International Workshop on Fundamental Problems in Subatmic Physics (FPSP2026)
ICC JeJu, 23 – 27 September, 2026

Effect of the gluon field in Singly Heavy Baryons

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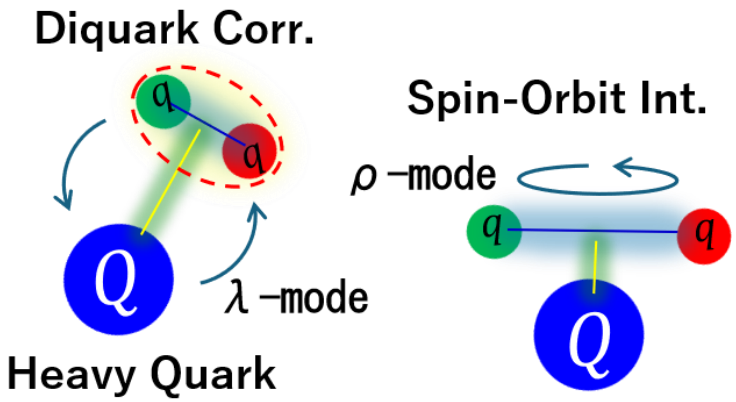
Spectroscopy of Heavy Baryons

New Platform of Hadron Physics with Heavy Baryon at J-PARC

Introducing Heavy Quark singles out Quark Motions

- **Variety of Excited States**
- **Production/Decay Properties**
- **Spin-Parity**

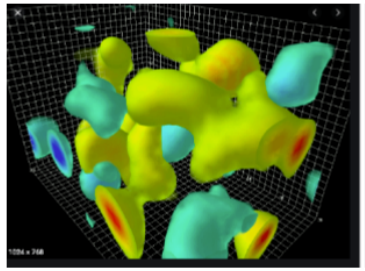
➢ **λ/ρ mode separation**
➢ **Diquark Correlation**
➢ **Spin-dependent Int.**



Source of the Strong Interaction: Verification of Gluon-Field Dynamics

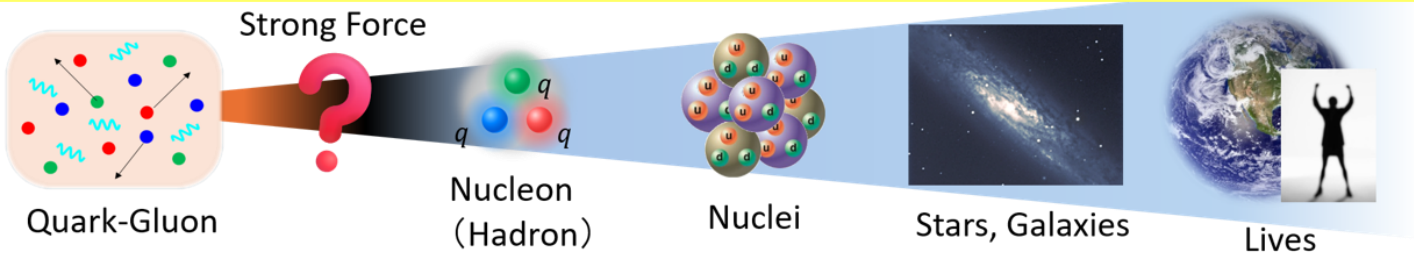
Topological Vacuum Configuration of the Gluon Field(Instanton)

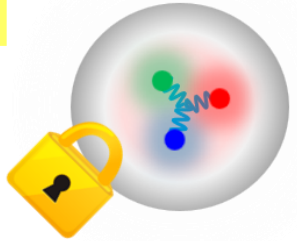
➢ **Color Confinement**
➢ **Spontaneous Breaking of Chiral Symmetry (Nambu mechanism**



Instanton demo. by Lattice QCD

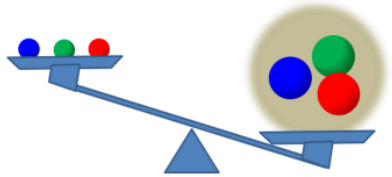
Unveil the Strong Int. that forms hadrons, the origin of matter evolution





Confinement

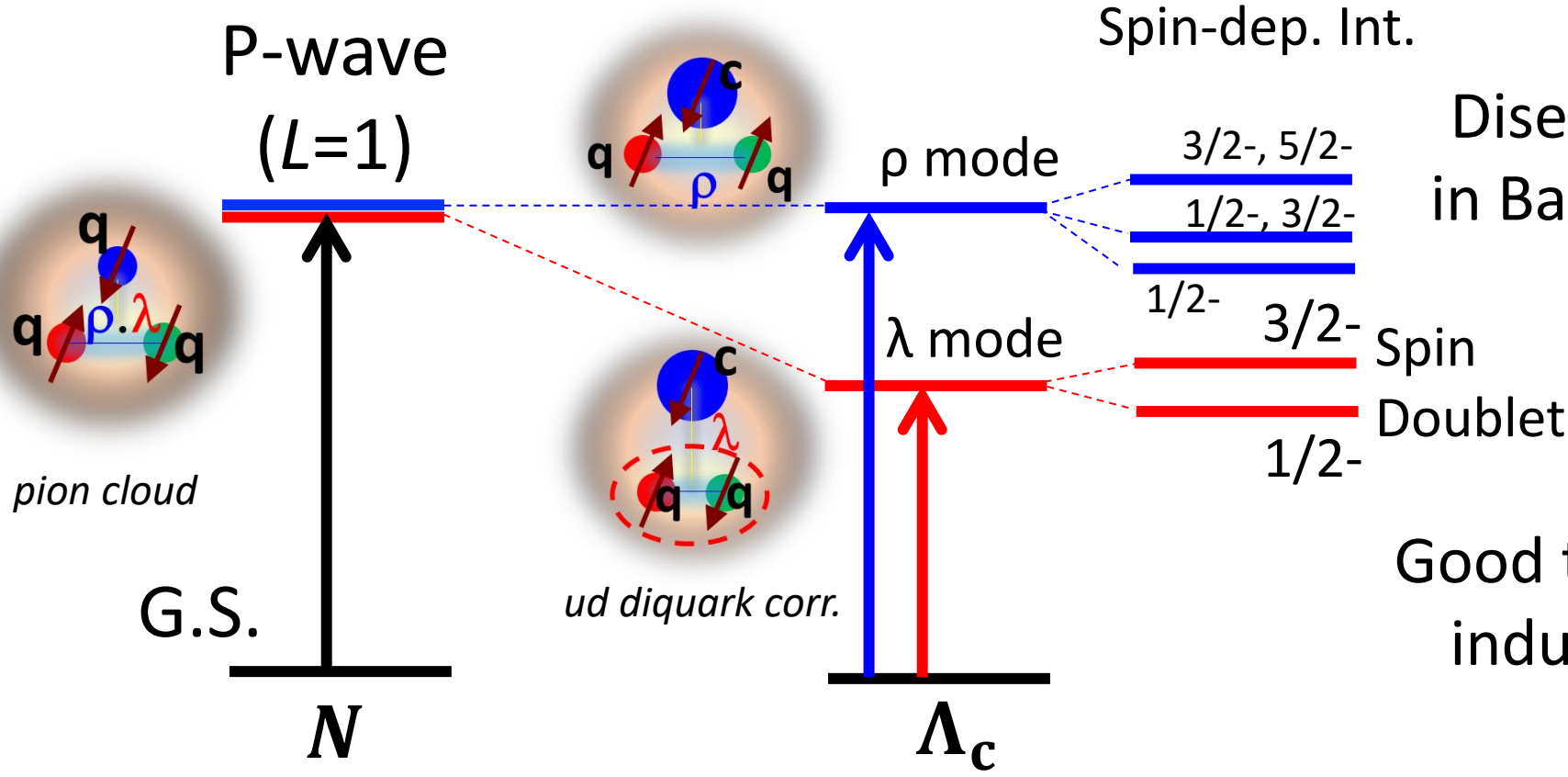
SBχS
Nambu mechanism



Dynamical Mass Gen.

Internal structure of baryons in terms of Eff. DoF

※Disentangle motions of a quark pair by introducing different flavors

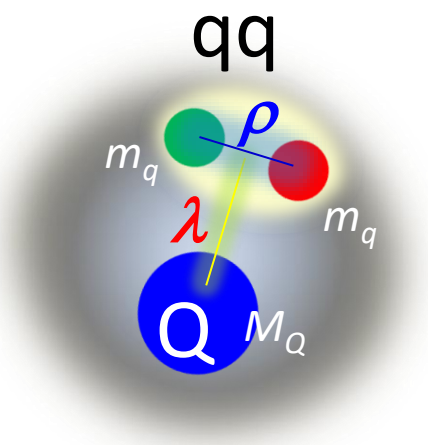


Disentangle "*qq*" motion in Baryon w/ Heavy Quark

Good to study *qq* correlation induced by Spin-Spin int.

T. Yoshida, E. Hiyama, A. Hosaka, M. Oka, K. Sadato, Phys. Rev. D**92** (2015) 114029

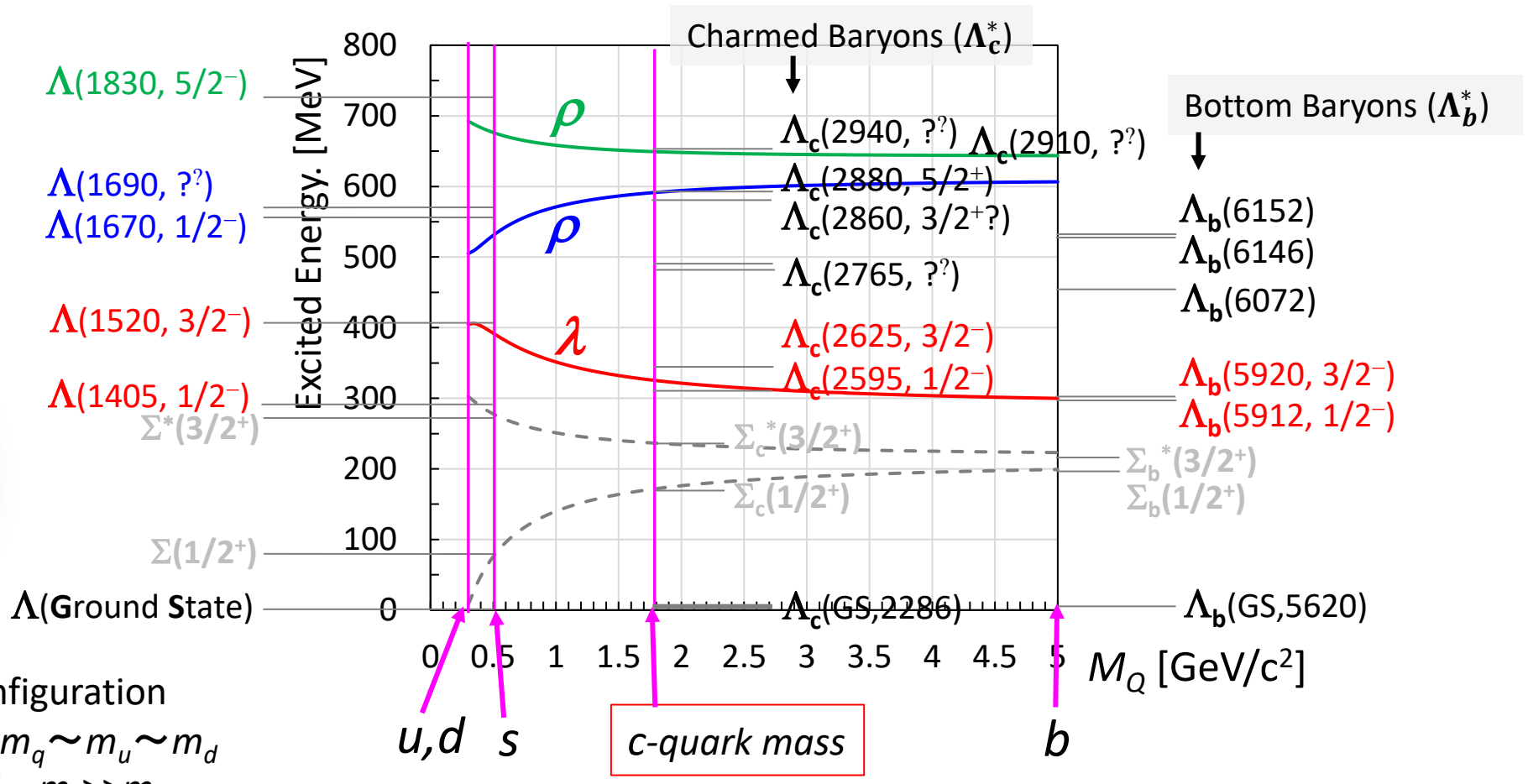
Level structure in Singly Heavy Baryons



Baryon with [*Qqq*] configuration

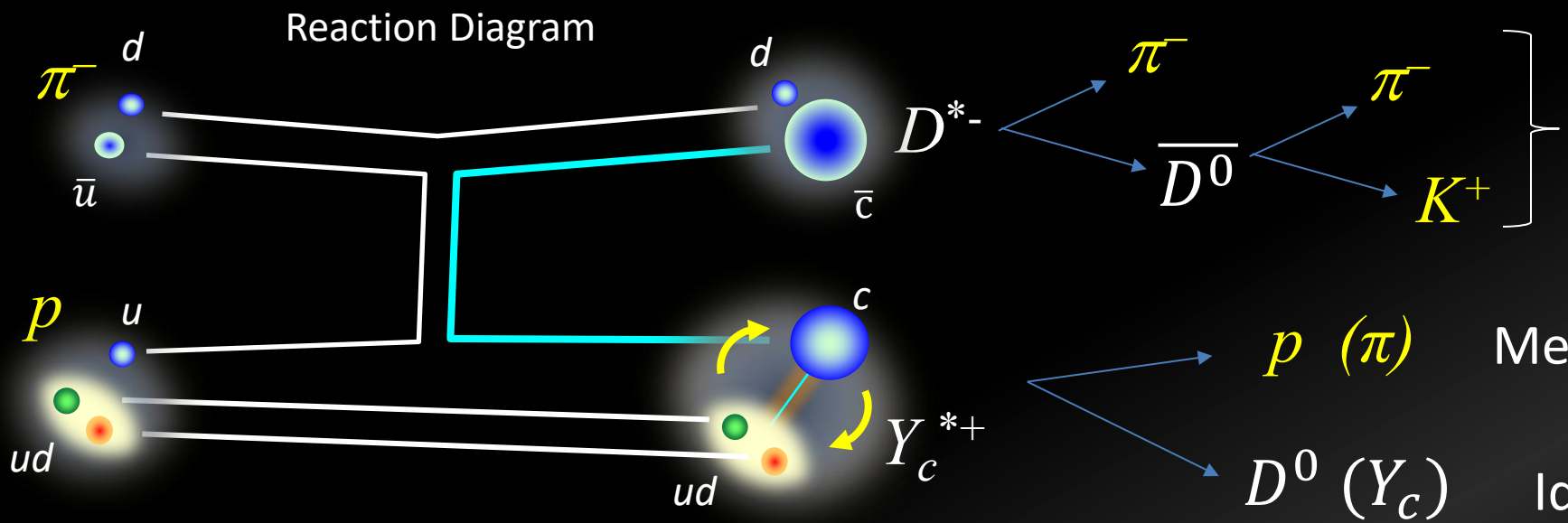
Light baryon : $M_Q = m_q \sim m_u \sim m_d$

Charmed Baryon : $M_Q = m_c >> m_q$



Level structure (Exp.) with curves calculated by T. Yoshida PRD 92, 114029 (2015)

Production and Decay of Charmed Baryons with *Missing Mass Spectroscopy* at J-PARC



Reconstruct D^{*-}
Identify Y_c^{*+} in the Missing mass spectrum

p (π) Measure Decay particles , too

D^0 (Y_c) Id. in missing mass

References for estimations on production cross sections:
Reggeon Exchange: S.H. Kim, A. Hosaka, H.C. Kim, and HN, Phys.Rev. D92 (2015) 094021
Single-quark involved process: S.H. Kim, A. Hosaka, H.C. Kim, and HN, PTEP, (2014) 103D01
Two-quark involved process: S.I. Shim, A. Hosaka, H.C. Kim, PTEP 2020, (2020) 5, 053D01

Production of Charmed Baryons: Theoretical Study

Cross sections for the Excited states

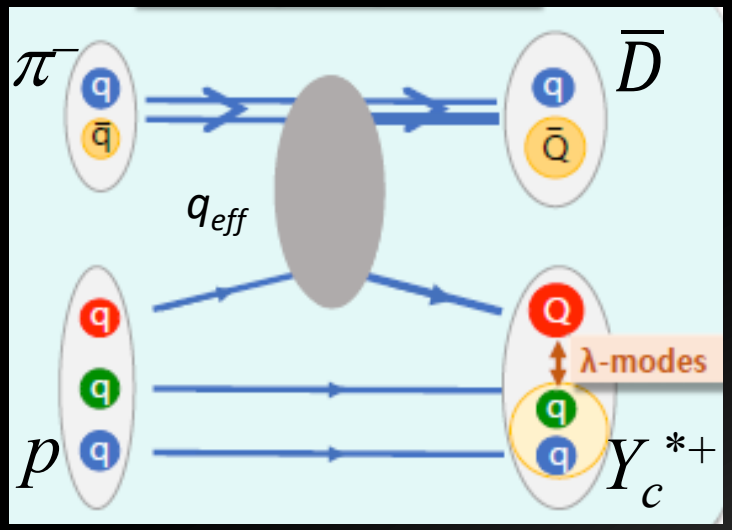
$$R \sim \left\langle \varphi_f \left| \sqrt{2}\sigma_- \exp(i\vec{q}_{eff}\vec{r}) \right| \varphi_i \right\rangle$$

$$I_L \sim (q_{eff}/\alpha)^L \exp(-q_{eff}^2/\alpha^2)$$

α~0.4 GeV ([Baryon size]$^{-1}$)
q_{eff}～1.4 GeV/c（one-quark)
～ 1 GeV/c (two quark)

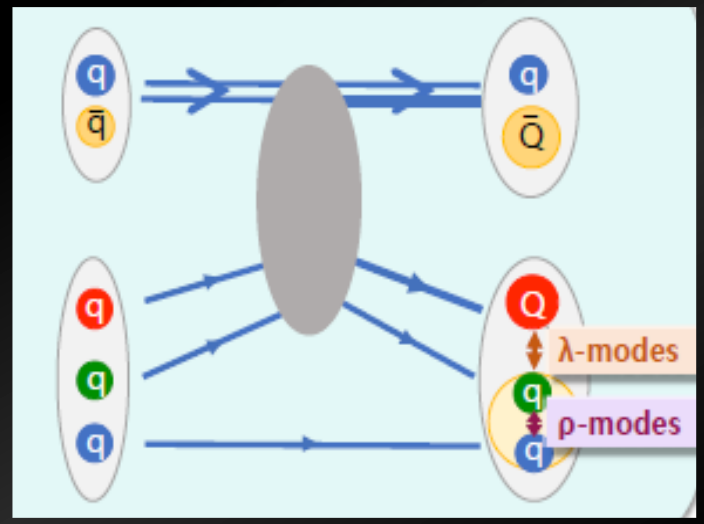
Populate higher *L* states
by factor $(q_{\mathrm{eff}}/\alpha)^L$

One-quark process



S.H. Kim, A. Hosaka, H.C. Kim, and HN
PTEP 2014 (2014) 103D01

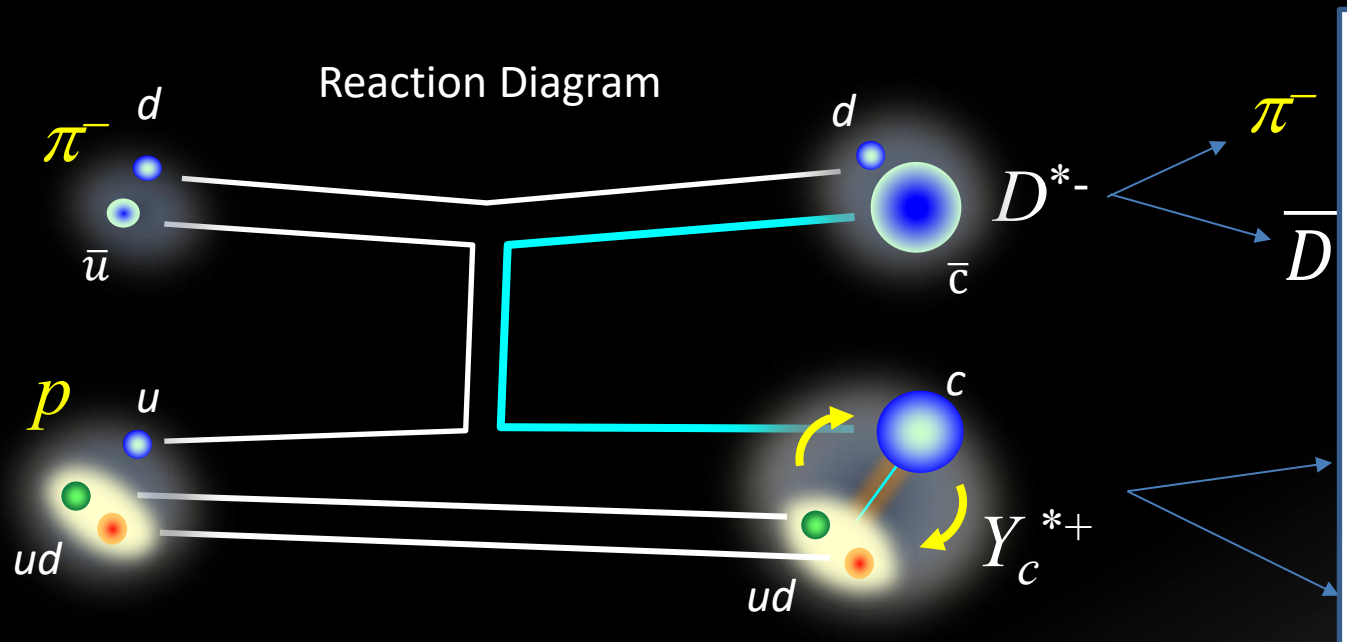
Two-quark process

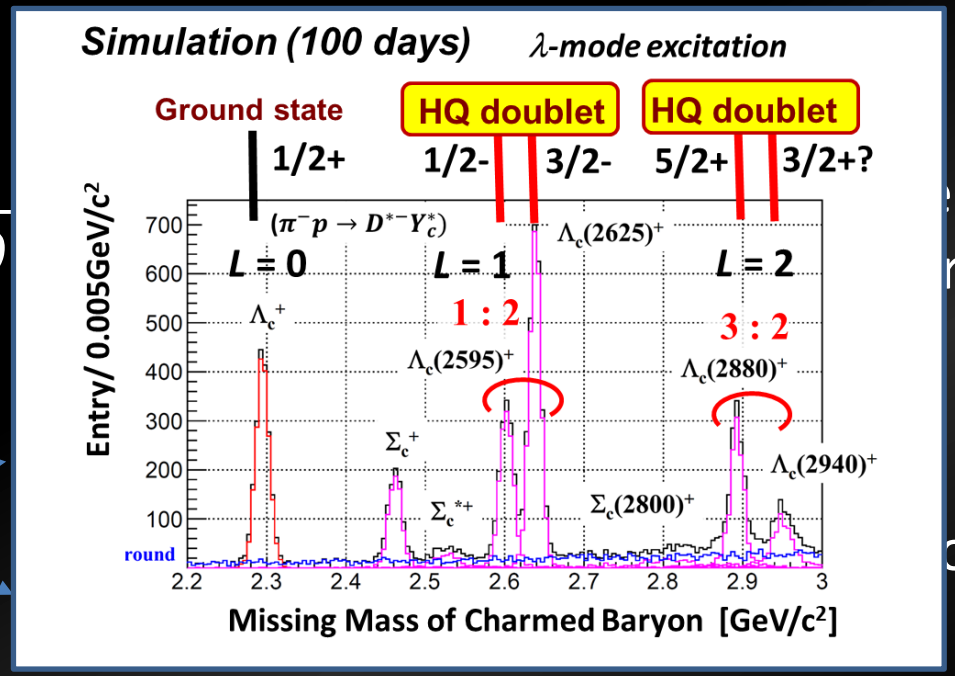


S.I. Shim, A. Hosaka, H.C. Kim,
PTEP 2020, (2020) 5, 053D01

※excite ρ-mode, giving how much the two-quark process contributes.

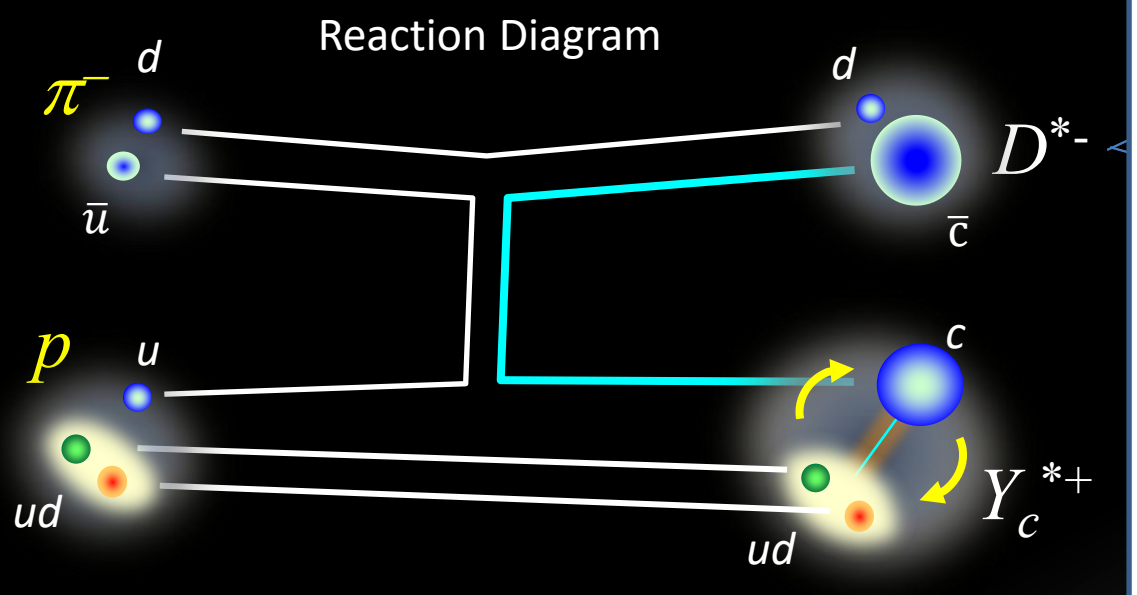
Production and Decay of Charmed Baryons

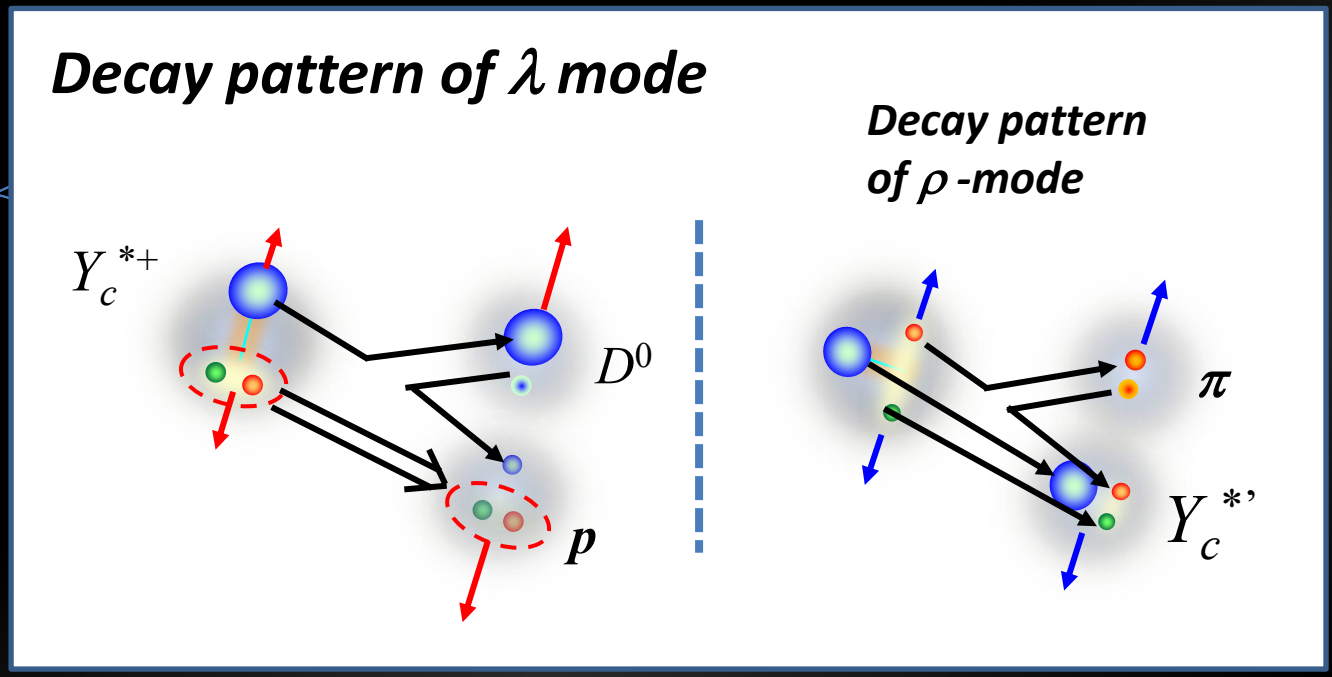




- *One-quark process* favors λ-mode sates, introducing a finite *L* btw *c* and *"ud".*
- *Two-quark process* favors ρ-mode sates as well.
- Production ratio of the HQ doublet to be *L*:*L*+1 ⇒ Spin, Parity.
- Production and Decay measurement ⇒ λ/ρ-mode identification

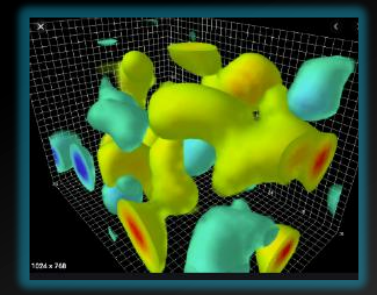
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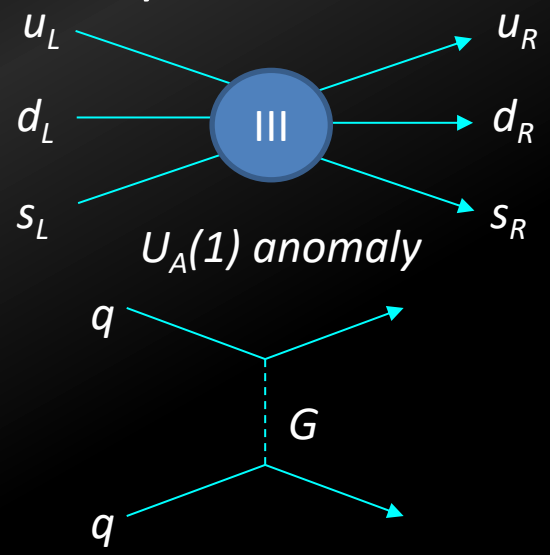


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Non-trivial vacuum of gluon field in baryons



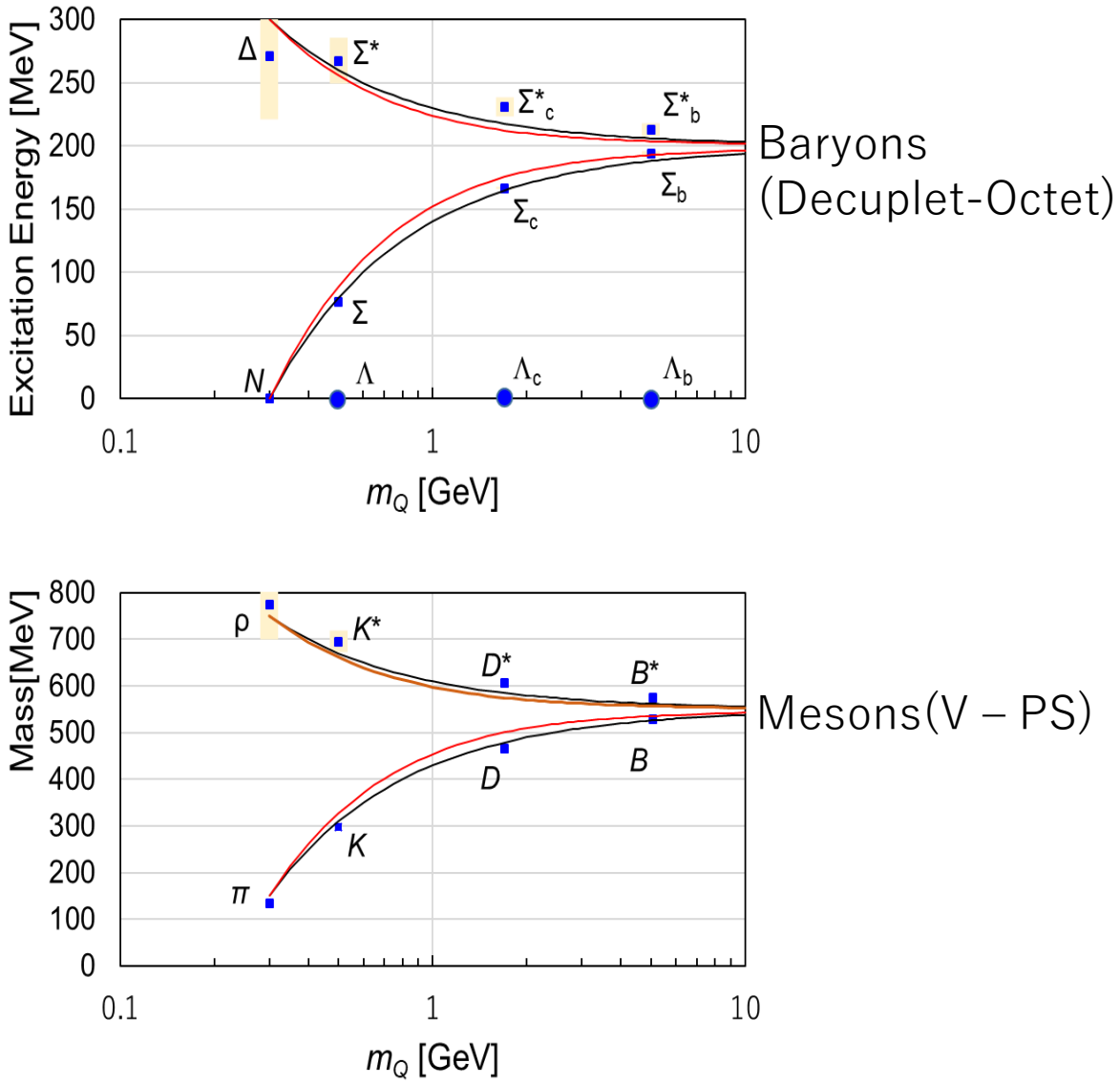
- "instanton" demonstrated in LQCD (D. Leinweber et al.)
  - $U_A(1)$ anomaly: explanation of $\eta - \eta'$ mass difference
  - 1 loop SBχS
- Instanton Induced Interaction (Kobayashi-Maskawa-t'Hooft Int.)
  - Introduces the spin-spin interaction btw two quarks (Oka, Takeuchi)
    - $V_{III}^{(2)} = \frac{1}{2} U_0^{(2)} \sum_{i>j} \xi_i \xi_j [\frac{2}{32} \lambda_i \lambda_j + \frac{9}{32} \lambda_i \lambda_j \sigma_1 \sigma_2] \delta(r_{ij}), \quad \xi_i = m_u / m_i$
  - Similar formula as that introduced by OGE
    - $V_{OGE}^{CMI} = -\frac{\alpha_s}{4} \sum_{i>j} \xi_i \xi_j \left[\frac{2\pi}{3} \lambda_i \lambda_j \sigma_1 \sigma_2\right] \delta(r_{ij})$
  - May solve the "too large α_S" problem in baryon spectrum
    - $\alpha_s \sim 1$ in order to explain the mass splitting of Δ to N



The origin of the spin-dependent interactions is an open question.

Naïve Demonstration: OGE + III in SS int

$$R_{OGE} + R_{III} \sim 0.6 + 0.4\exp\{-[m_Q - m_q]/\Lambda_\chi\}$$

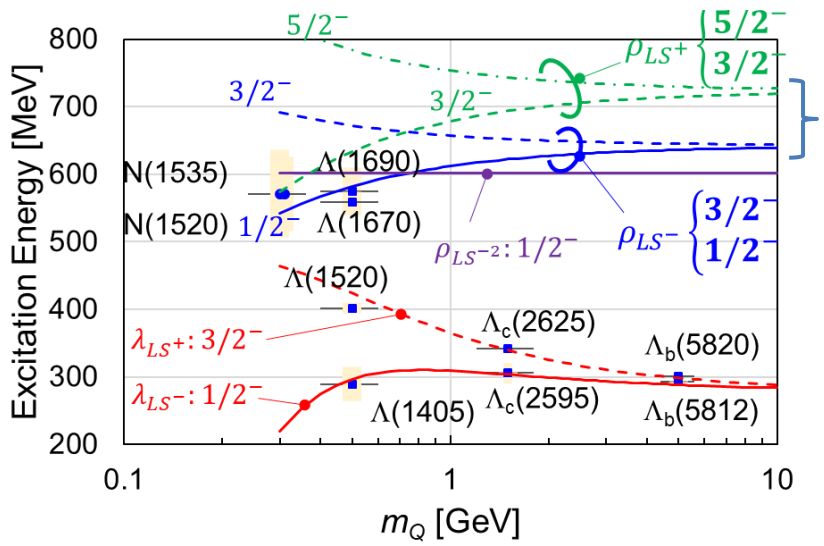


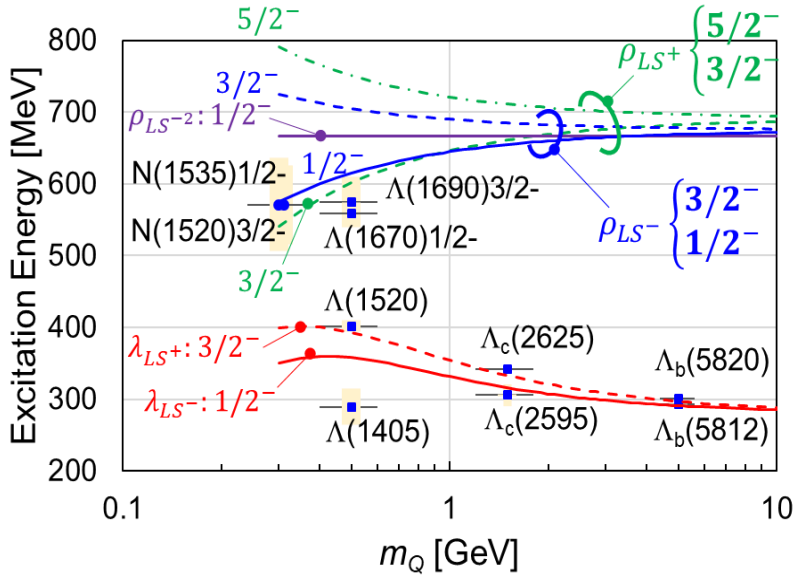
- *$\Delta M's$ btw 8tet and 10plet baryons are well explained by the SS int.*
  - *$\Delta M's$ btw PS and V mesons as well*
  - *CMI by OGE seems successful.*
  - OGE cannot explain the small LS splitting in N* and finite one in Heavy Baryons
- A cancellation scenario in LS
  - Instanton Induced Int. (III) [KMT int.]
    - Same structure as OGE
    - Effective for only light quarks
    - $U_A(1)$ anomaly in III introduces $\Delta M(\eta' - \eta)$
  - OGE + Instanton Induced Int. (III) in SS
    - No affect in SS splitting both in Baryons and Mesons
  - OGE – III in LS in lighter baryons

S. Takeuchi, Nucl. Phys. A **642**, 543 (1998).

Naïve Demonstration: OGE - III in LS int

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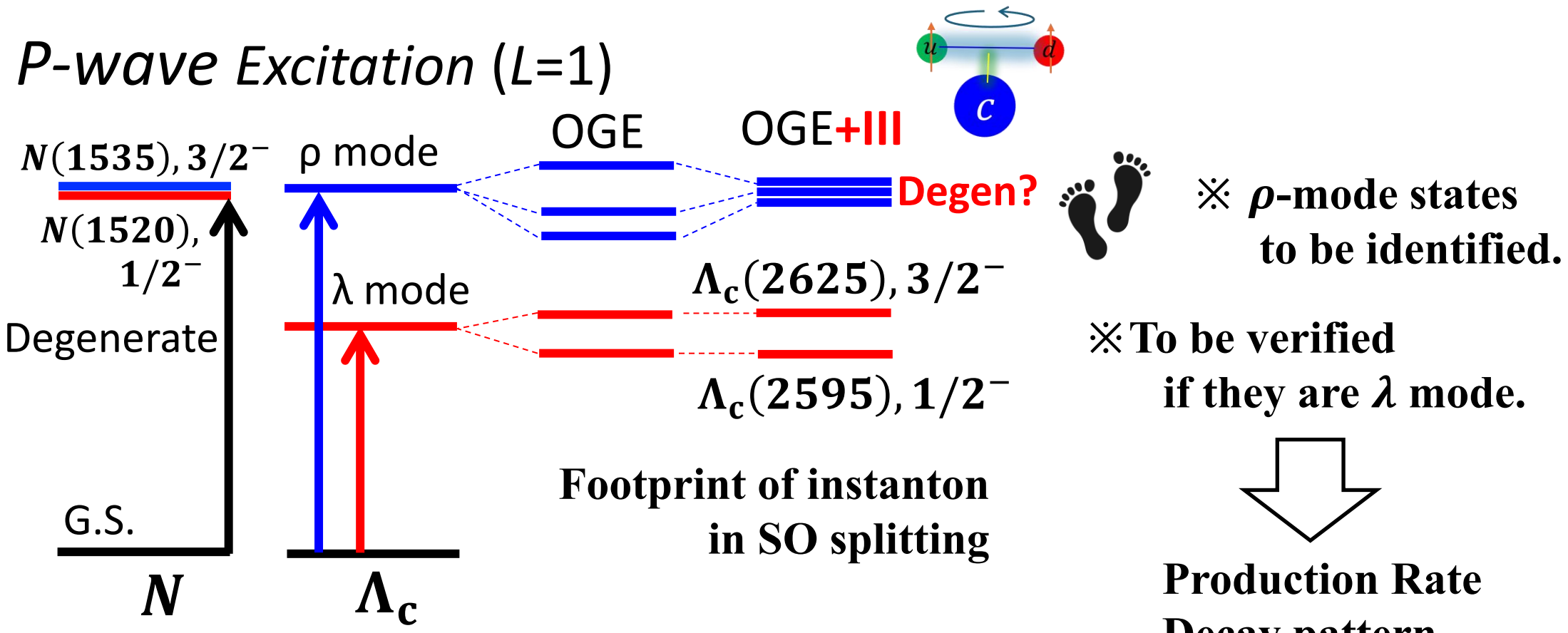




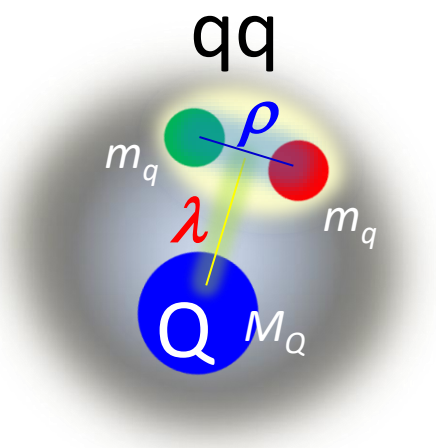
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S. Takeuchi, Nucl. Phys. A **642**, 543 (1998).

Issue 1: Footprint of Instanton in SO interaction



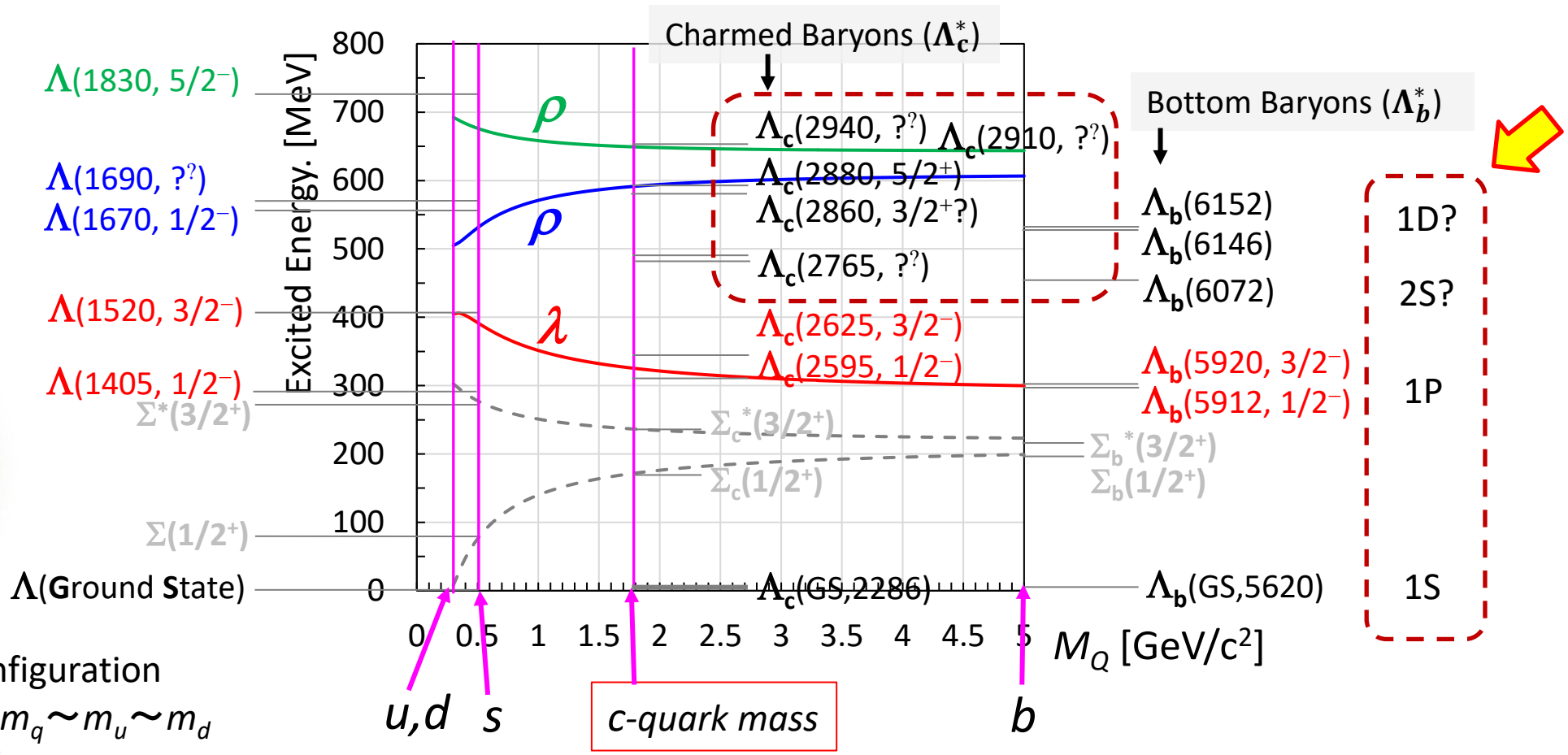
Recall level structure in singly heavy baryons



Baryon with [*Qqq*] configuration

Light baryon : $M_Q = m_q \sim m_u \sim m_d$

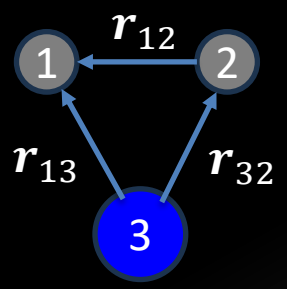
Charmed Baryon : $M_Q = m_c >> m_q$

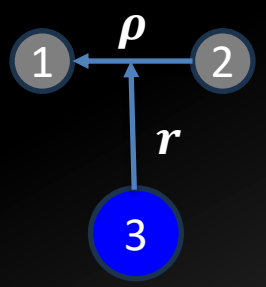


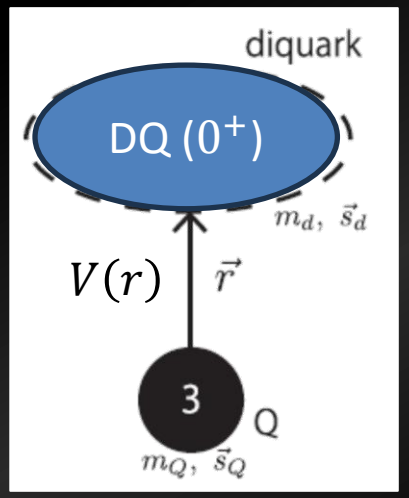
Level structure (Exp.) with curves calculated by T. Yoshida PRD 92, 114029 (2015)

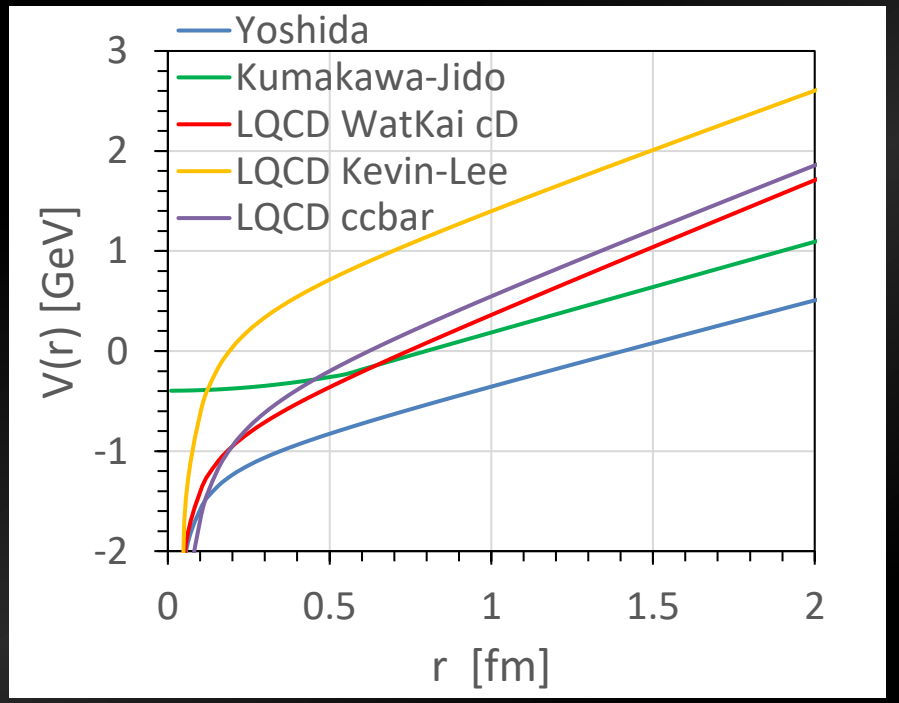
Color confinement in baryons

- Cornell potential well describes the spectra of Quarkonia
  - $V(r_{ij}) = A/r_{ij} + \sigma r_{ij}$
- It is a flavor blind interaction, thus would be applicable to baryon spectra…



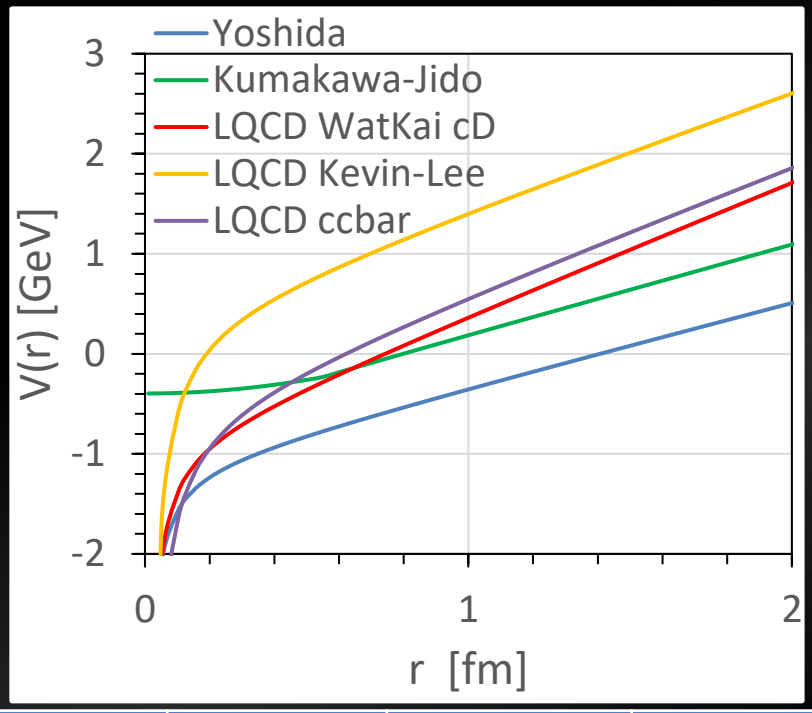






Models overestimate excitation energies in 1D/2S states

State	Exp. [GeV]		Yoshida		KJ [GeV]		Wat. HAL
$1D$	0.587 (2.8714)	0.531 (6.1500)	0.636	0.594	0.636	0.595	-
$2S$	0.479 (2.7666)	0.452 (6.1723)	0.572	0.535	0.605	0.570	-
$1P$	0.330 (2.6161)	0.298 (5.9174)	0.344	0.320	0.333	0.310	0.457
$1S$	0 (2.2864)	0 (5.6196)	0	0	0	0	0
	Λ_c	Λ_b	Λ_c	Λ_b	Λ_c	Λ_b	Λ_c



- Yoshida qqQ potential [PRD92, 114029(2015)]
  - $V(r) = \sum_{i<j}(-\frac{3\alpha_s}{2r_{ij}} - \frac{br_{ij}}{2}) + V_0 (+V_{spin-dep})$
- Kumakawa-Jido dQ pot. [PTEP, 2017, 123D01]
  - $V(r) = \begin{cases} -\frac{3\alpha_s}{2\rho} + \sigma\rho/2\left(1+\frac{4r^2}{3\rho^2}\right) + V_0\,, (r < \rho/2) \\ -\frac{3\alpha_s}{4r} + \sigma r\left(1+\frac{\rho^2}{12r^2}\right) + V_0\,, (r > \rho/2) \end{cases}$
- HAL QCD Q-dQ [PRD105, 074510 (2022)/arXiv:2606.19840]
  - $V(r) = \frac{A}{r} + Br + V_0$

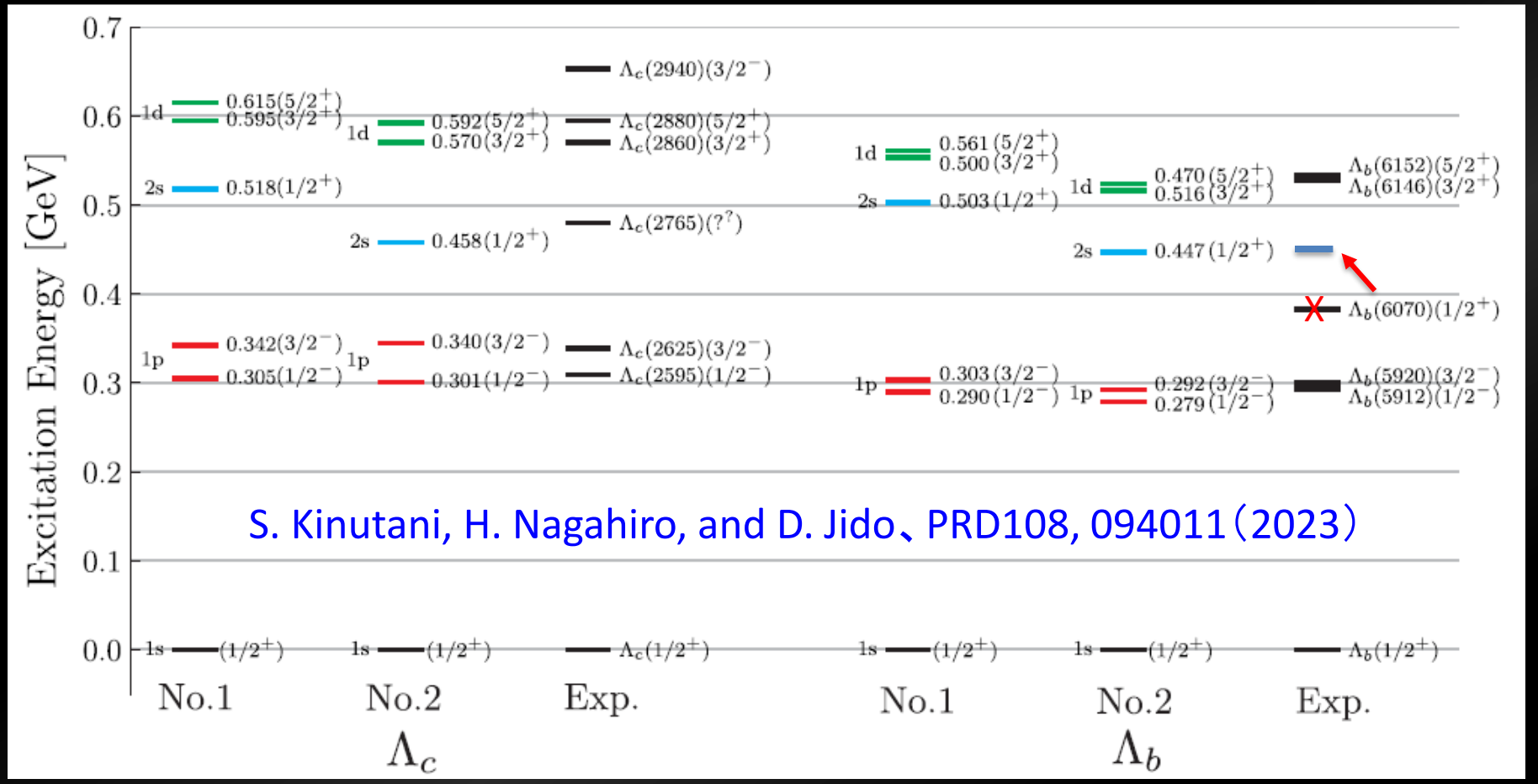
	Yoshida	KJ	Wat. HAL	Lee HAL
$4\alpha_s/3, A$ [GeVfm]	0.2686	0.10523	-0.065	-0.110
σ, B, b [GeV/fm]	**0.9**	**0.9**	1.315	1.15
ρ [fm]	-	1.1	-	-
V_0 [GeV]	-1.139	-0.7	-0.889	0.385
m_c [GeV]	1.7	1.5	1.77	∞
$m_D(2m_q)$ [GeV]	(0.6)	0.5	1.22	0.931

Rel. corr. does not solve but a smaller tension does.

TABLE I.

	α_{Coul}	α_{Hyp}	α_{Dar}	α_{tens}	α_{LS}	α_{oo}	k [GeV/fm]	Λ [fm^{-1}]
Number 1			0.37				~~0.9~~**0.65**	8.1
Number 2	0.40	0.32	0.22	0.54	0.46	0.65	~~0.9~~**0.5**	6.4

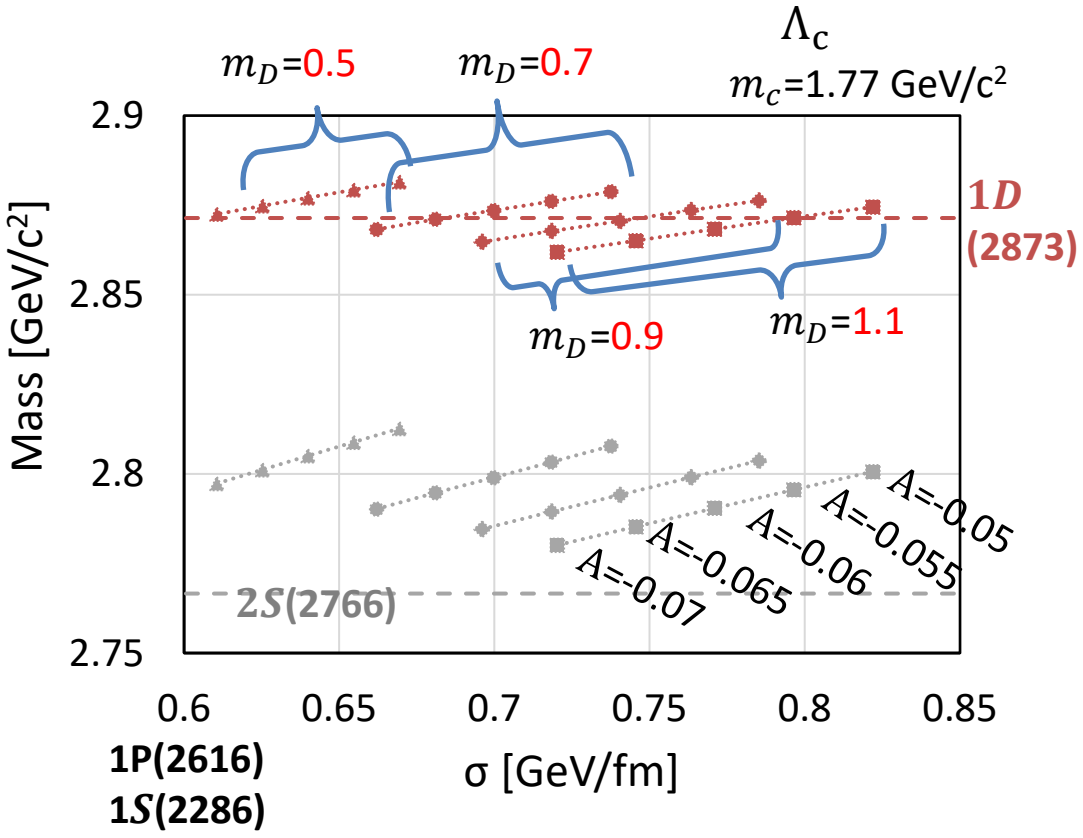
$m_c = 1.5\ \mathrm{GeV}/c^2$
$m_b = 4\ \mathrm{GeV}/c^2$
$m_d = 0.5\ \mathrm{GeV}/c^2$

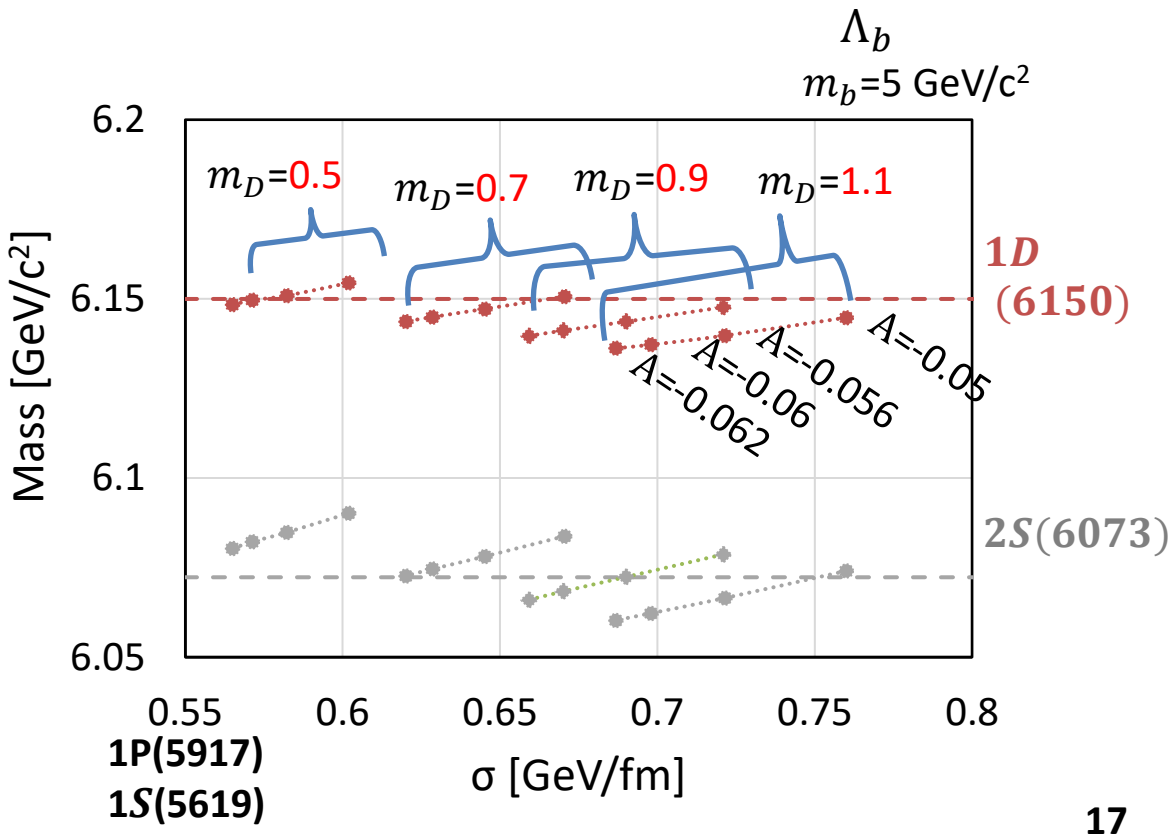


S. Kinutani, H. Nagahiro, and D. Jido、PRD108, 094011（2023）

Demo. in a Q-DQ model with $V(r) = \frac{A}{r} + \sigma r + V_0$

- A pair of A and σ is adjusted to reproduce 1S and 1P: a smaller σ is favored.
- The energy difference btw 2S and 1D is insensitive to the choice of A, σ.
- Λ_c : 30MeV overestimated for 2S.
- Λ_b : 2S,1D are reproduced within a few MeV, no A, σ reproduce 2S and 1D simultaneously.



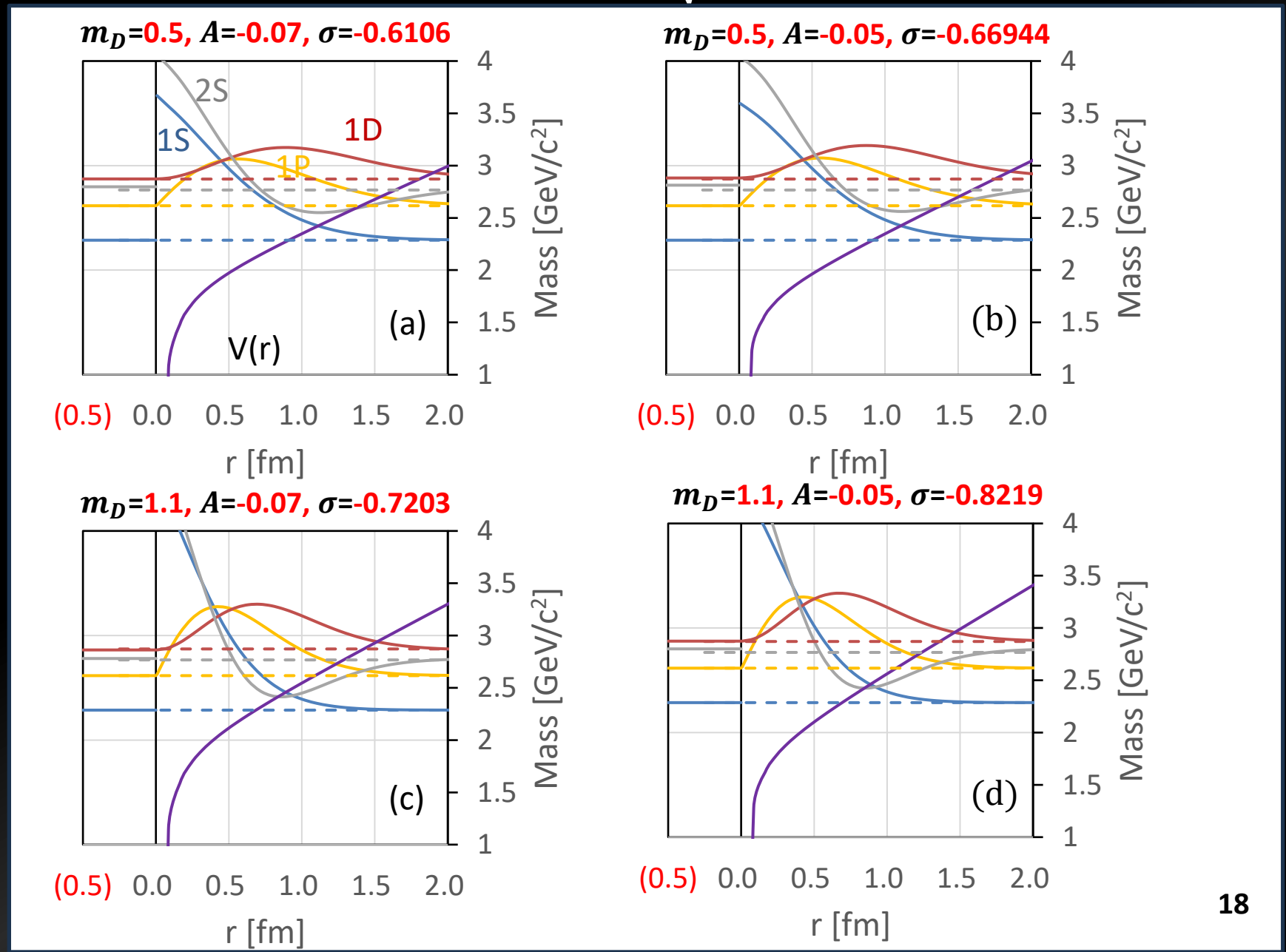


Potential params vs W.F.($\sqrt{\langle r^2 \rangle}$)

	(a)	(b)
R_{1D}^{rms}	1.25	1.22
R_{2S}^{rms}	1.24	1.22
R_{1P}^{rms}	0.98	0.97
R_{1S}^{rms}	0.67	0.67
	(c)	**(d)**
R_{1D}^{rms}	0.97	0.94
R_{2S}^{rms}	0.96	0.94
R_{1P}^{rms}	0.76	0.74
R_{1S}^{rms}	0.51	0.51

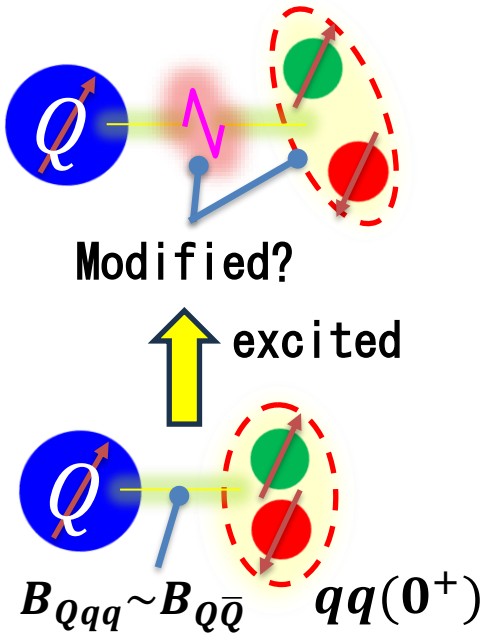
⇒provided from

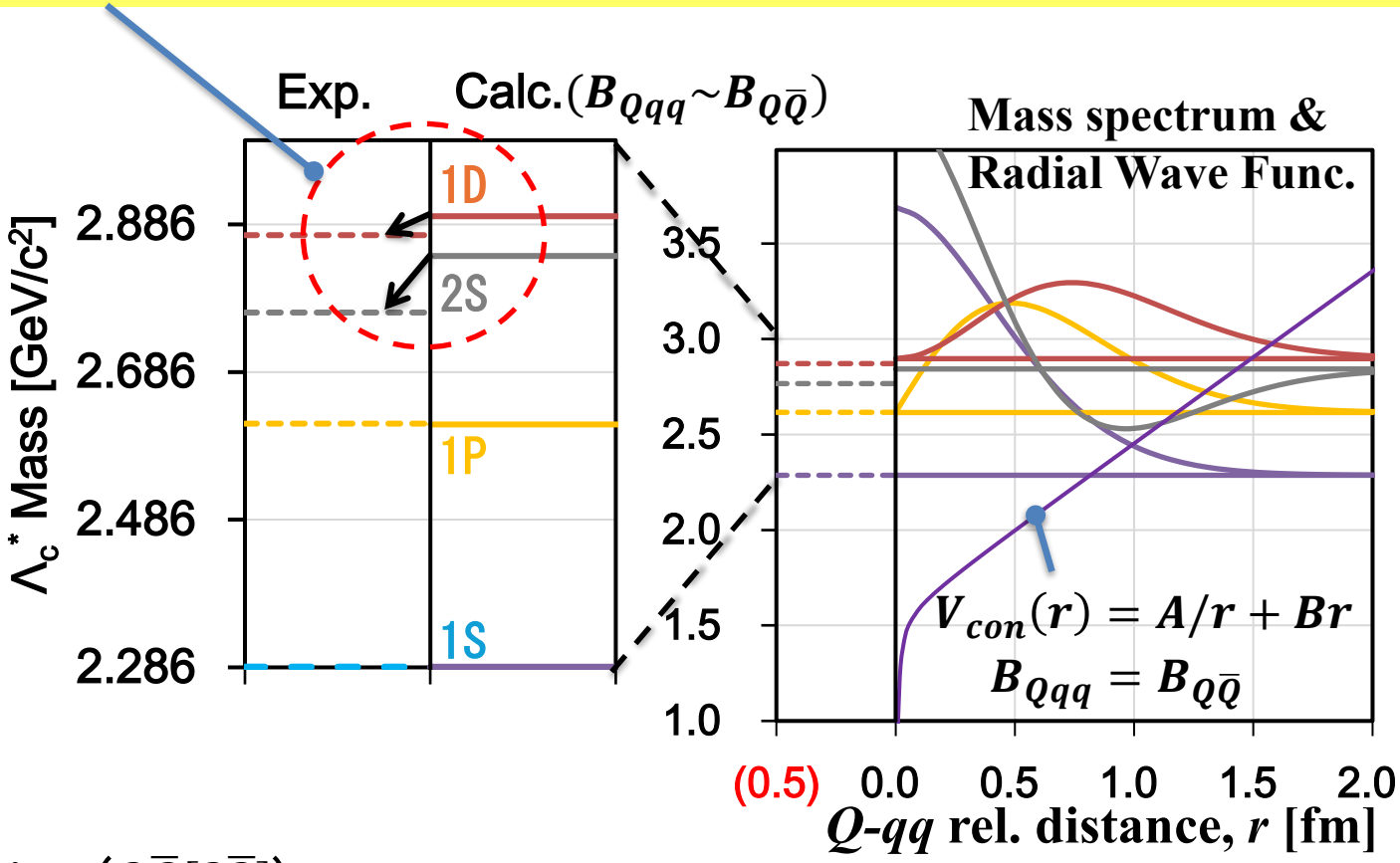
$$\frac{d\sigma}{d\Omega} \sim \left|\langle f | j_l(q_{eff} r) | i \rangle\right|^2$$



Issue 2: String Tension Puzzle in heavy baryons

Large discrepancy indicates dynamical changes of the tension/structure.





Baryon $Qqq[3\bar{3}]$

~Same color config. as quarkonium ($Q\bar{Q}[3\bar{3}]$)

※λ-mode 1D state to be identified. → Production and Decay

Summary

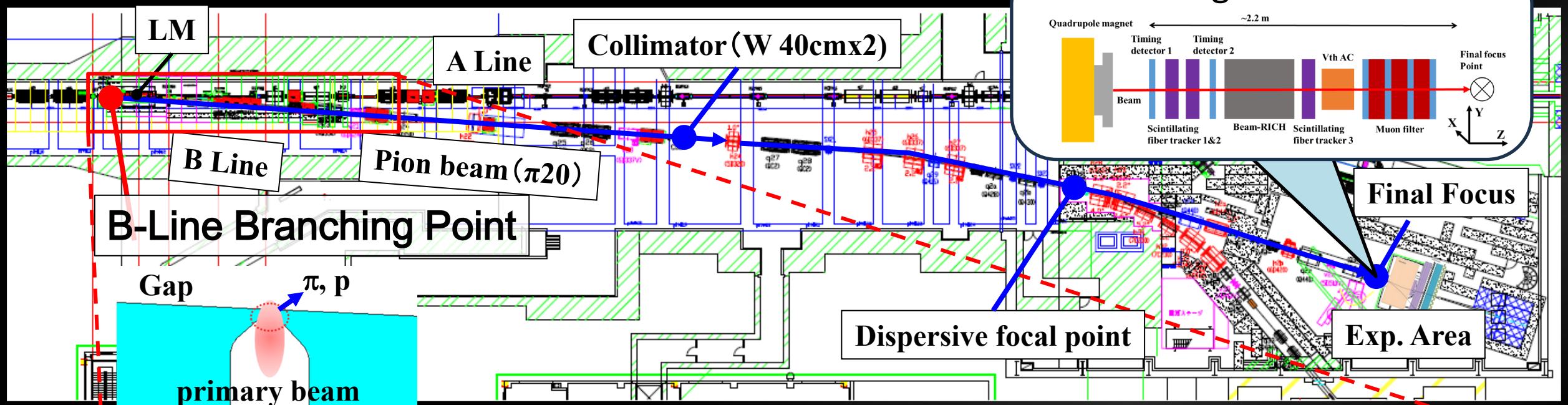
- QCD in low energy is characterized by the SBχS and color confinement, which may be caused by the non-trivial vacuum of the gluon field.
  - Its behavior is an issue in solving a fundamental question on the origin of matter evolution.
- The effect of the gluon field in heavy baryons provides hints:
  - Footprint of the instanton-induced interaction in spin-dependent interactions
    - LS splitting in ρ/λ-mode excited heavy baryons
  - String Tension Puzzle of confinement force in heavy baryons
    - Level structure of excited heavy baryons in (heavy) Quark-Diquark configuration

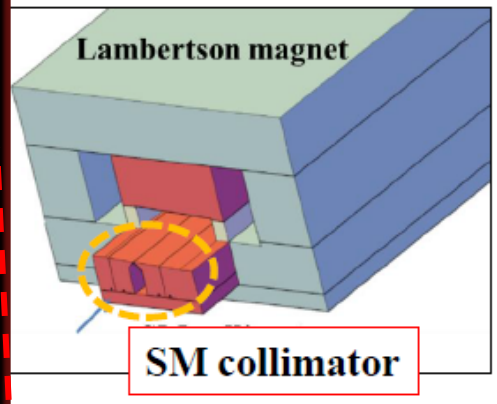
⇒ Spectroscopic study of heavy baryons at J-PARC

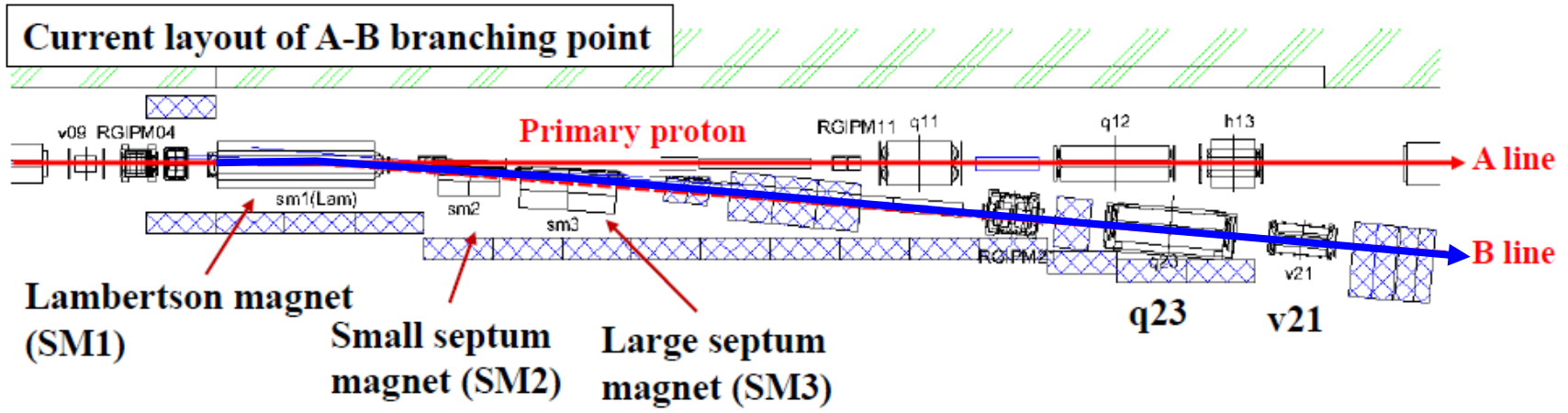
- Identifying ρ/λ-modes with characteristic production rates, decay patterns, etc.

Back up

Current Layout : B Line (primary p) & π20-phase 1 (secondary beams)

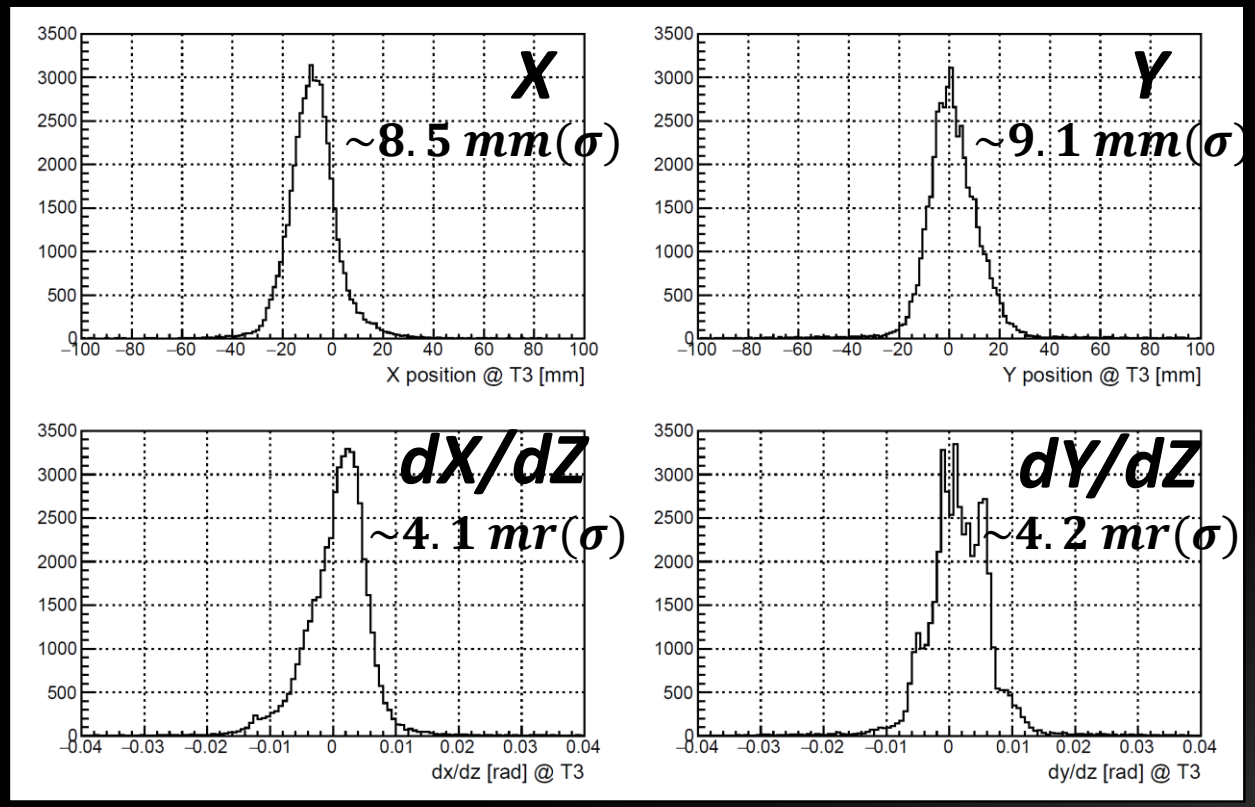






π20 (phase 1) has been launched !

Hadron beam at 5 GeV/c



Beam Profile measured at the Exp. Area

Measured Intensity:

in case of the expected loss of 230W at LM

- **3 GeV/c: ~200 k/spill**
- **5 GeV/c: ~600 k/spill**
- **10 GeV/c: ~1400 k/spill**

※ Spill: 2 sec extraction, 4.24 sec repetition cycle

Pion : proton (kaon ignored)

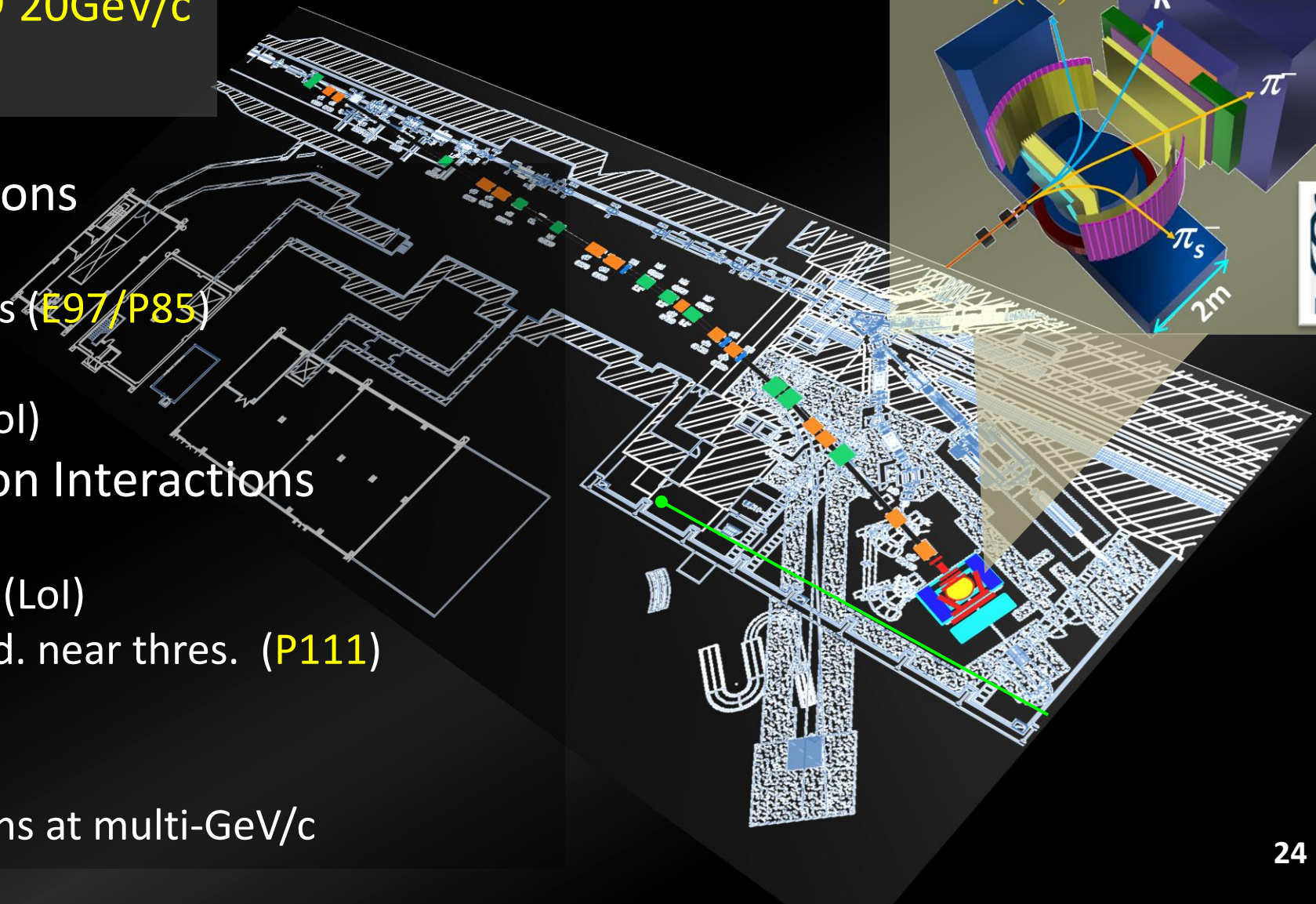
	Sanford-Wang sim.	Data
3 GeV/c	0.62 : 0.38	0.66 : 0.34
5 GeV/c	0.60 : 0.40	0.60 : 0.40
10 GeV/c	0.36 : 0.64	0.39 : 0.61

K. Shirotori *et al.*, *arXiv:2608.25374*
submitted to PTEP

Hadron Physics at the High-mom. 2ndary Beam Line (π20)

- π20 final specification :
  - 1.0 x 10^7 pions/sec @ 20GeV/c
  - $\Delta p/p$~0.1%

- Spectroscopy of Baryons
  - Charm Baryons (E50)
  - Multi-strange Baryons (E97/P85)
  - D_{30} dibaryon (E79)
  - Exclusive Drell-Yan (LoI)
- Exotic systems/Hadron Interactions
  - ϕn interaction (E95)
  - Lambda-N Scattering (LoI)
  - π^-- induced J/ψ prod. near thres. (P111)
  - $\bar{p}p \to \bar{Y}Y, \phi\phi, \ldots$
- Application
  - Radiography w/ muons at multi-GeV/c



π20 (Secondary beam mode), final layout

