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Prediction K* meson with hidden charm

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Based on the following papers:

XLR, B.B. Malabarba, Li-Sheng Geng, K.P. Khemchandani, A. Martínez Torres, PLB785(2018)112

XLR, B.B. Malabarba, K.P. Khemchandani, A. Martínez Torres, JHEP05(2019)1

Outline

RUB

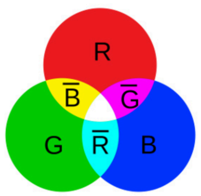
- Introduction
- Theoretical Framework
- Results and discussion
- Summary and perspectives

Low-energy QCD

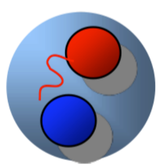
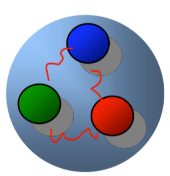
Quantum Chromo-Dynamics

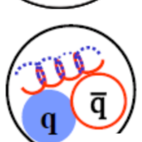
- Fundamental theory for strong interactions (up to now)

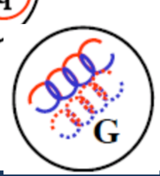
Color Confinement

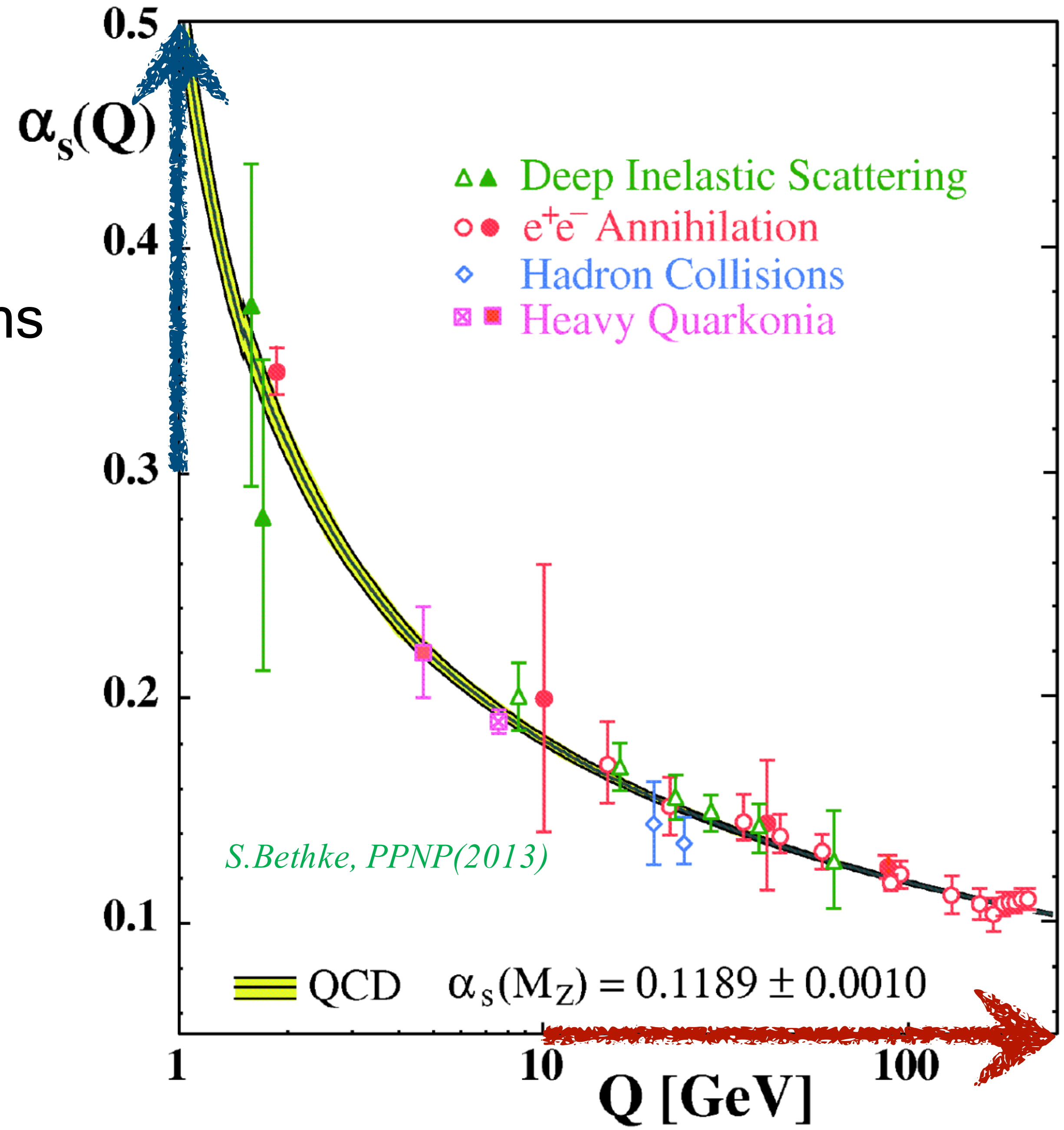


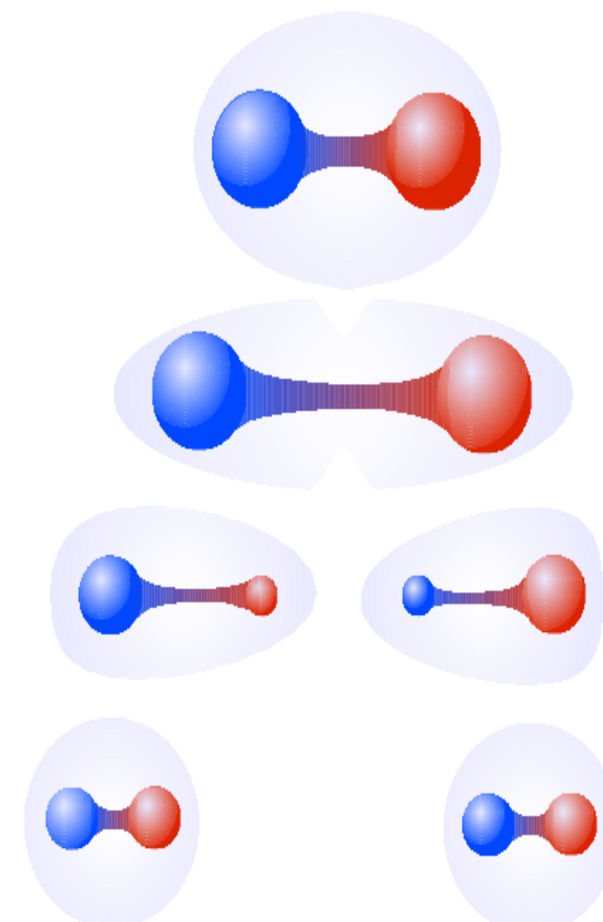
color singlet

- Conventional hadrons
  - Meson 
  - Baryon 
- **Exotic hadrons**
  - Multi-quark states

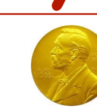
  - Hybrids 

  - Glueballs 





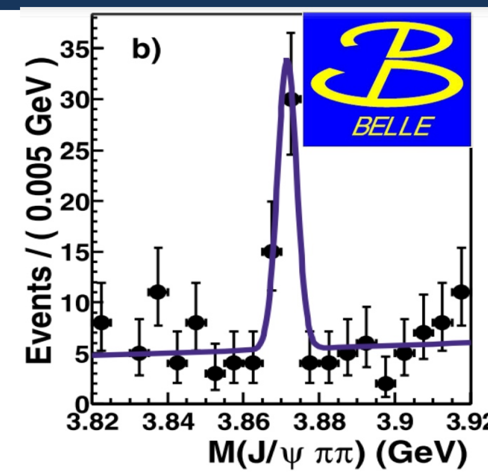
Asymptotic freedom

 Nobel Prize 2004

Milestone of exotic hadron spectroscopy

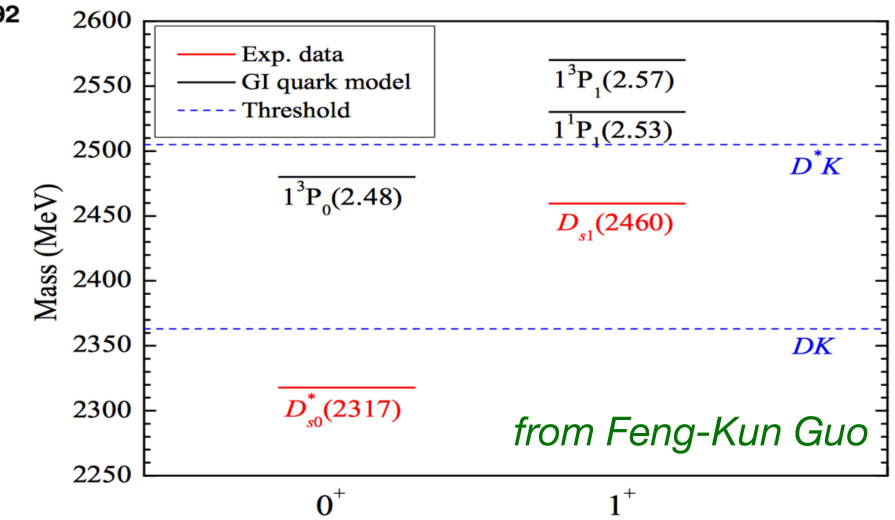
RUB

☐ Breakthrough @ 2003



Confirmed in many experiments: BaBar,BESIII,CDF,CMS,D0,LHCb, ...

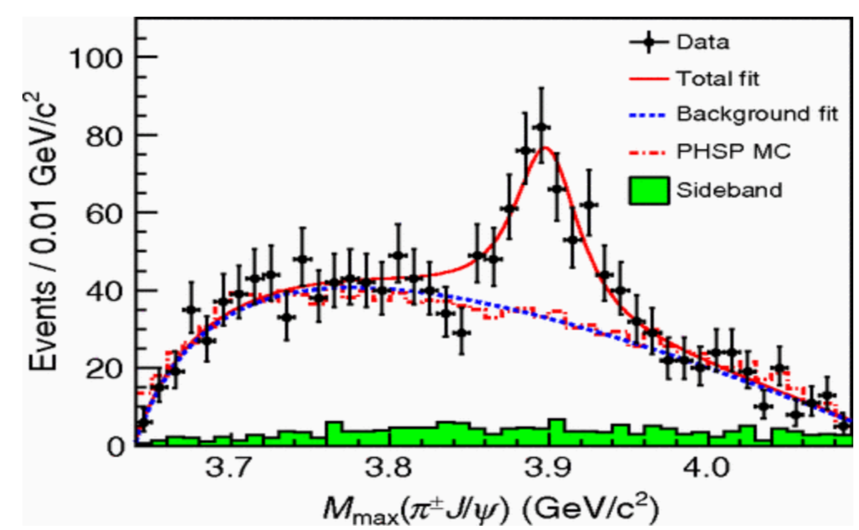
- $X(3872)$ *Belle, PRL91,262001(2003)*
  - ✓ The beginning of the XYZ story
- $D^*_{s0}(2317)$ *BaBar, PRL90,242001(2003)*
  - ✓ *160 MeV lower than the quark model prediction*
- $D_{s1}(2460)$ *CLEO PRD68,032002(2003)*
  - ✓ *70 MeV lower than the quark model prediction*



from Feng-Kun Guo

☐ Four-quark state @ 2013

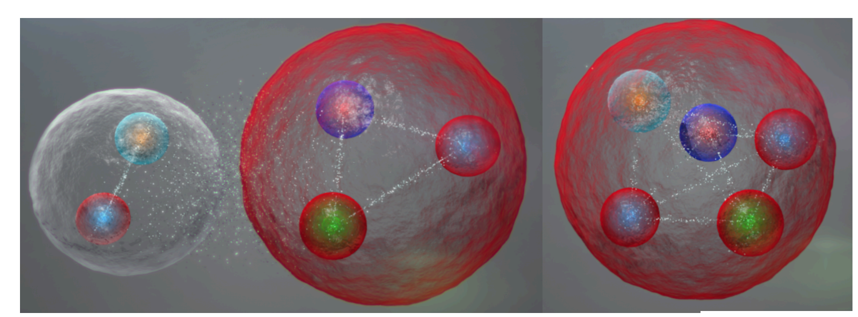
- Zc(3900) *BESIII, PRL110,252001(2013); Belle, PRL110,252002(2013)*
  - ✓ First very confirmed state of tetraquark



☐ Five-quark state @ 2015/2019

- Pc(4312), Pc(4440), Pc(4457)

LHCb, PRL115,072001(2015); 122, 222001 (2019)



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Milestone of exotic hadron spectroscopy

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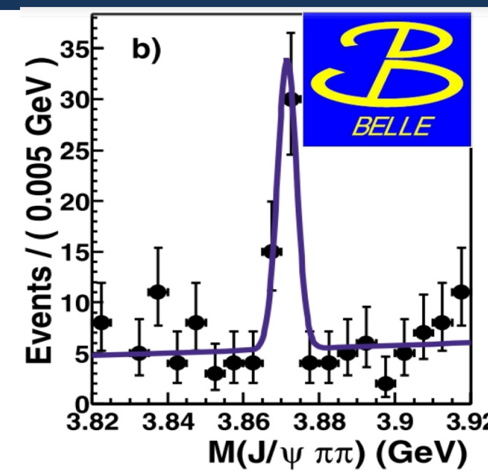

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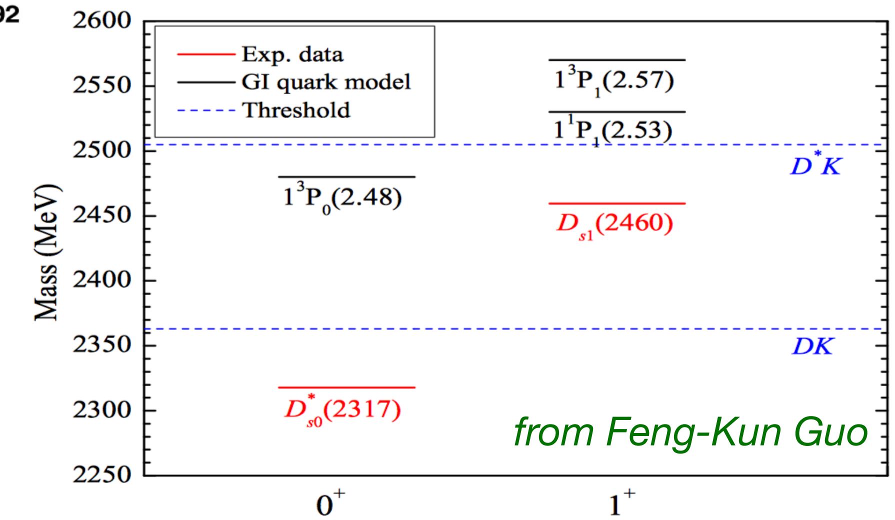

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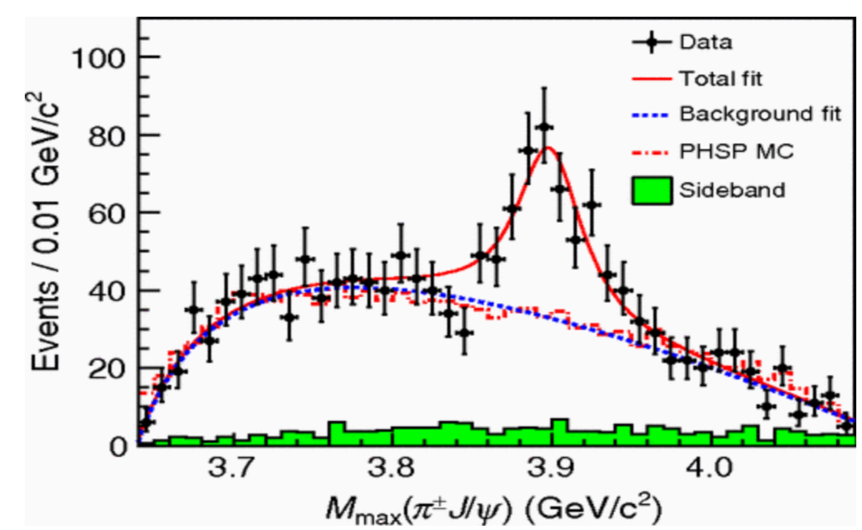

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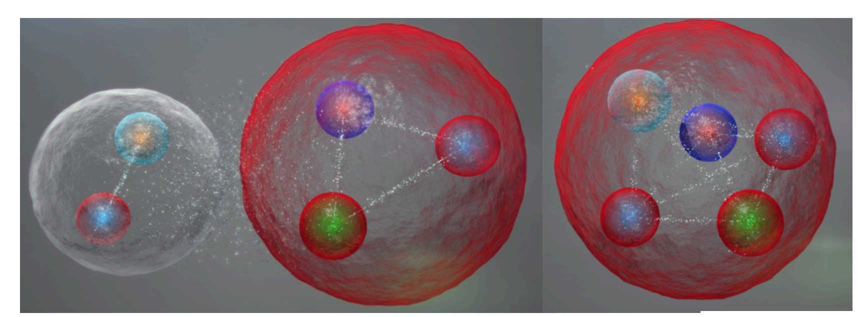

Dynamical generation in UChPT

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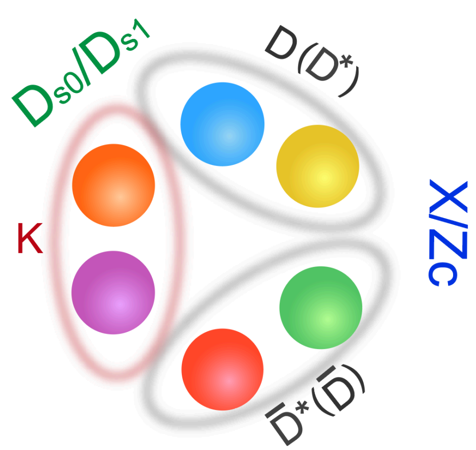
- Molecular picture
  - $D^*_{s0}(2317)$: s-wave DK bound state F.-K. Guo, et al., PLB641 (2006) 278–285
  - $D_{s1}(2460)$: s-wave D^*K bound state F.-K. Guo, et al., PLB647 (2007) 133–139
  - $X(3872)$: $D\bar{D}^*$ + c.c. D. Gamermann and E. Oset, Eur. Phys. J. A 33, 119 (2007)
  - $Z_C(3900)$: $D\bar{D}^*$ + c.c. F. Aceti, et al., PRD90 (2014) 016003

⇒ $KD, KD^*, D\bar{D}^*/\bar{D}D^*$ interactions are attractive!

LQCD: $K\bar{D}/K\bar{D}^*$: $I = 0$ moderately attractive, $I = 1$ slightly repulsive

L. Liu, et al., PRD87 (2013) 014508

- A nature question is that there exist the three-body bound state with the above building blocks or not.
  - $KD\bar{D}^*$
  - $K\bar{D}D^*$



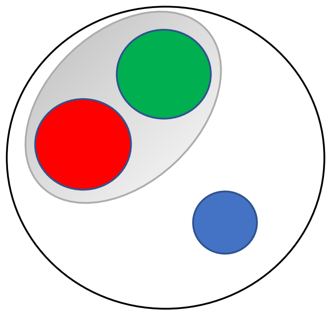
→ **Solve the three-body problem**

Three-body problem using Faddeev equations

- **Faddeev equations** *L. D. Faddeev, Zh. Eksp. Teor. Fiz. 39, 1459 (1960) [Sov. Phys. JETP 12, 1014 (1961)].*
  - Three coupled integrodifferential equations
  - It is not easy to solve exactly
- **Simplify or introduce the approximations**
  - Alt-Grassberger-Sandras approach *Nucl. Phys. B2, 167 (1967), Phys. Rev. C 17, 1981 (1978)*
    - ✓ Transforming the Faddeev equations to the two-body form
    - ✓ Easily be solved in a separable formulation
  - Faddeev equations with chiral unitary approach *A. Martínez Torres, et al., PRC77, 042203(2008)*
    - ✓ Using the on-shell two-body scattering amplitudes from the Bethe-Salpeter equation

Talk by Alberto Martínez Torres @ Session 3, 9:55, 8/21

  - Fixed Center Approximation (FCA) *R. Chand and R. H. Dalitz, Ann. Phys. 20, 1 (1962). R. C. Barrett and A. Deloff, PRC 60, 025201 (1999).*
    - ✓ **Criteria**: a heavy cluster formed by the first two particles
      a light third particle
      ➡ Reduce the Faddeev equations to the two-body form



Successful applications of FCA

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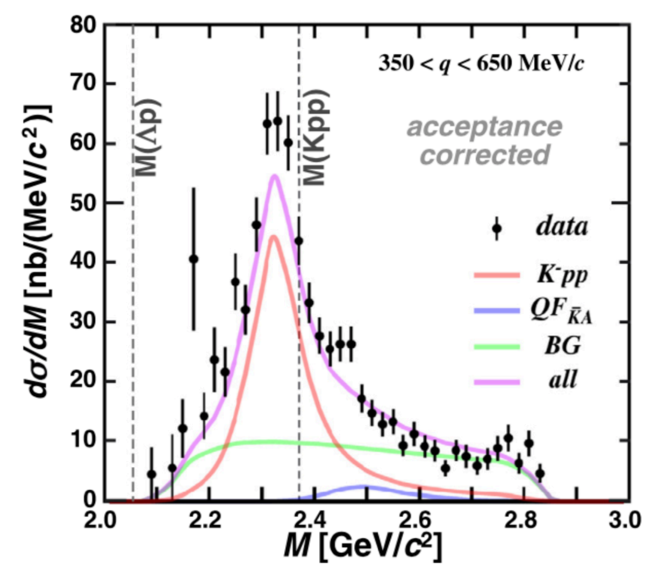
- **One-meson and two-baryon systems**
  - $\bar{K}NN/\bar{K}pp$ Bayar, PRC(2011),NPA(2012),PRC(2013)
    - ✓ *Predicted bound state* ***has been supported by J-PARC***



J-PARC, PLB789 (2019) 620

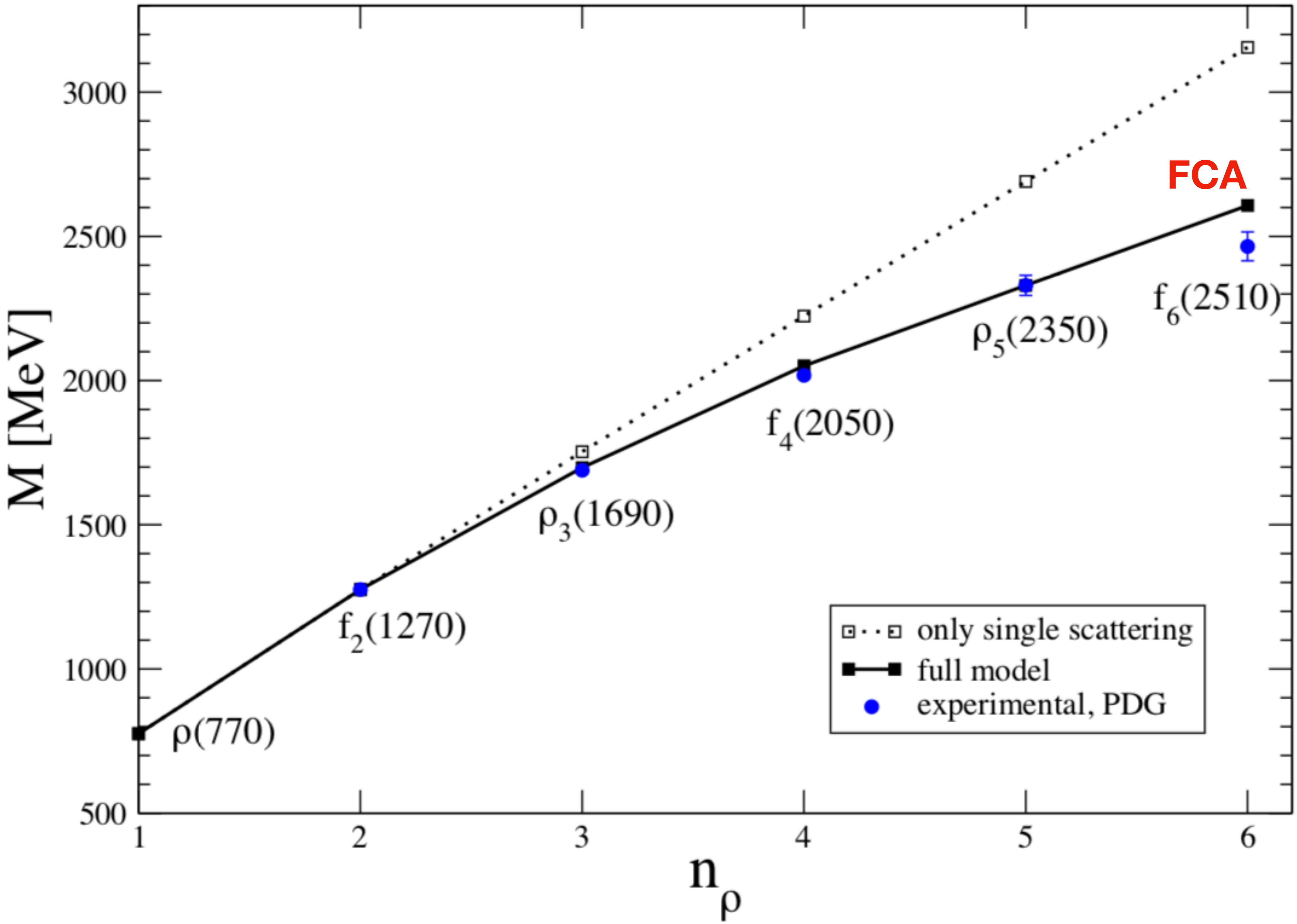
- **Two-meson and one baryon systems**
  - $\pi\rho\Delta$ Xie, PRC(2011) *Explain the structure of $\Delta_{5/2^+}(2000)$*
  - $K\bar{K}N$ Xie, PRD(2011) *Support the existence of N*(1920)*

Consistent with the Faddeev cal.

A. Martínez Torres, et al, PRC79,065207(2009)

- **Three-meson systems**
  - Light sector: $\rho K\bar{K}$ Bayar, EPJA(2014); $\eta^{(\prime)}K\bar{K}$ Liang, PRD(2013); $\phi K\bar{K}$ Martinez Torres, PRD(2011); $\pi K^*\bar{K}$ Zhang, PRD(2017); $\eta K^*\bar{K}$ Zhang, 1906.07340
  - Heavy sector: DKK, $DK\bar{K}$ Debastiani, PRD(2017); $\rho D\bar{D}$ Durkaya, PRD(2015); $\rho D^*\bar{D}^*$ Bayar, EPJA(2015); ρB^*B^* Bayar, EPJA(2016); BDD, $BD\bar{D}$ Dias, PRD(2017); $D^{(*)}B^{(*)}B^{(*)}$ Dias, PRD(2018)
- **Multi-meson systems**
  - multi-ρ Roca, PRD(2010);
  - $K^{(*)}$-multi-ρ Yamagata-Sekihara, PRD(2010); Xiao, PRD(2011); D^*-multi-ρ Xiao, PRD(2012)

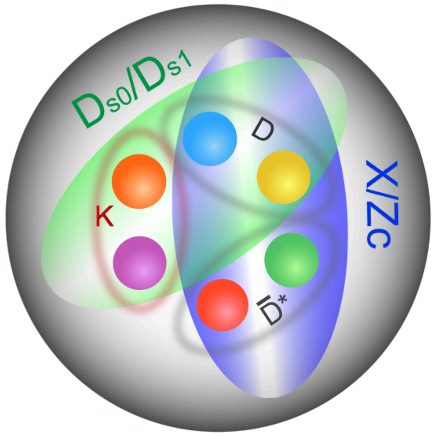
Multi-ρ systems in FCA



L. Roca and E. Oset, Phys. Rev. D 82, 054013 (2010)

In this work

- We study the three-body system, $KD\bar{D}^*$, by solving the Faddeev equation with the fixed center approximation
  - Heavy bound states of $D\bar{D}^*$ forming the cluster: X(3872) or Zc(3900)
  - Light particle K scattering off the cluster
- We find a bound state with hidden charm structure at the strangeness sector
  - Mass = 4307(2) MeV and Width = 18(2) MeV
  - Isospin: 1/2 and $J^P = 1^-$



- We also investigate the decay properties of our predicted state

XLR, B.B. Malabarba, Li-Sheng Geng, K.P. Khemchandani, A. Martínez Torres, PLB785(2018)112
XLR, B.B. Malabarba, K.P. Khemchandani, A. Martínez Torres, JHEP05(2019)1

Outline

RUB

- Introduction
- Theoretical Framework
  - Fixed center approximation of Faddeev equations
- Results and discussion
- Summary and perspectives

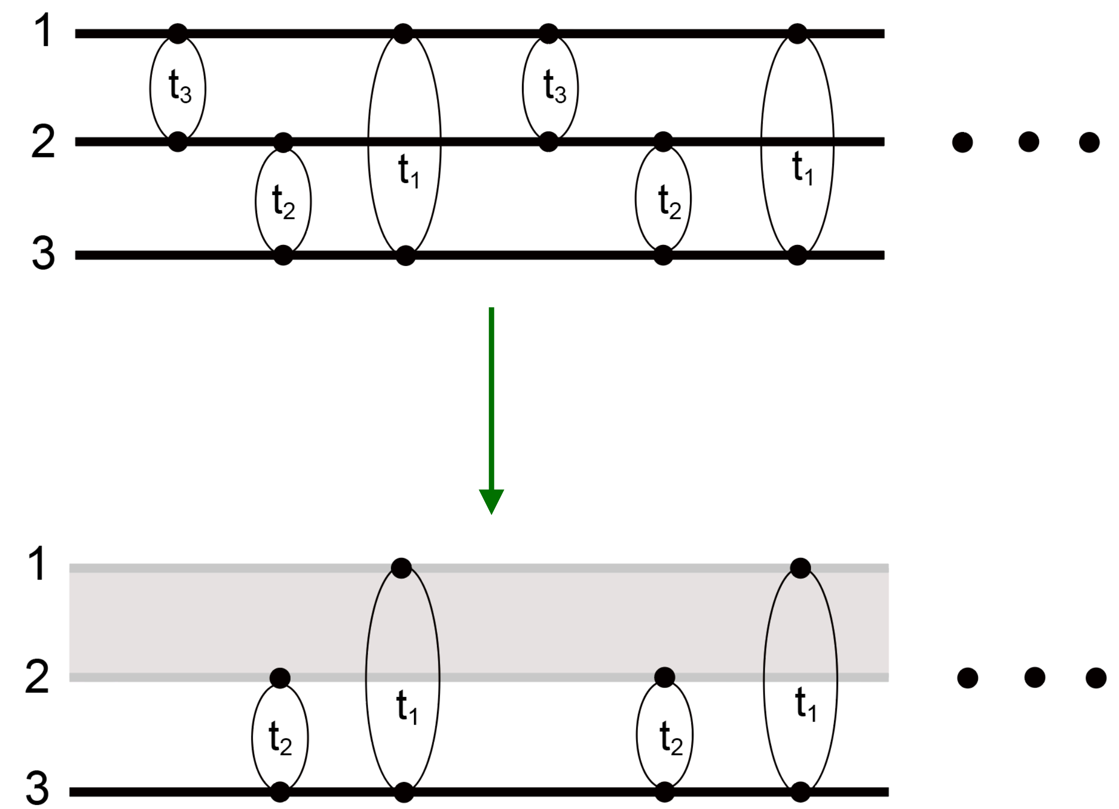
Fixed center approximation

RUB

Faddeev equations

- Scattering amplitude of 1,2,3 particles
  a set of three coupled equations

$$T = \sum_{i=1}^{3} T_i . \qquad T_i = t_i + t_i\, G_0\, T_j + t_i\, G_0\, T_k .$$



Fixed center approximation

- Exist a stable cluster, e.g., of (1, 2)
- Mass hierarchy: $m_3 << M_{12}$
- Scattering amplitude reduced as **two coupled equations**

$$T = T_1 + T_2 .$$

$$T_1 = t_1 + t_1\, G_0\, T_2 = t_1 + t_1\, G_0\, t_2 + t_1\, G_0\, t_2\, G_0\, t_1 + \cdots$$

$$T_2 = t_2 + t_2\, G_0\, T_1 = t_2 + t_2\, G_0\, t_1 + t_2\, G_0\, t_1\, G_0\, t_2 + \cdots$$

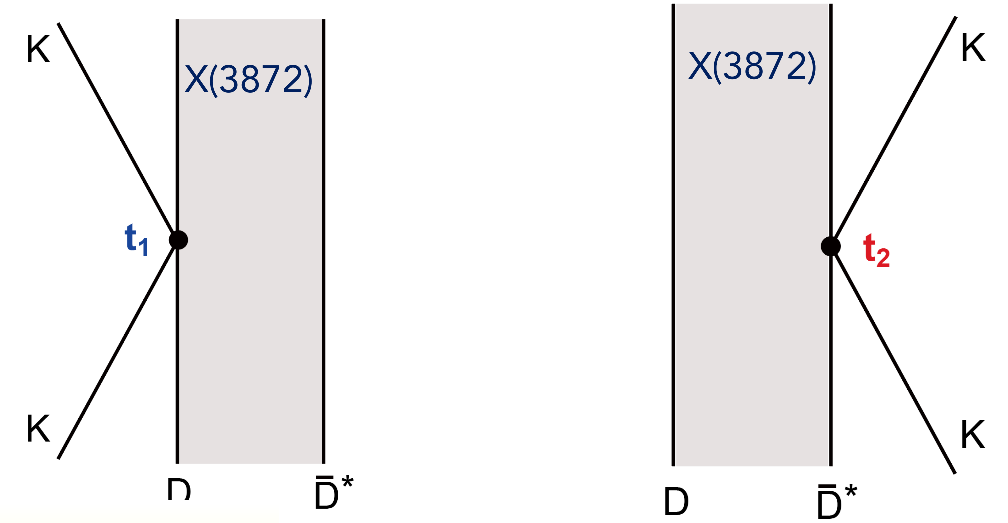
$K(D\bar{D}^*)_{X(3872)}$ scattering in FCA

RUB

Single scattering: t_i

$$\langle KX(3872)|\,\hat{t}_1\,|KX(3872)\rangle \equiv t_1 = \frac{3}{4}t^{I=1}_{KD} + \frac{1}{4}t^{I=0}_{KD}.$$

$$\langle KX(3872)|\,\hat{t}_2\,|KX(3872)\rangle \equiv t_2 = \frac{3}{4}t^{I=1}_{K\bar{D}^*} + \frac{1}{4}t^{I=0}_{K\bar{D}^*}.$$



➡ Inputs: KD and $K\bar{D}^*$ scattering amplitudes

➡ Totally fixed through UChPT with the heavy quark symmetry

F.-K. Guo, et al., PBL641 (2006) 278

Double scattering: $t_i\, G_0\, t_j$

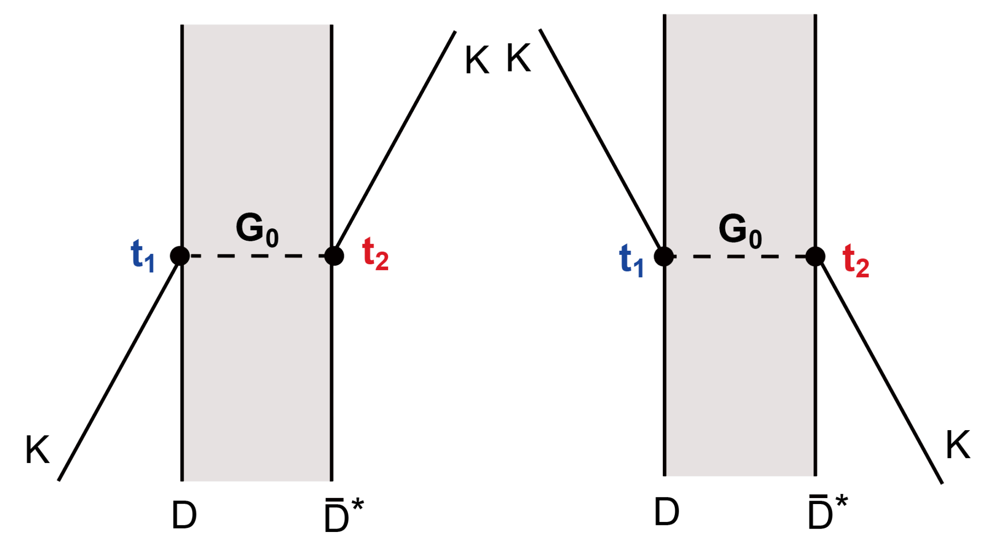
- G_0: K meson propagator inside the cluster X(3872)

$$G_0(\boldsymbol{q}) = \frac{1}{M_X}\int \frac{d^3\boldsymbol{q}}{(2\pi)^3}\frac{F_X(\boldsymbol{q})}{q^{0\,2} - \boldsymbol{q}^2 - m_K^2 + i\epsilon}.$$

- F_X: Form factor of X(3872)

$$F_X(\boldsymbol{q}) = \frac{1}{\mathcal{N}}\int_{|\boldsymbol{p}|,\,|\boldsymbol{p}-\boldsymbol{q}|<\Lambda} d^3\boldsymbol{p}\, f_X(\boldsymbol{p})\, f_X(\boldsymbol{p}-\boldsymbol{q}).$$

$$\mathcal{N} = F_X(0), \quad f_X(\boldsymbol{p}) = \frac{1}{\omega_D(\boldsymbol{p})\omega_{\bar{D}^*}(\boldsymbol{p})}\frac{1}{M_X - \omega_D(\boldsymbol{p}) - \omega_{\bar{D}^*}(\boldsymbol{p})}.$$



➡ Cutoff: fixed as the value used in the $D\bar{D}^*$ scattering to produce X(3872) in UChPT.

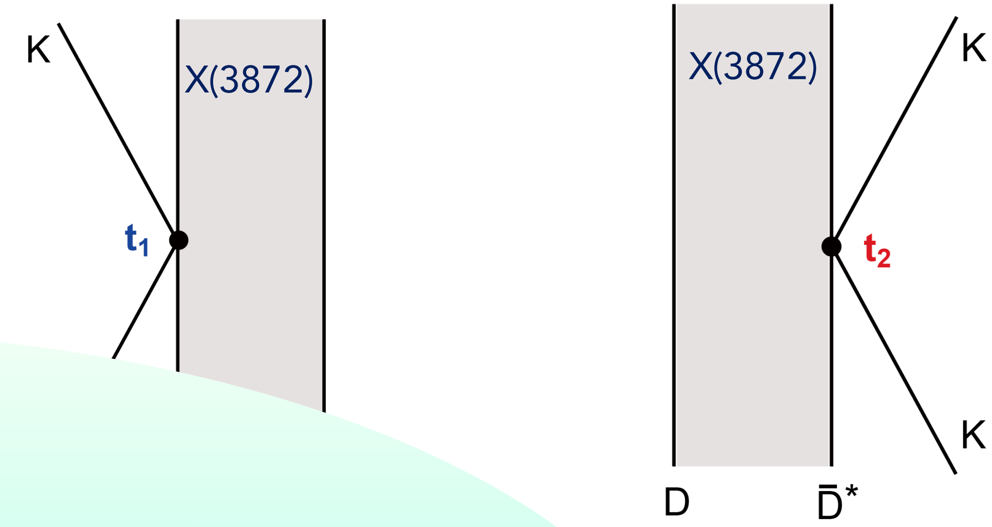
$K(D\bar{D}^*)_{X(3872)}$ scattering in FCA

RUB

Single scattering: t_i

$$\langle KX(3872)|\,\hat{t}_1\,|KX(3872)\rangle \equiv t_1 = \frac{3}{4}t_{KD}^{I=1} + \frac{1}{4}t_{KD}^{I=0}.$$

$\langle KX(3872)|\,\hat{t}_2\,|KX(3872)\rangle \equiv t_2 = \frac{3}{\ }\ldots$



➡ Inputs: KD and ...

➡ Totally fixed ...

...L641 (2006) 278

Parameter-free framework

Double s...

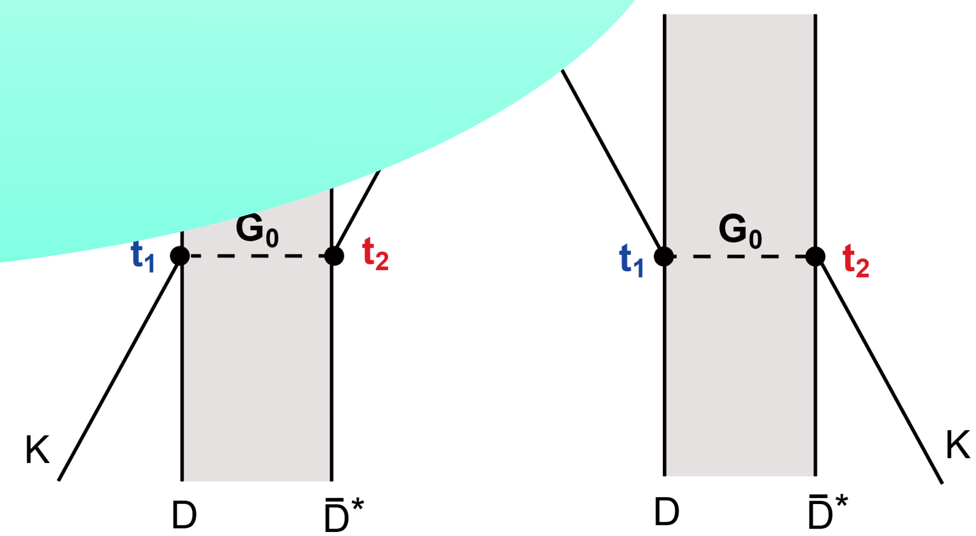
- G_0: K meson ...

$$G_0(\boldsymbol{q}) = \frac{1}{M_X}\int \frac{d\ldots}{(2\pi\ldots}$$

- F_X: Form facto... (3872)

$$F_X(\boldsymbol{q}) = \frac{1}{\mathcal{N}}\int_{|\boldsymbol{p}|,\,|\boldsymbol{p}-\boldsymbol{q}|<\Lambda} d^3\boldsymbol{p}\, f_X(\boldsymbol{p})\, f_X(\boldsymbol{p}-\boldsymbol{q}).$$

$$\mathcal{N} = F_X(0), \quad f_X(\boldsymbol{p}) = \frac{1}{\omega_D(\boldsymbol{p})\omega_{\bar{D}^*}(\boldsymbol{p})}\frac{1}{M_X - \omega_D(\boldsymbol{p}) - \omega_{\bar{D}^*}(\boldsymbol{p})}.$$



➡ Cutoff: fixed as the value used in the $D\bar{D}^*$ scattering to produce X(3872) in UChPT.

KX and KZc scattering in FCA

- Full scattering amplitude of KX(3872)

$$T = T_1 + T_2.$$

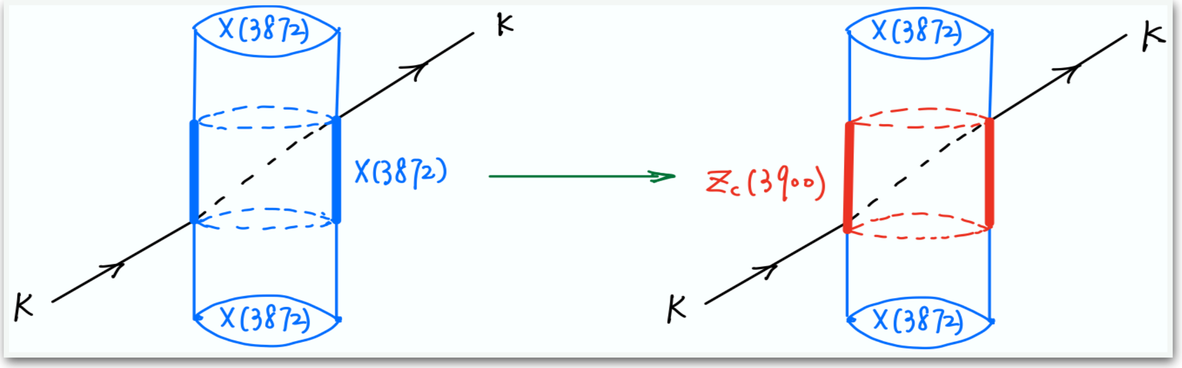
$$T_1 = t_1 + t_1\, G_0\, T_2$$

$$T_2 = t_2 + t_2\, G_0\, T_1$$

$$T = T_1 + T_2 = \frac{\tilde{t}_1 + \tilde{t}_2 + 2\tilde{t}_1\, \tilde{t}_2\, G_0}{1 - \tilde{t}_1\, \tilde{t}_2\, G_0^2}.$$

$$\tilde{t}_1 = \frac{M_X}{m_D}\, t_1, \quad \tilde{t}_2 = \frac{M_X}{m_{\bar{D}^*}}\, t_2.$$

- Consider the transition between X(3872) and Zc(3900)
  - X(3872)/Zc(3900): $D\bar{D}^*$ + *c.c.*
  - Total scattering amplitude



$$T = T_1 + T_2 = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix}.$$

  - Introduce the matrix form of t_1, t_2, G_0

$$t_1 = \begin{bmatrix} (t_1)_{11} & (t_1)_{12} \\ (t_1)_{21} & (t_1)_{22} \end{bmatrix}, \quad t_2 = \begin{bmatrix} (t_2)_{11} & (t_2)_{12} \\ (t_2)_{21} & (t_2)_{22} \end{bmatrix}, \quad G_0 = \begin{bmatrix} (G_0)_{11} & 0 \\ 0 & (G_0)_{22} \end{bmatrix}.$$

KX and KZc scattering amplitudes

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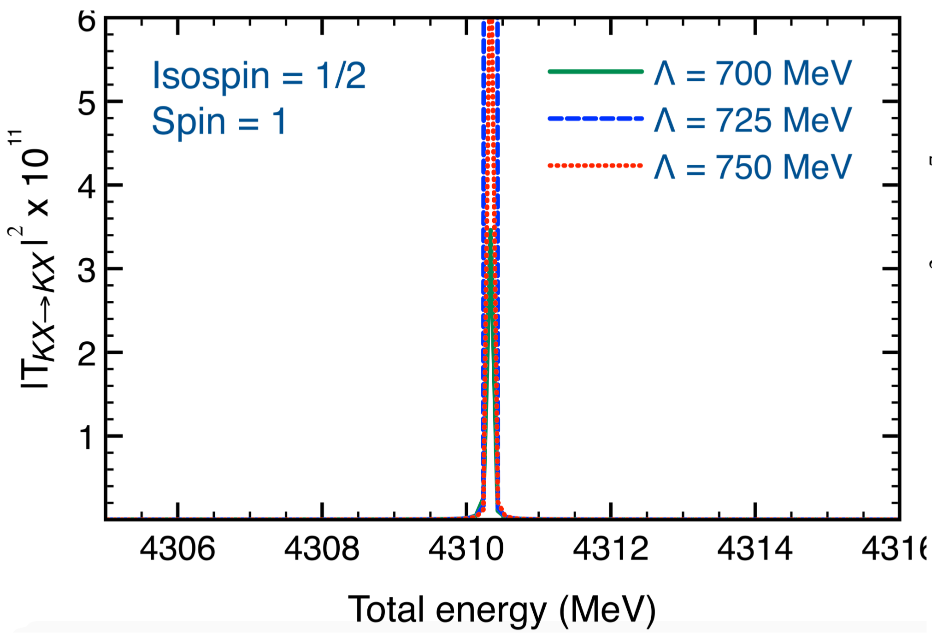
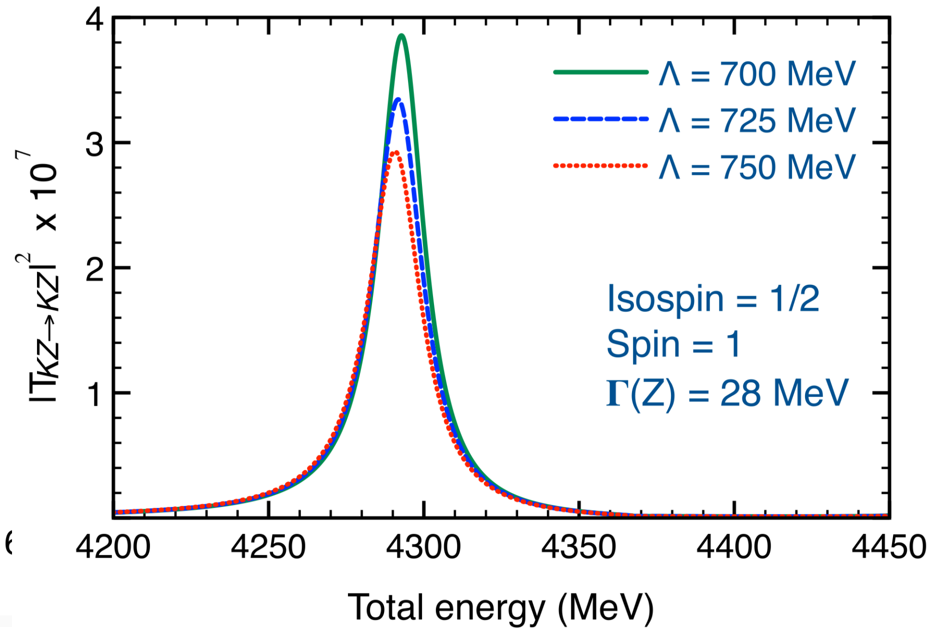
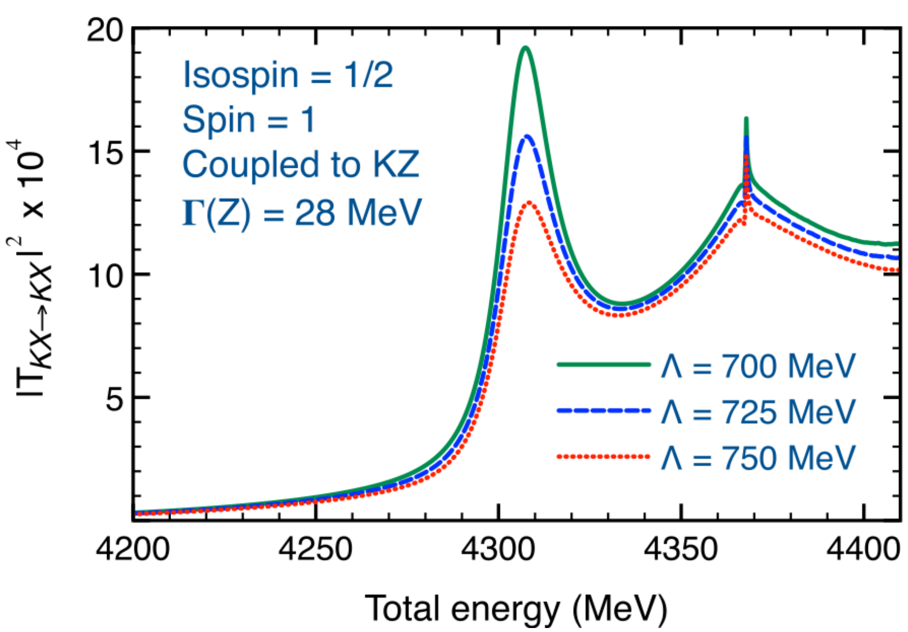
Modulus squared of scattering amplitudes

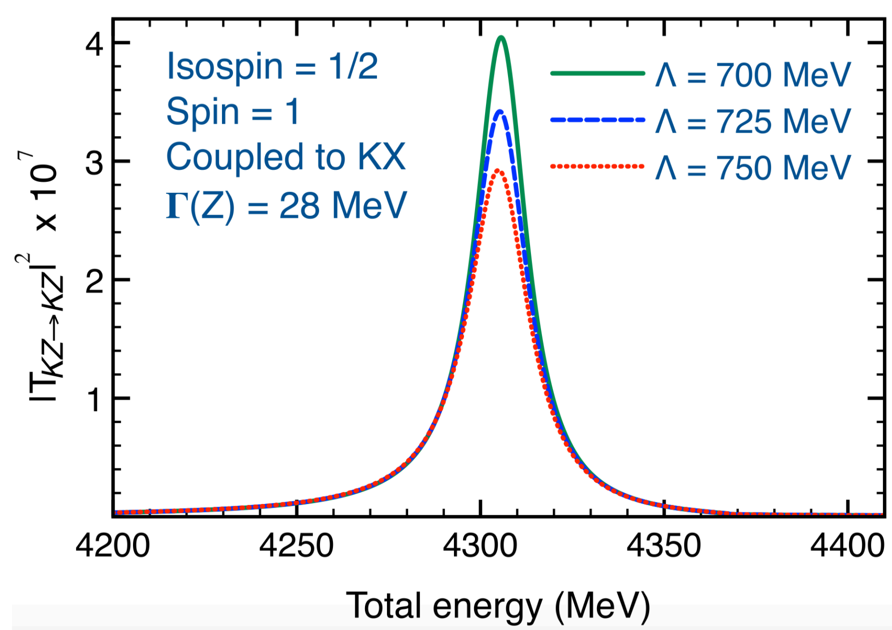
- Without considering the transition between KX and KZc





- Considering the transition between KX and KZc





✓ Couple channel effect is important

✓ Predicted state:

Mass: 4307(2) MeV

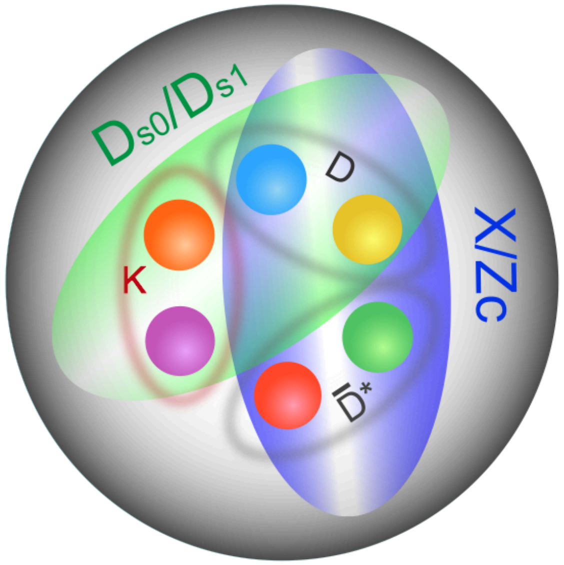
Width: 18(2) MeV

✓ Obtained width is from Zc's width

Predicted heavy K* meson

RUB

- **New meson** with hidden charm in the strangeness sector
  - Mass = 4307(2) MeV and Width = 18(2) MeV
  - Isospin: 1/2 and $J^P = 1^-$
  - Six-quark state with $e.g.\ K^{*+}(4307) : ud\bar{d}\bar{s}c\bar{c}$
  - Molecular component: $KD\bar{D}^*$
  - Our prediction is consistent with the one (4317 MeV) given by solving the three-body Schrodinger equation with Born-Oppenheimer approximation.



Li Ma, Qian Wang, Ulf-G. Meißner, Chin.Phys. C43 (2019) 014102

Talk by Li Ma @ Session 3, 11:50, 8/21

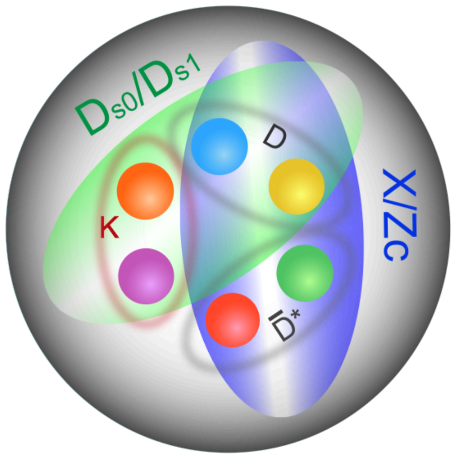
- We also investigate the $KD\bar{D}$ and $KD^*\bar{D}^*$ systems using the fixed center approximation of Faddeev equations

Systems	$I(J^P)$	Masses of bound states
$K(D\bar{D})_{X(3700)}$	$\frac{1}{2}(0^-)$	4162 MeV
$K(D^*\bar{D}^*)_{X(3915)}$	$\frac{1}{2}(2^-)$	4368 MeV

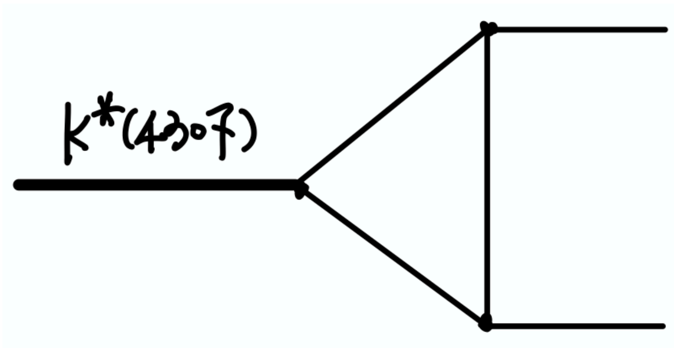
Decay properties of K*(4307)

RUB

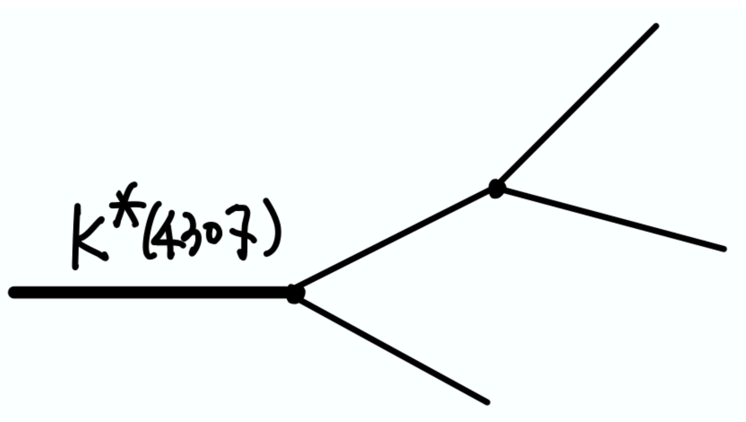
- In order to provide more information
  - Link to the internal structure of K*(4307)
  - Reliable for the experimental searches



- We studied the decay properties of K*(4307)
  - Calculate the decay to two-body channels
    - ✓ K*(4307) → $J/\psi K^*, \bar{D}D_s, \bar{D}^*D_s^*, \bar{D}D_s$
    - ✓ Via the triangle loop



  - Calculate the decay to three-body channel
    - ✓ K*(4307) → $J/\psi \pi K$
    - ✓ Via the tree diagram



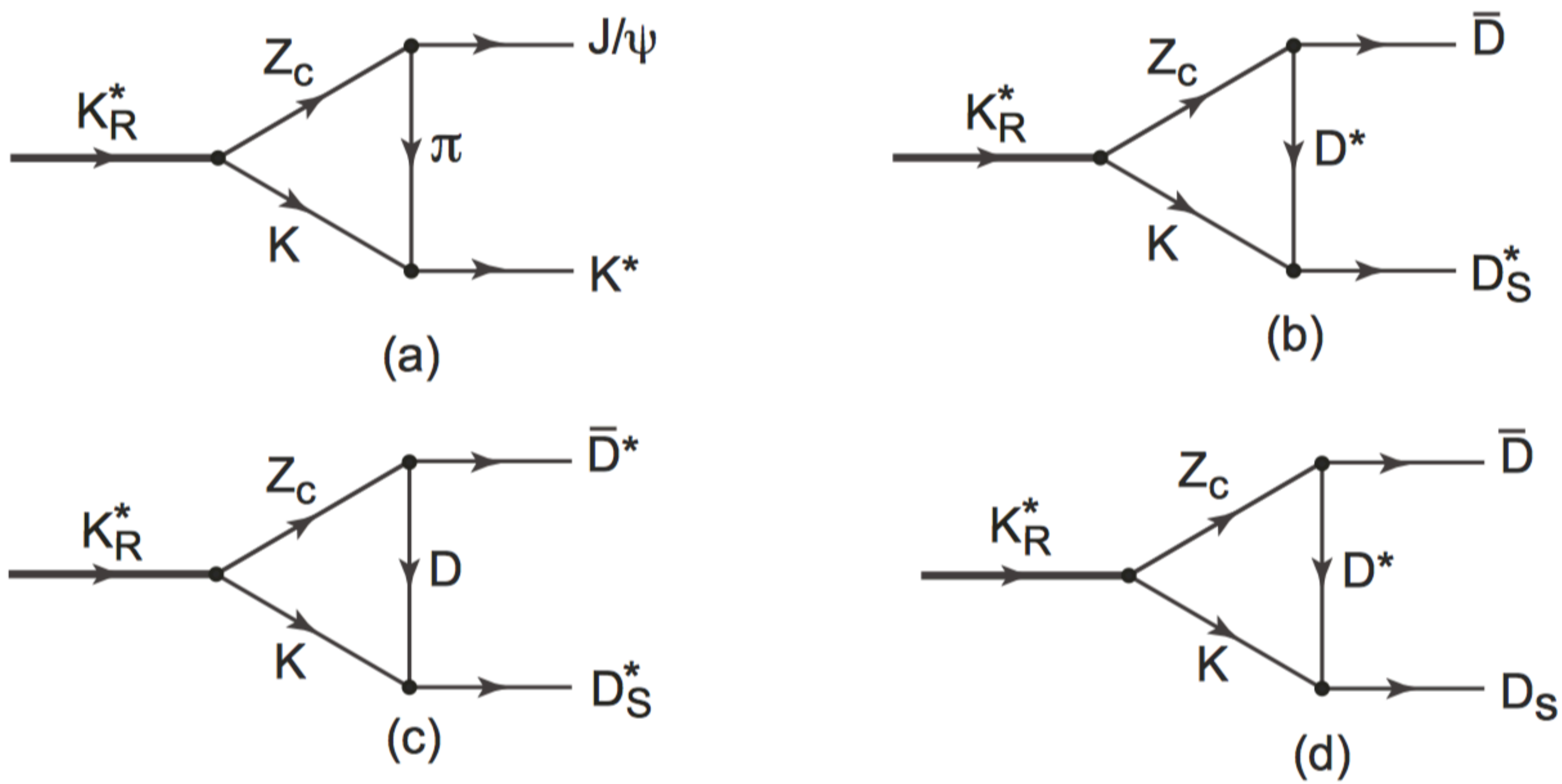
XLR, B.B. Malabarba, K.P. Khemchandani, A. Martinez Torres, JHEP05(2019)1

Decay processes of K*(4307)

- The estimated width of K*(4307) is from Zc's width
- The squared amplitude of KZc is around **200 times larger** than that of KX

➡ **We focus on the decay processes of K*(4307) via the Zc intermediate state**

- Four decay channels through triangle loops



Decay width

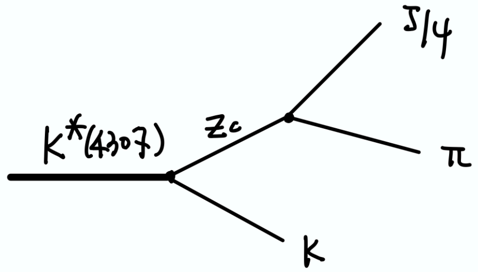
RUB

- Evaluate the decay processes in the charge basis
- Use the momentum cutoff to regularize the triangle loop
  - Vary the cutoff from 700 MeV to 800 MeV
- Decay width
  - Two-body decay channels can provide around 9 MeV

Process	Decay width (MeV)
$K^*(4307) \to J/\psi\, K^*$	6.97 ± 0.27
$K^*(4307) \to \bar{D}\, D_S^*$	0.54 ± 0.08
$K^*(4307) \to \bar{D}^*\, D_S^*$	0.54 ± 0.07
$K^*(4307) \to \bar{D}\, D_S$	1.14 ± 0.17

  - Three-body decay channel can provide 12 MeV

$$K^*(4307) \to J/\psi\, K\, \pi$$



  - In total, the width of K*(4307) is around 21 MeV

Consistent with the one given before.

Summary

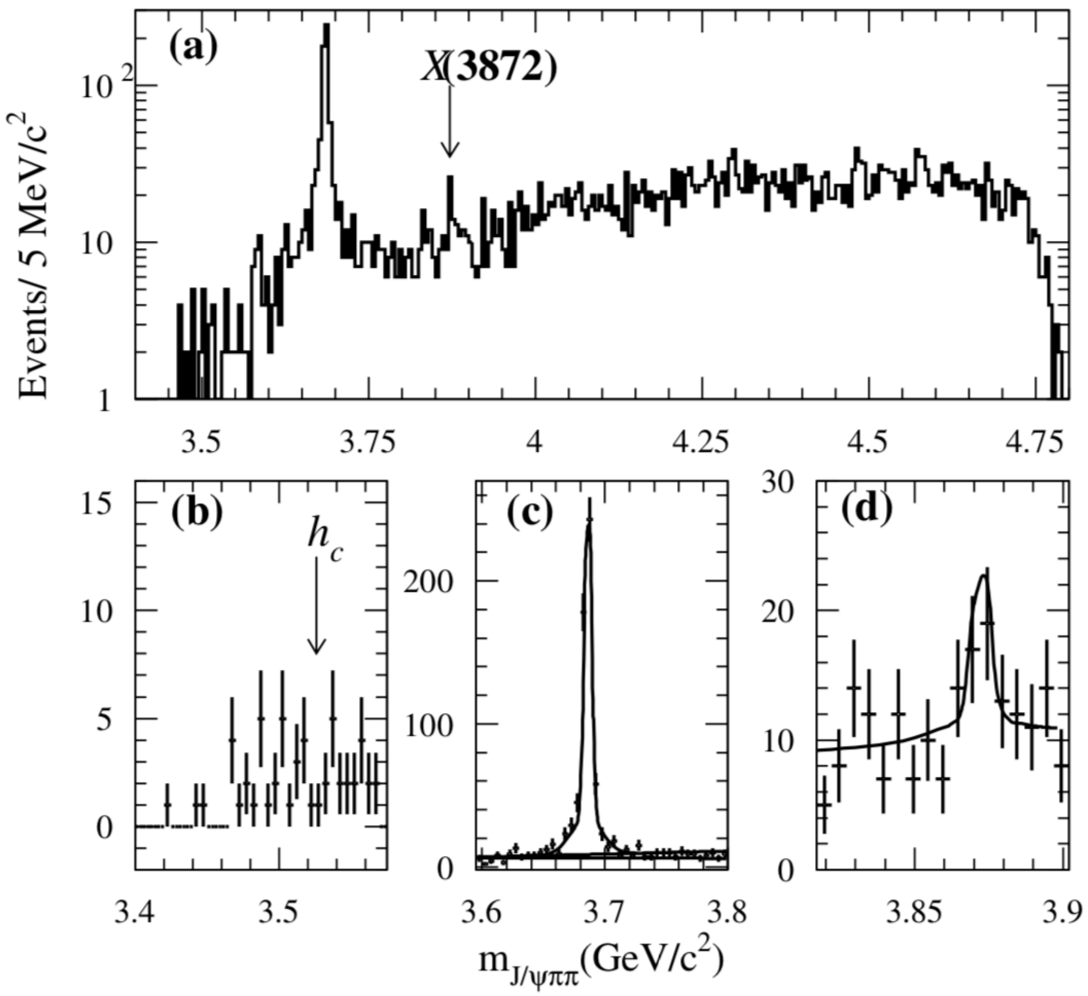
RUB

- We studied the three-body system, $K D \bar{D}^*$, in the fixed center approximation of Faddeev equations
- And predicted a six-quark state with hidden charm in the strangeness sector
  - **K*(4307)** with $I(J^P) = \frac{1}{2}(1^-)$ and $m \pm i\frac{\Gamma}{2} = 4307(2) \pm i9(1)$
- We also calculated the decay width of K*(4307) via the two-body and three-body final states
- In order to provide more favorable information for the experimental search, we are working on the production of K*(4307) through the decay of B meson to $J/\psi K \pi \pi$.

Invariant mass distribution of $J/\psi K\pi$

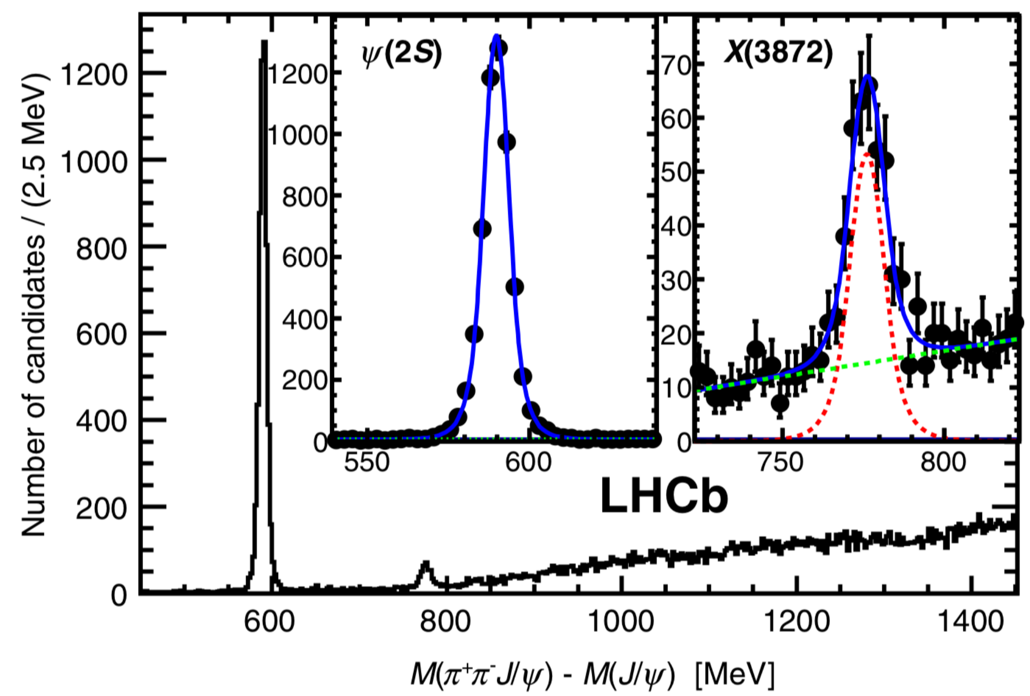
- X(3872) found in the $J/\psi\pi\pi$ invariant mass distribution

$B^- \to J/\psi K^-\pi^+\pi^-$



*BarBar, PRD**71**, 071103 (2005)*

$B^+ \to J/\psi K^+\pi^+\pi^-$



LHCb, PRL110, 222001 (2013)

- How about the invariant mass distribution of $J/\psi K\pi$?
- Our predicted K*(4307) can be found in there?

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THANK YOU FOR YOUR ATTENTION!