The observation of $Z_c(4025)$

Landiao Liu (刘兰雕)

PKU (北京大学)
UCAS (中国科学院大学)
BESIII Collaboration

Outline

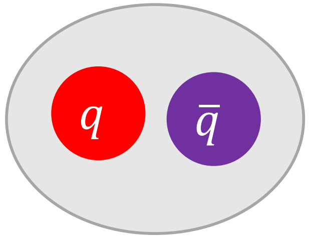
- Introduction
- The observation of $Z_c(4025)^{+/-}$
- The observation of $Z_c(4025)^0$
- Summary

PART 1

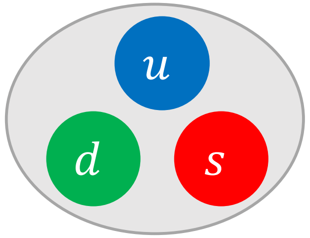
Introduction

Constitution of hadrons in QCD

- Quark Model

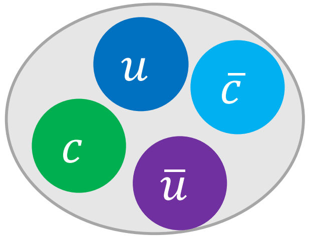


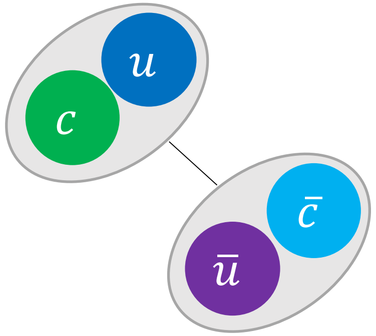
Mesons
Color-anticolor pairs

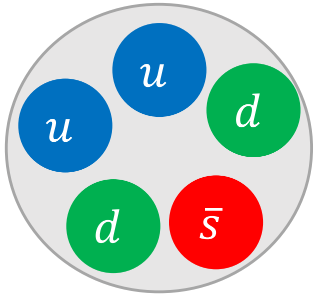


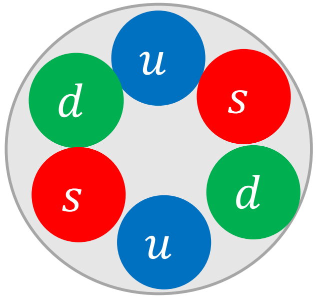
Baryons
Red-blue-green triplets

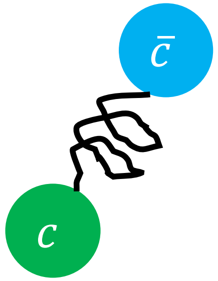
- Exotic states predicted by QCD











Tetraquark
Tightly bound
diquark&anti-diquark

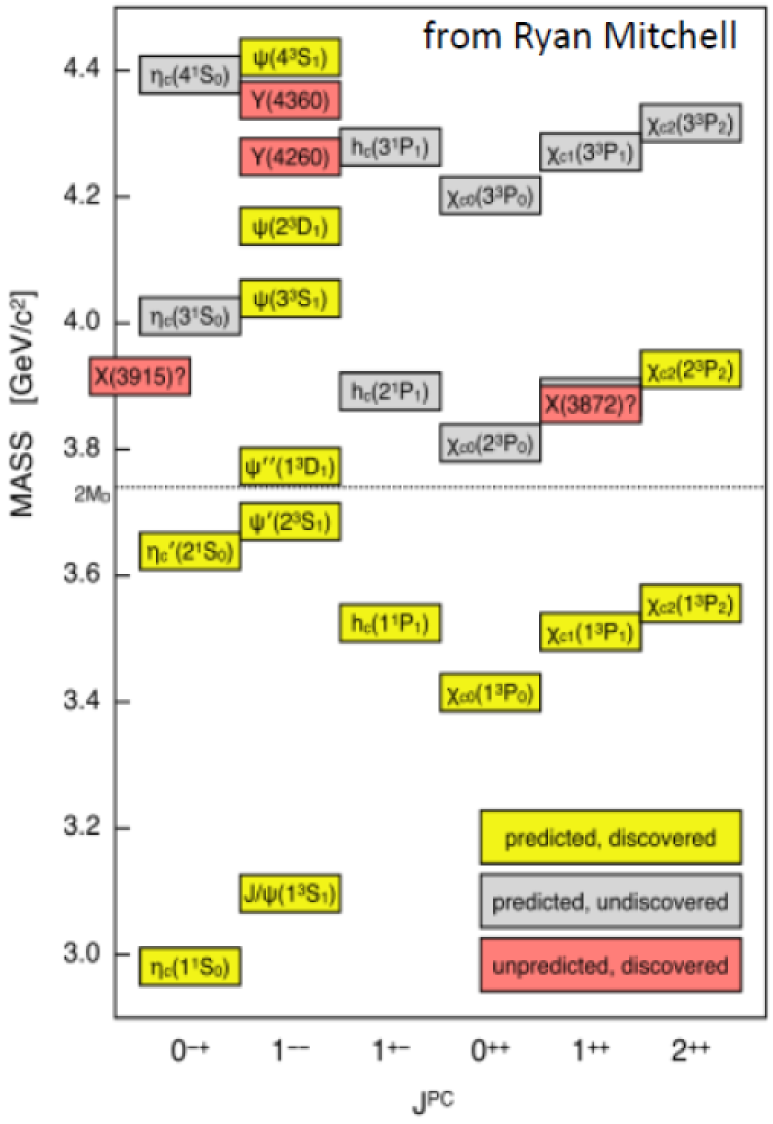
Molecule
Loosely bound
meson&anti-meson

Pentaquark
S=+1

Six-quark state
Tightly bound
6 quarks

Hybird
More than 2
quarks and gluon

Charmonium Spectroscopy



- **Below open charm threshold**

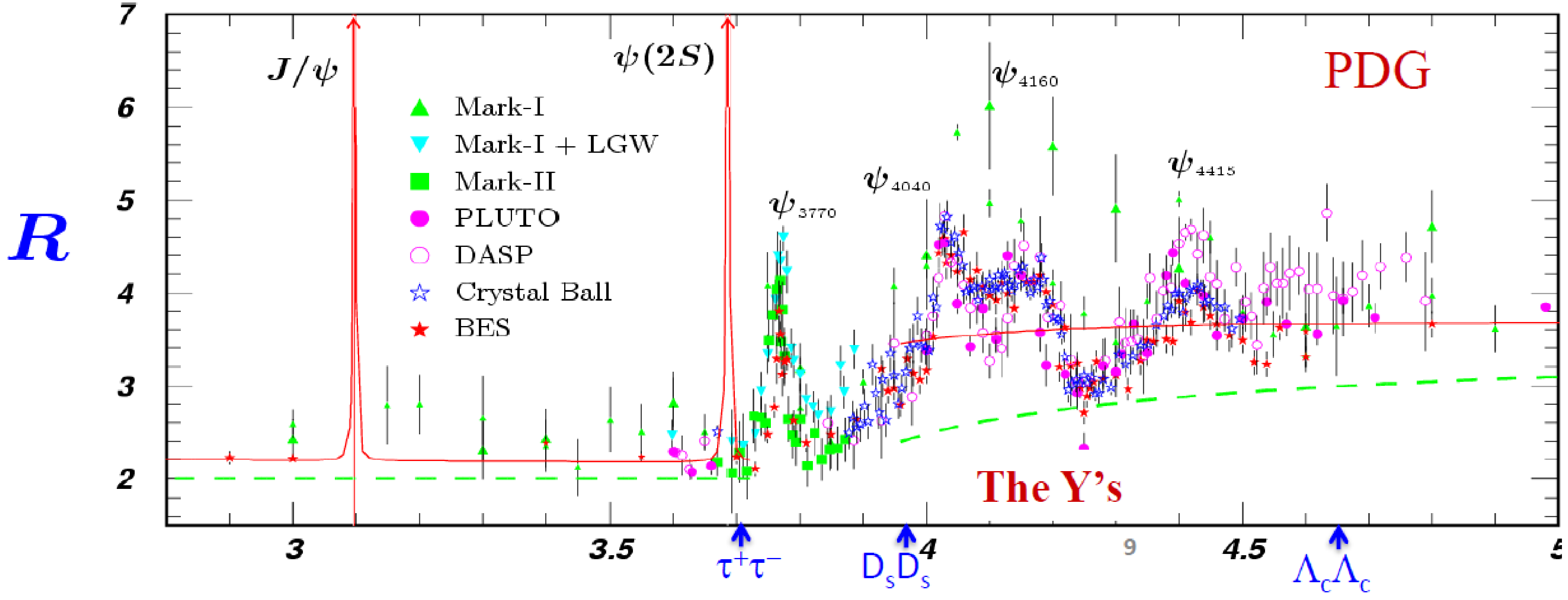
  Good agreement between discovery and theoretical prediction.

- **Above open charm threshold**

  Many expected states are not observed

  Many unexpected states are observed: XYZ states

Data samples for XYZ states at BESIII



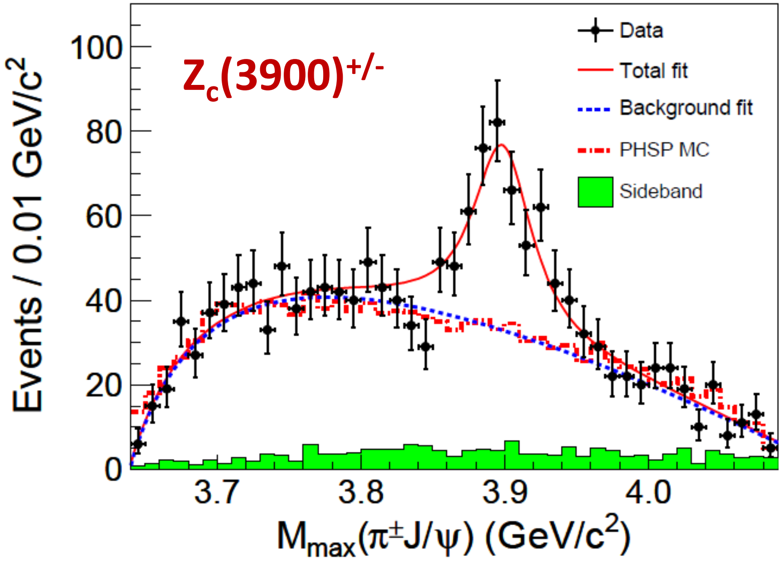
- Luminosity~5 fb^{-1}
- Large data samples around Ψ(4040), Y(4260), Y(4360), Ψ(4415) and Y(4660)

Z_c states at BESIII

- $Z_c(3900)^{+/-}$ in $e^+e^- \to \pi^+ \pi^- J/\Psi$ PRL 110,252001 (2013)
- $Z_c(3900)^0$ in $e^+e^- \to \pi^0 \pi^0 J/\Psi$ arXiv:1506.06018
- $Z_c(3885)^{+/-}$ in $e^+e^- \to \pi^+ (D\bar{D}^*)^-$ PRL 112, 022001 (2014)
- $Z_c(3885)^0$ in $e^+e^- \to \pi^0 (D\bar{D}^*)^0$ Preliminary
- $Z_c(4020)^{+/-}$ in $e^+e^- \to \pi^+ \pi^- h_c$ PRL 111.242001 (2013)
- $Z_c(4020)^0$ in $e^+e^- \to \pi^0 \pi^0 h_c$ PRL 113,212002 (2014)
- $Z_c(4025)^{+/-}$ in $e^+e^- \to \pi^+ (D^*\bar{D}^*)^-$ PRL 112,132001 (2013)
- $Z_c(4025)^0$ in $e^+e^- \to \pi^0 (D^*\bar{D}^*)^0$ arXiv:1507.02404

$e^+e^- \rightarrow \pi\, Z_c(3900)^{+/-/0} \rightarrow \pi\, \pi\, J/\Psi$

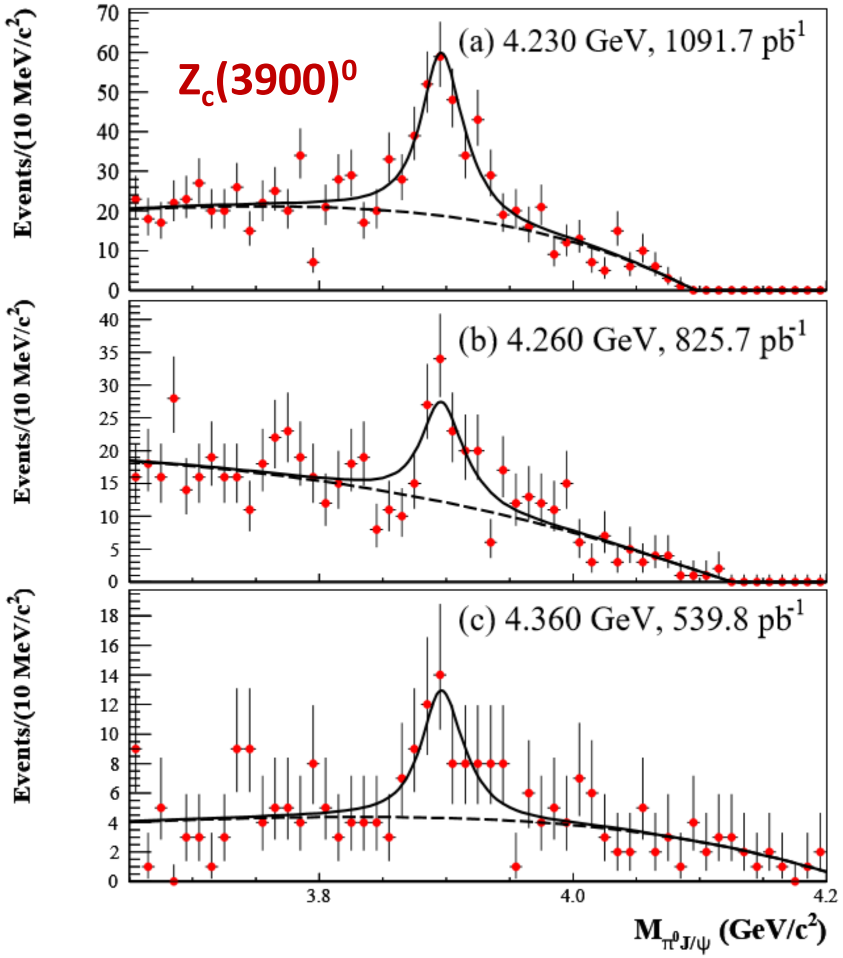
PRL 110,252001 (2013)



- $Z_c(3900)^{+/-}$, observed by BESIII, confirmed by Bell and CLEO-c data.
- $Z_c(3900)^0$, evidence with 3.7σ at CLEO-c, observed by BESIII.

$Z_c(3900)$	Mass(MeV)	Width(MeV)
$Z_c(3900)^{+/-}$	3899.0±3.6±4.9	46 ±10±20
$Z_c(3900)^0$	3894.8±2.3±2.7	29.6±8.2±8.2

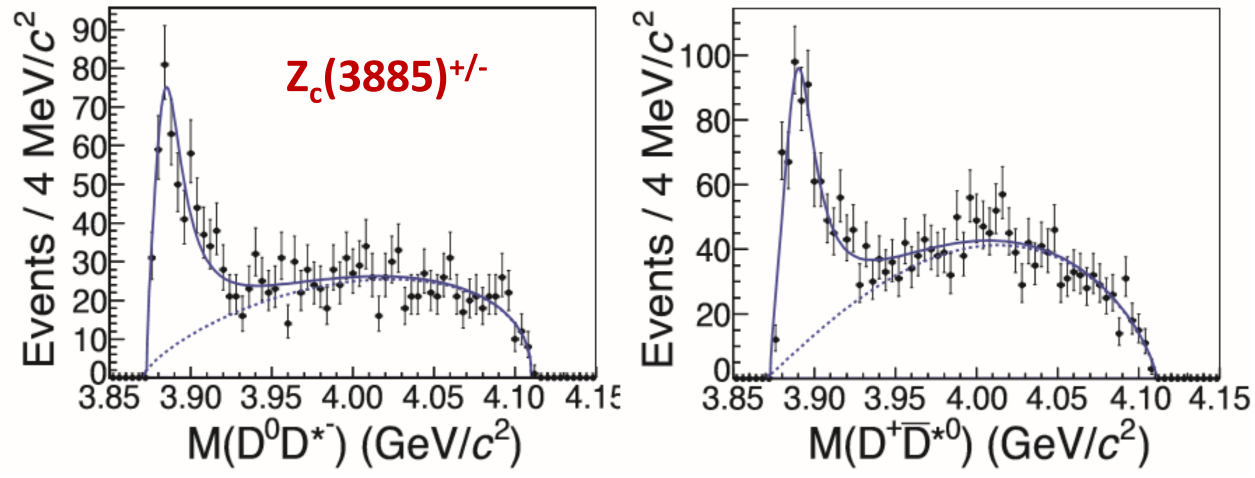
arXiv:1506.06018



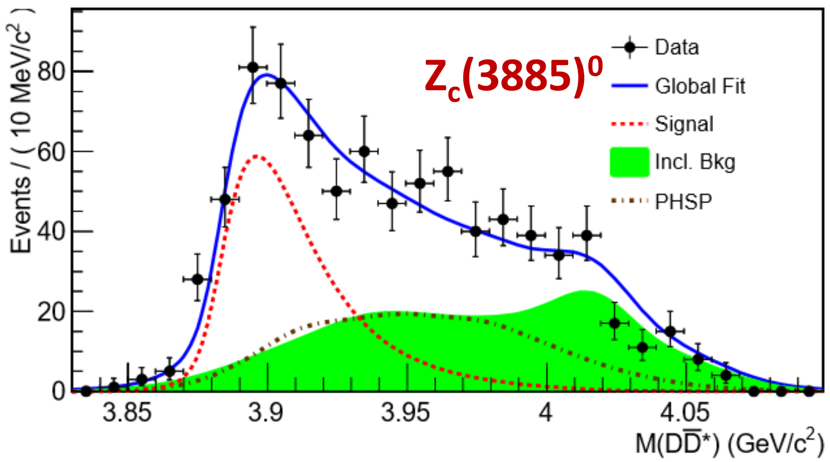
Iso-spin triplet is established!

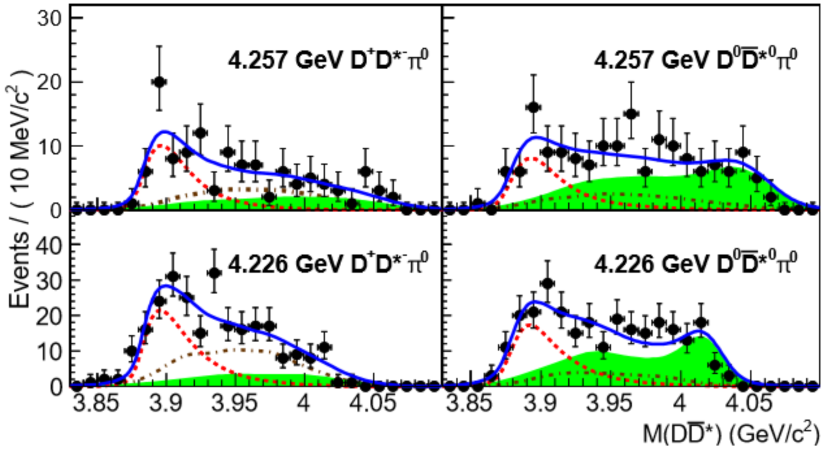
$e^+e^- \to \pi\, Z_c(3885)^{+/-/0} \to \pi\,(D\bar{D}^*)$

PRL 112.022001 (2014)



preliminary





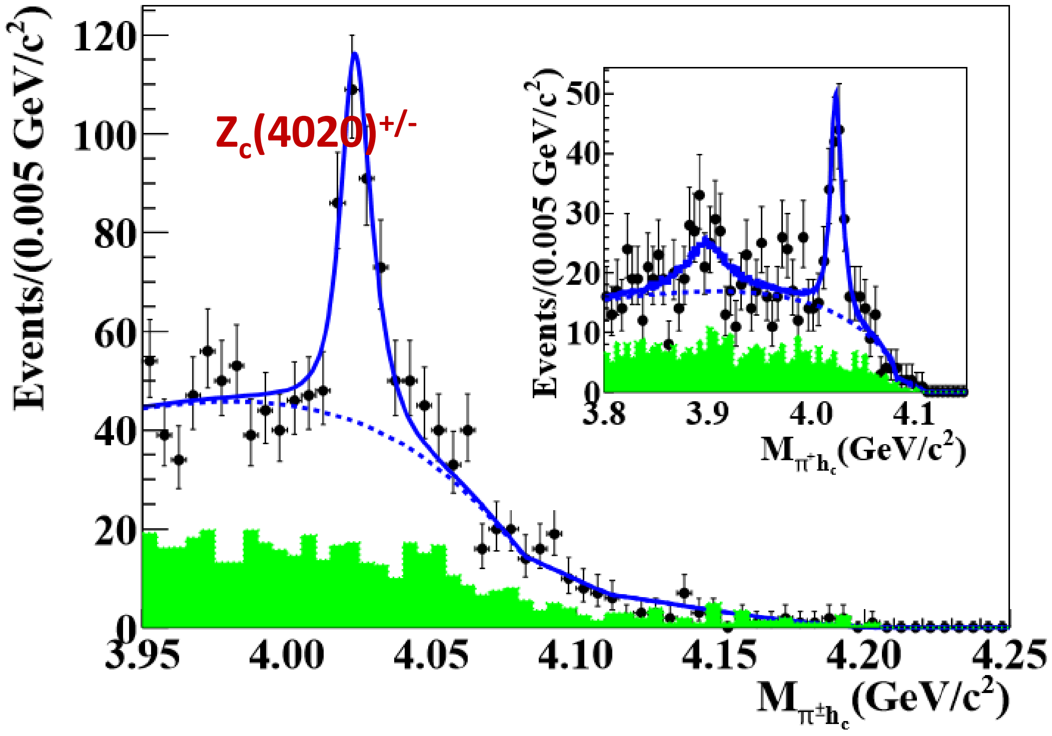
- $Z_c(3885)^{+/-/0}$, observed by BESIII.
- Have a mass and width close to $Z_c(3900)$.

$Z_c(3885)$	Mass(MeV)	Width(MeV)
$Z_c(3885)^{+/-}$	$3883.9\pm1.5\pm4.2$	$24.8\pm3.3\pm1.0$
$Z_c(3885)^0$	$3885.7\,^{+4.3}_{-5.7}\pm8.4$	$35\,^{+11}_{-12}\pm15$

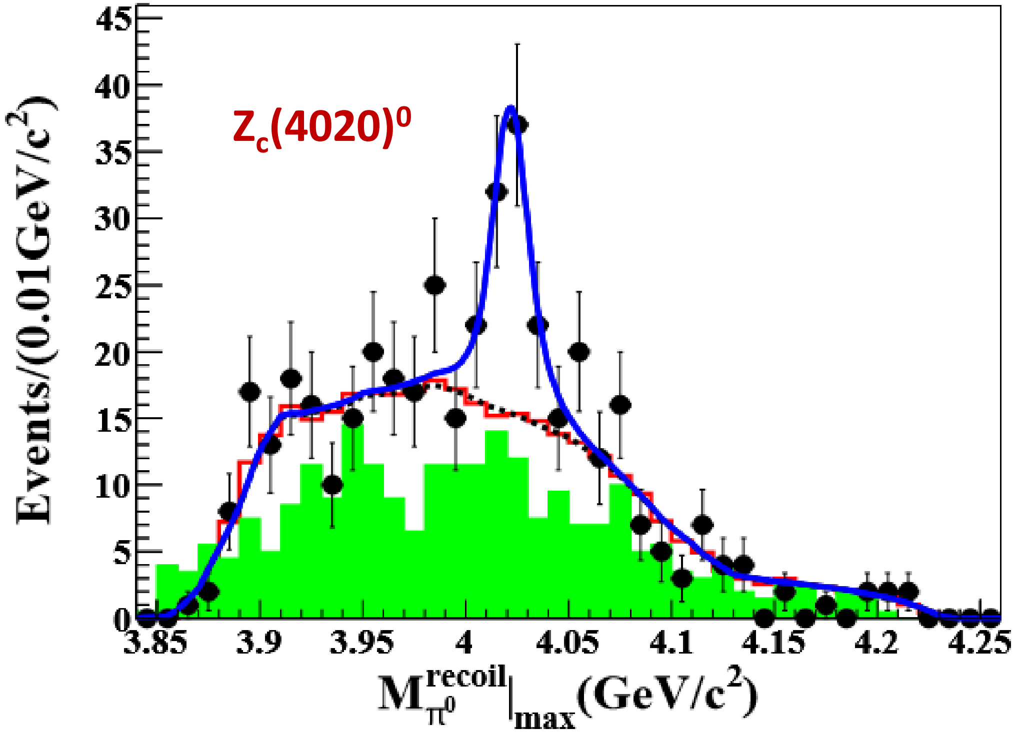
Iso-spin triplet is established!

$e^+e^- \to \pi\, Z_c(4020)^{+/-/0} \to \pi\, \pi\, h_c$

PRL 111,242001 (2013)



PRL 113,212002 (2014)



$Z_c(4020)$	Mass(MeV)	Width(MeV)
$Z_c(4020)^{+/-}$	4022.9±0.8±2.7	7.9±2.7±2.6
$Z_c(4020)^0$	4023.8±2.2±3.8	Fixed(=7.9)

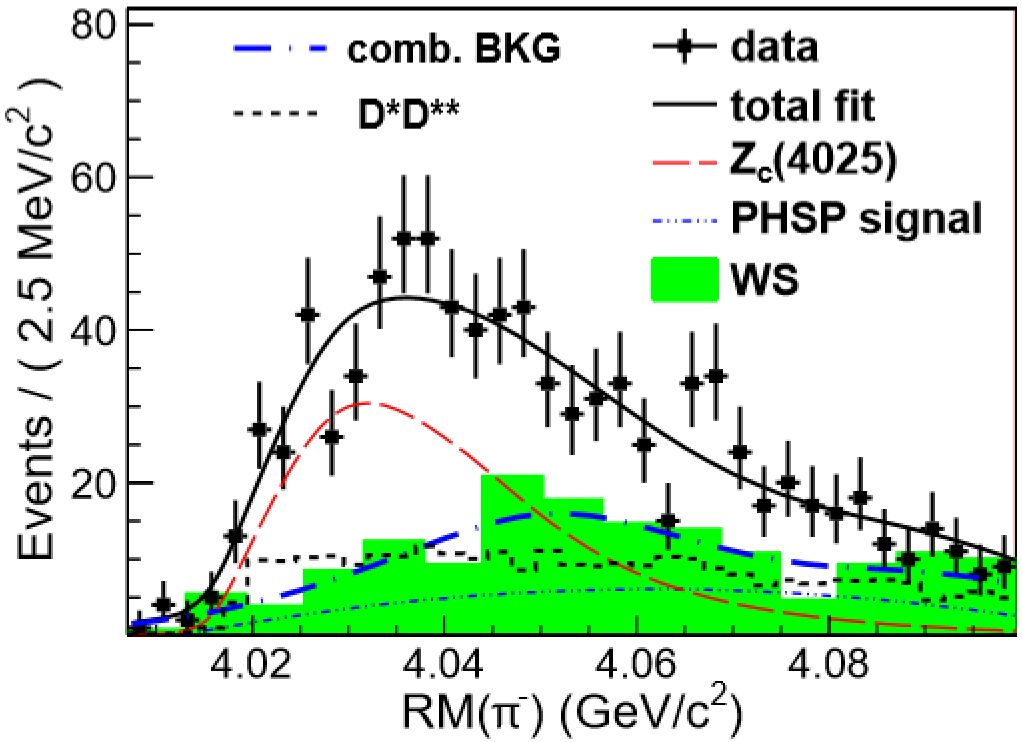
- $Z_c(4020)^{+/-/0}$, observed by BESIII.
- A hint for $Z_c(3900)^{+/-/} \to \pi^{+/-} h_c$.
- $Z_c(4020)$, near the $D^*\bar{D}^*$ threshold.

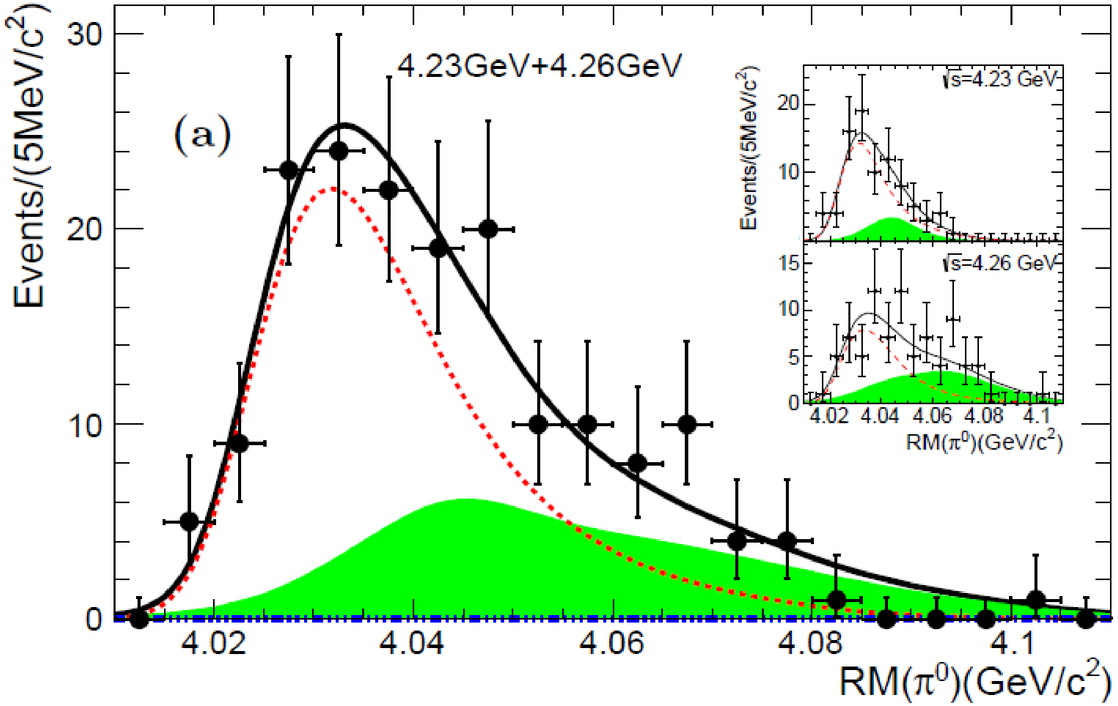
Iso-spin triplet is established!

$e^+e^- \to \pi\, Z_c(4025)^{+/-/0} \to \pi\, (D^* \bar{D}^*)$

PRL 111,242001 (2013)

arXiv:1507.02404





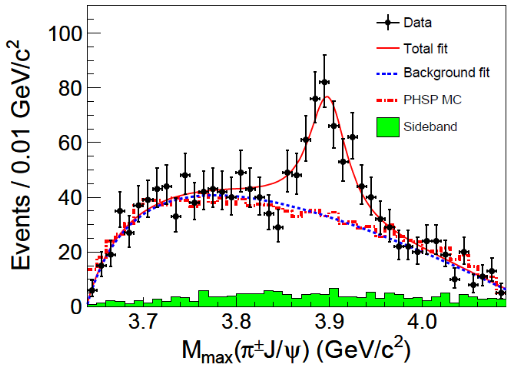
$Z_c(4020)$	Mass(MeV)	Width(MeV)
$Z_c(4020)^{+/-}$	$4026.3 \pm 2.6 \pm 3.7$	$24.8 \pm 5.6 \pm 7.7$
$Z_c(4020)^0$	$4025.5\ ^{+2.0}_{-4.7} \pm 3.1$	$23.0 \pm 6.0 \pm 1.0$

- $Z_c(4020)^{+/-/0}$, observed by BESIII.
- The $Z_c(4020)$ and $Z_c(4025)$ are consistent within 1.5σ.
- If they are the same state:

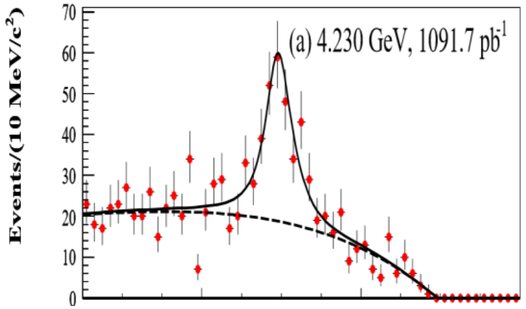
$$\frac{\Gamma(Z_c(4025) \to D^* \bar{D}^*)}{\Gamma(Z_c(4020) \to \pi h_c)} = 12 \pm 5$$

Iso-spin triplet is established!

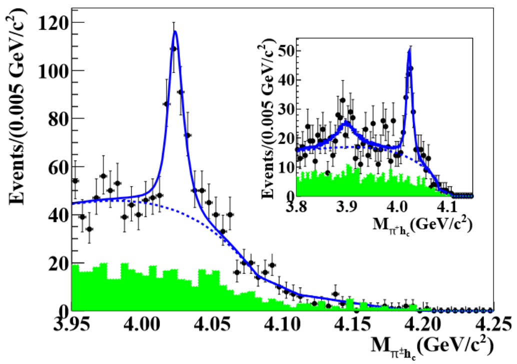
Summary of Z_c states at BESIII



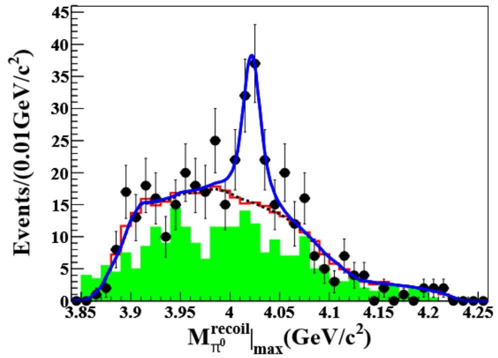
$e^+e^- \to \pi^+ \pi^- J/\Psi$



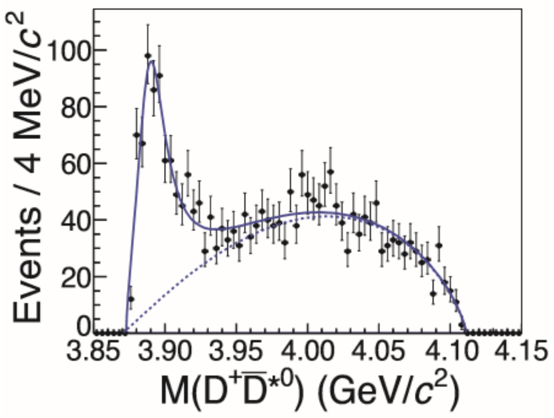
$e^+e^- \to \pi^0 \pi^0 J/\Psi$



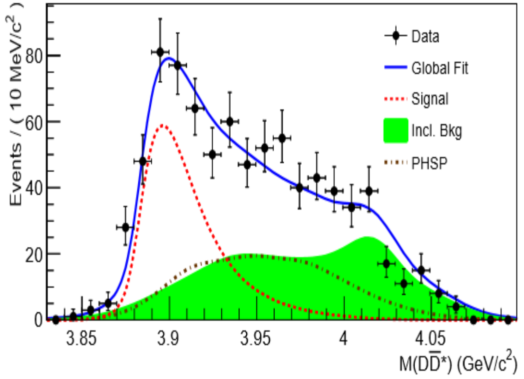
$e^+e^- \to \pi^+ \pi^- h_c$



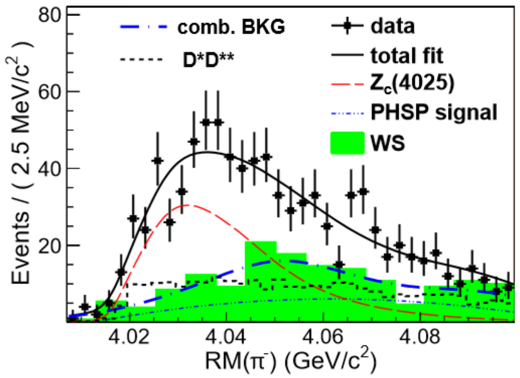
$e^+e^- \to \pi^0 \pi^0 h_c$



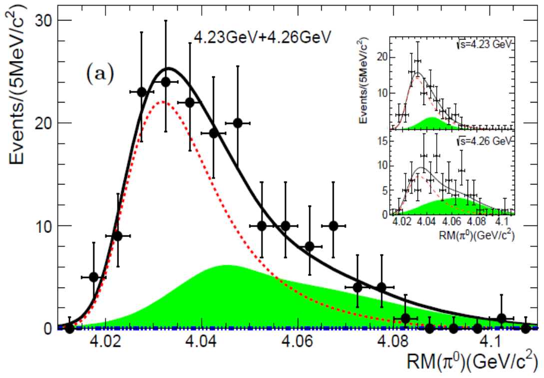
$e^+e^- \to \pi^+ (D\bar{D}^*)^-$



$e^+e^- \to \pi^0 (D\bar{D}^*)^0$



$e^+e^- \to \pi^+ (D\bar{D}^*)^-$



$e^+e^- \to \pi^0 (D\bar{D}^*)^0$

$Z_c(3900)^{+/-}$?

$Z_c(3900)^0$?

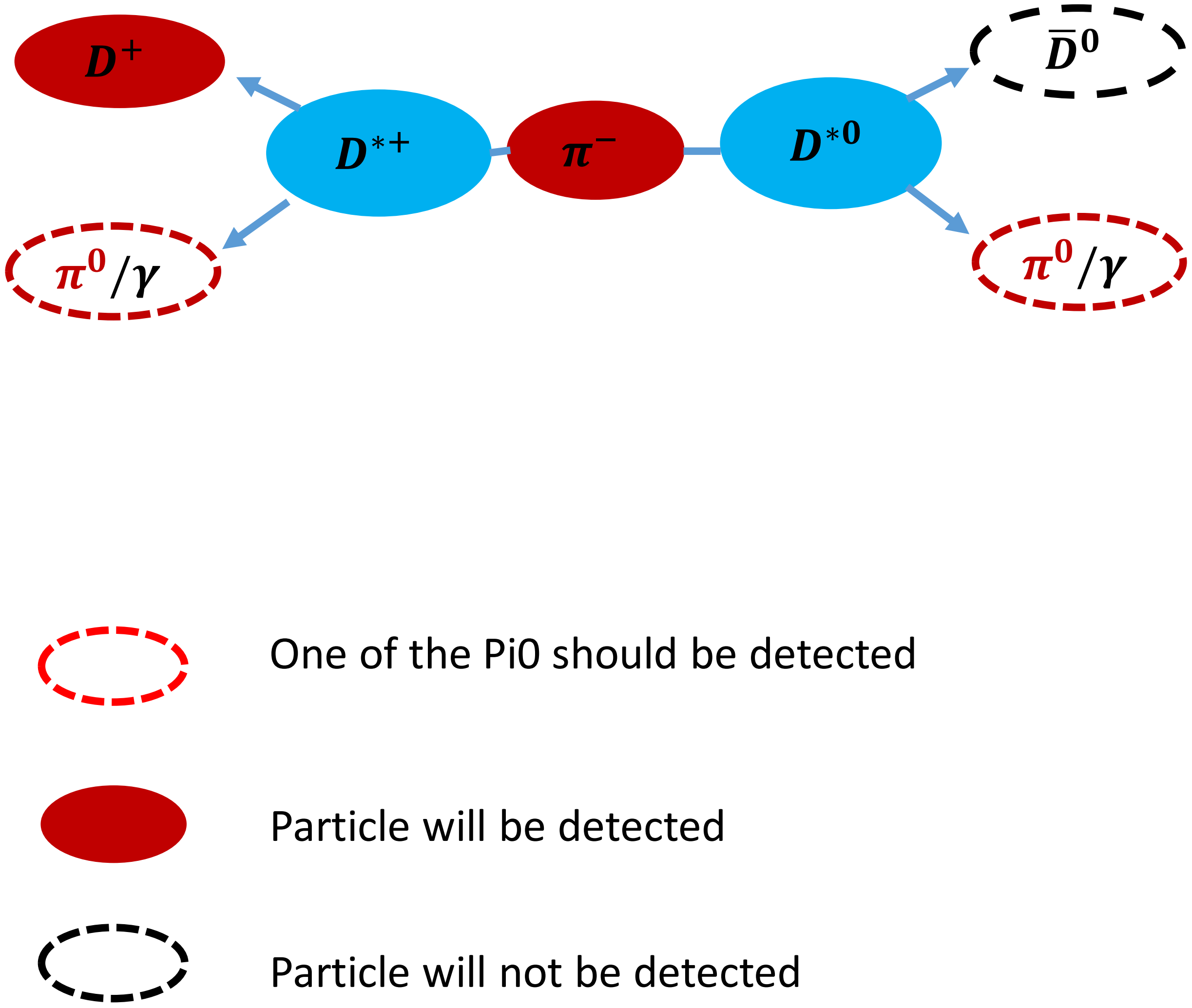
$Z_c(4020)^{+/-}$?

$Z_c(4020)^0$?

PART 2

$Zc(4025)^{+/-}$

Topology

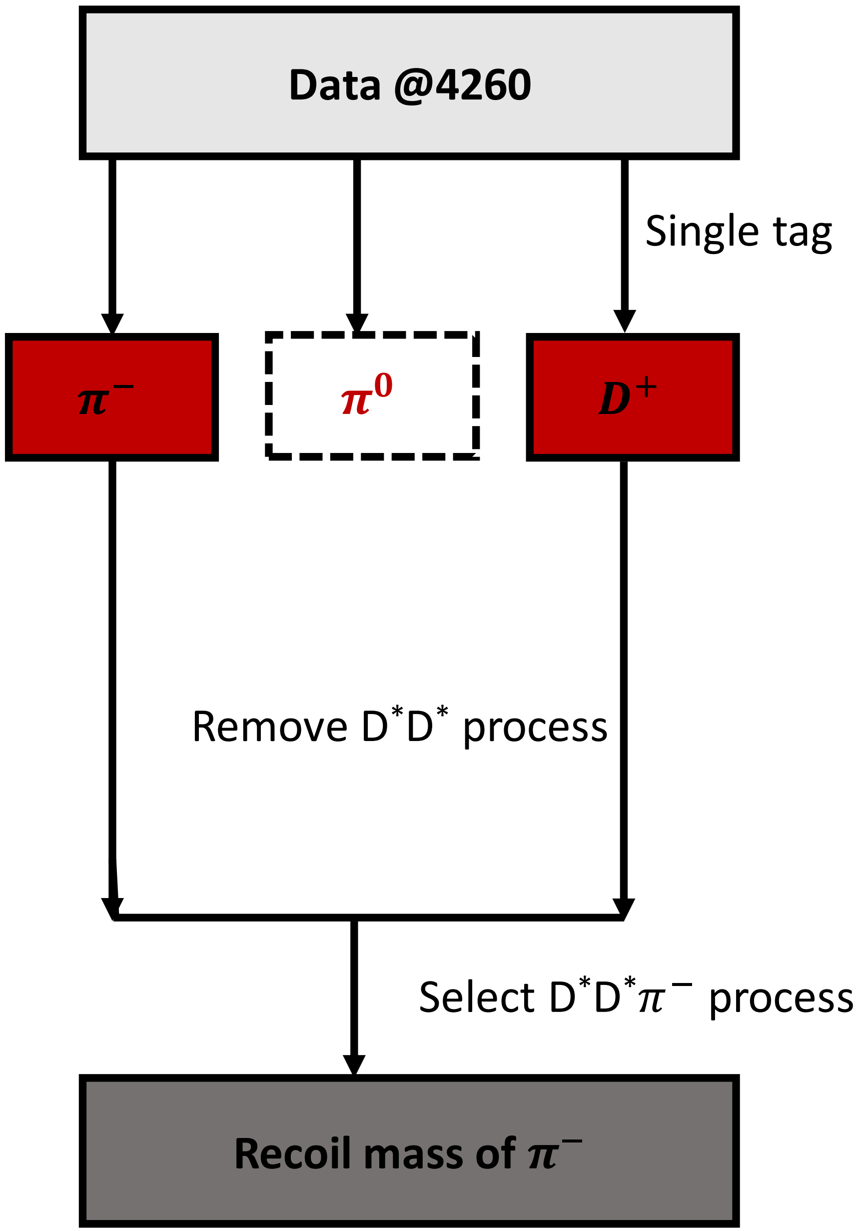


One of the Pi0 should be detected

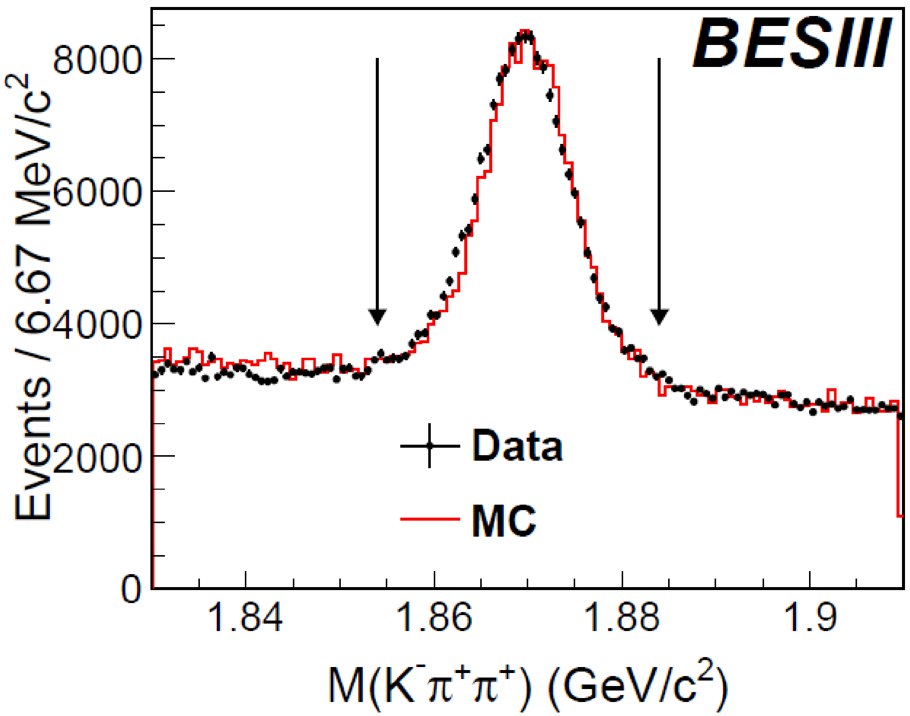
Particle will be detected

Particle will not be detected

Flow chart

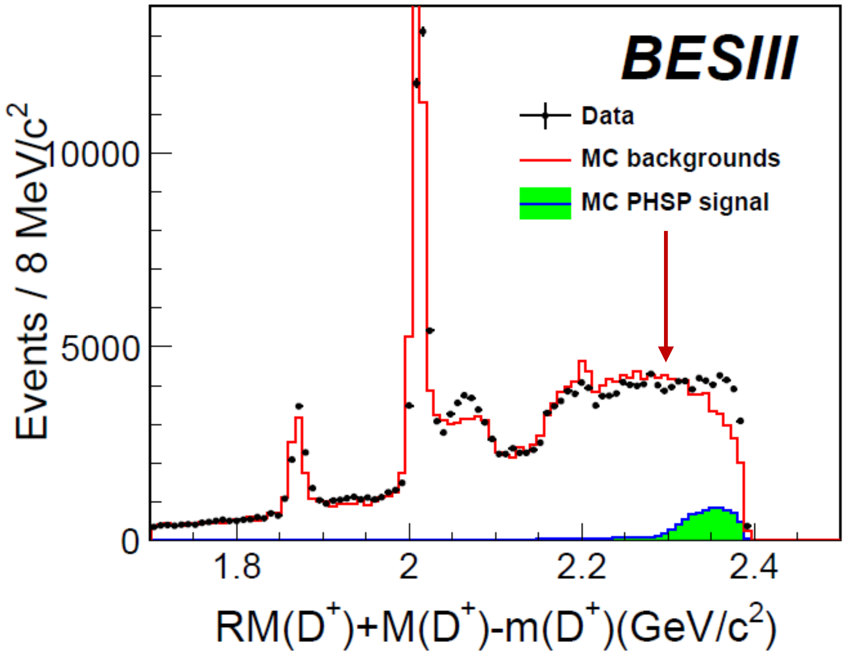


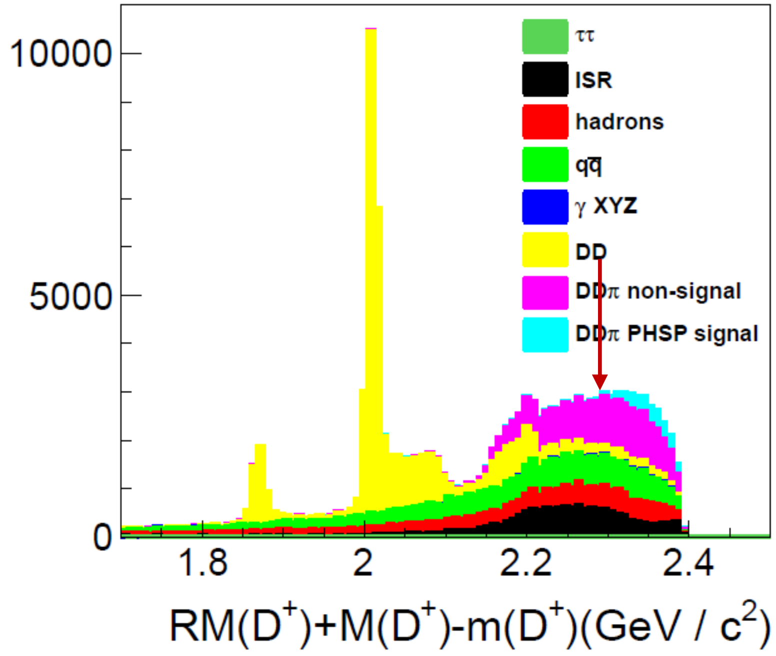
Invariant mass of $K^- \pi^+ \pi^+$



- We reconstruct a D^+ with only $K^- \pi^+ \pi^+$.
- The dots are data and histograms are MC.
- The $M(K^- \pi^+ \pi^+)$ is required to be in (1.854,1.884)GeV/c^2.

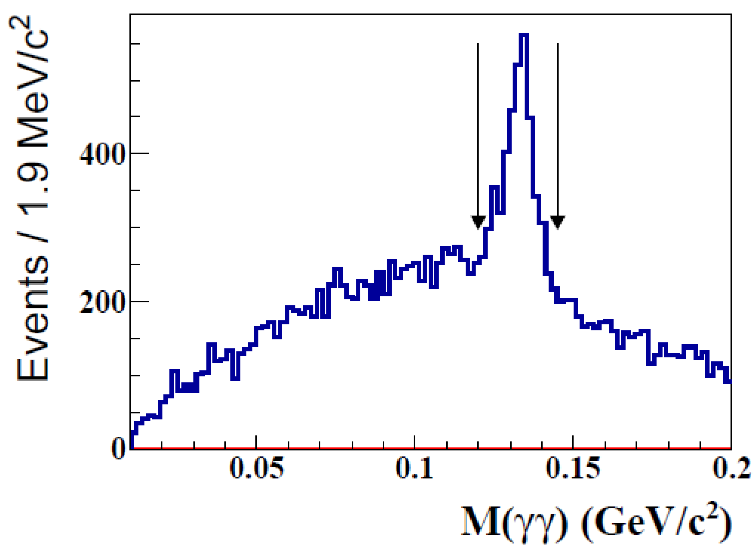
D^+ recoiling mass

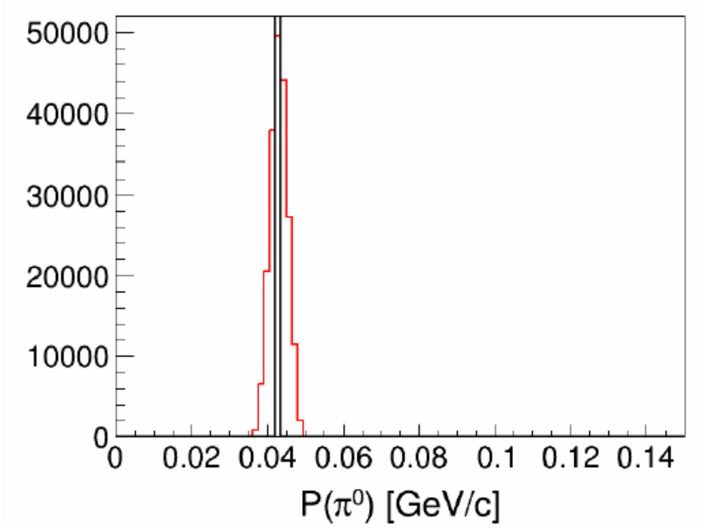


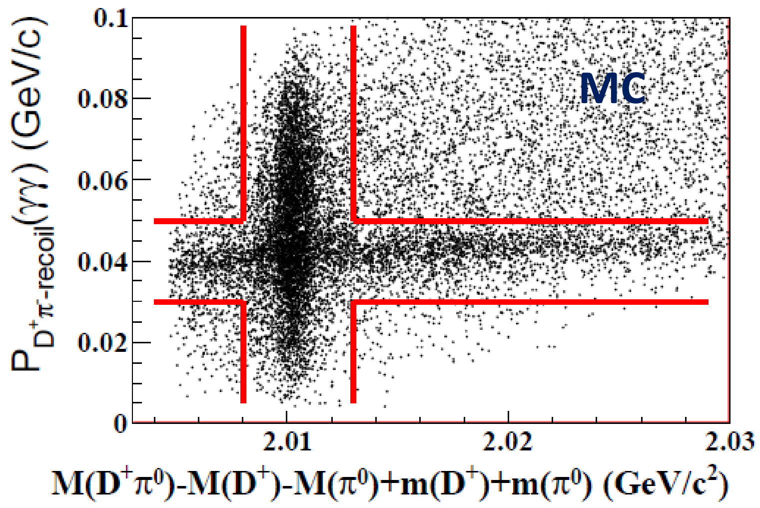


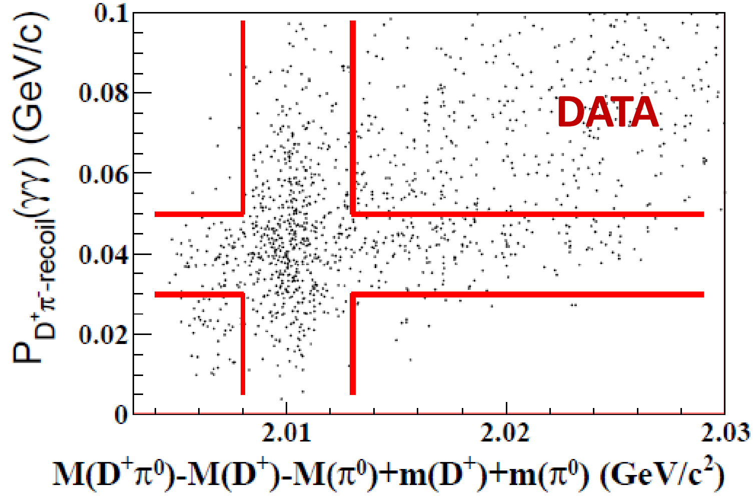
- The variable $RM(D^+)+M(D^+)-m(D^+)$ could improve the mass resolution by reducing the correlation of $RM(D^+)$ and $M(D^+)$.
- To remove the background $e^+e^- \to D^{(*)} D^{(*)}$, we require $RM(D^+)+M(D^+)-m(D^+) > 2.3 GeV/c^2$.

Require an additional π^0



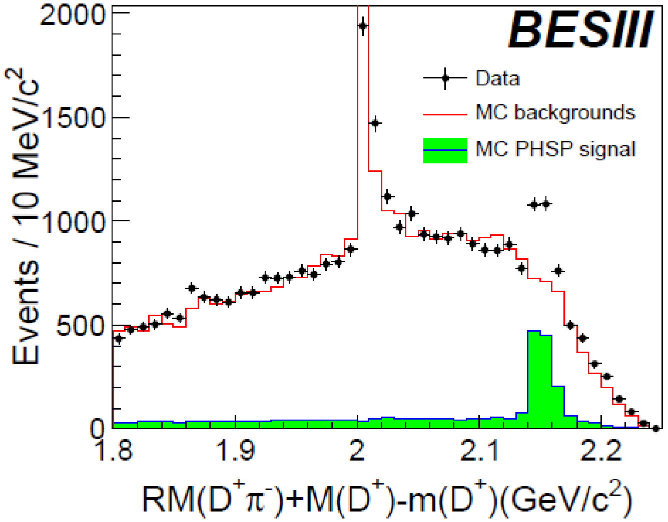


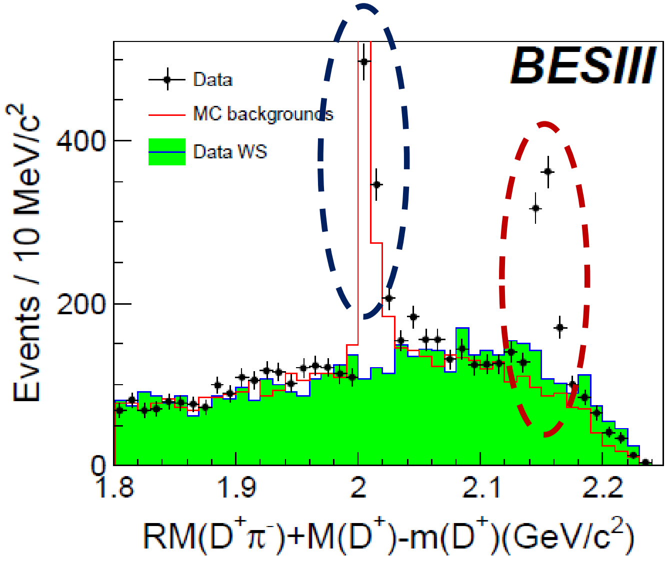


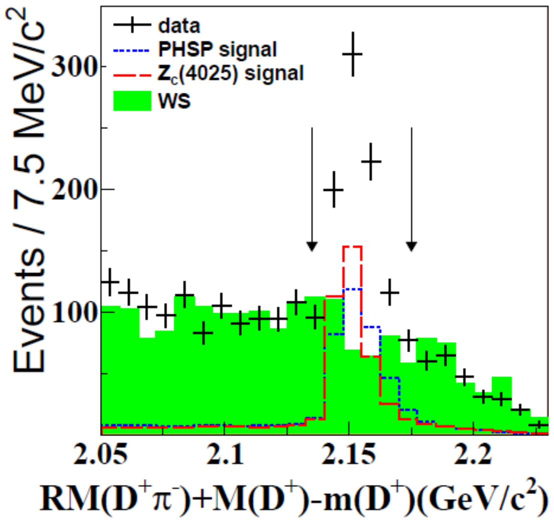


- M(γγ) lies in (0.12,0.145)GeV/c^2.
- π^0 comes from D^{*+} or D^{*0}.
- Momentum of π^0 in the RM($D^+\pi^-$) lies in (0.03,0.05)GeV/c or M($D^+\pi^0$)-M(D^+)+m(D^+)-M(π^0)+m(π^0) lies in (2.008,2.013)GeV/c^2.

$D^+ \pi^-$ recoiling mass





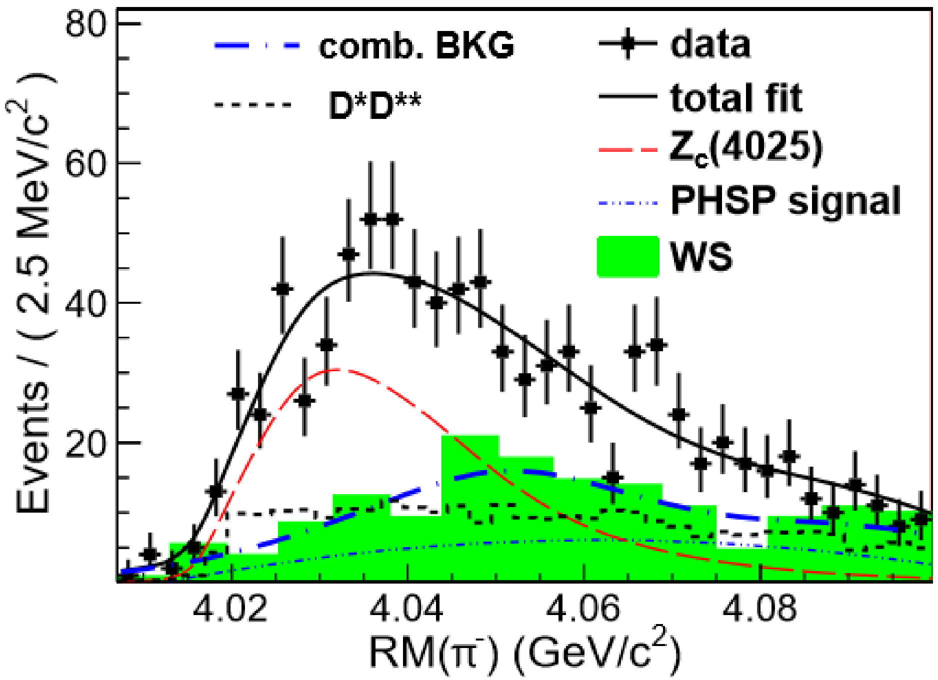


$DD^* \pi$ process

$D^* D^* \pi$ process

- The left peak corresponds to $DD^* \pi$ process while the right one corresponds to $D^* D^* \pi$ process
- The green histogram is Wrong Sign. We use it to describe the combinatorial backgrounds.

Fit to data

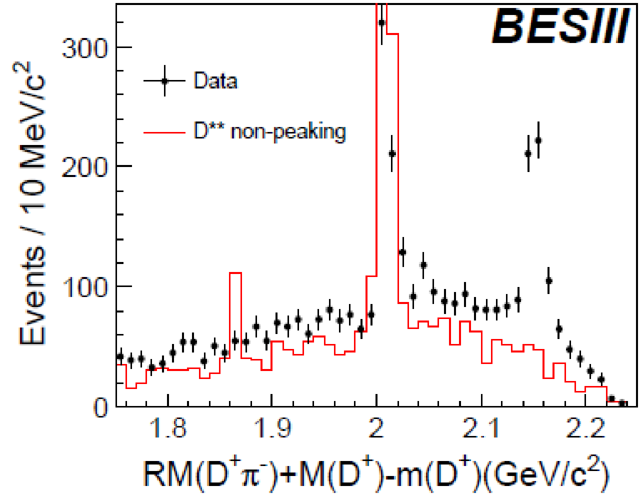


- Signal: efficiency-weighted S wave mass-dependent BW convoluted with a detector resolution function.
- Background: kernel-estimate of Wrong Sign Shape and its magnitude is fixed to the number of the fitted background.
- PHSP: The shape of the PHSP signal is taken from MC simulation and its amplitude is taken as a free parameter.

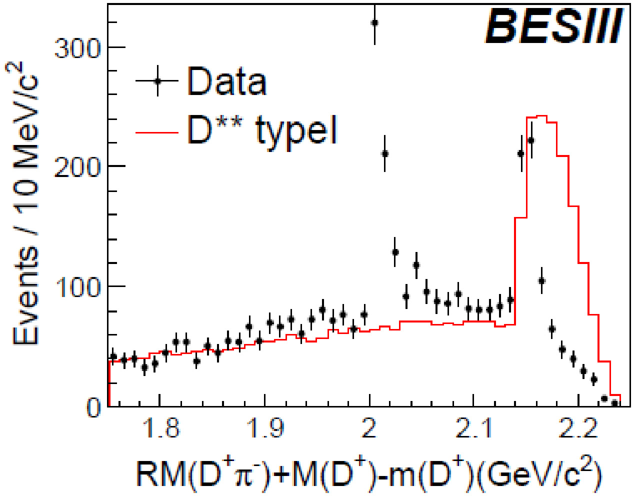
Systematic uncertainties

Source	$m(\mathrm{MeV}/c^2)$	$\Gamma(\mathrm{MeV})$	$\sigma_{\mathrm{tot}}(\%)$	$R(\%)$
Tracking			4	
Particle ID			5	
Tagging π^0			4	
Mass scale	1.8			
Signal shape	1.4	7.3	1	5
Backgrounds	1.5	0.6	5	5
Efficiencies	0.9	2.2	1	5
D^{**} states	2.2	0.7	5	2
Fit range	0.9	0.9	1	1
$D^{*+}\bar{D}^{*0}\pi^-$ line shape			4	
PHSP model			2	2
Luminosity			1.0	
Branching fractions			2.6	
total	3.7	7.7	11	9

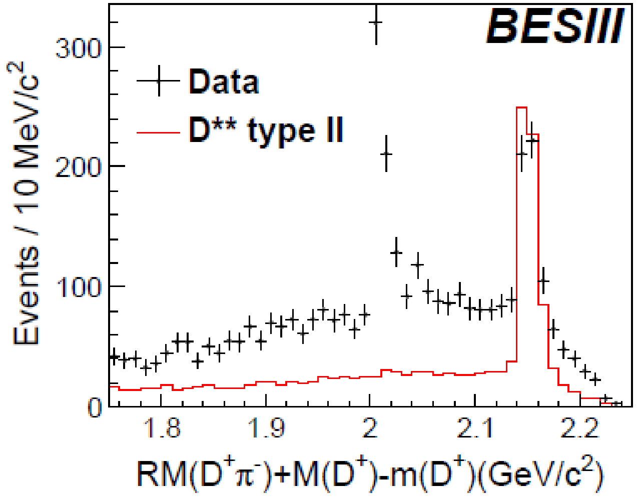
D^*D^{**} process



(a) Non-peaking: $e^+e^- \to D^{**}D \to D^{(*)}\pi D$

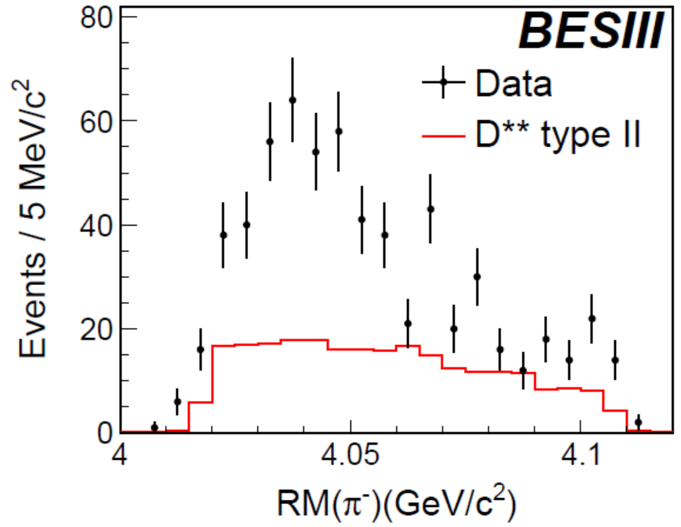


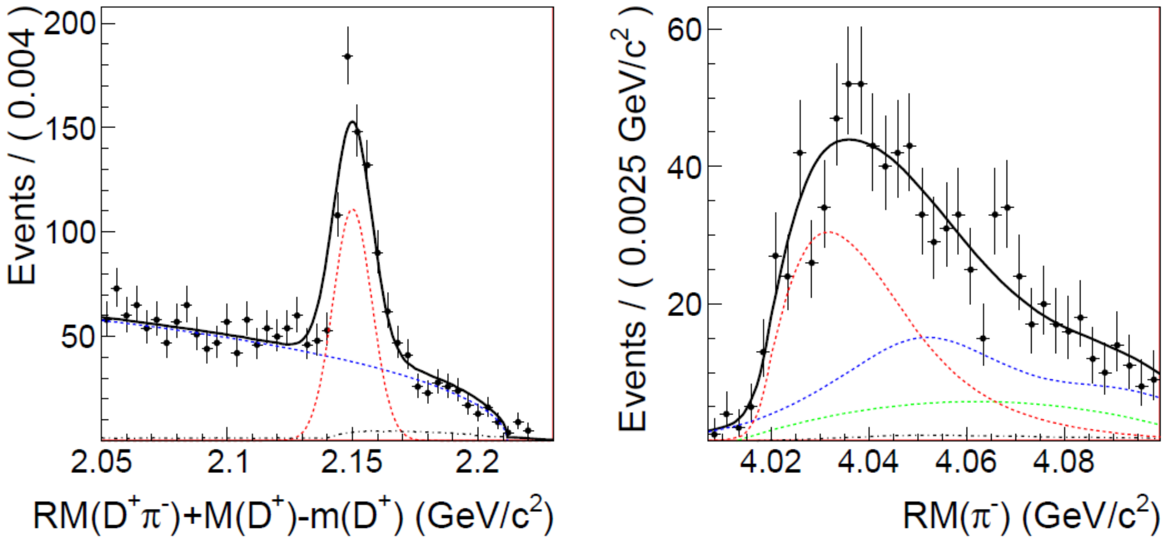
(b) Type-I: $e^+e^- \to D^{**}D \to D^*\pi\pi D$

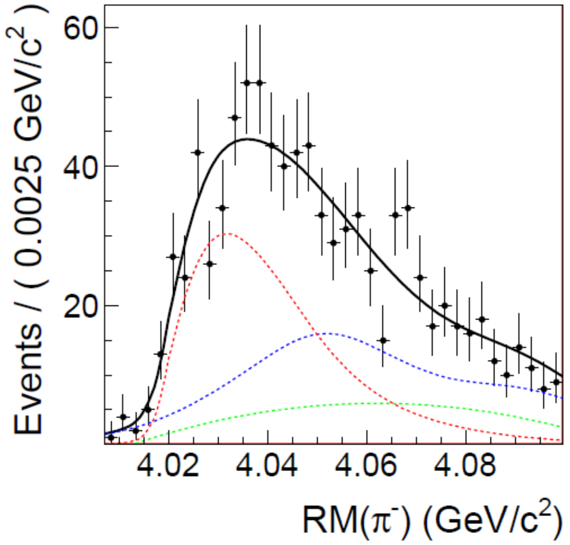


(c) Type-II: $e^+e^- \to D^{**}D^* \to D^*\pi D^*$

- Non-peaking type won't contribute to the peak.
- Type I: Much broader than the peak.
- Type II: may affect the result, its amplitude need to be decided through fit.







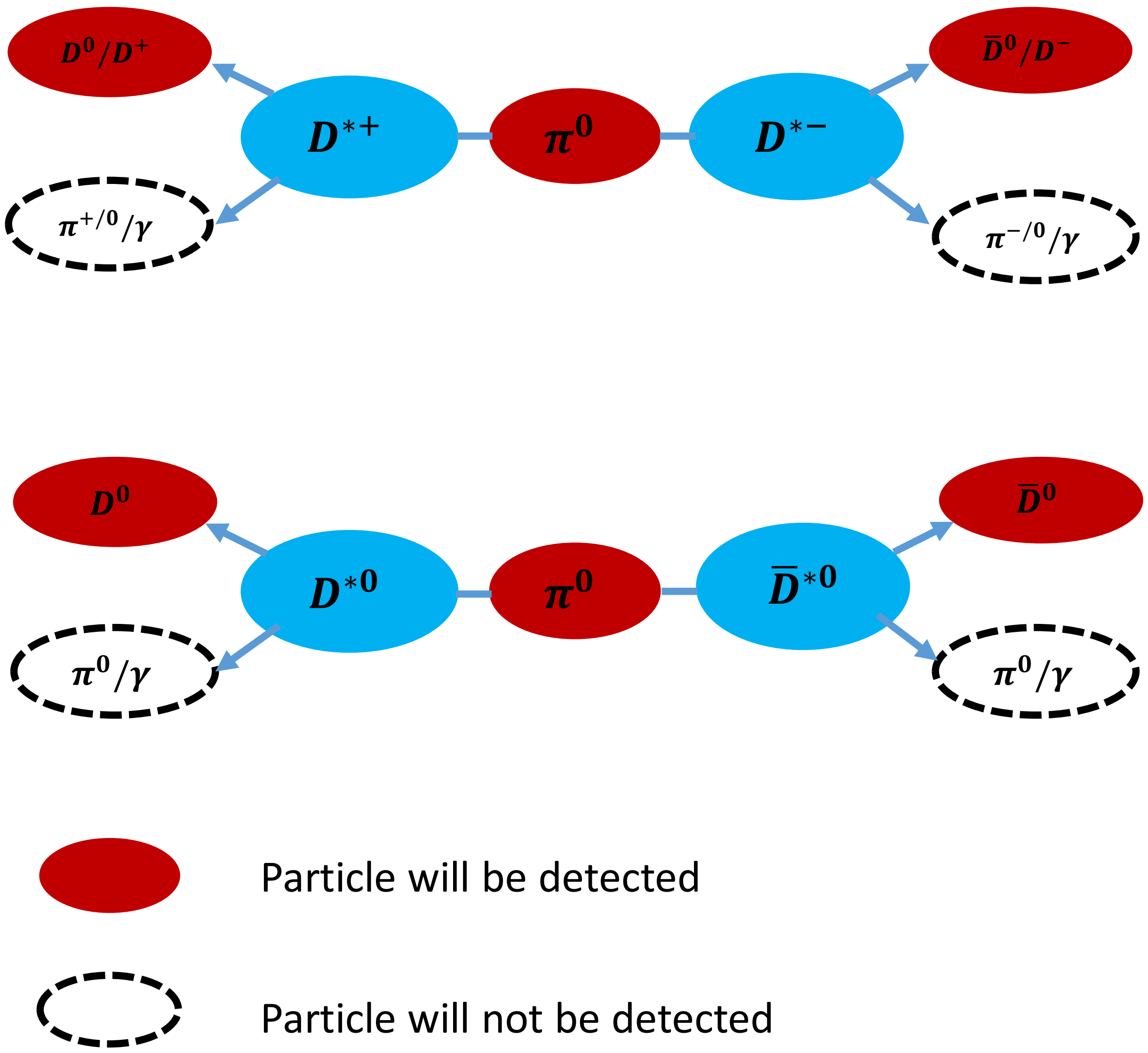
- Type I: add an additional component D^*D^{**}.
- Fix its amplitude and obtain the shape from MC.
- The resonance is still significance.
- The change of results are considered as systematic uncertainties.

- Type II: add an additional component D^*D^{**}.
- Float its amplitude and obtain the shape from MC.
- No sign of type II from the fit.

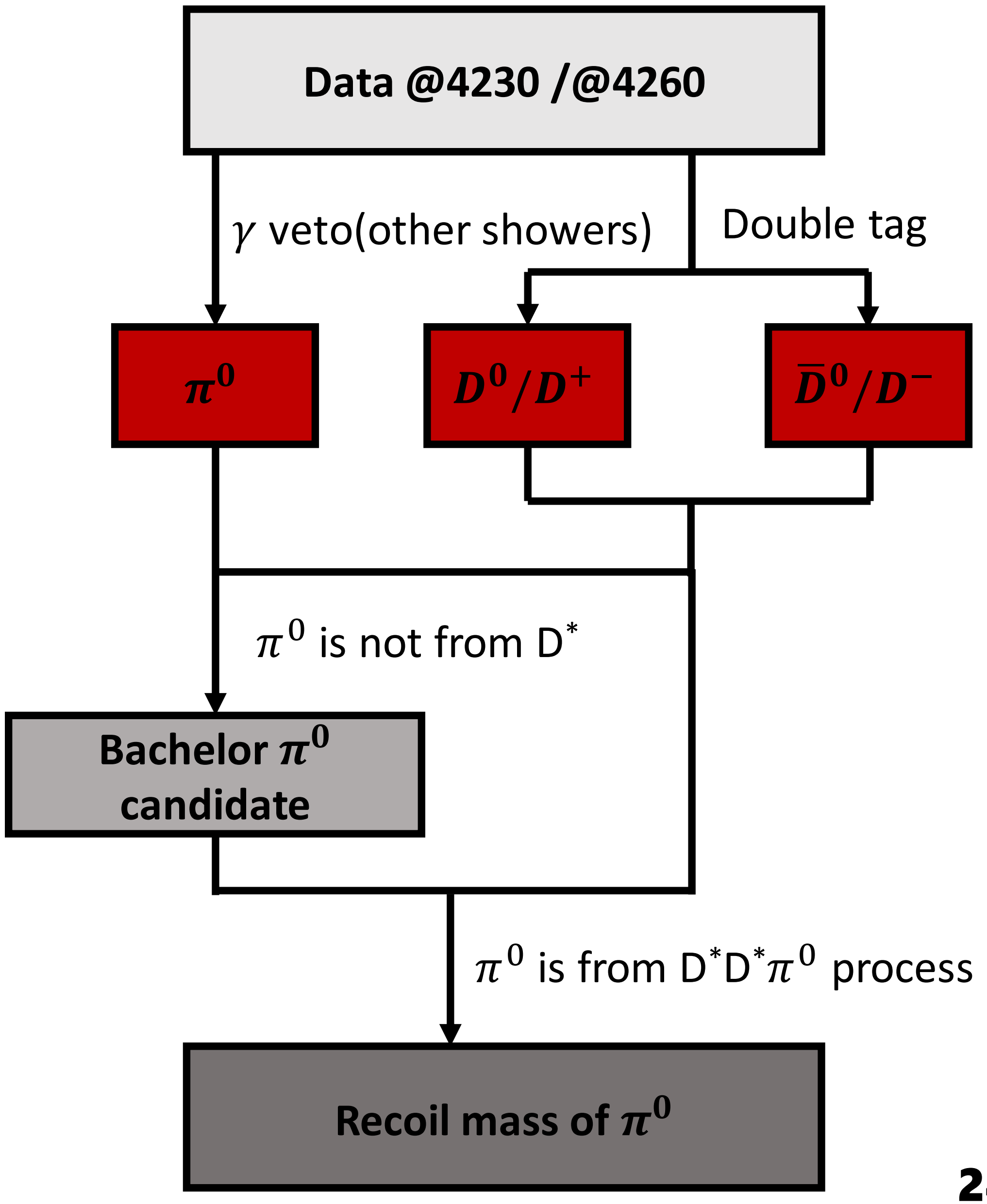
PART 3

$Zc(4025)^0$

Topology



Flow chart



Double tag method

- **Tag a $\mathbf{D}$ and a $\overline{\mathbf{D}}$**

  mode 0: $D^0 \rightarrow K^- \pi^+$ + c.c.

  mode 1: $D^0 \rightarrow K^- \pi^+ \pi^0$ +c.c.

  mode 3: $D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$ +c.c.

  mode 200: $D^+ \rightarrow K^- \pi^+ \pi^+$ +c.c.

- **Choose the best combination with minimum R**

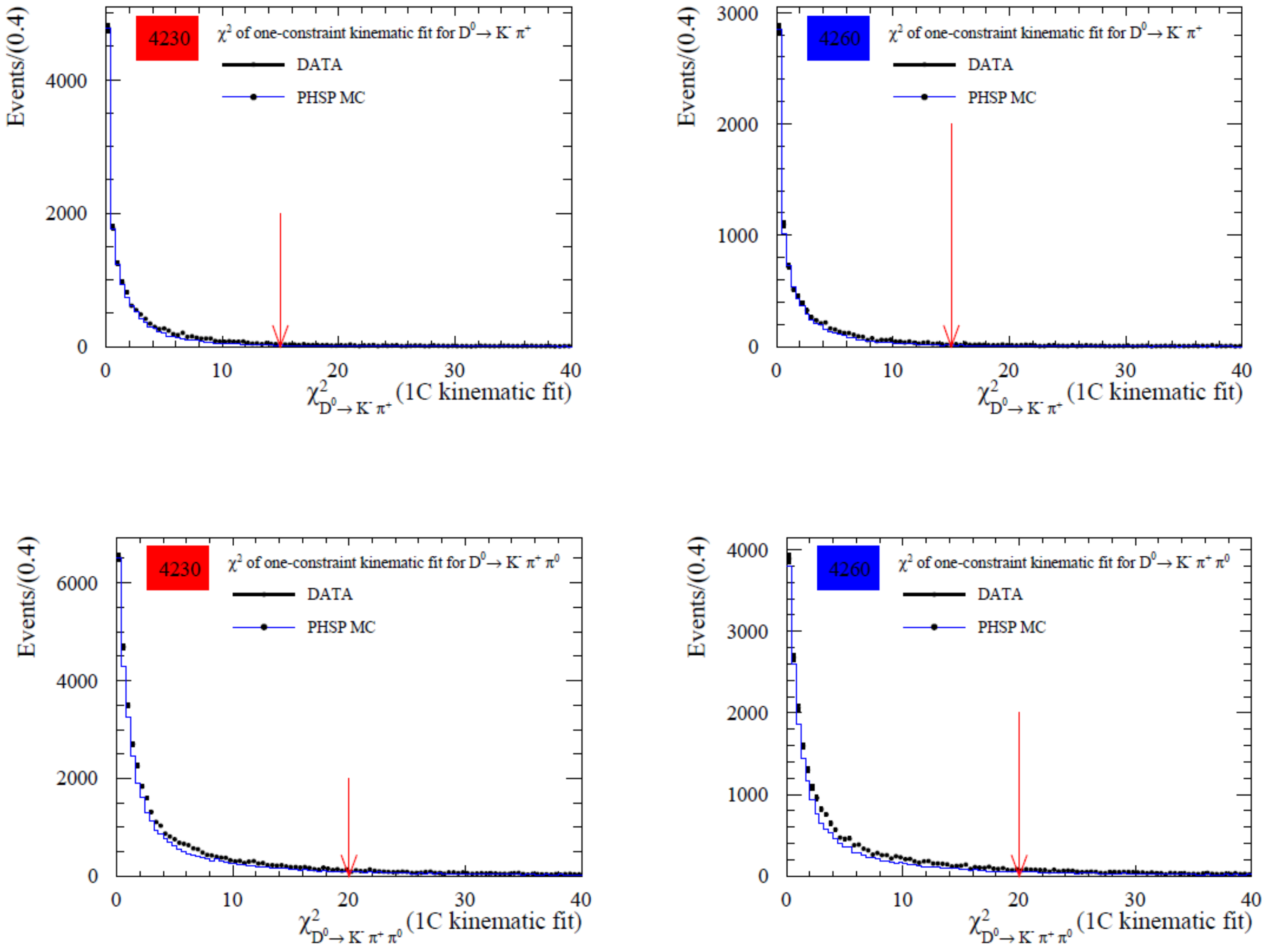
$$R = \sqrt{\chi^2_{KF}(D) + \chi^2_{KF}(\overline{D})}$$

- **Why double tag?**

  Double tag will reduce the efficiency dramatically, but it will also remove lots of backgrounds.

  In our analysis, how to suppress the background is crucial.

χ^2_{KF} of $K^- \pi^+ \pi^+$



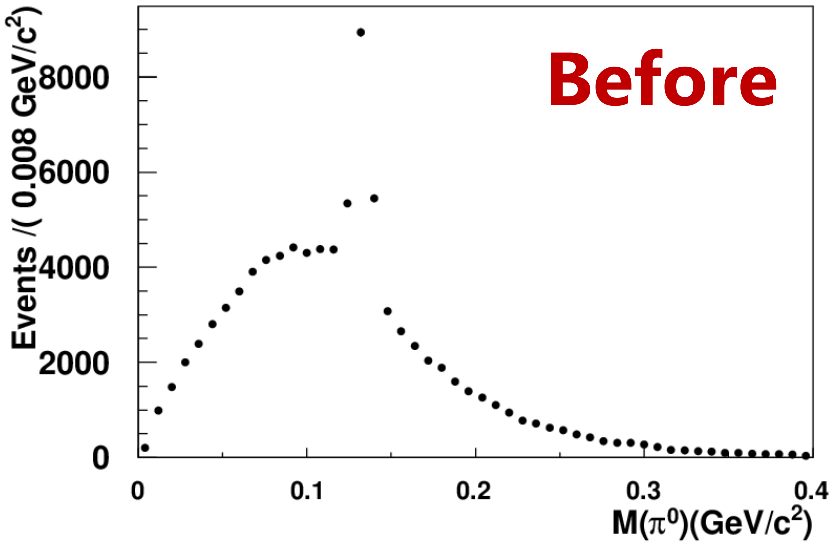
We apply different cut for different mode:

Mode 0, 3, 200: χ^2_{KF}<15

Mode 1 : χ^2_{KF}<20

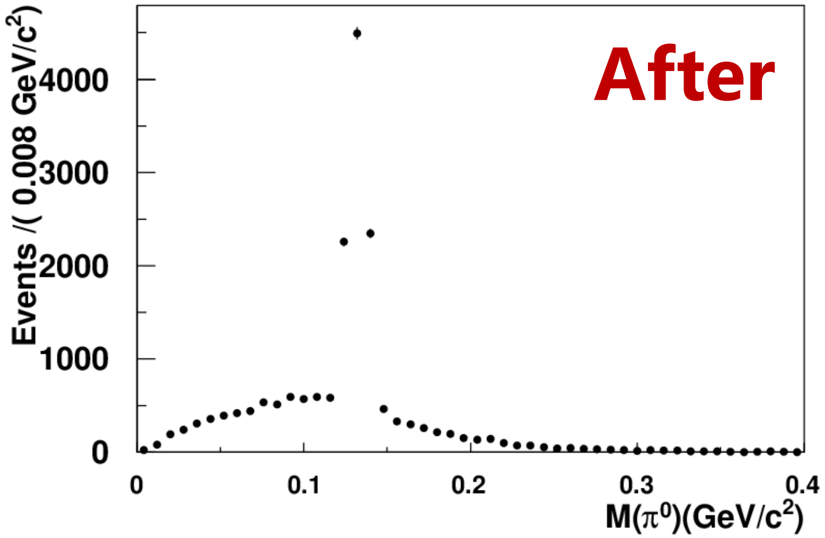
γ veto method

- To reject backgrounds, each photon candidate originating from the bachelor π^0 is required not to form a π^0 ($M(\gamma\ \gamma)$)with any other photon in the event.
- γ veto could rise the signal-to-background ratio dramatically.



Before veto

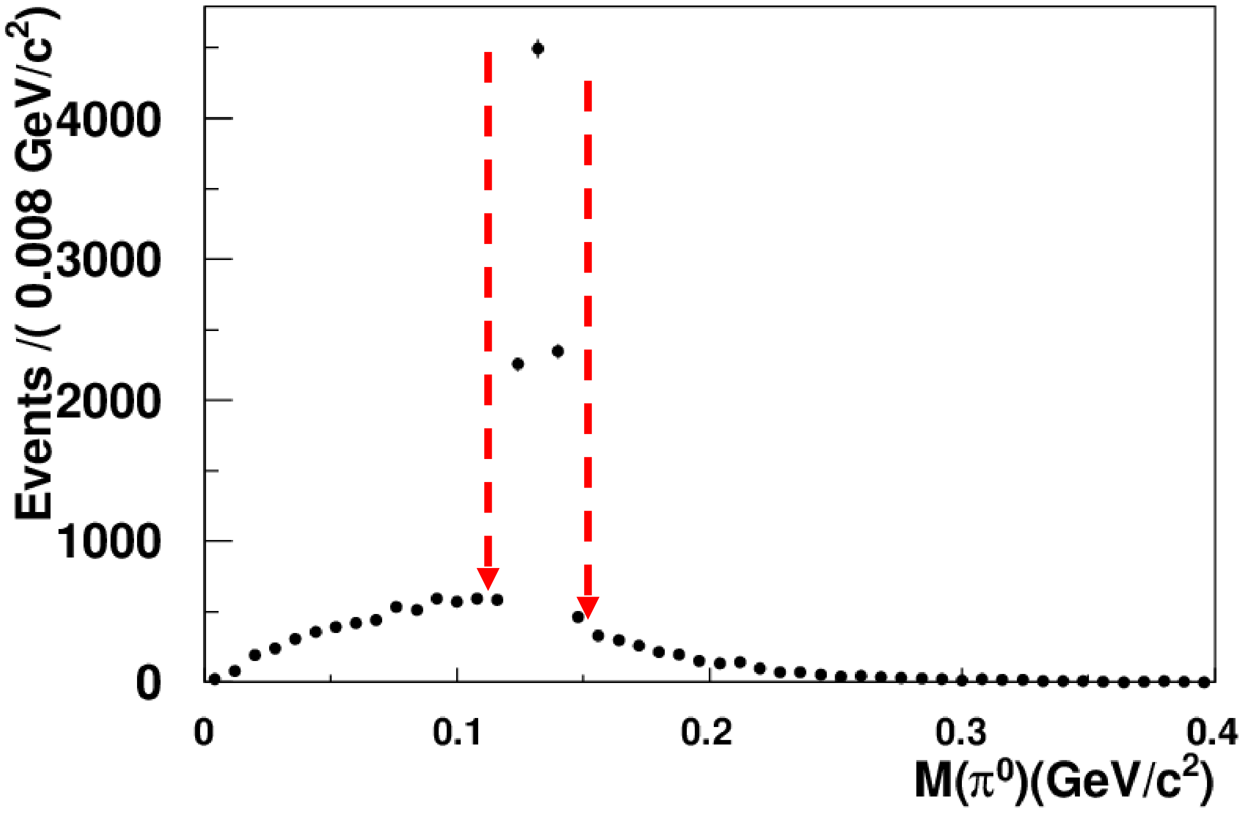
γ veto



After veto

Select a good π^0

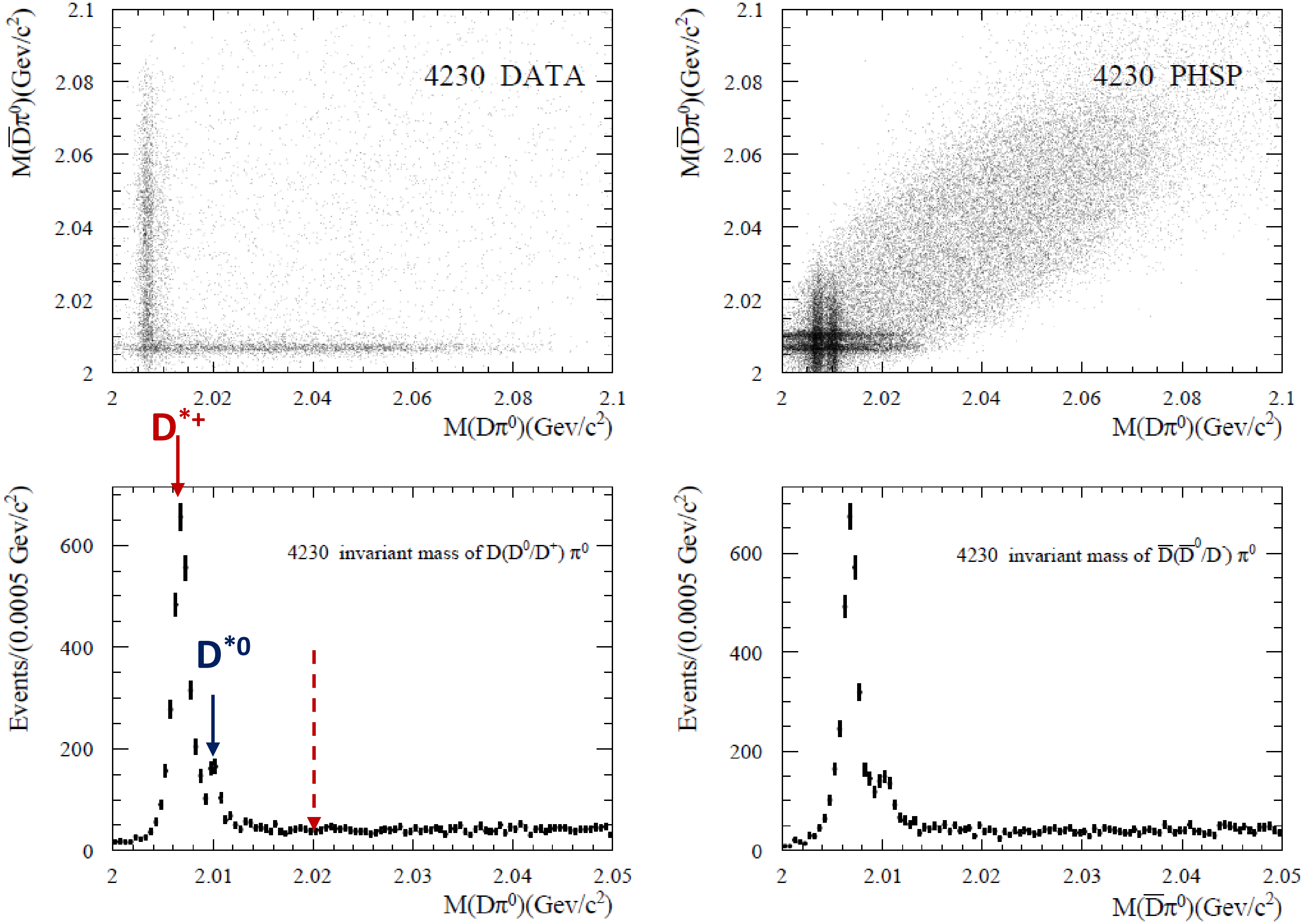
(0.12,0.145)GeV/c²



- After γ veto, the signal-to-background ratio becomes good.

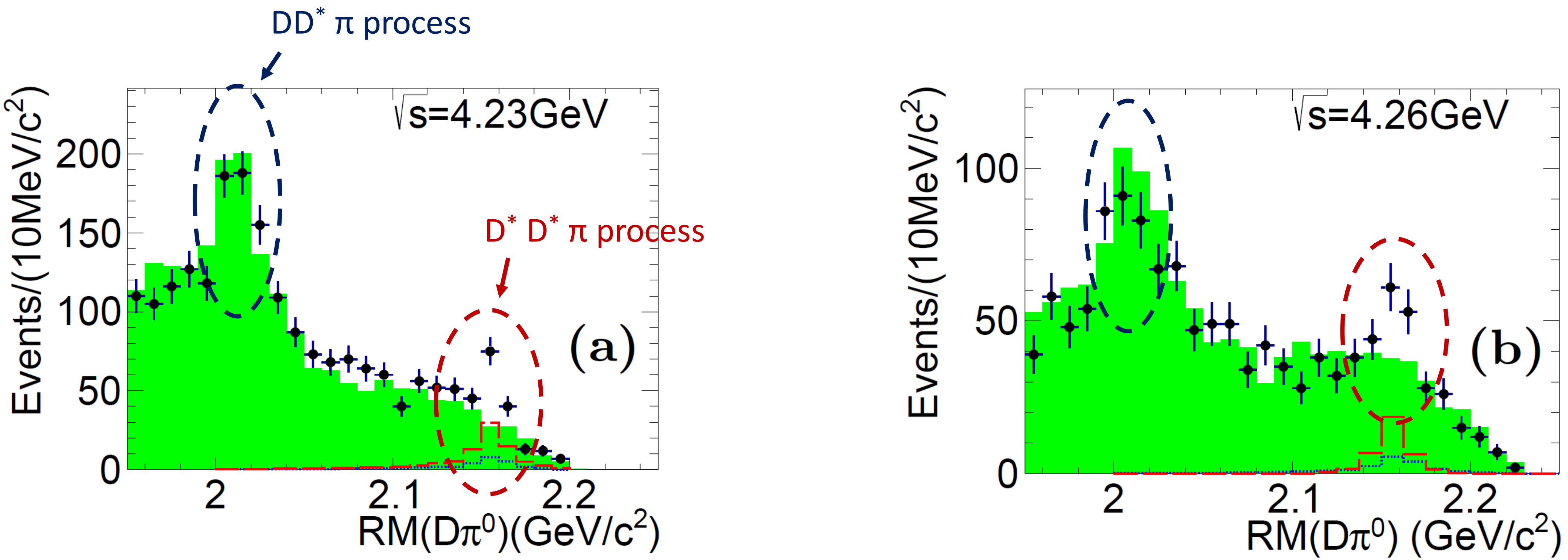
- We require the Invariant mass of π^0 lies in the region (0.12,0.145)GeV/c^2

The invariant mass of $D\,\pi^0\,(\bar{D}\,\pi^0)$

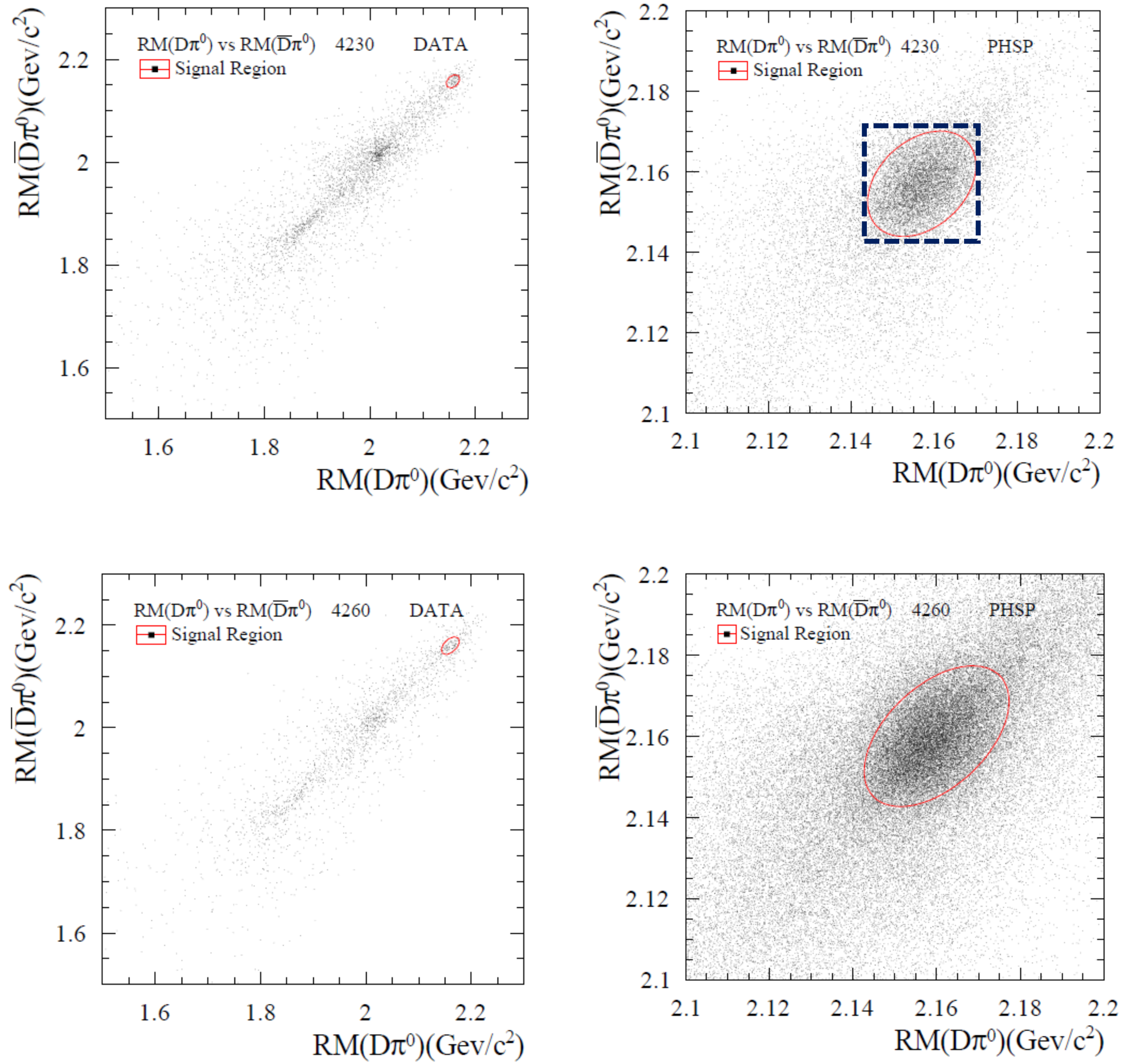


- The deep color region corresponds to the D^* peak
- Since we should remove the π^0 from D^*. We require $M(D\,\pi^0)$ and $M(\bar{D}\,\pi^0)$ are lager than 2.02GeV/c^2.

The recoil mass of $D\pi^0(\bar{D}\pi^0)$



- The left peak around 2GeV/c^2 corresponds to the D^* peak.
- The right peak around 2.15GeV/c^2 is produced by $D^* D^* \pi^0$ process.
- The phase space of missing energy is limit, which includes a D^* and a soft π. Because of the soft π, the peak of RM($D\pi^0$) will shift up from D^* to about 2.15GeV/c^2. The resolution of the peak will be broadened slightly.



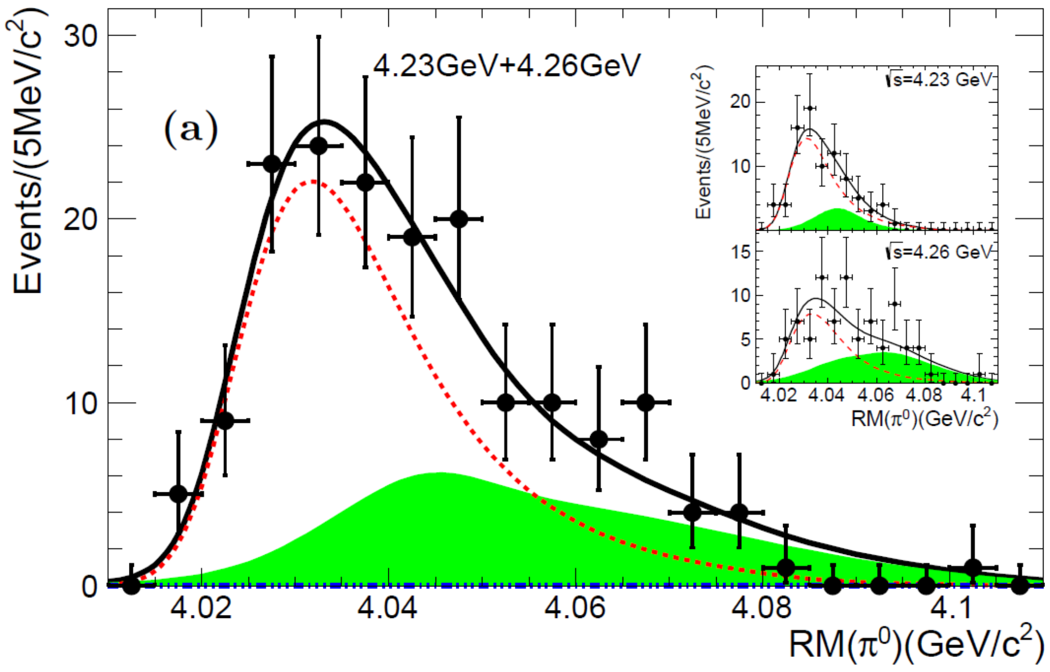
- **Why oval cut?**

  oval cut can removes more background than quadrate cut.

- **Why oval @4230 is smaller than @4260?**

  the phase-space of missing energy @4230 is smaller than @4260, so the peak @4230 is sharper than @4260.

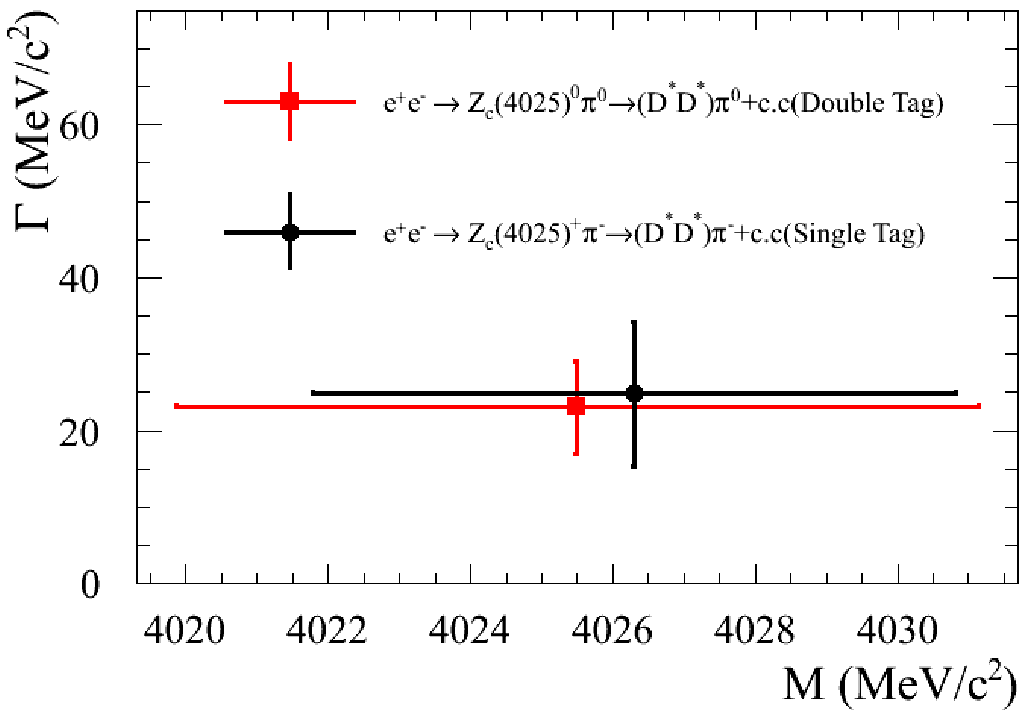
Simultaneous fit

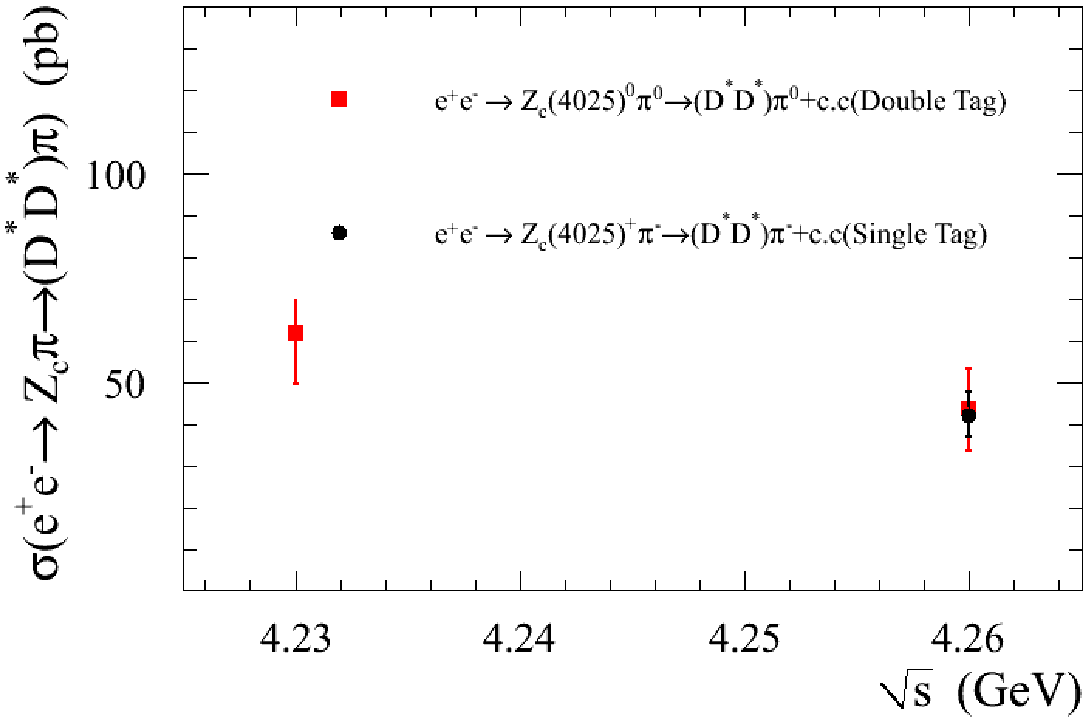


- Signal: efficiency-weighted S wave mass-dependent BW convoluted with a detector resolution function.
- Background: kernel-estimate of Wrong Sign Shape and its magnitude is fixed to the number of the fitted background.
- PHSP: The shape of the PHSP signal is taken from MC simulation and its amplitude is taken as a free parameter.

Source	$m(\mathrm{MeV}/c^2)$	$\Gamma(\mathrm{MeV})$	$\sigma_{4230}(\%)$	$\sigma_{4260}(\%)$
Tracking			5	5
Particle ID			5	5
π^0 reconstruction			4	4
Photon veto			4.2	4.2
Mass scale	2.6			
Detector resolution	0.2	0.1	0.3	0.5
Backgrounds	0.6	0.2	5.6	5.4
Oval cut	1.5	1.0	4.2	2.0
Fit range	$\cdots$	0.1	0.3	0.5
$D^*\bar{D}^*\pi^0$ line shape	$\cdots$	$\cdots$	6.0	3.0
Luminosity			1	1
$\mathcal{B}_1$ and $\mathcal{B}_2$	$\cdots$	$\cdots$	6.5	5.3
Isospin violation	$\cdots$	0.2	0.3	0.2
Vacuum polarization			0.5	0.5
Total	3.1	1.0	14.6	12.5

Comparison between $Z_c(4025)^0$ and $Z_c(4025)^+$





	Mass(MeV/c^2)	Width(MeV/c^2)	$\sigma(e^+e^- \to Z_c(4025)\,\pi \to D^*\bar{D}^*\pi)$(pb) @4.26GeV
$Z_c(4025)^0$	$4025.5^{+2.0}_{-4.7}\pm 3.1$	$23.0 \pm 6.0 \pm 1.0$	$43.4 \pm 8.0 \pm 5.4$
$Z_c(4025)^+$	$4026.3 \pm 2.6 \pm 3.7$	$24.8 \pm 5.6 \pm 7.7$	$42.2 \pm 2.8 \pm 4.6$

PART 3

Summary

- BESIII has observed serval Zc states. They should consist of at least four quarks and considered as candidates of tetra-quark state.

- Tetra-quarks or molecules?

- e^+e^-->Z_c ππ?

- More Z_c?

Thank you!