Spectroscopy experiment of charmed and multi-strange baryons using hadron beam at the J-PARC hadron facility

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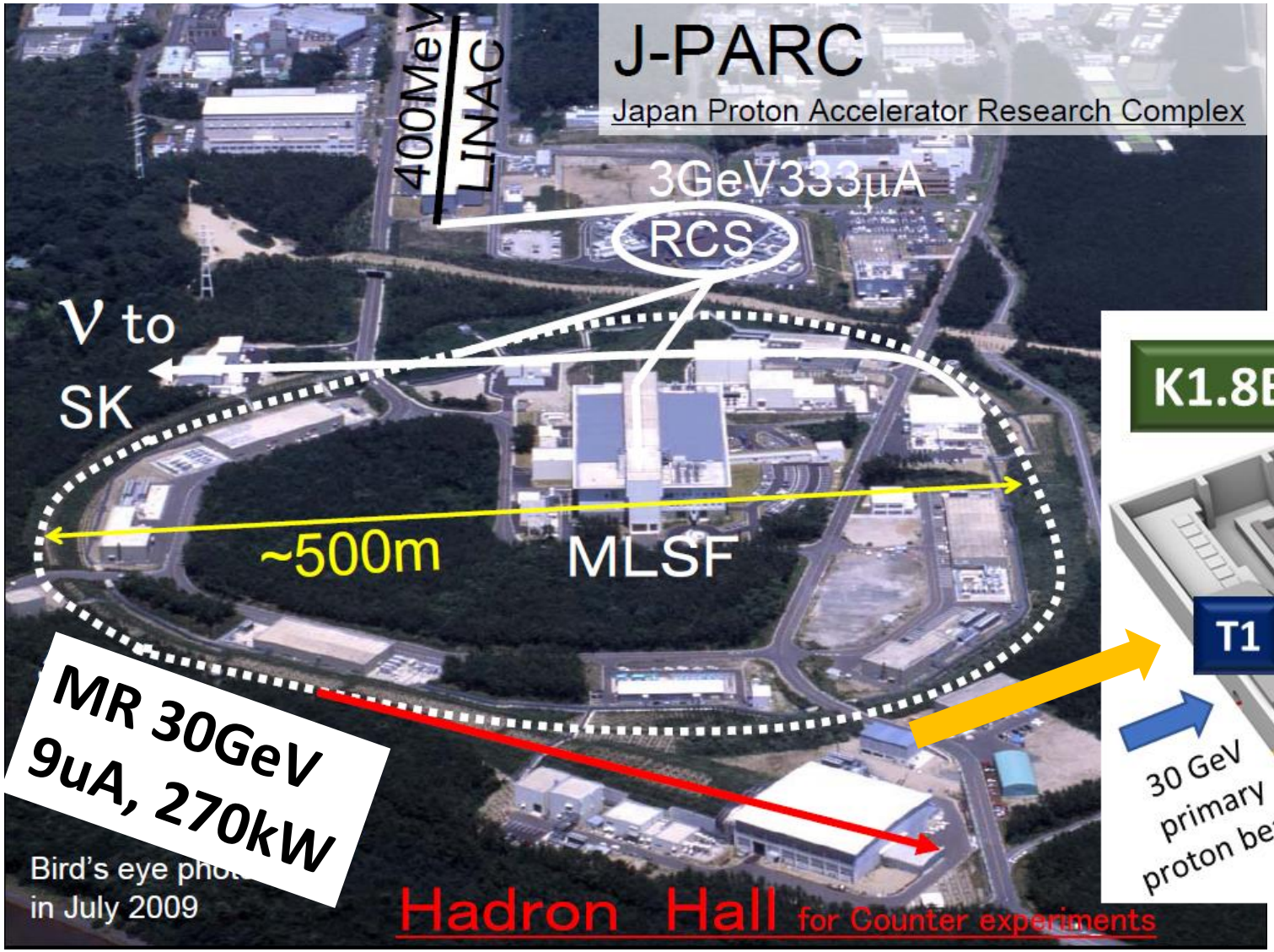
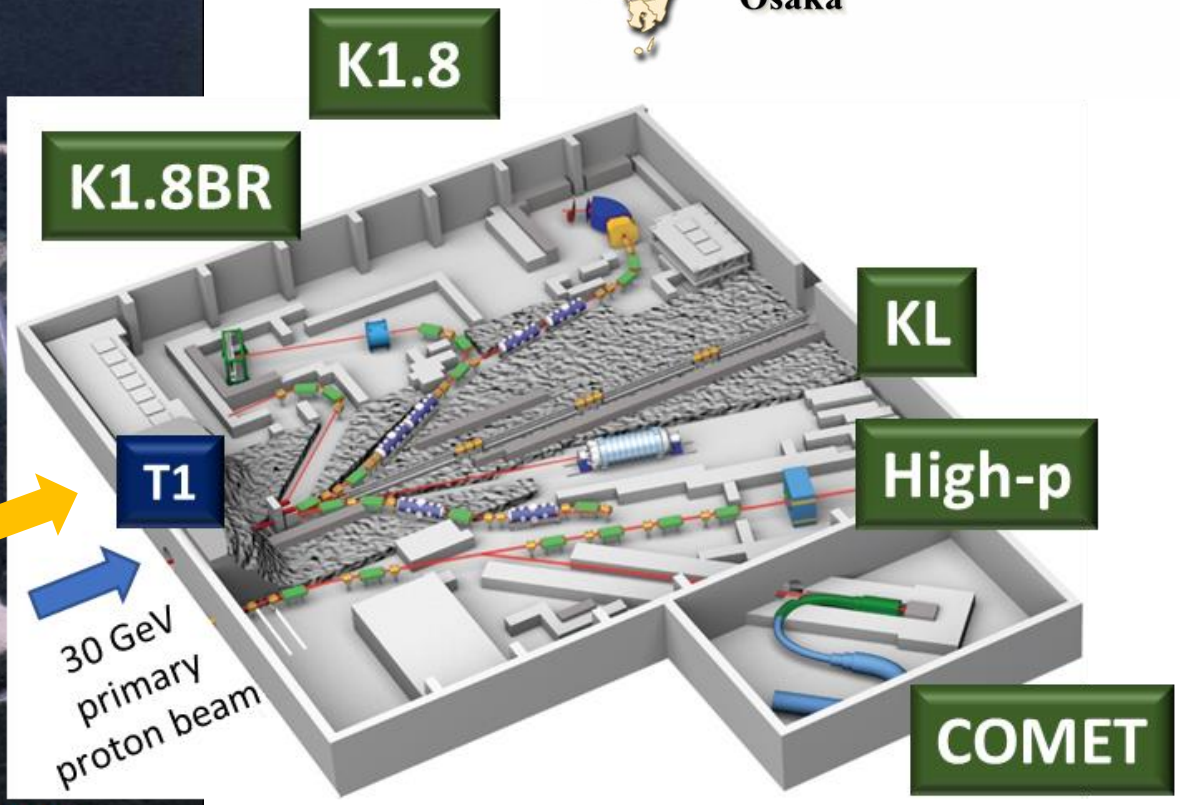
Science at the Luminosity Frontier: Jefferson Lab at 22 GeV

9th Dec. 2024

J-PARC & Hadron Experimental Facility



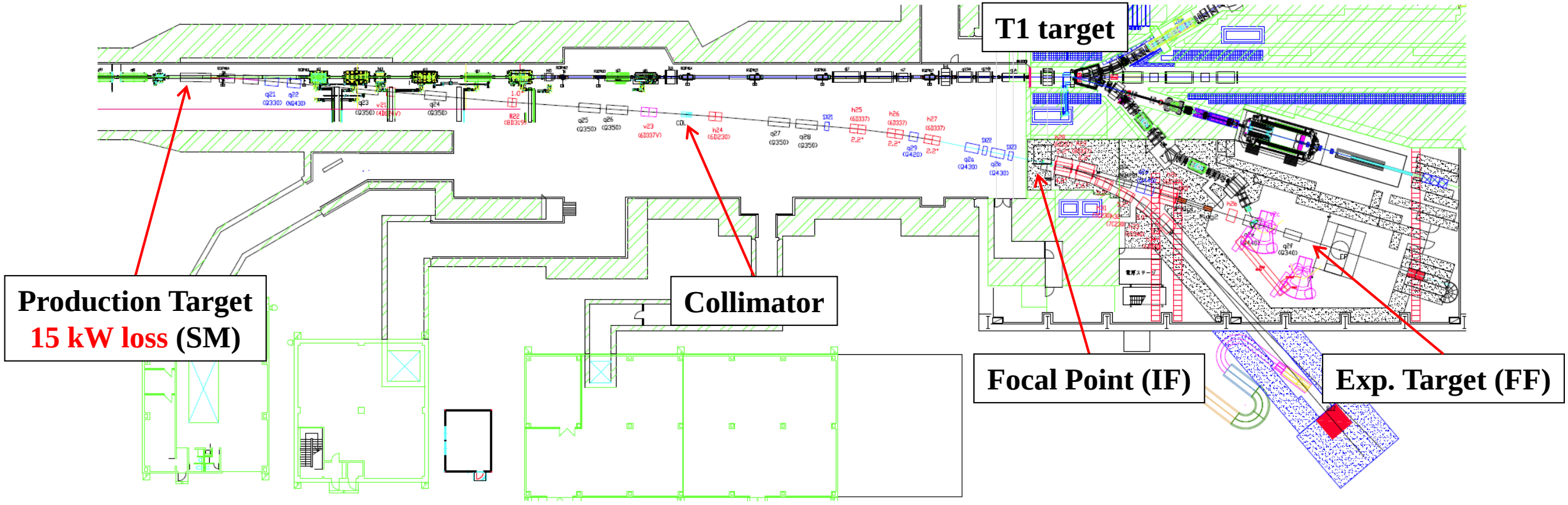


World's highest level intensity proton beam ⇒ Beam power 82 kW

High-p beam line for 2^{ndary} beam: π20

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

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



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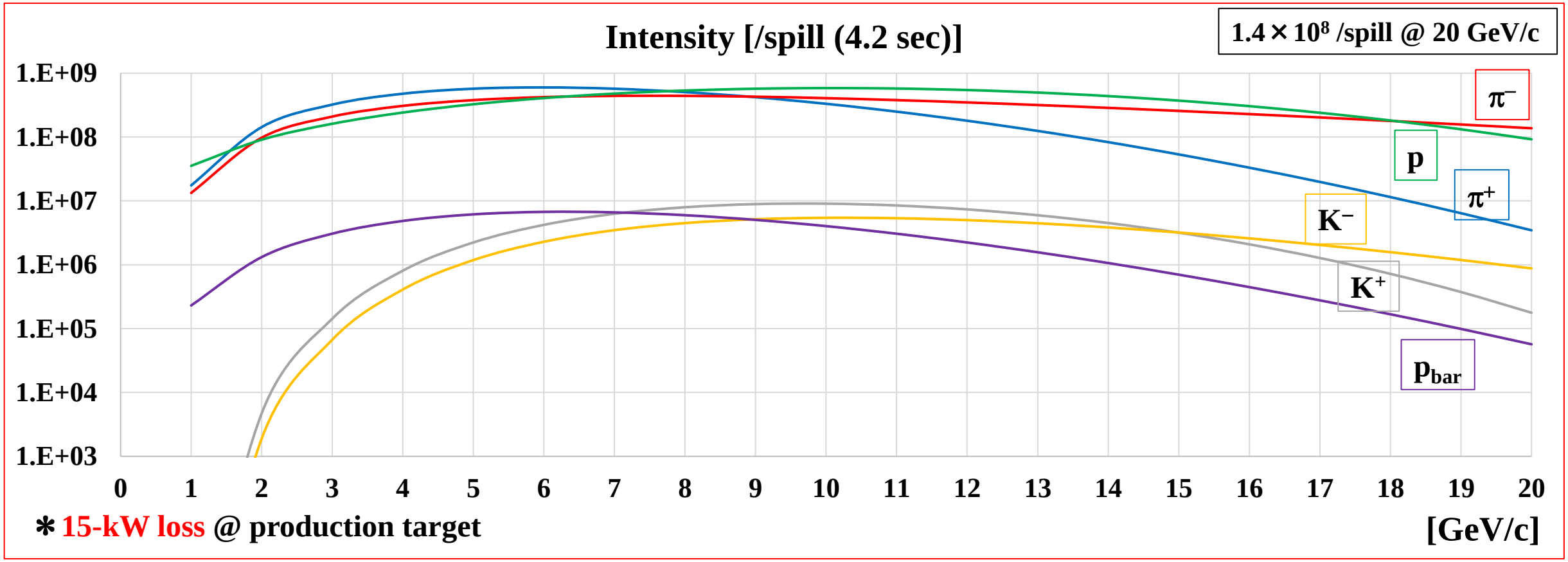
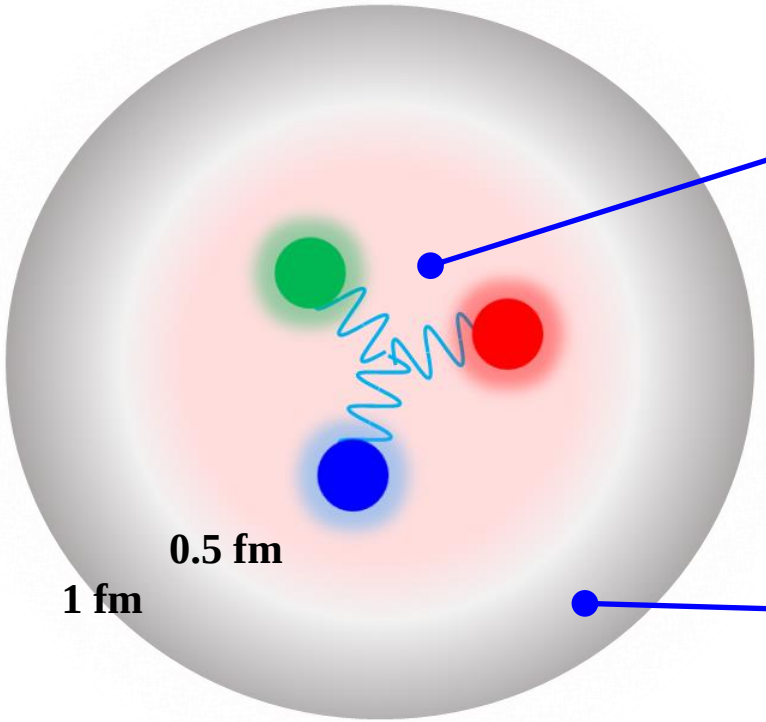


Investigation of baryon internal structure



- **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**
  - **Effective degrees of freedom: Diquark correlation**
  - **Origin of spin-dependent force: Systematics of spin-spin/spin-orbital forces**
  - **Quark motions in "quark core": Size of "core" and "cloud"**

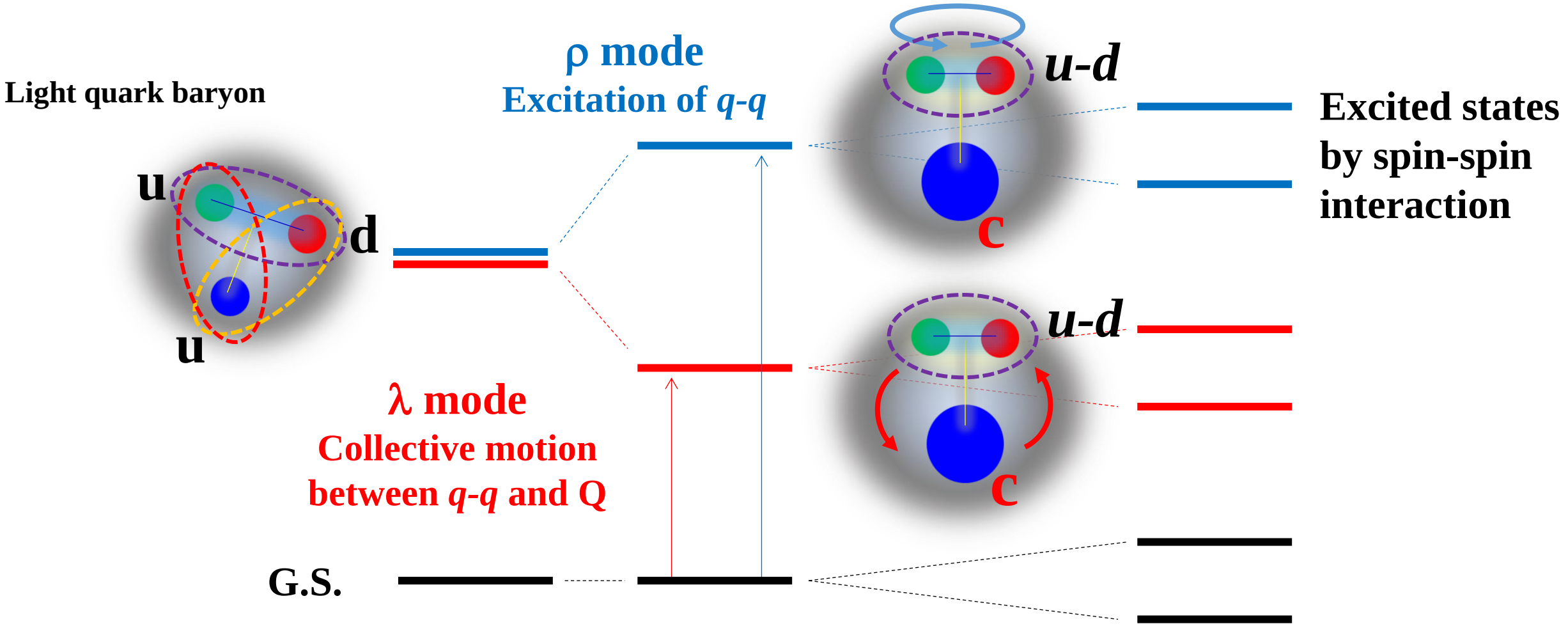
**Instanton*: *A topological object of gluon that mediates the $U_A(1)$ breaking interaction proposed by Kobayashi, Maskawa, and 't Hoot*

Charmed baryon spectroscopy: J-PARC E50

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

✻ Dynamical information: Production rates and absolute decay branching ratios

- Missing mass method: $\pi^- p \rightarrow D^{*-} Y_c^{*+}$ reaction at 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 → $R \sim \langle \varphi_f | \sqrt{2}\sigma_- \exp(i\vec{q}_{eff}\vec{r}) | \varphi_i \rangle$
  - ⇒ Production rates: λ/ρ mode assignment
    - Production rate of LS doublet = $L : L+1$
  - Large production rate of highly excited states → $I_L \sim (q_{eff}/\alpha)^L \exp(-q_{eff}^2/\alpha^2)$

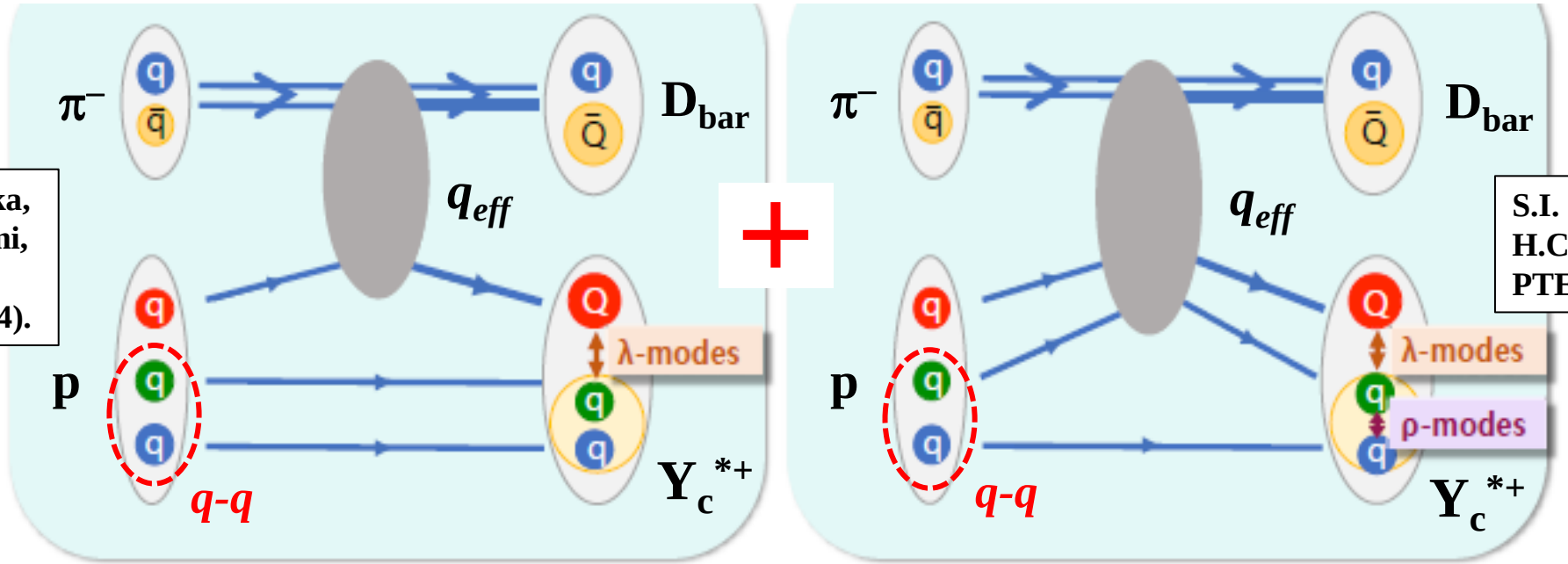
Mom. Trans. : q_{eff}~1.4 GeV/c
α~0.4 GeV ([Baryon size]$^{-1}$)

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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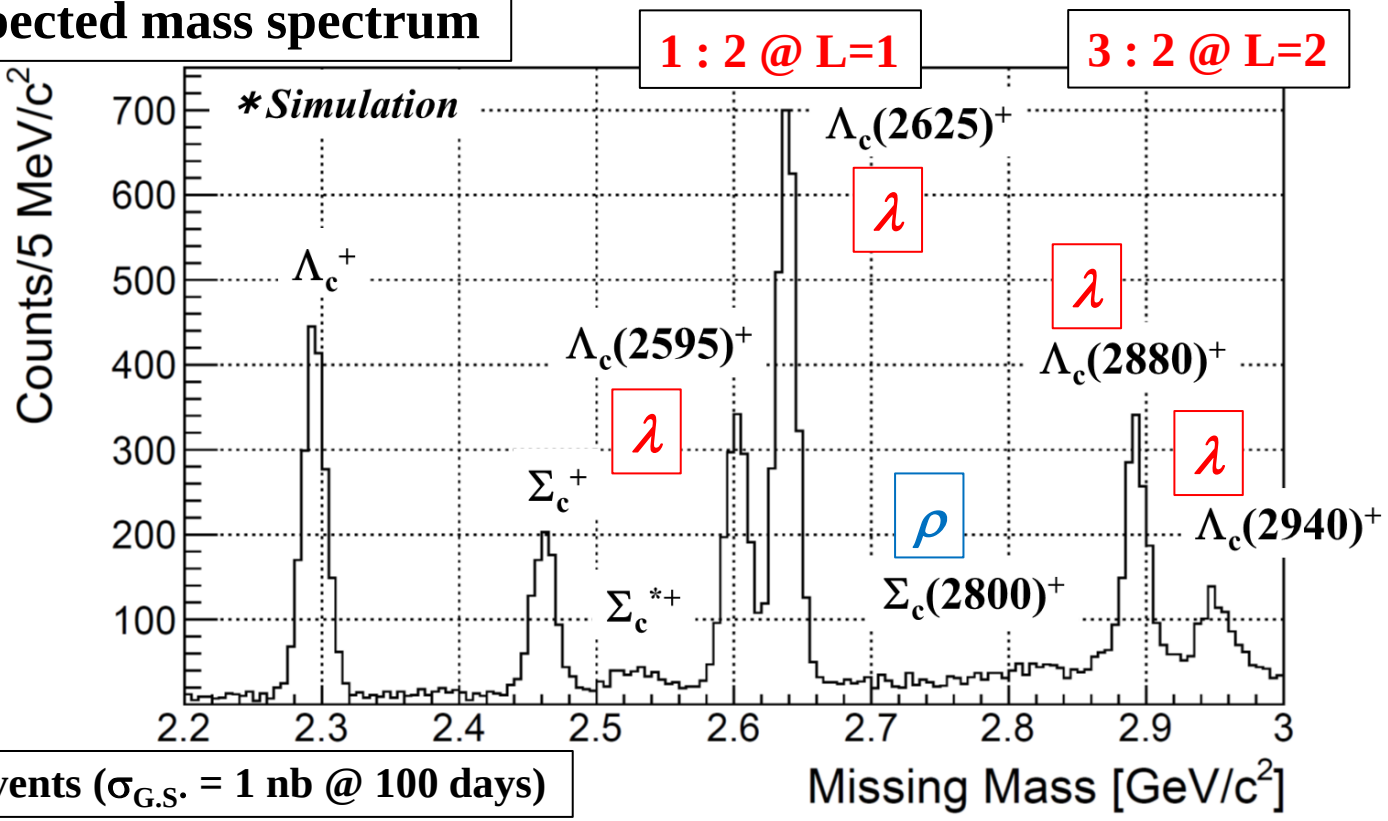
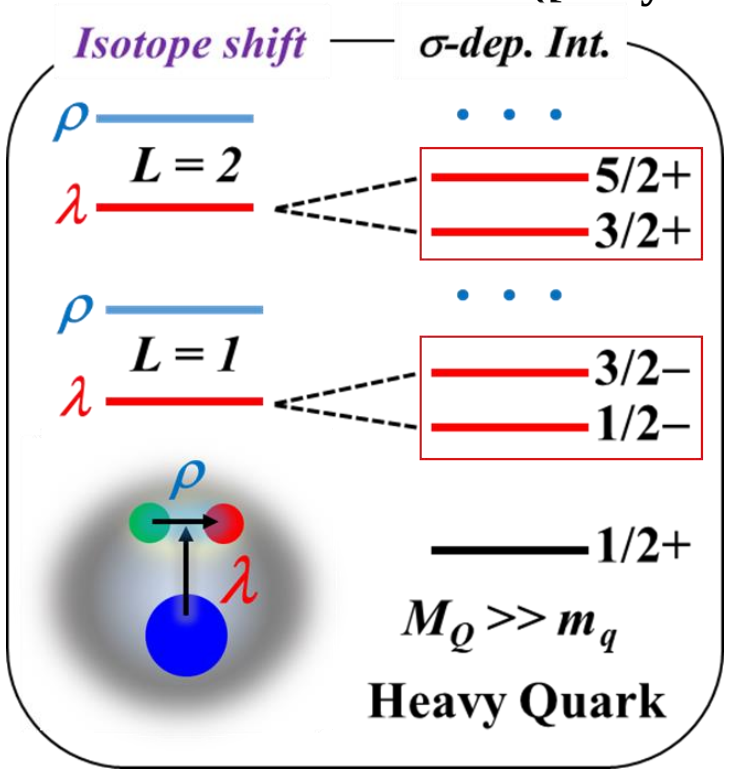
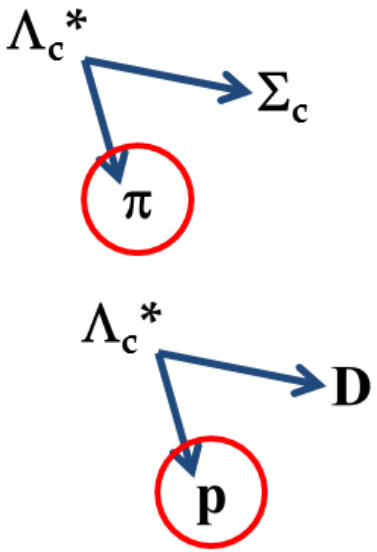
Expected mass spectrum



~2000 events ($\sigma_{G.S.}$ = 1 nb @ 100 days)

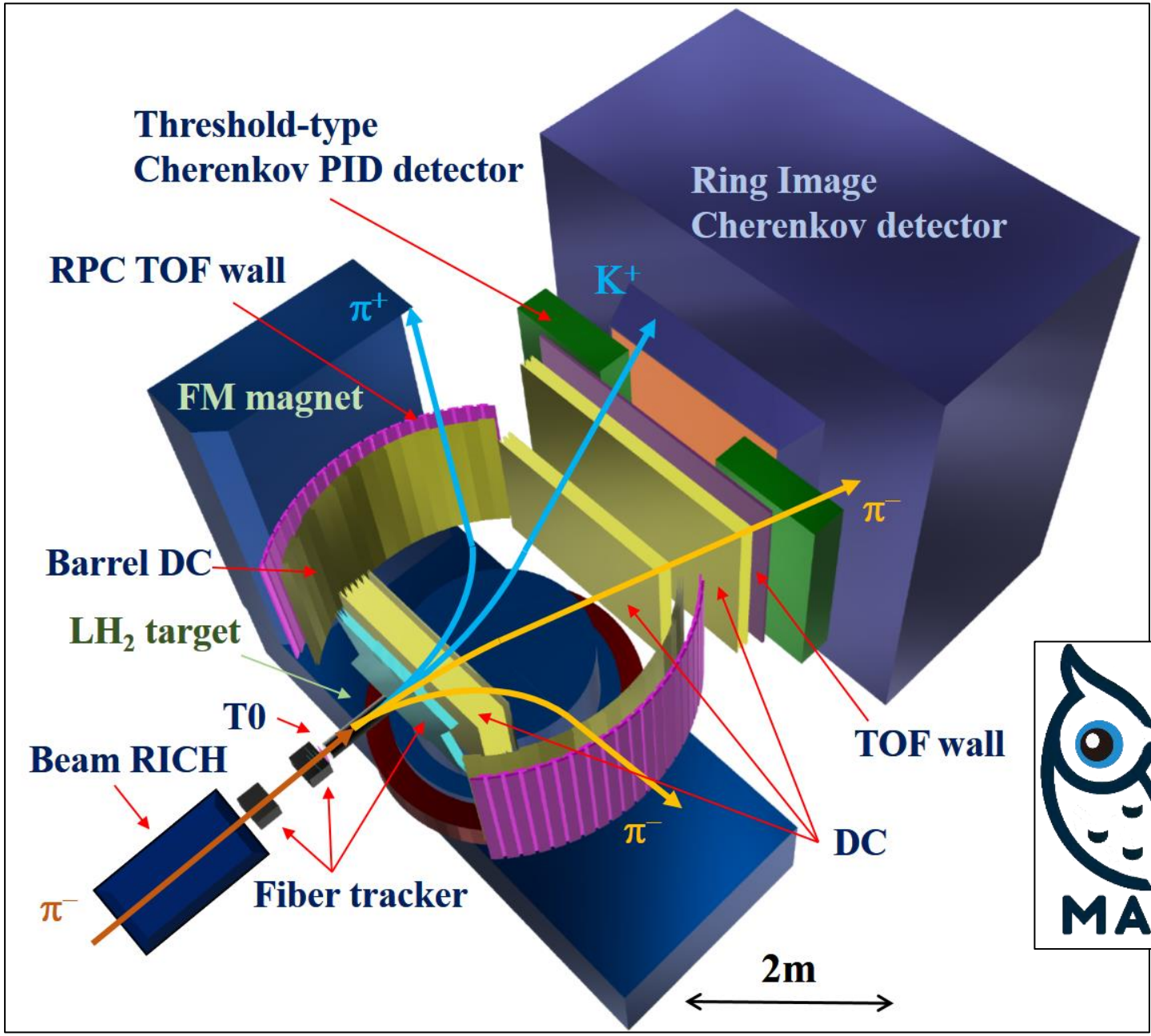


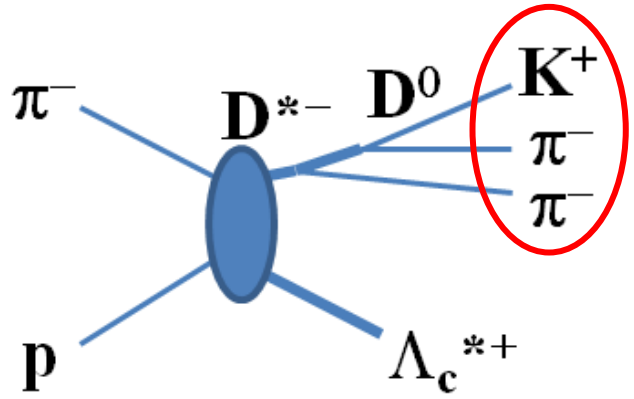
MARQ spectrometer at π20



Decay measurement
∗ Branching ratios

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



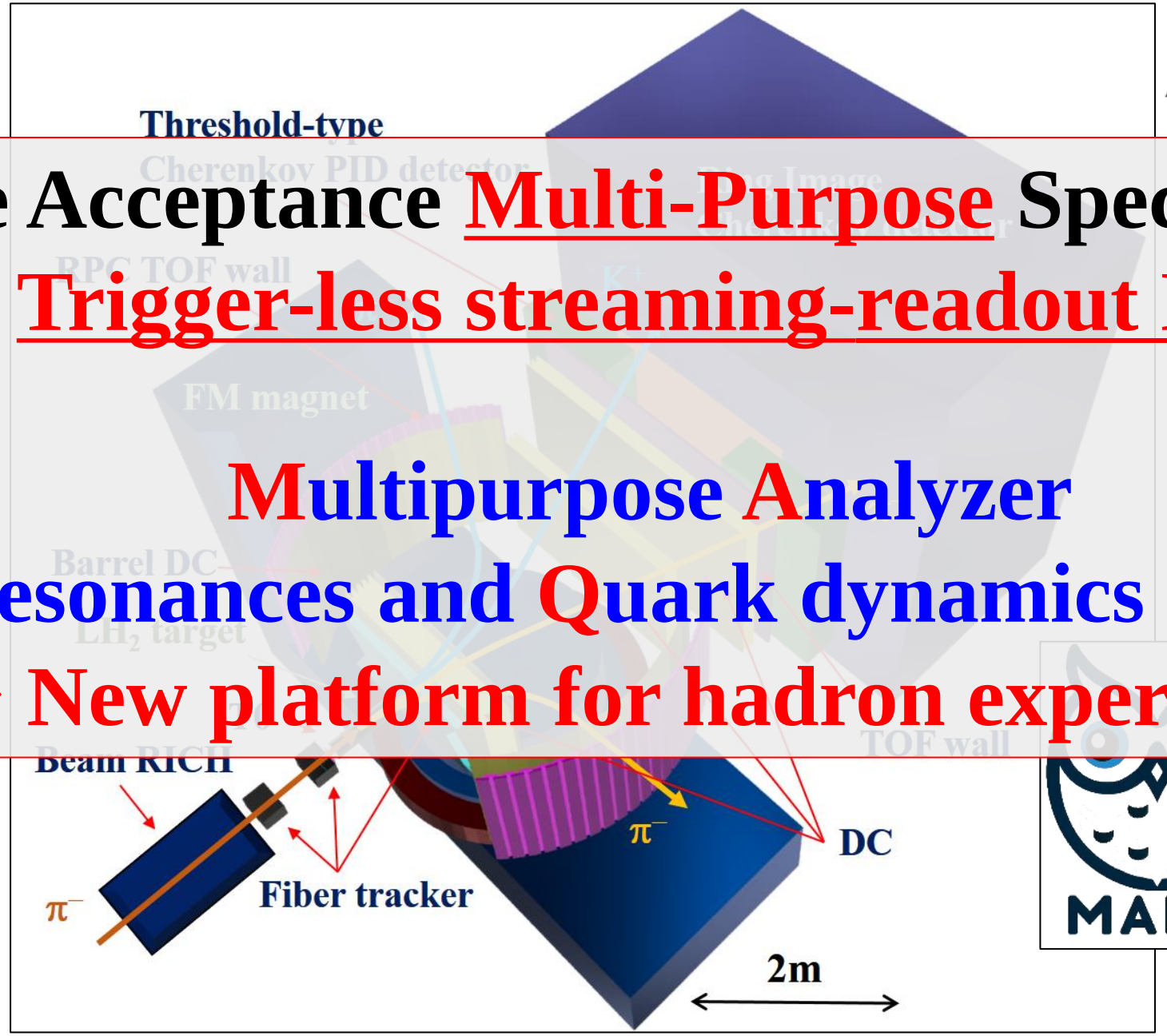


Missing mass measurement
∗ Production rate

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

MARQ

MARQ spectrometer at π20



Λ_c^* → Σ_c → π

Λ_c^* → D → p

π^- D^{*-} D^0 → K^+ π^- π^-

Λ_c^{*+}

Missing mass measurement
* Production rate

K^+ & π^-: 2–16 GeV/c

Decay measurement
* Bran

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

Large Acceptance Multi-Purpose Spectrometer

+ Trigger-less streaming-readout DAQ

Multipurpose Analyzer

for Resonances and Quark dynamics (MARQ)

⇒ New platform for hadron experiment

Hadron experiments at π20

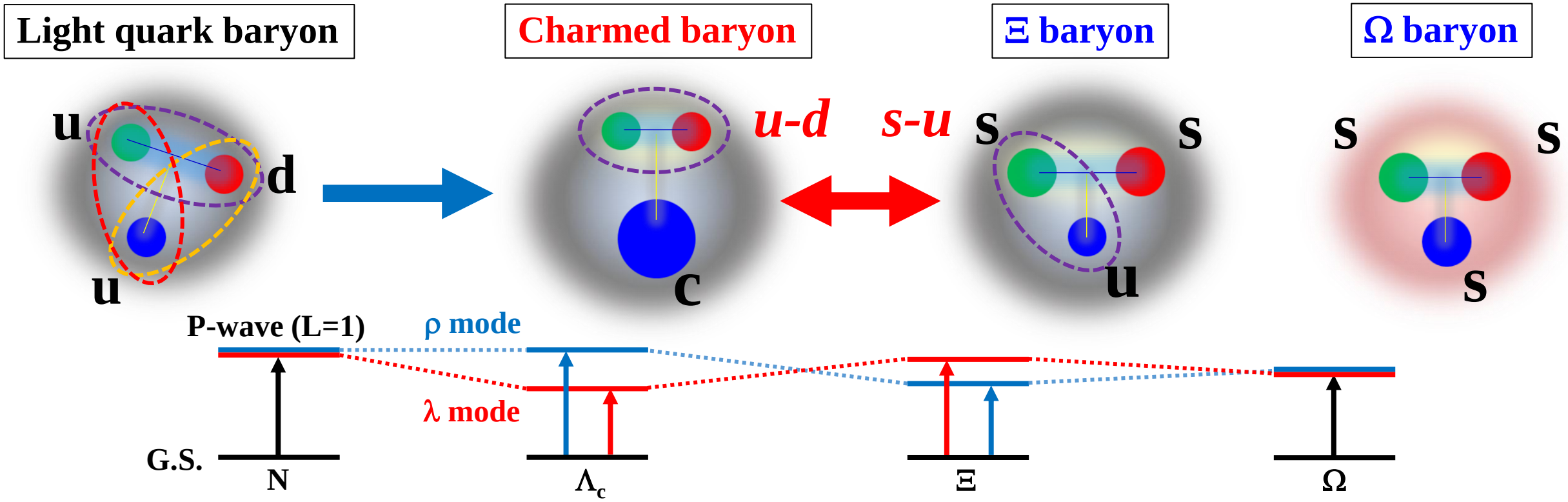
- **High-momentum 2ndary beam: 2–20 GeV/c**
- **MARQ spectrometer + Trigger–less streaming-readout type DAQ**

⇒ Various experiments can be conducted.: Simultaneously at the same beam momentum

- **Unseparated beam: e.g. $\pi^-/K^-/\bar{p}$ can be used simultaneously.**

Experiment	Beam particle	Momentum [GeV/c]	Intensity [Mcps]
Charmed baryon spectroscopy	π^-	20	30
Ξ baryon spectroscopy	K^-	5–8	> 0.5
Ω baryon spectroscopy	K^-	7–10	> 0.5
Non-strange dibaryon search	proton	2.85–4.00	> 1
ϕN interaction study via π^- induced reaction	π^-	1.8–2.4	> 1
Exclusive Drell-Yan measurement	π^-	15	30
Λ(1405) study by quark counting rule	π^-	5–10	> 10
Double Kaonic nucleus search	proton	8	30
Λ-p scattering experiment with high-momentum	π^-	8.5	30

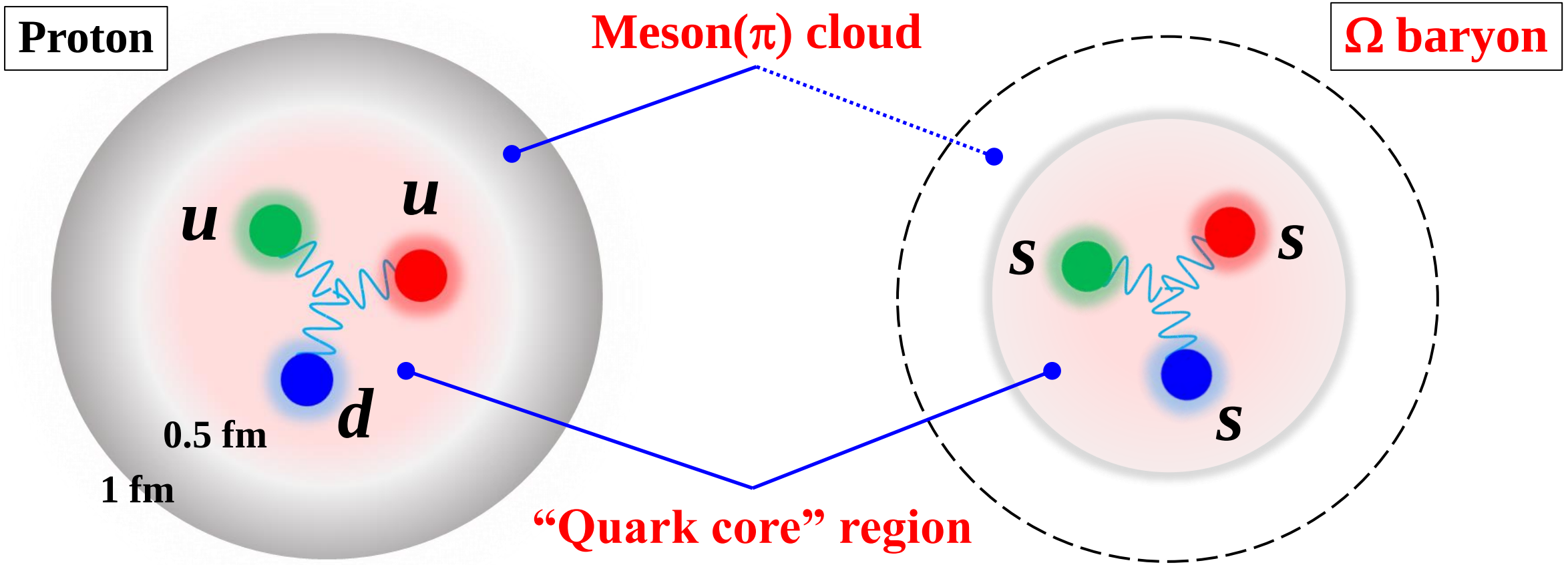
Heavy flavors for revealing diquark correlation



✻ **Systematic studies for baryon systems with heavier flavors: *c* & *s***

- **Charmed baryon (E50): *ud* diquark correlation**
- **Ξ baryon (E97): *us*/*ds* diquark correlation ⇒ Flavor dependence**
- **Ω baryon (P85): Only axial-vector diquark correlation ⇒ Reference system**

Ω baryon spectroscopy: J-PARC P85



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

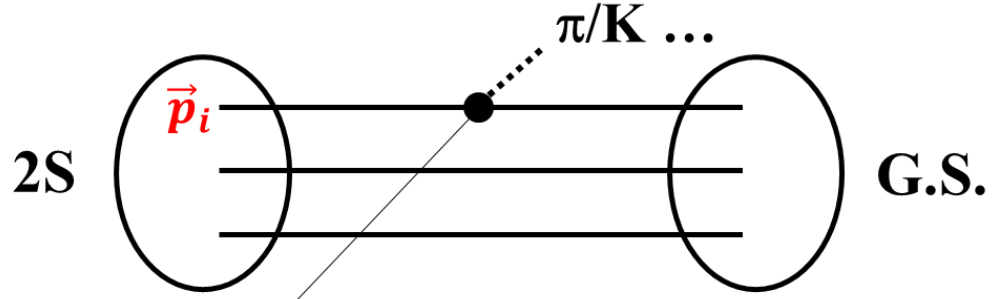
⇒ Origin of spin-dependent forces and quark motion

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

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

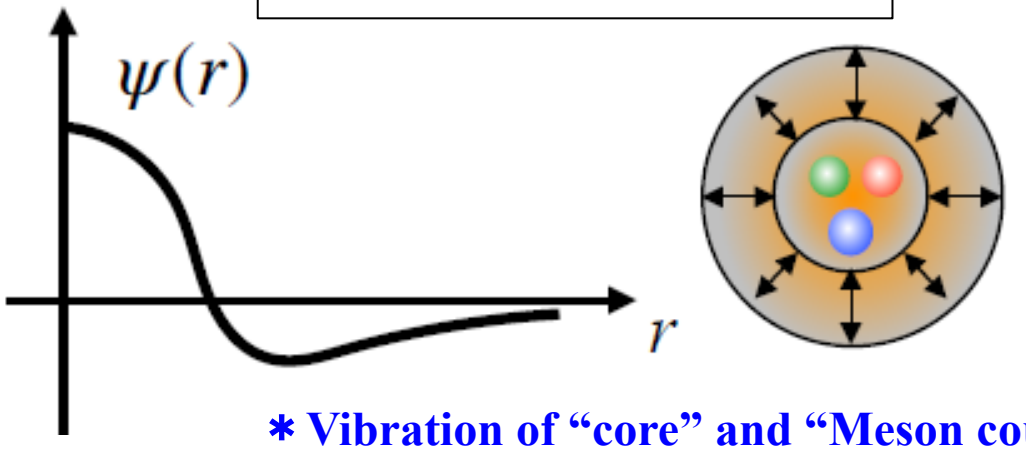
Next to leading order (NLO)

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

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

∗ $\Omega^{*-}(3/2^+)(2S)$: Γ = 50–100 MeV

Radial excitation 2S states



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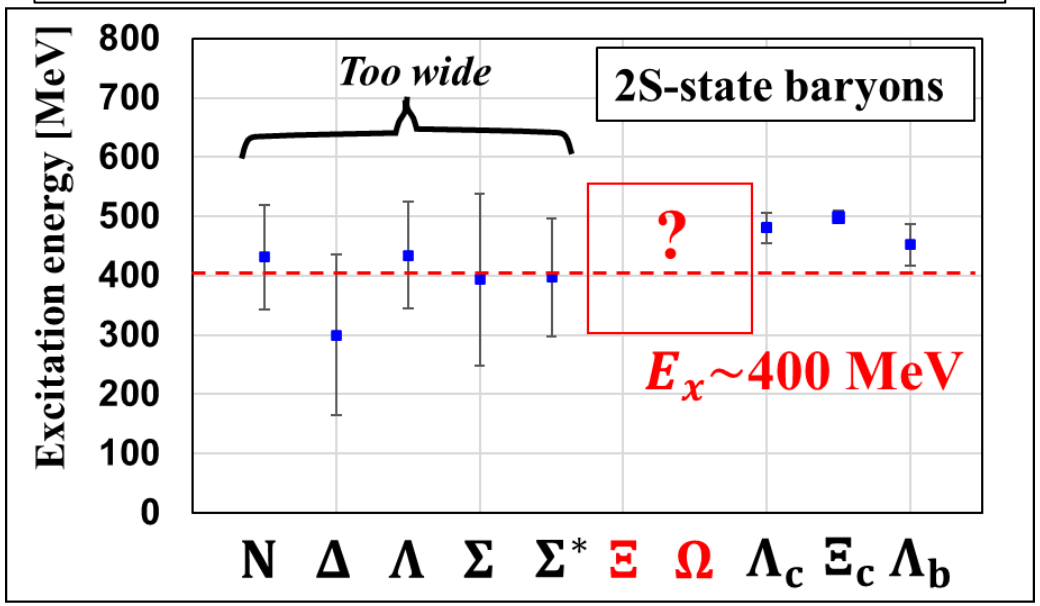
Systematics of the Roper-like resonances



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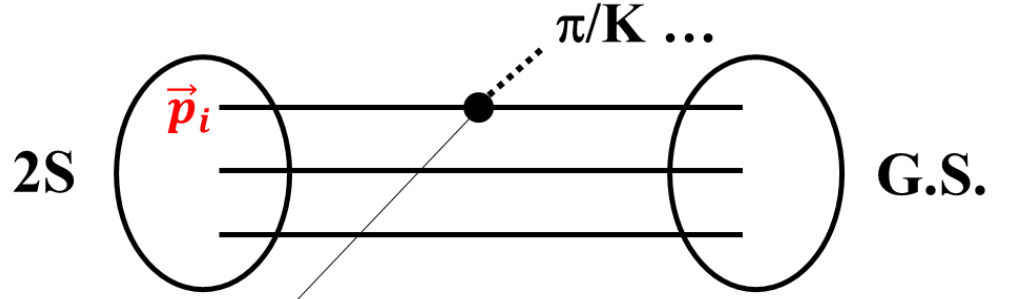

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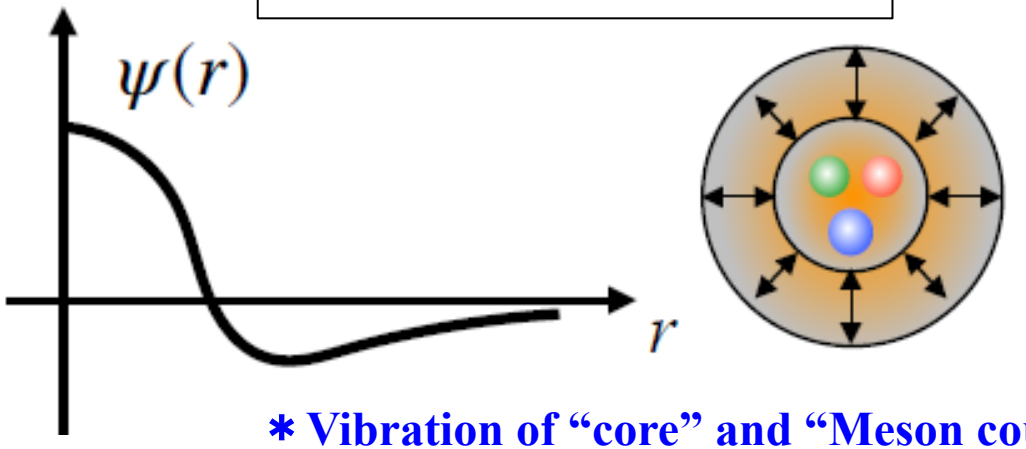

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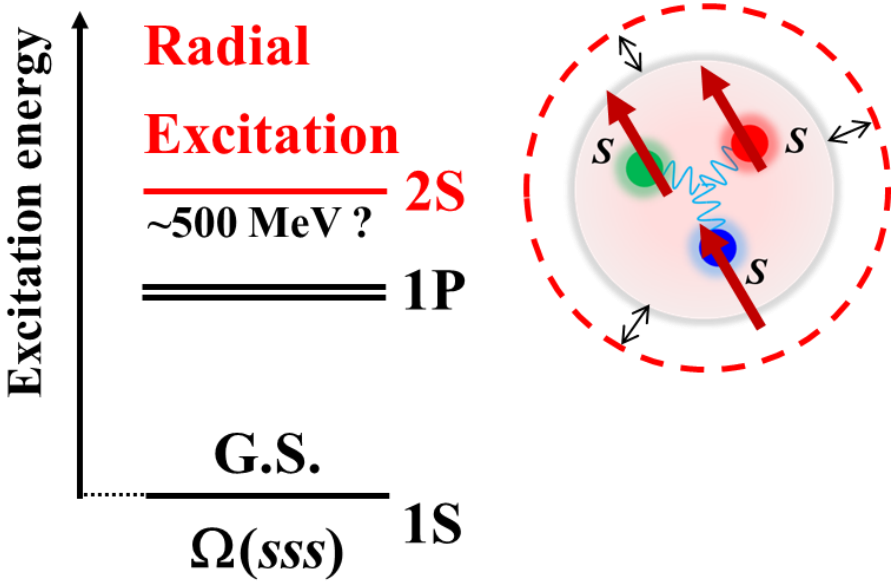
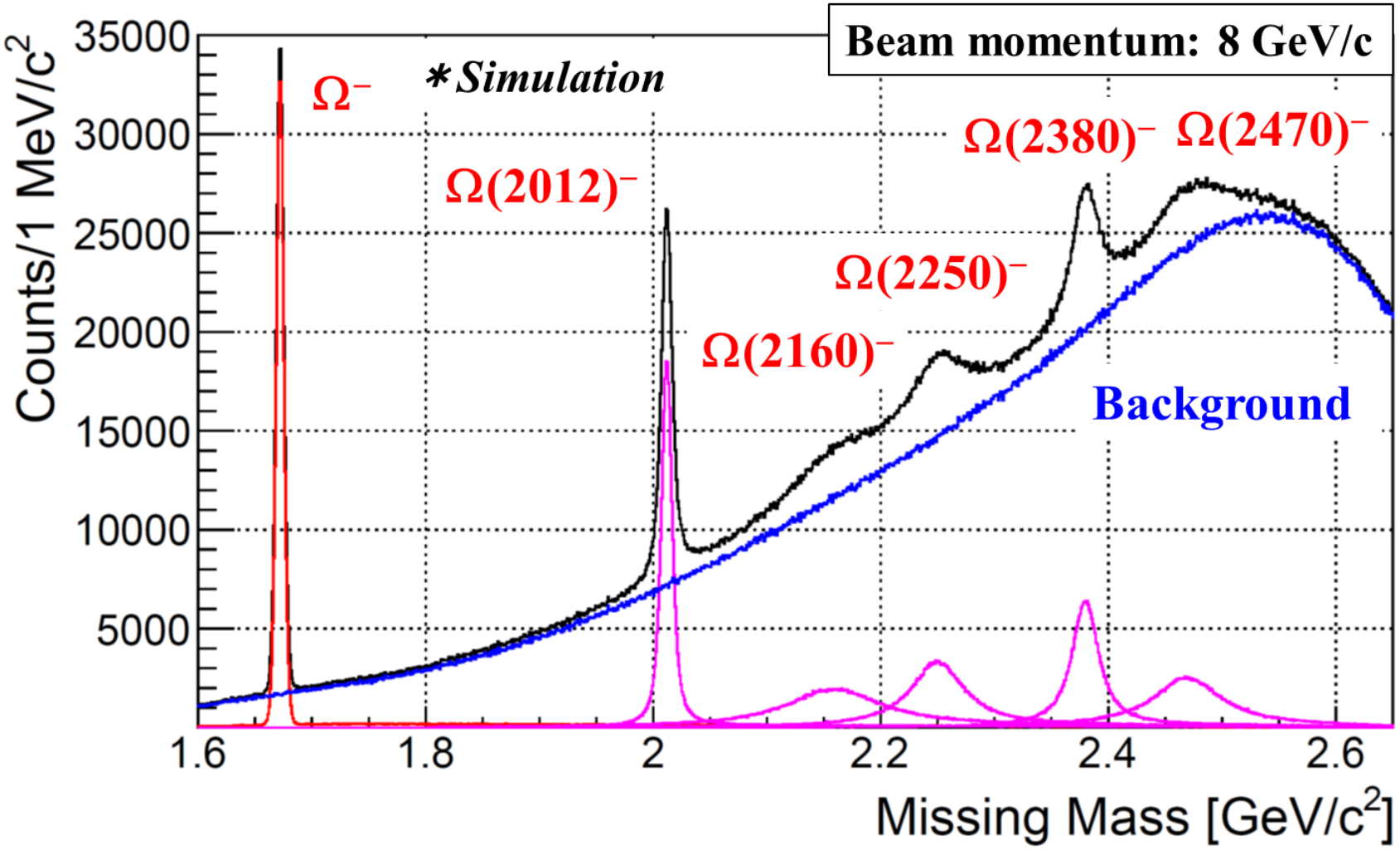


∗ $\langle r_q^2 \rangle \sim 1/\langle p_q^2 \rangle$: Quark core size ?

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

∗Known states in PDG and background by hadronic reaction code

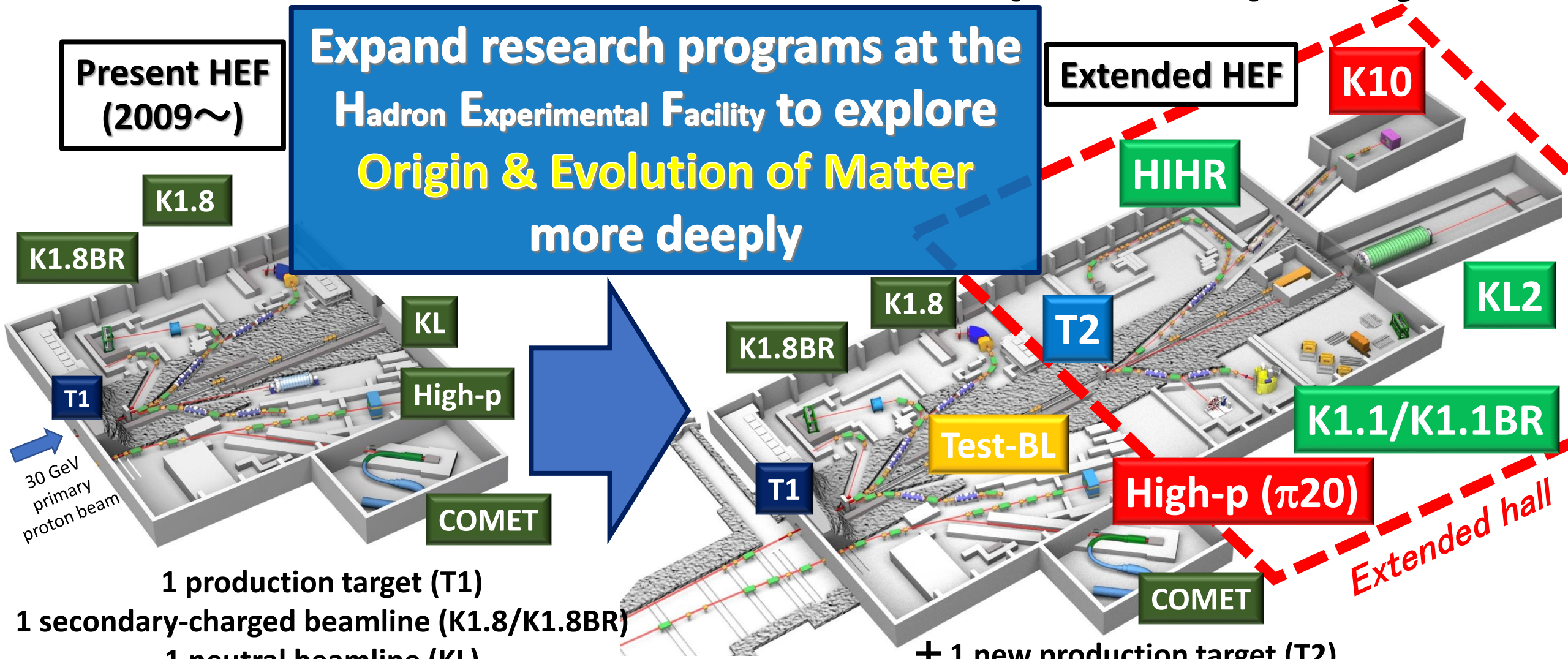
- Ω^{*-} events: ~10^5 events @ 100 days (63 nb: Same cross section for all resonances)
  - Estimated from $K^+ K^+ \pi^-$ mode ($K^0 K^+$ mode ×1/40)
- Mass resolution: ΔM ~5 MeV < Width (several 10 MeV)

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

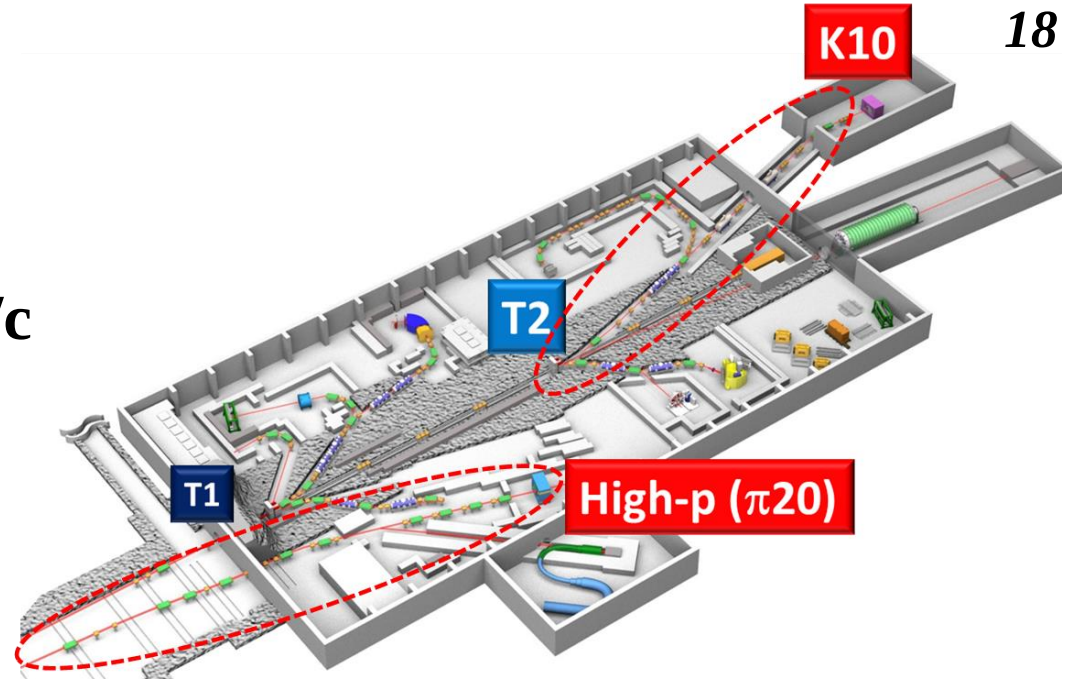


1 production target (T1)
1 secondary-charged beamline (K1.8/K1.8BR)
1 neutral beamline (KL)
1 primary beamline (High-p)
1 muon beamline (COMET)

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

Baryon spectroscopy at J-PARC

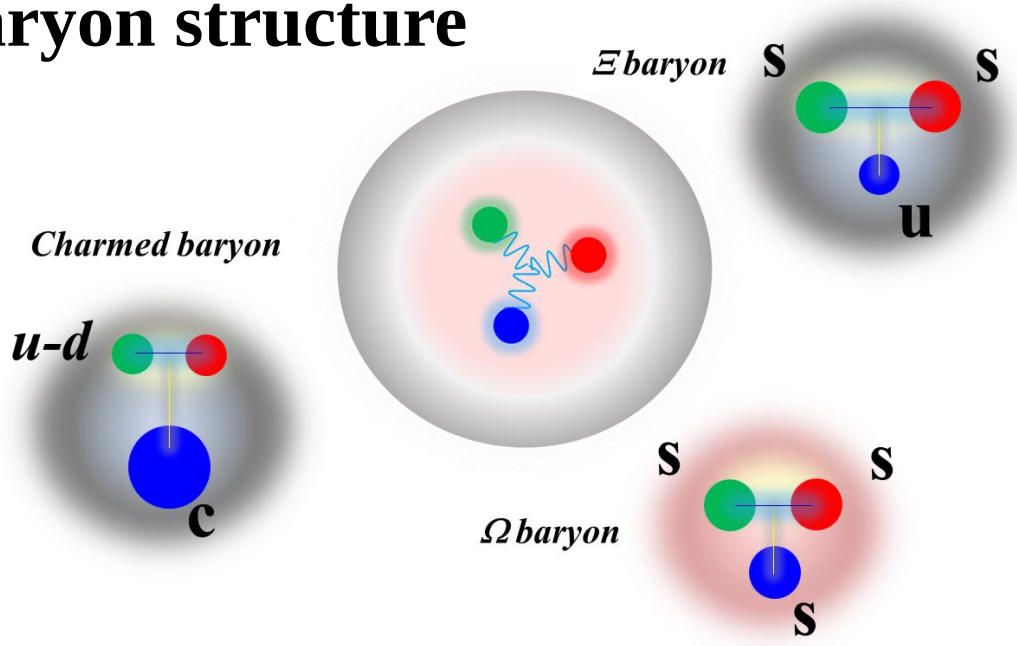
- **π20: π beam (unseparated beam)**
  - **High intensity: >10^7 /spill for π^- up to 20 GeV/c**
- **K10: K^- & $\bar{p}$ beam ($K/\pi \sim 1/2$, $\bar{p}/\pi \sim 2/1$)**
  - **High intensity: >10^6 /spill up to 10 GeV/c**



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

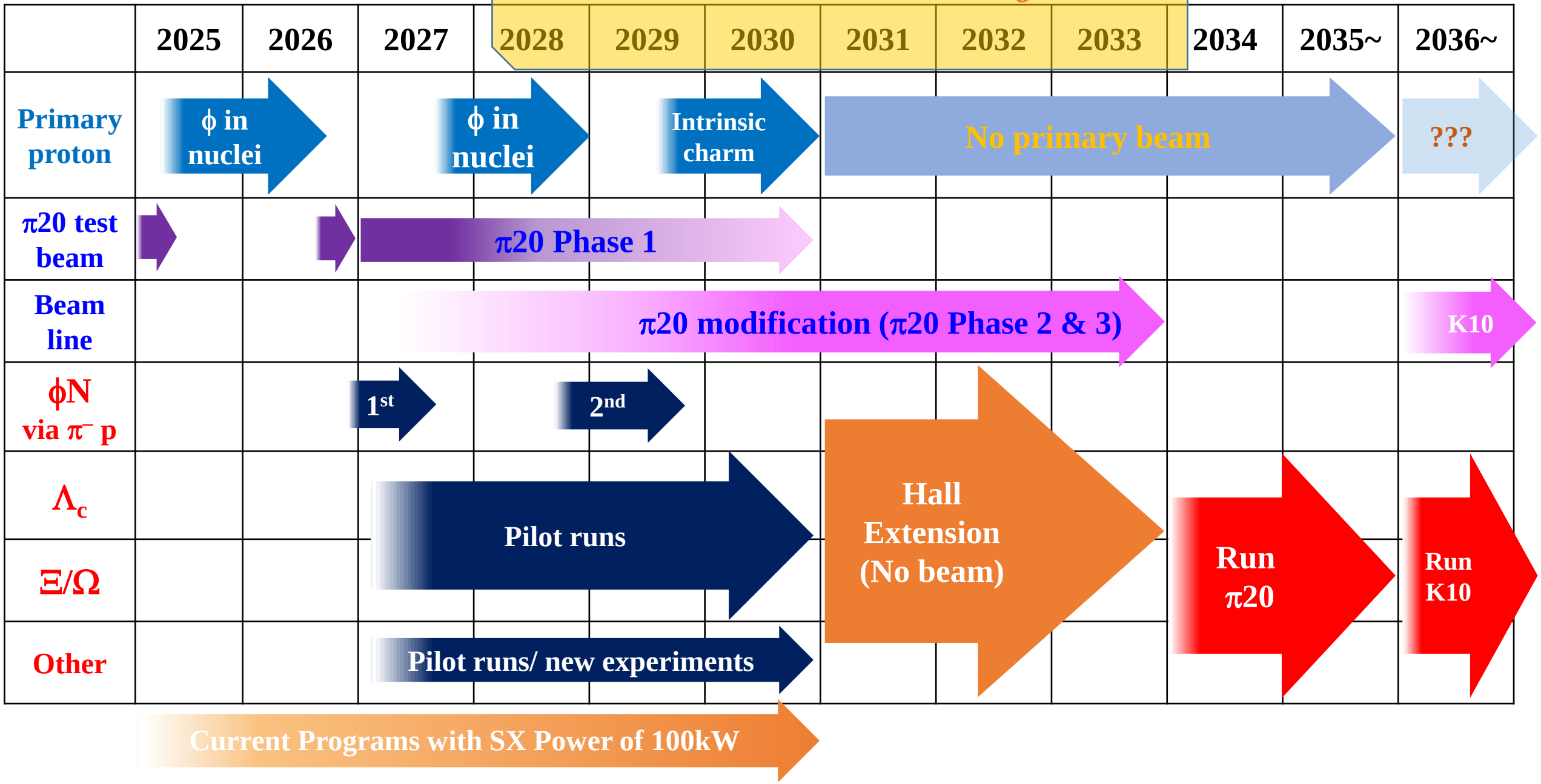
Dynamics of non-trivial QCD vacuum in baryon structure

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



Tentative schedule

The Extension Project



Summary

- **How quarks build hadrons ?**
  - **Disentangle QCD properties behind hadron formation**
  - **Understanding of dynamics of non-trivial QCD vacuum in baryon structure**
  - **Investigation of diquark correlation and origin of spin-dependent forces**
  - **Systematic study of heavier flavor baryons: Λ_c/Σ_c, Ξ, Ω**

- **Spectroscopy experiment of heavier flavor baryons**
  - **Systematic spectroscopy experiments of Λ_c/Σ_c, Ξ, Ω baryons**
  - **High-intensity & High-momentum hadron beam: π20 and K10**
  - **π20 beam line construction with staging**
  - **Construction of multi-purpose spectrometer: MARQ**

J-PARC hadron experimental facility promotes various hadron experiments.