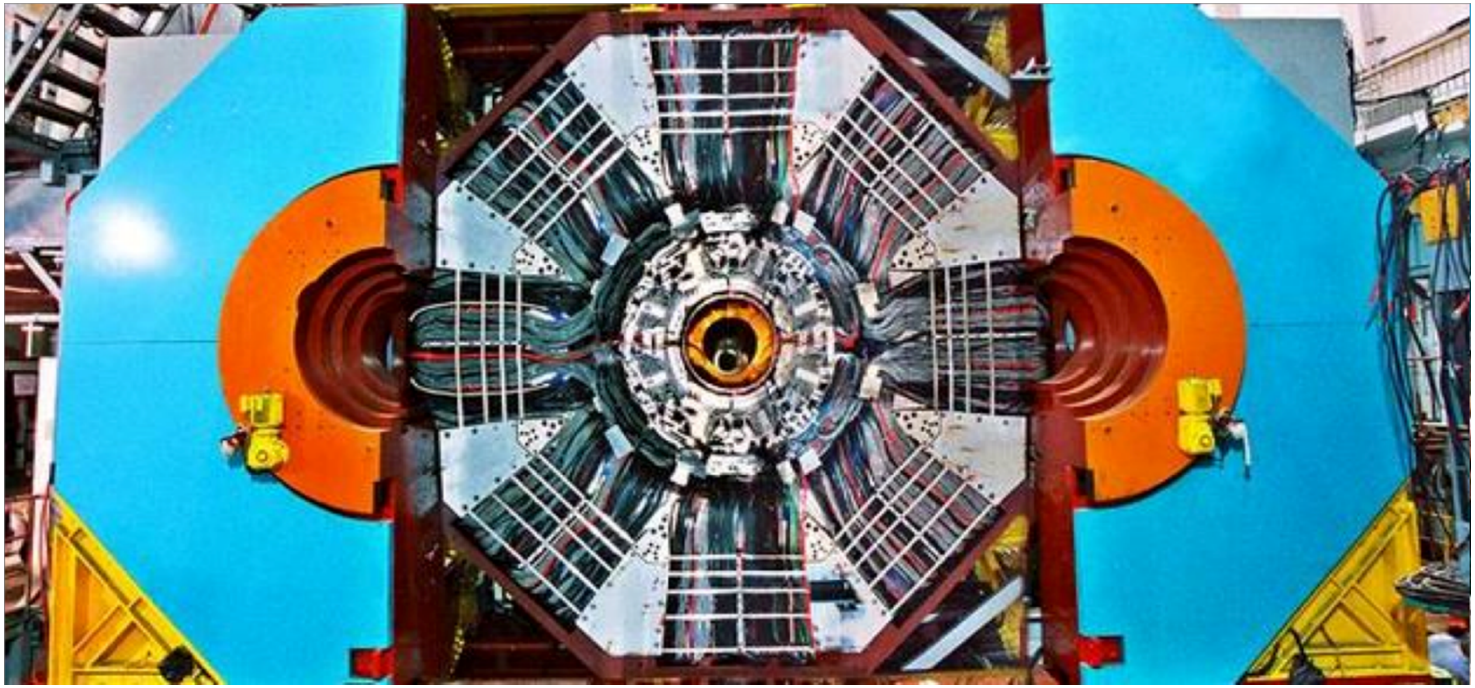

# Recent results and prospects at BESIII


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University of Chinese Academy Sciences

**(On behalf of the BESIII collaboration)**


**2018 年“基本粒子和相互作用协同创新 中心”牡丹江论坛**

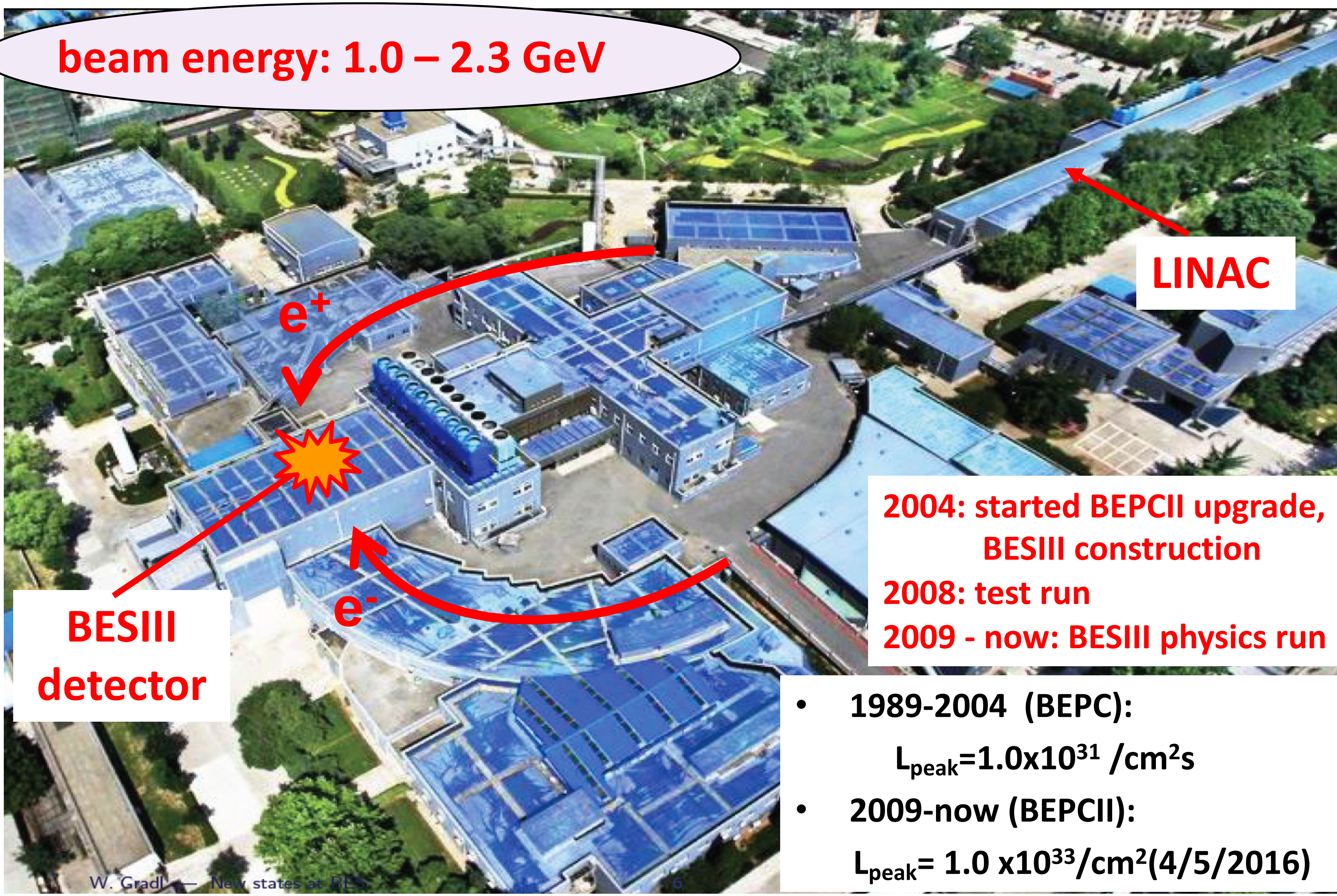
济南大学，山东

Sep. 15, 2018, Ji'Nan

# Outline

- **Introduction**
- **Recent (selected) results**
  - Hadron spectroscopy and exotics
  - Charmed hadron decays
  - Charmed baryon form factor
- **Prospects and Summary**

# Beijing Electron Positron Collider (BEPC)




2004: started BEPCII upgrade, BESIII construction

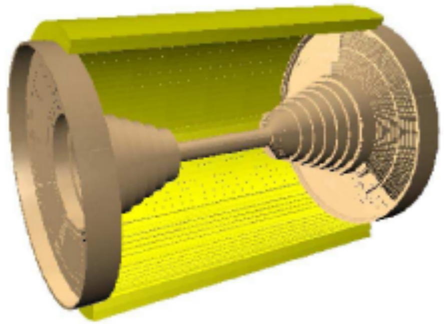
2008: test run

2009 - now: BESIII physics run

- 1989-2004 (BEPC):
  $L_{peak}$=1.0x$10^{31}$ /cm$^2$s
- 2009-now (BEPCII):
  $L_{peak}$= 1.0 x$10^{33}$/cm$^2$(4/5/2016)

# BESIII Detector

## MDC

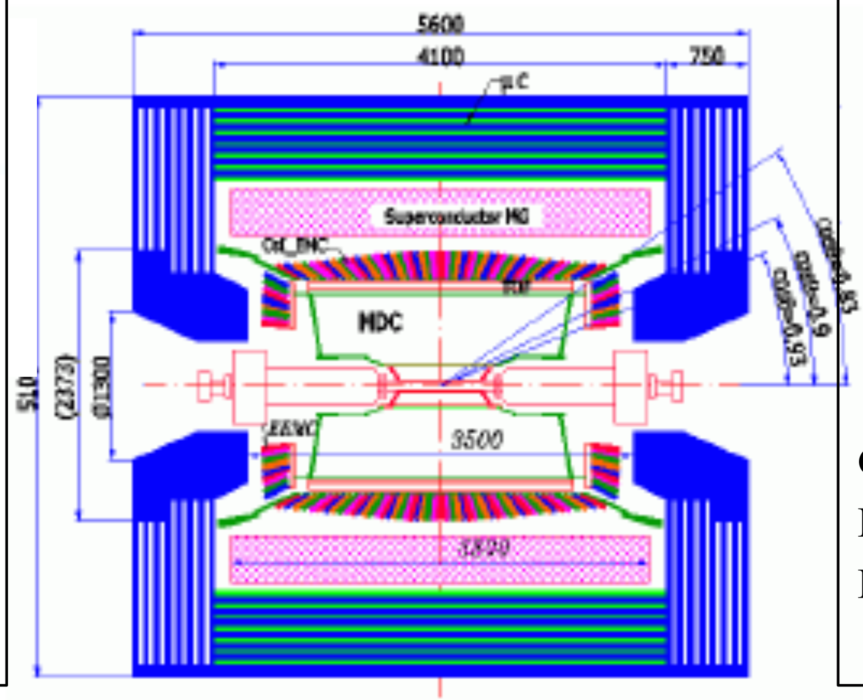


R inner: 63mm ;

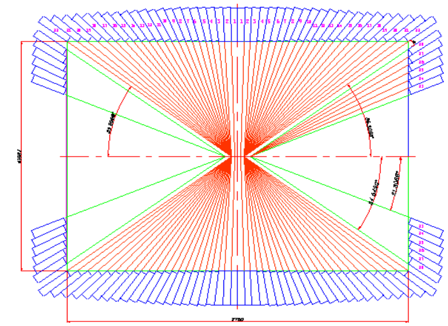
R outer: 810mm

Length: 2582 mm

Layers: 43




## CsI(Tl) EMC



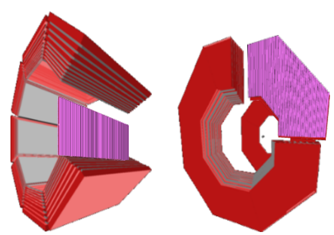
Crystals: 28 cm(15 $X_0$)

Barrel: |cosθ|<0.83

Endcap:

0.85 < |cosθ| < 0.93

## RPC MUC



BMUC: 9 layers – 72 modules

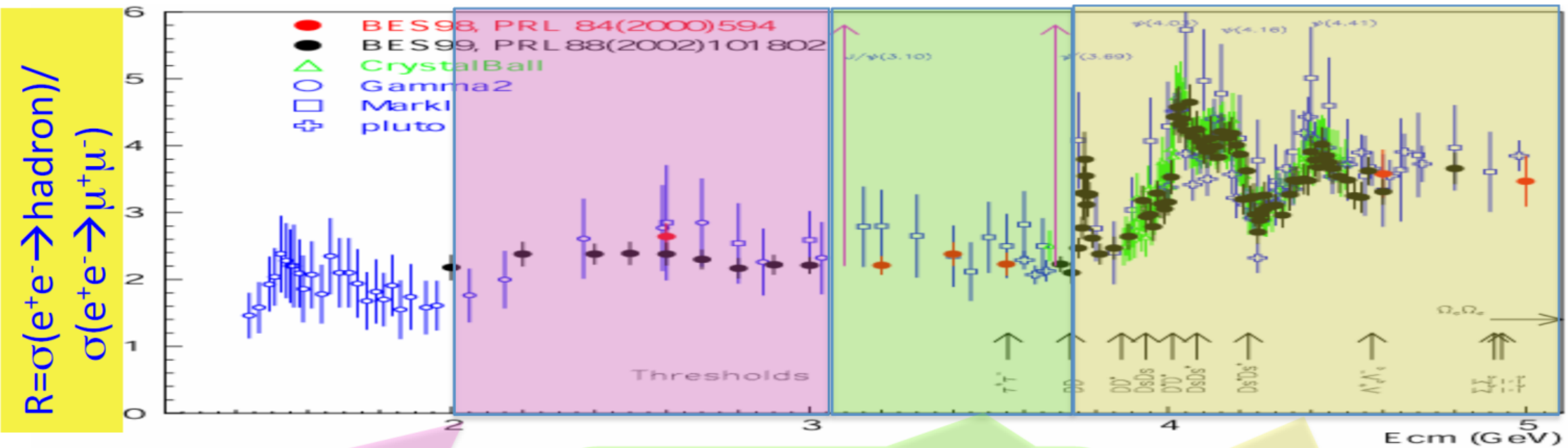
EMUC: 8 layers – 64 modules

## TOF

BTOF: two layers

ETOF: 48 crys. for each

# Physics at tau-charm Energy Region

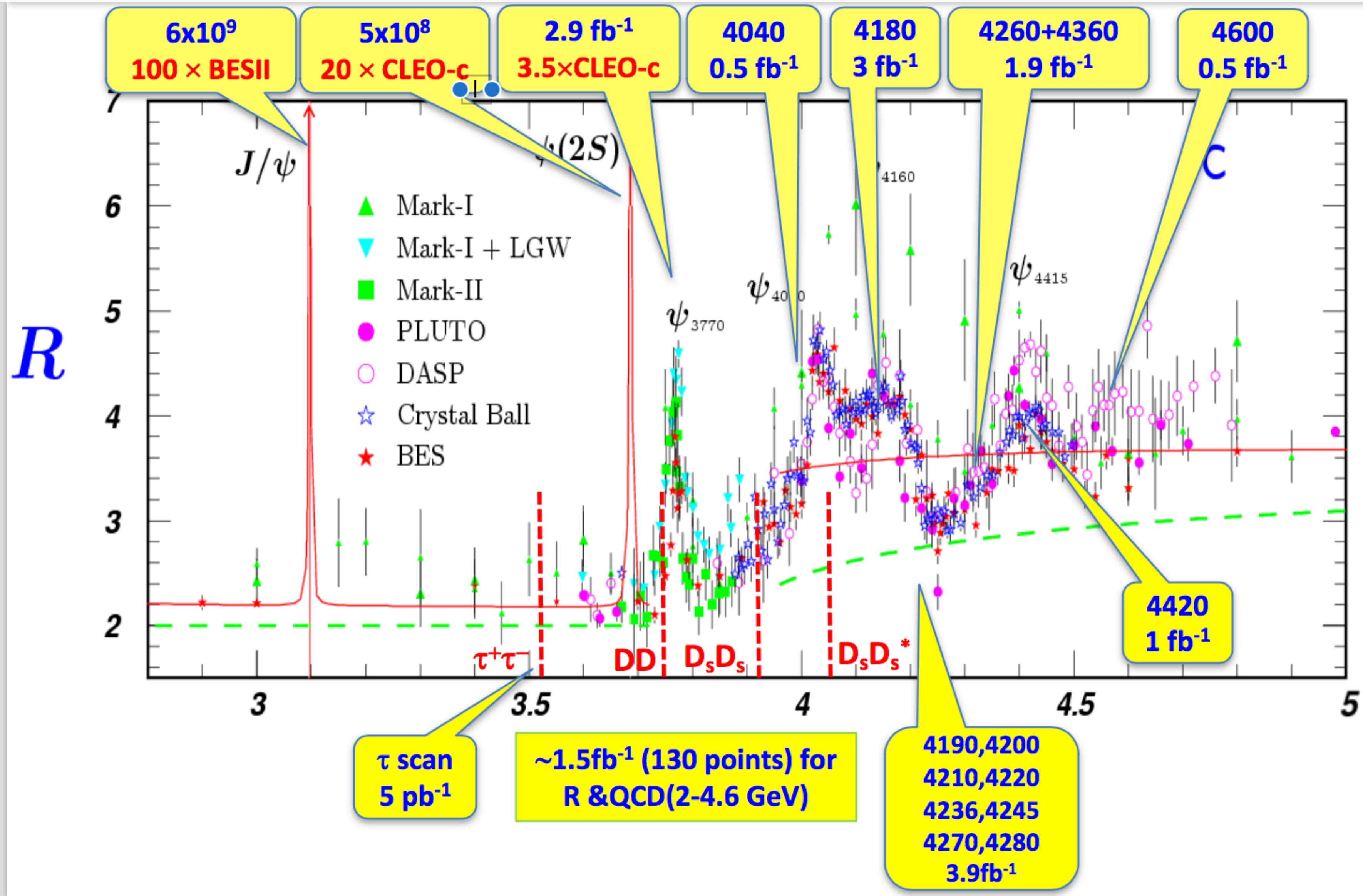



- Hadron form factors
- Y(2175) resonance
- Mutltiquark states with s quark, Zs
- MLLA/LPHD and QCD sum rule predictions

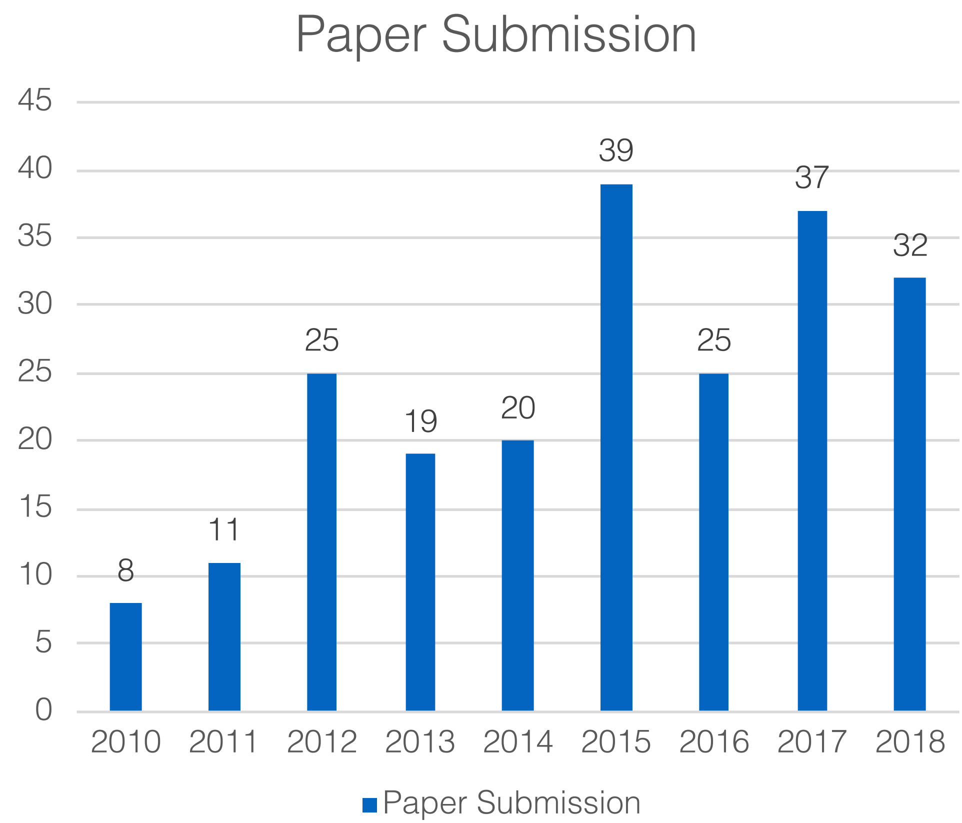
- Light hadron spectroscopy
- Gluonic and exotic states
- Process of LFV and CPV
- Rare and forbidden decays
- Physics with τ lepton

- XYZ particles
- D mesons
- $f_D$ and $f_{Ds}$
- $D_0$-$D_0$ mixing
- Charm baryons

# BESIII data samples



# Publications



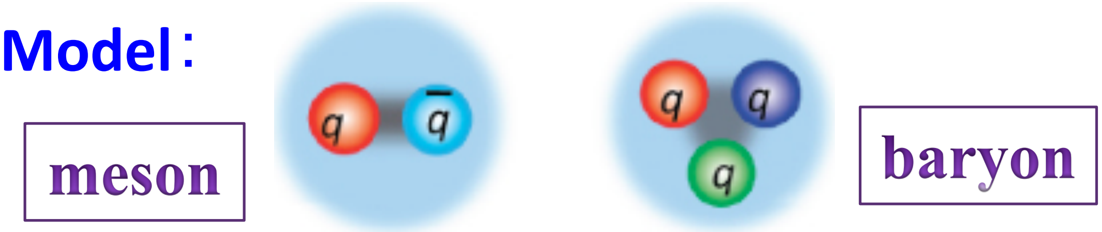

In total, we have submitted 221 papers out in 9 years.
Expect the same pace in the coming years.

# Hadron spectroscopy and exotics

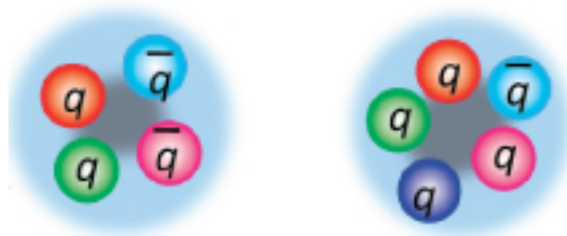
# New forms of hadrons

- **Conventional hadrons consist of 2 or 3 quarks：**

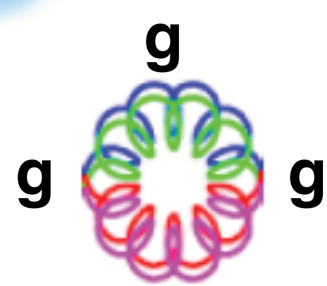
**Naive Quark Model：**

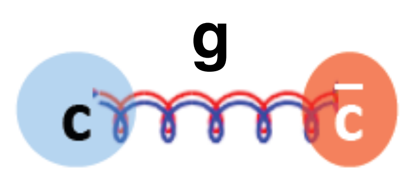



- **QCD predicts the new forms of hadrons:**
  - **Multi-quark states： Number of quarks >＝ 4**



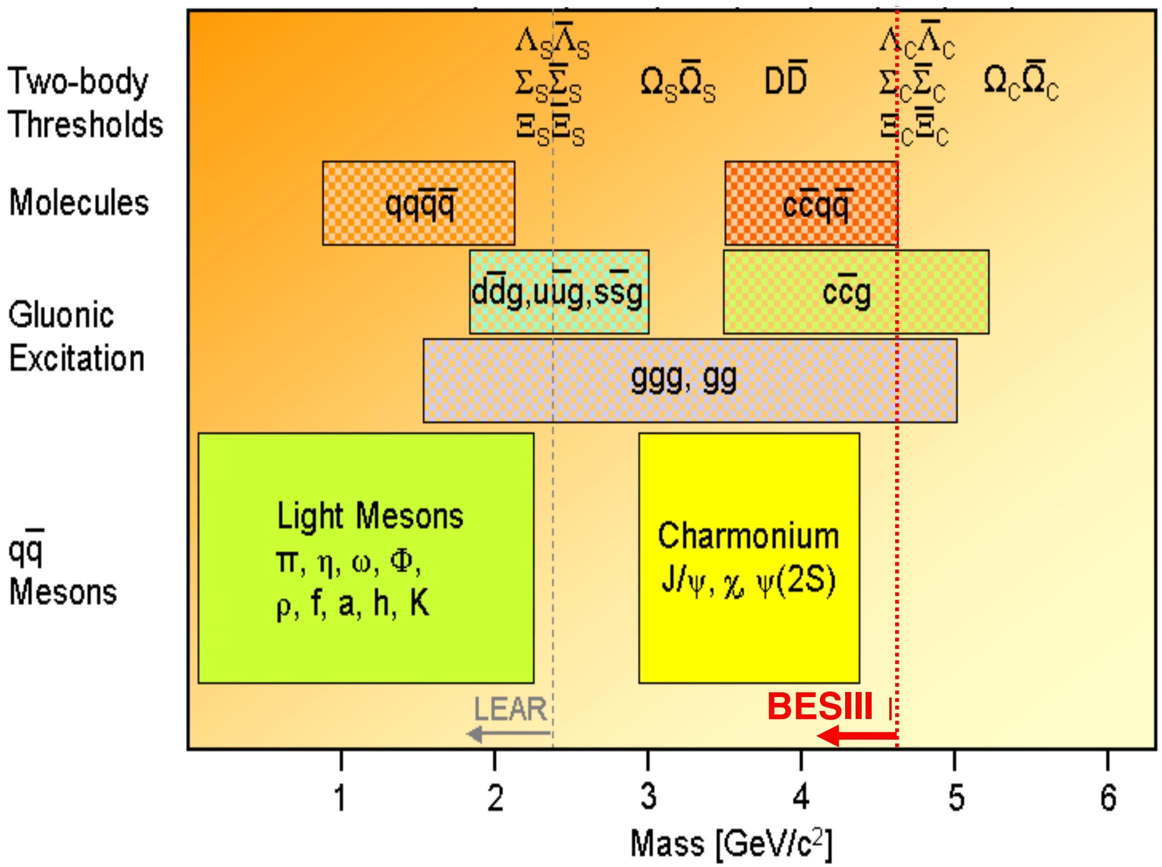

  - **Hybrids： $q\bar{q}g$， qqqg …**
  - **Glueballs： gg， ggg …**




**None of the new forms of hadrons is settled！**

# Hadron Landscape




Hadron-physics challenges:

- Understanding of established states: precision spectroscopy
- Nature of exotic states: search and spectroscopy of unexpected states

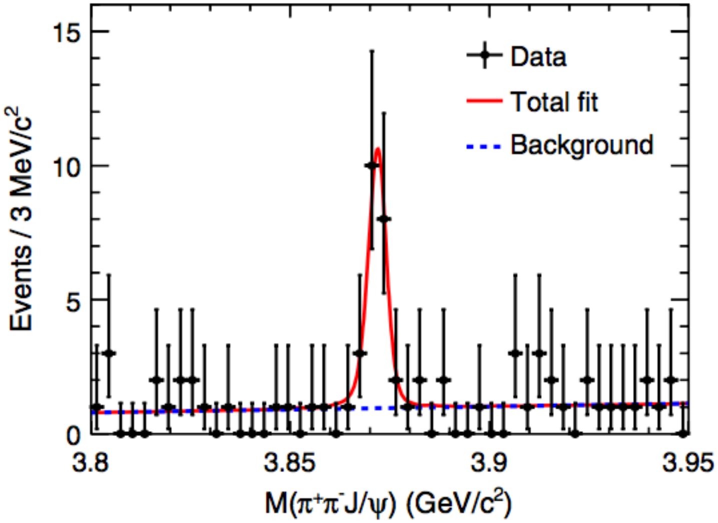
At BESIII, two golden measures to study hadron spectroscopy, *esp*., to search for exotics

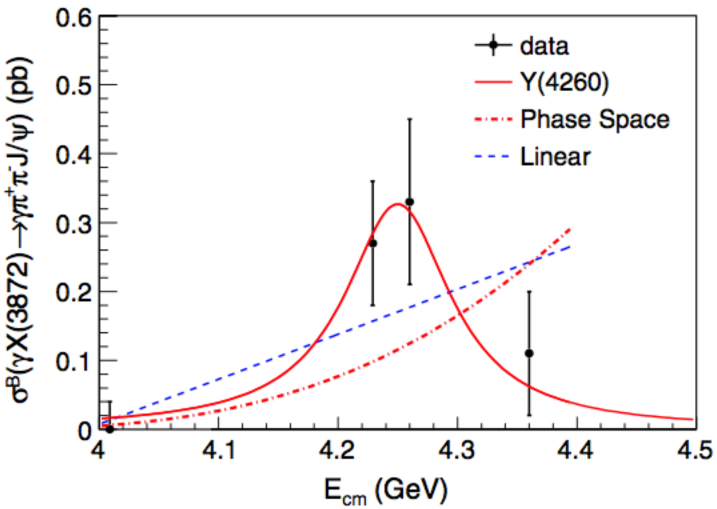
- Light hadrons: charmonium radiative decays (act as spin filter)
- Heavy hadrons: direct production, radiative and hadronic transitions

# The X(3872)

- BESIII previously observed: $e^+e^- \to \gamma X(3872), X(3872) \to \pi^+\pi^- J/\psi$
- The above process is dominated with $\rho J/\psi$
- Any more Isospin-violating decays?
- If the $X(3872)$ were the $\chi_{cJ}(2P)$ state of charmonium, $\Gamma(X(3872) \to \pi^0\chi_{c1}(1P)) \sim 0.06$ keV *(i.e. very small)*
  If the $X(3872)$ were a tetraquark state: $\Gamma(X(3872) \to \pi_0\chi_{c1}(1P))$ should be greatly enhanced.
  *[Dubynskiy, Voloshin, PRD 77, 014013 (2008)]*
- The $X(3872) \to \pi^0\chi_{cJ}$ decays are sensitive to the internal structure of the X(3872).

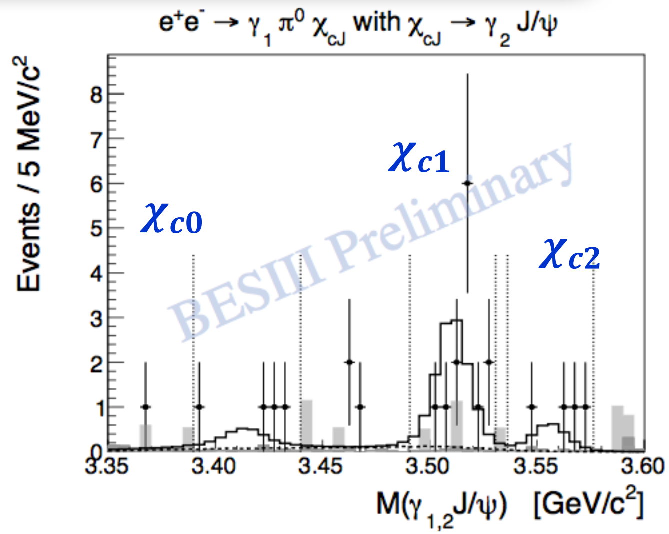
$e^+e^- \to \gamma X(3872)$ with $X(3872) \to \pi^+\pi^- J/\psi$
*[BESIII, PRL 112, 092001 (2014)]*



# Observation of $X(3872) \to \pi_0 \chi_{c1}(1P)$

9.0 fb$^{-1}$ for $4.15 < E_{CM} < 4.30$ GeV




We measure branching ratios

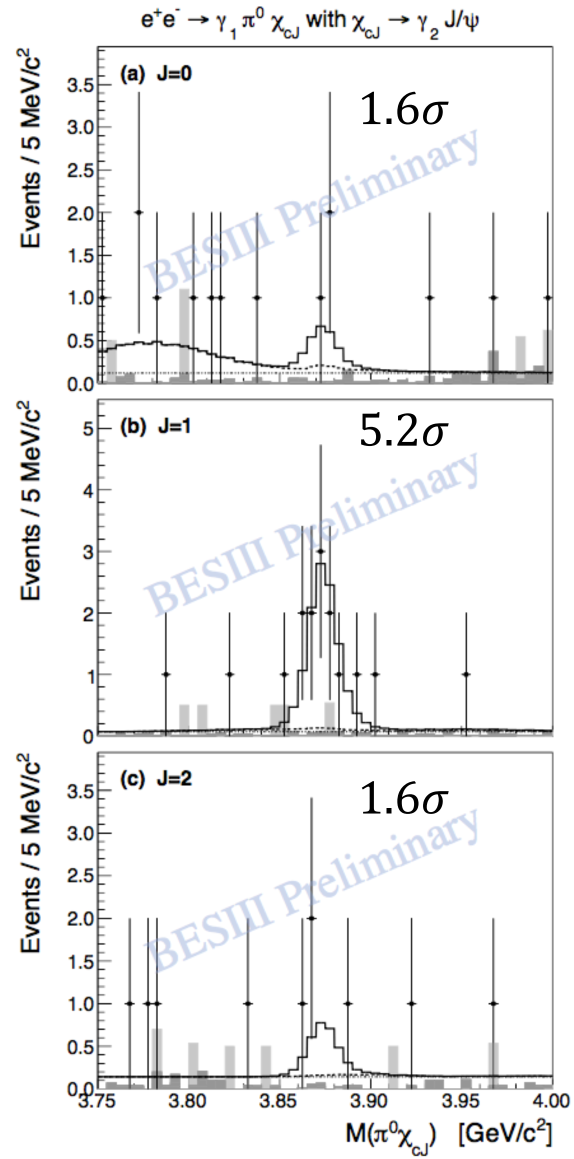
$R_J = B(X \to \pi^0\chi_{cJ}) / B(X \to \pi^+\pi^- J/\psi)$:

$R_0 < 19$ (90% U.L.)

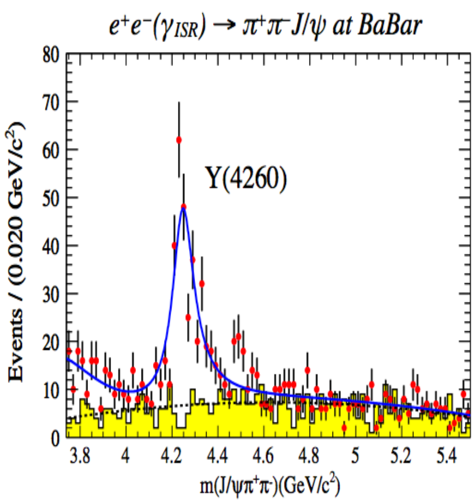
$R_1 = 0.88^{+0.31}_{-0.26} \pm 0.14$

$R_2 < 1.0$ (90% U.L.)

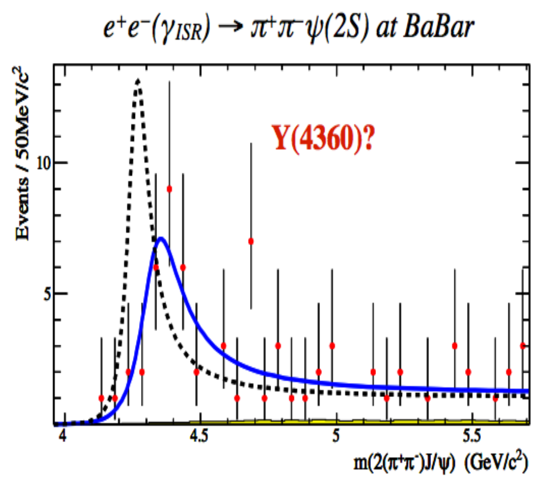
**The large value for $R$ disfavors the $\chi_{cJ}(2P)$ interpretation of the X(3872).**



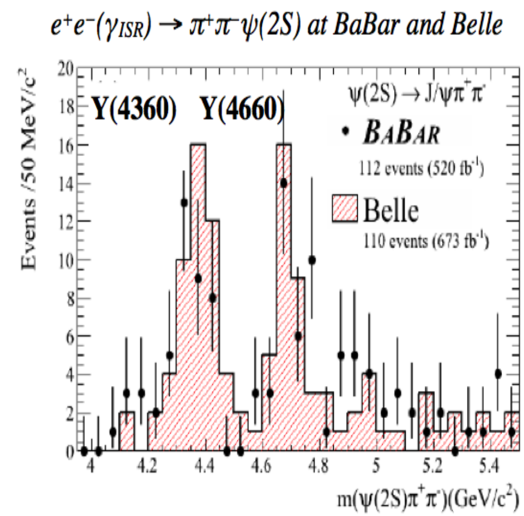
# The Y states




PRD 86, 051102(R) (2012)




PRL 98, 212001 (2007)




arXiv:1211.6271 and CHARM 2012

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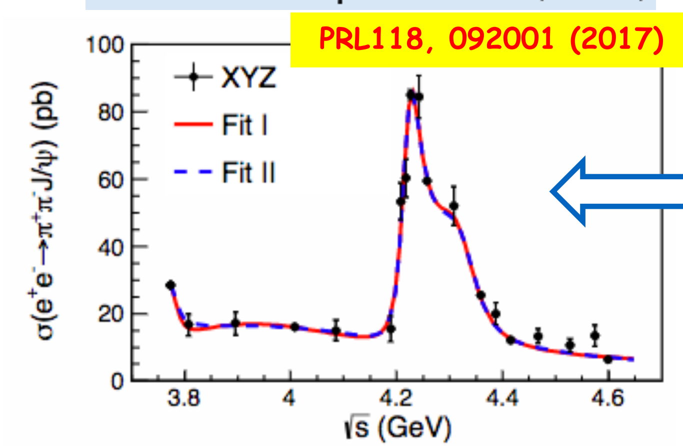
$e^+e^- \to \pi^+\pi^- J/\psi$ at BESIII (direct)

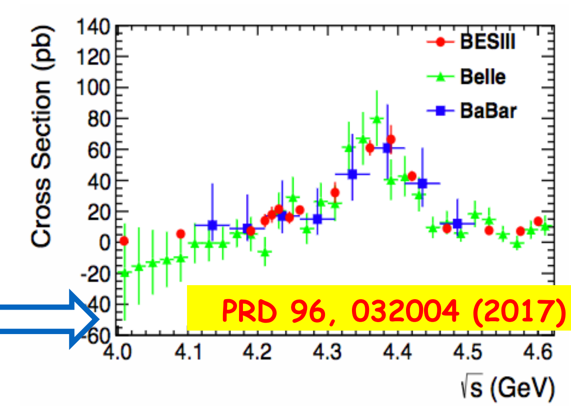



**Structure at 4260 is not a simple BW, but rather two:**

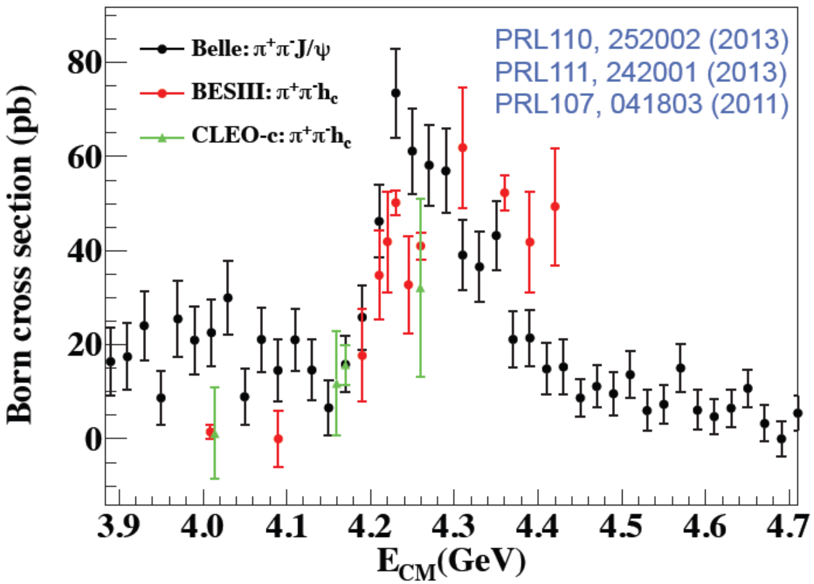
- $R_2$: consistent with the Y(4260), however narrower
- $R_3$: comparable to the Y(4360)

**BESIII confirms the Y(4360)**

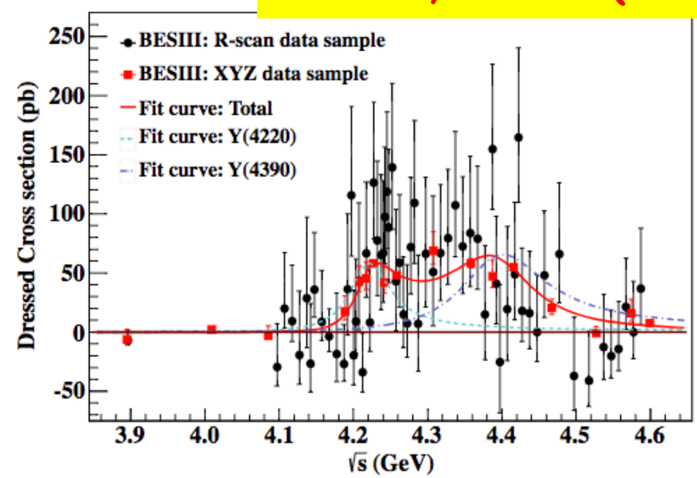
$e^+e^- \to \pi^+\pi^- \psi(2S)$



# $e^+e^- \to \pi^+\pi^- h_c$ cross sections

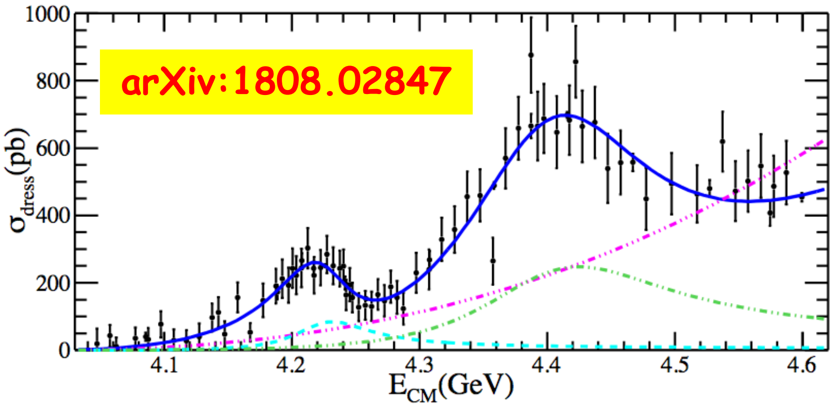



PRL118, 092002 (2017)

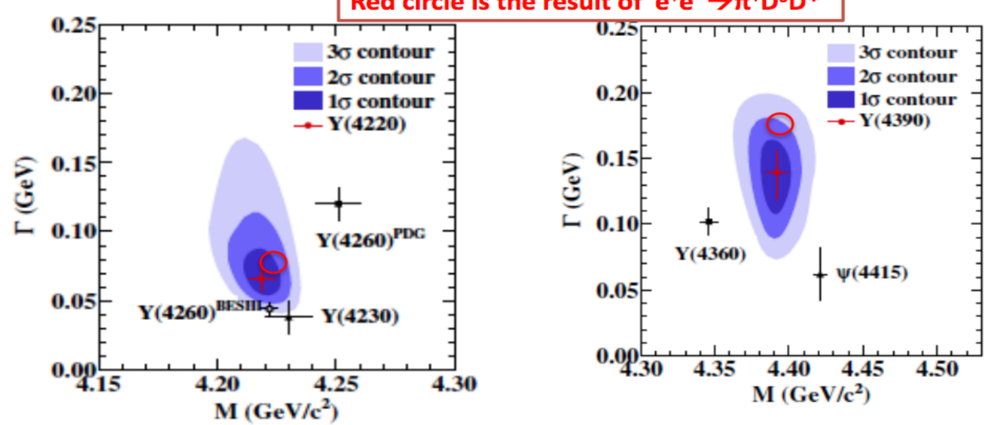



significant two structures

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



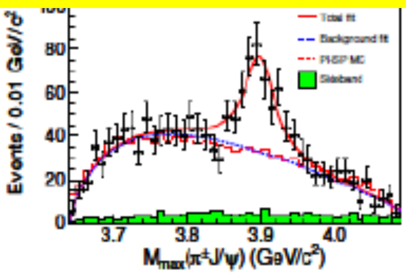

Red circle is the result of $e^+e^- \to \pi^+ D^0 D^{*-}$



# The Zc Family at BESIII

## Zc(3900)$^+$?

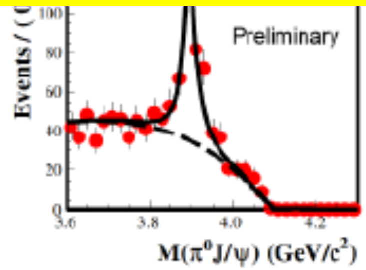
PRL 110, 252001 (2013)




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

## Zc(3900)$^0$?

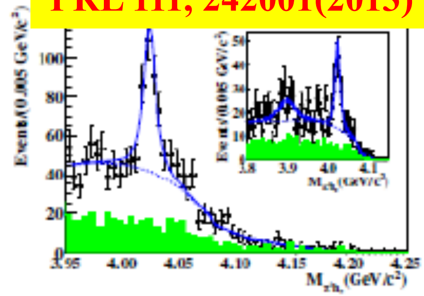
PRL 115, 112003 (2015)




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

## Zc(4020)$^+$?

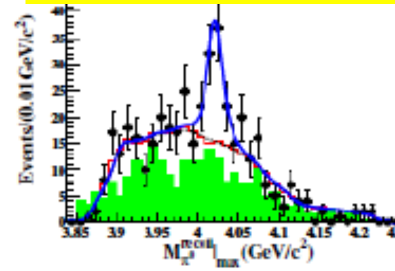
PRL 111, 242001(2013)




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

## Zc(4020)$^0$?

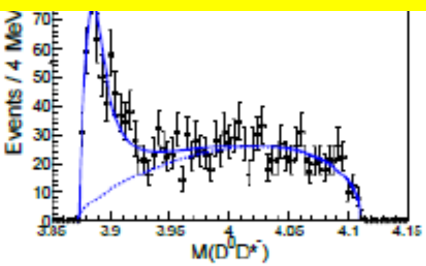
PRL113,212002 (2014)




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

## Zc(3885)$^+$?

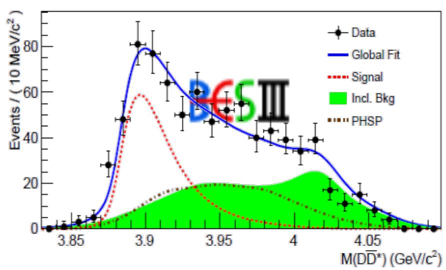
ST: PRL 112, 022001(2014)
DT: PRD92, 092006 (2015)




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

## Zc(3885)$^0$?

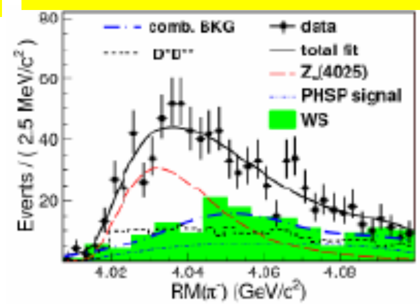
PRL 115, 222002 (2015)




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

## Zc(4025)$^+$?

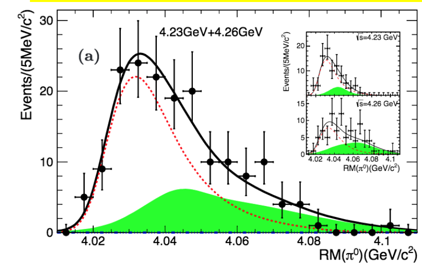
PRL 112, 132001 (2014)




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

## Zc(4025)$^0$?

PRL115, 182002 (2015)



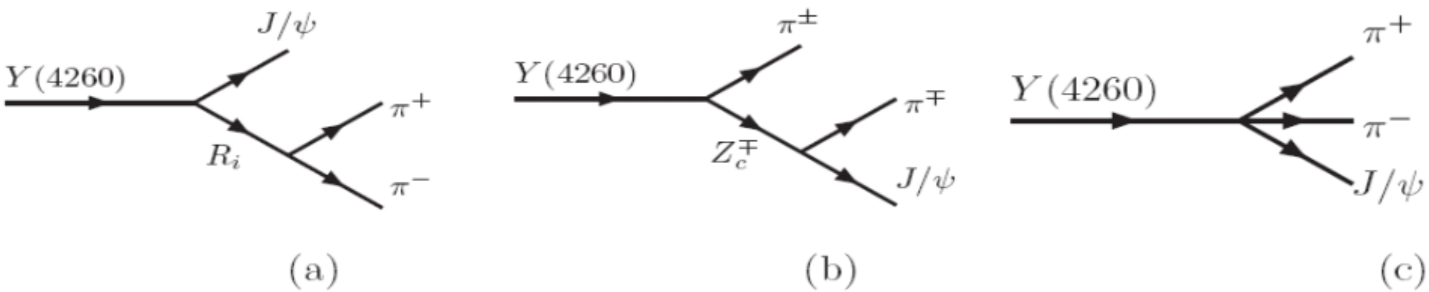

$e^+e^- \to \pi^0(D^*\bar{D}^*)^0$

Which is the nature of these states?

Different decay channels of the same observed states? Other decay modes?

# Amplitude analysis of $e^+e^- \to \pi^+\pi^- J/\psi$

PRL 119.072001 (2017)




**In the process $e^+e^- \to \gamma^* \to \pi^+\pi^- J/\psi$**

- **The helicity value of $\gamma^*$ is taken as $\lambda_0 = \pm 1$ due to from e+e- annihination**
- **$\gamma^* \to Z_c^\pm \pi^{m}$, $Z_c^\pm \to J/\psi\pi^\pm$, we try $J^p$ for X: $0^-$, $1^-, 1^+, 2^-, 2^+$, and $0^+$ is not allowed**
- **$Z_c^+$ and $Z_c^-$ states are assumed as isospin partner, with the same mass and coupling constant**
- **Six proceses are inclued in fitting to data:**

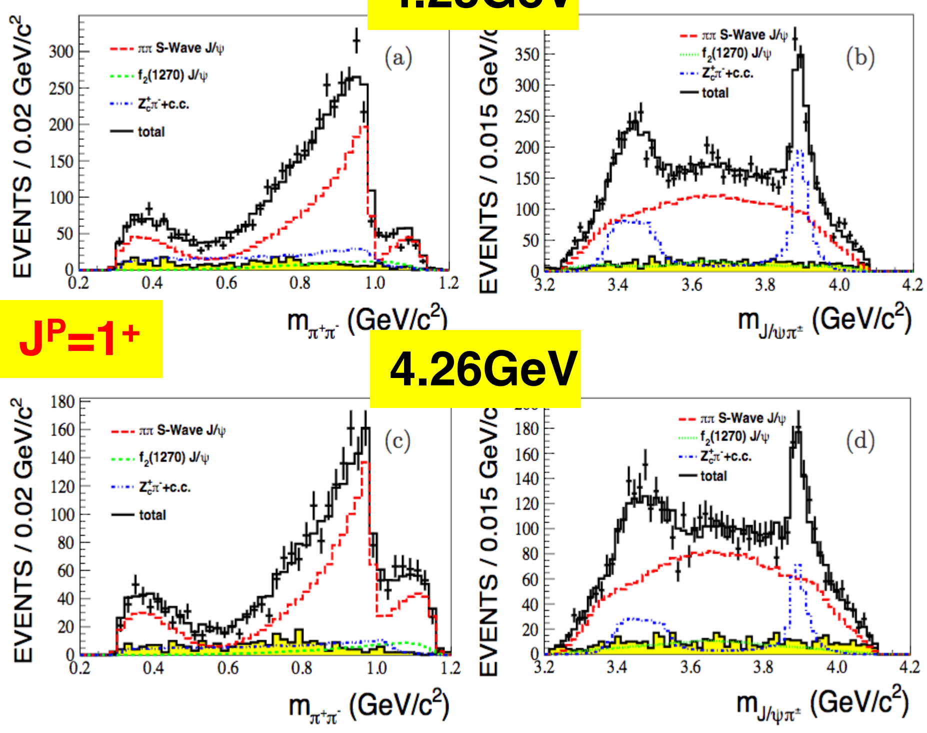
$$\sigma_0, f_0(980), f_2(1270), f_0(1370), Z_c^\pm, \text{and } \pi^+\pi^- J/\psi$$

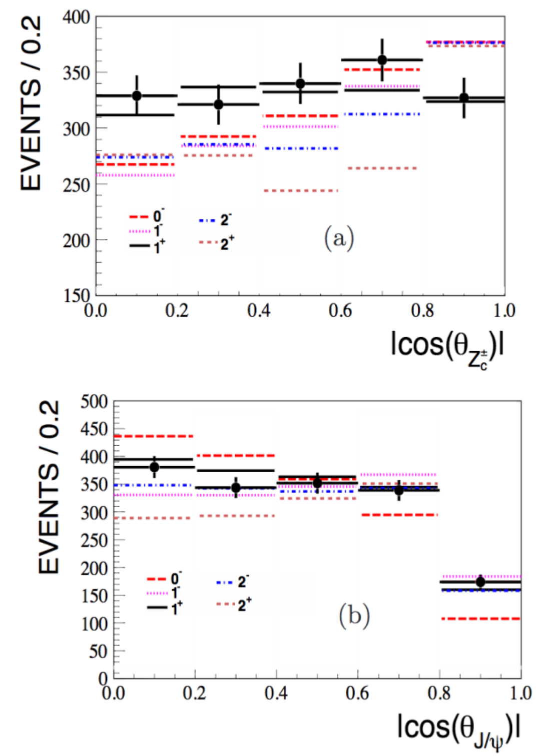
# Spin-parity determination of the $Z_c^+(3900)$

- Zc line shape parameterized with Flatte-like formula

**PRL 119.072001 (2017)**

$$BW(s) = \frac{1}{s - M^2 + i(g_1' \rho_{\pi J/\psi}(s) + g_2' \rho_{D^* D}(s))},$$




| Hypothesis | $\Delta(-2\ln L)$ | $\Delta$(ndf) | Significance |
|---|---|---|---|
| $1^+$ over $0^-$ | 94.0 | 13 | $7.6\sigma$ |
| $1^+$ over $1^-$ | 158.3 | 13 | $10.8\sigma$ |
| $1^+$ over $2^-$ | 151.9 | 13 | $10.5\sigma$ |
| $1^+$ over $2^+$ | 96.0 | 13 | $7.7\sigma$ |

$J^P$ is measured to be $1^+$ with significance larger than $7.6\boldsymbol{\sigma}$

# Search for $Z_c^{(\prime)} \rightarrow \rho\eta_c$

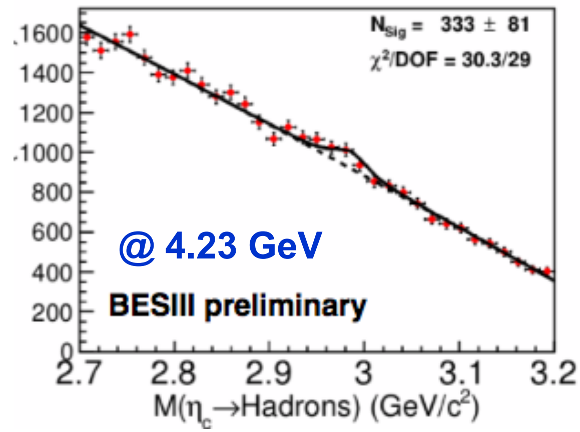
- Search for new decay mode of $Z_c(3900)$ and $Z_c(4020)$
- The ratios of $Z_c^{(\prime)} \rightarrow \rho\eta_c$ to $Z_c^{(\prime)} \rightarrow \pi J/\psi(\pi h_c)$ may discriminate **the tetra-quark** and **molecule** models.

**Date sets:**

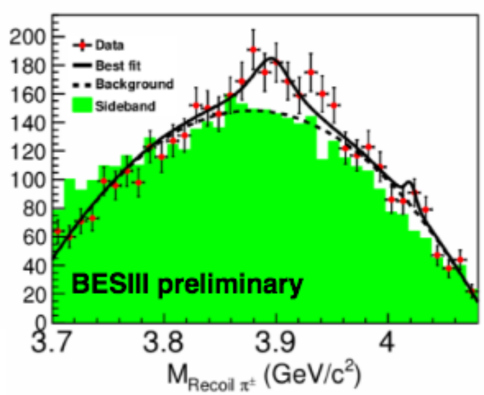
- ~4 $fb^{-1}$ data set distributed at $\sqrt{s} =$ 4.23,4.26,4.36,4.40,4.60 GeV

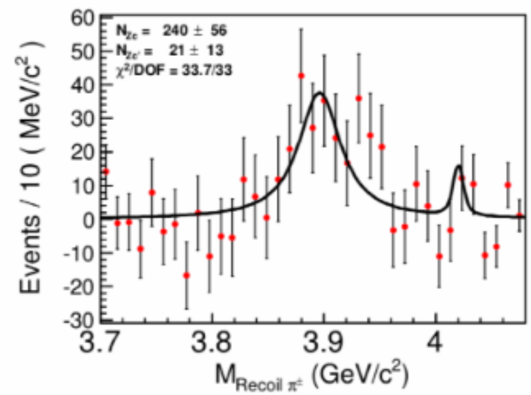
**Strategy of this analysis:**

- Start with looking for $e^+e^- \rightarrow \pi^+\pi^-\pi^0\eta_c, \eta_c \rightarrow 9$ hadronic decays




- Strong evidence of $e^+e^- \rightarrow \pi Z_c, Z_c \rightarrow \rho\eta_c$ is observed at $\sqrt{s} = 4.23$, statistical significance is 4.3σ. (3.9σ including systematics)
- $e^+e^- \rightarrow \pi Z_c', Z_c' \rightarrow \rho\eta_c$ is not seen in all data sets.




$e^+e^- \rightarrow \pi Z_c, Z_c \rightarrow \rho\eta_c$ @ 4.23 GeV

# Evidence for $Z_c \to \rho\eta_c$

- Measure Born cross section at 4.23 GeV:

*preliminary results*

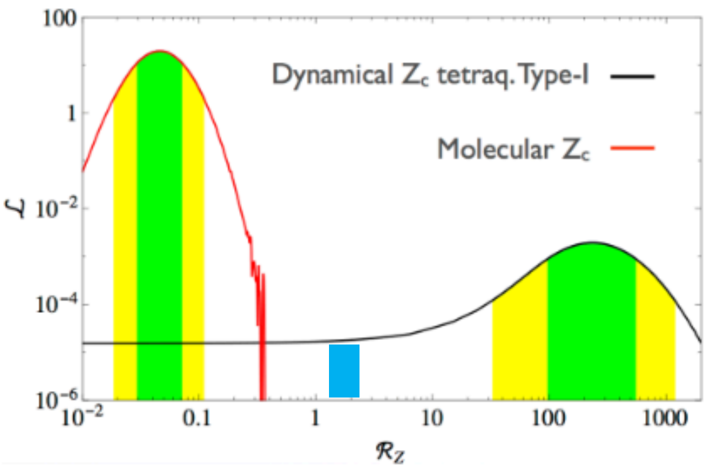
$\sigma^B(e^+e^- \to \pi^+\pi^-\pi^0\eta_c) = (46 \pm 12 \pm 10)$pb

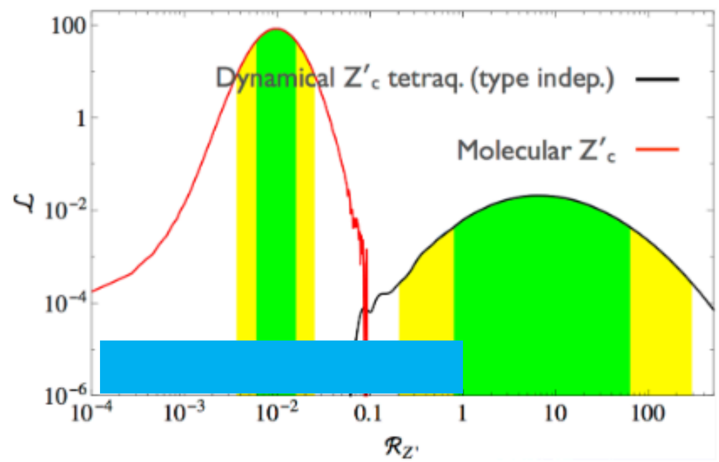
$\sigma^B(e^+e^- \to \pi Z_c, Z_c \to \rho\eta_c) = (47 \pm 11 \pm 11)$pb

**PLB 746, 194 (2015)**

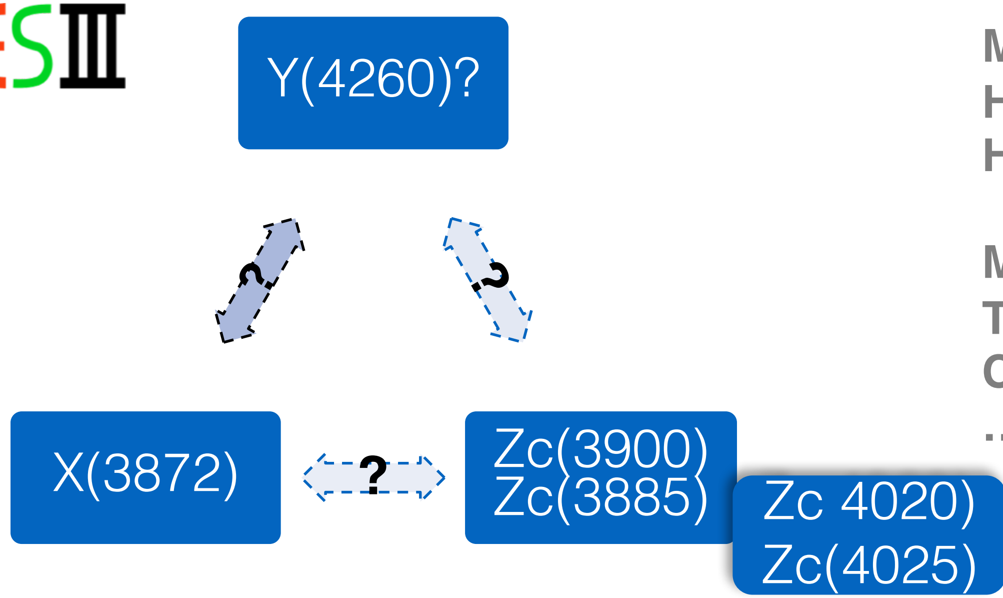
| | $\sqrt{s} = 4.23$ GeV | $\sqrt{s} = 4.26$ GeV | $\sqrt{s} = 4.36$ GeV | Tetra-quarks-I | Tetra-quarks-II | Molecule |
|---|---|---|---|---|---|---|
| $R_z = \frac{B(Z_c \to \rho\eta_c)}{B(Z_c \to \pi J/\psi)}$ | $2.1 \pm 0.8$ | $< 6.4$ | ... | $230^{+330}_{-140}$ | $0.27^{+0.40}_{-0.17}$ | $0.046^{+0.025}_{-0.017}$ |
| $R_{z'} = \frac{B(Z'_c \to \rho\eta_c)}{B(Z'_c \to \pi h_c)}$ | $< 1.9$ | $< 1.2$ | $< 1.0$ | | $6.6^{+56.8}_{-5.8}$ | $0.010^{+0.006}_{-0.004}$ |

*preliminary*




- $R_Z$: not consistent with any of the model calculations
- $R_{Z'}$: smaller than the calculations based on tetra-quarks model, while not in contradiction with the molecule model calculation




Multiquark
Hybrid
Hadrocharmonium

Molecule
Threshold effects
Cusps
…

**States or/and interactions**

# What is the role of threshold

--Many new observations near thresholds: D*D,D*D*, $D_1$D, …

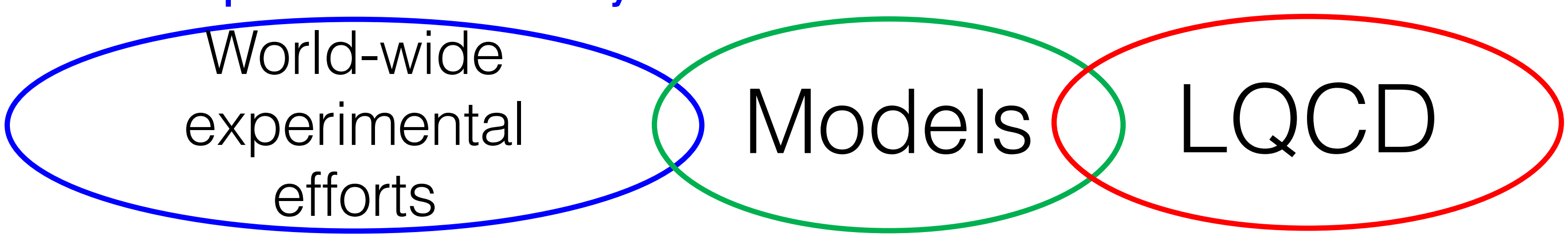
* Phase variations appear in many process: not unique for resonance

## To have a complete picture, more findings are desired

- **Energy-dependence**
- **Patterns in productions and decays**

**Pole properties**

**For XYZ, the picture is still unclear**

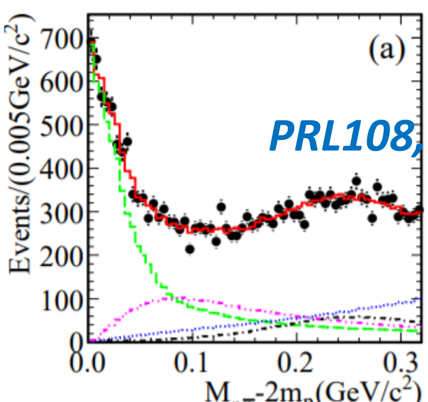


# Light hadron spectroscopy

- $X(p\bar{p})$/X(1835)
- X(2370)
- Y(2175) and Zs
- $a_0(980)$-$f_0(980)$ mixing

# X($p\bar{p}$)/X(1835)

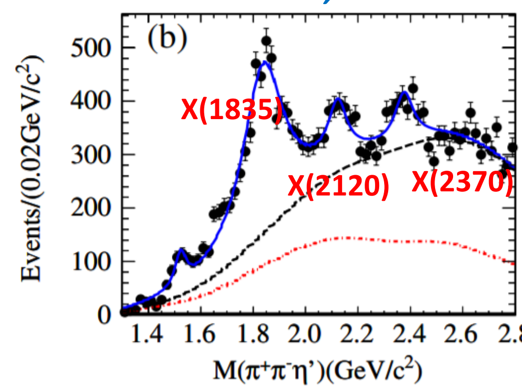
- X(ppbar)
  - An anomalous strong $p\bar{p}$ threshold enhancement structure which was first observed by BESII in $J/\psi \to \gamma p\bar{p}$
  - BESIII confirmed its existence with much higher significance and PWA (with FSI considered) is performed
    - $0^{-+}$
    - Mass = $1836.5^{+19}_{-5}{}^{+18}_{-17} \pm 19$ MeV/$c^2$
    - Width < 76 MeV/$c^2$ @ 90% C.L.




*PRL108, 112003*

- X(1835)
  - First observed by BESII in $J/\psi \to \gamma\eta'\pi^+\pi^-$
  - BESIII confirmed its existence with much higher significance
    - **Spin-parity is not known**
    - Mass = $1836.5 \pm 3.0^{+5.6}_{-2.1}$ MeV/$c^2$
    - Width = $190 \pm 9^{+38}_{-36}$ MeV/$c^2$

*PRL106, 072002*

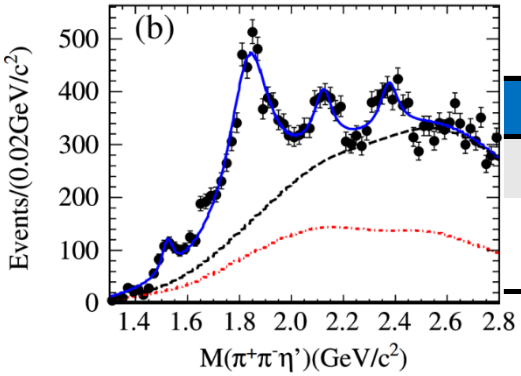



***Are they the same state? A $p\bar{p}$ bound state?***
***What's the spin-parity of X(1835)?***
***Why their widths are so different?***

# Anomalous line shape of $\eta'\pi^+\pi^-$ near $p\bar{p}$ mass threshold: connection between X(1835) and X($p\bar{p}$)

## X(1835) observed in $J/\psi \to \gamma\eta'\pi^+\pi^-$

Phys. Rev. Lett. 106, 072002 (2011)



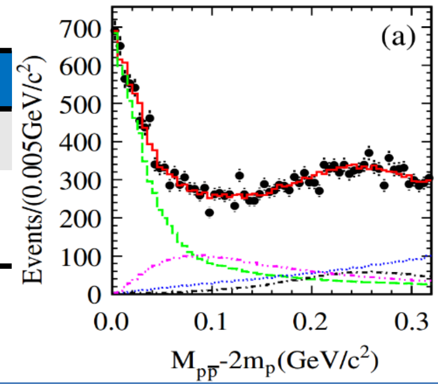

| X(1835) $J^{PC}=0^{-+}$ |
|---|
| $M = 1844 \pm 9^{+16}_{-25}$ MeV/$c^2$ |
| $\Gamma = 192^{+20+62}_{-17-43}$ MeV/$c^2$ |

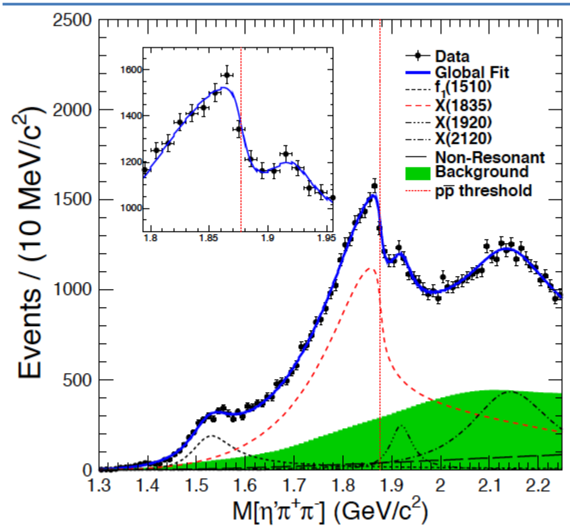
## X($p\bar{p}$) observed in $J/\psi \to \gamma p\bar{p}$

PRL 108, 112003 (2012)

PRL 115, 091803 (2015)

| X($p\bar{p}$) $J^{PC}=0^{-+}$ |
|---|
| $M = 1832^{+19}_{-5}{}^{+18}_{-17} \pm 19$ MeV/$c^2$ |
| $\Gamma = 13 \pm 19$ MeV/$c^2$ (< 76 MeV/$c^2$ @ 90% C.L.) |



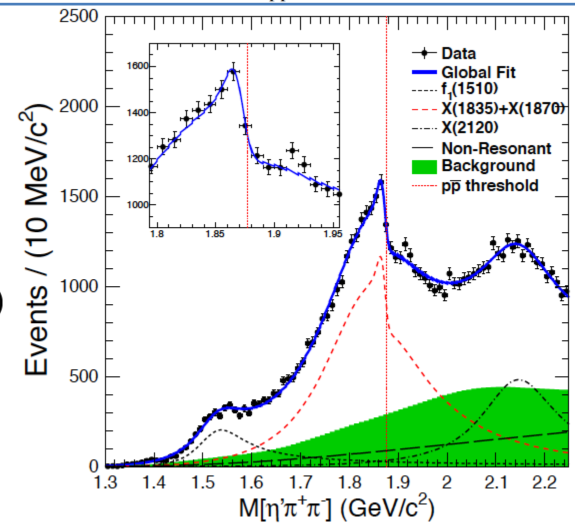




## Connection is emerging

**PRL 117, 042002 (2016)**

**Model 1:** Flatte lineshape with strong coupling to $p\bar{p}$ and one additional, narrow Breit-Wigner at ~1920 MeV/$c^2$

**Model 2:** Coherent sum of X(1835) Breit-Wigner and one additional, narrow Breit-Wigner at ~1870 MeV/$c^2$

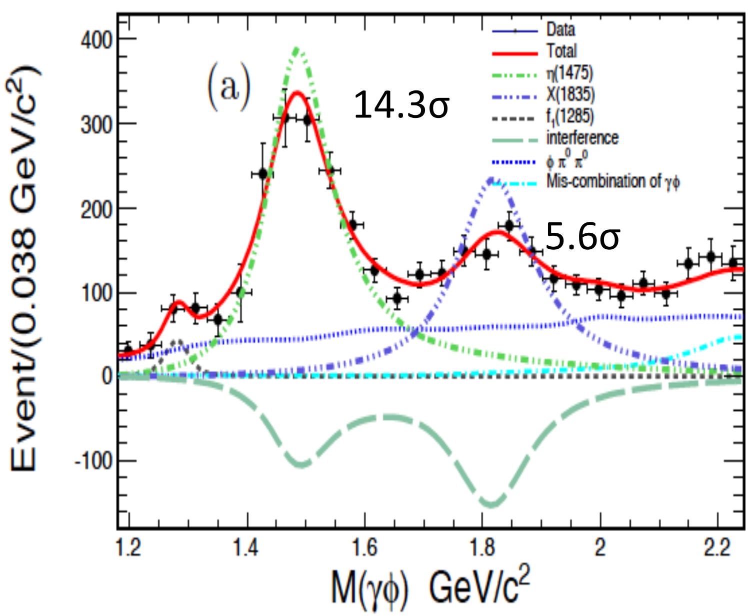


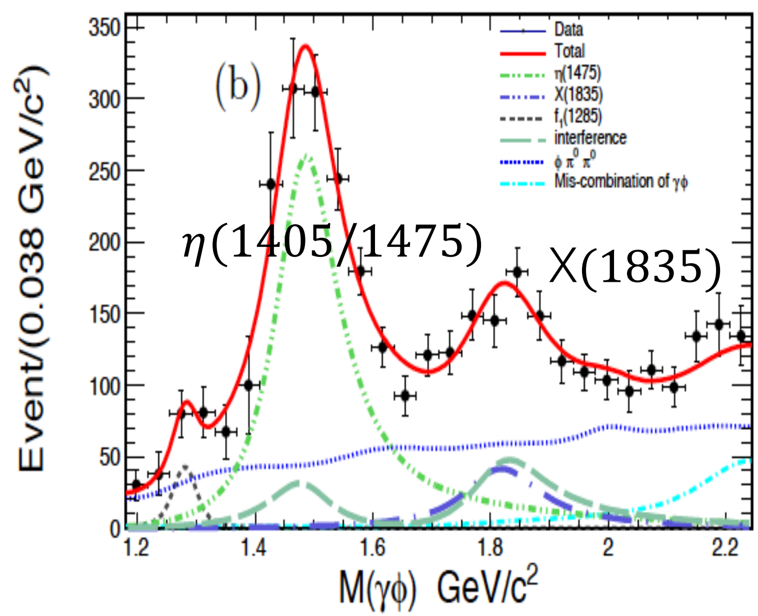

The anomalous line shape can be modeled two models with equally good fit quality.

- Suggest the existence of a state, either a broad state with strong couplings to $p\bar{p}$, or a narrow state just below the $p\bar{p}$ mass threshold
- Support the existence of a $p\bar{p}$ molecule-like state or bound state

# J/ψ→γγϕ

- First observation of X(1835)→γϕ *PRD97, 051101 (R) (2018)*
  – Sizeable $s\bar{s}$ components in X(1835): **more complicated than a pure $N\bar{N}$ state**
- First observation of η(1475)→γϕ *PLB594, 47 (2004)*
  – Measured Γ(η(1475)→γρ)/Γ(η(1475)→γϕ) = (11.1±3.5) or (7.5±2.5)
  – Theoretical prediction Γ(η(1440)→γρ)/Γ(η(1440)→γϕ) ≈ 3.8 *PRD87, 014023 (2013)*



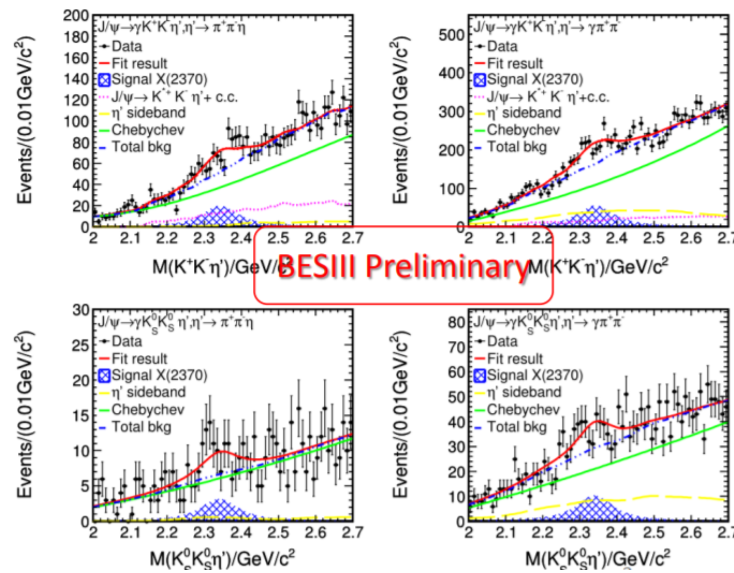



# Observation of X(2370) in $J/\psi \to \gamma KK\eta'$

- ✓ X(2120) and X(2370) were first observed in $J/\psi \to \gamma\eta'\pi^+\pi^-$
  - LQCD predicts the lowest lying $0^{-+}$ glueball has mass between 2.3-2.6 GeV/$c^2$
  - X(2120) and X(2370) are candidates?
- ✓ Combined study of $J/\psi \to \gamma K^+K^-\eta'/\gamma K_S K_S\eta'$

*Spin-parity is not yet determined*

  - First observation of X(2370) in this process
  - Mass/width are consistent with X(2370) in $J/\psi \to \gamma\eta'\pi^+\pi^-$
  - B [X(2370)→KKη′]/B[X(2370)→$\eta'\pi^+\pi^-$] ~ 1/15
  - A theoretical work predicts **$\Gamma_{G\to KK\eta'}/\Gamma_G$=0.011** and **$\Gamma_{G\to\eta'\pi\pi}/\Gamma_G$=0.090** for $M_G$=2.37 GeV/$c^2$ (PRD 87, 054036)
  - No clear signal of X(2120)




| | |
|---|---|
| $M$ (MeV/$c^2$) | $2343.91 \pm 6.88(stat.) \pm 1.23(sys.)$ |
| $\Gamma$ (MeV) | $117.73 \pm 12.75(stat.) \pm 4.14(sys.)$ |
| $B(J/\psi \to \gamma X(2370) \to \gamma K^+K^-\eta')$ | $(1.86 \pm 0.39\ (stat.) \pm 0.29\ (sys.)) \times 10^{-5}$ |
| $B(J/\psi \to \gamma X(2370) \to \gamma K^0_S K^0_S\eta')$ | $(1.19 \pm 0.37\ (stat.) \pm 0.18\ (sys.)) \times 10^{-5}$ |

# Search for glueball at BESIII

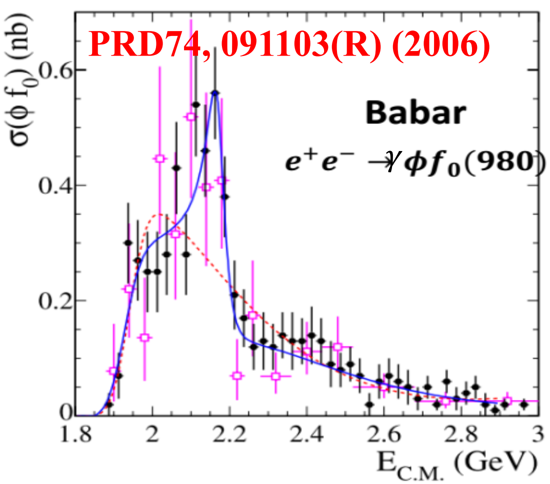
- $0^{++}$ sector
  - The production rate of $f_0(1710)$ is compatible with LQCD prediction for a pure gauge scalar glueball
- $2^{++}$ sector
  - $f_2(2340)$ seems to be a good candidate due to its large production rate in $J/\psi\to\gamma\phi\phi$ and $J/\psi\to\gamma\eta\eta$
- $0^{-+}$ sector
  - X(2370) might be a candidate for 0-+ glueball
  - X(2500) observed in $J/\psi\to\gamma\phi\phi$ and the structure around 2.6 GeV/$c^2$ observed in $J/\psi\to\gamma\eta'\pi^+\pi^-$

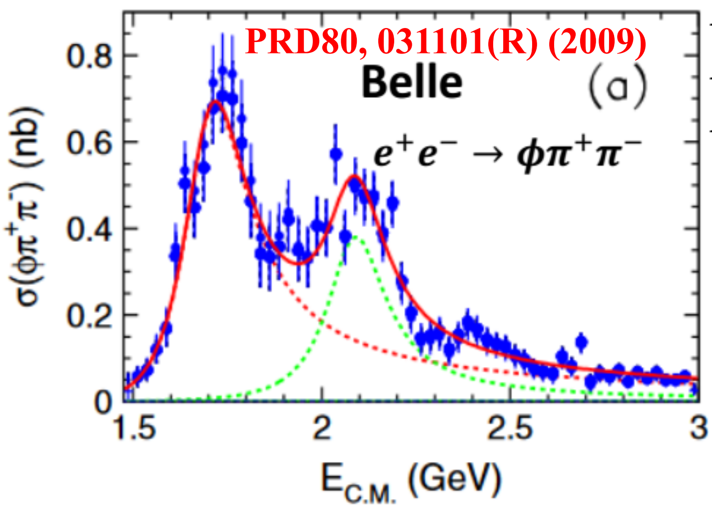
| $J/\psi\to\gamma PP$ | $J/\psi\to\gamma VV$ | $J/\psi\to\gamma PPP$ |
|---|---|---|
| $J/\psi\to\gamma\eta\eta$ | $J/\psi\to\gamma\omega\phi$ | $J/\psi\to\gamma KK\eta'$ |
| $J/\psi\to\gamma\pi^0\pi^0$ | $J/\psi\to\gamma\phi\phi$ | $J/\psi\to\gamma\eta\pi^0\pi^0$ |
| $J/\psi\to\gamma K_SK_S$ | $J/\psi\to\gamma\omega\omega$ | … |
| $J/\psi\to\gamma\eta\eta'$ | … | … |
| $J/\psi\to\gamma\eta'\eta'$ | … | … |
| … | … | … |

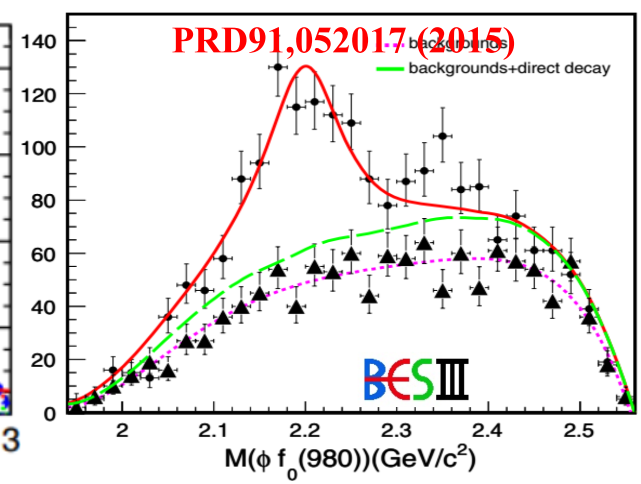
Published
Release is in schedule
Ongoing

# Y(2175) and the strangeonium-like $Z_S$

- **Y(2175) (denoted as $\phi(2170)$ by PDG) was observed by BaBar, and confirmed by Belle, BESII and BESIII**
  - A candidate for a tetraquark state, a strangeonium hybrid state, or a conventional $s\bar{s}$ state
- **Unique place to search for the $Z_S$:**
  - Y(2175) is regarded as strangeonium-like state analogous to Y(4260)
  - Mode: $Z_S \to \pi^{\pm}\phi$ **(Expected mass $M_{Z_S} \approx 1.4$ GeV/c$^2$)**



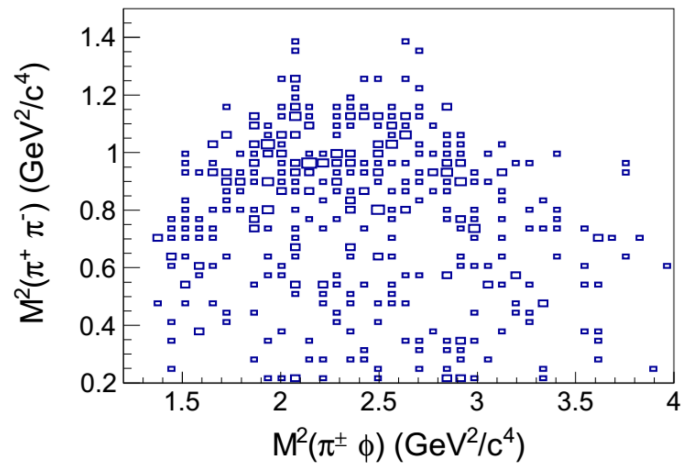



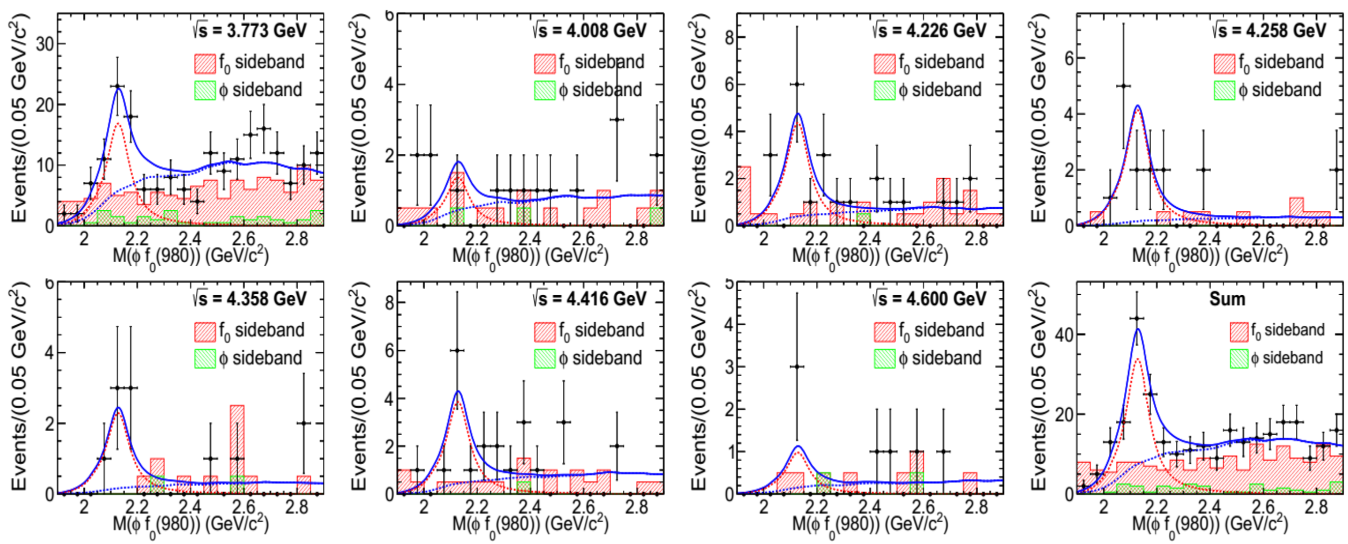



# Observation of $e^+e^-\to\eta Y(2175)$ at $\sqrt{s} > 3.7$ GeV

**arXiv:1709.04323**

- Perform the search for Y(2175) resonance in the process $e^+e^-\to\eta\phi f_0(980)$ at $\sqrt{s}$ between 3.7 and 4.6 GeV.
- Combined significance for Y(2175) signal is observed to be larger than **10σ**.
- No significant $Z_S$ signals in $\phi\pi^\pm$ spectrum.

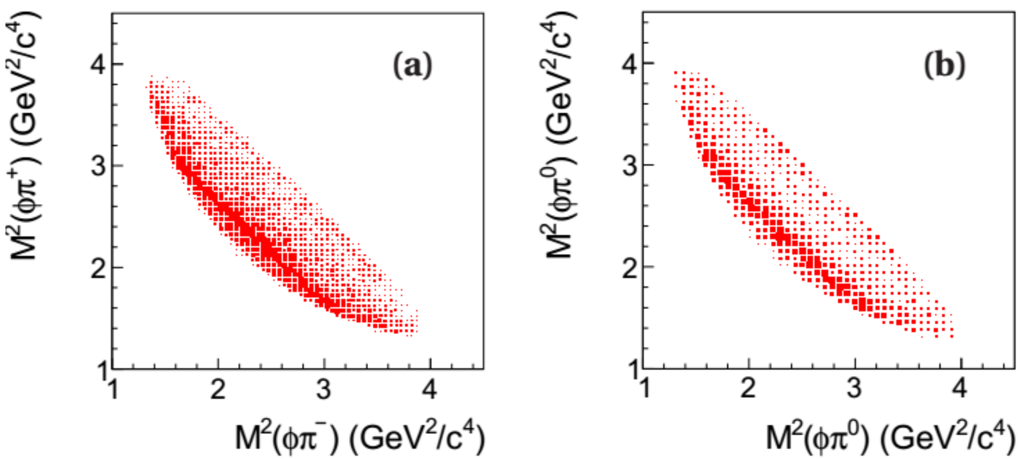


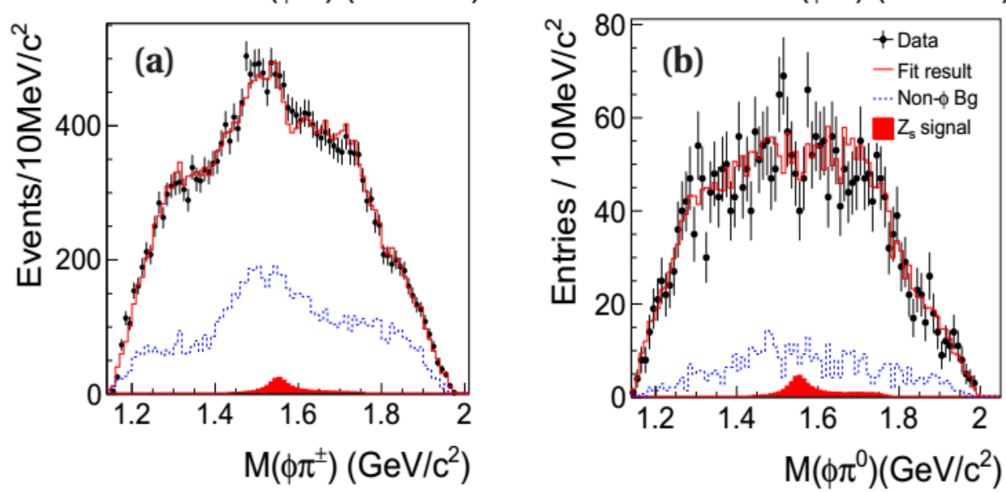
# Search for the $Z_S$ at 2.125 GeV

arXiv:1801.10384

- Perform the search for $Z_S$ via $e^+e^-\to\phi\pi^+\pi^-$ ($\phi\pi^0\pi^0$) using 108 $pb^{-1}$ data collected at $\sqrt{s} = 2.125$ GeV.
- PWA is performed
  - $\phi\sigma$
  - $\phi f_0(980)$
  - $\phi f_0(1370)$
  - $\phi f_2(1270)$
  - $Z_s\pi$




- No clear $Z_S$ signal is observed in the $\phi\pi$ mass spectrums around 1.5 $GeV/c^2$.



# $a_0(980)$-$f_0(980)$ mixing

- The lightest scalar nonet: σ, κ, $a_0(980)$, $f_0(980)$
- Theorists proposed $a_0(980)$-$f_0(980)$ mixing mechanism ~40 years ago, to clarify the nature of these two states
- BESIII reported evidence of $a_0(980)$-$f_0(980)$ mixing using 225 million J/ψ events and 106 million ψ′ events
  (suggested by *Wu, Zhao, and Zou, PRD 75, 114012 (2007)* )

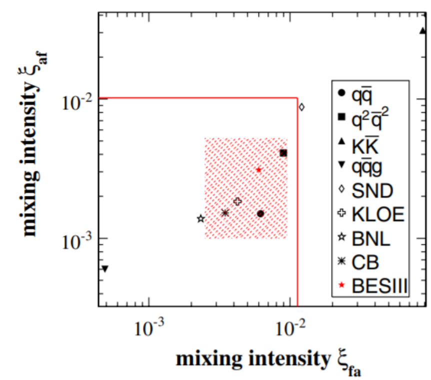
*PRD83, 032003 (2011)*

$$\xi_{fa} = \frac{\mathcal{B}[J/\psi \to \phi f_0(980) \to \phi a_0^0(980) \to \phi\eta\pi^0]}{\mathcal{B}[J/\psi \to \phi f_0(980) \to \phi\pi\pi]},$$

**3.4σ**
**< 1.1% @ 90% C.L.**

$$\xi_{af} = \frac{\mathcal{B}[\chi_{c1} \to \pi^0 a_0^0(980) \to \pi^0 f_0(980) \to \pi^0\pi^+\pi^-]}{\mathcal{B}[\chi_{c1} \to \pi^0 a_0^0(980) \to \pi^0\pi^0\eta]}.$$

**1.9σ**
**< 1.0% @ 90% C.L.**




- No affirmative experimental result for almost 40 years on the magnitude of the mixing

Editors' Suggestion

## Observation of $a_0^0(980)$–$f_0(980)$ Mixing

M. Ablikim *et al.* (BESIII Collaboration)

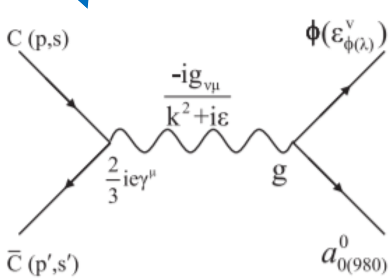
Phys. Rev. Lett. **121**, 022001 (2018) – Published 11 July 2018

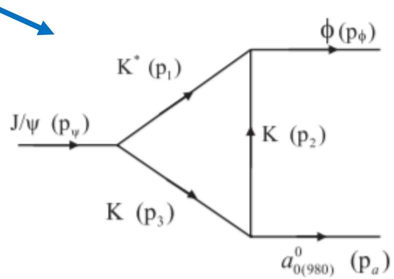
- With 1.3 billion J/ψ and 450 million ψ′, **$a_0(980)$-$f_0(980)$ mixing is observed for the first time**

TABLE II. The branching fractions ($\mathcal{B}$) and the intensities ($\xi$) of the $a_0^0(980)$-$f_0(980)$ mixing. The first uncertainties are statistical, the second ones are systematic, and the third ones are obtained using different parameters for $a_0^0(980)$ and $f_0(980)$ as described in the text.

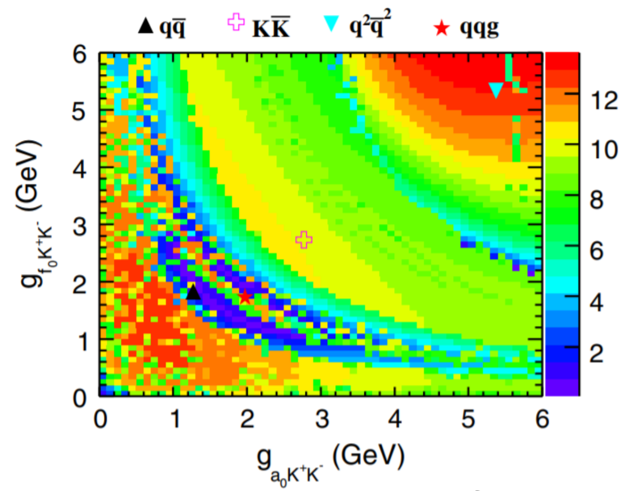
| | $f_0(980) \to a_0^0(980)$ | | |
|---|---|---|---|
| Channel | Solution I | Solution II | $a_0^0(980) \to f_0(980)$ |
| $\mathcal{B}$ (mixing) ($10^{-6}$) | $3.18 \pm 0.51 \pm 0.38 \pm 0.28$ | $1.31 \pm 0.41 \pm 0.39 \pm 0.43$ | $0.35 \pm 0.06 \pm 0.03 \pm 0.06$ |
| $\mathcal{B}$ (EM) ($10^{-6}$) | $3.25 \pm 1.08 \pm 1.08 \pm 1.12$ | $2.62 \pm 1.02 \pm 1.13 \pm 0.48$ | ... |
| $\mathcal{B}$ (total) ($10^{-6}$) | $4.93 \pm 1.01 \pm 0.96 \pm 1.09$ | $4.37 \pm 0.97 \pm 0.94 \pm 0.06$ | ... |
| $\xi$ (%) | $0.99 \pm 0.16 \pm 0.30 \pm 0.09$ | $0.41 \pm 0.13 \pm 0.17 \pm 0.13$ | $0.40 \pm 0.07 \pm 0.14 \pm 0.07$ |

7.4σ 5.5σ




from *PRD 75, 114012 (2007)*

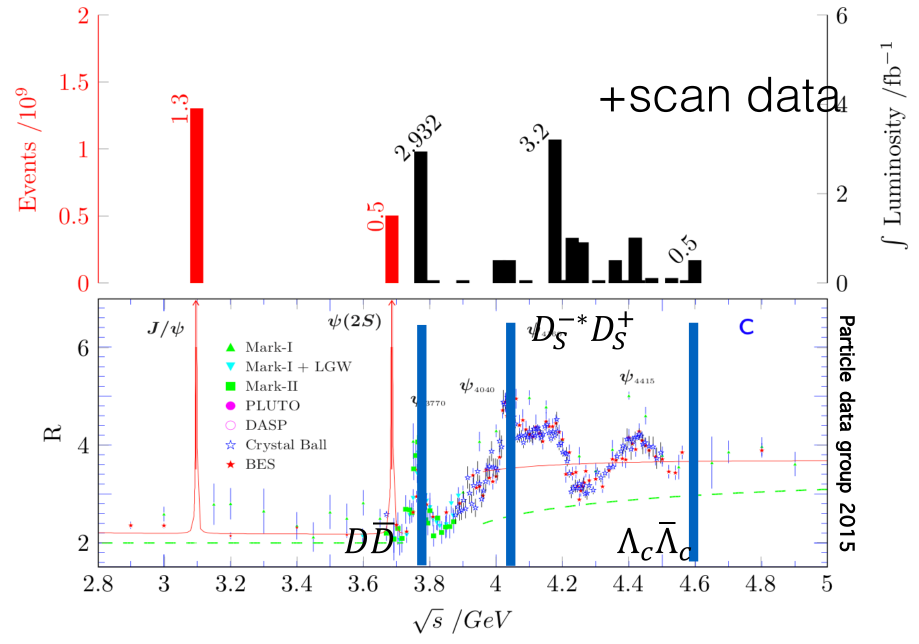



statistical significance

***Observed mixing between two light scalar mesons may help constrain their internal structure.***

# The charmed meson decays

- $D_{(s)}$ leptonic decay
- $D_s \to p\bar{n}$



# Precision measurement of CKM elements -- Test EW theory

**CKM matrix elements are fundamental SM parameters that describe the mixing of quark fields due to weak interaction.**

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

CKM matrix

BESIII + B factories + LQCD

Three generations of quark?

Unitary matrix?

Expected precision < 2% at BESIII

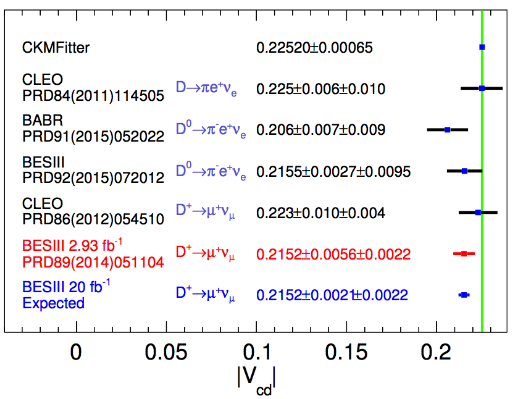
BESIII + B factories + LHCb + LQCD

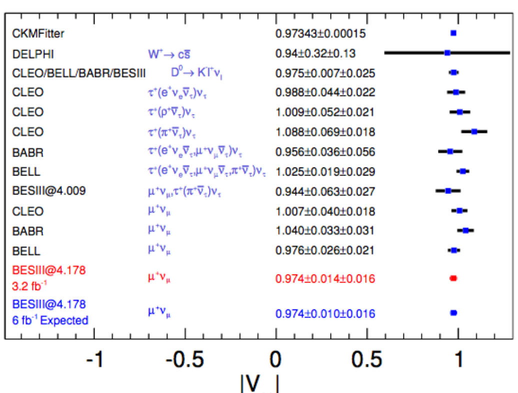
- Precision measurement of CKM matrix elements
- A precise test of SM model
- New physics beyond SM?

# $D_{(S)}$ Leptonic decays

**Purely Leptonic:**

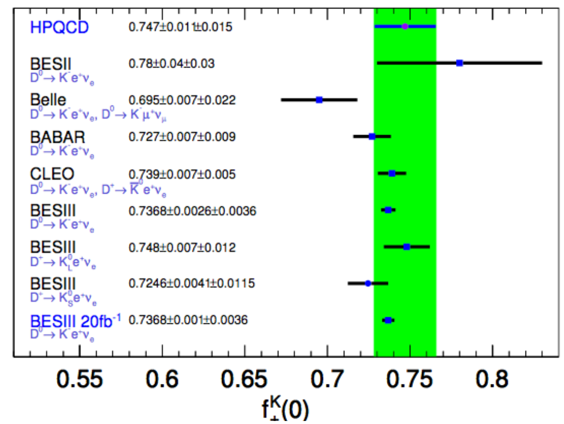
- Extract decay constant $f_{D(s)}$ incorporates the strong interaction effects (wave function at the origin)
- To validate Lattice QCD calculation of $f_{B(s)}$ and provide constrain of CKM-unitarity

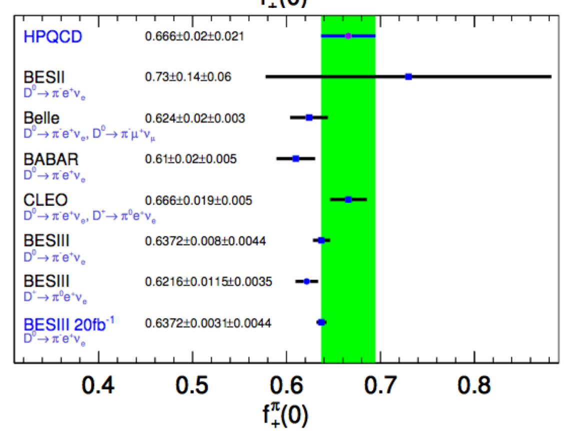



**Semi-leptonic**: form facotr (FF)

- Measure $|V_{cx}|$ x FF
- Charm physics:
  - CKM-unitarity ⇒ $|V_{cx}|$, extract FF, test LQCD
  - Input LQCD FF to test CKM-unitarity

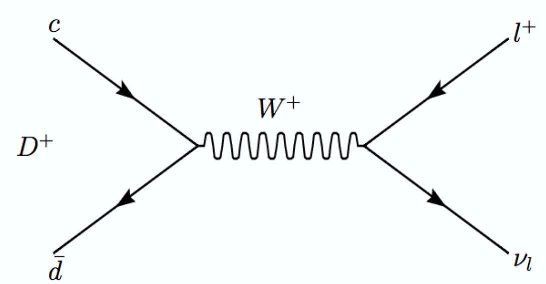


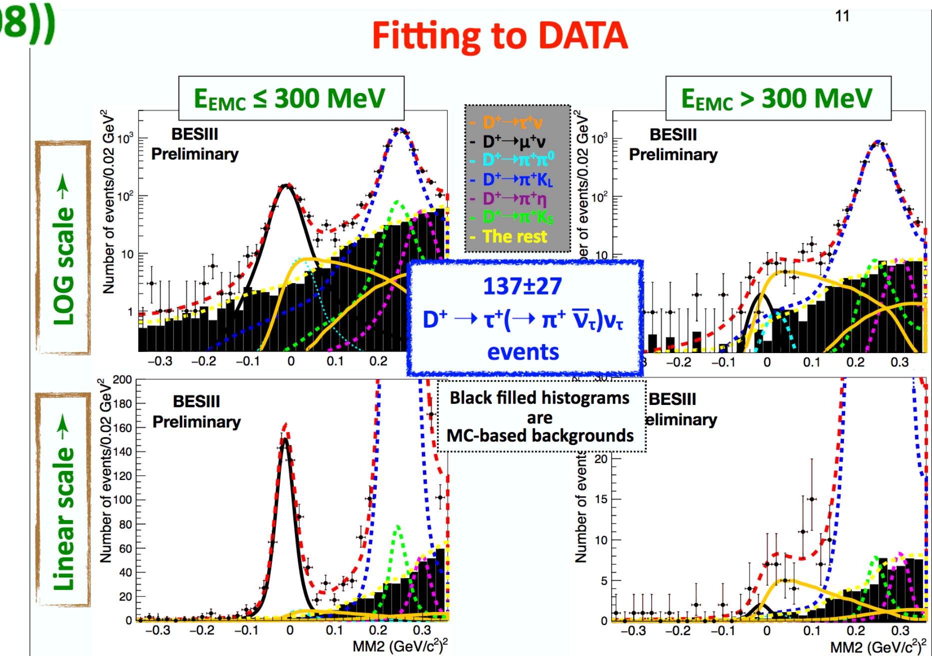
# Evidence for $D^+ \to \tau^+(\pi^+\nu)\nu$

**2.93/fb @3.773GeV**

- BF < $1.2\times10^{-3}$ @ 90% C.L. by CLEO.
  (818/pb @ 3774 MeV; PRD 78, 052003 (2008))
- A simple pure leptonic decay:




**with 6 dominant $D^-$ singly tag modes**




$$R \equiv \frac{\Gamma(D^+ \to \tau^+\nu)}{\Gamma(D^+ \to \mu^+\nu)} = \frac{m_{\tau^+}^2\left(1-\frac{m_{\tau^+}^2}{M_{D^+}^2}\right)^2}{m_{\mu^+}^2\left(1-\frac{m_{\mu^+}^2}{M_{D^+}^2}\right)^2}$$

**SM prediction: 2.66±0.01**

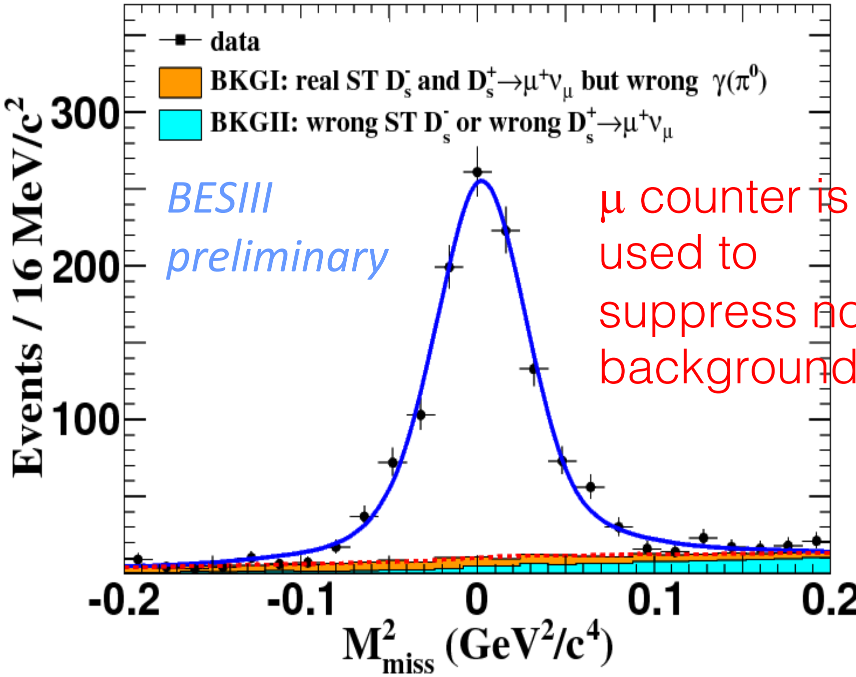
**BESIII: 3.21±0.64**

$1\sigma$ difference?

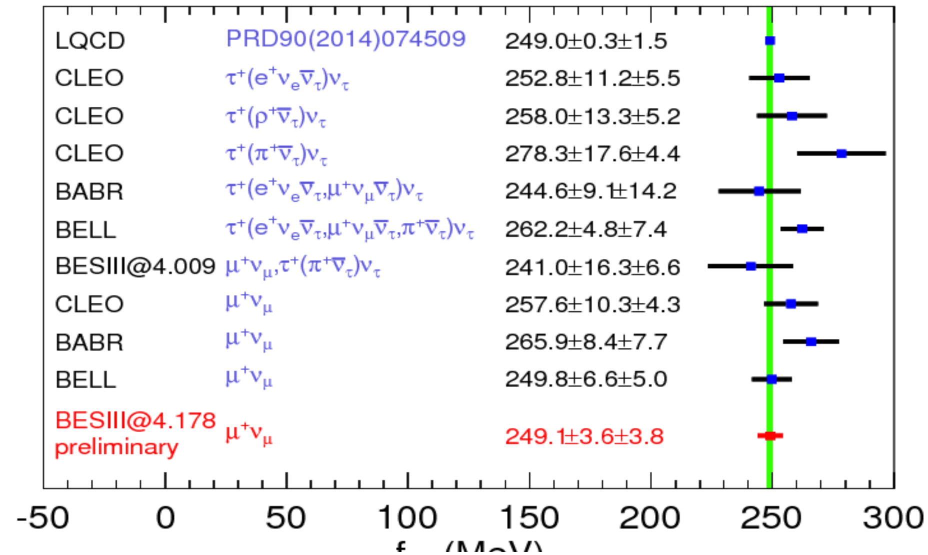
- > $4\sigma$ statistical significance. First evidence!
- BF($D^+ \to \tau^+\nu_\tau$) = $[1.20\pm0.24(\text{stat.})]\times10^{-3}$.

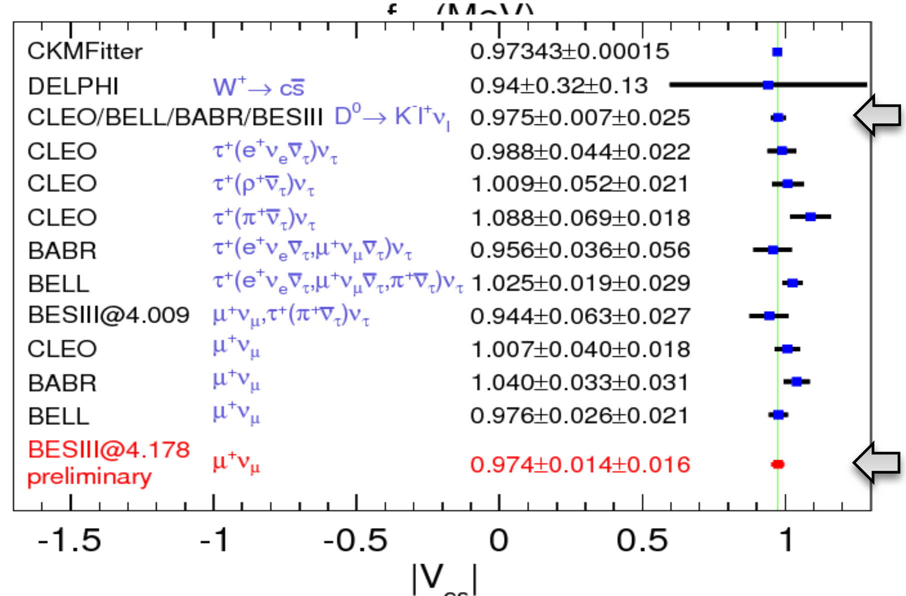
# Measurement of $B(D_s^+ \to \mu^+ \nu)$

✓ 14 ST channels are used to reconstruct $D_s^-$ mesons.




μ counter is used to suppress non-μ backgrounds

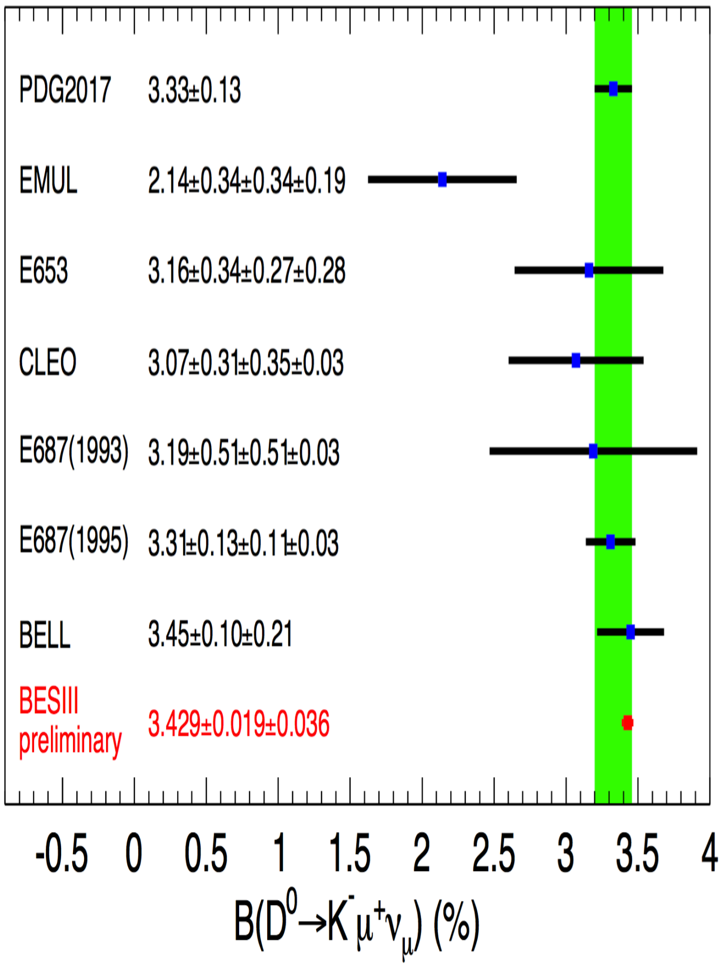


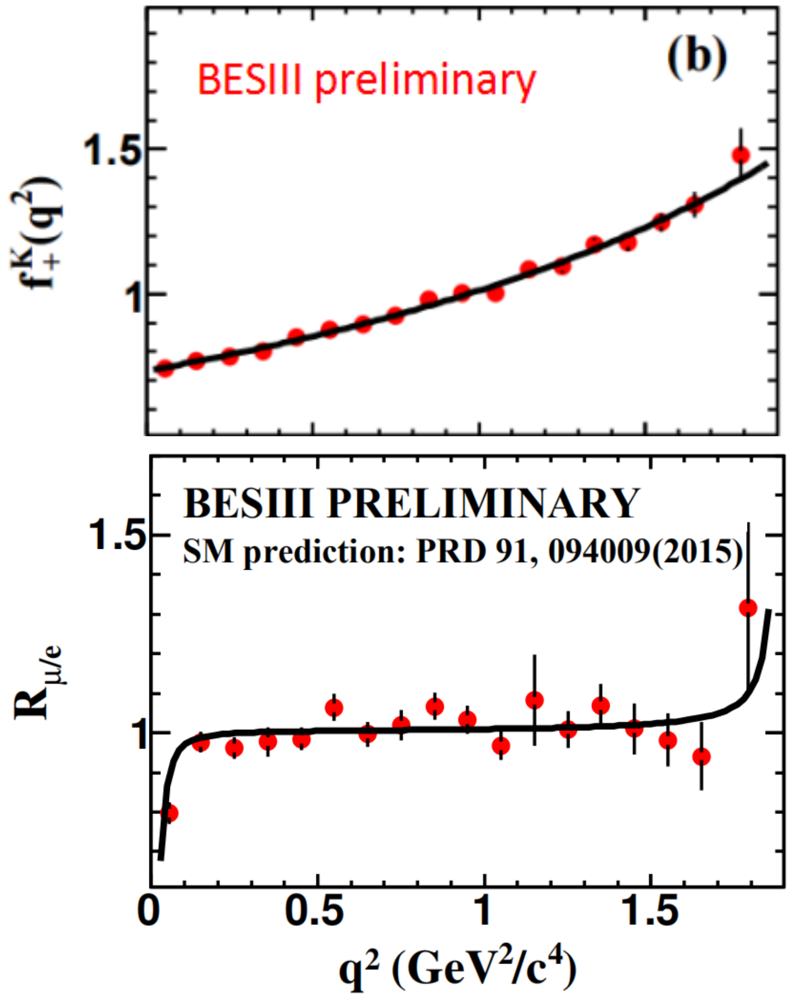




Preliminary results: $B(D_s^+ \to \mu^+ \nu)$ $= (5.28 \pm 0.15_{stat} \pm 0.14_{syst}) \times 10^{-3}$

# $D^0 \to K^- \mu^+ \nu$

**2.93 fb$^{-1}$ @$E_{cm}$ = 3.773 GeV**




$$R_{\mu/e} = \frac{\Gamma(D^+ \to K^- \mu^+ \nu_\mu)}{\Gamma(D^+ \to K^- e^+ \nu_e)[PRD92{,}072012(2015)]} = 0.978 \pm 0.007 \pm 0.012$$

*consistent with SM within 2σ*

# Observation of $D_s^+ \to p\,\bar{n}$

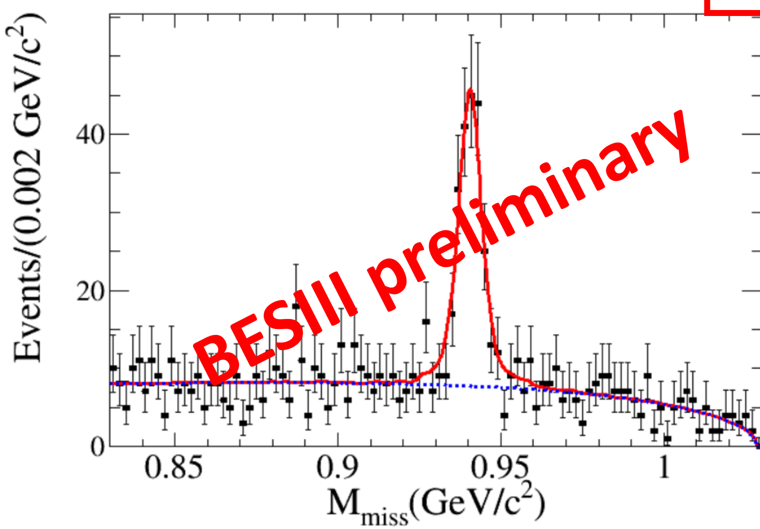
**3.19 fb$^{-1}$ @$E_{cm}$ = 4.178 GeV**

- Only kinematic allowed baryonic decay of charmed meson, and help for understanding the dynamical enhancement of W-annihilation
  - Short-distance expected: $Br \sim 10^{-6}$ PLB663, 326 (2008)
  - Long-distance enhance to: $Br \sim 10^{-3}$
- First evidence was observed by CLEO-c: $(1.30 \pm 0.36^{+0.12}_{-0.16}) \times 10^{-3}$

(PRL100, 181802(2008))

preliminary result

$$\mathcal{B}_{D_s^+ \to p\bar{n}} = (1.22 \pm 0.10) \times 10^{-3}$$




- Confirm CLEO-c's measurement with greatly improved accuracy
- Consistent with the prediction of the enhanced BR due to long-distance effect via hadronic loop

# The $\Lambda_c^+$ decays

*based on ~1 month data taking*

## *Hadronic decay*

$\Lambda_c^+ \rightarrow pK^-\pi^+$ + 11 CF hadronic modes :PRL 116, 052001 (2016)

$\Lambda_c^+ \rightarrow pK^+K^-, p\pi^+\pi^-$ :PRL 117, 232002 (2016)

$\Lambda_c^+ \rightarrow nK_S\pi^+$ :PRL 118, 12001 (2017)

$\Lambda_c^+ \rightarrow p\eta, p\pi^0$ :PRD 95, 111102(R) (2017)

$\Lambda_c^+ \rightarrow \Sigma^-\pi^+\pi^+\pi^0$ :PLB 772, 388 (2017)

$\Lambda_c^+ \rightarrow \Xi^{0(*)}K^+$ :PLB783, 200 (2018)

## *Semi-leptonic decay*

$\Lambda_c^+ \rightarrow \Lambda e^+\nu_e$ : PRL115, 221805(2015)

$\Lambda_c^+ \rightarrow \Lambda\mu^+\nu_\mu$ : PLB767, 42 (2017)

## *Inclusive decay*

$\Lambda_c^+ \rightarrow \Lambda X$ : PRL121, 062003 (2018)

$\Lambda_c^+ \rightarrow e^+ + X$ : arXiv:1805.09060

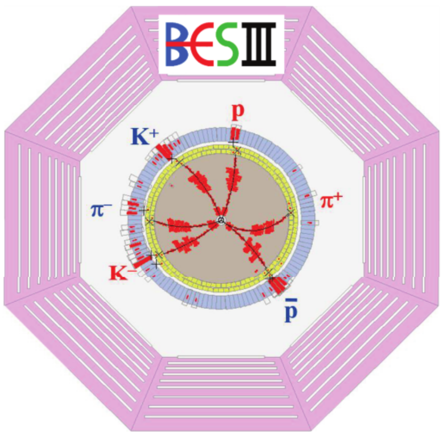
## *Production*

$\Lambda_c^+\Lambda_c^-$ cross section : PRL 120,132001(2018)

# $\Lambda_c$ threshold production at BESIII

In 2014, BESIII took data above $\Lambda_c$ pair threshold and run machine at 4.6GeV with excellent performance.

| Energy(GeV) | lum.(1/pb) |
|---|---|
| 4.575 | 47.67 |
| 4.580 | 8.54 |
| 4.590 | 8.16 |
| 4.600 | 567.93 |



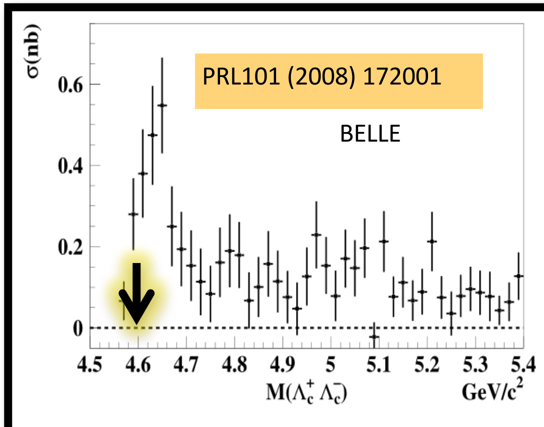




FIG. 4: The cross section for the exclusive process $e^+e^- \to \Lambda_c^+\Lambda_c^-$.

Measurement using the threshold pair-productions via $e^+e^-$ annihilations is unique: *the most simple and straightforward*

First time to systematically study charmed baryon at threshold!

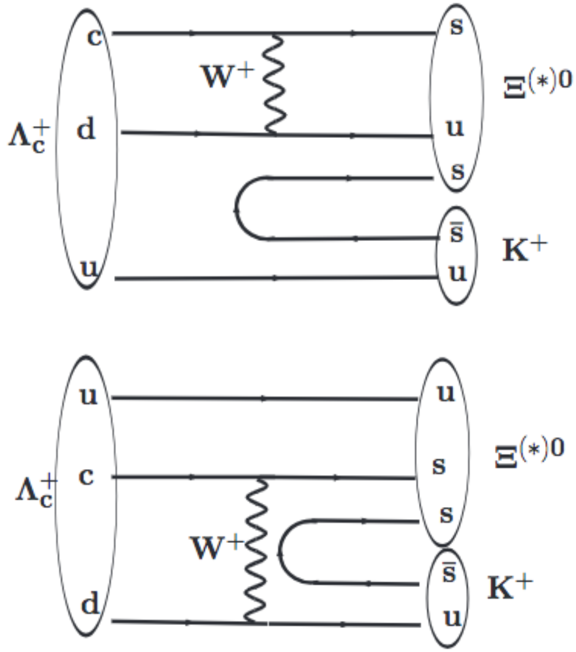
# The improvement after 2014

*EPJC 77, 895 (2017)* *PRL 116, 052001 (2016)* *PRL113, 042002 (2014)*

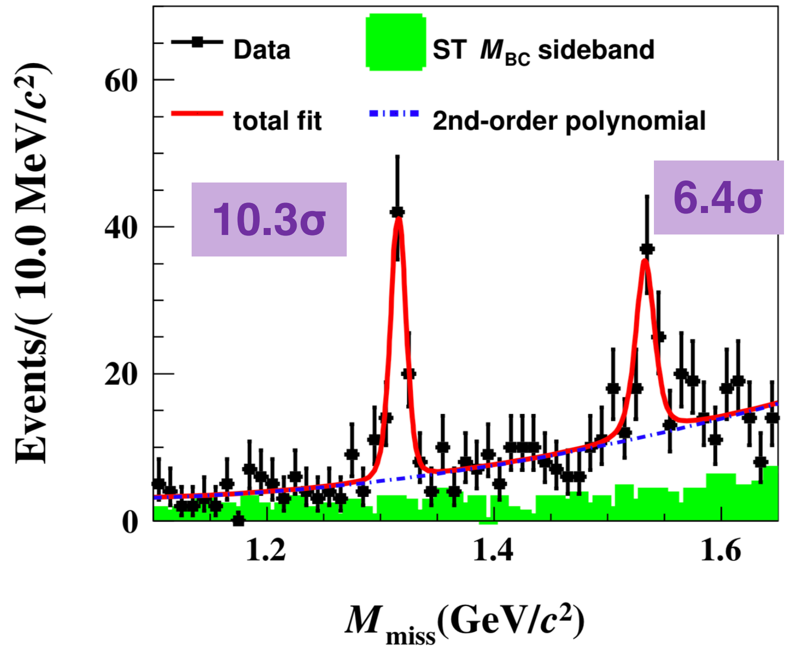
| Mode | HFLAV2016 | BESIII (%) | PDG 2014 (%) | BELLE (%) |
|---|---|---|---|---|
| $pK_S^0$ | $1.59 \pm 0.07$ | $1.52 \pm 0.08 \pm 0.03$ | $1.15 \pm 0.30$ | |
| $pK^-\pi^+$ | $6.46 \pm 0.24$ | $5.84 \pm 0.27 \pm 0.23$ | $5.0 \pm 1.3$ | $6.84 \pm 0.24^{+0.21}_{-0.27}$ |
| $pK_S^0\pi^0$ | $2.03 \pm 0.12$ | $1.87 \pm 0.13 \pm 0.05$ | $1.65 \pm 0.50$ | |
| $pK_S^0\pi^+\pi^-$ | $1.69 \pm 0.11$ | $1.53 \pm 0.11 \pm 0.09$ | $1.30 \pm 0.35$ | |
| $pK^-\pi^+\pi^0$ | $5.05 \pm 0.29$ | $4.53 \pm 0.23 \pm 0.30$ | $3.4 \pm 1.0$ | |
| $\Lambda\pi^+$ | $1.28 \pm 0.06$ | $1.24 \pm 0.07 \pm 0.03$ | $1.07 \pm 0.28$ | |
| $\Lambda\pi^+\pi^0$ | $7.09 \pm 0.36$ | $7.01 \pm 0.37 \pm 0.19$ | $3.6 \pm 1.3$ | |
| $\Lambda\pi^+\pi^-\pi^+$ | $3.73 \pm 0.21$ | $3.81 \pm 0.24 \pm 0.18$ | $2.6 \pm 0.7$ | |
| $\Sigma^0\pi^+$ | $1.31 \pm 0.07$ | $1.27 \pm 0.08 \pm 0.03$ | $1.05 \pm 0.28$ | |
| $\Sigma^+\pi^0$ | $1.25 \pm 0.09$ | $1.18 \pm 0.10 \pm 0.03$ | $1.00 \pm 0.34$ | |
| $\Sigma^+\pi^+\pi^-$ | $4.64 \pm 0.24$ | $4.25 \pm 0.24 \pm 0.20$ | $3.6 \pm 1.0$ | |
| $\Sigma^+\omega$ | $1.77 \pm 0.21$ | $1.56 \pm 0.20 \pm 0.07$ | $2.7 \pm 1.0$ | |
| $\Lambda e^+\nu_e$ | $3.18 \pm 0.32$ | $3.63 \pm 0.38 \pm 0.20$ | $2.1 \pm 0.6$ | |

**Improved precisions significantly with factors of 4~10**

# W-exchange-only process $\Lambda_c^+ \to \Xi^{(*)0} K^+$




**PLB783, 200 (2018)**




- First absolute measurement of the decay BF
- No models can accommodate the both rates

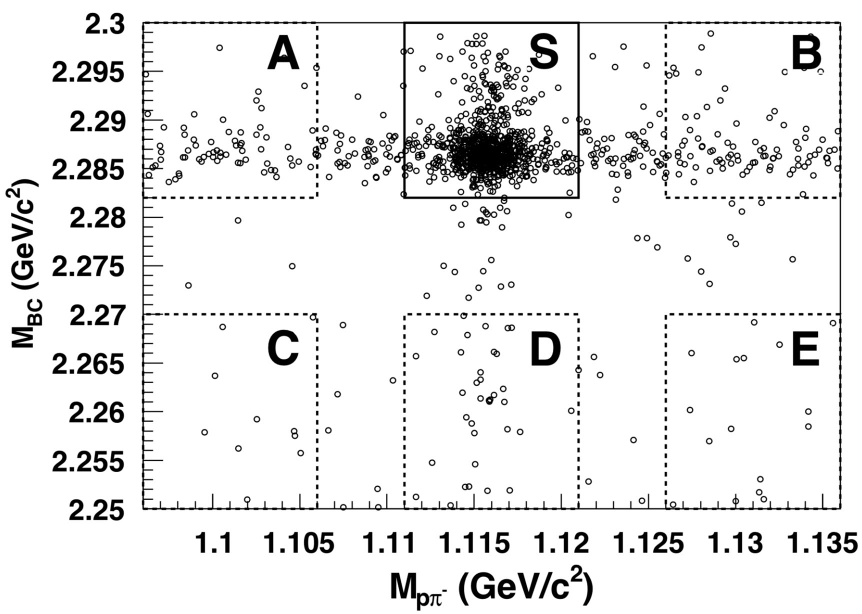
$$\mathcal{B}(\Lambda_c^+ \to \Xi^0 K^+) = (5.90 \pm 0.86 \pm 0.39) \times 10^{-3}$$

$$\mathcal{B}(\Lambda_c^+ \to \Xi(1530)^0 K^+) = (5.02 \pm 0.99 \pm 0.31) \times 10^{-3}$$

# The inclusive channel $\Lambda_c^+ \to \Lambda + X$

**PRL121, 062003 (2018)**

- Mediated by the *c*-*s* transition, essential input in the calculation of the $\Lambda_c^+$ life time
- Current PDG: BF($\Lambda_c^+ \to \Lambda$+X)=(35±11)% with large uncertainty
- The sum of known exclusive modes: $(24.5 \pm 2.1)\%$: need better understanding of the gap between exclusive and inclusive rates




- ST modes of $\Lambda_c^+ \to pK^-\pi^+$ and $pK_s^0$, to measure the probability of finding a $\Lambda$ in the final states
- Data-driven ($p-|cos\theta|$) 2D efficiency correction using several $\Lambda$ control samples
- $\mathcal{B}(\Lambda_c^+ \to \Lambda + X) = (38.2^{+2.8}_{-2.2} \pm 0.8)\%$

  indicates ~1/3 BFs are unknown
- $A_{cp} = (2.1^{+7.0}_{-6.6} \pm 1.4)\%$
  (No CPV is observed.)

# The inclusive channel $\Lambda_c^+ \to e^+ + X$

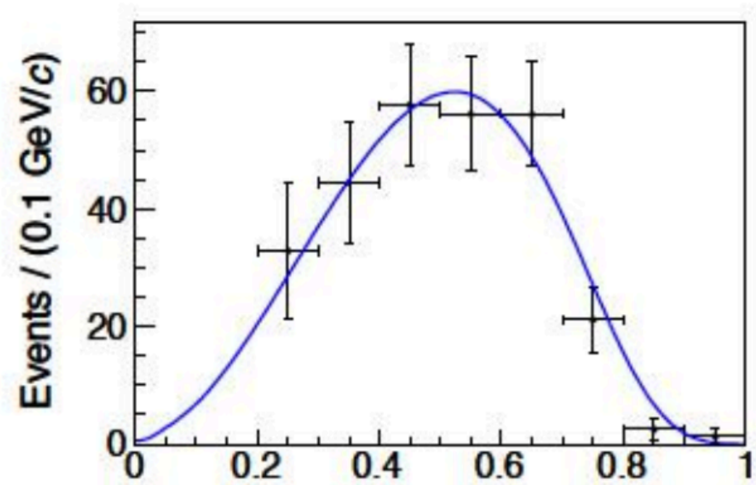
- **Current PDG: BF($\Lambda_c^+ \to e$+X)=(4.5±1.7)%.**

**arXiv:1805.09060**

- **Large rate, but also with large uncertainty**
- **Tagged with $\Lambda_c^+ \to pK^-\pi^+$ and $pK_S^0$**

=> $\mathcal{B}(\Lambda_c^+ \to Xe^+\nu_e) = (3.95 \pm 0.34 \pm 0.09)\%$

=> $\frac{\mathcal{B}(\Lambda_c^+ \to \Lambda e^+\nu_e)}{\mathcal{B}(\Lambda_c^+ \to Xe^+\nu_e)} = (91.9 \pm 12.5 \pm 5.4)\%$



e+ Momentum

- **The $\Lambda l^+\nu_l$ dominate the $l^+$+X =>$\mathcal{B}$ ($pKl^+\nu_l$)~$10^{-3}$.**

| Result | $\Lambda_c^+ \to Xe^+\nu_e$ | $\frac{\Gamma(\Lambda_c^+ \to Xe^+\nu_e)}{\bar{\Gamma}(D \to Xe^+\nu_e)}$ |
|---|---|---|
| BESIII | $3.95 \pm 0.35$ | $1.26 \pm 0.12$ |
| MARK II | $4.5 \pm 1.7$ | $1.44 \pm 0.54$ |
| Effective-quark Method | | 1.67 |
| Heavy-quark Expansion | | 1.2 |

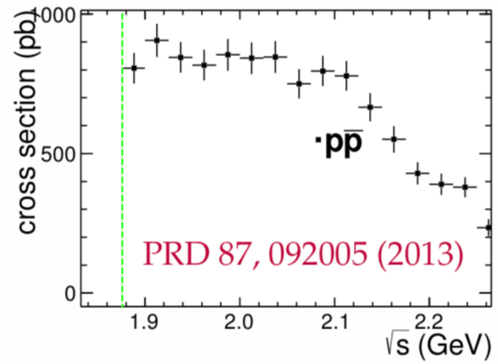
# The cross-section of baryon pair

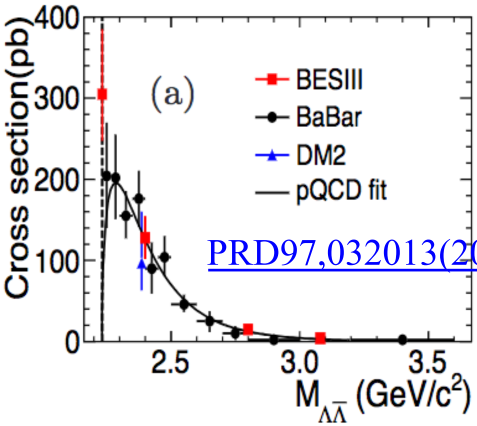
The Born cross section of the reaction $e^+e^- \to \gamma^* \to B\bar{B}$ can be parameterized in terms of electromagnetic form factors:

$$\sigma_{B\bar{B}}(q) = \frac{4\pi\alpha^2 C\beta}{3q^2}\left[|G_M(q)|^2 + \frac{1}{2\tau}|G_E(q)|^2\right]$$

- Baryon velocity $\beta = \sqrt{1 - 4m_B^2c^4/q^2}$, $\tau = q^2/(4m_B^2c^4)$
- For charged $B$, the Coulomb factor C will results in a non-zero cross section at threshold

- $e^+e^- \to p\bar{p}$: an enhancement and wide-range plateau in the line-shape
- $e^+e^- \to \Lambda\bar{\Lambda}$: non-zero cross section near threshold
- It can be anticipate that $\Lambda_c^+$ has a similar behaviour with proton
- Belle collaboration has measured the cross section of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ using ISR technique
  PRL 101, 172001 (2008)



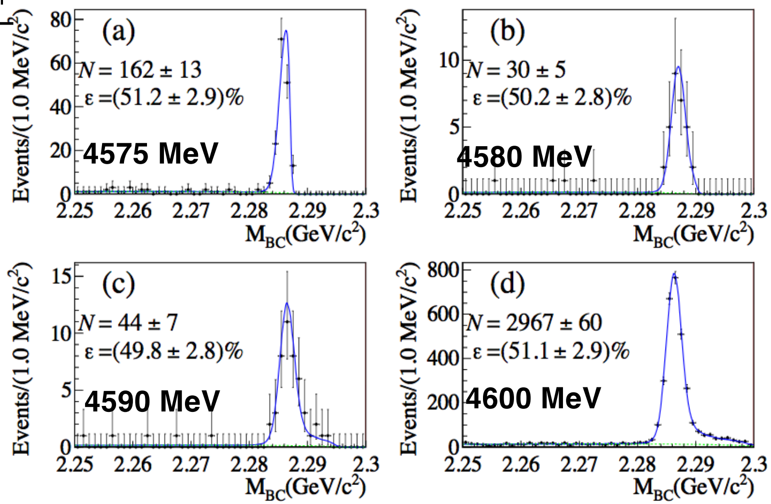

PRD97,032013(2018)

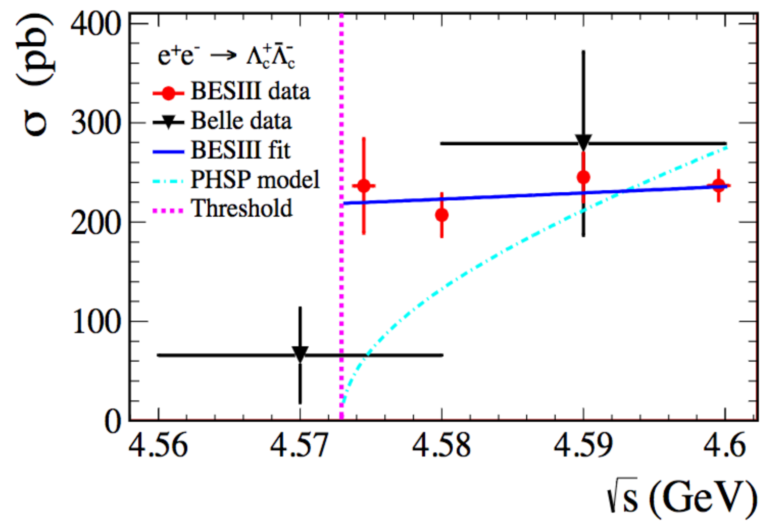
# Study of $e^+e^- \to \Lambda_c^+\Lambda_c^-$ near threshold

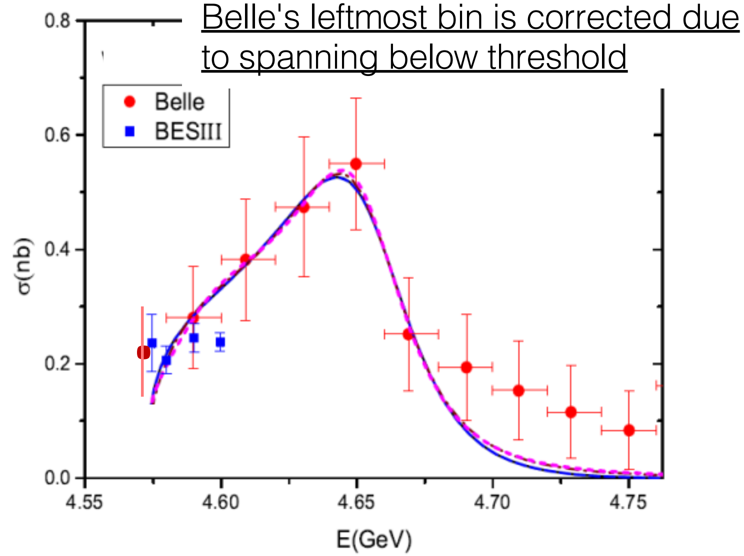
*Combined analysis of 10 ST hadronic modes*

**PRL 120, 132001 (2018)**

$pK^-\pi^+$




Belle's leftmost bin is corrected due to spanning below threshold

- **The cross sections are measured with unprecedented precision**
- **Enhanced cross section of reaction $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ near threshold is discerned for the first time**
- **The Coulomb enhanced factor?**

# BEPCII and BESIII upgrades

- **Increase of beam energy (<=2.3GeV)**
  – Step I: → 2.35 GeV (upgrade power cooling system. Done in this summer)
  – Step 2: → 2.45 GeV (Change ISPB magnet. Challenging)
- **Top-up injection:**
  – data taking efficiency increased by ~30%
- **MDC: Malter effect found in inner chamber in 2012**
  – New inner chamber is ready now.
  – CGEM as the inner chamber ongoing : Italy group in collaboration with other groups.
- **Super Conducting Magnet**
  – New valve box of SC magnet
- **Other possible upgrade plan is under discussion**

# Future plans at BESIII

*A BESIII physics white paper is under preparation*

| Energy | physics highlight | Current data # of events or integrated luminosity | Expected final data # of events or integrated luminosity |
|---|---|---|---|
| 1.8 - 2.0 GeV | R values cross-sections | N/A | Scan: 3 energy points |
| 2.0 - 3.1 GeV | R values cross-sections | Scan: 20 energy points | No requirement |
| $J/\psi$ peak | Light Hadron & Glueball Charmonium decay | 5.0 billion | 10.0 billion |
| $\psi(3686)$ peak | Light hadron& Glueball Charmonium decay | 0.5 billion | 3.0 billion |
| $\psi(3770)$ peak | $D^0/D^\pm$ decays Form-factor/CKM decay constant | 2.9 fb$^{-1}$ | 20.0 fb$^{-1}$ |
| 3.8 - 4.6 GeV | R value XYZ/Open charm | Scan: 105 energy points | No requirement |
| 4.180 GeV | $D_s$ decay XYZ/Open charm | 3.1 fb$^{-1}$ | 6.0 fb$^{-1}$ |
| 4.0 - 4.6 GeV | XYZ/Open charm Higher charmonia cross-sections | Scan: 12.0 fb$^{-1}$ | Scan: 30.0 fb$^{-1}$ 10 MeV step/0.5 fb$^{-1}$/point 30 energy points |
| 4.60 GeV | $\Lambda_c$/XYZ | 0.56 fb$^{-1}$ | 1.0 fb$^{-1}$ |
| 4.64 GeV | $\Lambda_c$/XYZ | N/A | 5.0 fb$^{-1}$ |
| 4.65 GeV | $\Lambda_c$/XYZ | N/A | 0.2 fb$^{-1}$ |
| 4.70 GeV | $\Lambda_c$/XYZ | N/A | 0.65 fb$^{-1}$ |
| 4.80 GeV | $\Lambda_c$/XYZ | N/A | 1.0 fb$^{-1}$ |
| 4.90 GeV | $\Lambda_c$/XYZ | N/A | 1.3 fb$^{-1}$ |
| $\Sigma_c^+\bar{\Lambda}_c^-$ 4.74 GeV | Charm Baryons | N/A | 1.0 fb$^{-1}$ |
| $\Sigma_c\bar{\Sigma}_c$ 4.91 GeV | Charm Baryons | N/A | 1.0 fb$^{-1}$ |
| $\Xi_c\bar{\Xi}_c$ 4.95 GeV | Charm Baryons | N/A | 1.0 fb$^{-1}$ |

***in the best case***

# Summary

- **Fruitful results with large varieties of physics outputs**
- **The hadron spectroscopy and exotics**
  - X states between 1.8~1.9 GeV/$c^2$
  - Glueball searches
  - Efforts on studies on the strangeonium-(like) and charmonium-(like) states
- **Charmed hadron decays**
  - Measurements of decay constants $f_{D(s)+}$ and form factors
  - Determinations of $|V_{cs(d)}|$: improved test on CKM matrix unitarity
  - Important testes on non-perturbative QCD
  - Significant improvement in charmed baryon sector
- **BEPCII upgrade and Detector upgrade**
  - ✓ **Top up mode :**
    30% going-up of data taking efficiency
  - ✓ **Increase the beam energy:**
    4.6 GeV → 4.7 GeV (done!) → 4.9 GeV (~2019 summer)
  - ✓ CGEM project

# Thank you!

# 谢谢！

# Determiend properties of the $Z_c^+(3900)$

PRL 119.072001 (2017)

- If $Z_c$ is parameterized with a Flatte-like formula

  $M_{\text{pole}} = 3881.2 \pm 4.2 \pm 52.7$ MeV, $\Gamma_{\text{pole}} = 51.8 \pm 4.6 \pm 36.0$ MeV

  $g_1' = 0.075 \pm 0.006 \pm 0.025 \text{GeV}^2$

  $g_2'/g_1' = 27.1 \pm 2.0 \pm 1.9$

  (consistent with the previous published results)

- Born cross section for $e^+e^- \to Z_c^+\pi^- + c.c. \to \pi^+\pi^- J/\psi$

  $21.8 \pm 1.0 \pm 4.4$ pb at 4.23 GeV

  $11.0 \pm 1.2 \pm 5.4$ pb at 4.26 GeV

- Search for $e^+e^- \to Z_c^+(4020)\pi^- + c.c. \to \pi^+\pi^- J/\psi$ gives

  upper limits at 90% C.L.:

  <0.9 pb at 4.23 GeV; <1.4 pb at 4.26 GeV

  then $$\frac{\sigma(e^+e^- \to Z_c^+(4020)\ \pi^- + c.c \to \pi^+\pi^- J/\psi)}{\sigma(e^+e^- \to Z_c^+(3900)\ \pi^- + c.c \to \pi^+\pi^- J/\psi)} < 4\% \text{ at 4.23 GeV}$$

  <13% at 4.26 GeV

# Comparison between experiment and theory

- Using $B(X(3872) \rightarrow \pi^+\pi^- J/\psi) > 3.2\%$ [PDG]

  *(obtained by comparing inclusive [Belle,PRD97,012005(2018)] and exclusive [BaBar,PRD77,111101(2008)] $B^+$ decays)*

  and $B(X(3872) \rightarrow \pi^+\pi^- J/\psi) < 6.4\%$,

  *(obtained by assuming all measured X(3872) decays add to less than 100%)*

  we find $\mathbf{B(X(3872) \rightarrow \pi^0\chi_{c1}) \sim 3\text{–}6\%}$.

- If the X(3872) were the $\chi_{c1}(2P)$ state of charmonium, then $\Gamma(X(3872) \rightarrow \pi^0\chi_{c1}) \sim 0.06$ keV,

  *(from the estimation of [Dubynskiy, Voloshin, PRD 77, 014013 (2008)])*

  which would imply an unrealistically small $\mathbf{\Gamma_{TOT}(X(3872)) \sim 0.5 - 1.0}$ **keV.**

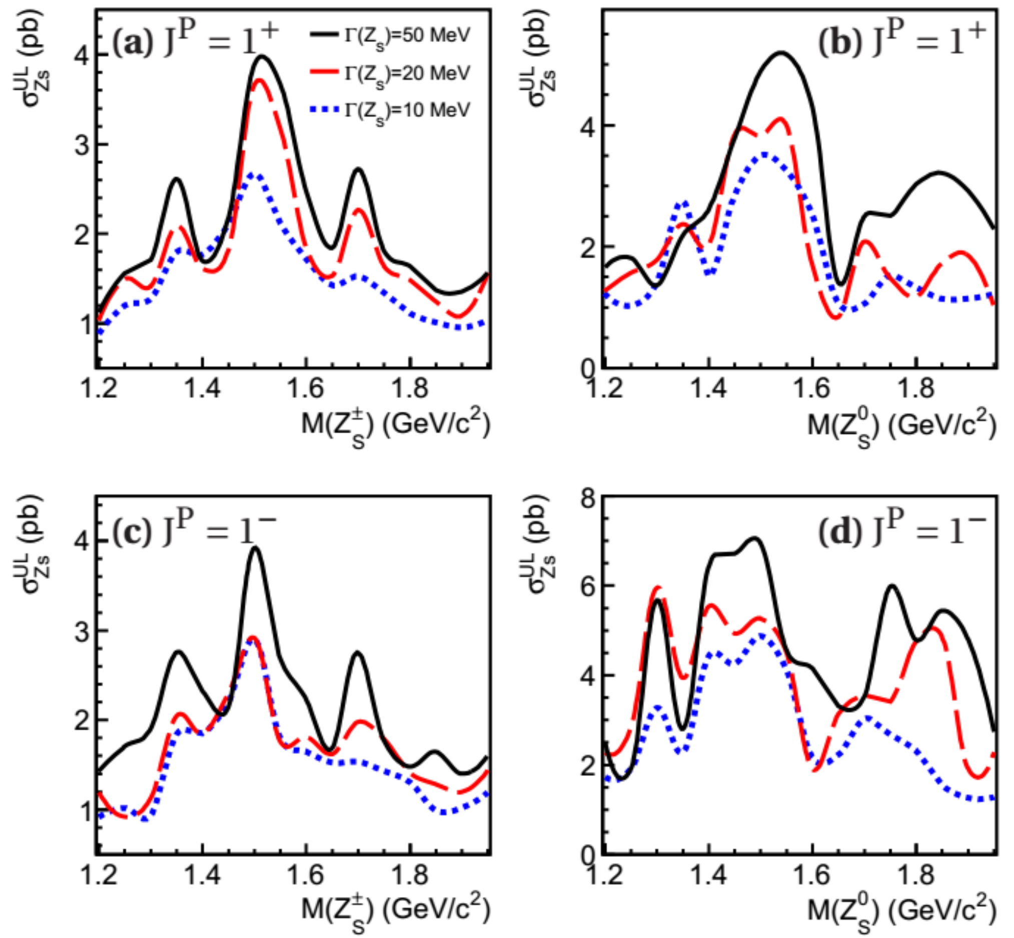
  *(for comparison, note that this is several orders of magnitude smaller than $\Gamma_{TOT}(J/\psi) \sim 100$ keV)*

- Therefore, our measurement of $B(X \rightarrow \pi^0\chi_{c1})/B(X \rightarrow \pi^+\pi^- J/\psi)$ **disfavors the $\chi_{c1}$(2P) interpretation of the X(3872)**.

# Search for $Z_S$ at 2.125 GeV

**arXiv:1801.10384 (2018) submitted to PRL**

- 90% C.L. upper limits on the cross-section for $Z_S$ production are determined.
  - ✓ Different assumptions of mass, width and $J^P$ of $Z_S$

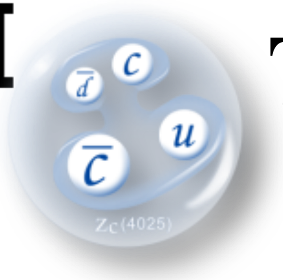



- In addition, the cross-sections of $e^+e^-\to\phi\pi^+\pi^-$ and $e^+e^-\to\phi\pi^0\pi^0$ at 2.125 GeV/c² are measured to be (343.0±5.1±25.1) pb and (208.3±7.6±13.5) nb, respectively.
  - ✓ The cross-section for $e^+e^-\to\phi\pi^+\pi^-$ slightly differs from previous measurements from BaBar ((510±50±21) pb at 2.1125 GeV) and Belle ((480±60±42) pb at 2.1125 GeV) measurements, but consistent within $3\sigma$.
  - ✓ The cross-section for $e^+e^-\to\phi\pi^0\pi^0$ is consistent with BaBar measurement (195±50±14) pb within uncertainty.


**BaBar Collaboration Phys. Rev. D 86, 012008 (2012)**

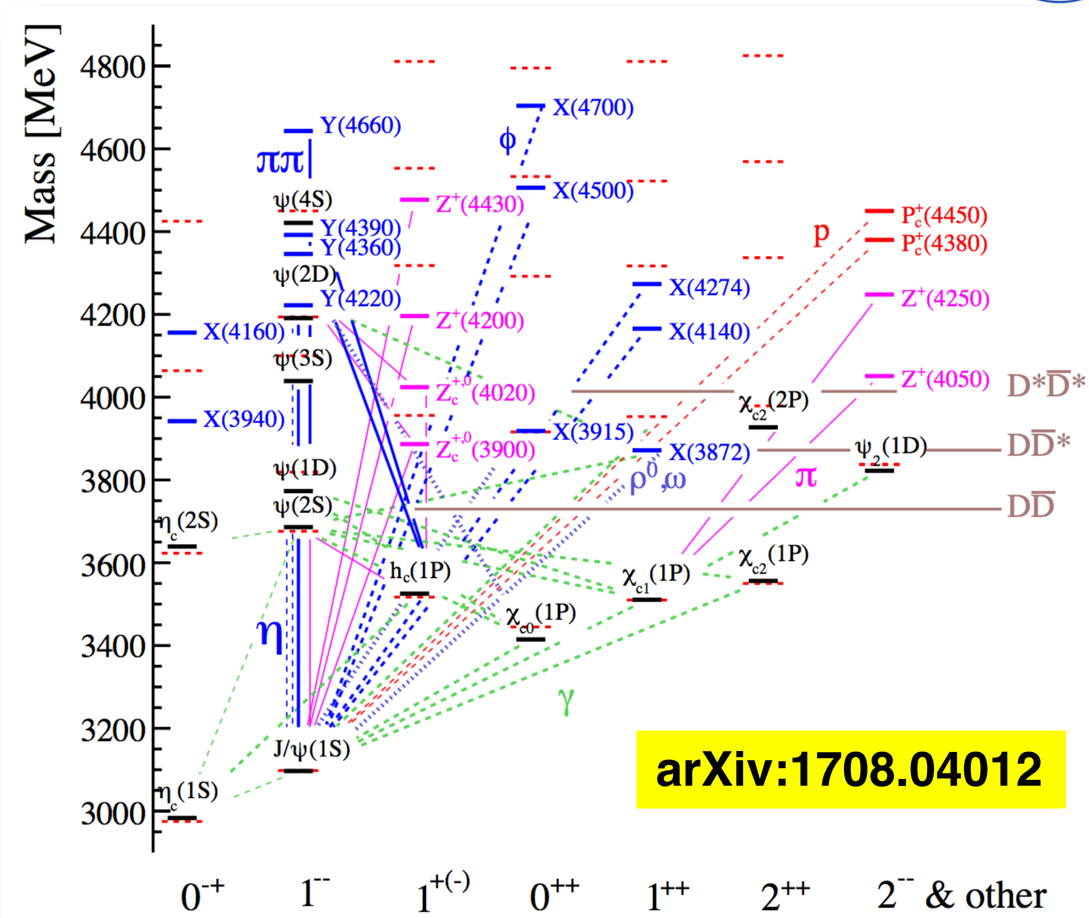
**BELLE Collaboration Phys. Rev. D 80, 031101 (2009)**

# The Zc Family at BESIII




| State | Mass (MeV/c²) | Width (MeV) | Decay | Process |
|---|---|---|---|---|
| $Z_c(3900)^{\pm}$ | $3899.0 \pm 3.6 \pm 4.9$ | $46 \pm 10 \pm 20$ | $\pi^{\pm} J/\psi$ | $e^+e^- \to \pi^+\pi^- J/\psi$ |
| $Z_c(3900)^0$ | $3894.8 \pm 2.3 \pm 2.7$ | $29.6 \pm 8.2 \pm 8.2$ | $\pi^0 J/\psi$ | $e^+e^- \to \pi^0\pi^0 J/\psi$ |
| $Z_c(3885)^{\pm}$ | $3883.9 \pm 1.5 \pm 4.2$ Single D tag | $24.8 \pm 3.3 \pm 11.0$ Single D tag | $(D\bar{D}^*)^{\pm}$ | $e^+e^- \to (D\bar{D}^*)^{\pm}\pi^{\mp}$ |
| | $3881.7 \pm 1.6 \pm 2.1$ Double D tag | $26.6 \pm 2.0 \pm 2.3$ Double D tag | $(D\bar{D}^*)^{\pm}$ | $e^+e^- \to (D\bar{D}^*)^{\pm}\pi^{\mp}$ |
| $Z_c(3885)^0$ | $3885.7^{+4.3}_{-5.7} \pm 8.4$ | $35^{+11}_{-12} \pm 15$ | $(D\bar{D}^*)^0$ | $e^+e^- \to (D\bar{D}^*)^0\pi^0$ |
| $Z_c(4020)^{\pm}$ | $4022.9 \pm 0.8 \pm 2.7$ | $7.9 \pm 2.7 \pm 2.6$ | $\pi^{\pm} h_c$ | $e^+e^- \to \pi^+\pi^- h_c$ |
| $Z_c(4020)^0$ | $4023.9 \pm 2.2 \pm 3.8$ | fixed | $\pi^0 h_c$ | $e^+e^- \to \pi^0\pi^0 h_c$ |
| $Z_c(4025)^{\pm}$ | $4026.3 \pm 2.6 \pm 3.7$ | $24.8 \pm 5.6 \pm 7.7$ | $D^*\bar{D}^*$ | $e^+e^- \to (D^*\bar{D}^*)^{\pm}\pi^{\mp}$ |
| $Z_c(4025)^0$ | $4025.5^{+2.0}_{-4.7} \pm 3.1$ | $23.0 \pm 6.0 \pm 1.0$ | $D^*\bar{D}^*$ | $e^+e^- \to (D^*\bar{D}^*)^0\pi^0$ |

# Many charged Charmonium-like states




| State | Decay modes | Seen by |
| --- | --- | --- |
| $Z_c(3900)^{\pm,0}$ | $\pi^{\mp}J/\psi$, $(D^*\bar{D})^{\mp}$ | BESIII, Belle CLEO |
| $Z_c(4020)^{\pm,0}$ | $\pi^{\mp}h_c$, $(D^*\bar{D}^*)^{\mp}$ | BESIII |
| $Z_c(4430)^{\pm}$ | $\pi^{\mp}\psi(2S)$ $\pi^{\pm}J/\psi$ | Belle, ~~BaBar,~~ LHCb |

in $e^+e^- \to \pi^- Zc$

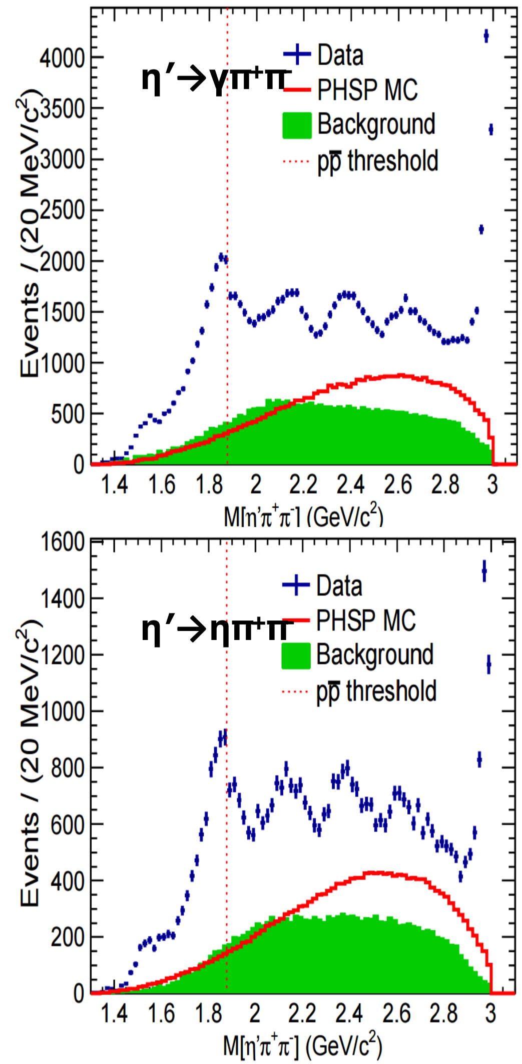
in $e^+e^- \to \pi^- Zc$

in $B \to KZc$

# New: connection is emerging

**PRL 117, 042002 (2016)**

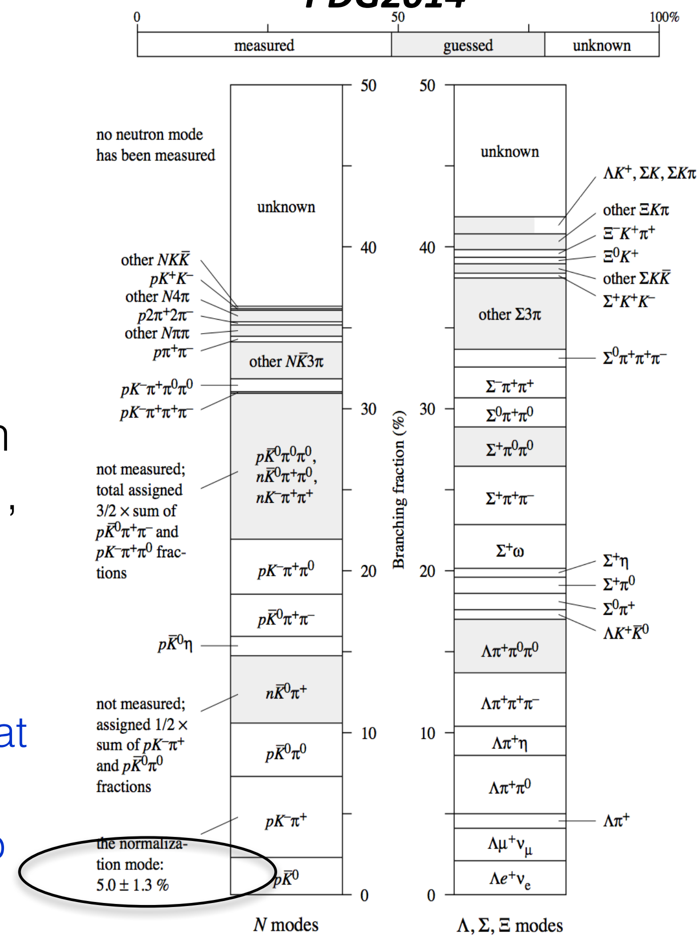
- **Use 1.09×10[9] J/ψ events collected by BESIII in 2012**
- **Two decay modes of η′**
  - **η′→γπ⁺π⁻**
  - **η′→ηπ⁺π⁻, η→γγ**
- **Clear peaks of X(1835), X(2120), X(2370), $\eta_c$, and a structure near 2.6 GeV$/c^2$**
- **A significant distortion of the η′π⁺π⁻ line shape near the $p\bar{p}$ mass threshold**



# BESIII Renaissance on the charmed heavy baryon

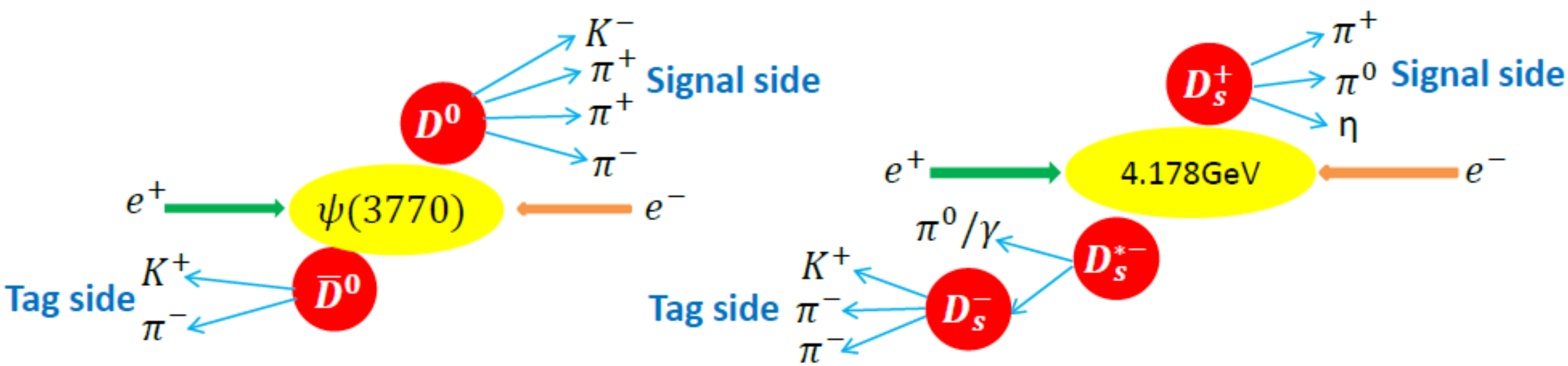
- Before 2014, the *c*-ed baryons have been produced and studied at many experiments, notably fixed-target experiments (such as FOCUS and SELEX) and e+e- B-factories (ARGUS, CLEO, BABAR, and BELLE).
- Large uncertainties in experiment; Retarded development in theory
- Afterwards, more extensive measurements on charmed baryons are performed at the BESIII, BELLE and LHCb
  - The absolute BF measurements at BESIII and BELLE
  - The observation of the DCS mode $\Lambda_c^+ \to pK^+\pi^-$ at BELLE
  - The observation of the *cc*-d baryon $\Xi_{cc}^{++}$ at LHCb
- These experimental progresses have revoked the activities in the theoretical efforts

**PDG2014**



# Double Tag (DT) techniques

- 100% of beam energy converted to *D* pair (Clean environment, kinematic constrains ν Recon. )
- $D_{(S)}$ generated in pair ⇒ absolute Branching fractions
- Fully reconstruct about 15% of $D_{(S)}$ decays




$$\Delta E = E_D - E_{\text{Beam}}$$

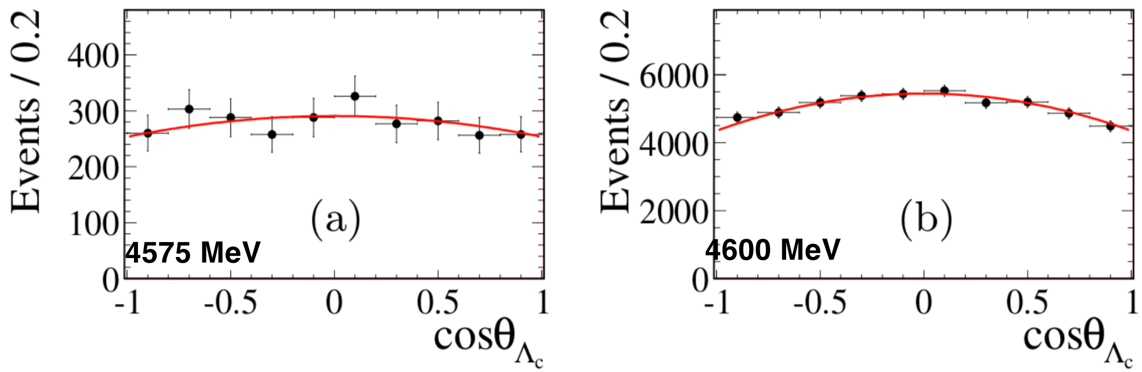
$$M_{\text{BC}} = \sqrt{E_{\text{Beam}}^2 - p_D^2}$$

◆ **Double tag techniques: Hadronic tag on one side, on the other side for missing-mass studies (Double tag efficiency is high.)**

# Angular dependence analysis of $e^+e^- \to \Lambda_c^+ \Lambda_c^-$ near threshold

**PRL 120, 132001 (2018)**

***combined data***



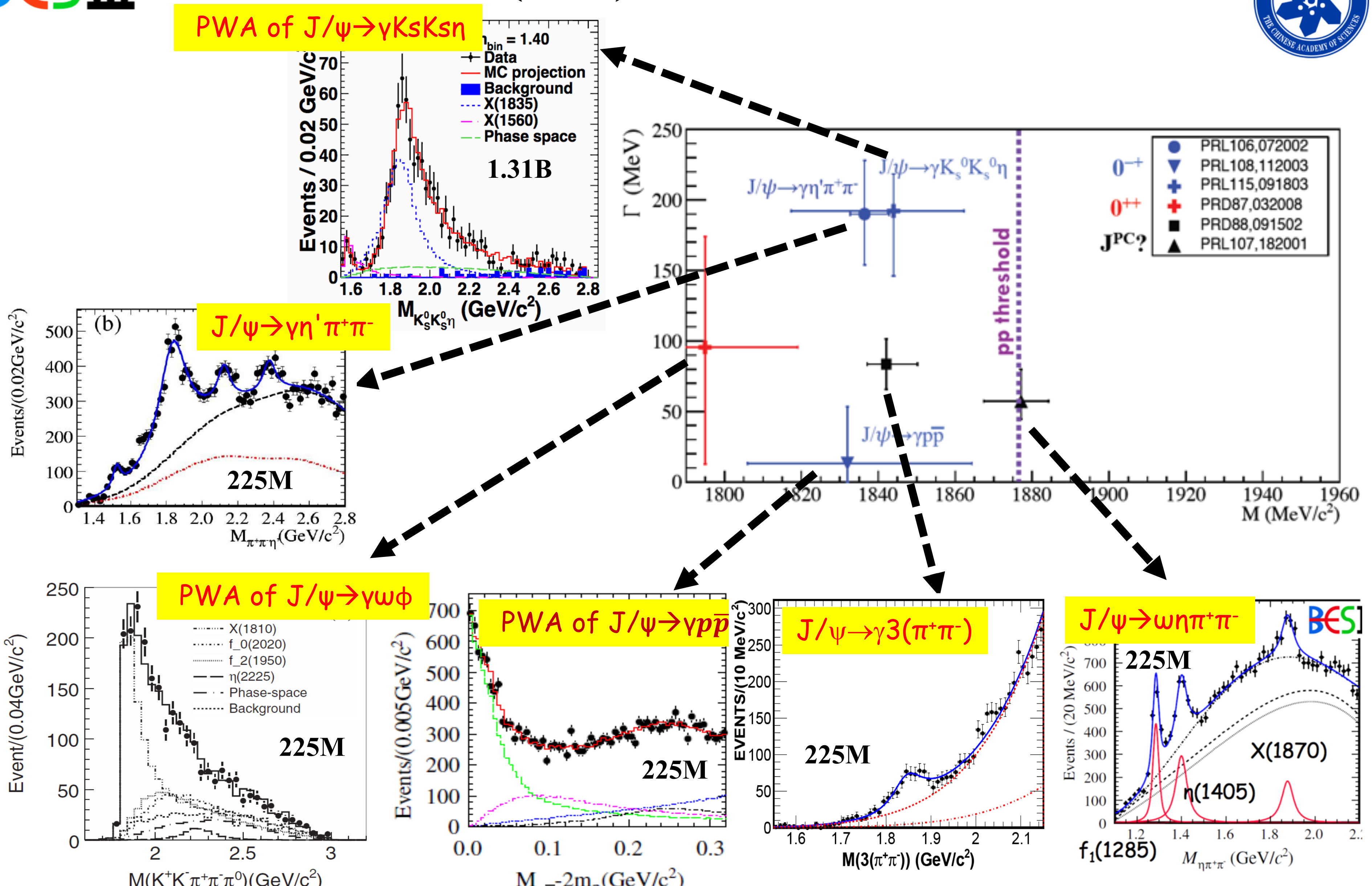

$$f(\theta) \propto (1 + \alpha_{\Lambda_c} \cos^2\theta)$$

$$|G_E/G_M|^2(1-\beta^2) = (1-\alpha_{\Lambda_c})/(1+\alpha_{\Lambda_c}).$$

| $\sqrt{s}$ (MeV) | $\alpha_{\Lambda_c}$ | $\vert G_E/G_M \vert$ |
|---|---|---|
| 4574.5 | $-0.13 \pm 0.12 \pm 0.08$ | $1.14 \pm 0.14 \pm 0.07$ |
| 4599.5 | $-0.20 \pm 0.04 \pm 0.02$ | $1.23 \pm 0.05 \pm 0.03$ |

- One of the most basic observables that intimately related to the internal structure of the nucleon.
- One of the most challenging questions in contemporary physics is why and how quarks are confined into hadrons.
- The electromagnetic form factors (EMFFs) have been a powerful tool in understanding the structure of nucleons.
- First measurements of the EMFFs of the $\Lambda_c^+$

# The X(18??) between 1.8~1.9 GeV




**Are they the same state? It is crucial to understand their connections.**