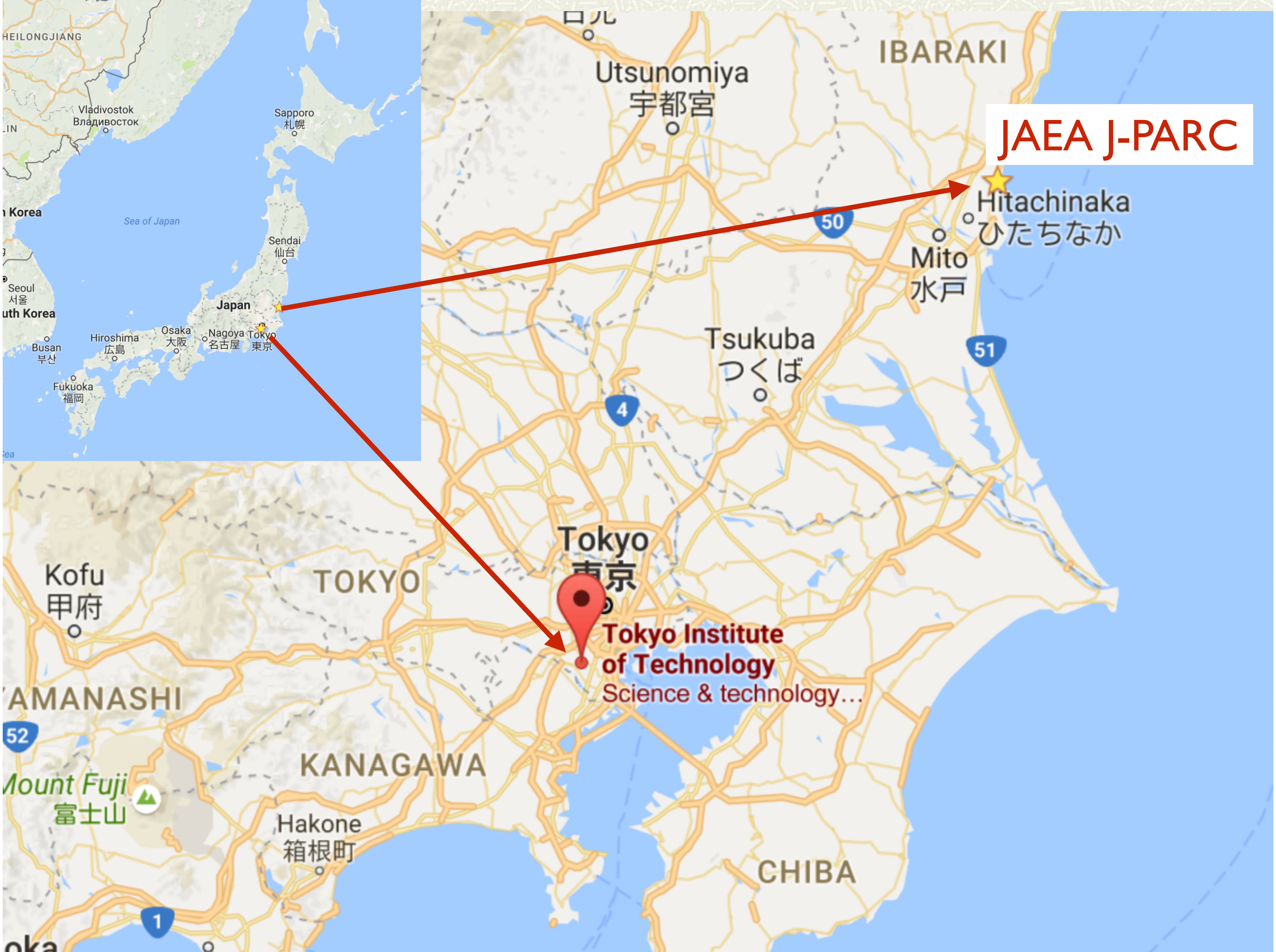
Heavy Quark Physics (at J-PARC)
and J-PARC Heavy Ion Project

Makoto Oka
Tokyo Institute of Technology
and
Advanced Science Research Center
Japan Atomic Energy Agency (JAEA)

Hadronic Matter under Extreme Conditions
JINR, Dubna, October 31, 2016


JAEA J-PARC
Hitachinaka
ひたちなか
Tokyo Institute
of Technology
Science & technology...
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Utsunomiya
宇都宮
Mito
水戸
Tsukuba
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Tokyo
東京
TOKYO
Kofu
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Osaka
大阪
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名古屋
Busan
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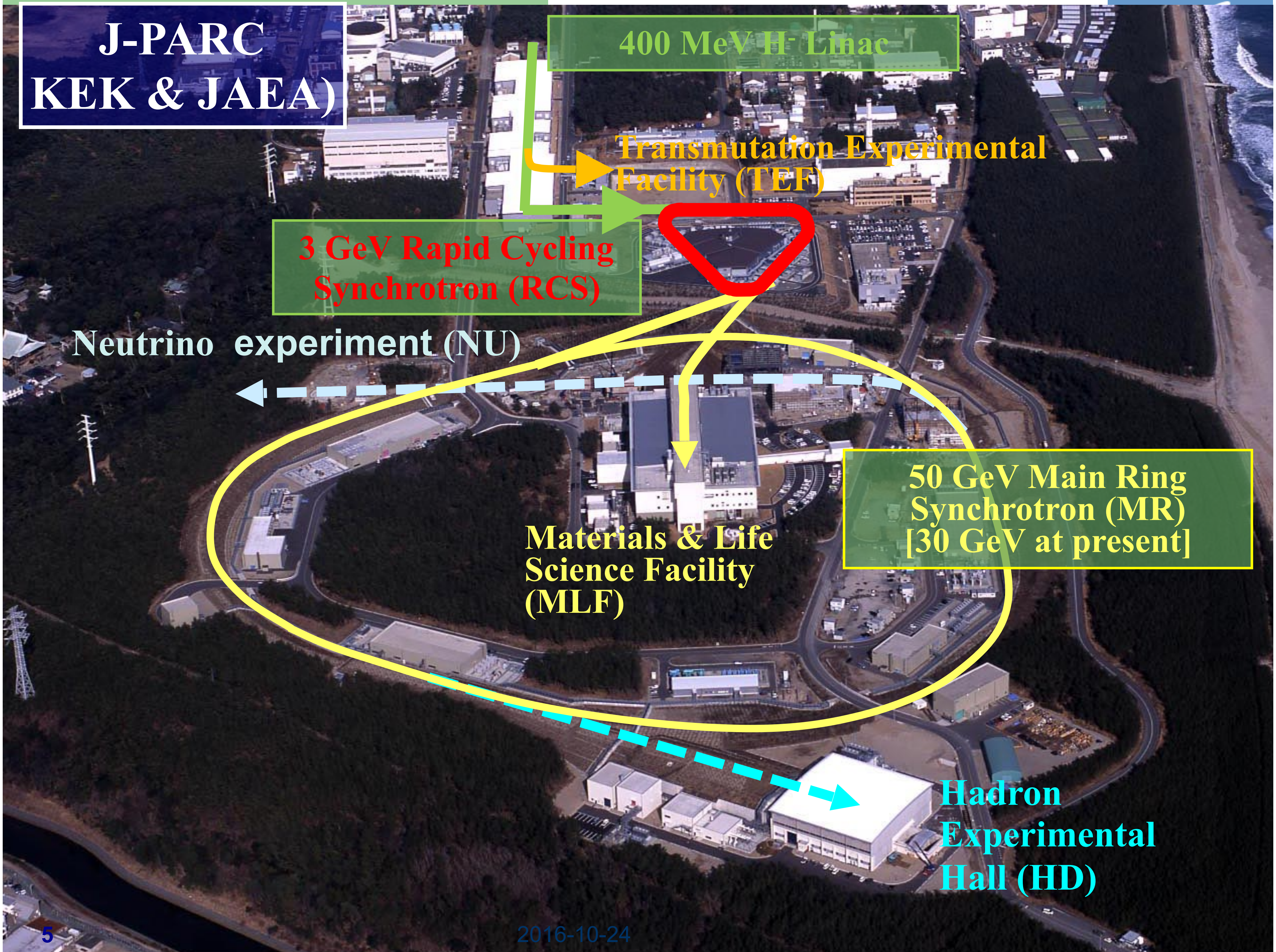
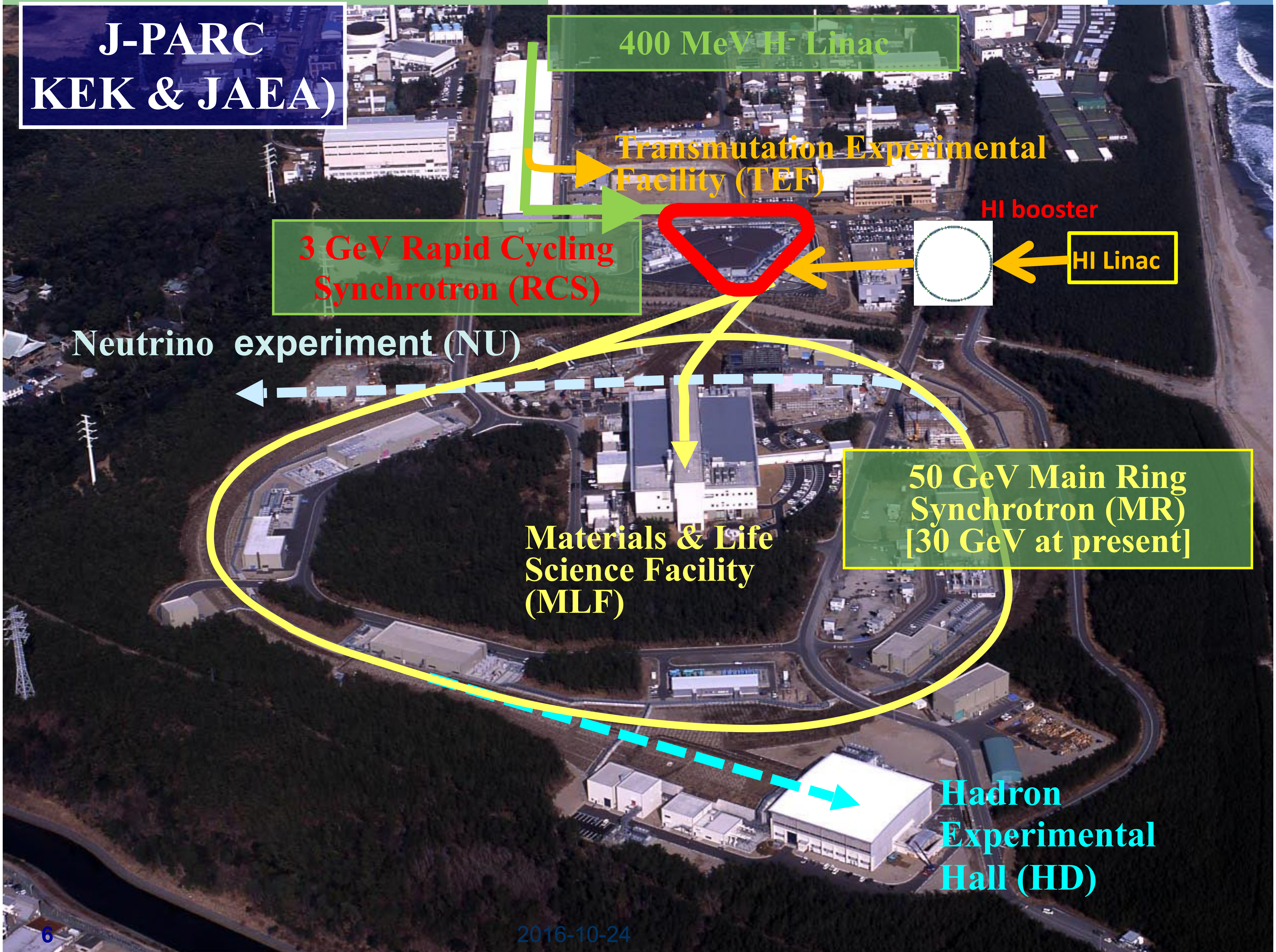
Fukuoka
福岡

Contents

J-PARC KEK & JAEA)


J-PARC
KEK & JAEA)
400 MeV H- Linac
Transmutation Experimental
Facility (TEF)
3 GeV Rapid Cycling
Synchrotron (RCS)
Neutrino experiment (NU)
50 GeV Main Ring
Synchrotron (MR)
[30 GeV at present]
Materials & Life
Science Facility
(MLF)
Hadron
Experimental
Hall (HD)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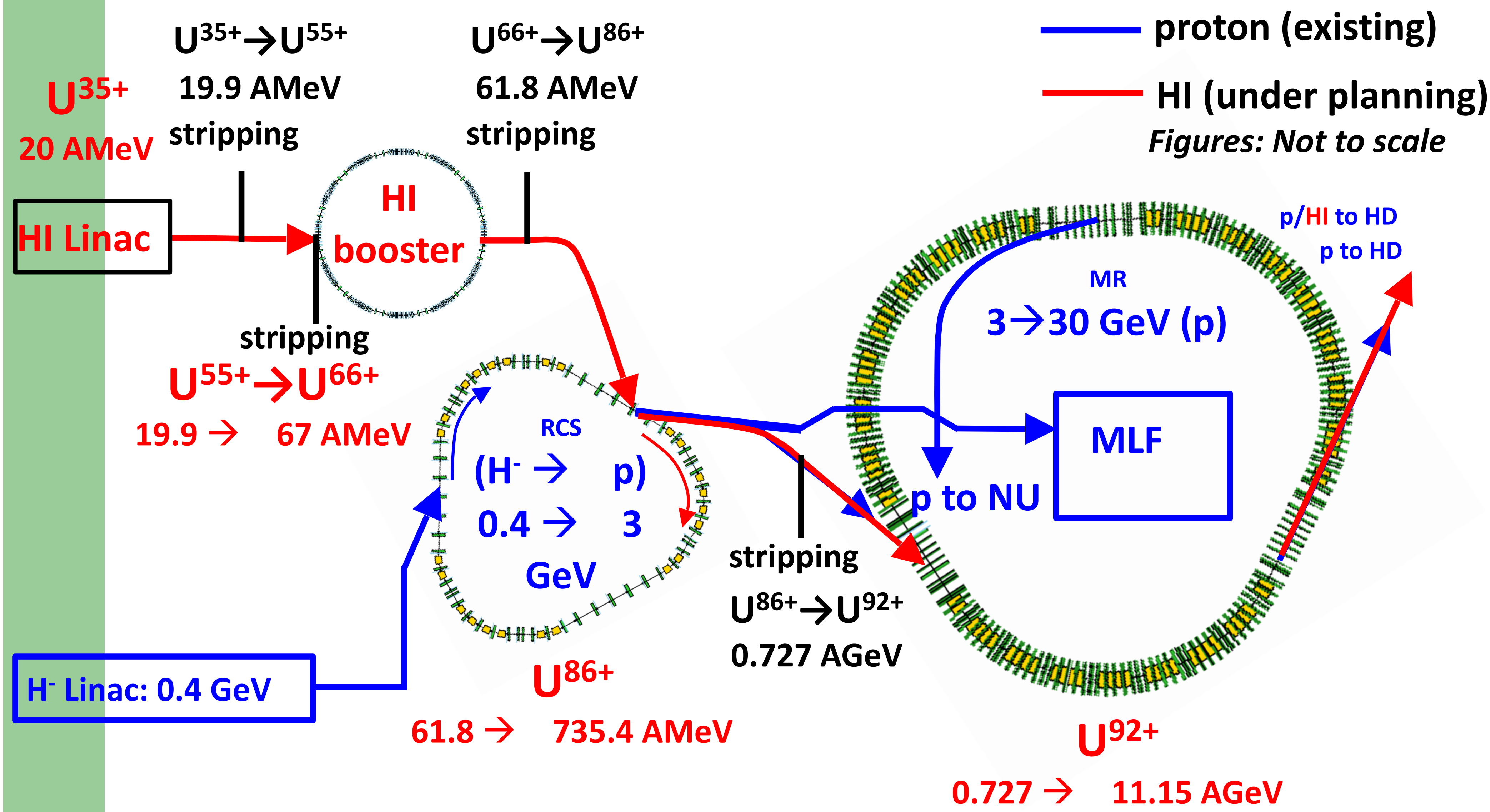
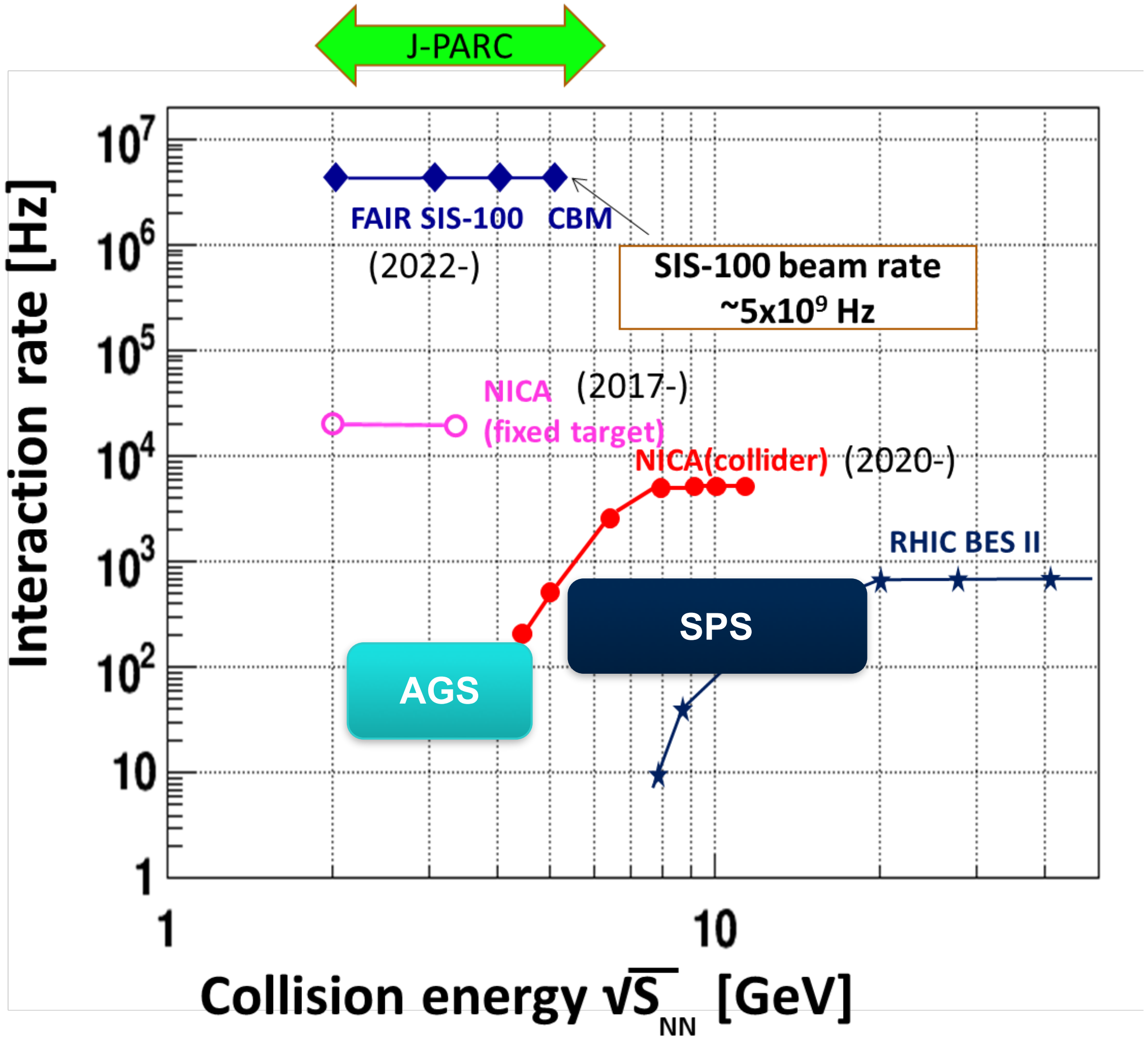
HI Accelerator scheme in J-PARC



This HI accelerator scheme has no interference/conflict with proton beam programs

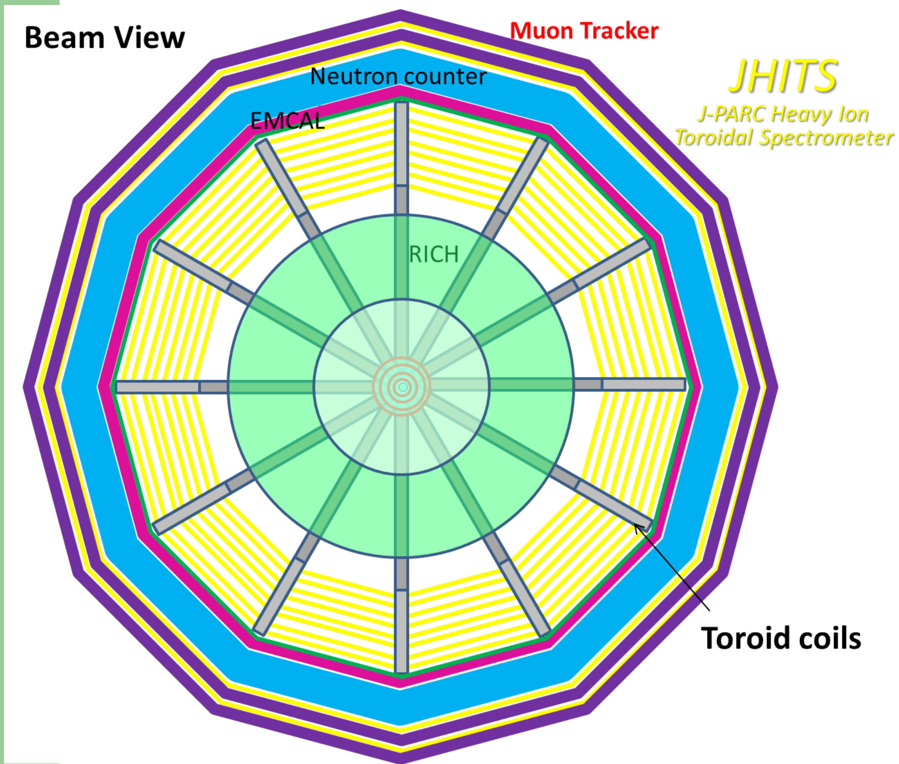
Available beam and rate

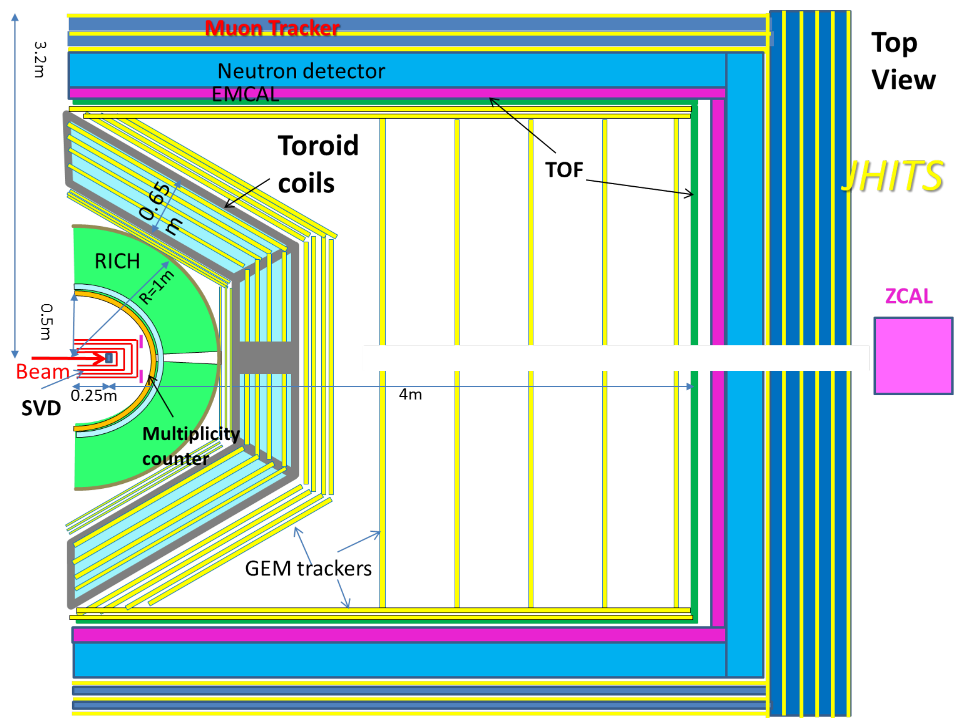
- *Very high intensity beam is a feature of J-PARC HI accelerator*
  - E_{lab}=1-19GeV/n, $\sqrt{s_{NN}}$=1.9-6.2GeV (~ AGS), >10^{11} $cycle^{-1}$(~6s cycle)
- Ion species: p, Si, Ar, Cu, Xe, Au(Pb), U, and also light ions for hypernuclei



Concept of measurement device

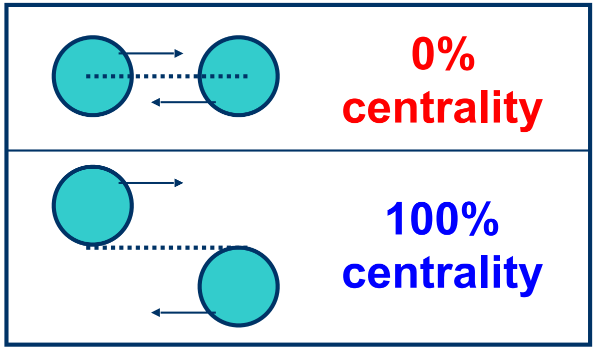
- Detector complex covering wide acceptance
  - High speed tracking, TOF, EM calorimeter, and muon detector
- 0.1% λ_I target: ~100MHz event rate, 1000 particles/event
- Collect data with minimum bias trigger (Data size: 1TB/s)
  - Continuously take data with no trigger (Import ALICE experience)
  - Select rare events in semi-online, using a high performance computing system





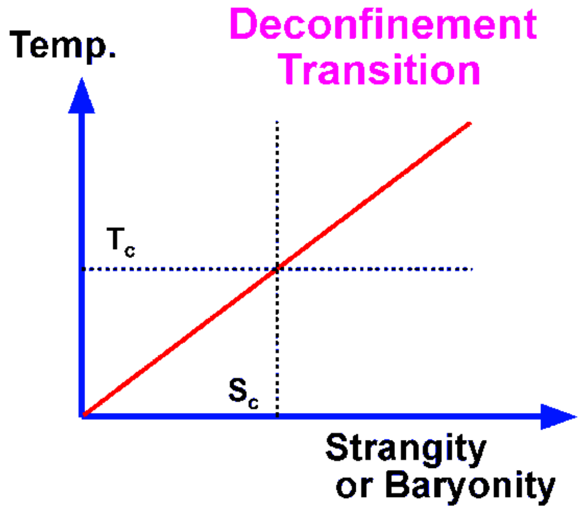
Event selection consideration

- Centrality: Event class variable proportional to impact parameters
  - 0%: b=0, Central collisions
  - 100%: b=bmax, Peripheral collisions
- Same event selection as we did in the past wouldn't yield new physics
- We add a new event selection
  - After pre-selecting most central collisions
- **Strangity, Baryonity**
  - Aggressively select interesting events relevant to the new phenomena found by the AGS experiment
  - Strangeness enhancement, baryon stopping
- Statistics-starved "very rare event" selection feasible with high luminosity beam at J-PARC-HI



$$Strangity \equiv \langle N(K^{+}) \rangle / \langle N_{ch} \rangle$$

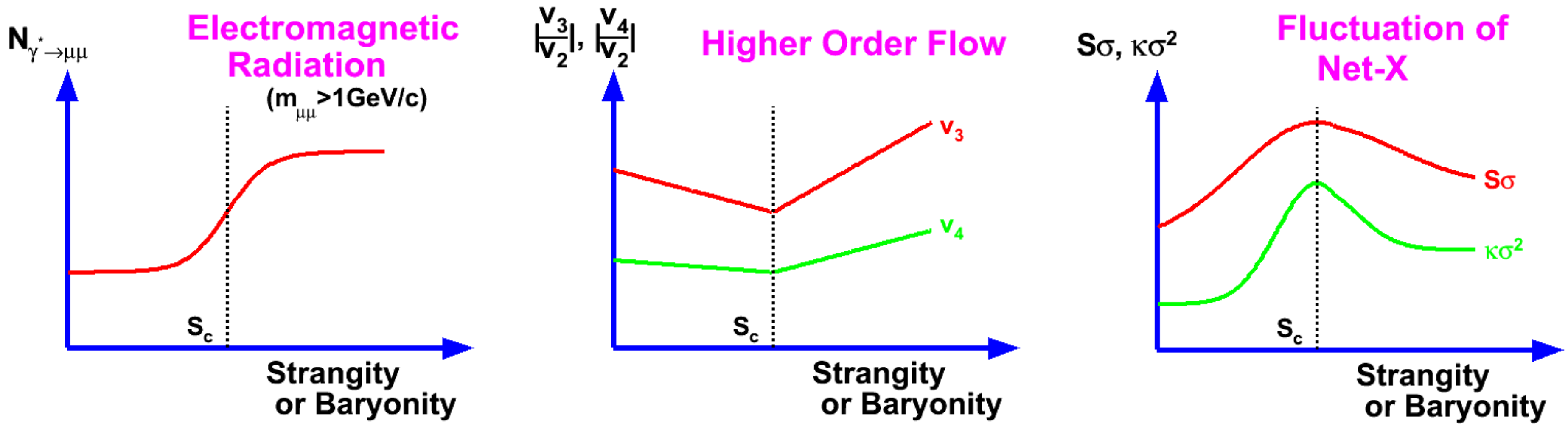
$$Baryonity \equiv \langle N(p) - N(\bar{p}) \rangle$$



TS, H. Sako and M. Kitazawa, in prep.

Physics observables at J-PARC-HI

- Primarily focus on new observables found at higher energy experiments
  - Based on knowledge gained at RHIC and LHC
- Study characteristics of high density matter
  - Particle emission anisotropy, fluctuation of conserved quantities
  - Lepton pairs, thermal photons



 2016-10-24 T. Sakaguchi Reimei@Inha, Korea

White paper for a Future J-PARC Heavy-Ion Program (J-PARC-HI)

Preliminary plan towards the proposal to J-PARC by an international research collaboration (J-PARC-HI Collaboration)

June, 2016

http://asrc.jaea.go.jp/soshiki/gr/hadron/jparc-hi/

Letter of Intent for J-PARC Heavy-Ion Program (J-PARC-HI)

August, 2016

J-PARC-HI Collaboration

Spokesperson H. Sako*[1,2],

J.K. Ahn[3], O. Busch[4], T. Chujo[4], P. Cirkovic[5], T. Csörgő[6,7], G. David[8], D. Devetak[5], M. Djordjevic[5], S. Esumi[4], P. Garg[9], T. Gunji[10], T. Hachiya[11], H. Hamagaki[12], S. Hasegawa[1], B. Hong[3], S.H. Hwang[13], Y. Ichikawa[1], K. Imai[1], M. Inaba[14], M. Kaneta[15], B.C Kim[4], E.-J. Kim[16], X. Luo[17], H. Masui[4], Y. Miake[4], J. Milosevic[5], D. Mishra[18], L. Nadjdjerdj[5], S. Nagamiya[1,11,19], T. Nakamura[19], M. Naruki[20], K. Nishio[1], T. Nonaka[4], K. Oyama[12], K. Ozawa[21], T.R. Saito[22,23], A. Sakaguchi[24], T. Sakaguchi[8], K. Sato[4], S. Sato[1], S. Sawada[21], K. Shigaki[25], S. Shimansky[26], M. Shimomura[27], M. Stojanovic[5], H. Sugimura[1], H. Tamura[15], K.H. Tanaka[21], Y. Tanaka[12], K. Tanida[1], N. Xu[17,28], S. Yokkaichi[11], I.-K. Yoo[29],

M. Kitazawa[24], H. Fujii[30], K. Fukushima[31], M. Harada[32], T. Hatsuda[11], T. Hirano[33], K. Itakura[21], T. Maruyama[1], K. Morita[34], K. Murase[31], Y. Nara[35], C. Nonaka[32], A. Ohnishi[34], M. Oka[1,36],

H. Harada[2], H. Hochi[2], J. Kamiya[2], S. Kato[2], M. Kinsho[2], A. Kovalenko[26], Y. Liu[21], K. Okabe[2], M. Okamura[8], P.K. Saha[2], Y. Shobuda[2], F. Tamura[2], J. Tamura[2], N. Tani[2], Y. Watababe[2], M. Yamamoto[2], M. Yoshii[21], and M. Yoshimoto[2]

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3. Quarkonium and Hadron Molecules

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+ J-PARC-HI Experimental Project (by Takao Sakaguchi)

Introduction:
From QCD to Hadron Spectrum

M.Oka (Tokyo Tech. and JAEA)

From QCD to Hadron Spectrum

QCD = quarks + gluons with color SU(3)$_c$ gauge symmetry

$$\mathcal{L} = \bar{q}(i\not{D} - m_q)q - \frac{1}{2}\mathrm{Tr}[G_{\mu\nu}G^{\mu\nu}]$$

expected low energy modes

massless gluons

***light quarks* (*m_q* < 10 MeV)**

But, in reality,

***massless gluons* => glueballs (m_{GB} ~ 1.4 GeV or larger)**

***light quarks* => mesons (500~800 MeV) except for the pion**

baryons (940 MeV ~)

QCD at low energy is strongly correlated.

=> color confinement, chiral symmetry breaking, . . .

Nontrivial QCD Vacuum

Properties of the QCD vacuum

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

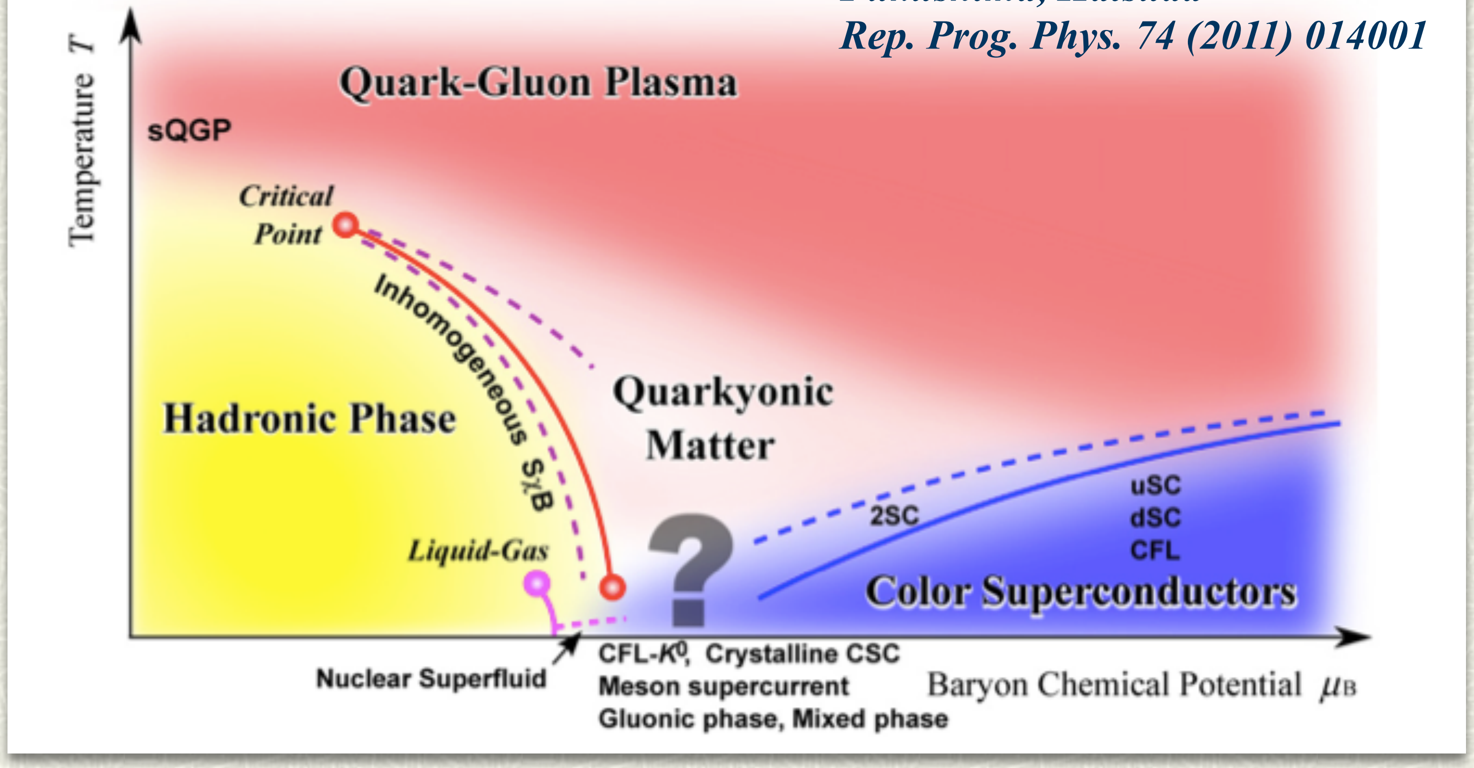
Hadrons are elementary modes, which probe the QCD vacuum.

What are the relevant degrees of freedom in hadron excitations?

Hadronic Matter @ Finite T and/or ρ

- Hot and Dense hadronic matters show diverse properties.
- Phase transitions to QGP @ high T *heavy ion collisions*
- Color superconductor @ high ρ, low T *neutron star*

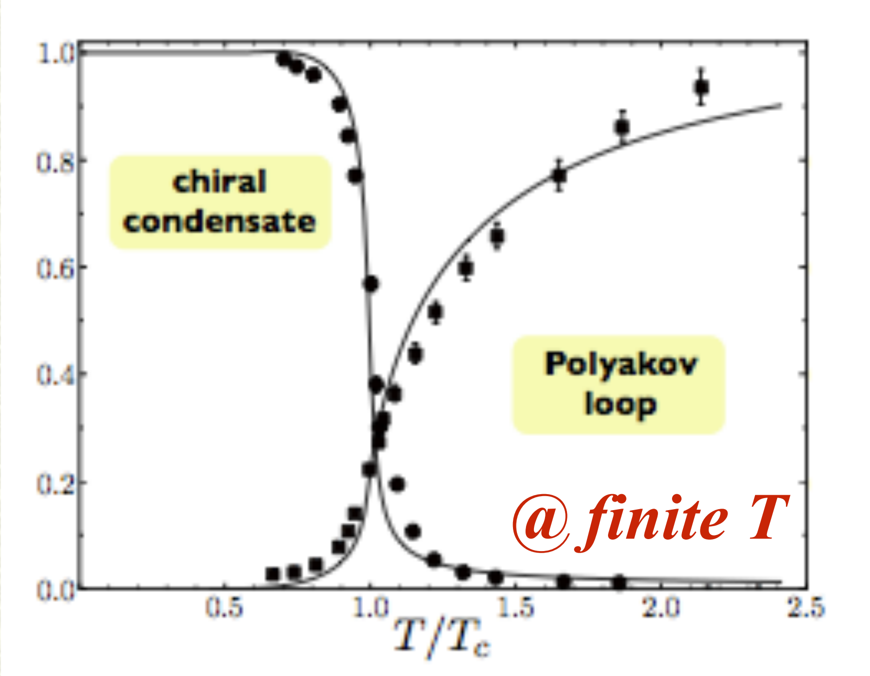
Fukushima, Hatsuda
Rep. Prog. Phys. 74 (2011) 014001



Hadrons in Matter

- **Hadrons in matter can probe the hadronic matter at finite T and/or ρ.**

- **Interplays of *chiral symmetry* and *color confinement* at finite T and/or ρ are intriguing.**

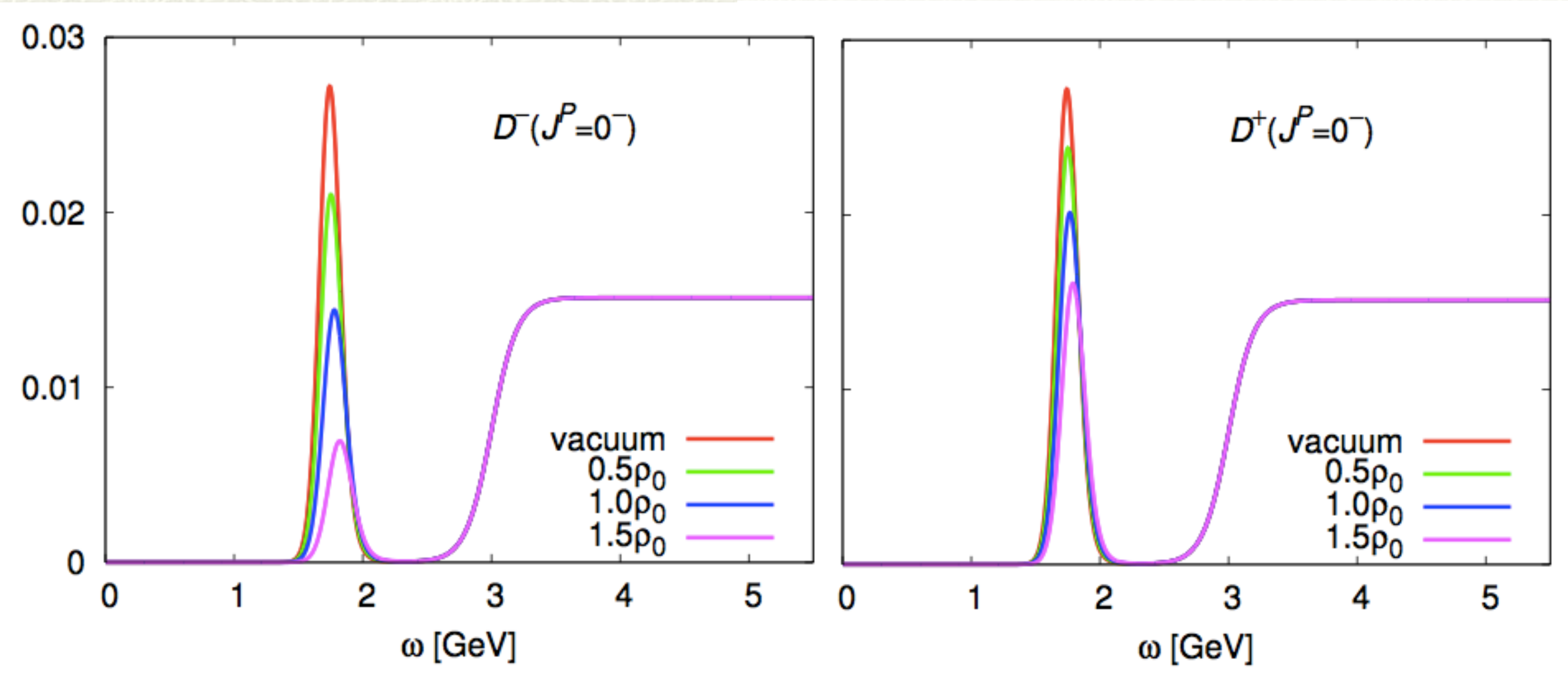


Hadrons in Matter

- ***Masses of D mesons may increase at finite density.***

QCD sum rule with the Maximum entropy method:

K. Suzuki, P. Gubler, MO, PR C 93, 045209 (2016)



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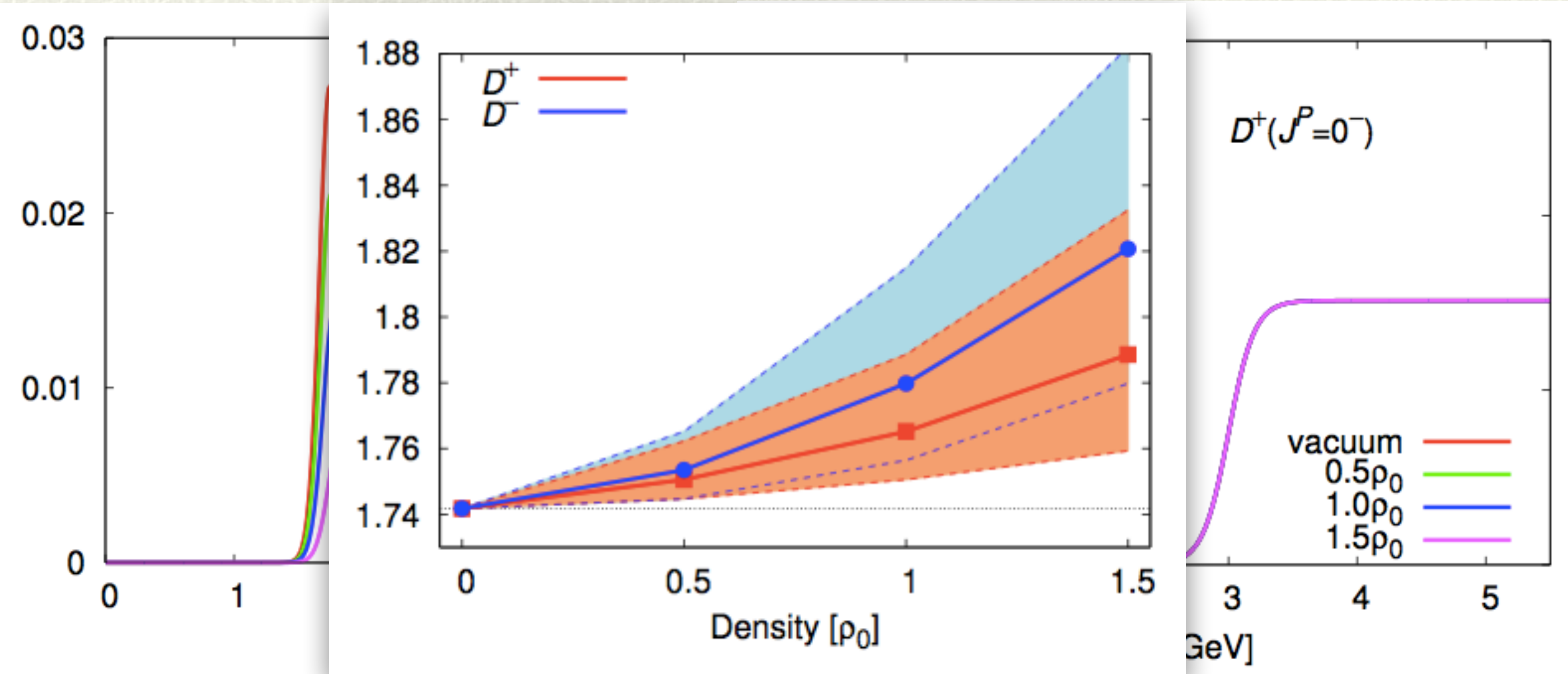
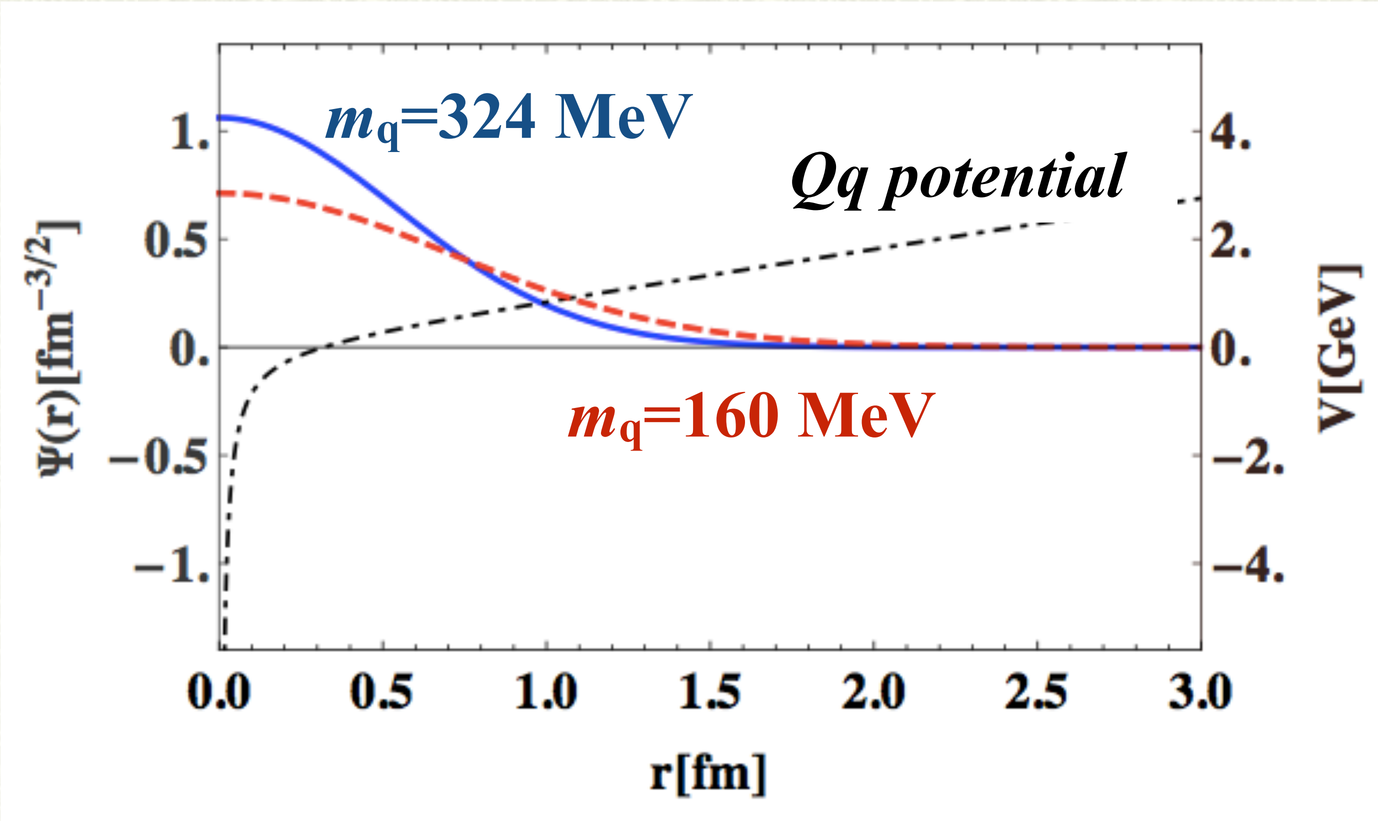


Hadrons in Matter

- **Interpretation in the constituent quark picture:**
  The wave function will extend to feel more repulsion.

A. Park, P. Gubler, M. Harada, S.H. Lee, C. Nonaka, W. Park, PR D93, 054035 (2016)



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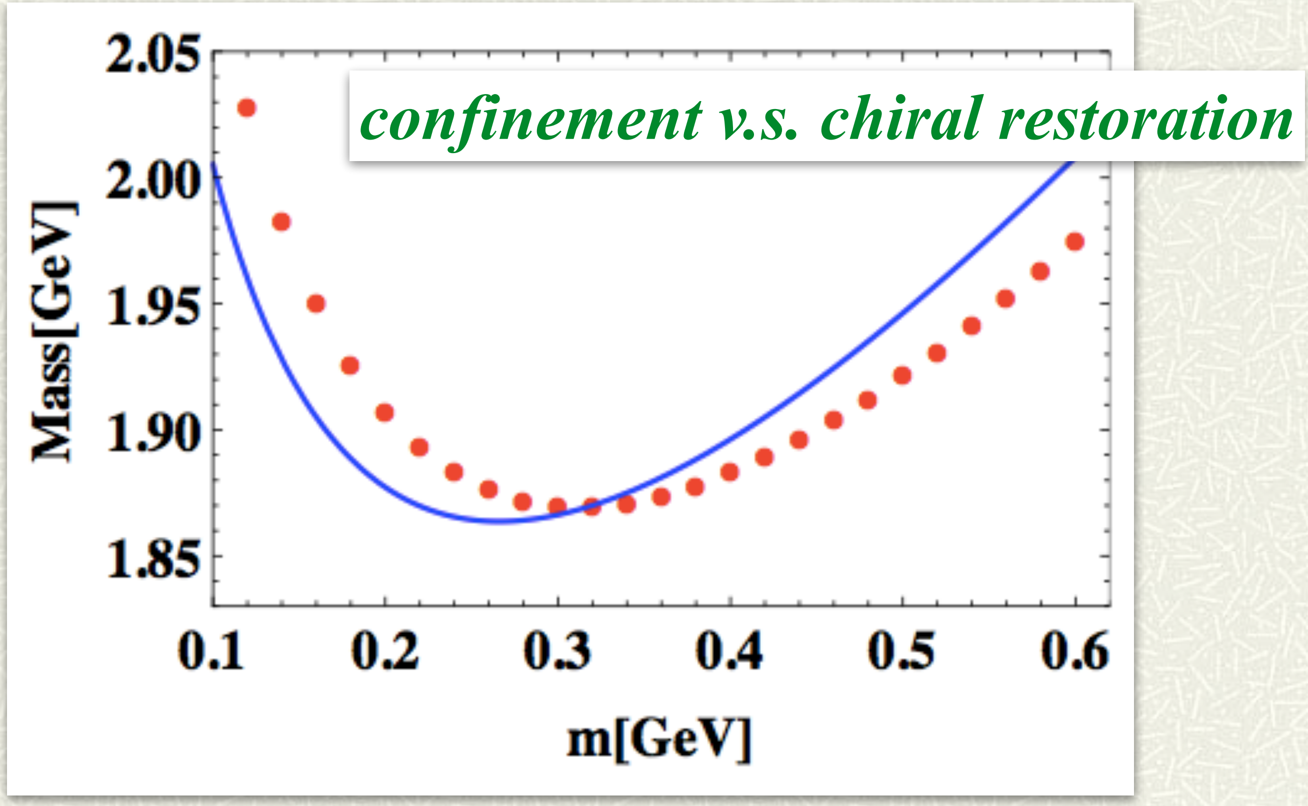
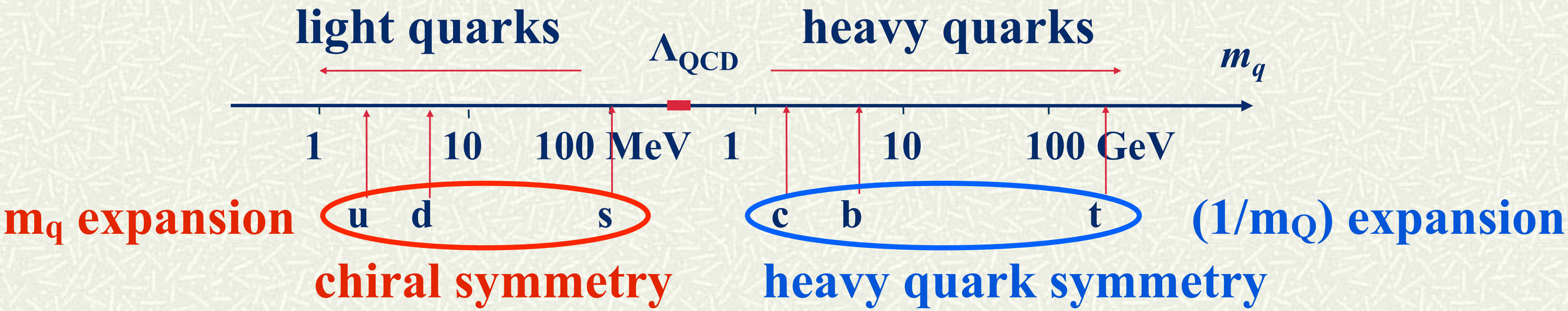
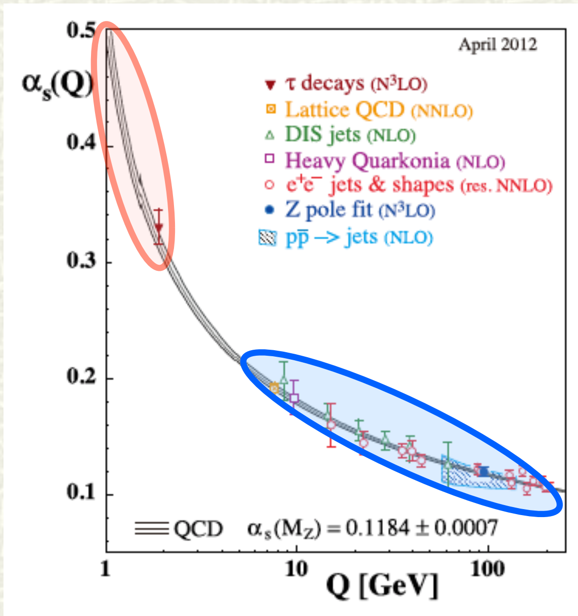


Why Heavy Quarks?

- QCD Lagrangian is flavor independent, but the coupling constant runs.



- Light quarks are nonperturbative/ relativistic.
- Heavy quarks are perturbative/ non-relativistic.



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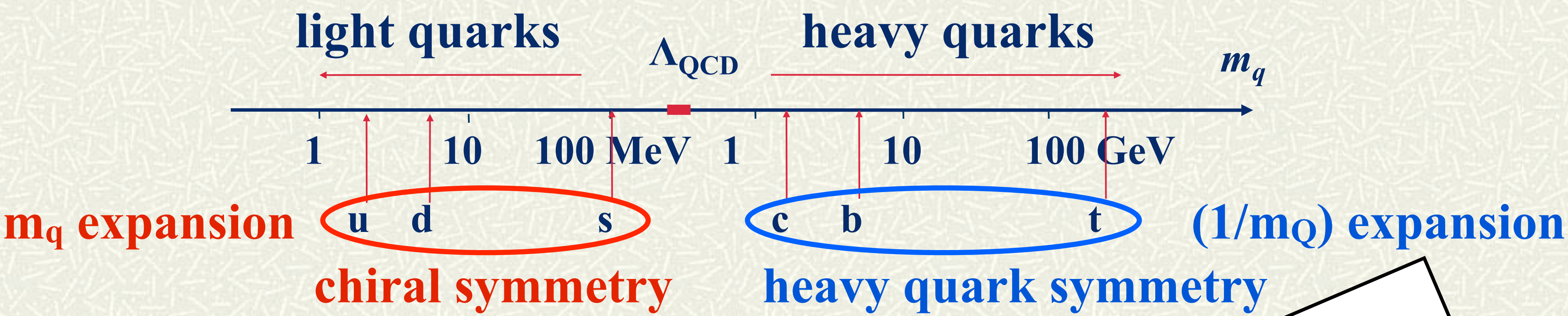

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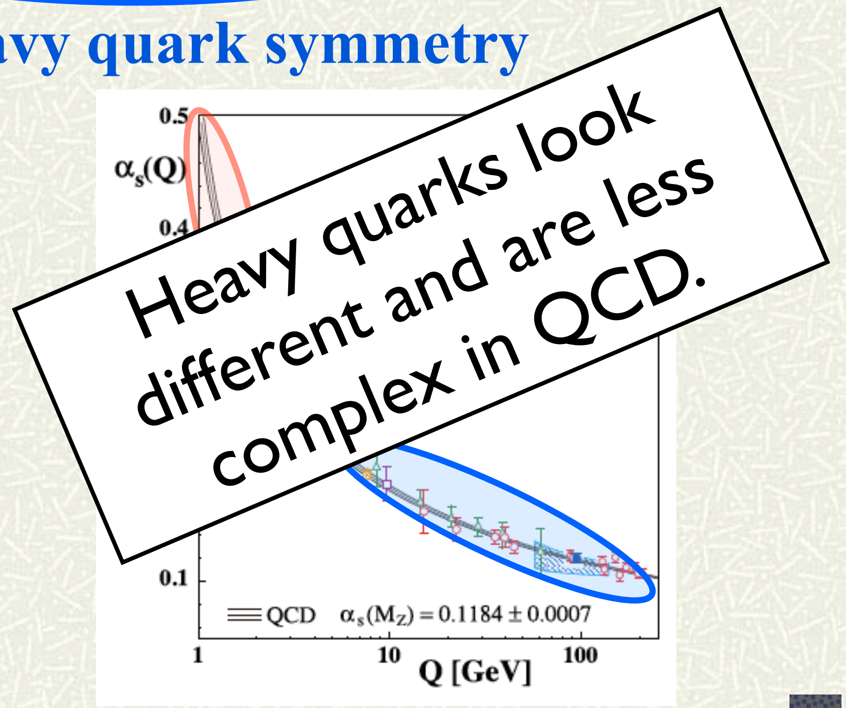
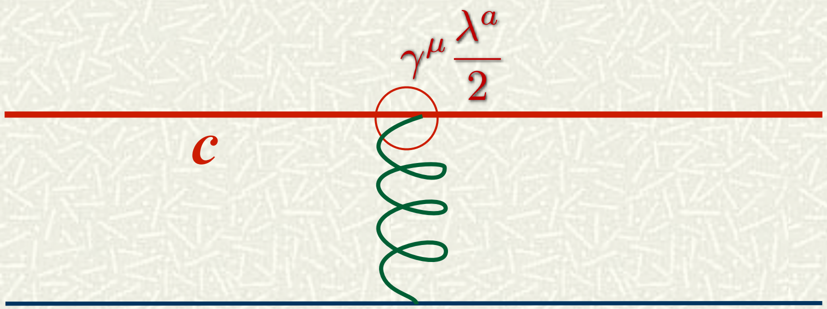


Charmed Baryons and Diquark

Heavy Quark Spin Symmetry

Magnetic gluon coupling is suppressed



$$\bar{\Psi}\gamma^\mu \frac{\lambda^a}{2} \Psi A^a_\mu \sim \Psi^\dagger \frac{\lambda^a}{2} \Psi A^a_0 - \Psi^\dagger \sigma \frac{\lambda^a}{2} \Psi \cdot \frac{1}{m_Q} (\nabla \times A^a)$$

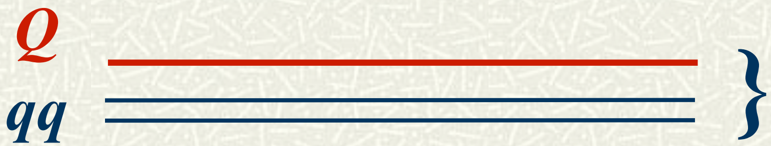
(Color Electric coupling) ≫ (Color Magnetic coupling)

HQ spin-flip amplitudes are suppressed by ($1/m_Q$).

⇨ Heavy Quark Spin Symmetry

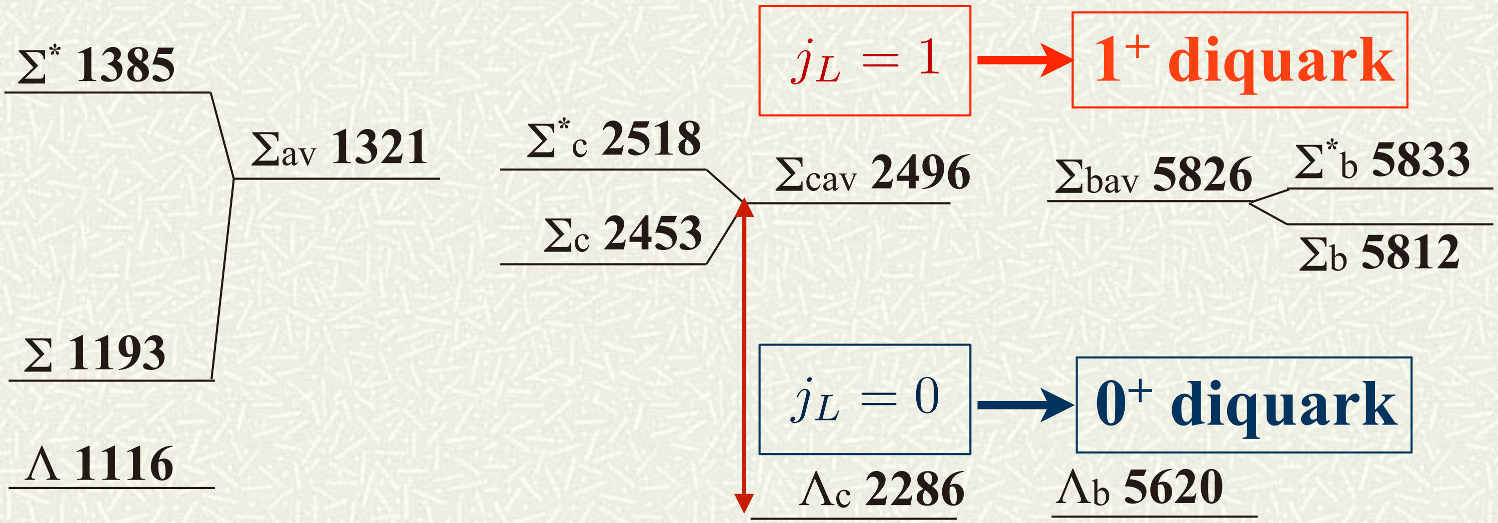
Heavy Quark Spin Symmetry

HQ spin symmetry $[S_Q, H] = O\left(\frac{1}{m_Q}\right)$



$\vec{J} = \vec{S}_Q + \vec{j}_L \qquad \vec{j}_L = \vec{S}_q + \vec{L}_q$

$J = j_L \pm \frac{1}{2}$ **states are degenerate in the HQ limit.**



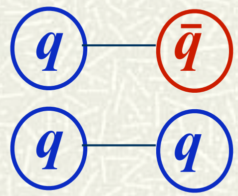
Diquark

- The Scalar (0^+) diquark is an analogue of the PS meson:

  PS meson qq^{bar} : color 1, $J^\pi=0^-$, flavor 1+8

  Scalar diquark $[qq]_0$: color 3^{bar}, $J^\pi=0^+$,

  flavor SU(3) 3^{bar} : $[ud]_0$, $[ds]_0$, $[sd]_0$



- **Quark model estimate: S(0^+) *v.s.* A(1^+)**

  $M(1^+)-M(0^+) = (2/3)\ [M(\Delta)- M(N)] \sim 200$ MeV

- **(Quenched) Lattice QCD**

  Hess, Karsch, Laermann, Wetzorke, PR D58, 111502 (1998)

  $M(1^+) - M(0^+) \sim 120$ MeV (Landau gauge)

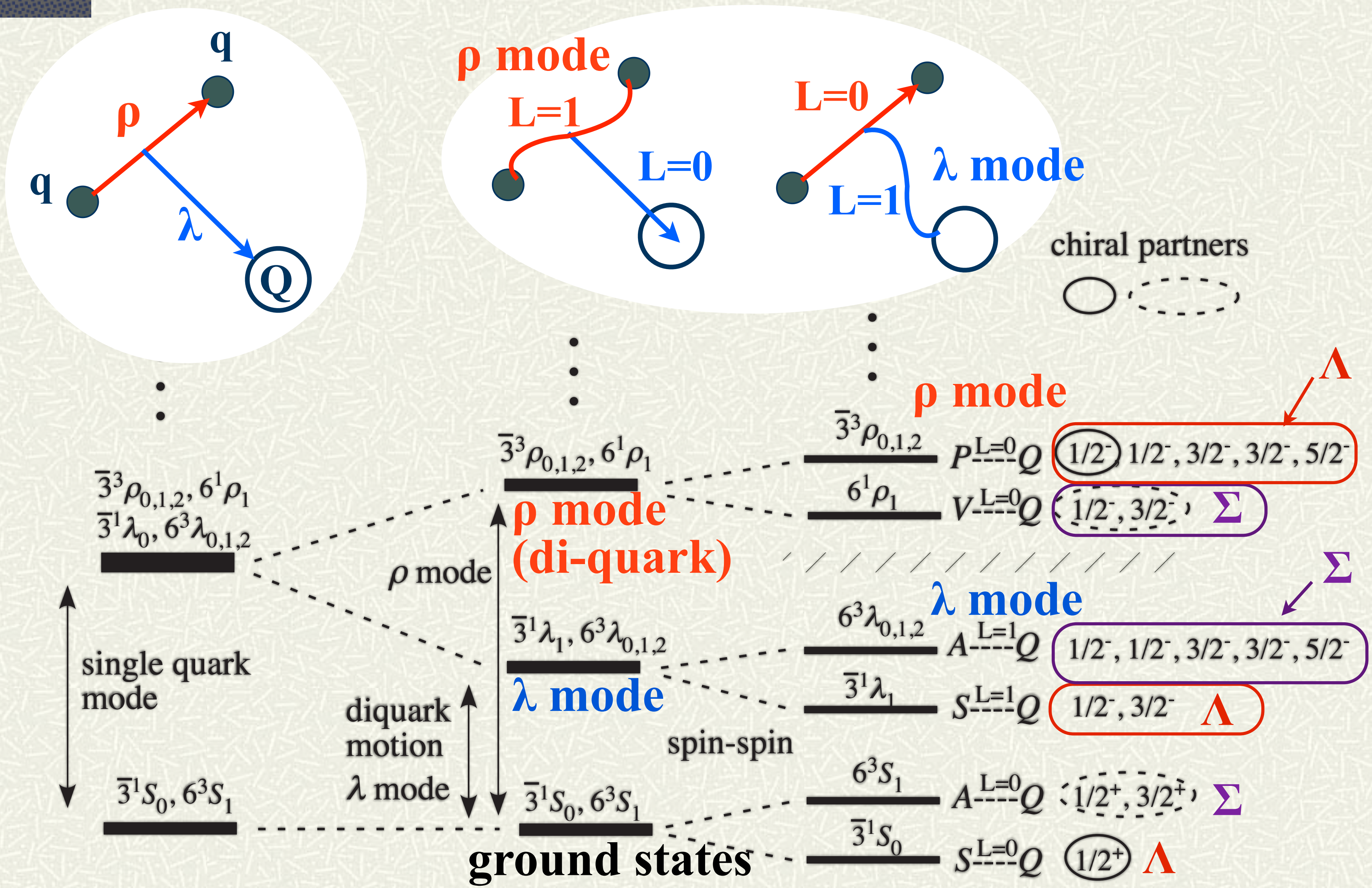
  Alexandrou, de Forcrand, Lucini, PRL 97, 222002 (2006)

  $M(1^+) - M(0^+) \sim 100\text{-}150$ MeV (in *Qqq system*)

  Babich, et al., PR D76, 074021 (2007)

  $M(1^+) - M(0^+) \sim 162$ MeV (Landau gauge)

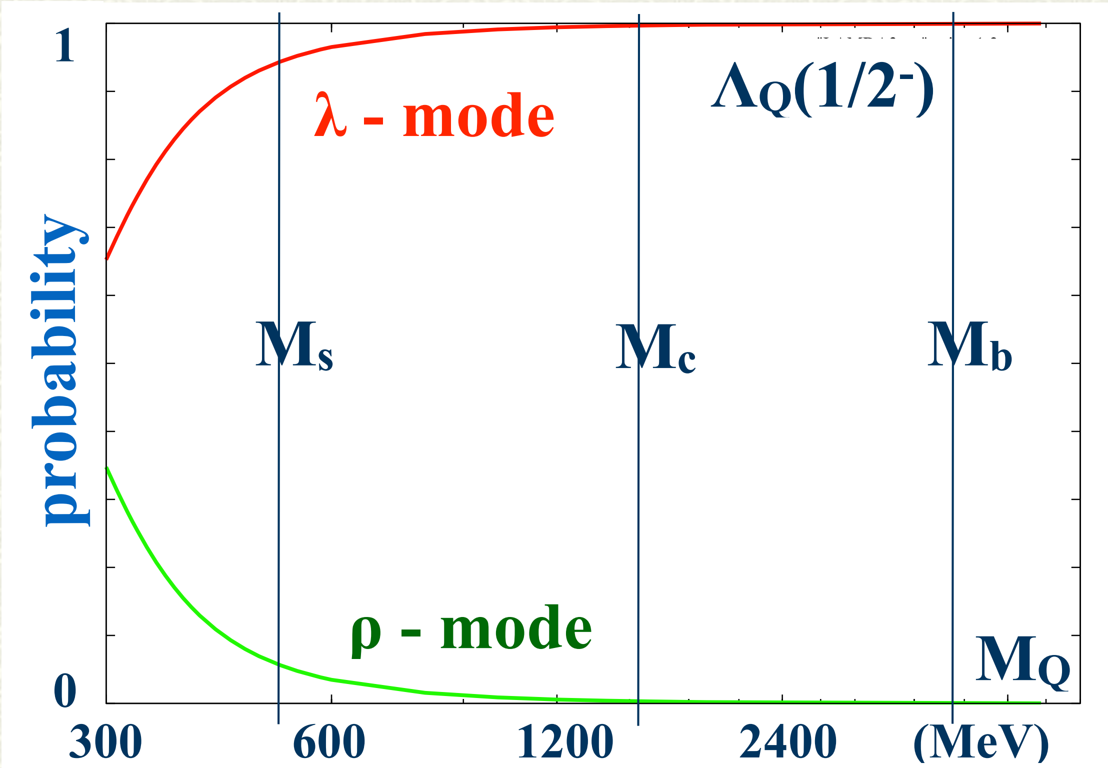
Diquarks in P-wave Baryons

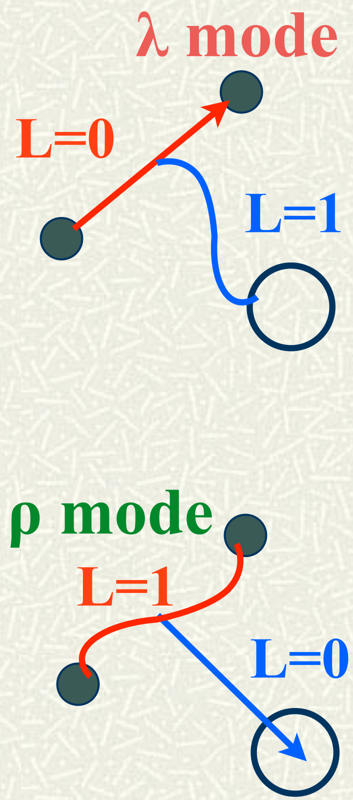


by A. Hosaka

Diquarks in P-wave Baryons

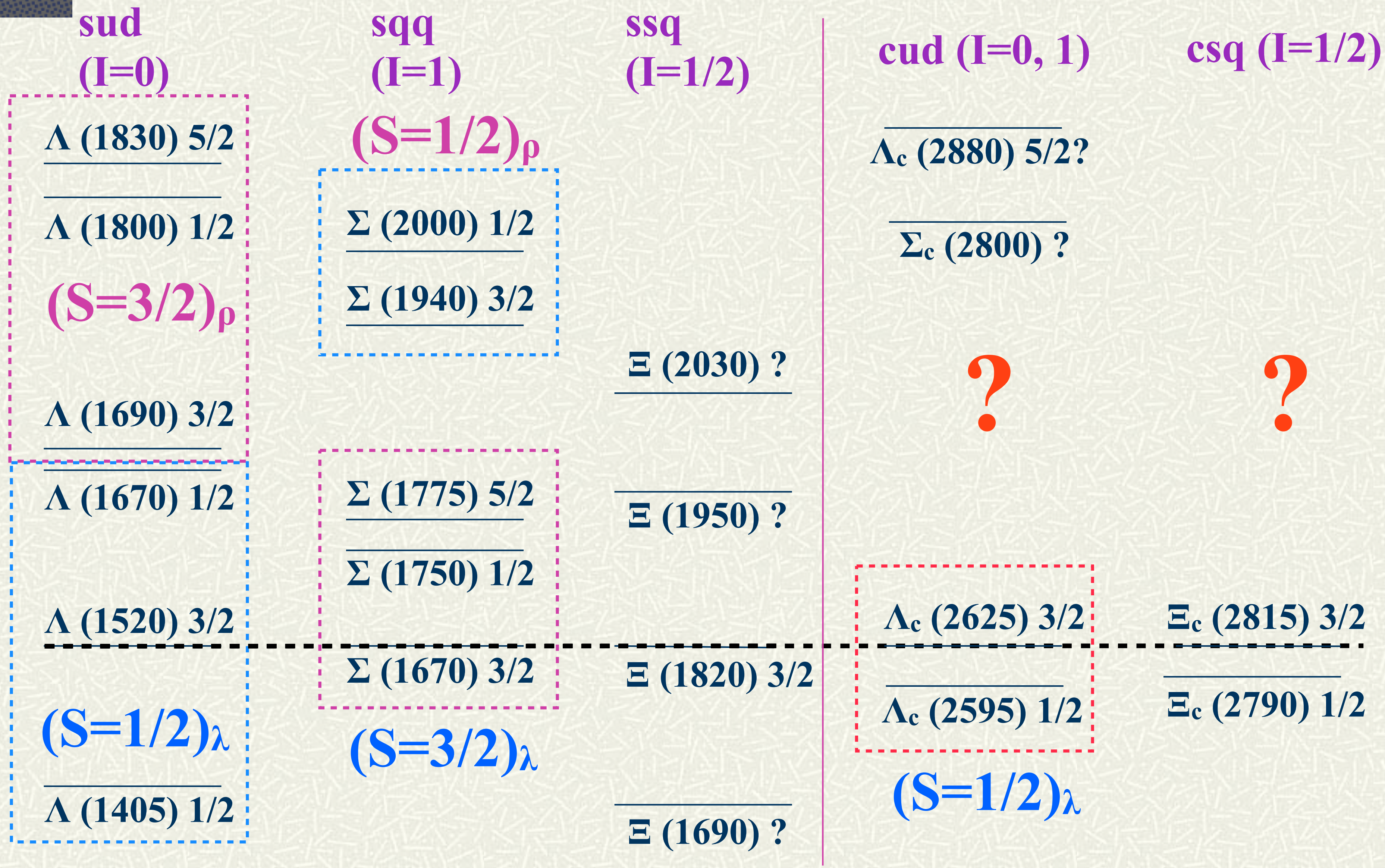
- **Probabilities of λ and ρ modes *v.s.* heavy quark mass by a Hamiltonian quark model with spin-spin, spin-orbit and tensor forces**





T. Yoshida, E. Hiyama, A. Hosaka, M. Oka, K. Sabato
PRD 92, 114029-1-19 (2015)

Diquarks in P-wave Baryons



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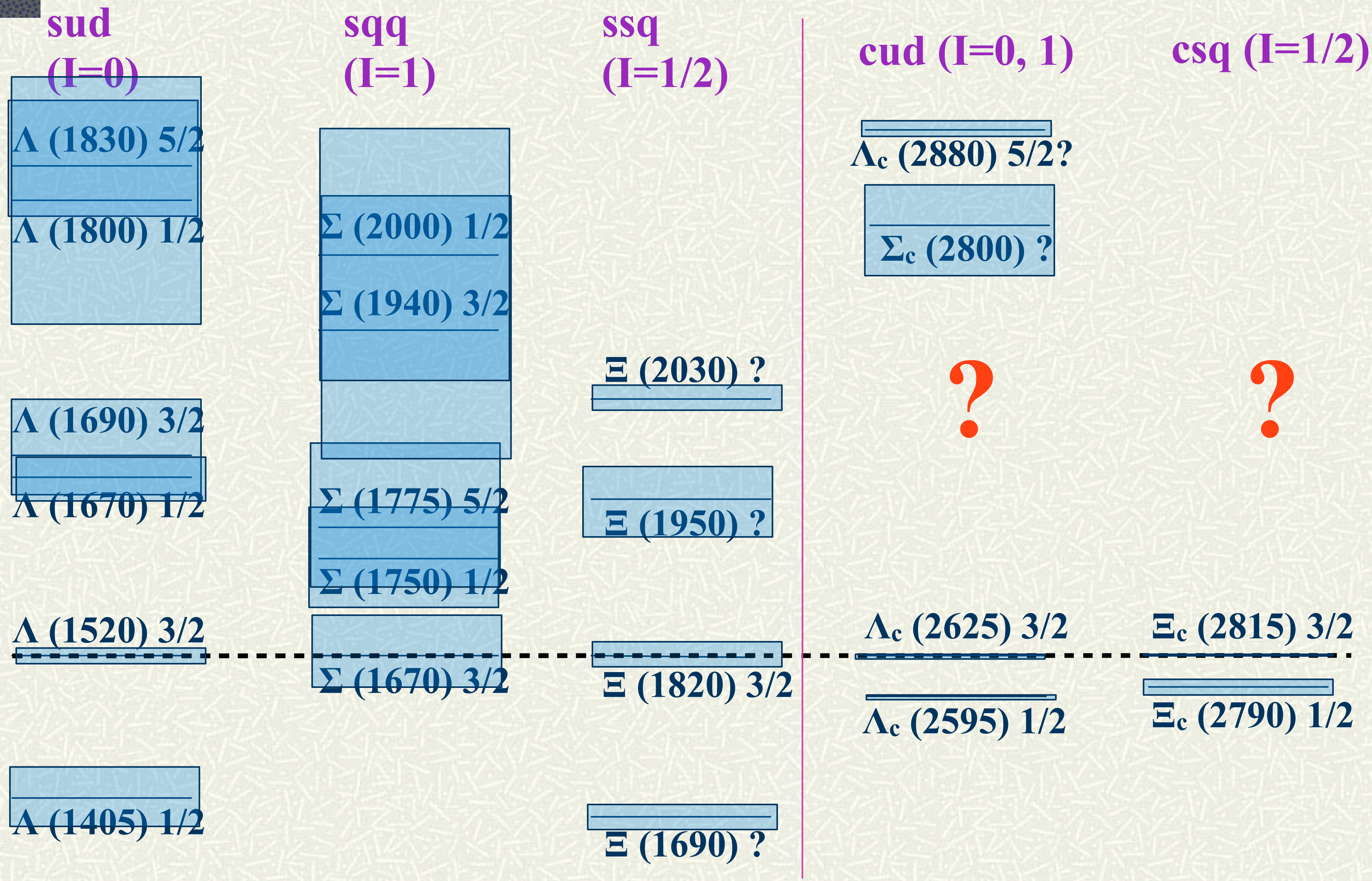

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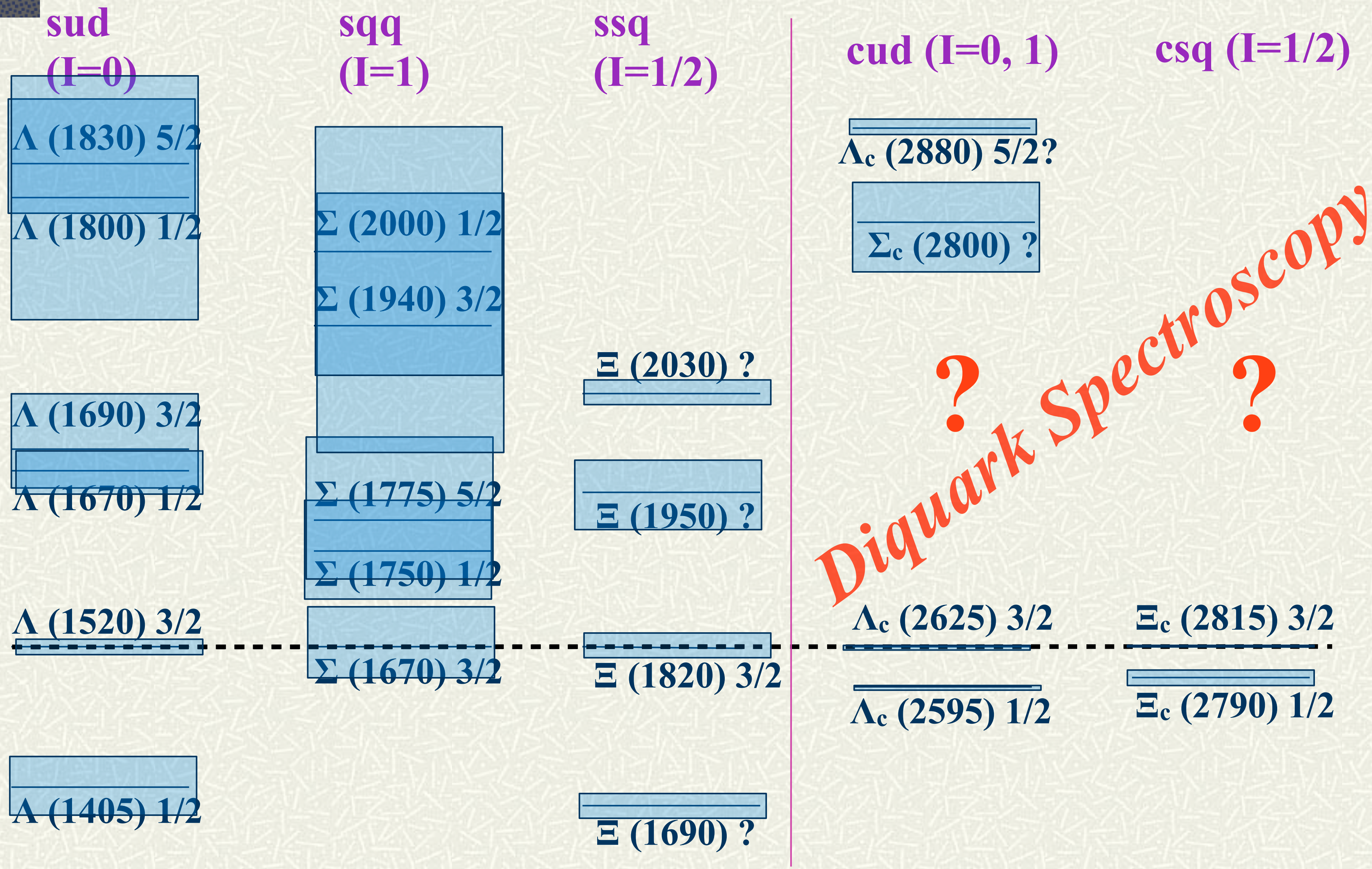
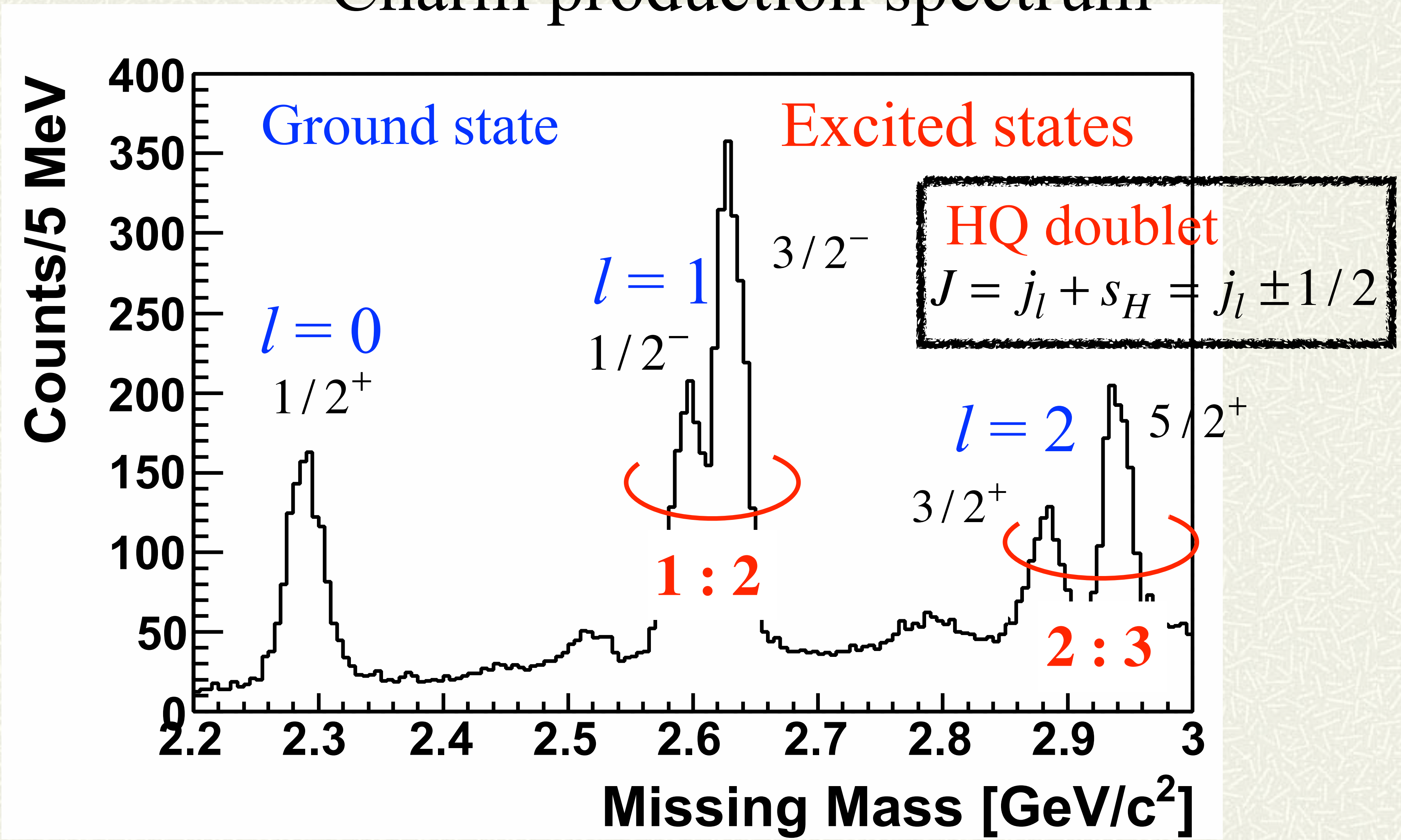


Charm production spectrum



Simulation by K. Shirotori for the J-PARC high momentum BL

S.H. Kim, et al.,

PTEP 2014 (2014) 103D01, and PRD92 (2015) 094021

Quarkonium and Hadron Molecule

Quarkonium

- After 50 years since it was born, the quark model gives very good guidelines to classify and interpret the hadron spectrum.

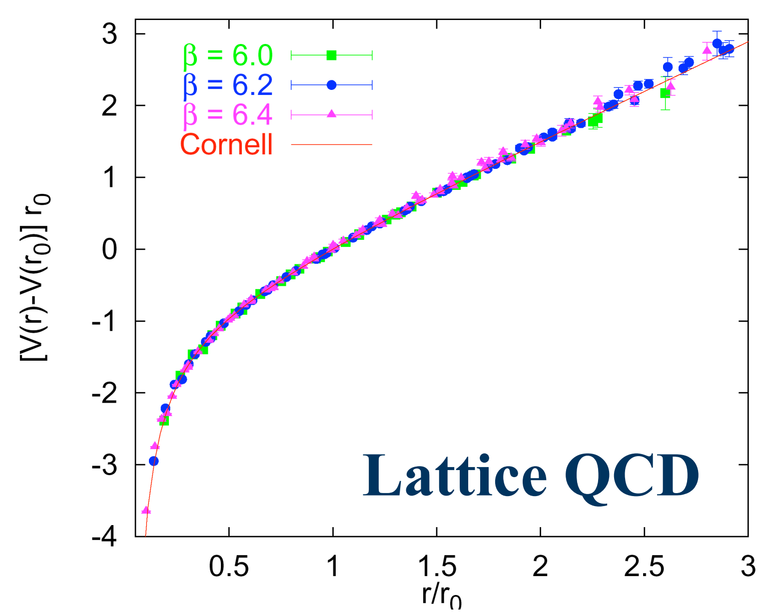
- The charmonium spectrum is a textbook example.
  "hydrogen atom" in QCD

- The Hamiltonian with a Linear + Coulomb potential

$$V(r) = -\frac{e}{r} + \sigma r$$

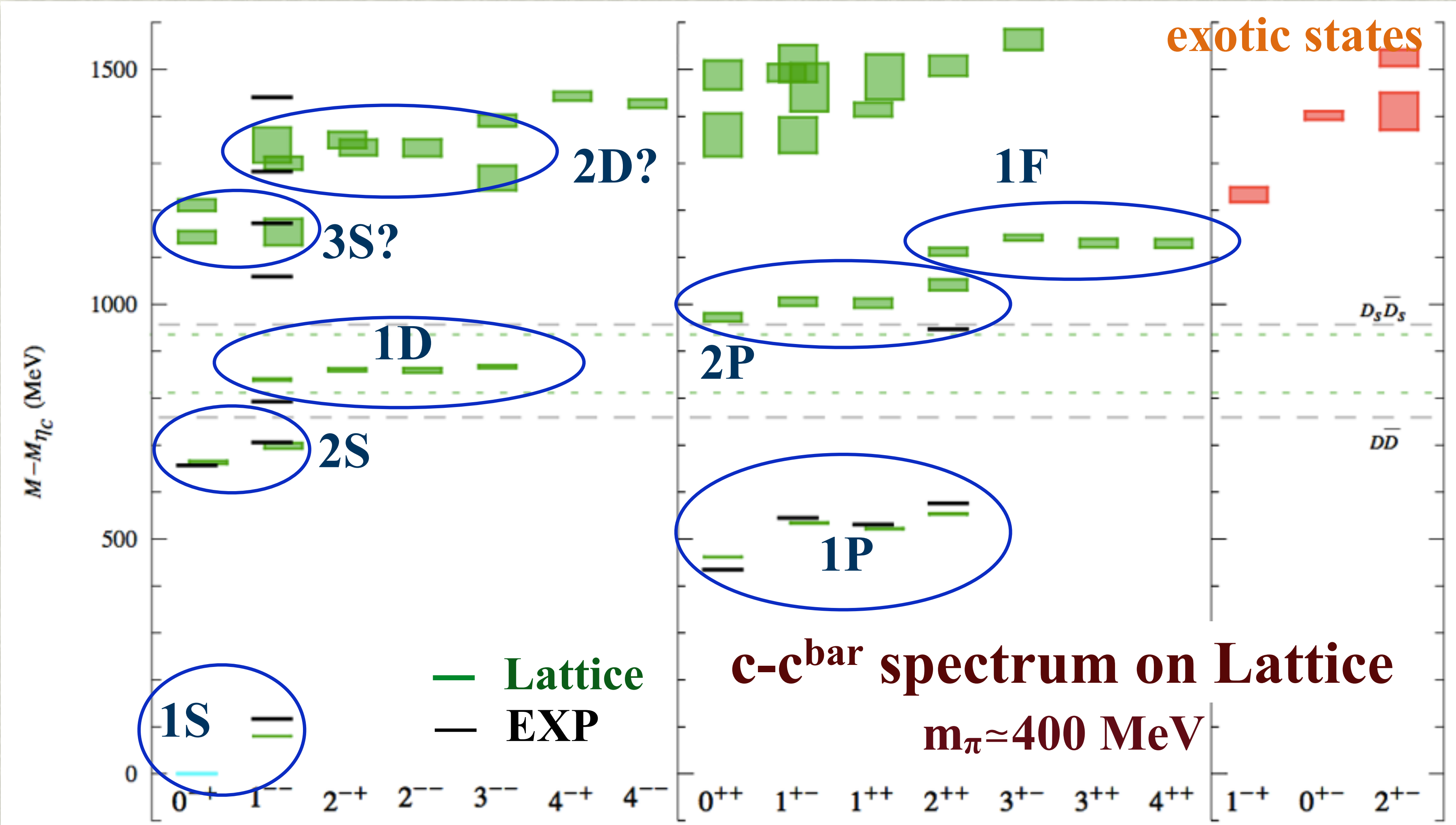
E. Eichten, et al., PRL 34 (1975) 369

gives a good fit to the 1S, 1P, 2S, . . charmonium (and bottomonium) states.



G.S. Bali, Phys. Rept. 343 (2001) 1

Charmonium spectra on Lattice

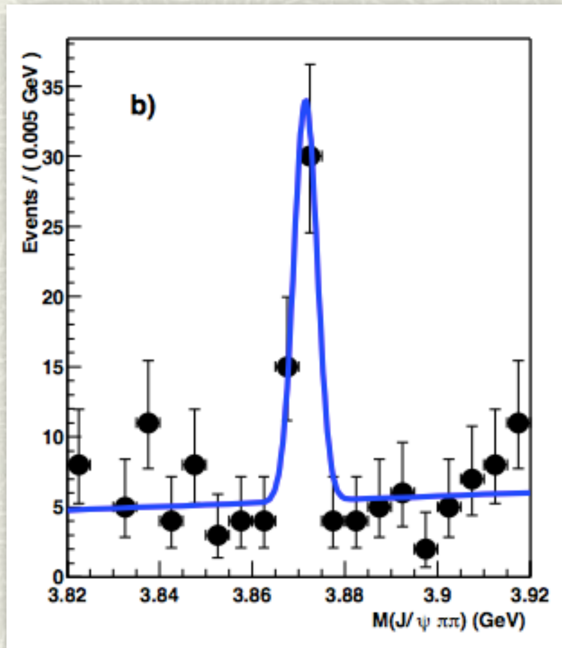


L. Liu, et al. (Hadron Spectrum Collaboration), JHEP 07, 126 (2012)

Charmonium

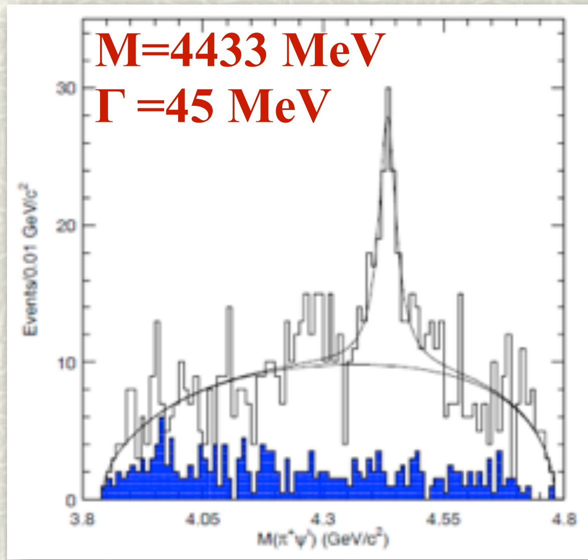
- **X(3872) found in 2003 by Belle (KEK)**
  → ***not reproduced by lattice QCD using only q-q^{bar} operators.***
- **Z(3900), Z(4430) etc. : charged hidden charm states**

X(3872) — ***Belle***



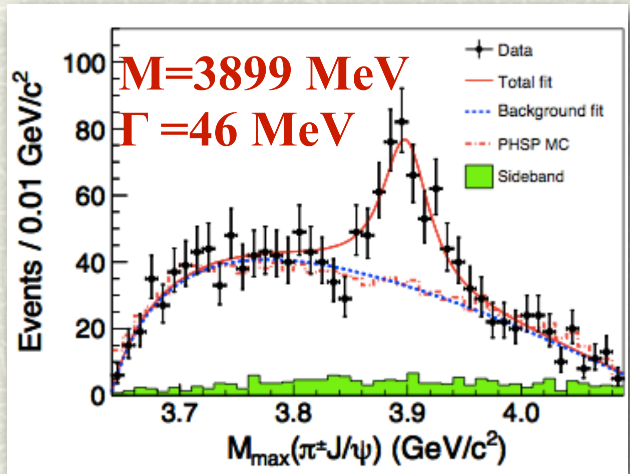
PRL 91 (2003) 262001

Z_c^+(4430) — ***Belle***



PRL 100 (2008) 142001

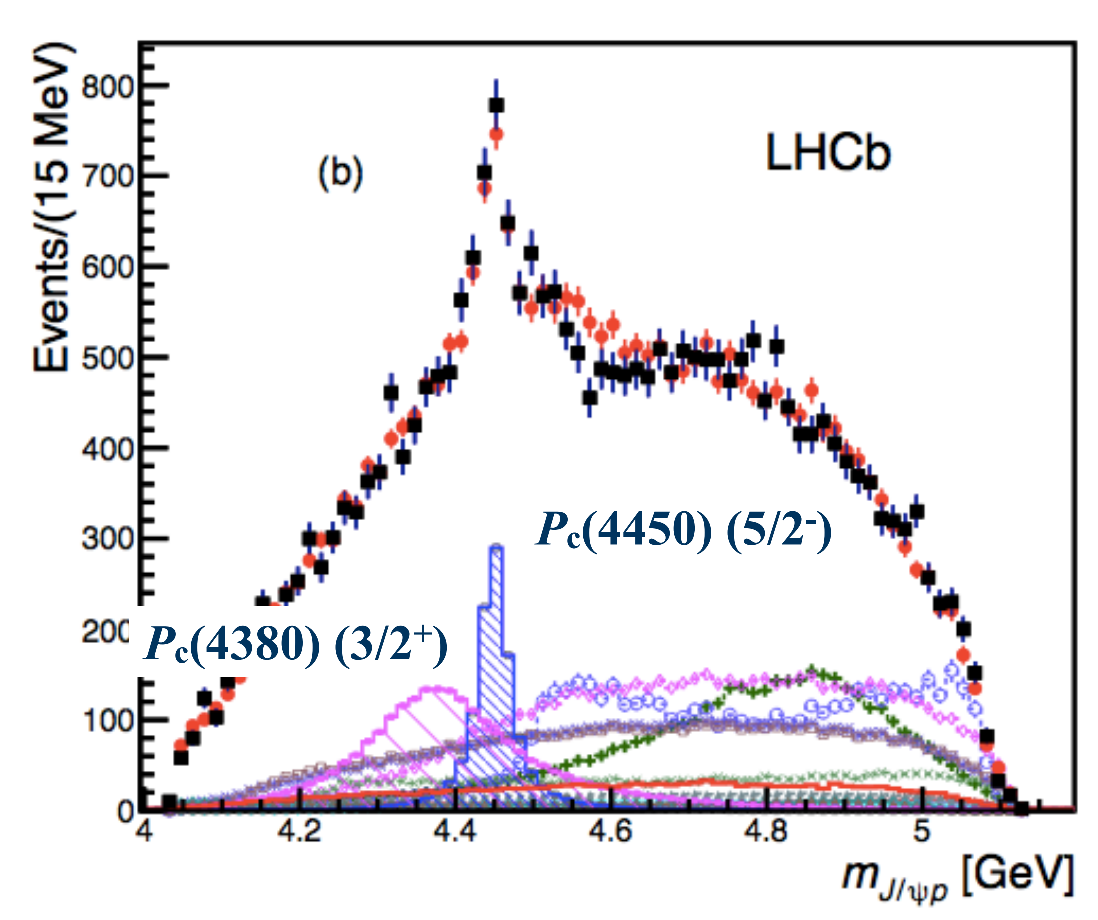
Z_c^+(3900) — ***BES III***



PRL 110 (2013) 252001

P_c Pentaquark@LHCb

- $P_c \rightarrow J/\psi + p$ ($cc^{bar}uud$)
  LHCb (*PRL 115 (2015) 07201*) found two penta-quark states with hidden cc^{bar}.



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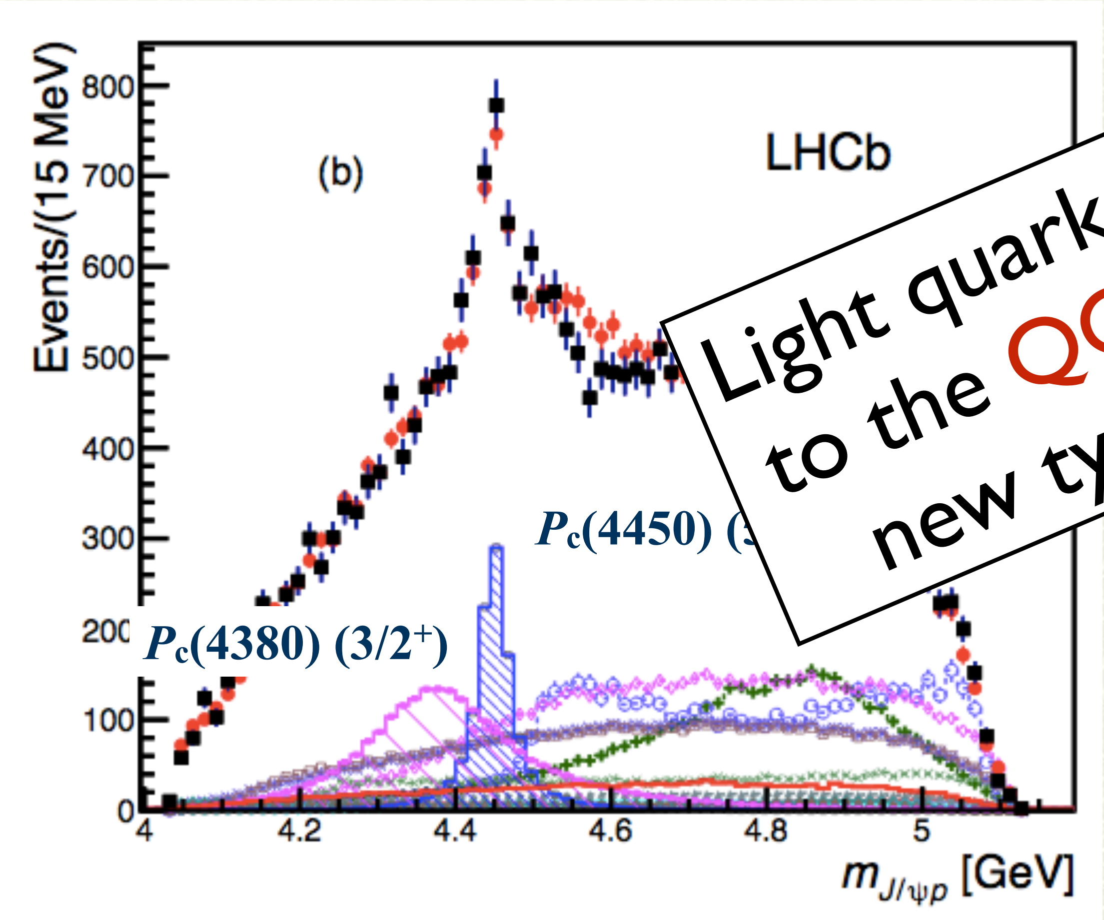
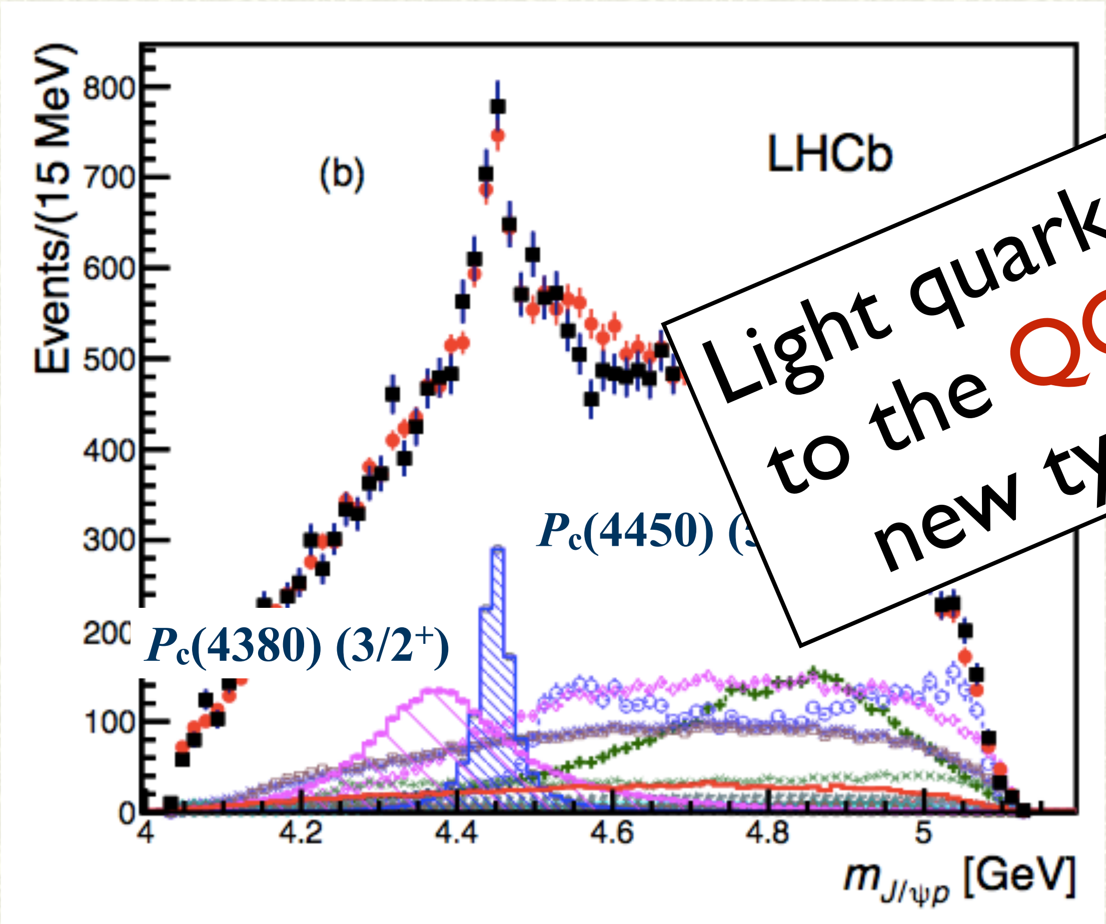


Light quarks tend to stick to the QQ^{bar} and form a new type of hadrons.

P_c Pentaquark@LHCb

- $P_c \to J/\psi + p$ ($cc^{bar}uud$)
  LHCb (*PRL 115 (2015) 07201*) found two penta-quark states with hidden cc^{bar}.

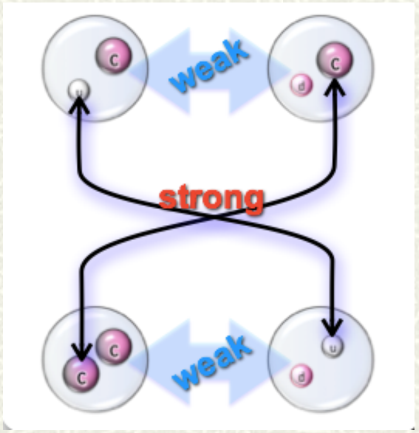


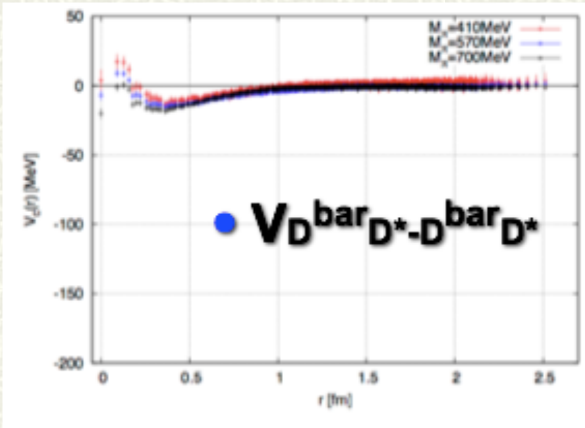
Light quarks tend to stick to the QQ^{bar} and form a new type of hadrons.

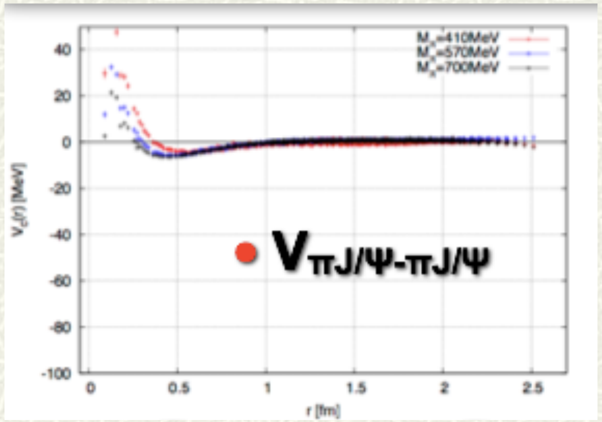
Why ?

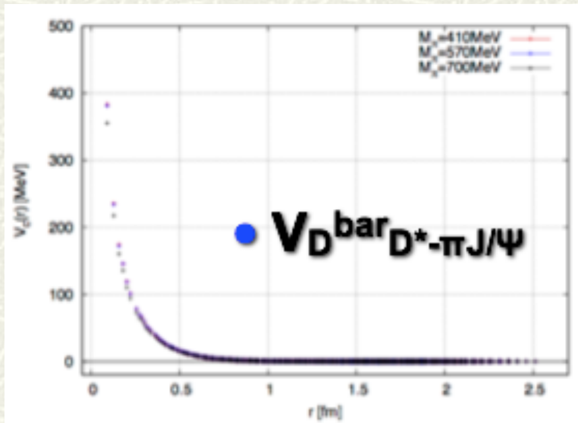
Exotic States on Lattice

- $Z_c(3900)$ v.s. $(D^{bar}D^*) + (\pi\ J/\psi)$ using the HAL QCD method
  Y. Ikeda (HALQCD), arXiv:1602.03465









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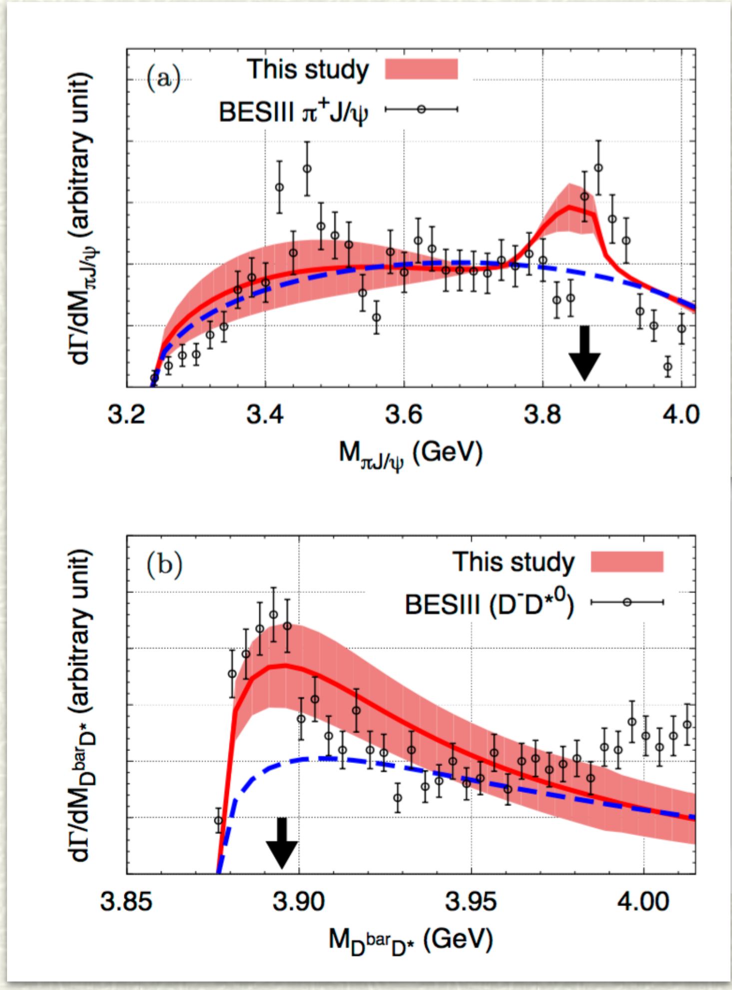
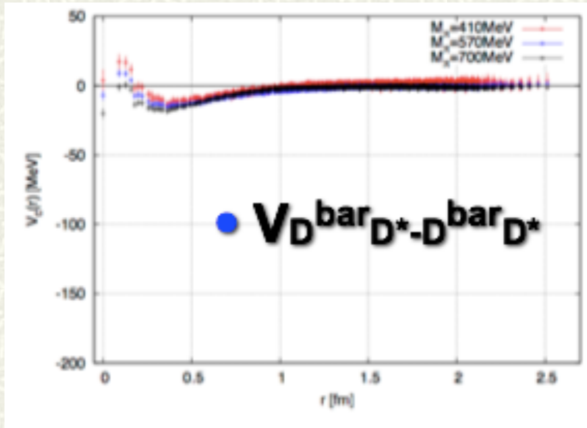
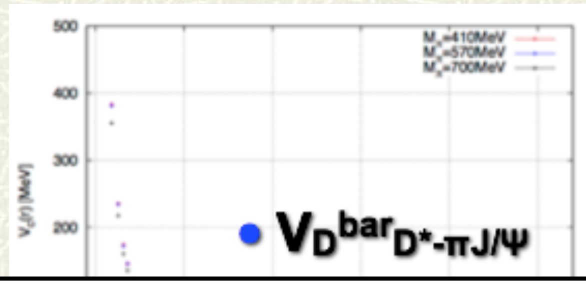




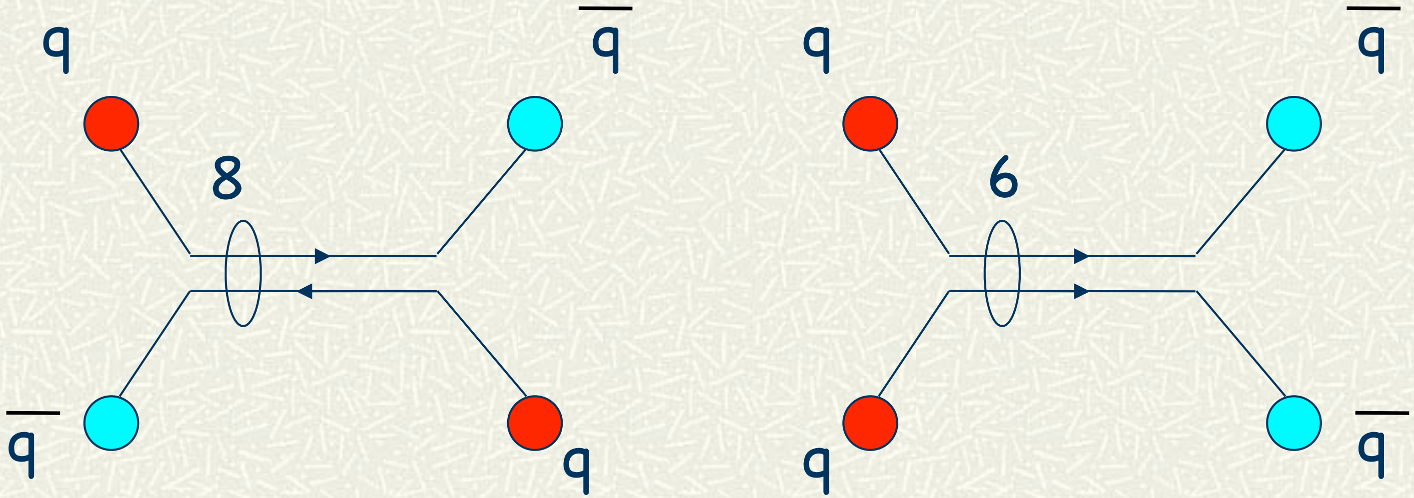


Strong (cusp) enhancement above the $D^{bar}D^*$ threshold

Exotic Hadrons

Exotics are "Colorful" !   (Lipkin@YKIS06)

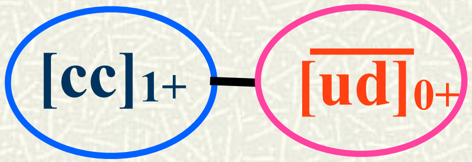
$(qq)_{8}$ or $(qq)_{6}$ are allowed only in the multi-quarks.



Double Charm Tetraquark

- **Double charm meson**

  T_{cc} ($ccu^{bar}d^{bar}$, 1^+, I=0) = $[cc]_{1+}$ $[u^{bar}d^{bar}]_{0+}$



  - The lowest strong-decay threshold is $D(0^-)$ – $D^*(1^-)$ (L=0).

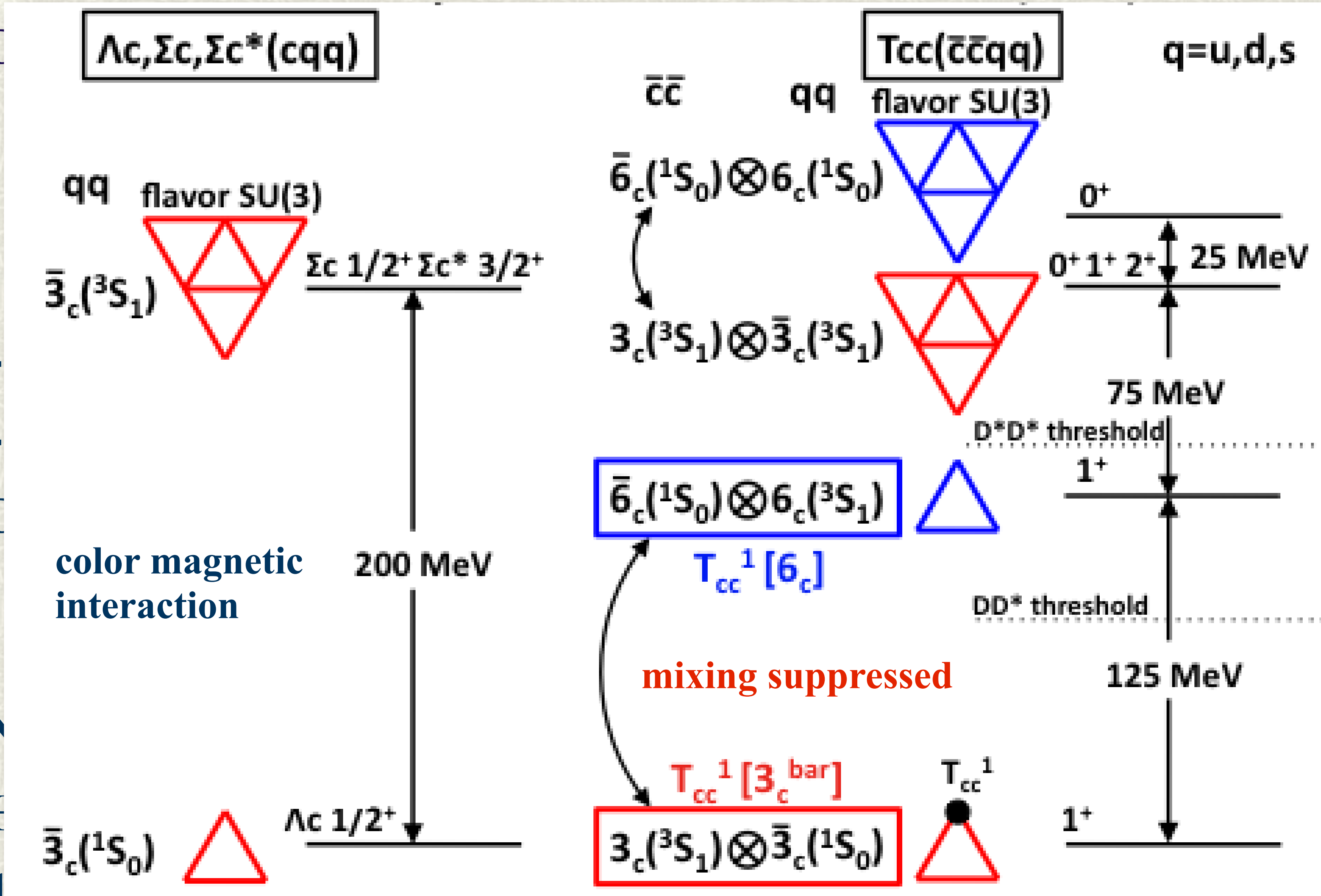
  - If the scalar diquark is light enough to make T_{cc} bound below DD* threshold, T_{cc} will be a stable tetra-quark resonance.

    S. Zouzou, et al., Z. Phys. C30 (1986)457
    H.J. Lipkin, Phys. Lett. B172 (1986) 242

- **New possible color correlations**

  Hyodo, Liu, Oka, Sudoh, Yasui, PLB721 (2013) 56-60, ArXiv 1209.6207

Double Charm Tetraquark



Hyodo, Liu, Oka, Sudoh, Yasui, PL B721 (2013) 56-60, ArXiv 1209.6207

Charmed Dibaryons

Heavy dibaryons

- H dibaryon (= $u^2d^2s^2$) predicted by Jaffe (1977)
  New Lattice QCD calculations of H dibaryon

- Bound H di-baryon in Flavor SU(3) Limit of Lattice QCD
  Takashi Inoue (HAL QCD Collaboration)
  PRL 106, 162002 (2011)

- Evidence for a Bound H di-baryon from Lattice QCD
  S. R. Beane et al. (NPLQCD Collaboration)
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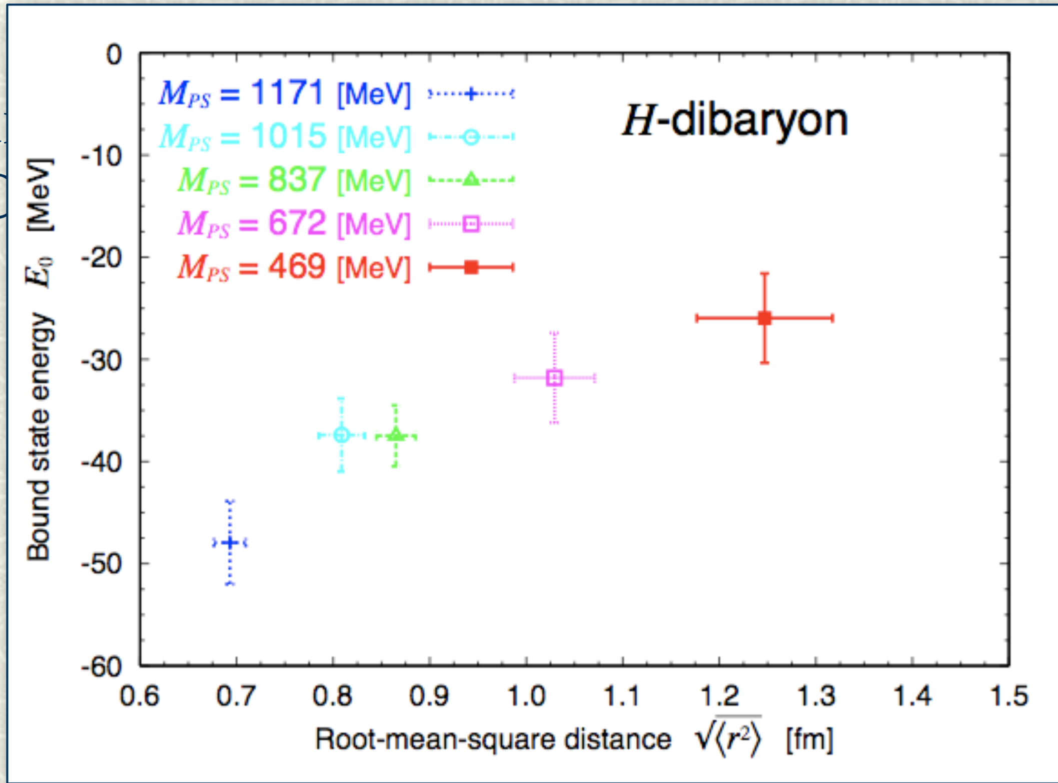
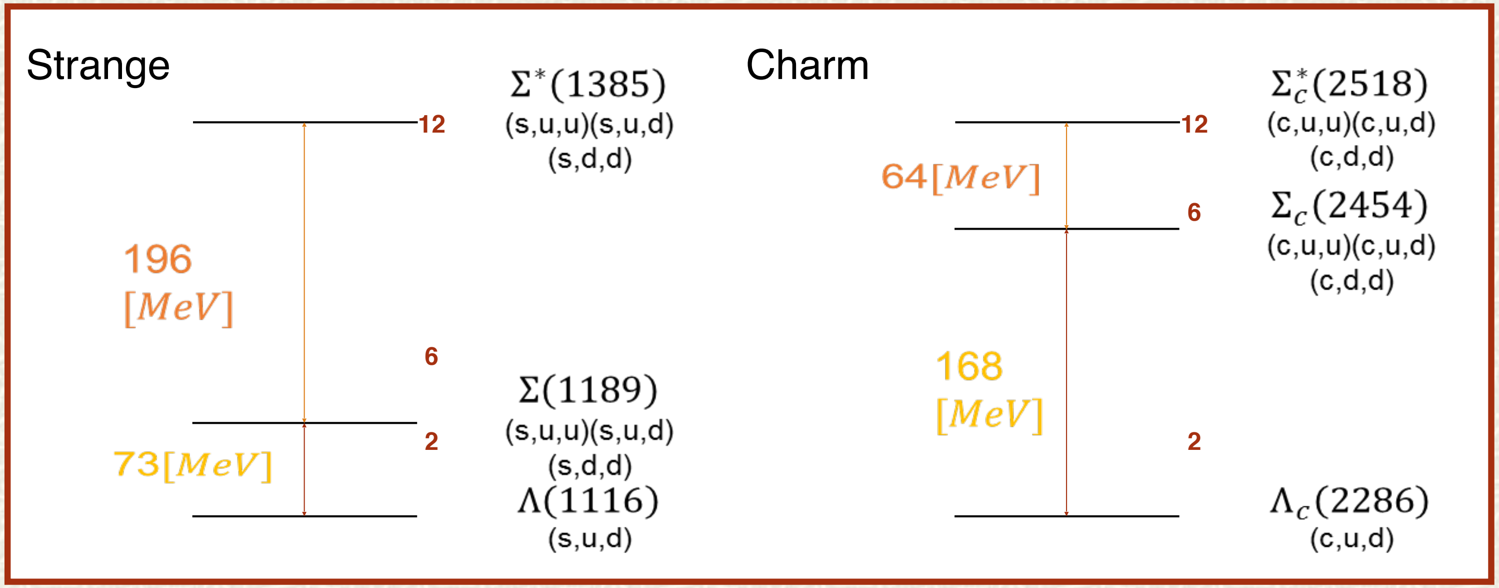


Heavy dibaryons

- Coupling between Σ_c and Σ_c^* is enhanced.



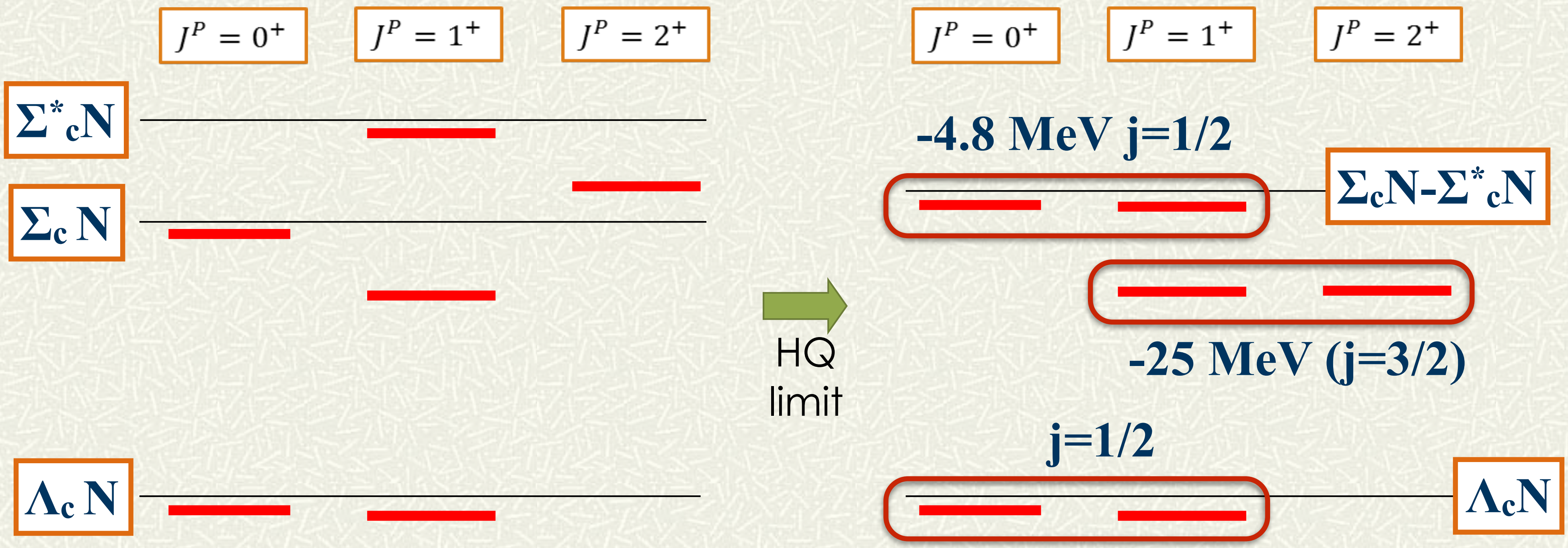
- $\Lambda_c N$-$\Sigma_c N$-$\Sigma_c^* N$ bound/resonance states are considered. S. Maeda et al., Prog. Theor. Exp. Phys. (2016) 023D02 and in preparation.

Heavy dibaryons

- **HQ doublets**

  A shallow bound state of Λ_c N with j=1/2

  A shallow (j=1/2) and deep bound (j=3/2) state of $\Sigma^{(*)}_c$ N.



S. Maeda et al.,
Prog. Theor. Exp. Phys. (2016) 023D02 and in preparation.

Conclusion

- Hadron Physics is developing from

  Up-Down → Strangeness → Charm/ Bottom

  Chiral symmetry → Confinement and HQ symmetry

- It is important to identify effective degrees of freedom in QCD resonances?
  constituent quarks → diquarks, glue/string vibration, hadrons

- Experiment:
  High statistics data of productions, decays, transitions will reveal the quantum numbers and structures of resonances

- Theory:
  Define effective quasi-particles in QCD and make systematic predictions of QCD resonances.