Zc decays to open charm states at BESIII

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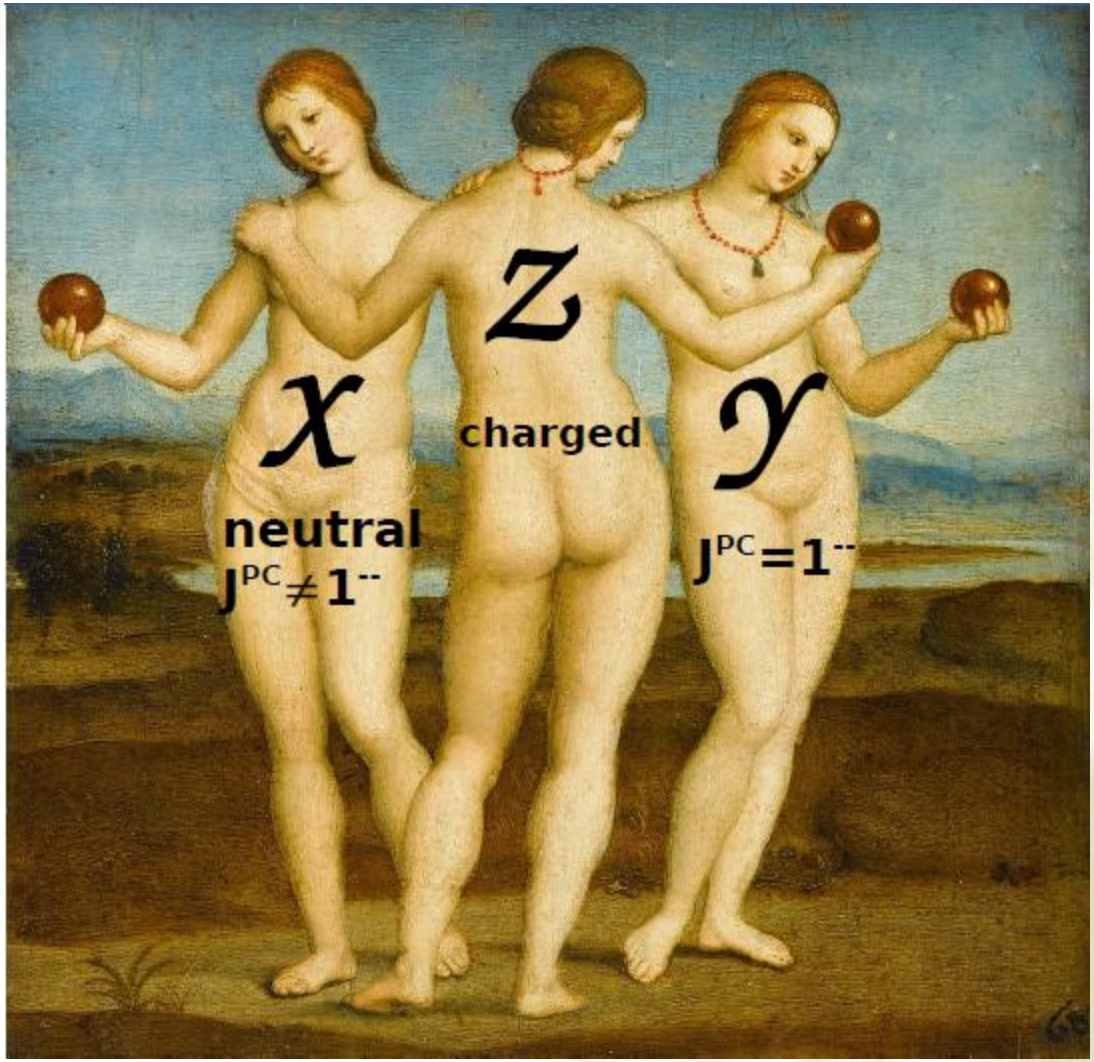
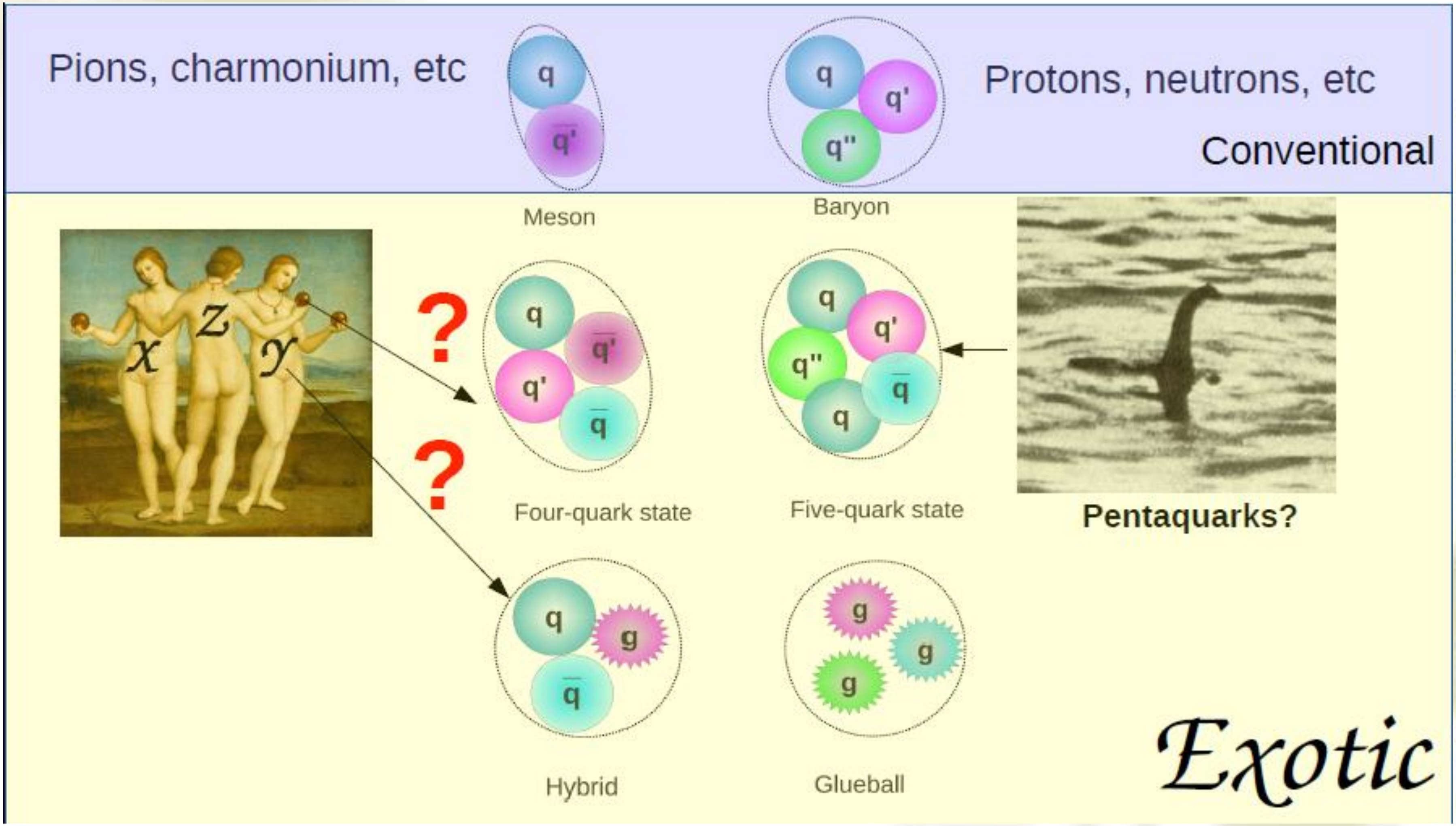
(representing the BESIII collaboration)

Exotic quarkonium-like spectroscopy

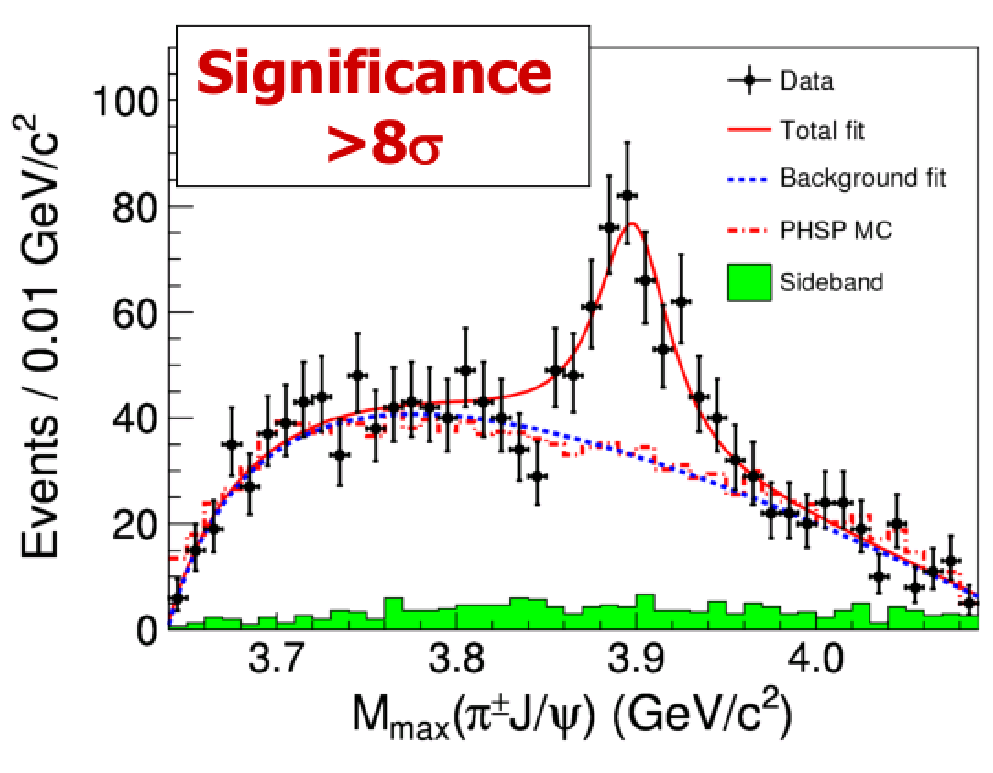


QCD predicted statess



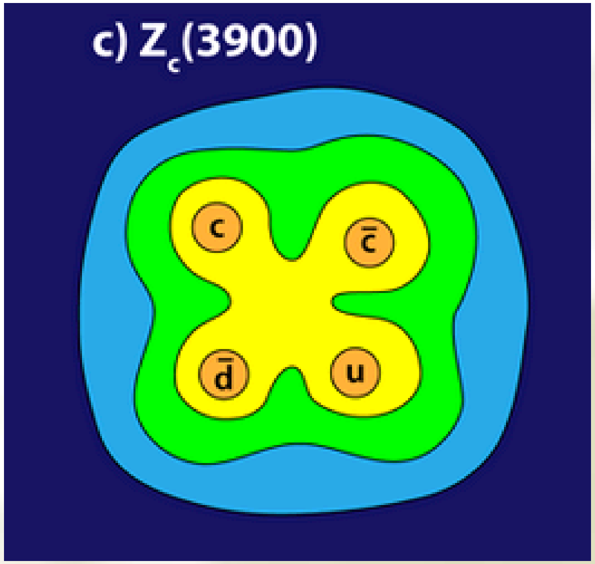
Zc^{+}(3900) discovered at BESIII

Phys. Rev. Lett(2013) 252001



Mass = (3899.0 ± 3.6 ± 4.9) MeV
Width = (46 ± 10 ± 20) MeV

confirmed by BELLE and with CLEO-c data



from APS/Alan Stonebraker

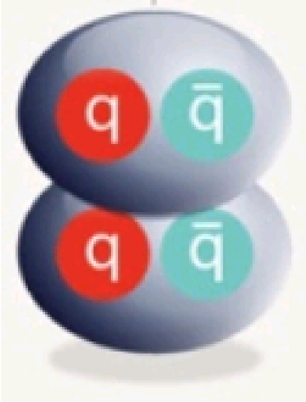
- Couples to $c\bar{c}$
- Has electric charge **1**

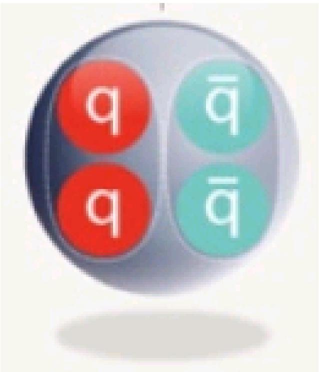
➔ consists of at least four quarks of $c\bar{c}u\bar{d}$

Nature of the exotic Zc$^+$(3900)

- Its mass lies close to the threshold of m(D)+m(D*)

meson molecule? ***tetraquark?***

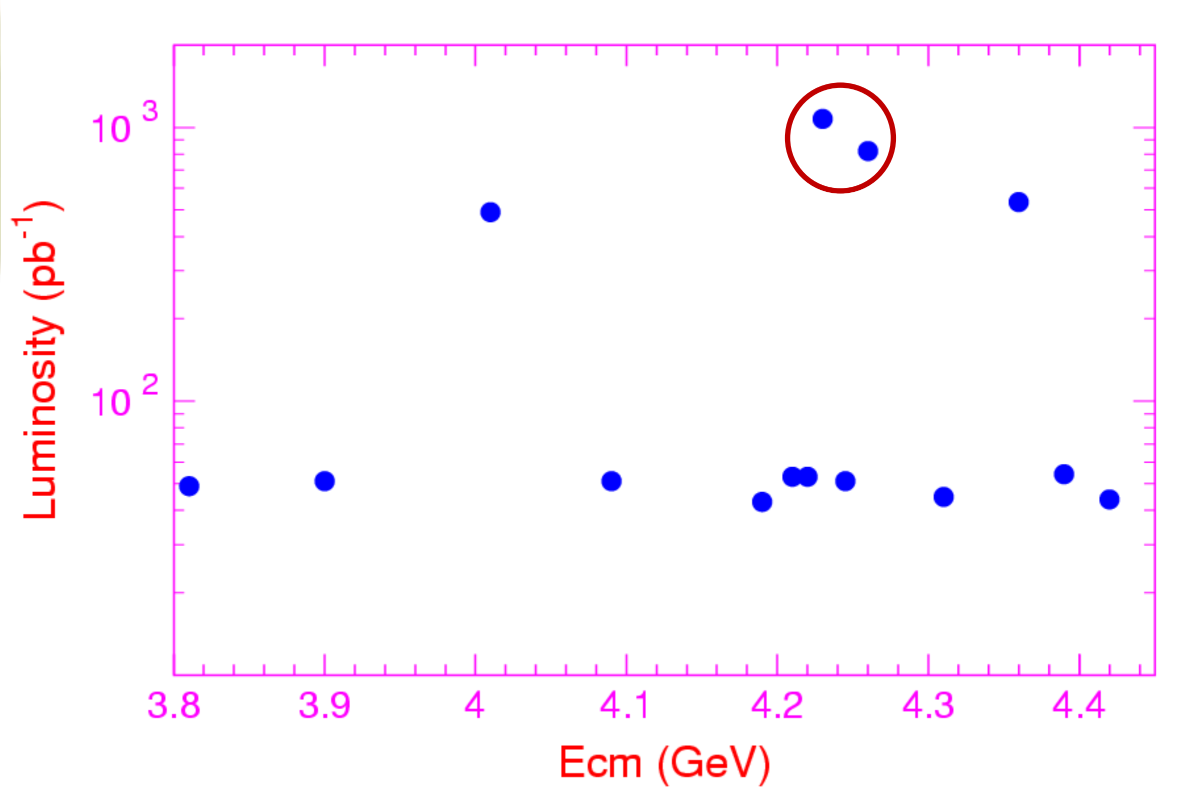




and other scenarios ...

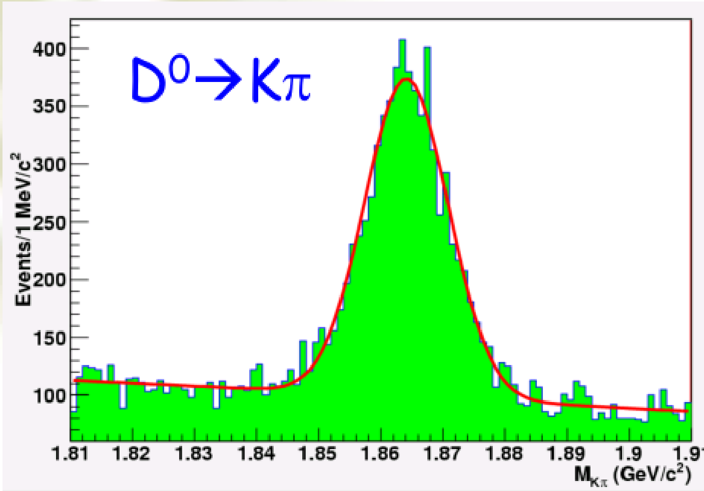
- Is there an excited partner Z'c?
- The Zc's probably decay to (DD*)$^\pm$ and (D*D*)$^\pm$ final states, especially if exists as meson *molecule*

Do search in $e^+e^- \to \pi^\pm(D^{(*)}\bar{D}^*)^\mp$



- ✓ We analyze data @4.23 and 4.26 GeV taken at BESIII
- ✓ Energy point is optimized
  - clean backgrounds of D**
  - larger phase space for the three body final states

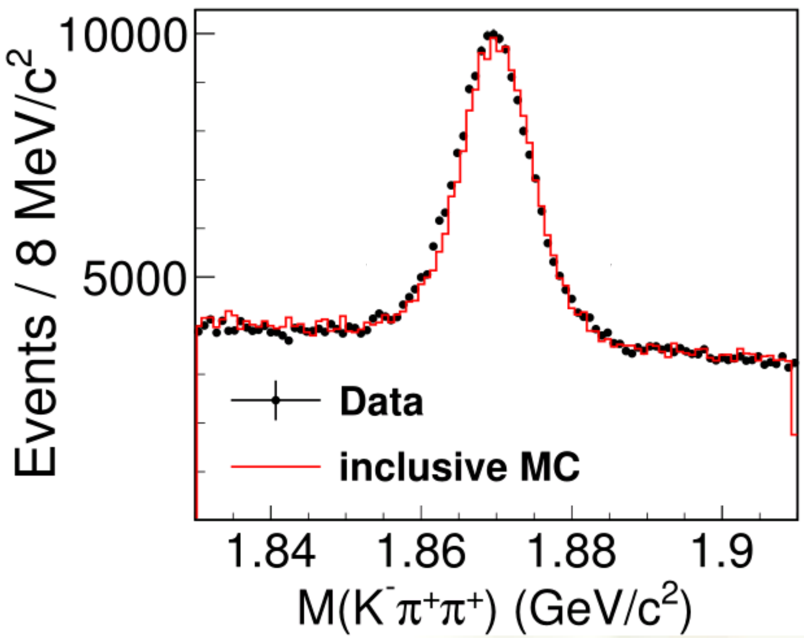
Data quality and MC simulation



$\Delta M_D = 0.5 \pm 0.2$ MeV

$\sigma M_D = 6.0 \pm 0.1$ MeV

$D^+ \to K\pi\pi$



- Detector in good shape
  - Low beam background, low noise, all sub-detectors excellent!
- Improved efficiency of the BESIII software
- Excellent agreement between data and MC simulation
  - well controlled systematic uncertainty

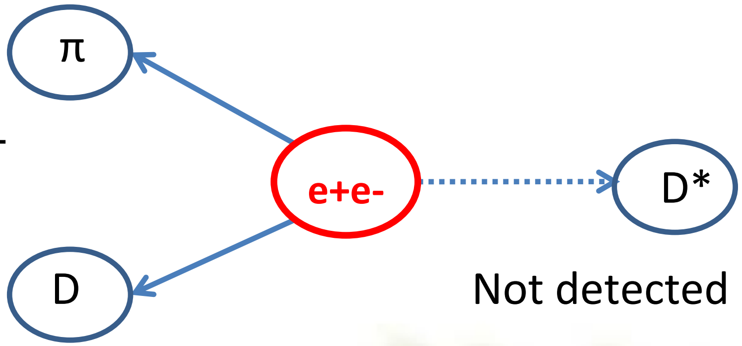
Partial reconstruction of $e^+e^- \to \pi^\pm(D\bar{D}^*)^\mp$

525/pb data @4.26 GeV

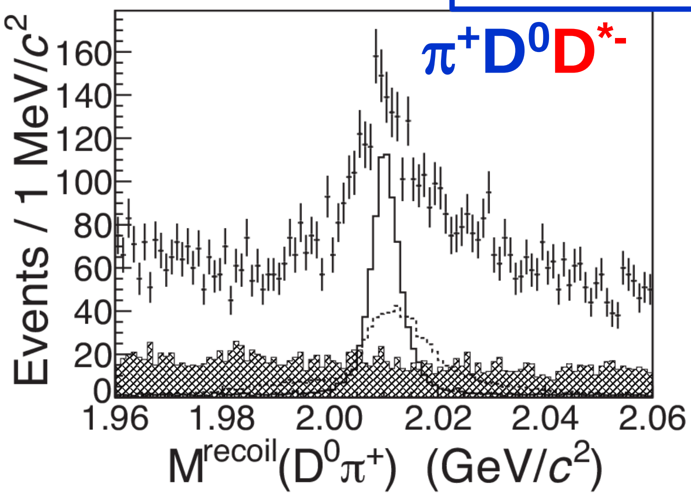
PRL112, 022001 (2014)

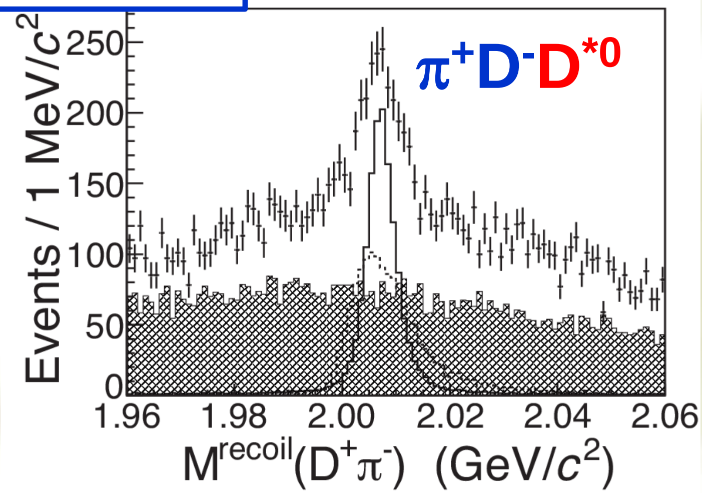
Single D reconstruction :

- reconstruct π^+ and $D^0 \to K^-\pi^+$
- infer D^{*-}
- analyze as well $\pi^+ D^- D^{*0}$



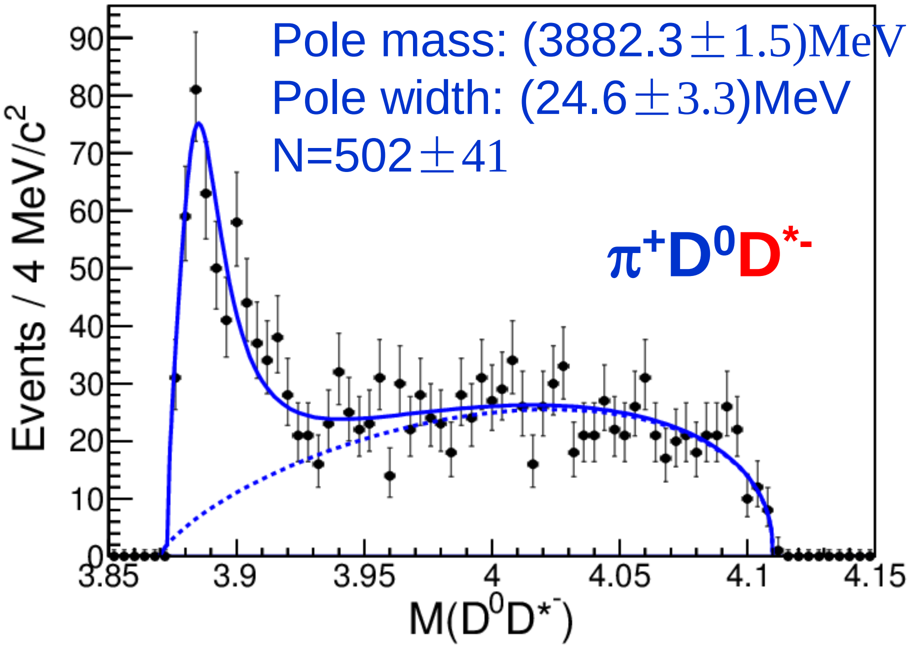
We can see clear signal of D*

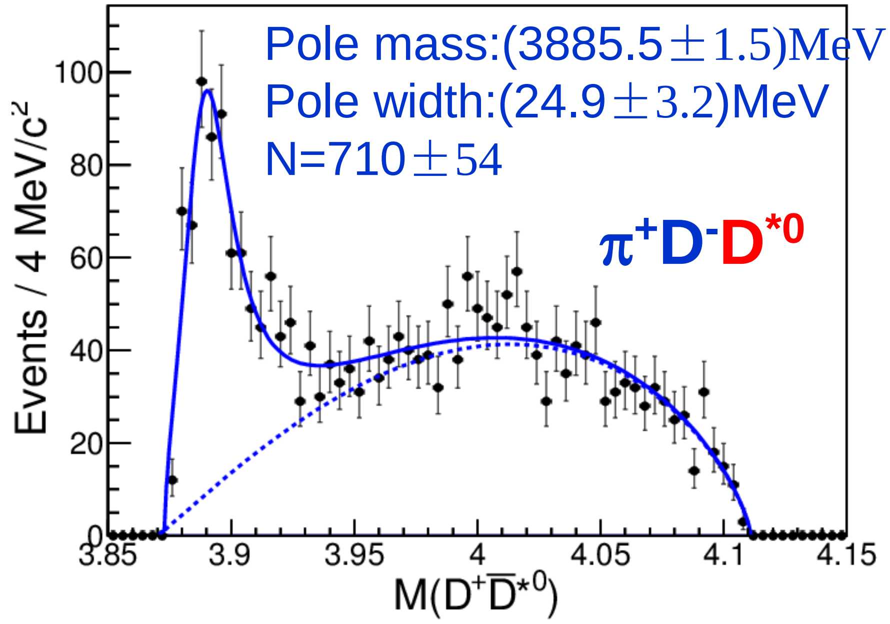




The Zc(3885)$^{\pm}$

PRL112, 022001 (2014)





- Clear bumps are seen in the two isospin modes
- Separated Breit-Wigner fits give consistent resonance properties
- One-resonance hypothesis fit to the combined data set gives:

M = (3883.9±1.5±4.2) MeV/c^2
Γ = (24.8±3.3±11) MeV

The Zc (3885)$^{\pm}$ and Zc(3900)$^{\pm}$

525/pb data @4.26 GeV

	Zc(3885)(MeV)	Zc(3900)(MeV)
Mass	$3883.9\pm1.5\pm4.2$	$3899\pm3.6\pm4.9$
Width	$24.8\pm3.3\pm11.0$	$46\pm10\pm26$
Number of events	502 and 710	307 ± 48
Production cross section	$83.5\pm6.6\pm22$pb	$13.5\pm2.1\pm4.8$pb

The mass and width are consistent within **2σ!**

If this is $Z_c(3900)^+$, open charm decays are suppressed, since

$$\frac{\mathcal{B}(Z_c \to D^* \bar{D})}{\mathcal{B}(Z_c \to J/\psi\,\pi)} = 6.2 \pm 1.1 \pm 2.7$$

Compared to e.g.

$$\frac{\mathcal{B}(\psi(4040) \to D^{(*)}\bar{D}^{(*)})}{\mathcal{B}(\psi(4040) \to J/\psi\,\eta)} = 192 \pm 27$$

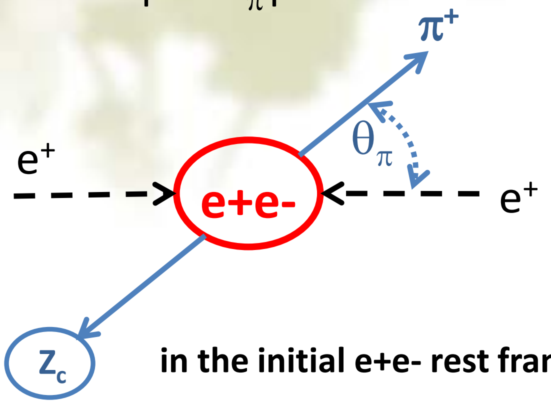
➡ Different dynamics in Y(4260)-Zc(3900) system!

Probe the J^P properties of the Zc(3885)

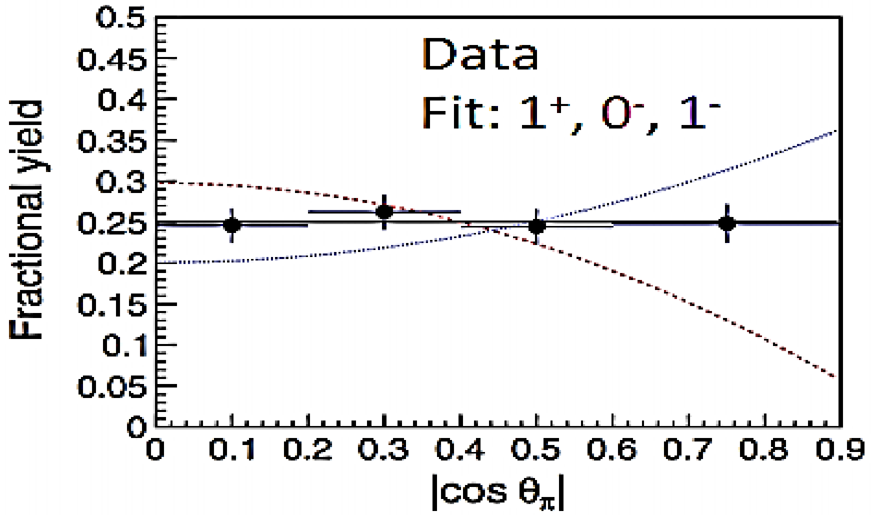
Angular distributions

-consider only lowest partial waves-

$|\cos\theta_\pi|$



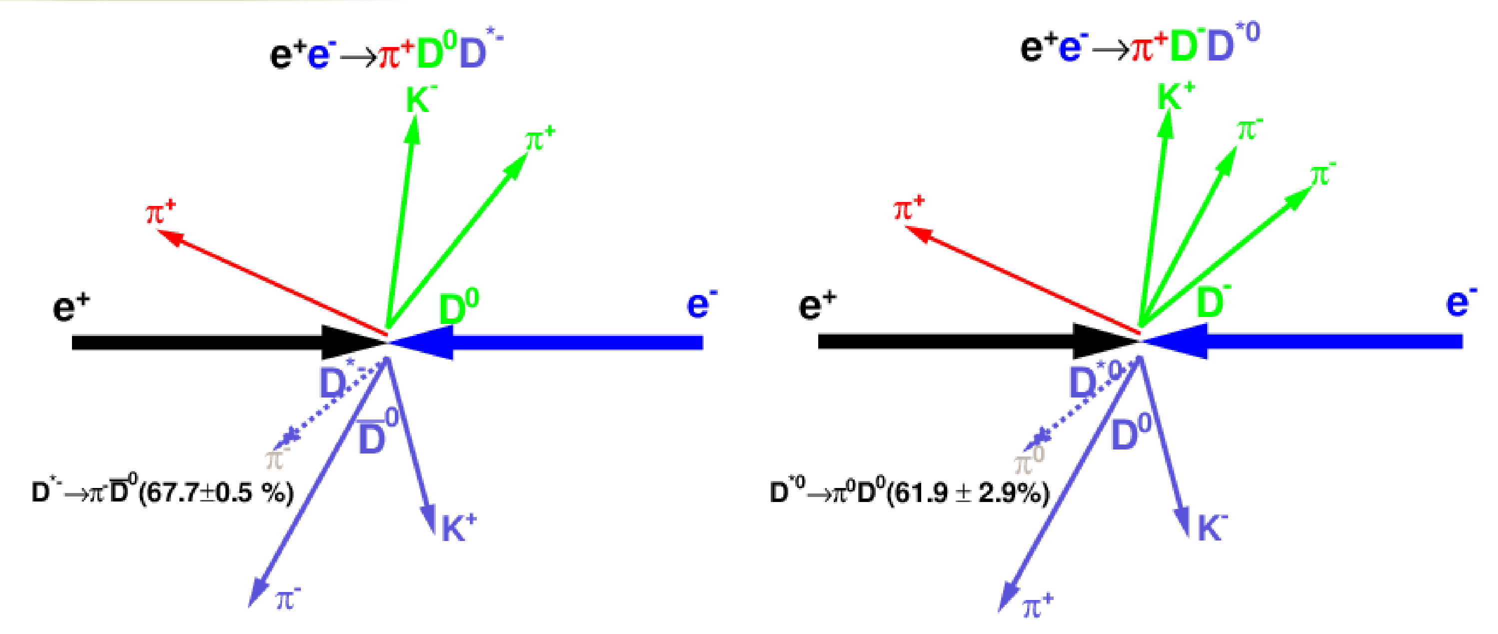
in the initial e+e- rest frame



Fit to angular distribution favors $J^P = 1^+$ over 0^- and 1^-

J^P	L	$dN/d\|\cos\theta_\pi\|$
1^+	S-wave	flat
0^-	P-wave	$\sin^2\theta_\pi$
1^-	P-wave	$1+\cos^2\theta_\pi$

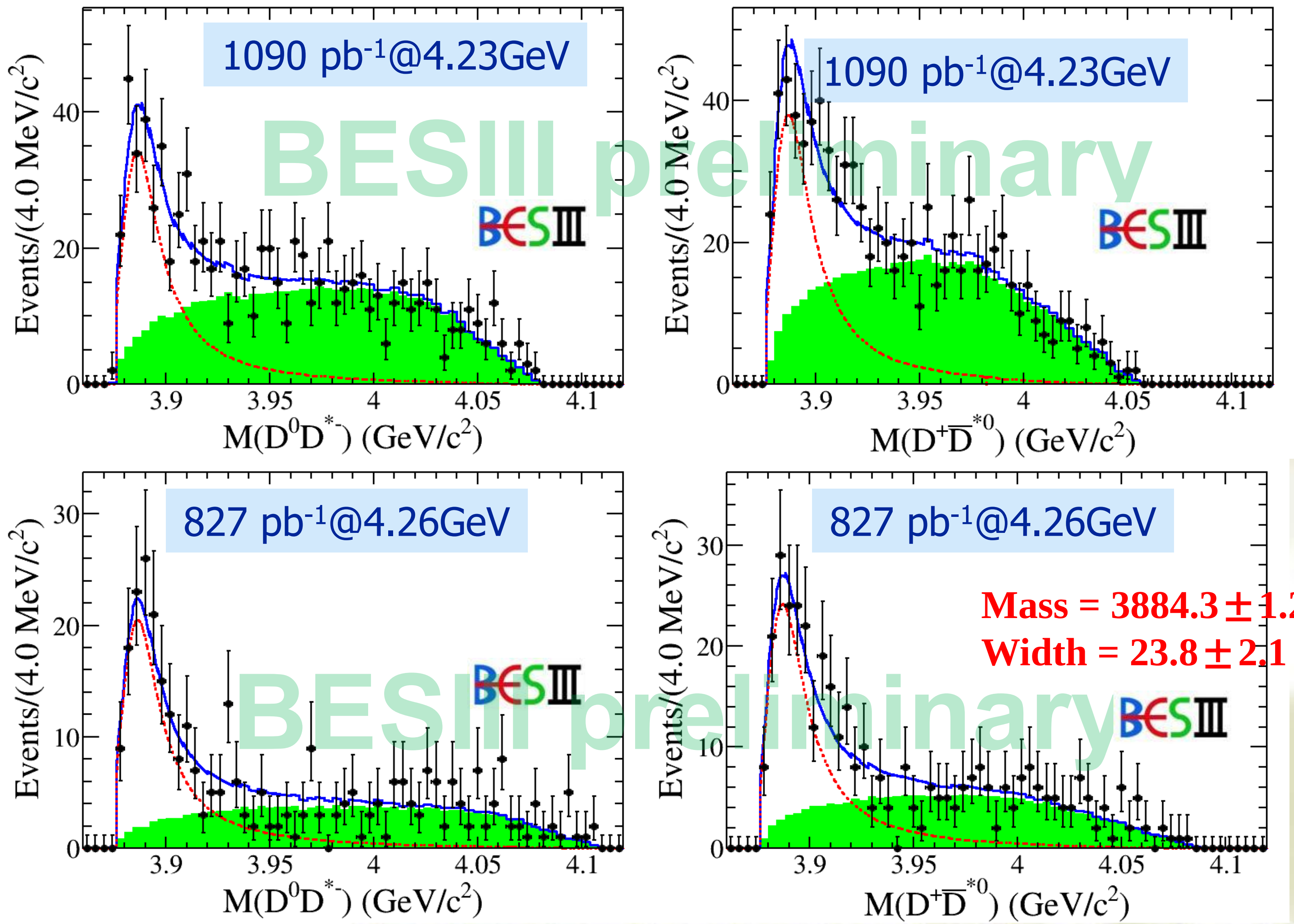
Confirmation of $Z_c(3885)^{\pm}$ in $e^+e^- \to \pi^{\pm}(D\bar{D}^*)^{\mp}$ using double D tag method



- "Double D tags" or DT: reconstruct the bachelor π and the $D\bar{D}$ pair;
- Combined study of $e^+e^- \to \pi^+ D^0 D^{*-}$ and $e^+e^- \to \pi^+ D^- D^{*0}$;
- Using data samples of **1090 pb^{-1}** at 4.23GeV and **827 pb^{-1}** at 4.26GeV;

Simultaneous fit

$e^+e^- \to \pi^+ D^0 D^{*-}$ $\qquad$ $e^+e^- \to \pi^+ D^- D^{*0}$

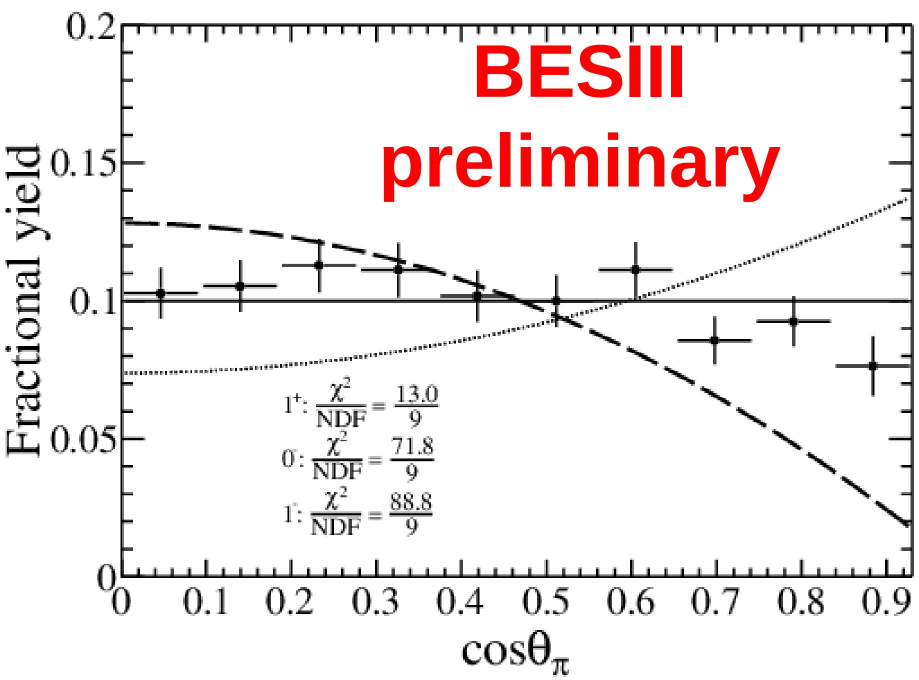


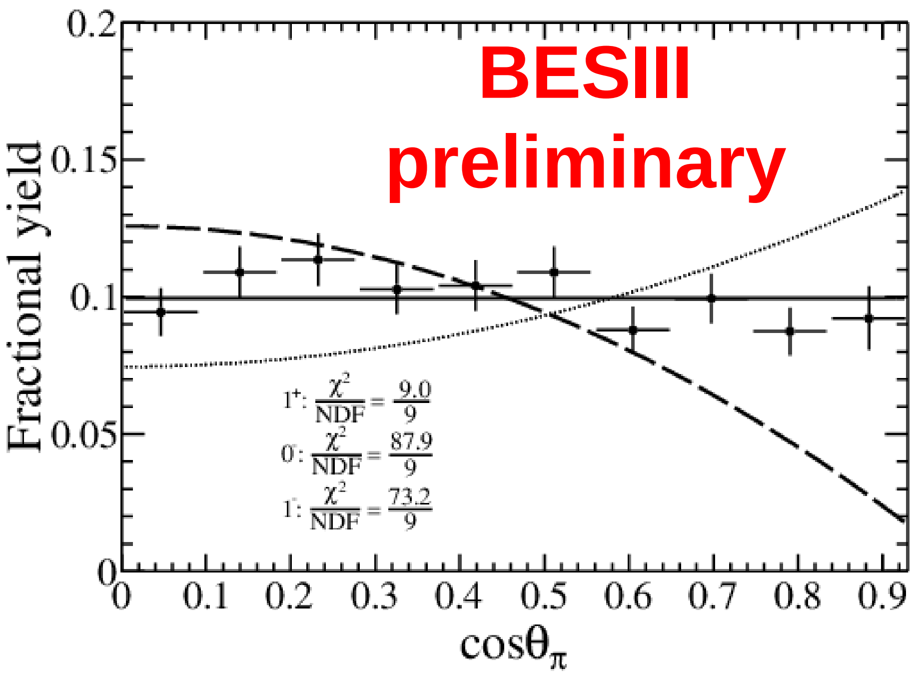
Mass = 3884.3 ± 1.2 ± 1.5 MeV,
Width = 23.8 ± 2.1 ± 2.6 MeV

double D tag method

Angular Distribution

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





- Dots with error bars: Combined data at $\sqrt{s}$=4.23GeV and at $\sqrt{s}$=4.26GeV;
- Solid Lines: Fits to the data using $J^P = 1^+$;
- Dashed curves: Fits to the data using $J^P = 0^-$;
- Dotted curves: Fits to the data using $J^P = 1^-$;
- **The data agrees well with $J^P = 1^+$ and disagrees with $J^P = 0^-/1^-$.**

agree with the JP hypothesis test based on single D tag method!

Results form single & double *D* reconstruction

	Double D tags (pre. rel.)	BESIII: Single D tags PRL 112, 022001 (2014)
M_{pole} (MeV/c^2)	$3884.3 \pm 1.2 \pm 1.5$	$3883.9 \pm 1.5 \pm 4.2$
Γ_{pole} (MeV)	$23.8 \pm 2.1 \pm 2.6$	$24.8 \pm 3.3 \pm 11.0$
$\sigma(e^+e^- \to \pi^\pm Z_c(3885)^\mp)$ $\times B\left(Z_c(3885)^\mp \to (D\bar{D}^*)^\mp\right)$ (pb)	$88.0 \pm 6.1 \pm 7.9$ @4.26GeV $106.8 \pm 7.1 \pm 9.5$ @4.23GeV	$83.5 \pm 6.6 \pm 22.0$@4.26GeV

- ✓ Double tag method provides more precise measurement
  - low backgrounds
  - larger data set
  - signal yields: ~400 in $\pi^+D^0D^{*-}$ and ~600 in $\pi^+D^-D^{*0}$
- ✓ Single tag method in full data set @4.23 and 4.26 GeV
  - signal yields: ~1800 in $\pi^+D^0D^{*-}$ and ~2500 in $\pi^+D^-D^{*0}$

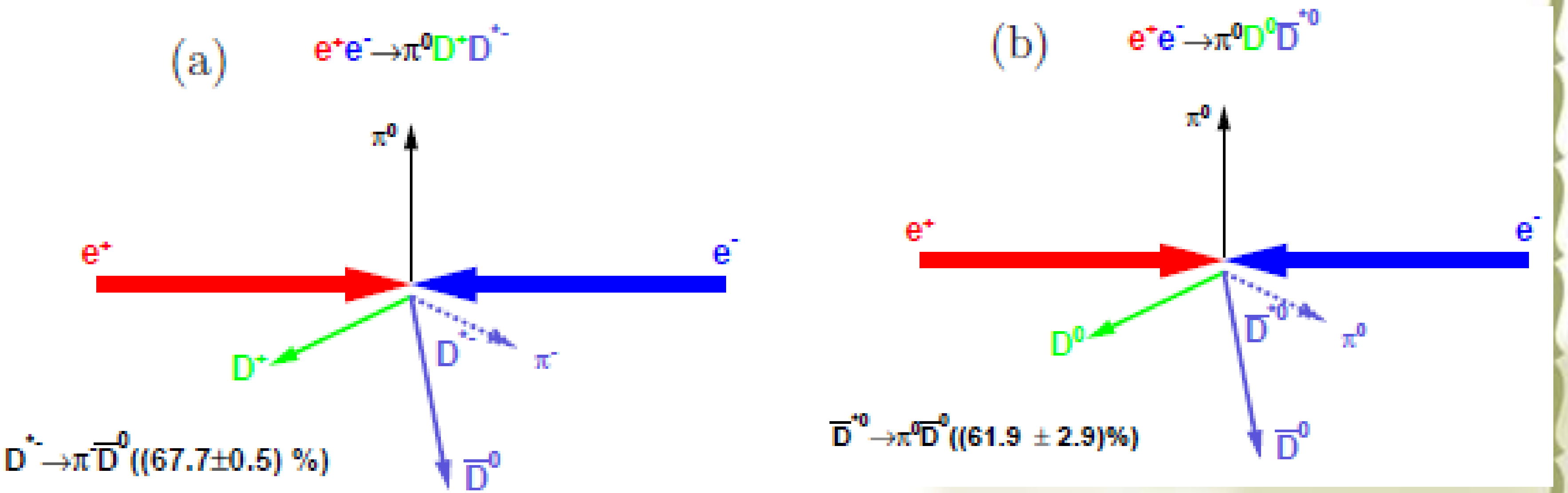
Search for $Z_c(3885)^0$ in $e^+e^- \to \pi^0(D\bar{D}^*)^0$

Compared to the charged mode, backgrounds are high due to π^0 detection

Double D tag method is required:

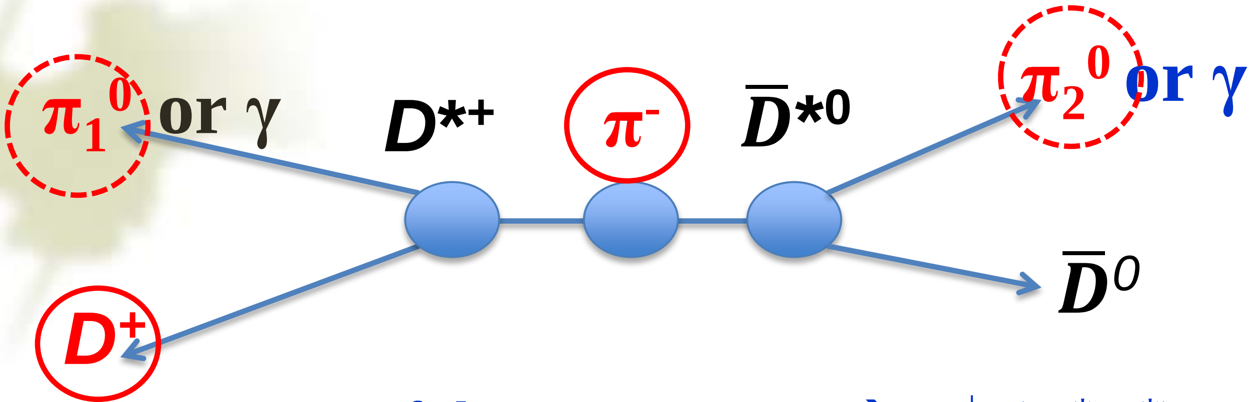
➔ Low signal efficiency: one thirds of the charged mode

- Combine the two isospin channels in one analysis



analysis is ongoing

Reconstruction of $e^+e^- \to \pi^\pm(D^*\bar{D}^*)^\mp$



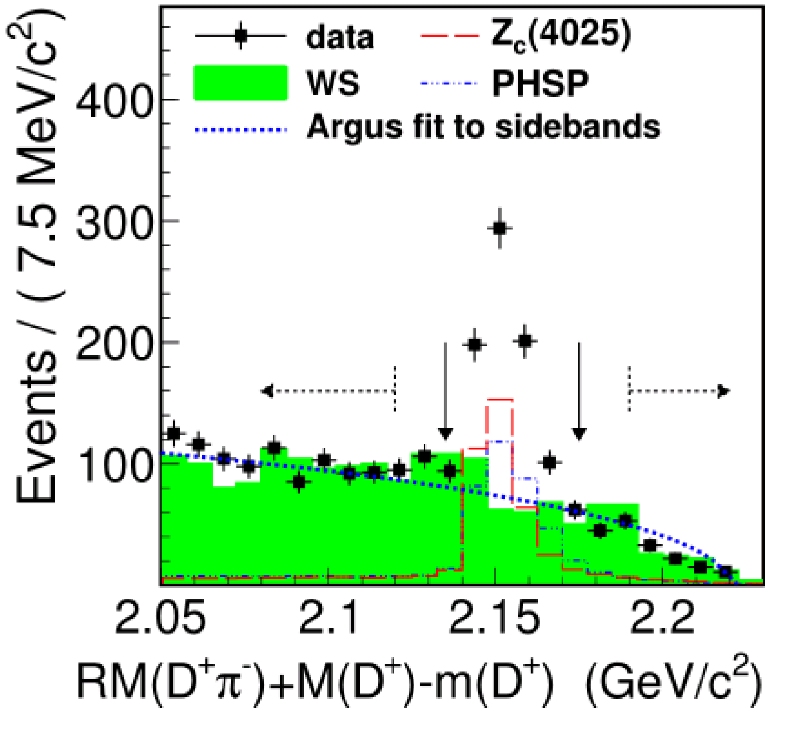
- Partial reconstruction of the process $e^+e^- \to \pi^\pm (D^*D^*)$
  - tag a D^+ meson in an event
  - find an additional charged π^-
  - reject backgrounds from $e^+e^- \to D^{(*)}D^{(*)}$
  - use signature in the recoil mass spectrum of $D^+ \pi^-$ to identify the process of $e^+e^- \to \pi^- D^{*+}\underline{D}^{*0}$
  - to improve the significance, at least one of the π_1^0/π_2^0 is detected
  - study the mass spectrum of recoil π^-

PRL 112, 132001 (2014)

To select signals of $D^{*+}D^{*0}\pi^-$

PRL 112, 132001 (2014)

- $\pi^{\pm}(D^*\bar{D}^*)^{\mp}$ peaks ~2.15GeV in the $D^+\pi^-$ recoil mass spectrum
- a data-driven method to understand combinatorial backgrounds:
  shape is well reproduced by the WS shape



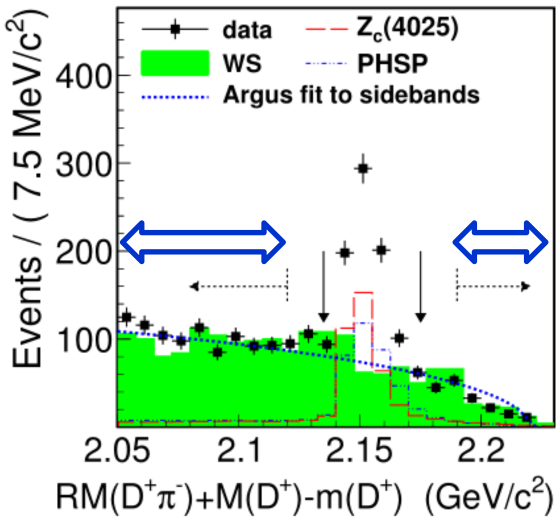
wrong-sign (WS) events

- to conserve charge and charm number, *D^+ only associates with bachelor π^-*
- we assign a π^+ with *D^+* to form WS events

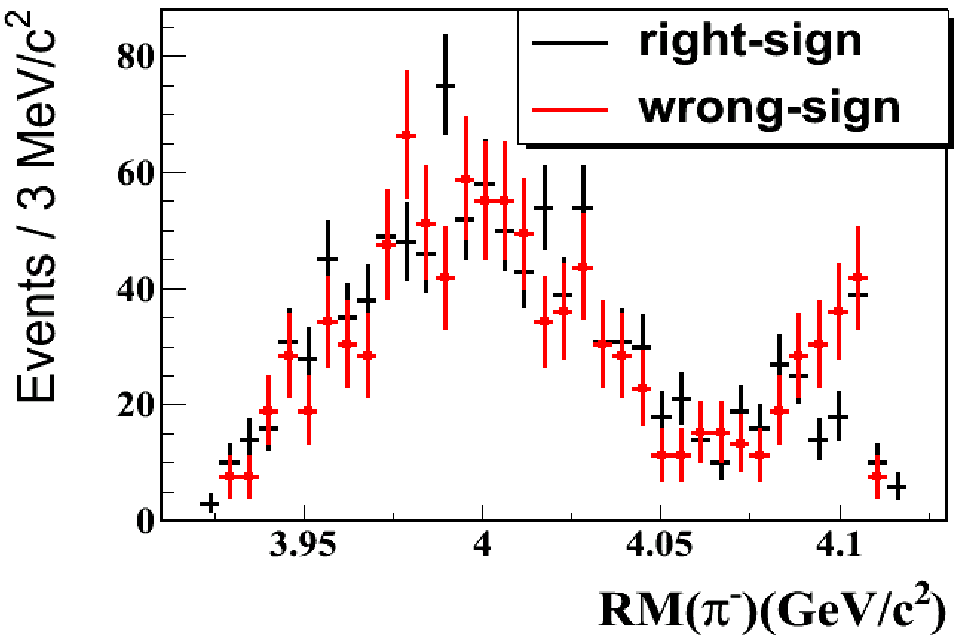
- very evident peak
- signal to background ratio is optimized

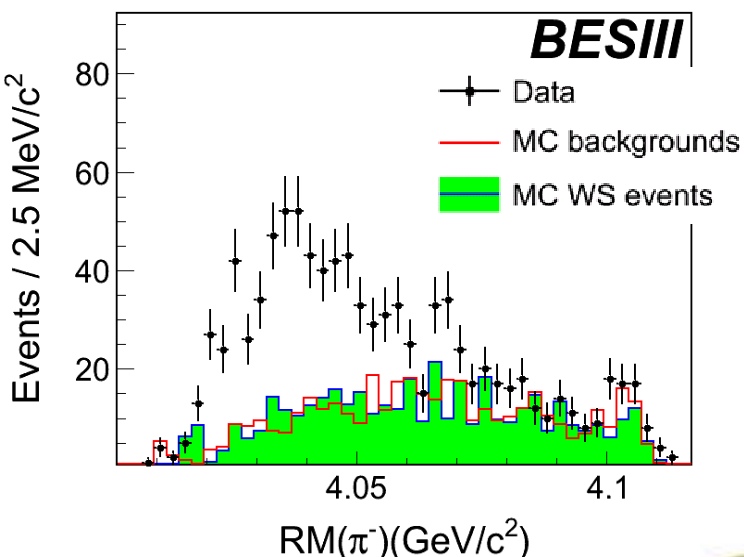
WS shape to describe the backgrounds

PRL 112, 132001 (2014)



use control sample of the sidebands in RM($D^+\pi^-$) spectrum





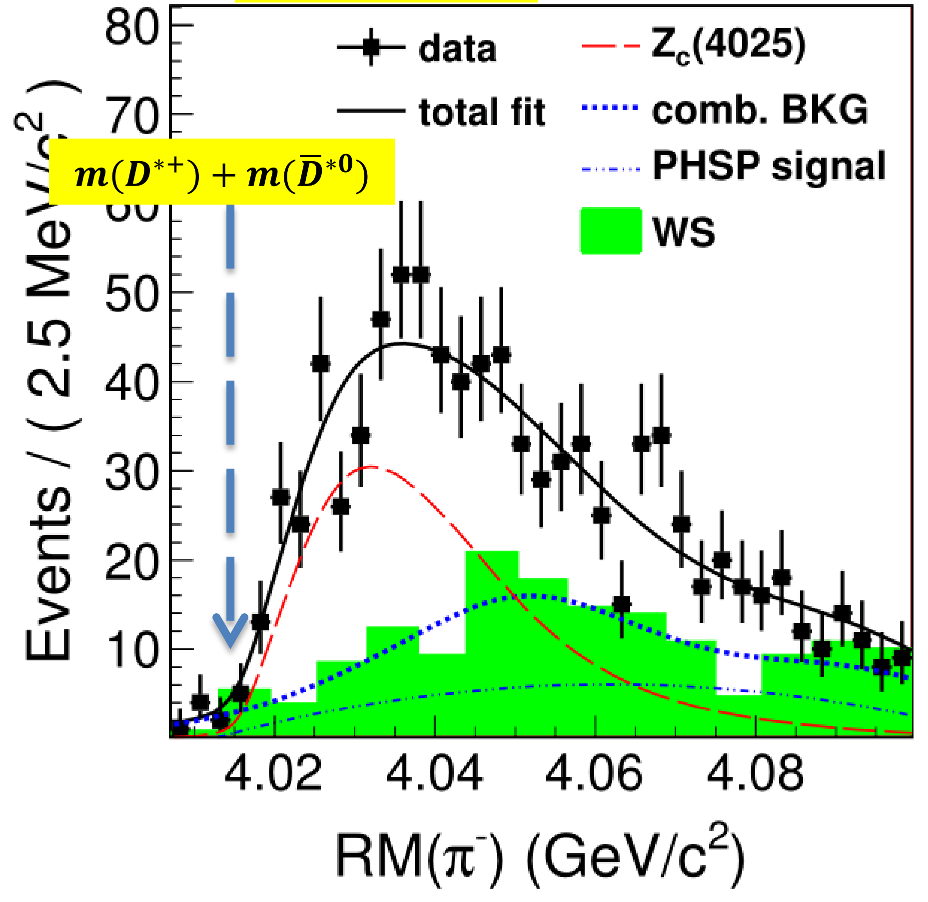
YES!

Both control sample of *RM($D^+\pi^-$)* sidebands and MC simulation demonstrate.

Measurement of the enhancement

yields~400

PRL 112, 132001 (2014)



assume it as a particle, Zc(4025), and fit to the π^- recoil mass distribution

- ✓ **Zc(4025) signal**: S-wave relativistic Breit-Wigner function with phase-space factor
- ✓ **three-body process (PHSP)**
- ✓ **combinatorial backgrounds**: the **WS** shape

resonance parameter:

$$m(Z_c(4025)) = 4026.3 \pm 2.6 \pm 3.7\,\mathrm{MeV}/c^2,$$
$$\Gamma(Z_c(4025)) = 24.8 \pm 5.6 \pm 7.7\,\mathrm{MeV}.$$

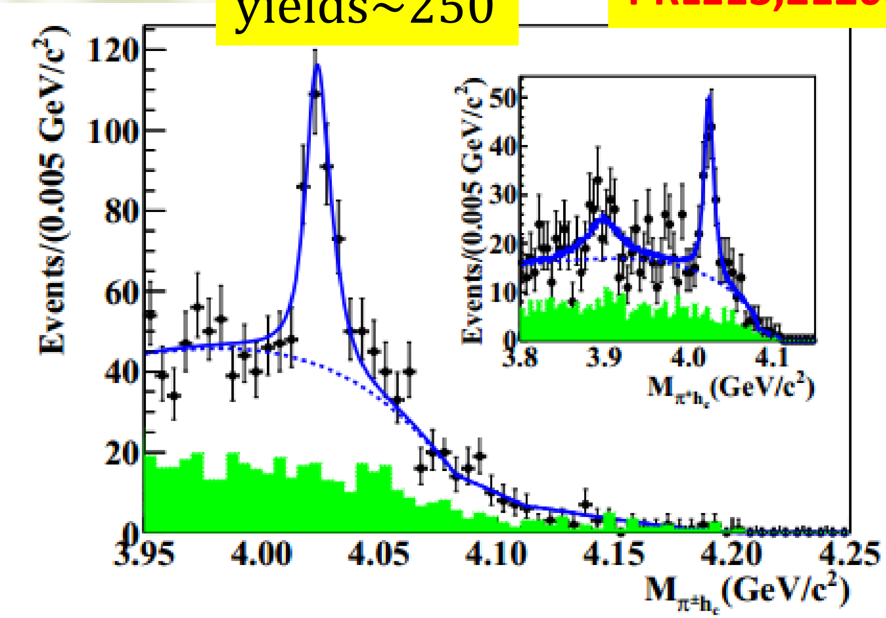
significance is > 10σ
χ^2/ndf= 30.4/33 = 0.92

The Zc(4020) and Zc(4025)

Observed $Z^+c(4020)$

yields~250

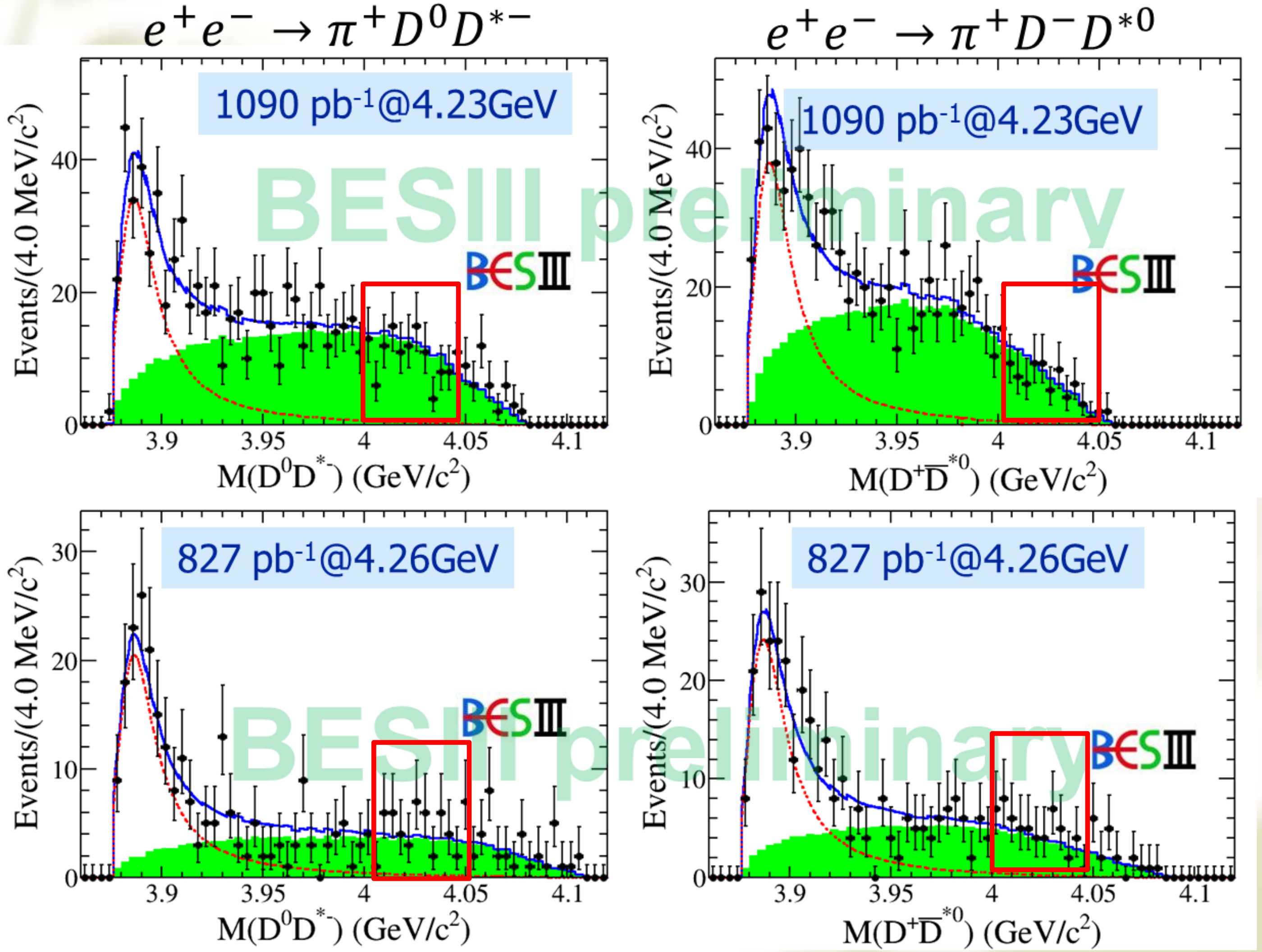
PRL113,212002 (2014)



Coupling to $\bar{D}^*D^*$ is much larger than to πh_c if $Z_c(4025)$ and $Z_c(4020)$ are the same state.

	$Z^+c(4025)$	$Z^+c(4020)$
Mass (MeV)	4026.3±2.6±3.7	4022.9±0.8±2.7
Width (MeV)	24.8±5.6±7.7	7.9±2.7±2.6
$\frac{Br(Z_c'^+ \to D^{*+}\bar{D}^{*0})}{Br(Z_c'^+ \to \pi^+ h_c)} \sim 12$		

Zc(4025) in mass spectra of $(D\bar{D}^*)^\pm$



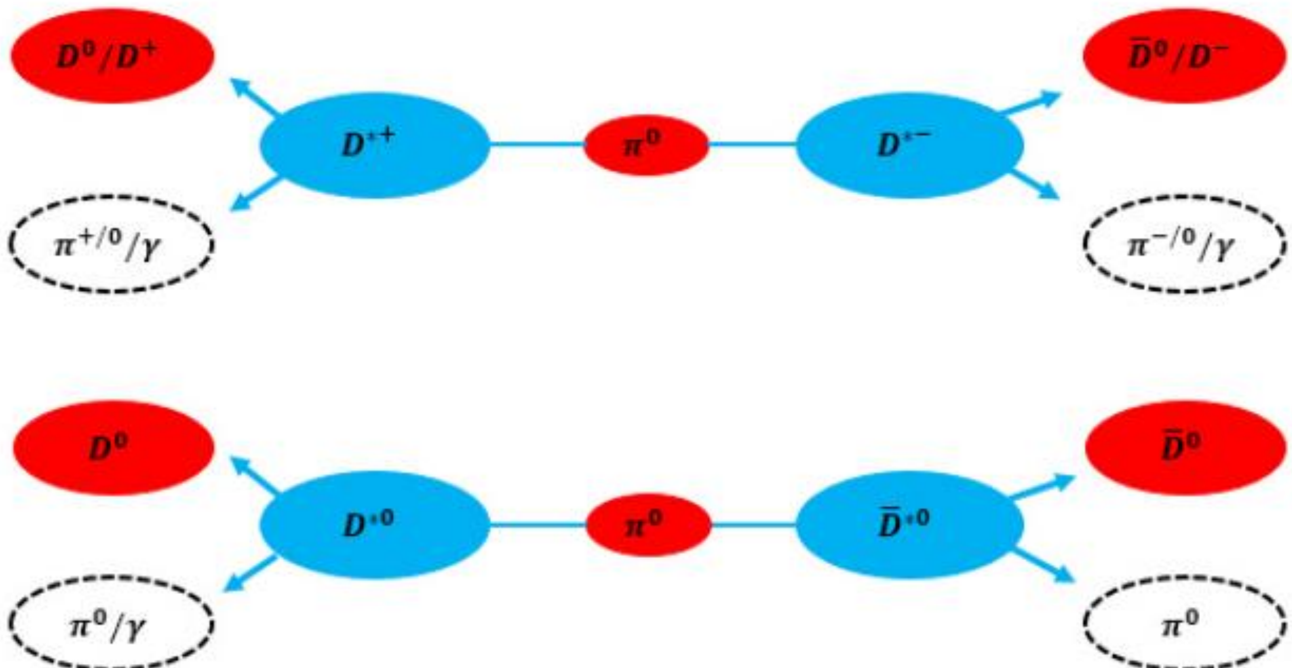
No signal of around 4025MeV?

Search for $Z_c(4025)^0$ in $e^+e^- \to \pi^0(D^*\bar{D}^*)^0$

Again, double D tag method is required:

➔ Low signal efficiency: one thirds of the charged mode

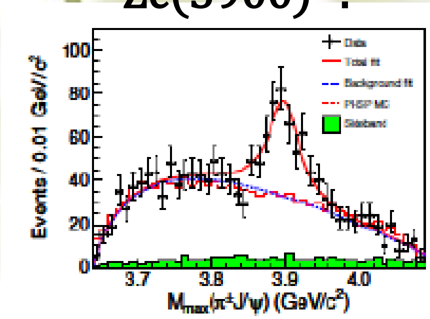
- Combine the two isospin channels in one analysis



analysis is ongoing

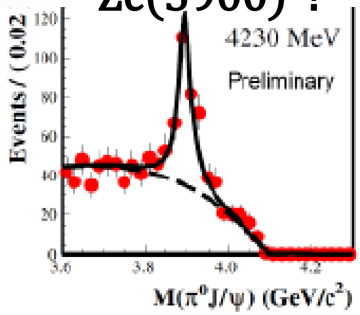
The Zc family at BESIII

Zc(3900)$^+$?



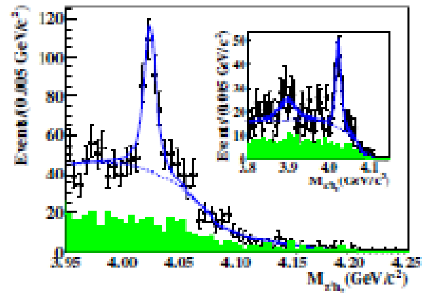
$e^+e^- \to \pi^-\pi^+J/\psi$

Zc(3900)^0?



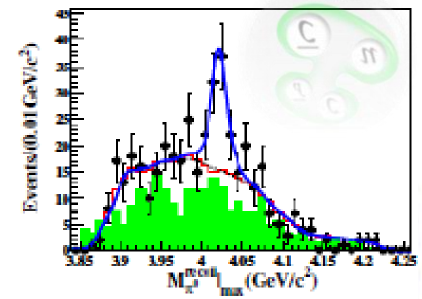
$e^+e^- \to \pi^0\pi^0J/\psi$

Zc(4020)$^+$?



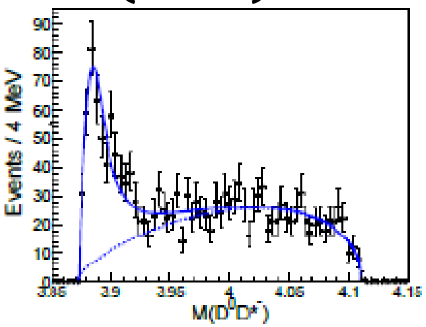
$e^+e^- \to \pi^-\pi^+h_c$

Zc(4020)^0?



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

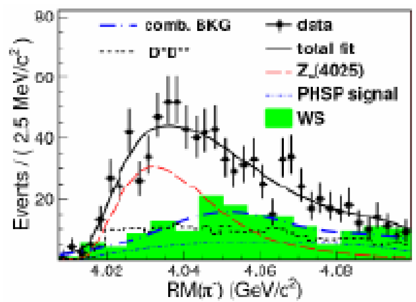
Zc(3885)$^+$?



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

Zc(3885)^0?

Zc(4025)$^+$?

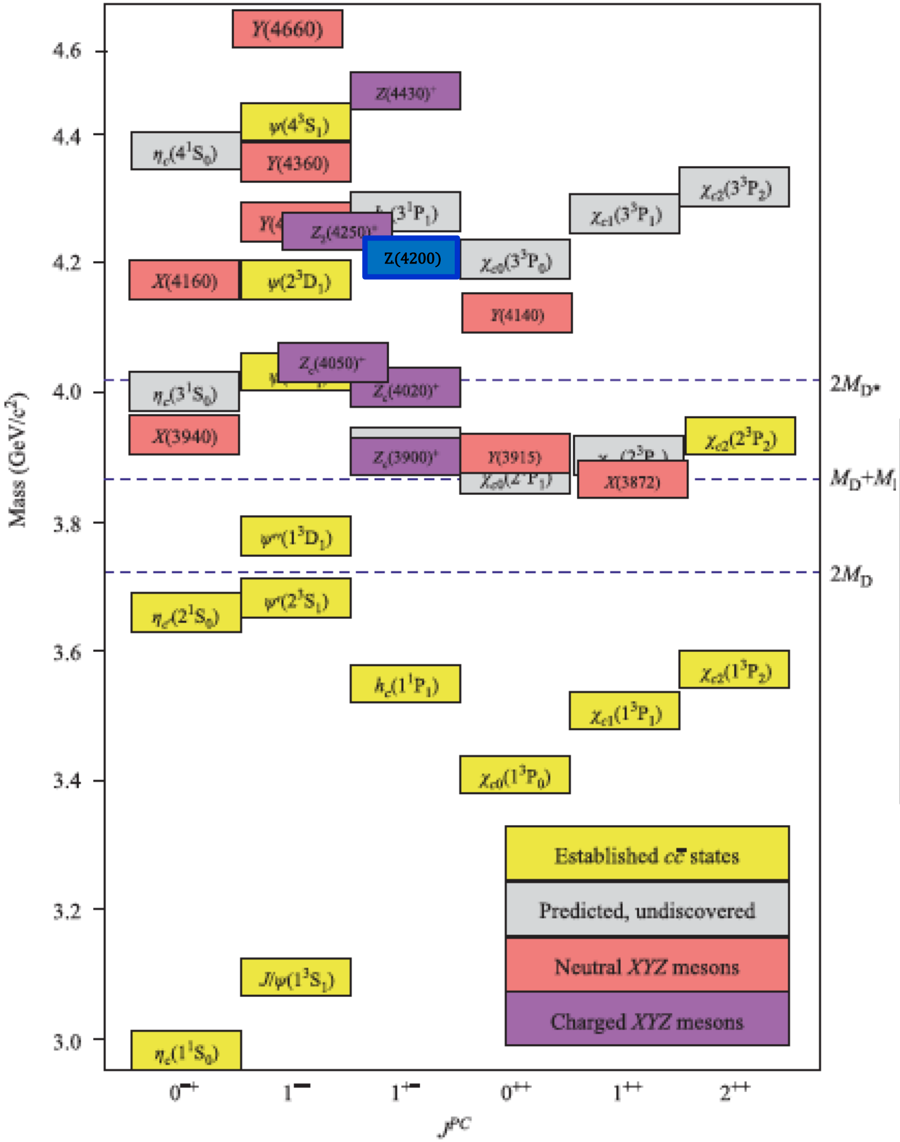


$e^+e^- \to \pi^-(D^*\bar{D}^*)^+$

Zc(4025)^0?

Which is the nature of these states? Isospin triplets?
Different decay channels of the same observed states? Other decay modes?

Reported charged charmonium-like states



Confirmed stats

State	Decay modes	Seen by	
$Z_c(3900)^{\pm,0}$	$\pi^{\mp}J/\psi$, $(D^*\overline{D})^{\mp}$	BESIII, Belle CLEO	in $e^+e^- \to \pi^- Zc$
$Z_c(4020)^{\pm,0}$	$\pi^{\mp}h_c$, $(D^*\overline{D^*})^{\mp}$	BESIII	in $e^+e^- \to \pi^- Zc$
$Z_c(4430)^{\pm}$	$\pi^{\mp}\psi(2S)$ $\pi^{\pm}J/\psi$	Belle, ~~BaBar,~~ LHCb	in $B \to KZc$

Future steps to understand these new findings?

at BESIII

- Search for isospin partners for the charged Zc states
  - **Zc(3885)^0→** $(D^0\underline{D}^{*0} + D^+D^{*-})$
  - **Zc(4025)^0→** $(D^{*0}\underline{D}^{*0} + D^{*+}D^{*-})$
- Search for more decay modes : $\pi\psi'$, $D^{(*)}D^{**}$, light hadrons ...
- PWA of the found charged Zc states: signal statistics is desired.
- Coupled channel analysis if we want to identify the same state
  - e.g., **Zc → $\pi J/\psi$, DD***; **Z'c → πh_c, D*D***

at other experiments

- It will provide very valuable knowledge if we do searches in *B* decays

PWA of the open charm decay modes

data @4.23&4.26GeV

- In current statistics of data set, we detect part of the final states πDD^* and πD^*D^* and leave the soft π/γ in D^* decays unreconstructed.
  - This strategy brings in relatively much combinatoric backgrounds
- Background understanding is crucial, as backgrounds are not trivial
  - Data driven method is required, since MC simulations of these backgrounds are not reliable above 4 GeV region
  - Wrong sign technique only works for single D reconstruction
    ➔ high backgrounds
- The soft π^0 from D^* decays need to be detected in **πDD^*** and **πD^*D^*** modes
  - Decrease the signal efficiencies : signals will be ~1k; but high bkg.
- Complexity in constructing amplitudes:
  - Need to involve the kinematic distributions in D^* decay final states
    πDD^* : 4 body final states **πD^*D^*:** 5 body final states
    multiple combinations of intermediate resonances.

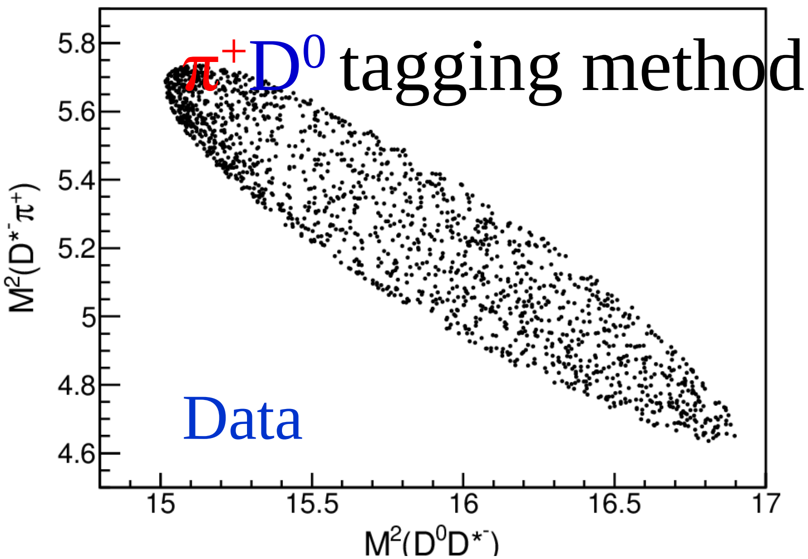
Summary

- We observed two charged charmonium-like resonant structures, Zc(3885) and Zc(4025), in open charm final states DD* and D*D*, respectively.
- More efforts are needed to identify the truth of these new findings
- Still unknown issues:
  - ✓ Establish the isospin partners between the observed charged and netural Zc states
  - ✓ Are the states same? Zc(3900) and Zc(3885), Zc(4020) and Zc(4025);
    ➔ Coupled channel analysis
  - ✓ PWA: challenging
  - ✓ These Zc states in B and LHCb factories? Important!

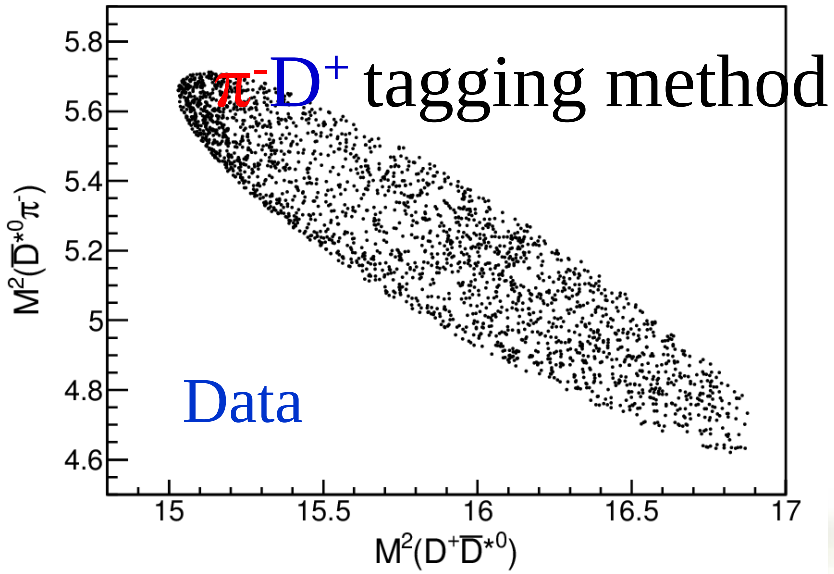
Thanks!
谢 谢！

Especially to the staff of BEPCII and the computing center, the funding agencies, and all the friends of BES!

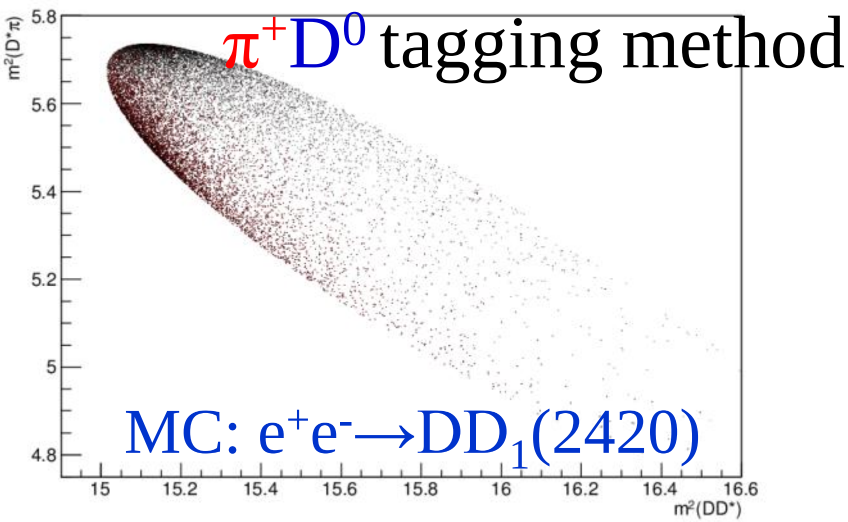
Dalitz Plot



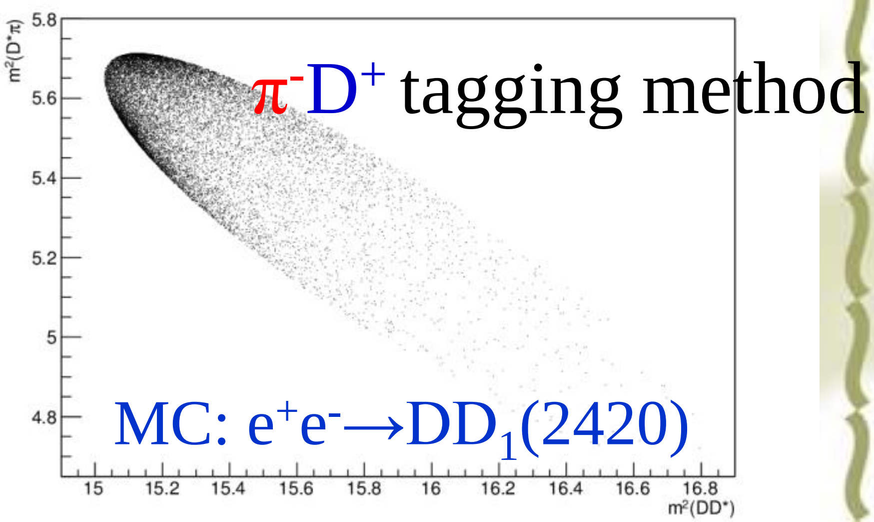
π^+D^0 tagging method
Data
$M^2(D^{*-}\pi^+)$
$M^2(D^0D^{*-})$



π^-D^+ tagging method
Data
$M^2(\bar{D}^{*0}\pi^-)$
$M^2(D^+\bar{D}^{*0})$



π^+D^0 tagging method
MC: $e^+e^-\to DD_1(2420)$
$m^2(D^*\pi)$
$m^2(DD^*)$

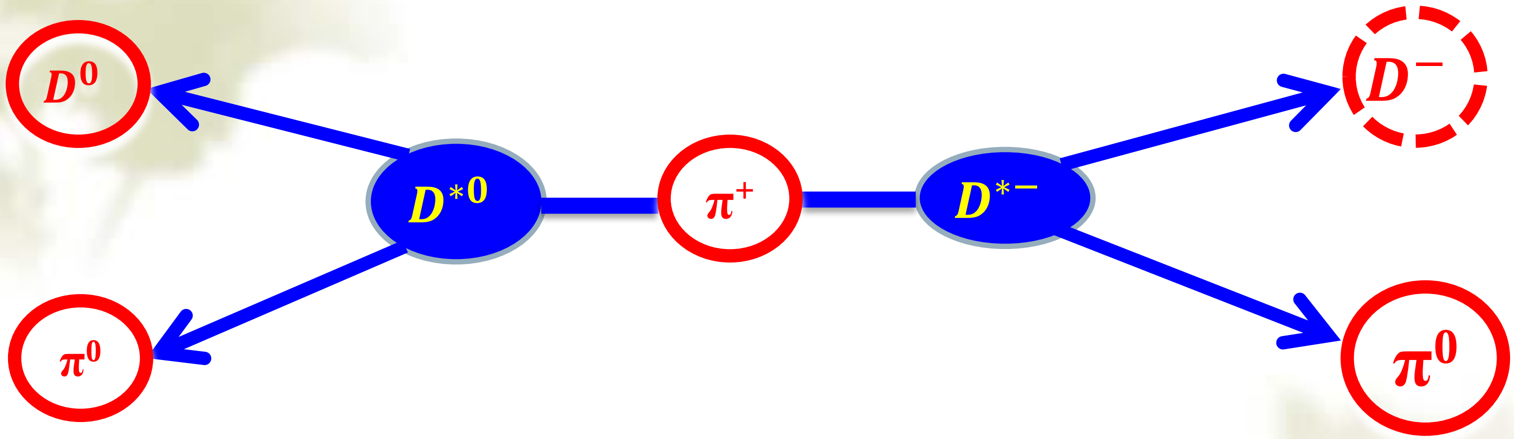


π^-D^+ tagging method
MC: $e^+e^-\to DD_1(2420)$
$m^2(D^*\pi)$
$m^2(DD^*)$

Highly excited D states

	Mass(MeV)	Width(MeV)
$D_0^*(2400)^0$	2318 ± 29	267 ± 40
$D_0^*(2400)^\pm$	2403 ± 40	283 ± 40
$D_1^*(2420)^0$	2421 ± 0.6	27.4 ± 2.5
$D_1^*(2420)^\pm$	2423.2 ± 2.4	25 ± 6
$D_1^*(2430)^0$	2427 ± 40	384^{+130}_{-110}
$D_2^*(2460)^0$	2462 ± 0.6	49.0 ± 1.3
$D_2^*(2460)^\pm$	2464.3 ± 1.6	37 ± 6
$D\,(2550)^0$	2539 ± 8	130 ± 18
$D\,(2600)$	2612 ± 6	93 ± 14
$D^*(2640)^\pm$	2637 ± 6	< 15

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



The Zc(4430)

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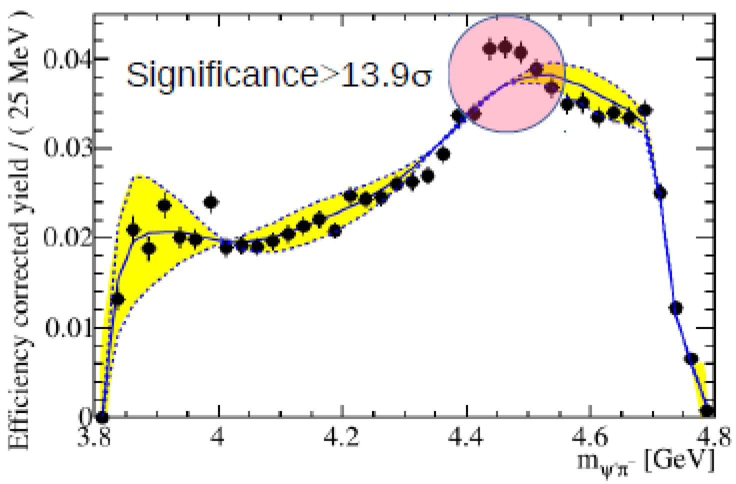
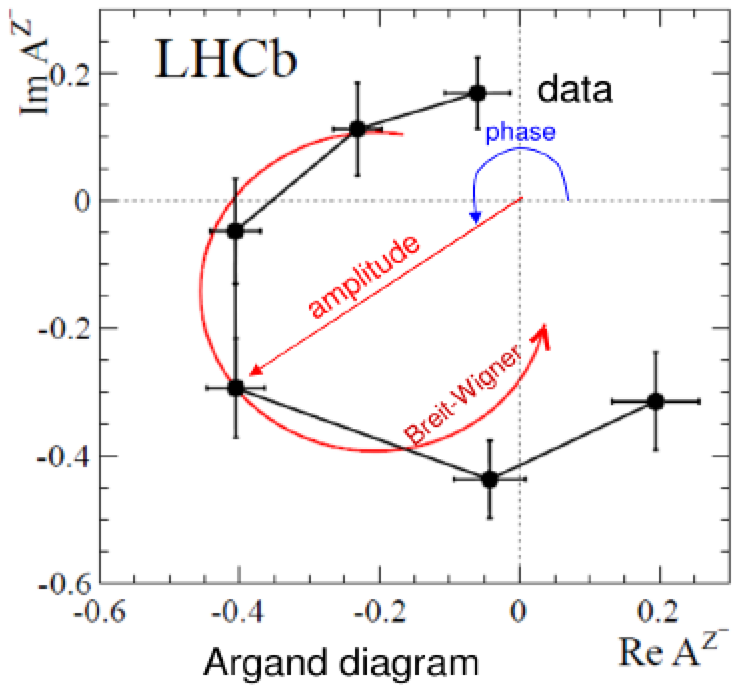
In $B^0 \rightarrow K^+\pi^-\psi(2S)$





Argand diagram

$M = 4475 \pm 7^{+15}_{-25}$ MeV/c^2

$\Gamma = 172 \pm 13^{+37}_{-34}$ MeV

$J^P = 1^+$ Measured for the first time

Argand diagram is consistent with the resonant behaviour