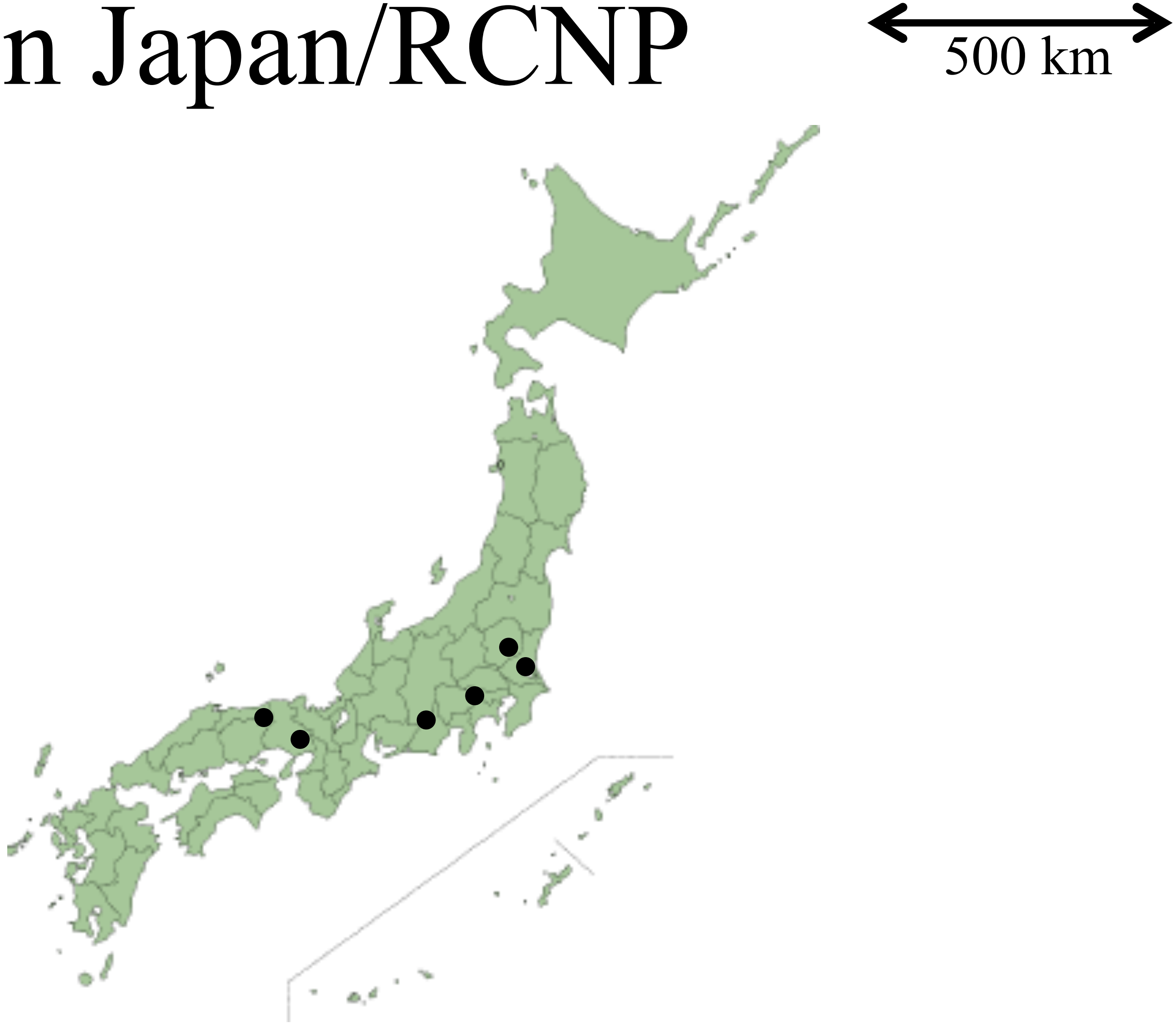
Seminars at FEFU, Vladivostok

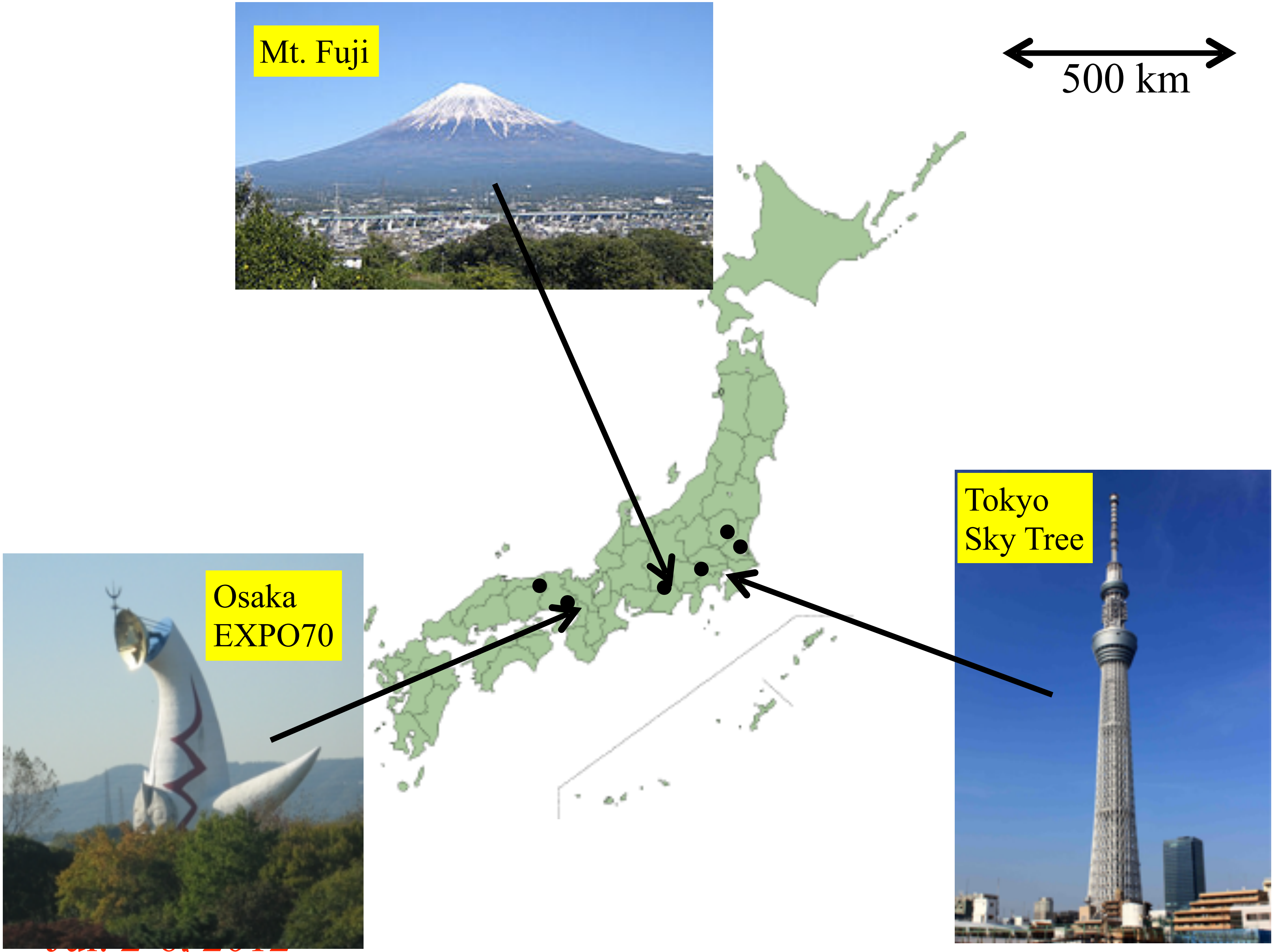
Atsushi Hosaka
Research Center for Nuclear Physics (RCNP)
Osaka Univ

Physics in Japan/RCNP

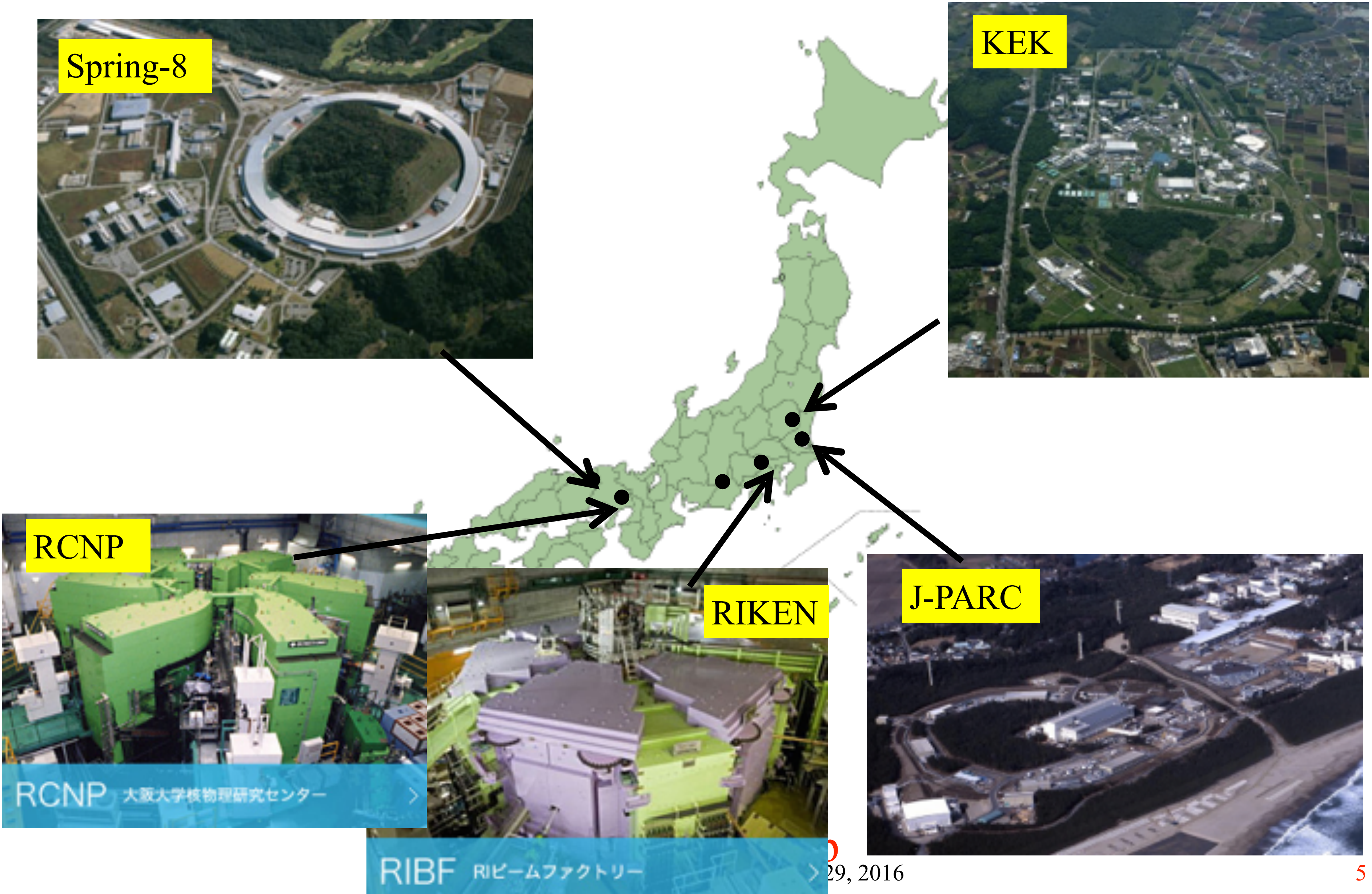


1500 km


Калининград
Мурманск
Санкт-Петербург
Москва
Нижний Новгород
Казань
Пермь
Краснодар
Самара
Екатеринбург
Астрахань
Омск
Новосибирск
Красноярск
Иркутск
Чита
Якутск
Хабаровск
Владивосток
Детальное покрытие
Базовое покрытие


Mt. Fuji
500 km
Osaka
EXPO70
Tokyo
Sky Tree

Accelerators in Japan



RCNP Cyclotron Facility

Mono-energetic neutron
核データ

RI Beam
原子核物理

Ultra Cold Neutron source
基礎科学

Ring Cyclotron
K=400 MeV, Since 1992

Grand Raiden
精密核物理

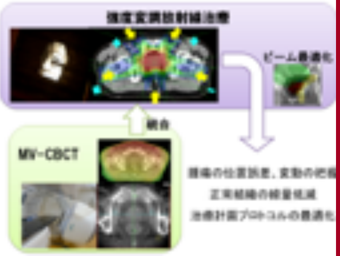
MuSIC
Muon science

White neutron
半導体ソフトエラー試験

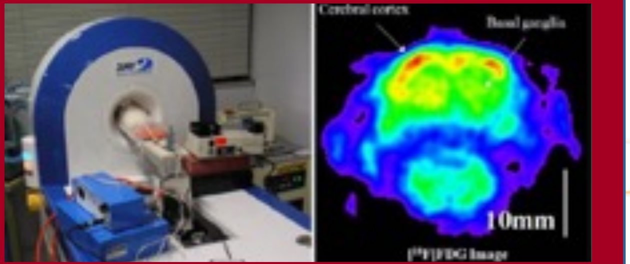
AVF Cyclotron
K=140 MeV, Since 1973

Osaka University Undertaking by cooperation among RCNP and Graduate School of Medicine and Science

Graduate School of Medicine



Radio therapy



PET&SPECT inspection

Medical and clinical applications of accelerator science, nuclear physics, radiation physics

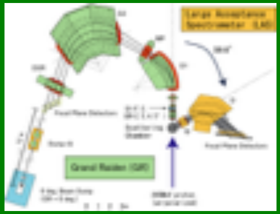
Training of medical physicists by higher education using accelerators

- Heavy-particle gantry
- Next generation BNCT
- High intensity compact accelerator

- Diagnostics
- Nuclear data

RI separation and synthesis

RCNP

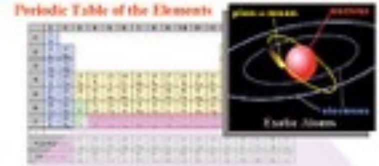


Nuclear physics

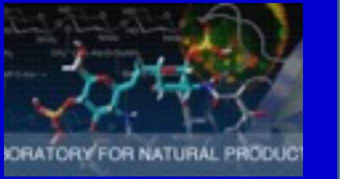
Accelerator

R I production

Graduate School of Science



Nuclear chemistry



Organic chemistry

LEPS@SPRing-8

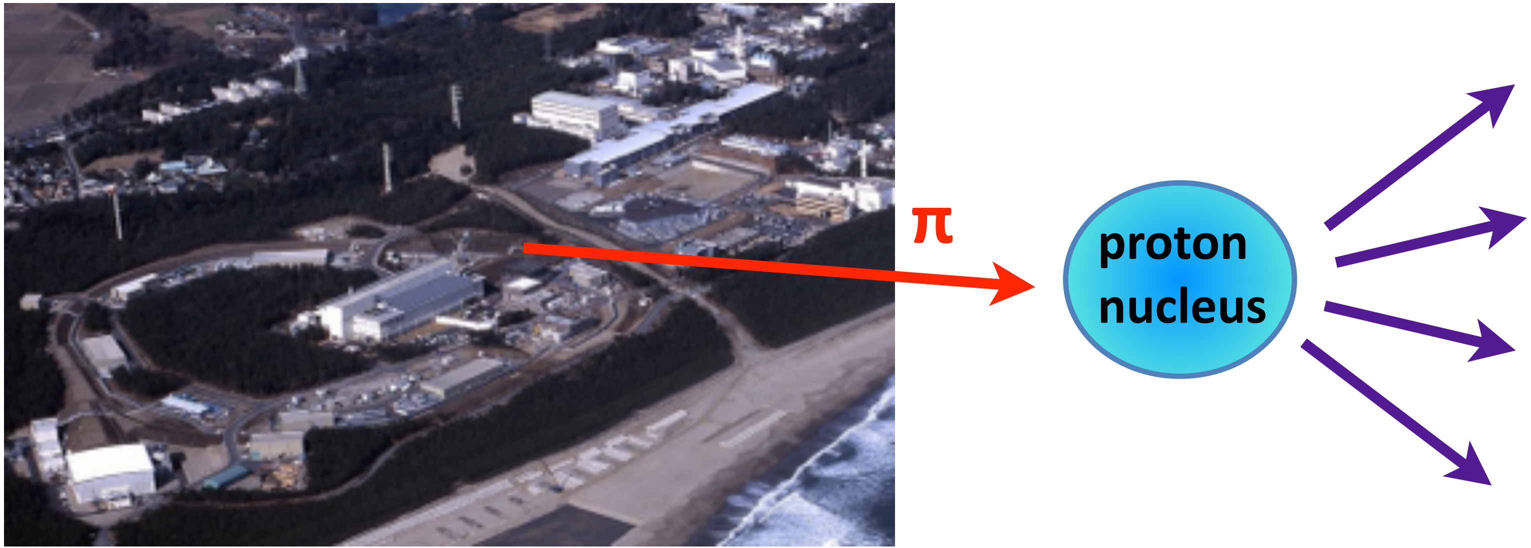
120 km distance from RCNP

Super Photon ring -8 GeV

- Third-generation synchrotron radiation facility
- Circumference: 1436 m
- 8 GeV, 100 mA
- 62 beamlines (Max)

- Physics objectives
  - Θ^+ study
  - $\Lambda(1405)$ with K^* photo-production
  - Modification of mesons in nucleus
  - Missing resonance search
  - K-NN search
  - Hyperon-nucleon interaction

J-PARC 600 km east from Osaka



50 GeV proton —> 30 GeV pion beam

Physics of charm hadrons

- Primarily single charm baryons, excited states
- Hidden charm baryons, pentaquark
- D, D* mesons and excited states
- Charmed nuclei

Proposal approved and physics discussions are going

Supercomputer

- Cooperating **SX-ACE (NEC)** vector processor ~ **393 TF**
- Spend about 20 million yen (~ 0.2 million dollar)/year
- ~ 100 users (about 10 foreign uses), ~ 30 active users
- Lattice QCD, Nuclear structure, Few-body, Supernova
- About 10-20 publications/year

Role in the community

High Performance Computer Infra
with the Japan largest supercomputer. KEI

Our recent activities

Exotic hadrons beyond qqq and qq^{bar}

Phenomena near and above thresholds

Hadronic molecules

Heavy quarks to disentangle correlations

Hadrons are strongly correlated systems

What are the effective degrees of freedom

Constituent quarks, diquarks, glueons*, …

I. Exotic hadrons beyond $q\bar{q}$, qqq

1. Introduction

QED: Lagrangian is ***simple*** and physics is ***understandable***

$$L = \bar{\psi}\left(i\not{\partial} + e\not{A} - m\right)\psi - \frac{1}{4}F^2$$

Can be a small parameter

QCD: Lagrangian is ***simple*** BUT physics is ***not easy***

$$L = \sum_f \bar{q}_f\left(i\not{\partial} + g\not{A} - m_f\right)q_f - \frac{1}{4}F^2$$

Depends on the physics scale

Basic features

- Elementary quarks and gluons are not observed/confined
- Observed hadrons are composites of strongly correlated quarks-gluons
- Vacua for quarks and hadrons are different→Phase structure
- Hadron properties are environment/vacuum dependent

– Chiral symmetry breaking
quark condensate

$$\langle \bar{q} q \rangle \neq 0$$

– Scale invariance violation
gluon condensate

$$\langle G_{\mu\nu} G_{\mu\nu} \rangle \neq 0$$

– Topological density
instanton vacuum

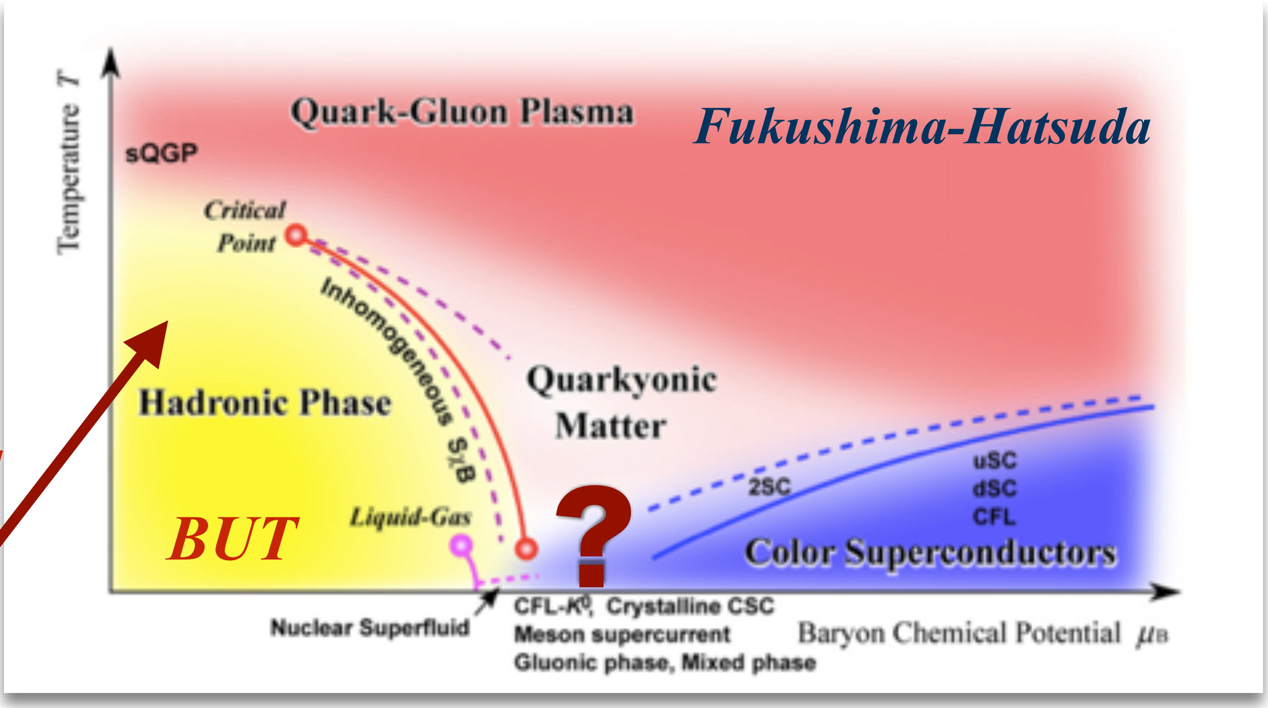
$$\langle G_{\mu\nu} \tilde{G}_{\mu\nu} \rangle \neq 0$$

– Color confinement
Polyakov loop

$$\left\langle \mathcal{P} \exp \left(i \int d\tau A_4 \right) \right\rangle = 0$$

Phases in QCD

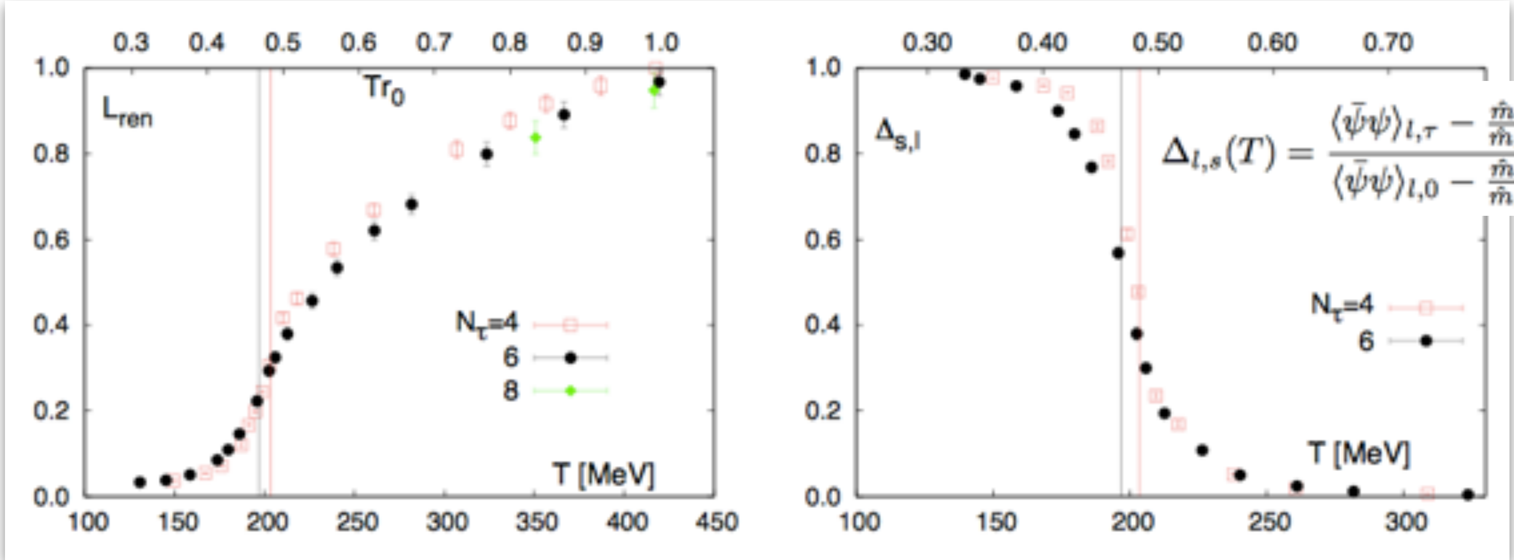
@ finite T
OK



Fukushima-Hatsuda

BUT

?



$$\Delta_{l,s}(T) = \frac{\langle\bar\psi\psi\rangle_{l,\tau} - \frac{\hat m_l}{\hat m_s}\langle\bar\psi\psi\rangle_{s,\tau}}{\langle\bar\psi\psi\rangle_{l,0} - \frac{\hat m_l}{\hat m_s}\langle\bar\psi\psi\rangle_{s,0}}$$

Spectroscopy

- Ground states are well described (lattice)
- Excited states/resonances are less described

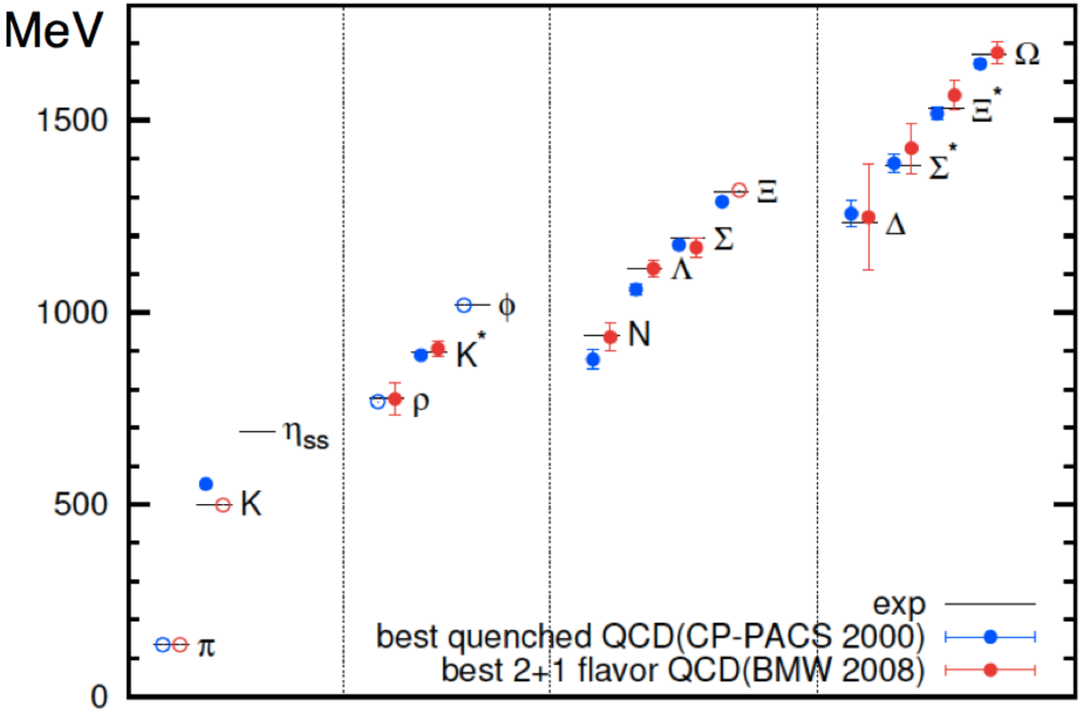
➡ Reactions (productions and decays) are neither

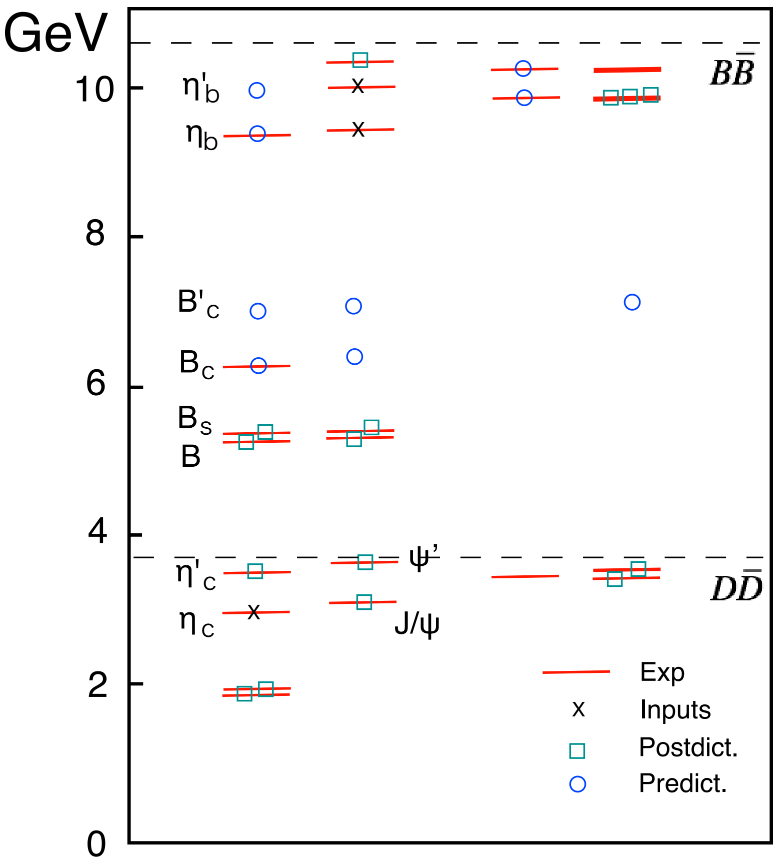
Focus on

- Why many hadrons are qqq and qq^{bar}?

Ground states are well described (lattice)

S. Aoki et al., Phys.Rev.Lett., **84**, 238–241 (2000), arXiv:hep-lat/9904012.
S. Durr, Z. Fodor, J. Frison, C. Hoelbling, R. Hoffmann, et al., Science, **322**, 1224–1227 (2008) arXiv:0906.3599.





K.A. Olive et al., Chin.Phys., **C38**, 090001 (2014).

Aoki Hatsuda Ishii, Phys.Rev.Lett. 99 (2007) 022001

⌗ **HAL QCD data are consistent with the quark Pauli effects.**

S=0

1 [33]

8_s [51]

27 [33], [51]

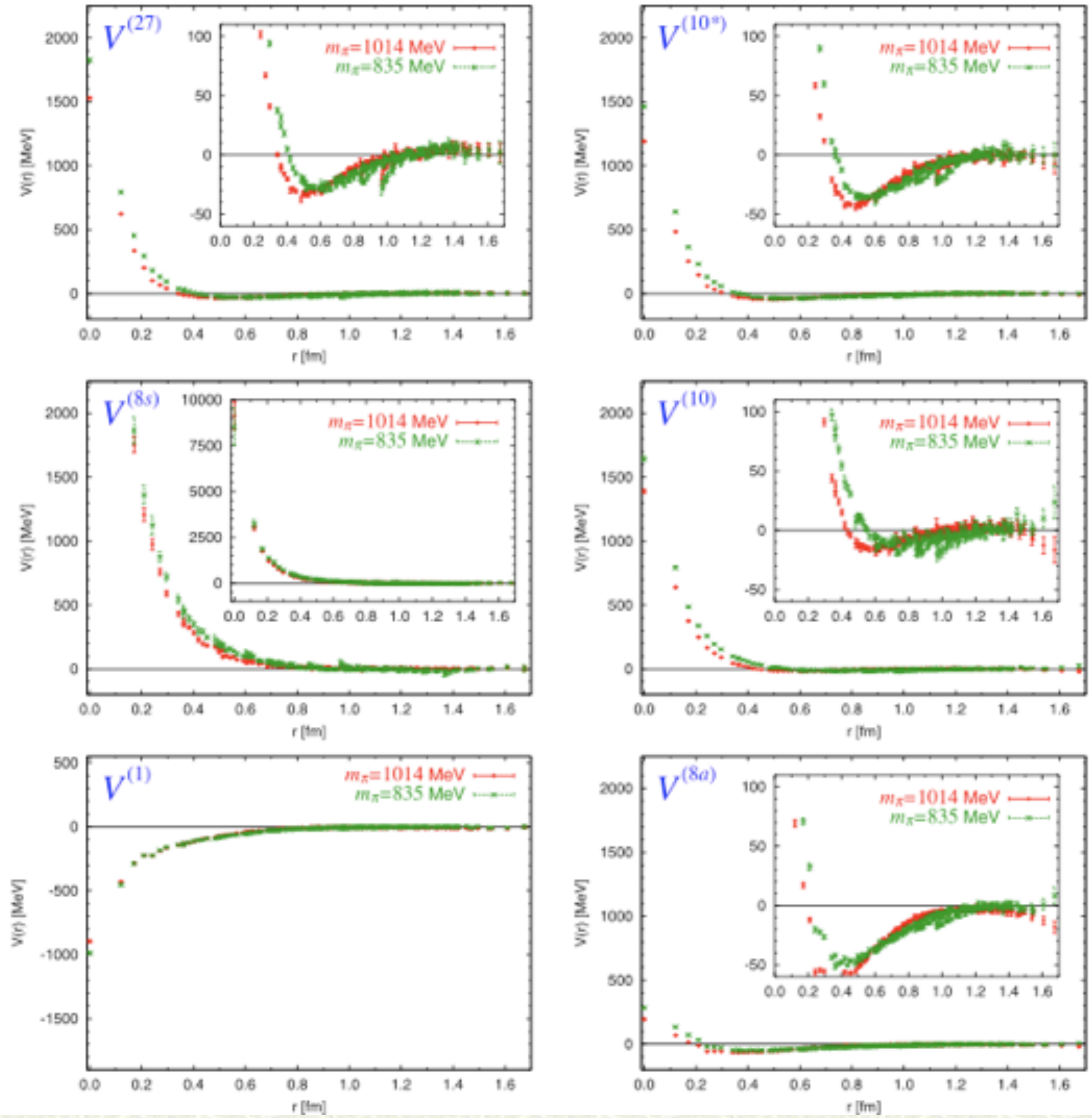
S=1

8_a [33], [51]

10 [33], [51]

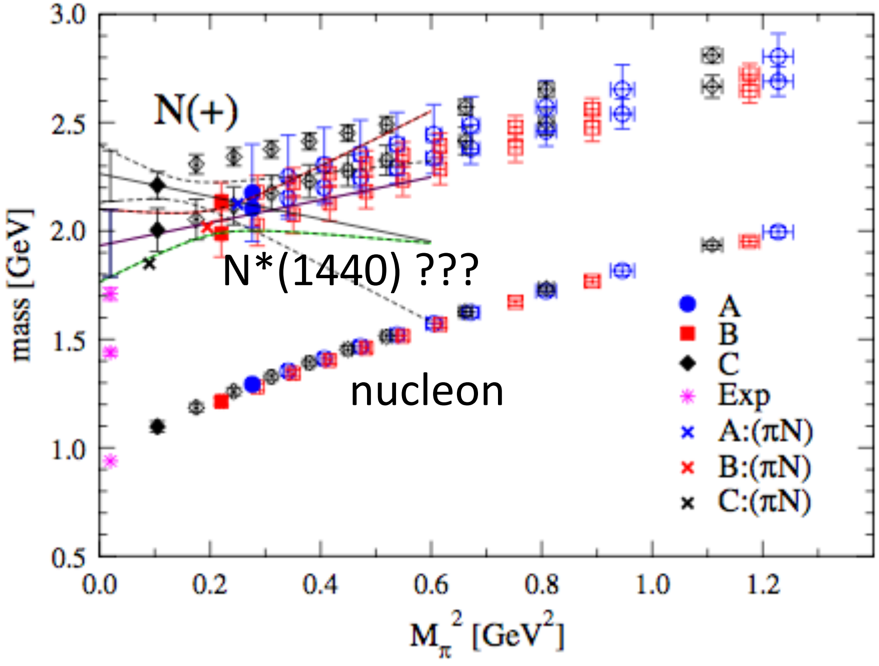
10* [33], [51]

T. Inoue et al., (HAL QCD) PTP 124, 591 (2010)



Excited states/resonances are less described

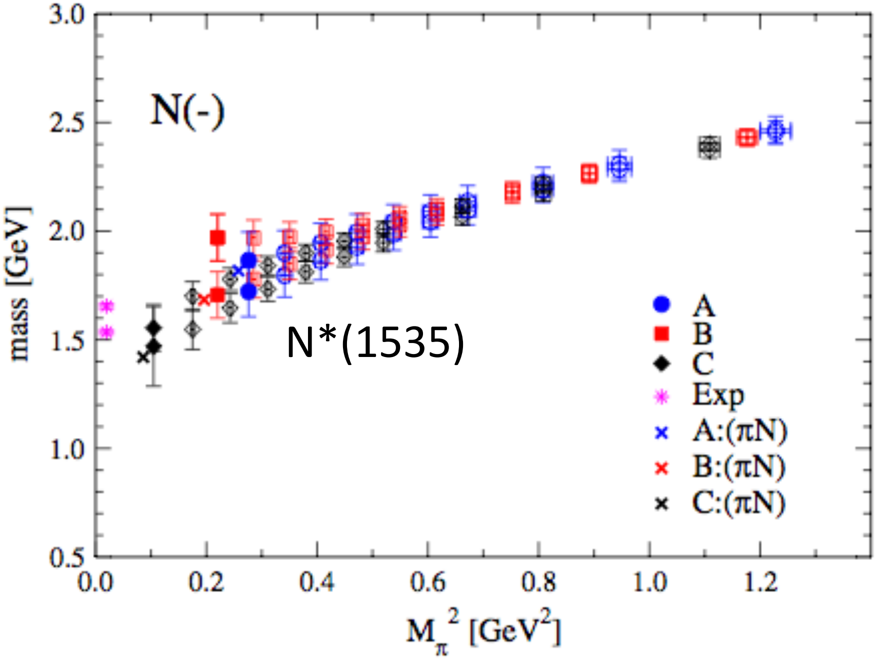
$N^*(1/2^+)$



N*(1440) ???

nucleon

$N^*(1/2^-)$

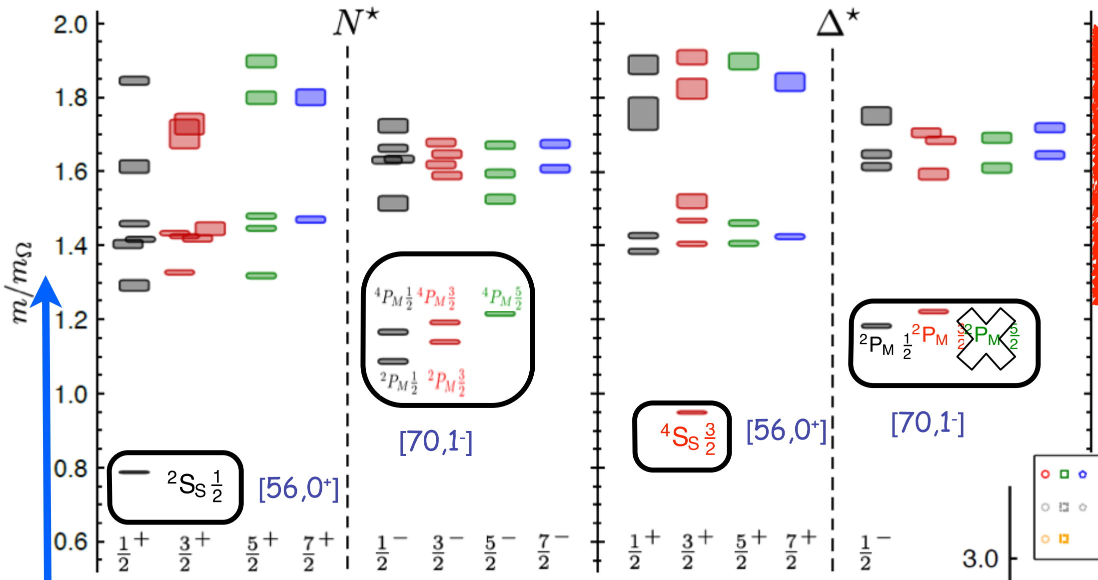


N*(1535)

G.P.Engel et al., BGR Coll., PRD82(2010)034505

Excited states/resonances are less described

David Richard, Talk at YITP, HHIQCD, Feb. 2015

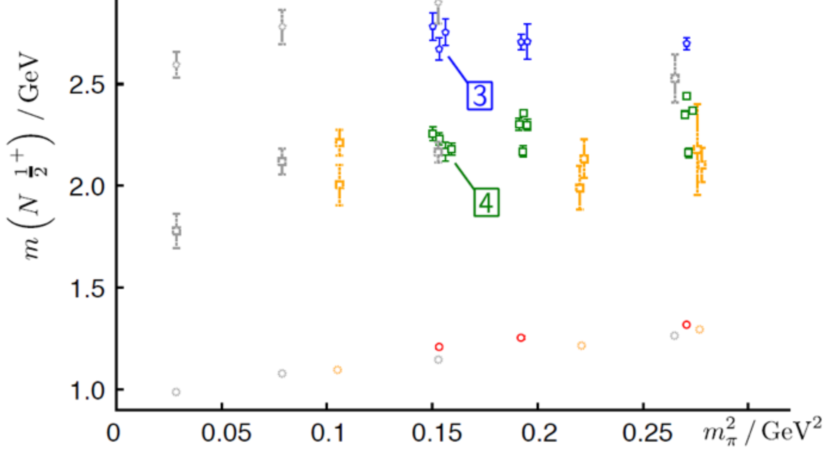


Broad features of SU(6)xO(3) symmetry.

Counting of states consistent with NR quark model.

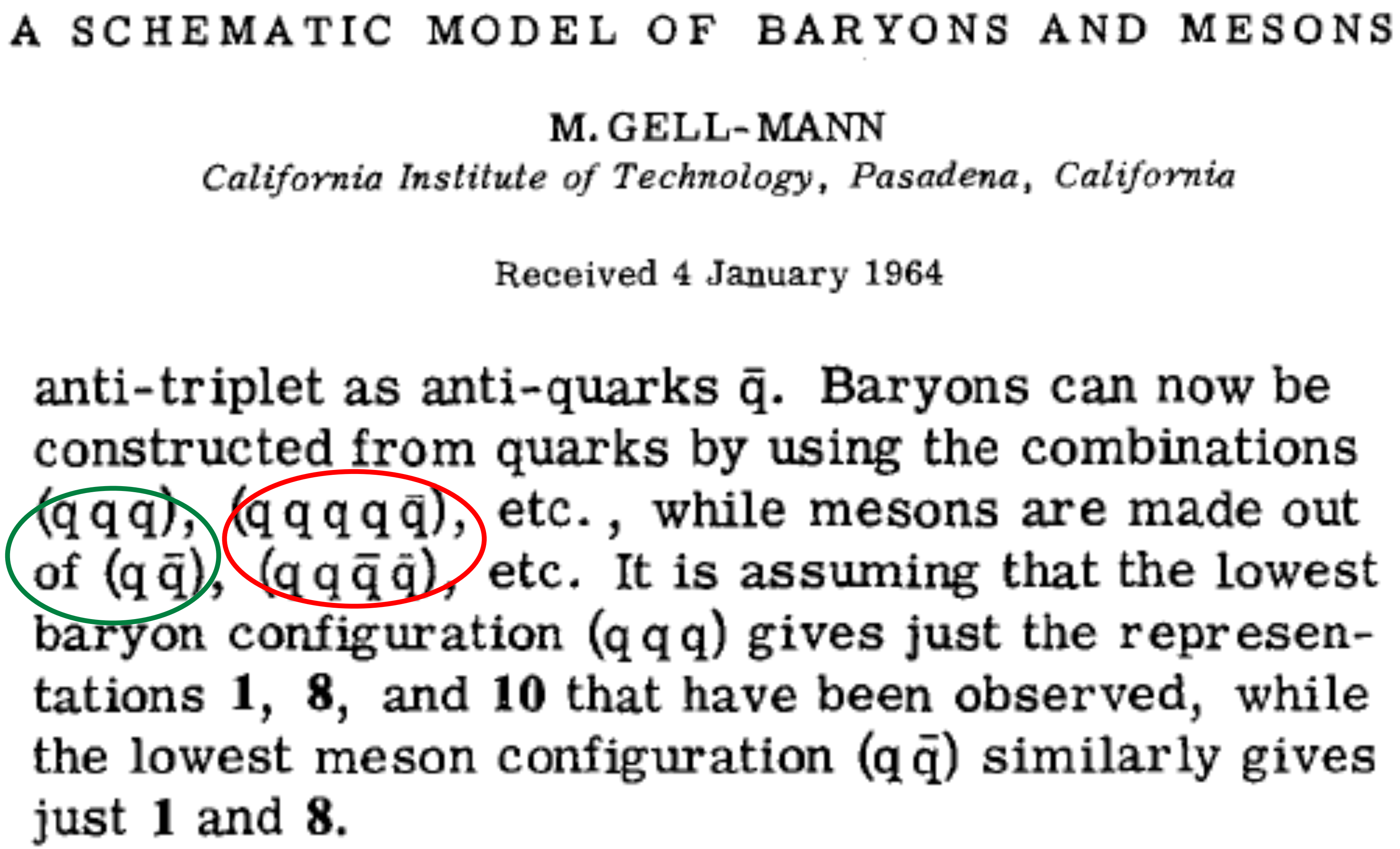
$[70,0^+],[56,2^+],[70,2^+],[20,1^+]$

N $^{1/2+}$ sector: need for complete basis to faithfully extract states



Why many hadrons are qqq and qq^{bar}?

Why many hadrons are qqq and qq^{bar}?



A SCHEMATIC MODEL OF BARYONS AND MESONS

M. GELL-MANN

California Institute of Technology, Pasadena, California

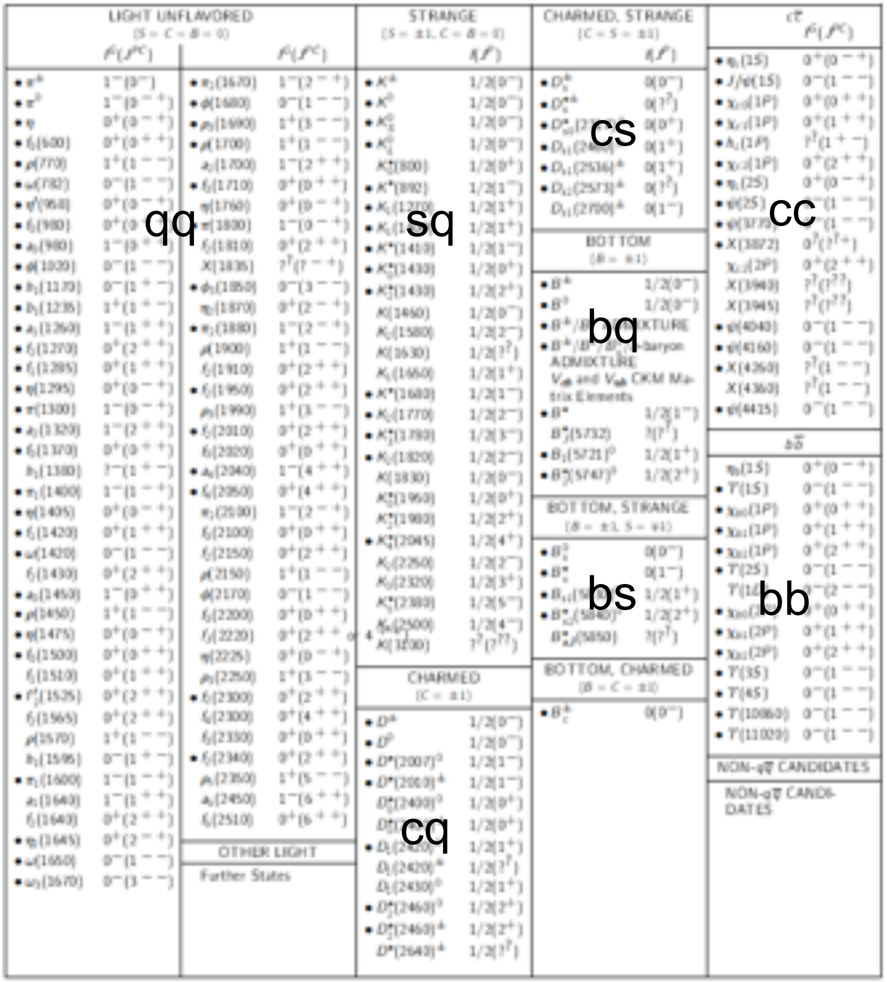
Received 4 January 1964

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 representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

Why many hadrons are qqq and qq^{bar}?

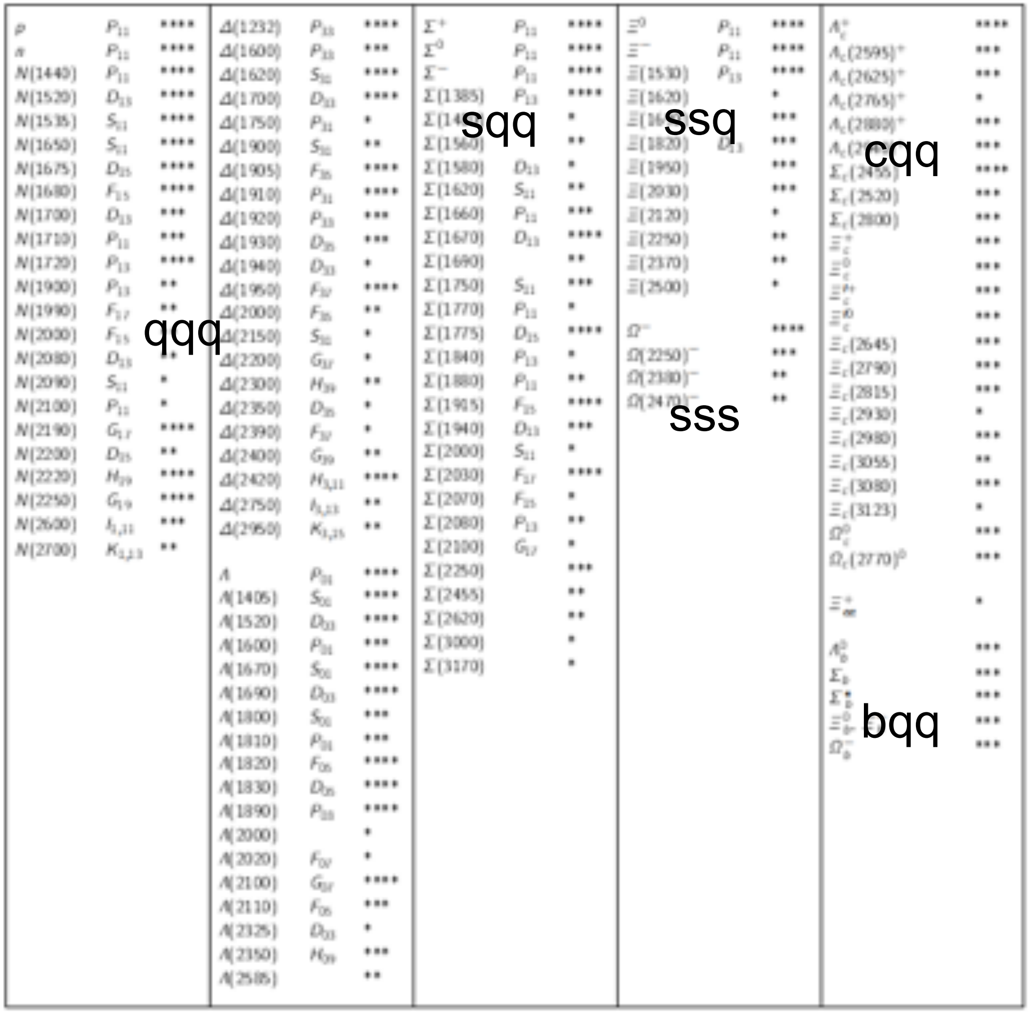
Particle Data Group

Mesons



25 kinds

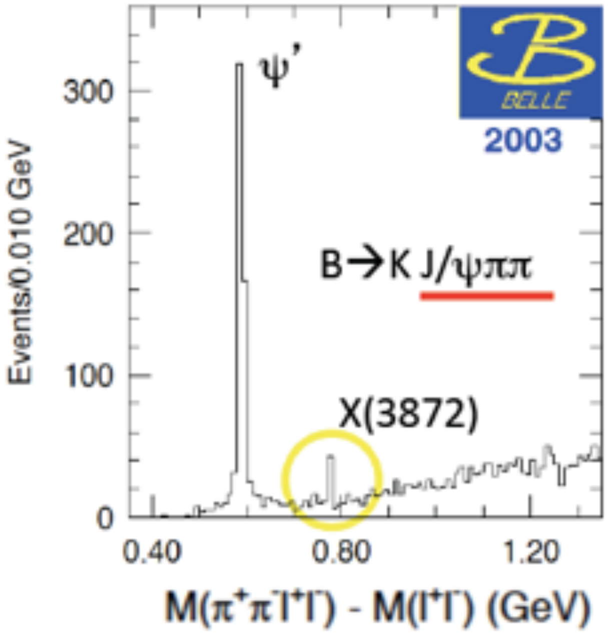
Baryons

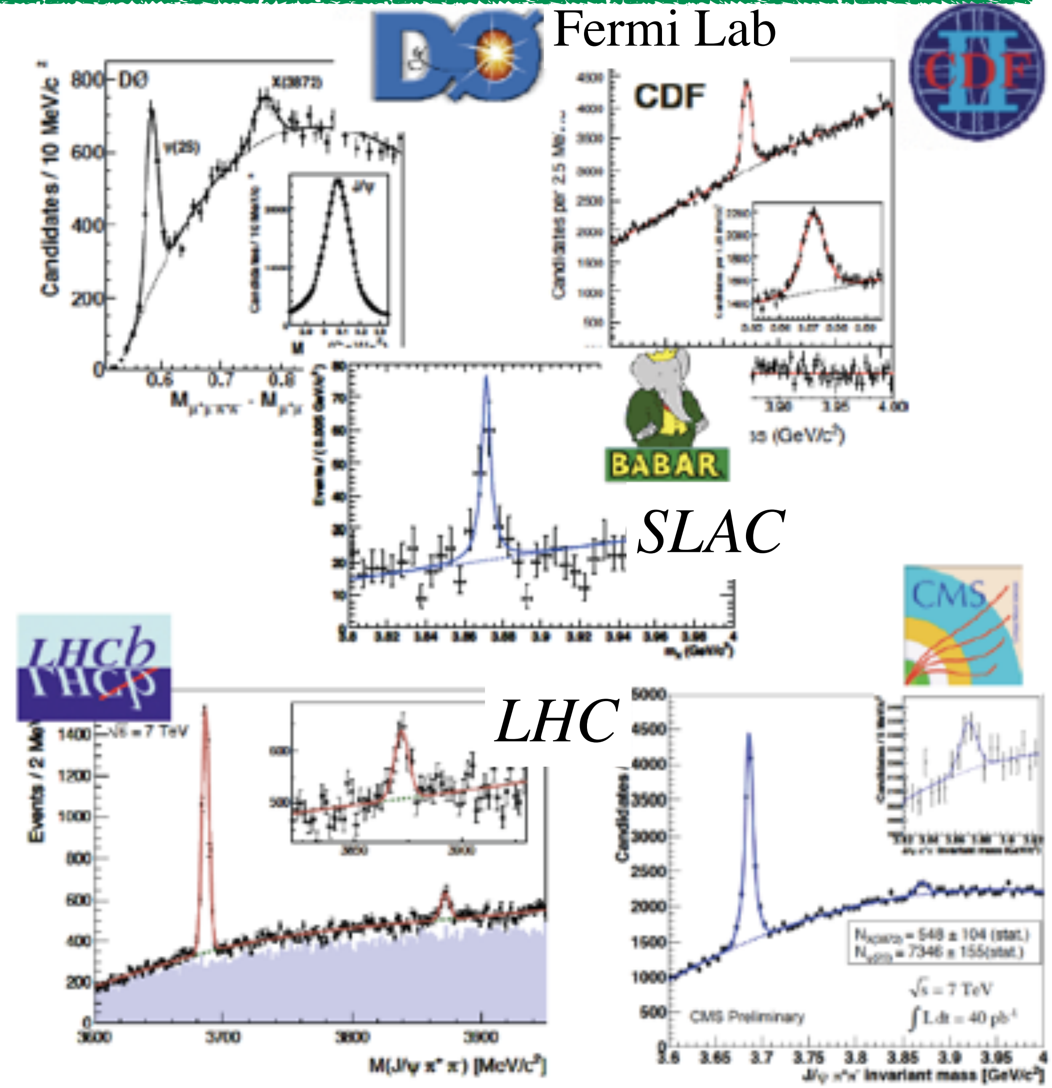


22 kinds

X (3872)

Discovery by Belle in 2003, followed by D0, CDF, BaBar **BES**





Fermi Lab

SLAC

LHC

And more recently also by LHCb, CMS

LHCb confirmed the tetraquark Z$^+$(4430)

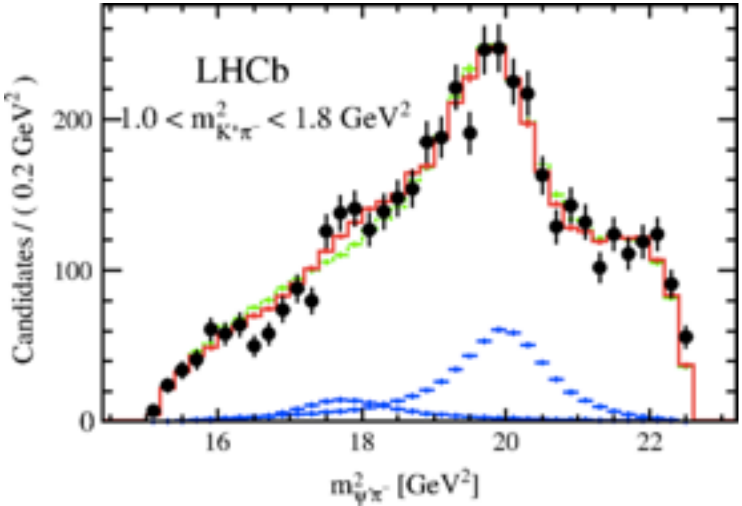
http://www.theguardian.com/science/life-and-physics/2014/apr/13/quarks-bonding-differently-at-lhcb

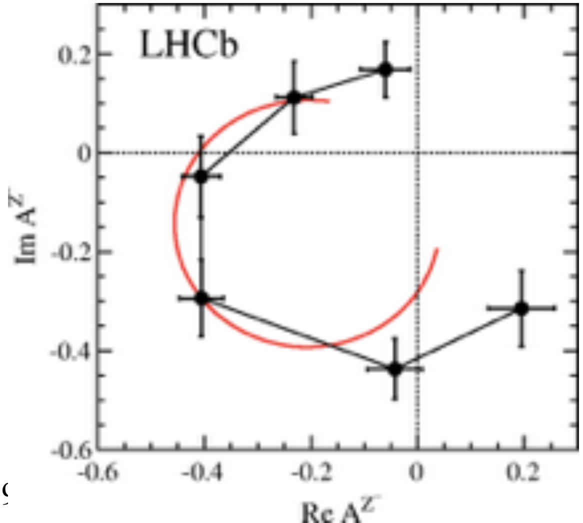
So until last week there were *two known types of hadron*.

……

LHCb has just confirmed what data from other experiments had already led us to suspect. *There is a third way.*

Phys. Rev. Lett. **112**, 222002

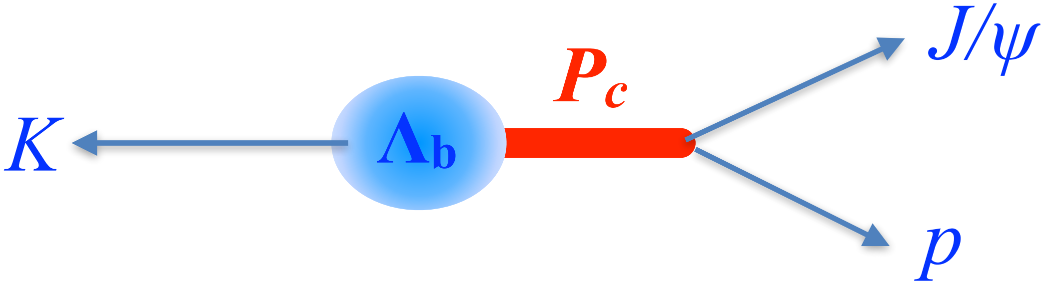


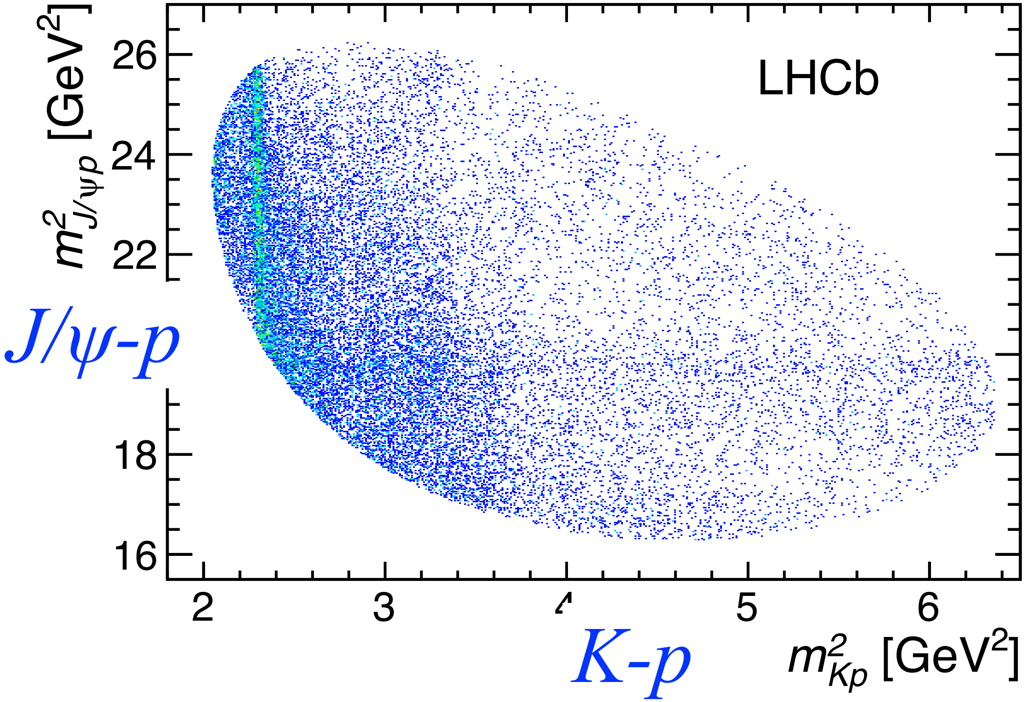


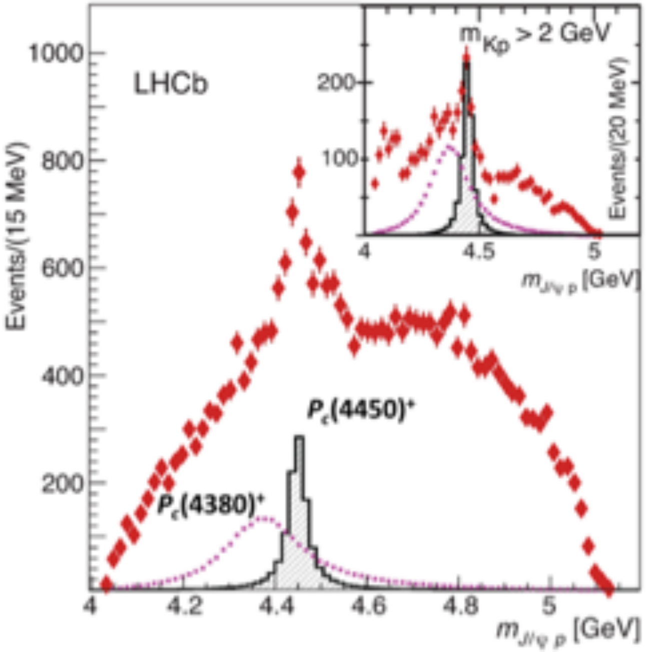
LHCb observed the Pentaquark P_c

R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **115**, 072001 (2015)

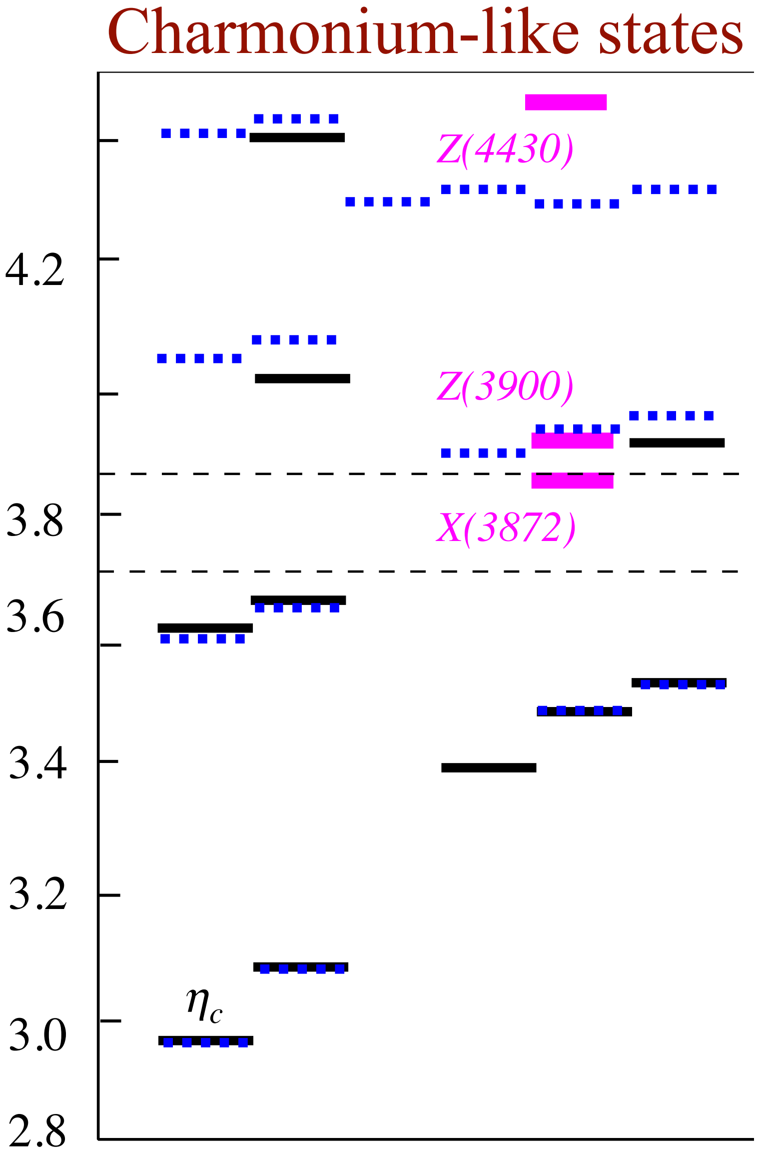
7-8 TeV pp collision —> Λ_b





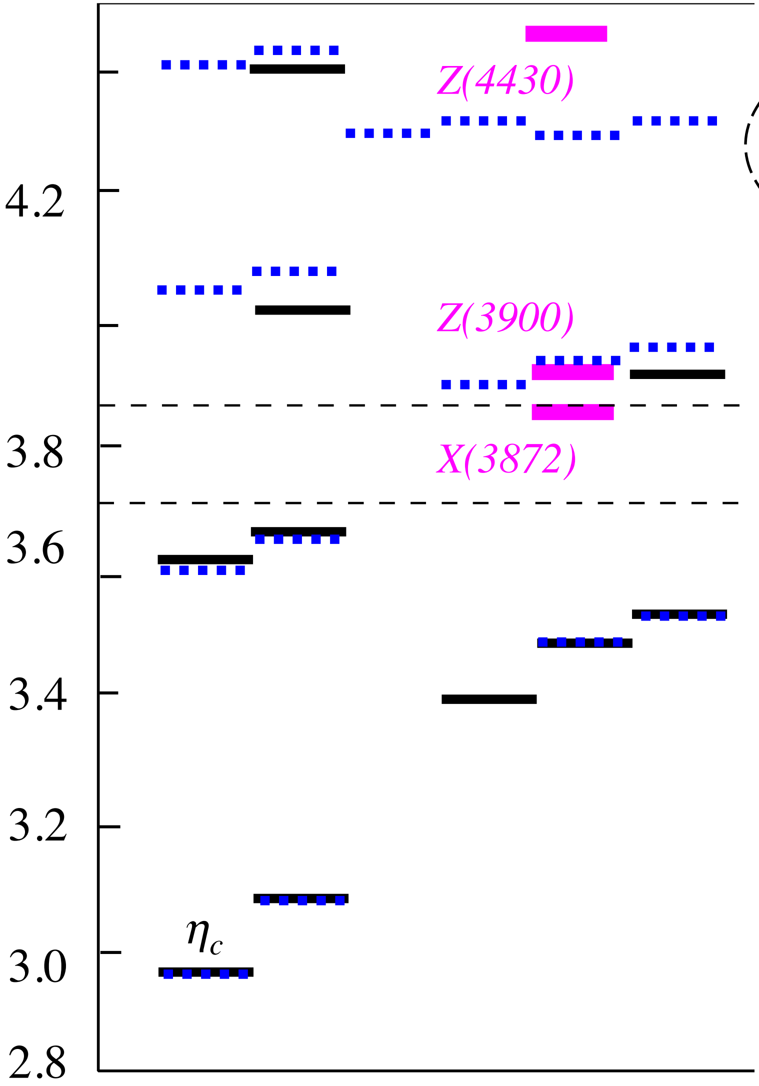


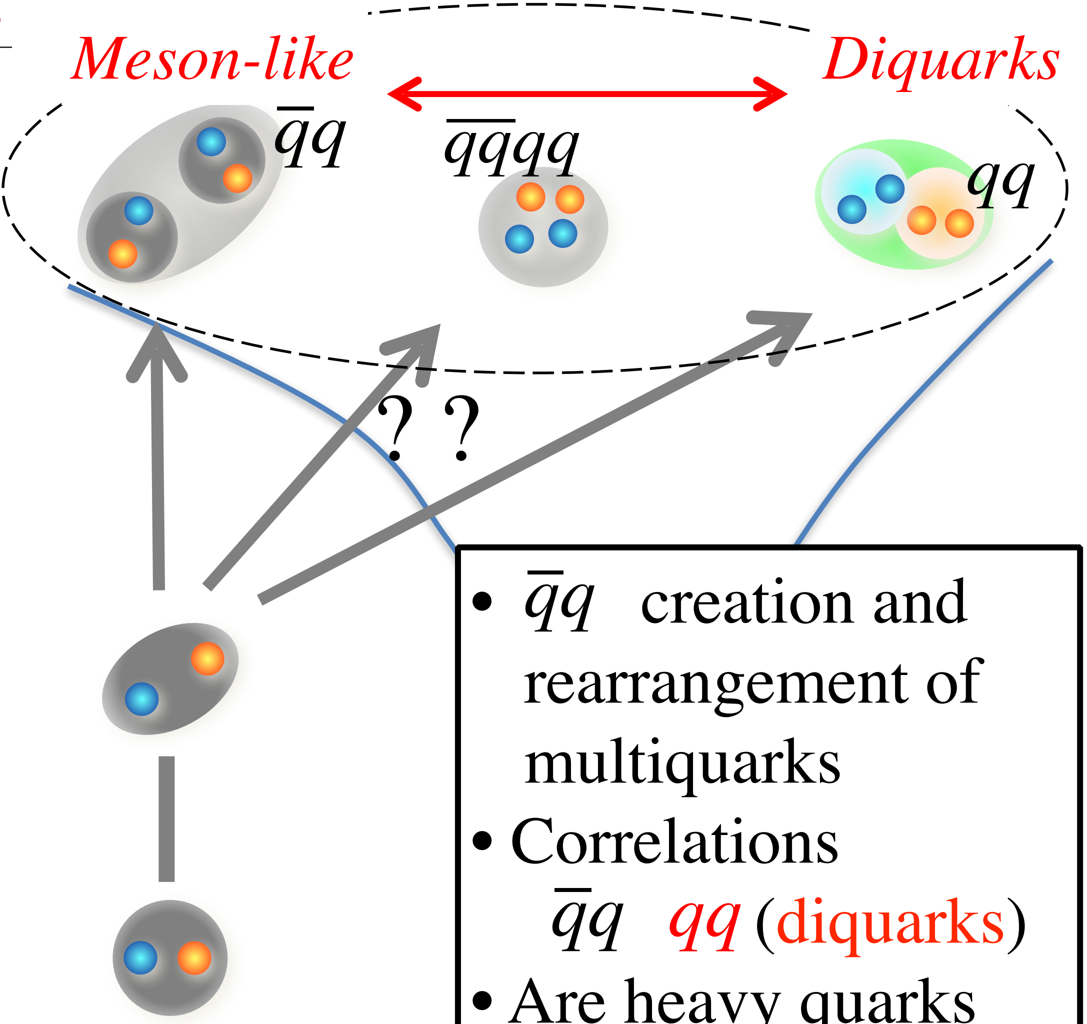
Threshold phenomena



Threshold phenomena

Charmonium-like states





- $\bar{q}q$ creation and rearrangement of multiquarks
- Correlations
  $\bar{q}q$ qq (diquarks)
- Are heavy quarks useful to know it?

Important ingredients

- Heavy particles are easily bound

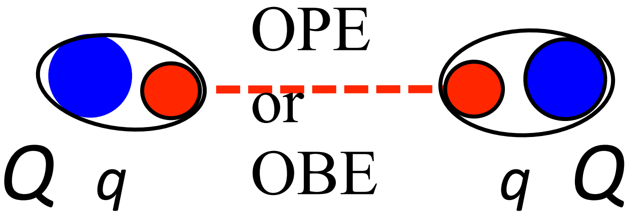
Kinetic energy is suppressed

Spin dependent int. is suppressed

$$\mathcal{L}_{\rm heavy} = \bar{Q}_v \left(v\cdot iD + i\not{D}_\perp \frac{1}{2m_{\rm Q} + v\cdot iD} i\not{D}_\perp \right) Q_v$$

Spin-dependent term

- Pion (meson) exchange between light quarks



Hadron dynamics based on **chiral symmetry**

Hadronic molecules

- $\Lambda(1405)$ as KN

  $s\bar{u}$ uud ~ $K^{-}p$ molecule

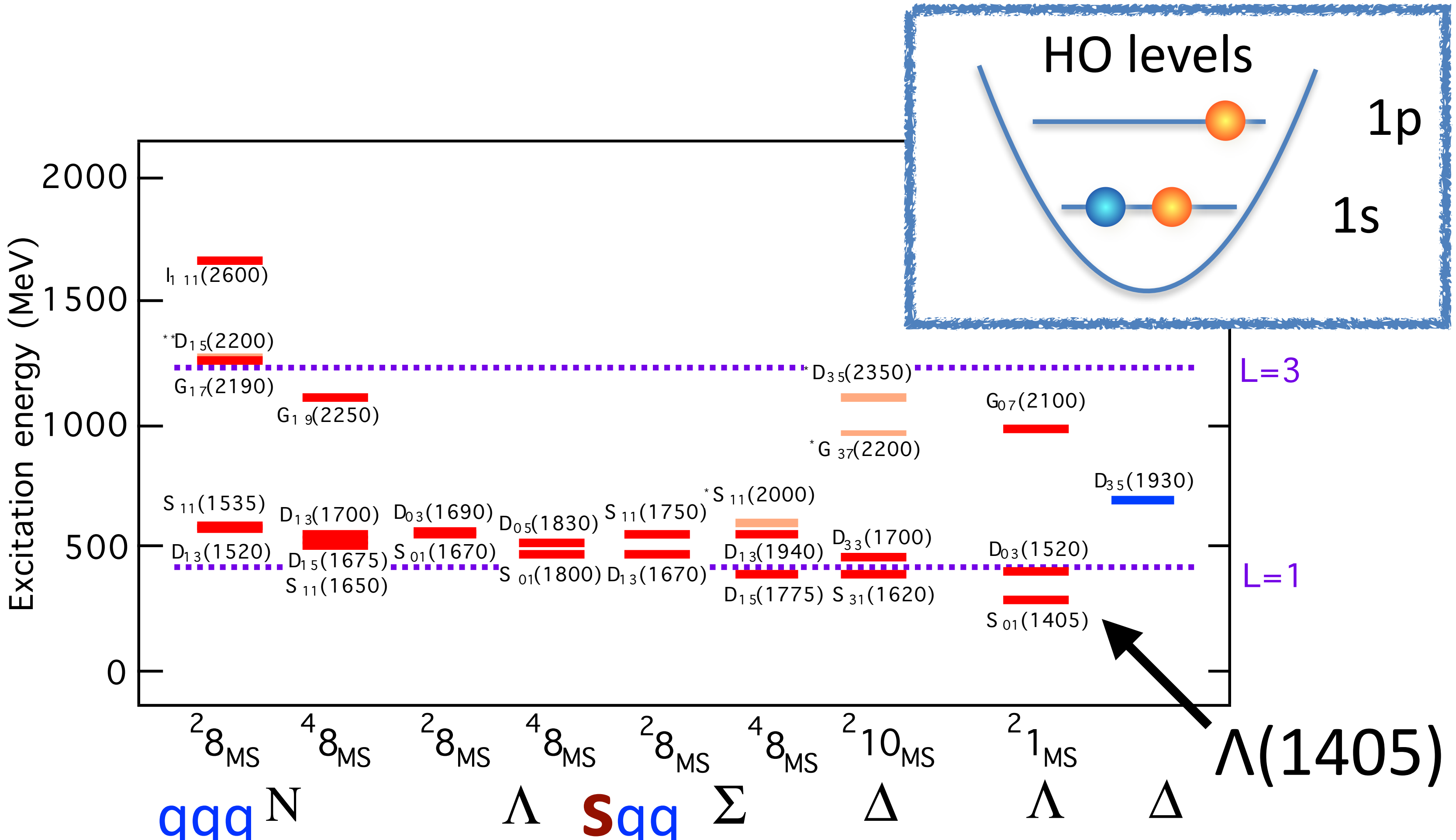
- $\bar{D}N$ and BN

  $\bar{c}qqqq$ $\bar{b}qqqq$

- Z_b and related

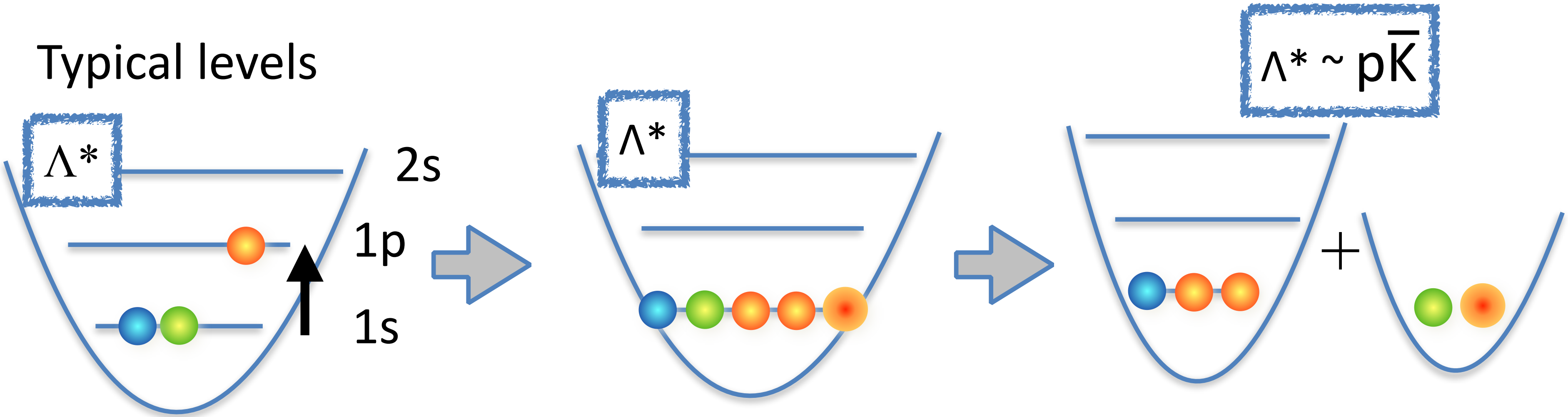
(1) Λ(1405) as $\bar{K}N$

The lightest negative parity baryon excitation of strangers –1 though it contains the strange quark



(1) $\Lambda(1405)$ as $\bar{K}N$

The lightest negative parity baryon excitation of strangers –1 though it contains the strange quark



Sufficient energy to create $q\bar{q}$

sud can be $s\bar{u}$ uud ~ K^-p molecule

R. H. Dalitz and S. F. Tuan, Ann. Phys. 10 (1960) 307

SU(3) coupled channel model

E. Oset and A. Ramos, Nucl. Phys. **A635**, 99 (1998)
Hyodo, Nam, Jido, Hosaka, Phys.Rev. C68 (2003) 018201

$$\begin{array}{cc|cccc}
S=-1 & & & I=0 & & \\
 & & \bar{K}N & \pi\Sigma & \eta\Lambda & K\Xi \\
\hline
I=0 & \bar{K}N & 3 & -\sqrt{\frac{3}{2}} & \frac{3}{\sqrt{2}} & 0 \\
 & \pi\Sigma & & 4 & 0 & \sqrt{\frac{3}{2}} \\
 & \eta\Lambda & & & 0 & -\frac{3}{\sqrt{2}} \\
 & K\Xi & & & & 3
\end{array}$$

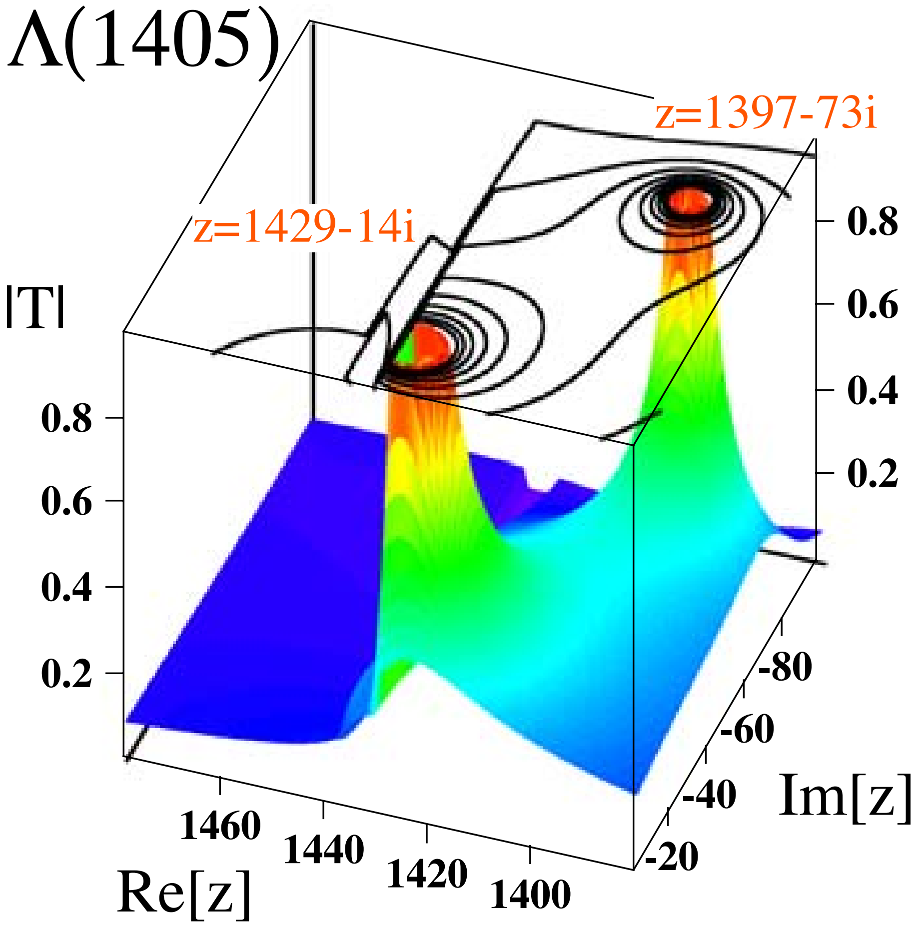
⬅ channels, *i*, *j*, ...

⬅ Interaction strengths

Chiral Lagrangian
Weinberg-Tomozawa

Two poles for Λ(1405)

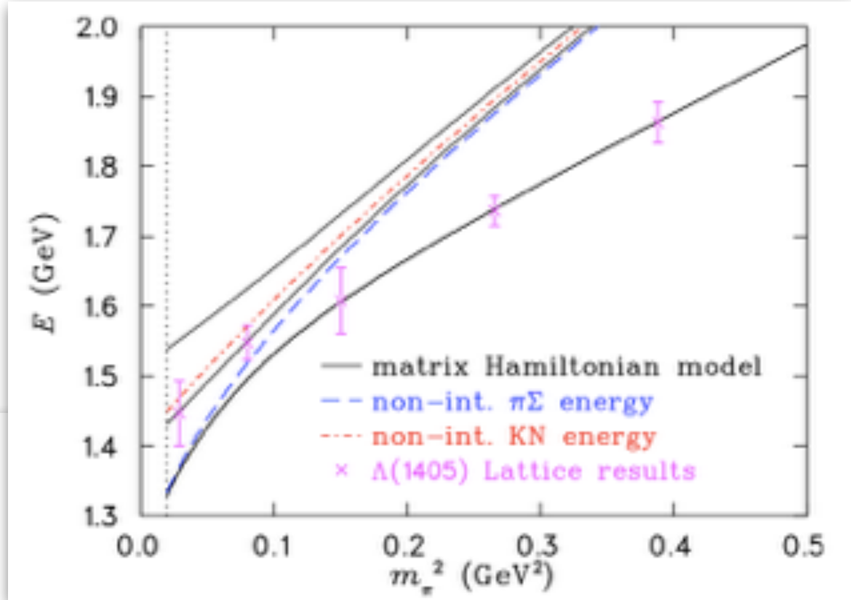
Hyodo-Jido-Hosaka, Phys.Rev. C78 (2008) 025203
T. Hyodo, Doctor thesis, 2006

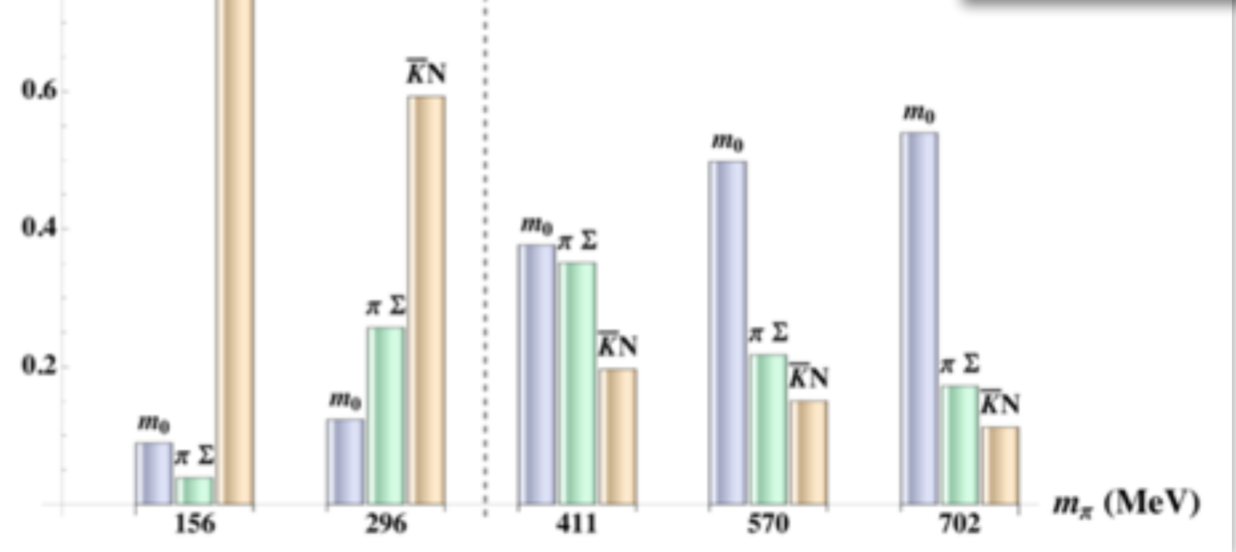


Λ(1405) in a lattice

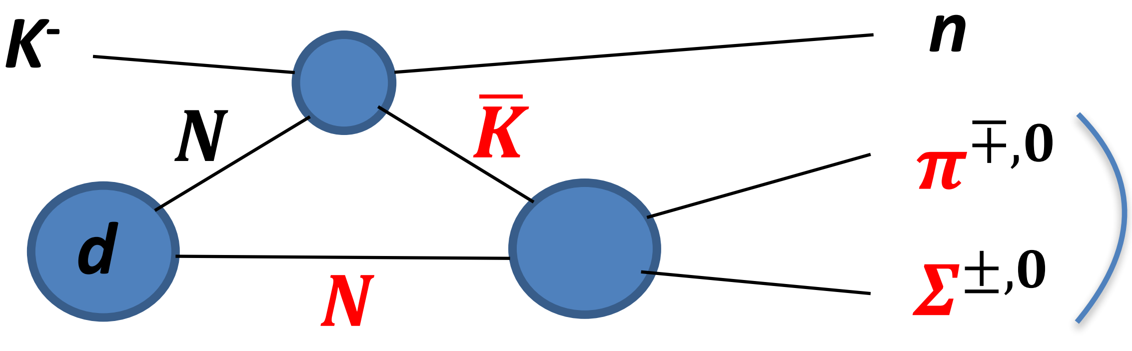
Jonathan M. M. Hallet al (Adelaide)
Phys.Rev.Lett. 114 (2015) no.13, 132002

KN dominance
toward the physical point

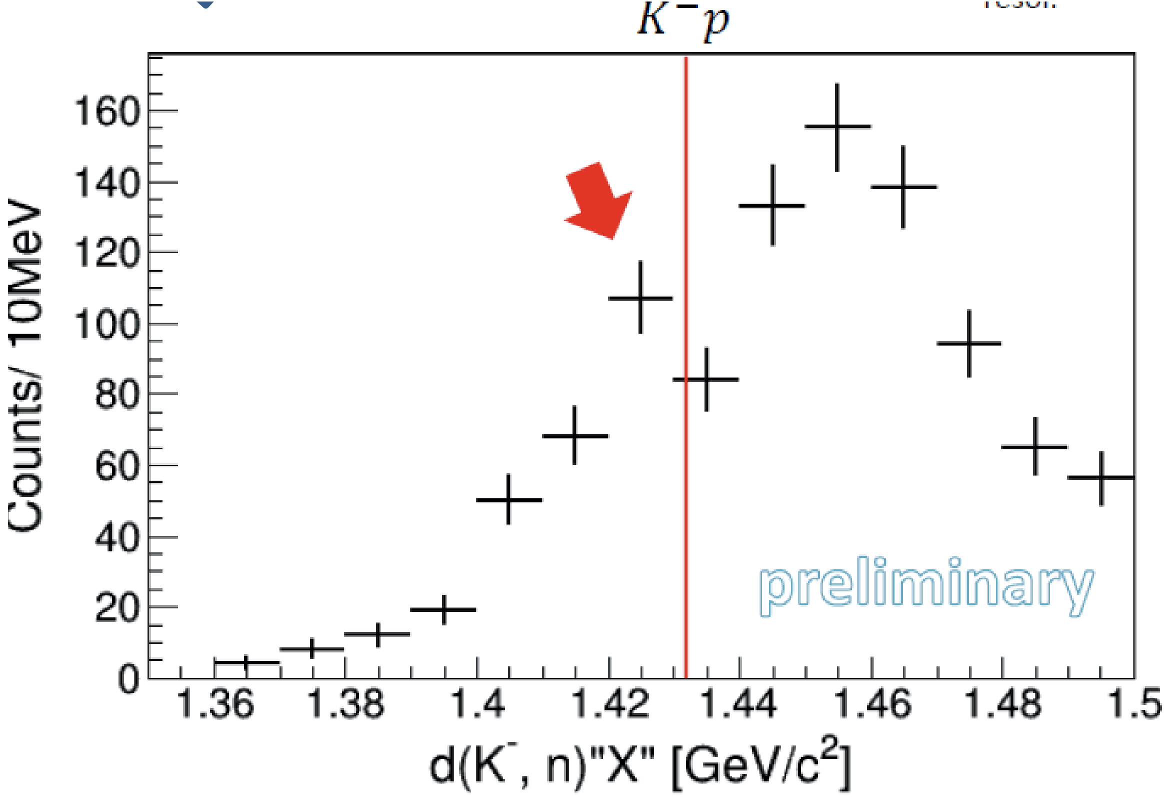




J-PARC experiments



Missing Mass Spectrum



$\Lambda(1405) \sim \bar{K}N \sim s\bar{u}uud$

has an annihilation channel ~ sud

$\Theta^{+}(1520) \sim KN \sim \bar{s}uudd$

has no annihilation channel

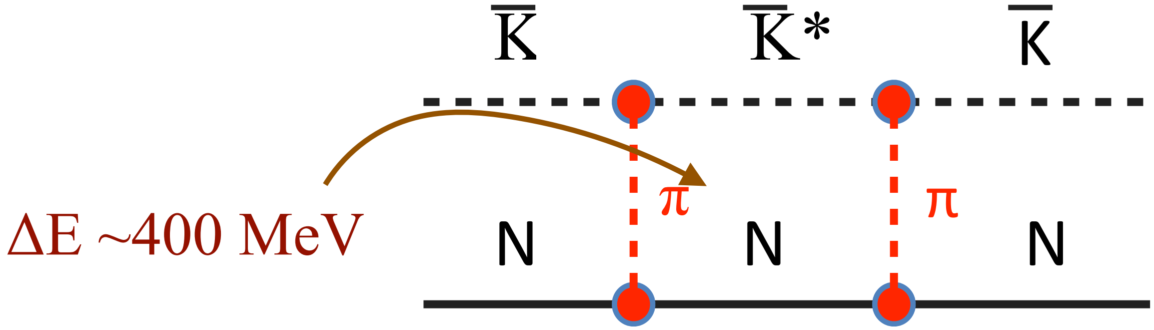
Comparison: sud ($\bar{K}N$) vs $\bar{s}$uudd (KN: Pentaquark)

$\bar{K}N$

- Sufficient attraction due to annihilation channel
- Kaon has two faces
  light (chiral dynamics) and
  heavy (kinetic motion suppressed)

KN

- No KN coupling from WT
- OPEP is possible but does not work sufficiently



ΔE ~400 MeV

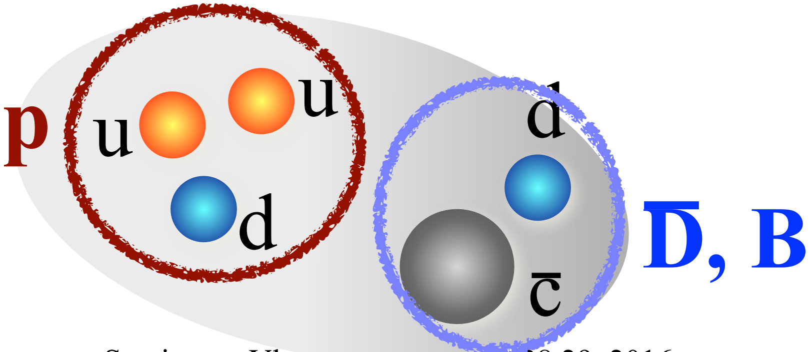
This is to be compared with the NN force ΔE = 0

(2) $\bar{D}N$ and BN

Yamaguchi, Yamaguchi, Yasui and Hosaka
Phys.Rev.D84:014032 (2011), D85,054003 (2012)

Ohkoda, Yamaguchi, Yasui and Hosaka
Phys.Rev. D86: 034019, 014004, 117502 (2012)

Genuinely exotics with no annihilation



$\bar{D}N$ loosely bound and resonance states

Yasui-Sudoh, PRD80, 034008, 2009

Yamaguchi-Ohkoda-Yasui and Hosaka, PRD84:014032,2011

Heavy Q symmetry
$\bar{D} \sim \bar{D}^*$

→

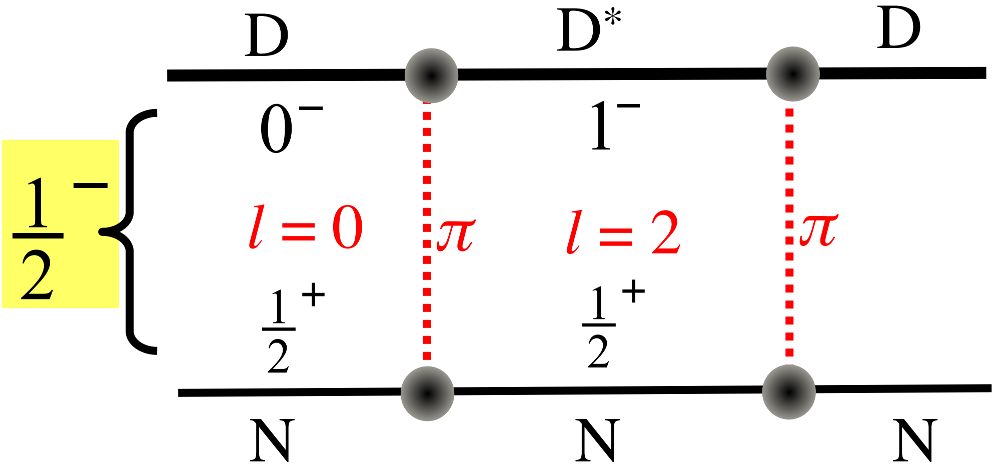
Coupled channels
of $\bar{D}N(S)$, $\bar{D}^*N(S)$, $\bar{D}^*N(D)$

Spin-dependent force suppressed

$$m_{K^*} - m_K \sim 400\ MeV$$

$$m_{D^*} - m_D \sim 140\ MeV$$

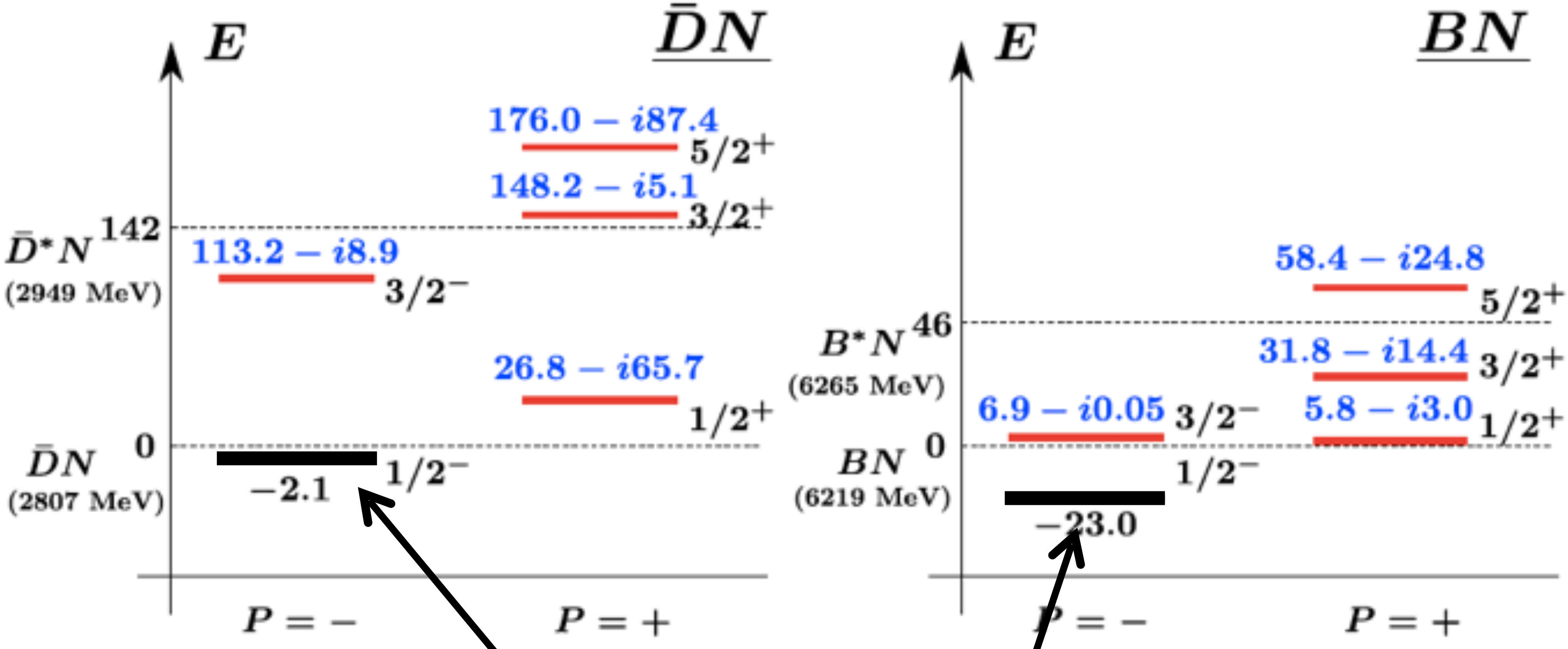
$$m_{B^*} - m_B \sim 45\ MeV$$



Tensor of OPEP

$\bar{D}N$ loosely bound and resonance states

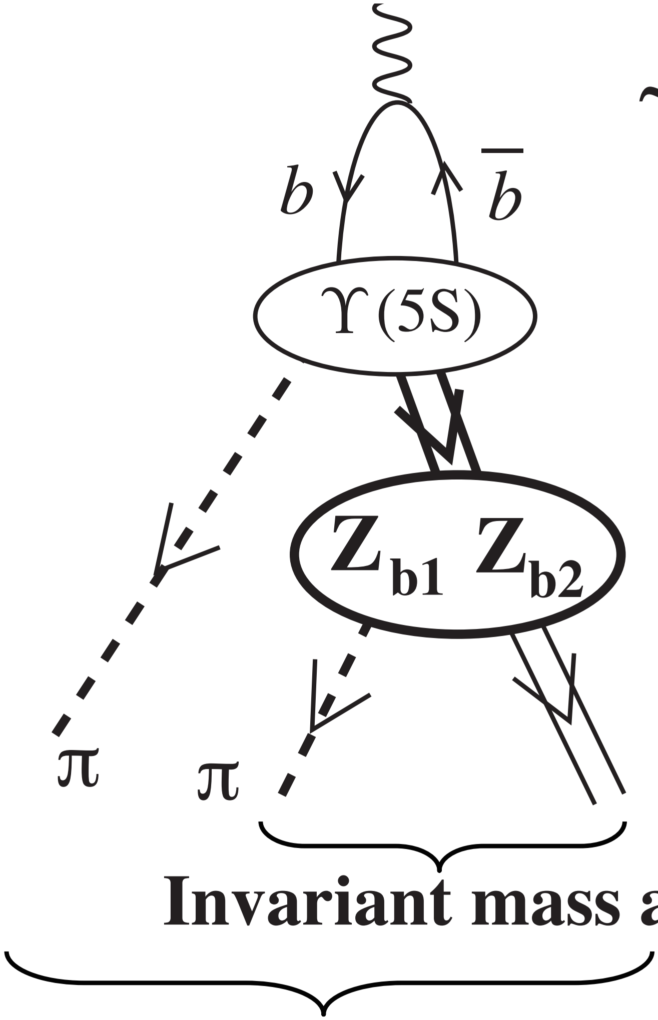
Phys.Rev.D85,054003 (2012)



	$\bar{D}N$	BN
E_B	2.14 MeV	23.0 MeV
size	3.2 fm	1.2 fm

$Z_b(10610, 10650)$ $b\bar{b}u\bar{d}$

arXiv:1105.4583v1 [hep-ex];
PRL 108, 032001 (2012)



~11 GeV

10860

- Charged particle

==>

- Must contain $b\bar{b}$
- and light $q\bar{q}$

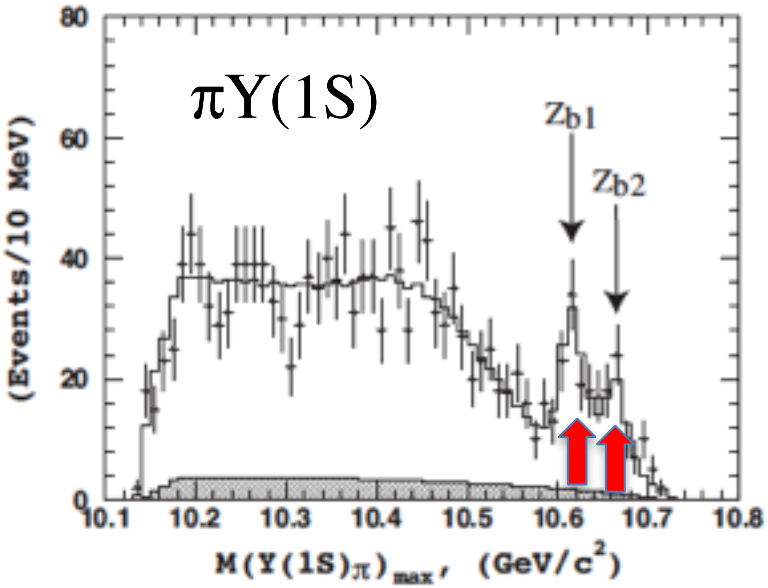
10653, 10608 $I^G(J^P) = 1^+(1^+)$

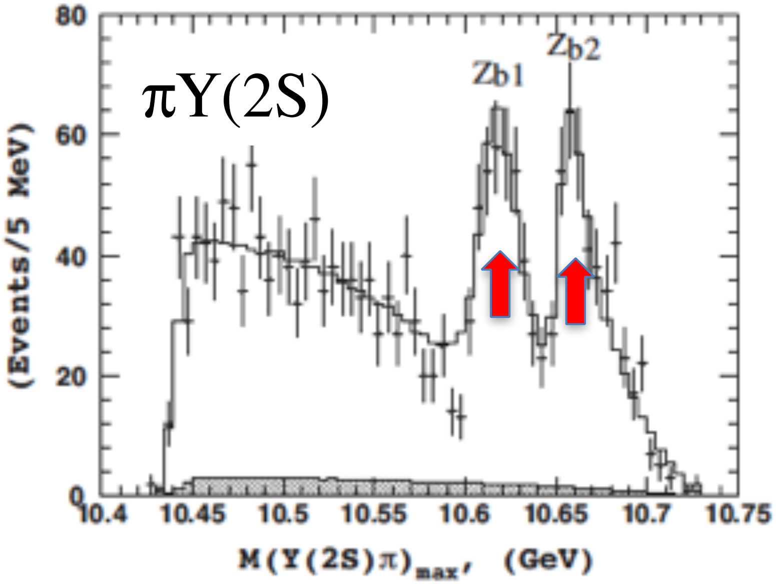
$\left\{\begin{array}{ll} \Upsilon(3S, 10355) & h_b(2P, 10259) \\ \Upsilon(2S, 10023) & h_b(1P, 9898) \\ \Upsilon(1S, 9460) & \end{array}\right.$

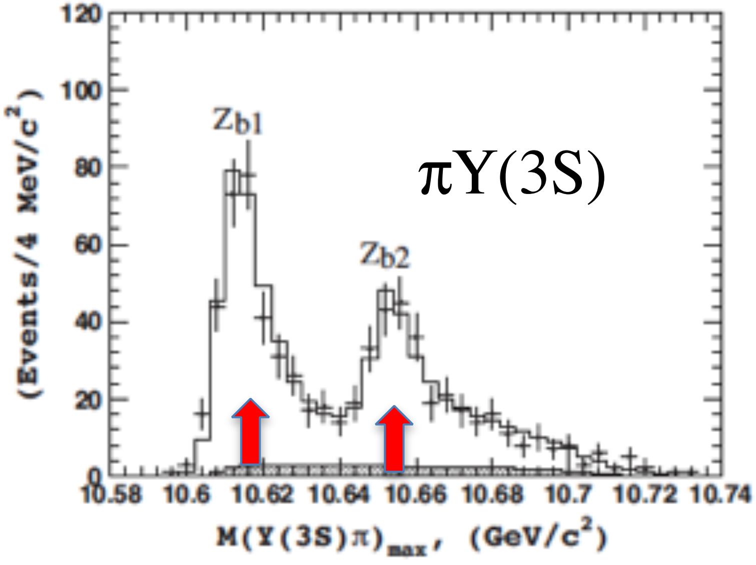
Invariant mass analysis

Three-body decay

Invariant mass of πϒ(nS)







In all cases,
twin peaks are observed

Unique features of Z_b resonances

- States appear near the thresholds
- Masses of $Z_b(10610)$, $Z_b(10650)$ are similar
- Heavy spin changing processes occur

$$\Upsilon(5S) \rightarrow Z_b \rightarrow \upuparrows \Upsilon\pi$$

$$\upuparrows \qquad h_b\pi \; \uparrow\downarrow$$

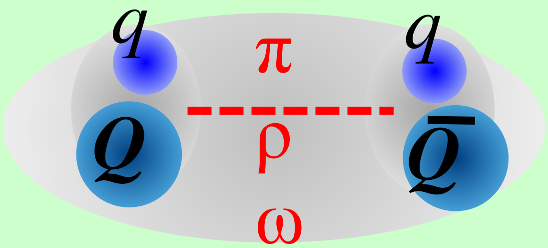
HQ forbidden process occurs equally with allowed ones

Explained by BB* molecules

Z_b as a $B\bar{B}^*$ molecules

Bondar et al, Phys.Rev. D84 (2011) 054010
Ohkoda, Yamaguchi, Yasui, Sudoh and Hodaka,
Phys.Rev. D86 (2012) 014004

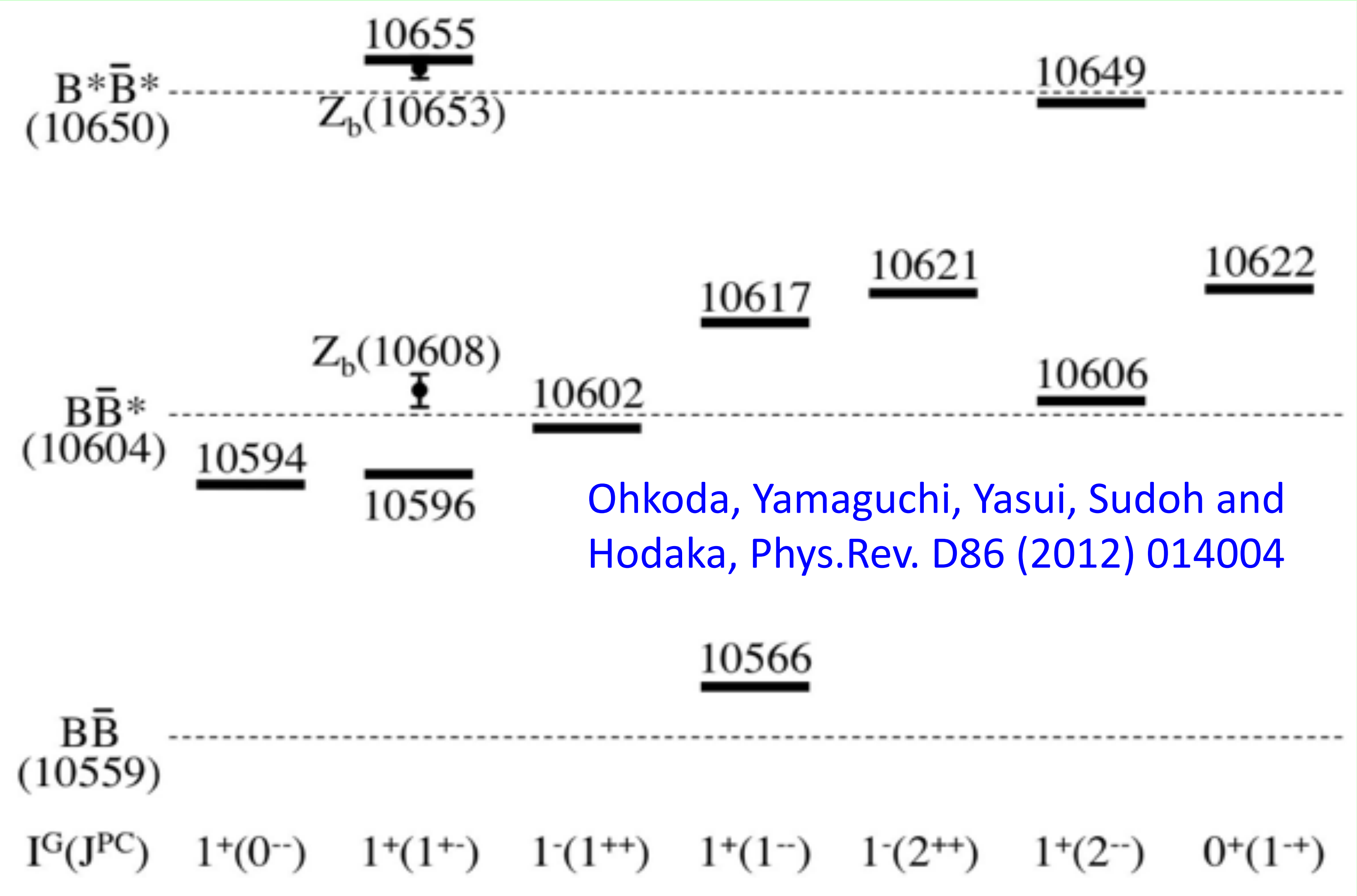
1. Masses
2. Transitions: Heavy quark selection rules
3. Decays into bottomonium



Coupled channels of
BB, BB*, B*B*
in a π, ρ, ω potential model

Z_b as a $B\bar{B}^*$ molecules

Similar to the model for the DN

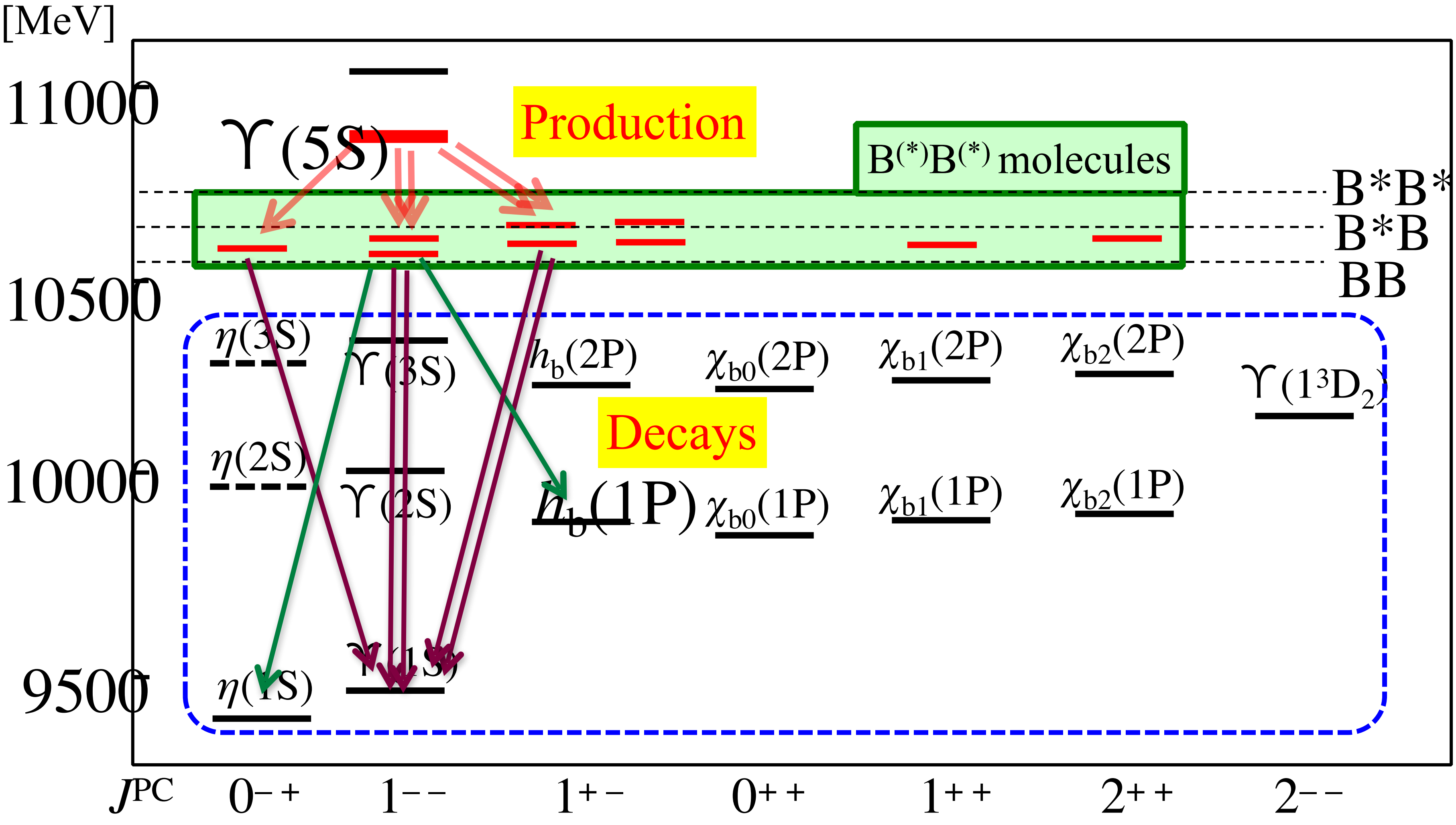


Ohkoda, Yamaguchi, Yasui, Sudoh and Hodaka, Phys.Rev. D86 (2012) 014004

2. Transitions: Heavy quark selection rules

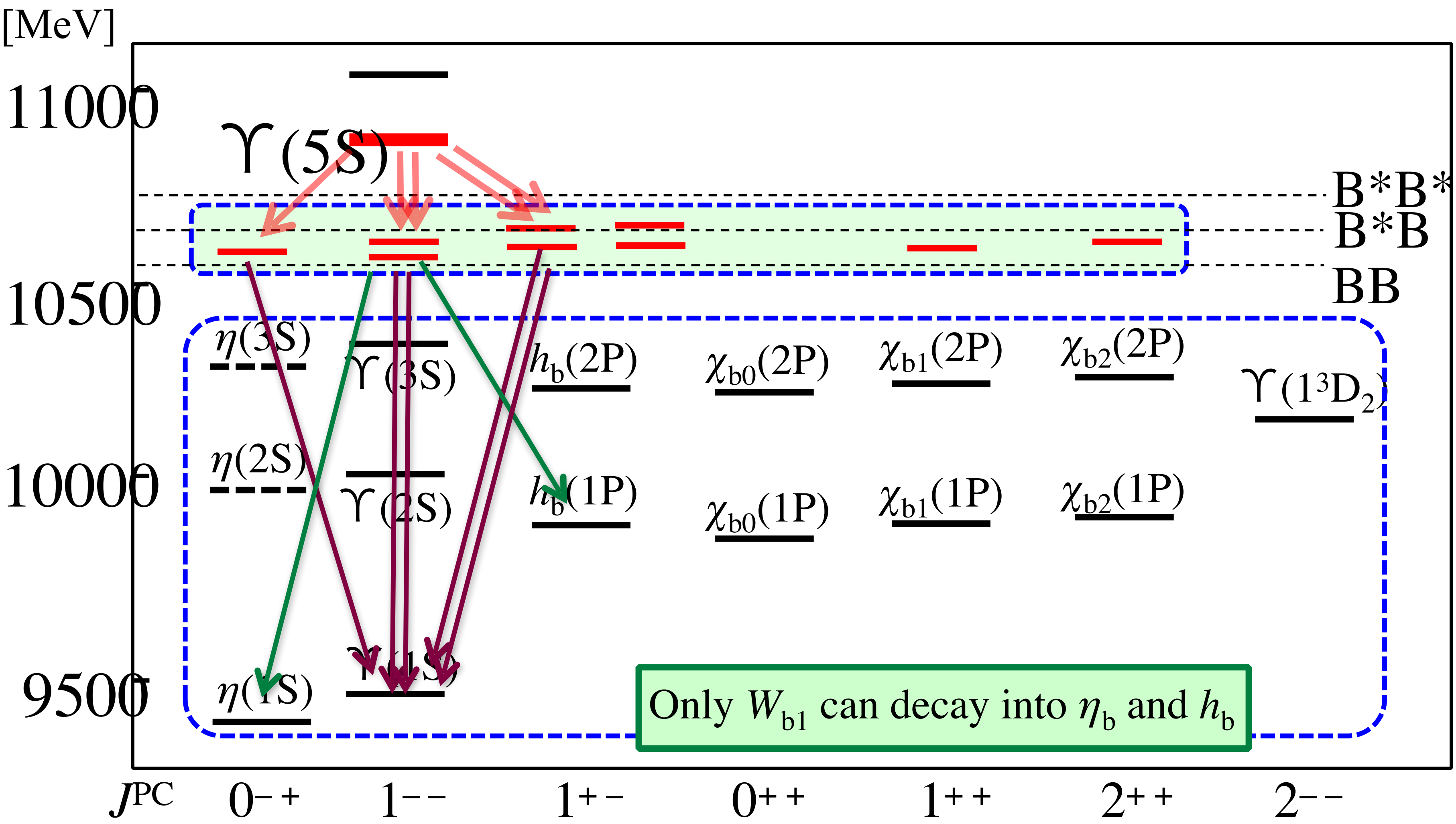
M. B. Voloshin, Phys. Rev. D 84, 031502 (2011)

Ohkoda, Yamaguchi, Yasui, Hosaka, Phys.Rev. D86 (2012) 117502



Production

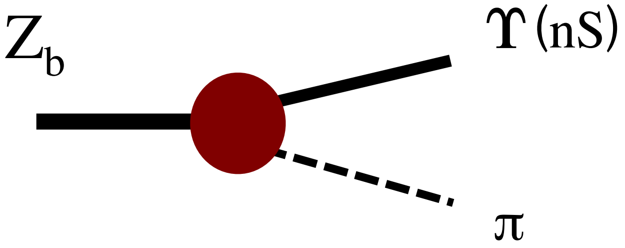
$$\begin{array}{ccccccccc} f(W_{b0}^{--}\pi) & : & f(W_{b1}'^{--}\pi) & : & f(W_{b1}^{--}\pi) & : & f(W_{b2}'^{--}\pi) & : & f(W_{b2}^{--}\pi) \\ 2 & : & 9 & : & 4.5 & : & 9 & : & 12 \end{array}$$

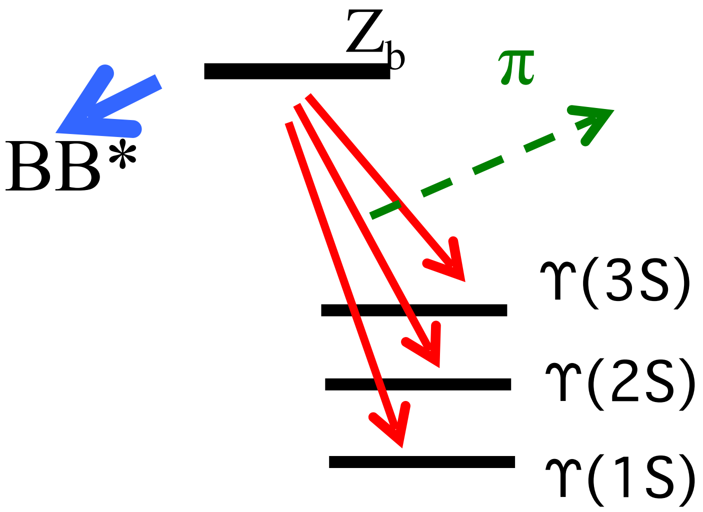


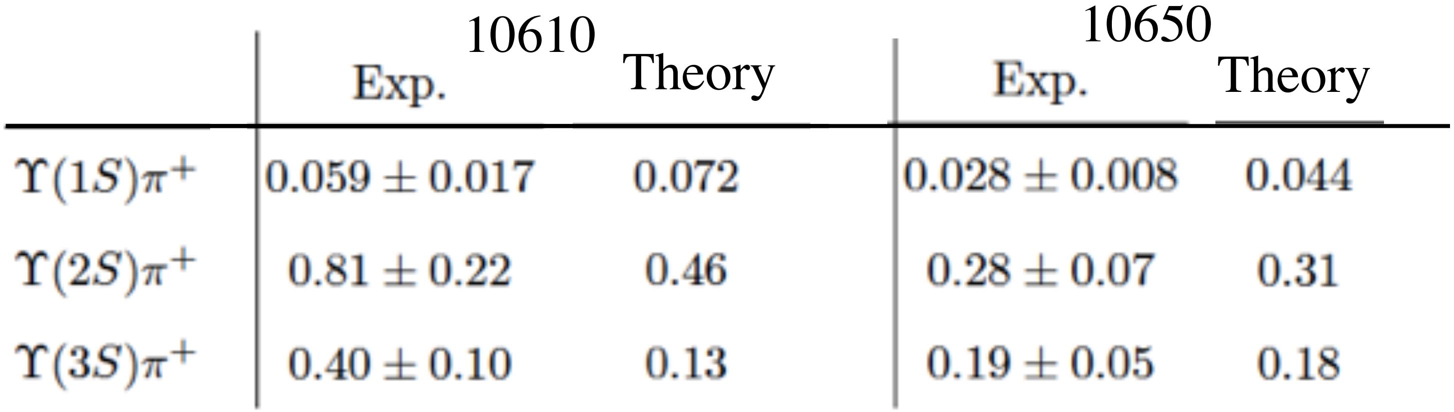
Only W_{b1} can decay into η_b and h_b

$$\begin{array}{ccccccccc} \Gamma(W_{b0}^{--}\to\Upsilon\pi) & : & \Gamma(W_{b1}'^{--}\to\Upsilon\pi) & : & \Gamma(W_{b1}^{--}\to\Upsilon\pi) & : & \Gamma(W_{b2}'^{--}\to\Upsilon\pi) & : & \Gamma(W_{b2}^{--}\to\Upsilon\pi) \\ 4 & : & 1 & : & 1 & : & 3 & : & 1 \end{array}$$

$Z_b(10610, 10650) \rightarrow \Upsilon(nS) + \pi$

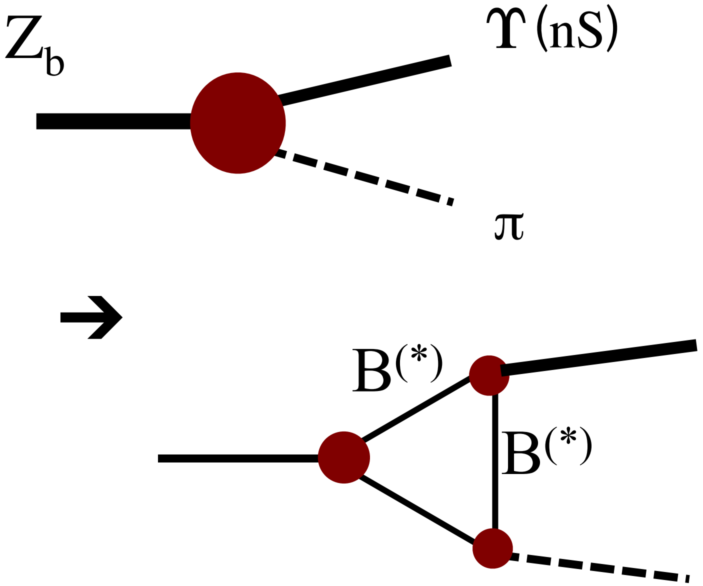


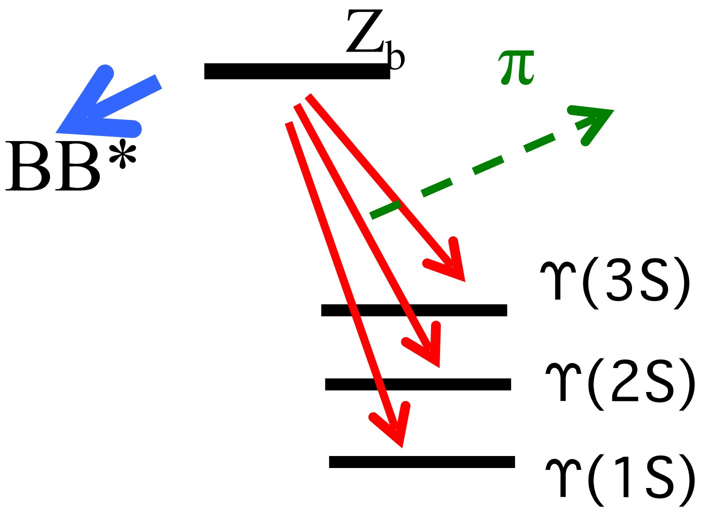




	10610 Exp.	Theory	10650 Exp.	Theory
$\Upsilon(1S)\pi^+$	0.059 ± 0.017	0.072	0.028 ± 0.008	0.044
$\Upsilon(2S)\pi^+$	0.81 ± 0.22	0.46	0.28 ± 0.07	0.31
$\Upsilon(3S)\pi^+$	0.40 ± 0.10	0.13	0.19 ± 0.05	0.18

$Z_b(10610, 10650) \rightarrow Y(nS) + \pi$





	10610		10650	
	Exp.	Theory	Exp.	Theory
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Summary

- Many new hadrons are found beyond qqq and $q\bar{q}$
- Multiquarks may form hadronic molecules
- Coupled channel dynamic is crucial near the threshold

- Further to be studied
  - Hadron-hadron interactions
  - Diquarks, gluons, compact multiquarks…

Y. Ikeda: arXiv:1602.03465 [hep-lat]

Potential matrix ($\pi J/\Psi$ - $\rho\eta_c$ - $D^{bar}D^*$)