Hyperon Resonance Studies from Charm Baryon Decays

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Overview

1. Formalism

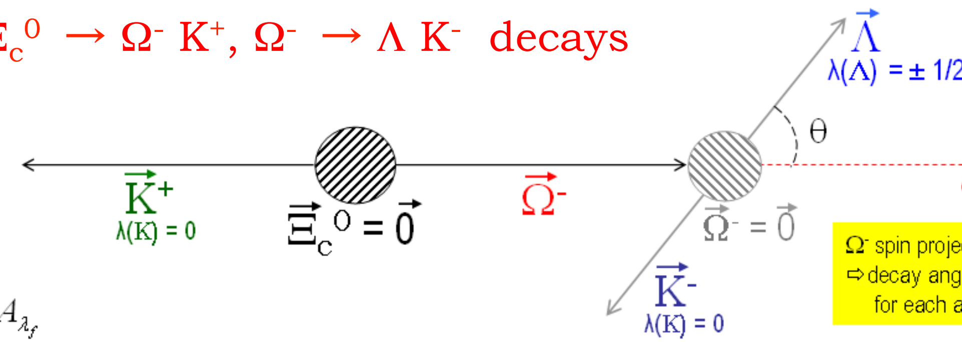
2. Quasi-two-body Λ_c^+ decays:
   - Study of the $\Xi(1530)^0$ in the decay $\Lambda_c^+ \rightarrow (\Xi^- \pi^+) K^+$
   - Properties of the $\Xi(1690)^0$ from an isobar model analysis of the $\Lambda_c^+ \rightarrow (\Lambda \overline{K}^0) K^+$ Dalitz plot

     (hep-ex/0607043, SLAC R-868)

3. Summary & Conclusions

Helicity Formalism used in Analysis of Hyperons produced from charm baryon decay

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

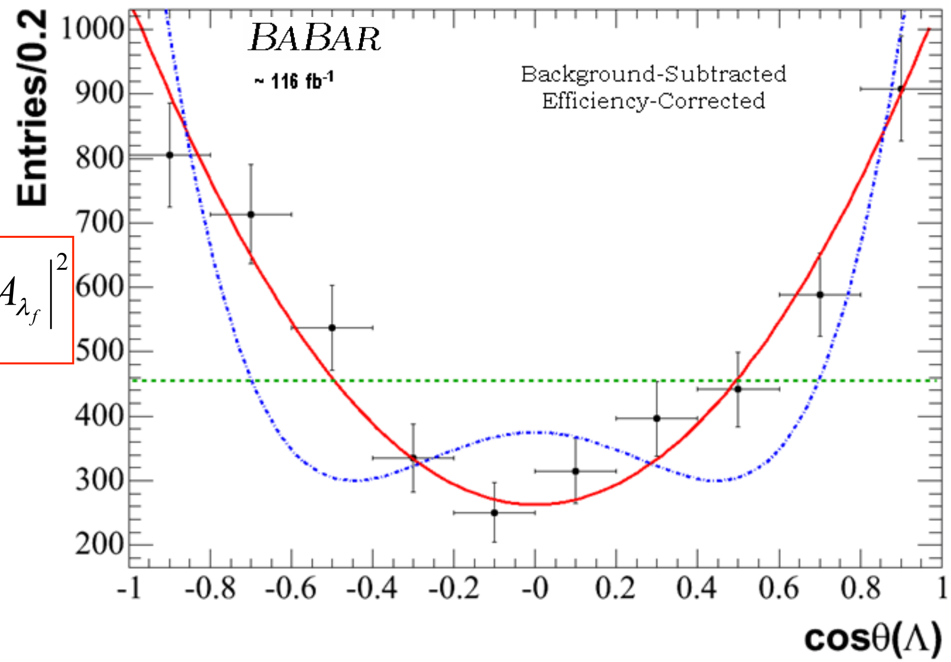


Ω^- spin projection ± ½ only
⇨ decay angular distr. different for each assumed spin, J

- Initial helicity, $\lambda_i = \lambda(\Omega) = \pm 1/2$
- Final state helicity, $\lambda_f = \lambda(\Lambda) - \lambda(\text{pseudoscalar}) = \pm 1/2$
- Decay amplitude for $\Omega^- \rightarrow \Lambda K^-$: $A^J_{\lambda_i \lambda_f} = D^{J*}_{\lambda_i \lambda_f}(\phi,\theta,0) A_{\lambda_f}$

$$I \propto \frac{1}{2}\sum_{\lambda_i,\lambda_f} \rho_{\lambda_i} \left|A^J_{\lambda_i \lambda_f}\right|^2 = \frac{1}{2}\sum_{\lambda_i,\lambda_f} \rho_{\lambda_i} \left|D^{J*}_{\lambda_i \lambda_f}(\phi,\theta,0) A_{\lambda_f}\right|^2$$

[density matrix element for Ω^- spin projection λ_i
= density matrix element for charm baryon parent]



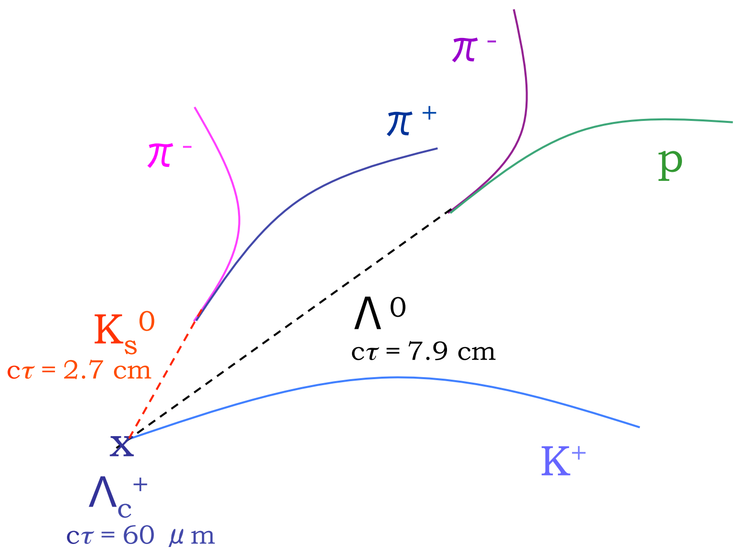
······· (green dotted)	$J_\Omega = 1/2$	$\Rightarrow I \propto 1$	→ Fit Prob = 10^{-17}
—— (red solid)	$J_\Omega = 3/2$	$\Rightarrow I \propto (1+3\cos^2\theta)$	→ Fit Prob = 0.64
- - - (blue dashed)	$J_\Omega = 5/2$	$\Rightarrow I \propto (1-2\cos^2\theta+5\cos^4\theta)$	→ Fit Prob = 10^{-7}

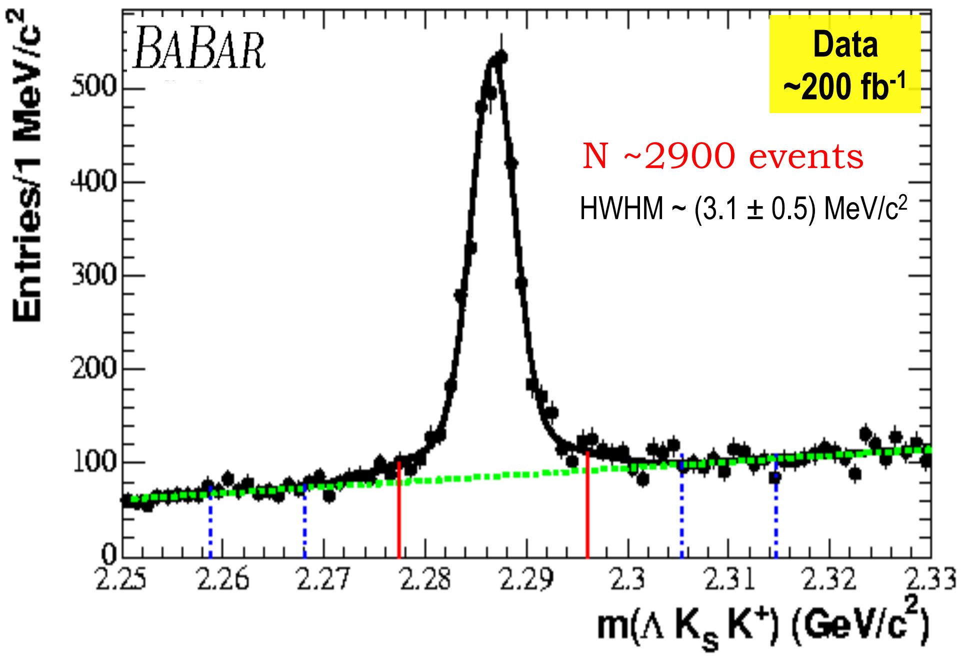
$J_\Omega \geq 7/2$ **also excluded**: angular distribution increases more steeply near cosθ ~ ±1 and has ($2 J_\Omega$ -2) turning points.

Study of Cascade Resonances Using 3-body Λ_c^+ Charm Baryon Decays

The $\Xi(1690)^0$ From $\Lambda_c^+ \rightarrow \Lambda\, \overline{K}^0\, K^+$ Decay

Reconstructed $\Lambda_c^+ \rightarrow \Lambda\ K_S\ K^+$ Events



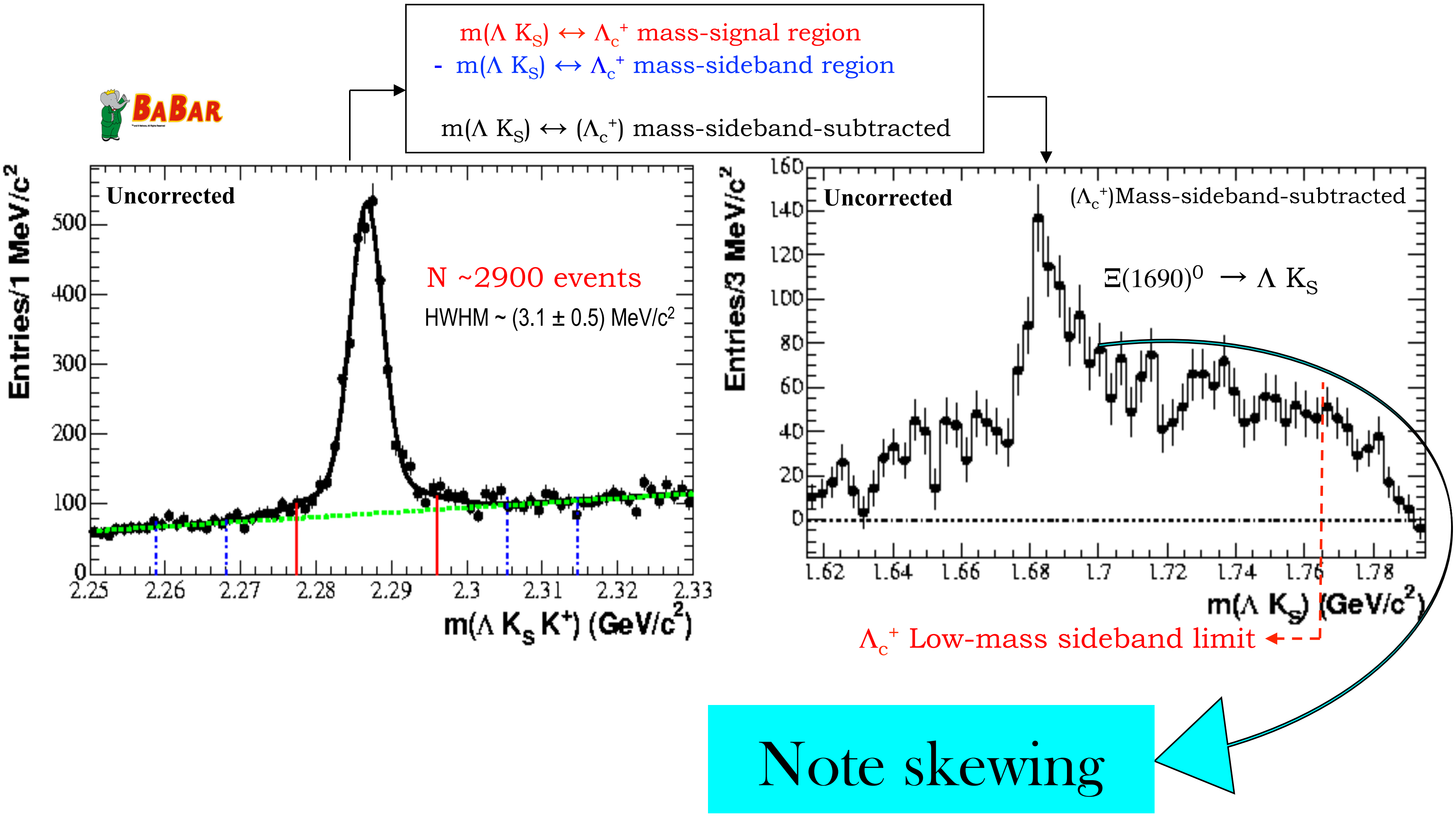


<u>Selection Criteria</u>:

- PID Information
  - →Proton
  - →Kaon
  - →π^+, π^-

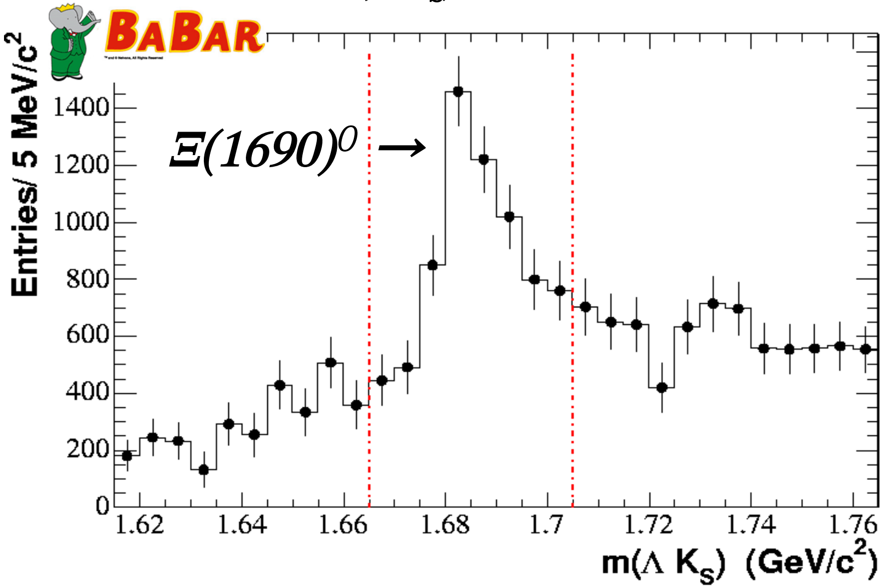
  } dE/dx & Cherenkov info (DIRC)
- 3-σ mass cut on intermediate states
- interm^d. states *mass-constrained [Λ , K_S]*
- **p*(Λ_c^+) > 1.5 GeV/c (reduces background)**
- **L_Λ, L_{K_S} > *+2.0, +1.0* mm *[sign ⇨ outgoing]*.**

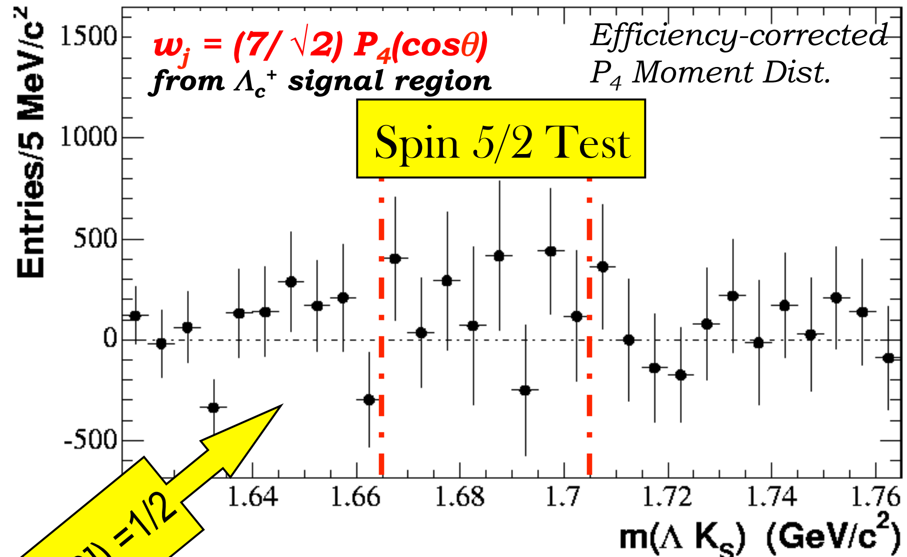
The $\Xi(1690)^0$ from $\Lambda_c^+ \rightarrow (\Lambda\, K_S)\, K^+$ Decay

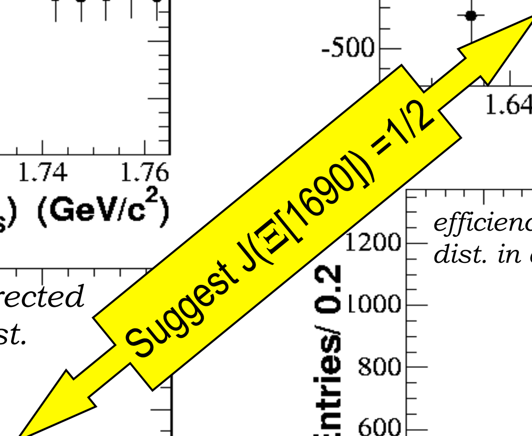


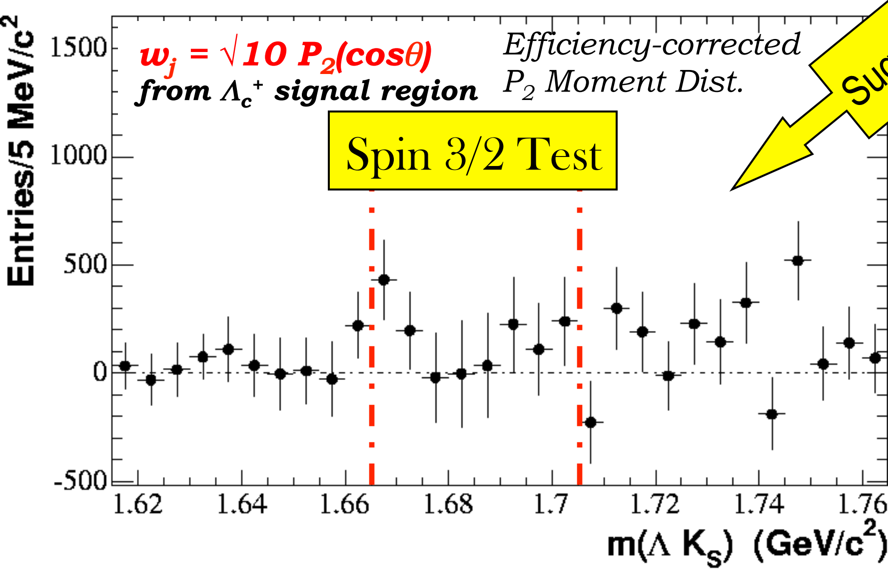
Using Legendre Polynomial Moments to Obtain Ξ(1690) Spin Information

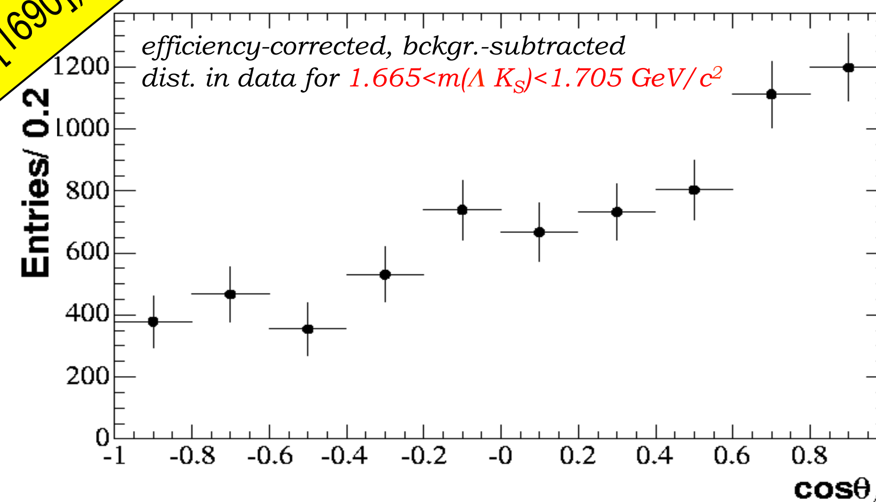
– ***efficiency-corrected, background-subtracted unweighted m(Λ K_S) distribution in data***





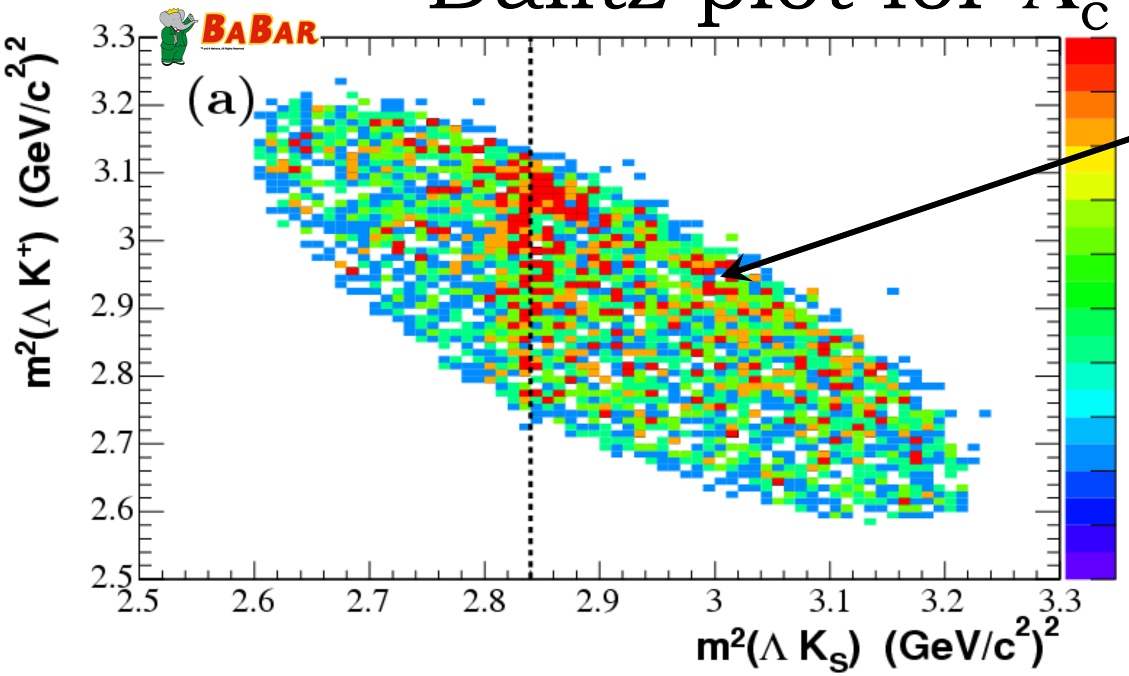




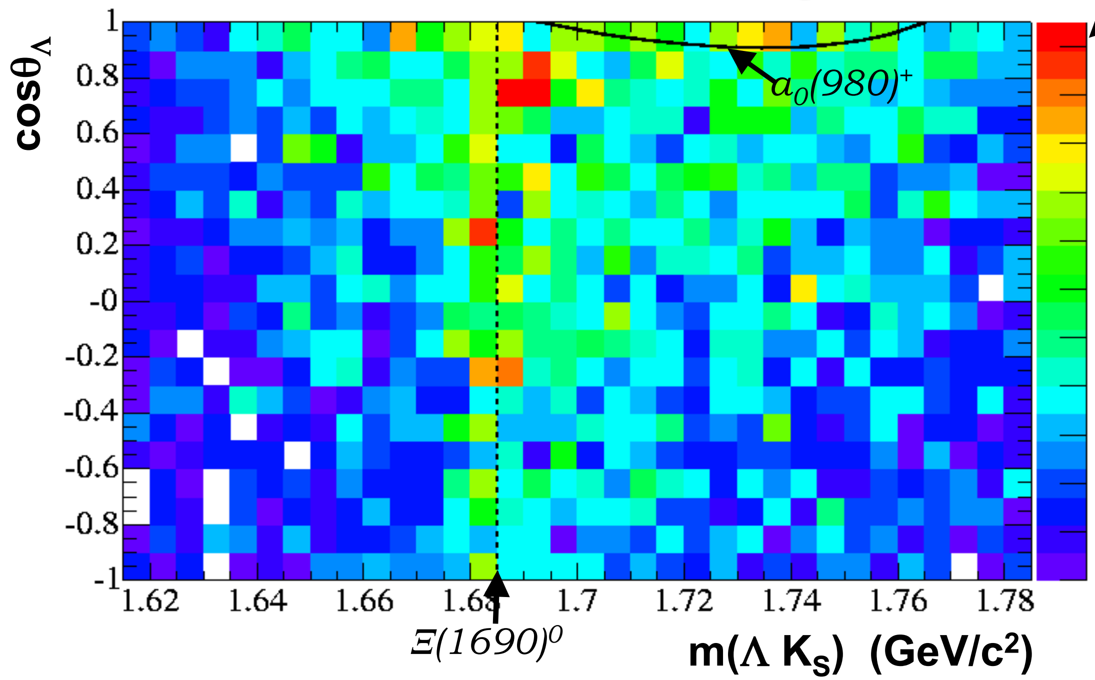


➔ Fit Dalitz plot with Spin ½ assumption

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



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

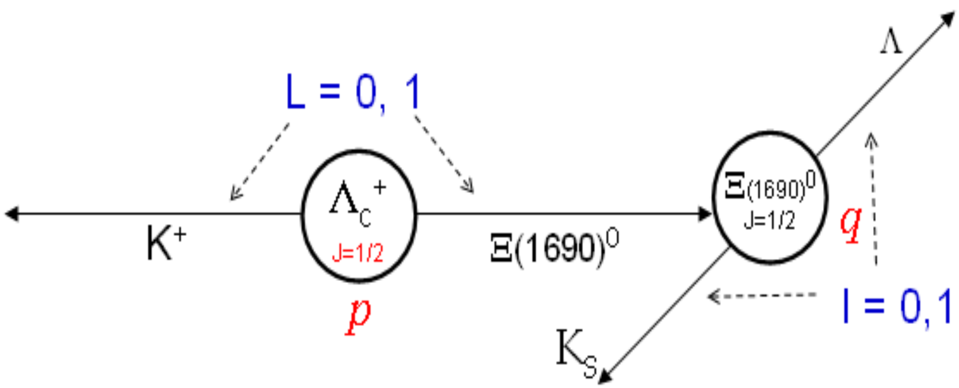


Rectangular Dalitz plot

- ✓ Easy background (Λ_c^+ mass sidebands) parametrization
- ✓ Same kinematic variables used for efficiency parametrization
- ➢ *Phase-space is:* $m.\left(\frac{p}{m_{\Lambda_c}}\frac{q}{m}\right)$

where p = *momentum of K^+ in Λ_c^+ rest-frame;*
and q = *momentum of Λ in (ΛK_S) rest-frame.*

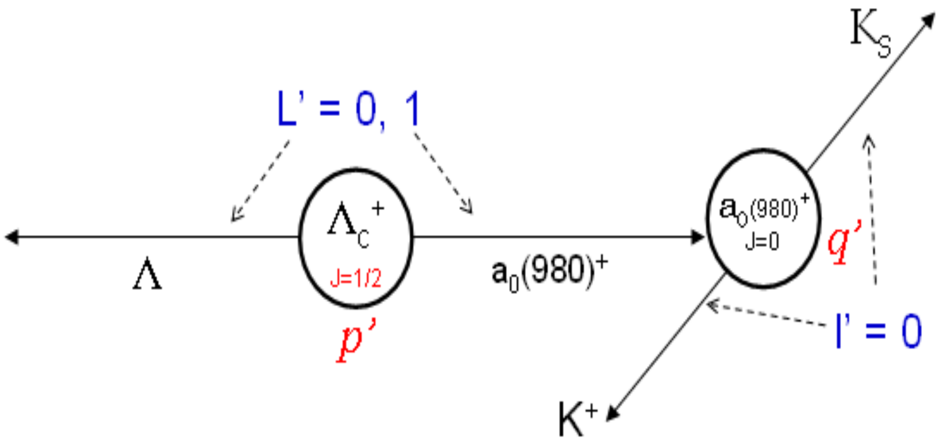
Isobar Model Description of the $\Lambda_c^+ \rightarrow \Lambda\ \overline{K}^0\ K^+$ Dalitz Plot



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

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

Fit for m_0 & $\Gamma(m_0)$ with $L=0$, $l=0$



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

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

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

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

$g_{K\bar{K}} = 473 \pm 49\ MeV$

[BaBar Exp.]

B. Aubert *et al.*, Phys. Rev. D72, 052008 (2005)

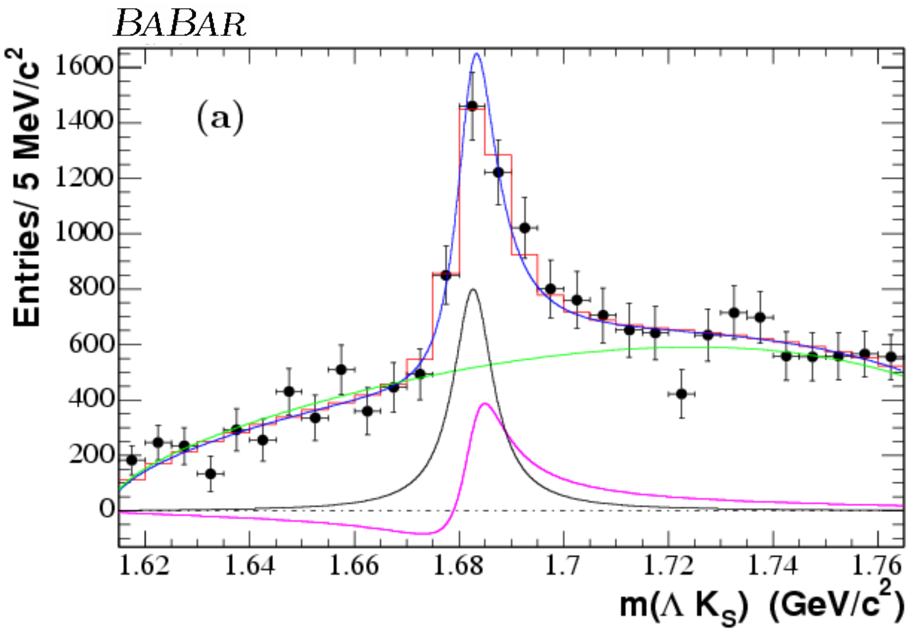
$g_{\eta\pi} = 324 \pm 15\ MeV$

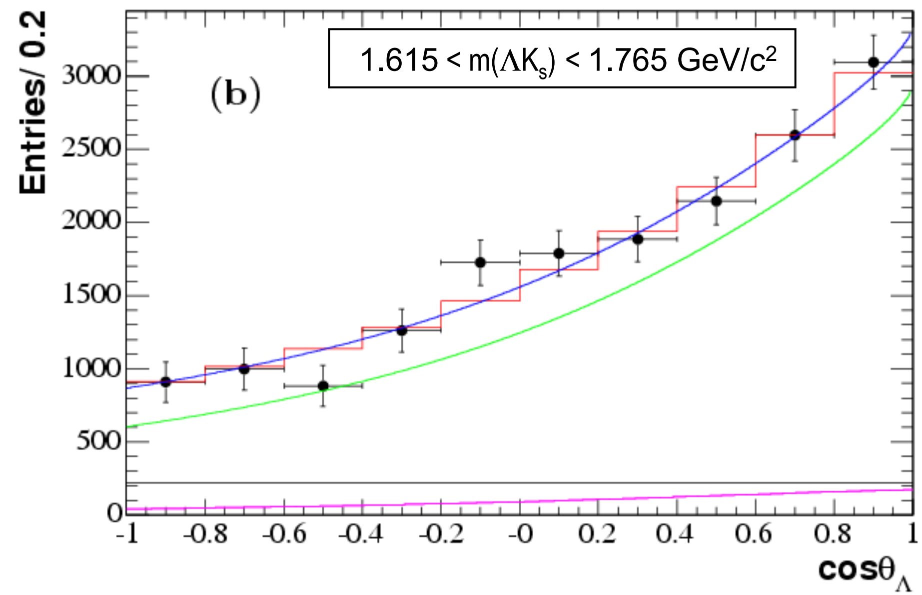
[Crystal Barrel Exp.]

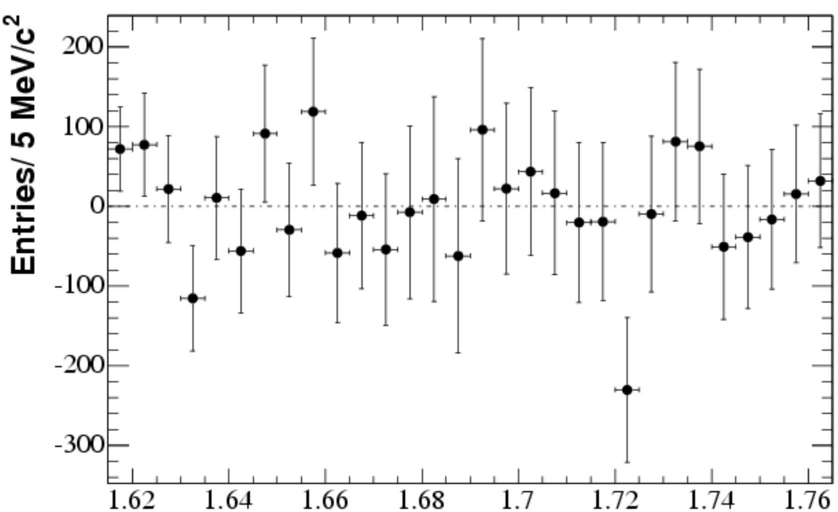
A. Abele *et al.*, Phys. Rev. D57, 3860 (1998).

For J(Ξ[1690]) = 1/2

Comparison of Max. Likelihood Fit Result to the Signal Projections







(fit residuals)

● 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

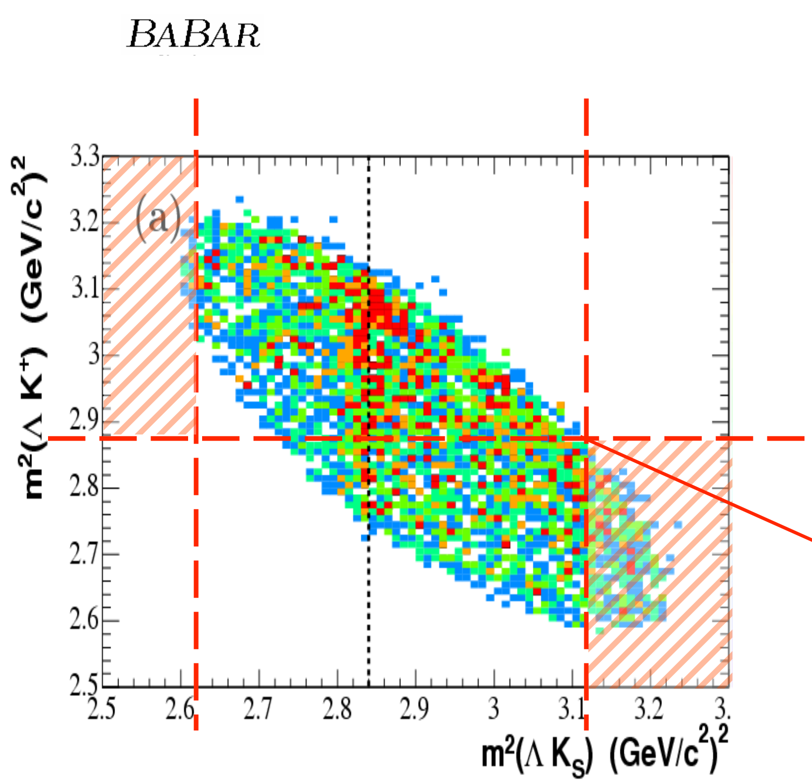
— $|A(\Xi(1690)|^2$ contribution

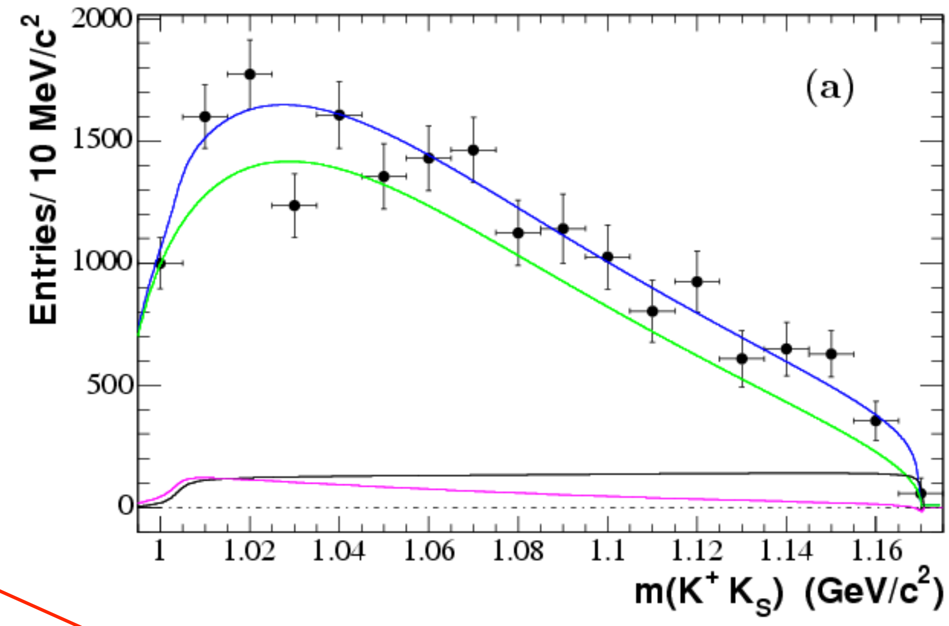
— *Interference* term contribution

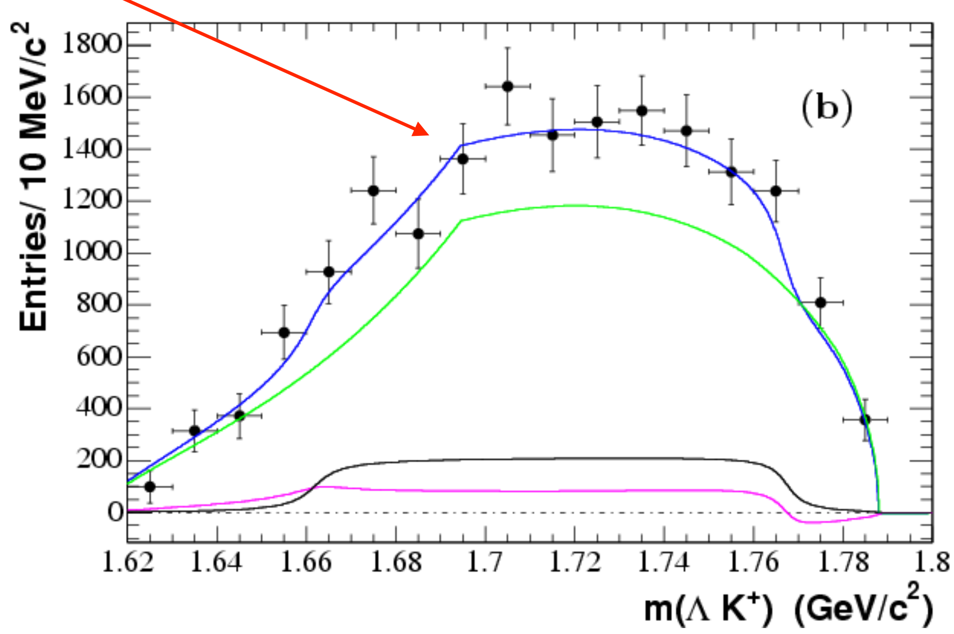
☞ Excellent reproduction of skewed lineshape and of cosθ$_Λ$ distribution

Fit χ^2/NDF = 188.4/192
Prob. = 56.4%

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





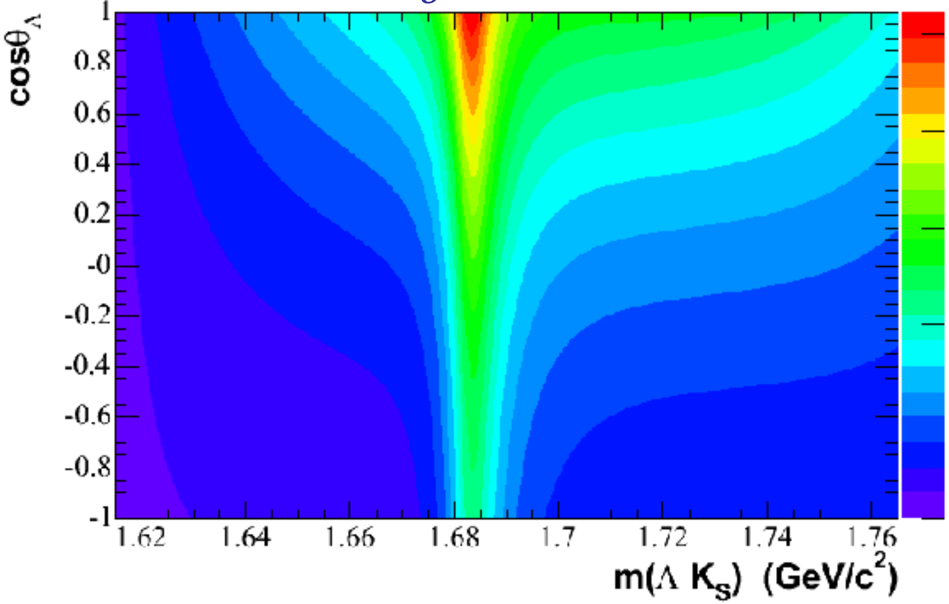


$m(\Lambda K_S)$ mass cut-off
$[1.62 < m(\Lambda K_S) < 1.765\ GeV/c^2]$
introduces a kink because of restricted range of (ΛK^+) helicity cosine

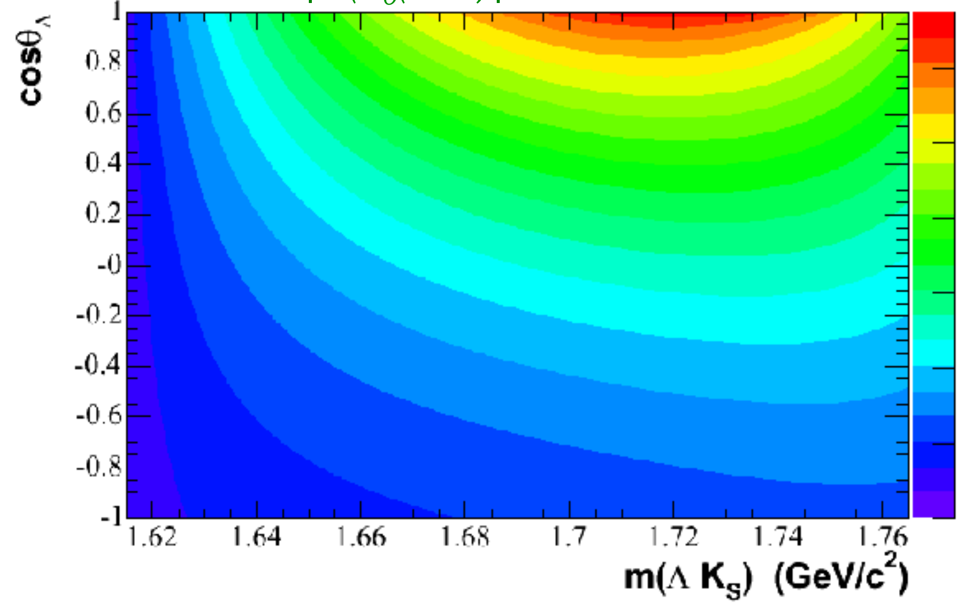
Fit Results‡ (different relative intensity scale)

‡ no smearing

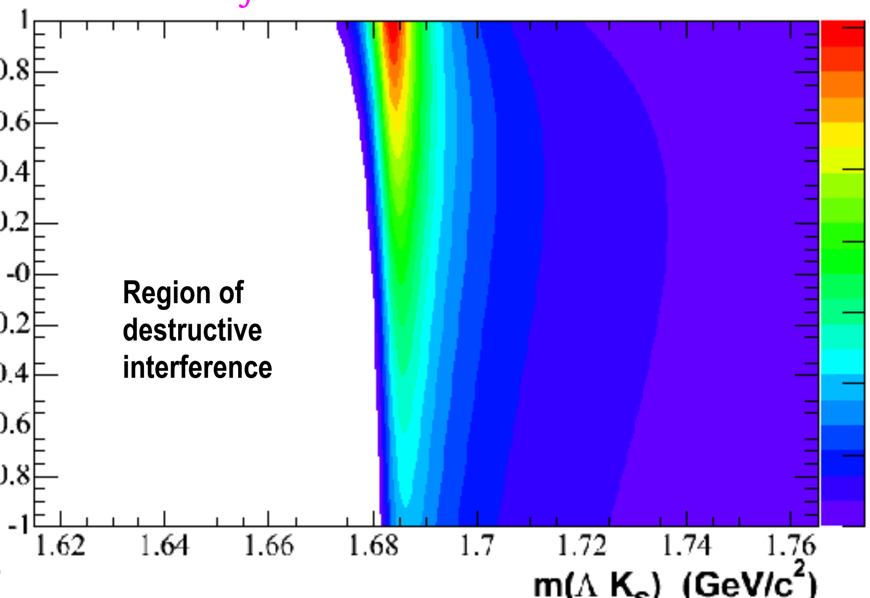
Signal function



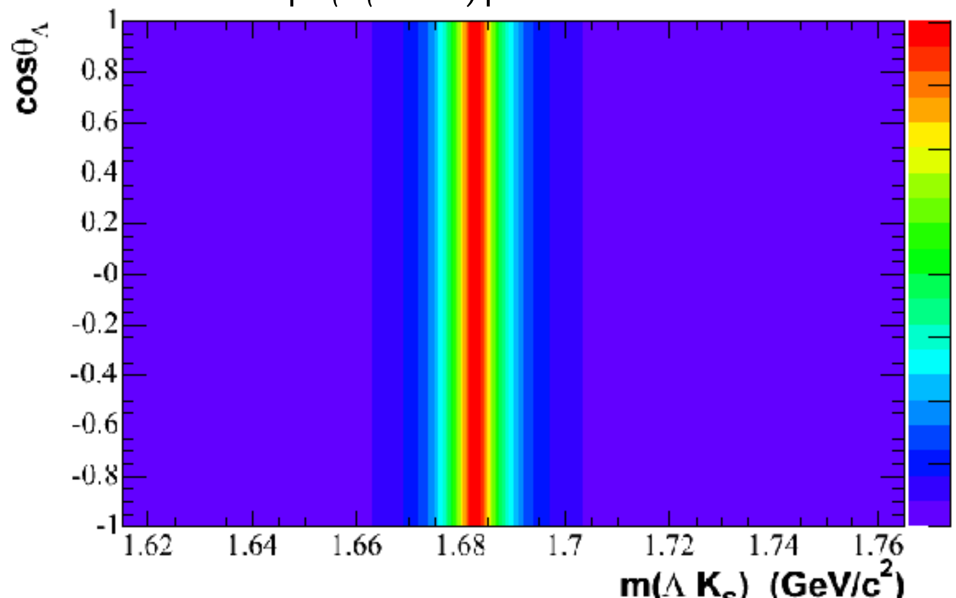
|*A(a₀(980)*|² contribution



Interference term contribution

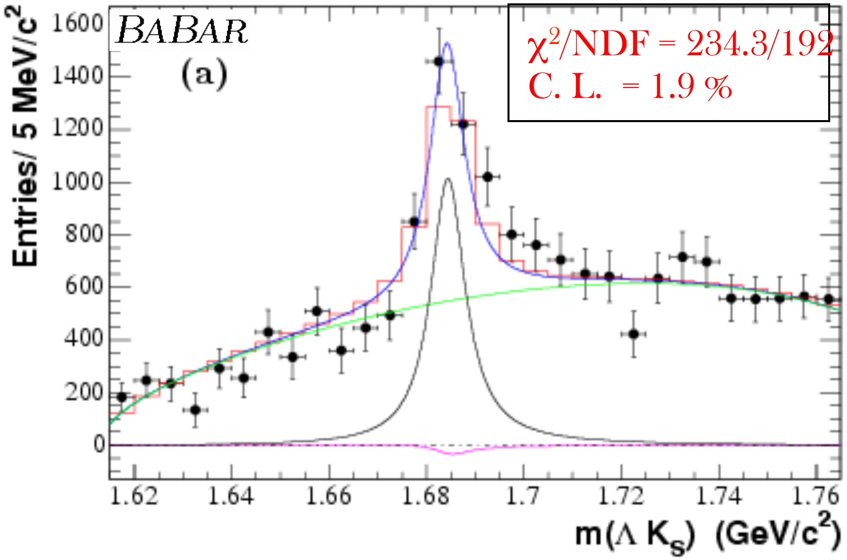


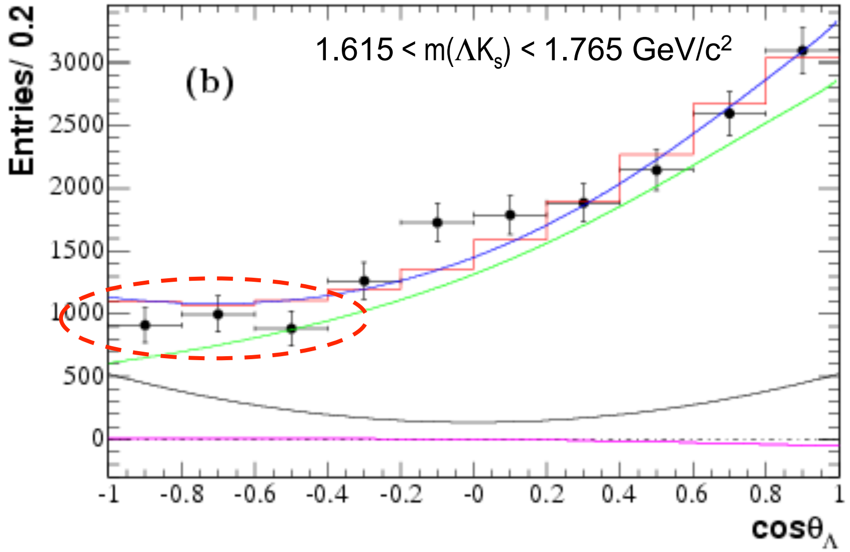
|*A(Ξ(1690)*|² contribution



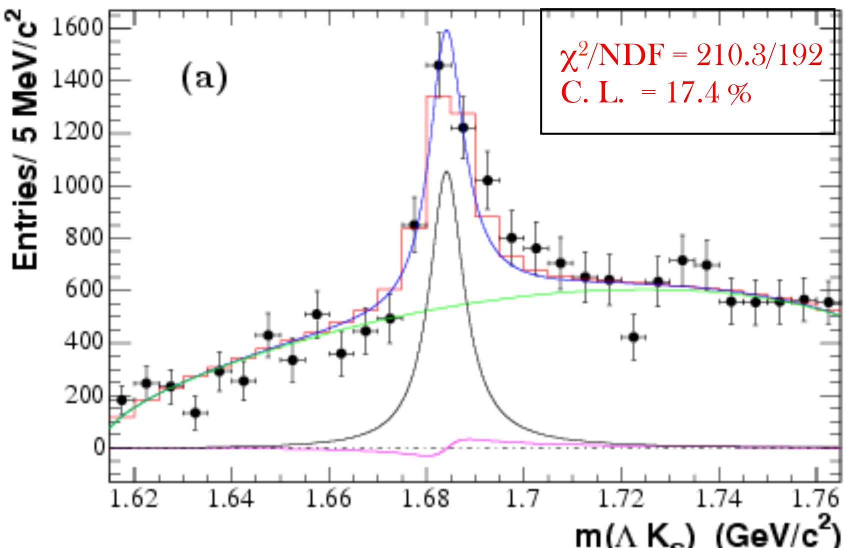
Comparison of Max. Likelihood Fit Result to the Signal Projections

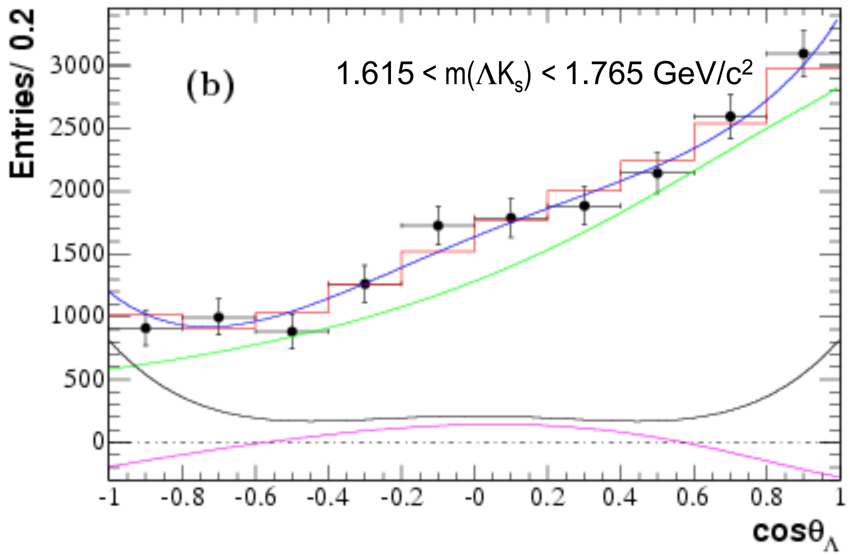
Under the assumption of spin 3/2 for the Ξ(1690):





Under the assumption of spin 5/2 for the Ξ(1690):





- Skewing of the lineshape not reproduced
- Net interference term very small ⇨ equiv. to incoherent superposition of amplitudes

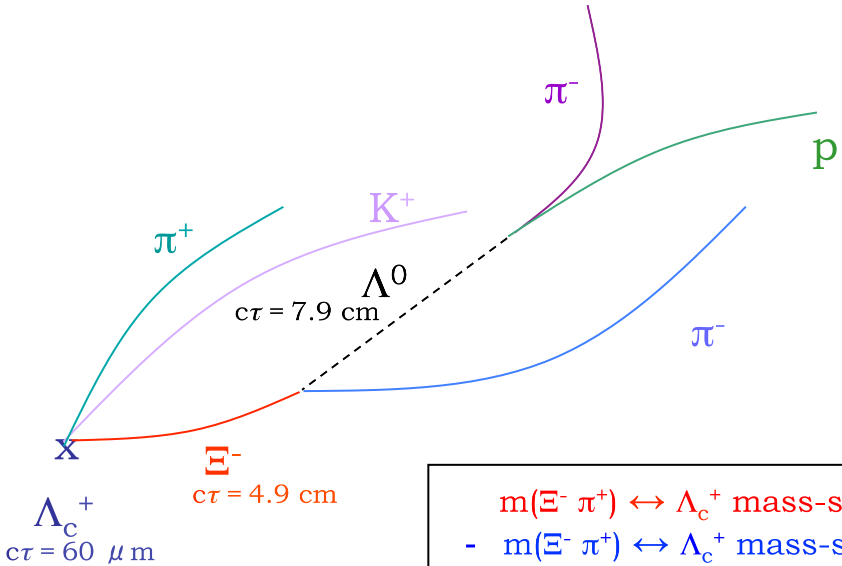
$\Xi(1690)^0$ Spin Study Conclusions

- Model based on coherent superposition of amplitudes describing Λ_c^+ isobar modes describes the data well

- $J[\Xi(1690)] = 1/2$ favored by the data (C.L. 56.4%)
- $J[\Xi(1690)] = 3/2$ (C.L. 1.9%) & $5/2$ (C.L. 17.4%) yield poorer fits and systematically fail to reproduce the skewed $\Xi(1690)^0$ lineshape

The $\Xi(1530)^0$ From $\Lambda_c^+ \rightarrow \Xi^- \pi^+ K^+$ Decay

Reconstructed $\Lambda_c^+ \to \Xi^- \pi^+ K^+$, $\Xi^- \to \Lambda \pi^-$ Events

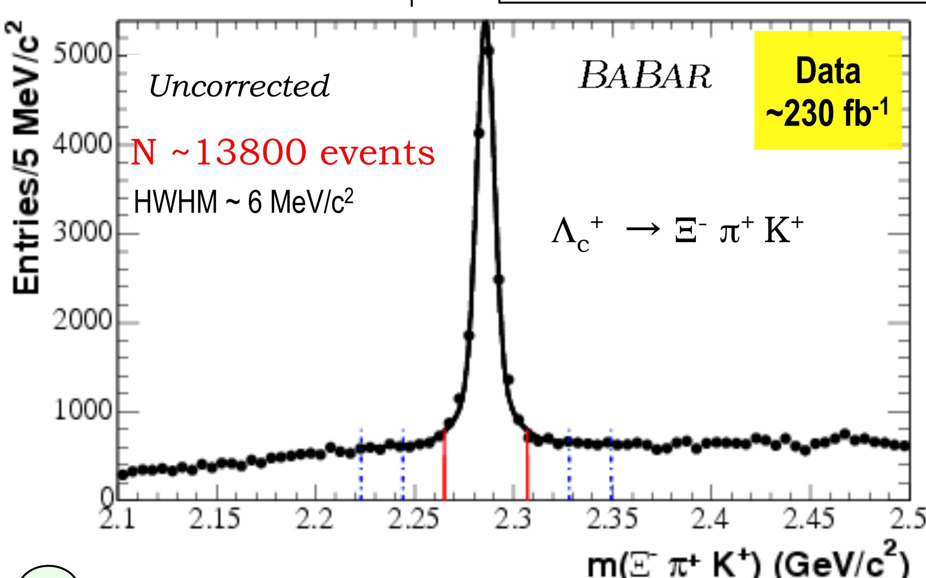


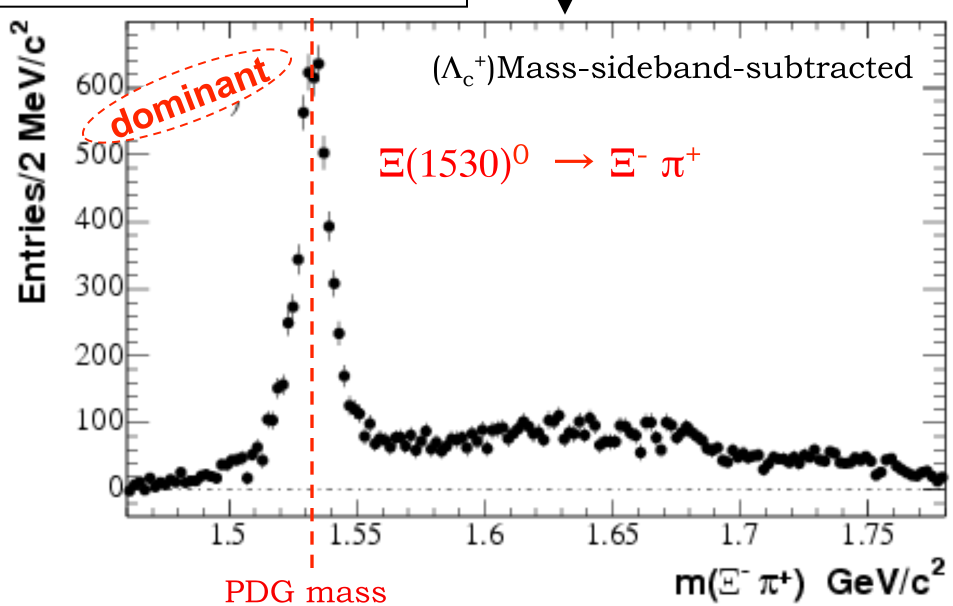
- ❑ PID Information
  - →Proton
  - →Kaon
  - →π^+, π^-

  } dE/dx & Cherenkov info (DIRC)
- ❑ 3-σ mass cut on intermediate states
- ❑ interm[d]. states *mass-constrained [Λ, Ξ^-]*
- ❑ p* > 2.0 GeV/c *[reduces background]*.
- ❑ L_Λ > 2.0 mm r_Ξ > +1.5 mm *[outgoing]*.

m(Ξ^- π^+) ↔ Λ_c^+ mass-signal region
\- m(Ξ^- π^+) ↔ Λ_c^+ mass-sideband region

m(Ξ^- π^+) ↔ (Λ_c^+) mass-sideband-subtracted



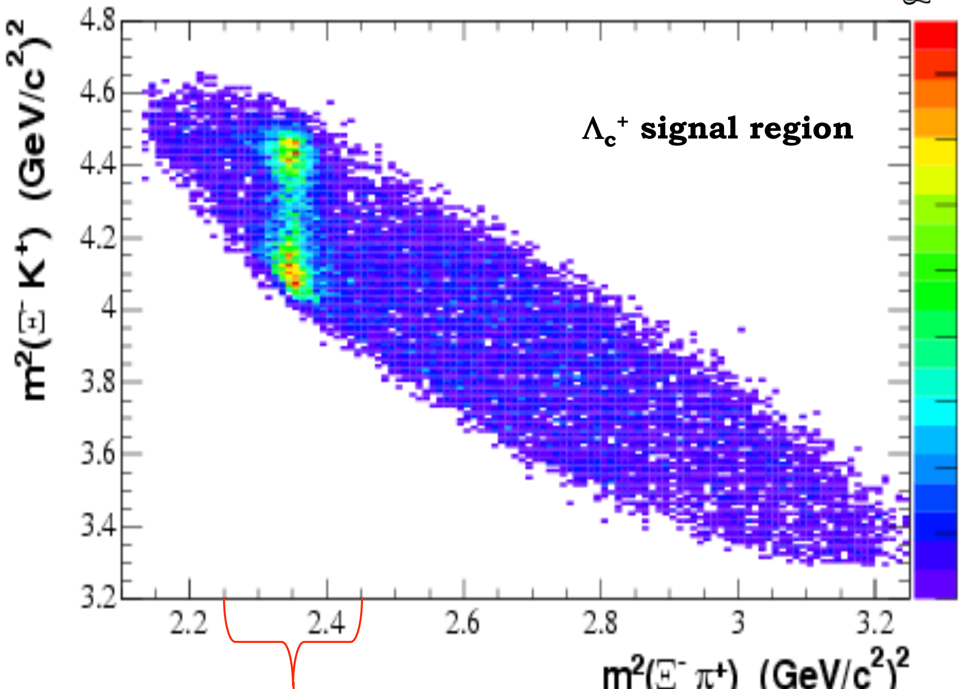


Analysis of $\Lambda_c^+ \rightarrow \Xi^- \pi^+ K^+$ to obtain $\Xi(1530)$ spin information

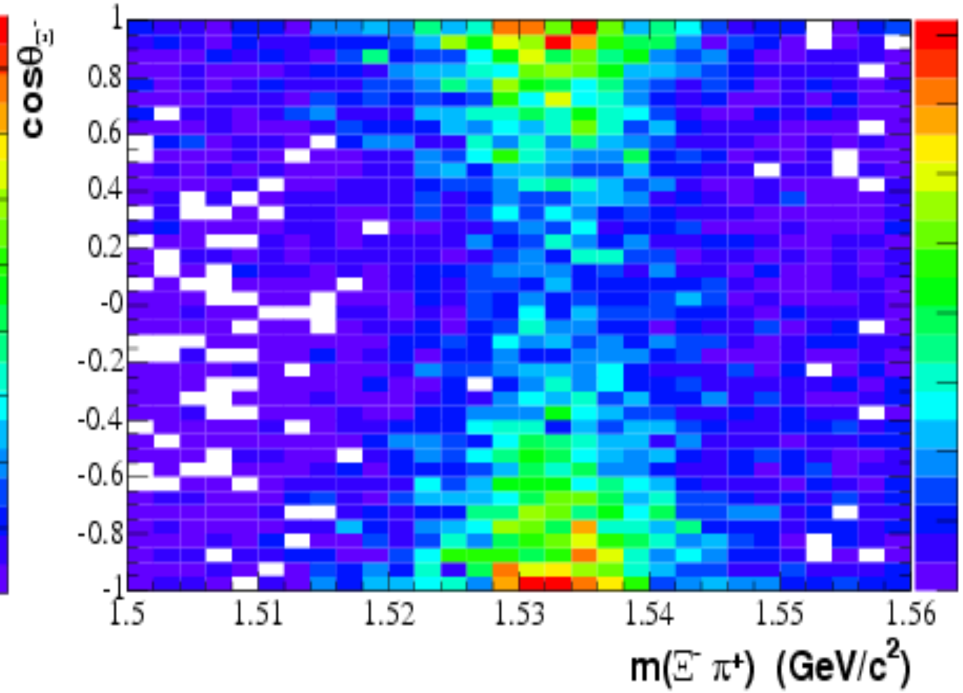
Phys.Rev.D78:034008,2008

Only *obvious* structure:

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

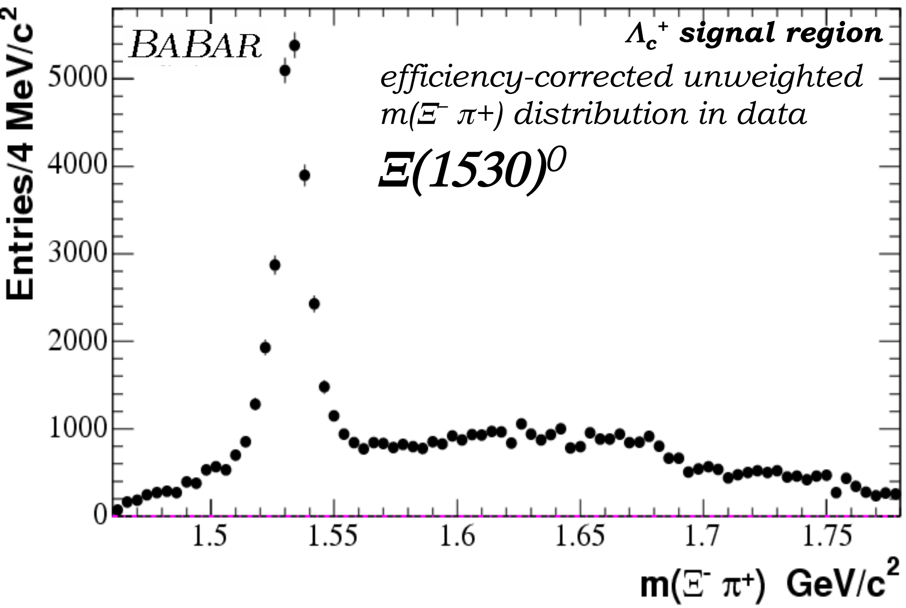


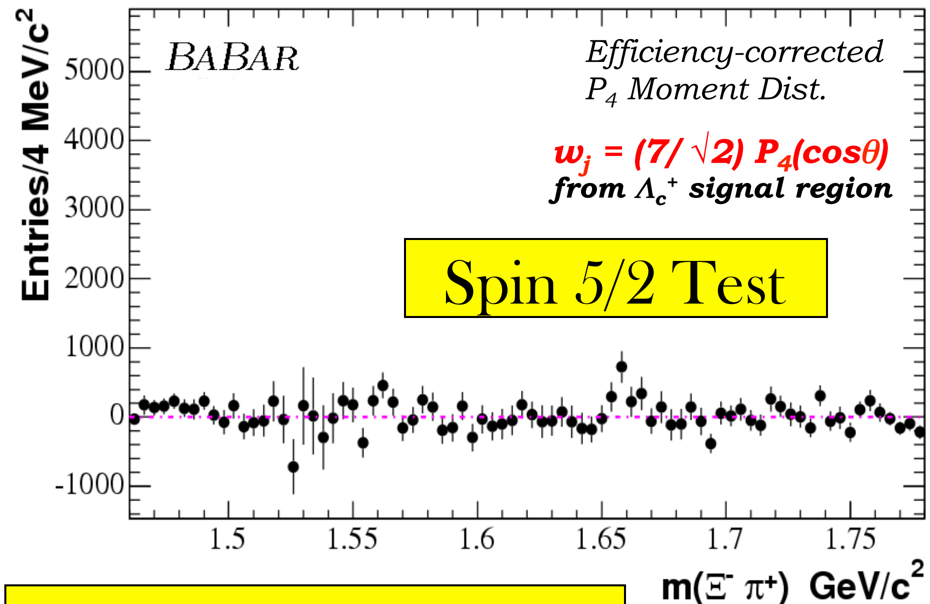
Rectangular Dalitz plot



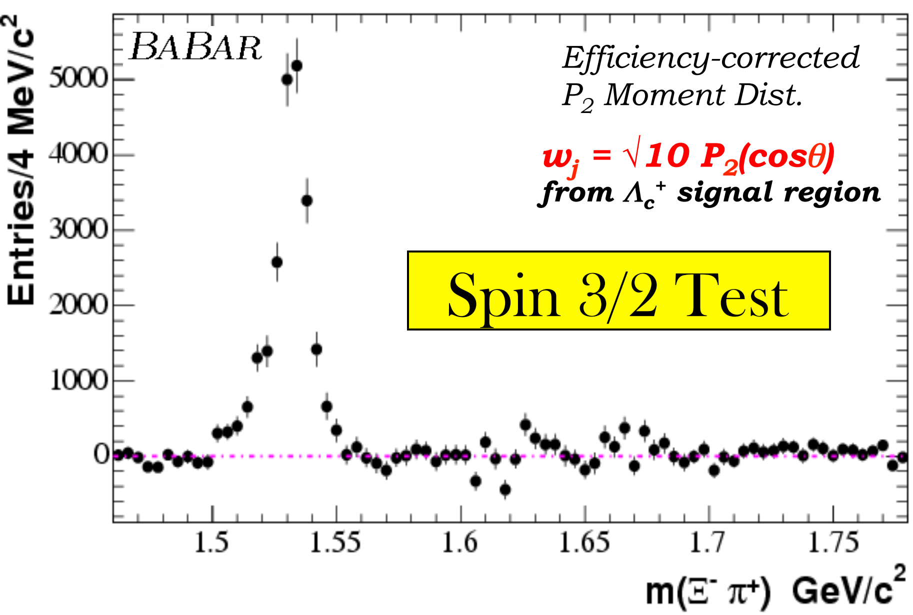
Note: $m^2(\Xi^- K^+)$ depends linearly on $\cos\theta_{\Xi}$

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





• ***P_L* moments (L ≥ 6) give no signal**



⇨ spin 3/2 *clearly* established

⇨ spin 5/2 ruled out

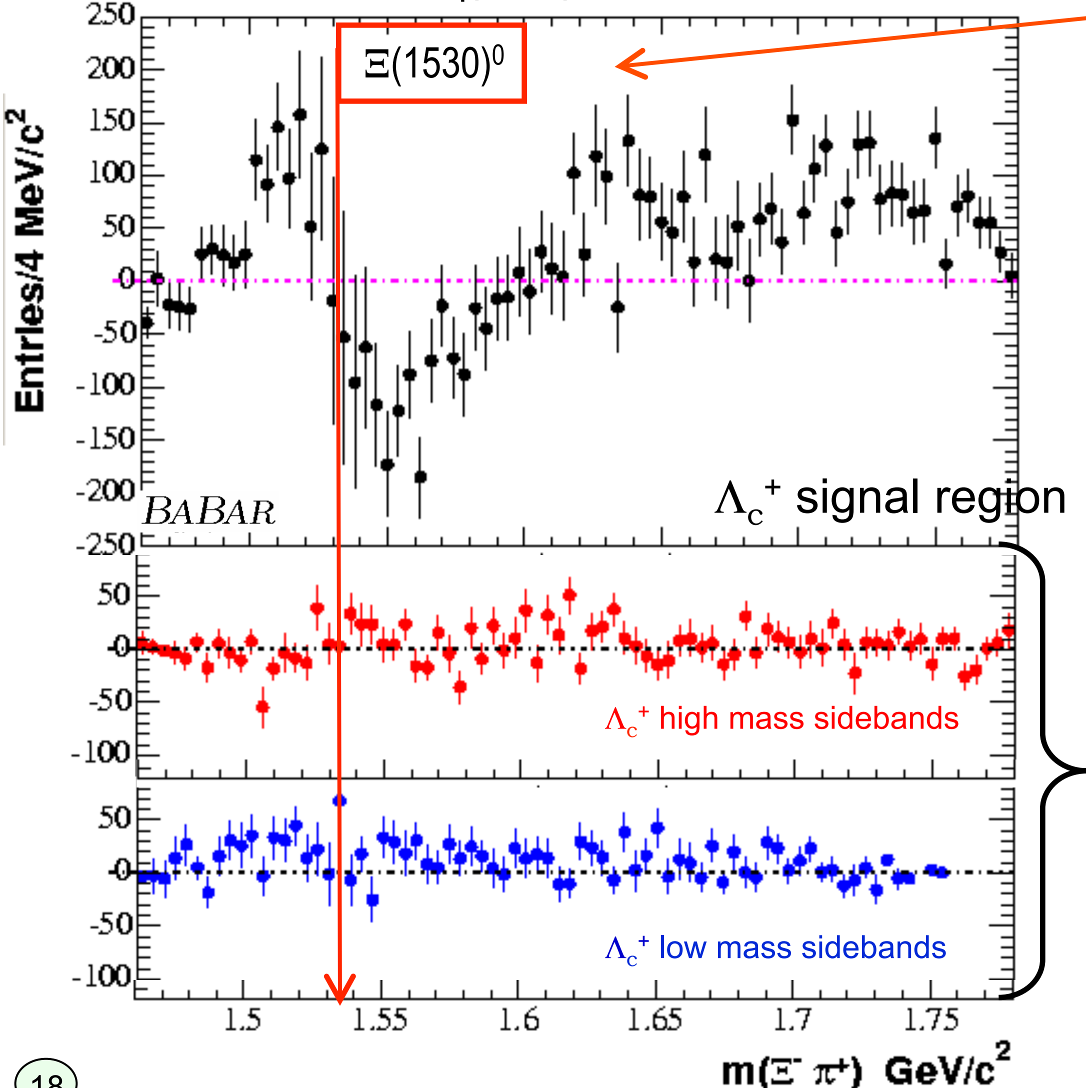
Schlein et *al.* showed $J^P = 3/2^+$ or $J^P = 5/2^-$, and claimed J>3/2 *not required.* [Phys.Rev.Lett.11, 167 (1963), Phys.Rev. 142,883 (1966)]

" Spin-parity $3/2^+$ is favored by the

⇨ Present analysis by establishing J=3/2 will also establish <u>positive</u> parity *by implication*

Evidence for S-P wave interference in the ($\Xi^- \pi^+$) system produced in the decay $\Lambda_c^+ \rightarrow \Xi^- \pi^+ K^+$

Efficiency-corrected m($\Xi^- \pi^+$) distributions weighted by $P_1(\cos\theta)$:



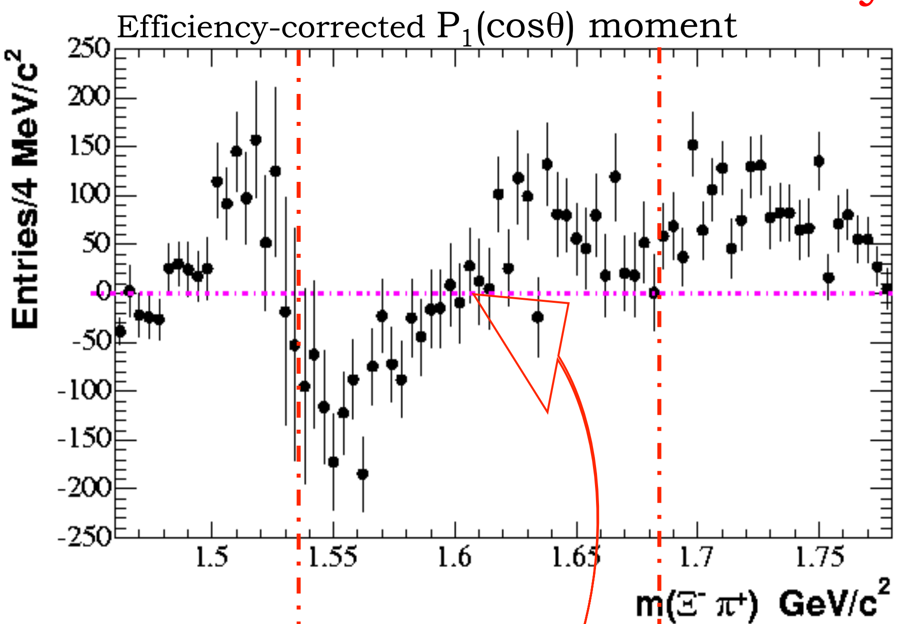
Classic S-P wave interference pattern as a function of m($\Xi^- \pi^+$)

- Oscillation due to rapid Breit-Wigner P-wave phase motion & slowly varying S-wave phase.

Eg. Kπ scattering, [D. Aston *et al.*, Nucl.Phys.B**296**, 493 (1998)] & $D^0 \rightarrow K^0 K^+ K^-$ for similar behaviour in ϕ region [Phys.Rev.D**72**, 052008(2005), BABAR]

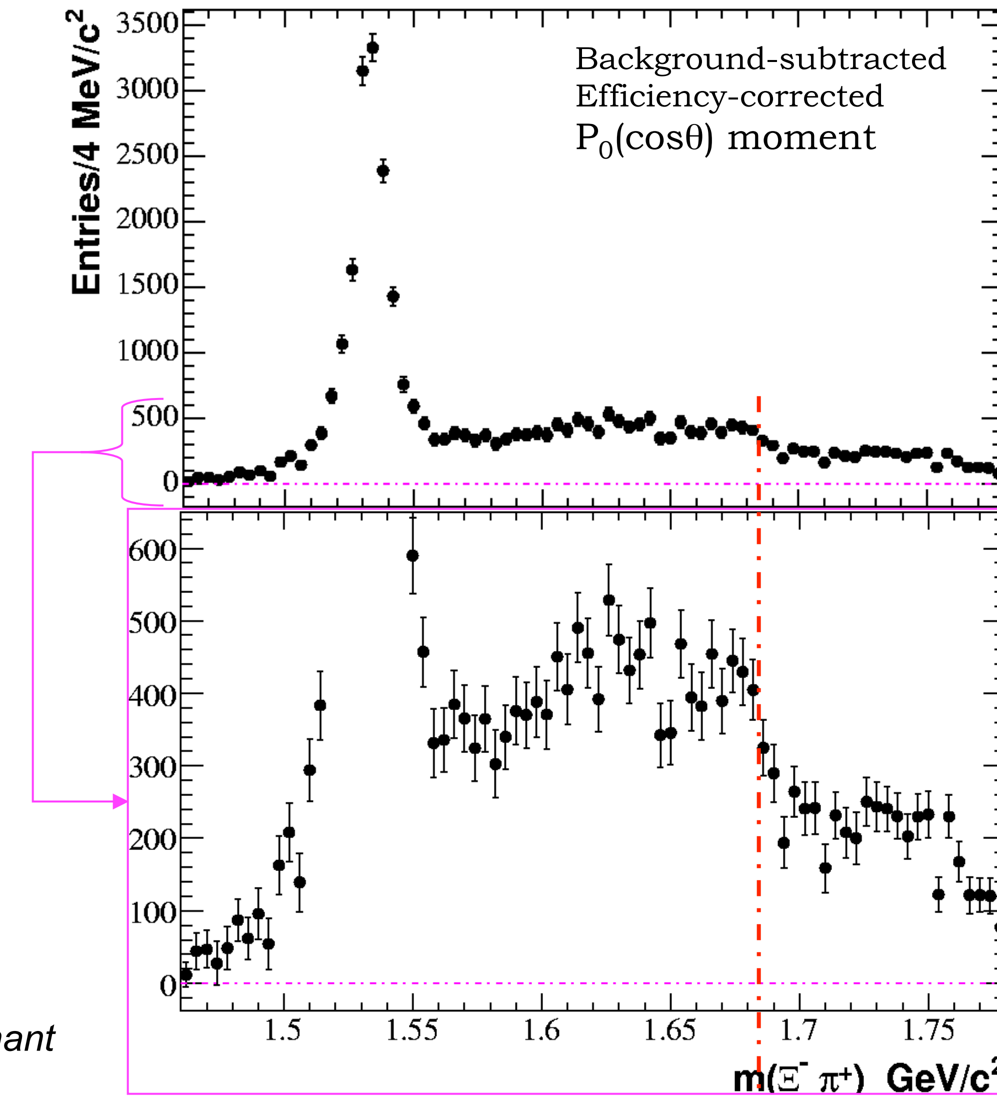
- First clear evidence of $\Xi(1530)^0$ Breit-Wigner **phase motion**

Evidence for S-P wave interference in the ($\Xi^- \pi^+$) system produced in the decay $\Lambda_c^+ \to \Xi^- \pi^+ K^+$



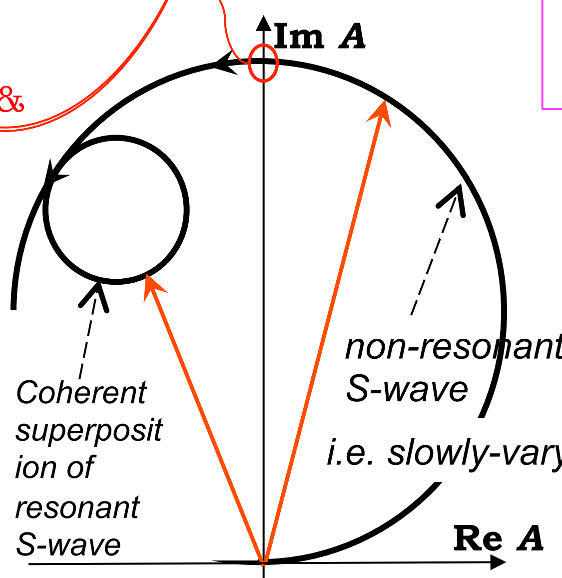
$\Xi(1530)^0$

$\Xi(1690)^0$



$\Xi(1690)^0$

S-wave accelerates & *catches* up on the P-wave



i.e. slowly-varying amplitudes & phase

Speculation:

Dip (~1680 MeV/c^2) may be due to *resonant* $\Xi(1690)^0$ S-wave ⇨ *negative parity for* $\Xi(1690)^0$

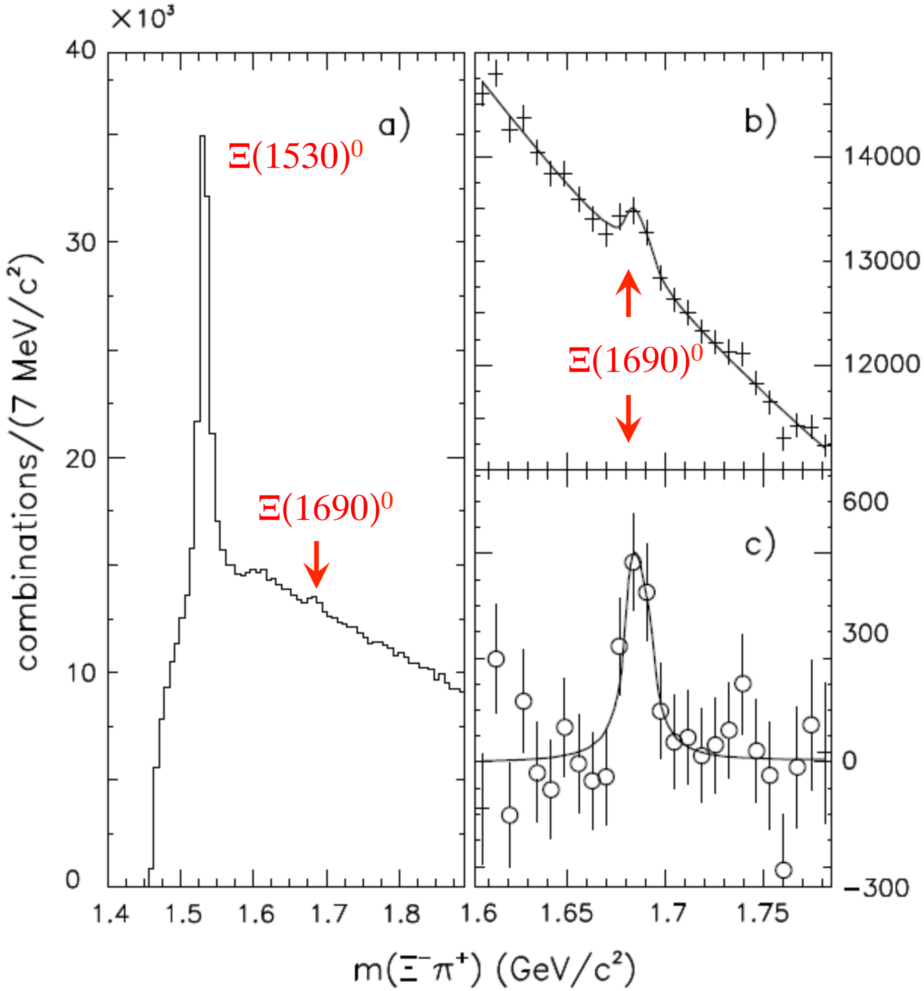
Does a small $\Xi(1690)^0 \to \Xi^- \pi^+$ decay rate make sense?

$\Xi(1690)^0$ Decay to $\Xi^- \pi^+$

345 GeV/c Σ^- beam on Cu and C

M.I. Adamovich *et al.* Eur.Phys.J. C**5**, 621 (1998)

$M = 1686 \pm 4$ MeV/c^2
$\Gamma = 10 \pm 6$ MeV
} consistent with BaBar values



- This $\Xi(1690)$ decay mode exists

- Product of the production cross section and branching fraction, $\sigma.BF$, is small compared to that for $\Xi(1530)^0$:

$$\frac{\sigma.BF(\Xi(1690)^0 \to \Xi^-\pi^+)}{\sigma.BF(\Xi(1530)^0 \to \Xi^-\pi^+)} = (2.2 \pm 0.5)\%$$

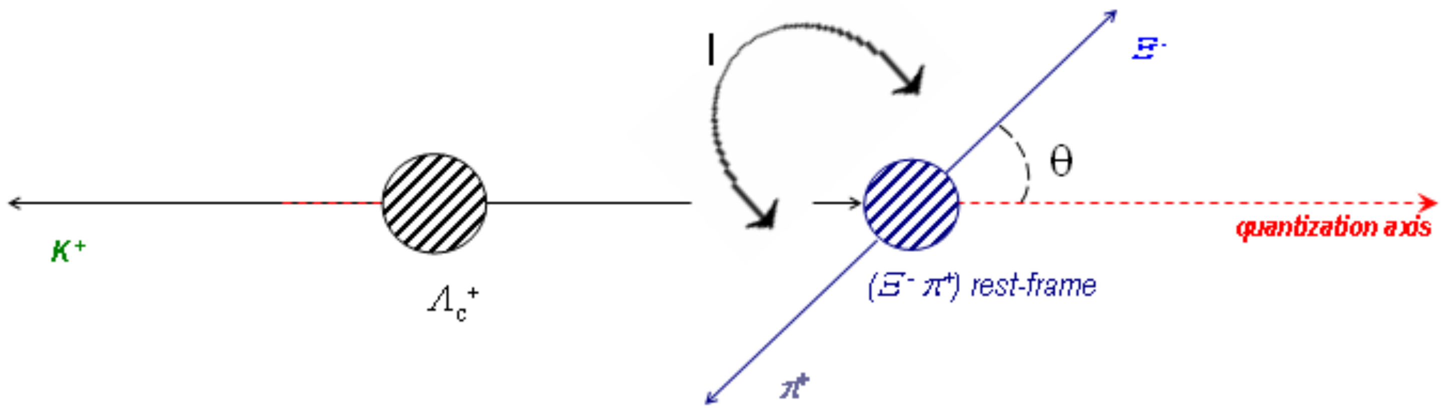
Summary of Results

Assuming that the Λ_c^+ has spin 1/2:

- used the decay mode $\Lambda_c^+ \rightarrow \Xi^- \pi^+ K^+$
  - to show that the spin of **the** $\Xi(1530)$ **is 3/2**
  - there is some indication that the $\Xi(1690)$ has negative parity
- used the decay mode $\Lambda_c^+ \rightarrow \Lambda K_S^0 K^+$
  - to obtain precise **(M, Γ) measurements** for the $\Xi(1690)^0$
  - to show that the preferred spin of **the** $\Xi(1690)$ **is 1/2**

Shortcomings of a quasi-two-body approach

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



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 = ±1/2) → density matrix elements describing the spin population of the Λ_c^+

where, λ_i = helicity of $\left(\Xi^- \ \pi^+\right)$ 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

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

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

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

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

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

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

$\boldsymbol{A}^{\mathrm{J}}_{\lambda}$ in terms of **S, P, D waves**

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

J=1/2 J=3/2 Interference

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

→ S-P interf.

→ P-D interf.

Cannot distinguish between ($\mathrm{S}^{1/2} + \mathrm{P}^{3/2}$) nor between ($\mathrm{P}^{3/2} + \mathrm{D}^{3/2}$) ~ however **strong $\mathrm{P}^{3/2}$ wave** suggests **term containing $\mathrm{S}^{1/2}$, $\mathrm{P}^{3/2}$ amplitudes dominates**

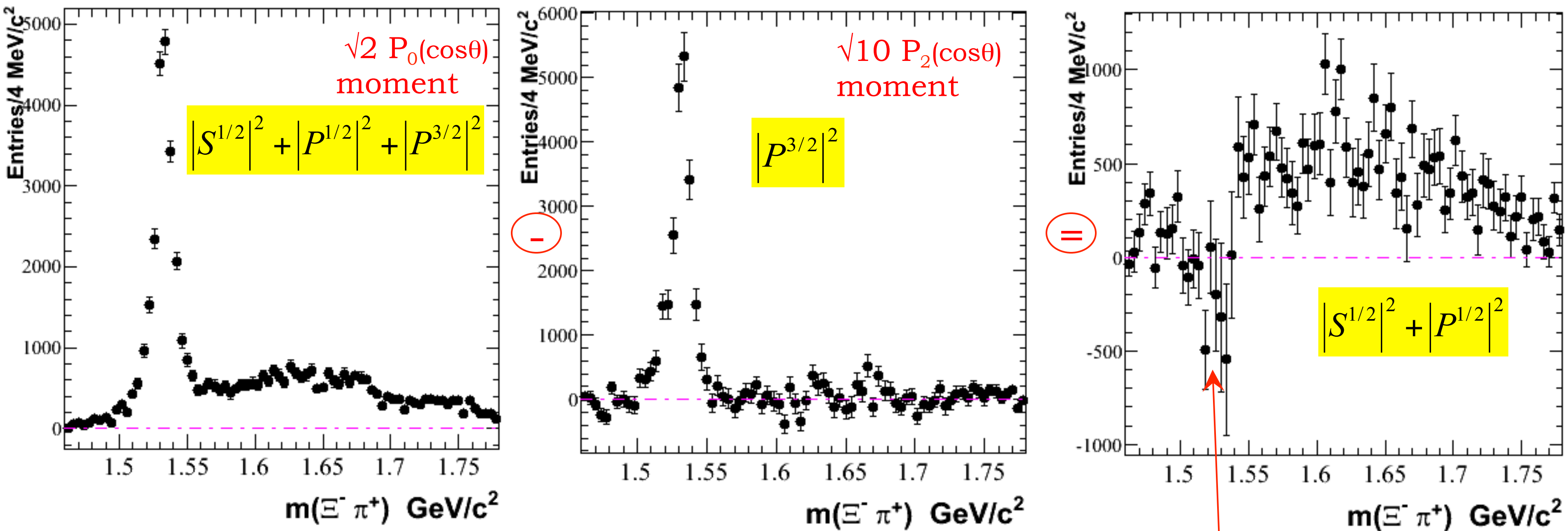
[Minami ambiguity]

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

Amplitude Analysis Assuming S and P Waves

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

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

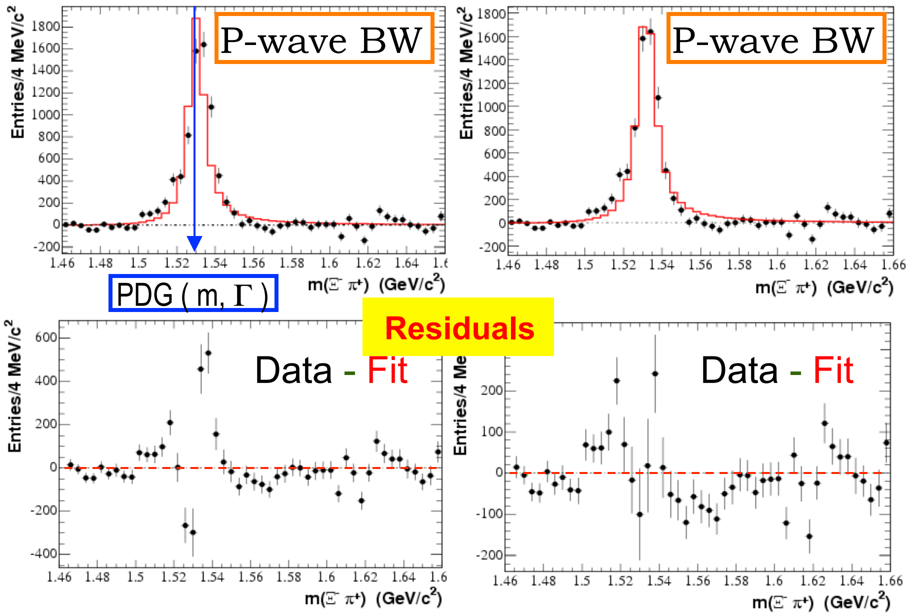


$\sqrt{10}\, P_2(\cos\theta)$ moment projects too much signal!!

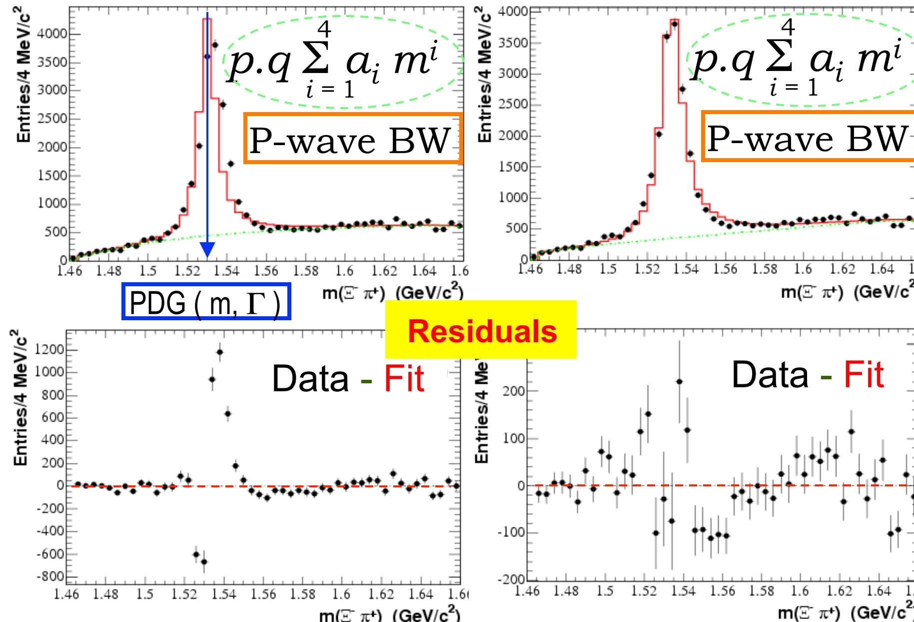
➔ need more than S and P waves

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

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?

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

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

Possible Ξ Studies with K_L^0 Beam

- Possible production of multi-body systems with a Ξ, or a Ξ^* :

e.g. $K_L^0 p \to (\Xi^- \pi^+) K^+, \quad (\Xi^0 \pi^0) K^+$
$\to (\Lambda K_S^0) K^+$

States analyzed in Λ_c^+ decay can be observed in different context

e.g. $K_L^0 p \to \pi^+ (\Xi^- \pi^+) K^0, \pi^+ (\Xi^- \pi^0) K^+$
$\to \pi^+ (\Xi^0 \pi^-) K^+, \pi^+ (\Xi^0 \pi^0) K^0$
$\to \pi^+ (\Lambda K^-) K^+$

Summary

- Similar studies for Cascade resonance production and associated spectra done at BaBar using charm baryon production can be done at GlueX with K_L beam.

- Three-body systems involving two-body Cascade resonance decays require analysis of the entire Dalitz plot when the statistical level is such that the shortcomings of a quasi-two-body approach become apparent. Therefore it is essential to have high statistics to allow for a proper to fit to the entire Dalitz plot.

BACKUPS

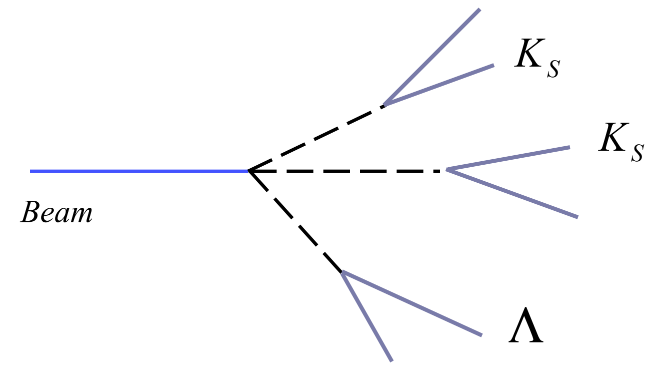
Effect of Constrained Kinematic Fits

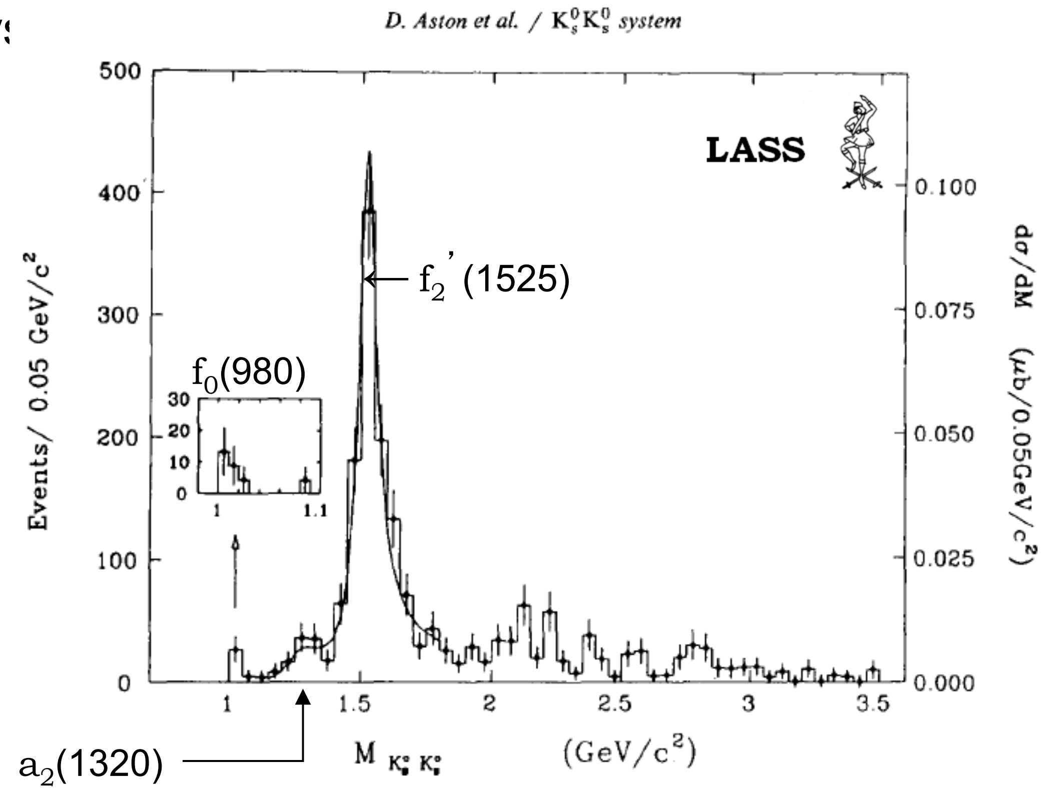
LASS: $K^- p \rightarrow \Lambda K_S K_S$

Inclusive Λ and K_S studies required flight length > 2 cm.

For this exclusive reaction, after kinematic and topological fit, no flight length requirements necessary.

[Nucl.Phys





Low statistics, but very clean !