# BESIII Exotics

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On behalf of the BESIII Collaboration

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# Outline

1) BESIII perspective in Exotics searches

2) Hot takes from BESIII exotics searches

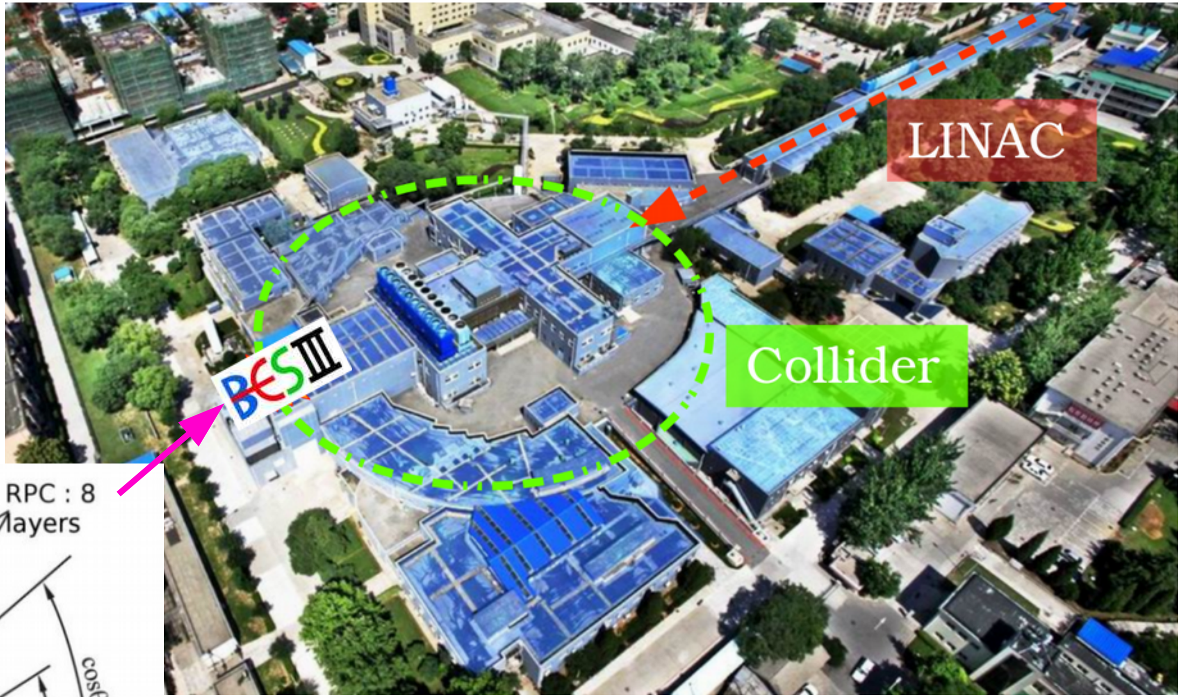
3) BESIII and Y(4660)

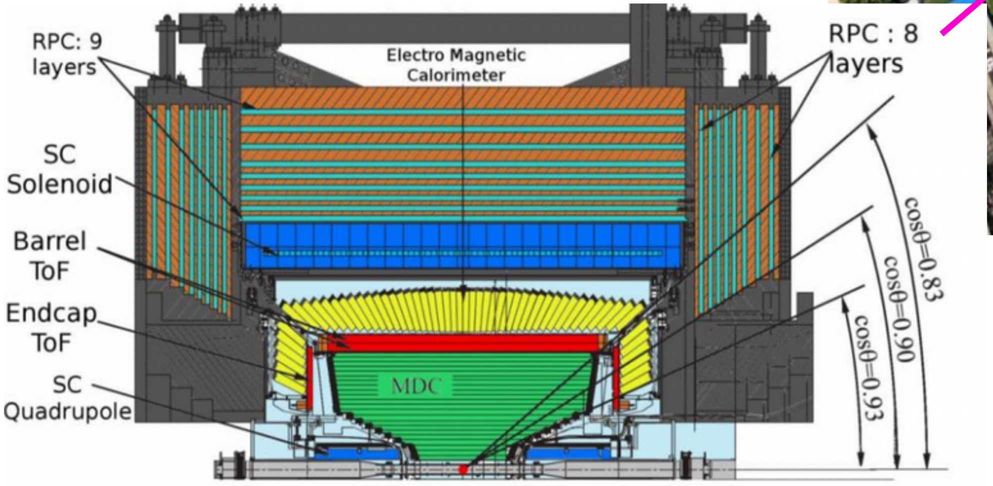
# BESIII @ BEPCII

$e^+e^-$ central collider

Center of mass energy can be set between 2 - 4.6 GeV

$L_{design}$(@3.77 GeV): $10^{33}$ $cm^{-2}s^{-1}$



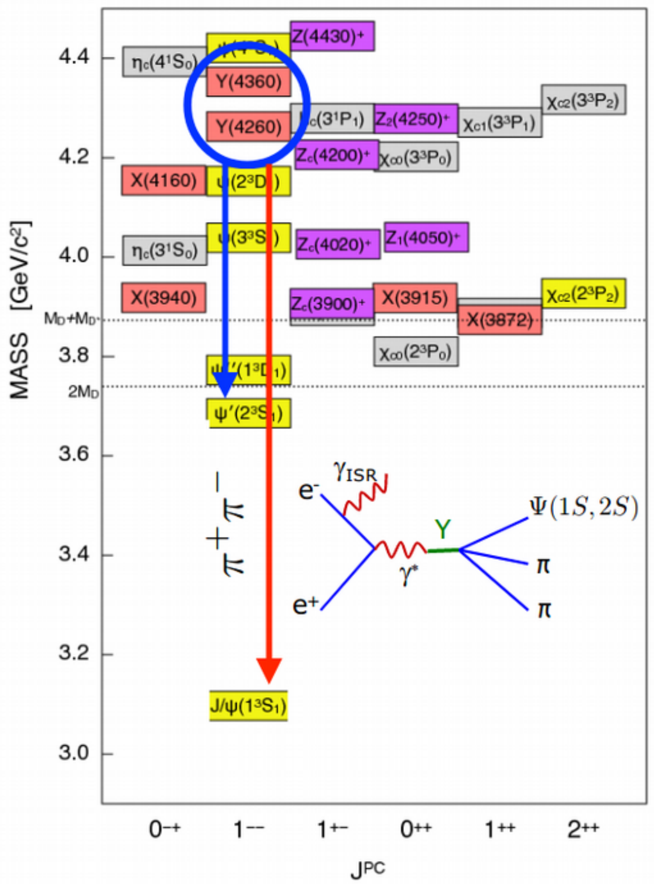



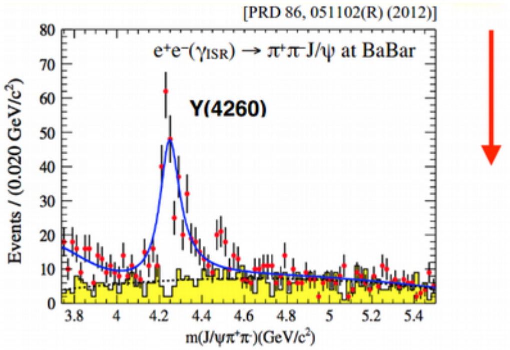

J/ψ data are the world largest single data sample at $e^+e^-$ collider (achieved in February this year)

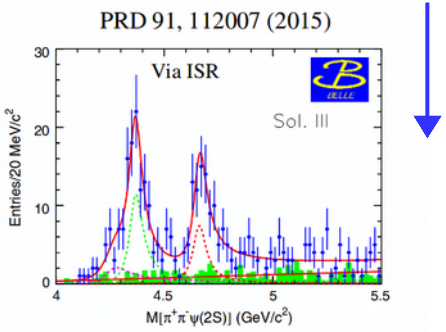
More than 12/fb data between 3.8 and 4.6 GeV dedicated to XYZ studies, and more to come

# BESIII unique perspective in charmonium exotics

B-factories can use **ISR** to access $1^{--}$ states and B decays for X ones



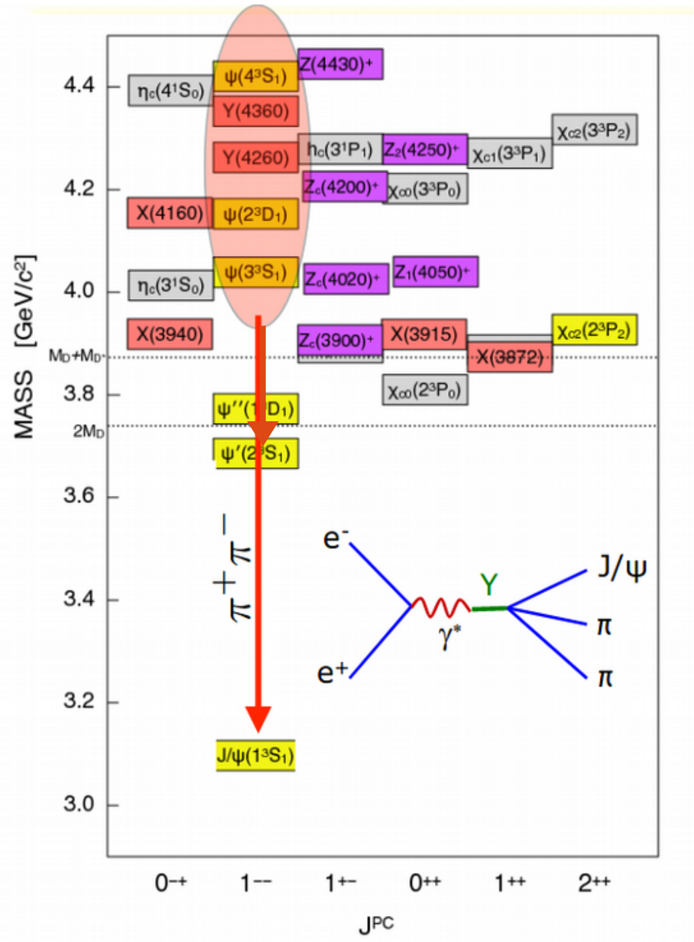




Use the **full statistic** to access to the Y

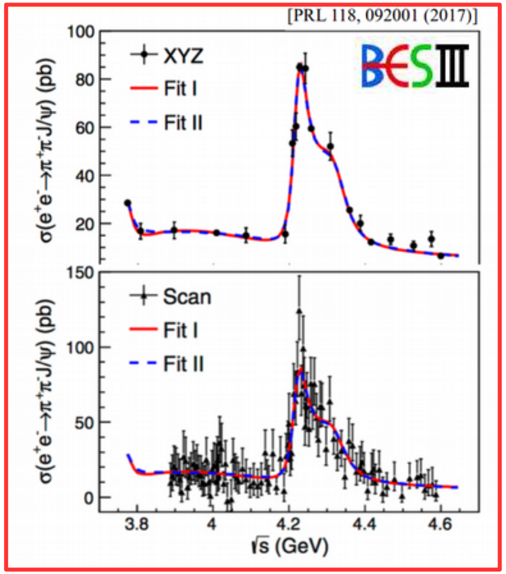
However, **precision** is **lower**

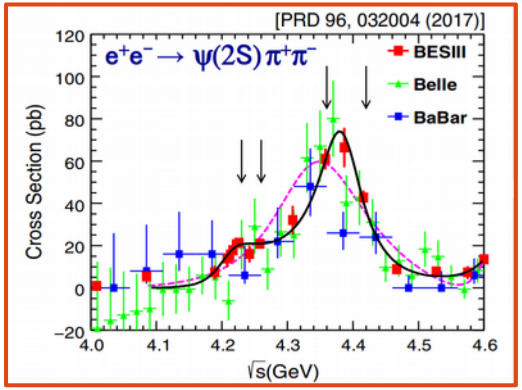
# BESIII unique perspective in charmonium exotics




BESIII can **directly** access to the $1^{--}$ states

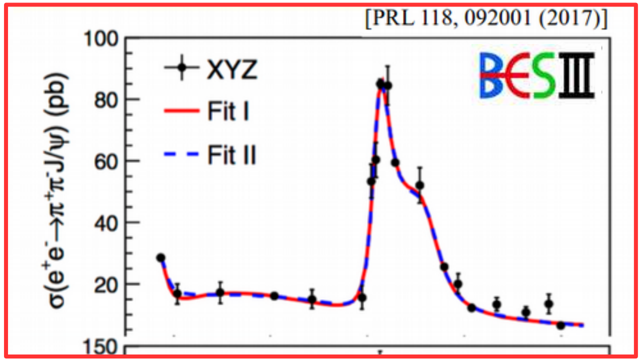
Scan their lineshape to perform **high precision** physics



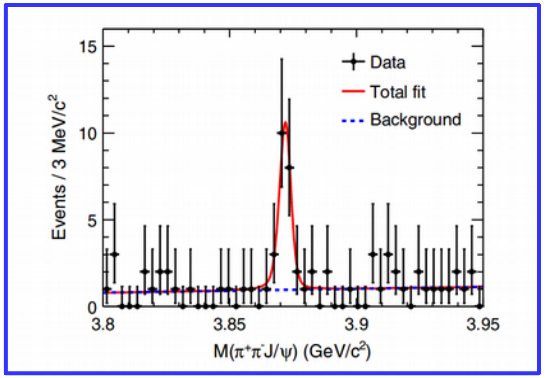
# BESIII unique perspective in charmonium exotics

With the incredible **luminosity** collected at the $1^{--}$ resonances it is possible to study the **transition** between these states and to the conventional charmonia to create **connections** in order to understand their **nature**

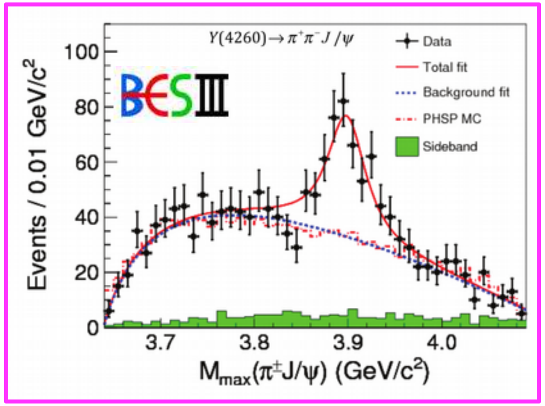



γ?

π




Unique features @ BESIII



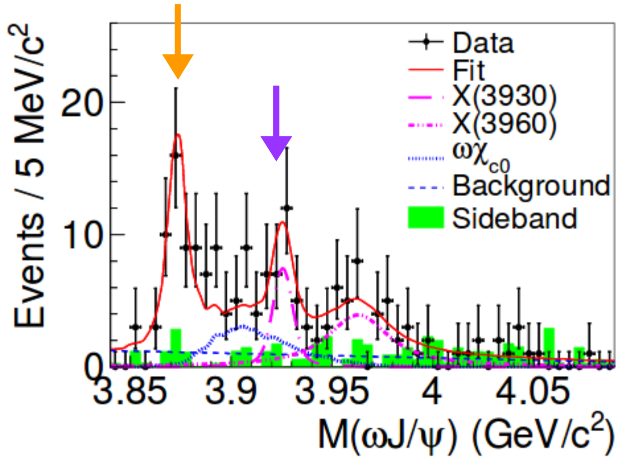
# Recent takes in exotics searches

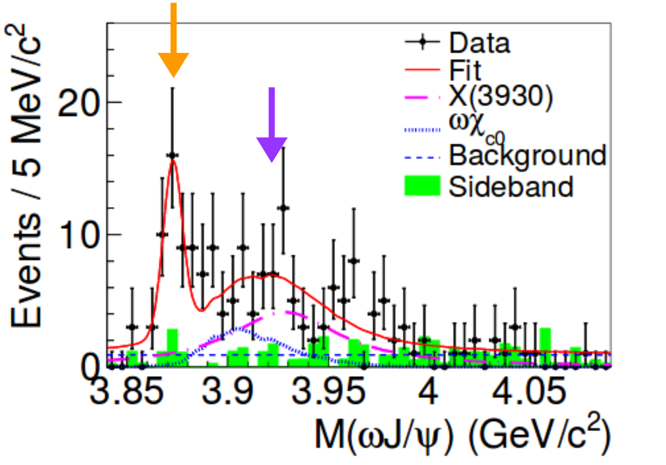
- $X(3872) \to J/\psi\omega$ and $e^+e^- \to \gamma J/\psi\omega$ cross section (arXiv: 1903.04695)
- $X(3872) \to \pi^0\chi_{c1}(1P)$ (arXiv: 1901.03992)
- $e^+e^- \to \pi Z^{(\prime)}_c, Z^{(\prime)}_c \to \rho\eta_c$ (preliminary)
- $e^+e^- \to \pi^+D^0D^{*-}$ (PRL 122, 102002 (2019))
- $e^+e^- \to \omega\chi_{c0}(1P)$ cross section (Accepted by PRD(RC) - arXiv: 1903.02359)
- $e^+e^- \to \pi^+\pi^-\psi(3770)$ and $D_1(2420)^0\overline{D}^0$ + c.c. (arXiv: 1903.08126)

# $e^+e^- \to \gamma\omega J/\psi$ and observation of X(3872) → $\omega J/\psi$

arXiv: 1903.04695

Search for other final states of the X(3872) to understand its nature




First evidence by BaBar
Phys.Rev. D82 (2010) 011101

Clear observation of X(3872) with more than 5.1σ significance

$$M_{X(3872)} = (3873 \pm 1.1 \pm 1.0)\,\mathrm{MeV}/c^2$$

**First observation in this final state!**

To describe the part of the spectrum above 3.9 GeV, one additional resonance X(3930) is necessary

$$M_{X(3930),1} = (3926.4 \pm 2.2 \pm 1.2)\,\mathrm{MeV}/c^2$$
$$\Gamma_{X(3930),1} = (3.8 \pm 7.5 \pm 2.6)\,\mathrm{MeV}$$

$$M_{X(3930),2} = (3932.6 \pm 8.7 \pm 4.7)\,\mathrm{MeV}/c^2$$
$$\Gamma_{X(3930),2} = (59.7 \pm 15.5 \pm 3.7)\,\mathrm{MeV}$$

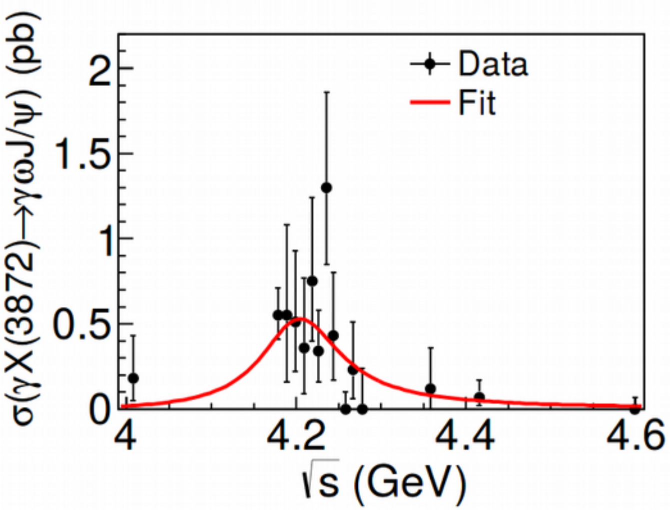
# $e^+e^- \rightarrow \gamma X(3872)$

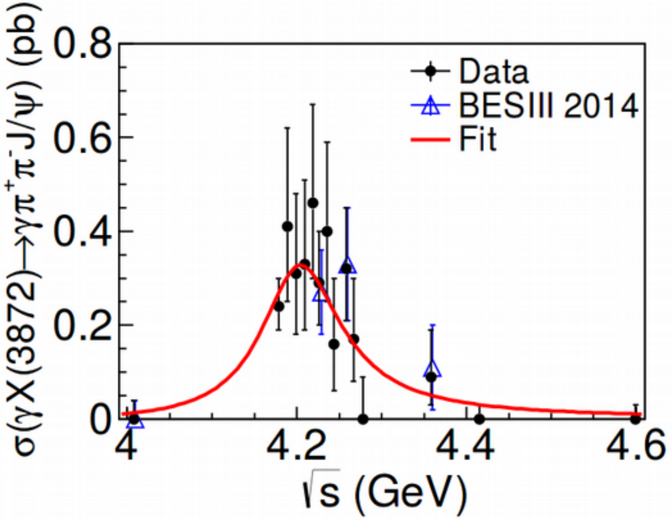
arXiv: 1903.04695

Simultaneous **maximum-likelihood fit** to both **X(3872)→ ωJ/ψ** and **X(3872)→ ππJ/ψ** taking in account ISR.

Single Breit-Wigner with **free mass** and **width** parametrization

**Ratio** of the two branching fraction energy by energy is also taken in account in the fit.




$$M = (4200.6^{+7.9}_{-13.3} \pm 3)\,\mathrm{MeV}/c^2$$

$$\Gamma = (115^{+38}_{-26} \pm 12)\,\mathrm{MeV}$$

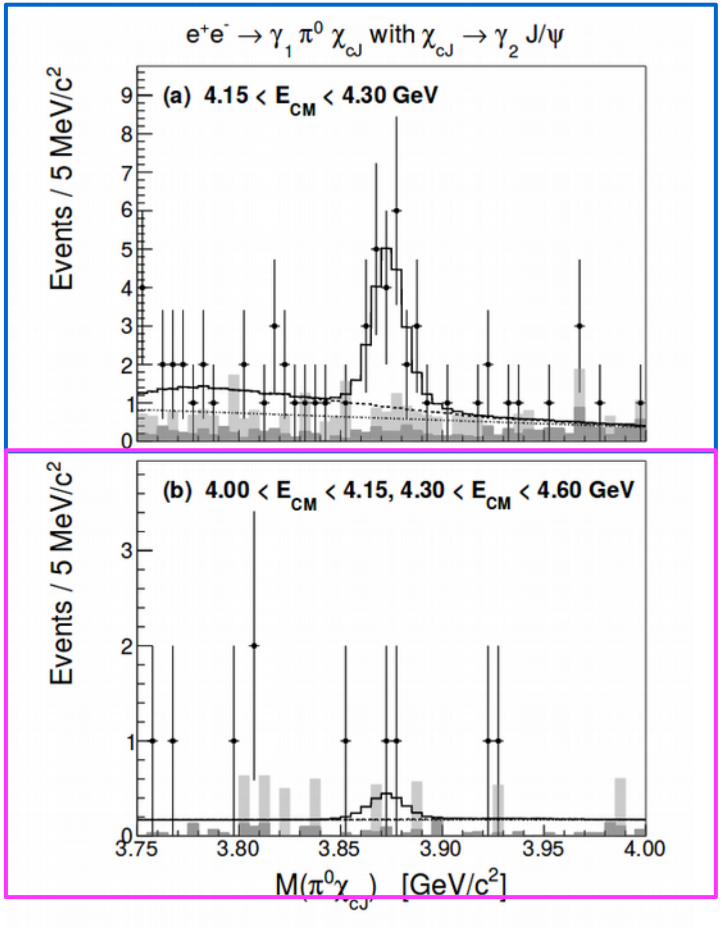
Compatible with Y(4220) or ψ(4150)

$$\mathcal{R} = \frac{\mathcal{B}[X(3872) \to \omega J/\psi]}{\mathcal{B}[X(3872) \to \pi^+\pi^- J/\psi]} = 1.6^{+0.4}_{-0.3} \pm 0.2$$

Relevant for the understanding of the nature of X(3872)

# Observation of X(3872) → $\pi^0\chi_{c1}(1P)$

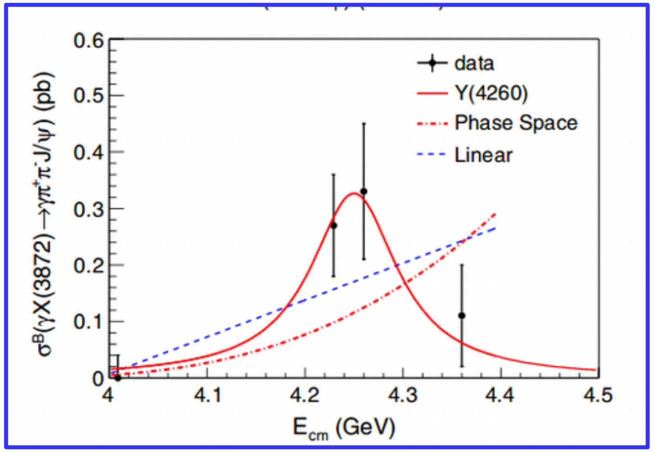
ArXiv: 1901.03992




Search for X(3872) → $\pi^0$ $\chi_{cj}$(1P), $\chi_{cj}$(1P) →γJ/ψ

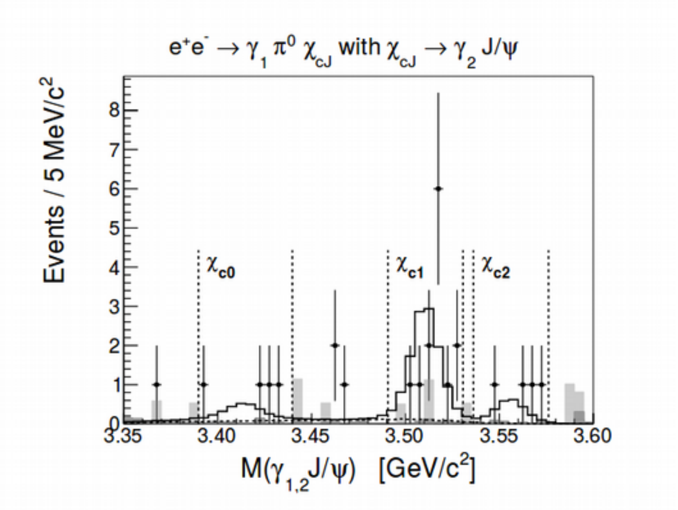
**Clear evidence** for center of mass between 4.15 and 4.3 GeV, **no signal** for others energy values

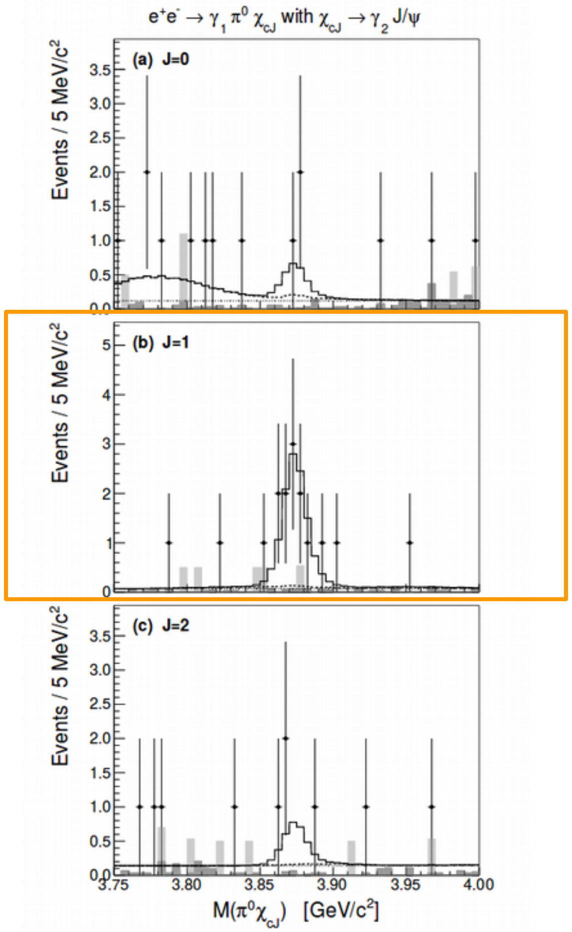
As expected if **Y(42xx) → γX(3872) dominates** production mechanism as it seems also in **$e^+e^-$ → γππJ/ψ** and e+e- → γωJ/ψ



# Observation of X(3872) → $\pi^0\chi_{c1}(1P)$

arXiv: 1901.03992




By selecting the X(3872) mass window and the proper photon energy is possible to isolate the different $\chi_{cj}$**(1P)**

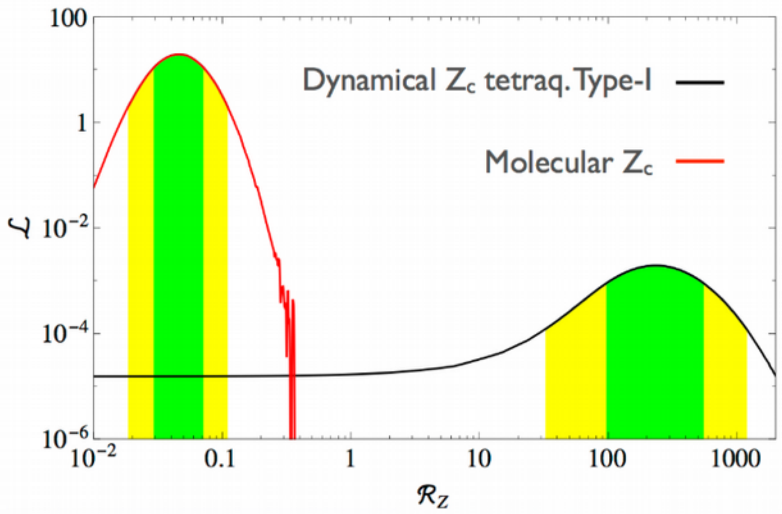
**First observation of the transition X(3872) → $\pi^0\chi_{c1}$(1P)!**

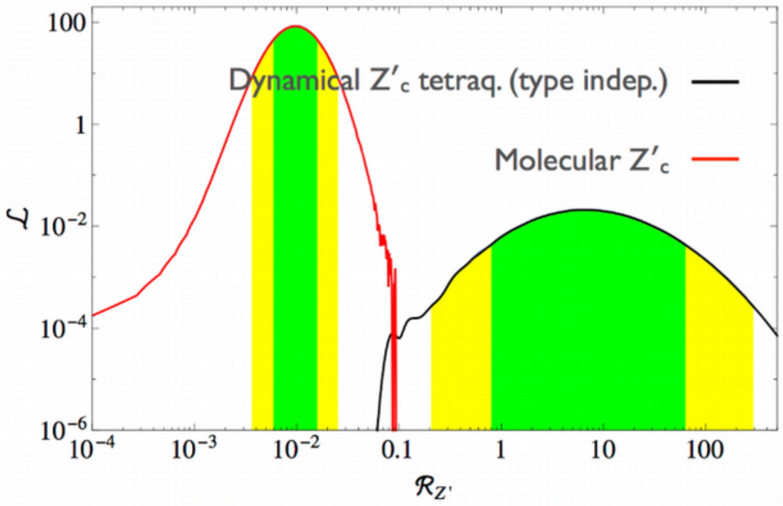
Measurement **highly disfavors** the interpretation of X(3872) as a **conventional $\chi_{c1}$(2P)**

Based on Dubynskiy, Voloshin, PRD 77, 014013 (2008)

# Search for $e^+e^- \to \pi Z^{(\prime)}_{c}, Z^{(\prime)}_{c} \to \rho\eta_c$

Ratio of $\mathbf{Z^{(\prime)}_c \to \rho\eta_c}$ and $\mathbf{Z^{(\prime)}_c \to \pi J/\psi\ (\pi h_c)}$ can help to experimentally distinguish between **tetraquark** and **molecular** nature of the $Z^{(\prime)}_c$




$$R_z = \frac{Br(Z_c \to \rho\eta_c)}{Br(Z_c \to \pi J/\psi)}$$

$$R_{Z'} = \frac{Br(Z_c' \to \rho\eta_c)}{Br(Z_c' \to \pi h_c)}$$

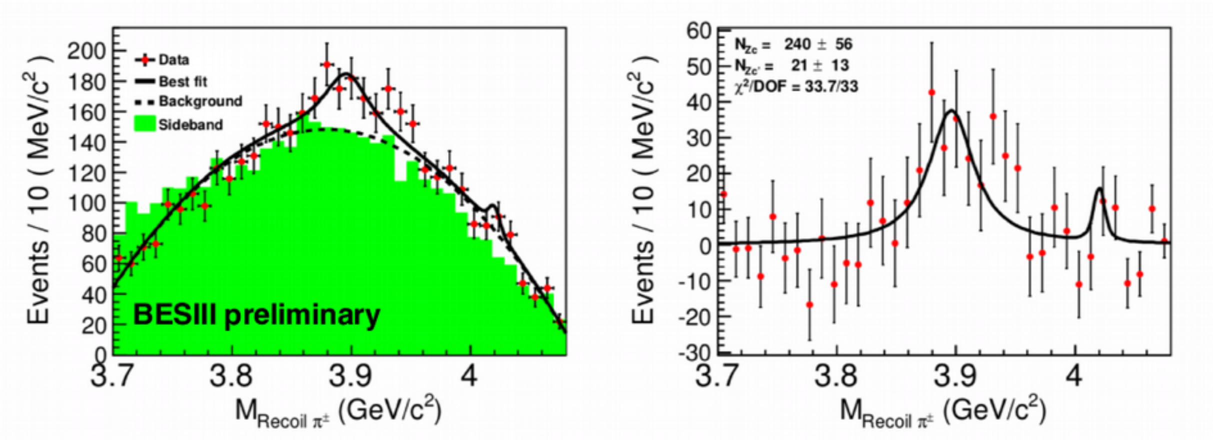


***Phys. Lett. B 746, 194 (2015)***

# Search for $e^+e^- \to \pi Z^{(\prime)}_c, Z^{(\prime)}_c \to \rho\eta_c$ (preliminary)

$\eta_c$ is reconstructed in 9 different states and fitted simultaneously

Parameters of $\eta_c$ and $Z_c$ are fixed to PDG or latest measurement



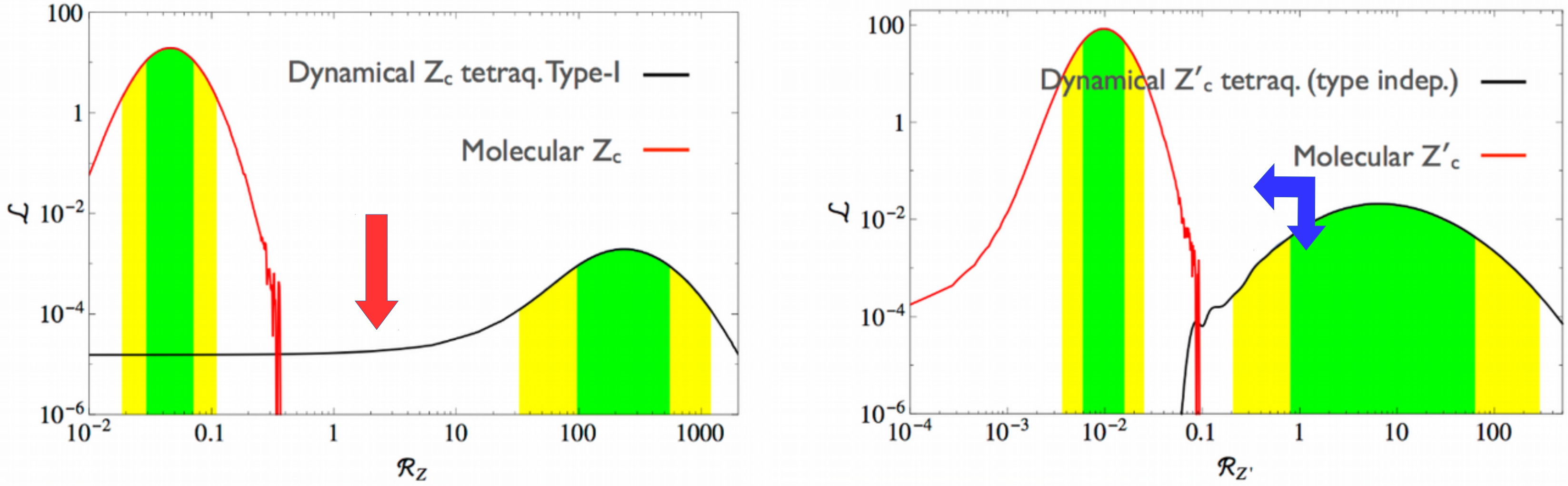

$$e^+e^- \to \pi Z_c, Z_c \to \rho\eta_c \ @\ 4.23\ \text{GeV}$$

**Evidence of $e^+e^- \to \pi Z_c, Z_c \to \rho\eta_c$ is observed at $E_{cm}$ = 4.23 GeV**

$e^+e^- \to \pi Z'_c, Z'_c \to \rho\eta_c$ is not seen in any data seta

# Search for $e^+e^- \to \pi Z^{(\prime)}_c, Z^{(\prime)}_c \to \rho\eta_c$

| | $\sqrt{s} = 4.23$ GeV | $\sqrt{s} = 4.26$ GeV | $\sqrt{s} = 4.36$ GeV | Tetra-quarks-I | Tetra-quarks-II | Molecule |
|---|---|---|---|---|---|---|
| $R_{Z_c(3900)}$ | $2.1 \pm 0.8$ | $< 6.4$ | ... | $230^{+330}_{-140}$ | $0.27^{+0.40}_{-0.17}$ | $0.046^{+0.025}_{-0.017}$ |
| $R_{Z_c(4020)}$ | $< 1.9$ | $< 1.2$ | $< 1.0$ | $6.6^{+56.8}_{-5.8}$ | | $0.010^{+0.006}_{-0.004}$ |




$$R_z = \frac{Br(Z_c \to \rho\eta_c)}{Br(Z_c \to \pi J/\psi)}$$

$$R_{Z'} = \frac{Br(Z_c' \to \rho\eta_c)}{Br(Z_c' \to \pi h_c)}$$

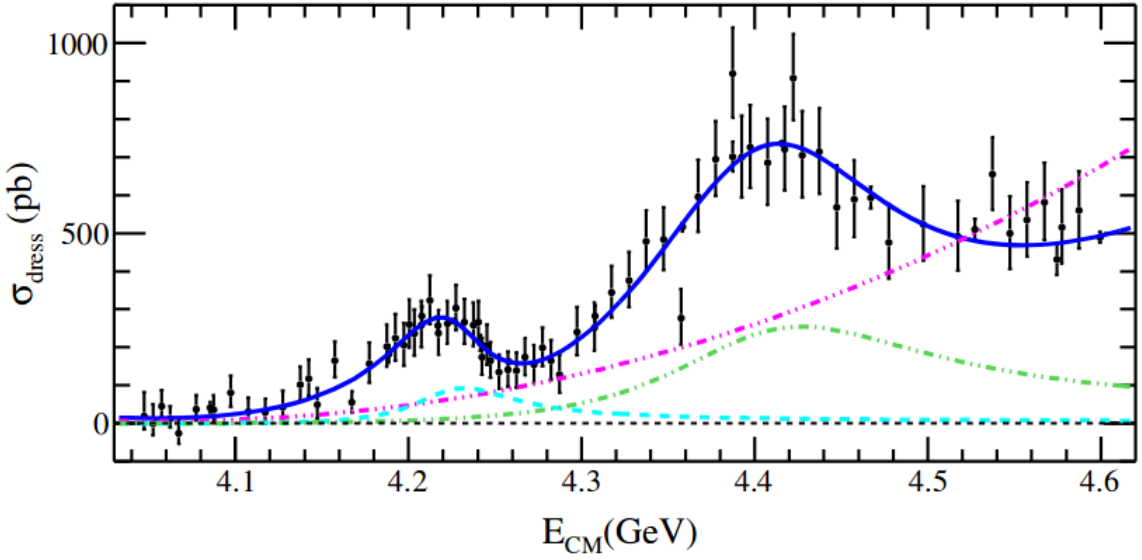
**Phys. Lett. B 746, 194 (2015)**

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

PRL 122, 102002 (2019)

**Coherent sum** of two **Breit Wigner amplitudes** plus a polinomial continuum is used to fit 84 energy values from 4.05 to 4.6 GeV.

$$\sigma_{\text{dress}}(m) = \left| c\sqrt{P(m)} + e^{i\phi_1} B_1(m)\sqrt{P(m)/P(M_1)} + e^{i\phi_2} B_2(m)\sqrt{P(m)/P(M_2)} \right|^2,$$




Two structures are needed to fit the data with a significance larger than 10σ.

Higher mass structure parameters vary largerly with the parametrization chosen. Detailed amplitude analysis needed.

Mass and width of the structure at low mass are

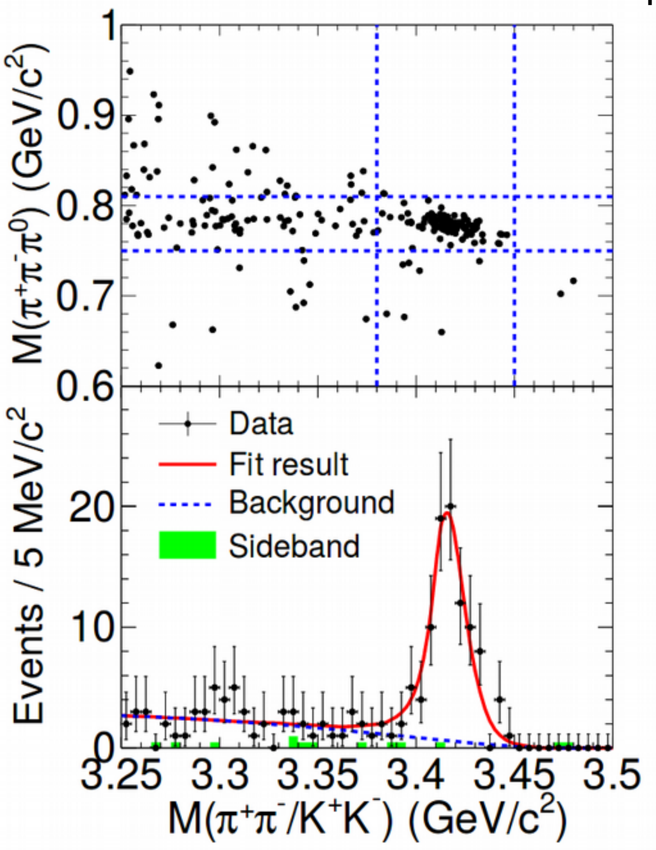
$$M(R_1) = (4228.6 \pm 4.1 \pm 6.3)\ \text{MeV}/c^2$$
$$\Gamma(R_1) = (77.0 \pm 6.8 \pm 6.3)\text{MeV}$$

Mass compatible with Y(4220) observed in $\pi\pi h_c$ and $\pi\pi\psi(2S)$, slightly higher than the one in $\omega\chi_{c0}$ and $\pi\pi J/\psi$.

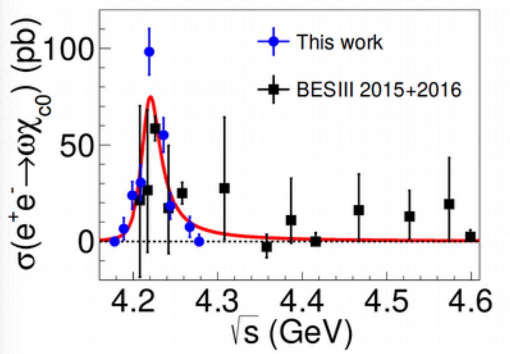
First observation of a Y(4220) in open charm final state. Y(4220) as $DD_1(2420)$ molecule? *PRD90, 074039 (2014)*

# Measurement of $e^+e^- \to \omega\chi_{c0}$ from 4.178 to 4.278 GeV

Accepted by PRD(RC) - ArXiv: 1903.02359

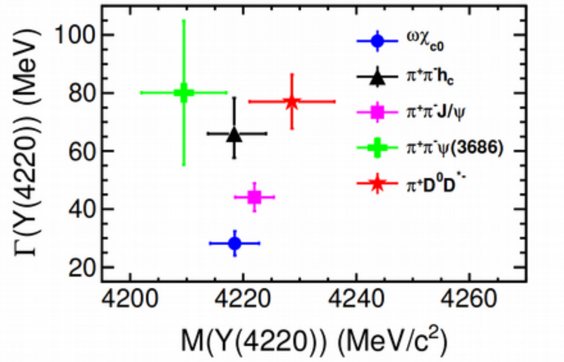



Update of previous measurement
(PRL 114, 092003 and PRD 93, 011102)
with the data collected in 2017




$$\sigma(\sqrt{s}) = \frac{12\pi\Gamma_{ee}\mathcal{B}(\omega\chi_{c0})\Gamma}{(s-M^2)^2+M^2\Gamma^2} \times \frac{\Phi(\sqrt{s})}{\Phi(M)}$$

It is also possible to see that mass seems to be in good agreement between different final states



arXiv: 1903.08126

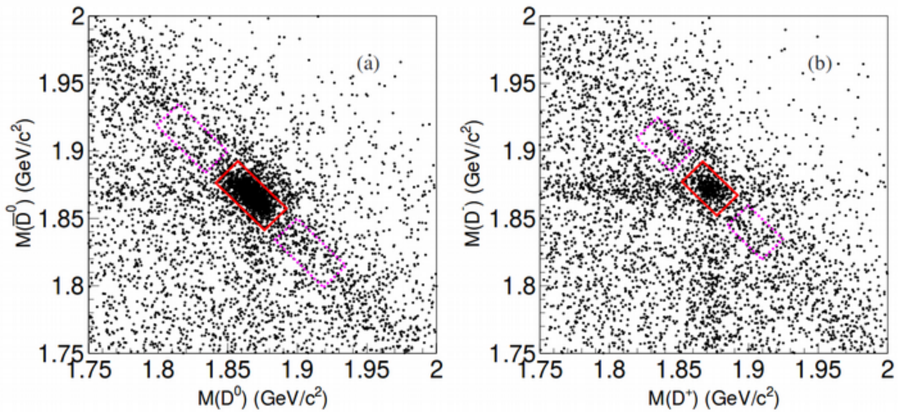
# Study of $e^+e^- \to \pi^+\pi^- D\bar{D}$

$e^+e^- \to \pi^+\pi^- D\bar{D}$ final state can be used to search for exotic final states and study connections:

- **X(3872)** heavy quark symmetry partner in $\rho X_2(4013)$ (*PLB 588, 189 (2004) and PLB590, 209 (2004)*)
- Y states with ψ(3770) and test of the **molecular nature** of **Y(4220)** (*PRD90, 074039 (2014)*)
- $Z^+_c$ state in ψ(3770)π as a natural estention.

BESIII has studied this final states in 15 energy values between 4.09 and 4.6 GeV by reconstructing both D (double-tag approach):

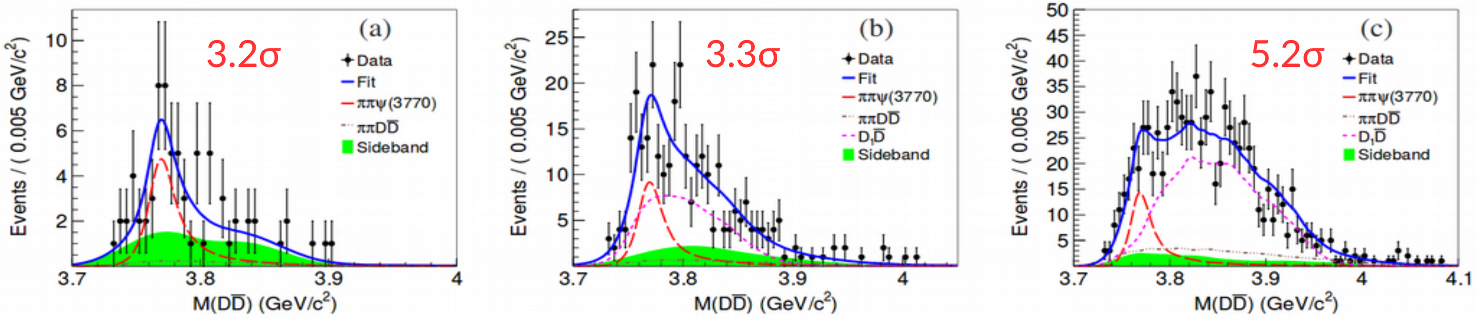
- Charged D in 5 different final states ($K^-\pi^+\pi^+$, $K^-\pi^+\pi^+\pi^0$,$K_s\pi^+$,$K_s\pi^+\pi^0$,$K_s\pi^+\pi^-\pi^+$)
- Neutral D in 4 different final states ($K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$,$K^-\pi^+\pi^+\pi^-\pi^0$)



arXiv: 1903.08126

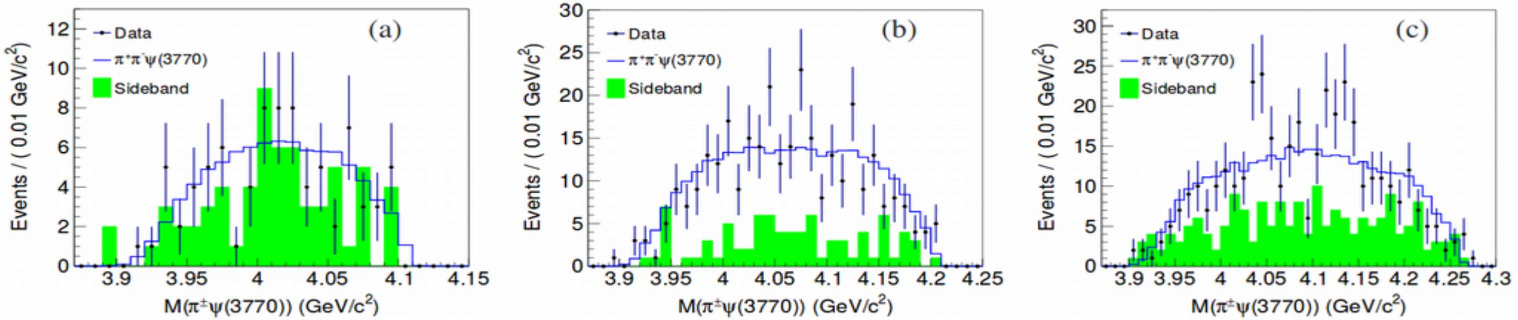
# Study of $e^+e^- \to \pi^+\pi^- D\bar{D}$

$e^+e^- \to \pi^+\pi^-\psi(3770)$ @ 4.26 GeV (a), 4.36 GeV (b), 4.42 GeV (c)




Search for $Z_c \to \pi\psi(3770)$ @ 4.26 GeV (a), 4.36 GeV (b), 4.42 GeV (c)

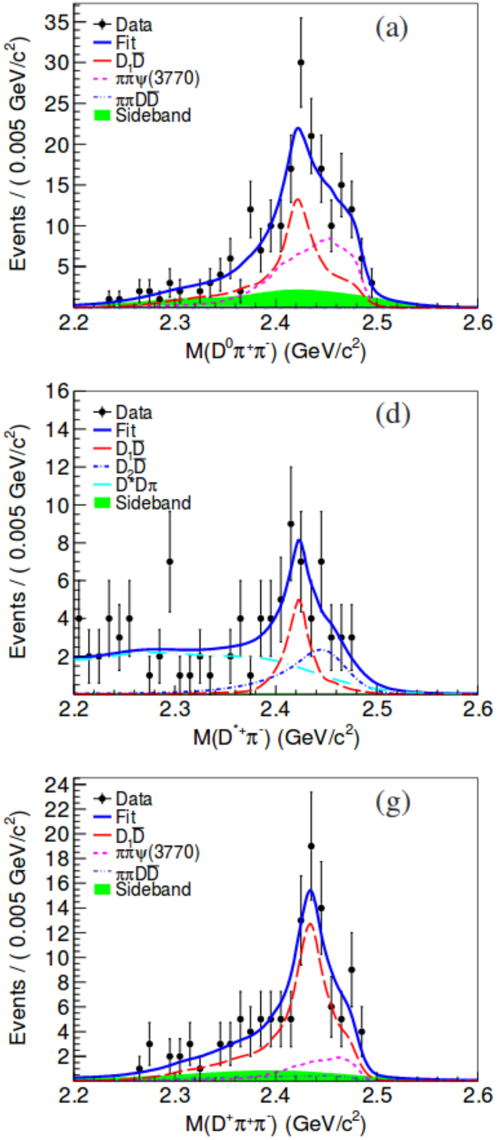
No statistical evidence




No hints of $e^+e^- \to \rho X_2(4013)$ at any center of mass value

arXiv: 1903.08126

# Study of $e^+e^- \rightarrow \pi^+\pi^- D\bar{D}$




The process $e^+e^- \rightarrow D_1(2420)D$ is studied in three different final states:

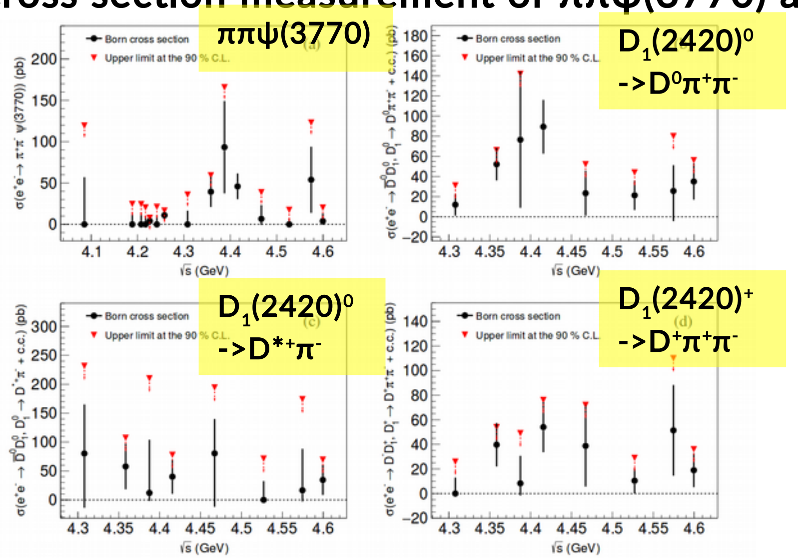
1) $D_1(2420)^0 \rightarrow D^0\pi^+\pi^-$

2) $D_1(2420)^0 \rightarrow D^{*+}\pi^-$

3) $D_1(2420)^+ \rightarrow D^+\pi^+\pi^-$

For the full spectrum of data analysed. **Observation of 1)** at 4.42 GeV, **no evidence of 2)** at any center of mass, **evidence of 3)** at 4.36 and 4.42 GeV.

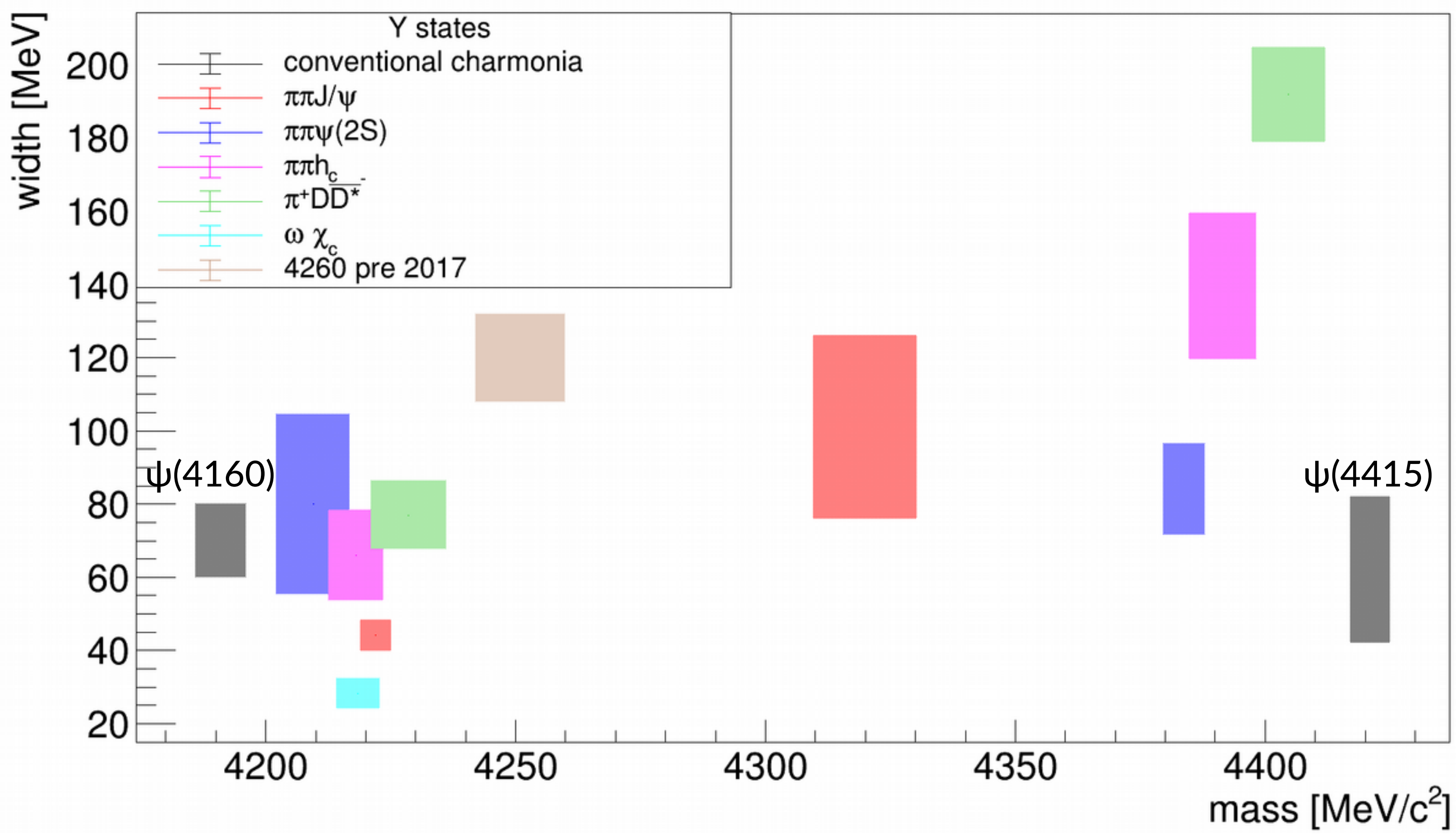
## Cross section measurement of $\pi\pi\psi(3770)$ and $D_1(2420)D$ final states




1) $\pi\pi\psi(3770)$ to be compared with the one of $\pi\pi\psi(1^3D2)$ *PRL 112 011803 (2015)* to understand its origin

2) No sharp rise of the D(2420)D cross section. **Molecular interpretation of Y(4220) seems disfavoured** as pointed out by *EPJ C78, 276 (2018)*

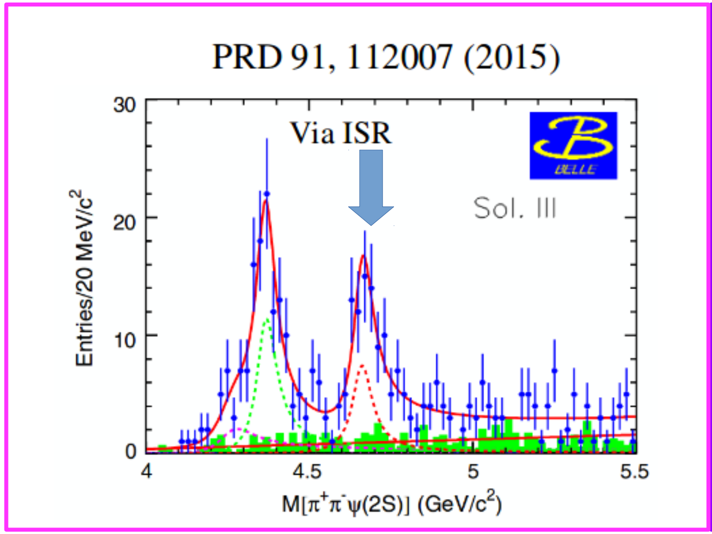
# Summary plot of Y states – Recent BESIII measurement

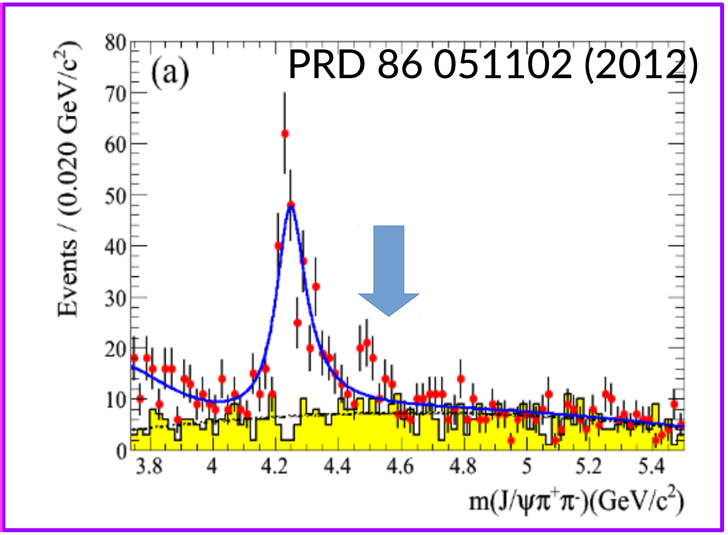


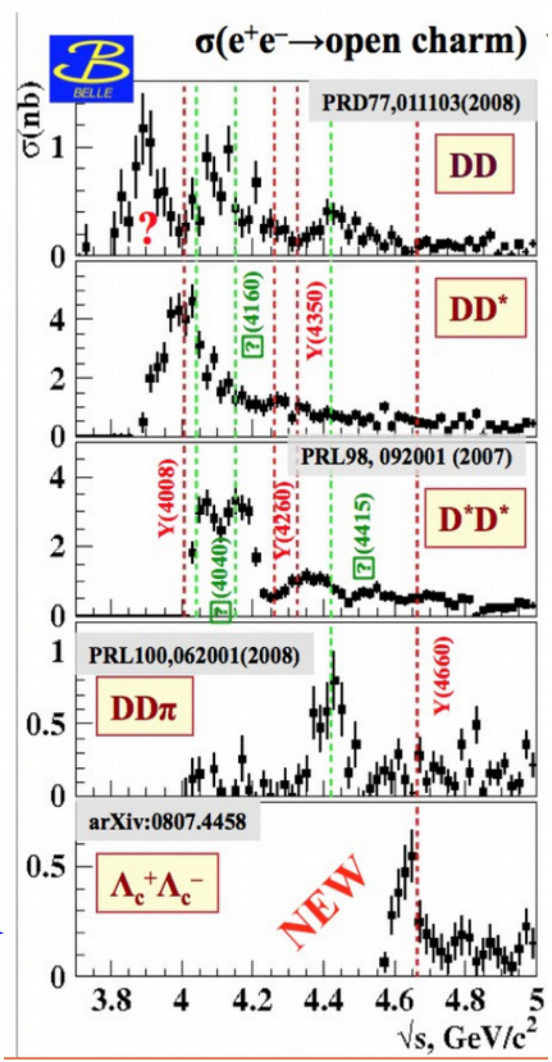

# Y(4660) @ BESIII

# Y(4660)

Discovered by BELLE in $\pi\pi\psi(2S)$ decay thanks to ISR return
No signal is present in $J/\psi\pi\pi$




Only observation in open charm final state is in $\Lambda_c\bar{\Lambda}_c$ →

# Y(4660)

By studying the cross section:

- $Y(4660) \rightarrow \Lambda_c \bar{\Lambda}_c$ ~ 0.55 nb @ peak
- $Y(4660) \rightarrow \pi\pi\psi(2S)$ ~ 0.04 nb @ peak

Baryonic coupling ~ 11*mesonic coupling

Another mesonic final state exists and it can match the difference

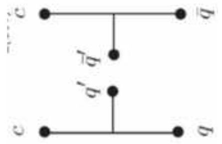
$\psi(2S)f_0(980)$ Hadronic molecule

PRD 82, 094008 (2010)

Slightly disfavored by the missing open charm decays

Charmed baryonium

PRL 104, 132005 (2010)



Nucl Phys. B 123, 507 (1977)

# Y(4660) @ BESIII

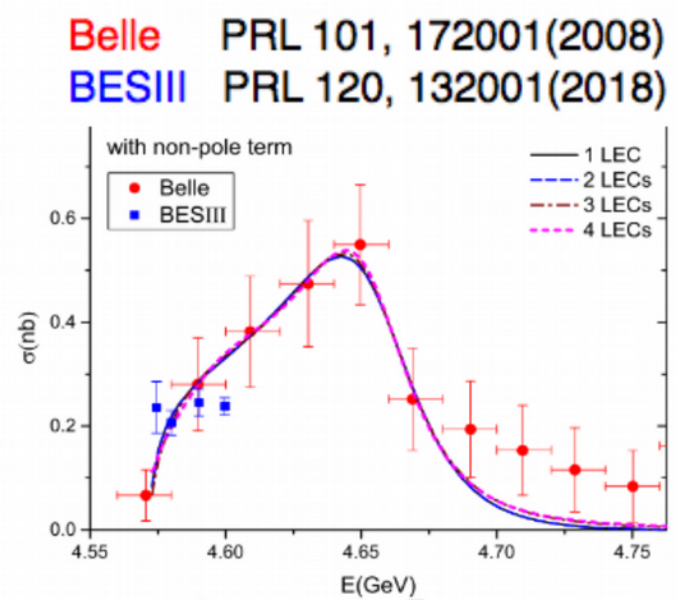
BESIII has already measured 4 $\Lambda_c\bar{\Lambda}_c$ cross sections just above thresholds. But at present time it cannot say more on Y(4660)

Agreement with BELLE data, but trend seems different.

With the planned energy upgrade BESIII will be able to explore this energy region

- More on the upgrade in the additional material

- If BESIII and BELLE data agree, precise measurement of the Y(4660)
- If trend will remain different:
  - More complicated to interpret Y(4660) as charmed baryonium



# Summary

- BESIII plays **unique** role with respect to B-factories and hadron colliders in the search for exotic states
  - Possibility to **directly access** the vector charmonium-like states allow BESIII to accumulate **large data sample** to study their decays and lineshape
  - With this large samples, **create connections** between these state

- Recent **observation** of different new final states allow to deep the **knowledge** on the **nature** of **X(3872), Y(4220)**, and $Z^{(\prime)}$ and the **interconnection** between the these states
  - A new fine scan (500/pb per energy, 10 energies between 4.18 and 4.4 GeV) is going during this year data taking

- With the planned **upgrade**, BESIII will access to **Y(4660)** to shed new light on this state

- What are the **theoretical implications**? For which final states BESIII can additionally use its unique perspective? This is my first question to the next speaker, **Mikhail Voloshin**

THANKS

谢谢

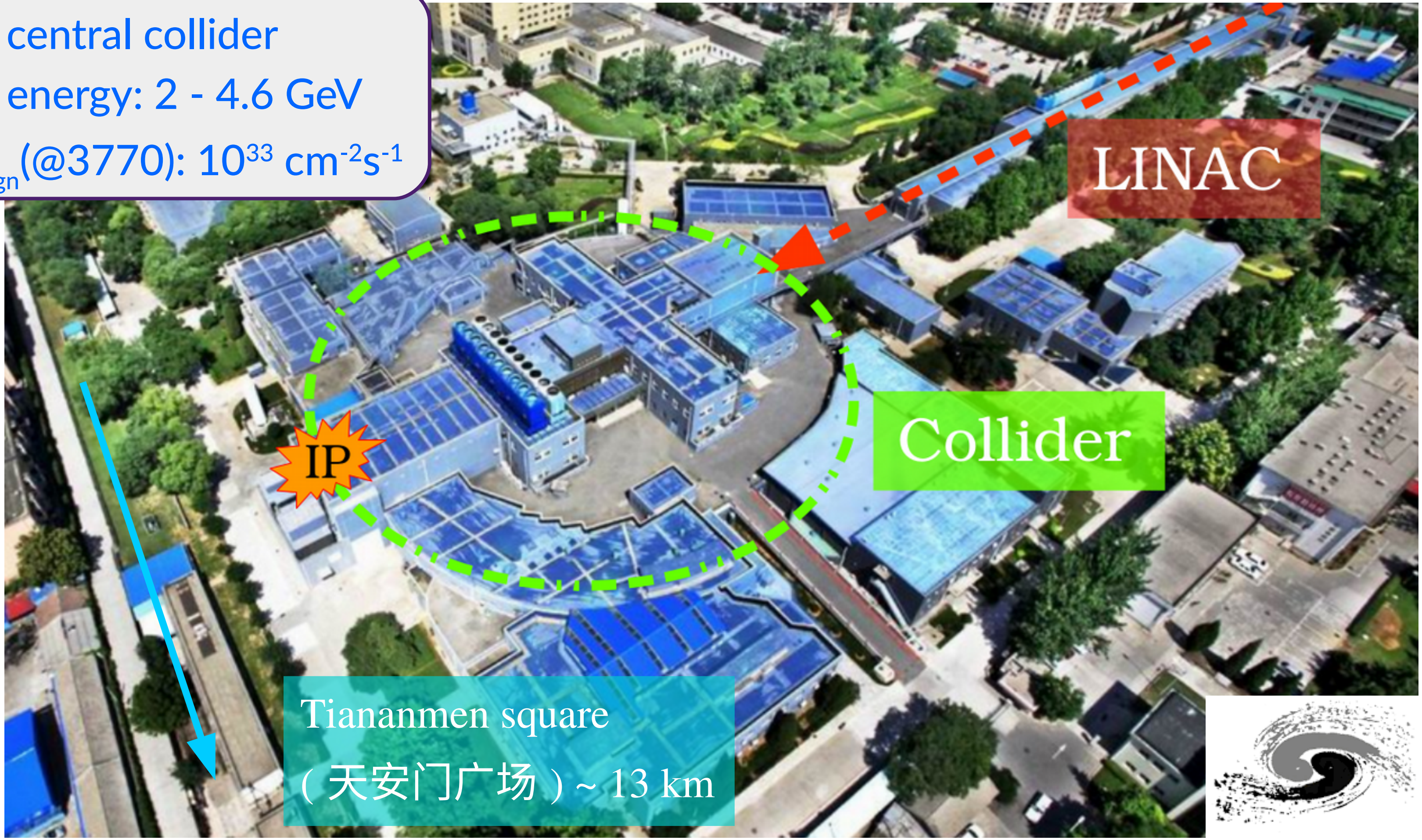
# Additional materials

# BEPCII @ IHEP (Beijing, PRC)

$e^+e^-$ central collider

CM energy: 2 - 4.6 GeV

$L_{design}$(@3770): $10^{33}$ $cm^{-2}s^{-1}$

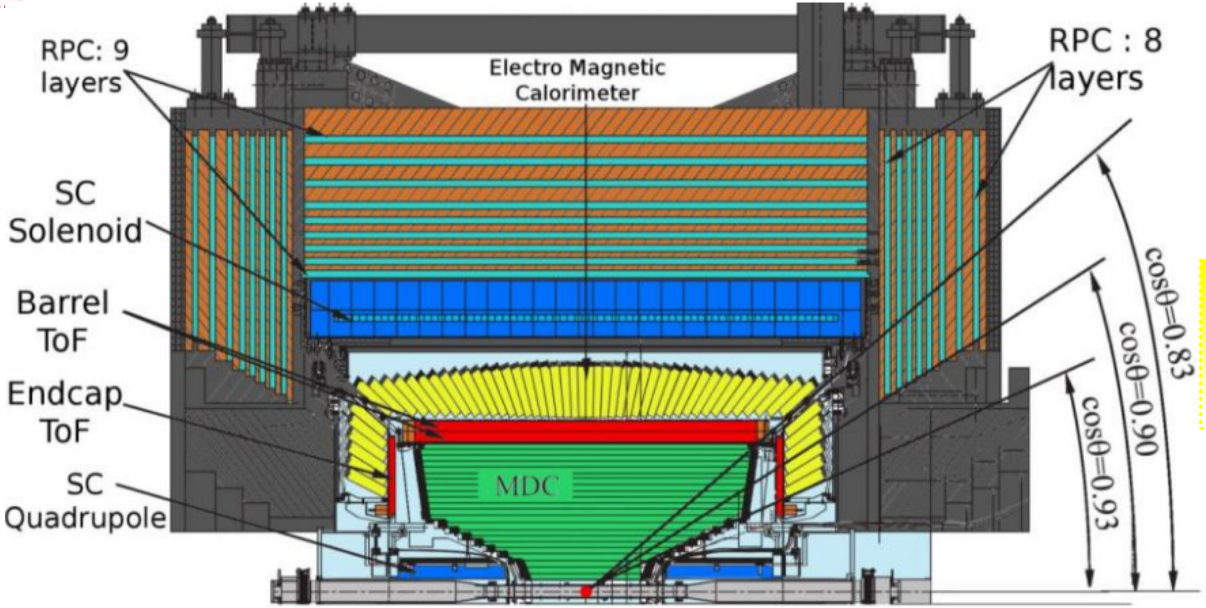


# BESIII @ BEPCII

Time Of Flight:
$\sigma_t$ (barrel) = 90 ps
$\sigma_t$ (endcap) = 110 ps

1 Tesla Magnetic field

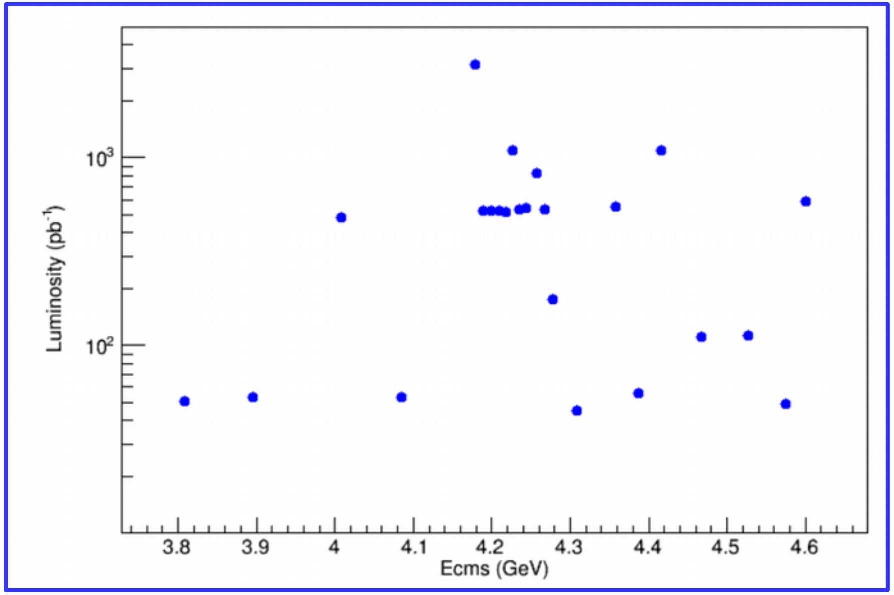
Muon counters:
$\delta_{r\varphi}$ = 1.4 cm – 1.7 cm

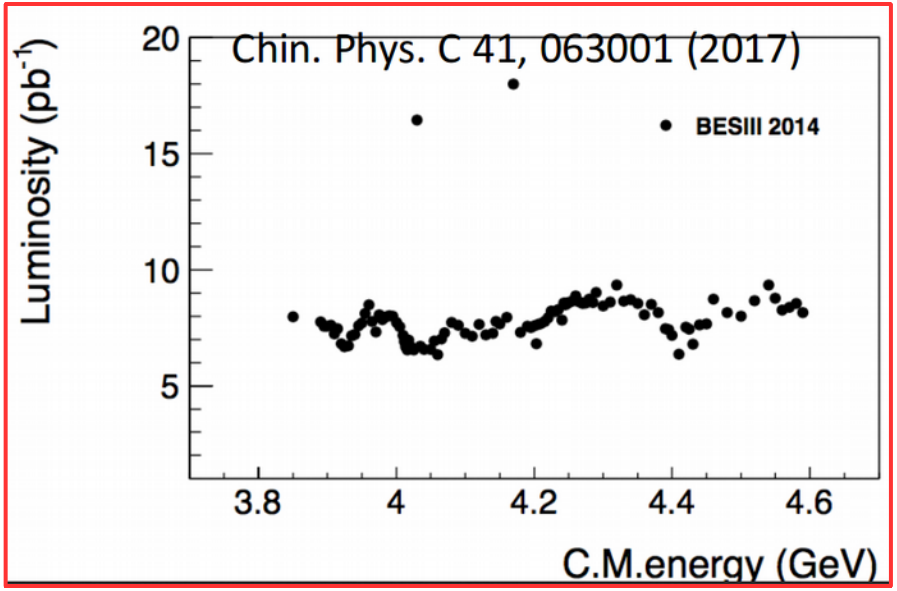



Electromagnetic
Calorimeter:
$dE/\sqrt{E}$ (1 GeV) = 2.5 %

Main Drift Chamber:
$\sigma_x$ (1 GeV/c) ~ 130 μm
dp/p (1 GeV/c) = 0.5 %

# Collected datasets for Exotics searches

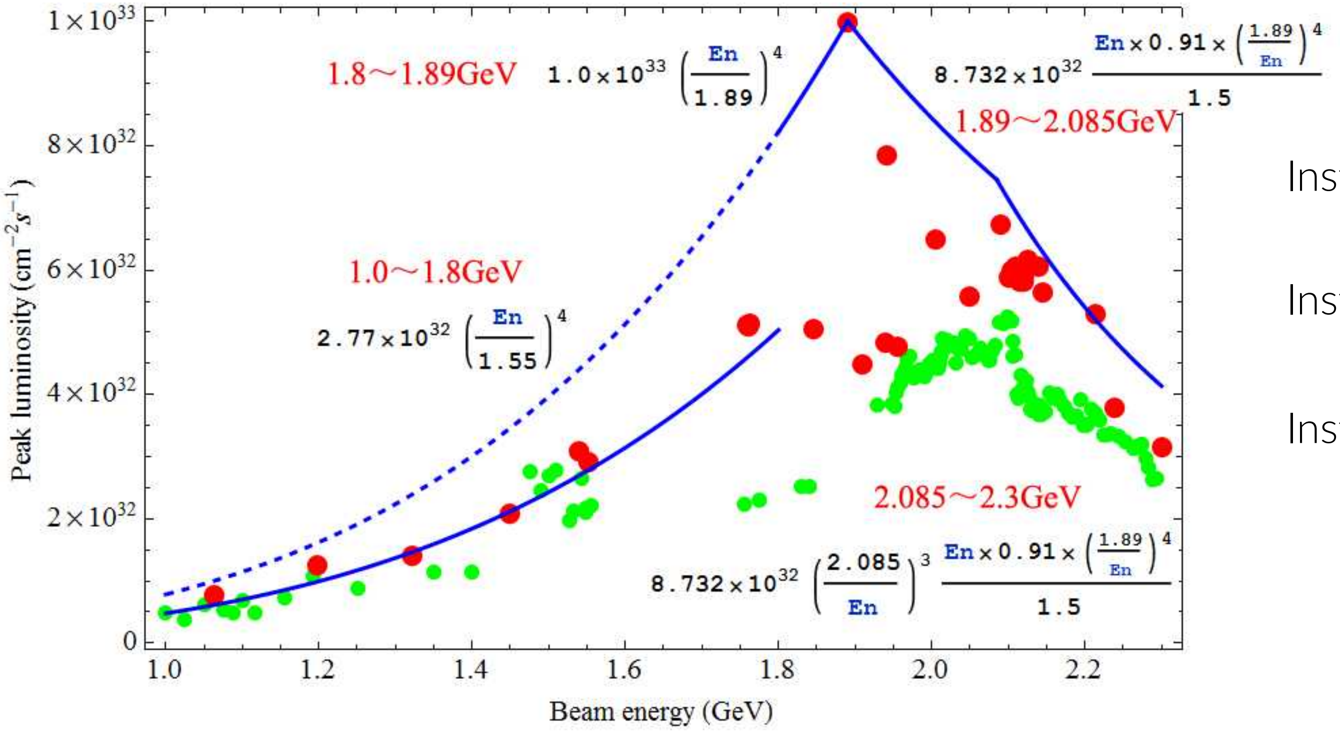



Dataset can be splitted in two:

1) XYZ data: high integrated luminosity but few energy values
2) Rscan data: fine scan  but low integrated luminosity

# Luminosity vs Energy



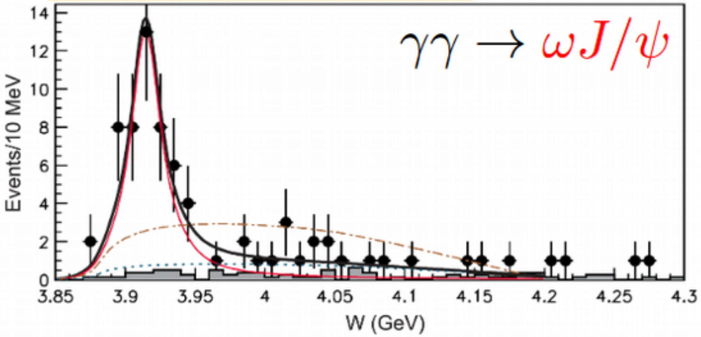

Inst. Lumin. @ J/ψ = 0.28 $10^{33}$ $cm^{-2}$ $s^{-1}$

Inst. Lumin. @ ψ(2S) = 0.9 $10^{33}$ $cm^{-2}$ $s^{-1}$

Inst. Lumin. @ 4.6 GeV = 0.41 $10^{33}$ $cm^{-2}$ $s^{-1}$

# X(3915) →ωJ/ψ

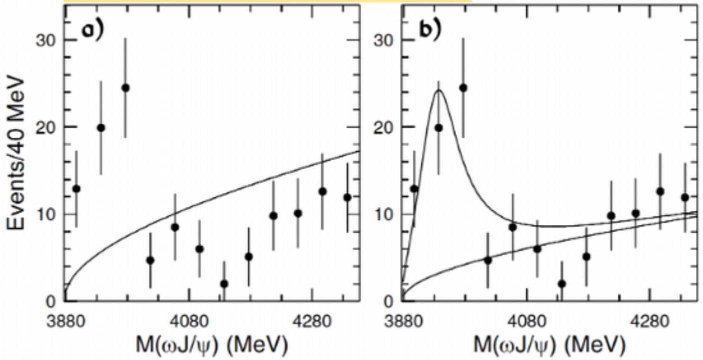
PRL 104, 092001 (2010)




$M = (3915 \pm 3 \pm 2)\ \mathrm{MeV/c^2}$

$\Gamma = (17 \pm 10 \pm 3)\ \mathrm{MeV}$

PRL 94, 182002 (2005) $B \to K\omega J/\psi$



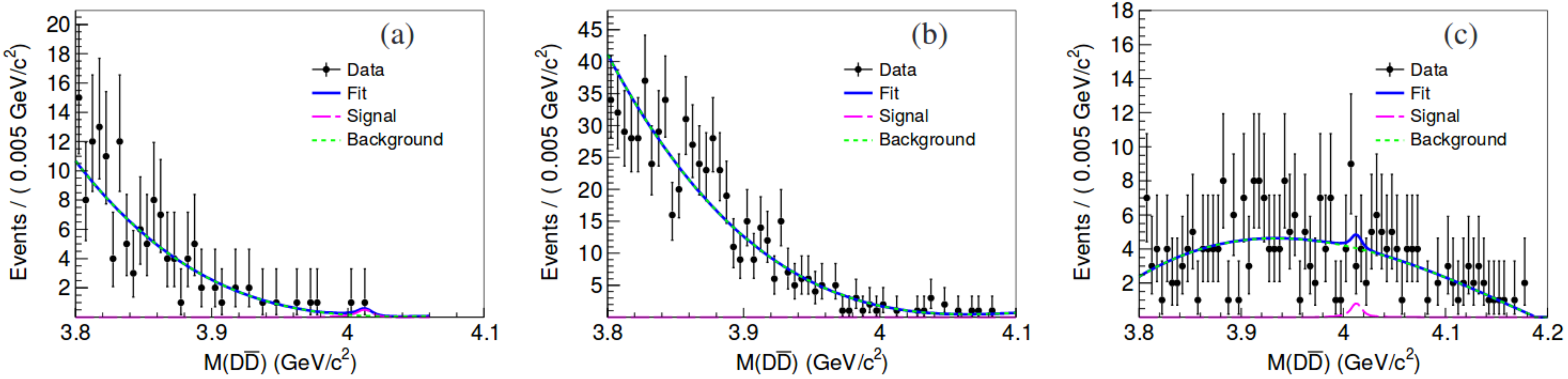

$M = (3943 \pm 11 \pm 13)\ \mathrm{MeV/c^2}$

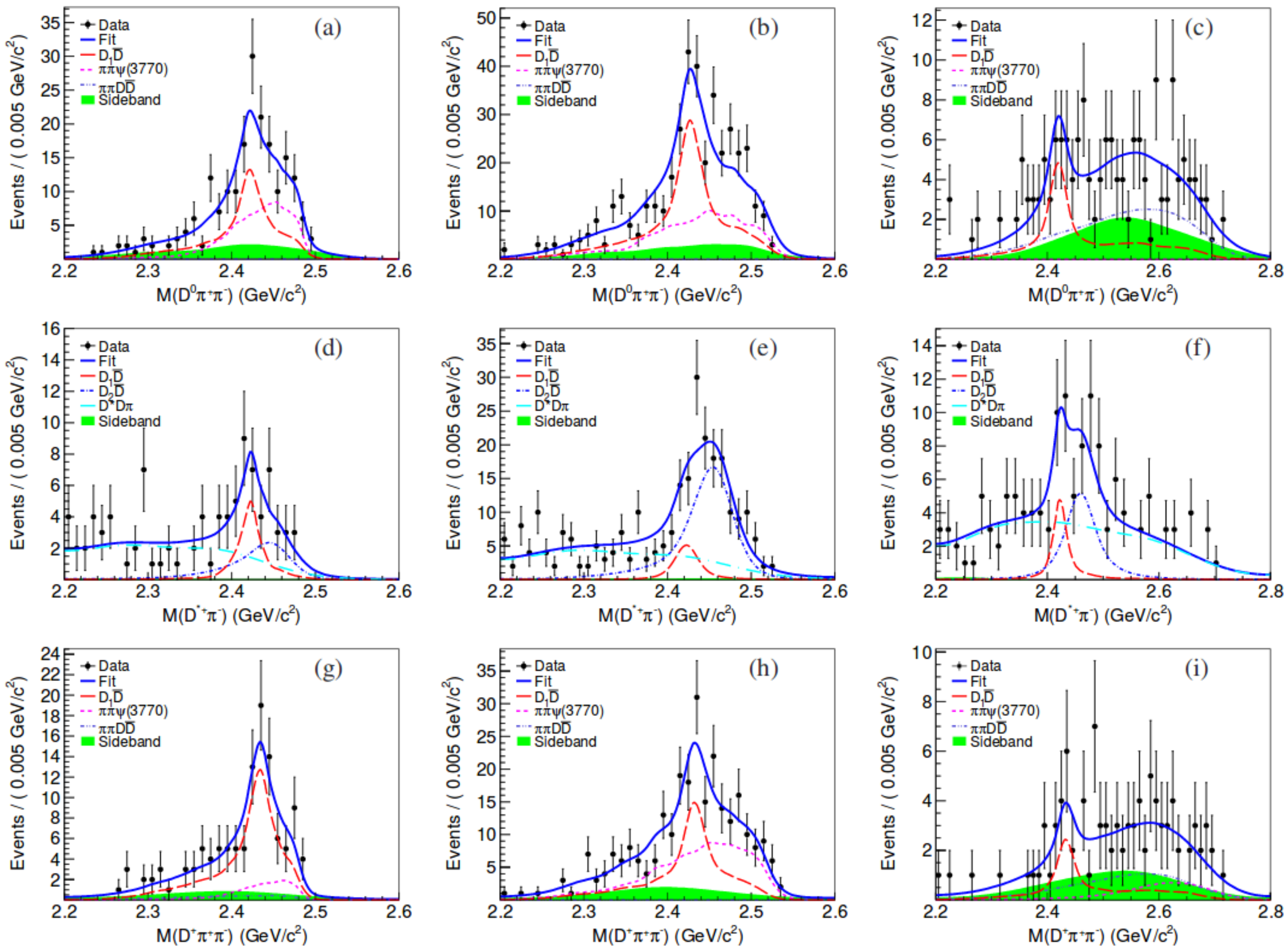
$\Gamma = (87 \pm 22 \pm 26)\ \mathrm{MeV}$

- Y(3940) and X(3915) were the same resonance suggested by PDG
- Underlying nature of X(3915) is still unclear
- Radiative transition of $e^+e^- \to \gamma\omega J/\psi$ can provide additional data on X(3915)

Based on 11.6 $fb^{-1}$ data at $\sqrt{s}$=4.01~4.60 GeV taken by BESIII, study the processes $e^+e^- \to \gamma X(3872) \to \gamma\omega J/\psi$ and $e^+e^- \to \gamma X(3872) \to \gamma\pi^+\pi^- J/\psi$

# $\rho X_2(4013)$





(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
Data
Fit
$D_1\bar{D}$
$\pi\pi\psi(3770)$
$\pi\pi D\bar{D}$
$D_2\bar{D}$
$D^*D\pi$
Sideband
Events / ( 0.005 GeV/$c^2$)
$M(D^0\pi^+\pi^-)$ (GeV/$c^2$)
$M(D^{*+}\pi^-)$ (GeV/$c^2$)
$M(D^+\pi^+\pi^-)$ (GeV/$c^2$)

# Measurement of $e^+e^- \to \omega\chi_{c0}$ from 4.178 to 4.278 GeV

Accepted by PRD(RC) - ArXiv: 1903.02359

Using **three large statistics** energy values (4.219, 4.226, and 4.236 GeV) is possible to study the **angular distribution** to improve the knowledge of **underlying dynamics**

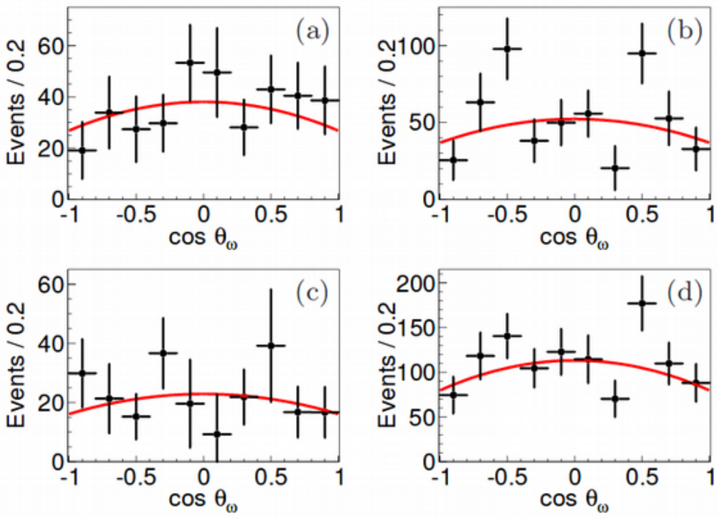



FIG. 3. Simultaneous fit to the angular distributions for data taken at $\sqrt{s}$ = 4.219 (a), 4.226 (b) and 4.236 (c) GeV. (d) shows the summed result of the three center-of-mass energies.

Both **S-** and **D-wave** can contribute

**Simultaneous fit** prefers the option with both **S-** and **D-wave** with a result of:

$$\alpha = -0.30 \pm 0.18 \pm 0.05$$

However the significance is only 2σ over the pure S-wave.

# BESIII/BEPCII upgrade plan

# The general plan

- BESIII just started its **tenth year** of successfull **data taking** (first collision in Sep. 2009)
- The data taking will proceed up to 2024, with a likely extension up to 2028.

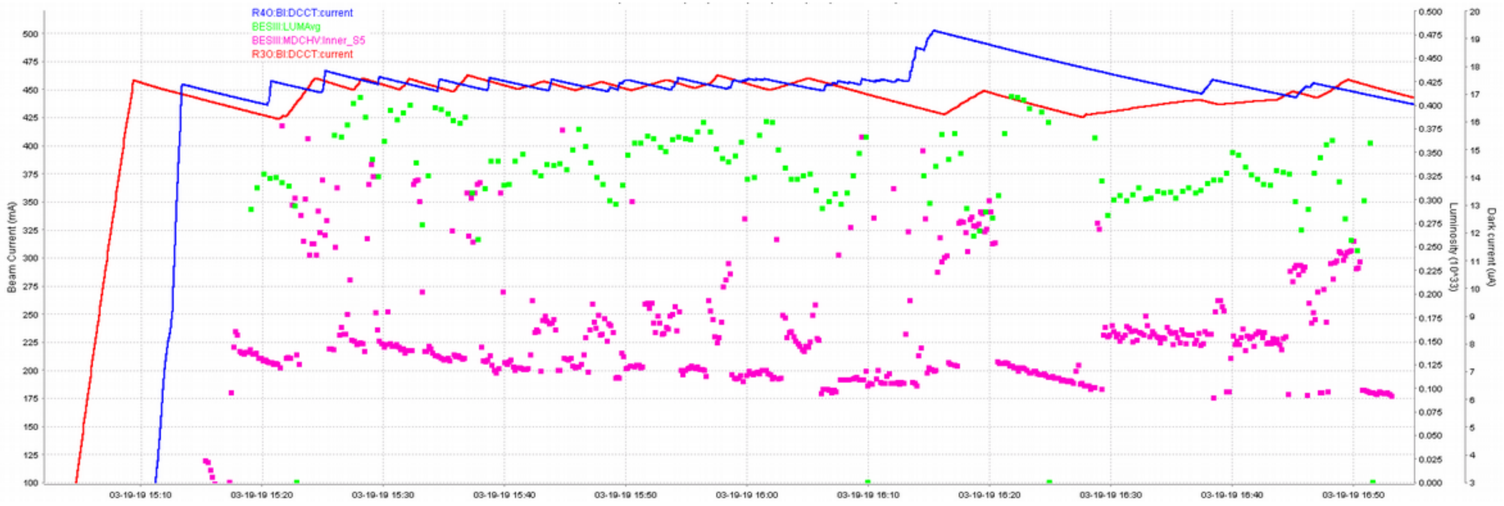
A program for the **upgrade** of both the **accelerator** and the **detector** is on-going.

- Continuous injection
- Increase of the center of mass energy:
  - Up to 4.7 GeV (from next year)
  - Up to 4.9 GeV (funding already approved)

- New ETOF based on MultiGap resistive place chambers
  - Time resolution down to 60 ps
- New Inner Tracker based on Cylindrical GEM
  - Improve of primary and secondary vertexes determination

# BEPCII upgrade

- Continous injection **successfully achieved** during this year data taking
  - Expected **30% increase** of **integrated luminosity** per round
  - On-going to finalize and make operative by the next year data taking

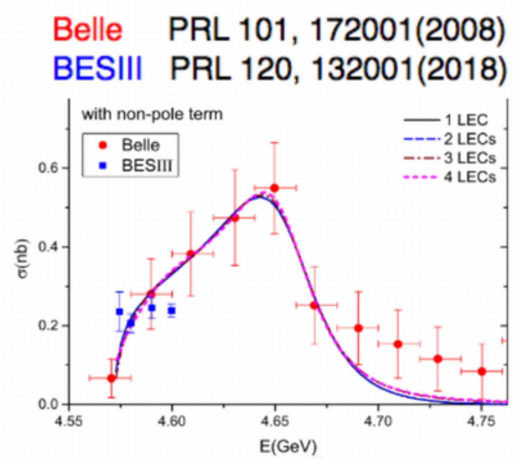



Beam current (red and blue)
Luminosity (green)
MDC dark current (magenta)

# BEPCII upgrade

- Data taking at center of mass energies $\mathbf{E_{cm}}$ **> 4.6 ( <= 4.7) GeV** *feasible* already during this year
  - Power supply needed already in place.

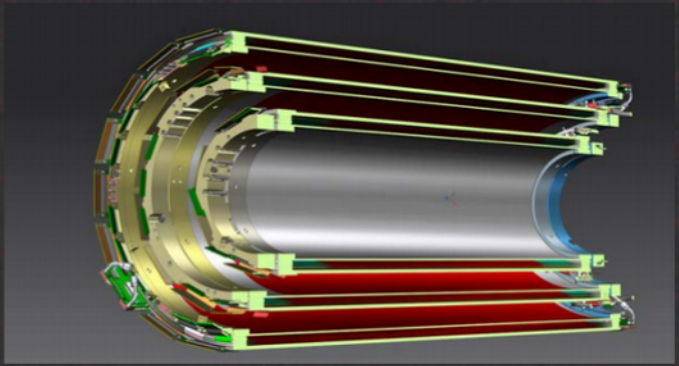
- Possibility to explore the Y(4660) region and increase the increase the number of $\Lambda_c$ pairs
  - With **additional 3 fb**$^{-1}$ it will be possible to push the **precision of charmed baryon decays** at the level of **charmed mesons**



# Inner Tracker Upgrade

- Build a **cylindrical GEM** Inner Tracker (CGEM-IT) to replace the BESIII Inner MDC since aging is affecting its performance.
- Match the MDC tracking performance →
  - Low Material budget ≤ 1.5% of $X_0$ for all layers
  - High Rate capability: ~$10^4$ Hz/cm$^2$
  - Spatial resolution: $\sigma_{xy}$ =~130 μm, $\sigma_z$=~1 mm
  - Momentum resolution:: σpt/Pt =~0.5% @1 GeV
  - Coverage: 93%
- Improve rate capability and the radiation hardness
- Improvement in z resolution
- Possibility of a further improvement of the tracking performance with single-layer 3D tracking.

Diapositiva 83



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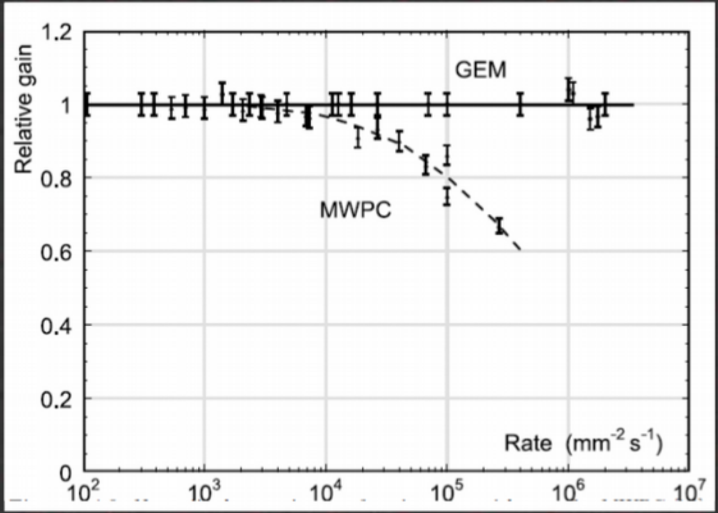


- **Improve rate capability and the radiation hardness**
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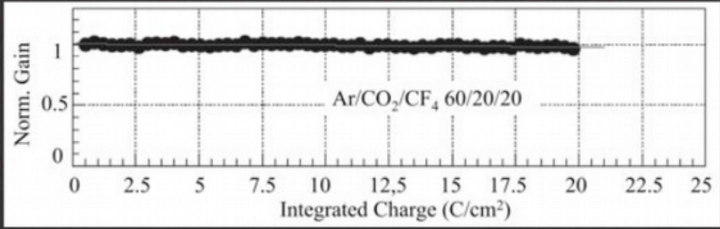
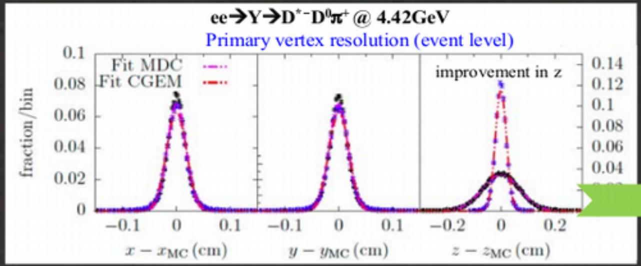


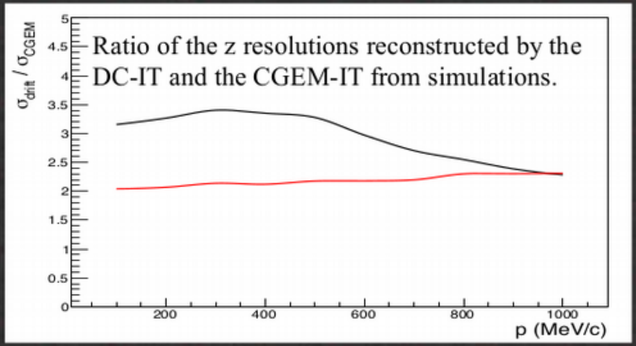
# Inner Tracker Upgrade

larger stereo angle

significant improvement of the polar angle measurement.




benefit for those decay channels including Λ or Ks

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