BESIII粲强子物理及重大项目研讨会

Physics via open charm production at BESIII

PhysRevLett.126.102001(2021)
PhysRevLett.129.112003(2022)
ChinPhysC47.033001(2023)
PhysRevLett.130.121901(2023)

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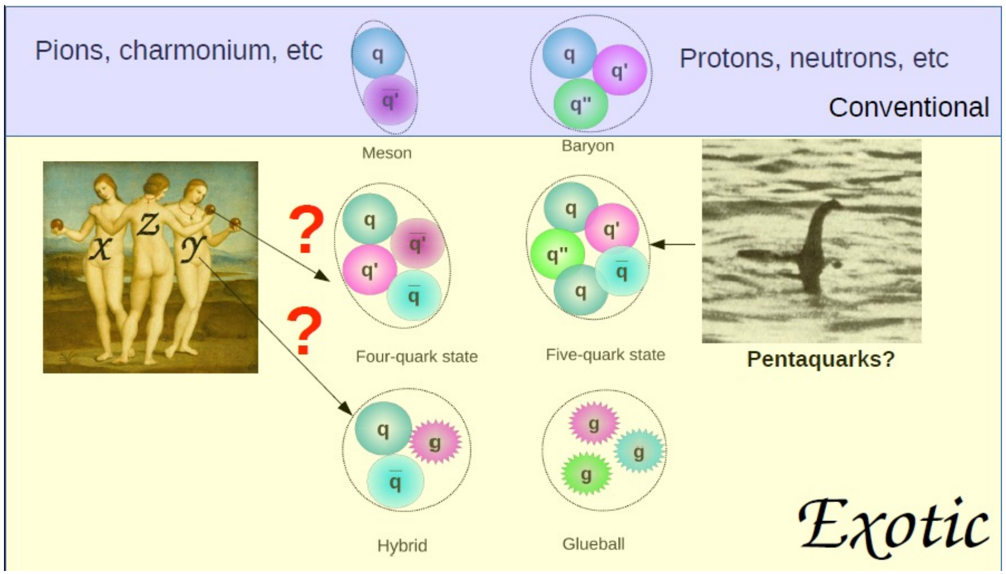
合肥，2023/04/07

QCD predicted states

- Exotic hadrons: states composed of quarks and gluons beyond conventional mesons ($q\bar{q}$) and baryons (qqq).



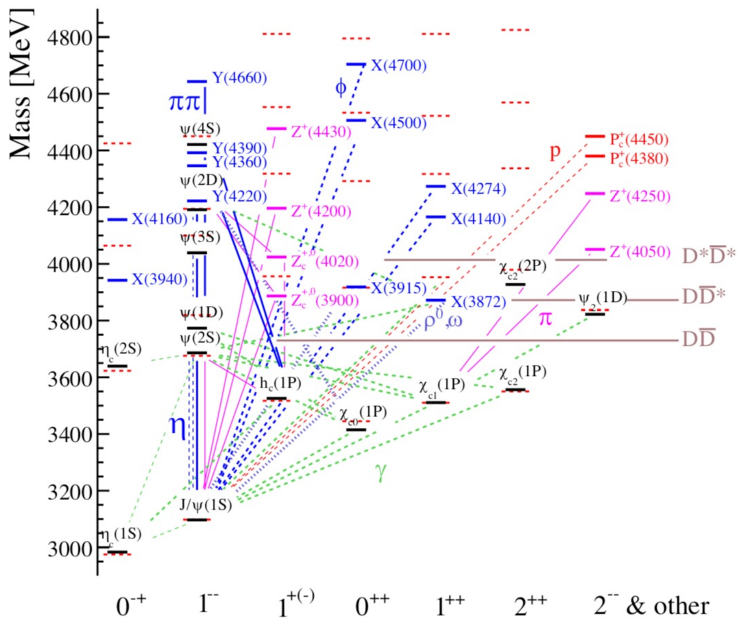
Different compositions and binding schemes:

- Hybrid : N_{quarks} = 2 + excited gluon
- Glueball: N_{quarks} = 0 (gg, ggg, …)
- Molecular state: **bound state of more than 2 hadrons**
- Compact multiquark state: $N_{quarks} > 3$

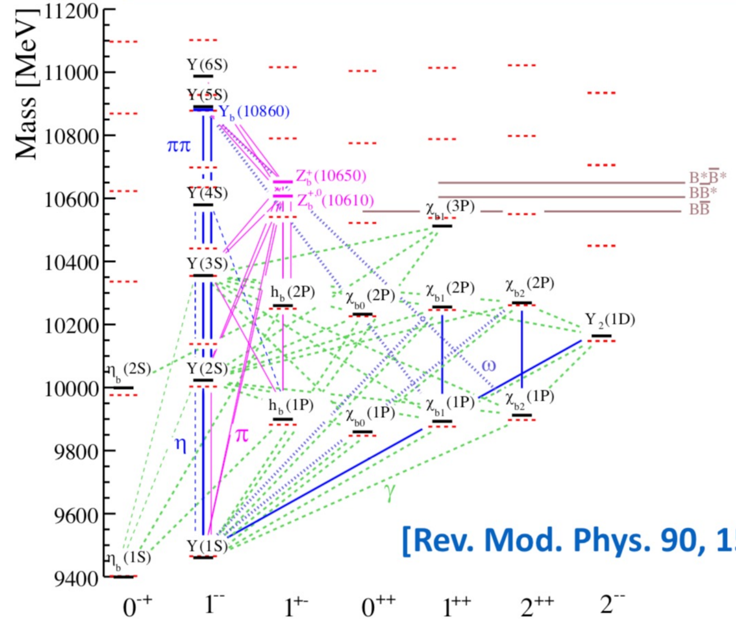
- Provide new insights into internal structure and dynamics of hadrons.
- Unique probe to non-perturbative behavior of QCD.

Exotic hadrons in heavy-heavy systems $c\bar{c}$ or $b\bar{b}$

Charmonium ($c\bar{c}$)-like spectrum



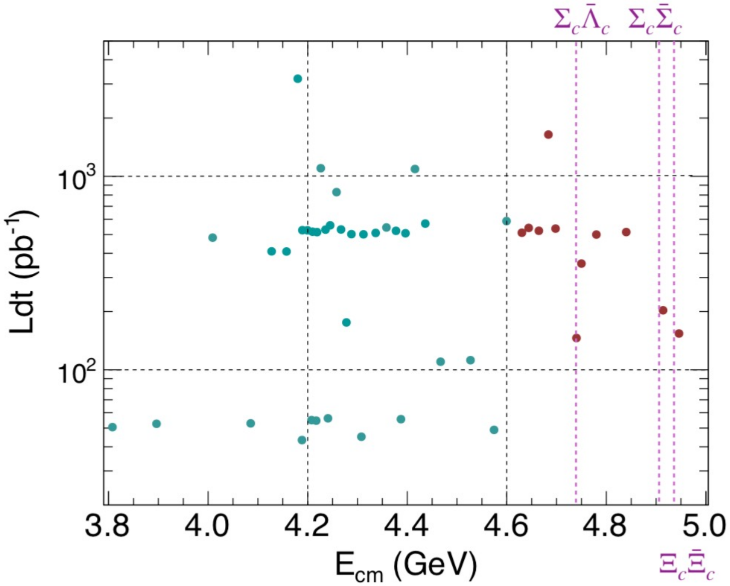
Bottomonium ($b\bar{b}$)-like spectrum

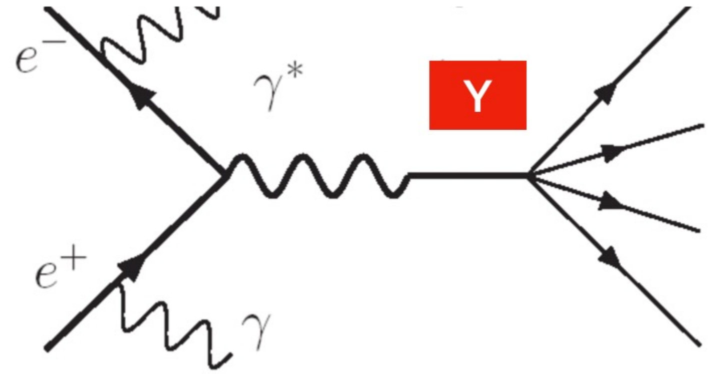


[Rev. Mod. Phys. 90, 15003 (2018)]

- Theoretical models are well-established for conventional states: QCD potential modes are well constructed.
- Experimentally easier to measure: relative narrow compared with light hadron systems.
- Quarkonium-like exotic states is an ideal place for exotic search.

BESIII data Samples for XYZ study

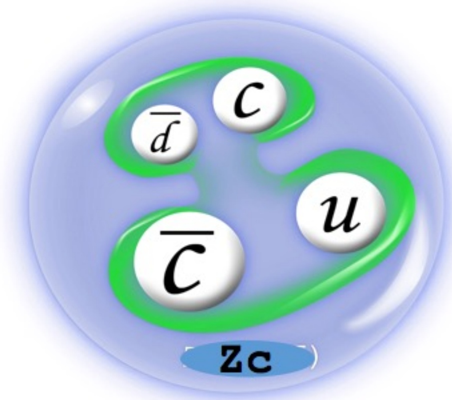


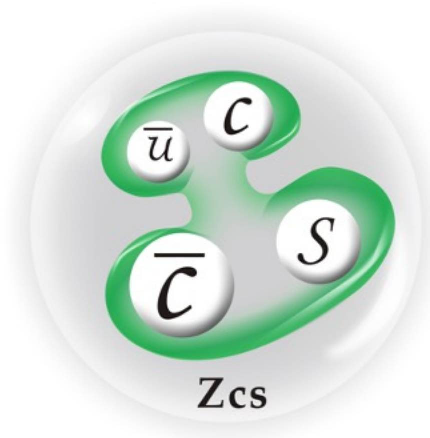


- BESIII can directly generate Y(1^{--}) states by e^+e^- annihilation.
- Study X and Z by radiative decay or hadronic transition from Y.
- BESIII accumulate ~24fb^{-1} e^+e^- collision data events from 3.8-4.946GeV.
- Data sample taken above 4.6GeV has been finished in 2020=>Y(4660) study.
- Search for more XYZ states, study their properties and new decays modes.
- Look for transitions between different states.

The $Z_{c(s)}$ states

Charmonium-like states **carrying** electric charge; must contain at least $c\bar{c}$ and a light $q\bar{q}$ pair

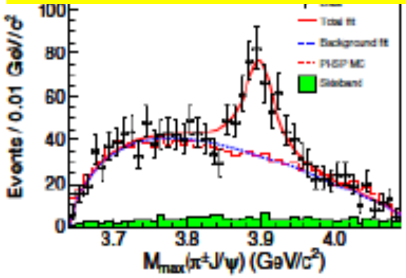




The Zc Family at BESIII

$Zc(3900)^+$

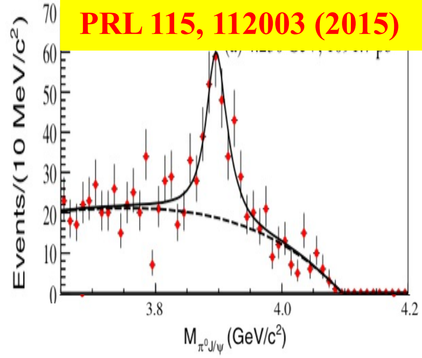
PRL 110, 252001 (2013)



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

$Zc(3900)^0$

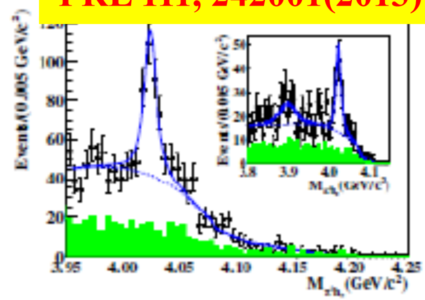
PRL 115, 112003 (2015)



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

$Zc(4020)^+$

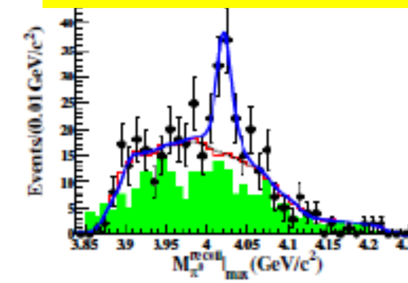
PRL 111, 242001(2013)



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

$Zc(4020)^0$

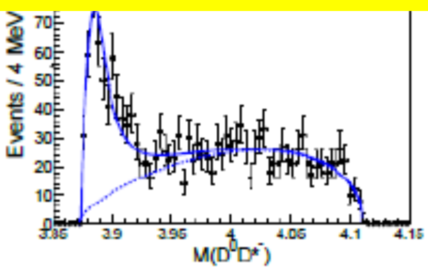
PRL113,212002 (2014)



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

$Zc(3885)^+$

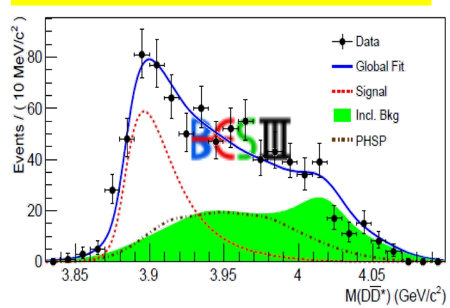
ST: PRL 112, 022001(2014)
DT: PRD92, 092006 (2015)



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

$Zc(3885)^0$

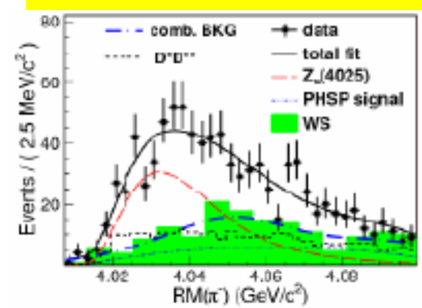
PRL115, 222002 (2015)



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

$Zc(4025)^+$

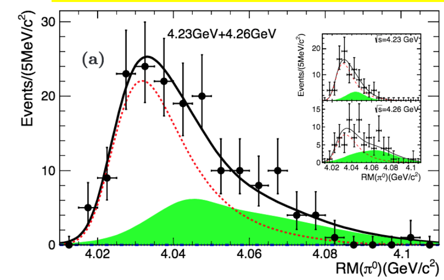
PRL 112, 132001 (2014)



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

$Zc(4025)^0$

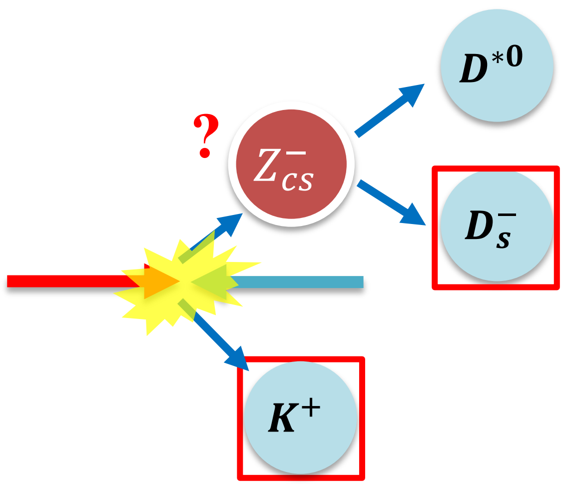
PRL115, 182002 (2015)



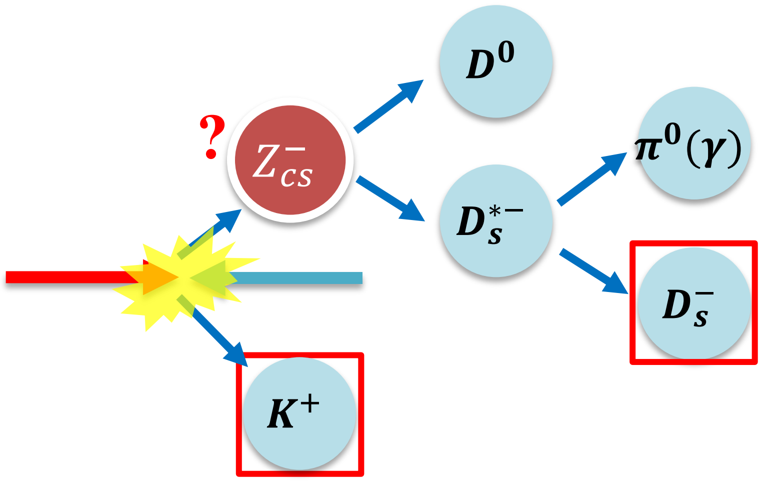
$e^+e^- \to \pi^0(D^*\bar{D}^*)^0$

- What is the nature of these states?
- Different decay channels of the same observed states? Other decay modes? J^P?
- Searches for Z_{cs} partners were proposed few years ago. e.g., $Z_{cs}/Z'_{cs} \to KJ/\psi$, D_sD^*, D_s^*D, $D_s^*D^*$ etc. => decay rate of Z_{cs} to open-charm final states is supposed to be larger than hidden-charm.

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



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

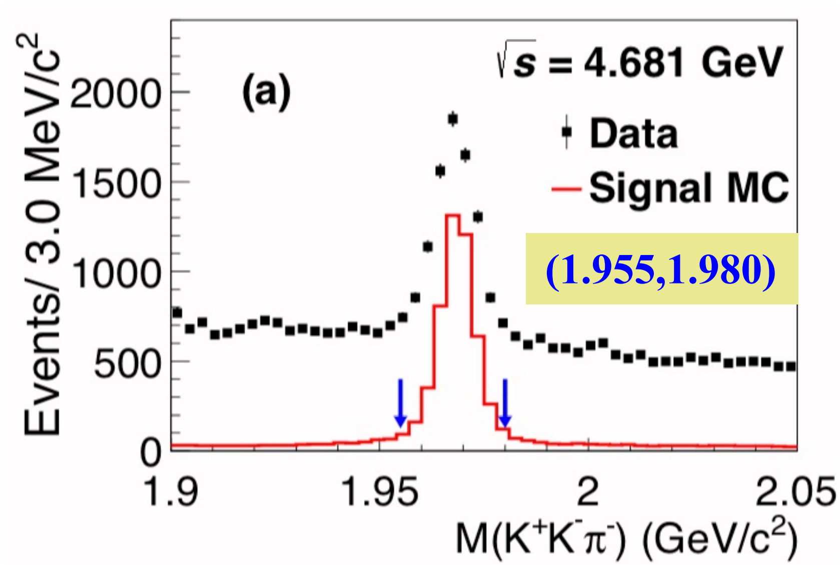


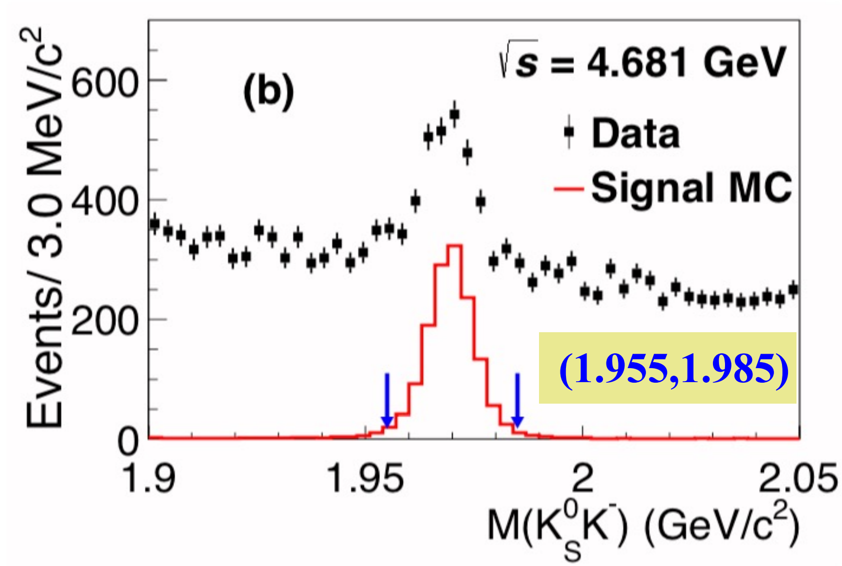
$e^+e^- \to K^+ D_s^{*-} D^0$

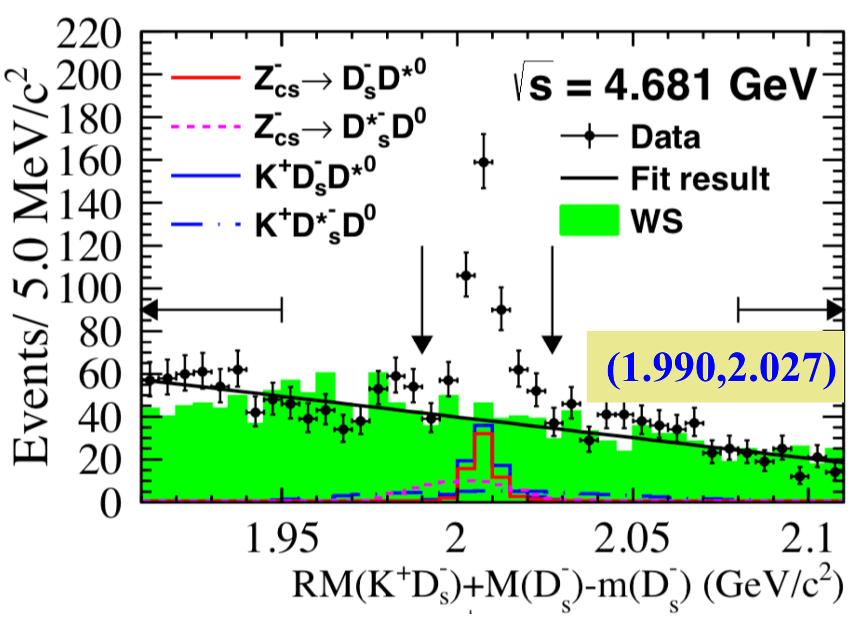
- **Partial reconstruction** of the process $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$
  - Reconstruct a $\boldsymbol{D_s^-}$ with two tag modes: $D_s^- \to K_S^0 K^-$ and $D_s^- \to K^+K^-\pi^-$.
  - Tag a bachelor charged $\boldsymbol{K^+}$.
  - Use signature in the **recoil mass spectrum of $K^+D_s^-$** to identify the process of $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$.
  - Study the mass spectrum of recoil mass of $\boldsymbol{K^+}$.
  - The charge conjugated channels are also implied.

Similar technique with the paper of **Zc(4025)$^+$** observation.
PRL 112, 132001 (2014)

Tag a D_s^- and select $K^+(D_s^- D^{*0} + D_s^{*-} D^0)$ signals







For $D_s^- \to K^+K^-\pi^-$ process, keep the events only in

1) $D_s^- \to \pi^-\phi(K^-K^+)$: $M(K^-K^+) < 1.05$ GeV/c².

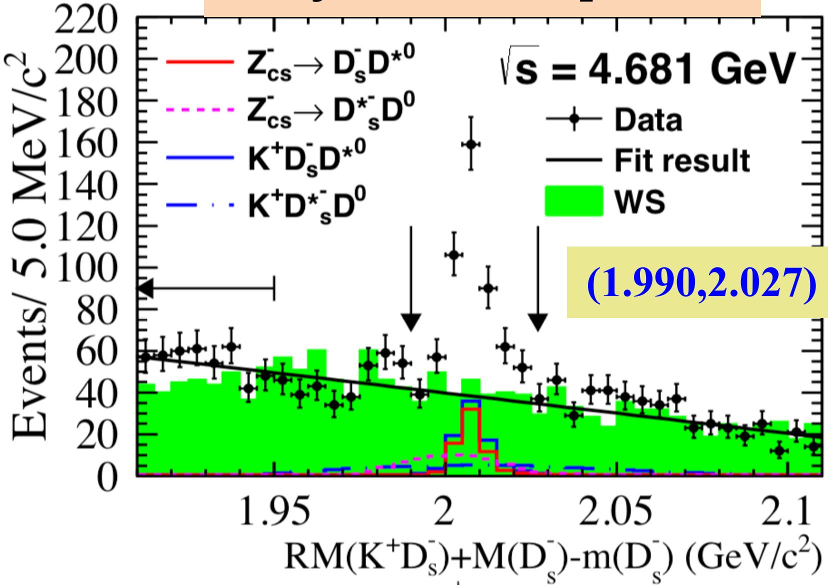
2) $D_s^- \to K^-K^*(892)(K^+\pi^-)$:

$M(K^+\pi^-) \in (0.85, 0.93)$ GeV/c².

- $RM(K^+D_s^-)$: the recoil mass of $K^+D_s^-$.
- $M(D_s^-)$: the reconstructed mass.
- $m(D_s^-)$: the mass taken from PDG.

Select candidates for $K^+(D_s^- D^{*0} + D_s^{*-} D^0)$

very evident peak

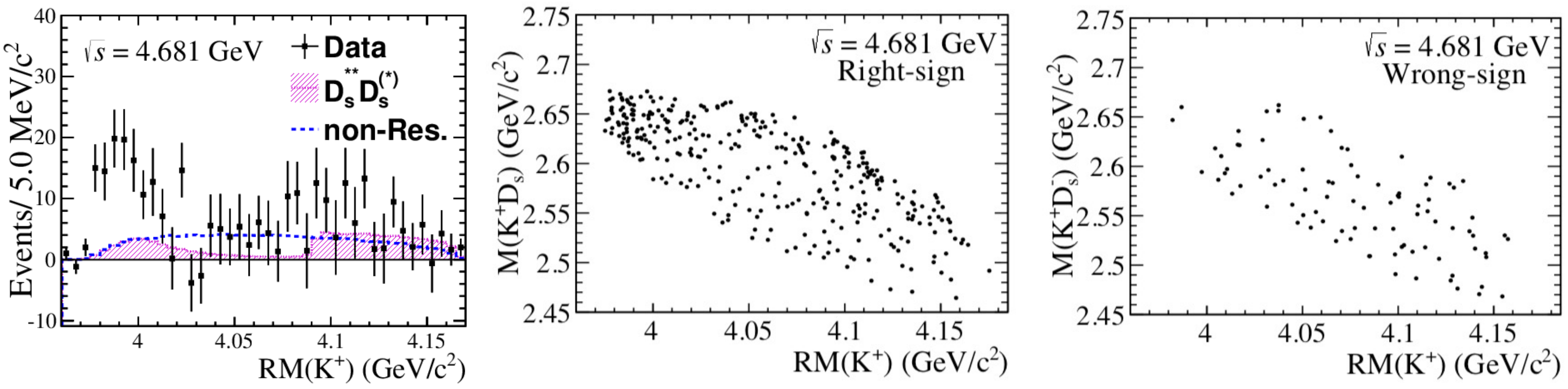


(1.990,2.027)

- Data-driven technique to describe combinatorial background.
- Right Sign(RS): combination of D_s^- and K^+.
- Wrong Sign(WS): combination of D_s^- and K^- to mimic combinatorial background.

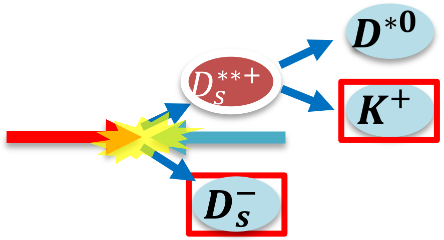
- No peaking background observed in WS events; => **WS technique is well validated by MC simulations and data sideband events.**
- Both $e^+e^- \to K^+ D_s^- D^{*0}$ and $e^+e^- \to K^+ D_s^{*-} D^0$ can survive with this criterion.
- Fitting to $RM(K^+ D_s^-)$ sideband events give number of WS in signal region: 282.6 ± 12.0;
- This WS number will be fixed in $RM(K^+)$ spectrum fitting.

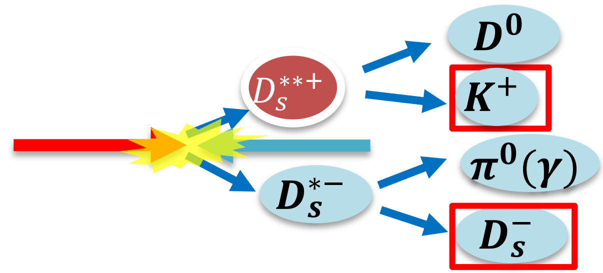
Recoil-mass spectra of K^+ and two-dimensional distributions of $M(K^+D_s^-)$ vs. $RM(K^+)$



- The K^+ recoil-mass spectrum in data at 4.681GeV.
- Combinatorial backgrounds are subtracted.
- A structure next to threshold raging from 3.96 to 4.02GeV/c^2.
- The enhancement cannot be attributed to the non-resonant (NR) signal process $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$.

Check with high excited D_s^{**} states



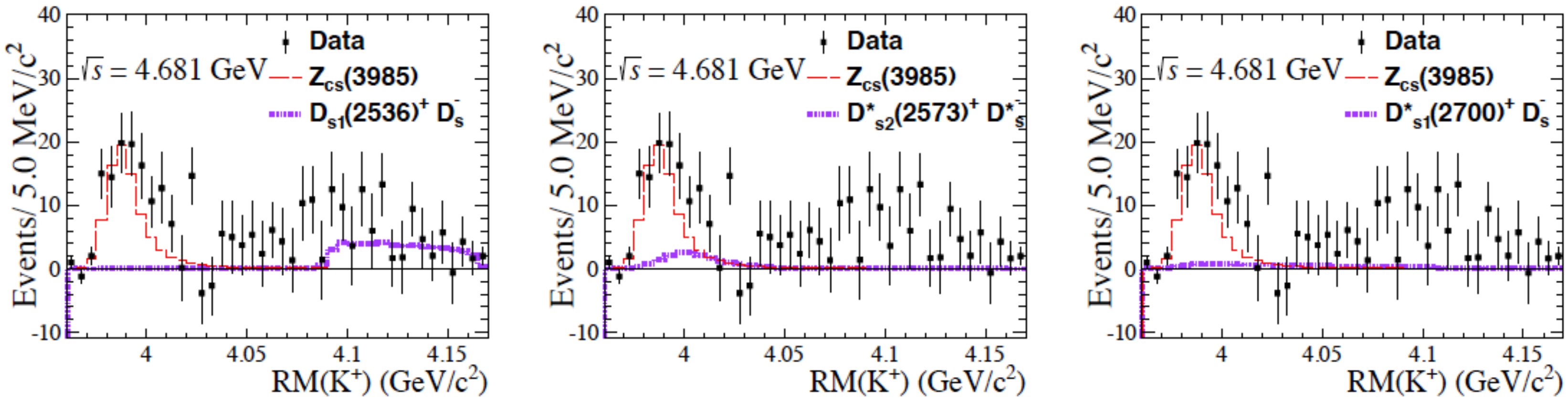


D_s^{**+}	mass(MeV/c²)	width(MeV)	J^P	$D_s^{**+}(K^+D^{*0})D_s^-$	$D_s^{**+}(K^+D^0)D_s^{*-}$
$D_{s1}(2536)^+$	2535.11±0.06	0.92±0.05	1⁺	(*) Fixed in nominal fitting	Parity Violation in decay
$D_{s2}^*(2573)^+$	2569.1±0.8	16.9±0.7	2⁺	Not decay to KD*	(*) Fixed in nominal fitting
$D_{s1}^*(2700)^+$	$2708.3^{+4.0}_{-3.4}$	120±11	1⁻	(*) Fixed in nominal fitting	Q=-139.3MeV P-wave suppression in production.
$D_{s1}^*(2860)^+$	2859±27	159±80	1⁻	(*)less contribution than $D_{s1}^*(2700)^+$; Q=-146MeV.	Q=-290MeV; P-wave suppression in production.
$D_{s3}^*(2860)^+$	2860±7	53±10	3⁻	(*)F-wave suppression; Q=-147MeV	Q=-291MeV

• $D_s^\pm$	$0(0^-)$
• $D_s^{*\pm}$	$0(?^?)$
• $D_{s0}^*(2317)^\pm$	$0(0^+)$
• $D_{s1}(2460)^\pm$	$0(1^+)$
• $D_{s1}(2536)^\pm$	$0(1^+)$
• $D_{s2}^*(2573)$	$0(2^+)$
• $D_{s1}^*(2700)^\pm$	$0(1^-)$
$D_{s1}^*(2860)^\pm$	$0(1^-)$
$D_{s3}^*(2860)^\pm$	$0(3^-)$
$D_{sJ}(3040)^\pm$	$0(?^?)$

- Most high excited D_s^{**} states have negative Q value or forbidden due to Parity Violation.
- $D_{s1}^*(2536)^+(K^+D^{*0})D_s^-$, $D_{s2}^*(2573)^+(K^+D^0)D_s^{*-}$ and $D_{s1}^*(2700)^+(K^+D^{*0})D_s^-$ are studied using control sample.
- Most high excited $D_{(s)}^{**}$ states contribute a broad peak around 4 GeV which could not describe the enhancement in $RM(K^+)$.

Check with high excited D_s^{**} states



(a) $D_{s1}(2536)^+(\to D^{*0}K^+)D_s^-$ (b) $D^*_{s2}(2573)^+(\to D^0K^+)D_s^{*-}$ (c) $D^*_{s1}(2700)^+(\to D^{*0}K^+)D_s^-$

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

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

$$\frac{\mathcal{B}(D^*_{s1}(2700)^+ \to D^{*0}K^+)}{\mathcal{B}(D^*_{s1}(2700)^+ \to D^0K^+)} = 0.91 \pm 0.18,$$

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

BaBar_PhysRevD.80.092003(2009)

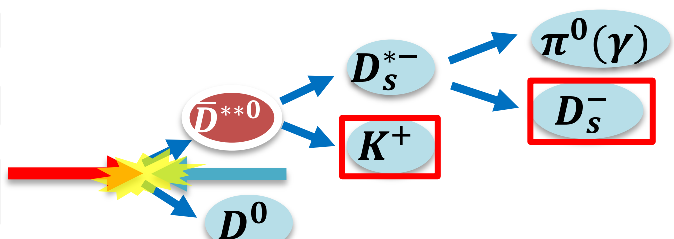
$\sqrt{s}$(GeV)	4.628	4.641	4.661	4.681	4.698
$D_{s1}(2536)^+(K^+D^{*0})D_s^-$	41.2 ± 6.3	26.2 ± 5.4	23.9 ± 5.6	54.4 ± 8.0	15.3 ± 4.2
$D^*_{s2}(2573)^+(K^+D^0)D_s^{*-}$	–	–	–	19.1 ± 7.6	17.3 ± 7.3
$D^*_{s1}(2700)^+(K^+D^{*0})D_s^-$	0.0 ± 1.8	18.6 ± 8.7	16.6 ± 7.8	15.0 ± 13.3	7.7 ± 8.4

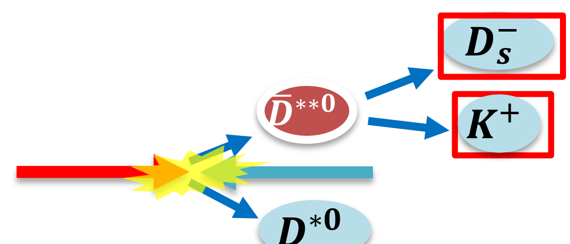
- The estimated sizes of excited D_s^{**} contributions at each energy point.
- "-" means the production is not allowed kinematically.

Check with high excited $\bar{D}^{**0}$ states

$\bar{D}^{**0}$	mass(MeV/c²)	width(MeV)	J^P	$\bar{D}^{**0}(K^+D_s^{*-})D^0$	$\bar{D}^{**0}(K^+D_s^-)D^{*0}$
$\bar{D}_1(2430)^0$	2427 ± 40	384^{+130}_{-110}	1^+	below KDs* threshold; Q=-72.22MeV soft Kaon	Parity Violation decay
$\bar{D}_2^*(2460)^0$	2460.7 ± 0.4	47.5 ± 1.1	2^+	below KDs* threshold; Q=-39.52MeV soft Kaon	(*)Test fit
$\bar{D}(2550)^0$	2564 ± 20	135 ± 17	0-	(*)Test fit	Parity Violation in decay
$\bar{D}_J^*(2600)^0$	2623 ± 12	139 ± 31	1^-	(*)Test fit	(*)Control sample & nominal fit
$\bar{D}^*(2640)^0$	2637 ± 6	<15	?	(*)Test fit	(*)Test fit
$\bar{D}(2740)^0$	2737 ± 12	73 ± 28	2^-	(*)Test fit	Parity Violation in decay
$\bar{D}_3^*(2750)^0$	2763 ± 3.4	66 ± 5	3-	(*)Control sample	P-wave suppressed. Q=-89.8MeV

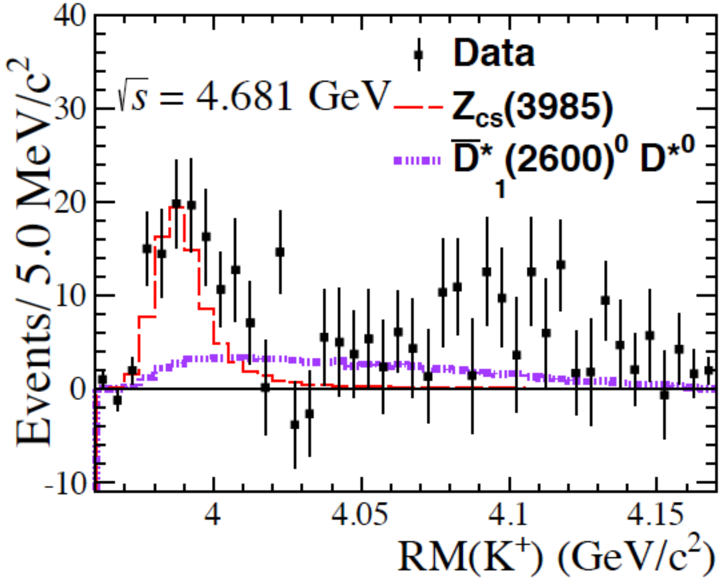
$D_1(2420)^\pm$	$1/2(?^?)$
$D_1(2430)^0$	$1/2(1^+)$
• $D_2^*(2460)^0$	$1/2(2^+)$
• $D_2^*(2460)^\pm$	$1/2(2^+)$
$D(2550)^0$	$1/2(?^?)$
$D_J^*(2600)$	$1/2(?^?)$
was $D(2600)$	
$D^*(2640)^\pm$	$1/2(?^?)$
$D(2740)^0$	$1/2(?^?)$
$D_3^*(2750)$	$1/2(3^-)$
$D(3000)^0$	$1/2(?^?)$





- ◆ $D(2640)$ is quite narrow and not confirmed by any high statistic experiment including LHCb.
- ◆ Most $\bar{D}^{**0}$ states are not favored from the check of test fit.=>Systematic uncertainties.

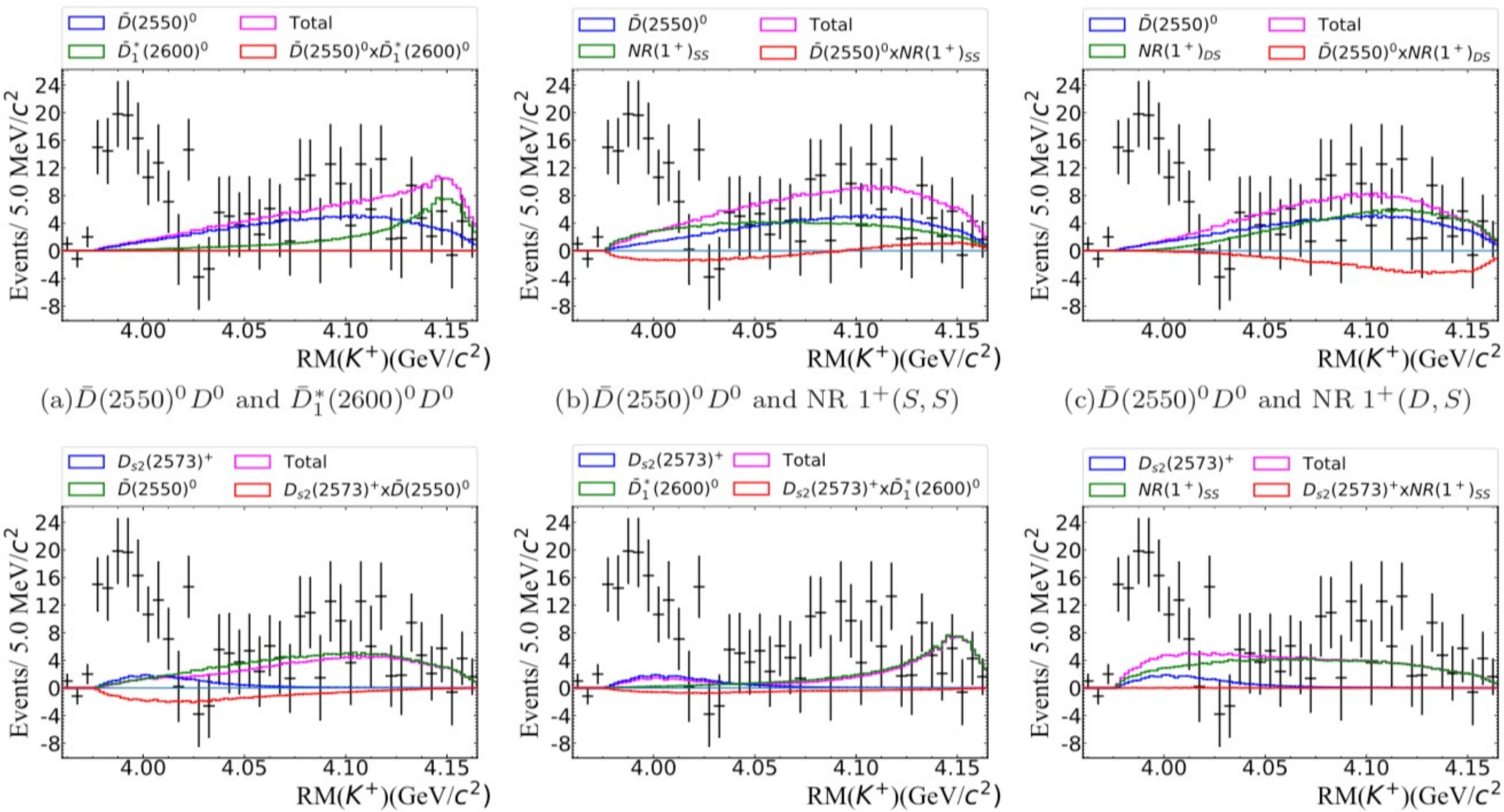
Check with high excited non-strange $\bar{D}_1^*(2600)^0$ states



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

- The $RM(K^+)$ spectrum is distorted due to limited production phase space. However, it is much broader than the observed enhancement.
- $e^+e^- \to D^{*0}\bar{D}_1^*(2600)^0(\to D_s^- K^+)$ is studied using an PWA of control sample $e^+e^- \to D^{*0}\bar{D}_1^*(2600)^0(\to D^-\pi^+)$.
- The ratio R= $B(\bar{D}_1^*(2600)^0 \to D_s^- K^+)/B(\bar{D}_1^*(2600)^0 \to D^-\pi^+)$ is unknown.
  => difficult to produce absolute size.
- Determine the ratio in nominal simultaneous fit, providing constraint on its size.

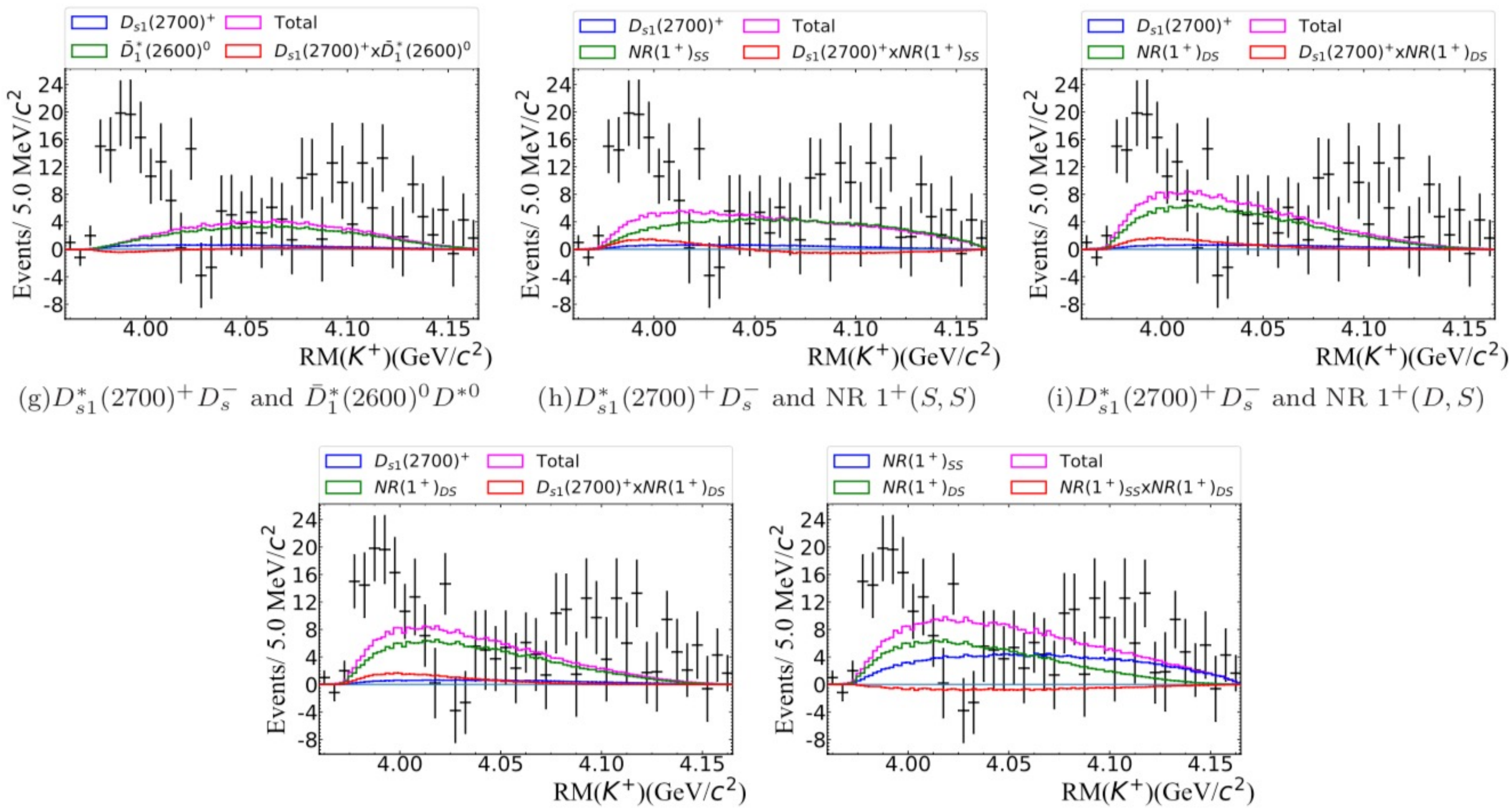
Interference effect of $K^+ D_s^{*-} D^0$ final states (1)



(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 $1^+(S, S)$

- Data subtracted with WS backgrounds.
- Any two MC simulated backgrounds with interferences are taken into account.
- The interference angle is tuned to give the largest interference effect around 4.0GeV/c^2.

Interference effect of $K^+ D_s^- D^{*0}$ final states (2)



(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 $1^+(D,S)$

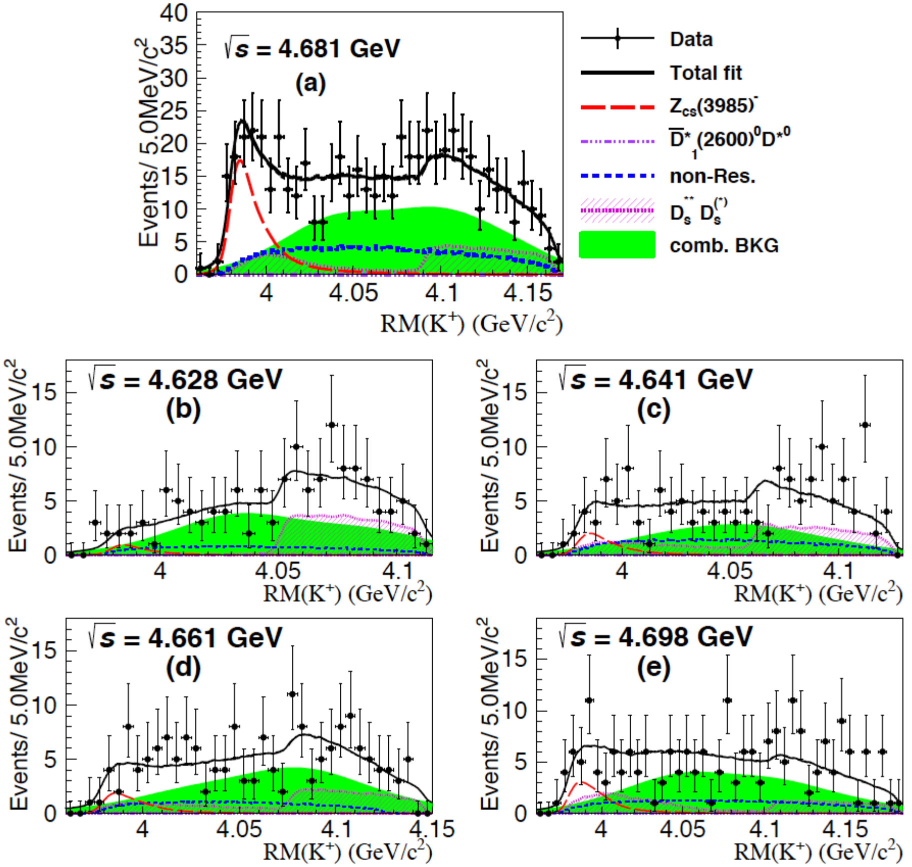
(k)NR $1^+(S,S)$ and NR $1^+(D,S)$

Interference between any two $D_{(s)}^{**}$/NR will not produce such a narrow peak we observed in data.

What do we studied?

- Do you clearly see $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$ events? **Yes**
- Can the WS shape represent the combinatorial backgrounds? **Yes**
- Do you see an excess of data over the backgrounds? **Yes**
- Is the enhancement due to the $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$ non-resonant process? **NO**
- Is the enhancement due to the $D_{(s)}^{**}$ resonant process? **NO**
- Is the enhancement due to interference effect between any $D_{(s)}^{**}$/NR? **NO**
- Can we try the assumption of $e^+e^- \to K^+ Z_{cs}^-, Z_{cs}^- \to D_s^- D^{*0} / D_s^{*-} D^0$ to interpret it? **Yes, we could.**

Study of recoil-mass spectra of K^+



Resonance parameter:

$m_0(Z_{cs}(3985)^-) = 3985.2^{+2.1}_{-2.0}(stat.)$ MeV/c²;

$\Gamma_0(Z_{cs}(3985)^-) = 13.8^{+8.1}_{-5.2}(stat.)$MeV.

- Assume the structure as a $D_s^- D^{*0}/D_s^{*-} D^0$ resonance, denote it as $Z_{cs}(3985)^-$.
- Simultaneous unbinned maximum likelihood fit to five energy points.
- $Z_{cs}(3985)^-$ signal shape: S-wave Breit-Wigner with mass dependent width with phase-space factor.

$$\boxed{\mathcal{F}_j(M) \propto \left| \frac{\sqrt{q \cdot p_j}}{M^2 - m_0^2 + i m_0 (f \Gamma_1(M) + (1-f)\Gamma_2(M))} \right|^2}$$

$$\boxed{\Gamma_j(M) = \Gamma_0 \cdot \frac{p_j}{p_j^*} \cdot \frac{m_0}{M}}$$

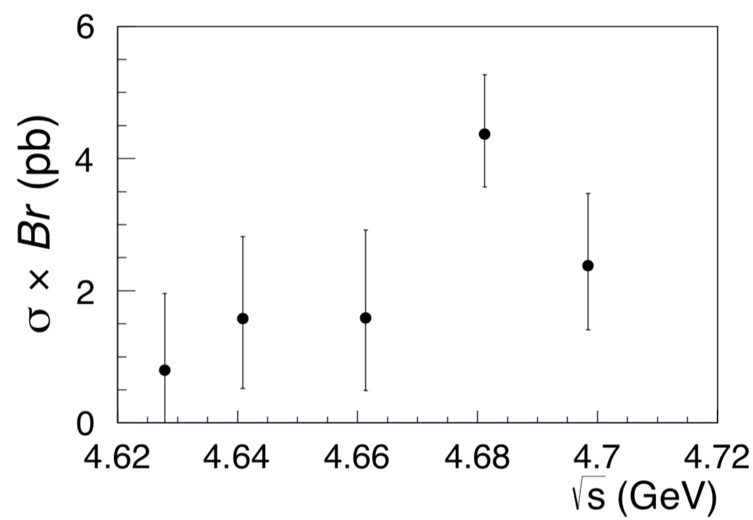
- The potential interference effects are neglected.
- The J^P of $Z_{cs}(3985)^-$ is assumed as 1^+; =>(S,S) is the most promising configuration.
- The significance with systematic uncertainties and look-elsewhere effect considered is evaluated to 5.3σ.
- $e^+e^- \to D^{*0}\bar{D}_1^*(2600)^0(\to D_s^- K^+)$ is fitted to be negligible.

Cross-section measurement at each energy point

- Born cross section:

$$\sigma^{Born}(e^+e^- \to K^+Z_{cs}^- + c.c.) \cdot \mathfrak{B}\big(Z_{cs}^- \to (D_s^- D^{*0} + D_s^{*-} D^0)\big)$$
$$= \frac{N_{obs}}{\mathcal{L}_{int}\cdot(1+\delta)\cdot f_{vp}\cdot(\tilde{\epsilon}_1+\tilde{\epsilon}_2)/2}.$$

$\sqrt{s}$(GeV)	$\mathcal{L}_{\rm int}$(pb^{-1})	$n_{\rm sig}$	$f_{\rm corr}\bar{\varepsilon}$(%)	$\sigma^B \cdot \mathcal{B}$ (pb)
4.628	511.1	$4.2^{+6.1}_{-4.2}$	1.03	$0.8^{+1.2}_{-0.8} \pm 0.6\,(<3.0)$
4.641	541.4	$9.3^{+7.3}_{-6.2}$	1.09	$1.6^{+1.2}_{-1.1} \pm 1.3\,(<4.4)$
4.661	523.6	$10.6^{+8.9}_{-7.4}$	1.28	$1.6^{+1.3}_{-1.1} \pm 0.8\,(<4.0)$
4.681	1643.4	$85.2^{+17.6}_{-15.6}$	1.18	$4.4^{+0.9}_{-0.8} \pm 1.4$
4.698	526.2	$17.8^{+8.1}_{-7.2}$	1.42	$2.4^{+1.1}_{-1.0} \pm 1.2\,(<4.7)$



- Uncertainty is quite large,

- Any Y states around 4.68GeV?

Systematics uncertainties

TABLE III. Summary of systematic uncertainties on the $Z_{cs}(3985)^-$ resonance parameters and cross sections at $\sqrt{s}$=4.628, 4.641, 4.661, 4.681 and 4.698 GeV. The total systematic uncertainty corresponds to a quadrature sum of all individual items. "…" signifies that the uncertainty is negligible.

Source	Mass (MeV/c^2)	Width (MeV)	$\sigma_{4.628}\cdot\mathcal{B}(\%)$	$\sigma_{4.641}\cdot\mathcal{B}(\%)$	$\sigma_{4.661}\cdot\mathcal{B}(\%)$	$\sigma_{4.681}\cdot\mathcal{B}(\%)$	$\sigma_{4.698}\cdot\mathcal{B}(\%)$
Tracking			3.6	3.6	3.6	3.6	3.6
Particle ID			3.6	3.6	3.6	3.6	3.6
K_S^0			0.4	0.4	0.4	0.4	0.4
$RM(K^+D_s^-)$	…	…	4.0	0.3	0.4	0.6	0.2
Mass scale	0.5						
Resolution	0.2	1.0	0.2	1.0	1.9	1.1	0.8
f factor	0.2	1.0	7.8	7.7	6.7	6.4	5.9
Signal model	1.0	2.6	20.5	14.4	16.6	21.9	11.2
Backgrounds	0.5	0.5	54.8	5.9	12.0	3.1	7.8
Efficiencies	0.1	0.2	0.2	0.2	0.2	0.5	0.1
$D_{(s)}^{**}$ states	1.0	3.4	47.1	82.2	35.3	15.7	35.3
$\sigma^B(K^+Z_{cs}(3985)^-)$	0.6	1.7	11.9	5.7	22.1	13.4	32.1
Luminosity			1.0	1.0	1.0	1.0	1.0
Input BFs			2.7	2.7	2.7	2.7	2.7
total	1.7	4.9	76.8	84.5	47.3	31.5	50.3

Resonance parameter:

$$m_0(Z_{cs}(3985)^-) = 3985.2^{+2.1}_{-2.0}(stat.) \pm 1.7(sys.)\mathrm{MeV/c^2},$$

$$\Gamma_0(Z_{cs}(3985)^-) = 13.8^{+8.1}_{-5.2}(stat.) \pm 4.9(sys.)\mathrm{MeV}.$$

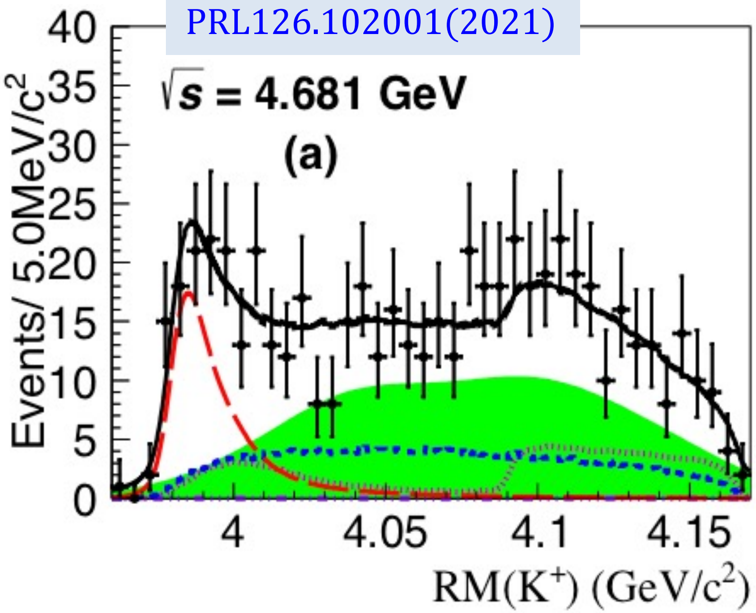
Pole position:

$$m_{pole}(Z_{cs}(3985)^-) = 3982.5^{+1.8}_{-2.6}(stat.) \pm 2.1(sys.)\mathrm{MeV/c^2},$$

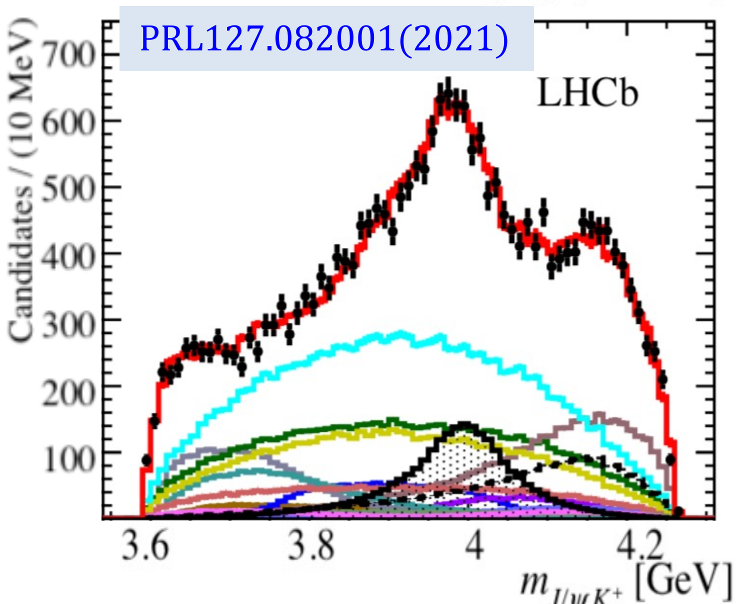
$$\Gamma_{pole}(Z_{cs}(3985)^-) = 12.8^{+5.3}_{-4.4}(stat.) \pm 3.0(sys.)\mathrm{MeV}.$$

$Z_{cs}(3985)^-$ and $Z_{cs}(4000)^-$

PRL126.102001(2021)



PRL127.082001(2021)



$m_0(Z_{cs}(3985)^-) = 3985.2^{+2.1}_{-2.0}(stat.) \pm 1.7(sys.)\ MeV/c^2$

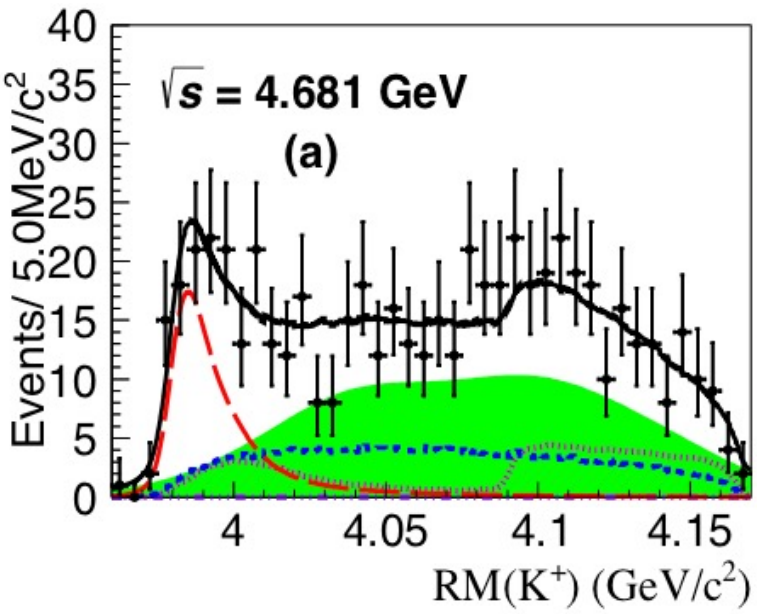
$\Gamma_0(Z_{cs}(3985)^-) = 13.8^{+8.1}_{-5.2}(stat.) \pm 4.9(\text{sys.})MeV.$

$m_0(Z_{cs}(4000)^-) = 4003 \pm 6(stat.)^{+4}_{-14}\ (sys.)\ \text{MeV/c}^2$

$\Gamma_0(Z_{cs}(4000)^-) = 131 \pm 15(stat.) \pm 26(\text{sys.})\text{MeV}.$

- Could $Z_{cs}(3985)^-$ and $Z_{cs}(4000)^-$ are the same state? =>Mass consistent within 1σ while width differs significantly.
- A tetraquark state or a molecule-like? Or threshold kinematic effects ? Or other scenario?
- Study $D_s^- D^{*0}/D_s^{*-} D^0/\ K^+ J/\psi$ system from B decay in $\boldsymbol{e^+e^-}$ annihilation are needed.
  =>No clear structure from Belle study in $\boldsymbol{e^+e^-} \to\ K^+K^-J/\psi$ PRD89, 072015 (2014).

Discussion on $Z_{cs}(3985)^{-}$

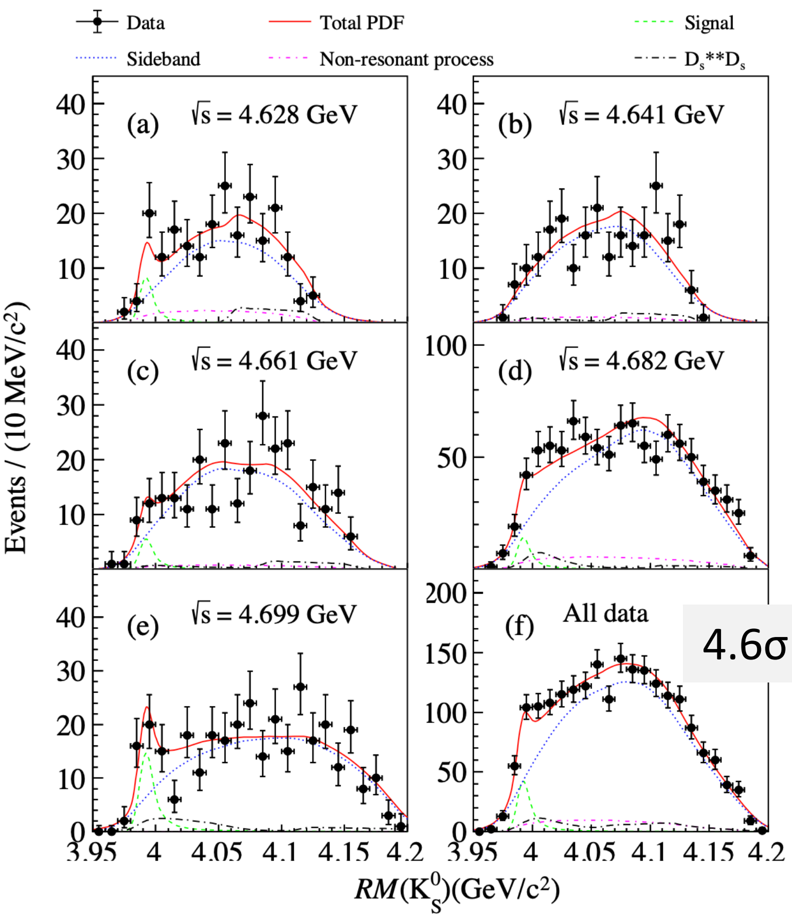


- Only a few MeV higher than the threshold of $D_s^- D^{*0}/D_s^{*-}D^0$ (3975.2/3977.0)MeV/c^2.
- At least four quark state (***$c\bar{c}s\bar{u}$***) and a charged hidden-charm state with strangeness.

- They are observed in a combination of $D_s^- D^{*0}$ and $D_s^{*-}D^0$ final states.
- The production is dominated at $\sqrt{s} = 4.681$ GeV. Any Y contribution?
- A tetraquark state or a molecule-like? Or threshold kinematic effects ? Or other scenario?
- Search for other decay modes Z_{cs}^0/ Z_{cs}^{*-} can help to pin down its properties.

$Z_{cs}(3985)^0$

PRL129.112003(2022)



4.6σ

- $e^+e^- \to K_S^0(D_s^+ D^{*-} + D_s^{*+} D^-)$
- Similar technique, check in the recoil against K_S^0

$m_0(Z_{cs}(3985)^-) = 3985.2^{+2.1}_{-2.0}(stat.) \pm 1.7(sys.)\ MeV/c^2$

$\Gamma_0(Z_{cs}(3985)^-) = 13.8^{+8.1}_{-5.2}(stat.) \pm 4.9(\mathrm{sys.}) MeV.$

$m_0(Z_{cs}(3985)^0) = 3992.2 \pm 1.7(stat.) \pm 1.6(sys.)\ \mathrm{MeV/c^2}$

$\Gamma_0(Z_{cs}(3985)^0) = 7.7^{+4.1}_{-3.8}(stat.) \pm 4.3(\mathrm{sys.}) MeV$

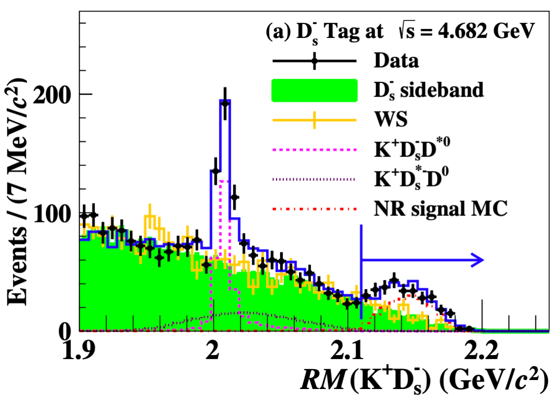
TABLE V. Born cross sections multiplied by branching fraction of $\bar{K}^0 Z_{cs}(3985)^0$ and $K^- Z_{cs}(3985)^+$ at the five energy points. The χ^2/ndf quantifies the compatibility of the five measurements.

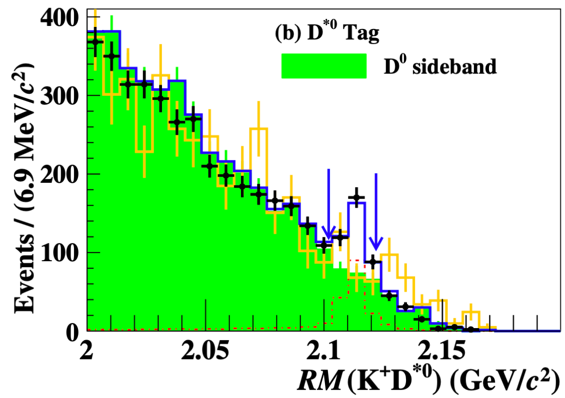
	$\sigma^{\mathrm{Born}} \times \mathcal{B}$(pb)			
$\sqrt{s}$ (MeV)	$\bar{K}^0 Z_{cs}(3985)^0$	$K^- Z_{cs}(3985)^+$	χ^2	χ^2_{total}/ndf
4628	$4.4^{+2.6}_{-2.2} \pm 2.0$	$0.8^{+1.2}_{-0.8} \pm 0.6$	1.2	
4641	$0.0^{+1.6}_{-0.0} \pm 0.2$	$1.6^{+1.2}_{-1.1} \pm 1.3$	0.5	
4661	$2.8^{+1.8}_{-1.6} \pm 0.6$	$1.6^{+1.3}_{-1.1} \pm 0.8$	0.3	5.1/5
4682	$2.2^{+1.2}_{-1.0} \pm 0.8$	$4.4^{+0.9}_{-0.8} \pm 1.4$	1.0	
4699	$7.0^{+2.2}_{-2.0} \pm 1.8$	$2.4^{+1.1}_{-1.0} \pm 1.2$	2.1	

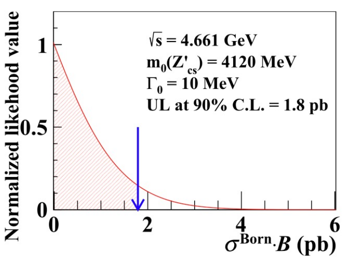
We conclude $Z_{cs}(3985)^0$ is the isospin partner of the $Z_{cs}(3985)^+$

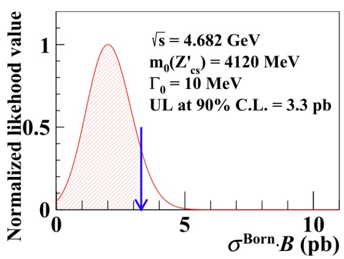
The charged Z'^{-}_{cs}

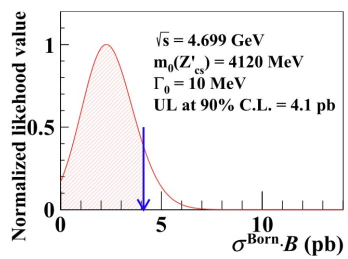
Chin. Phys. C 47, 033001 (2023)

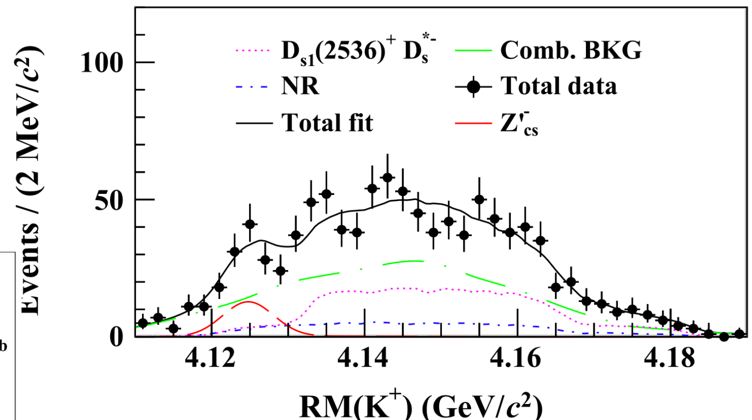










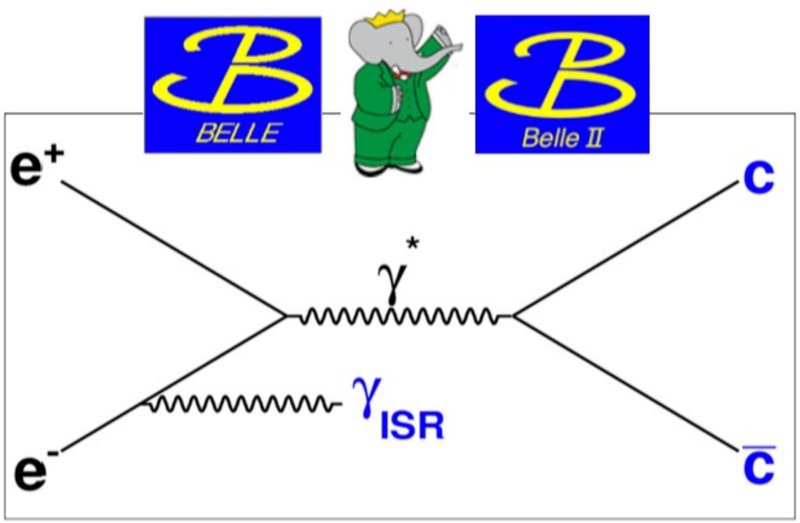


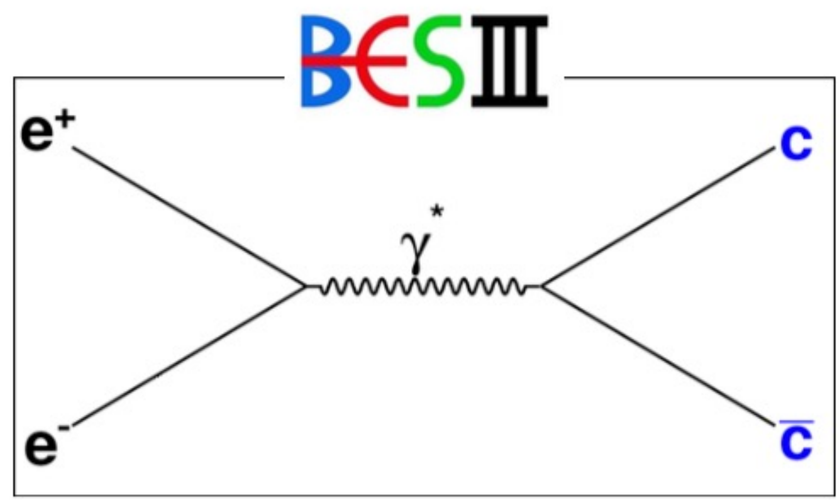
- Search for excited partner of $Z_{cs}(3985)^+$ in $e^+e^- \to K^+D_s^{*-}D^{*0}+c.c.$
- Two different tag-methods (D_s^--tag and D^{*0}-tag) are adopted.
- Evidence for Z'^{-}_{cs} state $M(Z'^{-}_{cs}) = 4123.5 \pm 0.7(stat.) \pm 4.7(sys.)$ MeV/c^2
- Significance is 2.1σ (3.9σ) w/o considering systematic uncertainties.
- Statistics limited, decay width hypotheses are tested.

  $=> M(Z'^{-}_{cs}) = 4124.1$MeV/$c^2$ under 10MeV decay width with local significance 4.1σ.
- Cross section upper limit @C.L.90% are estimated to $\mathcal{O}(1)$ pb.

The Y states

Measurements of more final states for the Y and ψ states

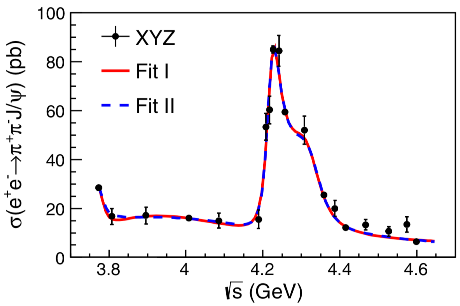




Y(4220)

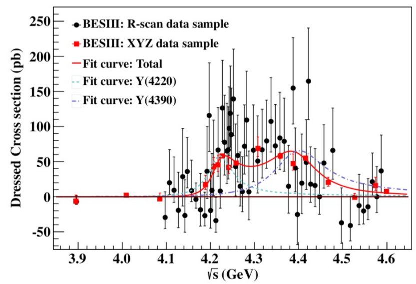
PRL.118.092001(2017)

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



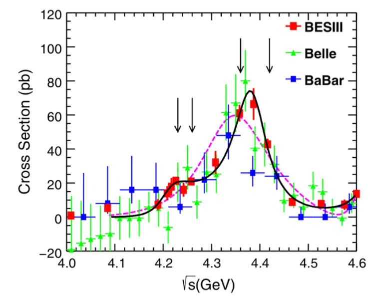
PRL.118.092002(2017)

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



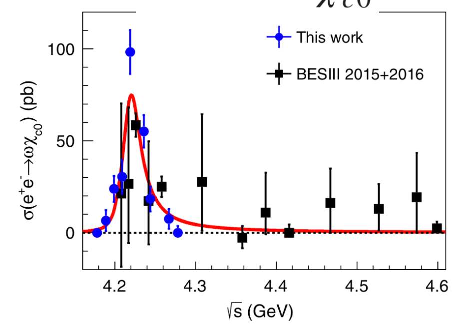
PRD.96.032004(2017)

$e^+e^- \to \pi^+\pi^- \psi(3686)$

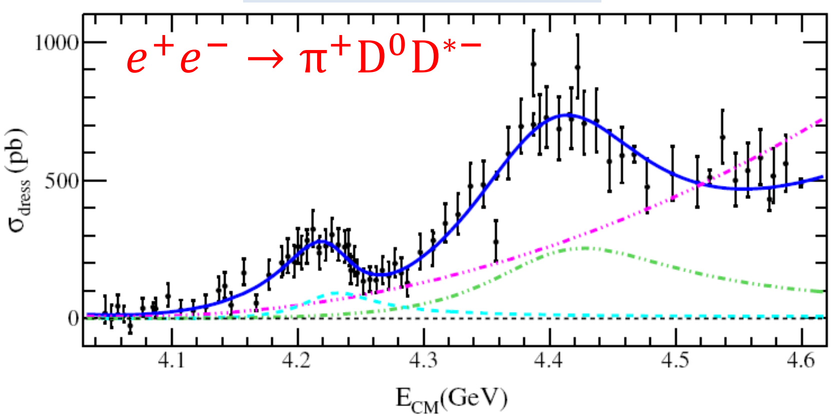


PRD.99. 091103(2019)

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



PRL. 122, 102002 (2019)



Y(4220) appeared in above processes.
Mass:4220MeV, Width~60 MeV!

- Y(4260) has been discovered by BaBar experiment in the mass spectrum m($\pi^+\pi^- J/\psi$) and confirmed by Belle.
- BESIII measured the cross section of different processes.
- The mass and width of Y(4220) and Y(4360) from the different processes are measured.
- Two resonances describe the data with high significance than the fit with single peak.
- The intrinsic scenario for the difference on width is still unknown.

Recent progress on Y studies at BESIII

$e^+e^- \to \pi^0\pi^0 J/\psi$ PRD.102.012009(2020)

$e^+e^- \to \eta J/\psi$ PRD.102.031101(RC)(2021)

$e^+e^- \to \eta' J/\psi$ PRD101.012008(2020)

$e^+e^- \to \eta_c \pi^+\pi^-\pi^0$ PRD103.032006(2021)

$e^+e^- \to K^+K^- J/\psi$ Chin. Phys. C 46, 111002 (2022)

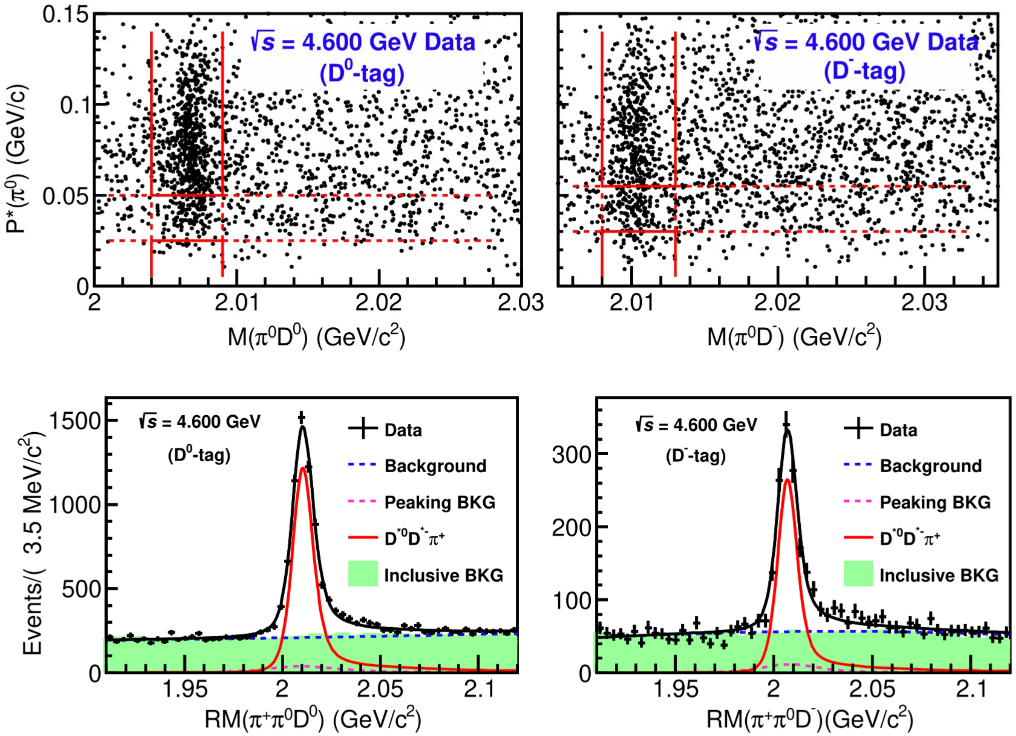
$e^+e^- \to \pi^+\pi^- D^+D^-$ PRD106.052012(2022)

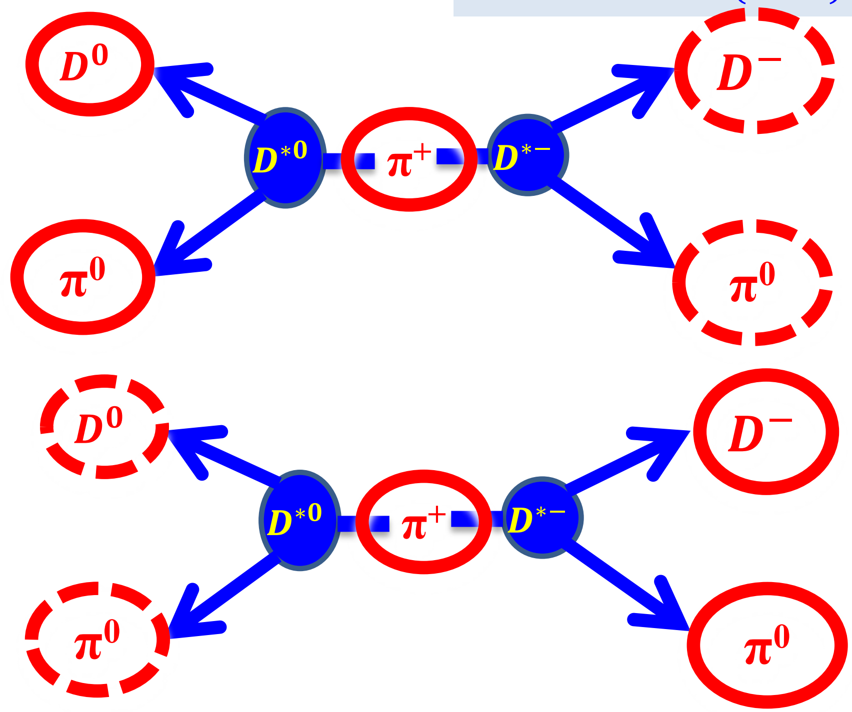
$e^+e^- \to D^{*+}D^{*-}$、 $D^{*+}D^-$ JHEP05.155(2022)

Y(4220) couple to hidden-charm final states more easier?

Cross section of $e^+e^- \to D^{*0}D^{*-}\pi^+$

PRL130.121901(2023)

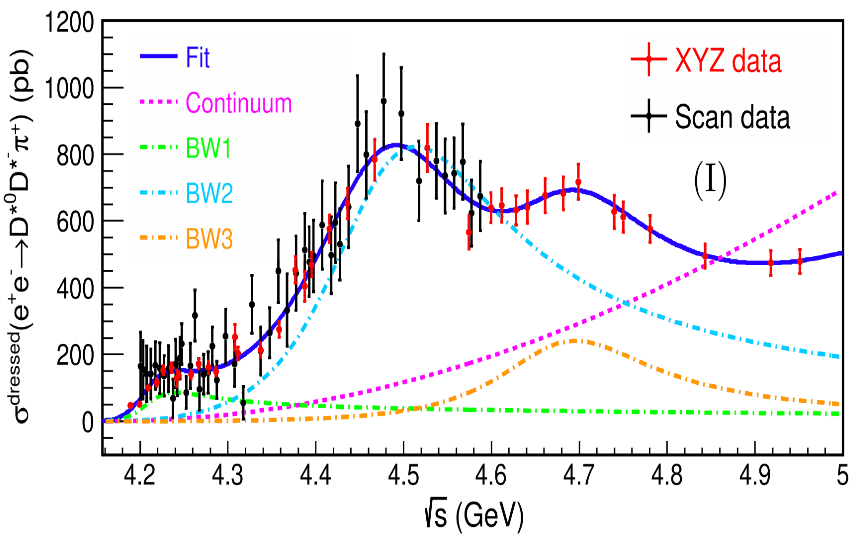




- Similar technique is adopted with the paper on $Z_c(4025)^+$ in $e^+e^- \to \pi^+D^{*0}D^{*-}+c.c.$
- Two different tag-methods (D^{*0}-tag and D^{*-}-tag) are simultaneously considered.
- Evident $e^+e^- \to \pi^+D^{*0}D^{*-}$ signals.
- No peaking background observed in background MC samples but some low level unmatched events from fake photon;

Three charmonium-like structures are observed in $D^{*0}D^{*-}\pi^{+}$

PRL130.121901(2023)



$m_1 = 4209.6 \pm 4.7 \pm 5.9\ \mathrm{MeV}/c^2$
$\Gamma_1 = 81.6 \pm 17.8 \pm 9.0\ \mathrm{MeV}$

$m_2 = 4469.1 \pm 26.2 \pm 3.6\ \mathrm{MeV}/c^2$
$\Gamma_2 = 246.3 \pm 36.7 \pm 9.4\ \mathrm{MeV}$

$m_3 = 4675.3 \pm 29.5 \pm 3.5\ \mathrm{MeV}/c^2$
$\Gamma_3 = 218.3 \pm 72.9 \pm 9.3\ \mathrm{MeV}$

- Cross section at 86 energy points are measured.
- Three charmonium-like structures found in $D^{*0}D^{*-}\pi^{+}$ final state(>10σ).
- Left and right structures consistent with Y(4230) and Y(4660)

  =>Disfavor hybrid interpretation of Y(4230). Same order with $D^{0}D^{*-}\pi^{+}$.

  =>First observation of Y(4660) in open charm final states.
- Center structure compatible with Y(4500) observed in K^+K^-J/ψ

  =>two order lager coupling, disfavor hidden-strangeness tetraquark nature

Summary

- **Lots of progress in the study charmonium like states at BESIII.**

- $Z_{cs}(3985)^-$ **was observed in** $\boldsymbol{e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)}$.
  - Strangeness-partner of $Z_c(3900)$?
  - The evidence of neutral Isospin partner $Z_{cs}(3985)^0$ is established.
  - High excited partner $Z_{cs}'^-$ is searched .

- **Cross section of** $e^+e^- \to D^{*0}D^{*-}\pi^+$ **are measured and three structure are observed.**

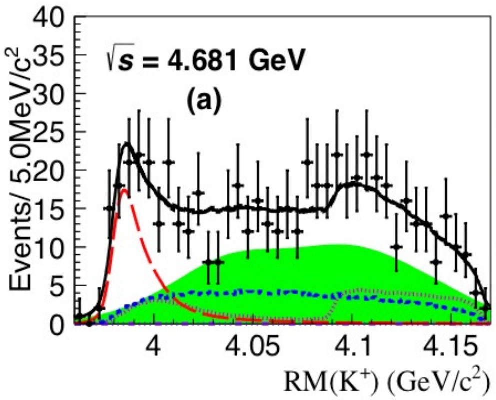
- **Unique data samples from 4.0 to 4.9GeV.**
  - Y stated above open charm threshold could be detailed studied.

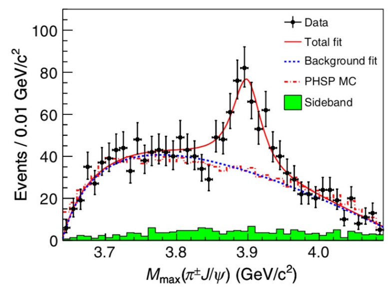
- **More analysis results on XYZ are in progress.**

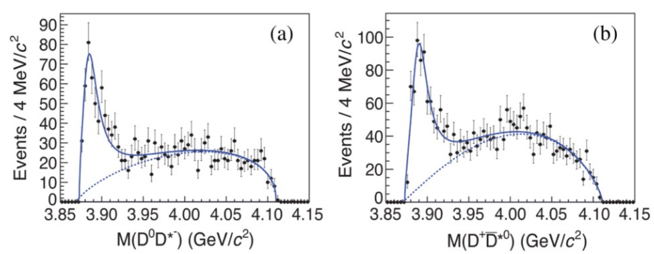
Thanks!

The Zcs (3985)$^{\pm}$ and Zc(3900)$^{\pm}$

	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
$\sigma^{Born} \cdot \mathfrak{B}$ (pb)	$4.4^{+0.9}_{-0.8} \pm 1.4$	13.5±2.1±4.8	83.5±6.6±22.0







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

from Marek Karliner

Z_{cs}(3985)

Z_c(3900)

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

neutral/charged = 1

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

neutral/charged = 1/2

SU(3) partner of Zc(3900)?

2011.08656

TABLE II. Numerical results for masses, widths and partial widths. We use "†" to label input. The ratios Γ_3/Γ_2 are estimated with central values of coupling constants. The lower limit of ratios Γ_i/Γ_1 are estimated with upper limits of v_{12}. M and Γ are in unites of MeV and Λ_i are in unites of GeV.

(M, Γ)	$Z_c(3900)$	$Z_c(4020)$	$Z_{cs}(3985)$	Z'_{cs}
Exp. [1, 47, 48]	$(3881.7 \pm 2.3, 26.6 \pm 2.9)^\dagger$	$(4026.3 \pm 4.5, 24.8 \pm 9.5)^\dagger$	$(3982.5^{+1.8}_{-2.6} \pm 2.1, 12.8^{+5.3}_{-4.4} \pm 3.0)$	
$\Lambda_{2/3} = 1.0$	$(3881.3 \pm 3.3, 26.3 \pm 6.1)$	$(4028.0 \pm 2.6, 28.0 \pm 6.5)$	$(3984.2 \pm 3.3, 27.6 \pm 7.3)$	$(4130.7 \pm 2.5, 29.1 \pm 6.4)$
	$\frac{\Gamma_2}{\Gamma_1} \gtrsim 13.7$	$\frac{\Gamma_3}{\Gamma_2} \approx 0.51,\ \frac{\Gamma_3}{\Gamma_1} \gtrsim 12.1$	$\frac{\Gamma_2}{\Gamma_1} \gtrsim 16.1$	$\frac{\Gamma_3}{\Gamma_2} \approx 0.48,\ \frac{\Gamma_3}{\Gamma_1} \gtrsim 13.7$
$\Lambda_{2/3} = 0.5$	$(3881.5 \pm 3.5, 26.4 \pm 5.8)$	$(4027.3 \pm 3.3, 27.0 \pm 6.7)$	$(3983.7 \pm 4.1, 26.7 \pm 5.8)$	$(4129.4 \pm 3.3, 27.3 \pm 9.2)$
	$\frac{\Gamma_2}{\Gamma_1} \gtrsim 11.2$	$\frac{\Gamma_3}{\Gamma_2} \approx 2.5,\ \frac{\Gamma_3}{\Gamma_1} \gtrsim 11.0$	$\frac{\Gamma_2}{\Gamma_1} \gtrsim 12.8$	$\frac{\Gamma_3}{\Gamma_2} \approx 2.3,\ \frac{\Gamma_3}{\Gamma_1} \gtrsim 11.6$

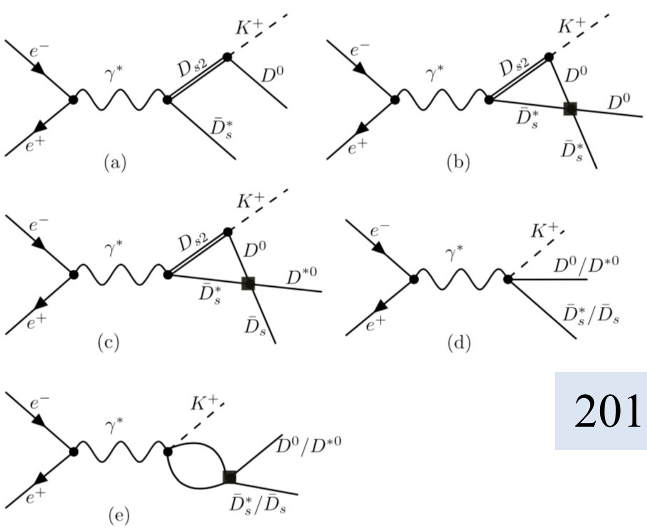
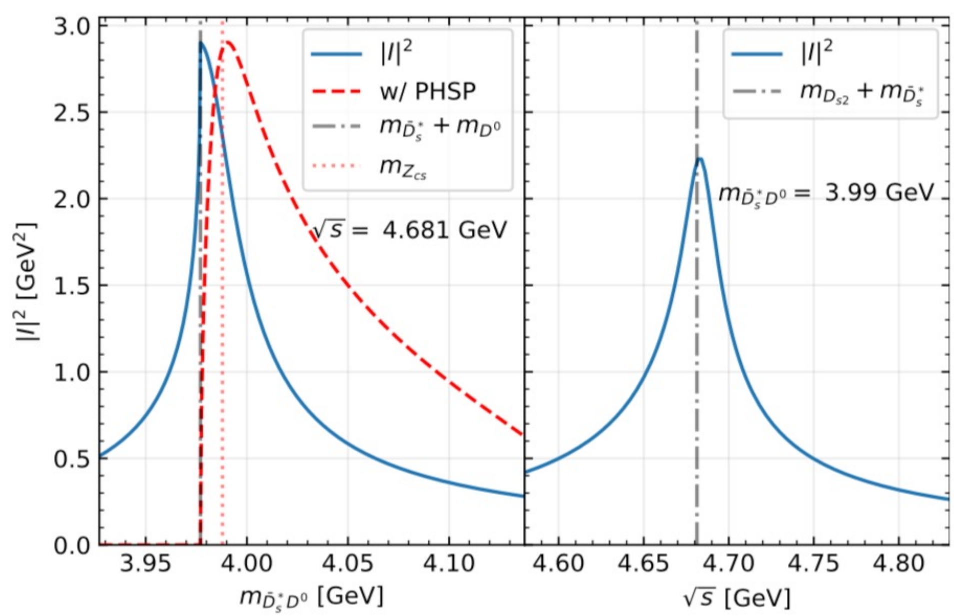


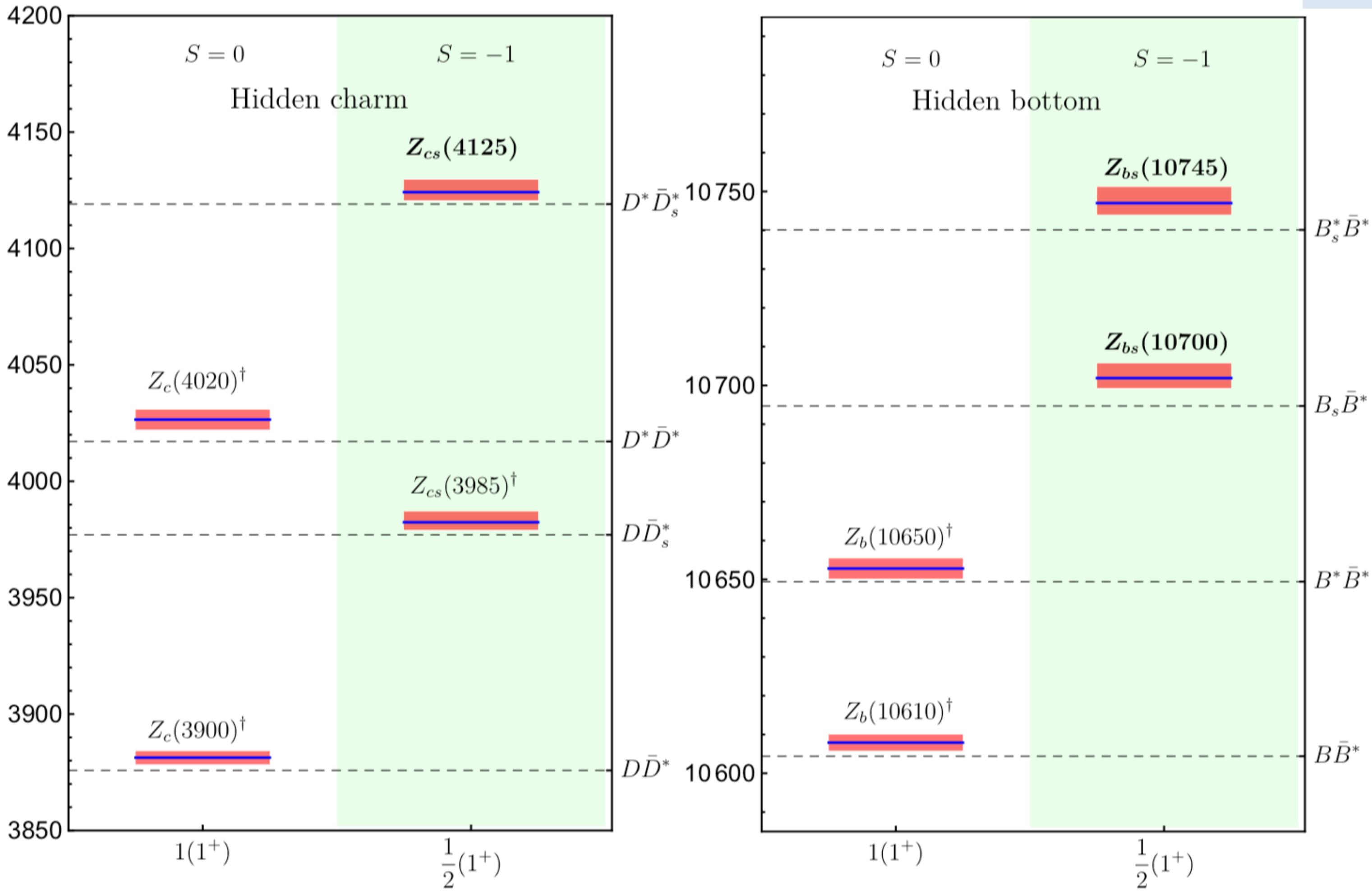
FIG. 1. Feynman diagrams for the production mechanisms considered in this work: (a) and (b) for the $K^+D_s^*\bar{D}^0$; (c) for the $K^+D_s\bar{D}^{*0}$; (d) and (e) for both final states. The filled squares denote the T-matrix elements which include the effects of the generated Z_{cs} state.

2011.08725

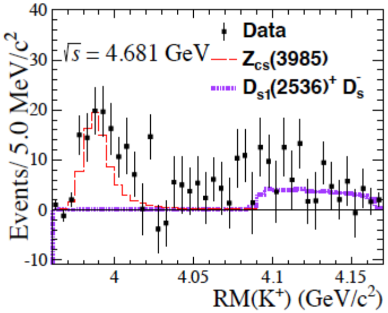


$Z_{c(s)}^{(\prime)}$ and $Z_{b(s)}^{(\prime)}$

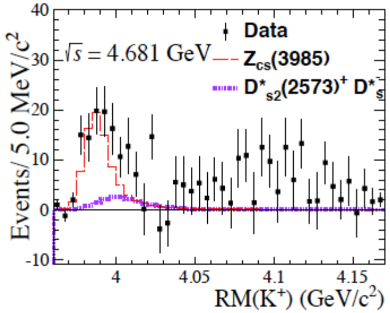
2011.10922



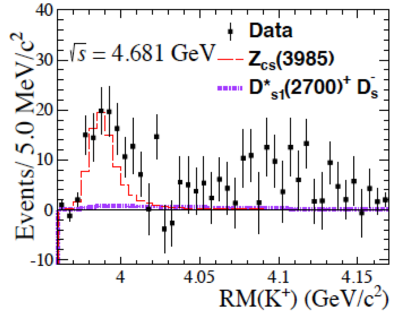
Check with high excited $D_{(s)}^{**}$ states



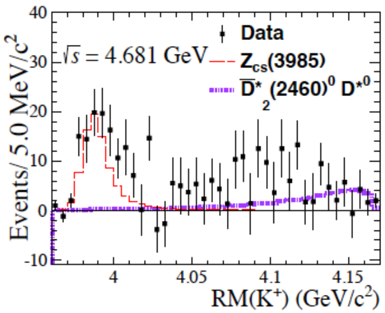
(a) $D_{s1}(2536)^{+}(\to D^{*0}K^{+})D_{s}^{-}$



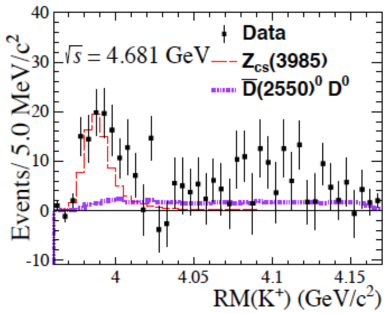
(b) $D_{s2}^{*}(2573)^{+}(\to D^{0}K^{+})D_{s}^{*-}$



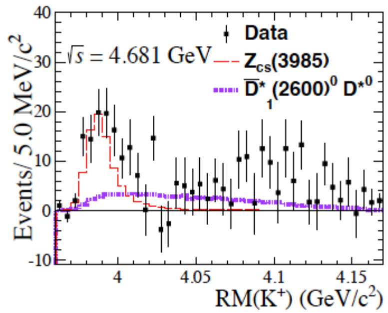
(c) $D_{s1}^{*}(2700)^{+}(\to D^{*0}K^{+})D_{s}^{-}$



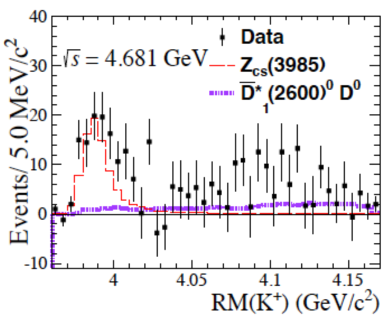
(a) $\bar{D}_{2}^{*}(2460)^{0}(\to D_{s}^{-}K^{+})D^{*0}$



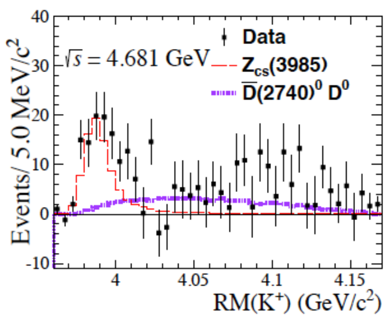
(b) $\bar{D}(2550)^{0}(\to D_{s}^{*-}K^{+})D^{0}$



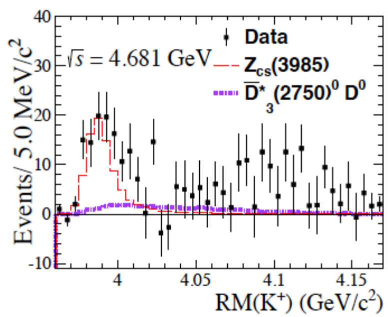
(c) $\bar{D}_{1}^{*}(2600)^{0}(\to D_{s}^{-}K^{+})D^{*0}$



(d) $\bar{D}_{1}^{*}(2600)^{0}(\to D_{s}^{*-}K^{+})D^{0}$



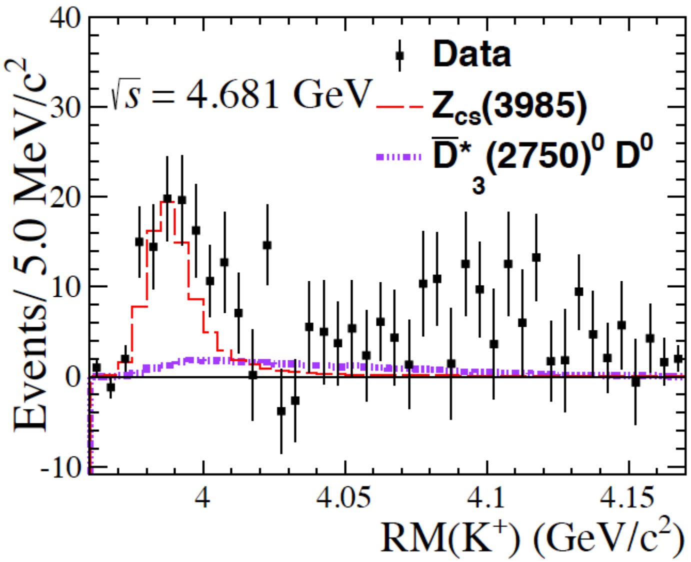
(e) $\bar{D}(2740)^{0}(\to D_{s}^{*-}K^{+})D^{0}$



(f) $\bar{D}_{3}^{*}(2750)^{0}(\to D_{s}^{*-}K^{+})D^{0}$

- Data subtracted with WS backgrounds.
- $Z_{cs}(3985)^{-}$ shapes are normalized to yields observed in data.
- D_{s}^{**} are scaled to the size determined by control sample.
- $\bar{D}^{**0}$ state shapes are arbitrary.
- **None of the excited $D_{(s)}^{**}$ can explain the narrow peaking structure.**

Check with high excited non-strange $\overline{D}_3^*(2750)^0$ states



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

- Study $D^0\overline{D}_3^*(2750)^0(\rightarrow D_s^{*-}K^+)$ by $e^+e^- \rightarrow D^0\overline{D}_3^*(2750)^0(\rightarrow D^- \pi^+)$.
- $B(\overline{D}_3^*(2750)^0 \rightarrow D_s^{*-}K^+)/\ B(\overline{D}_3^*(2750)^0 \rightarrow D^-\pi^+)$=4.1%

Godfrey_PhysRevD.93.034035(2016)

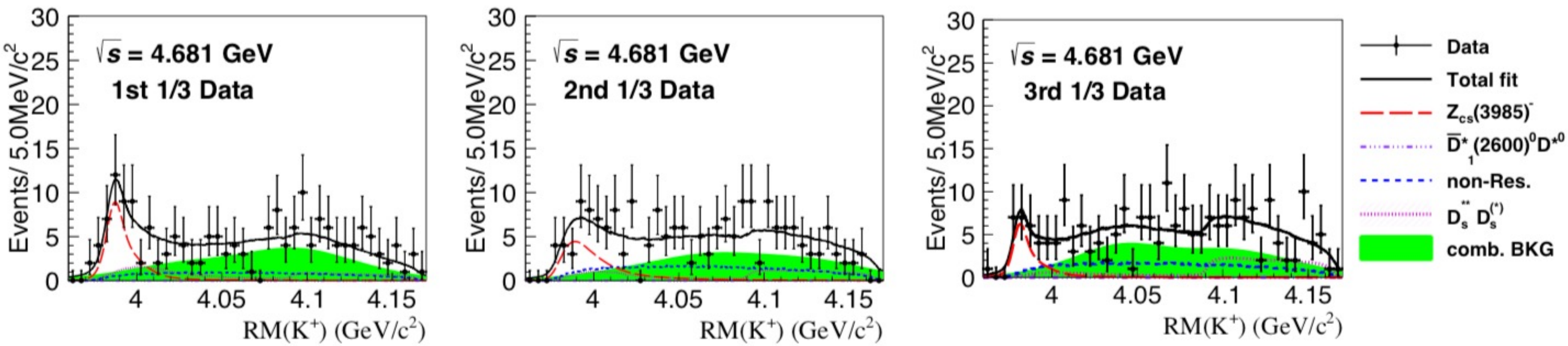
Initial state	Final state	Width (cu, cd) (MeV)	BR (cu, cd) (%)
$D(1^3D_3)$ 2833	$D(1^3P_2)\gamma$	0.69, 0.07	1.34, 0.14
	$D\pi$	20.1	39.2
	$D\rho$	1.30	2.5
	$D\eta$	1.24	2.4
	$D^*\pi$	15.5	30.2
	$D^*\rho$	7.56	14.8
	$D^*\omega$	1.1	2.2
	$D(1^3P_2)\pi$	0.9	1.8
	D_sK	1.1	2.20
	Total	51	100

$\sqrt{s}$(GeV)	4.628	4.641	4.661	4.681	4.698
$\bar{D}_3^*(2750)^0(\rightarrow D_s^{*-}K^+)D^0$	0.0 ± 0.1	0.0 ± 0.2	0.0 ± 0.2	0.0 ± 0.4	0.0 ± 0.5

- The estimated sizes of excited $\overline{D}_3^*(2750)$ contributions at each energy point is negligible.
- Both decay and production of $e^+e^- \rightarrow D^0\overline{D}_3^*(2750)^0(\rightarrow D_s^{*-}K^+)$is F-wave.

Fit results based on three subsets of data set at 4.681GeV

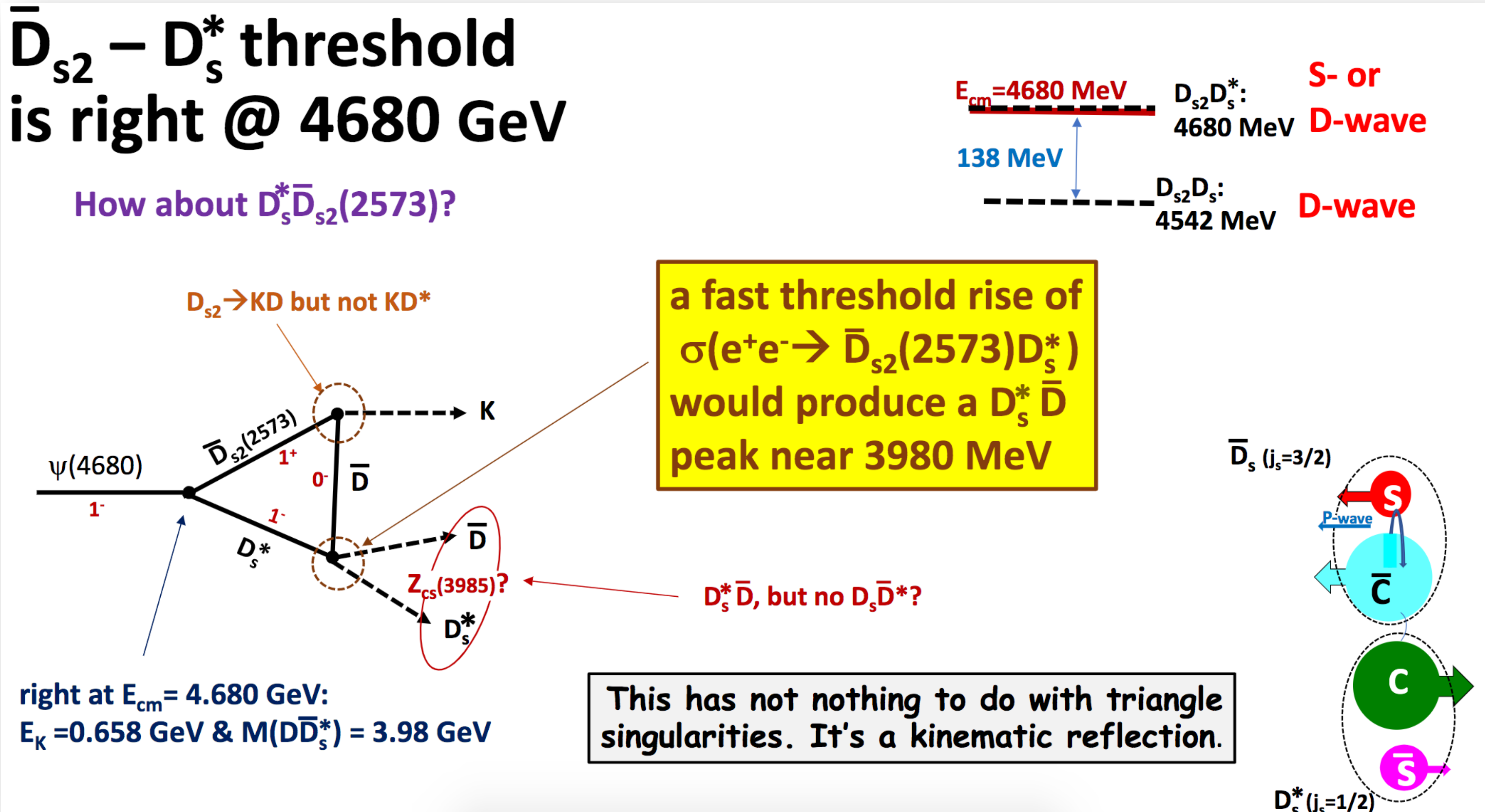
- Two-thirds of the data set at 4.681GeV was kept blinded until after the analysis strategy was established and validated.



Data set	Mass (MeV/c^2)	Width (MeV)	$\sigma_{4.681} \cdot \mathcal{B}$(pb)	Statistical Significance
1st one-third	$3987.0^{+2.1}_{-2.4}$	$6.9^{+6.1}_{-4.1}$	$5.1^{+1.4}_{-1.2}$	4.9σ
2nd one-third	$3990.2^{+5.6}_{-5.5}$	$24.2^{+31.0}_{-12.4}$	$5.0^{+2.3}_{-1.8}$	2.9σ
3rd one-third	$3980.9^{+2.0}_{-2.2}$	$4.7^{+9.9}_{-4.7}$	$2.8^{+1.2}_{-1.0}$	3.9σ
nominal	$3985.2^{+2.1}_{-2.0}$	$13.8^{+8.1}_{-5.2}$	$4.4^{+0.9}_{-0.8}$	6.3σ

- Overall, three sets of fit results are compatible.
- Structures are stable with respect to different data-taking periods.

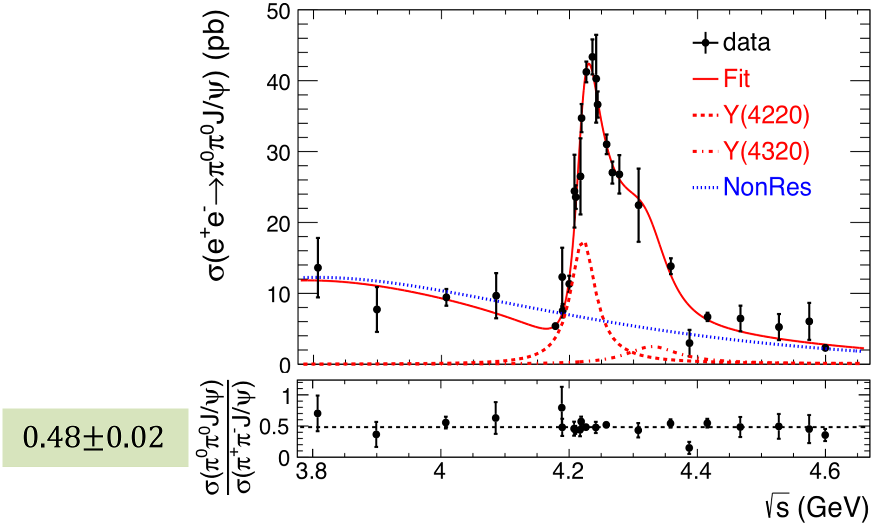
from Steve Olsen

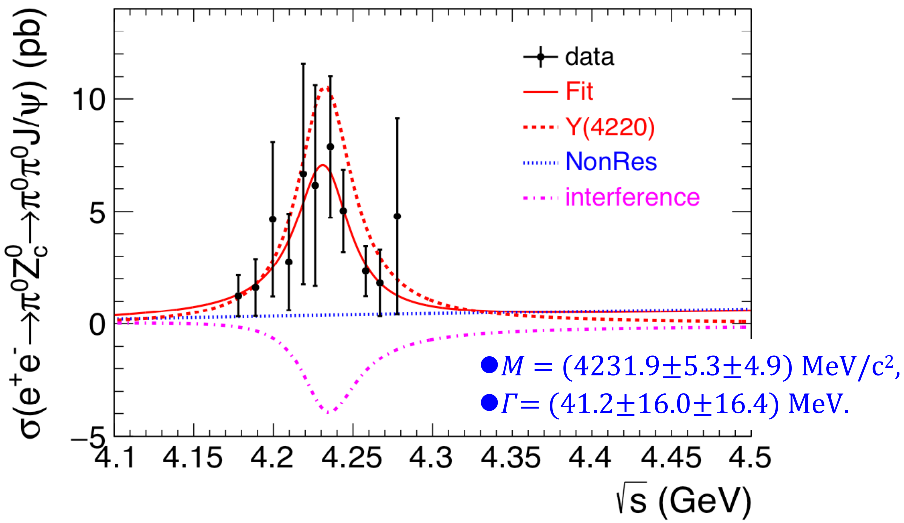


- We observer the Z_{cs} in both $D_s^* D$ and $D_s D^*$ modes, not only in $D_s^* D$.
- Our control sample of $D_s^* D_{s2}(2573)$ show it size is very small.
- Not in favor of this scenario.

Cross section of $e^+e^-\to\pi^0\pi^0 J/\psi$ and $e^+e^-\to\pi^0 Z_c(3900)^0$, $Z_c(3900)^0 \to\pi^0 J/\psi$

PhysRevD.102.012009(2020)

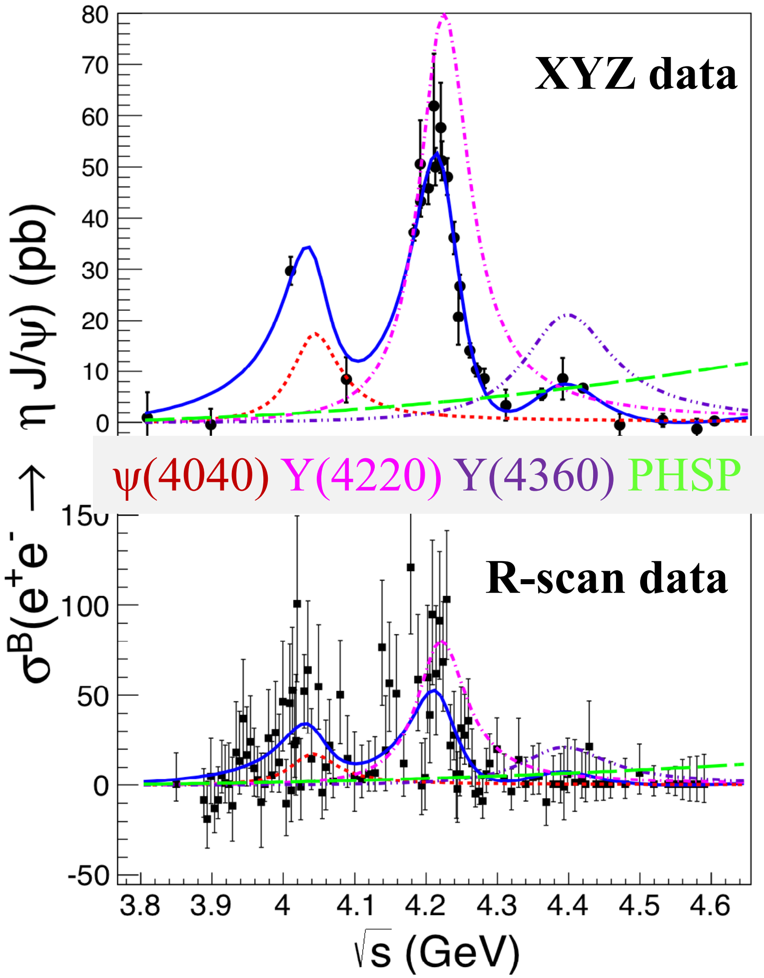




- Cross section of $e^+e^-\to\pi^0\pi^0 J/\psi$ is measured with 12.4fb^{-1} dataset between 3.808 to 4.6 GeV.
- Confirms the existence of the charmonium-like state Y(4220).
- Mass and width of Y(4320) are fixed at the reported value in PRL118.092001(2017).
- Mass and width of Y(4220) is consistent with $e^+e^-\to\pi^+\pi^- J/\psi$.
  - $M(\text{Y}(4220))$ = (4220.4±2.4±2.3) MeV/c^2,
  - Γ(Y(4220)) = (46.2±4.7±2.1) MeV.
- Strong correlation between the production of the Y(4220) and Z$_c$(3900).

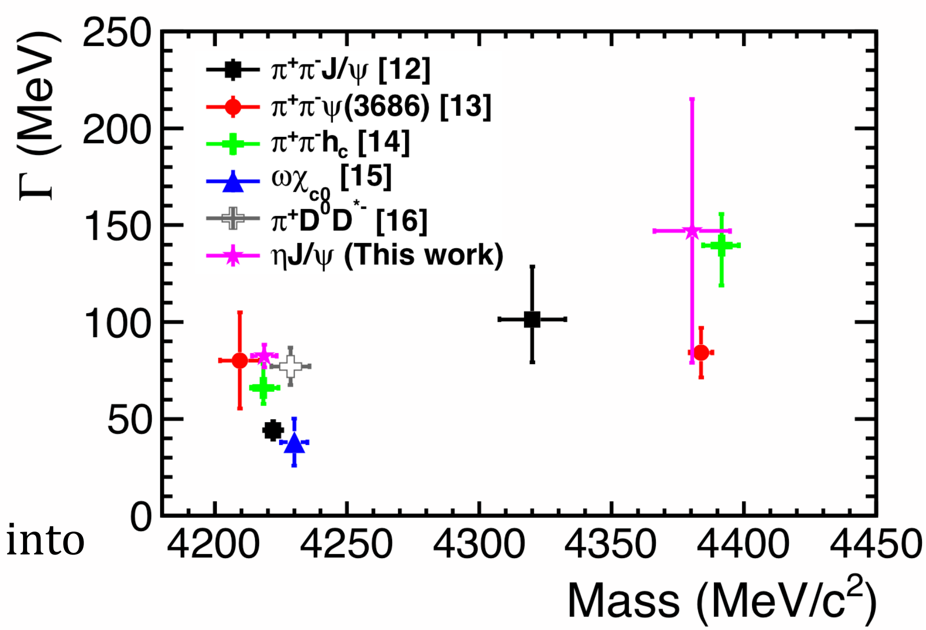
Cross section of $e^+e^- \to \eta J/\psi$

PhysRevD.102.031101(RC)(2021)



- Using data from center-of-mass 3.81 to 4.60GeV
- Assuming the lowest lying structure is the $\psi(4040)$.
- Consistent with those of the Y(4220) and Y(4360) from previous measurements of different final states.

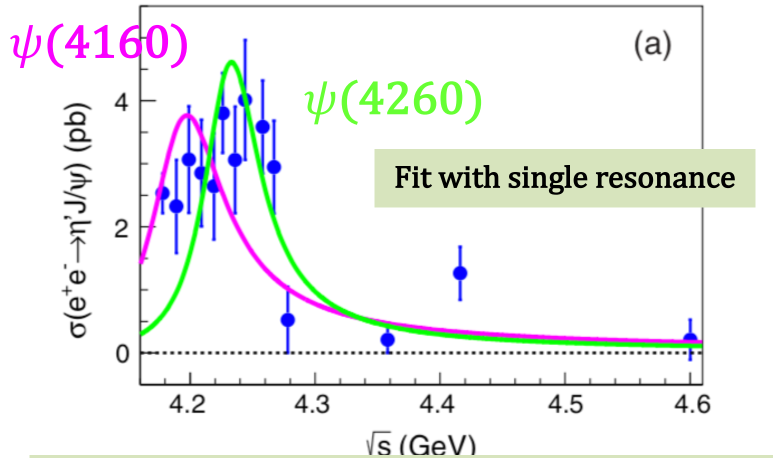
- $M(Y(4220)) = (4218.7 \pm 4.0 \pm 2.5)$ MeV/c^2,
- $\Gamma(Y(4220)) = (82.5 \pm 5.9 \pm 0.5)$ MeV.
- $M(Y(4360)) = (4380.4 \pm 14.2 \pm 1.8)$ MeV/c^2,
- $\Gamma(Y(4360)) = (147.0 \pm 63.0 \pm 25.8)$ MeV.



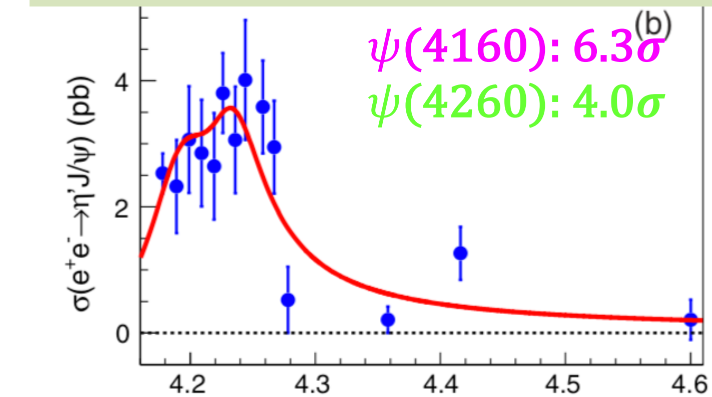
- The decays of the Y(4220) and Y(4360) into $\eta J/\psi$ final states are observed first time.

Cross section of $e^+e^- \to \eta' J/\psi$

PRD101.012008(2020)



Coherent sum of ψ(4160) and ψ(4260) resonance

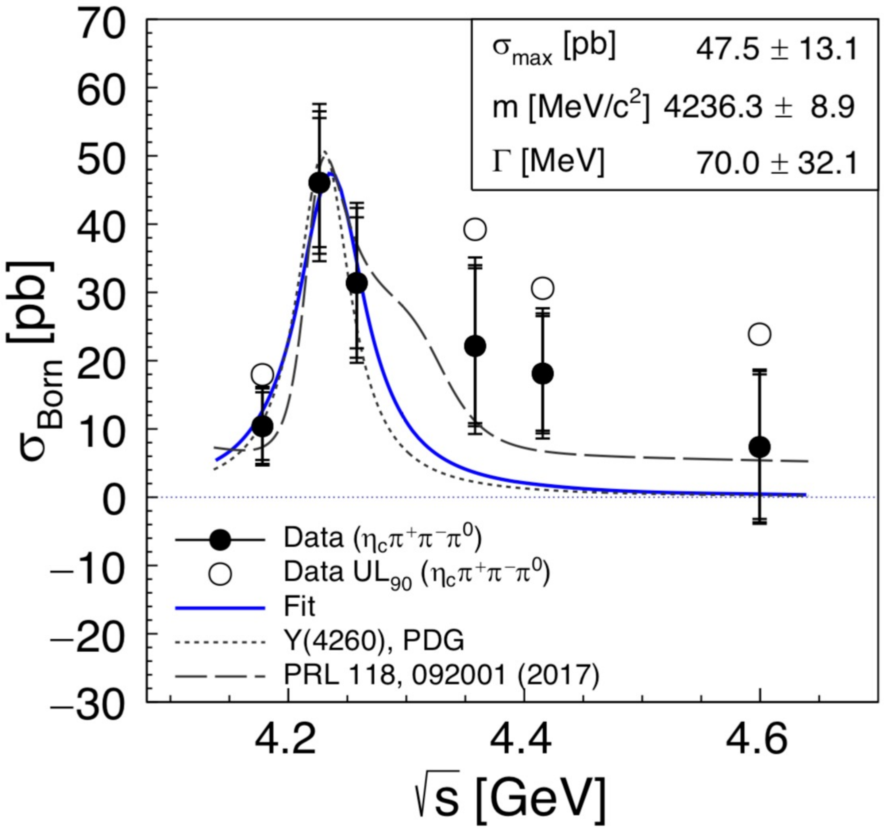


Parameter	Solution I	Solution II
$\Gamma_{ee}^{\psi(4160)}\mathcal{B}(\psi(4160)\to\eta' J/\psi)$ (eV)	0.17 ± 0.04	1.07 ± 0.09
$\Gamma_{ee}^{\psi(4260)}\mathcal{B}(\psi(4260)\to\eta' J/\psi)$ (eV)	0.06 ± 0.03	1.38 ± 0.11
ϕ (rad)	-0.03 ± 0.44	2.54 ± 0.04

- Using 11fb^{-1}data from center-of-mass 4.178 to 4.600 GeV.
- The dependence of the cross section on $\sqrt{s}$ shows an enhancement around 4.2GeV.
- The shape of the cross section cannot be fully explained with single $\psi(4160)$ or $\psi(4260)$ (Fix mass and width to PDG value).
- A coherent sum of $\psi(4160)$ and $\psi(4260)$ (Fix mass and width to PDG value) provide a reasonable description of data .

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

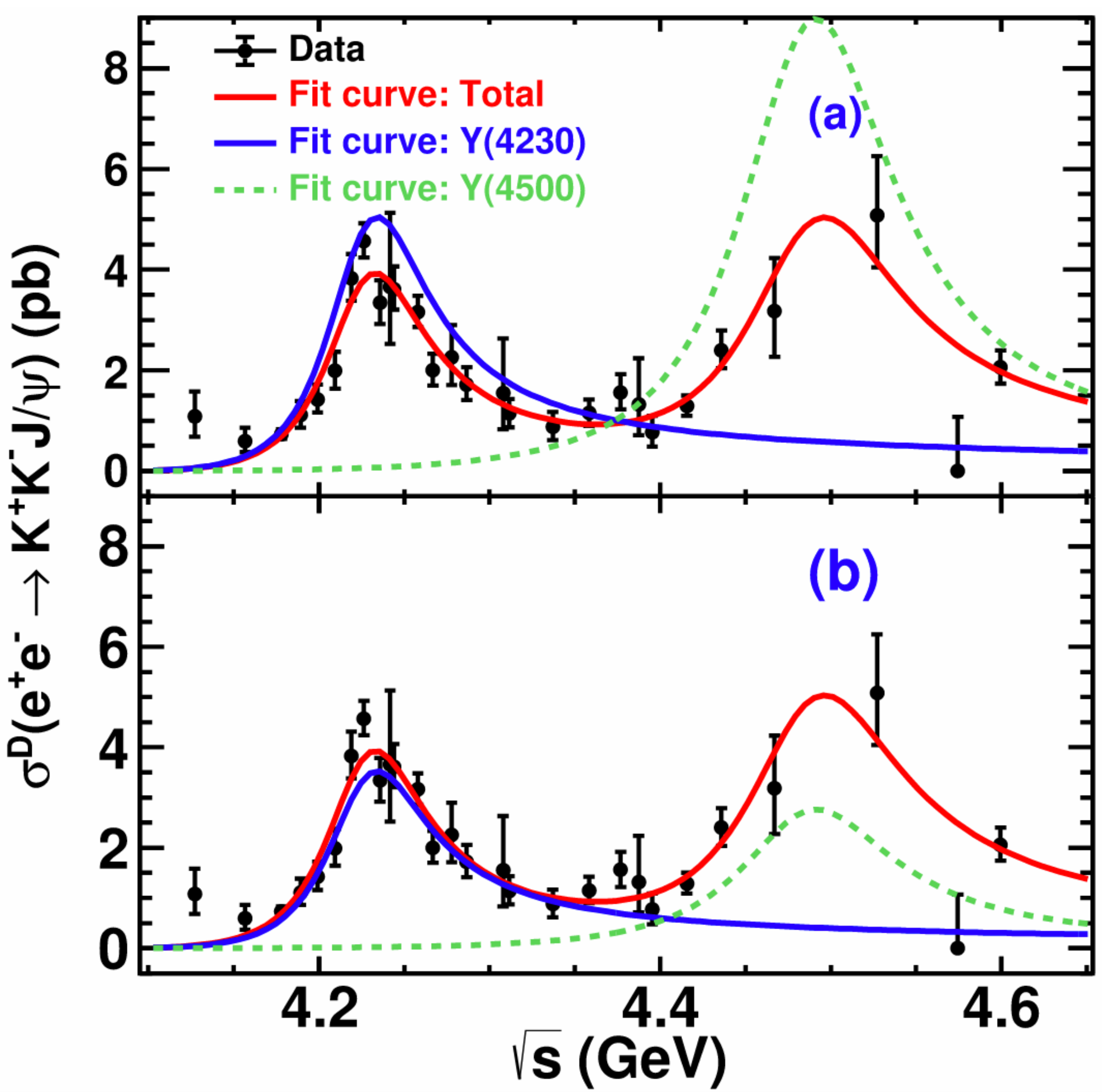
PRD103.032006(2021)



- The Born cross section is fitted with a Breit-Wigner function, shown as blue line in the plot.

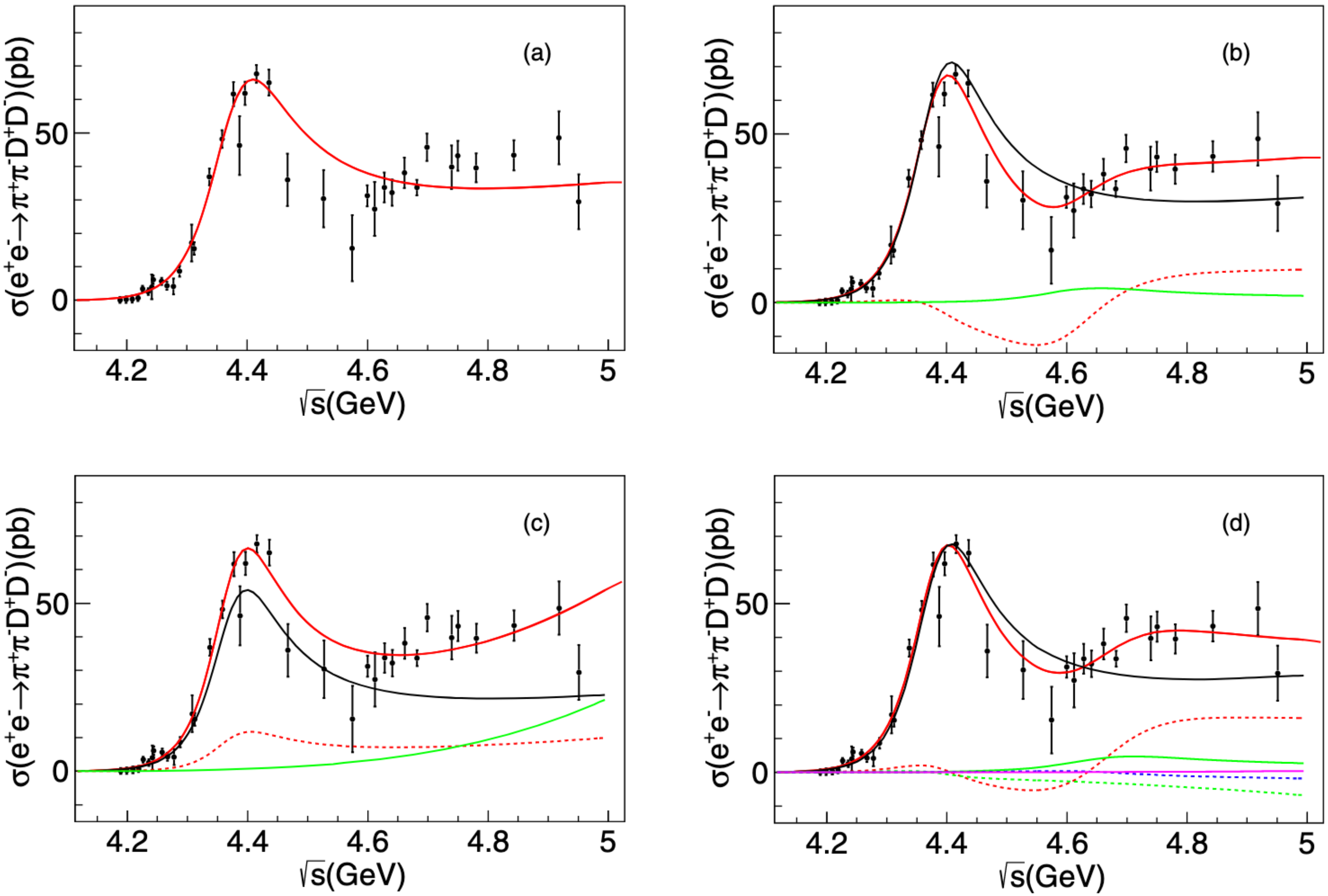
- Using data taken at center-of-mass energies $\sqrt{s}$ from 4.18 to 4.6GeV.
- Significant $e^+e^- \to \eta_c\pi^+\pi^-\pi^0$ production at $\sqrt{s}$=4.23GeV and 4.26GeV(>3.0σ), and larger than 5.0σ summing up different $\sqrt{s}$ points.
- Observe a significant energy-dependent Born cross section measured to be consistent with the production via the intermediate Y(4260) resonance.

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



Data
Fit curve: Total
Fit curve: Y(4230)
Fit curve: Y(4500)
(a)
(b)
$\sigma^D(e^+e^- \to K^+K^-J/\psi)$ (pb)
0
2
4
6
8
4.2
4.4
4.6
$\sqrt{s}$ (GeV)

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



$e^+e^- \rightarrow D^{*+}D^{*-}$、 $D^{*+}D^-$