Hadron spectroscopy with high-momentum hadron beams

K. Shirotori
for the E50 collaboration

Research Center for Nuclear Physics (RCNP)
Osaka University

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Contents

Motivations of Hadron Physics

Hadron physics investigations

- **Excited states**
  - **Effective degree of freedoms**
    - **Constituent quark + Diqaurk correlation & Hadron molecule**

  ⇒ Spectroscopy experiment with heavy quark
    - **Excites energy, spin and parity, production cross section, decay branching ratio**

- **Properties in nuclear medium**
  - **Origin of mass**
    - **Spontaneous breaking of chiral symmetry**

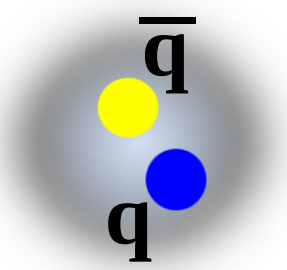
  ⇒ Measurement on nuclear target
    - **Change of mass, shape, decay branching ratio, cross section**

∗ J-PARC: High-intensity Secondary Hadron beams

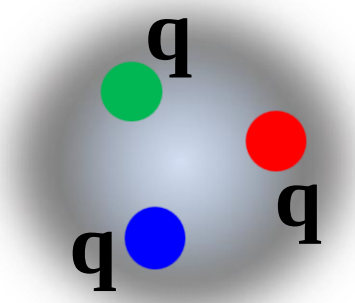
Excited states: Observation of exotic hadrons

Constituent quark

Meson

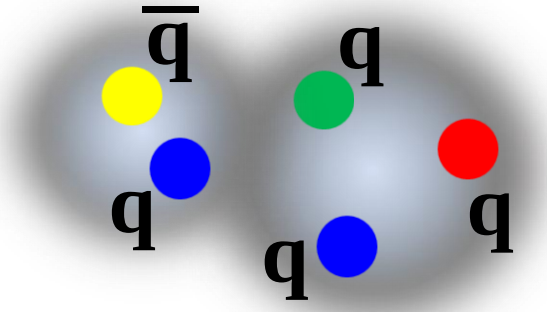


Baryon

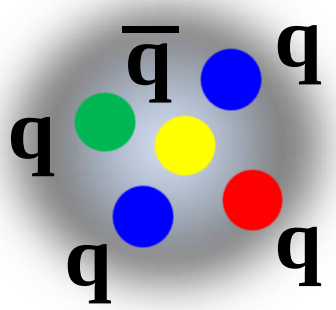


Exotic hadrons

Hadron molecule



Multi-quark



∗ Excited states: Rich properties

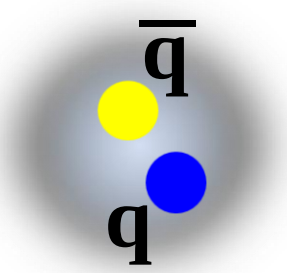
⇒ Mass, width, decay branching ratio, spin and parity

from new effective degree of freedoms extended to ordinary constituent quark model

Excited states: Observation of exotic hadrons

Constituent quark

Meson



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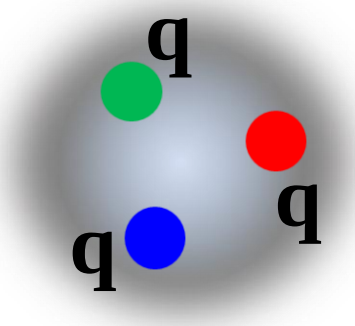
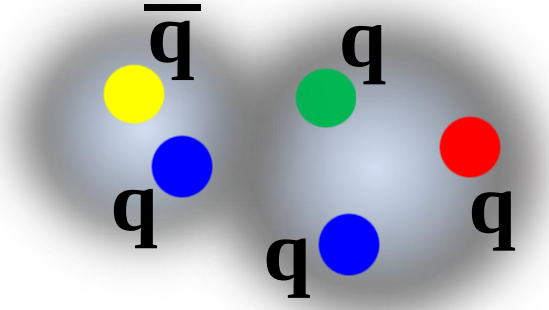
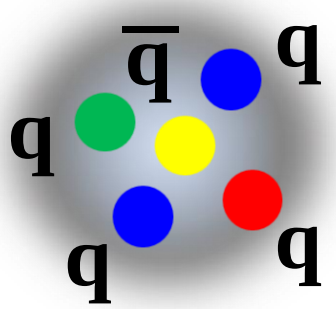


Exotic hadrons

Hadron molecule



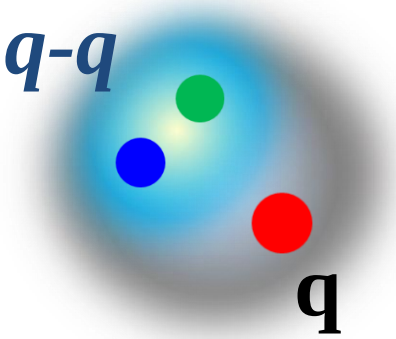
Multi-quark



Diquark correlation

Diquark correlation
&
Hadron molecule

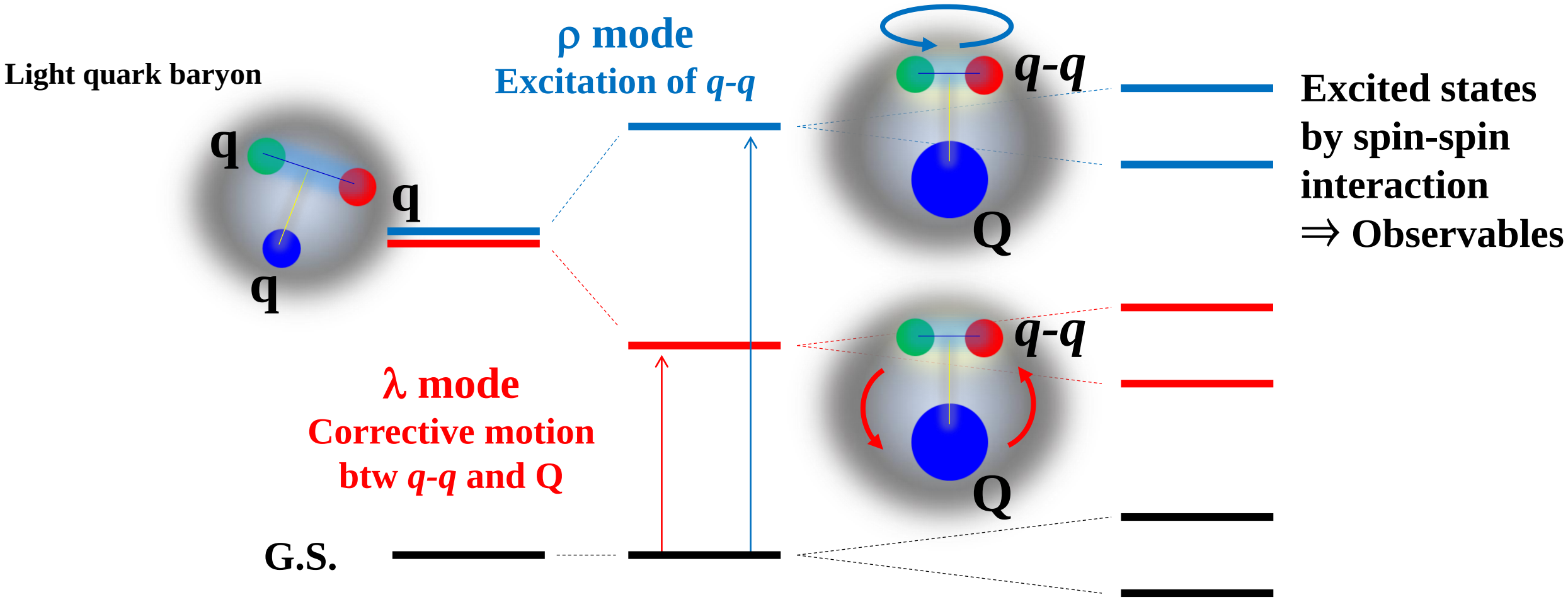
q-q



Excited states with heavy quark: Diquark

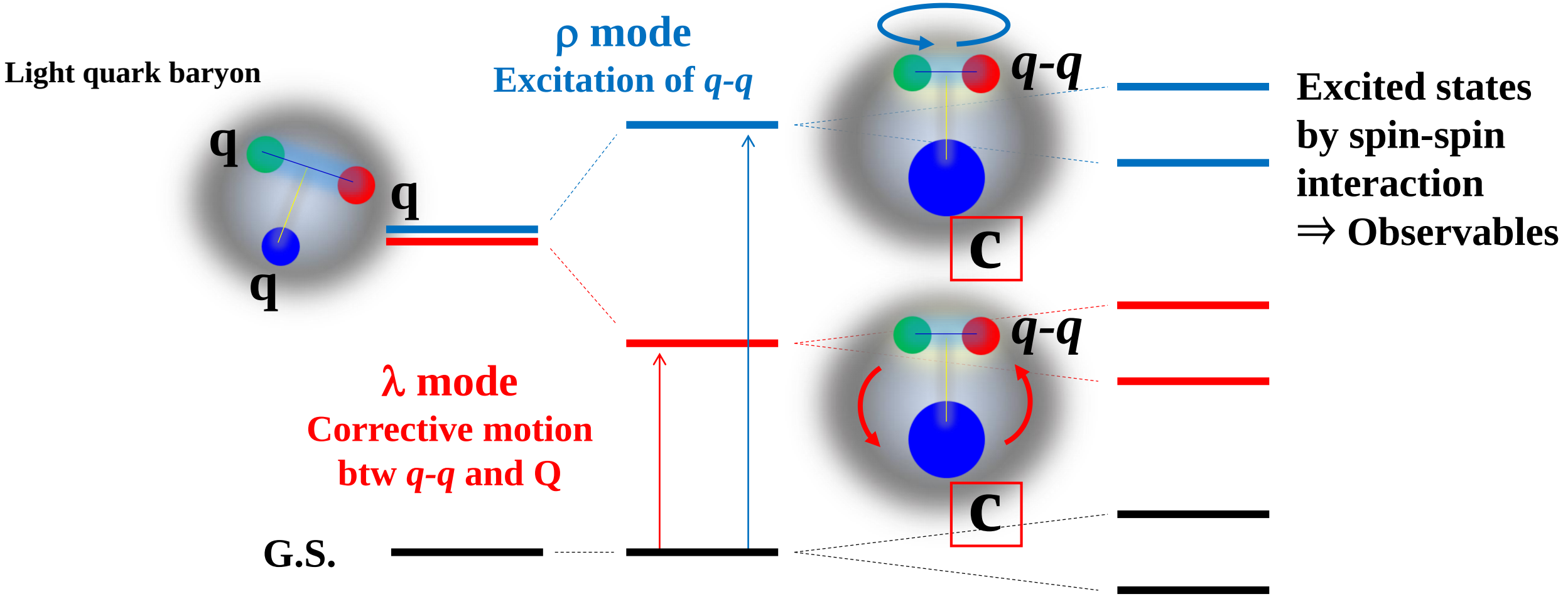
"Excited mode": λ and ρ modes in heavy baryon excited states (*q*-*q* + Q system)

⇒ Diquark correlation: *q*-*q* isolated and developed



Charmed baryon spectroscopy experiment: J-PARC E50

* $\pi^- + p \rightarrow Y_c^{*+} + D^{*-}$ reaction @ 20 GeV/c
  - High-intensity π^- beam: 6.0×10^7 /spill
- Production rates & Decay branching ratios



Production rates by hadronic reaction

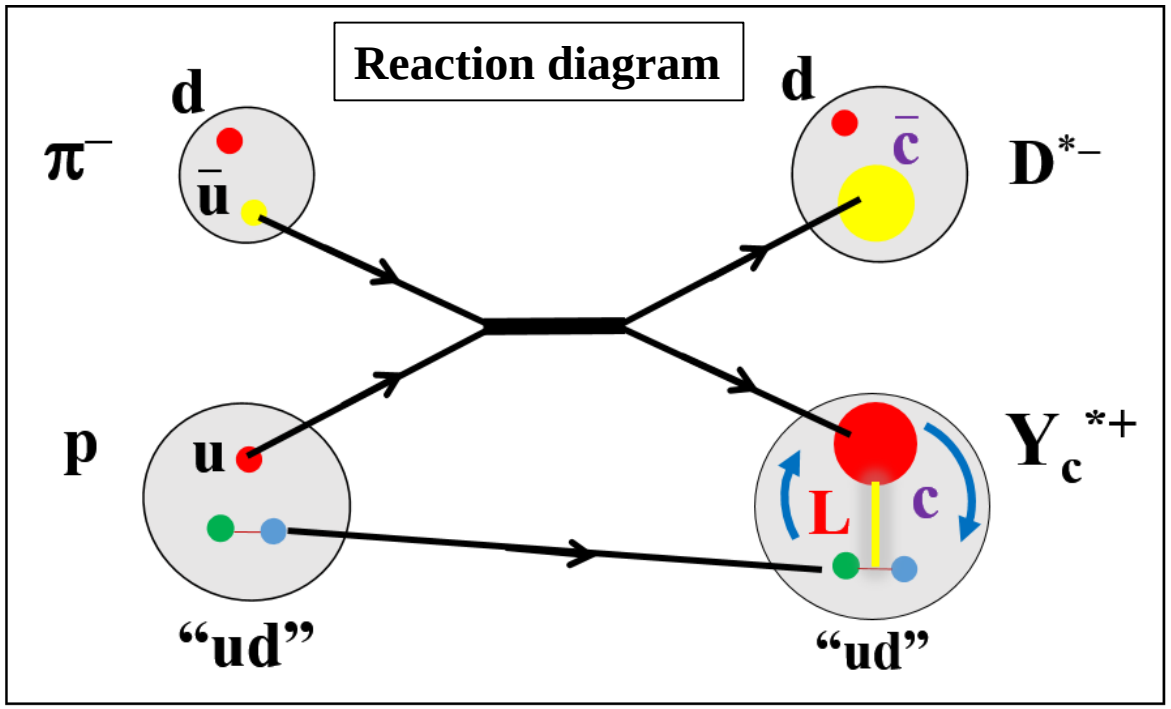
- $\pi^- + p \rightarrow Y_c^{*+} + D^{*-}$ reaction: Missing mass method

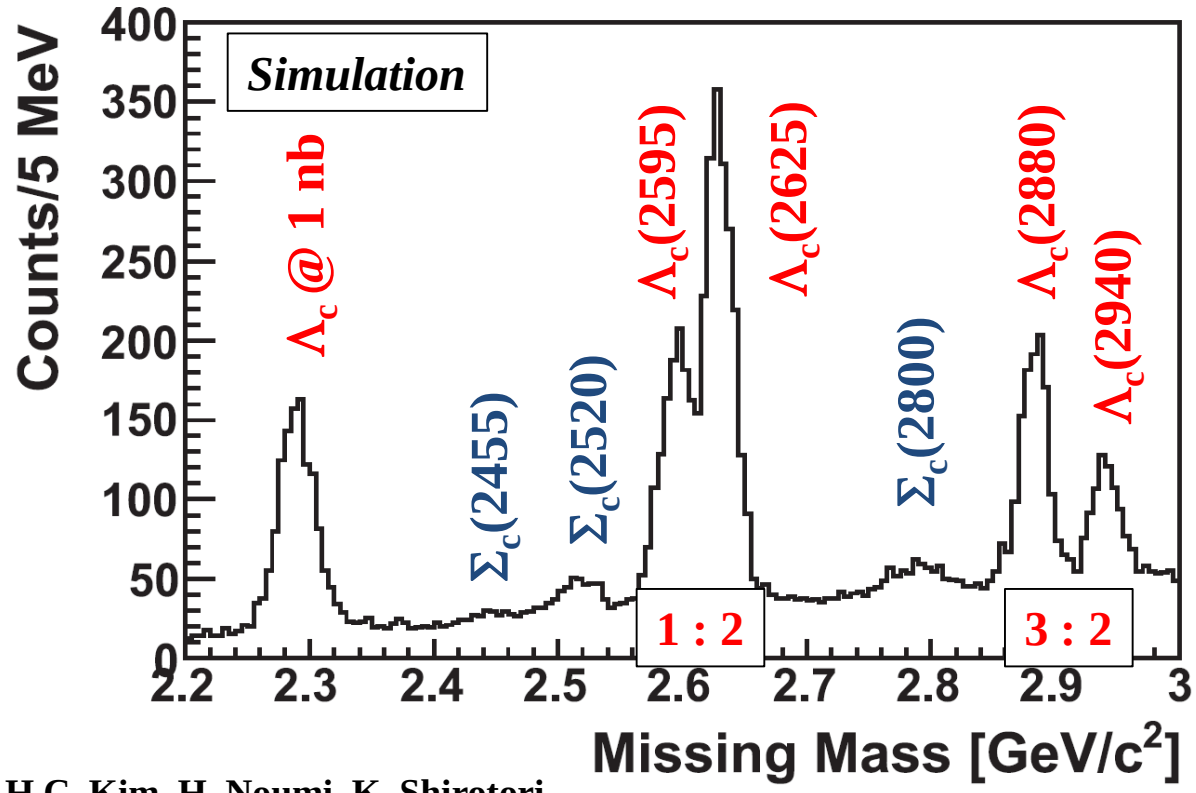
∗ Production rates ⇔ Internal structure of excited states

⇒ Selective production of corrective motion: λ mode

∗ Production cross section
⇒ Overlap of wave function
∗ charm and *q*-*q* (spectator)

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





∗ Angular momentum transfer between diquark (*q*-*q*) and charm quark

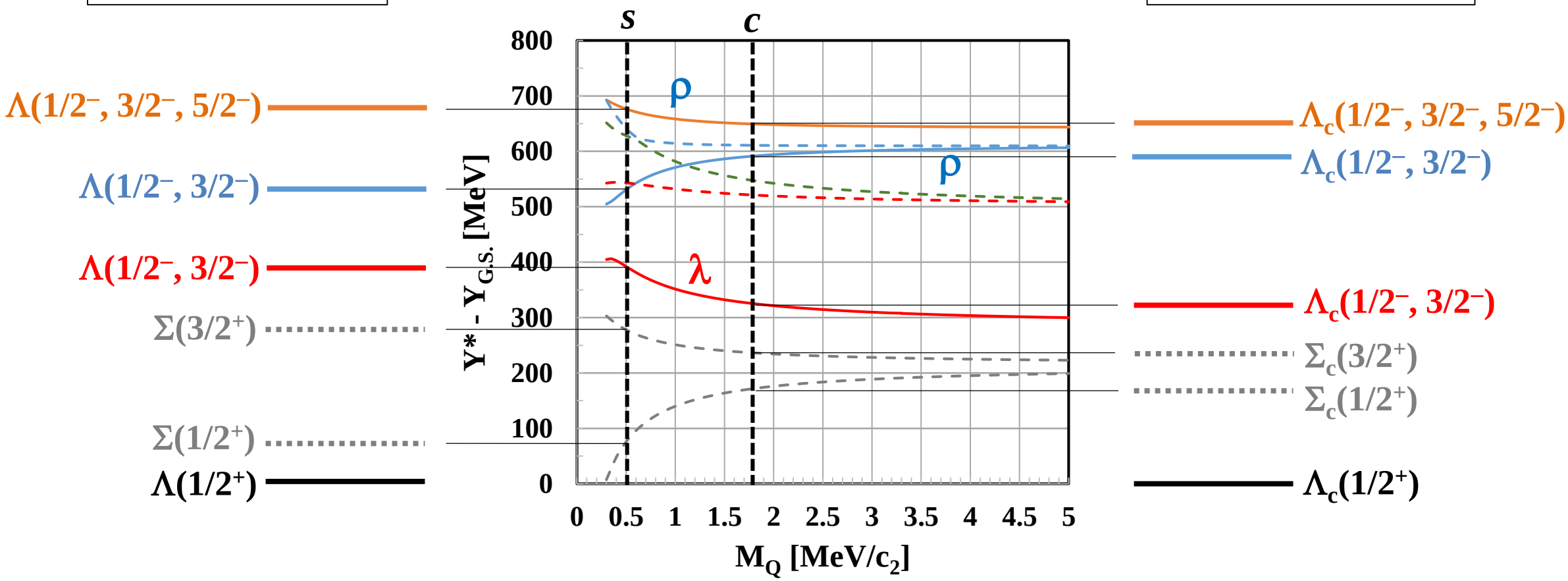
S.H. Kim, A. Hosaka, H.C. Kim, H. Noumi, K. Shirotori
Prog. Theor. Exp. Phys. 103D01 (2014).

Excitation spectrum: *q*-*q* + Q

Strange baryons

P-wave states

Charmed baryons



- **Non-rel. QM: $H = H_0 + V_{conf} + V_{SS} + V_{LS} + V_T$**
- **λ-ρ mixing**

(cal. By T. Yoshida, Nucl.Phys. A954 (2016) 341)

∗ Heavy quark sector (charm)
⇒ Light quark sectors (u, d, s)

Strange baryon systems

- Λ^*/Σ^* : *q-q* + Q system

⇒ Systematics with charmed baryon

  - Production rate: λ and ρ selection
  - Decay branching ratio

- Ξ^* : q + QQ system

⇒ Excitation with two heavy quarks

- Ω^* : QQQ system

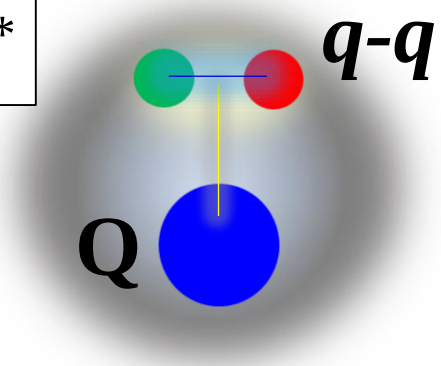
⇒ Same weight of three heavy quarks

∗ Spectroscopy by high-momentum K^- beam

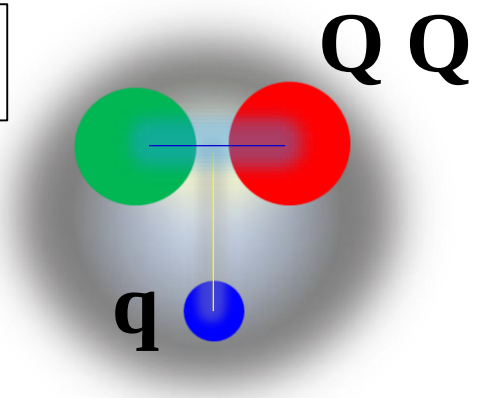
  - Several GeV/c beam
  - Poor data of Ξ and Ω states
  - Exotic states

⇒ Systematic measurement

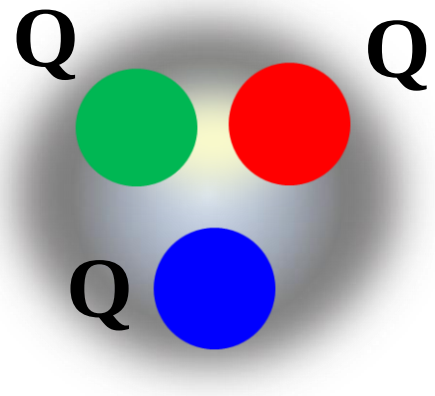
Λ^*/Σ^*



Ξ^*



Ω^*



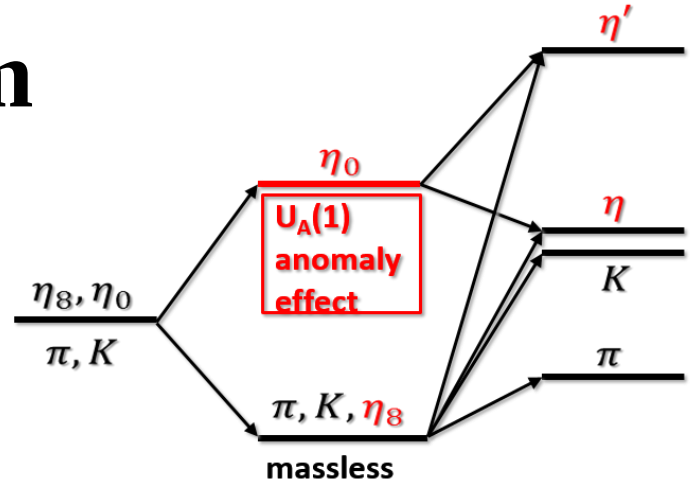
Hadron in nuclear medium

- **Properties in finite density**
  - **Origin of hadron mass**

  ⇒ Vector mesons
    - **Quark condensation: $<qq_{bar}>$**

∗ Different mesons:

Different aspect on QCD vacuum



ϕ/ω/ρ

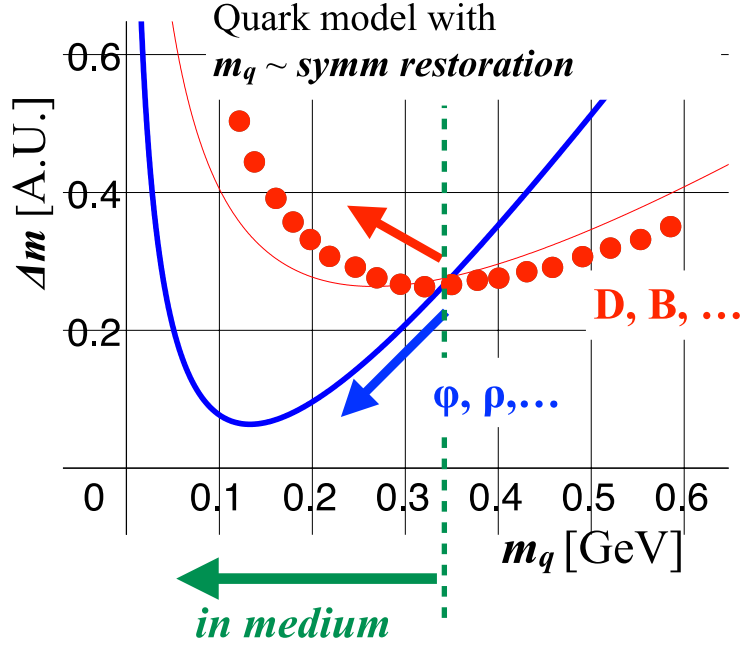
∗ Spontaneous breaking of chiral symmetry

η/η'

$U_A(1)$ anomaly + SBCS

∗ Mass shift in medium
Chiral origin ~ Constituent mass

Park et al, PRD93, 054035 (2016)
Quark model with
m_q ~ symm restoration



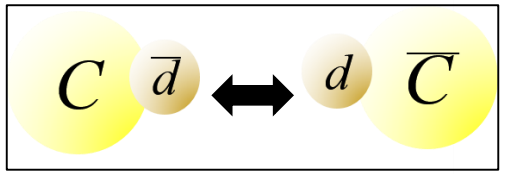
- **Experimental signals on nuclear target**
  - **Mass spectrum: Shift & Shape change**
  - **Decay branching ratio**
  - **Production cross section**
  - **A-dependence**
  - **Quark configuration: Light and heavy quarks**

Experimental approaches

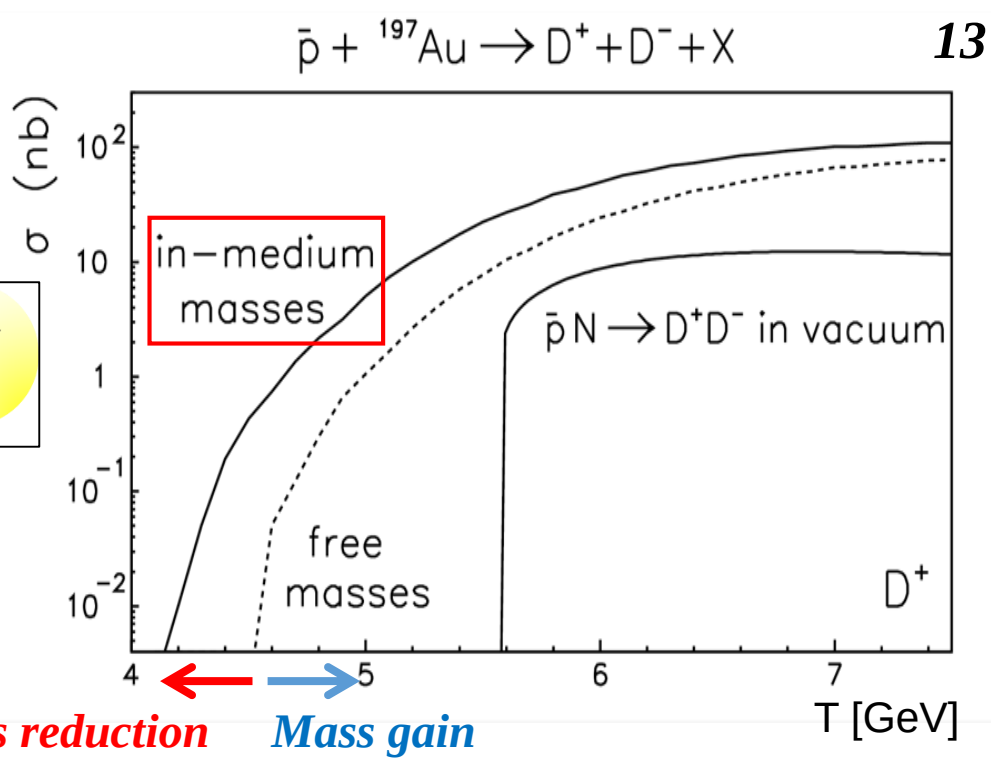
- DD_{bar} production at threshold region
  - c/c_{bar}: No effect
  - q/q_{bar}: Change of mass

  ⇒ Cross section in medium
    - $p_{bar} + p \rightarrow D + D_{bar}$

      $\Leftrightarrow p_{bar} + A \rightarrow D + D_{bar} + X$



$D \neq D_{bar}$



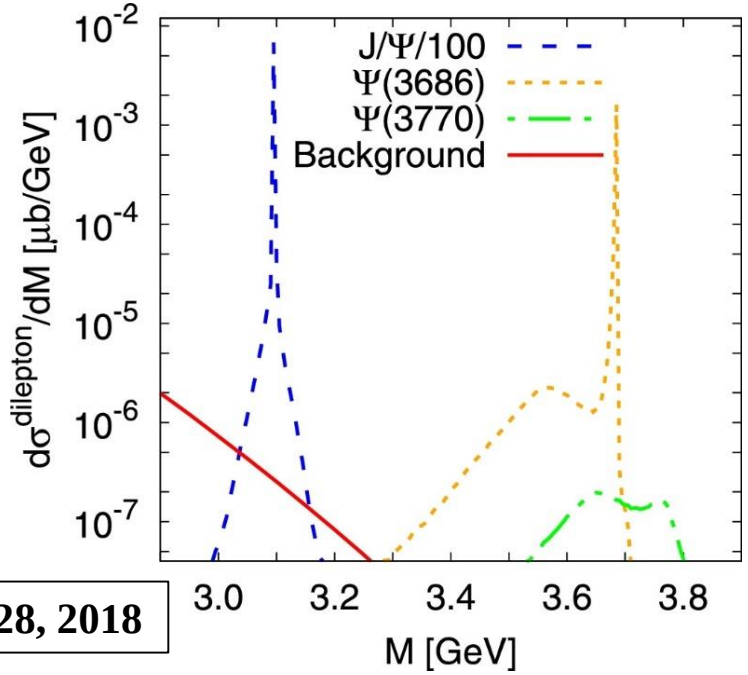
∗ Effects to q/q_{bar} w/o other light quarks

- Charmonium states

⇒ Access to gluon condensation
  - Mass shape (Production cross section)
  - Decay branching ratio

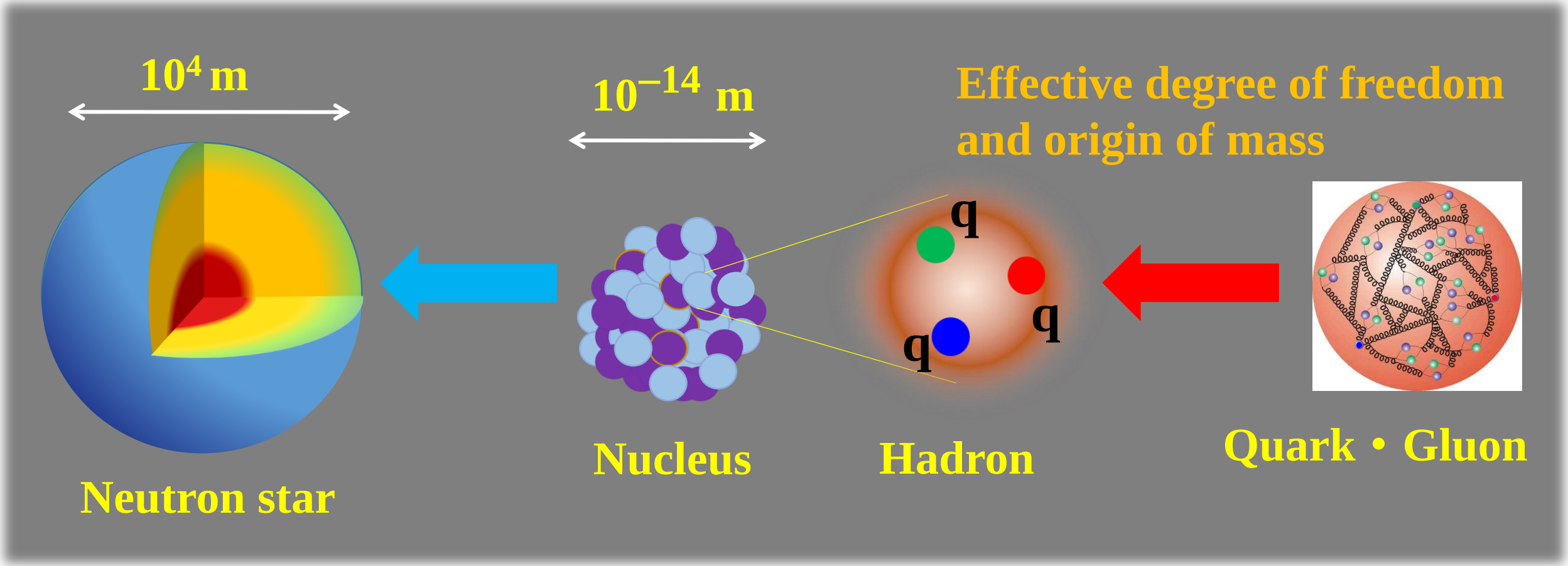
  ⇒ Suppression of decay modes
    - $p_{bar} + A \rightarrow M(cc_{bar}) + X$
    - Ex. $M(cc_{bar}) \rightarrow DD_{bar}$ mode forbidden

∗ High-momentum p_{bar} beam on nuclear target
  - Several GeV/c beam
  - Fixed target experiment



Gy. Wolf at al., PLB 780, 25-28, 2018

Question to hadron/nuclear physics



- Neutron star: High-density nuclear matter
  - Quark • Gluon → Hadron → Hadron interaction → Nucleus → Neutron Start

∗ Hadron properties: Effective degree of freedom, origin of mass
  - Roles of light quarks (u, d, s) from studies of heavy quark (charm) @ J-PARC

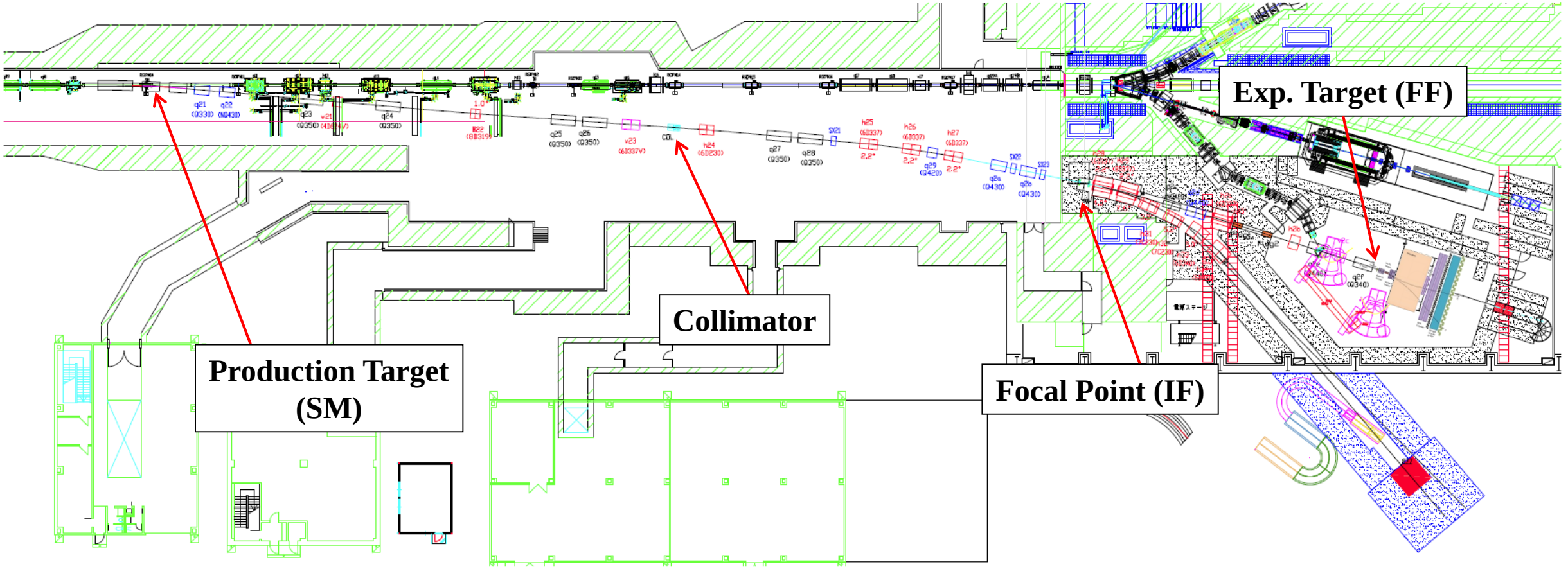
J-PARC Facility

High-momentum beam line

Hadron hall extension: K10 beam line

High-momentum beam line for 2ndary beam

- **High-intensity** beam: > 1.0×10^7 Hz π (< 20 GeV/c)
  - Unseparated beam: $\pi/K/p_{bar}$
- **High-resolution** beam: $\Delta p/p \sim 0.1\%$(rms)
  - Momentum dispersive optics method



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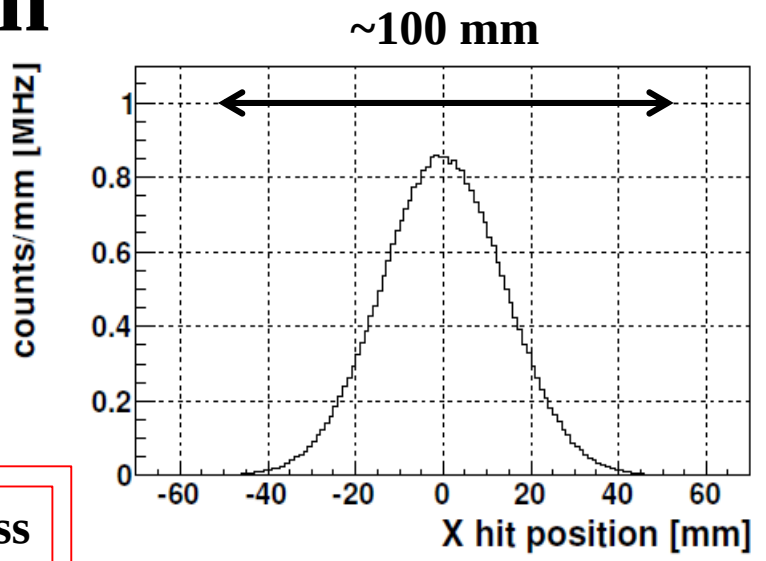
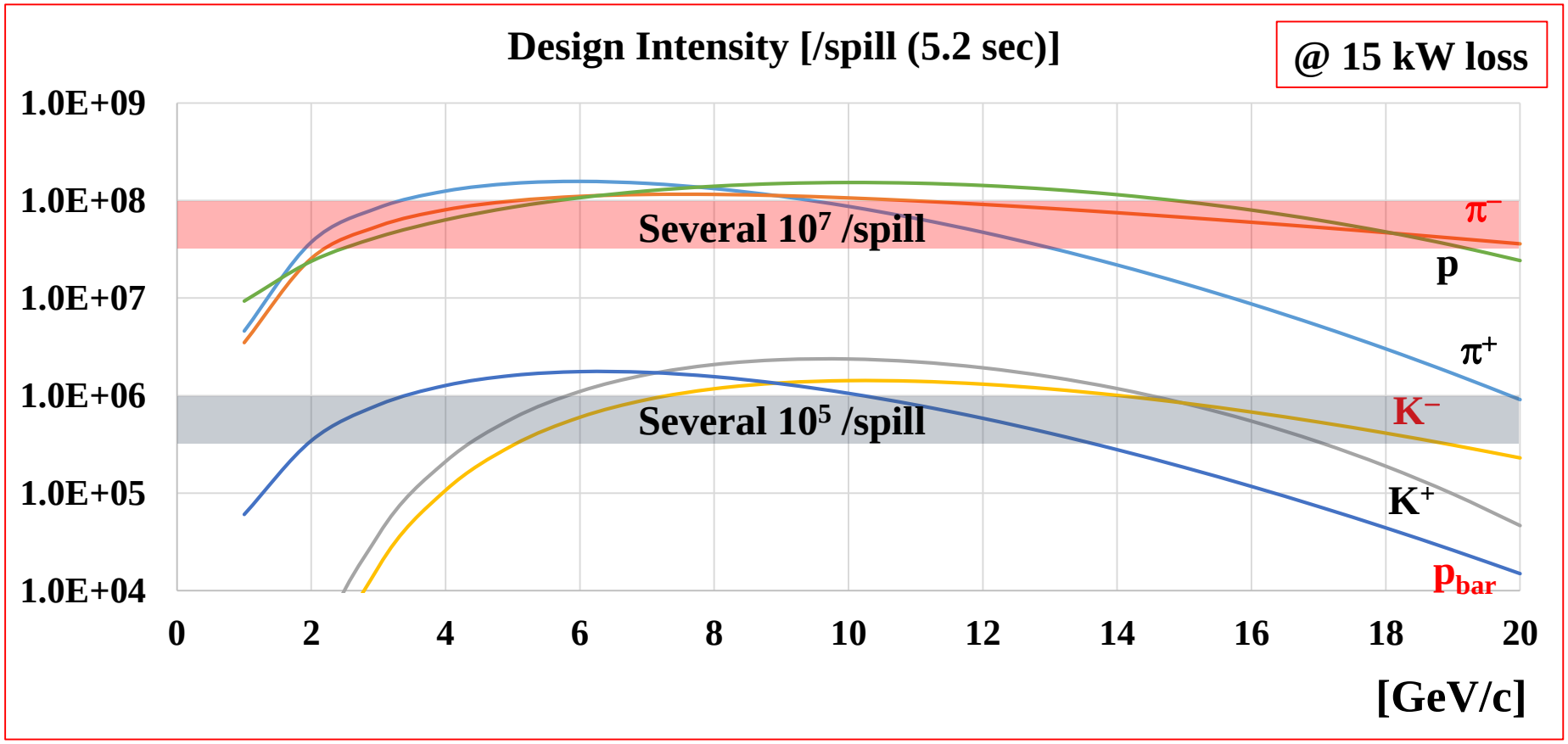
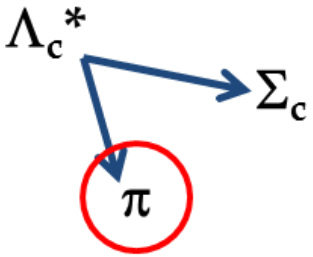


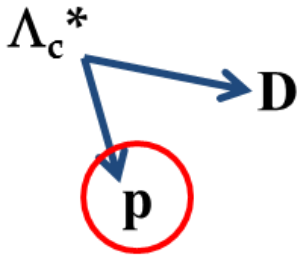
- Size: 100 mm×100 mm
- 1 MHz / 1 mm
  - 6.0×10^7 /spill (30 MHz)

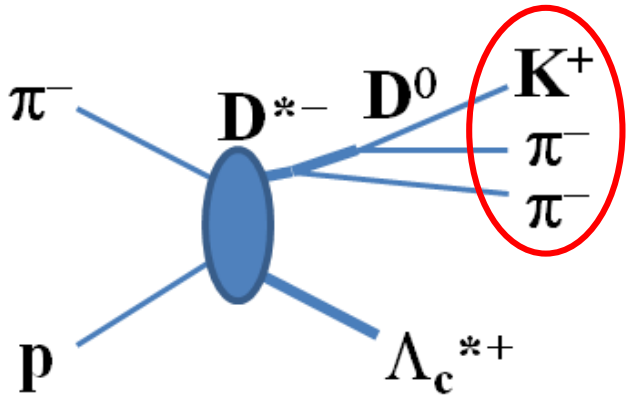
@ 20GeV/c

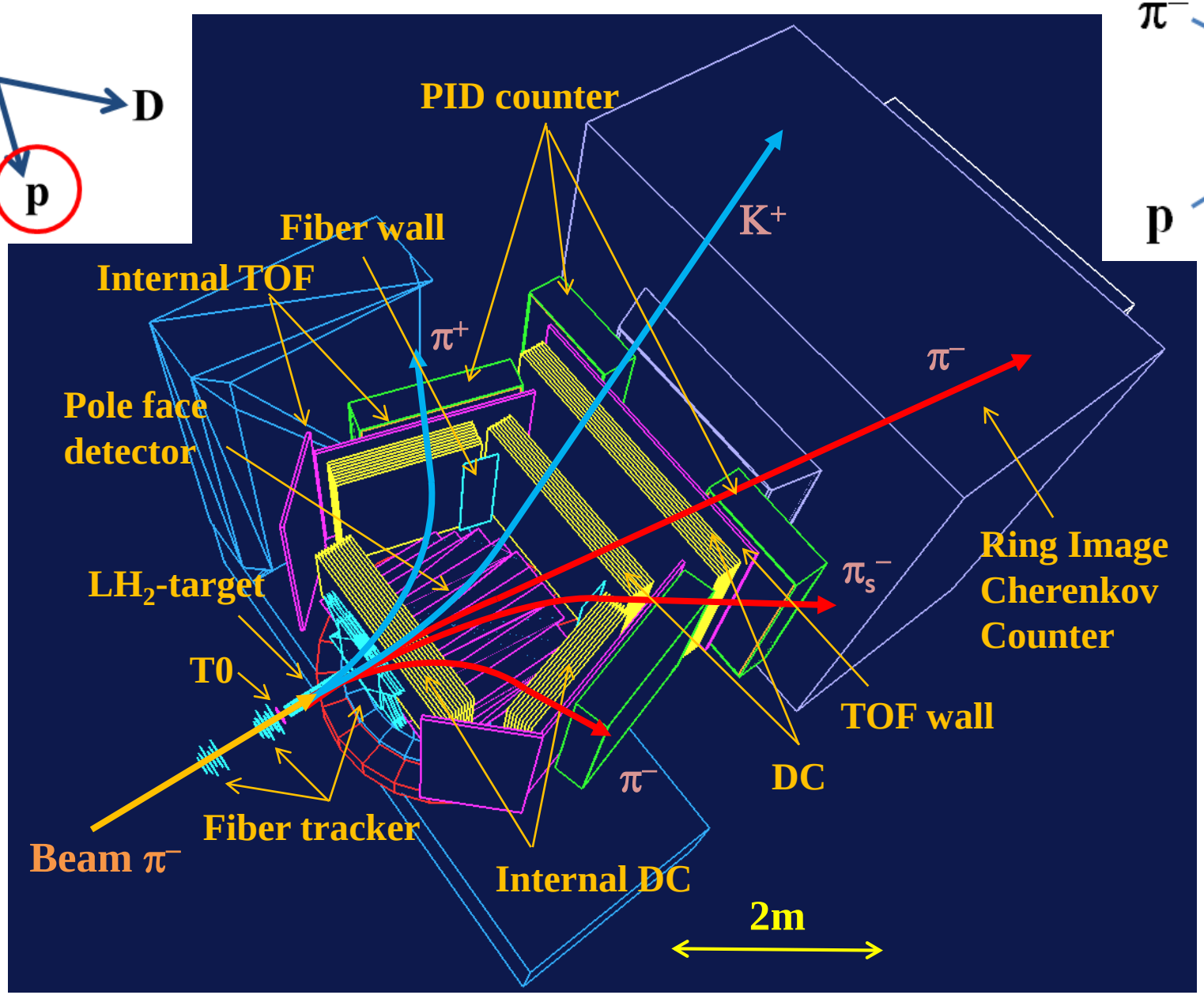


Charmed baryon spectrometer









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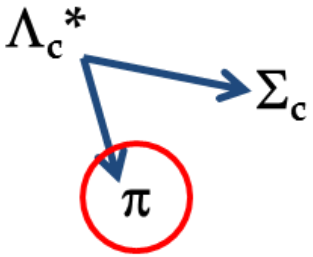
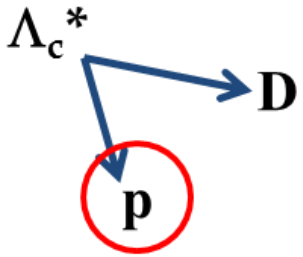
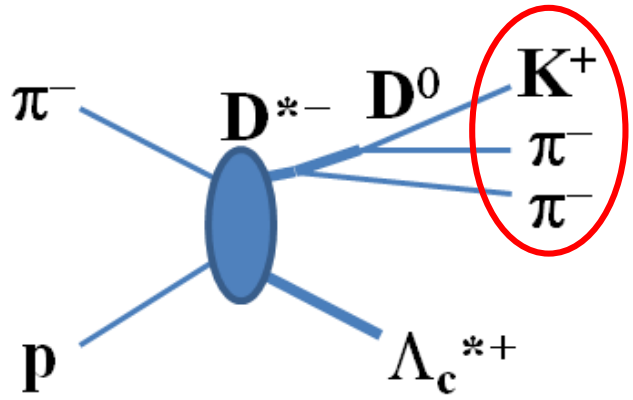
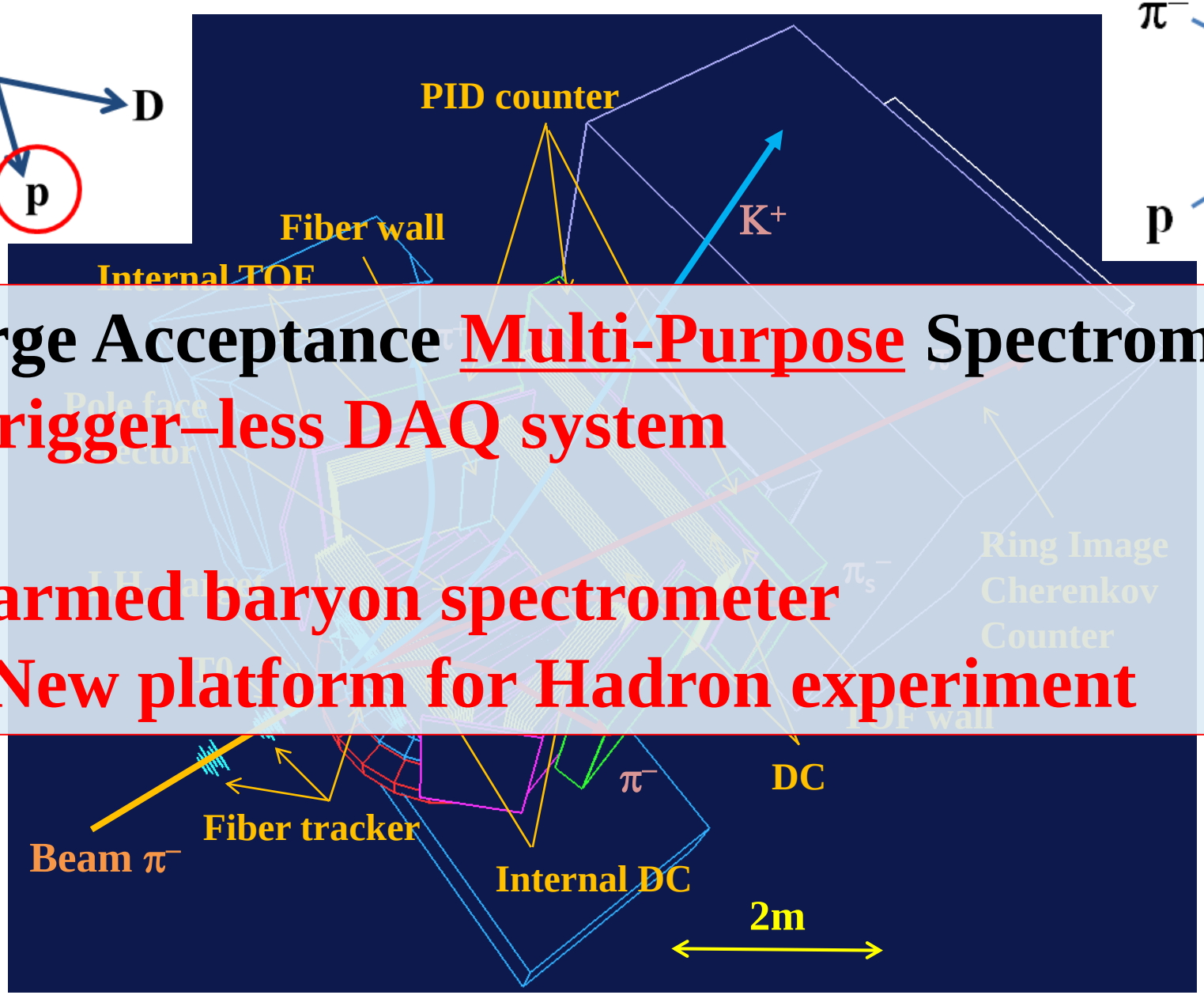






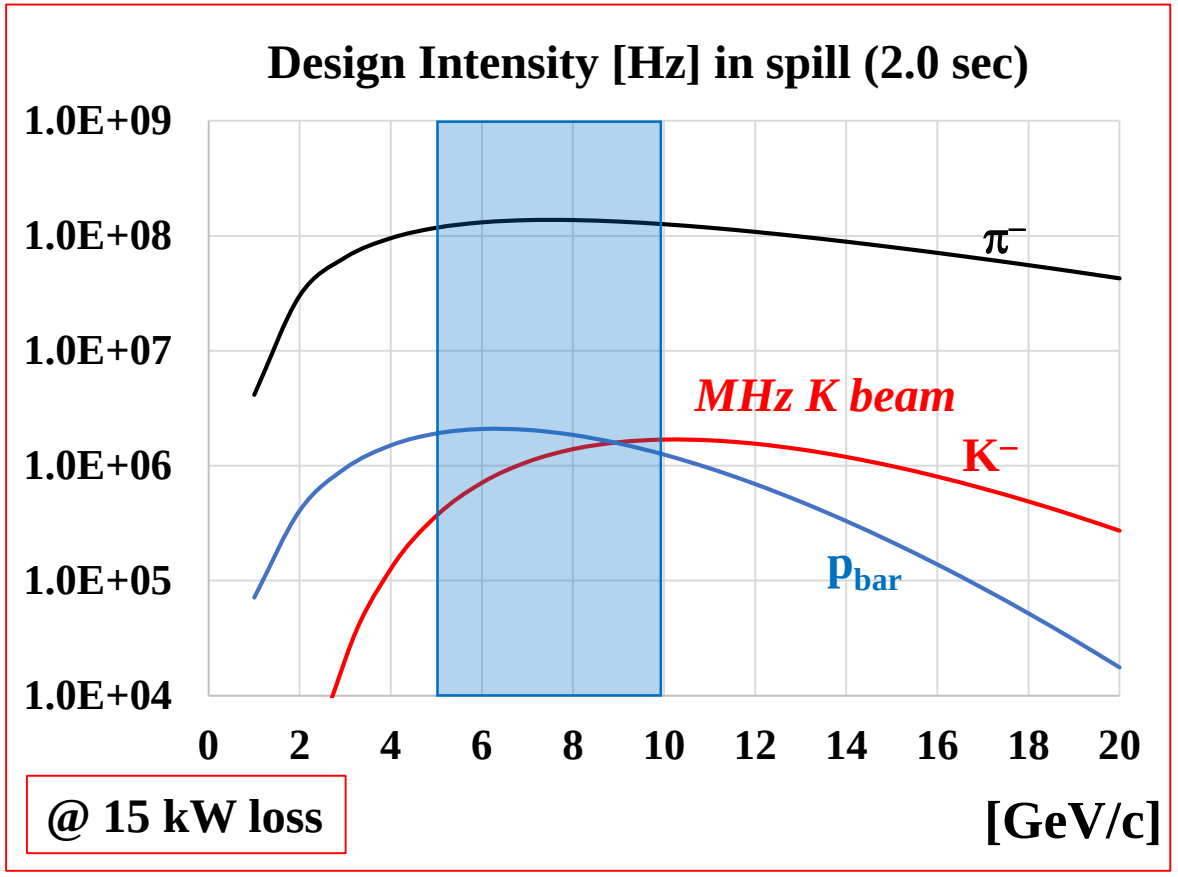


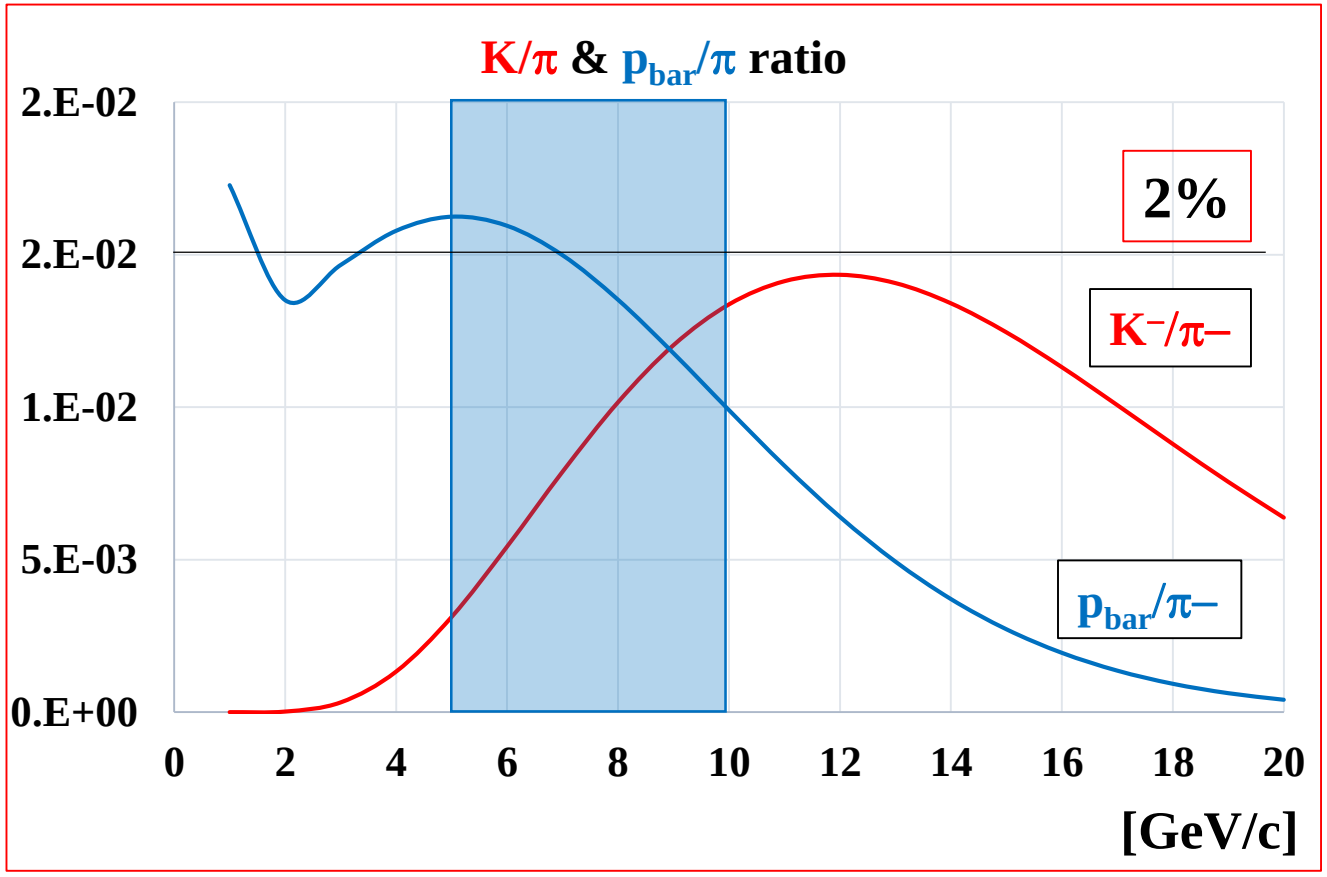
Large Acceptance Multi-Purpose Spectrometer
+ Trigger–less DAQ system

Charmed baryon spectrometer
⇒ New platform for Hadron experiment

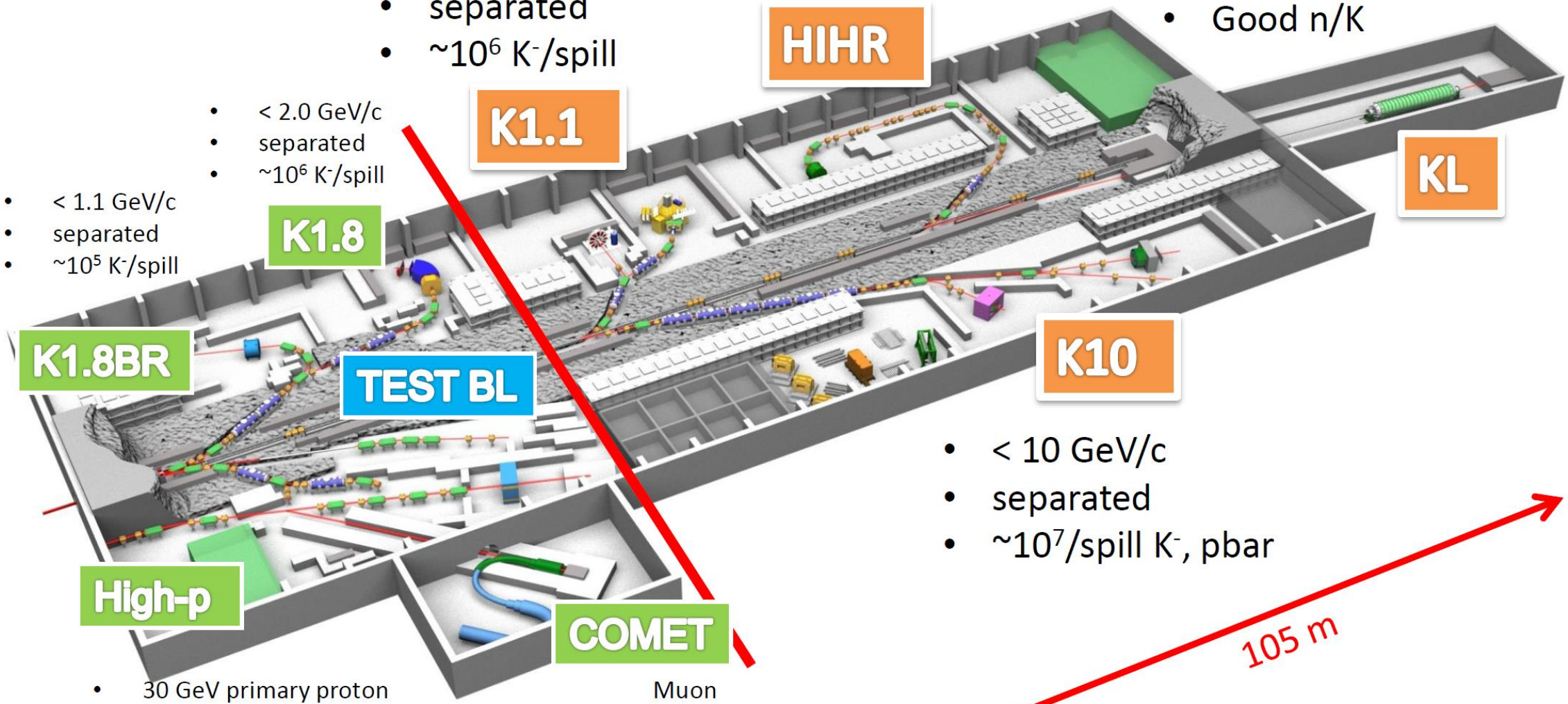
Beam intensity for K and p_{bar} experiment

- **Several GeV/c beam for Ξ^*/Ω^*, DD_{bar} and charmonium**
  - **> 1 MHz K/p_{bar} beam ⇔ > 100 MHz π beam**
- **Beam measurement is bottleneck. ⇒ Dedicated K/p_{bar} beam line**





Hadron hall extension



- < 2.0 GeV/c
- separated
- > 10^8 pion/spill
- x10 better $\Delta p/p$

- 5 deg extraction
- ~5.2 GeV/c K^0
- Good n/K

- < 1.2 GeV/c
- separated
- ~10^6 K^-/spill

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- separated
- ~10^6 K^-/spill

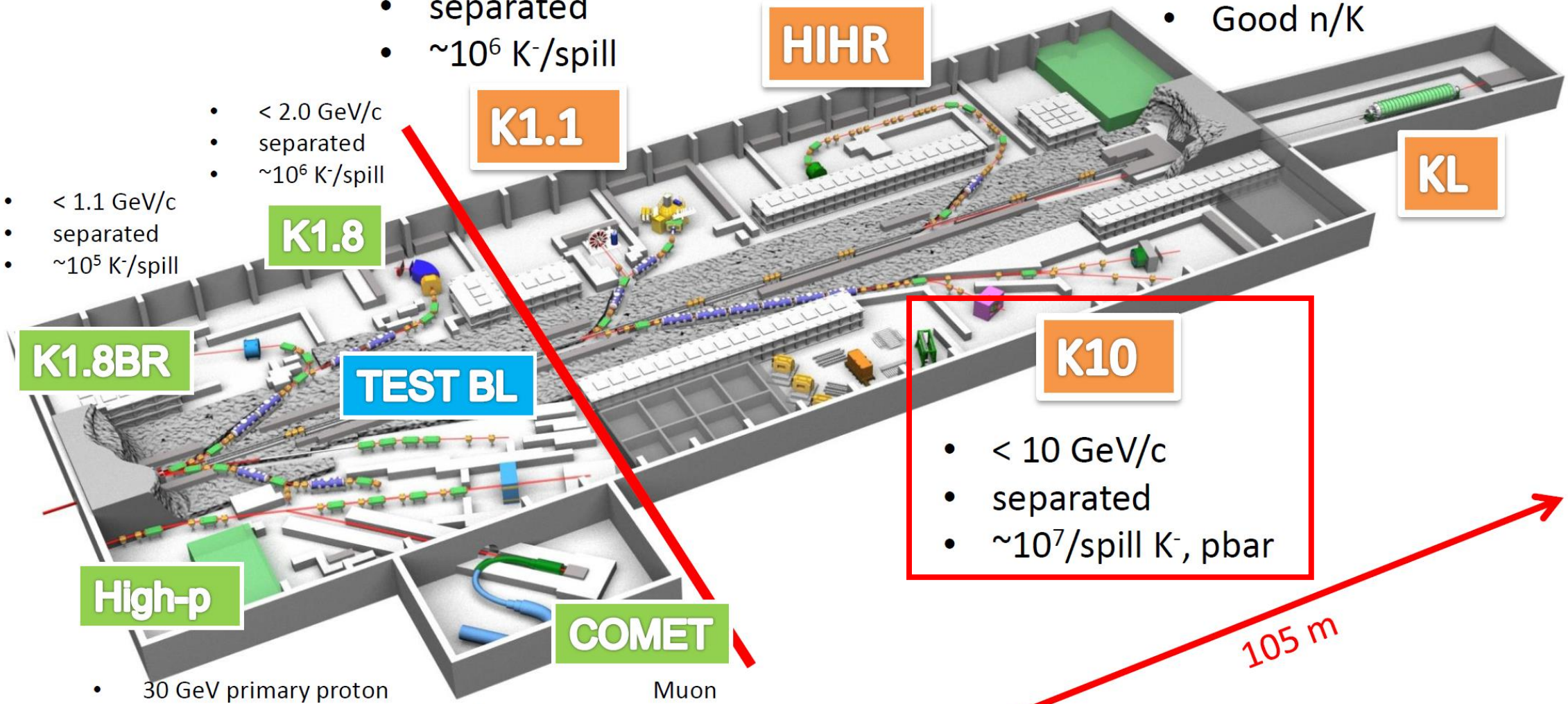
- < 1.1 GeV/c
- separated
- ~10^5 K^-/spill

- < 10 GeV/c
- separated
- ~10^7/spill K^-, pbar

- 30 GeV primary proton
- <31 GeV/c unseparated 2ndary beams (mostly pions), ~10^7/spill

Muon

Hadron hall extension



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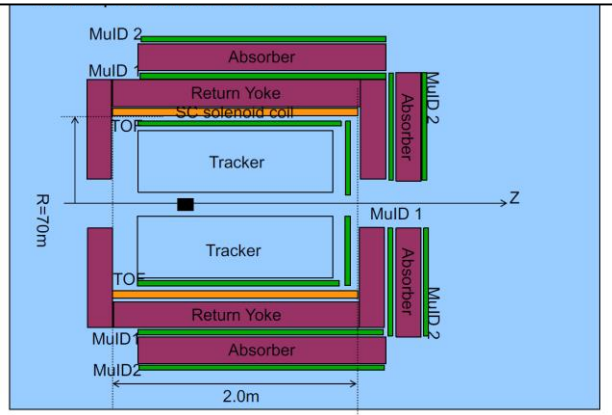
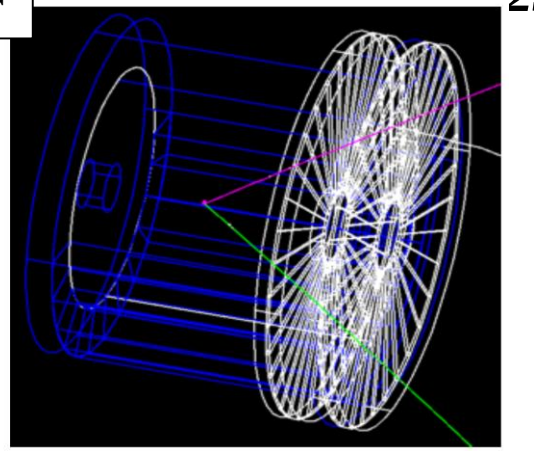
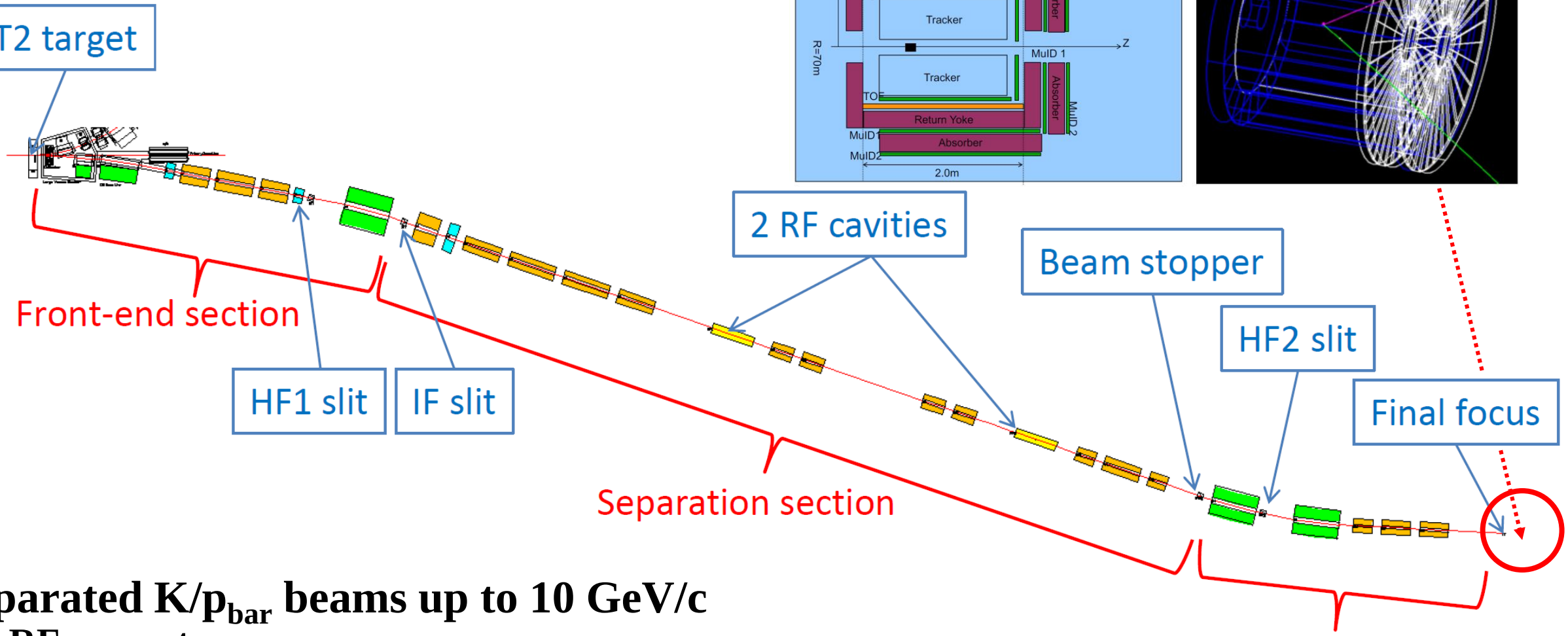
Muon

K10 beam line

Conceptual design of Di-muon spectrometer







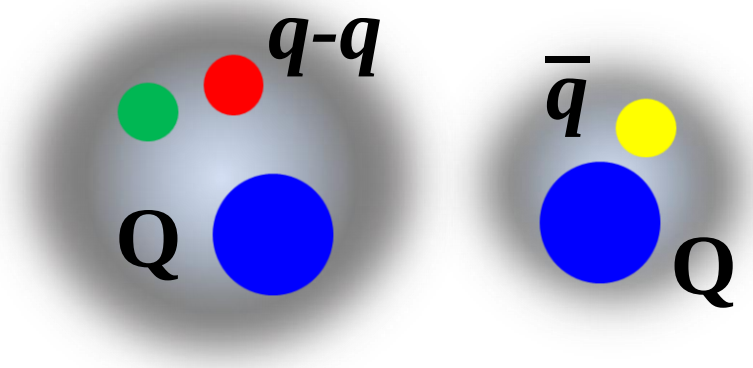
- **Separated K/p_{bar} beams up to 10 GeV/c**
  - **RF separator**

⇒ ~10^7 /spill beam

＊High intensity, purity and momentum hadron beams

Summary

**Key: Hadron with heavy quark*



- **Motivations of hadron physics**
  - **Effective degree of freedom of hadrons**
    - **Spectroscopy of excited states**
  - **Properties in finite density**
    - **Measurement of hadron properties in nuclear medium**

- **Experimental approaches to understand hadrons**
  - **Spectroscopy of hadrons with heavy quarks**
    - **Charmed baryon, Ξ^* and Ω^***
  - **Meson in nuclei**
    - **Vector meson(ϕ), DD_{bar}, Charmonium**

- **J-PARC facility: High-intensity**

& High-momentum hadrons beams

  - **High-momentum beam line**
    - **Unseparated beam**
    - **Multi-propose spectrometer**
  - **K10 beam line in extended hadron hall**
    - **Separated K/p_{bar} beams**