Exotic hadrons with strangeness and charm

Feng-Kun Guo

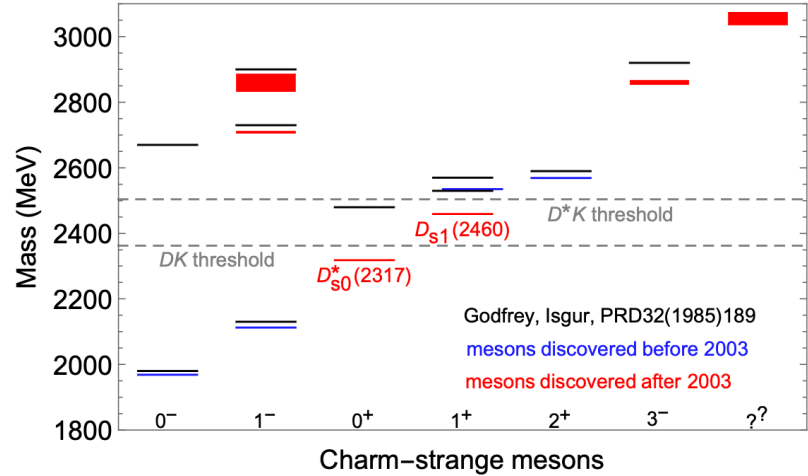Institute of Theoretical Physics, CAS

HYP 2022 PRAGUE
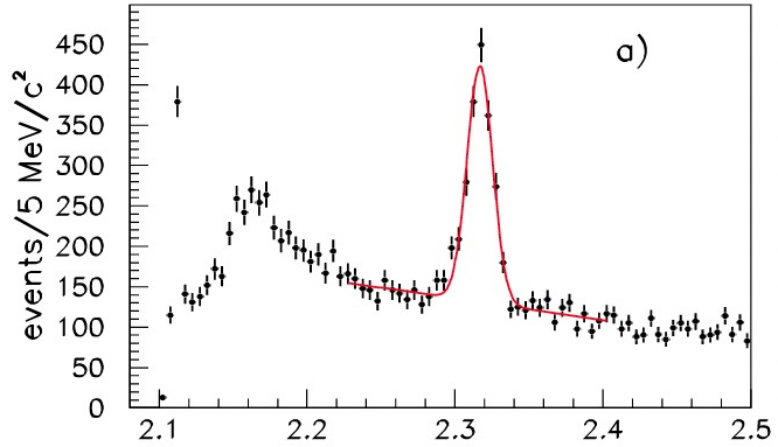
14th International Conference on Hypernuclear and Strange Particle Physics
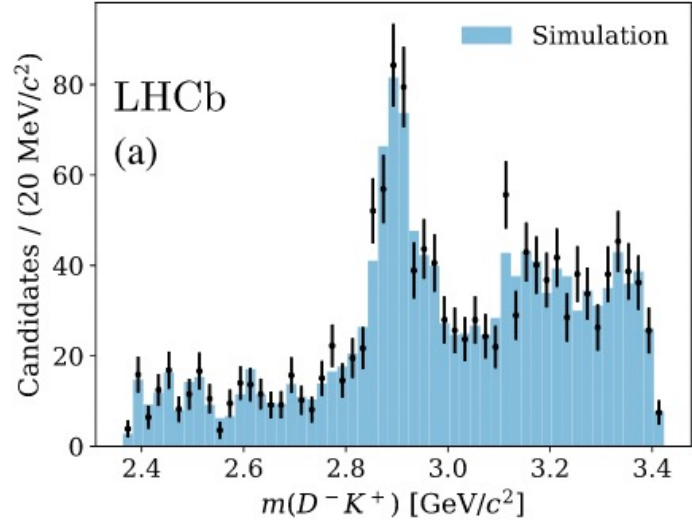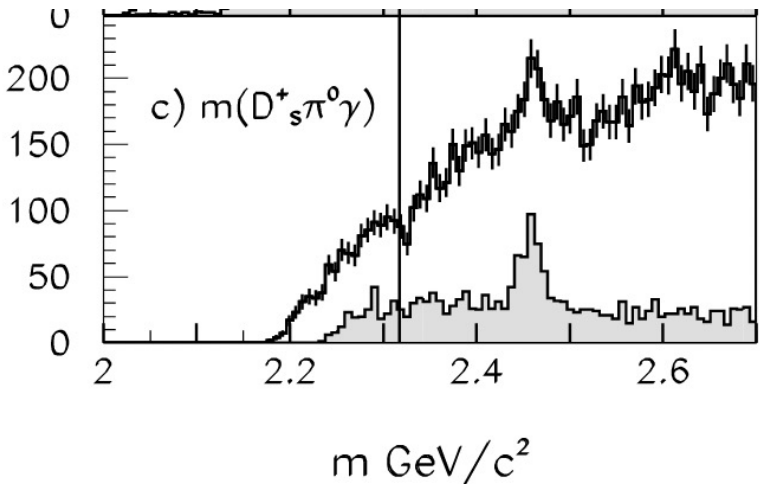
June 27 – July 1, 2022
Prague, Czech Republic

Exotic mesons with open-charm and strangeness

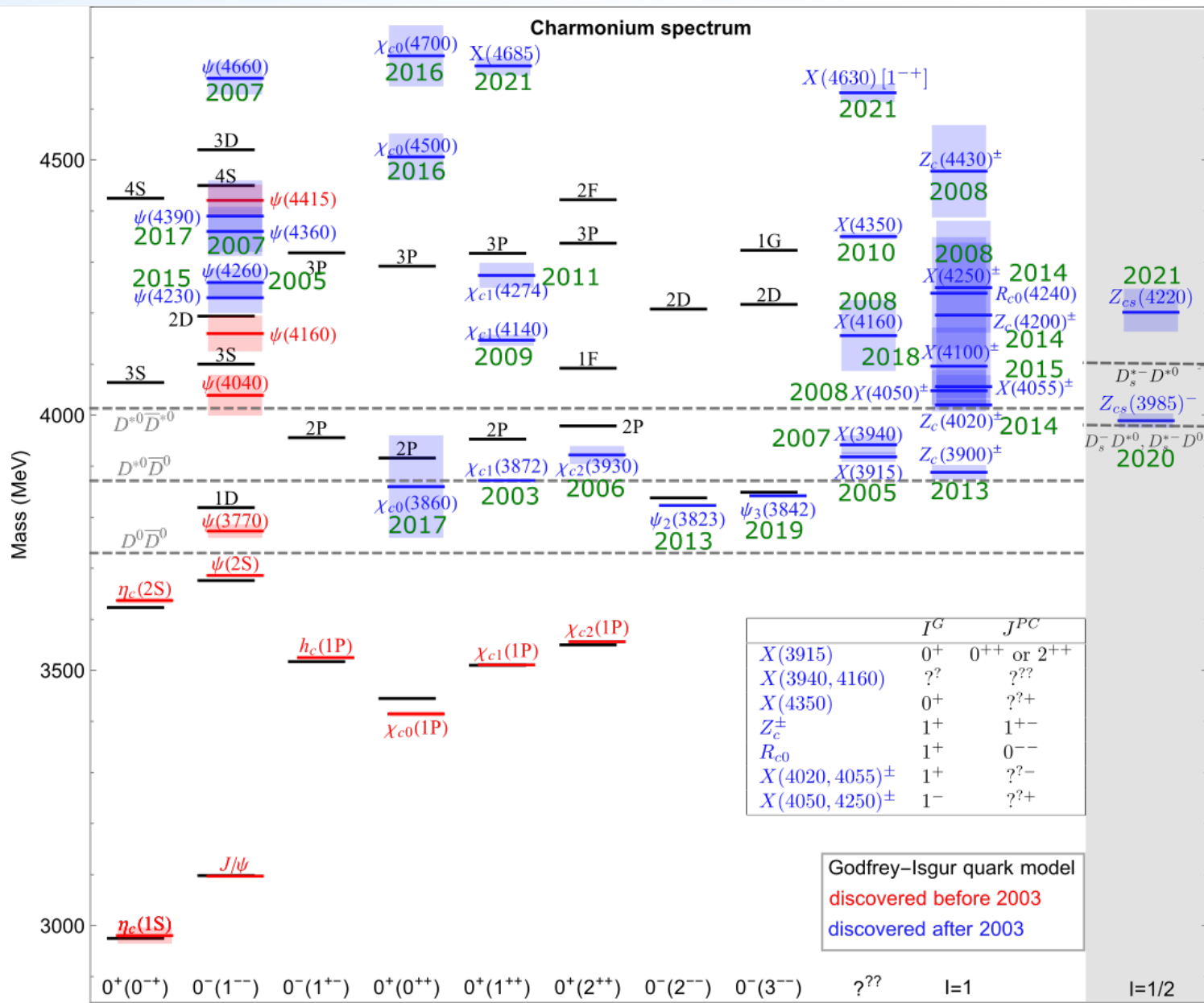- $D_{s0}^*(2317)$ and $D_{s1}(2460)$: $C = 1, S = 1$

Godfrey, Isgur, PRD32(1985)189
mesons discovered before 2003
mesons discovered after 2003

D^*K threshold
DK threshold
$D_{s1}(2460)$
$D_{s0}^*(2317)$

Charm−strange mesons

c) m($D_s^+\pi^0\gamma$)

Inclusive e^+e^-, BaBar, PRL 90 (2003) 242001;
CLEO, PRD 68 (2003) 032002

- $X(2900)$: $C = 1, S = -1$, explicitly exotic

$B \to D^+D^-K^+$, LHCb, PRL 125 (2020) 242001

Hidden-charm states

Charmonium spectrum

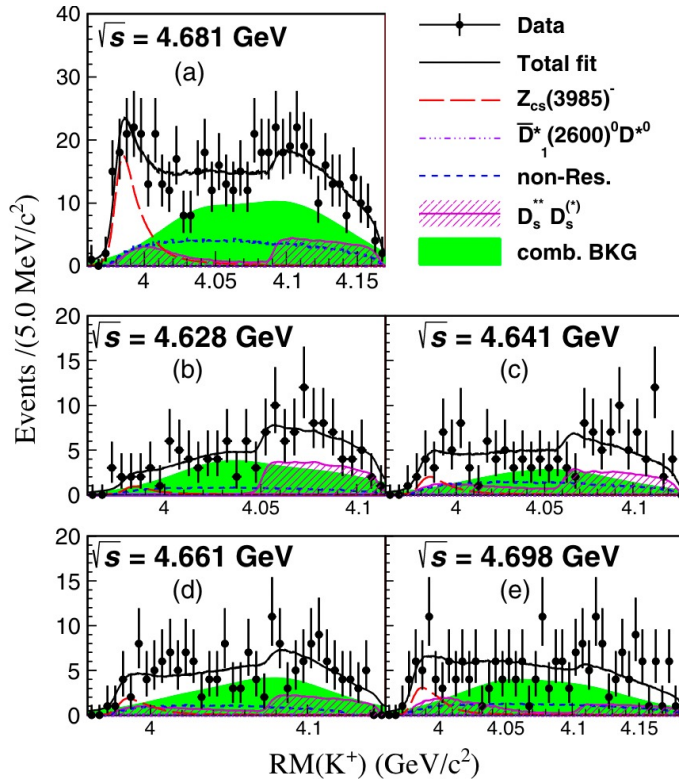Z_{cs}'s:
Hidden-charm w/ strangeness

BESIII, PRL 126 (2021) 102001;
LHCb, PRL 127 (2021) 082001

Z_{cs}: hidden-charm exotics with strangeness

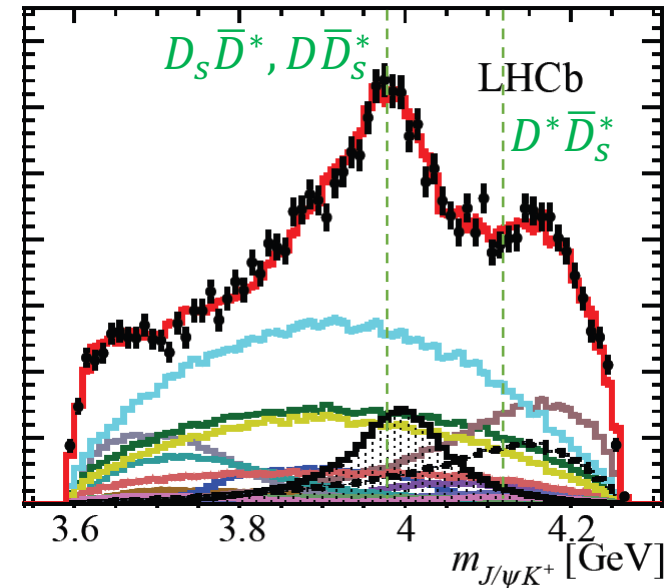- $Z_{cs}(3985)$: BESIII, PRL 126 (2021) 102001
  - $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$
  - close to the $\overline{D}_s^* D, \overline{D}_s D^*$ thresholds
  - Most prominent in data with

    $\sqrt{s}_{e^+e^-} = 4.681$ GeV
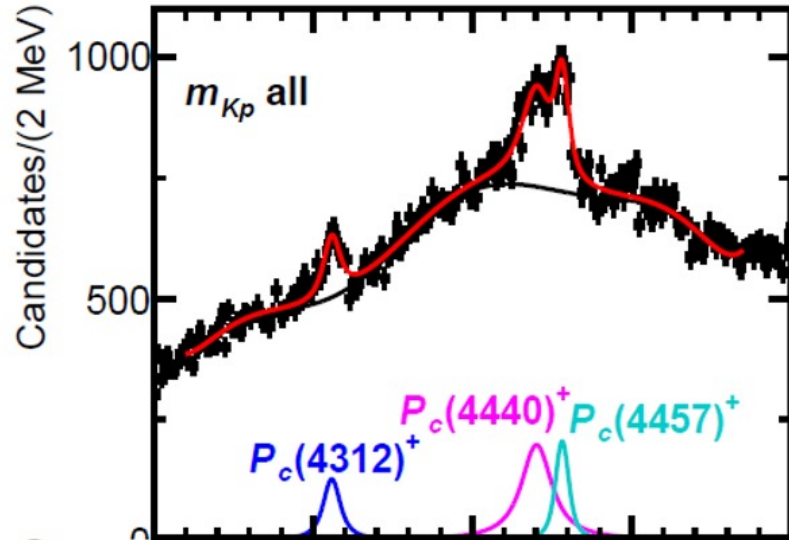
- $Z_{cs}(4000, 4220)$: LHCb, PRL 127 (2021) 082001
  - $B^+ \to K^+ J/\psi\phi$
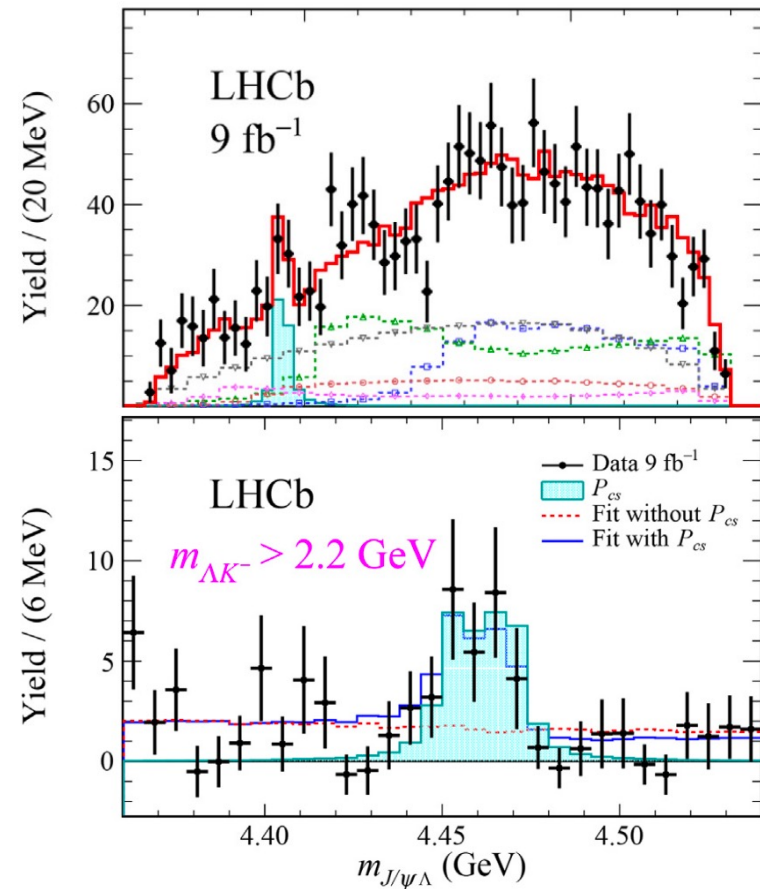 - $J^P = 1^+$ favored

Hidden-charm pentaquarks

Hidden-charm P_c in $\Lambda_b^0 \to J/\psi\, p\, K^-$

LHCb, PRL 115 (2015) 072001;
       PRL 122 (2019) 222001

Hidden-charm P_{cs} in $\Xi_b^- \to J/\psi\, \Lambda\, K^-$

LHCb, Sci.Bull. 66 (2021) 1391

Open-charm exotic mesons with strangeness

- Lattice QCD studies

  - ☐ Early work using only $c\bar{s}$-type interpolators typically gives a mass larger than that for $D_{s0}^*(2317)$ G. Bali (2003); UKQCD (2003); HadSpec (2013); . . .

  - ☐ $c\bar{s} + DK$ interpolators: $\sim$ the right mass D. Mohler et al., PRL 111 (2013) 222001
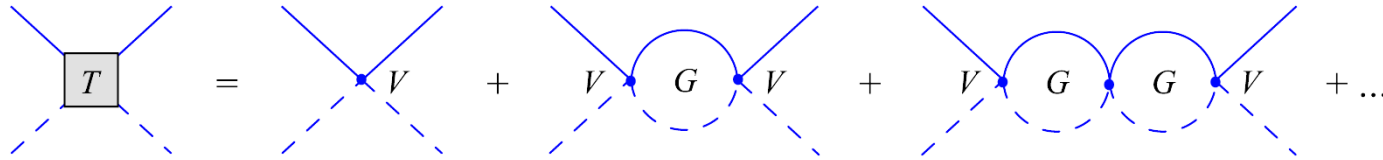
$$M_{D_{s0}^*} - \frac{1}{4}\left(M_{D_s} + 3M_{D_s^*}\right)$$

D. Mohler et al.	PDG2022
(266 ± 16) MeV	(241.5 ± 0.8) MeV

  - ☐ Calculation with $M_\pi = 150$ MeV G. Bali et al. [RQCD Col.], PRD 96 (2017) 074501

	Energy [MeV]	**Expt** [MeV]
m_{0^-}	1976.9(2)	1966.0(4)
m_{1^-}	2094.9(7)	2111.3(6)
m_{0^+}	2348(4)(+6)	2317.7(0.6)(2.0)
m_{1^+}	2451(4)(+1)	2459.5(0.6)(2.0)

Open-charm exotic mesons with strangeness

- S-wave interactions between charm mesons (D, D_s) and light pseudoscalar mesons (π, K, η)

- not far from the thresholds $\Rightarrow$ chiral EFT for matter field
- D_{s0}^*/D_0^* should appear as poles in scattering amplitudes:

$$D_{s0}^* : DK, D_s\eta; \qquad D_0^* : D\pi, D\eta, D_s\bar{K}$$
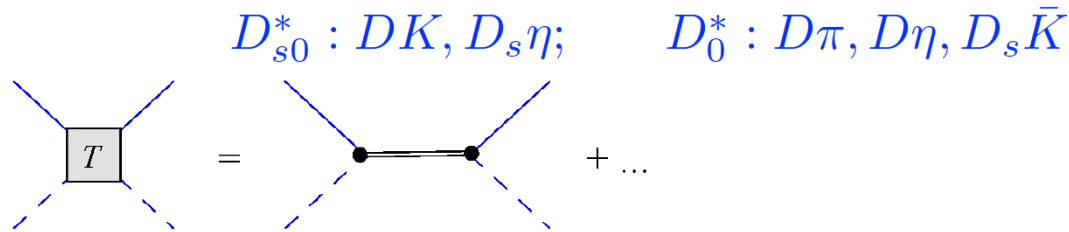
$\Rightarrow$ needs a nonperturbative treatment: ChPT + unitarization

Truong (1988); Oller, Oset (1997); Oller, Oset, Pelaez (1998); Nieves, Ruiz Arriola (1999); Oller, Meißner (2001); . . .

$$T^{-1}(s) = V^{-1}(s) - G(s)$$

$V(s)$: from SU(3) chiral Lagrangian, 6 LECs up to NLO   fixed from exp. + lat. data

$G(s)$: 2-point scalar loop functions, regularized with a subtraction constant $a(\mu)$

Open-charm exotic mesons with strangeness

● Predictions of heavy-strangeness meson masses

meson	J^P	prediction (MeV)	PDG2022 (MeV)	lattice (MeV)
D_{s0}^*	0^+	2315_{-28}^{+18}	2317.8 ± 0.5	2348_{-4}^{+7} [1]
D_{s1}	1^+	2456_{-21}^{+15}	2459.5 ± 0.6	2451 ± 4 [1]
B_{s0}^*	0^+	5720_{-23}^{+16}	–	5711 ± 23 [2]
B_{s1}	1^+	5772_{-21}^{+15}	–	5750 ± 25 [2]

[1] RQCD, PRD 96 (2017) 074501
[2] Lang et al., PLB 750 (2015) 17

● D_{s0}^* and D_{s1} as DK and D^*K hadronic molecules

Barnes, Close, Lipkin (2003); van Beveren, Rupp (2003); Kolomeitsev, Lutz (2004); FKG et al. (2006); Gamermann et al. (2007); Faessler et al. (2007); FKG, Hanhart, Meißner (2009); . . .

● Compositeness of $D_{s0}^*(2317)$ from lattice

Liu et al., PRD 87 (2013) 014508
Martinez Torres et al., JHEP 05 (2015) 153
RQCD, PRD 96 (2017) 074501
HadSpec, JHEP 02 (2021) 100
Yang et al., PRL 128 (2022) 112001
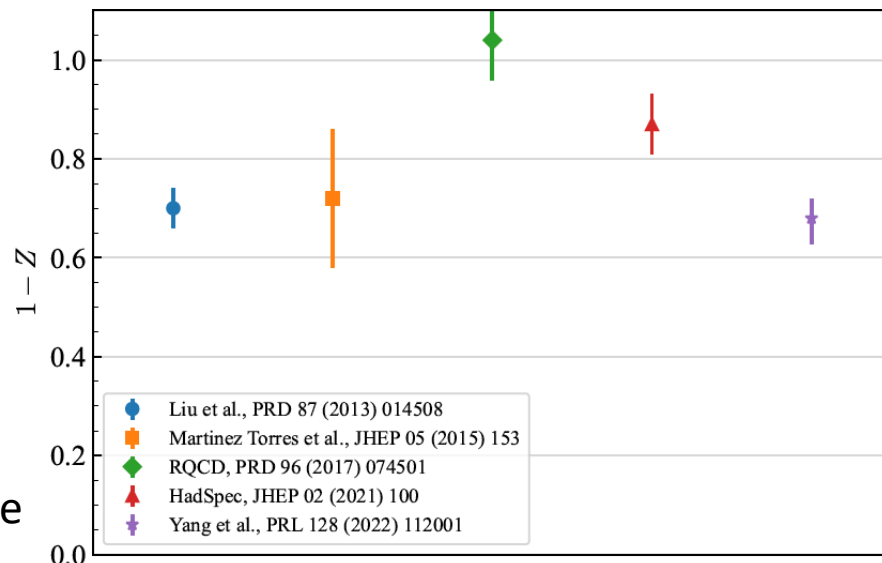
Open-charm exotic mesons with strangeness

- Special roles of kaons:

  - ☐ Light enough so that the dynamics can be approximately treated using chiral symmetry

  - ☐ Heavy enough so that the WT term leads to nonperturbative phenomena

- More kaonic bound states are expected   FKG, U.-G. Meißner, PRD84(2011)014013

  - ☐ The matter field can be any hadron with a small width Γ ≪ inverse of force range

Constituents	$D_1(2420)K$	$D_2(2460)K$	$\bar{B}_1(5720)K$	$\bar{B}_2(5747)K$
J^P	1^-	2^-	1^-	2^-
Predictions (MeV)	2870 ± 9	2910 ± 9	6151 ± 33	6169 ± 33
Decays	$D^{(*)}K, D_s^{(*)}\eta$	$D^*K, D_s^*\eta$	$\bar{B}^{(*)}K, \bar{B}_s^{(*)}\eta$	$\bar{B}^*K, \bar{B}_s^*\eta$

$D_{s1}^*(2860)$?

- ☐ Doubly-charmed strange baryons coupled to $B_{cc}\bar{K}$

  FKG, U.-G. Meißner, PRD 84 (2011) 014013; Z.-H. Guo,
  PRD 96 (2017) 074004; J. Dias et al., PRD 98 (2018)
  094017; L. Meng, S.-L. Zhu, PRD 100 (2019) 014006;
  Q.-X. Yu et al., EPJC 79 (2019) 1025; …
  For a recent review, see L. Meng et al.,
  arXiv:2204.08716

  - ➤ Complications due to P-wave excitation
    within the QQ-diquark

    M.-J. Yan et al., PRD 98 (2018) 091502
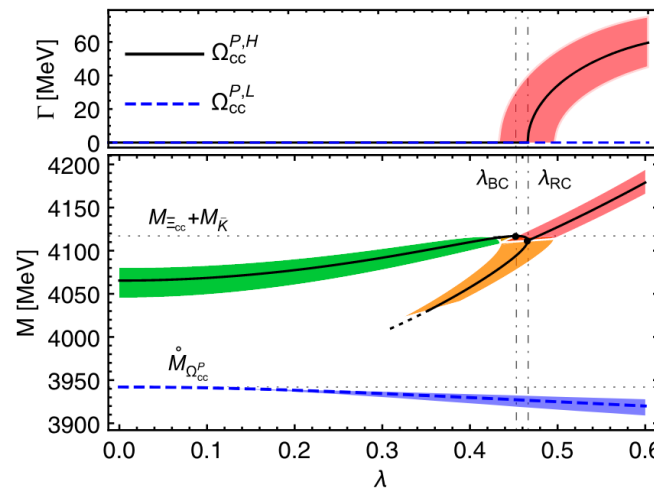
Open-charm exotic mesons with strangeness

- $D\bar{K}$ virtual state
  - ☐ SU(3) irreps: $\mathbf{\bar{3}} \otimes \mathbf{8} = \mathbf{\overline{15}} \oplus \mathbf{6} \oplus \mathbf{\bar{3}}$

M. Albaladejo et al., PLB 767 (2017) 465
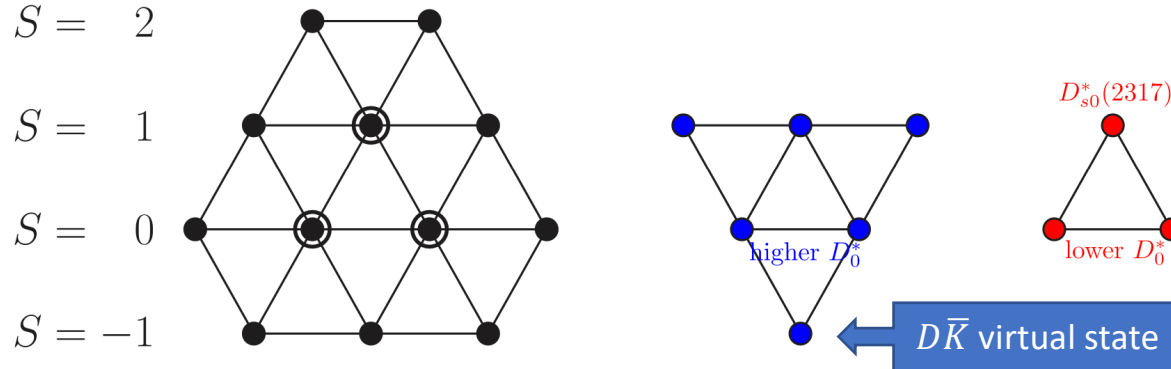
WT term: $\mathbf{\overline{15}}$: repulsive; $\mathbf{6}$: attractive; $\mathbf{\bar{3}}$: most attractive

  - ☐ Virtual state found with lattice QCD

HadSpec, JHEP 02 (2021) 100
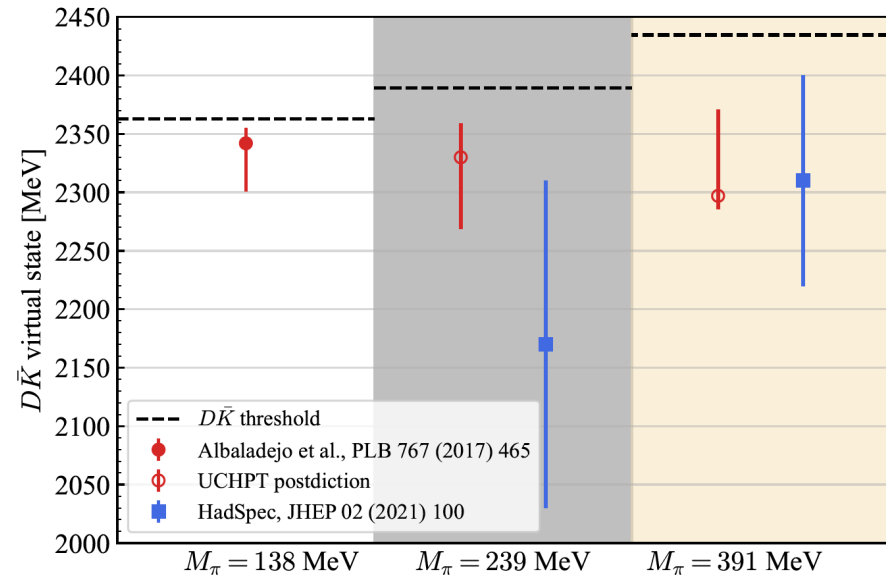
Open-charm exotic mesons with strangeness

- Kaons are pseudo-Goldstone bosons, interactions of K^* could be stronger

  □ $D^{(*)}\overline{K}$ form isoscalar virtual states $\Rightarrow$ reasonable to expect $D^{(*)}\overline{K}^*$ bound states

  □ $X(2900)$: resonant structure around $D^*\overline{K}^*$ threshold

  ➤ $X_{0,1}(2900)$, but fine structures not resolved

  ➤ $J^P = (0,1,2)^+$ $D^*\overline{K}^*$ bound states predicted

  R. Molina, T. Branz, E. Oset, PRD 82 (2010) 014010;
  R. Molina, E. Oset, PLB 811 (2020) 135870; …

  ➤ There must be partners
  - Spin partner: $D\overline{K}^*$ with $J^P = 1^+$, M ~ 2760 MeV
  - Bottom partners: $B\overline{K}^*$ ~ 6175 MeV;
    $\qquad\qquad\qquad B^*\overline{K}^* \sim 6220$ MeV

  ➤ $J^P = 1^-$ $D_1\overline{K}$ virtual/bound state is also expected

  See also H. Chen, H.-R. Qi, H.-Q. Zheng; …
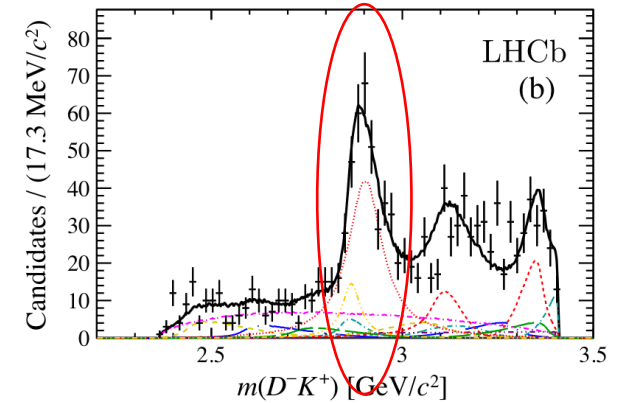
LHCb, PRL 125 (2020) 242001

Z_{cs}: hidden-charm exotics with strangeness

- $Z_{cs}(3985)$ as a $(D_s^- D^{*0} + D_s^{*-} D^0)$ molecular state   Z. Yang et al., PRD 103 (2021) 074029

  ☐ Role of triangle singularity for $e^+ e^- \to K^+ (D_s^- D^{*0} + D_s^{*-} D^0)$ at $\sqrt{s}_{e^+e^-} = 4.681$ GeV

  ☐ Two Z_{cs} states: virtual or resonant

  ~ 3.99 GeV, 4.12 GeV
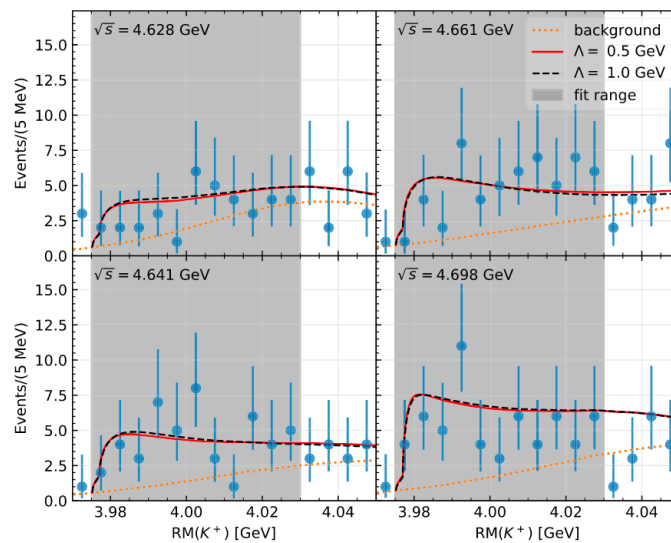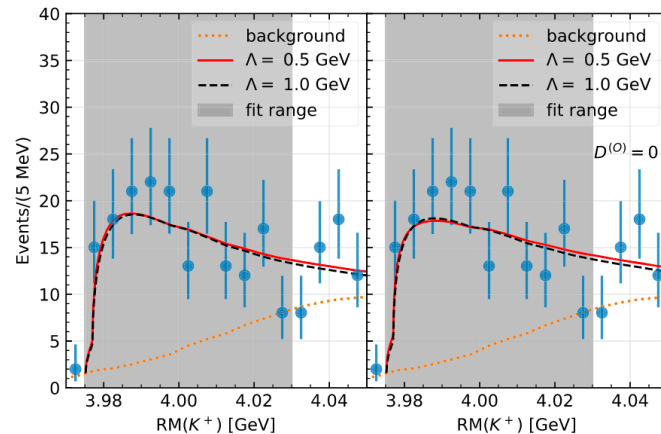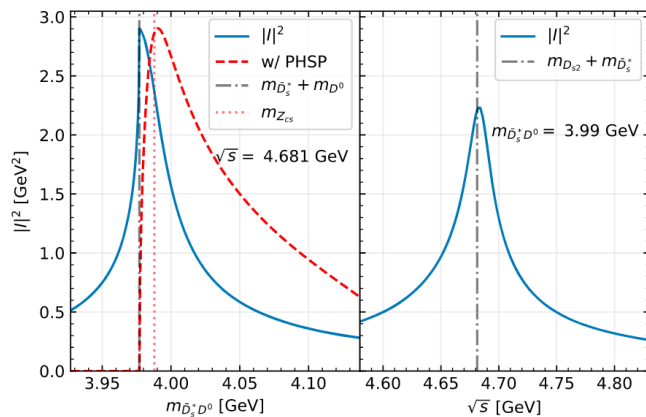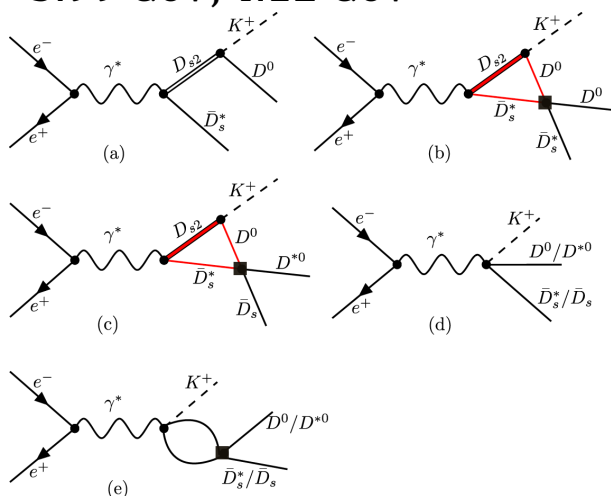
Z_{cs}: hidden-charm exotics with strangeness

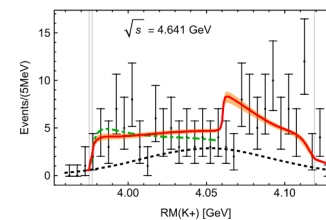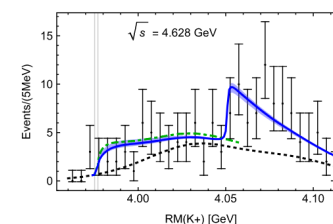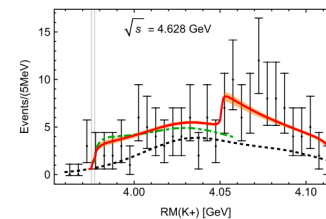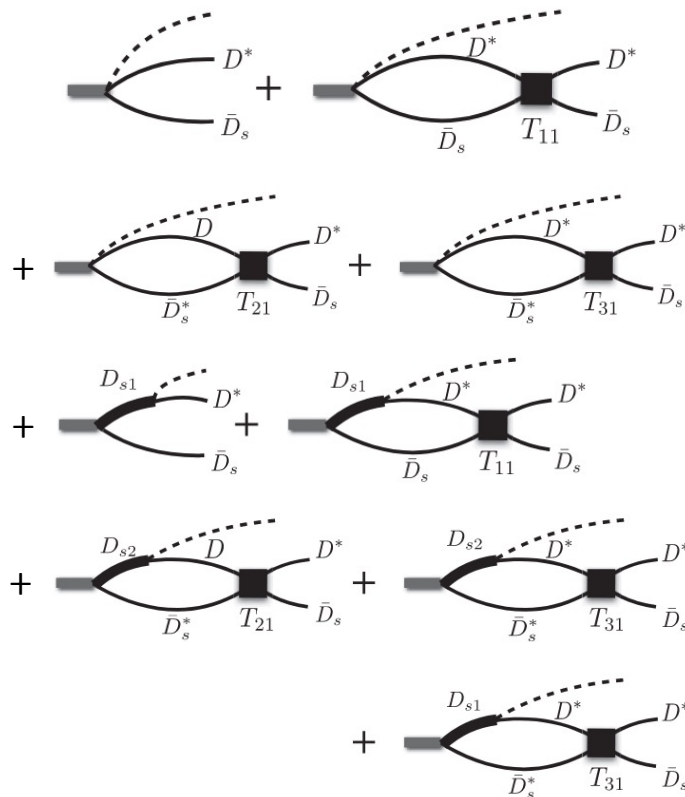- $Z_{cs}(3985)$ as a $(D_s^- D^{*0} + D_s^{*-} D^0)$ molecular state   V. Baru et al., PRD 105 (2022) 034014

  ☐ Fit to BESIII data in the full range

  ☐ Scenarios: two

     or one Z_{cs} (strong ch. coupling)

  ☐ Both $D_{s2}\bar{D}_s^* D^{(*)}$ and $D_{s1}\bar{D}_s^{(*)} D^*$ triangles
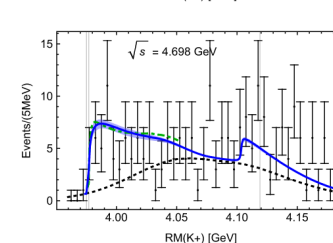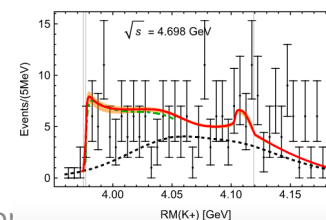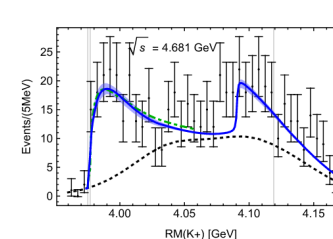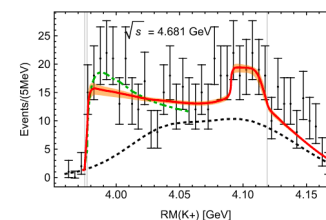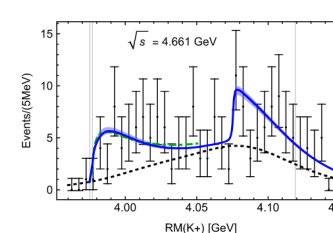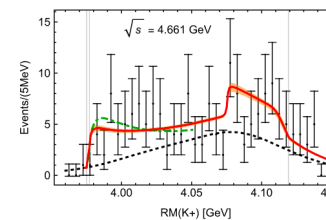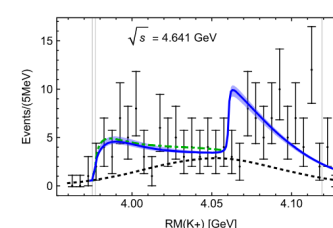
Z_{cs}: hidden-charm exotics with strangeness

- Models that the broad $Z_{cs}(4000)$ by LHCb and the narrow $Z_{cs}(3985)$ by BESIII are different states

  L. Maiani, A. D. Polosa, V. Riquer, Sci.Bull. 66 (2021) 1616; L. Meng, B. Wang, S.-L. Zhu, Sci.Bull. 66 (2021) 2065; …

- Line shapes depend on reactions: the broad $Z_{cs}(4000)$ and the narrow $Z_{cs}(3985)$ structures might correspond to the same state;   Z. Yang et al., PRD 103 (2021) 074029

  ☐ Fits to both BESIII and LHCb data with $Z_{cs}(3985)$ and $Z_{cs}(4110)$ virtual states
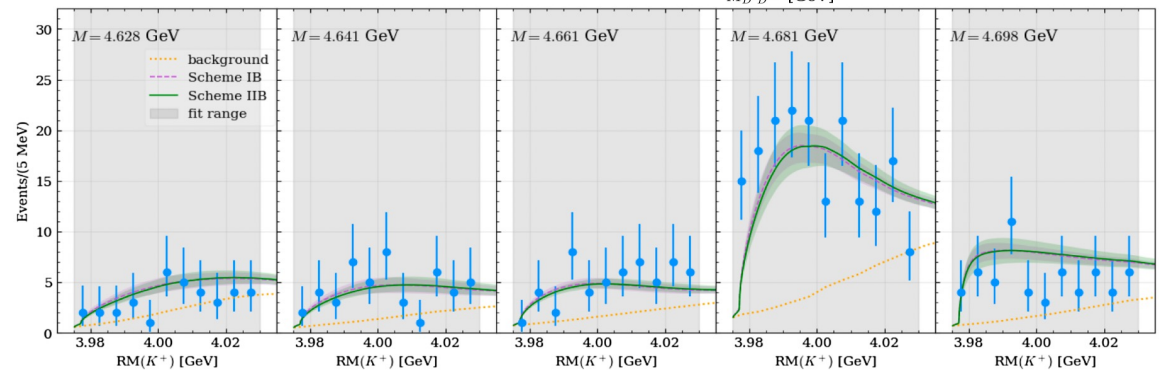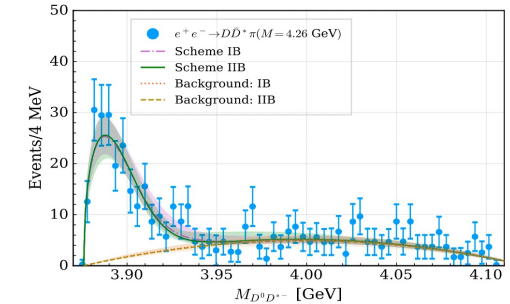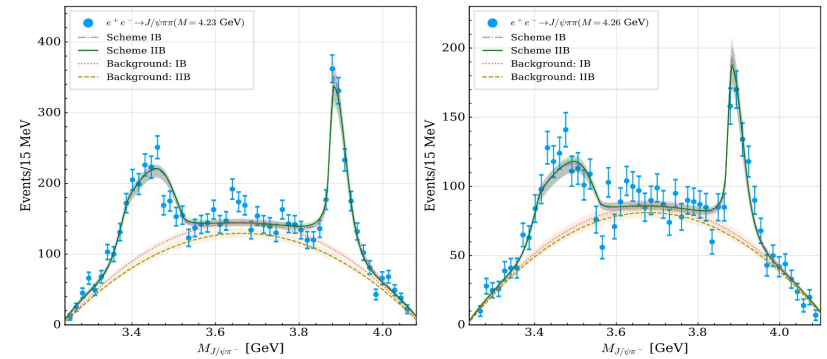
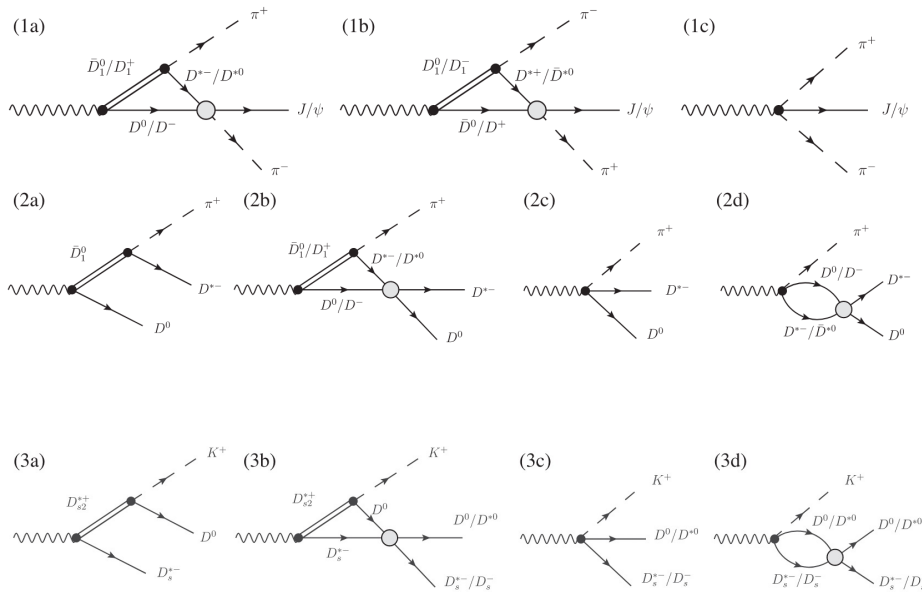 P. Ortega, D. Entem, F. Fernandez, PLB 818 (2021) 136382
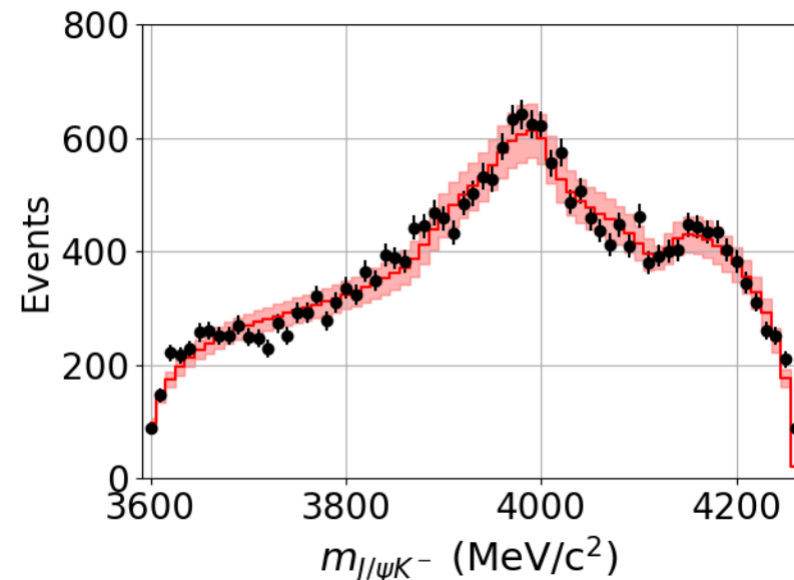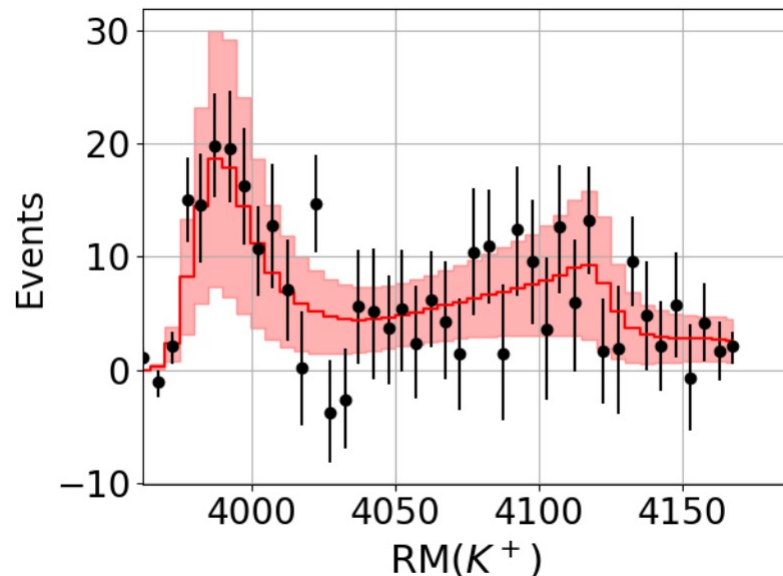
Z_{cs} : hidden-charm exotics with strangeness

- $Z_c(3900)^{\pm}$ and $Z_{cs}(3985)$ are SU(3) partners

 - ☐ Simultaneous description of the BESIII data

M.-L. Du, M. Albaladejo, FKG, J. Nieves, PRD 105 (2022) 074018

P_{cs}: hidden-charm pentaquarks with strangeness

- P_c and P_{cs} as $\bar{D}\Sigma_c$ and $\bar{D}\Xi_c$ hadronic molecules in the above 4 GeV region first predicted in

  J.-J. Wu, R. Molina, E. Oset, B.-S. Zou, PRL 105 (2010) 232001

- More $\bar{D}^{(*)}\Sigma_c^{(*)}$ and $\bar{D}^{(*)}\Xi_c^{(*)}$ hadronic molecules expected from heavy quark spin symmetry

  C.-W. Xiao, J. Nieves, E. Oset, PRD 88 (2013) 056012; PRD 100 (2019) 014021; PLB 799 (2019) 135051;
  M.-Z. Liu et al., PRD 98 (2018) 114030; M.-Z. Liu et al., PRL 122 (2019) 242001; B. Wang, L. Meng, S.-L. Zhu, PRD
  101 (2020) 034018; M.-L. Du et al., PRL 124 (2020) 072001; …

- A survey of the P_{cs} spectrum with the simple vector-meson exchange model

  X.-K. Dong, FKG, B.-S. Zou, Progr.Phys. 41 (2021) 65
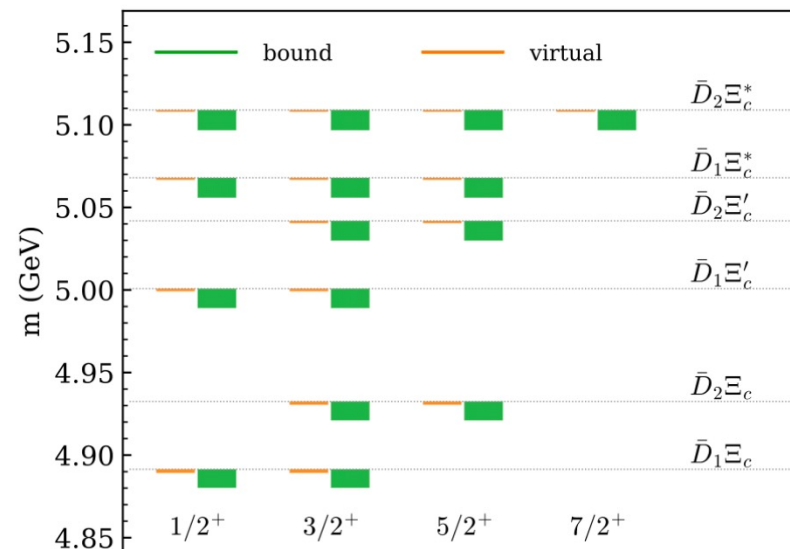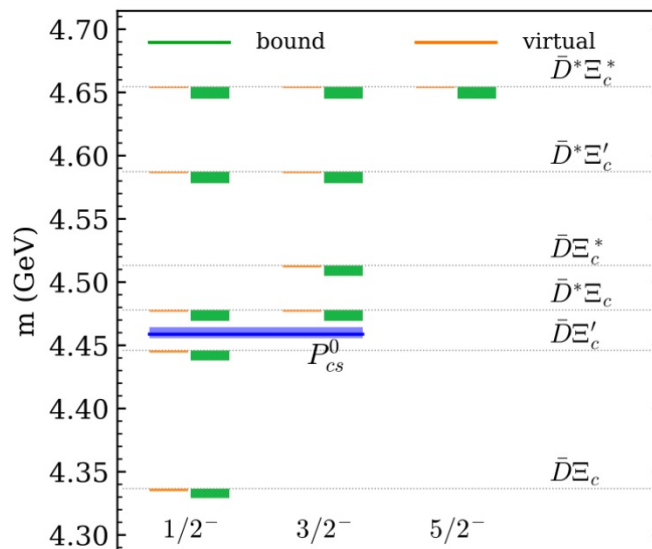
Summary

- Lots of exotic hadron candidates observed in the last two decades; an overall understanding is still lacking

- I only focused on those with strangeness and charm as hadronic molecules

  - ❑ Kaonic bound states: universal due to chiral symmetry

    - ➢ Chiral symmetry + lattice + exp.: $D_{s0}^*(2317)$ and $D_{s1}(2460)$ are the best understood among the exotic candidates

  - ❑ P_{cs}, Z_{cs} with hidden-charm

    - ➢ Heavy quark symmetry is important

    - ➢ No lattice calculation so far

    - ➢ Better data are urged

Thank you for your attention!