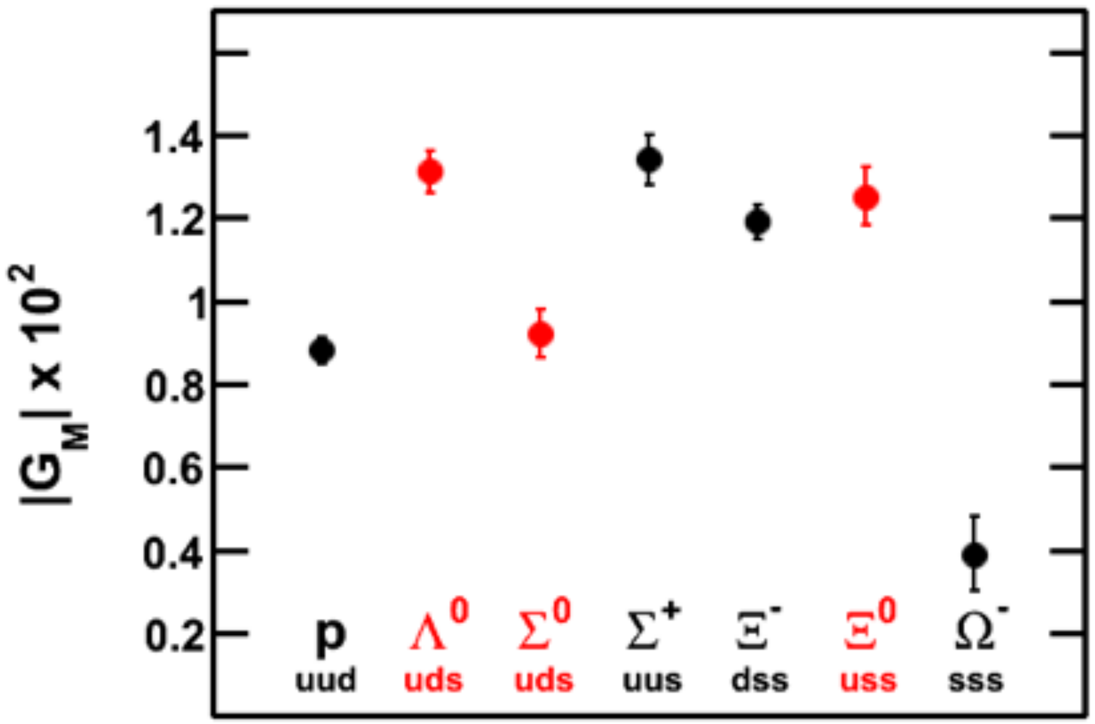
- Partially reconstructed events show clean peaks with larger statistics than fully reconstructed events.

Partially Reconstructed ψ(3770) → Hyperon + Antihyperon

[$\mathscr{L}$(3770) = 805 pb^{-1}, preliminary, stat. uncertainty only]

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

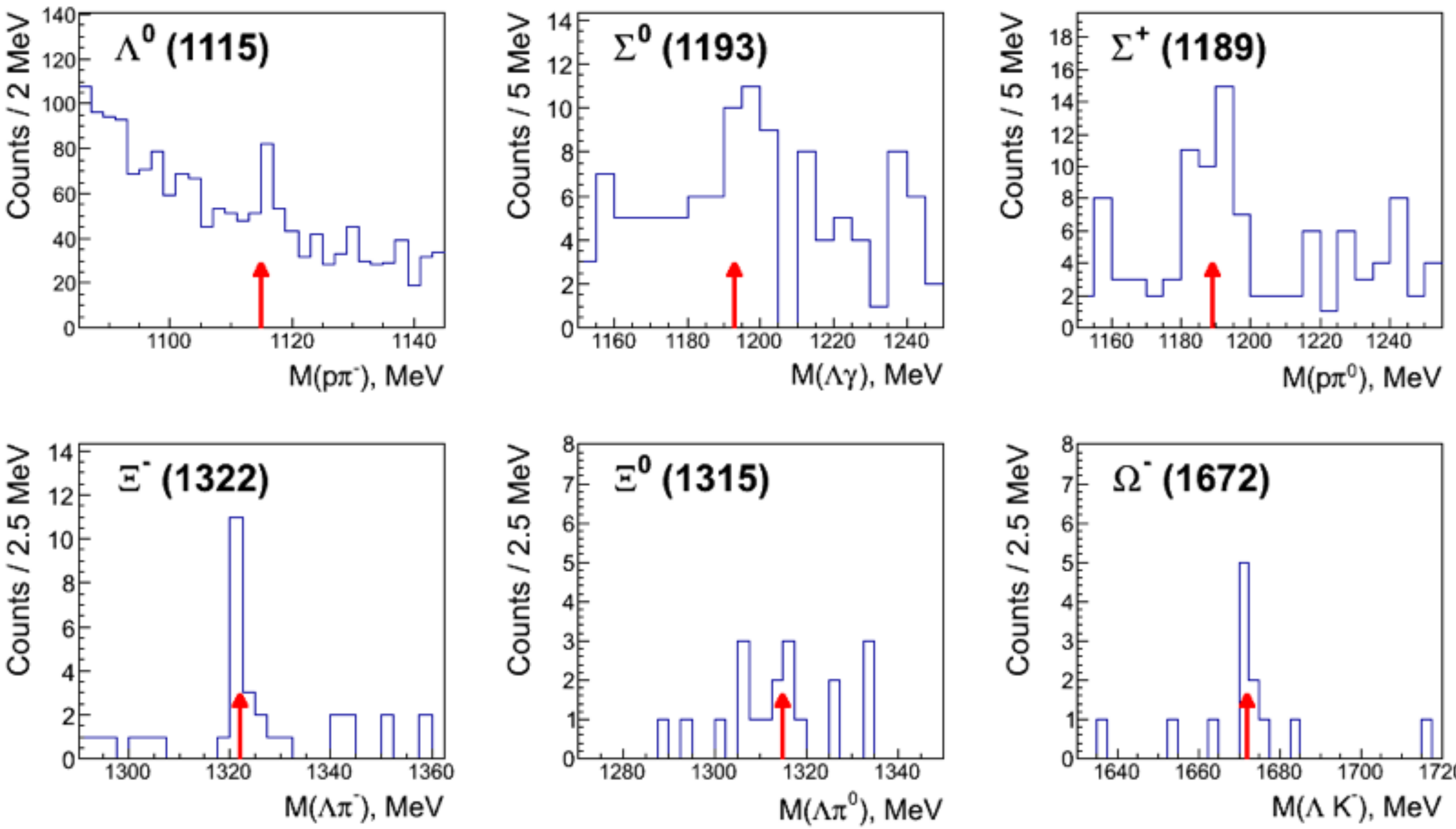
Hyperon EM Form Factors for $|Q^2|$ = 14.2 GeV^2



- Event yields ~3—5 times larger than fully reconstructed decays. Only statistical uncertainties shown.
- **Note: $G_M(\Lambda^0)$ / $G_M(\Sigma^0)$ = 1.4(1).**

Partially Reconstructed ψ(4170) → Hyperon + Antihyperon

[$\mathscr{L}$(4170) = 586 pb^{-1}, preliminary]



E(B or B̄)/E(beam) = 0.99 — 1.01

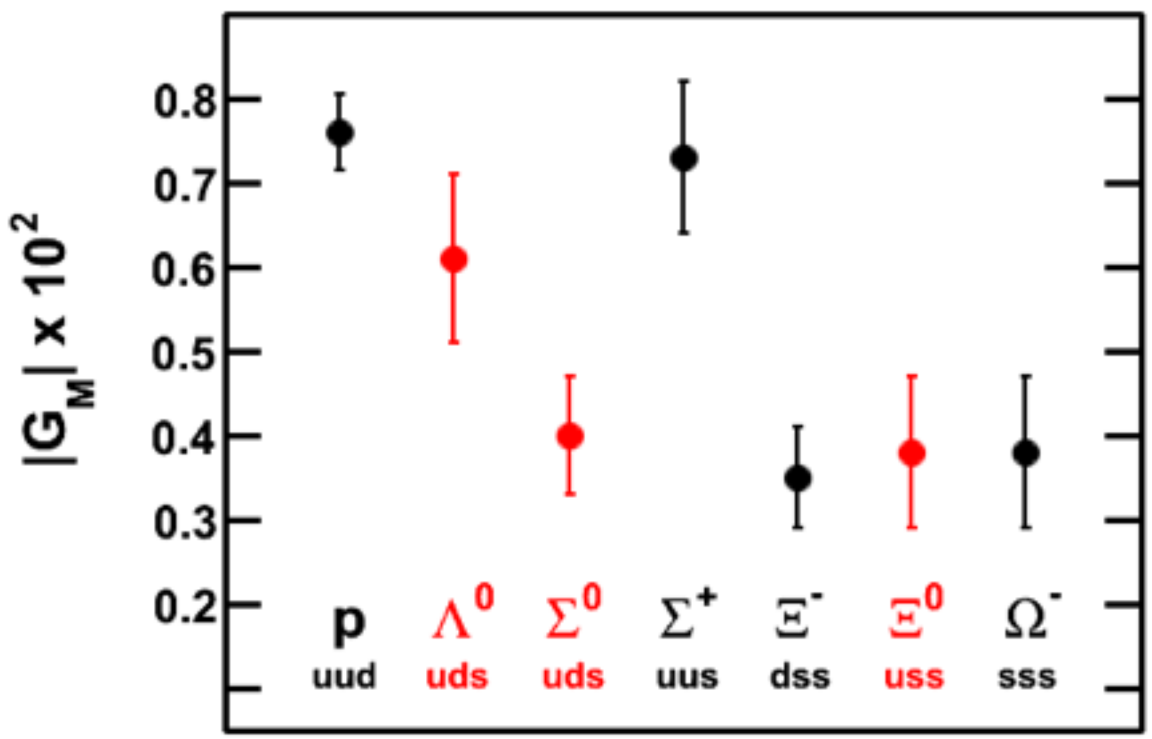
- With larger efficiencies, we can extend our measurements to $\sqrt{s}$ = 4170 MeV. Expected cross sections are much smaller due to s^{-5} dependence.

Partially Reconstructed ψ(4170) → Hyperon + Antihyperon

[$\mathscr{L}$(4170) = 586 pb^{-1}, preliminary, stat. uncertainty only]

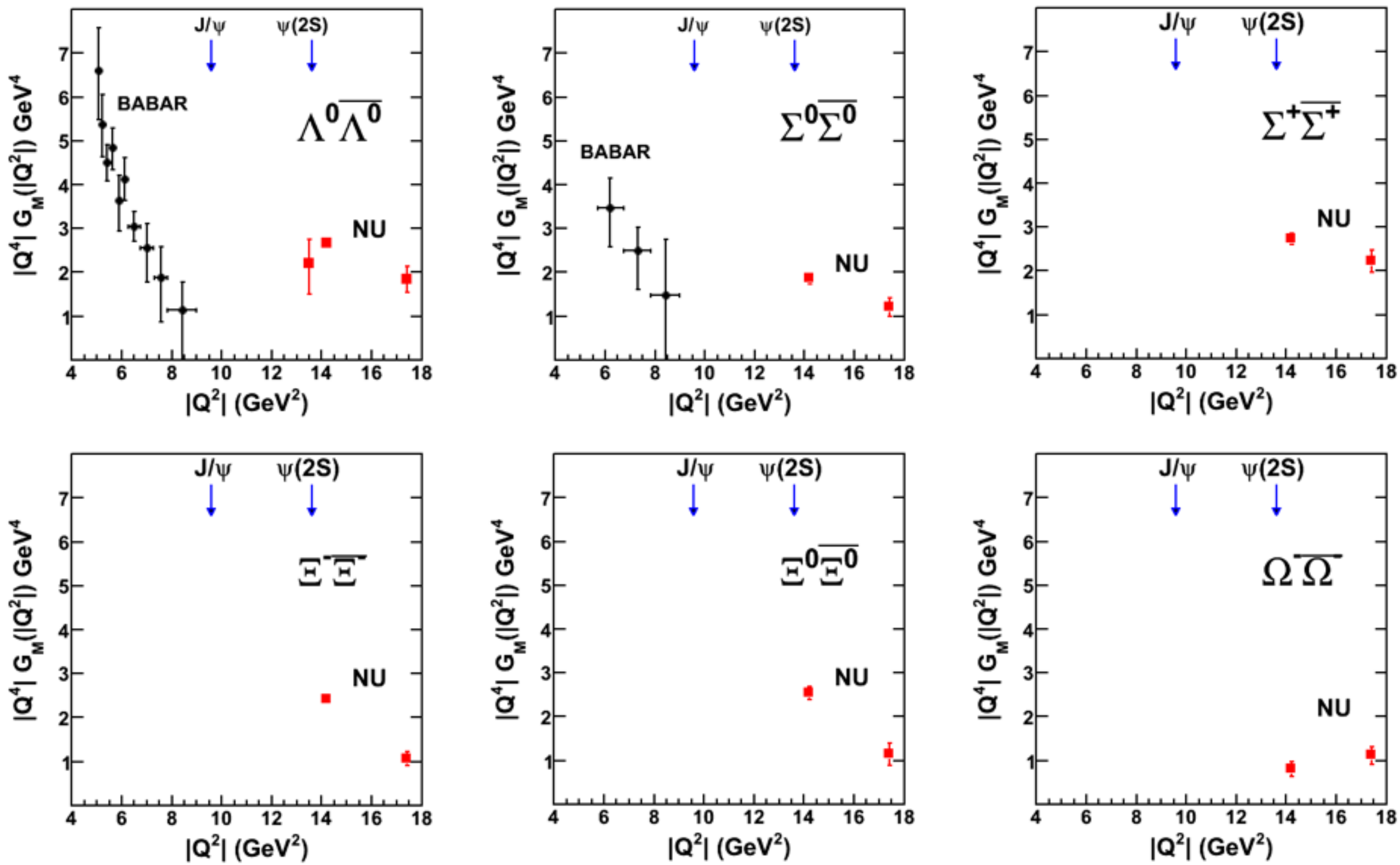
	N(obs) B or $\bar{B}$	ε %	σ pb	$G_M \times 10^2$
p (uud)	92(10)		0.29(4)	0.76(4)
Λ^0 (uds)	47(16)	72.2	0.18(6)	0.61(10)
Σ^0 (uds)	14(6)	49.0	0.08(3)	0.40(7)
Σ^+ (uus)	28(7)	31.3	0.26(6)	0.73(9)
Ξ^0 (uss)	6(3)	24.1	0.07(3)	0.38(9)
Ξ^- (dss)	13(4)	56.5	0.06(2)	0.35(6)
Ω^- (sss)	8(3)	34.9	0.06(2)	0.38(9)

Hyperon EM Form Factors for $|Q^2|$ = 17.4 GeV^2



- Form factor ratios similar to those at $|Q^2|$ = 14.2 GeV^2, except for cascades.
- Note: $G_M(\Lambda^0)$ / $G_M(\Sigma^0)$ ~ 1.6

Hyperon Form Factors

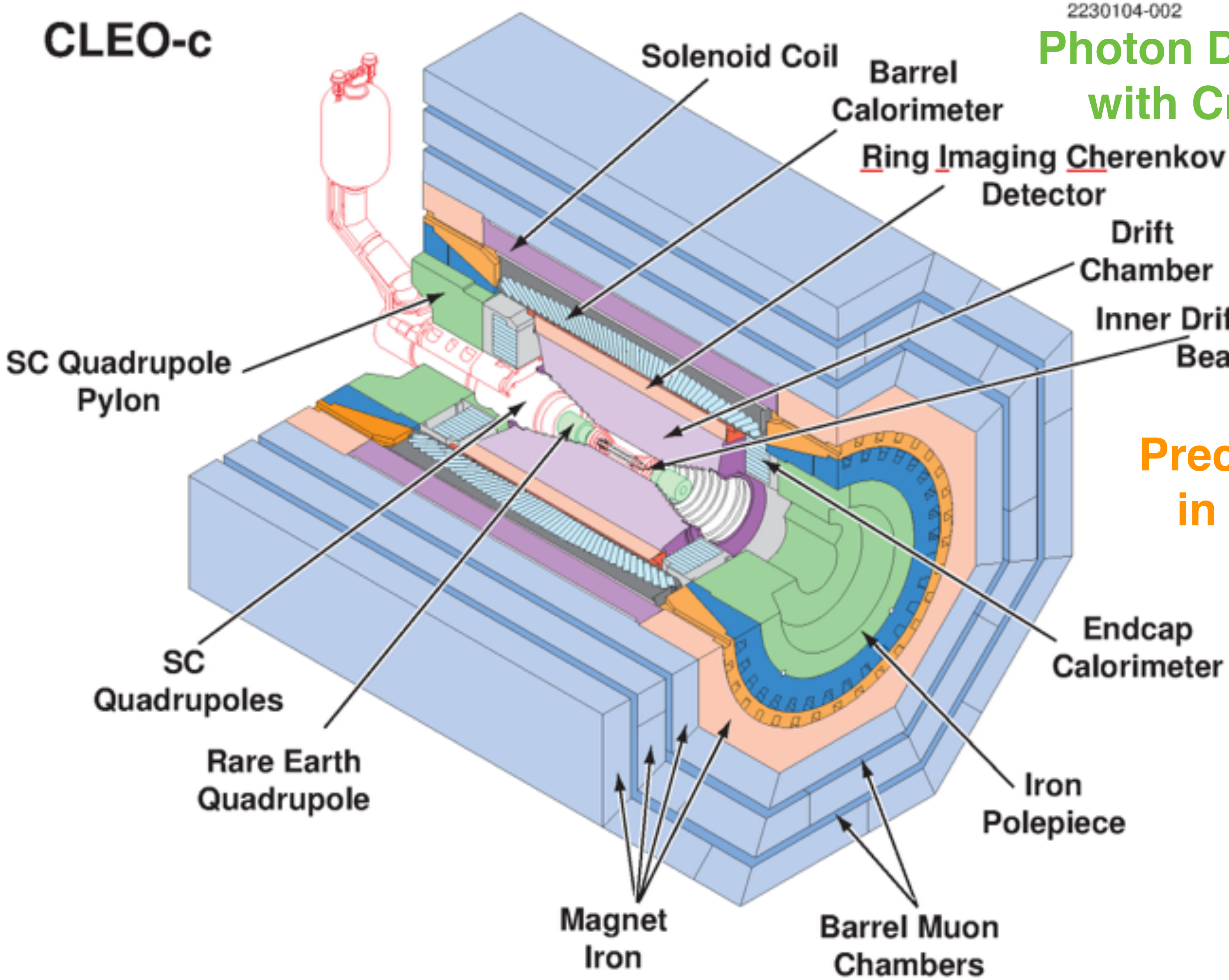


Discussion

- No calculations of timelike hyperon form factors exist besides the VDM predictions of Körner and Kuroda [PRD **16**, 2165 (1977)], which differ from our measurements by factor ~10.
- The Λ^0 (*uds*, I=0) and Σ^0 (*uds*, I=1) have *same* quark content but *different* isospin. Overall antisymmetrization of the wave function requires:
  - Isoscalar Λ^0 has *ud* in S=0 "good diquark" configuration.
  - Isovector Σ^0 has *ud* in S=1 "bad diquark" configuration.
- Jaffe, Selem, Wilczek et al. have discussed the potential effects of diquark correlations in detail, including a predicted large Λ^0/Σ^0 ratio in production in e^+e^- annihilation (seen e.g. in LEP measurements). We find:
  - $Br(\psi(2S) \to \Lambda^0\Lambda^0) / Br(\psi(2S) \to \Sigma^0\Sigma^0) =$ **1.51 ± 0.03 (stat)**
  - $\psi(3770)$: $G_M(\Lambda^0) / G_M(\Sigma^0) =$ **1.4 ± 0.1 (stat)**
- We believe these measurements provide evidence for important diquark correlations in Λ^0 / Σ^0 hyperons.

Backup Slides

CLEO-c Detector



Photon Detection with Crystal Calorimeter

π/K separation using RICH and DC dE/dx

Precision tracking in 1T B field

Acceptance:
$|\cos\theta| < 0.93$

Charged particles:
$\sigma_p/p = 0.6\%$ @ 1 GeV/c

Photons:
$\sigma_E/E = 2.2\%$ @ 1 GeV
$\sigma_p/p = 5\%$ @ 100 MeV

Fully Reconstructed ψ(3770) → Hyperon—Antihyperon

B	μ_B	N_{res}(est.)	N_{ff}	ϵ_B, %	σ_0^B, pb	$\lvert G_M^B \rvert \times 10^2$
p	2.79	1.3	215(15)	71.3	0.46(3)(3)	0.88(3)(2)
Λ^0	0.61	0.9	105(10)	21.1	0.80(8)(5)	1.18(6)(4)
Σ^0	0.78	0.2	15(4)	8.36	0.29(7)(2)	0.71(9)(3)
Σ^+	2.46	0.2	29(5)	4.68	0.99(18)(6)	1.32(13)(4)
Ξ^-	0.65	0.2	38(6)	8.69	0.71(11)(5)	1.14(9)(4)
Ξ^0	1.25	0.05	$5^{+2.8}_{-2.3}$	2.30	$0.35^{+0.20}_{-0.16}(3)$	0.81(21)(3)
Ω^-	2.02	0.03	$3^{+2.3}_{-1.9}$	2.94	$0.16^{+0.13}_{-0.10}(2)$	$0.64^{+0.21}_{-0.25}(3)$
$\Lambda^0\Sigma^0$	1.61		30(5)	10.8	0.45(8)(3)	0.79(7)(3)

Partially Reconstructed $\psi(2S) \to$ Hyperon—Antihyperon

[N(ψ(2S)) = 24.5M, preliminary, statistical uncertainty only]

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