Z_c and Z_{cs} studies at BESIII

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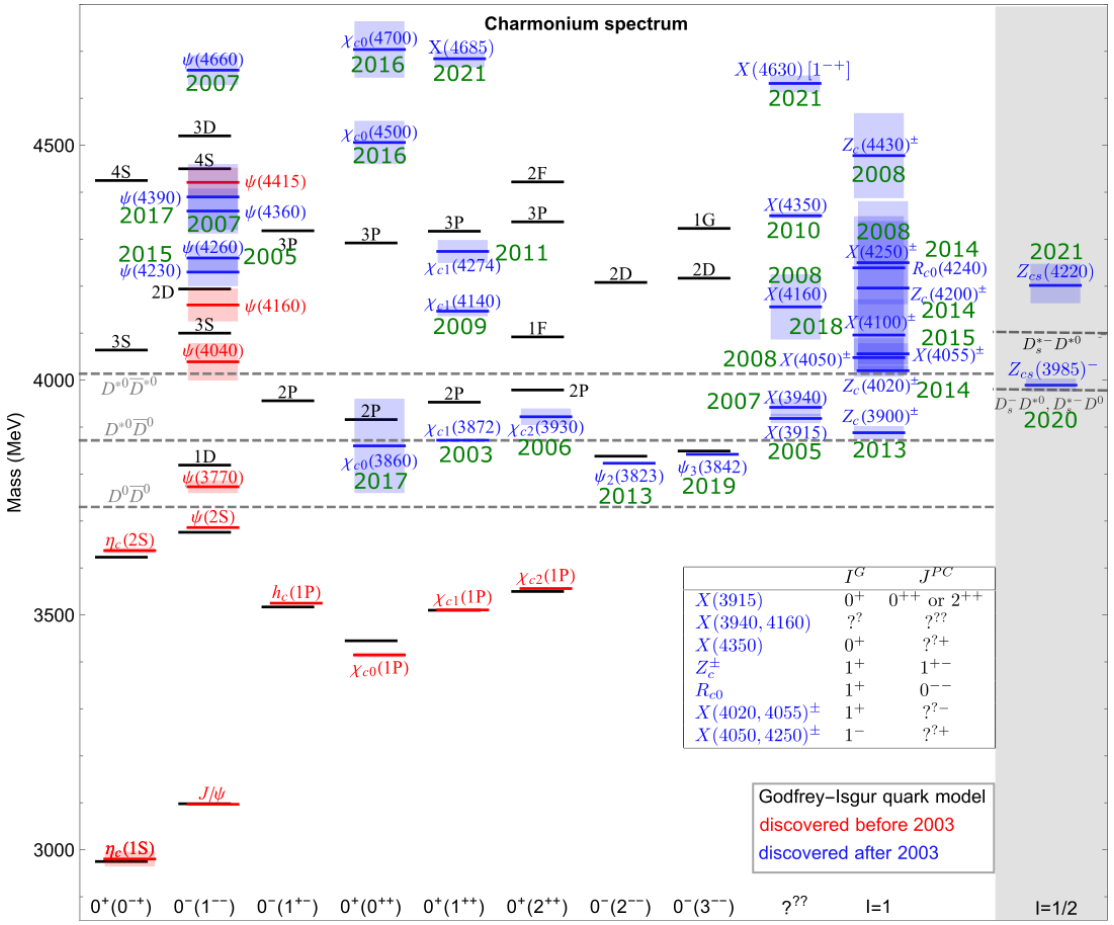
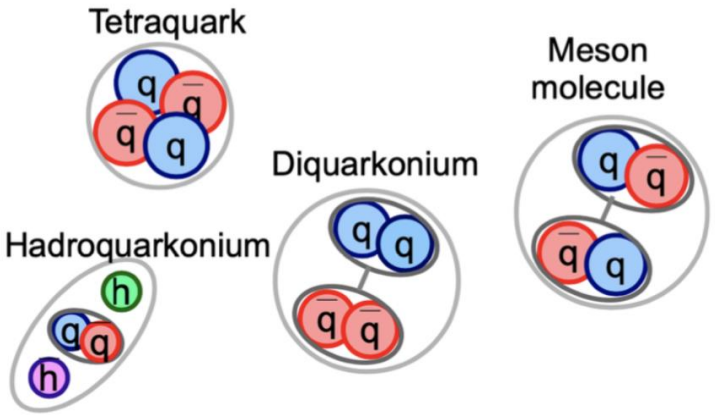
- **Summary**



Charmonium(-like) structures[1]

- Many charmonium and charmonium -(like) states are observed.
- A series of **theoretical models** for ***XYZ*** states:

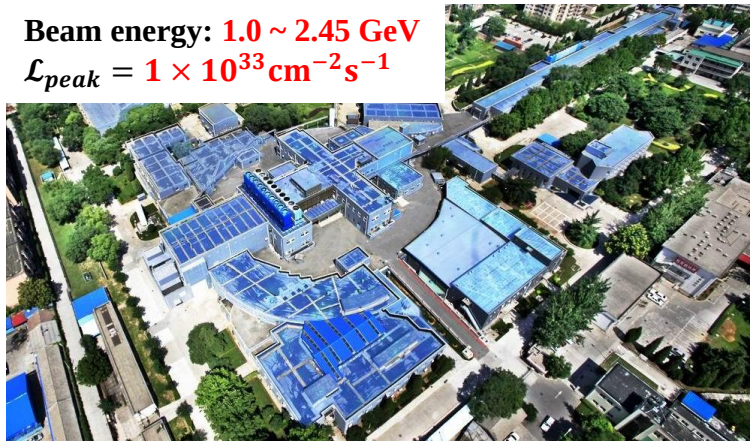


- **Joint efforts from both theories and experiments are needed to understand the nature of the *XYZ* states.**

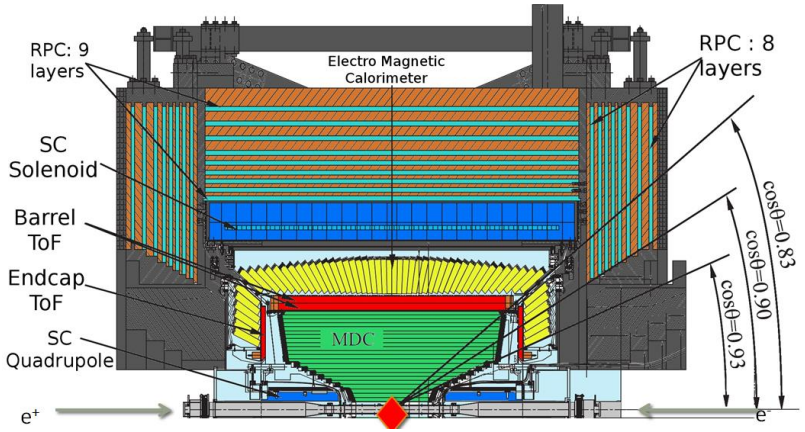
[1] From Fengkun's talk on the *XYZ* Workshop in China

Beam energy: 1.0 ~ 2.45 GeV

$\mathcal{L}_{peak} = 1 \times 10^{33}\text{cm}^{-2}\text{s}^{-1}$

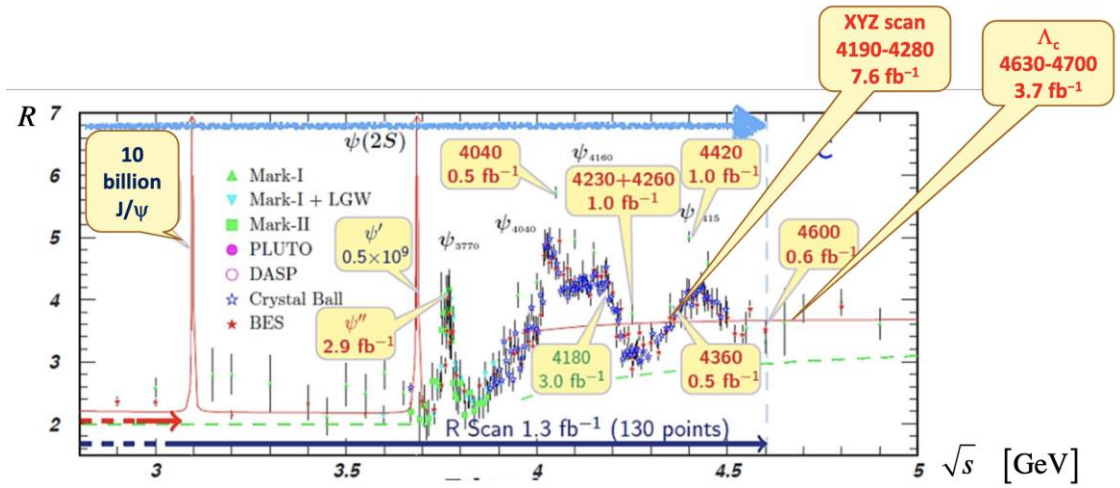


BEPCII



BESIII

Sub-system	Performance
MDC	$\sigma_{xy} = 130\ \mu m$ $\Delta P/P = 0.5\%$ @ 1GeV $\sigma_{dE/dx} = 6\%$
TOF	$\sigma_T = 68$ ps (barrel) 60 ps (endcaps)
EMC	$\Delta E/\sqrt{E} = 2.5\%$ @ 1GeV $\sigma_z = 0.5$cm @ 1GeV
Magnet	1.0 Tesla
MUC	$0.9\times 4\pi$



- **Datasets in BESIII (~13 years):**
  - The worldwide largest e^+e^- datasets in τ-charm region
  - 46 datasets with $\sqrt{s} > 3.8$ GeV, $\sum L_i = 21.9\ \text{fb}^{-1}$
  - 29 energy points with $L_i > 0.4\ \text{fb}^{-1}$
- **Large datasets for *XYZ* analyses!**

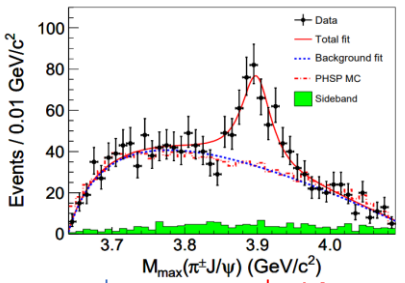
Overview of Z_c analyses @ BESIII

- The ~4 fb^{-1} data with $\sqrt{s}$ from **4.23 to 4.42 GeV** collected **in 2013 and 2014 years**.

- ✓ **Observation** of the **charmonium-like Z_c and Z_c^*** states in both **open charm** and **hidden charm** final states!

$Z_c(3900)^+$

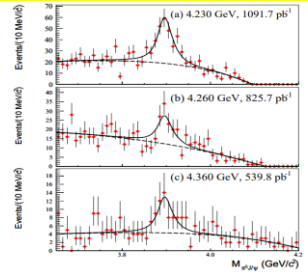
PRL 110, 252001 (2013)



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

$Z_c(3900)^0$

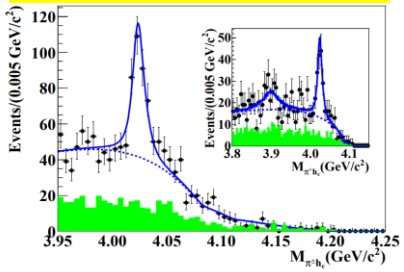
PRL 115, 112003 (2015)



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

$Z_c(4020)^+$

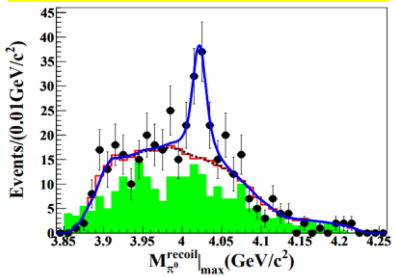
PRL 111, 242001 (2013)



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

$Z_c(4020)^0$

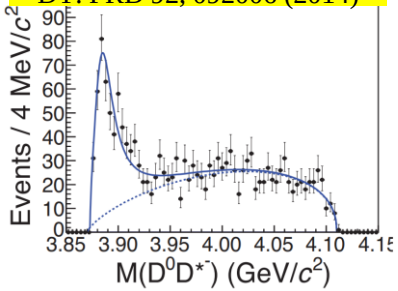
PRL 113, 212002 (2014)



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

$Z_c(3885)^+$

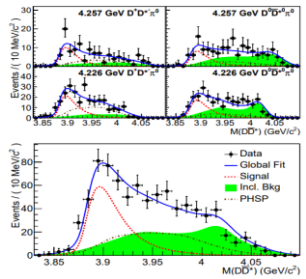
ST: PRL 112, 022001 (2014)
DT: PRD 92, 092006 (2014)



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

$Z_c(3885)^0$

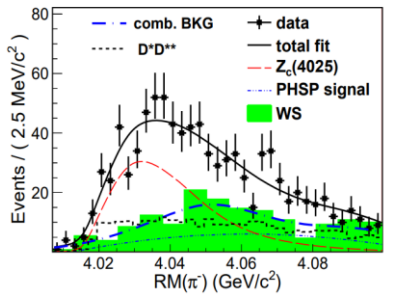
PRL 115, 222002 (2015)



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

$Z_c(4025)^+$

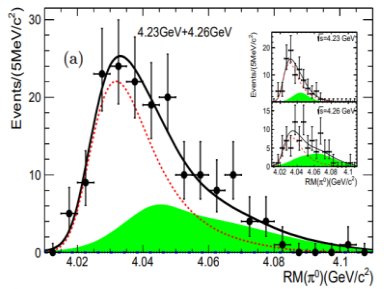
PRL 112, 132001 (2014)



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

$Z_c(4025)^0$

PRL 115, 182002 (2015)



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

- The ~13 fb^{-1} data with $\sqrt{s}$ from **4.13 to 4.70 GeV** collected **in 2016 ~ 2020**.

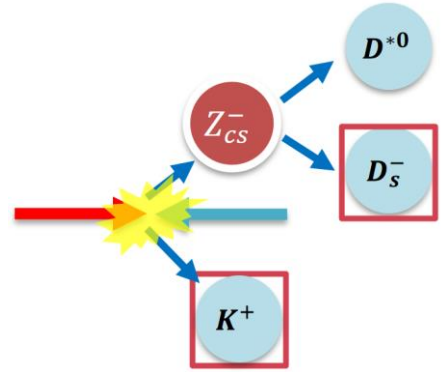
- ✓ Understanding **the nature of the exotic Z_c states** && Potential **SU(3) counter-part Z_{cs} state**?

The observation of Z_{cs} state @ BESIII

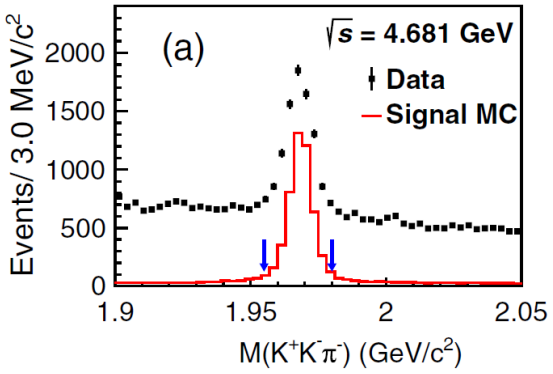
The observation of $Z_{cs}(3985)^+$ at BESIII

PRL 126, 102001 (2021)

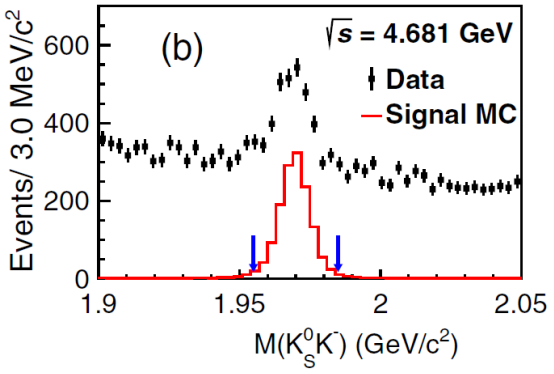
- $e^+e^- \to K^+ Z_{cs}^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$
  - BESIII collected ~3.7 fb^{-1} datasets with $\sqrt{s}$ from 4.626 to 4.7 GeV in 2020.
  - Allow to search for the Z_{cs} $(c\bar{c}u\bar{s})$ state.
  - Search for charged Z_{cs} state in the open charm $D_s^- D^{*0}$ and $D_s^{*-} D^0$ final states.
- **Partial reconstruction method:** Tag the D_s^- and bachelor K^+.
- **Wrong sign:** D_s^- K^- combinations to model the combinatorial backgrounds.
- $RM(K^+ D_s^-)$ **spectrum** is selected to distinguish the signal process.



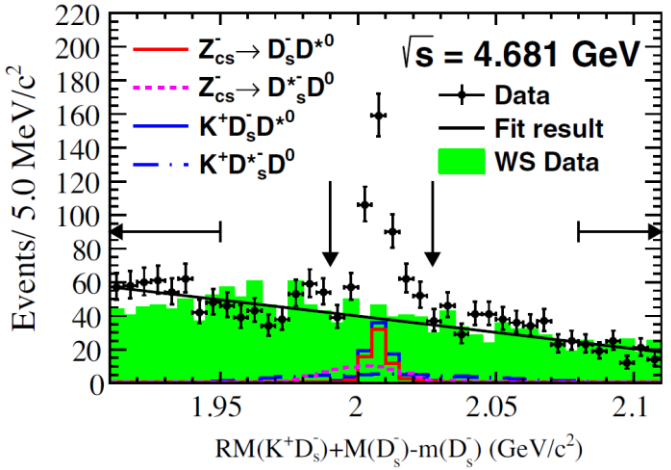
$e^+e^- \to K^+ D_s^- D^{*0}$

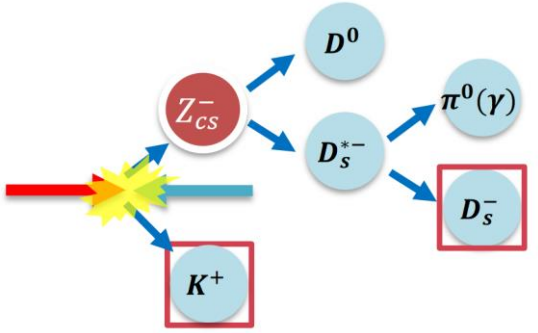


$D_s^- \to K^+ K^- \pi^-$



$D_s^- \to K_S^0 K^-$





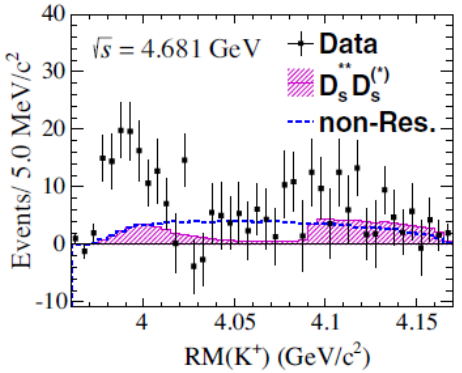
$e^+e^- \to K^+ D_s^{*-} D^0$

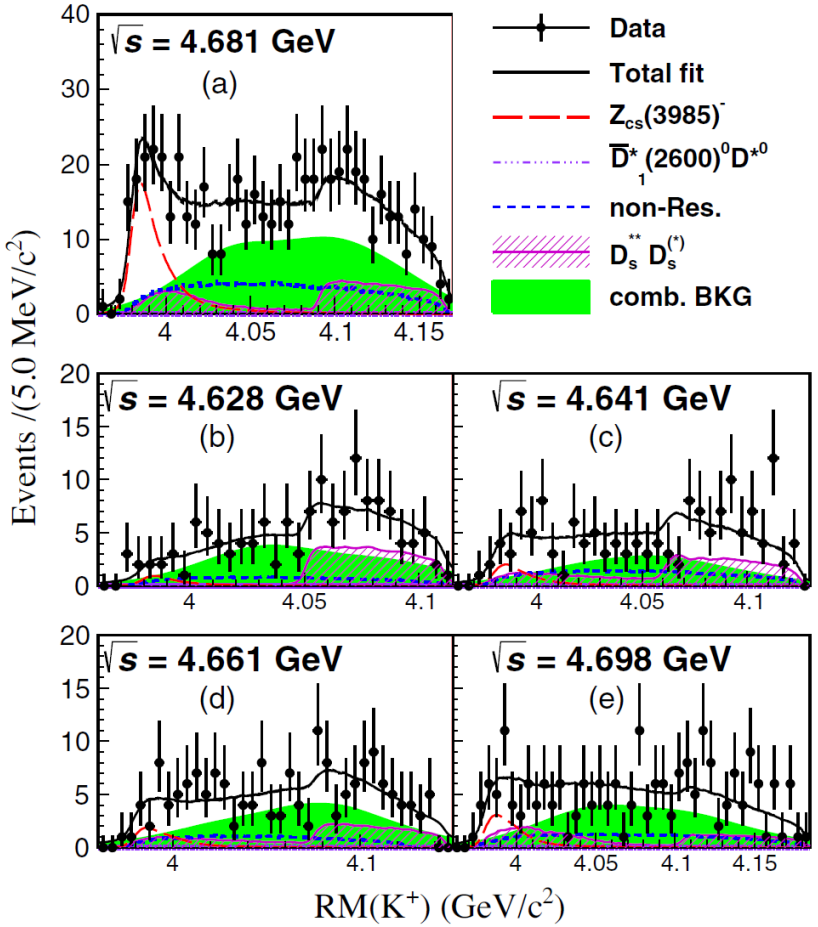
The observation of $Z_{cs}(3985)^+$ at BESIII

PRL 126, 102001 (2021)

- $e^+e^- \to K^+ Z_{cs}^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$

  - A structure near the threshold of $D_s^- D^{*0}$ and $D_s^{*-} D^0$ is found to be peaked at the left side of $RM(K^+)$ **spectrum,** and **cannot be described by** $D_{(s)}^{**}$ **decays**.





  - **Simultaneous fit** is performed to the all the datasets with $\sqrt{s} > 4.626$ GeV.
  - ✓ The **mass and width** are measured to be (with $J^P = 1^+$ Breit-Wigner):

$$m(Z_{cs}(3985)^+) = (3985.2^{+2.1}_{-2.0} \pm 1.7)\ \mathrm{MeV}/c^2$$

$$\Gamma(Z_{cs}(3985)^+) = (13.8^{+8.1}_{-5.2} \pm 4.9)\ \mathrm{MeV}$$

  - ✓ **The significance is** 5.3σ after consider the look elsewhere effect.

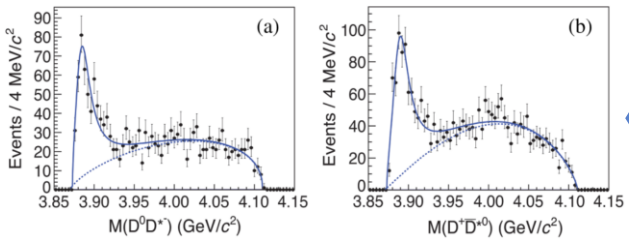
- **First observation of the open-strange hidden-charm tetraquark candidates.**

The observation of $Z_{cs}(3985)^+$ at BESIII

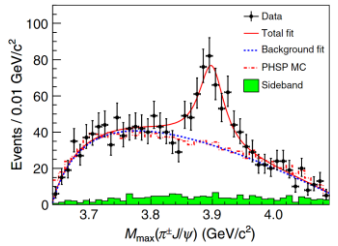
PRL 126, 102001 (2021)

- $e^+e^- \to K^+ Z_{cs}^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$
  - **Compare with $Z_c(3885)^-$.**

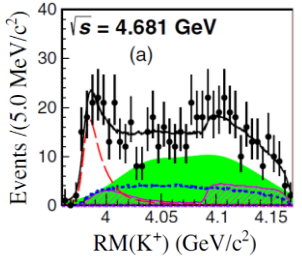
	$Z_{cs}(3985)^-$	$Z_c(3885)^-$
Mass (MeV/c^2)	$3985.2^{+2.1}_{-2.0} \pm 1.7$	$3883.9 \pm 1.5 \pm 4.2$
Width (MeV)	$13.8^{+8.1}_{-5.2} \pm 4.9$	$24.8 \pm 3.3 \pm 11.0$
$D^0 D^{*-}_{(s)}$ **(MeV/c^2)**	3977.04	3875.10
$D^{*0} D^-_{(s)}$ **(MeV/c^2)**	3975.20	3876.51



$Z_c(3885)^- \to (D^- D^{*0} + D^{*-} D^0)$



$Z_c(3900)^- \to \pi^- J/\psi$



$Z_{cs}(3985)^- \to (D_s^- D^{*0} + D_s^{*-} D^0)$

?

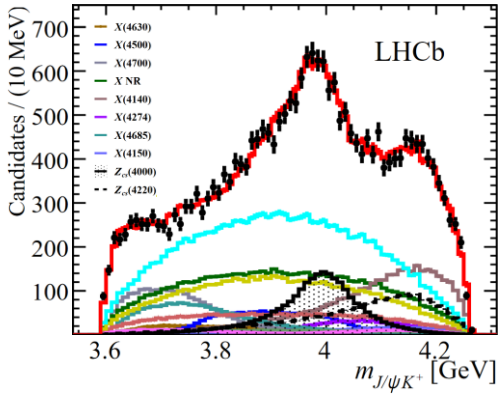
$Z_{cs}^- \to K^- J/\psi$

- ✓ **~10 MeV/c^2** above $D^{*0}D^-_{(s)}/D^0 D^{*-}_{(s)}$ mass. -- **SU(3) counter-part.**
- ✓ Search for Z_{cs} in **hidden charm decays**.

  - **Compare to $Z_{cs}(4000)^-$ observed by LHCb.**

	$Z_{cs}(3985)^-$	$Z_{cs}(4000)^-$
M_{ploe} **(MeV/c^2)**	$3985.2^{+2.1}_{-2.0} \pm 1.7$	$4003 \pm 6^{+4}_{-14}$
Γ_{ploe} **(MeV)**	$13.8^{+8.1}_{-5.2} \pm 4.9$	$131 \pm 15 \pm 26$

- ✓ Mass is **consistent**, but width is **one order larger** than BESIII result.
- ✓ They are same things?



$Z_{cs}(4000)^- \to K^- J/\psi$

Recent Z_c analyses @ BESIII

Study of the $Z_c(3900)^0$ state with PWA

PRD 102, 012009 (2020)

- $e^+e^- \to \pi^0 Z_c(3900)^0 \to \pi^0\pi^0 J/\psi$

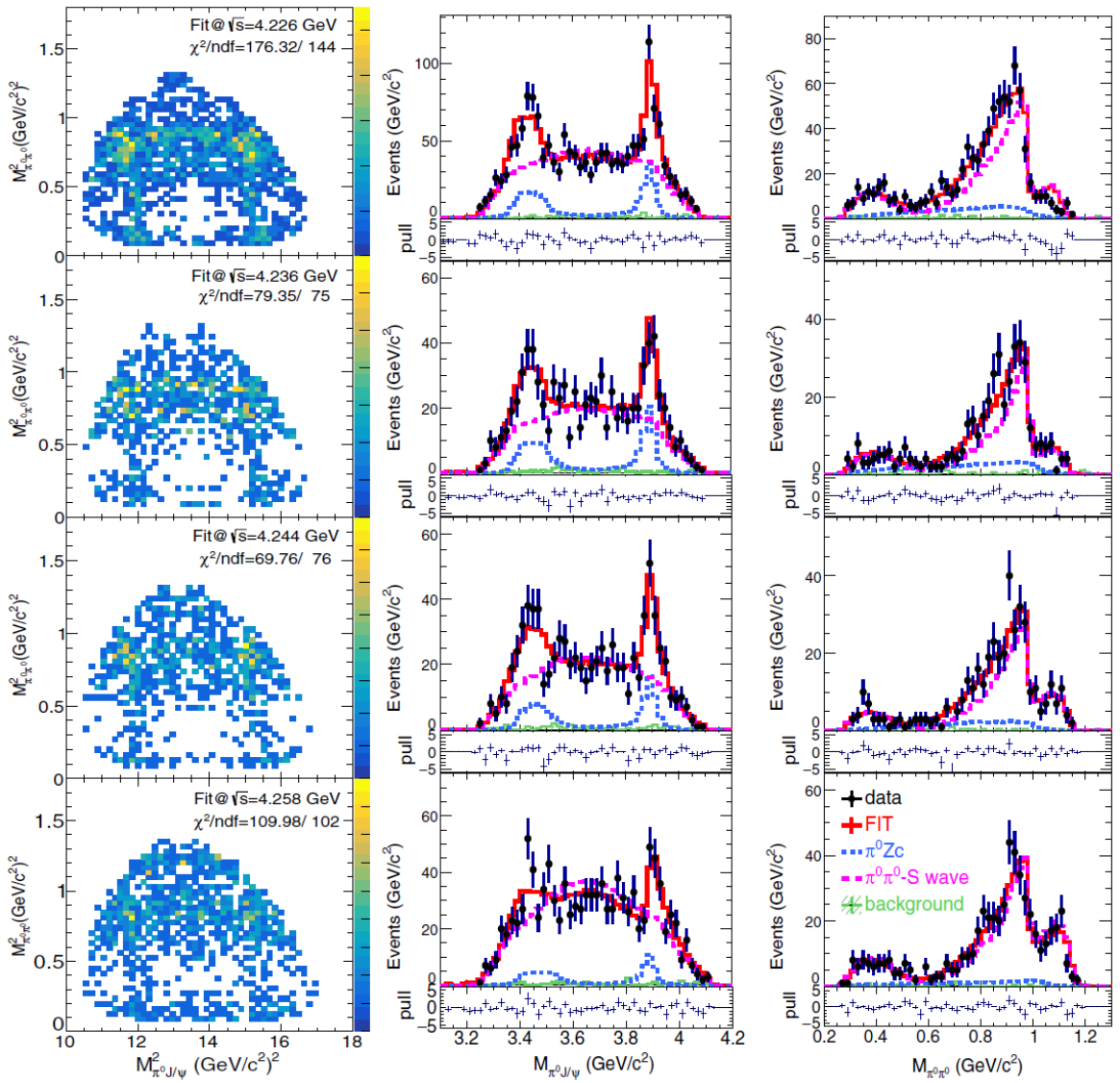
➢ **A simultaneous PWA** is performed on the four data samples of $\sqrt{s} = 4.226, 4.236, 4.244$ and 4.258 GeV.

➢ **The fitting model** includes four intermediate processes: $\pi^0 Z_c(3900)^0$, $e^+e^- \to \sigma J/\psi$, $f_0(980)J/\psi$, $f_0(1370)J/\psi$.

✓ **The mass and width** of $Z_c(3900)^0$ is determined to be:

$$m\left(Z_c(3900)^0\right) = (3893.0 \pm 2.3 \pm 3.2)\ \mathrm{MeV}/c^2$$
$$\Gamma\left(Z_c(3900)^0\right) = (44.2 \pm 5.4 \pm 8.3)\ \mathrm{MeV}$$

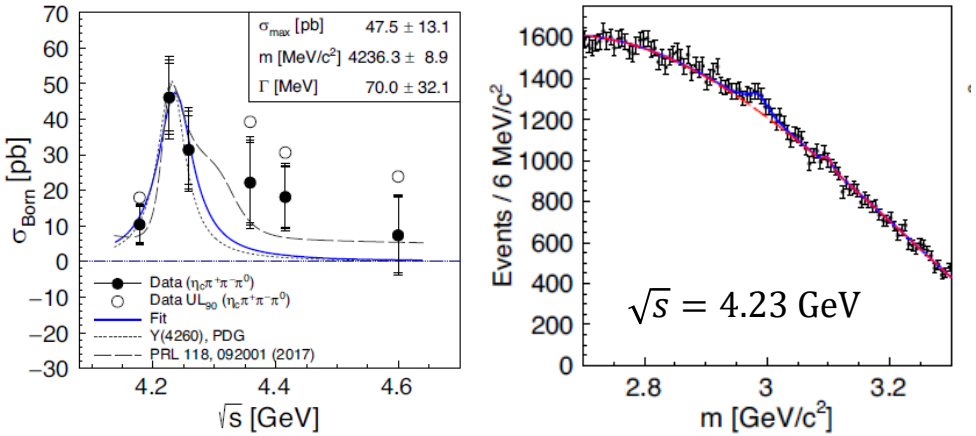
✓ **The spin-parity** of the $Z_c(3900)^0$ is determined to be $J^P = 1^+$ with a statistical significance of **more than** 9σ over alternative J^P hypotheses.



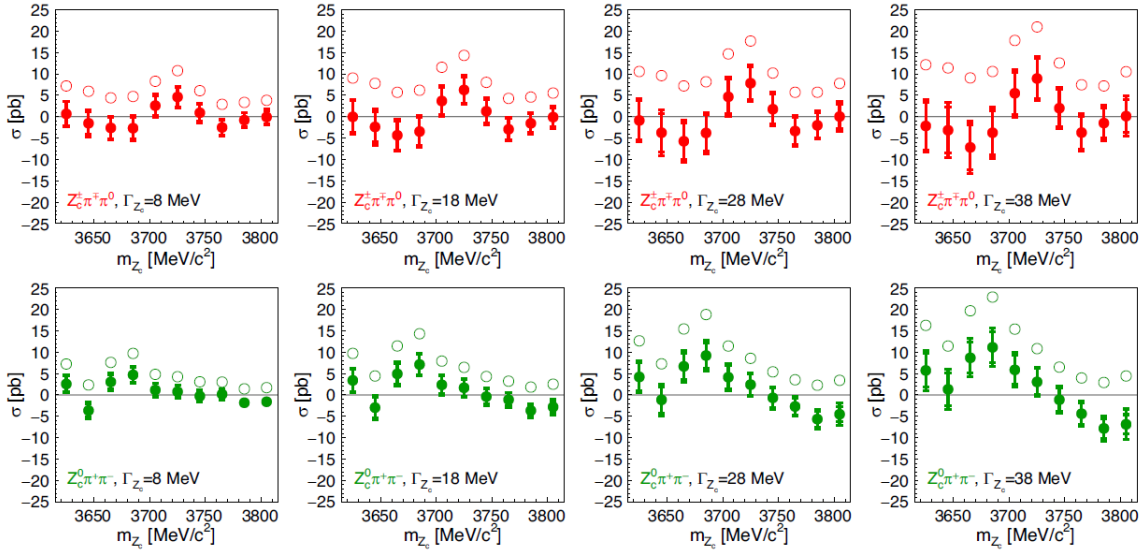
Search for Z_c states in $\eta_c\pi$ final states

PRD 103, 032006 (2021)

- $e^+e^- \to \eta_c\pi^+\pi^-\pi^0, \eta_c\pi^+\pi^-, \eta_c\pi^0\gamma$
  - ➢ Several theoretical studies suggest to search for charmonium-like **Z_c state** with $J^P = 0^+$ in $\eta_c\pi$ final states.
  - ➢ The LHCb Collaboration reported an $\eta_c\pi$ resonance, $Z_c(4100)^+$, in $B^0 \to K^+\eta_c\pi^-$ decays[1].
  - ➢ The cross sections of $e^+e^- \to \eta_c\pi^+\pi^-\pi^0, \eta_c\pi^+\pi^-, \eta_c\pi^0\gamma$ are studied in this analysis.
  - ✓ Only the $e^+e^- \to \eta_c\pi^+\pi^-\pi^0$ process was observed with **5.2σ** after summing up all the datasets.
  - ✓ The **upper limits** of the cross section of $e^+e^- \to Z_c^+\pi^-\pi^0$ and $e^+e^- \to Z_c^0\pi^+\pi^-$ with different Z_c mass and width assumptions are extracted at $\sqrt{s} = 4.23$ GeV.



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

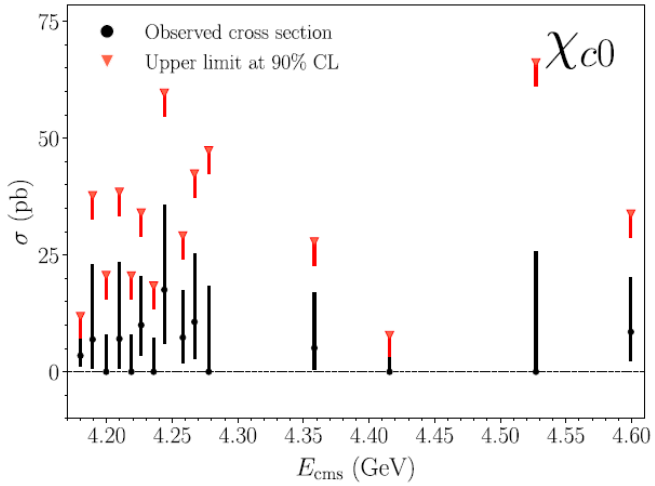


[1] EPJC 78, 1019 (2018)

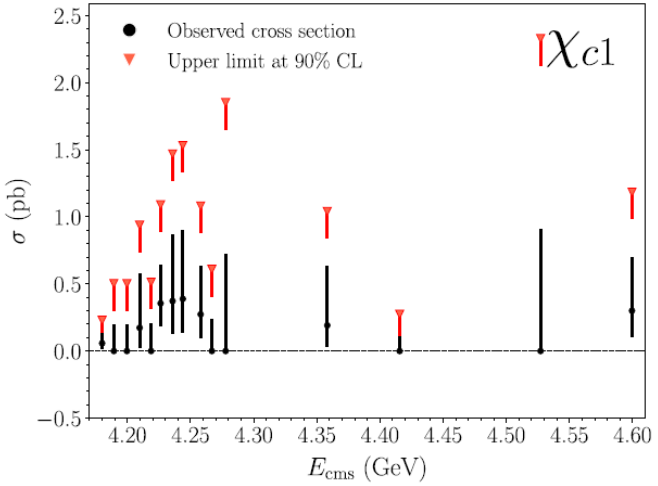
Search for Z_c states in $\chi_{cJ}\pi$ final states

PRD 103, 052010 (2021)

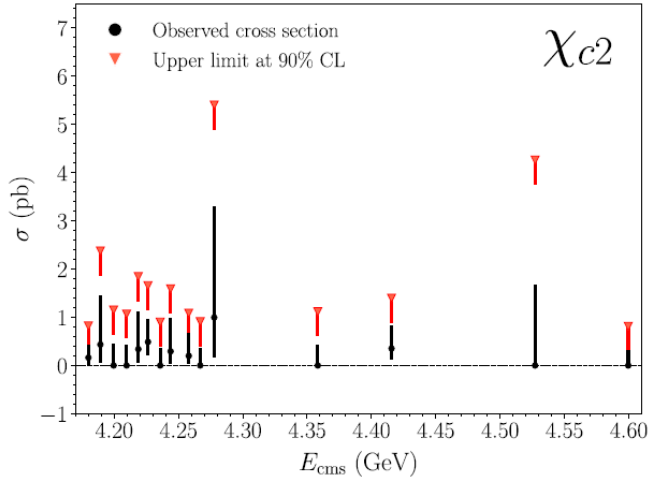
- $e^+e^- \to \pi^+\pi^-\chi_{cJ}$
  - Two charmonium-like states, $Z_c(4050)^+$ and $Z_c(4250)^+$ are observed by Belle collaboration in $\bar{B}^0 \to K^-\pi^+\chi_{c1}$ decays[1], but not confirmed by *BaBar*[2].
  - The $e^+e^- \to \pi^+\pi^+\chi_{cJ}, \chi_{cJ} \to \gamma J/\psi$ processes are searched in BESIII with $\sqrt{s}$ form **4.18 GeV to 4.60 GeV.**
  - **Non of the three $\pi^+\pi^+\chi_{cJ}$ processes** are found in the datasets.
  - ✓ The upper limits of the **born cross sections of $\pi^+\pi^+\chi_{cJ}$** are reported in the analysis.



$e^+e^- \to \pi^+\pi^-\chi_{c0}$



$e^+e^- \to \pi^+\pi^-\chi_{c1}$



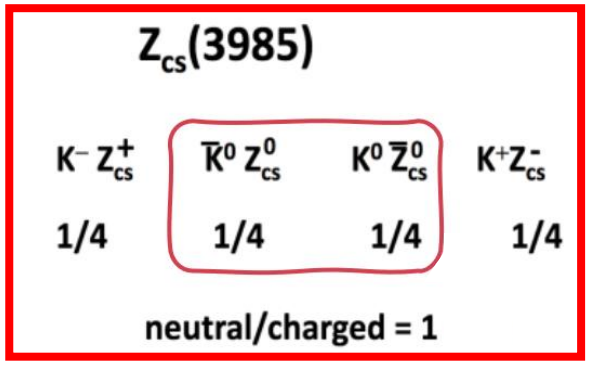
$e^+e^- \to \pi^+\pi^-\chi_{c2}$

[1] PRD 78, 072004 (2008) [2] PRD 85, 052003 (2012)

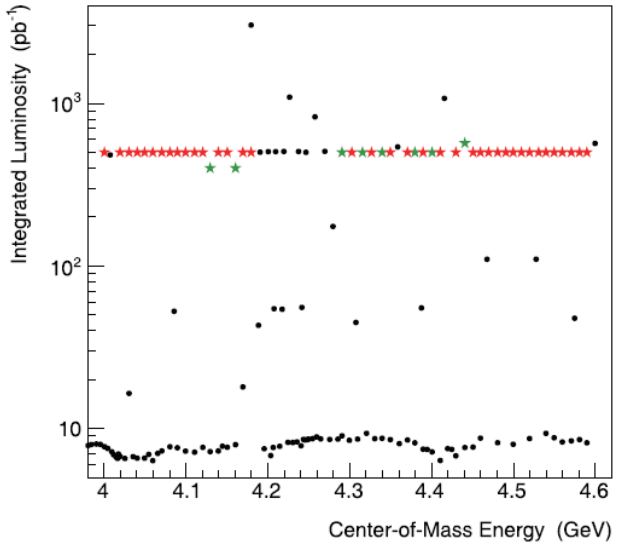
Future Z_c and Z_{cs} analyses at BESIII

CPC Vol. 44 No.126, 102001 (2021)

- **On going analyses:**
  - $e^+e^- \to K^+K^-J/\psi$
  - $e^+e^- \to K_S^0(D_S^-D^{*+} + D_S^{*-}D^+)$
  - $e^+e^- \to K_S^0K_S^0J/\psi$



The plan for *XYZ* data taking



- **Data taking:**
  - About **1.8 fb^{-1}** datasets with $\sqrt{s}$ from **4.74 ~ 4.95 GeV** @ 2021.
  - Possibilities for **future *XYZ* data taking** at BESIII.
  - **Detailed Z_c and Z_{cs} analyses with large statistic and more energy point will come soon!**

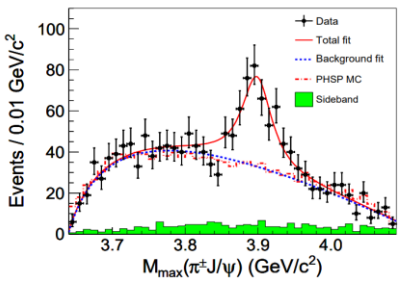
Table 3.4. Data taking requirements for *XYZ* physics and charmonium physics.

plan	data sets
XYZ plan (1)	500 pb^{-1} at a large number of points between 4.0 and 4.6 GeV
XYZ plan (2)	5 fb^{-1} at 4.23, 4.42 GeV for large Z_c samples
XYZ plan (3)	5 fb^{-1} above 4.6 GeV
charmonium plan	3×10^9 $\psi(3686)$ decays

Summary

$Z_c(3900)^+$

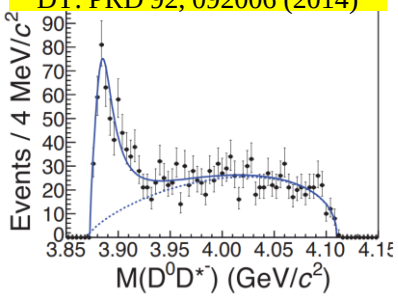
PRL 110, 252001 (2013)



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

$Z_c(3885)^+$

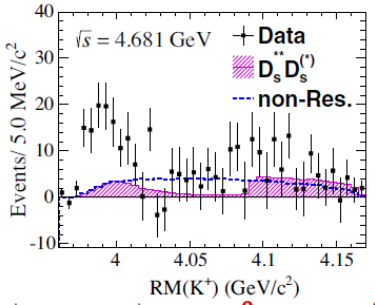
ST: PRL 112, 022001 (2014)
DT: PRD 92, 092006 (2014)



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

$Z_{cs}(3985)^+$

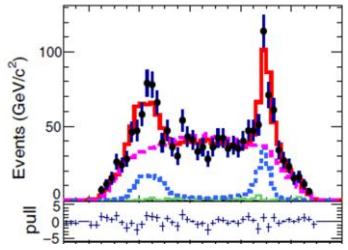
PRL 126, 102001 (2021)



$e^+e^- \to K^+(D_s^-D^{*0} + D_s^{*-}D^0)$

$Z_c(3900)^0$ in $Y(4220)$

PRD 102, 012009 (2020)



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

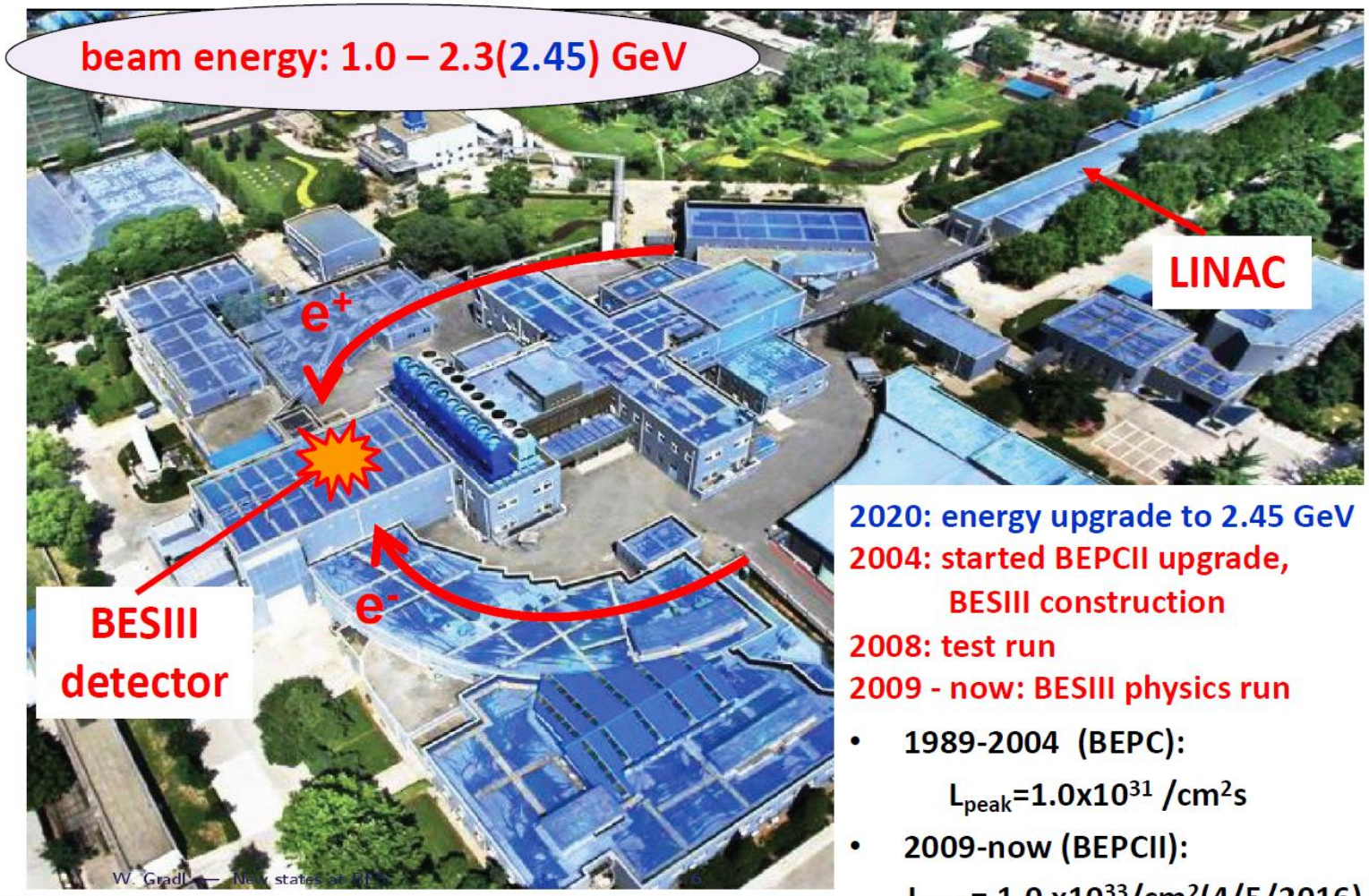
What's Next?

- More than **20 fb^{-1}** data samples above **3.8 GeV** have been collected by BEPCII/BESIII Collaboration.
- Several **Z_c and Z_c^* states** have been observed by BESIII during **2013-2015**.
  - $Z_c(3885)^+ \to \pi^+J/\psi$, $Z_c(3900)^+ \to (DD^*)^+$ … …
- Recently, based on the new datasets collected in **2017-2020**, more highlight results on ***Z* physics** are published:
  - ✓ The observation of **$Z_{cs}(3985)^+$**.
  - ✓ **PWA** result of $e^+e^- \to \pi^0\pi^0J/\psi$ for **$Z_c(3900)^0$**.
  - ✓ Searching for **Z_c** states in **$\eta_c\pi$, $\chi_{cJ}\pi$** final states.
- ➢ More detailed analyses on Z_c and Z_{cs} states are **ongoing.**
- ➢ The BESIII Collaboration planed to **collected more *XYZ* datasets**, to further understanding the nature of ***Z* states**.

Thank you!

Back Up

Beijing Electron Positron Collider (BEPCII)

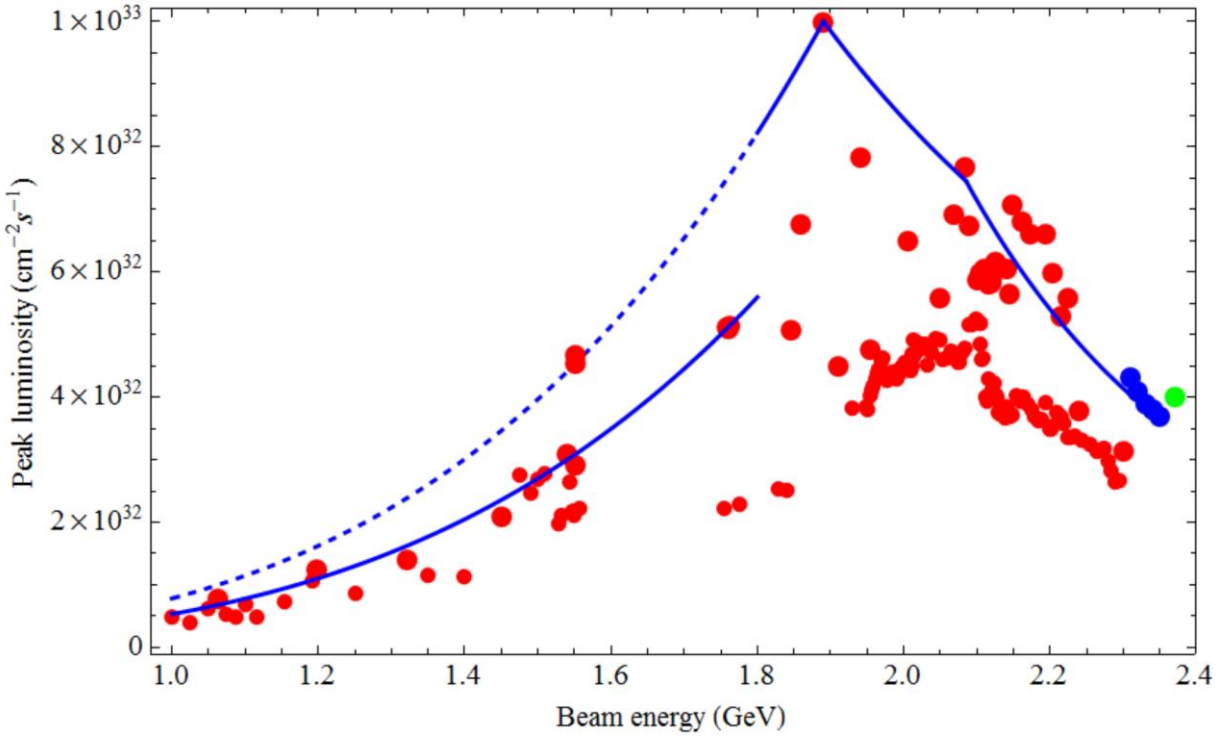


2020: energy upgrade to 2.45 GeV
2004: started BEPCII upgrade,
BESIII construction
2008: test run
2009 - now: BESIII physics run

- 1989-2004 (BEPC):
  L_{peak}=1.0x10^{31} /cm^{2}s
- 2009-now (BEPCII):
  L_{peak}= 1.0 x10^{33}/cm^2(4/5/2016)

BEPCII peaking luminosity

- **Increase of beam energy** 2.30 → 2.35 (2018) → 2.45 GeV (2020)
  - → 2.35 GeV in 2018 summer (done).
  - → 2.45 GeV in 2020 summer (done).
- **Top-up injection (done)**
  - Data taking efficiency increases by 20~30%.



BESIII data samples

2009: 106M $\psi(2S)$
225M J/ψ
2010: 975 pb^{-1} at $\psi(3770)$
2011: 2.9 fb^{-1} *(total)* at $\psi(3770)$
482 pb^{-1} at 4.01 GeV
2012: 0.45B *(total)* $\psi(2S)$
1.3B *(total)* J/ψ
2013: 1092 pb^{-1} at 4.23 GeV
826 pb^{-1} at 4.26 GeV
540 pb^{-1} at 4.36 GeV
10 × 50 pb^{-1} scan 3.81 — 4.42 GeV
2014: 1029 pb^{-1} at 4.42 GeV
110 pb^{-1} at 4.47 GeV
110 pb^{-1} at 4.53 GeV
48 pb^{-1} at 4.575 GeV
567 pb^{-1} at 4.6 GeV
0.8 fb^{-1} R-scan 3.85 — 4.59 GeV
2015: R-scan 2 — 3 GeV + 2.175 GeV
2016: ~3fb^{-1} at 4.18 GeV (for D_s)
2017: 7 × 500 pb^{-1} scan 4.19 — 4.27 GeV
2018: more J/ψ *(and tuning new RF cavity)*
2019: 10B *(total)* J/ψ
8 × 500 pb^{-1} scan 4.13, 4.16, 4.29 — 4.44 GeV
2020: 5 × 500 pb^{-1} scan 4.63 — 4.70 GeV *(+ extra)*