Ω baryon spectroscopy at the K10 beam line

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International Workshop on the Extension Project
for the J-PARC Hadron Experimental Facility (J-PARC HEF-ex WS)
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  - Role of Ω baryon
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  - K10 beam line and spectrometer
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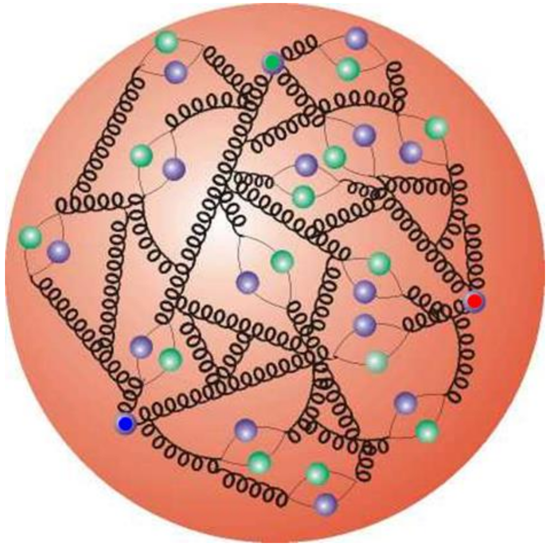
Introduction

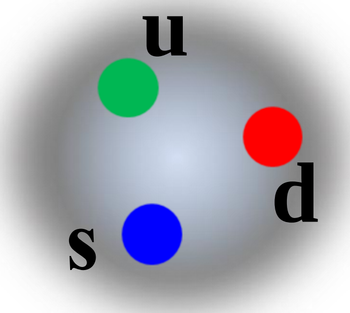
How quarks build hadrons ?

Hadron



http://ppssh.phys.sci.kobeu.ac.jp/~yamazaki/lectures/07/modernphys-yamazaki07.pdf

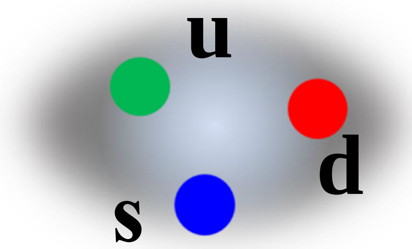
Ground state



Baryon: 3q

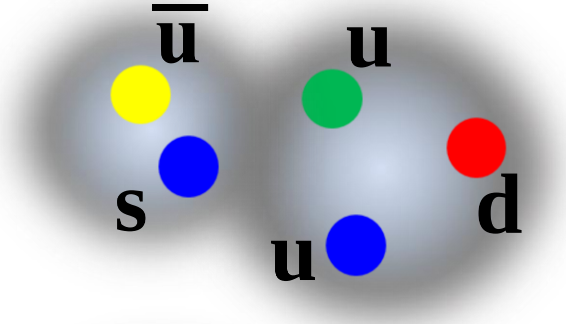
???

Excited state



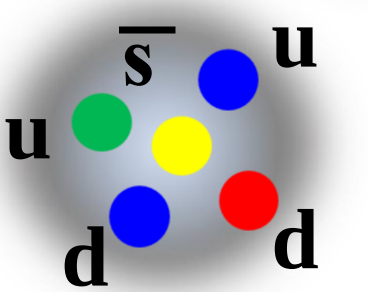
Minimal 3q

Hadron Molecule ?



Exotic hadron

Multi-quark ?



- Understand mechanism how quarks build hadrons ?

- Investigations of internal structure

for revealing effective degrees of freedom and their interactions

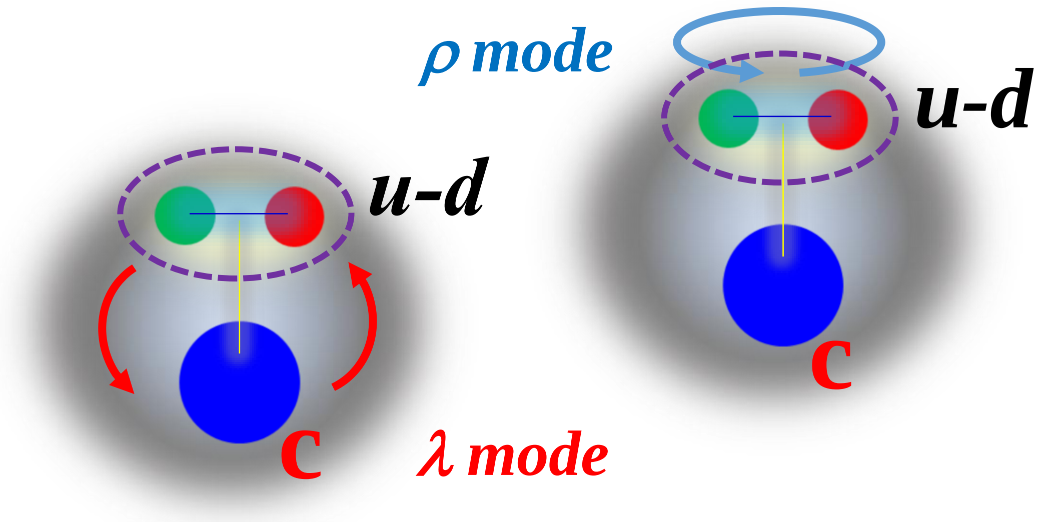
Hadron spectroscopy at J-PARC

- **Dynamics of non-trivial QCD vacuum in baryon structure**
  - ※Chiral condensate $\langle \bar{q}q \rangle \neq 0$, $U_A(1)$ anomaly
  - ⇒ Constituent quarks and NG bosons (effective degrees of freedom)
  - Their dynamics has yet to be understood, keeping a link to QCD.

- ***s*- and *c*-baryon spectroscopy: Disentangle quark correlation and spin-dependent forces**

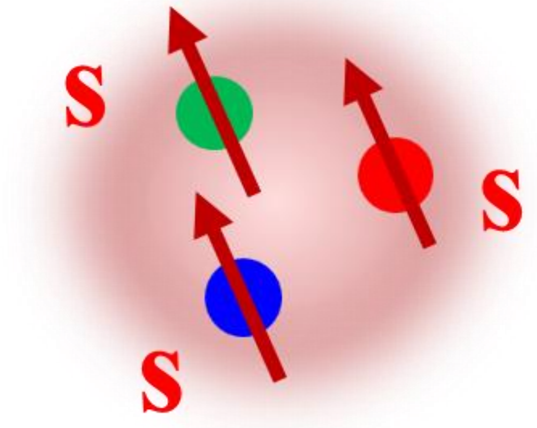
• Diquark correlation
via heavy baryon spectroscopy @ High-p

Charmed baryon

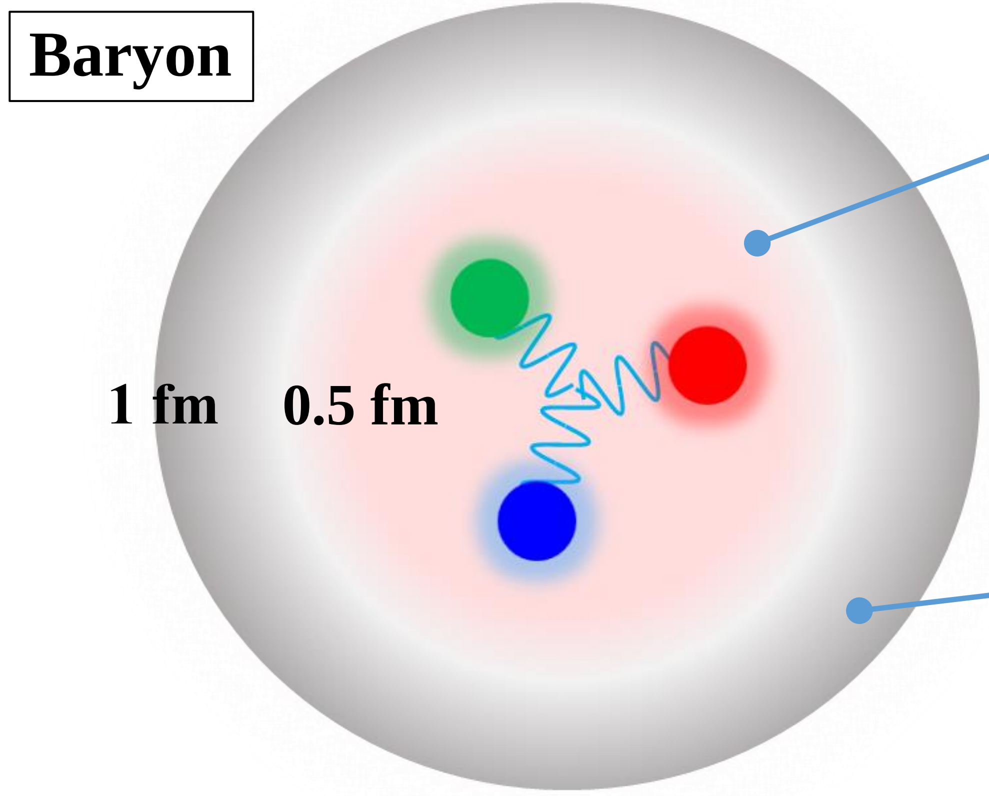


• Spin-dependent forces
• Internal quark motion
via Ω baryon spectroscopy @ K10

Ω (sss) baryon



Baryon structure: QCD vacuum



- **Non-perturbative region**

⇒ "Quark core" region

- **Non-trivial gluon field: Instanton**

⇔ Chiral condensate $\langle \bar{q}q \rangle \neq 0$

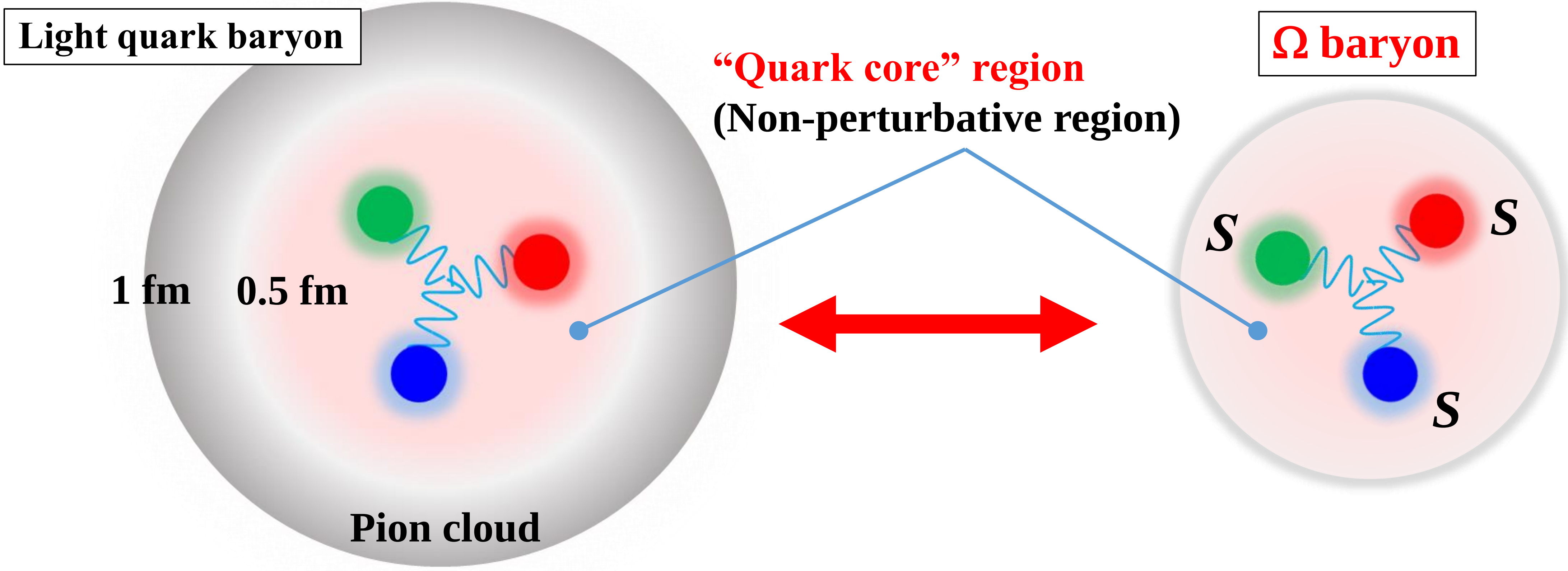
  - **Dressed quark (Constituent quark)**
  - **Emergence of π**

- **Pion Cloud**

Short-range q-q correlation & Origin of spin-dependent forces

- **Long-standing problems**
  - **Too large α_S^{ss} (>1): Spin-Spin interaction**
  - **Missing LS force: Disappearance in N*, but heavy quark baryons have.**
  - **Roper-like resonances: Small excitation energy and wide decay width(quark motion)**

Role of Ω baryon: Single flavor system



- Ω baryon: "3 strange quark single flavor system" ⇒ Free from Pion cloud

＊Direct access to "Quark core" region

⇒ Clear extraction of interactions from studies of excited states

  - One Gluon Exchange(OGE) and Instanton Induced Interaction(III)

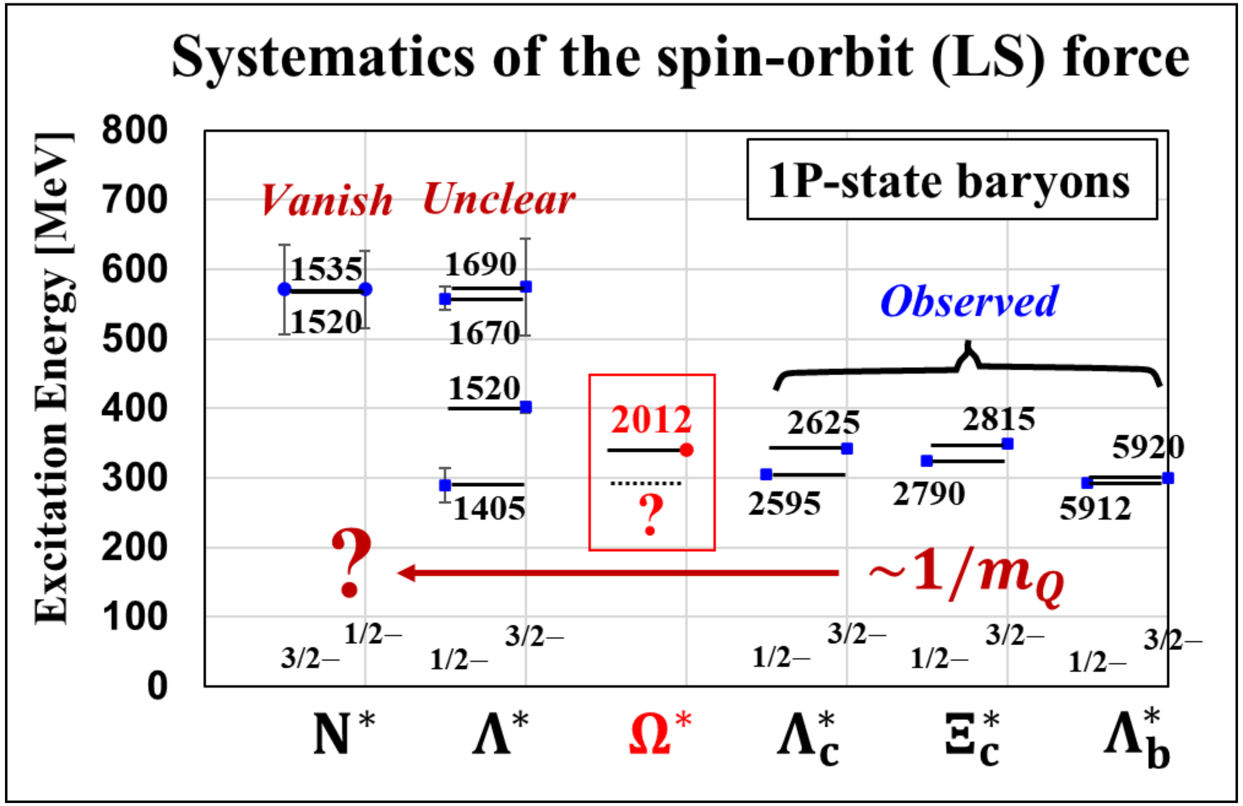
Spin-dependent forces

- **Investigate short-range q-q correlation and quark motion**
  - **In terms of One Gluon Exchange(OGE), Instanton Induced Interaction(III) and Meson cloud**

- **Systematics of spin-orbital interaction**
  - **Disappears in N* (OGE/III cancelled)**
  - **Appears in Λ_c^*, Ξ_c^* and Λ_b^* (OGE only)**

- **Ω^* baryon**
  - **Flavor-symmetric system**
  - **Free from pion cloud**

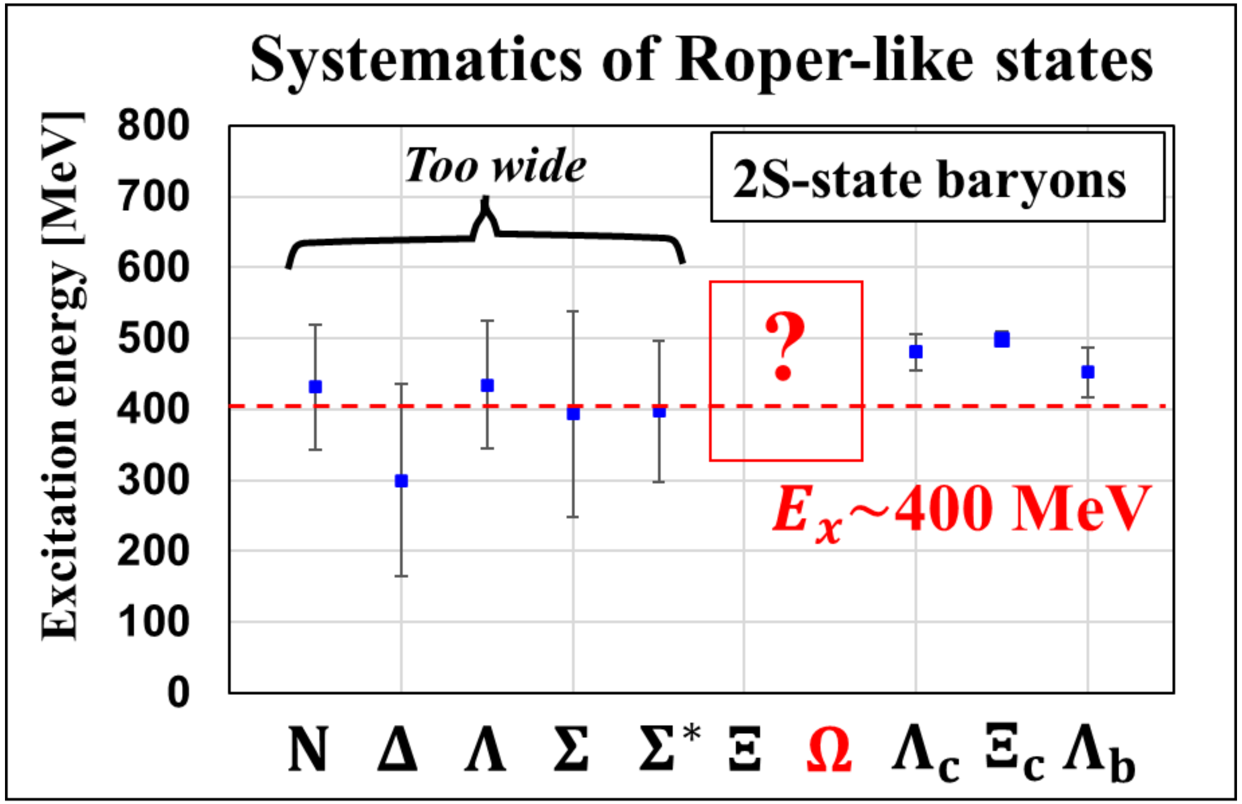
⇒ LS splitting: OGE (III forbidden)
  - **$\Omega(2012)^-(3/2^-?)$ ⇔ $\Omega^{*-}(1/2^-?)$**
    - **1P state baryons**
    - **Degenerate ?**
  - **LS partners (2D states)**



Roper-like resonances

- **Investigate short-range q-q correlation and quark motion**
  - **In terms of One Gluon Exchange(OGE), Instanton Induced Interaction(III) and Meson cloud**

- **Systematics of Roper-like states (Radial excitation 2S states)**
  - **Mass universality ?**
  - **What does determine its width ?**



- **Ω^* baryon**
  - **Flavor-symmetric system**
  - **Free from pion cloud**

∗ Width tells quark motion.: $\Gamma \sim \langle p_q \rangle$

⇒ Size of "quark core": $\langle r_q \rangle \sim 1/\langle p_q \rangle$

- **Roper-like state: Where is it ?**

Ω baryon spectroscopy at K10

＊Systematic measurements: Properties of excited states

- Mass, width, spin-parity, decay branching ratio
- Production rate ⇔ Ground state vs Excited states

1. **$\Omega(2012)^-$ (3/2$^-$?, Molecular state ?)**
   - Determination of J^p by decay angular distribution
   - Search for LS partner(1/2$^-$) (Mass, Γ, J^p and B.R.)
   - Absolute decay branching ratio: $K^- + \Xi$, $K^- + \Xi^*$, $K^- + \Xi + \pi$ modes

2. **Roper-like resonance: $\Omega(2160)^-$?**
   - Mass & Width
   - Determination of J^p by decay angular distribution
   - Absolute decay branching ratio: $K^- + \Xi$, $K^- + \Xi^*$, $K^- + \Xi + \pi$ modes

3. **Searching for resonances (Γ < 100 MeV and ~1-GeV excitation energy)**
   - Mass & Width
   - Determination of J^p by decay angular distribution
   - Absolute decay branching ratio (all measurable modes)
   - Search for LS partners (Mass, Γ, J^p and B.R.)

Measured Ω^{*-} states by PDG

2021 Review of Particle Physics.
P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020) and 2021 update

Ω BARYONS ($S = -3$, $I = 0$)

$\Omega^- = s\,s\,s$

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

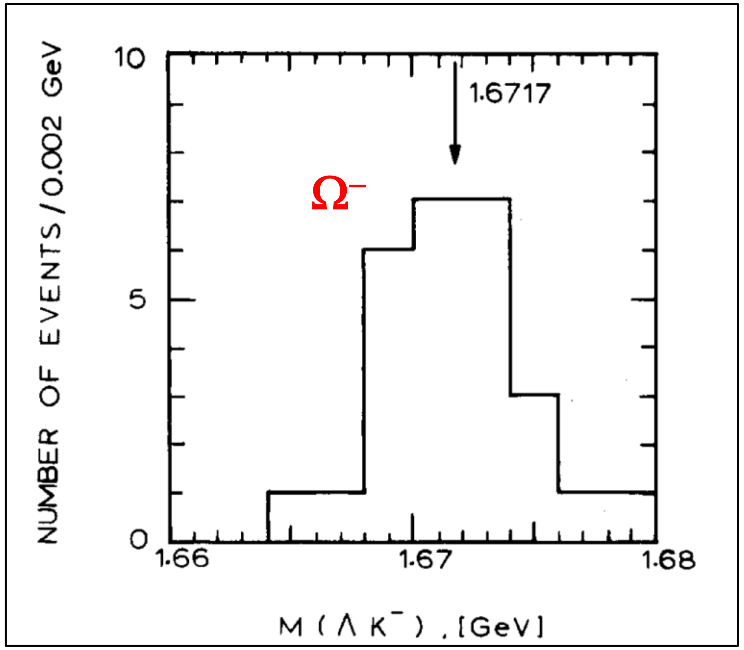
**** Existence is certain, and properties are at least fairly explored.

*** Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, etc. are not well determined.

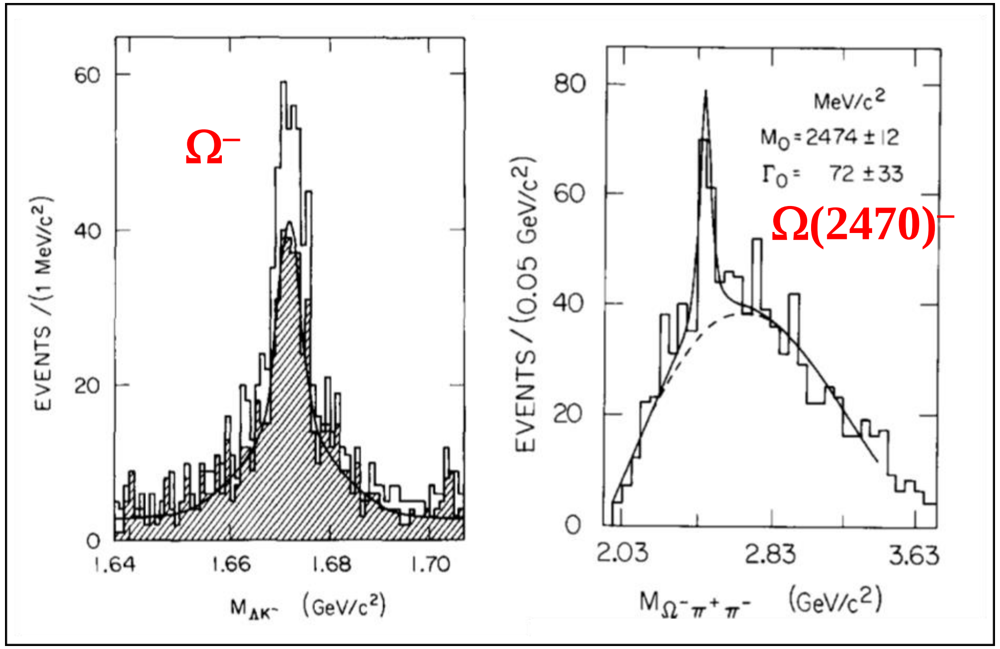
** Evidence of existence is only fair.

- **Most of spins/parities/decay branches have not been determined yet.**
- **$\Omega(2380)^-$ and $\Omega(2470)^-$ are discarded from PDG table.**

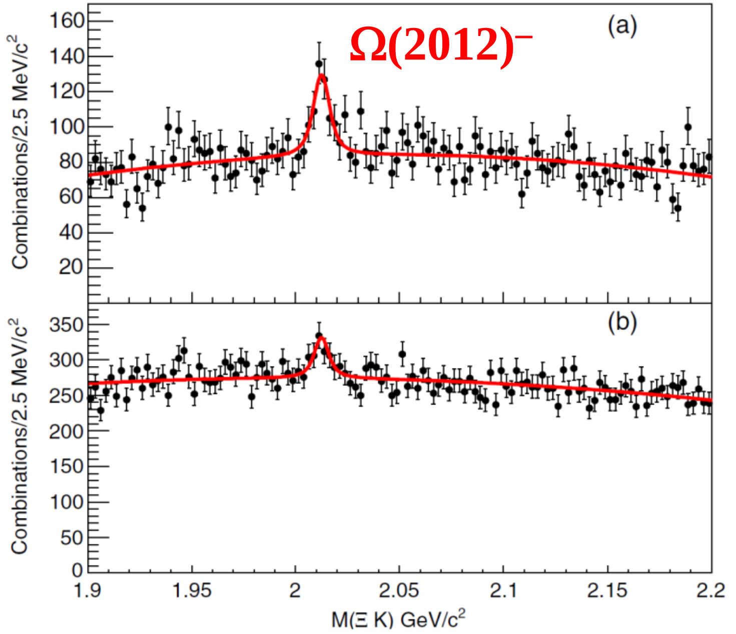
Experimental situations: K⁻ p reaction



4.2 GeV/c data
R.J. Hemingway *et al.*,
Nucl. Phys. B142 205-219 (1978)



11 GeV/c data by LAS
D. Aston *et al.*,
Phys. Rett. B 215 799-804 (1988)



Belle collaboration
J. Yelton *et al.*,
Phys. Rev. Lett. 121, 052003 (2018)

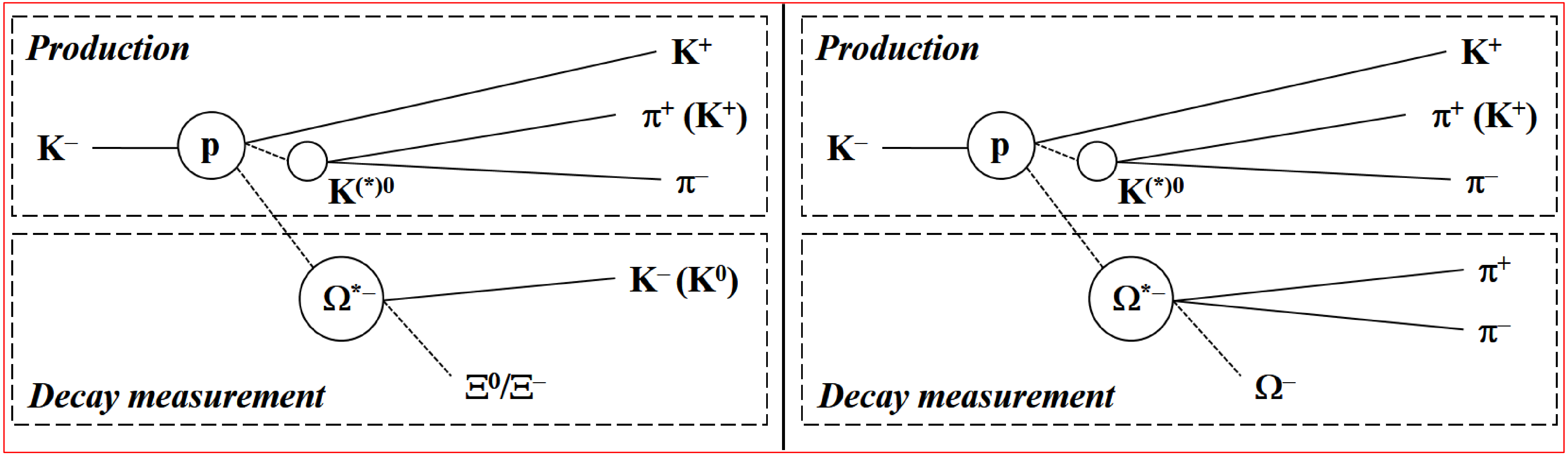
- **Need data by experiment with modern technique**

⇒ **High-performance facility and suitable experimental setup**

- **High-intensity K⁻ beam and large acceptance spectrometer**

Experiment

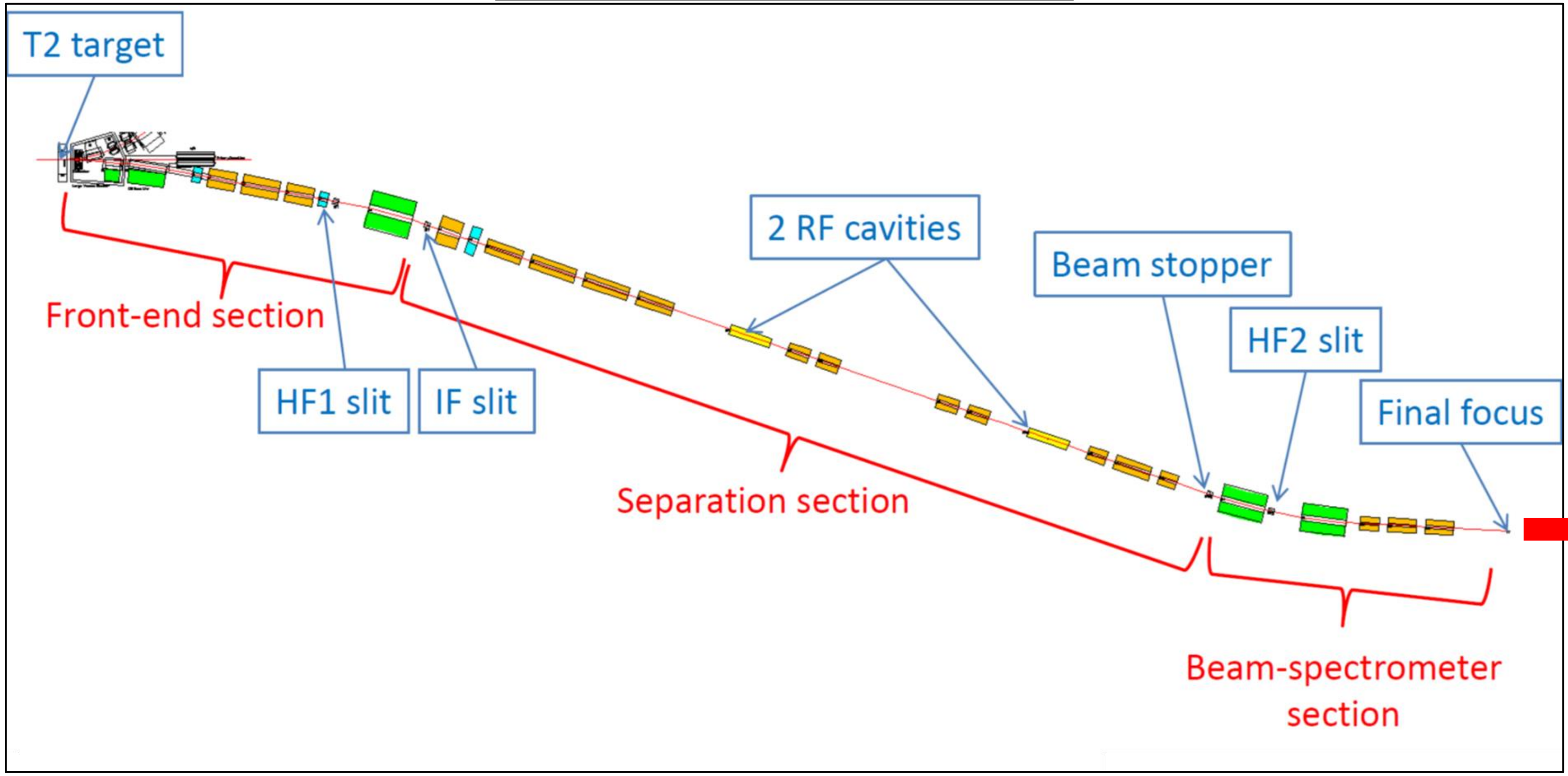
Experimental method: Ω baryon spectroscopy



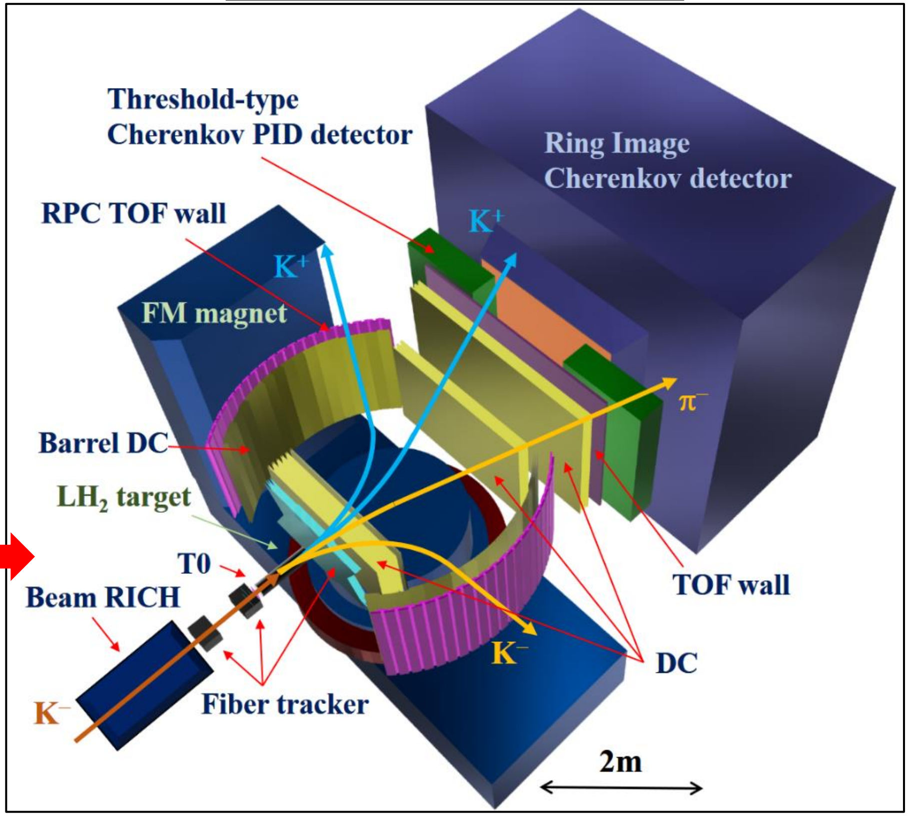
- **Reaction: $K^- + p \rightarrow \Omega^{*-} + K^{*0}(K^0) + K^+$**
  - **Beam momentum: 7–10 GeV/c for producing up to 1-GeV excited states**
- **Missing mass method: K^{*0} & K^+ / $K^0(K_s^0)$ & K^+**
  - **K^{*0} channel ⇒ Expect good S/N by using s = –3 tagged reaction**
- **Decay measurement: $\Xi^{(*)0}$ & K^- / Ω^- & $\pi^+ \pi^-$**
  - **Decay products obtained as missing mass**

K10 beam line and spectrometer

Layout of K10 beam line



K10 Spectrometer



- **K10 beam line**
  - **High-intensity high-momentum K⁻ beam with high purity**
- **Spectrometer**
  - **Multi-purpose system to detect Ω baryon production events**

K10 beam line specification

- **Beam Intensity: Several 10^6 /spill (2-second extraction)**
  - **High-purity K⁻ beam (K/π ~ 1/2)**
- **Beam-spectrometer resolution: Δp/p ~ 0.1%(σ)**
  - **By QQDDQ magnet configuration for analyzing beam momentum**

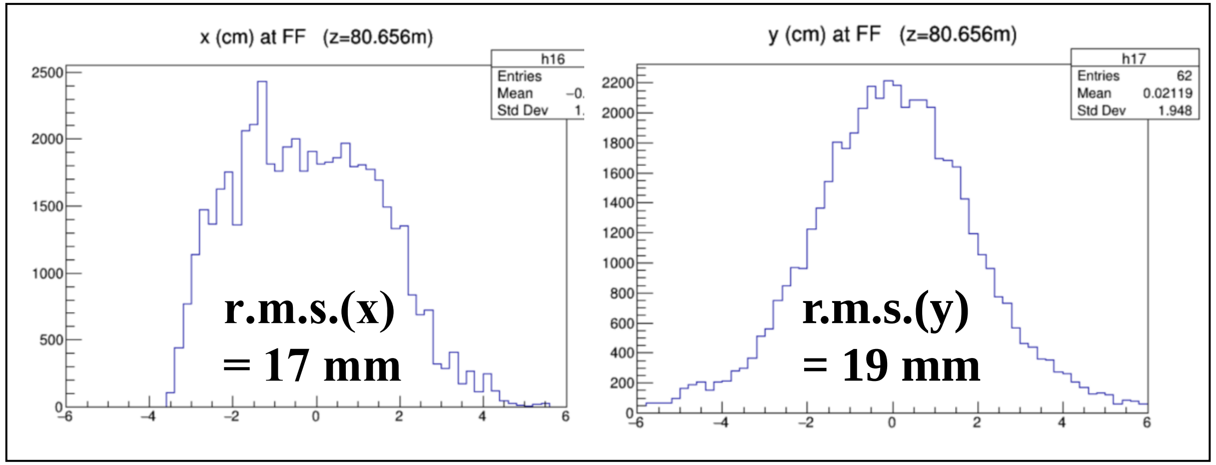
K⁻ intensity [× 10^6 /spill]
(Purity: K⁻/π⁻)

- Primary proton beam power: 50 kW
- Production target: 50% loss
- Spill cycle: 5.2sec

	7 GeV/c	8 GeV/c	9 GeV/c	10 GeV/c
QQDDQ (central stopper)	8.3 (1/2.1)	7.9 (1/2.1)	6.7 (1/2.1)	4.7 (1/2.5)

∗ Purity K⁻/π⁻ = 1/2 case
⇒ 8.0 M/spill (K⁻) w/ 16 M/spill (π⁻)
Total = 24 M/spill (12 Mcps)

Beam profiles @ experimental target



100 mm × 100 mm size (Similar to high-p BL conditions)

Detector configuration of spectrometer system

- **High-rate beam detectors**
  - **Scintillating Fiber Tracker**
  - **Cherenkov Timing detector**

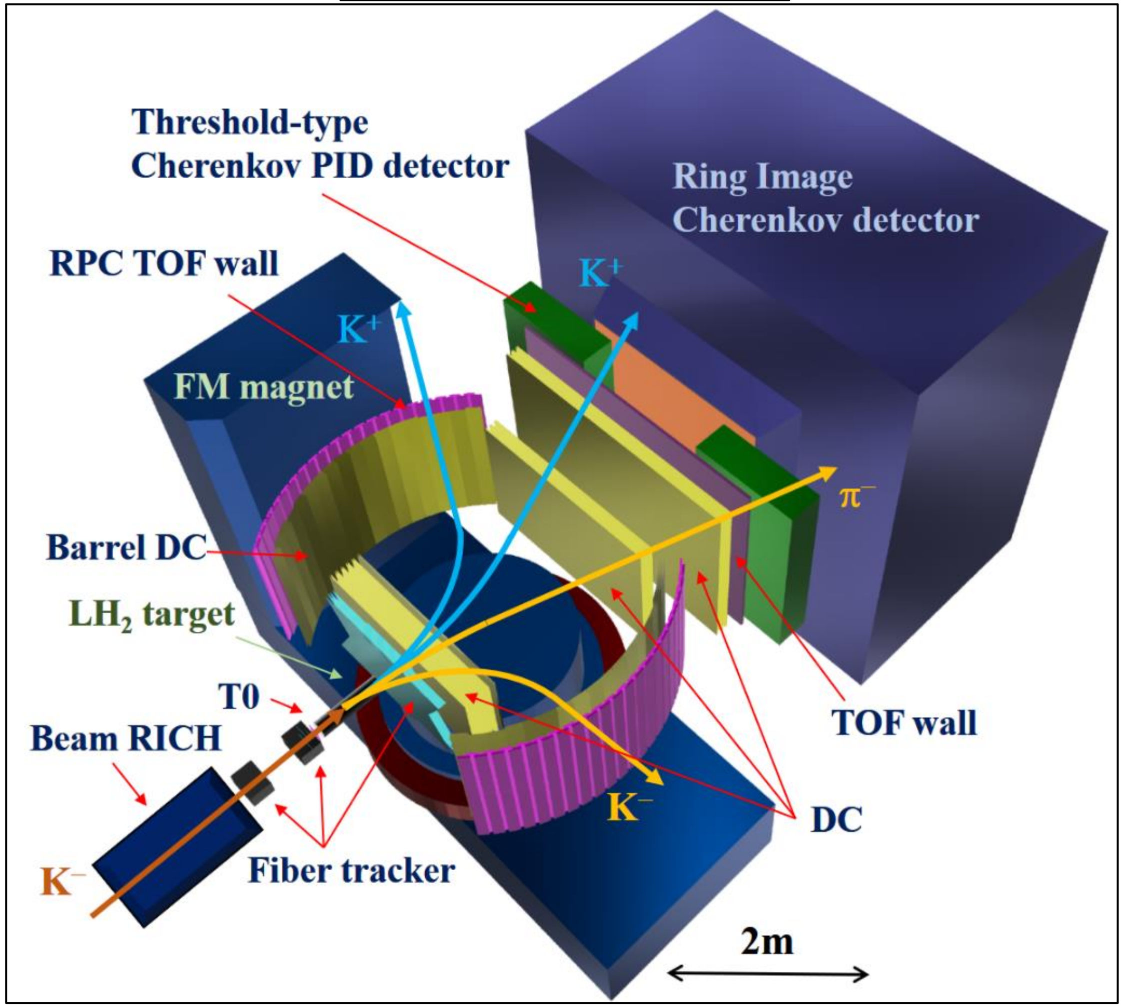
- **High-performance PID detectors**
  - **RICH and Beam RICH**
  - **High timing-resolution TOF wall: RPC**
  - **Threshold-type Cherenkov detector: Vth AC**

- **Large size detectors for scattered particles**
  - **Large size drift chambers**
  - **Forward TOF wall**
  - **Side and pole face RPC wall**

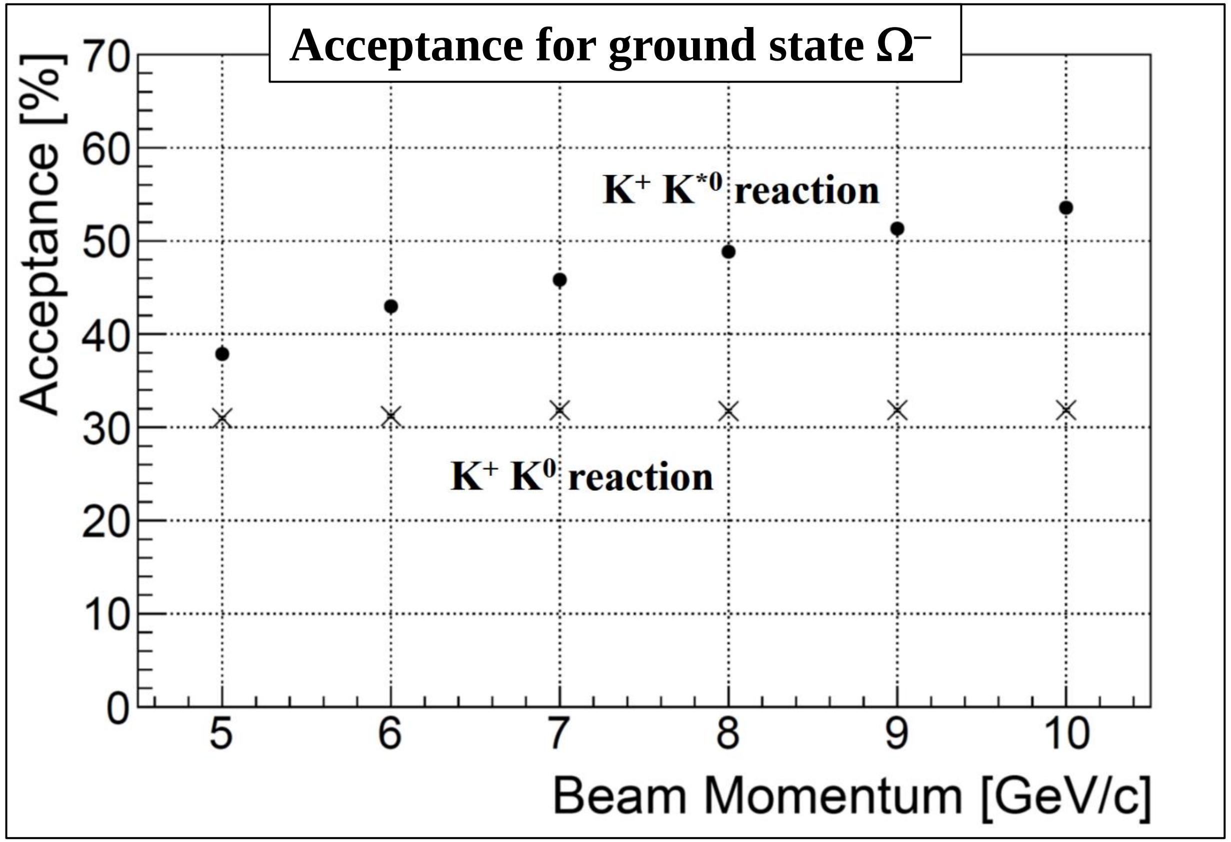
W/ Trigger-less DAQ by streaming method

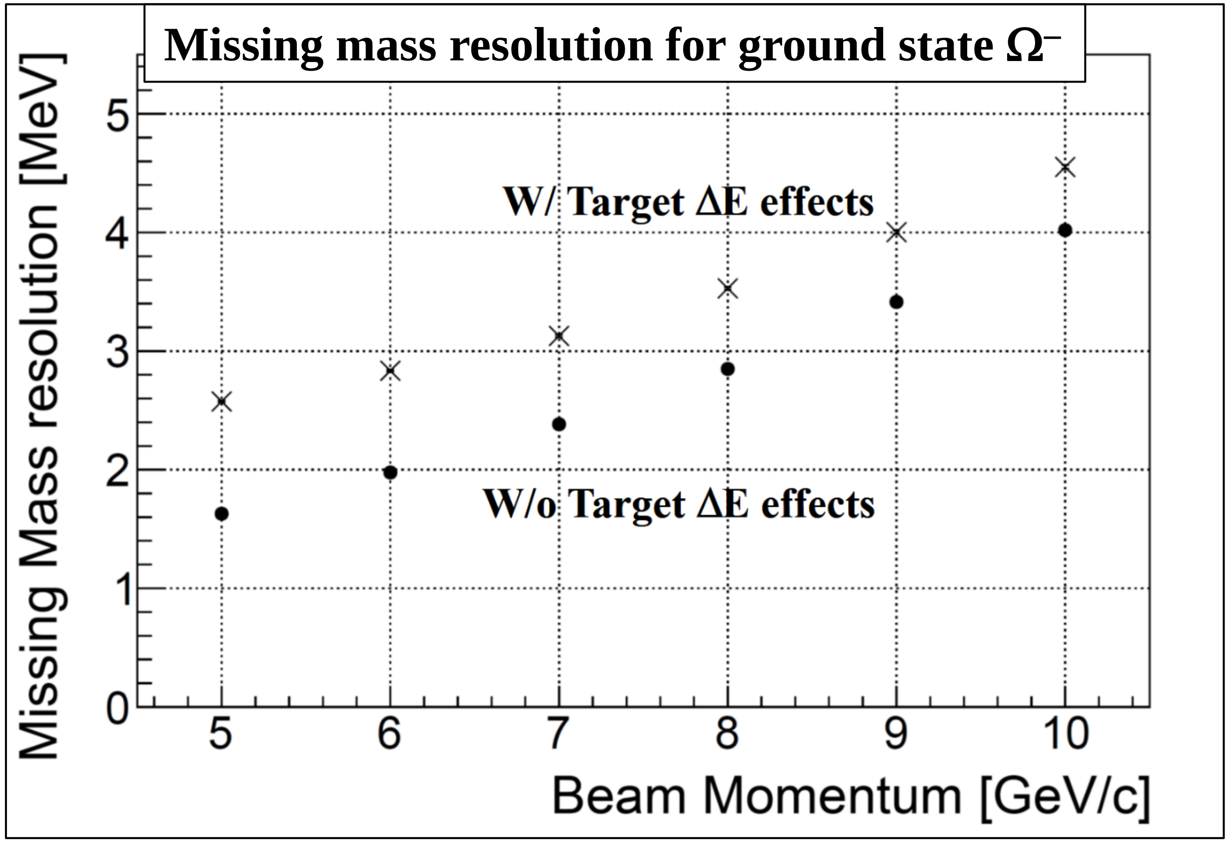
- **Detection of all possible reactions simultaneously**

K10 spectrometer



Acceptance and missing mass resolution





- **Acceptance (isotropic distribution): 30–50% (K^{*0}) and ~30% (K_s^0)**
  - **Flat acceptance for excited states**
- **Missing mass resolution: 3–5 MeV(rms) (K^{*0})**
  - **Better resolution of excited state than that of ground state.**

⇒ Width (< 10 MeV) can directly be measured.

  - **Beam line: Δp/p ~ 0.1%(σ) & E50 spectrometer: Δp/p ~ 0.2%(σ) @ 5 GeV/c**
  - **Effect of energy loss straggling by target: 2 MeV(σ)**

Yield estimation

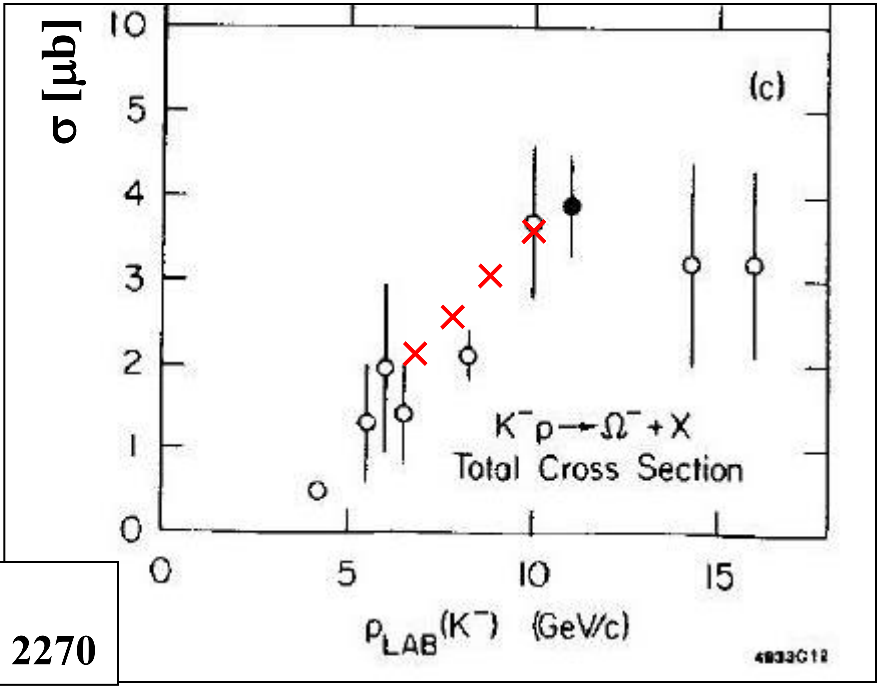
Reaction mode	Beam [GeV/c]	σ_{ch} [μb]	B.R. (K^0, K^*)	Beam [/spill]	Efficiency	Acceptance	Yield (100 days)
$K^- p \to \Omega^{*-} K_s^0 K^+$	8.0	2.50	0.35	7×10^6	0.66	0.28	4.6×10^6 (4.6M)
$K^- p \to \Omega^{*-} K_s^0 K^+$	10.0	3.50	0.35	7×10^6	0.66	0.30	6.4×10^6 (6.4M)
$K^- p \to \Omega^{*-} K^{*0} K^+$	8.0	0.063	0.67	7×10^6	0.66	0.43	3.3×10^5 (330k)
$K^- p \to \Omega^{*-} K^{*0} K^+$	10.0	0.088	0.67	7×10^6	0.66	0.50	4.6×10^5 (460k)

- Assumption of cross sections

⇒ σ_{Total} = 2.0, 2.5, 3.0, 3.5 μb (7, 8, 9, 10 GeV/c)
  - $\sigma_{K0} = \sigma_{Total} \times 1/1$ ($K^- p \to \Omega^- K_s^0 K^+$)
  - $\sigma_{K*} = \sigma_{Total} \times 1/40$ ($K^- p \to \Omega^- K^+ K^+ \pi^-$)
    - From old date @ 4.2 GeV/c

＊We will measure $\sigma_{G.S.}$ at the high-p beam line.

- Conditions
  - Target thickness: 4.0 g/cm^2 (E50 target)
  - Efficiencies and acceptance
  - Spill cycle: 5.2 sec



D. Aston et al., Phys. Rev. D 32 (1985) 2270

Background cross section from JAM simulation

Reaction	Beam [GeV/c]	σ_{ch} [mb]	Final state 1 (K^+, π^-) [μb]	Final state 2 (K^+, K^+, π^-) [μb]	Signal 1 (K^0) [μb]	Signal 2 (K^{*0}) [μb]	Ratio $K^0/(K^+, \pi^-)$	Ratio $K^{*0}/(K^+, K^+, \pi^-)$
$K^- p$	7.0	25.6	463	1.80	2.00	0.050	0.43%	2.8%
$K^- p$	8.0	23.6	503	2.46	2.50	0.063	0.50%	2.6%
$K^- p$	9.0	23.2	548	3.16	3.00	0.075	0.55%	2.4%
$K^- p$	10.0	22.6	585	4.22	3.50	0.088	0.60%	2.0%

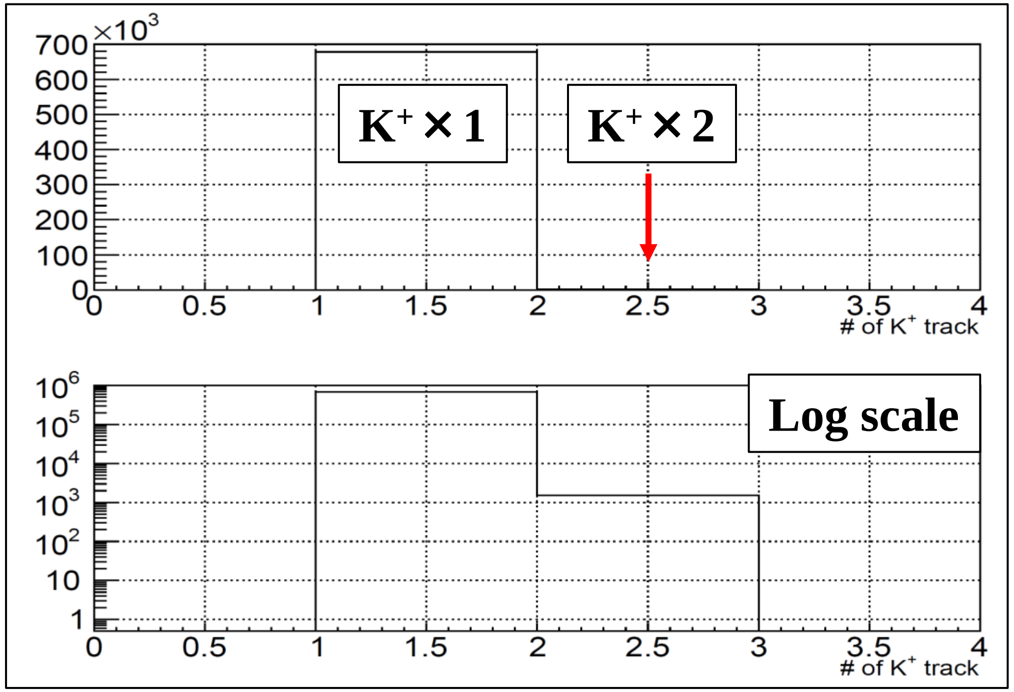
- **Background by hadron reaction generator**
  - **JAM (Jet AA Microscopic transport model)**

Y. Nara et.al. Phys. Rev. C61 (2000) 024901

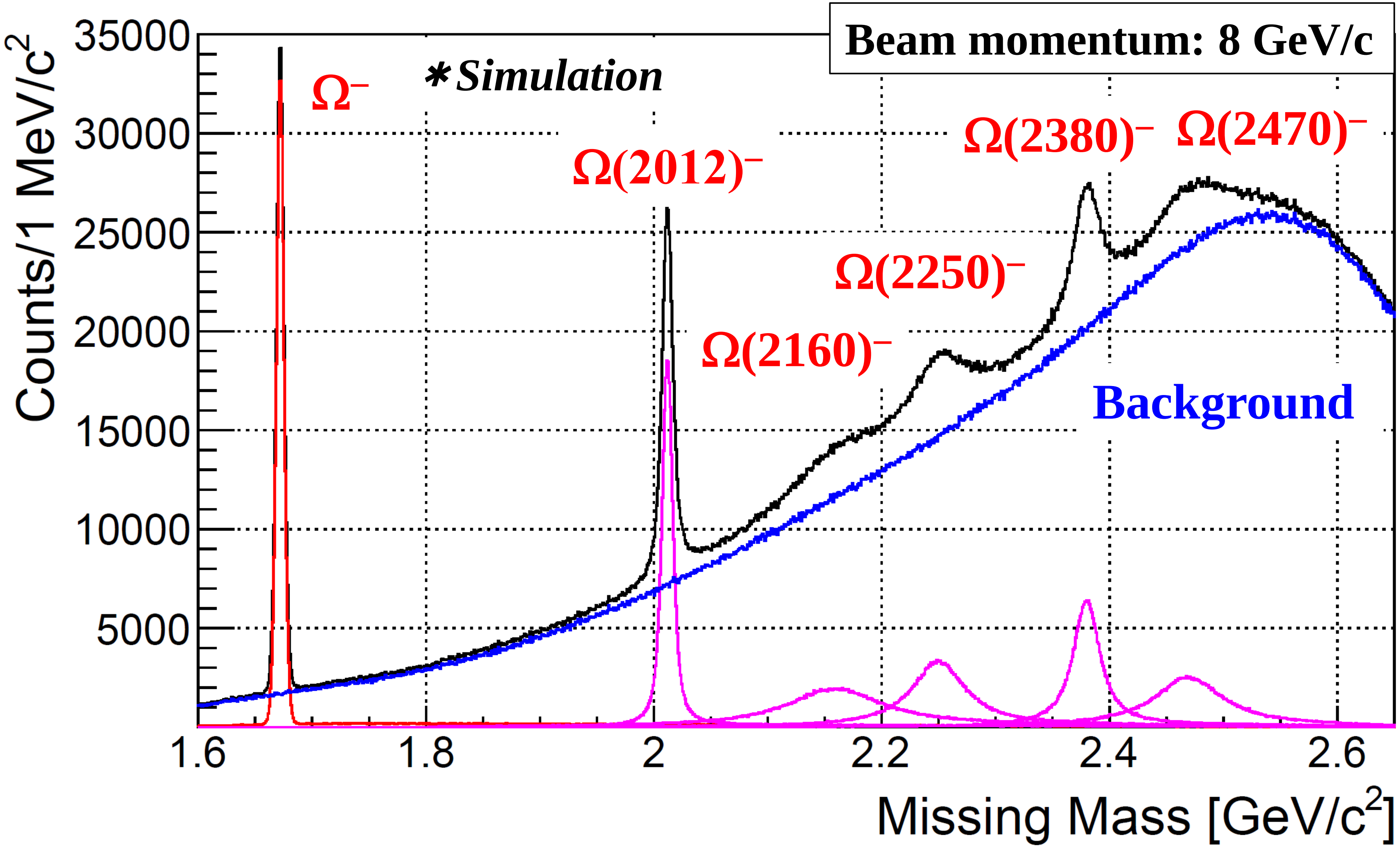
⇒ Cross section of multi-K^+ production is small.

- ×1/200~1/100 smaller than single K^+ production
- Good S/N of K^{*0} than K^0

- **JAM results were checked by studies for charmed baryon spectroscopy.**
  - Cross check with PYTHIA: Similar results
  - Actual measurements at the high-p beam line



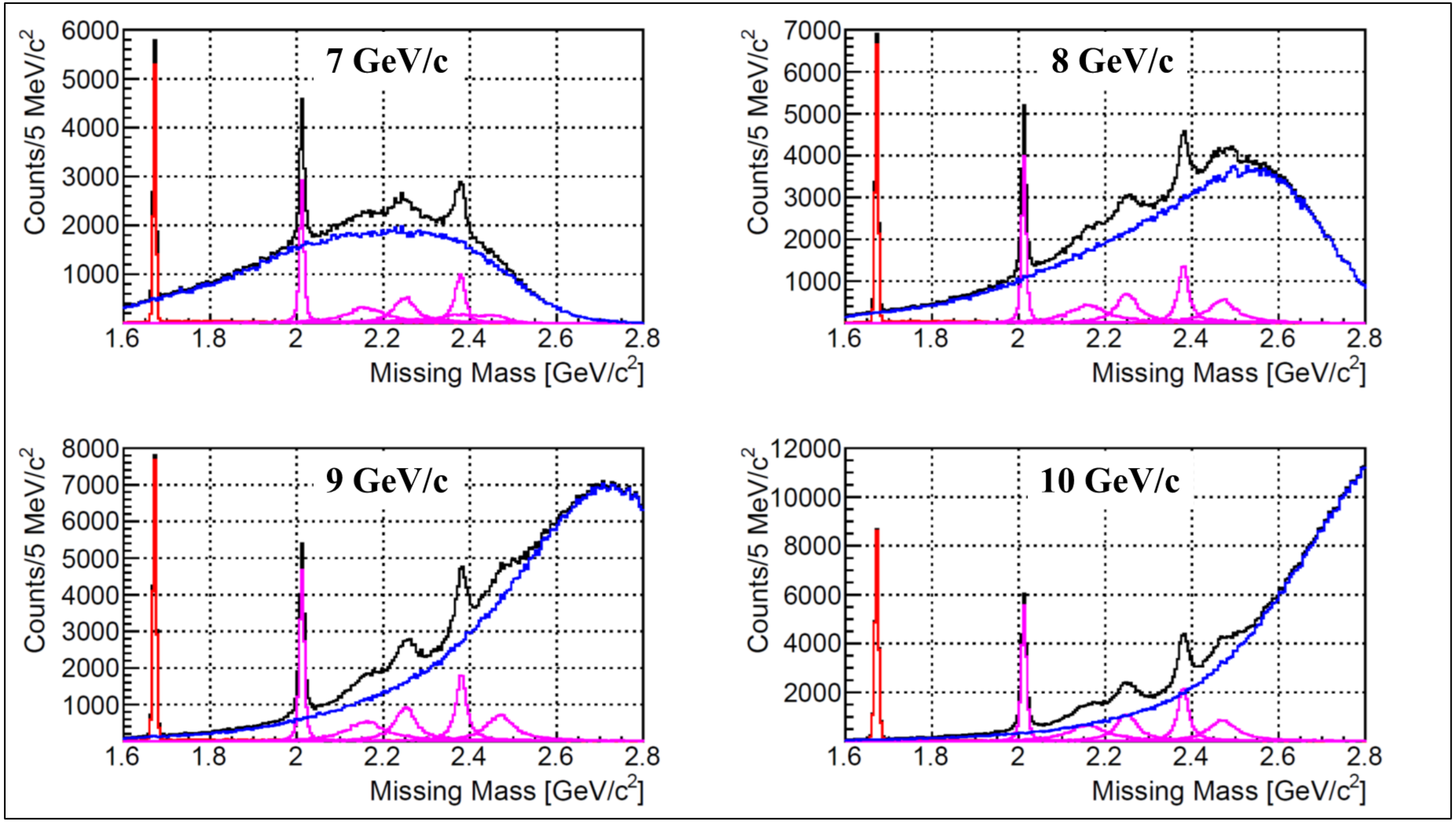
Expected missing mass spectrum: $K^- p \rightarrow \Omega^{*-} K^{*0} K^+$



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

- Ω^{*-} events: 3.3×10^5 events (63 nb: Same cross section for all resonances)
  - 100-days beam time events (1.0×10^{13} K^- on target)

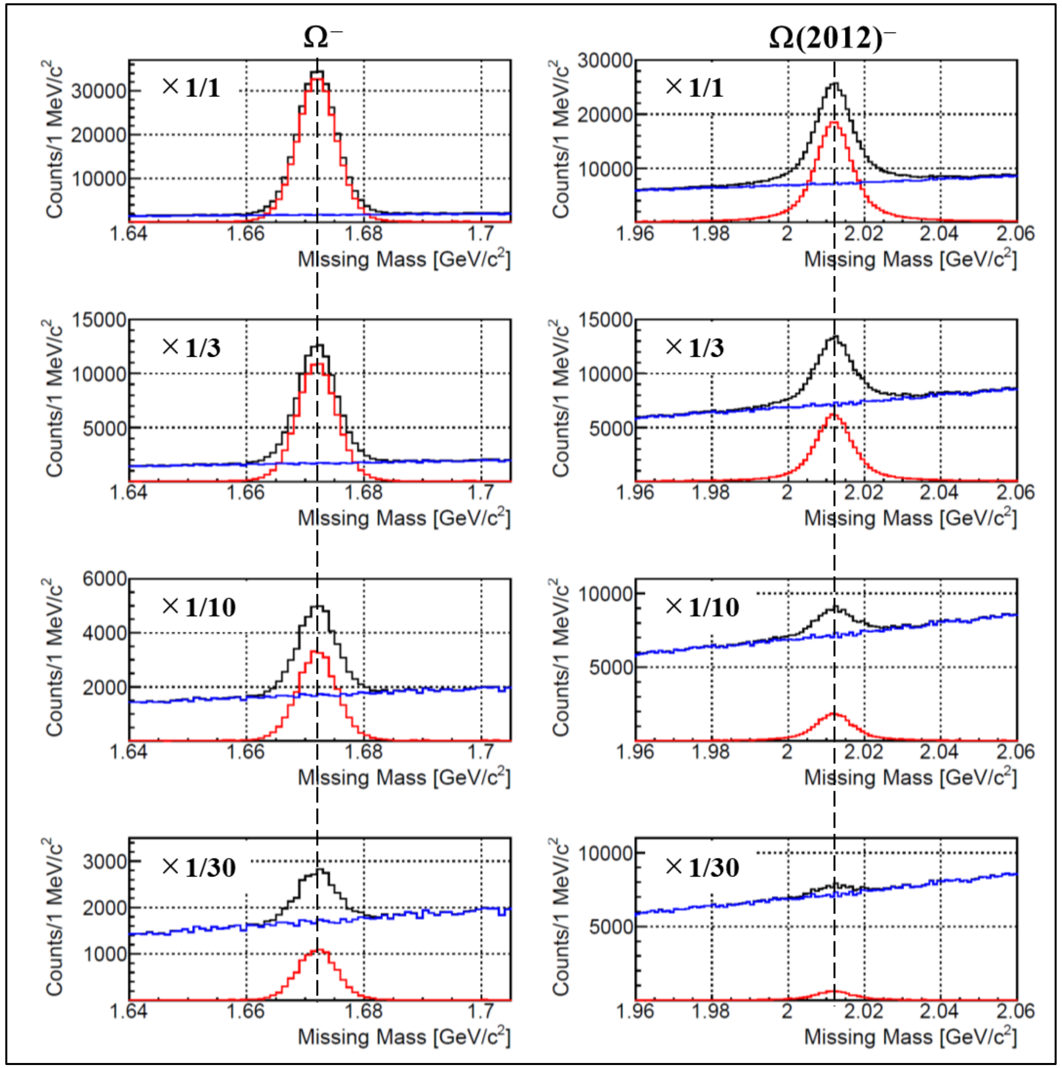
Momentum dependence data: 7–10 GeV/c

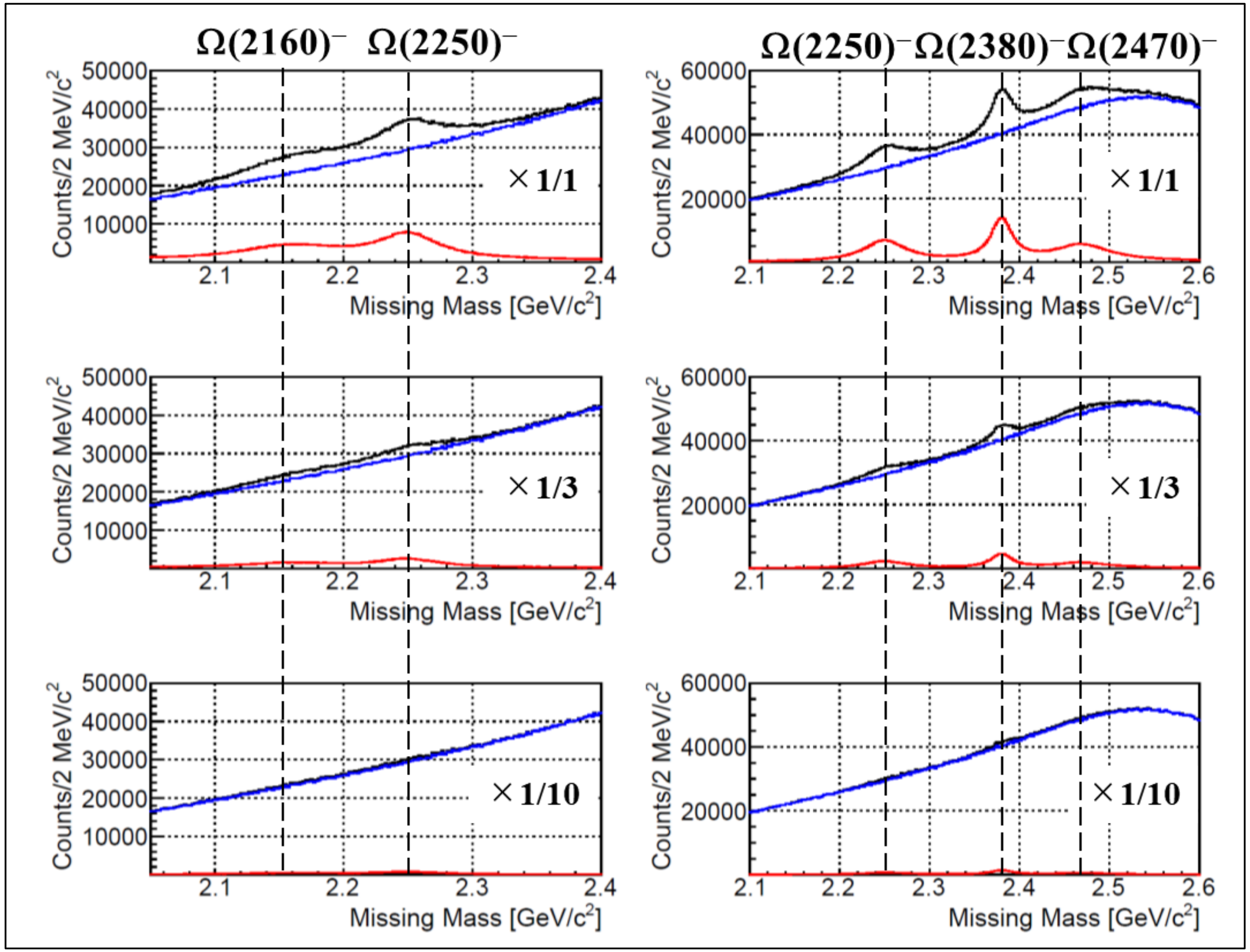


- Ω^{*-} states in PDG are generated.
- Roper-like state: $\Omega(2160)^-$, Γ = 100 MeV (assumed)
- Briet-Wigner type resonances

- Higher resonance search: Up to 1.5 GeV excitation energy by 10 GeV/c beam
- Determination of width (Different missing mass resolution condition)
- Identify fake structures coming from the kinematic effects

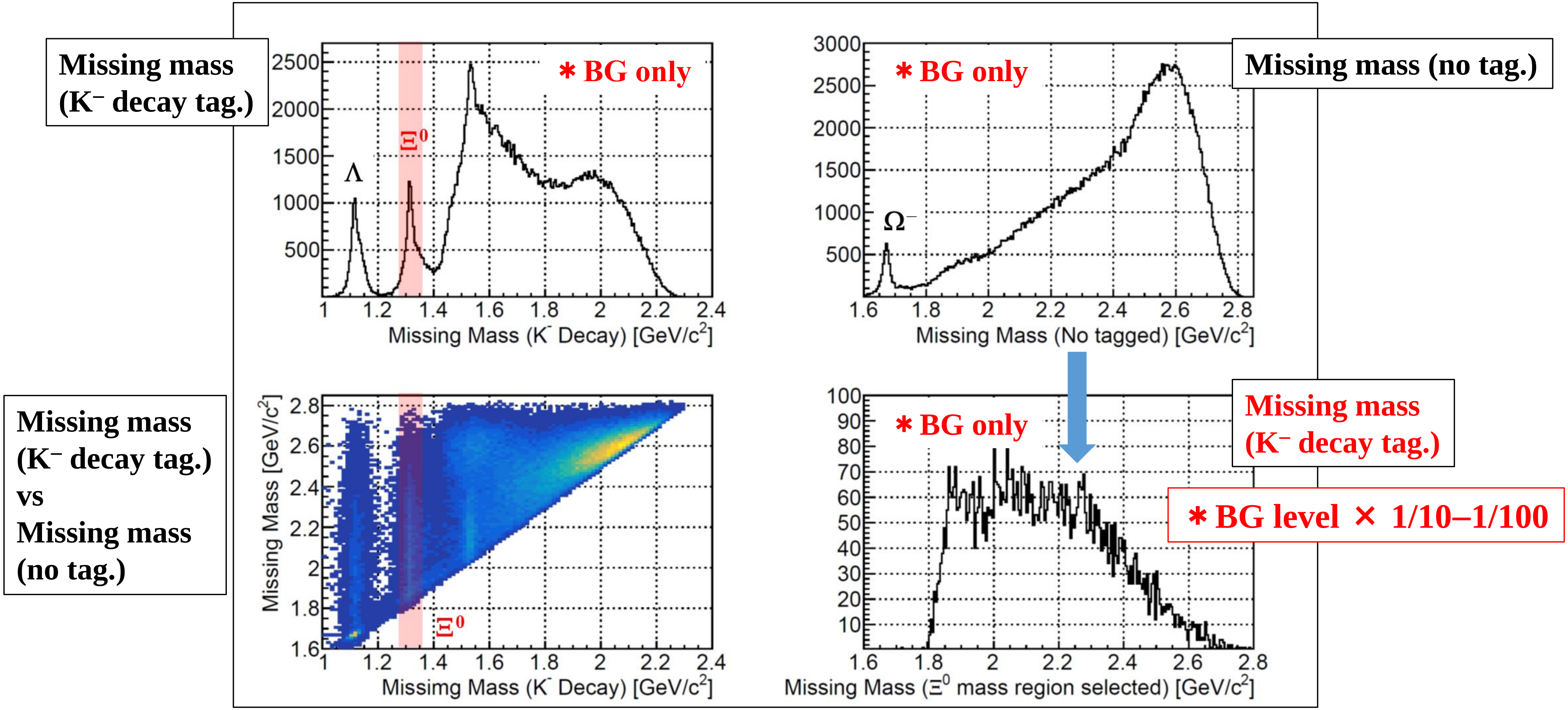
Missing mass spectrum (K^{*0} K^+ reaction) @ 8 GeV/c





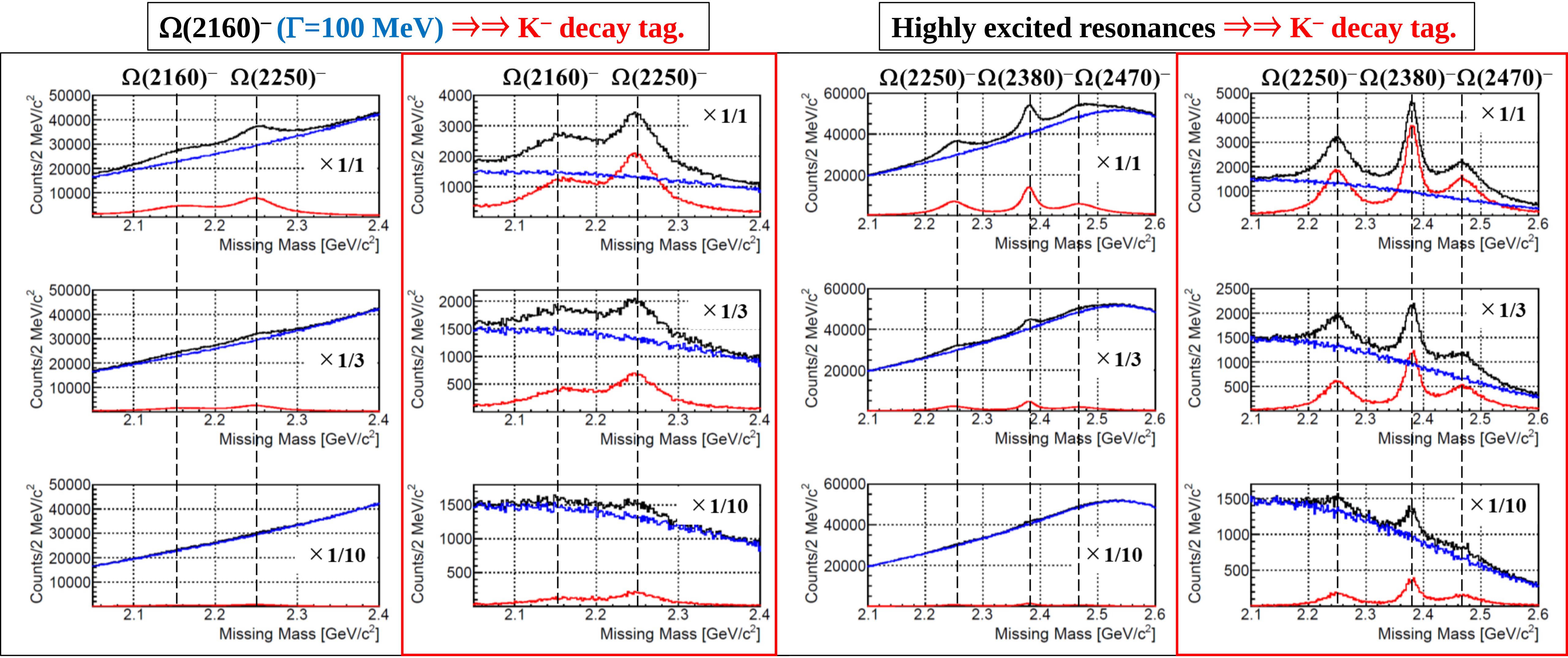
- **Smaller cross section cases**
  - **Searching for highly excited resonances with wide widths ⇒ Improvement of S/N**

Decay event selection: K^- decay detection ($\Omega^{*-} \rightarrow \Xi^0 + K^-$)



- **For searching resonance, decay event selection can be used. : 1.30 < M_Ξ < 1.33**
- **Signal ⇒ 0.25 (Branching ratio: ~0.3 × Acceptance: ~0.8)**

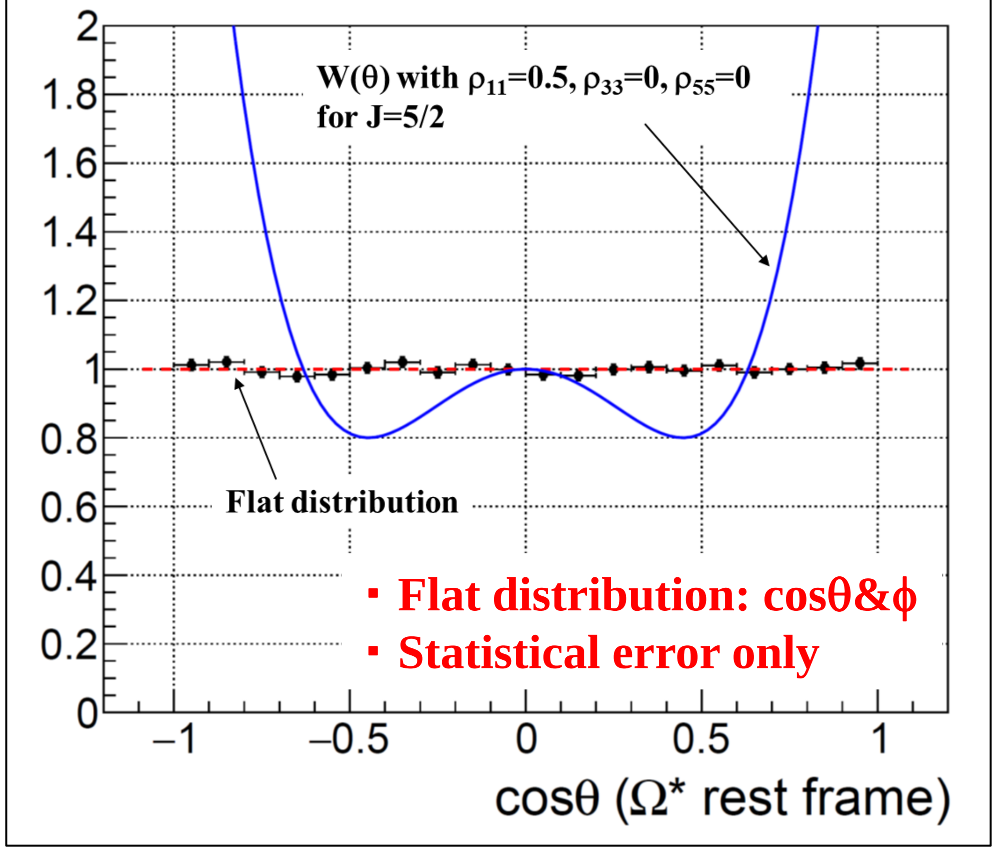
Missing mass spectrum (K^{*0} K^+ reaction) @ 8 GeV/c



- **Signal: ×0.25 ⇔ Background: ×1/40 ⇒ S/N×10**
- **Smooth background case: Sensitivity (5σ) ~1 nb for Γ = 100 MeV**

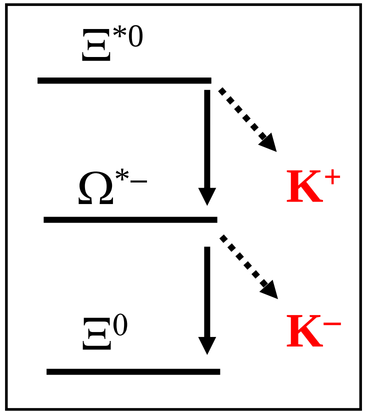
Decay angular analysis: Determination of J^P

Corrected angular distribution



*** Angular correlation: $\Xi^{*0} \rightarrow \Omega^{*-} K^+$, $\Omega^{*-} \rightarrow \Xi^0 K^-$**

- $K^- p \rightarrow \Xi^{*0} K^{*0} \rightarrow \Omega^{*-} K^+ K^{*0}$



1. $J^P = 3/2^\pm, 5/2^\pm$ cases
   ⇒ Angular distribution: J^P

2. $J^P = 1/2^\pm$ cases
   ⇒ Angular distribution: $J = 1/2$

3. Parity determination in J = 1/2 case
   - Ξ^0 polarization along polarization axis of Ω^{*-}
   - Angular distribution of $\Xi^0 \rightarrow \Lambda \pi^0$

4. (Parity from decay properties)

- # of signal = ~4,000 counts / 20 bin (B.R = 0.3): < 1% stat. error

⇒ To perform determination of spin and parity combined with other information

- Model independent analysis can be performed by combining Ξ^* data.

Ω baryon spectroscopy at K10

＊Systematic measurements: Properties of excited states

- Mass, Width, spin-parity, decay branching ratio
- Production rate ⇔ Ground state vs Excited states

1. **$\Omega(2012)^-$ ($3/2^-$?, Molecular state ?)**
   - Determination of J^P by decay angular distribution
   - Search for LS partner($1/2^-$) (Mass, Γ, J^P and B.R.)
   - Absolute decay branching ratio: $K^- + \Xi$, $K^- + \Xi^*$, $K^- + \Xi + \pi$ modes

2. **Roper-like resonance: $\Omega(2160)^-$?**
   - Mass & Width
   - Determination of J^P by decay angular distribution
   - Absolute decay branching ratio: $K^- + \Xi$, $K^- + \Xi^*$, $K^- + \Xi + \pi$ modes

3. **Searching for resonances (Γ < 100 MeV)**
   - Mass & Width
   - Determination of J^P by decay angular distribution
   - Absolute decay branching ratio (all measurable modes)
   - Search for LS partners (Mass, Γ, J^P and B.R.)

Summary

- **How quarks build hadrons ?**

⇒ Dynamics of non-trivial QCD vacuum in baryon structure
  - **Their dynamics has yet to be understood, keeping a link to QCD.**
  - ***s*- and *c*-baryon spectroscopy: Disentangle quark correlation and spin-dependent forces**

- **Ω (sss) baryon: Single flavor system**
  - **Only 3 strange quark system: Simple structure of excites states**
  - **Pion cloud less system: Clear extraction of information of quark interactions**

⇒ Investigations of "quark core" region of baryon
  - **Spin-dependent forces and quark motions**

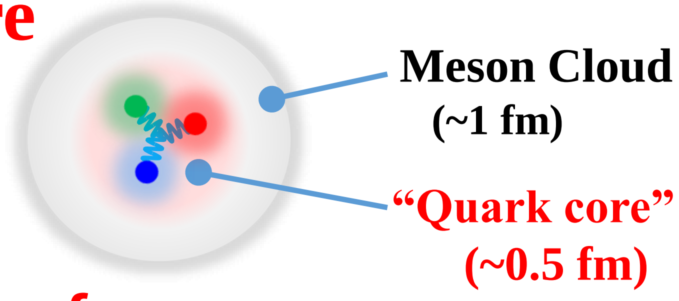
- **Ω baryon spectroscopy**
  - **K10 beam line and large acceptance spectrometer**
  - **Missing mass (production) + decay measurement (J^P)**
    - **$K^- + p \rightarrow \Omega^{*-} + K^{*0} + K^+$ reaction is essential.**
  - **Large acceptance(~50%) and high mass resolution(< 5 MeV)**
  - **Expected mass spectrum: High S/N ratio**
  - **J^P can be determined from decay measurements.**

Backup slides

How quarks build hadrons?

Dynamics of non-trivial QCD vacuum in baryon structure

※Chiral condensate $\langle \bar{q}q \rangle \neq 0$ ($U_A(1)$ anomaly)
⇒ Constituent q and NG boson (effective DoF).

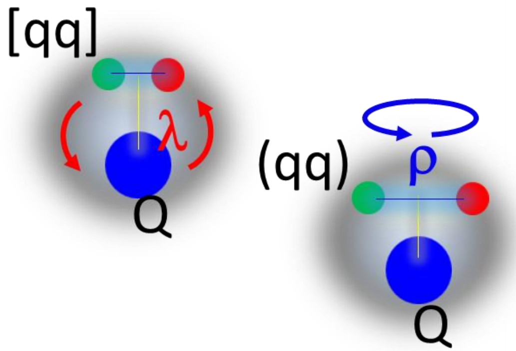


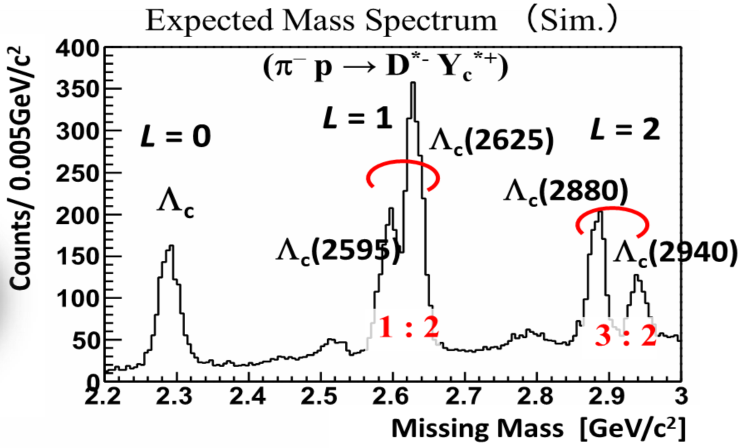
s- and c-baryon spectroscopy: q correlation and spin-dep. force

- Charmed Baryon (High-p)

Disentangle the diquark correlation
→ λ/ρ mode assignment
→ $U_A(1)$ anomaly: $[qq](0^+) \leftrightarrow (qq)(0^-)$

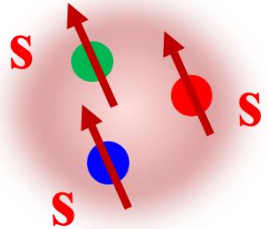
III: Instanton Induced Interaction

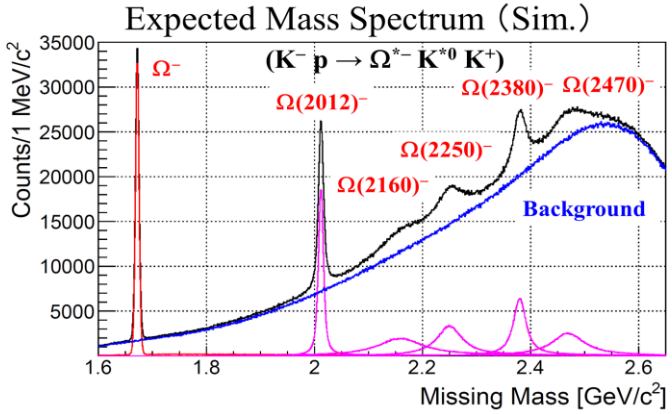


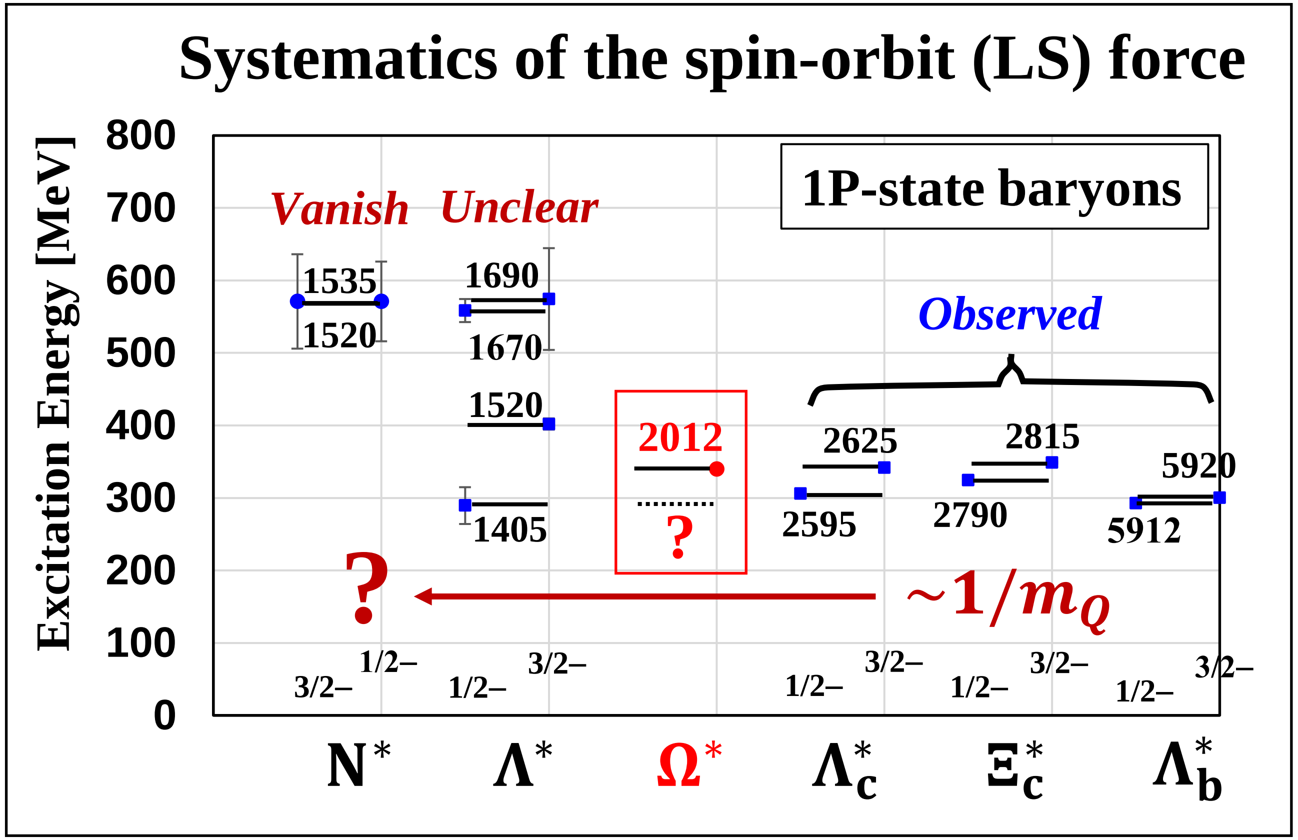


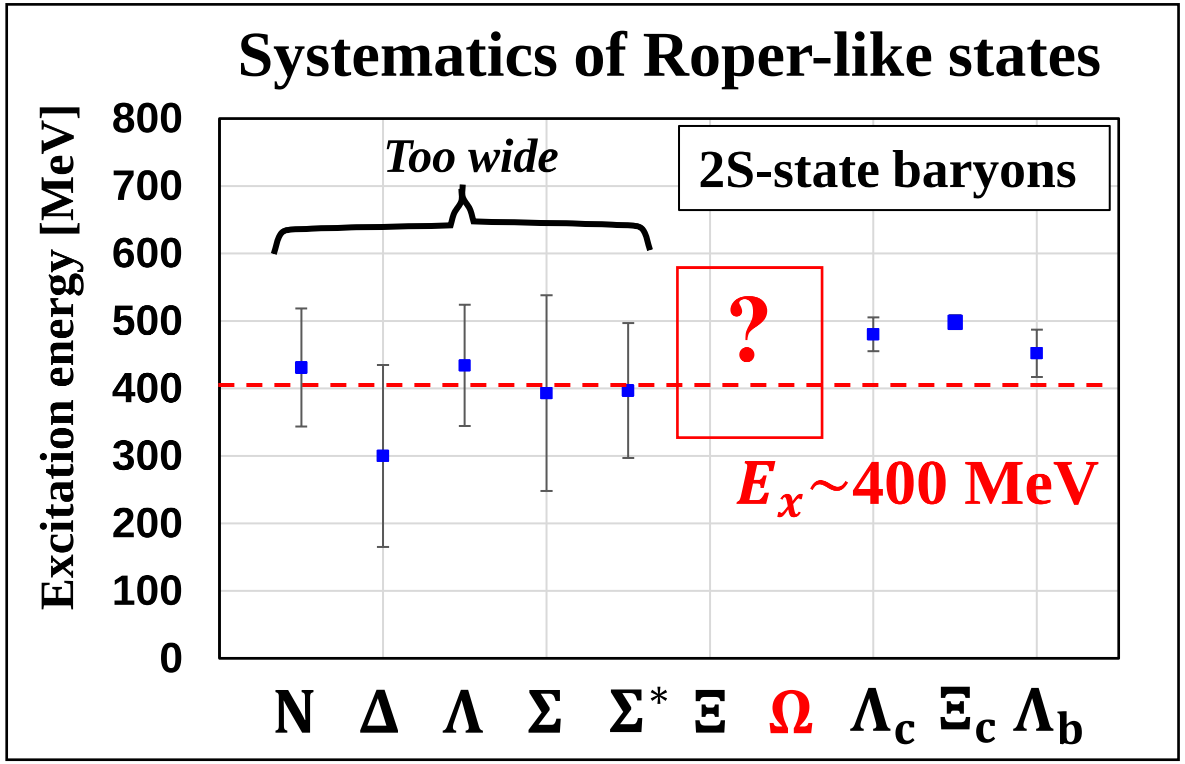
- Ω^* (*sss*) Baryon (K10)

Single-flavored (Flavor-symmetric) system
Free from pion cloud
→Spin-orbit Force (One Gluon Exchange)
→Roper-like (2S, 3/2+) states("quark core" size)





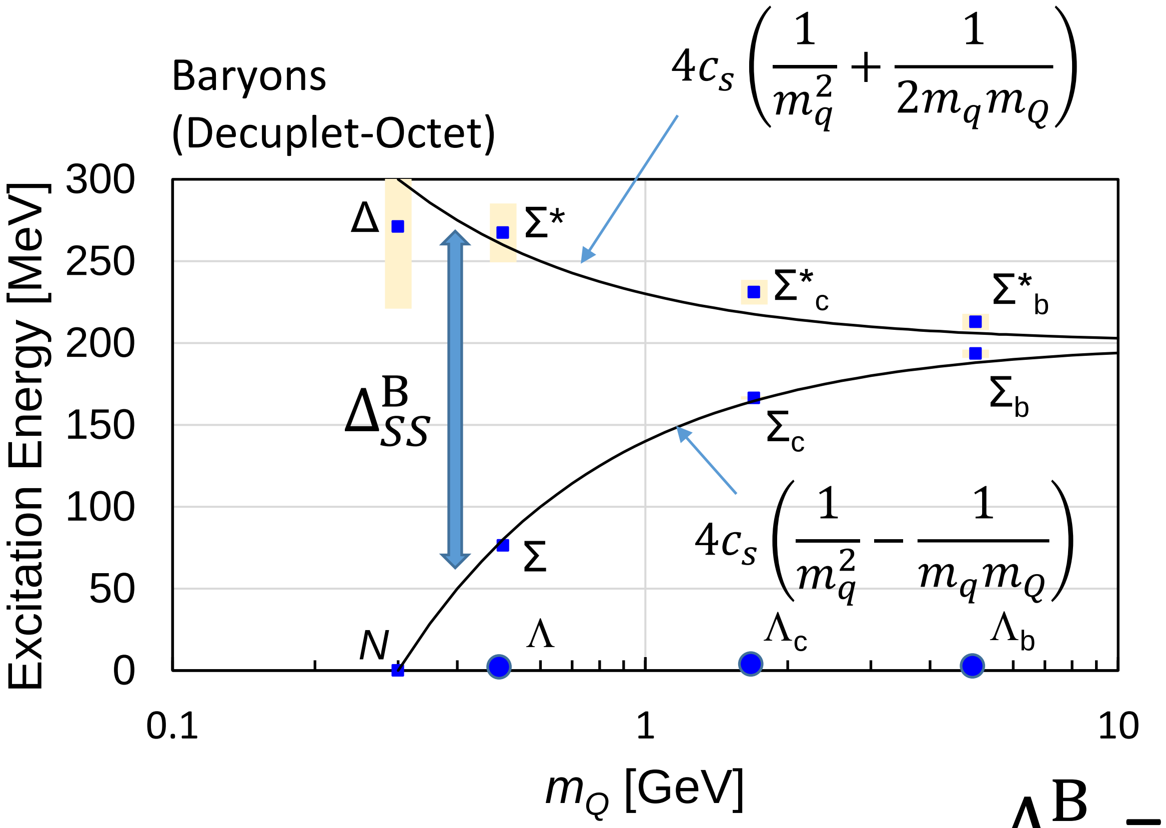

Systematics of the spin-orbit (LS) force
Excitation Energy [MeV]
800
700
600
500
400
300
200
100
0
1P-state baryons
Vanish
Unclear
1535
1520
1690
1670
1520
1405
2012
?
Observed
2625
2595
2815
2790
5920
5912
?
~1/m_Q
3/2–
1/2–
1/2–
3/2–
1/2–
3/2–
1/2–
3/2–
1/2–
3/2–
N*
Λ*
Ω*
Λc*
Ξc*
Λb*

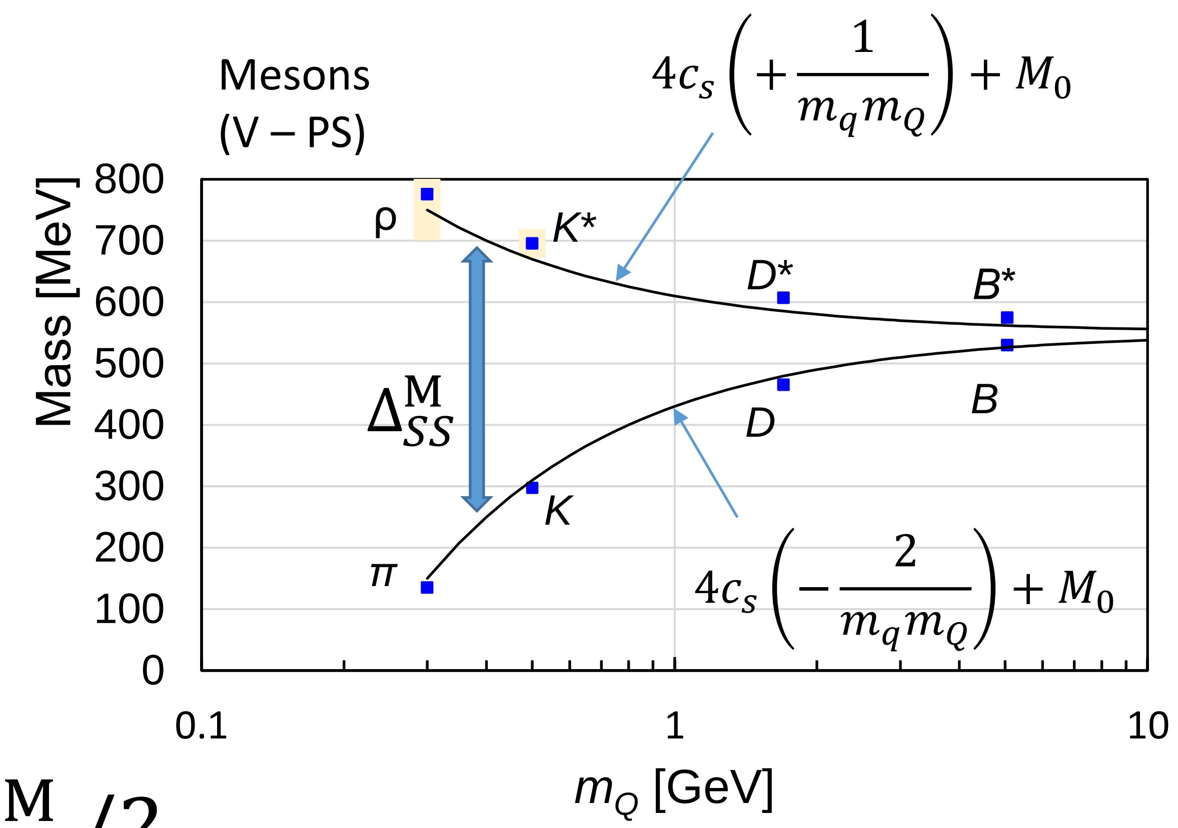

Systematics of Roper-like states
Excitation energy [MeV]
800
700
600
500
400
300
200
100
0
Too wide
2S-state baryons
?
Ex~400 MeV
N
Δ
Λ
Σ
Σ*
Ξ
Ω
Λc
Ξc
Λb

Systematic behavior of Spin-Spin(*SS*) Int.

$$V^{SS} = \sum_{i<j} \alpha_S^{SS} \frac{16\pi}{9m_i m_j} \delta(r_{ij}) \vec{s_i} \cdot \vec{s_j}$$

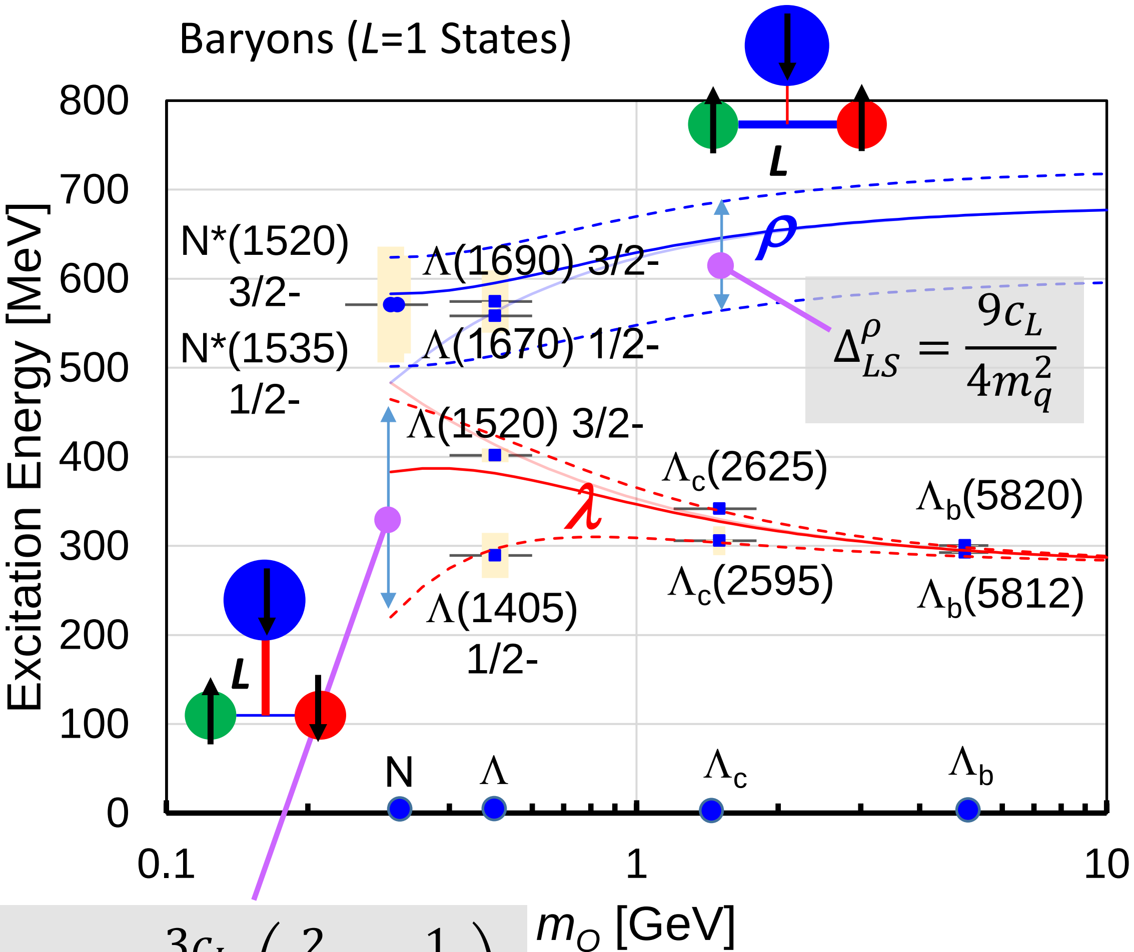
- ***SS* int. seems well described by CQM (OGE).**





$$\Delta_{SS}^{B}=\Delta_{SS}^{M}/2$$

Systematic behavior of Spin-Orbit(*LS*) Int.



$$\Delta_{LS}^{\rho} = \frac{9c_L}{4m_q^2}$$

$$\Delta_{LS}^{\lambda} = \frac{3c_L}{2m_Q}\left(\frac{2}{m_q} + \frac{1}{m_Q}\right)$$

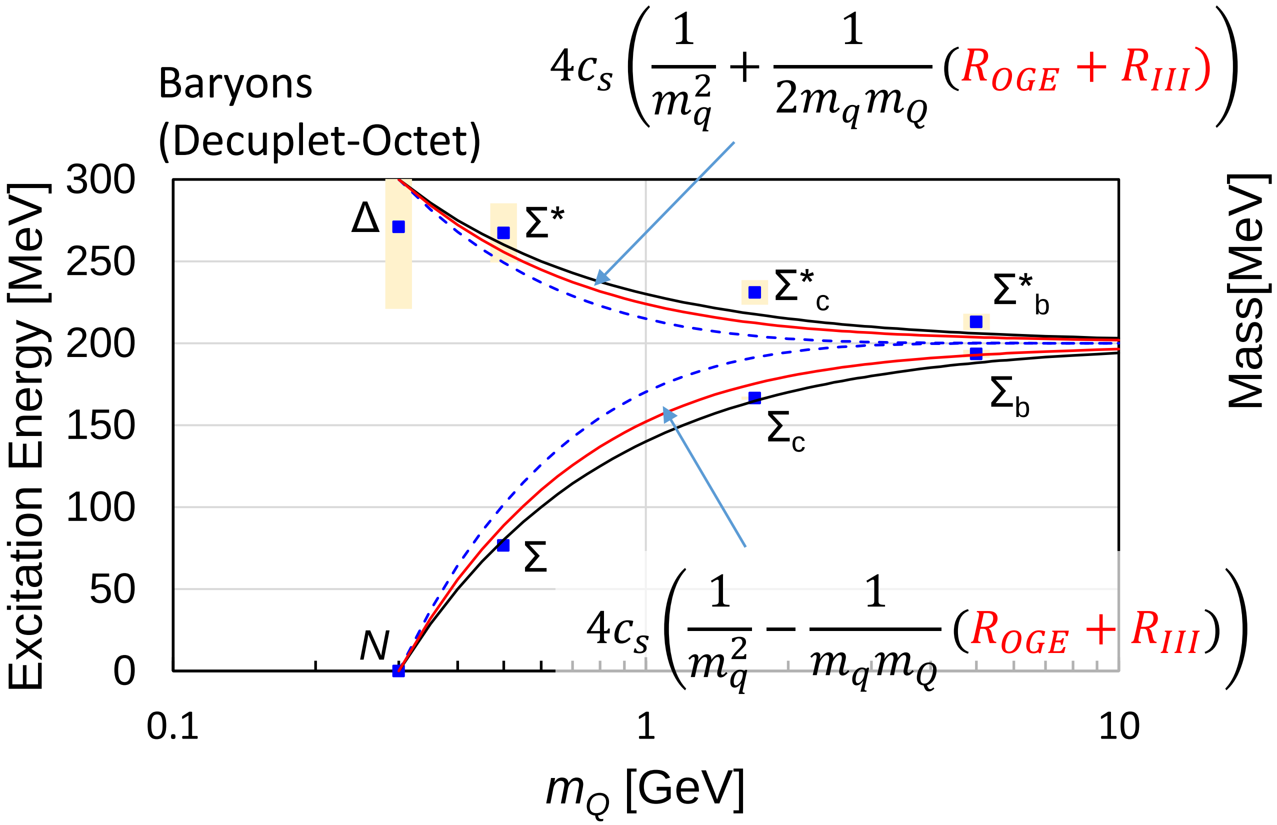
- ***LS* splitting vanishes in light baryons.**
  - **CQM, which suggests Δ_{LS}^{ρ}~100 MeV, does not reproduce the *LS* splitting.**
- **Cancellation mechanism exists?**
  - **Instanton Induced Interaction (III)**

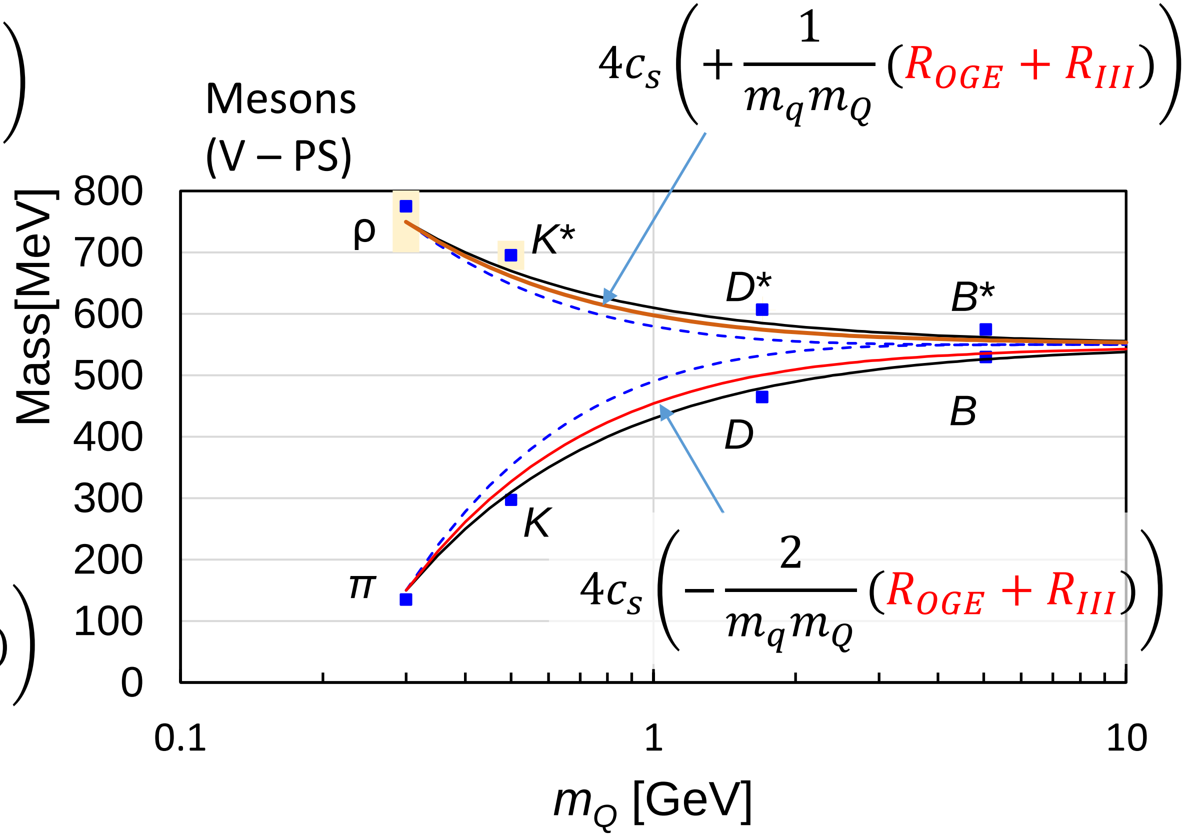
Systematic behavior of Spin-Spin(SS) Int.

$$R_{OGE} + R_{III} \sim 0.6 + 0.4\exp\left(-\frac{m_Q - m_q}{\Lambda_\chi}\right)$$

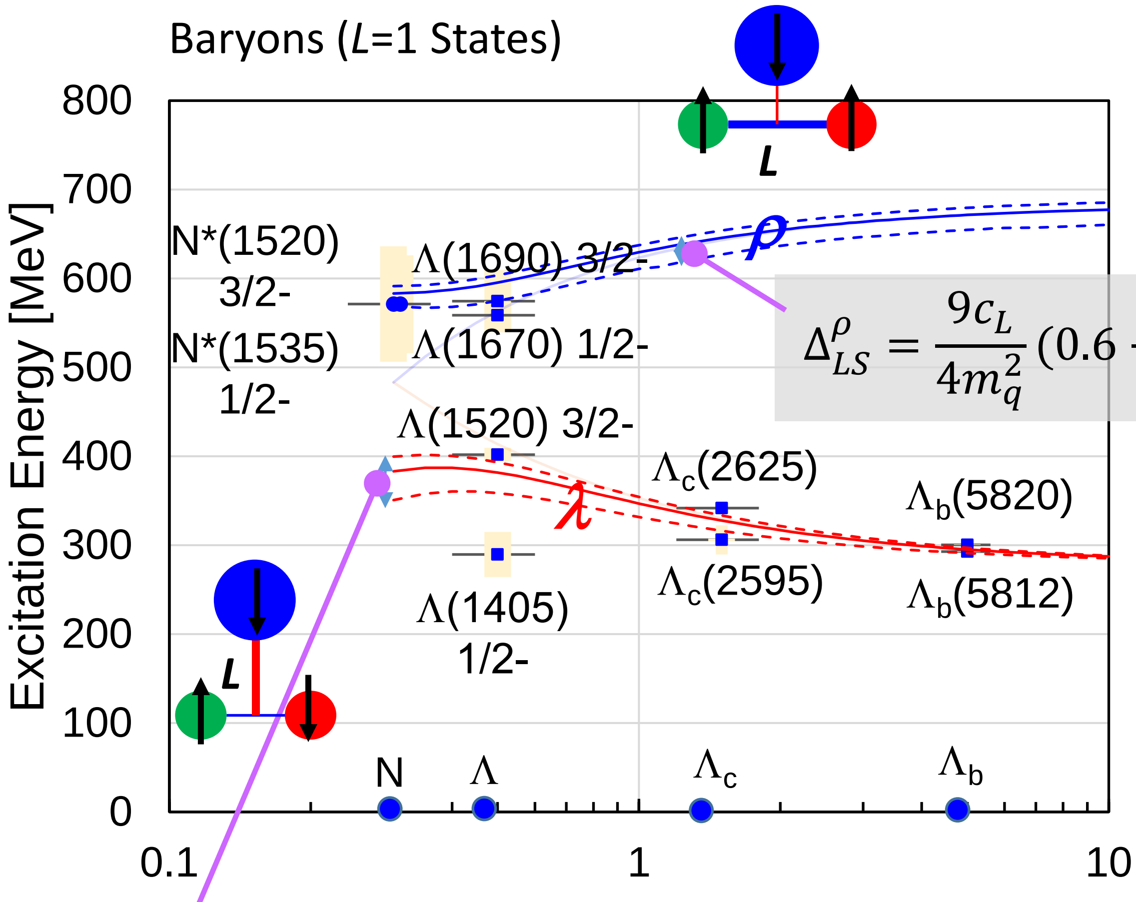
Constructive for SS

- **Very Naive demo.: OGE + III seems work well.**
  - **III is comparable to OGE to explain $\eta - \eta'$ mass diff.**
  - **III works only in flavor-antisymmetric system in light quarks (u,d,s).**





Systematic behavior of Spin-Orbit(*LS*) Int.



$$\Delta_{LS}^{\rho} = \frac{9c_L}{4m_q^2}(0.6-0.4)$$

$$\Delta_{LS}^{\lambda} = \frac{3c_L}{2m_Q}\left(\frac{2}{m_q}+\frac{1}{m_Q}\right)\left[0.6-0.4\exp\left(-\frac{m_Q-m_q}{\Lambda_\chi}\right)\right]$$

- ***LS* splitting vanishes in light baryons.**
  - **CQM, which suggests Δ_{LS}^{ρ}~100 MeV, does not reproduce the *LS* splitting.**
- **Cancellation mechanism exists?**
  - **Instanton Induced Interaction (III)**

$$V^{LS} \sim (R_{OGE} - R_{III})\Delta$$

Destructive for *LS*

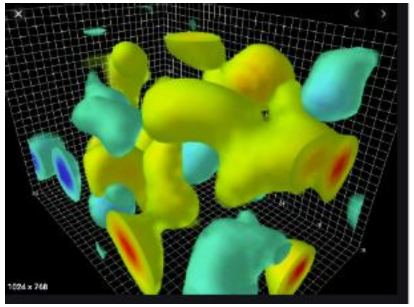
- *LS* splitting in heavier systems are to be investigated with identifying if they are λ/ρ-mode excitations

How quarks build hadrons?

Dynamics of non-trivial QCD vacuum in baryon structure

※Chiral condensate $\langle \bar{q}q \rangle \neq 0$ ($U_A(1)$ anomaly)
⇒ Constituent q and NG boson (effective DoF).

- **Dynamics of Effective Degrees of Freedom**



Non-trivial gluon filed (Instantons), LQCD demo. by D. Leinweber

$$H = K + V^{Conf} + V^{Coul} + V^{SS} + V^{LS} + V^{T}$$

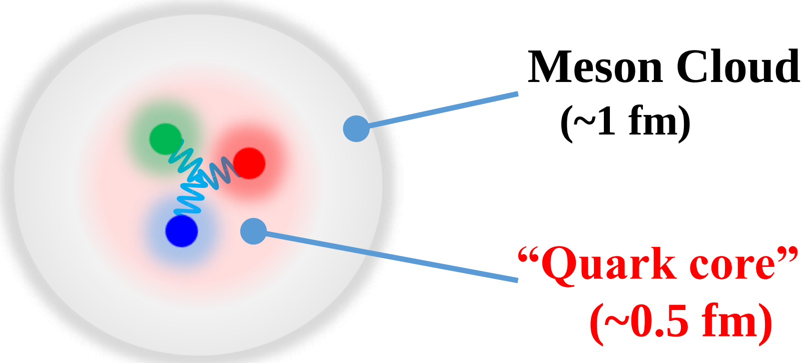
$$K + V^{Conf} = \sum_i \left(m_i + \frac{p_i^2}{2m_i}\right) + \sum_{i<j} b r_{ij} + C$$

Short-range qq int.

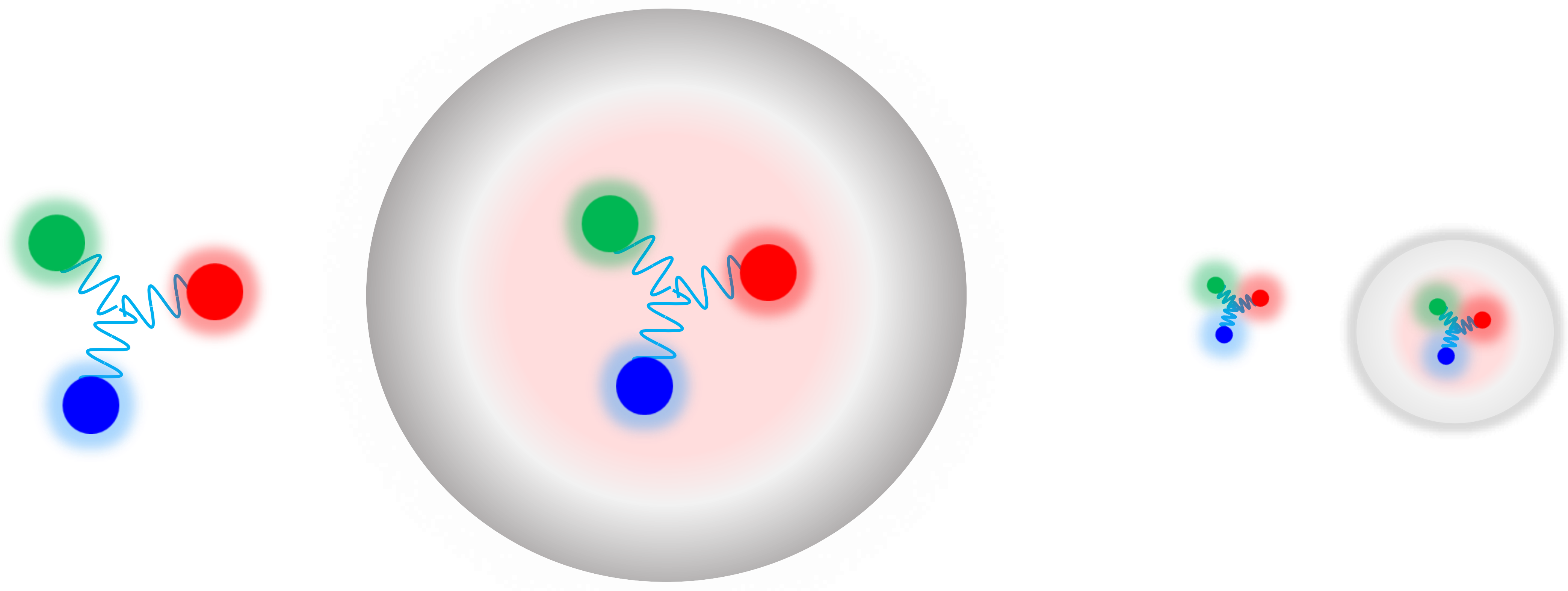
$$V^{Coul} = \sum_{i<j} -\alpha_S^{Coul} \frac{2}{3r_{ij}}$$

$$V^{SS} = \sum_{i<j} \alpha_S^{SS} \frac{16\pi}{9m_i m_j} \delta(r_{ij}) \vec{s_i} \cdot \vec{s_j}$$

$$V^{LS} = \sum_{i<j} \frac{\alpha_S^{LS}}{3r_{ij}^3} \left\{ \left[\left(\frac{1}{m_i^2} + \frac{1}{m_j^2} + \frac{4}{m_i m_j} \right) \overrightarrow{L_{ij}} \cdot (\vec{s_i} + \vec{s_j}) \right] + \left(\frac{1}{m_i^2} - \frac{1}{m_j^2} \right) \overrightarrow{L_{ij}} \cdot (\vec{s_i} - \vec{s_j}) \right\}$$



Role of Ω baryon: Simple system



- Ω baryon: "3 strange quark simple system" ⇒ Free from Pion cloud

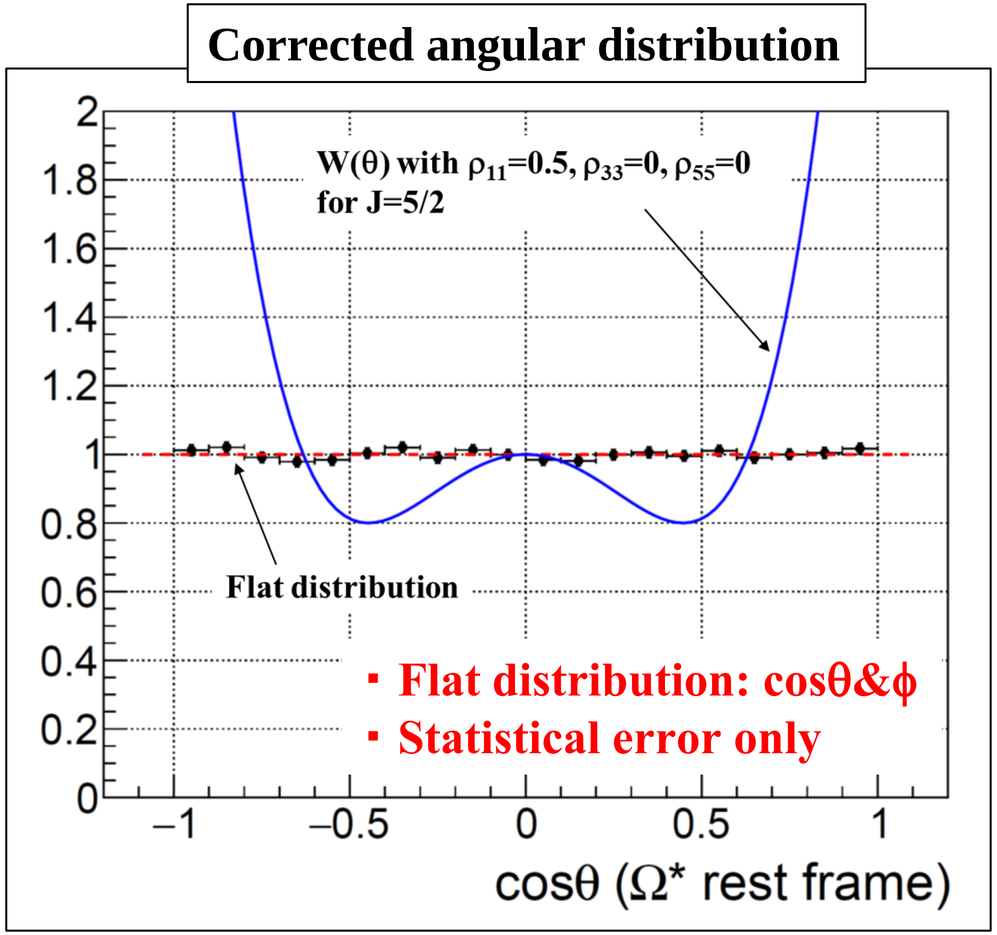
＊Direct access to "Quark core" region.

⇒ Clear extraction of interactions from studies of excited states

- Origin of spin-dependent interaction

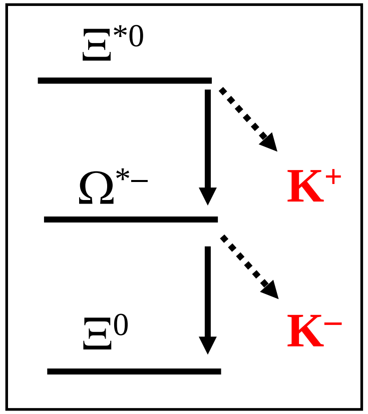
⇒ Systematic measurement of baryon systems

Decay angular analysis: Determination of J^P



✱ Angular correlation: $\Xi^{*0} \rightarrow \Omega^{*-} K^+$, $\Omega^{*-} \rightarrow \Xi^0 K^-$

- $K^- p \rightarrow \Xi^{*0} K^{*0} \rightarrow \Omega^{*-} K^+ K^{*0}$



1. Analysis of J^P of initial Ξ^{*0}

- $\Xi^{*0}(J^P?) \rightarrow \Omega^-(3/2^+) K^+ \rightarrow \Xi^0(1/2^+) K^-$

2. Analysis of angular correlation

- $\Xi^{*0}(J^P) \rightarrow \Omega^{*-} (J^P?) K^+ \rightarrow \Xi^0(1/2^+) K^-$

⇒ Not flat distribution ⇒ $J^P = 3/2^\pm, 5/2^\pm$

⇒ Flat distribution ⇒ J = 1/2

3. Parity determination of J = 1/2 case

- Ξ^0 polarization along polarization axis of Ω^{*-}
- Angular distribution of $\Xi^0 \rightarrow \Lambda \pi^0$

⇒ Flat (s-wave): Parity = +

⇒ Asymmetry (p-wave): Parity = –

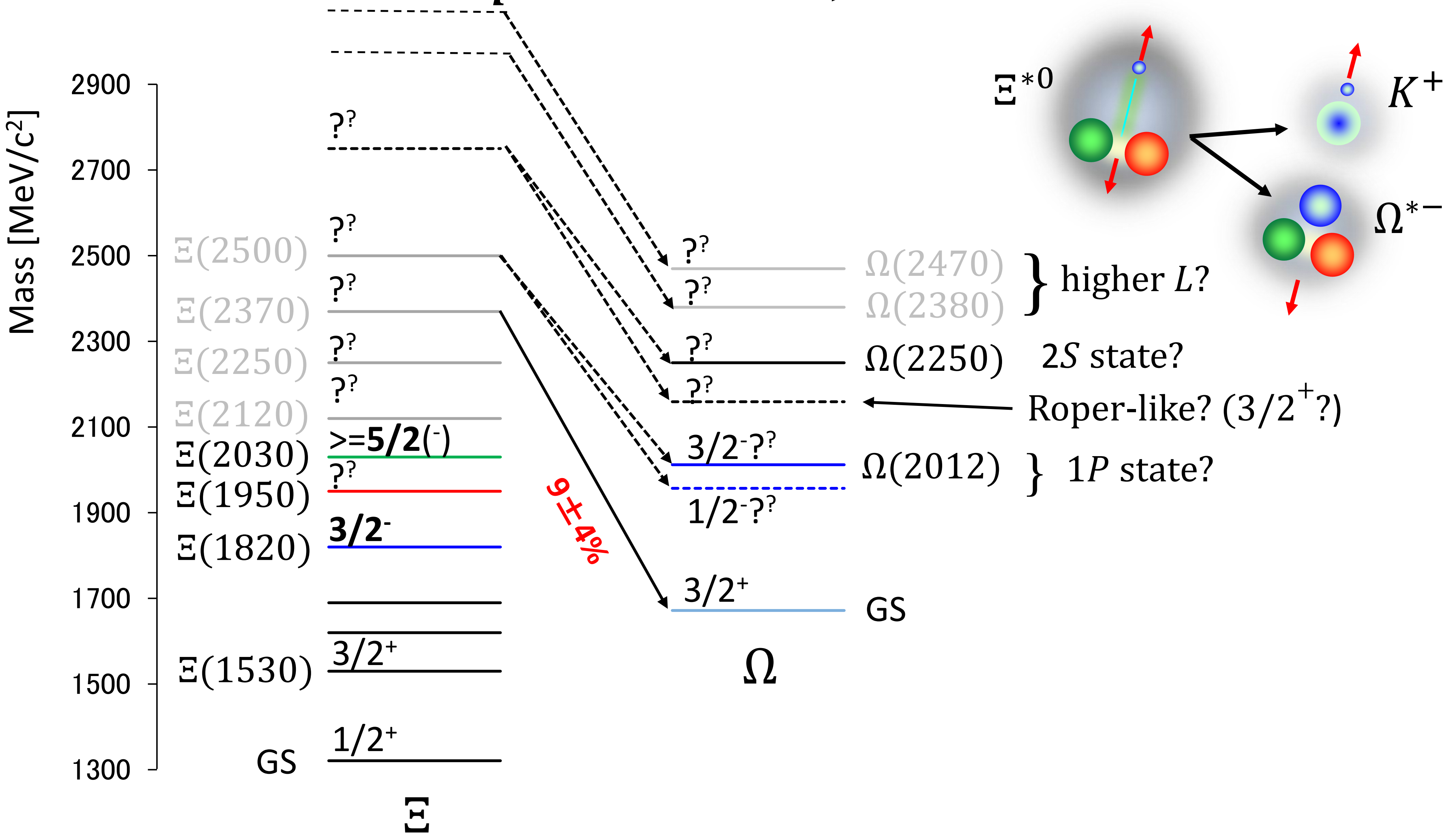
- (Parity from decay properties)

- # of signal = ~4,000 counts / 20 bin (B.R = 0.3): < 1% stat. error

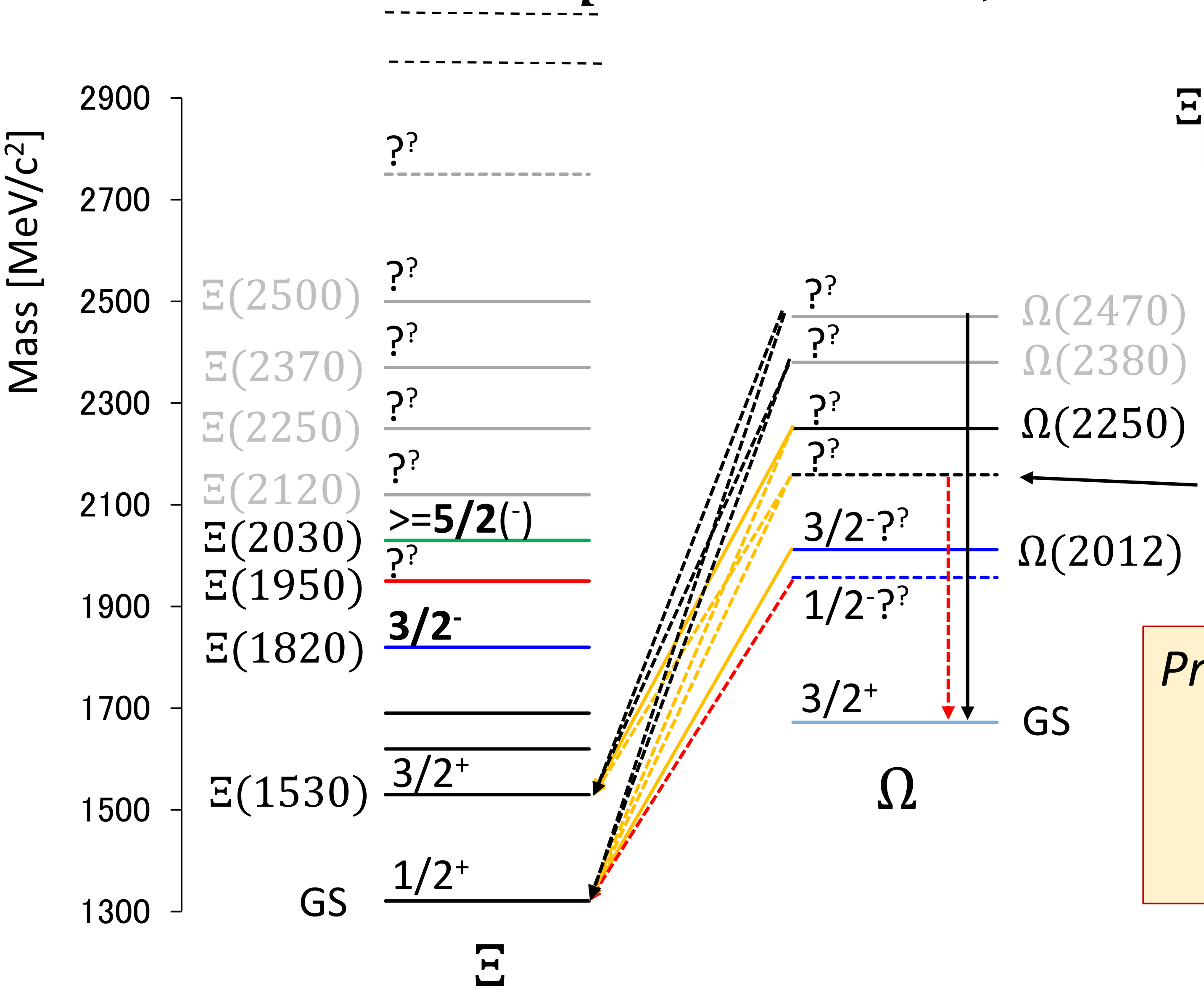
⇒ To perform determination of spin and parity combined with other information

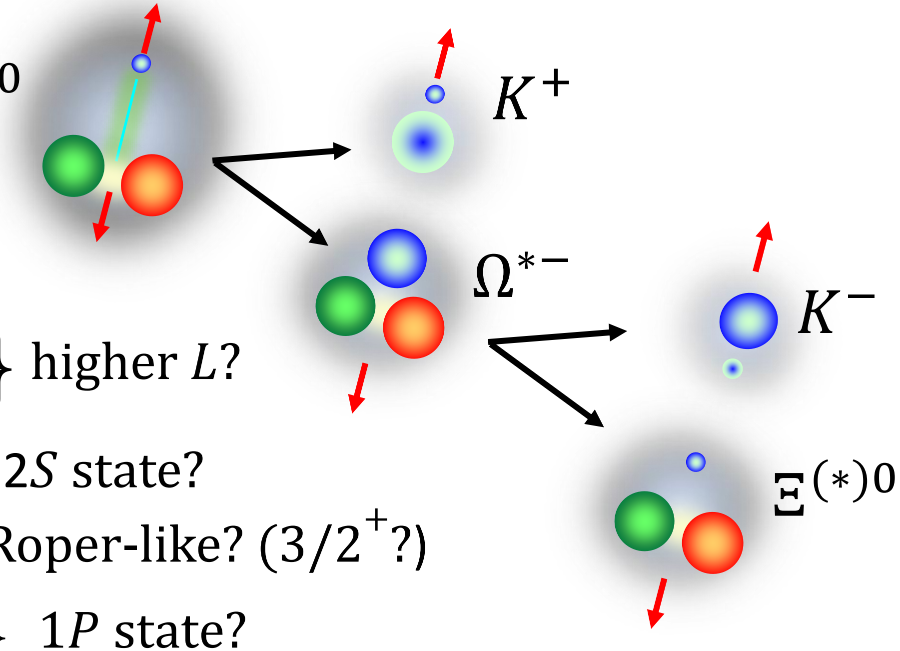
- Model independent analysis can be performed by combining Ξ^* data.

$$K^- p \to K^{*0}\Xi^{*0},\ \Xi^{*0} \to \Omega^{*-}K^+$$



$K^- p \to K^{*0}\Xi^{*0},\ \Xi^{*0} \to \Omega^{*-}K^+$





*Properties of Ω**

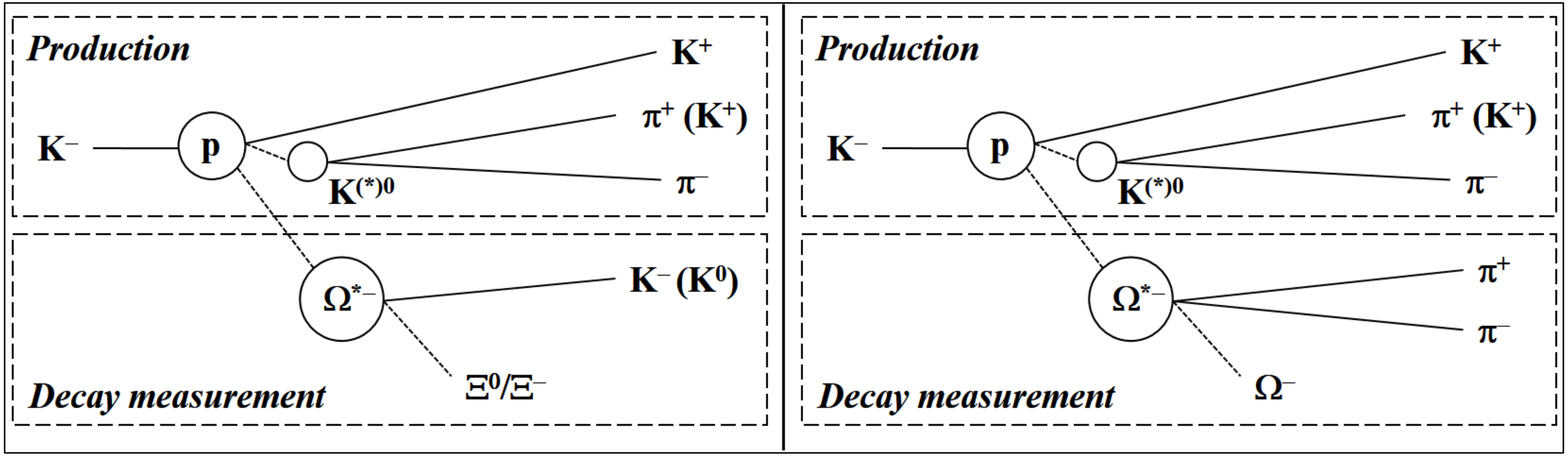
Decay Ang. Corr. → J^P (J>1/2)

Polarization → Parity (J=1/2)

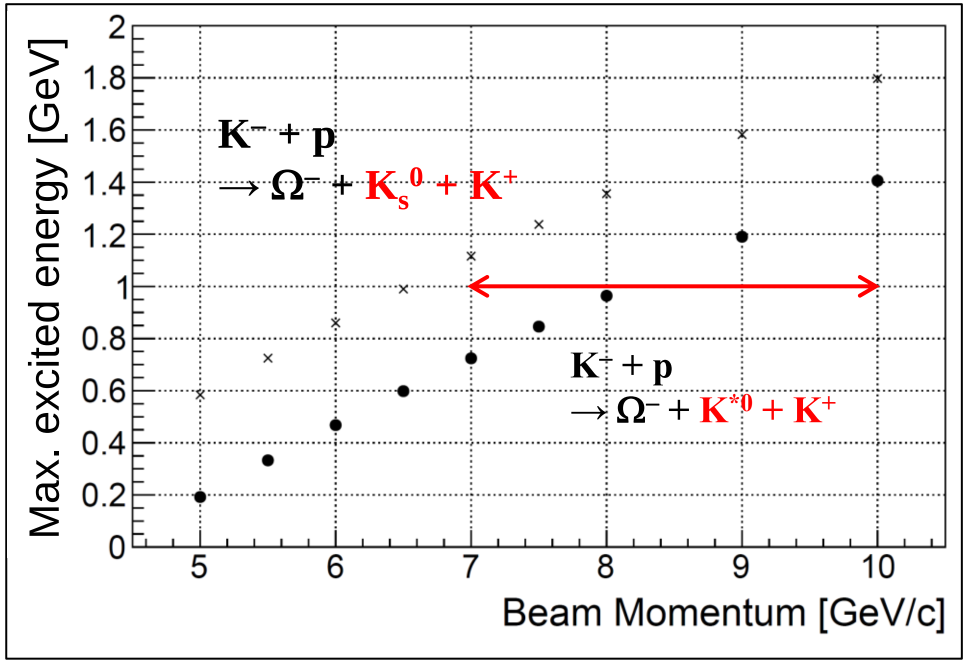
Decay Branch (width) → w.f.

Properties of Initial $\Xi^*(J^P)$
to be determined as well

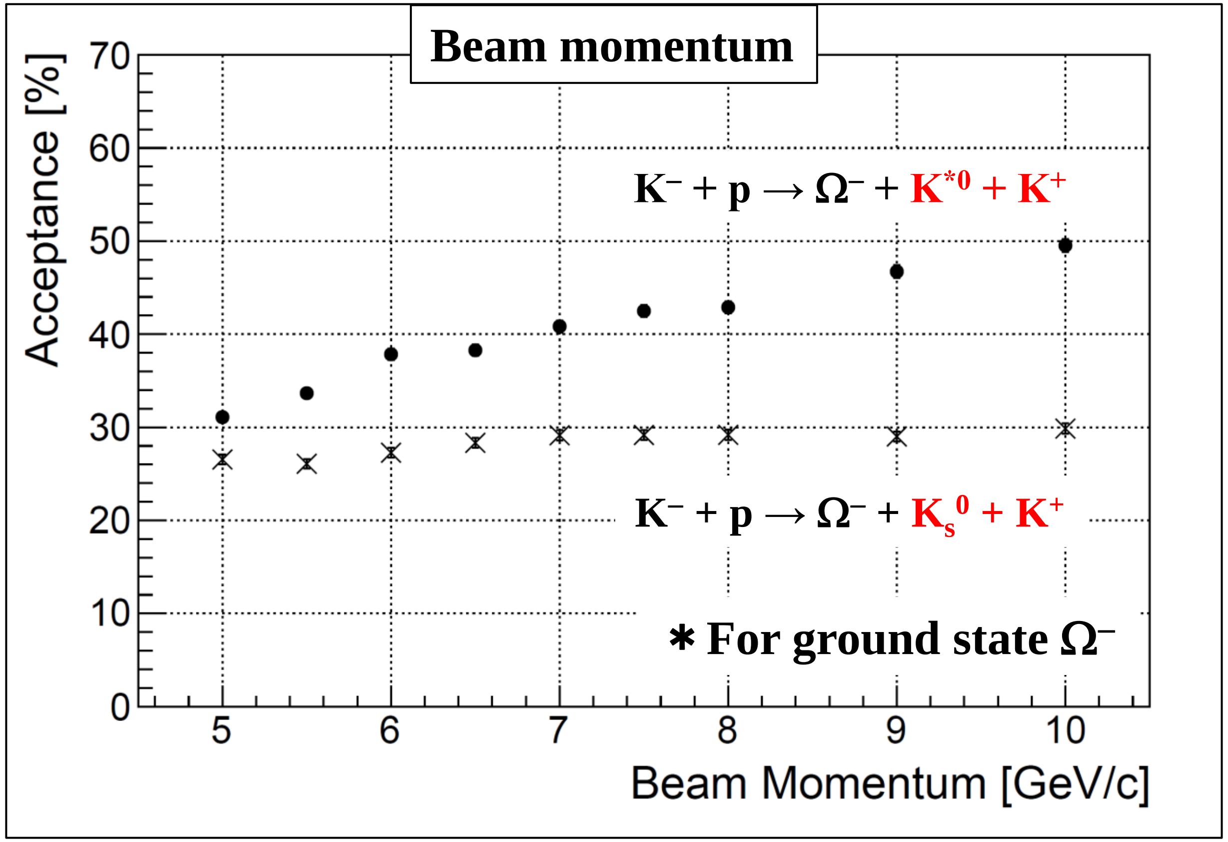
Simulation conditions: Ω baryon spectroscopy

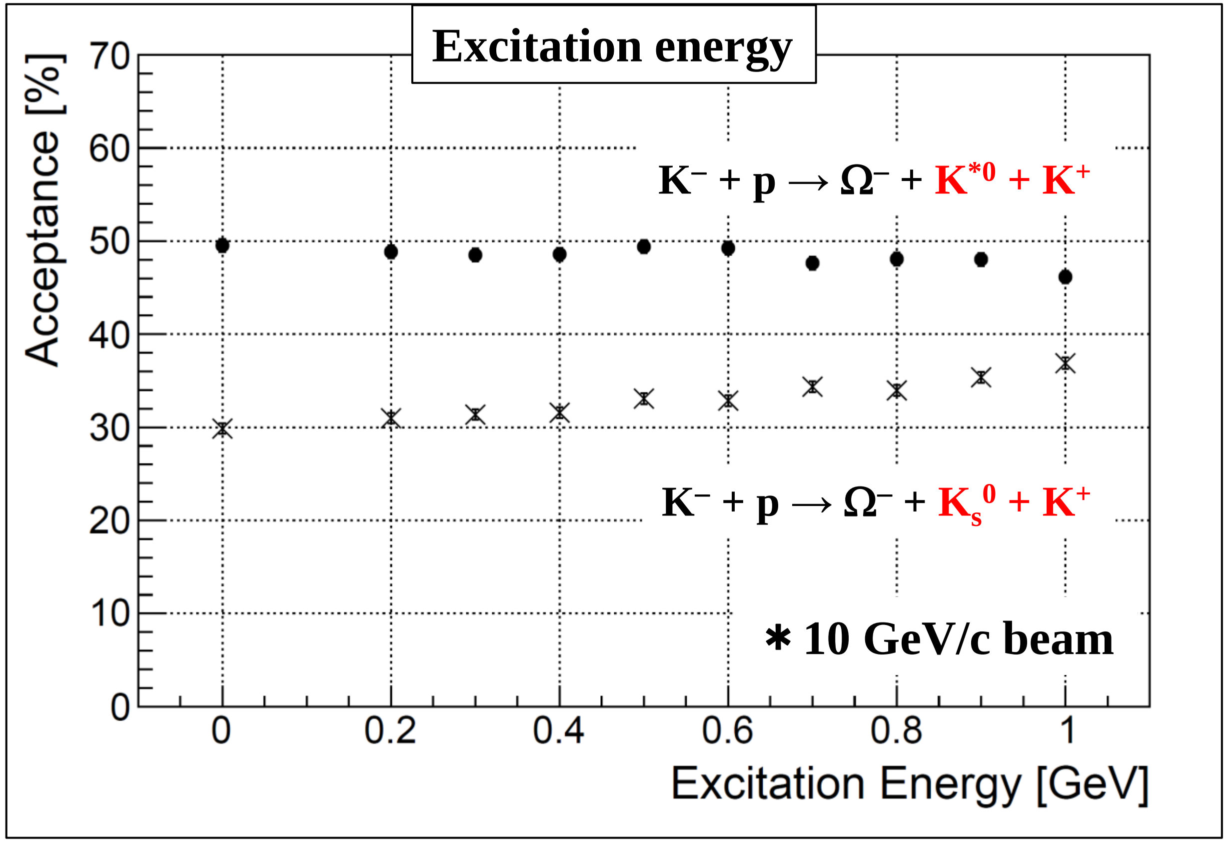


- **Reaction: $K^- + p \rightarrow \Omega^{*-} + K^{*0}(K_s^0) + K^+$**
  - **Isotropic angular distribution in CM**
    - **Production: 3-body phase space**
    - **K^{*0} (K_s^0) decay: 2-body uniform distribution**
  - **Beam: 7.0, 8.0, 9.0, 10.0 GeV/c ($\sqrt{s}$ = 3.8–4.5 GeV)**
- **Reconstruction: Invariant and missing mass**
  - **$K^+(\pi^+)$ and $\pi^- \Rightarrow K^{*0}(K_s^0)$ invariant mass**
  - **$K^{*0}(K_s^0)$ and $K^+ \Rightarrow \Omega^-$ missing mass**



Acceptance: Missing mass measurement

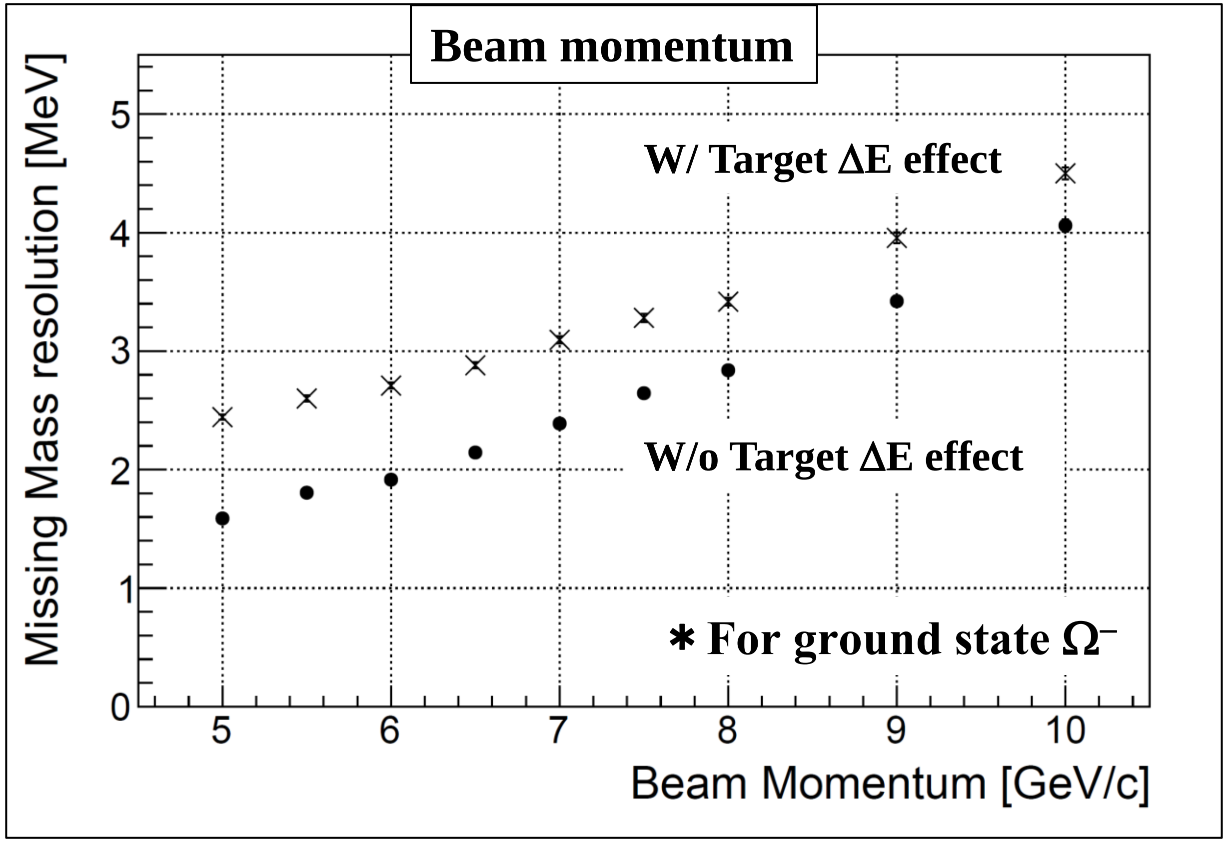


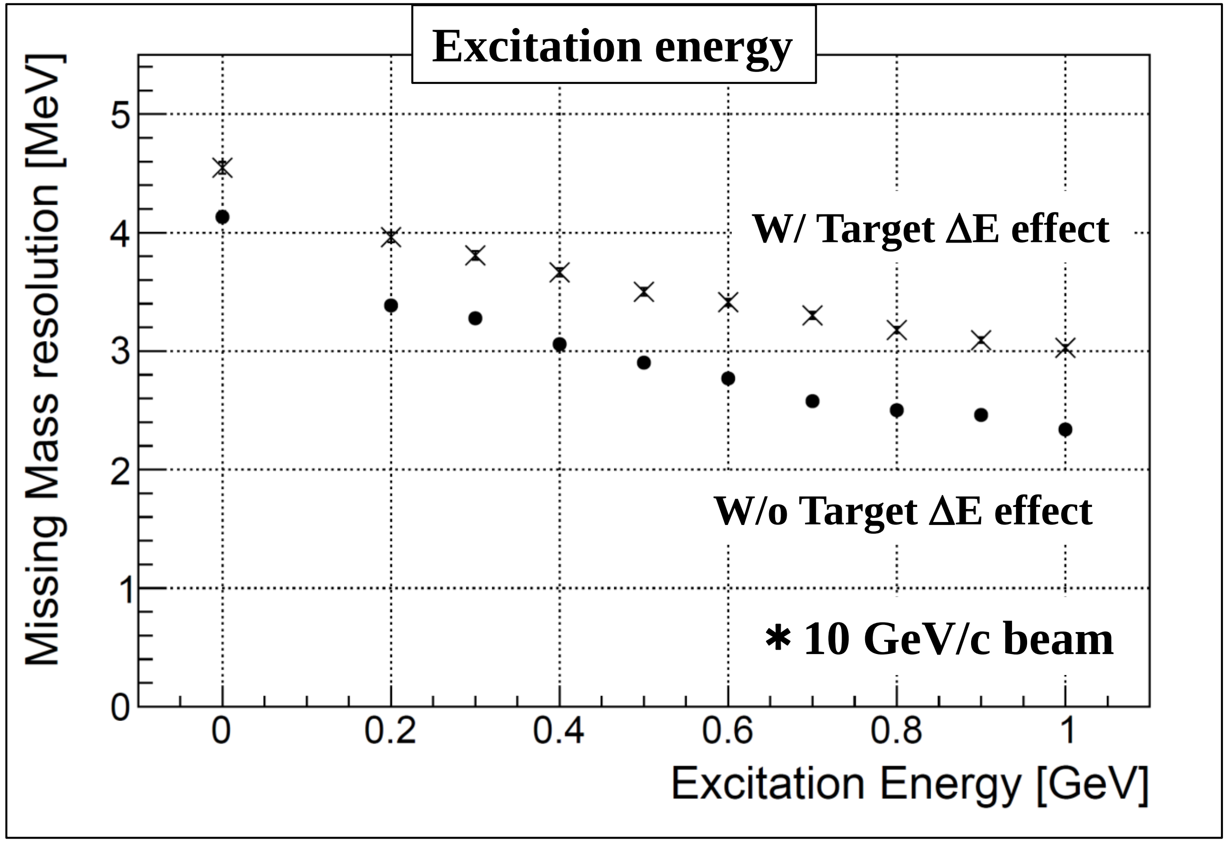


- **Acceptance (isotropic distribution): 30–50% (K^{*0}) and ~30% (K_s^0)**
  - **In-flight decay of K and π are included.**

  ⇒ K^{*0} channel shows beam momentum dependence.
  - **Similar acceptance for excited states**

Missing mass resolution: $K^- p \to \Omega^{*-} K^{*0} K^+$

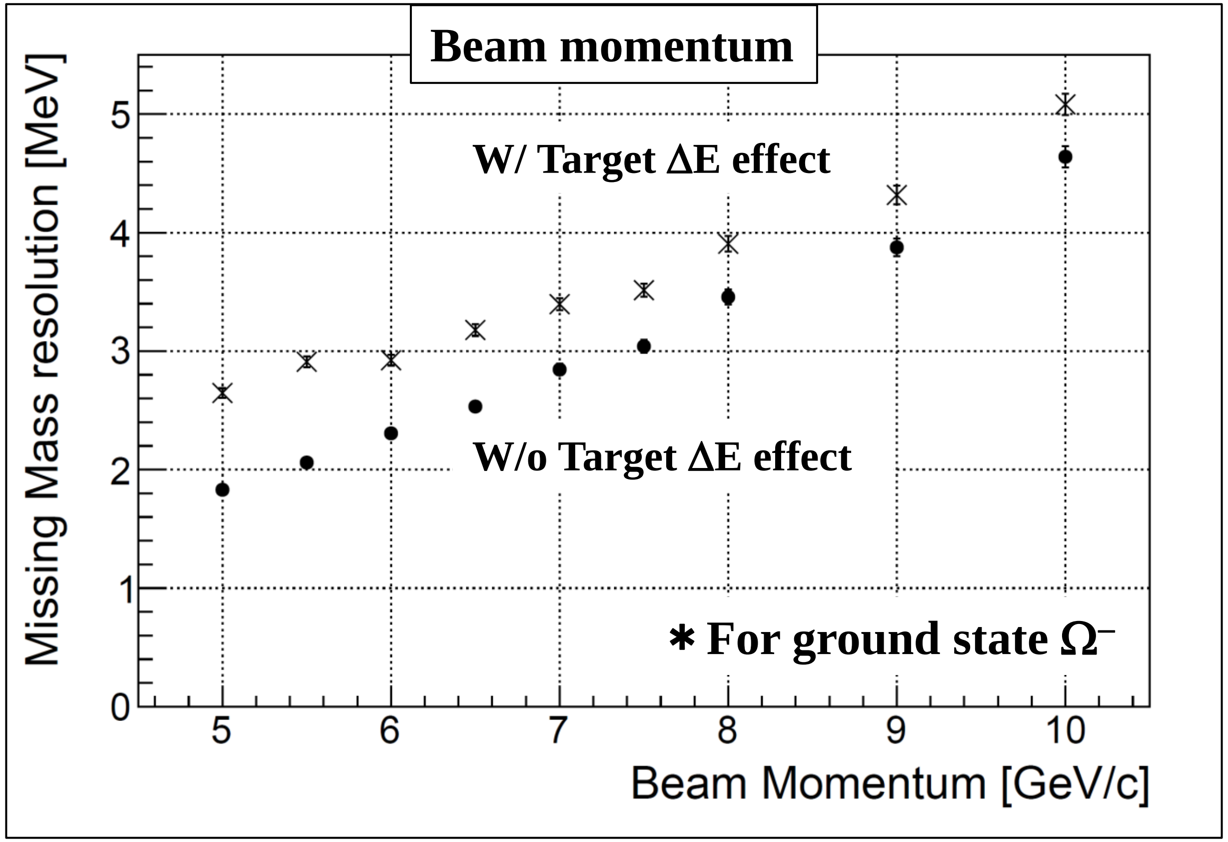


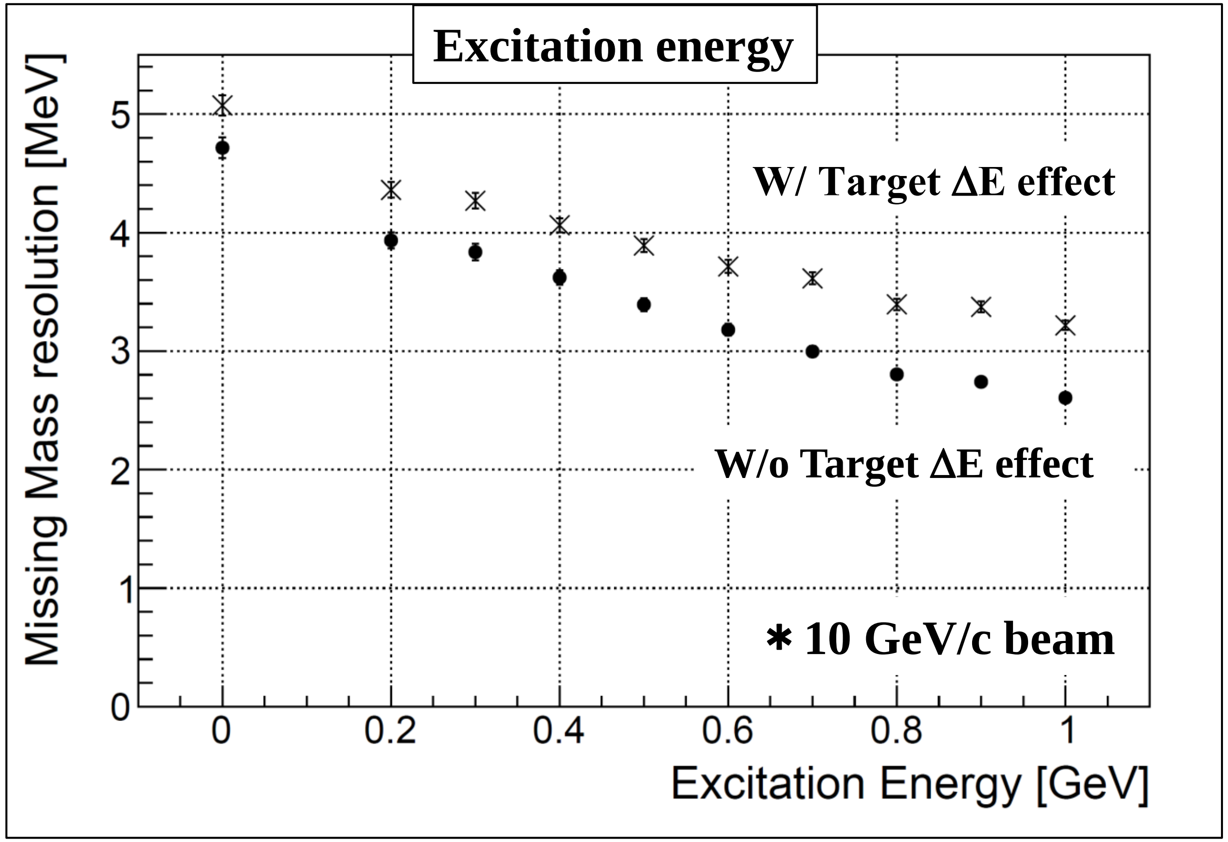


- **Beam line: $\Delta p/p \sim 0.1\%$(rms)**
- **E50 spectrometer: $\Delta p/p \sim 0.2\%$(rms) @ 5 GeV/c**
  - **Effect of energy loss straggling by target: 2 MeV(rms)**
- **Missing mass resolution: 3–5 MeV(rms) (K^{*0}) @ 7–10 GeV/c beam**

⇒ Width (< 10 MeV) can directly be measured.

Missing mass resolution: K_s^0 channel





- **Beam line: Δp/p ~ 0.1%(rms)**
- **E50 spectrometer condition: Δp/p ~ 0.2%(rms) @ 5 GeV/c**
  - **Effect of energy loss straggling by target: 2 MeV(rms)**
- **Missing mass resolution: 3–5 MeV(rms) (K_s^0) @ 7–10 GeV/c beam**

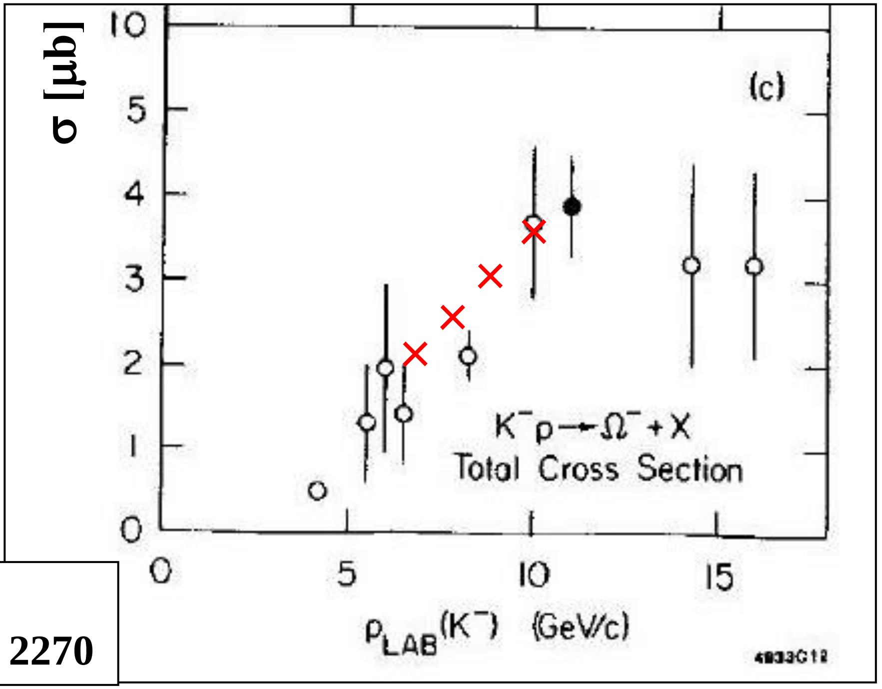
⇒ Width (several 10 MeV) can directly be measured.

Yield estimation

Reaction mode	Beam [GeV/c]	σ_{ch} [μb]	B.R. (K^0, K^*)	Beam [/spill]	Efficiency	Acceptance	Yield (100 days)
$K^- p \rightarrow \Omega^{*-} K_s^0 K^+$	8.0	2.50	0.35	7×10^6	0.66	0.28	4.6×10^6 (4.6M)
$K^- p \rightarrow \Omega^{*-} K_s^0 K^+$	10.0	3.50	0.35	7×10^6	0.66	0.30	6.4×10^6 (6.4M)
$K^- p \rightarrow \Omega^{*-} K^{*0} K^+$	8.0	0.063	0.67	7×10^6	0.66	0.43	3.3×10^5 (330k)
$K^- p \rightarrow \Omega^{*-} K^{*0} K^+$	10.0	0.088	0.67	7×10^6	0.66	0.50	4.6×10^5 (460k)

- **Estimate conditions**
  - σ_{ch}: σ_{Total} = 2.0, 2.5, 3.0, 3.5 μb (7, 8, 9, 10 GeV/c)
    - $\sigma_{K0} = \sigma_{Total} \times 1/1$
    - $\sigma_{K*} = \sigma_{Total} \times 1/40$
  - Branching ratios of K^{*0} and K_s^0
  - In-flight decay of scattered particle: K_s^0, K^+, π^-
  - Efficiency: Tracking(90%), PID(97%), DAQ(99%)

  ⇒×# of particles = 3: $(0.90\times0.97)^3\times0.99 = 0.66$
  - Target thickness: 4.0 g/cm^2 (E50 target)
  - K10 beam intensity: 7×10^6 /spill
  - Spill/hour = ~692 (3600 sec/5.2 sec)
  - Shift: 8 hours (30 days = 90 shifts)



D. Aston et al.,
Phys. Rev. D 32 (1985) 2270

Ω production at p_{K^-}=4.15 GeV/c

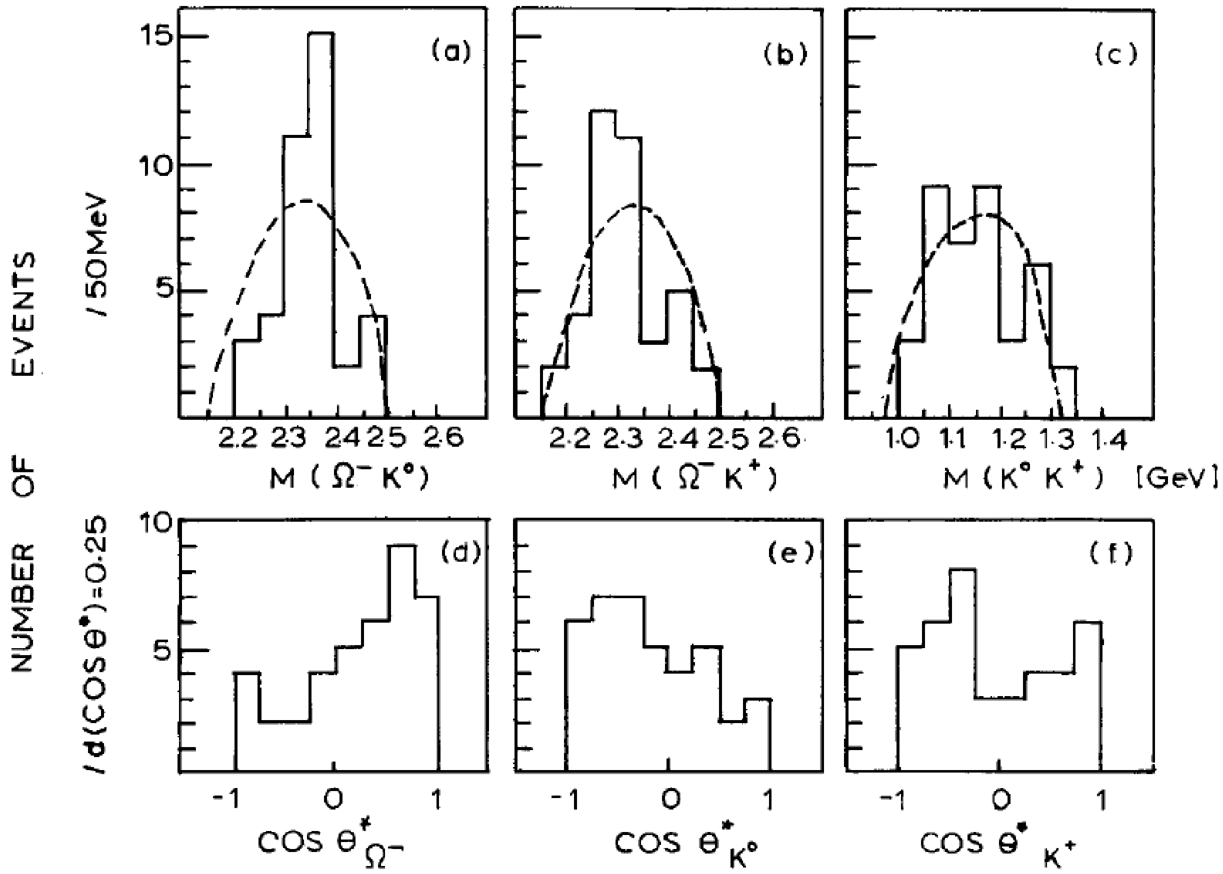
- **NPB142, 205(1978)**

JAM（by Aoki)とコンシステント

Table 1
Topological breakdown of observed events

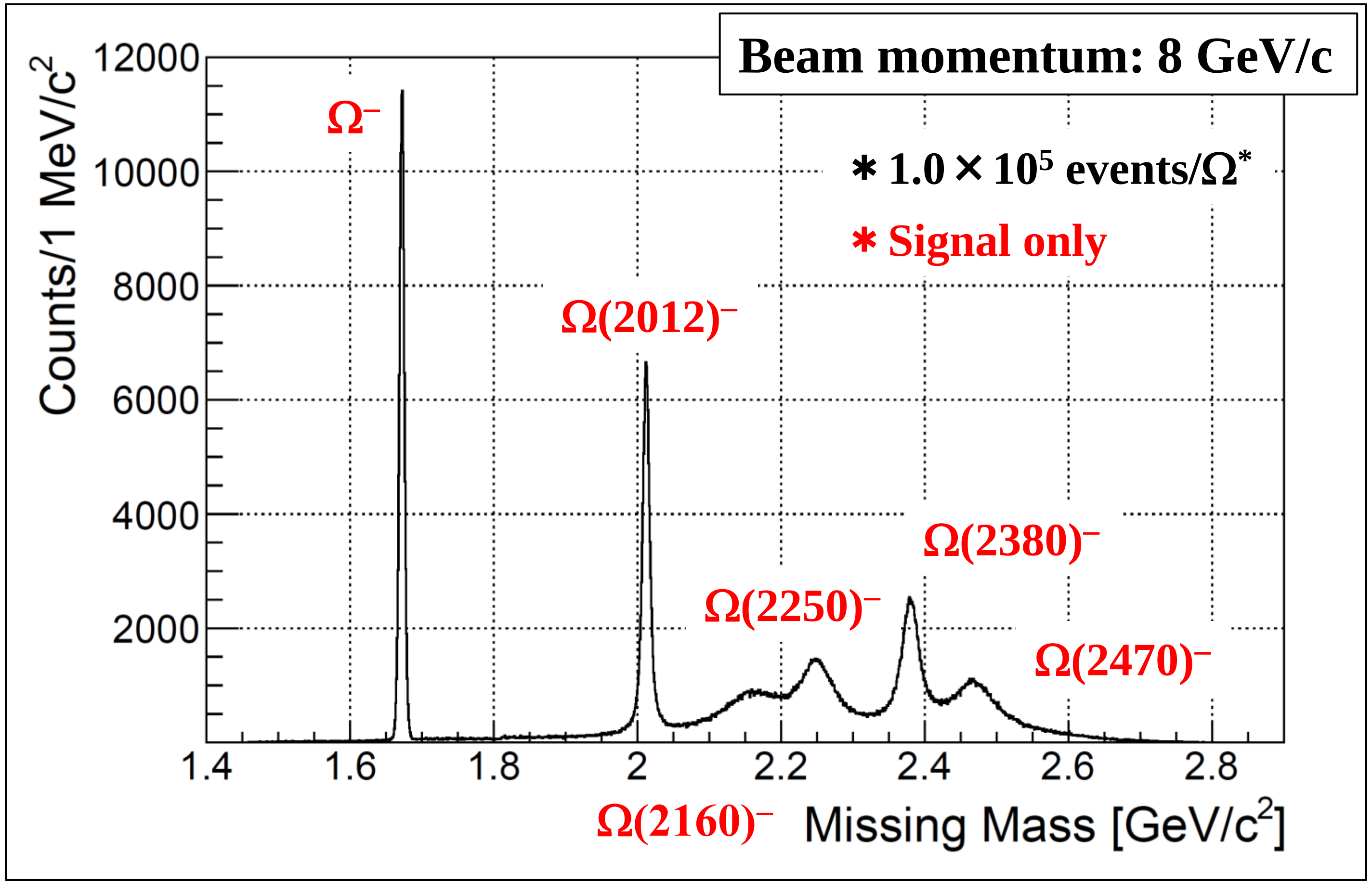
Production channel	Decay channel	Number of events
$K^+K_1^0\Omega^-$	Λ_1K^-	11
$K^+K_2^0\Omega^-$	Λ_1K^-	17
$K^+K_1^0\Omega^-$	Λ_2K^-	2
$K^+K^+\pi^-\Omega^-$	Λ_1K^-	1
$K^+K_1^0\Omega^-$	$\Xi_1^0\pi^-$	3
$K^+K_2^0\Omega^-$	$\Xi_1^0\pi^-$	3
$K^+K_1^0\Omega^-$	$\Xi_2^0\pi^-$	1
$K^+K_2^0\Omega^-$	$\Xi_1^-\pi^0$	2

1/40



Exclusive:～0.3 μb、Inclusive 0.5±0.1 μb
K0がKs→π+π-だけかどうか不明(BR:69.2%)

Missing mass spectrum: Signal events ($K^- p \rightarrow \Omega^{*-} K^{*0} K^+$)



State	Mass [MeV/c^2]	Γ [MeV]
Ω(2470)	2470	72
Ω(2380)	2380	26
Ω(2250)	2250	55
Ω(2160)	2159	100
Ω(2012)	2012	6.4
Ω(g.s)	1672	-

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

Measured Ω^{*-} states by PDG

Threshold

$\Xi^0 K^{*-}$ 2109

$\Xi^{0*} K^-$ 2024

$\Xi^0 K^- \pi^0$ 1956

$\Omega \pi^0 \pi^0$ 1942

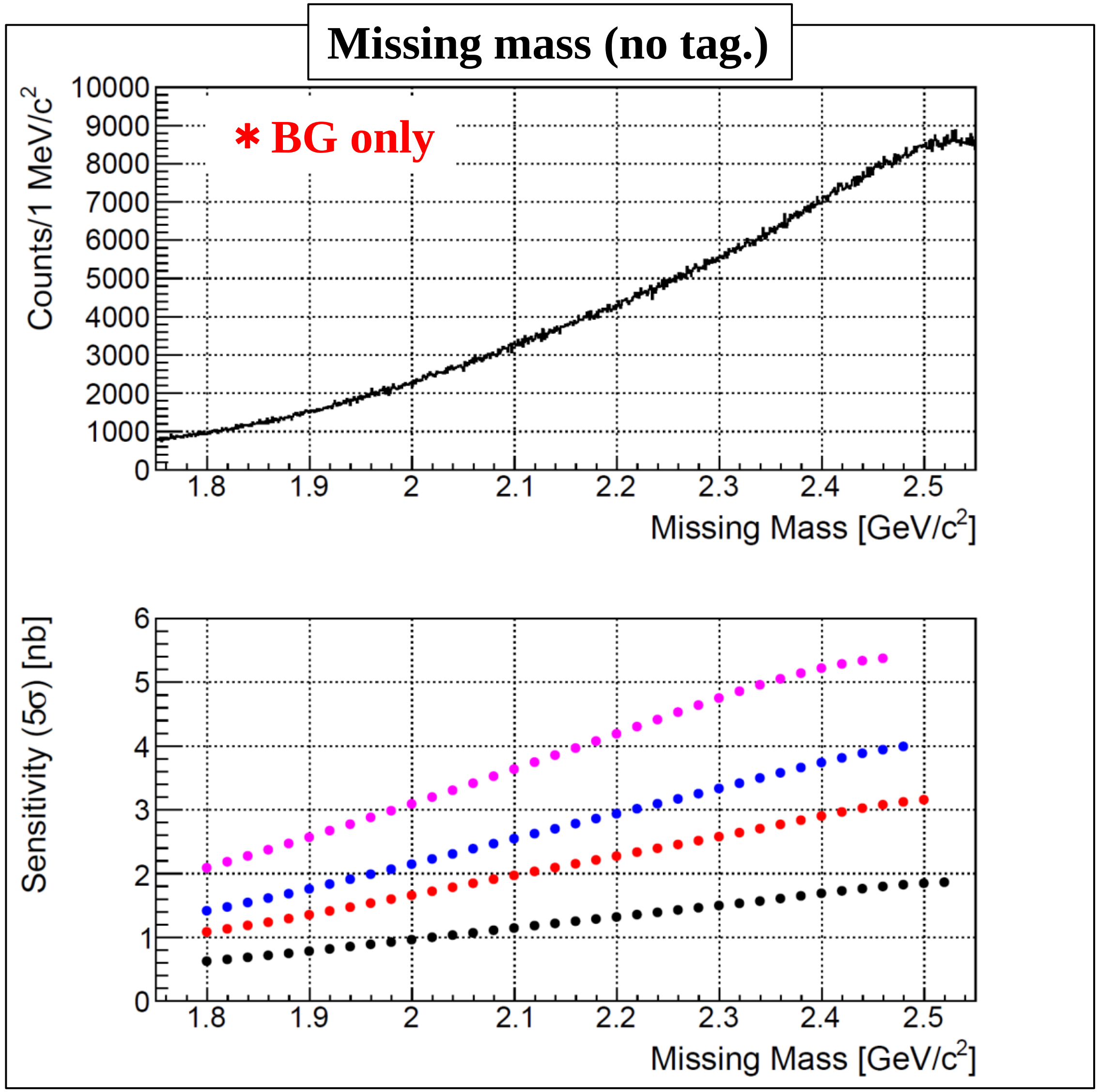
$\Xi^0 K^-$ 1811

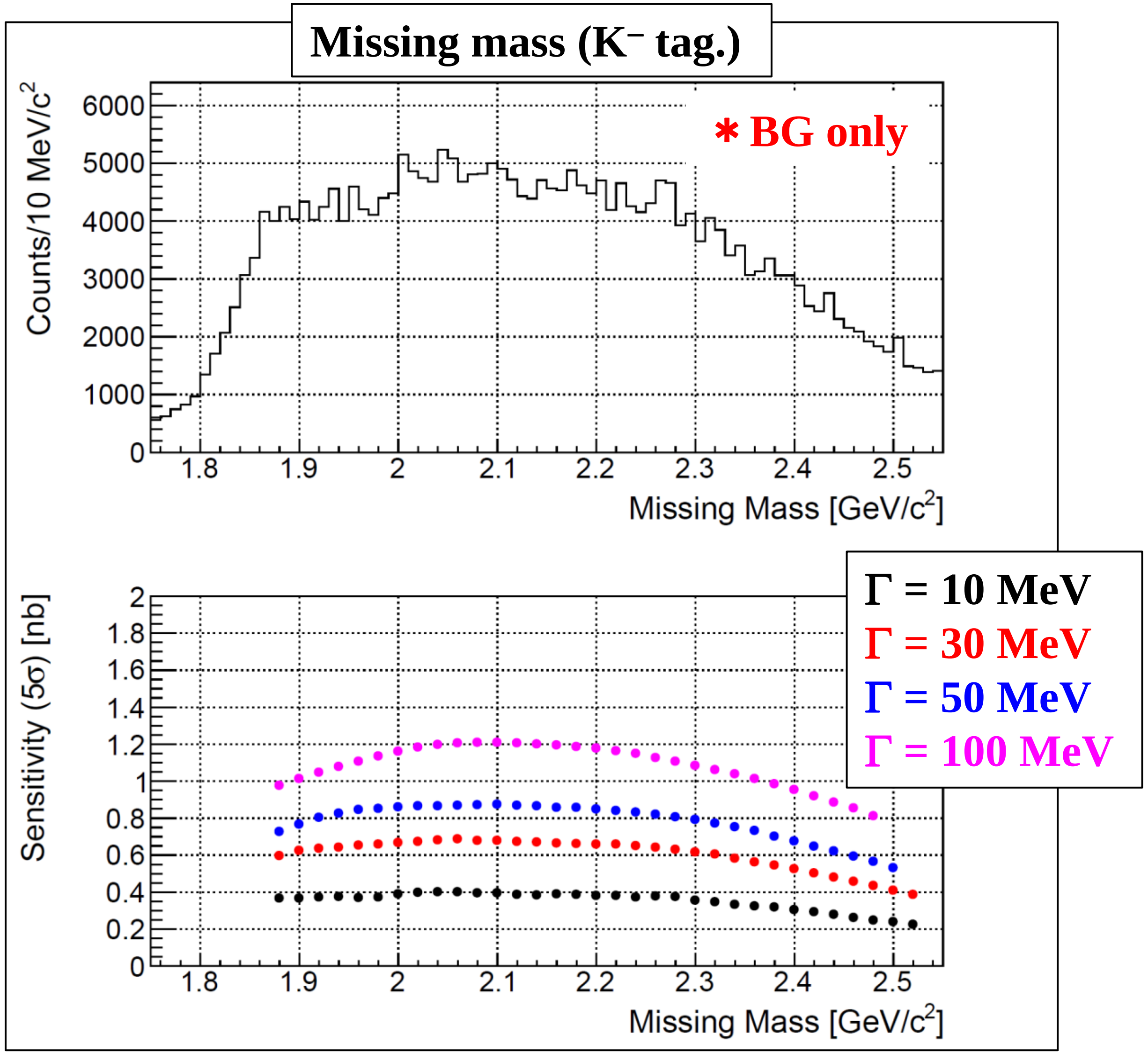
$\Omega \pi^0$ 1807

	JP	Rating	Γ [MeV]	→ΞK (1)	→Ξ*K (2)	→ΞK* (3)	→ΞKπ (4)	→Ωππ (5)	
Ω(2470)	??	2*	72±33					Seen	LASS (113M K^-, 11 GeV/c) (290±90)/(5) nb
Ω(2380)	??	2*	26±23		< 0.44 to (4)	0.5±0.3 to (4)			Ξ Beam
Ω(2250)	??	3*	55±18		0.7±0.2 to (4)		Seen		Ξ Beam LASS (113M K^-, 11 GeV/c) (630±180)/(2) nb
Ω(2012)	?–	3*	$6.4^{+2.5}_{-2.0}$ +-1.6	1.2±0.3 (=Ξ^0/Ξ^0)	< 0.119 /(1)				->Ξ^*K dominant if Ξ^*K mol?
Ω(g.s)	$3/2^+$	4*	-						

- Most of spins/parities/decay branches have yet to be determined.
- Ω(2380) and Ω(2470) are discarded from PDG table.
- Roper-like state: Ω(2160), Γ = 100 MeV (assumed)

Sensitivity





- **Smooth background case: Sensitivity (5σ) ~1 nb for Γ = 100 MeV**

Situations for background studies: K^- p reaction

- No good reference data for hadron beam of several GeV/c

- Estimation by hadron reaction generator

⇒ JAM (Jet AA Microscopic transport model)

Y. Nara et.al. Phys. Rev. C61 (2000) 024901

  - Include many elementary processes in low-high energy
  - Lund model also used by PYTHIA

- JAM results were checked by studies for charmed baryon spectroscopy.
  - π^- p reaction @ 20 GeV/c
  - No order difference from old data
  - Cross check with PYTHIA: Similar results

⇒ It can be used for estimation with factor differences.

Charged track multiplicity from JAM

# of charged track $\pi^- p \to X$ @ 16 GeV/c

Track数	2T [mb]	4T [mb]	6T [mb]	8T [mb]	10T [mb]	Total [mb]
Data	9.78	9.02	4.85	1.37	0.2	25.22
JAM	8.03	8.81	6.17	1.42	0.08	24.51
PYTHIA	8.84	9.72	5.21	0.79	0.03	24.59

# of charged track $\pi^- p \to \Lambda + X$ @ 15 GeV/c

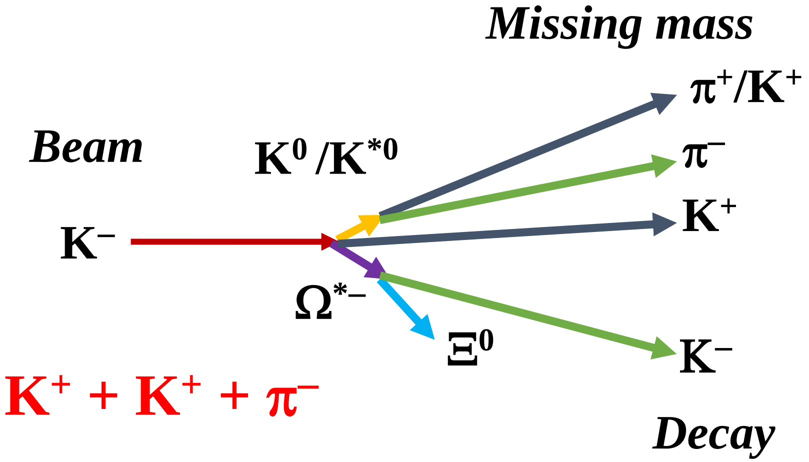
Track数	2T [μb]	4T [μb]	6T [μb]	8T [μb]	10T [μb]	Total [μb]
Data	466	480	200	26.6	1.8	1174
JAM	363	482	155	9.00	0.02	1009
PYTHIA	509	549	127	5.84	0.05	1191

# of charged track $\pi^- p \to K^0 + X$ @ 15 GeV/c

Track数	2T [μb]	4T [μb]	6T [μb]	8T [μb]	10T [μb]	Total [μb]
Data	714	787	266	45.2	2.4	1815
JAM	810	1069	345	23.8	0.2	2248
PYTHIA	960	1203	302	13.1	0.1	2478

- **No K^- beam data ?**
- **No K^+ multiplicity data ?**

Choice of reactions



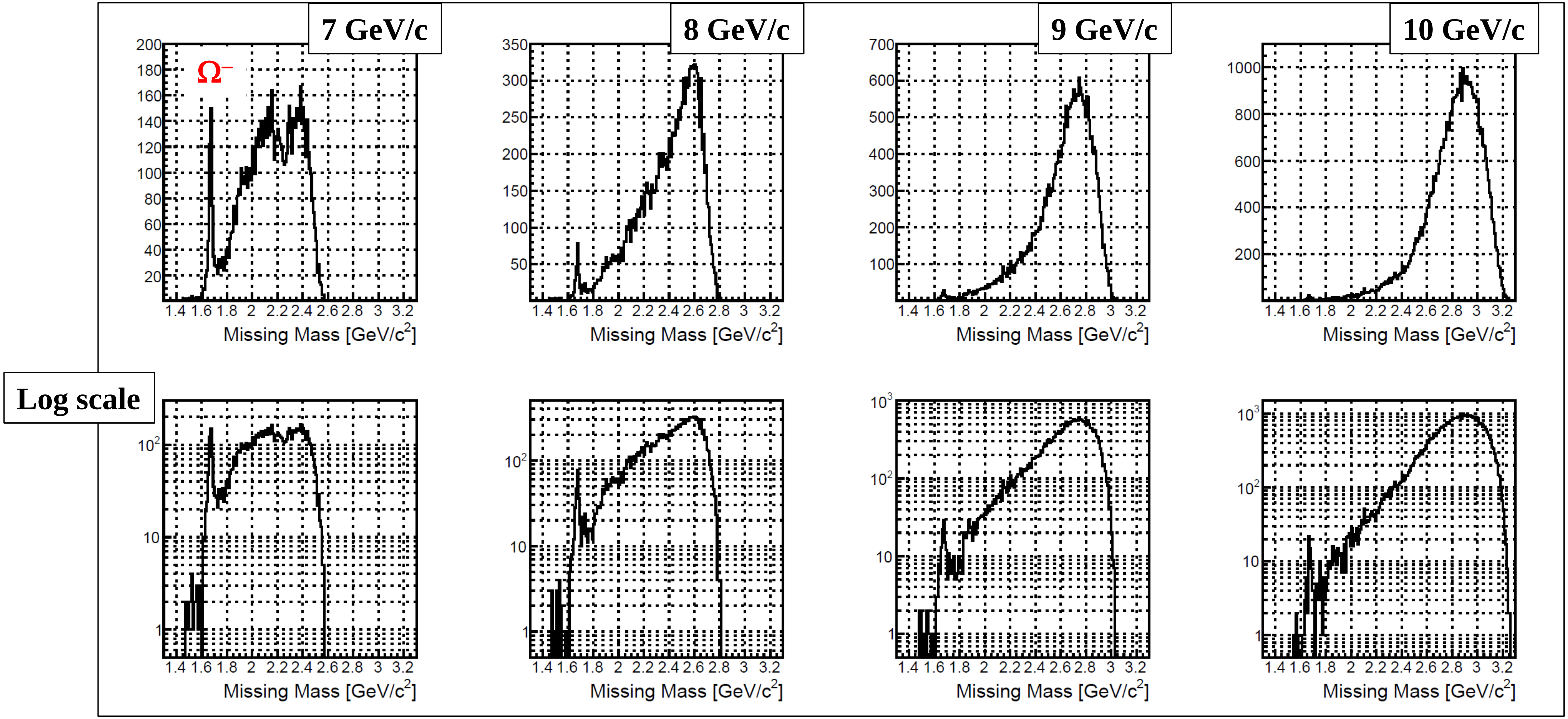
- Ω^{*-}(sss): $P_{K\ beam}$ = 7–10 GeV/c
  - $\sqrt{s}$ = 3.8–4.5 GeV ⇒ Up to 2.5–3.0 GeV/c^2 excited states

- Background reactions w/ s = –2 production : $K^- + p \rightarrow$"X" + $K^+ + K^+ + \pi^-$
  - $(K^+ + K)/(K^+ + K^*)$ pair production ×2 + π production (+N^*, Δ^*)
  - $(K^+ + K)/(K^+ + K^*)$ pair production ×2 + π from K^0/K^* decay
  - $(K^+ + K)/(K^+ + K^*)$ pair ×1 + Ξ production + π production
  - $(K^+ + K)/(K^+ + K^*)$ pair ×1 + Ξ production + π from $K^0/K^*/\Xi^*$ decay
  - …….

- Background reactions w/ s = –1 production : $K^- + p \rightarrow$"X" + $K^+ + \pi^+ + \pi^-$
  - $(K^+ + K)/(K^+ + K^*)$ pair production ×1 + π production (+N^*, Δ^*)
  - $(K^+ + K)/(K^+ + K^*)$ pair production ×1 + π from K^0/K^* decay
  - $(K^+ + K)/(K^+ + K^*)$ pair production ×1 + $K^- \rightarrow K^0$ exchange + π from K^0/K^* decay
  - $(K^+ + K)/(K^+ + K^*)$ pair production ×1 + Λ/Σ production + π production
  - $(K^+ + K)/(K^+ + K^*)$ pair production ×1 + Λ/Σ production + π from $K^0/K^*/\Lambda^*/\Sigma^*$ decay
  - Ξ production + π production (π from Ξ^* decay)
  - Ξ production + π from Ξ^* decay
  - …….

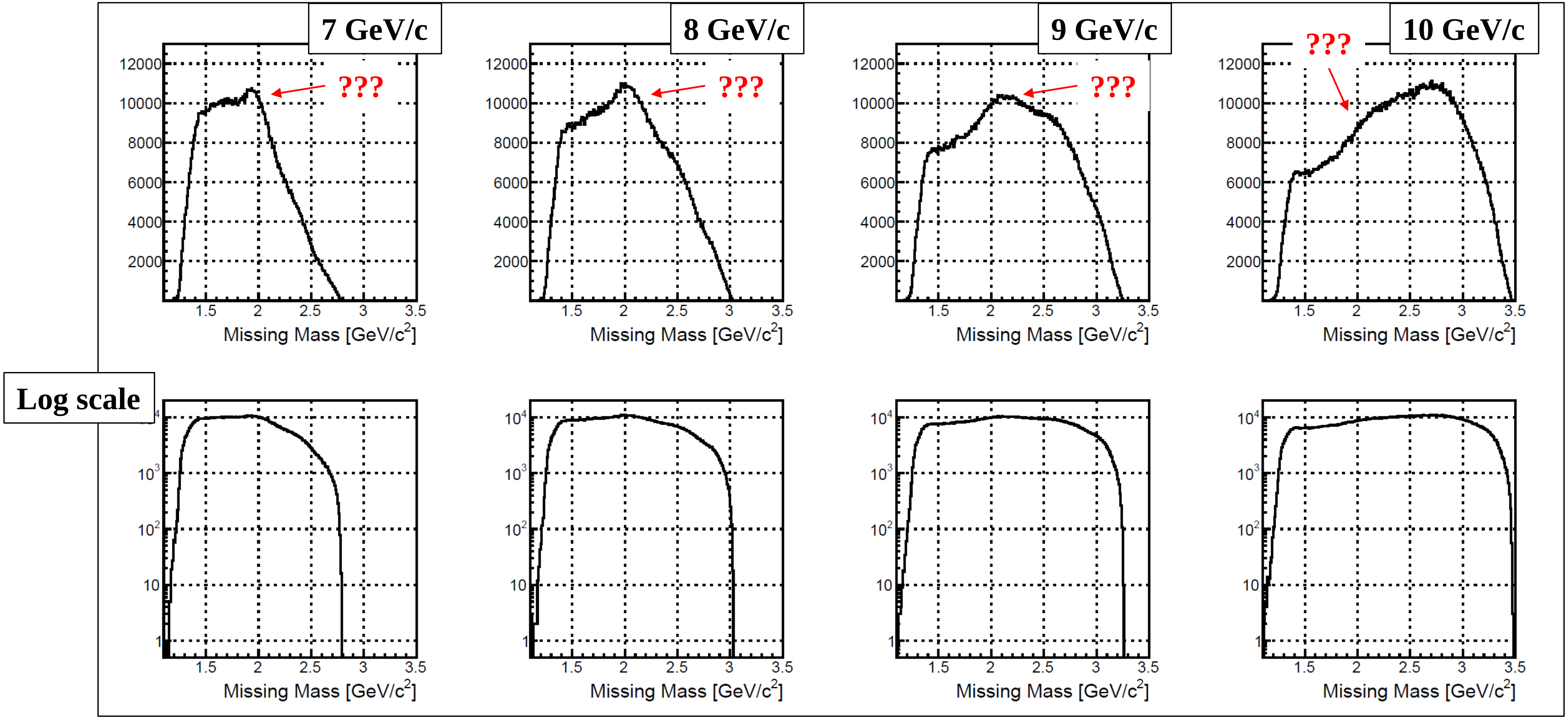
＊Expect good S/N by using s = –3 tagged reaction

Missing mass spectrum: Background events (K^{*0})



- Input Ω⁻ (ΔM~15 MeV ?) and other resonances(?) are reconstructed.
- Smooth background in the higher mass region

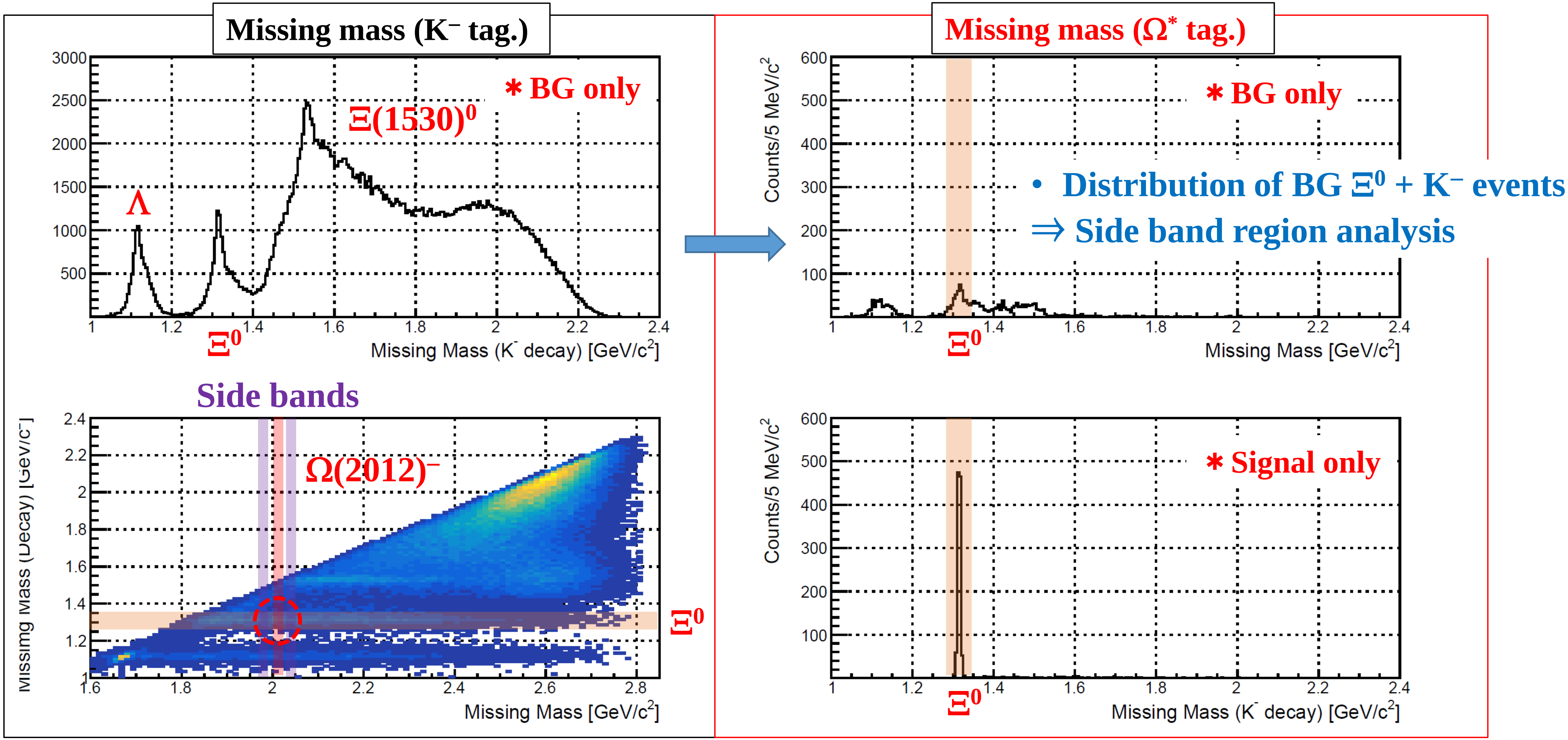
Missing mass spectrum: Background events (K_s^0)



- **Strange shape by contribution from resonances ? (s≠−3 events)**

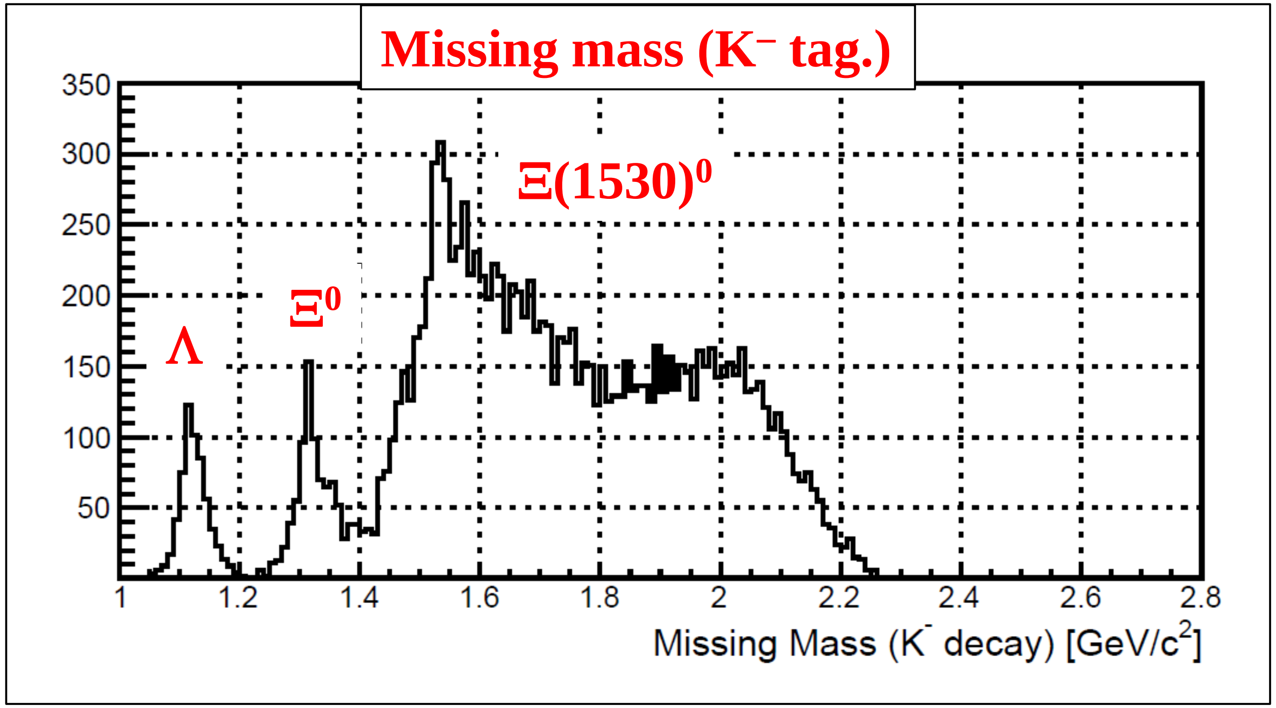
⇒ Under investigation

Decay analysis: $\Omega^{*-} \to \Xi^0 + K^-$ mode (B.R. = 0.3)



- Decay events selection: $2.000 < M_{\Omega*} < 2.025$ GeV/c² and $1.30 < M_{\Xi} < 1.33$ GeV/c²
- Both Ω^* and Ξ mass selection ⇒ Background is well reduced. (Distribution almost flat)

Background channels



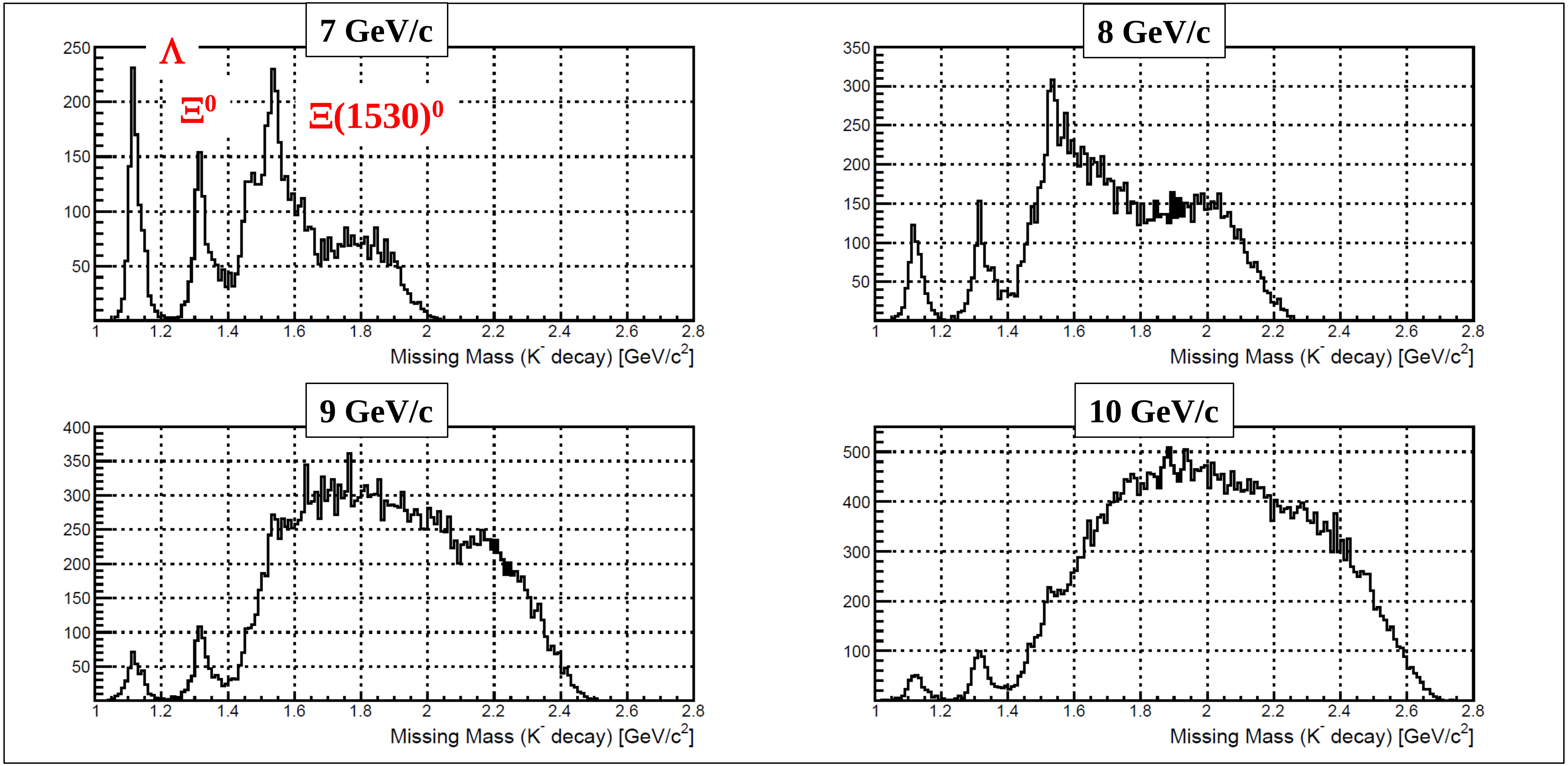
- $K^- + p \rightarrow$ "X" + $K^+ + K^+ + \pi^-$

$\Rightarrow$ **Decay by tagging K^-**

- Signal: Ω^- or Ω^{*-}
- Ω^- Decay: $K^- + \Lambda$
- $K^- + \Xi^0$
- $K^- + \Xi^{*0}$
- $K^- + \Xi^0 + \pi$: Mass = 1315 + 140 = 1455
- $K^- + \Xi^0 + \pi \times 2$: Mass = 1315 + 280 = 1595
- $K^- + \Lambda + K^0$: Mass = 1115 + 498 = 1613
- $K^- + \Sigma^0 + K^0$: Mass = 1192 + 498 = 1690
- $K^- + \Sigma^+ + K^-$: Mass = 1189 + 494 = 1683
- $K^- + K + K + N$: Mass = $494 \times 2 + 938 \sim 1930$

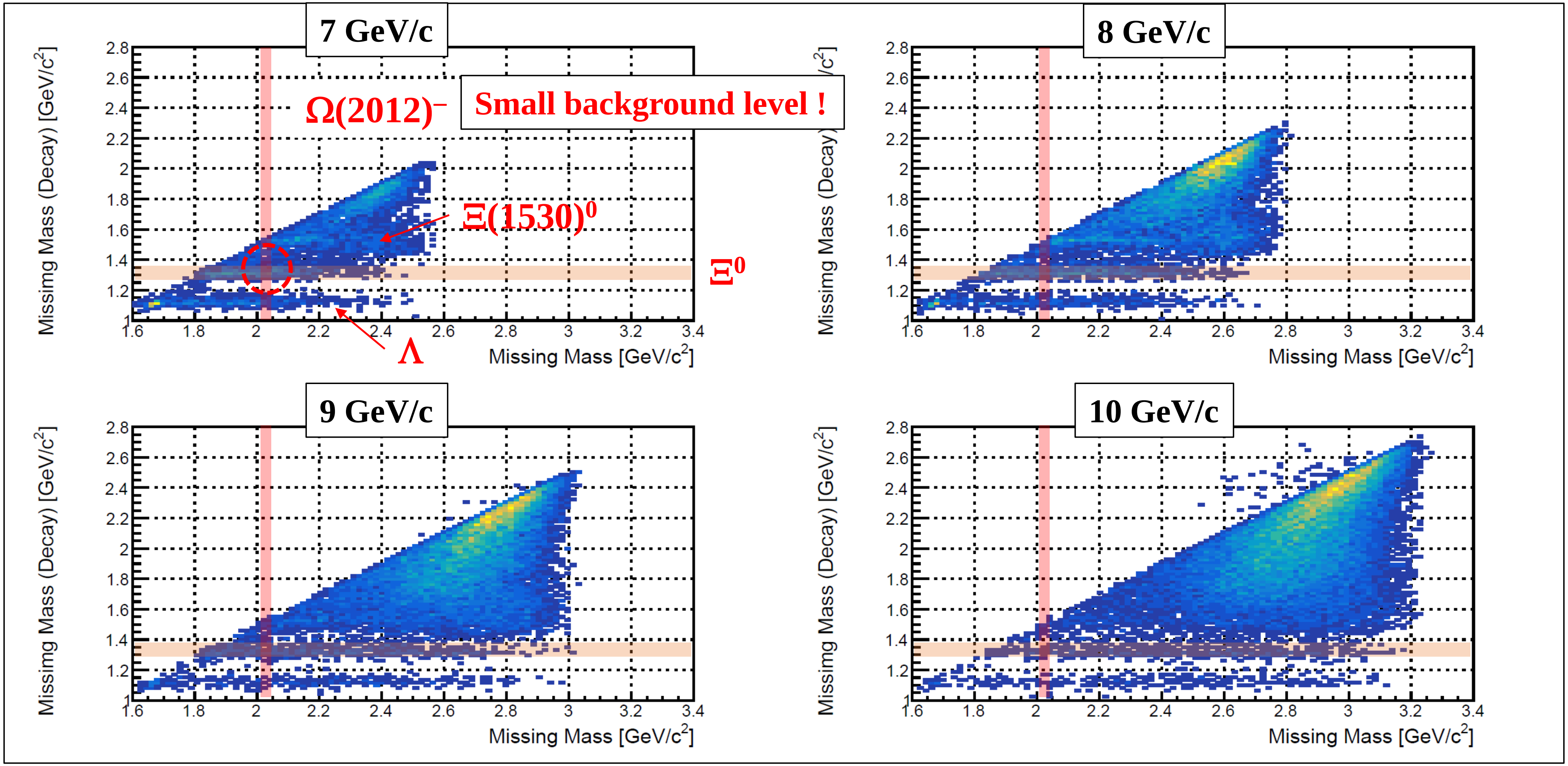
....

Decay measurement: K⁻ detection background from JAM



- **Analysis of JAM events ⇒ K⁻ decay mode from input resonance states and reactions**

Decay measurement: K⁻ detection background from JAM



- **Analysis of JAM events ⇒ K⁻ decay mode from input resonance states and reactions**

⇒ Under investigation

Requitements: Spectrometer for K10

- Forward dipole type magnet: Forward scattering due to fixed target
  - Acceptance for forward scattered particles
    - Wide angler coverage ($\theta < 45°$) for both missing mass and decay measurement
  - Good momentum resolution for forwarded scattered particles with high-momentum
    - $\Delta p/p$ ~0.2%(rms) level
  - Slow bending magnet system: Large size magnet pole and not so strong magnetic field
    - Detector configuration with effective coverage

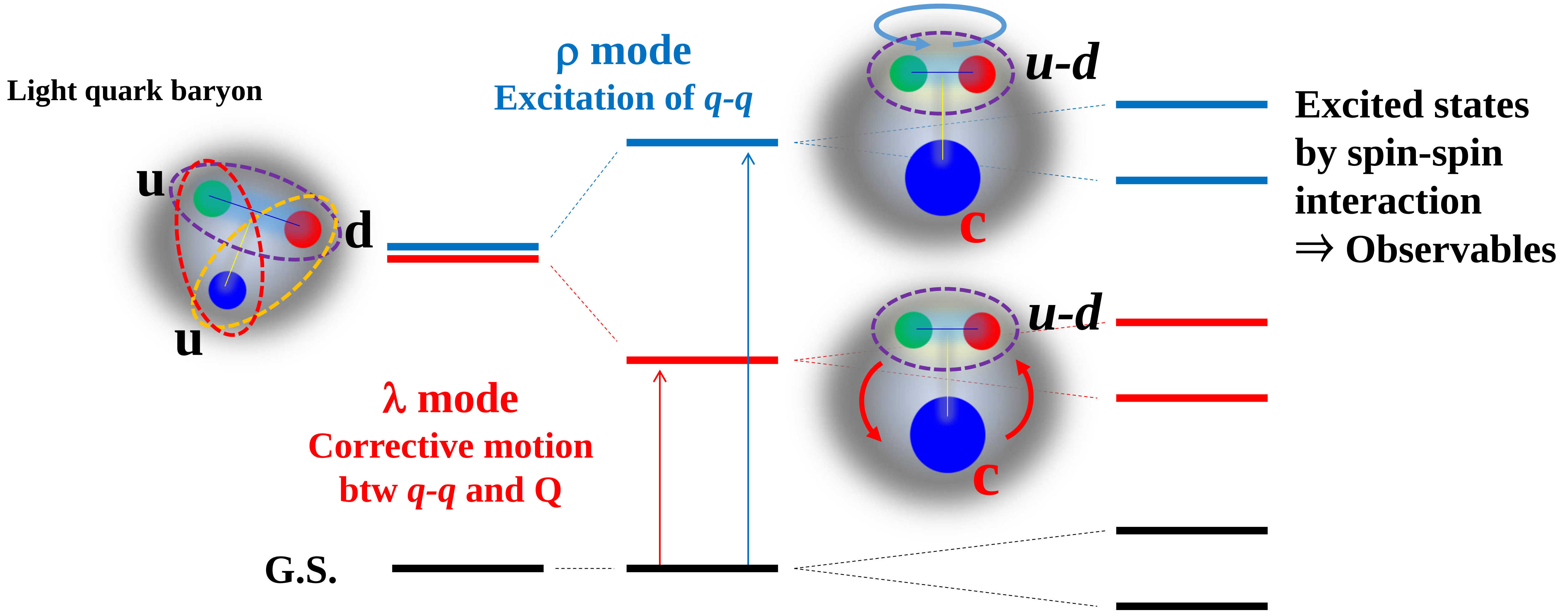
- Detectors for spectrometer system
  - High-rate detectors for high-intensity K^- beam measurement
  - Good PID system with both good efficiency and no miss-identification
  - Multi-layer tracking system for measuring multi-track events
  - Large size detectors for covering widely scattered particles

＊Suitable one: Spectrometer for charmed baryon spectroscopy (J-PARC E50)
- New one will be designed based on E50 system. ⇒ Templary used for estimation

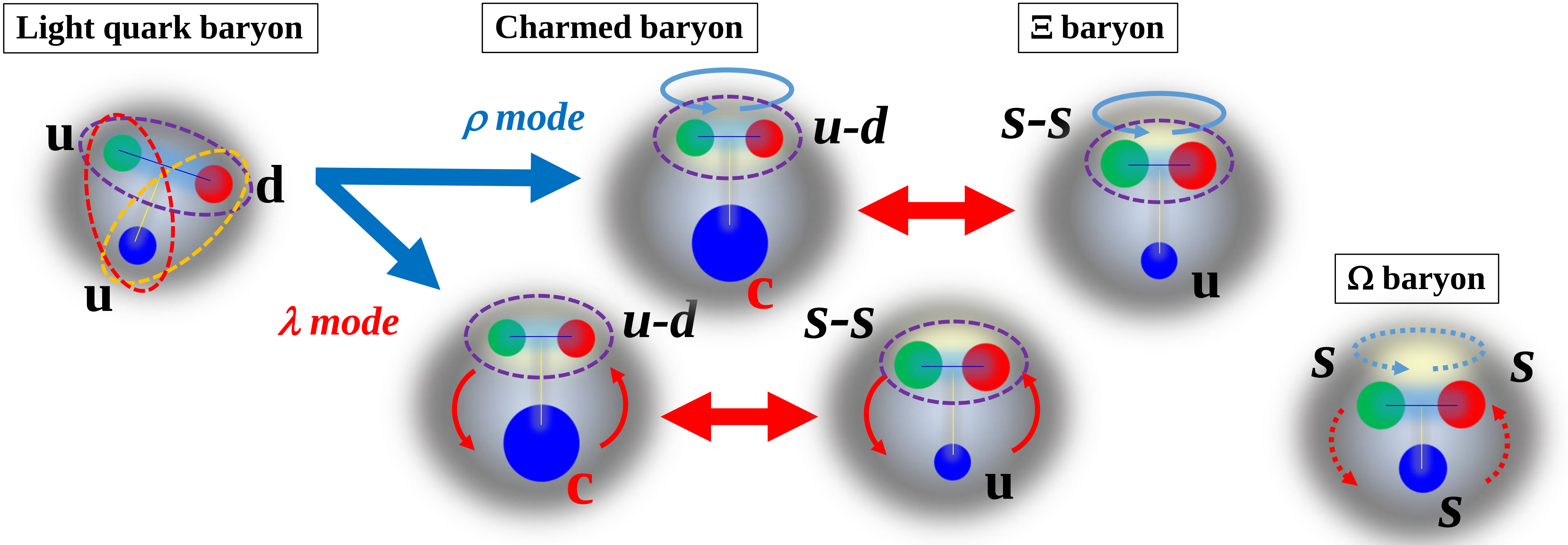
Excited states with heavy quark: Diquark

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

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



Heavy flavors for revealing internal structure of baryons



- Effective degree of freedoms by internal motion of quarks

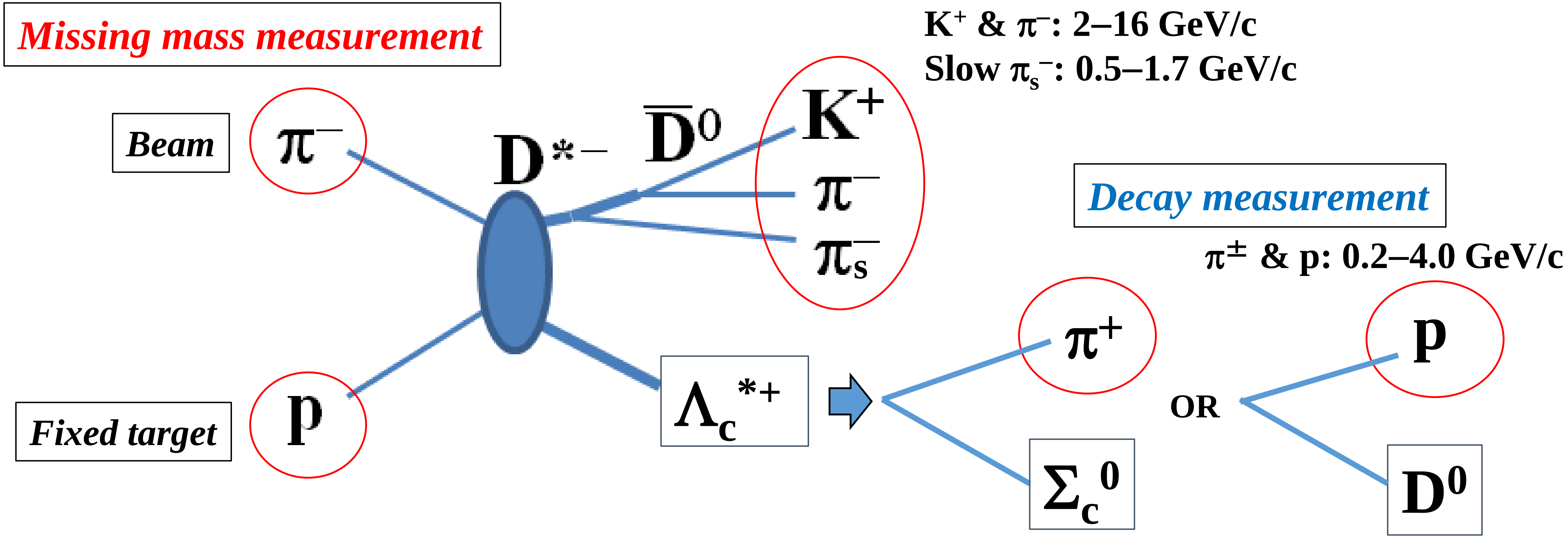
⇒ It is essential to understand baryon system.

- Diquark correlation by charmed baryon
- Ξ baryon: similar q-q correlation

@ High-momentum beam line

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

Experiment: Missing mass technique



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

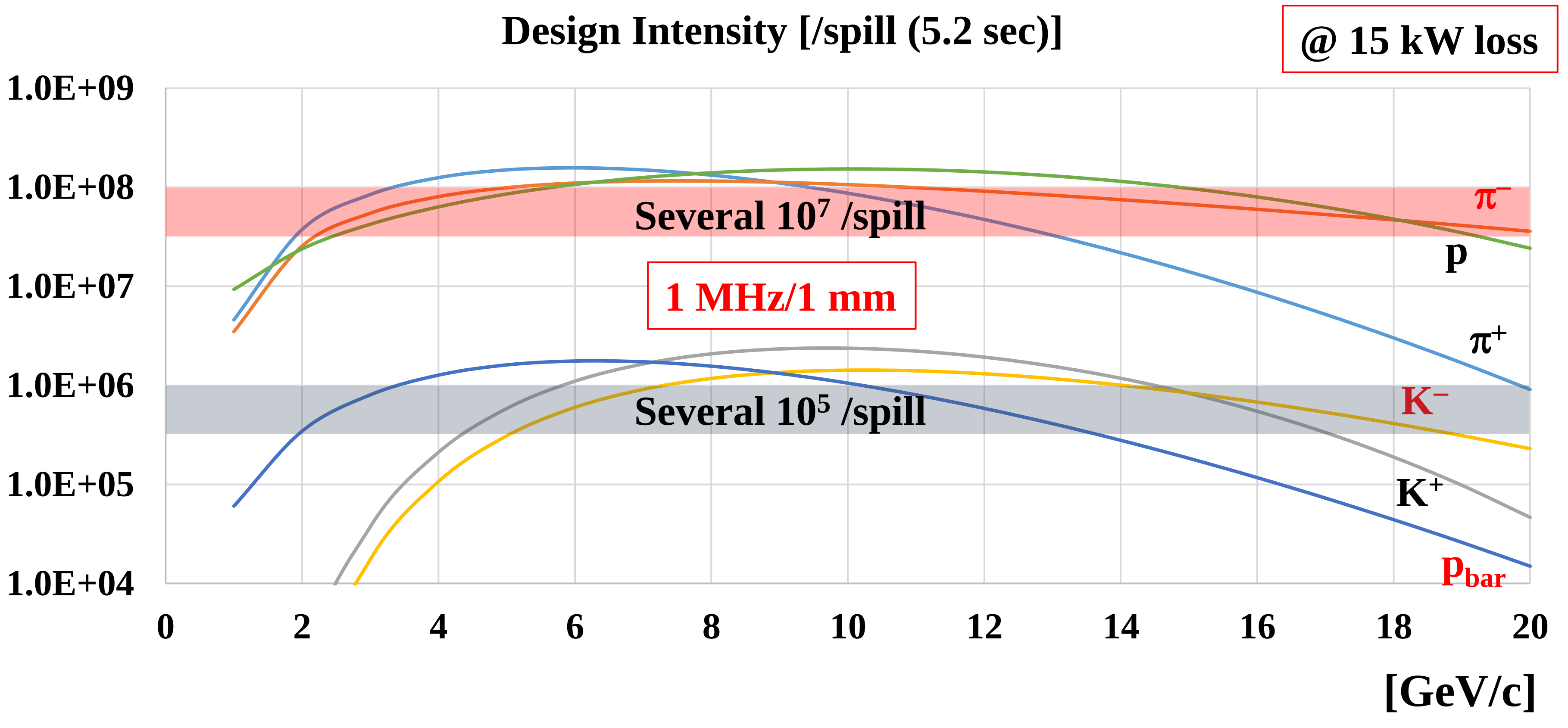
1) **Missing mass spectroscopy: Y_c^{*+} mass (>1 GeV excited states)**
- $D^{*-} \rightarrow \bar{D}^0 \pi_s^- \rightarrow K^+ \pi^- \pi_s^-$: $D^{*-} \rightarrow \bar{D}^0 \pi_s^-$ (67.7%), $\bar{D}^0 \rightarrow K^+ \pi^-$ (3.88%)

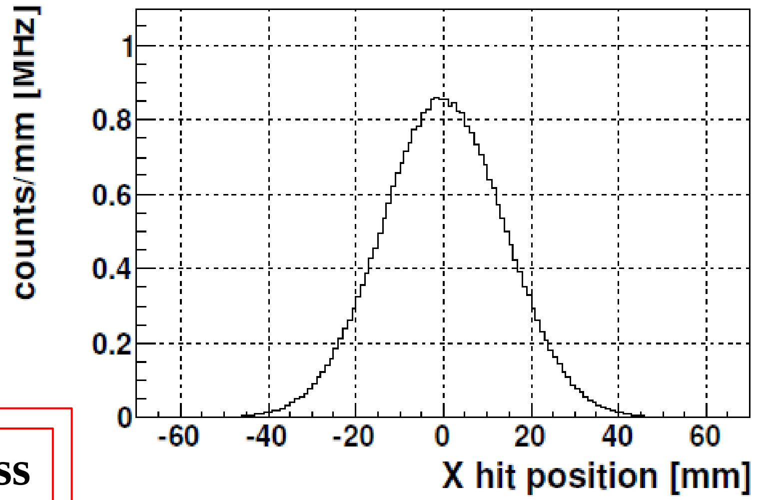
2) **Decay measurement: Absolute B.R. and angular distribution**
- **Decay particles ($\pi^\pm$& proton) from Y_c***

High-momentum beam line for 2ndary beam

＊Beam measurement is essential.

- High-intensity beam: > 1.0×10^7 Hz π (< 20 GeV/c)
  - Unseparated beam: π/K/p_{bar} (PID by detector)
- High-resolution beam: Δp/p ~ 0.1%(rms)
  - Momentum dispersive optics method





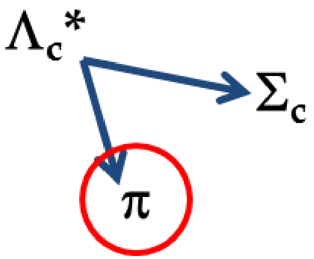
Counting rate / 1 mm

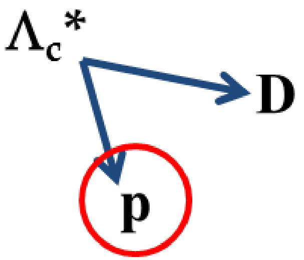
- 6.0×10^7 /spill (30 MHz)
- Size: 100 mm × 100 mm

@ 20 GeV/c

Reduced by collimator to Several 10^7 /spill
⇒ Limit of detector operation and DAQ data transfer

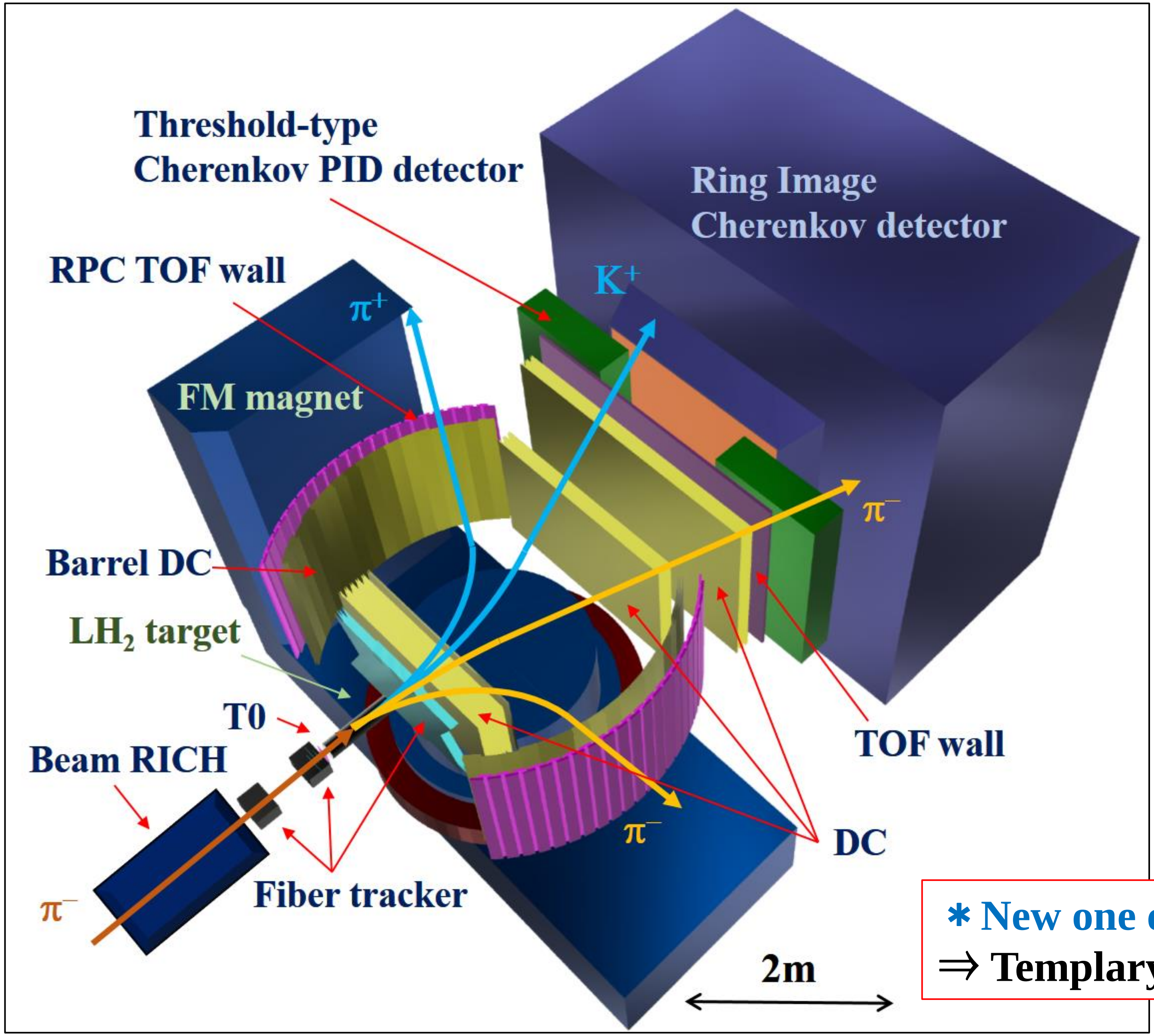
Spectrometer system based on charmed baryon experiment

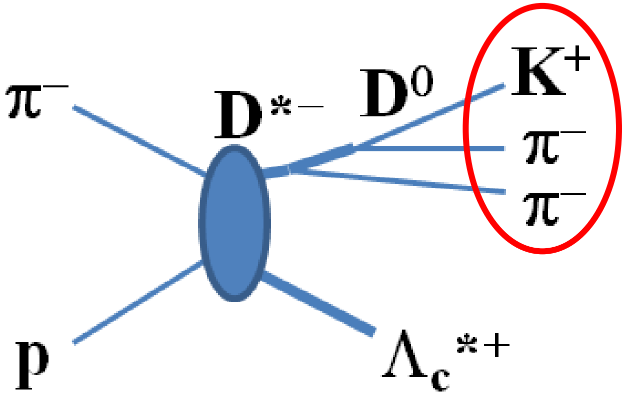




Decay measurement
∗ Branching ratios

$\pi^{\pm}$&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

∗ New one designed based on this one
⇒ Templary used for estimation