Hadron physics at J-PARC

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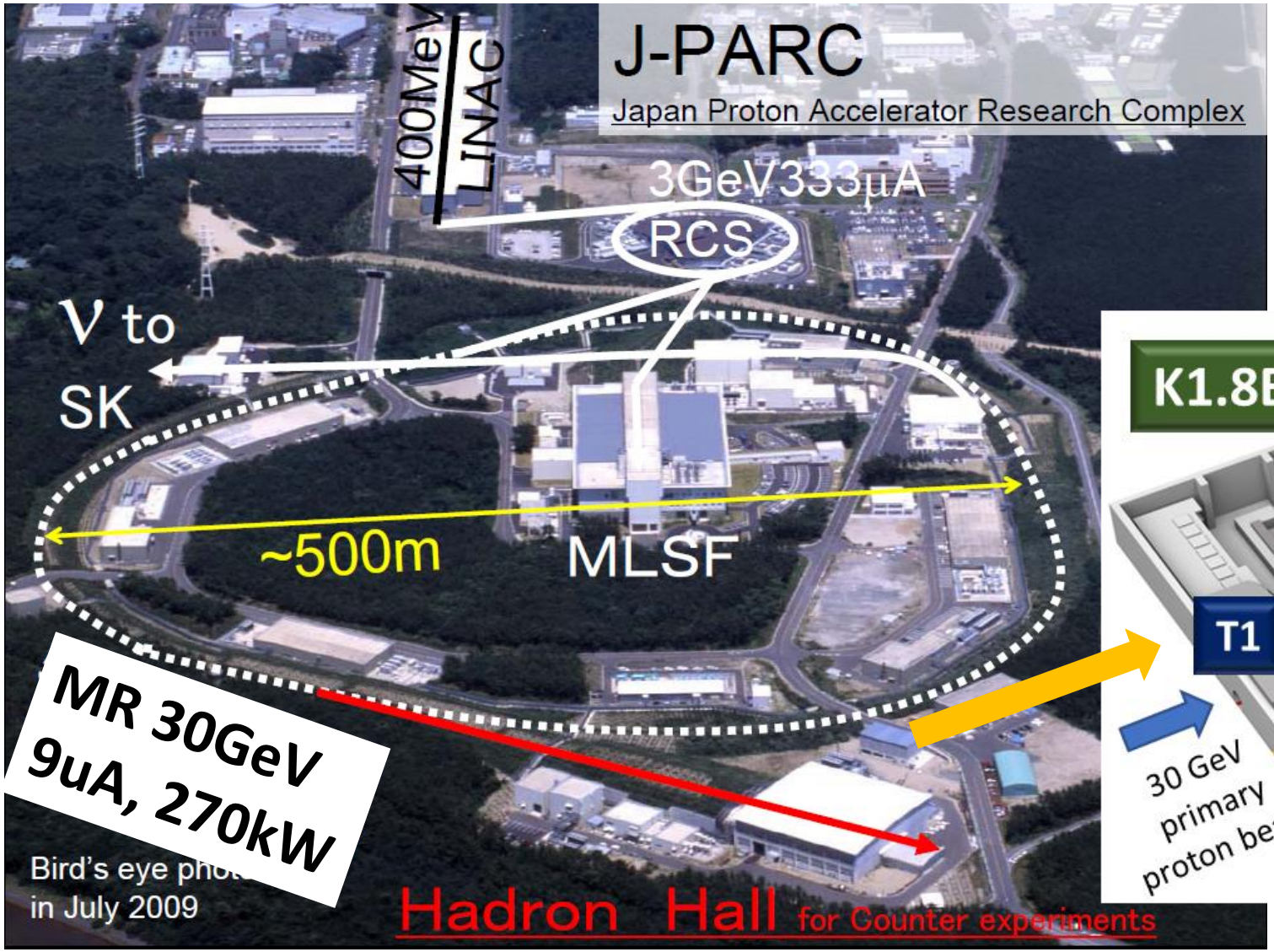
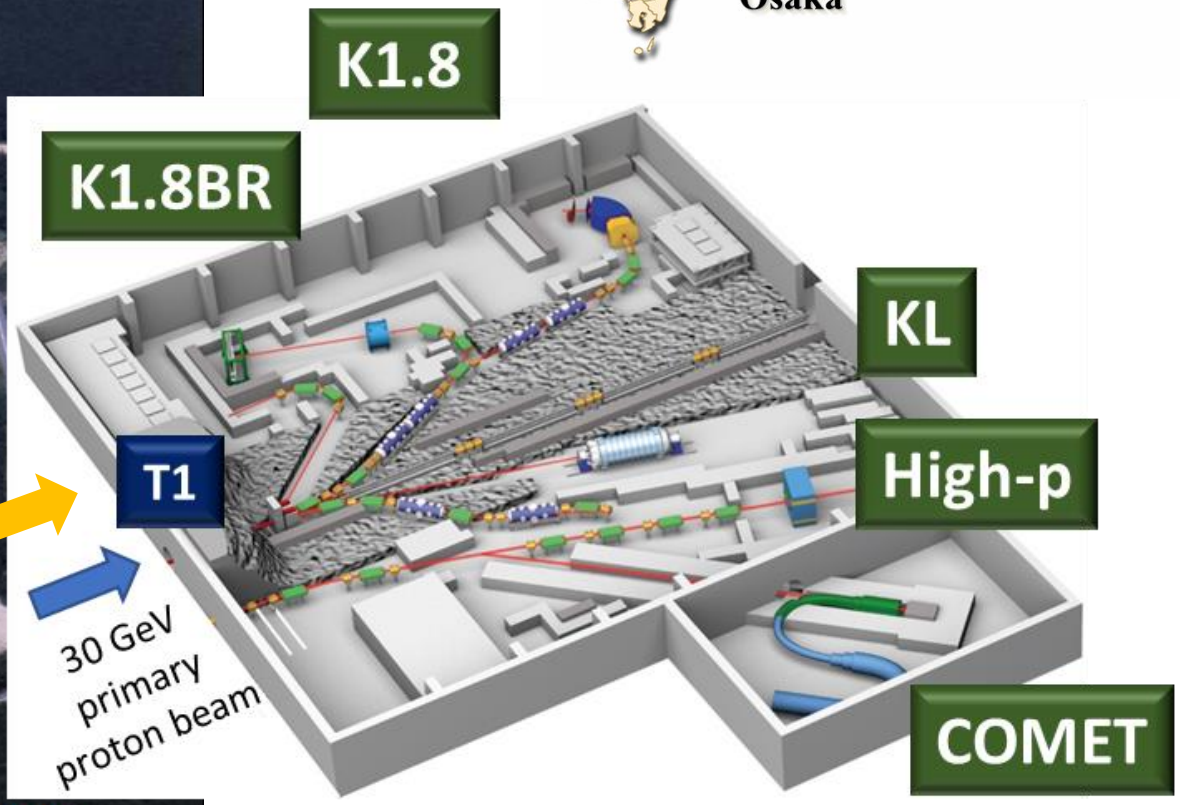
Osaka University

Strong QCD from Hadron Structure Experiments - VI

14th May. 2024

J-PARC & Hadron Experimental Facility





World's highest level intensity proton beam ⇒ Beam power 80 kW

Hadron physics at J-PARC hadron facility

✱ Explore Origin & Evolution of Matter more deeply

⇒ Experiments using hadron beams: $\pi^{\pm}$, K^{-}, proton/anti-proton

- Secondary beams: < 2 GeV/c by current beam lines

⇒ 2–20 GeV/c by high-p(π20) beam line

- Primary proton beam @ 30 GeV

Current beam line		π20 beam line
Hadron in nuclei	*Hadron structure*	Nucleon structure
Λ^{*} resonance		Charmed baryon spectroscopy
H dibaryon search		Ξ/Ω baryon spectroscopy
Kaonic nuclei	*Hadron interaction*	Non-strange dibaryon search
Hyperon-N scattering		High-mom. Hyperon-N scattering
Λ hypernuclear spectroscopy		ϕn resonance study
Ξ hypernuclear spectroscopy		Ξ-N/ Ω-N scattering

Topics of hadron investigation at J-PARC

- **Spectroscopy of heavier flavors for understanding "Baryon system"**

⇒ **Systematic spectroscopic measurements by high-momentum beams**

  - **Charmed (Λ_c/Σ_c), Ξ, Ω baryons**

- **Hadron in nuclei for understanding "Mass generation"**

⇒ **Hadron property measurements in nuclei**

  - **Modification of mass: e.g., Vector meson (ϕ)**

- **Investigation of exotic states for understanding "Exotic property"**

⇒ **Specific measurements by dedicated experiments**

  - **$\Lambda(1405)$, narrow Λ^*, ϕN resonances**

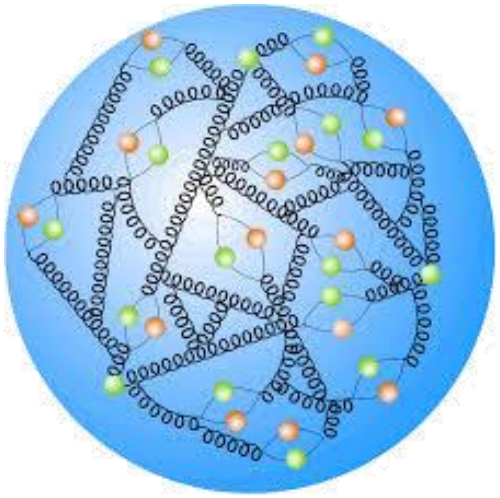
Hadron spectroscopy with high-momentum hadron beam

Charmed (Λ_c/Σ_c), Ξ, Ω baryons

Baryon structure in the low-energy regime

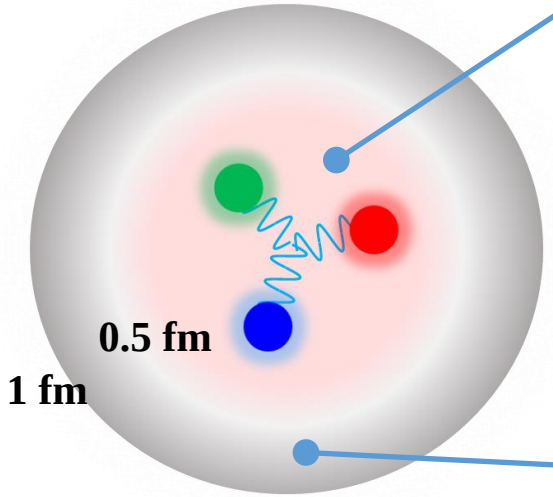
High energy

perturbative



Low energy

non-perturbative



- **Non-perturbative region**

⇒ **"Quark core" region**

  - **Non-trivial gluon field: Instanton***
  - **Chiral condensate $\langle \bar{q}q \rangle \neq 0$**
    - **Dressed quark (Constituent quark)**
    - **Emergence of π**

- **Meson (pion) Cloud**

∗How quarks build hadrons ?

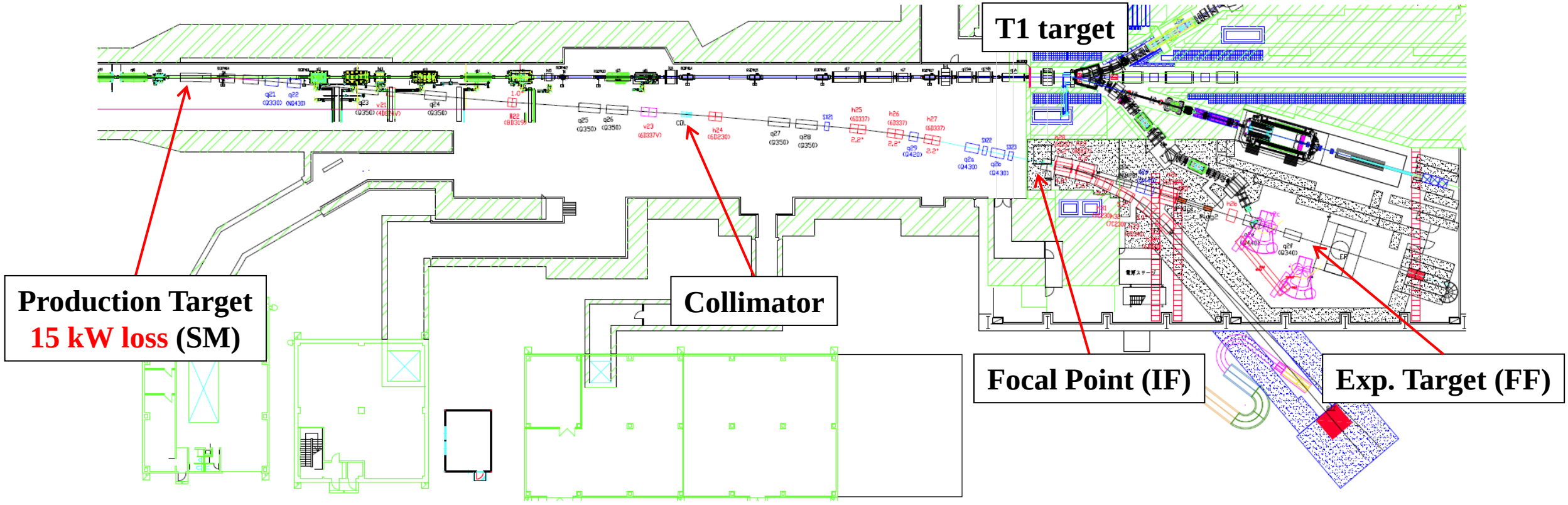
- **Dynamics of non-trivial QCD vacuum ⇒ Dynamics of Effective DoF**
  - **Short-range spin-spin correlation: Diquark correlation**
  - **Origin of spin-dependent force**
  - **Quark motions in "quark core" with "cloud"**

**Instanton*: *A topological object of gluon that mediates the $U_A(1)$ breaking interaction proposed by Kobayashi, Maskawa, and 't Hoot*

High-p beam line for 2ndary beam: π20

∗ High-p: 2ndary beams can be provided from the primary proton beam.

- High intensity: >10^7 /spill for $\pi^{\pm}$, p (>10^5 /spill for K^-, anti-p) up to 20 GeV/c
- High momentum-resolution beam: $\Delta p/p = 0.1\%(\sigma)$

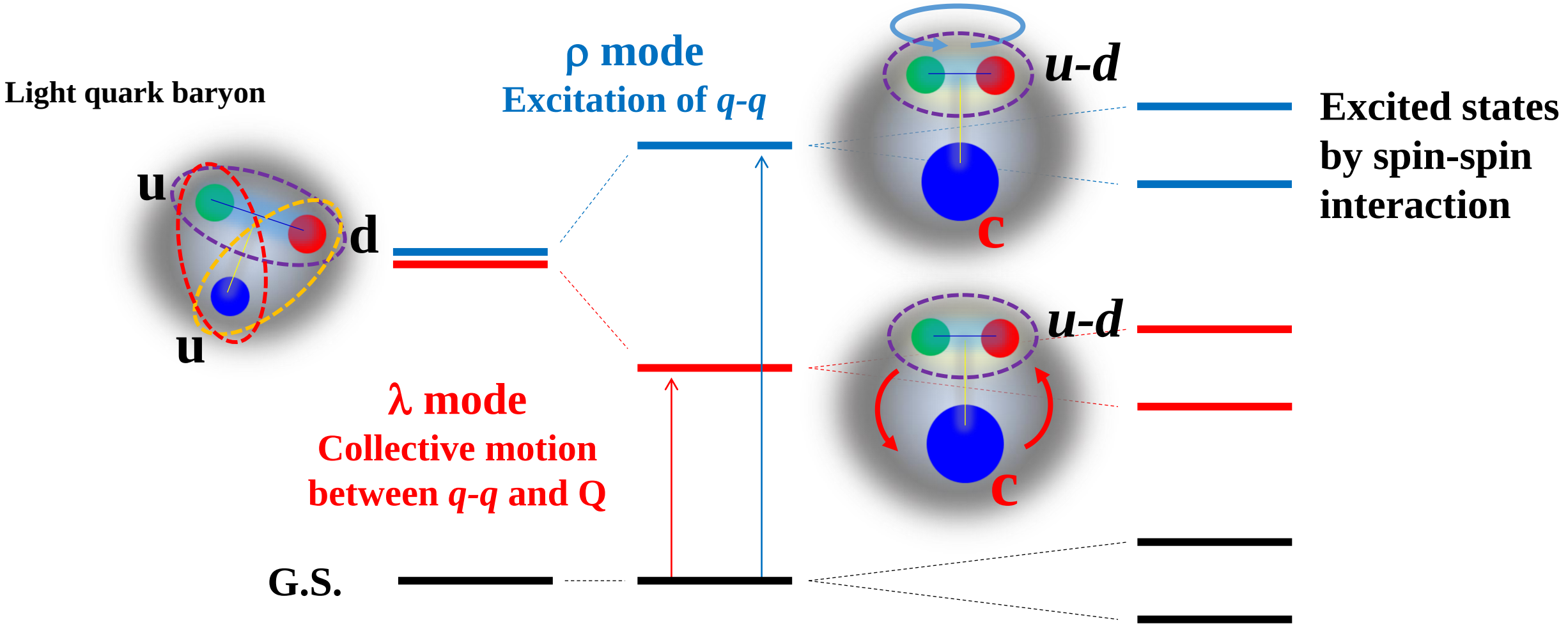


Charmed baryon spectroscopy experiment

"Excitation mode": λ and ρ modes reflected by Diquark correlation

✻ Dynamical information: Production rates and absolute decay branching ratios

- $\pi^- p \rightarrow D^{*-} Y_c^{*+}$ reaction @ 20 GeV/c



Production rates by hadronic reaction

- $\pi^- p \rightarrow D^{*-} Y_c^{*+}$ reaction @ 20 GeV/c
  - Production cross section(0°): Overlap of wave function → $R \sim \langle \varphi_f | \sqrt{2}\sigma_- \exp(i\vec{q}_{eff}\vec{r}) | \varphi_i \rangle$
  - ⇒ Sensitive to excitation modes
  - Large production rate of highly excited states → $I_L \sim (q_{eff}/\alpha)^L \exp(-q_{eff}^2/\alpha^2)$
  - Both one- and two-quark processes (σ_Λ:σ_Σ = 2:1)

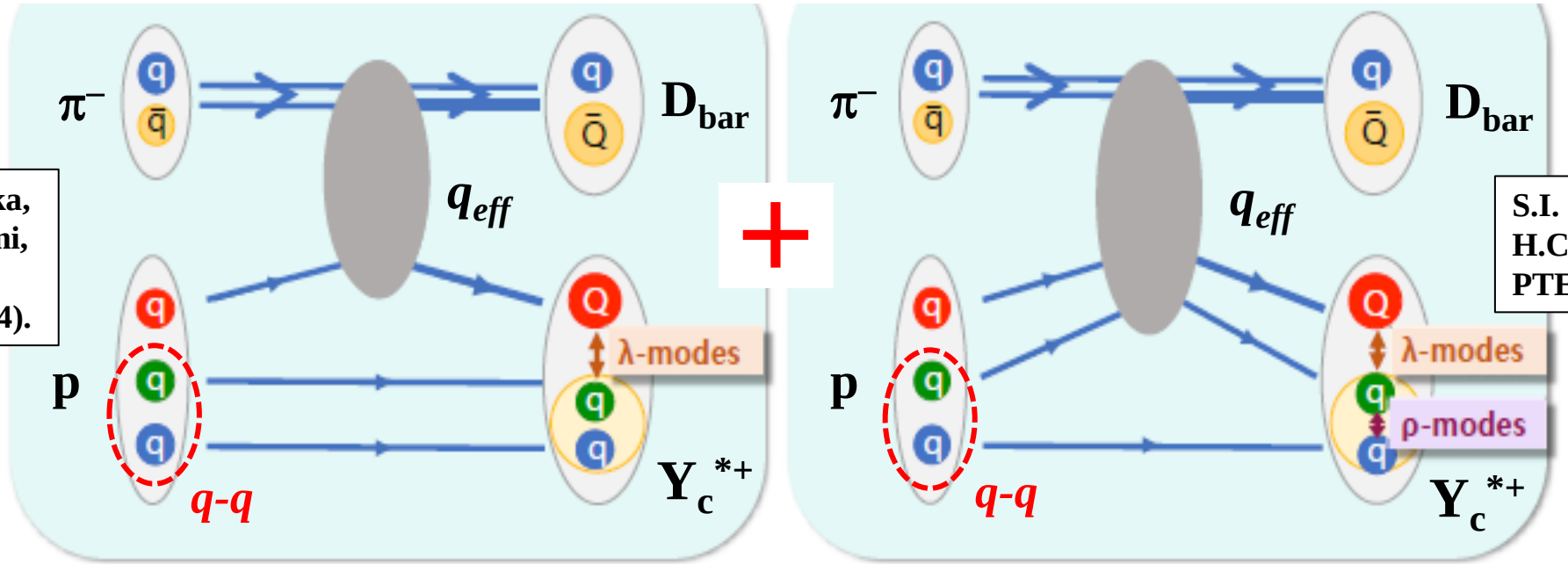
Mom. Trans. : q_{eff}~1.4 GeV/c
α~0.4 GeV ([Baryon size]$^{-1}$)

One-quark process

∗ λ-mode states w/ finite *L* are populated.

Two-quark process

∗ Comparable ρ-mode states are expected.



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

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

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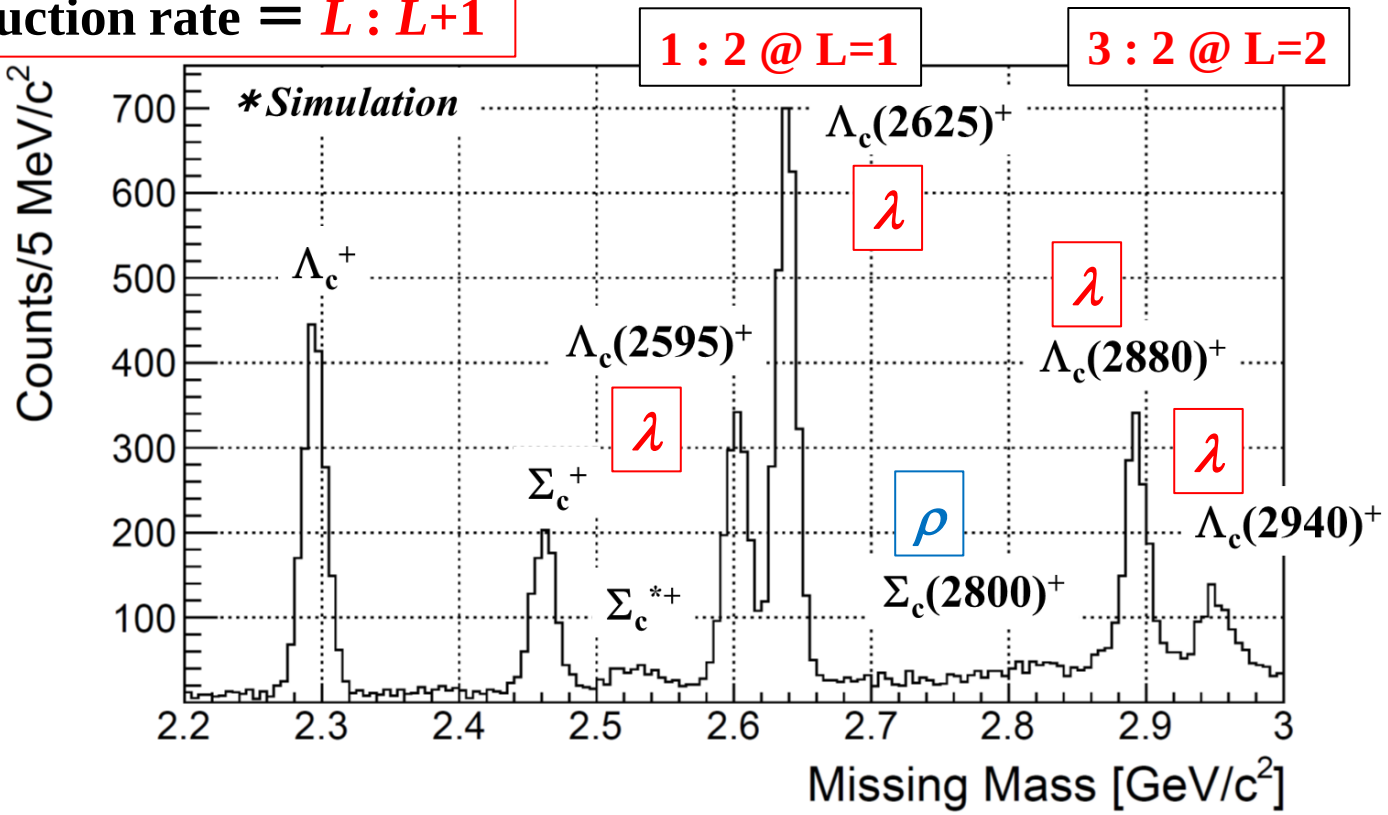
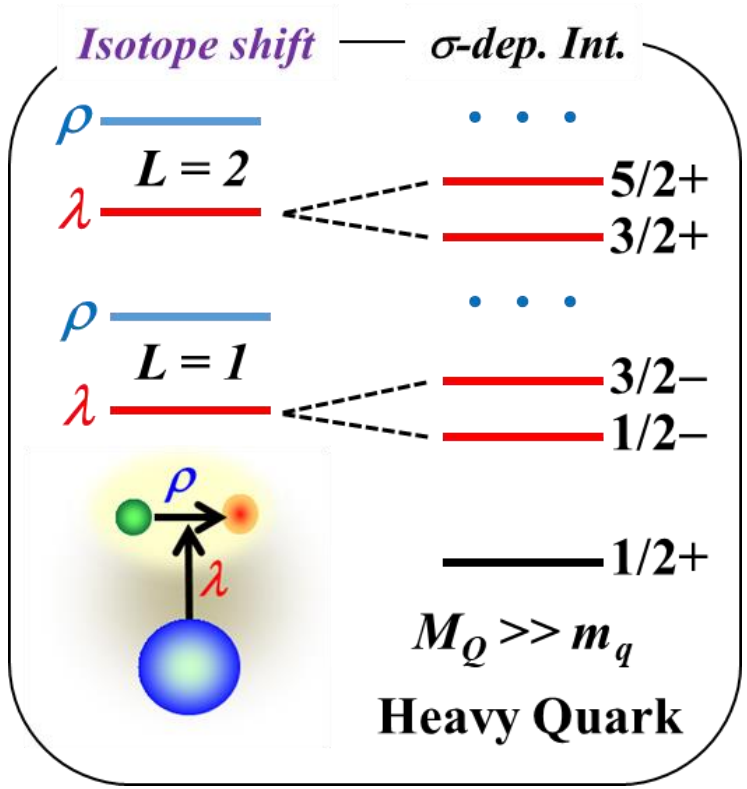
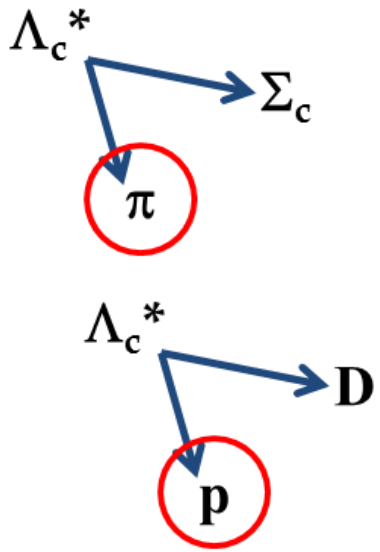
∗ Production rate = L : L+1



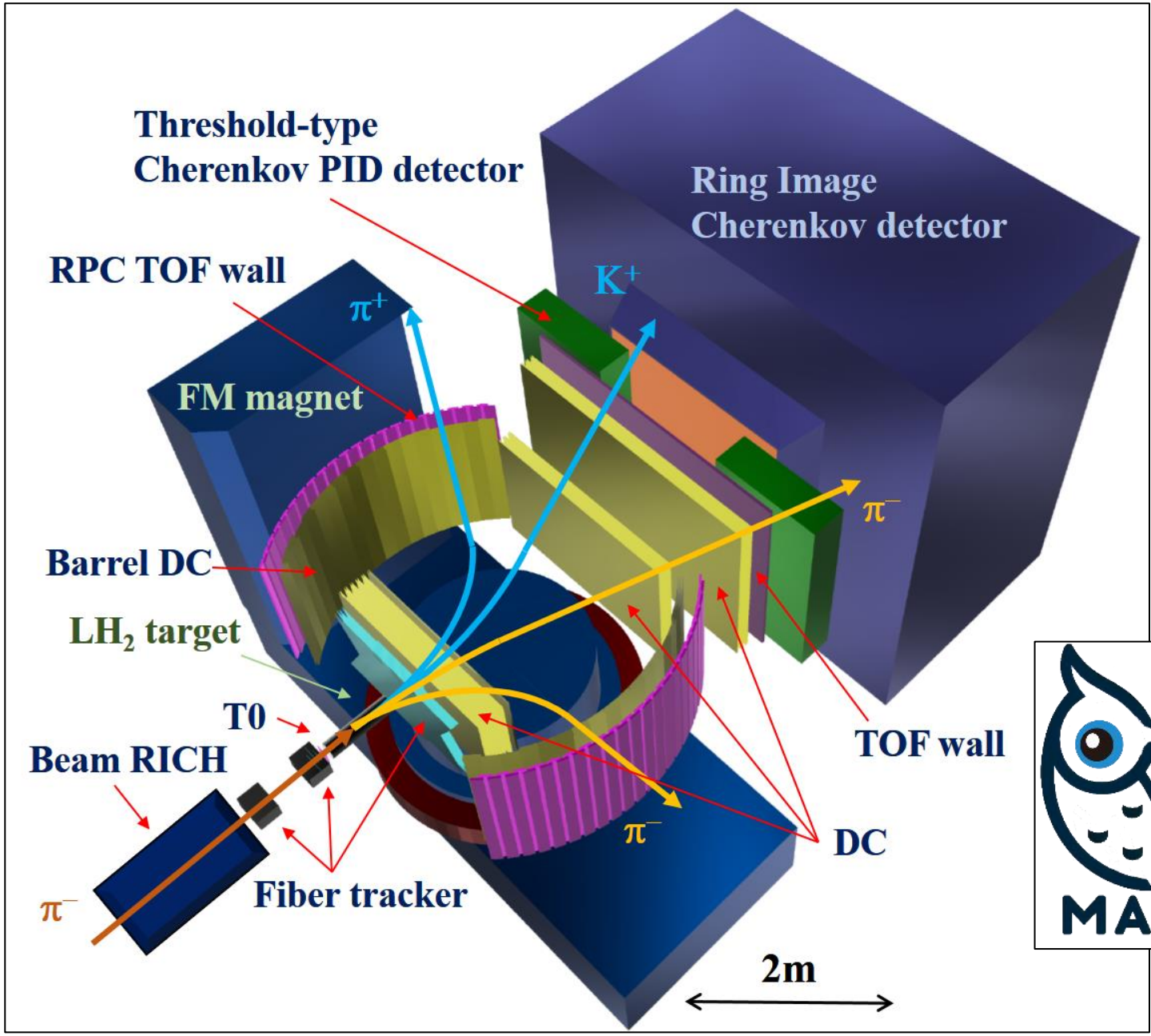


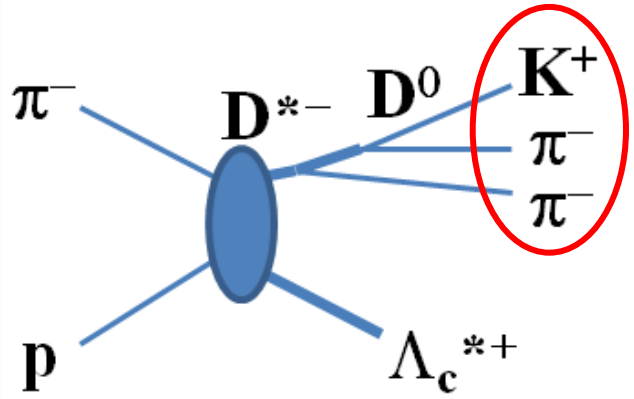
MARQ spectrometer



Decay measurement
∗ Branching ratios

$\pi^{\pm}$&p: < 4.0 GeV/c

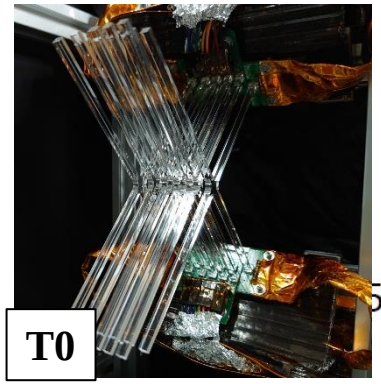




Missing mass measurement
∗ Production rate

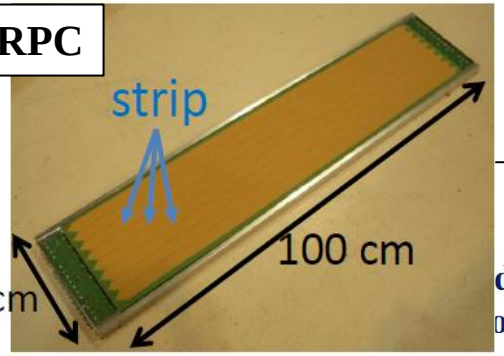
K^+ & π^-: 2–16 GeV/c
Slow π_s^-: 0.5–1.7 GeV/c

MARQ

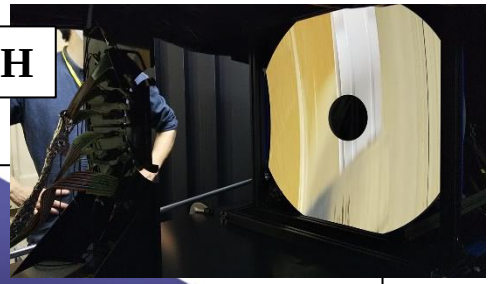


T0

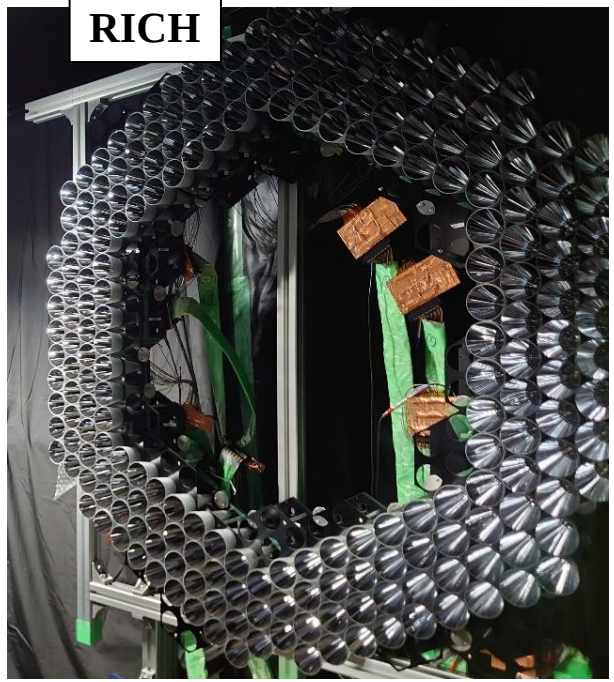
RPC

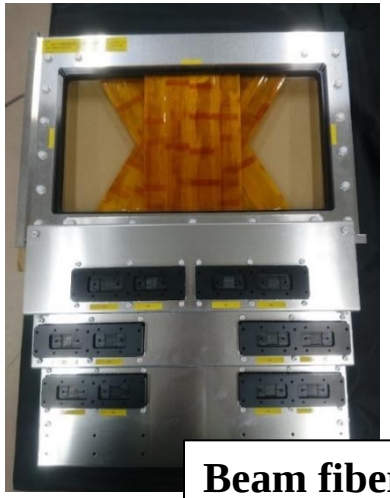


Beam RICH

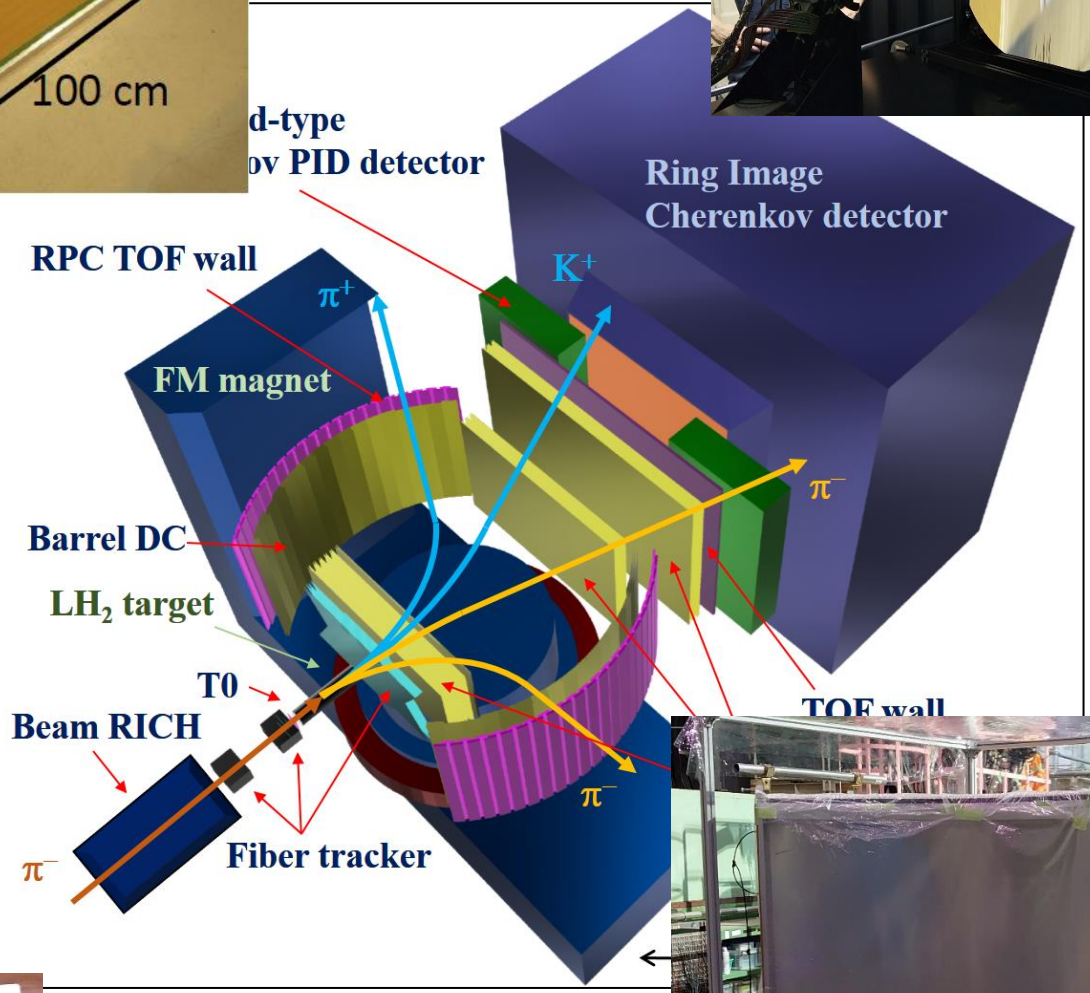


RICH

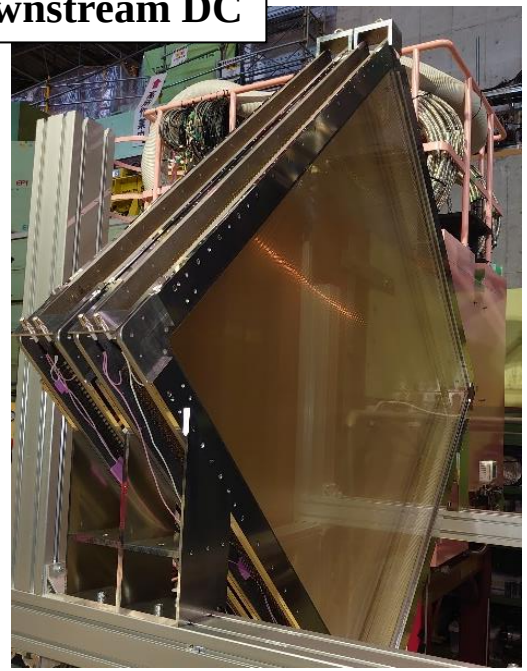


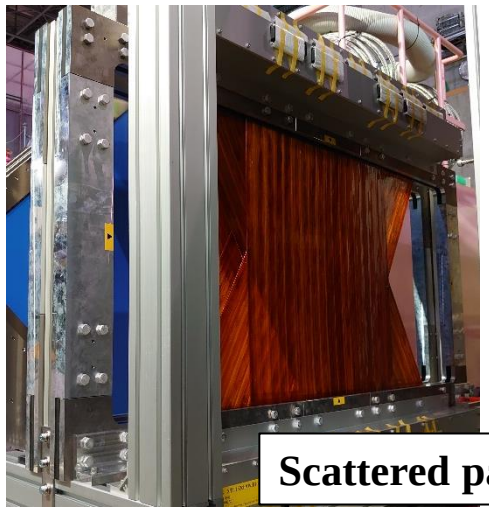


Beam fiber tracker



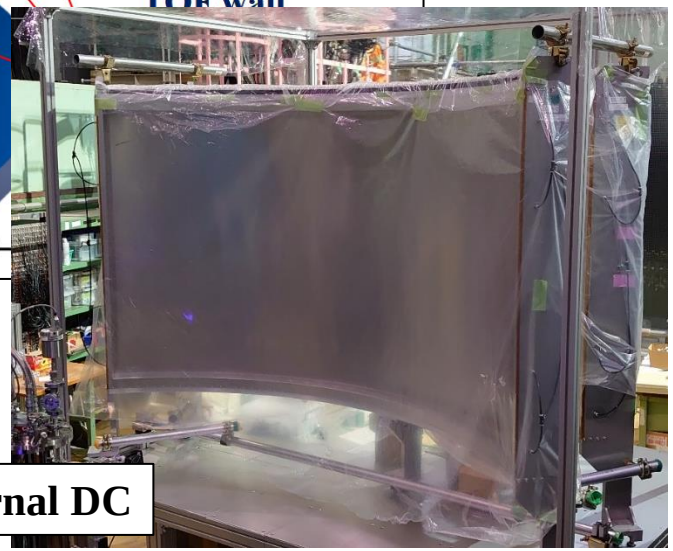
Target downstream DC



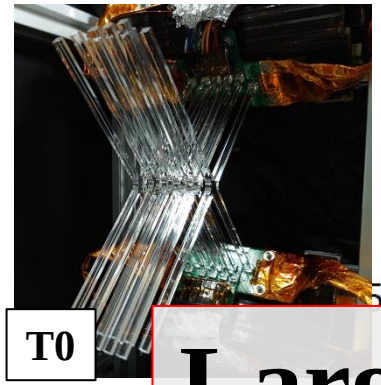


Scattered particle fiber tracker

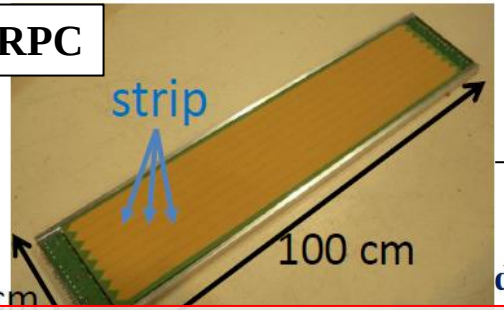
MPPC array



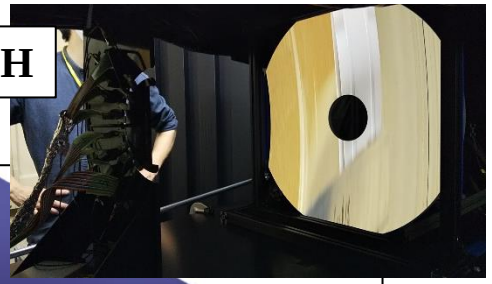
Internal DC



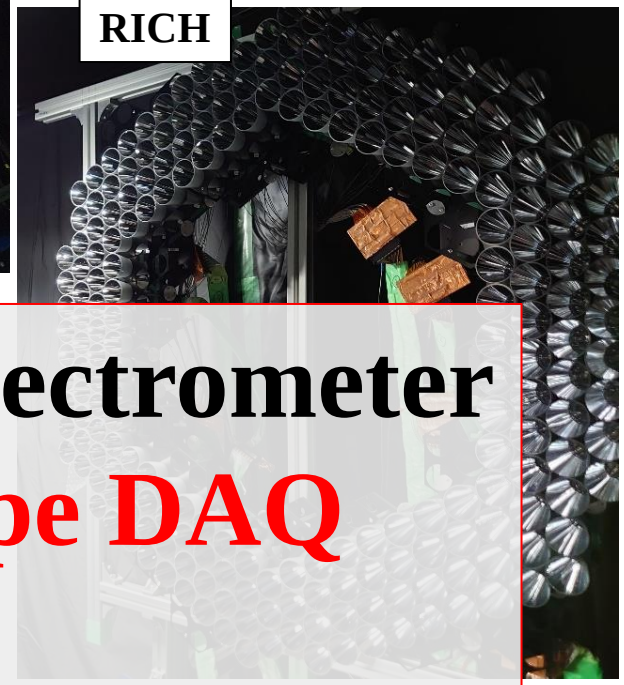
RPC



Beam RICH



RICH



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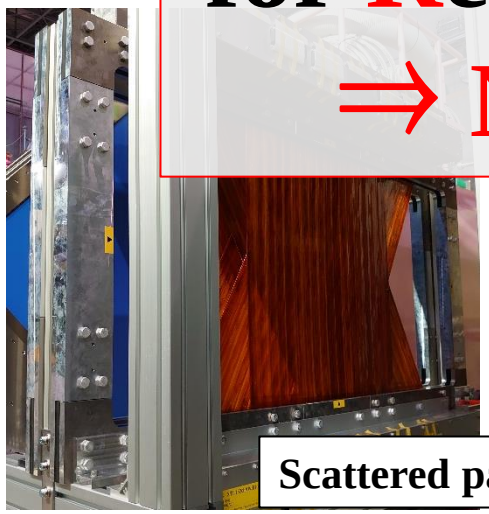
Large Acceptance Multi-Purpose Spectrometer
+ Trigger–less data-streaming type DAQ

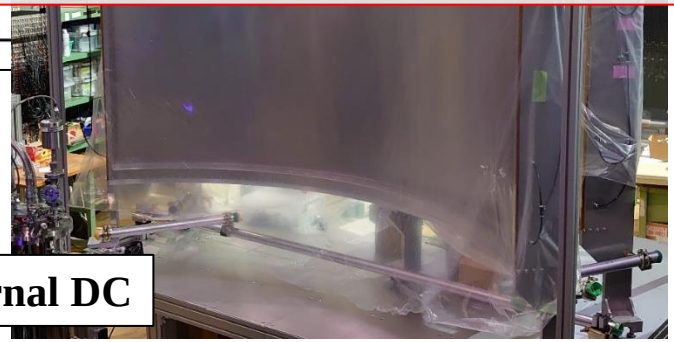
Multipurpose Analyzer for Resonances and Quark dynamics (MARQ)

⇒ New platform for Hadron experiment



Scattered particle fiber tracker

MPPC array



Internal DC

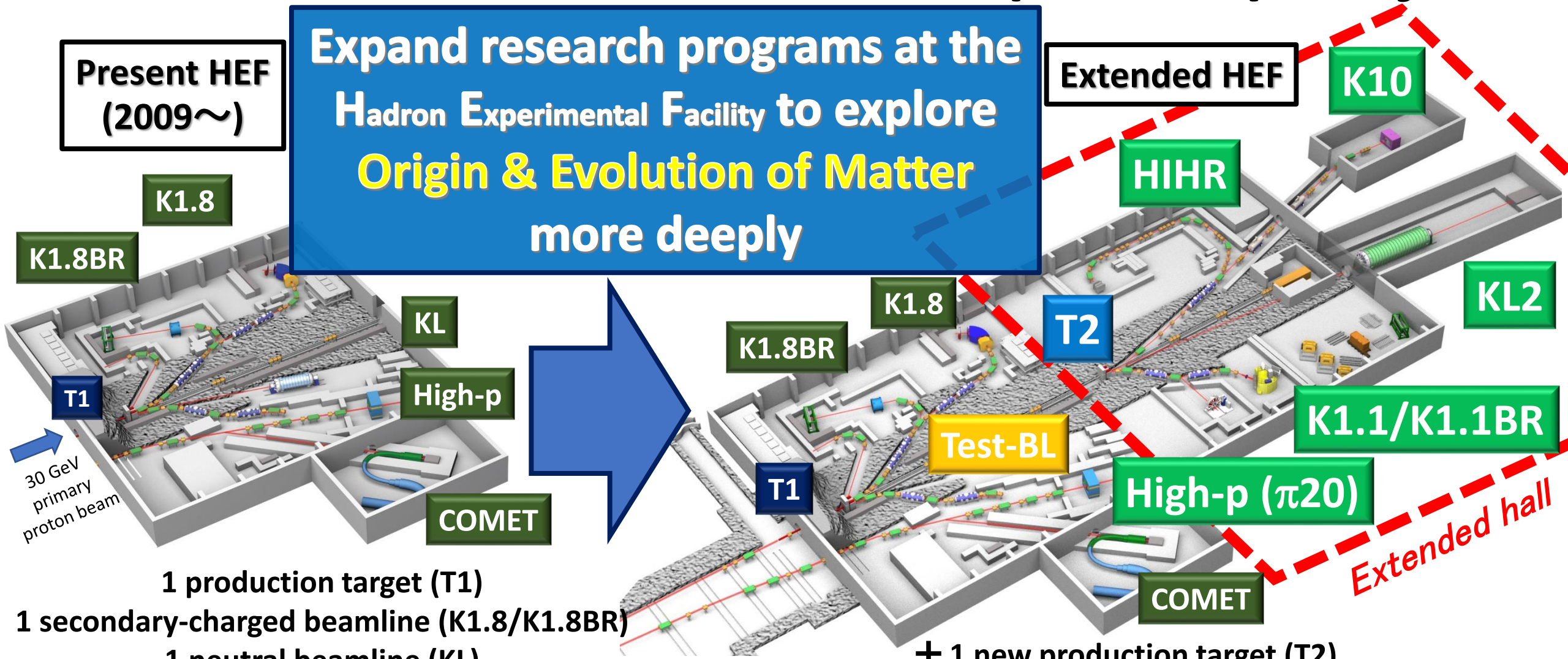
Target downstream DC

Hadron Experimental Facility eXtension (HEF-ex) Project

Present HEF (2009～)

Expand research programs at the Hadron Experimental Facility to explore Origin & Evolution of Matter more deeply

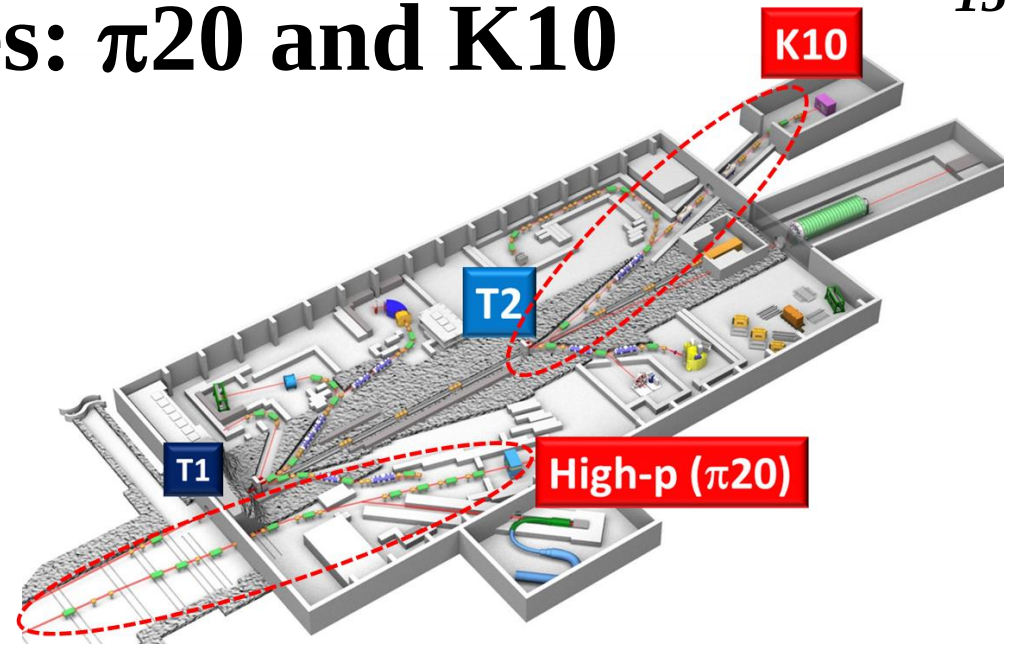
Extended HEF



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)

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

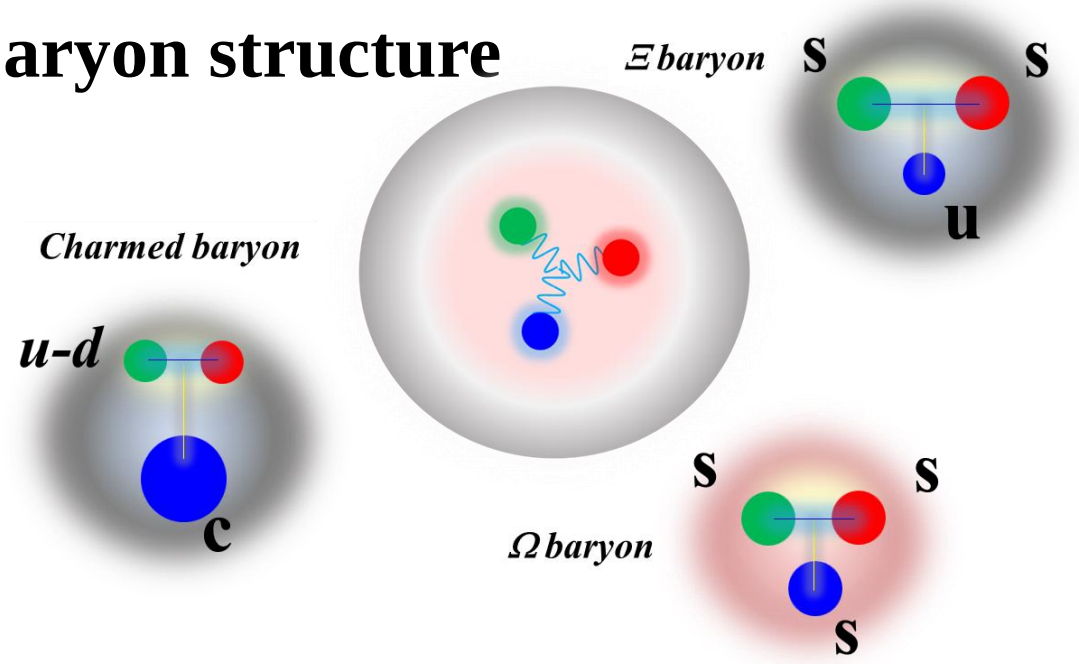
High-momentum hadron beam lines: π20 and K10



- π20: 2ndary beam (unseparated, mainly π)
  - High intensity: >10^7 /spill for π^- up to 20 GeV/c
- K10: K^- beam (K/π ~ 1/2, anti-p/π ~ 2/1)
  - High intensity: >10^6 /spill for K^- up to 10 GeV/c
  - Anti-p intensity: >10^6 /spill

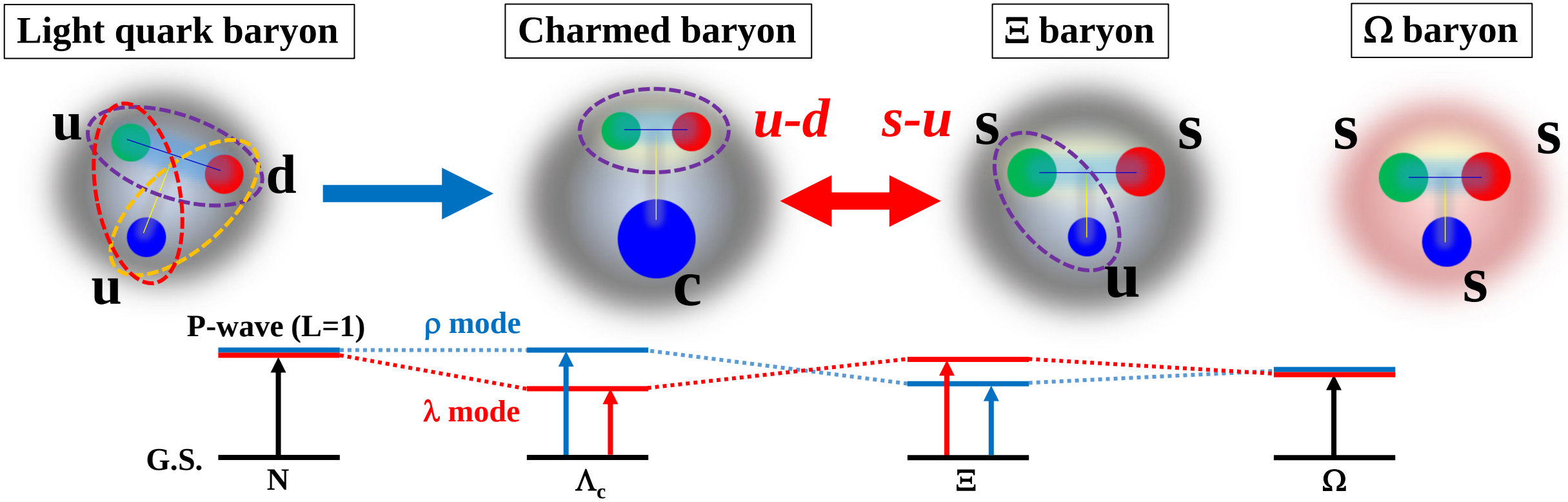
✻ Systematic *c*- and *s*-baryon spectroscopy:

Dynamics of non-trivial QCD vacuum in baryon structure



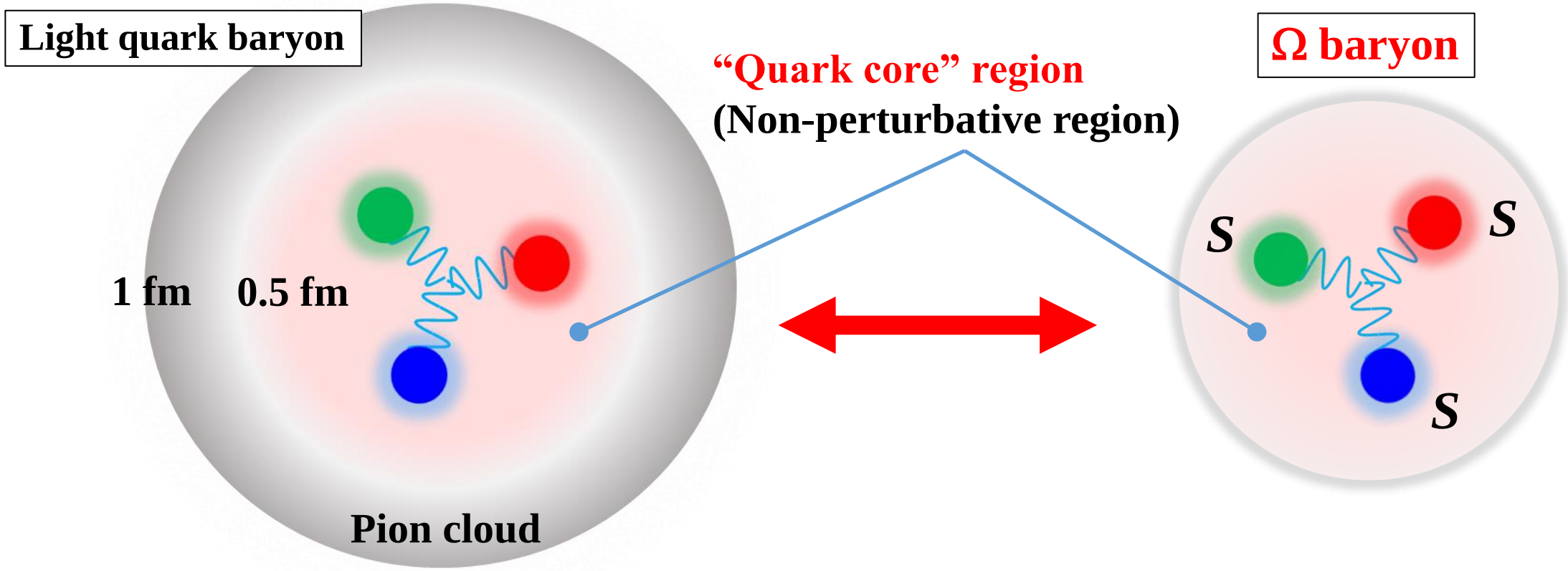
- Diquark correlation
  - *ud* diquark: Λ_c/Σ_c
  - *us/ds* diquark: Ξ
  - Only axial-vector diquark: Ω
- Spin-dependent forces
  - Excited state data of Λ_c/Σ_c, Ξ, Ω systems

Heavy flavors for revealing diquark correlation



- **Systematic studies for baryon systems with heavier flavors: *c* & *s***
  - **Charmed baryon: Disentangle *ud* diquark correlation**
  - **Ξ baryon: *us*/*ds* diquark correlation ⇒ Flavor dependence**
  - **Ω baryon: Only axial-vector diquark correlation ⇒ Reference system**

Role of Ω baryon: Single flavor system



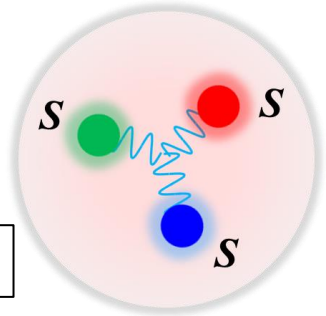
- Ω(sss) baryon: Flavor symmetric system
- Free from Pion Cloud: Investigation of "Quark core" region (Non-perturbative region)

⇒ Origin of spin-dependent forces and quark motion

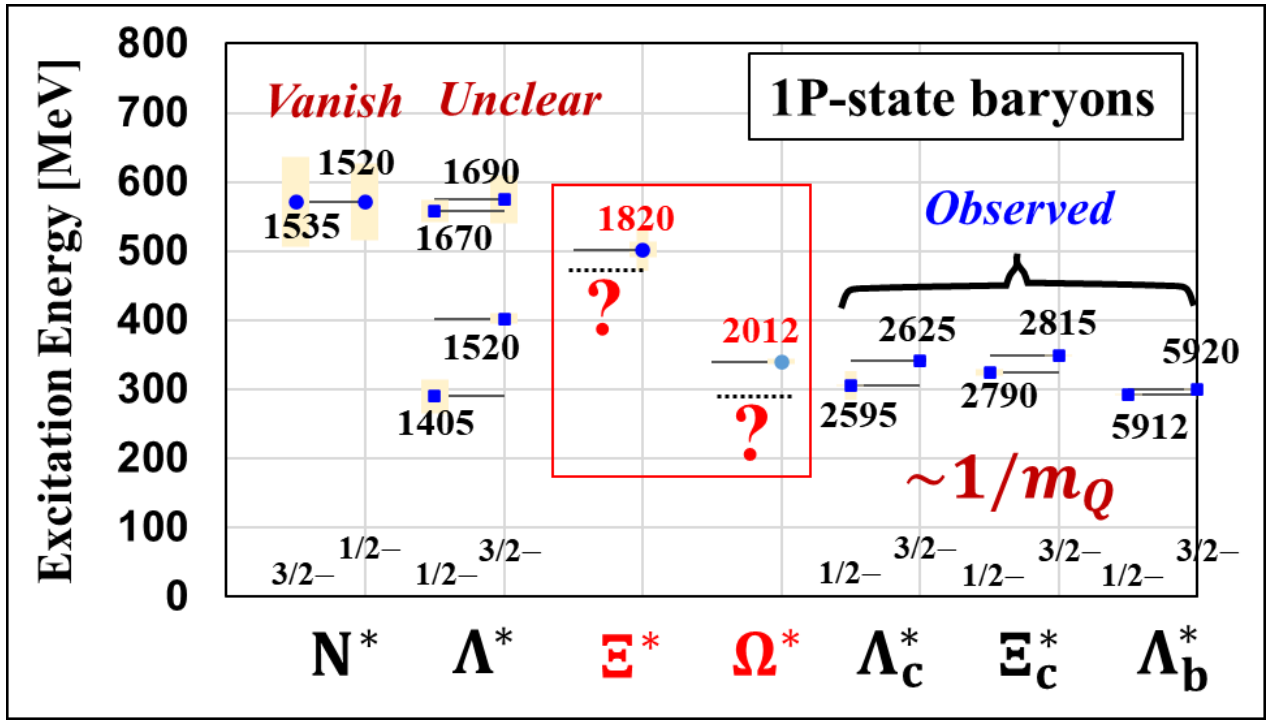
- In terms of One Gluon Exchange(OGE), Instanton Induced Interaction(III) and Pion cloud

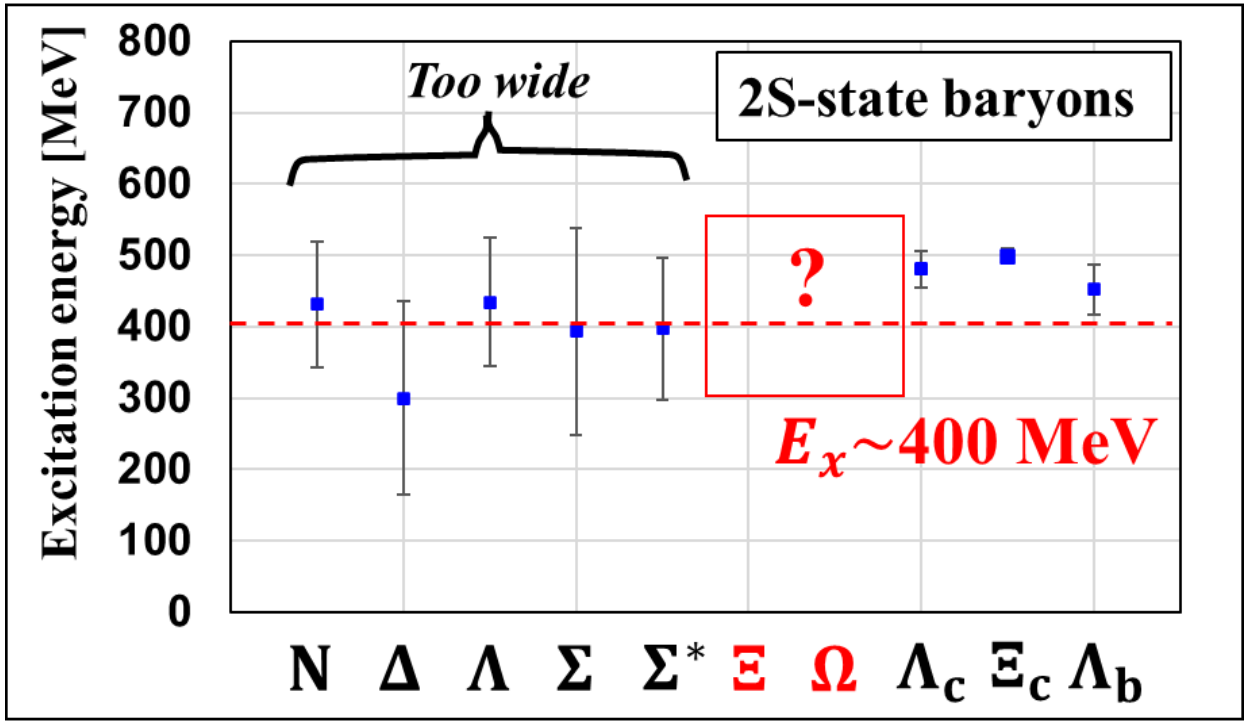
Studies of Ξ/Ω baryons

- **Investigate spin-dependent forces and quark motion**
  - **From LS partners and Roper-like resonances**



Ω baryon





- **Systematics of LS force**
  - Ω(2012)⁻(3/2⁻?) ⇔ Ω*⁻(1/2⁻?)
  - Ξ(1820)⁻(3/2⁻?) ⇔ Ξ*⁻(1/2⁻?)
  - **LS partners (L=2 states)**

- **Systematics of Roper-like resonances**
  - **Small excitation energy and wide width ?**
  - **Mass & width of Ω w/o π cloud**

  ⇒ **Width: Quark core size**

Ω baryon 2S state

∗ **Measurement of 2S state width(Γ)**

$\Rightarrow \Gamma \sim \langle p_q^2 \rangle$

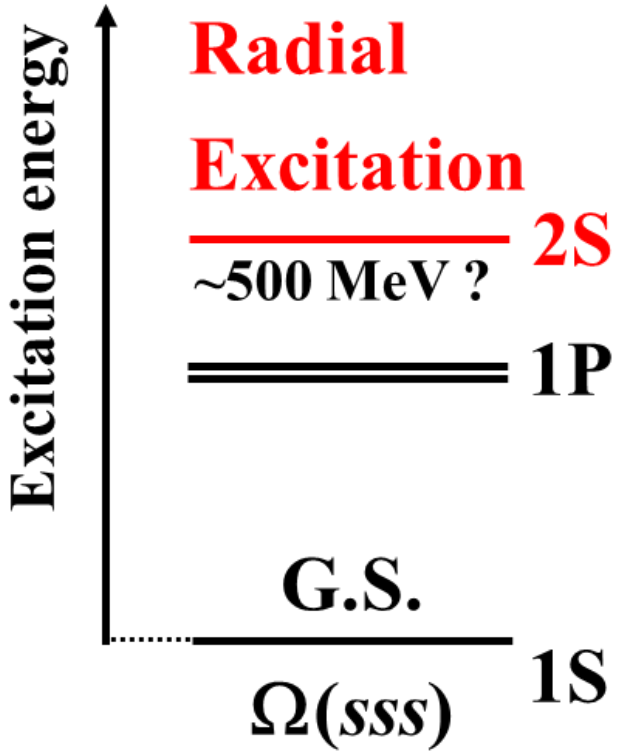
- Internal quark momentum: $\langle p_q^2 \rangle$

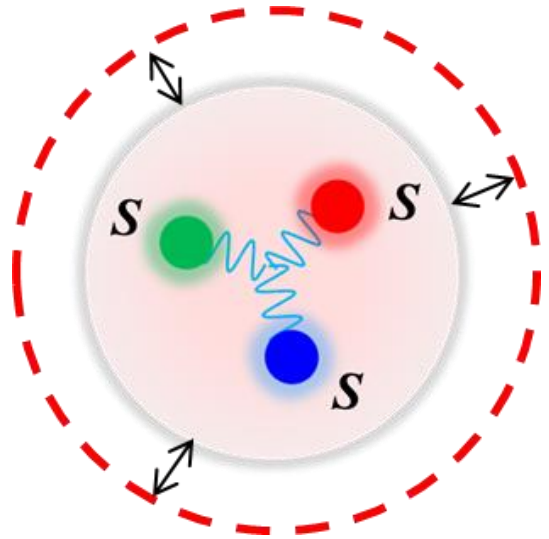
$\Rightarrow \langle r_q^2 \rangle \sim 1/\langle p_q^2 \rangle$

- J. Arifi *et al.*, PRD105, 094006 (2023)
- J. Arifi *et al.*, PRD103, 094003 (2021)

$\Rightarrow$ **Size of "quark core": $\langle r_q^2 \rangle$**

- Essential of free from π cloud

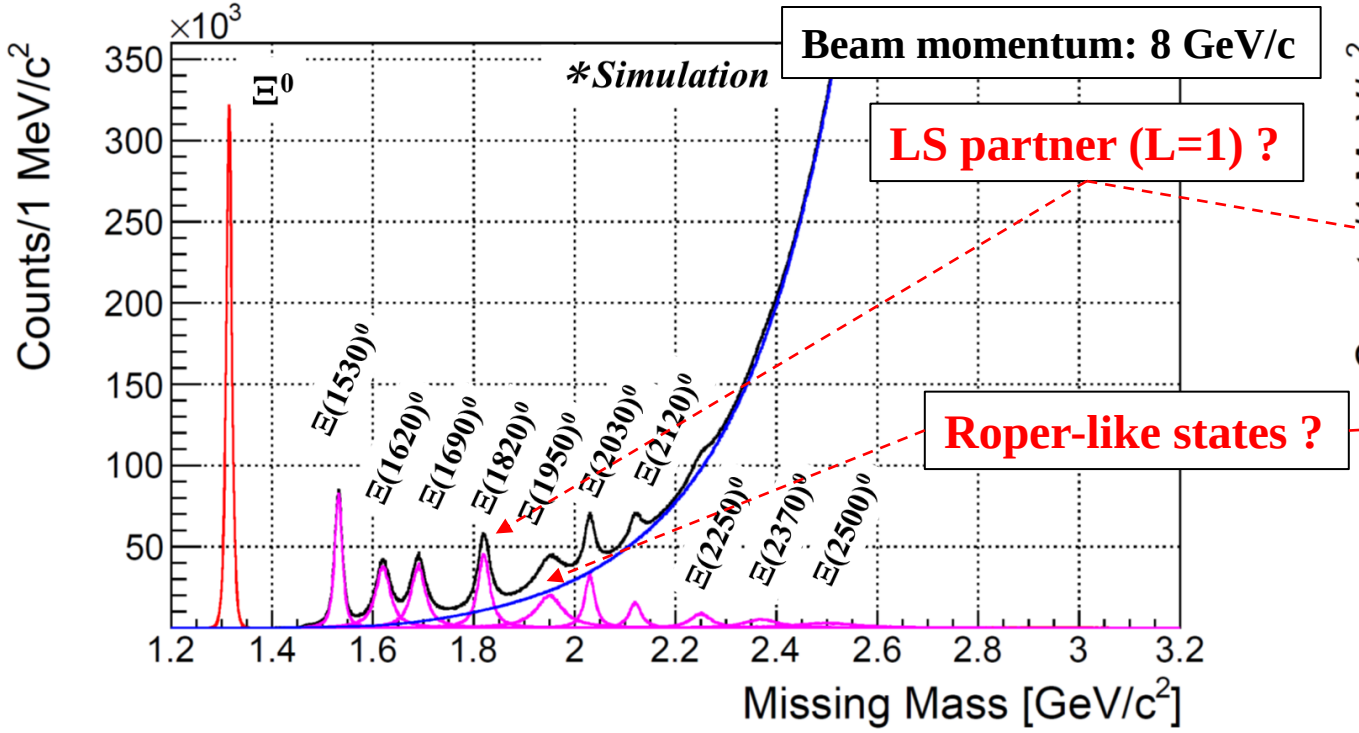


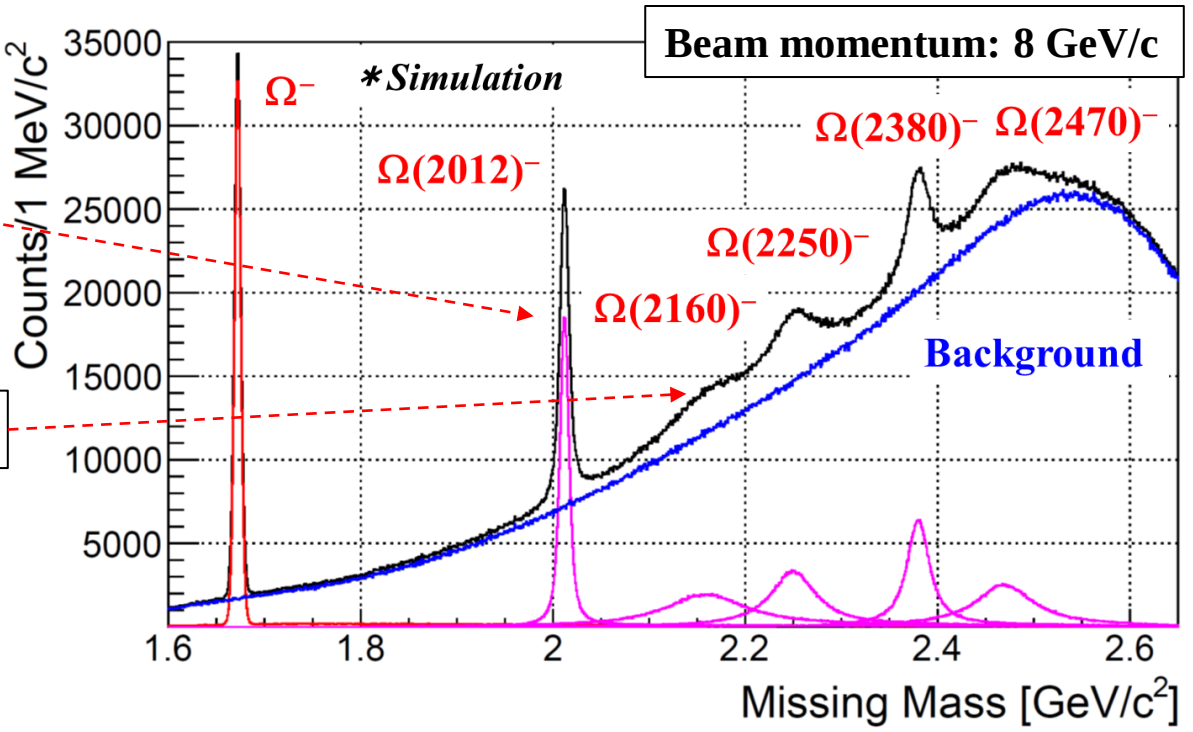


∗ **Effects of K cloud need to be investigated.**

- **Minor contribution ?: $M_K/M_\pi = 3.5 \Rightarrow$ Range of Yukawa coupling ~0.4 fm**
- **Branching ratio of $\Omega^{*-} \rightarrow K + \Xi$: Coupling of K and Ω**
- **(Future study) ΩN bound state: Strength of K meson exchange**

Expected mass spectra: K^- p reactions





- **Reaction: $K^- p \rightarrow K^+ \Xi^{*-}$ / $K^- p \rightarrow K^{*0} \Xi^{*0}$**
  - **Beam: 5–8 GeV/c**
- **Missing mass: K^+ / K^{*0}**
  - **Mass resolution: ΔM ~7 MeV(σ)**

- **Reaction: $K^- p \rightarrow \Omega^{*-} K^{*0} K^+$**
  - **Beam: 7–10 GeV/c**
- **Missing mass: K^{*0} & K^+**
  - **Mass resolution: ΔM ~5 MeV(σ)**

∗ Only a few established states in PDG

⇒ Systematic measurements: Identification of λ/ρ mode and SS/LS studies

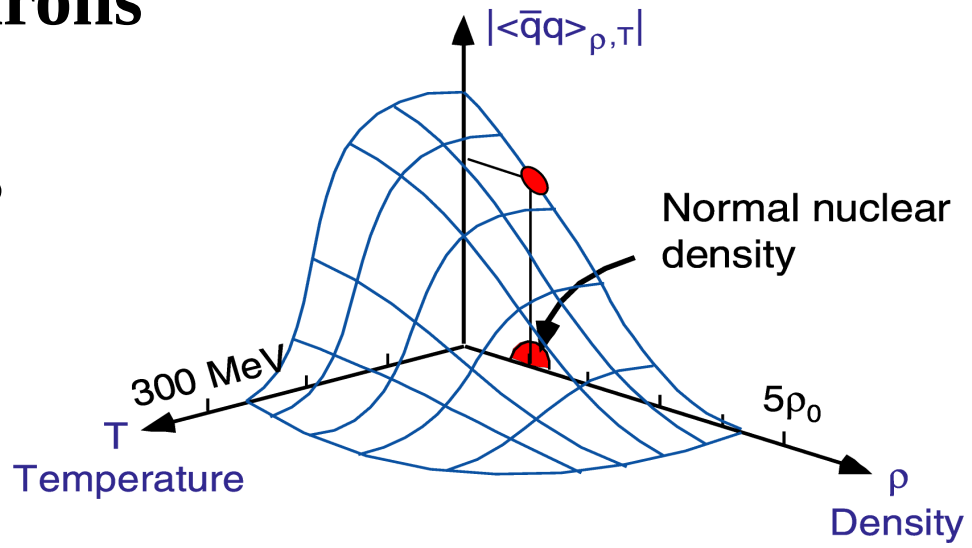
Hadron in nuclei

Current physics program at high-p beam line

Measurement of spectral modification of ϕ meson in nuclei (E16)

W.Weise NPA553, 59 (1993).

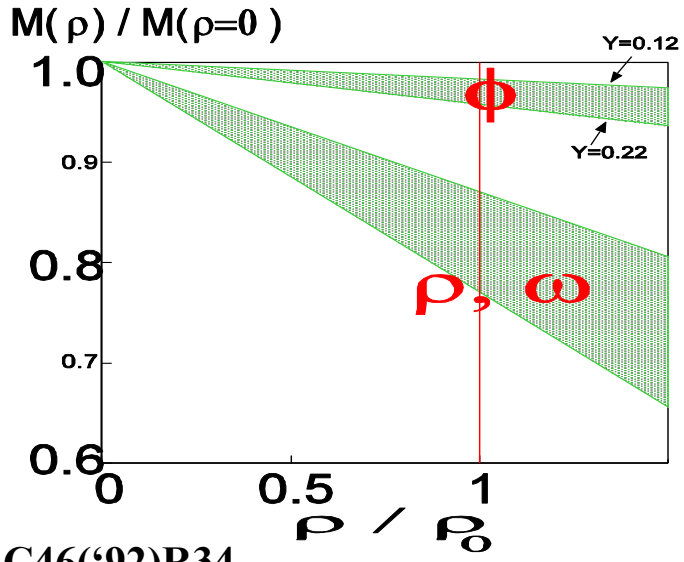
∗ Attack **mass-generation mechanism** of hadrons



- QCD vacuum: Quark-Gluon condensations
  - 98% of proton mass: Dynamically generated
- How to examine ?
  - To probe property of QCD condensation

  ⇒ Hadron mass modification in nuclei

- Experiment on nuclear targets
  - Vector meson produced in 30 GeV p + A reaction
  - Dilepton measurement: $\phi \rightarrow e^+e^-$ (B.R.~10^{-4})
  - Velocity & nuclear size dependences
  - Momentum dependence



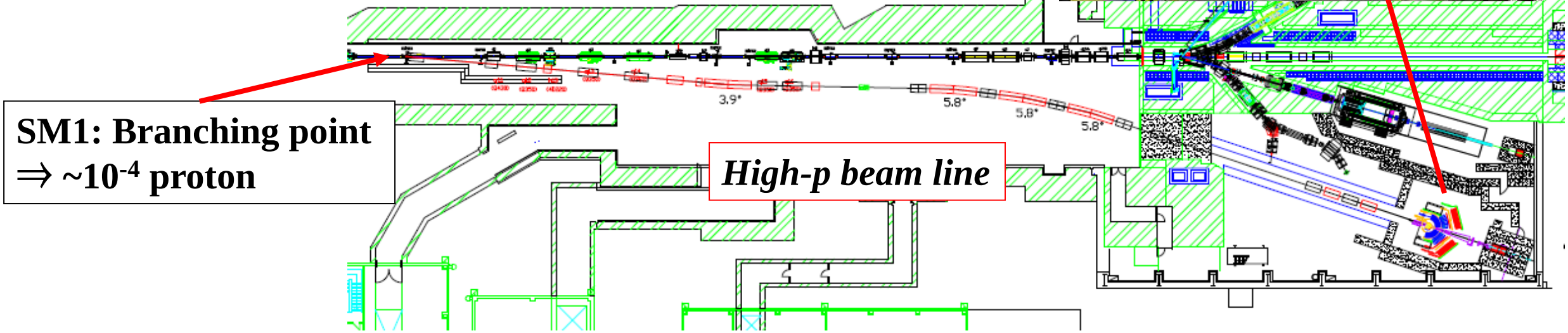
Hatsuda & Lee, PRC46('92)R34

High-p beam line and preparation status

- Protons branches off from the primary line at SM1
- 30 GeV primary proton: 10^{10} /spill (2 seconds)

- High statistics experiment
  - Reaction rate: 10M (10^{10} /spill×0.1% targets (C, Cu, Pb))
  - High-rate capability: 100k detector channel
  - High mass resolution: ΔM = 7 MeV

Experimental setup



SM1: Branching point
⇒ ~10^{-4} proton

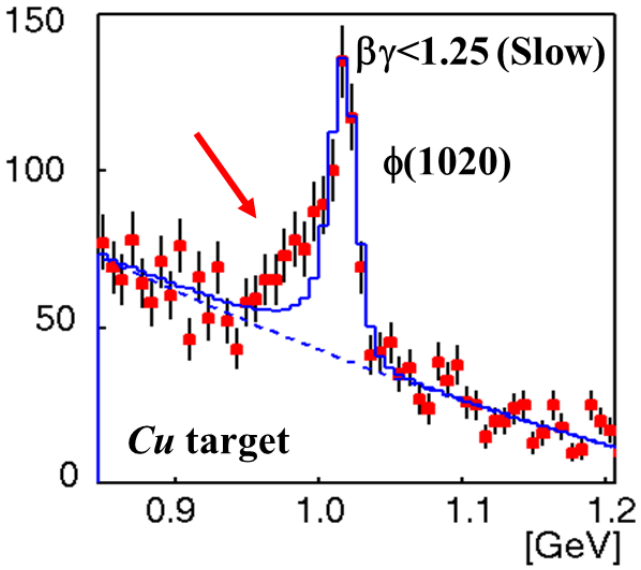
High-p beam line

- On-going commissioning finalized until May 2024

⇒ Physics run from Autumn 2024 (Beam time in November)

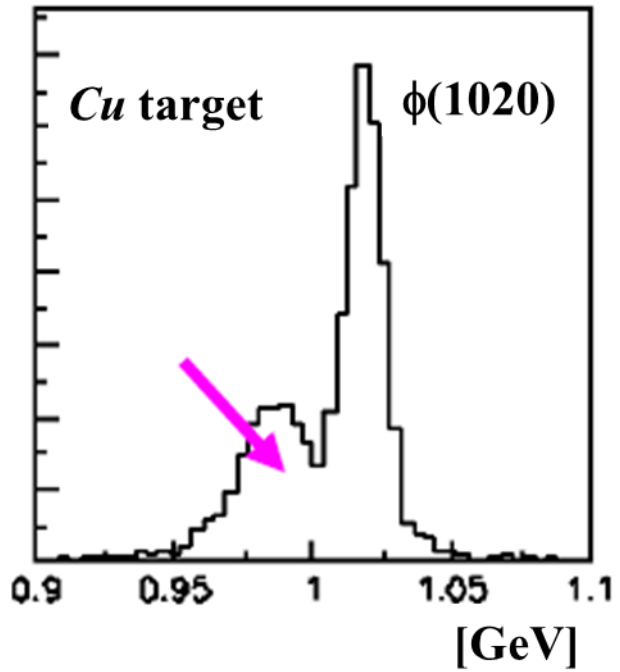
Expected spectrum

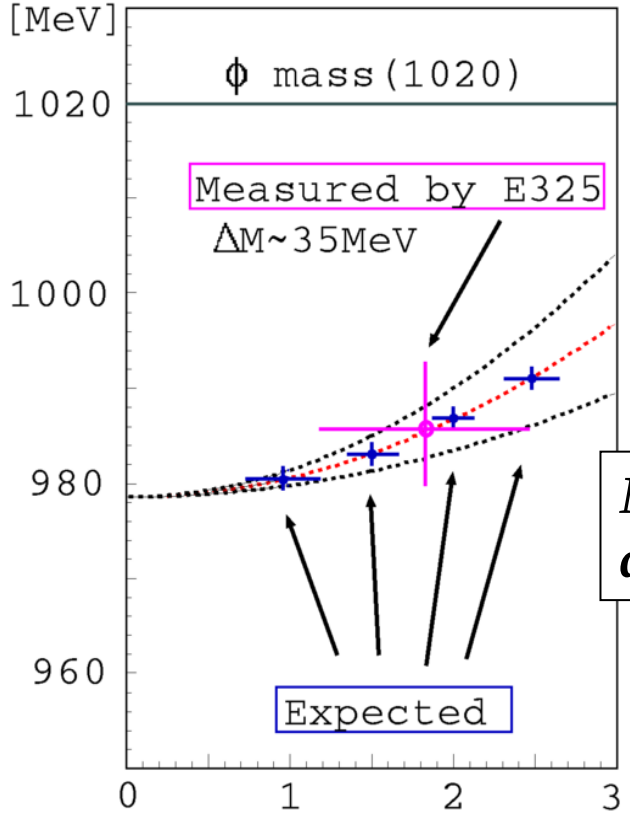
Previous data @ KEK PS



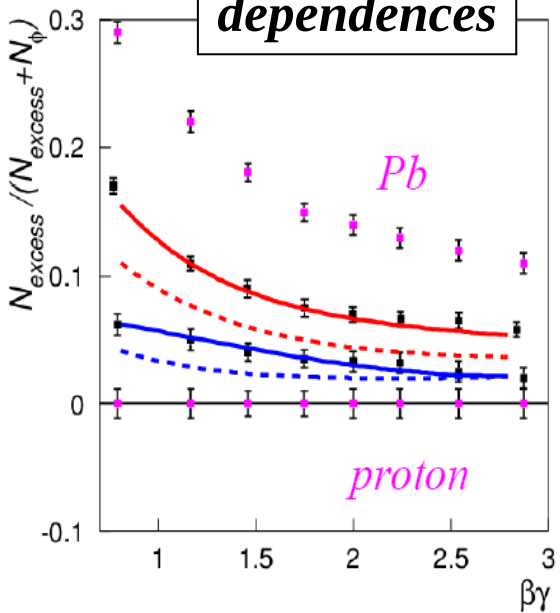
R. Muto *et al.*, PRL 98(2007)042501

J-PARC data





Momentum dependence



Nuclear size dependences

- **Several points for the dispersion relation**
  by J-PARC intense beam and dedicated experiment setup

⇒ Further related studies

- **$\phi \rightarrow K^+K^-$ measurement (E88)**
- **Intrinsic charm production by $\mu^+\mu^-$ measurement (P91)**

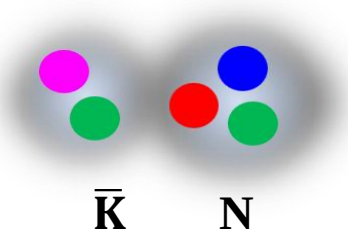
Hadron spectroscopy by dedicated experiments

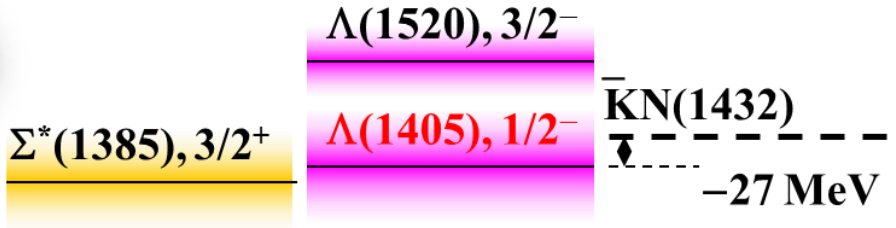
Recent results: Λ(1405)

Narrow Λ^*, ϕN resonances

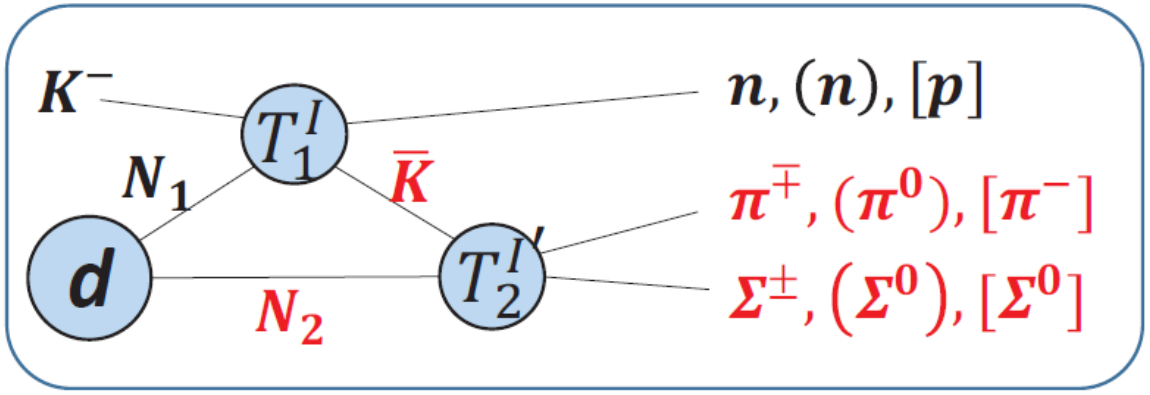
Λ(1405): Hadron molecule state (Near $\bar{K}N$ threshold)

∗ $J^P = 1/2^-$, I = 0, $M_{\Lambda(1405)} < M_{KbarN}$





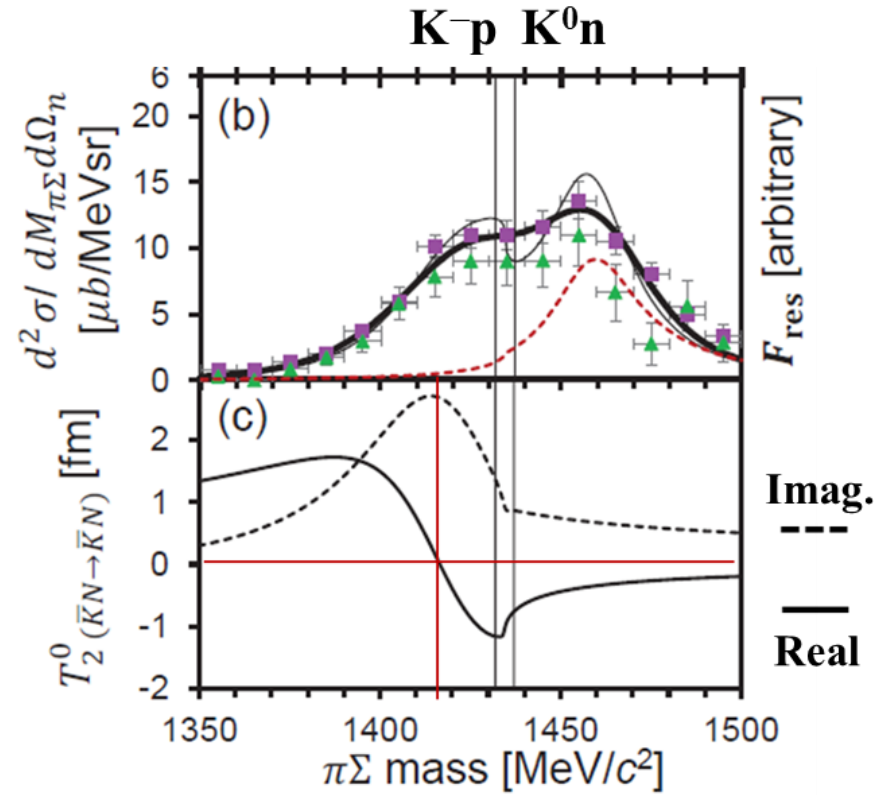
- Study by $K^- d \rightarrow \pi \Sigma n$ @ 1 GeV/c (E31)
  - S-wave $\bar{K}N \rightarrow \pi\Sigma$ scattering below $\bar{K}N$ threshold



- Scattering amplitude analysis

⇒ Pole: $1417.7^{+6.0\ +1.1}_{-7.4\ -1.0} + \left[-26.1^{+6.0+1.7}_{-7.9\ -2.0}\right] i\ MeV/c^2$

  - S. Aikawa et al., Phys. Lett. B 837 (2023) 137637
  - Higher pole ($\bar{K}N$) consists with the Chiral Unitary Model based calculations

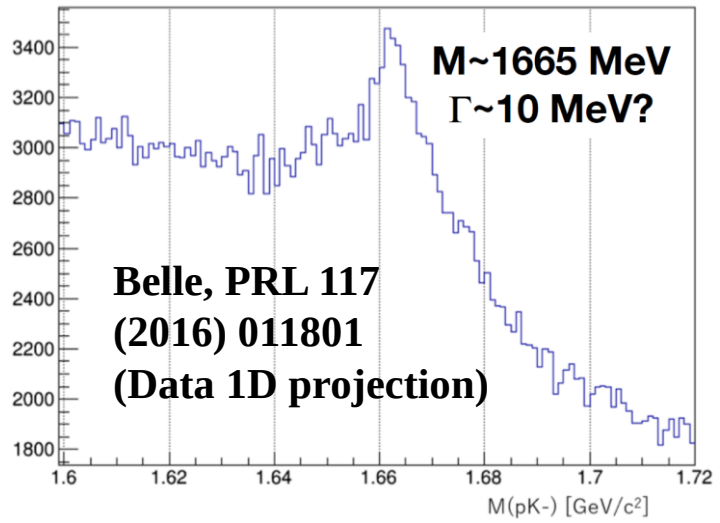


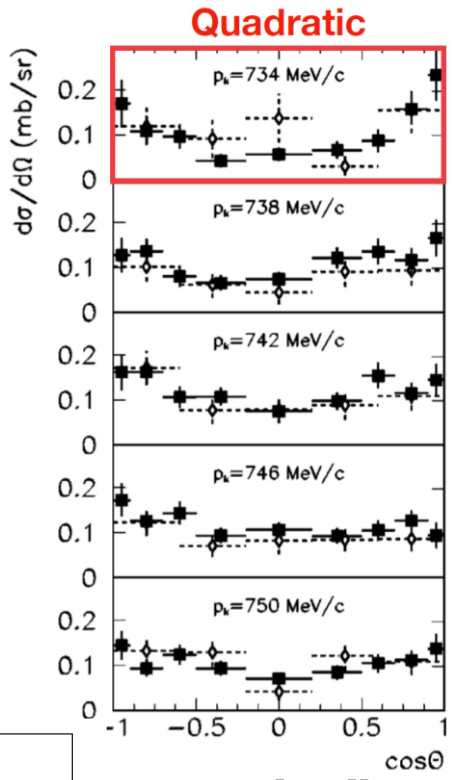
Hadron resonance studies

- **Search for a narrow Λ^* resonance (E72)**
  - **Near $\Lambda\eta$ threshold: ~1.66 GeV/c^2**
  - **Narrow width: ~10 MeV**
  - **Spin/parity ?: $J = 1/2^- \Leftrightarrow J = 3/2^-$**

$\Rightarrow K^- p \rightarrow \eta \Lambda$ reaction @ 0.73 GeV/c

- **Maturement of angular distribution: J = 3/2**





Crystal Ball, PRC 64 (2001) 055205

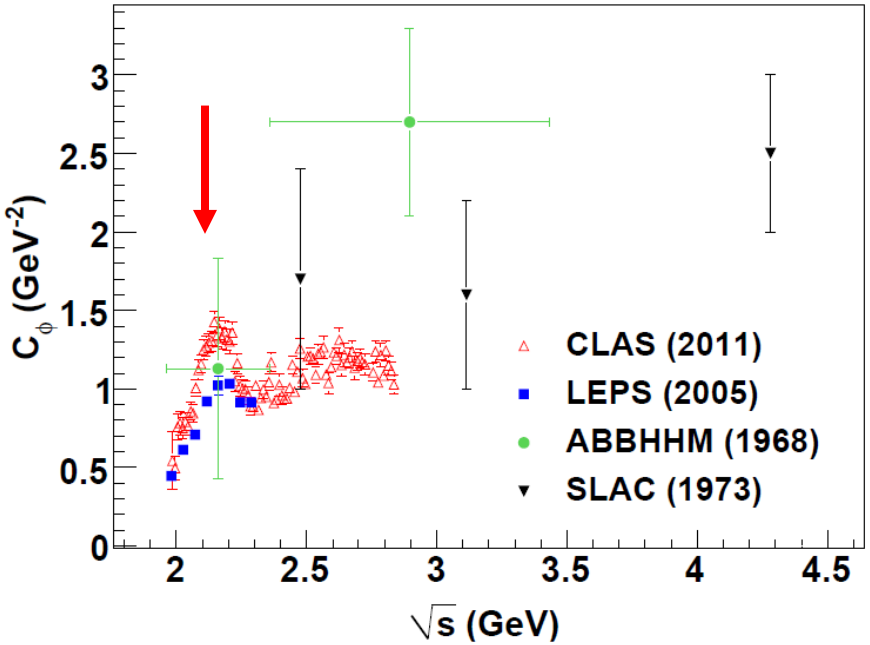
- **Study of ϕN resonance (P95)**
  - **Bump structure by photon reaction**
  - **Hidden $q\bar{q}$ pentaquark ? : $P_c \Leftrightarrow P_s$**

$\Rightarrow \pi^- p \rightarrow \phi n$ reaction @ 1.6–2.4 GeV/c

- ***s*-channel production (π^- beam)**

$\Leftrightarrow$ *t*-channel pomeron dominance (γ beam)

- **Confirm bump structure**
- **Measure decay angular distribution**



B. Dey et al., PRC89, 055208 (2014).

Summary

Hadron physics at J-PARC hadron facility

✱ Explore Origin & Evolution of Matter more deeply

⇒ Experiments using hadron beams: $\pi^{\pm}$, K^{-}, proton/anti-proton

- Secondary beams: < 2 GeV/c by current beam lines

⇒ 2–20 GeV/c by high-p(π20) beam line

- Primary proton beam @ 30 GeV

Current beam line		π20 beam line
Hadron in nuclei	*Hadron structure*	Nucleon structure
Λ^{*} resonance		Charmed baryon spectroscopy
H dibaryon search		Ξ/Ω baryon spectroscopy
Kaonic nuclei	*Hadron interaction*	Non-strange dibaryon search
Hyperon-N scattering		High-mom. Hyperon-N scattering
Λ hypernuclear spectroscopy		ϕn resonance study
Ξ hypernuclear spectroscopy		Ξ-N/ Ω-N scattering

Summary

- **Hadron physics at J-PARC hadron facility**
  - **Explore Origin & Evolution of Matter more deeply**
  - **Experiments using hadron beams: $\pi^{\pm}$, K^{-}, proton/anti-proton**

- **Spectroscopy of heavier flavors for understanding "Baryon system"**
  - **Systematic spectroscopy of Λ_c/Σ_c, Ξ, Ω baryons with high-momentum beams**

- **Hadron in nuclei for understanding "Mass generation"**
  - **Vector meson (ϕ) property measurements on nuclear targets**

- **Investigation of exotic states for understanding "Exotic property"**
  - **Specific measurements of exotics state property by dedicated experiments**

∗ J-PARC hadron experimental facility provides us unique opportunities for hadron physics experiments.