Hidden-strange partners of LHCb pentaquarks

何军

南京师范大学

中国物理学会高能物理分会第十届全国会员代表大会暨学术年会
上海，2018年6月20-24日

Outline

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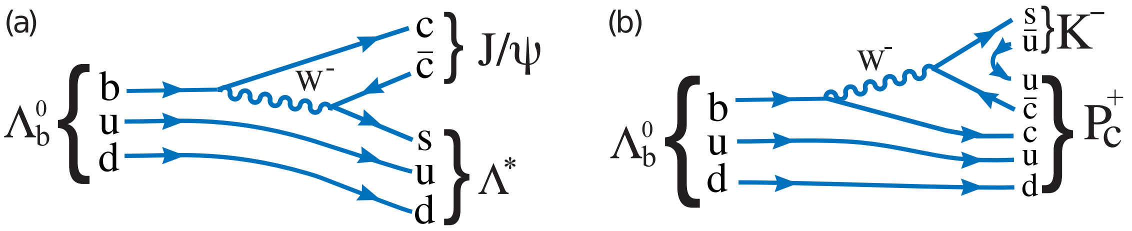
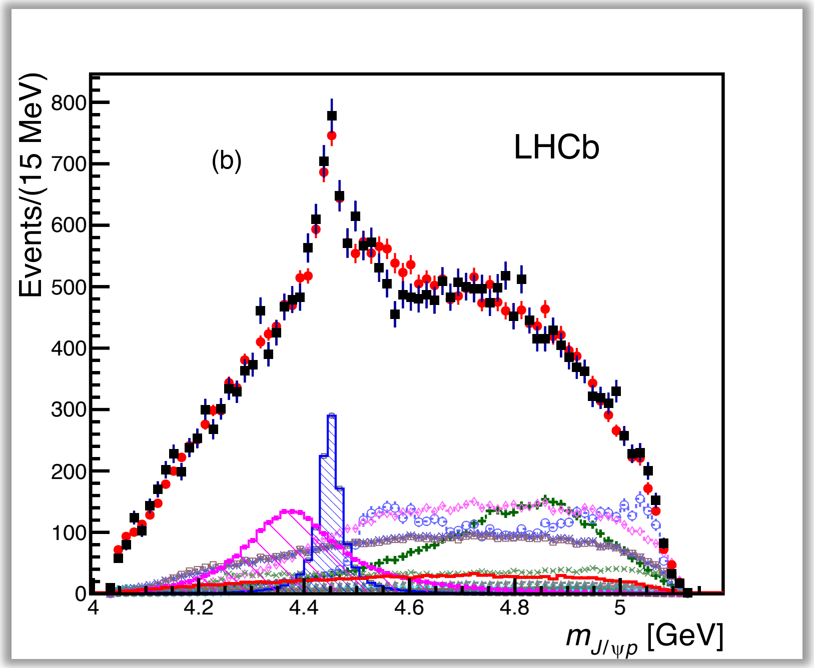
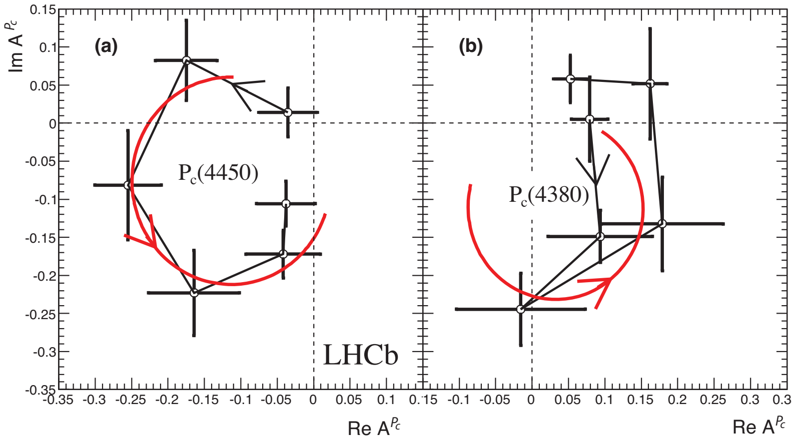
- Pc（4380）and Pc（4450）as hadronic molecules
- Nucleon resonances near 2 GeV
- Hidden-strange partners of LHCb pentaquarks
- Summary

Introduction

LHCb pentaquarks



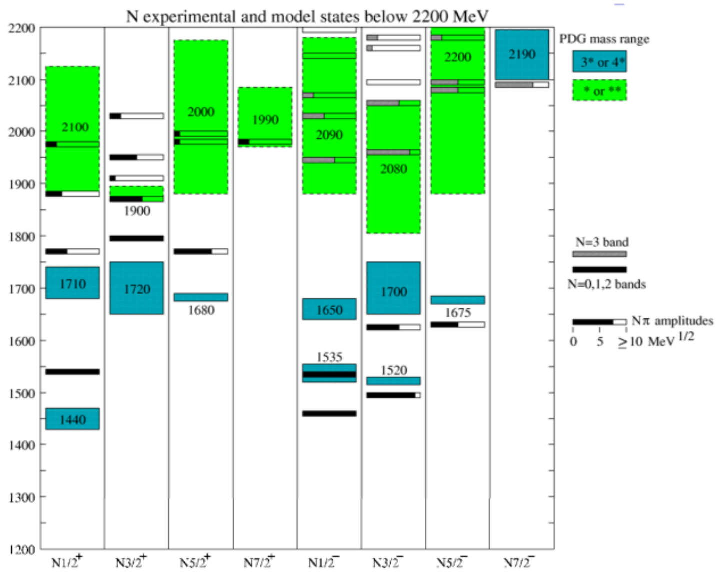


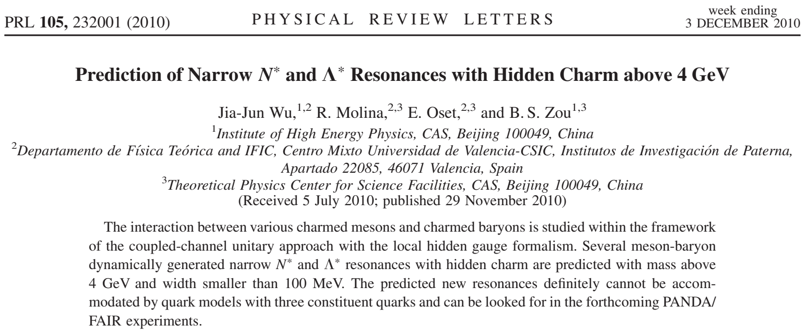


J=3/2 or 5/2; opposite parities

核子共振态超重岛

质量在4 GeV附近的核子共振态(含正反粲夸克）





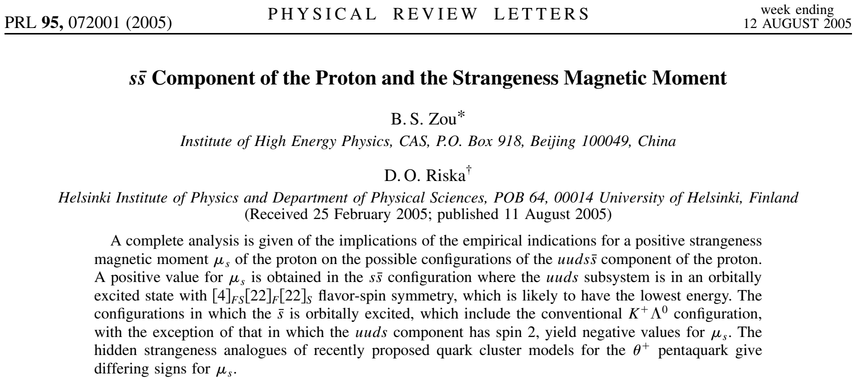
PRL **105,** 232001 (2010) PHYSICAL REVIEW LETTERS week ending 3 DECEMBER 2010

Prediction of Narrow N^* and Λ^* Resonances with Hidden Charm above 4 GeV

Jia-Jun Wu,[1,2] R. Molina,[2,3] E. Oset,[2,3] and B. S. Zou[1,3]
[1]*Institute of High Energy Physics, CAS, Beijing 100049, China*
[2]*Departamento de Física Teórica and IFIC, Centro Mixto Universidad de Valencia-CSIC, Institutos de Investigación de Paterna, Apartado 22085, 46071 Valencia, Spain*
[3]*Theoretical Physics Center for Science Facilities, CAS, Beijing 100049, China*
(Received 5 July 2010; published 29 November 2010)

The interaction between various charmed mesons and charmed baryons is studied within the framework of the coupled-channel unitary approach with the local hidden gauge formalism. Several meson-baryon dynamically generated narrow N^* and Λ^* resonances with hidden charm are predicted with mass above 4 GeV and width smaller than 100 MeV. The predicted new resonances definitely cannot be accommodated by quark models with three constituent quarks and can be looked for in the forthcoming PANDA/FAIR experiments.

仅预言了1/2-态



PRL **95,** 072001 (2005) PHYSICAL REVIEW LETTERS week ending 12 AUGUST 2005

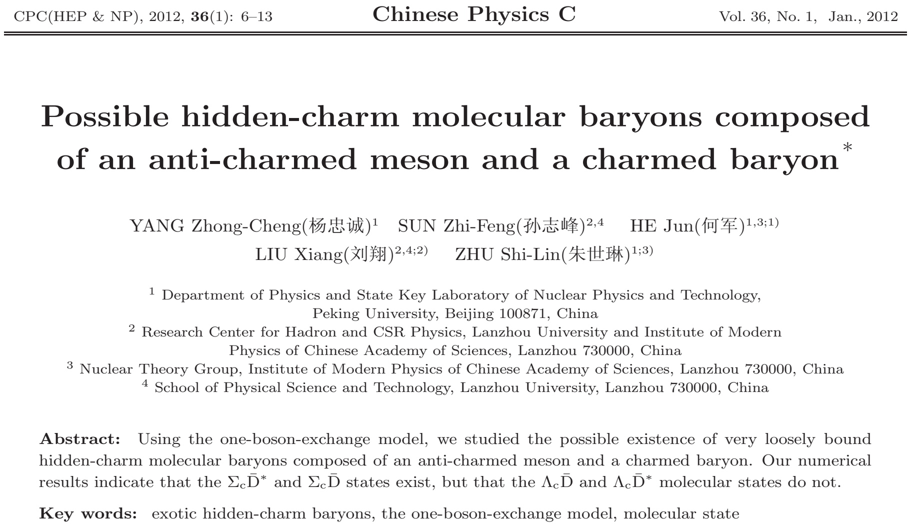
$s\bar{s}$ Component of the Proton and the Strangeness Magnetic Moment

B. S. Zou*
Institute of High Energy Physics, CAS, P.O. Box 918, Beijing 100049, China

D. O. Riska†
Helsinki Institute of Physics and Department of Physical Sciences, POB 64, 00014 University of Helsinki, Finland
(Received 25 February 2005; published 11 August 2005)

A complete analysis is given of the implications of the empirical indications for a positive strangeness magnetic moment μ_s of the proton on the possible configurations of the $uuds\bar{s}$ component of the proton. A positive value for μ_s is obtained in the $s\bar{s}$ configuration where the $uuds$ subsystem is in an orbitally excited state with $[4]_{FS}[22]_F[22]_S$ flavor-spin symmetry, which is likely to have the lowest energy. The configurations in which the $\bar{s}$ is orbitally excited, which include the conventional $K^+\Lambda^0$ configuration, with the exception of that in which the $uuds$ component has spin 2, yield negative values for μ_s. The hidden strangeness analogues of recently proposed quark cluster models for the θ^+ pentaquark give differing signs for μ_s.

One-boson-exchange model（molecular state）



CPC(HEP & NP), 2012, **36**(1): 6–13 Chinese Physics C Vol. 36, No. 1, Jan., 2012

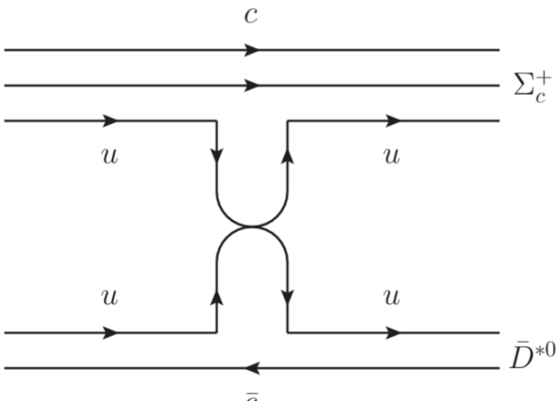
Possible hidden-charm molecular baryons composed of an anti-charmed meson and a charmed baryon*

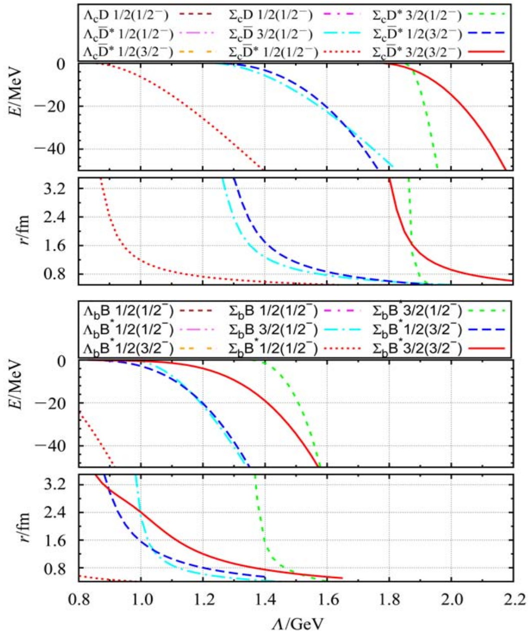
YANG Zhong-Cheng(杨忠诚)[1] SUN Zhi-Feng(孙志峰)[2,4] HE Jun(何军)[1,3;1)]
LIU Xiang(刘翔)[2,4;2)] ZHU Shi-Lin(朱世琳)[1;3)]

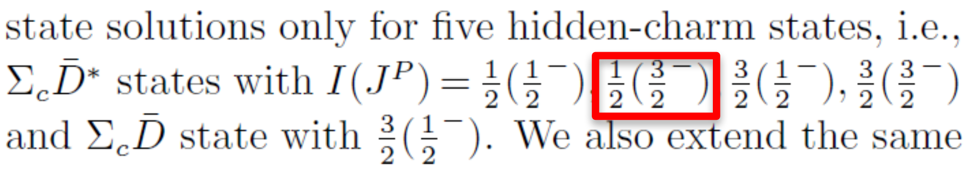
[1] Department of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China
[2] Research Center for Hadron and CSR Physics, Lanzhou University and Institute of Modern Physics of Chinese Academy of Sciences, Lanzhou 730000, China
[3] Nuclear Theory Group, Institute of Modern Physics of Chinese Academy of Sciences, Lanzhou 730000, China
[4] School of Physical Science and Technology, Lanzhou University, Lanzhou 730000, China

Abstract: Using the one-boson-exchange model, we studied the possible existence of very loosely bound hidden-charm molecular baryons composed of an anti-charmed meson and a charmed baryon. Our numerical results indicate that the $\Sigma_c\bar{D}^*$ and $\Sigma_c\bar{D}$ states exist, but that the $\Lambda_c\bar{D}$ and $\Lambda_c\bar{D}^*$ molecular states do not.

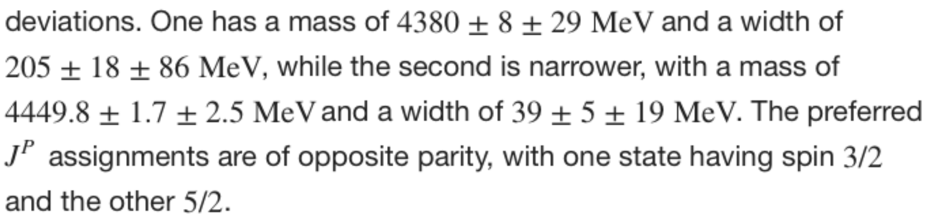
Key words: exotic hidden-charm baryons, the one-boson-exchange model, molecular state





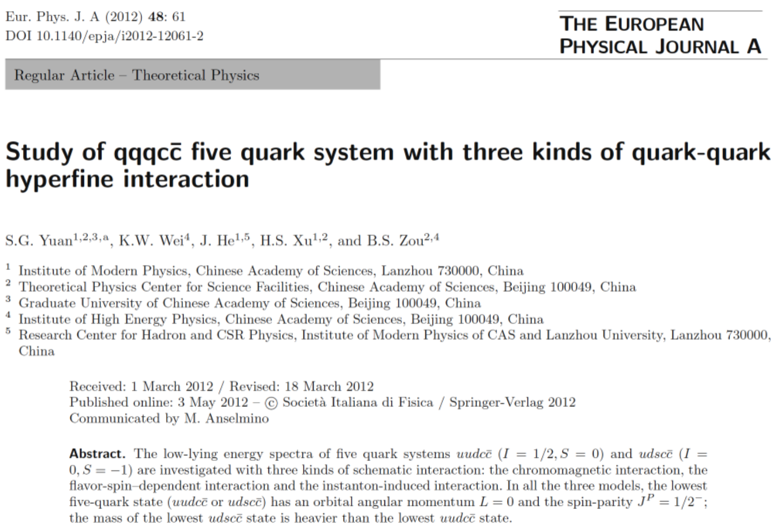


state solutions only for five hidden-charm states, i.e., $\Sigma_c\bar{D}^*$ states with $I(J^P)=\frac{1}{2}(\frac{1}{2}^-)$, $\boxed{\frac{1}{2}(\frac{3}{2}^-)}$ $\frac{3}{2}(\frac{1}{2}^-)$, $\frac{3}{2}(\frac{3}{2}^-)$ and $\Sigma_c\bar{D}$ state with $\frac{3}{2}(\frac{1}{2}^-)$. We also extend the same



deviations. One has a mass of $4380 \pm 8 \pm 29$ MeV and a width of $205 \pm 18 \pm 86$ MeV, while the second is narrower, with a mass of $4449.8 \pm 1.7 \pm 2.5$ MeV and a width of $39 \pm 5 \pm 19$ MeV. The preferred J^P assignments are of opposite parity, with one state having spin 3/2 and the other 5/2.

Constituent quark model



Eur. Phys. J. A (2012) **48**: 61
DOI 10.1140/epja/i2012-12061-2

THE EUROPEAN PHYSICAL JOURNAL A

Regular Article – Theoretical Physics

Study of qqqc$\bar{c}$ five quark system with three kinds of quark-quark hyperfine interaction

S.G. Yuan[1,2,3,a], K.W. Wei[4], J. He[1,5], H.S. Xu[1,2], and B.S. Zou[2,4]

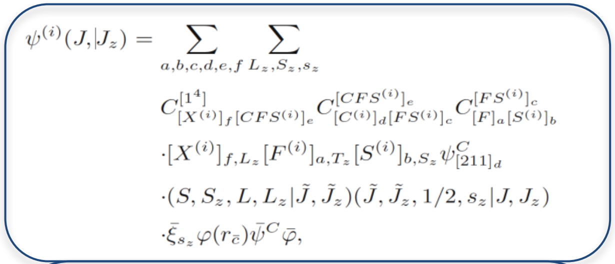
[1] Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
[2] Theoretical Physics Center for Science Facilities, Chinese Academy of Sciences, Beijing 100049, China
[3] Graduate University of Chinese Academy of Sciences, Beijing 100049, China
[4] Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
[5] Research Center for Hadron and CSR Physics, Institute of Modern Physics of CAS and Lanzhou University, Lanzhou 730000, China

Received: 1 March 2012 / Revised: 18 March 2012

Communicated by M. Anselmino

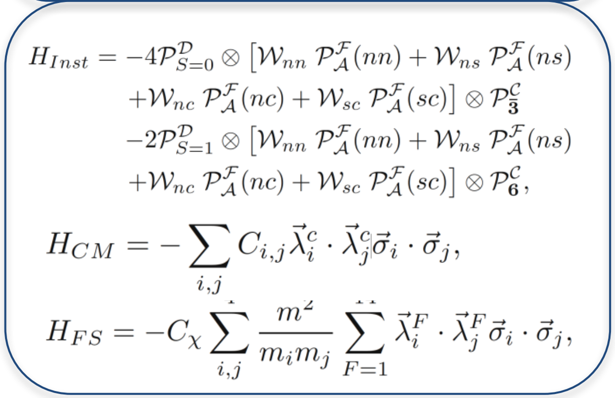
Abstract. The low-lying energy spectra of five quark systems $uudc\bar{c}$ ($I = 1/2, S = 0$) and $udsc\bar{c}$ ($I = 0, S = -1$) are investigated with three kinds of schematic interaction: the chromomagnetic interaction, the flavor-spin–dependent interaction and the instanton-induced interaction. In all the three models, the lowest five-quark state ($uudc\bar{c}$ or $udsc\bar{c}$) has an orbital angular momentum $L = 0$ and the spin-parity $J^P = 1/2^-$; the mass of the lowest $udsc\bar{c}$ state is heavier than the lowest $uudc\bar{c}$ state.

Wave function



$$\psi^{(i)}(J,|J_z) = \sum_{a,b,c,d,e,f} \sum_{L_z,S_z,s_z} C^{[1^4]}_{[X^{(i)}]_f[CFS^{(i)}]_e} C^{[CFS^{(i)}]_e}_{[C^{(i)}]_d[FS^{(i)}]_c} C^{[FS^{(i)}]_c}_{[F]_a[S^{(i)}]_b}$$
$$\cdot[X^{(i)}]_{f,L_z}[F^{(i)}]_{a,T_z}[S^{(i)}]_{b,S_z}\psi^C_{[211]_d}$$
$$\cdot(S,S_z,L,L_z|\tilde{J},\tilde{J}_z)(\tilde{J},\tilde{J}_z,1/2,s_z|J,J_z)$$
$$\cdot\bar{\xi}_{s_z}\varphi(r_{\bar{c}})\bar{\psi}^C\bar{\varphi},$$

Hamiltonian



$$H_{Inst} = -4\mathcal{P}^{\mathcal{D}}_{S=0} \otimes \left[\mathcal{W}_{nn}\,\mathcal{P}^{\mathcal{F}}_{\mathcal{A}}(nn) + \mathcal{W}_{ns}\,\mathcal{P}^{\mathcal{F}}_{\mathcal{A}}(ns)\right.$$
$$\left.+\mathcal{W}_{nc}\,\mathcal{P}^{\mathcal{F}}_{\mathcal{A}}(nc) + \mathcal{W}_{sc}\,\mathcal{P}^{\mathcal{F}}_{\mathcal{A}}(sc)\right] \otimes \mathcal{P}^{\mathcal{C}}_{\bar{\mathbf{3}}}$$
$$-2\mathcal{P}^{\mathcal{D}}_{S=1} \otimes \left[\mathcal{W}_{nn}\,\mathcal{P}^{\mathcal{F}}_{\mathcal{A}}(nn) + \mathcal{W}_{ns}\,\mathcal{P}^{\mathcal{F}}_{\mathcal{A}}(ns)\right.$$
$$\left.+\mathcal{W}_{nc}\,\mathcal{P}^{\mathcal{F}}_{\mathcal{A}}(nc) + \mathcal{W}_{sc}\,\mathcal{P}^{\mathcal{F}}_{\mathcal{A}}(sc)\right] \otimes \mathcal{P}^{\mathcal{C}}_{\mathbf{6}},$$

$$H_{CM} = -\sum_{i,j} C_{i,j}\vec{\lambda}^c_i \cdot \vec{\lambda}^c_j\vec{\sigma}_i \cdot \vec{\sigma}_j,$$

$$H_{FS} = -C_\chi \sum_{i,j} \frac{m^2}{m_i m_j} \sum_{F=1} \vec{\lambda}^F_i \cdot \vec{\lambda}^F_j \vec{\sigma}_i \cdot \vec{\sigma}_j,$$

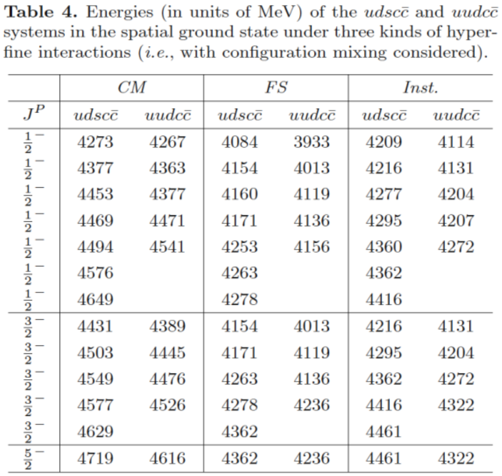


Table 4. Energies (in units of MeV) of the $udsc\bar{c}$ and $uudc\bar{c}$ systems in the spatial ground state under three kinds of hyperfine interactions (*i.e.*, with configuration mixing considered).

	CM		*FS*		*Inst.*	
J^P	$udsc\bar{c}$	$uudc\bar{c}$	$udsc\bar{c}$	$uudc\bar{c}$	$udsc\bar{c}$	$uudc\bar{c}$
$\frac{1}{2}^-$	4273	4267	4084	3933	4209	4114
$\frac{1}{2}^-$	4377	4363	4154	4013	4216	4131
$\frac{1}{2}^-$	4453	4377	4160	4119	4277	4204
$\frac{1}{2}^-$	4469	4471	4171	4136	4295	4207
$\frac{1}{2}^-$	4494	4541	4253	4156	4360	4272
$\frac{1}{2}^-$	4576		4263		4362	
$\frac{1}{2}^-$	4649		4278		4416	
$\frac{3}{2}^-$	4431	4389	4154	4013	4216	4131
$\frac{3}{2}^-$	4503	4445	4171	4119	4295	4204
$\frac{3}{2}^-$	4549	4476	4263	4136	4362	4272
$\frac{3}{2}^-$	4577	4526	4278	4236	4416	4322
$\frac{3}{2}^-$	4629		4362		4461	
$\frac{5}{2}^-$	4719	4616	4362	4236	4461	4322

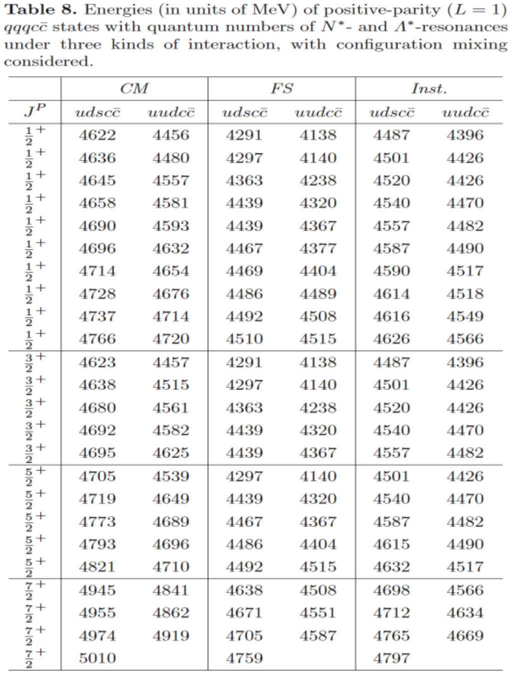
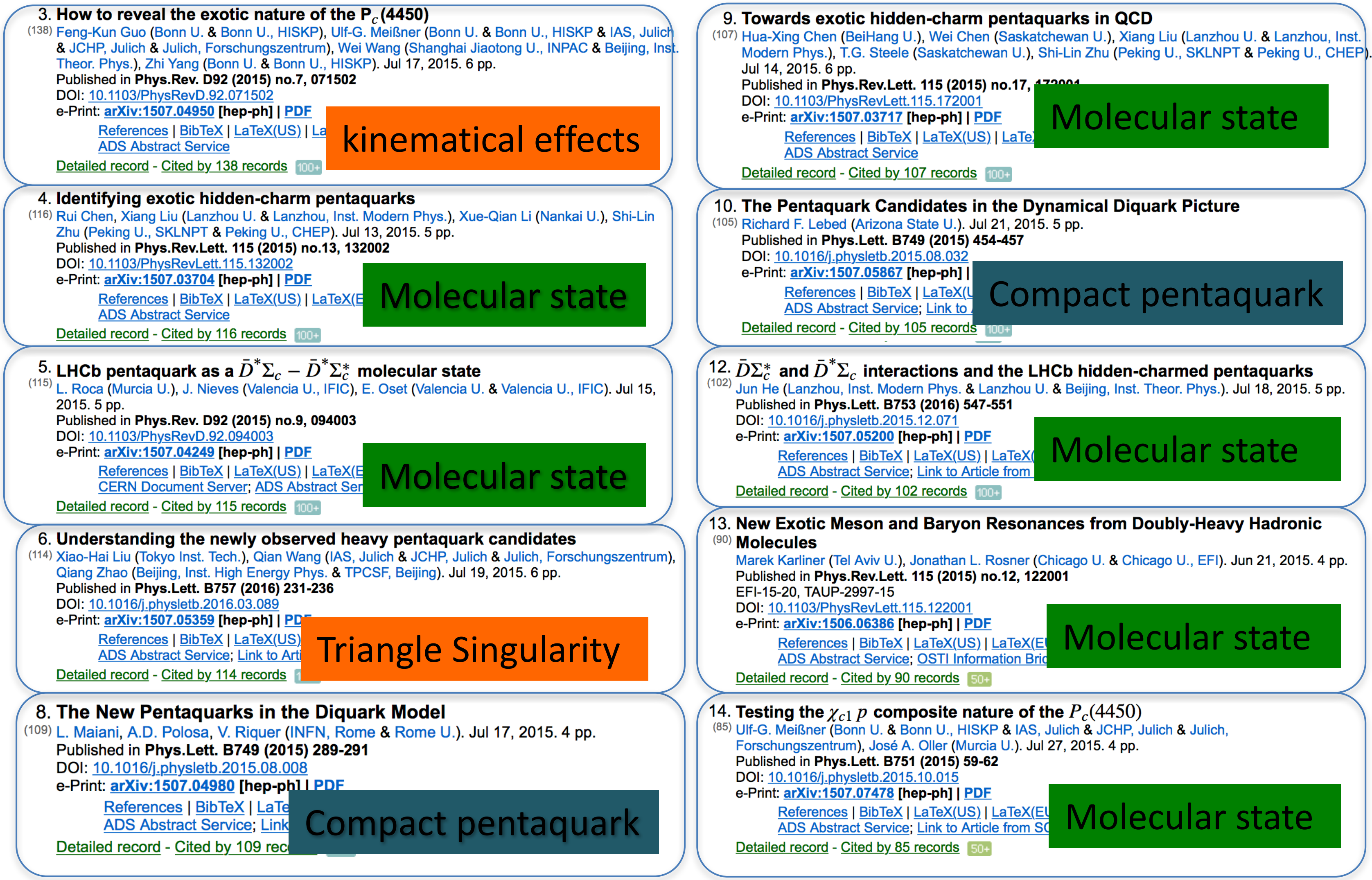


Table 8. Energies (in units of MeV) of positive-parity ($L = 1$) $qqqc\bar{c}$ states with quantum numbers of N^*- and Λ^*-resonances under three kinds of interaction, with configuration mixing considered.

	CM		*FS*		*Inst.*	
J^P	$udsc\bar{c}$	$uudc\bar{c}$	$udsc\bar{c}$	$uudc\bar{c}$	$udsc\bar{c}$	$uudc\bar{c}$
$\frac{1}{2}^+$	4622	4456	4291	4138	4487	4396
$\frac{1}{2}^+$	4636	4480	4297	4140	4501	4426
$\frac{1}{2}^+$	4645	4557	4363	4238	4520	4426
$\frac{1}{2}^+$	4658	4581	4439	4320	4540	4470
$\frac{1}{2}^+$	4690	4593	4439	4367	4557	4482
$\frac{1}{2}^+$	4696	4632	4467	4377	4587	4490
$\frac{1}{2}^+$	4714	4654	4469	4404	4590	4517
$\frac{1}{2}^+$	4728	4676	4486	4489	4614	4518
$\frac{1}{2}^+$	4737	4714	4492	4508	4616	4549
$\frac{1}{2}^+$	4766	4720	4510	4515	4626	4566
$\frac{3}{2}^+$	4623	4457	4291	4138	4487	4396
$\frac{3}{2}^+$	4638	4515	4297	4140	4501	4426
$\frac{3}{2}^+$	4680	4561	4363	4238	4520	4426
$\frac{3}{2}^+$	4692	4582	4439	4320	4540	4470
$\frac{3}{2}^+$	4695	4625	4439	4367	4557	4482
$\frac{5}{2}^+$	4705	4539	4297	4140	4501	4426
$\frac{5}{2}^+$	4719	4649	4439	4320	4540	4470
$\frac{5}{2}^+$	4773	4689	4467	4367	4587	4482
$\frac{5}{2}^+$	4793	4696	4486	4404	4615	4490
$\frac{5}{2}^+$	4821	4710	4492	4515	4632	4517
$\frac{7}{2}^+$	4945	4841	4638	4508	4698	4566
$\frac{7}{2}^+$	4955	4862	4671	4551	4712	4634
$\frac{7}{2}^+$	4974	4919	4705	4587	4765	4669
$\frac{7}{2}^+$	5010		4759		4797	

Theoretical interpretation of the LHCb pentaquark



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kinematical effects

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Molecular state

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Molecular state

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(114) Xiao-Hai Liu (Tokyo Inst. Tech.), Qian Wang (IAS, Julich & JCHP, Julich & Julich, Forschungszentrum), Qiang Zhao (Beijing, Inst. High Energy Phys. & TPCSF, Beijing). Jul 19, 2015. 6 pp.
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Triangle Singularity

8. **The New Pentaquarks in the Diquark Model**
(109) L. Maiani, A.D. Polosa, V. Riquer (INFN, Rome & Rome U.). Jul 17, 2015. 4 pp.
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Compact pentaquark

9. **Towards exotic hidden-charm pentaquarks in QCD**
(107) Hua-Xing Chen (BeiHang U.), Wei Chen (Saskatchewan U.), Xiang Liu (Lanzhou U. & Lanzhou, Inst. Modern Phys.), T.G. Steele (Saskatchewan U.), Shi-Lin Zhu (Peking U., SKLNPT & Peking U., CHEP). Jul 14, 2015. 6 pp.
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Molecular state

10. **The Pentaquark Candidates in the Dynamical Diquark Picture**
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Compact pentaquark

12. **$\bar{D}\Sigma_c^*$ and $\bar{D}^*\Sigma_c$ interactions and the LHCb hidden-charmed pentaquarks**
(102) Jun He (Lanzhou, Inst. Modern Phys. & Lanzhou U. & Beijing, Inst. Theor. Phys.). Jul 18, 2015. 5 pp.
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DOI: 10.1016/j.physletb.2015.12.071
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Molecular state

13. **New Exotic Meson and Baryon Resonances from Doubly-Heavy Hadronic Molecules**
(90) Marek Karliner (Tel Aviv U.), Jonathan L. Rosner (Chicago U. & Chicago U., EFI). Jun 21, 2015. 4 pp.
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EFI-15-20, TAUP-2997-15
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Molecular state

14. **Testing the $\chi_{c1}\, p$ composite nature of the $P_c(4450)$**
(85) Ulf-G. Meißner (Bonn U. & Bonn U., HISKP & IAS, Julich & JCHP, Julich & Julich, Forschungszentrum), José A. Oller (Murcia U.). Jul 27, 2015. 4 pp.
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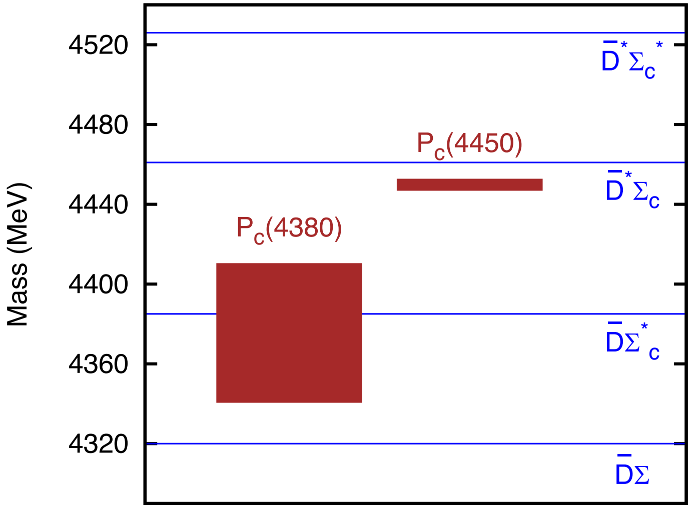
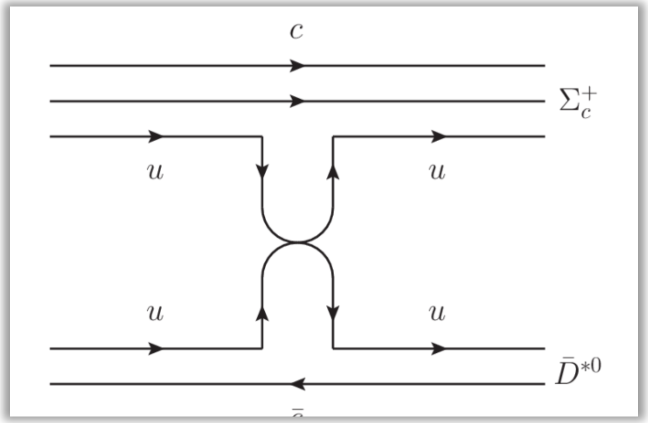
Molecular state

Pc（4380）and Pc（4450）

as hadronic molecules

LHCb pentaquarks as molecular states





$$\mathcal{L}_{\mathcal{B}_6\mathcal{B}_6\mathbb{P}} = -\frac{g_1}{4f_\pi}\,\epsilon^{\alpha\beta\lambda\kappa}\langle\bar{\mathcal{B}}_6\,\overleftrightarrow{\partial}^{\kappa}\gamma_\alpha\gamma_\lambda\partial_\beta\mathbb{P}\,\mathcal{B}_6\rangle,$$

$$\mathcal{L}_{\mathcal{B}_6\mathcal{B}_6\mathbb{V}} = -i\frac{\beta_S g_V}{2\sqrt{2}}\,\langle\bar{\mathcal{B}}_6\,\overleftrightarrow{\partial}\cdot\mathbb{V}\,\mathcal{B}_6\rangle$$
$$-\frac{i m_{\mathcal{B}_6}\lambda_S g_V}{3\sqrt{2}}\,\langle\bar{\mathcal{B}}_6\gamma_\mu\gamma_\nu(\partial^\mu\mathbb{V}^\nu-\partial^\nu\mathbb{V}^\mu)\mathcal{B}_6\rangle,$$

$$\mathcal{L}_{\mathcal{B}_6\mathcal{B}_6\sigma} = -\ell_S m_{\mathcal{B}_6}\langle\bar{\mathcal{B}}_6\,\sigma\,\mathcal{B}_6\rangle,$$

$$\mathcal{L}_{\tilde{\mathcal{P}}\tilde{\mathcal{P}}\mathbb{V}} = \frac{\beta g_V}{\sqrt{2}}\tilde{\mathcal{P}}_a^\dagger\overleftrightarrow{\partial}_\mu\tilde{\mathcal{P}}_b\mathbb{V}_{ab}^\mu,$$

$$\mathcal{L}_{\tilde{\mathcal{P}}\tilde{\mathcal{P}}\sigma} = -2g_s m_{\mathcal{P}}\tilde{\mathcal{P}}_b\tilde{\mathcal{P}}_b^\dagger\sigma,$$

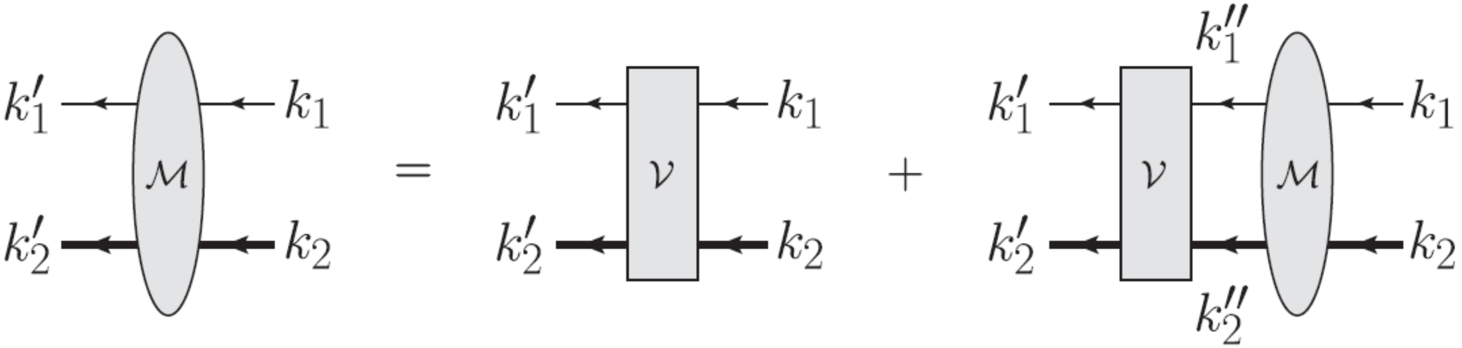
$$\mathcal{L}_{\tilde{\mathcal{P}}^*\tilde{\mathcal{P}}^*\mathbb{P}} = -\frac{g}{f_\pi}\varepsilon_{\alpha\beta\lambda\kappa}\tilde{\mathcal{P}}_a^{*\beta\dagger}\overleftrightarrow{\partial}^\alpha\tilde{\mathcal{P}}_b^{*\kappa}\partial^\lambda\mathbb{P}_{ab},$$

$$\mathcal{L}_{\tilde{\mathcal{P}}^*\tilde{\mathcal{P}}^*\mathbb{V}} = -i\frac{\beta g_V}{\sqrt{2}}\tilde{\mathcal{P}}_a^{*\dagger\mu}\overleftrightarrow{\partial}^\nu\tilde{\mathcal{P}}_{b\mu}^*\mathbb{V}_{ab\nu}$$
$$-\,i2\sqrt{2}m_{\mathcal{P}^*}\lambda g_V\tilde{\mathcal{P}}_a^{*\mu\dagger}\tilde{\mathcal{P}}_b^{*\nu}(\partial_\mu\mathbb{V}_\nu-\partial_\nu\mathbb{V}_\mu)_{ab},$$

$$\mathcal{L}_{\tilde{\mathcal{P}}^*\tilde{\mathcal{P}}^*\sigma} = 2g_s m_{\mathcal{P}^*}\tilde{\mathcal{P}}_b^*\cdot\tilde{\mathcal{P}}_b^{*\dagger}\sigma$$

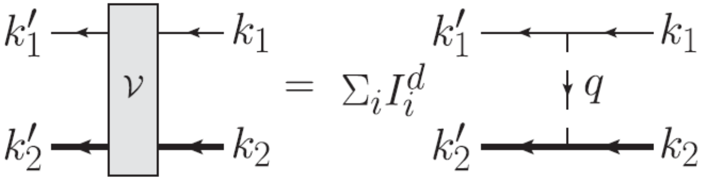
JH, Phys.Lett. B753 (2016) 547

Quasipotential Bethe-Salpeter equation



$$i\mathcal{M}^{J^P}_{\lambda'\lambda}(\mathrm{p}',\mathrm{p}) = i\mathcal{V}^{J^P}_{\lambda',\lambda}(\mathrm{p}',\mathrm{p}) + \sum_{\lambda''\geq 0}\int\frac{\mathrm{p}''^2 d\mathrm{p}''}{(2\pi)^3} \cdot i\mathcal{V}^{J^P}_{\lambda'\lambda''}(\mathrm{p}',\mathrm{p}'')G_0(\mathrm{p}'')i\mathcal{M}^{J^P}_{\lambda''\lambda}(\mathrm{p}'',\mathrm{p}),$$

$$G_0 = 2\pi i\frac{\delta^+(k_1^2-m_1^2)}{k_2^2-m_2^2} = 2\pi i\frac{\delta^+(k_1^0-E_1(\boldsymbol{k}))}{2E_1(\boldsymbol{k})[W-E_1(\boldsymbol{k})^2-E_2^2(\boldsymbol{k})]},$$



$$i\mathcal{V}^{J^P}_{\lambda'\lambda}(\mathrm{p}',\mathrm{p}) = 2\pi\int d\cos\theta\,[d^J_{\lambda\lambda'}(\theta)i\mathcal{V}_{\lambda'\lambda}(\boldsymbol{p}',\boldsymbol{p}) + \eta d^J_{-\lambda\lambda'}(\theta)i\mathcal{V}_{\lambda'-\lambda}(\boldsymbol{p}',\boldsymbol{p})],$$

- Form factors with cutoff $\boldsymbol{\Lambda}$ are introduced at the vertex for the offshell particles.

LHCb五夸克态的分子态解释

我们可以得到以下对应于LHCb五夸克态的束缚态

$$P_c(4380):\quad \bar{D}\Sigma_c^*\ [3/2^-, 0.7-1.4],\quad \bar{D}\Sigma_c^*\ [3/2^+, 2.8-5.0],\quad \bar{D}^*\Sigma_c[3/2^-, 3.0-3.7];$$
$$P_c(4450):\quad \bar{D}^*\Sigma_c[5/2^+, 2.7-2.8],\quad \bar{D}^*\Sigma_c[5/2^-, 2.8-2.9],\quad \bar{D}^*\Sigma_c^*[5/2^+, 2-2.1].$$

与实验值比较

$$P_c(4380):\quad M = 4380 \pm 8 \pm 29\ \text{MeV},\quad J^P = 3/2^-.$$
$$P_c(4450):\quad M = 4449.8 \pm 1.7 \pm 2.5\ \text{MeV},\quad J^P = 5/2^+.$$

LHCb五夸克态可以解释为

$$P_c(4380) : \bar{D}\Sigma_c^*[3/2^-];\quad P_c(4450) : \bar{D}^*\Sigma_c[5/2^+].$$

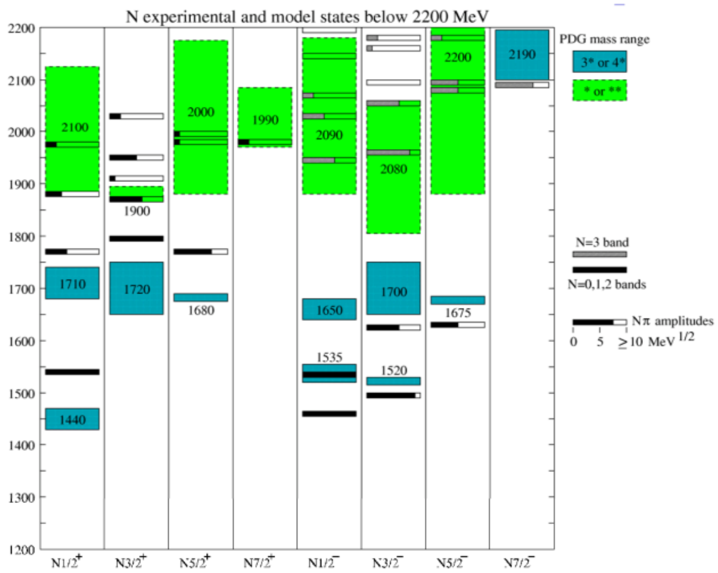
S-wave state

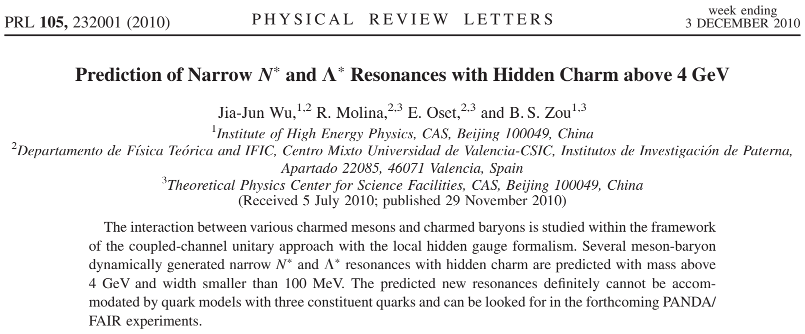
P-wave state

JH, Phys.Lett. B753 (2016) 547

核子共振态超重岛

质量在4 GeV附近的核子共振态(含正反粲夸克）





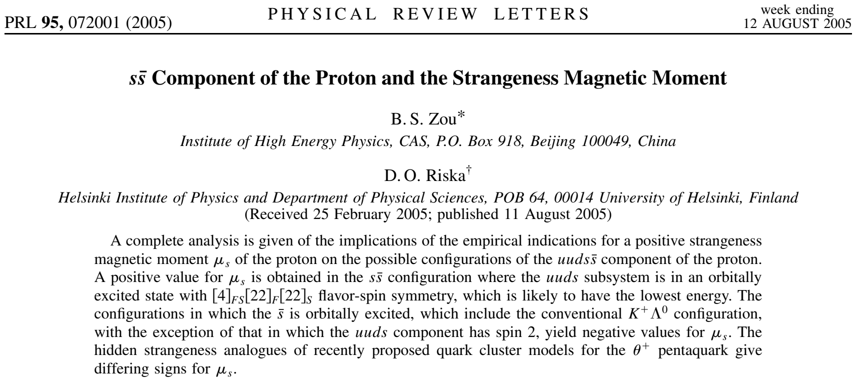
PRL 105, 232001 (2010) PHYSICAL REVIEW LETTERS week ending 3 DECEMBER 2010

Prediction of Narrow N^* and Λ^* Resonances with Hidden Charm above 4 GeV

Jia-Jun Wu,[1,2] R. Molina,[2,3] E. Oset,[2,3] and B. S. Zou[1,3]
[1]*Institute of High Energy Physics, CAS, Beijing 100049, China*
[2]*Departamento de Física Teórica and IFIC, Centro Mixto Universidad de Valencia-CSIC, Institutos de Investigación de Paterna, Apartado 22085, 46071 Valencia, Spain*
[3]*Theoretical Physics Center for Science Facilities, CAS, Beijing 100049, China*
(Received 5 July 2010; published 29 November 2010)

The interaction between various charmed mesons and charmed baryons is studied within the framework of the coupled-channel unitary approach with the local hidden gauge formalism. Several meson-baryon dynamically generated narrow N^* and Λ^* resonances with hidden charm are predicted with mass above 4 GeV and width smaller than 100 MeV. The predicted new resonances definitely cannot be accommodated by quark models with three constituent quarks and can be looked for in the forthcoming PANDA/FAIR experiments.

仅预言了$1/2^-$态



PRL 95, 072001 (2005) PHYSICAL REVIEW LETTERS week ending 12 AUGUST 2005

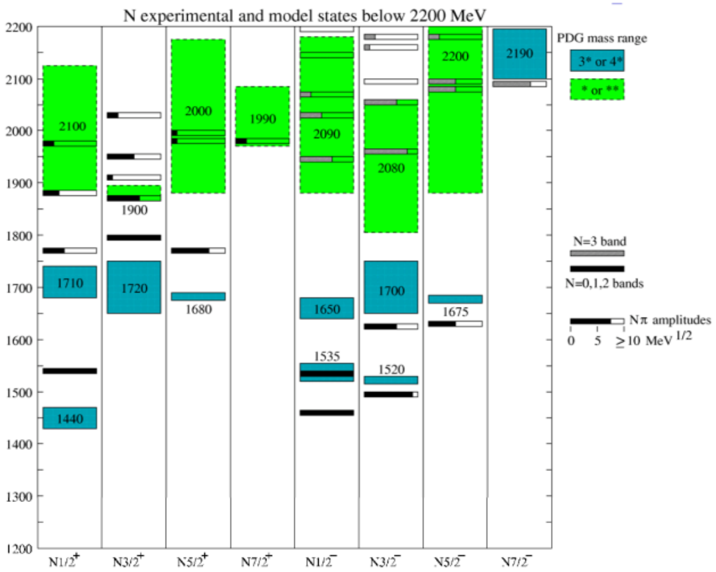
$s\bar{s}$ Component of the Proton and the Strangeness Magnetic Moment

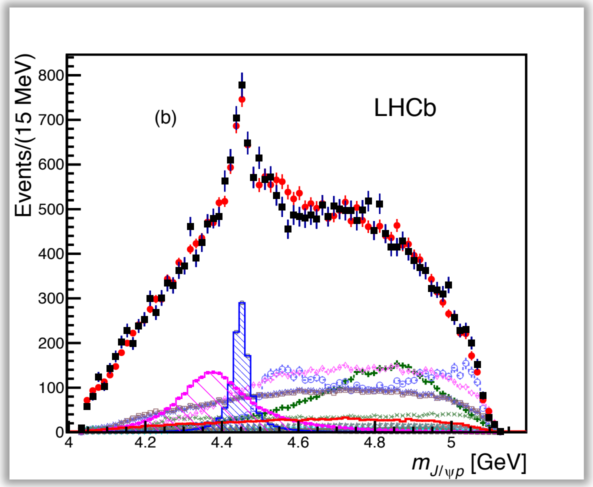
B. S. Zou*
Institute of High Energy Physics, CAS, P.O. Box 918, Beijing 100049, China

D. O. Riska†
Helsinki Institute of Physics and Department of Physical Sciences, POB 64, 00014 University of Helsinki, Finland
(Received 25 February 2005; published 11 August 2005)

A complete analysis is given of the implications of the empirical indications for a positive strangeness magnetic moment μ_s of the proton on the possible configurations of the $uuds\bar{s}$ component of the proton. A positive value for μ_s is obtained in the $s\bar{s}$ configuration where the $uuds$ subsystem is in an orbitally excited state with $[4]_{FS}[22]_F[22]_S$ flavor-spin symmetry, which is likely to have the lowest energy. The configurations in which the $\bar{s}$ is orbitally excited, which include the conventional $K^+\Lambda^0$ configuration, with the exception of that in which the $uuds$ component has spin 2, yield negative values for μ_s. The hidden strangeness analogues of recently proposed quark cluster models for the θ^+ pentaquark give differing signs for μ_s.

Pc(4450) and Pc(4380)





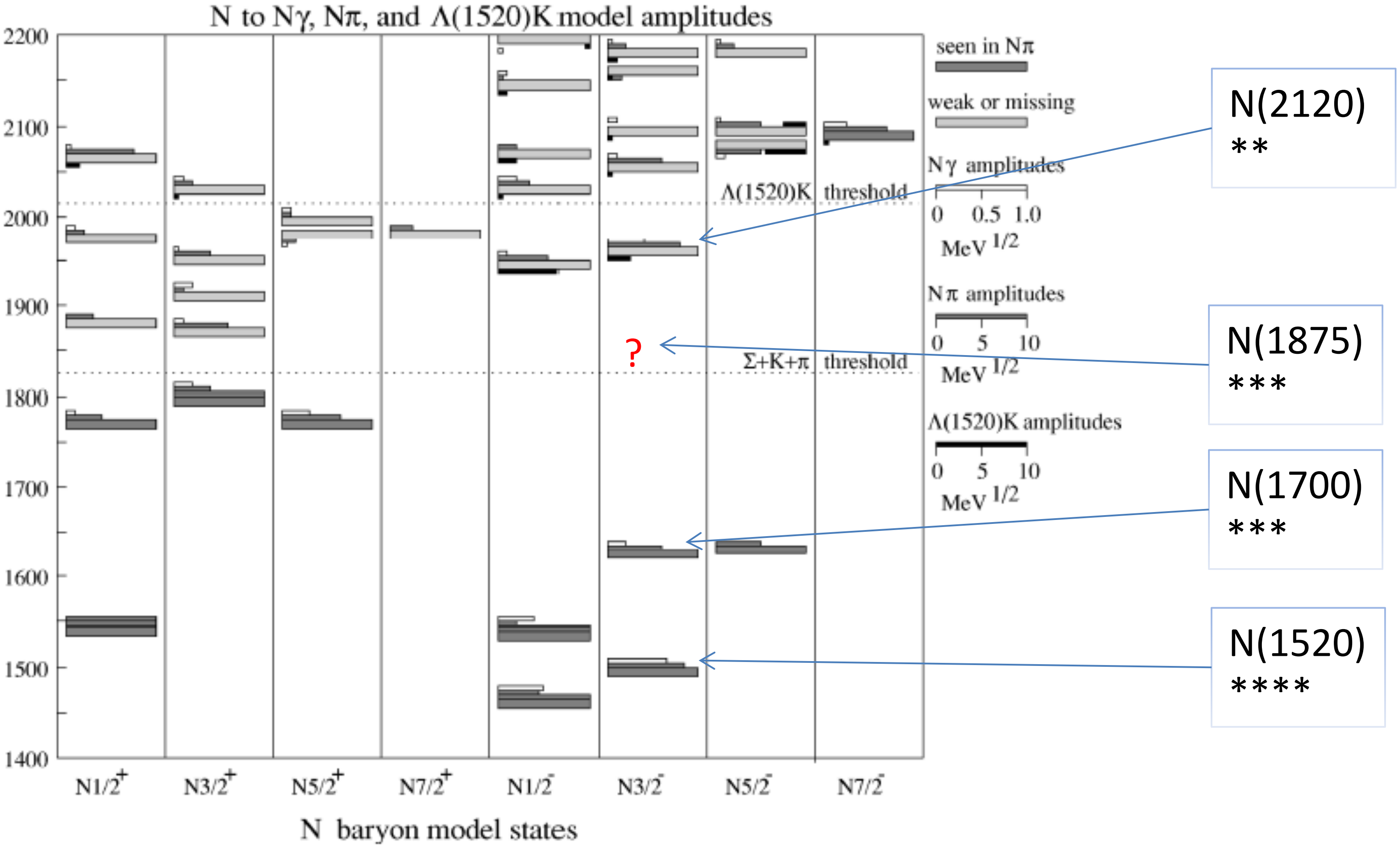
Hidden-Charm pentaquark

Hidden-strange pentaquark?

Nucleon resonances near 2 GeV

$3/2^-$ N*

PDG



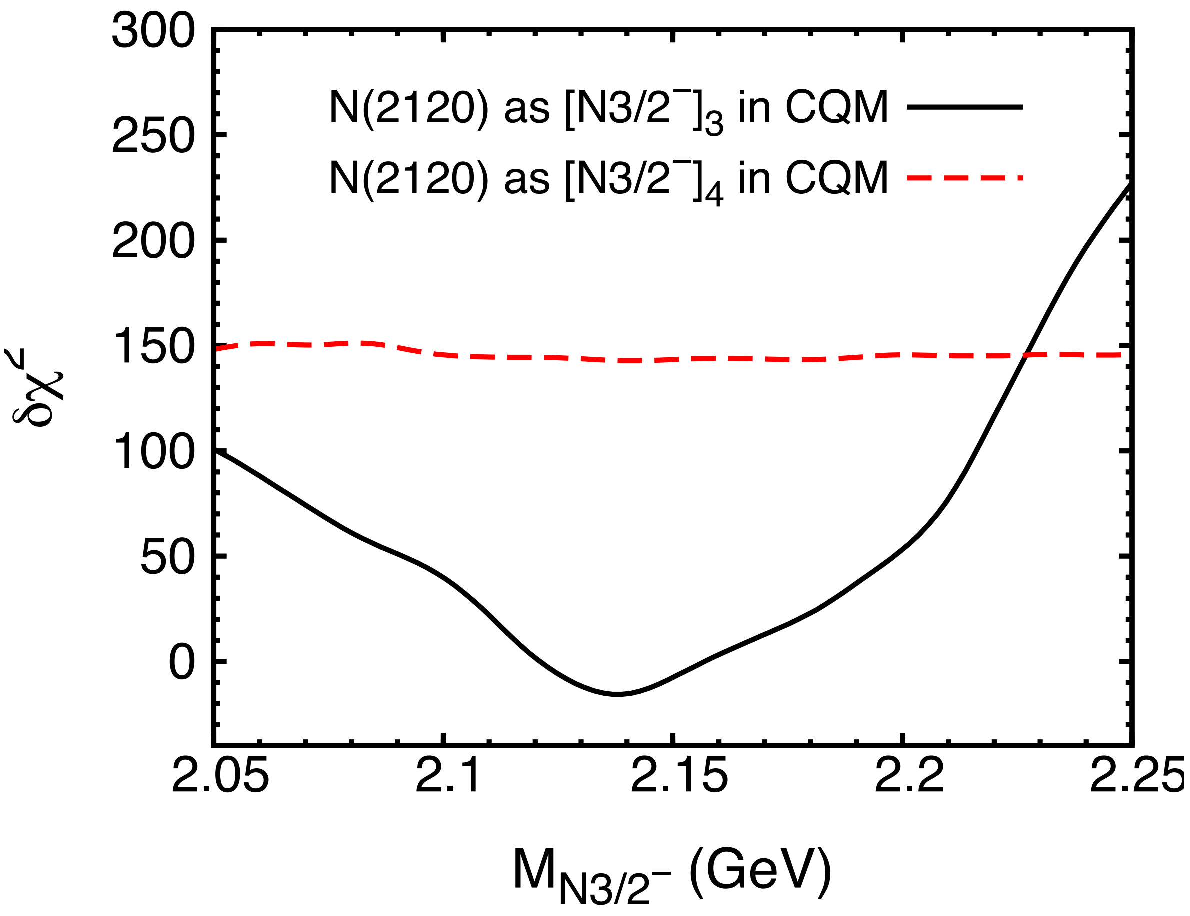
N(2120) **

N(1875) ***

N(1700) ***

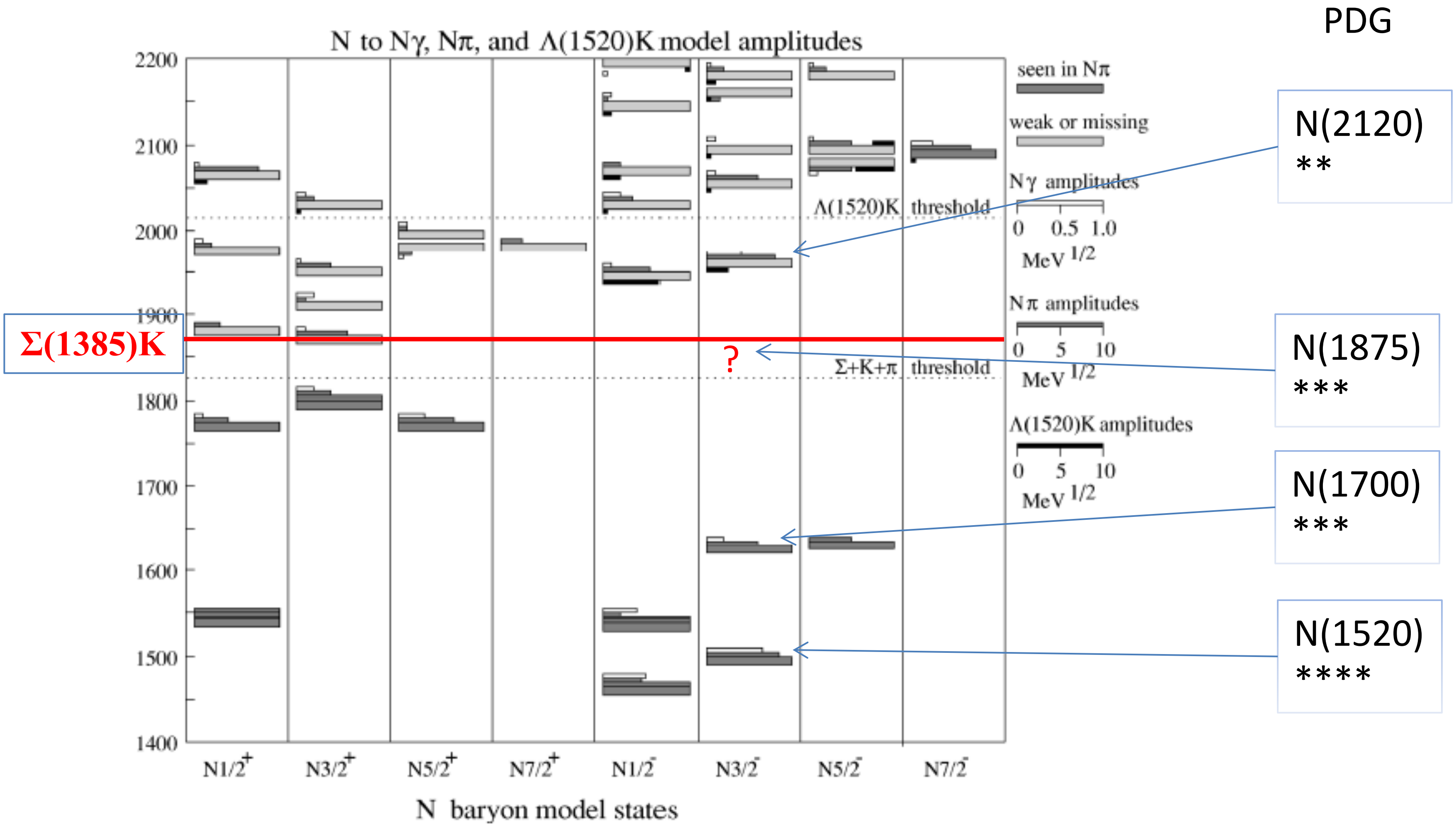
N(1520) ****

拟合Λ(1520)光致产生数据



The N(2120) is essential to reproducing the experimental data with assumption it is the third state with spin parity $3/2^-$.

JH, Chen, Phys.Rev. C86(2012)035204
JH, Nucl.Phys.A927(2014)24-35



PDG

N(2120)
**

N(1875)
***

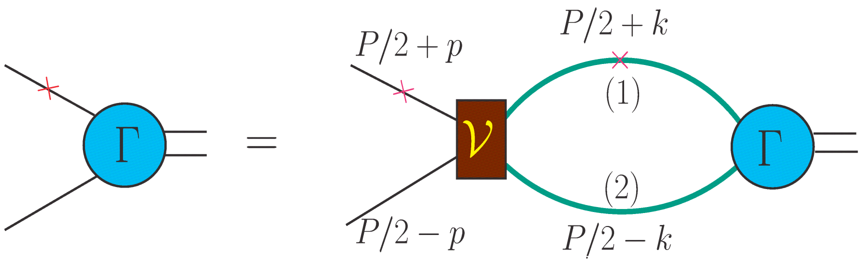
N(1700)
***

N(1520)
****

N(1875) is close to Σ(1835)K threshold

N(1875) as a bound state from Σ(1385)K interaction

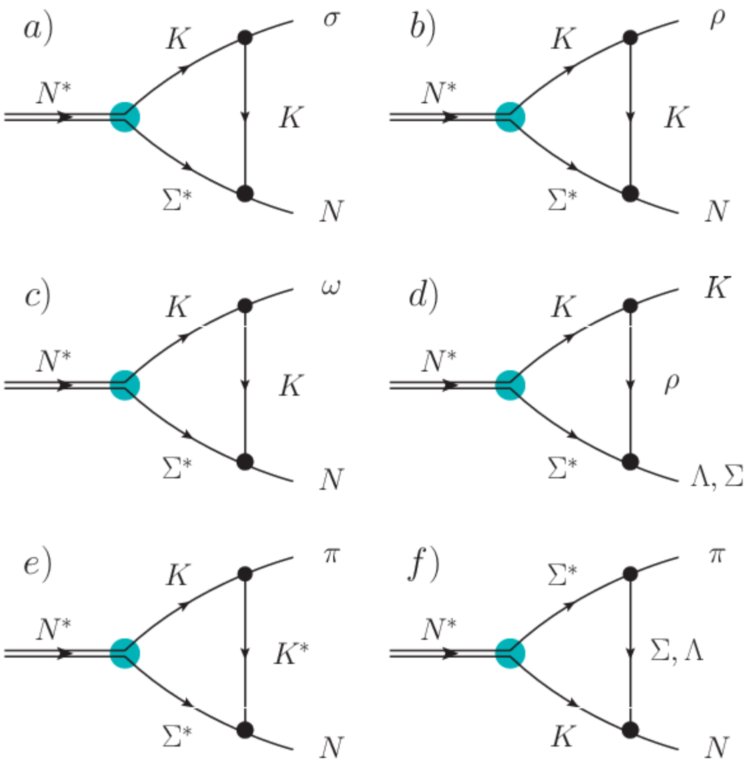
Bethe-Salpeter equation for vertex



$$|\Gamma_\lambda\rangle = \sum_{\lambda'} \mathcal{V}_{\lambda\lambda'}\, G_0\, |\Gamma_{\lambda'}\rangle.$$

$$G_0 = 2\pi i \frac{\delta^+(k_1^2 - m_1^2)}{k_2^2 - m_2^2}$$

Decay through hadronic loop mechanism



$$\mathcal{M} = \sum_{\lambda} A_\lambda G_0 |\Gamma_\lambda\rangle$$

Jun He. Phys.Rev. C91 (2015) 1, 018201

Binding energy and branch ratio

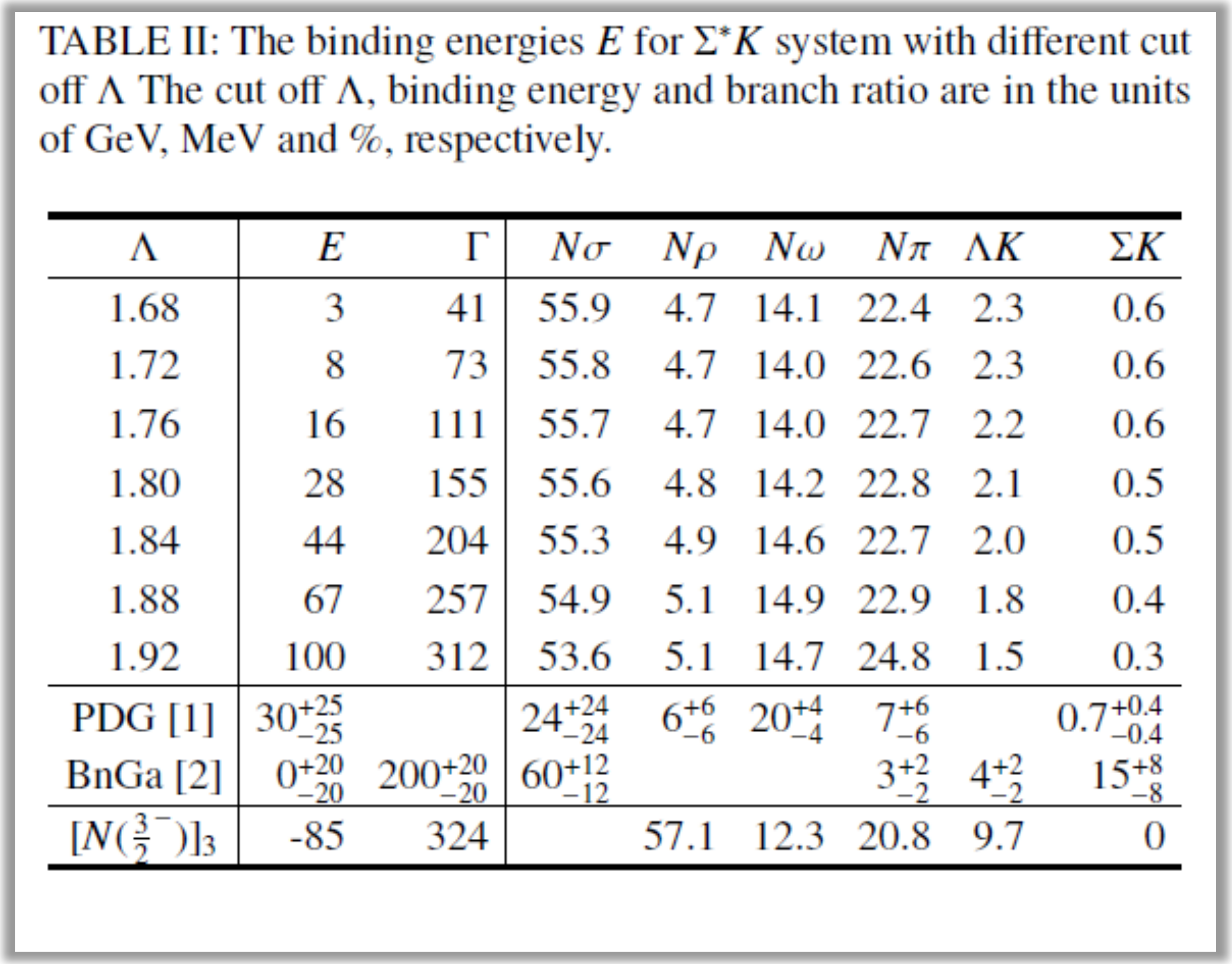


TABLE II: The binding energies E for $\Sigma^* K$ system with different cut off Λ The cut off Λ, binding energy and branch ratio are in the units of GeV, MeV and %, respectively.

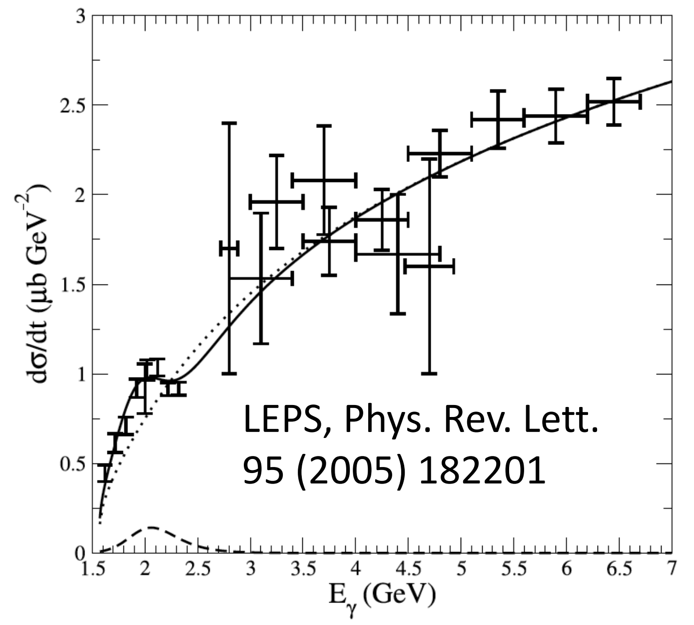
Λ	E	Γ	$N\sigma$	$N\rho$	$N\omega$	$N\pi$	ΛK	ΣK
1.68	3	41	55.9	4.7	14.1	22.4	2.3	0.6
1.72	8	73	55.8	4.7	14.0	22.6	2.3	0.6
1.76	16	111	55.7	4.7	14.0	22.7	2.2	0.6
1.80	28	155	55.6	4.8	14.2	22.8	2.1	0.5
1.84	44	204	55.3	4.9	14.6	22.7	2.0	0.5
1.88	67	257	54.9	5.1	14.9	22.9	1.8	0.4
1.92	100	312	53.6	5.1	14.7	24.8	1.5	0.3
PDG [1]	30^{+25}_{-25}		24^{+24}_{-24}	6^{+6}_{-6}	20^{+4}_{-4}	7^{+6}_{-6}		$0.7^{+0.4}_{-0.4}$
BnGa [2]	0^{+20}_{-20}	200^{+20}_{-20}	60^{+12}_{-12}			3^{+2}_{-2}	4^{+2}_{-2}	15^{+8}_{-8}
$[N(\frac{3}{2}^-)]_3$	-85	324		57.1	12.3	20.8	9.7	0

Branch ratio is not sensitive to the cut off

The results support molecular state assumption

Jun He. Phys.Rev. C91 (2015) 1, 018201

N(2100) in ϕ photoproduction



LEPS, Phys. Rev. Lett. 95 (2005) 182201

Fig. 2. Differential cross section of $\gamma p \to \phi p$ at forward direction as a function of photon energy E_γ. The dotted, dashed, and solid lines denote contributions from nonresonant, resonance with $J^P = 3/2^-$, and their sum, respectively. Data are from Refs. [10,17].

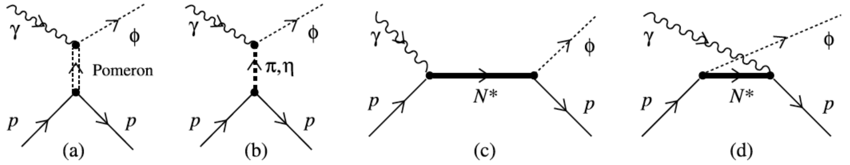


Fig. 1. (a) Pomeron-exchange, (b) (π, η)-exchange, and (c,d) s- and u-channel N^*-exchange diagrams for $\gamma p \to \phi p$ reaction.

Kiswandhi, Xie, Yang, Phys. Lett. B 691 (2010) 214
Kiswandhi, Yang, Phys. Rev. C 86(2012) 015203
Kiswandhi, Yang, Dong, Phys. Rev. C94(2016) 015202

A nucleon resonance with a mass about 2.10 GeV in ϕp channel with 3/2-

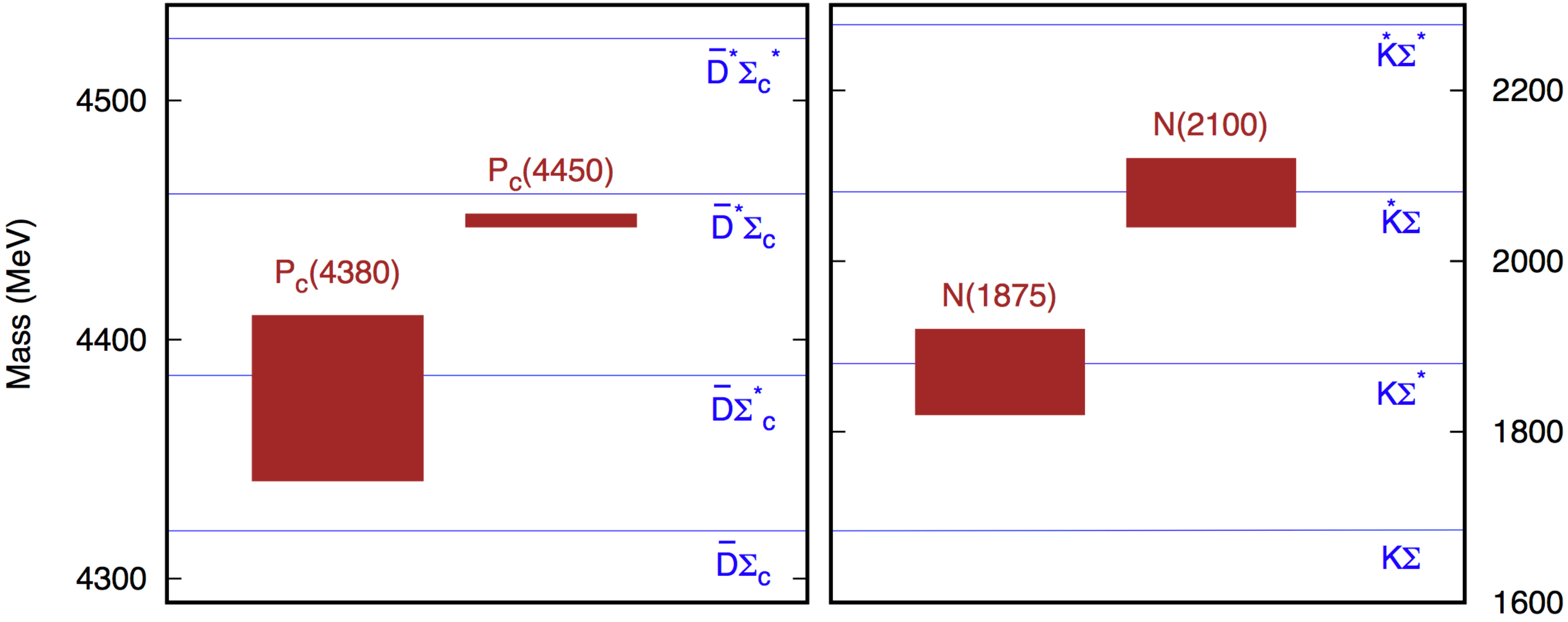
---

OZI rule ➠ N* decay to ϕp should be suppressed in three quark picture

If we recall that the Pc(4450) was observed in J/ψp channel,
N(2100) may be its partner in the strange sector observed ϕp channel.

Hidden-strange partners of LHCb pentaquarks

Threshold and mass



Pc(4380) is close to Σ_c^*D threshold
Pc(4450) is close to $\Sigma_c D^*$ threshold

↔

N(1875) is close to Σ^*K threshold
N(2100) is close to ΣK^* threshold

Lagrangians for Σ*K and Σ K* interactions

$$\begin{aligned}
\mathcal{L}_{\Sigma^*\Sigma^*\rho} &= -g_{\Sigma^*\Sigma^*\rho}\,\bar{\Sigma}^{*\mu}[\gamma^\nu - \frac{\kappa_{\Sigma^*\Sigma^*\rho}}{2m_{\Sigma^*}}\sigma^{\nu\rho}\partial_\rho]\boldsymbol{\rho}_\nu \cdot \boldsymbol{T}\Sigma^*_\mu,\\
\mathcal{L}_{\Sigma^*\Sigma^*\omega} &= -g_{\Sigma^*\Sigma^*\omega}\,\bar{\Sigma}^{*\mu}[\gamma^\nu - \frac{\kappa_{\Sigma^*\Sigma^*\omega}}{2m_{\Sigma^*}}\sigma^{\nu\rho}\partial_\rho]\omega_\nu\Sigma^*_\mu,\\
\mathcal{L}_{\Sigma^*\Sigma^*\phi} &= -g_{\Sigma^*\Sigma^*\phi}\,\bar{\Sigma}^{*\mu}[\gamma^\nu - \frac{\kappa_{\Sigma^*\Sigma^*\phi}}{2m_{\Sigma^*}}\sigma^{\nu\rho}\partial_\rho]\phi_\nu\Sigma^*_\mu,
\end{aligned}$$

$$\begin{aligned}
\mathcal{L}_{\Sigma\Sigma\pi} &= -\frac{f_{\Sigma\Sigma\pi}}{m_\pi}\bar{\Sigma}\gamma^5\gamma^\mu\partial_\mu\boldsymbol{\pi}\cdot\boldsymbol{T}\Sigma,\\
\mathcal{L}_{\Sigma\Sigma\eta} &= -\frac{f_{\Sigma\Sigma\eta}}{m_\pi}\bar{\Sigma}\gamma^5\gamma_\mu\partial_\mu\eta\Sigma,
\end{aligned}$$

$$\begin{aligned}
\mathcal{L}_{\Sigma\Sigma\rho} &= -g_{\Sigma\Sigma\rho}\bar{\Sigma}[\gamma^\nu - \frac{\kappa_{\Sigma\Sigma\rho}}{2m_\Sigma}\sigma^{\nu\rho}\partial_\rho]\boldsymbol{\rho}_\nu\cdot\boldsymbol{T}\Sigma,\\
\mathcal{L}_{\Sigma\Sigma\omega} &= -g_{\Sigma\Sigma\omega}\bar{\Sigma}[\gamma^\nu - \frac{\kappa_{\Sigma\Sigma\omega}}{2m_\Sigma}\sigma^{\nu\rho}\partial_\rho]\omega_\nu\Sigma,\\
\mathcal{L}_{\Sigma\Sigma\phi} &= -g_{\Sigma\Sigma\phi}\bar{\Sigma}[\gamma^\nu - \frac{\kappa_{\Sigma\Sigma\phi}}{2m_\Sigma}\sigma^{\nu\rho}\partial_\rho]\phi_\nu\Sigma,
\end{aligned}$$

$$\begin{aligned}
\mathcal{L}_{\Sigma^*\Sigma\pi} &= \frac{f_{\Sigma^*\Sigma\pi}}{m_\pi}\bar{\Sigma}^\mu\partial_\mu\boldsymbol{\pi}\cdot\boldsymbol{T}\Sigma,\\
\mathcal{L}_{\Sigma^*\Sigma\eta} &= \frac{f_{\Sigma^*\Sigma\eta}}{m_\pi}\bar{\Sigma}^\mu\partial_\mu\eta\Sigma,
\end{aligned}$$

$$\begin{aligned}
\mathcal{L}_{\Sigma^*\Sigma\rho} &= -i\frac{f_{\Sigma^*\Sigma\rho}}{m_\rho}\bar{\Sigma}^{*\mu}\gamma^5\gamma^\nu[\partial_\mu\boldsymbol{\rho}_\nu - \partial_\nu\boldsymbol{\rho}_\mu]\cdot\boldsymbol{T}\Sigma,\\
\mathcal{L}_{\Sigma^*\Sigma\omega} &= -i\frac{f_{\Sigma^*\Sigma\omega}}{m_\rho}\bar{\Sigma}^{*\mu}\gamma^5\gamma^\nu[\partial_\mu\omega_\nu - \partial_\nu\omega_\mu]\Sigma,\\
\mathcal{L}_{\Sigma^*\Sigma\phi} &= -i\frac{f_{\Sigma^*\Sigma\phi}}{m_\rho}\bar{\Sigma}^{*\mu}\gamma^5\gamma^\nu[\partial_\mu\phi_\nu - \partial_\nu\phi_\mu]\Sigma,
\end{aligned}$$

$$\begin{aligned}
\mathcal{L}_{KK\rho} &= -ig_{KK\rho}\,K\boldsymbol{\rho}^\mu\cdot\boldsymbol{\tau}\partial_\mu K,\\
\mathcal{L}_{KK\omega} &= -ig_{KK\omega}\,K\omega^\mu\partial_\mu K,\\
\mathcal{L}_{KK\phi} &= -ig_{KK\phi}\,K\phi^\mu\partial_\mu K,
\end{aligned}$$

$$\begin{aligned}
\mathcal{L}_{K^*K^*\pi} &= g_{K^*K^*\pi}\,\epsilon^{\mu\nu\alpha\beta}\partial_\mu K^*_\nu\partial_\alpha\boldsymbol{\pi}\cdot\boldsymbol{\tau}K^*_\beta,\\
\mathcal{L}_{K^*K^*\eta} &= g_{K^*K^*\eta}\,\epsilon^{\mu\nu\sigma\tau}\partial_\mu K^*_\nu\partial_\alpha\eta K^*_\beta,
\end{aligned}$$

$$\begin{aligned}
\mathcal{L}_{K^*K^*\rho} &= i\frac{g_{K^*K^*\rho}}{2}(K^{*\mu}\boldsymbol{\rho}_{\mu\nu}K^{*\nu} + K^{*\mu\nu}\boldsymbol{\rho}_\mu K^{*\nu} + K^{*\mu}\boldsymbol{\rho}_\nu K^{*\nu\mu})\cdot\boldsymbol{\tau},\\
\mathcal{L}_{K^*K^*\omega} &= i\frac{g_{K^*K^*\omega}}{2}(K^{*\mu}\omega_{\mu\nu}K^{*\nu} + K^{*\mu\nu}\omega_\mu K^{*\nu} + K^{*\mu}\omega_\nu K^{*\nu\mu}),\\
\mathcal{L}_{K^*K^*\phi} &= i\frac{g_{K^*K^*\phi}}{2}(K^{*\mu}\phi_{\mu\nu}K^{*\nu} + K^{*\mu\nu}\phi_\mu K^{*\nu} + K^{*\mu}\phi_\nu K^{*\nu\mu}),
\end{aligned}$$

$$\begin{aligned}
\mathcal{L}_{K^*K\pi} &= -ig_{K^*K\pi}K^{*\mu}(\boldsymbol{\pi}\partial_\mu - \partial_\mu\boldsymbol{\pi})\cdot\boldsymbol{\tau}K,\\
\mathcal{L}_{K^*K\eta} &= -ig_{K^*K\pi}K^{*\mu}(\eta\partial_\mu - \partial_\mu\eta)K,
\end{aligned}$$

$$\begin{aligned}
\mathcal{L}_{K^*K\rho} &= g_{K^*K\rho}\epsilon^{\mu\nu\sigma\tau}\partial_\mu K^*_\nu\boldsymbol{\rho}\cdot\boldsymbol{\tau}\partial_\sigma K,\\
\mathcal{L}_{K^*K\omega} &= g_{K^*K\omega}\epsilon^{\mu\nu\sigma\tau}\partial_\mu K^*_\nu\omega\partial_\sigma K,\\
\mathcal{L}_{K^*K\phi} &= g_{K^*K\phi}\epsilon^{\mu\nu\sigma\tau}\partial_\mu K^*_\nu\phi\partial_\sigma K,
\end{aligned}$$

The coupling constants are obtained with SU(3) symmetry.

The bound states from the Σ^*K interaction

with vector meson (ρ, ω, ϕ) exchanges

$$i\mathcal{V}_{\mathbb{V}} = f_I \frac{g_{KK\mathbb{V}}\, g_{\Sigma^*\Sigma^*\mathbb{V}}}{q^2 - m_{\mathbb{V}}^2}\, \bar{u}^\mu \left\{ -\not{k}_1 + \frac{q\cdot k_1 \not{q}}{m_{\mathbb{V}}^2} - \frac{\kappa_{\Sigma^*\Sigma^*\mathbb{V}}}{4m_{\Sigma^*}} [\not{k}_1, \not{q}] \right\} u_\mu$$

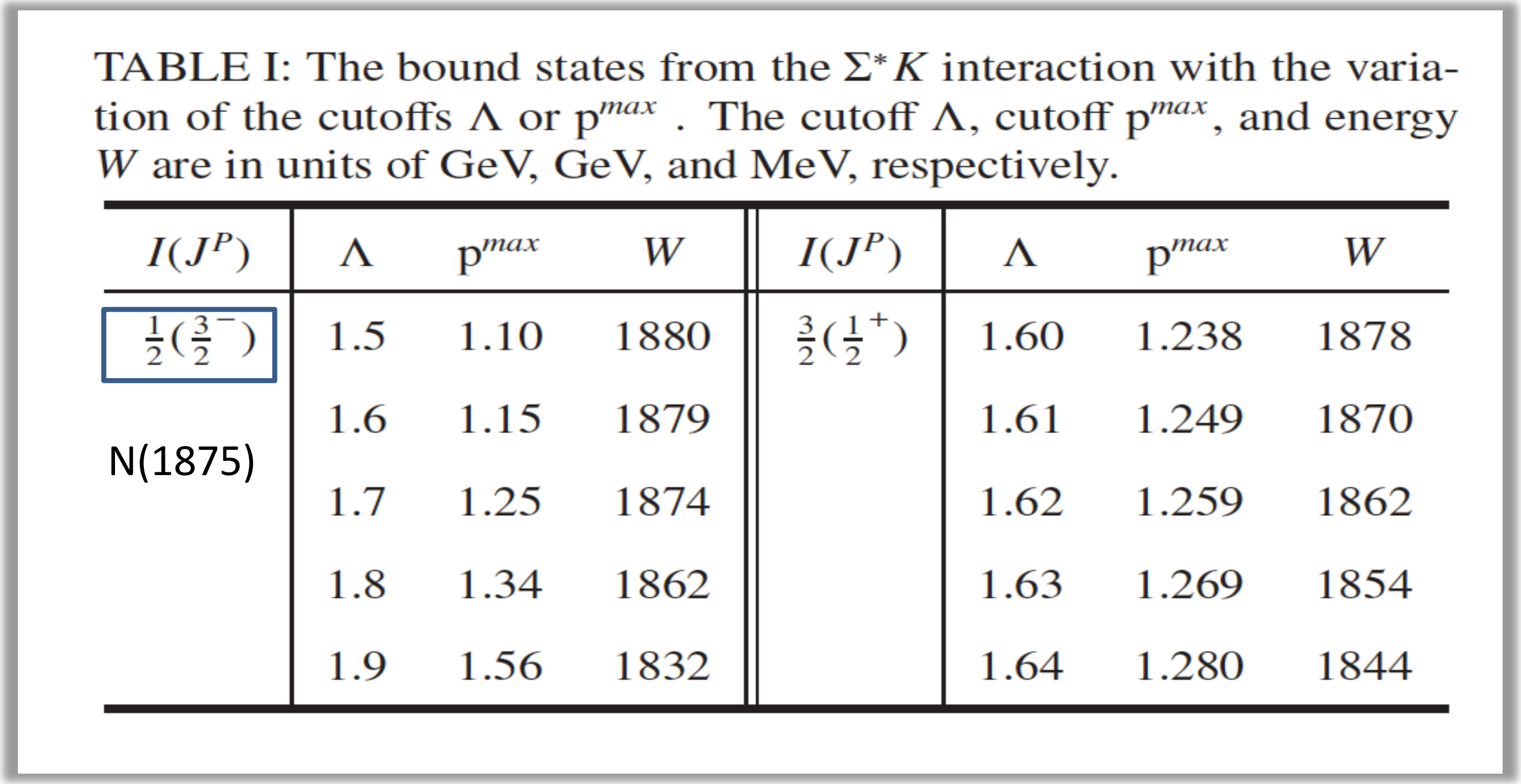


TABLE I: The bound states from the $\Sigma^* K$ interaction with the variation of the cutoffs Λ or p^{max} . The cutoff Λ, cutoff p^{max}, and energy W are in units of GeV, GeV, and MeV, respectively.

$I(J^P)$	Λ	p^{max}	W	$I(J^P)$	Λ	p^{max}	W
$\boxed{\frac{1}{2}(\frac{3}{2}^-)}$	1.5	1.10	1880	$\frac{3}{2}(\frac{1}{2}^+)$	1.60	1.238	1878
	1.6	1.15	1879		1.61	1.249	1870
	1.7	1.25	1874		1.62	1.259	1862
	1.8	1.34	1862		1.63	1.269	1854
	1.9	1.56	1832		1.64	1.280	1844

N(1875)

JH, Phys.Rev. D95 (2017), 074031

The bound states from the ΣK^* interaction

with vector (**ρ**, **ω**, **ϕ**)meson and pseudoscalar (**η**,**π**) meson exchanges.

$$iV_{\mathbb{V}} = f_I \frac{g_{K^*K^*\mathbb{V}}\, g_{\Sigma\Sigma\mathbb{V}}}{2}[\epsilon^\dagger \cdot q\epsilon^\nu + (k_1 + k_1')^\nu\, \epsilon^\dagger \cdot \epsilon - \epsilon^{\dagger\nu}\epsilon \cdot q - k_1 \cdot \epsilon\epsilon^{\dagger^\nu} - k_1' \cdot \epsilon^\dagger\epsilon^\nu] \cdot \frac{g_{\nu\nu'} - q_\nu q_{\nu'}/m_{\mathbb{V}}^2}{q^2 - m_{\mathbb{V}}^2}\, \bar{u}(\gamma^{\nu'} - i\frac{\kappa_{\Sigma\Sigma\mathbb{V}}}{2m_\Sigma}\sigma^{\nu'\rho}q_\rho)u$$

$$iV_{\mathbb{P}} = f_I \frac{g_{K^*K^*\mathbb{P}}\, f_{\Sigma\Sigma\mathbb{P}}}{m_\pi(q^2 - m_{\mathbb{P}}^2)}\, \epsilon^{\mu\nu\alpha\beta}k'_{1\mu}\epsilon^\dagger_\nu k_{1\alpha}\epsilon_\beta\, \bar{u}\gamma_5 \not{q} u,$$

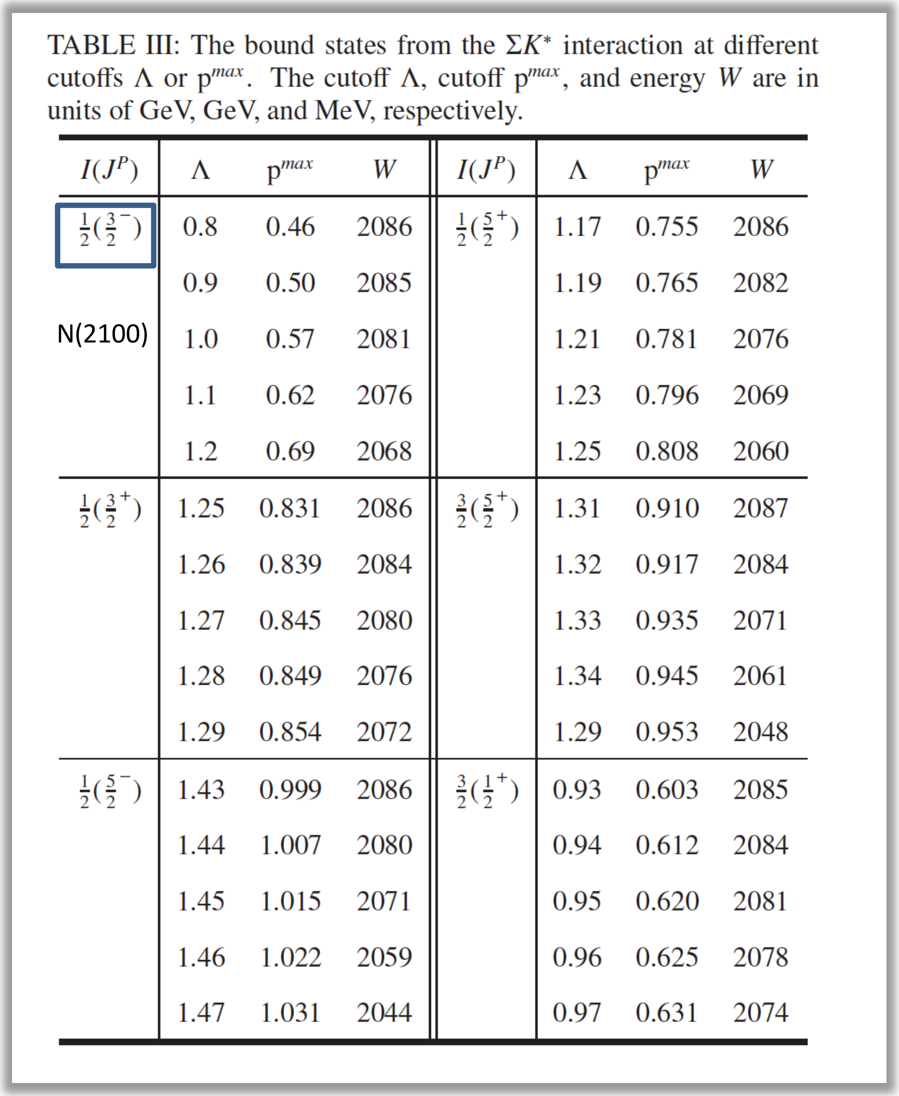


TABLE III: The bound states from the ΣK^* interaction at different cutoffs Λ or p^{max}. The cutoff Λ, cutoff p^{max}, and energy W are in units of GeV, GeV, and MeV, respectively.

$I(J^P)$	Λ	p^{max}	W	$I(J^P)$	Λ	p^{max}	W
$\frac{1}{2}(\frac{3}{2}^-)$	0.8	0.46	2086	$\frac{1}{2}(\frac{5}{2}^+)$	1.17	0.755	2086
	0.9	0.50	2085		1.19	0.765	2082
N(2100)	1.0	0.57	2081		1.21	0.781	2076
	1.1	0.62	2076		1.23	0.796	2069
	1.2	0.69	2068		1.25	0.808	2060
$\frac{1}{2}(\frac{3}{2}^+)$	1.25	0.831	2086	$\frac{3}{2}(\frac{5}{2}^+)$	1.31	0.910	2087
	1.26	0.839	2084		1.32	0.917	2084
	1.27	0.845	2080		1.33	0.935	2071
	1.28	0.849	2076		1.34	0.945	2061
	1.29	0.854	2072		1.29	0.953	2048
$\frac{1}{2}(\frac{5}{2}^-)$	1.43	0.999	2086	$\frac{3}{2}(\frac{1}{2}^+)$	0.93	0.603	2085
	1.44	1.007	2080		0.94	0.612	2084
	1.45	1.015	2071		0.95	0.620	2081
	1.46	1.022	2059		0.96	0.625	2078
	1.47	1.031	2044		0.97	0.631	2074

JH, Phys.Rev. D95 (2017), 074031

$3/2^-$ state in the Σ^*K-ΣK^* interaction

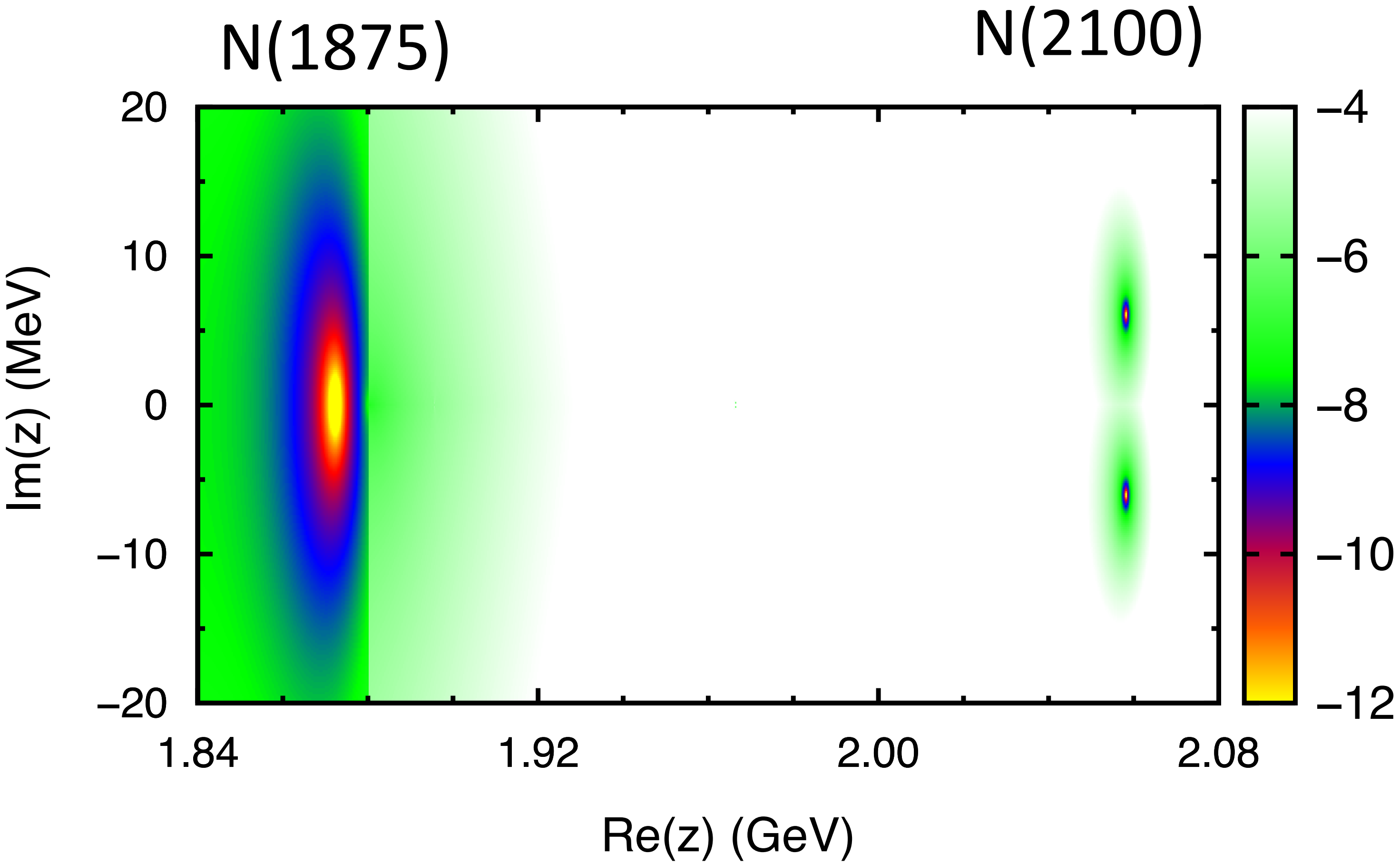
with vector (**ρ**, **ω**, **ϕ**)meson and pseudoscalar (**η**,**π**) meson exchanges.

$$
\begin{aligned}
i\mathcal{V}_{\mathbb{V}} &= f_I g_{K^*K\mathbb{V}} \frac{f_{\Sigma^*\Sigma\mathbb{V}}}{m_{\mathbb{V}}} \epsilon^{\mu\nu\sigma\tau} k_{1\mu}\epsilon_\nu q_\sigma \\
&\quad \cdot [\bar{u}^\rho \gamma^\tau q_\rho - \bar{\Sigma}^\tau \gamma^\rho q_\rho]\gamma_5 u \frac{1}{q^2-m_{\mathbb{V}}^2}, \\
i\mathcal{V}_{\mathbb{P}} &= i f_I g_{K^*K\pi}\frac{f_{\Sigma^*\Sigma\mathbb{P}}}{m_{\mathbb{P}}}\epsilon^\mu (k_1'+q)_\mu \bar{u}^\nu q_\nu u \frac{1}{q^2-m_{\mathbb{P}}^2}.
\end{aligned}
$$

$\Lambda_{\Sigma K^*}$ $\Lambda_{\Sigma^* K}$	0.8	1.0	1.2	1.4	1.6
1.5	$2086+i$	$2081+i2$	$2068+i4$	$2046+i8$	$1994+i12$
	1880	1879	1879	1878	1878
1.7	$2086+i$	$2081+i2$	$2067+i4$	$2046+i8$	$1995+i11$
	1874	1874	1873	1871	1869
1.9	$2086+i$	$2081+i3$	$2067+i5$	$2046+i8$	$1.995+i10$
	1831	1828	1824	1819	1810
2.1	$2086+i$	$2081+i3$	$2067+i5$	$2045+i7$	$1993+i8$
	1786	1779	1768	1759	1740

3/2$^-$ state in the Σ*K-ΣK* interaction

$\Lambda_{\Sigma^* K} = 1.7$ GeV $\qquad \Lambda_{\Sigma K^*} = 1.3$ GeV



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The quark delocalization color screening model

$$
\begin{aligned}
H &= \sum_{i=1}^{5}\left(m_i + \frac{p_i^2}{2m_i}\right) - T_{CM} + \sum_{j>i=1}^{5}\left(V_{ij}^{C} + V_{ij}^{G} + V_{ij}^{\chi}\right), \\
V_{ij}^{C} &= -a_c \boldsymbol{\lambda}_i^c \cdot \boldsymbol{\lambda}_j^c (r_{ij}^2 + v_0), \\
V_{ij}^{G} &= \frac{1}{4}\alpha_s \boldsymbol{\lambda}_i^c \cdot \boldsymbol{\lambda}_j^c \left[\frac{1}{r_{ij}} - \frac{\pi}{2}\delta(\boldsymbol{r}_{ij})\left(\frac{1}{m_i^2} + \frac{1}{m_j^2} + \frac{4\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j}{3m_i m_j}\right) - \frac{3}{4m_i m_j r_{ij}^3} S_{ij}\right] \\
V_{ij}^{\chi} &= V_{\pi}(\boldsymbol{r}_{ij}) \sum_{a=1}^{3} \lambda_i^a \cdot \lambda_j^a + V_K(\boldsymbol{r}_{ij}) \sum_{a=4}^{7} \lambda_i^a \cdot \lambda_j^a + V_{\eta}(\boldsymbol{r}_{ij}) \left[\left(\lambda_i^8 \cdot \lambda_j^8\right)\cos\theta_P - (\lambda_i^0 \cdot \lambda_j^0)\sin\theta_P\right] \\
V_{\chi}(\boldsymbol{r}_{ij}) &= \frac{g_{ch}^2}{4\pi}\frac{m_{\chi}^2}{12 m_i m_j}\frac{\Lambda_{\chi}^2}{\Lambda_{\chi}^2 - m_{\chi}^2} m_{\chi} \left\{ (\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j) \left[Y(m_{\chi} r_{ij}) - \frac{\Lambda_{\chi}^3}{m_{\chi}^3} Y(\Lambda_{\chi} r_{ij}) \right] \right. \\
&\quad \left. + \left[H(m_{\chi} r_{ij}) - \frac{\Lambda_{\chi}^3}{m_{\chi}^3} H(\Lambda_{\chi} r_{ij}) \right] S_{ij} \right\}, \qquad \chi = \pi, K, \eta, \\
S_{ij} &= \left\{ 3\frac{(\boldsymbol{\sigma}_i \cdot \boldsymbol{r}_{ij})(\boldsymbol{\sigma}_j \cdot \boldsymbol{r}_{ij})}{r_{ij}^2} - \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j \right\}, \\
H(x) &= (1 + 3/x + 3/x^2) Y(x), \qquad Y(x) = e^{-x}/x.
\end{aligned}
$$

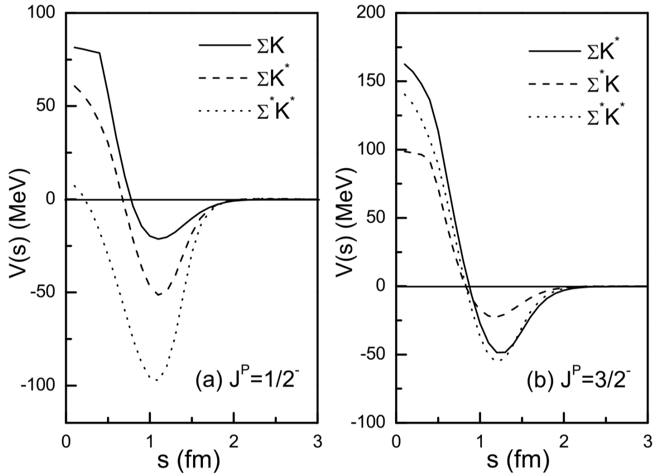


FIG. 1: The potentials of different channels for the $J^P = \frac{1}{2}\frac{1}{2}^-$ and $J^P = \frac{1}{2}\frac{3}{2}^-$ systems.

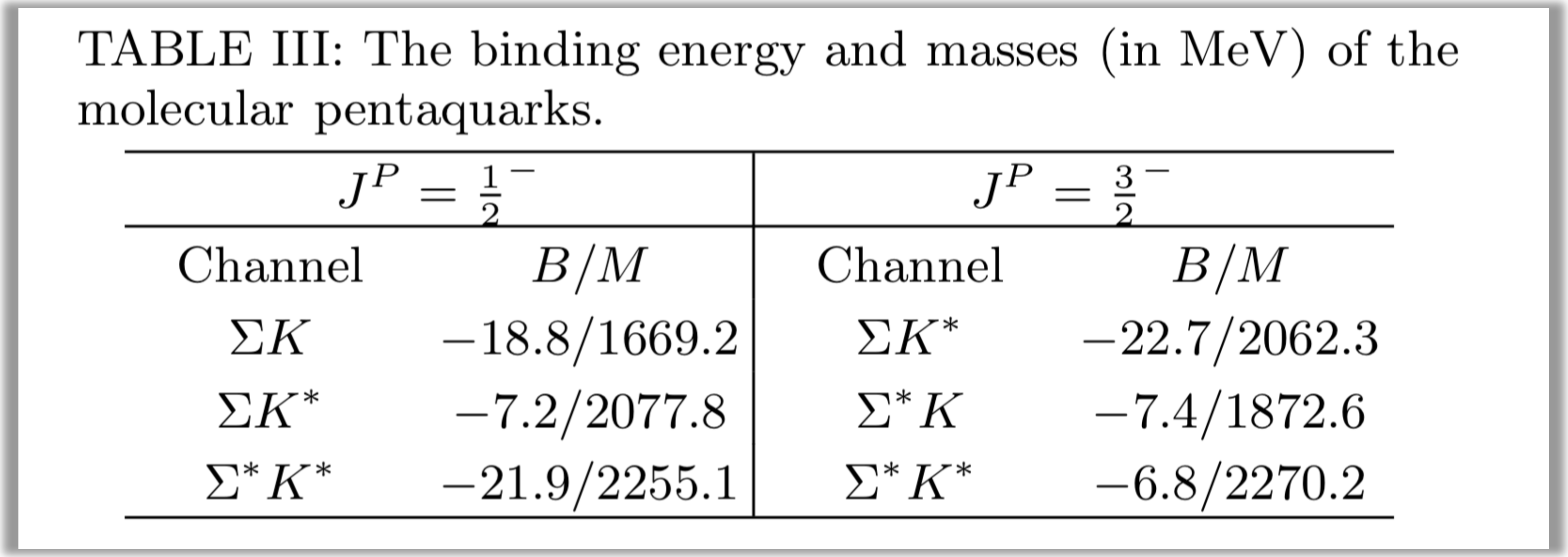
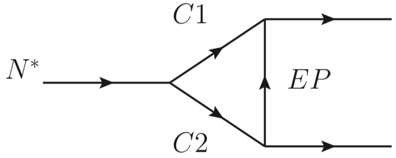


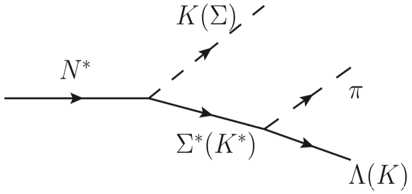
TABLE III: The binding energy and masses (in MeV) of the molecular pentaquarks.

$J^P = \frac{1}{2}^-$		$J^P = \frac{3}{2}^-$	
Channel	B/M	Channel	B/M
ΣK	$-18.8/1669.2$	ΣK^*	$-22.7/2062.3$
ΣK^*	$-7.2/2077.8$	$\Sigma^* K$	$-7.4/1872.6$
$\Sigma^* K^*$	$-21.9/2255.1$	$\Sigma^* K^*$	$-6.8/2270.2$

Huang, Zhu, Phys.Rev. D97 (2018) no.9, 094019

Decay behaviors in the effective Lagrangian approach





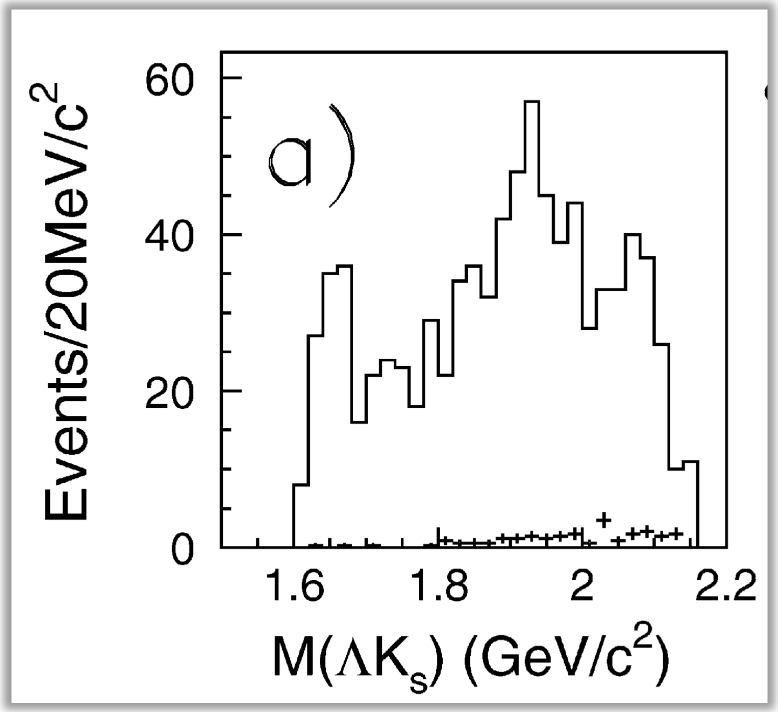
Mode	Widths (MeV)		
	$J^P = 3/2^-$		$J^P = 1/2^-$
	$N(1875)\ K\Sigma^*$	$N(2080)\ K^*\Sigma$	$N(2080)\ K^*\Sigma$
$N\sigma(500)$	2.6	0.05	0.3
πN	3.8	0.2	22.7
ρN	2.3	3.8	6.1
ωp	6.6	11.3	18.2
$K\Sigma$	0.03	1.4	9.1
$K\Lambda$	0.7	3.7	19.3
ηp	0.6	0.4	1.8
$\pi\Delta$	201.4	82.6	46.9
$K^*\Lambda$	-	2.4	7.9
ϕp	-	19.2	27.0
$K\Sigma^*$	-	7.3	1.3
$K\Lambda(1520)$	-	0.1	1.3
$K\Lambda(1405)$	-	8.0	8.8
$K\pi\Lambda$	10.1	-	-
$K\pi\Sigma$	-	41.3	46.1
Total	228.2	181.7	216.8

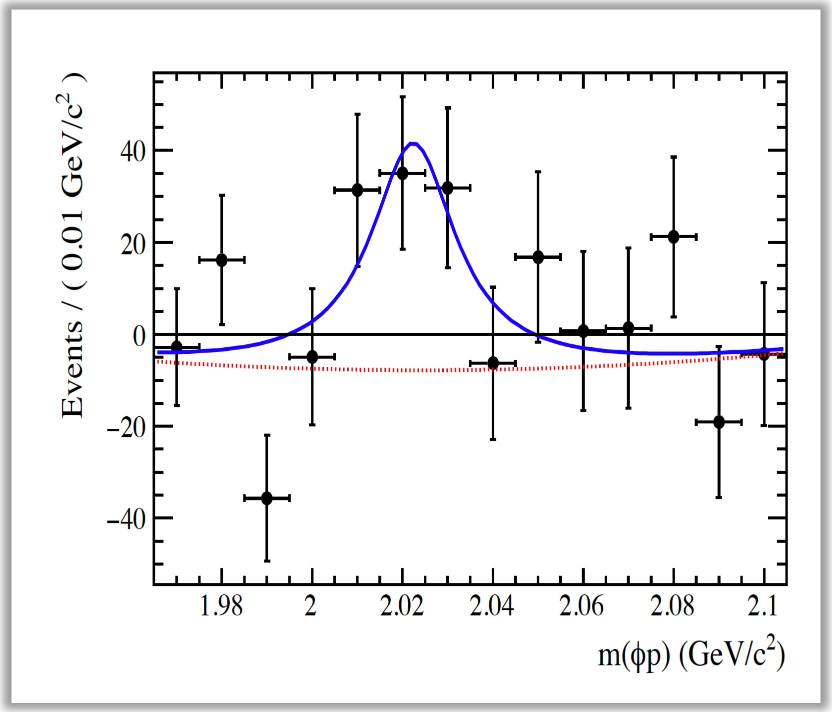
Lin, Shen, Zhou, arXiv:1805.06843

Experiment

$$J/\psi \to n K_S^0 \bar{\Lambda} + \mathrm{c.c.}$$

$$\Lambda_c^+ \to \phi p \pi^0$$





BESII, Phys.Lett. B659 (2008) 789-795

Belle, Phys. Rev., 2017, D96, 051102

Summary

Two hidden-charm pentaquarks were observed at LHCb.

It can be interpreted a $\Sigma_c^* D$ and $\Sigma_c D^*$ molecular states.

Three 3/ 2^- nucleon resonances:

- N (1875):

  Σ^*K molecular state, partner of Pc(4380)

- N (2100) in ϕ photoproduction:

  ΣK* molecular state, partner of Pc(4450)

- N (2120) in KΛ(1520) photoproduction

  $[N(3/2^-)]_3$ in constituent quark model

Further experiments at Belle II, JLab ……

谢谢！