# Measurement of the branching fraction of $\eta_c \to K^+K^-\pi^0$ and $\eta_c \to 2(\pi^+\pi^-\pi^0)$

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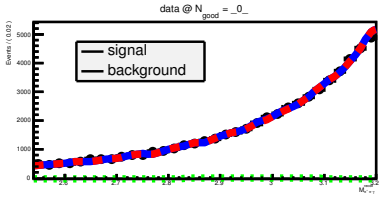
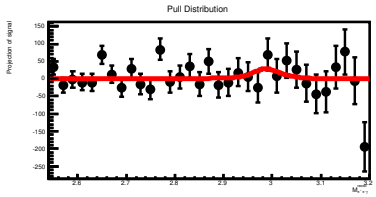
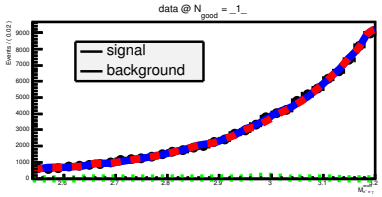
# Overview

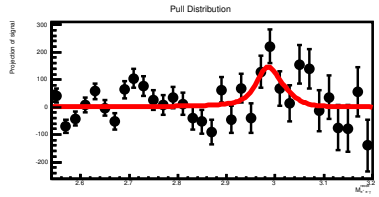
# Part I: Multiplicity

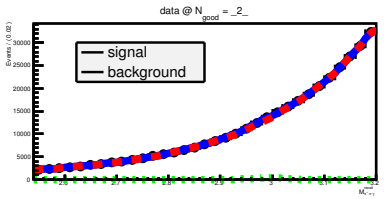
# Fit data @ 4260 MeV simultaneously

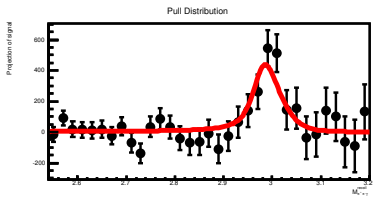


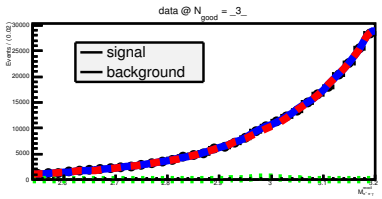



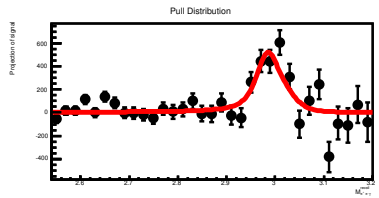



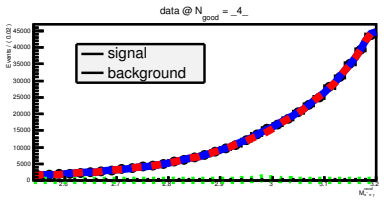



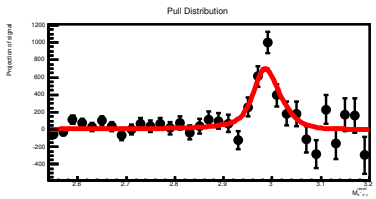



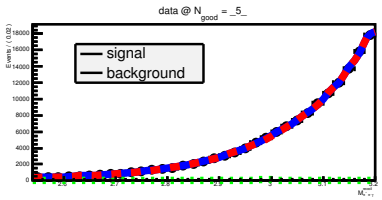



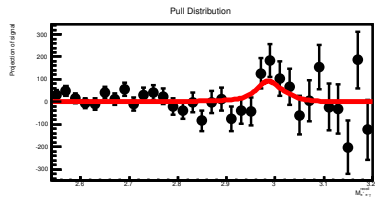



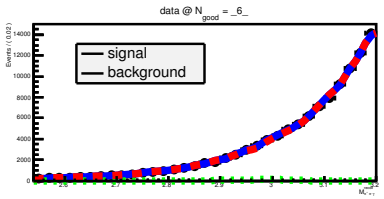



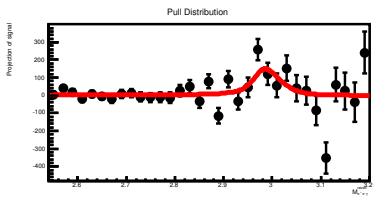



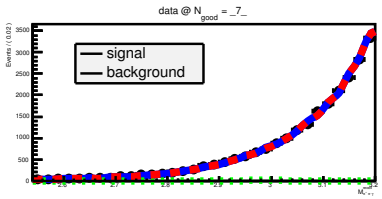



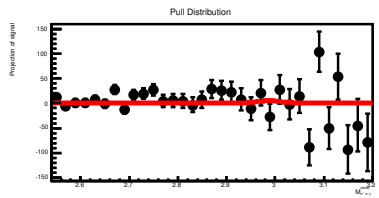



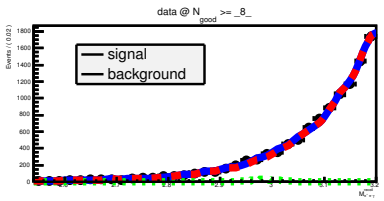



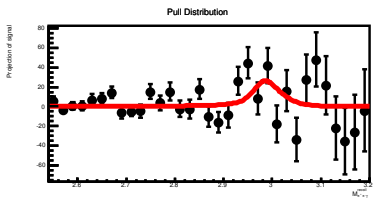



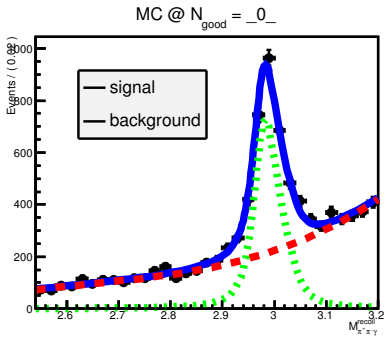



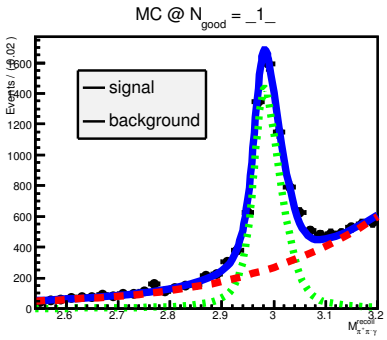



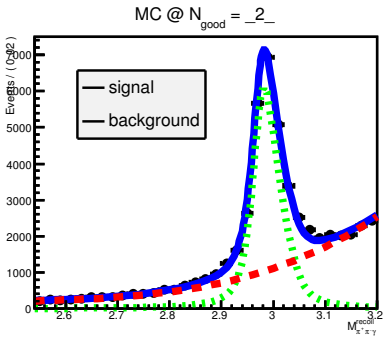



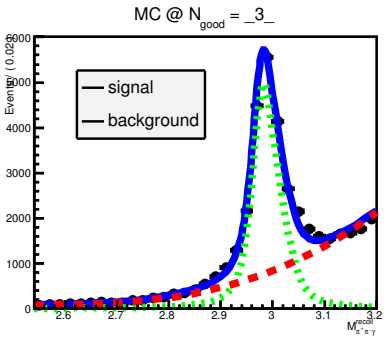



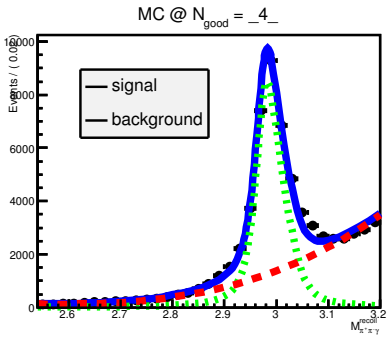
# Fit MC @ 4260 MeV simultaneously

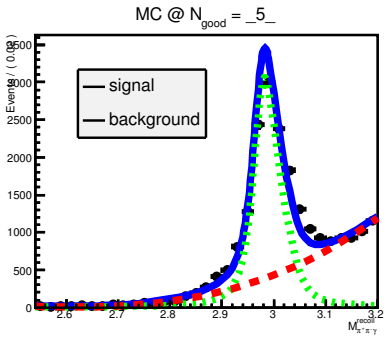


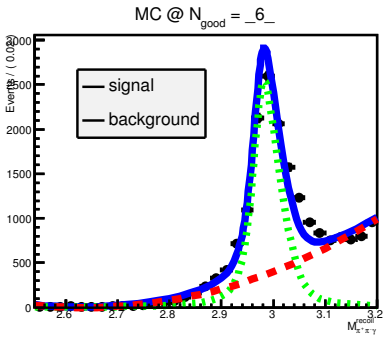



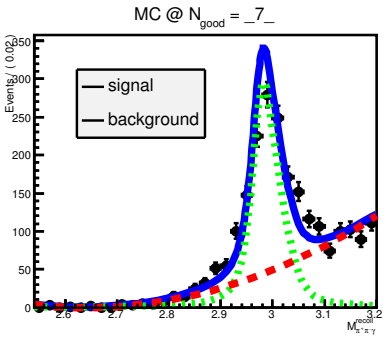



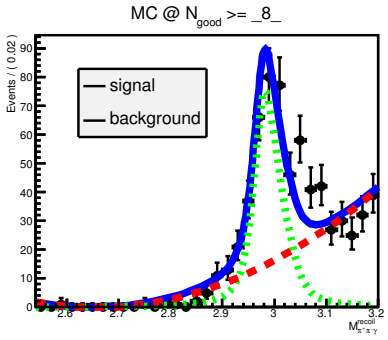



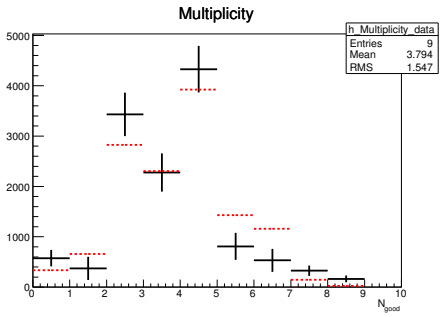



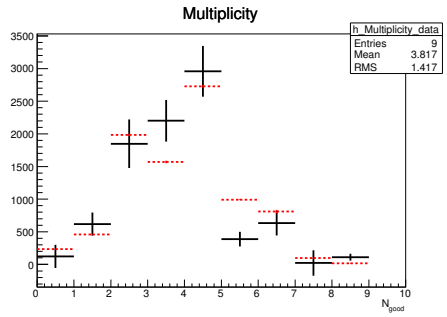



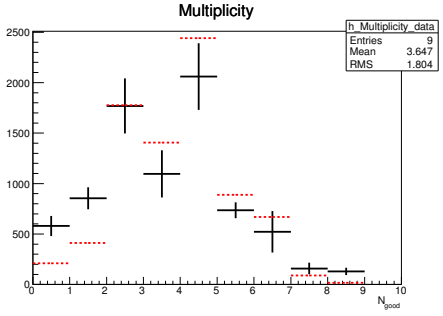
# Multiplicity @ 4.23, 4.26, 4.36, 4.42 GeV




4230




4260

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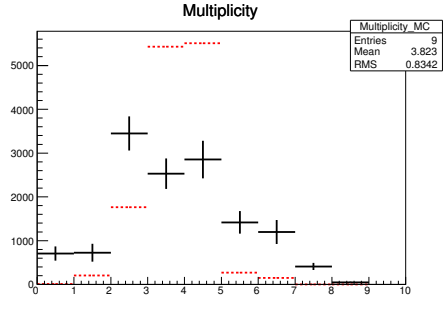
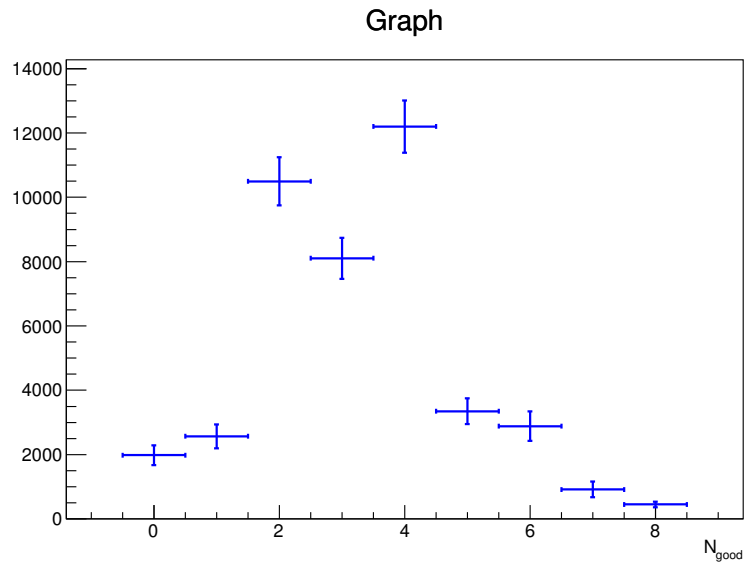



4420




Sum of the 4 energy points

# Part II: Measurement of the Branching Fractions

# 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 $\eta_c$ decays are essential for the M1 transition measurement.
- However the current measured precision for the $\eta_c$ 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 $J/\psi$ 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 $J/\psi$ and $\psi\prime$ data samples.
- Up to now, we have collected a large $XYZ$ data sample around $4.26 GeV$. 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];
- $N_{good} = 4$ , $3 \leq N_\gamma \leq 20$ [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

## $\pi^0$ Reconstruction

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

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

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

## for the exclusive modes

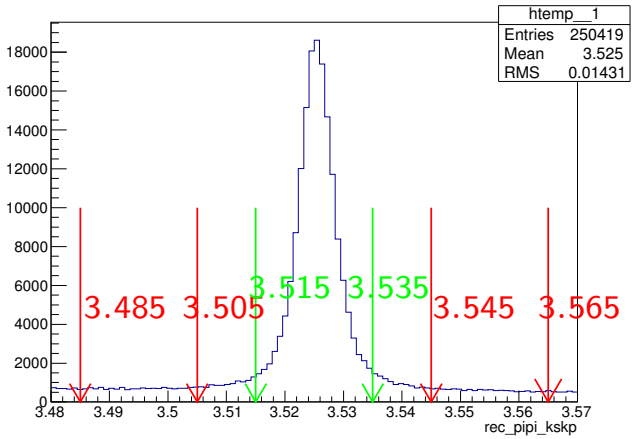
- $N_{\pi^0} \geq 1$ [for $\eta_c \to K^+K^-\pi^0$]
- $N_{\pi^0} \geq 2$ [for $\eta_c \to 2(\pi^+\pi^-\pi^0)$]
- Combination with the minimum

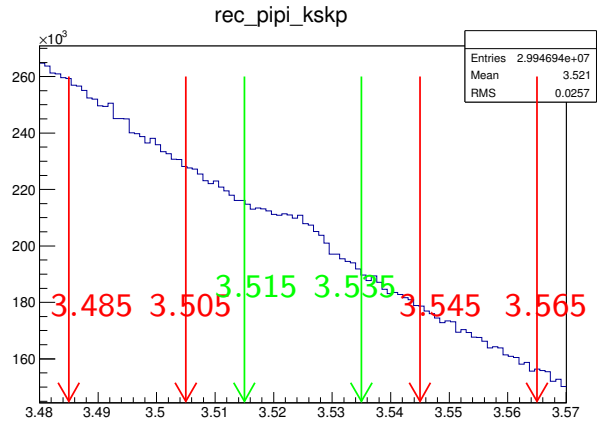
$$\chi^2 = \chi^2_{4C} + \sum_{i=1}^{N} \chi^2_{PID}(i) + \sum_{i=1}^{2} \chi^2_{\pi^0}(i)$$

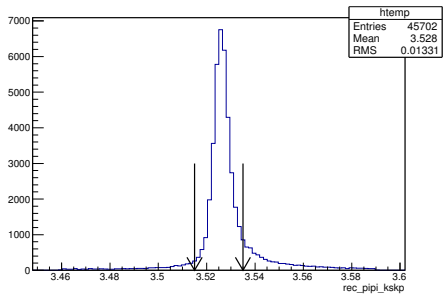
  is kept

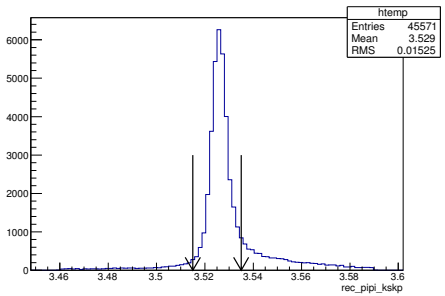
# the Optimized Selections

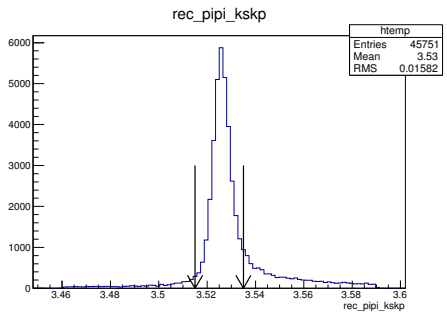
We choose the same range of $M^{recoil}_{\pi^+\pi^-}$ for both inclusive and exclusive processes.[ $3.515 < M^{recoil}_{\pi^+\pi^-} < 3.535$ ( $M_{h_c} \pm 3\sigma$ )],
and use the sideband method to analyze the background shape of the inclusive mode

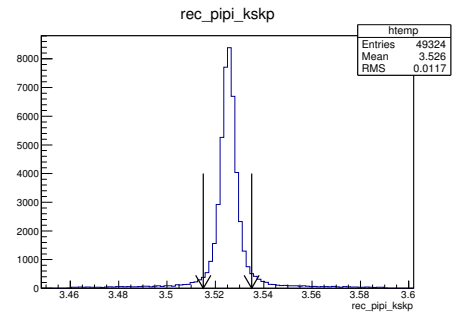


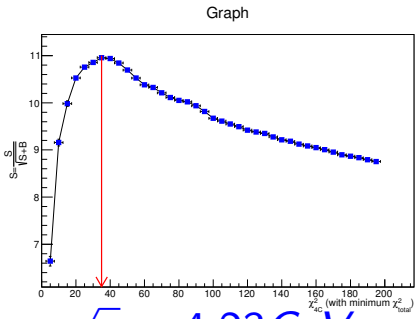



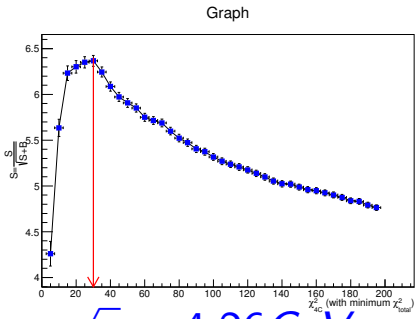



# Optimized Selections [Exclusive Modes]

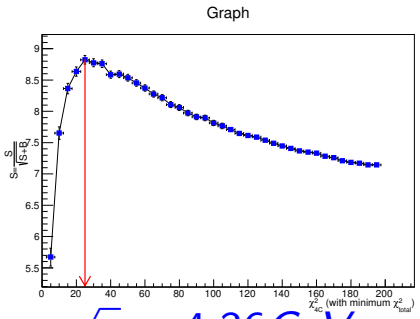
- The $\chi^2_{4C}$ cut is optimized with the figure of merit($FOM$)$\frac{S}{\sqrt{S+B}}$



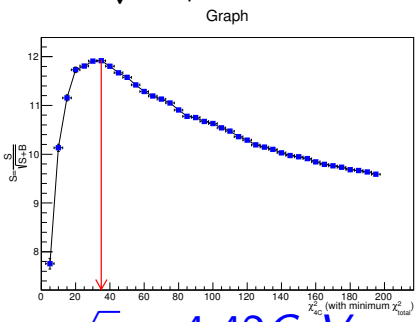

$\sqrt{s} = 4.23GeV$




$\sqrt{s} = 4.26GeV$




$\sqrt{s} = 4.36GeV$



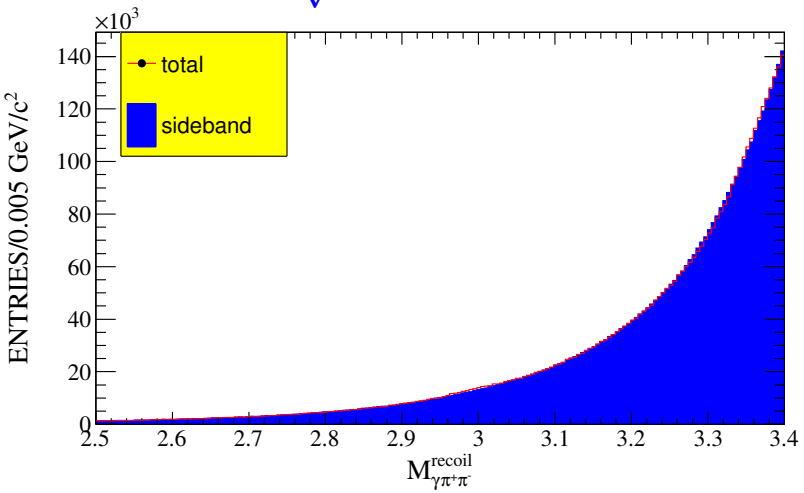

$\sqrt{s} = 4.42GeV$

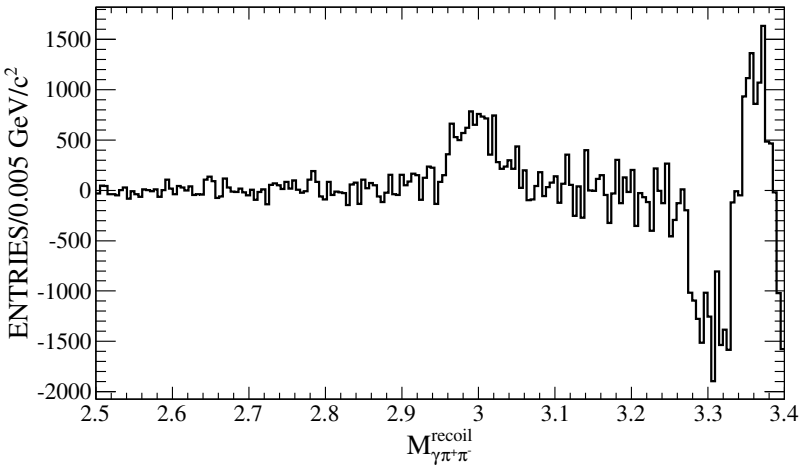
- Table for $\chi^2_{4C}$ cut

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

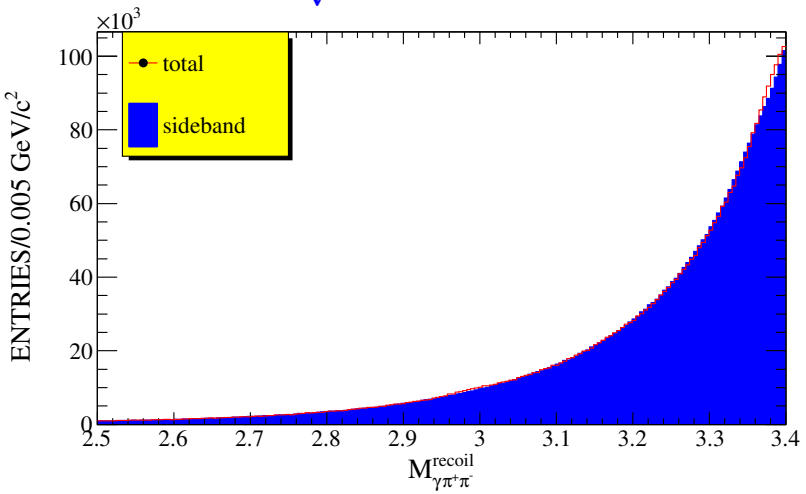
# $M^{recoil}_{\pi^+\pi^-\gamma}$ results of sideband ( the inclusive mode )

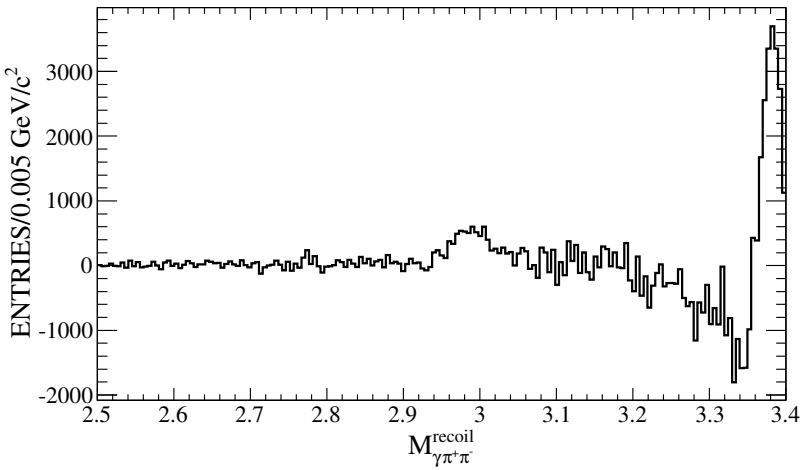
$\sqrt{s} = 4.23 GeV$




$\sqrt{s} = 4.26 GeV$

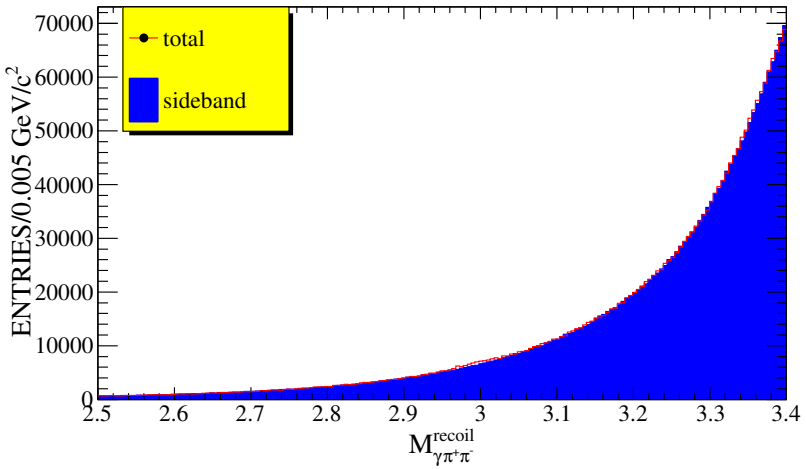


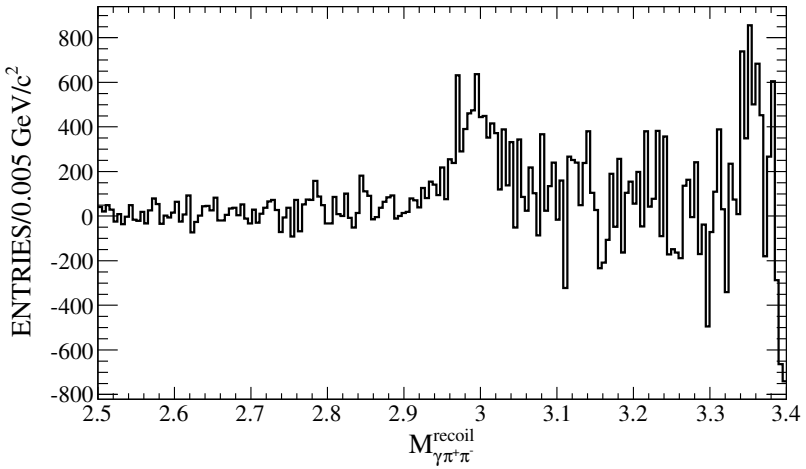




The upper ones draw the sideband and signal regions together,
while the lower ones draw net events

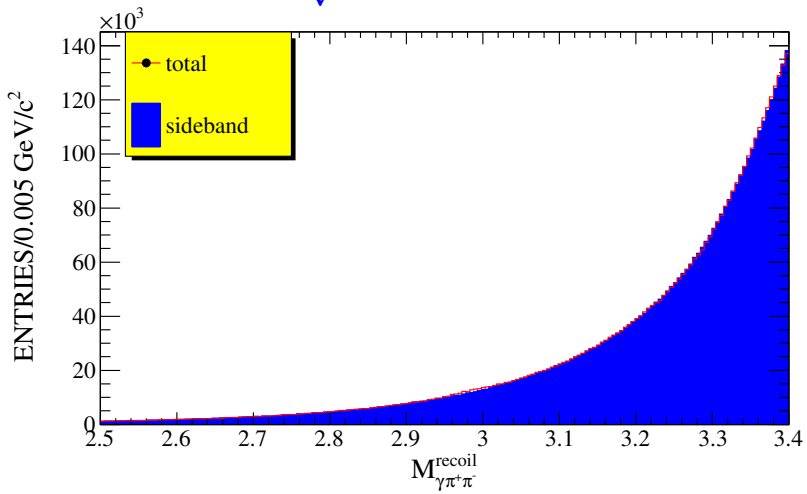
# $M^{recoil}_{\pi^+\pi^-\gamma}$ results of sideband ( the inclusive mode )

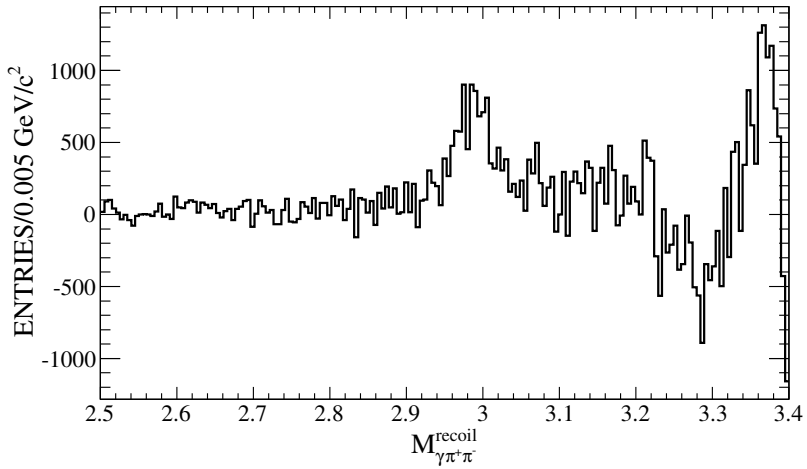
$\sqrt{s} = 4.36 GeV$




$\sqrt{s} = 4.42 GeV$




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

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

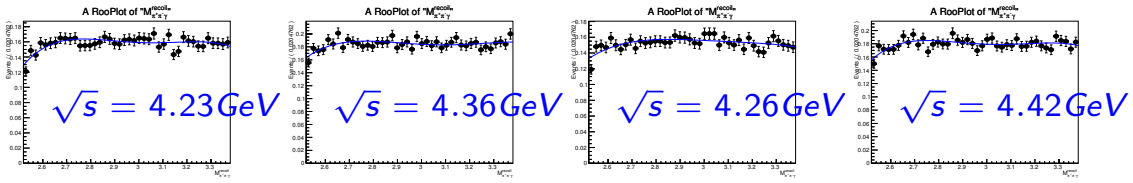
where

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

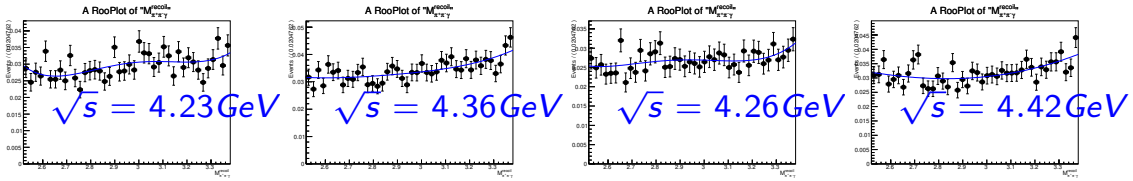
# Efficiency Curves

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.

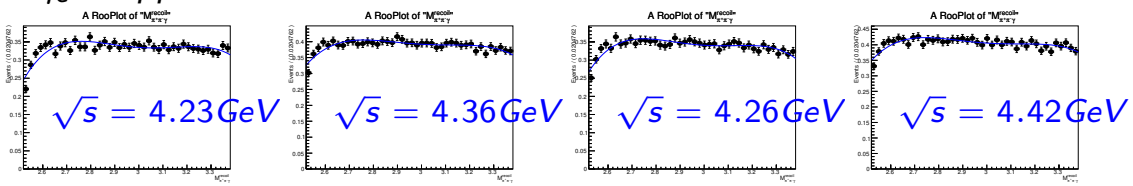
$\eta_c \to K^+K^-\pi^0$:



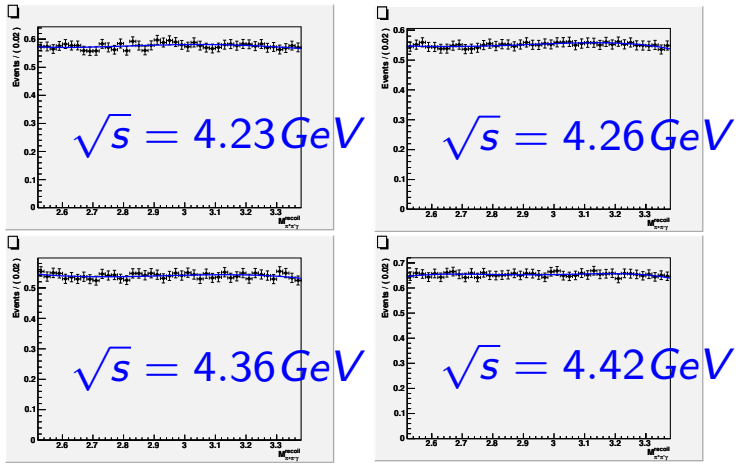

$\eta_c \to 2(\pi^+\pi^-\pi^0)$:




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




Inclusive Processes:

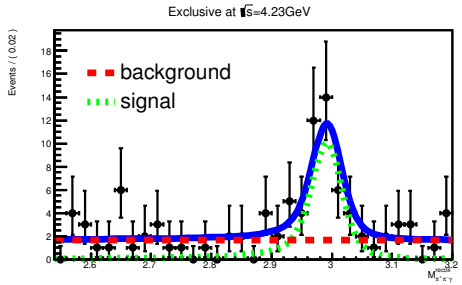


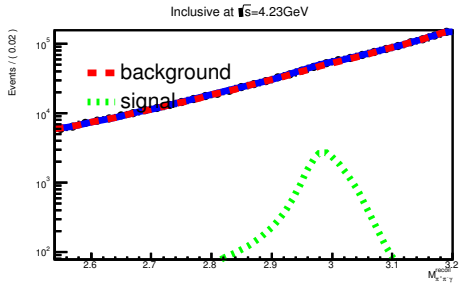
# Resolution and Efficiency

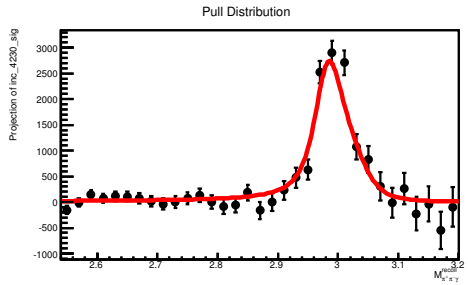
We generated signal Monto Carlo samples, and fit the signal with a Gaussian or double-Gaussian shape.

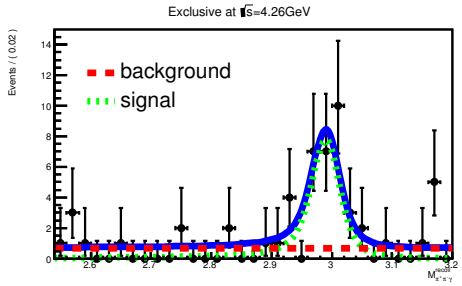
| Category | | Gaussian 1 | | Gaussian 2 | | Coefficient | Efficiency(%) |
|---|---|---|---|---|---|---|---|
| | | $M_1(MeV)$ | $\sigma_1(MeV)$ | $M_2(MeV)$ | $\sigma_2(MeV)$ | | |
| $K^+K^-\pi^0$ | 4230 | 12.55 | 17.41 | - | - | - | 16.04 |
| | 4260 | 10.73 | 15.46 | - | - | - | 15.04 |
| | 4360 | 12.64 | 17.26 | - | - | - | 18.96 |
| | 4420 | 12.13 | 16.78 | - | - | - | 18.00 |
| $2(\pi^+\pi^-\pi^0)$ | 4230 | 13.18 | 20.87 | - | - | - | 2.95 |
| | 4260 | 11.04 | 18.16 | - | - | - | 2.63 |
| | 4360 | 13.87 | 19.50 | - | - | - | 3.42 |
| | 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 | 48.12 |
| | 4260 | 1.73 | 10.79 | 20.13 | 23.70 | 6.04471e-01 | 44.14 |
| | 4360 | 1.64 | 10.73 | 20.54 | 23.52 | 6.01291e-01 | 42.59 |
| | 4420 | 2.45 | 11.28 | 22.10 | 25.76 | 6.34061e-01 | 51.15 |

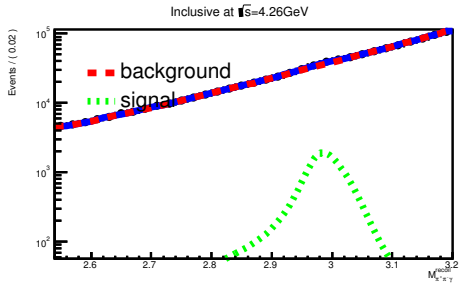
# Simultaneous Fit ( $\eta_c \to K^+K^-\pi^0$ )

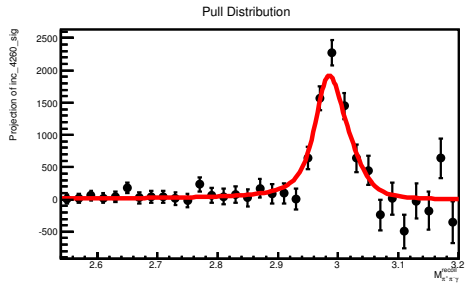


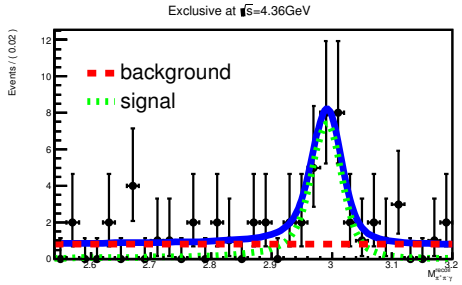



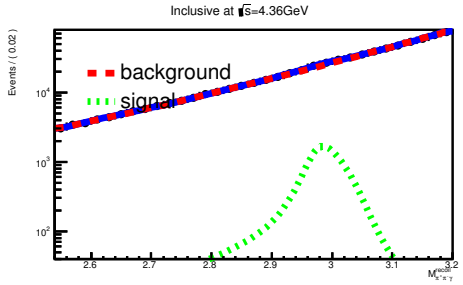



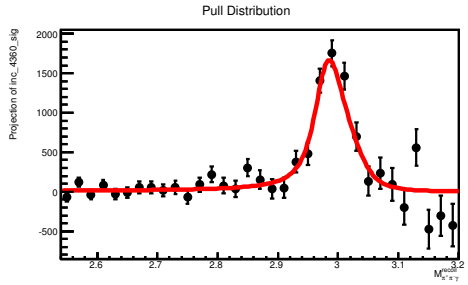



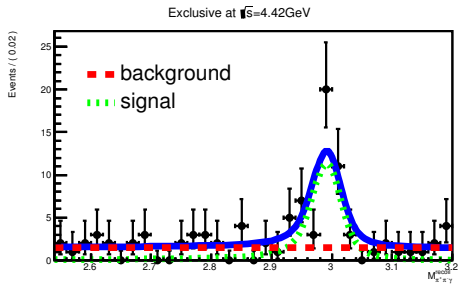



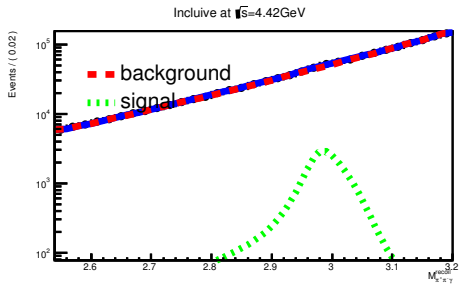



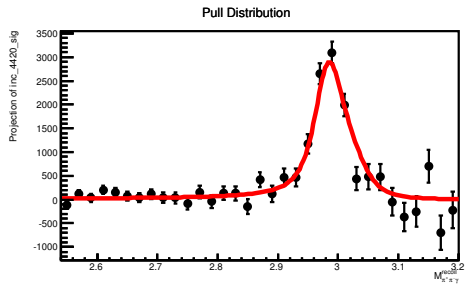



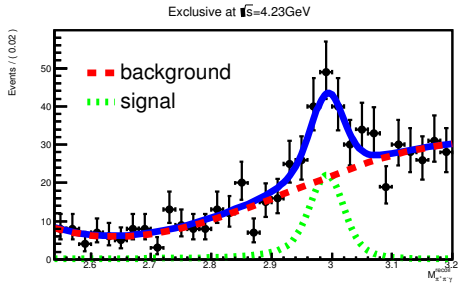



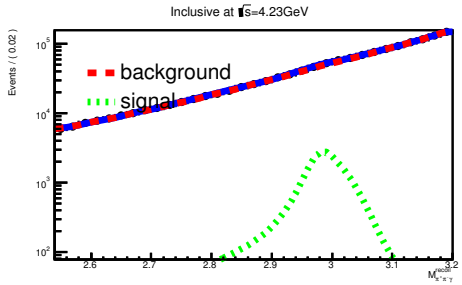



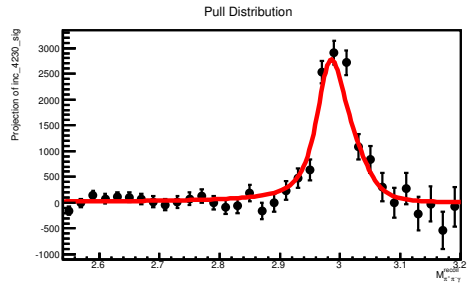



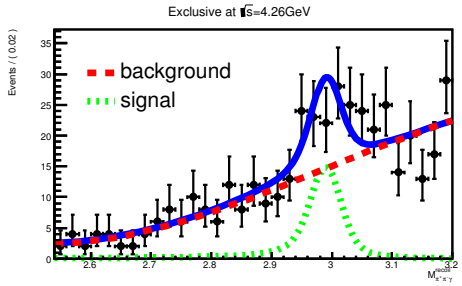



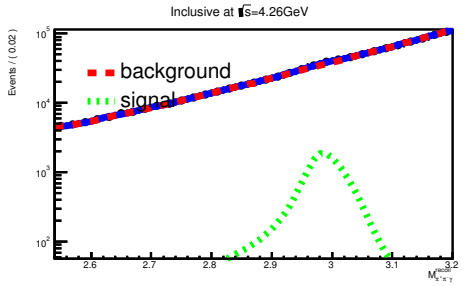
# Simultaneous Fit ( $\eta_c \to 2(\pi^+\pi^-\pi^0)$ )

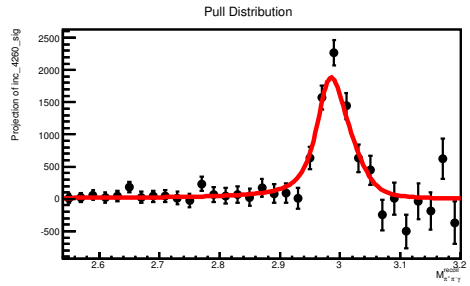


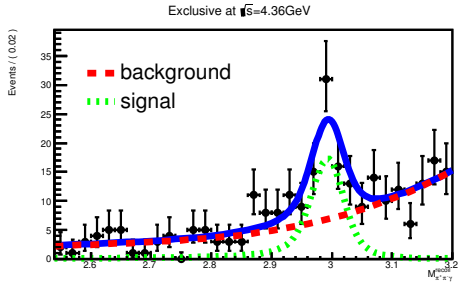



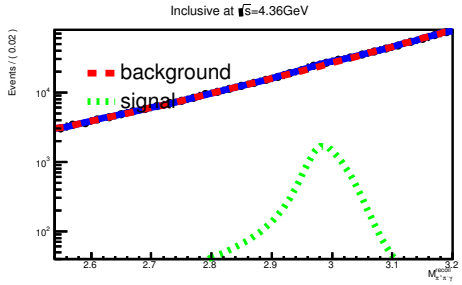



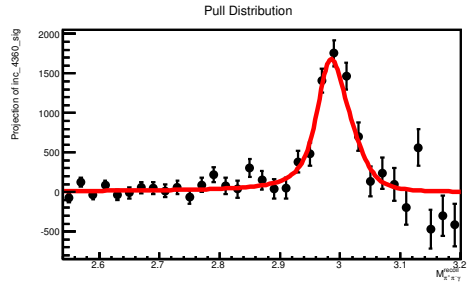



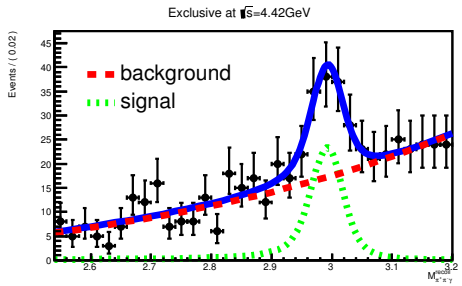



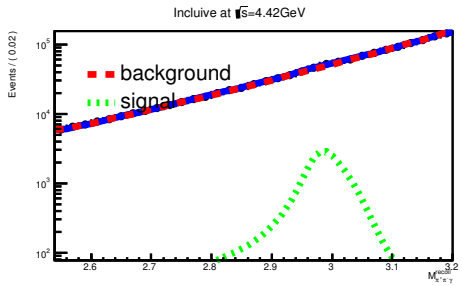



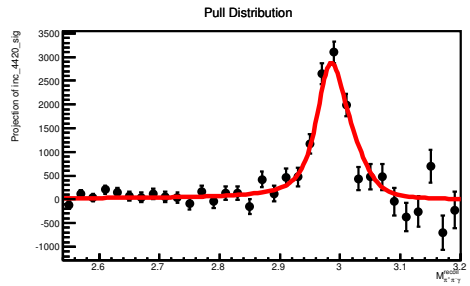



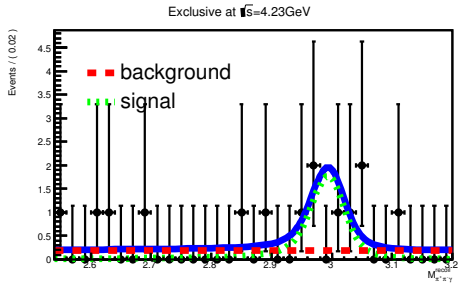



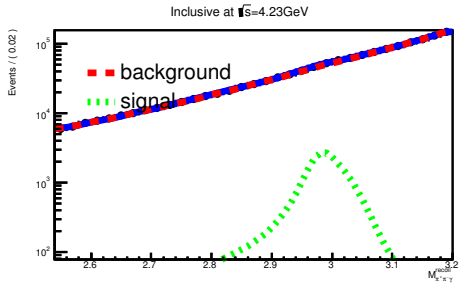



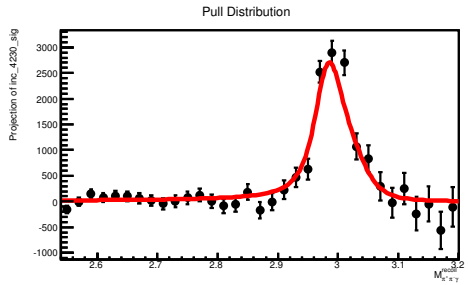



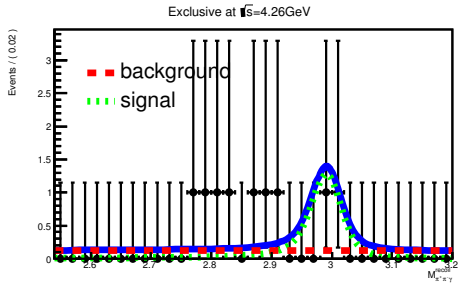



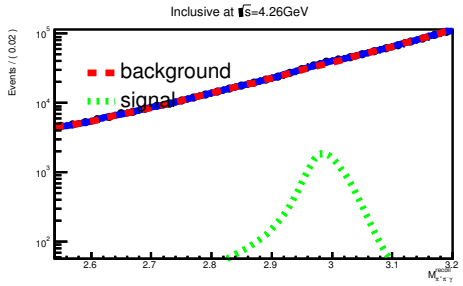
# Simultaneous Fit ( $\eta_c \to p\bar{p}$ )

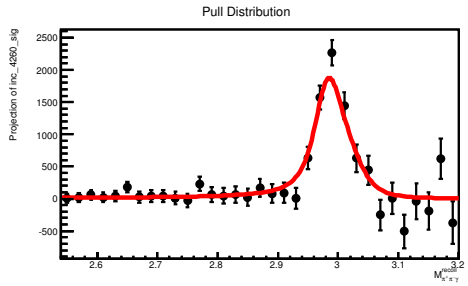


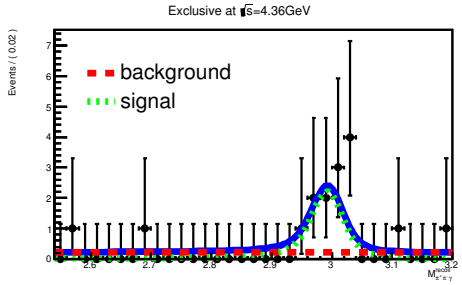



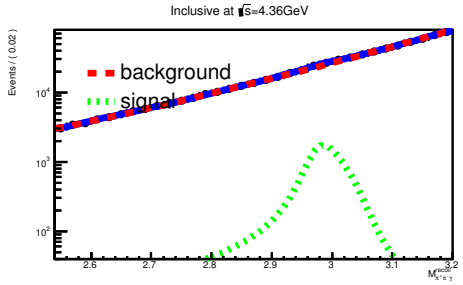



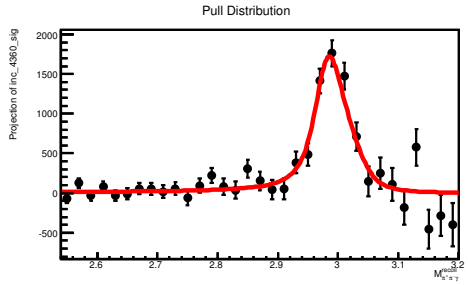



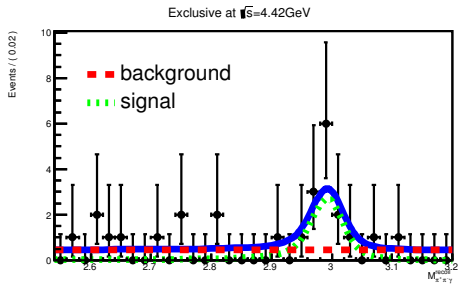



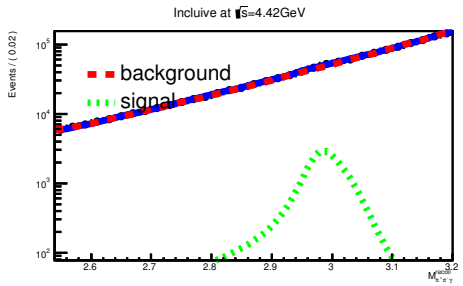



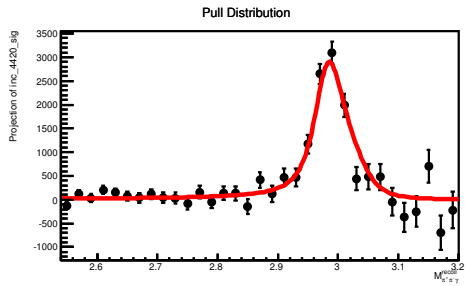



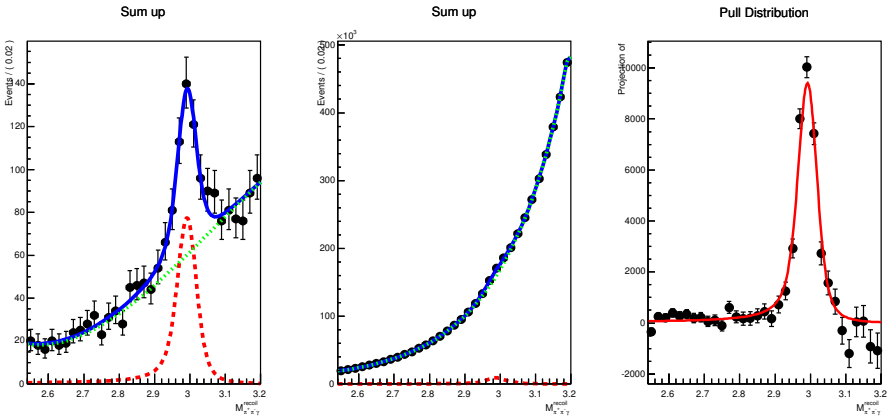



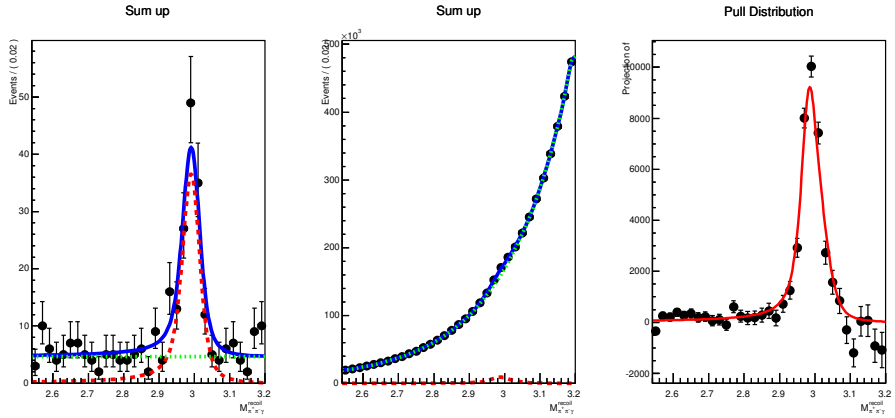
# Sum up

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

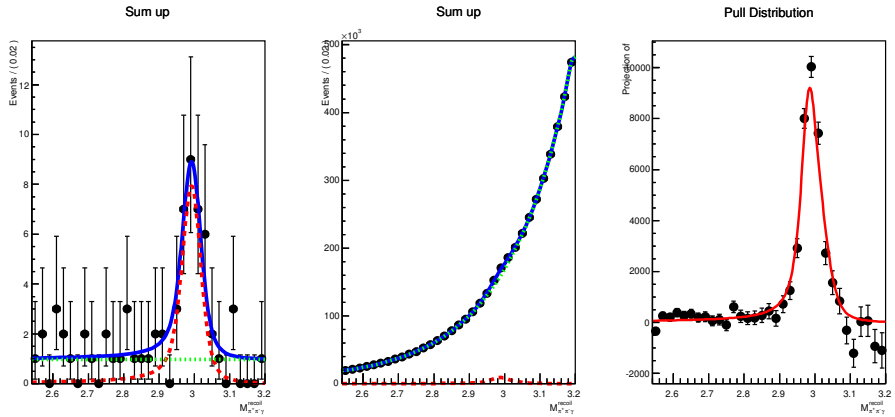
$\eta_c \to 2(\pi^+\pi^-\pi^0)$




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




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



# the Branching Fraction of $\eta_c \to K^+K^-\pi^0$

| Category | | Number of signal | Branching Fraction(%) |
|---|---|---|---|
| $K^+K^-\pi^0$ | 4230 | 39.8 | $1.01 \pm 0.11$ |
| | 4260 | 28.3 | |
| | 4360 | 31.3 | |
| | 4420 | 43.9 | |
| $2(\pi^+\pi^-\pi^0)$ | 4230 | 95.4 | $13.13 \pm 1.54$ |
| | 4260 | 60.7 | |
| | 4360 | 73.2 | |
| | 4420 | 96.9 | |
| $p\bar{p}$ | 4230 | 8.9 | $0.104 \pm 0.022$ |
| | 4260 | 6.6 | |
| | 4360 | 7.2 | |
| | 4420 | 10.6 | |

# Summary

We measured the multiplicity of the good charged tracks of the inclusive mode of $\eta_c$ for the first time;

So far we measured the branching fractions of four $\eta_c$ 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] |
|---|---|---|
| $\eta_c \to K_S^0 K^{\pm}\pi^{\mp}$ | $2.39 \pm 0.20$ | $2.60 \pm 0.29 \pm 0.34 \pm 0.25$ |
| $\eta_c \to K^+K^-\pi^0$ | $1.01 \pm 0.11$ | $1.04 \pm 0.17 \pm 0.11 \pm 0.10$ |
| $\eta_c \to 2(\pi^+\pi^-\pi^0)$ | $13.13 \pm 1.54$ | $17.23 \pm 1.70 \pm 2.29 \pm 1.66$ |
| $\eta_c \to p\bar{p}$ | $0.104 \pm 0.022$ | $0.15 \pm 0.04 \pm 0.02 \pm 0.01$ |

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