Observation of the first hidden-charm strange tetraquark at BESIII

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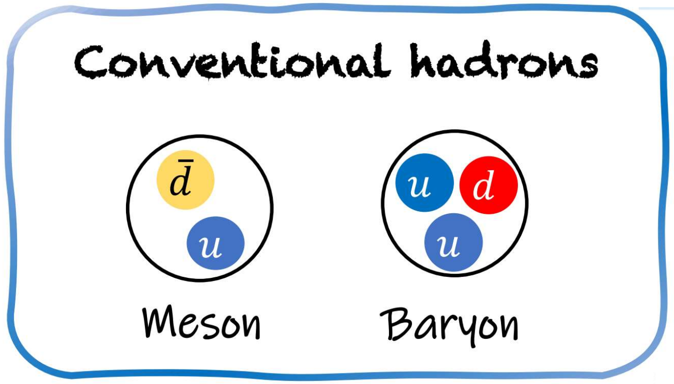
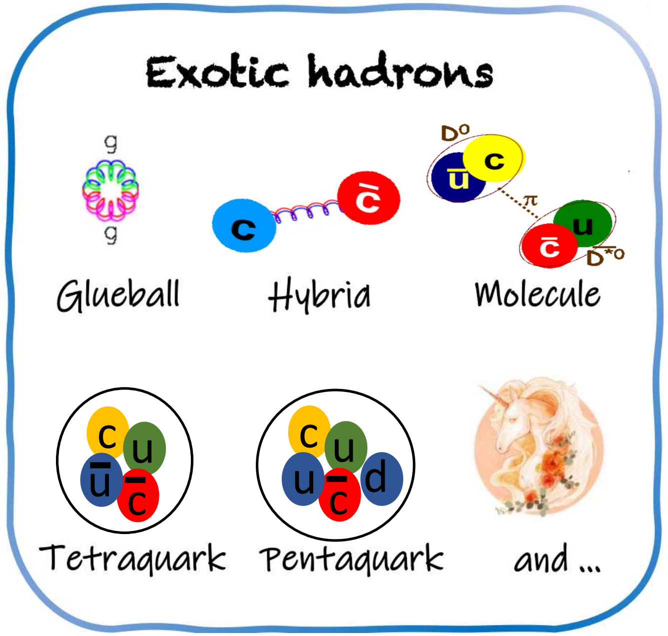
Outline

- Introduction
- Event selection
- Background study
- Study of recoil-mass spectra of K^+
- Cross section measurement
- Discussion and summary

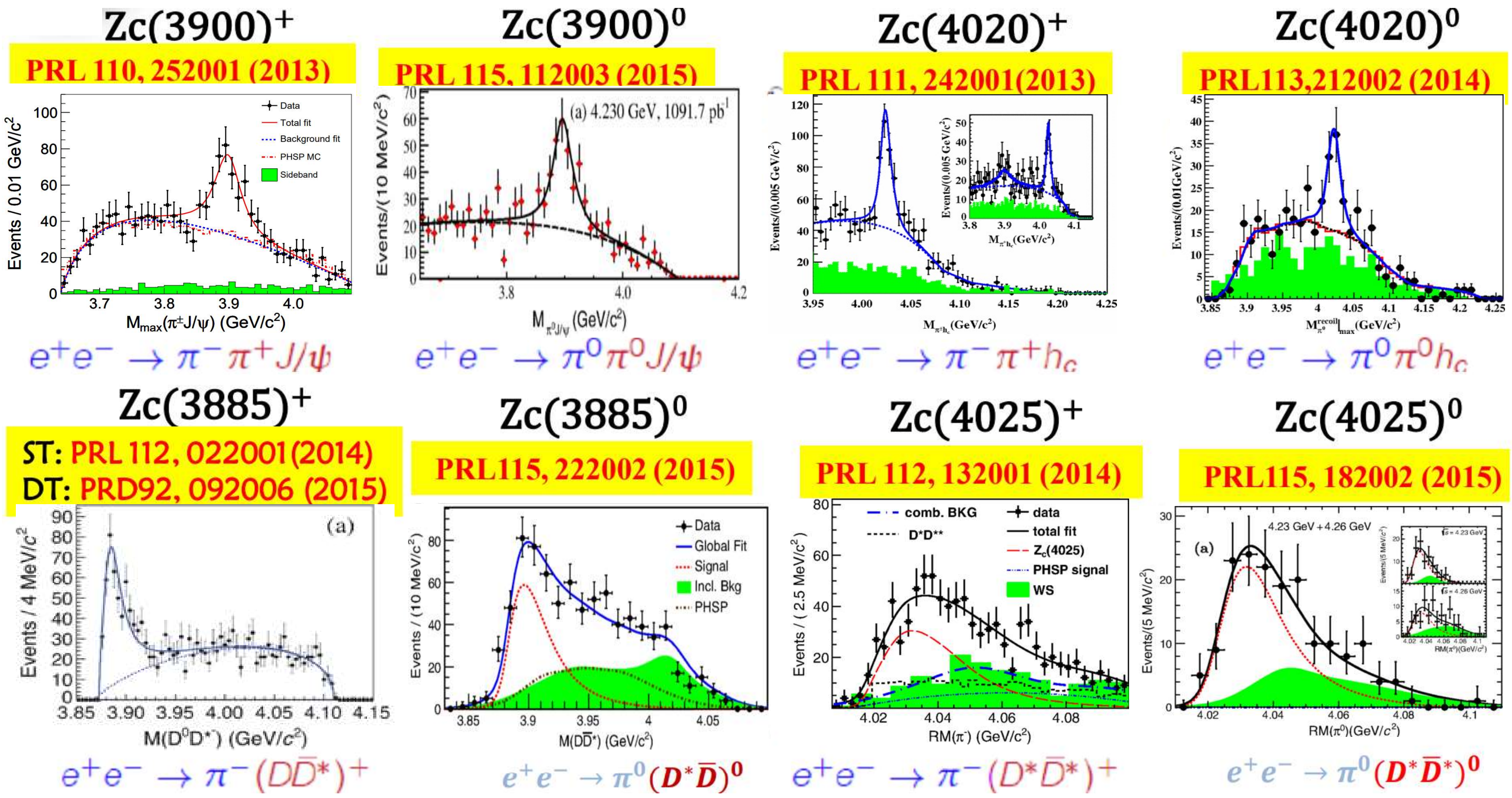
Introduction





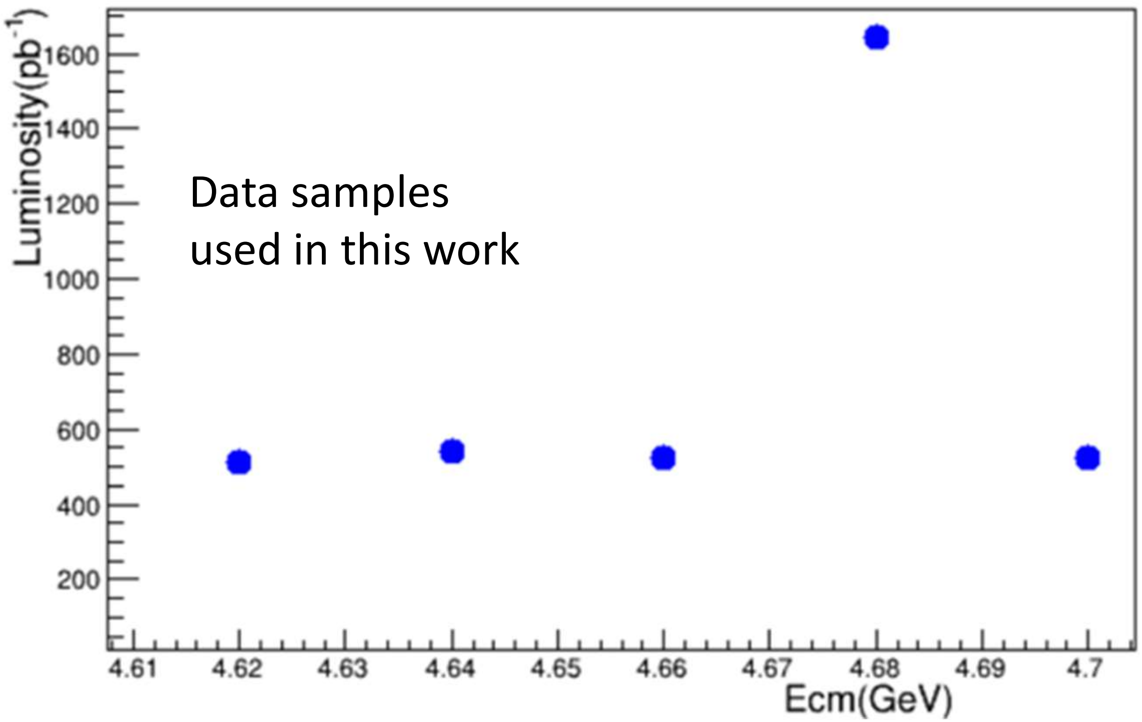
- QCD predicted the existence of exotic hadrons.
- Exotic hadrons include glueball, hybrid, molecule, tetraquark, pentaquark, and so on.
- Provide new insights into internal structure and dynamics of hadrons.
- Unique probe to non-perturbative behavior of QCD.

The Z_c Family at BESIII



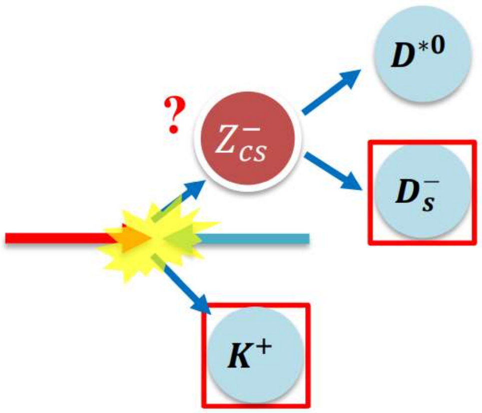
- Observation of non-strange hidden-charm tetraquark candidate opened a new chapter in hadron spectroscopy.
- Assuming SU(3) flavor symmetry, one would expect the existence of Z_{cs}.
- Searches for Z_{cs} were proposed few years ago. e.g., $Z_{cs} \rightarrow KJ/\psi$, $D_s D^*$, $D_s{}^* D$ etc.

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

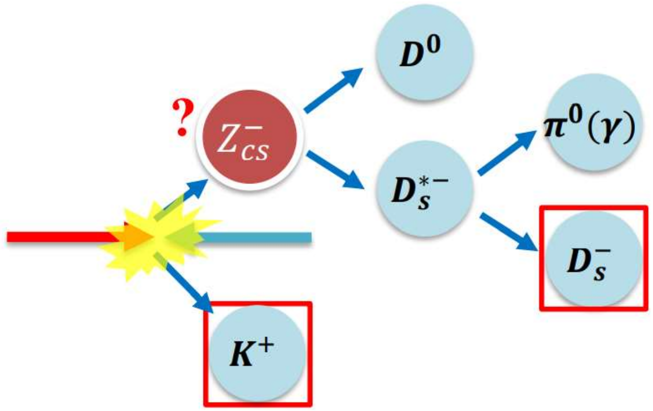


- BEPCII extended the energy limit to 4.7 GeV in 2019-2020.
- We analyze 3.7 fb^{-1} data accumulated above 4.62 GeV.

Identify Z_{cs}^- in $e^+e^- \to K^+ Z_{cs}^-$, $Z_{cs}^- \to D_s^- D^{*0} + D_s^{*-} D^0$



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

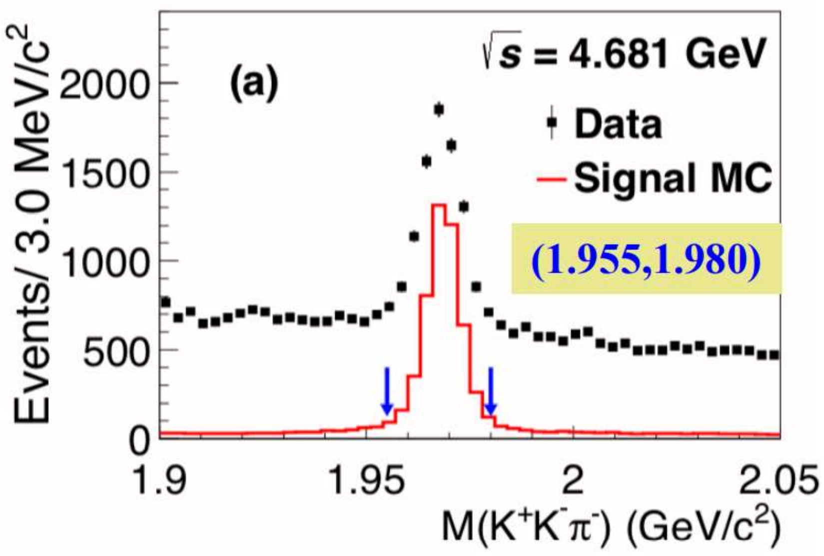


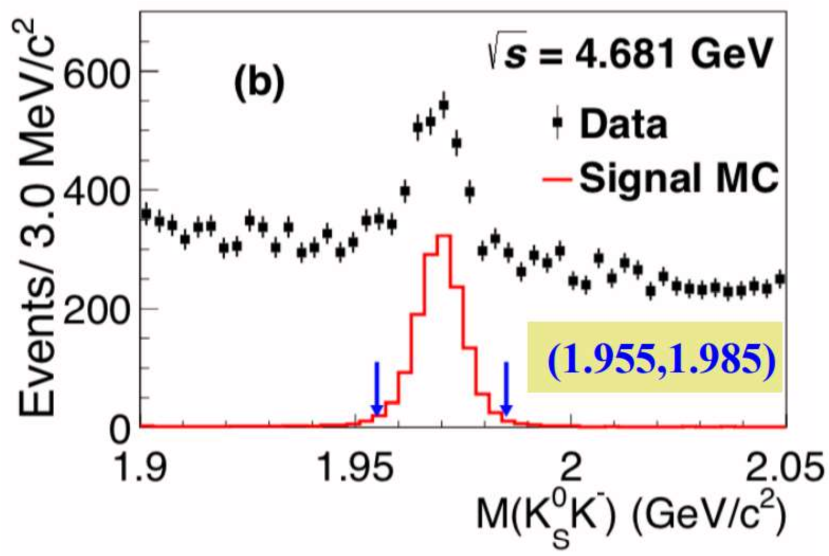
$e^+e^- \to K^+ D_s^{*-} D^0$

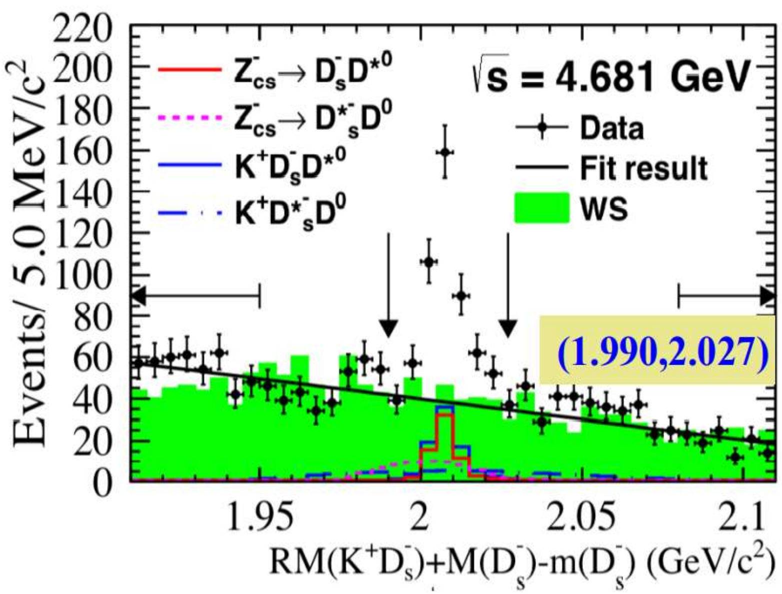
- Partial reconstruction of the process $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$
  - Reconstruct a $\boldsymbol{D_s^-}$ with two tag modes: $D_s^- \to K_S^0 K^-$ and $D_s^- \to K^+ K^- \pi^-$.
  - Tag a bachelor charged $\boldsymbol{K^+}$.
  - Use signature in the recoil mass spectrum of $\boldsymbol{K^+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

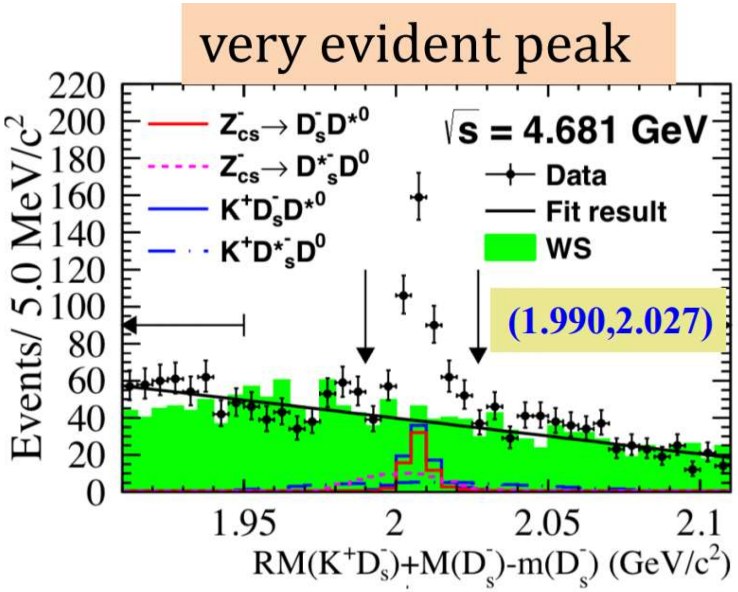
1) $D_s^- \to \pi^-\phi(K^-K^+)$: $M(K^-K^+) < 1.05$ GeV/c^2.

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

$M(K^+\pi^-) \in (0.85, 0.93)$ GeV/c^2.

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

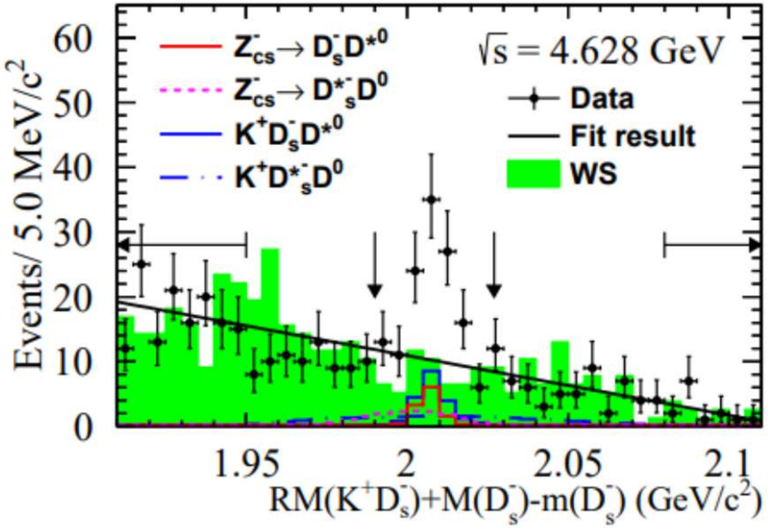
Select candidates for $K^{+}(D_s^{-}D^{*0}+D_s^{*-}D^{0})$



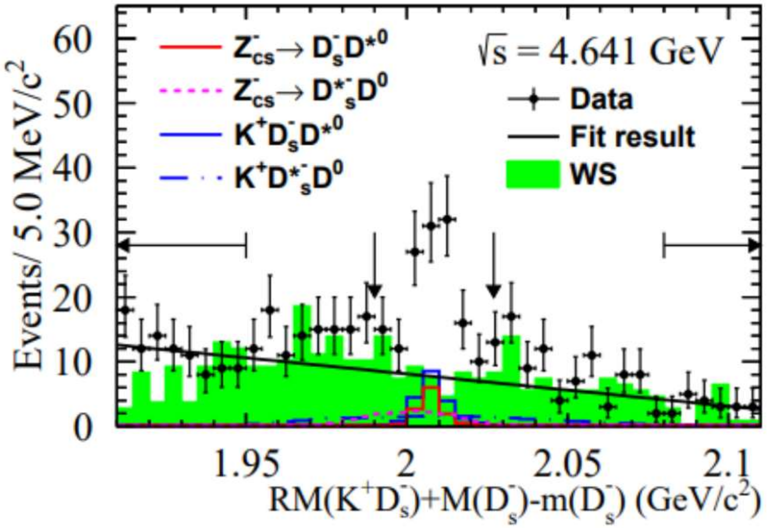
- Data-driven technique to describe combinatorial background.
- Right Sign(RS): combination of D_s^- and K^+.
- Wrong Sign(WS): combination of D_s^- and K^- to mimic combinatorial background.

- 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.

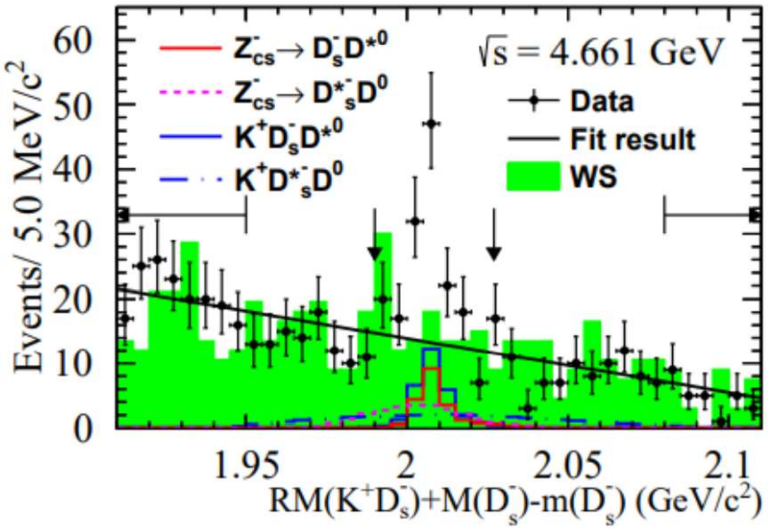
$RM(K^+D_s^-)$ distributions at other four energy points



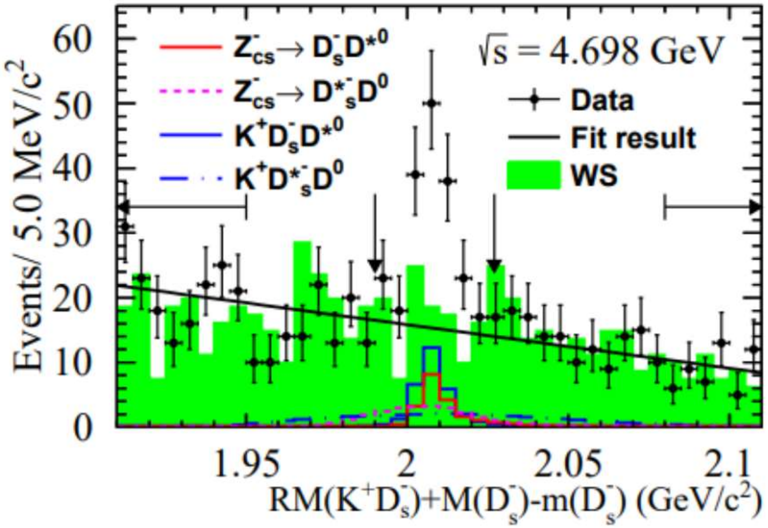
(a)Recoil mass of $K^+D_s^-$ at $\sqrt{s} = 4.628$ GeV.



(b)Recoil mass of $K^+D_s^-$ at $\sqrt{s} = 4.641$ GeV.

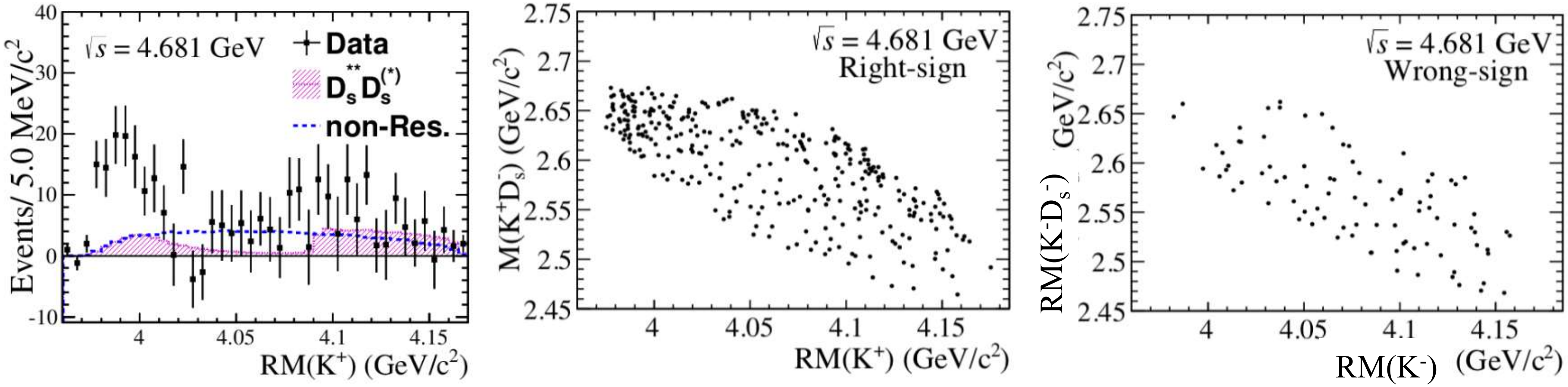


(c)Recoil mass of $K^+D_s^-$ at $\sqrt{s} = 4.661$ GeV.



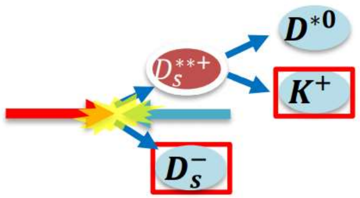
(d)Recoil mass of $K^+D_s^-$ at $\sqrt{s} = 4.698$ GeV.

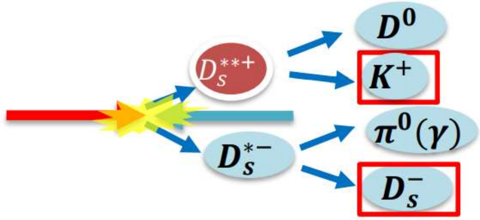
Recoil-mass spectra of K^+ and two-dimensional distributions of $M(K^+D_s^-)$ vs. $RM(K^+)$



- The K^+ recoil-mass spectrum in data at 4.681 GeV.
- Combinatorial backgrounds are subtracted.
- A structure next to threshold raging from 3.96 to 4.02 GeV/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	PV 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

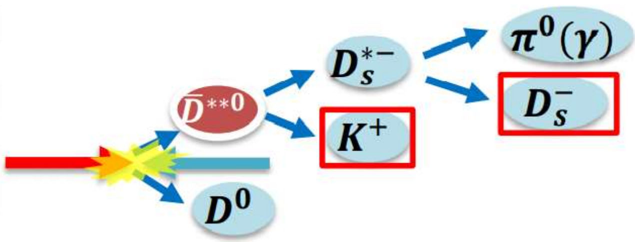
• $D_s^\pm$	$0(0^-)$
• $D_s^{*\pm}$	$0(?^?)$
• $D_{s0}^*(2317)^\pm$	$0(0^+)$
• $D_{s1}(2460)^\pm$	$0(1^+)$
• $D_{s1}(2536)^\pm$	$0(1^+)$
• $D_{s2}^*(2573)$	$0(2^+)$
• $D_{s1}^*(2700)^\pm$	$0(1^-)$
$D_{s1}^*(2860)^\pm$	$0(1^-)$
$D_{s3}^*(2860)^\pm$	$0(3^-)$
$D_{sJ}(3040)^\pm$	$0(?^?)$

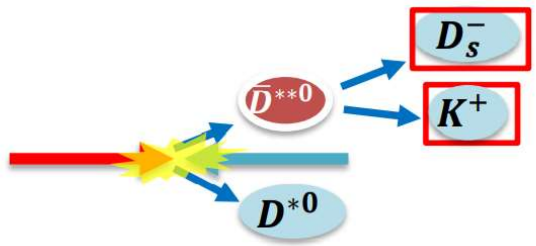
- Most high excited D_s^{**} states have negative Q value or forbidden due to Parity Violation.
- $D_{s1}^*(2536)^+(K^+D^{*0})D_s^-$, $D_{s2}^*(2573)^+(K^+D^0)D_s^{*-}$ and $D_{s1}^*(2700)^+(K^+D^{*0})D_s^-$ are studied using control sample.
- Most high excited $D_{(s)}^{**}$ states contribute a broad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

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

$\bar{D}^{**0}$	mass(MeV/c^2)	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	PV 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	PV 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	PV in decay
$\bar{D}_3^*(2750)^0$	2763±3.4	66±5	3-	(*)Control sample	P-wave suppressed. Q=-89.8MeV

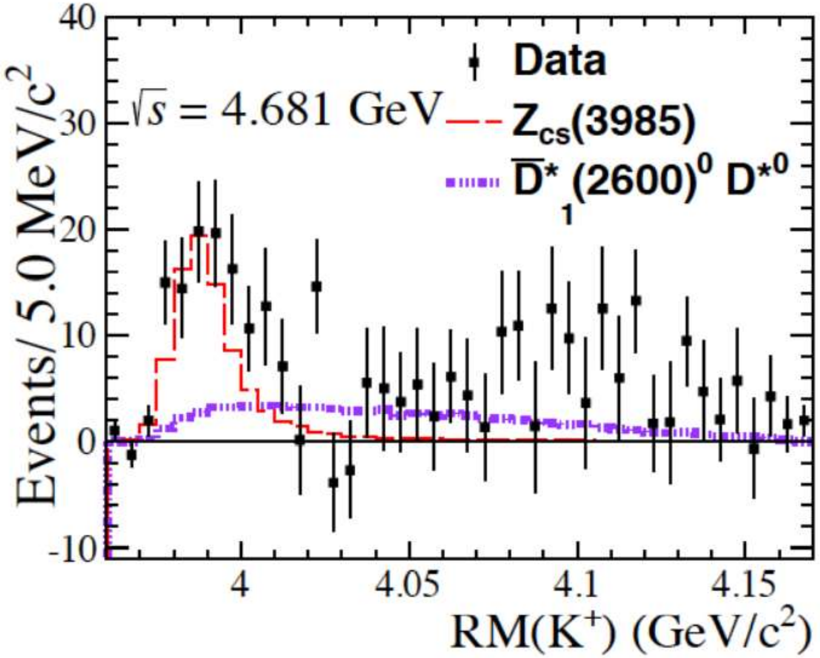
$D_1(2420)^\pm$	$1/2(?^?)$
$D_1(2430)^0$	$1/2(1^+)$
• $D_2^*(2460)^0$	$1/2(2^+)$
• $D_2^*(2460)^\pm$	$1/2(2^+)$
$D(2550)^0$	$1/2(?^?)$
$D_J^*(2600)$	$1/2(?^?)$
was $D(2600)$	
$D^*(2640)^\pm$	$1/2(?^?)$
$D(2740)^0$	$1/2(?^?)$
$D_3^*(2750)$	$1/2(3^-)$
$D(3000)^0$	$1/2(?^?)$





$D(2640)$ is quite narrow and not confirmed by any high statistic experiment including LHCb.

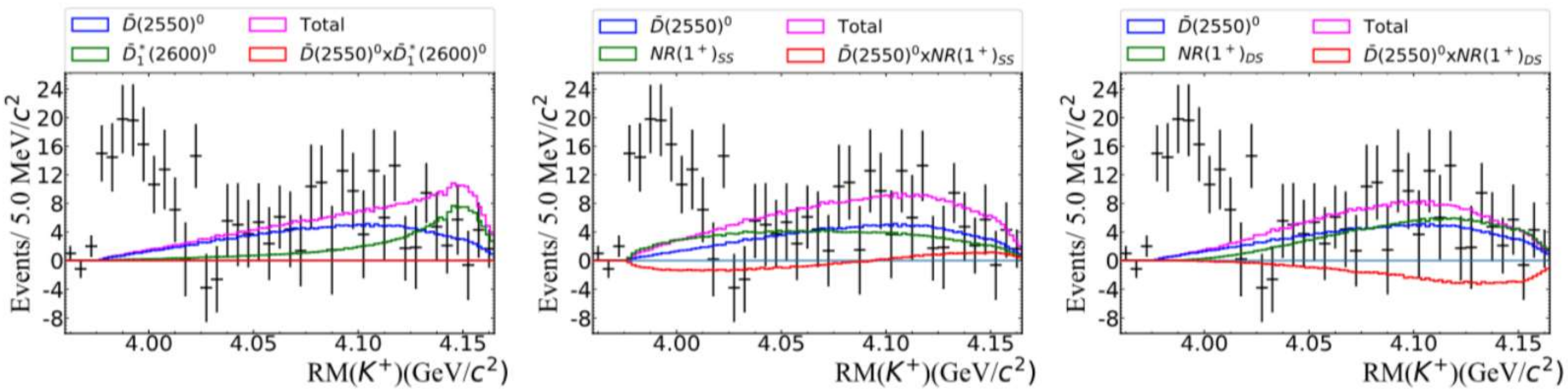
Check with high excited non-strange $\overline{D}_1^*(2600)^0$ states



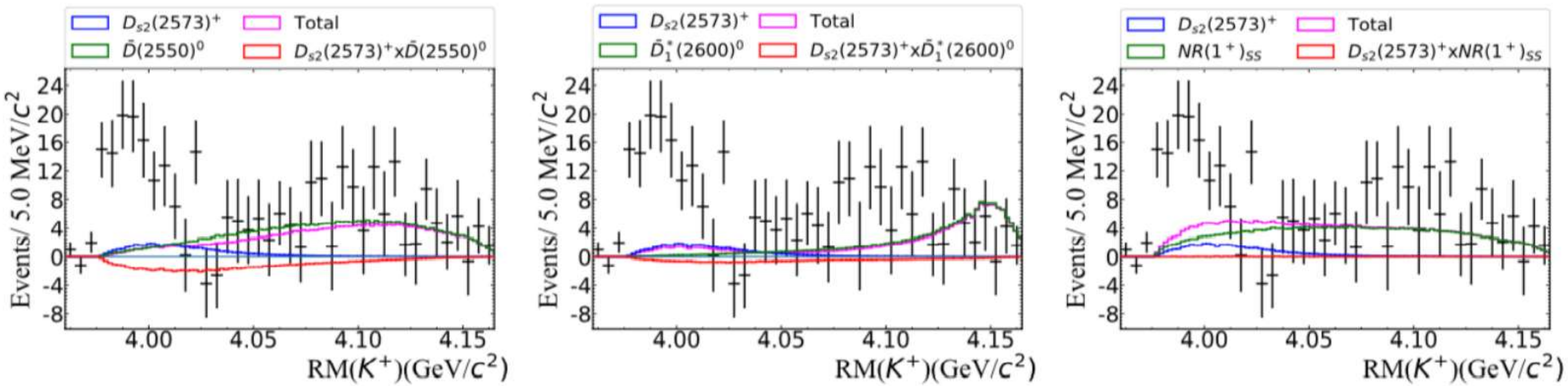
(c) $\bar{D}_1^*(2600)^0(\rightarrow D_s^- K^+)D^{*0}$

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

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



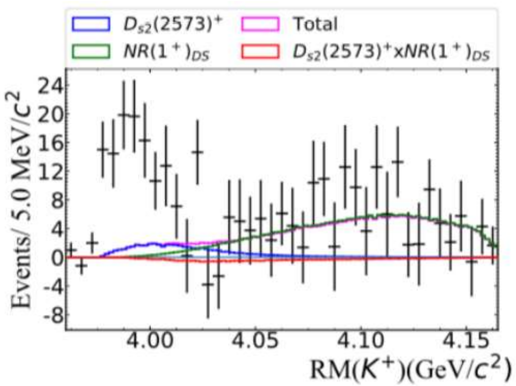
(a) $\bar{D}(2550)^0 D^0$ and $\bar{D}_1^*(2600)^0 D^0$ (b) $\bar{D}(2550)^0 D^0$ and NR $1^+(S,S)$ (c) $\bar{D}(2550)^0 D^0$ and NR $1^+(D,S)$



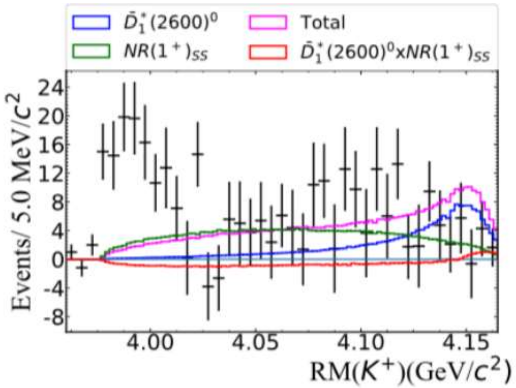
(d) $D_{s2}^*(2573)^+ D_s^{*-}$ and $\bar{D}(2550)^0 D^0$ (e) $D_{s2}^*(2573)^+ D_s^{*-}$ and $\bar{D}_1^*(2600)^0 D^0$ (f) $D_{s2}^*(2573)^+ D_s^{*-}$ and NR $1^+(S,S)$

- 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/c2 .

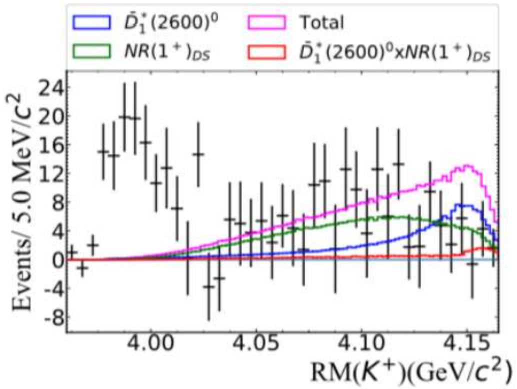
Interference effect of $K^{+}D_s^{*-}D^{0}$ final states (2)



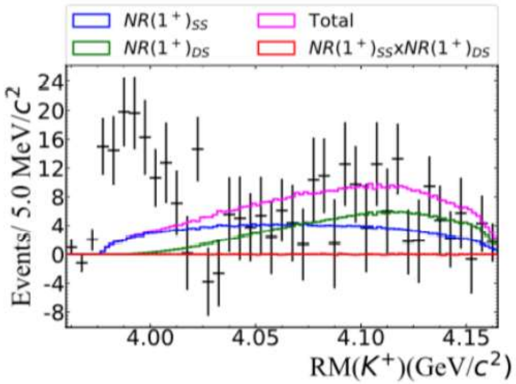
(g)$D_{s2}^{*}(2573)^{+}D_s^{*-}$ and NR $1^{+}(D,S)$



(h)$\bar{D}_1^{*}(2600)^{0}D^{0}$ and NR $1^{+}(S,S)$



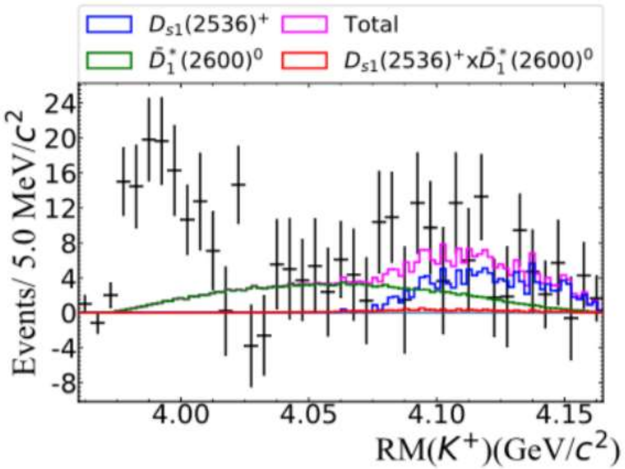
(i)$\bar{D}_1^{*}(2600)^{0}D^{0}$ and NR $1^{+}(D,S)$



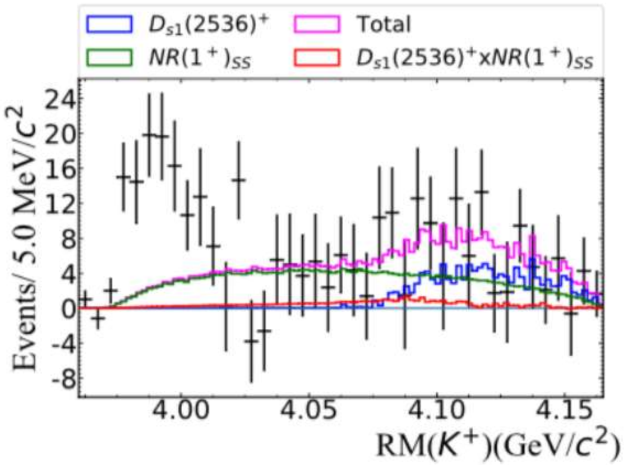
(j)NR $1^{+}(S,S)$ and NR $1^{+}(D,S)$

- The component of non-resonant process is also considered under different angular momentum assumption.
- Normalizations are scaled according to the observed yields in control samples.

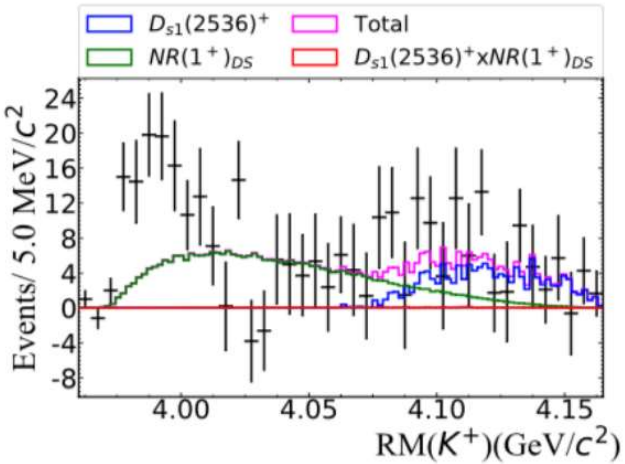
Interference effect of $K^+D_s^-D^{*0}$ final states (1)



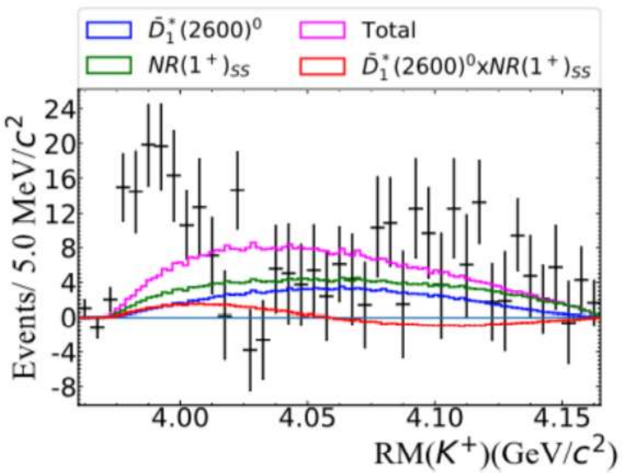
(a)$D_{s1}(2536)^+D_s^-$ and $\bar{D}_1^*(2600)^0D^{*0}$



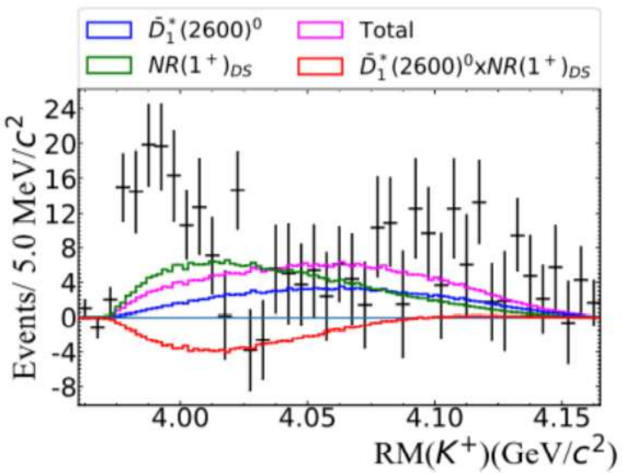
(b)$D_{s1}(2536)^+D_s^-$ and NR $1^+(S,S)$



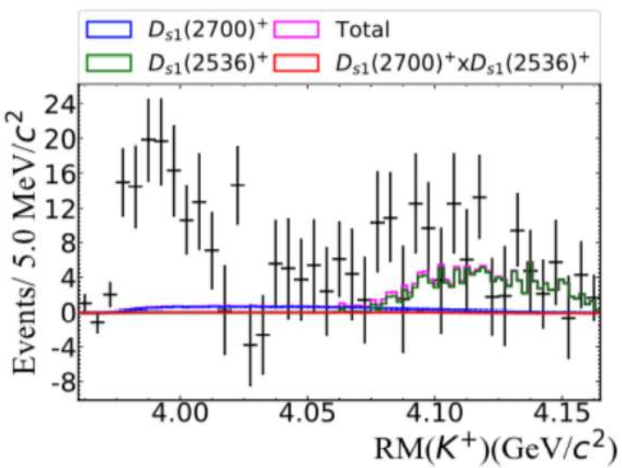
(c)$D_{s1}(2536)^+D_s^-$ and NR $1^+(D,S)$



(d)$\bar{D}_1^*(2600)^0D^{*0}$ and NR $1^+(S,S)$

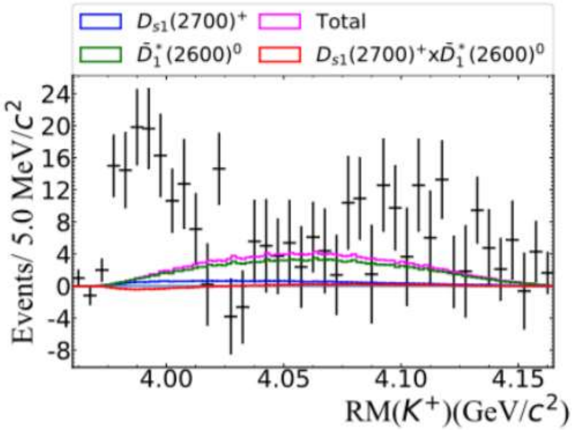


(e)$\bar{D}_1^*(2600)^0D^{*0}$ and NR $1^+(D,S)$

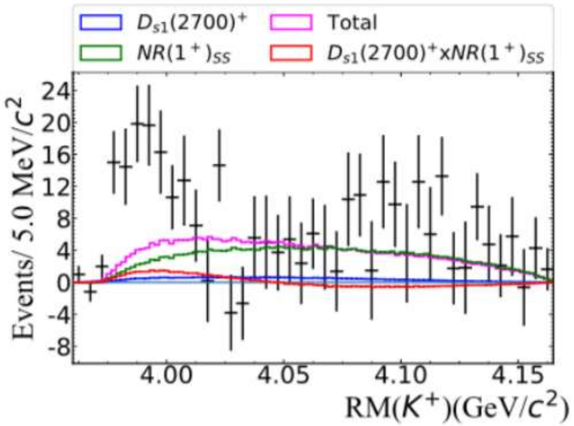


(f)$D_{s1}^*(2700)^+D_s^-$ and $D_{s1}(2536)^+D_s^-$

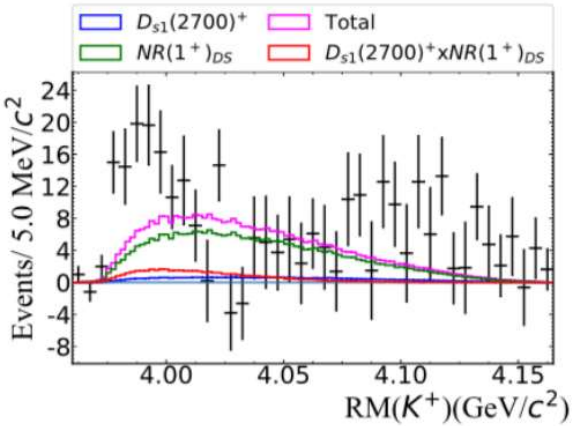
Interference effect of $K^{+}D_{s}^{-}D^{*0}$ final states (2)



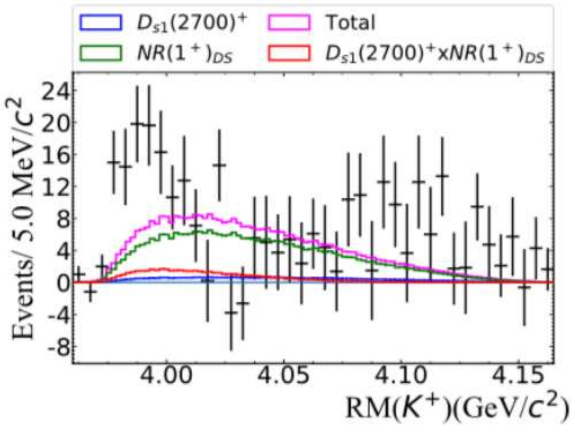
(g)$D_{s1}^{*}(2700)^{+}D_{s}^{-}$ and $\bar{D}_{1}^{*}(2600)^{0}D^{*0}$



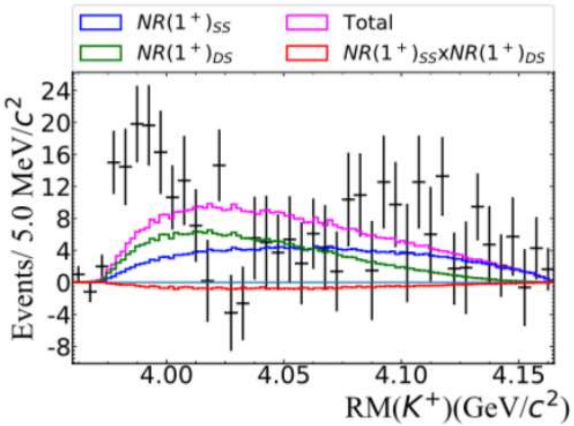
(h)$D_{s1}^{*}(2700)^{+}D_{s}^{-}$ and NR $1^{+}(S,S)$



(i)$D_{s1}^{*}(2700)^{+}D_{s}^{-}$ and NR $1^{+}(D,S)$



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

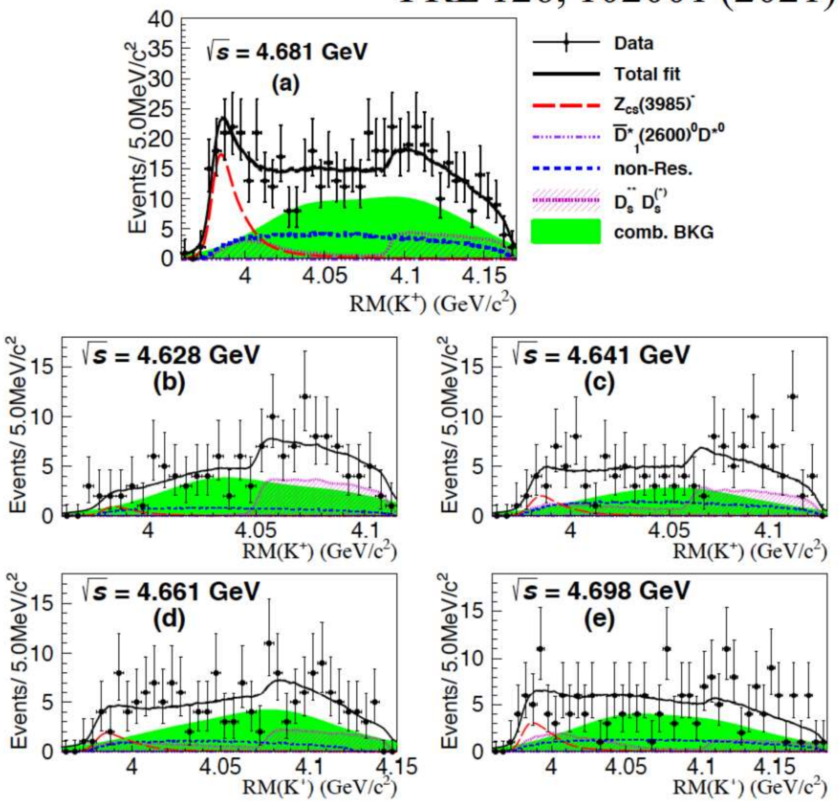


(k)NR $1^{+}(S,S)$ and NR $1^{+}(D,S)$

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

Study of recoil-mass spectra of K^+

PRL 126, 102001 (2021)



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.

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

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

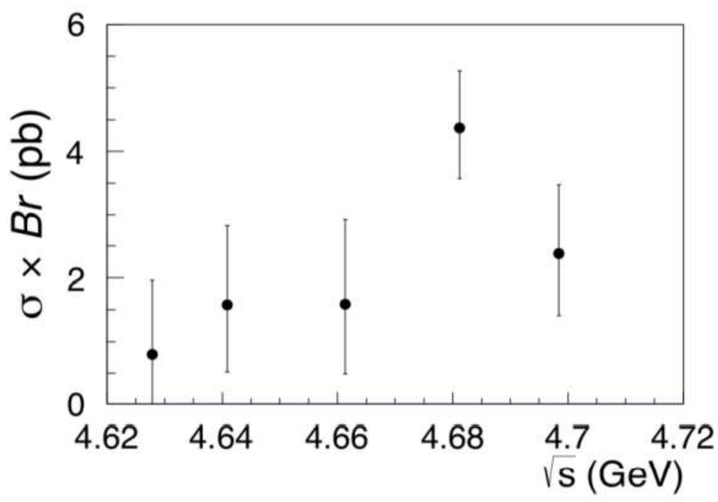
- The potential interference effects are neglected.
- The J^P of $Z_{cs}(3985)^-$ is assumed as 1^+; =>(S,S) is the most promising configuration.
- The significance with systematic uncertainties and look-elsewhere effect considered is evaluated to 5.3σ.

Cross-section measurement at each energy point

- Born cross section:

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

$\sqrt{s}$(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	$0.8^{+1.2}_{-0.8}\pm0.6\,(<3.0)$
4.641	541.4	$9.3^{+7.3}_{-6.2}$	1.09	$1.6^{+1.2}_{-1.1}\pm1.3\,(<4.4)$
4.661	523.6	$10.6^{+8.9}_{-7.4}$	1.28	$1.6^{+1.3}_{-1.1}\pm0.8\,(<4.0)$
4.681	1643.4	$85.2^{+17.6}_{-15.6}$	1.18	$4.4^{+0.9}_{-0.8}\pm1.4$
4.698	526.2	$17.8^{+8.1}_{-7.2}$	1.42	$2.4^{+1.1}_{-1.0}\pm1.2\,(<4.7)$



- 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:

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

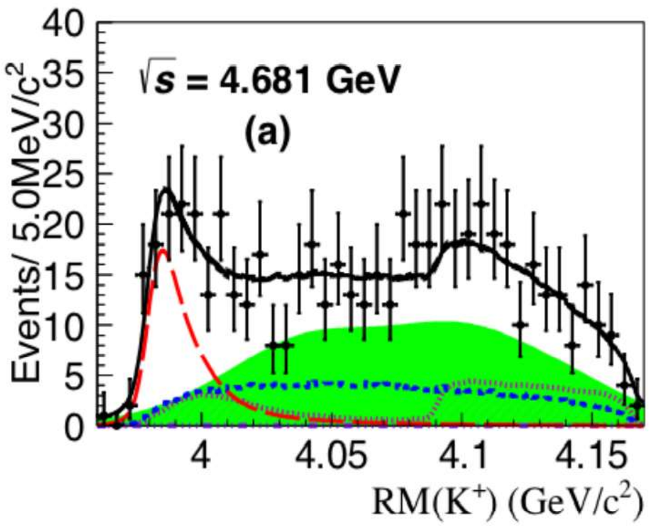
$$\Gamma_0(Z_{cs}(3985)^-) = 13.8^{+8.1}_{-5.2}(stat.) \pm 4.9(sys.)\mathrm{MeV}.$$

Pole position:

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

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

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

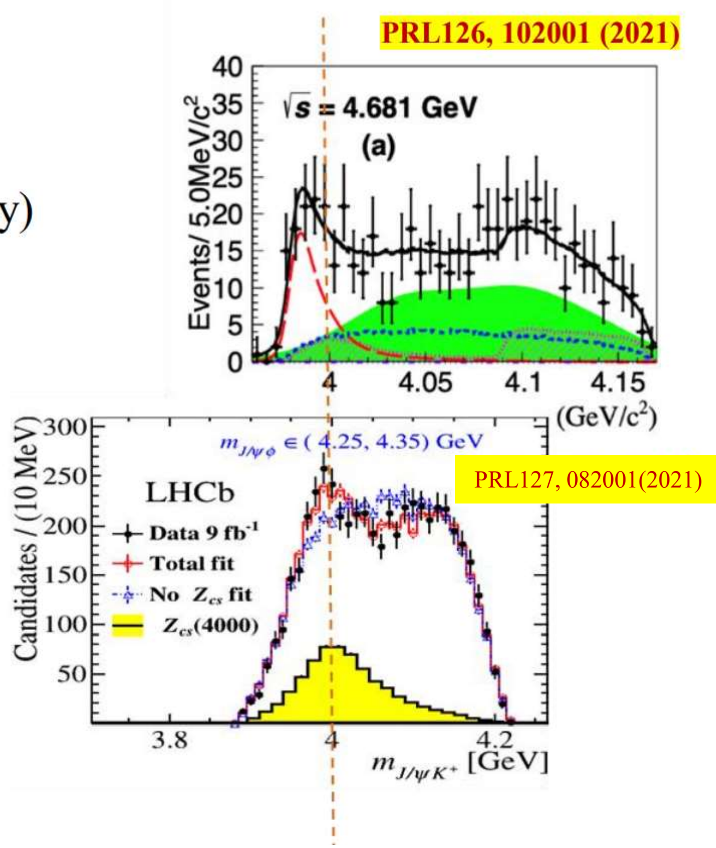


- Only a few MeV higher than the threshold of $D_s^- D^{*0}/D_s^{*-} D^0$ (3975.2/3977.0)MeV/c^2.
- At least four quark state ($c\bar{c}s\bar{u}$) and a charged hidden-charm state with strangeness.

- 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.

Discussions on the nature of $\boldsymbol{Z_{cs}(3985)^{\pm}}$

- **Various interpretations are possible for the structure**
  - Tetraquark state
  - Molecule
  - $D_{s2}^{*}(2573)^{+}D_{s}^{*-}$ threshold kinematic effects (Re-scattering , Reflection, 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

$$m_{pole}(Z_{cs}(3985)^-) = 3982.5^{+1.8}_{-2.6}(stat.) \pm 2.1(sys.)\mathrm{MeV/c^2},$$
$$\Gamma_{pole}(Z_{cs}(3985)^-) = 12.8^{+5.3}_{-4.4}(stat.) \pm 3.0(sys.)\mathrm{MeV}.$$

$$m_{pole}(Z_{cs}(4000)^-) = 4003 \pm 6(stat.)\,^{+4}_{-14}(sys.)\mathrm{MeV/c^2},$$
$$\Gamma_{pole}(Z_{cs}(4000)^-) = 131 \pm 15(stat.) \pm 26(sys.)\mathrm{MeV}.$$

Summary

- We observed an enhancement near $D_s^- D^{*0}/D_s^{*-} D^0$ mass thresholds in $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$ (c.c.) at the center-of-mass energy 4.681GeV (significance > 5σ).
  - an exotic state with at least four-quark constituent $c\bar{c}s\bar{u}$
- It matches a hypothesis of $D_s^- D^{*0}$ and $D_s^{*-} D^0$ resonant structure $Z_{cs}(3985)^-$ with a mass-dependent-width Breit-Wigner line shape well; Pole position is measured to be

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

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

- The Born cross section $\sigma^{Born} \cdot \mathfrak{B}$ at five energy points are determined.
- It is not a charmonium and the nature is yet unknown.
- New fields in experimental studies, more to be measured/understood!
- More results will come out ...

Thanks!