Observation of the Zcs(3985) state at BESIII

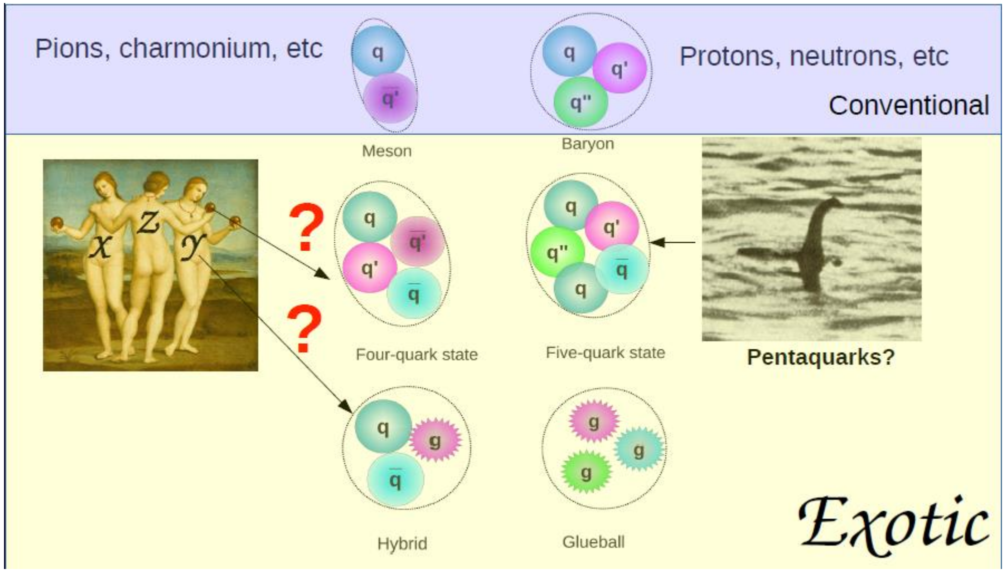
Ying-Chao Xu
UCAS, Beijing
(for the BESIII collaboration)

Experimental and theoretical status of and perspectives for XYZ states

(virtual) Darmstadt, Apr. 12 – 15, 2021

QCD predicted states

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



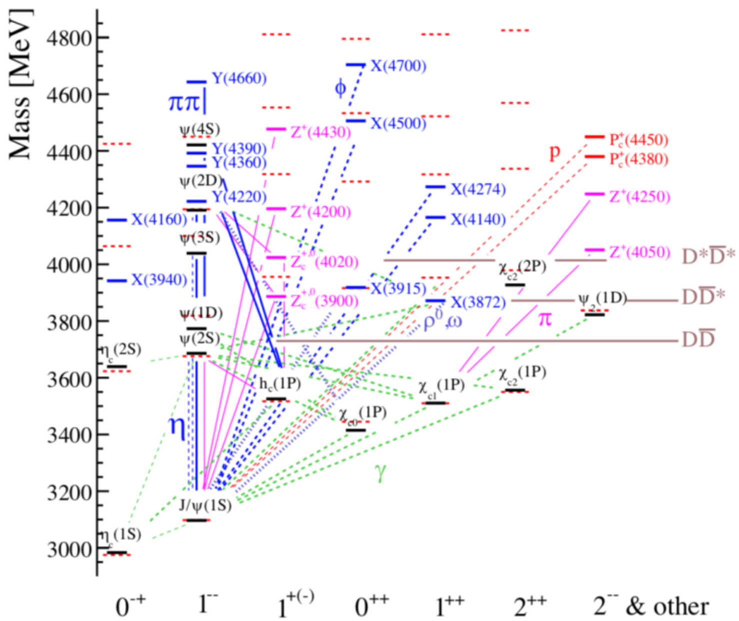
Different compositions and binding schemes:

- 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**

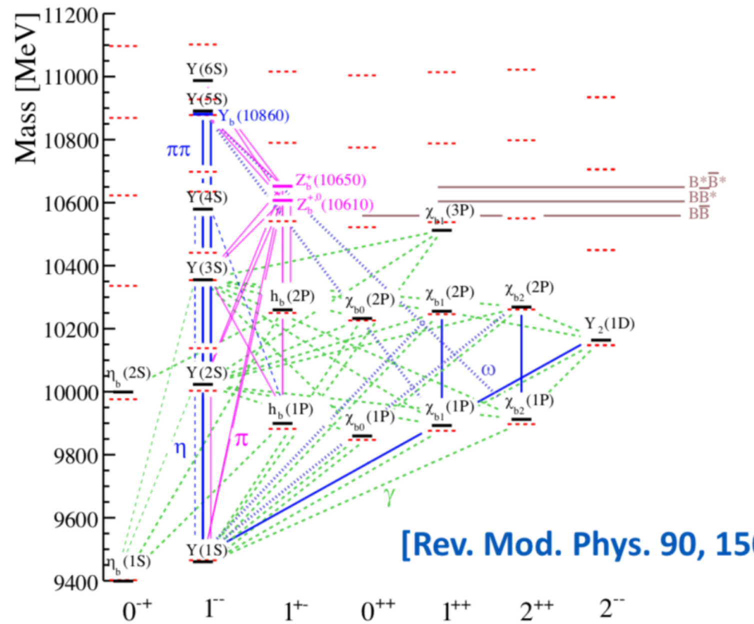
- Provide new insights into internal structure and dynamics of hadrons.
- Unique probe to non-perturbative behavior of QCD.

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



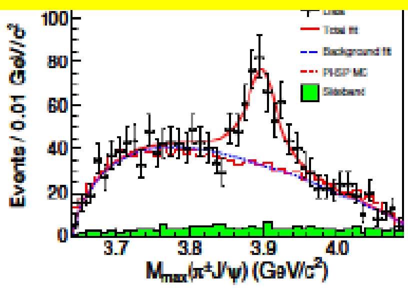
[Rev. Mod. Phys. 90, 15003 (2018)]

- 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.

The Zc Family at BESIII

Zc(3900)$^+$

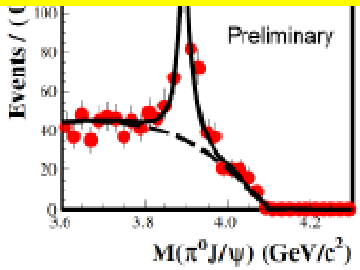
PRL 110, 252001 (2013)



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

Zc(3900)^0

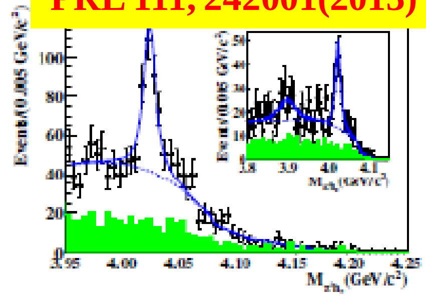
PRL 115, 112003 (2015)



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

Zc(4020)$^+$

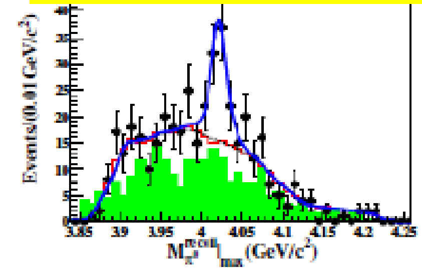
PRL 111, 242001(2013)



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

Zc(4020)^0

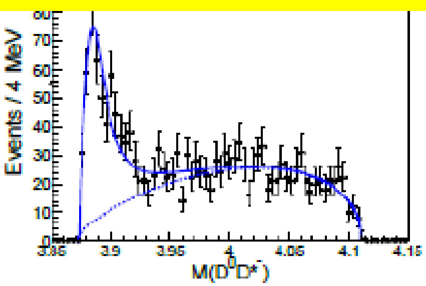
PRL113,212002 (2014)



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

Zc(3885)$^+$

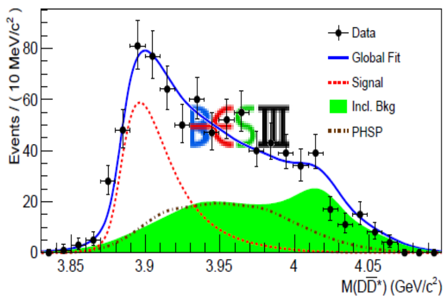
ST: PRL 112, 022001(2014)
DT: PRD92, 092006 (2015)



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

Zc(3885)^0

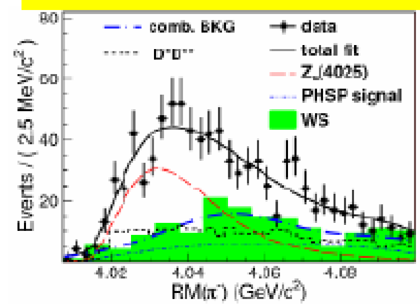
PRL115, 222002 (2015)



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

Zc(4025)$^+$

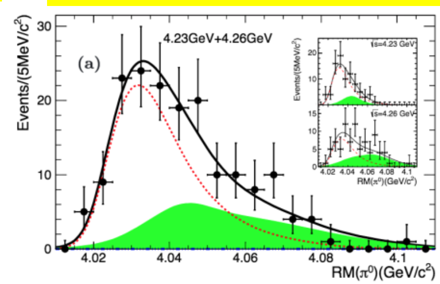
PRL 112, 132001 (2014)



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

Zc(4025)^0

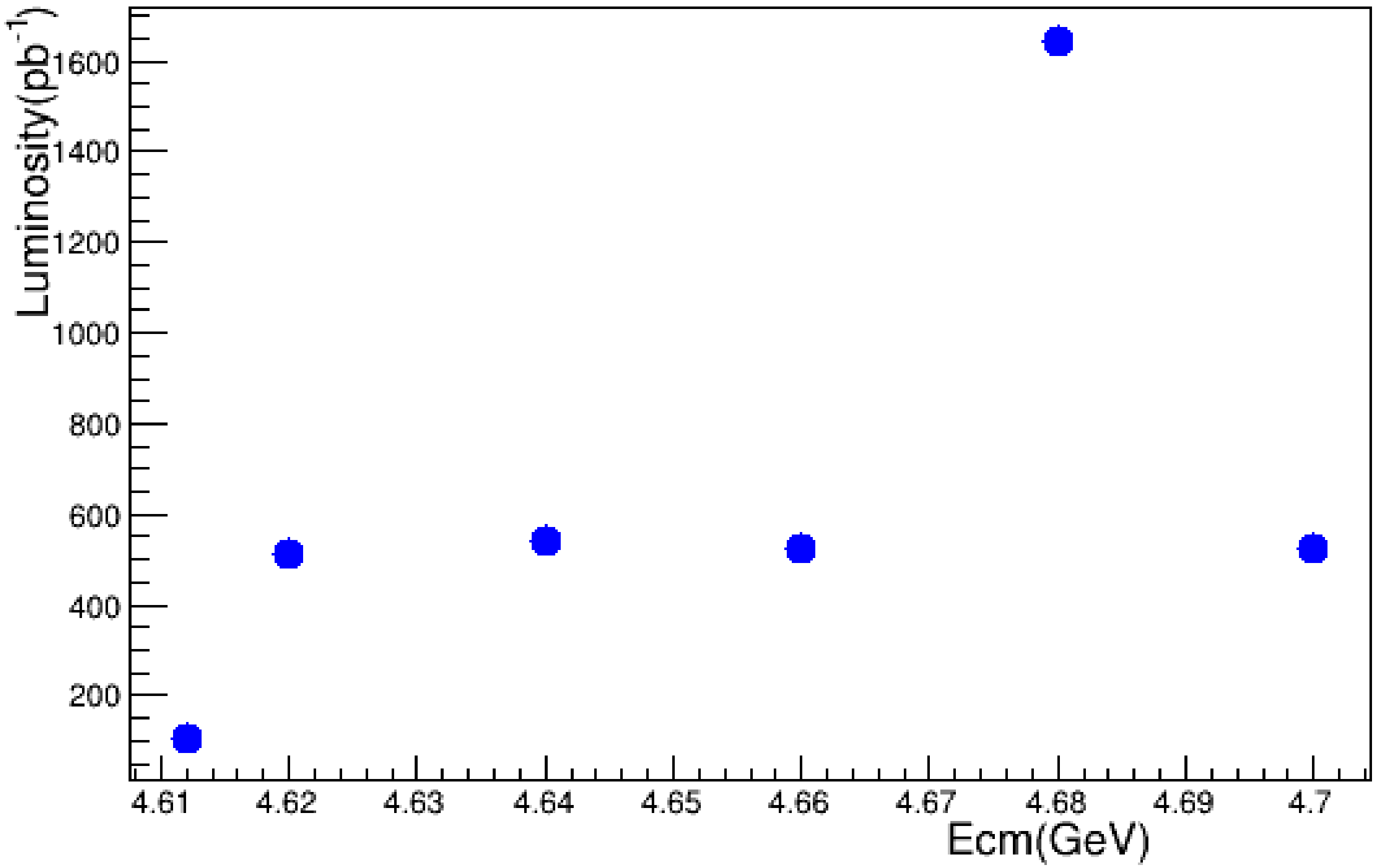
PRL115, 182002 (2015)



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

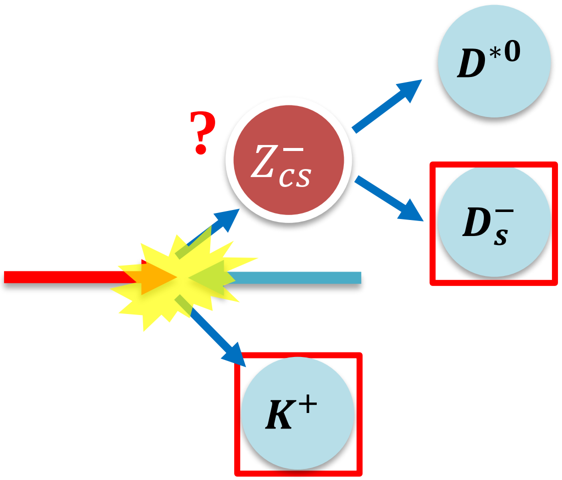
- What is the nature of these states?
- Different decay channels of the same observed states? Other decay modes? J^P?
- Searches for Z_{cs} partners were proposed few years ago. e.g., $Z_{cs}/Z'_{cs} \to KJ/\psi$, D_sD^*, D_s^*D, $D_s^*D^*$ etc. => decay rate of Z_{cs} to open-charm final states is supposed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

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

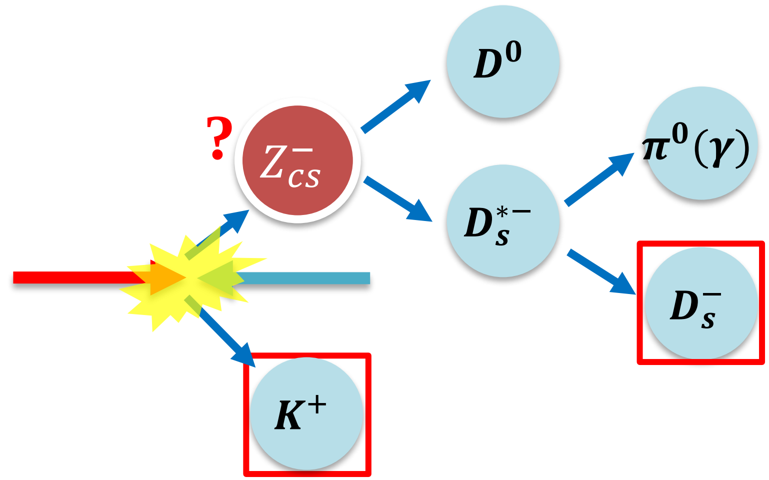


- BEPCII extend the energy limit to 4.7GeV in 2019-2020.
- We analyze 3.7fb^{-1} data accumulated at 4.628, 4.641, 4.681, 4.698GeV.

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



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

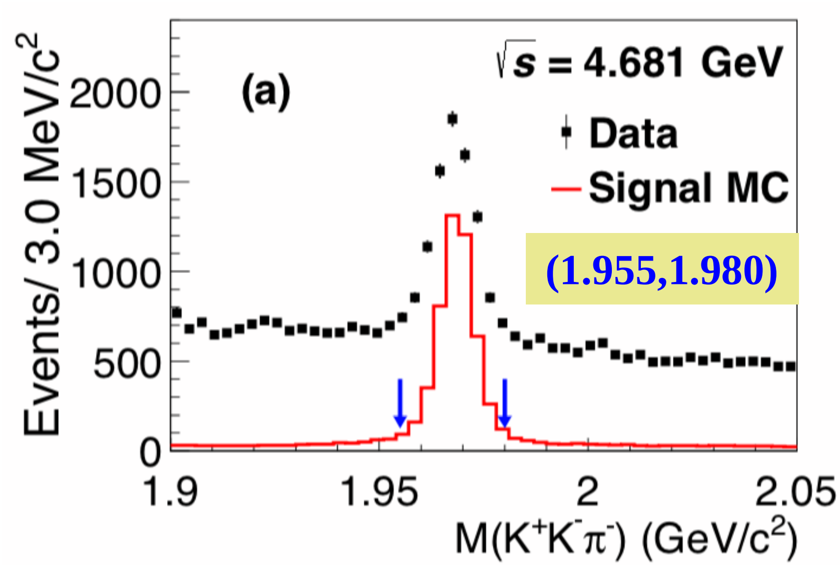


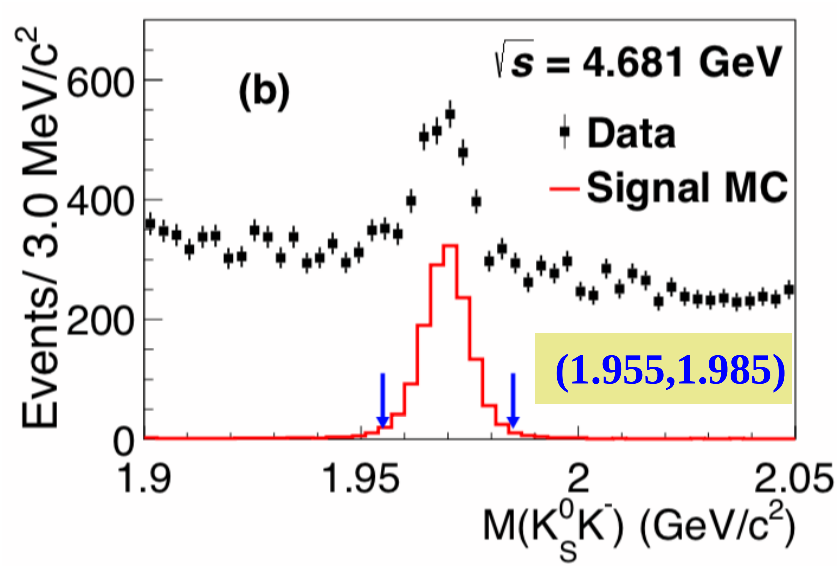
$e^+e^- \to K^+ D_s^{*-} D^0$

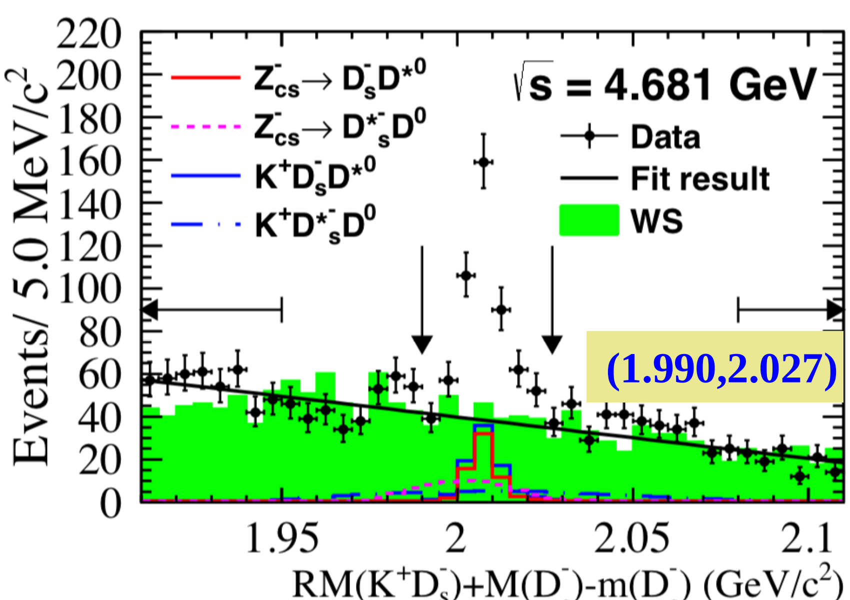
- **Partial reconstruction** of the process $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$
  - Reconstruct a $\boldsymbol{D_s^-}$ with two tag modes: $D_s^- \to K_S^0 K^-$ and $D_s^- \to K^+ K^- \pi^-$.
  - Tag a bachelor charged $\boldsymbol{K^+}$.
  - Use signature in the **recoil mass spectrum of $K^+ D_s^-$** 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/c^2.

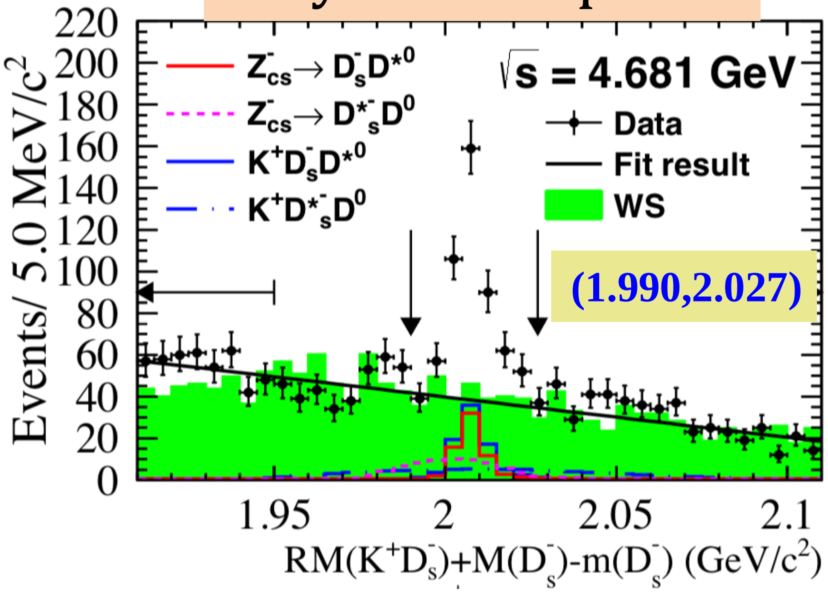
2) $D_s^- \to K^-K^*(892)(K^+\pi^-)$:

$M(K^+\pi^-) \in (0.85, 0.93)$ 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 $K^+(D_s^- D^{*0} + D_s^{*-} D^0)$

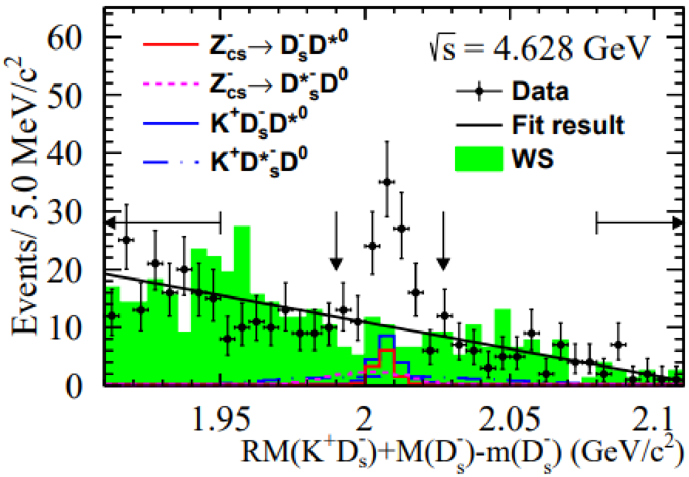
very evident peak



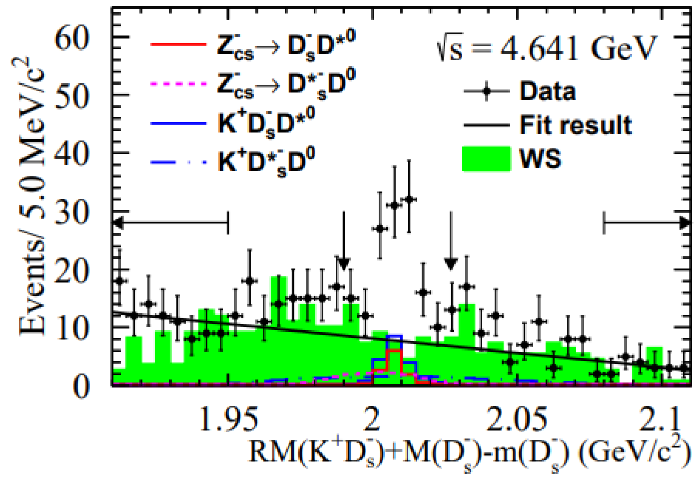
- Data-driven technique to describe combinatorial background.
- Right Sign(RS): combination of D_s^- and K^+.
- Wrong Sign(WS): combination of D_s^- and K^- to mimic combinatorial background.

- 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.

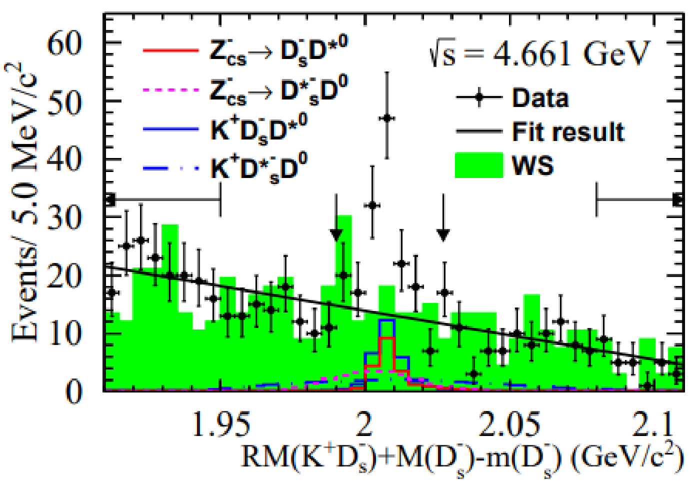
$RM(K^+D_s^-)$ distributions at other four energy points



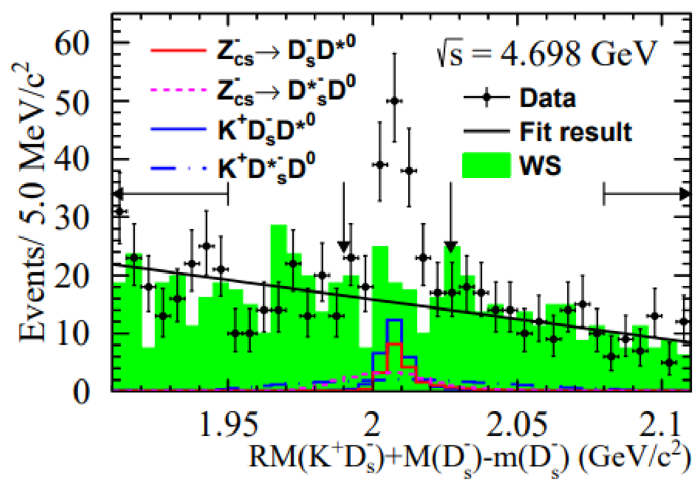
(a)Recoil mass of $K^+D_s^-$ at $\sqrt{s} = 4.628$ GeV.



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

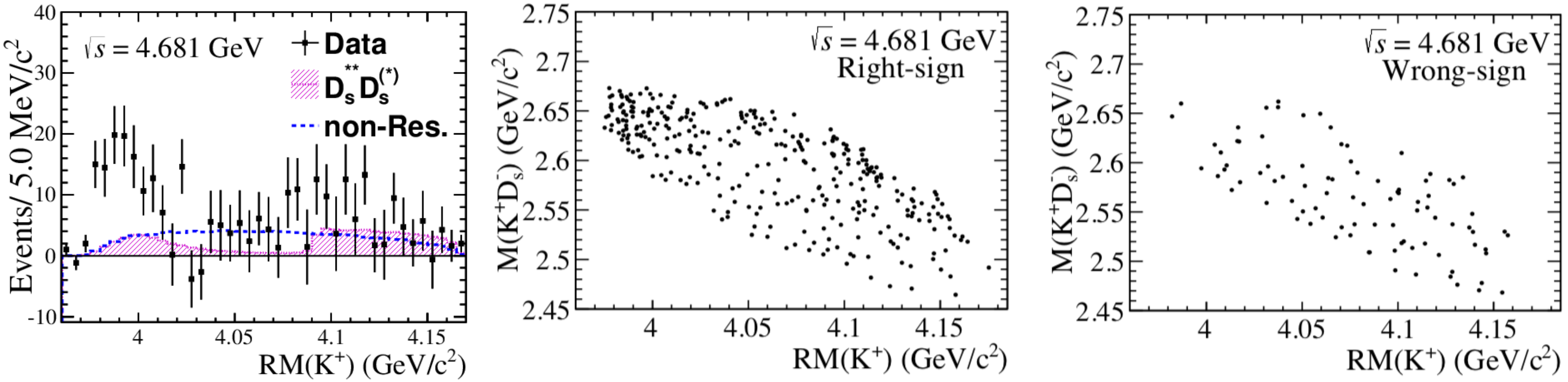


(c)Recoil mass of $K^+D_s^-$ at $\sqrt{s} = 4.661$ GeV.



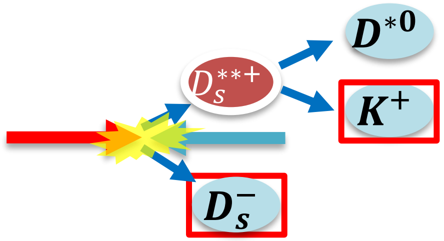
(d)Recoil mass of $K^+D_s^-$ at $\sqrt{s} = 4.698$ GeV.

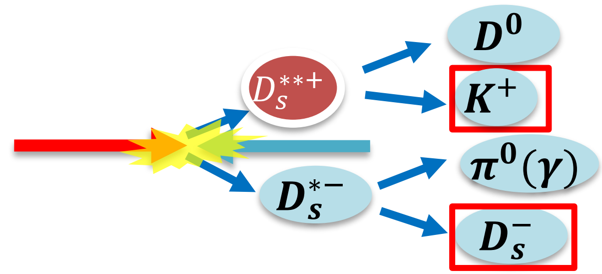
Recoil-mass spectra of K^+ and two-dimensional distributions of $M(K^+D_s^-)$ vs. $RM(K^+)$



- The K^+ recoil-mass spectrum in data at 4.681GeV.
- 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/c^2)	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

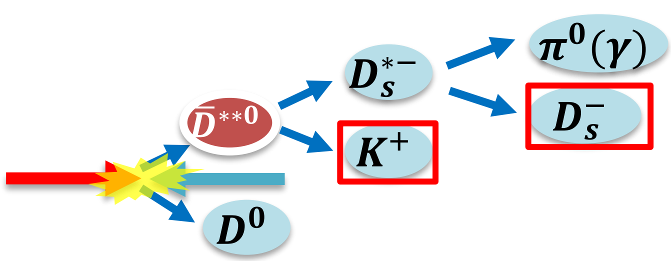
• $D_s^\pm$	$0(0^-)$
• $D_s^{*\pm}$	$0(?^?)$
• $D_{s0}^*(2317)^\pm$	$0(0^+)$
• $D_{s1}(2460)^\pm$	$0(1^+)$
• $D_{s1}(2536)^\pm$	$0(1^+)$
• $D_{s2}^*(2573)$	$0(2^+)$
• $D_{s1}^*(2700)^\pm$	$0(1^-)$
$D_{s1}^*(2860)^\pm$	$0(1^-)$
$D_{s3}^*(2860)^\pm$	$0(3^-)$
$D_{sJ}(3040)^\pm$	$0(?^?)$

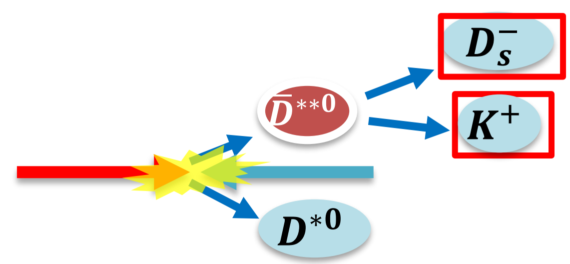
- Most high excited D_s^{**} states have negative Q value or forbidden due to Parity Violation.
- $D_{s1}^*(2536)^+(K^+D^{*0})D_s^-$, $D_{s2}^*(2573)^+(K^+D^0)D_s^{*-}$ and $D_{s1}^*(2700)^+(K^+D^{*0})D_s^-$ are studied using control sample.
- Most high excited $D_{(s)}^{**}$ states contribute a broad 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

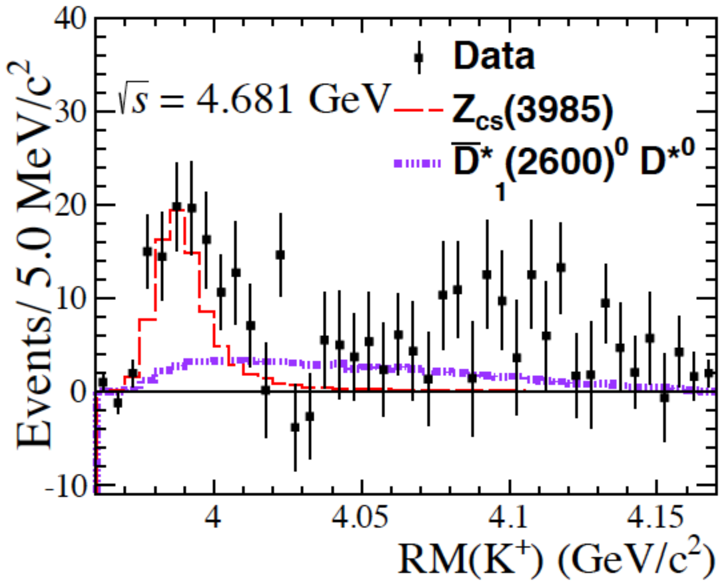
$D_1(2420)^\pm$	$1/2(?^?)$
$D_1(2430)^0$	$1/2(1^+)$
• $D_2^*(2460)^0$	$1/2(2^+)$
• $D_2^*(2460)^\pm$	$1/2(2^+)$
$D(2550)^0$	$1/2(?^?)$
$D_J^*(2600)$	$1/2(?^?)$
was $D(2600)$	
$D^*(2640)^\pm$	$1/2(?^?)$
$D(2740)^0$	$1/2(?^?)$
$D_3^*(2750)$	$1/2(3^-)$
$D(3000)^0$	$1/2(?^?)$





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

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

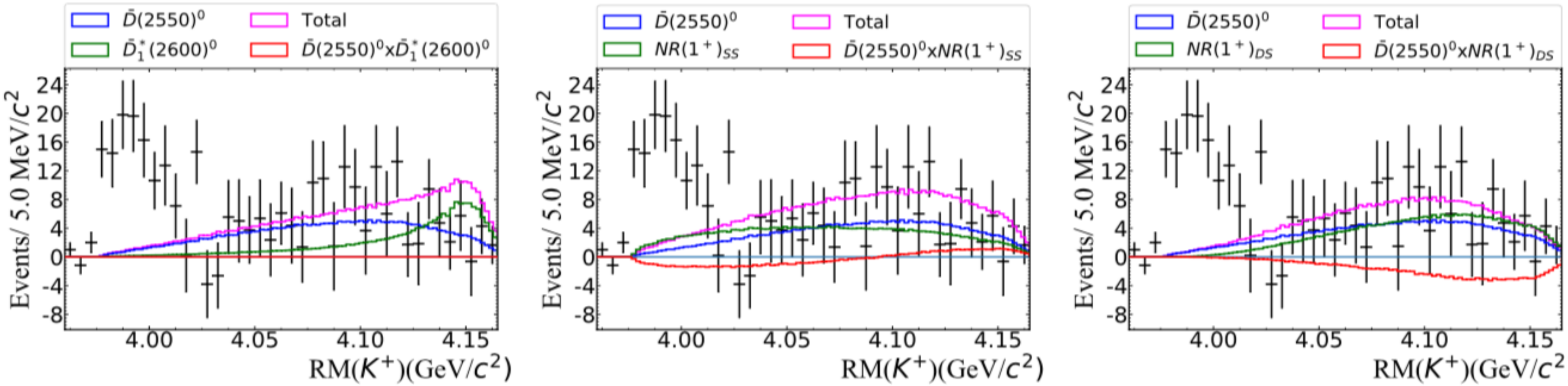


(c) $\bar{D}_1^*(2600)^0(\to D_s^- K^+)D^{*0}$

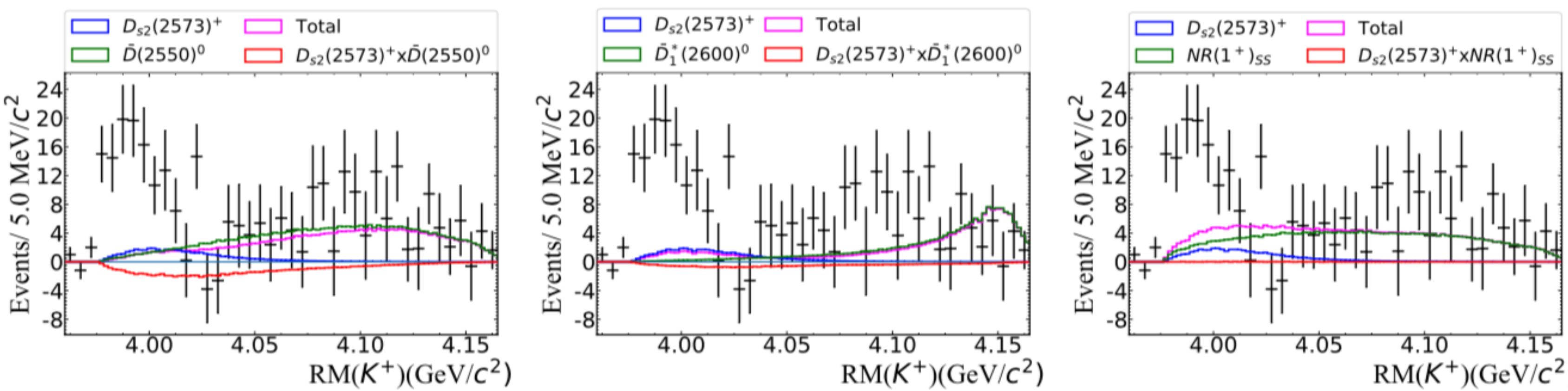
- The $RM(K^+)$ spectrum is distorted due to limited production phase space. However, it is much broader than the observed enhancement.
- $e^+e^- \to D^{*0}\bar{D}_1^*(2600)^0(\to D_s^- K^+)$ is studied using an PWA of control sample $e^+e^- \to D^{*0}\bar{D}_1^*(2600)^0(\to D^-\pi^+)$.
- The ratio R= $B(\bar{D}_1^*(2600)^0 \to D_s^- K^+)/B(\bar{D}_1^*(2600)^0 \to D^-\pi^+)$ 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)



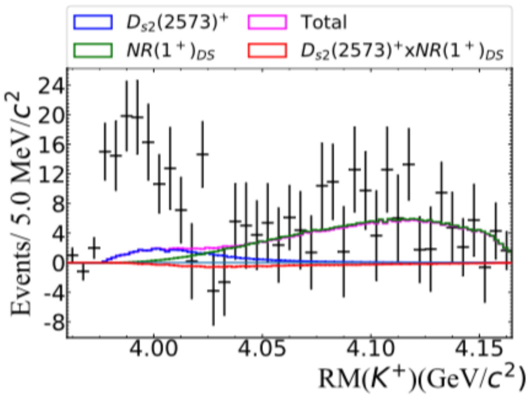
(a) $\bar{D}(2550)^0 D^0$ and $\bar{D}_1^*(2600)^0 D^0$ (b) $\bar{D}(2550)^0 D^0$ and NR $1^+(S,S)$ (c) $\bar{D}(2550)^0 D^0$ and NR $1^+(D,S)$



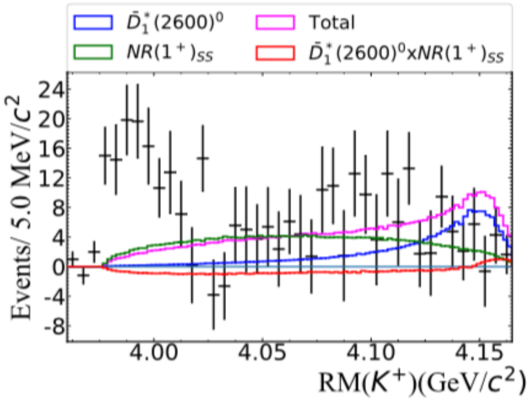
(d) $D_{s2}^*(2573)^+ D_s^{*-}$ and $\bar{D}(2550)^0 D^0$ (e) $D_{s2}^*(2573)^+ D_s^{*-}$ and $\bar{D}_1^*(2600)^0 D^0$ (f) $D_{s2}^*(2573)^+ D_s^{*-}$ and NR $1^+(S,S)$

- 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.

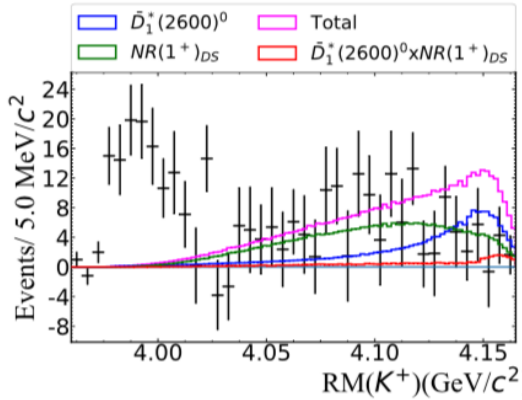
Interference effect of $K^+D_s^{*-}D^0$ final states（2）



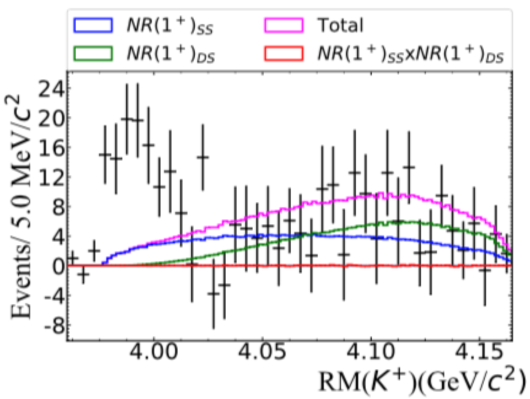
(g)$D^*_{s2}(2573)^+D_s^{*-}$ and NR $1^+(D,S)$



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



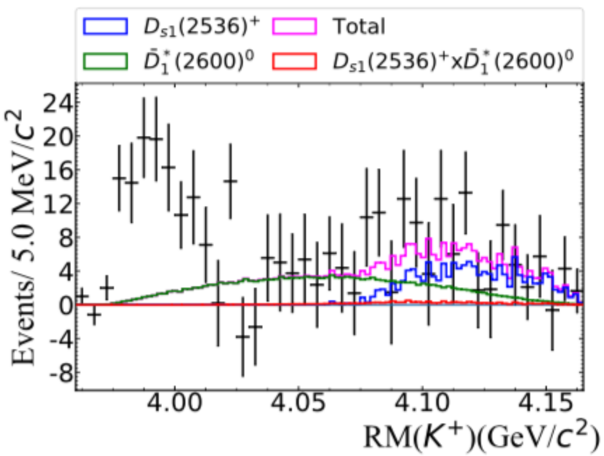
(i)$\bar{D}_1^*(2600)^0D^0$ and NR $1^+(D,S)$



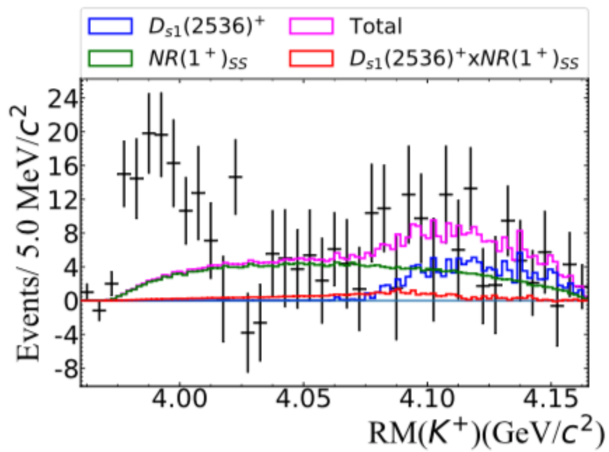
(j)NR $1^+(S,S)$ and NR $1^+(D,S)$

- The component of non-resonant process is also considered under different angular momentum (L_{KX}, $L_{D_s^{*-}D^0}$) assumption.
- Normalizations are scaled according to the observed yields in control samples.

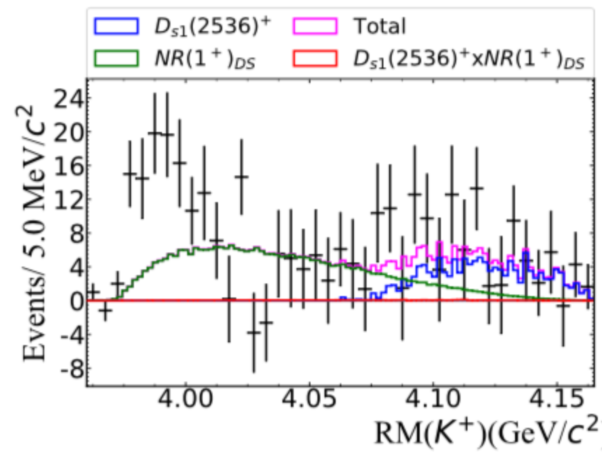
Interference effect of $K^+ D_s^- D^{*0}$ final states (1)



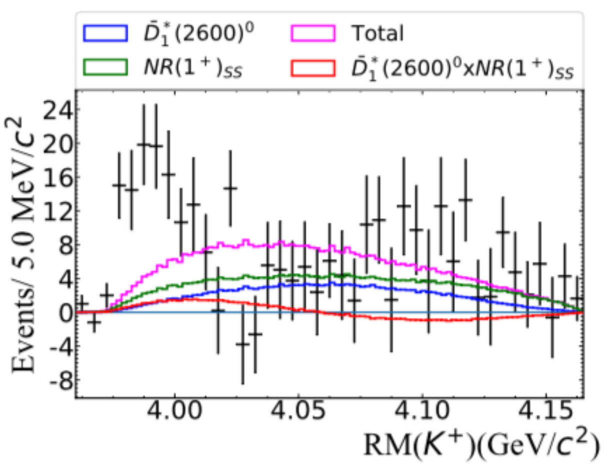
(a) $D_{s1}(2536)^+ D_s^-$ and $\bar{D}_1^*(2600)^0 D^{*0}$



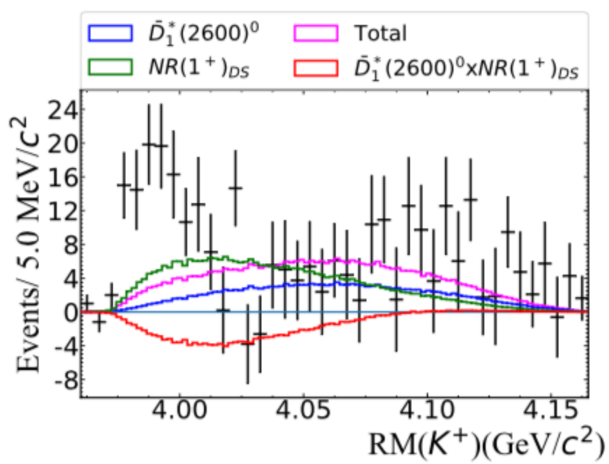
(b) $D_{s1}(2536)^+ D_s^-$ and NR $1^+(S, S)$



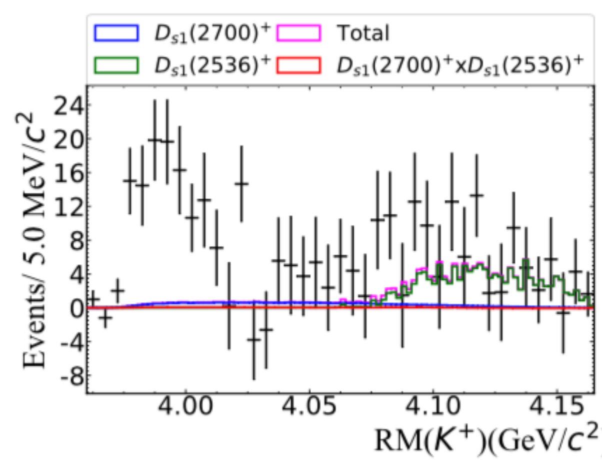
(c) $D_{s1}(2536)^+ D_s^-$ and NR $1^+(D, S)$



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

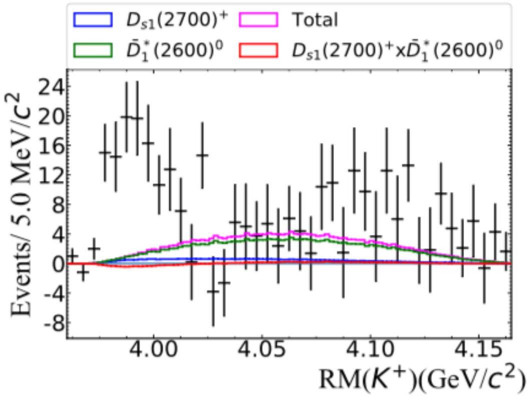


(e) $\bar{D}_1^*(2600)^0 D^{*0}$ and NR $1^+(D, S)$

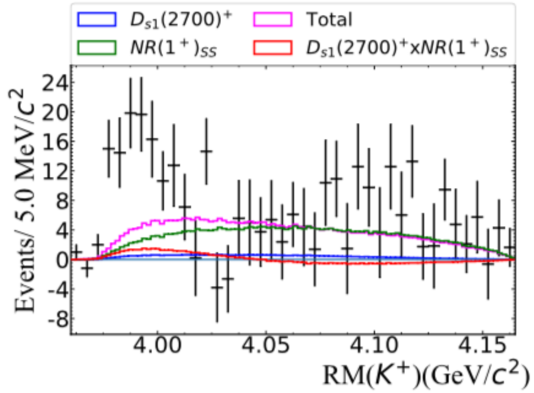


(f) $D_{s1}^*(2700)^+ D_s^-$ and $D_{s1}(2536)^+ D_s^-$

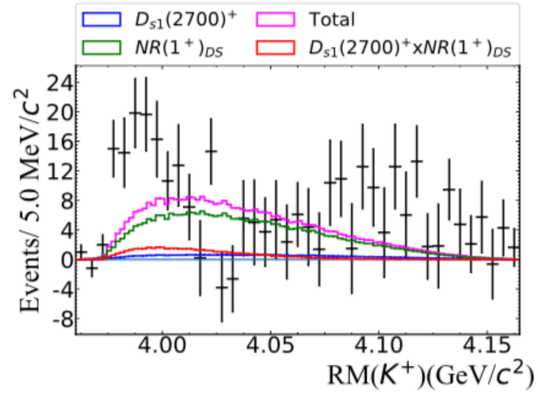
Interference effect of $K^+ D_s^- D^{*0}$ final states (2)



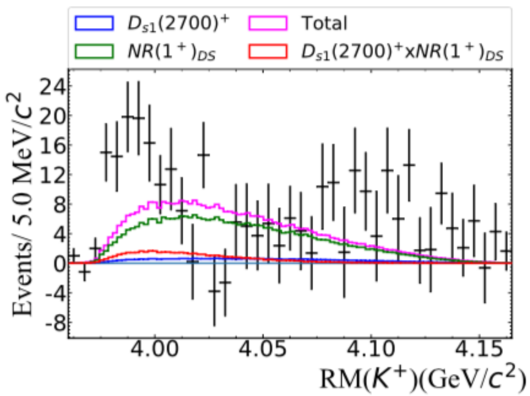
(g)$D_{s1}^*(2700)^+ D_s^-$ and $\bar{D}_1^*(2600)^0 D^{*0}$



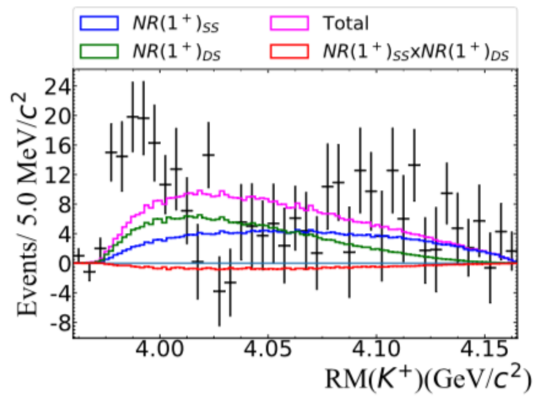
(h)$D_{s1}^*(2700)^+ D_s^-$ and NR $1^+(S, S)$



(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 $1^+(D, S)$

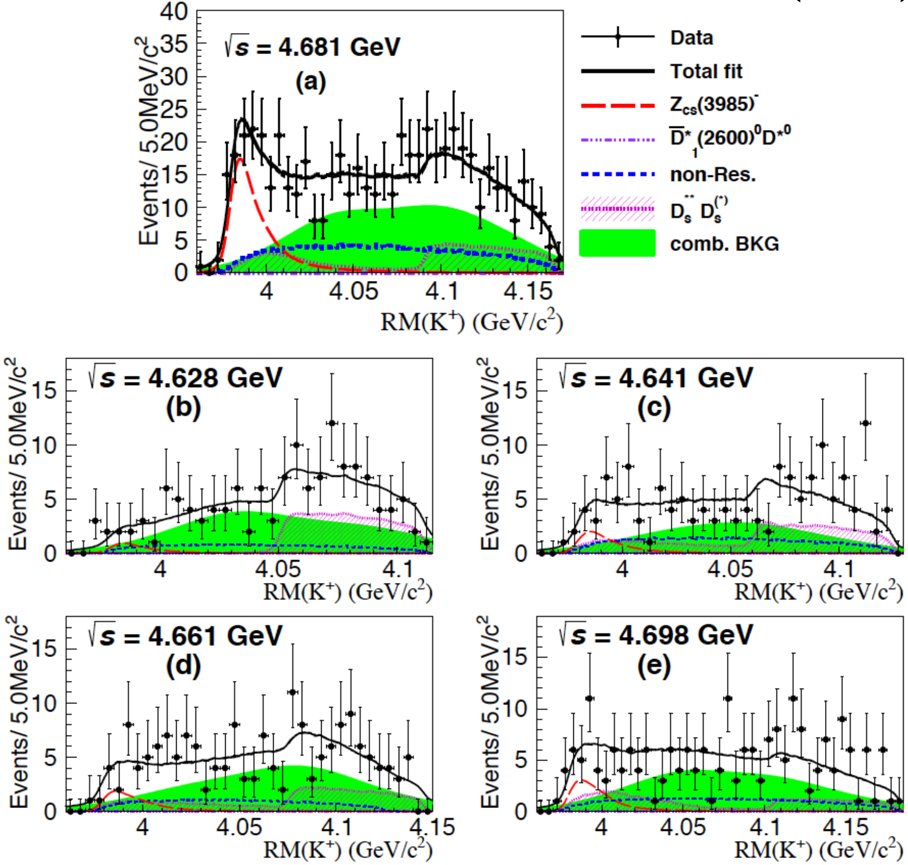
Interference between any two $D_{(s)}^{**}$/NR will not produce such a narrow peak we observed in data.

What do we learn

- 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^+

PRL 126, 102001 (2021)



Resonance parameter:

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

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

- 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.

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

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

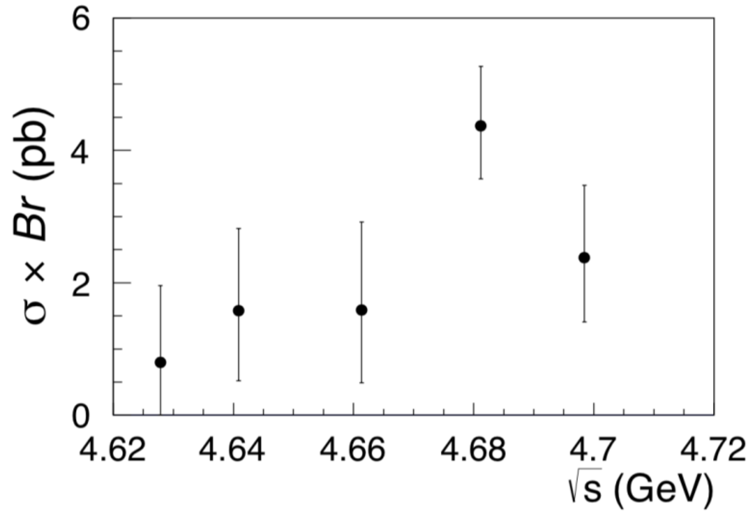
- The potential interference effects are neglected.
- The J^P of $Z_{cs}(3985)^-$ is assumed as 1^+; =>(S,S) is the most promising configuration.
- The significance with systematic uncertainties and look-elsewhere effect considered is evaluated to 5.3σ.
- $e^+e^- \to D^{*0}\bar{D}_1^*(2600)^0(\to D_s^-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

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

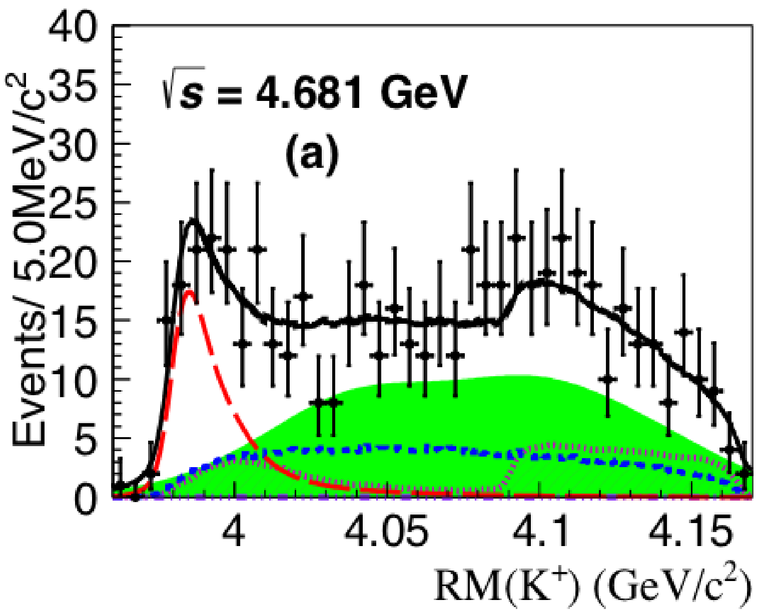
$$\Gamma_0(Z_{cs}(3985)^-) = 13.8^{+8.1}_{-5.2}(stat.) \pm 4.9(sys.)\mathrm{MeV}.$$

Pole position:

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

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

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

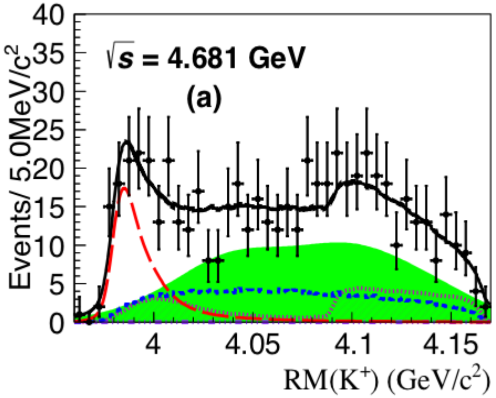


- Only a few MeV higher than the threshold of $D_s^- D^{*0}/D_s^{*-} D^0$ (3975.2/3977.0)MeV/c^2.
- At least four quark state ($c\bar{c}s\bar{u}$) and a charged hidden-charm state with strangeness.

- 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.

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

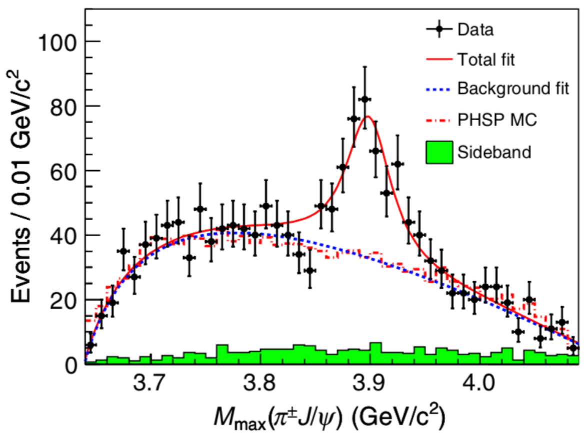
	1643/pb data @4.681 GeV	525/pb data @4.26 GeV
	$Z_{cs}(3985)^{\pm}$	$Z_c(3900)^{\pm}$
Mass (MeV/c^2)	$3985.2^{+2.1}_{-2.0} \pm 1.7$	$3899 \pm 3.6 \pm 4.9$
Width (MeV)	$13.8^{+8.1}_{-5.2} \pm 4.9$	$46 \pm 10 \pm 26$
$\sigma^{Born} \cdot \mathfrak{B}$ (pb)	$4.4^{+0.9}_{-0.8} \pm 1.4$	$13.5 \pm 2.1 \pm 4.8$



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

two general comments about
charm-tau factory program

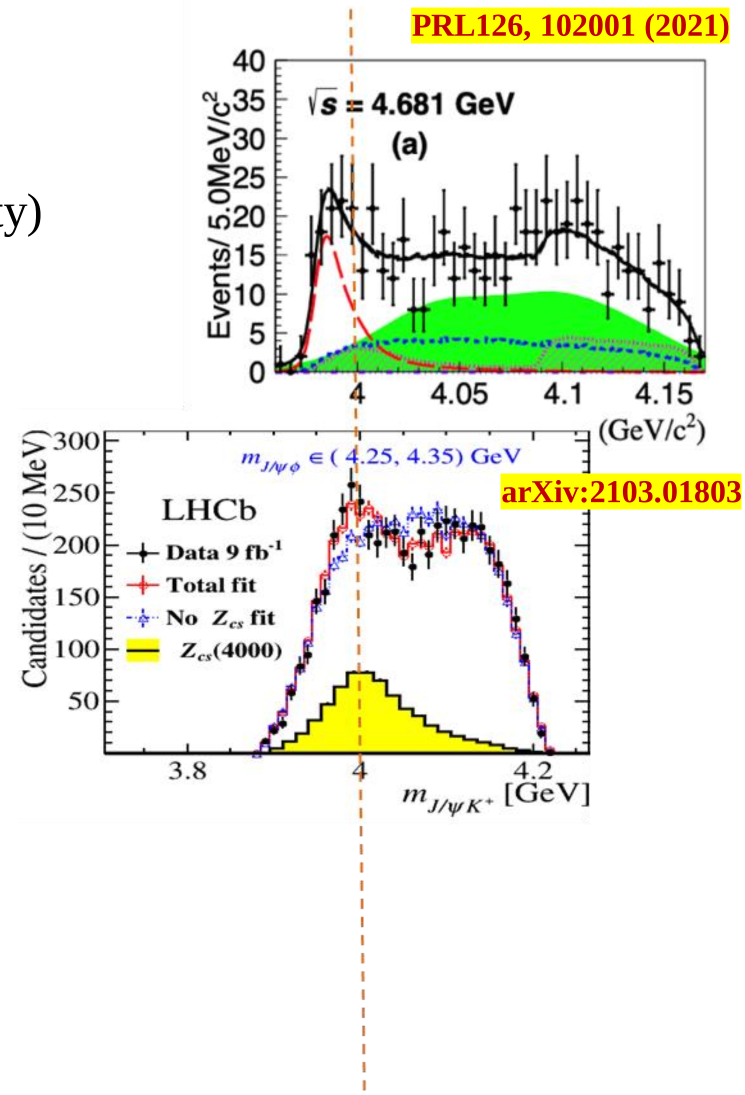
- $J/\psi K^{\pm}$ resonances:
  $Z_c(3900)$ analogue?
  $Z_c(3900)^+ = (c\bar{c}u\bar{d})$; $d \to s$: $(c\bar{c}u\bar{s}) \sim D_s\bar{D}^*$
  no natural molecular binding,
  so if discovered, would indicate
  Tq or a novel mechanism

from Marek Karliner

SU(3) partner of Zc(3900)?

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

- **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
- If they are same, why width so different?
- If they are not same, is there the corresponding wide Zc(3900)?
- Looking for more channels will be useful

What next?

- We are proposing more data taking near 4.681GeV.
- Precise resonant parameters.
- Spin-parity [PWA].
- More decay modes, like $K^{(*)-}J/\psi$,$K^{(*)-}h_c$, $K^{(*)-}\eta_c$ or $K^{(*)-}\chi_{cJ}$.
- Production mechanisms.
- Test various theoretical models.
- Neutral partner of Z_{cs}^0[on going] : $K_s^0(D_s^- D^{*+} + D_s^{*+} D^-)$.
- Other Z_{cs}^- states? Z_{cs}^{*-} states? [on going] : $K^+ D_s^{*-} D^{*0}$.
- Search Z_{cs}^- state in LHCb using open-charm is important.
- Other Z_{bs}^- states? Z_{bs}^{*-} states?

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

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

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

- 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!

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

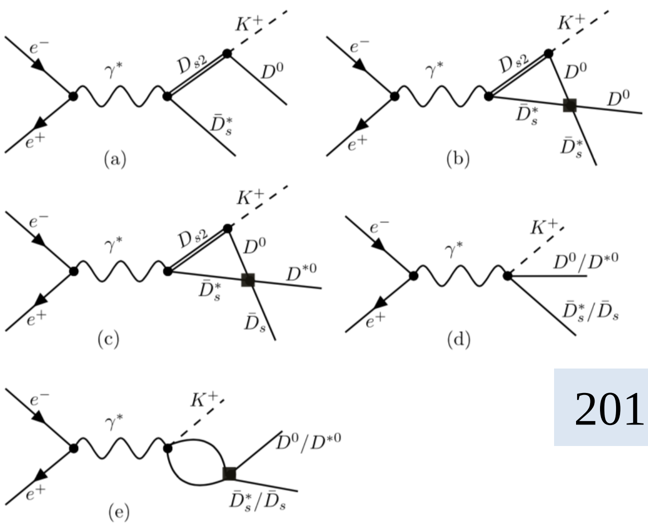
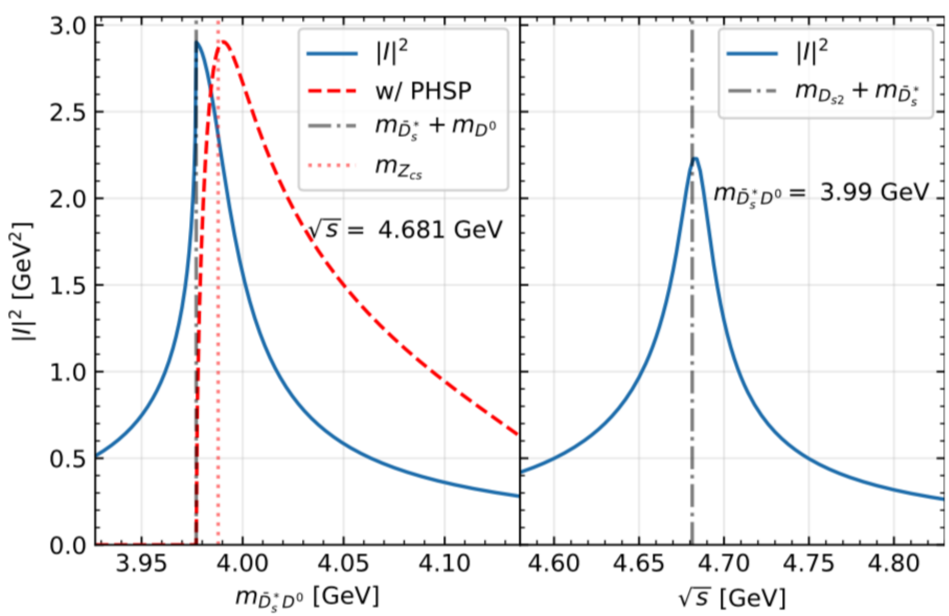


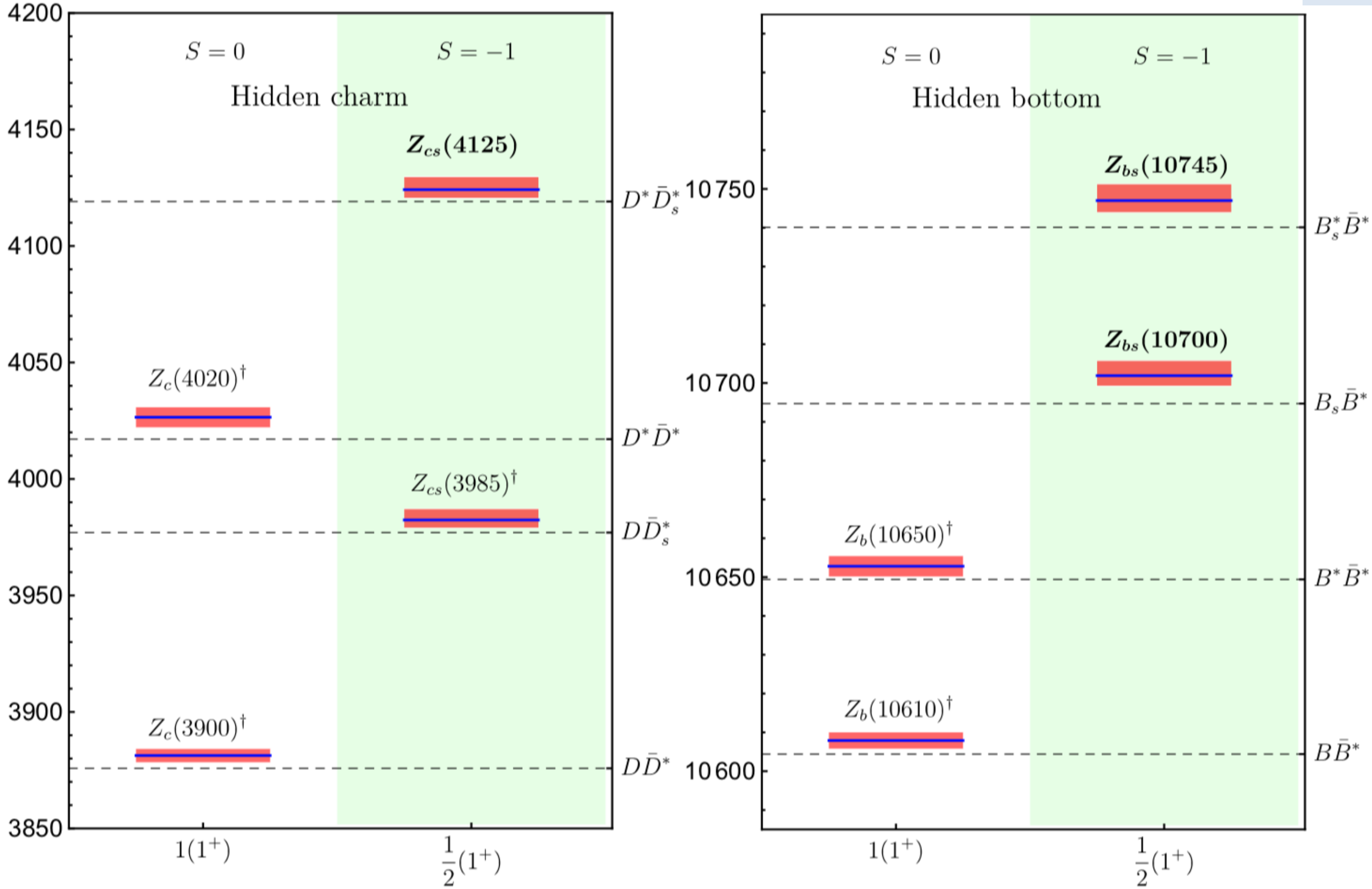
FIG. 1. Feynman diagrams for the production mechanisms considered in this work: (a) and (b) for the $K^+ D_s^* \bar{D}^0$; (c) for the $K^+ D_s \bar{D}^{*0}$; (d) and (e) for both final states. The filled squares denote the T-matrix elements which include the effects of the generated Z_{cs} state.

2011.08725

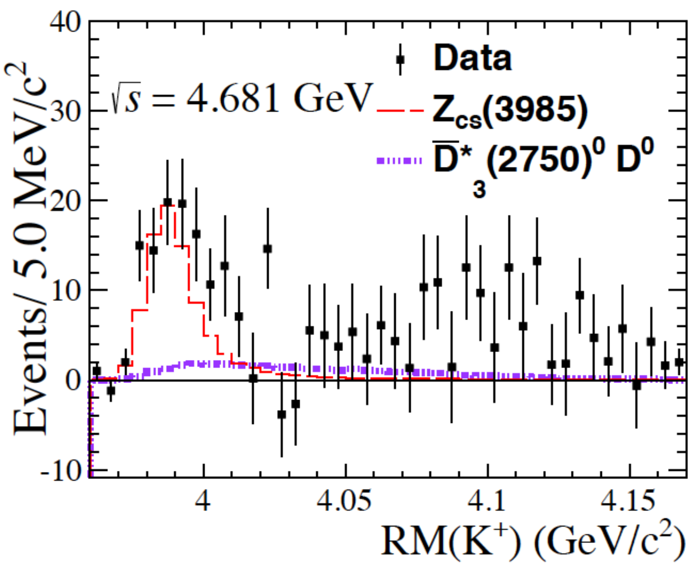


$Z_{c(s)}^{(\prime)}$ and $Z_{b(s)}^{(\prime)}$

2011.10922



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



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

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

Godfrey_PhysRevD.93.034035(2016)

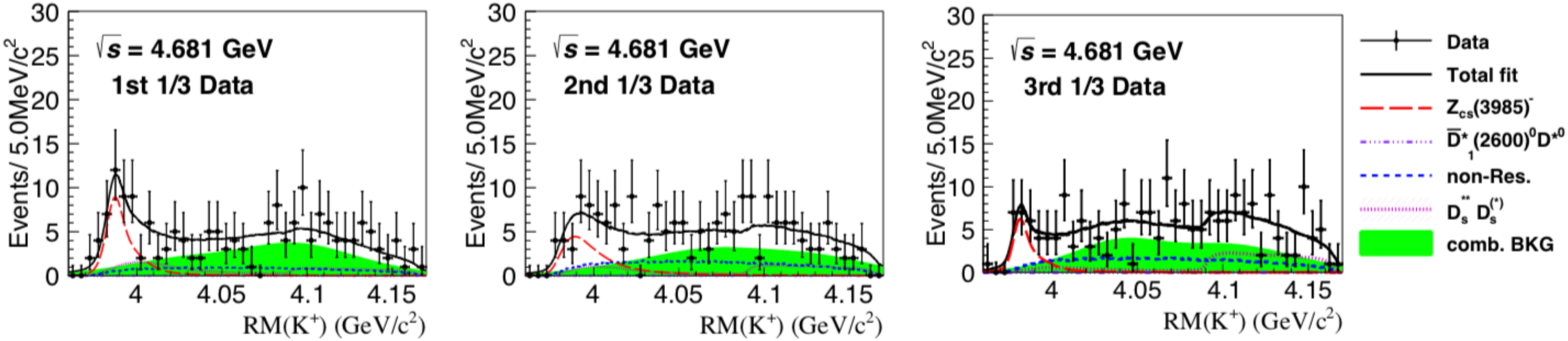
Initial state	Final state	Width (cu, cd) (MeV)	BR (cu, cd) (%)
$D(1^3D_3)$ 2833	$D(1^3P_2)\gamma$	0.69, 0.07	1.34, 0.14
	$D\pi$	20.1	39.2
	$D\rho$	1.30	2.5
	$D\eta$	1.24	2.4
	$D^*\pi$	15.5	30.2
	$D^*\rho$	7.56	14.8
	$D^*\omega$	1.1	2.2
	$D(1^3P_2)\pi$	0.9	1.8
	D_sK	1.1	2.20
	Total	51	100

$\sqrt{s}$(GeV)	4.628	4.641	4.661	4.681	4.698
$\bar{D}_3^*(2750)^0(\to D_s^{*-}K^+)D^0$	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 $\bar{D}_3^*(2750)$ contributions at each energy point is negligible.
- ☐ Both decay and production of $e^+e^- \to D^0\bar{D}_3^*(2750)^0(\to D_s^{*-}K^+)$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.

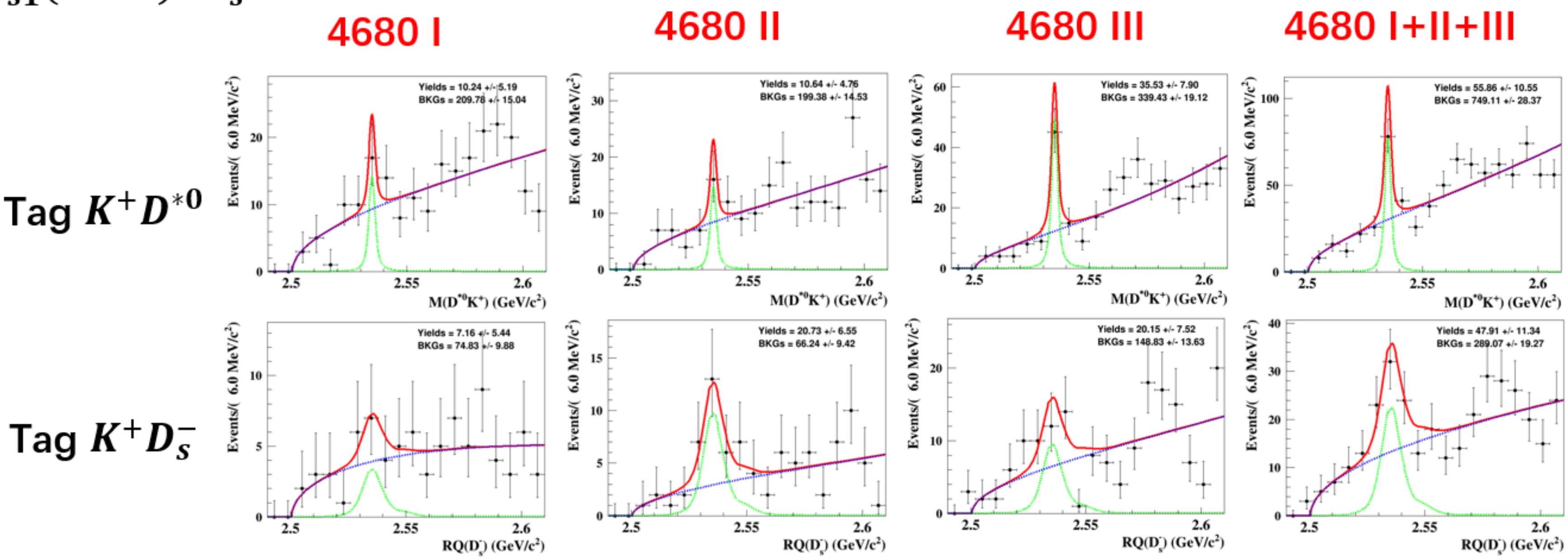


Data set	Mass (MeV/c^2)	Width (MeV)	$\sigma_{4.681} \cdot \mathcal{B}$(pb)	Statistical Significance
1st one-third	$3987.0^{+2.1}_{-2.4}$	$6.9^{+6.1}_{-4.1}$	$5.1^{+1.4}_{-1.2}$	4.9σ
2nd one-third	$3990.2^{+5.6}_{-5.5}$	$24.2^{+31.0}_{-12.4}$	$5.0^{+2.3}_{-1.8}$	2.9σ
3rd one-third	$3980.9^{+2.0}_{-2.2}$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

D_s^{**} background ($D_{s1}(2536)^+D_s^-$)

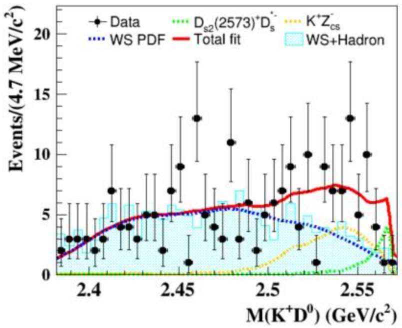
$D_{s1}(2536)^+D_s^-$

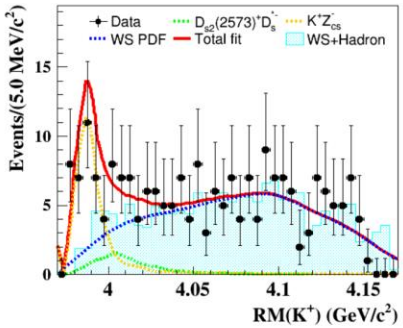


	4680 I	4680 II	4680 III	4680 I+II+III
K^+D^{*0}	10.2 ± 5.2	10.6 ± 4.8	35.5 ± 7.9	55.9 ± 10.6
$K^+D_s^-$	7.2 ± 5.4	20.7 ± 6.5	20.2 ± 7.5	47.9 ± 11.3
N^{exp}	9.2 ± 3.9	14.8 ± 5.6	28.9 ± 5.7	54.4 ± 8.0

D_s^{**} background ($D_{s2}^*(2573)^+ D_s^{*-}$) Data I+II+III @4.681 GeV

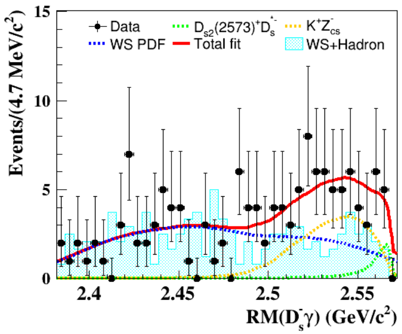
Tag $K^+D^0\gamma$ WS + Hadron + Hadron WS本底

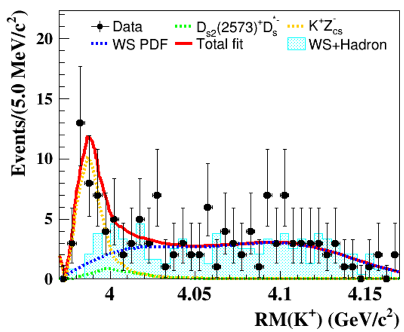




	N_{obs}	σ^{obs}
$D_{s2}(2573)^+ D_s^{*-}$	12.0 ± 5.3	1.14 ± 0.50
$K^+Z_{cs}^-$	43.6 ± 7.9	6.25 ± 1.13

Tag $K^+D_s^{*-}$

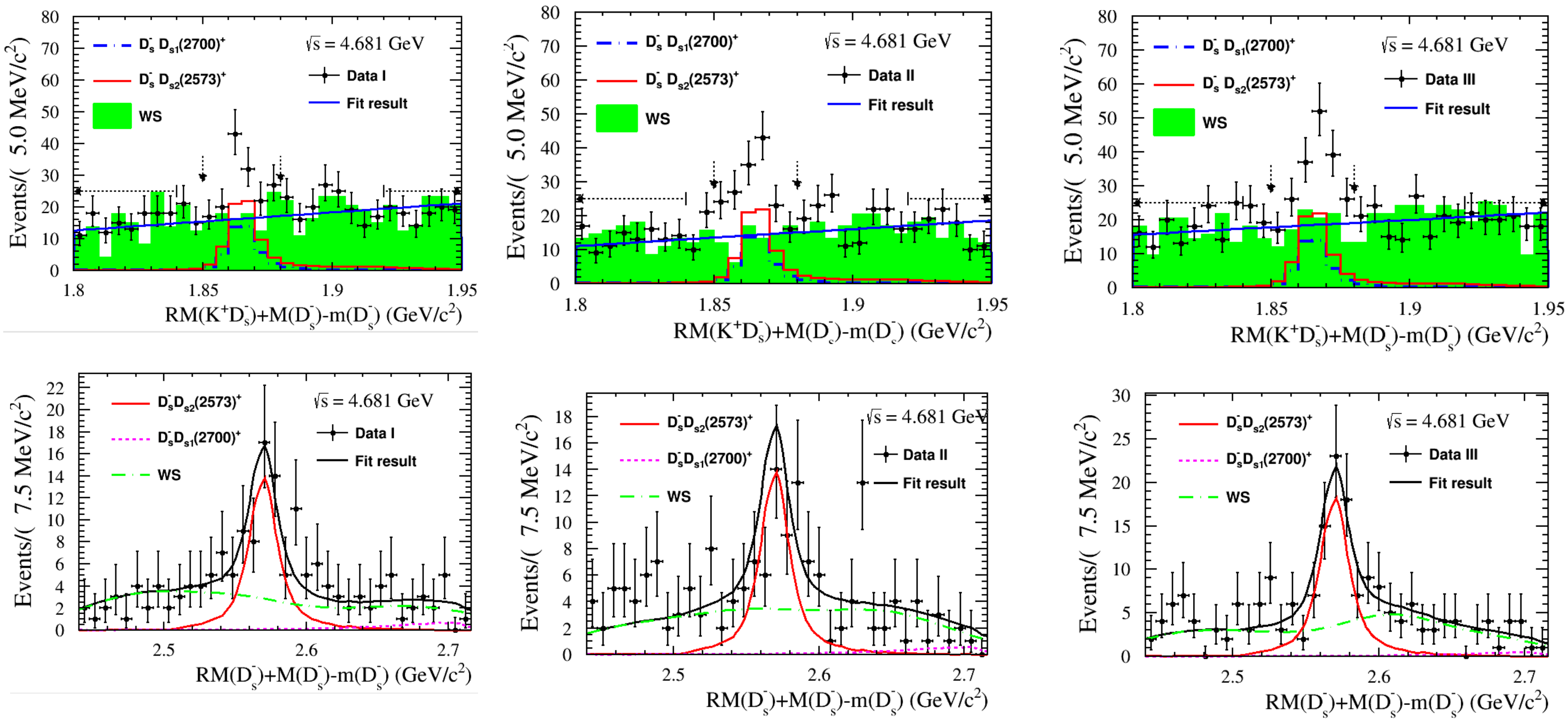




	N_{obs}	σ^{obs}
$D_{s2}(2573)^+ D_s^{*-}$	5.76 ± 4.78	0.68 ± 0.57
$K^+Z_{cs}^-$	38.8 ± 7.55	4.9 ± 0.9

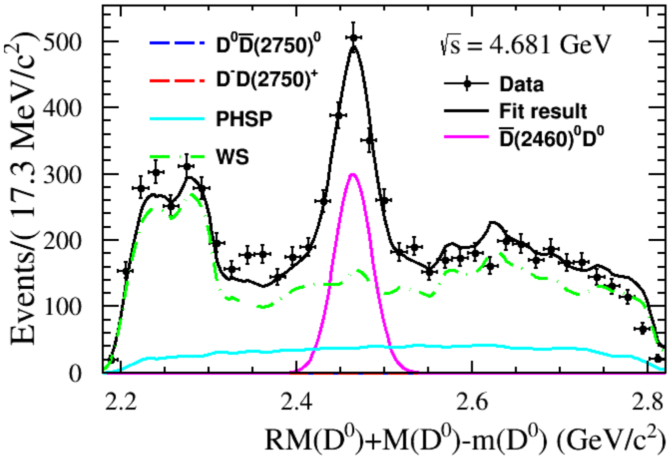
Average: 0.94 ± 0.38 pb   **Yields: 19.07 ± 7.63**

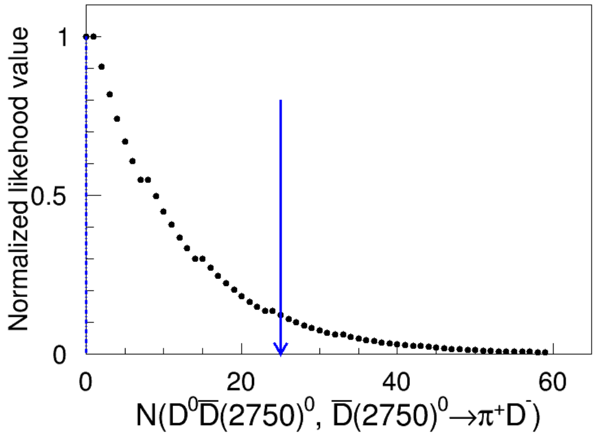
D_s^{**} background ($D_{s1}^*(2700)^+D_s^-$)



	Data I	Data II	Data III	Data I+II+III
$N(D_{s1}^*(2700)^+D_s^-)$	8.03 ± 7.99	5.49 ± 7.68	5.26 ± 7.39	15.03 ± 13.33

$D^0\bar{D}(2750)^0, \bar{D}(2750)^0 \to D^-\pi^+$





$$n_{D(2750)} = 0.0 \pm 5.8$$

$$n_{D(2750)}^{upper} = 25 \ (90\% \ C.L.)$$

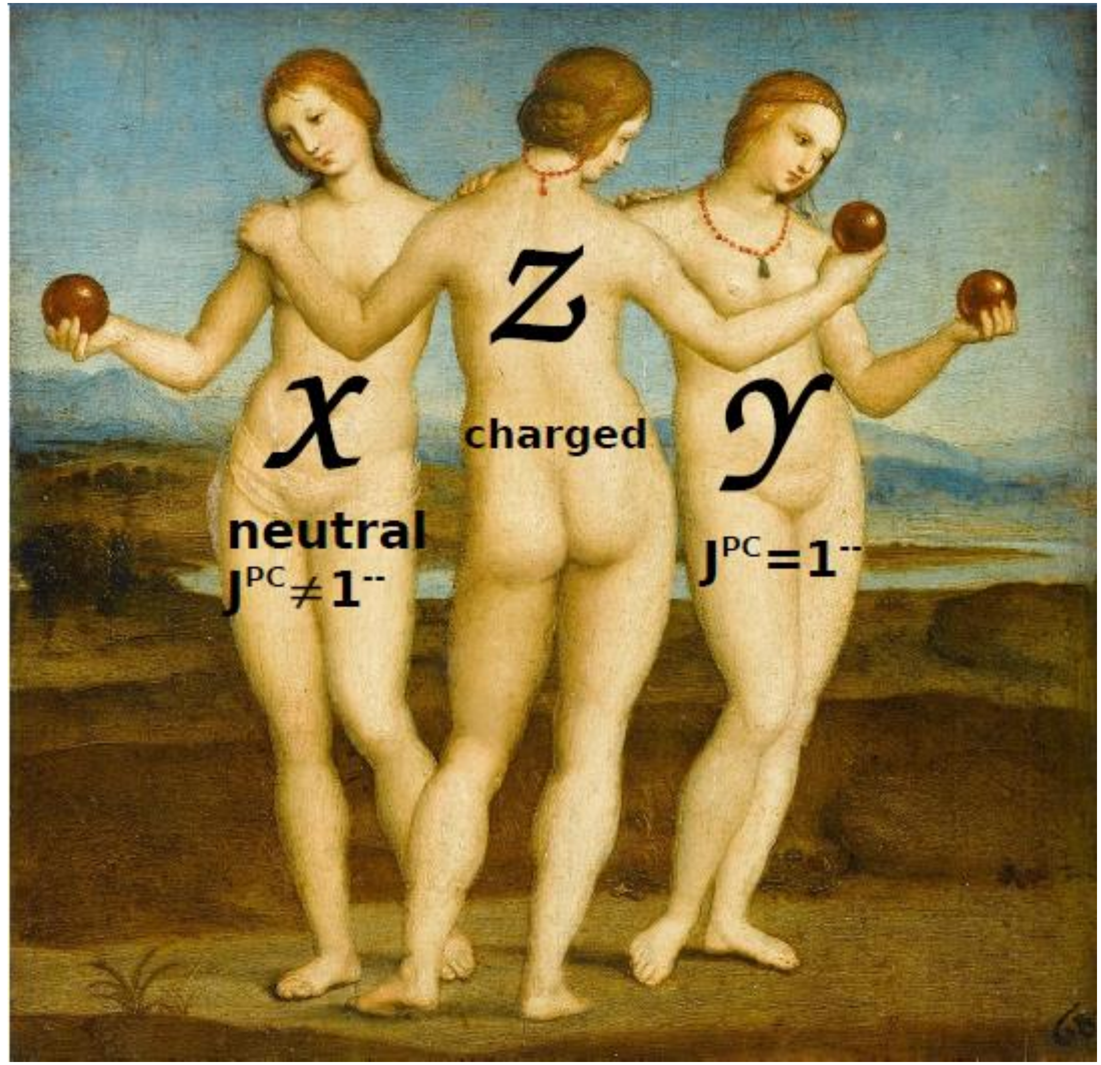
For $D^0\bar{D}(2750)^0, \bar{D}(2750)^0 \to D^-\pi^+$: $\varepsilon(\pi D) = 7.0 \pm 0.1\%$
For $D^0\bar{D}(2750)^0, \bar{D}(2750)^0 \to D_s^{*-}K^+$: $\varepsilon(KD_s^*) = 12.0 \pm 0.1\%$

$D(1^3D_3)$ 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

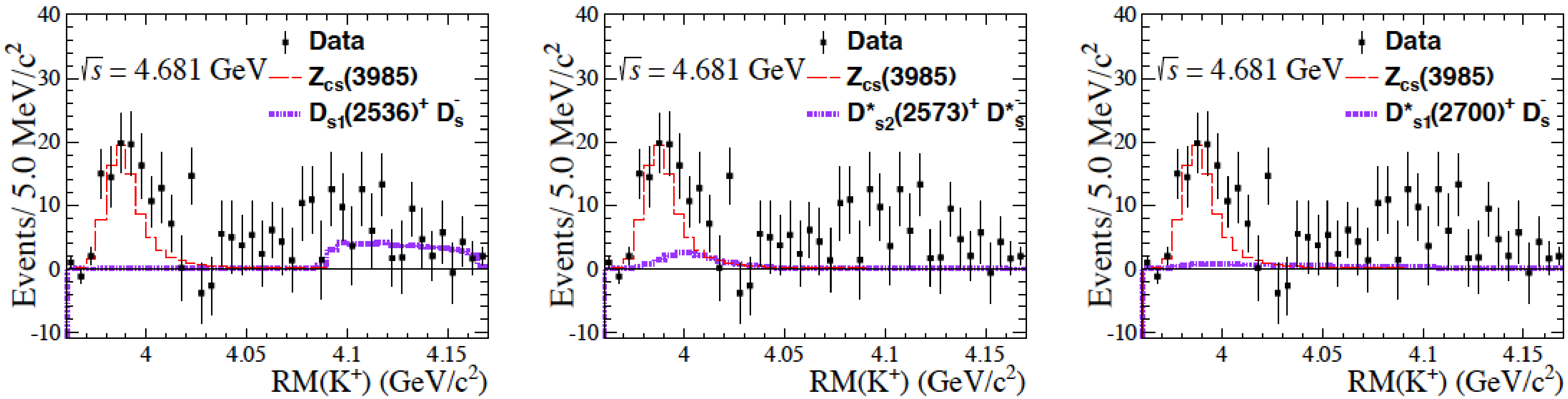
$$\frac{B(KD_s^*)}{B(\pi D)} = \frac{1.1 \cdot (0.75)}{20.1} = 4.1\%$$

$$n^{obs}(KD_s^*) = n^{obs}(\pi D) \cdot \frac{B(KD_s^*)}{B(\pi D)} \cdot \frac{\varepsilon(KD_s^*)}{\varepsilon(\pi D)} = 0.0 \pm 0.4(< 1.8)$$

Exotic quarkonium-like spectroscopy



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

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

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

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

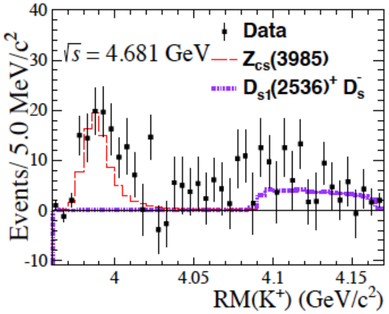
BaBar_PhysRevD.80.092003(2009)

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

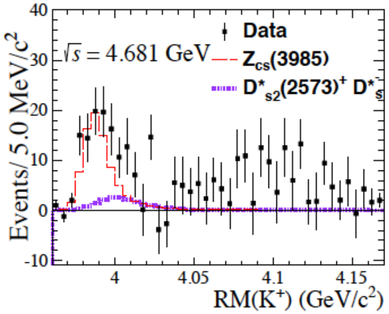
$\sqrt{s}$(GeV)	4.628	4.641	4.661	4.681	4.698
$D_{s1}(2536)^+(K^+D^{*0})D_s^-$	41.2 ± 6.3	26.2 ± 5.4	23.9 ± 5.6	54.4 ± 8.0	15.3 ± 4.2
$D^*_{s2}(2573)^+(K^+D^0)D_s^{*-}$	–	–	–	19.1 ± 7.6	17.3 ± 7.3
$D^*_{s1}(2700)^+(K^+D^{*0})D_s^-$	0.0 ± 1.8	18.6 ± 8.7	16.6 ± 7.8	15.0 ± 13.3	7.7 ± 8.4

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

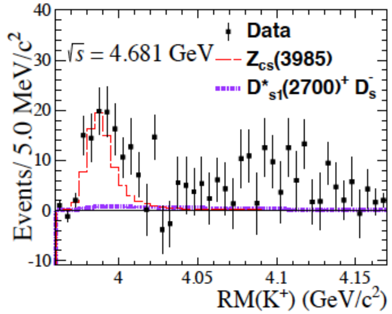
Check with high excited $D_{(s)}^{**}$ states



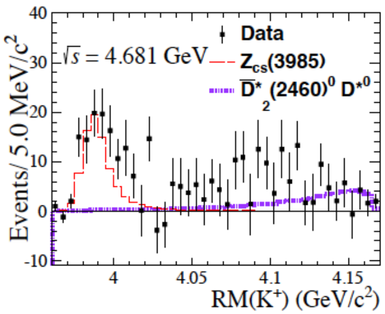
(a) $D_{s1}(2536)^+(\to D^{*0}K^+)D_s^-$



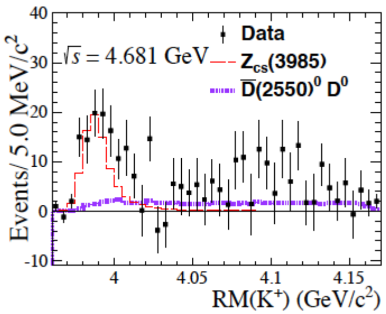
(b) $D_{s2}^*(2573)^+(\to D^0K^+)D_s^{*-}$



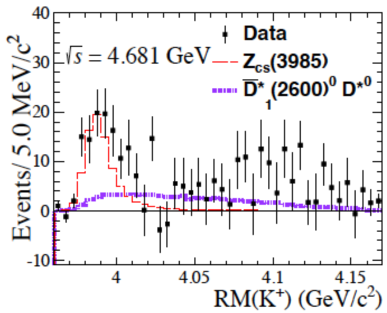
(c) $D_{s1}^*(2700)^+(\to D^{*0}K^+)D_s^-$



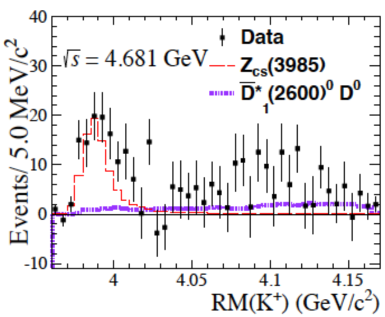
(a) $\bar{D}_2^*(2460)^0(\to D_s^-K^+)D^{*0}$



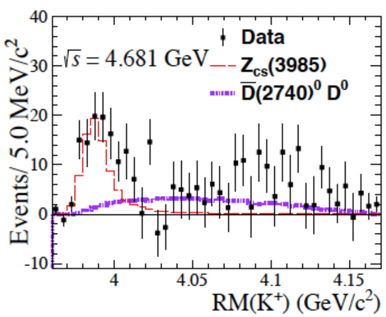
(b) $\bar{D}(2550)^0(\to D_s^{*-}K^+)D^0$



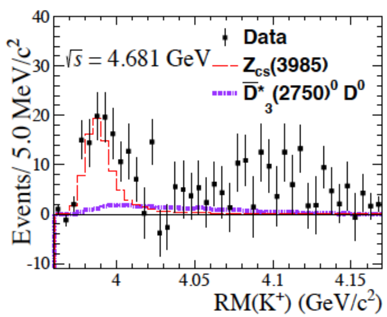
(c) $\bar{D}_1^*(2600)^0(\to D_s^-K^+)D^{*0}$



(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.**