强子物理在线论坛

Hadron Physics Online Forum (HAPOF)

# Latest results on exotic hadrons at BESIII

□ Observation of the charged $Z_{cs}(3985)^-$ in $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$

arXiv: 2011.07855


**Pei-Rong Li (李培荣)**

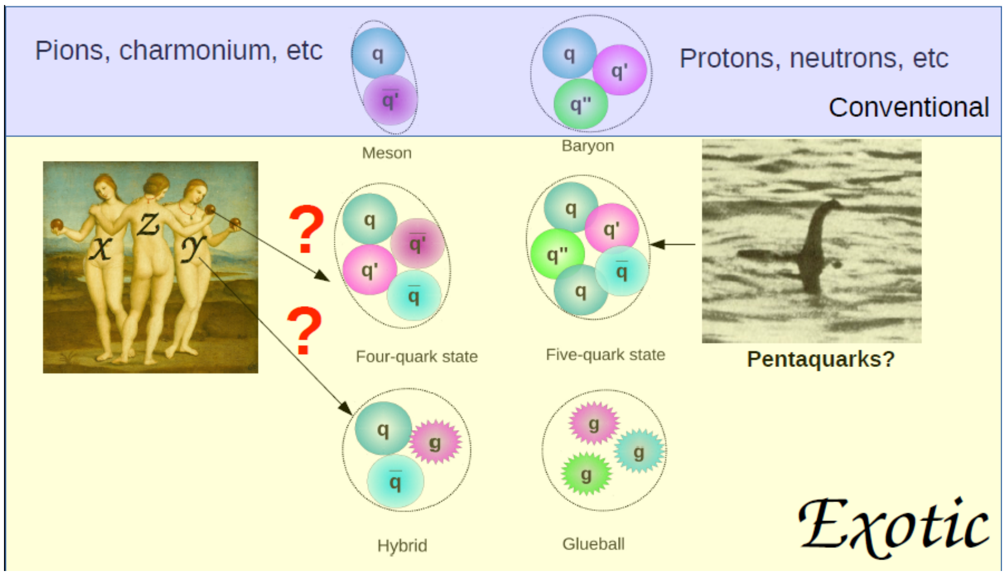
**(Lanzhou University)**


**On behalf of the BESIII Collaboration**

**2020.11.27**

# QCD predicted states

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



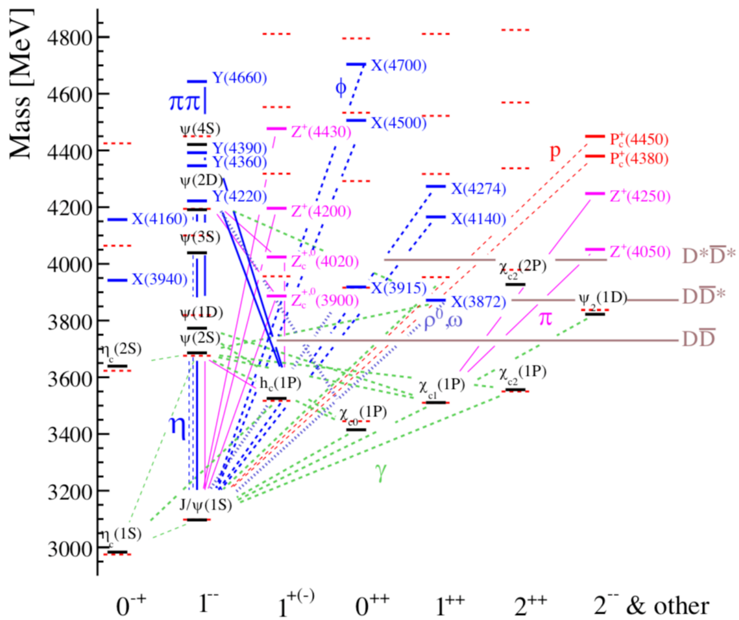

Different compositions and binding schemes:

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

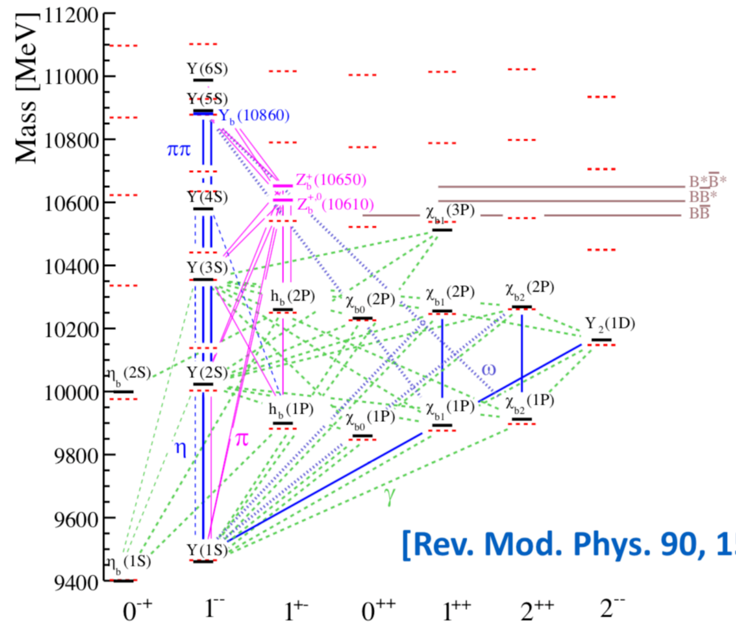
- Provide new insights into internal structure and dynamics of hadrons.
- Unique probe to non-perturbative behavior of QCD.

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

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



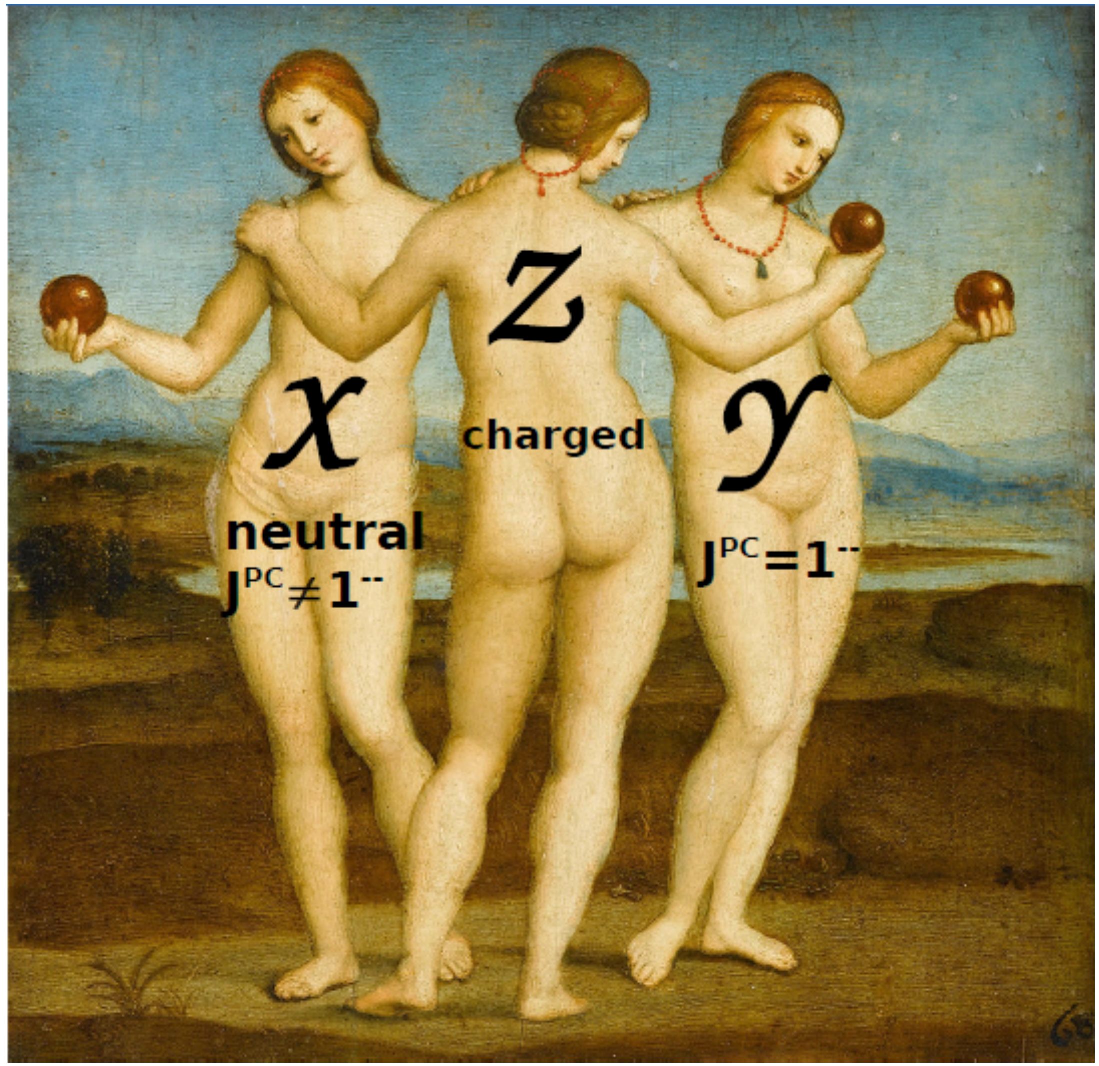

**Bottomonium ($b\bar{b}$)-like spectrum**




[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.

# Exotic quarkonium-like spectroscopy

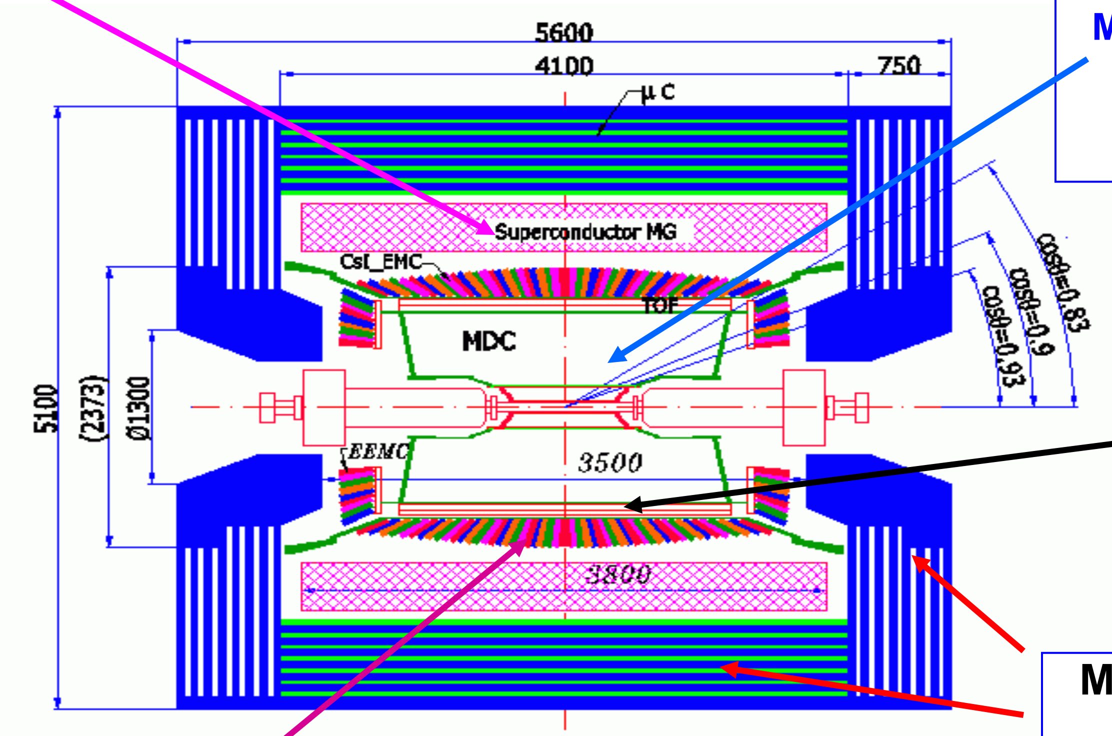


# The BESIII Detector

*NIM A614, 345 (2010)*

**Magnet: 1T Super conducting**

**MDC: small cell & He gas**
$\sigma_{xy}$=130 μm
$\sigma_p/p$ = 0.5% @1GeV
dE/dx=6%




**TOF:**
$\sigma_T$ = 60 ps Barrel
70 ps Endcap

**Muon ID: 8~9 layer RPC**
$\sigma_{R\Phi}$=1.4 cm~1.7 cm

**EMCAL: CsI crystal**
$\Delta E/E$ = 2.5% @1 GeV
$\sigma_{\varphi,z}$ = 0.5~0.7 cm/$\sqrt{E}$

**Data Acquisition:**
Event rate = 3 kHz
Throughput ~ 50 MB/s

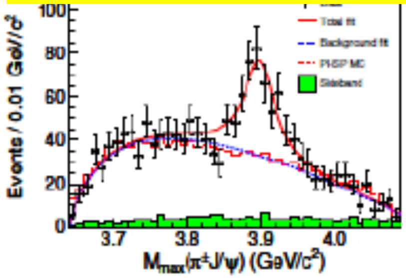
**Trigger: Tracks & Showers**
Pipelined; Latency = 6.4 μs

**The new BESIII detector is hermetic for neutral and charged particle with excellent resolution, PID, and large coverage.**

# The Zc Family at BESIII

**Zc(3900)$^+$**

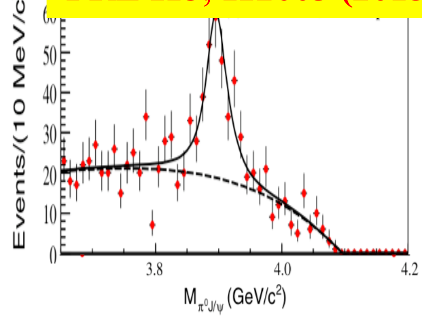
PRL 110, 252001 (2013)




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

**Zc(3900)$^0$**

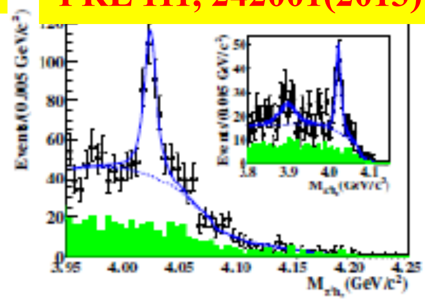
PRL 115, 112003 (2015)




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

**Zc(4020)$^+$**

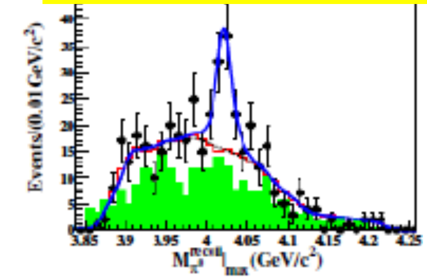
PRL 111, 242001(2013)



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

**Zc(4020)$^0$**

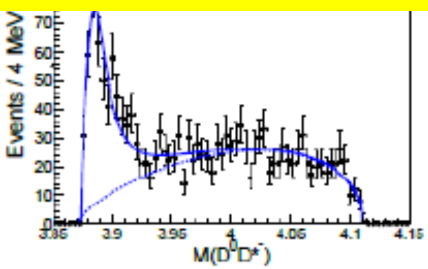
PRL113,212002 (2014)



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

**Zc(3885)$^+$**

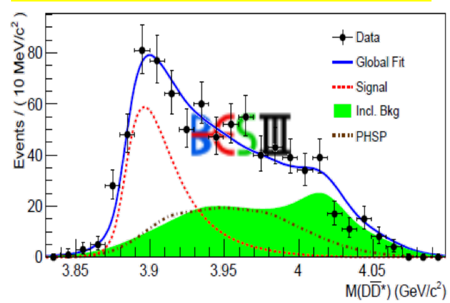
ST: PRL 112, 022001(2014)
DT: PRD92, 092006 (2015)




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

**Zc(3885)$^0$**

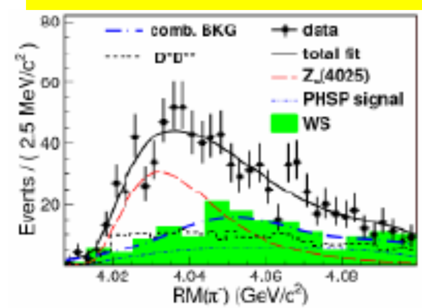
PRL115, 222002 (2015)




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

**Zc(4025)$^+$**

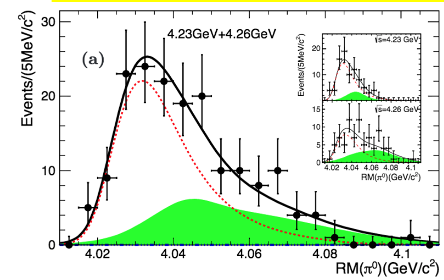
PRL 112, 132001 (2014)




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

**Zc(4025)$^0$**

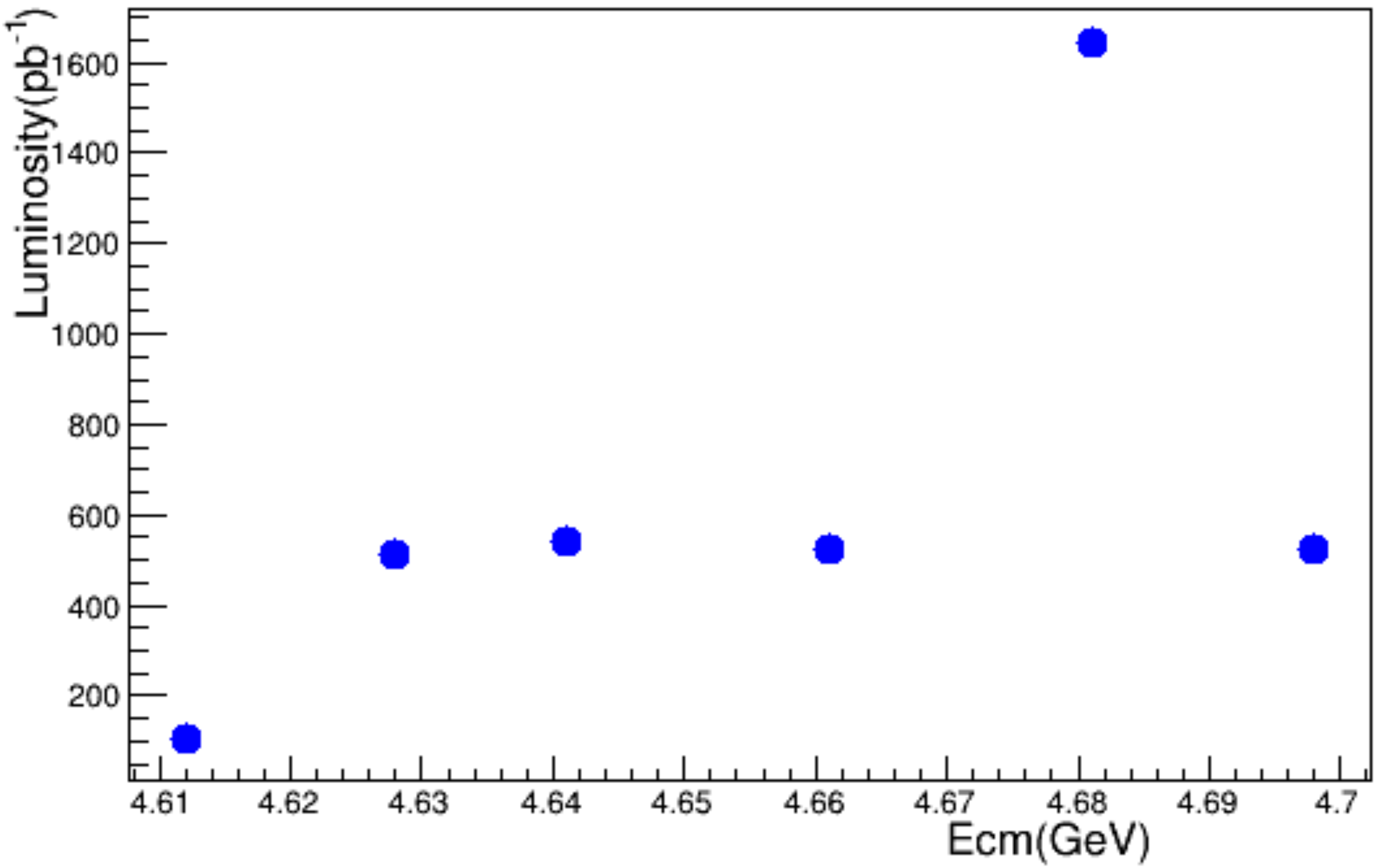
PRL115, 182002 (2015)




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

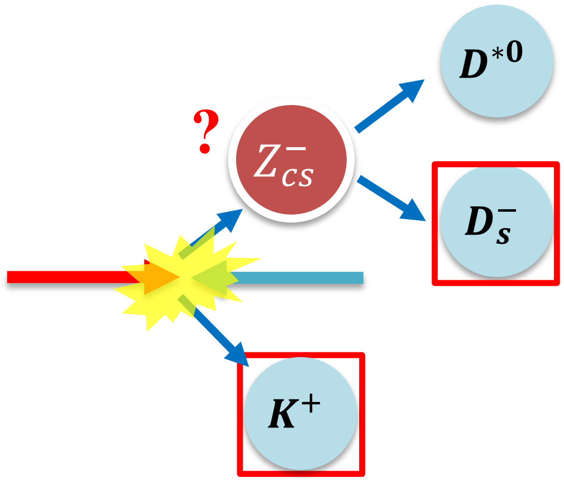
- What is the nature of these states?
- Different decay channels of the same observed states? Other decay modes? $J^P$?
- Searches for $Z_{cs}$ partners were proposed few years ago. e.g., $Z_{cs}/Z'_{cs} \to KJ/\psi$, $D_sD^*$, $D_s^*D$, $D_s^*D^*$ etc. => decay rate of $Z_{cs}$ to open-charm final states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

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

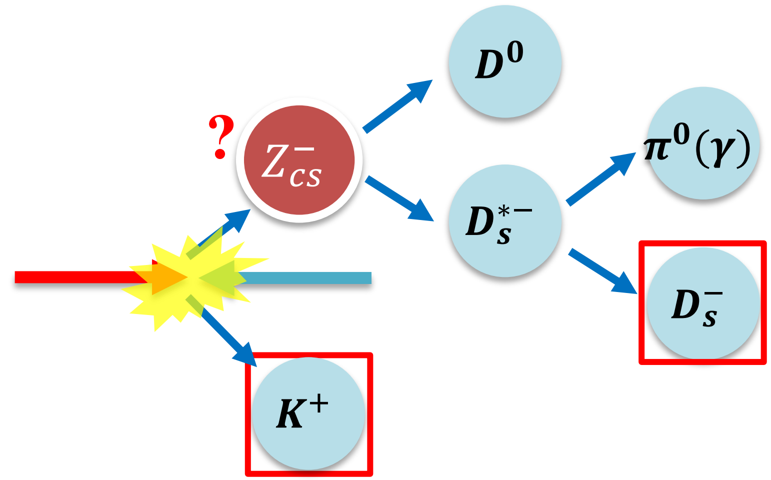



- BEPCII extend the energy limit to 4.7GeV in 2019-2020.
- We analyze 3.7fb$^{-1}$ data accumulated at 4.628, 4.641, 4.661, 4.681, 4.698GeV.

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




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

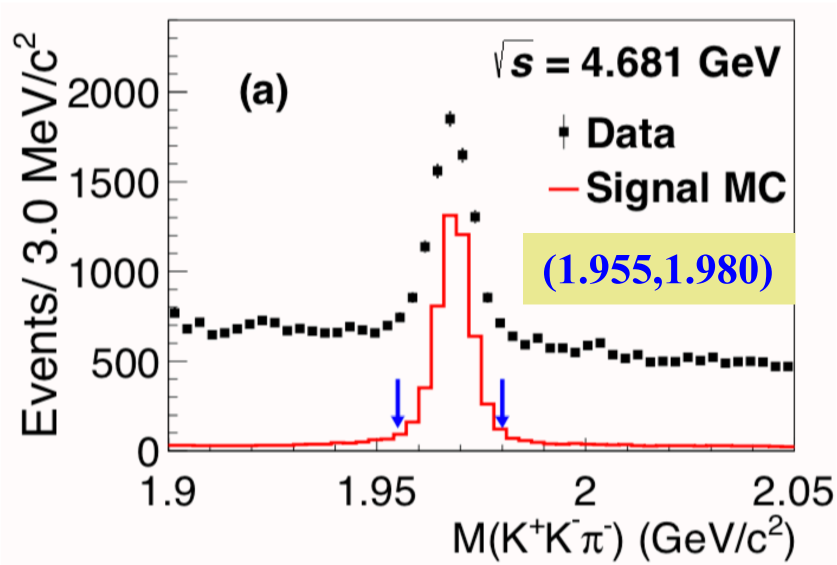


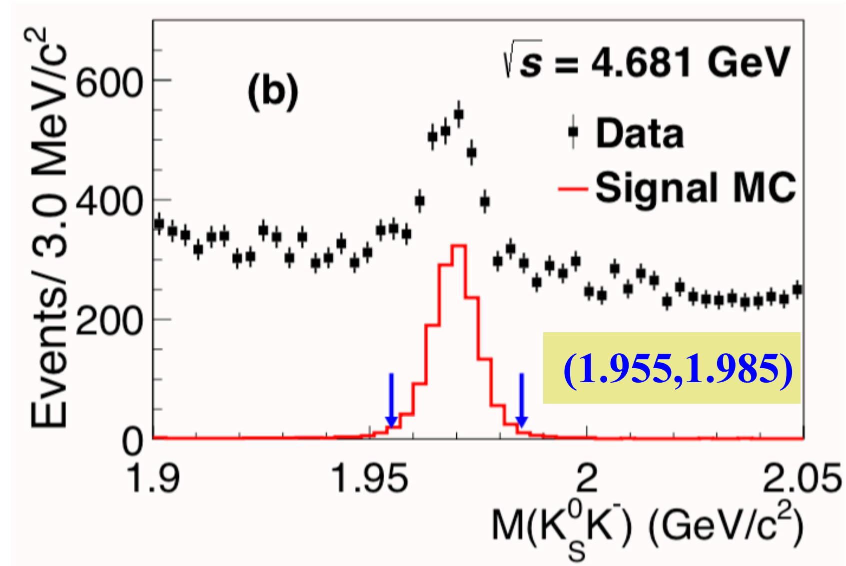

$e^+e^- \to K^+ D_s^{*-} D^0$

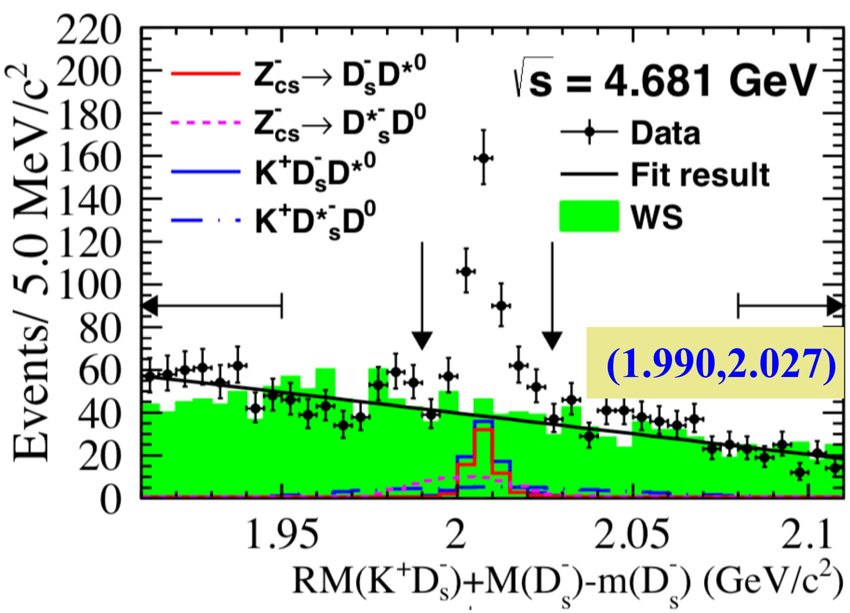
- **Partial reconstruction** of the process $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$
  - Reconstruct a $\boldsymbol{D_s^-}$ with two tag modes: $D_s^- \to K_S^0 K^-$ and $D_s^- \to K^+ K^- \pi^-$.
  - Tag a bachelor charged $\boldsymbol{K^+}$.
  - Use signature in the **recoil mass spectrum of $K^+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

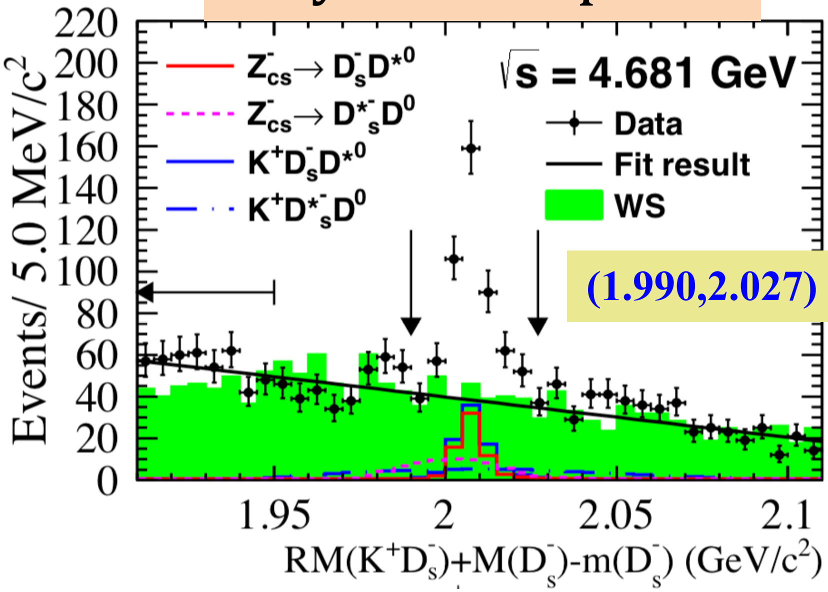
2) $D_s^- \to K^-K^*(892)(K^+\pi^-)$:

$M(K^+\pi^-) \in (0.85, 0.93)$ 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

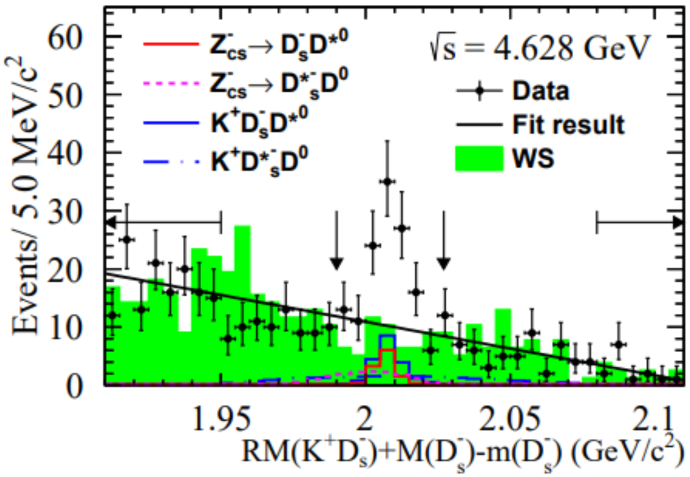



(1.990,2.027)

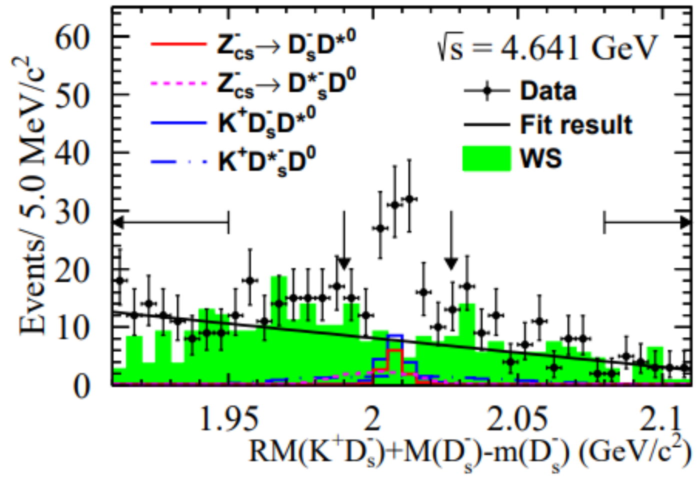
- Data-driven technique to describe combinatorial background.
- Right Sign(RS): combination of $D_s^-$ and $K^+$.
- Wrong Sign(WS): combination of $D_s^-$ and $K^-$ to mimic combinatorial background.

- 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: $282.6 \pm 12.0$;
- This WS number will be fixed in $RM(K^+)$ spectrum fitting.

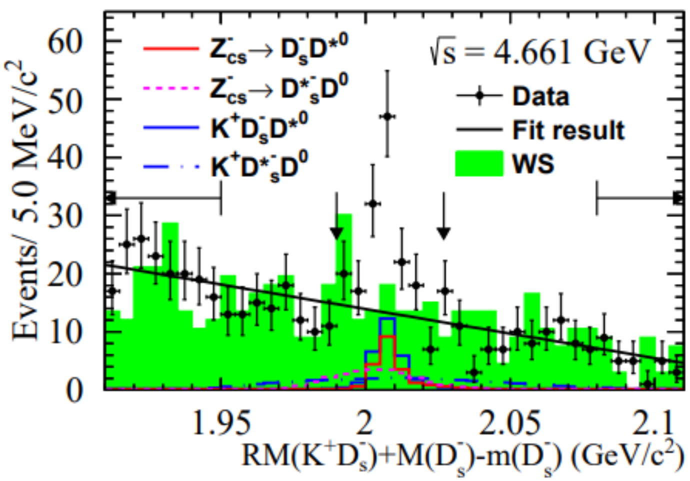
# $RM(K^+D_s^-)$ distributions at other four energy points



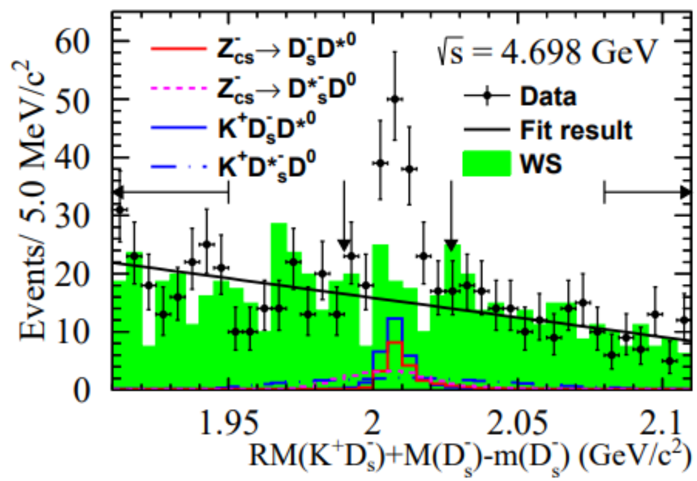

(a)Recoil mass of $K^+D_s^-$ at $\sqrt{s} = 4.628$ GeV.




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

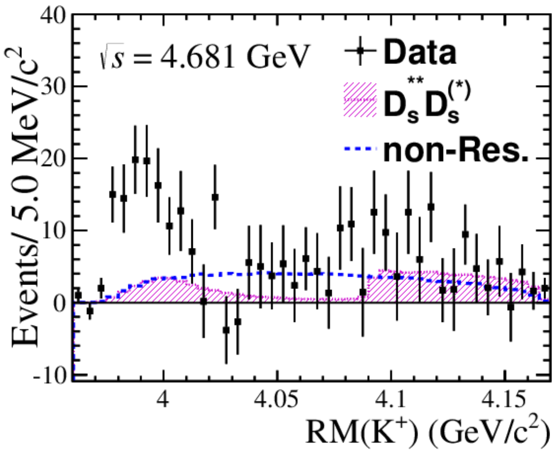


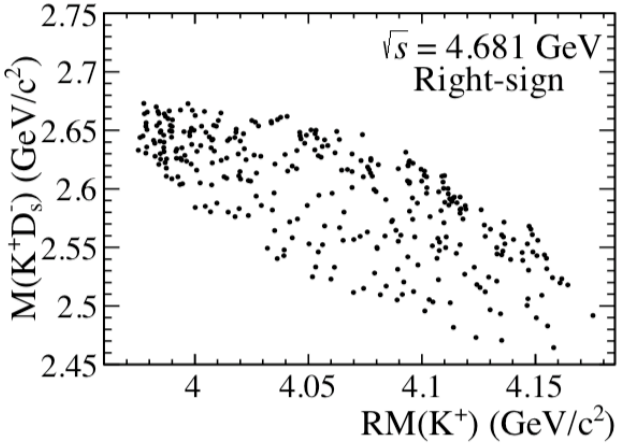

(c)Recoil mass of $K^+D_s^-$ at $\sqrt{s} = 4.661$ GeV.

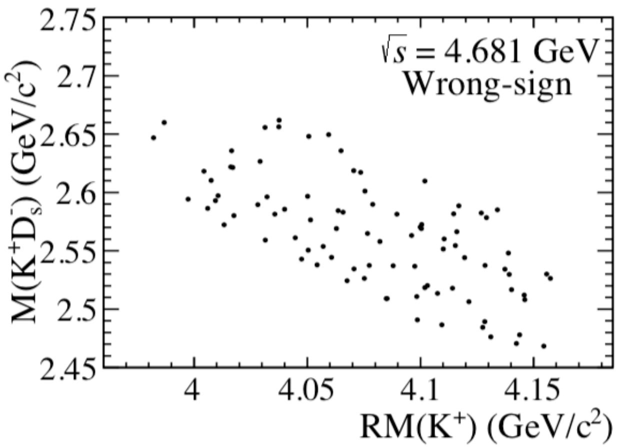



(d)Recoil mass of $K^+D_s^-$ at $\sqrt{s} = 4.698$ GeV.

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

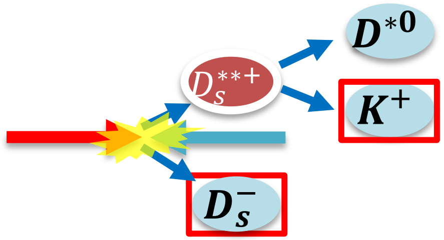


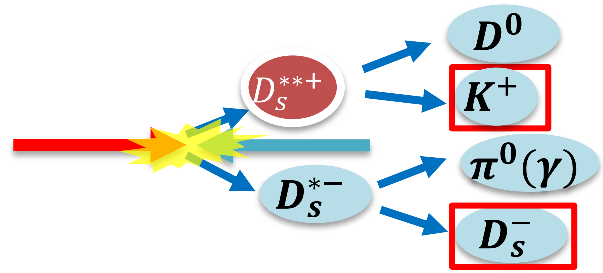




- The $K^+$ recoil-mass spectrum in data at 4.681GeV.
- Combinatorial backgrounds are subtracted.
- A structure next to threshold raging from 3.96 to 4.02GeV/c$^2$.
- The enhancement cannot be attributed to the non-resonant (NR) signal process $e^+e^- \to K^+(D_s^-D^{*0} + D_s^{*-}D^0)$.

# Check with high excited $D_s^{**}$ states



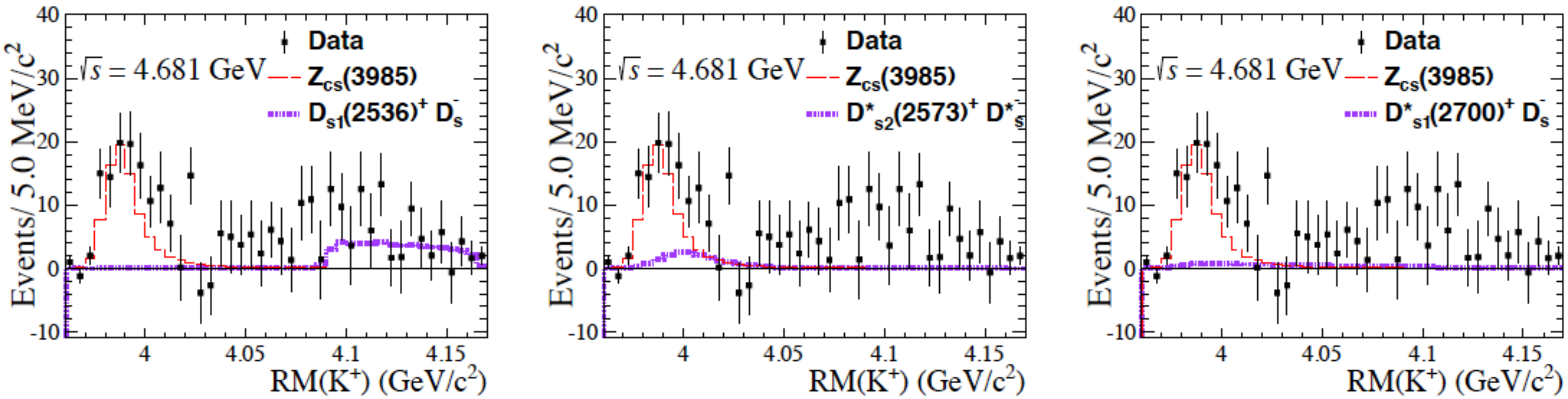




| $D_s^{**+}$ | mass(MeV/c²) | width(MeV) | J^P | $D_s^{**+}(K^+D^{*0})D_s^-$ | $D_s^{**+}(K^+D^0)D_s^{*-}$ |
|---|---|---|---|---|---|
| $D_{s1}(2536)^+$ | $2535.11\pm0.06$ | $0.92\pm0.05$ | $1^+$ | (*) Fixed in nominal fitting | Parity Violation in decay |
| $D_{s2}^*(2573)^+$ | $2569.1\pm0.8$ | $16.9\pm0.7$ | $2^+$ | Not decay to KD* | (*) Fixed in nominal fitting |
| $D_{s1}^*(2700)^+$ | $2708.3^{+4.0}_{-3.4}$ | $120\pm11$ | $1^-$ | (*) Fixed in nominal fitting | Q=-139.3MeV<br>P-wave suppression in production. |
| $D_{s1}^*(2860)^+$ | $2859\pm27$ | $159\pm80$ | $1^-$ | (*)less contribution than $D_{s1}^*(2700)^+$;<br>Q=-146MeV. | Q=-290MeV;<br>P-wave suppression in production. |
| $D_{s3}^*(2860)^+$ | $2860\pm7$ | $53\pm10$ | $3^-$ | (*)F-wave suppression;<br>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) $D^*_{s1}(2700)^+(\to D^{*0}K^+)D_s^-$

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

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

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

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

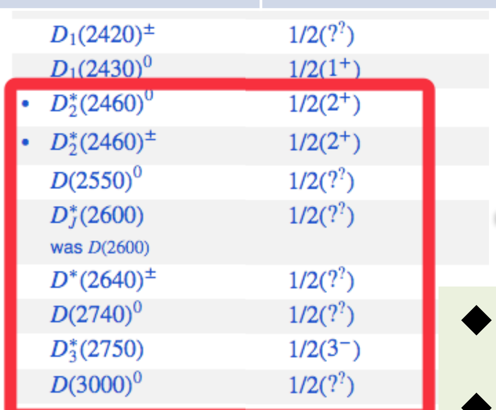
BaBar_PhysRevD.80.092003(2009)

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

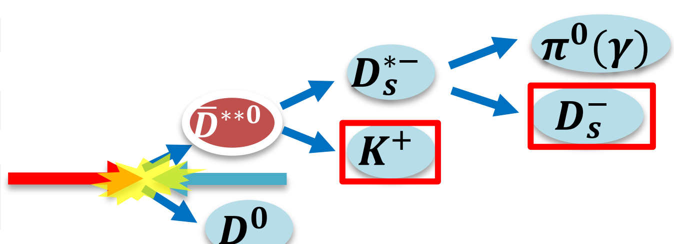
- The estimated sizes of excited $D_s^{**}$ contributions at each energy point.
- “-” means the production is not allowed kinematically.

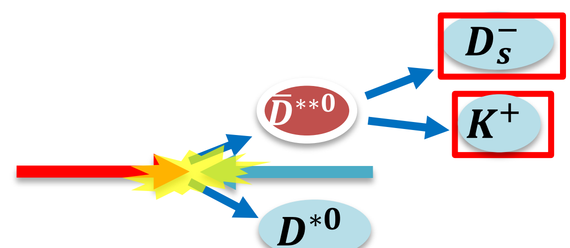
# Check with high excited $\bar{D}^{**0}$ states

| $\bar{D}^{**0}$ | 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 |



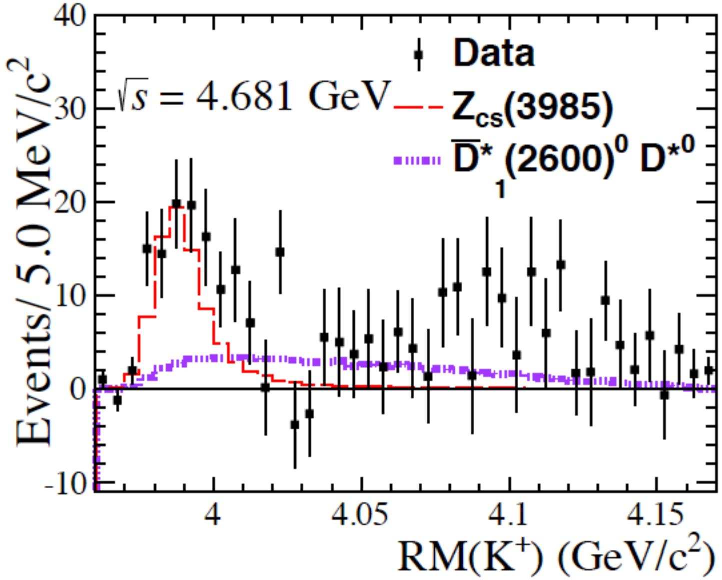
| | |
|---|---|
| $D_1(2420)^\pm$ | $1/2(?^?)$ |
| $D_1(2430)^0$ | $1/2(1^+)$ |
| $D_2^*(2460)^0$ | $1/2(2^+)$ |
| $D_2^*(2460)^\pm$ | $1/2(2^+)$ |
| $D(2550)^0$ | $1/2(?^?)$ |
| $D_J^*(2600)$ | $1/2(?^?)$ |
| was $D(2600)$ | |
| $D^*(2640)^\pm$ | $1/2(?^?)$ |
| $D(2740)^0$ | $1/2(?^?)$ |
| $D_3^*(2750)$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




- ◆ $D(2640)$ 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.

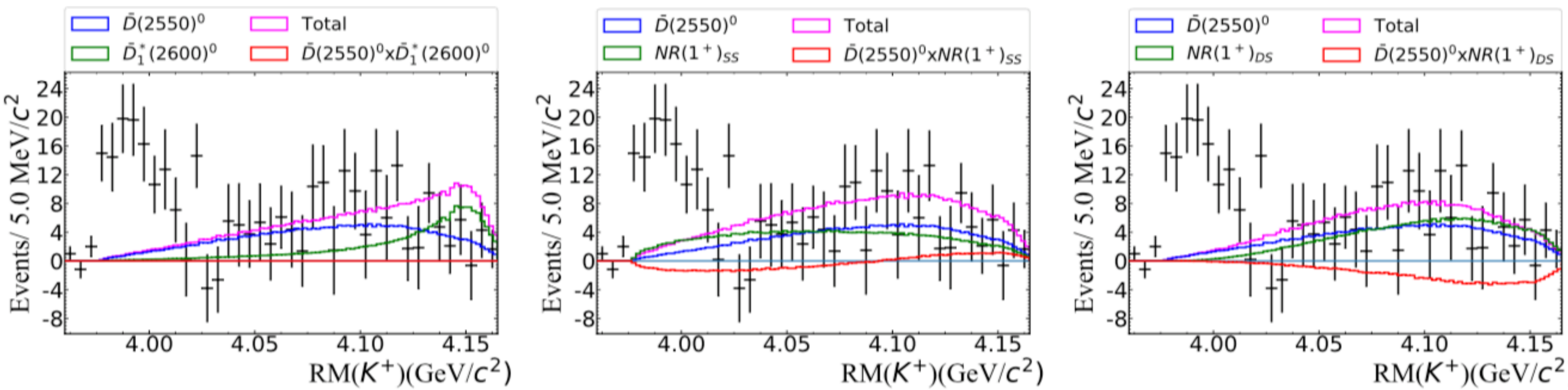
# Check with high excited non-strange $\bar{D}_1^*(2600)^0$ states



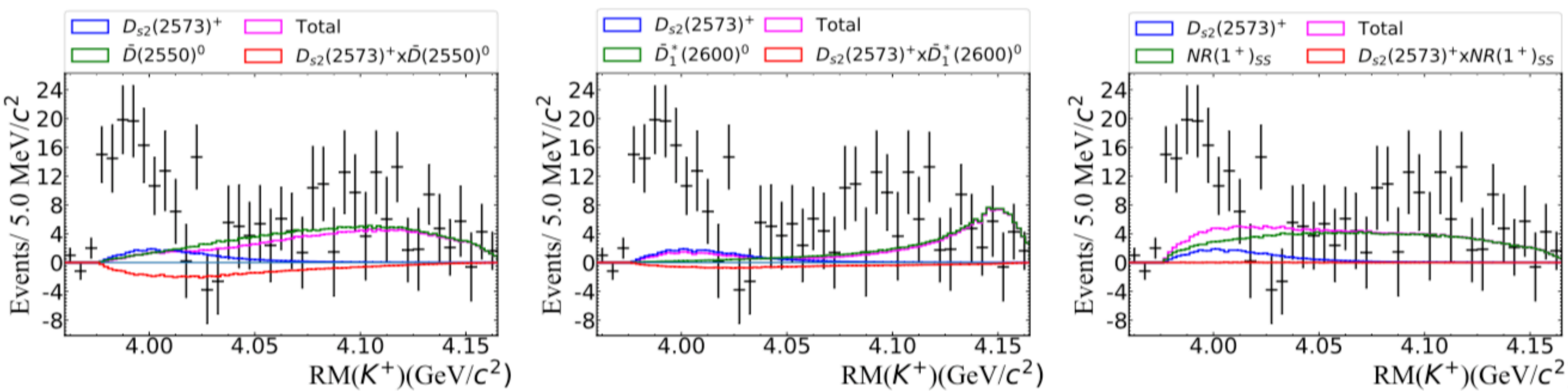

(c) $\bar{D}_1^*(2600)^0(\to D_s^- K^+)D^{*0}$

- 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)



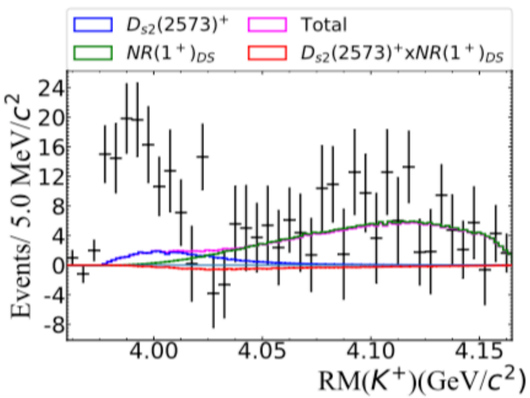

(a)$\bar{D}(2550)^0D^0$ and $\bar{D}_1^*(2600)^0D^0$ (b)$\bar{D}(2550)^0D^0$ and NR $1^+(S,S)$ (c)$\bar{D}(2550)^0D^0$ and NR $1^+(D,S)$



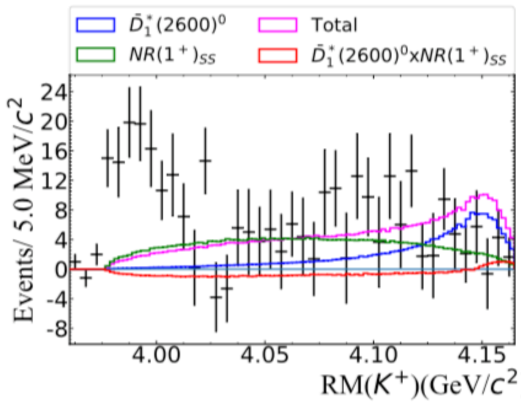

(d)$D_{s2}^*(2573)^+D_s^{*-}$ and $\bar{D}(2550)^0D^0$ (e)$D_{s2}^*(2573)^+D_s^{*-}$ and $\bar{D}_1^*(2600)^0D^0$ (f)$D_{s2}^*(2573)^+D_s^{*-}$ and NR $1^+(S,S)$

- 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$^2$.

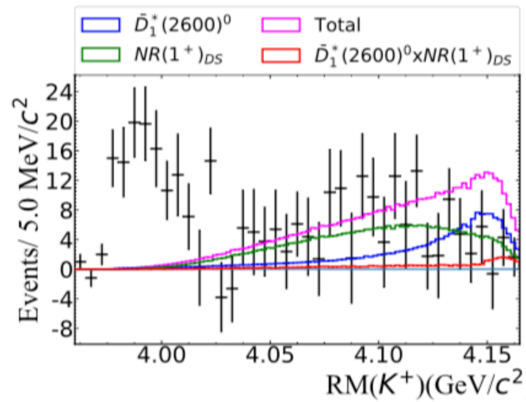
# Interference effect of $K^+ D_s^{*-} D^0$ final states（2）



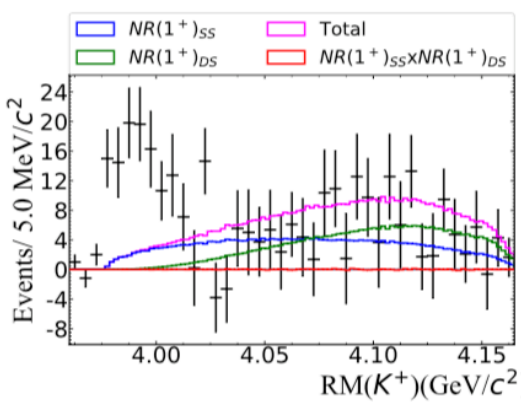

(g)$D^*_{s2}(2573)^+ D_s^{*-}$ and NR $1^+(D,S)$




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



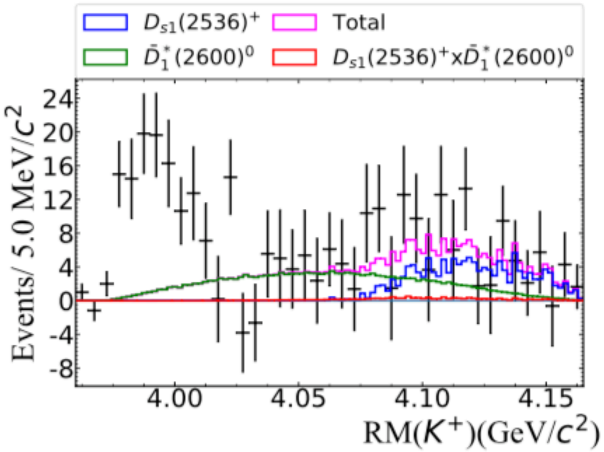

(i)$\bar{D}_1^*(2600)^0 D^0$ and NR $1^+(D,S)$



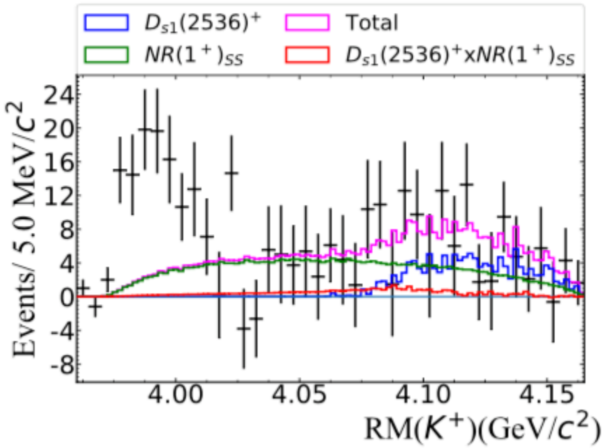

(j)NR $1^+(S,S)$ and NR $1^+(D,S)$

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

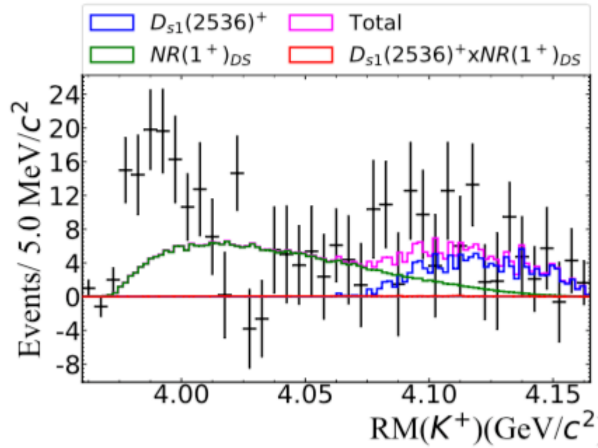
# Interference effect of $K^+D_s^-D^{*0}$ final states (1)



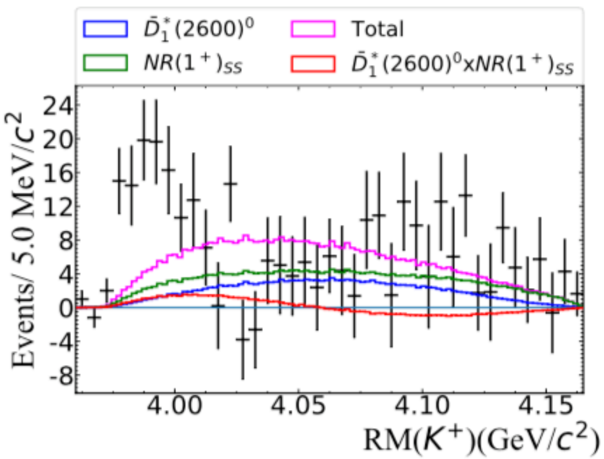

(a) $D_{s1}(2536)^+D_s^-$ and $\bar{D}_1^*(2600)^0D^{*0}$



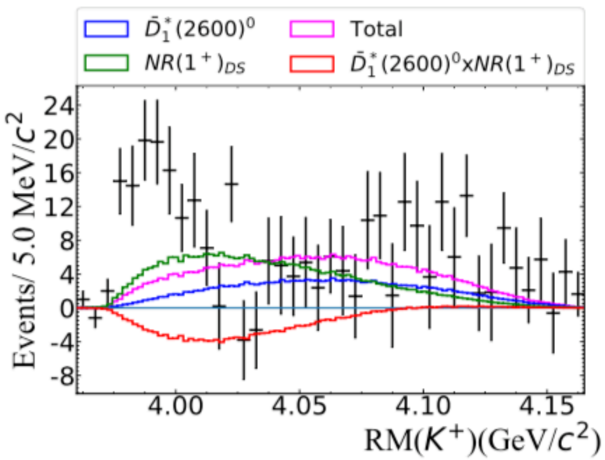

(b) $D_{s1}(2536)^+D_s^-$ and NR $1^+(S,S)$



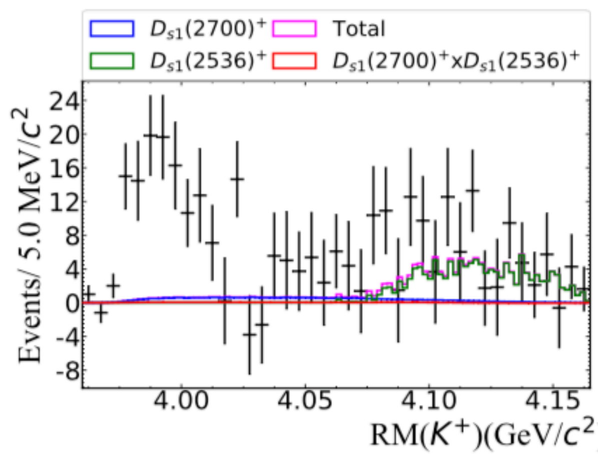

(c) $D_{s1}(2536)^+D_s^-$ and NR $1^+(D,S)$




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

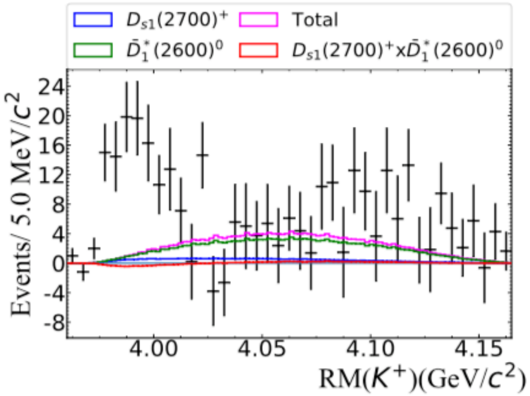



(e) $\bar{D}_1^*(2600)^0D^{*0}$ and NR $1^+(D,S)$

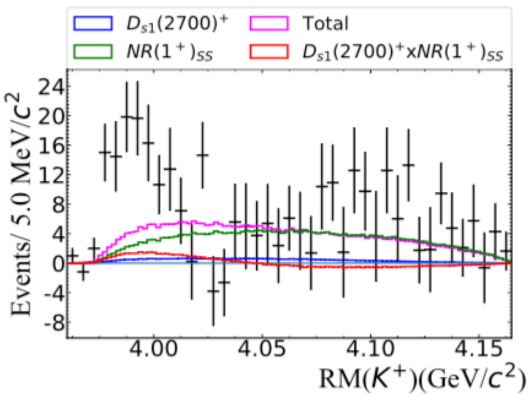



(f) $D_{s1}^*(2700)^+D_s^-$ and $D_{s1}(2536)^+D_s^-$

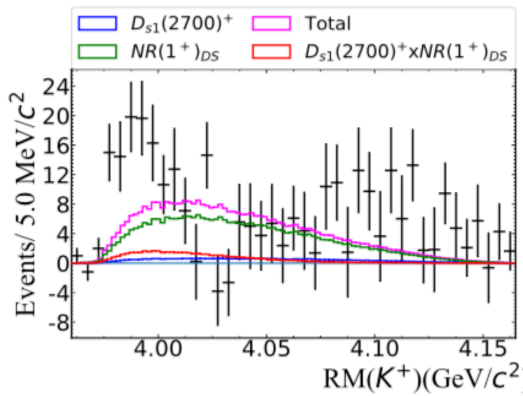
# Interference effect of $K^+ D_s^- D^{*0}$ final states (2)



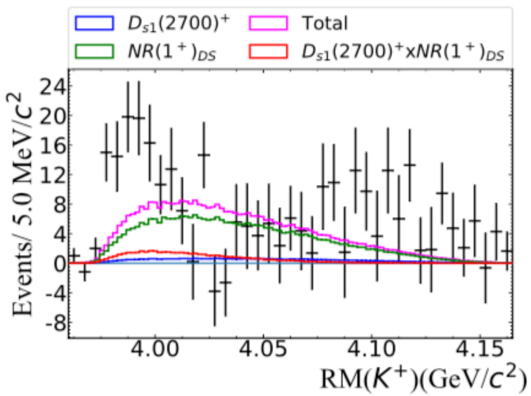

(g)$D_{s1}^*(2700)^+ D_s^-$ and $\bar{D}_1^*(2600)^0 D^{*0}$



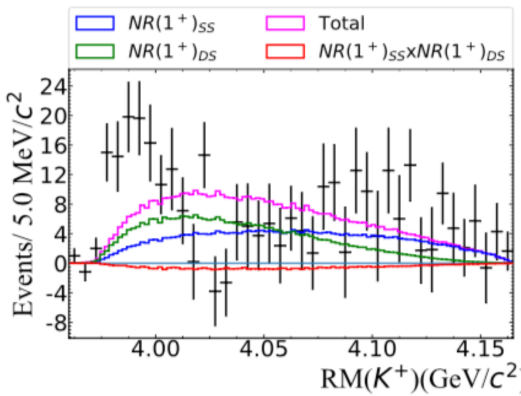

(h)$D_{s1}^*(2700)^+ D_s^-$ and NR $1^+(S,S)$




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




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



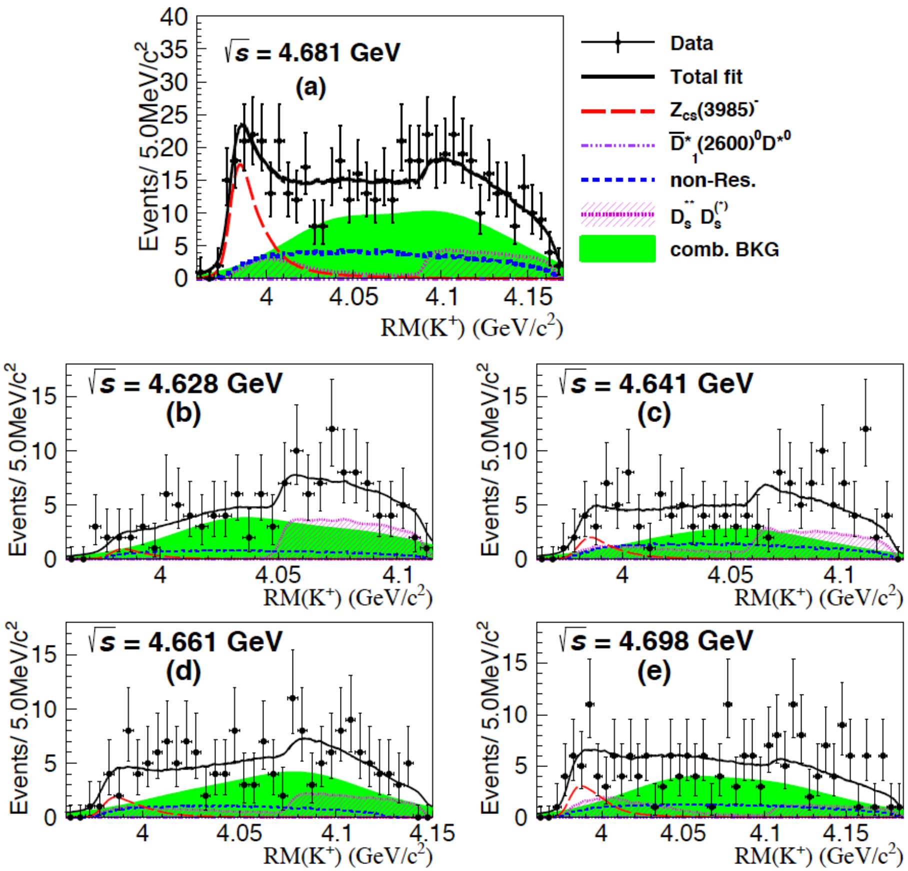

(k)NR $1^+(S,S)$ and NR $1^+(D,S)$

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

# 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 $K^+$




***Resonance parameter:***

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

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

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

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

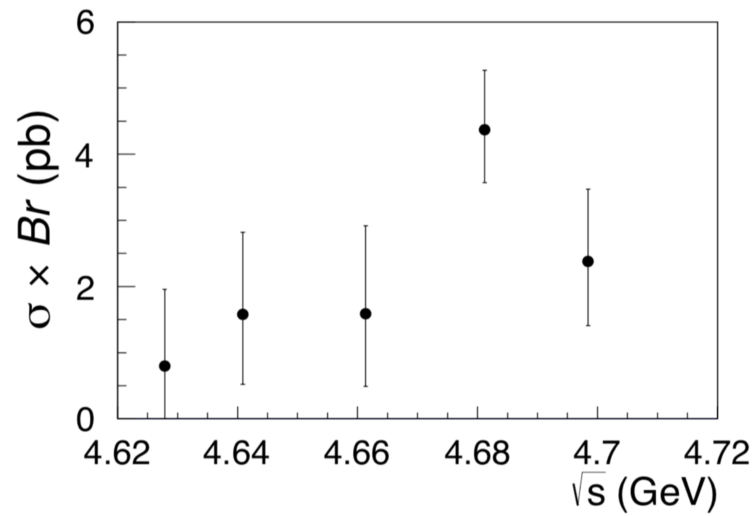
- The potential interference effects are neglected.
- The $J^P$ of $Z_{cs}(3985)^-$ is assumed as $1^+$; =>(S,S) is the most promising configuration.
- The significance with systematic uncertainties and look-elsewhere effect considered is evaluated to 5.3σ.
- $e^+e^- \to D^{*0}\overline{D}_1^*(2600)^0(\to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

# Cross-section measurement at each energy point

- Born cross section:

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

| $\sqrt{s}$ (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 |

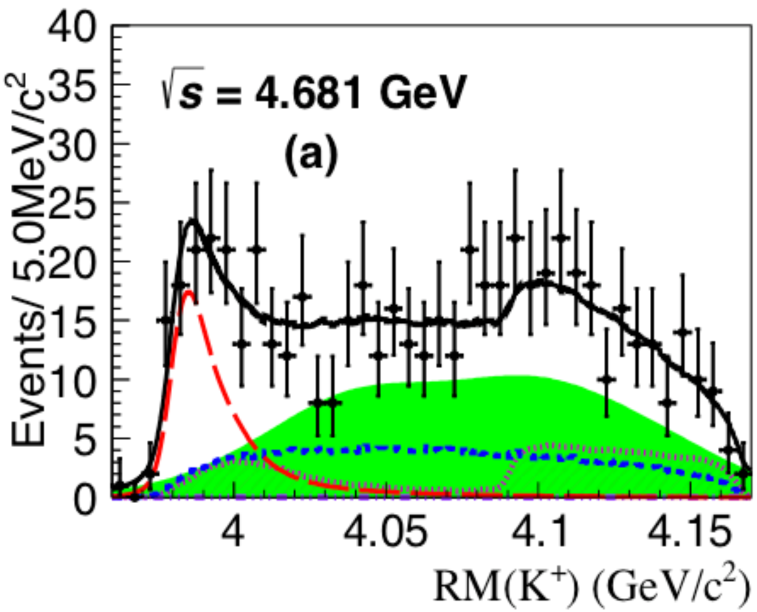
***Resonance parameter:*** $m_0(Z_{cs}(3985)^-) = 3985.2^{+2.1}_{-2.0}(stat.) \pm 1.7(sys.)\mathrm{MeV/c^2}$,

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

***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 $Z_{cs}(3985)^-$

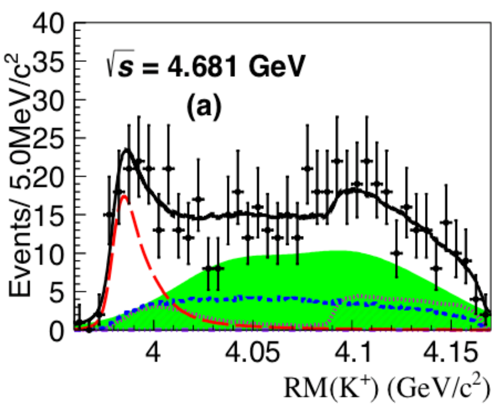


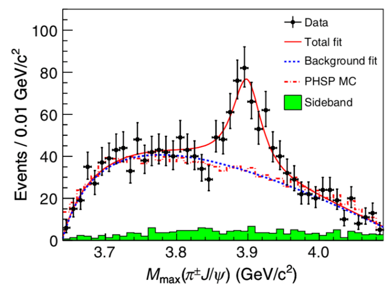

- Only a few MeV higher than the threshold of $D_s^- D^{*0}/D_s^{*-} D^0$ (3975.2/3977.0)MeV/c$^2$.
- At least four quark state (***$c\bar{c}s\bar{u}$***) and a charged hidden-charm state with strangeness.

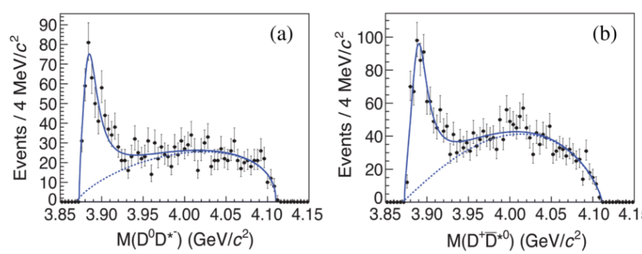
- They are observed in a combination of $D_s^- D^{*0}$ and $D_s^{*-} D^0$ final states.
- The production is dominated at $\sqrt{s} = 4.681$ GeV. Any Y contribution?
- A tetraquark state or a molecule-like? Or threshold kinematic effects ? Or other scenario?
- Search for other decay modes $Z_{cs}^0$/ $Z_{cs}^{*-}$ 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 | |
|---|---|---|---|
| | $Z_{cs}(3985)^{\pm}$ | $Z_c(3900)^{\pm}$ | $Z_c(38850)^{\pm}$ |
| 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** |

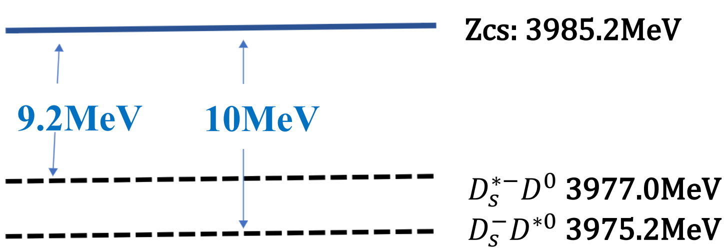
**neutral/charged = 1/2**

SU(3) partner of Zc(3900)?

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

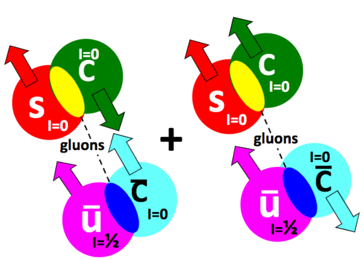
- **Various interpretations are possible for the structure**
  - 1) Tetraquark state
  - 2) Molecule
  - 3) $D_{s2}^{*}(2573)^{+}D_{s}^{*-}$ threshold kinematic effects
    (Re-scattering , Reflection, Triangle singularity)
  - 4) Mixture of molecular and tetraquark
  - 5) …

arXiv:2011.08501
arXiv:2011.08628
arXiv:2011.08656
arXiv:2011.08725
arXiv:2011.08747
arXiv:2011.09156
arXiv:2011.09225
arXiv:2011.09244
arXiv:2011.09404
arXiv:2011.10495
arXiv:2011.10922
arXiv:2011.10959
arXiv:2011.11488
arXiv:2011.12230
arXiv:2011.12326

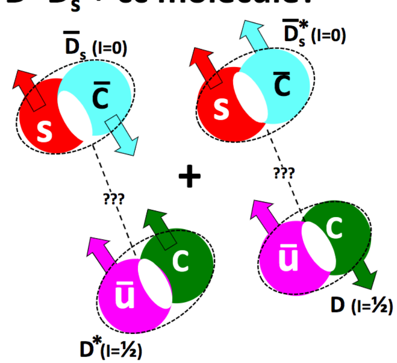



~10 MeV above $D_sD^*/D_sD$ thresholds
similar to $Z_c(3900)$ & $Z_b(10,610)$
(DD*) (BB*)

diquark-antidiquark?



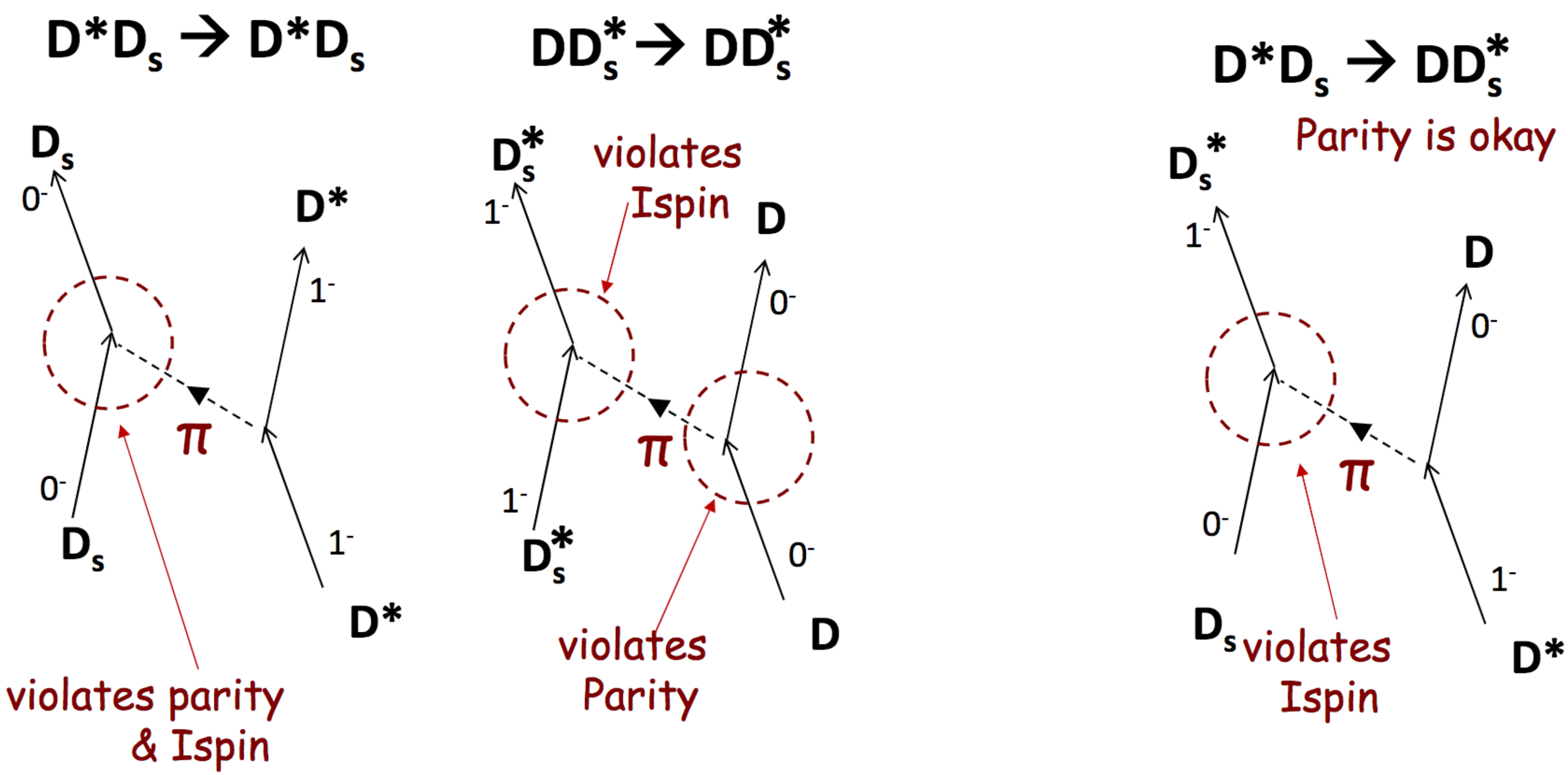

D*$\bar{D}_s$ + cc molecule?



*from Steve Olsen*

# If it's a molecule, what holds it together

Yukawa force dominated by π-exchange ← not allowed for $D_sD^*/D_s^*D$




K/$\eta$ exchange?

# 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] : $K^+ D_s^{*-} D^{*0}$.
- Other $Z_{bs}^-$ states? $Z_{bs}^{*-}$ states?
- **Search $Z_{cs}^-$ state in LHCb and B factories? Important!**
- …

# 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).
- 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;
  - an exotic state with at least four-quark constituent $c\bar{c}s\bar{u}$

  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 type of resonances? more to be measured/understood!
- More results will come out ...

# Thanks!

**Especially to the staff of BEPCII and the computing center, the funding agencies, and all the friends of BES!**

2011.08656

TABLE II. Numerical results for masses, widths and partial widths. We use "†" to label input. The ratios $\Gamma_3/\Gamma_2$ are estimated with central values of coupling constants. The lower limit of ratios $\Gamma_i/\Gamma_1$ are estimated with upper limits of $v_{12}$. $M$ and $\Gamma$ are in unites of MeV and $\Lambda_i$ are in unites of GeV.

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

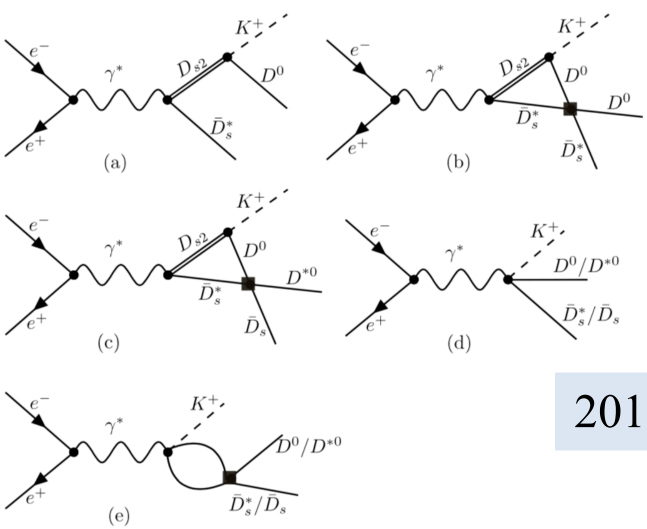
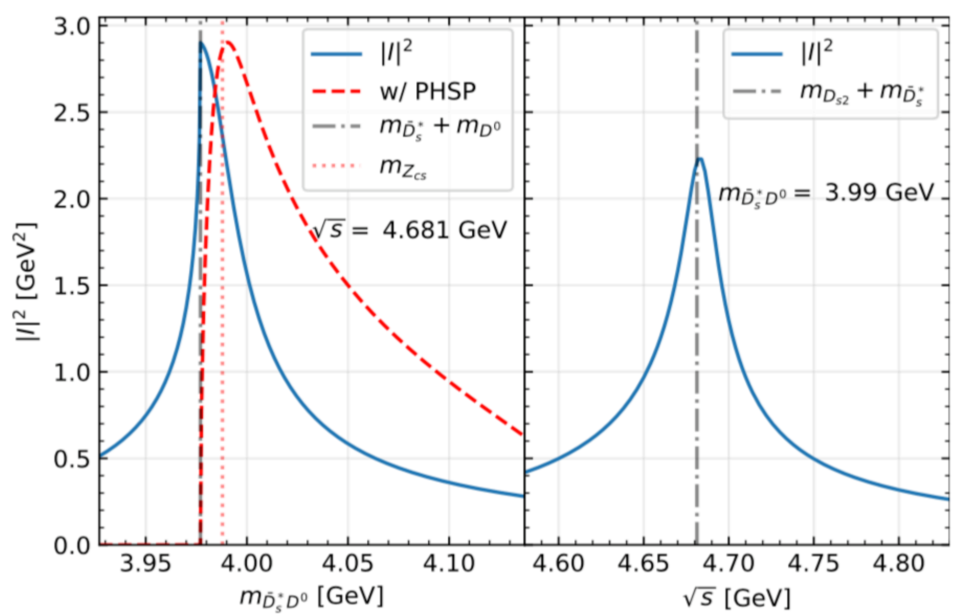


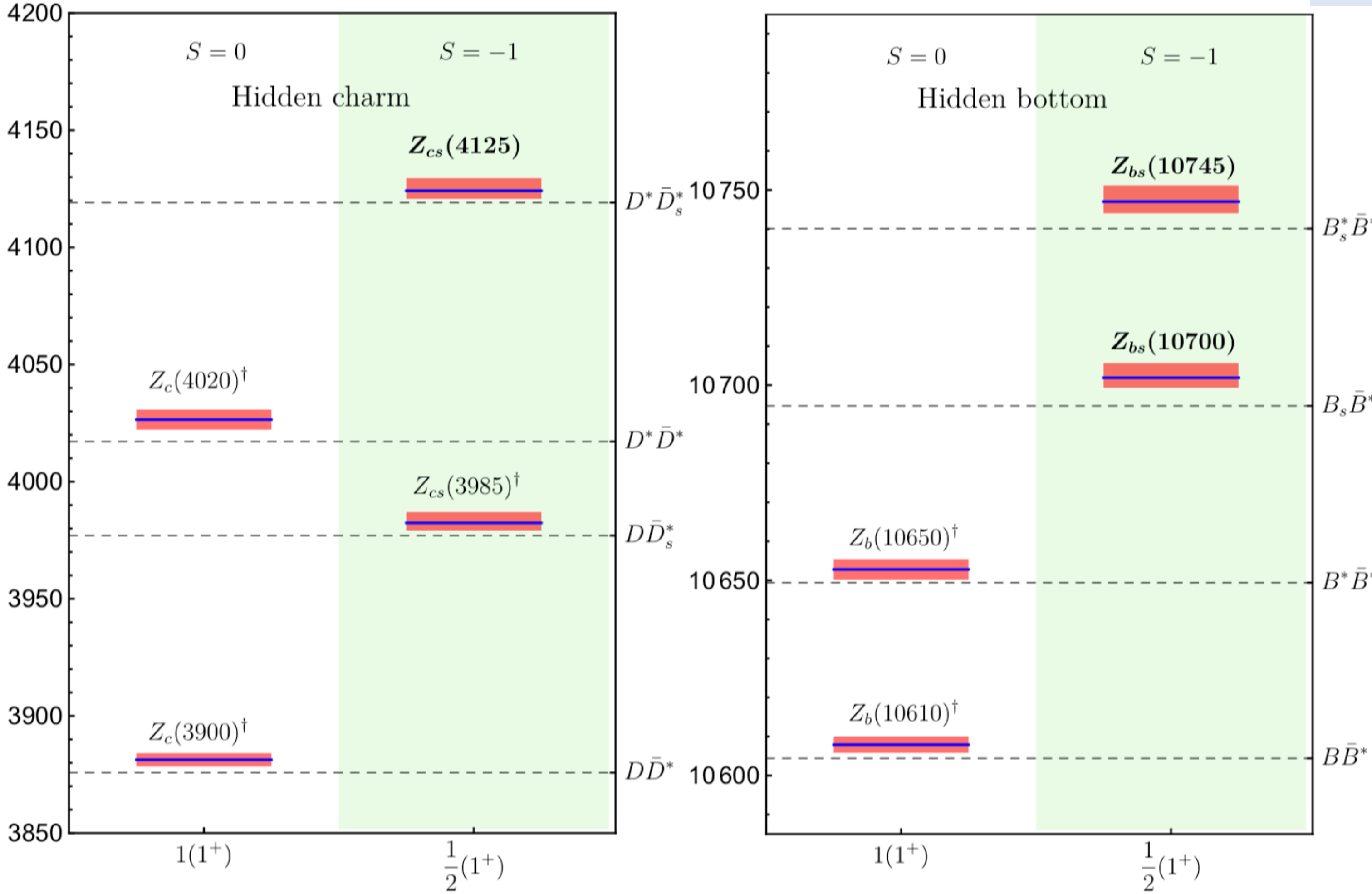

FIG. 1. Feynman diagrams for the production mechanisms considered in this work: (a) and (b) for the $K^+ D_s^* \bar{D}^0$; (c) for the $K^+ D_s \bar{D}^{*0}$; (d) and (e) for both final states. The filled squares denote the $T$-matrix elements which include the effects of the generated $Z_{cs}$ state.

2011.08725

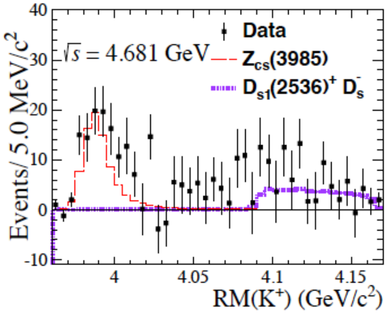


# $Z_{c(s)}^{(\prime)}$ and $Z_{b(s)}^{(\prime)}$

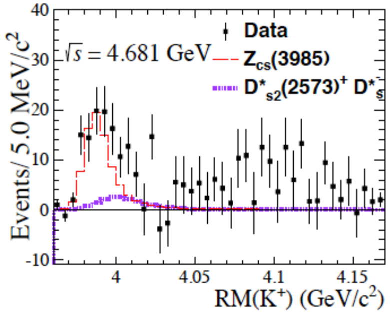
2011.10922



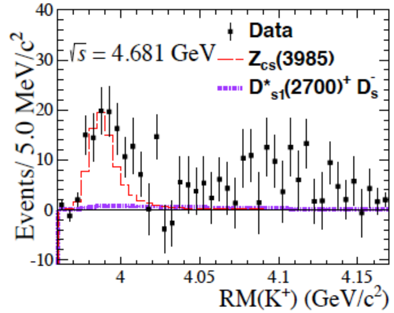
# Check with high excited $D_{(s)}^{**}$ states



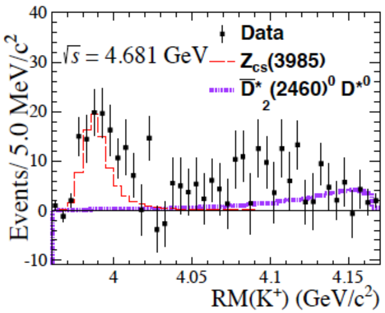

(a)$D_{s1}(2536)^{+}(\rightarrow D^{*0}K^{+})D_s^{-}$



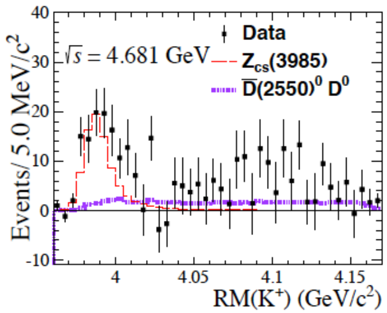

(b)$D_{s2}^{*}(2573)^{+}(\rightarrow D^{0}K^{+})D_s^{*-}$



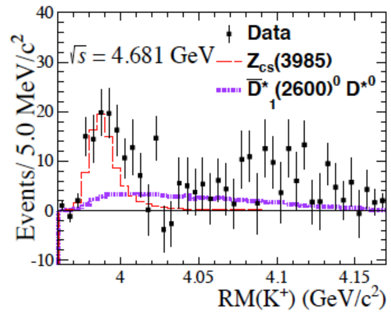

(c)$D_{s1}^{*}(2700)^{+}(\rightarrow D^{*0}K^{+})D_s^{-}$



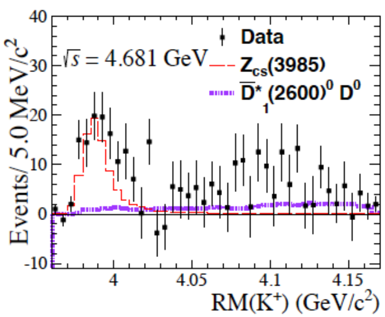

(a)$\bar{D}_2^{*}(2460)^{0}(\rightarrow D_s^{-}K^{+})D^{*0}$



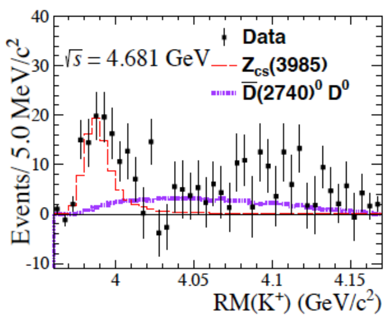

(b)$\bar{D}(2550)^{0}(\rightarrow D_s^{*-}K^{+})D^{0}$



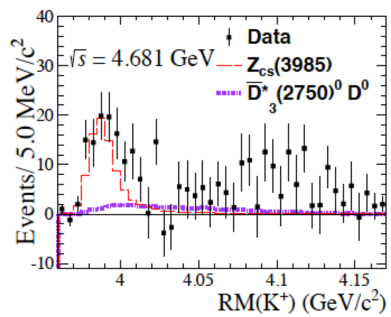

(c)$\bar{D}_1^{*}(2600)^{0}(\rightarrow D_s^{-}K^{+})D^{*0}$




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



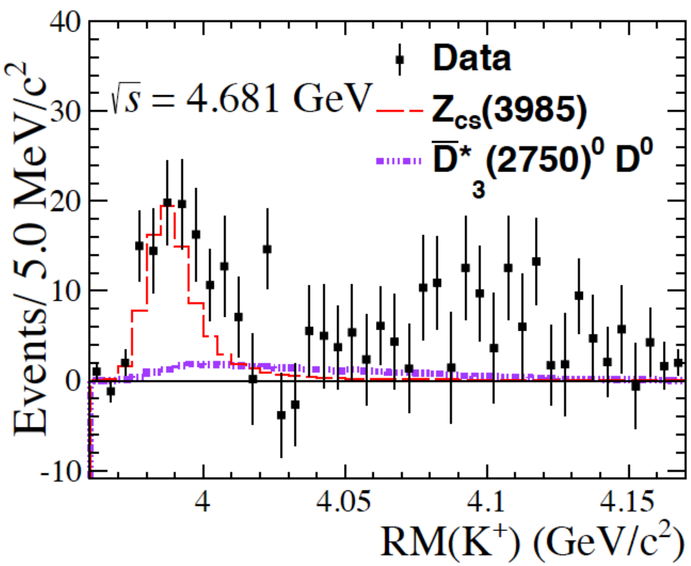

(e)$\bar{D}(2740)^{0}(\rightarrow D_s^{*-}K^{+})D^{0}$




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

- 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 $\bar{D}_3^*(2750)^0$ 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)

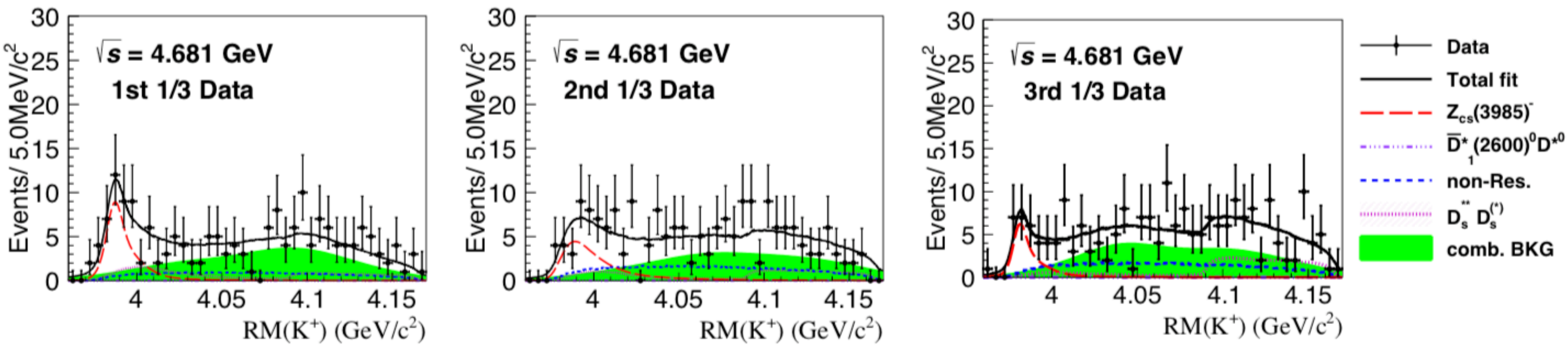
| Initial state | Final state | Width ($cu$, $cd$) (MeV) | BR ($cu$, $cd$) (%) |
|---|---|---|---|
| $D(1^3D_3)$ 2833 | $D(1^3P_2)\gamma$ | 0.69, 0.07 | 1.34, 0.14 |
| | $D\pi$ | 20.1 | 39.2 |
| | $D\rho$ | 1.30 | 2.5 |
| | $D\eta$ | 1.24 | 2.4 |
| | $D^*\pi$ | 15.5 | 30.2 |
| | $D^*\rho$ | 7.56 | 14.8 |
| | $D^*\omega$ | 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 |
|---|---|---|---|---|---|
| $\bar{D}_3^*(2750)^0(\to D_s^{*-}K^+)D^0$ | $0.0 \pm 0.1$ | $0.0 \pm 0.2$ | $0.0 \pm 0.2$ | $0.0 \pm 0.4$ | $0.0 \pm 0.5$ |

- ☐ 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

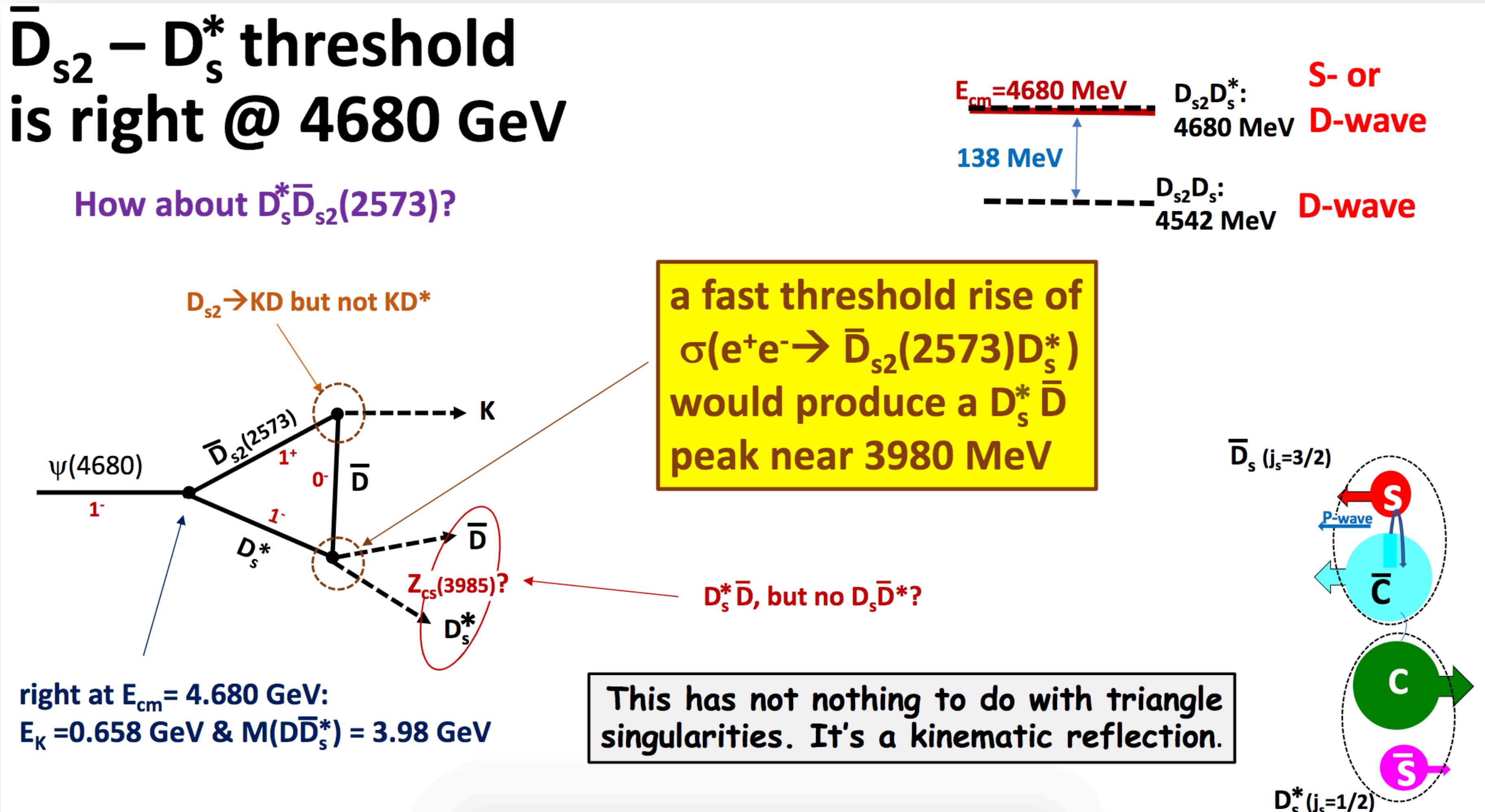
- Two-thirds of the data set at 4.681GeV was kept blinded until after the analysis strategy was established and validated.




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

- 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.