# Charm physics and XYZ states at BESIII

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On behalf of BESIII collaboration

FAIRNESS2016
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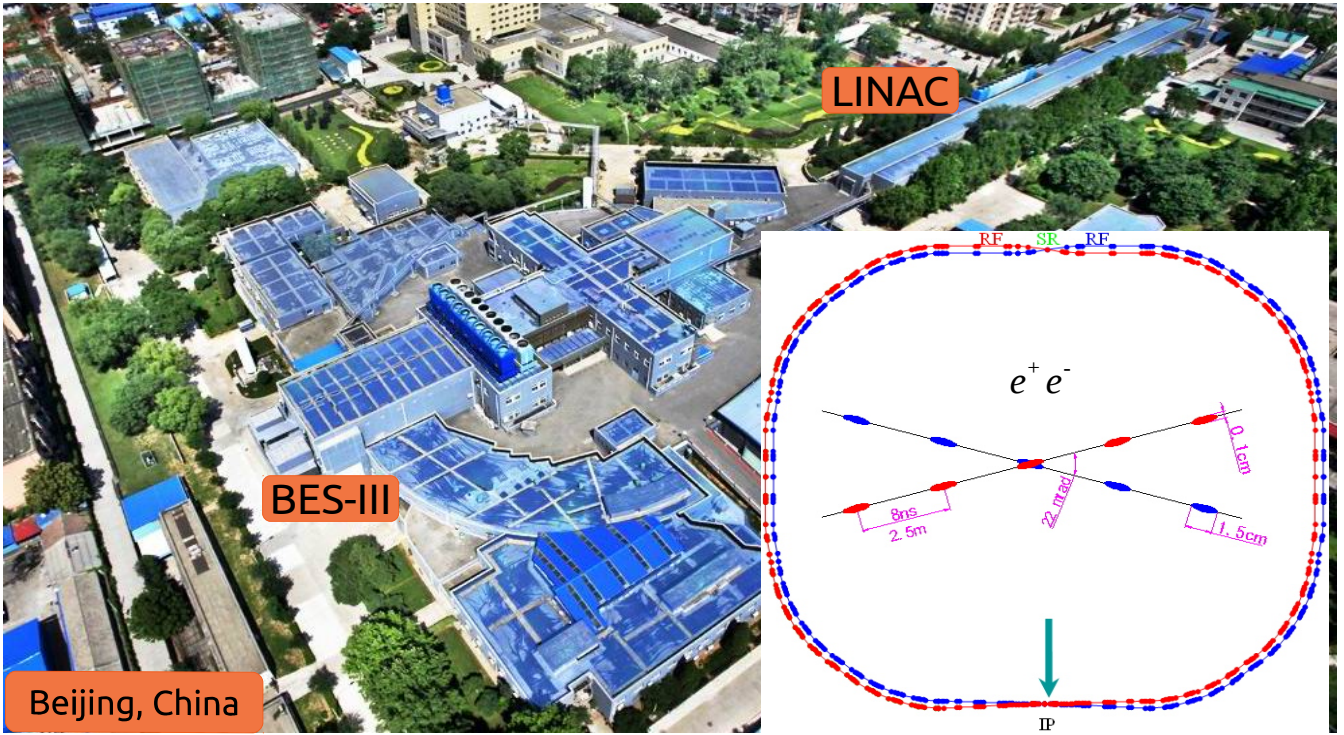
# Outline

- BESIII experiment
- Charm physics
- Recent XYZ results

# BEPC II

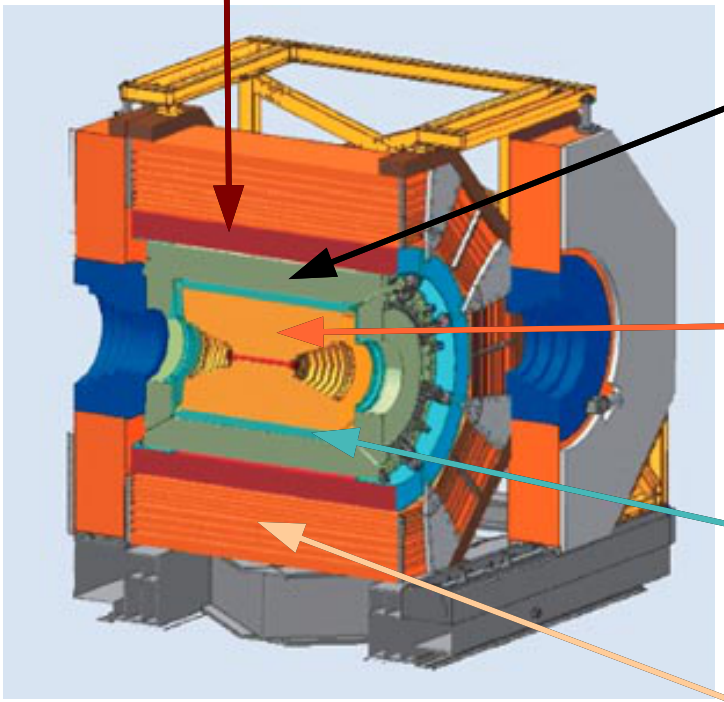



Beam energy: **1 - 2.3 GeV**
Beam current: **0.91A**

Achieved luminocity: $8 \times 10^{32} cm^{-2} s^{-1}$

# BESIII Detector

1T superconducting magnet



**EMC:**
- CsI crystals
- Energy resolution: 2.5%@1GeV
- Spatial resulution: 6mm

**MDC:**
- Spatial resulution: $\sigma_{xy}$ **= 120μm**
- Momentum resolution: **0.5%@1GeV**
- dE/dx resolution: **6%**

**TOF**
- Two layers of scintillator
- Time resolution:
  **90 ps (barel), 120 ps (endcaps)**

**Muon ID**
- 8 layers of RPC inside the yoke
  (9 in endcaps)

# BESIII Data Sample

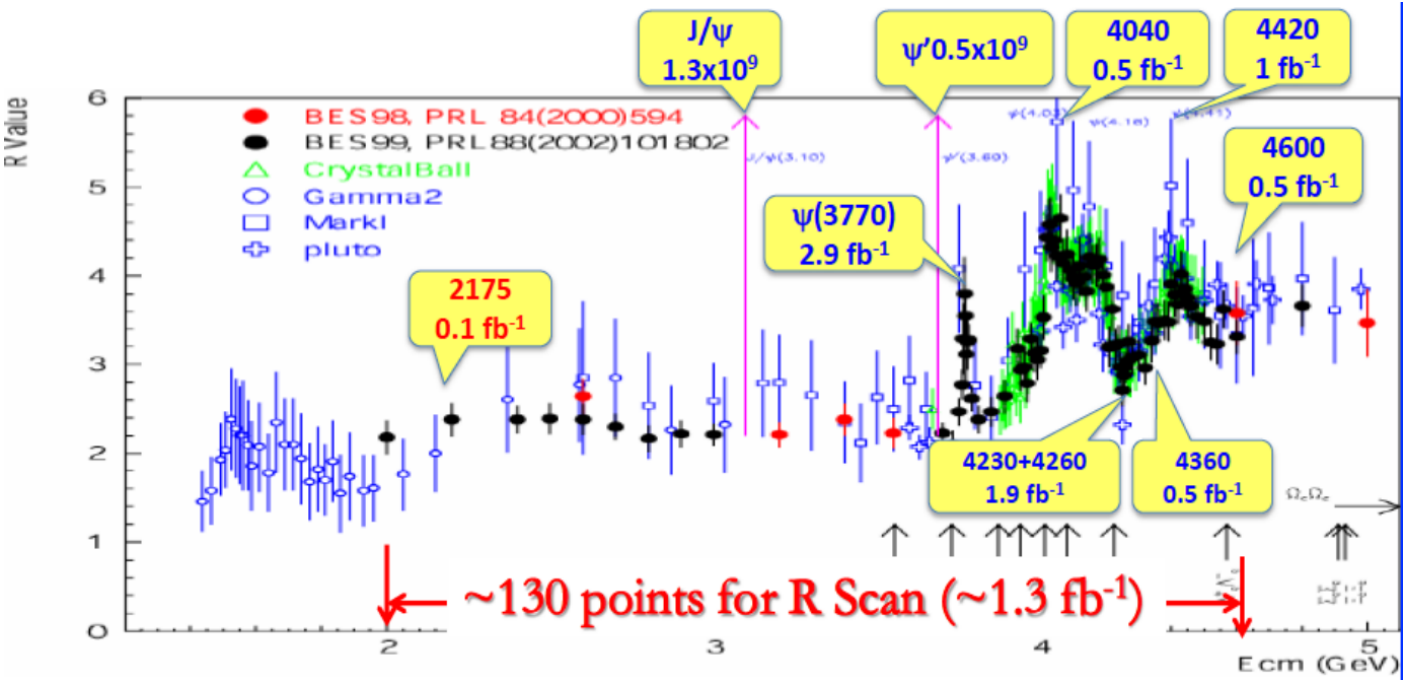



Image from S. Spataro – Spectroscopy in the charm range: from BESIII to PANDA

- Data taking since 2008
- World largest sample in $e^+e^- \rightarrow$ : J/ψ, ψ(2S), ψ(3770), Y(4260)

# Charm physics at BESIII: Motivation

- Unitarity test of CKM matrix: measuring $|V_{cs}|$ and $|V_{cd}|$
- LQCD calibration: $f_{D->K/\pi}(q^2)$ and other FFs, $f_{D(s)+}$ decay constant
- New Physics: finding evidence of CP violation, rare decays, significant deviations from CKM unitarity or from LQCD calculations
- Providing inputs for b-physics

# Charm physics: data samples

$2.93\,fb^{-1}@3.773\,GeV\ for\ D^0\overline{D^0}, D^+D^-$

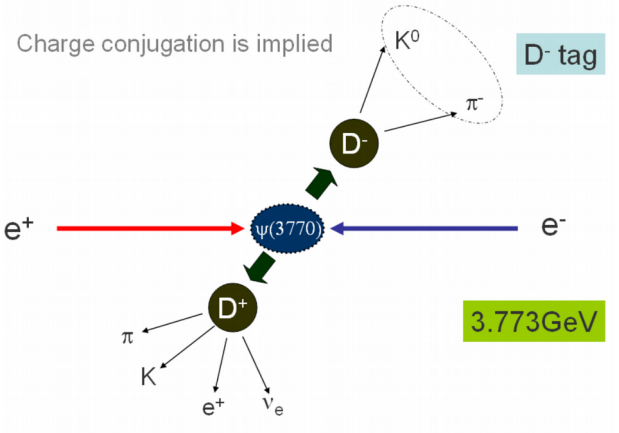
$0.48\,fb^{-1}@4.009\,GeV\ for\ D_s^+D_s^-$

$0.57\,fb^{-1}@4.599\,GeV\ for\ \Lambda_c^+\Lambda_c^-$

# Analysis Technique

- Pure $D\bar{D}$ final state, no additional hadrons
- «Tag» D-meson is fully reconstructed
- Signal is searched at the recoiling side

Example: $e^+e^- \rightarrow \psi(3770) \rightarrow D\bar{D}$




- Tag selection based on two variables: $\Delta E = E_D - E_{beam}$ $m_{BC} = \sqrt{E_{beam}^2 - |\vec{p}_D|}$
- Tag yeild is obtained by fitting $m_{BC}$

# Analysis of $D^+ \to K^-\pi^+e^+\nu_e$

- Branching fractions

arxiv:1512.08627

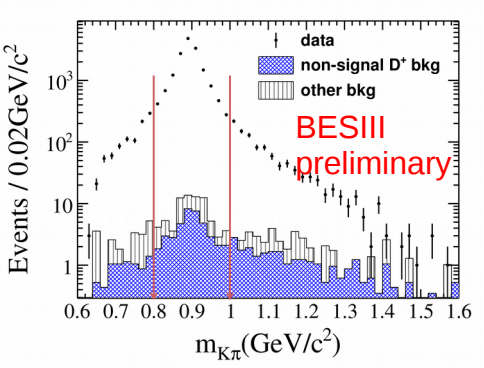
BESIII preliminary

$$\mathcal{B}(D^+ \to K^-\pi^+e^+\nu_e) = (3.71 \pm 0.03 \pm 0.08)\%,$$
$$\mathcal{B}(D^+ \to K^-\pi^+e^+\nu_e)_{[0.8,1]} = (3.33 \pm 0.03 \pm 0.07)\%$$

- Amplitude analysis
  - Fitted fractions (S+P)

BESIII preliminary

| | |
|---|---|
| $f_S(\%)$ | $6.05 \pm 0.22 \pm 0.18$ |
| $f_{\bar{K}^*(892)^0}(\%)$ | $93.93 \pm 0.22 \pm 0.18$ |




- S-wave phase measurement
  - Consistent with LASS parameterization

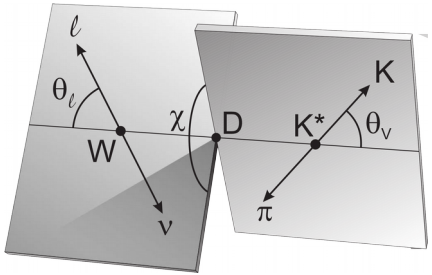
$N_{sig}$ = 18262

background level: 0.7%

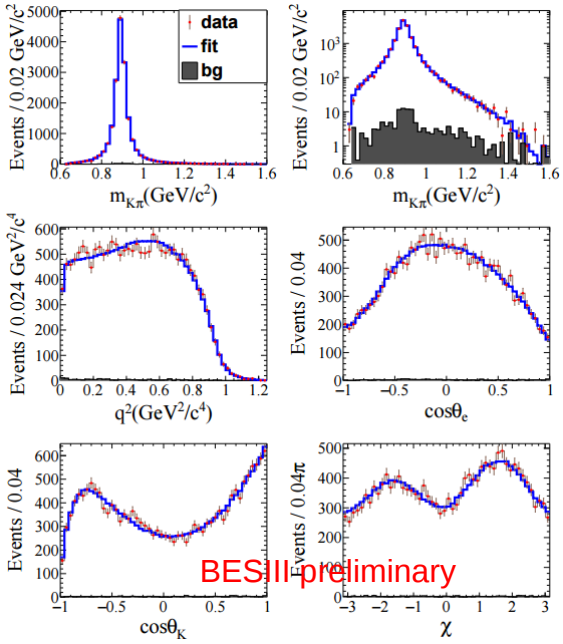
- Model-independent helicity basis FF study
  - Consistent with the PWA solution and CLEO-c results

Cont.

# PWA of $D^+ \to K^-\pi^+e^+\nu_e$




Projections of data and PWA solution MC (S+P)




| Variable | $S+P$ |
|---|---|
| $r_S(\mathrm{GeV})^{-1}$ | -11.57±0.58±0.46 |
| $r_S^{(1)}$ | 0.08±0.05±0.05 |
| $a_{\mathrm{S,BG}}^{1/2}(\mathrm{GeV}/c)^{-1}$ | 1.94±0.21±0.29 |
| $b_{\mathrm{S,BG}}^{1/2}(\mathrm{GeV}/c)^{-1}$ | -0.81±0.82±1.24 |
| $m_{\bar{K}^*(892)^0}(\mathrm{MeV}/c^2)$ | 894.60±0.25±0.08 |
| $\Gamma^0_{\bar{K}^*(892)^0}(\mathrm{MeV}/c^2)$ | 46.42±0.56±0.15 |
| $r_{\mathrm{BW}}\ (\mathrm{GeV}/c)^{-1}$ | 3.07±0.26±0.11 |
| $m_V\ (\mathrm{GeV}/c^2)$ | $1.81^{+0.25}_{-0.17}$±0.02 |
| $m_A\ (\mathrm{GeV}/c^2)$ | $2.61^{+0.22}_{-0.17}$±0.03 |
| $r_V$ | 1.411±0.058±0.007 |
| $r_2$ | 0.788±0.042±0.008 |

BESIII preliminary

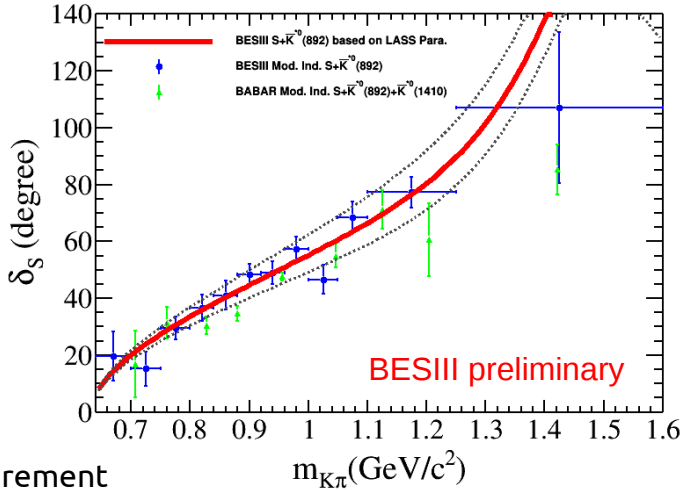
| | |
|---|---|
| $f_S(\%)$ | 6.05±0.22±0.18 |
| $f_{\bar{K}^*(892)^0}(\%)$ | 93.93±0.22±0.18 |

First measureme of SPD V pole mass

arxiv:1512.08627

# $D^+ \to K^-\pi^+e^+\nu_e$ S-wave phase

S-wave phase $\delta_s$ is independently fitted in 12 $m_{K\pi}$ bins

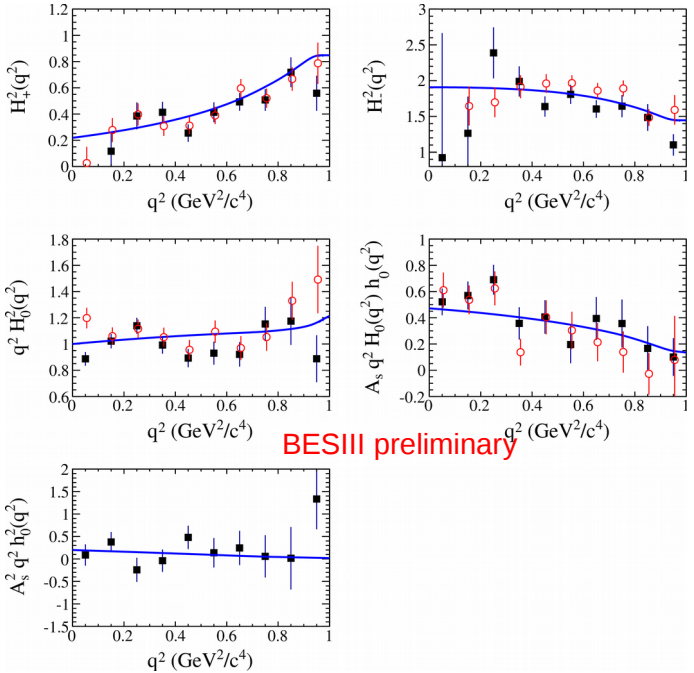



Blue dots: BESIII model-independent measurement
Red and dotted lines: predicted by fit based on LASS parameterization
Green dots: BABAR model-independent measurement with S+D+P

Model-independent measurement of BESIII are consistent with its result from amplitude analysis within 1σ .

# *Model-Independent Measurement of Form Factors*

- Events located in the K* window [0.8,1] GeV/$c^2$, are used to measure the form factors by a Projective Weighting Technique [Phys. Rev. D 81, 112001 (2010)].
- Signal is assumed to be composed of K* and a non-resonant S-wave.
- Helicity basis form factors include:
  - P-wave related: $H_{\pm}(q^{2})$
  - S-wave related: $h_0(q^2)$
- Five weighted $q^2$ histograms are built. Weight is assigned to each event based on kinematic variables.
- Form factors are independently computed in each bin.
- The model-independent measurements are generally consistent with CLEO-c and with SPD-model results from amplitude analysis




Red dots : BESIII model-independent measurement
Black dots : CLEO model-independent measurement
Blue Line : BESIII result from amplitude analysis (it's **not** the fit!)

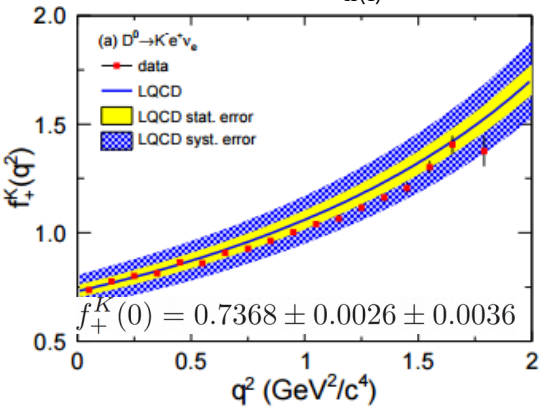
arxiv:1512.08627

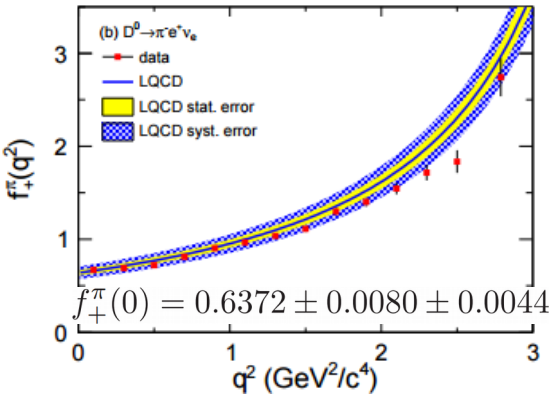
# Study of $D^0 \to K^-/\pi^- e^+ \nu_e$

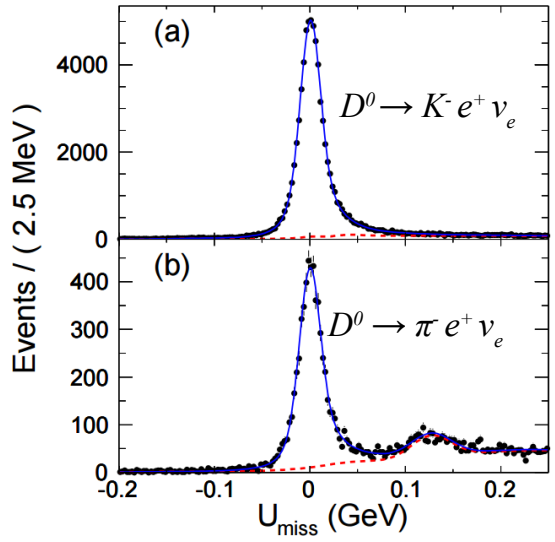
Using CKMFitter $|V_{cs(d)}|$ as input

Measure $|V_{cs(d)}| \times f_+^{K(\pi)}$

PRD92 (2015) 072012



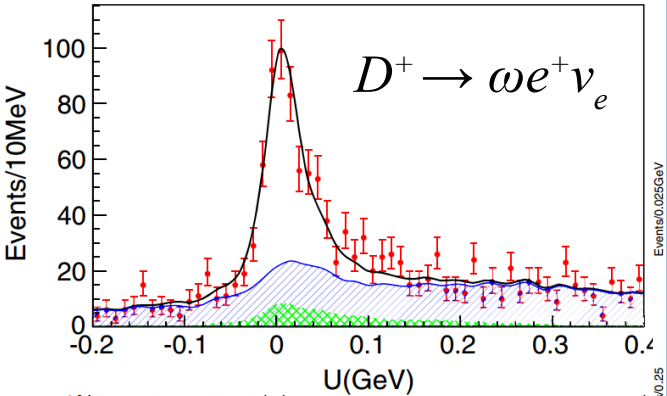



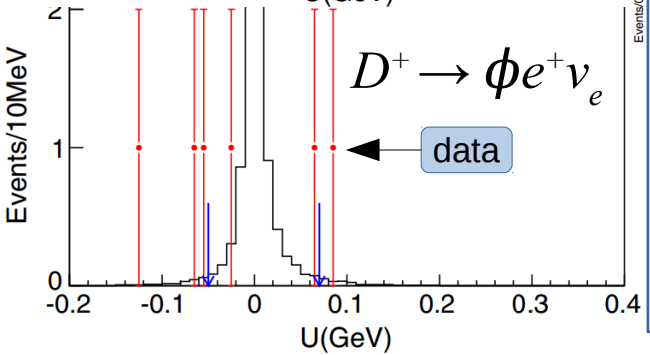




$$\mathcal{B}(D^0 \to K^- e^+ \nu_e) = (3.505 \pm 0.014 \pm 0.033)\%$$

$$\mathcal{B}(D^0 \to \pi^- e^+ \nu_e) = (0.295 \pm 0.004 \pm 0.003)\%,$$

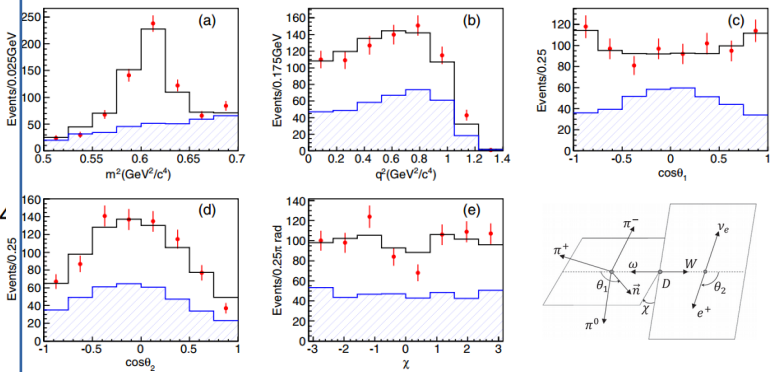
# Study of $D^+ \to \omega e^+ \nu_e$ and search for $D^+ \to \phi e^+ \nu_e$




## First $D^+ \to \omega e^+ \nu_e$ form factor measurement

PRD 92, 071101(R) (2015)




### Form factor ratios:

$$r_V = V(0)/A_1(0) = 1.24 \pm 0.09 \pm 0.06$$

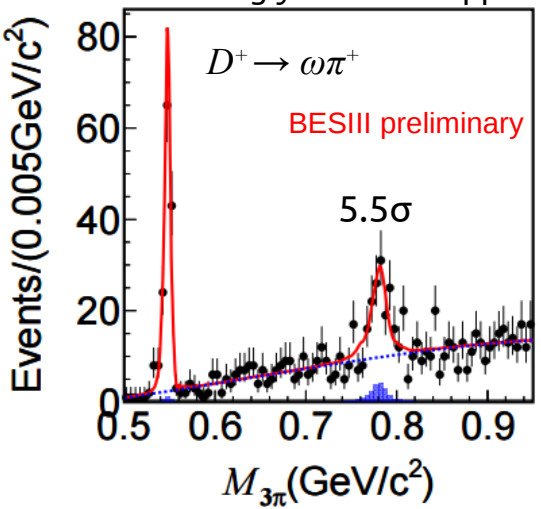
$$r_2 = A_2(0)/A_1(0) = 1.06 \pm 0.15 \pm 0.05$$

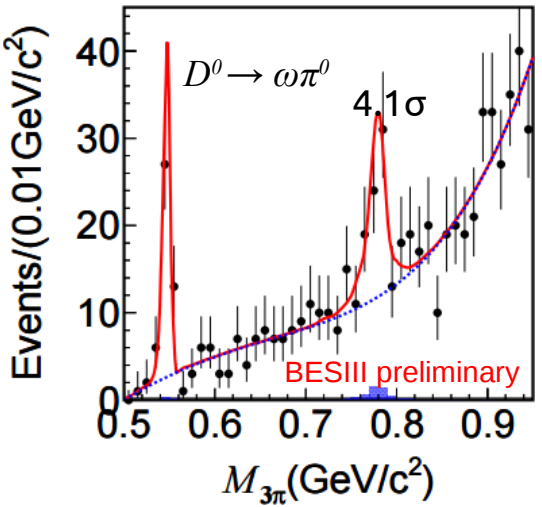
## Branching ratios:

| Mode | This work | Previous |
|---|---|---|
| $\omega e^+ \nu_e$ | $(1.63 \pm 0.11 \pm 0.08) \times 10^{-3}$ | $(1.82 \pm 0.18 \pm 0.07) \times 10^{-3}$ |
| $\phi e^+ \nu_e$ | $< 1.3 \times 10^{-5}$ (@90%C.L.) | $< 9.0 \times 10^{-5}$ (@90%C.L.) |

# Observation of $D^+ \to \omega\pi^+$ and evidence for $D^0 \to \omega\pi^0$

$D^+ \to \omega\pi^+$ is singly Cabibbo-suppressed



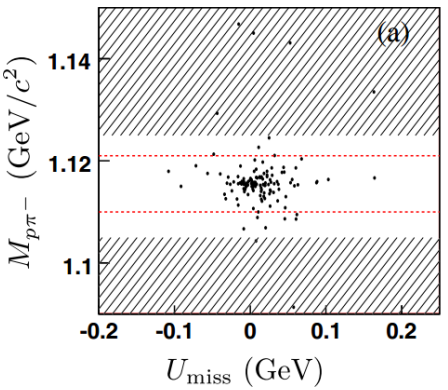



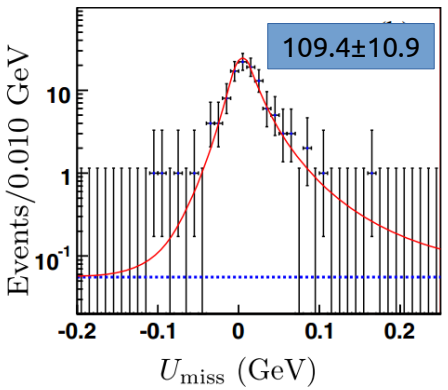

arXiv:1512.06998

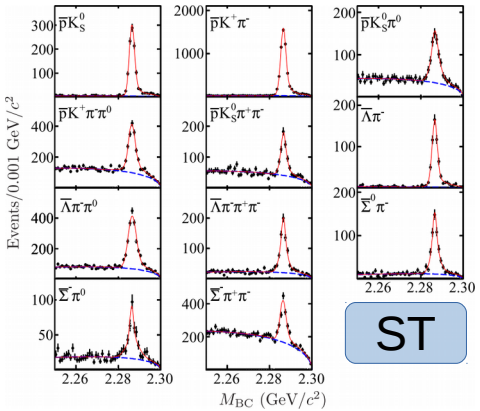
| Mode | This work | Previous measurements |
|---|---|---|
| $D^+ \to \omega\pi^+$ | $(2.79 \pm 0.57 \pm 0.16) \times 10^{-4}$ | $< 3.4 \times 10^{-4}$ at 90% C.L. |
| $D^0 \to \omega\pi^0$ | $(1.17 \pm 0.34 \pm 0.07) \times 10^{-4}$ | $< 2.6 \times 10^{-4}$ at 90% C.L. |
| $D^+ \to \eta\pi^+$ | $(3.07 \pm 0.22 \pm 0.13) \times 10^{-3}$ | $(3.53 \pm 0.21) \times 10^{-3}$ |
| $D^0 \to \eta\pi^0$ | $(0.65 \pm 0.09 \pm 0.04) \times 10^{-3}$ | $(0.68 \pm 0.07) \times 10^{-3}$ |

BESIII preliminary

# Absolute BF for $\Lambda^+_c \to \Lambda\, e^+ \nu_e$




$BF(\Lambda_c^+ \to \Lambda\, e^+ \nu_e)$

Theoretical predictions: 1.4% to 9.2%

Previous indirect measurements: $(2.9 \pm 0.5)\%$

First direct measurement $BF(\Lambda_c^+ \to \Lambda\, e^+ \nu_e) = (3.63 \pm 0.38 \pm 0.20)\%$

PRL115(2015)221805

# XYZ States

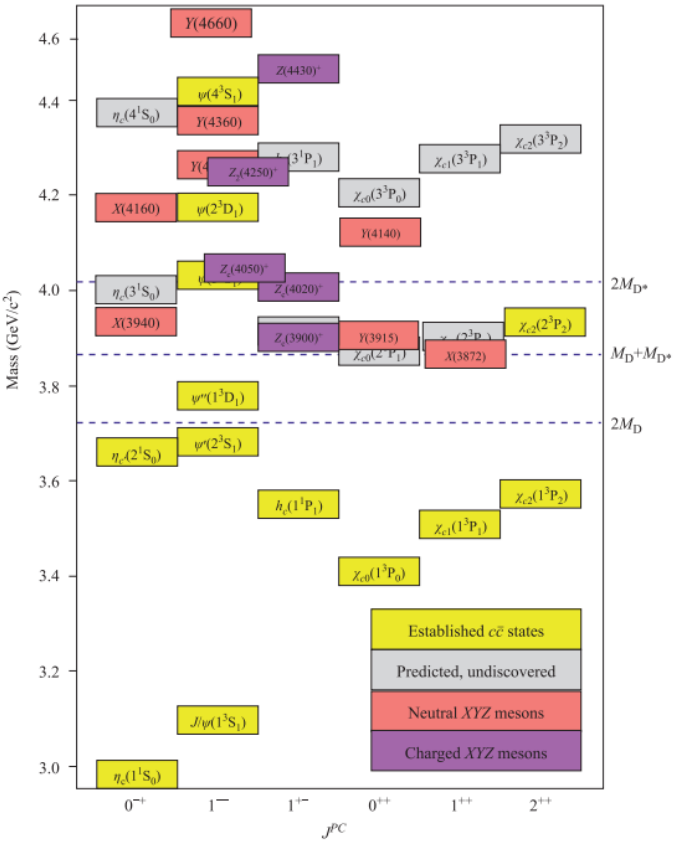
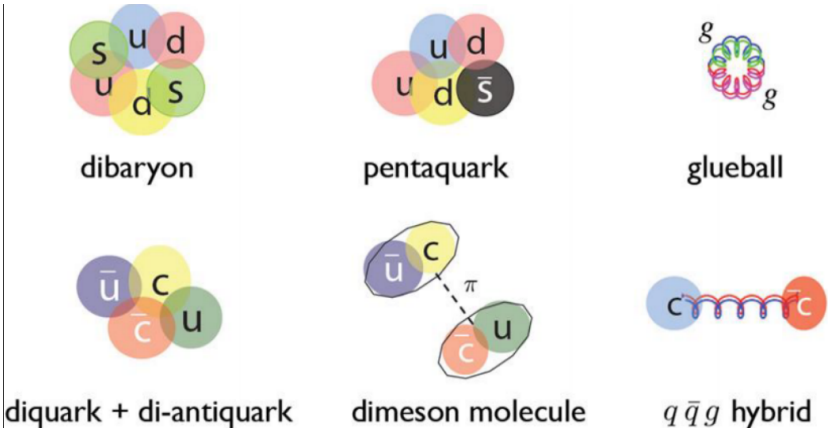



Image from S. Olsen Front. Phys. 10, 101401 (2015)

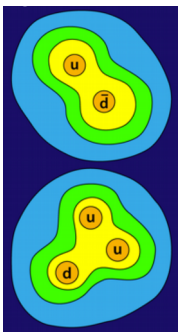
"XYZ" states:

- Charmonium ($c\bar{c}$) in the final state
- Do not fit into the conventional quark model of charmonium

# Exotic Hadrons




- Conventional hadrons: 2 or 3 quarks
- QCD doesn't forbid exotic hadrons:
  - Glueball (no quarks)
  - Hybrid (quarks + excited gluon)
  - Multiquark (N > 3)
  - Hardon molecule (bound state of hadrons)

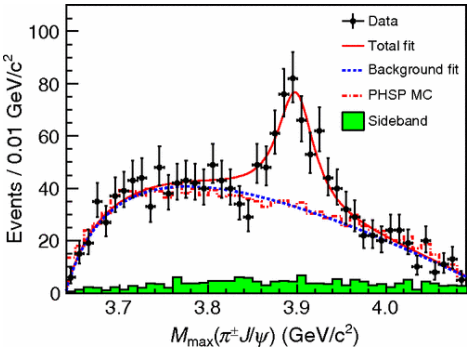


# BESIII Data Sets

2011: ~482 pb$^{-1}$ at **4.01 GeV**
2013: ~1054 pb$^{-1}$ at **4.23 GeV**
~806 pb$^{-1}$ at **4.26 GeV**
~523 pb$^{-1}$ at **4.36 GeV**
~50 pb$^{-1}$ at **3.81, 3.90, 4.09, 4.19, 4.21, 4.22, 4.245, 4.31, 4.39, 4.42 GeV**
2014: ~993 pb$^{-1}$ at **4.42 GeV**
~42 pb$^{-1}$ at **4.575 GeV**
~100 pb$^{-1}$ at **4.47 GeV**
~506 pb$^{-1}$ at **4.6 GeV**

# $Z_c$ states at BESIII

$Z_c(3900)^+$

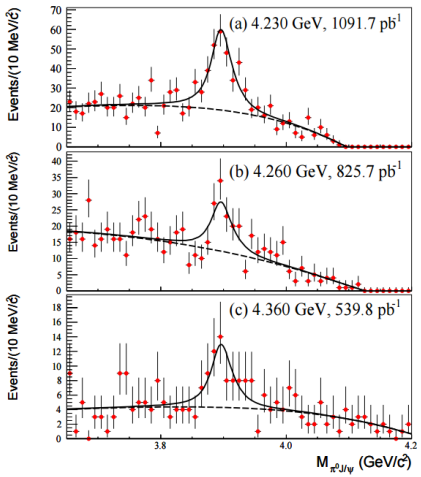



Charged charmonium-like state

- M = (3899.0 ± 3.6 ± 4.9) MeV/c²
- Γ = (46 ± 10 ± 20) MeV/c²
- Significance > 8σ

Neutral partner is found in $e^+e^- \to \pi^+\pi J/\psi$

$Z_c(3900)^0$



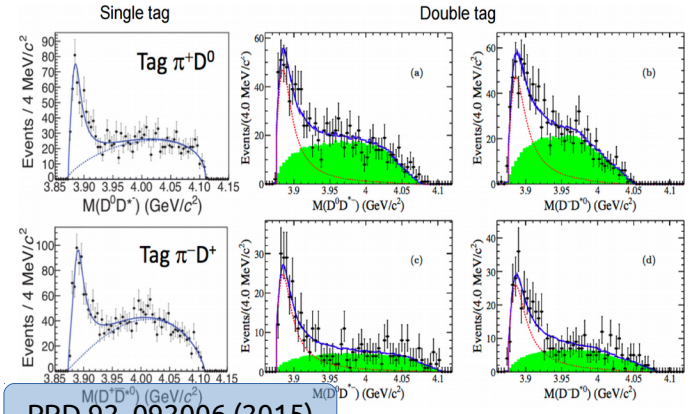

- M = 3894.8 ± 2.3 ± 3.2 MeV/c²
- Γ = 29.6 ± 8.2 ± 8.2 MeV/c²
- Significance = 10.4σ

Isospin triplet

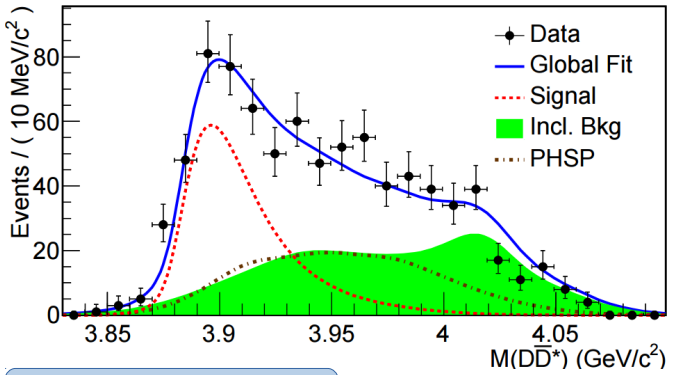
PRL110, 252001[2013]

PRL 115, 112003 (2015)

# $Z_c$ states at BESIII




PRD 92, 092006 (2015)




PRL 115, 222002 (2015)

## $Z_c(3885)^+$

Found in $e^+e^- \to \pi^+(D\bar{D}^*)^-$ *@ 4.26 GeV (ST)*
confirmed @ 4.23, 4.26 GeV (DT)

- M = 3881.7 ± 1.6 ± 2.1 MeV/c²
- Γ = 26.6 ± 2.0 ± 2.3 MeV/c²
- Significance > 10σ
- Angular distribution consistent with $J^P=1^+$

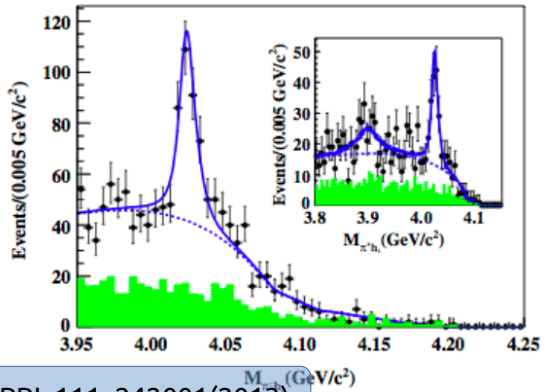
Isospin triplet

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

- M = $3885.7\ ^{+4.3}_{-5.7} \pm 8.4$ MeV/c²
- Γ = $35\ ^{+11}_{-12} \pm 15$ MeV/c²
- Significance > 12σ

Image from XYZ states at the BESIII experiment by Gianfranco Morello

# $Z_c$ states at BESIII

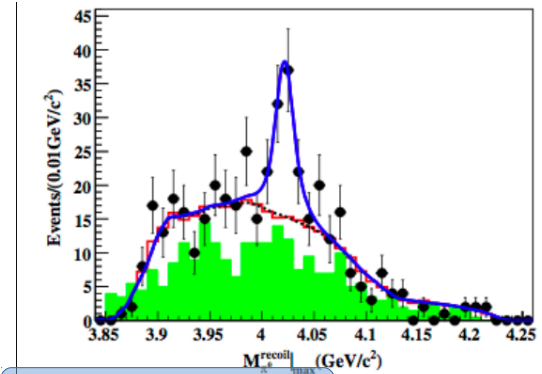



PRL 111, 242001(2013)

$Z_c(4020)^+$ $\quad e^+e^- \to \pi^+\pi^- h_c$

- M = (4022.9 ± 0.8 ± 2.7) MeV/c²
- Γ = (7.9 ± 2.7 ± 2.6) MeV/c²
- Significance > 8.9σ

Isospin triplet



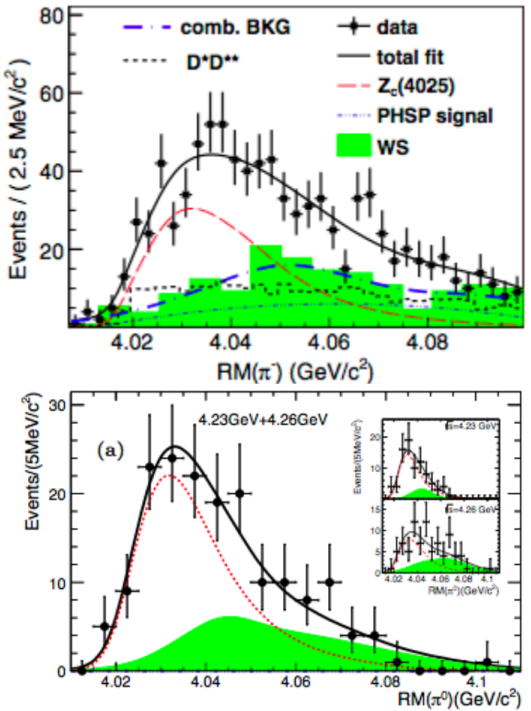

PRL 113, 212002(2014)

$Z_c(4020)^0$ $\quad e^+e^- \to \pi^0\pi^0 h_c$

- M = 4023.9 ± 2.2 ± 3.8 MeV/c2
- Γ fixed to $Z_c(4020)^+$
- Significance: 5σ

# $Z_c$ states at BESIII

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




$Z_c(4025)^+$

- M = (4026.3 ± 2.6 ± 3.7) MeV/c²
- Γ = (24.8 ± 5.6 ± 7.7) MeV/c²
- Significance > 10σ

Isospin triplet

$Z_c(4025)^0$

- M = $(4025.5^{+2.0}_{-4.7} \pm 3.1)$ MeV/c²
- Γ = (23.0 ± 6.0 ± 1.0) MeV/c²
- Significance > 5.9σ

PRL112, 132001 (2014)

# $Z_c$ states at BESIII: Summary

| State | Mass (MeV/$c^2$) | Width (MeV) | Decay | Process | [Ref] |
|---|---|---|---|---|---|
| $Z_c(3900)^{\pm}$ | $3899.0 \pm 3.6 \pm 4.9$ | $46 \pm 10 \pm 20$ | $\pi^{\pm} J/\psi$ | $e^+e^- \to \pi^+\pi^- J/\psi$ | 1* |
| $Z_c(3900)^0$ | $3894.8 \pm 2.3 \pm 2.7$ | $29.6 \pm 8.2 \pm 8.2$ | $\pi^0 J/\psi$ | $e^+e^- \to \pi^0\pi^0 J/\psi$ | 2* |
| $Z_c(3885)^{\pm}$ | $3883.9 \pm 1.5 \pm 4.2$ Single D tag | $24.8 \pm 3.3 \pm 11.0$ Single D tag | $(D\bar{D}^*)^{\pm}$ | $e^+e^- \to (D\bar{D}^*)^{\pm}\pi^{\mp}$ | 3* |
| | $3881.7 \pm 1.6 \pm 2.1$ Double D tag | $26.6 \pm 2.0 \pm 2.3$ Double D tag | $(D\bar{D}^*)^{\pm}$ | $e^+e^- \to (D\bar{D}^*)^{\pm}\pi^{\mp}$ | 4* |
| $Z_c(3885)^0$ | $3885.7^{+4.3}_{-5.7} \pm 8.4$ | $35^{+11}_{-12} \pm 15$ | $(D\bar{D}^*)^0$ | $e^+e^- \to (D\bar{D}^*)^0\pi^0$ | 5* |
| | | | | | |
| $Z_c(4020)^{\pm}$ | $4022.9 \pm 0.8 \pm 2.7$ | $7.9 \pm 2.7 \pm 2.6$ | $\pi^{\pm} h_c$ | $e^+e^- \to \pi^+\pi^- h_c$ | 6* |
| $Z_c(4020)^0$ | $4023.9 \pm 2.2 \pm 3.8$ | fixed | $\pi^0 h_c$ | $e^+e^- \to \pi^0\pi^0 h_c$ | 7* |
| $Z_c(4025)^{\pm}$ | $4026.3 \pm 2.6 \pm 3.7$ | $24.8 \pm 5.6 \pm 7.7$ | $D^*\bar{D}^*$ | $e^+e^- \to (D^*\bar{D}^*)^{\pm}\pi^{\mp}$ | 8* |
| $Z_c(4025)^0$ | $4025.5^{+2.0}_{-4.7} \pm 3.1$ | $23.0 \pm 6.0 \pm 1.0$ | $D^*\bar{D}^*$ | $e^+e^- \to (D^*\bar{D}^*)^0\pi^0$ | 9* |

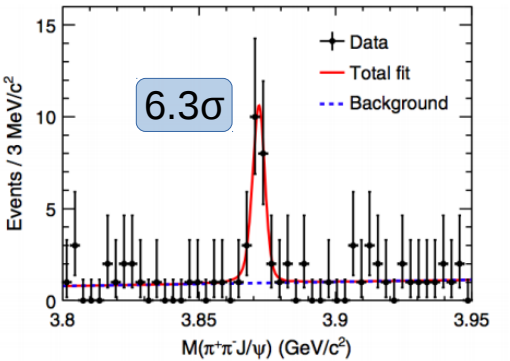
References:

*1*: PRL 110, 252001; 2*: PRL 115, 112003 ; 3*: PRL 112, 022001;*
*4*: PRD 92, 092006; 5*: arXiv:1509.05620; 6*: PRL 110, 252001;*
*7*: PRL 113, 212002; 8*: PRL 112, 132001 ; 9*: PRL 115, 182002*

Table by Guangshun Huang «Overview of the BESIII Experiment» 4th LNF Workshop on Cylindrical GEM Detectors

# X States at BESIII

*X(3872)*



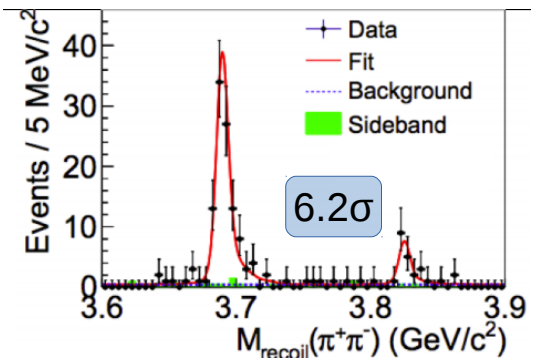

$e^+e^- \to \gamma X(3872)$
$X(3872) \to \pi^+\pi^- J/\psi$

- M = 3871.9 ± 0.7 ± 0.2 MeV/c²
- Γ < 2.4 MeV/c² @ 90% C.L

$Y(4260) \to \gamma X(3872)$ decay was recently observed at BESIII

PRL 112, 092001 (2014)

*X(3823)*



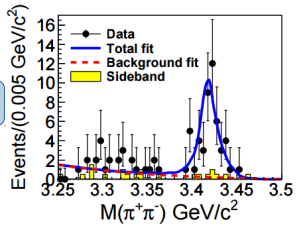

X(3823) observed in $e^+e^- \to \pi^+\pi^- X(3823)$
$X(3823) \to \gamma\chi_{C1}$

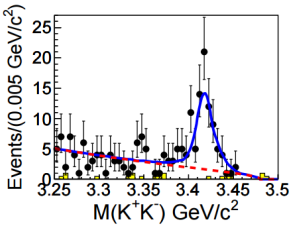
- M = 3821.9 ± 1.3 ± 0.7MeV/c²
- Consistent with $\psi(1^3D_2)$

PRL 115, 011803 (2015)

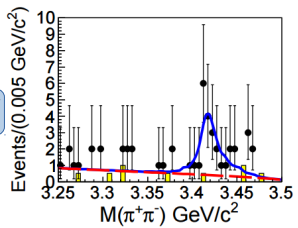
# Y States

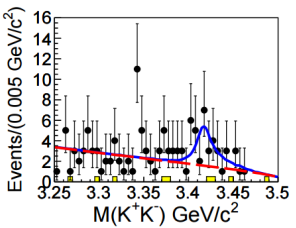
4.23 GeV




4.26 GeV




Y(4230)

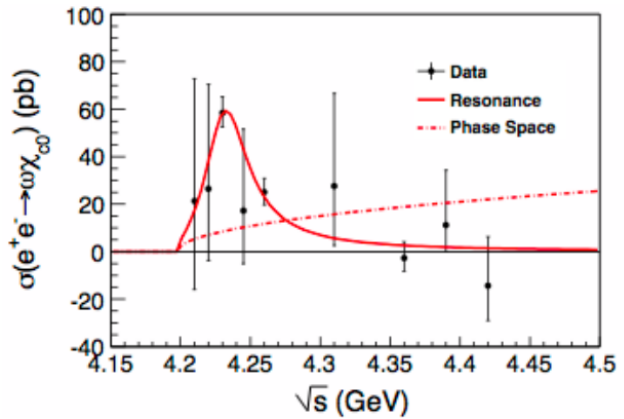
PRL, 114, 092003

$e^+e^- \rightarrow \omega\chi_{c0}$

M = 4230 ± 8 ± 6 MeV/c2

Γ = 38 ± 12 ± 2 MeV

Significance > 9σ




Possible interpretations:

- Tetraquark
- $\psi(4S)$
- threshold effect?

# Summary

- Charm physics
  - Semileptonic analyses (hadronic FF and decay constant)
    - $D^+ \to K^-\pi^+e^+\nu_e$, $D^0 \to K^-/\pi^- e^+\nu_e$, $D^+ \to \omega e^+\nu_e$
- Recent progress in $XYZ$:
  - Neutral $Z_c$ partners are found:
    - $Z_c(3900)^0$, $Z_c(3885)^0$, $Z_c(4020)^0$, $Z_c(4025)^0$
  - $\psi(1^3D_2)$ (X(3823)) is observed
  - Y(4230)
- BESIII continues to take data
  - More interesting results are expected soon