Non-Vector charmonium-like studies at BESIII

Rong-Gang Ping

Institute of High Energy Physics, CAS
pingrg@ihep.ac.cn

Hadron2021, 26th to 31st of July 2021

Outline

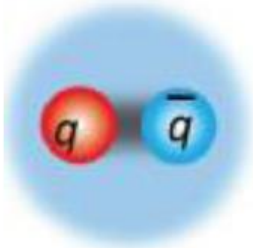
- Introduction
- Observation of charged $Z_{cs}(3985)^-$
  - $e^+e^- \to K^+(D_S^-D^{*0} + D_S^{*-}D^0)$
- Search for Z_c states
  - $e^+e^- \to \chi_{cJ}\pi^+\pi^-$
  - $e^+e^- \to \eta_c\pi^+\pi^-\pi^0$
- Search for $X(3872)$ state
  - $e^+e^- \to \pi^0 X(3872)\gamma$
- Observation of threshold enhancement of $\Lambda\bar{\Lambda}$
  - $e^+e^- \to \phi\Lambda\bar{\Lambda}$
- Summary

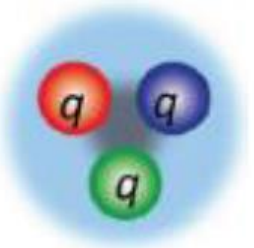
New forms of hadron

- Conventional hadrons consist of 2 or 3 quarks:

Naive Quark Model:

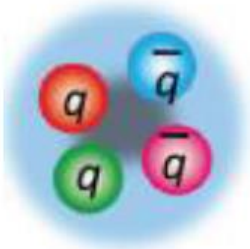
meson

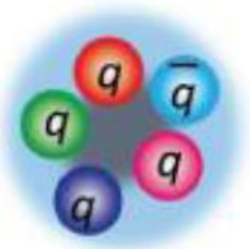




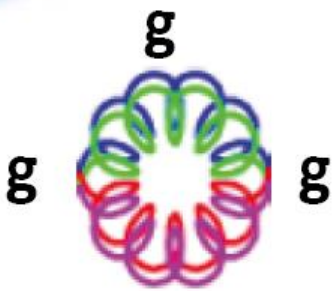
baryon

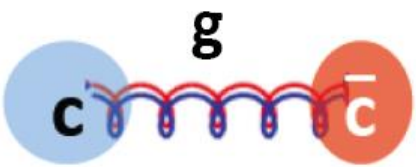
- QCD predicts the new forms of hadrons:
  - Multi-quark states： Number of quarks >= 4



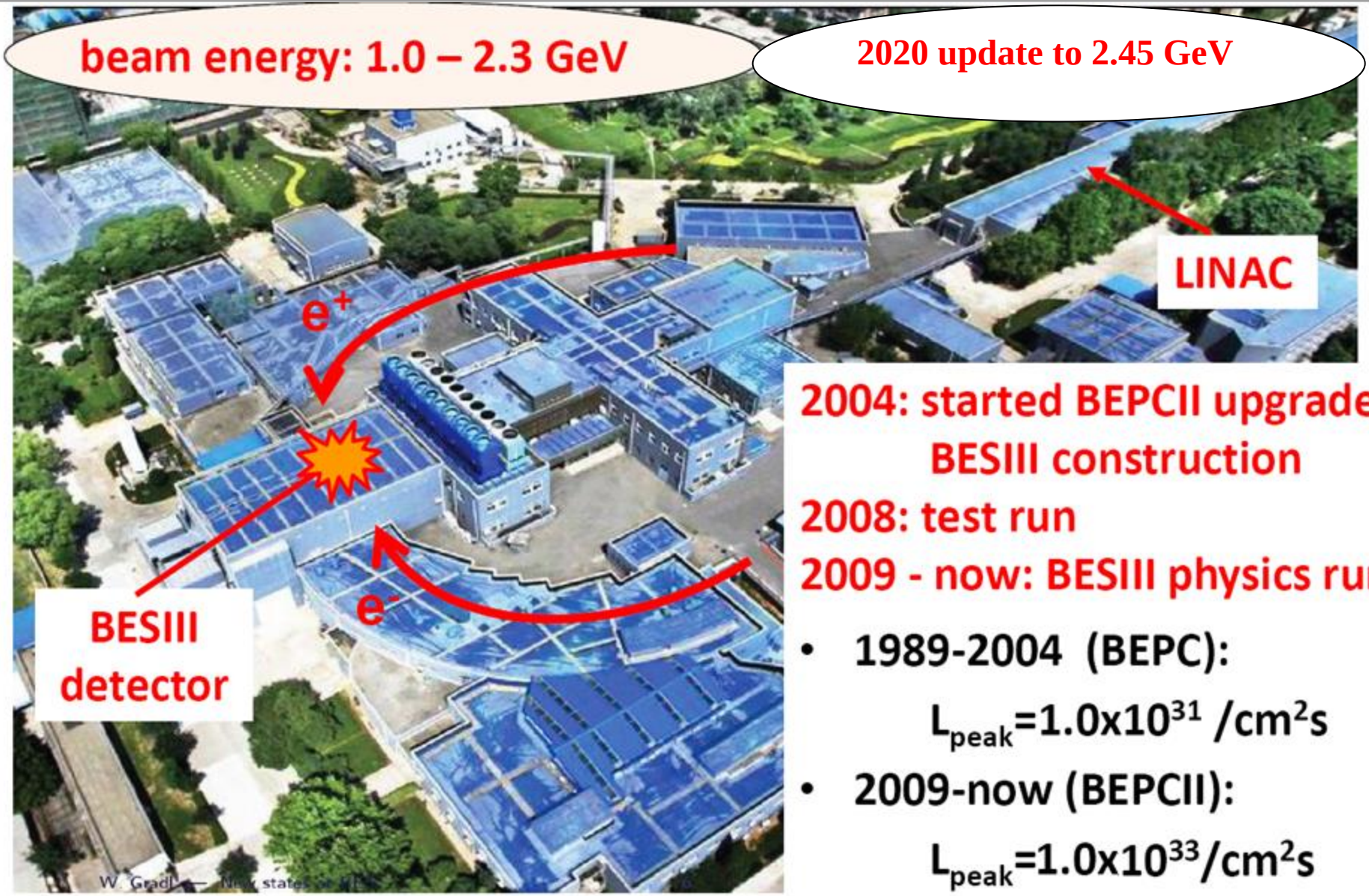


  - Hybrids： $q\bar{q}g$， qqqg …
  - Glueballs： gg， ggg …





Beijing Electron Positron Collider (BEPC)



2004: started BEPCII upgrade,
BESIII construction

2008: test run

2009 - now: BESIII physics run

- 1989-2004 (BEPC):

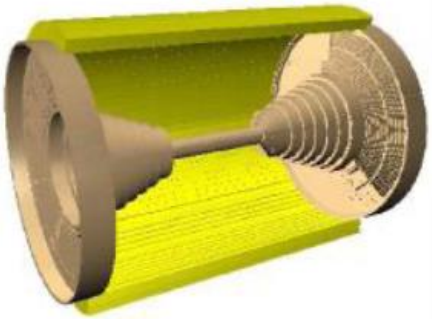
  $L_{peak}=1.0\times10^{31}$ /cm^{2}s

- 2009-now (BEPCII):

  $L_{peak}=1.0\times10^{33}$/cm^{2}s

BESIII Detector

MDC

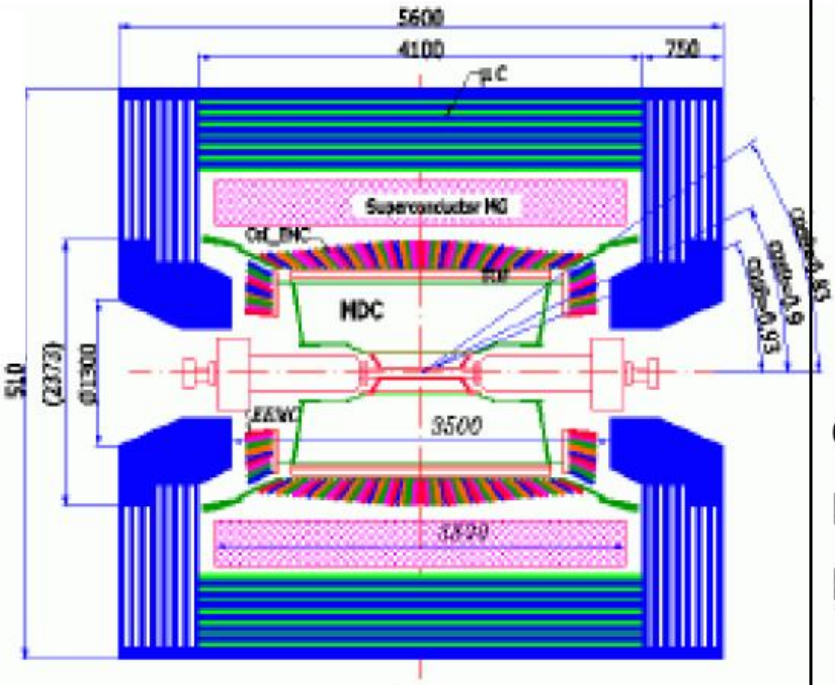


R inner: 63mm ;

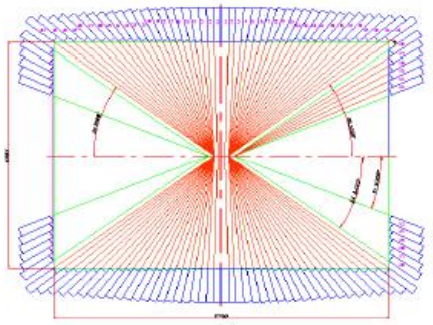
R outer: 810mm

Length: 2582 mm

Layers: 43



CsI(Tl) EMC



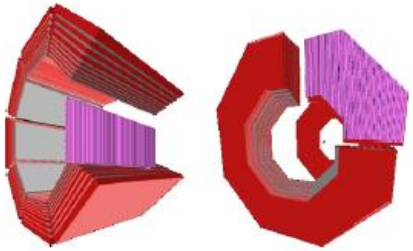
Crystals: 28 cm(15 X_0)

Barrel: $|\cos\theta|<0.83$

Endcap:

$0.85 < |\cos\theta| < 0.93$

RPC MUC



BMUC: 9 layers – 72 modules

EMUC: 8 layers – 64 modules

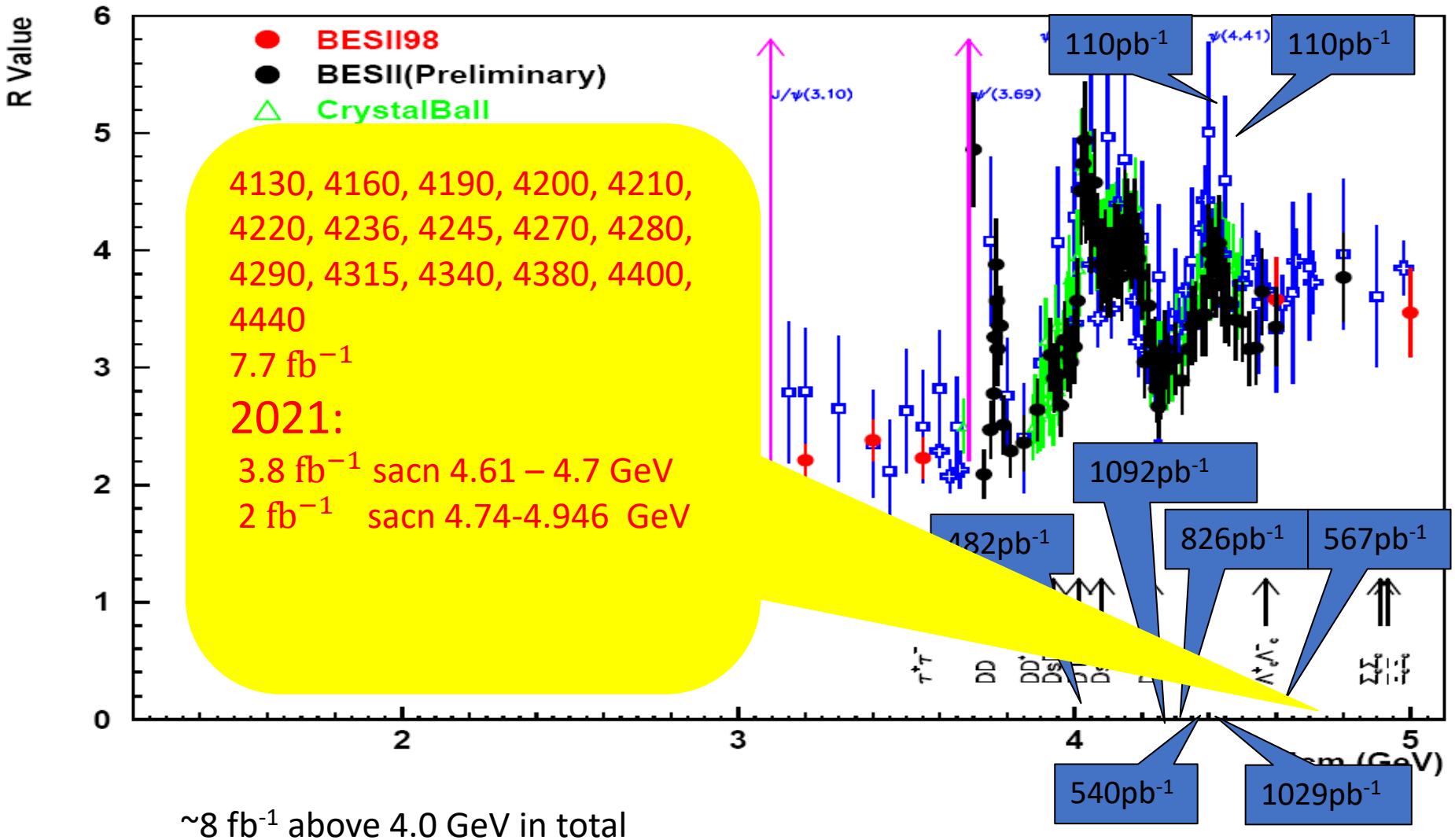
TOF

BTOF: two layers

ETOF: 48 scintillators for each

MRPC --- new ETOF

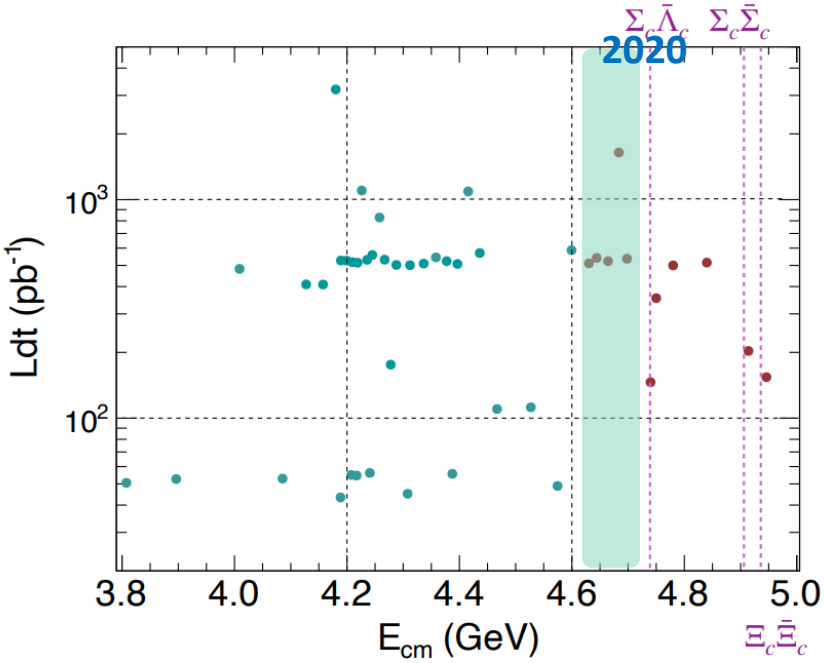
Data sets for *XYZ* study

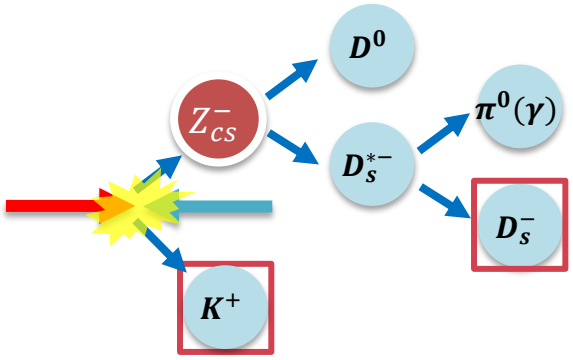


~8 fb^{-1} above 4.0 GeV in total

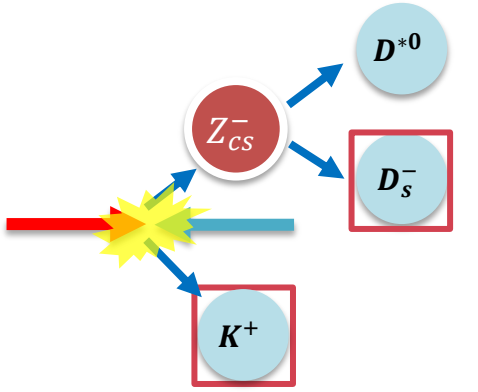
Observation of charged $Z_{cs}(3985)^-$

- $e^+e^- \to K^+\left(D_s^- D^{*0} + D_s^{*-} D^0\right)$
  - ✓ 3.7fb^{-1} data accumulated at 4.628, 4.641, 4.661, 4.681 and 4.698GeV in 2020.
  - ✓ **Partial reconstruction of K^+ and D_s^-.**
  - ✓ Signature in the **recoil mass spectrum of $K^+ D_s^-$** to identify the process of $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$.



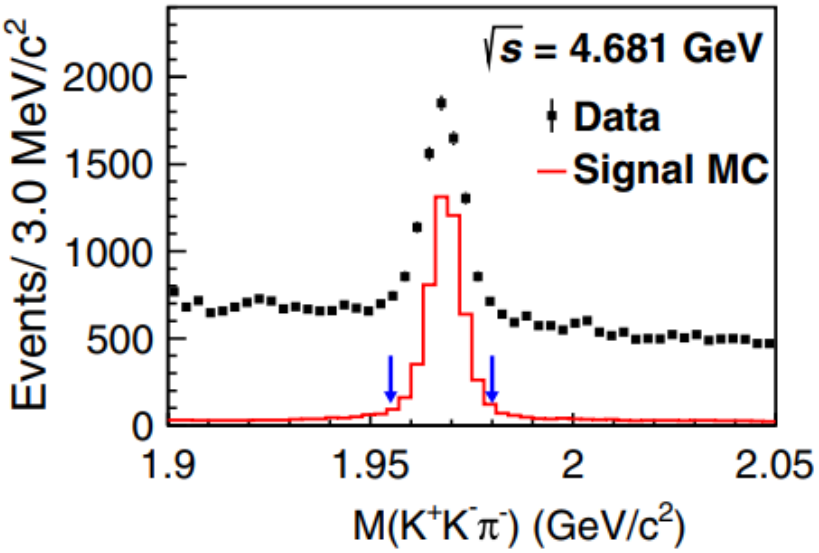


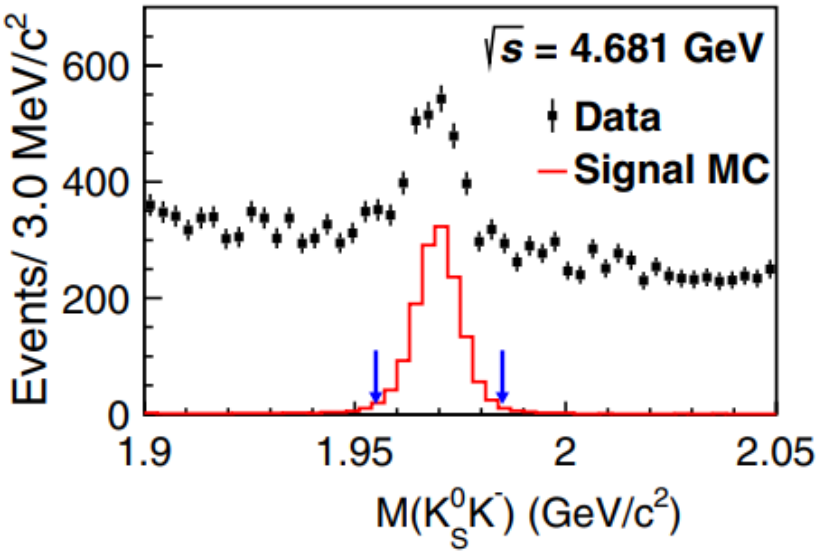
$e^+e^- \to K^+ D_s^{*-} D^0$

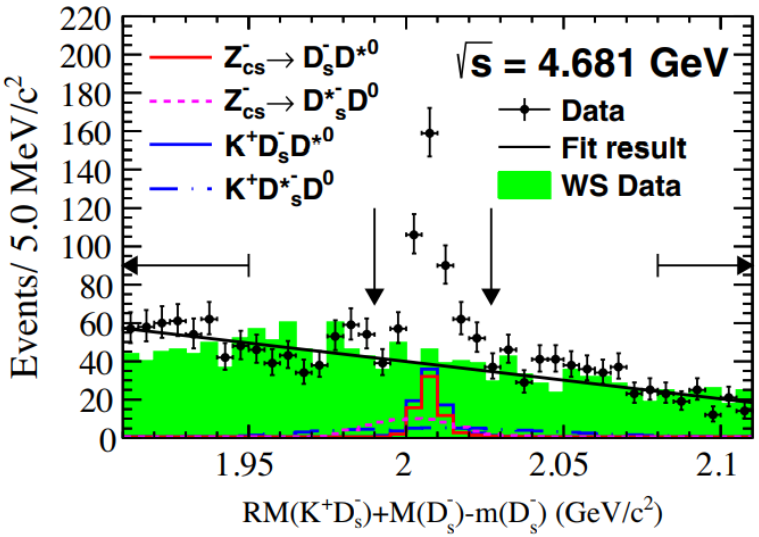


$e^+e^- \to K^+ D_s^- D^{*0}$

Observation of charged $Z_{cs}(3985)^-$ (cont.)





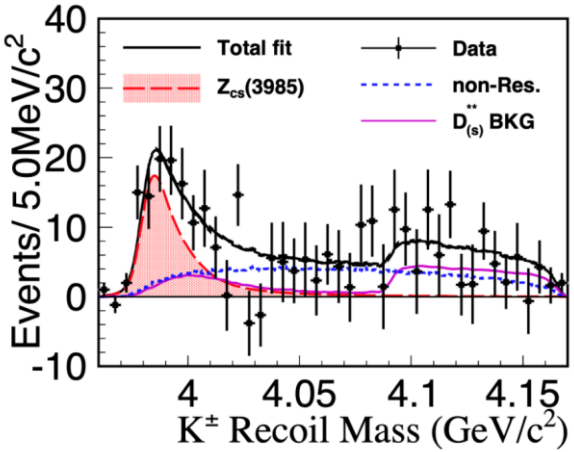


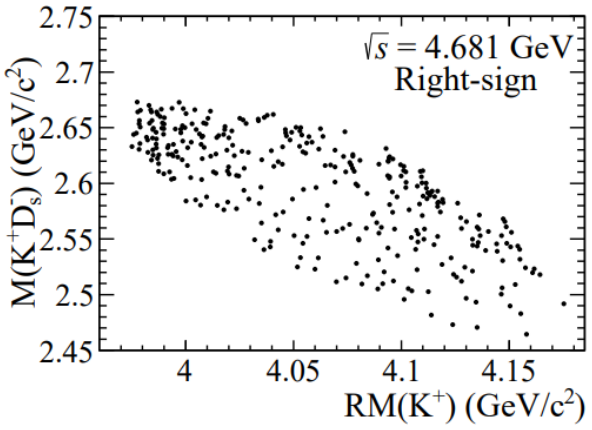
PRL 126, 102001 (2021)

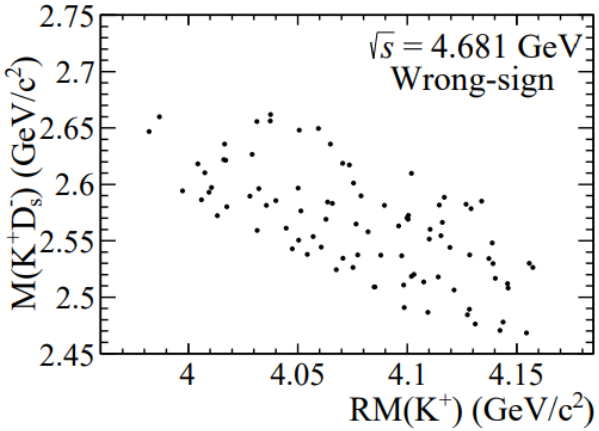
- ✓ D_s^- reconstructed with $K^+K^-\pi^+$ ($\phi\pi$ or K^*K) and $K_s^0K^-$.
- ✓ Both decay modes can survive the selection.
- ✓ Data driven background description:
  Wrong Sign (WS) combination of D_s^- and K^-.
- ✓ Absolute contribution in signal region determined from a fit to $RM(K^+D_s^-)$.

Observation of charged $Z_{cs}(3985)^-$ (cont.)

PRL 126, 102001 (2021)







- ✓ Conventional charmed mesons can not describe the enhancement below 4.0 GeV/c^2.

  (With a sufficient study for all possible $D^{**}_{(s)}$ background and their interference effect, see Appendix.)

- ✓ Assume the structure as a $D_s^- D^{*0}/D_s^{*-} D^0$ resonance, denoting it as the $Z_{cs}(3985)^-$.
- ✓ A fit of $J^P = 1^+$ S-wave Breit-Wigner with mass dependent width returns:

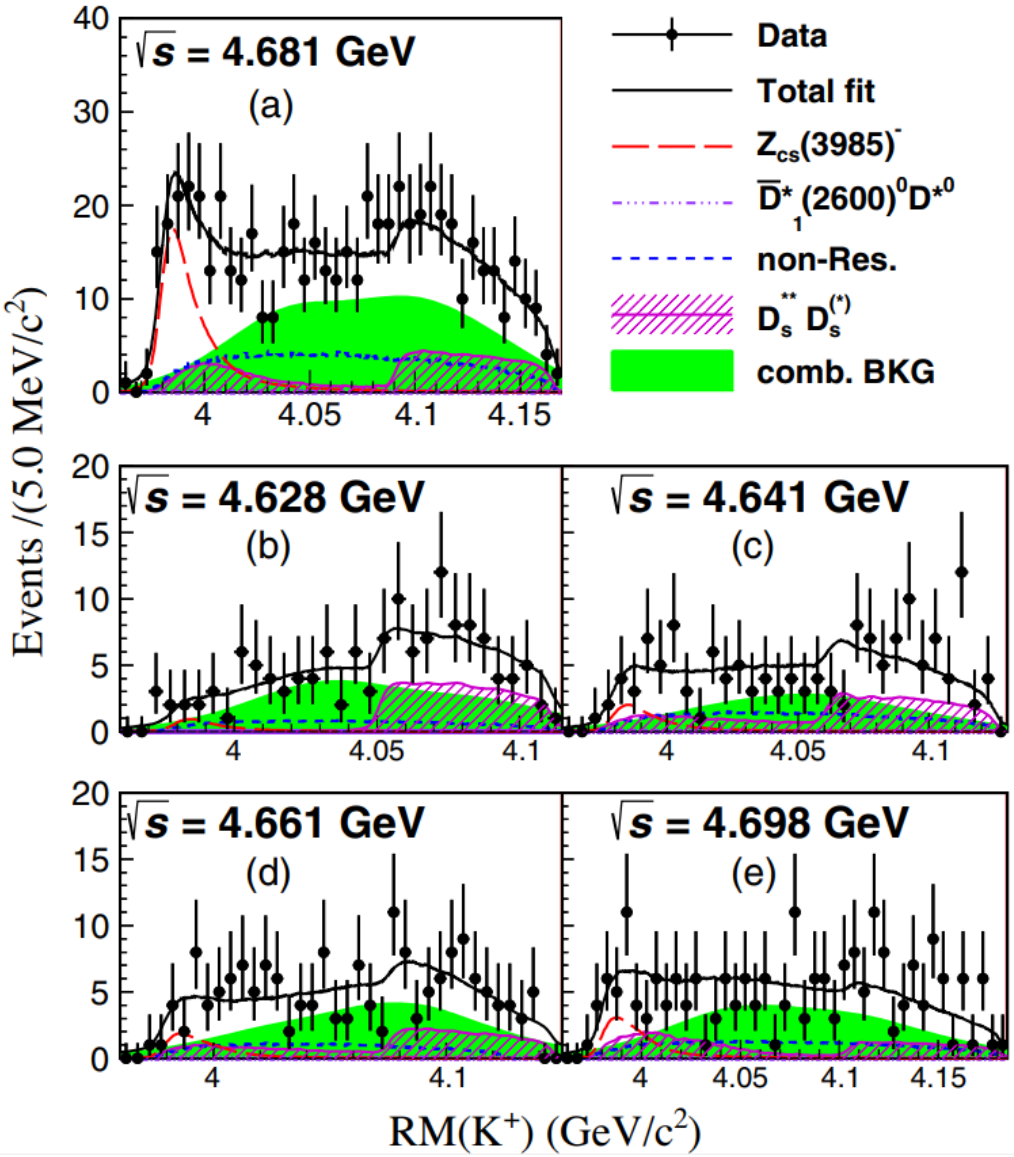
$$M = 3985.2^{+2.1}_{-2.0} \pm 1.7\ \mathrm{MeV/c^2}$$

$$\Gamma = 13.8^{+8.1}_{-5.2} \pm 4.9\ \mathrm{MeV}$$

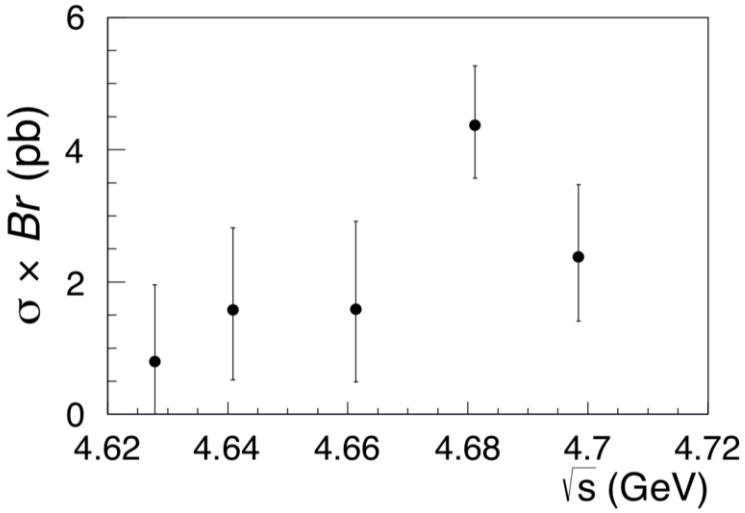
- ✓ Global significance: $> 5.3\,\sigma$

First candidate of the hidden-charm tetraquark with strangeness

Observation of charged $Z_{cs}(3985)^-$ (cont.)



PRL 126, 102001 (2021)



- ✓ Simultaneous fit to the five energy points.
- ✓ Largest cross sections around 4.681 GeV.

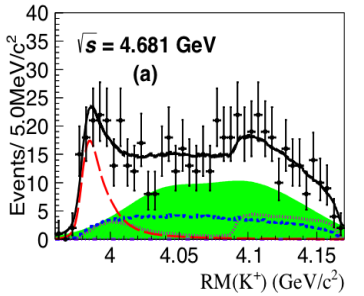
Observation of charged $Z_{cs}(3985)^-$ (cont.)

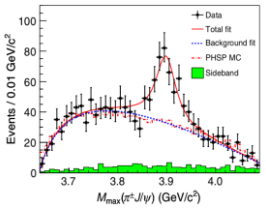
1643/pb data @4.681 GeV 525/pb data @4.26 GeV

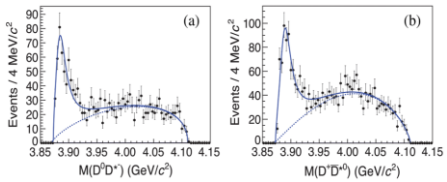
	$Z_{cs}(3985)^{\pm}$	$Z_c(3900)^{\pm}$	$Z_c(3885)^{\pm}$
Mass (MeV/c^2)	$3985.2^{+2.1}_{-2.0} \pm 1.7$	3899.0±3.6±4.9	3883.9±1.5±4.2
Width (MeV)	$13.8^{+8.1}_{-5.2} \pm 4.9$	46±10±26	24.8±3.3±11.0
$\sigma^{Born} \cdot \mathcal{B}$ (pb)	$4.4^{+0.9}_{-0.8} \pm 1.4$	13.5±2.1±4.8	83.5±6.6±22.0

~10 MeV above D_sD^*/D_sD thresholds
similar to $Z_c(3900)$ & $Z_b(10,610)$
(DD*) (BB*)

SU(3) partner of Z_c (3900)?







$Z_{cs}(3985)$

$K^- Z_{cs}^+$	$\bar{K}^0 Z_{cs}^0$	$K^0 \bar{Z}_{cs}^0$	$K^+ Z_{cs}^-$
1/4	1/4	1/4	1/4

neutral/charged = 1

$Z_c(3900)$

$\pi^- Z_c^+$	$\pi^0 Z_c^0$	$\pi^+ Z_c^-$
1/3	1/3	1/3

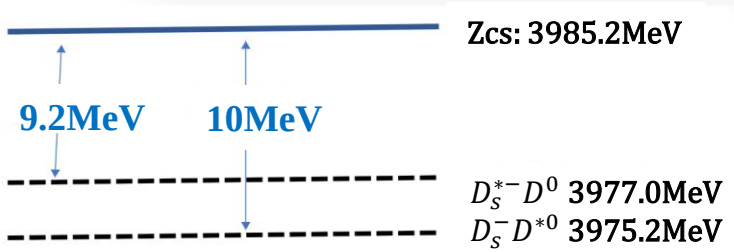
neutral/charged = 1/2

In process

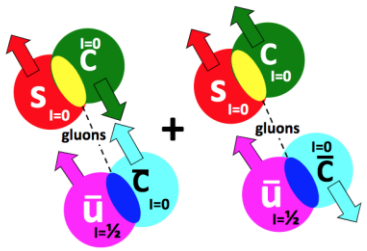
from Marek Karliner in Nov. 2020

two general comments about
charm-tau factory program

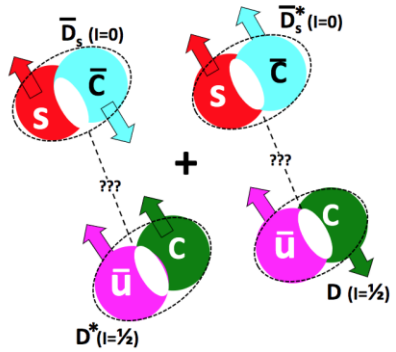
- $J/\psi\, K^{\pm}$ resonances:
  $Z_c(3900)$ analogue?
  $Z_c(3900)^+ = (c\bar{c}u\bar{d})$; $d \to s$: $(c\bar{c}u\bar{s}) \sim D_s\bar{D}^*$
  no natural molecular binding,
  so if discovered, would indicate
  Tq or a novel mechanism



diquark-antidiquark?



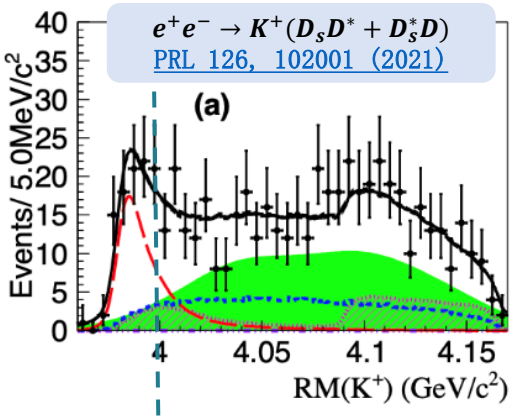
$D^*\bar{D}_s$ + cc molecule?

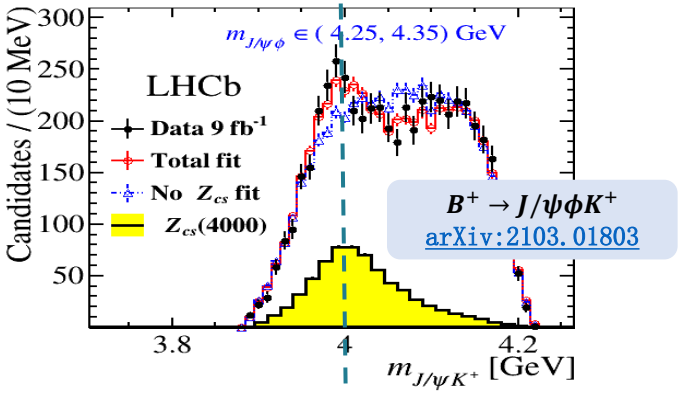


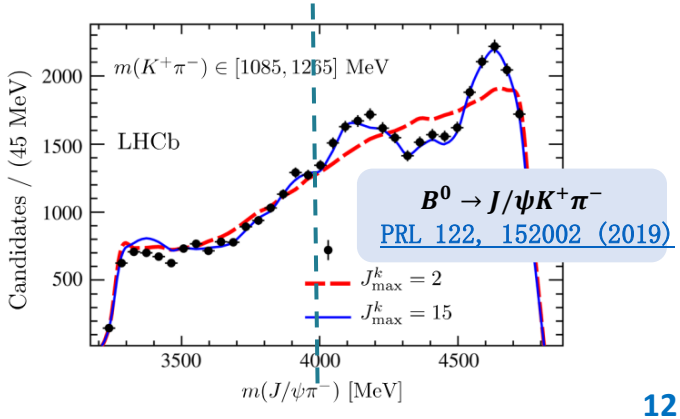
Observation of charged $Z_{cs}(3985)^-$ (cont.)

- **Various interpretations are possible for the structure**
  - ✓ Molecule.
  - ✓ $D_{s2}^*(2573)^+ D_s^{*-}$ threshold kinematic effects / reflecting.
  - ✓ Re-scattering / Triangle singularity.
  - ✓ Mixture of molecular and tetraquark.
  - ✓ …

- **$Z_{cs}(3985)$ from e^+e^- annihilations and $Z_{cs}(4000)$ from B decays.**
  - ✓ their masses are close, but widths are different.
  - ✓ If they are same, why width so different?
  - ✓ If they are not same, is there the corresponding wide $Z_c(3900)$?
  - ✓ Looking for more channels will be useful.



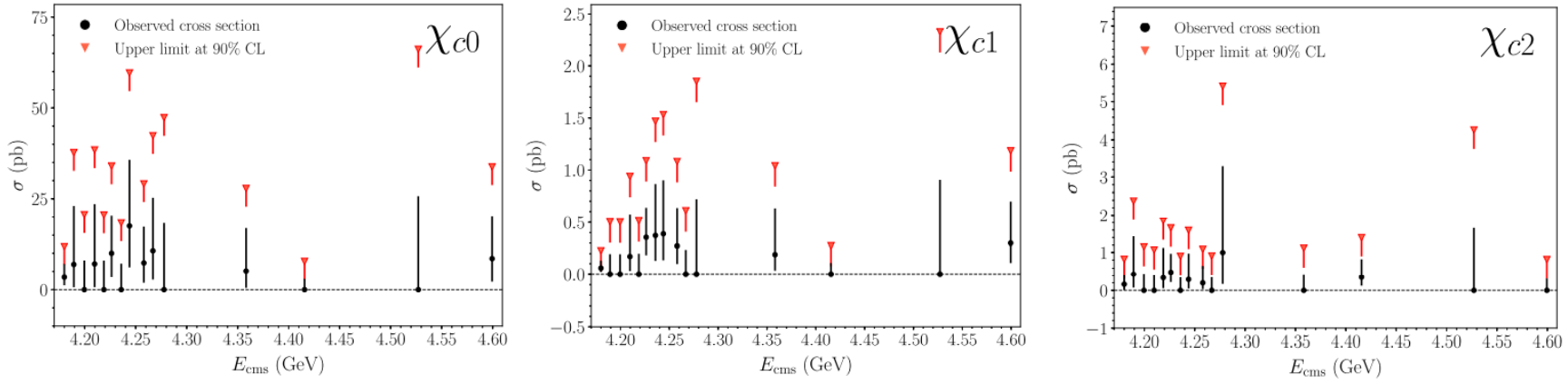




Search for Z_c in $e^+e^- \to \chi_{cJ}\pi^+\pi^-$

- ✓ Belle reported the results of $Z_c(4050)^+$ and $Z_c(4025)^+$ in $\bar{B}^0 \to K^- Z_c^+, Z_c^+ \to \pi^+ \chi_{cJ}$ [PRD 78, 072004(2008)], while BaBar did not confirm them.
- ✓ BESIII studies $e^+e^- \to \pi^+\pi^-\chi_{cJ}, \chi_{cJ} \to \gamma J/\psi(l^+l^-)$ from 4.178 GeV to 4.600 GeV
- ✓ None of the process are observed and upper limits of the production cross sections are determined.
- ✓ Hence, they can be the upper limits of the product cross sections of

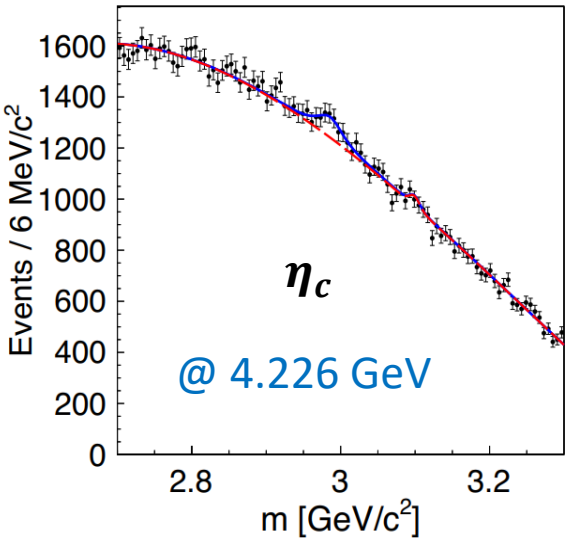
$$e^+e^- \to \pi^- Z_c(4050)^+ + c.c., Z_c(4050)^+ \to \pi^+ \chi_{cJ}$$

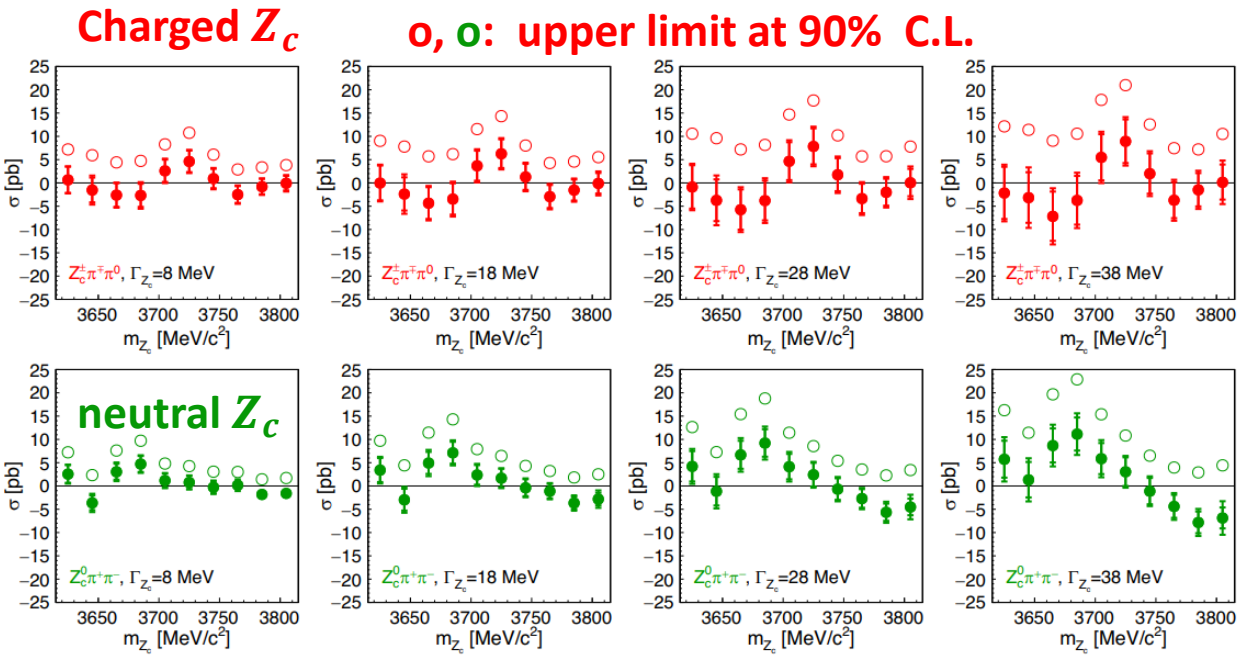


PRD 103, 052010 (2021)

Search for Z_c state in $e^+e^- \to \eta_c\pi^+\pi^-\pi^0$

- ✓ LHCb reported an evidence of $Z_c(4100)^+ \to \pi^+\eta_c$ in $\bar{B}^0 \to K^- Z_c(4100)^+$ with 3σ. with $M = 4096 \pm 20^{+18}_{-22}$ MeV/c^2, $\Gamma = 152 \pm 58^{+60}_{-35}$ MeV and $J^P = 0^+/1^-$. [EPJC 78, 1019 (2018)]
- ✓ Studies of $e^+e^- \to \pi^+\pi^-\pi^0\eta_c, \pi^+\pi^-\eta_c, \gamma\pi^0\eta_c$ at 6 energy points from 4.178 GeV to 4.600 GeV. η_c is reconstructed in 16 decay modes.
- ✓ Only evidence of $e^+e^- \to \pi^+\pi^-\pi^0\eta_c$ @ 4.226 GeV ($\mathbf{4.1\sigma}$).
- ✓ Different mass and width assumptions in the vicinity of $D\bar{D}$ mass are tested for $Z_c^+ \to \pi^+\eta_c$ and $Z_c^0 \to \pi^0\eta_c$ in $e^+e^- \to \pi^+\pi^-\pi^0\eta_c$ @ 4.226 GeV and found to be not significant.



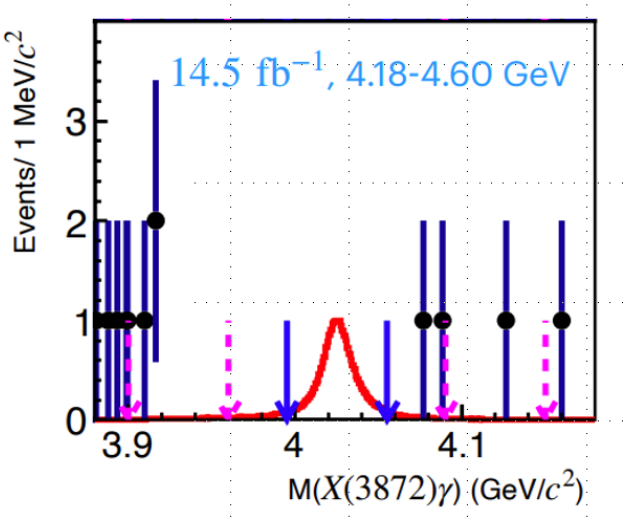


PRD 103, 032006 (2021)

Search for $X(3872)$ state in $e^+e^- \to \pi^0 X(3872)\gamma$

- ✓ Connection between Z_c and X states in the $D\bar{D}^*$ molecule picture.
- ✓ Branching fractions of $Z_c(4020)^0 \to \gamma X(3872)$ and $Z_c(4020)^\pm \to \pi^\pm X(3872)$ are predicted with quite different results. [PRD 99, 054028]
- ✓ Studies of $e^+e^- \to \pi^0 X(3872)\gamma$ at center-of mass energies from 4.178 to 4.600 GeV.
- ✓ No significant signal for $e^+e^- \to \pi^0 Z_c(4020)^0, Z_c(4020)^0 \to \gamma X(3872)$:

$$\frac{\mathcal{B}\left[Z_c(4020)^0 \to \gamma X(3872)\right] \cdot \mathcal{B}[X(3872) \to \pi^+\pi^- J/\psi]}{\mathcal{B}[Z_c(4020)^0 \to (D^*\bar{D}^*)^0]} < 0.24\% \ (@4.23\ \text{GeV})$$



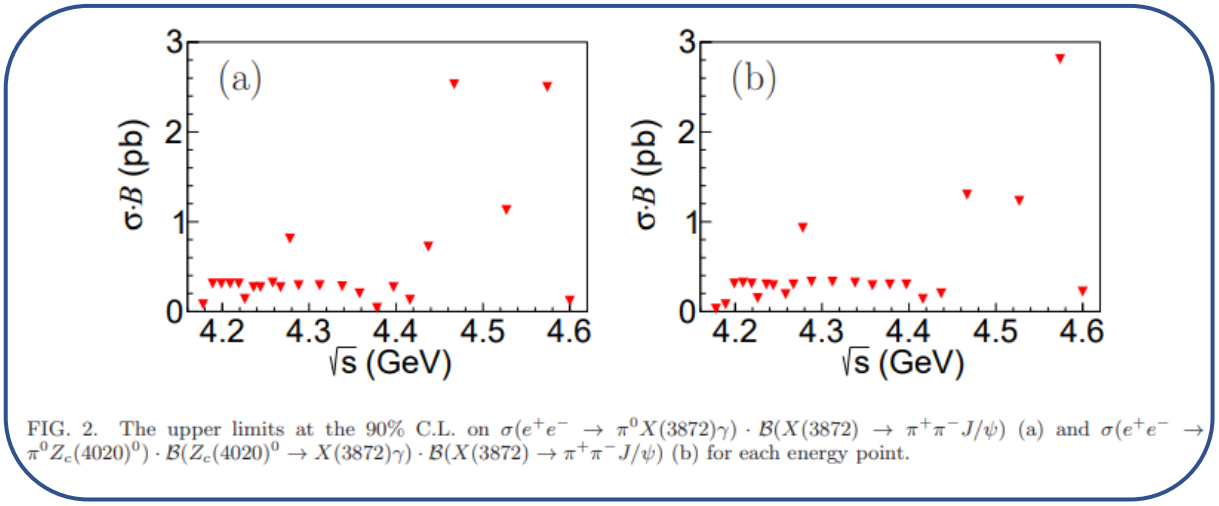
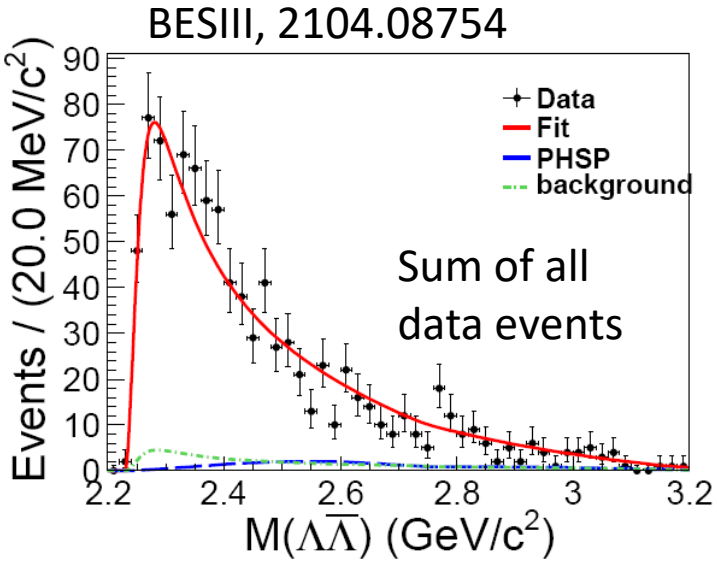


FIG. 2. The upper limits at the 90% C.L. on $\sigma(e^+e^- \to \pi^0 X(3872)\gamma) \cdot \mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)$ (a) and $\sigma(e^+e^- \to \pi^0 Z_c(4020)^0) \cdot \mathcal{B}(Z_c(4020)^0 \to X(3872)\gamma) \cdot \mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)$ (b) for each energy point.

arXiv: 2102.00644

Observation of threshold enhancement in $e^+e^- \to \phi\Lambda\bar{\Lambda}$

- ✓ $\eta(2225)$ interpreted to be $\Lambda\bar{\Lambda}$ bound states. (PRD87, 054034)
- ✓ Threshold enhancement of baryon anti-baryon pair observed in $J/\psi \to \gamma p\bar{p}$ (PRL91, 022001), $B \to Kp\bar{p}$ (PLB659,80) , $B^0 \to K\Lambda\bar{\Lambda}$ (PRD79,052006)
- ✓ 28 data sets with $\sqrt{s} = 3.51 \sim 4.6$ GeV, with total luminosity $\mathcal{L} = 19.462\ \mathrm{fb}^{-1}$
- ✓ Events reconstructed with $\phi \to K^+K^-, \Lambda \to p\pi^-, \bar{\Lambda} \to \bar{p}\pi^+$
- ✓ Breit-Wigner parametrization: $M = (2262 \pm 4 \pm 28)$ MeV, $\Gamma = (72 \pm 5 \pm 43)$ MeV. (25σ)
- ✓ Angular distribution analysis: $J^{PC} = 1^{++}$ or 2^{-+} or 2^{++}



- ✓ 0^{-+} rejected with significance of 7σ.
- ✓ Nambu model is rejected
- ✓ The enhancement consistent with that observed in $B \to K\Lambda\bar{\Lambda}$ by Belle (**Phys.Rev.D79, 052006**).

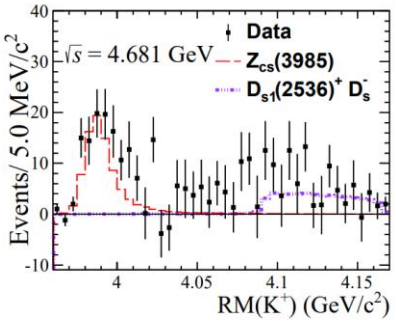
Summary

- **BESIII is successfully operating since 2008 and will continue to run for 5-10 years.**
- **Unique data samples from 3.8 GeV to 4.95 GeV. Many exciting results have been published covering many aspects on $Z_{c(s)}$ states.**
  - ✓ **Observation of the $Z_{cs}(3985)$**
  - ✓ **New modes of $Z_c \to \eta_c\pi$, $\chi_{cJ}\pi$, and $\gamma X(3872)$ are searched, but no significant signals are seen.**
  - ✓ **More results about the production & decay of $Z_{c(s)}$, structure properties are in process**
- **Search for the new $Z_{c(s)}$ decay modes are in process.**

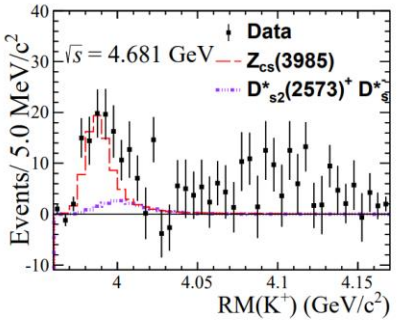
Thanks for your attention

Backup

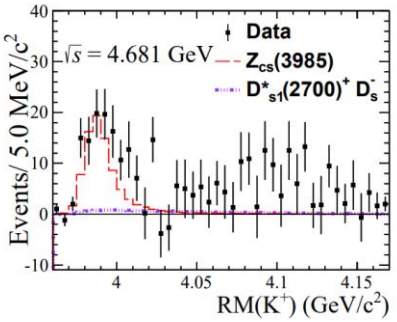
Appendix - $Z_{cs}(3985)$: All possible $D^{**}_{(s)}$ backgrounds



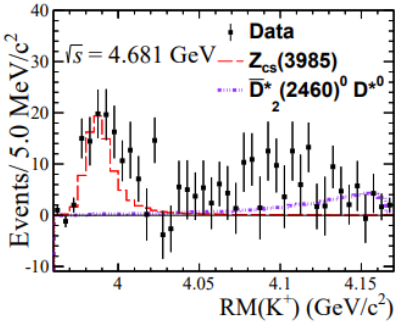
(a)$D_{s1}(2536)^+(\to D^{*0}K^+)D_s^-$



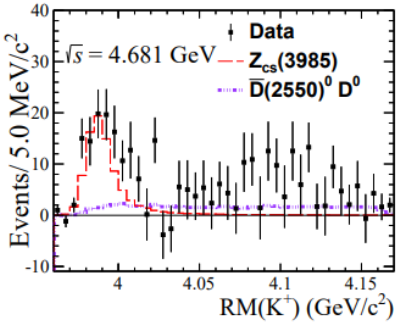
(b)$D^*_{s2}(2573)^+(\to D^0K^+)D_s^{*-}$



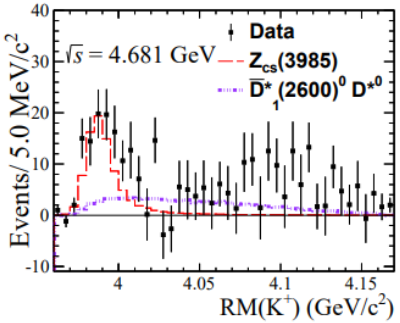
(c)$D^*_{s1}(2700)^+(\to D^{*0}K^+)D_s^-$



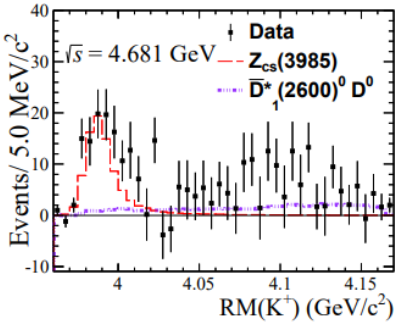
(a)$\bar{D}^*_2(2460)^0(\to D_s^- K^+)D^{*0}$



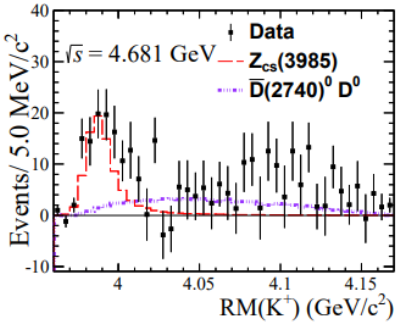
(b)$\bar{D}(2550)^0(\to D_s^{*-} K^+)D^0$



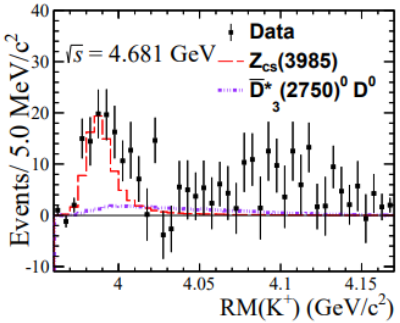
(c)$\bar{D}^*_1(2600)^0(\to D_s^- K^+)D^{*0}$



(d)$\bar{D}^*_1(2600)^0(\to D_s^{*-} K^+)D^0$

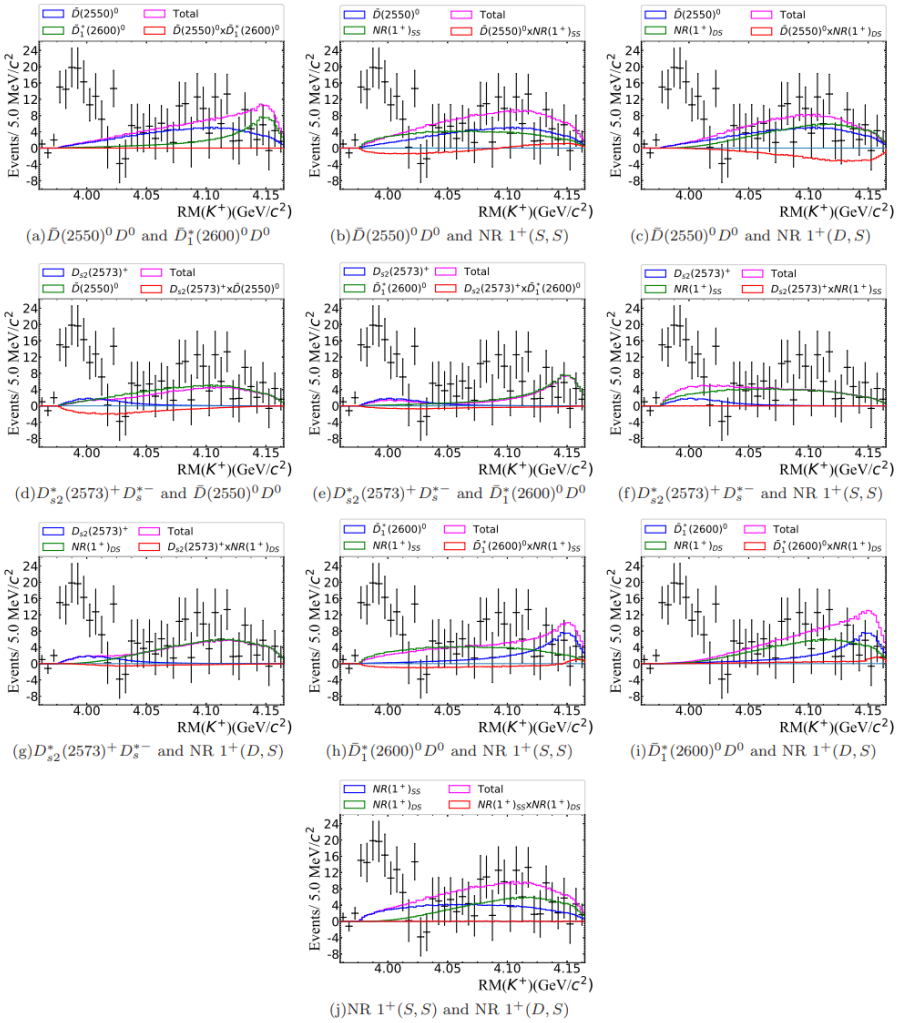


(e)$\bar{D}(2740)^0(\to D_s^{*-} K^+)D^0$



(f)$\bar{D}^*_3(2750)^0(\to D_s^{*-} K^+)D^0$

Appendix - $Z_{cs}(3985)$: Interference of $D^{**}_{(s)}$ states

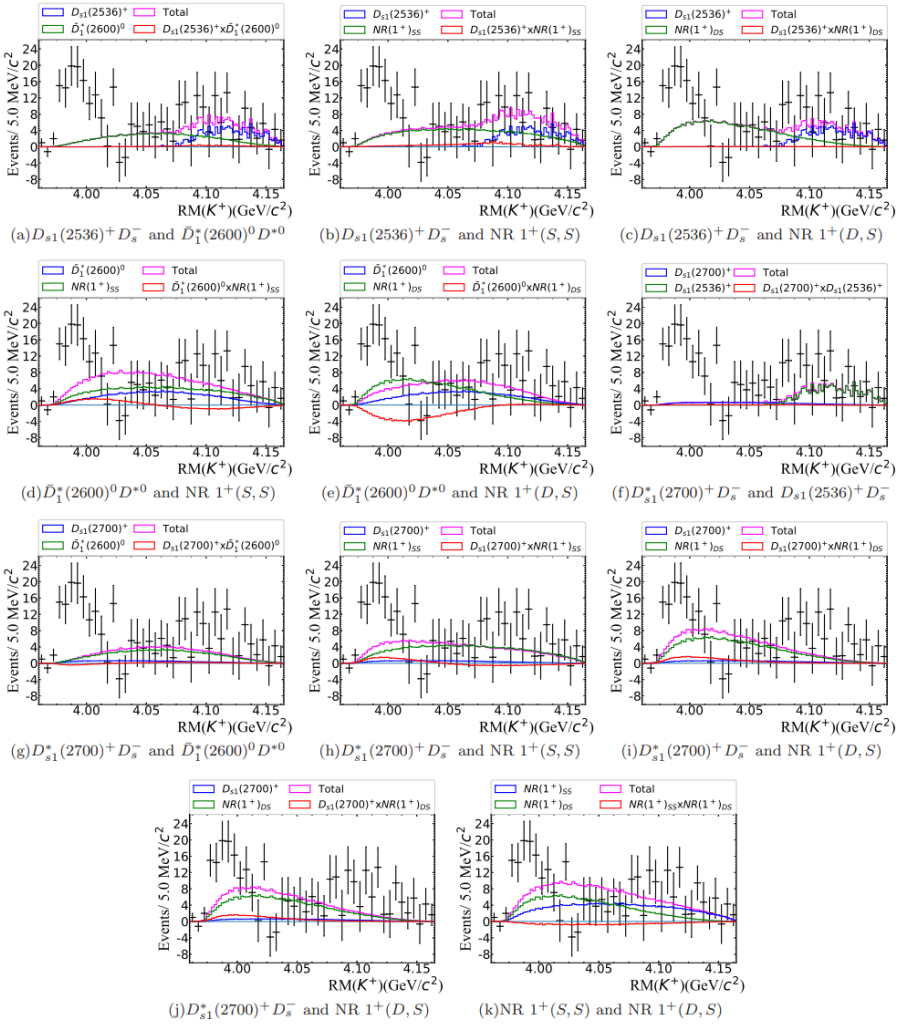


(a) $\bar{D}(2550)^0 D^0$ and $\bar{D}_1^*(2600)^0 D^0$ (b) $\bar{D}(2550)^0 D^0$ and NR $1^+(S,S)$ (c) $\bar{D}(2550)^0 D^0$ and NR $1^+(D,S)$

(d) $D_{s2}^*(2573)^+ D_s^{*-}$ and $\bar{D}(2550)^0 D^0$ (e) $D_{s2}^*(2573)^+ D_s^{*-}$ and $\bar{D}_1^*(2600)^0 D^0$ (f) $D_{s2}^*(2573)^+ D_s^{*-}$ and NR $1^+(S,S)$

(g) $D_{s2}^*(2573)^+ D_s^{*-}$ and NR $1^+(D,S)$ (h) $\bar{D}_1^*(2600)^0 D^0$ and NR $1^+(S,S)$ (i) $\bar{D}_1^*(2600)^0 D^0$ and NR $1^+(D,S)$

(j) NR $1^+(S,S)$ and NR $1^+(D,S)$



(a) $D_{s1}(2536)^+ D_s^-$ and $\bar{D}_1^*(2600)^0 D^{*0}$ (b) $D_{s1}(2536)^+ D_s^-$ and NR $1^+(S,S)$ (c) $D_{s1}(2536)^+ D_s^-$ and NR $1^+(D,S)$

(d) $\bar{D}_1^*(2600)^0 D^{*0}$ and NR $1^+(S,S)$ (e) $\bar{D}_1^*(2600)^0 D^{*0}$ and NR $1^+(D,S)$ (f) $D_{s1}^*(2700)^+ D_s^-$ and $D_{s1}(2536)^+ D_s^-$

(g) $D_{s1}^*(2700)^+ D_s^-$ and $\bar{D}_1^*(2600)^0 D^{*0}$ (h) $D_{s1}^*(2700)^+ D_s^-$ and NR $1^+(S,S)$ (i) $D_{s1}^*(2700)^+ D_s^-$ and NR $1^+(D,S)$

(j) $D_{s1}^*(2700)^+ D_s^-$ and NR $1^+(D,S)$ (k) NR $1^+(S,S)$ and NR $1^+(D,S)$

✓ For $K^+ D_s^{*-} D^0$ final states

✓ For $K^+ D_s^- D^{*0}$ final states

Angular distribution in $e^+e^- \to \phi\Lambda\bar{\Lambda}$

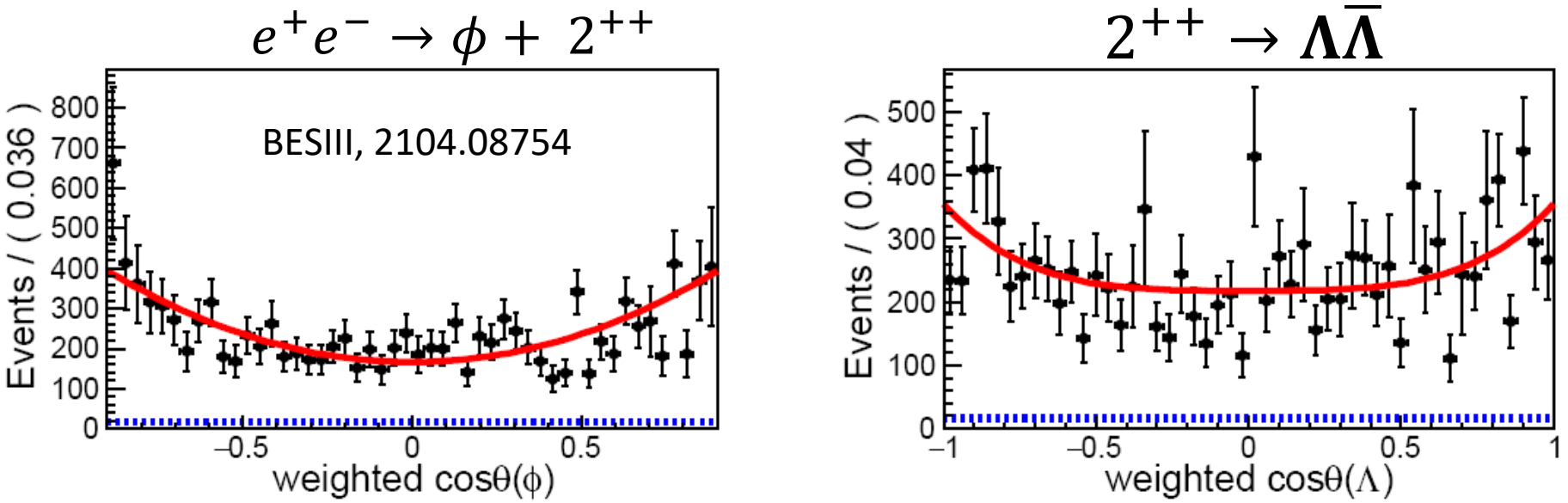


FIG. 4: Efficiency-corrected angular distribution of the ϕ (left) and Λ (right) candidates combining all the data samples and the simultaneous fit results with the hypotheses of $J^{PC} = 2^{++}$. The data (dots) are overlaid by the result of the fit (red solid line) described in the text, the blue dotted curve are the components consisting of the PHSP signal and the sideband background.