Non-Vector charmonium-like studies at BESIII

Yunxuan Song（宋昀轩）

Peking University

University of Chinese Academy of Sciences

(On behalf of the BESIII collaboration)

Outline

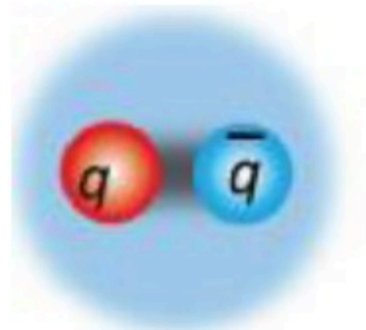
- Introduction
- Observation of charged $Z_{cs}(3985)^-$
  - $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$
- Observation of threshold enhancement of $\Lambda\bar{\Lambda}$
  - $e^+e^- \to \phi\Lambda\bar{\Lambda}$
- Search for $X(3872)$ state
  - $e^+e^- \to \pi^0 X(3872)\gamma$
- Search for new decay modes of $\psi_2(3823)$
  - $e^+e^- \to \pi^+\pi^-\psi_2(3823)$
  - $e^+e^- \to \pi^0\pi^0\psi_2(3823)$

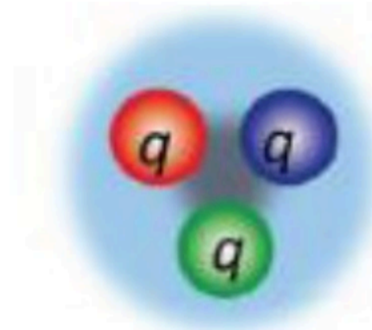
New forms of hadron

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

Naive Quark Model：

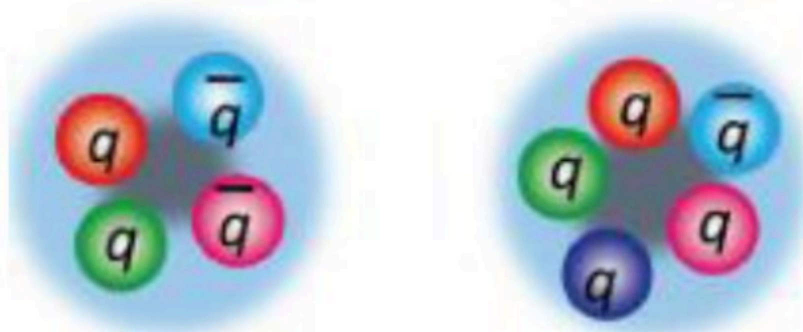
meson



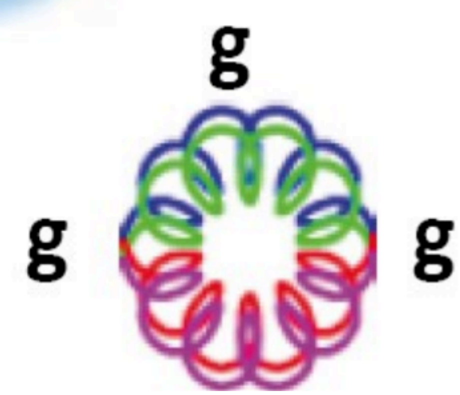


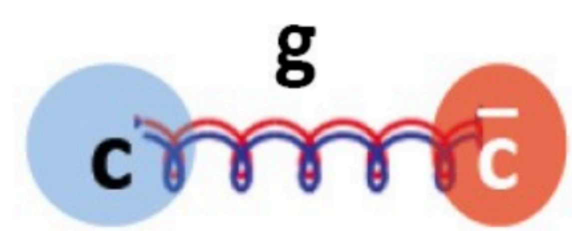
baryon

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

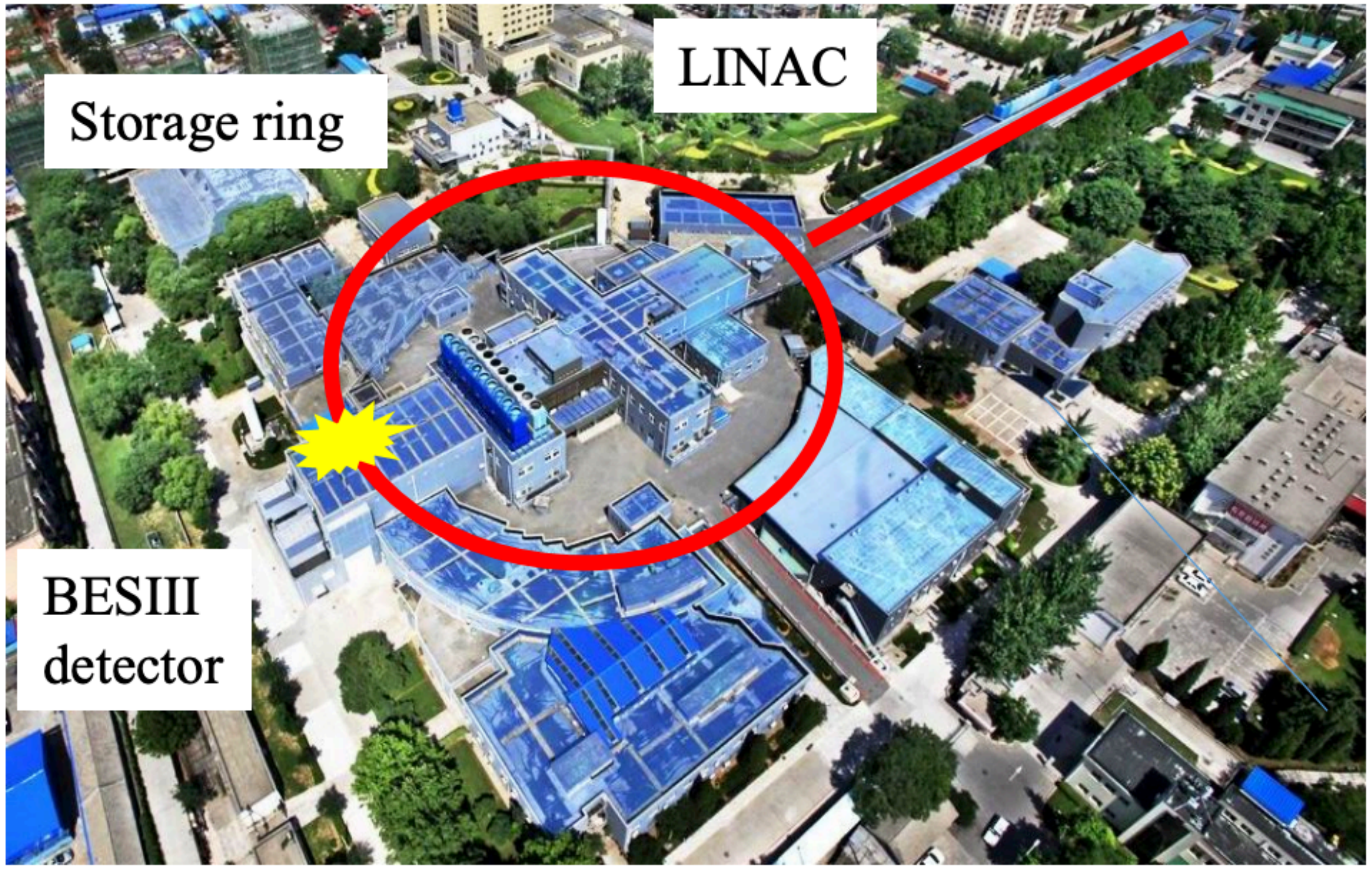


  - **Hybrids：** $q\bar{q}g$, $qqqg$ …
  - **Glueballs：** gg, ggg …

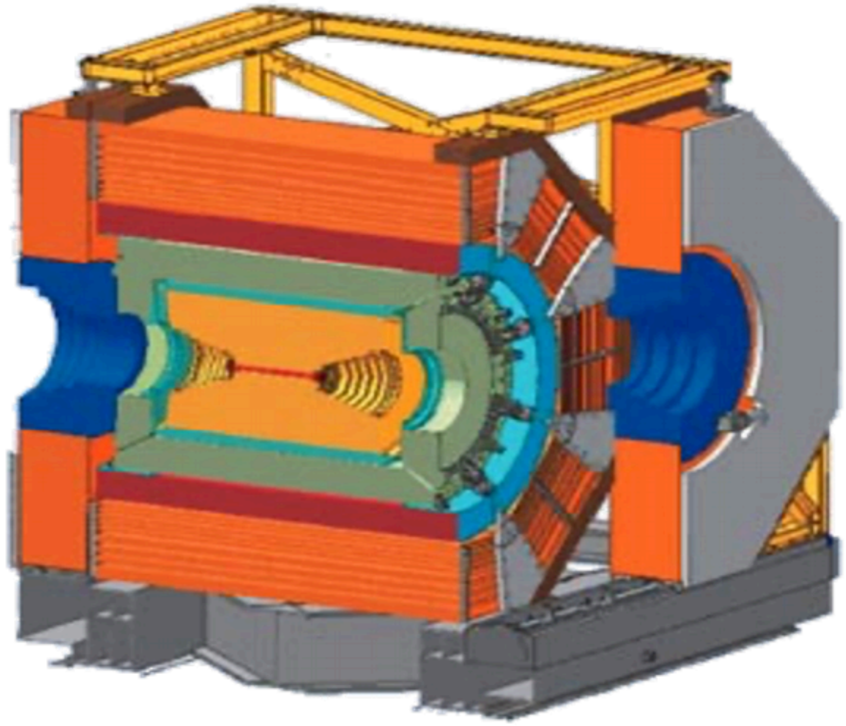




BEPCII and BESIII



BEPCII:
- First collision in 2008, physics run in 2009
- Energy region: 2.0 – 4.95 GeV
- Designed luminosity: 1×10^{33} $cm^{-2}s^{-1}$ @ $\psi(3770)$, reach in April 2016



MDC
- small cell & Gas, He/C_3H_8 (60/40)
- σ_{xy} = 120 μm
- σ_p/p = 0.5% @ 1 GeV/c
- dE/dx = 6%

TOF
- σ_t = 80 ps (Barrel)
  60 ps(Endcap)

EMC:
- CsI(Tl)
- ΔE/E = 2.5% @ 1 GeV
- σ_z=0.6 cm

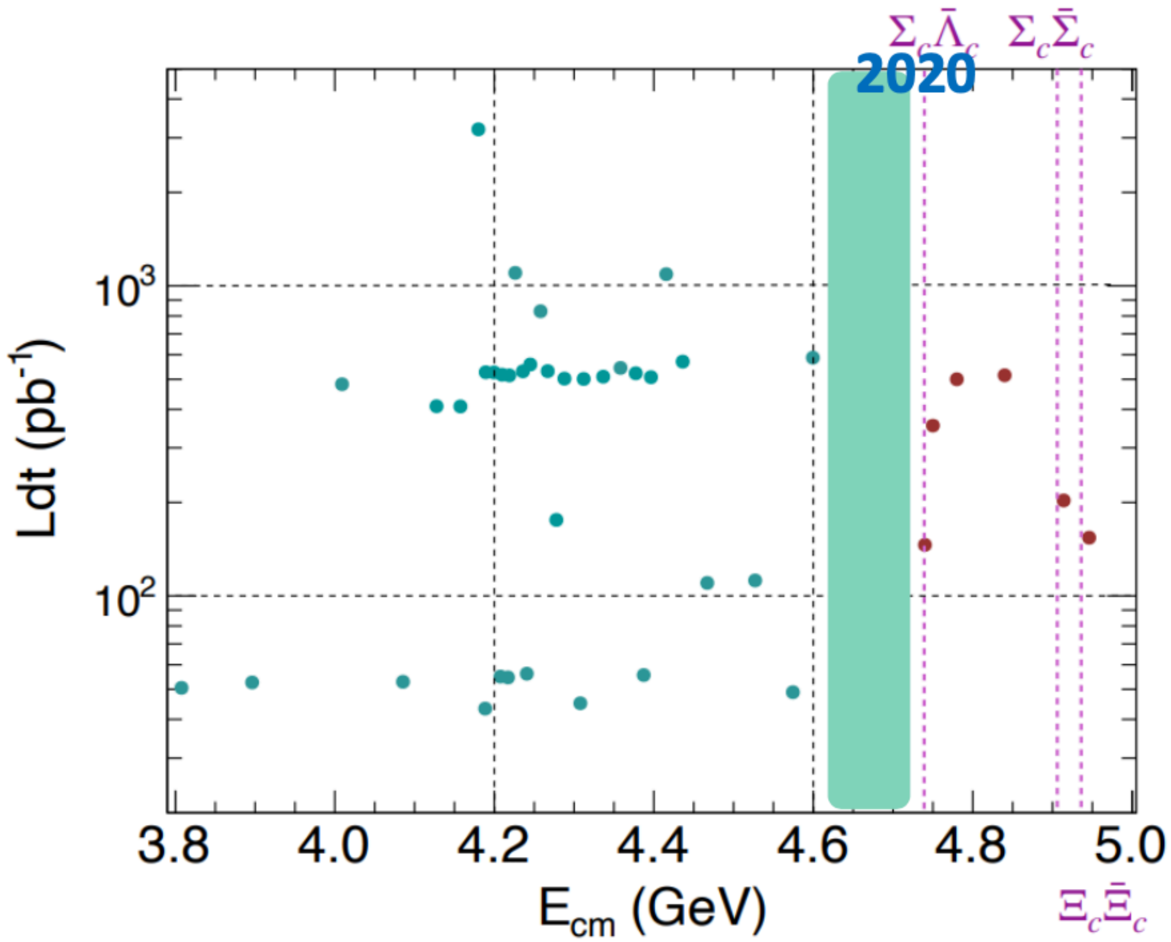
MUC
- 9 layers RPC for barrel
- 8 layers RPC for endcap

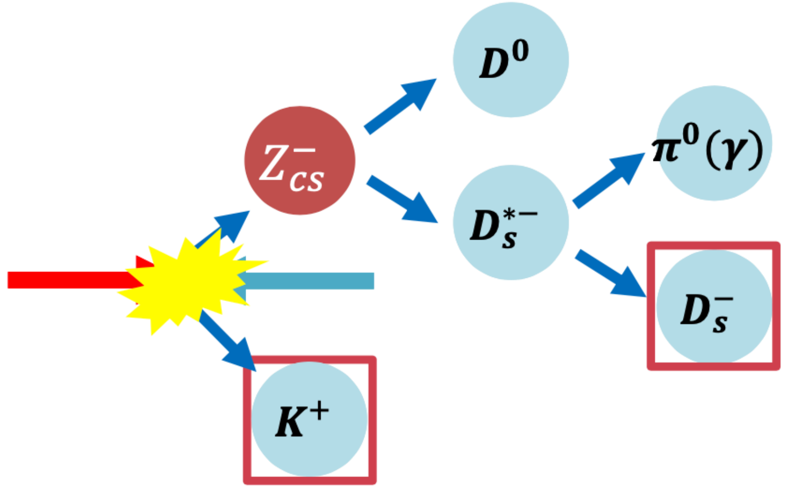
Superconducting magnet (1T)

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

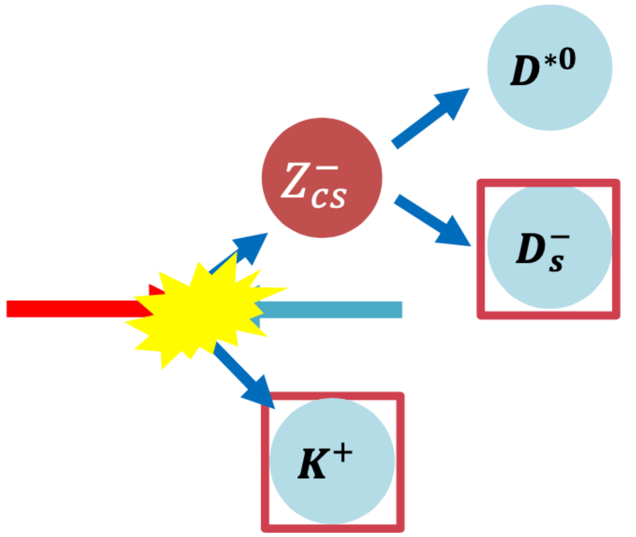
➔ $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$

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



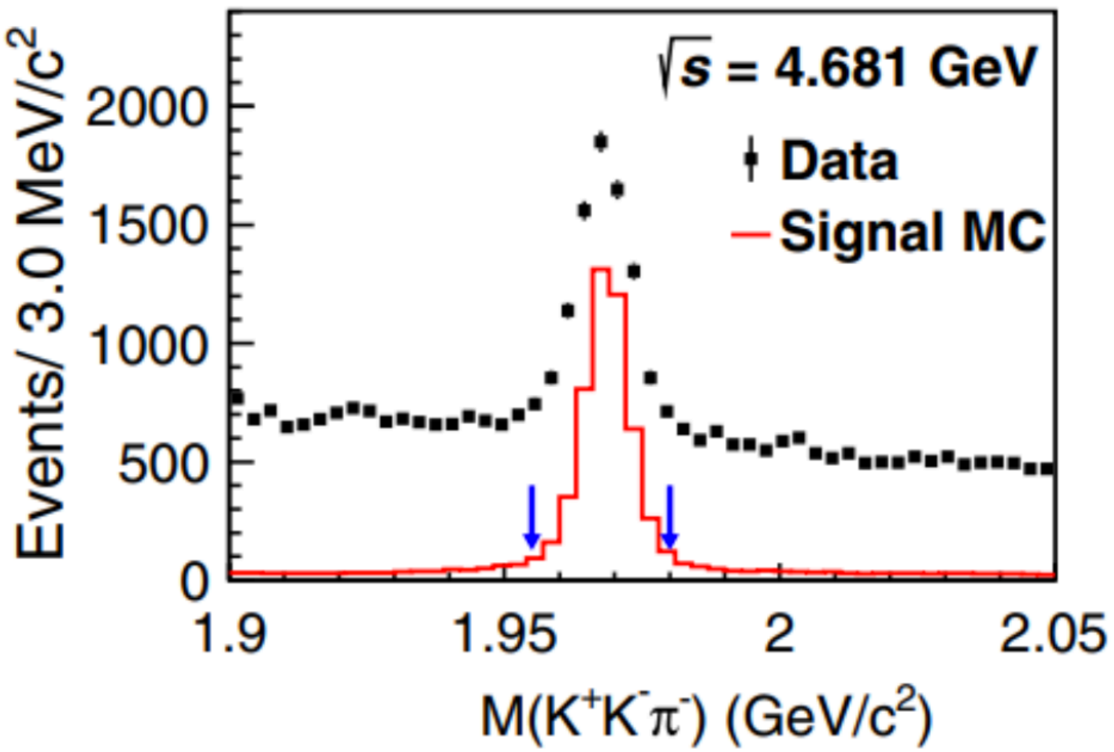


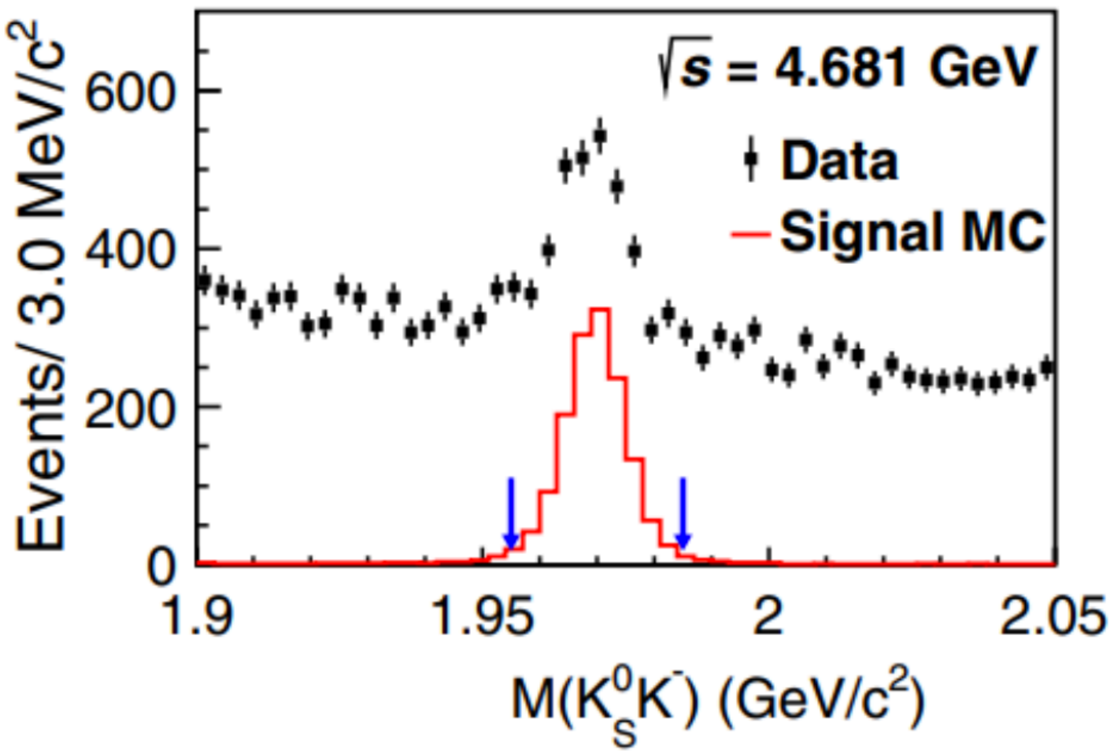
$e^+e^- \to K^+D_s^{*-}D^0$

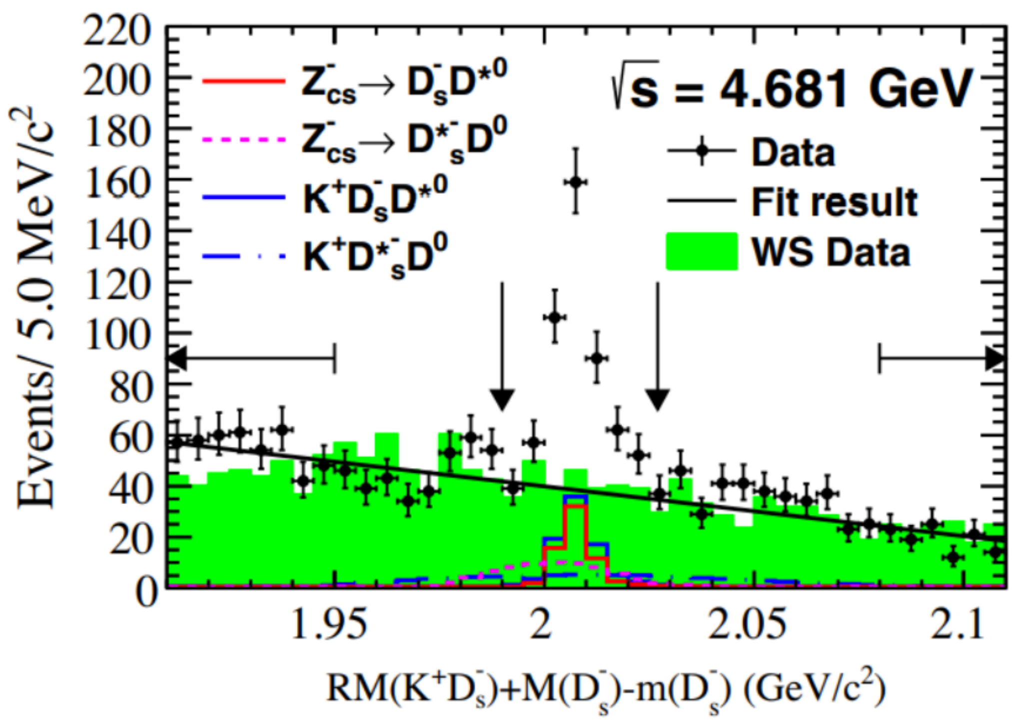


$e^+e^- \to K^+D_s^-D^{*0}$

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





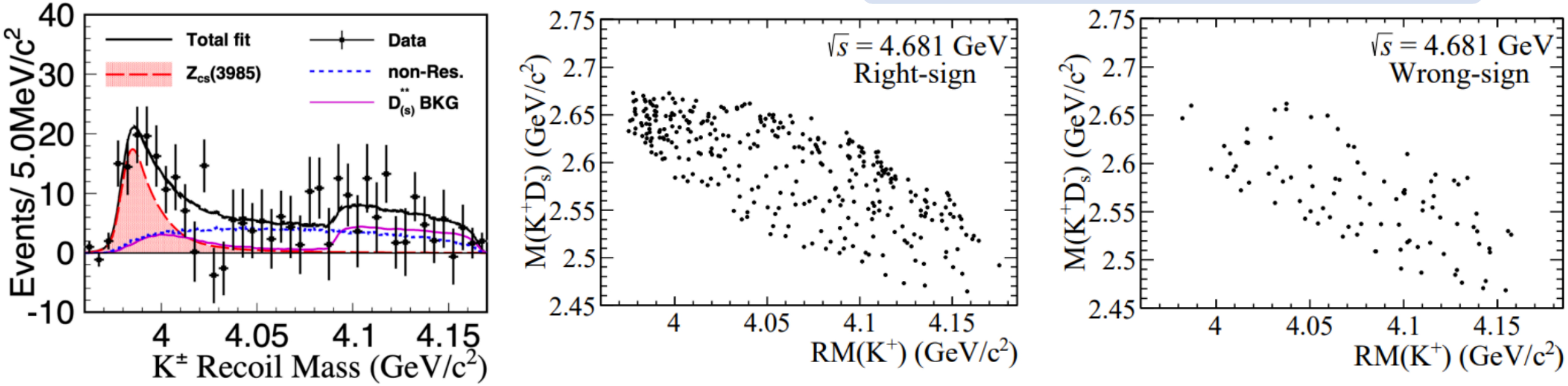


PRL 126, 102001 (2021)

- ✓ 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 $Z_{cs}(3985)^-$

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:

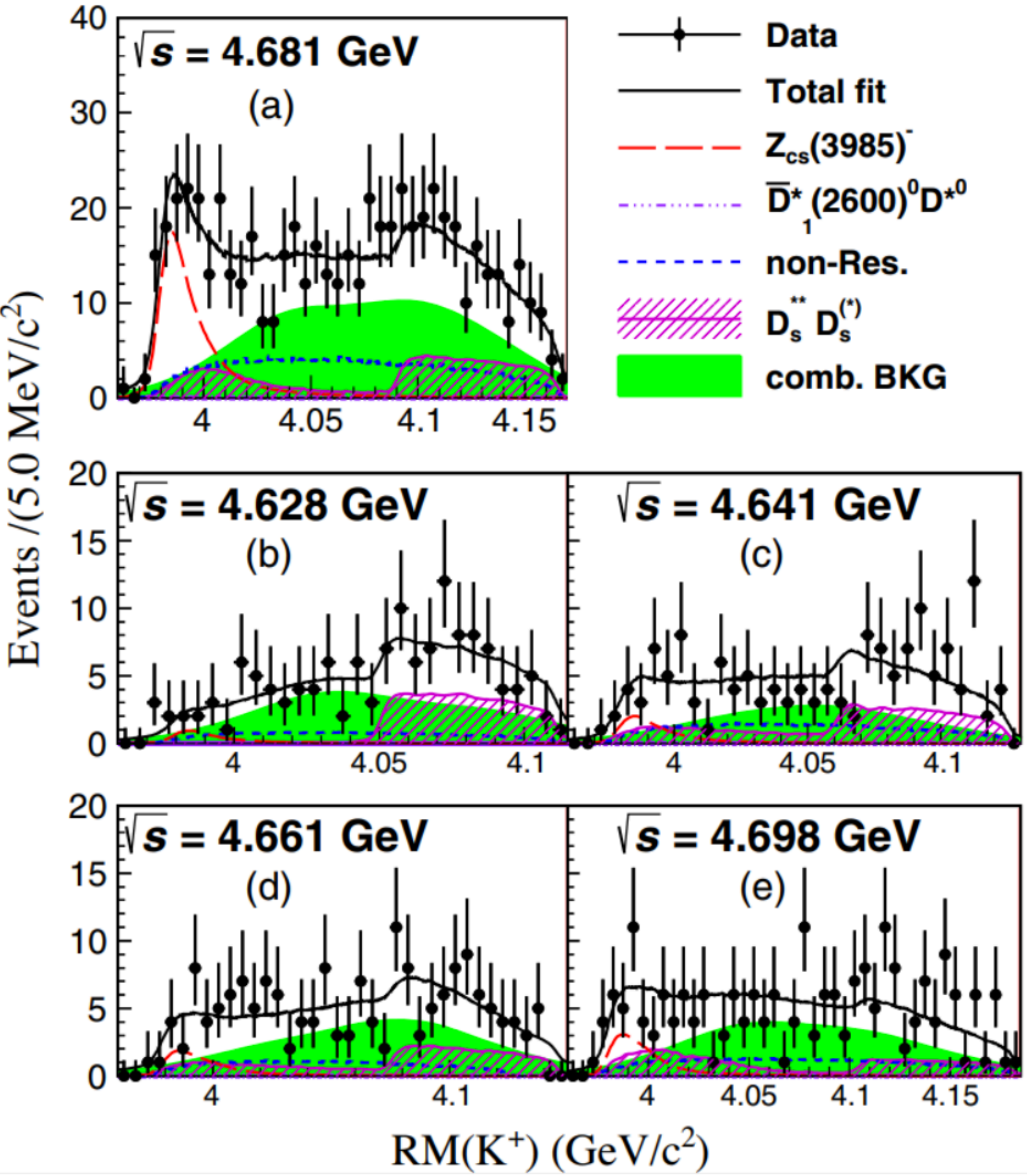
$$\boldsymbol{M = 3985.2^{+2.1}_{-2.0} \pm 1.7\ \mathrm{MeV/c^2}}$$

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

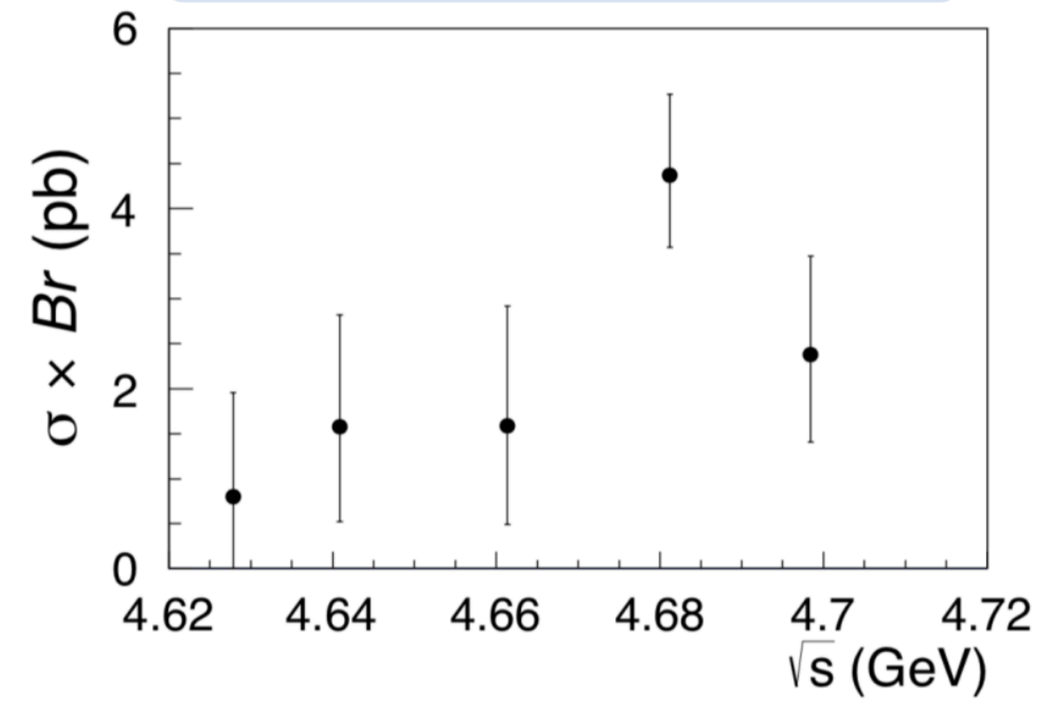
✓ Global significance: $> 5.3\,\sigma$

First candidate of the hidden-charm tetraquark with strangeness

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



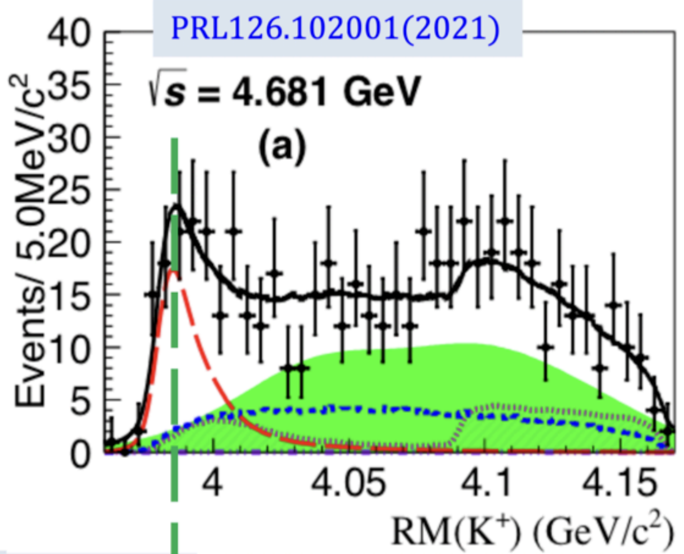
PRL 126, 102001 (2021)

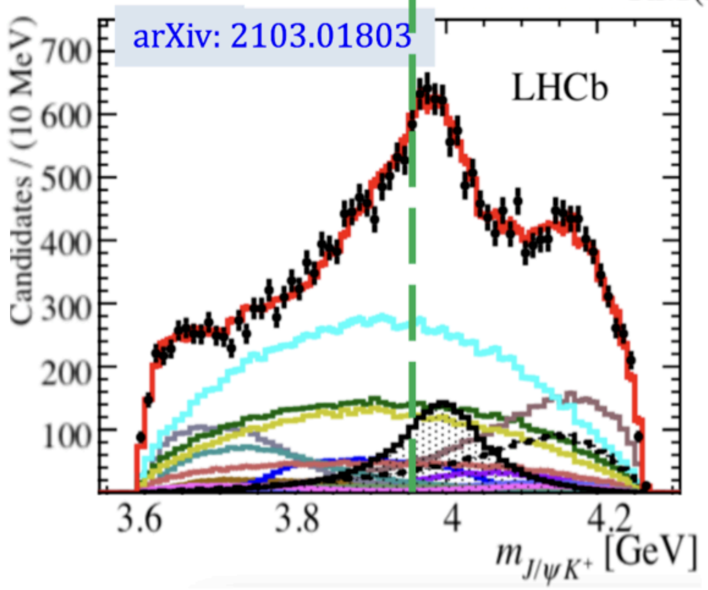


- ✓ Simultaneous fit to the five energy points.
- ✓ Largest cross sections around 4.681 GeV.

Discussions on the nature of $Z_{cs}(3985)^-$

- 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.





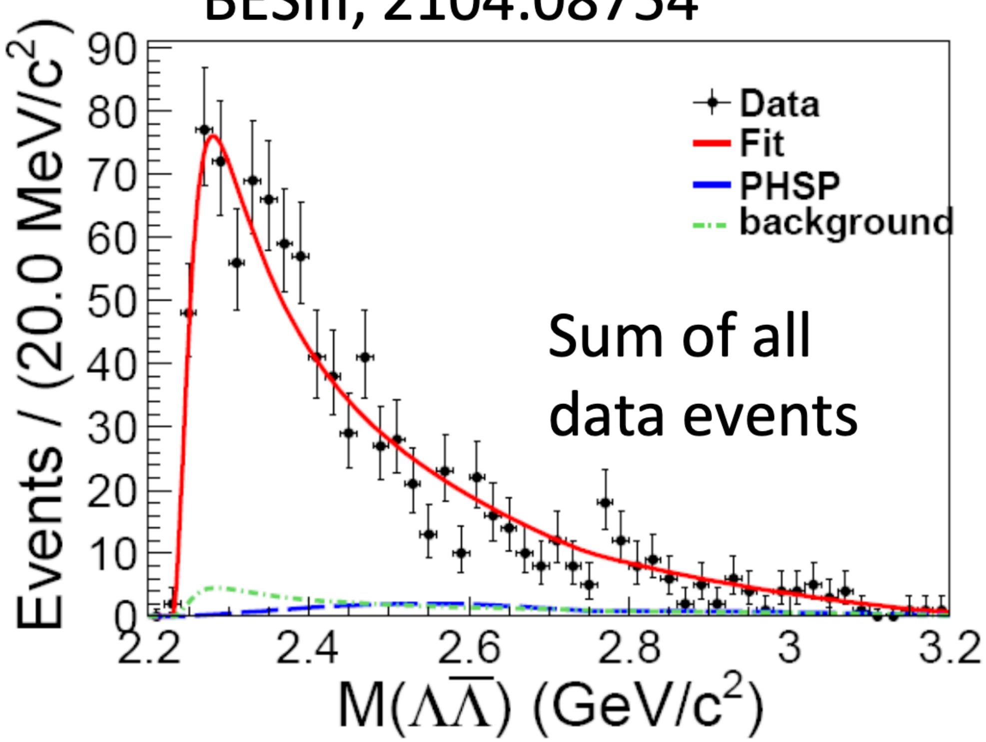
- $Z_{cs}(3985)^-$:
  $J^P = 1^+$
  $M = 3985.2^{+2.1}_{-2.0} \pm 1.7\ \mathrm{MeV}/c^2$
  $\Gamma = 13.8^{+8.1}_{-5.2} \pm 4.9\ \mathrm{MeV}$
- $Z_{cs}(4000)^-$:
  $J^P = 1^+$
  $M = 4003 \pm 6^{+4}_{-14}\ \mathrm{MeV}/c^2$
  $\Gamma = 131 \pm 15 \pm 26\ \mathrm{MeV}$

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

arXiv: 2104.08754

- $\eta(2225)$ 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), $B^0 \to K\Lambda\bar{\Lambda}$ (PRL79, 052006).
- 28 data sets with $\sqrt{s} = 3.51 \sim 4.6\ \mathrm{GeV}$, with total luminosity 19.462 fb^{-1}.
- Events reconstructed with $\phi \to K^+K^-, \Lambda \to p\pi^-(\text{or } \bar{\Lambda} \to \bar{p}\pi^+)$.
- Breit-Wigner parametrization: $M = (2262 \pm 4 \pm 28)\ \mathrm{MeV/c^2}, \Gamma = (72 \pm 5 \pm 43)\ \mathrm{MeV}$. ($25\sigma$)
- Angular distribution analysis: $J^{PC} = 1^{++} \text{ or } 2^{-+} \text{ or } 2^{++}$

BESIII, 2104.08754



- 0^{-+} rejected with significance of 7σ.
- Nambu model is rejected.
- The enhancement consistent with that observed in $B^0 \to K\Lambda\bar{\Lambda}$ by Belle. (PRL79, 052006).

Search for $Z_c(4020)^0 \to X(3872)\gamma$

PRD104, 012001 (2021)

- $e^+e^- \to \pi^0 Z_c(4020)^0 \to \pi^0 X(3872)\gamma$ at energies from 4.178 to 4.600 GeV.
- The enhancement around 4.2 GeV in the $e^+e^- \to X(3872)\gamma$ and the observation of the $Y(4220)$ resonance in $e^+e^- \to \pi^0 Z_c(3900)^0$ suggest the connections between $X-Y$ and $Y-Z$ states.
- 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. [PRD99.054028]
- No significant signal is found
- $$\frac{\mathscr{B}[Z_c(4020)^0 \to X(3872)\gamma] \cdot \mathscr{B}[X(3872) \to \pi^+\pi^- J/\psi]}{\mathscr{B}[Z_c(4020)^0 \to (D^*\bar{D}^*)^0]} < 0.24\,\%\ (@4.23\mathrm{GeV})$$

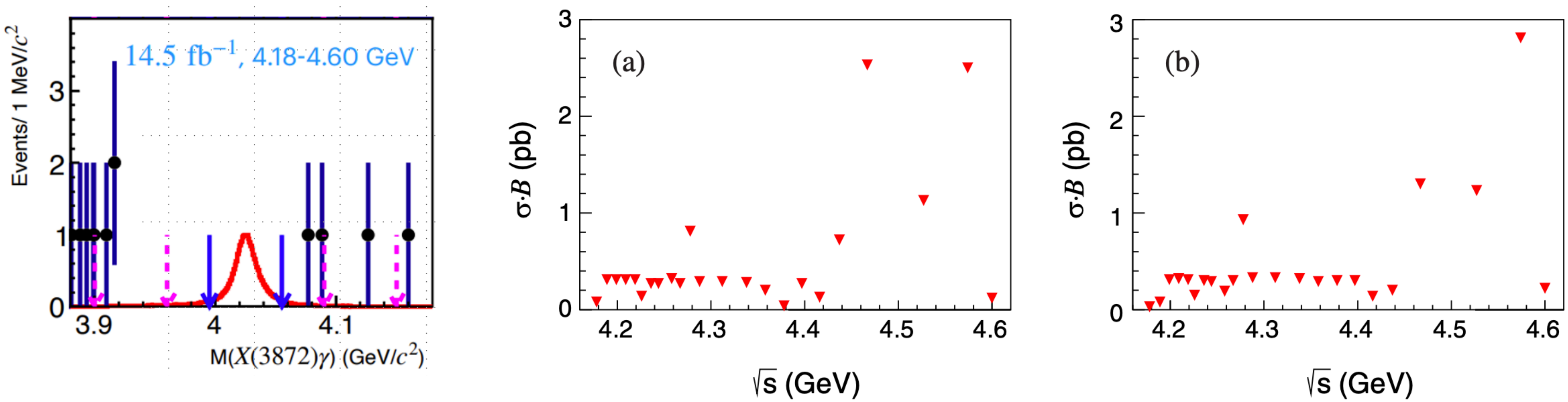


FIG. 2. The upper limits at the 90% C.L. on $\sigma(e^+e^- \to \pi^0 X(3872)\gamma) \cdot \mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)$ (a) and $\sigma(e^+e^- \to \pi^0 Z_c(4020)^0) \cdot \mathcal{B}(Z_c(4020)^0 \to X(3872)\gamma) \cdot \mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)$ (b) for each energy point.

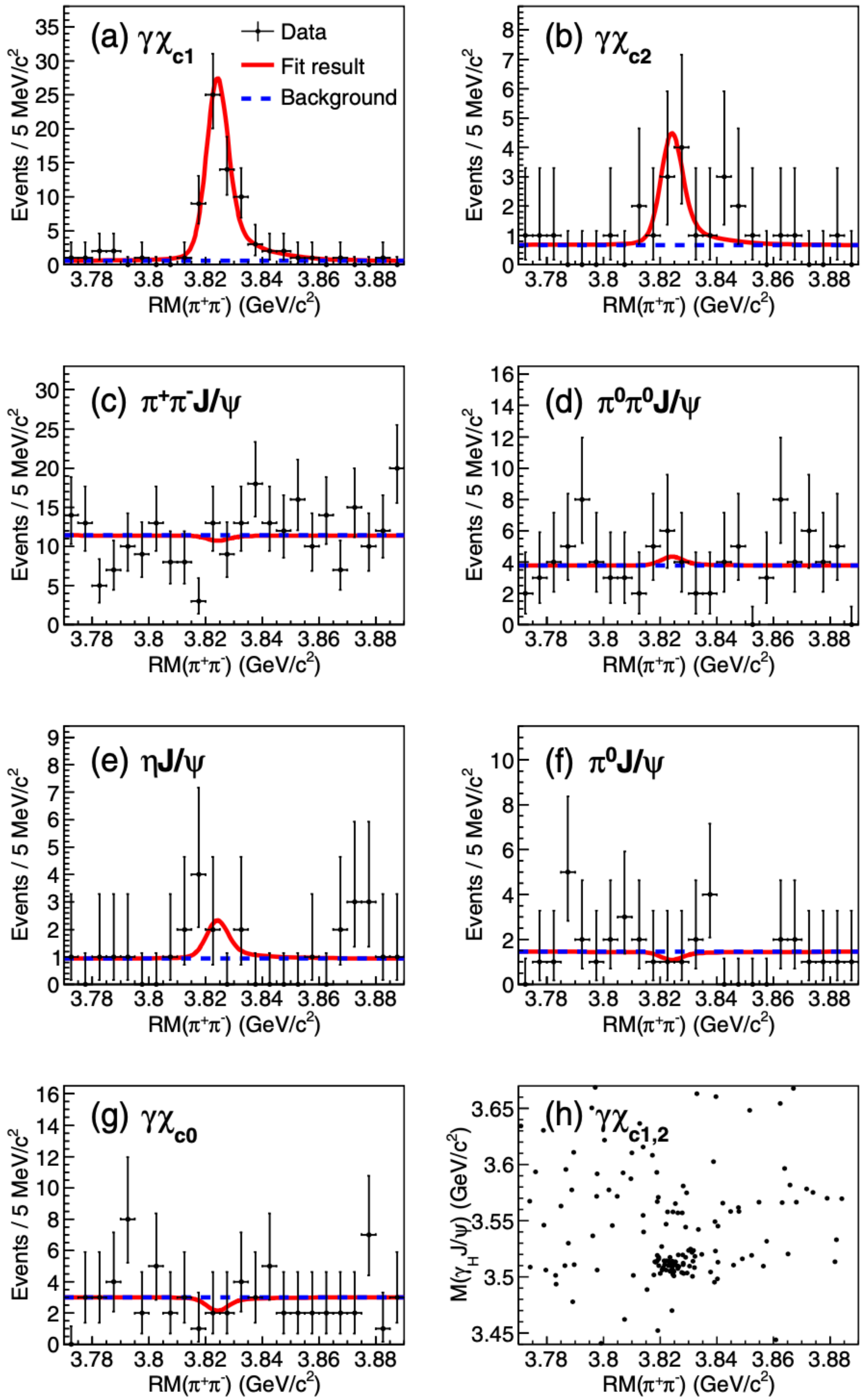
$\psi_2(3823)$

- Evidence of $\psi_2(3823)$ from Belle experiment in $B \to (\psi_2(3823)\gamma\chi_{c1})K$
  - 772×10^6 $B\bar{B}$ events, 3.8σ. Phys.Rev.Lett. 111, 032001(2013)
  - $M = 3823.1 \pm 1.8 \pm 0.7$ MeV, $\Gamma_{\text{tot}} < 24$ MeV
- Observed by BESIII experiment in $e^+e^- \to \pi^+\pi^-\psi_2(3823), \psi_2(3823) \to \gamma\chi_{c1}$
  - Scan data sample at $\sqrt{s} = 4.23,\ 4.26,\ 4.36,\ 4.42,\ 4.60$ GeV, 6.2σ
  - $M = 3821.7 \pm 1.3 \pm 0.7$ MeV, $\Gamma_{\text{tot}} < 16$ MeV Phys.Rev.Lett. 115, 011803(2015)
- Decays of $\psi_2(3823)$ to $\gamma\chi_{c1}$, $\pi^+\pi^-J/\psi, ggg, \gamma gg$ have been predicted by various theoretical work
  - $\Gamma_{\psi_2(3823)\to\gamma\chi_{c1}} \sim 200 - 350$ KeV, $\Gamma_{\psi_2(3823)\to\gamma\chi_{c2}} \sim 40 - 90$ KeV
  - $\Gamma_{\psi_2(3823)\to\gamma\chi_{c3}} \sim 45 - 200$ KeV

Phys.Rev.D. 55, 4001(1997)
Phys.Rev.Lett. 89, 162002(2002)
Phys.Rev.D. 67, 014027(2003)
Phys.Rev.D. 69, 054008(2004)
Phys.Rev.D. 72, 054026(2005)
Phys.Rev.D. 79, 094004(2009)
Phys.Rev.D. 94, 034005(2016)
Front.Phys. 11, 111402(2016)
arXiv:1501.08269

New decay modes of $\psi_2(3823)$

PRD103, L091102 (2021)



- Using process $e^+e^- \to \pi^+\pi^-\psi_2(3823)$ in a $9fb^{-1}$ data sample between 4.3 and 4.6 GeV, several decay channels are studied.
- Evidence for the $\psi_2(3823) \to \gamma\chi_{c2}$ is found. $\psi_2(3823) \to \gamma\chi_{c1}$ is rediscovered, no significant $\psi_2(3823)$ signals for other channels.
- $e^+e^- \to \pi^0\pi^0\psi_2(3823)$ is found with 4.3σ.
- No significant $e^+e^- \to \pi^+\pi^-\psi_3(3842)$ signals in all channels.
- Consistent with the theoretical predictions.

Channel	$N^{\psi_2(3823)}$	$\frac{\mathcal{B}(\psi_2(3823)\to\cdots)}{\mathcal{B}(\psi_2(3823)\to\gamma\chi_{c1})}$
$\gamma\chi_{c1}$	63.1 ± 8.5	$\cdots$
$\gamma\chi_{c2}$	$8.8^{+4.3}_{-3.4}$	$0.28^{+0.14}_{-0.11} \pm 0.02$
$\pi^+\pi^- J/\psi$	<21.0	<0.06
$\pi^0\pi^0 J/\psi$	<10.0	<0.11
$\eta J/\psi$	<9.8	<0.14
$\pi^0 J/\psi$	<5.6	<0.03
$\gamma\chi_{c0}$	<6.3	<0.24

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 $Z_{cs}(3985)$.
  - Threshold enhancement of $\Lambda\bar{\Lambda}$ is observed in $e^+e^- \to \phi\Lambda\bar{\Lambda}$.
  - New modes of $Z_c(4020)^0 \to \gamma X(3872)$ is searched, but no significant signals are seen.
  - New modes of $\psi_2(3823)$ are searched, evidence for the $\psi_2(3823) \to \gamma\chi_{c2}$ is found.
- More searches for the new $Z_{c(s)}$ decay modes are in process.