Theoretical Understanding of Light and Heavy Hadrons

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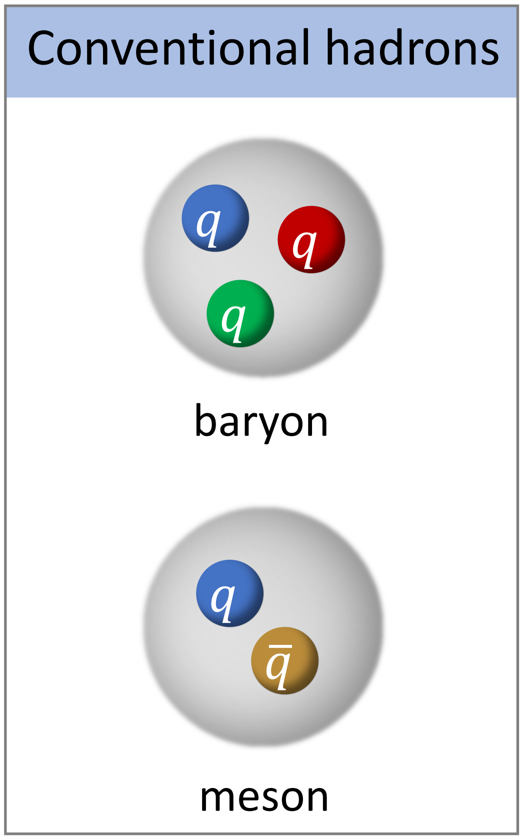
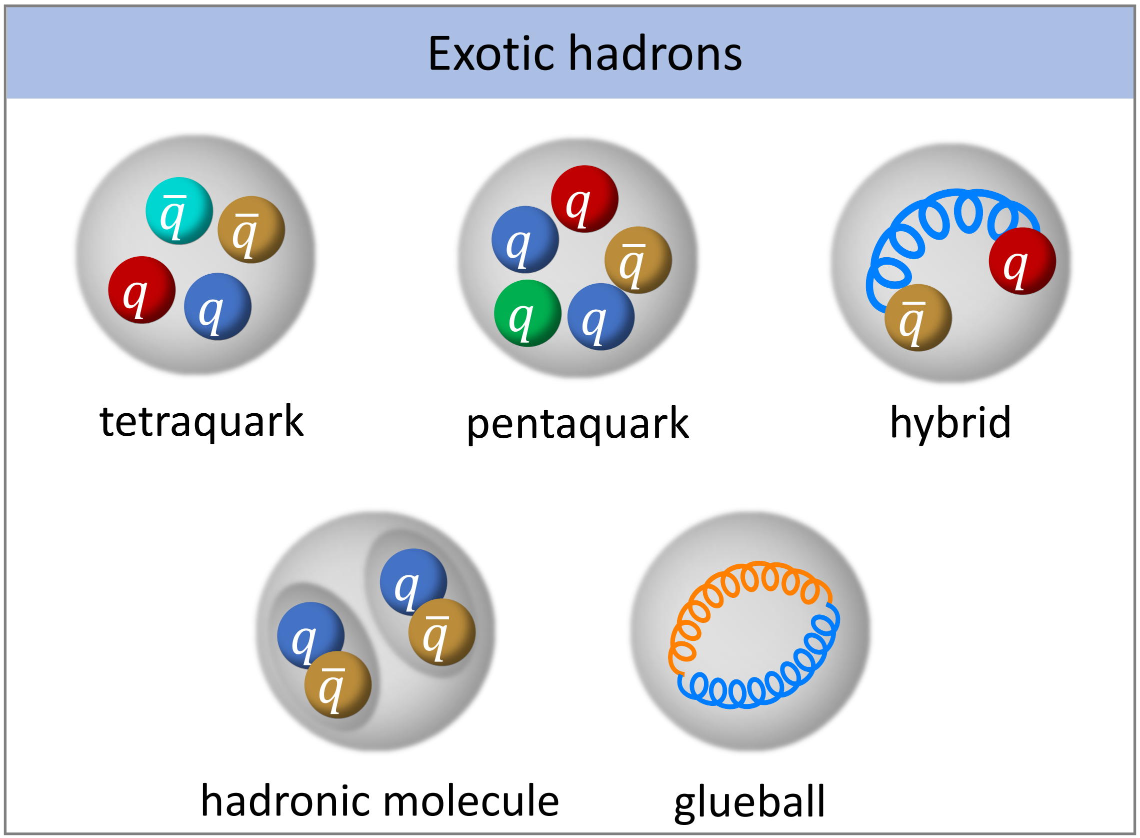
PANIC 2021, 5-11 Sept. 2021

Conventional and exotic hadrons

- Hadrons are colorless; what types of color singlets should exist?
- Confinement: clue from hadron spectrum?
- Quark model: conventional and exotic hadrons

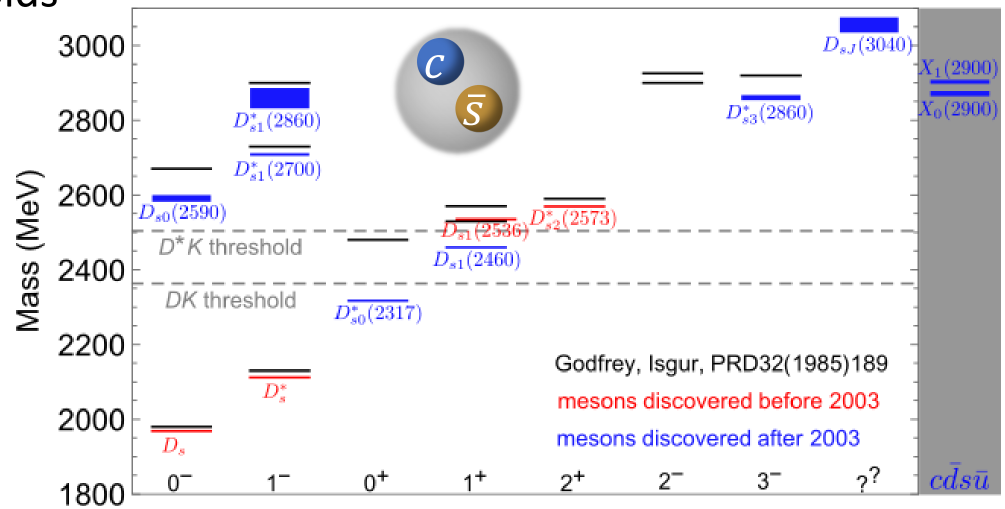




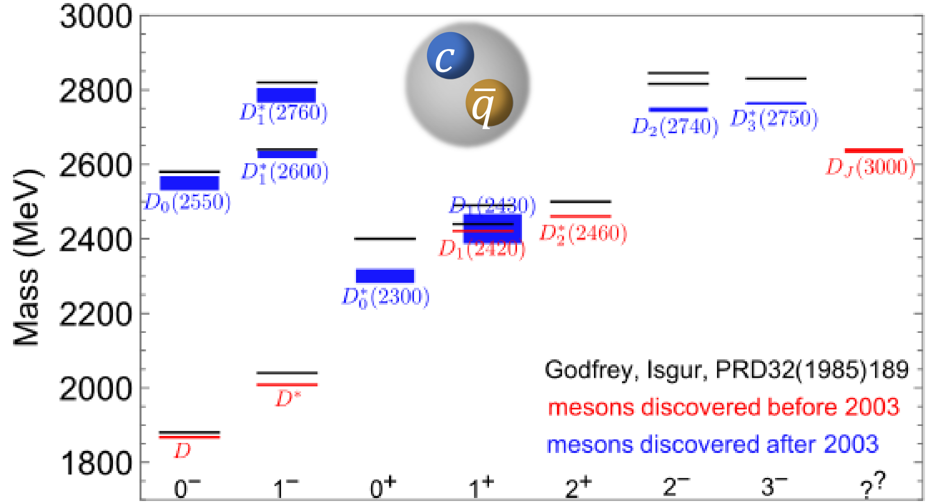
Disclaimer: NOT a general review; will discuss challenges from my personal point of view

Hadron spectrum: charmonium(-like)

- Quark model provides qualitative guidance, but the physics is much richer, in particular for energies close to or above thresholds
  - Abundance of new states from peak hunting
    - b-hadron (B, Λ_b) decays
    - e^+e^- collisions
    - Hadron collisions
    - Heavy-ion collisions
  - Example: open-charm mesons



Charm−strange mesons



Charm−nonstrange mesons

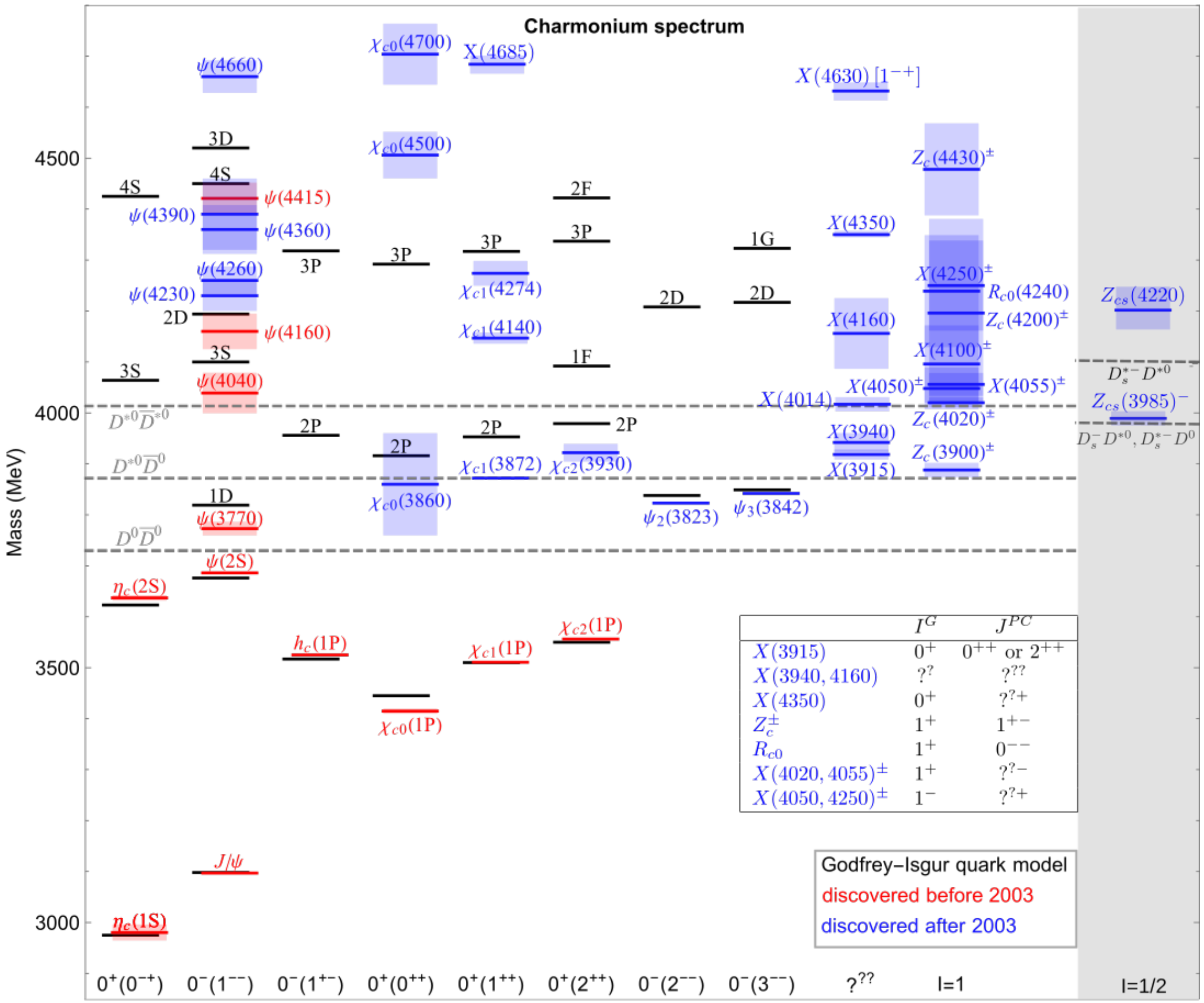
Predictions of the 2^- states taken from Godfrey, Moats, PRD93(2016)034035

Hadron spectrum: charmonium(-like)

- Quark model provides qualitative guidance, but the physics is much richer, in particular for energies close to or above thresholds

  - Abundance of new states from peak hunting
    - b-hadron (B, Λ_b) decays
    - e^+e^- collisions
    - Hadron collisions
    - Heavy-ion collisions
  - Example: charmonium(-like) spectrum

Next talk by C.-Z. Yuan



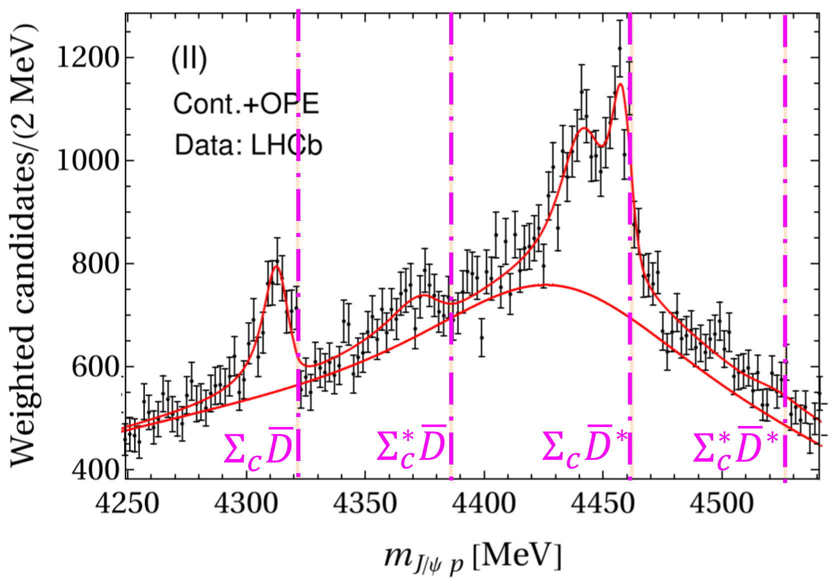
Near-threshold states

- Prominent features: many are narrow and near-threshold; spectrum of explicitly exotic states is emerging

$X(3872)$[aka $\chi_{c1}(3872)$], $Z_c(3900)^{\pm}$, $Z_c(4020)^{\pm}$, $Z_{cs}(3985)$, …

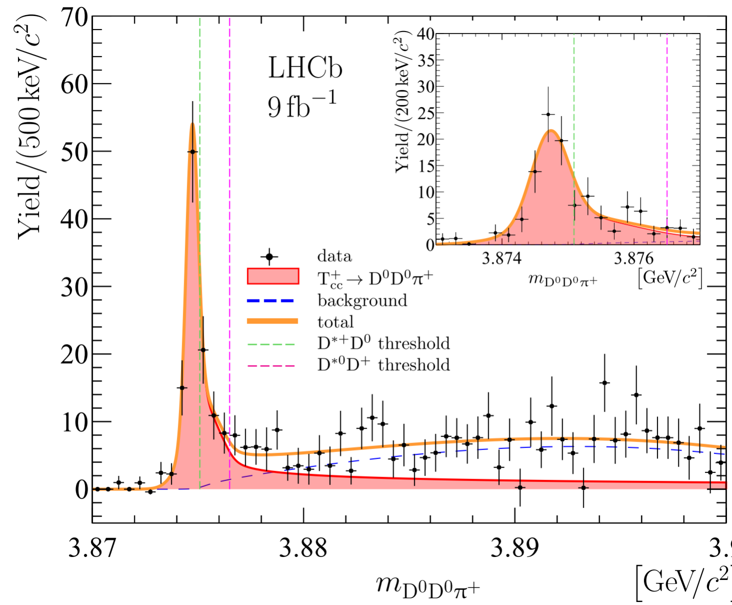
Belle(2003) | BESIII, Belle (2013) | BESIII (2013) | BESIII (2020), LHCb (2021)

P_c states: hidden-charm baryon



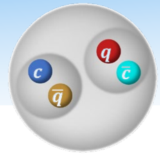
data from LHCb, PRL122 (2019) 222001;
fit from
M.-L. Du, Baru, FKG, Hanhart, Meißner, Oller, Q. Wang, PRL124 (2020) 072001

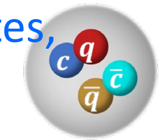
T_{cc}: double-charm meson

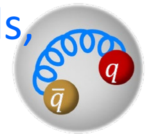


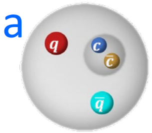
LHCb, arXiv:2109.01038; arXiv:2109.01056

Models



- Candidates of hadronic molecules
- Other models: compact multiquark states, 

hybrids, 

hadrocharmonia 
- >10 reviews in the last 5 years:
  - H.-X. Chen et al., *The hidden-charm pentaquark and tetraquark states*, Phys. Rept. 639 (2016) 1
  - A. Hosaka et al., *Exotic hadrons with heavy flavors: X, Y, Z, and related states*, PTEP 2016 (2016) 062C01
  - J.-M. Richard, *Exotic hadrons: review and perspectives*, Few Body Syst. 57 (2016) 1185
  - R. F. Lebed, R. E. Mitchell, E. Swanson, *Heavy-quark QCD exotica*, PPNP 93 (2017)143
  - A. Esposito, A. Pilloni, A. D. Polosa, *Multiquark resonances*, Phys. Rept. 668 (2017) 1
  - FKG, C. Hanhart, U.-G. Meißner, Q. Wang, Q. Zhao, B.-S. Zou, *Hadronic molecules*, RMP 90 (2018) 015004
  - A. Ali, J. S. Lange, S. Stone, Exotics: *Heavy pentaquarks and tetraquarks*, PPNP 97 (2017) 123
  - S. L. Olsen, T. Skwarnicki, *Nonstandard heavy mesons and baryons: Experimental evidence*, RMP 90 (2018) 015003
  - Y.-R. Liu et al., *Pentaquark and tetraquark states*, PPNP107 (2019) 237
  - N. Brambilla et al., *The XYZ states: experimental and theoretical status and perspectives*, Phys. Rept. 873 (2020) 154
  - Y. Yamaguchi et al., *Heavy hadronic molecules with pion exchange and quark core couplings: a guide for practitioners*, JPG 47 (2020) 053001
  - FKG, X.-H. Liu, S. Sakai, *Threshold cusps and triangle singularities in hadronic reactions*, PPNP 112 (2020) 103757
  - G. Yang, J. Ping, J. Segovia, *Tetra- and penta-quark structures in the constituent quark model*, Symmetry 12 (2020) 1869
  - ……
- And a book:
  - A. Ali, L. Maiani, A. D. Polosa, *Multiquark Hadrons*, Cambridge University Press (2019)

Hadronic molecules & tetraquarks

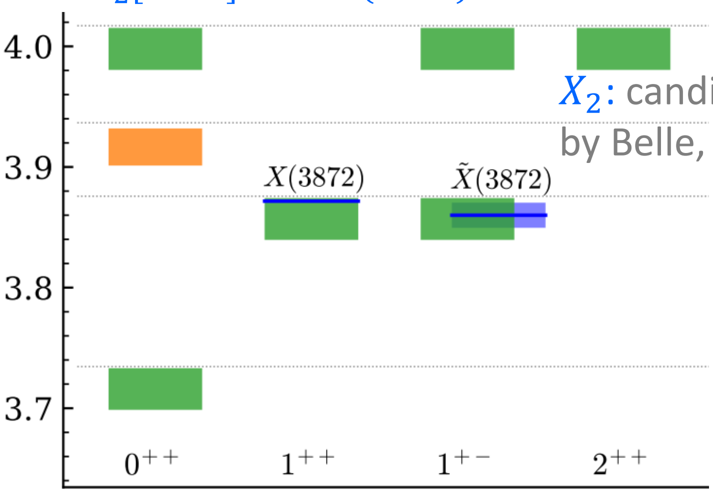
- Different models predict distinct mass spectra and decay patterns, e.g., charmonium-like

➢ $P = +$ states in a molecular model

N.A. Törnqvist, ZPC61(1994)525;
C.-Y. Wong, PRC69(2004)055202;
E. Swanson, JPCS9(2005)79;
J. Nieves, M.P. Valderrama, PRD86(2012)056004;
FKG, C. Hidalgo-Duque, J. Nieves, M.P. Valderrama, PRD88(2013)054007;
V. Baru et al. PLB763(2016)20;…

Heavy-quark spin symmetry:

$$M_{X_2[D^*\bar{D}^*]} - M_{X(3872)} \approx M_{D^*} - M_D$$



X_2: candidate reported by Belle, 2105.06605

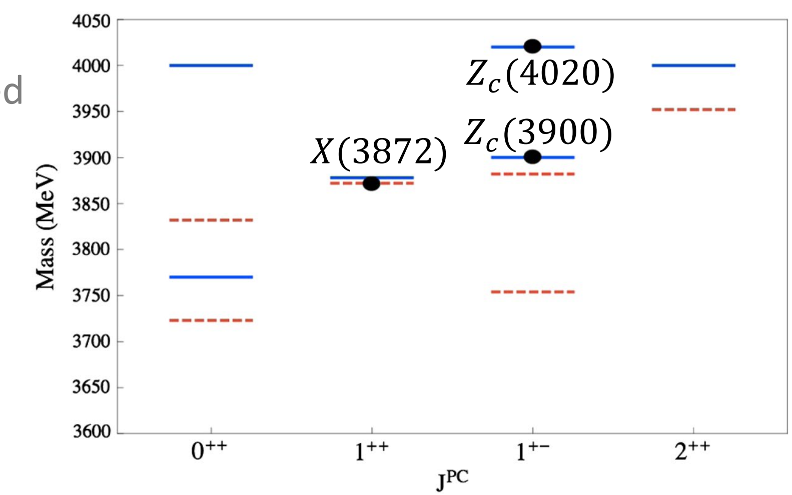
X.-K. Dong, FKG, B.-S. Zou, Progr.Phys.41(2021)65

➢ $P = +$ states in a tetraquark model

$$\mathcal{H} \approx 2\kappa_{qc}(s_q \cdot s_c + s_{\bar{q}} \cdot s_{\bar{c}})$$

Spectrum similar with molecular model from fixing κ_{qc} using

$$M_{Z_c(4020)} - M_{Z_c(3900)} \approx M_{D^*} - M_D$$

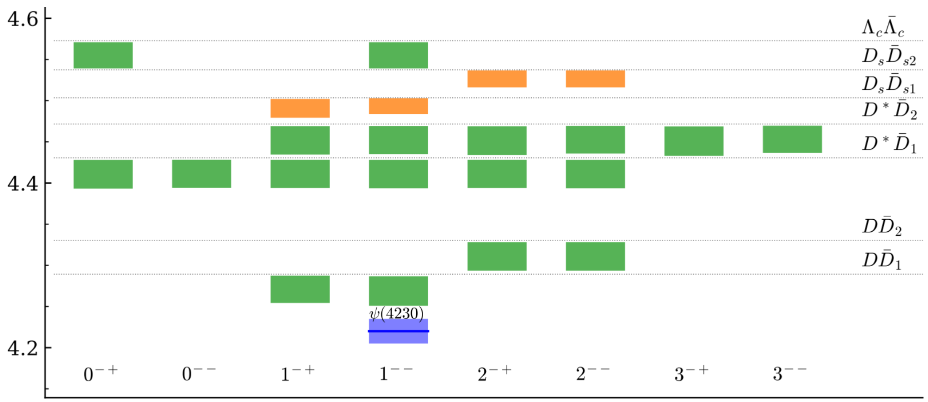


L. Maiani, F. Piccinini, A. D. Polosa, V. Riquer, PRD89(2014)114010

Hadronic molecules & tetraquarks

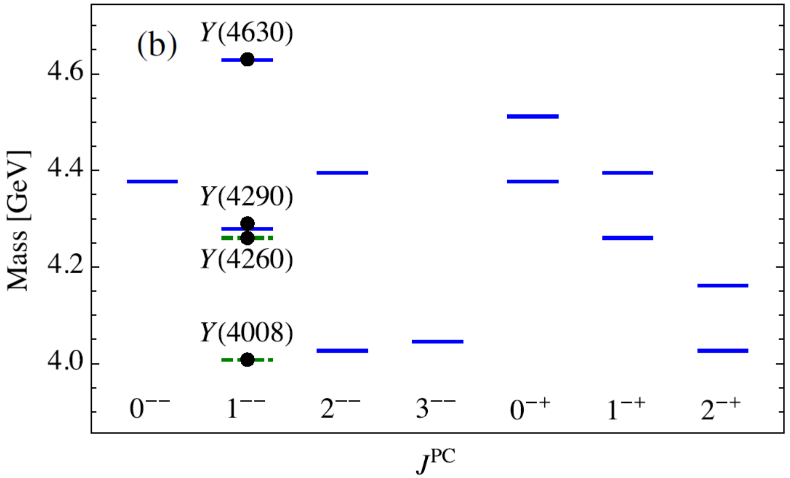
- Different models predict distinct mass spectra and decay patterns, e.g., charmonium-like
  - $P = -$ states in a molecular model
  - $P = -$ states in a tetraquark model

$$M = M_{00} + B_c \frac{L(L+1)}{2} + a[L(L+1) + S(S+1) - J(J+1)] + \kappa_{cq}[s(s+1) + \bar{s}(\bar{s}+1) - 3].$$



Mol. spectrum using a VMD interaction

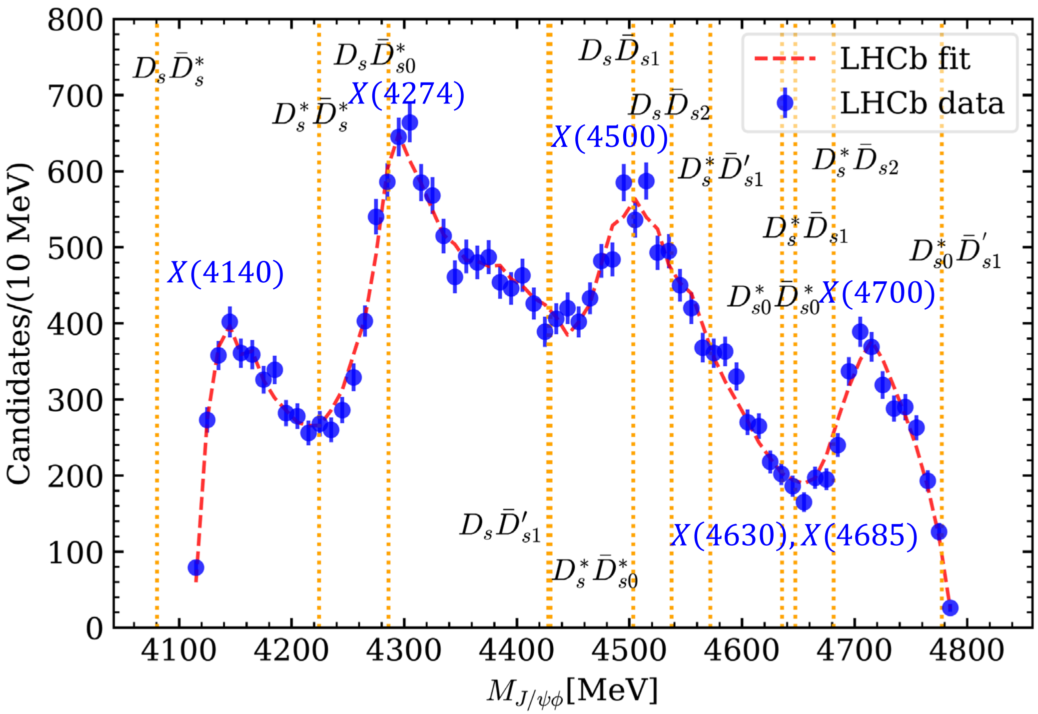
X.-K. Dong, FKG, B.-S. Zou, Progr.Phys.41(2021)65



M. Cleven, FKG, C. Hanhart, Q. Wang, Q. Zhao, PRD92(2015)014005
using inputs from
L. Maiani, F. Piccinini, A. D. Polosa, V. Riquer, PRD89(2014)114010

Challenges

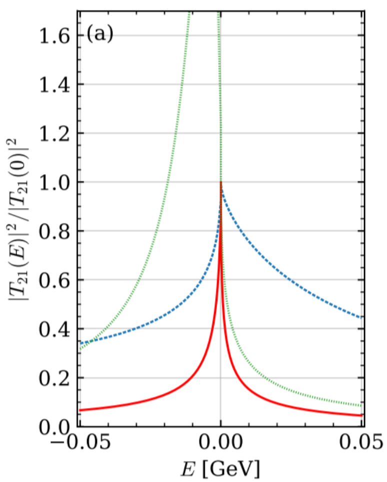
- To reveal the underlying physics, we need to have a faithful spectrum to start with
- In most cases, resonance parameters are extracted using Breit-Wigner
  - ☐ Potentially sizeable corrections due to coupled channels and thresholds



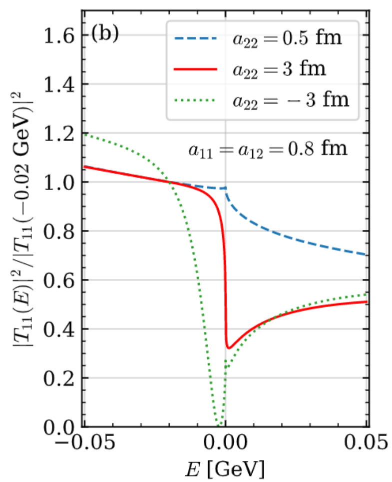
LHCb data: PRL127(2021)082001
Figure from X.-K. Dong, FKG, B.-S. Zou, Progr.Phys.41(2021)65

Challenges

- Unitarity: the same resonance may behave completely different in different processes
- Resonance does not necessarily show up as a peak, may also be a dip



$$T_{21} \propto \frac{1}{a_{22,\text{eff}}^{-1} - i\sqrt{2\mu_2 E}}$$



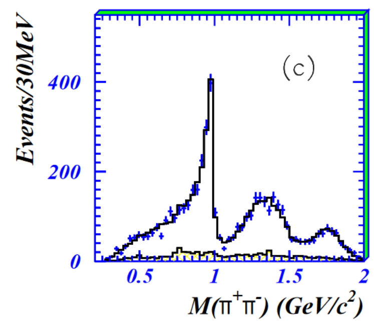
$$T_{11} \propto \frac{a_{22}^{-1} - i\sqrt{2\mu_2 E}}{a_{22,\text{eff}}^{-1} - i\sqrt{2\mu_2 E}}$$

Line shapes of the same poles in different processes

X.-K. Dong, FKG, B.-S. Zou, PRL126(2021)152001

- E.g., $f_0(980)$:

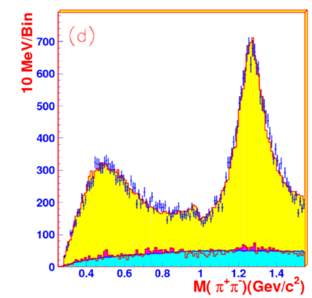
peak in $J/\psi \to \phi\pi^+\pi^-$



BES, PLB607(2005)243

$K\bar{K} \to \pi\pi$

dip in $J/\psi \to \omega\pi^+\pi^-$



BES, PLB598(2004)149

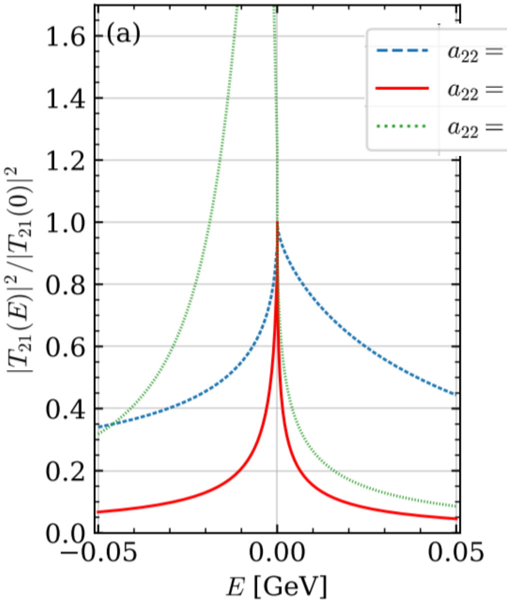
$\pi\pi \to \pi\pi$

Challenges

- In most cases, resonance parameters are extracted using Breit-Wigner
  - Peaks exactly at threshold for S-wave attraction that is not strong enough to form a bound state:

X.-K. Dong, FKG, B.-S. Zou, PRL126(2021)152001

    - Virtual state pole
    - Half-maximum width of the cusp $\propto \frac{1}{\mu\, a_0^2}$ $\Rightarrow$ narrow threshold structures easier for heavy hadron pairs



virtual states

bound state

Challenges

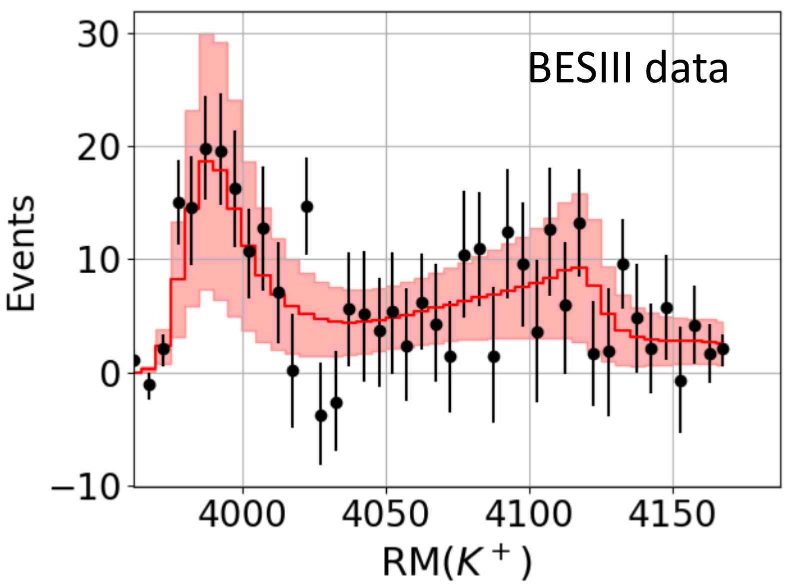
- Unitarity: the same resonance may behave completely different in different processes;
- Resonance does not necessarily show up as a peak, may also be a dip

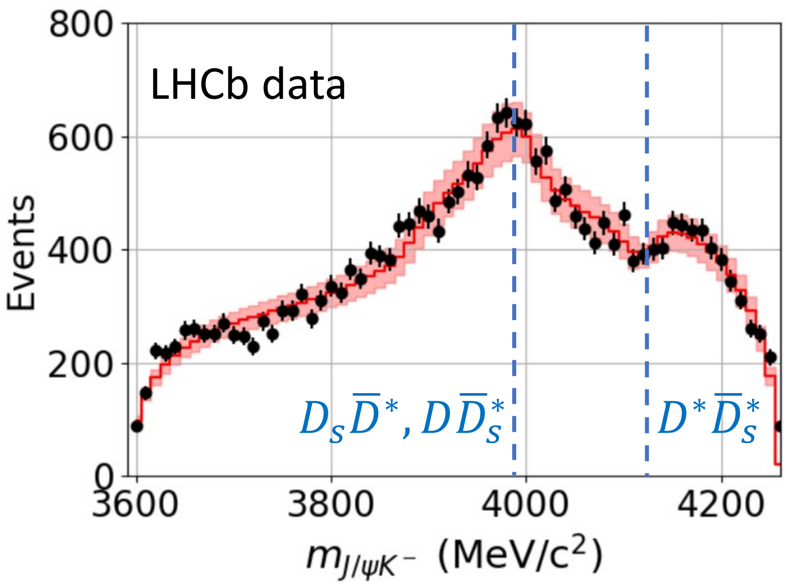
✓ BESIII: narrow $Z_{cs}(3985)$ PRL126(2021)102001

✓ LHCb: broad $Z_{cs}(4000)$, and $Z_{cs}(4200)$ PRL127(2021)082001

✓ A simultaneous fit to the BESIII and LHCb Z_{cs} data: two virtual states $Z_{cs}(3990, 4110)$

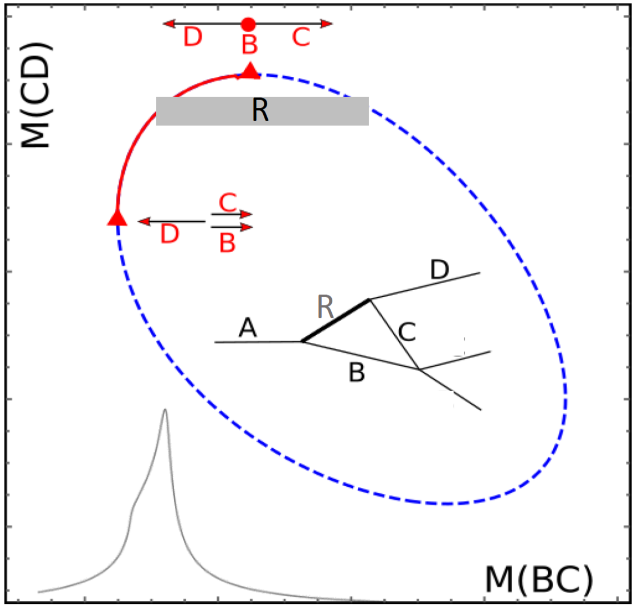
Ortega, Entem, Fernandez, PLB818(2021)136382





Challenges

- A peak is not necessarily due to a resonance
  - Triangle singularities
    - on shell and collinear intermediate particles
    - determined by kinematic variables such as masses and energies
    - sensitive to energies and processes



For a review of triangle singularities and threshold cusps, FKG, X.-H.Liu, S. Sakai, PPNP 112 (2020) 103757;

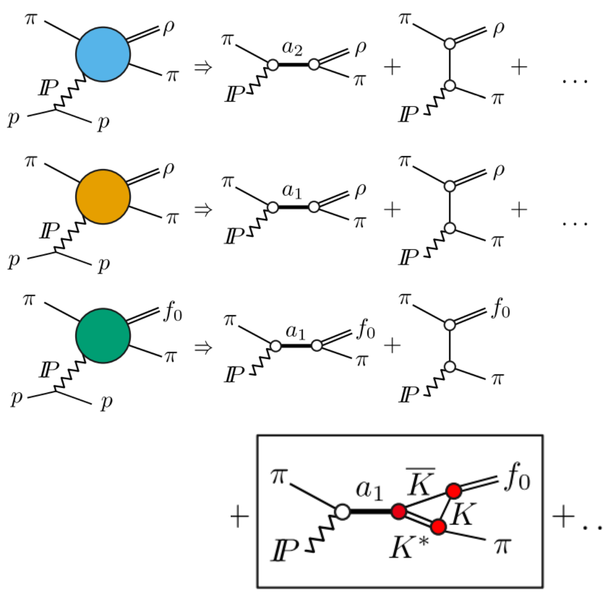
see also talk by F. Llanes-Estrada @ Session-HadronSpec., Sept.05

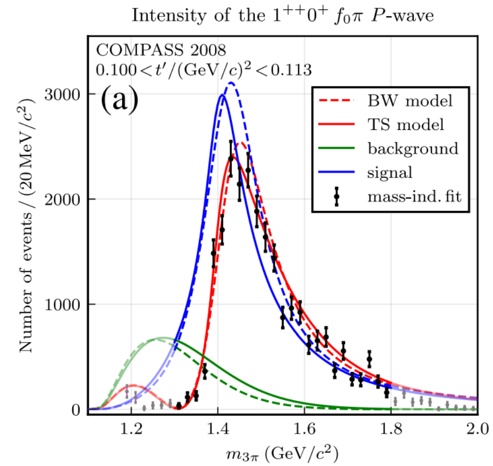
$$m_{A,\mathrm{TS}}^2 \in \left[(m_R+m_B)^2,\ (m_R+m_B)^2 + \frac{m_B}{m_C}\left[(m_R-m_C)^2 - m_D^2 \right] \right]$$

$$m_{BC,\mathrm{TS}}^2 \in \left[(m_B+m_C)^2,\ (m_B+m_C)^2 + \frac{m_B}{m_R}\left[(m_R-m_C)^2 - m_D^2 \right] \right]$$

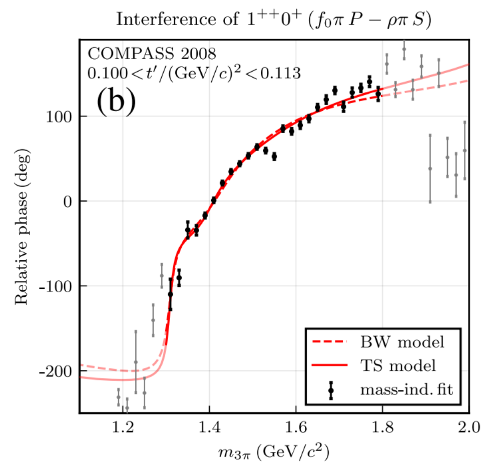
Challenges

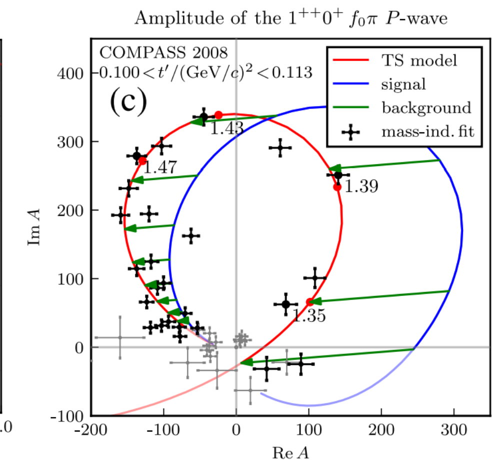
- **A peak is not necessarily due to a resonance**
  - Triangle singularities: E.g., $a_1(1420)$ can be well described by either a resonance or a triangle singularity (TS) effect





COMPASS, PRL127(2021)082501

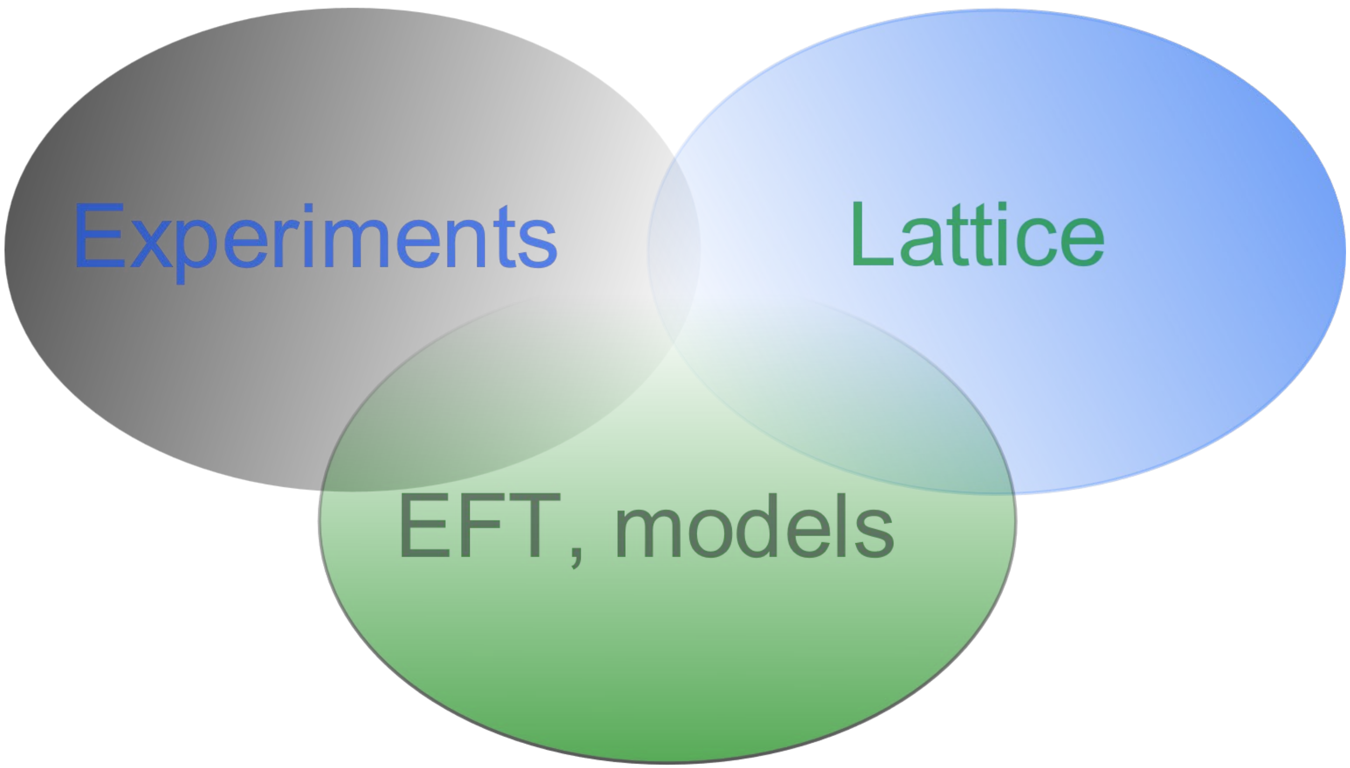




Discussions of TS for $a_1(1420)$, see also:
Q. Zhao @ Hadron2013;
M. Mikhasenko et al., PRD91(2015)094015;
F. Aceti, L.R. Dai, E. Oset, PRD94(2016)096015

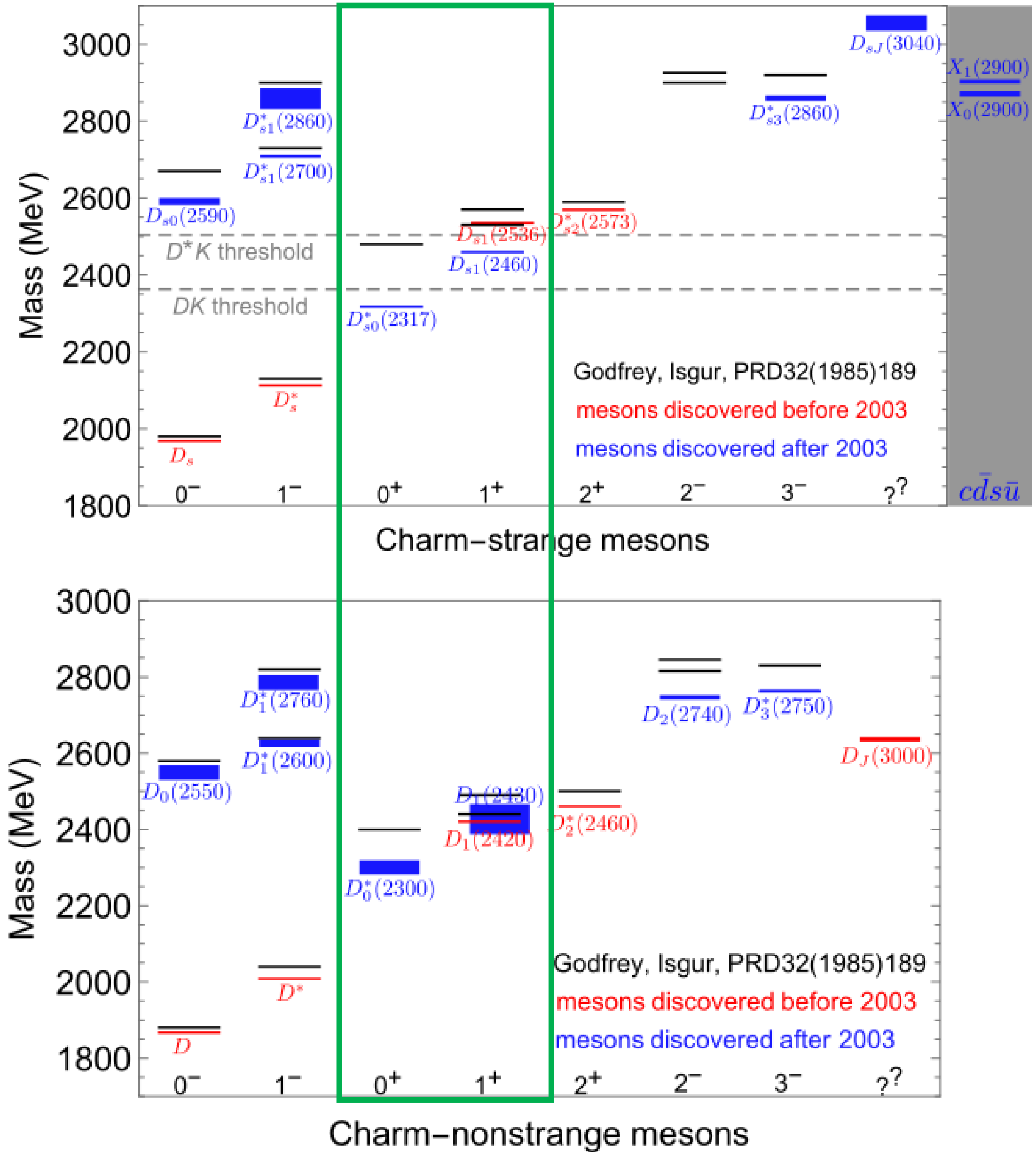
Exp., theory and lattice

- Precise data and lattice QCD calculations are needed
- Theoretical methods constrained by symmetry, unitarity and analyticity as a bridge



- Example: positive-parity charm mesons

Example: positive-parity charm mesons



Positive-parity charm mesons: SU(3)

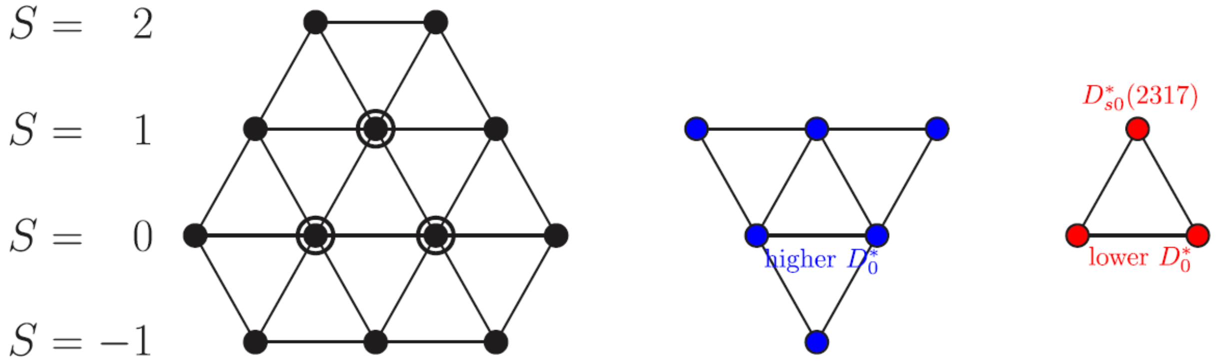
- Different SU(3) flavor group structures
  - $c\,\bar{q}$ mesons: $\bar{3}$
  - Diquark-antidiquark ($[cq][\bar{q}\bar{q}]$) type tetraquark model

$$3 \otimes 3 = \bar{3} \oplus 6, \qquad 3 \otimes \bar{6} = \bar{3} \oplus 15$$

  - Hadronic molecular model ($D_{s0}^*(2317)$: DK; $D_{s1}(2460)$: D^*K)

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

SU(3) irreps: $\bar{\mathbf{3}} \otimes \mathbf{8} = \overline{\mathbf{15}} \oplus \mathbf{6} \oplus \bar{\mathbf{3}}$

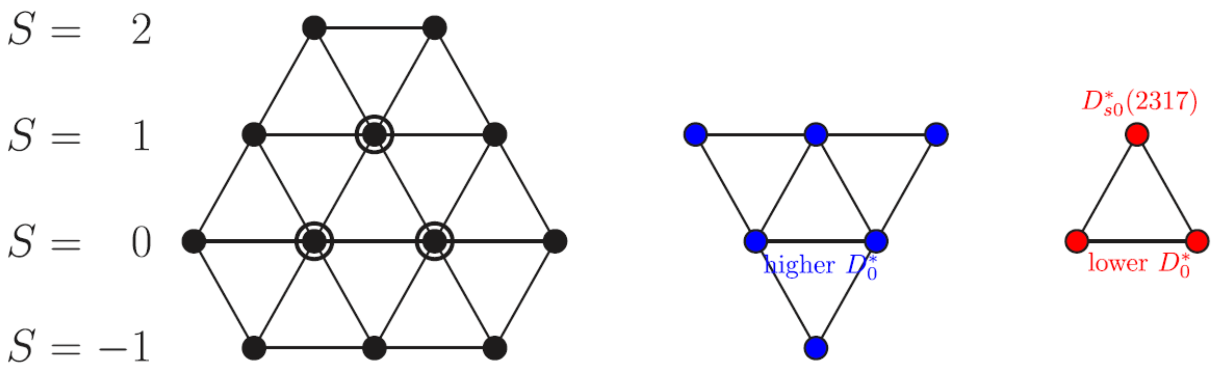


Weinberg-Tomozawa term: $\overline{\mathbf{15}}$: repulsive; $\mathbf{6}$: attractive; $\bar{\mathbf{3}}$: most attractive

Positive-parity charm mesons

- Different SU(3) flavor group structures
  - Hadronic molecular model ($D_{s0}^*(2317)$: DK; $D_{s1}(2460)$: D^*K)

SU(3) irreps: $\bar{3} \otimes 8 = \overline{15} \oplus 6 \oplus \bar{3}$



WT term: $\overline{15}$: repulsive; 6: attractive; $\bar{3}$: most attractive

$(S, I) = (1, 1)$: deep in the complex plane on wrong Riemann sheets

$(S, I) = (-1, 0)$: virtual state at 2342^{+13}_{-41} MeV at the physical mass

$(S, I) = (0, 1/2)$: two D_0^* states, Chiral EFT + lattice inputs L. Liu et al., PRD87(2013)014508

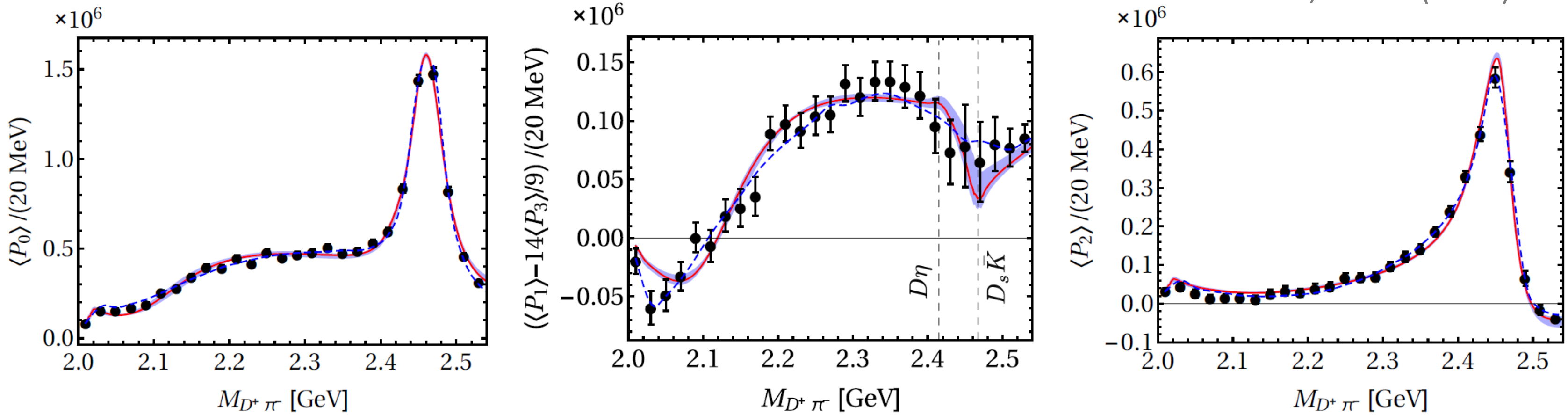
$(M, \Gamma/2)$	Lower (MeV)	Higher (MeV)	PDG2020 (MeV)
D_0^*	$(2105^{+6}_{-8}, 102^{+10}_{-11})$	$(2451^{+36}_{-26}, 134^{+7}_{-8})$	$(2300 \pm 29, 137 \pm 20)$

Albaladejo et al., PLB767(2017)465;
See also X.-Y. Guo, M. Lutz, PRD98(2018)014510

Positive-parity charm mesons: chiral + unitarity

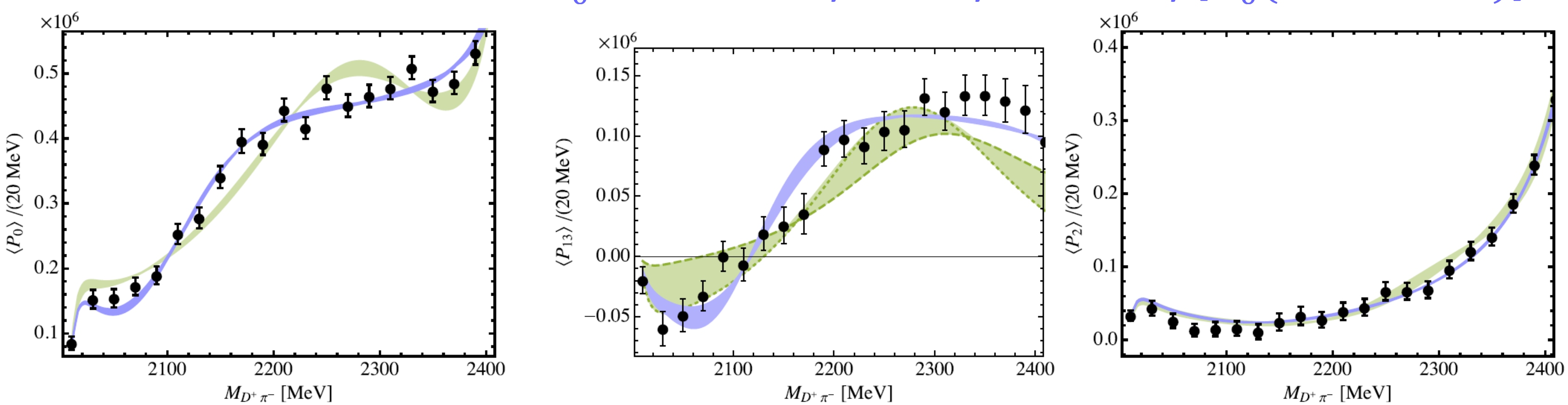
- Fit to LHCb data with amplitude constrained by chiral symmetry + unitarity
  - Angular moments reproduced well by two D_0^* (fixed before hand from lattice inputs)

M.-L. Du et al., PRD98(2018)094018



  - S-wave $D\pi$ phase from BW for $D_0^*(2300)$ not preferred

v.s. two D_0^* from chiral symmetry + unitarity [$D_0^*(2100, 2450)$]



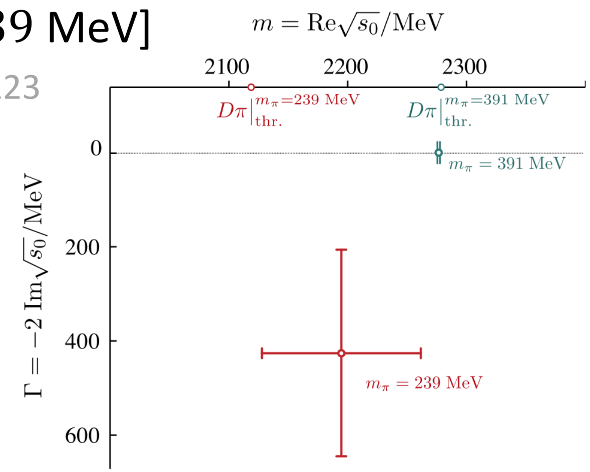
Khuri-Treiman dispersive analysis

M.-L. Du, FKG, Hanhart, Kubis, Meißner, PRL126(2021)192001

Positive-parity charm mesons: lattice QCD

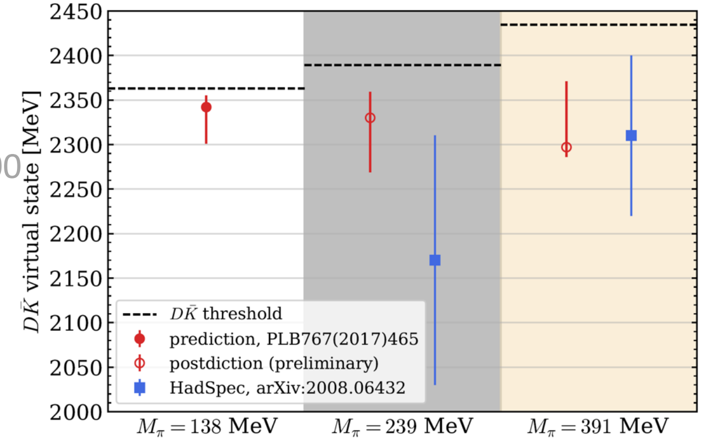
- Lattice support for a low-mass D_0^*: $M \approx 2.2$ GeV [$M_\pi = 239$ MeV]

  L. Gayer et al. [HadSpec], JHEP07(2021)123



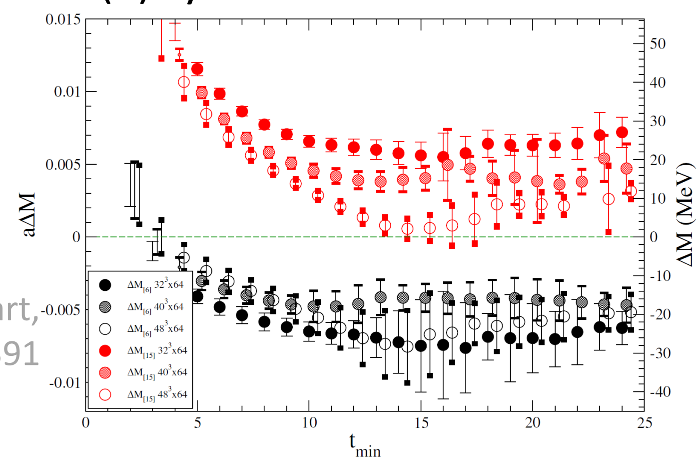
- Lattice evidence for the flavor-exotic sextet state:
  - $[D\bar{K}]$ virtual state

Cheung et al. [HadSpec], JHEP02(2021) 100

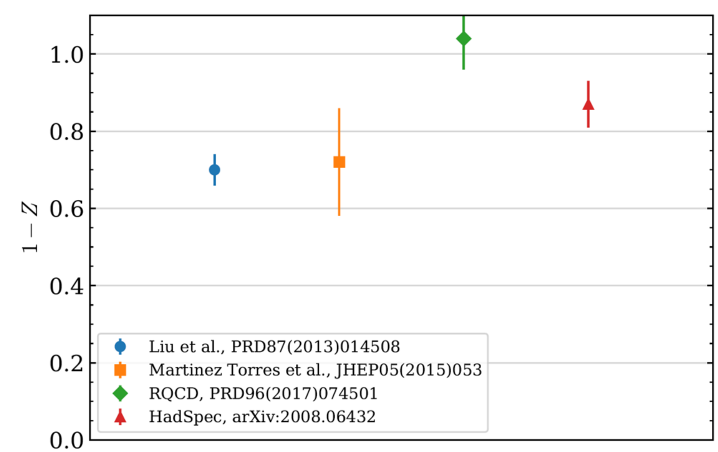


  - Sextet (attractive bound or virtual) and $\overline{15}$ (repulsive) in an SU(3) symmetric world

Gregory, FKG, Hanhart, Krieg, Luu, 2106.15391



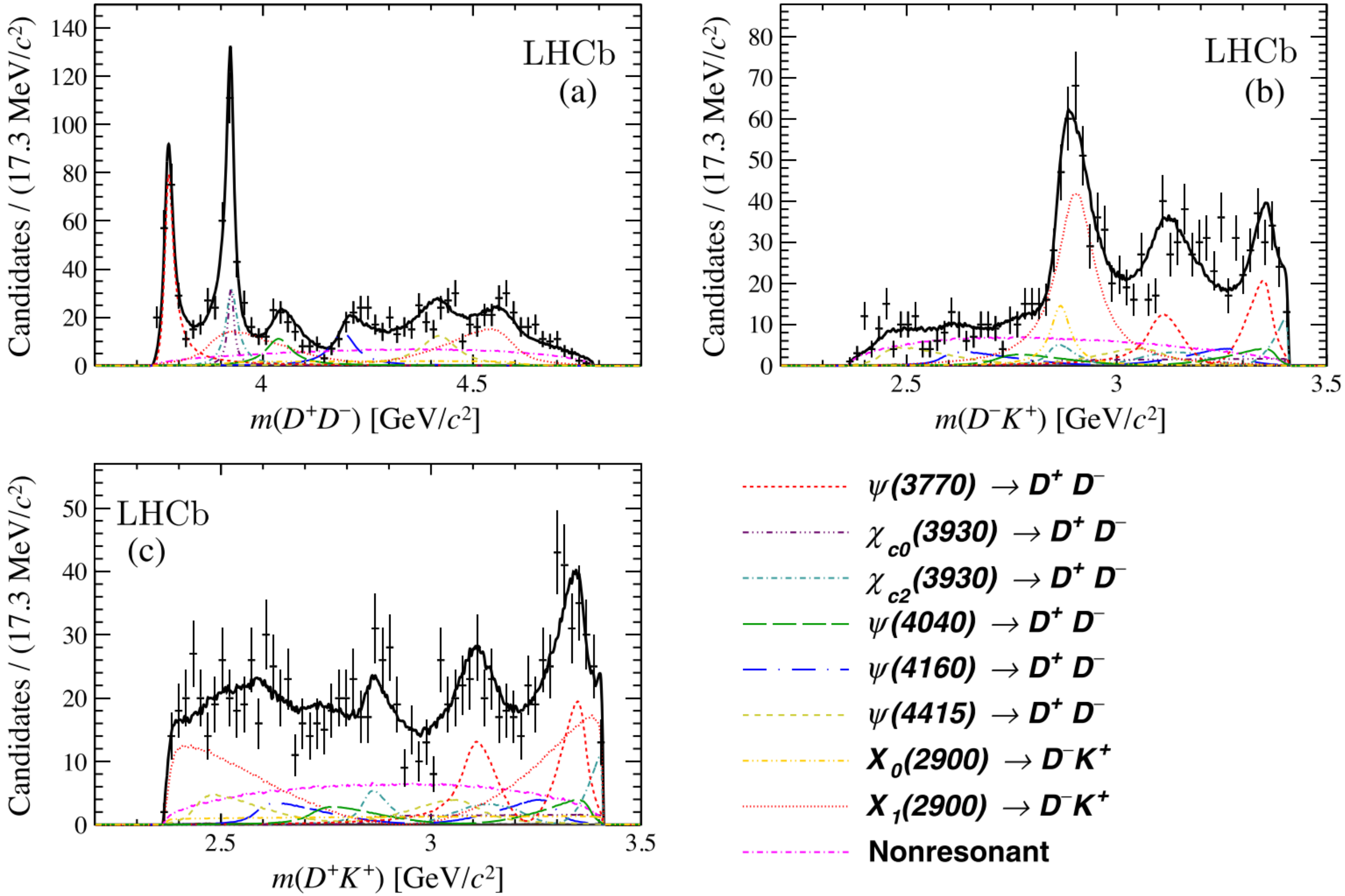
- Compositeness of $D_{s0}^*(2317)$ $[DK]$:



Flavor-sextet charm mesons?

- $X_0(2900)$ and $X_1(2900)$ $[\bar{c}\bar{s}ud]$

LHCb, PRD102(2020)112003



Summary and outlook

- Many new discoveries, calling for an overall understanding of the hadron spectroscopy
- Hadron spectroscopy in a controlled manner
  - Complementary experiments
  - Sophisticated analysis tools taking into theory constraints: unitarity, analyticity (including triangle singularities);

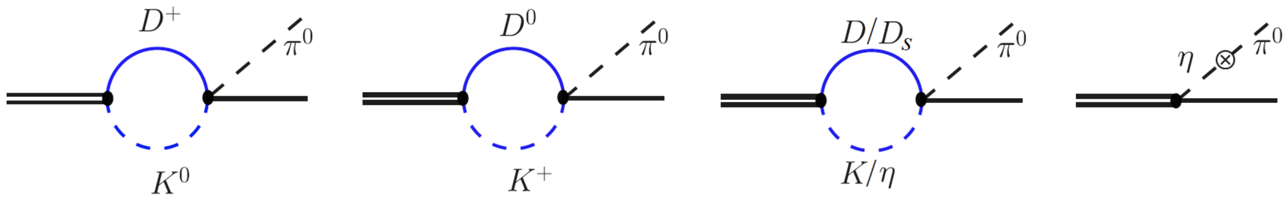
    for an early analysis of light mesons, e.g., Anisovich, Bugg, Sarantsev, B.S. Zou, PRD50(1994)1972
  - Lattice formalisms for coupled channels

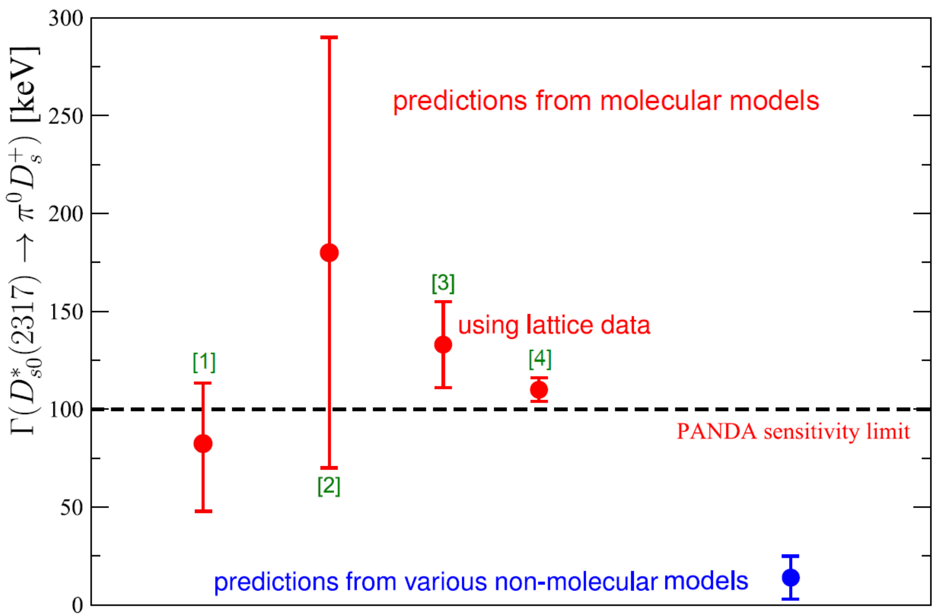
Thank you for your attention

Stay safe

Positive-parity charm mesons

- Decisive measurements to be done





measurement planned at $\overline{\text{P}}$ANDA

molecular: [1] Faessler et al., PRD76(2007)014005; [2] FKG et al.,PLB666(2008)251;

[3] L. Liu et al.,PRD87(2013)014508; [4] X. Guo, Heo, Lutz,PRD98(2018)014510

non-molecular: e.g., Colangelo, De Fazio, PLB570(2003)180; Bardeen, Eichten, Hill, PRD68(2003)054024