APCTP Workshop on Nuclear Physics 2022: Physics of Excited Hadrons in the Present and Future Facilities
11-16 July, 2022

Studies of excited baryons with heavy flavors at J-PARC

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2. Spectroscopic Studies of Baryons with heavy flavors
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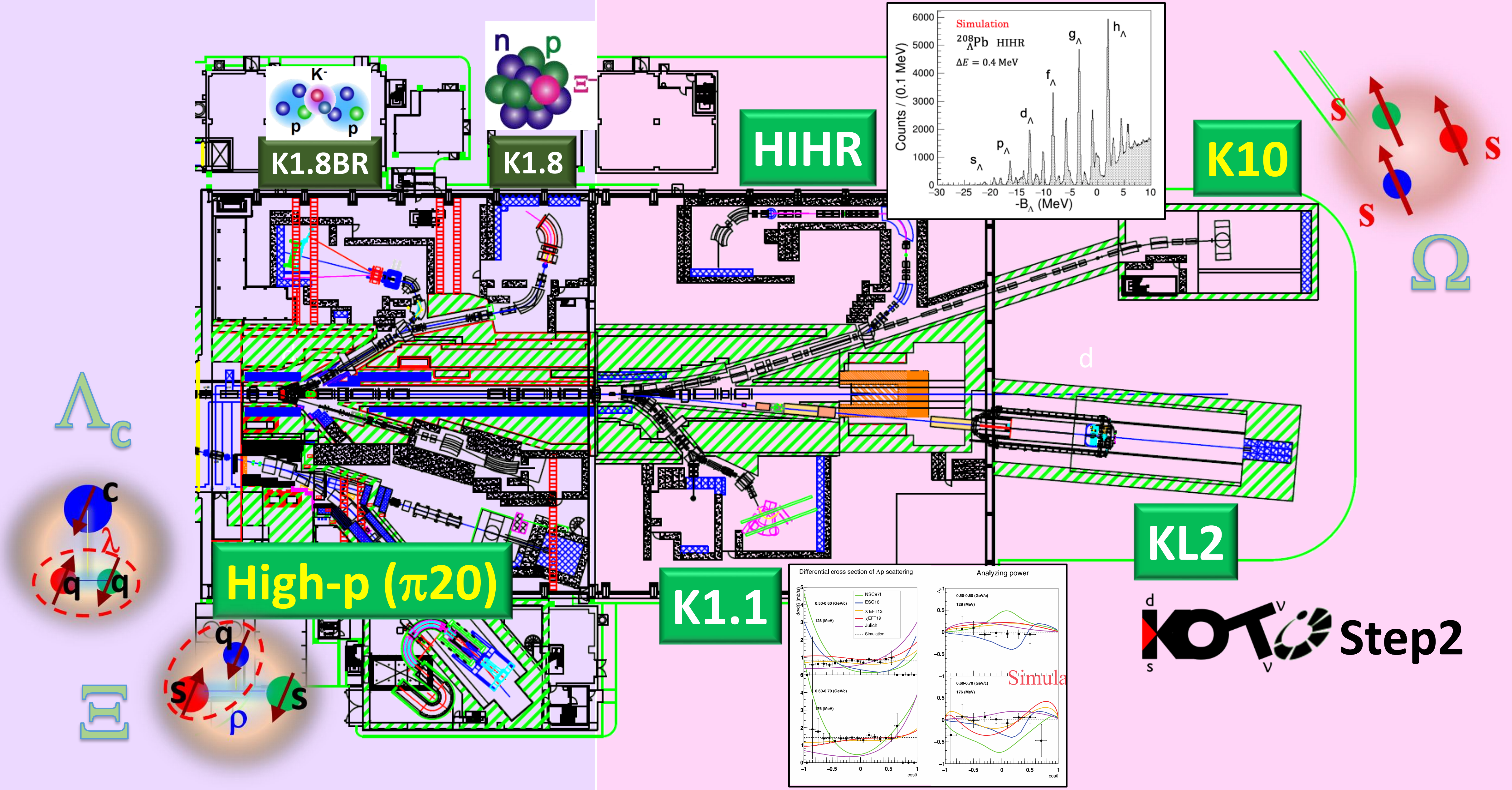
arXiv:2110.04462

Extension of the J-PARC Hadron Experimental Facility
- Third White Paper -

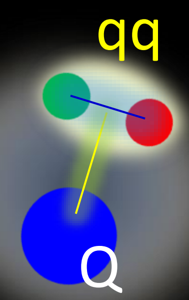
Taskforce on the extension of the Hadron Experimental Facility,

Contents

Current and Extended Hadron Experimental Facility



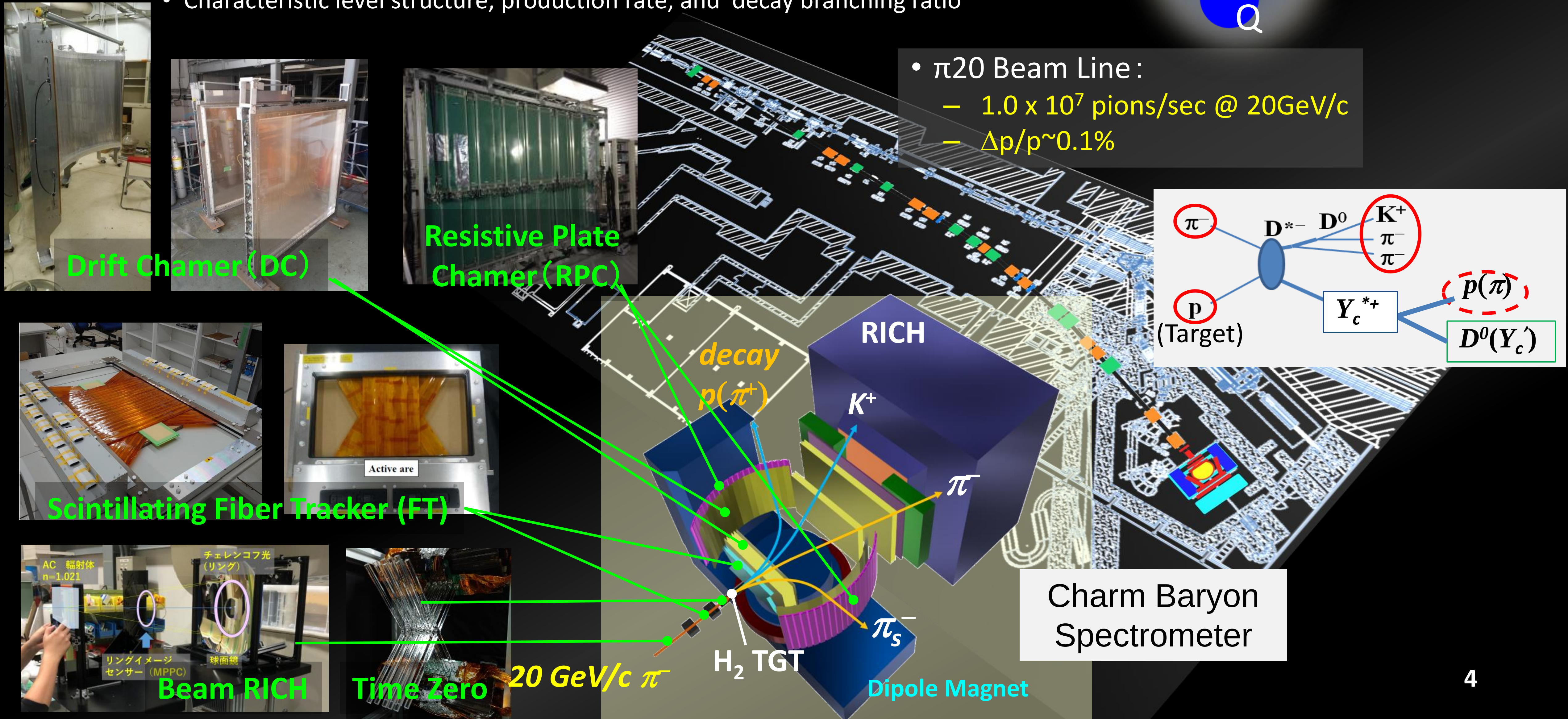
Charm Baryon Spectroscopy at High-p (π20)



Diquark [qq]: an effective degree of freedom to describe hadrons

- [qq] would be singled out by Introducing a Heavy Quark
- Characteristic level structure, production rate, and decay branching ratio

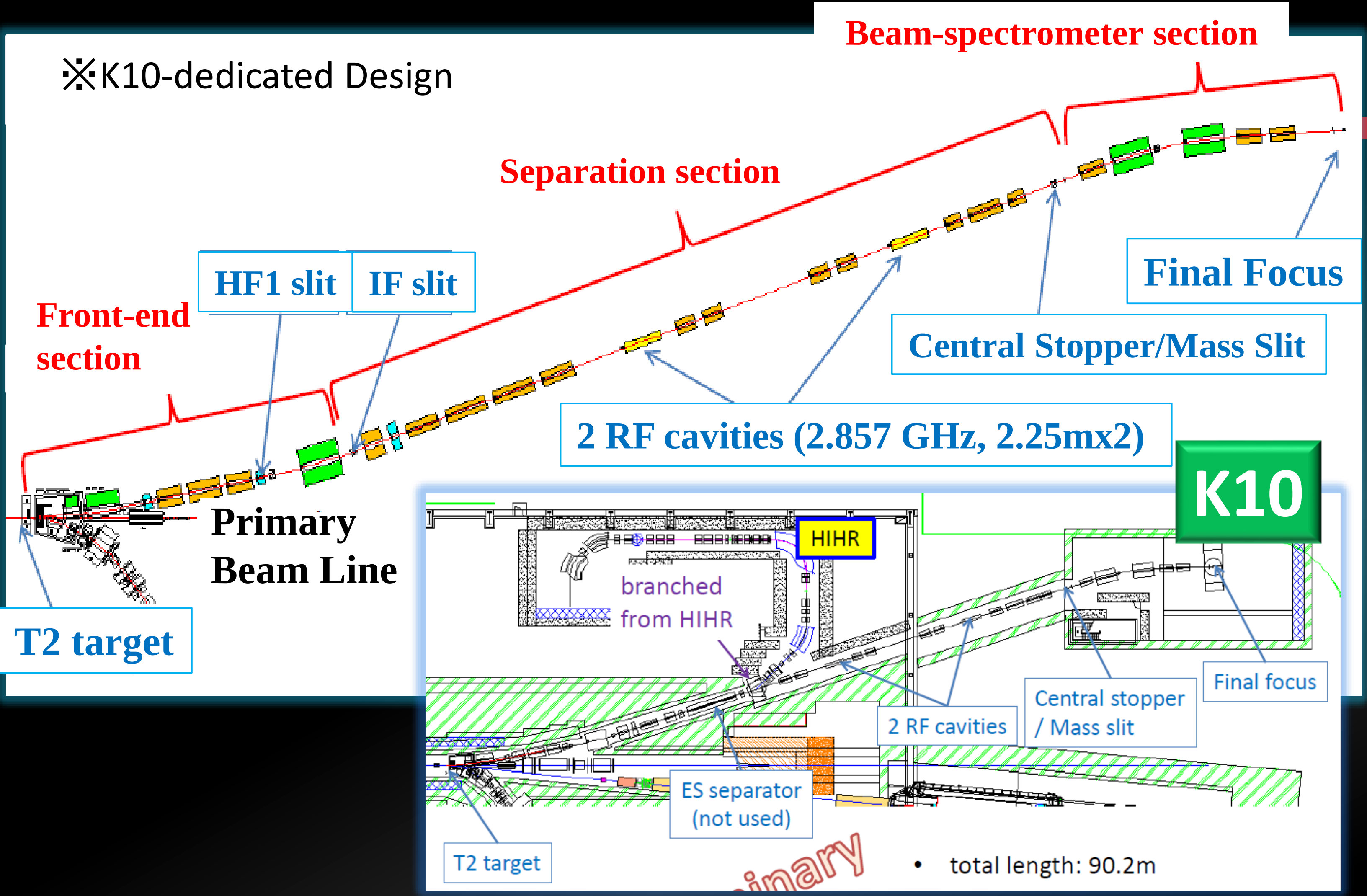
- π20 Beam Line :
  - 1.0×10^7 pions/sec @ 20GeV/c
  - Δp/p~0.1%

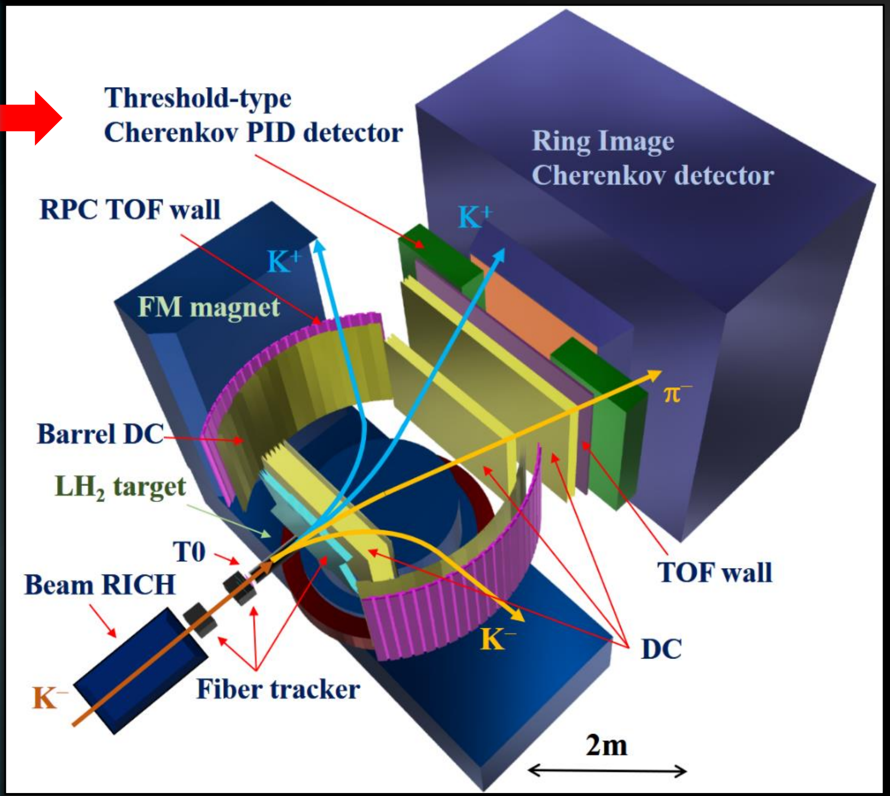


Charm Baryon Spectrometer

Xi/Omega Baryon Spectroscopy at K10

- Intense Kaon Beam: K- 7.9M/spill@8 GeV/c (50-kW p on T2 [Au 66mm])
- RF-separated Kaon Beam: $K^-/\pi^- \sim$ 1:2.1@8 GeV/c (1:2.5@10 GeV/c)





※Design to share upstream w/ HIRH is in progress https://www.kek.jp/ja/assessment/roadmap/

KEK-PIP2022 has been released !

※The Project Implementation Plan (PIP) 2022 was developed as a concrete implementation plan for the realization of the KEK Roadmap 2021, particularly from the viewpoint of funding resources.

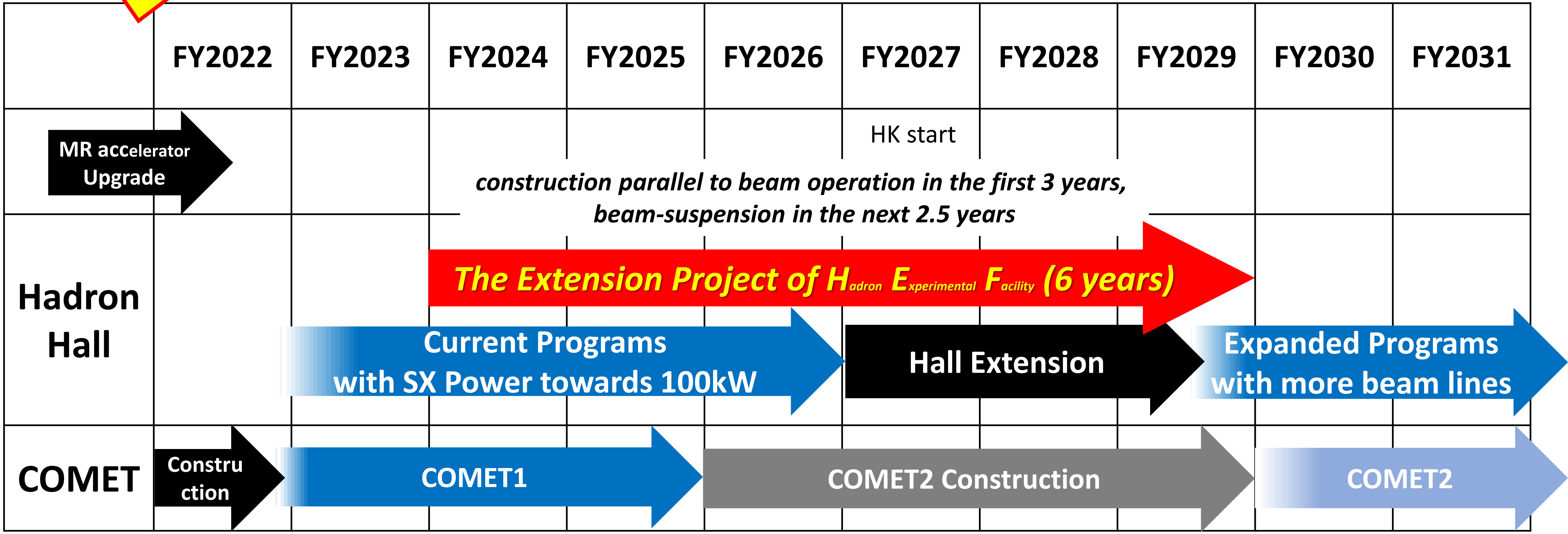
II-1. Extension of the J-PARC Hadron Experimental Facility ⇦ Selected as the Top-Priority Project

In the J-PARC hadron experimental facility, various elementary particle and nuclear experiments are being conducted using kaons and muons obtained from high-intensity protons. The proposed program aims to greatly extend the diversity of research by expanding the hadron experimental facility to increase the energy range, intensity, and momentum resolution of the secondary beams. This project has high scientific significance and international competitiveness in a wide range of sciences, from nuclear and particle physics to cosmology, with unique beamlines and apparatuses. Timely realization of the project will benefit both the international research community and KEK by extending its capability and efficiency in the high-intensity frontier. Because considerable in-kind and personnel contributions in the construction phase are expected from universities and institutes, synchronized cooperation with them will be required to minimize the shutdown period.

Though to funding agency would be tough……

FAQ

Timeline of the Project

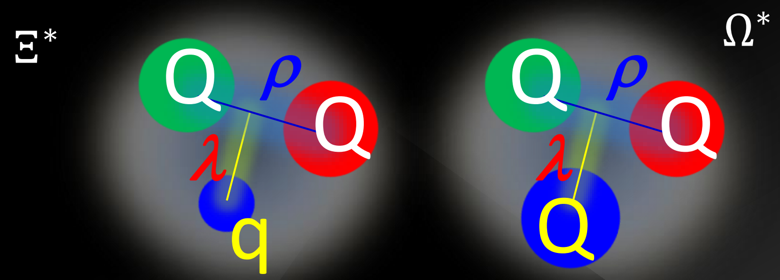


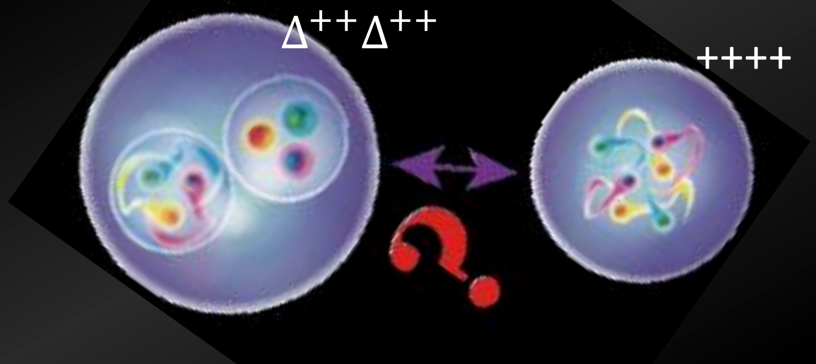
We will start the project in FY2024

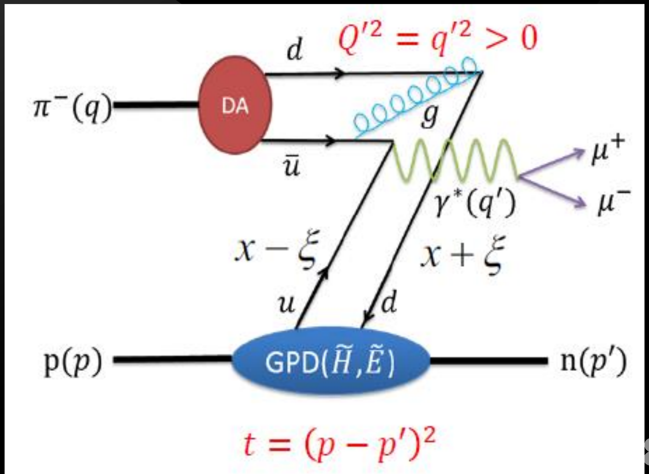
→ We are working on getting the timeline consistent with current programs

Hadron Physics Programs with High-p Beams at J-PARC

- Baryon Spectroscopy
  - $\pi^- p \to D^{*-} Y_c^{*+}$ (E50)
  - $K^- p \to K^* \Xi_{ss}^*$ (LoI:KEK/J-PARC-PAC 2014-4,)
  - $K^- p \to K^{*0} K^+ \Omega_{sss}^{*-}$ (P85)
  - Search for D_{30} Dibaryon State in $pp \to \pi^-\pi^- D_{30}$ (E79)
  - $\pi^- p \to \phi n$ (P… : T. Ishikawa, discussion yesterday)
  - p(π^-,K*)Λ(1405) at large *s*, *t* (to be proposed)
- Hadron Tomography
  - Exclusive DY, $\pi^- p \to \mu^- \mu^+ n$ (LoI: KEK/J-PARC-PAC 2019-7)
- For Strangeness Nuclear Physics
  - Λp Scattering for the study of high-dense nuclear matter (LoI: KEK/J-PARC-PAC 2020-08)
- For Neutrino Physics
  - Hadron Production for neutrino beams

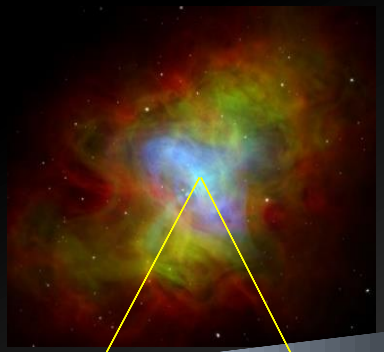
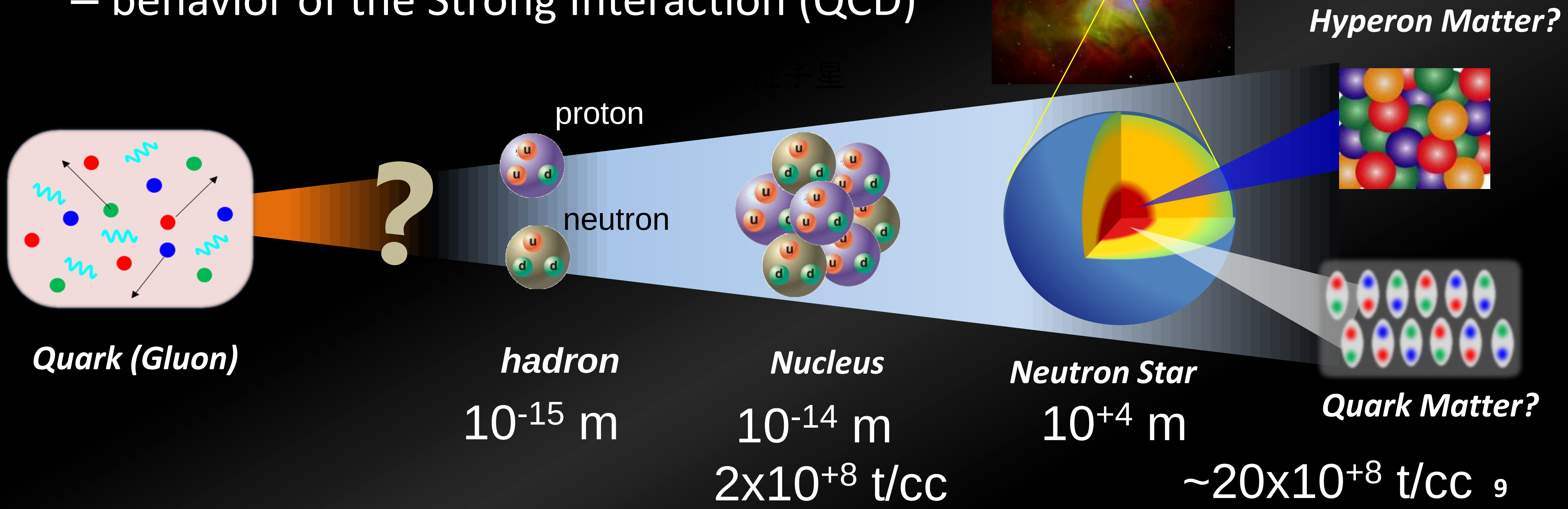






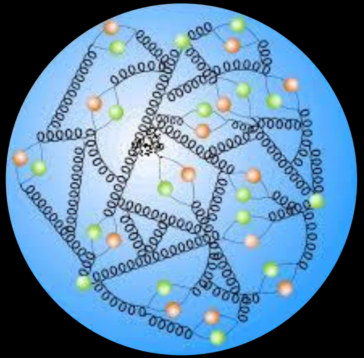
Matter Evolution in the Universe

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

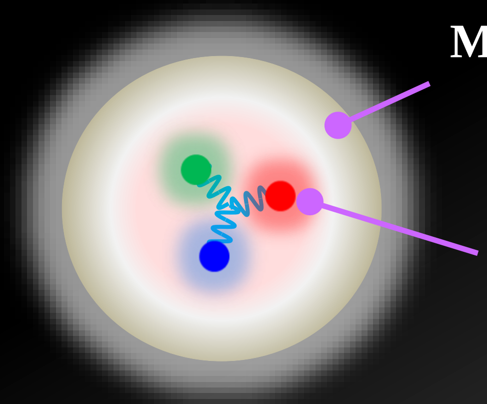
Issue: How does QCD build baryons?

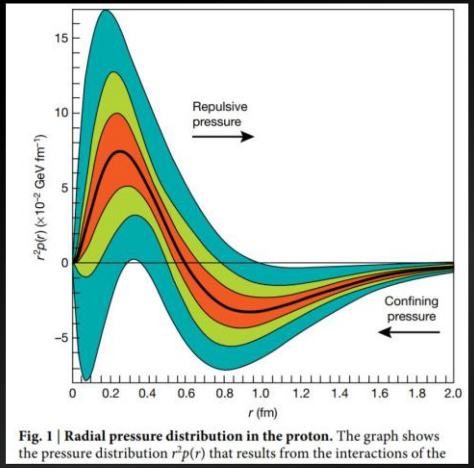
High *E*
perturbative



$\alpha_s = \infty$
at Λ_{QCD}

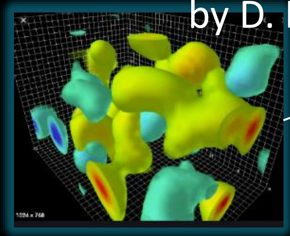
Low *E*
non-perturbative



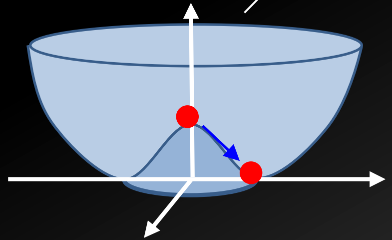


Nature 557, 396 (2018)

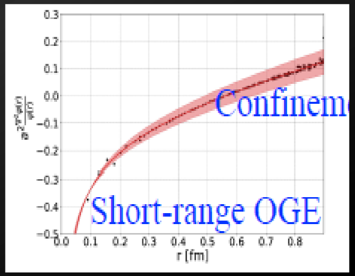
Instanton (LQCD demo. by D. Leinweber)



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

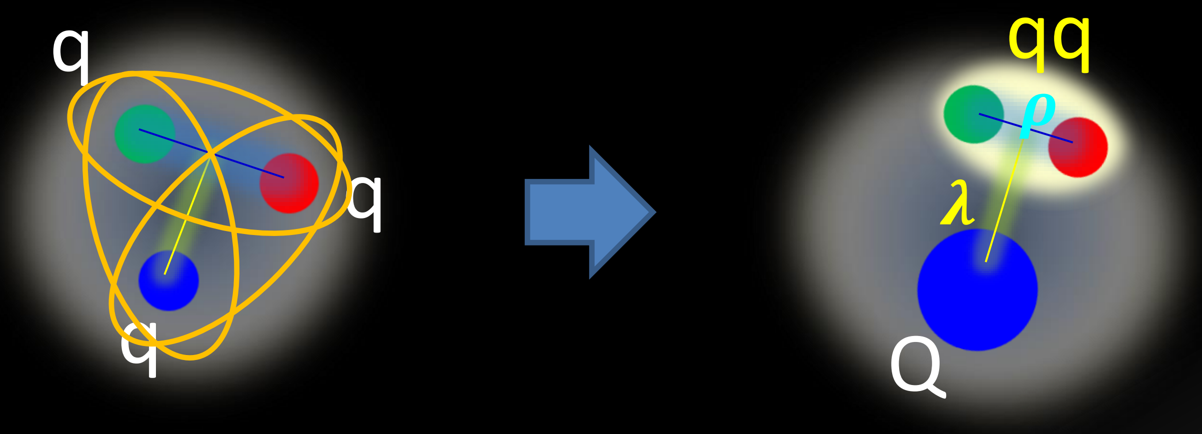


Eff. DoF emerge:
Dynamical mass gene.
NG bosons (pion, …)



Q-Diquark Pot. in LQCD cal.

Roles of Heavy Quark: *to see dynamics of EoF*



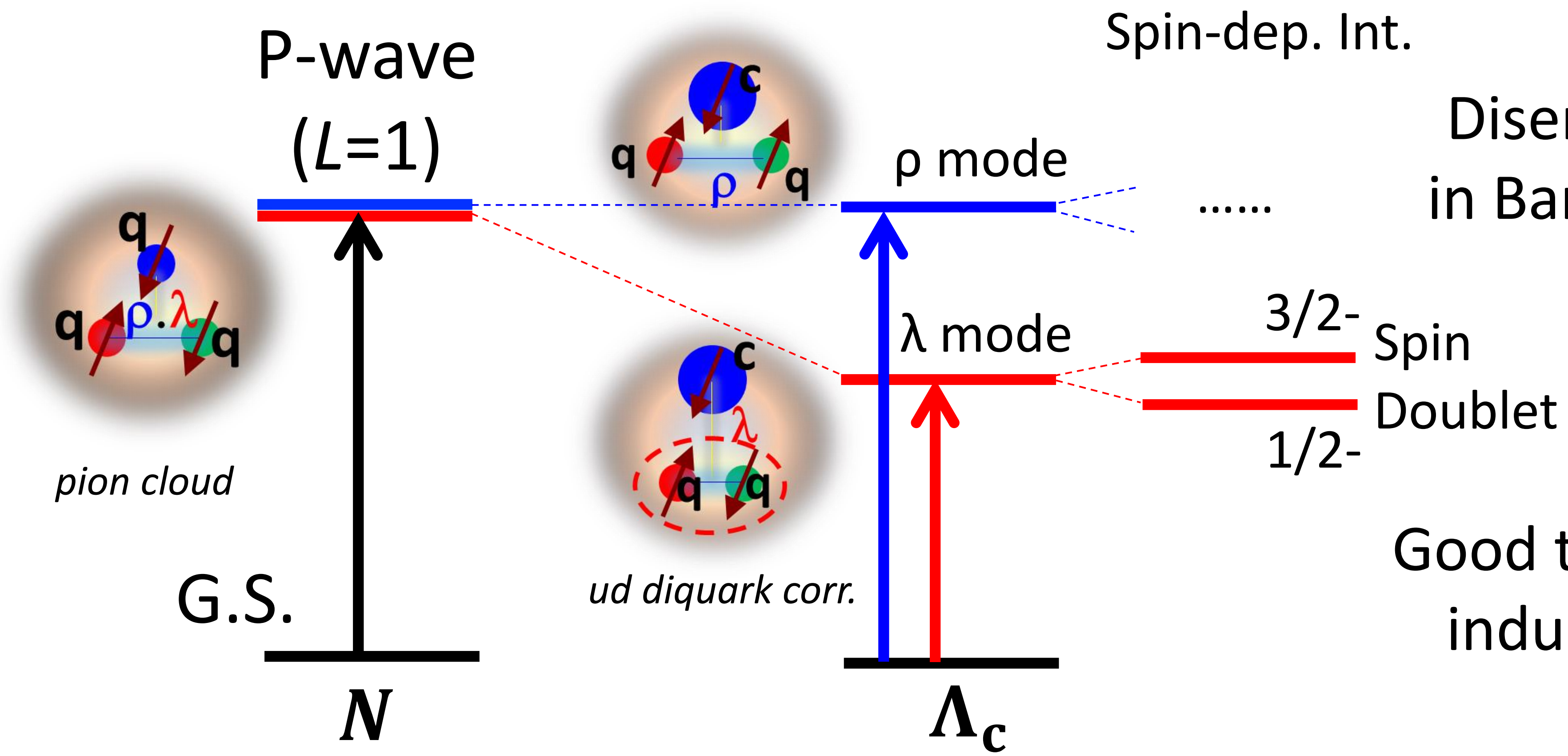
$$V_{CMI} \sim [\alpha_s/(m_i m_j)]*(\lambda_i,\lambda_j)(\sigma_i,\sigma_j)$$
$$\to 0 \text{ if } m_{i,j} \to \infty$$

$$\underset{[qq]}{V_{CMI}(^1S_0, \bar{3}_c)} = 1/2 * \underset{[\bar{q}q]}{V_{CMI}(^1S_0, 1_c)}$$

- 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 EoF

※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.

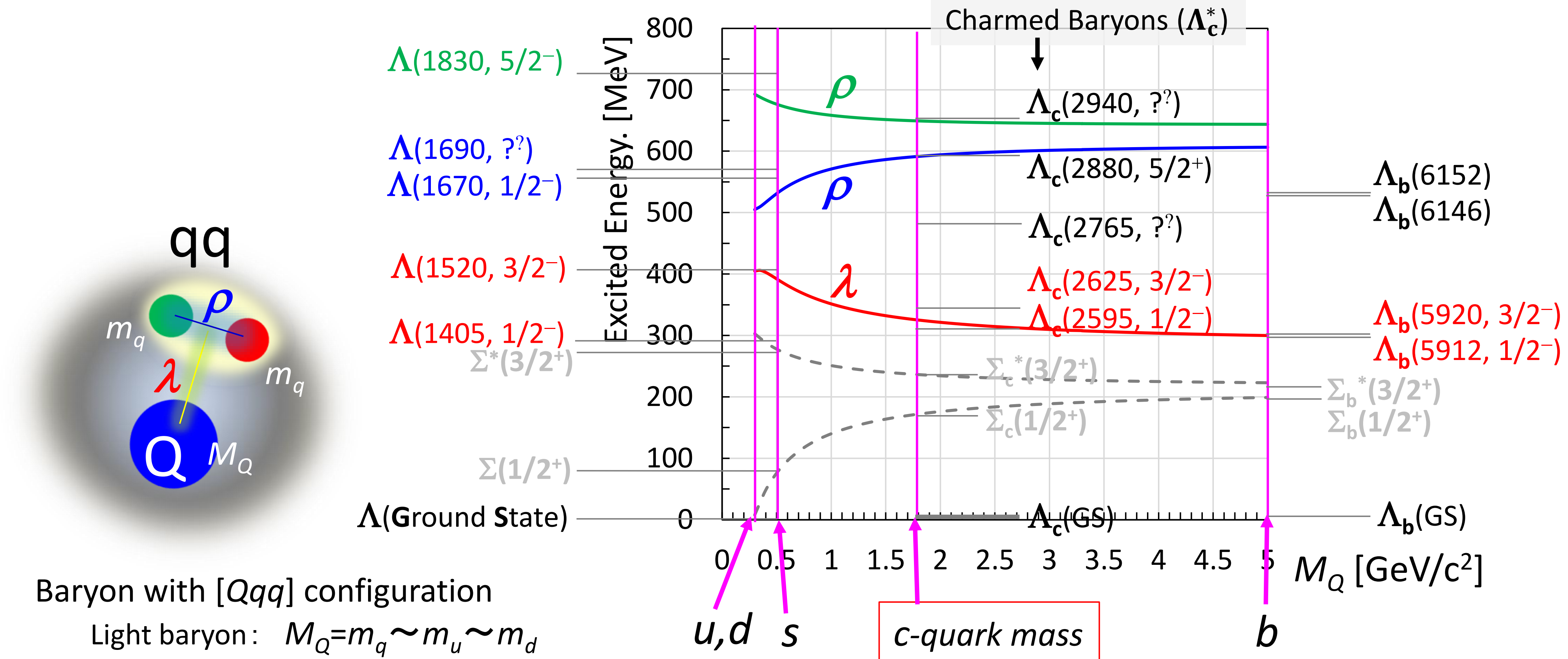
T. Yoshida, E. Hiyama, A. Hosaka, M. Oka, K. Sadato, Phys. Rev. D**92** (2015) 114029

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

Effect of the Isotope Shift

Quark Model Calculation (curves) for Excitation Energy Spectra as a function of Heavy quark mass (M_Q)

※Mass/spin/parity of Λ, $Λ_c$, $Λ_b$ observed so far are shown below : Their excitation modes (internal structure) to be clarified



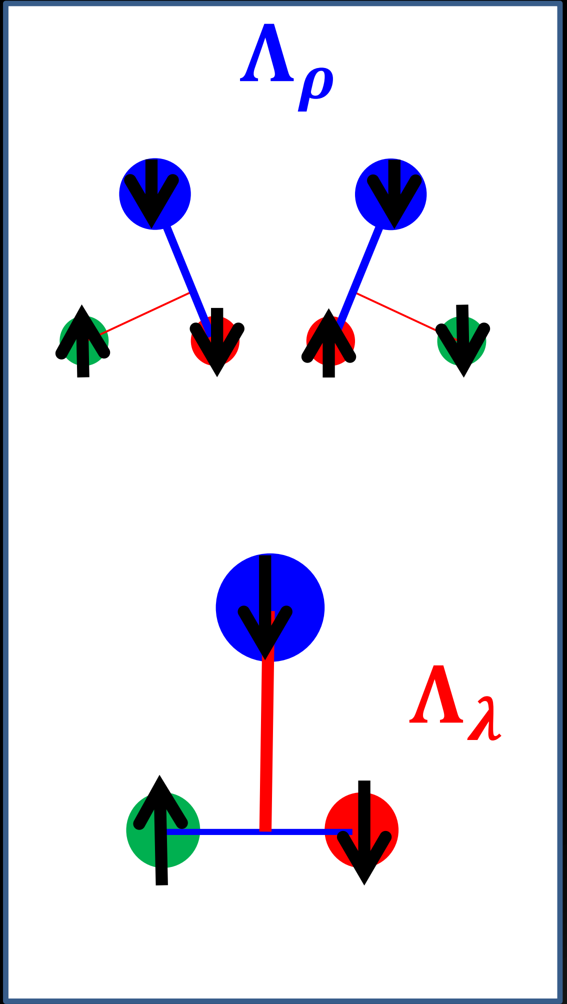
Baryon with [*Qqq*] configuration

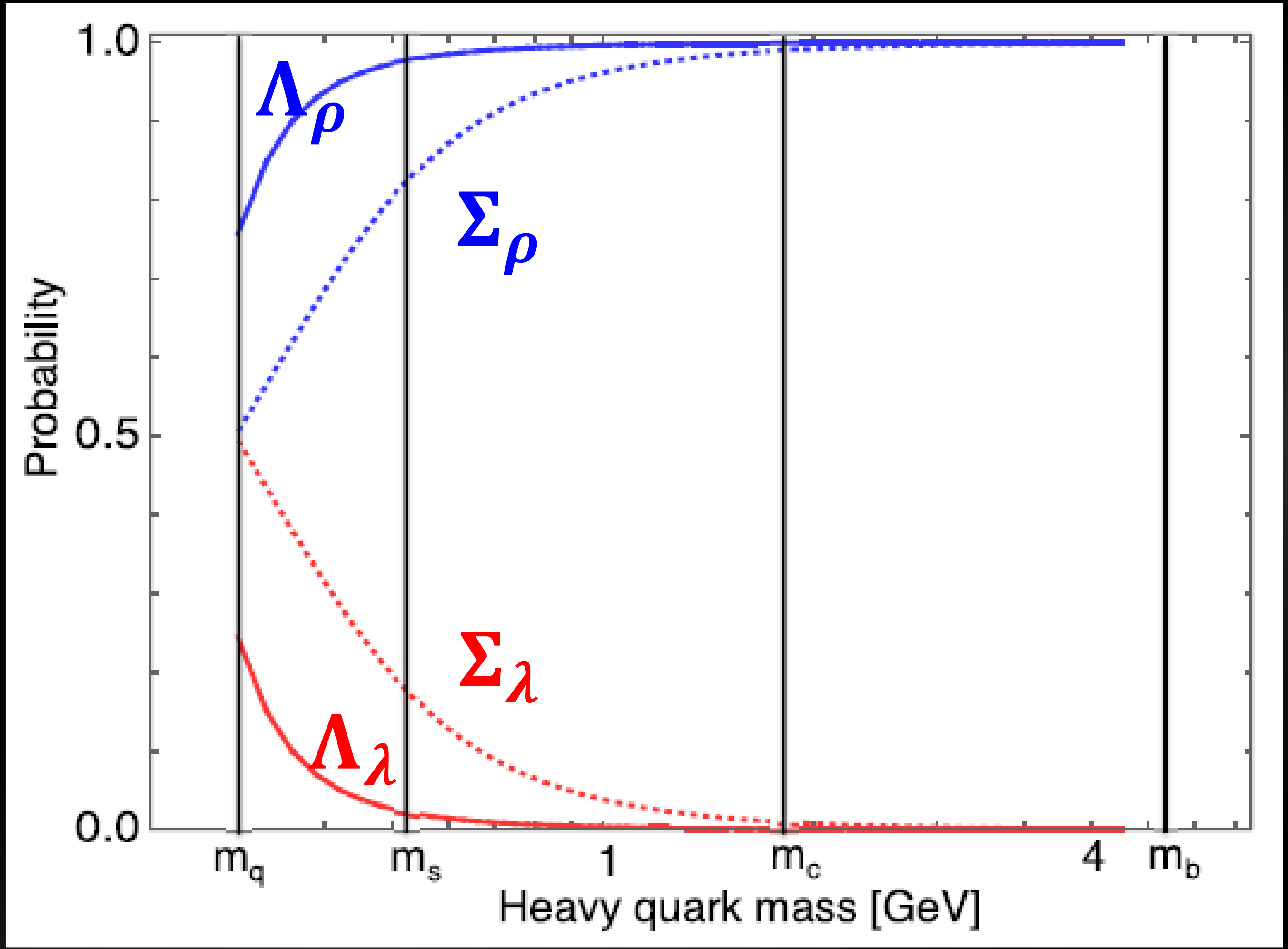
Light baryon : $M_Q = m_q \sim m_u \sim m_d$

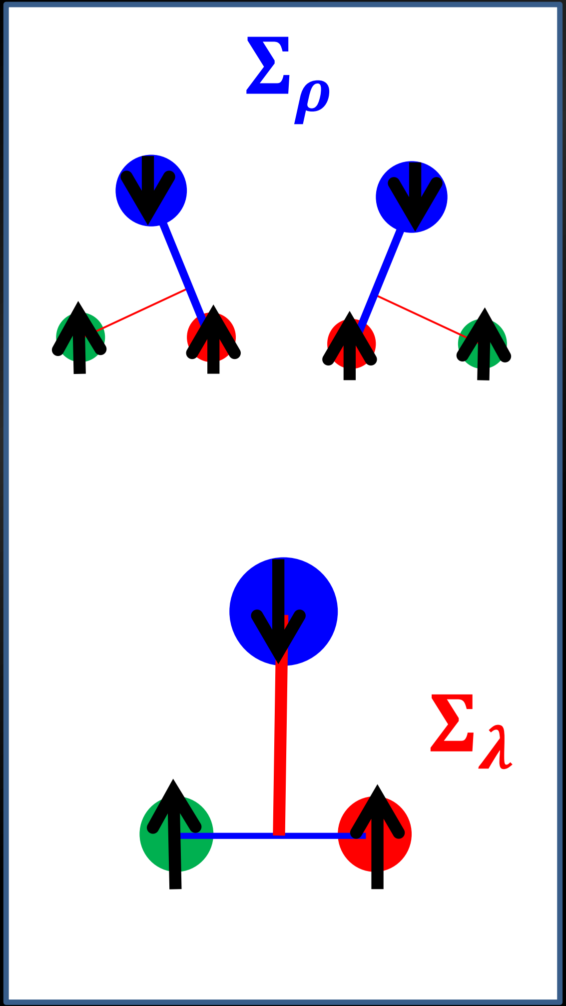
Charmed Baryon : $M_Q = m_c >> m_q$

※Further understanding of baryon structure though systematic change of the excitation modes in different flavors

ρ, λ-mode separation w/ a "Heavy" Quark is excellent. (s-quark is "heavy" enough!)

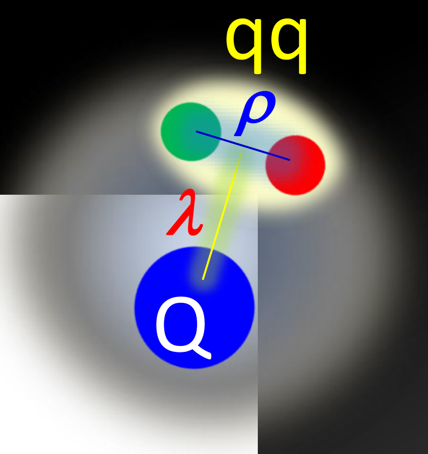


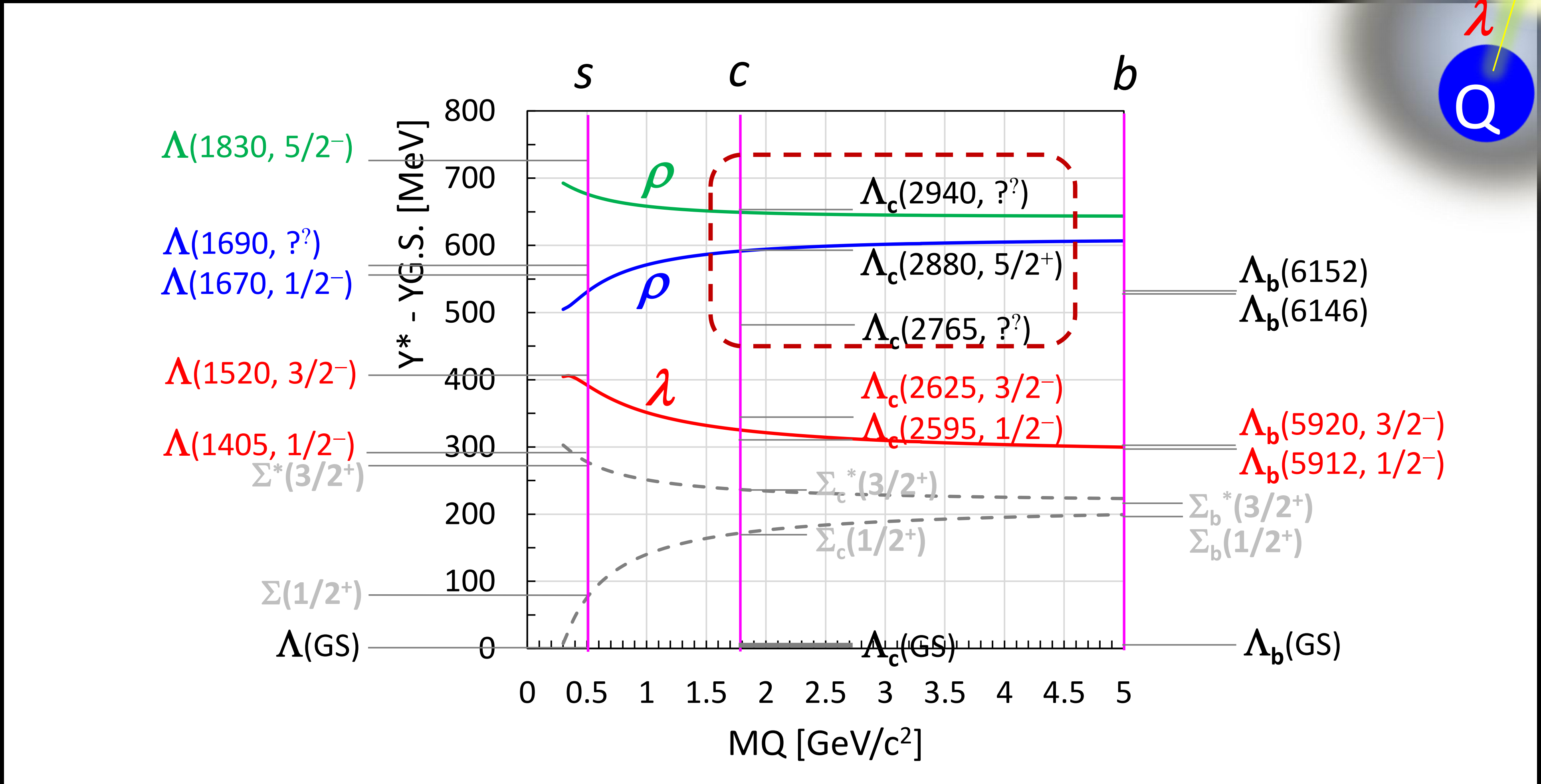




T. Yoshida et al., Phys. Rev. D**92**, 114029(2015)

Lambda Baryons (LS averaged)

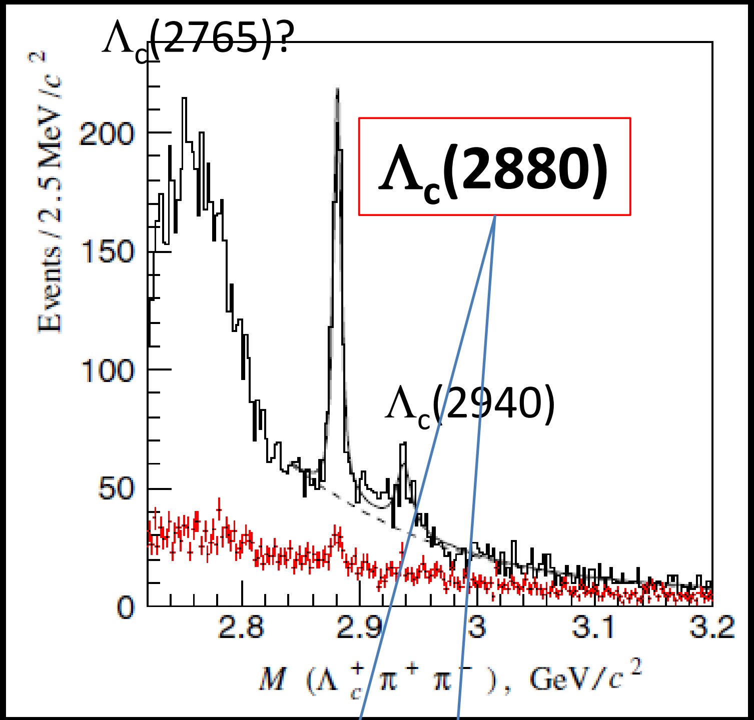


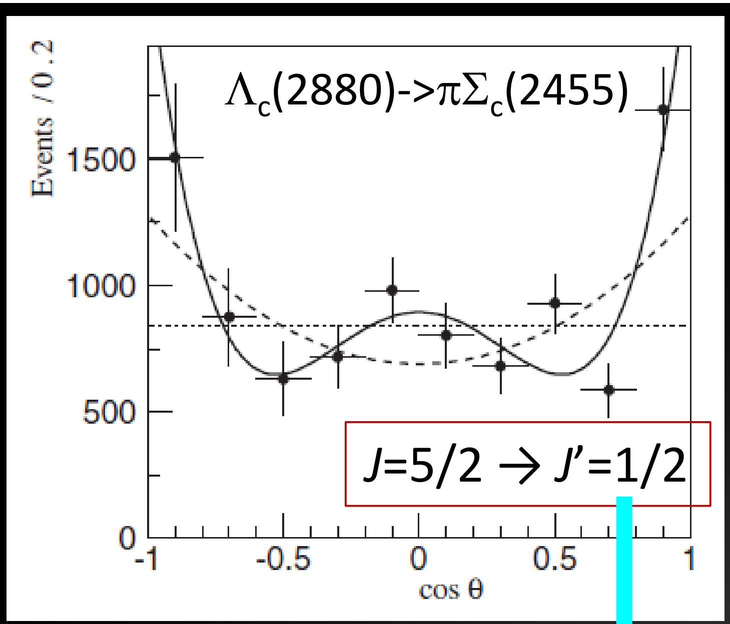


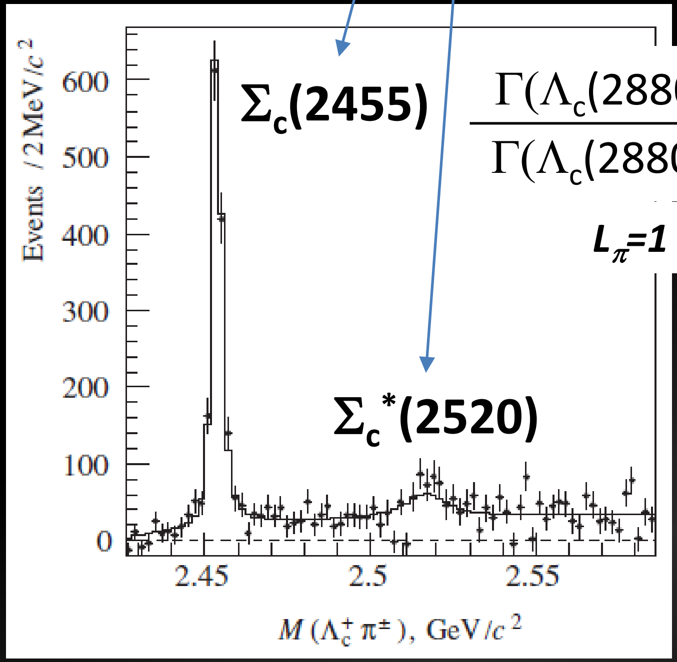
non-rel. QM: $H=H_0+V_{conf}+V_{SS}+V_{LS}+V_T$
ρ–λ mixing (cal. By T. Yoshida)

T. Yoshida et al.,
Phys. Rev. D**92**, 114029(2015)

Lc(2880)Belle, PRL98, 262001('07)







$$\frac{\Gamma(\Lambda_c(2880)\to\pi\Sigma_c^*(2520))}{\Gamma(\Lambda_c(2880)\to\pi\Sigma_c(2455))} = \mathbf{0.23}$$

L_π=3 transition

L_π=1 contribution may affect…

$J^P=5/2^+$ for $\Lambda_c(2880)$

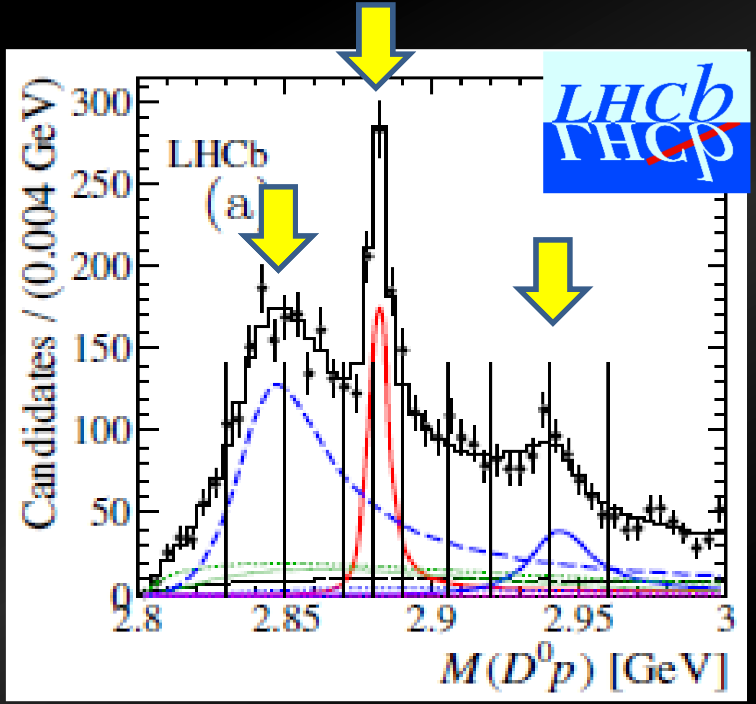
Is it a D-wave Lambda-c Baryon?

If so, where is a spin partner ?

LHCb data in Λ_c^*

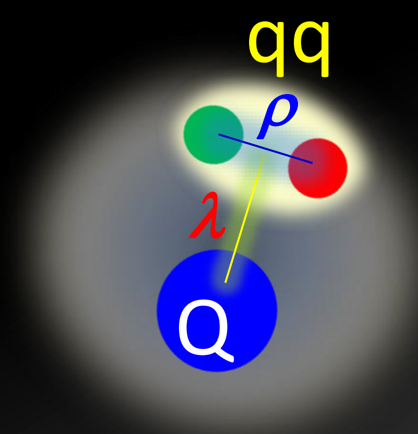
J. High Energ. Phys. (2017) 2017

- $D^0 p$ invariant mass in $\Lambda_b \to D^0 p \pi^-$
  - $\Lambda_c(2940)$: known
    - likely 3/2-, (acceptable 1/2, 7/2)
  - $\Lambda_c(2880)$: known
    - 5/2+ confirmed
  - $\Lambda_c(2860)$: new
    - likely 3/2+, D-wave (*L*=2) resonance?



- Questions arise;
  - Is $\Lambda_c(2940)$ an *L*=3 state (λ mode)?
  - Are $\Lambda_c(2880)$ and $\Lambda_c(2860)$ *LS* partners of *L*=2 (λ modes)?
- Production rates in p(π^-,D^{*-})Y_c^* will give answer.

Λ(2880) likely to be $\lambda\rho$ mode?



H. Nagahiro et al., PRD95 (2017) no.1, 014023

- P-wave transition seems to be suppressed in

$$\Lambda_c(2880)\frac{5}{2}^+ \rightarrow \Sigma_c^*(2520)\frac{3}{2}^+ + \pi(0^-).$$

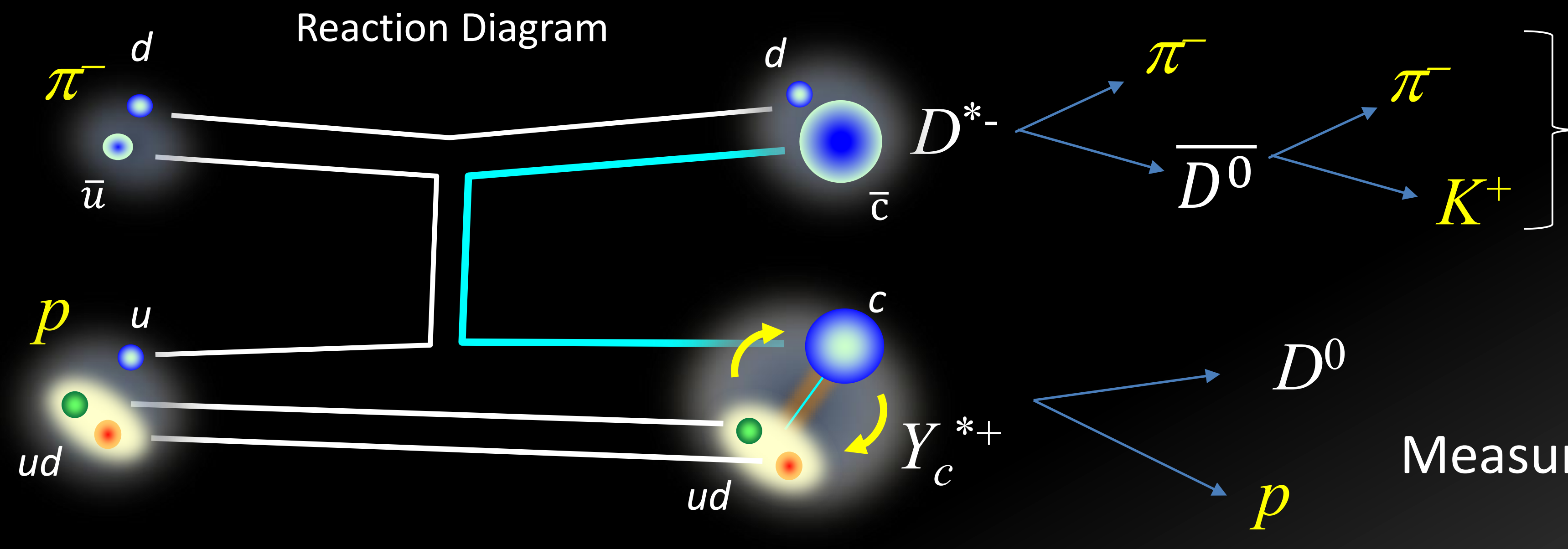
- It would be forbidden only in the case of $J_{BM}^P = 3^+$: "5/2-" state have large widths.
- $\Lambda_c(2880)\frac{5}{2}^+$ is likely to be a $\lambda\rho$ mode (λ=1, ρ=1) state.

Λ_c(2880) 5/2+	$\lambda\lambda$	$\lambda\rho$	$\rho\rho$
color	Asymm.		
Isospin	Asymm. (I=0)		
Diquark spin Diquark orbit	Asymm. 0 Symm. 0	Symm. 1 Asymm. 1	Asymm. 0 Symm, 2
Lambda orbit	2	1	0
J_{BM}^P	2+	1+, 2+, **3+**	2+

Σ_c^*(2520) 3/2+
Asymm
Symm. (I=1)
Symm. 1 Symm, 0
0
1+

To be confirmed by measuring the prod. ratio

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

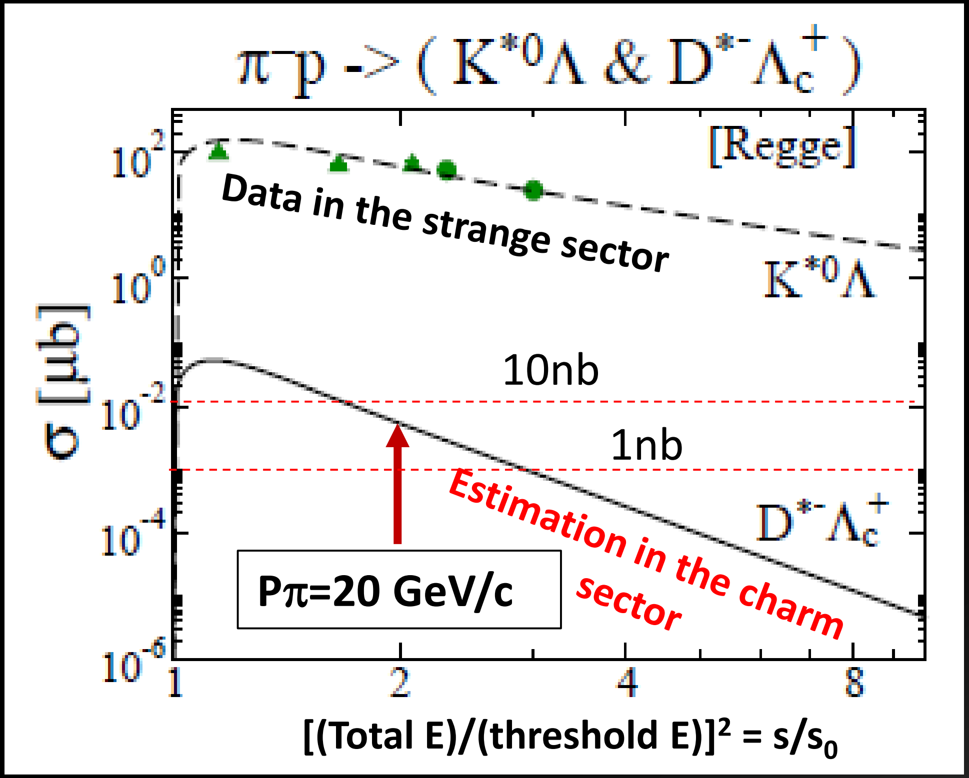
Single-quark involved process: S.H. Kim, A. Hosaka, H.C. Kim, and HN, PTEP, (2014) 103D01

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

Production of Charmed Baryons: Theoretical Study

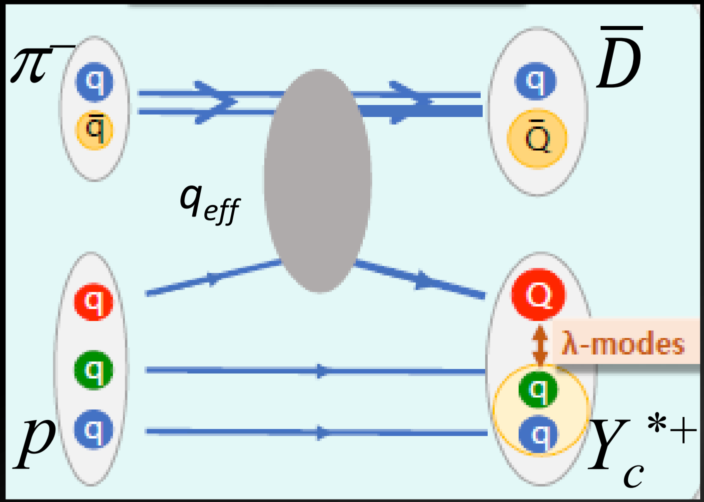
Reggeon Exchange Model in 2-body reaction

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

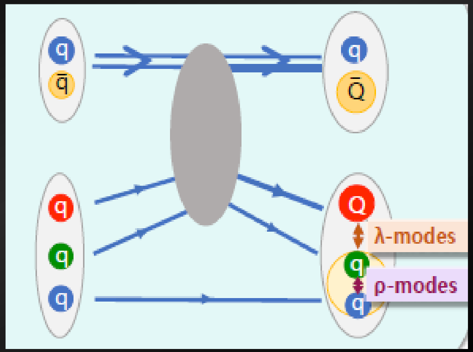


※no data available is in the charm sector.

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

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

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

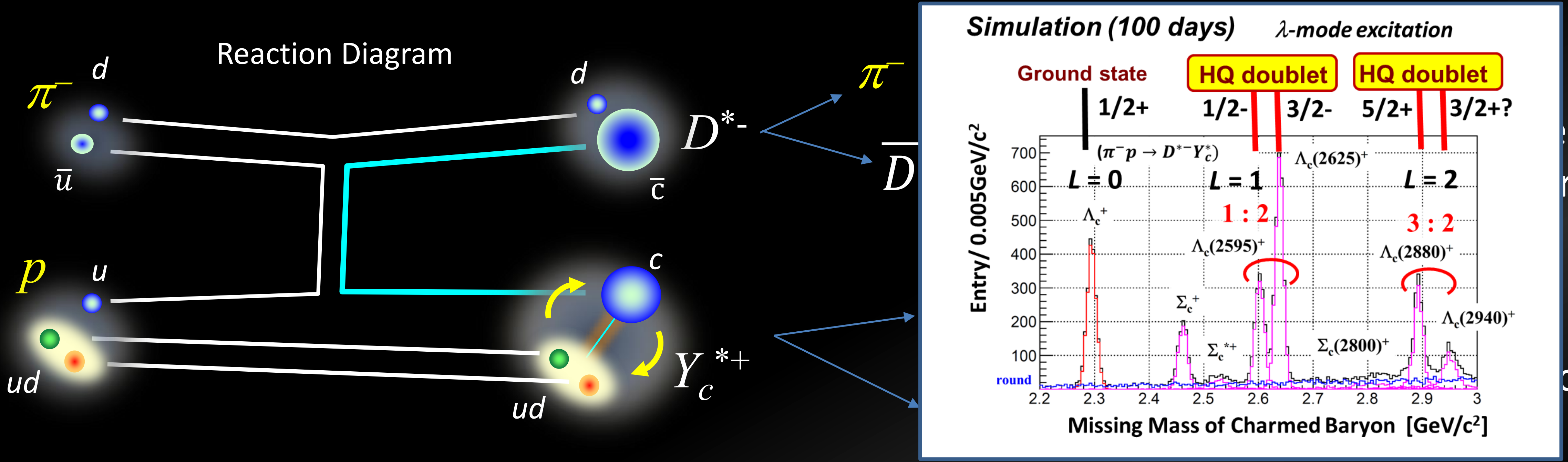
Mom. Trans.: q_{eff}∼1.4 GeV/c
α~0.4 GeV ([Baryon size]$^{-1}$)

※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

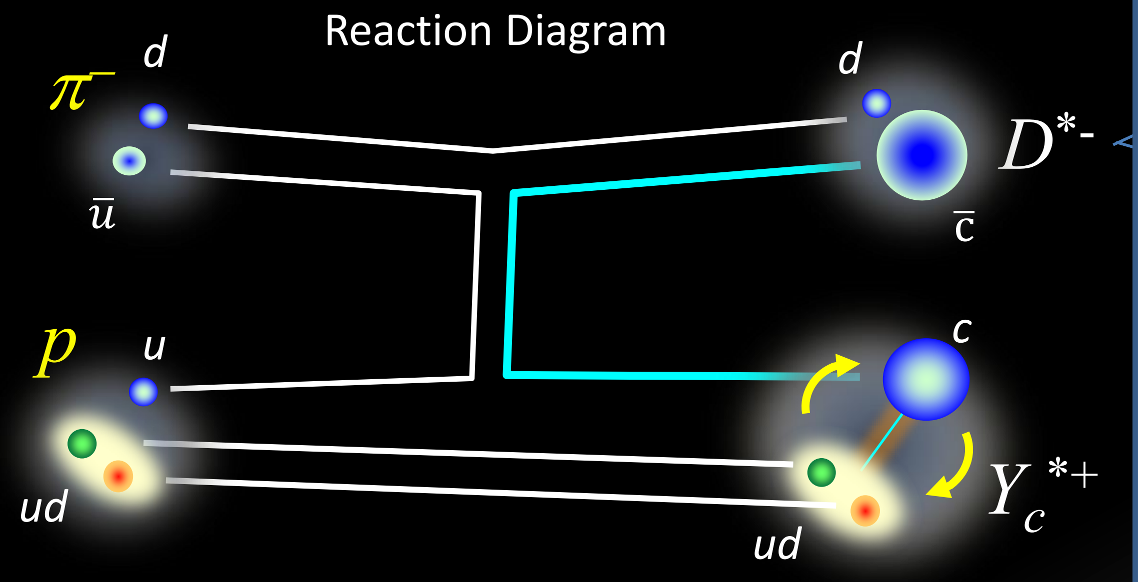
※excite ρ-mode, giving how much the two-quark process contributes.

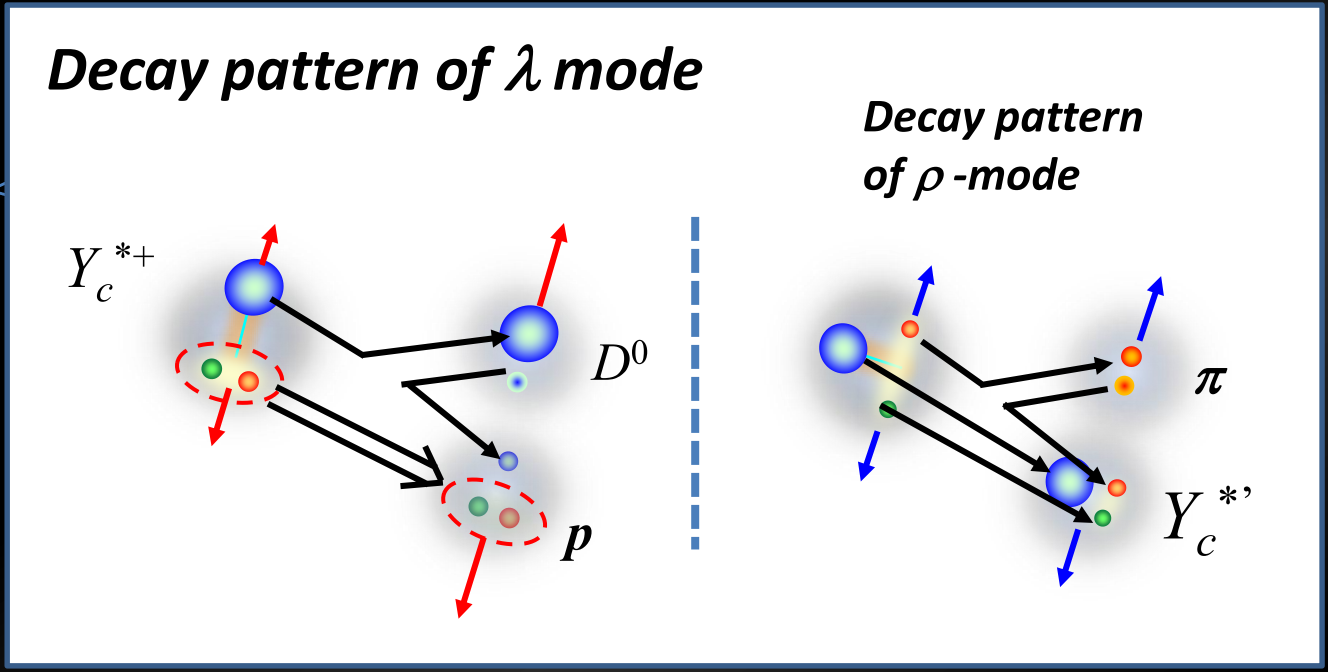
Production and Decay of Charmed Baryons



- 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

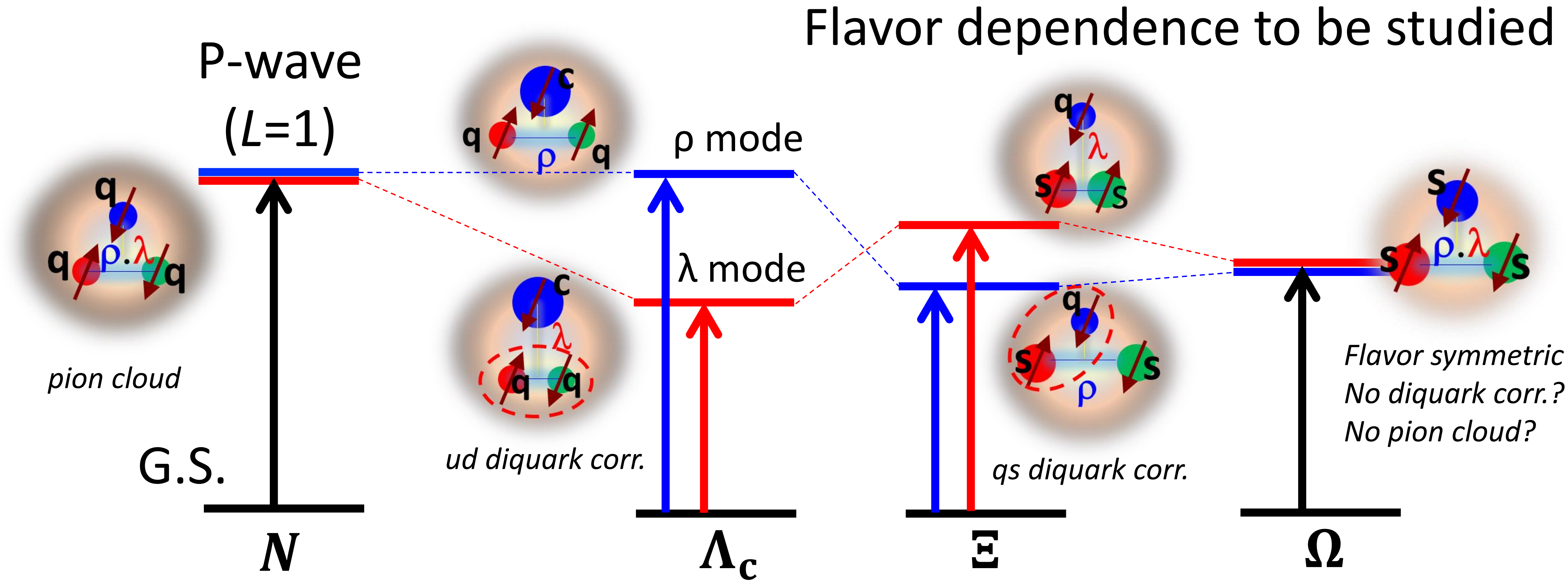




- Introducing a finite orbital angular momentum *L* ⇒ favor λ-mode excitations
  - Establish "*ud*" diquark motion in baryon
- Production ratio of the HQ doublet to be *L*:*L*+1 ⇒ Spin, Parity
  - The ratio would be a measure of how "*ud*" is correlated.
- Production and Decay measurement ⇒ Branching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

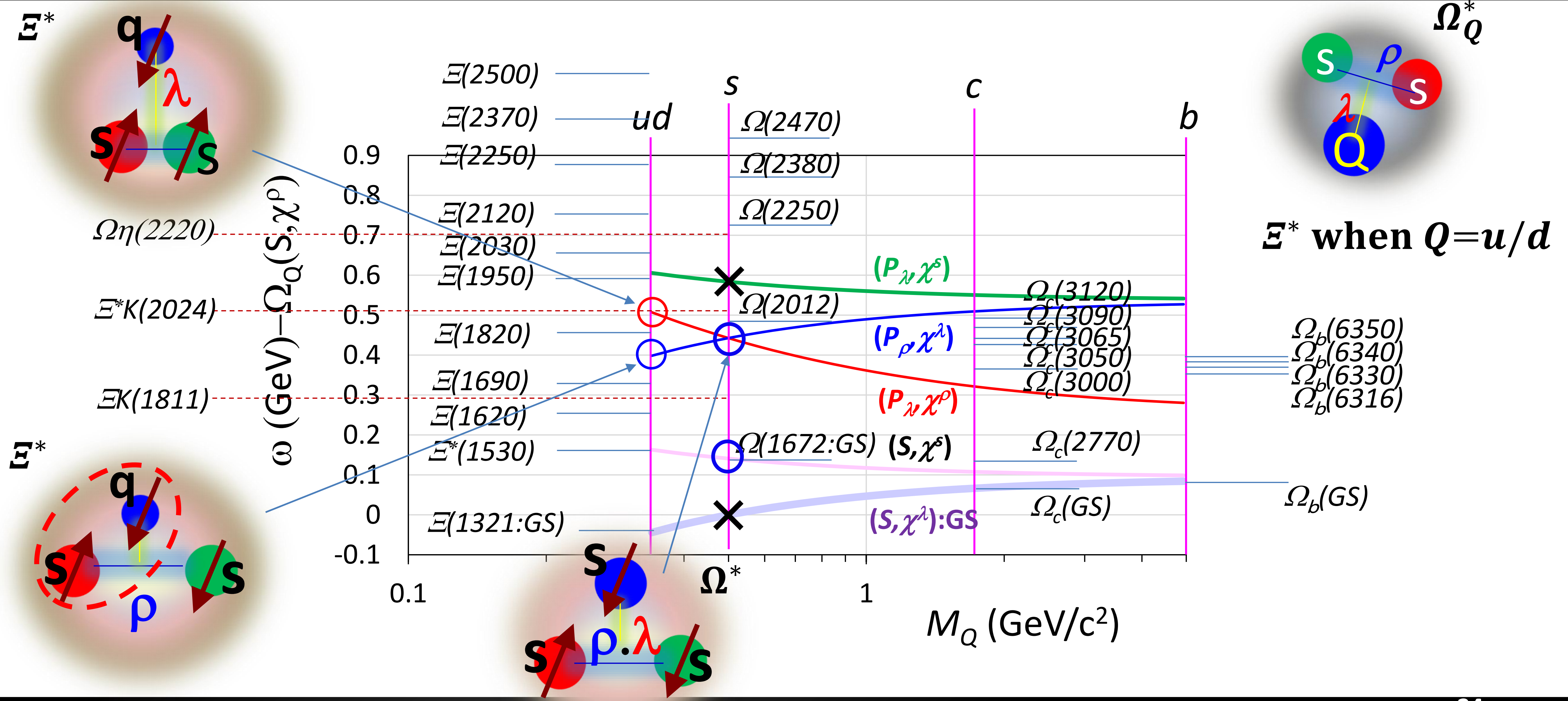
Spectroscopy of strange and charmed baryons

※Disentangle motions of a quark pair by introducing different flavors



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

Systematics of Qss Baryons – Ξ and Ω –



Properties of Ξ^* are limited.

Threshold

$\Omega\bar{K}$(2166)

$\Sigma\bar{K}^*$(1983)

$\Sigma^*\bar{K}$(1878) $\Lambda\bar{K}^*$(1908)

$\Xi^*\pi$(1665) $\Sigma\bar{K}$(1685)

$\Lambda\bar{K}$(1610)

$\Xi\pi$(1450)

	JP	rating	Width [MeV]	→$\Xi\pi$ [%]	→ΛK [%]	→ΣK [%]	
Ξ(2500)	??	1*	150?				
Ξ(2370)	??	2*	80?				ΩK~9±4%
Ξ(2250)	??	2*	47+-27?				
Ξ(2120)	??	1*	25?				
Ξ(2030)	>=5/2?	3*	20^{+15}_{-5}	small	~20	~80	Why ΣK?
Ξ(1950)	??	3*	60+-20	seen	seen		
Ξ(1820)	3/2-	3*	24^{+15}_{-10}	small	Large	Small	
Ξ(1690)	??	3*	<30	seen	seen	seen	
Ξ(1620)	??	1*	20~40?				
Ξ(1530)	3/2+	4*	19	100			

- ✓ *Most of spins/parities have NOT been determined yet.*
- ✓ *Why the Ξ* -> $\pi\Xi$* decay seems to be suppressed?
  - ✓ expected to reflect QQq configuration.

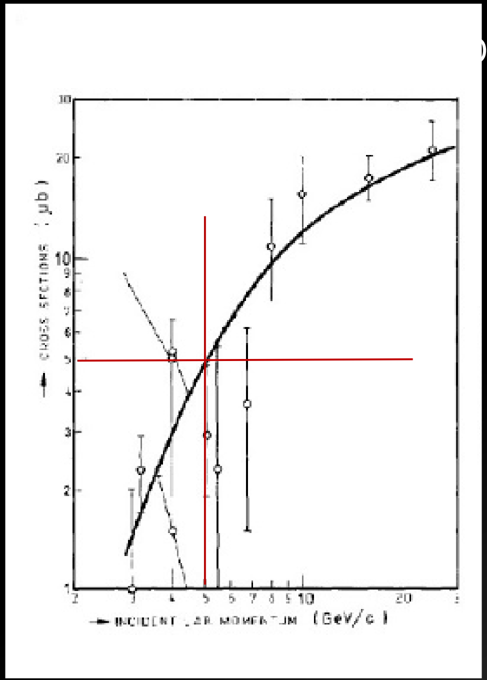
Ξ Baryon Spectroscopy w/ the High-p Secondary Beam

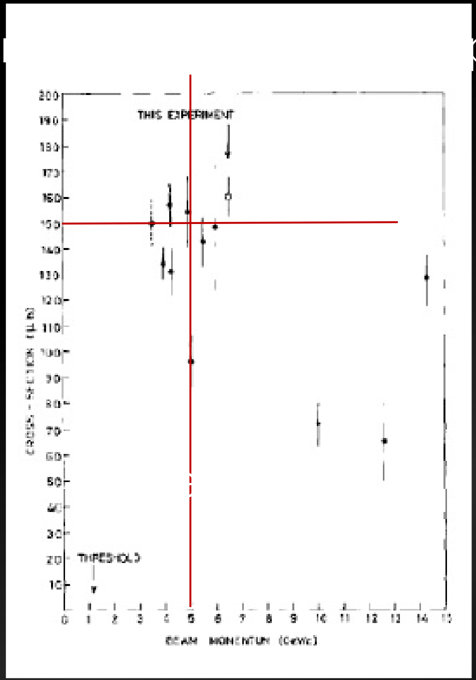
Proposal in preparation by M. Naruki and K. Shirotori

- Sizable yields are expected for a month.

Reaction	σ [μb]	Beam [/spill]	B.R.	Acceptance [%]	Y_{Total}	$Y_{Decay/bin}$
$K^-p \to \Xi^{*-}K^+$	1.0	10^6	1.0	50	3.1×10^5	2500
$K^-p \to \Xi^{*-}K^{*+}$	1.0	10^6	0.23	50	0.7×10^5	580
$K^-p \to \Xi^{*0}K^{*0}$	1.0	10^6	0.67	50	2.1×10^5	1700
$\pi^-p \to \Xi^{*-}K^{*0}K^+$	0.1	10^7	0.67	50	3.1×10^5	2500

- Past exp.

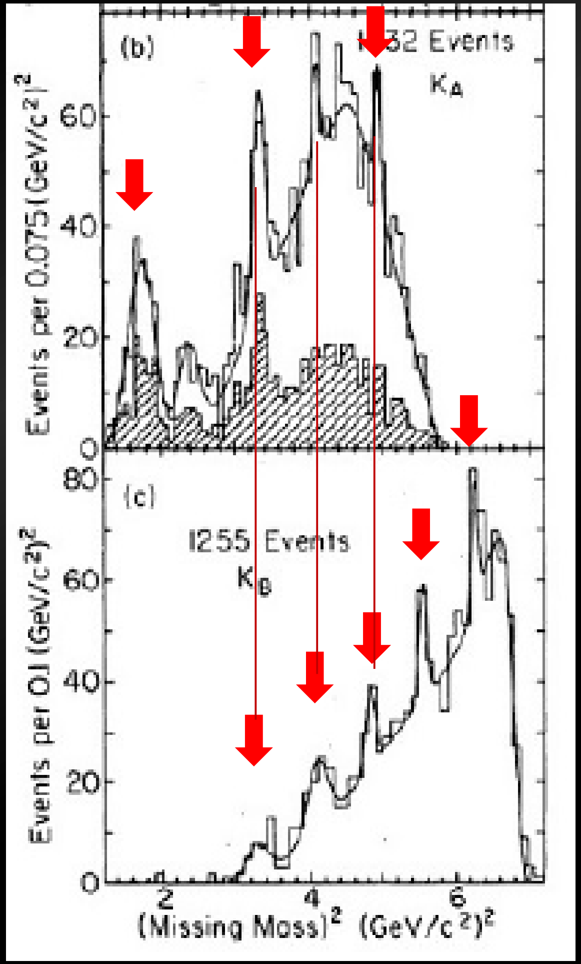




Kaon beams:
productive in Ξ*

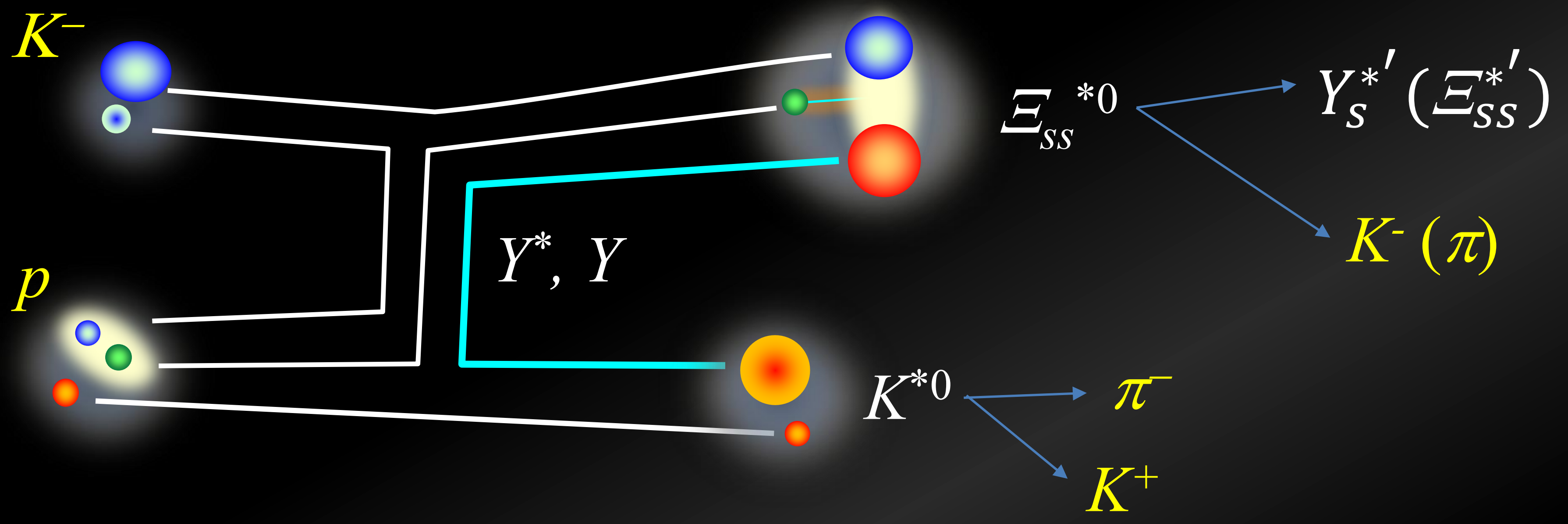
p(K⁻,K⁺) spectra
C.M. Jenkins et al.,
PRL51, 951(1983)

2030
1820 2250



Multi-Strangeness Baryon Spectroscopy Using Missing Mass Techniques

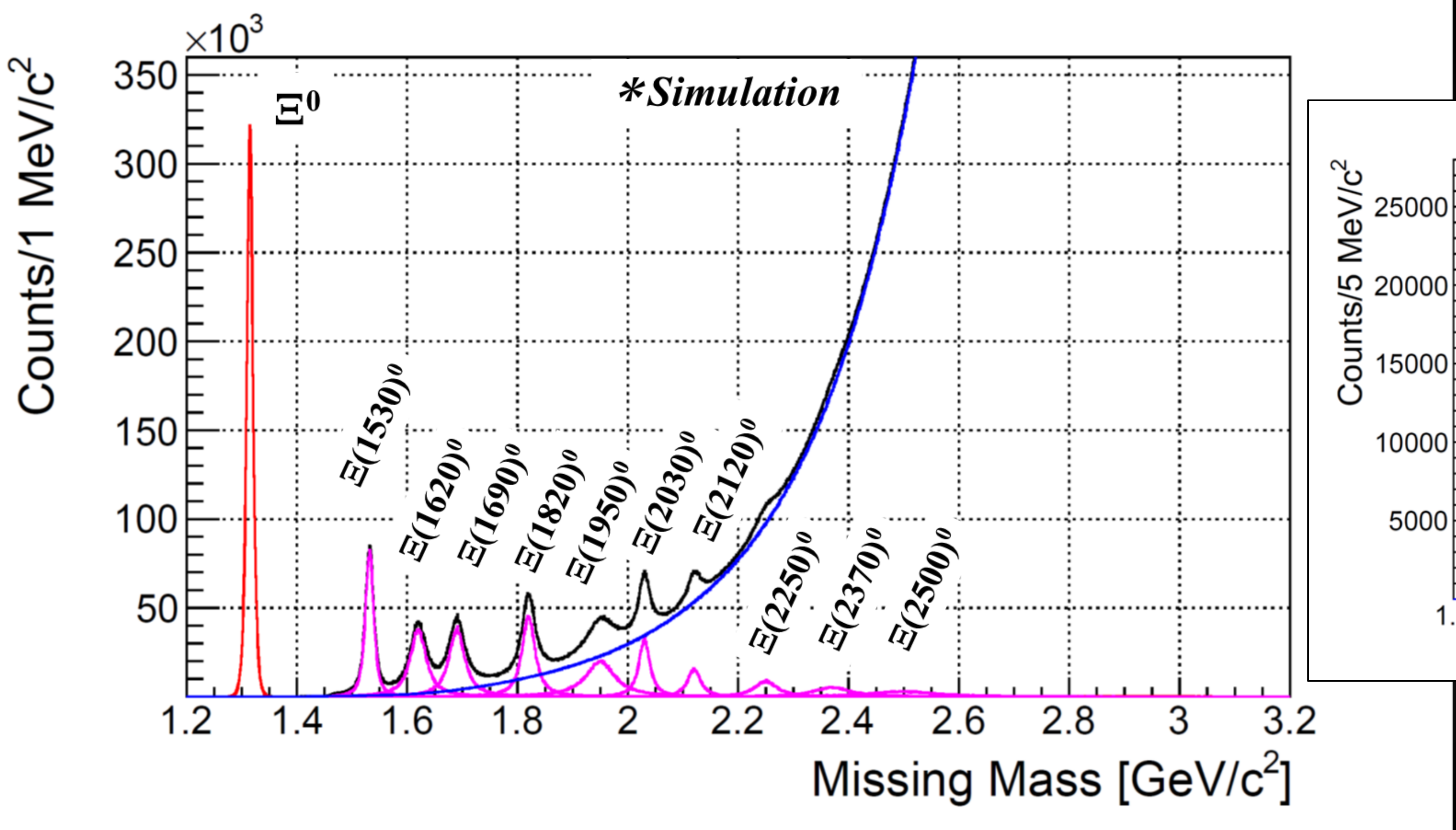
M. Naruki and K. Shirotori, LoI submitted to the 18th J-PARC PAC in May, 2014(KEK/J-PARC-PAC 2014-4)



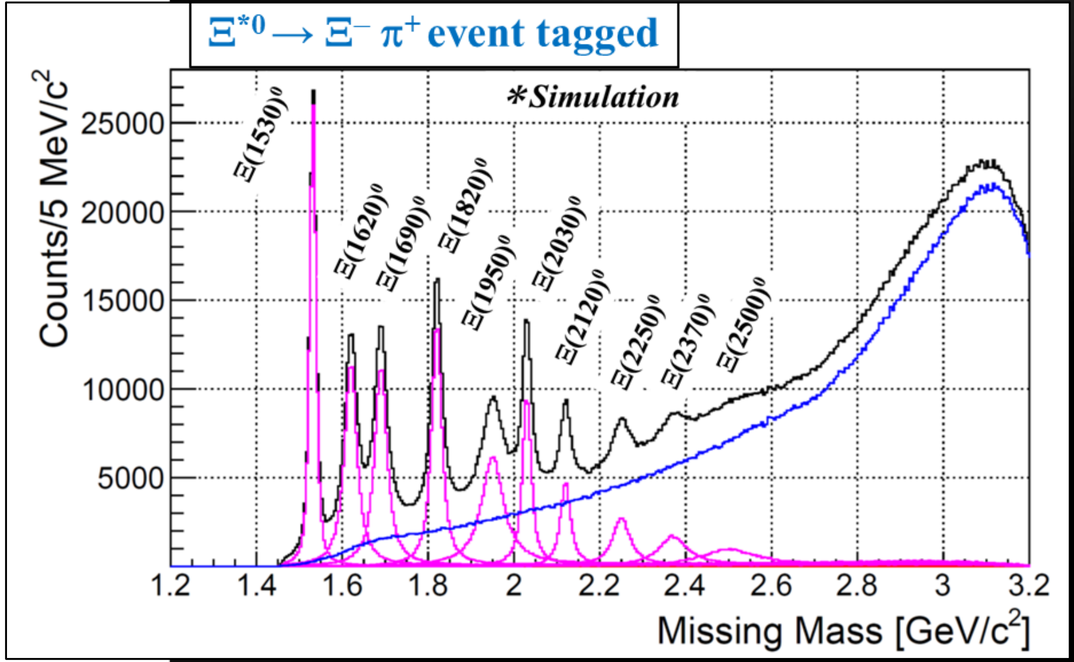
- ✓ Production and Decay reflect [QQ] correlation
- ✓ *Two-quark-involved reaction →Both ρ/λ mode excitations*

Expected Spectra in $K^{-}p \rightarrow K^{*0}\Xi^{*0}$ at 8 GeV/c

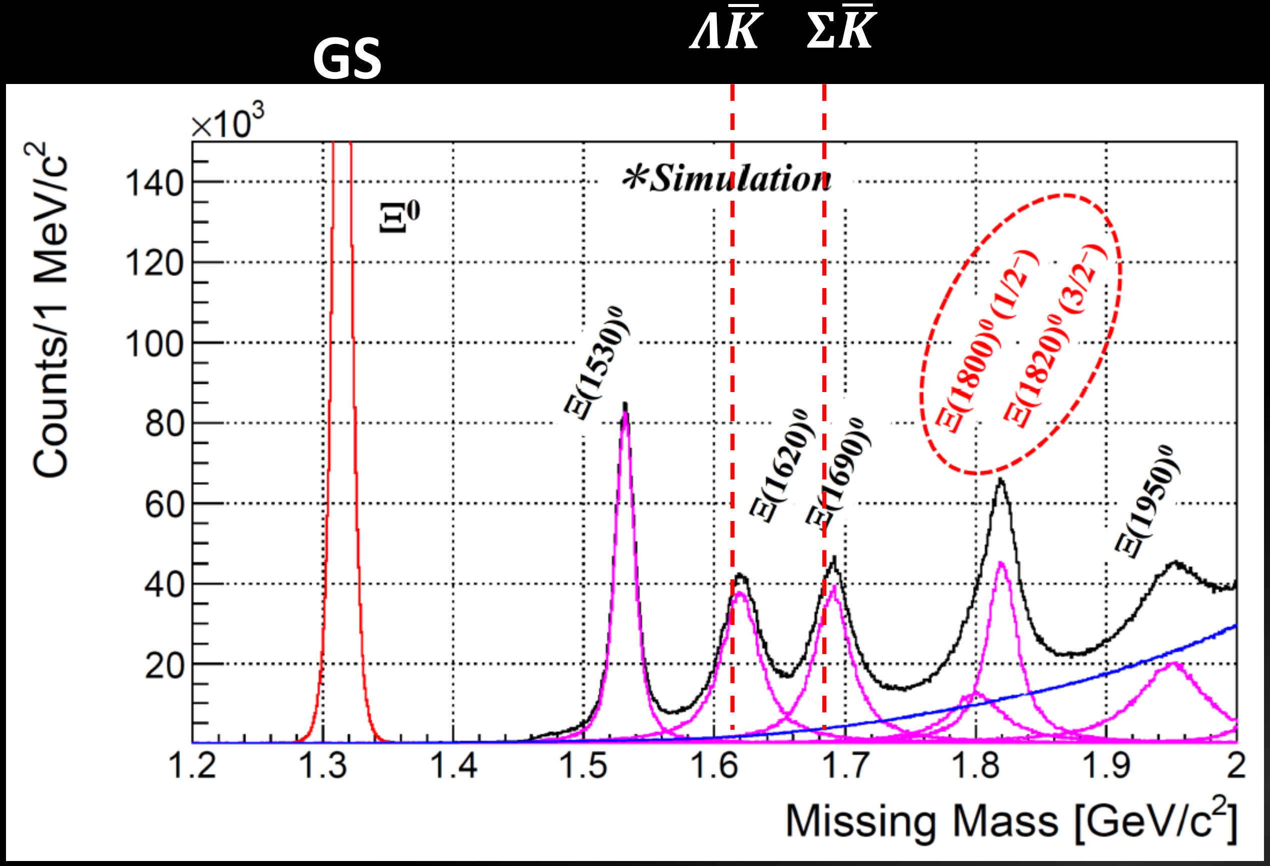
※simulation: known states are included w/ BG estimated by JAM.
Many of their J^P have yet to be determined.



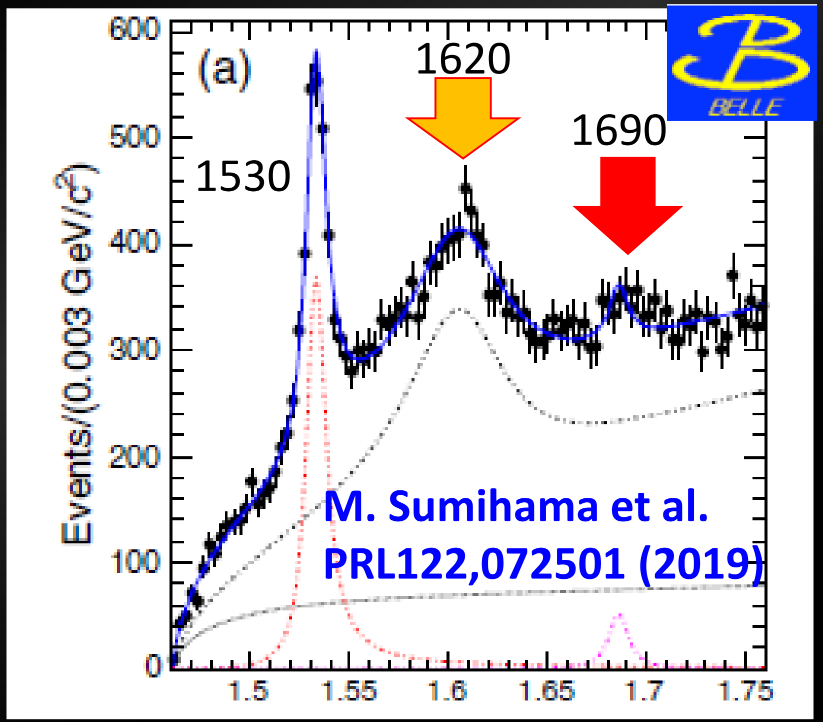
Tagged spectrum showing BG reduction.



Closed-up the low-lying Ξ states



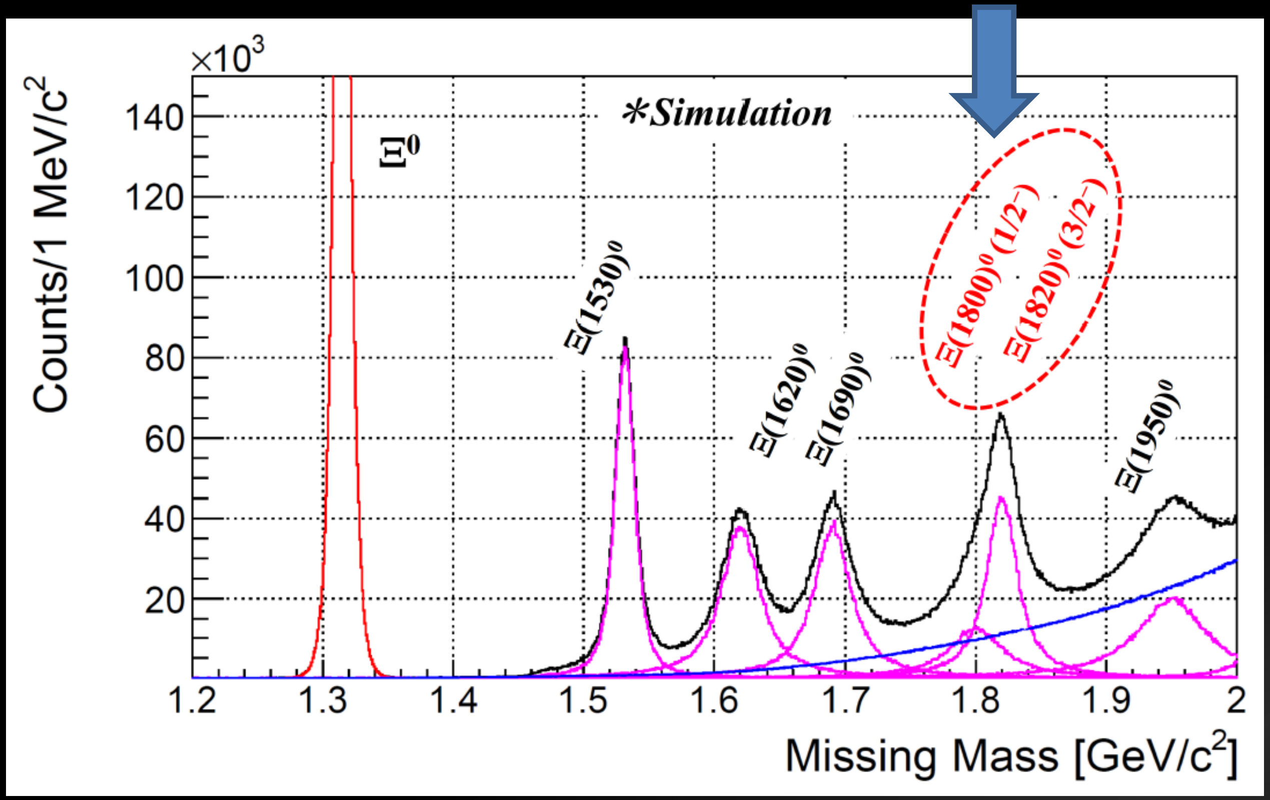
- Unexpected states in CQM?
  - Ξ(1620) nearby $\Lambda\bar{K}$ threshold
  - Ξ(1690) nearby $\Sigma\bar{K}$ threshold
- $Y\bar{K}$ molecular state or casp?
  - Prod. rates would be reduced.



Closed-up the low-lying Ξ states

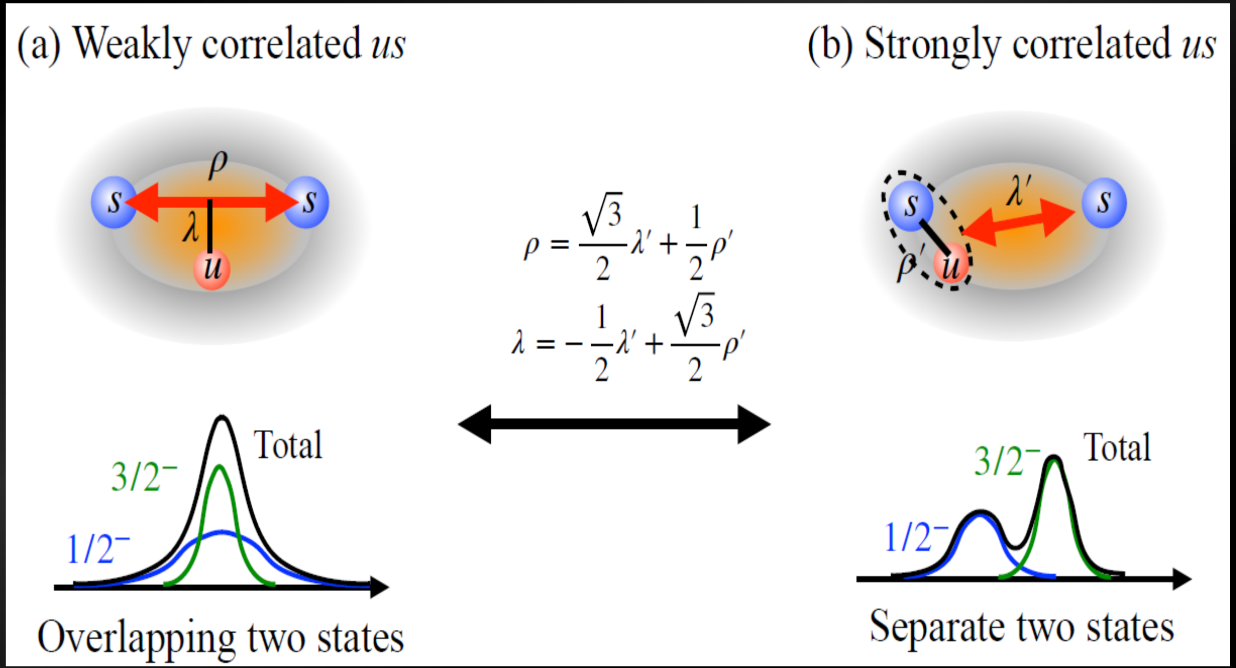
GS

1*P* states
(*ρ*-mode)



※Ξ(1800)1/2- assumed for demo.

- Interest of *ρ*-mode excited states
  - Ξ(1820)3/2- to be confirmed
  - *LS* partner (1/2-) to be found
  - Reveal *us*-diquark correlation



Properties of Ω* are limited, too

Threshold

- Ξ0K*- 2109
- Ξ0*K- 2024
- Ξ0K-π0 1956
- Ωπ0π0 1942
- Ξ0K- 1811
- (Ωπ0 1807)

	JP	rating	Width [MeV]	→ΞK (1)	→Ξ*K (2)	→ΞK* (3)	→ΞKπ (4)	→Ωππ (5)	
Ω(2470)	??	2*	72+-33					seen	LASS (113MK-,11GeV/c) (290+-90)/(5) nb
Ω(2380)	??	2*	26+-23		<0.44 to (4)	0.5+-0.3 to (4)			Xi Beam
Ω(2250)	??	3*	55+-18		0.7+-0.2 to (4)		Seen		Xi Beam LASS (113MK-, 11GeV/c) (630+-180)/(2) nb
Ω(2012)	?-	3*	$6.4^{+2.5}_{-2.0}$ +-1.6	1.2+-0.3 (=X0/X-)	<0.119 /(1)				->Ξ*K dominant if Ξ*K mol?
Ω(1672)	3/2+	4*	-						

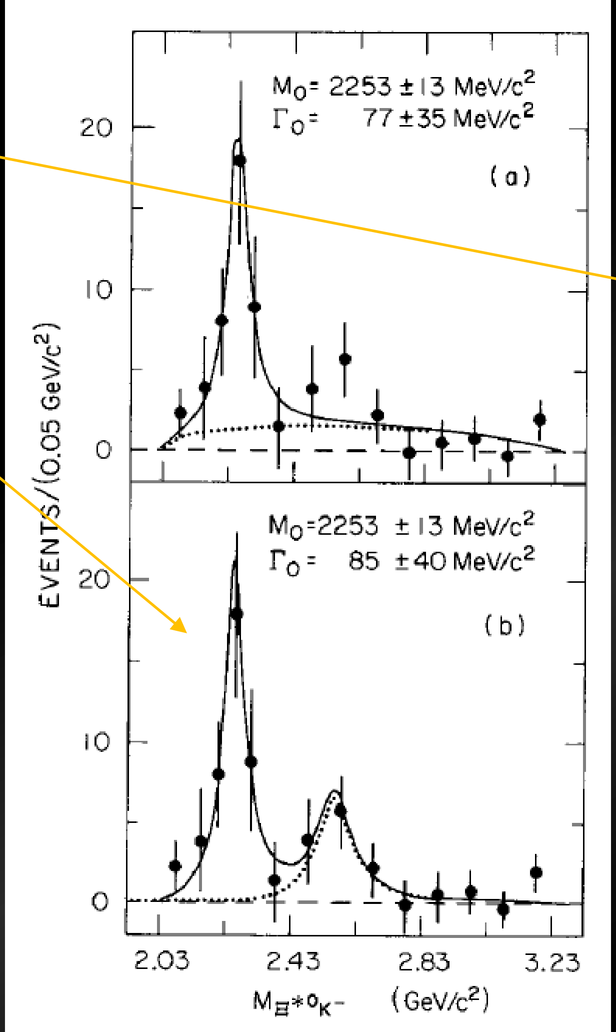
✓*Most of spins/parities/decay branches have yet to be determined.*

✓*What the production Ξ* -> Ω*K* and *Ω** decay modes tell us *Ω**'s internal structure.

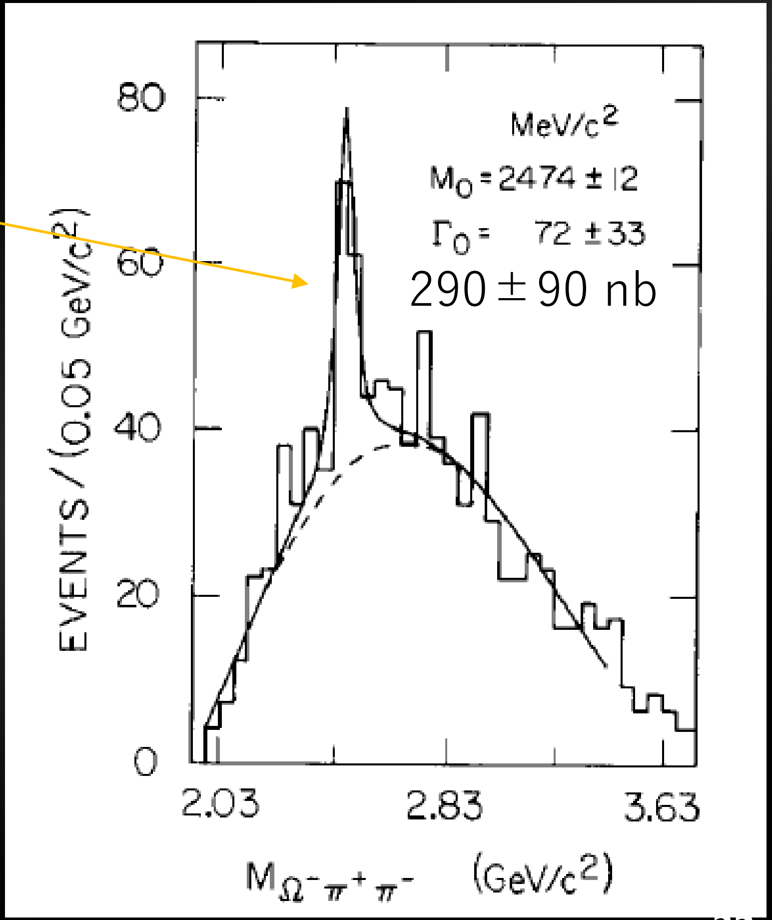
Omega*: Productive Kaon Beams

	J^P	
Ω(2470)	??	**
Ω(2380)	??	**
Ω(2250)	??	***
Ω(2012)	?-	***
Ω(GS)	3/2+	****

PLB194,574(1987)
11 GeV/c K-



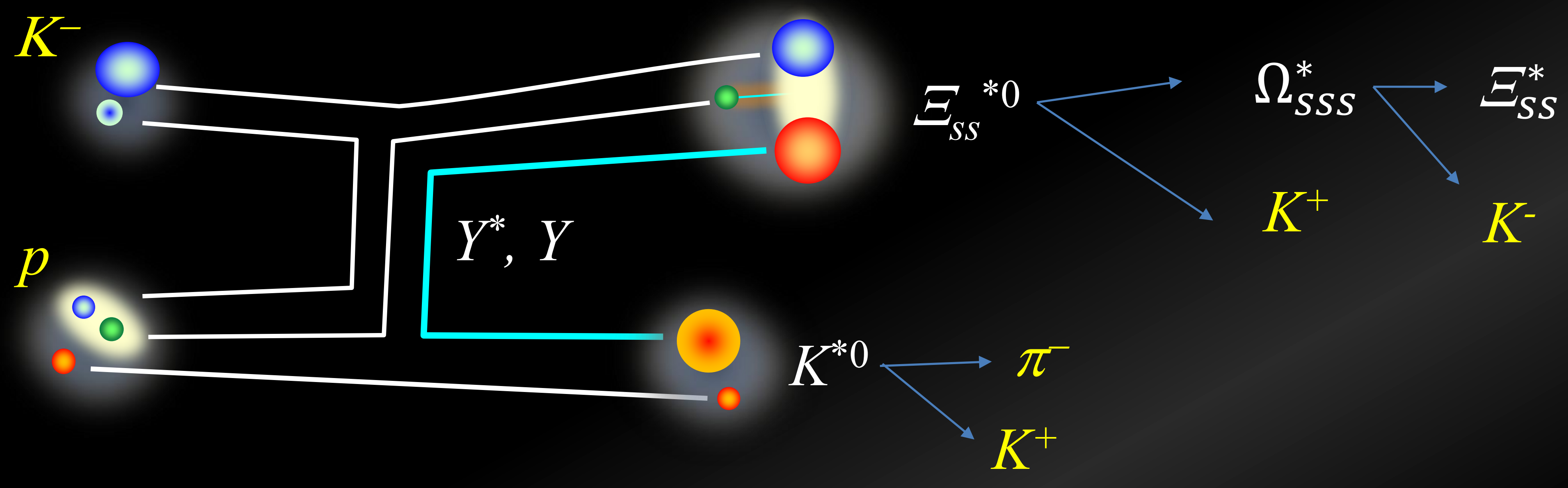
PLB215,799(1989)
11 GeV/c K-



Pilot Exp. for Omega* at High-p 2nd (π20)

Multi-Strangeness Baryon Spectroscopy Using Missing Mass Techniques

K. Shirotori et al., Proposal P85 submitted to the 32nd J-PARC PAC, 2021(KEK/J-PARC-PAC 2021-10)

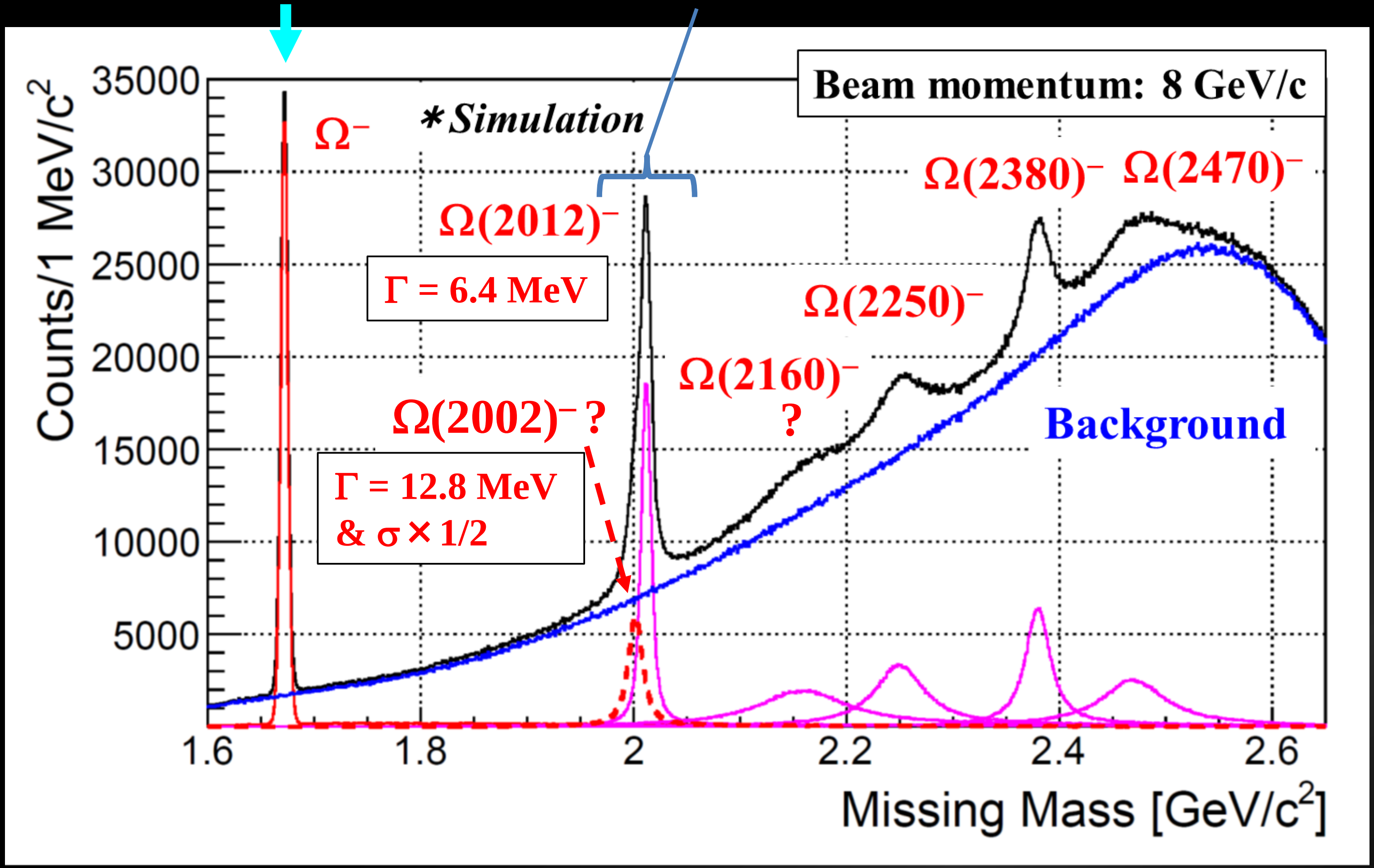


✓ *Doorway channel to Ω* production* (*via* $\Xi^*_{ss} \rightarrow \Omega^*_{sss} + K^+$)

Expected Spectra in $K^- p \to K^{*0} K^+ \Omega^{*-}$ at 8 GeV/c

63 nb assumed

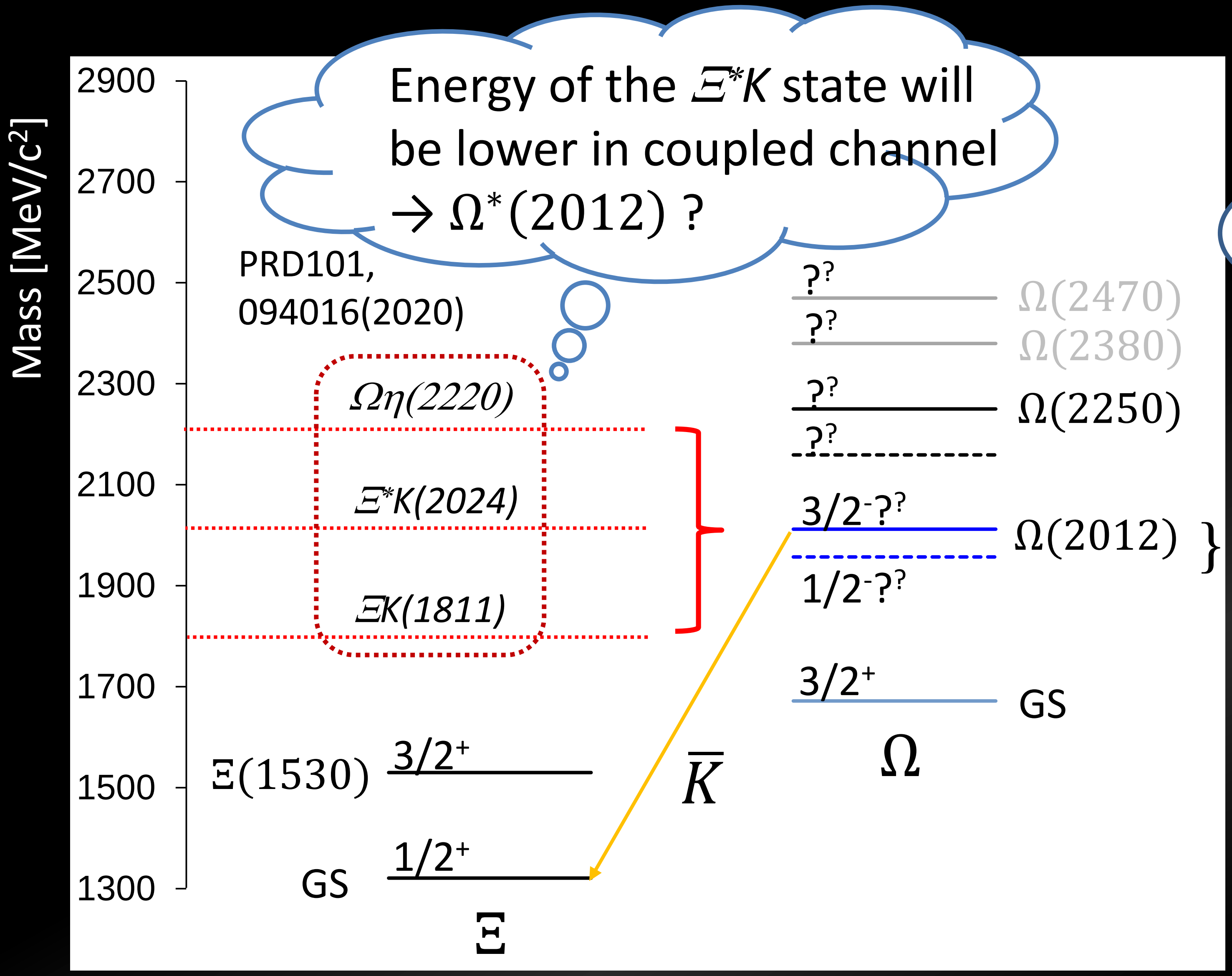
1P states?



Physics Highlight

- 1P excited states
  - $\Omega(2012)$ J^P to be measured
    - 3/2-?
  - *LS* partner (1/2-) to be found
    - No LS splitting by CQM due to flavor symmetry
  - If a Finite *LS* splitting, Relativistic effect in confinement force?
- Is $\Omega(2012)$: $\Xi^* \bar{K}$ Molecular?
  - PRD101, 094016(2020)

$\Omega^*(2012)$: a Molecular State?

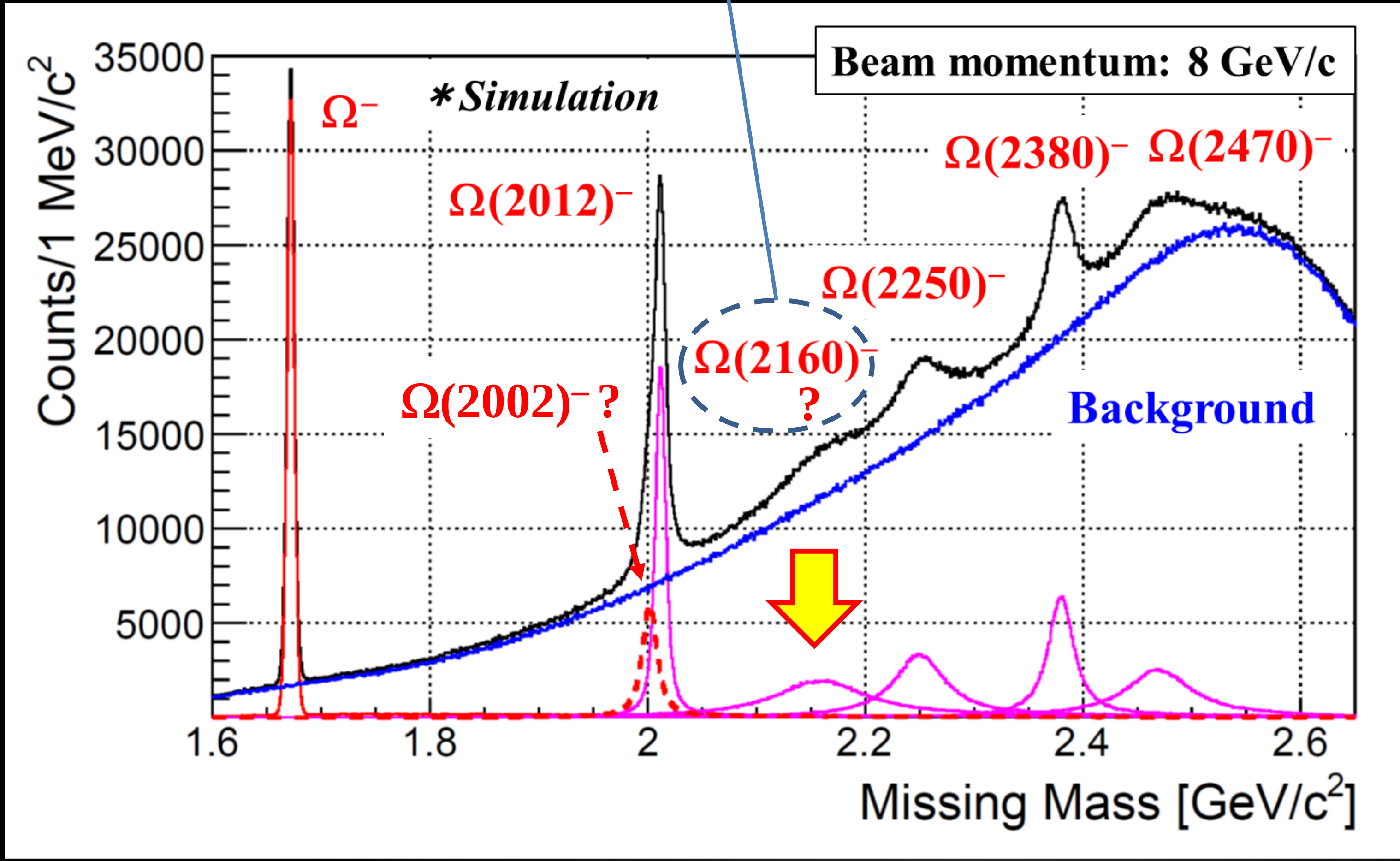


$1P$ state?

If so, how is it different from its LS partner ($1/2^-$)?

Expected Spectra in $K^- p \rightarrow K^{*0} K^+ \Omega^{*-}$ at 8 GeV/c

Roper (2S state)?



Physics Highlight

- 2S excited states
  - Radial excitation
  - So-called Roper-like state, yet to be found
    - $\Omega(2160), \Gamma \sim 100$ MeV assumed in the Sim.
  - The width
    - $\propto \langle p^2 \rangle$: "Quark core" size no pion cloud
  - The excitation energy
    - Universality?

A. Jafar Arifi's Talk, 11:20-, 15 July

Summary

- A heavy quark plays an inert particle in a hadron and is quite helpful to investigate internal motions and/or correlations of quarks, though which we can learn dynamics of EoF emerged in Low-Energy QCD and mechanism behind their behaviors.
  - Excitation Energy, Production Rate, and Decay Branching Ratio
- We conduct spectroscopy of multi-strange and charmed baryons with intense pion and kaon beams at π20 and K10.
  - New platform of hadron physics will be covered owing to the general purpose spectrometer

Backup