Measurement of the branching fractions of $\eta_c \to K_S^0 K^\pm \pi^\mp$, $\eta_c \to K^+ K^- \pi^0$, $\eta_c \to 2(\pi^+\pi^-\pi^0)$ and $\eta_c \to p\bar{p}$

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Motivation

- The experimental measurement on the M1 transition processes can be used to test QCD and other theoretical models. And the branching fractions of the η_c decays are essential for the M1 transition measurement.
- However the current measured precision for the η_c decays is not high.

- The awfully large uncertainty from $Br(J/\psi \to \gamma\eta_c)$ is hard to avoid, though we have the most sizable J/ψ sample in the world. The statistics if not large if we use the $\psi\prime \to \gamma\eta_c$ process. In addition, the interference problem should be considered with both J/ψ and $\psi\prime$ data samples.
- Up to now, we have collected a large XYZ data sample around $4.26GeV$. And the process $e^+e^- \to \gamma h_c$, $h_c \to \gamma\eta_c$ has been observed. In principle, the signal can be extracted by recoil mass (RM) of $\gamma\pi^+\pi^-$ by limiting $RM(\pi^+\pi^-)$ in the h_c mass region.

Methods [Take $\eta_c \to K^+K^-\pi^0$ as example]

Methods to measure the branching fraction

- We measure the branching fraction of $\eta_c \to K^+K^-\pi^0$ via the decays
  - $e^+e^- \to \pi^+\pi^- h_c, h_c \to \gamma\eta_c, \eta_c \to K^+K^-\pi^0$(exclusive mode)
  - $e^+e^- \to \pi^+\pi^- h_c, h_c \to \gamma\eta_c, \eta_c \to X$(inclusive mode)
- The Branching fraction is

$$Br(\eta_c \to K^+K^-\pi^0) = \frac{N_{signal}^{exclusive}}{N_{signal}^{inclusive}} \bullet \frac{\epsilon^{inclusive}}{\epsilon^{exclusive}} \bullet \frac{1}{Br(\pi^0 \to \gamma\gamma)}.$$

- And via this method we can also cancel parts of the system errors.

Data Sets and Monto Carlo Samples

BOSS version

6.6.4.p01

Data Sets

We currently used the XYZ data at the energy points of

$$4.23GeV,\ 4.26GeV,\ 4.36GeV,\ 4.42GeV$$

Monto Carlo Samples

$200K$ Monto Carlo Samples are generated for each decay mode at each of the four energy points which are

$$4.23GeV,\ 4.26GeV,\ 4.36GeV \text{ and } 4.42GeV.$$

Event Selections

Good Charged tracks selections

- $V_{xy} < 1cm$, $|V_z| < 10cm$ (except for the two tracks from K_S^0)
- $|\cos\theta < 0.93|$

Good photon selections

- $E_\gamma > 25MeV$ for $|\cos\theta| < 0.8$
- $E_\gamma > 50MeV$ for $0.86 < |\cos\theta| < 0.92$
- $0 \leq TDC \leq 14$(in unit of $50ns$)

- $N_{good} \geq 2$, $1 \leq N_\gamma \leq 20$ [for the inclusive mode];
- $N_{good} = 6$, $1 \leq N_\gamma \leq 20$ [for $\eta_c \to K_S^0 K^\pm \pi^\mp$].
- $N_{good} = 4$, $3 \leq N_\gamma \leq 20$ [for $\eta_c \to K^+ K^- \pi^0$];
- $N_{good} = 6$, $5 \leq N_\gamma \leq 20$ [for $\eta_c \to 2(\pi^+\pi^-\pi^0)$].
- $N_{good} = 4$, $1 \leq N_\gamma \leq 20$ [for $\eta_c \to p\bar{p}$].

Event Selections

preliminary $\gamma\pi^+\pi^-$ list

- $3.46 < m^{recoil}_{\pi^+\pi^-} < 3.59 GeV$ (h_c mass region)
- $2.5 < m^{recoil}_{\pi^+\pi^-\gamma} < 3.4 GeV$ (η_c mass region)

K^0_S reconstruction($N_{K^0_S} \geq 1$) (for $\eta_c \to K^0_S K^\pm \pi^\mp$)

- $L/\sigma_L > 2$ (L:decay length; σ_L error of decay length)
- $|m_{\pi^+\pi^-} - m_{K^0_S}| \leq 20 MeV$
- We choose the one with the minimum $\chi^2_{K^0_S} = \chi^2_{1^{st}V} + \chi^2_{2^{nd}V}$

Event Selections

π^0 Reconstruction

- $0.12 GeV < M_{\gamma\gamma} < 0.15 GeV$;
- 1-C Kinematic Fit

for the exclusive modes

- $N_{\pi^0} \geq 1$ [for $\eta_c \to K^+ K^- \pi^0$]
- $N_{\pi^0} \geq 2$ [for $\eta_c \to 2(\pi^+ \pi^- \pi^0)$]

Combination with the minimum

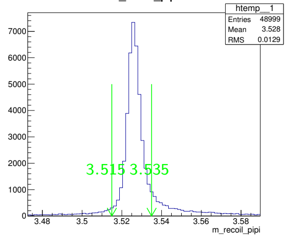
$$\chi^2 = \chi^2_{4C} + \sum_{i=1}^{N} \chi^2_{PID}(i) + \sum_{i=1}^{N} \chi^2_{K^0_S/\pi^0}(i)$$

is kept

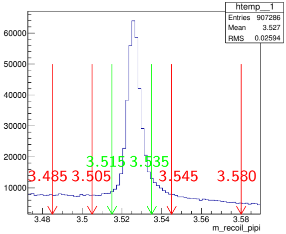
Optimized Selections

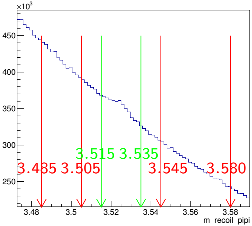
We choose the same range of $M^{recoil}_{\pi^+\pi^-}$ for both inclusive and exclusive processes.[$3.515 < M^{recoil}_{\pi^+\pi^-} < 3.535$ ($M_{h_c} \pm 3\sigma$)],
and use the sideband method to analyze the background shape of the inclusive mode

Exclusive Modes

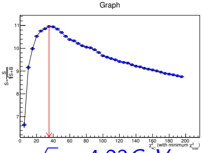


Inclusive Modes

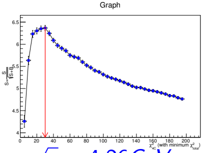




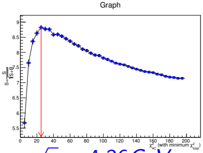
- The χ^2_{4C} cut is optimized with the figure of merit$(FOM)\frac{S}{\sqrt{S+B}}$



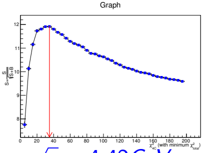
$\sqrt{s} = 4.23GeV$



$\sqrt{s} = 4.26GeV$



$\sqrt{s} = 4.36GeV$



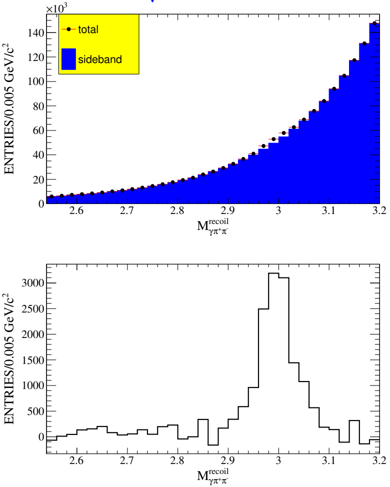
$\sqrt{s} = 4.42GeV$

- Table for χ^2_{4C} cut

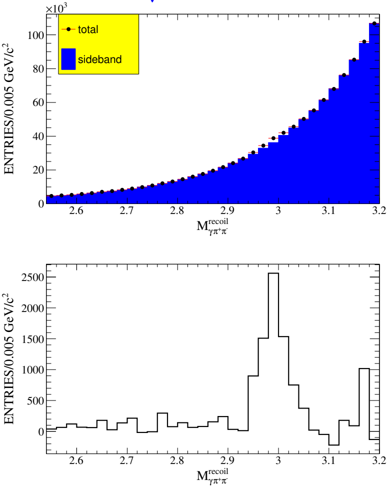
χ^2_{4C} cut	$\eta_c \to K^0_S K^\pm \pi^\mp$	$\eta_c \to K^+ K^- \pi^0$	$\eta_c \to 2(\pi^+\pi^-\pi^0)$	$\eta_c \to p\bar{p}$
4230	45	25	35	75
4260	45	15	30	25
4360	45	25	25	40
4420	50	20	35	45

$M^{recoil}_{\pi^+\pi^-\gamma}$ results of sideband (the inclusive mode)

$\sqrt{s} = 4.23GeV$



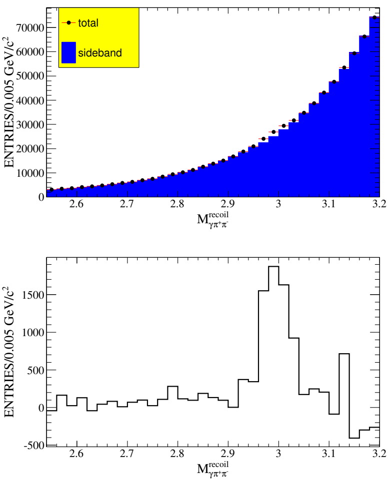
$\sqrt{s} = 4.26GeV$



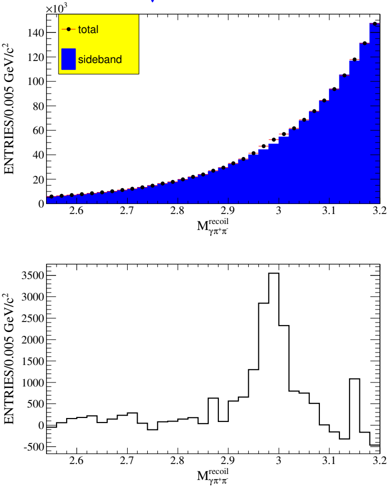
The upper ones draw the sideband and signal regions together, while the lower ones draw net events

$M^{recoil}_{\pi^+\pi^-\gamma}$ results of sideband (the inclusive mode)

$\sqrt{s} = 4.36 GeV$



$\sqrt{s} = 4.42 GeV$



The upper ones draw the sideband and signal regions together,
while the lower ones draw net events

Fit Simultaneously

To fit the distribution of $M^{recoil}_{\pi^+\pi^-\gamma}$, we use the fit function

$$F(m) = \sigma \otimes [\epsilon(m) \times |S(m)|^2 \times E_\gamma^3 \times d(E_\gamma)] + B(m),$$

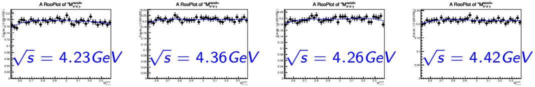
where

- $d(E_\gamma) = \frac{E_0^2}{E_\gamma E_0 + (E_\gamma - E_0)^2}$,
- $\sigma \rightarrow$ Double-Gaussian or Gaussian shape,
- $S(m)$ $\rightarrow$Breit-Wigner shapes with common fixed $M(\eta_c)$ and $\sigma(\eta_c)$,
- $B(m) \rightarrow$
  - Chebyshev Polynomial for the exclusive mode,
  - Events from sideband of h_c for inclusive mode.

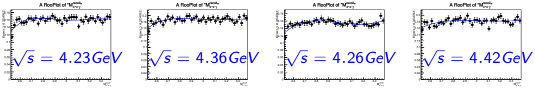
Efficiency Curves

We generate large-width signal Monto Carlo samples,
and divide the MC truth after selection by the truth before selection to get the efficiency curve.

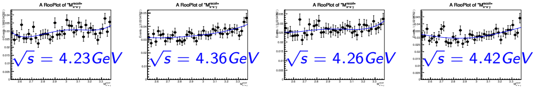
$\eta_c \to K^0_S K^{\pm}\pi^{\mp}$:



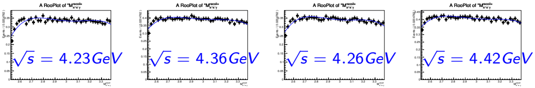
$\eta_c \to K^+K^-\pi^0$:



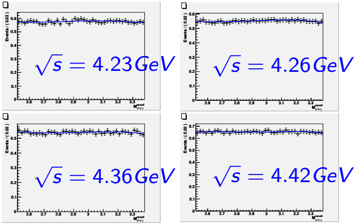
$\eta_c \to 2(\pi^+\pi^-\pi^0)$:



$\eta_c \to p\bar{p}$:

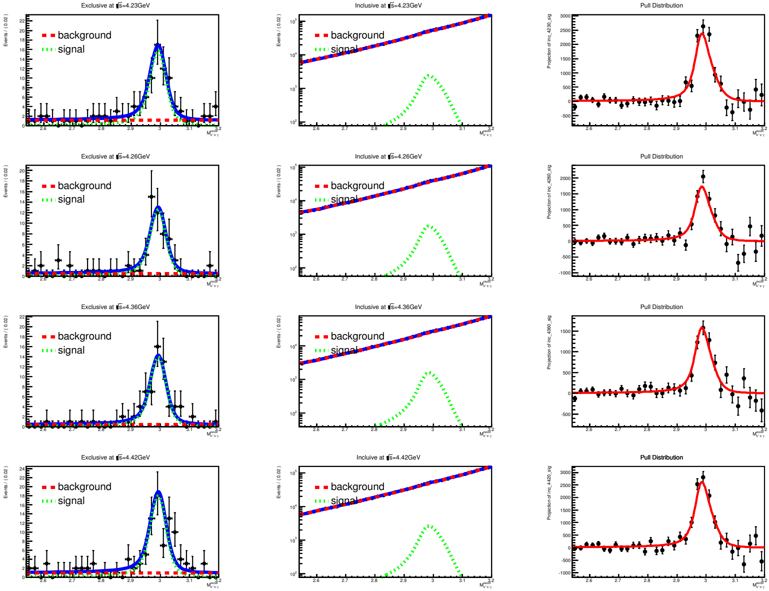


Inclusive Processes:



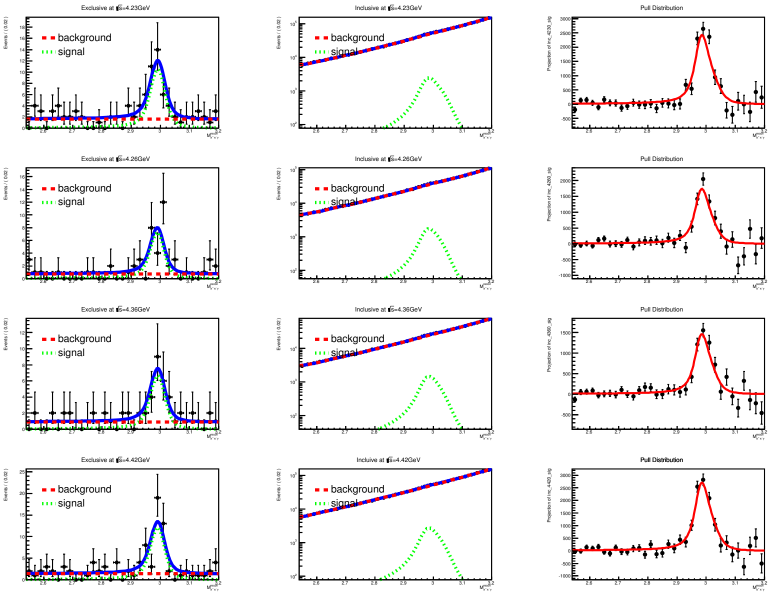
We generated signal Monto Carlo samples, and fit the signal with a Gaussian or double-Gaussian shape.

Category		Gaussian 1		Gaussian 2		Coefficient	Efficiency(%)
		$M_1(MeV)$	$\sigma_1(MeV)$	$M_2(MeV)$	$\sigma_2(MeV)$		
$K_S^0K^{\pm}\pi^{\mp}$	4230	13.21	19.91	-	-	-	17.68
	4260	13.28	19.17	-	-	-	19.87
	4360	13.64	19.37	-	-	-	20.88
	4420	13.79	19.65	-	-	-	21.44
$K^+K^-\pi^0$	4230	11.92	17.65	-	-	-	16.09
	4260	10.11	15.63	-	-	-	15.46
	4360	11.84	17.26	-	-	-	18.98
	4420	11.45	16.50	-	-	-	18.08
$2(\pi^+\pi^-\pi^0)$	4230	12.34	20.74	-	-	-	2.95
	4260	10.51	18.40	-	-	-	2.63
	4360	13.05	19.62	-	-	-	3.41
	4420	13.03	18.96	-	-	-	3.10
$p\bar{p}$	4230	14.46	20.19	-	-	-	35.04
	4260	11.78	17.21	-	-	-	35.46
	4360	13.35	18.82	-	-	-	40.35
	4420	13.35	19.03	-	-	-	42.00
Inclusive	4230	2.61	11.29	23.61	26.37	6.44614e-01	47.73
	4260	1.73	10.79	20.13	23.70	6.04471e-01	50.11
	4360	1.64	10.73	20.54	23.52	6.01291e-01	50.21
	4420	2.45	11.28	22.10	25.76	6.34061e-01	50.31

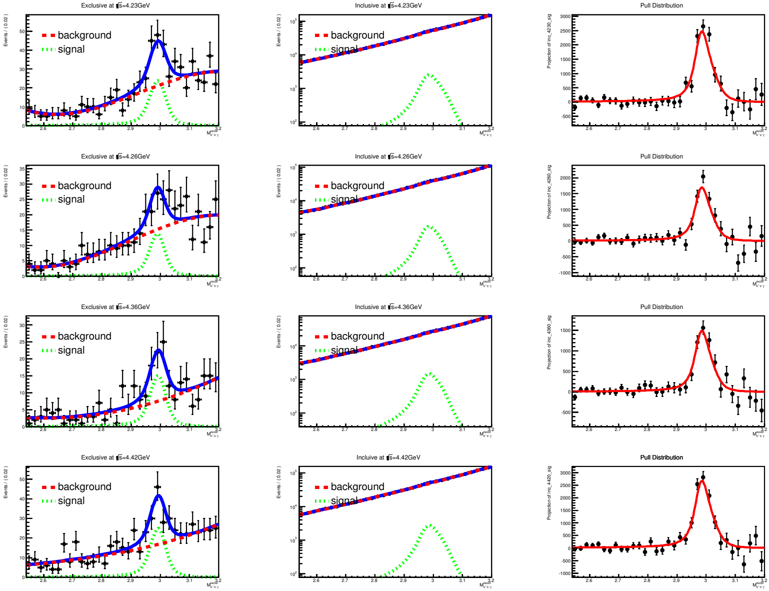


Exclusive at √s=4.23GeV
Inclusive at √s=4.23GeV
Pull Distribution
Exclusive at √s=4.26GeV
Inclusive at √s=4.26GeV
Pull Distribution
Exclusive at √s=4.36GeV
Inclusive at √s=4.36GeV
Pull Distribution
Exclusive at √s=4.42GeV
Incluive at √s=4.42GeV
Pull Distribution
background
signal
Events / (0.02)

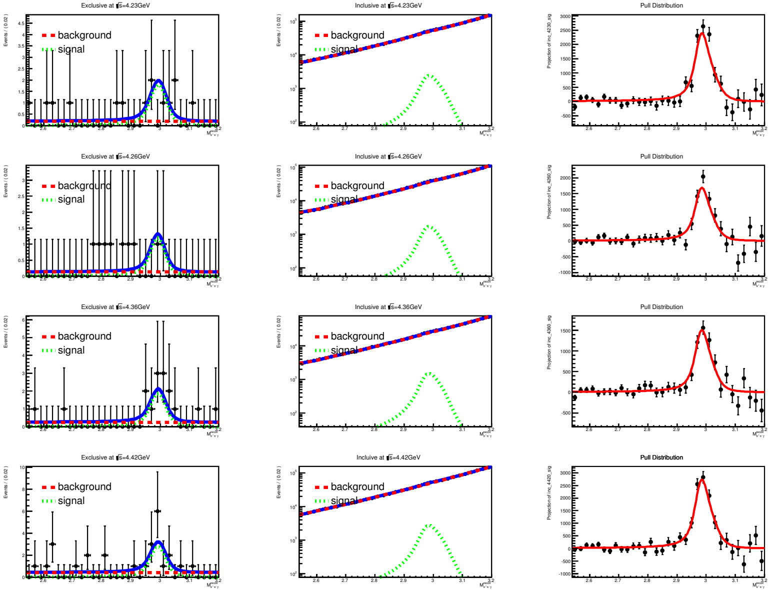
Simultaneous Fit ($\eta_c \to K^+K^-\pi^0$)



Simultaneous Fit ($\eta_c \to 2(\pi^+\pi^-\pi^0)$)

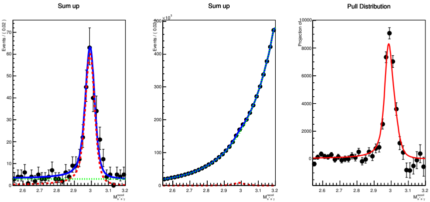


Simultaneous Fit ($\eta_c \to p\bar{p}$)

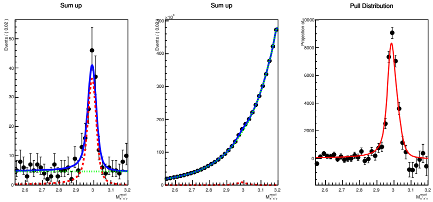


sum-up plots

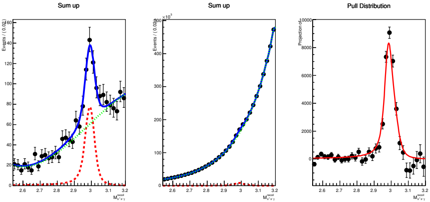
$\eta_c \to K_S^0 K^\pm \pi^\mp$



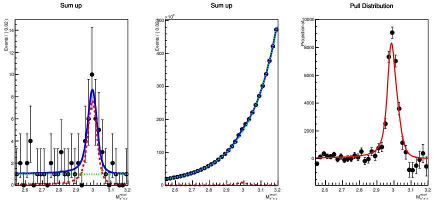
$\eta_c \to K^+ K^- \pi^0$



$\eta_c \to 2(\pi^+ \pi^- \pi^0)$



$\eta_c \to p\bar{p}$



the Branching Fractions

Category		Number of signal	Branching Fraction(%)
$K_S^0 K^\pm \pi^\mp$	4230	69.9	2.62 ± 0.21
	4260	51.5	
	4360	48.6	
	4420	83.0	
$K^+ K^- \pi^0$	4230	42.2	1.20 ± 0.13
	4260	26.3	
	4360	26.7	
	4420	47.3	
$2(\pi^+ \pi^- \pi^0)$	4230	102.4	15.71 ± 1.81
	4260	56.4	
	4360	63.0	
	4420	103.8	
$p\bar{p}$	4230	9.2	0.120 ± 0.027
	4260	5.9	
	4360	5.9	
	4420	11.1	

Systematic Uncertainty

	Category(%)	$\eta_c \to K_S^0 K^\pm \pi^\mp$	$\eta_c \to K^+ K^- \pi^0$	$\eta_c \to 2(\pi^+ \pi^- \pi^0)$	$\eta_c \to p\bar{p}$
	tracking	1	2	1	2
	photon	0	2	4	0
	Kinematic Fit	?	?	?	?
Fitting	fitting range	?	?	?	?
	resolution	?	?	?	?
	sideband range	1.400	1.330	1.617	1.025
	signal shape	?	?	?	?
	background shape	?	?	?	?
MC	middle states 1	?	?	?	?
	middle states 2	0.434	?	?	?
	inclusive MC	0.213	0.203	0.184	0.183
	K_S^0/π^0 reconstruction	?	-	?	-
	Brs of middle states	?	-	?	-

Summary

So far we measured the branching fractions of four η_c decay modes, which are $\eta_c \to K_S^0 K^\pm \pi^\mp$, $\eta_c \to K^+ K^- \pi^0$, $\eta_c \to 2(\pi^+\pi^-\pi^0)$ and $\eta_c \to p\bar{p}$, and the results are

decay mode	branching fraction(%)	reference value(%) [1]
$\eta_c \to K_S^0 K^\pm \pi^\mp$	2.62 ± 0.21	$2.60 \pm 0.29 \pm 0.34 \pm 0.25$
$\eta_c \to K^+ K^- \pi^0$	1.20 ± 0.13	$1.04 \pm 0.17 \pm 0.11 \pm 0.10$
$\eta_c \to 2(\pi^+\pi^-\pi^0)$	15.72 ± 1.81	$17.23 \pm 1.70 \pm 2.29 \pm 1.66$
$\eta_c \to p\bar{p}$	0.120 ± 0.027	$0.15 \pm 0.04 \pm 0.02 \pm 0.01$

And we improve the accuracy of the branching fractions of these channels.

[1] PHYSICAL REVIEW **D86,** 092009 (2012) (BESIII)