Exotic hadrons with heavy quarks in EFT approach

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Hadron 2023

Long-term fruitful collaboration with colleagues from Germany, China, Spain is gratefully acknowledged!

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- X. K. Dong, F. K. Guo, A. Nefediev, J. T. Castellà, "Chromopolarizabilities of fully-heavy baryons," Phys. Rev. D **107**,034020 (2023)
- V. Baru, E. Epelbaum, A. A. Filin, C. Hanhart, A. V. Nefediev, "Emergence of heavy quark spin symmetry breaking in heavy quarkonium decays," Phys. Rev. D **107**, 014027 (2023)
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- V. Baru, E. Epelbaum, A. A. Filin, C. Hanhart, A. V. Nefediev, "Is $Z_{cs}(3982)$ a molecular partner of $Z_c(3900)$ and $Z_c(4020)$ states?," Phys. Rev. D **105**, 034014 (2022)
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Hadronic physics before and after 2003

Consensus before 2003:

- Quark model provides a decent description of low-lying hadrons
- Quark model works surprisingly well even for light flavours
- Heavy flavours (c and b) comply with nonrelativistic theory
- Relativistic corrections improve the description
- Experiment gradually fills "missing states"
- Lattice provides additional/alternative source of information

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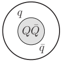
Situation after 2003:

- $X(3872)$ observed by Belle with properties at odds with quark model
- Number of such unconventional hadrons with heavy quarks grows fast
- New branch of hadrons spectroscopy — exotic XYZ states

"Exotic" versus "ordinary"

- "Ordinary" hadron = $\bar{Q}Q$ meson or QQQ baryon
- "Exotic" hadron = not ordinary hadron
- Simplest exotic hadron = tetraquark ($Q\bar{Q}q\bar{q}$)

Compact tetraquarks (bound by confinement)



Hadro-Quarkonium (compact $\bar{Q}Q$ core plus light-quark cloud)

Hadronic molecule (extended object)

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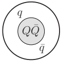
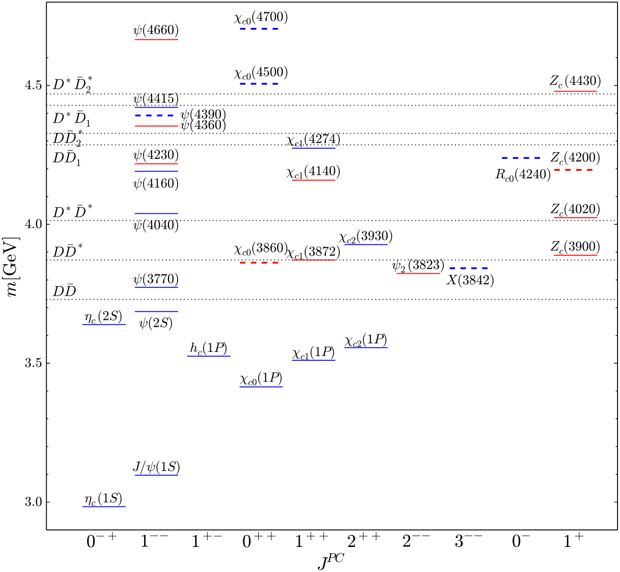


Hadro-Quarkonium (compact $\bar{Q}Q$ core plus light-quark cloud)

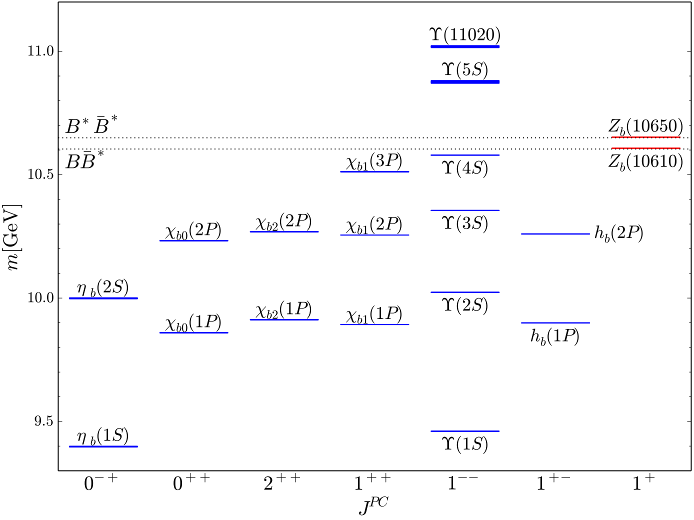
Hadronic molecule (extended object)

Molecule = large probability to observe resonance in hadron-hadron channel

Spectrum of charmonium

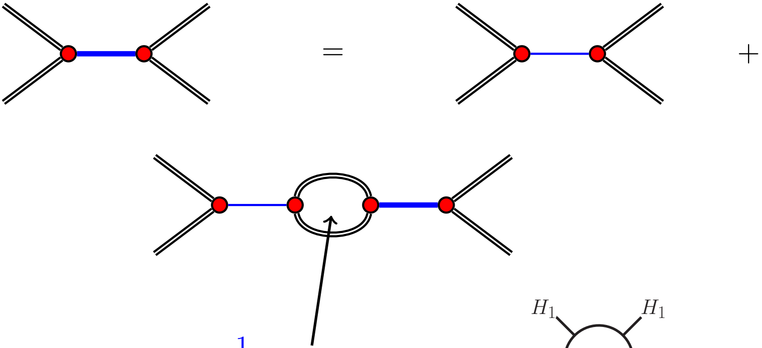


Spectrum of bottomonium

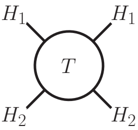


Effect of hadronic loops

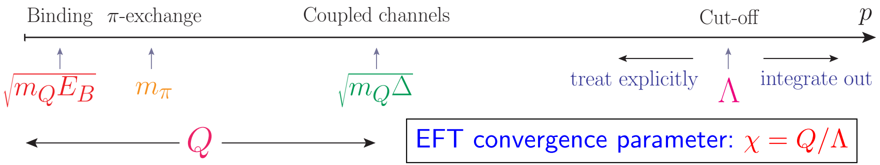
$$|\Psi\rangle = \begin{pmatrix} \sqrt{Z}|\psi_0\rangle \\ \chi(\boldsymbol{p})|H_1 H_2\rangle \end{pmatrix}$$



Flatté: $$\frac{-\frac{1}{2}g}{E-E_f+\frac{i}{2}g\sqrt{2\mu E}} \Longrightarrow$$

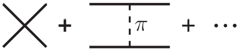


Effective field theory for hadronic molecules



Interaction potential between heavy hadrons:

- Includes all relevant interactions
- Complies with relevant symmetries
- Incorporates coupled-channel dynamics
- Expanded in powers of p^2/Λ^2 and truncated at necessary order (LO, NLO...)
- Iterated to all orders via (multichannel) Lippmann-Schwinger equation



$$T = V - VGT$$

Effective field theory for hadronic molecules

Free parameters:

- Low-energy constants
- Couplings to hadronic channels

Input (combined analysis):

- Line shapes (Dalitz plots)
- Partial branchings

Output:

- Pole position M_0 (“mass” $= \mathrm{Re}(M_0)$, “width” $= 2 \times \mathrm{Im}(M_0)$)
- Nature of state (compositeness as a cross check)

Predictions:

- New properties of “old” state: line shapes, partial widths,...
- Properties of “new” states: poles, line shapes, partial widths,...
- Chiral extrapolations (lattice data interpretation)

Heavy quark symmetry

- Exotic XYZ states contain heavy quarks (HQ)
- In the limit $m_Q \to \infty$ $(m_Q \gg \Lambda_{\text{QCD}})$ spin of HQ decouples

  $\Longrightarrow$ Heavy Quark Spin Symmetry (HQSS)
- For realistic m_Q's HQSS is approximate but accurate symmetry of QCD
- HQSS relates properties of states with different HQ spin orientation

  $\Longrightarrow$ Spin partners

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Prediction!

Combined analysis

Multiple individual analises $\Longrightarrow$ Single combined analysis

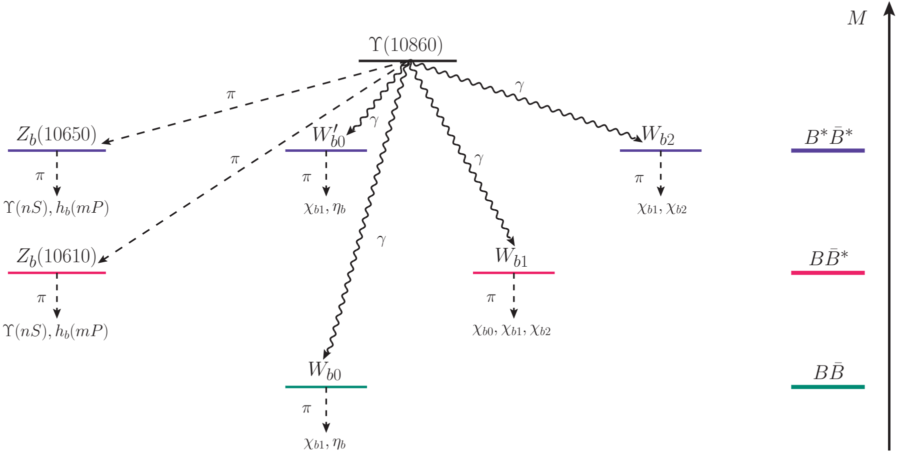
Twins $Z_b(10610)$ & $Z_b(10650)$

$$I = 1 \quad J^{PC} = 1^{+-}$$

Minimal quark content: $\bar{b}b\bar{q}q$

$$\Upsilon(10860) \to \pi Z_b^{(\prime)} \to \pi\left[B\bar{B}^{(*)}\right]$$
$$\Upsilon(10860) \to \pi Z_b^{(\prime)} \to \pi\left[\pi h_b(1,2P)\right]$$
$$\Upsilon(10860) \to \pi Z_b^{(\prime)} \to \pi\left[\pi \Upsilon(1,2,3S)\right]$$

Z_b's ($J^{PC}=1^{+-}$) and W_{bJ}'s ($J^{PC}=J^{++}$) in decays of $\Upsilon(10860)$



$$Z_b(10610) \quad \sim \quad B\bar{B}^* \sim 0^-_{\bar{q}b} \otimes 1^-_{\bar{b}q} \;\sim\; 1^-_{\bar{b}b} \otimes 0^-_{\bar{q}q} + 0^-_{\bar{b}b} \otimes 1^-_{\bar{q}q}$$

$$Z'_b(10650) \quad \sim \quad B^*\bar{B}^* \sim 1^-_{\bar{q}b} \otimes 1^-_{\bar{b}q} \;\sim\; 1^-_{\bar{b}b} \otimes 0^-_{\bar{q}q} - 0^-_{\bar{b}b} \otimes 1^-_{\bar{q}q}$$

(Bondar et al'2011,Voloshin'2011,...)

Coupled-channel problem

Elastic potential:

$$V_{\text{el-el}} = V_{\text{CT}}(\text{to order } O(p^0))$$

Coupled channels:

$$1^{+-}: B\bar{B}^*({}^3S_1,-), B^*\bar{B}^*({}^3S_1)$$
$$0^{++}: B\bar{B}({}^1S_0), B^*\bar{B}^*({}^1S_0)$$
$$1^{++}: B\bar{B}^*({}^3S_1,+)$$
$$2^{++}: B^*\bar{B}^*({}^5S_2)$$

Coupled-channel problem

Elastic potential:

$$V_{\text{el-el}} = V_{\text{CT}}(\text{to order } O(p^2)) + V_\pi$$

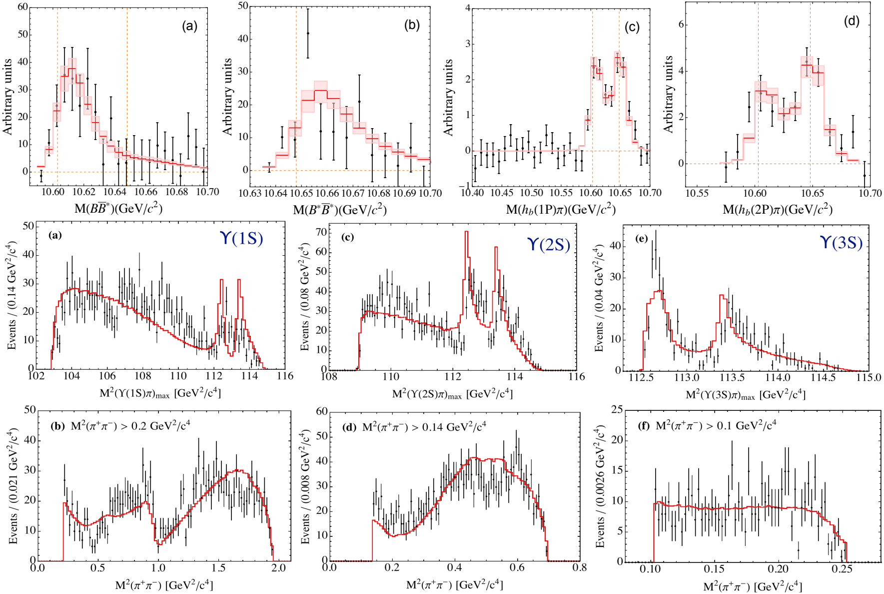
Coupled channels:

$$\begin{aligned}
1^{+-} &: B\bar{B}^*({}^3S_1,-), B^*\bar{B}^*({}^3S_1), B\bar{B}^*({}^3D_1,-), B^*\bar{B}^*({}^3D_1)\\
0^{++} &: B\bar{B}({}^1S_0), B^*\bar{B}^*({}^1S_0), B^*\bar{B}^*({}^5D_0)\\
1^{++} &: B\bar{B}^*({}^3S_1,+), B\bar{B}^*({}^3D_1,+), B^*\bar{B}^*({}^5D_1)\\
2^{++} &: B^*\bar{B}^*({}^5S_2), B\bar{B}({}^1D_2), B\bar{B}^*({}^3D_2),\\
&\quad B^*\bar{B}^*({}^1D_2), B^*\bar{B}^*({}^5D_2), B^*\bar{B}^*({}^5G_2)
\end{aligned}$$

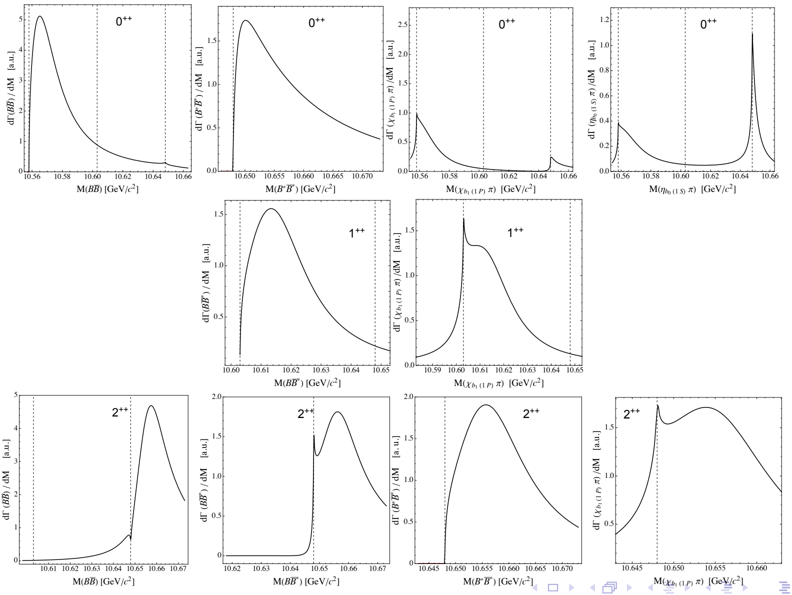
Lippmann-Schwinger equation ($V^{\text{eff}} = V_{\text{el-el}} + \sum_{\text{inel}} V_{\text{el-inel-el}}$):

$$T_{\alpha\beta}(M,\boldsymbol{p},\boldsymbol{p}') = V^{\text{eff}}_{\alpha\beta}(\boldsymbol{p},\boldsymbol{p}') - \sum_\gamma \int \frac{d^3q}{(2\pi)^3} V^{\text{eff}}_{\alpha\gamma}(\boldsymbol{p},\boldsymbol{q}) G_\gamma(M,\boldsymbol{q}) T_{\gamma\beta}(M,\boldsymbol{q},\boldsymbol{p}')$$

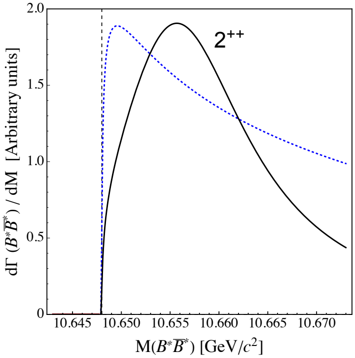
Fitted line shapes for Z_b's

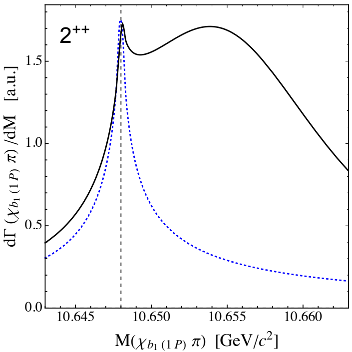


Predicted line shapes for W_{bJ}'s



Role of pions





- Blue dashed line — prediction of the pionless theory
- Black solid line — prediction of the full theory with pions

Strange $Z_{cs}(3982)$

$$J^{PC} = 1^{+-}$$

Minimal quark content: $c\bar{c}s\bar{q}$

$$e^+e^- \to K^+\left[D_s^- D^{*0} + D_s^{*-} D^0\right]$$

Expectations

- Twin bottomonium-like Z_b states $(I = 1,\ J^{PC} = 1^{+-})$ as $B^{(*)}\bar{B}^*$ molecules

$$Z_b(10610) \quad \sim \quad B\bar{B}^* \sim 0^-_{\bar{q}b} \otimes 1^-_{\bar{b}q} \sim 1^-_{\bar{b}b} \otimes 0^-_{\bar{q}q} + 0^-_{\bar{b}b} \otimes 1^-_{\bar{q}q}$$
$$Z_b'(10650) \quad \sim \quad B^*\bar{B}^* \sim 1^-_{\bar{q}b} \otimes 1^-_{\bar{b}q} \sim 1^-_{\bar{b}b} \otimes 0^-_{\bar{q}q} - 0^-_{\bar{b}b} \otimes 1^-_{\bar{q}q}$$

- Similar pattern in the spectrum of charmonium

$$Z_c(3900) \quad \sim \quad D\bar{D}^*$$
$$Z_c'(4020) \quad \sim \quad D^*\bar{D}^*$$

- Flavour $SU(3)$ for light quarks
  - $\Longrightarrow$ Accurate for couplings & potentials
  - $\Longrightarrow$ Explicit breaking via $m_s \gg m_{u,d}$
  - $\Longrightarrow$ Simple relation between potentials in $I = 1/2$ and $I = 1$ channels

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- Twin bottomonium-like Z_b states $(I=1,\ J^{PC}=1^{+-})$ as $B^{(*)}\bar{B}^*$ molecules

$$\begin{aligned} Z_b(10610) &\sim B\bar{B}^* \sim 0^-_{\bar{q}b}\otimes 1^-_{\bar{b}q} \sim 1^-_{\bar{b}b}\otimes 0^-_{\bar{q}q} + 0^-_{\bar{b}b}\otimes 1^-_{\bar{q}q} \\ Z_b'(10650) &\sim B^*\bar{B}^* \sim 1^-_{\bar{q}b}\otimes 1^-_{\bar{b}q} \sim 1^-_{\bar{b}b}\otimes 0^-_{\bar{q}q} - 0^-_{\bar{b}b}\otimes 1^-_{\bar{q}q} \end{aligned}$$

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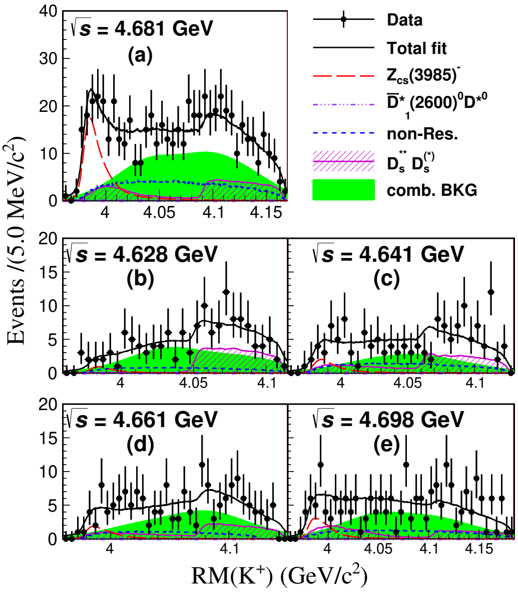
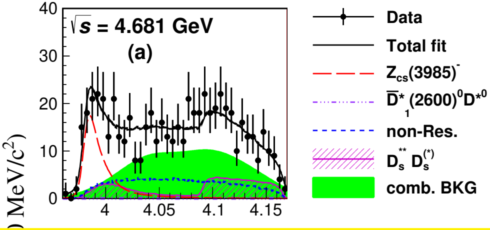
Expect: Z_{bs} ($\sqrt{s} \gtrsim 11.2$ GeV) and Z_{cs} ($\sqrt{s} \gtrsim 4.5$ GeV) molecular states exist

Z_{cs} @ BES III (Phys.Rev.Lett. 126 (2021) 10, 102001)

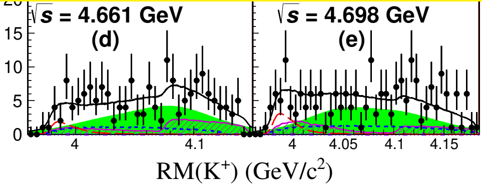


Z_{cs} @ BES III (Phys.Rev.Lett. 126 (2021) 10, 102001)



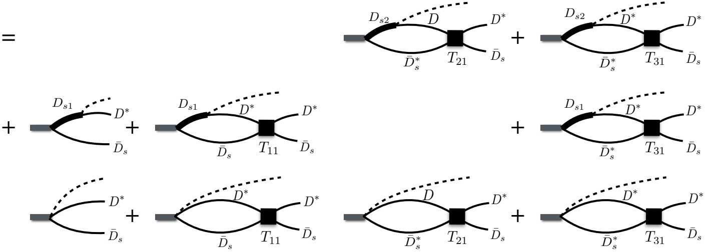
Discovery of $Z_{cs}(3982)$

$M = 3982.5^{+1.8}_{-2.6} \pm 2.1$ MeV $\quad \Gamma = 12.8^{+5.3}_{-4.4} \pm 3.0$ MeV

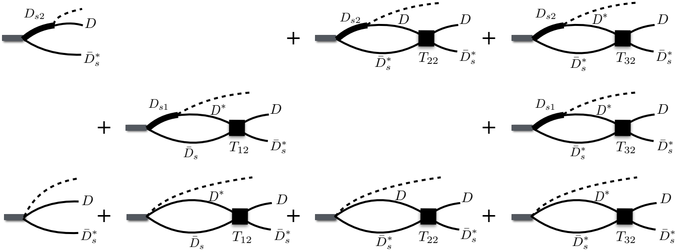


Amplitudes

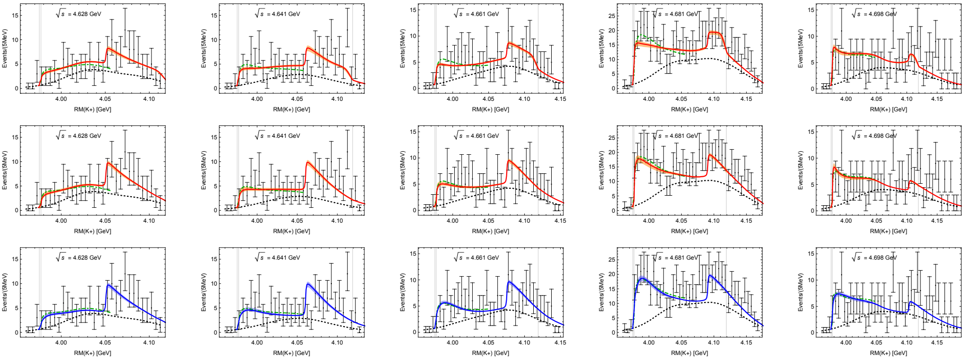
$M_{Y\to KD^*\bar{D}_s} =$



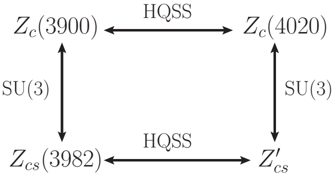
$M_{Y\to KD\bar{D}_s^*} =$



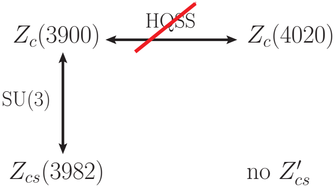
Fit results and different scenarios



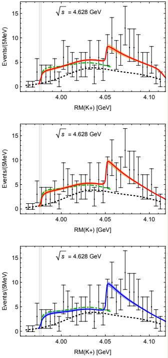
Scenario 1



Scenario 2

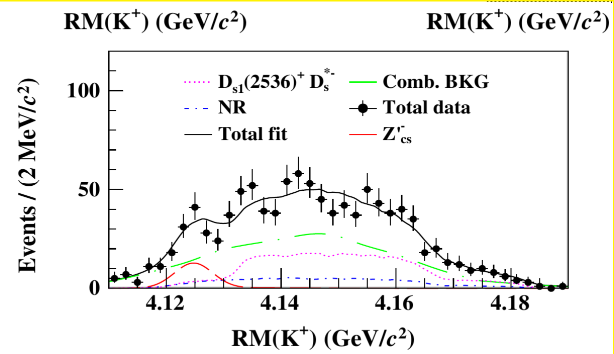


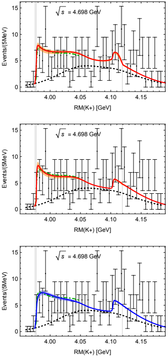
Fit results and different scenarios

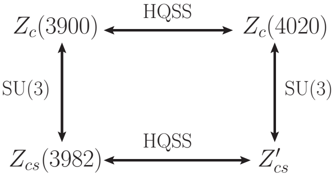


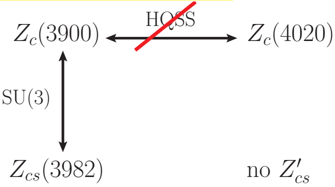
BES III: Chin. Phys. C **47**, 033001 (2023)

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







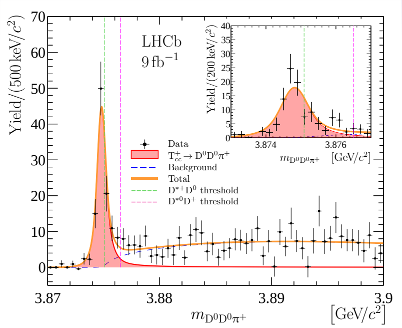


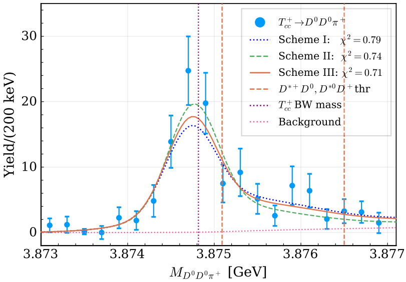
Double-charm state T_{cc}^+

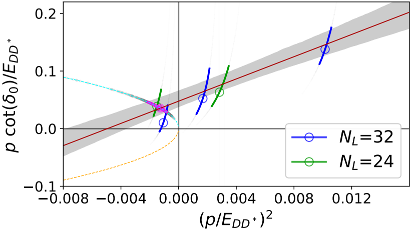
$$I = 0 \quad J^P = 1^+$$

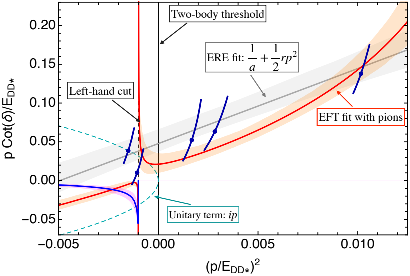
Minimal quark content: $cc\bar{u}\bar{d}$

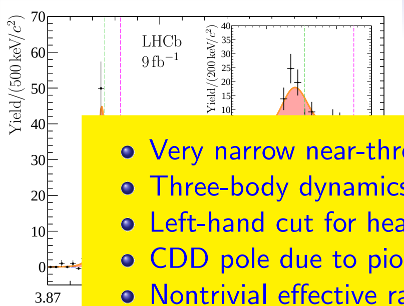
$$T_{cc}^+ \to D^0 D^{*+} \to D^0 D^0 \pi^+$$

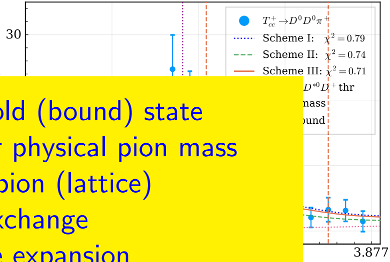

LHCb
9 fb^{-1}
Yield/(500 keV/c^2)
Data
$T_{cc}^+ \to D^0D^0\pi^+$
Background
Total
$D^{*+}D^0$ threshold
$D^{*0}D^+$ threshold
Yield/(200 keV/c^2)
$m_{D^0D^0\pi^+}$ [GeV/c^2]


$T_{cc}^+ \to D^0D^0\pi^+$
Scheme I: $\chi^2 = 0.79$
Scheme II: $\chi^2 = 0.74$
Scheme III: $\chi^2 = 0.71$
$D^{*+}D^0, D^{*0}D^+$ thr
T_{cc}^+ BW mass
Background
Yield/(200 keV)
$M_{D^0D^0\pi^+}$ [GeV]

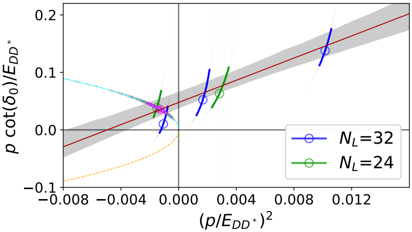

$p\ \cot(\delta_0)/E_{DD^*}$
N_L=32
N_L=24
$(p/E_{DD^*})^2$

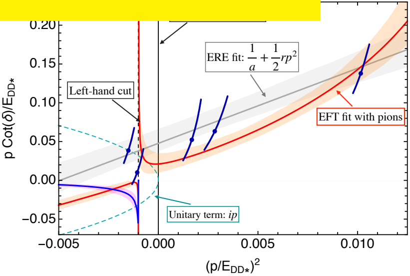

Two-body threshold
ERE fit: $\frac{1}{a} + \frac{1}{2}rp^2$
Left-hand cut
EFT fit with pions
Unitary term: ip
p Cot(δ)/E_{DD*}
$(p/E_{DD*})^2$

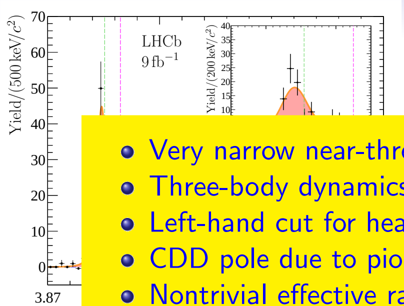


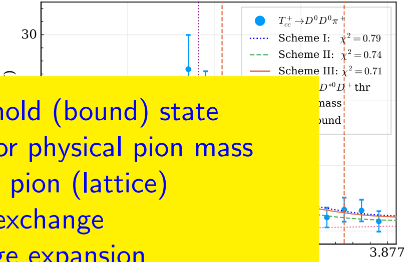


- Very narrow near-threshold (bound) state
- Three-body dynamics for physical pion mass
- Left-hand cut for heavy pion (lattice)
- CDD pole due to pion exchange
- Nontrivial effective range expansion
- ...



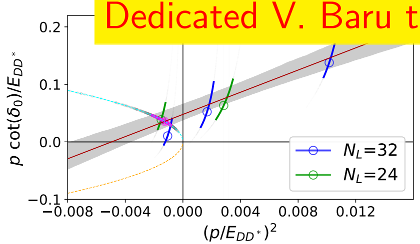


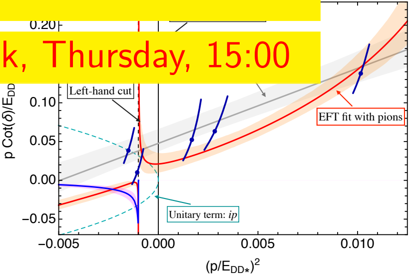




- Very narrow near-threshold (bound) state
- Three-body dynamics for physical pion mass
- Left-hand cut for heavy pion (lattice)
- CDD pole due to pion exchange
- Nontrivial effective range expansion
- ...

Dedicated V. Baru talk, Thursday, 15:00





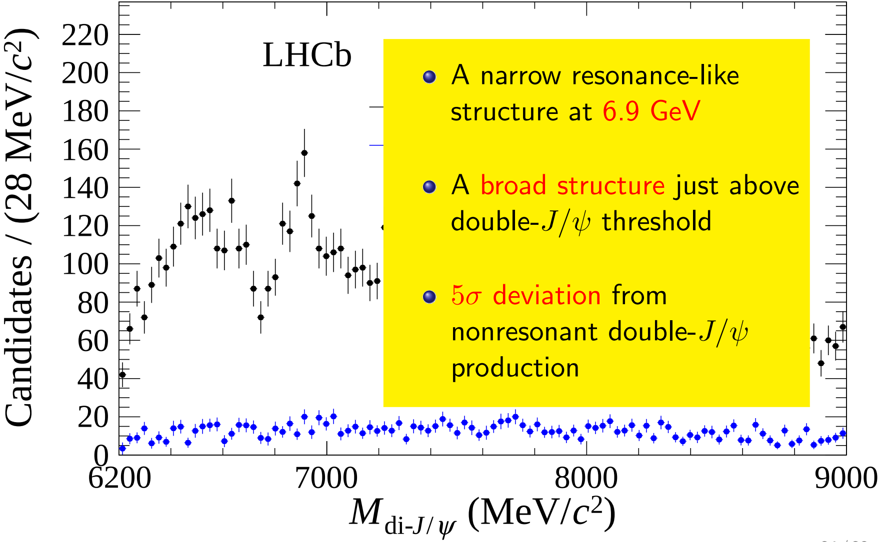
Double-J/ψ spectrum

$X(6200)$ vs $X(6900)$

$$I = 0 \quad J^{PC} = 0^{++}/2^{++}$$

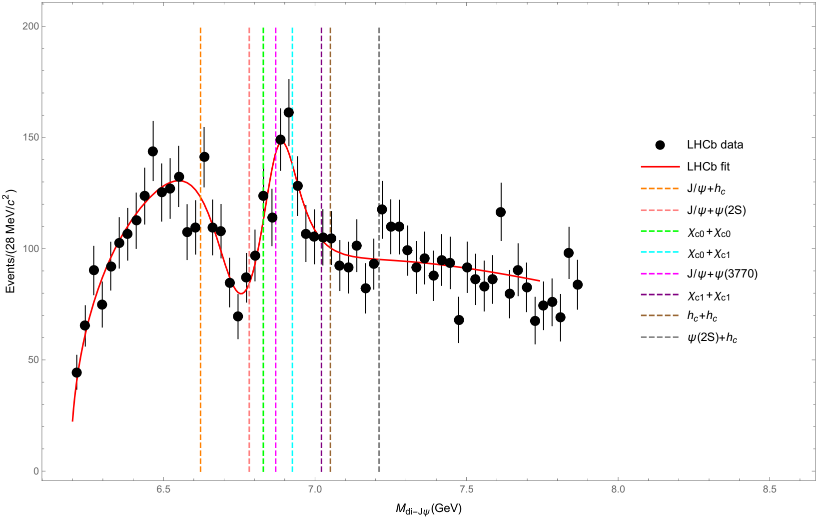
Minimal quark content: $\bar{c}\bar{c}cc$

Double-J/ψ production @ LHCb (Sc.Bull. 65 (2020) 1983)

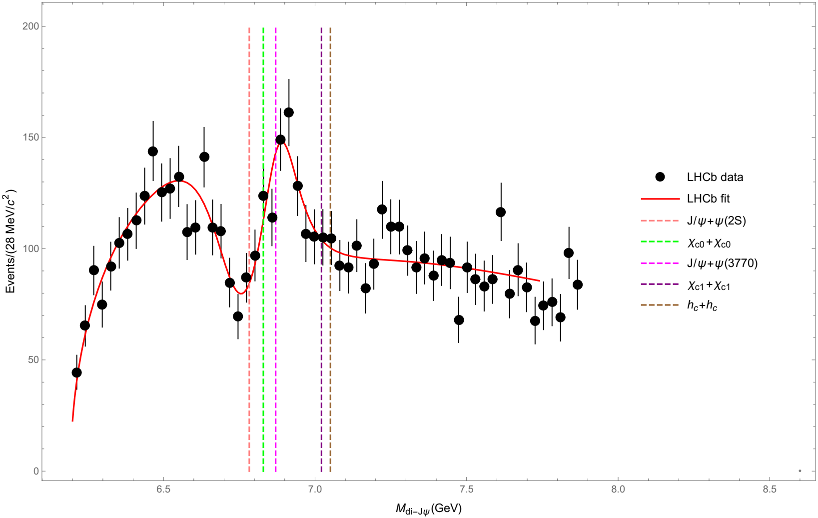


- A narrow resonance-like structure at 6.9 GeV
- A broad structure just above double-J/ψ threshold
- 5σ deviation from nonresonant double-J/ψ production

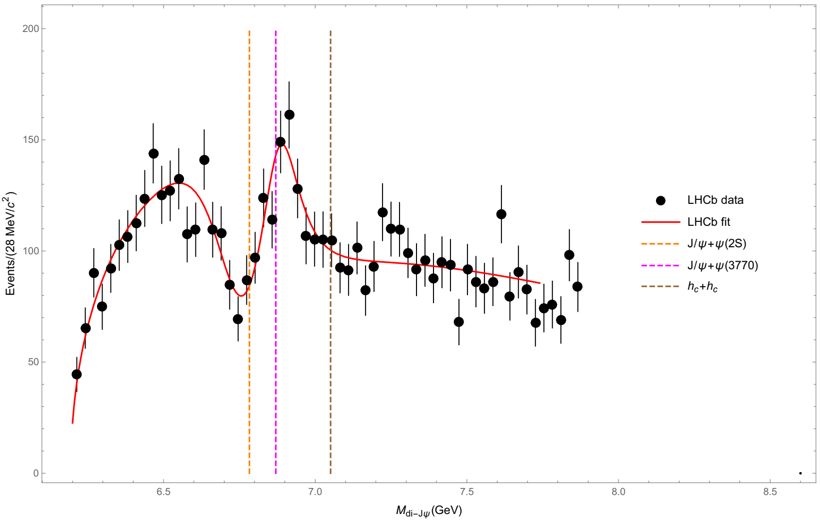
All channels



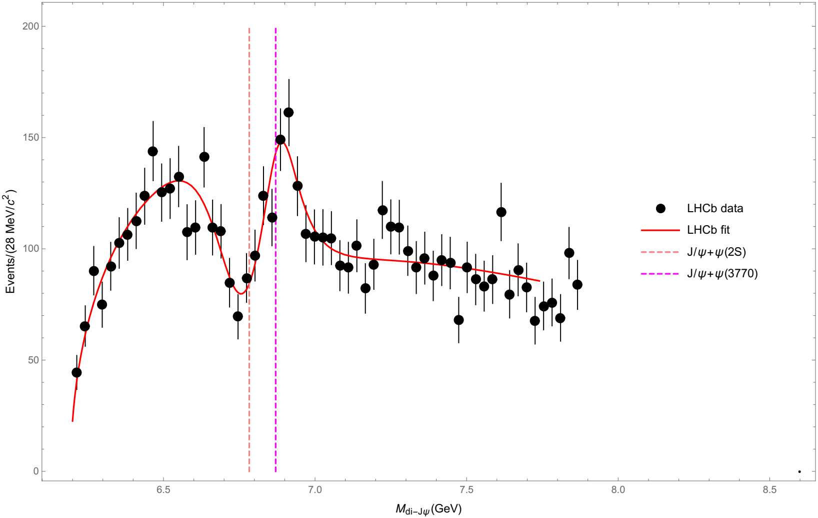
Only S-wave channels (no $J/\psi h_c$, $\psi(2S)h_c$, $\chi_{c0}\chi_{c1}$)



No heavy exchanges (no $\chi_{c0}\chi_{c0}$, $\chi_{c1}\chi_{c1}$)

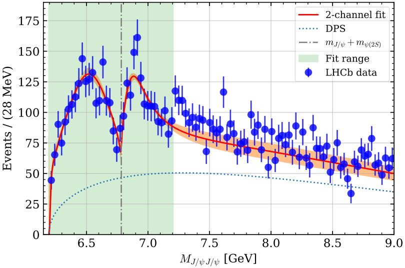


Only HQSS-allowed channels (no $h_c h_c$)

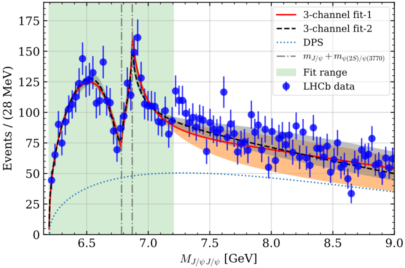


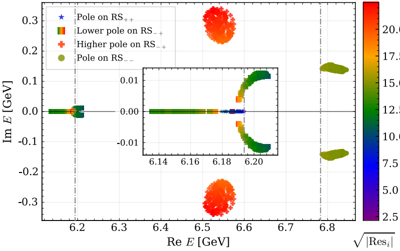
Models, fits & poles

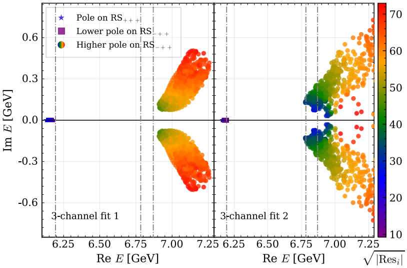
$J/\psi J/\psi$ & $J/\psi\psi(2S)$



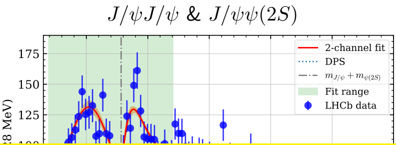
$J/\psi J/\psi$, $J/\psi\psi(2S)$ & $J/\psi\psi(3770)$

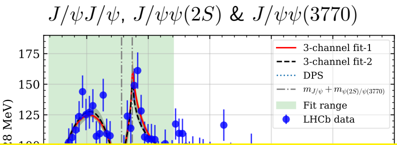




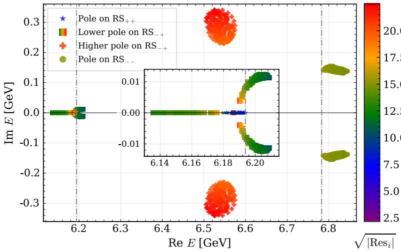


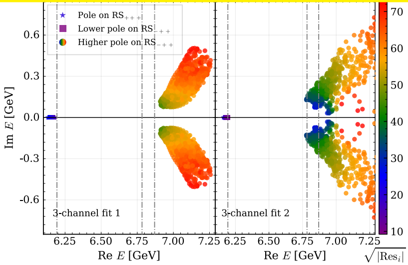
Models, fits & poles



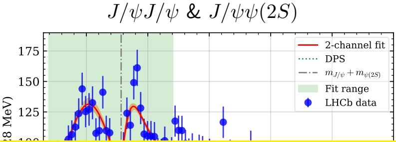


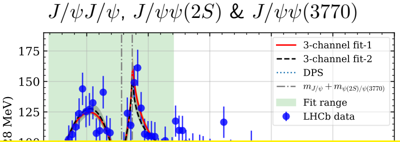
- Poles above double-J/ψ threshold are vaguely fixed by data
- $X(6200)$ near the double-J/ψ threshold is robust
- Molecular model for $X(6200)$ is plausible and compatible with data





Models, fits & poles



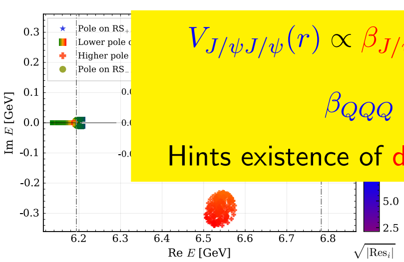


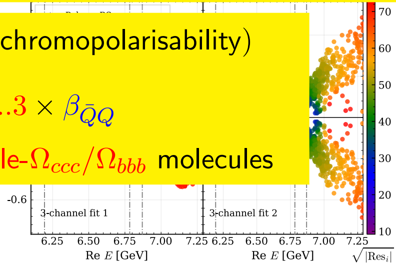
- Poles above double-J/ψ threshold are vaguely fixed by data
- $X(6200)$ near the double-J/ψ threshold is robust
- Molecular model for $X(6200)$ is plausible and compatible with data

$$V_{J/\psi J/\psi}(r) \propto {\beta_{J/\psi}}^2 \text{ (chromopolarisability)}$$

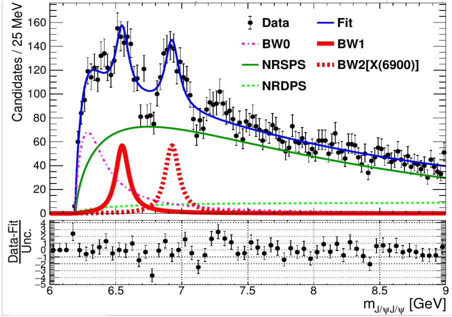
$$\beta_{QQQ} \simeq 2..3 \times \beta_{\bar{Q}Q}$$

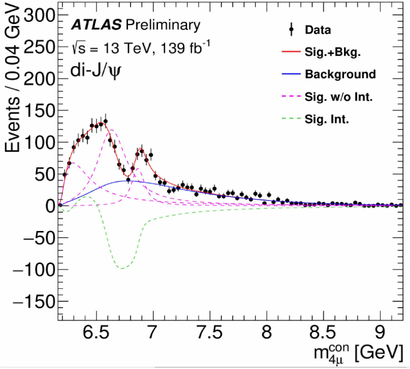
Hints existence of double-$\Omega_{ccc}/\Omega_{bbb}$ molecules



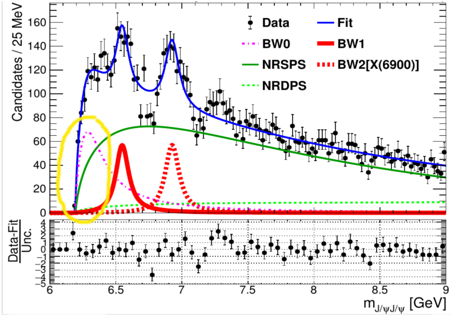


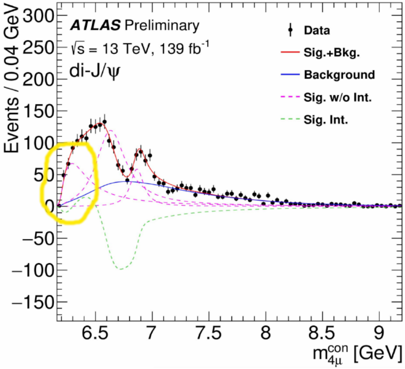
Comment on CMS and ATLAS data





Comment on CMS and ATLAS data





Conclusions

- Collider experiments at energies above open-flavour thresholds started new era in hadronic physics
- Threshold phenomena, coupled channels, pion exchange are important
- Multibody unitarity and analyticity of amplitude need to be preserved
- Line shapes of non-Breit-Wigner form is current reality
- From "mass" and "width" to pole position and residues (couplings)
- EFT is model-independent, systematically improvable analysis and prediction tool
- Results of EFT analysis are input for QCD-inspired models
- Lattice simulations are important to fill the gap in experimental data