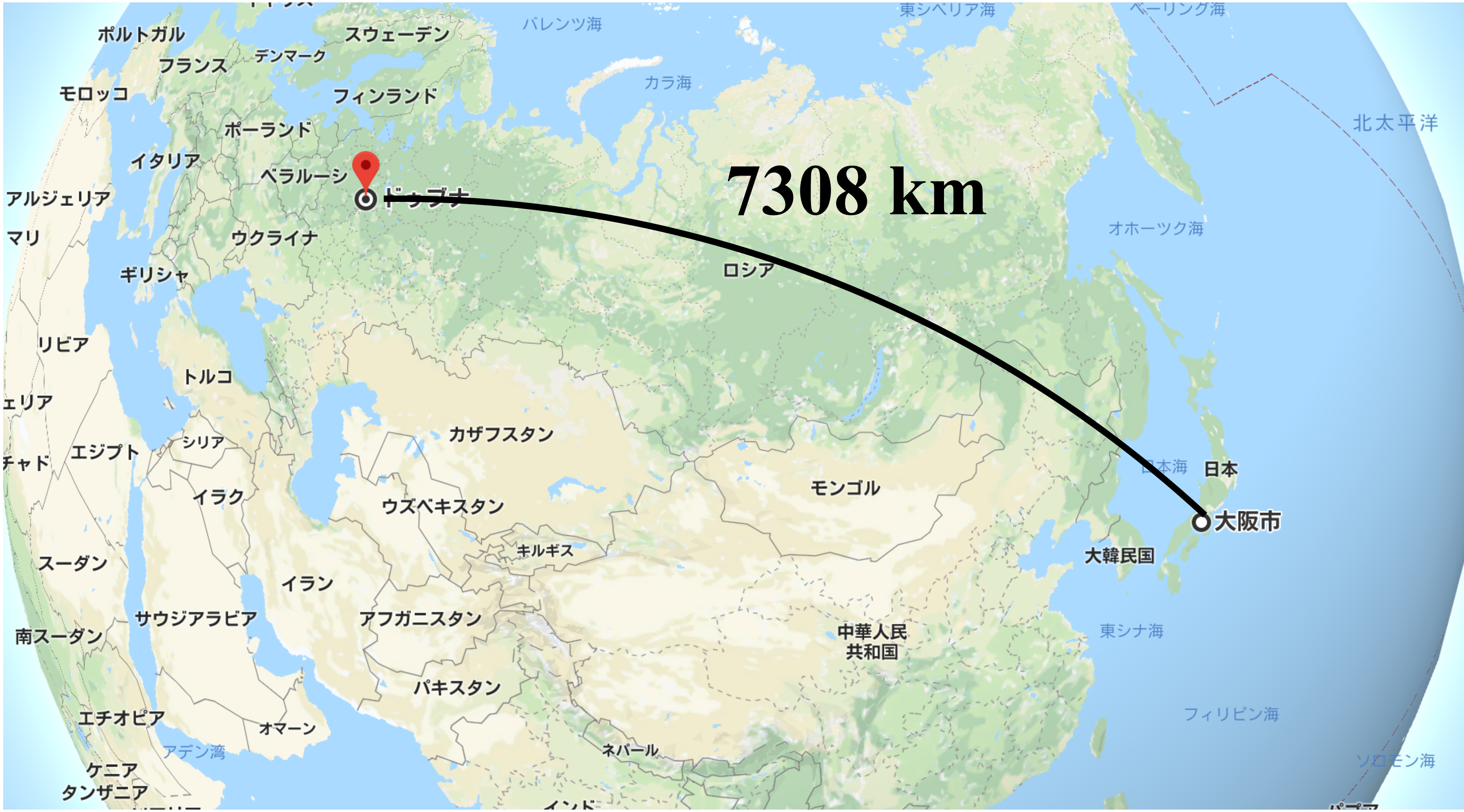
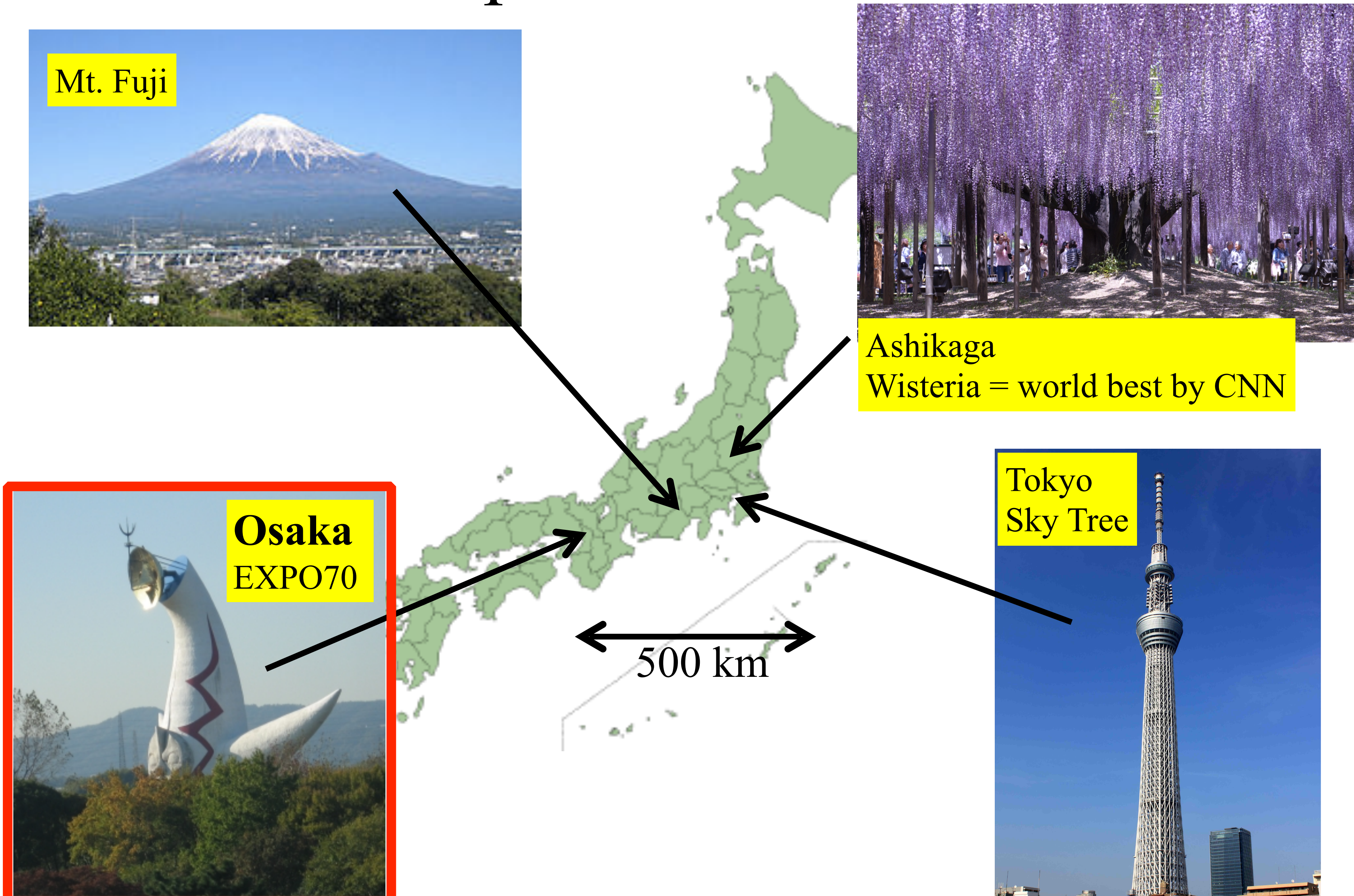
Heavy quark baryons

Hadronic molecules as exotic candidates — P_c

Atsushi Hosaka
RCNP/Osaka & JAEA/Tokai & RIKEN


7308 km
ポルトガル
フランス
デンマーク
スウェーデン
バレンツ海
東シベリア海
ベーリング海
モロッコ
カラ海
フィンランド
ポーランド
北太平洋
イタリア
ベラルーシ
アルジェリア
マリ
ウクライナ
オホーツク海
ロシア
ギリシャ
リビア
トルコ
カザフスタン
シリア
エジプト
日本
イラク
モンゴル
ウズベキスタン
大阪市
キルギス
大韓民国
スーダン
イラン
サウジアラビア
アフガニスタン
中華人民
共和国
南スーダン
東シナ海
パキスタン
エチオピア
フィリピン海
オマーン
アデン湾
ネパール
ケニア
タンザニア

Japan and Osaka



Instant noodle is from Osaka in 1958
Ikeda city Next to the OU campus

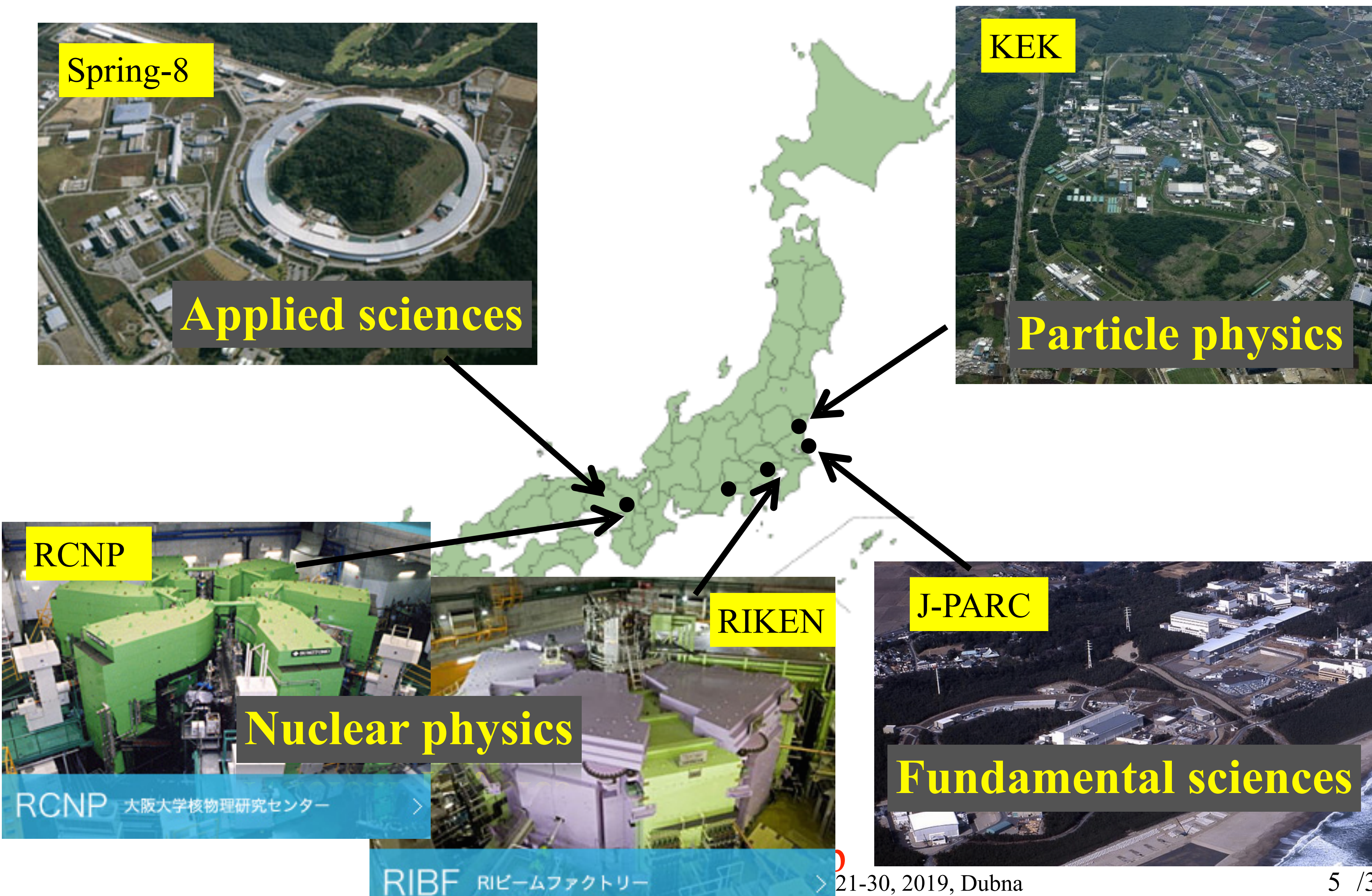
Chicken ramen (noodle) **Cup noodle**

World eats:

8.5×10^{10} eats/year ~12 eats/person/year

Facilities in Japan

500 km



Physics Department, Osaka University

- H. Nagaoka (Atom: nucleus + electron)
  - Firtst president

- H. Yagi (Yagi antenna)
  - First chairman

- S. Kikuchi (First cyclotron in Japan)
  - Electron diffraction

- H. Yukawa (First Nobel Laurite)
  - Meson theory

- Y. Nambu (Special professor)
  SSB chiral symmetry

Heavy quark baryons

Hadronic molecules as exotic candidates — P_c

Atsushi Hosaka
RCNP/Osaka & JAEA/Tokai & RIKEN

1. Hadrons — Standard and beyond, exotics
2. New data P_c from LHC
3. Interpretation
   — hadronic ***molecule*** with ***tensor force*** —

(4. Other exotics — Doubly heavy)

5. Summary

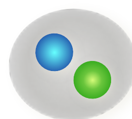
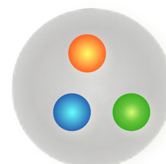
Heavy and chiral dynamics result in molecules

1.Hadrons

Standard and beyond, exotics

Standard (minimal) structure

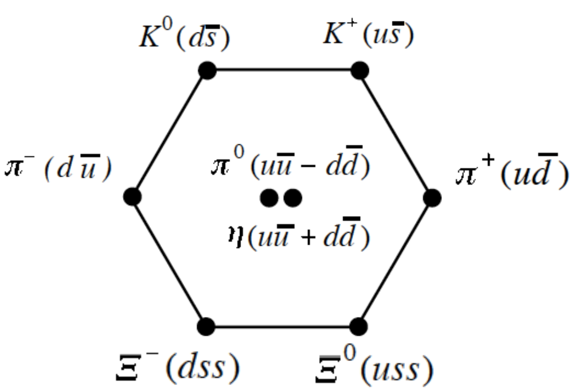
p, n, Δ, Λ, Σ: **Baryons** ~ ***qqq***
π, ρ, K, η, σ: **Mesons** ~ ***qq***

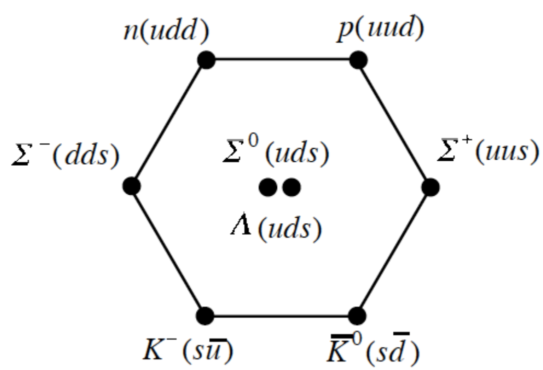
M. Gell-Mann

G. Zweig

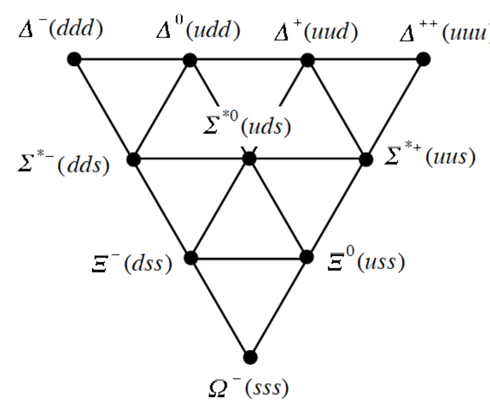
Peudoscalar meson octet



Baryon octet



Baryon decuplet



- Successful for ground state properties; masses, magnetic moments…

Exotics

Beyond the standard: $qq\bar{q}\bar{q}$ mesons, $qqqq\bar{q}$ baryons and **more**

Multiquarks

A SCHEMATIC MODEL OF BARYONS AND MESONS

M. GELL-MANN
California Institute of Technology, Pasadena, California

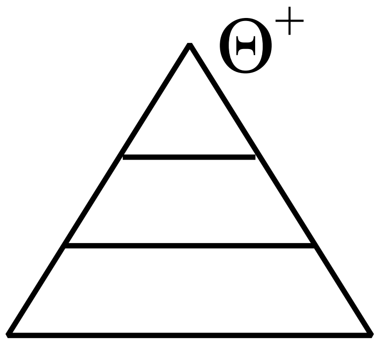
Received 4 January 1964

anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the represen-

Where and how??

Discussions started by Θ^+ and $X(3872)$

D. Diakonov in Osaka

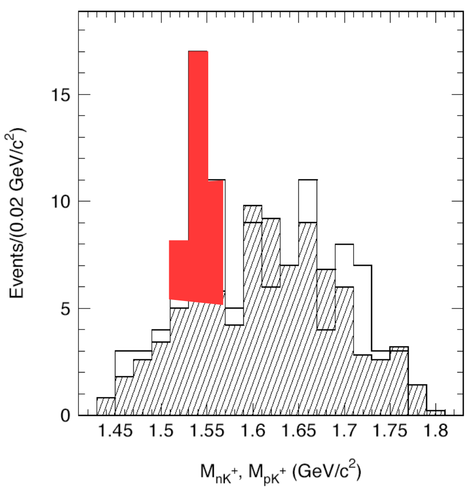


$uudd\bar{s}$

Exotic anti-decuplet of Baryons: Prediction by the chiral Solitons

Z.Phys. A359 (1997) 305-314

T. Nakano



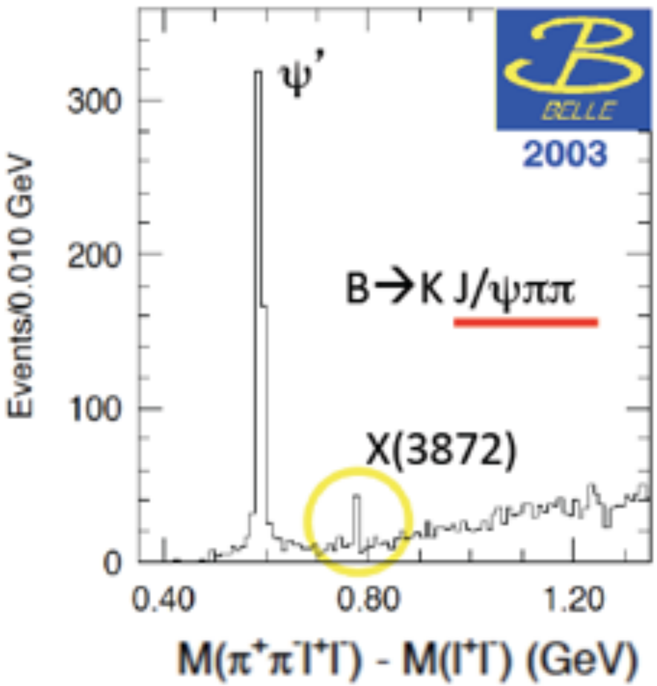
PRL91, 012002 (2003)

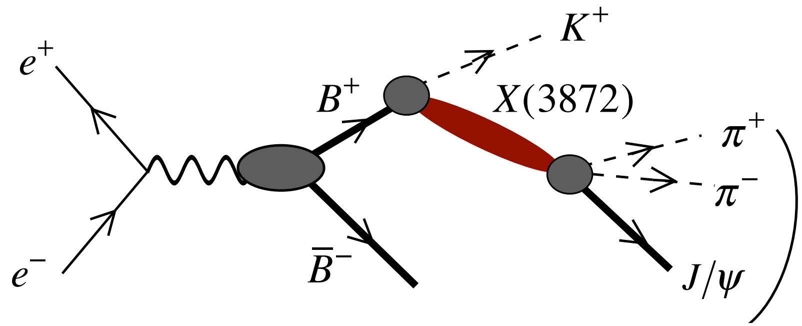
LEPS experiment@SPring-8

Originally designed for ϕ production with A.I. Titov

Discussions started by Θ^+ and $X(3872)$

Belle@KEK, PRL91, 262001 (2003)





Confirmed by other facilities,
Fermi Lab, SLAC, LHC, BEP, …

$u\bar{u}$**$c\bar{c}$**, $d\bar{d}$**$c\bar{c}$**

Heavy quarks

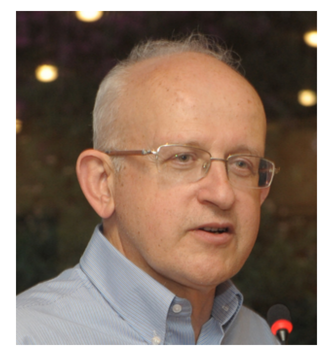
More new particles

Exotic signals

More in the **heavy** flavor sectors near the **thresholds**

The relevant questions:
Do they exist? If they do, which ones? What is their internal structure? How best to look for them?
Marek Karliner, QNP proceedings, 2018@Tsukuba

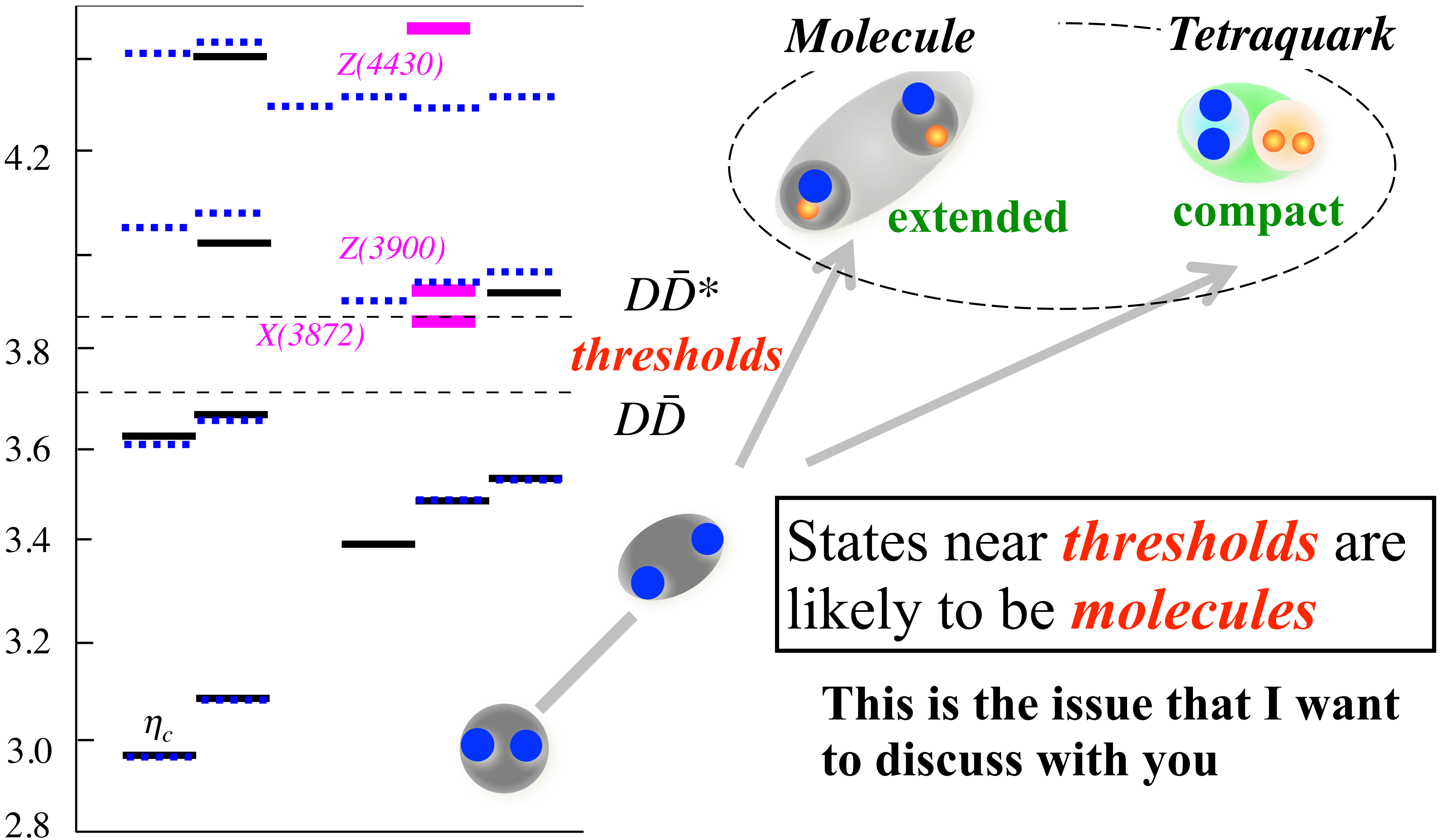
Studying heavy exotic hadrons is somewhat similar to investigating the social life of heavy quarks:
(a) Who with whom?
(b) For how long?
(c) A short episode? or
(d) "Till Death Us Do Part"?



Marek Karliner

Where and how

Example: Charmonium-like states



States near ***thresholds*** are likely to be ***molecules***

This is the issue that I want to discuss with you

Molecular charmonium

Molecular Charmonium: A New Spectroscopy?*

PRL37,317,1977

A. De Rújula, Howard Georgi,† and S. L. Glashow
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 23 November 1976)

Recent data compel us to interpret several peaks in the cross section of e^-e^+ annihilation into hadrons as being due to the production of four-quark molecules, i.e., resonances between two charmed mesons. A rich spectroscopy of such states is predicted and may be studied in e^-e^+ annihilation.

$\Lambda(1405)$

POSSIBLE RESONANT STATE IN PION-HYPERON SCATTERING*

R. H. Dalitz and S. F. Tuan
Enrico Fermi Institute for Nuclear Studies and Department of Physics,
University of Chicago, Chicago, Illinois
(Received April 27, 1959)

PhysRevLett.2.425

....

will be pointed out here that this situation makes it quite probable that there should exist a resonant state for pion-hyperon scattering at an energy of about 20 Mev below the $K^- - p$ (c.m.) threshold energy. In the present discussion, charge-

....

2. New data from LHC

For baryons

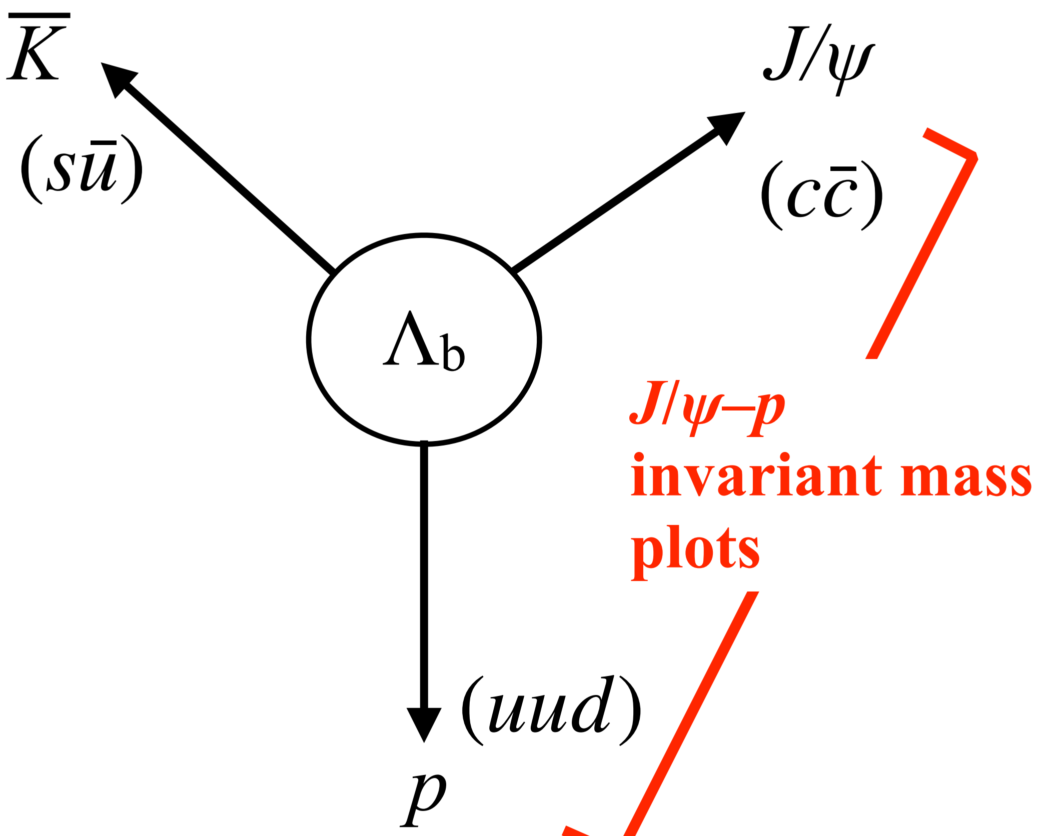
New Pc's from LHC

7-8 TeV pp collision

$$\Lambda_b \to p, J/\psi, K^-$$

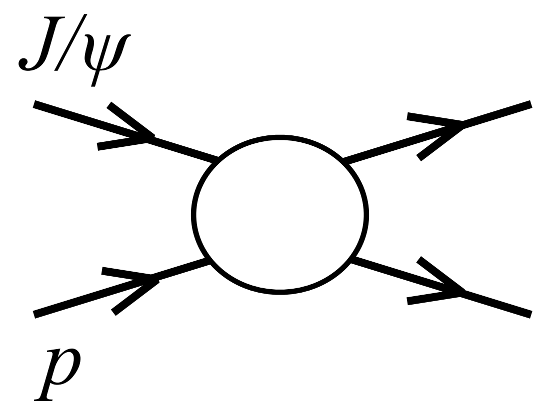
$$bud \to uds c\bar{c} \to (uud)(c\bar{c})(s\bar{u})$$

Three-body: Dalitz plots



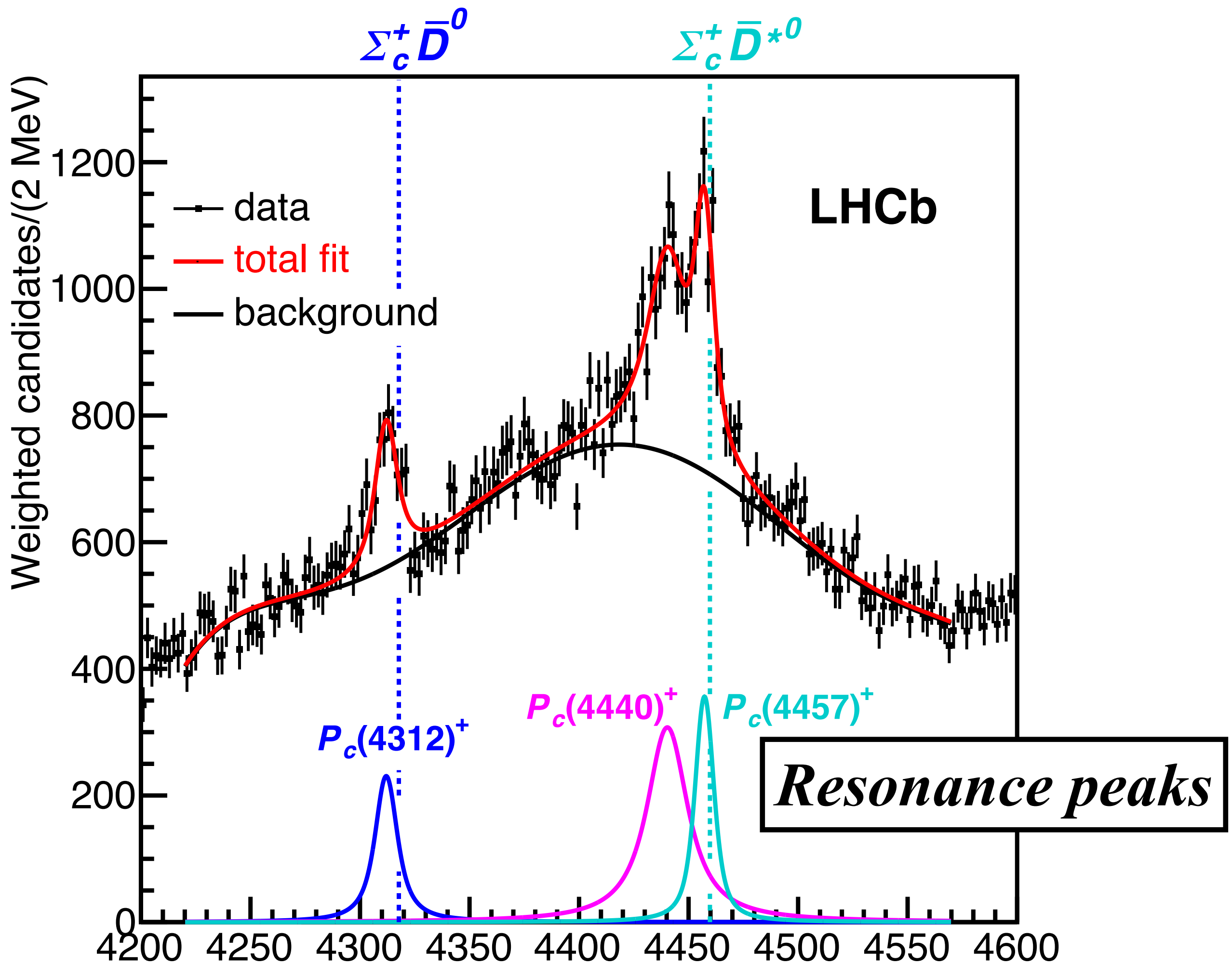
Equivalent to

J/ψ–p scattering



New Pc's from LHC

PRL122 (2019) no.22, 222001



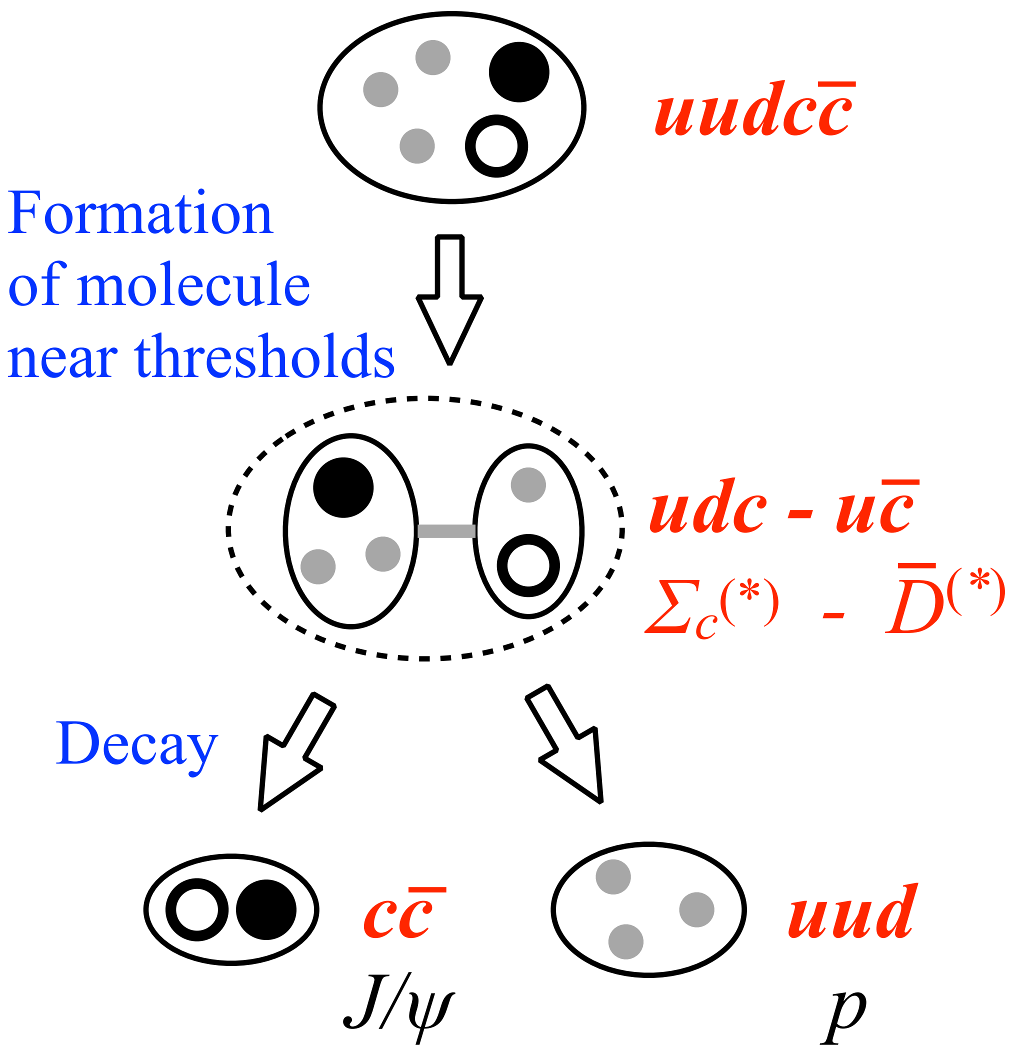
$m_{J/\psi p}$ [GeV] = $J/\psi p$ scattering energy

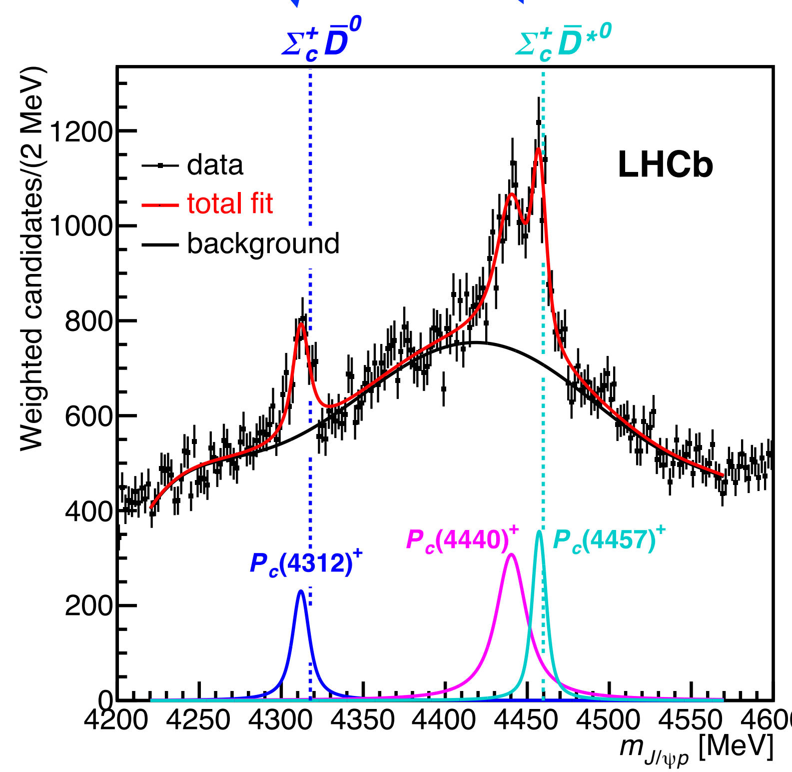
3. Interpretation

Thresholds, $\Sigma_c\bar{D}$ and $\Sigma_c\bar{D}^*$

2455 1870 2010

Three states are just below the thresholds





Constituents $\Sigma_c^{(*)}$-$D^{(*)}$

Σ_c : $J = 1/2$
Σ_c^*: $J = 3/2$

D: $J = 0$
D^*: $J = 1$

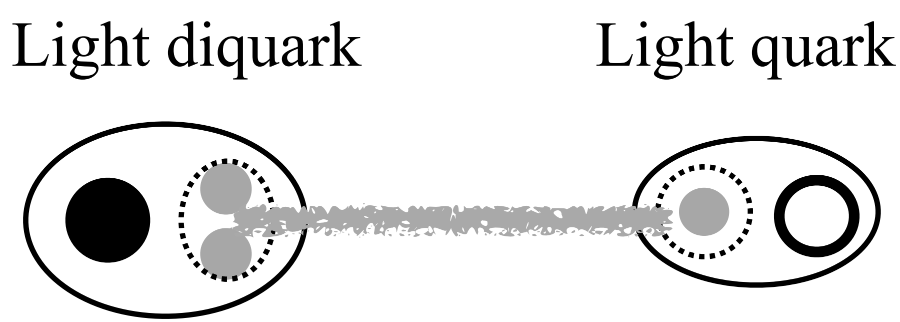
Particle channels	Threshold masses	Possible spins
$\Sigma_c^* D^*$	4520	1/2, 3/2, 5/2
$\Sigma_c D^*$	4460	1/2, 3/2
$\Sigma_c^* D$	4385	1/2, 3/2
$\Sigma_c D$	4310	1/2

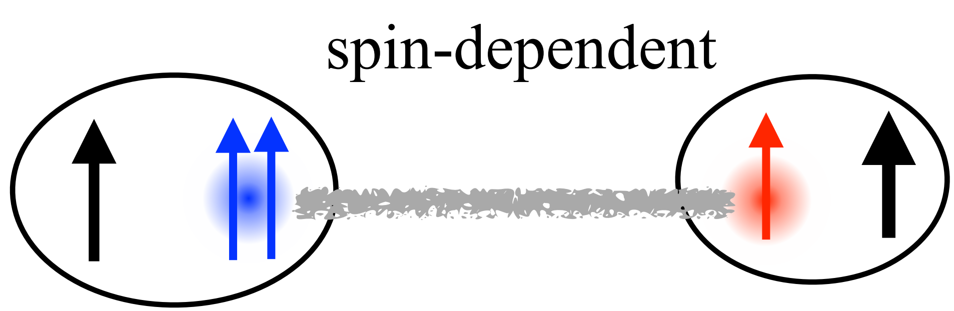
There are seven near threshold states

Interactions

Dormant **Heavy** quark and active **Chiral**

Between hadrons, color force is suppressed
=> **Meson exchange** force for light quarks





Pion exchange force

Yukawa

Work done at Osaka in 1934

Spontaneous symmetry breaking **Nambu**

Special professor at Osaka 2006 - 2015

Pion (meson) exchange

$$V(\vec{q}) = -\left(\frac{g_A}{2f_\pi}\right)^2 \frac{\vec{s}_1 \cdot \vec{q}\;\vec{s}_2 \cdot \vec{q}}{\vec{q}^{\,2} + m_\pi^2}$$

Pion:

= NG boson of $\boldsymbol{J^P = 0^-}$

Pseudoscalar coupling

Tensor force of OPEP

$$S_{12}(\hat{q}) = \vec{s}_1 \cdot \hat{q}\ \vec{s}_2 \cdot \hat{q} - \frac{1}{3}\vec{s}_1 \cdot \vec{s}_2$$

Tensor operator flips the orbital angular momentum $\boldsymbol{\Delta L = 2}$

S-waves may **couple** to **D**-waves

$[\Sigma_c D]^{1/2}$, $[\Sigma_c^* D]^{1/2}$, $[\Sigma_c D^*]^{1/2}$, $[\Sigma_c D^*]^{3/2}$, $[\Sigma_c^* D^*]^{1/2}$, $[\Sigma_c^* D^*]^{3/2}$, $[\Sigma_c^* D^*]^{5/2}$

Coupled channels $\quad {}^{2s+1}L_J$

$J = 1/2$: $\boldsymbol{\Sigma_c \bar{D}\ ({}^2S_{1/2})}$ - $\Sigma_c \bar{D}^*\ ({}^2S_{1/2})$ - $\Sigma_c \bar{D}^*\ ({}^4D_{1/2})$

$J = 1/2$: $\Sigma_c \bar{D}\ ({}^2S_{1/2})$ - $\boldsymbol{\Sigma_c \bar{D}^*\ ({}^2S_{1/2})}$ - $\Sigma_c \bar{D}^*\ ({}^4D_{1/2})$

$J = 3/2$: $\boldsymbol{\Sigma_c \bar{D}^*\ ({}^4S_{3/2})}$ - $\Sigma_c \bar{D}^*\ ({}^2D_{3/2})$ - $\Sigma_c \bar{D}^*\ ({}^4D_{3/2})$

*** *J* = 3/2 state has more D-wave couplings**

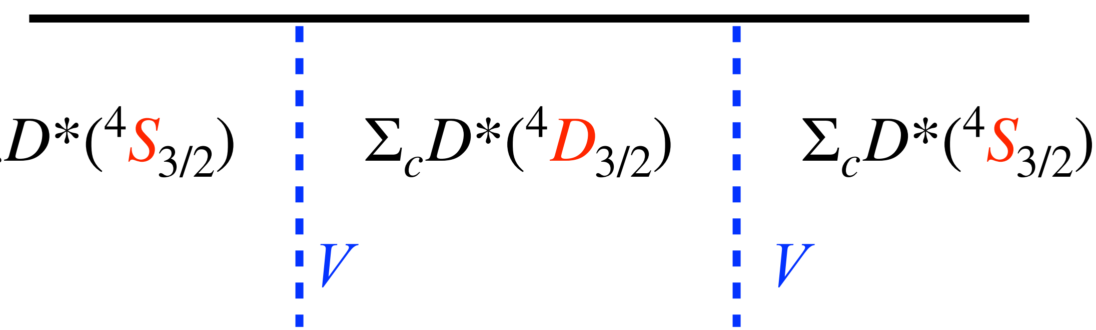
2nd order nature

$$\langle \Sigma_c D^*(^4S_{3/2}) \,|\, T \,|\, \Sigma_c D^*(^4S_{3/2}) \rangle$$

$$\sim \langle \Sigma_c D^*(^4S_{3/2}) \,|\, V \,|\, \Sigma_c D^*(^4D_{3/2}) \rangle \frac{1}{E_S - E_D} \langle \Sigma_c D^*(^4D_{3/2}) \,|\, V \,|\, \Sigma_c D^*(^4S_{3/2}) \rangle$$

$$\sim \frac{|\langle \Sigma_c D^*(^4S_{3/2}) \,|\, V \,|\, \Sigma_c D^* \rangle|^2}{E_S - E_D} < 0$$

Attractive!



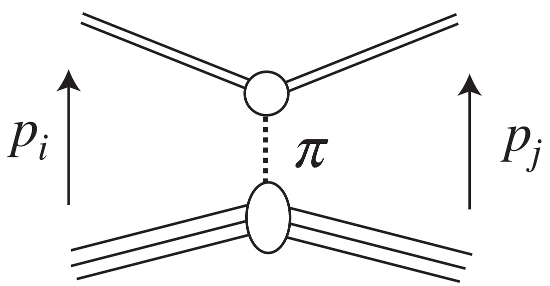
Model calculation

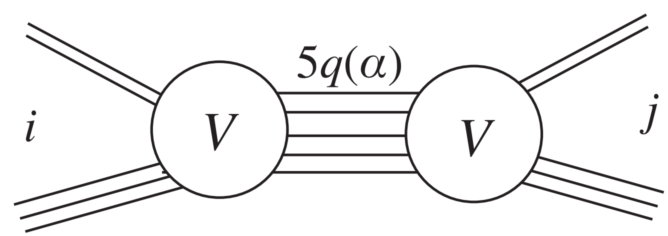
Yasuhiro Yamaguchi, Alessandro Giachino, Atsushi Hosaka, Elena Santopinto, Sachiko Takeuchi, Makoto Takizawa.
arXiv:1709.00819 [hep-ph].
Phys.Rev. D96 (2017) no.11, 114031.

Yasuhiro Yamaguchi, Hugo Garcia-Tecocoatzi, Alessandro Giachino, Atsushi Hosaka, Elena Santopinto, Sachiko Takeuchi, Makoto Takizawa.
arXiv:1907.04684 [hep-ph]

Hadronic molecule with OPEP + 5q core

$$M \equiv \bar{D}, \bar{D}^*$$





$$B \equiv \Sigma_c, \Sigma_c^*, \Lambda_c$$

Coupled channels of MB and 5q

$$H^{MB}\psi^{MB} + V\psi^{5q} = E\psi^{MB},$$
$$V^{\dagger}\psi^{MB} + H^{5q}\psi^{5q} = E\psi^{5q}.$$

5q states are eliminated

$$\left(K^{MB} + V^{\pi} + V\frac{1}{E - H^{5q}}V^{\dagger}\right)\psi^{MB} = E\psi^{MB}$$

Kinetic term

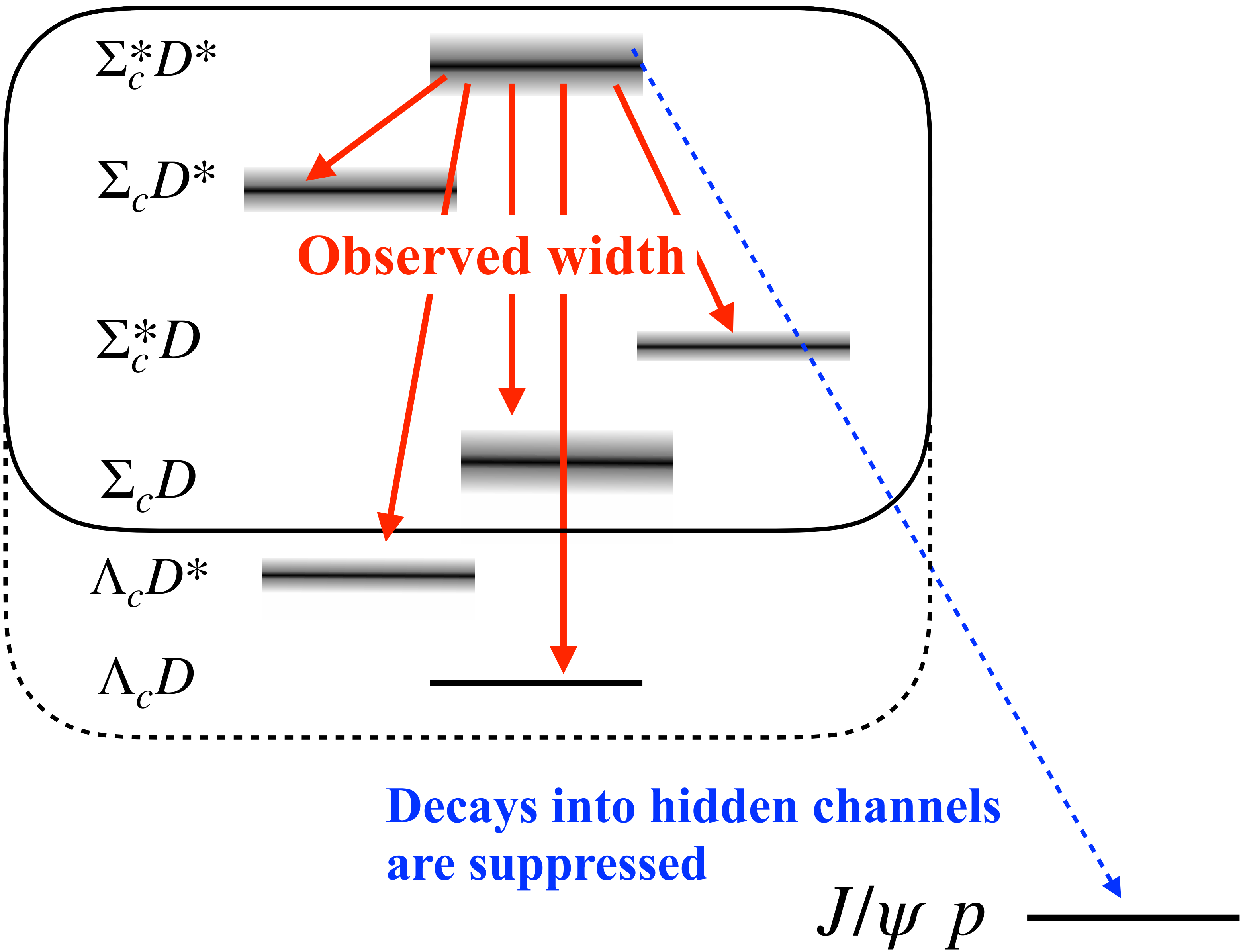
OPEP

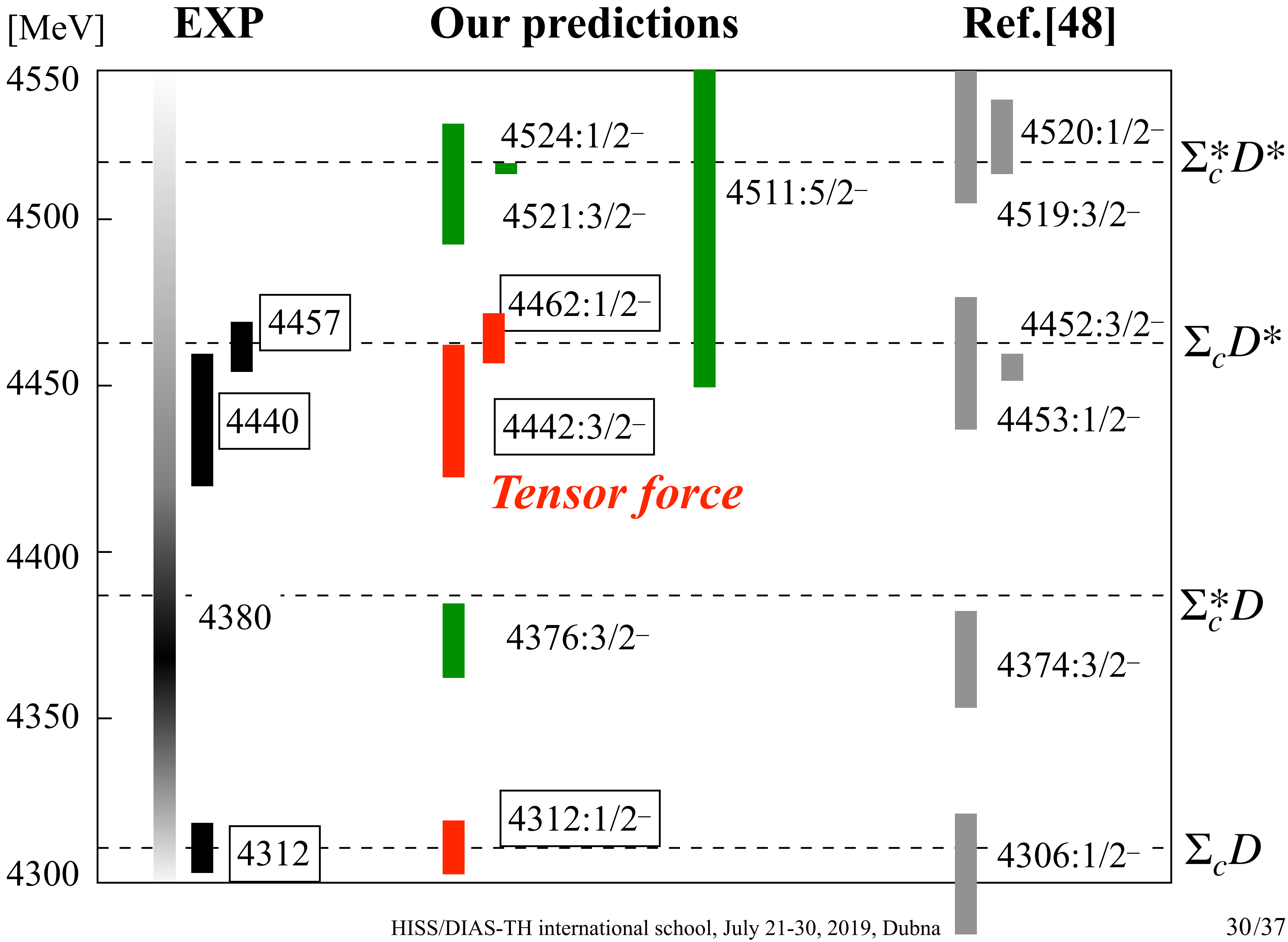
Effective potential from 5q

Solving this equation, eigenstates (resonances), phase shits, …

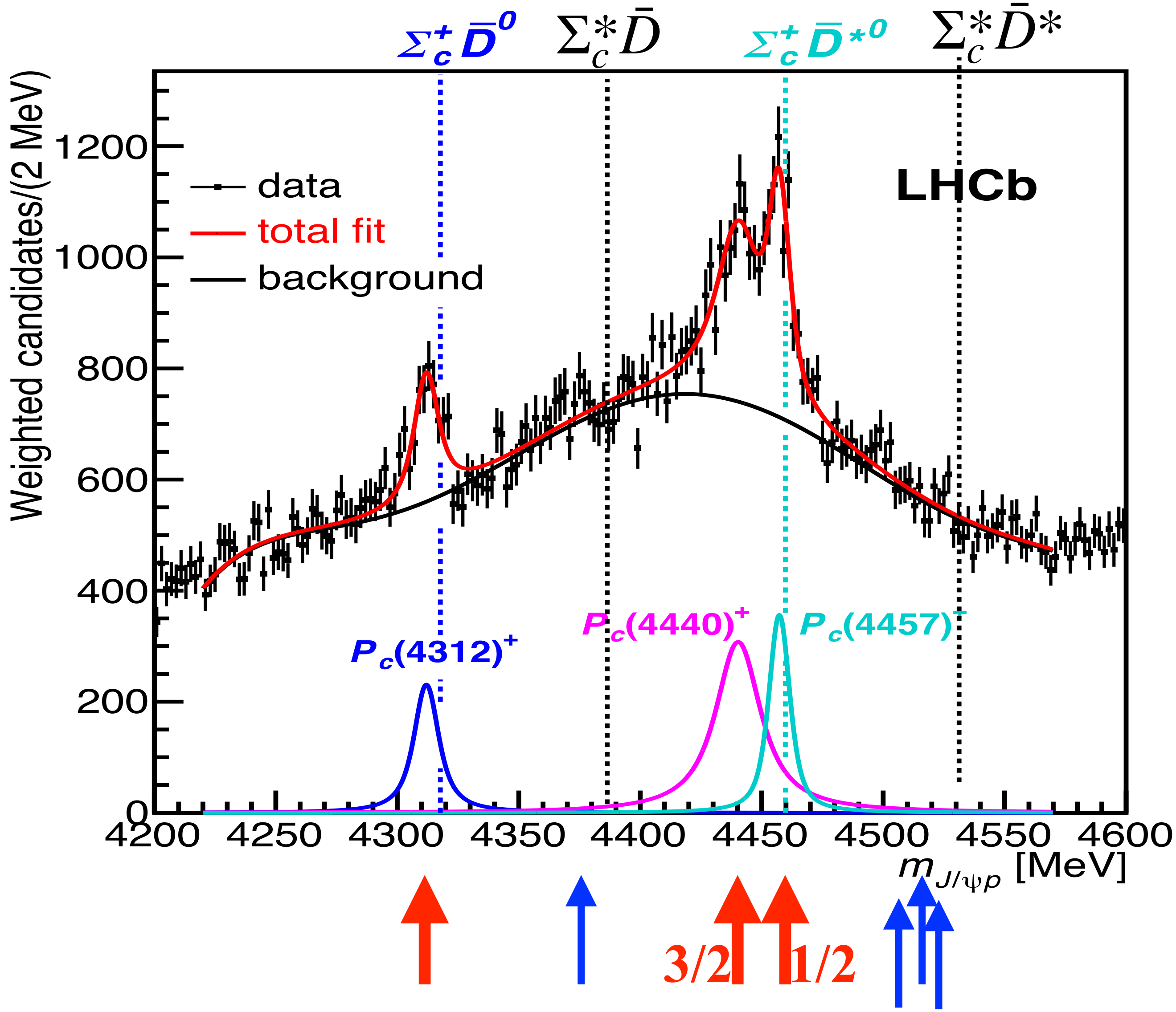
One parameter *V*

Actual coupled channels of MB





[MeV]
EXP
Our predictions
Ref.[48]
4550
4500
4450
4400
4350
4300
4457
4440
4380
4312
4524:1/2−
4521:3/2−
4511:5/2−
4462:1/2−
4442:3/2−
Tensor force
4376:3/2−
4312:1/2−
4520:1/2−
4519:3/2−
4452:3/2−
4453:1/2−
4374:3/2−
4306:1/2−
$\Sigma_c^* D^*$
$\Sigma_c D^*$
$\Sigma_c^* D$
$\Sigma_c D$



- **More predicted**: one at $\Sigma_c^* \bar{D}$ and three at $\Sigma_c^* \bar{D}^*$
- $E(J = 3/2) < E(J = 1/2)$: This is due to the tensor

$$E(J = 3/2) < E(J = 1/2)$$

$$\uparrow\uparrow \qquad\qquad \uparrow\downarrow$$

This contradicts with naive expectation of spin-spin interaction

$$E(\uparrow\uparrow) > E(\uparrow\downarrow)$$

Determination of the spin is very important

Seven states under HQSS

Ming-Zhu Liu, Ya-Wen Pan, Fang-Zheng Peng,
Mario Sánchez Sánchez, Li-Sheng Geng, Atsushi Hosaka,
Manuel Pavon Valderrama.
arXiv:1903.11560 [hep-ph].
Phys.Rev.Lett. 122 (2019) no.24, 242001.

Masses of seven states are determined by two parameters

$$L = C_a Tr[H_c^\dagger H_c] S_c \cdot S_c^\dagger + C_b \sum_{i=1}^{3} Tr[H_c^\dagger \sigma_i H_c] S_c \cdot (J_i S_c^\dagger)$$

$$H_c = \frac{1}{\sqrt{2}}(D + \vec{D}^* \vec{\sigma}) \qquad S_c = \frac{1}{\sqrt{3}}(\Sigma_c \vec{\sigma} + \vec{\Sigma}^*{}_c)$$

$M_{J=3/2} < M_{J=1/2}$

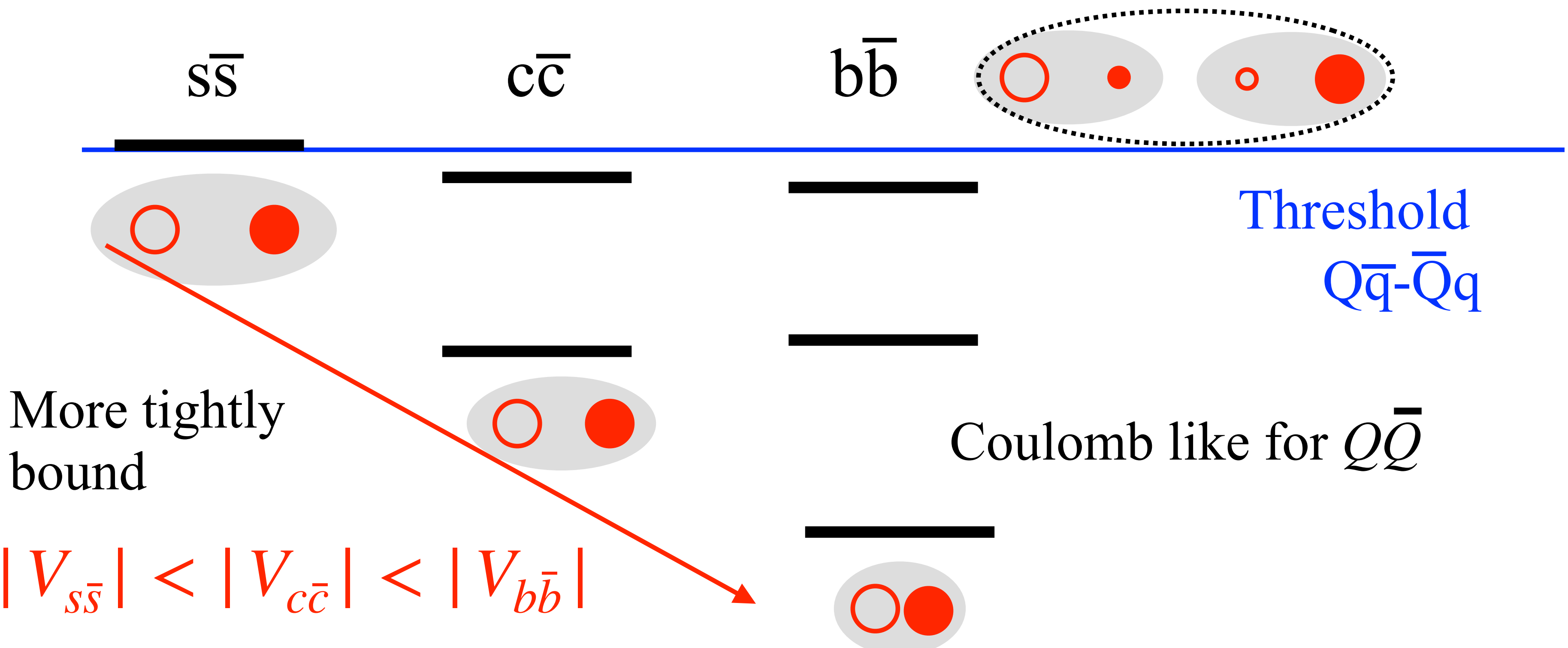
$M_{J=3/2} > M_{J=1/2}$

Scenario	Molecule	J^P	B (MeV)	M (MeV)
A	$\bar{D}\Sigma_c$	$\frac{1}{2}^-$	13.1 – 14.5	4306.3 – 4307.7
A	$\bar{D}\Sigma_c^*$	$\frac{3}{2}^-$	13.6 – 14.8	4370.5 – 4371.7
A	$\bar{D}^*\Sigma_c$	$\frac{1}{2}^-$	Input	4457.3
A	$\bar{D}^*\Sigma_c$	$\frac{3}{2}^-$	Input	4440.3
A	$\bar{D}^*\Sigma_c^*$	$\frac{1}{2}^-$	3.1 – 3.5	4523.2 – 4523.6
A	$\bar{D}^*\Sigma_c^*$	$\frac{3}{2}^-$	10.1 – 10.2	4516.5 – 4516.6
A	$\bar{D}^*\Sigma_c^*$	$\frac{5}{2}^-$	25.7 – 26.5	4500.2 – 4501.0
B	$\bar{D}\Sigma_c$	$\frac{1}{2}^-$	7.8 – 9.0	4311.8 – 4313.0
B	$\bar{D}\Sigma_c^*$	$\frac{3}{2}^-$	8.3 – 9.2	4376.1 – 4377.0
B	$\bar{D}^*\Sigma_c$	$\frac{1}{2}^-$	Input	4440.3
B	$\bar{D}^*\Sigma_c$	$\frac{3}{2}^-$	Input	4457.3
B	$\bar{D}^*\Sigma_c^*$	$\frac{1}{2}^-$	25.7 – 26.5	4500.2 – 4501.0
B	$\bar{D}^*\Sigma_c^*$	$\frac{3}{2}^-$	15.9 – 16.1	4510.6 – 4510.8
B	$\bar{D}^*\Sigma_c^*$	$\frac{5}{2}^-$	3.2 – 3.5	4523.3 – 4523.6

4. Other exotics — Doubly heavy

Hidden heavy $Q\bar{Q}$

Strong $V = Q\bar{Q}$ Coulomb attraction $\sim M_Q$

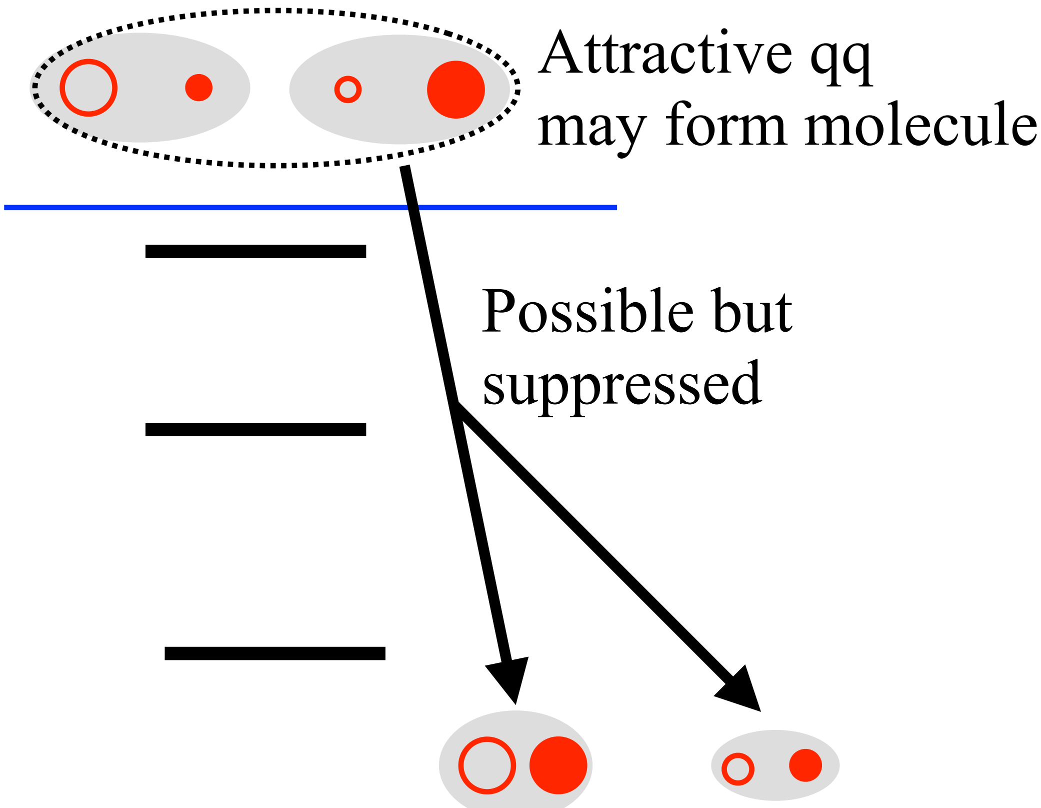


$|V_{s\bar{s}}| < |V_{c\bar{c}}| < |V_{b\bar{b}}|$

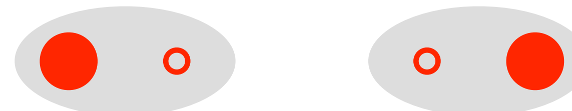
Color electric potential $\sim \alpha^2 M$

4. Other exotics — Doubly heavy

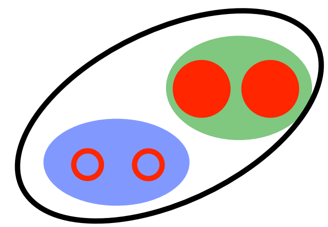
$Q\bar{Q}q\bar{q}$



$QQ\bar{q}\bar{q}$



Weak qq
may NOT form molecule

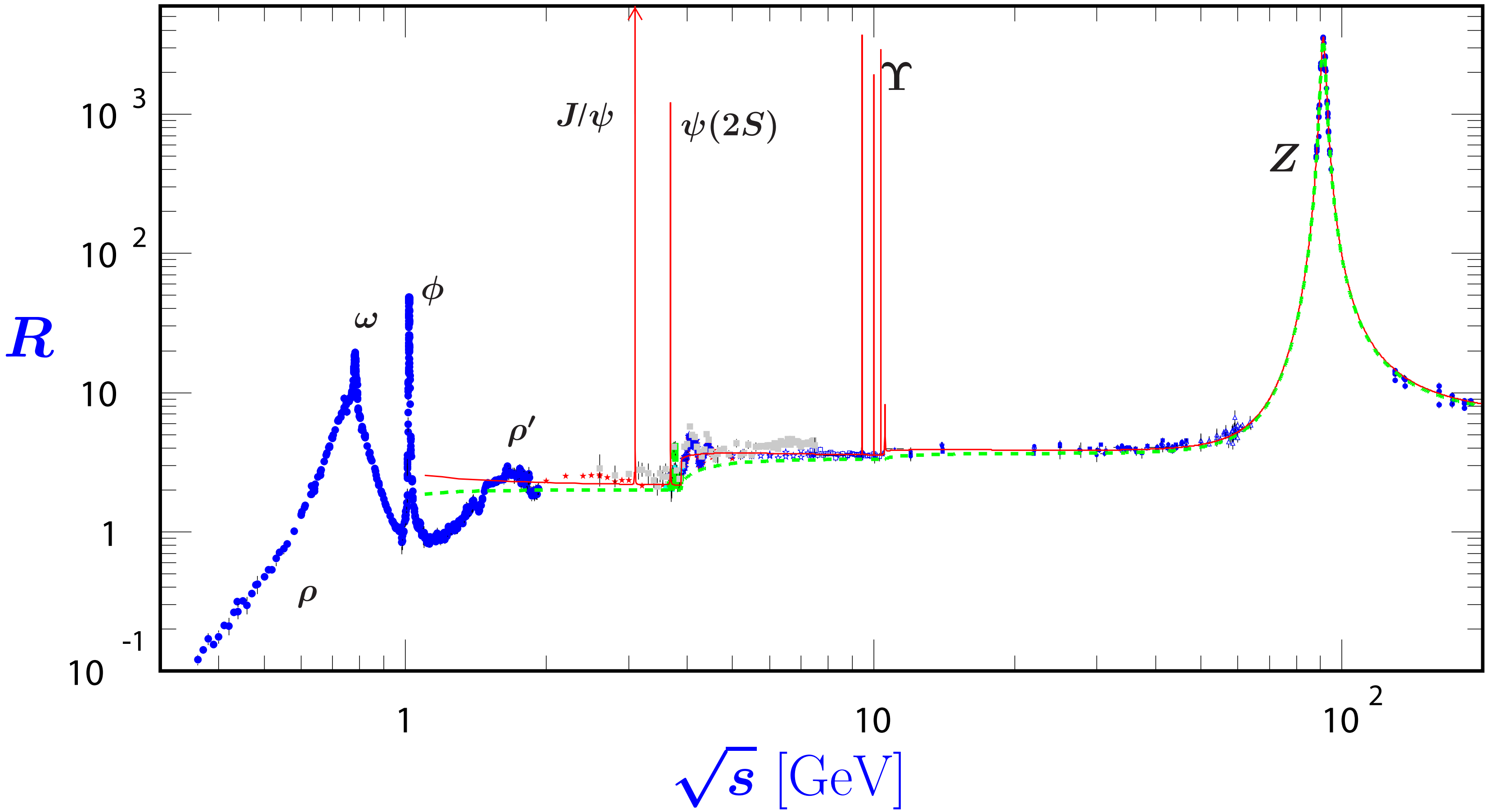


Strong *QQ* may form
absolutely stable states

Summary

- Hadronic molecule is formed for hidden heavy system.
- Recent LHCb's finding could be a good example.
- Heavy and chiral interplay:
  Suppression of kinetic energy
  Interaction between light quarks
- The spin doublet $J = 1/2,\ 3/2$ is the unique system to test the tensor force, first example.
- Doubly heavy quark system may exist absolutely stable.

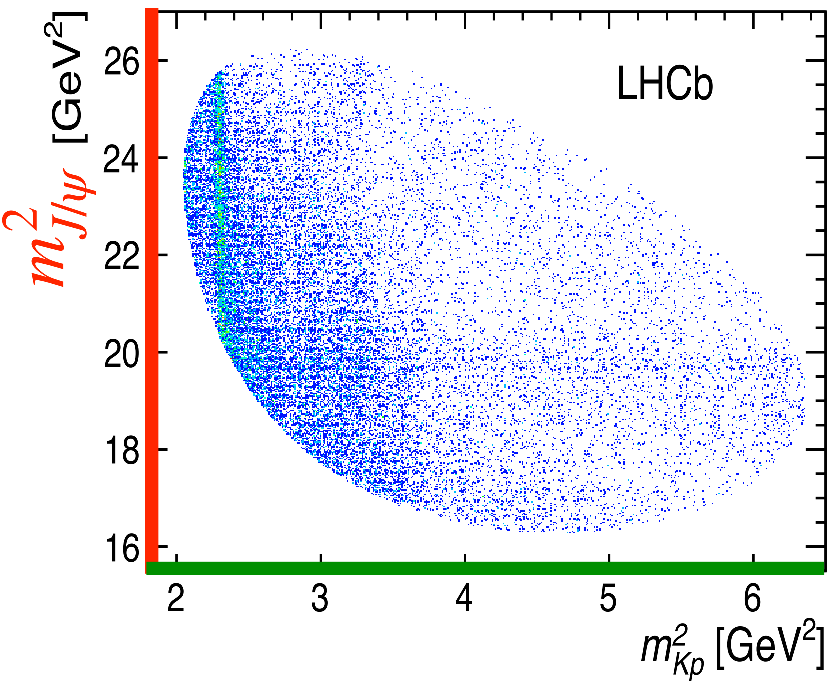
From quarks of QCD to hadrons

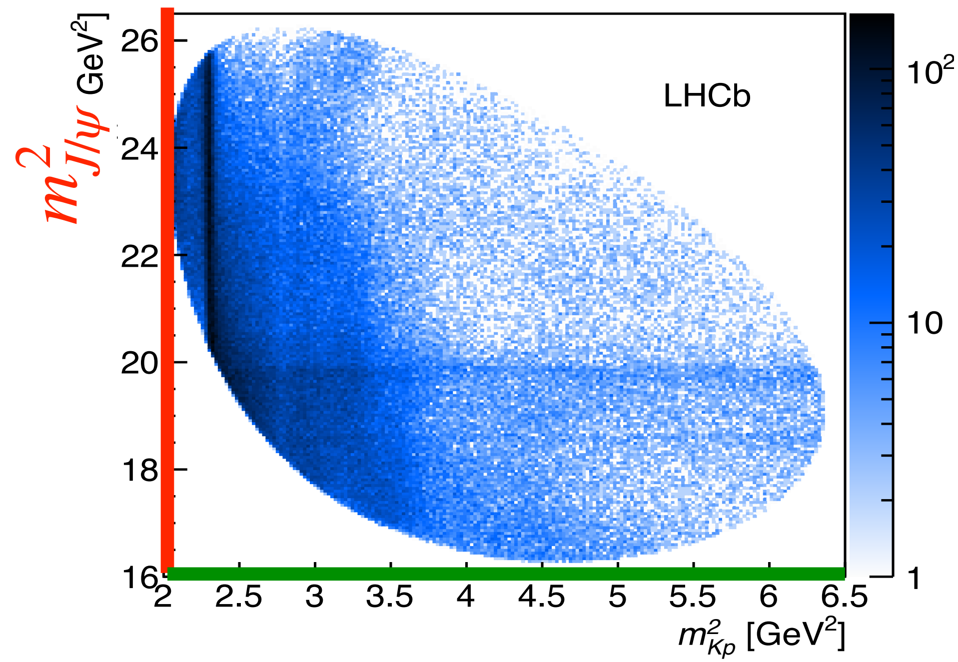


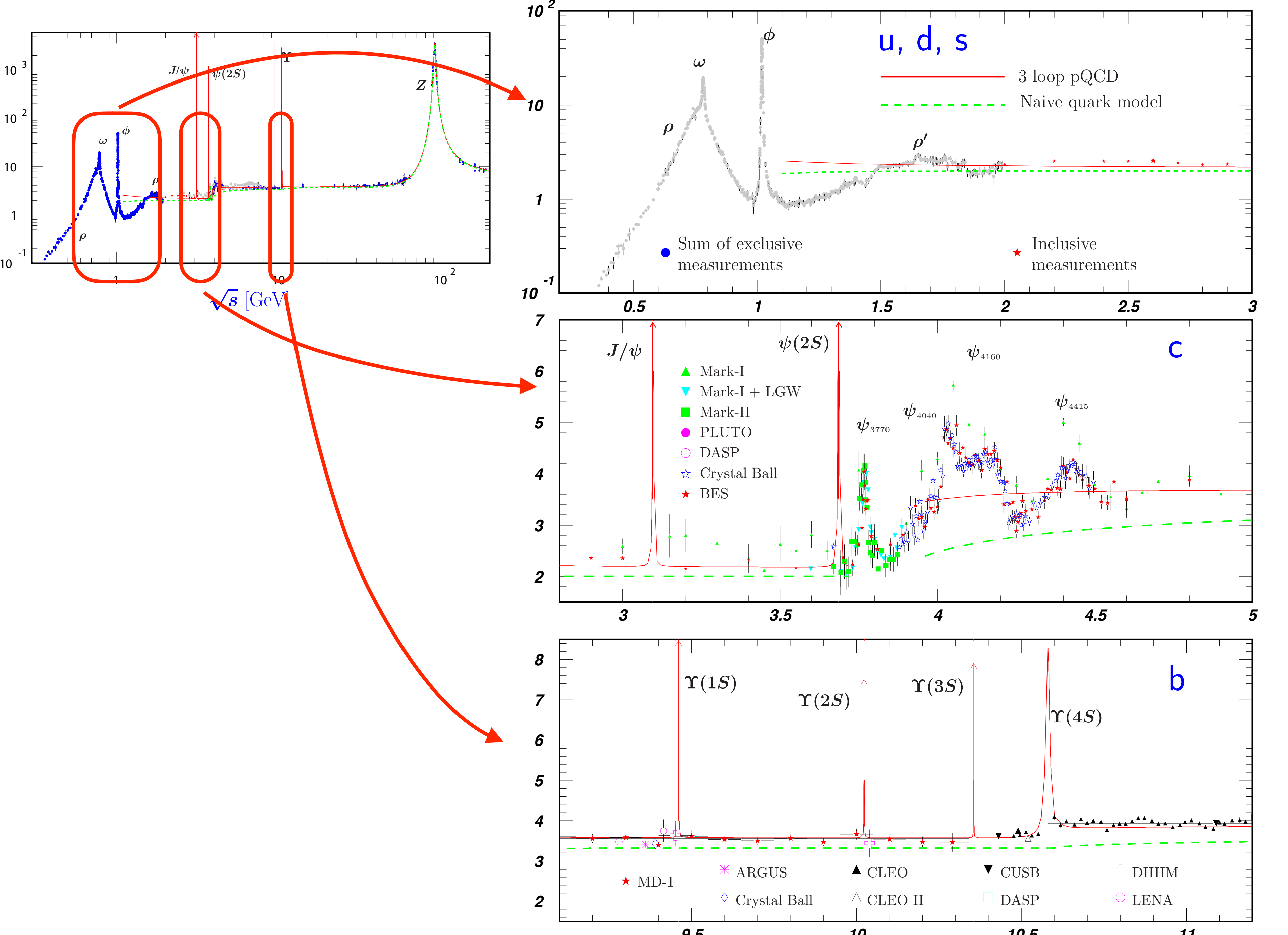
New Data from LHC

Dalitz plots for $m(\bar{K}p)$, $m(J/\psi\ p)$

2015 nine times more statistics → **2019**







J/ψ
ψ(2S)
Υ
Z
ρ
ω
φ
√s [GeV]
u, d, s
3 loop pQCD
Naive quark model
ρ′
Sum of exclusive measurements
Inclusive measurements
c
Mark-I
Mark-I + LGW
Mark-II
PLUTO
DASP
Crystal Ball
BES
ψ3770
ψ4040
ψ4160
ψ4415
b
Υ(1S)
Υ(2S)
Υ(3S)
Υ(4S)
MD-1
ARGUS
Crystal Ball
CLEO
CLEO II
CUSB
DASP
DHHM
LENA

Deuteron

Coupled channels of $N(s=1/2)$, $N(s=1/2)$

$J=0$ $NN(L=0)$, ~~but no $NN(L=2)$~~
$^1S_0$

$J=1$ $NN(L=0)$, $NN(L=2)$
$^3S_1$ $^3D_1$

Deuteron channel has attraction
due to the second order of the tensor force