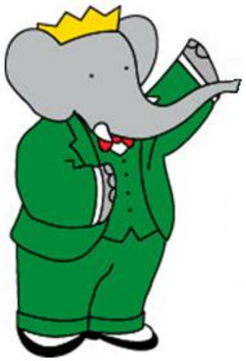
Charm Baryon Results from BaBar

Veronique Ziegler
SLAC National Accelerator Laboratory

Representing the BaBar Collaboration



MENU 2010

Williamsburg, May 31-June 4, 2010

Outline

- Introduction: BaBar as a charm factory
- Spectroscopy
- Production studies
- Studies of excited Cascade states produced in charm baryon decays
- Future possibilities

BaBar as a Charm Baryon Factory

Present data sample contains:

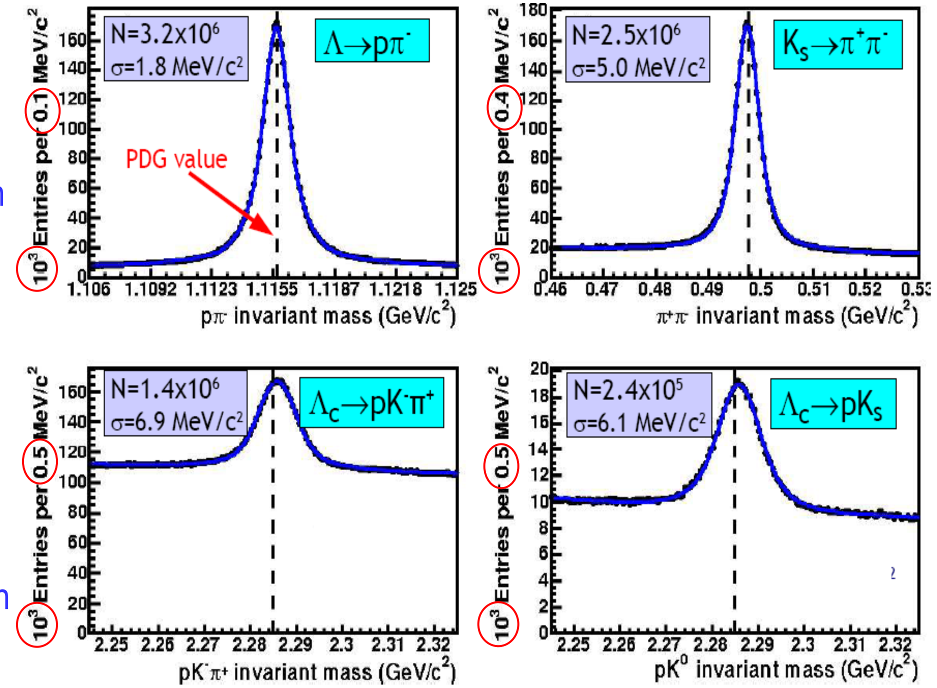
> **450 M $\Upsilon(4S) \rightarrow B\bar{B}$ events** (σ = 1.05 nb)

> **1600 M $e^+e^- \rightarrow q\bar{q}$ events** (σ = 3.39 nb)

> **610 M $e^+e^- \rightarrow c\bar{c}$ events** (σ = 1.30 nb)

Excellent resolution

High statistics charm baryon production



Provides access to rare decay modes &
High precision studies of charm baryon properties ...

Charm Baryon Spectroscopy

Observation of new decay modes

First observation of charm baryon to charm meson decay

Evidence for new states

Charm Baryon to Charm Meson Decay

Λ_c^+
$u\,d\,c$

- Observation of two states decaying to D^0 p
  - previously observed $\Lambda_c(2880)^+$ (*in* $\Lambda_c\, \pi^+\, \pi^-$) [Q~317 MeV/$c^2$]
  - BaBar measurements from D^0p [Q~79 MeV/c^2 ➔ **much greater precision**]:

    M = 2881.9±0.1(stat)±0.5(syst) MeV/c^2

    Γ = 5.8±1.5(stat)±1.1(syst) MeV [First measurement]

    PRL **98**, 012001 (2007)

  - **new state:**

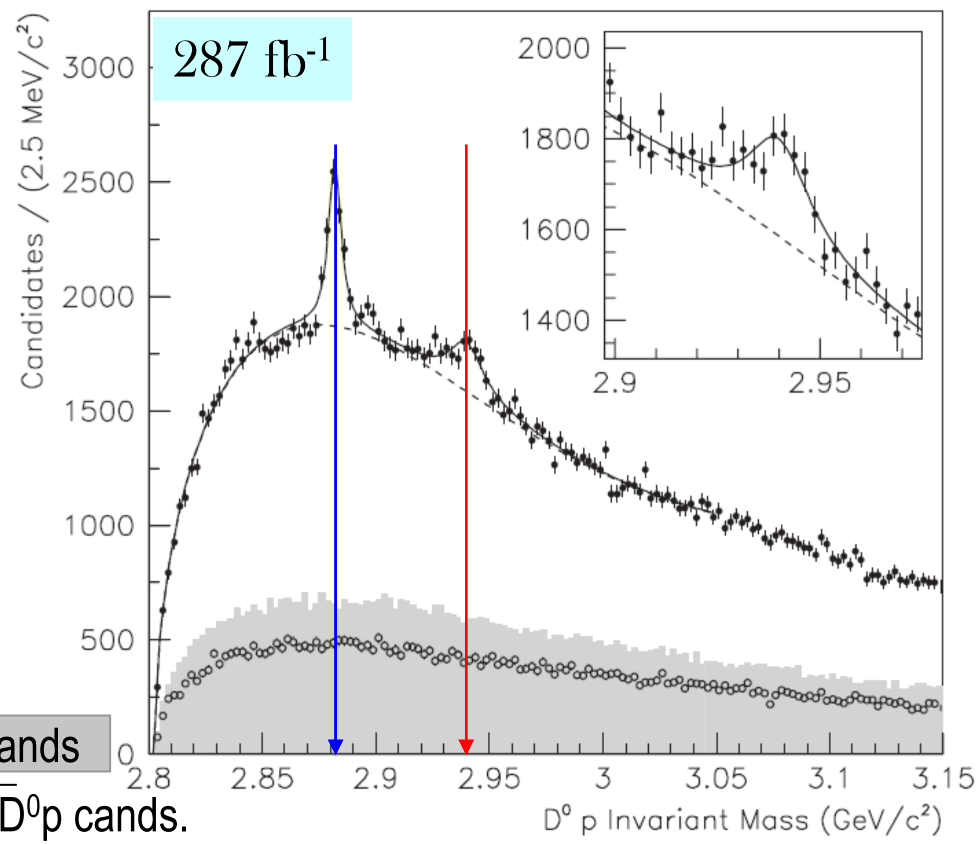
    M = 2939.8±1.3(stat)±1.0(syst) MeV/c^2

    Γ = 17.5±5.2(stat)±5.9(syst) MeV

  ► First observation of a charm baryon decaying to a charm meson

- No evidence in D^+p of doubly charged partners

  ► Signals correspond to observation of *excited* Λ_c states, not Σ_c states



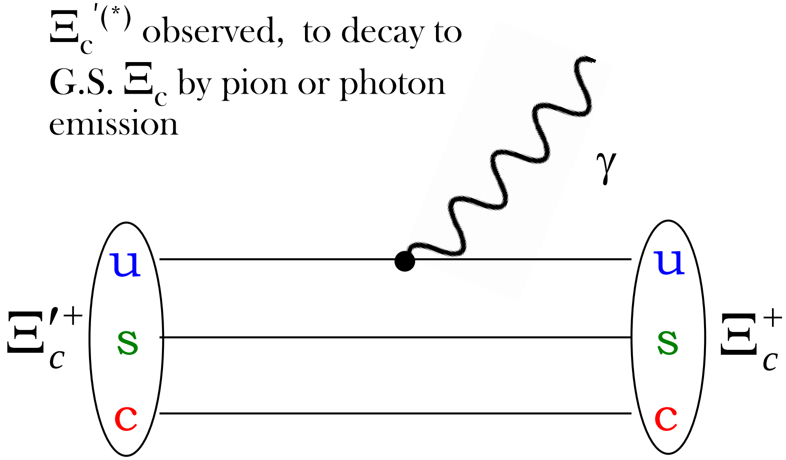
D⁰ mass sidebands

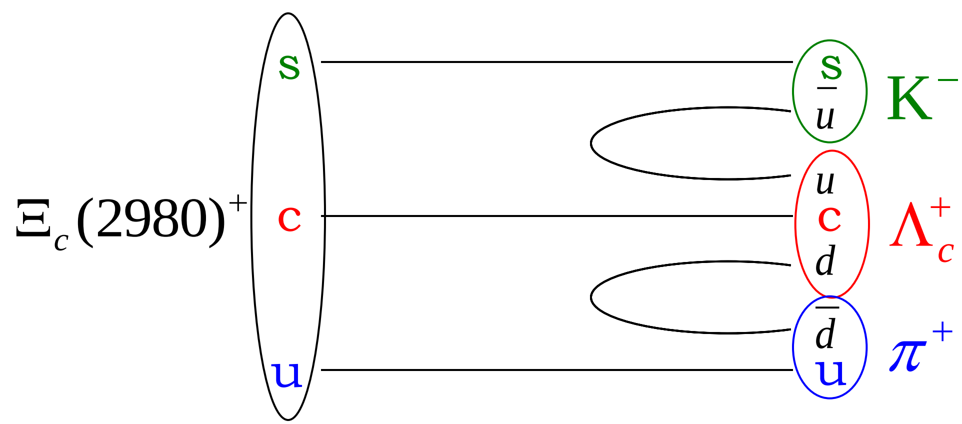
○ wrong-sign $\bar{D}^0$p cands.

$\Xi_{c}^{0,+}$ The Search for *charm* Cascades Decaying to $\Lambda_c^+ K^-(K_S)\ \pi^{+(-)}$ and $\Lambda_c^+ K^-(K_S)\ \pi^-\pi^+$ Final States

- Confirmation of the existence of the $\Xi_c(2980)^+$, $\Xi_c(3077)^+$ and $\Xi_c(3077)^0$
- Evidence for the $\Xi_c(3055)^+$ and $\Xi_c(3123)^+$
  → natural widths consistent with strongly decaying states

Excited Cascade charm baryons $\Xi_c^{'(*)}$ observed, to decay to G.S. Ξ_c by pion or photon emission





The $\Xi_c(2980)^{+,0}$ and $\Xi_c(3077)^{+,0}$ seen in decays in which the **s** and **c** quark are in separate hadrons

➔ implications for the internal quark interactions inside these states

- predicted excited charm baryons with $J^P = 1/2^{\pm}$, $3/2^{\pm}$

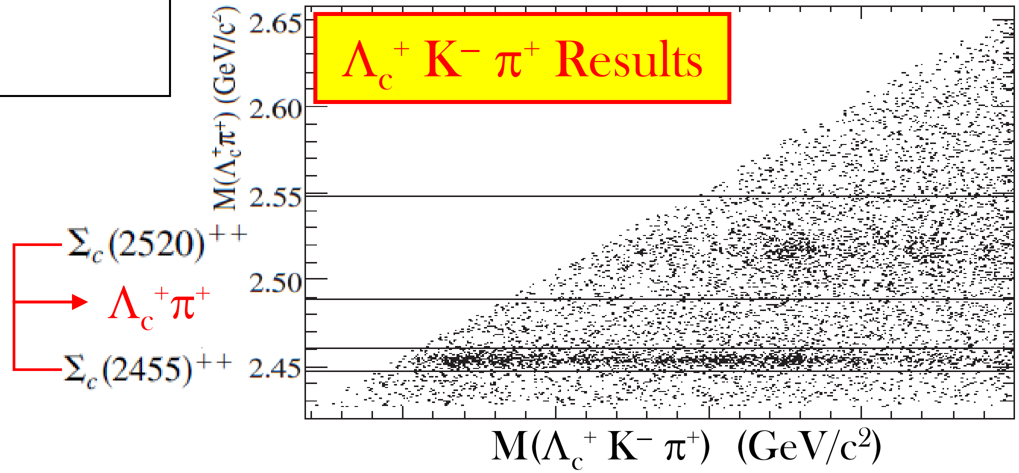
S. Migura, D. Merten, B. Metsch, and H. R. Petry, Eur. Phys. J. A **28**, 41 (2006).
H. Garcilazo, J. Vijande, and A. Valcarce, J. Phys. G **34**, 961 (2007).

- $J^P = 5/2^+$
- radial excitations

J. L. Rosner, J. Phys. G **34**, S127 (2007).
C. Chen, X. L. Chen, X. Liu, W. Z. Deng, and S. L. Zhu, Phys. Rev. D **75**, 094017 (2007).

Results on excited charm Cascades decaying to $\Lambda_c^+ K \pi$

PHYSICAL REVIEW D 77, 012002 (2008)



Mode
$\Lambda_c^+ \rightarrow pK^-\pi^+$
$\Lambda_c^+ \rightarrow pK_S^0$
$\Lambda_c^+ \rightarrow pK_S^0\pi^+\pi^-$
$\Lambda_c^+ \rightarrow \Lambda\pi^+$
$\Lambda_c^+ \rightarrow \Lambda\pi^+\pi^-\pi^+$

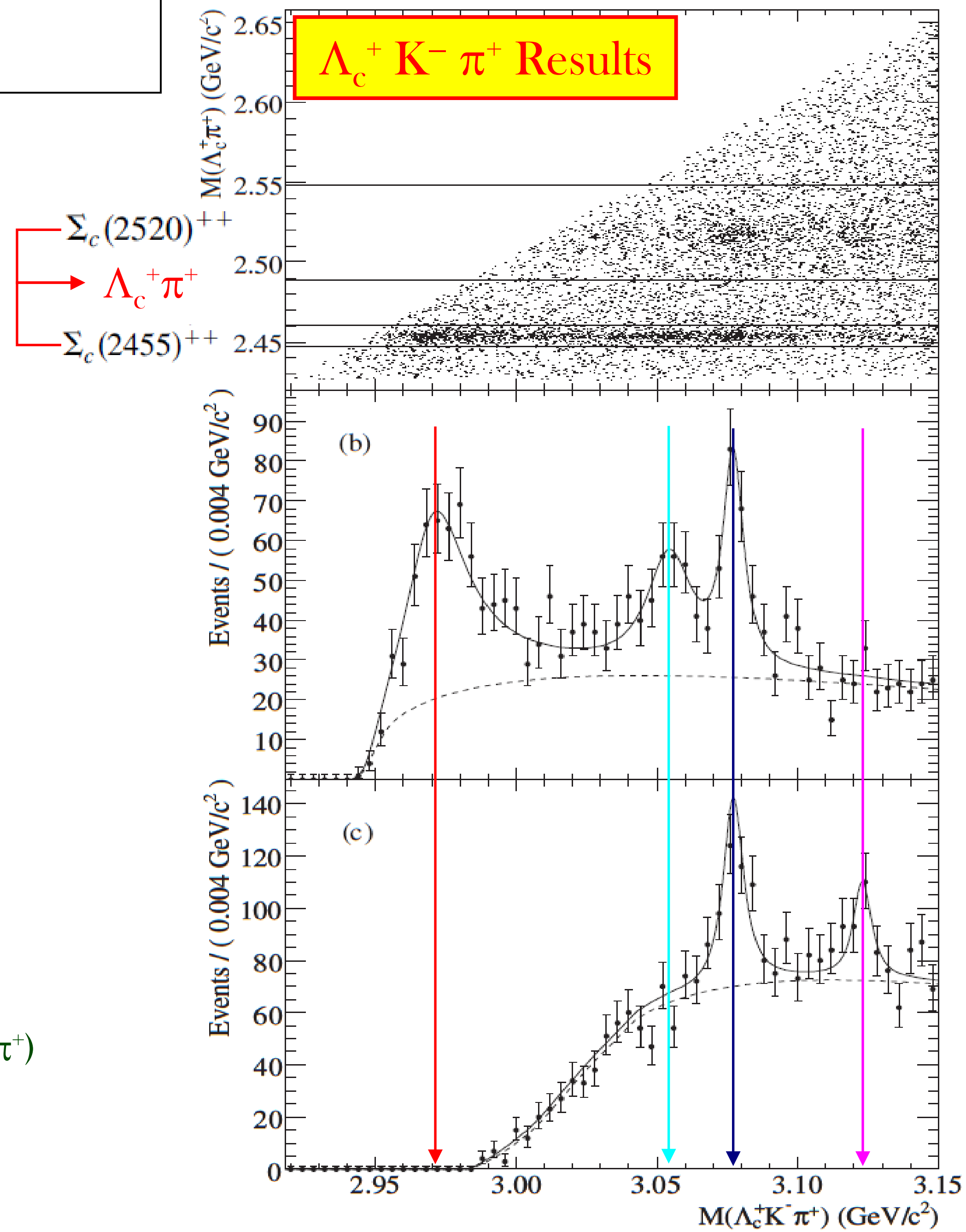
- Fit to two-dimensional invariant mass distribution $M(\Lambda_c^+ K^- \pi^+)$ versus $M(\Lambda_c^+ \pi^+)$
  - ➢ incorporate intermediate resonances $\Sigma_c(2520)^{++}$ and $\Sigma_c(2455)^{++}$ in the fit
  - ➢ show the $M(\Lambda_c^+ K^- \pi^+)$ distribution for $M(\Lambda_c^+ \pi^+)$ ranges w/in 3-σ of the $\Sigma_c(2455)^{++}$ and 2-σ of the $\Sigma_c(2520)^{++}$

Results on excited charm Cascades decaying to Λ_c^+ K π

Very close to threshold
→ very important to take account of phase space

	$\Xi_c(2980)^+$	$\Xi_c(2980)^0$
Mass (MeV/c^2)	$2969.3 \pm 2.2 \pm 1.7$	$2972.9 \pm 4.4 \pm 1.6$
Width (MeV)	$27 \pm 8 \pm 2$	$31 \pm 7 \pm 8$
Yield	$756 \pm 178 \pm 104$	$67 \pm 33 \pm 29$
Resonant (%)	$55 \pm 7 \pm 13$	⋯
Significance	$>9.0\sigma$	1.7σ
	$\Xi_c(3077)^+$	$\Xi_c(3077)^0$
Mass (MeV/c^2)	$3077.0 \pm 0.4 \pm 0.2$	$3079.3 \pm 1.1 \pm 0.2$
Width (MeV)	$5.5 \pm 1.3 \pm 0.6$	$5.9 \pm 2.3 \pm 1.5$
Yield	$403 \pm 54 \pm 27$	$90 \pm 22 \pm 15$
Resonant (%)	>80	$78 \pm 21 \pm 5$
$\Sigma_c(2455)$ (%)	$45 \pm 5 \pm 5$	$44 \pm 12 \pm 7$
Significance	$>9.0\sigma$	4.5σ
	$\Xi_c(3055)^+$	$\Xi_c(3123)^+$
Mass (MeV/c^2)	$3054.2 \pm 1.2 \pm 0.5$	$3122.9 \pm 1.3 \pm 0.3$
Width (MeV)	$17 \pm 6 \pm 11$	$4.4 \pm 3.4 \pm 1.7$
Yield	$218 \pm 53 \pm 79$	$101 \pm 34 \pm 9$
Significance	6.4σ	3.6σ (3.0σ)

PHYSICAL REVIEW D 77, 012002 (2008)



- Similar results for $M(\Lambda_c^+ K_S \pi^+)$ versus $M(\Lambda_c^+ \pi^+)$ although more statistically limited
- No evidence for structure in $(\Lambda_c^+ K_S \pi^+\pi^+)$ nor $(\Lambda_c^+ K^- \pi^+\pi^+)$

The Search for the Ω_c^* (J^P=3/2$^+$)

PRL **97**, 232001 (2006)

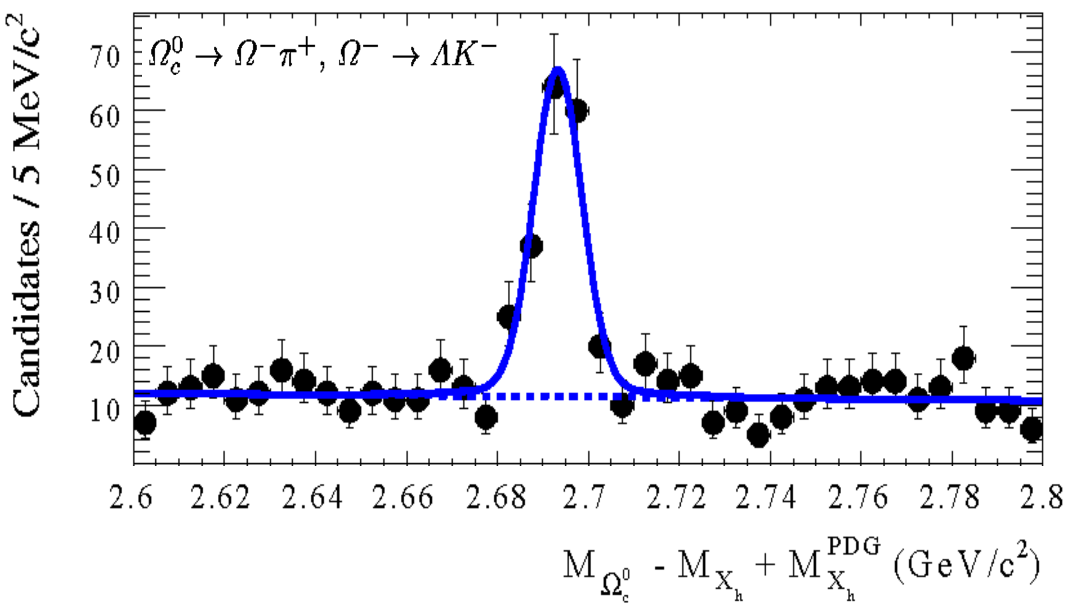
- All L=0 singly-charm baryons discovered, $J^P=3/2^+$ Ω_c^*(*css*) state missing
- Splitting $M(\Omega_c^*)$-$M(\Omega_c)$ predictions range from ~70 -100 MeV/c^2
- Search for Ω_c^* in $e^+e^- \to \Omega_c^*$ X processes

$\boxed{\Omega_c^0 \to \Omega^-\pi^+,\ \Omega^- \to \Lambda K^-}$

$\Omega_c^0 \to \Omega^-\pi^+\pi^0,\ \Omega^- \to \Lambda K^-$

$\Omega_c^0 \to \Omega^-\pi^+\pi^-\pi^+,\ \Omega^- \to \Lambda K^-$

$\Omega_c^0 \to \Xi^-K^-\pi^+\pi^+,\ \Xi^- \to \Lambda\pi^-$



Observation of $\Omega_c^* \to \Omega_c^0 \gamma$

- Splitting $M(\Omega_c^*)$-$M(\Omega_c^0)$

$$= 70.8 \pm 1.0(stat) \pm 1.1(syst)\ \mathrm{MeV/c^2}$$

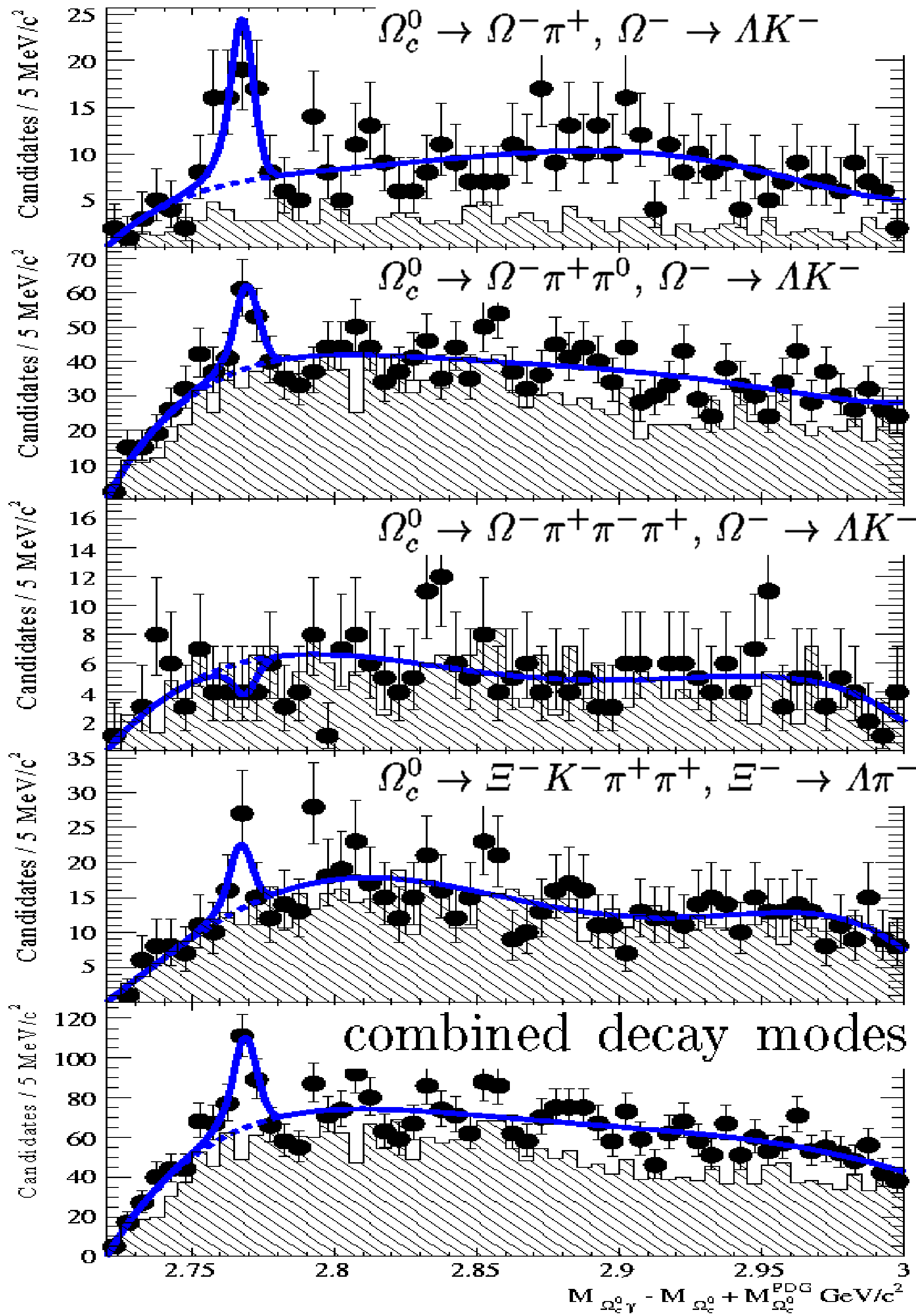
➢ **consistent with pQCD predictions**

➔$M(\Omega_c^*)$=2768.3±3.0 MeV/c^2

- Ratio of the inclusive production cross sections

$$R = \frac{\sigma\left(e^+e^- \to \Omega_c^* X, x_p(\Omega_c^* > 0.5)\right)}{\sigma\left(e^+e^- \to \Omega_c^0 X, x_p(\Omega_c^0 > 0.5)\right)}$$

$$= 1.01 \pm 0.23(stat) \pm 0.11(syst)$$

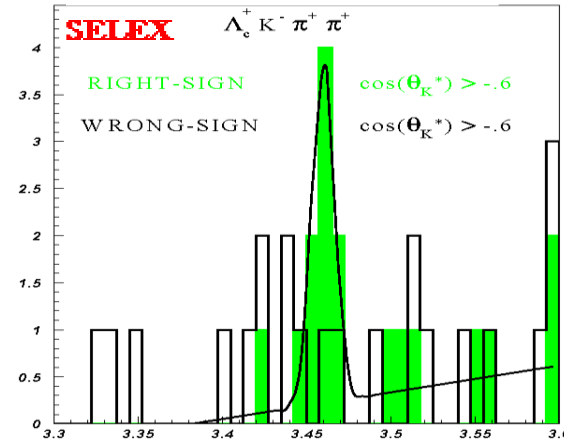


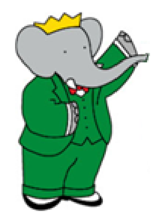
The Search for the $\Xi_{cc}^{+(+)}$ Baryons in the $\Lambda_c^+ K^- \pi^+ (\pi^+)$ and $\Xi_c^0 \pi^+ (\pi^+)$ Final States

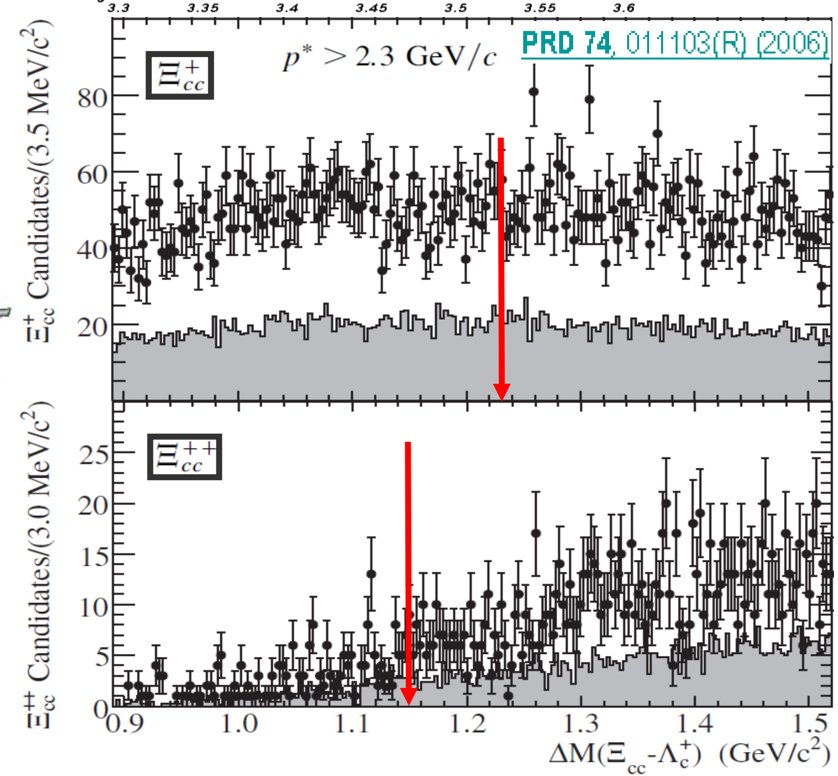
$\Xi_{cc}^{+,++}$
$u,d \ cc$

- SELEX [*using Fermilab 600 GeV/c charged hyperon beam*] reported evidence for ***cc*** baryons with mass 3518.7 MeV/c^2 decaying to $\Lambda_c^+ K^- \pi^+$ and p $D^+ K^-$ and with mass 3460 MeV/c^2 decaying to $\Lambda_c^+ K^- \pi^+ \pi^+$ PRL **89**, 112001(2002), Phys.Lett. **B 628**, 18(2005)
- The mass difference $\Xi_{cc}^{+} - \Xi_{cc}^{++} \sim 60$ MeV/c^2 measured by SELEX inconsistent with the J=1/2 isodoublet interpretation
- The photoproduction experiment FOCUS observed ~**12 x** more Λ_c^+'s than SELEX ***and yet*** did **not observe Ξ_{cc} states** Nucl.Phys. **B**, Proc.Suppl. **115**, 33 (2003)
- Predicted cross section values for doubly charm production in e+e- collisions at c.m. energy near 10.58 GeV range from 1 to 250 fb corresponding to rates $\mathcal{O}(10^{-4} - 10^{-2})$
- BaBar searched for Ξ_{cc} states in 232 fb^{-1} of data and found no evidence of doubly charm baryons PRD **74**, 011103(R) (2006)

Phys. Rev. Lett. 89, 112001 (2002)







Charm Baryon Production at the $\Upsilon(4S)$ Resonance

Production from B decays

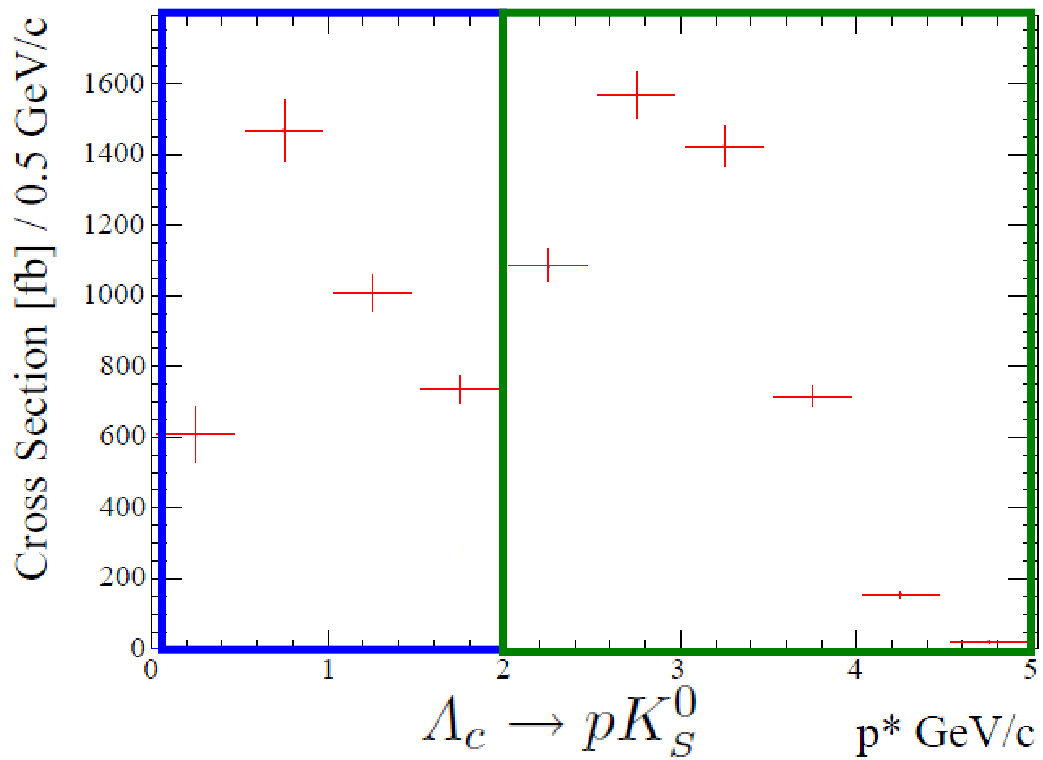
e^+e^- Continuum Production

Charm Baryon Production at the Υ(4S) Resonance

Typical c.m. momentum (p^*) distribution

Production from B decays (+some continuum)

Continuum production



Measurements of BR($\bar{B}^0 \to \Lambda_c^+ \bar{p}$) and BR($B^- \to \Lambda_c^+ \bar{p}\pi^-$) and Studies of $\Lambda_c^+\pi^-$ Resonances

Σ_c^0
$d\ d\ c$

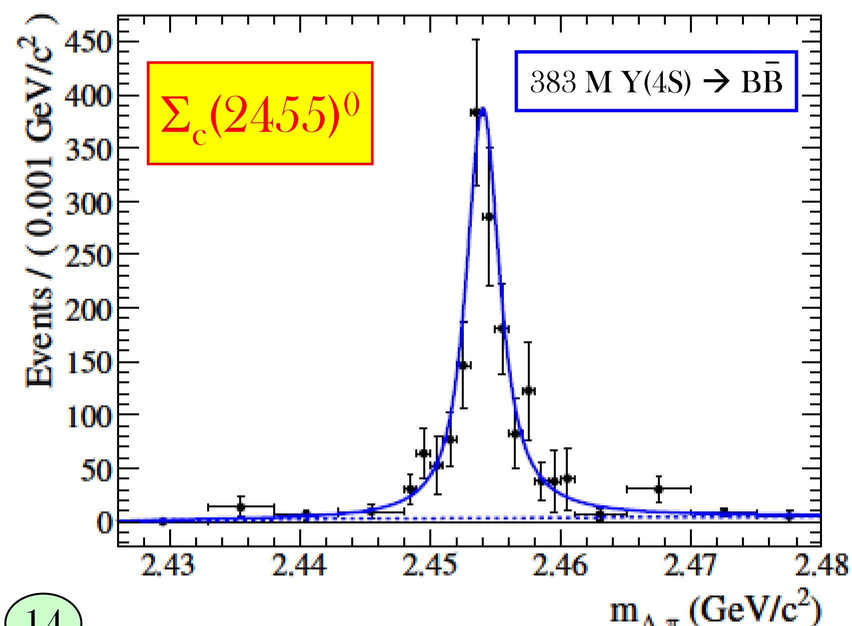
PHYSICAL REVIEW D **78,** 112003 (2008)

$$\boxed{\frac{\mathcal{B}(B^- \to \Lambda_c^+ \overline{p}\pi^-)}{\mathcal{B}(\overline{B}^0 \to \Lambda_c^+ \overline{p})} = 15.4 \pm 1.8 \pm 0.3}$$

$$\frac{\mathcal{B}(B^- \to \Sigma_c(2455)^0 \overline{p})}{\mathcal{B}(B^- \to \Lambda_c^+ \overline{p}\pi^-)} = (12.3 \pm 1.2 \pm 0.8) \times 10^{-2}$$

$$\frac{\mathcal{B}(B^- \to \Sigma_c(2800)^0 \overline{p})}{\mathcal{B}(B^- \to \Lambda_c^+ \overline{p}\pi^-)} = (11.7 \pm 2.3 \pm 2.4) \times 10^{-2}$$

$$\frac{\mathcal{B}(B^- \to \Sigma_c(2520)^0 \overline{p})}{\mathcal{B}(B^- \to \Lambda_c^+ \overline{p}\pi^-)} < 0.9 \times 10^{-2} \text{ (90\% C.L.)}$$



- Predicted favored B to baryon—anti-baryon decay rate for baryon and anti-baryon close in phase space (i.e. 3-body final state)

W.-S. Hou and A. Soni, Phys. Rev. Lett. **86**, 4247 (2001).

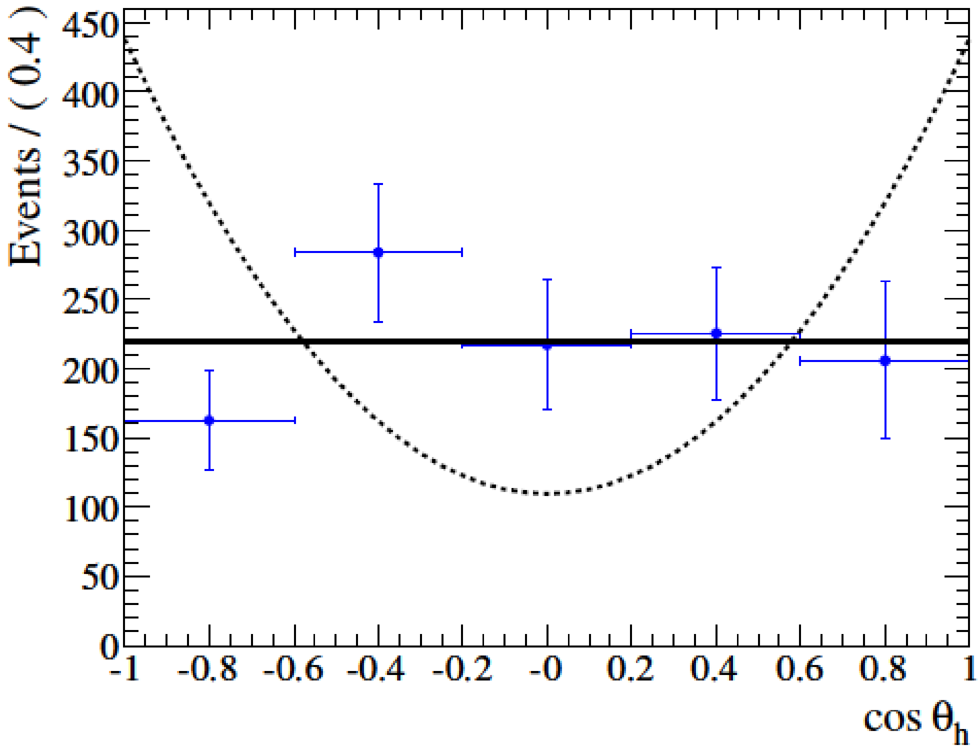
- Study of baryon production in B decays by comparison of ($\bar{B}^0 \to \Lambda_c^+ \bar{p}$) and ($B^- \to \Lambda_c^+ \bar{p}\,\pi^-$) decay rates
- Use of 3-body decay to study $\Lambda_c^+\pi^-$ resonant structures
    - mass, width of $\Sigma_c(2455)$
    - spin of $\Sigma_c(2455)$

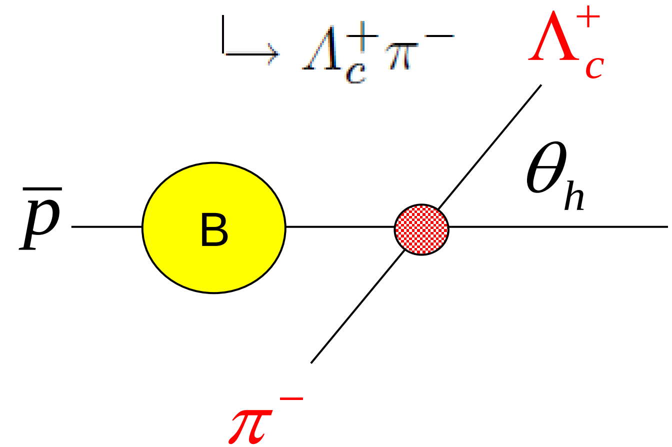
Fit Parameter	Value	PDG Value [8]
$Y_{\rm sig}$	1522 ± 149	
m_R (GeV/c^2)	2.4540 ± 0.0002	2.4538 ± 0.0002
Γ_R (MeV)	2.6 ± 0.5	2.2 ± 0.4

Spin Measurement of the $\Sigma_c\,(2455)^0$ Resonance

angular analysis of the decay $B^- \rightarrow \Sigma_c(2455)^0\overline{p}$

$\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\hookrightarrow \Lambda_c^+\pi^-$





Σ_c(2455) produced with helicity ±1/2

assume $J(\Lambda_c^+) = 1/2$

$$\boxed{J(\Sigma_c^0) = \frac{1}{2} : \quad \frac{dN}{d\cos\theta_h} \propto 1}$$

$$J(\Sigma_c^0) = \frac{3}{2} : \quad \frac{dN}{d\cos\theta_h} \propto 1 + 3\cos^2\theta_h$$

with much more data can use joint decay angular distribution to measure the spin of the Λ_c^+ also

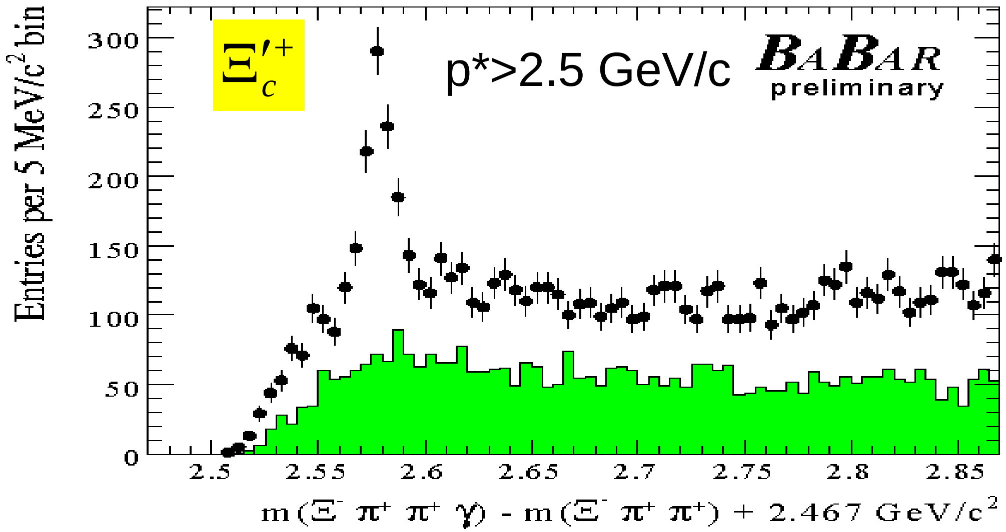
Ξ_c' Production

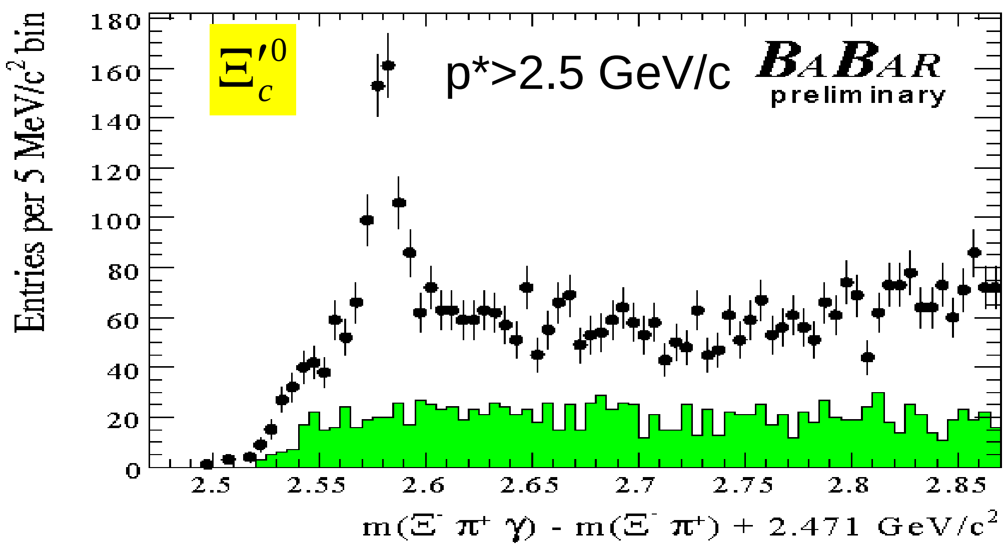
232 fb^{-1}

- Confirmation of CLEO [0.5fb^{-1}] observation of Ξ_c'

$$\Xi_c'^{+} \rightarrow \Xi_c^{+}\gamma$$
$$\mapsto \Xi^{-}\pi^{+}\pi^{+}$$
$$\mapsto \Lambda\pi^{-}$$
$$\Xi_c'^{0} \rightarrow \Xi_c^{0}\gamma$$
$$\mapsto \Xi^{-}\pi^{+}$$

- Charm baryons produced in e$^+$e$^-$ continuum (p$^*\gtrsim$2 GeV/c) ***and in B decays*** **(p* $\lesssim$ 2 GeV/c)**





Ξ_c' Momentum Spectra

- Substantial B meson decay to $\Xi_c'^{+,0}$
  - first observation of these decays
  - stat. significance > 12 σ

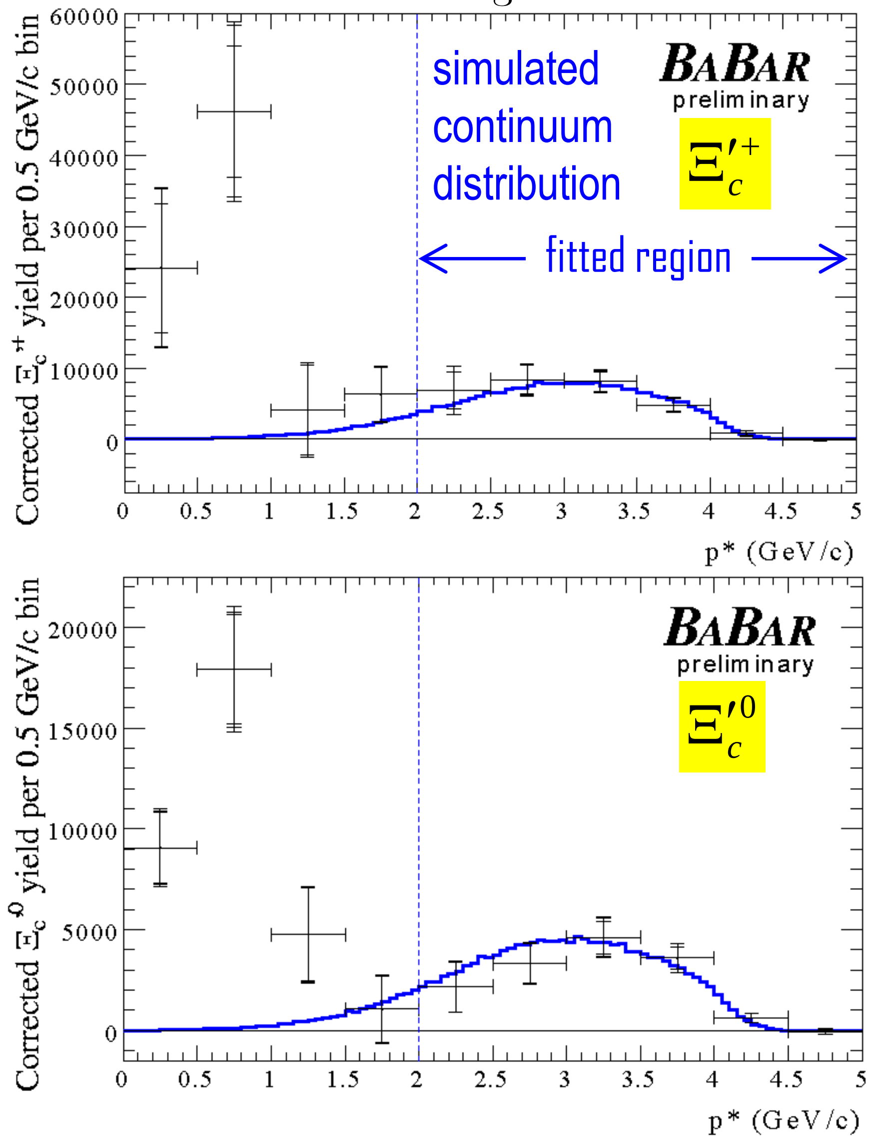
- Product branching fractions

$$BF\left(B \to \Xi_c'^{+} X\right) \times BF\left(\Xi_c^{+} \to \Xi^{-}\pi^{+}\pi^{+}\right)$$
$$= \left[1.69 \pm 0.17(\text{exp}) \pm 0.10(\text{model})\right] \times 10^{-4}$$
$$BF\left(B \to \Xi_c'^{0} X\right) \times BF\left(\Xi_c^{0} \to \Xi^{-}\pi^{+}\right)$$
$$= \left[0.67 \pm 0.07(\text{exp}) \pm 0.03(\text{model})\right] \times 10^{-4}$$

- Cross sections at $\sqrt{s}$=10.58 GeV

$$\sigma\left(e^{+}e^{-} \to \Xi_c'^{+} X\right) \times BF\left(\Xi_c^{+} \to \Xi^{-}\pi^{+}\pi^{+}\right)$$
$$= \left[141 \pm 24(\text{exp}) \pm 19(\text{model})\right] \text{ fb}$$
$$\sigma\left(e^{+}e^{-} \to \Xi_c'^{0} X\right) \times BF\left(\Xi_c^{0} \to \Xi^{-}\pi^{+}\right)$$
$$= \left[70 \pm 11(\text{exp}) \pm 6(\text{model})\right] \text{ fb}$$

efficiency-corrected
background-subtracted



Light Quark Spectroscopy

Excited Cascades produced in charm baryon decays

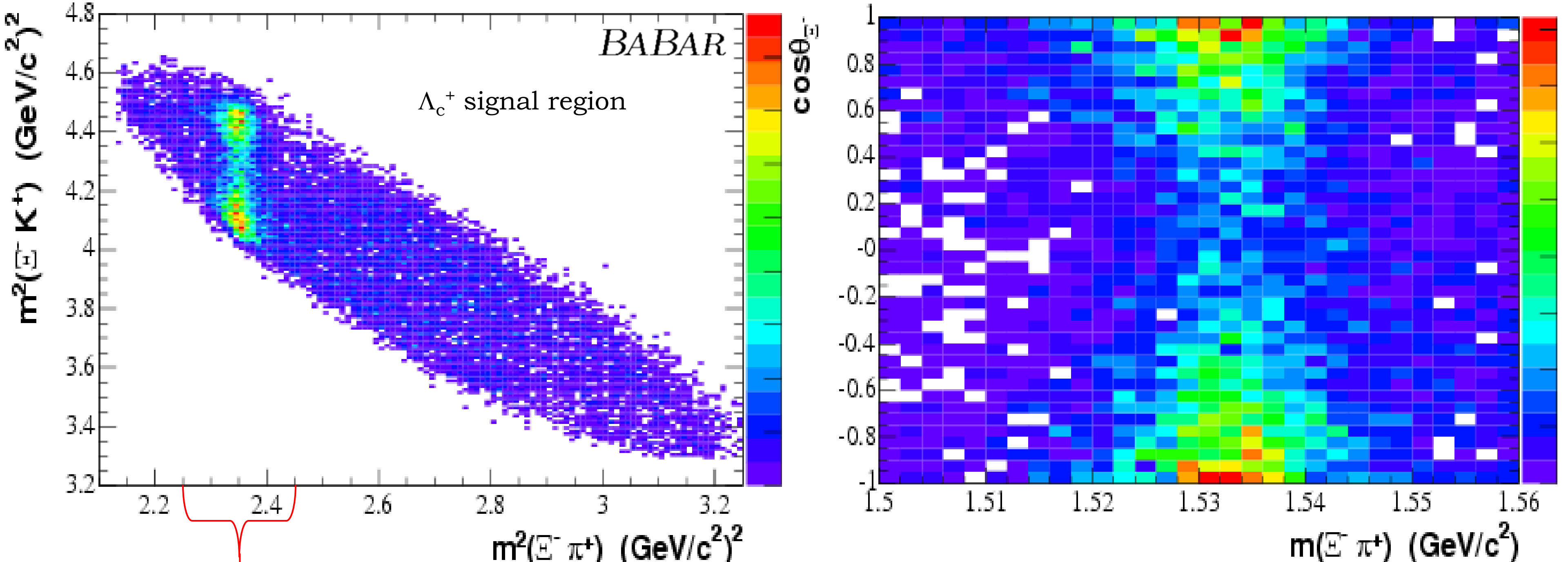
Resonant Structures in the $\Lambda_c^+ \rightarrow \Xi^- \pi^+ K^+$ Signal Region

Phys.Rev.D78:034008,2008

Only ***obvious*** structure:

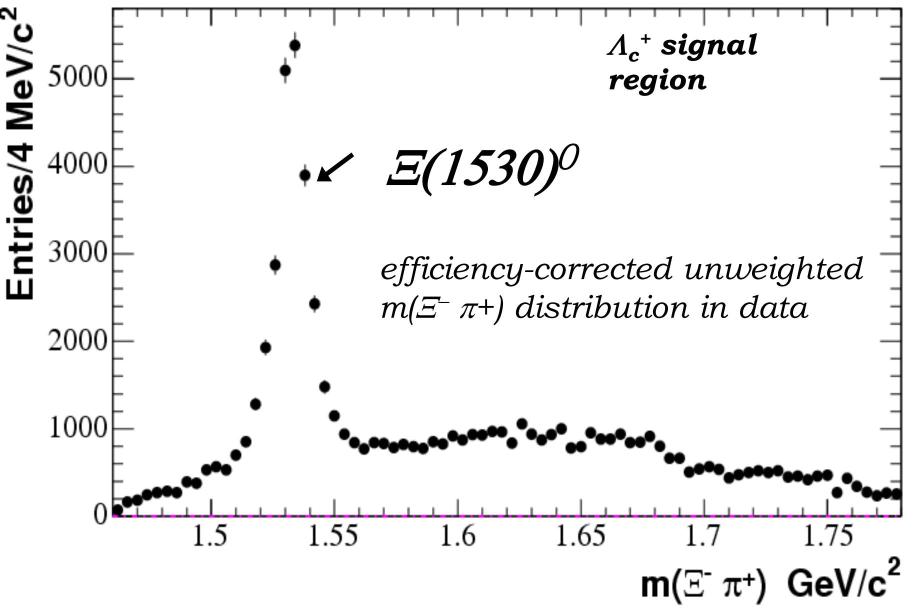
$\Xi(1530)^0 \rightarrow \Xi^- \pi^+$

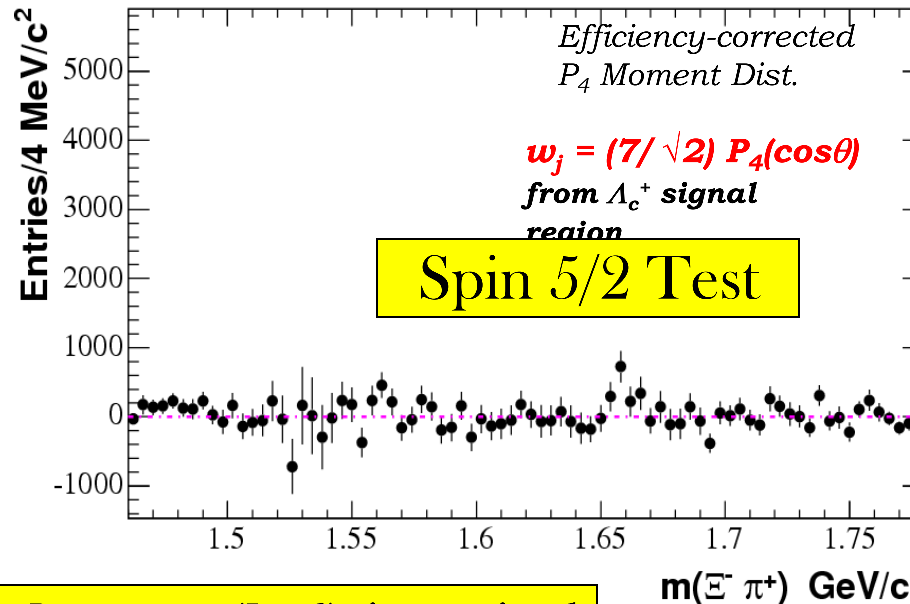
Rectangular Dalitz plot



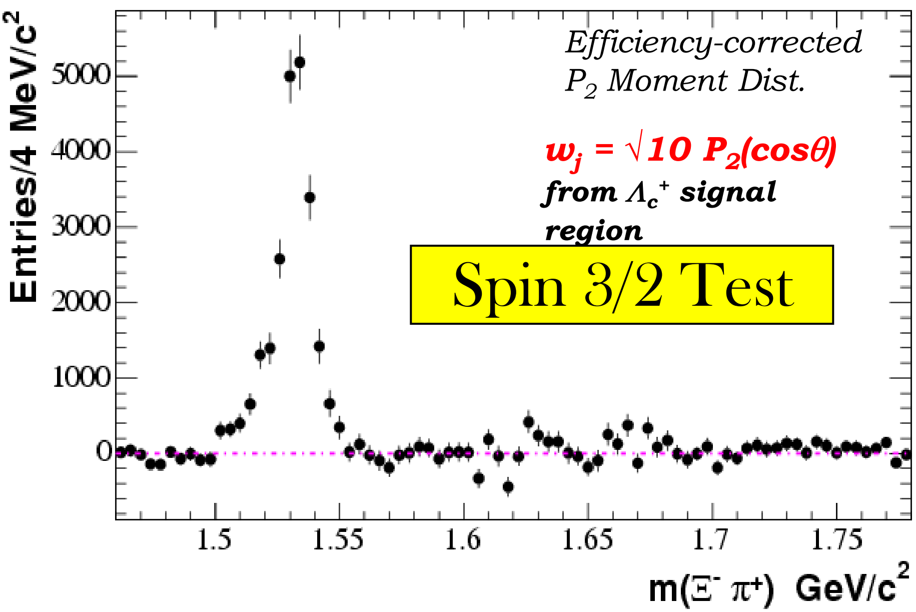
Note: $m^2(\Xi^- K^+)$ depends linearly on $\cos\theta_\Xi$

Using Legendre Polynomial Moments to Obtain Ξ(1530) Spin Information





• **P_L moments ($L \geq 6$) give no signal**



⇨ spin 3/2 *clearly* established

⇨ spin 5/2 ruled out

Schlein et *al.* showed $J^P = 3/2^+$ or $J^P = 5/2^-$, and claimed J>3/2 *not required.*
[Phys.Rev.Lett.11, 167 (1963), Phys.Rev.142,883 (1966)]

" Spin-parity $3/2^+$ is favored by the data" [PDG (2006)]

⇨ Present analysis by establishing J=3/2 also establishes positive parity *by implication* **[i.e. P-wave resonance]**

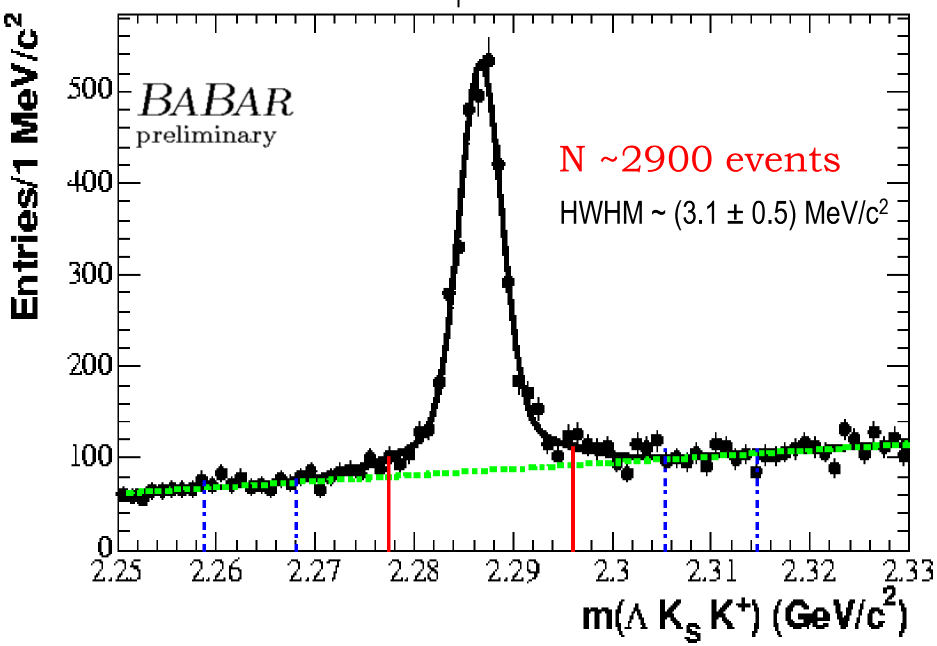
• *Other interesting aspects of Dalitz plot – not as simple as it first appears !*

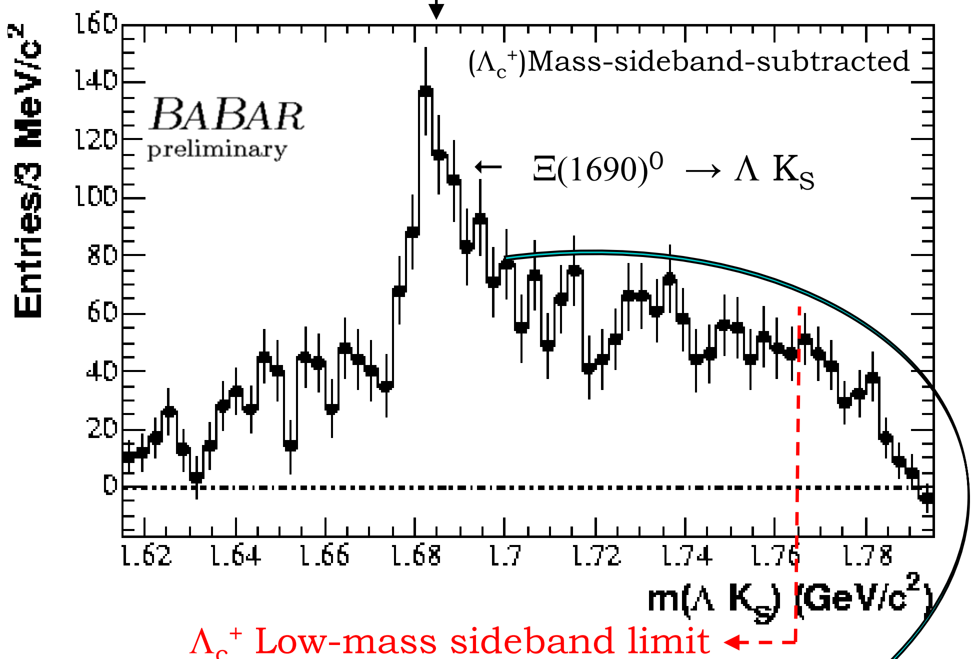
The $\Xi(1690)^0$ from $\Lambda_c^+ \rightarrow (\Lambda\, K_S)\, K^+$ Decay

$m(\Lambda\, K_S) \leftrightarrow \Lambda_c^+$ mass-signal region

□ $m(\Lambda\, K_S) \leftrightarrow \Lambda_c^+$ mass-sideband region

$m(\Lambda\, K_S) \leftrightarrow (\Lambda_c^+)$ mass-sideband-subtracted

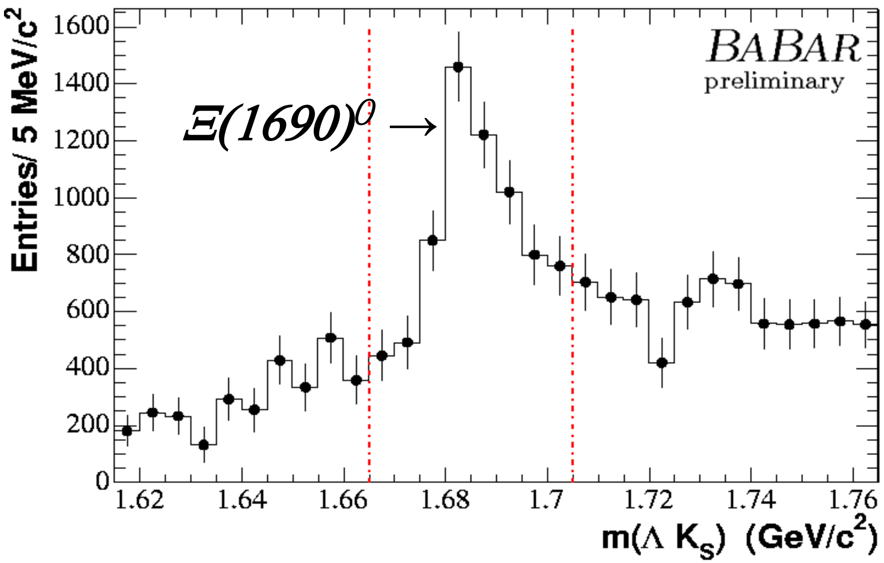


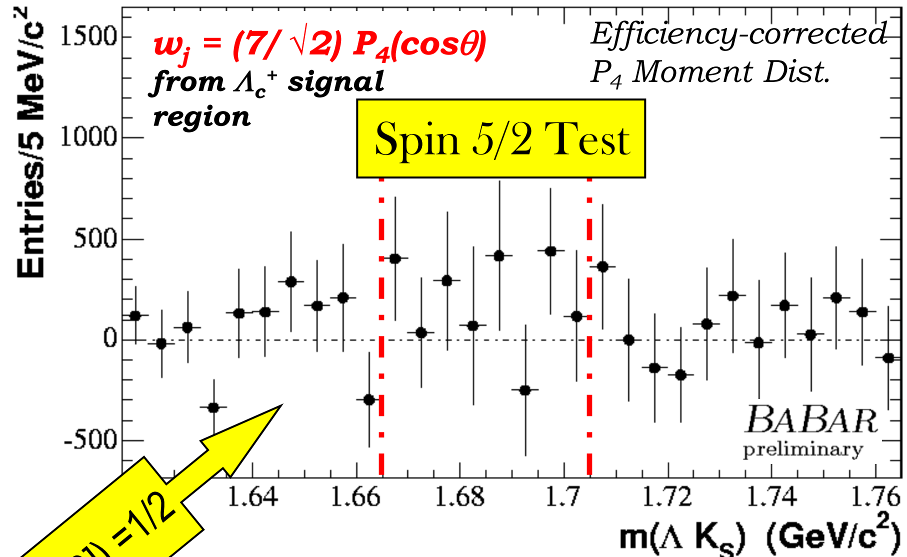


Note skewing

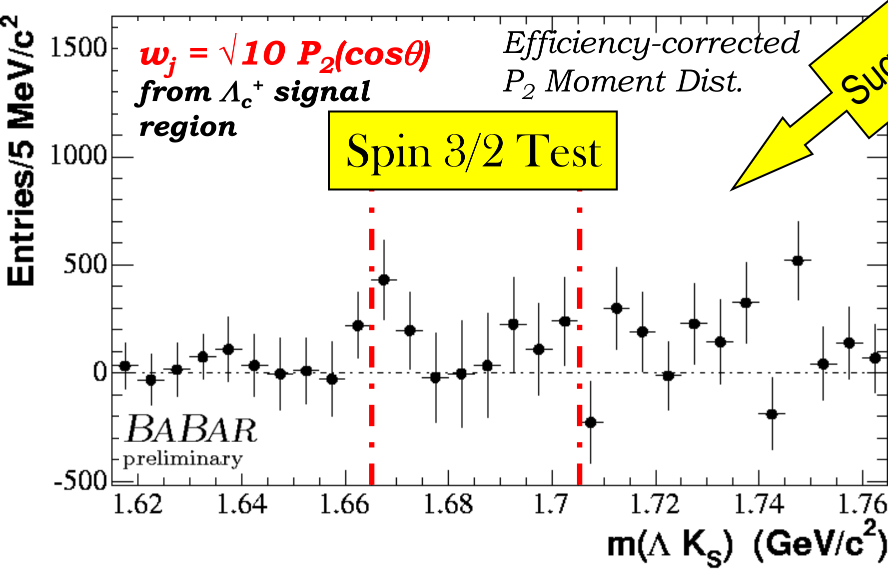
Using Legendre Polynomial Moments to Obtain Ξ(1690) Spin Information

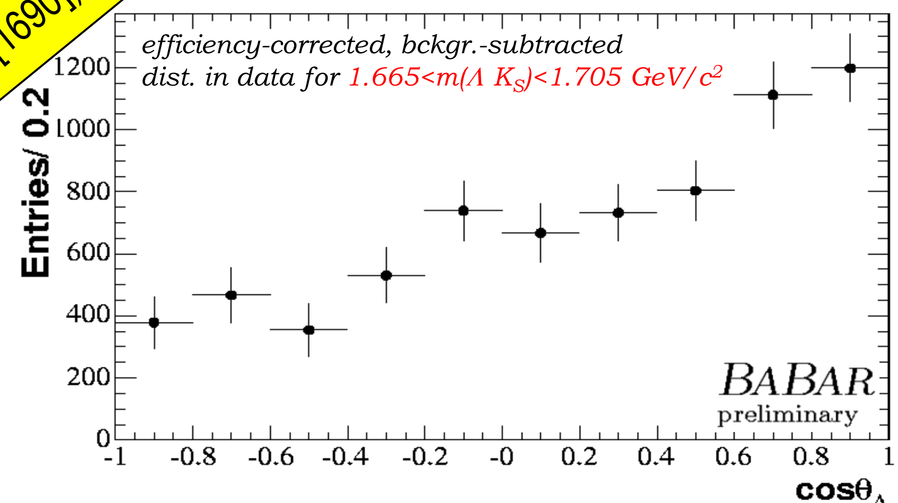
— *efficiency-corrected, background-subtracted unweighted m(Λ K$_S$) distribution in data*





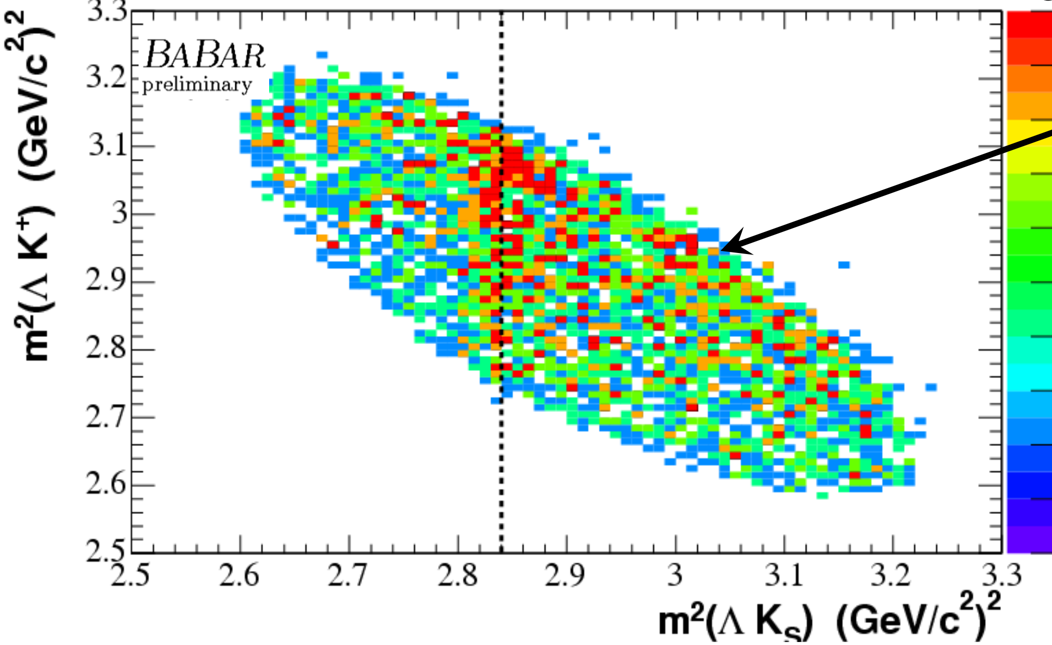
Suggest J(Ξ[1690]) =1/2





…however cosθ$_Λ$ clearly not flat
as expected for J = 1/2
WHY?

Dalitz plot for $\Lambda_c^+ \rightarrow \Lambda K_S K^+$



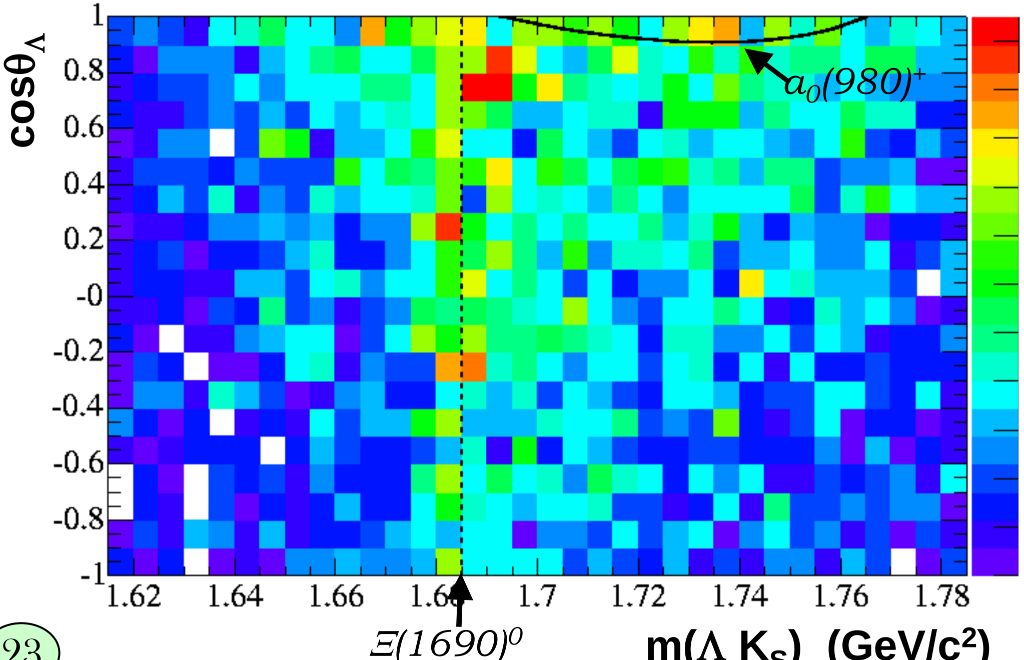
Accumulation of events in $K_S K^+$ near threshold ⇨ evidence of $a_0(980)^+$

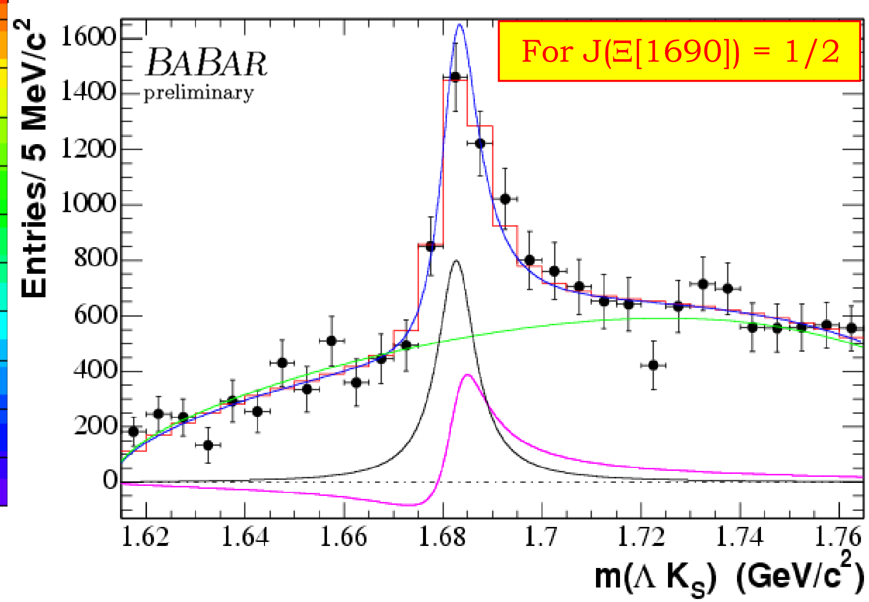
$m = 1682.9 \pm 0.9(stat) \pm 0.8(syst)$ MeV/c^2

$\Gamma = 9.3^{+2.0}_{-1.7}(stat) \pm 0.4(syst)$ MeV

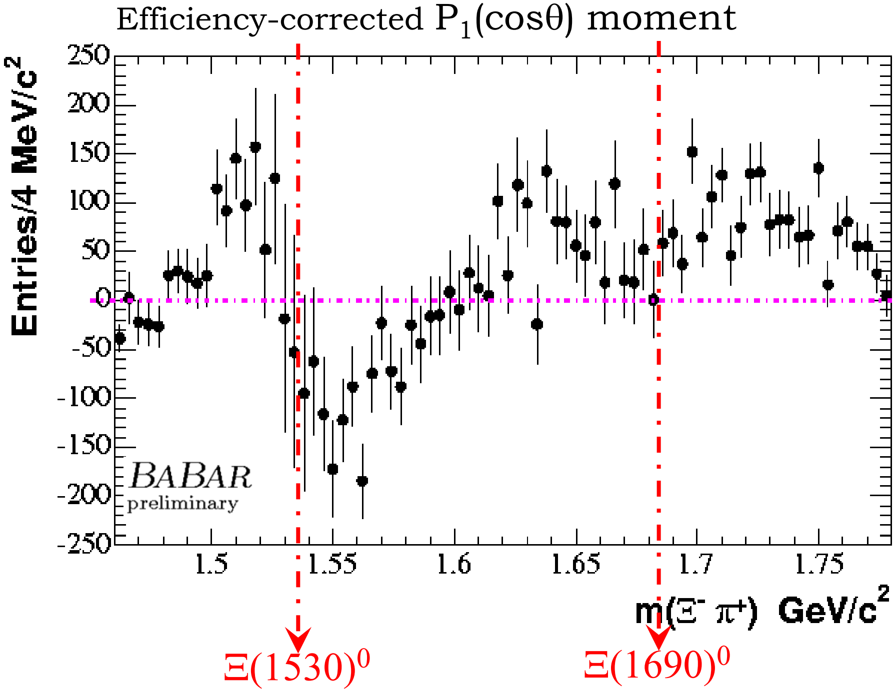
$J = 1/2$ favored

- ● Background-subtracted, efficiency-corrected data
- — Integrated signal function ***smeared*** by mass resolution [Histogram]
- — Signal function with no ***resolution smearing***
- — $|A(a_0(980)|^2$ contribution
- — $|A(\Xi(1690)|^2$ contribution
- — *Interference* term contribution





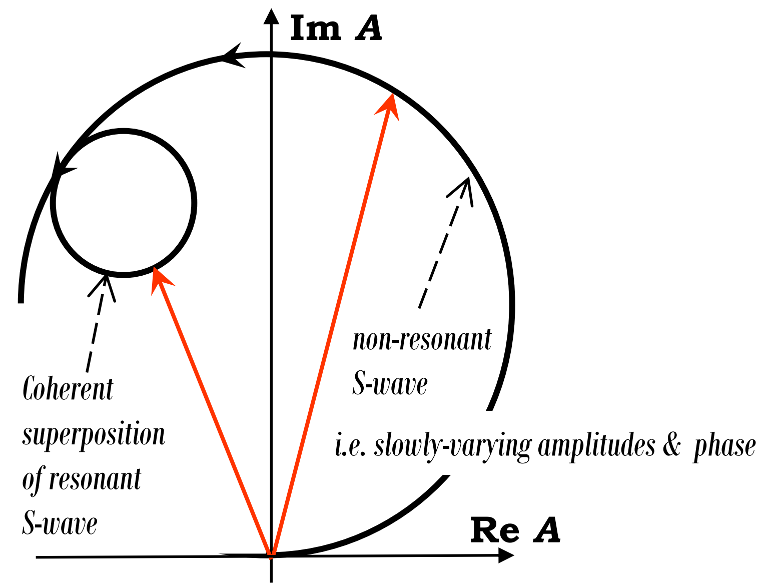
Evidence for the $\Xi(1690)$ in $\Lambda_c^+ \rightarrow \Xi^- \pi^+ K^+$



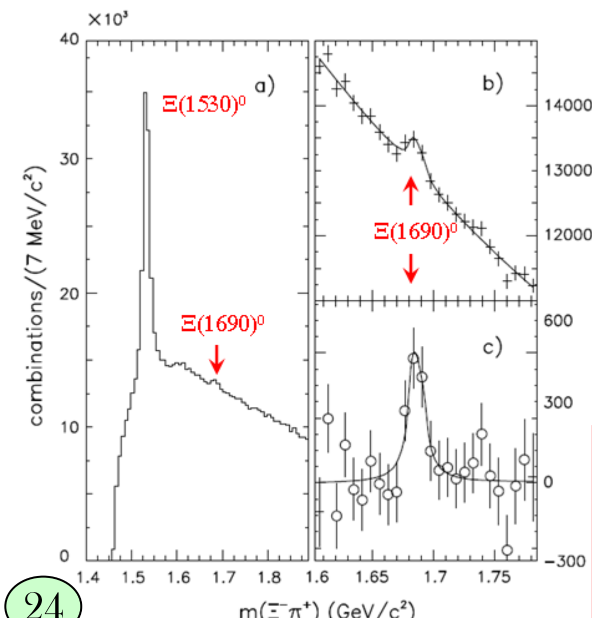
$\Xi(1690)$ seen in inclusive environment in hyperon beam expt.

M.I. Adamovich *et al.* Eur.Phys.J. C5, 621 (1998)

S-P interference -- dip at 1690 MeV/c



➯ *negative parity for* $\Xi(1690)$



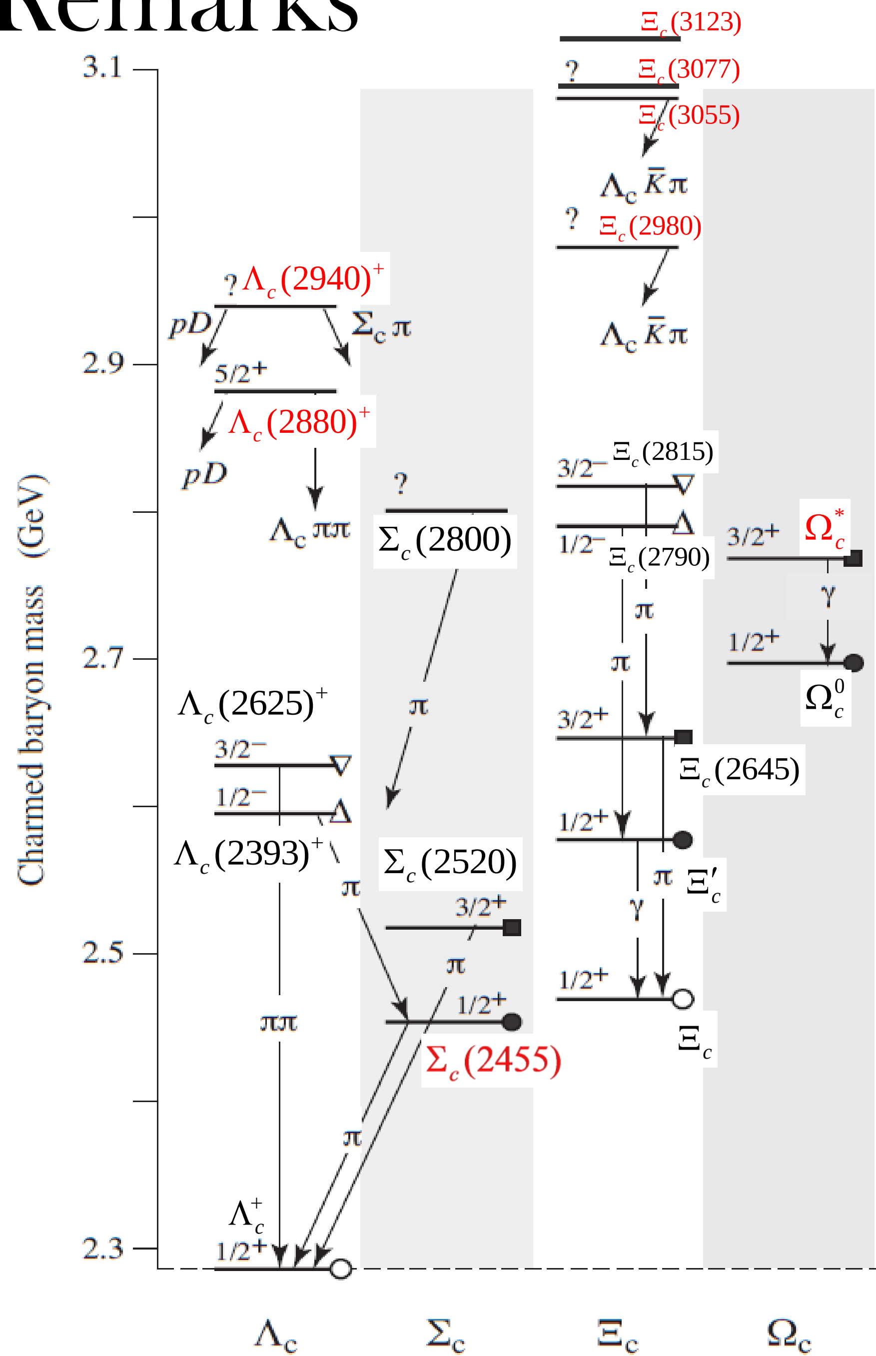
Speculation:

Dip (~1680 MeV/c²) may be due to *resonant* $\Xi(1690)^0$ S-wave

Implications for Lattice calculations and models of level structure of Ξ excited states

Concluding Remarks

- Lots of progress in charm baryon spectroscopy
- Insight into charm baryon production
- Measurements of charm baryon spin from exclusive B decay processes
- Insight into light quark spectroscopy from hyperon resonances produced in charm baryon decay

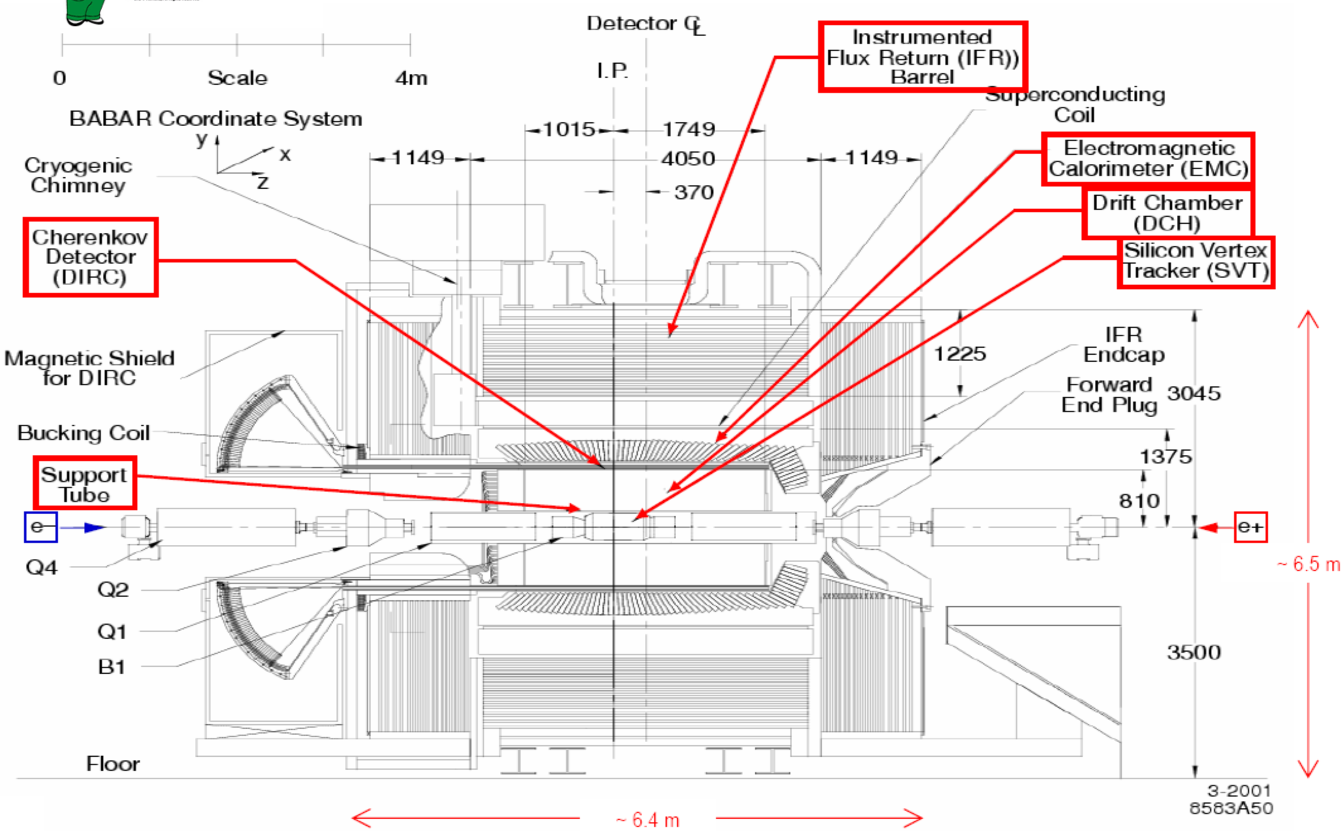


Concluding Remarks

- Future experiments expected to provide large charm baryon samples to further our understanding of heavy flavor baryons
  - LHCb
  - Super-B
  - GlueX [associated production; e.g. $\gamma p \rightarrow \Lambda_c^+ \overline{D}^0$]

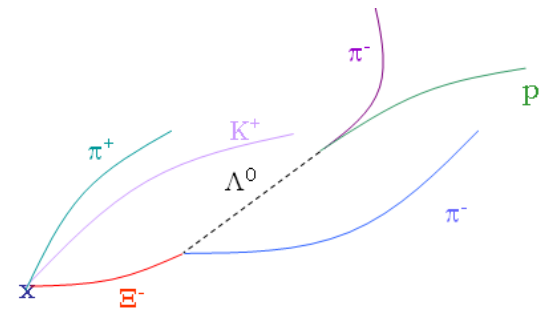
BACKUP SLIDES

BaBar-GlueX Comparisons



Reminder:

Ξ topology Diagram

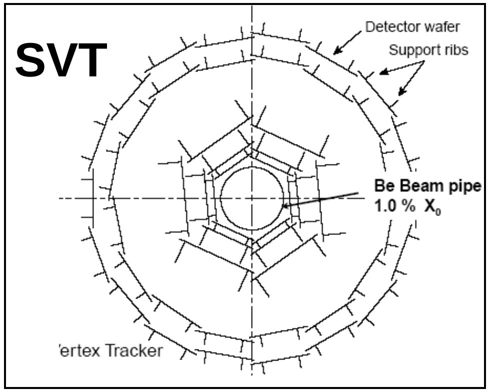


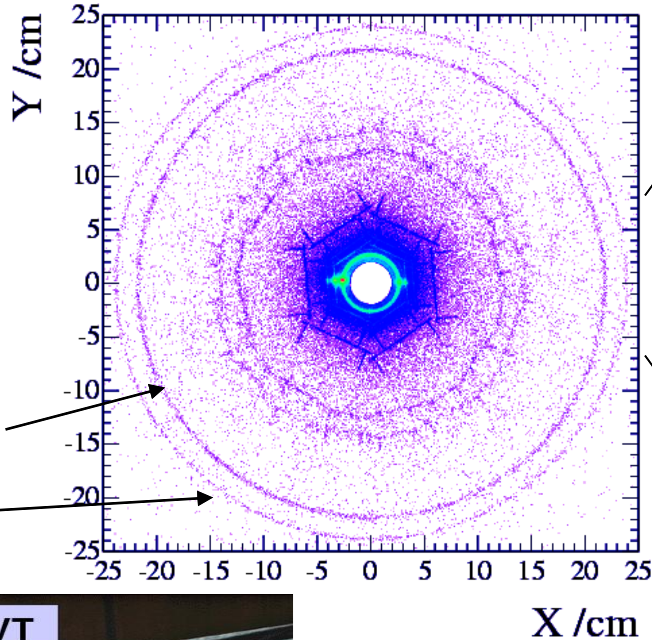
(*) Would also like to reconstruct Ξ^0.
[Note: 1st Ω^- event in BC was $\Omega^- \to \Xi^0\ \pi^-$]

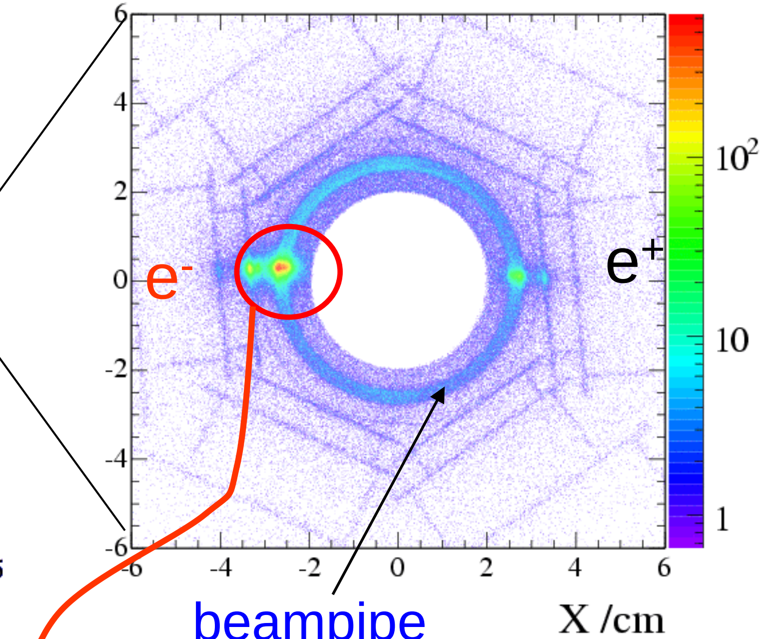
- Large acceptance, multi-pupose detector
  - Acceptance: $-0.92 < \cos\theta^* < 0.85$ (θ^* : c.m.s. polar angle w.r.t. collision axis)
- Excellent charged particle tracking (SVT & Drift Chamber) and P.I.D. (& DIRC)
- Excellent γ measurement (i.e. $\pi^0 \to \gamma\ \gamma$, $\eta \to \gamma\ \gamma$, etc.) in EMC

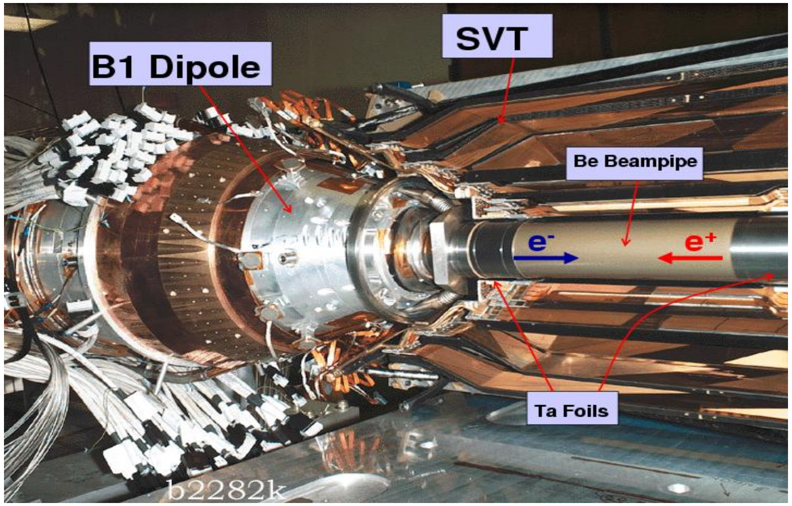
Excellent Vertex Reconstruction Capability (1)

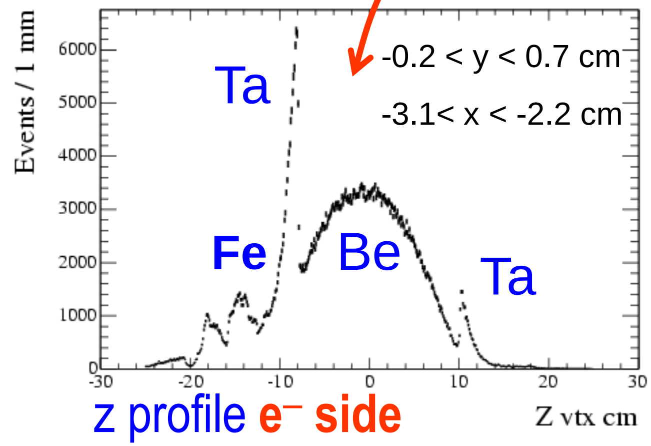
233 fb^{-1} $e^+ e^-$ data

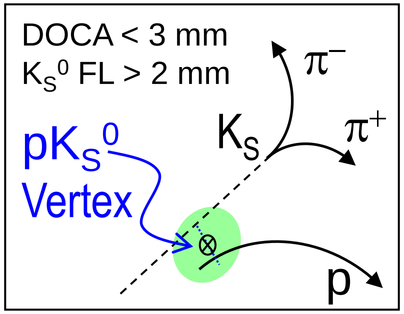




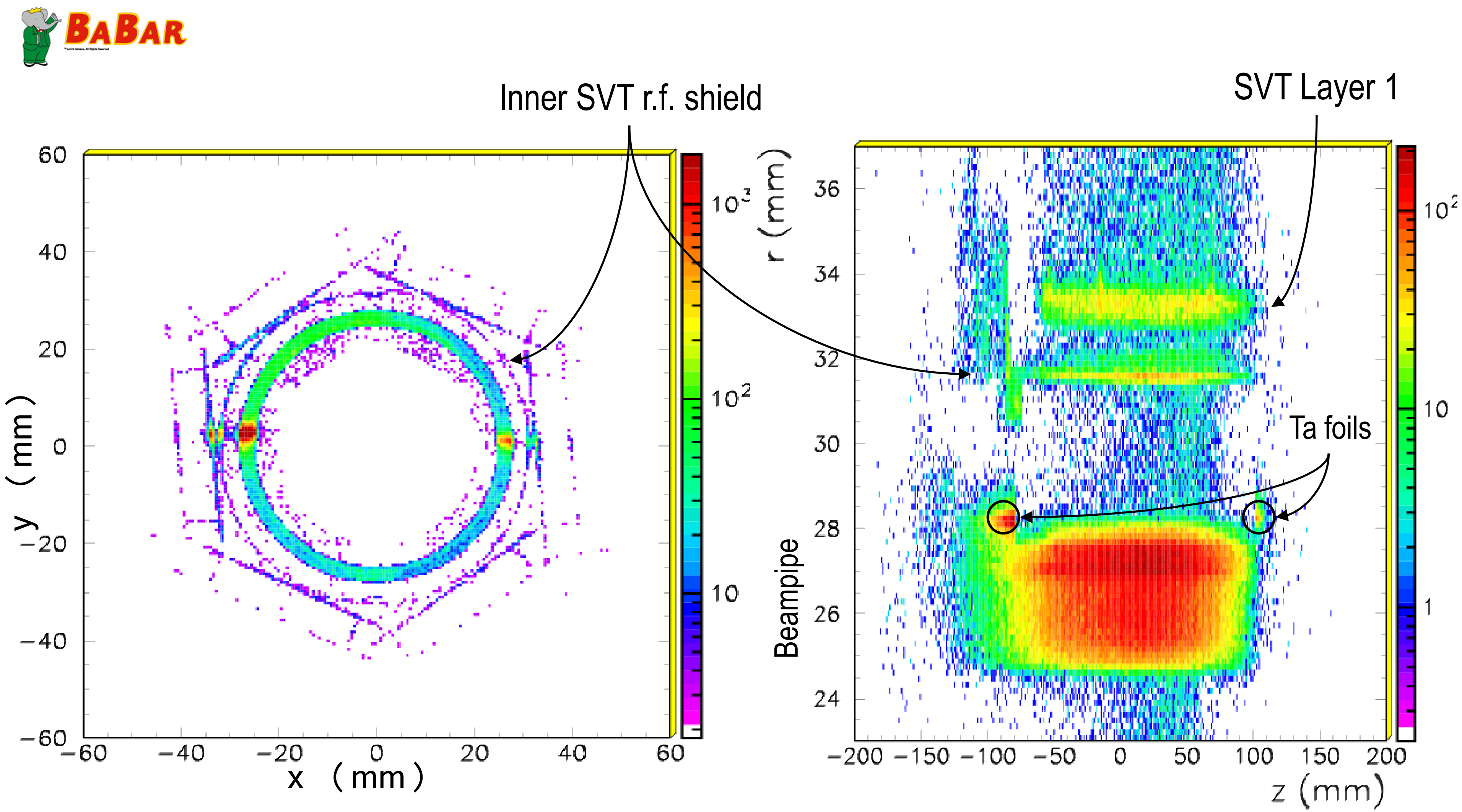




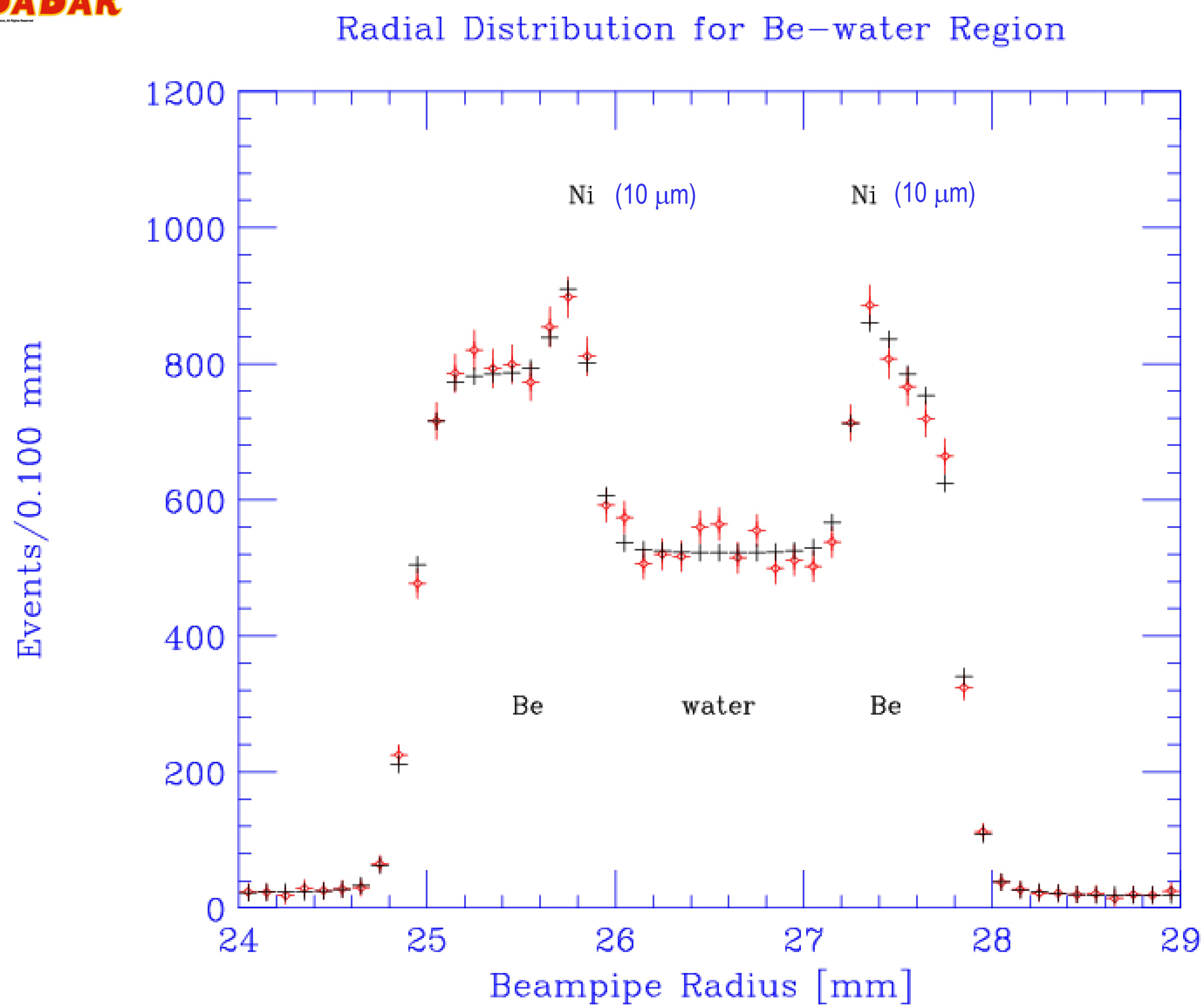




Excellent Vertex Reconstruction Capability (2)



Excellent Vertex Reconstruction Capability (3)

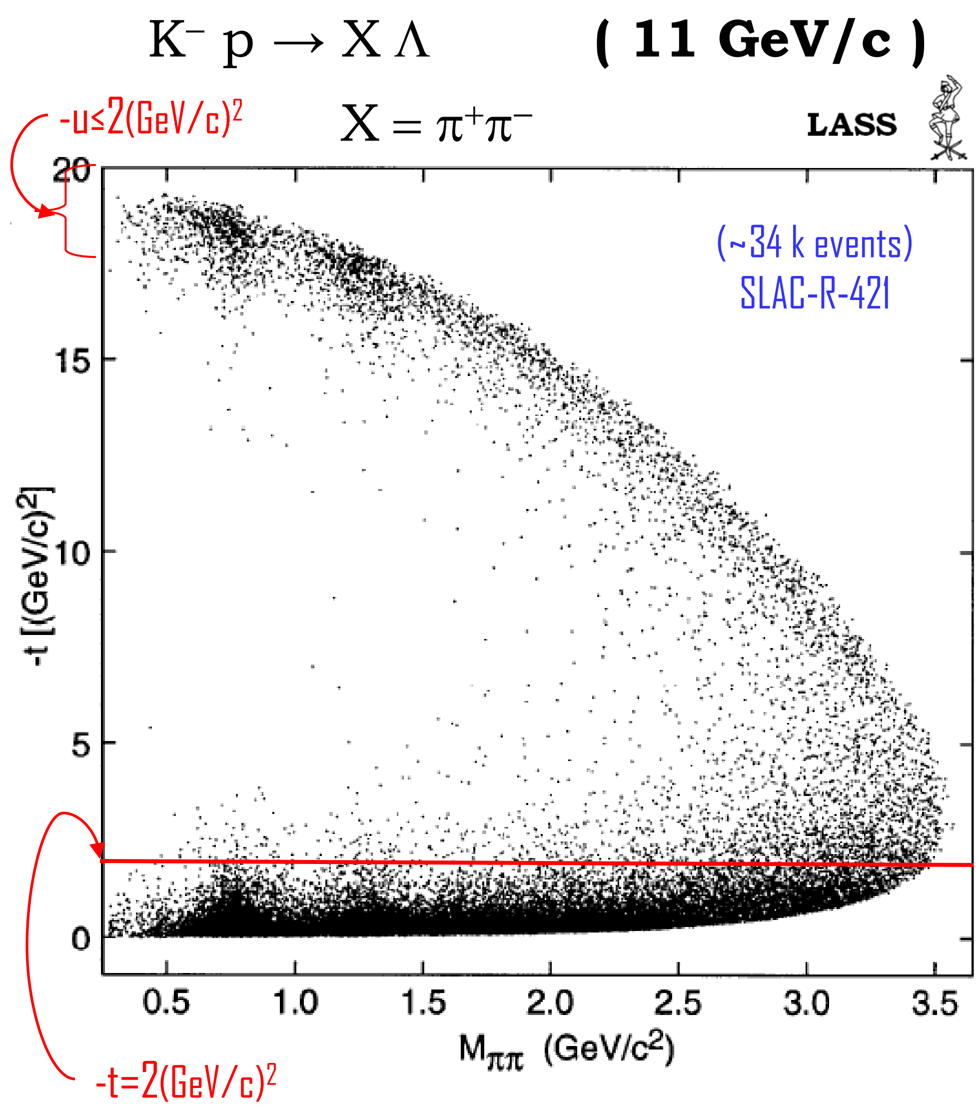


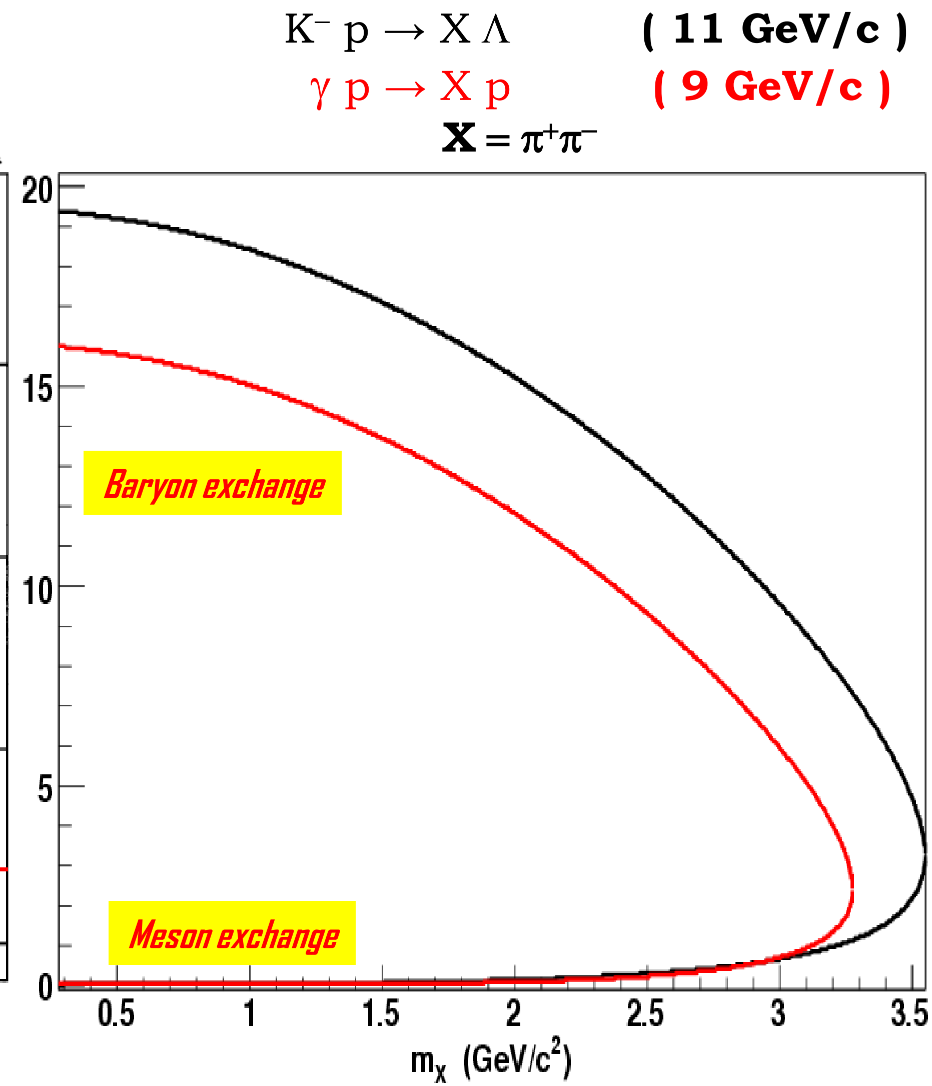
Radial Vertex Resolution ~ 90 μm

measured

\+ fit

Chew-Low Plot Acceptance





Possible Ξ Studies with GlueX

1. Survey Processes to Provide an Overview of $\Xi(*)$ Photoproduction
   - Inclusive Ξ^- (Ξ^0 ?) Production
     - Feynman x and p_T^2 distributions
     - Chew-Low plot(s)
     - Polarization measurements
     - Etc…

   - Similar Studies for Cascade Resonance Production (e.g. $\Xi(1530)\rightarrow\Xi^-\pi^+$) and Associated Spectra
     - Note: In the LASS search for Ω^{*-} states, the inclusive mass distribution for ($\Xi^-\pi^+K^-$) showed nothing; however when the ($\Xi^-\pi^+$) was selected to correspond to the $\Xi(1530)^0$, a signal for the $\Omega(2250)^-$ was observed.

Possible Ξ Studies with GlueX (ctd.)

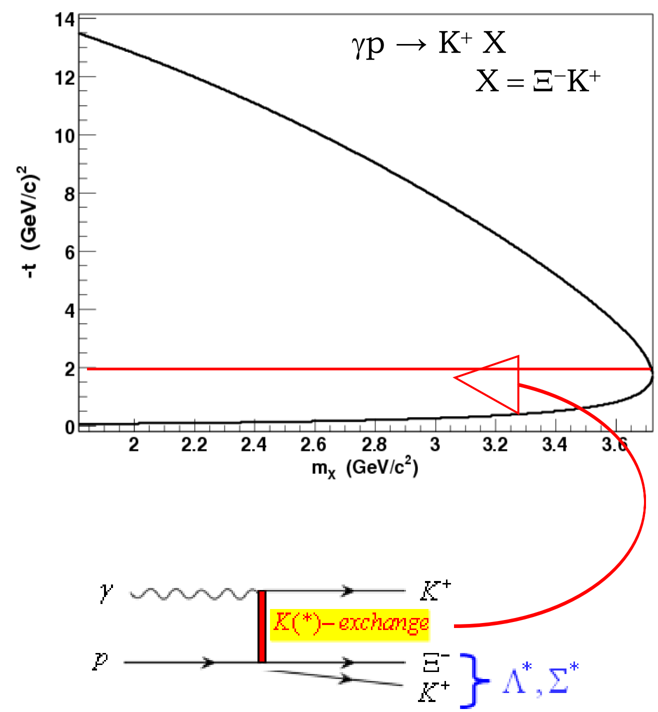
2. Exclusive t-channel (i.e. meson exchange) Processes
   - Production of two-body systems with a Ξ

     e.g. $\gamma\, p \rightarrow K^+\ (\Xi^- K^+)$

     $\rightarrow K^+\ (\Xi^0 K^0)$

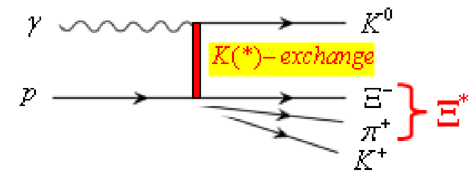
     $\rightarrow K^0\ (\Xi^0 K^+)$

     would enable the study of high mass Λ^* and Σ^* states decaying via these Ξ modes.



Possible Ξ Studies with GlueX (ctd.)

- Production of three-body systems with a Ξ, or a Ξ* system with two-body decay:



with a forward K^0:

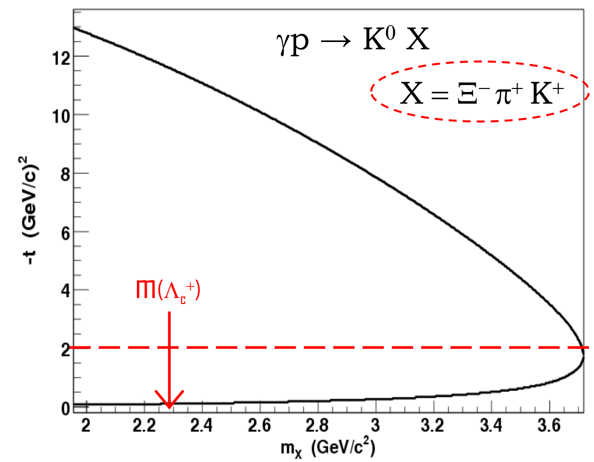
Σ^*, Λ^*

e.g. $\gamma p \rightarrow K^0$ $\boxed{(\Xi^- \pi^+)\ K^+}$, K^0 $(\Xi^0 \pi^0)$ K^+, K^0 $(\Xi^0 K^0)$

$\rightarrow K^0$ $\boxed{(\Lambda \overline{K^0})\ K^+}$

States analyzed in Λ_c^+ decay

- can observe in a totally different context



with a forward K^+:

e.g. $\gamma p \rightarrow K^+$ $(\Xi^- \pi^+)$ K^0, K^+ $(\Xi^- \pi^0)$ K^+

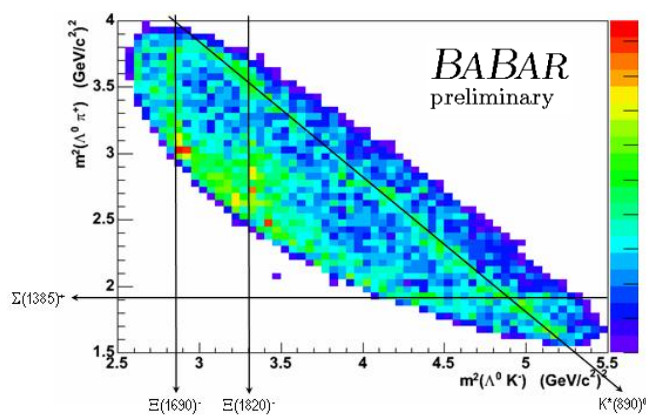
$\rightarrow K^+$ $(\Xi^0 \pi^-)$ K^+, K^+ $(\Xi^0 \pi^0)$ K^0

$\rightarrow K^+$ (ΛK^-) K^+

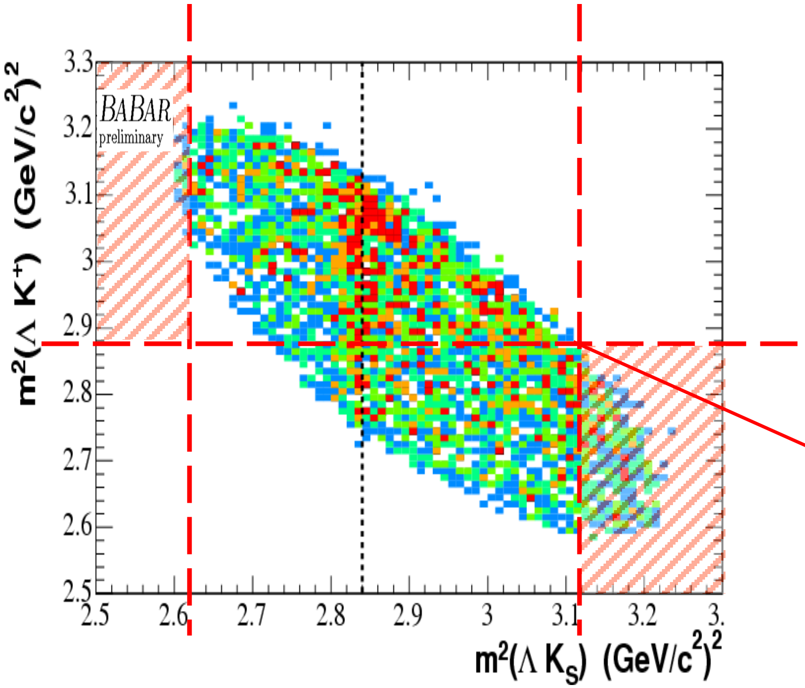
- Interesting four-body possibilities when add pion

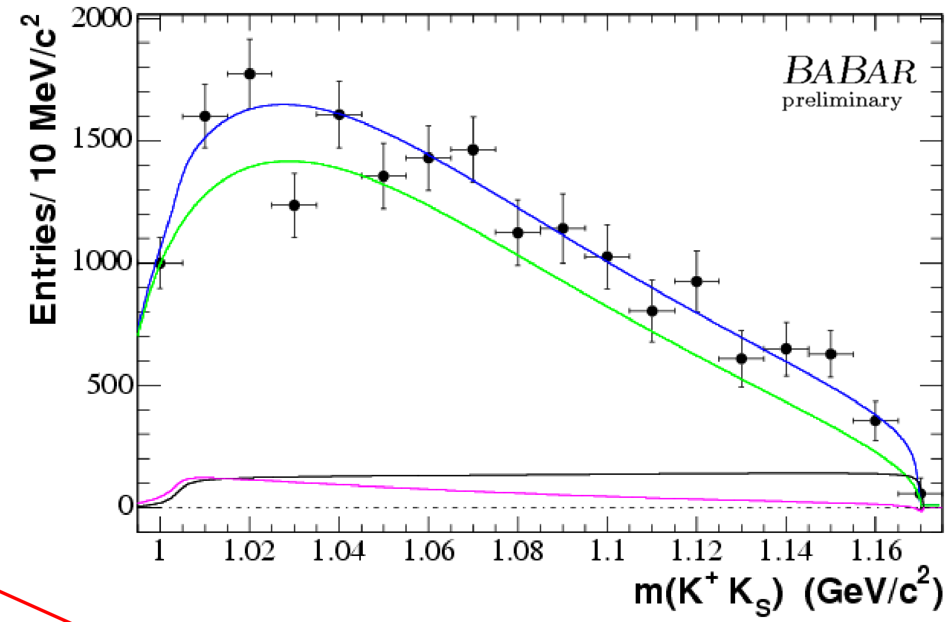
e.g. $\gamma p \rightarrow K^+$ $(\Lambda K^- \pi^+)$ K^+,

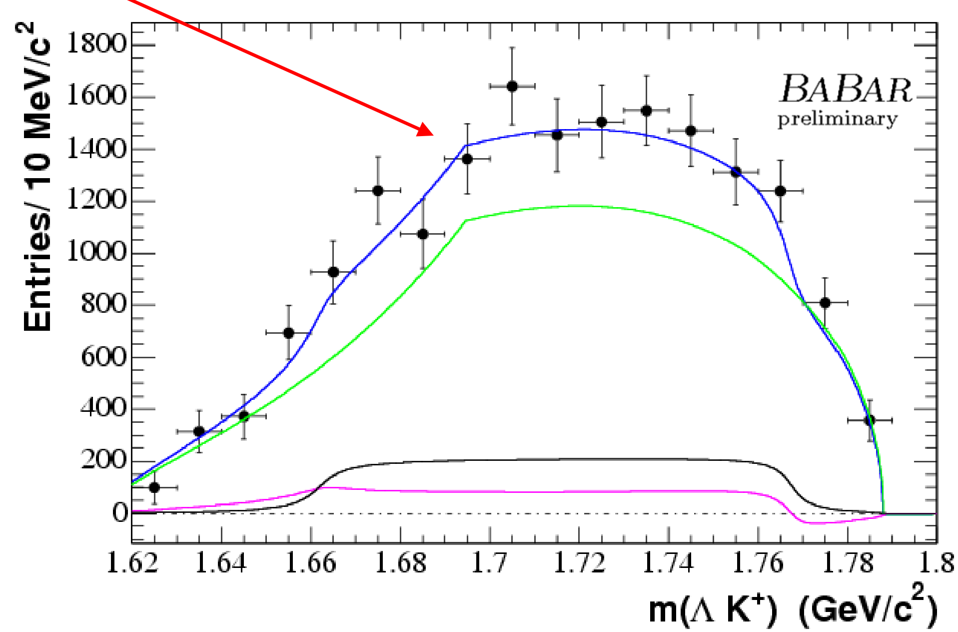
  - accessible at BaBar via $\Xi_c^0 \rightarrow \Lambda K^- \pi^+$, complicated Dalitz plot



Fit Results: $(K^+ K_S)$ & (ΛK_S) Mass Projections







$m(\Lambda K_S)$ mass cut-off

$[1.62 < m(\Lambda K_S) < 1.765\ GeV/c^2]$

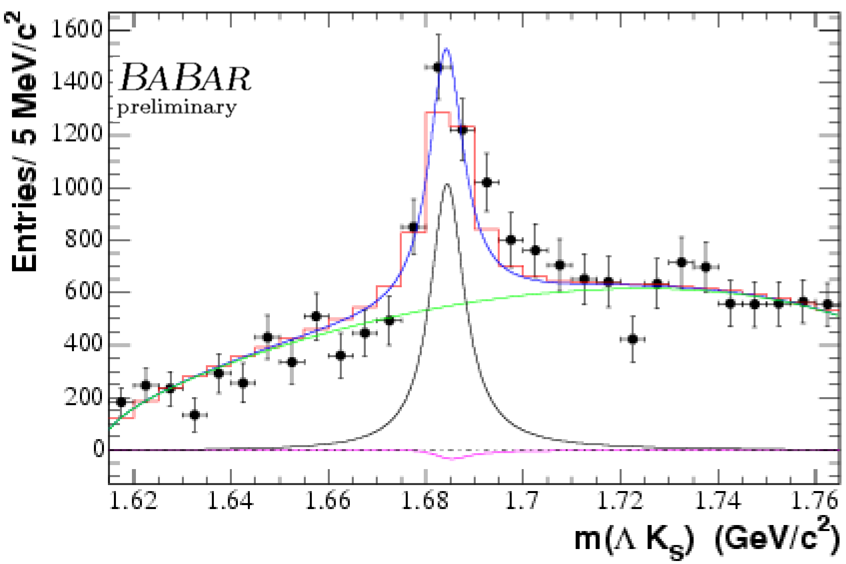
introduces a kink because of restricted range of (ΛK^+) helicity cosine

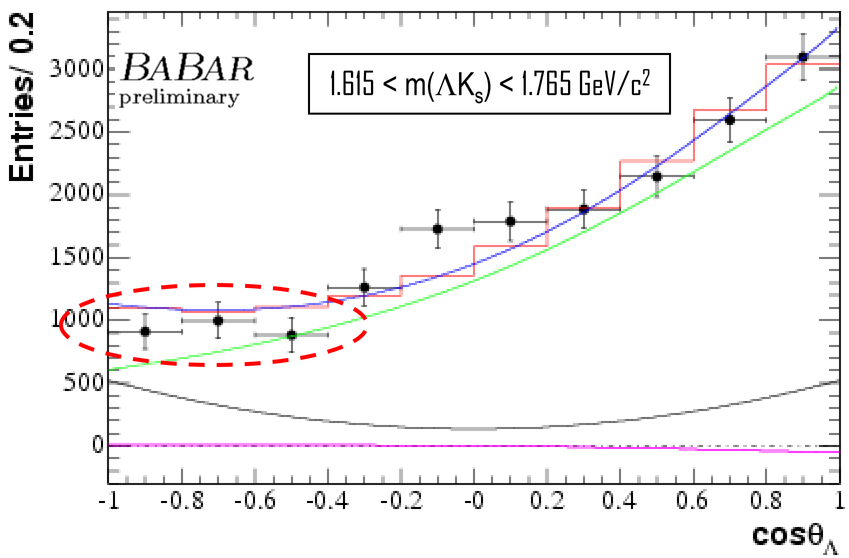
Comparison of Max. Likelihood Fit Result to the Signal Projections

Under the assumption of spin 3/2 for the $\Xi(1690)$:

$$I = pq\, C \left[p_0^2 I_1 \left(\frac{3\cos^2\theta_\Lambda + 1}{4} \right) + \frac{g_{\bar{K}K}^2 I_2}{2} + \frac{k}{\sqrt{2}} (\cos\theta_\Lambda)\, p_0 g_{\bar{K}K} I_1 I_2 \left[(M_1 M_2 + G_1 G_2)\cos\delta + (\mathrm{G}_1\mathrm{M}_2 - \mathrm{G}_2\mathrm{M}_1)\sin\delta \right] \right]$$

$\chi^2/\mathrm{NDF} = 234.3/192$
C. L. = 1.9 %





Interference term very small
⇨ Equiv. to incoherent superposition of amplitudes

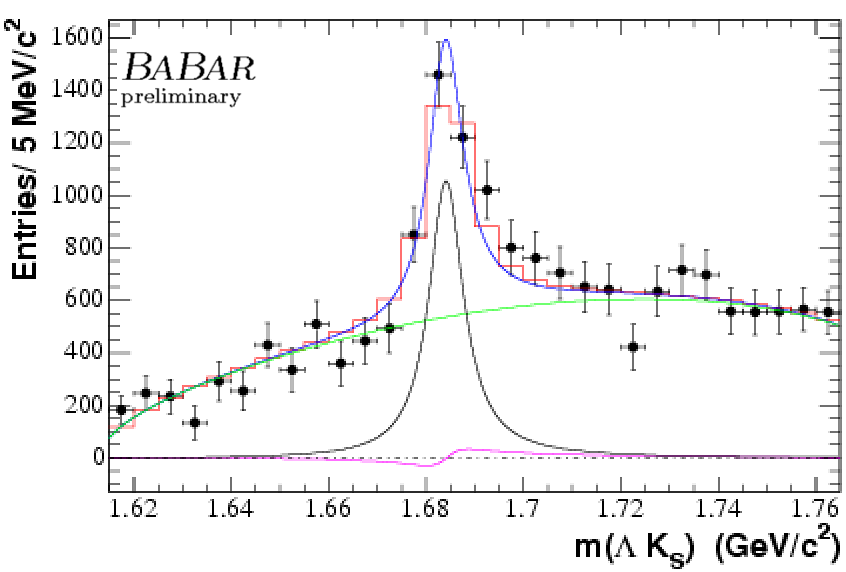
Lineshape skewing not reproduced!

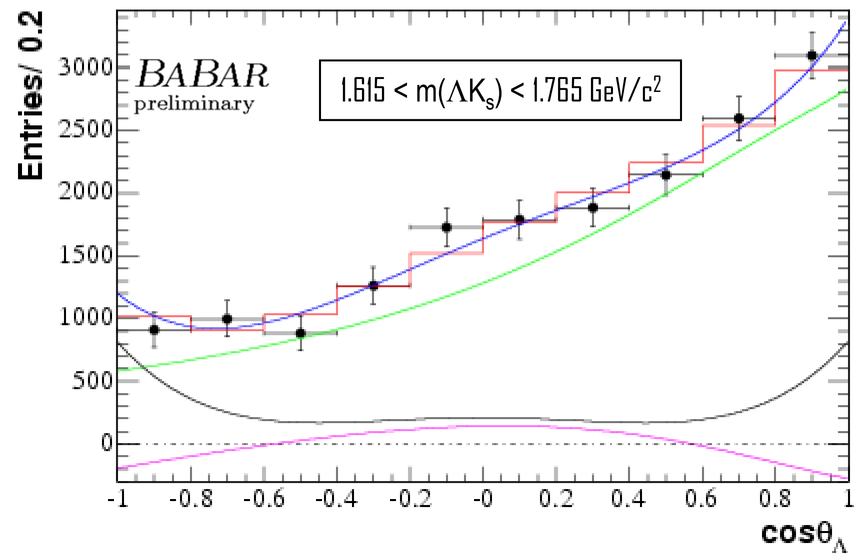
Comparison of Max. Likelihood Fit Result to the Signal Projections

Under the assumption of spin 5/2 for the $\Xi(1690)$:

$$I = pq\,C\left[p_0^2 I_1\, 3\left(\frac{5\cos^4\theta_\Lambda - 2\cos^2\theta_\Lambda + 1}{8}\right) + \frac{g_{\bar{K}K}^2 I_2}{2} + \frac{\sqrt{3}k}{4}\left(3\cos^2\theta_\Lambda - 1\right) p_0 g_{\bar{K}K} I_1 I_2\left[(M_1M_2 + G_1G_2)\cos\delta + (G_1M_2 - G_2M_1)\sin\delta\right]\right]$$

$\chi^2/NDF = 210.3/192$
C. L. $= 17.4\ \%$





Net interference term very small
⇨ Equiv. to incoherent superposition of amplitudes

Lineshape skewing not reproduced!

Summary of Results & Systematic Uncertainties

Source	Estimated Systematic Uncertainty	Spin 1/2
Background Normalization and Parametrization	$\Xi(1690)^0$ Mass [MeV/c^2]	0.0
	$\Xi(1690)^0$ Width [MeV]	±0.2
Resolution Function Lineshape	$\Xi(1690)^0$ Mass [MeV/c^2]	0.0
	$\Xi(1690)^0$ Width [MeV]	±0.1
Efficiency Parametrization	$\Xi(1690)^0$ Mass [MeV/c^2]	±0.1
	$\Xi(1690)^0$ Width [MeV]	±0.1
Orbital Ang. Momentum Variation	$\Xi(1690)^0$ Mass [MeV/c^2]	±0.2
	$\Xi(1690)^0$ Width [MeV]	±0.1
$a_0(980)^+$ Parameter Values	$\Xi(1690)^0$ Mass [MeV/c^2]	±0.1
	$\Xi(1690)^0$ Width [MeV]	±0.3
Detector Effects	$\Xi(1690)^0$ Mass [MeV/c^2]	±0.1
	$\Xi(1690)^0$ Width [MeV]	0.0
Total Systematic Uncertainty	$\Xi(1690)^0$ Mass [MeV/c^2]	±0.3
	$\Xi(1690)^0$ Width [MeV]	±0.4

Spin 1/2 favored

$\Xi(1690)$ Spin	$\Xi(1690)$ Mass [MeV/c^2]	$\Xi(1690)$ Width [MeV]	k	δ [rad]	χ^2/NDF	C.L. (%)
1/2	1682.9 ± 0.9	9.3 ± 1.9	0.4 ± 0.2	0.3 ± 0.5	188.4/192	56.4
3/2	1684.9 ± 0.8	8.8 ± 2.1	0.2 ± 0.2	-2.7 ± 1.1	234.3/192	1.9
5/2	1684.9 ± 0.8	9.0 ± 2.0	0.9 ± 0.2	2.4 ± 0.2	210.3/192	17.4

Poor C.L.

Accept. C.L.

Fail to reproduce skewed lineshape; fit mass value moves higher in attempt to compensate

MIGRAD FIT PARAMETER VALUES

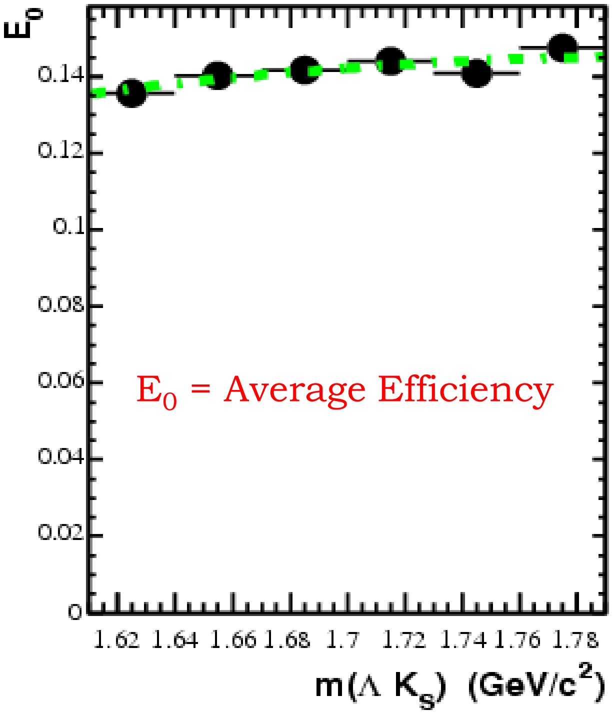
Fit Parameter	Value	Neg. Error	Pos. Error
$\Xi(1690)$ Ampl. Rel. Strength [MeV] (p_0)	24 ± 8	–	–
$\Xi(1690)$ Mass [MeV/c^2]	1682.9 ± 0.9	-0.9	+0.9
$\Xi(1690)$ Width [MeV]	9.3 ± 1.9	-1.7	+2.0
Effective Phase δ [rad.]	0.3 ± 0.5	-0.4	+0.6
Effective Scale k	0.4 ± 0.2	-0.2	+0.3
Overall Normalization Factor	1205 ± 726	–	–
$g_{\bar{K}K}$ [MeV]	349 ± 136	–	–
Coupling Ratio Squared (r^2)	0.5 ± 0.4	–	–

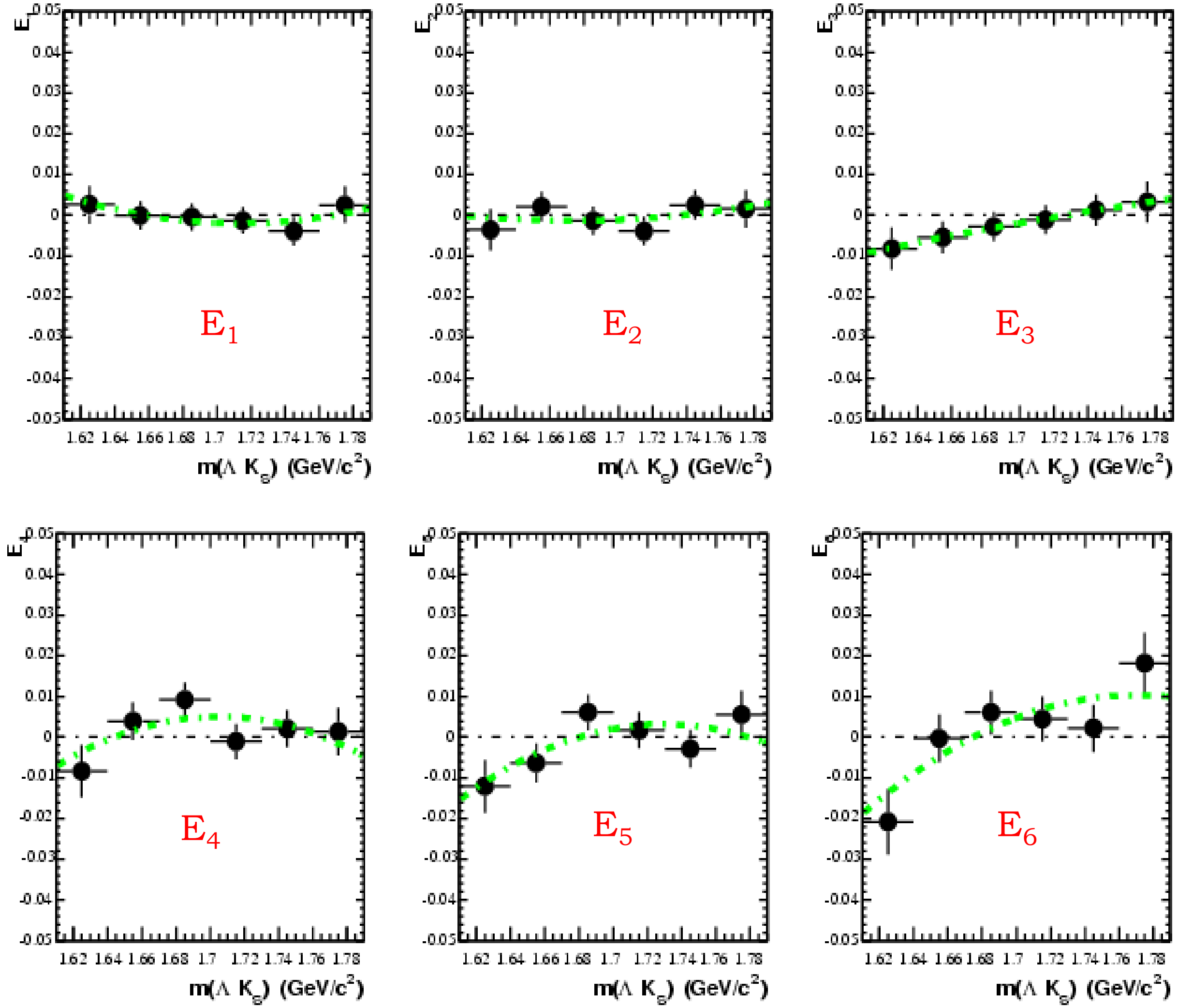
Fit χ^2/NDF = 188.4/192
Prob. = 56.4%

SLAC-R-868

Very uniform $\Lambda_c^+ \to \Lambda\, \overline{K}^0\, K^+$ Dalitz Plot Acceptance

Efficiency Parametrization as a Function of $m(\Lambda K_S)$



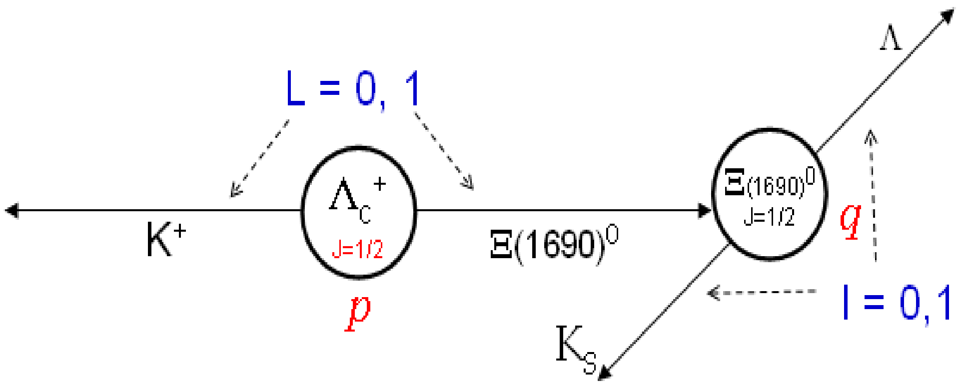


Smooth **efficiency as a fcn of (m, cosθ)**

E_i = fcn(mass)
= 2nd order polynomial

Weak dependence on $\cos\theta_\Lambda$

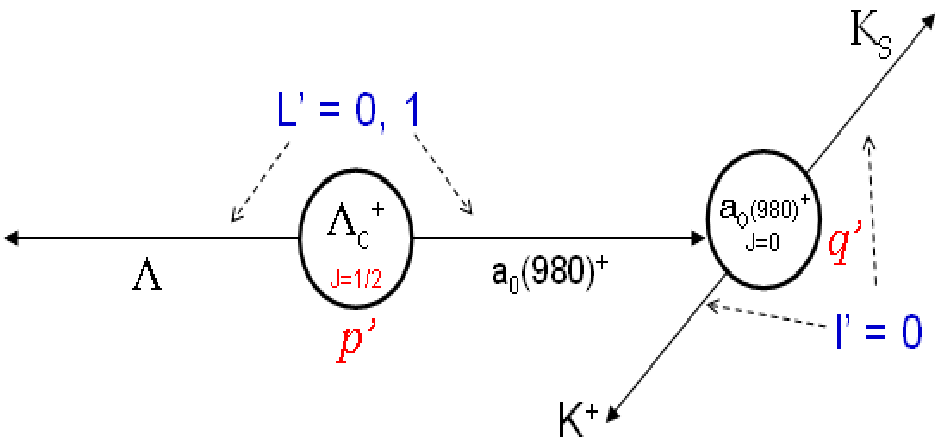
Isobar Model Description of the $\Lambda_c^+ \to \Lambda\, \overline{K}^0 K^+$ Dalitz Plot



$$A(\Xi[1690]) = \frac{p^L \cdot q^l}{(m_0^2 - m^2) - i m_0 \Gamma(m)}$$

$$\Gamma(m) = \Gamma(m_0)\frac{q^{2l+1}}{m}\frac{m_0}{q_0^{2l+1}}$$

$\boxed{\text{Fit for } m_0 \ \& \ \Gamma(m_0) \text{ with } L=0,\ l=0}$



$$A(a_0[980]) = \frac{g_{\bar{K}K}}{m_a^2 - m_{\bar{K}K}^2 - i g_{\bar{K}K}^2 \left(\rho_{\bar{K}K} + \frac{1}{r^2}\rho_{\eta\pi}\right)}$$

$m_a = 999\ MeV/c^2$ $\quad \rho_j(m) = 2q_j/m$

$r = g_{\bar{K}K}/g_{\eta\pi}$

$\boxed{\text{Fit for } g_{\bar{K}K} \ \& \ r \text{ with } m_a \text{ fixed}}$

$g_{\eta\pi} = 324 \pm 15\ MeV$ [Crystal Barrel Exp.]

$g_{\bar{K}K} = 473 \pm 49\ MeV$ [BaBar Exp.]

A. Abele *et al.*, Phys. Rev. D57, 3860 (1998). B. Aubert *et al.*, Phys. Rev. D72, 052008 (2005)

Isobar Model Description of the $\Lambda_c^+ \rightarrow \Lambda\, \bar{K}^0\, K^+$ Dalitz Plot

relative strength

Under the assumption of spin 1/2 for the Ξ(1690):

$\Lambda a_0(980)^+$ - $\Xi(1690)^0 K^+$ Interference

$$|A|^2 = C\left\{\boxed{p_0^2 I_1 + g_{\bar{K}K}^2 I_2} + \underbrace{\boxed{2p_0 g_{\bar{K}K} I_1 I_2 k\left[(M_1M_2 + G_1G_2)\cos\delta + (G_1M_2 - G_2M_1)\sin\delta\right]}}_{\Lambda a_0(980)^+ - \Xi(1690)^0 K^+ \text{ Interference}}\right\}$$

Weak decay
yields 4 terms with same structure but different amplitude and phase
Hence define:

effective scale

effective phase

$$M_2 = (m_a^2 - m_{\bar{K}K}^2)$$

$$m_{\bar{K}K} = \sqrt{m_{\bar{K}}^2 + m_K^2 + 2\left(E_{\bar{K}}E_K - qp'\cos\theta_\Lambda\right)}$$

where p' = *momentum of* K^+ *in* ($\Lambda\, K_S$) *rest-frame.*

$$G2 = \rho_{\eta\pi} g_{\eta\pi}^2 + \rho_{\bar{K}K} g_{\bar{K}K}^2$$

$$M_1 = (m_0^2 - m^2)$$

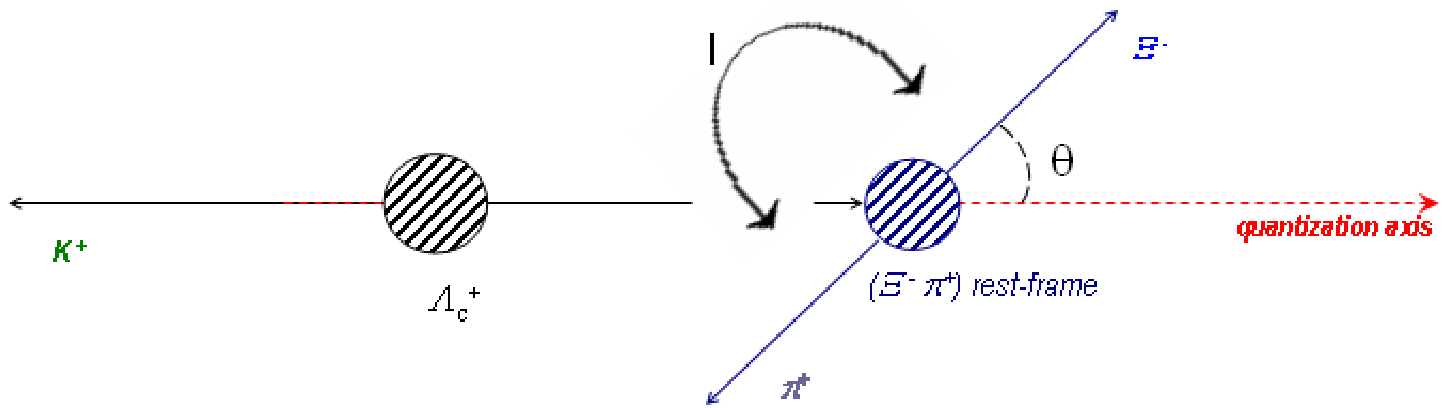
$$G_1 = m_0\Gamma(m)$$

$$I_1 = \frac{1}{M_1^2 + G_1^2}$$

$$I_2 = \frac{1}{M_2^2 + G_2^2}$$

Individual Breit-Wigner Intensity Contributions

Partial wave amplitude description of the $(\Xi^-\pi^+)$ system produced in the decay $\Lambda_c^+ \to$ □ $\Xi\,\pi^+ K^+$



Amplitudes of the $(\Xi^- \pi^+)$ system: $A^{3/2}_{\lambda_f}$ ($\Xi(1530)$) & $A^{1/2}_{\lambda_f}$ (non-resonant)

Angular distribution of the Ξ^- produced in the decay of the $(\Xi^- \pi^+)$ system:

⇨ Total Intensity $I = \sum_{\substack{\lambda_i = \pm 1/2, \\ \lambda_f = \pm 1/2}} \rho_{\lambda_i} \left| D^{1/2*}_{\lambda_i\,\lambda_f}(\phi,\theta,0) A^{1/2}_{\lambda_f} + D^{3/2*}_{\lambda_i\,\lambda_f}(\phi,\theta,0) A^{3/2}_{\lambda_f} \right|^2$

ρ_{λ_i} $(i = \pm 1/2) \rightarrow$ density matrix elements describing the spin population of the Λ_c^+

where, λ_i = helicity of $(\Xi^-\,\pi^+)$ system $= \lambda_i(\Lambda_c^+)$

$\lambda_f = \lambda_{\Xi^-} - \lambda_{\pi^+} = \lambda_{\Xi^-}$

Helicity Formalism

$$I = \sum_{\substack{\lambda_i=\pm 1/2,\\ \lambda_f=\pm 1/2}} \rho_{\lambda_i} \left| d^{1/2}_{\lambda_i\,\lambda_f}(\theta) A^{1/2}_{\lambda_f} + d^{3/2}_{\lambda_i\,\lambda_f}(\theta) A^{3/2}_{\lambda_f} \right|^2$$

$$= \rho_{1/2}\left[\left| d^{1/2}_{1/2\;1/2}(\theta) A^{1/2}_{1/2} + d^{3/2}_{1/2\;1/2}(\theta) A^{3/2}_{1/2} \right|^2 + \left| d^{1/2}_{1/2\;\text{-}1/2}(\theta) A^{1/2}_{-1/2} + d^{3/2}_{1/2\;\text{-}1/2}(\theta) A^{3/2}_{-1/2} \right|^2 \right]$$

$$+ \rho_{-1/2}\left[\left| d^{1/2}_{-1/2\;1/2}(\theta) A^{1/2}_{1/2} + d^{3/2}_{-1/2\;1/2}(\theta) A^{3/2}_{1/2} \right|^2 + \left| d^{1/2}_{-1/2\;\text{-}1/2}(\theta) A^{1/2}_{-1/2} + d^{3/2}_{-1/2\;\text{-}1/2}(\theta) A^{3/2}_{-1/2} \right|^2 \right]$$

Relationship between |L, S> states & helicity states
[M. Jacob & C.G. Wick
On the General Theory of Collisions for Particles with Spin
Annals of Physics 7, 401 (1959)]

$$\left| JM, \lambda_1\lambda_2 \right\rangle = \sum_{L,S} \beta_{LS} \left| JM, LS \right\rangle; \quad \beta_{LS} = \left\langle JM, LS \middle| JM, \lambda_1\lambda_2 \right\rangle, \qquad \text{where } \lambda_1 = \lambda(\Xi) \text{ and } \lambda_2 = \lambda(\pi) = 0,$$

$$= \sqrt{\frac{2L+1}{2J+1}} \left\langle L,0; s, \lambda_1-\lambda_2 \middle| \mathrm{J}, \lambda_1-\lambda_2 \right\rangle \left\langle s_1, \lambda_1; s_2, -\lambda_2 \middle| \mathrm{S}, \lambda_1-\lambda_2 \right\rangle.$$

$$\Rightarrow A^{1/2}_{1/2} = \left| 1/2\;\, 1/2,\; 1/2\;\, 0 \right\rangle = \frac{1}{\sqrt{2}}\left[\mathrm{S}^{1/2} - \mathrm{P}^{1/2} \right]$$

$$\Rightarrow A^{1/2}_{-1/2} = \left| 1/2\;\, \text{-}1/2,\; \text{-}1/2\;\, 0 \right\rangle = \frac{1}{\sqrt{2}}\left[\mathrm{S}^{1/2} + \mathrm{P}^{1/2} \right]$$

$$\Rightarrow A^{3/2}_{1/2} = \left| 3/2\;\, 1/2,\; 1/2\;\, 0 \right\rangle = \frac{1}{\sqrt{2}}\left[\mathrm{P}^{3/2} - \mathrm{D}^{3/2} \right]$$

$$\Rightarrow A^{3/2}_{-1/2} = \left| 3/2\;\, 1/2,\; 1/2\;\, 0 \right\rangle = \frac{1}{\sqrt{2}}\left[\mathrm{P}^{3/2} + \mathrm{D}^{3/2} \right]$$

$\boldsymbol{A}^{J}_{\lambda}$ in terms of

S, P, D waves

(Assuming $\rho_{1/2} = \rho_{-1/2}$)

J=1/2 J=3/2 Interference

$$\frac{dN}{d\cos\theta} = \left[\begin{array}{l} \frac{1}{2}\left|S^{1/2}\right|^2 + \left|P^{3/2}\right|^2 \left(\frac{1+3\cos^2\theta}{4} \right) + \boxed{\sqrt{2}\,\mathrm{Re}\left(S^{1/2} P^{3/2*} \right)\cos\theta} \\ \frac{1}{2}\left|P^{1/2}\right|^2 + \left|D^{3/2}\right|^2 \left(\frac{1+3\cos^2\theta}{4} \right) + \boxed{\sqrt{2}\,\mathrm{Re}\left(P^{1/2} D^{3/2*} \right)\cos\theta} \end{array} \right]$$

→ S-P interf.

→ P-D interf.

Cannot distinguish

between ($S^{1/2}$ + $P^{3/2}$)

nor between ($P^{3/2}$ + $D^{3/2}$)

[Minami ambiguity]

~ however **strong $P^{3/2}$ wave** suggests **term containing $S^{1/2}$, $P^{3/2}$ amplitudes dominates**

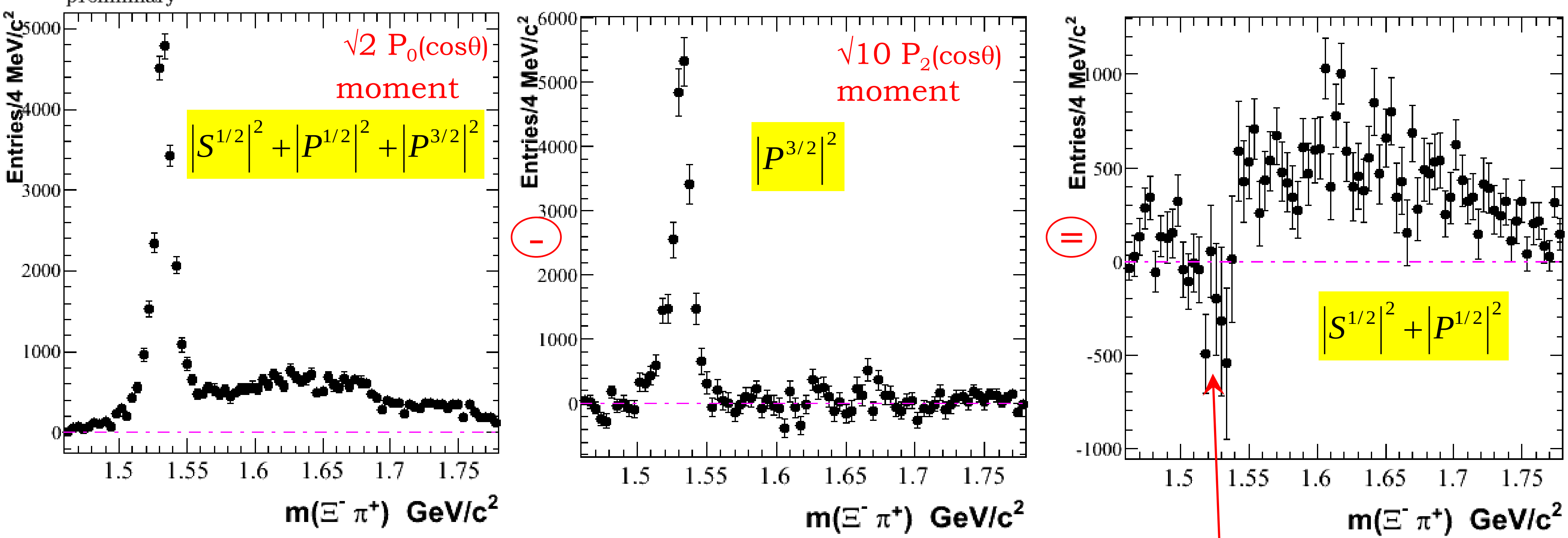
Try simple model assuming only $S^{1/2}$ and $P^{3/2}$ amplitudes

Amplitude Analysis Assuming S and P Waves

$$\frac{dN}{d\cos\theta} = \frac{\left(\left|S^{1/2}\right|^2 + \left|P^{1/2}\right|^2 + \left|P^{3/2}\right|^2\right)}{\sqrt{2}} P_0(\cos\theta) + \sqrt{\frac{1}{10}}\left|P^{3/2}\right|^2 P_2(\cos\theta)$$

$$+ \frac{2}{\sqrt{3}}\left|S^{1/2}\right|\left|P^{3/2}\right|\cos(\varphi_S - \varphi_P) P_1(\cos\theta)$$

BABAR preliminary



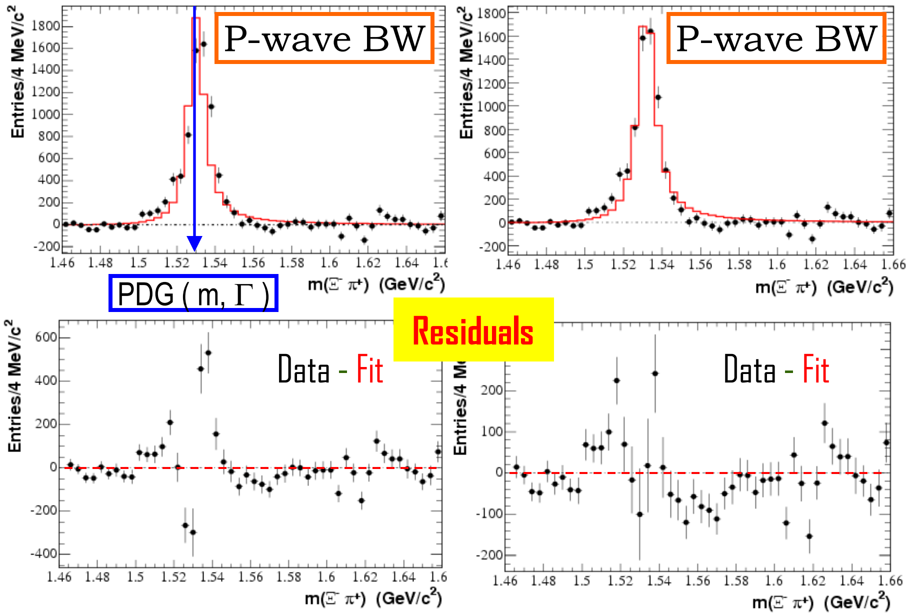
√10 $P_2(\cos\theta)$ moment projects too much signal!!

⇨ need more than S and P waves

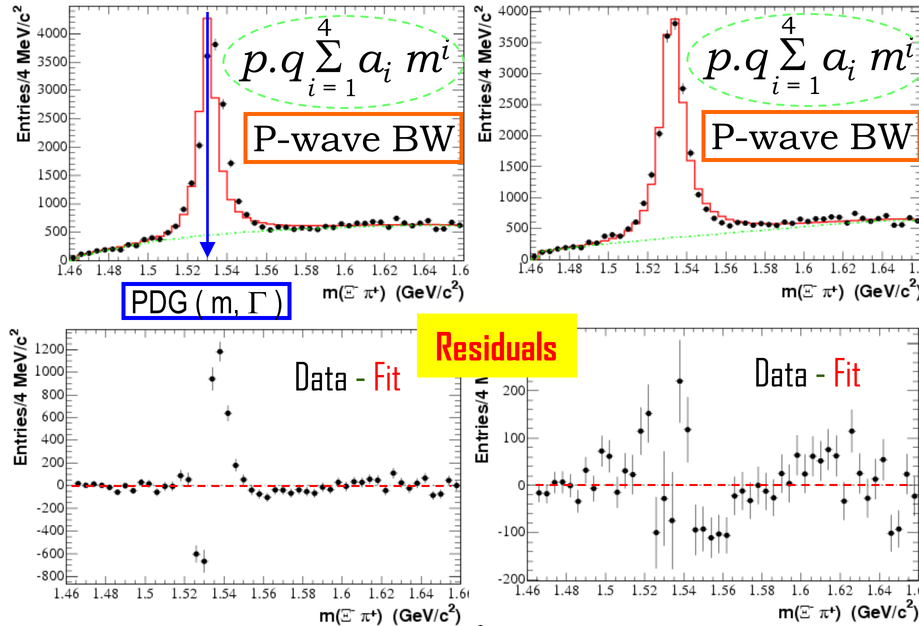
Implication of Fits to the $\Xi(1530)^0$ Lineshape

BABAR preliminary

Efficiency-corrected $P_2(\cos\theta)$ moment



Efficiency-corrected $P_0(\cos\theta)$ moment



Poor fit
⇨due to interference with other waves?

Effect should disappear in $P_0(\cos\theta)$ moment distribution

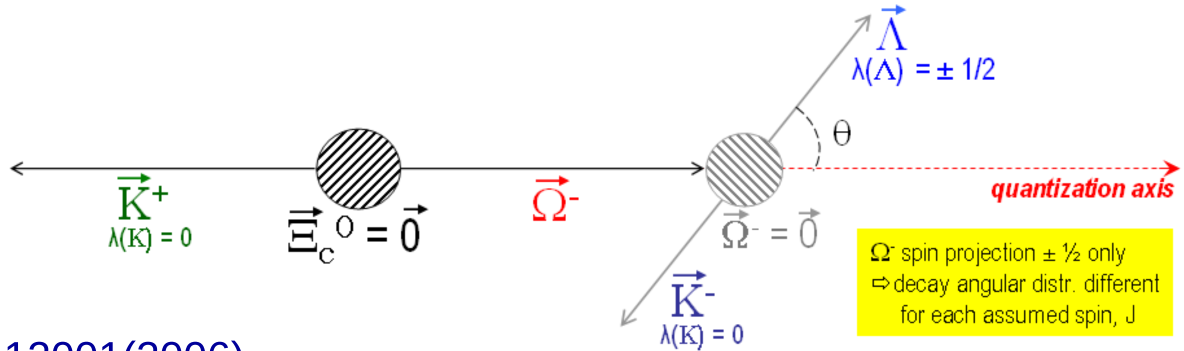
Expected improvement in fit quality not realized

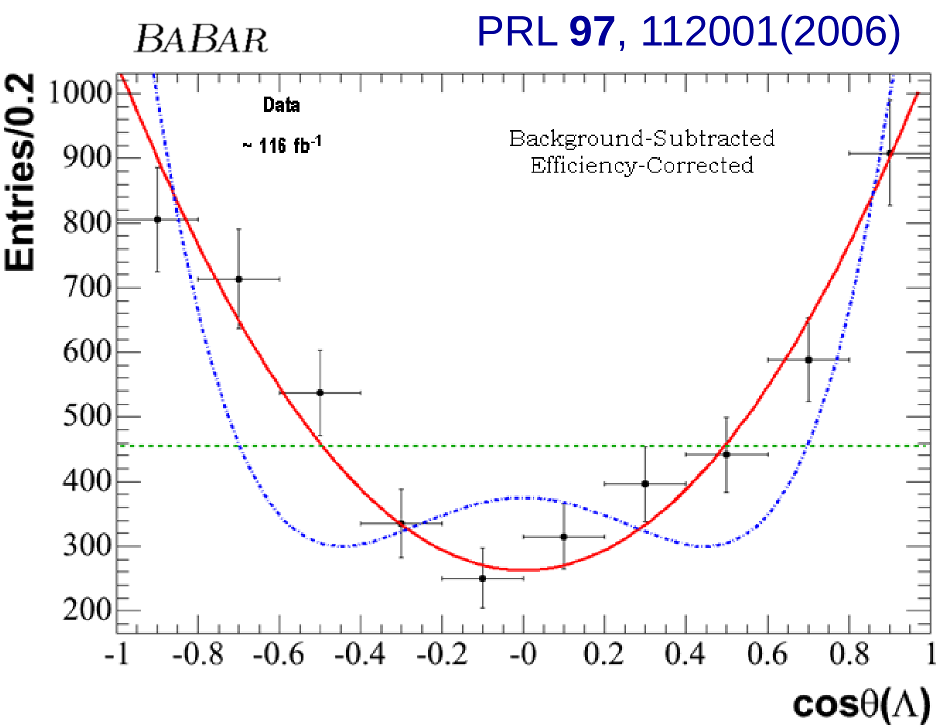
Structure in $\Xi^- K^+$ i.e. another isobar ? Or $(K^+\pi^+)$ I=3/2 amplitude contribution?

$$\langle P_2 \rangle = \sqrt{10}\left(\left|P^{3/2}\right|^2 + \left|D^{3/2}\right|^2 + \frac{8}{7}\left|D^{5/2}\right|^2 + \sqrt{20}Re\left(S^{1/2}D^{5/2*}\right)\right)$$

$$\langle P_4 \rangle = \frac{\sqrt{2}}{7}\left|D^{5/2}\right|^2$$

Spin measurement of Ω^- from $\Xi_c^0 \to \Omega^- K^+$, $\Omega^- \to \Lambda K^-$ Decays





$J_\Omega = 1/2 \quad \Rightarrow I \propto 1 \quad \rightarrow$ Fit Prob = 10^{-17}

$J_\Omega = 3/2 \quad \Rightarrow I \propto (1 + 3\cos^2\theta) \quad \rightarrow$ Fit Prob = 0.64

$J_\Omega = 5/2 \quad \Rightarrow I \propto (1 - 2\cos^2\theta + 5\cos^4\theta) \quad \rightarrow$ Fit Prob = 10^{-7}

$J_\Omega \geq 7/2$ **also excluded**: angular distribution increases more steeply near cosθ ~ ±1 and has ($2J_\Omega - 2$) turning points.

Exclusive B Decay Processes

Measurements of BF($\bar{B}^0 \to \Xi_c \bar{\Lambda}_c^-$) and BF($\bar{B}^0 \to \Lambda_c^+ \bar{\Lambda}_c^- \bar{K}$)

PHYSICAL REVIEW D 77, 031101(R) (2008)

- Predictions for B decays to final states with 2 charm baryons $\mathcal{O}(10^{-3})$
- Belle measurement for BF($B \to \Xi_c \bar{\Lambda}_c$) of ~1% comparable with predictions

Belle Collaboration, R. Chistov *et al.*, Phys. Rev. D **74**, 111105 (2006).
Belle Collaboration, N. Gabyshev *et al.*, Phys. Rev. Lett. **97**, 202003 (2006).

- B decays to final states with only singly-charm final states ~$\mathcal{O}(10^{-5})$

Belle Collaboration, N. Gabyshev *et al.*, Phys. Rev. Lett. **90**, 121802 (2003).

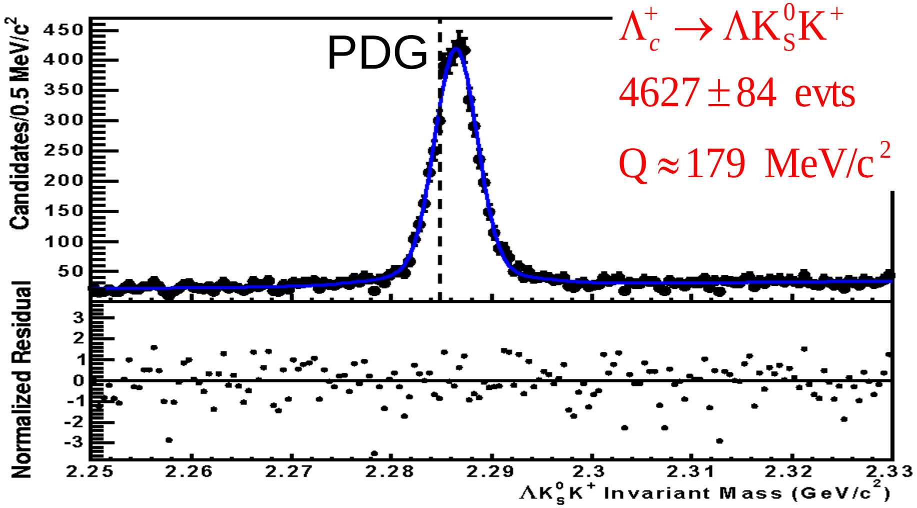
- Rate difference due to final state interactions or intermediate charmonium resonances ?
- Use of 3-body decay to study $\Lambda_c^+ \bar{\Lambda}_c^- \bar{K}$ to investigate resonant structures
  - BF measurement consistent with predictions
  - 2-body mass projections indicative of Ξ_c^0 resonant decay contribution

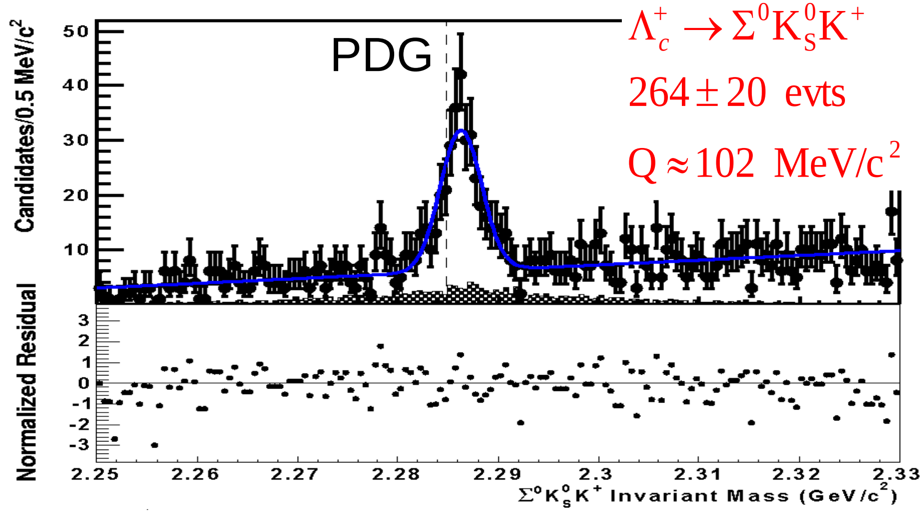
A Precision Measurement of the Λ_c^+ Mass

Using low Q-value decay modes

Phys.Rev.D72:052006,2005

First Observation





$$m(\Lambda_c^+)_{\Lambda K_S^0 K^+} = 2286.501 \pm 0.042(stat) \pm 0.144(syst)\ \text{MeV/c}^2$$

$$m(\Lambda_c^+)_{\Sigma^0 K_S^0 K^+} = 2286.303 \pm 0.181(stat) \pm 0.126(syst)\ \text{MeV/c}^2$$

Combined measurement

$$m(\Lambda_c^+) = 2286.46 \pm 0.14\ \text{MeV/c}^2$$

$$\text{PDG 2004}: \quad 2284.9 \pm 0.6\ \text{MeV/c}^2$$

Baryon (decaying to a Λ_c^+) masses estimated as mass differences w.r.t. the Λ_c^+ with PDG Λ_c^+ mass added → more precise Λ_c^+ mass measurement affects these baryon mass measurements