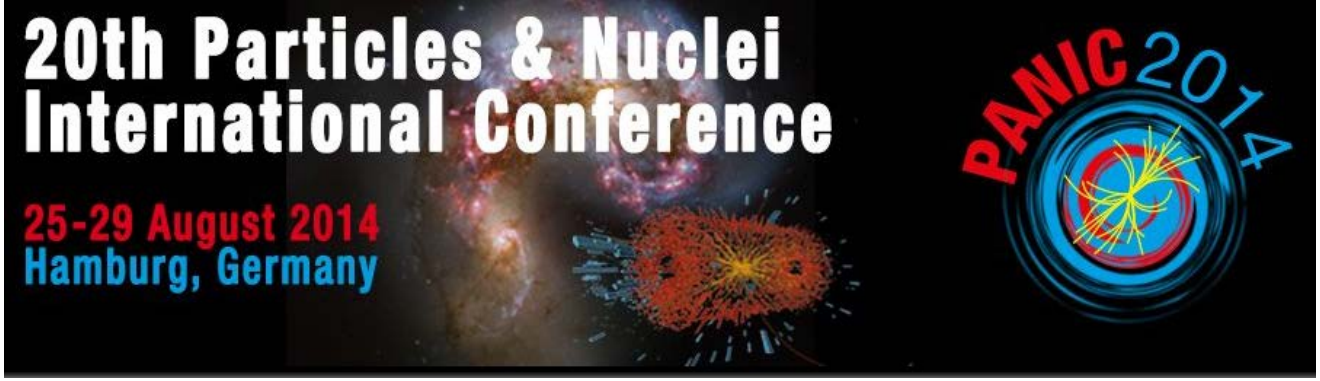

Resent results on the charmed hadron systems at Belle

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Aug, 26, 2014

Outline

- CP violation and mixing in the neutral D meson system
  - $D^0 \to K_S^0 \pi^+ \pi^-$ - [PRD 89, 091103(2014)]
  - $D^0 \to \pi^0 \pi^0$ - [PRL 112, 211601(2014)]
  - $D^0 \to K^+ \pi^-$ - [PRL 112, 111801(2014)]
- New measurements of M, Γ, B.F. of charm baryon
  - B.R. of $\Lambda_c^+ \to p K^- \pi^+$ - [PRL 113, 042002(2014)]
  - M, Γ of $\Sigma_c(2455/2520)^{0/++}$ - [PRD 89, 091102(2014)]
- Searching new charm baryon
  - $\Xi_{cc}^{+(+)}$, $\Xi_c(3055/3123)^+$ search - [PRD 89, 052003(2014)]

Outline

- CP violation and mixing in the neutral D meson system
  - $D^0 \to K_S^0 \pi^+ \pi^-$ - [PRD 89, 091103(2014)]
  - $D^0 \to \pi^0 \pi^0$ - [PRL 112, 211601(2014)]
  - $D^0 \to K^+ \pi^-$ - [PRL 112, 111801(2014)]

Neutral D meson system

- The time evolution is given by

$$i\frac{d}{dt}\begin{pmatrix}|D^0(t)\rangle\\ |\bar{D}^0(t)\rangle\end{pmatrix} = \underbrace{(\mathbf{M}-\frac{i}{2}\mathbf{\Gamma})}_{\mathcal{H}}\begin{pmatrix}|D^0(t)\rangle\\ |\bar{D}^0(t)\rangle\end{pmatrix}$$

- Flavor eigenstate is different from the mass eigenstate.

$$|D_{H,L}\rangle = p\,|D^0\rangle \pm q\,|\bar{D}^0\rangle \quad \text{(eigenstates of } \mathcal{H})$$
$$|D_{H,L}\rangle \text{ are mass eigenstates with masses } m_H,\ m_L \text{ and widths } \Gamma_H,\ \Gamma_L$$

- Using effective hamiltonian approximation, the solution is

$$|D^0(t)\rangle = e^{-(\Gamma/2+im)t}[\cosh\left(\tfrac{y+ix}{2}\Gamma t\right)|D^0\rangle + \tfrac{q}{p}\sinh\left(\tfrac{y+ix}{2}\Gamma t\right)|\bar{D}^0\rangle]$$
$$|\bar{D}^0(t)\rangle = e^{-(\Gamma/2+im)t}[\tfrac{p}{q}\sinh\left(\tfrac{y+ix}{2}\Gamma t\right)|D^0\rangle + \cosh\left(\tfrac{y+ix}{2}\Gamma t\right)|\bar{D}^0\rangle]$$

$$x = \frac{m_H - mL}{\Gamma},\ y = \frac{\Gamma_H - \Gamma_L}{2\Gamma},\ \Gamma = \frac{\Gamma_H + \Gamma_L}{2},\ m = \frac{m_H + m_L}{2}$$

CP violation

- For the small mixing system, |x|,|y|<<1

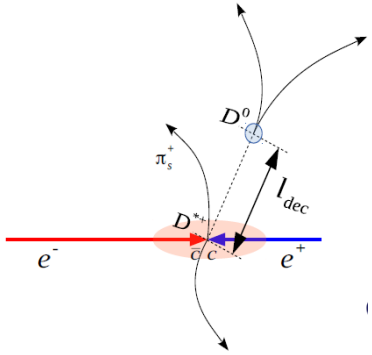
$$\frac{\mathrm{d}}{\mathrm{d}t}\left(N_{D^0\to f}\right) \propto e^{-\Gamma t}\left|\left\langle f\left|\mathcal{H}\right|D^0\right\rangle + \frac{q}{p}\left(\frac{y+ix}{2}\Gamma t\right)\left\langle f\left|\mathcal{H}\right|\bar{D}^0\right\rangle\right|^2$$

- Indirect CP violation
  - |p/q| ≠ 1 : CP violation in mixing
  - arg(p/q) ≠ 0, π : CP violation in interference of decay w/ and w/o mixing
- Direct CP violation
  - $|A(D^0 \to f)|^2 \neq \left|A\left(\bar{D}^0 \to \bar{f}\right)\right|^2$
- In the SM, CP violation on Singly Cabibbo-suppressed(SCS) charm decay is suppressed by $O(V_{cb}V_{ub}/V_{cs}V_{us})\sim 10^{-3}$ to compare with CP conserving decay.
- Observing CP violation in experiment could indicate new physics.

$D^0 \to K_s^0 \pi^+ \pi^-$ Introduction

- Search for indirect CP violation analysis using time dependent amplitude analysis of $D^0 \to K_s^0 \pi^+ \pi^-$.
  - So far no evidence of indirect CP violation
  - $1-|q/p| = +0.12 \pm 0.17$ [HFAG]
- Direct measurement of x, y w/, w/o CP conservation.

$D^0 \to K_s^0 \pi^+ \pi^-$ Analysis



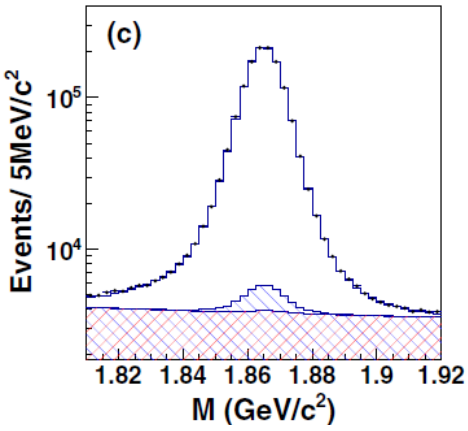
- Decay chain

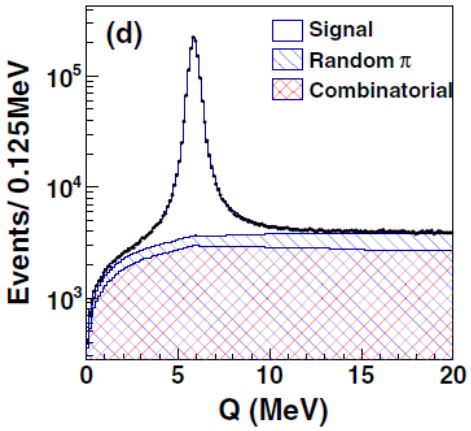
$D^{*+} \to D^0 \pi_s^+$

$D^0 \to K_s^0 \pi^+ \pi^-$

$K_s^0 \to \pi^+ \pi^-$

D D*



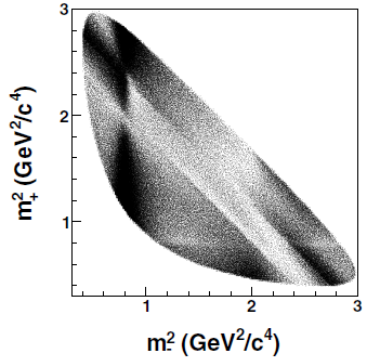


$M = M_{K_S^0 \pi^+ \pi^-}$

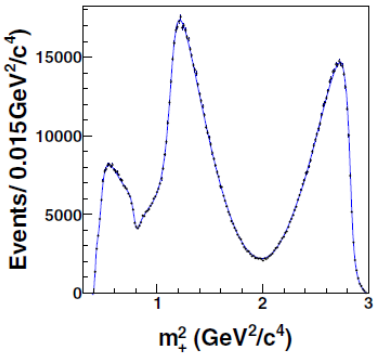
$Q = (M_{K_S^0 \pi^+ \pi^- \pi_s} - M_{K_S^0 \pi^+ \pi^-} - m_{\pi_s})c^2$

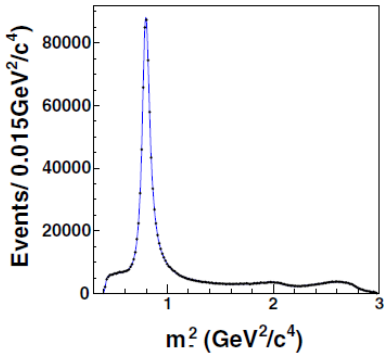
Signal yield is 1231731±1633(purity 95.5%) from the 2D fit over M-Q

- Dalitz plot and analysis



$(m^2_{K_S^0\pi^+}, m^2_{K_S^0\pi^-}) = (m^2_+, m^2_-)$

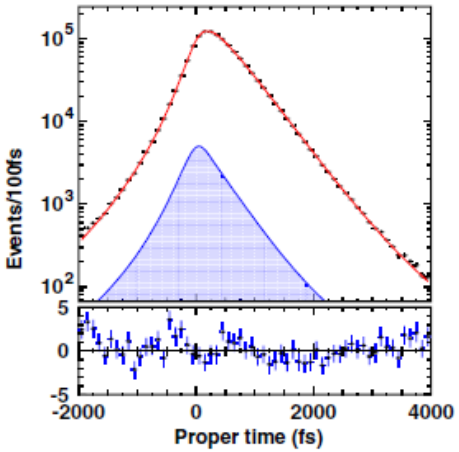




Resonance	Amplitude	Phase (deg)	Fit fraction
$K^*(892)^-$	1.590 ± 0.003	131.8 ± 0.2	0.6045
$K_0^*(1430)^-$	2.059 ± 0.010	-194.6 ± 1.7	0.0702
$K_2^*(1430)^-$	1.150 ± 0.009	-41.5 ± 0.4	0.0221
$K^*(1410)^-$	0.496 ± 0.011	83.4 ± 0.9	0.0026
$K^*(1680)^-$	1.556 ± 0.097	-83.2 ± 1.2	0.0016
$K^*(892)^+$	0.139 ± 0.002	-42.1 ± 0.7	0.0046
$K_0^*(1430)^+$	0.176 ± 0.007	-102.3 ± 2.1	0.0005
$K_2^*(1430)^+$	0.077 ± 0.007	-32.2 ± 4.7	0.0001
$K^*(1410)^+$	0.248 ± 0.010	-145.7 ± 2.9	0.0007
$K^*(1680)^+$	1.407 ± 0.053	86.1 ± 2.7	0.0013
$\rho(770)$	1 (fixed)	0 (fixed)	0.2000
$\omega(782)$	0.0370 ± 0.0004	114.9 ± 0.6	0.0057
$f_2(1270)$	1.300 ± 0.013	-31.6 ± 0.5	0.0141
$\rho(1450)$	0.532 ± 0.027	80.8 ± 2.1	0.0012
$\pi\pi$ S wave			0.1288
β_1	4.23 ± 0.02	164.0 ± 0.2	
β_2	10.90 ± 0.02	15.6 ± 0.2	
β_3	37.4 ± 0.3	3.3 ± 0.4	
β_4	14.7 ± 0.1	-8.9 ± 0.3	
f_{11}^{prod}	12.76 ± 0.05	-161.1 ± 0.3	
f_{12}^{prod}	14.2 ± 0.2	-176.2 ± 0.6	
f_{13}^{prod}	10.0 ± 0.5	-124.7 ± 2.1	
$K\pi$ S wave	Parameters		
M (MeV/c^2)	1461.7 ± 0.8		
Γ (MeV/c^2)	268.3 ± 1.1		
F	0.4524 ± 0.005		
ϕ_F (rad)	0.248 ± 0.003		
R	1(fixed)		
ϕ_R (rad)	2.495 ± 0.009		
a (GeV/c^{-1})	0.172 ± 0.006		
r (GeV/c^{-1})	-20.6 ± 0.3		
$K^*(892)$	Parameters		
$M_{K^*(892)}$ (MeV/c^2)	893.68 ± 0.04		
$\Gamma_{K^*(892)}$ (MeV/c^2)	47.49 ± 0.06		

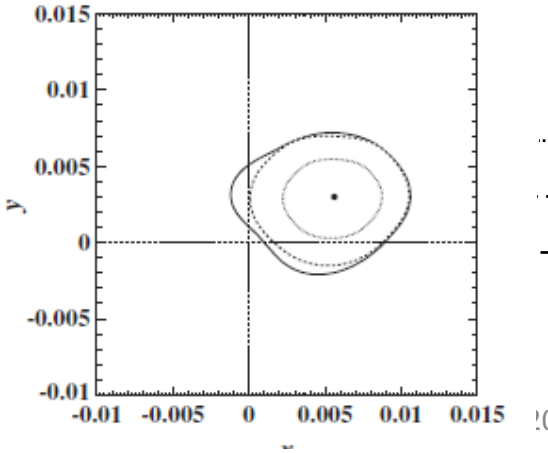
$D^0 \to K_s^0 \pi^+ \pi^-$ Result

Fit type	Parameter	Fit result
No *CPV*	$x(\%)$	$0.56 \pm 0.19^{+0.03+0.06}_{-0.09-0.09}$
	$y(\%)$	$0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.06}$
CPV	$x(\%)$	$0.56 \pm 0.19^{+0.04+0.06}_{-0.08-0.08}$
	$y(\%)$	$0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.07}$
	$\lvert q/p \rvert$	$0.90^{+0.16+0.05+0.06}_{-0.15-0.04-0.05}$
	$\arg(q/p)(^\circ)$	$-6 \pm 11 \pm 3^{+3}_{-4}$



Mixing parameter shows no difference between w/, w/o CP.
The |q/p| value is consistent with no CP.

Proper decay time : 410.3±0.6fs.
Consistent with W.A.



68.3% CL – CP conserved
95.0% CL – CP conserved
95.0% CL – CPV allowed

$D^0 \to \pi^0\pi^0$ – direct CP violation

- Time integrated asymmetry

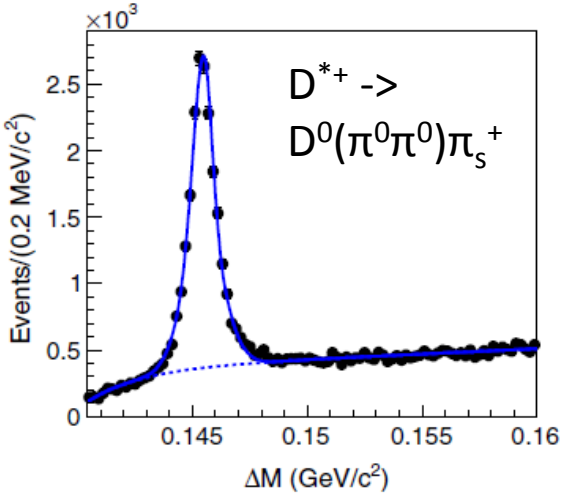
$$A_{CP} = \frac{\Gamma(D^0 \to \pi^0\pi^0) - \Gamma(\overline{D}^0 \to \pi^0\pi^0)}{\Gamma(D^0 \to \pi^0\pi^0) + \Gamma(\overline{D}^0 \to \pi^0\pi^0)}$$

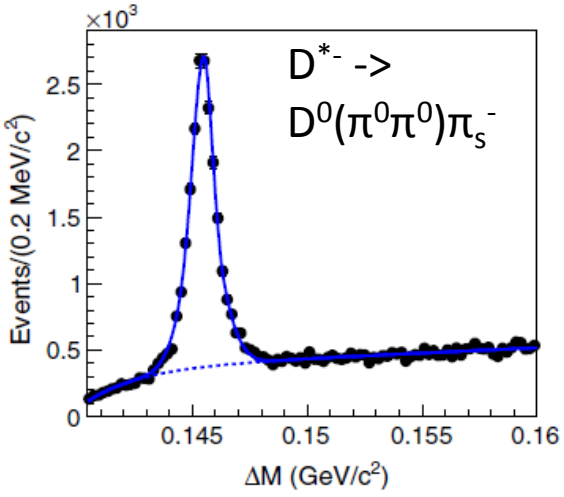
- Because of flavor tagging, study D*

$$A^{\mathrm{reco}} = \frac{N(D^{*+}) - N(D^{*-})}{N(D^{*+}) + N(D^{*-})}$$

- The only existing measurement of $D^0 \to \pi^0\pi^0$ is from CLEO, A_{CP} = (+0.1 ± 4.8)%. PRD 63, 071101 (2001).

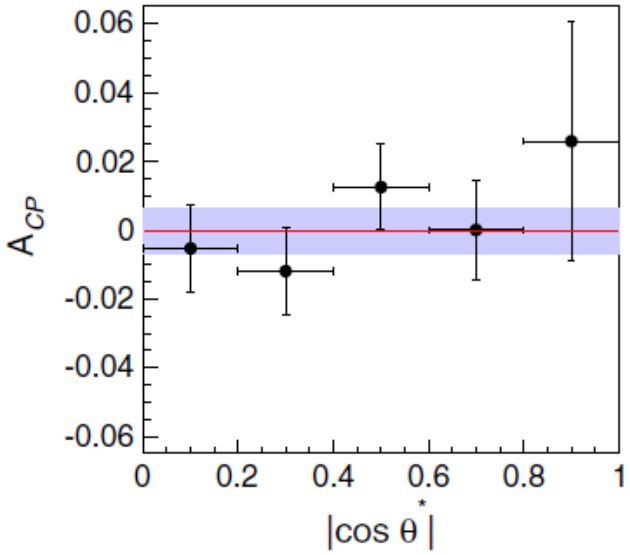
$D^0 \to \pi^0\pi^0$ - Analysis



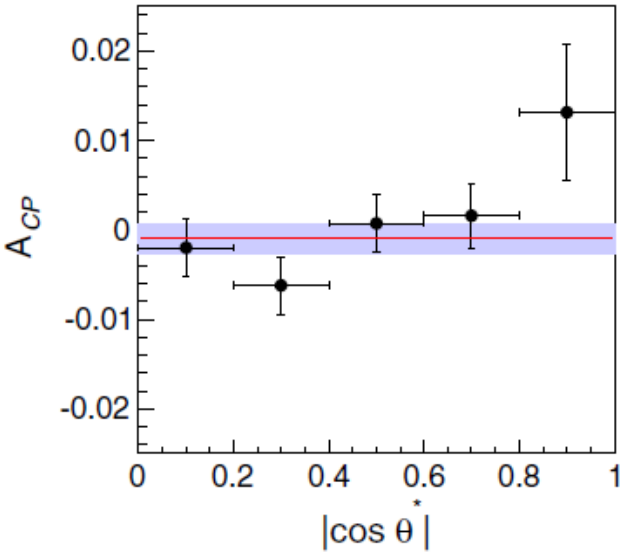


- $D^{*+/-} \to D^0(\pi^0\pi^0)\pi_s^{+/-}$, $D^0(K_s^0\pi^0)\pi_s^{+/-}$
- D^0 signal yield : 34460 ± 273

$D^0 \to \pi^0\pi^0$



$D^0 \to K_S^0\pi^0$



$D^0 \to \pi^0\pi^0$ - Result

- $D^0 \to \pi^0\pi^0$ mode

$$A_{CP}(D^0 \to \pi^0\pi^0) = (-0.03 \pm 0.64 \pm 0.10)\%$$

An order of magnitude better precision than prev result.

No evidence of CP violation.

- $D^0 \to K_S^0\pi^0$ mode (K^0 mixing subtracted)

$$A_{CP}(D^0 \to K_S^0\pi^0) = (-0.21 \pm 0.16 \pm 0.07)\%$$

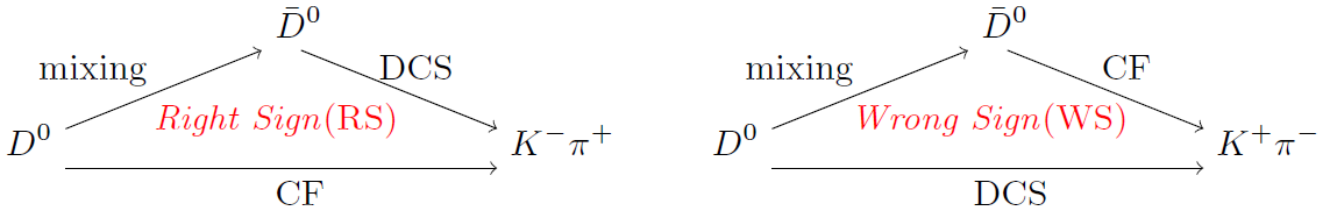
No evidence of CP violation

$D^0 \to K^+\pi^-$ - $D^0\overline{D}^0$ mixing

- Mixing phenomena are well established for K^0, B^0, B_s^0 mesons.
- D^0 mixing has also recently been observed in hadron collider. [PRL 110,010001(2012), PRL 111, 231802(2013)]
- This is first observation of D^0 mixing in an e^+e^- collision experiment.

D^0->$K^+\pi^-$ - $D^0\bar{D}^0$ mixing with decay

- D^0->$K^+\pi^-$: Wrong sign decay
- D^0->$K^-\pi^+$: Right sign decay



- Time dependent ratio of WS to RS decay rate

$$R(\tilde{t}/\tau) = \frac{\Gamma_{\mathrm{WS}}(\tilde{t}/\tau)}{\Gamma_{\mathrm{RS}}(\tilde{t}/\tau)} \approx R_D + \sqrt{R_D}y'\frac{\tilde{t}}{\tau} + \frac{x'^2 + y'^2}{4}\left(\frac{\tilde{t}}{\tau}\right)^2$$

- With |x|<<1 , |y|<<1, $\tilde{t}$ is proper decay time, τ is D^0 decay time, R_D is the ratio of DCS and CF decay amplitude,

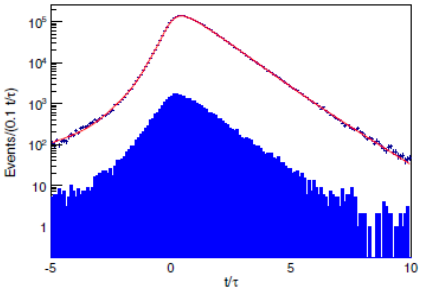
$x' = xcos\delta + ysin\delta, y' = xcos\delta - ysin\delta$

δ is strong phase difference between DCS and CF decay amp.

$D^0 \to K^+\pi^-$ - Analysis

- In the B factory, time resolution effect must be taken into account.

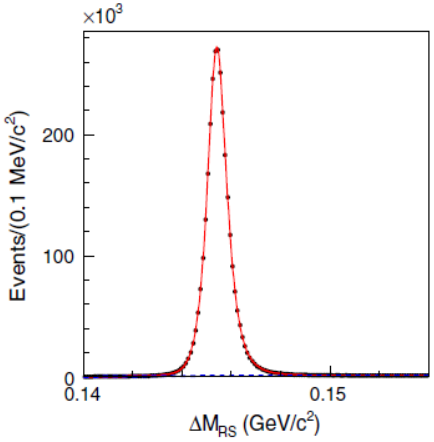
$$R(t/\tau) = \frac{\int_{-\infty}^{+\infty} \Gamma_{WS}(\tilde{t}/\tau)\mathcal{R}(t/\tau - \tilde{t}/\tau)d(\tilde{t}/\tau)}{\int_{-\infty}^{+\infty} \Gamma_{RS}(\tilde{t}/\tau)\mathcal{R}(t/\tau - \tilde{t}/\tau)d(\tilde{t}/\tau)}$$



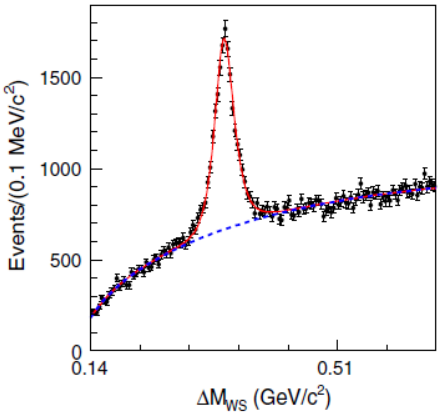
- Resolution function : $\mathcal{R}(t/\tau - \tilde{t}/\tau)$

- Time integrated D* reconstruction.

RS



WS



$$\Delta M \equiv M(D^{*+} \to D^0(\to K\pi)\pi_s^+) - M(D^0 \to K\pi)$$

N(RS) = 2980710 ± 1885

N(WS) = 11478 ± 177

$D^0 \to K^+\pi^-$ - Result

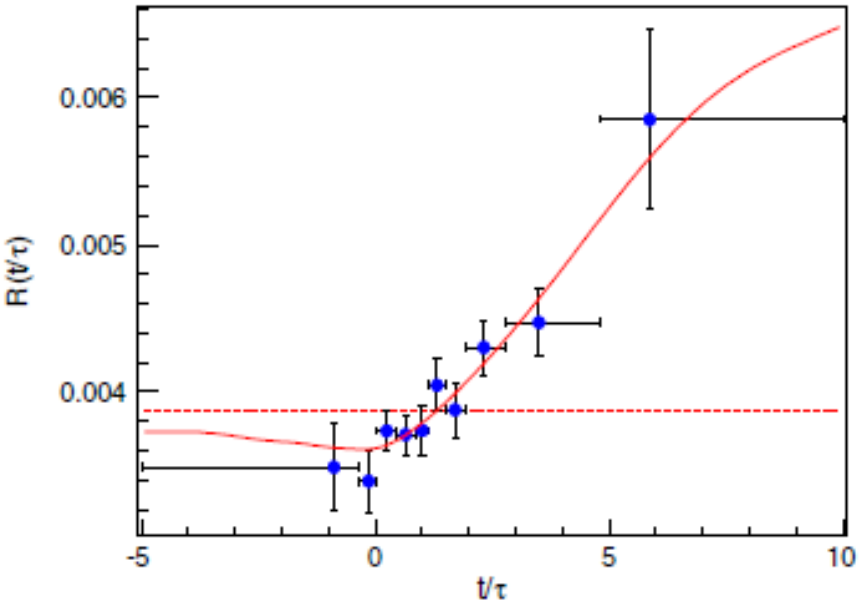


TABLE I. Results of the time-dependent fit to $R(t/\tau)$, where DOF stands for the degrees of freedom. The uncertainties are statistical and systematic combined.

Test hypothesis (χ^2/DOF)	Parameters	Fit results (10^{-3})	Correlation coefficient R_D	y'	x'^2
Mixing (4.2/7)	R_D	3.53 ± 0.13	1	−0.865	+0.737
	y'	4.6 ± 3.4		1	−0.948
	x'^2	0.09 ± 0.22			1
No mixing (33.5/9)	R_D	3.864 ± 0.059			

- "Mixing" hypothesis excludes the "non-mixing" hyphothesis at χ^2/DOF = 29.3/2, 5.1σ.
- This is first observation of D^0 mixing in an e^+e^- collision experiment.

Outline

- New measurements of M, Γ, B.F. of charm baryon
  - B.R. of $\Lambda_c^+ \to pK^-\pi^+$ - [PRL 113, 042002(2014)]
  - M, Γ of $\Sigma_c(2455/2520)^{0/++}$ - [PRD 89, 091102(2014)]

B.F. of $\Lambda_c^+ \to pK^-\pi^+$ - Introduction

- A number of charmed baryon s decay into Λ_c^+.
- $\Lambda_c^+ \to pK^-\pi^+$ is the reference mode for the measurement of branching fractions of the Λ_c^+ baryon, it's important to measure the absolute branching fraction.

	Mode		Fraction (Γ_i/Γ)
	Hadronic modes with a p: $S = -1$ final states		
Γ_1	$p\overline{K}^0$		(2.3 ± 0.6) %
Γ_2	$pK^-\pi^+$	[a]	(5.0 ± 1.3) %
Γ_3	$p\overline{K}^*(892)^0$	[b]	(1.6 ± 0.5) %

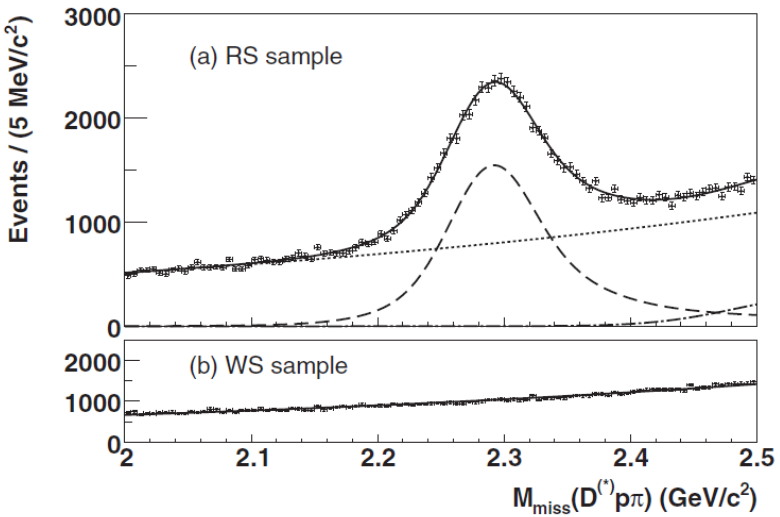
- PDG B.F. is model dependent.
- Estimating the precise B.F. with model independent is important

B.F. of Λ_c^+->p$K^-\pi^+$ - Analysis

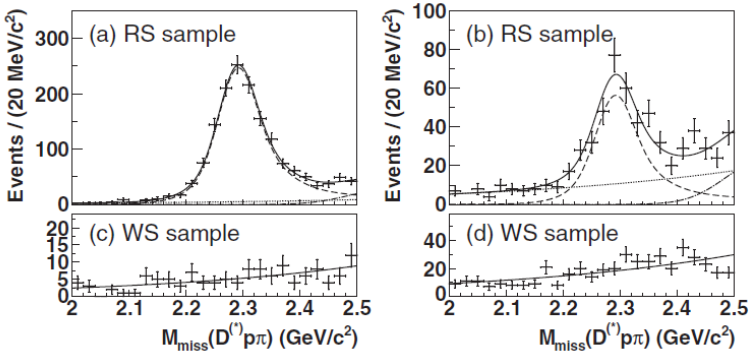
- Reconstruct the Λ_c^+- inclusively using missing mass of decay

$$e^+e^- \rightarrow c\bar{c} \rightarrow D^{(*)-}\bar{p}\pi^+\Lambda_c^+$$

  - $N_{inc}^{\Lambda_c}$ = 36447 ± 432



- Reconstruct the Λ_c^+->p$K^-\pi^+$ exclusively within inclusive sample of Λ_c^+.
  - N_{excl}^{SR} = 1457 ± 44
  - N_{excl}^{SB} = 332 ± 27



B.R. of Λ_c^+->$pK^-\pi^+$ - Result

- $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$ = 6.84 ± 0.24(stat) $^{+0.21}_{-0.27}$(sys) %
- Cross check
  - Using different fitting method, $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$ = (6.78 ± 0.24)%
  - Using $e^+e^- \to D^{(*)0}\bar{p}\Lambda_c^+$, $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$ = (7.04 ± 0.38)%
- Good agreement with result.
- This result improves the previous measurement

by factor of 5.

$\Sigma_c(2455/2520)^{0/++}$ - Introduction

	Bag model	Quark model	Relativistic quark diquark	QCD	Lattic non-relativistic QCD
$\Sigma_c(2455)$	2.393(GeV/c^2)	2.455	2.439	2.40±0.31	2.407/2.452
$\Sigma_c(2520)$	2.489	2.519	2.518	2.56±0.24	2.482/2.538

- The Σ_c^{++} is heavier than Σ_c^{0} with large error although u quark is lighter than d quark.
- Property of $\Sigma_c(2455/2520)^{0/++}$ has large uncertainty, decay width uncertainty is 10% of their central value.
- Precise measurement of mass and width of $\Sigma_c(2455/2520)^{0/++}$ is necessary.

$\Sigma_c(2455)^{++}$ MASS

VALUE (MeV)

2453.98±0.16 OUR FIT

$\Sigma_c(2455)^{0}$ MASS

VALUE (MeV)

2453.74±0.16 OUR FIT

$\Sigma_c(2455)^{++}$ WIDTH

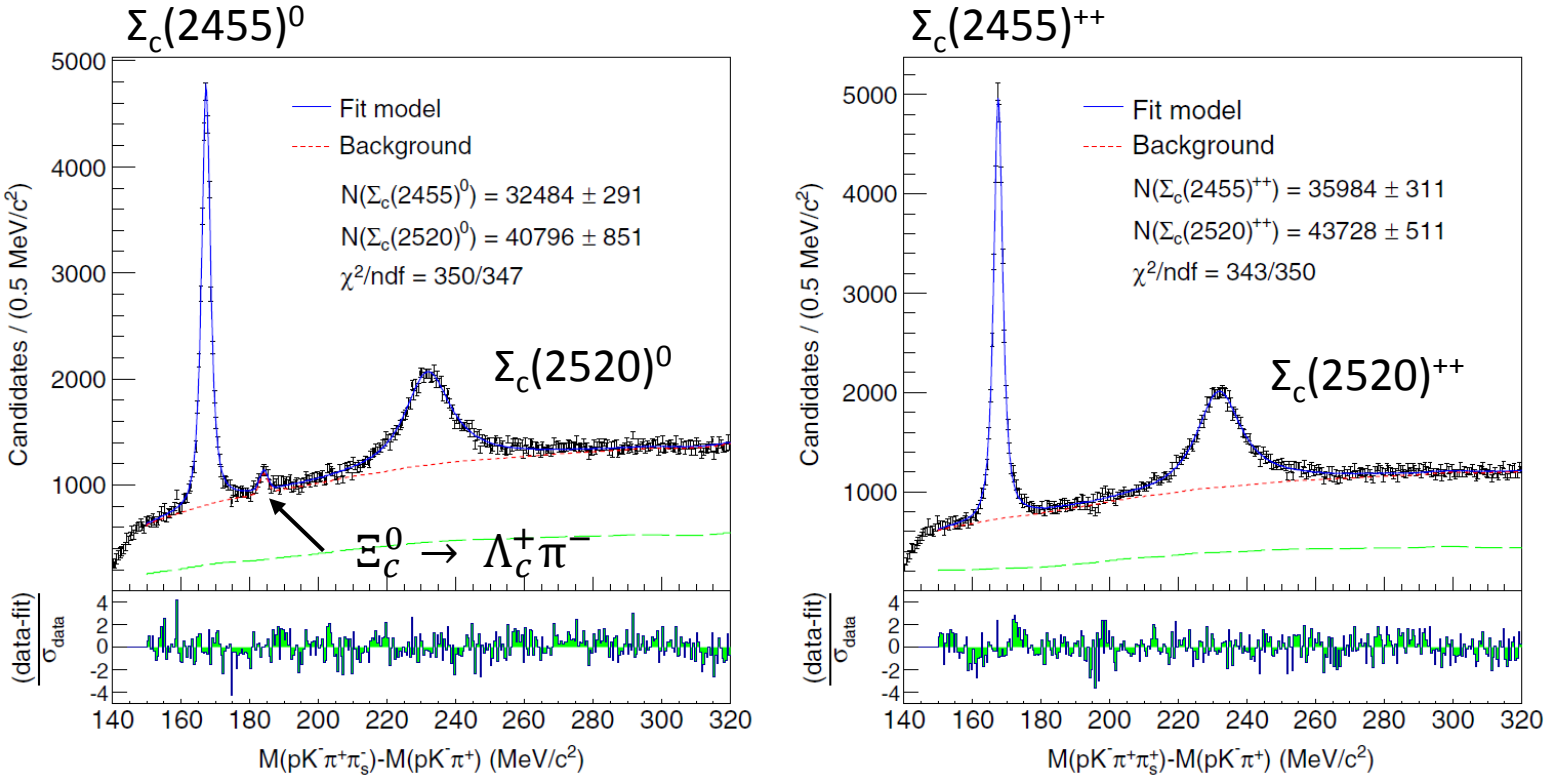
VALUE (MeV)	*EVTS*
2.26±0.25 OUR AVERAGE	

$\Sigma_c(2455)^{0}$ WIDTH

VALUE (MeV)	*EVTS*
2.16±0.26 OUR AVERAGE	

$\Sigma_c(2455/2520)^{0/++}$ - Analysis

- $\Sigma_c(2455/2520)^{0/++}$ -> $\Lambda_c^+(->pK^-\pi^+)\ \pi_s^{0/+}$



- χ^2/ndf = 350/347 and χ^2/ndf = 343/350 for $\Sigma_c^{0/++}$.

$\Sigma_c(2455/2520)^{0/++}$ - Result

	ΔM_0 (MeV/c^2)	Γ (MeV/c^2)	M_0 (MeV/c^2)
$\Sigma_c(2455)^0$	$167.29 \pm 0.01 \pm 0.02$	$1.76 \pm 0.04^{+0.09}_{-0.21}$	$2453.75 \pm 0.01 \pm 0.02 \pm 0.14$
$\Sigma_c(2455)^{++}$	$167.51 \pm 0.01 \pm 0.02$	$1.84 \pm 0.04^{+0.07}_{-0.20}$	$2453.97 \pm 0.01 \pm 0.02 \pm 0.14$
$\Sigma_c(2520)^0$	$231.98 \pm 0.11 \pm 0.04$	$15.41 \pm 0.41^{+0.20}_{-0.32}$	$2518.44 \pm 0.11 \pm 0.04 \pm 0.14$
$\Sigma_c(2520)^{++}$	$231.99 \pm 0.10 \pm 0.02$	$14.77 \pm 0.25^{+0.18}_{-0.30}$	$2518.45 \pm 0.10 \pm 0.02 \pm 0.14$

- The result shows better uncertainty than previous result in PDG.

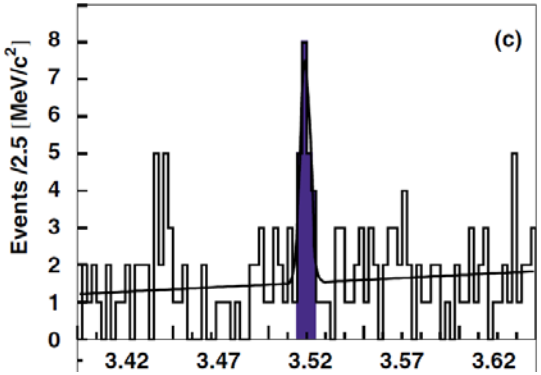
PDG value	Mass(MeV)	Width(MeV)
$\Sigma_c(2455)^{++}$	2453.98 ± 0.16	2.26 ± 0.25
$\Sigma_c(2455)^0$	2753.74 ± 0.16	2.16 ± 0.26
$\Sigma_c(2520)^{++}$	2517.9 ± 0.6	14.9 ± 1.5
$\Sigma_c(2520)^0$	2518.8 ± 0.6	14.5 ± 1.5

Outline

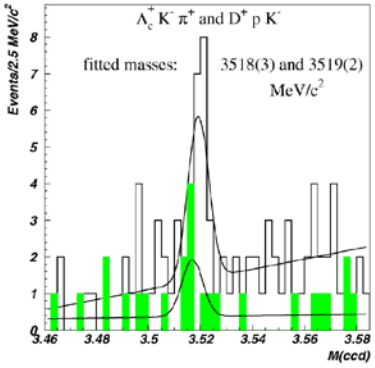
- Searching new charm baryon
  - $\Xi_{cc}^{+(+)}$, $\Xi_c(3055/3123)^+$ search - [PRD 89, 052003(2014)]

$\Xi_{cc}^{+(+)}$ Search - Introduction

- There are no experimentally established doubly charmed baryons.
- The SELEX collaboration reported evidence of Ξ_{cc}^{+} in the $\Lambda_c^+ K^- \pi^+$ and pD^+K^- final state with a mass of about 3.52GeV/c^2.



[PRL 89, 112001 (2002)]

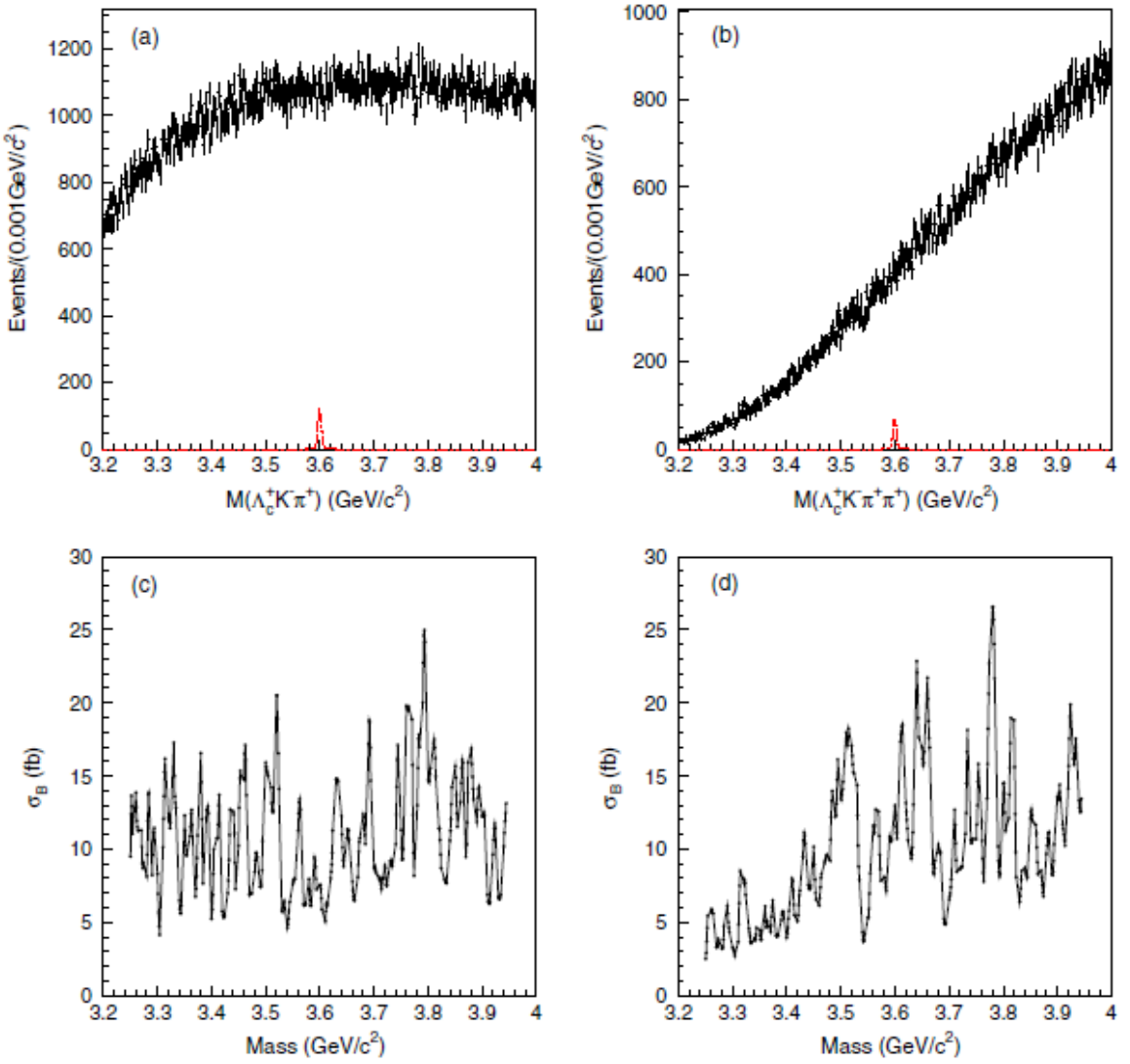


[PLB 628, 18 (2005)]

- However, the result have not been supported by FOCUS, BABAR, Belle, LHCb.
- This study improves the search using more data and decay channel.

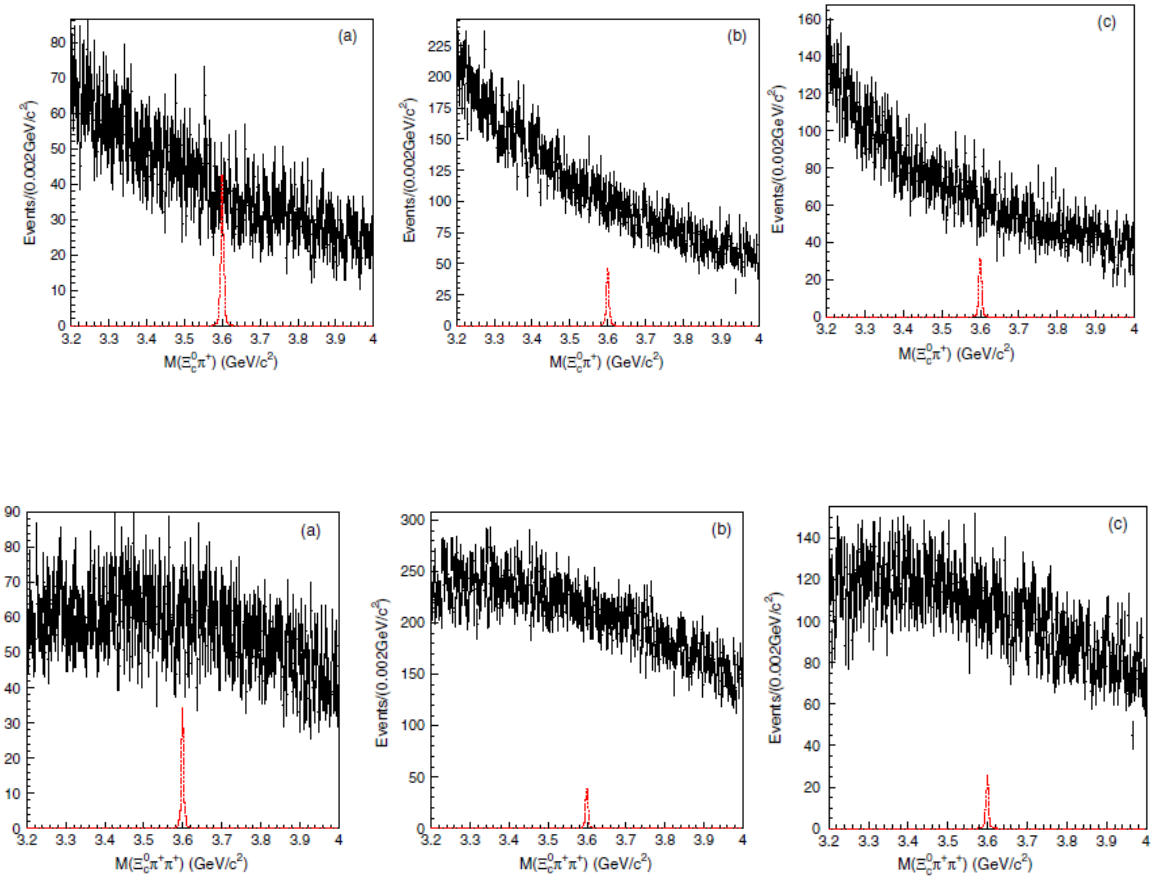
$\Xi_{cc}^{+(+)}$ Search – Reconstruction (1)

- $\Xi_{cc}^{+(+)} \rightarrow \Lambda_c^+ K^- \pi^+ (\pi^+)$
- $\Lambda_c^+ \rightarrow p K^- \pi^+$, $p K_s^0$.
- Mass range 3.2~4.0GeV/c^2
- Local significance is lower than 3δ for whole mass region.
- Upper limit of production cross section and B.F. with 95% C.L. is around 10fb^{-1}.



$\Xi_{cc}^{+(+)}$ Search – Reconstruction (2)

- $\Xi_{cc}^{+(+)} \rightarrow \Xi_c^0\pi^+(\pi^+)$.
- $\Xi_c^0 \rightarrow \Xi^-\pi^+$, $\Lambda K^-\pi^+$, $pK^-K^-\pi^+$.
- No significant signal.
- The highest signal is around 3.553GeV/c^2.
- This signal it not significant with look elsewhere effect.



$\Xi_c(3055/3123)^+$ Search

- Search the $\Xi_c(3055/3123)^+$
- Ξ_c -> $\Lambda_c^+ K^- \pi^+$
- $\Xi_c(3055)^+$ signal with 6.8σ.
- No peak of $\Xi_c(3123)^+$
  - 95%C.L. upper limit of Cross section and B.F is $1.6 \pm 0.6 \pm 0.2$fb

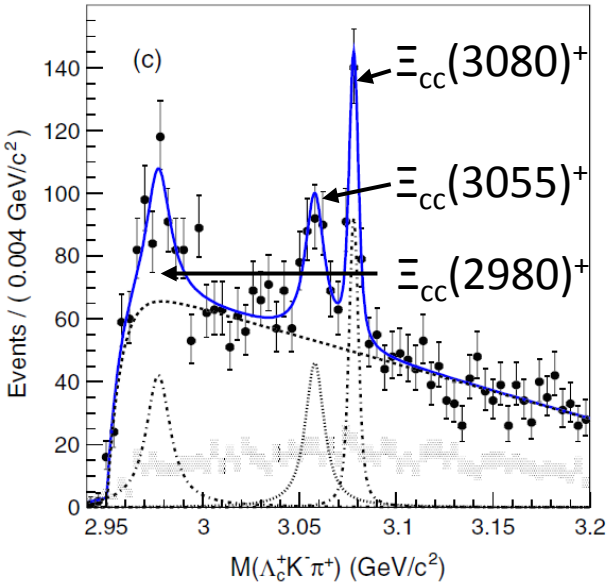
$\Xi_c(3055)$

$I(J^P) = ?(?^?)$ Status: **

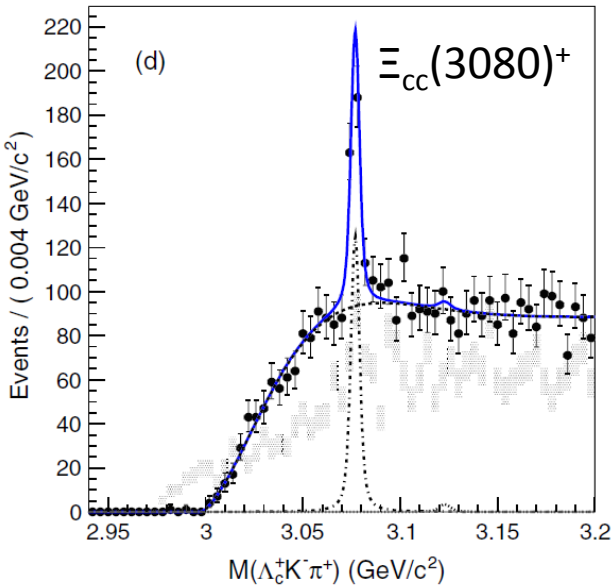
$\Xi_c(3123)$

$I(J^P) = ?(?^?)$ Status: *

$\Sigma_c(2455)$ cut



$\Sigma_c(2520)$ cut



$\Xi_{cc}^{+(+)}$, $\Xi_c(3055/3123)^+$Conclusion

- Search the $\Xi_{cc}^{+(+)}$
  - Using more data (980fb^{-1})
  - Using additional decay channel
  - No significant signal.
- Search the $\Xi_c(3055/3123)^+$
  - $\Xi_c(3055)^+$ signal with 6.8σ.
  - No peak of $\Xi_c(3123)^+$

Summary

- CP violation and mixing in the neutral D meson system.
  - $D^0 \to K_s^0 \pi^+ \pi^-$ - Indirect CPV measurement : no CPV.
  - $D^0 \to \pi^0 \pi^0$ - Direct CPV measurement : no CPV.
  - $D^0 \to K^+ \pi^-$ - First observation of D^0 mixing in e^+e^- collider.
- New measurements of M, Γ, B.F. of charm baryon.
  - B.R. of $\Lambda_c^+ \to pK^-\pi^+$ - B.F. measurement with factor 5 improvement.
  - M, Γ of $\Sigma_c(2455/2520)^{0/++}$ - Precise M, Γ measurement.
- Searching new charm baryon
  - $\Xi_{cc}^{+(+)}$ Search – No evidence of $\Xi_{cc}^{+(+)}$.
  - $\Xi_c(3055)^+$ signal, no peak of $\Xi_c(3123)^+$.