

Precision measurements of charm hadron properties at BABAR

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Representing the BaBar Collaboration

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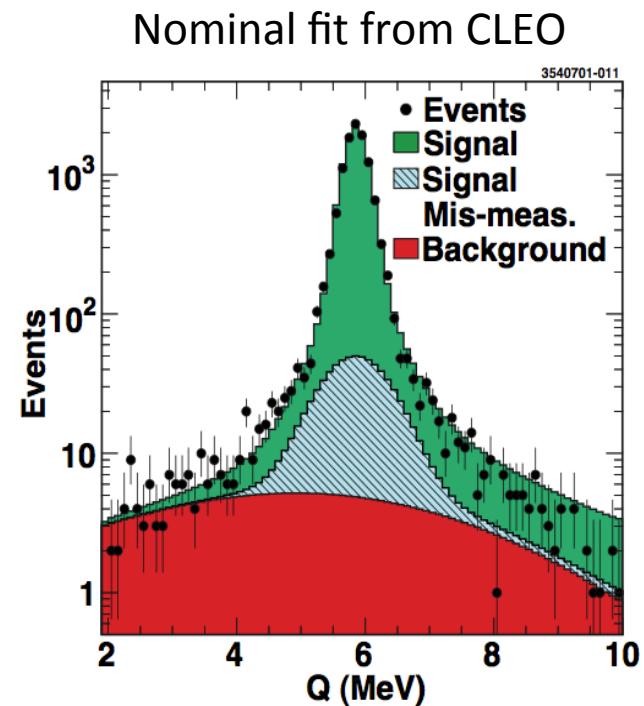
Outline

- Measurement of the $D^*(2010)^+$ total width and the $D^*(2010)^+ - D^0$ mass difference
- Measurement of the mass, width, quasi-two-body branching ratios from excited charm baryon $\Lambda_c(2880)^+ \rightarrow \Lambda_c^+ \pi^+ \pi^-$
- Summary

*Note: The use of the charge conjugate reactions is implied throughout

D^{*+} total width measurement - Motivation

- $\Gamma(D^{*+})$ offers a window into nonperturbative strong physics involving heavy quarks
 - Related to strong coupling (g) between heavy vector mesons, pseudoscalar mesons and the pion
 - Paper by M. Di Pierro and E. Eichten ([Phys. Rev. D 64, 114004 \(2001\)](#)) showed agreement between measurements and this idea
 - However, using updated measurements there is a disagreement
- Previous measurement:
 - $\Gamma(D^{*+}) = 96 \pm 4 \pm 22 \text{ keV}$
 - 11,000 $D^0 \rightarrow K^- \pi^+$ candidate sample ($\int L = 9 \text{ fb}^{-1}$)



[Phys. Rev. D 65, 032003 \(2002\)](#)

BaBar analysis

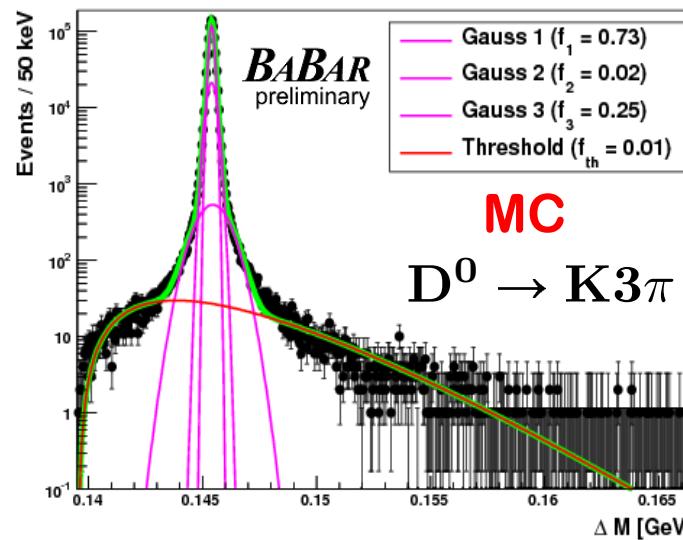
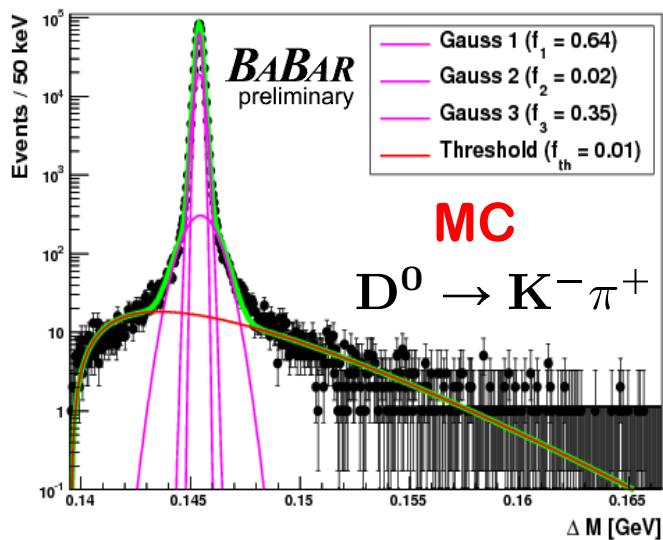
- Use $D^{*+} \rightarrow D^0 \pi_s^+$ from $\int L = 480 \text{ fb}^{-1}$
 - $p(\pi_s) \approx 40 \text{ MeV/c}$ in D^* CM (s = “slow”)

Decay Mode	# of Events in Fit
$D^0 \rightarrow K^- \pi^+$	142000
$D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$	231000

- A relativistic Breit-Wigner (RBW) lineshape is convolved with the experimental resolution function (obtained from MC simulation) to describe the $D^*(2010)^+$ signal.

Modeling experimental resolution

- There is no control sample from which to extract the experimental resolution
- We use truth-matched MC simulation to obtain the resolution function. We include a scale factor, $1+\varepsilon$, in the fit to data to allow for MC-data differences
- Model as triple-Gaussian and an additional contribution which describes the effect due to π_s^+ decay in flight



Observed shape
due entirely to
resolution effects

Relativistic Breit-Wigner

Partial width: $\Gamma_{D^* D\pi}(m) = \Gamma_0 \left(\frac{1 + r^2 p_0^2}{1 + r^2 p^2} \right) \left(\frac{p}{p_0} \right)^3 \left(\frac{m_0}{m} \right)$

m, p = running $D\pi$ mass, momentum

m_0, p_0 = m, p at pole position

r = Blatt-Weisskopf radius = 1.6 GeV (≈ 0.3 fm)

value taken from
Phys. Lett. B 308, 435 (1993)

RBW:
$$\frac{dN}{dm} = \left(\frac{p}{p_0} \right)^3 \left(\frac{1 + r^2 p_0^2}{1 + r^2 p^2} \right) \frac{(m_0 \Gamma_0)^2}{(m_0^2 - m^2)^2 + (m_0 \Gamma_{\text{Total}}(m))^2}$$

$$\Gamma_{\text{Total}}(m) = \Gamma_{D^* D\pi}(m) + \Gamma_{D^* D\gamma}(m) \approx \Gamma_{D^* D\pi}(m)$$

Fit model for data

- Signal:
$$\begin{aligned} & f_a^{MC} \times \textcolor{blue}{T}(\Delta m; p, \alpha)^{MC} \\ & + f_1^{MC} \times G(\Delta m; \mu_1^{MC} + \delta, \sigma_1^{MC}(1 + \epsilon)) \otimes RBW(\Delta m; \Gamma, m_0) \\ & + f_2^{MC} \times G(\Delta m; \mu_2^{MC} + \delta, \sigma_2^{MC}(1 + \epsilon)) \otimes RBW(\Delta m; \Gamma, m_0) \\ & + (1 - f_a^{MC} - f_1^{MC} - f_2^{MC}) \times G(\Delta m; \mu_3^{MC} + \delta, \sigma_3^{MC}(1 + \epsilon)) \otimes RBW(\Delta m; \Gamma, m_0) \end{aligned}$$

$$\Delta m = m(K\pi\pi_s) - m(K\pi)$$

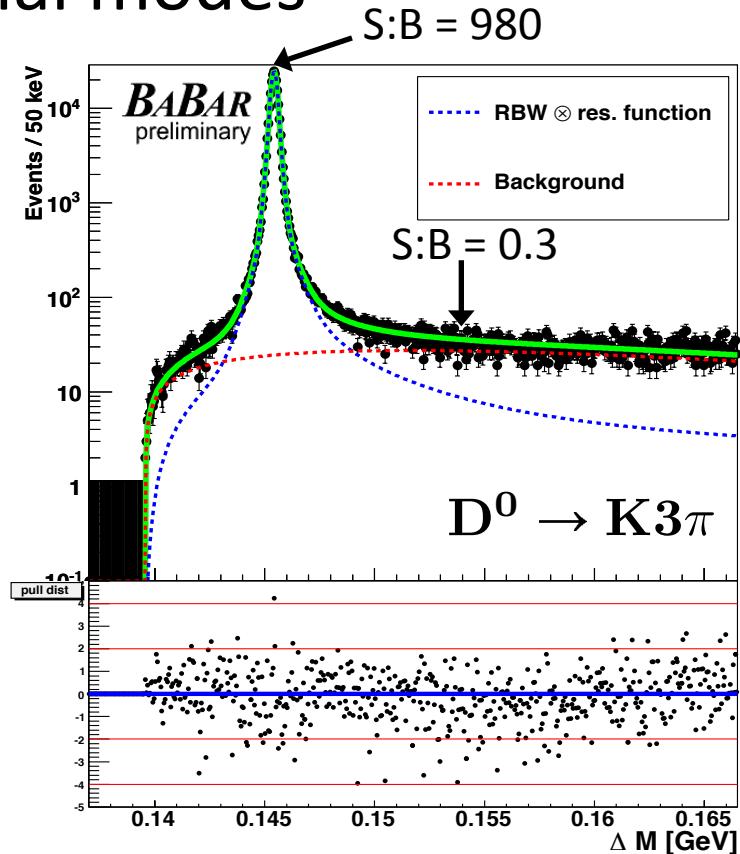
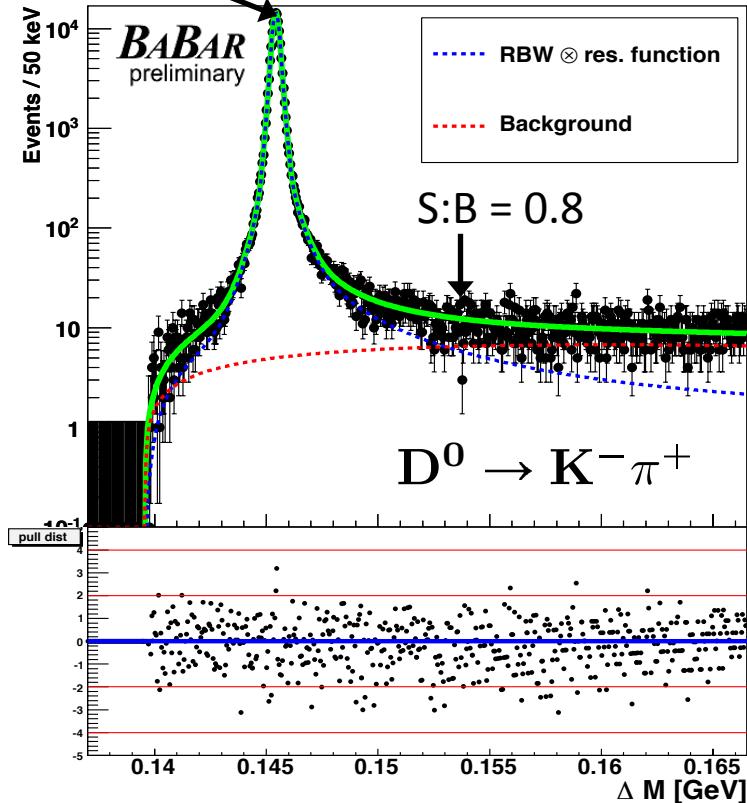
$$\Delta m = m(K\pi\pi\pi\pi_s) - m(K\pi\pi\pi)$$

- Background: two-body phase space near kinematic threshold

Fit is performed using a binned maximum likelihood fit.
Nominal bin width is 50 keV (varied in systematic checks)

S:B = 2700

Fit to data for signal modes



	K π	K3 π
Width, Γ (keV)	83.5 ± 1.7	$XX.X \pm 1.4$
Scale factor, ε	$+0.06 \pm 0.01$	$+0.07 \pm 0.01$
Δm pole (keV)	145425.5 ± 0.6	145426.5 ± 0.4
Projection χ^2/NDF	613/540	722/540

Systematic studies
affecting the K3 π width
measurement are ongoing

$$\chi^2_{proj} = \sum \frac{(N_{measured} - N_{predicted})^2}{N_{measured}}$$

Sources of systematic uncertainty

- The model of the detector material, and the scale of the magnetic field
- The region of Δm used in the fit
 - Nominal end point is 166.5 MeV. Take 1 MeV steps toward the signal and use the largest deviation from the nominal fit as the uncertainty
- The shape parameters of the resolution function
 - Use shape of the resolution function and generate 100 variations within errors. Use RMS of the fitted width and pole position as estimates of uncertainty
- The size of the Δm interval used in the fit
 - Nominal binning is 50 keV; reduce to 25 keV.

Preliminary systematic uncertainties

Source	$\sigma_{\text{sys}}(\Gamma)$ (keV)		$\sigma_{\text{sys}}(\text{RBW pole})$ (keV)	
	K π	K3 π	K π	K3 π
Azimuthal dependence	0.45	0.65	2.5	2.5
$m(D^0_{\text{reco}})$ dependence	0.0	1.12	0.01	0.0
$p_{\text{lab}}(D^{*+})$ dependence	0.57	0.19	0.2	0.2
Detector material and magnetic field	0.3	1.3	0.7	0.75
Δm fit range	0.8	0.3	0.1	0.0
Resolution shape parameters	0.41	0.3	0.17	0.14
Blatt-Weisskopf radius	0.04	0.03	0.0	0.0
Fit bin width	0.1	0.1	0.1	0.1
MC validation	0.0	5.7	0.0	0.0
Total	1.2	6.0	2.6	2.6

Studied using
10 disjoint
subsamples

Observe bias
from peaking
 D^0 background.
(Investigating)
Pole is unaffected.

Using full MC bias
on width for now

Summary of D^{∗+} width and mass-difference results

- BaBar **PRELIMINARY** results:

$$\Gamma(K\pi) = 83.5 \pm 1.7 \pm 1.2 \text{ keV}$$

$$\Delta m \text{ pole } (K\pi) = 145425.5 \pm 0.6 \pm 2.6 \text{ keV}$$

$$\Delta m \text{ pole } (K3\pi) = 145426.5 \pm 0.4 \pm 2.6 \text{ keV}$$

- We have discovered a bias in the K3π validation fits, which we are working to remove/reduce. Currently we are not reporting the width result for this mode.
- CLEO measurement:

$$\Gamma = 96 \pm 4 \pm 22 \text{ keV}$$

$$\Delta m \text{ pole: } 145412 \pm 2 \pm 12 \text{ keV}$$

Chiral coupling, g

- Width is related to effective coupling of pseudoscalar to quark (g)

$$\Gamma(D^{*+}) = \frac{2g^2}{12\pi f_\pi^2} p_{\pi^+}^3 + \frac{g^2}{12\pi f_\pi^2} p_{\pi^0}^3 + \frac{\alpha g_{D^* \rightarrow D\gamma}^2}{3} p_\gamma^3$$

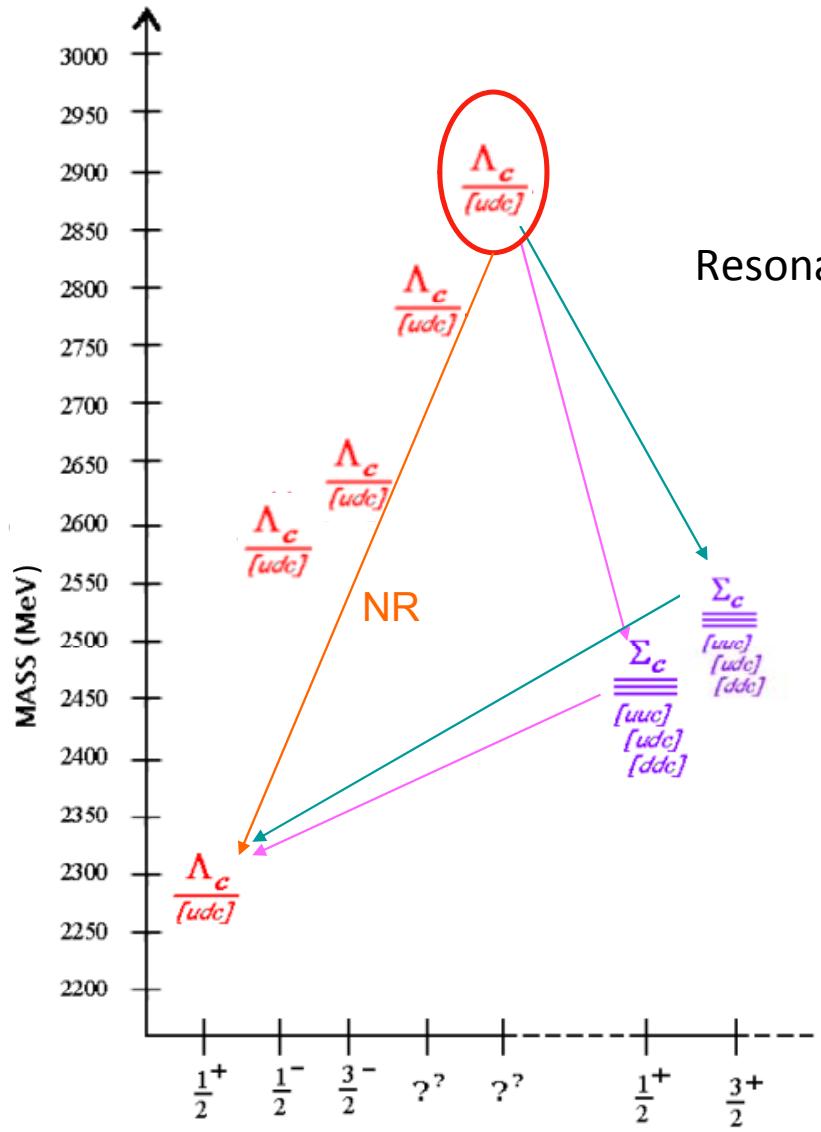
- g can also be used to calculate the coupling in the B system where there is no direct exp. window (no phase space for $B^* \rightarrow B\pi$)
- M. Di Pierro and E. Eichten ([Phys. Rev. D 64, 114004 \(2001\)](#)) provide Γ/g ratio for multiple decay modes
- BaBar results show a disagreement

Mode	Width	g
CLEO $D^*(2010)^+$	92 ± 22 keV	0.82 ± 0.09
Lattice (from D&E)		0.51 ± 0.11
$D_1(2420)^0$	31.4 ± 1.4 MeV	1.40 ± 0.04
$D_2^*(2460)^0$	50.5 ± 0.9 MeV	1.15 ± 0.01
$D^*(2010)^+$ (This analysis)	83.5 ± 2.1 keV (preliminary)	0.764 ± 0.007

From BaBar paper
[Phys. Rev. D 82, 111101\(R\)
\(2010\)](#)

Measurement of the mass, width, quasi-two-body branching ratios from excited charm baryon $\Lambda_c(2880)^+$

$\Lambda_c(2880)^+$ decays investigated



Non-resonant decay:

$$\Lambda_c(2880)^+ \rightarrow \Lambda_c(2286)^+ \pi^+ \pi^-$$

Resonant (i.e. quasi-two-body) decay modes:

$$\begin{aligned} \Lambda_c(2880)^+ &\rightarrow \Sigma_c(2455)^0 \pi^+ \\ &\downarrow \Lambda_c(2286)^+ \pi^- \end{aligned}$$

$$\begin{aligned} \Lambda_c(2880)^+ &\rightarrow \Sigma_c(2455)^{++} \pi^- \\ &\downarrow \Lambda_c(2286)^+ \pi^+ \end{aligned}$$

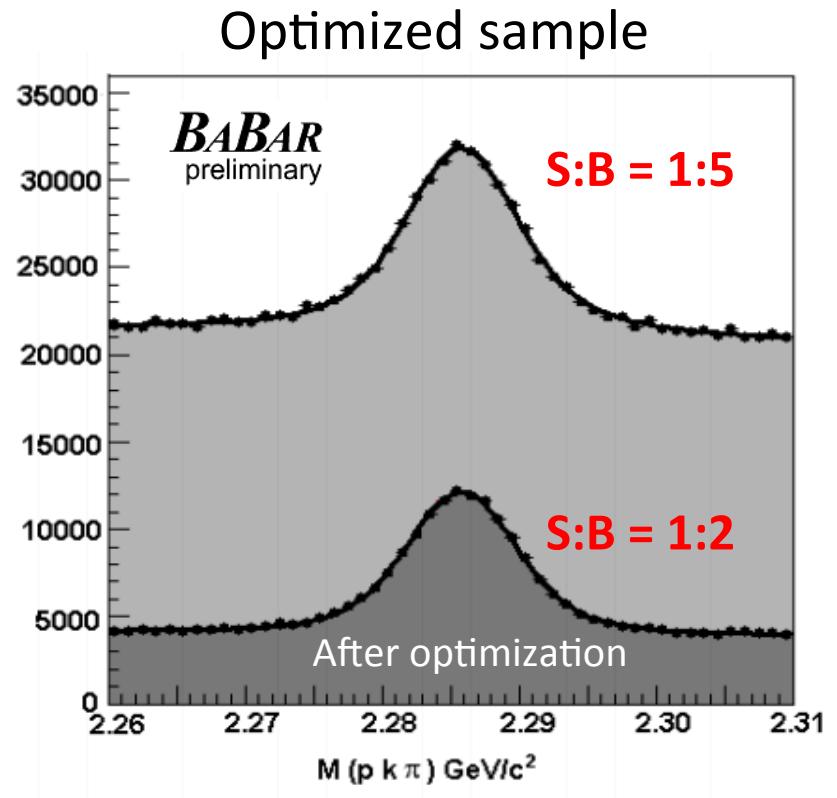
$$\begin{aligned} \Lambda_c(2880)^+ &\rightarrow \Sigma_c(2520)^0 \pi^+ \\ &\downarrow \Lambda_c(2286)^+ \pi^- \end{aligned}$$

$$\begin{aligned} \Lambda_c(2880)^+ &\rightarrow \Sigma_c(2520)^{++} \pi^- \\ &\downarrow \Lambda_c(2286)^+ \pi^+ \end{aligned}$$

BaBar $\Lambda_c^+(2880)^+$ analysis

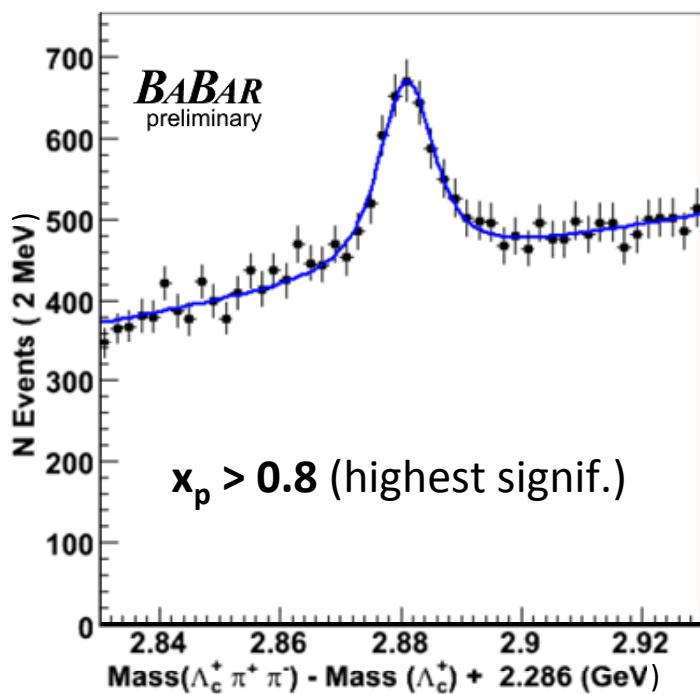
- Analysis uses $\int L \approx 316 \text{ fb}^{-1}$
- Optimize $\Lambda_c^+ \rightarrow p K^- \pi^+$ selection criteria using $S/\sqrt{S+B}$ on 21.8 fb^{-1}
- $x_p > 0.4$ to reduce B backgrounds, where

$$x_p = \frac{p^*}{p_{\max}^*} = \frac{p^*}{\sqrt{(s/4) - M_{\Lambda_c}^2}}$$



- Measure mass and width using $\Lambda_c^+ \pi^+ \pi^-$ distribution
- $\Sigma_c \pi$ branching ratios calculated with respect to the $\Lambda_c^+ \pi^+ \pi^-$ mode

Determining intrinsic mass and width of $\Lambda_c(2880)^+$



PDG values (J. of Phys. G37, 075021 (2010))

$$\Delta M = 595.1 \pm 0.4 \text{ MeV}$$

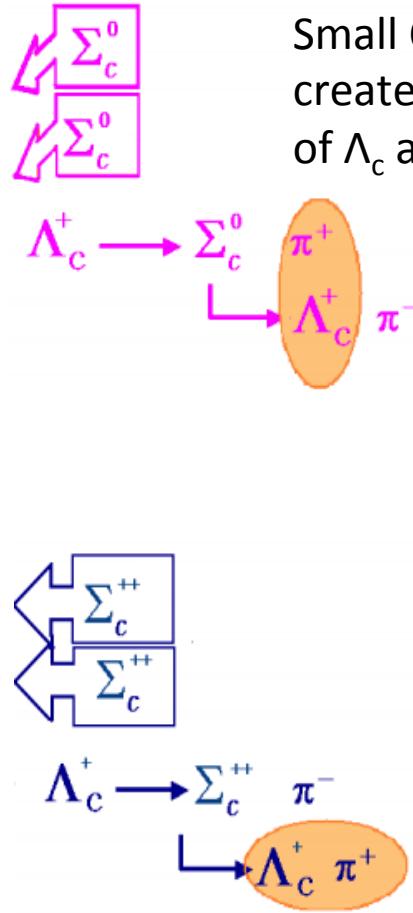
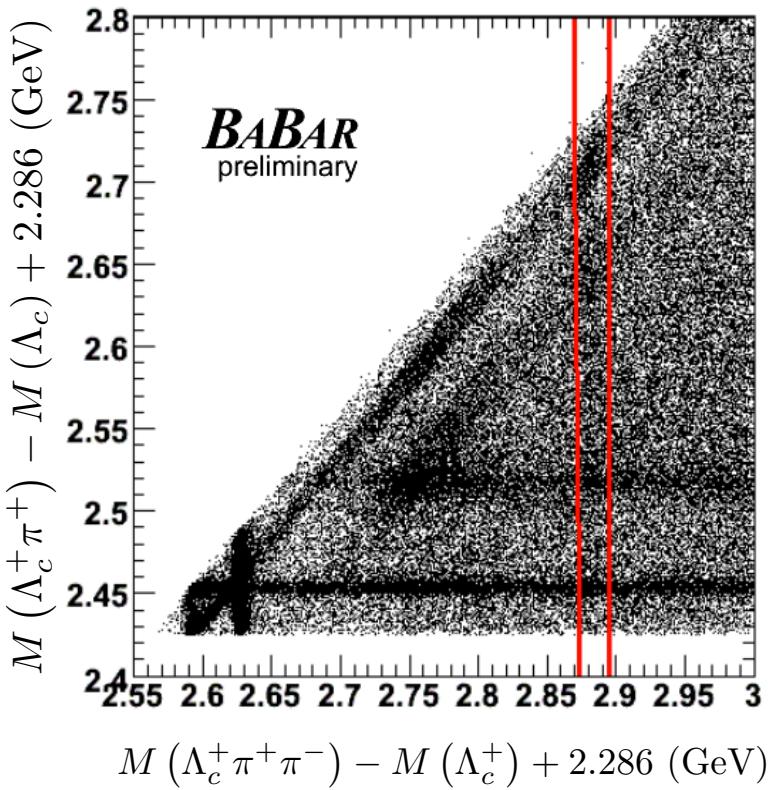
$$\Gamma = 5.8 \pm 1.1 \text{ MeV}$$

$$\Delta M \equiv m(\Lambda_c(2880)^+) - m(\Lambda_c(2286)^+)$$

$$\Delta M = XXX.X \pm 0.4 \text{ (stat.)} \pm 0.3 \text{ (syst.) MeV}$$

$$\Gamma = X.XX \pm 1.35 \text{ (stat.)} \pm 1.4 \text{ (syst.) MeV}$$

- Fit with RBW convolved with Gaussian resolution function, and a polynomial background function
 - Gaussian width fixed to detector resolution 1.79 MeV (from MC)
- Sources of systematic uncertainty:
 - Magnetic field (solenoid)
 - Tracking and SVT material
 - Fit model
 - Fit range
 - x_p momentum criterion
 - Detector resolution



No visible overlap in the 2880 signal region.

1. Assuming no interference effects, select 2880 signal and sideband regions
2. Fit the $\Lambda_c \pi$ projections with Σ_c signals and polynomial background
3. Use sideband subtraction to obtain the yield for each decay mode

$$\frac{\mathcal{B}(\Lambda_c(2880)^+ \rightarrow \Sigma_c \pi)}{\mathcal{B}(\Lambda_c(2880)^+ \xrightarrow{\text{all}} \Lambda_c^+ \pi^+ \pi^-)} = \frac{Y(\Lambda_c(2880)^+ \rightarrow \Sigma_c \pi)}{Y(\Lambda_c(2880)^+ \rightarrow \Lambda_c^+ \pi^+ \pi^-)} \times \frac{\epsilon(\Lambda_c(2880)^+ \rightarrow \Lambda_c^+ \pi^+ \pi^-)}{\epsilon(\Lambda_c(2880)^+ \rightarrow \Sigma_c \pi)}$$

	Resonant $\Sigma_c(2455)^0 \pi^+$	Resonant $\Sigma_c(2520)^0 \pi^+$	Resonant $\Sigma_c(2455)^{++} \pi^-$	Resonant $\Sigma_c(2520)^{++} \pi^-$
Yield in Signal Band	605.0 ± 21.5	573.8 ± 35.9	468.2 ± 18.3	488.6 ± 67.2
Yield in Side Band 1:	322.1 ± 16.8	202.4 ± 12.9	270.7 ± 30.3	272.2 ± 23.7
Yield in Side Band 2:	371.3 ± 17.1	310.1 ± 29.5	236.0 ± 13.5	217.7 ± 32.1

10-20 MeV
Above/below

Yields from fit using RBW convolved with Gaussian, and a polynomial background function

Resulting Raw Yield:	323.22 ± 28.91	314.83 ± 48.31	404.55 ± 26.07	208.26 ± 87.69
Scaled Efficiency %	19.25 ± 0.6	17.02 ± 0.85	16.16 ± 0.6	15.09 ± 0.71
Corrected Yield	1679.3 ± 168.8	1849.38 ± 185.03	2504.0 ± 250.44	1380.07 ± 138.57

(Values extracted assuming negligible interference and uniform backgrounds)

Preliminary Results

$$\Delta M = m\left(\Lambda_c(2880)^+\right) - m\left(\Lambda_c(2286)^+\right) = \text{XXX.X} \pm 0.4 \text{ (stat.)} \pm 0.3 \text{ (syst.) MeV}$$

$$\Gamma\left(\Lambda_c(2880)^+\right) = \text{X.XX} \pm 1.35 \text{ (stat.)} \pm 1.4 \text{ (syst.) MeV}$$

Branching ratios values (assuming $\text{BF}(\Sigma_c \rightarrow \Lambda_c \pi) = 100\%$),

$$\text{Br}\left(\Sigma_c(2455)^0 \pi^+\right) / \text{Br}(\text{all } \Lambda_c^+ \pi^+ \pi^-) = 0.13 \pm 0.02 \text{ (stat.)} {}^{+0.02}_{-0.01} \text{ (syst.)}$$

$$\text{Br}\left(\Sigma_c(2520)^0 \pi^+\right) / \text{Br}(\text{all } \Lambda_c^+ \pi^+ \pi^-) = 0.15 \pm 0.03 \text{ (stat.)} {}^{+0.02}_{-0.01} \text{ (syst.)}$$

$$\text{Br}\left(\Sigma_c(2455)^{++} \pi^-\right) / \text{Br}(\text{all } \Lambda_c^+ \pi^+ \pi^-) = 0.2 \pm 0.03 \text{ (stat.)} {}^{+0.03}_{-0.01} \text{ (syst.)}$$

$$\text{Br}\left(\Sigma_c(2520)^{++} \pi^-\right) / \text{Br}(\text{all } \Lambda_c^+ \pi^+ \pi^-) = 0.11 \pm 0.05 \text{ (stat.)} {}^{+0.02}_{-0.00} \text{ (syst.)}$$

$$\text{Br}(\text{NR } \Lambda_c^+ \pi^+ \pi^-) / \text{Br}(\text{all } \Lambda_c^+ \pi^+ \pi^-) = 0.41 \pm 0.10 \text{ (stat.)} {}^{+0.08}_{-0.05} \text{ (syst.)}$$

Non-resonant yield = total yield - \sum resonant yields

Summary

- PRELIMINARY results for the $D^{\ast+}$ analysis:

$$\Gamma(K\pi) = 83.5 \pm 1.7 \pm 1.2 \text{ keV}$$

$$\Delta m \text{ pole } (K\pi) = 145425.5 \pm 0.6 \pm 2.6 \text{ keV}$$

$$\Delta m \text{ pole } (K3\pi) = 145426.5 \pm 0.4 \pm 2.6 \text{ keV}$$

- Preliminary results for the $\Lambda_c(2880)^+$ analysis:

$$\Delta M = \text{XXX.X} \pm 0.4 \text{ (stat.)} \pm 0.3 \text{ (syst.) MeV}$$

$$\Gamma = \text{X.XX} \pm 1.35 \text{ (stat.)} \pm 1.4 \text{ (syst.) MeV}$$

Branching ratios for quasi-two-body modes:

$$\begin{array}{ll} \text{Br} \left(\Lambda_c(2880)^+ \rightarrow \Sigma_c(2455)^0 \pi^+ \right) & \text{Br} \left(\Lambda_c(2880)^+ \rightarrow \Sigma_c(2455)^{++} \pi^- \right) \\ \text{Br} \left(\Lambda_c(2880)^+ \rightarrow \Sigma_c(2520)^0 \pi^+ \right) & \text{Br} \left(\Lambda_c(2880)^+ \rightarrow \Sigma_c(2520)^{++} \pi^- \right) \end{array}$$

Backup Slides

Modeling Experimental Resolution

- There is no control sample to extract the experimental resolution from track reconstruction
- We use truth-matched MC simulation to fit the resolution function. We include a scale factor, $1+\varepsilon$, in the fit to data
- Model of the resolution function:

$$\begin{aligned} & f_1 \times G(\Delta m; \mu_1, \sigma_1) \\ & + f_2 \times G(\Delta m; \mu_2, \sigma_2) \\ + (1 - f_a - f_1 - f_2) \times & G(\Delta m; \mu_3, \sigma_3) \\ & + f_a \times T(\Delta m; p, \alpha) \end{aligned}$$

Threshold function:

$$m u^p e^{\alpha u}$$
$$u = \left(\frac{m}{m_{th}} \right)^2 - 1$$

α, p float in fit

Relativistic Breit-Wigner (RBW)

Partial width: $\Gamma_{D^* D\pi}(m) = \Gamma_0 \underbrace{\left(\frac{1 + r^2 p_0^2}{1 + r^2 p^2} \right)}_{\text{Blatt-Weisskopf Form factors}} \left(\frac{p}{p_0} \right)^3 \left(\frac{m_0}{m} \right)$

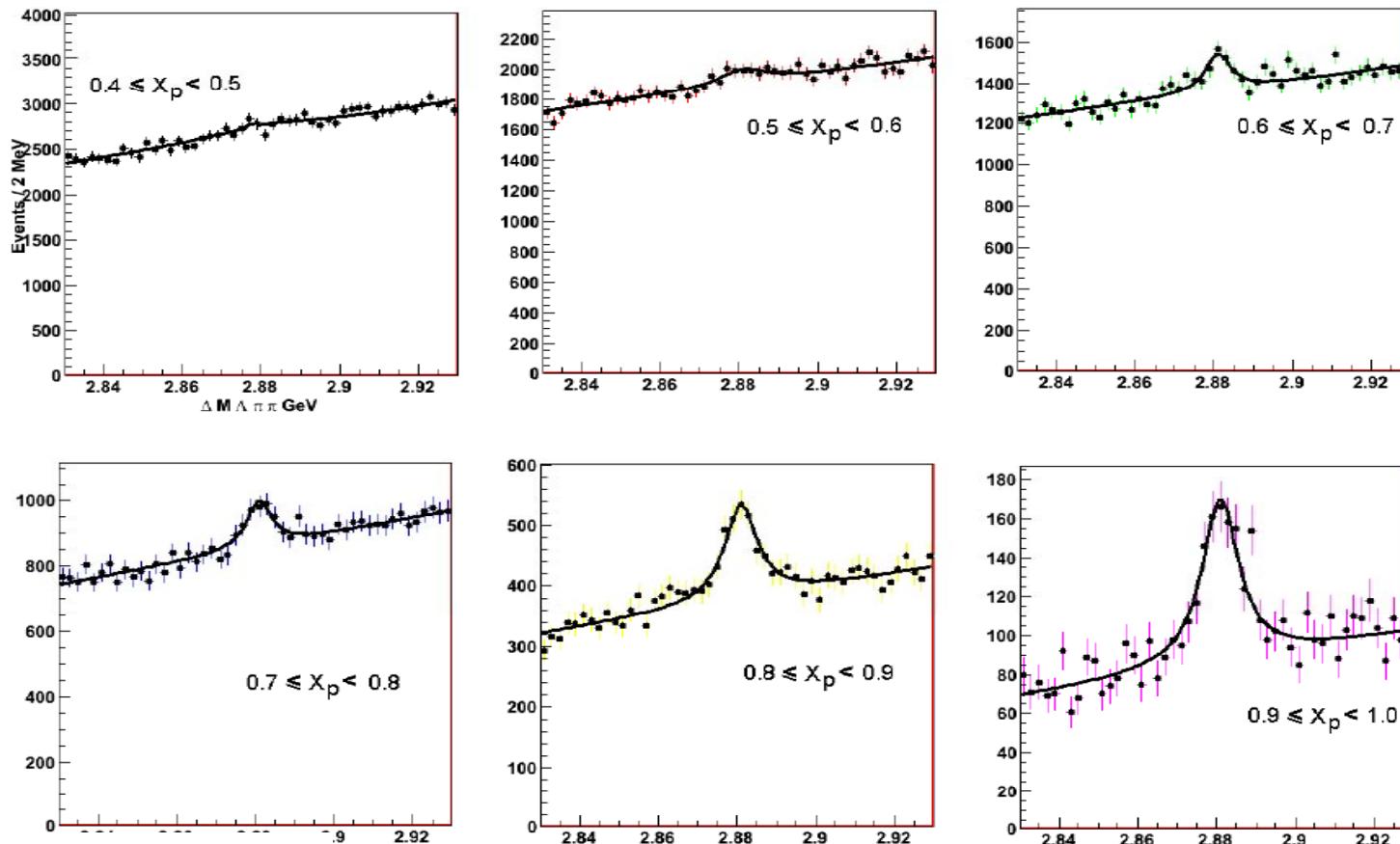
$$\frac{dN}{dm} = \left(\frac{p}{p_0} \right)^3 \left(\frac{1 + r^2 p_0^2}{1 + r^2 p^2} \right) \frac{(m_0 \Gamma_0)^2}{(m_0^2 - m^2)^2 + (m_0 \Gamma_{\text{Total}}(m))^2}$$

where,

$$m = m(D^0\pi) \quad p_0 = p(m_0)$$
$$p(m) = \frac{1}{2m} \sqrt{(m^2 - m_\pi^2 - m_{D^0}^2)^2 - 4m_\pi^2 m_{D^0}^2}$$
$$\Gamma_{\text{Total}}(m) = \Gamma_{D^* D\pi}(m) + \underbrace{\Gamma_{D^* D\gamma}(m)}_{\approx 1.6\%} \approx \Gamma_{D^* D\pi}(m)$$

Data in bins of x_p

$$x_p = \frac{p^*}{\sqrt{(s/4) - M_{\Lambda_c}^2}}$$



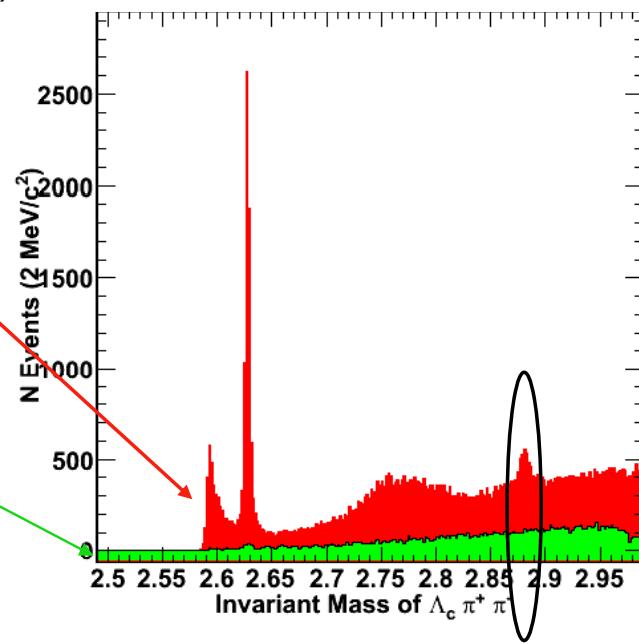
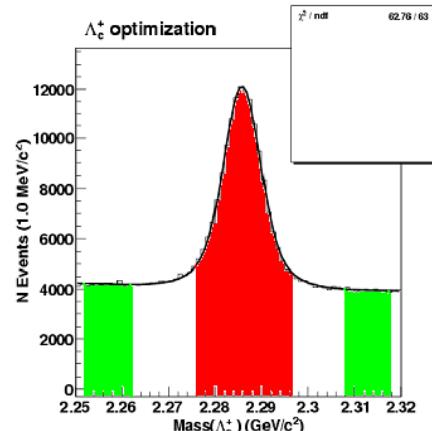
$\Lambda_c(2286)^+$ Side Band Comparison:

We select ($p\ K\ \pi^+$) combinations with invariant mass either in the $\Lambda_c(2286)^+$ massband, or in the sidebands regions, 20 –10 MeV/c² below or above the fitted $\Lambda_c(2286)^+$ mass.

Histogram of invariant mass of $(\Lambda_c^+ \pi^+ \pi^-)$ combinations, where $\Lambda_c^+ \rightarrow p\ K\ \pi^+$

Invariant mass of the $\Lambda_c^+ \pi^+ \pi^-$ for candidates with $p\ K\ \pi^+$ combinations from the $\Lambda_c^+ (2286)$ mass band

Invariant mass of the $\Lambda_c^+ \pi^+ \pi^-$ for candidates with $p\ K\ \pi^+$ from the $\Lambda_c^+ (2286)$ side bands



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