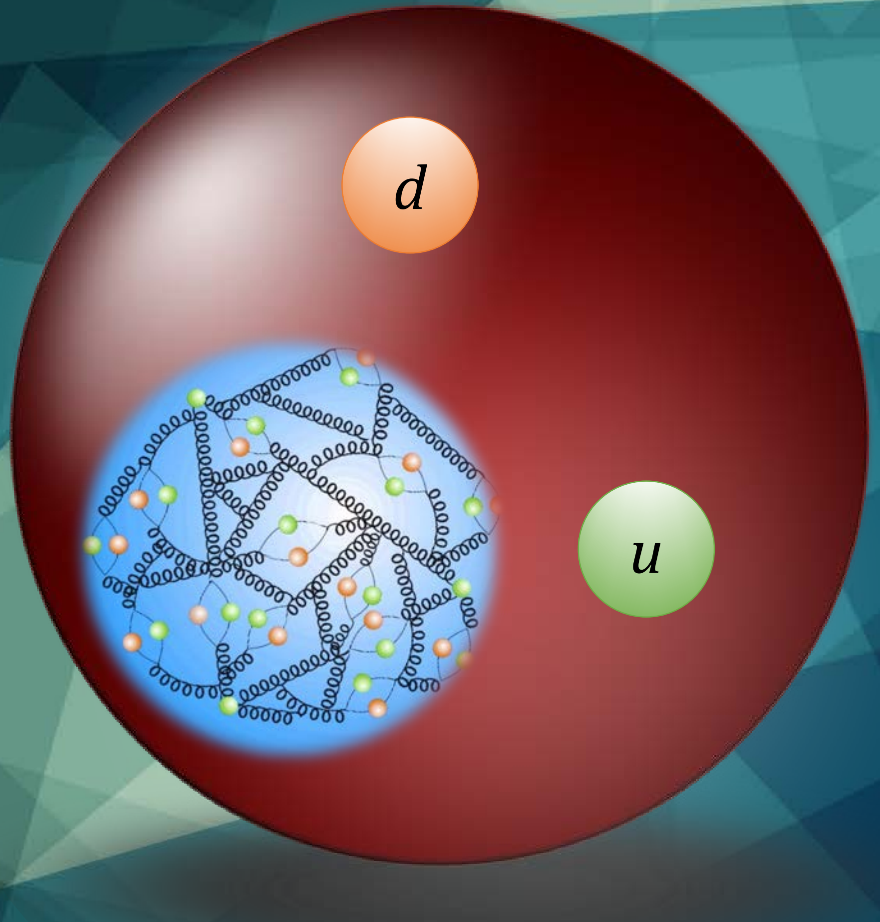
Cascade baryon spectroscopy with meson beams

M. Naruki (Kyoto Univ.) 2020/9/25, クラスター研究会

Outline

- Introduction
  - Physics motivation
  - Current Status of Cascades
- Experimental opportunities with kaon beams
- Future Plans
  - Strange to Charm
- Summary

BARYON
as basic building blocks of Matter

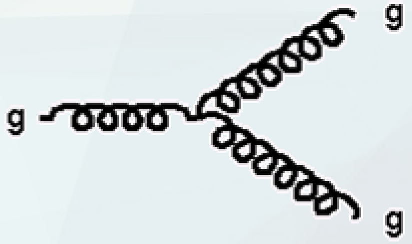


proton

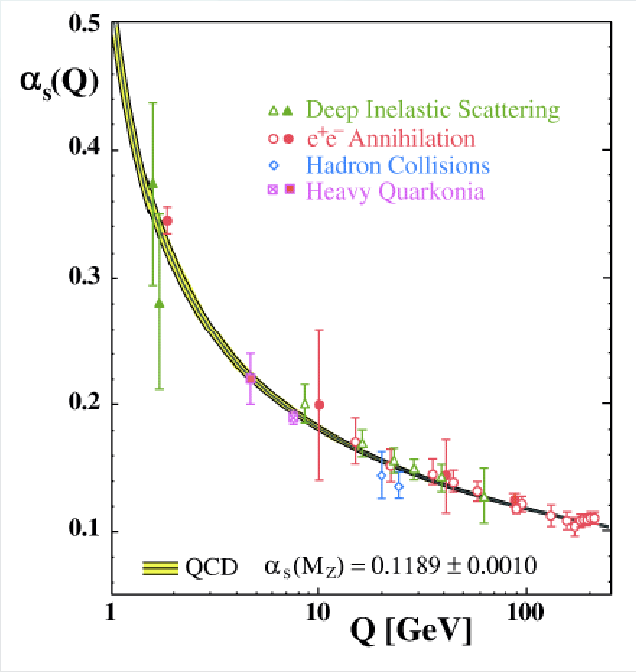
QCD

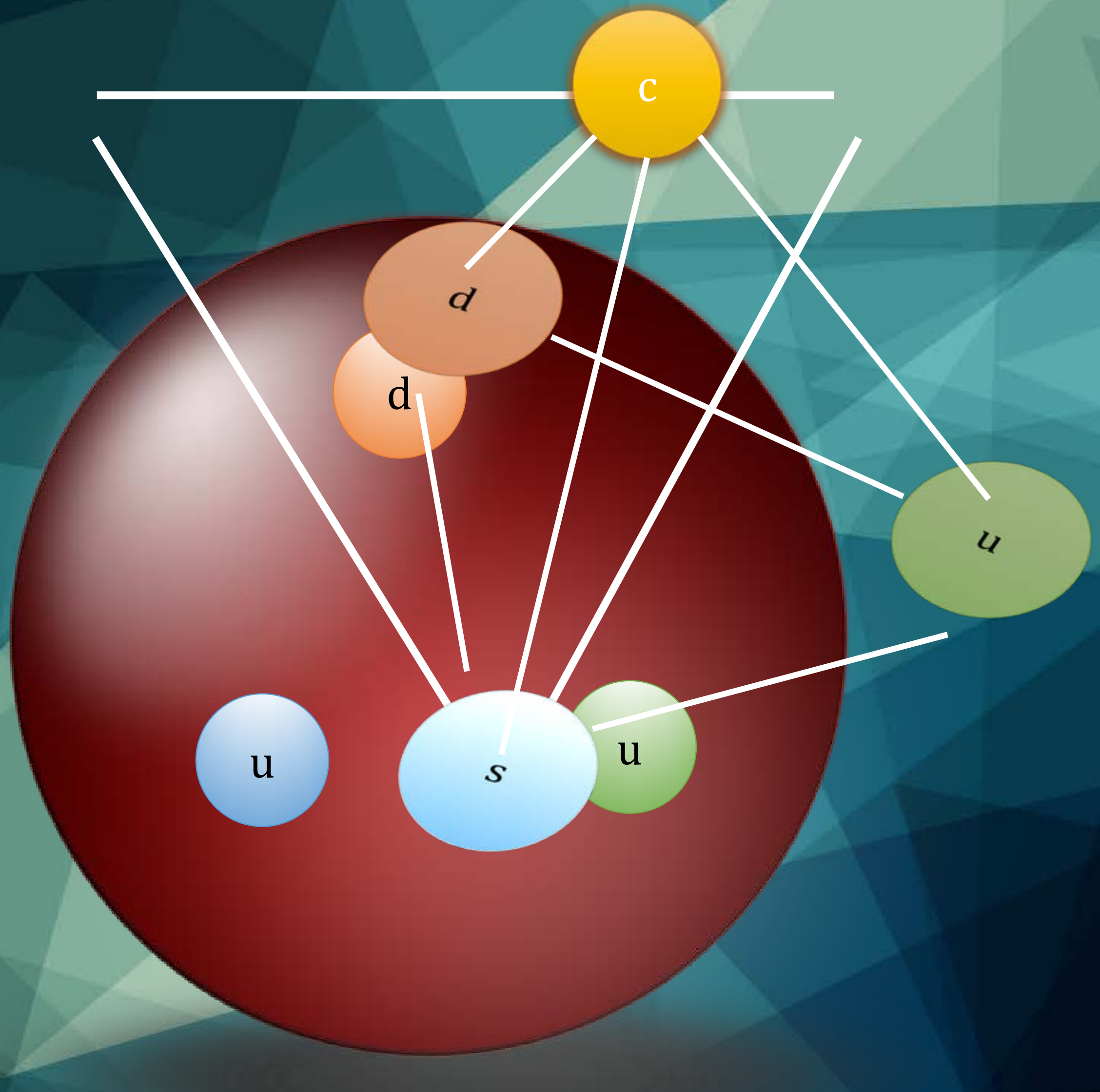
強い相互作用の動力学 Quantum ChromoDynamics

$$\mathcal{L}_{QCD} = \sum_q \left(\bar{\psi}_{qi} i\gamma^\mu \left[\delta_{ij}\partial_\mu + ig\left(G^\alpha_\mu t_\alpha\right)_{ij} \right] \psi_{qj} - m_q \bar{\psi}_{qi}\psi_{qi} \right) - \frac{1}{4} G^\alpha_{\mu\nu} G_\alpha^{\mu\nu}$$



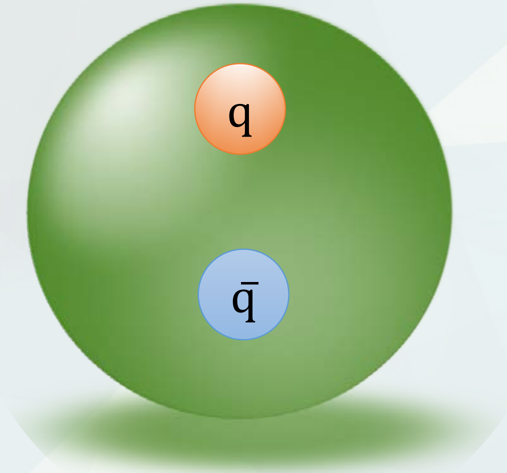
- 色荷（赤、緑、青） – グルーオンが媒介
- 摂動論的QCDの成功@高エネルギー
  - –漸近的自由, Gross, Politzer & Wilczek, 2004 
- 低エネルギー領域でのQCD
  - 強結合の非摂動的現象
  - カラーの閉じ込め -ミレニアム問題
  - 自発的対称性の破れ Nambu 2008 

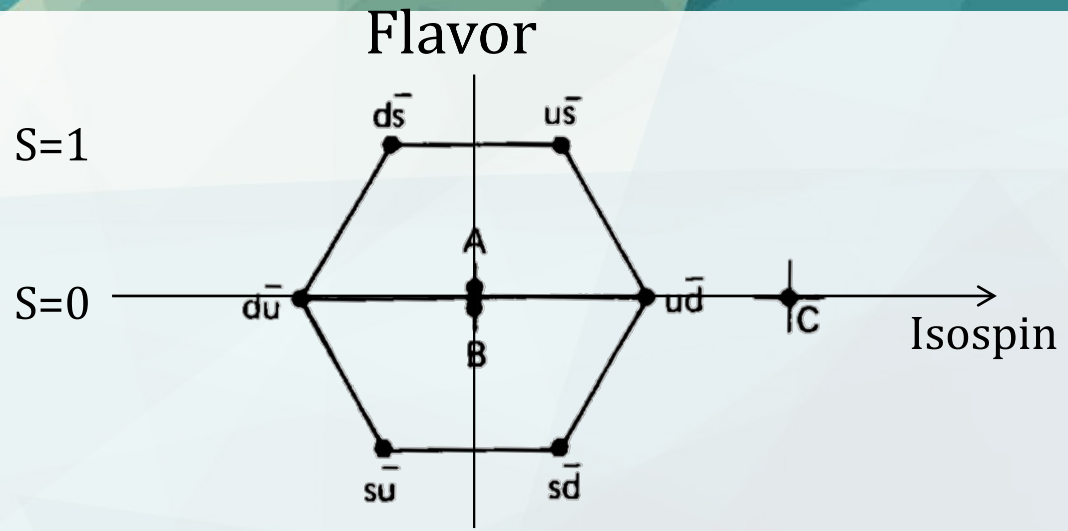



c
d
d
u
u
s
u

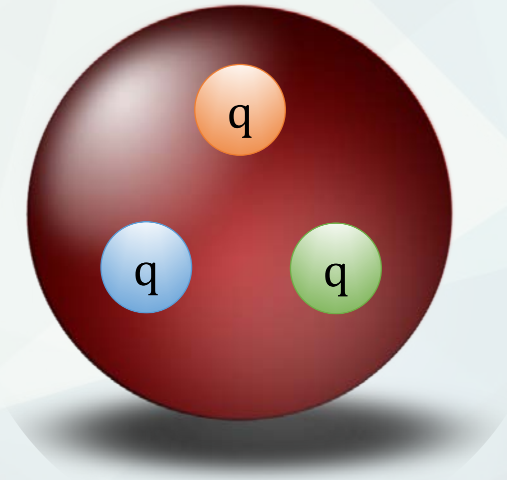
Hadron

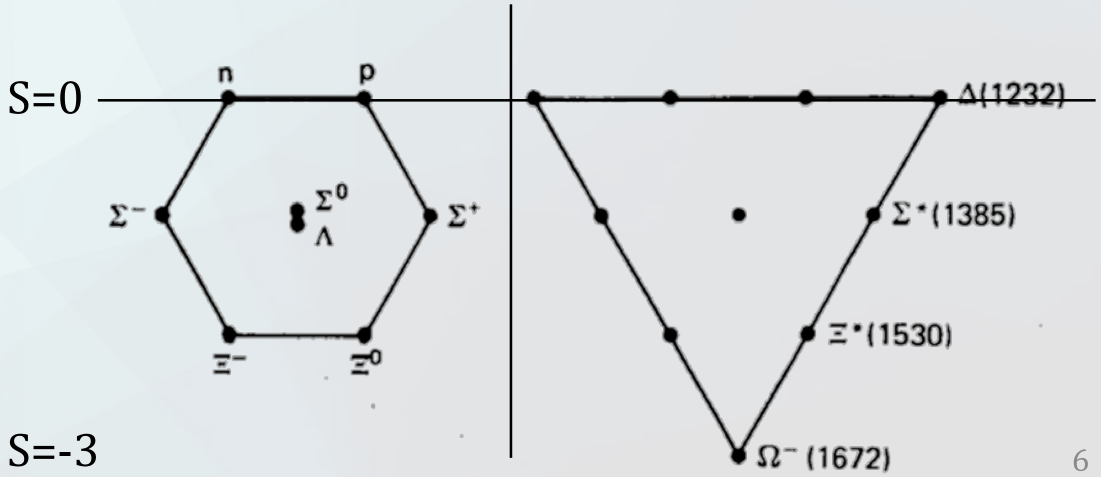
- Meson
  - π, K, η





- Baryon
  - N, Δ





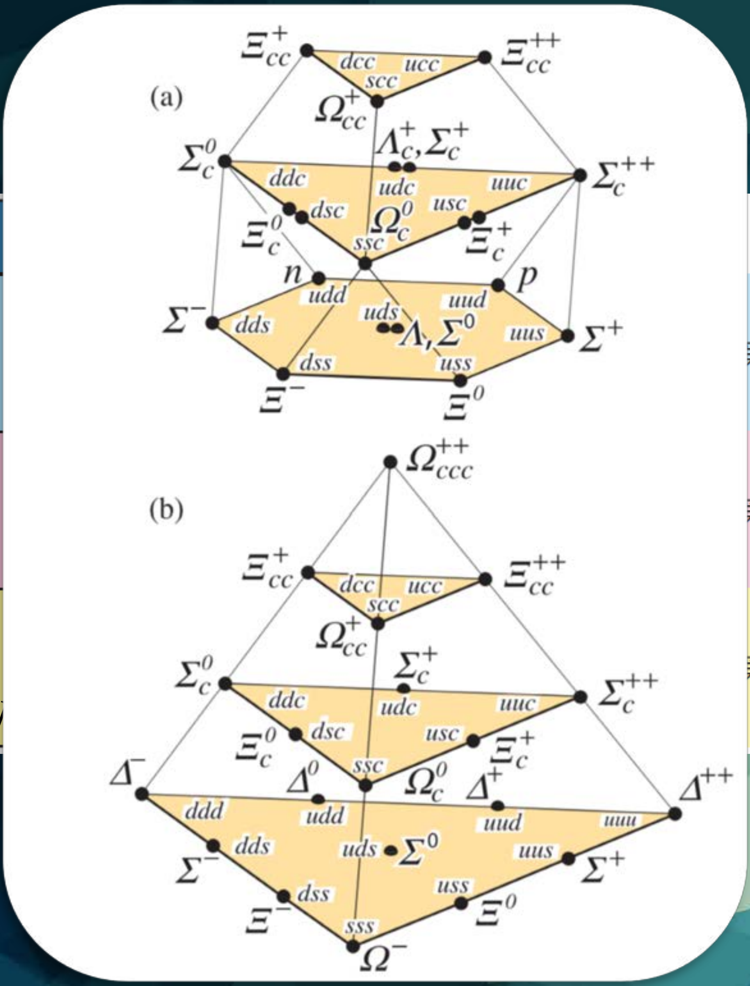
Baryon Table

アップ 2 MeV
チャーム 1.3 GeV
トップ 173 GeV

第1世代

第2世代

第3世代



p	$1/2^+$	****
n	$1/2^+$	****
$N(1440)$	$1/2^+$	****
$N(1520)$	$3/2^-$	****
$N(1535)$	$1/2^-$	****
$N(1650)$	$1/2^-$	****
$N(1675)$	$5/2^-$	****
$N(1680)$	$5/2^+$	****
$N(1700)$	$3/2^-$	***
$N(1710)$	$1/2^+$	****
$N(1720)$	$3/2^+$	****
$N(1860)$	$5/2^+$	**
$N(1875)$	$3/2^-$	***
$N(1880)$	$1/2^+$	***
$N(1895)$	$1/2^-$	****
$N(1900)$	$3/2^+$	****
$N(1990)$	$7/2^+$	**
$N(2000)$	$5/2^+$	**
$N(2040)$	$3/2^+$	*
$N(2060)$	$5/2^-$	***
$N(2100)$	$1/2^+$	***
$N(2120)$	$3/2^-$	***
$N(2190)$	$7/2^-$	****
$N(2220)$	$9/2^+$	****
$N(2250)$	$9/2^-$	****
$N(2300)$	$1/2^+$	**
$N(2570)$	$5/2^-$	**
$N(2600)$	$11/2^-$	***
$N(2700)$	$13/2^+$	**

$\Delta(1232)$	$3/2^+$	****
$\Delta(1600)$	$3/2^+$	****
$\Delta(1620)$	$1/2^-$	****
$\Delta(1700)$	$3/2^-$	****
$\Delta(1750)$	$1/2^+$	*
$\Delta(1900)$	$1/2^-$	***
$\Delta(1905)$	$5/2^+$	****
$\Delta(1910)$	$1/2^+$	****
$\Delta(1920)$	$3/2^+$	***
$\Delta(1930)$	$5/2^-$	***
$\Delta(1940)$	$3/2^-$	**
$\Delta(1950)$	$7/2^+$	****
$\Delta(2000)$	$5/2^+$	**
$\Delta(2150)$	$1/2^-$	*
$\Delta(2200)$	$7/2^-$	***
$\Delta(2300)$	$9/2^+$	**
$\Delta(2350)$	$5/2^-$	*
$\Delta(2390)$	$7/2^+$	*
$\Delta(2400)$	$9/2^-$	**
$\Delta(2420)$	$11/2^+$	****
$\Delta(2750)$	$13/2^-$	**
$\Delta(2950)$	$15/2^+$	**

S=-1

Λ	$1/2^+$	****
Λ	$1/2^-$	**
$\Lambda(1405)$	$1/2^-$	****
$\Lambda(1520)$	$3/2^-$	****
$\Lambda(1600)$	$1/2^+$	****
$\Lambda(1670)$	$1/2^-$	****
$\Lambda(1690)$	$3/2^-$	****
$\Lambda(1710)$	$1/2^+$	*
$\Lambda(1800)$	$1/2^-$	***
$\Lambda(1810)$	$1/2^+$	***
$\Lambda(1820)$	$5/2^+$	****
$\Lambda(1830)$	$5/2^-$	****
$\Lambda(1890)$	$3/2^+$	****
$\Lambda(2000)$	$1/2^-$	*
$\Lambda(2050)$	$3/2^-$	*
$\Lambda(2070)$	$3/2^+$	*
$\Lambda(2080)$	$5/2^-$	*
$\Lambda(2085)$	$7/2^+$	**
$\Lambda(2100)$	$7/2^-$	****
$\Lambda(2110)$	$5/2^+$	***
$\Lambda(2325)$	$3/2^-$	*
$\Lambda(2350)$	$9/2^+$	***
$\Lambda(2585)$		**

Σ^+	$1/2^+$	****
Σ^0	$1/2^+$	****
Σ^-	$1/2^+$	****
$\Sigma(1385)$	$3/2^+$	****
$\Sigma(1580)$	$3/2^-$	*
$\Sigma(1620)$	$1/2^-$	*
$\Sigma(1660)$	$1/2^+$	***
$\Sigma(1670)$	$3/2^-$	****
$\Sigma(1750)$	$1/2^-$	***
$\Sigma(1775)$	$5/2^-$	****
$\Sigma(1780)$	$3/2^+$	*
$\Sigma(1880)$	$1/2^+$	**
$\Sigma(1900)$	$1/2^-$	**
$\Sigma(1910)$	$3/2^-$	***
$\Sigma(1915)$	$5/2^+$	****
$\Sigma(1940)$	$3/2^+$	*
$\Sigma(2010)$	$3/2^-$	*
$\Sigma(2030)$	$7/2^+$	****
$\Sigma(2070)$	$5/2^+$	*
$\Sigma(2080)$	$3/2^+$	*
$\Sigma(2100)$	$7/2^-$	*
$\Sigma(2160)$	$1/2^-$	*
$\Sigma(2230)$	$3/2^+$	*
$\Sigma(2250)$		***
$\Sigma(2455)$		**
$\Sigma(2620)$		**
$\Sigma(3000)$		*
$\Sigma(3170)$		*

S=-2

Ξ^0	$1/2^+$	****
Ξ^-	$1/2^+$	****
$\Xi(1530)$	$3/2^+$	****
$\Xi(1620)$		*
$\Xi(1690)$		***
$\Xi(1820)$	$3/2^-$	***
$\Xi(1950)$		***
$\Xi(2030)$	$\geq \frac{5}{2}$?	***
$\Xi(2120)$		*
$\Xi(2250)$		**
$\Xi(2370)$		**
$\Xi(2500)$		*

S=-3

Ω^-	$3/2^+$	****
$\Omega(2012)^-$	$?^-$	***
$\Omega(2250)^-$		***
$\Omega(2380)^-$		**
$\Omega(2470)^-$		**

C>0

Λ_c^+	$1/2^+$	****
$\Lambda_c(2595)^+$	$1/2^-$	***
$\Lambda_c(2625)^+$	$3/2^-$	***
$\Lambda_c(2765)^+$		*
$\Lambda_c(2860)^+$	$3/2^+$	***
$\Lambda_c(2880)^+$	$5/2^+$	***
$\Lambda_c(2940)^+$	$3/2^-$	***
$\Sigma_c(2455)$	$1/2^+$	****
$\Sigma_c(2520)$	$3/2^+$	***
$\Sigma_c(2800)$		***
Ξ_c^+	$1/2^+$	***
Ξ_c^0	$1/2^+$	****
$\Xi_c^{\prime +}$	$1/2^+$	***
$\Xi_c^{\prime 0}$	$1/2^+$	***
$\Xi_c(2645)$	$3/2^+$	***
$\Xi_c(2790)$	$1/2^-$	***
$\Xi_c(2815)$	$3/2^-$	***
$\Xi_c(2930)$		**
$\Xi_c(2970)$		***
$\Xi_c(3055)$		***
$\Xi_c(3080)$		***
$\Xi_c(3123)$		*
Ω_c^0	$1/2^+$	***
$\Omega_c(2770)^0$	$3/2^+$	***
$\Omega_c(3000)^0$		***
$\Omega_c(3050)^0$		***
$\Omega_c(3065)^0$		***
$\Omega_c(3090)^0$		***
$\Omega_c(3120)^0$		***
Ξ_{cc}^{++}		***

B'=1

Λ_b^0	$1/2^+$	***
$\Lambda_b(5912)^0$	$1/2^-$	***
$\Lambda_b(5920)^0$	$3/2^-$	***
$\Lambda_b(6146)^0$	$3/2^+$	***
$\Lambda_b(6152)^0$	$5/2^+$	***
Σ_b	$1/2^+$	***
Σ_b^*	$3/2^+$	***
$\Sigma_b(6097)^+$		***
$\Sigma_b(6097)^-$		***
Ξ_b^0, Ξ_b^-	$1/2^+$	***
$\Xi_b'(5935)^-$	$1/2^+$	***
$\Xi_b(5945)^0$	$3/2^+$	***
$\Xi_b(5955)^-$	$3/2^+$	***
$\Xi_b(6227)$		***
Ω_b^-	$1/2^+$	***

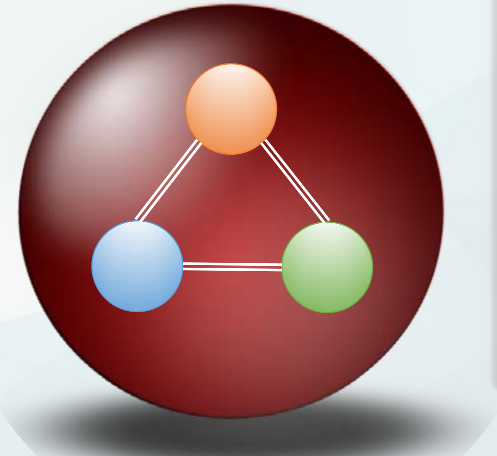
$P_c(4312)^+$		*
$P_c(4380)^+$		*
$P_c(4440)^+$		*
$P_c(4457)^+$		*

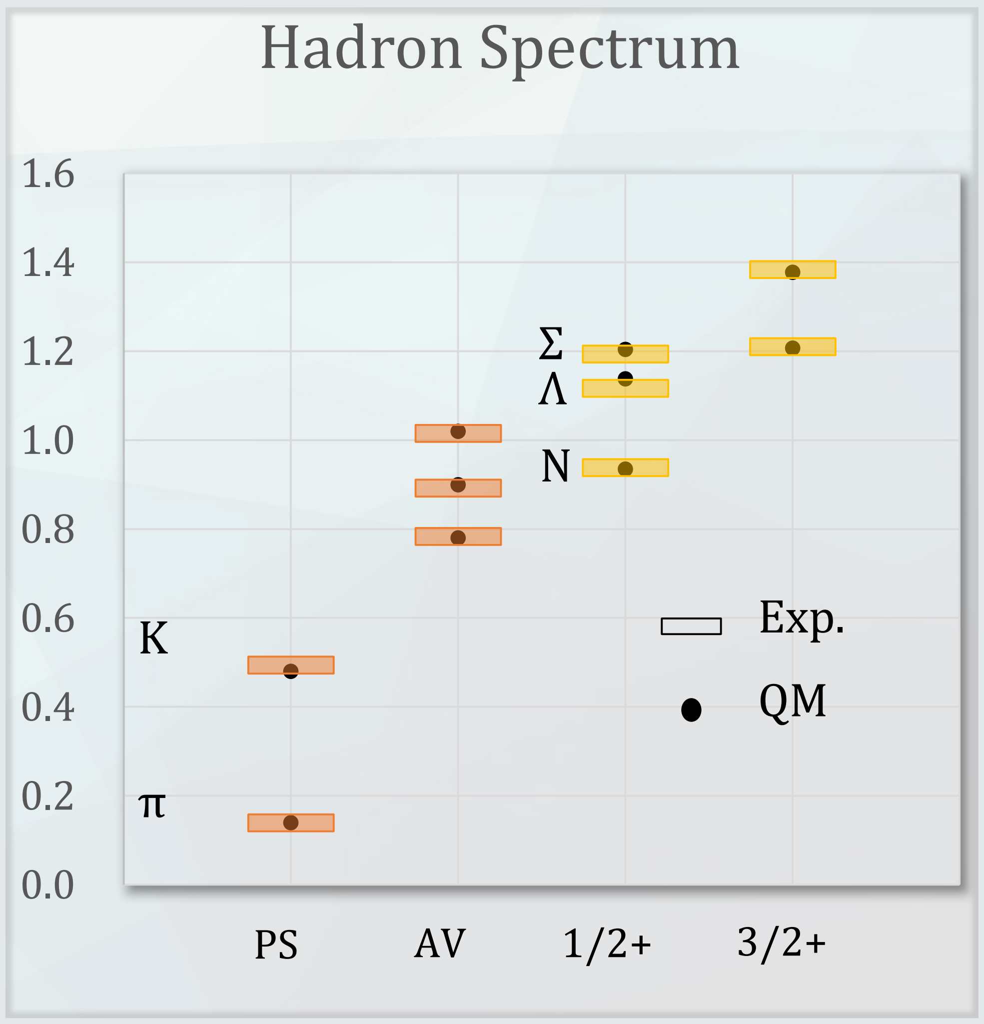
PDG

Quark Model

- 量子数による分類
  - フレーバー(アイソスピン、ハイパー荷)、スピン　OK
- 質量：QCD Hyperfine Splitting
  - one gluon exchange (1st correction)
  - meson : $m_{q\bar{q}} = m_{q1} + m_{q2} + \boldsymbol{a}\frac{3\alpha_s}{4}\frac{\sigma_1 \cdot \sigma_2}{m_1 m_2}$
  - baryon : $m_{qqq} = m_{q1} + m_{q2} + m_{q3} + \boldsymbol{a}\frac{2\alpha_s}{3}\sum\frac{\sigma_i \cdot \sigma_j}{m_i m_j}$

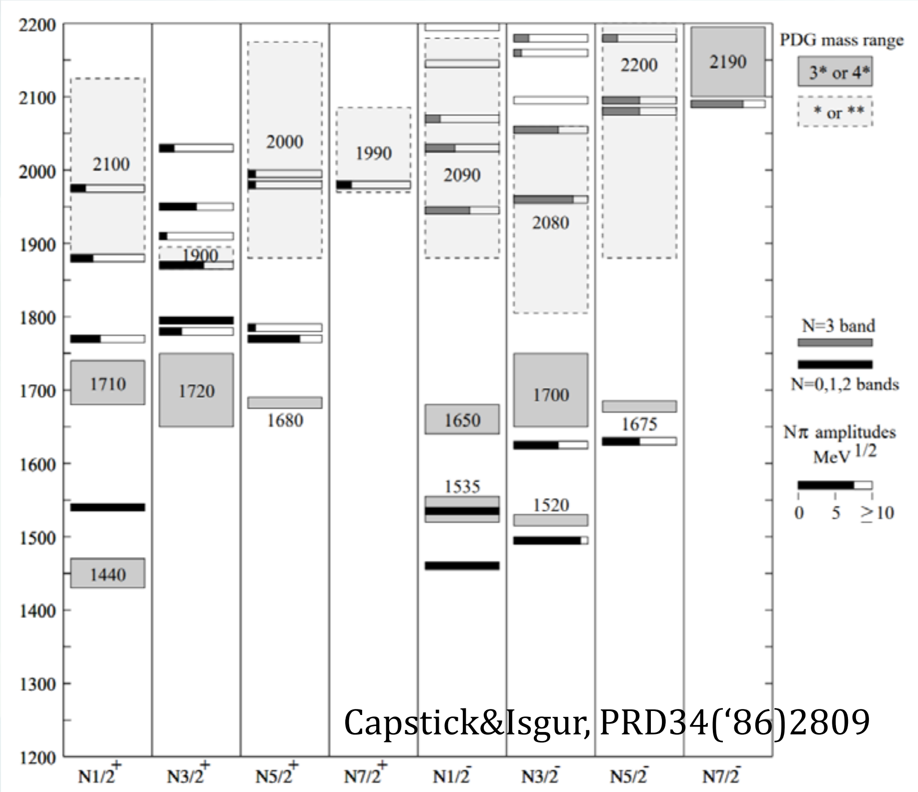
基底状態：
universalなm_q, m_s, aで再現できる
m_q≈300MeV, m_s≈500MeV



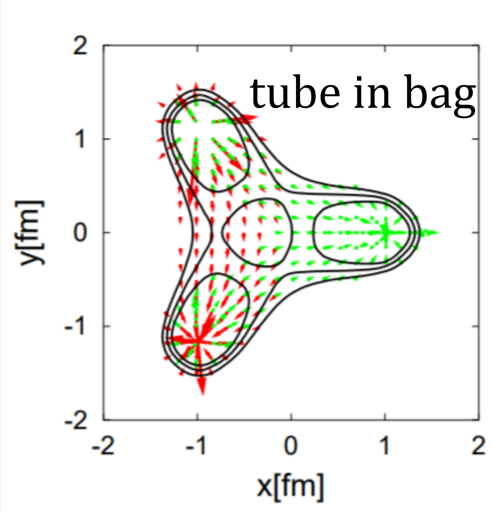


ハドロン描像

- 基底状態：有効質量を持つ構成子クォーク＋HFI(1グルーオン交換相互作用)でOK
- Quark Modelはどこまでよい描像か
  - relativized, LS, flux-tube, instanton-induced, diquark degree of freedom
- missing resonances
- exotic hadron
  - multi-quark states
  - hadron molecule
- 次の自由度は何か



Capstick&Isgur, PRD34('86)2809

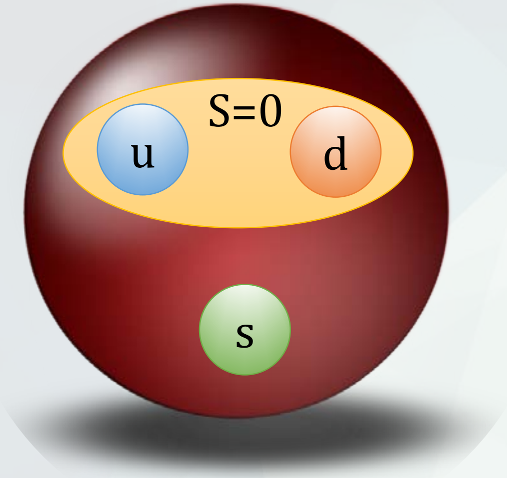


Martens et al. EPJ

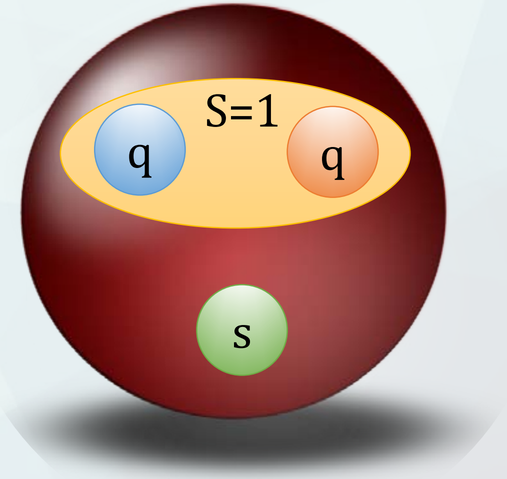
Hyperon – Λ/Σ

qq pair inside hyperon

Λ



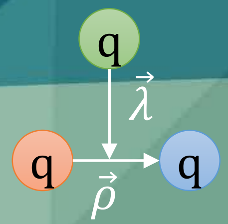
Σ

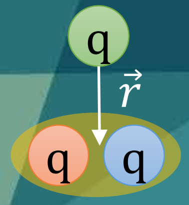


(isospin: anti-symmetric)
flavor: anti-symmetric
spin: anti-symmetric

(isospin: symmetric)
flavor: symmetric
spin: symmetric

Diquark Model





- Gell-mann '64, Ida&Kobayashi '66, Lichtenberg&Tassie '67
  - Regge trajectory
  - ΔI=1/2 rule
  - σ(Λ)/σ(Σ)=3.5
  - missing resonances
  - PDF

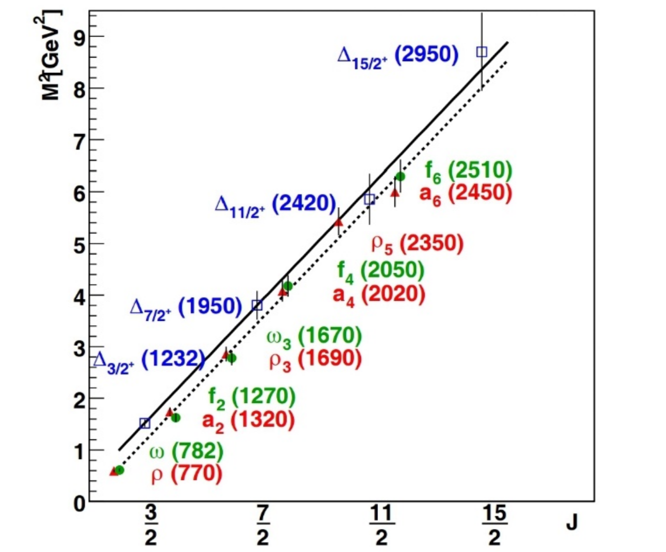
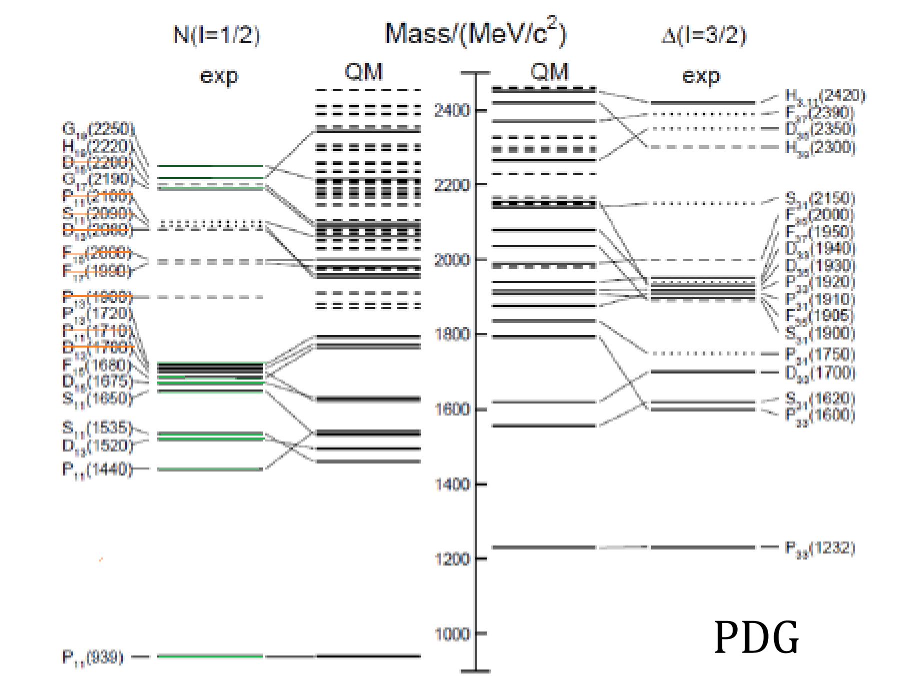
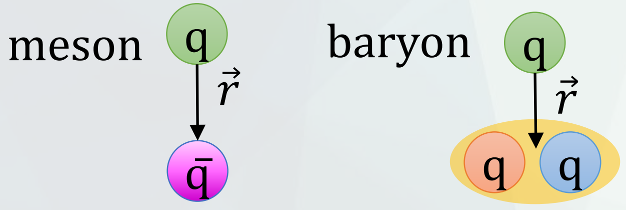


Fig. 1. The leading Regge trajectory: Δ resonances with maximal J in a given mass range. Also shown is the Regge trajectory for mesons with $J = L + S$.

Klempt et al. EPJA48(2012)127

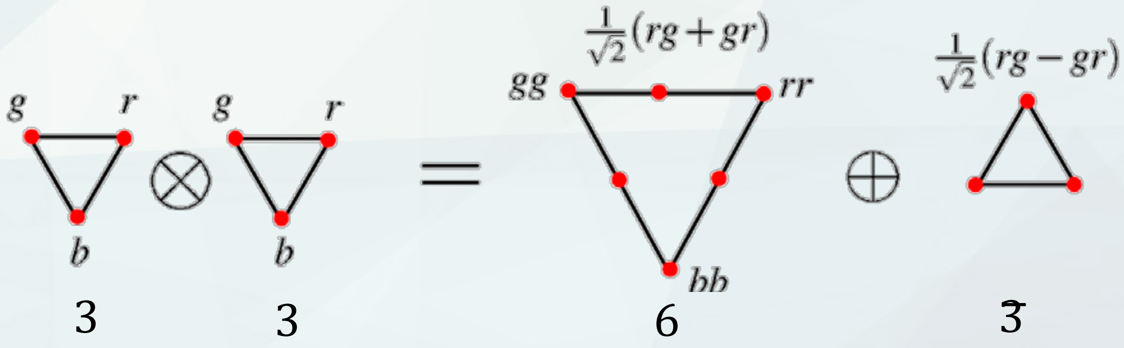




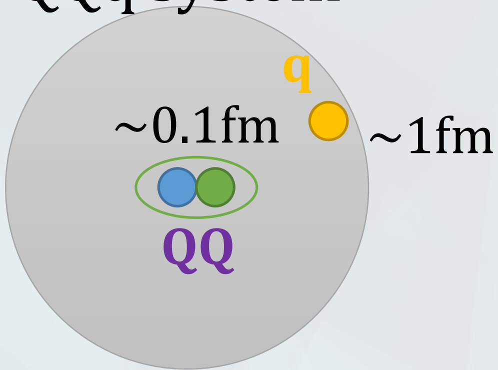
$$M^2 \propto \sigma J$$
$$\because M \propto \sigma L, J \propto \sigma L^2$$

Diquark as key component of hadrons

- diquark interaction
  - color-magnetic グルーオン交換力
  - color-electric　閉じ込め力
  - ✓ $(qq)_{\bar{3}}$では強い引力となる
  - Cornell potential : $-\frac{4}{3}\frac{\alpha_s}{r} + \sigma r$
    (OGE) (confinement)

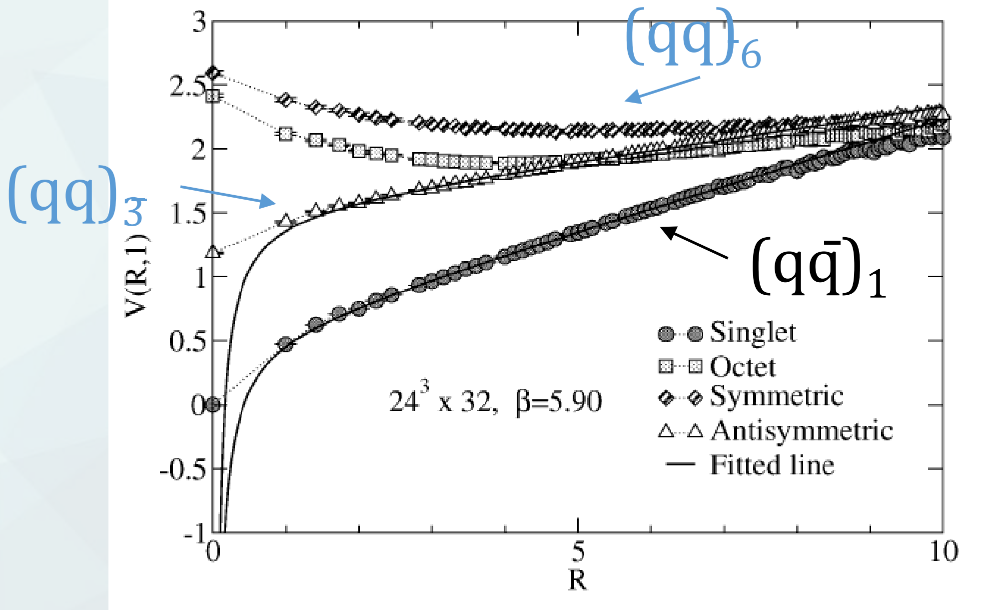


QQq system



V(r): flavor independent
heavy <-> small kinetic energy

compact diquark + q/Q → 2-body system

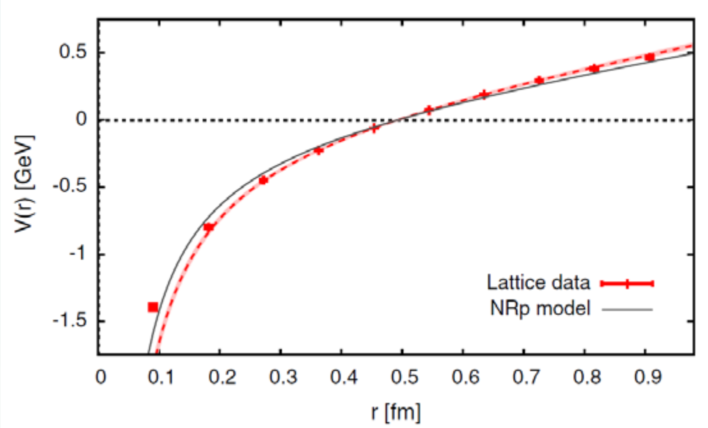


q LQCD, Nakamura & Saito, PLB621(2005)171

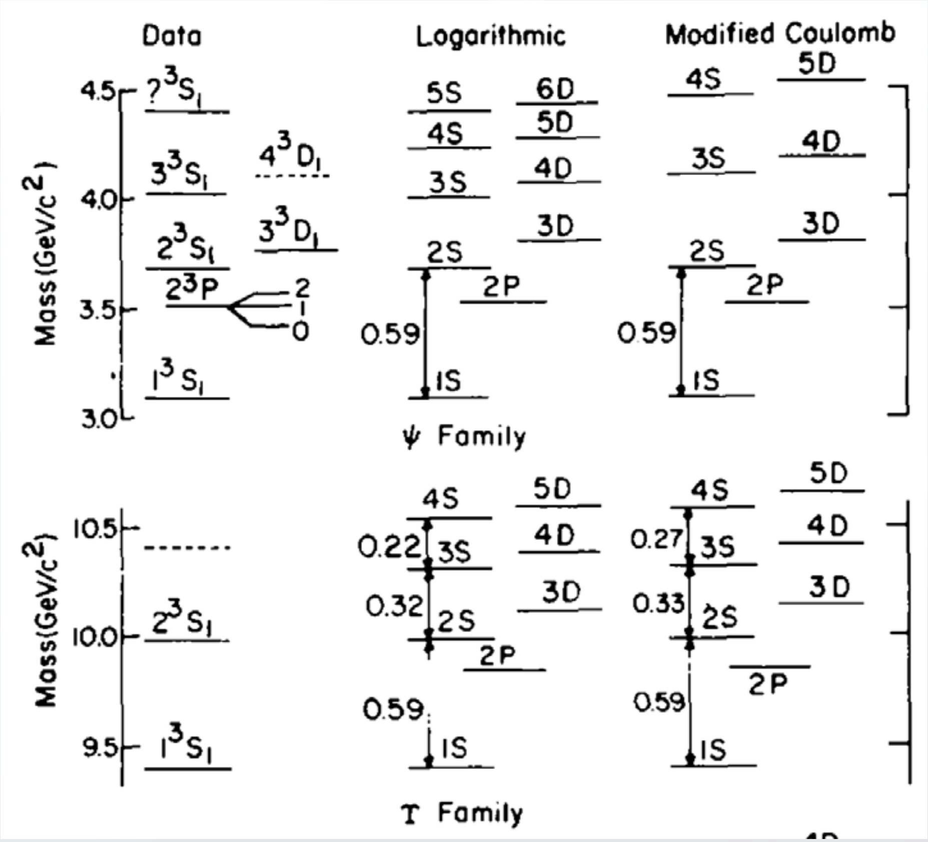
Heavy Meson

Charmonium

- $q\bar{q}$ 相互作用
- Cornell potential : $-\frac{4}{3}\frac{\alpha_s}{r} + \sigma r$
  - w/o $q\bar{q}$ pair creation



Kawanai & Sasaki, PRD85(2012)091503(R)

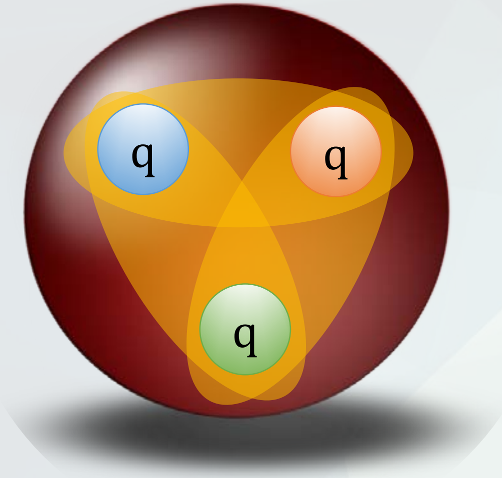


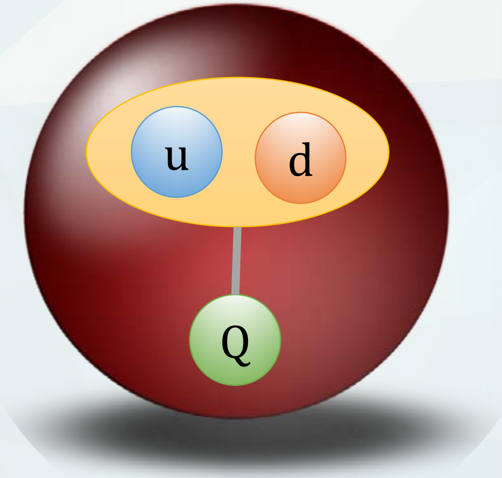
Quigg & Roser, PL 71B('77)153

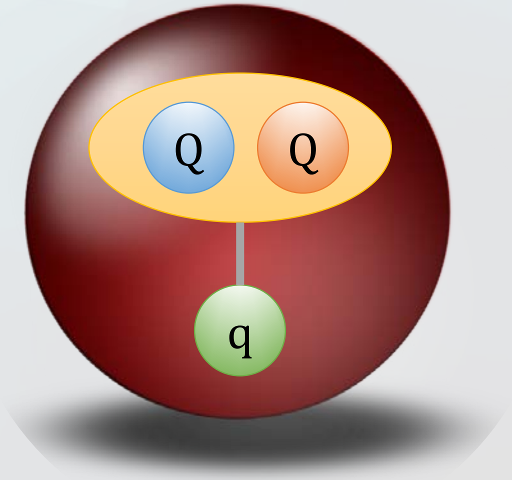
軽いところでは、$q\bar{q}$対生成などの効果がありそう単純ではない。

Heavy Baryon Spectroscopy

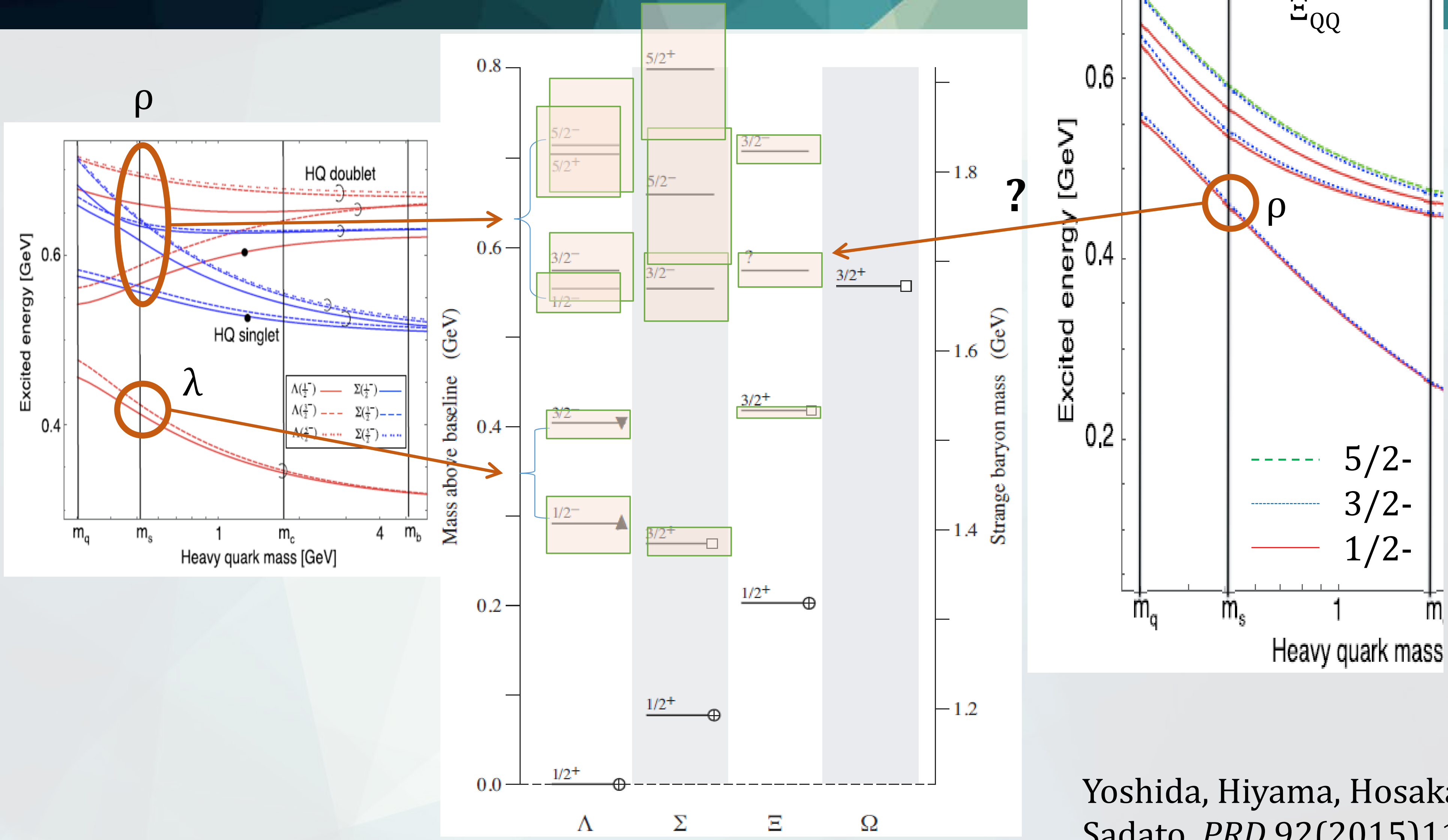
- バリオンではどうか？







Experimental CLUES for QQq



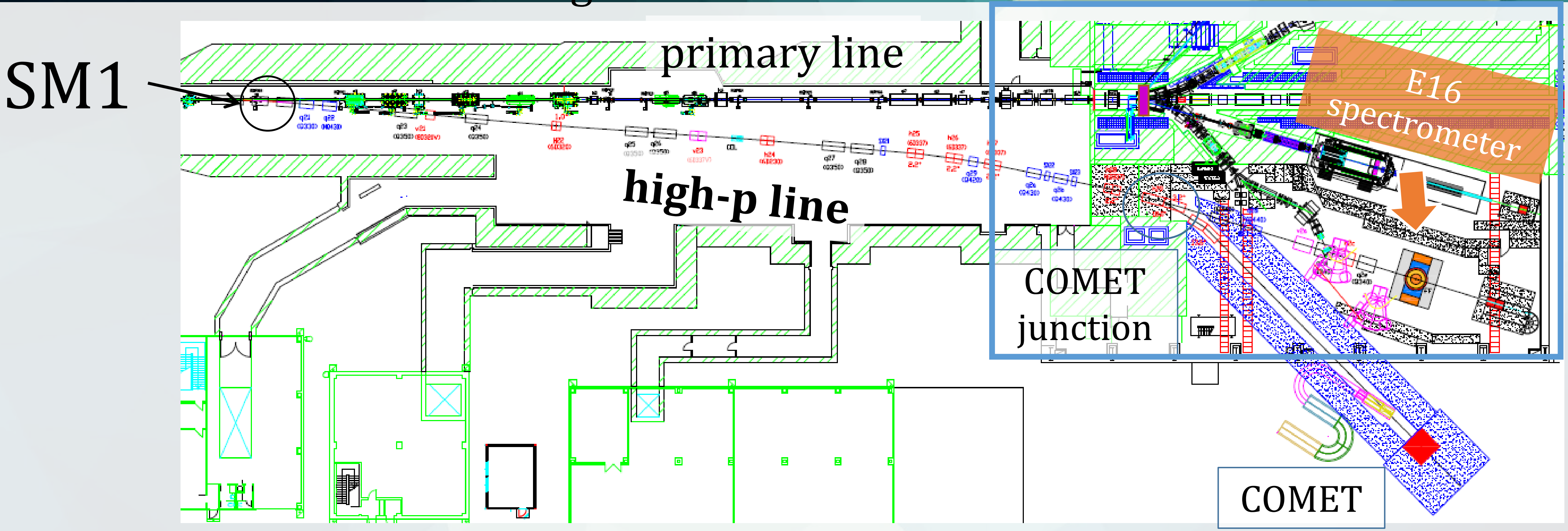
Yoshida, Hiyama, Hosaka, Oka, Sadato, *PRD* 92(2015)114029

Qqq/QQq spectroscopies

- Weak decay
  - heavy → light and/or heavy → heavy
  - characteristic decay patterns
- Strong decay
  - KY / DYc systems
- Production dynamics
  - bottom up
  - similarity with quarkonium

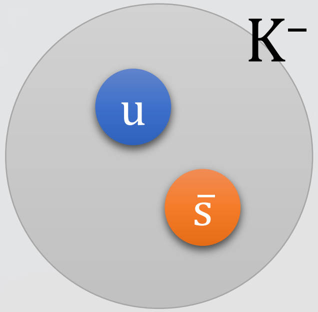
High-momentum beam line at J-PARC

branch angle : 5°



at SM1 high-p beam branches off from the primary line

- 30 GeV primary proton (10^{10}/s)
- 8 GeV primary proton for COMET
- **secondary particles like π, K up to 20 GeV/c**

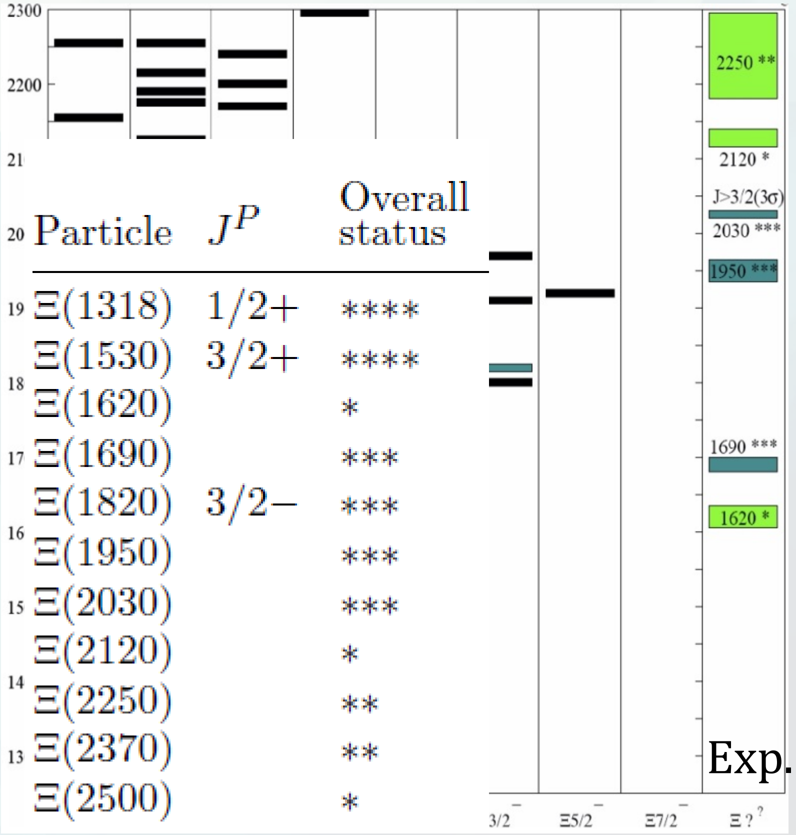


Observed States of Ξ

- So far, 11 states were reported.
- existence is certain : 2
- need confirmation : 4
- evidence is fair : 2
- evidence is poor : 3

- Quark Model prediction
  - 44 states up to 2.3 GeV

QM calc. by Chao, Isgur & Karl



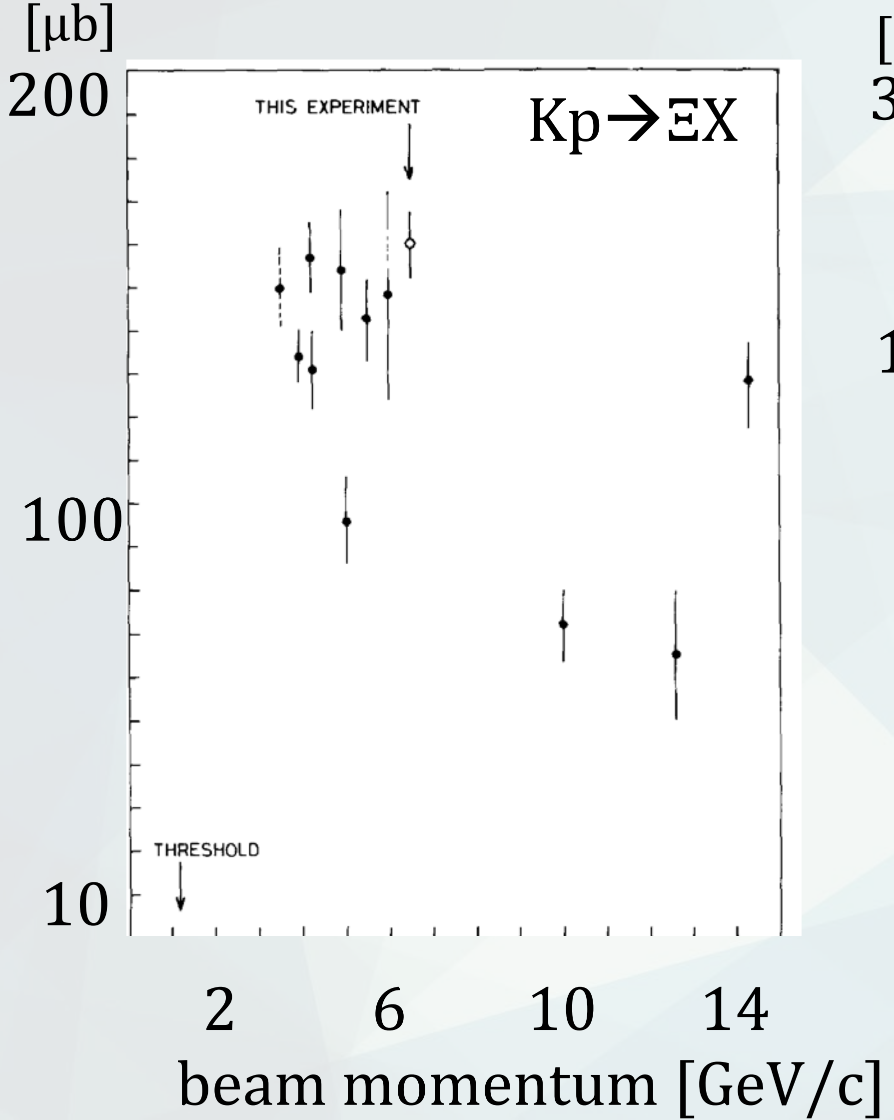
Particle	J^P	Overall status
Ξ(1318)	1/2+	****
Ξ(1530)	3/2+	****
Ξ(1620)		*
Ξ(1690)		***
Ξ(1820)	3/2−	***
Ξ(1950)		***
Ξ(2030)		***
Ξ(2120)		*
Ξ(2250)		**
Ξ(2370)		**
Ξ(2500)		*

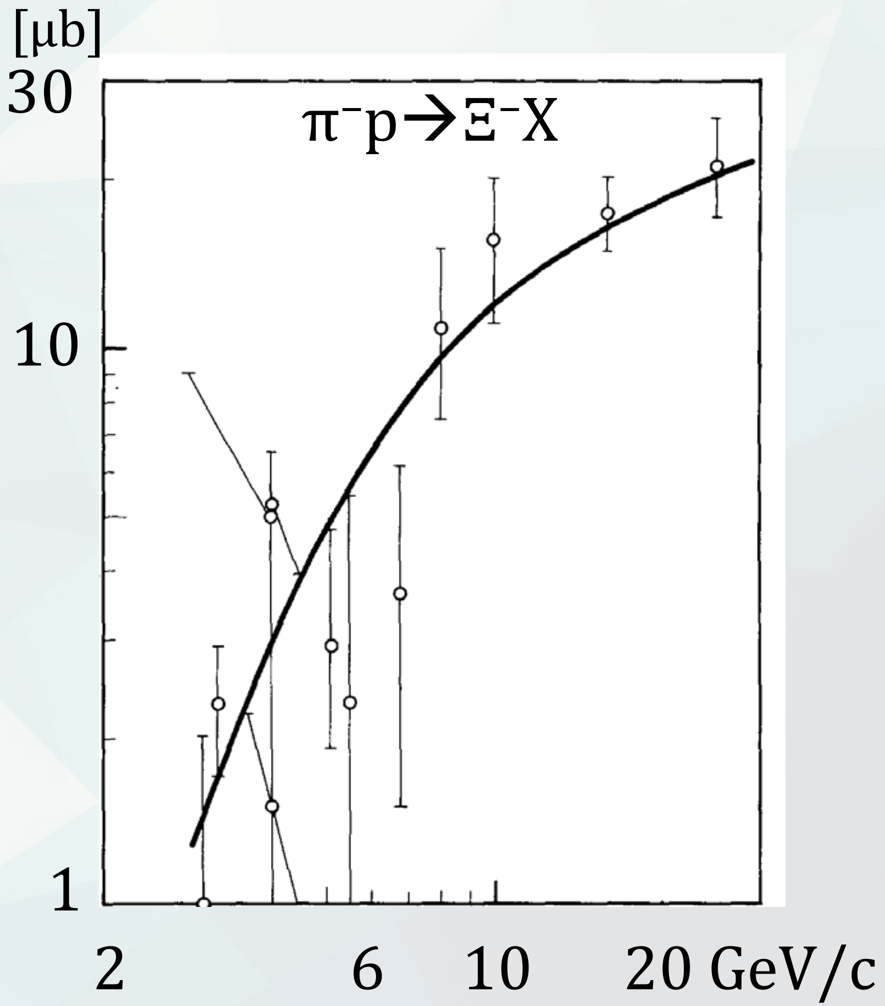
Ξ^* Production

- Medium Energy Separated beam
  - 3~5 GeV/c K^- p σ~10μb
  - bubble chamber experiment in 60-70's
- High Energy Separated beam
  - ~20, 345 GeV/c π^-p inclusive σ~1μb
  - bubble chamber exp. at CERN
- Hyperon Beam
  - 116GeV/c Ξ^- Be at CERN-SPS

Clean Kaon Beam is desirable

Cross Section

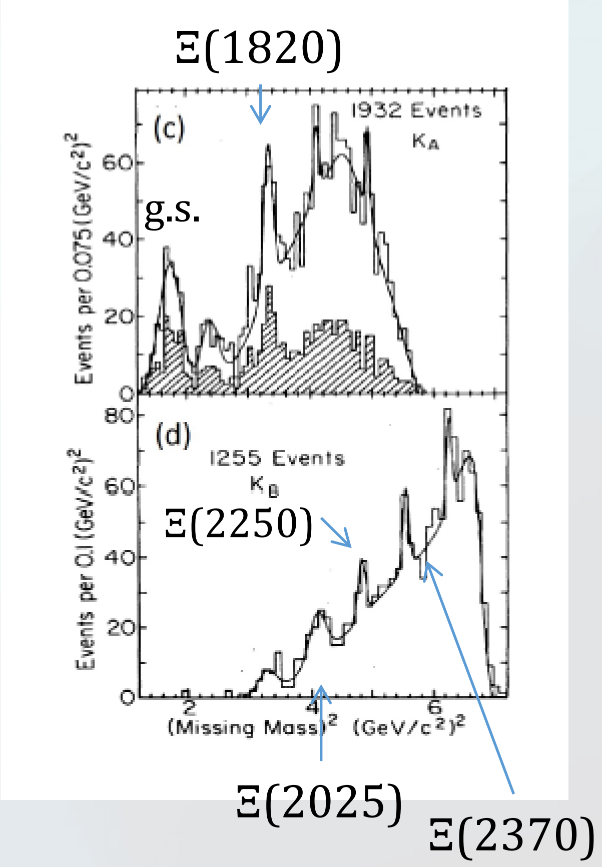




K-p qualities

- $K^-p \rightarrow K^+X$ at 5GeV/c
- Medium Energy Separated Beamline at AGS
- two arms on both sides of MPS.
- statistics is not so high, however higher excited states seem to be identified on the missing mass spectra of the $K^-p \rightarrow K^+X$ reaction.

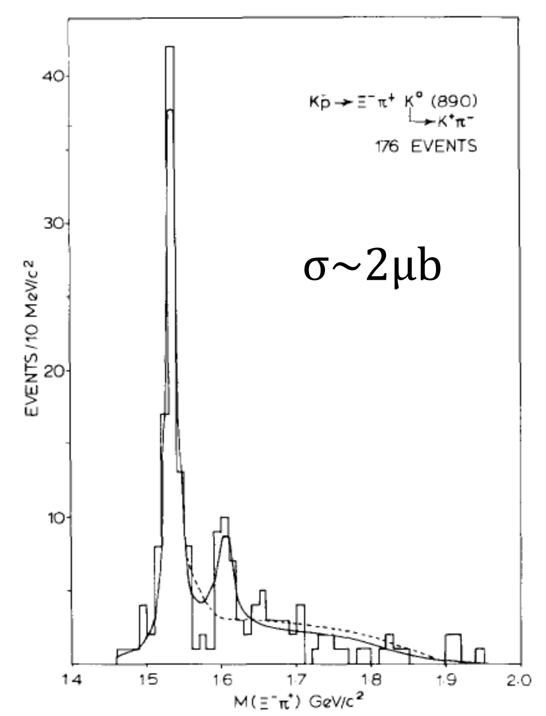
5GeV/c $K^-p \rightarrow K^+X$
Jenkins at al., PRL51('83)951

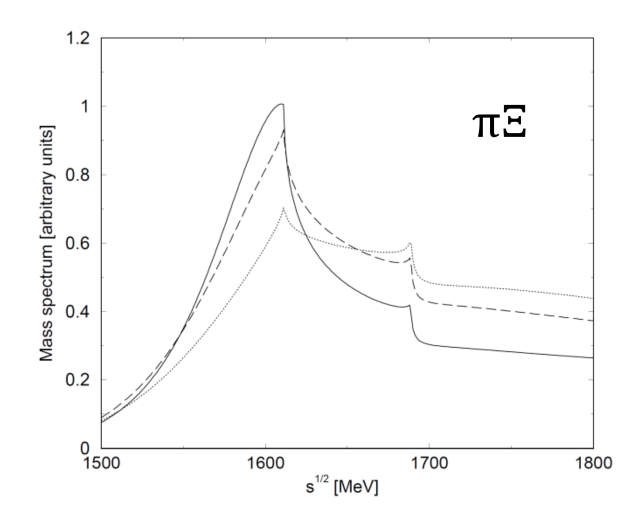


$\Delta M \sim 30MeV$

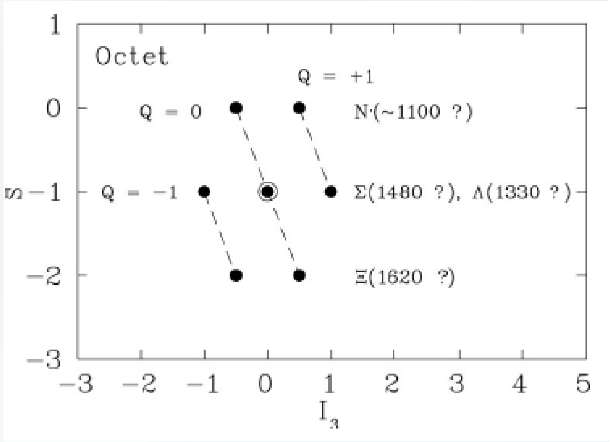
Ξ(1620)*

- first excited state, if exist.
  - Is this a Roper-like state?
- dynamically generated resonance
- candidate for exotic baryon; 5q

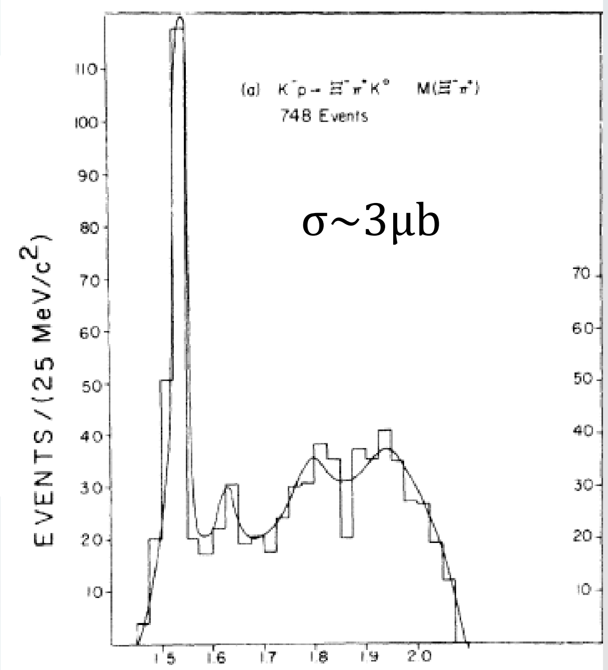




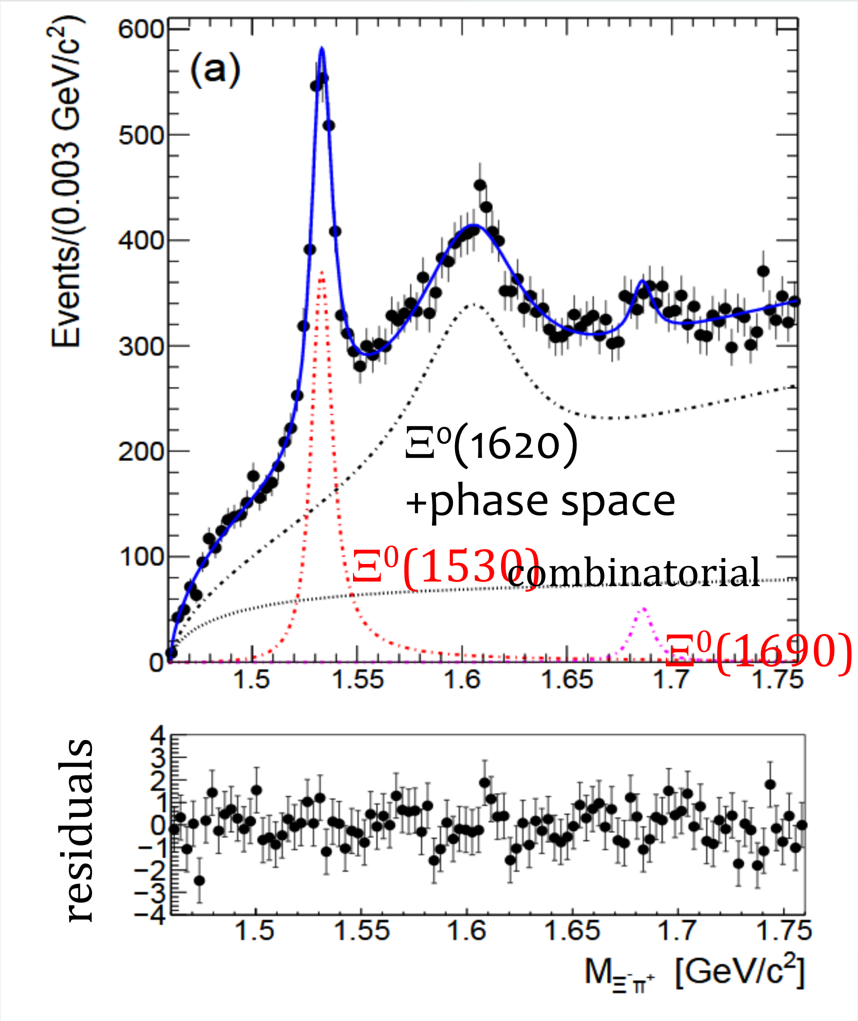
Ramos, PRL89 (‘02) 252001



Azimov,
PRC68(03)045204



From Belle



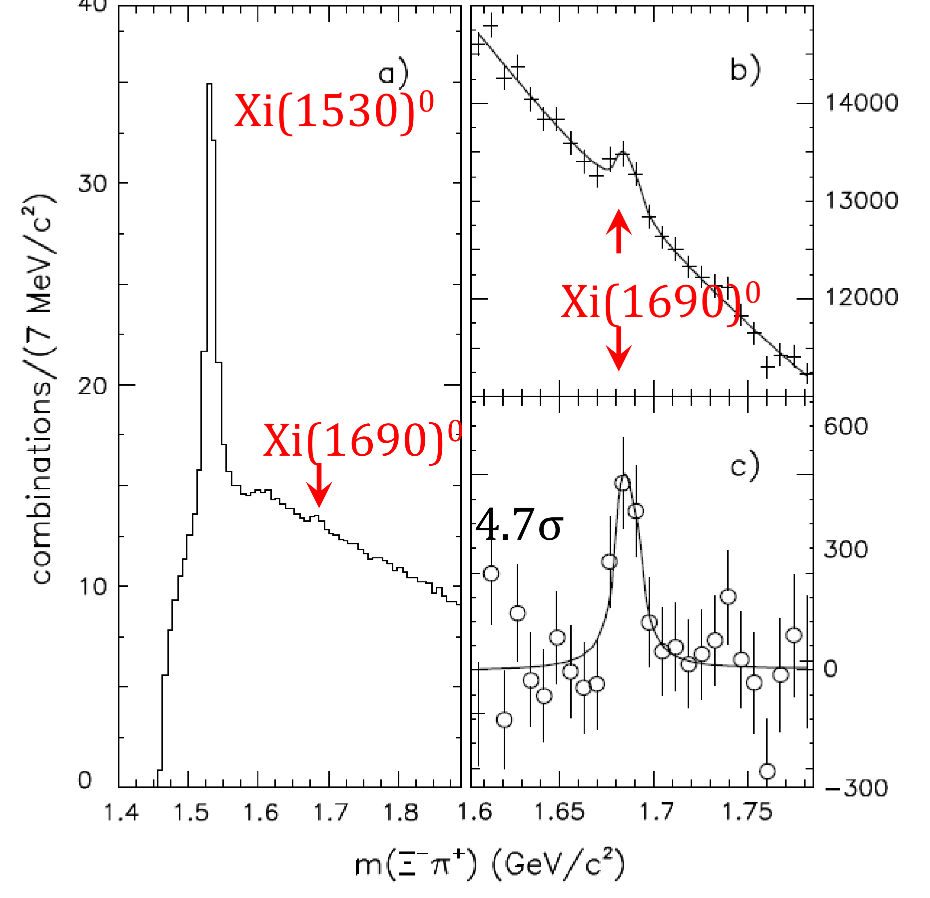
PRL 122 (2019) 072501

- fitting functions
  - Ξ(1530) : p-wave BW w/1.38 G
  - Ξ(1620) : s-wave BW
  - Ξ(1690) : s-wave BW w/2.04 G
  - non-resonant & combinatorial
- fitting parameters
  - mass & width of Ξ(1530) & Ξ(1620)
- Results
  - significance : 25σ / 4.0σ for Ξ(1620) / Ξ(1690)
  - Ξ(1530)

    M : 1533.4 ± 0.4 MeV   Γ: 11.2 ± 1.5 MeV
  - Ξ(1620)

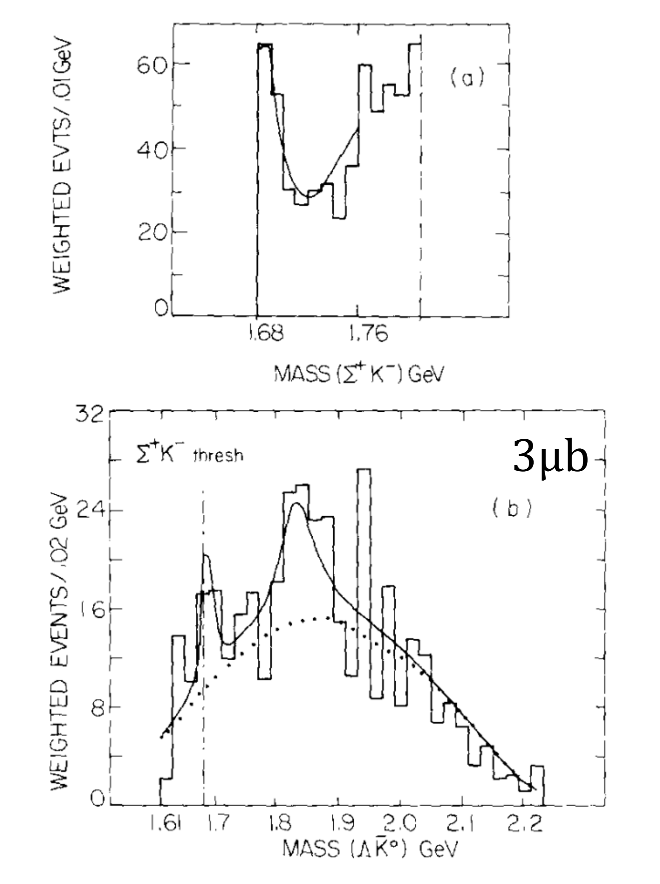
    M : 1610.4 ± 6.0 MeV   Γ: 60.0 ± 4.8 MeV

Ξ(1690)***



Adamovich et al., EPJ,C5('98)621

4.2GeV/c $K^-p \rightarrow YKK\pi$

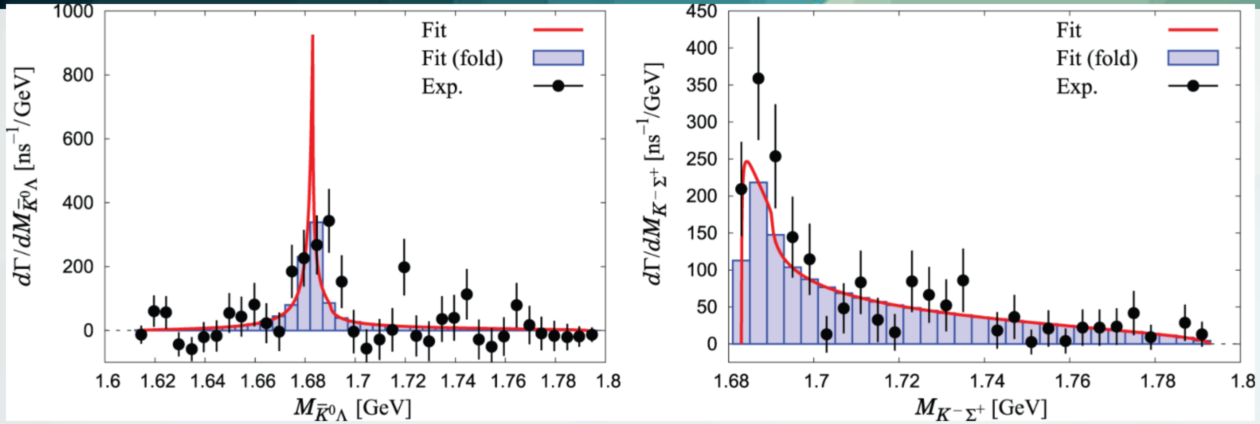


Dionisi et al., PL,80B,('78)145

$\Gamma(\Xi\pi)/\Gamma(\Sigma K)<0.09$

Ξπ / ΣK / ΛK

Ξ(1690)***



Decay channel : KΛ KΣ

Yield : 93±26 82±15 32.6/fb

20 times

711/fb

† Ξ(1690) as analog state of Λ(1405)

- too light compared with QM calculations.
- K̄Σ molecular state T. Sekihara, PTEP (2015) 091D01
- Based on Belle data PLB 524(2002)33

Ξ Spectroscopy with kaon beam

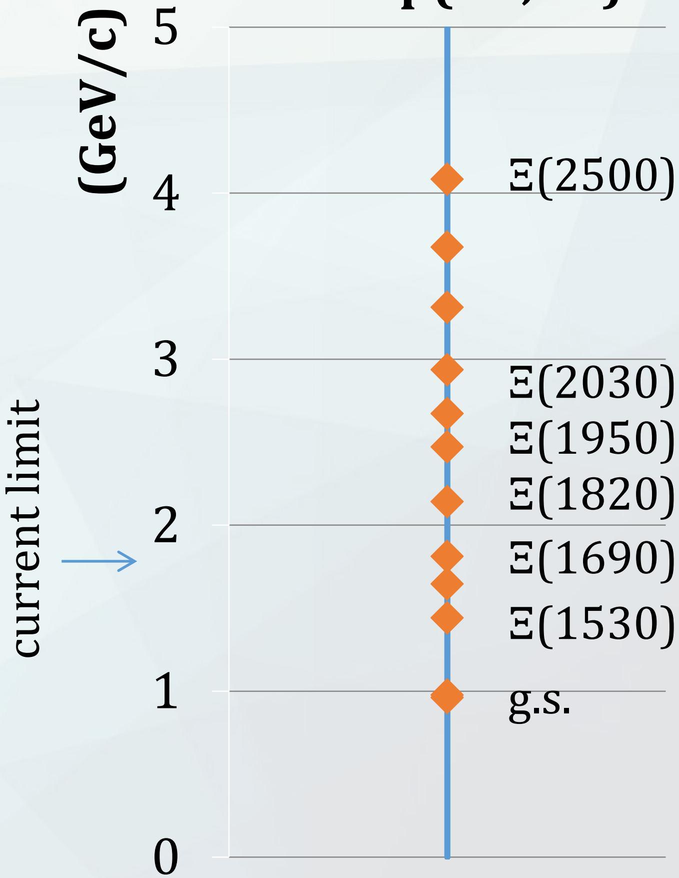
- Missing & Invariant Mass Spectroscopy
- 5 GeV/c K− p reaction up to 2.5 GeV Ξ
  - * by K* tagging, threshold momentum for 2.5 GeV Ξ production is 5.5 GeV/c.

Yield Estimation

$I_K=10^6$/spill
σ=1μb
dΩ/4π = 50%
$4g/cm^2$ LH2 target

→ Y ~10^4/day :
5days for 50k events

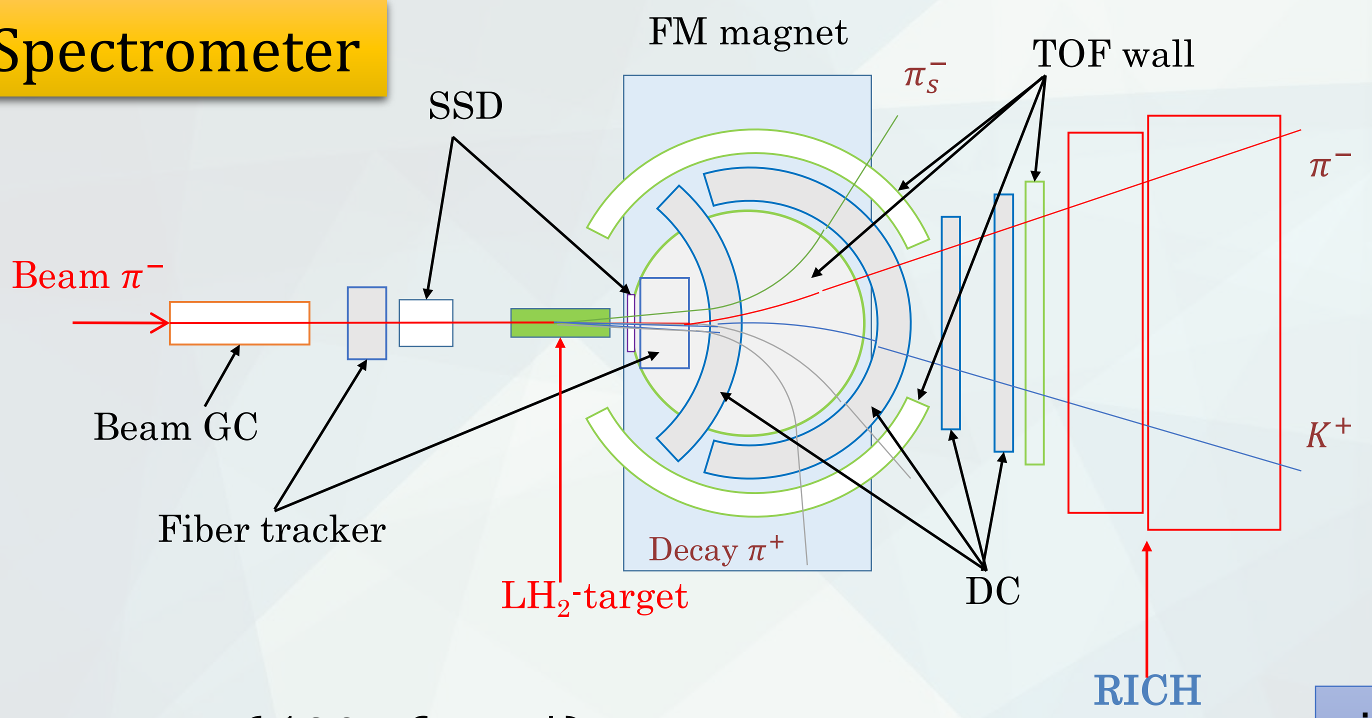
Threshold momentum in p(K−,K+)



LoI: Ξ Baryon Spectroscopy with High-momentum Secondary Beam

Spectrometer Design

J-PARC E50 Spectrometer



for Ξ:

P_{beam} = 4GeV/c

scattered K 1~3GeV/c <40°

p 1 ~ 2.5GeV/c <30°

π 0.3 ~ 0.8GeV/c 20~60°

sideway : π/K dE/dx
forward : π/K/p TOF < 2.4GeV/c

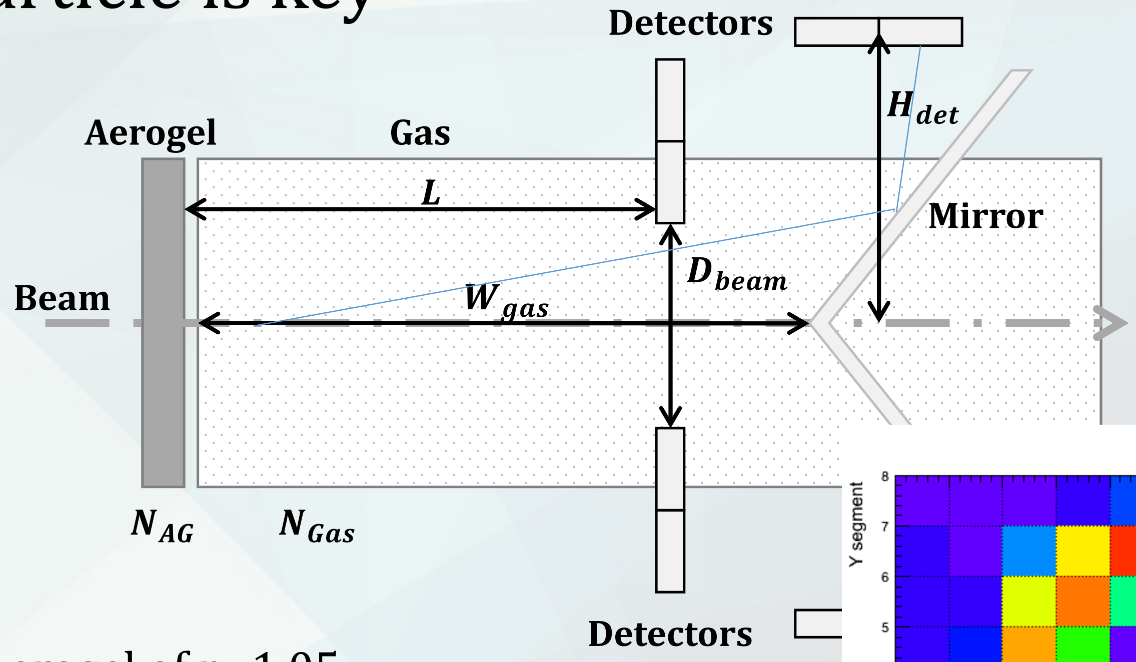
- Large acceptance (50% for K*)
- high-resolution (ΔM~10MeV)
  - Possible decay mode measurement: Ξ→Ξπ/YK⁻
  - Multi-particle detection in the high rate environment

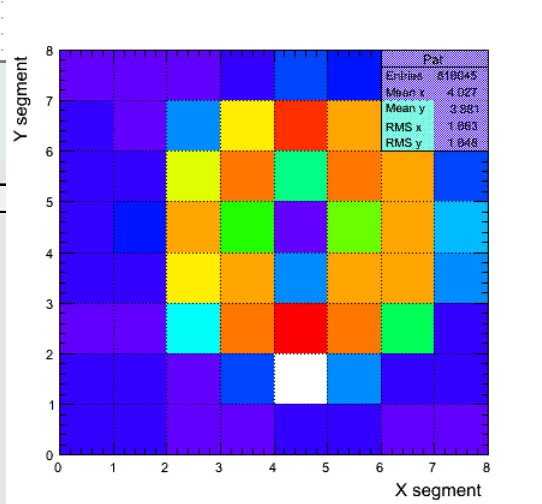
Beam Particle Identification

- π/K separation for beam particle is key
  - $I_\pi/I_K \sim 100$
- 5 GeV/c K - 20 GeV/c π

- Test Exp.
  - #photon ~ 10
    - cf. #photon(dark current) ~2
  - Δθ = 2.8mrad
    - Δθ(π/K)=23mrad at 4GeV/c w/Aerogel of n=1.05

- working member: S. Kajikawa, R. Honda, K. Shirotori





Summary

- Experimental information of Cascades is largely lacking.
- Cascades provide an unique opportunity to investigate QQq systems.
- Physics behind the Ξ^* seems interesting. Some exotic states are expected.
- The mid-energy separated kaon beam enable us to study Cascade Baryons.