International Conference on the Structure of Baryons (Baryons 2025)
ICC JeJu, 10 – 14 November, 2025

Spectroscopic Study of Quark Dynamics in Baryons at J-PARC

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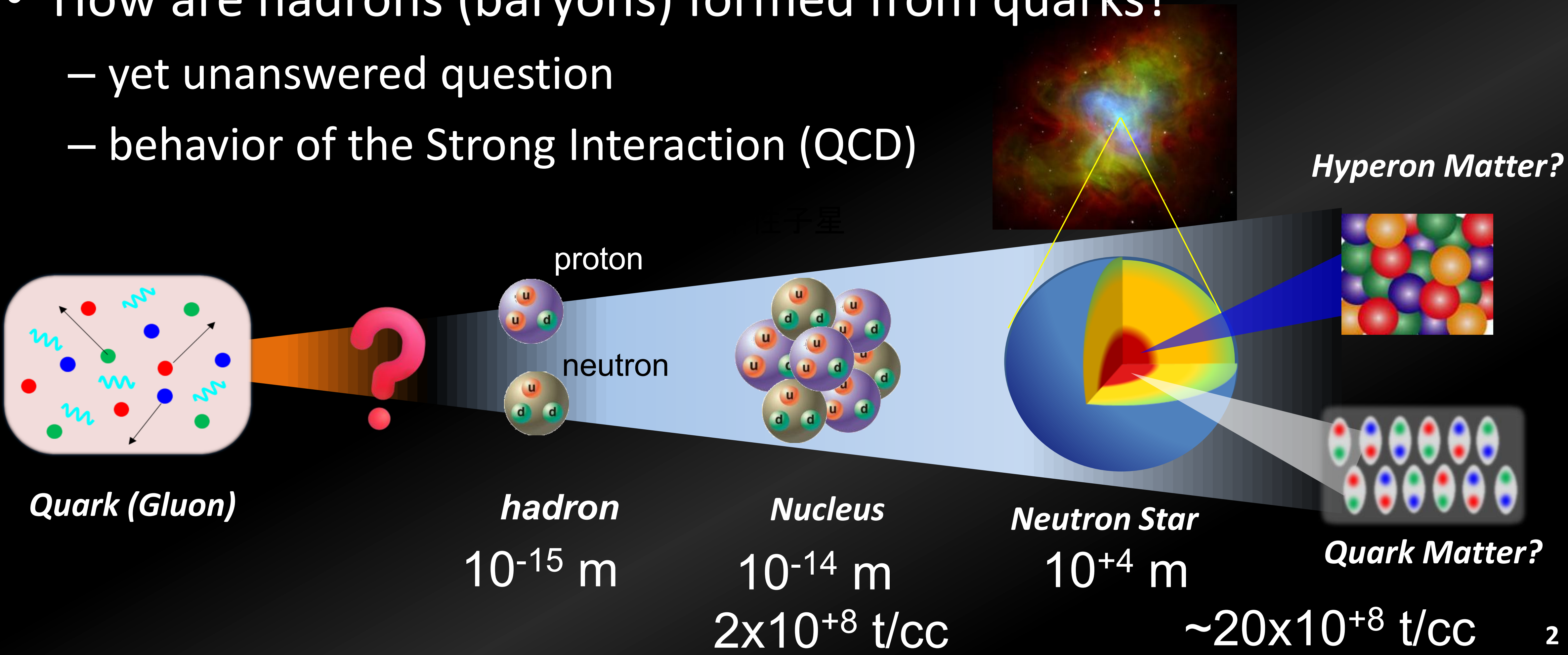
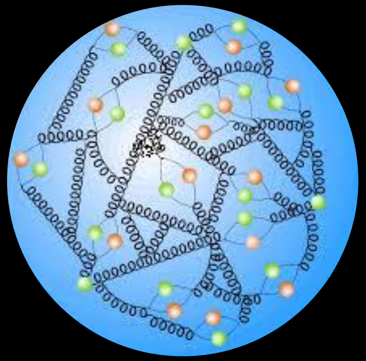
Elucidation of Matter Evolution in the Universe

- Hadrons (baryons) : complex system of quarks (and gluons)
- How are hadrons (baryons) formed from quarks?
  - yet unanswered question
  - behavior of the Strong Interaction (QCD)



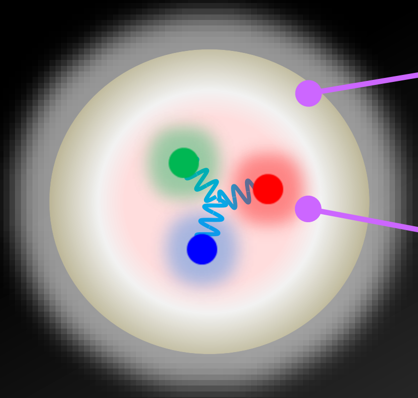
How does QCD build baryons?

High E
perturbative



$\alpha_s = \infty$
at Λ_{QCD}

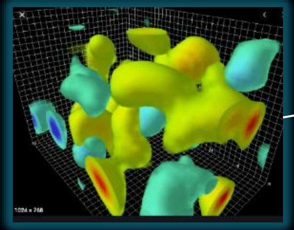
Low E
non-perturbative

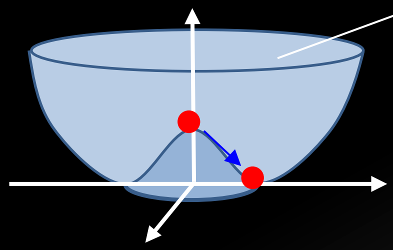


Meson Cloud

"Constituent" Quark (CQ)

Instanton
(LQCD demo.
by D. Leinweber)

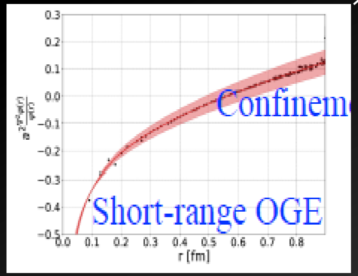




- Non-trivial vacuum
- Spontaneous Breaking of Chiral Symmetry
- Confinement

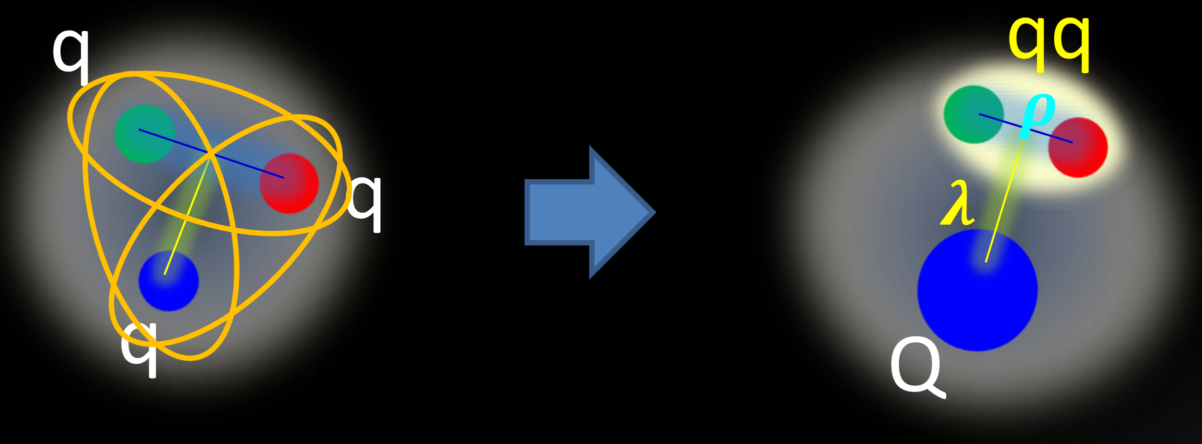
Eff. DoF dynamically emerge:
"Massive" CQ
NG bosons (pion, ...)

Dynamics of CQ reflects the nature of QCD in Low E



Q-Diquark Pot. in LQCD cal.

Roles of Heavy Quark: *to see dynamics of Eff. DoF*



$V_{CMI} \sim [\alpha_s/(m_i m_j)] * (\lambda_i, \lambda_j)(\sigma_i, \sigma_j)$

$\rightarrow 0$ if $m_{i,j} \rightarrow \infty$

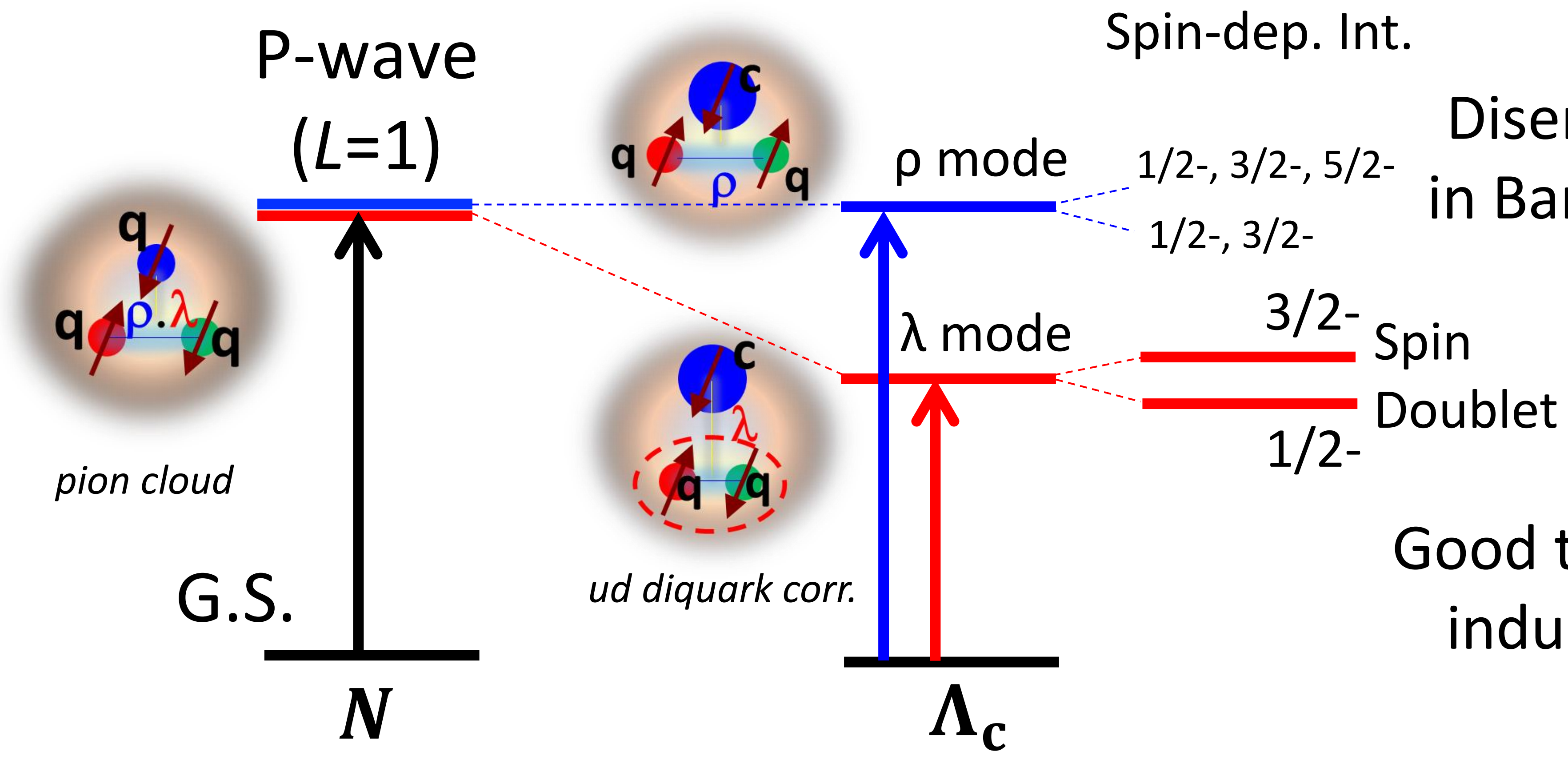
$V_{CMI}({}^1S_0, \bar{3}_c) = 1/2 * V_{CMI}({}^1S_0, 1_c)$

[qq] $\qquad$ $[\bar{q}q]$

- Motion of "*qq*" is singled out by a heavy Q
  - Diquark correlation
- Level structure, Production rate, Decay properties
  - sensitive to the internal quark(diquark) WFs in baryons
- Properties are expected to depend on a Q mass.

Internal structure of baryons in terms of Eff. DoF

※Disentangle motions of a quark pair by introducing different flavors

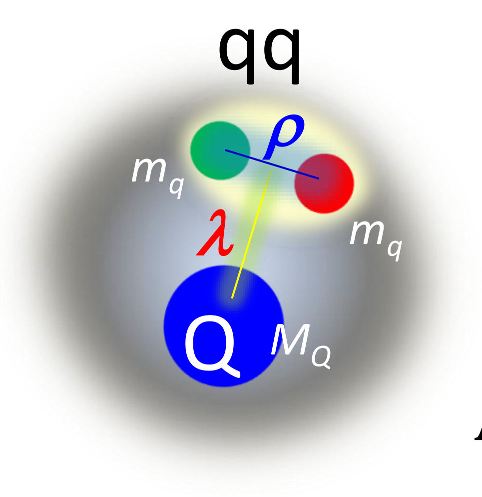


Disentangle "*qq*" motion in Baryon w/ Heavy Quark

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

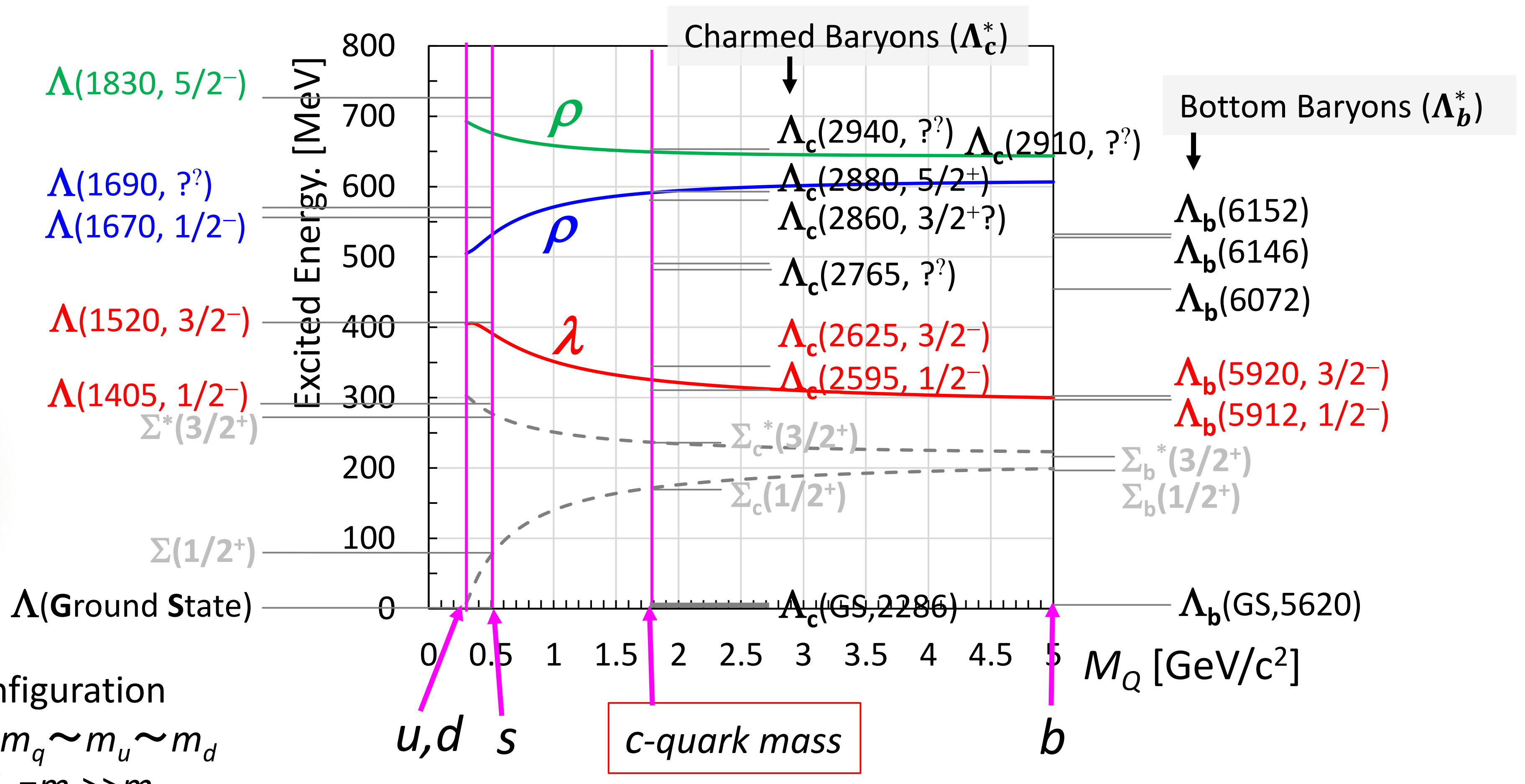
Level structure in Singly Heavy Baryons



Baryon with [Qqq] configuration

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

Charmed Baryon : $M_Q = m_c >> m_q$

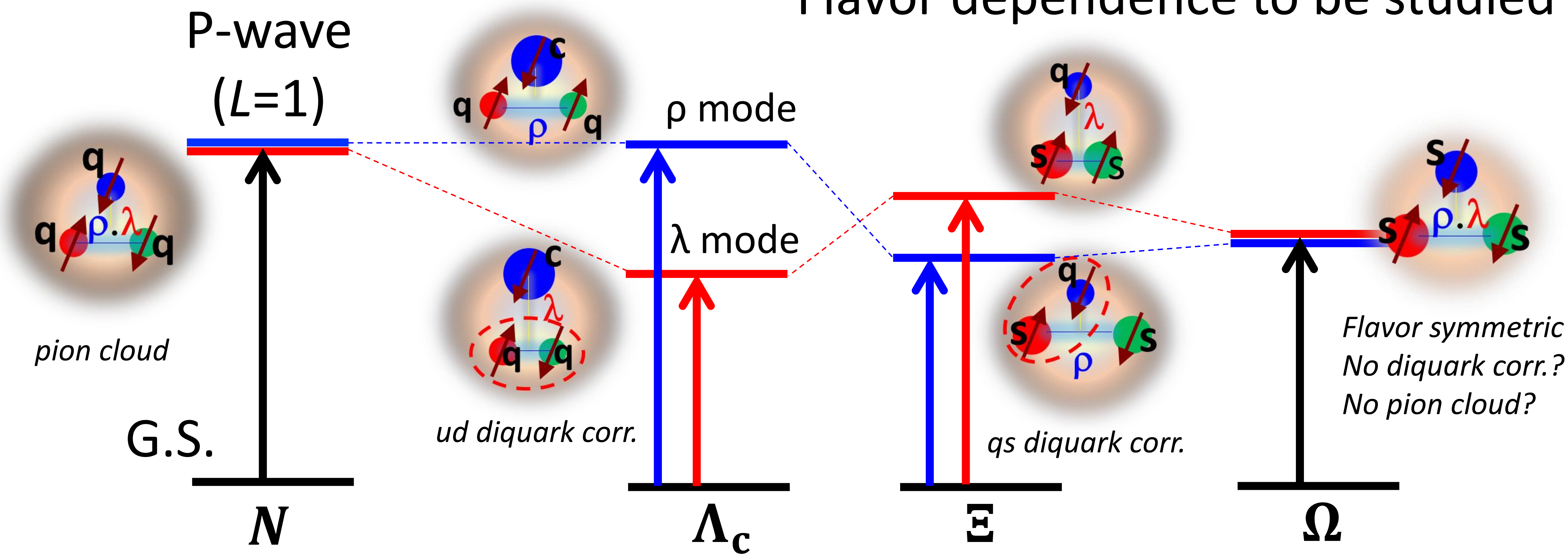


Level structure (Exp.) with curves calculated by T. Yoshida
PRD 92, 114029 (2015)

Spectroscopy of strange and charmed baryons

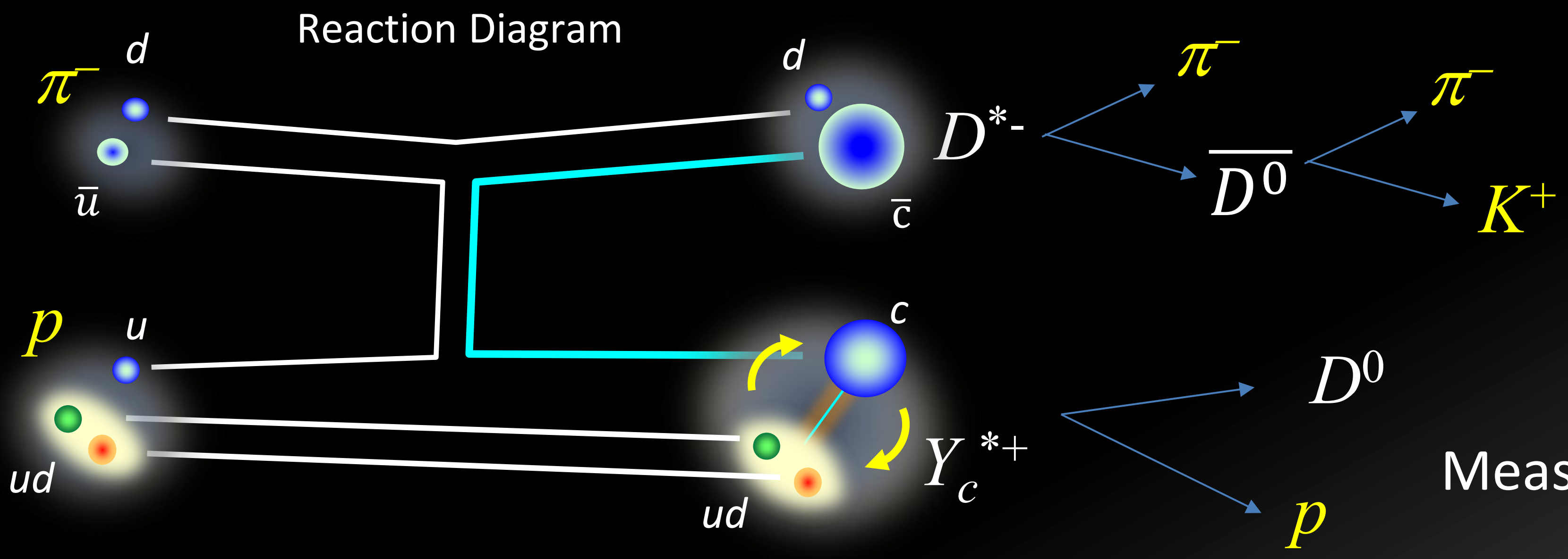
※Disentangle motions of a quark pair by introducing different flavors

Flavor dependence to be studied



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

Production and Decay of Charmed Baryons



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

Measure Decay particles , too

References for estimations on production cross sections:

Reggeon Exchange: S.H. Kim, A. Hosaka, H.C. Kim, and HN, Phys.Rev. D92 (2015) 094021

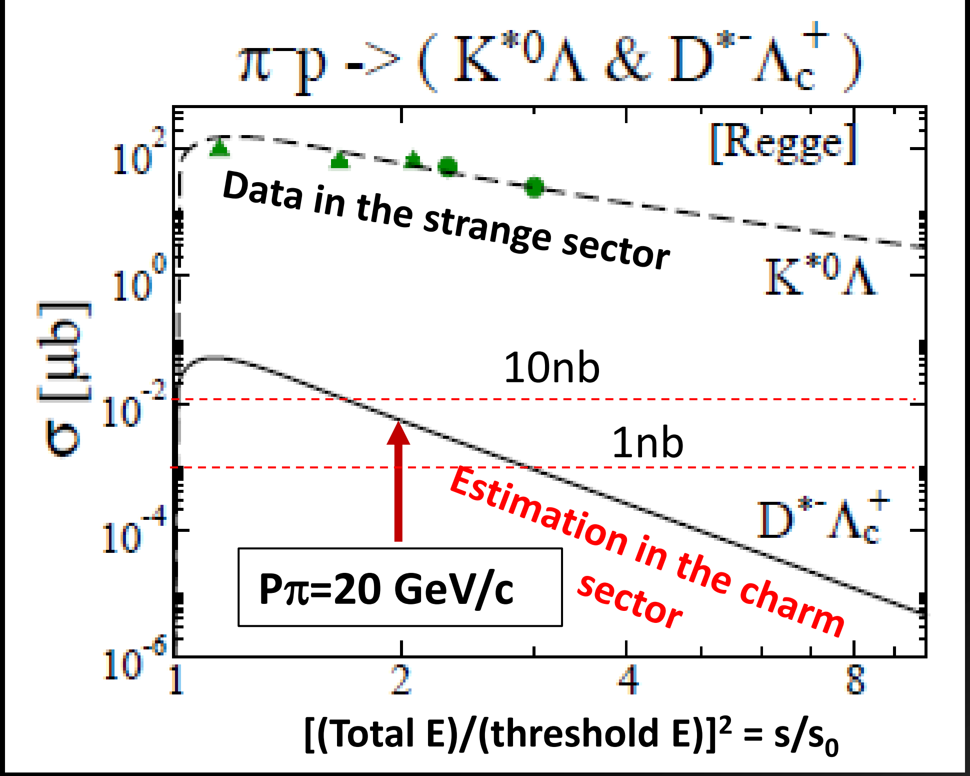
Single-quark involved process: S.H. Kim, A. Hosaka, H.C. Kim, and HN, PTEP, (2014) 103D01

Two-quark involved process: S.I. Shim, A. Hosaka, H.C. Kim, PTEP 2020, (2020) 5, 053D01

Production of Charmed Baryons: Theoretical Study

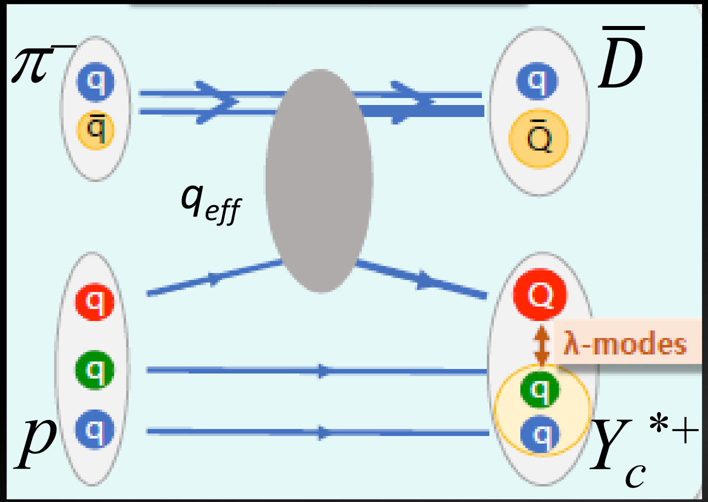
Reggeon Exchange Model in 2-body reaction

S.H. Kim, A. Hosaka, H.C. Kim, and H. Noumi
PRD92 (2015) 094021

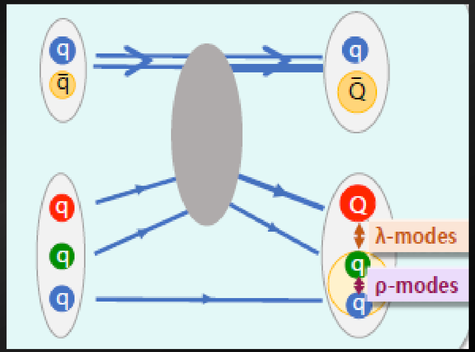


※no data available is in the charm sector.

One-quark process



Two-quark process



Production rate in excited state

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

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

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

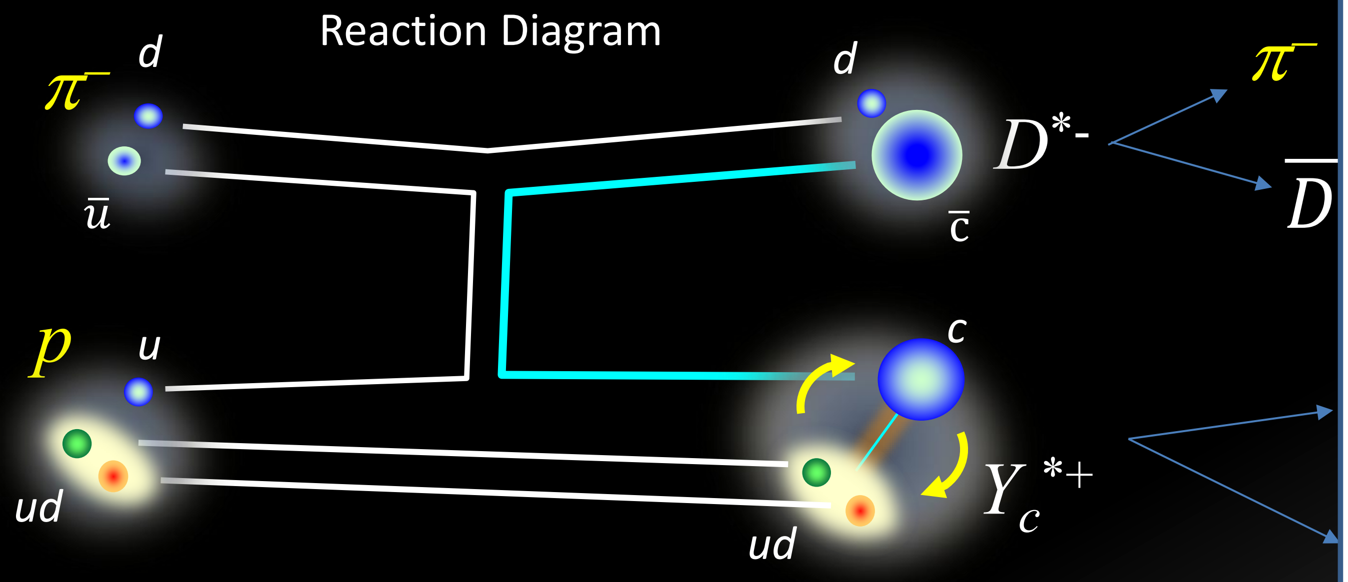
Mom. Trans. : q_{eff}∼1.4 GeV/c
α~0.4 GeV ([Baryon size]$^{-1}$)

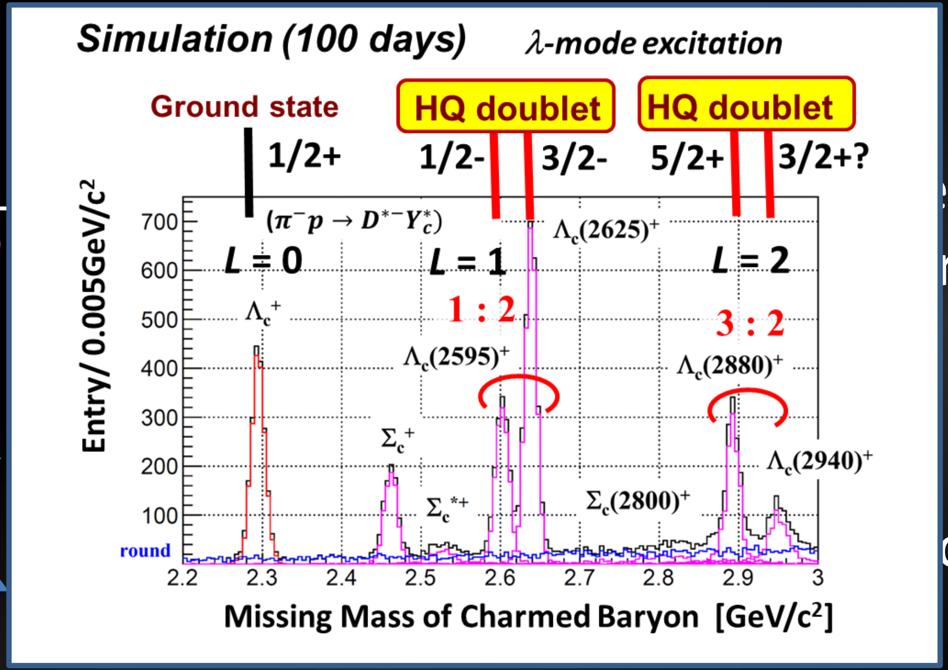
※favor λ-mode excited state with finite L is populated by factor $(q_{\mathrm{eff}}/\alpha)^L$

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

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

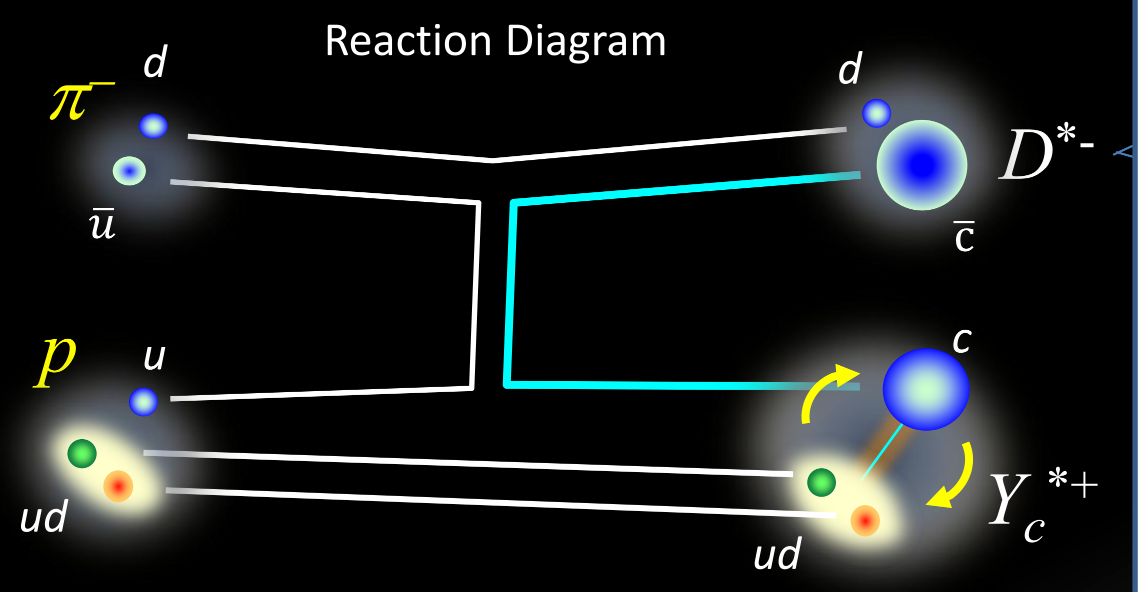
Production and Decay of Charmed Baryons

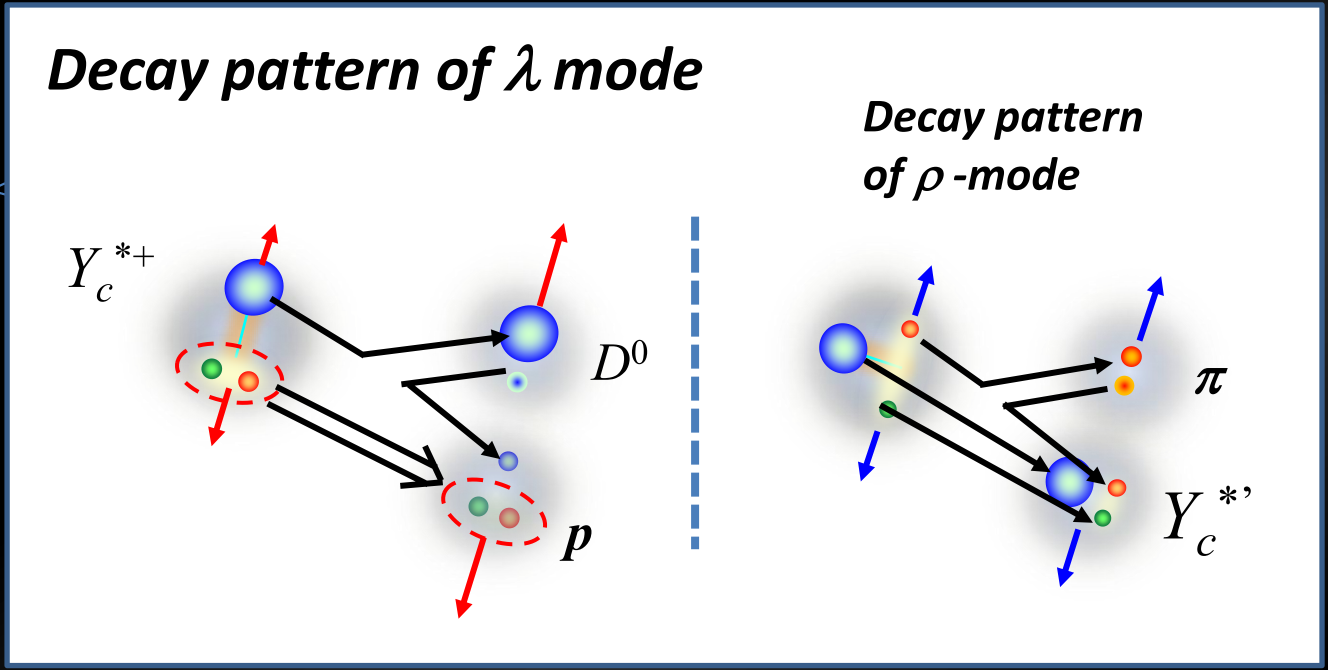




- Introducing a finite orbital angular momentum L ⇒ favor λ-mode excitations
  - Establish "*ud*" diquark motion in baryon
- Production ratio of the HQ doublet to be L:L+1 ⇒ Spin, Parity
  - The ratio would be a measure of how "*ud*" is correlated.
- Production and Decay measurement ⇒ Branching Ratio (partial width)
  - Decay rates would be a measure of how "*ud*" is firmly correlated

Production and Decay of Charmed Baryons





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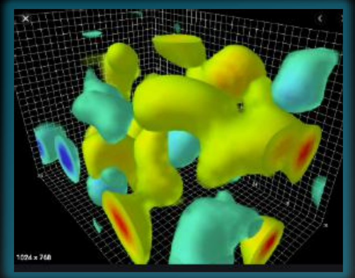
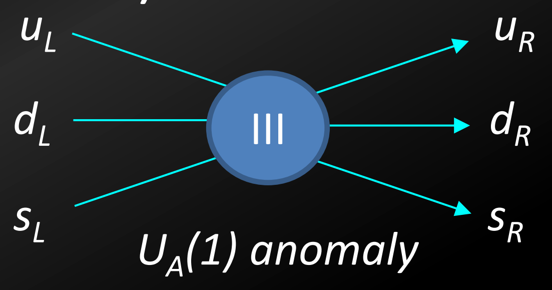
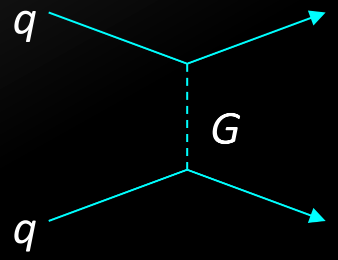
Non-trivial vacuum of gluon field in baryons



- "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

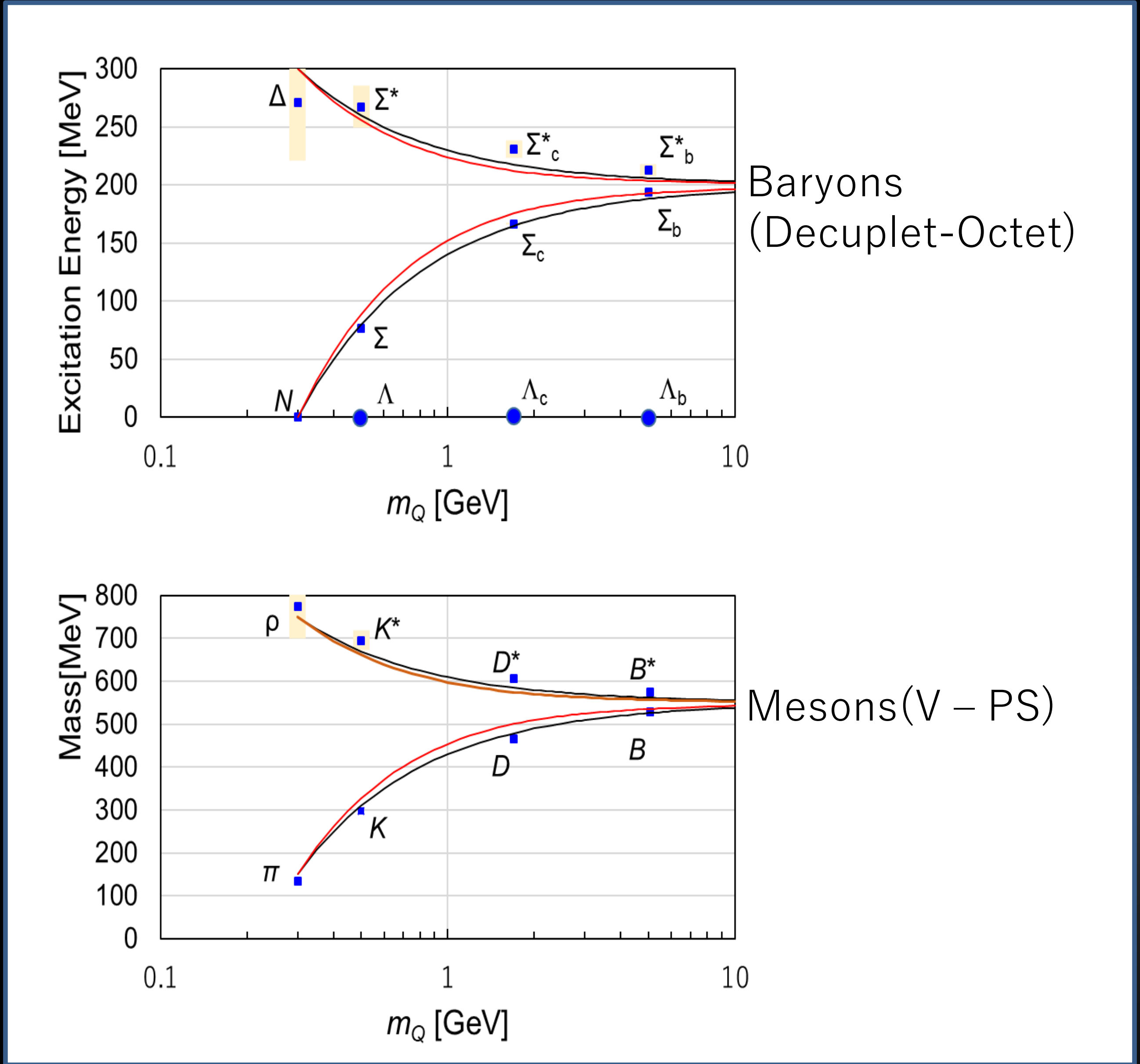




The origin of the spin-dependent interactions is an open question.

Naïve Demonstration: OGE + III in SS int

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

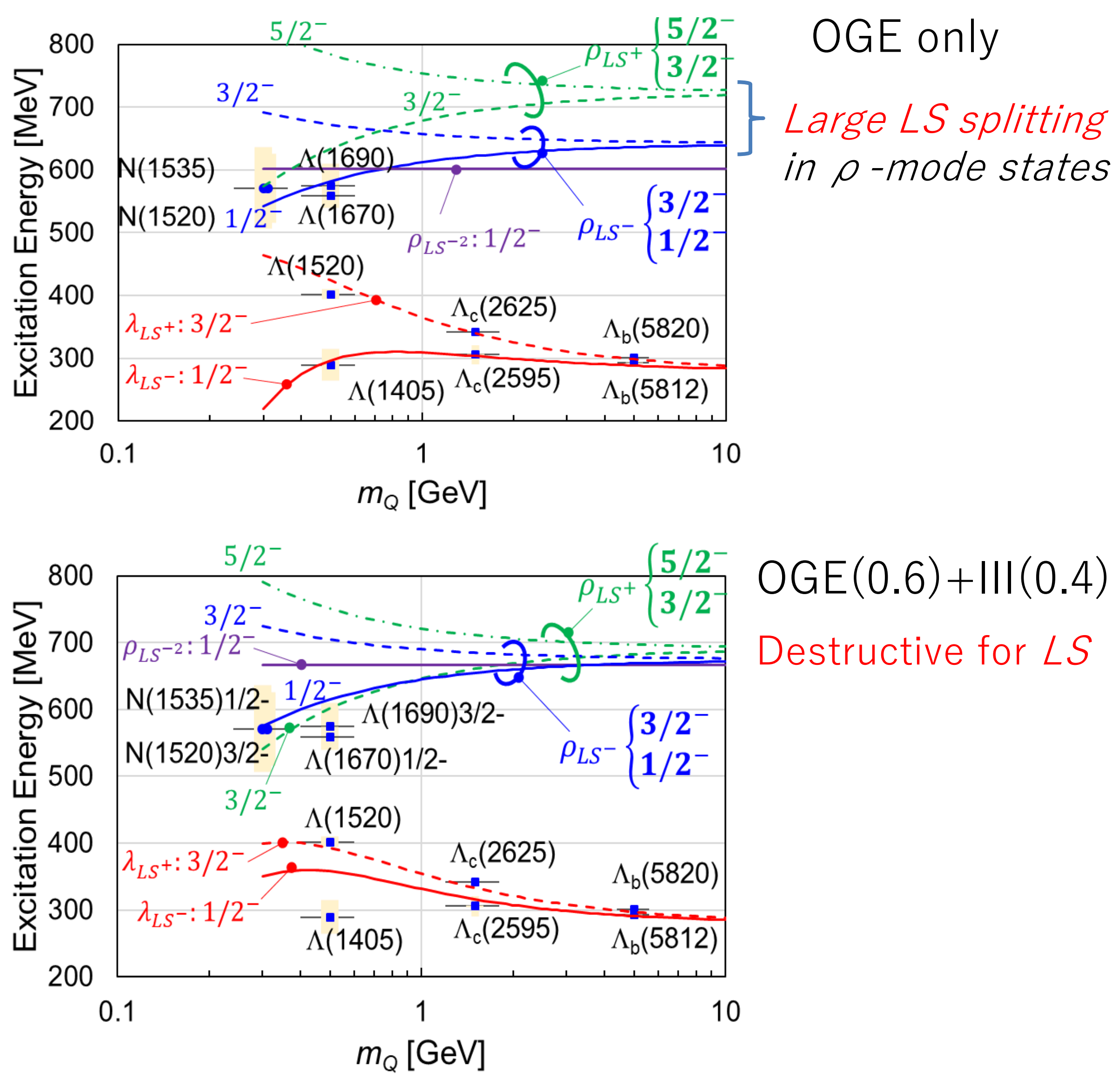


- *ΔM's btw 8tet and 10plet baryons are well explained by the SS int.*
  - *ΔM's btw PS and V mesons as well*
  - *CMI by OGE seems successful.*
  - OGE cannot explain the small LS splitting in N* and finite one in Heavy Baryons
- A cancellation scenario in LS
  - Instanton Induced Int. (III) [KMT int.]
    - 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

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



- *$\Delta M'$s btw 8tet and 10plet baryons are well explained by the SS int.*
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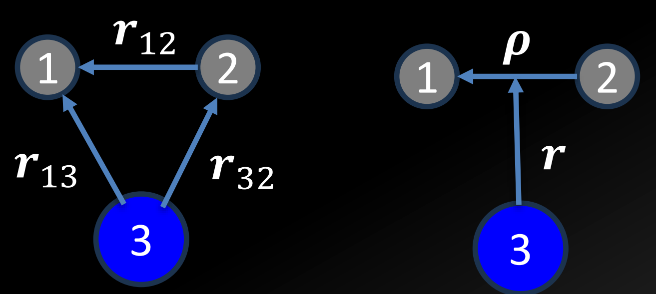
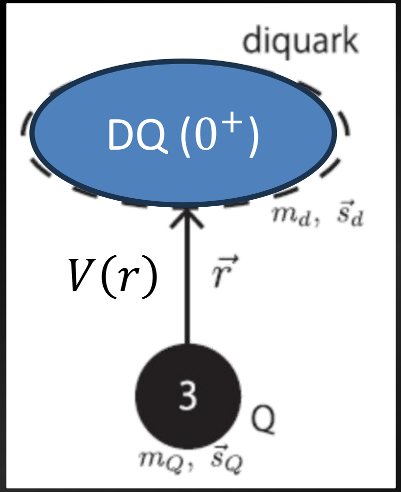
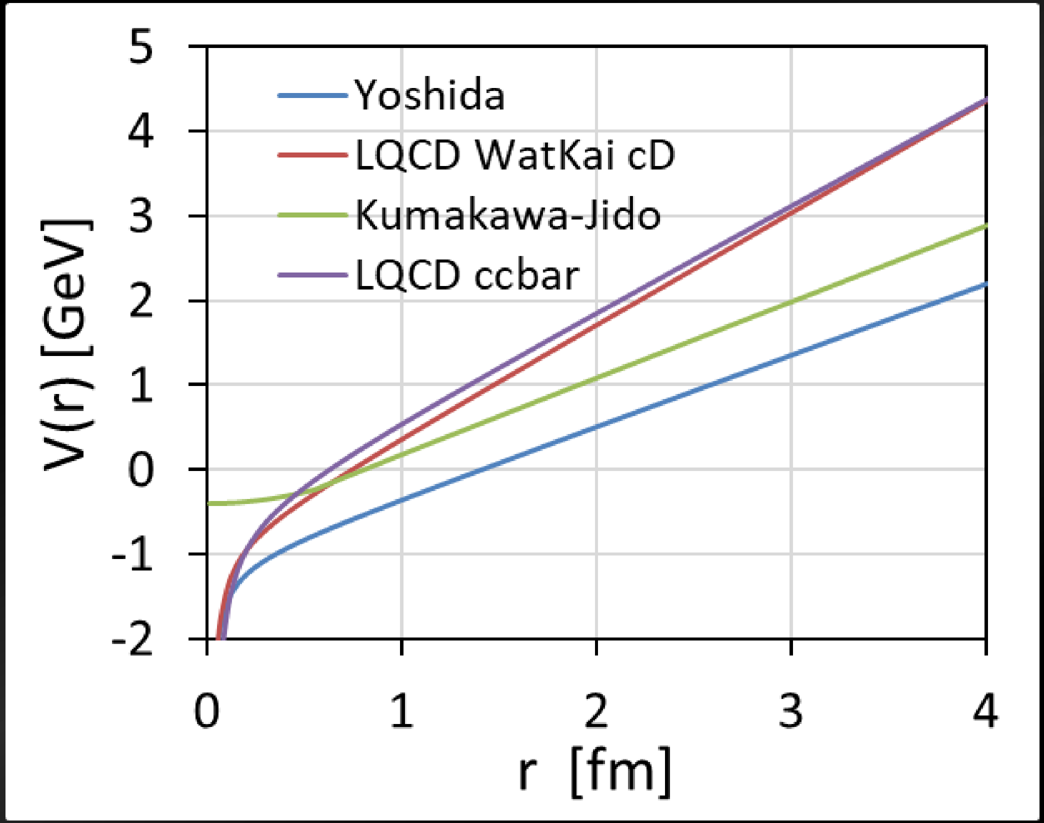
S. Takeuchi, Nucl. Phys. A **642**, 543 (1998).

Color confinement in baryons

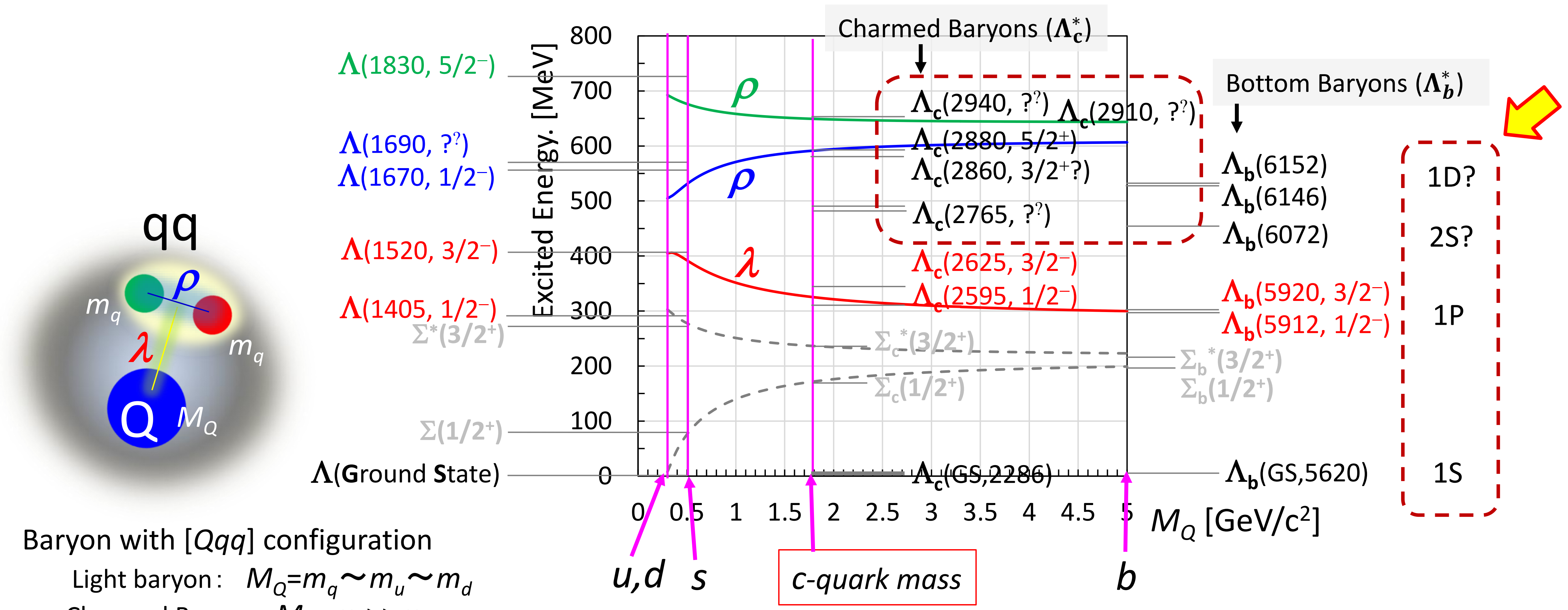
- Cornell potential well describes the spectra of Quarkonia
  - $V(r_{ij}) = A/r_{ij} + \sigma r_{ij}$
- It is a flavor blind interaction, thus would be applicable to baryon spectra…







Recall level structure in singly heavy baryons



Baryon with [Qqq] configuration

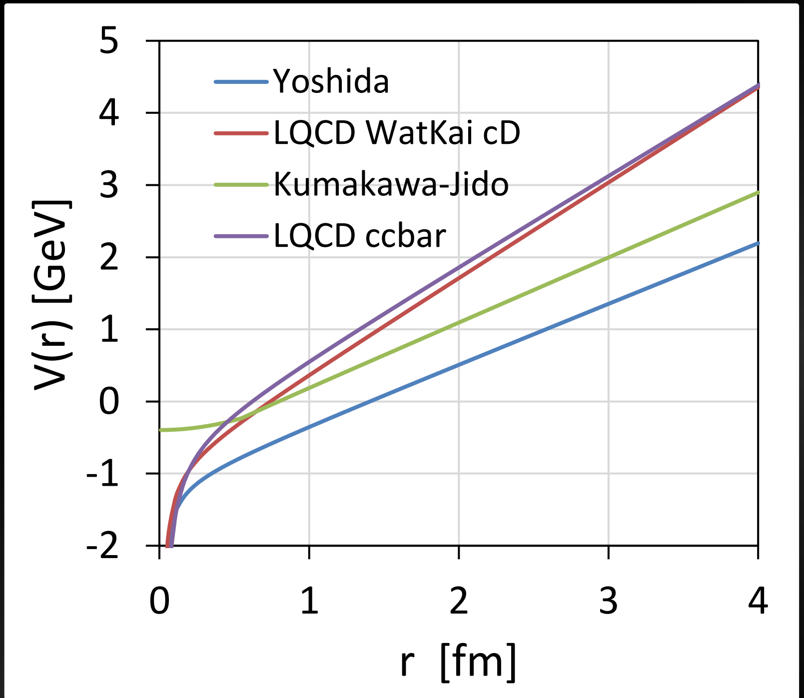
Light baryon: $M_Q = m_q \sim m_u \sim m_d$

Charmed Baryon: $M_Q = m_c >> m_q$

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

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

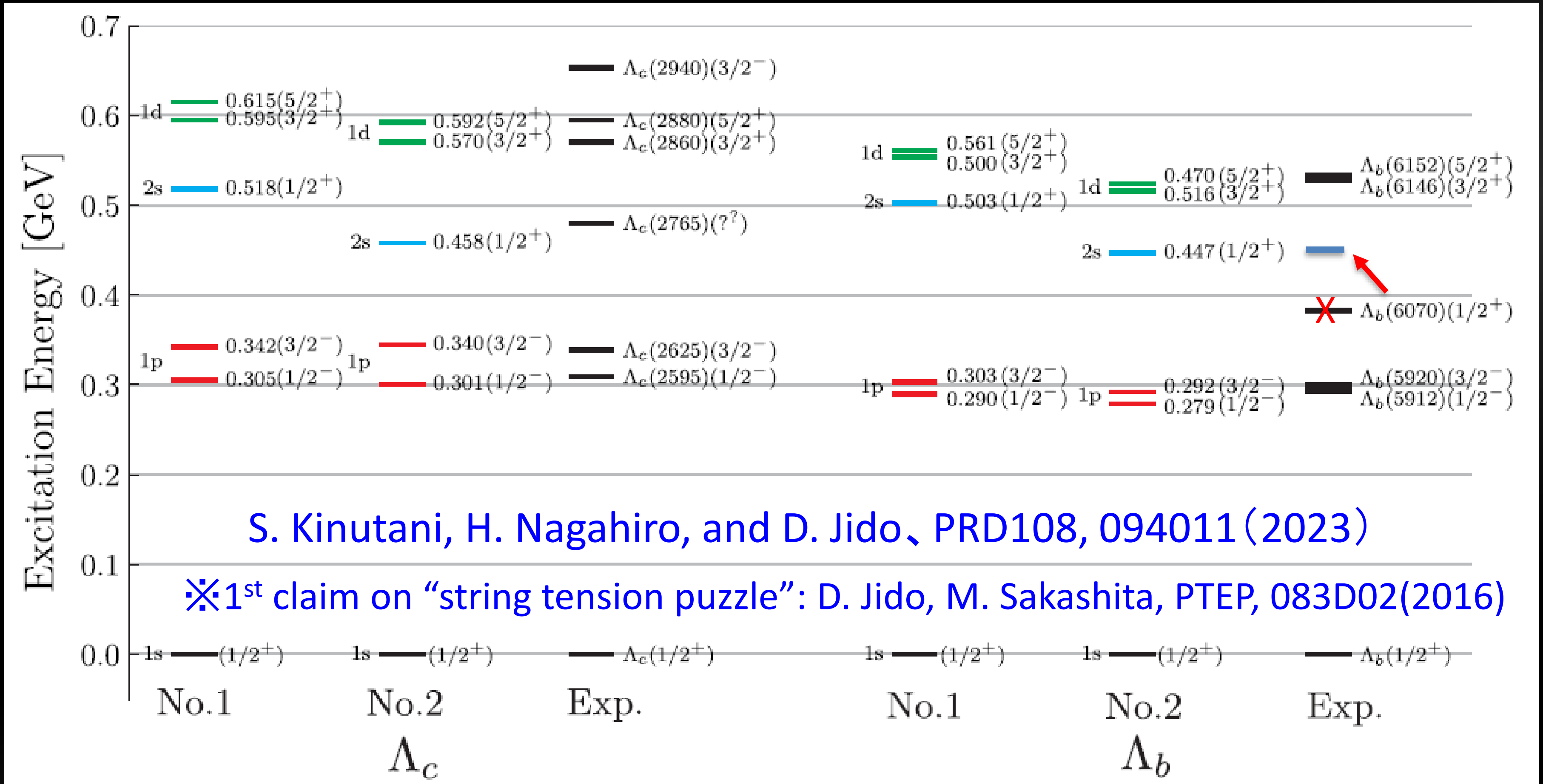
	Yoshida	KJ	Wat. HAL
$4\alpha_s/3, A$ [GeVfm]	0.2686	0.10523	-0.065
σ, B, b [GeV/fm]	0.9	0.9	1.315
ρ [fm]	-	1.1	-
V_0 [GeV]	-1.139	-0.7	-0.889
m_c [GeV] $m_D(2m_q)$ [GeV]	1.7 (0.6)	1.5 0.5	1.77 1.22

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

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

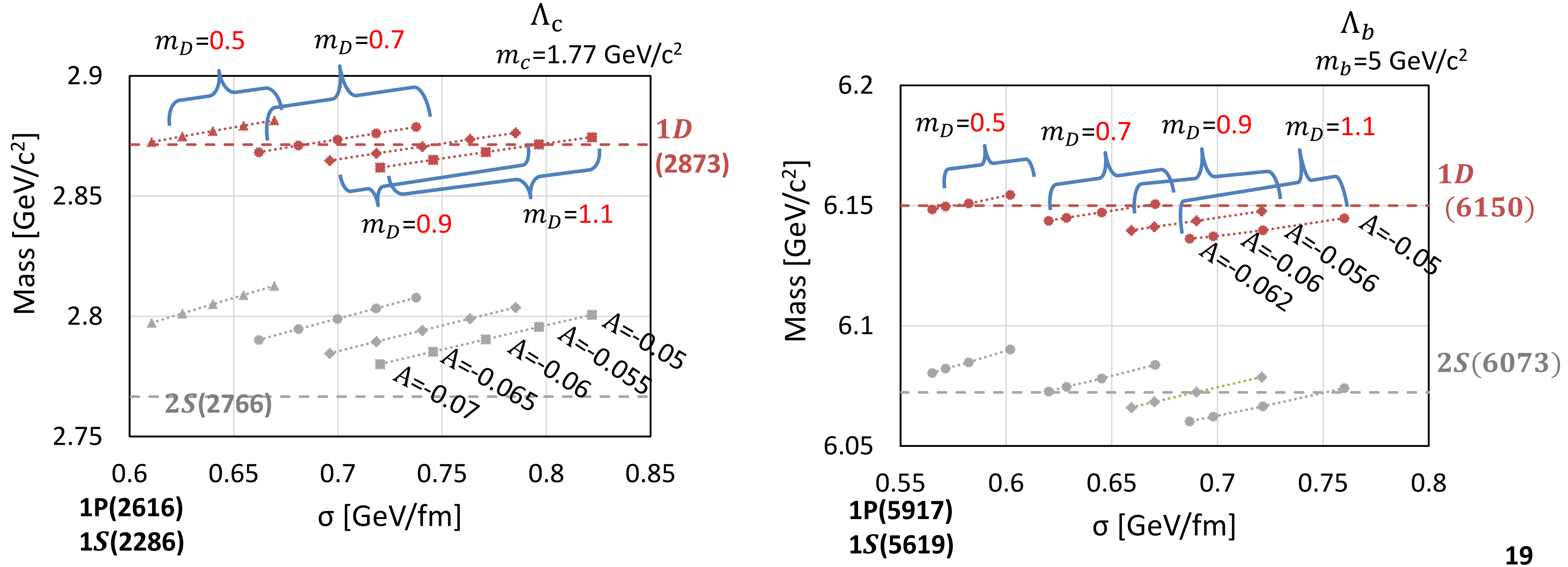


S. Kinutani, H. Nagahiro, and D. Jido、PRD108, 094011（2023）

※1st claim on "string tension puzzle": D. Jido, M. Sakashita, PTEP, 083D02(2016)

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.

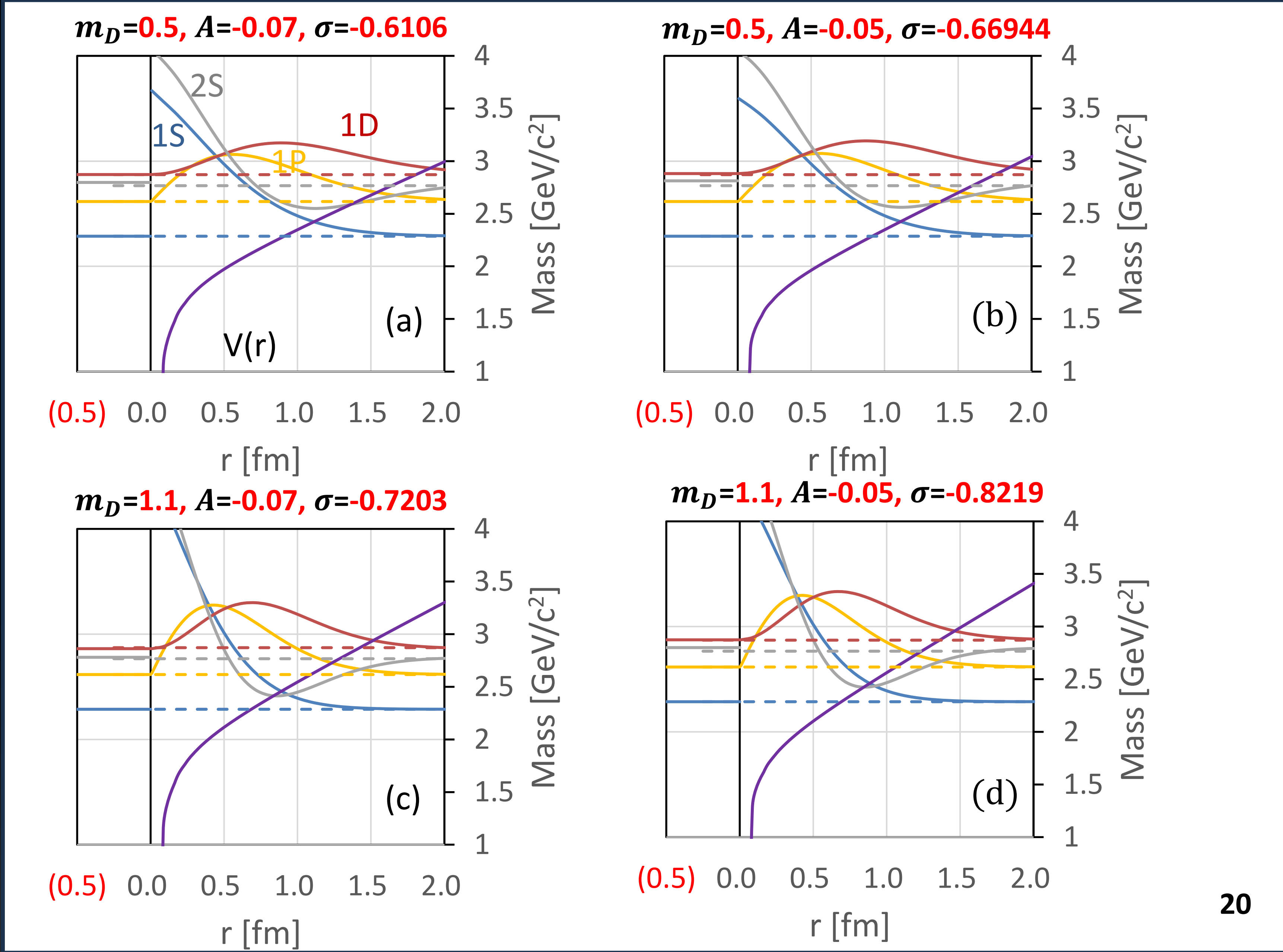


Potential params vs W.F.($\sqrt{\langle r^2 \rangle}$)

	(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

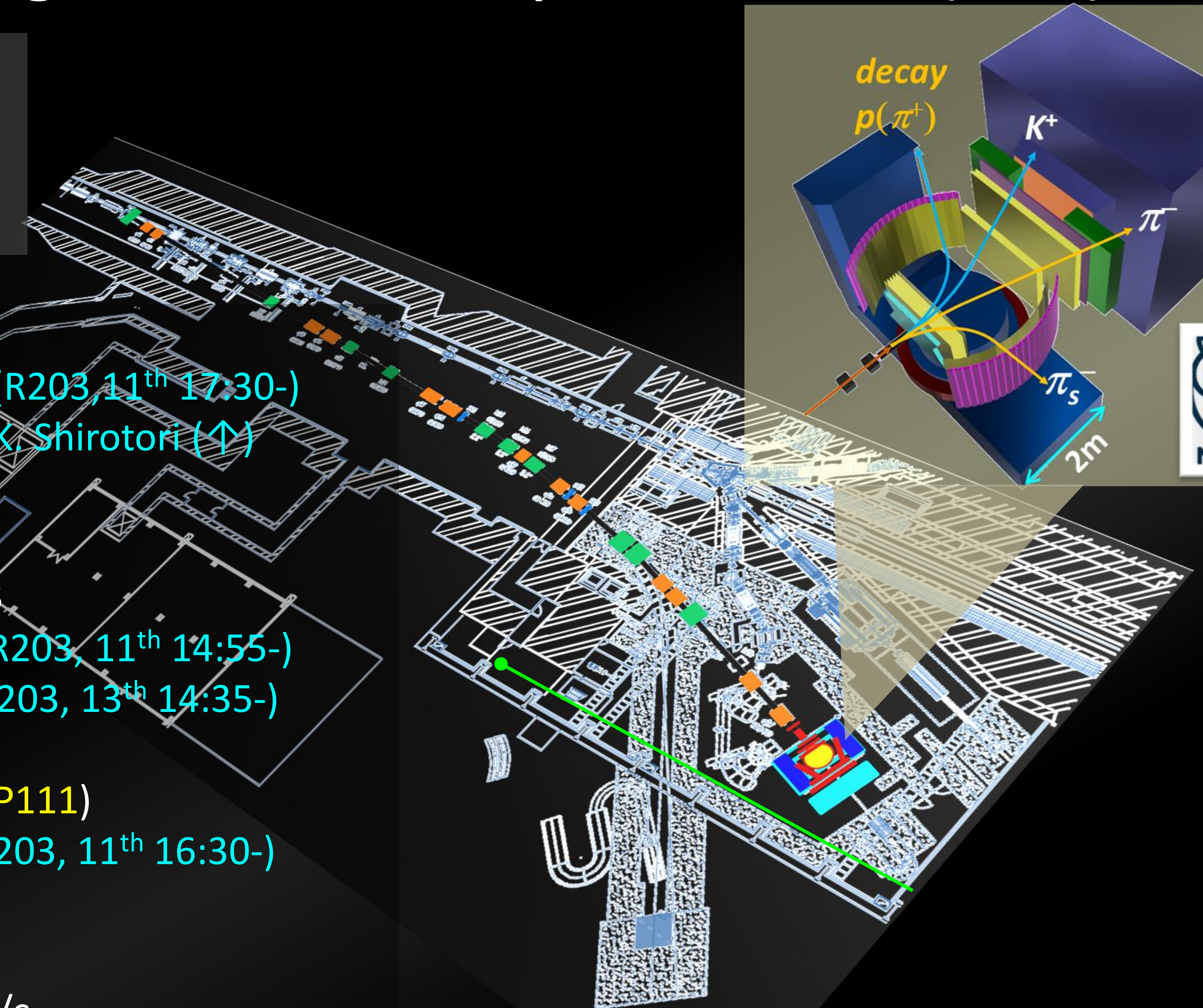
⇒provided from

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



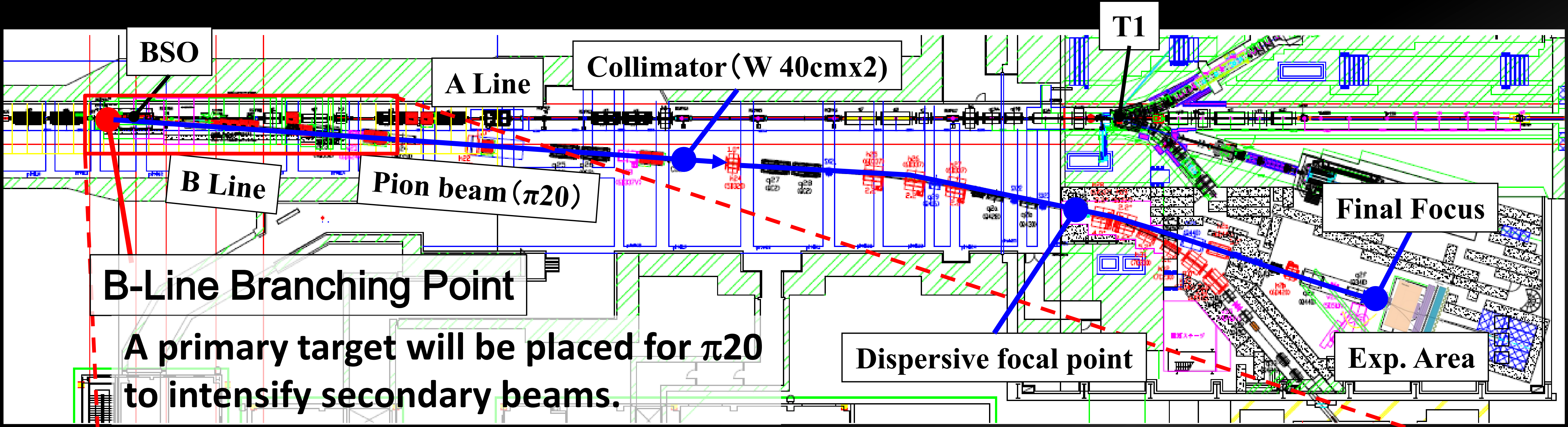
Hadron Physics at the High-mom. 2ndary Beam Line (π20)

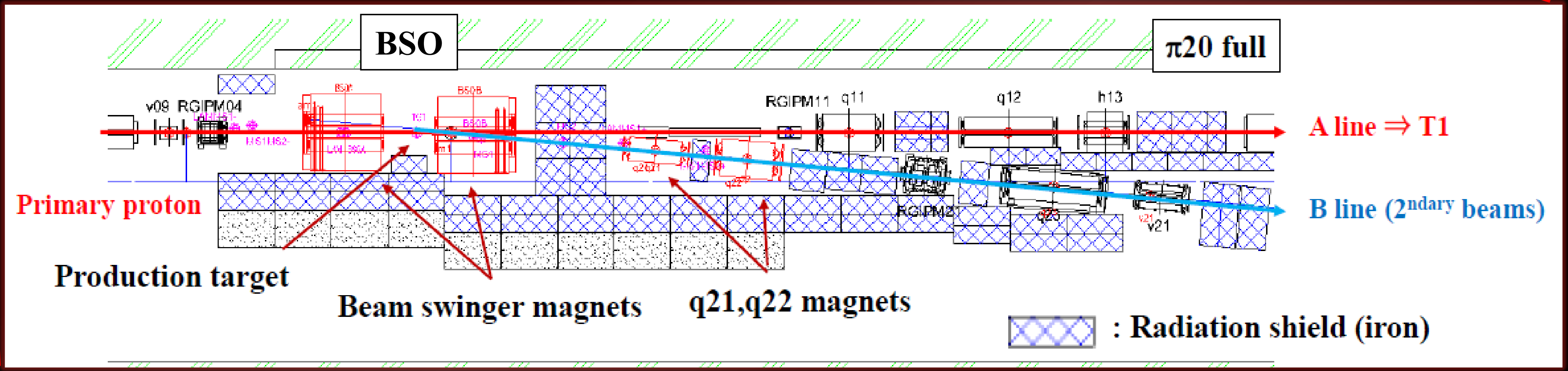
- π20 final specification :
  - 1.0 x 10^7 pions/sec @ 20GeV/c
  - $\Delta p/p$~0.1%



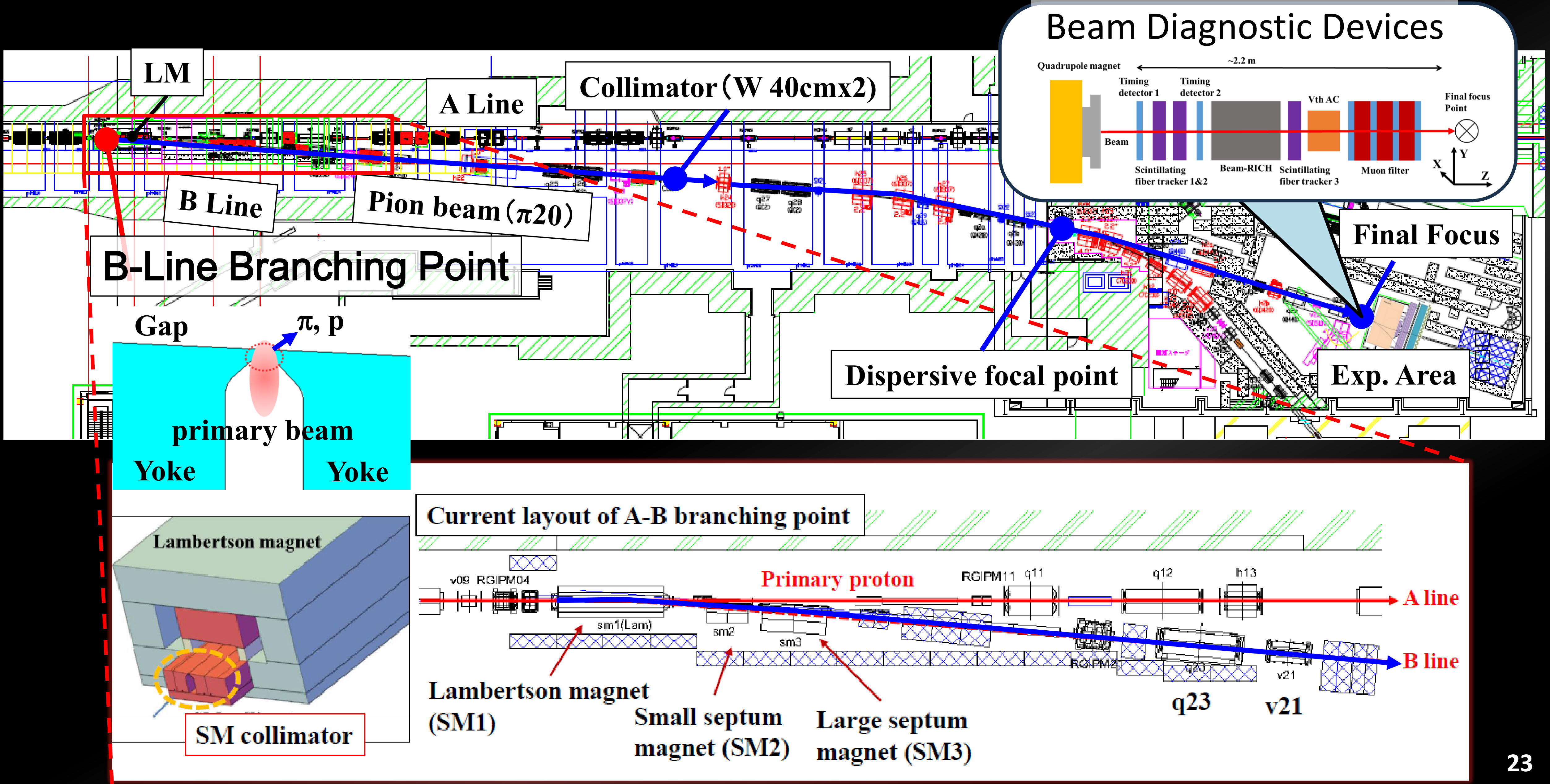
- Spectroscopy of Baryons
  - Charm Baryons (E50) → K. Shirotori (R203,11th 17:30-)
  - Multi-strange Baryons (E97/P85) → K. Shirotori (↑)
  - D_{30} dibaryon (E79)
  - Exclusive Drell-Yan (LoI)
- Exotic systems/Hadron Interactions
  - ϕn interaction (E95) → T. Ishikawa (R203, 11th 14:55-)
  - → A. Higashi (R203, 13th 14:35-)
  - Lambda-N Scattering (LoI)
  - π^-- induced J/ψ prod. near thres. (P111) → S.Y. Ryu (R203, 11th 16:30-)
  - $\bar{p}p \to \bar{Y}Y, \phi\phi, \ldots$
- Application
  - Radiography w/ muons at multi-GeV/c

π20 (Secondary beam mode), final layout



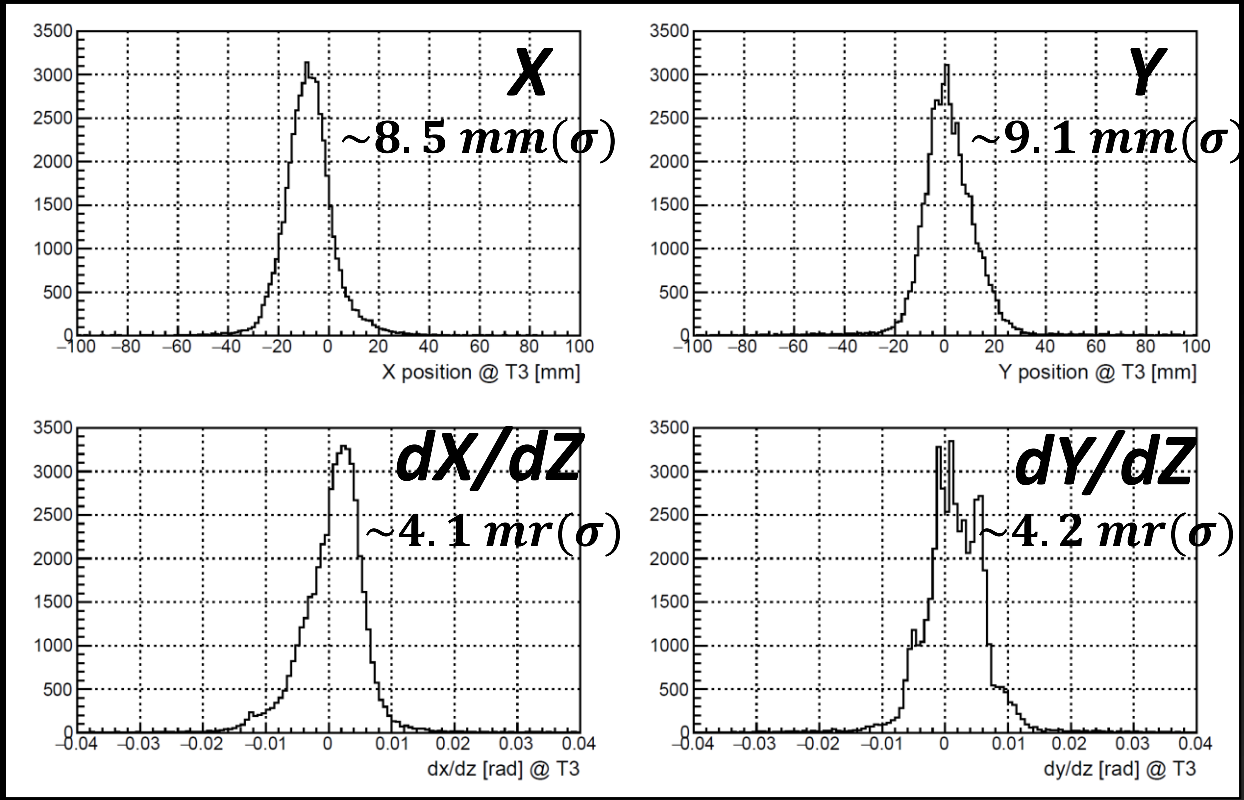


Current Layout：B Line (primary p) & π20-phase 1 (secondary beams)



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

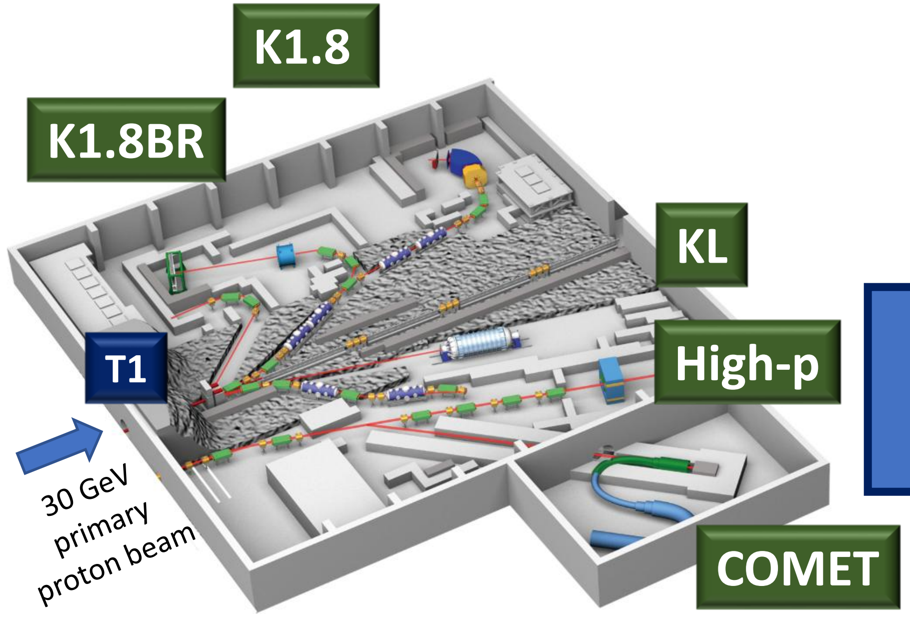
Pion : proton (kaon ignored)

	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

By K. Shirotori

Hadron Experimental Facility extension (HEF-ex) Project

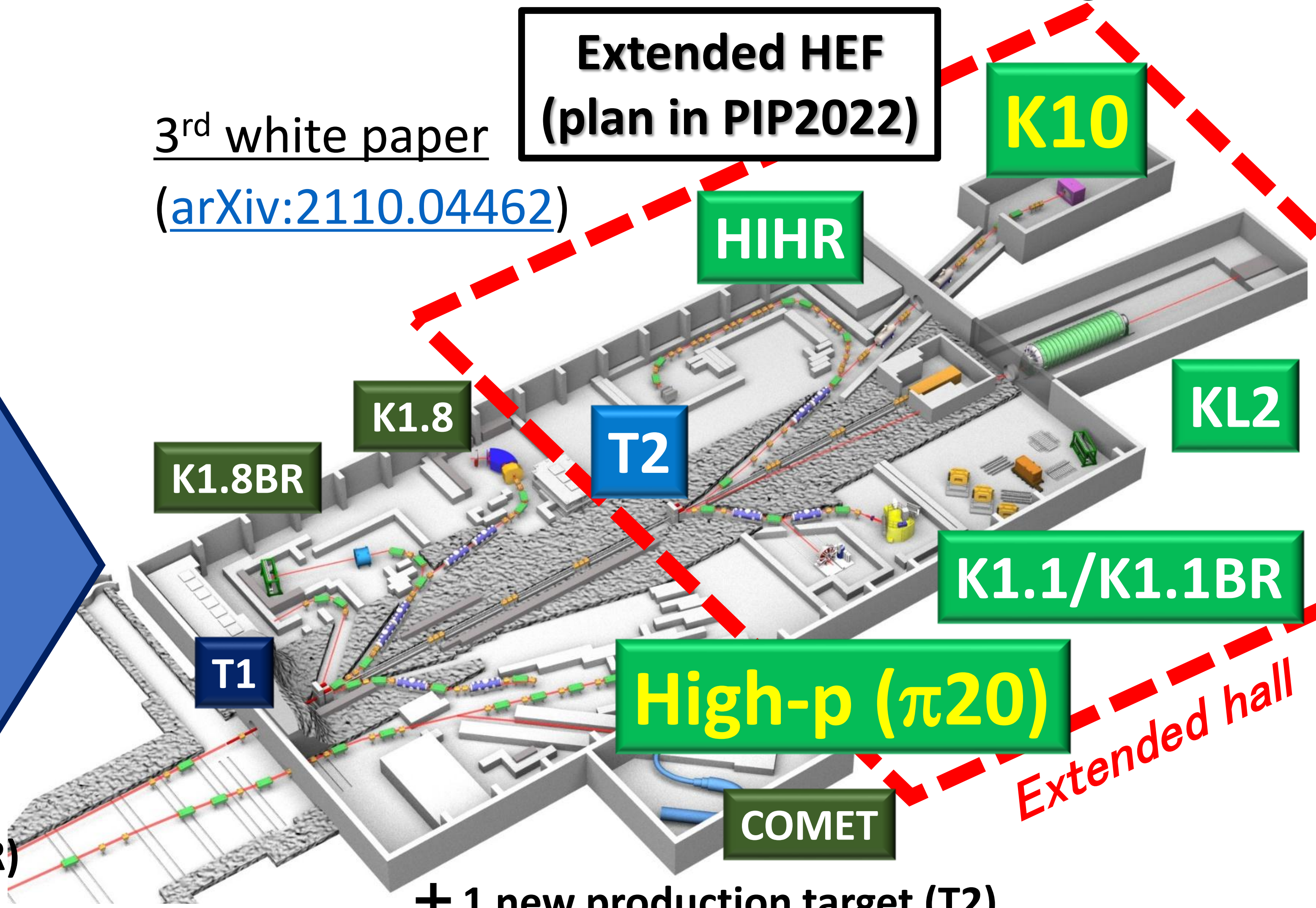
Present HEF (2009～)



1 production target (T1)
1 secondary-charged beamline (K1.8/K1.8BR)
1 neutral beamline (KL)
1 primary beamline (High-p)
1 muon beamline (COMET)

3rd white paper (arXiv:2110.04462)

Extended HEF (plan in PIP2022)



＋1 new production target (T2)
＋4 new beamlines (HIHR, K1.1/K1.1BR, KL2, K10)
＋ 2 updated beamlines (High-p (π20), Test-BL)

Summary

- Spectroscopic study of baryons with heavy flavors reveals quark dynamics in baryons
  - Disentangle motion of heavy quark(s) to the other(s), which is reflected in production rates and decay branching ratios
- The origin of spin-dependent interactions btw quarks is an issue;
  - An effect of non-trivial vacuum of gluon field may affect the LS splitting in excited (singly heavy) baryons
- Confinement force in baryons is an issue;
  - Production cross sections in excited (singly heavy) baryons
- The J-PARC Hadron Exp. Facility provides unique research platforms for hadron physics
  - π20 (phase 1) has been launched, which will boost the HEF extension project.