Nuclear and Hadron Physics in Japan
Heavy Baryons: Structure, Productions and Decays

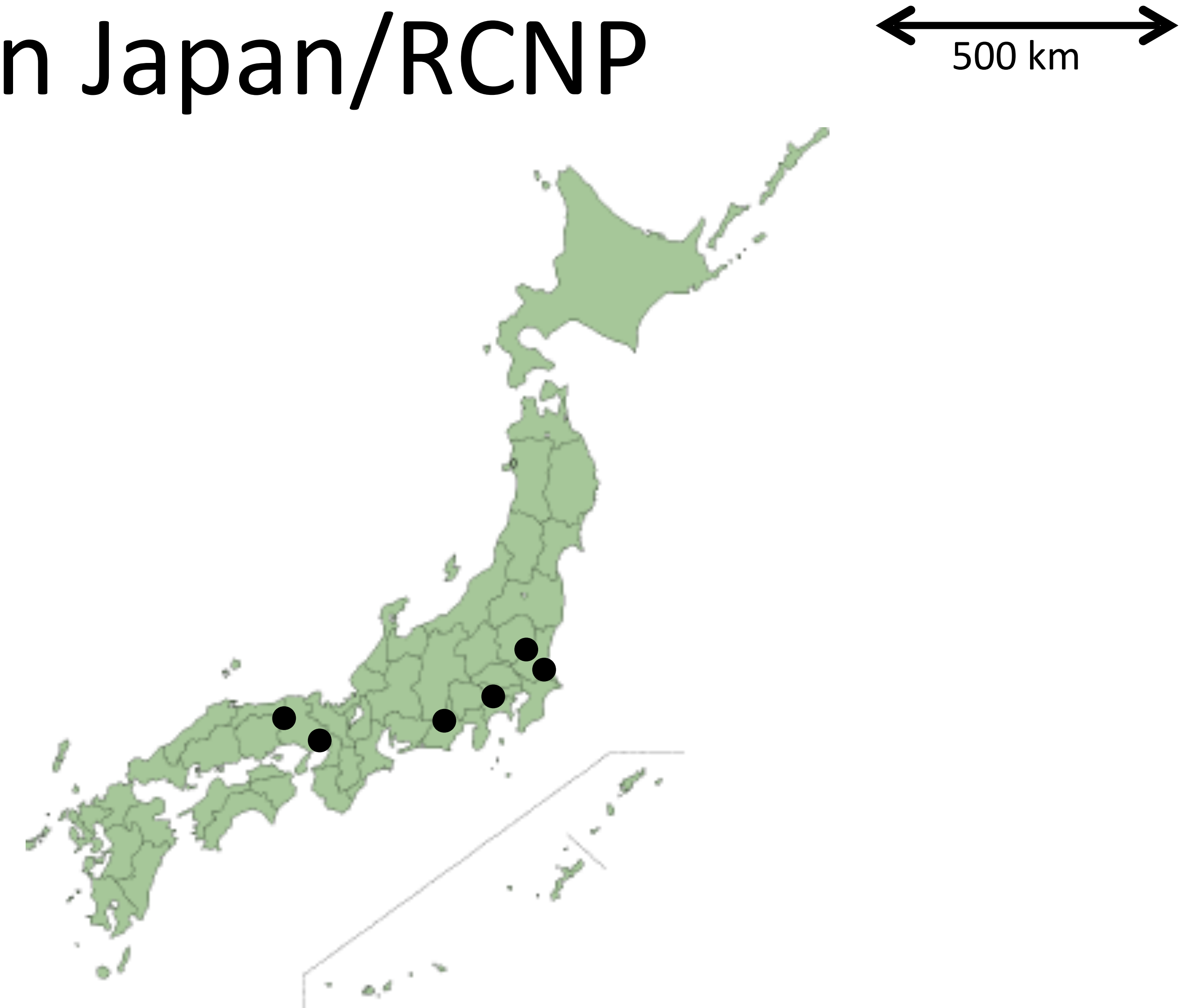
Atsushi Hosaka
RCNP, Osaka University

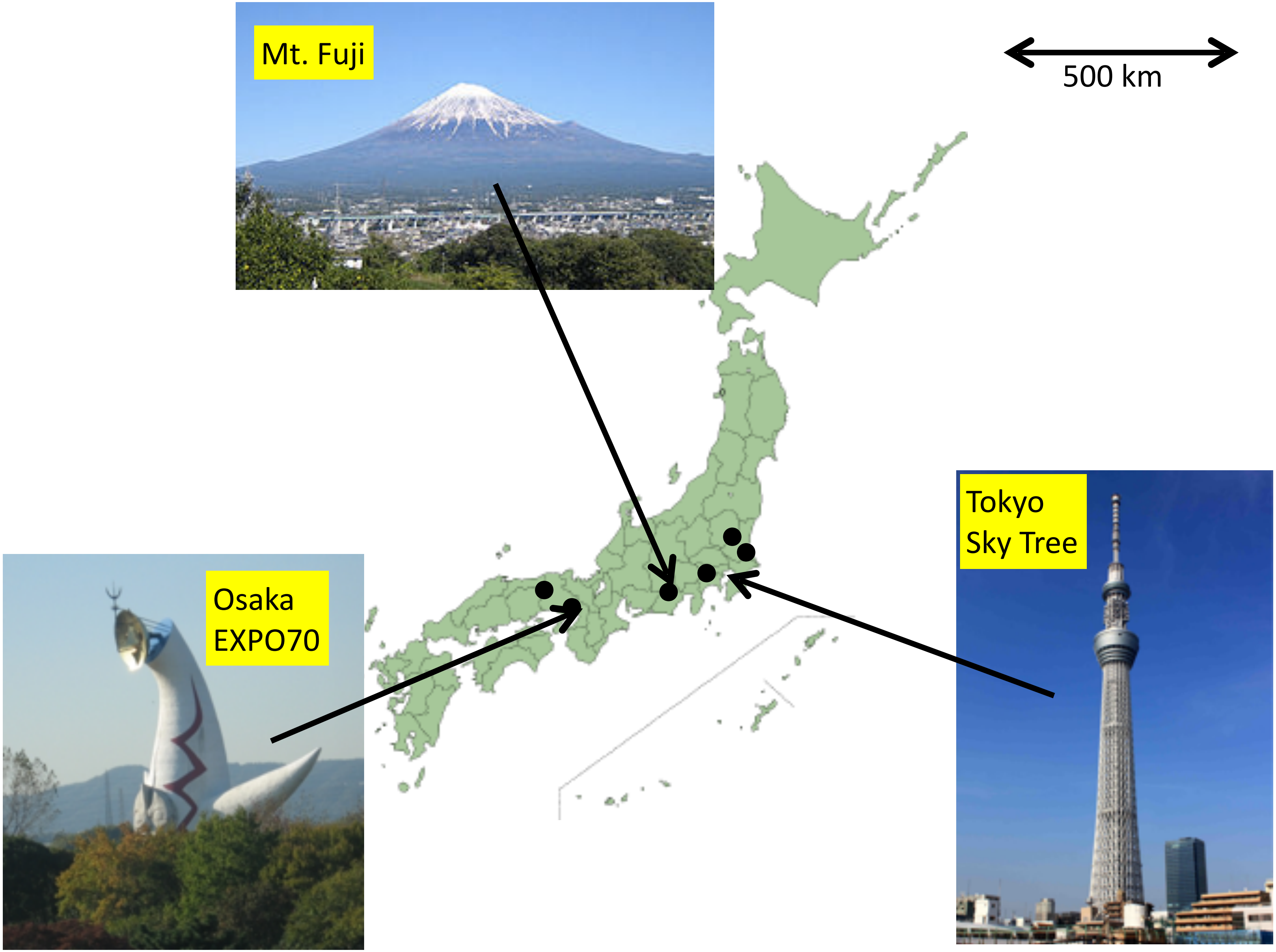
The 9th APCTP-BLTP JINR Joint Workshop in Kazakhstan
Modern Problems in Nuclear and Elementary Particle Physics
June 29 — July 3, 2015, Almaty

Contents

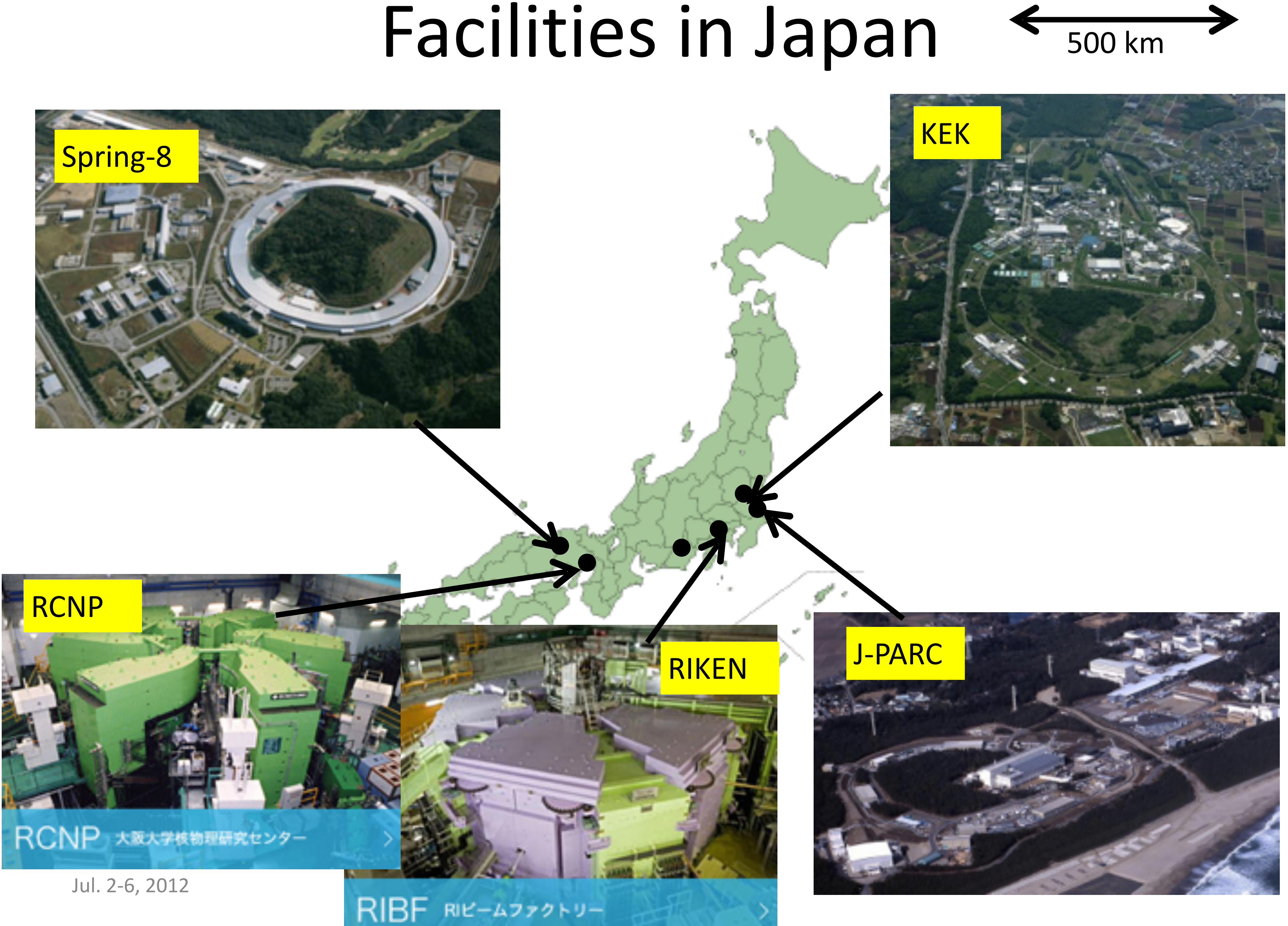
- Physics in Japan/RCNP
  Cyclotron, LEPS, J-PARC, Supercomputer, etc
  Education
- Heavy Baryons: Structure, Productions and Decays

Physics in Japan/RCNP




Mt. Fuji
500 km
Tokyo
Sky Tree
Osaka
EXPO70

Facilities in Japan



Grant-in-Aid for Scientific Research Priority Areas

~ Since 2007, 5 years with a few million dollars/year

2007-2012: Computational science for particle-nuclear-astro physics

2008-2013: Elucidation of New Hadrons with a Variety of Flavors

Cosmological Inflation and Dark Matter

2009-2014: Topological Quantum Phenomena

2010-2015: Tera scale Physics @ LHC

2012-2017: Astrophysics by Gravitational Waves

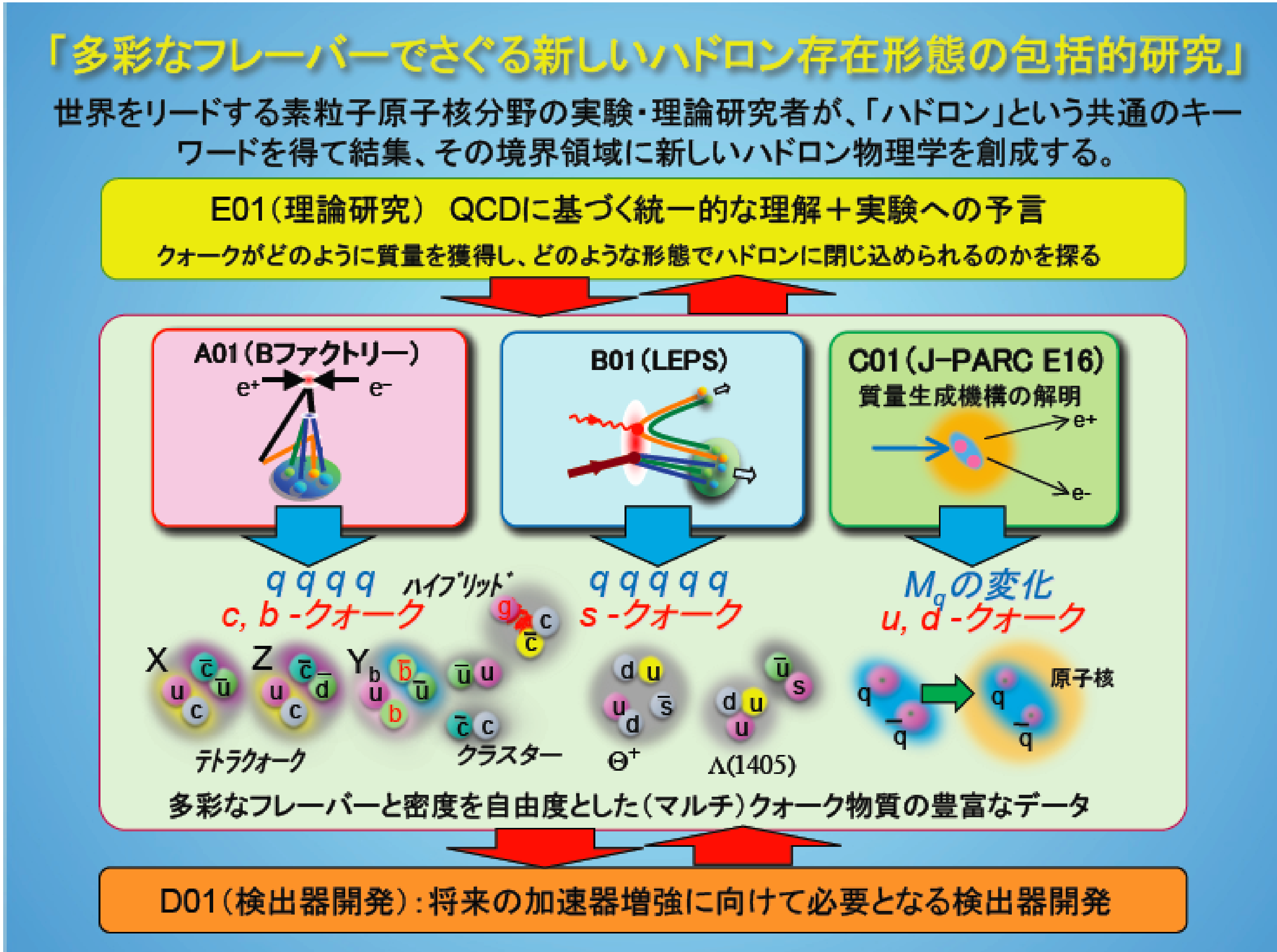
Nuclear Matter in Neutron Star

2013-2018: Neutrino Science Frontier

2014-2019: Underground Nuclear and Particle Physics

Elucidation of new hadrons with variety of flavors (2009 - 2013)

About 30 regular members were involved (staffs, postdocs)



Research Center for Nuclear Physics

The only Lab for collaboration of nuclear physics made in a university

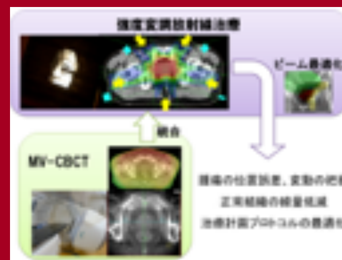
- **The largest cyclotron**
- **Working with other facilities; SPring-8, J-PARC <— Noumi**
- **Super computer**

RCNP Cyclotron Facility

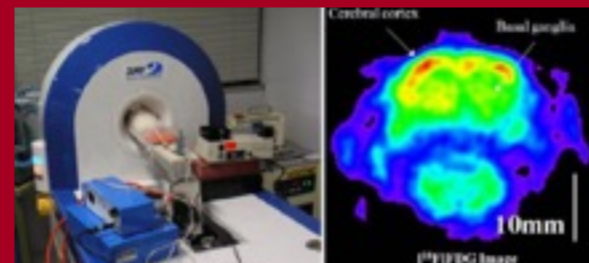
Osaka University Undertaking by cooperation among RCNP and Graduate School of Medicine and Science

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

Graduate School of Medicine



Radio therapy



PET&SPECT inspection

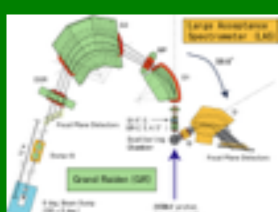
Training of medical physicists by higher education using accelerators

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

・Diagnostics
・Nuclear data

RI separation and synthesis

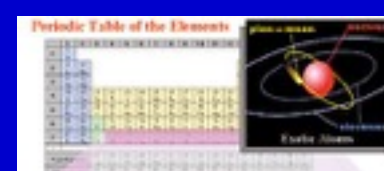
RCNP

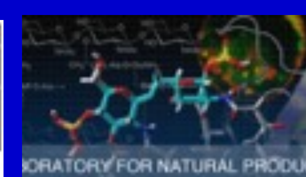


Nuclear physics **Accelerator**

R I production

Graduate School of Science

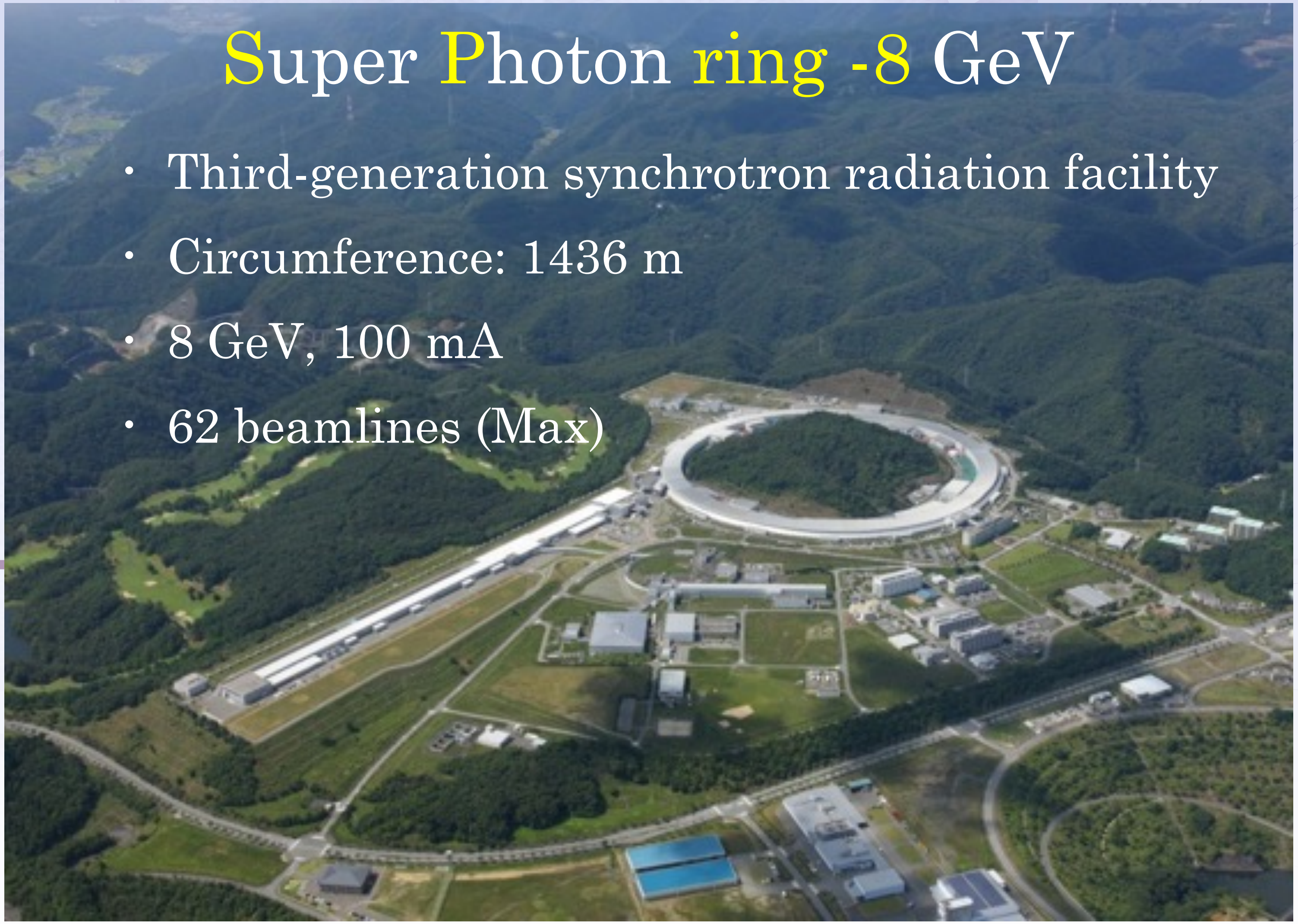




Nuclear chemistry **Organic chemistry**

LEPS AND LEPS2 @SPring-8

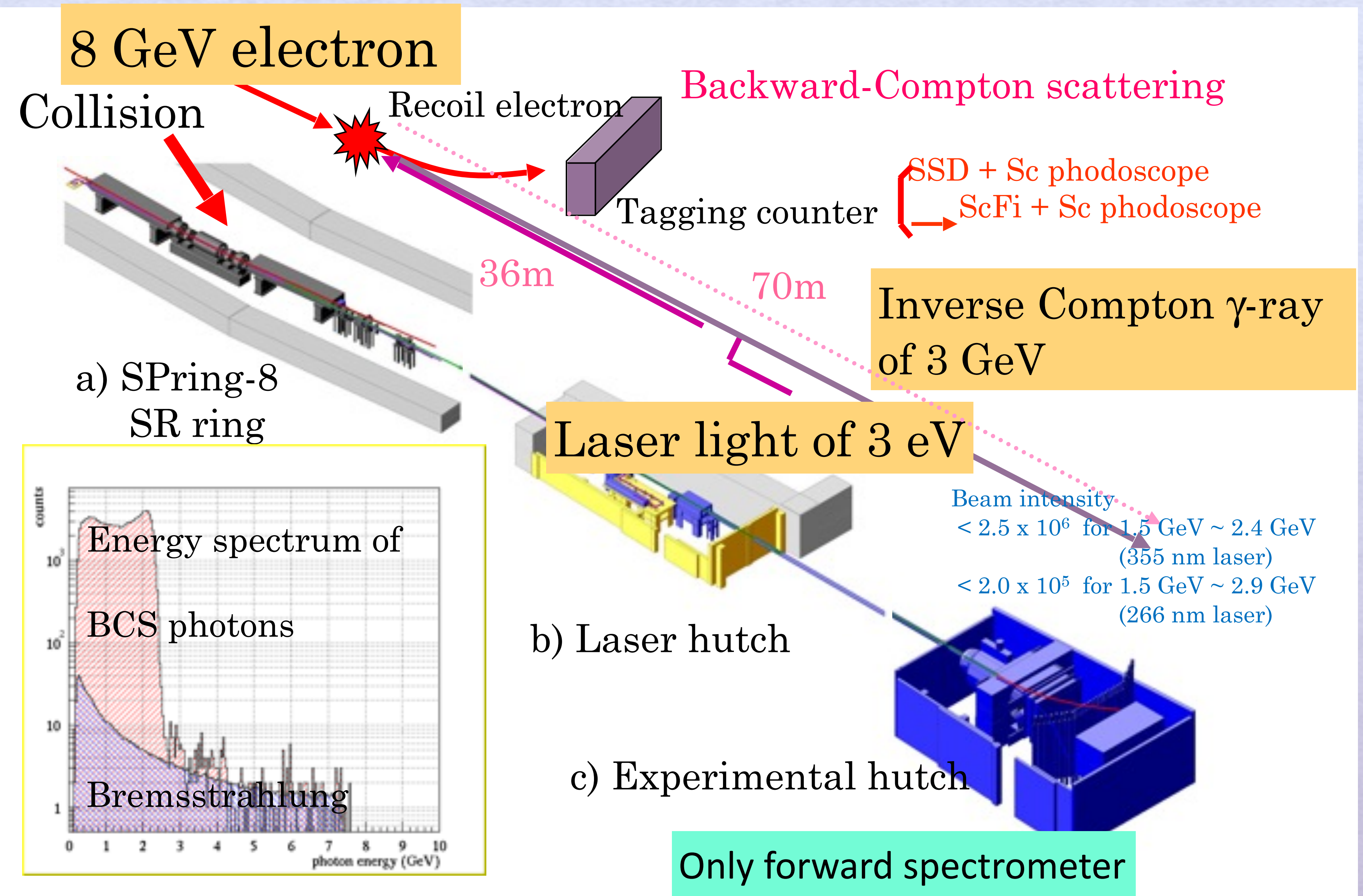
120 km distance from RCNP



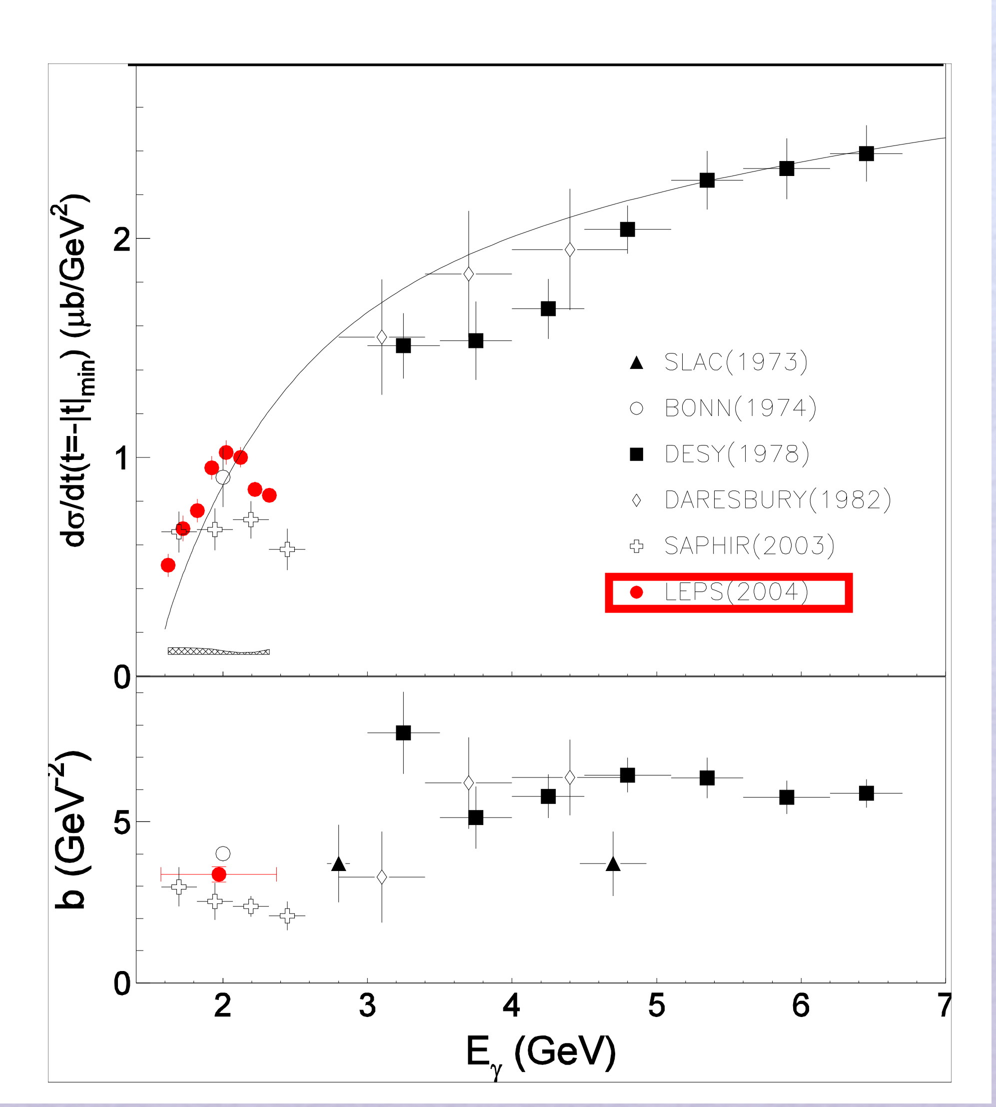
Super Photon ring -8 GeV

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

LEPS facility



Vector meson φ photoproduction



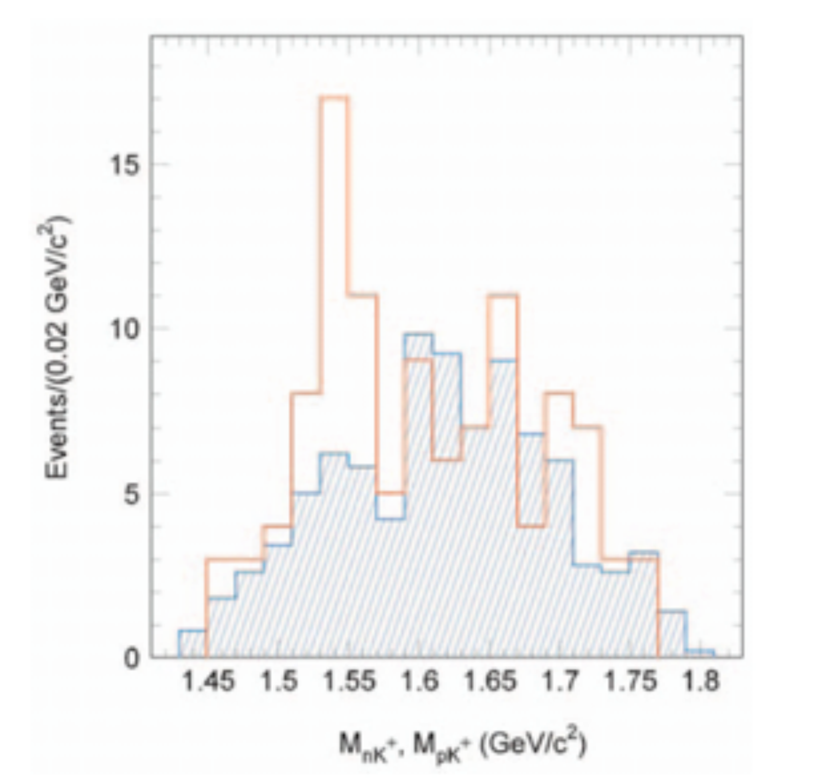
$$\frac{d\sigma}{dt} = \left(\frac{d\sigma}{dt}\right)_{t=-|t|_{\min}} \exp\left(b\left(t+|t|_{\min}\right)\right)$$

Curve : Pomeron + Pseudo scalar exchange model (A. Titov et. al, PRC 67, 065205)

A peaking structure is seen in dσ/dt near E_γ=2 GeV, which has not been explained by a simple model calculation.

A peak is dominated by natural parity exchange ~ Pomeron like

1st report for Θ^+ from LEPS



T. Nakano et al.,

PRL91, 012002(2003)

Search for penta-quark Θ^+

Its existence is still controversial!

LEPS2 with a new laser beam and a detector (from BNL)

Physics with LEPS2

- Unique features
  - High intensity beam, Polarized beam (Linearly/Circularly) (~10^7/s @E_{max}=2.4 GeV, ~10^6/s @E_{max}=2.9 GeV)
  - Large acceptance for charged particles / photons
    - Reaction (missing mass) & Decay(invariant mass)
    - Kinematical constraint, Coplanarity
    - Angular distribution

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

} **High priority** (covers the first three objectives)

More idea welcome !

Theory

Hadrons and Nuclei

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

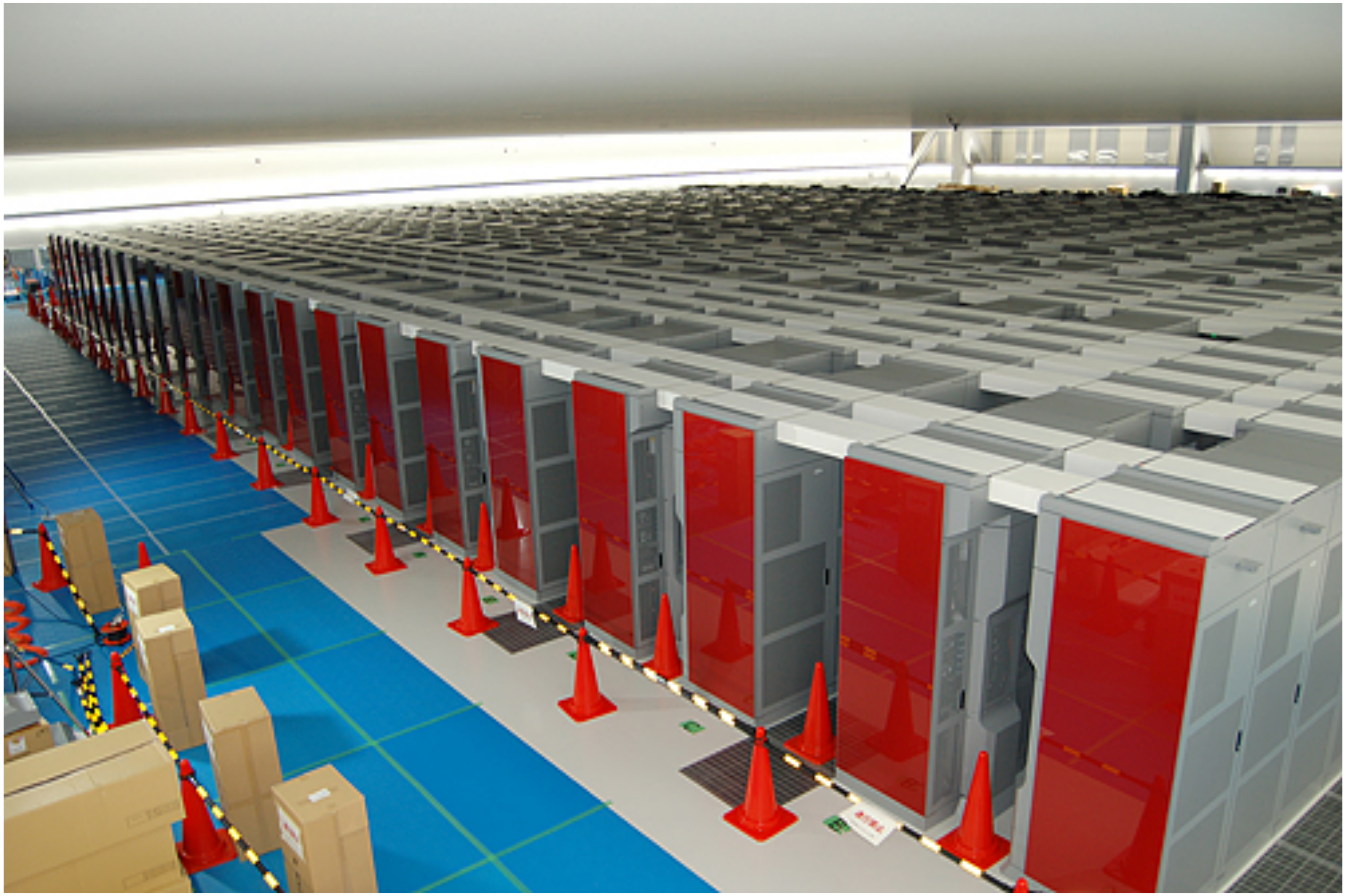
Role in the community = HPCI

High Performance Computer Infra

with the Japan largest supercomputer, KEI

Kei computer (京) at Kobe

~ billion dollars



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

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

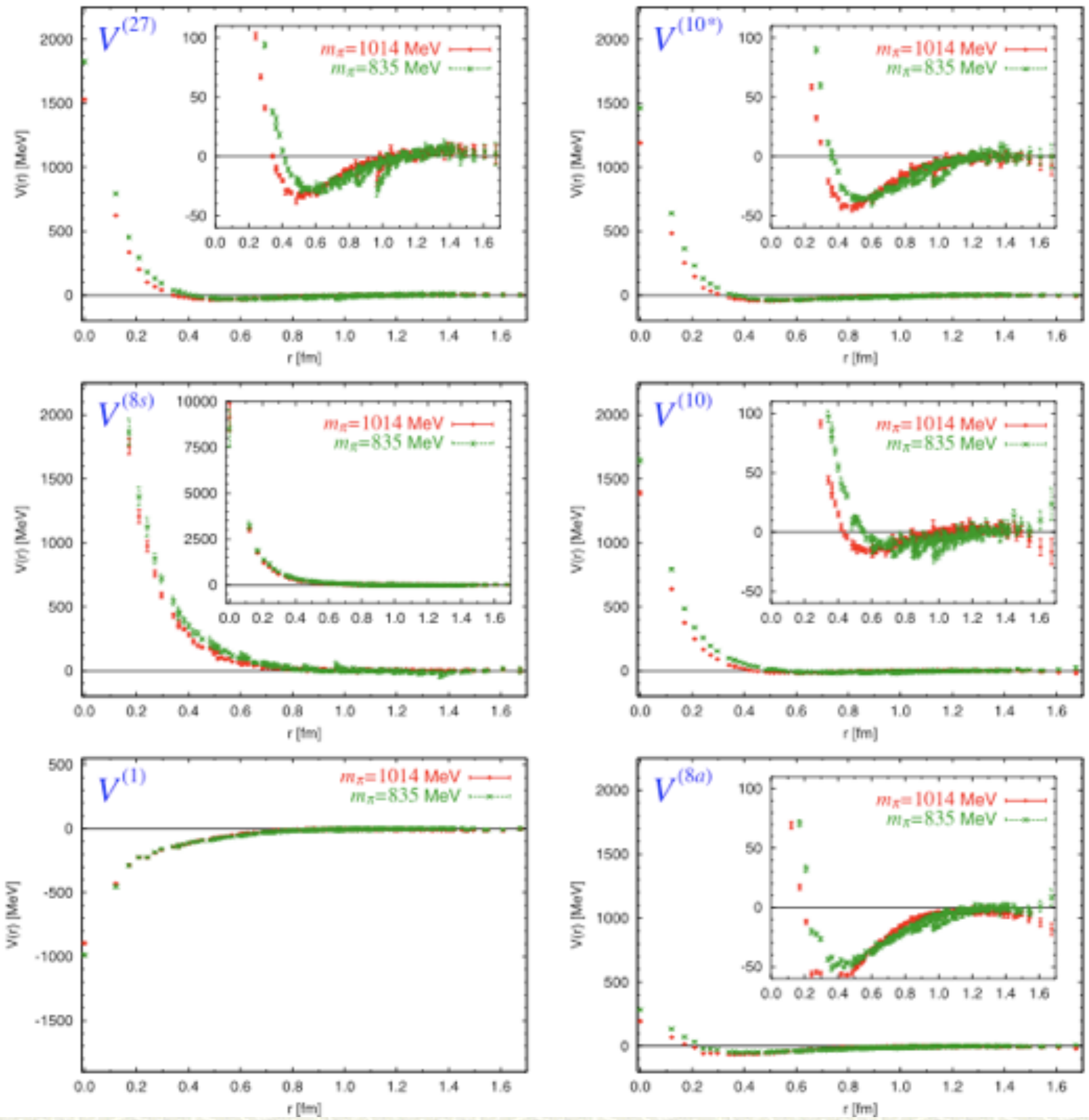
S=0

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)

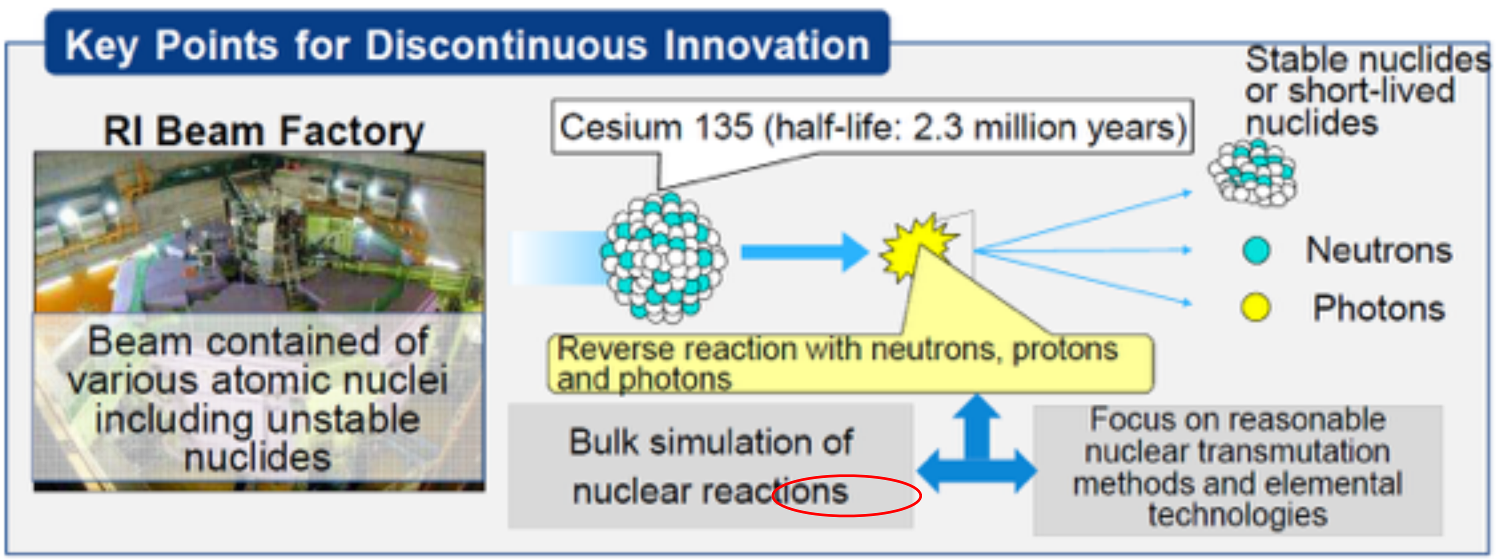


Nuclear Transmutation studies

***Im**pulsing **P**aradigm **C**hange through Disruptive **T**echnologies Program*

- Launched FY2014 and 12 programs approved.
- will end at Dec. 31, 2018.
- Keyword: high risk and high impact

Reduction and Resource Recycle of High Level Radioactive Wastes with Nuclear Transmutation (PM: Reiko Fujita)



Microscopic Effective Reaction Theory

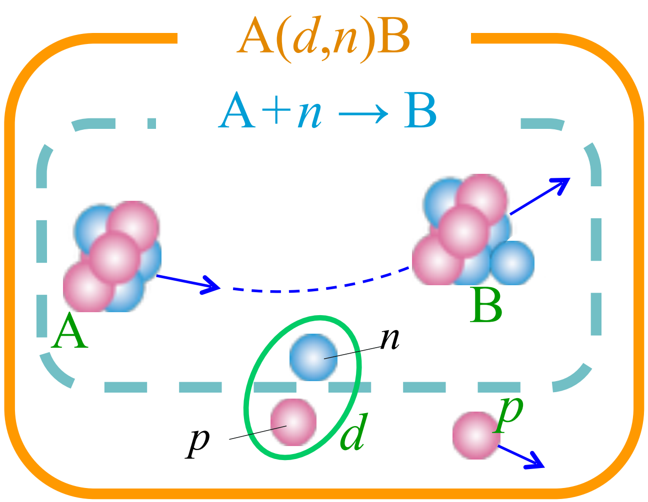
Kazuyuki Ogata

Extraction genuine data w/ MERT

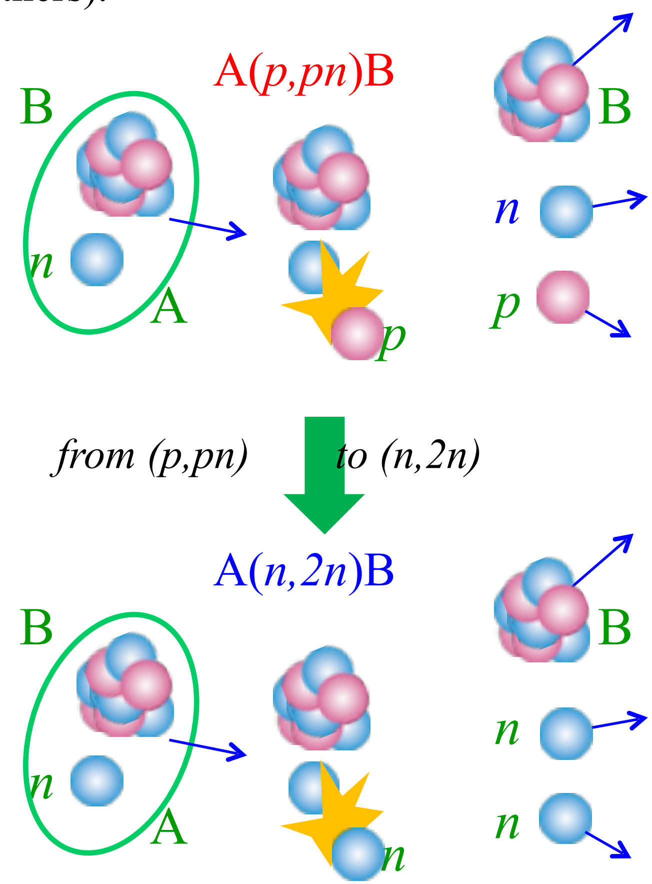
Microscopic Effective Reaction Theory

Kazuyuki Ogata

- Model space is determined by analysis of alternative reaction data.
- Structural information is given by Tsukuba group (or others).
- MERT generates the objective reaction data.



from neutron pickup
to neutron capture



International Physics Course (IPC): theoretical physics and experiments at Osaka University

http://www.rcnp.osaka-u.ac.jp/~ipc/

Program concept and design of the IPC

- Offers **Master** and **Ph.D.** programs (not undergraduate programs)
- Organized inside the **Department of Physics** but includes groups at the **Institute of Laser Engineering**, **the Research Center for Nuclear Physics**, and the **Department of Earth Science and Astronomy**
- Students can work from the start as **active members of international collaborations** in theory or experiment
- Students can work with our own large-scale facilities, including **high-power lasers** and **high-energy accelerators**
- Education and research program conducted in **English**

See [**http://www.rcnp.osaka-u.ac.jp/~ipc/**](http://www.rcnp.osaka-u.ac.jp/~ipc/)

Education at the IPC

1: **broad** knowledge and abilities

Lectures

Electrodynamics
Quantum Mechanics
Mathematics for Physics

Condensed Matter Theory
Fluid and Plasma Physics
Field Theory
Nuclear and Particle Physics
General Relativity
Optical Properties of Matter
Quantum Field Theory
Solid State Theory
Quantum Many-Body Systems
…

See http://www.rcnp.osaka-u.ac.jp/~ipc/

2: **deep** knowledge and abilities in one subject

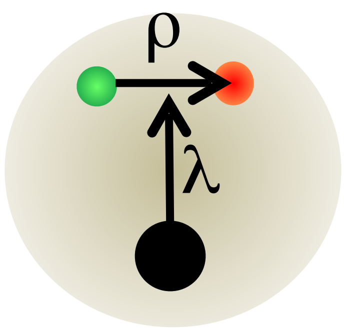
Advanced seminars on frontier topics
and special intensive lectures

Heavy Baryons: Structure, Productions and Decays

Baryons with heavy quark(s) may disentangle light quark dynamics

Atsushi Hosaka, RCNP, Osaka

With Noumi, Shirotori, Kim, Sadato, Yoshida, Oka, Hiyama, Nagahiro, Yasui



Contents

1. Introduction
2. Structure: *How* ***ρλ modes*** *appear in the spectrum*
3. Productions
4. Decays

1. Introduction

Quark model and **EXOTICS**: Now 51 years old

A SCHEMATIC MODEL OF BARYONS AND MESONS

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

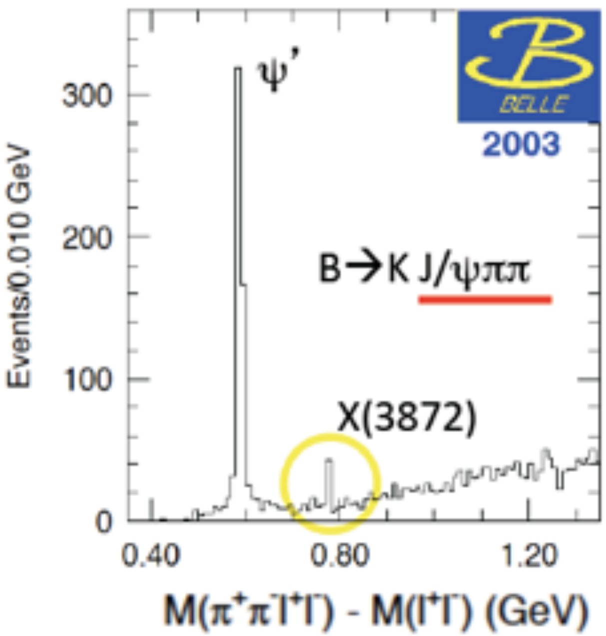
Received 4 January 1964

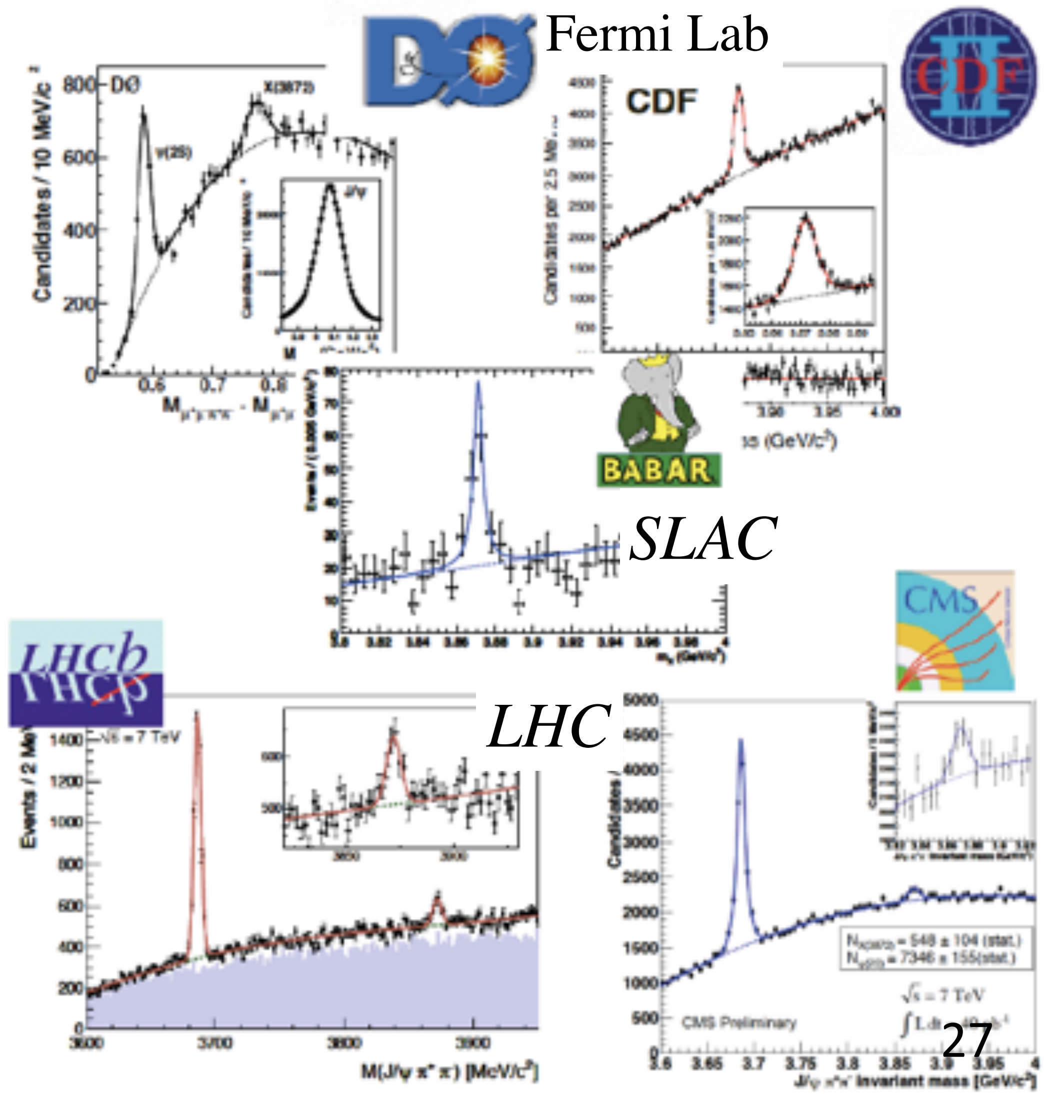
anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

But no colors ~ glues

X (3872)

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





And more recently also by LHCb, CMS

Quarks bonding differently at LHCb $Z^+(4430)$

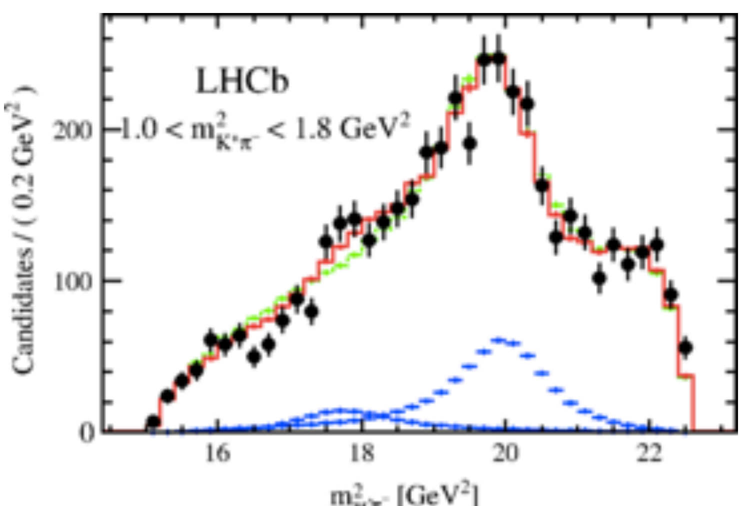
http://www.theguardian.com/science/life-and-physics/2014/apr/13/quarks-bonding-differently-at-lhcb

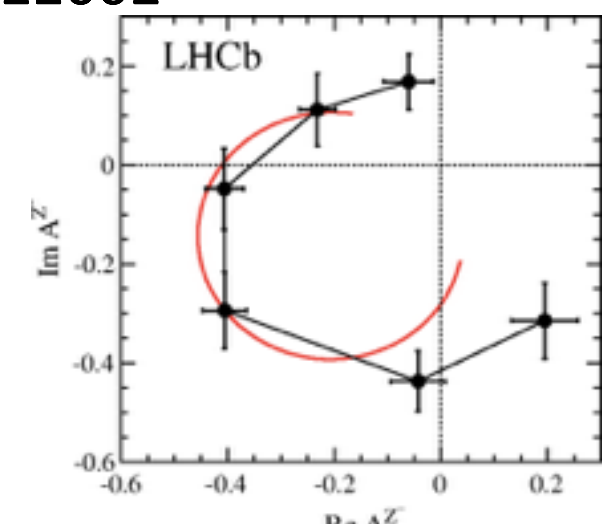
So until last week there were two known types of hadron.

……

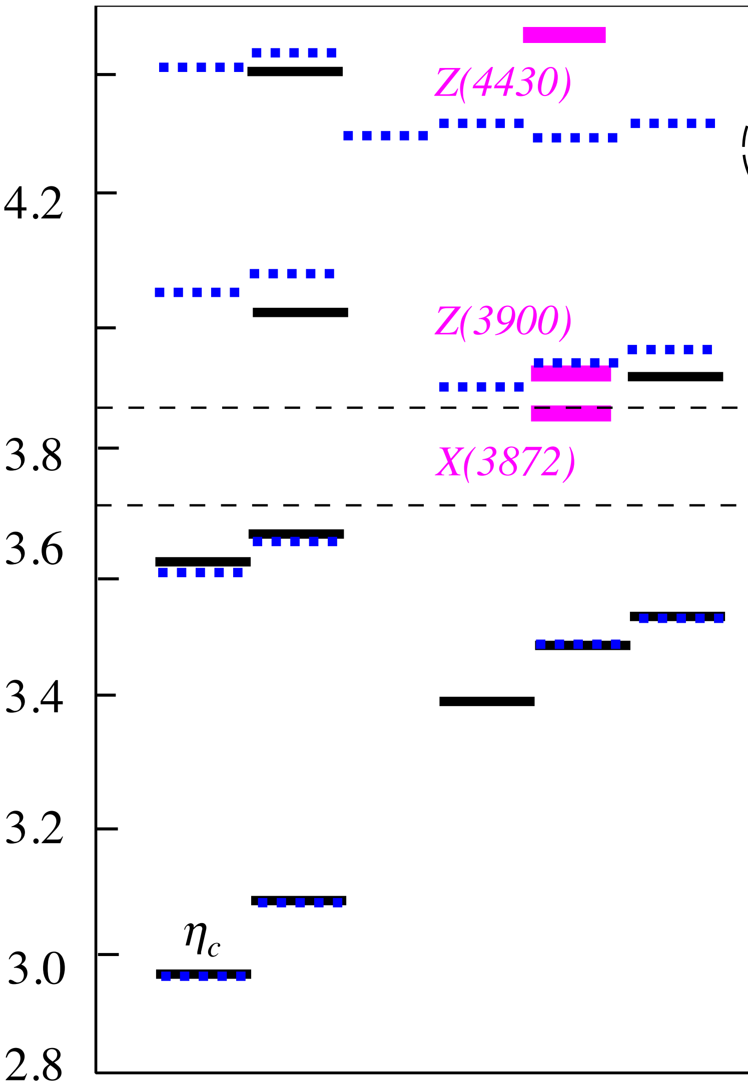
LHCb has just confirmed what data from other experiments had already led us to suspect. There is a third way.

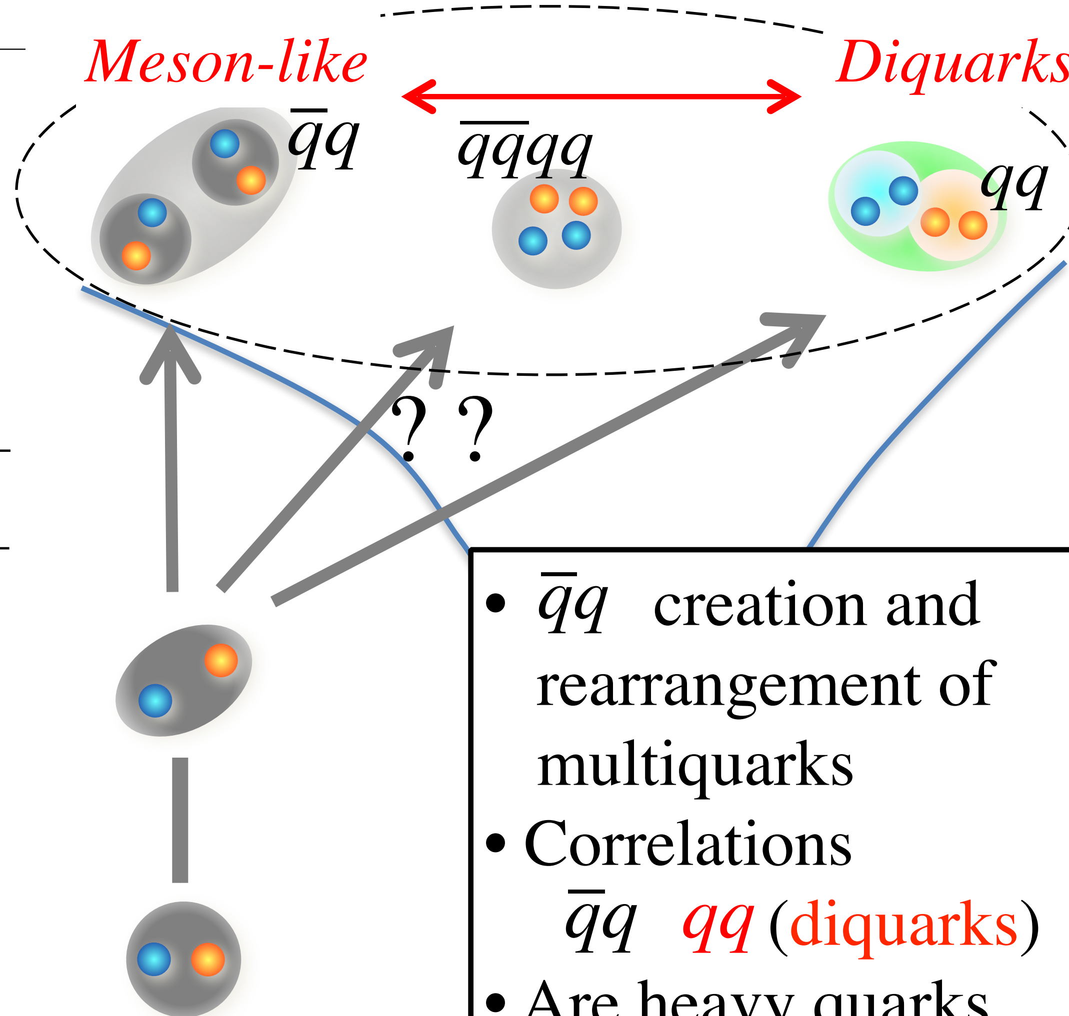
Phys. Rev. Lett. **112**, 222002





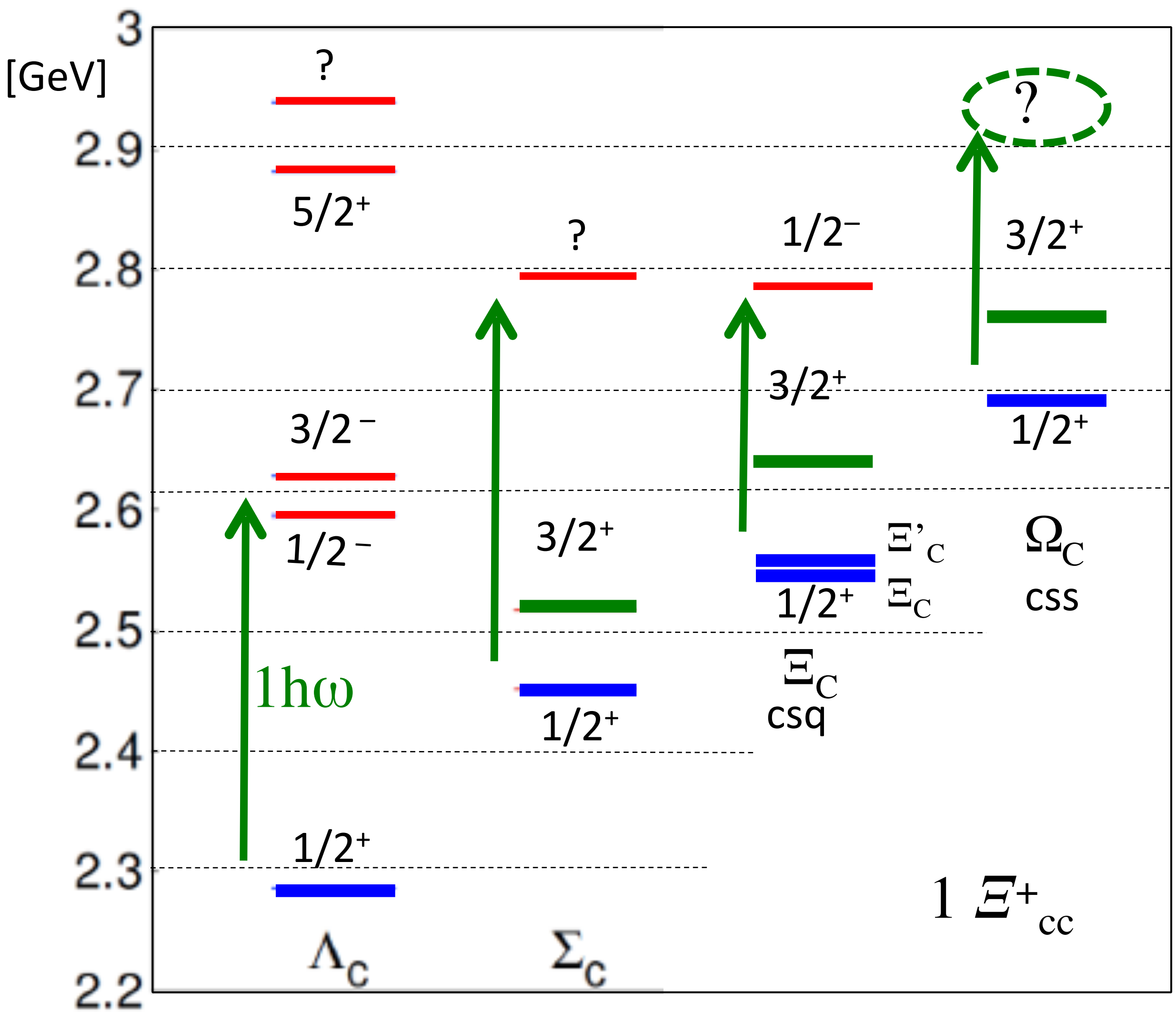
Near and above the threshold

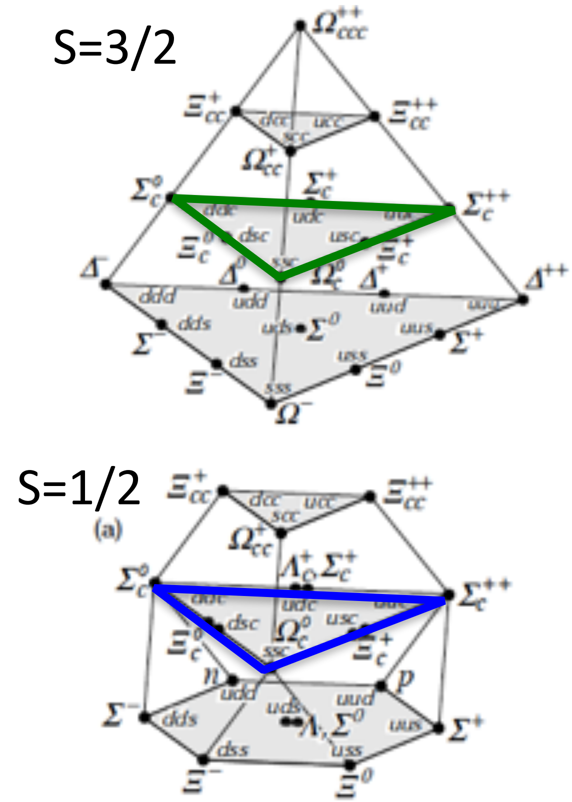




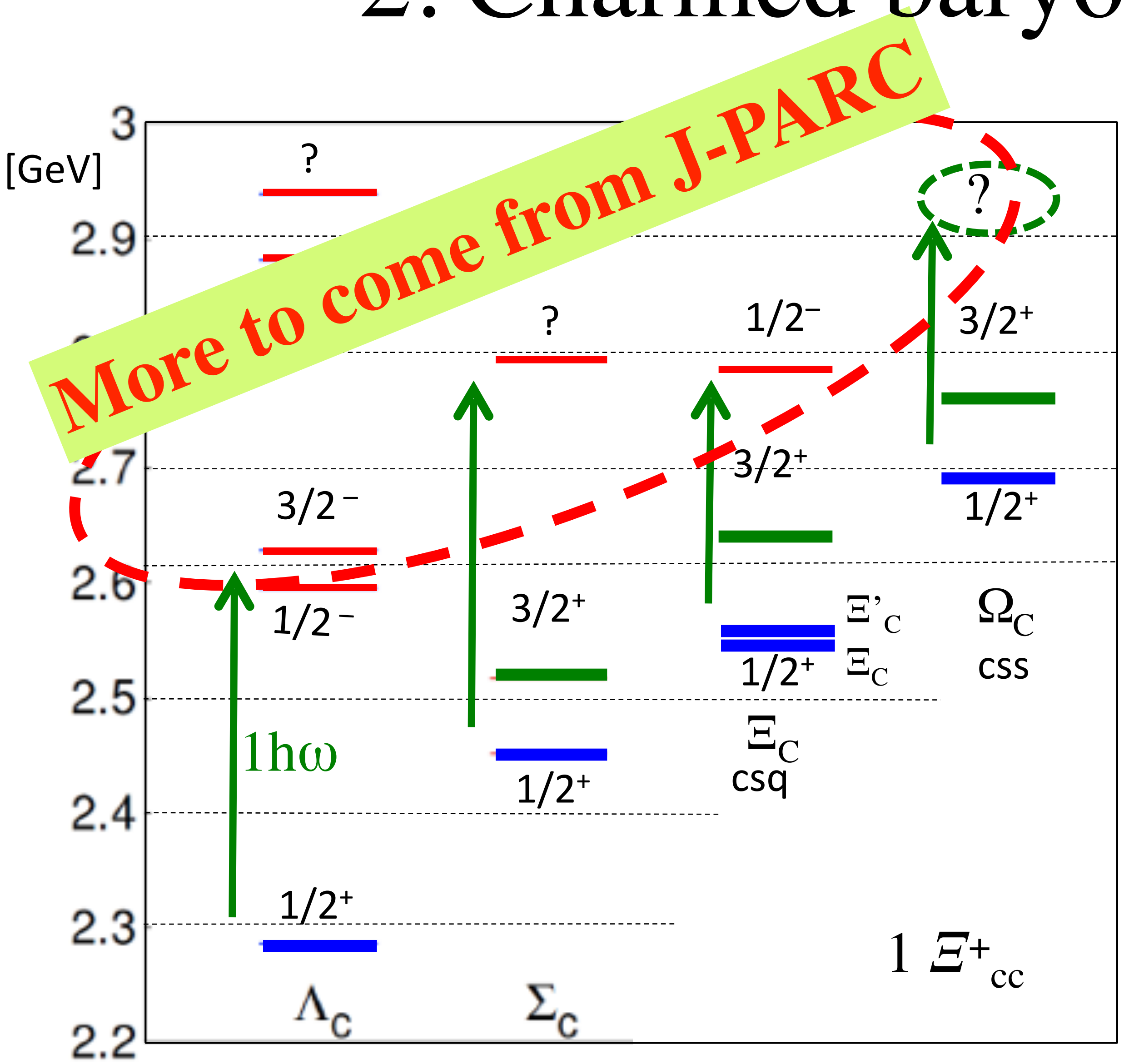
- $\bar{q}q$ creation and rearrangement of multiquarks
- Correlations
  $\bar{q}q$ qq (diquarks)
- Are heavy quarks useful to know it?

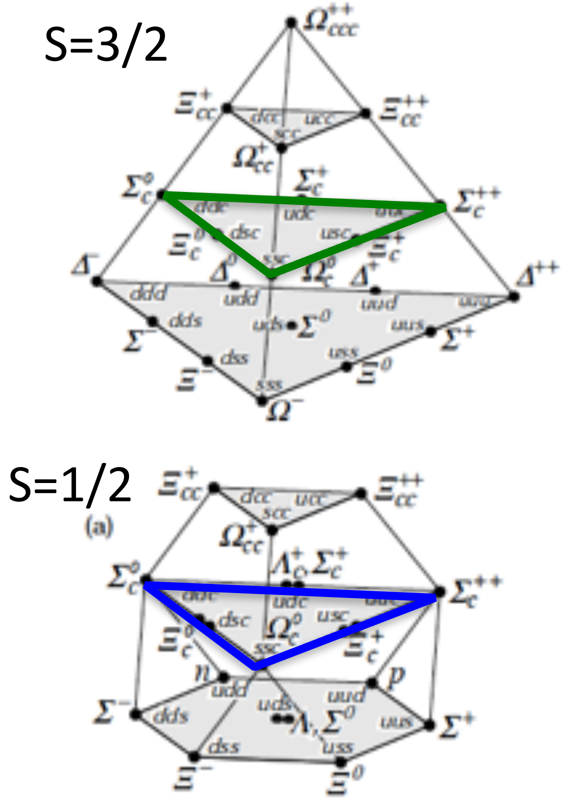
2. Charmed baryons





2. Charmed baryons

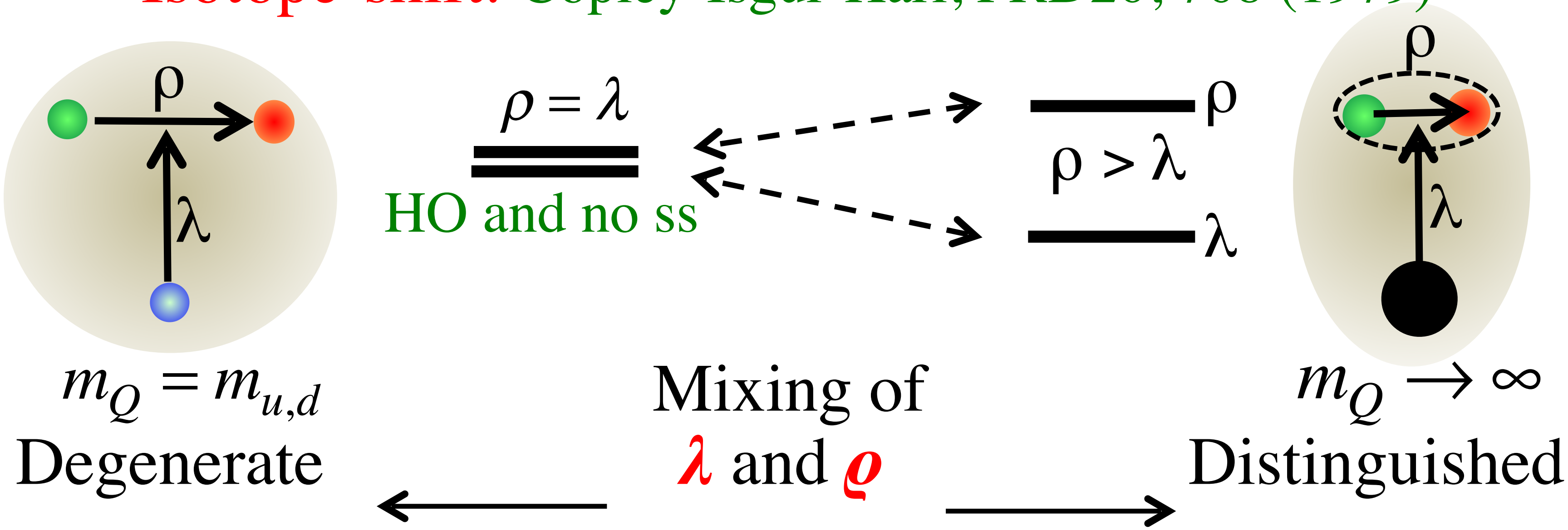




What do we expect to study?

A heavy quark may distinguish
the fundamental modes λ and ϱ
➔ place to look at diquark correlations

Isotope-shift: Copley-Isgur-Karl, PRD20, 768 (1979)



Spectrum and WF's as M_Q is varied

Roberts-Pervin, IJMPA, 23, 2817 (2008)

Yoshida, Sadato, Hiyama, Oka, Hosaka

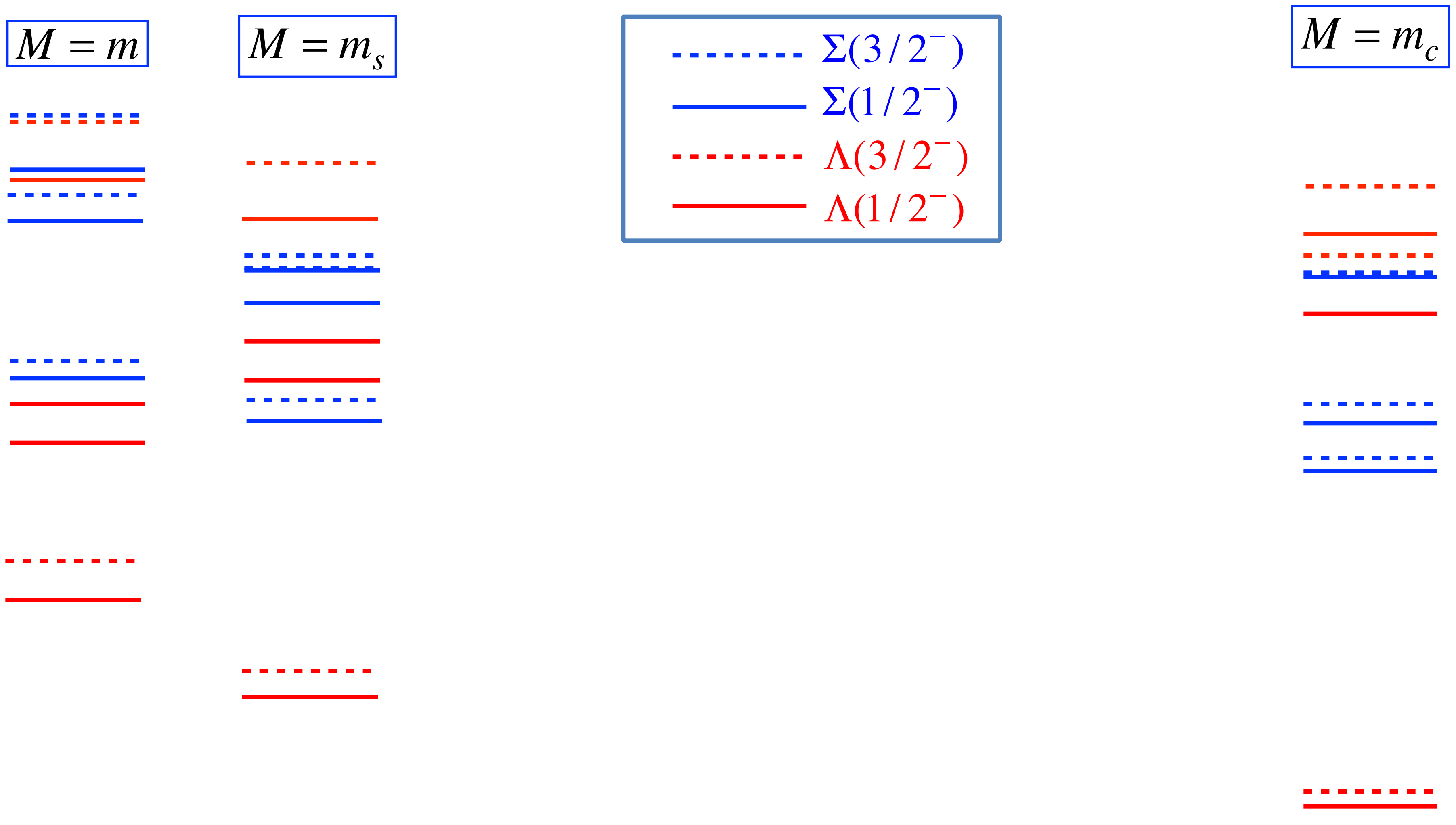
- Model Hamiltonian

$$H = \frac{p_1^2}{2m_q} + \frac{p_2^2}{2m_q} + \frac{p_3^2}{2M_Q} - \frac{P^2}{2M_{tot}}$$

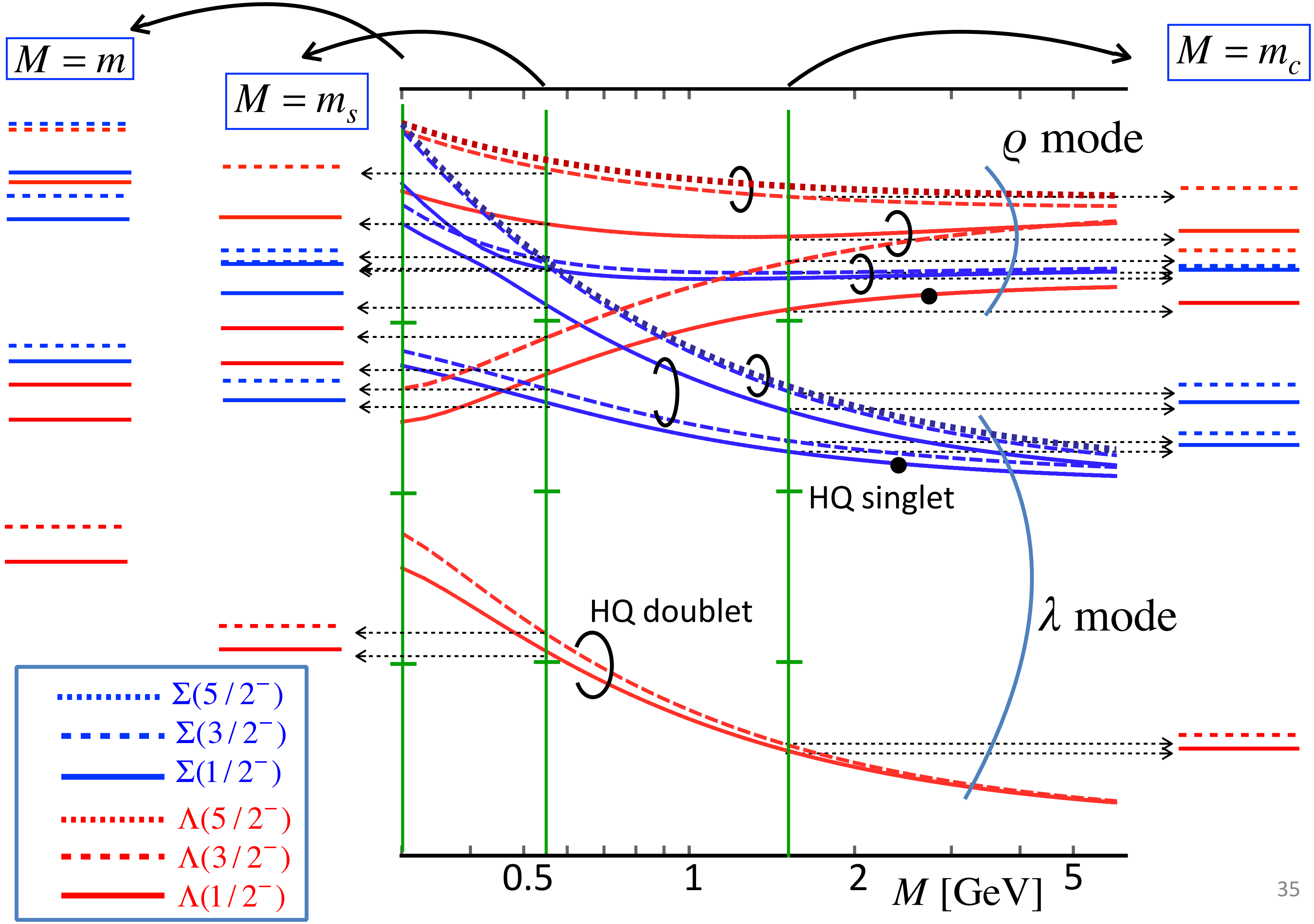
$$+ V_{conf}(HO) + V_{spin-spin}(Color - magnetic) + \ldots$$

- Solved by the Gaussian expansion method

Negative parity states — p-wave excitations - 1/2⁻, 3/2⁻



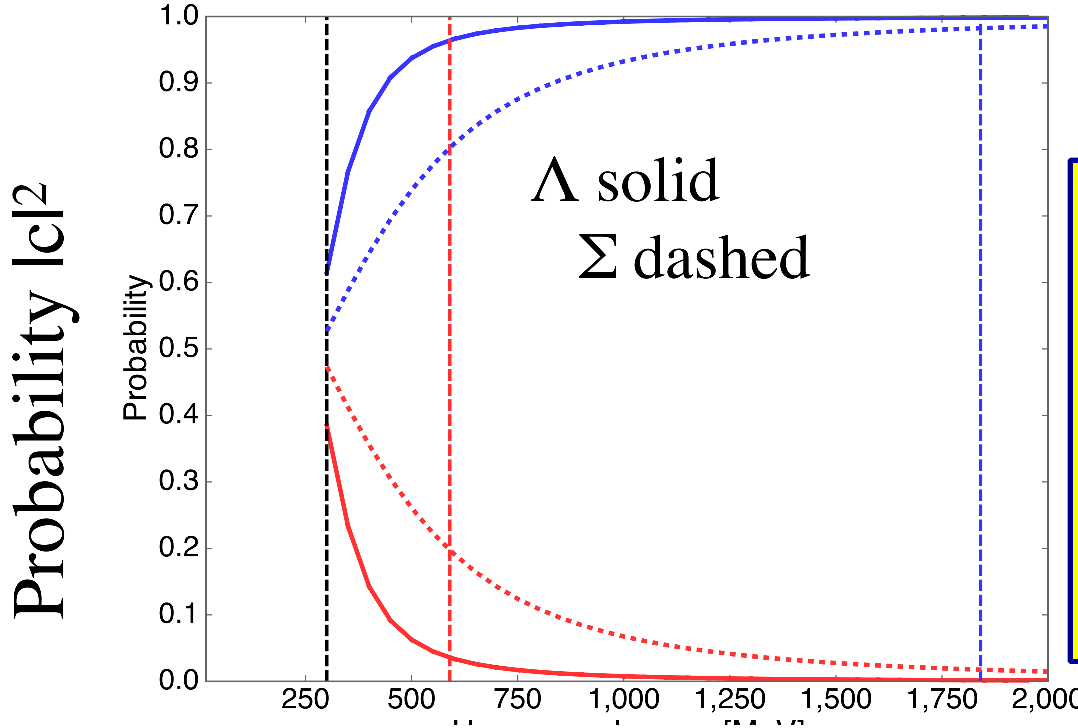
Negative parity states — p-wave excitations - 1/2⁻, 3/2⁻



Wave function

Mixing of $\Lambda(\text{phys}) = c_\lambda \Lambda({}^2\lambda) + c_\rho \Lambda({}^2\rho)$

e.g. λ-mode dominant state: How much the other mode mixes?



M_Q [GeV]

Λ_c^* is almost pure λ mode
➔
Reflect more ***qq*** nature

SU(3) ⟷ Heavy quark

Intermediate summary

- Heavy quark spectroscopy will give more information on constituents
- Isotope shift may resolve two diquark modes

  collective and *internal*
- Λ baryons may have more chance to see the two modes separately
- Systematic study from strange to heavy is useful

3. Productions

$\pi + N \rightarrow \quad D^* + \Lambda_c$ reactions

Production rate (Λ_c / Λ) and Ratios (B_c^* / B_c)

Strategy:

Forward peak (high energy) → t-channel dominant

Next figure

We look at:

(1) Absolute values

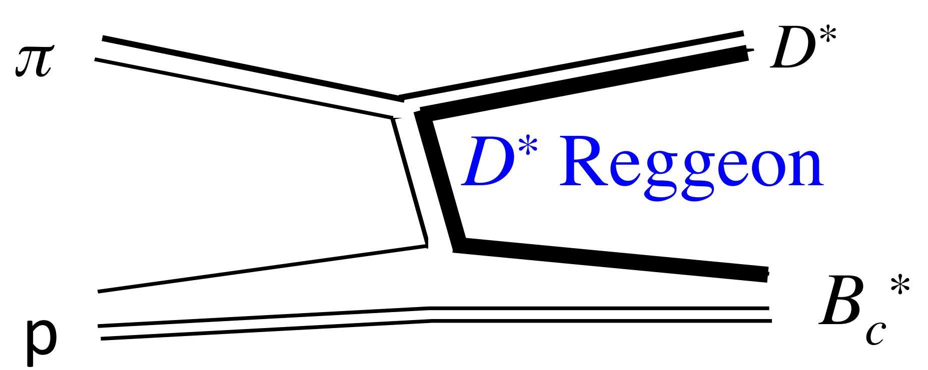
by (Λ_c/Λ_s) by the Regge model, D^* Reggeon

(2) Ratios of $B_c{}^*$(λ modes) / B_c

by a one step process of *Qd* picture for *λ*-mode

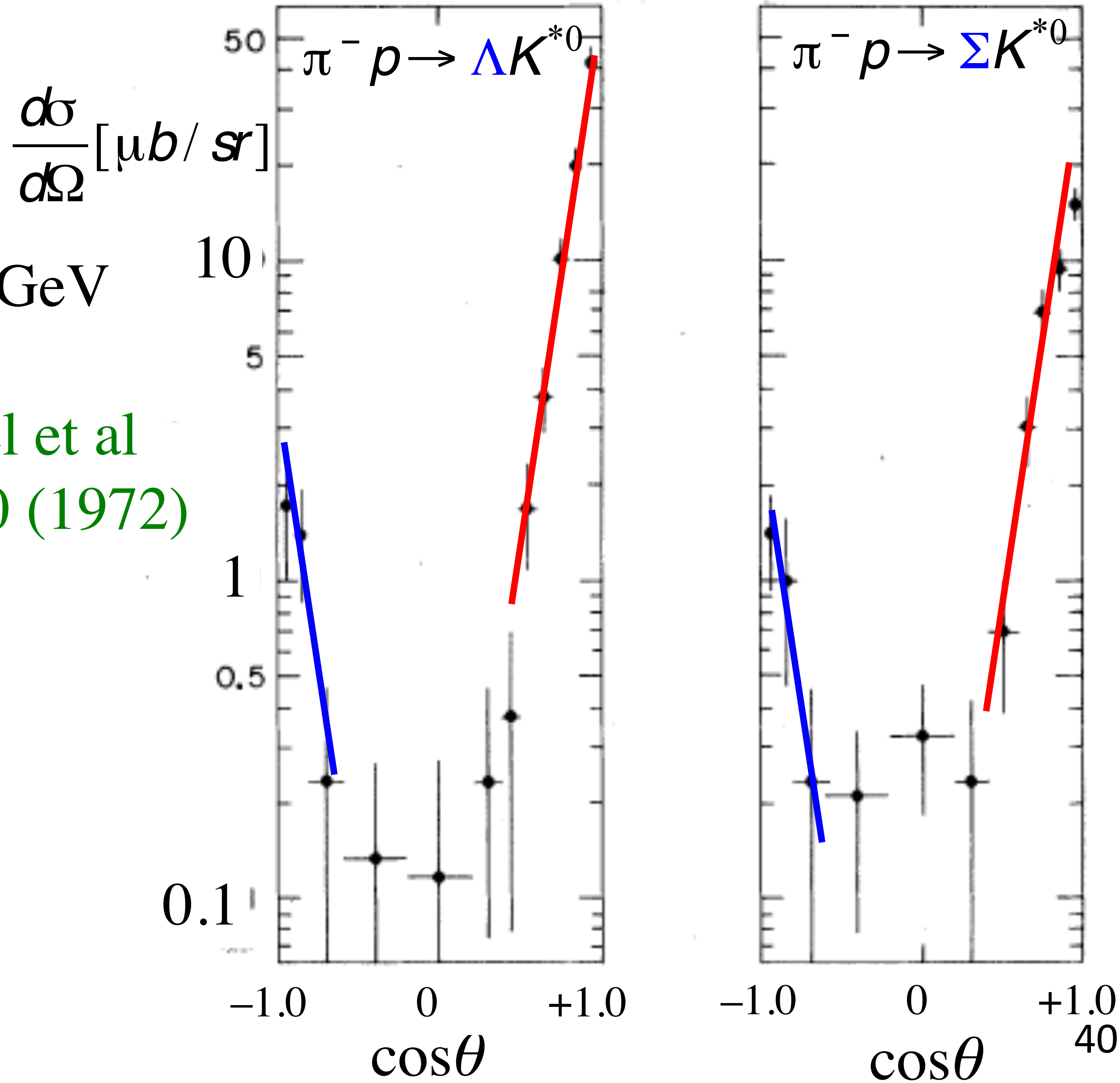
Pion-induced reaction

$\pi + p \rightarrow D^* + B_c{}^*$



$p_{\pi,\mathrm{Lab}} = 4.5$ GeV

D.J. Krennel et al
PRD6, 1220 (1972)



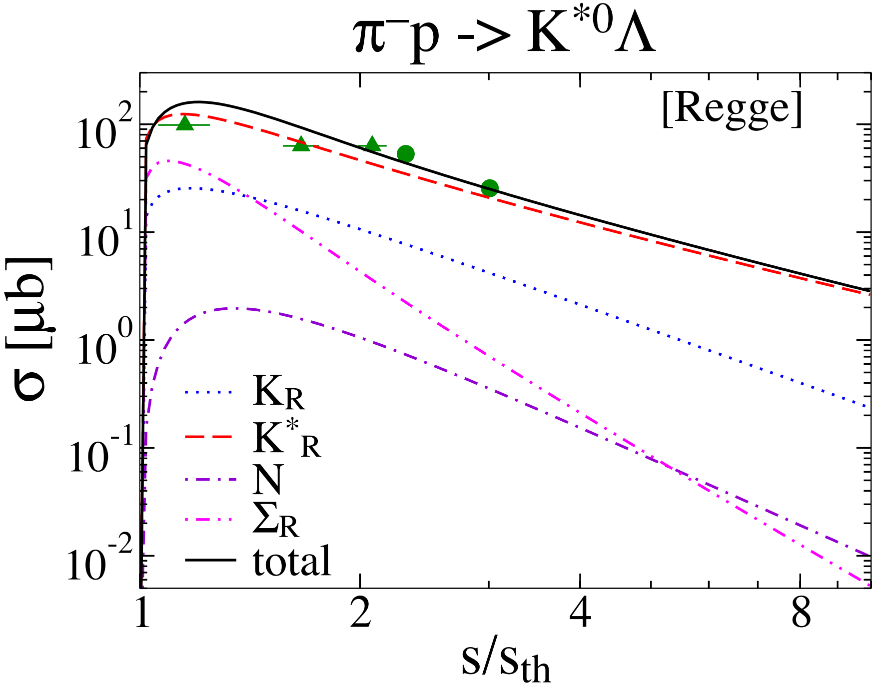
Absolute values

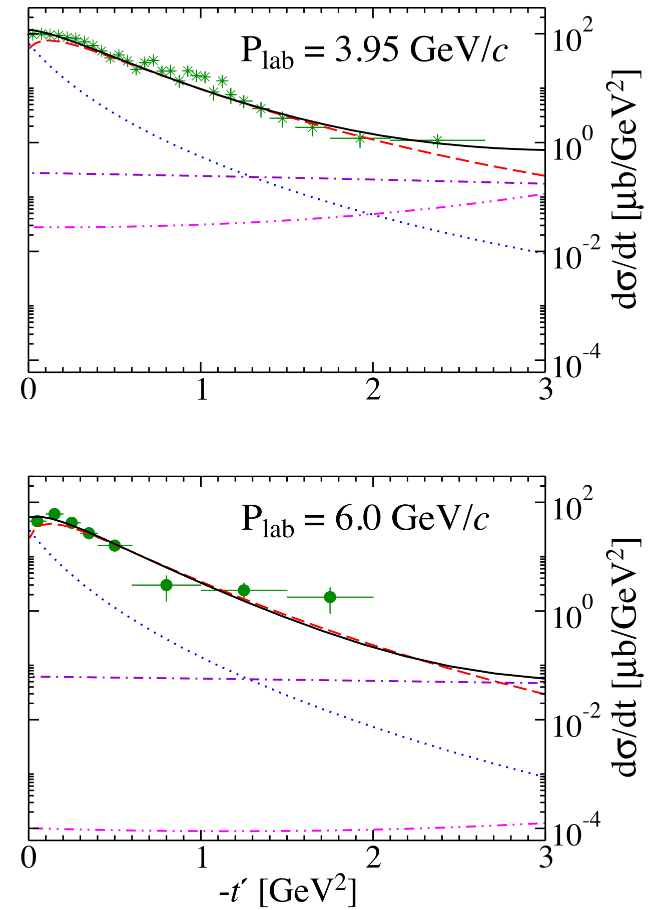
Regge model (Sang-Ho Kim, in preparation)

We have examined:

- K^*(strange) productions
- K^* (D^*) Reggeon dominance
- Angular dependence
- Small u-channels
  - ~ Baryon Regge
- Normalizations

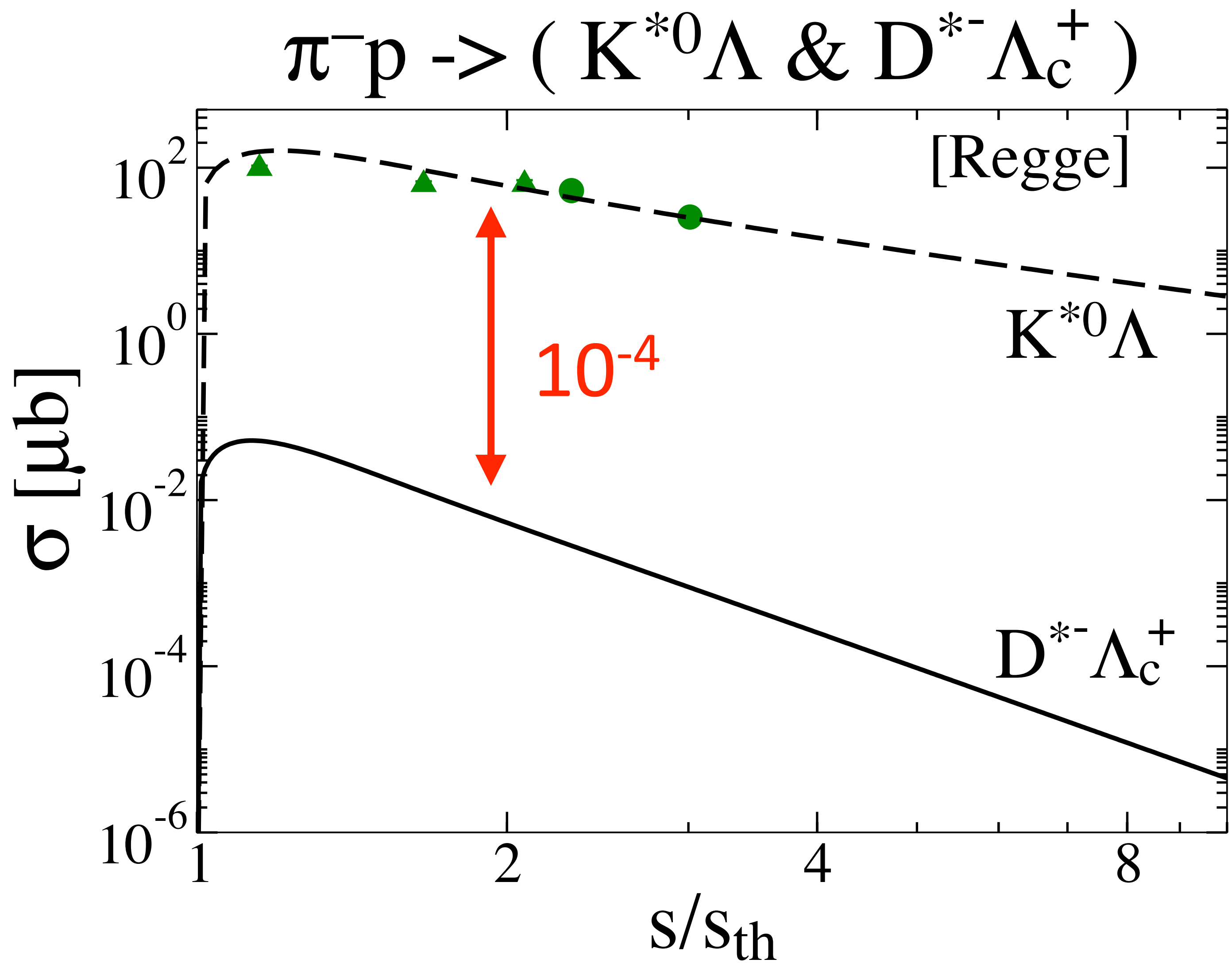
Vector Reggeon dominance





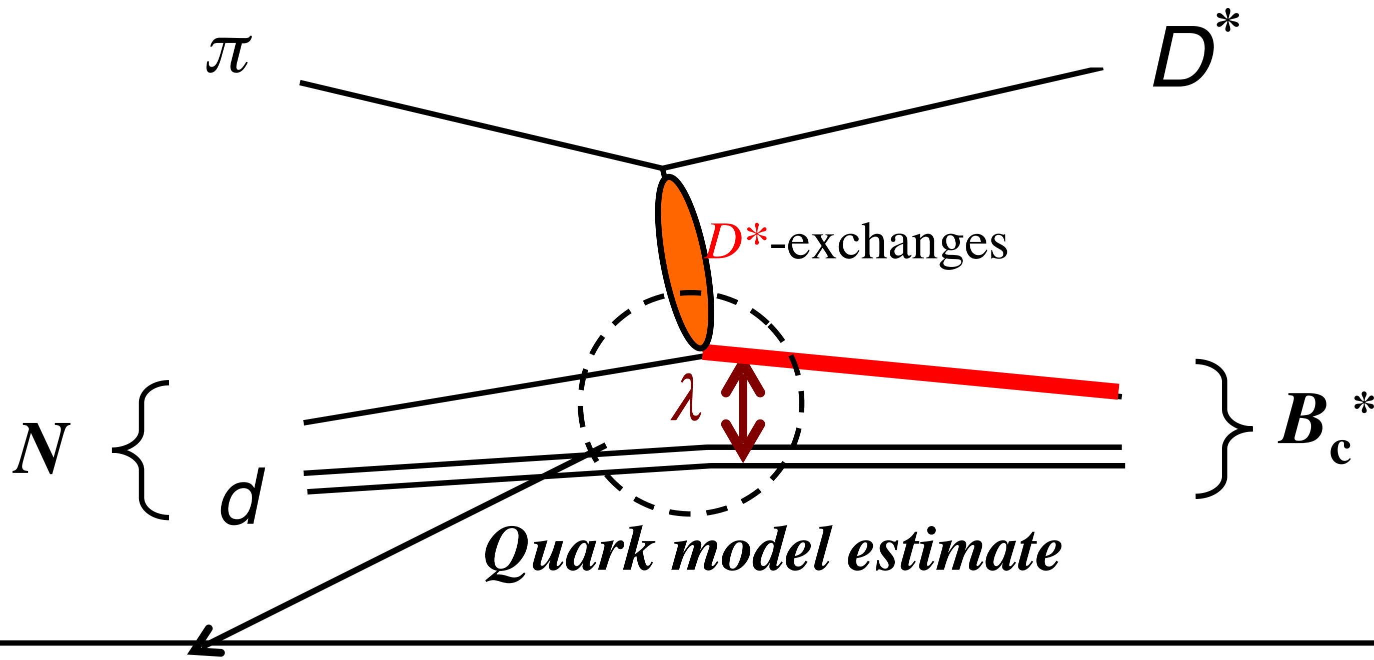
- Angular dependence prefers vector-Reggeon
- Energy dependence seems
- There is some discrepancy in the very forward region

D* meson productions



Relative rates of (B_c^*/B_c)

One step process for Qd λ-mode



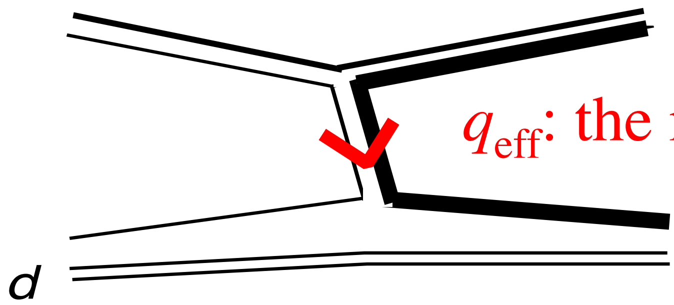
$$t_{fi} \sim \vec{k}_\pi \times \vec{e} \cdot \vec{J}_{fi}$$

$$\sim \left\langle B_c^* \middle| \vec{e}_\perp \cdot \vec{\sigma} e^{i\vec{q}_{eff}\cdot\vec{x}} \middle| N \right\rangle = \text{(Geometric)} \times \text{(Dynamic)}$$

D ~ Transverse*

CG coefficients

Dynamical part ~ radial integral



$q_{\rm eff}$: the momentum transfer ~ Large

$$\text{GS} \quad \langle B_c(\text{S-wave})|\vec{e}_\perp \cdot \vec{\sigma} e^{i\vec{q}_{eff}\cdot\vec{x}}|N(\text{S-wave})\rangle_{radial} \sim 1 \times \exp\left(-\frac{q_{eff}^2}{4A^2}\right)$$

Excited states

$$\langle B_c(P\text{-wave})|\vec{e}_\perp \cdot \vec{\sigma} e^{i\vec{q}_{eff}\cdot\vec{x}}|N(\text{S-wave})\rangle_{radial} \sim \left(\frac{q_{eff}}{A}\right)^1 \times \exp\left(-\frac{q_{eff}^2}{4A^2}\right)$$

$$\langle B_c(D\text{-wave})|\vec{e}_\perp \cdot \vec{\sigma} e^{i\vec{q}_{eff}\cdot\vec{x}}|N(\text{S-wave})\rangle_{radial} \sim \left(\frac{q_{eff}}{A}\right)^2 \times \exp\left(-\frac{q_{eff}^2}{4A^2}\right)$$

Transitions to excited states are not suppressed

Results

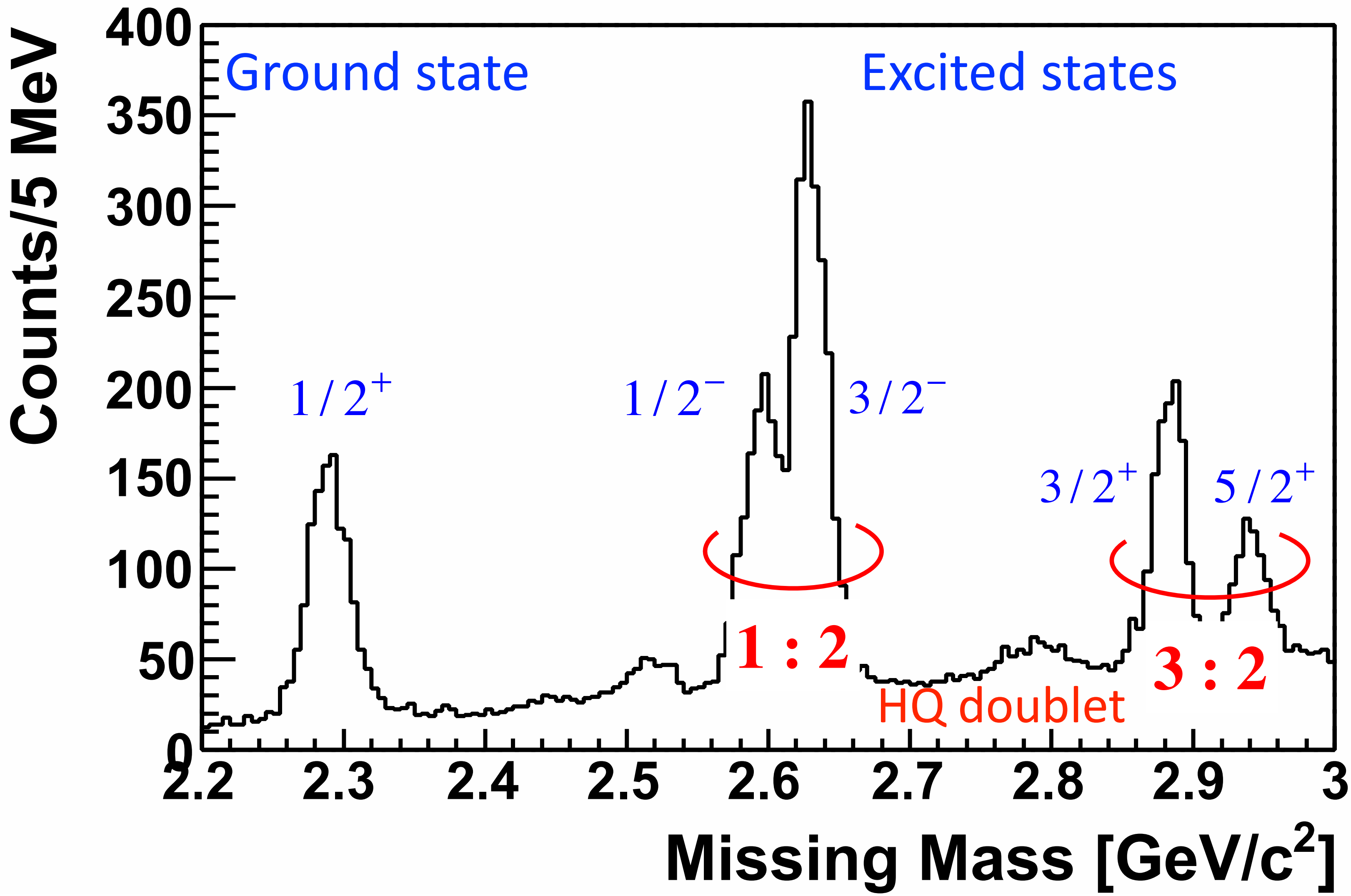
Charm $k_{\pi}^{CM} = 2.71$ [GeV] , $k_{\pi}^{Lab} = 16$ [GeV]

$l=0$	$\Lambda_c(\frac{1}{2}^+)$	$\Sigma_c(\frac{1}{2}^+)$	$\Sigma_c(\frac{3}{2}^+)$					
	1.00	0.02	0.16					
$l=1$	$\Lambda_c(\frac{1}{2}^-)$	$\Lambda_c(\frac{3}{2}^-)$	$\Sigma_c(\frac{1}{2}^-)$	$\Sigma_c(\frac{3}{2}^-)$	$\Sigma'_c(\frac{1}{2}^-)$	$\Sigma'_c(\frac{3}{2}^-)$	$\Sigma'_c(\frac{5}{2}^-)$	
	0.90	1.70	0.02	0.03	0.04	0.19	0.18	
$l=2$	$\Lambda_c(\frac{3}{2}^+)$	$\Lambda_c(\frac{5}{2}^+-)$	$\Sigma_c(\frac{3}{2}^+)$	$\Sigma_c(\frac{5}{2}^+)$	$\Sigma'_c(\frac{1}{2}^+)$	$\Sigma'_c(\frac{3}{2}^+)$	$\Sigma'_c(\frac{5}{2}^+)$	$\Sigma'_c(\frac{5}{2}^+)$
	0.50	0.88	0.02	0.02	0.01	0.03	0.07	0.07

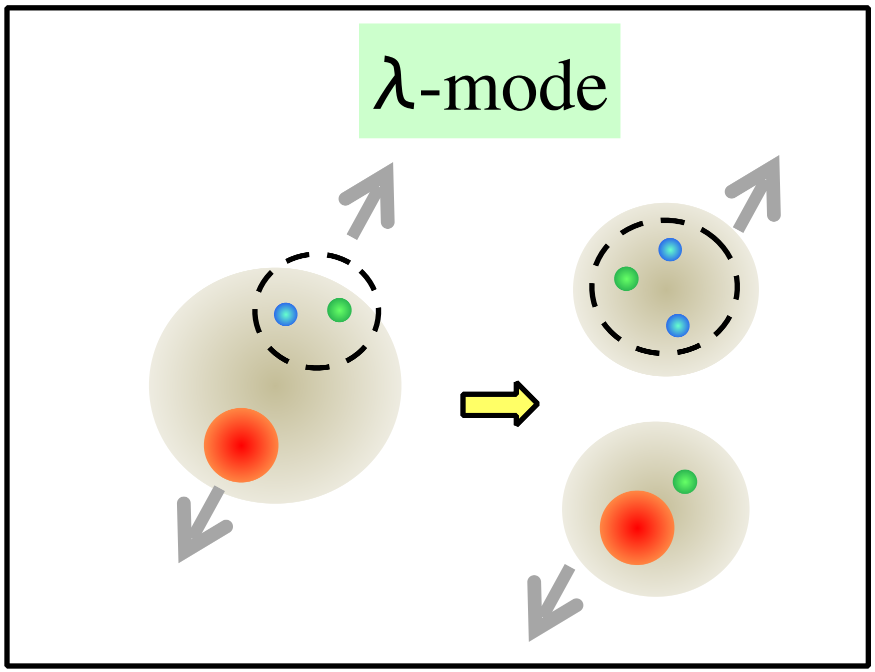
Strange $k_{\pi}^{CM} = 1.59$ [GeV], $k_{\pi}^{Lab} = 5.8$ [GeV]

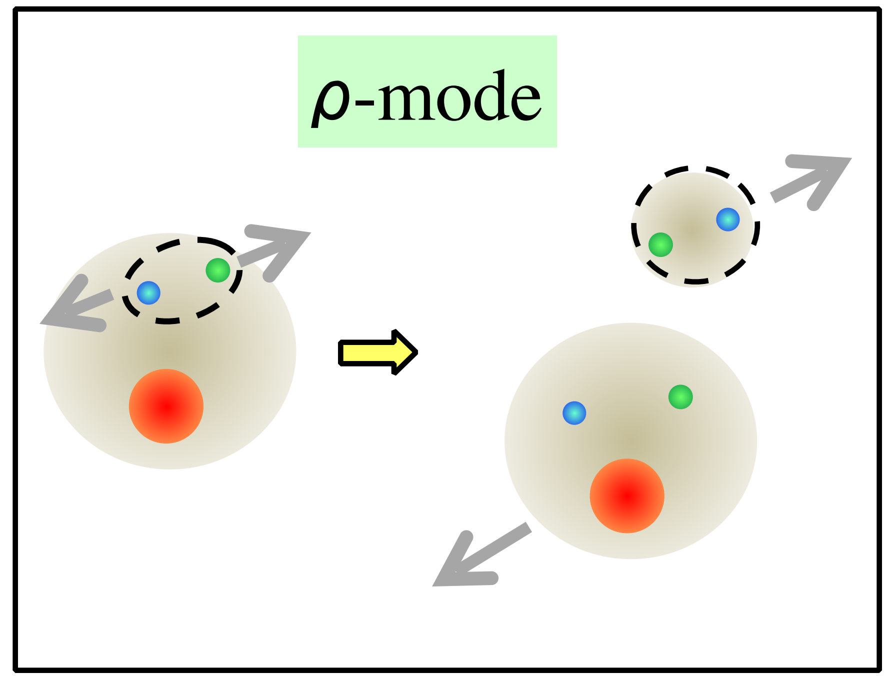
$l=0$	$\Lambda(\frac{1}{2}^+)$	$\Sigma(\frac{1}{2}^+)$	$\Sigma(\frac{3}{2}^+)$					
	1.00	0.067	0.44					
$l=1$	$\Lambda(\frac{1}{2}^-)$	$\Lambda(\frac{3}{2}^-)$	$\Sigma(\frac{1}{2}^-)$	$\Sigma(\frac{3}{2}^-)$	$\Sigma'(\frac{1}{2}^-)$	$\Sigma'(\frac{3}{2}^-)$	$\Sigma'(\frac{5}{2}^-)$	
	0.11	0.23	0.007	0.01	0.01	0.07	0.067	
$l=2$	$\Lambda(\frac{3}{2}^+)$	$\Lambda_c(\frac{5}{2}^+-)$	$\Sigma(\frac{3}{2}^+)$	$\Sigma(\frac{5}{2}^+)$	$\Sigma'(\frac{1}{2}^+)$	$\Sigma'(\frac{3}{2}^+)$	$\Sigma'(\frac{5}{2}^+)$	$\Sigma'(\frac{5}{2}^+)$
	0.13	0.20	0.007	0.01	0.004	0.02	0.038	0.04

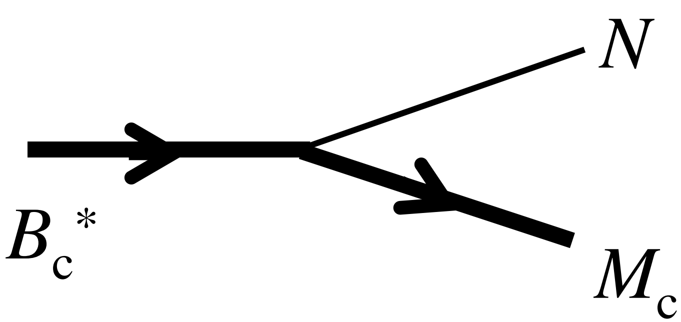
Expected charm production spectrum

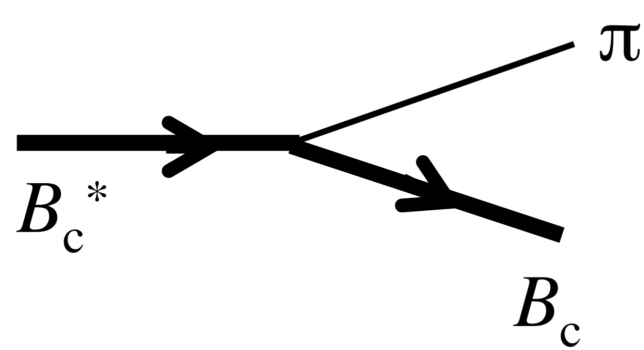


4. Decays





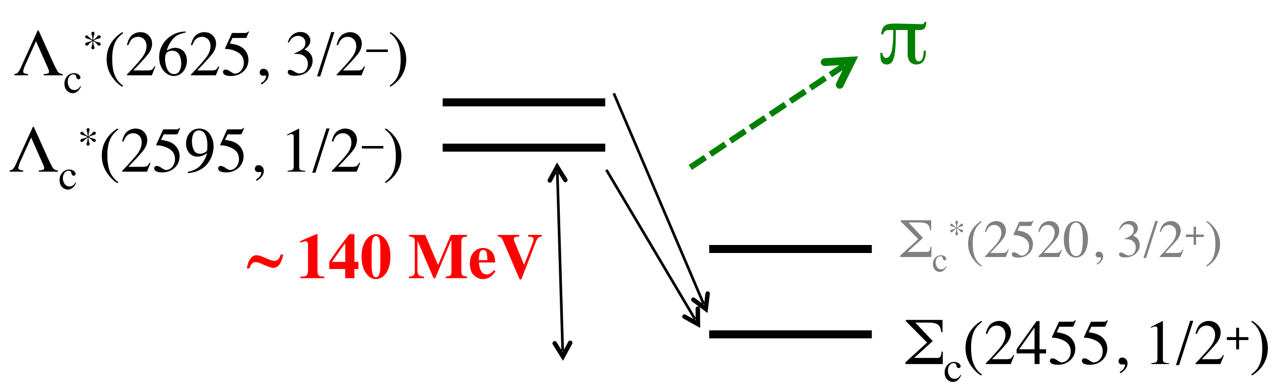




Pion emission – quark model --on going

Things to be looked at:

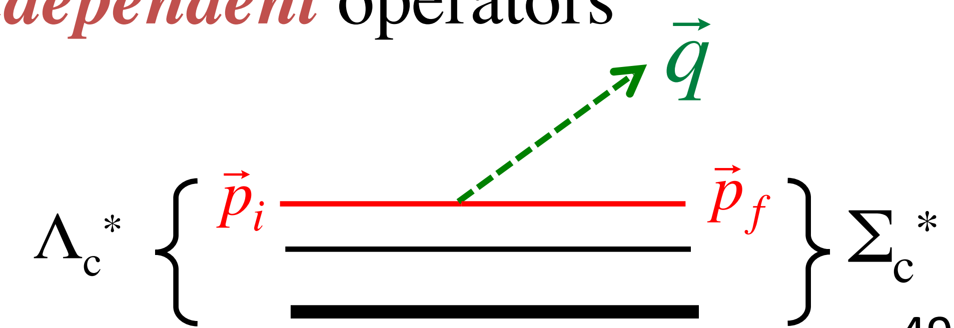
- Pion emission ~ **very near the threshold**



Place to look at the ***two independent*** operators

$$\bar{q}\gamma_5 q\phi_\pi, \ \bar{q}\gamma^\mu\gamma_5 q\partial_\mu\phi_\pi$$

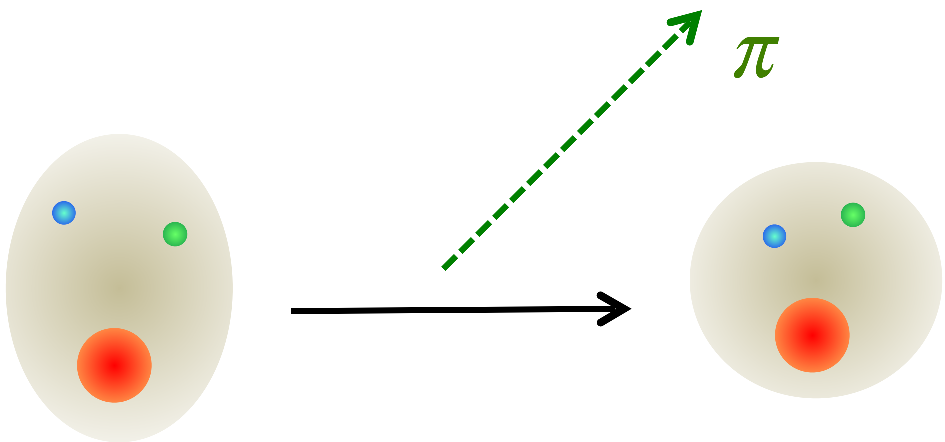
$$\vec{\sigma}\cdot\vec{p}_i, \ \vec{\sigma}\cdot\vec{p}_f \ (\vec{\sigma}\cdot\vec{q})$$



Possible selection rules

ϱ-modes

Decays of baryons = of diquarks

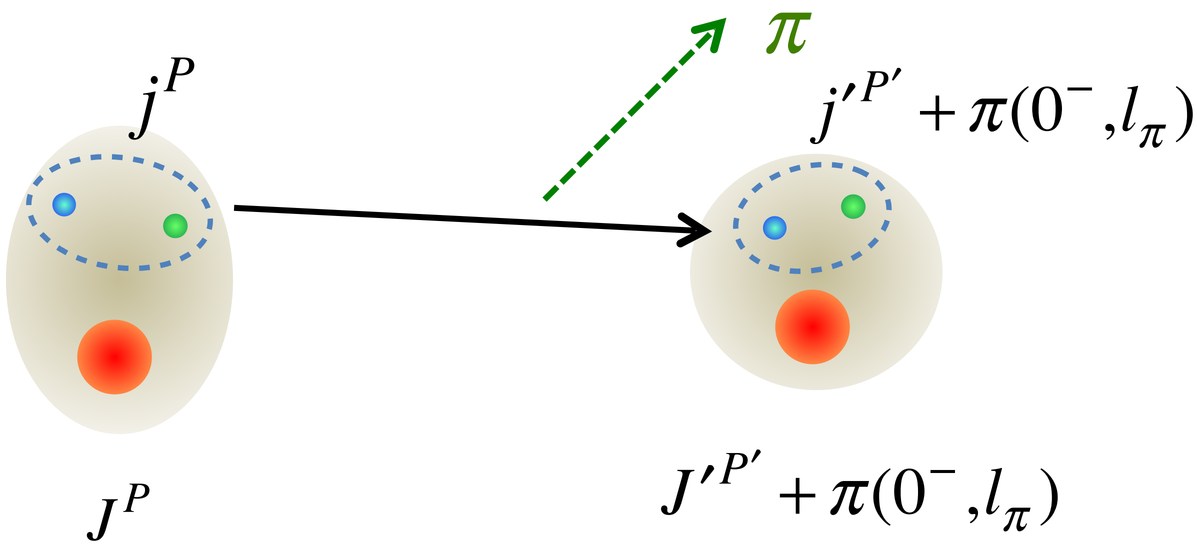


J^P $\quad$ $J'^{P'} + \pi(0^-, l_\pi)$

Possible selection rules

ϱ-modes

Decays of baryons = of diquarks



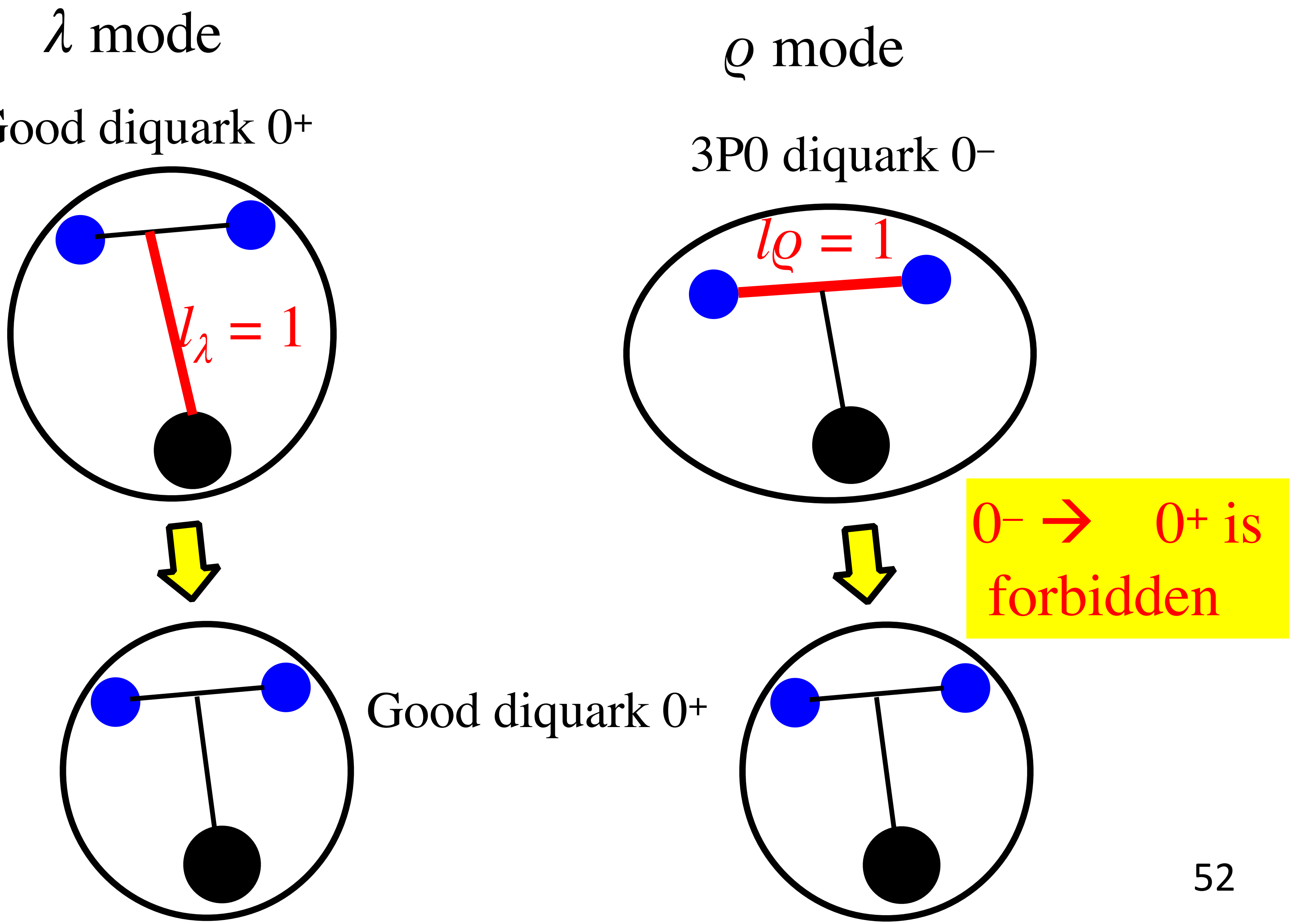
Two conditions must be satisfied for baryons and for diquarks

$$\Lambda_c(1/2^-, \rho) \rightarrow \Sigma_c(1/2^+, GS) + \pi$$

$$d(^3P_0) \rightarrow d(^3S_1) + \pi$$

is not allowed

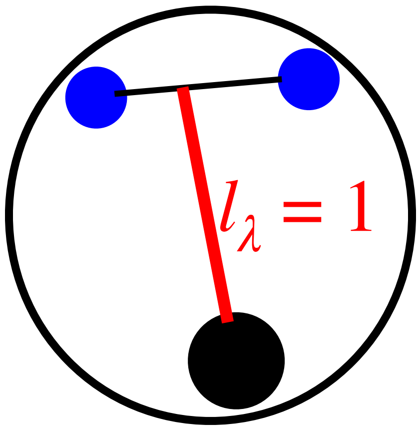
Radiative decay: $1/2^- \rightarrow 1/2^+$ E1



Radiative decay: $5/2^- \rightarrow 1/2^+$ M2, E3

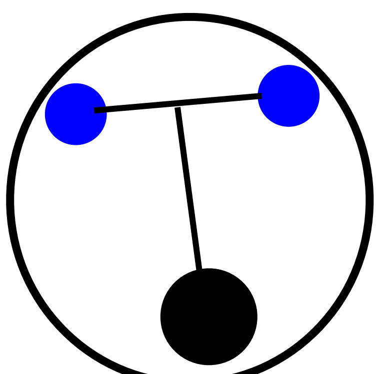
λ mode

$^3S_1$ diquark 1^+



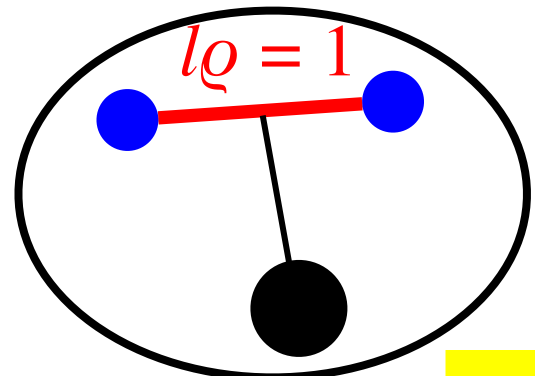
Both M2 E3

Good diquark 0^+

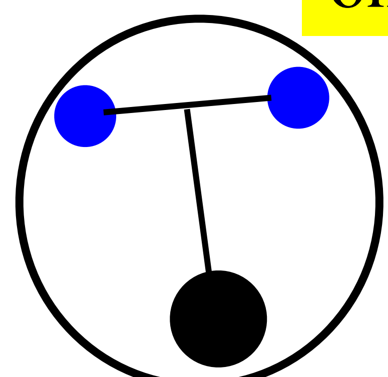


ϱ mode

$^3P_2$ diquark 2^-



$2^- \rightarrow 0^+$ is only M2



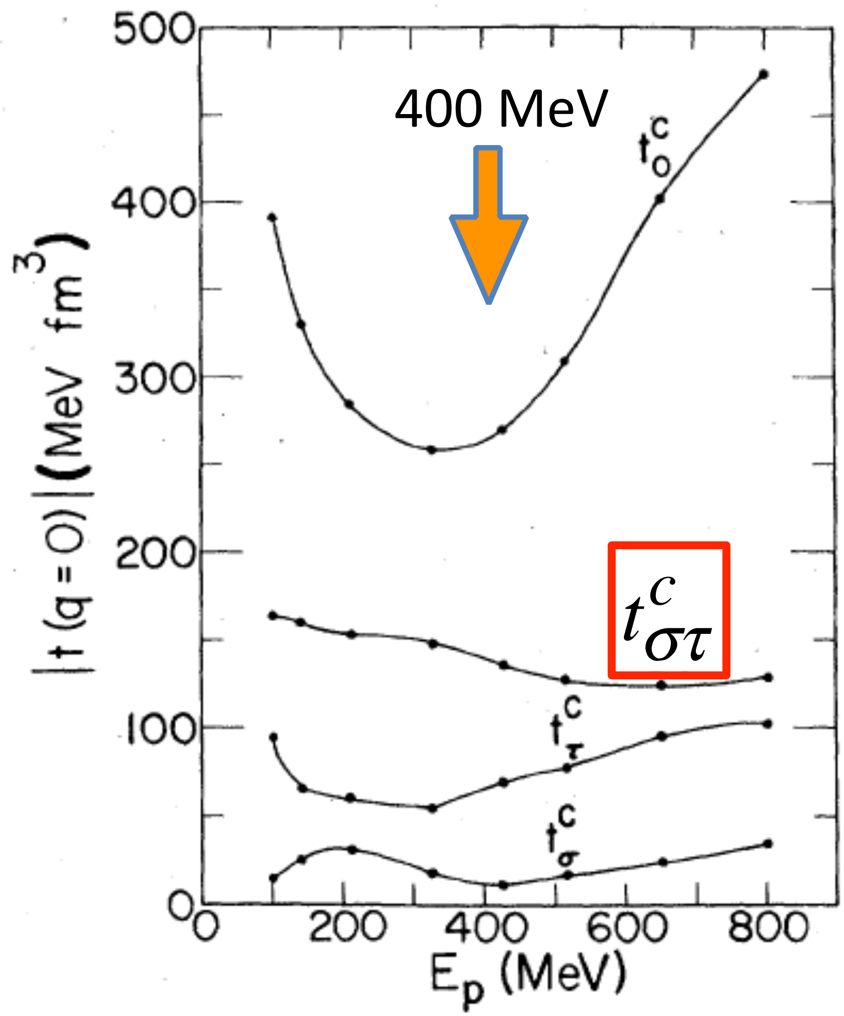
Summary

- Charmed baryons: there are many open issues
- J-PARC plans to study them

- Production rate: Charm/Strangeness: 10^{-4} or less
- Abundant production of excited states

- Decay selection rules are helpful

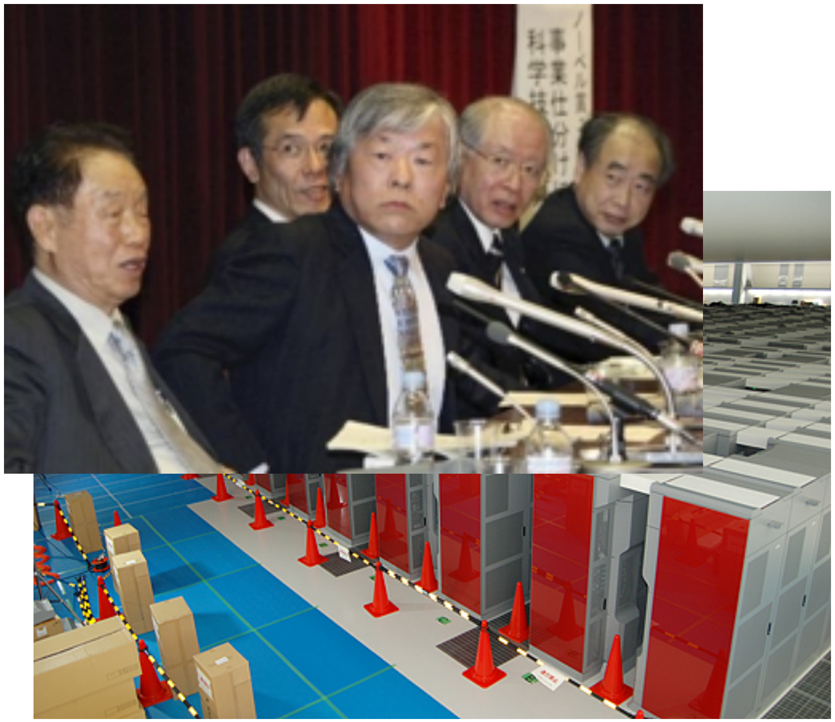
Energy dependence of the NN interaction



Kei computer (京) at Kobe

Famous screening for government driven projects

Why No. 1!! not No. 2!?



igures

,300

Machine

HPCI consortium

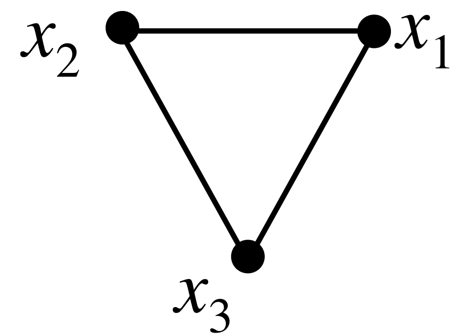
Users office

Users

Harmonic oscillator

$$H = \frac{{p_1}^2}{2m} + \frac{{p_2}^2}{2m} + \frac{{p_3}^2}{2M} + \frac{k}{2}\left((x_1 - x_2)^2 + (x_2 - x_3)^2 + (x_3 - x_1)^2\right)$$

$$= \frac{{p_\rho}^2}{2m_\rho} + \frac{{p_\lambda}^2}{2m_\lambda} + \frac{k_\rho \rho^2}{2} + \frac{k_\lambda \lambda^2}{2}$$



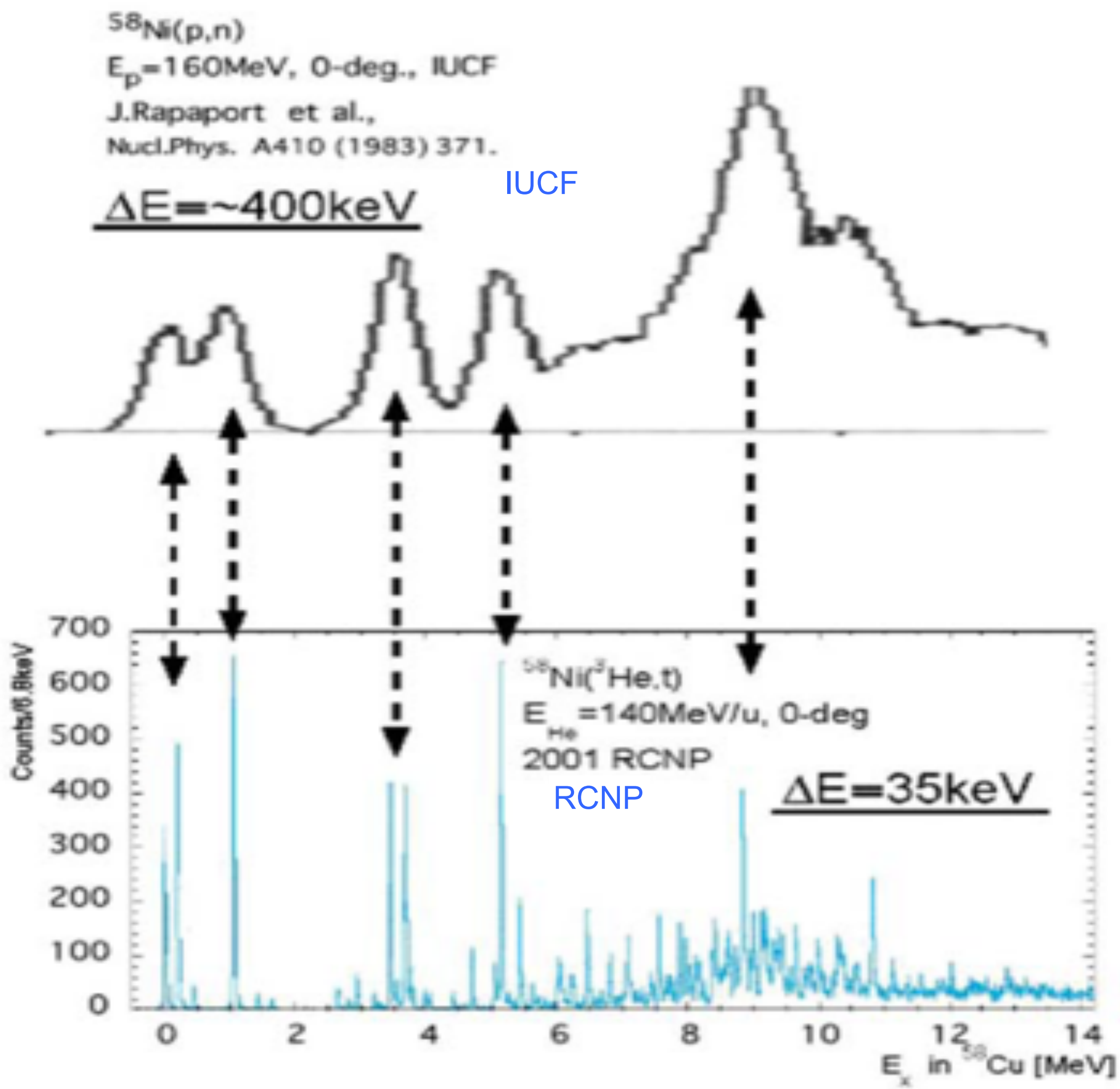
$$m_\rho = \frac{m}{2}, \quad m_\lambda = \frac{2mM}{M + 2m}$$

$$k_\rho = \frac{3}{2}k, \quad k_\lambda = 2k$$

$$\omega_\rho = \sqrt{3}\omega \quad > \quad \omega_\lambda = \sqrt{\frac{M + 2m}{M}}\omega$$

World best resolution

$^{58}Ni(p,n)$



Beamline map of SPring-8