Study of internal structure of baryons using hadron beam

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研究会「EICで展開する新たな原子核・素粒子物理」

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  - **Study of hadrons with specific properties: Λ^*, Ω**
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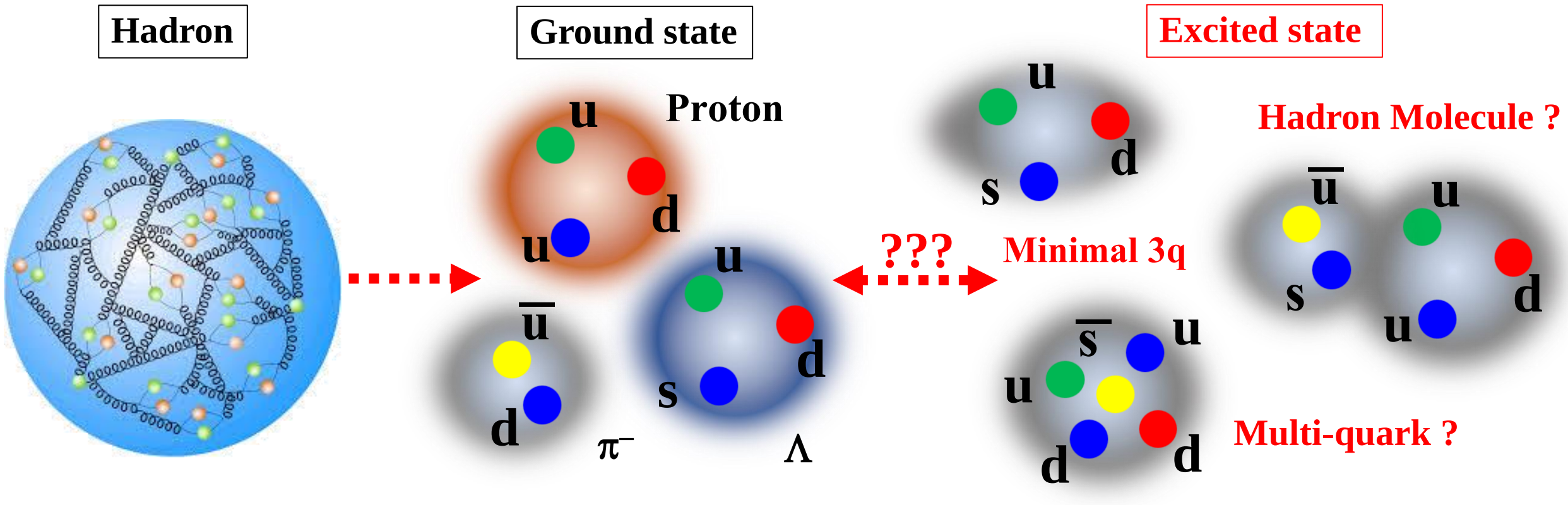
Introduction

Baryon spectroscopy with high-momentum hadron beams at J-PARC

How quarks build hadrons ?



∗ Dynamics of non-trivial QCD vacuum in low energy regime

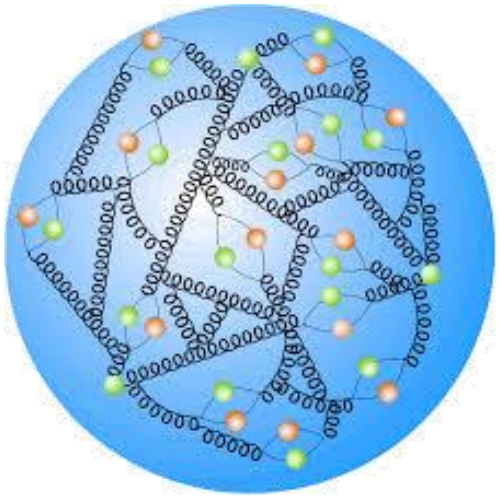
• Investigation of effective degrees of freedom and their interactions

⇒ Spectroscopy experiment for investigating excited states by hadron beam

Baryon structure in the low-energy regime

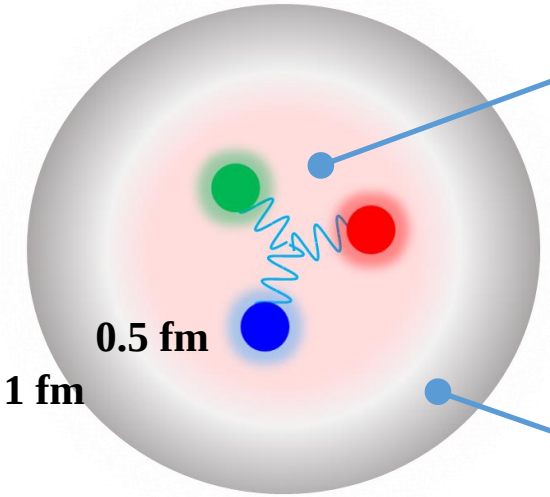
High energy

perturbative



Low energy

non-perturbative



- **Non-perturbative region**

⇒ "Quark core" region

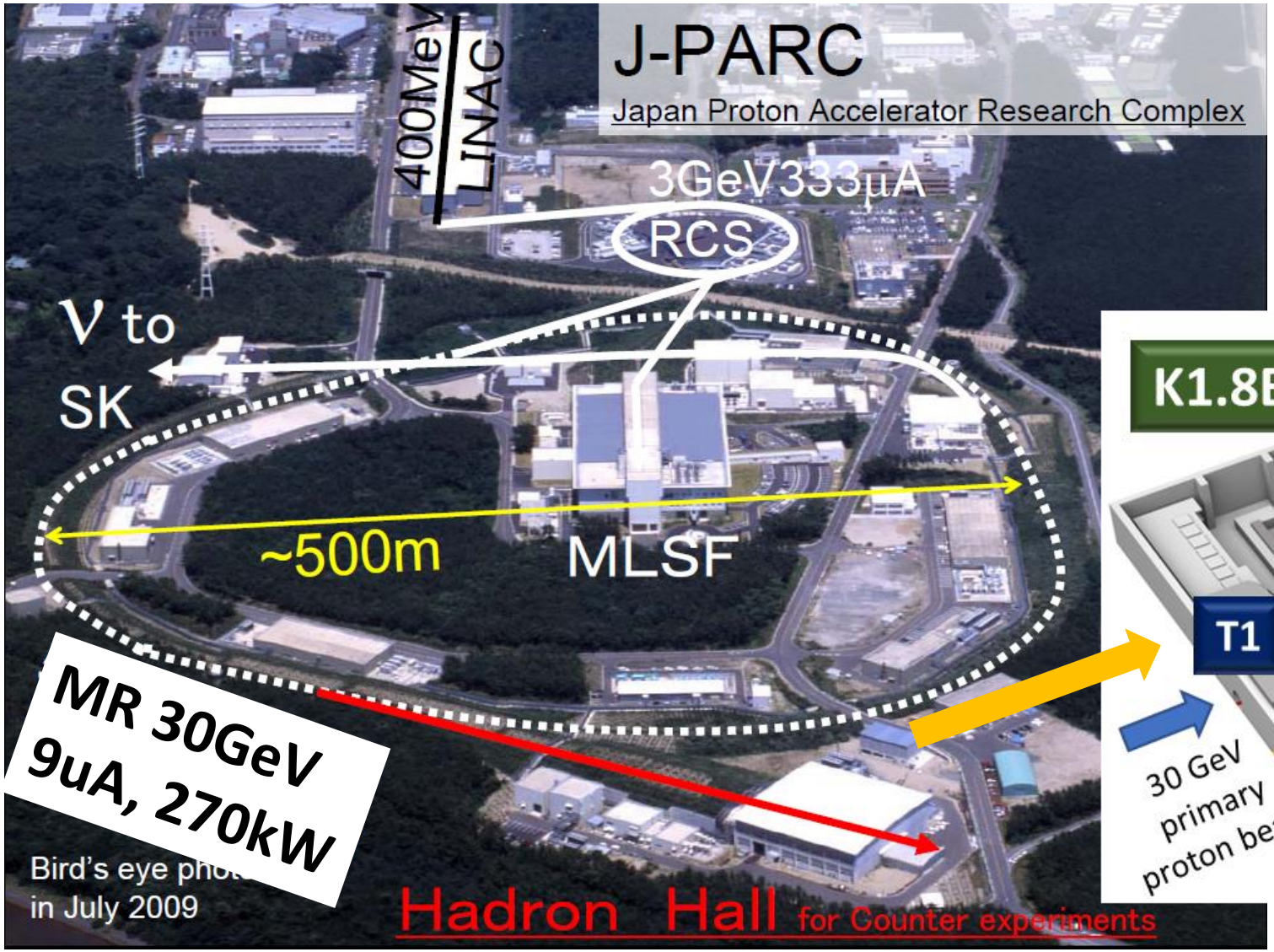
- **Non-trivial gluon field: Instanton***
- **Chiral condensate $\langle \bar{q}q \rangle \neq 0$**
  - **Dressed quark (Constituent quark)**
  - **Emergence of π**

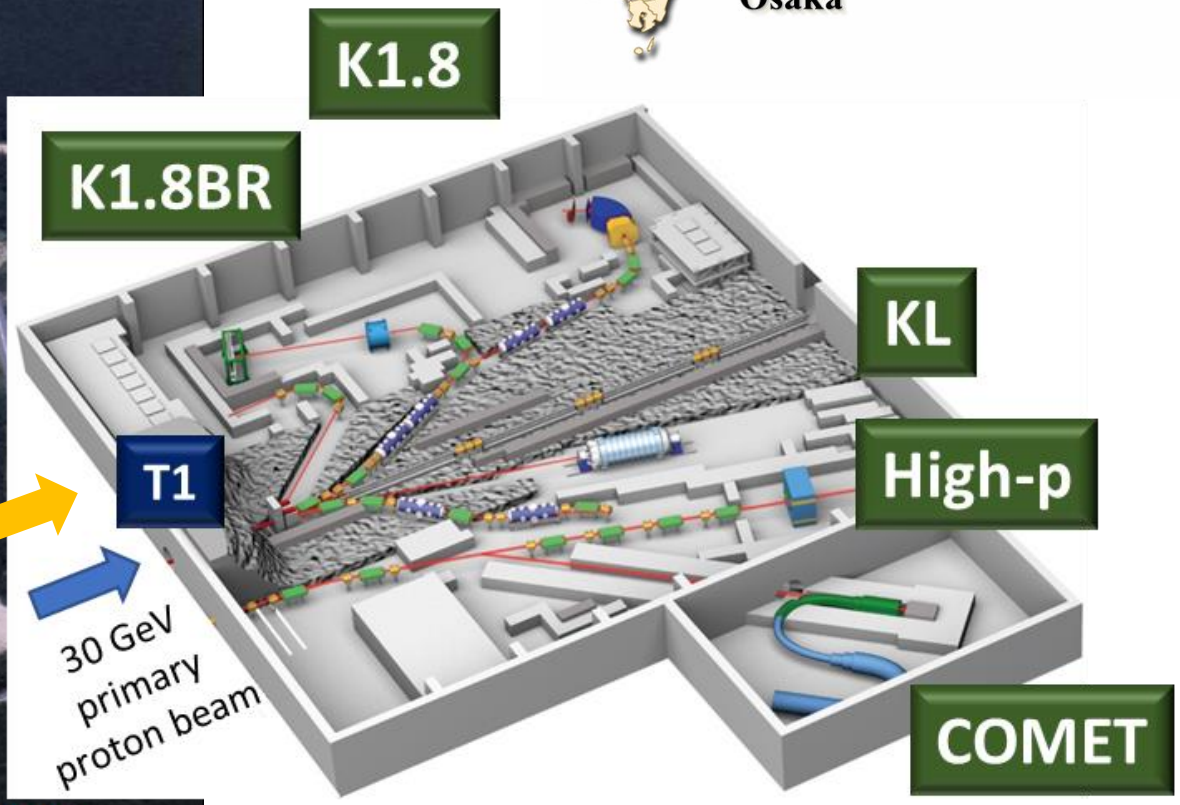
- **Meson (π) Cloud**

- **Dynamics of non-trivial QCD vacuum ⇒ Dynamics of Effective DoF**
  - **Degrees of freedom: Diquark correlation, hadron molecule**
  - **Origin of spin-dependent force**
  - **Quark motion 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*

J-PARC & Hadron Experimental Facility



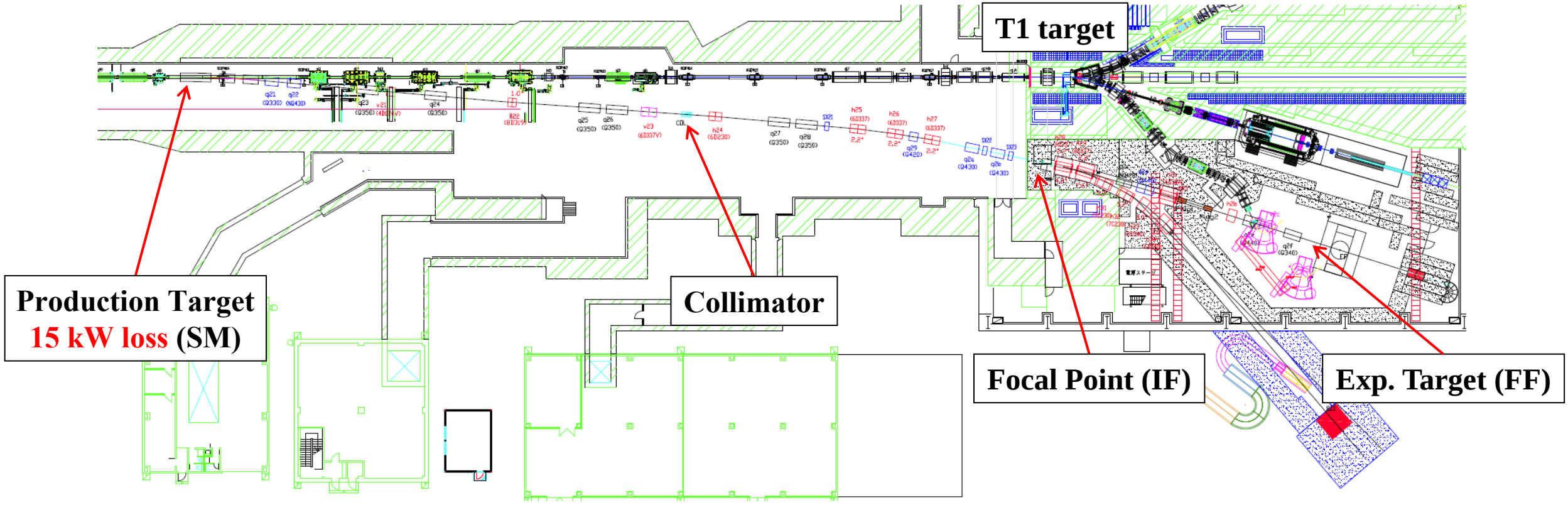


World's highest level intensity proton beam ⇒ Beam power 80 kW

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: $\Delta p/p = 0.1\%(\sigma)$

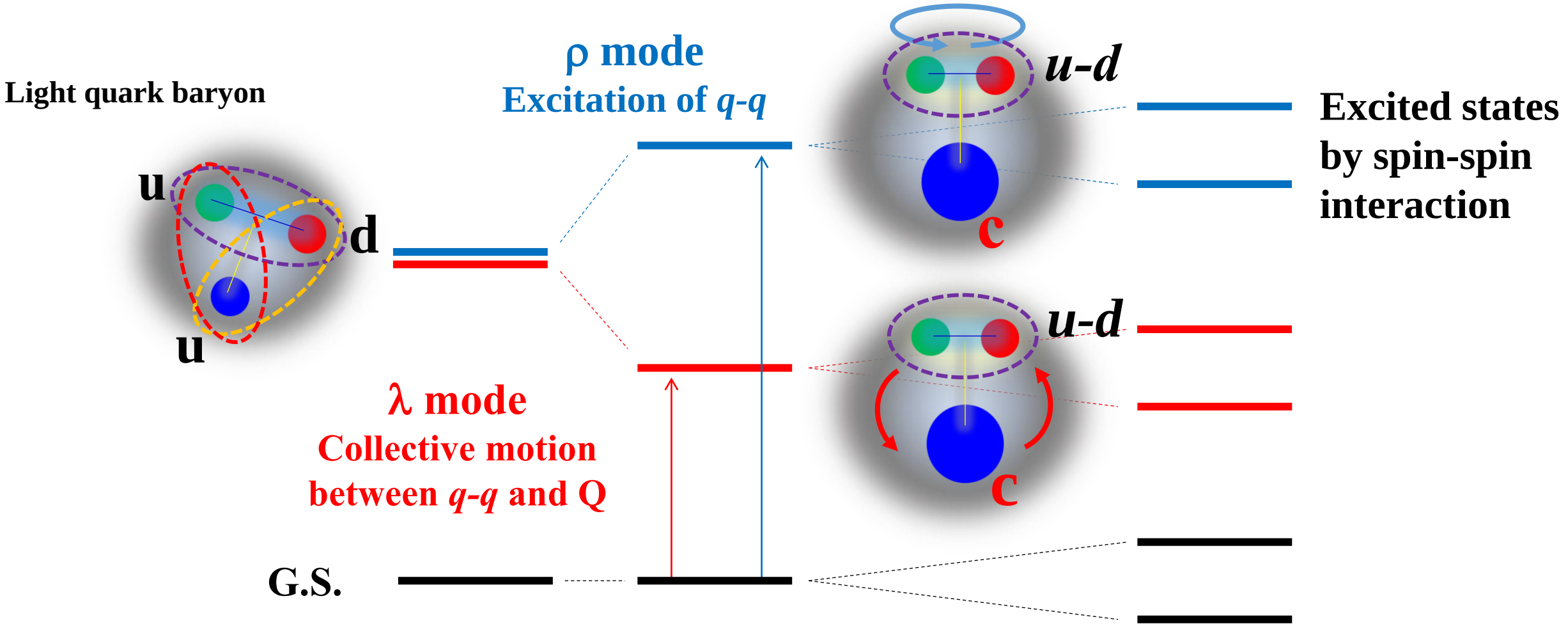


Charmed baryon spectroscopy

Disentangle diquark correlation: 1st identification of "Excitation mode"(λ and ρ modes)

＊Dynamical information: Production rates and absolute decay branching ratios

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



Charmed baryon spectroscopy

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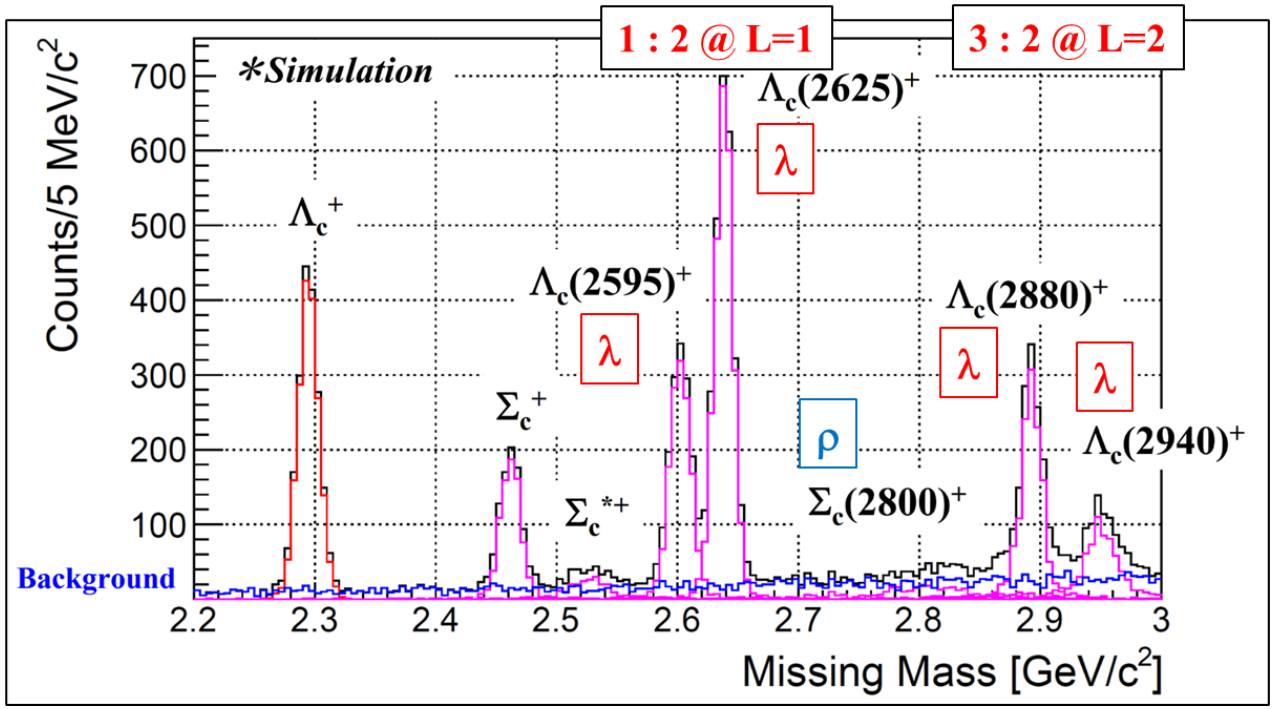
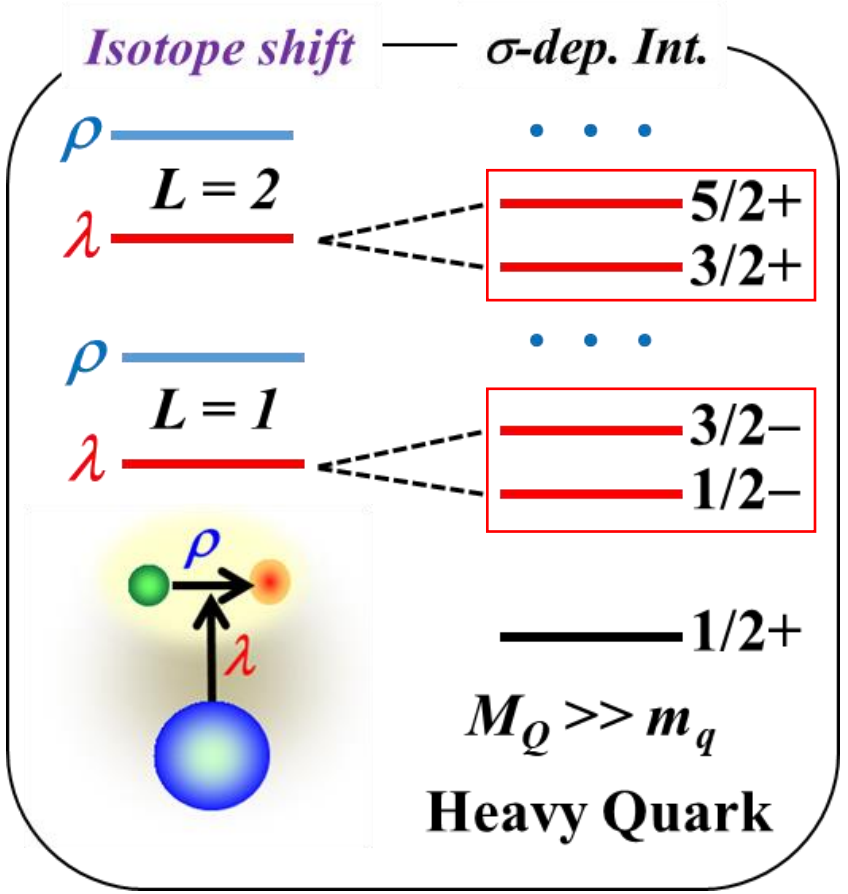
- **$\pi^- p \rightarrow D^{*-} Y_c^{*+}$ reaction @ 20 GeV/c**

Expected spectrum: Missing mass of Y_c^{*+}



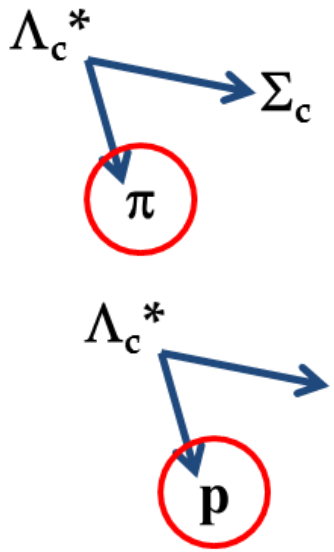


∗ Production rates ⇒ λ/ρ mode assignment

- **Production rate of spin double = *L* : *L*+1**

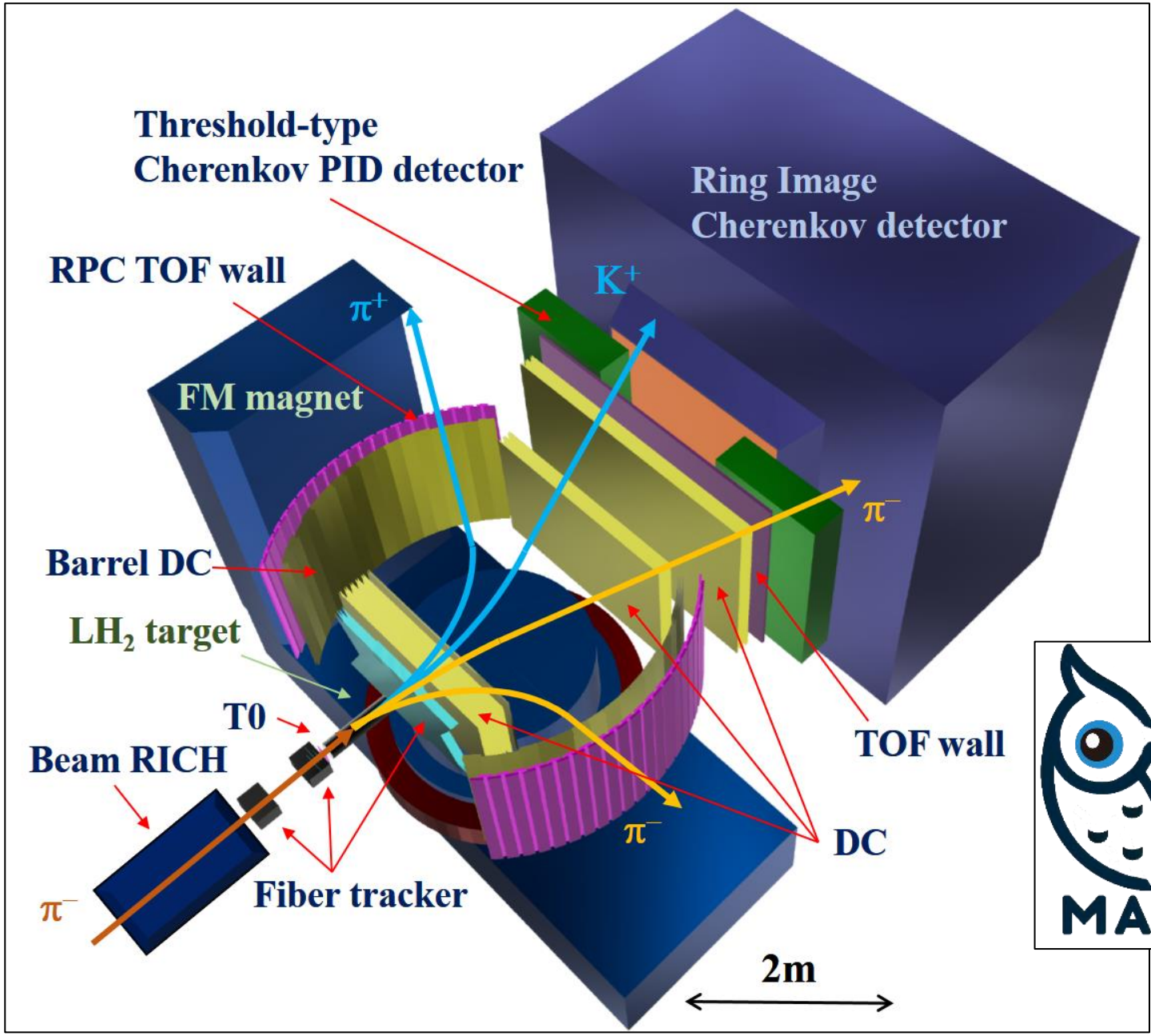
HQ doublet

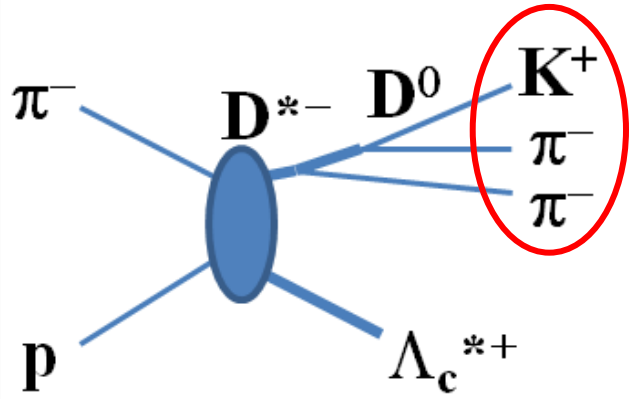
MARQ spectrometer



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

MARQ spectrometer

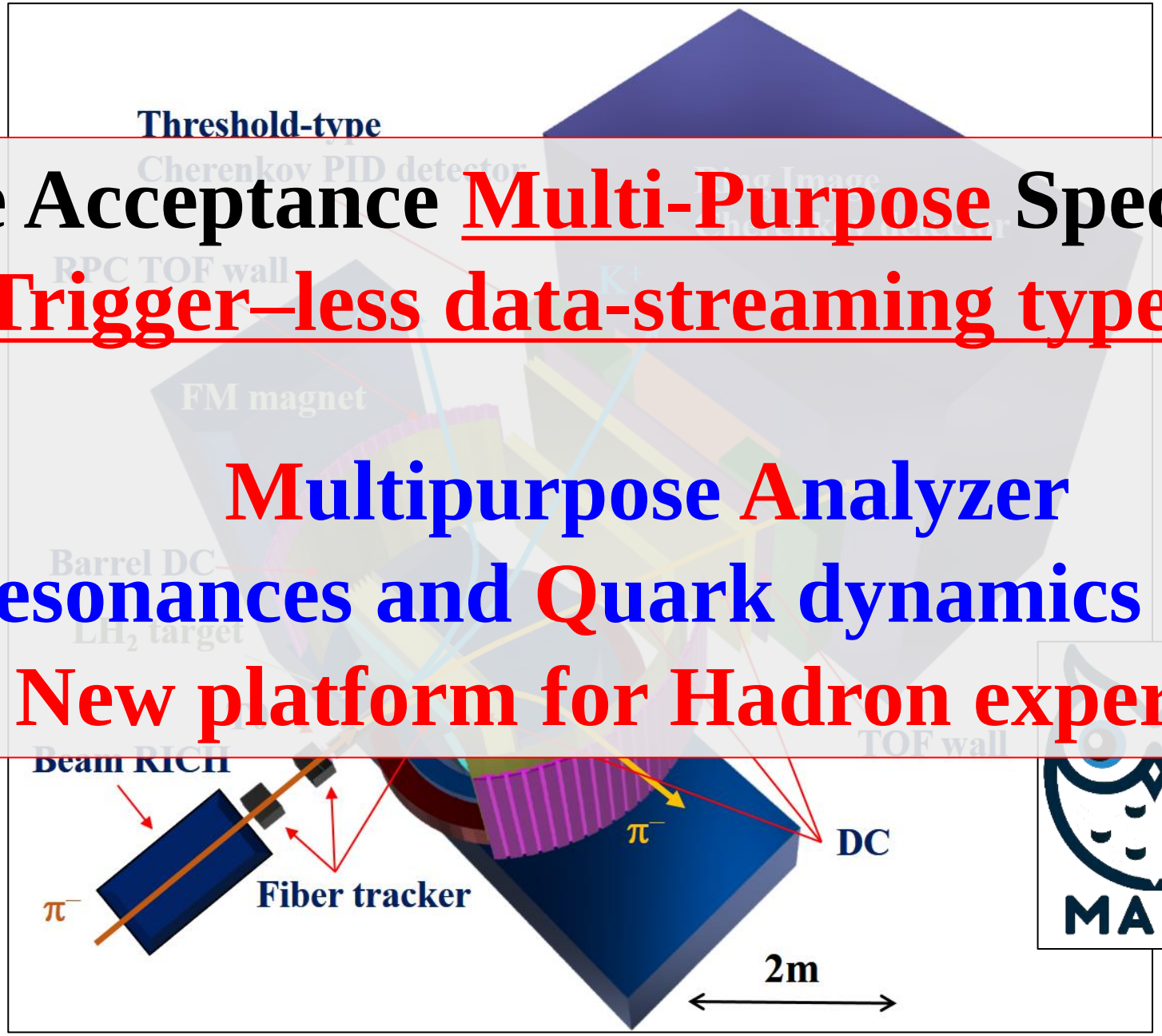
Large Acceptance Multi-Purpose Spectrometer

+ Trigger–less data-streaming type DAQ

Multipurpose Analyzer

for Resonances and Quark dynamics (MARQ)

⇒ New platform for Hadron experiment

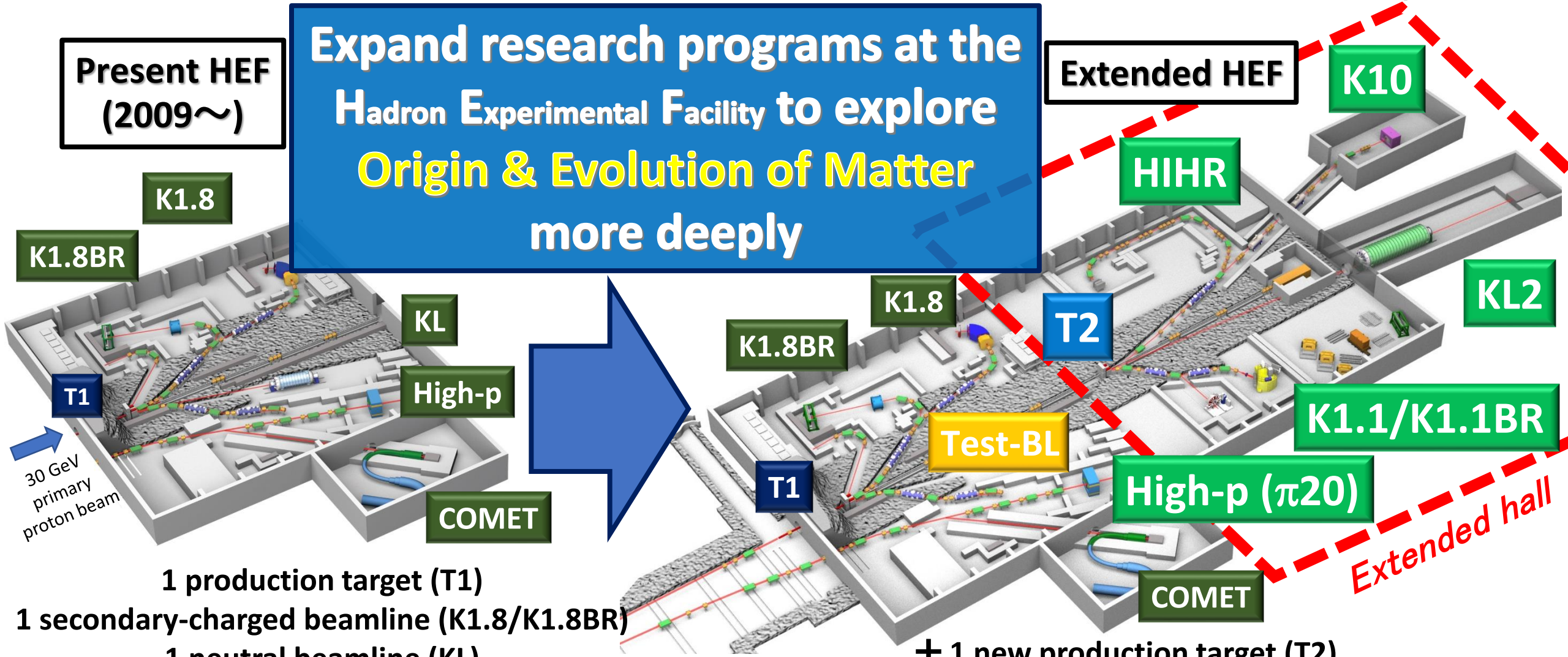


Hadron Experimental Facility eXtension (HEF-ex) Project

Present HEF (2009～)

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

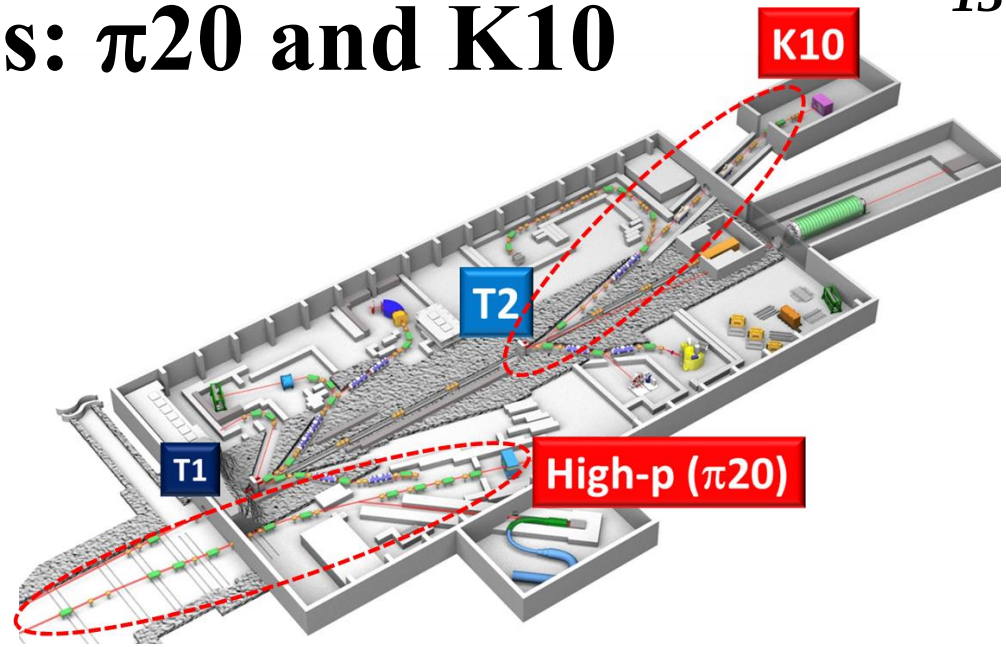
Extended HEF



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

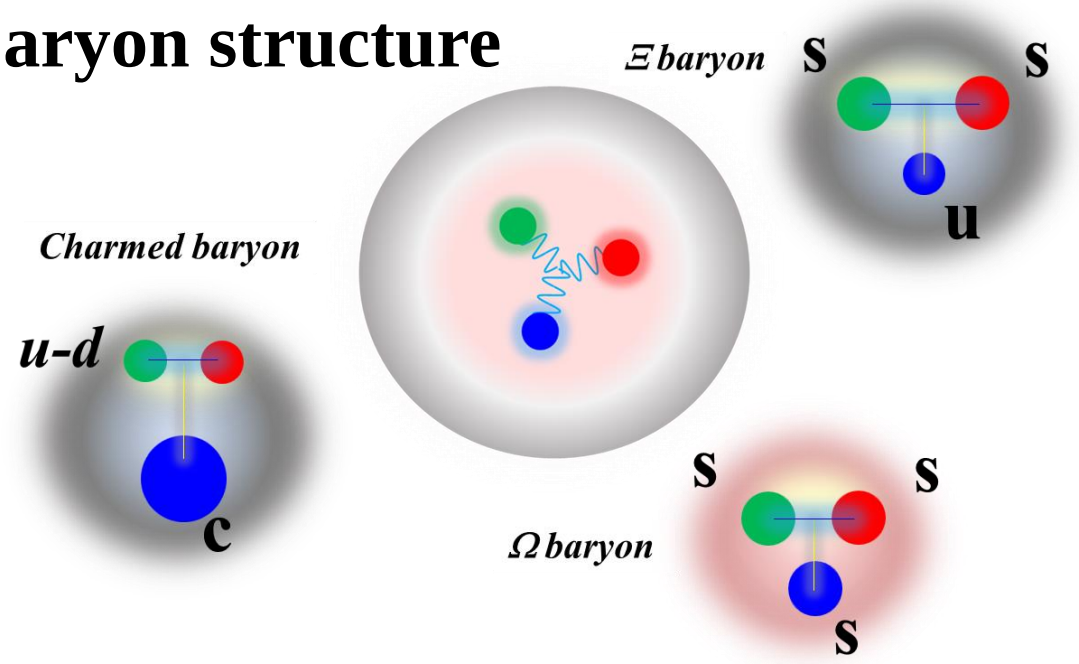


- **π20: 2ndary beam (unseparated, mainly π)**
  - High intensity: >10^7 /spill for π^- up to 20 GeV/c
- **K10: K^- beam (K/π ~ 1/2)**
  - High intensity: >10^6 /spill up to 10 GeV/c
    - Anti-p intensity: >10^6 /spill (anti-p/π ~ 2/1)

✱ 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

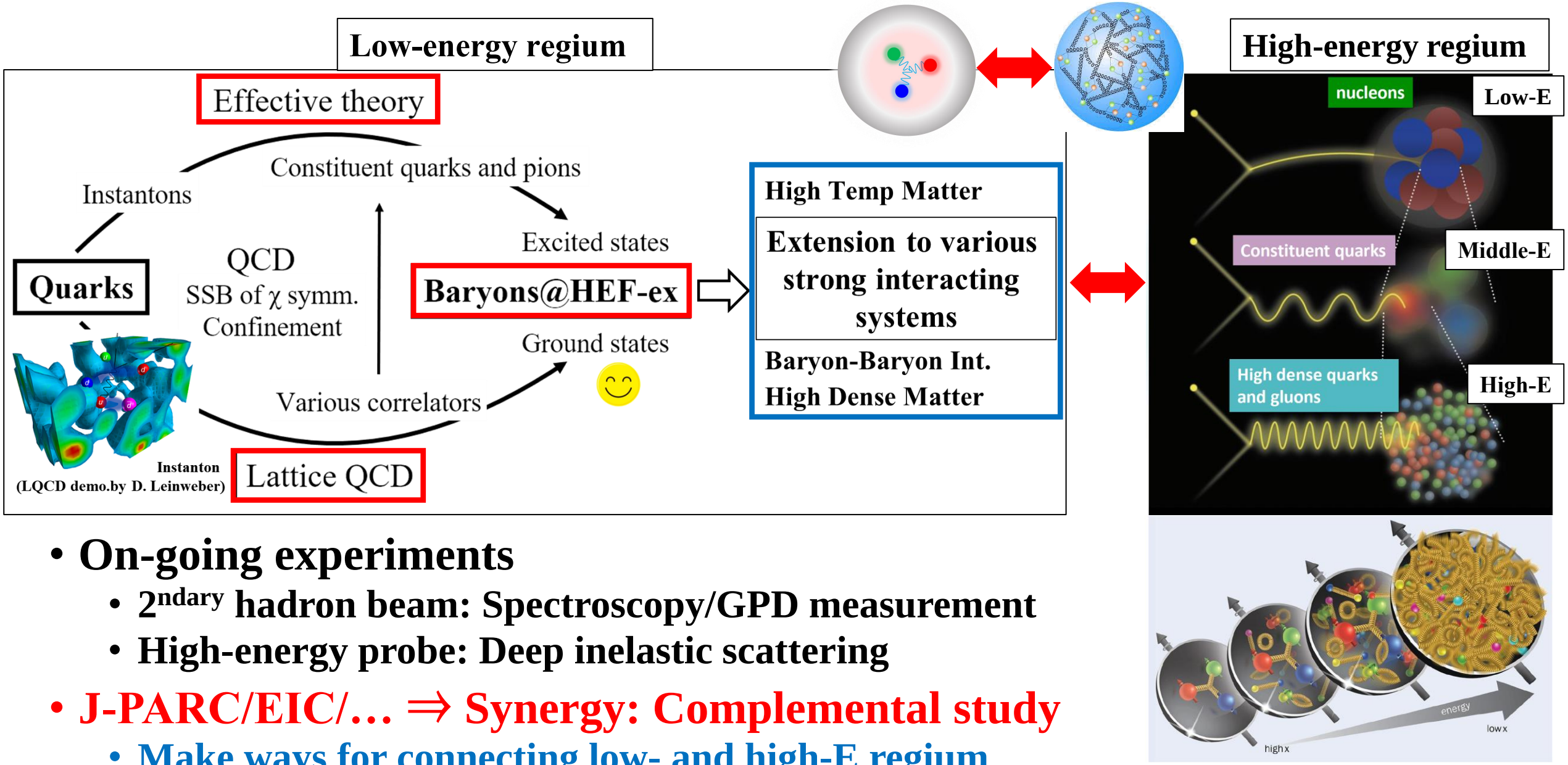


Study of internal structure of baryons

Systematic study of baryons

Hadron with specific properties: Λ^*, Ω

Synergy with high-energy probe study

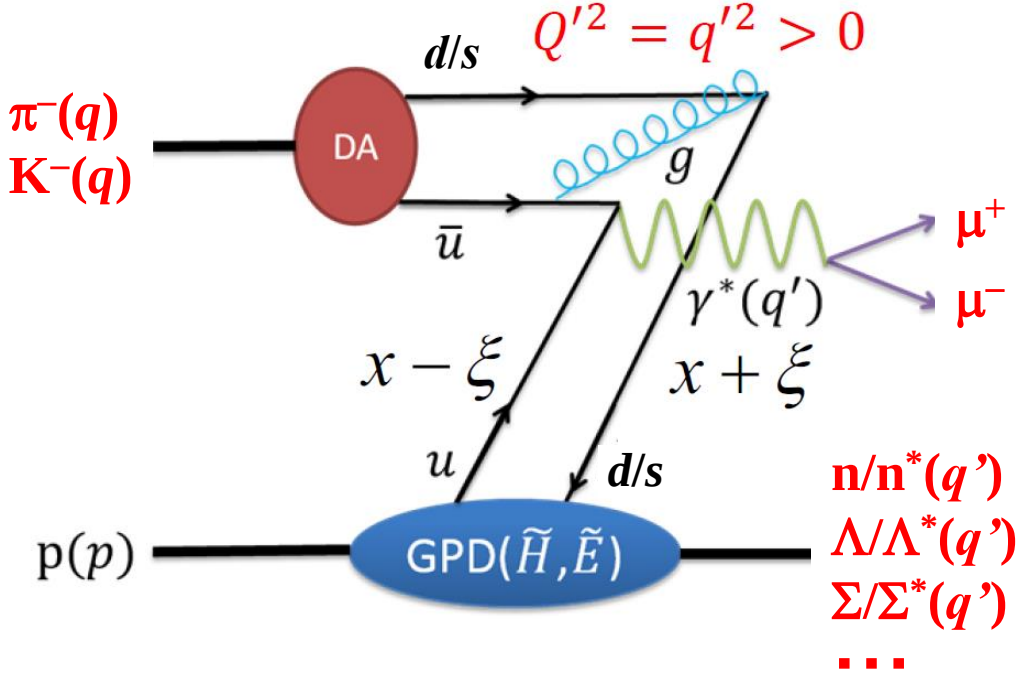


- **On-going experiments**
  - **2ndary hadron beam: Spectroscopy/GPD measurement**
  - **High-energy probe: Deep inelastic scattering**
- **J-PARC/EIC/… ⇒ Synergy: Complemental study**
  - **Make ways for connecting low- and high-E regium**

Systematic study of baryons

- **Spectroscopy and GPD measurement by 2ndary hadron beam**
  - **Systematic spectroscopy experiments**
    - $\pi^- p \rightarrow N\ \pi/\rho,\ N^*\ \pi/\rho,\ \Delta\ \pi/\rho,\ \Delta^*\ \pi/\rho,$
    - $\pi^- p \rightarrow D^{*-}\ \Lambda_c^{*+}/\Sigma_c^{*+},\ K^{*0}\ \Lambda^*/\Sigma^*$
    - $K^- p \rightarrow K^{*0}/K^+\ \Xi^{*0,-},\ \Omega^{*-}\ K^+\ K^{*0}$
  - **Systematic study by exclusive Drell-Yan process**
    - $\pi^- p \rightarrow N/N^*\ \gamma^*,\ \Delta/\Delta^*\ \gamma^*$
    - $K^- p \rightarrow \Lambda/\Lambda^*\ \gamma^*,\ \Sigma/\Sigma^*\ \gamma^*$
    - $K^- p \rightarrow \Xi/\Xi^*\ \gamma^*\ K$ (3-body FS ⇒ How to extract ?)
    - $K^- p \rightarrow \Omega/\Omega^*\ \gamma^*\ K\ K^*$ (4-body FS ⇒ How to extract ?)

⇒ **Structure of degrees of freedom on GPD: Quark, gluon, diquark…**



∗ **Further studies of baryons at EIC**

- **Systematic/Complemental measurements of GPD**
- **Production of baryons ($\Lambda_c/\Sigma_c/\Lambda/\Sigma/\Xi/\Omega$) in nuclei ⇒ Modification of properties**

⇔ **Longer lifetime hadron ($\Lambda/\Sigma/\Xi/\Omega$) measurement ?**

- **Hyperons are out of ePIC detector range…?**

Study of hadron with specific properties

- **$\Lambda(1405)$ via $K^- p \to \Lambda(1405)\,\gamma^*$**
  - **Hadron molecule DoF ($\bar{K}N$: 5 quark state)**
    - **GPD on exotic hadron**
  - **Comparison: Λ, $\Lambda(1520)$, …**

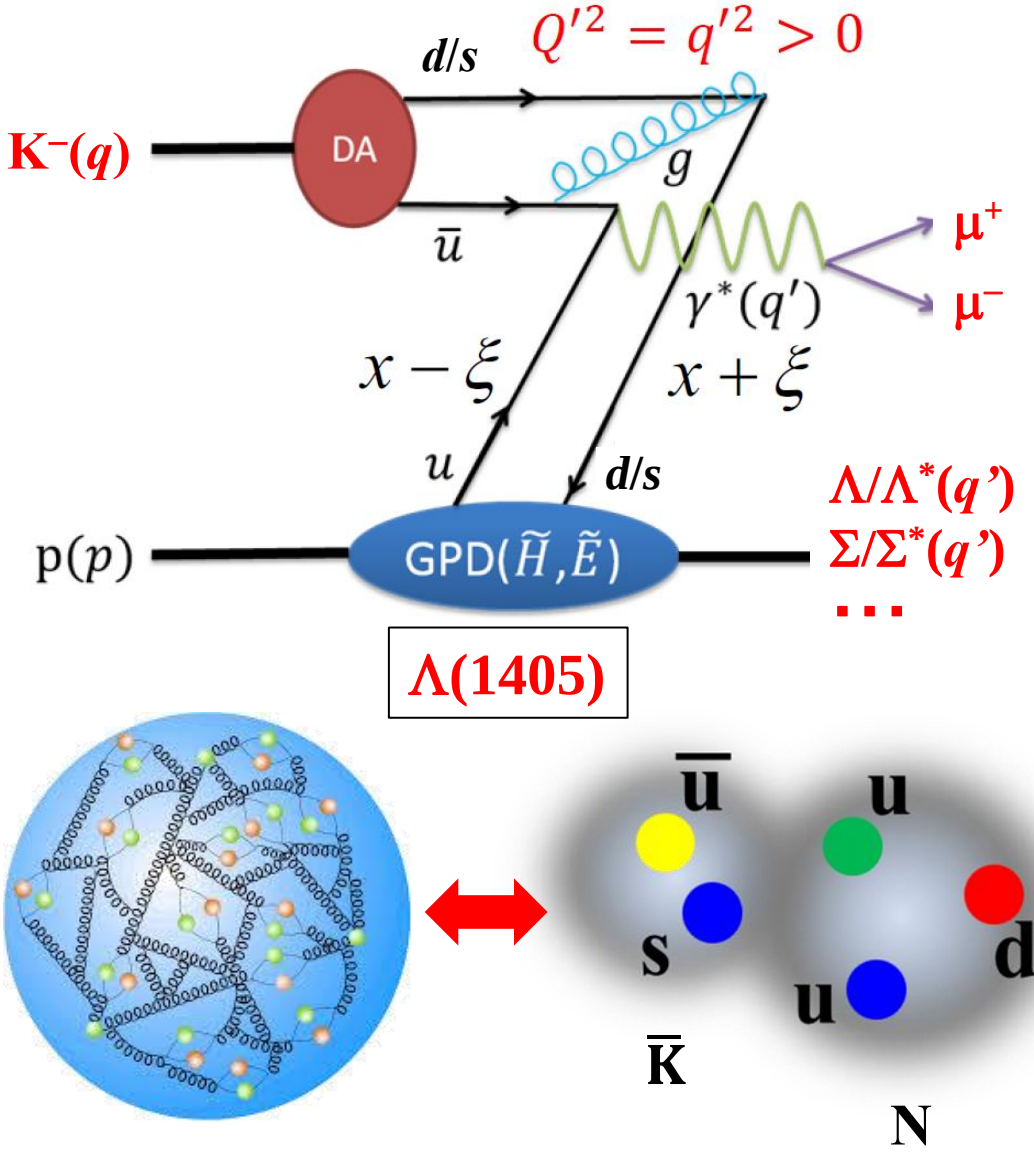
+ Study by quark counting rule

$\Rightarrow$ $\sqrt{s}$ dependence of $d\sigma/dt$ from 3q and 5q

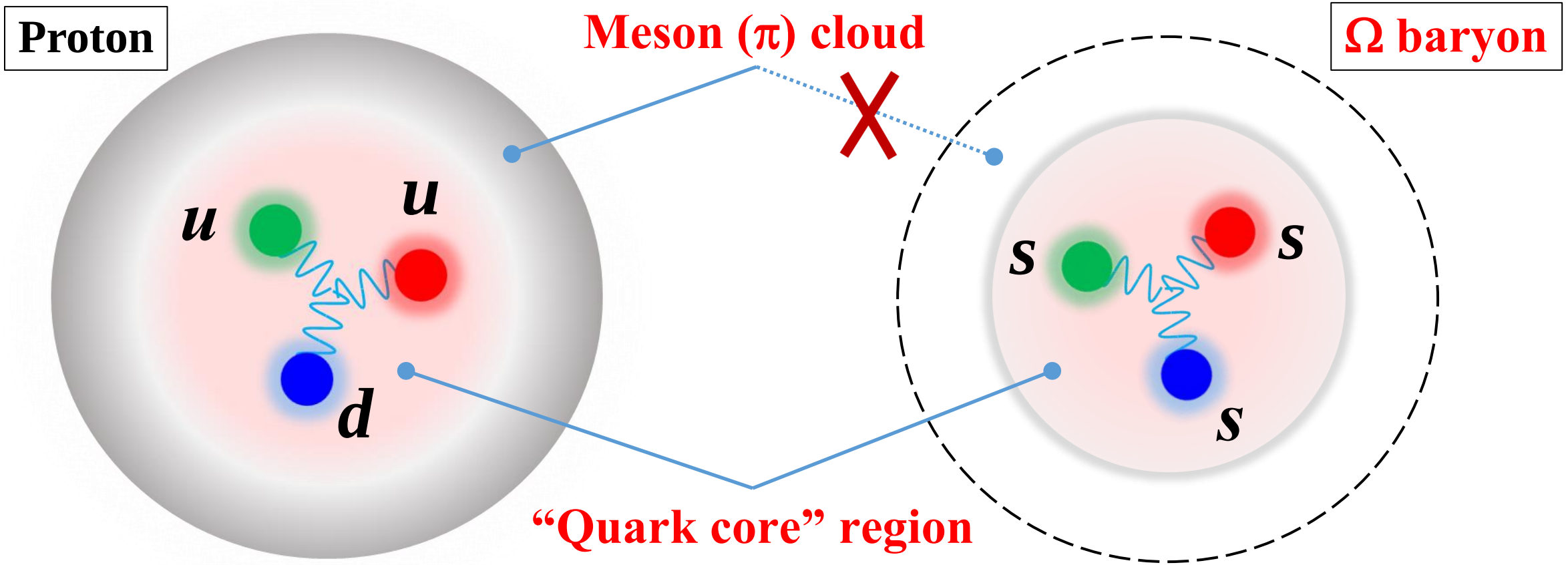
- **Reaction: $\pi^- p \to \Lambda(1405)\,K^0$**
  - **J-PARC beam : 3–10 GeV/c $\Leftrightarrow$ $\sqrt{s}$ = 2.5–4.5 GeV**
  - **Comparison: Λ, Σ, $\Sigma(1385)$, $\Lambda(1405)$, $\Lambda(1520)$**

∗ Complemental experiment at EIC

- **Ω baryon**
  - **Free from π cloud**
  - **"Quark core" size and pressure distribution**



Ω baryon: Single flavor system



- Ω(sss) baryon

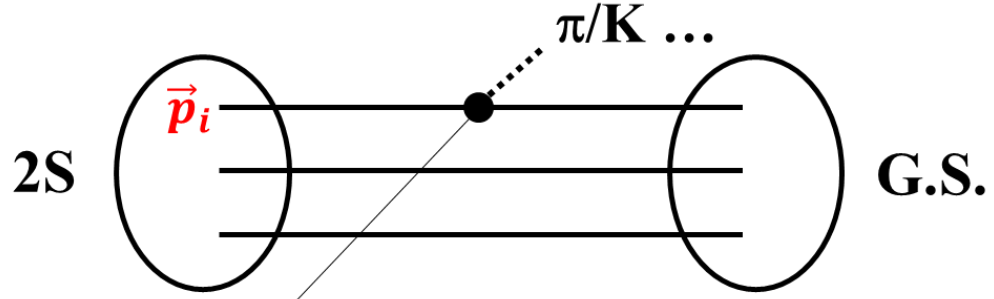
1. **Simple excited state property** due to **flavor symmetric** system
2. **Free from π cloud:** Discriminate "π" contribution
   - No *u* and *d* quarks which strongly couple to π meson.

⇒ **Direct access to "Quark core" region: Quark motion in "quark core" with "cloud"**

Roper-like resonances: 2S state

- Systematics of Roper-like states
  - Small excitation energy and wide width
  - Mass universality ?
  - What does determine its width ?

- Decay width of 2S state



NR expansion of meson emission

$$< \text{Roper}|\mathcal{O}|\text{G.S.} > \sim < \vec{\sigma}\cdot\vec{p} > (a_0 + a_2\vec{p}_i^{\,2} + \cdots)$$

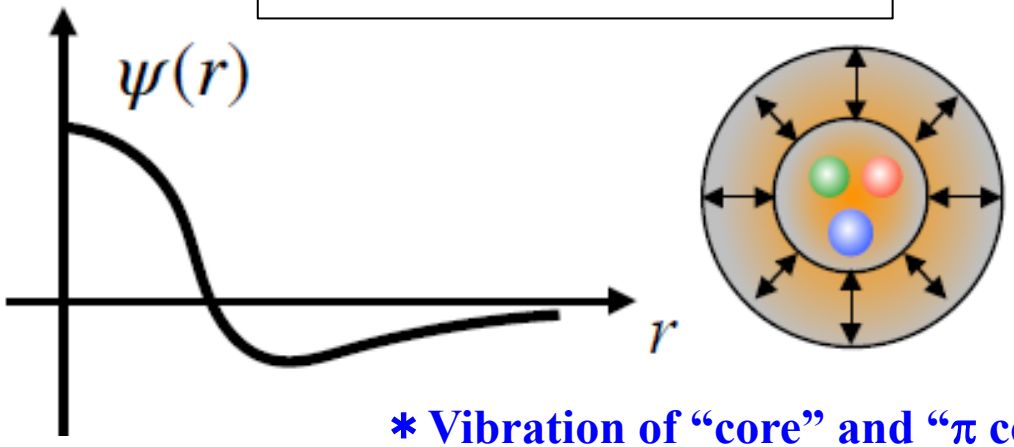
Leading order (LO)
suppressed by selection rule

Next to leading order (NLO)

$\Rightarrow \Gamma \sim \langle p_q^2 \rangle$ internal quark motion

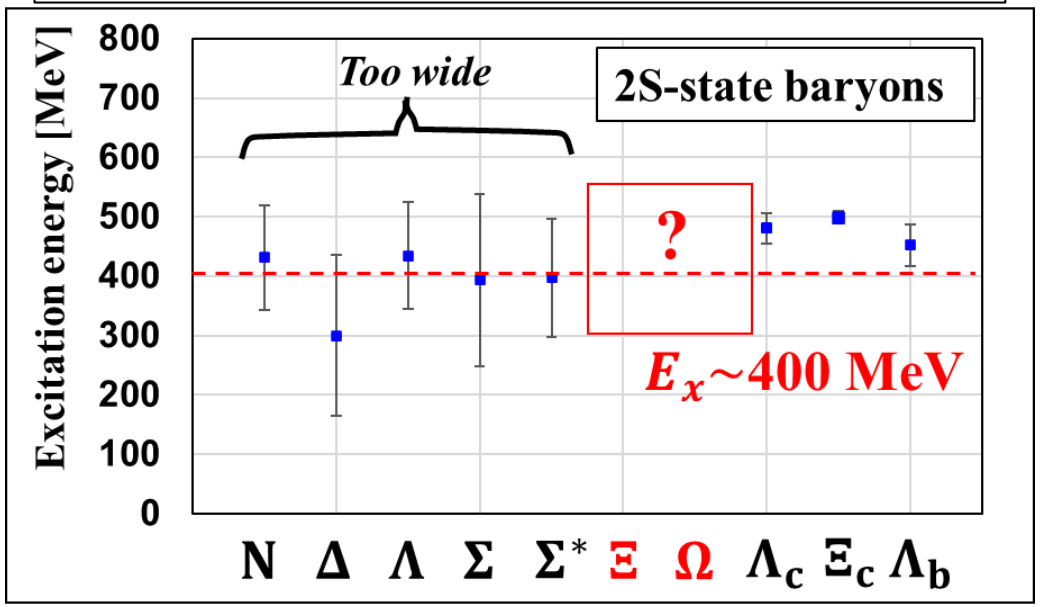
J. Arifi *et al.*, PRD105, 094006 (2023)
J. Arifi *et al.*, PRD103, 094003 (2021)

Radial excitation 2S states



∗ Vibration of "core" and "π could" ?

Systematics of the Roper-like resonances



Ω baryon 2S state: Extraction of "quark core" size

- **Calculation including NLO: 50–100 MeV for Ω^{*-}(2159 MeV, $3/2^+$)**

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

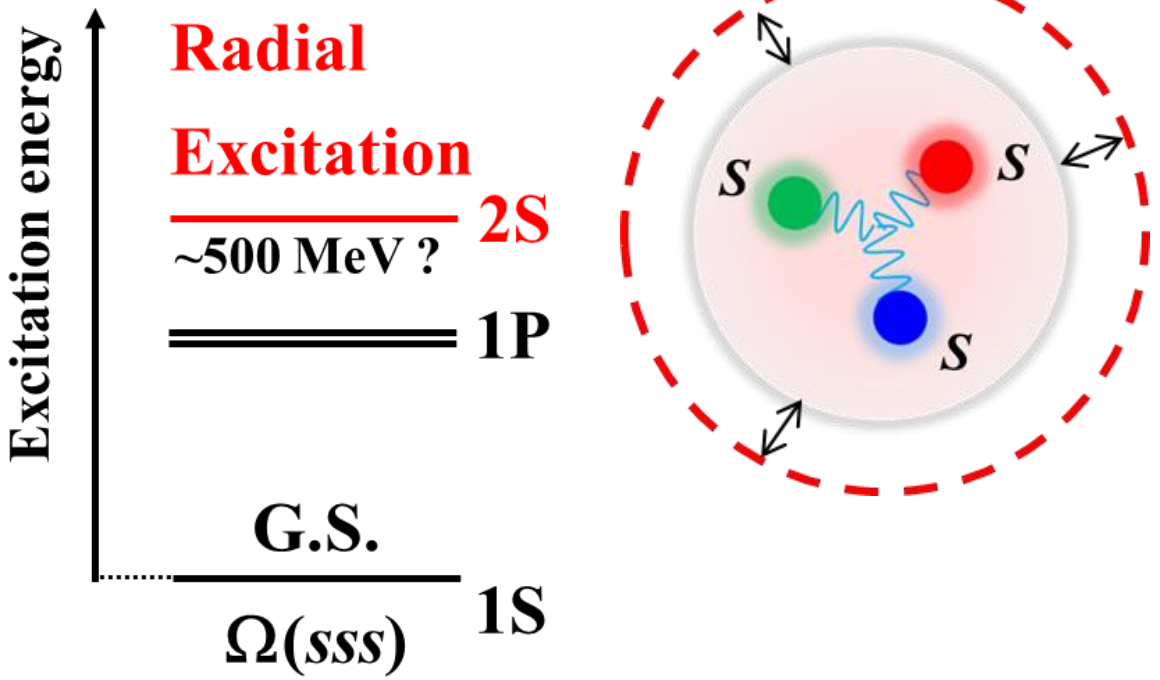
⇒ $\Gamma \sim \langle p_q^2 \rangle$

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

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

⇒ **"Quark core" size: $\langle r_q^2 \rangle$**

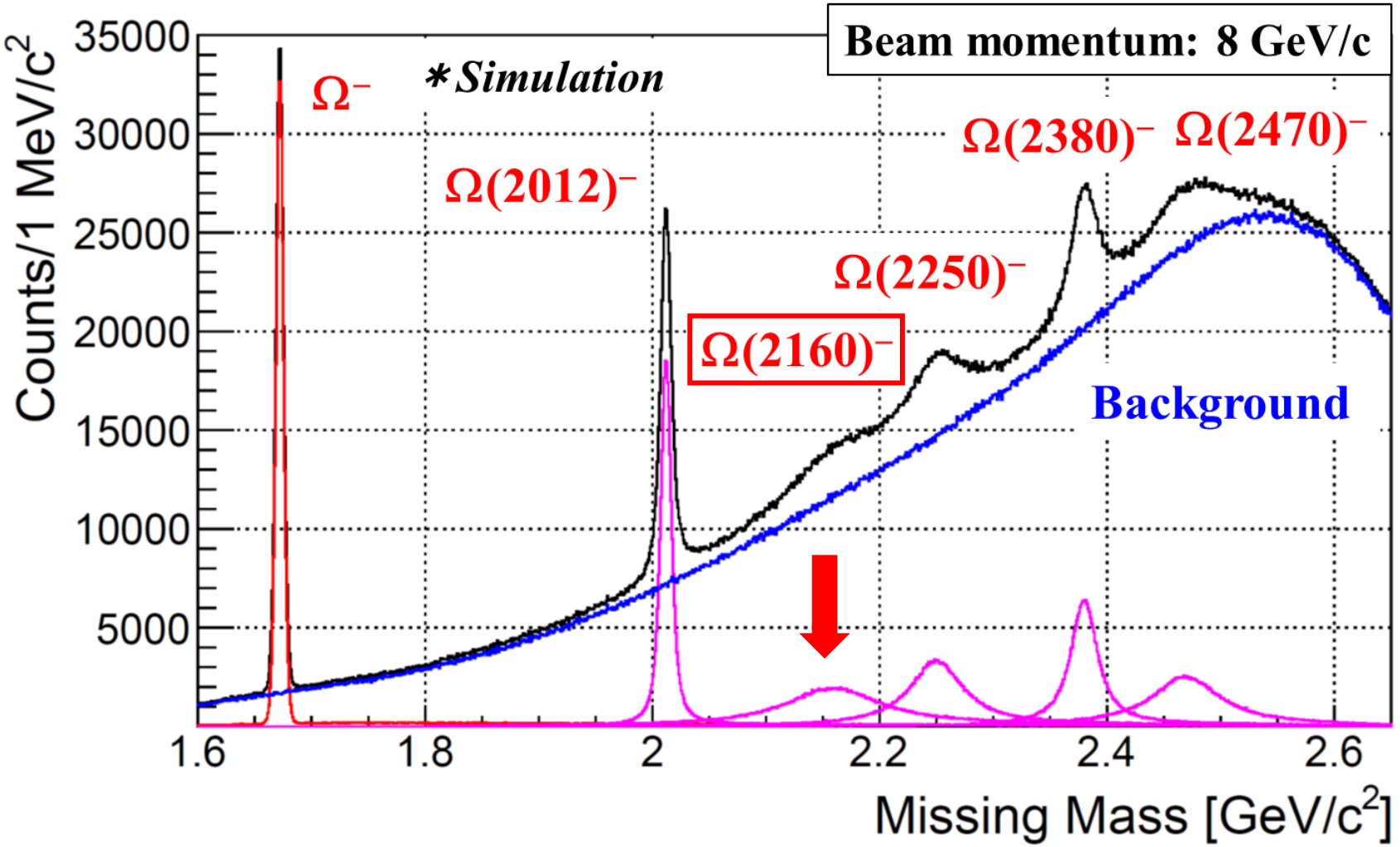
- Essential of free from π cloud



∗ **Effects of K cloud need to be investigated. (and other mesons: σ, η…)**

- **Minor contribution ?: $M_K/M_\pi \sim 3.5$ ⇒ 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 spectrum: $K^- p \rightarrow \Omega^{*-} K^{*0} K^+$



- Ω^{*-} states in PDG are generated.
- Roper-like state: $\Omega(2160)^-$, Γ = 100 MeV (assumed)
- Breit-Wigner type resonances

∗ Background events
- Generated by JAM
- $K^- p$ reaction @ 8 GeV/c

- **Missing mass** method: **Production cross section** and **absolute branching ratio**
- Ω^{*-} events: 3.3×10^5 events (63 nb: Same cross section for all resonances)
  - Mass resolution: ΔM ~5 MeV < Width (several 10 MeV)

"Quark core" size

- **Quark confinement:**

  Size of "Quark core" region
  - "Core" (~0.6 fm)
  - "Cloud" (>0.6 fm)

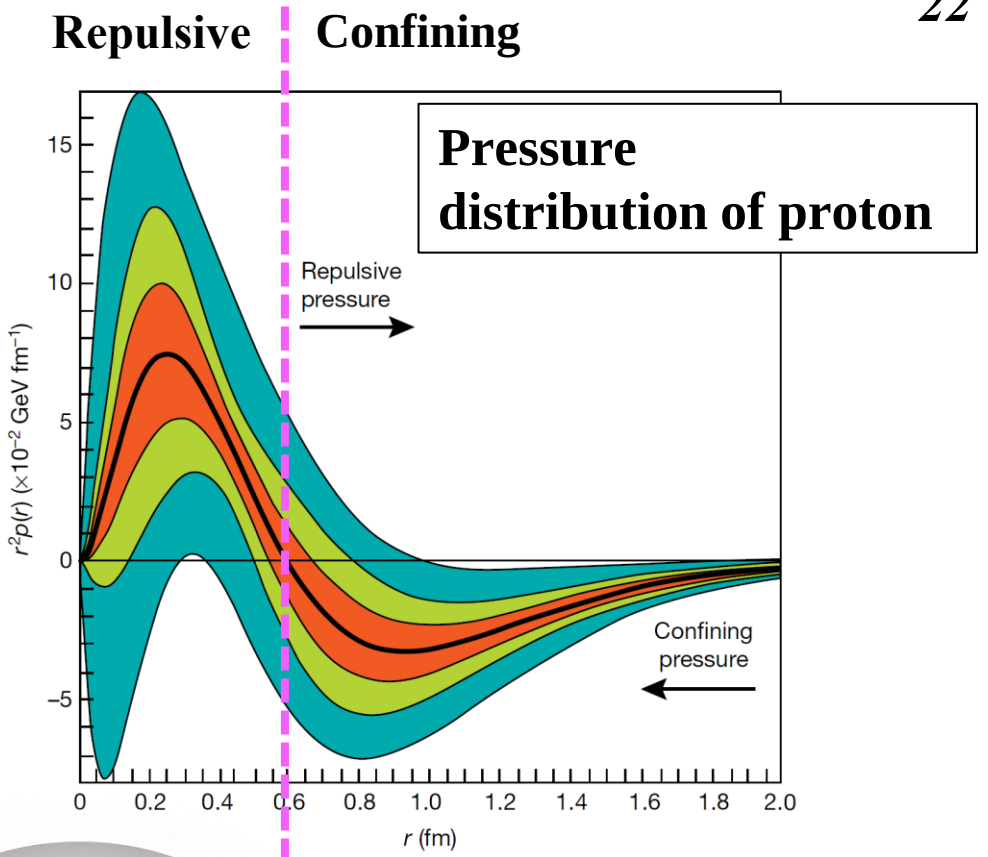
$$\int x\,[H(x,\xi,t)+E(x,\xi,t)]\,dx = 2J(t)$$

$$\int xH(x,\xi,t)dx = M_2(t) + \frac{4}{5}\xi^2 d_1(t)$$

$$d_1(t) \propto \int \frac{j_0(r\sqrt{-t})}{2t} p(r)\,d^3r$$

$d_1(t)$: gravitational form factor

$p(r)$: radial pressure distribution

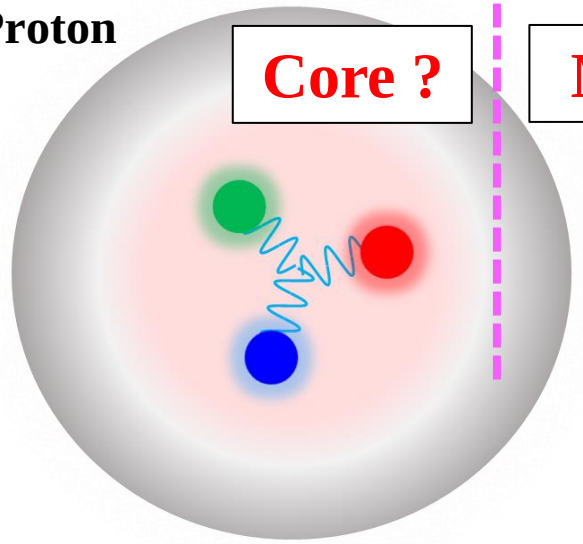


∗ Distinguish "Core" and "Cloud"

⇒ Ω baryon: Free from π could
- Understanding of baryon "Core" from unique property of Ω baryon

- **Lattice QCD calculation:**

  Ω charge radius = 0.5–0.6 fm
  - K.U. Can *et al.*, PRD 92, 114515 (2015)



V.D. Burkert, L. Elouadrhiri & F. X. Girod
Nature volume 557, pages 396–399 (2018)

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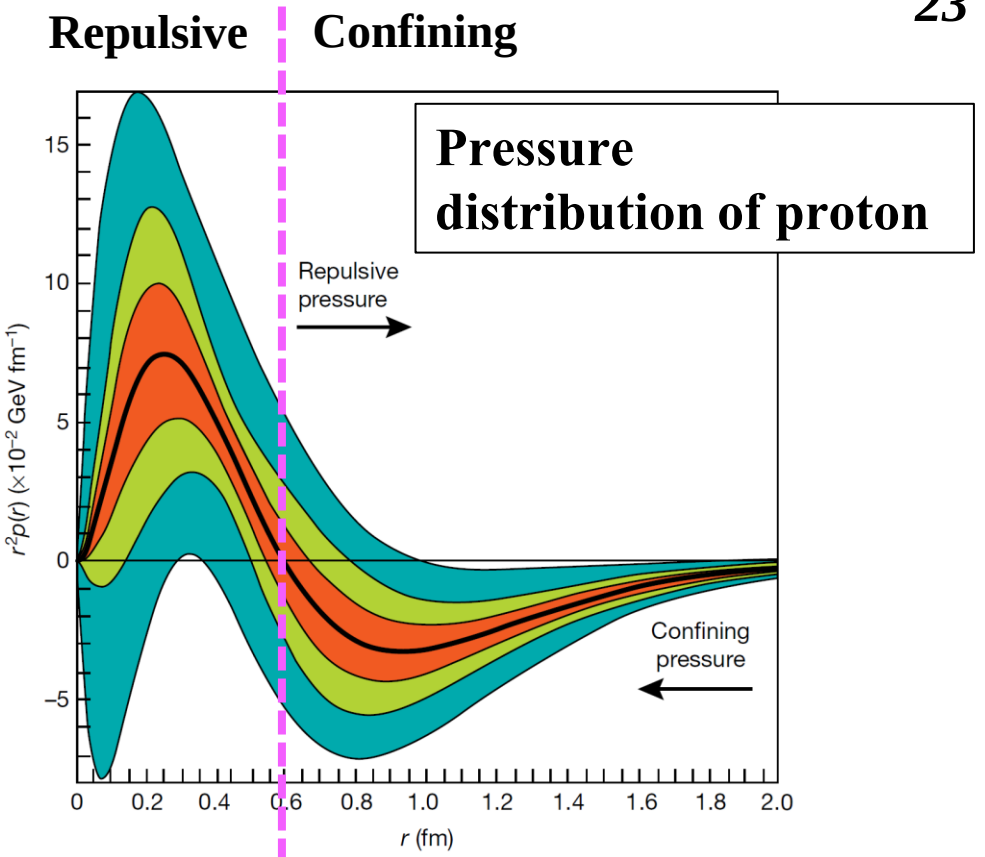

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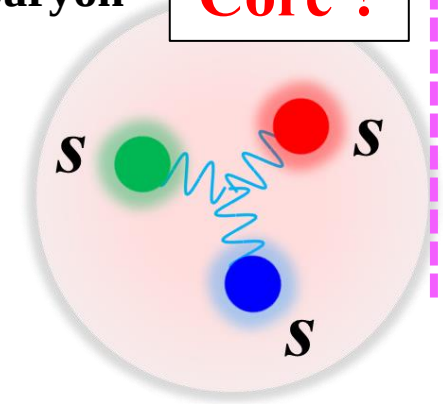
Ω baryon

Core ?

Meson (π) cloud ?



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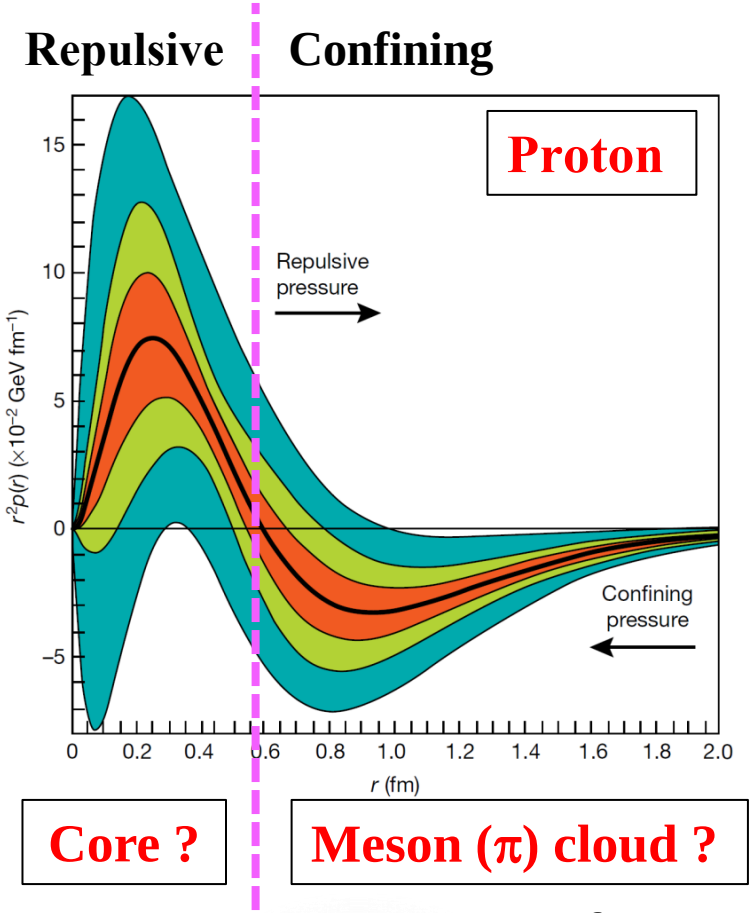
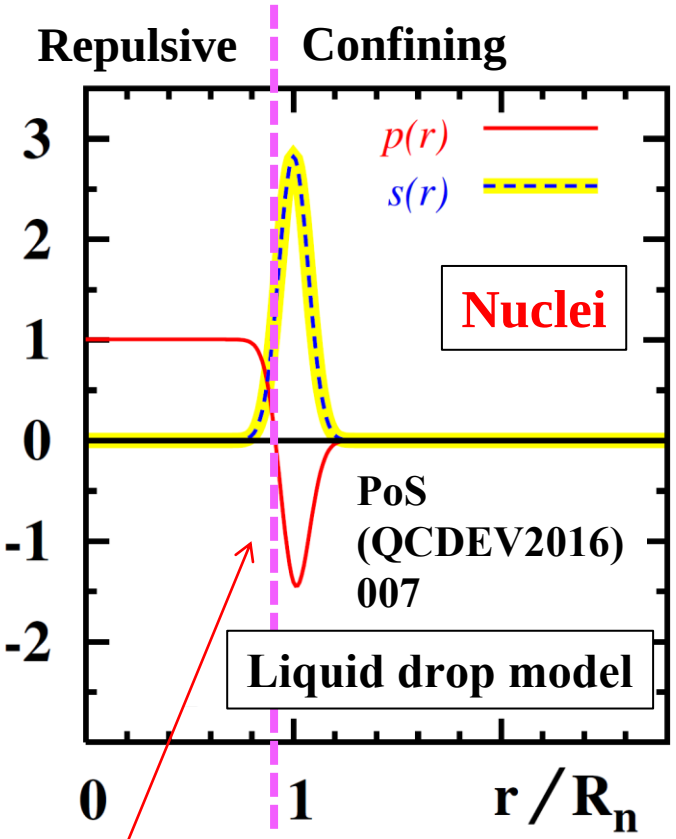
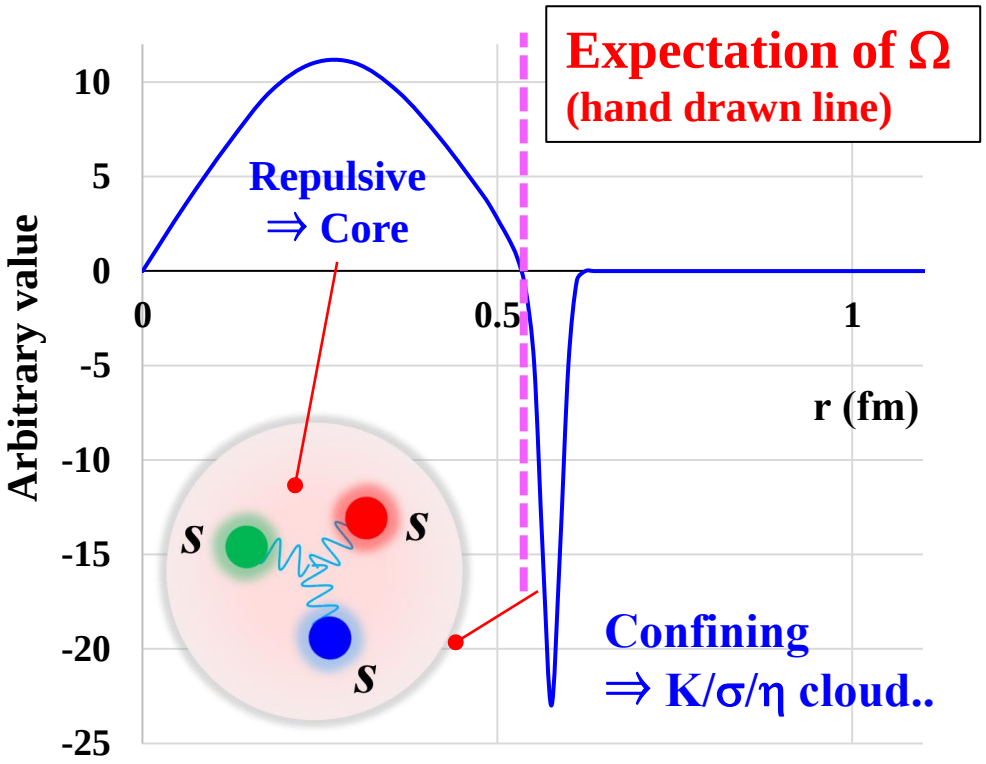
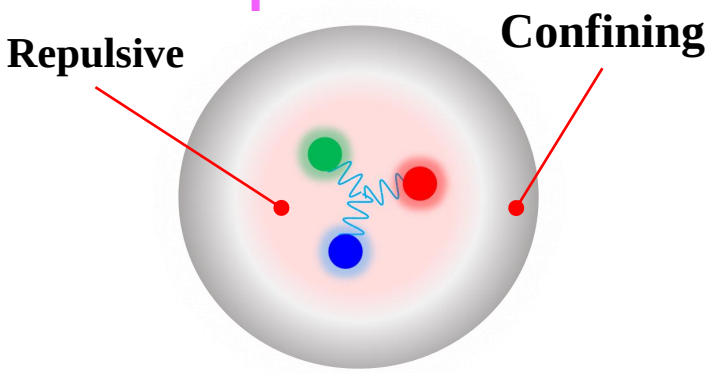
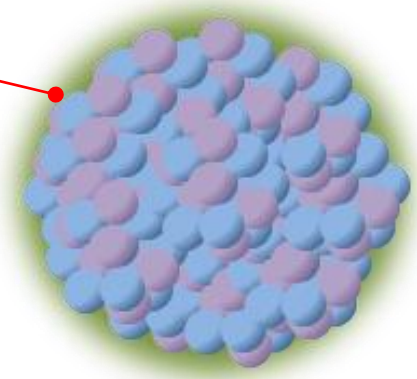
Pressure distribution of Ω: Analogy from nuclei











- ∗Ω pressure distribution
- No π cloud contribution

⇒ Comparison with proton

∗Gravitational form factor of Ω

Summary

- **How quarks build hadrons ?**
  - **Investigation of effective degrees of freedom and their interactions**

- **Systematic spectroscopy of Λ_c/Σ_c, Ξ, Ω baryons**
  - **Disentangle diquark correlation and spin-dependent forces**
  - **High-intensity & High-momentum hadron beam: π20 and K10 at J-PARC**

- **Study of internal structure of baryons**
  - **Synergy with low- and high- energy probes**

  $\Rightarrow$ Systematic study: Spectroscopy and GPD measurements

- **Study of specific hadron properties**
  - **Λ(1405) by using high-E probe**
  - **Ω baryon: Free from π cloud $\Rightarrow$ "Quark core" size and pressure distribution**