Theoretical models of exotic hadrons

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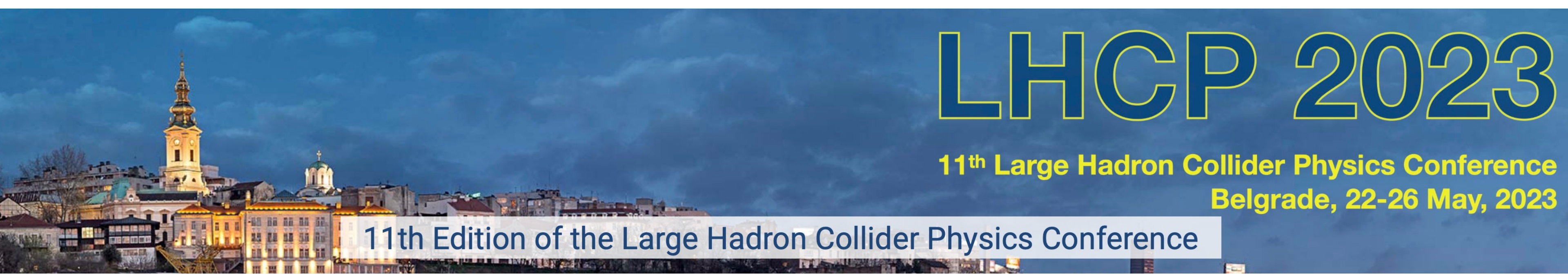
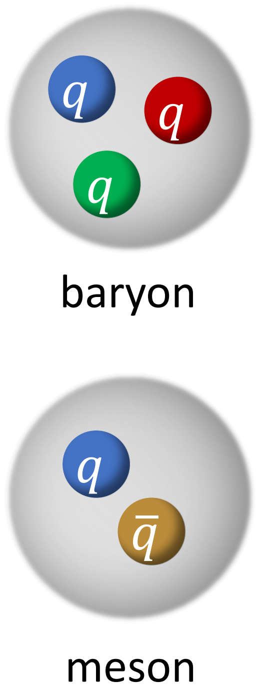


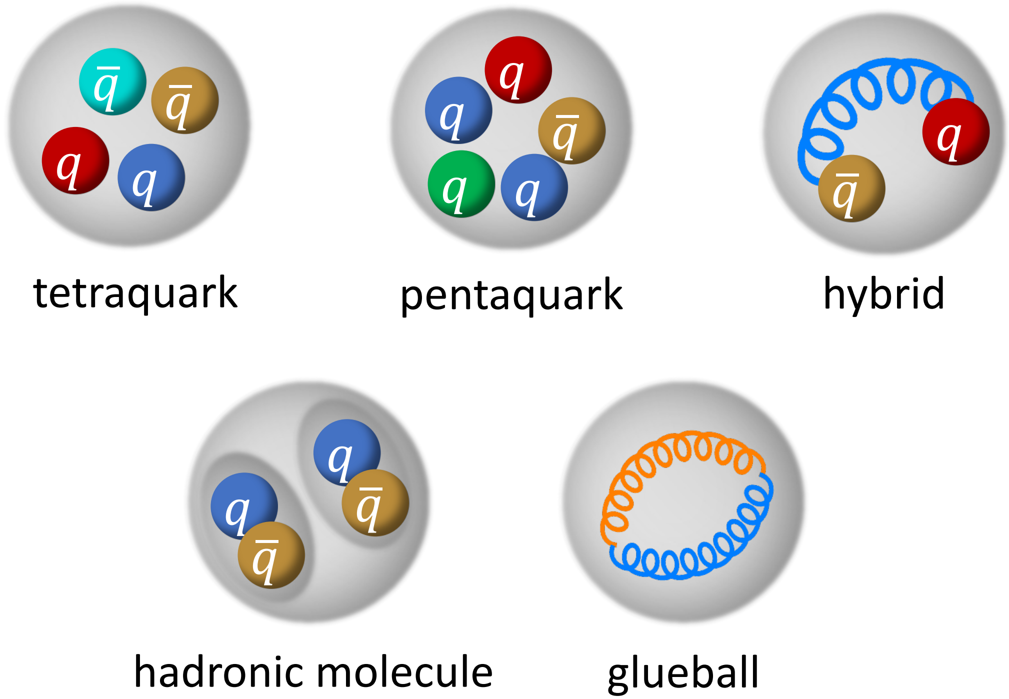
Conventional and exotic hadrons

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

Conventional hadrons



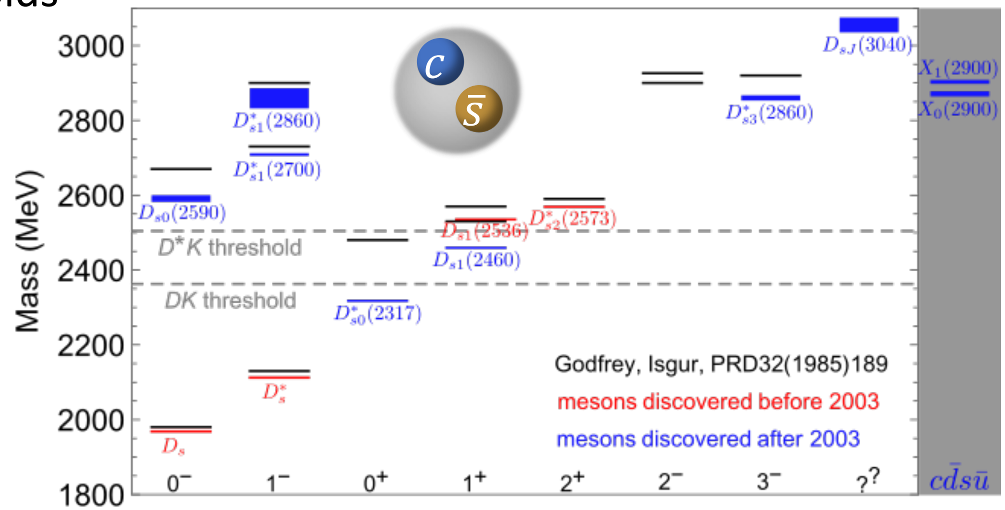
Exotic hadrons



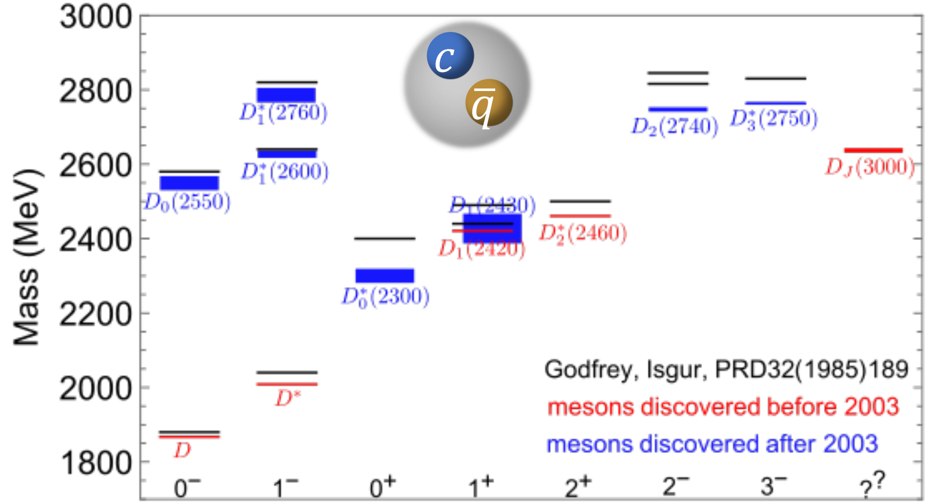
Disclaimer: NOT a general review; will discuss challenges from my personal point of view

Hadron spectrum: charm mesons

- 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



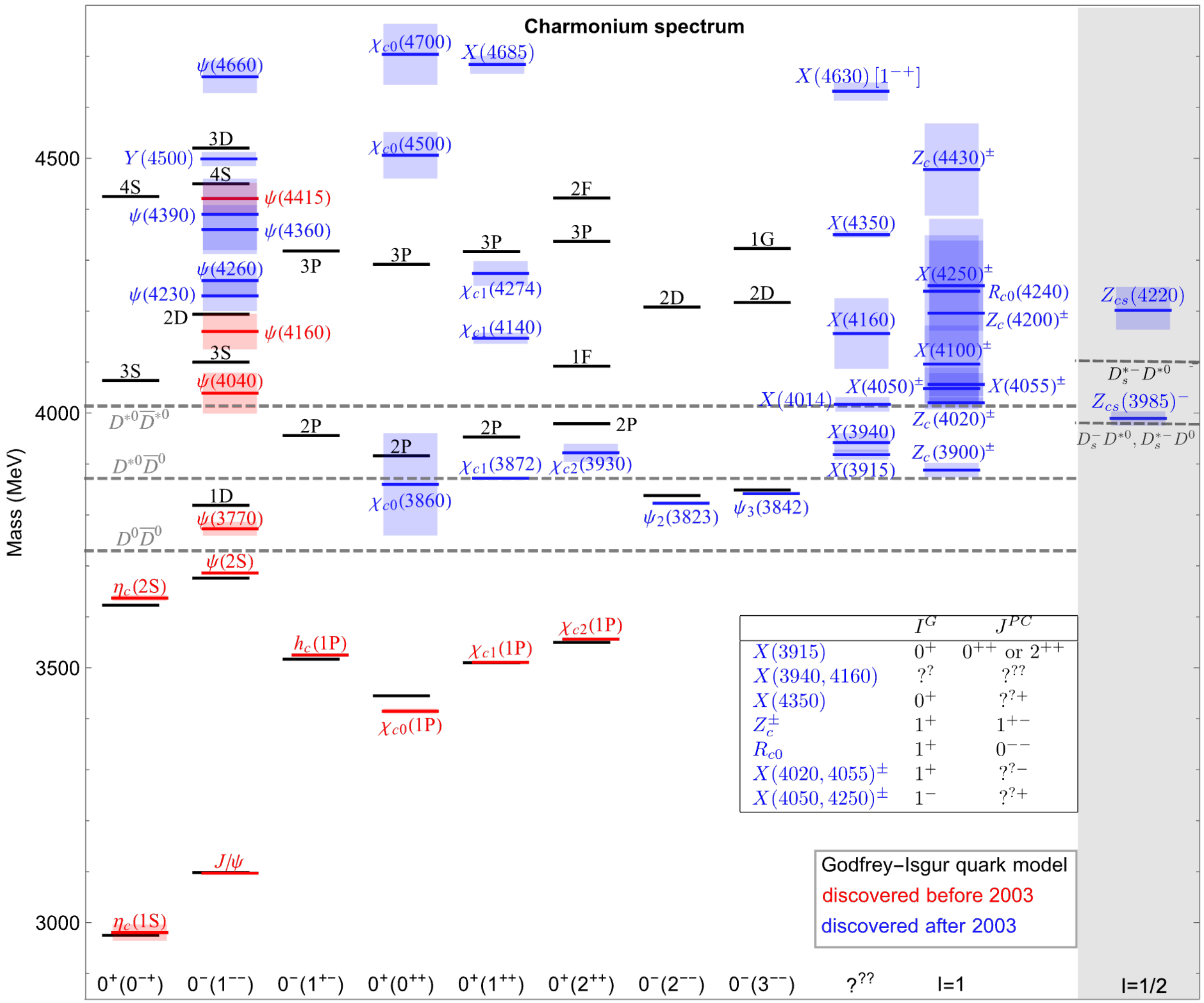
Charm−nonstrange mesons

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

Hadron spectrum: charmonium(-like) mesons

- 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



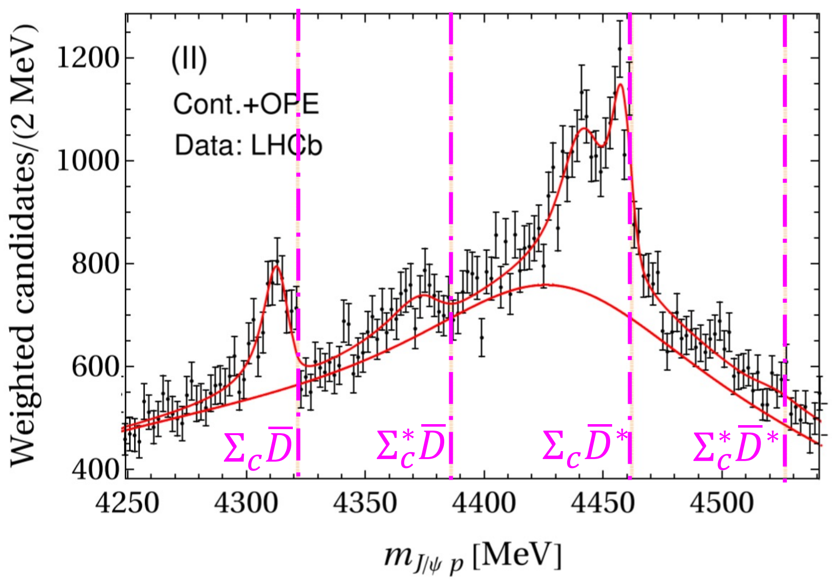
Near-threshold states

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

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

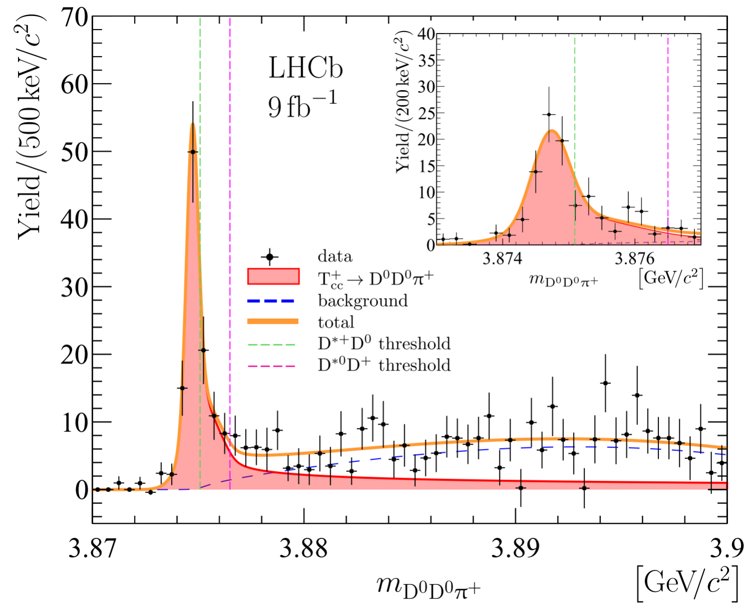
Belle(2003) BESIII, Belle (2013) BESIII (2013) BESIII (2020), LHCb (2021)

P_c states: hidden-charm baryon



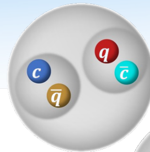
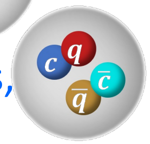
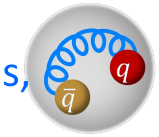
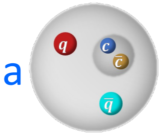
data from LHCb, PRL122 (2019) 222001;
fit from
M.-L. Du, Baru, FKG, Hanhart, Meißner, Oller, Q. Wang, PRL124 (2020) 072001

T_{cc}: double-charm meson



LHCb, Nature Phys. 18 (2022) 751

Models

- Candidates of hadronic molecules 
- Other models: compact multiquark states,  hybrids,  hadrocharmonia 
- >10 reviews in the last 7 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
  - H.-X. Chen, W. Chen, X. Liu, Y.-R. Liu, S.-L. Zhu, *An updated review of the new hadron states*, RPP 86 (2023) 026201
  - L. Meng, B. Wang, G.-J. Wang, S.-L. Zhu, *Chiral perturbation theory for heavy hadrons and chiral effective field theory for heavy hadronic molecules*, Phys. Rept. 1019 (2023) 2266
  - ……
- And a book:
  - A. Ali, L. Maiani, A. D. Polosa, *Multiquark Hadrons*, Cambridge University Press (2019)

Hadronic molecules & tetraquarks

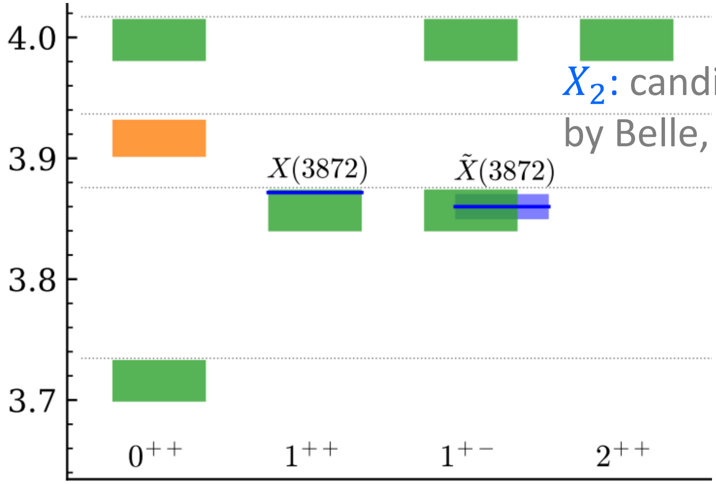
- Different models predict distinct mass spectra and decay patterns, e.g., charmonium-like

➢ $P = +$ 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

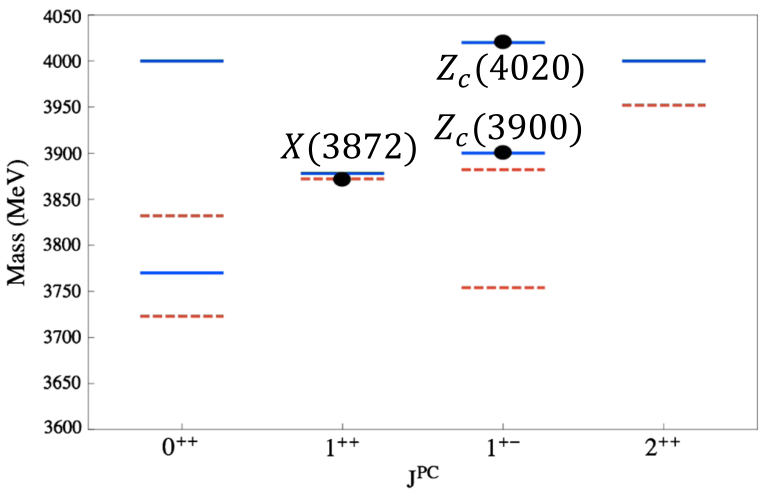
X.-K. Dong, FKG, B.-S. Zou, Progr.Phys.41(2021)65

➢ $P = +$ 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

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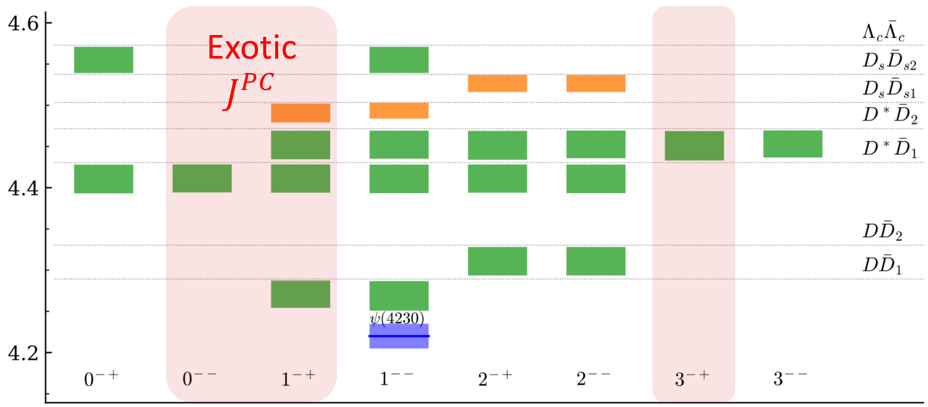
➤ $P = -$ states in a molecular model

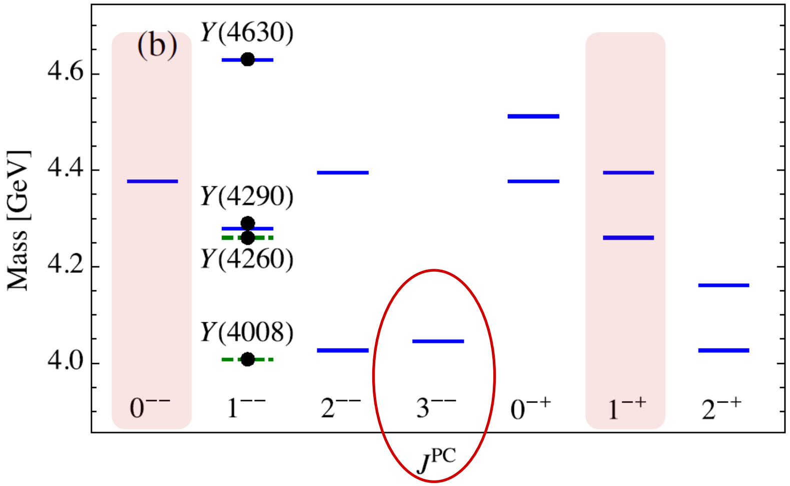


Mol. spectrum using a VMD interaction

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

➤ $P = -$ states in a tetraquark model

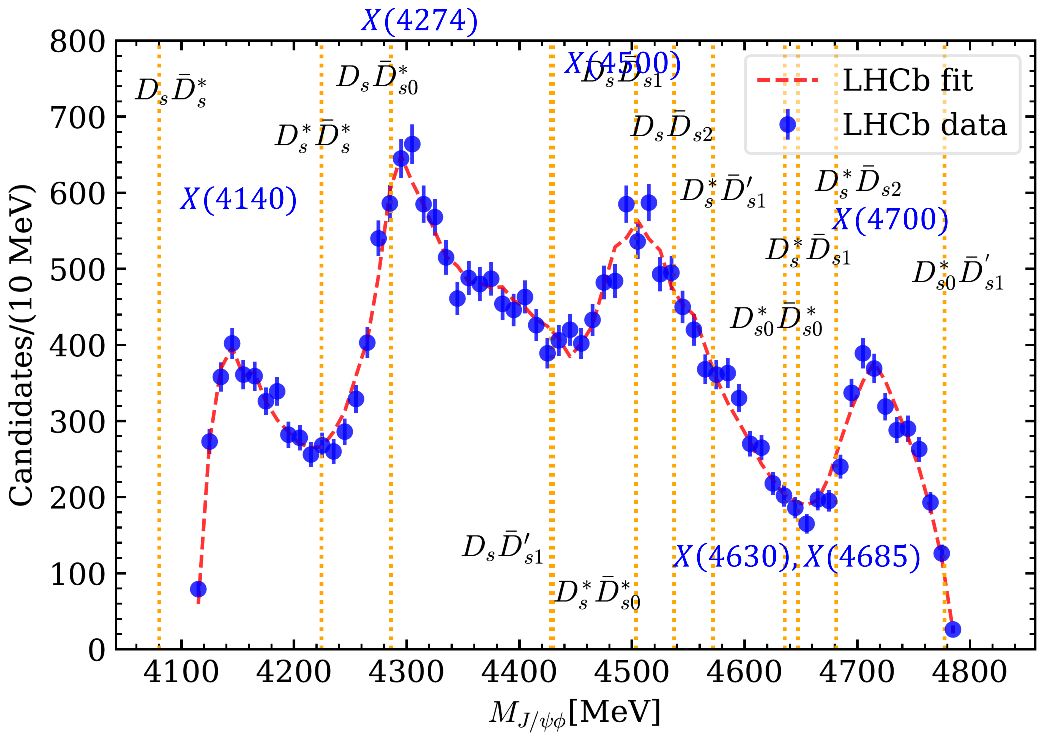
$$M = M_{00} + B_c \frac{L(L+1)}{2} + a[L(L+1) + S(S+1) - J(J+1)] + \kappa_{cq}[s(s+1) + \bar{s}(\bar{s}+1) - 3].$$



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

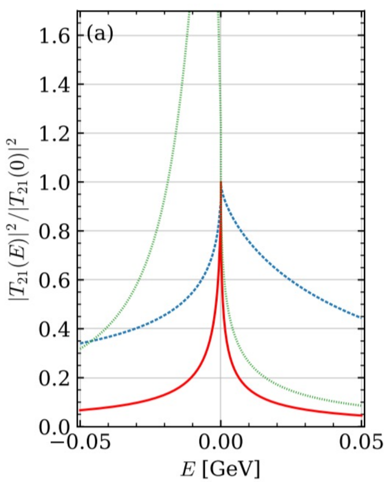
- To reveal the underlying physics, we need to have a faithful spectrum to start with
- In most cases, resonance parameters are extracted using Breit-Wigner
  - Potentially sizeable corrections due to coupled channels and thresholds
    - K-matrix formalism with coupled channels



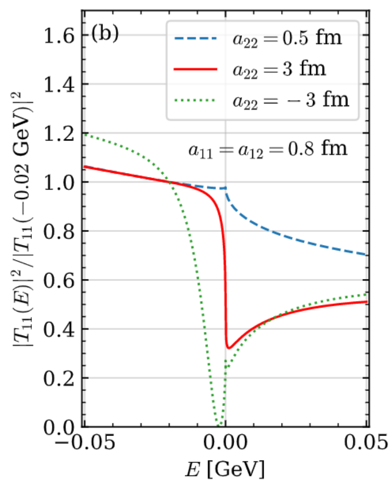
LHCb data: PRL127(2021)082001
Figure from X.-K. Dong, FKG, B.-S. Zou, Progr.Phys.41(2021)65

Challenges

- In most cases, resonance parameters are extracted using Breit-Wigner
  - BW: for isolated, narrow resonances away from strongly-coupled thresholds
  - 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



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



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

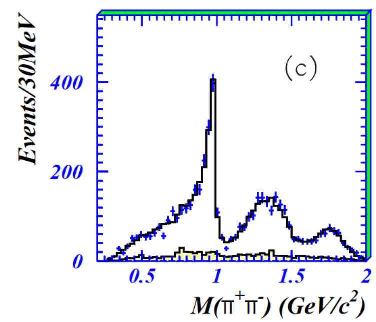
Line shapes of the same poles in different processes

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

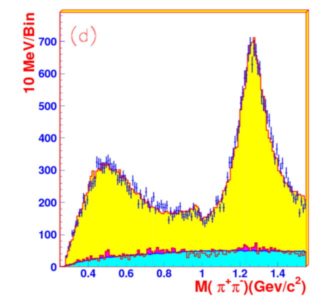
- E.g., $f_0(980)$:

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

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

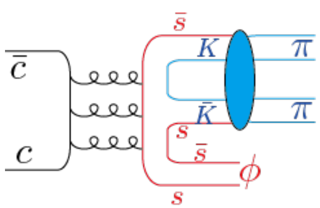


BES, PLB607(2005)243

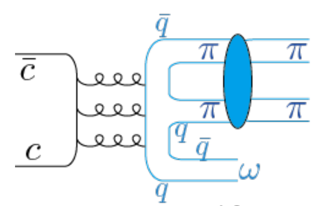


BES, PLB598(2004)149

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



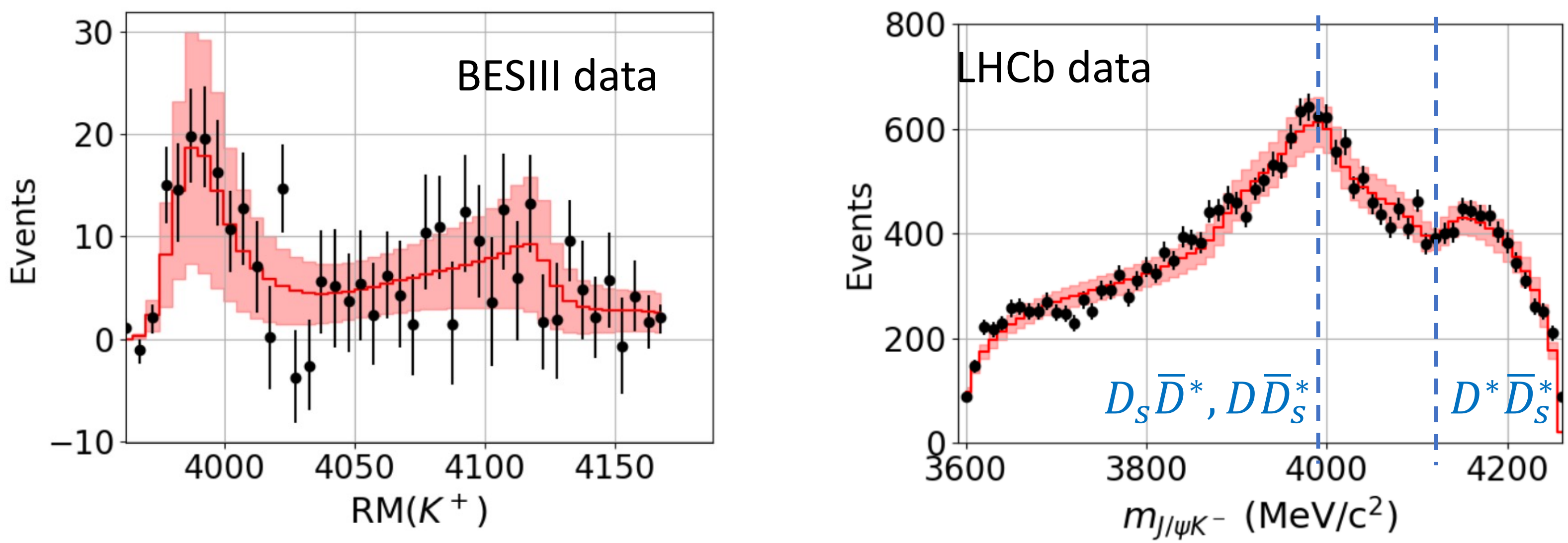
$\pi\pi \to \pi\pi$



Challenges

- In most cases, resonance parameters are extracted using Breit-Wigner
  - BW: for isolated, narrow resonances away from strongly-coupled thresholds
  - 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; PRL129(2022)112003
    - ✓ LHCb: broad $Z_{cs}(4000)$, and $Z_{cs}(4200)$ PRL127(2021)082001; arXiv:2301.04899
    - ✓ A simultaneous fit to the BESIII and LHCb $Z_{cs}^{\pm}$ data: two virtual states $Z_{cs}(3990, 4110)$

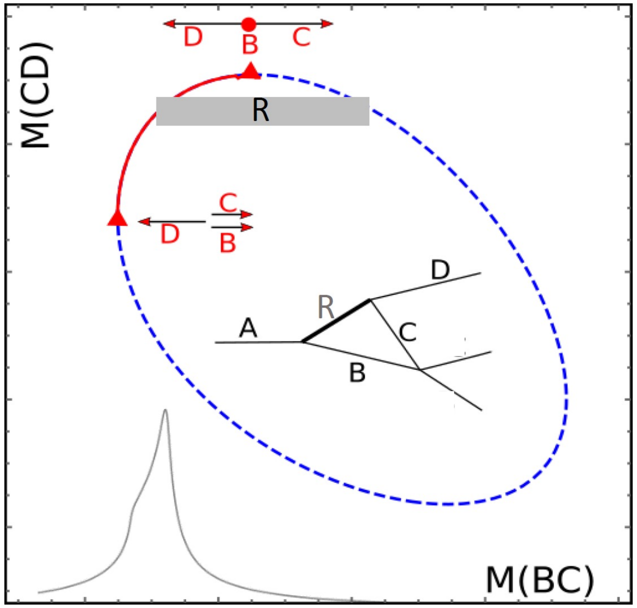
Ortega, Entem, Fernandez, PLB818(2021)136382



See also Yang et al., PRD103(2021)074029; Baru et al., PRD105(2022)034014

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



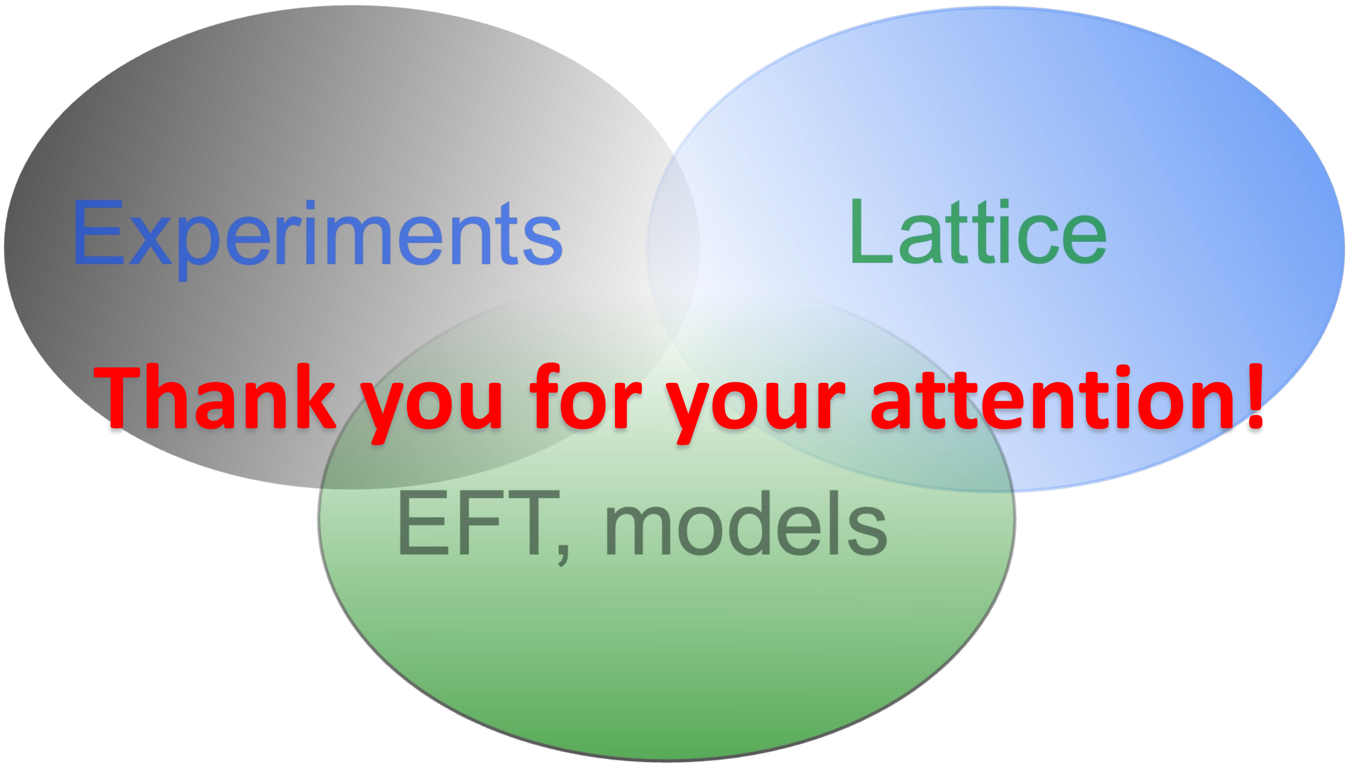
For a review of triangle singularities and threshold cusps, FKG, X.-H.Liu, S. Sakai, PPNP 112 (2020) 103757

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

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

Summary and outlook

- Unified description of the "new hadron spectroscopy" is missing
- Precise data and lattice QCD calculations are needed
- Theoretical methods constrained by symmetry, unitarity and analyticity as a bridge
- Looking forward to more discoveries at LHC



Thank you for your attention!