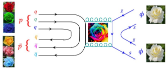
Exotic Hadron Spectroscopy

From Quarkless to Multiquark States

Jung Keun Ahn
(Korea University)



Toward Drip Line of Multiquark States

0 Glueballs

- H dibaryon in (K^-, K^+), γd, and Λp reactions
- Θ^+, P_s, and $P_{\bar{s}}(\Theta^*)$ in γp, γd, $\pi^- p$, $K^+ p$, and $K^+ d$ reactions
- $\Lambda(1405)$, $\Sigma(1670)$, $\Xi(1690)$ in γp and $K^- p$ reactions
- Ω^* $(\Omega(2470) \to \Omega\pi\pi)$
- $\bar{p}p \to \phi\phi$, $K^*\overline{K}^*$, $\gamma\gamma^*$
- $\gamma^*\gamma \to p\bar{p}$, $\Lambda\overline{\Lambda}$
- Vector meson production near threshold:

$$\frac{\sigma(\pi^- p \to \phi n)}{\sigma(\gamma p \to \phi p)} \gg \frac{\sigma(\pi^- p \to J/\psi n)}{\sigma(\gamma p \to J/\psi p)}$$

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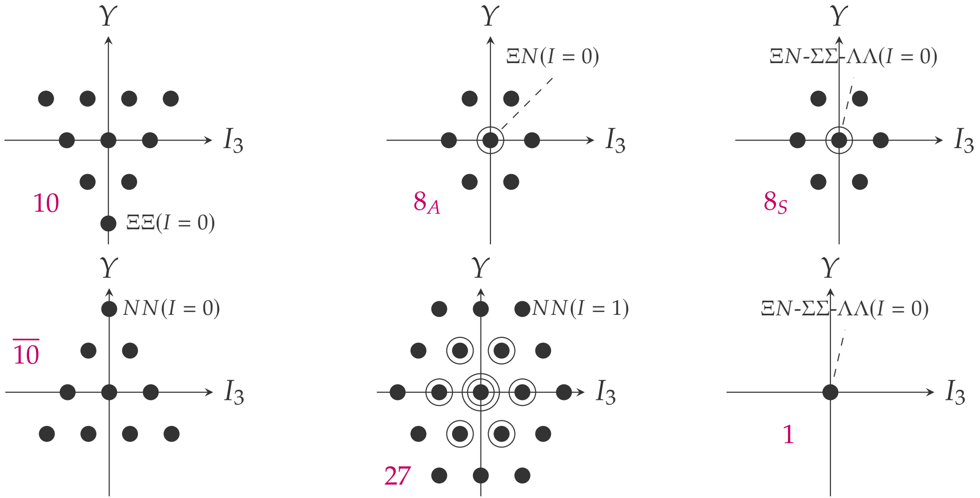
Dibaryon Multiplets in $SU(3)_f$



The Most Promising Candidate in the Strange Sector

H-dibaryon

- The H-Dibaryon ($J = 0, I = 0$) is a stable $SU(3)_f$ singlet hexaquark state consisting of $uuddss$ quarks due to QCD color magnetic force.
- H is named after Hexa-quark states.

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Perhaps a Stable Dihyperon*

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(Received 1 November 1976)

In the quark bag model, the same gluon-exchange forces which make the proton lighter than the $\Delta(1236)$ bind six quarks to form a stable, flavor-singlet (with strangeness of -2) $J^P = 0^+$ dihyperon (H) at 2150 MeV. Another isosinglet dihyperon (H^*) with $J^P = 1^+$ at 2335 MeV should appear as a bump in $\Lambda\Lambda$ invariant-mass plots. Production and decay systematics of the H are discussed.

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The History of H-Dibaryon Searches

- 1977 — Deeply-bound di-hyperon predicted by R. Jaffe
- 1980-2000 — No evidence for the deeply-bound H from KEK, BNL, and CERN experimental efforts by more than 80 MeV
- 2001 — Mass constraint from observation of ${}^{6}_{\Lambda\Lambda}\mathrm{He}$ (E373)
- 1998,2007 — Enhanced $\Lambda\Lambda$ production near threshold was reported from E224 and E522 at KEK-PS
- 2011 — LQCD calculations predict the H-dibaryon near $m_{\Lambda\Lambda}$
- 2013-2015 — No evidence for $H \to \Lambda p \pi^-$ and $H \to \Lambda\Lambda$ in high-energy e^+e^-, pp and AA experiments
- 2021 — LQCD calculations point to the mass of the H-dibaryon very close to ΞN threshold ($m_\pi \approx 146$ MeV)
- 2021 — **J-PARC E42 has successfully completed with HypTPC.**
- 2024 — We are nearing the final stage of data analysis.

H-Dibaryon Search at J-PARC : E42

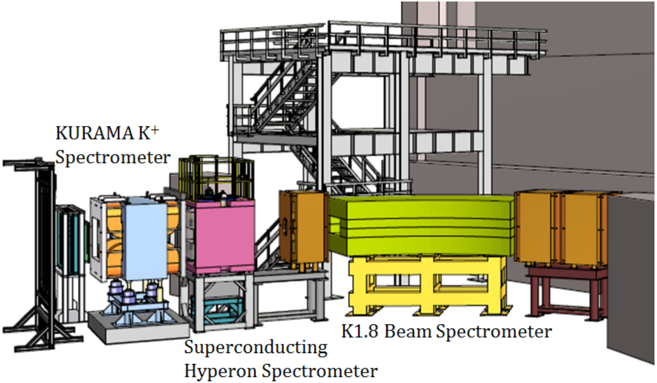
The existence of the H-dibaryon still awaits definitive experimental confirmation or exclusion.

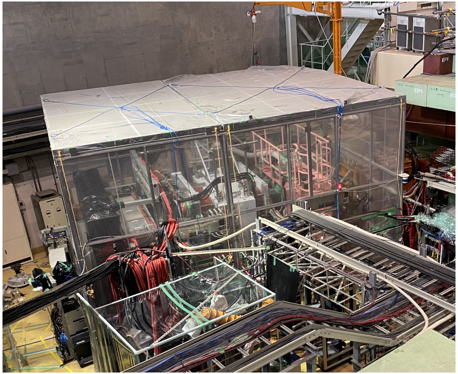
- Weakly-bound : $H \to \Lambda p \pi^-$
- Virtual state : $\Lambda\Lambda$ or $\Xi^- p$ threshold effect
- Resonance : Breit-Wigner peak in $\Lambda\Lambda$ and $\Xi^- p$ masses

J-PARC-E42 experiment

1. in $\Lambda p \pi^-$, $\Lambda\Lambda$ and $\Xi^- p$ channels
2. by tagging the $S = -2$ system production
3. via (K^-, K^+) reactions at 1.8 GeV/c with a diamond target
4. with Hyperon Spectrometer : 1 MeV $\Lambda\Lambda$ mass resolution

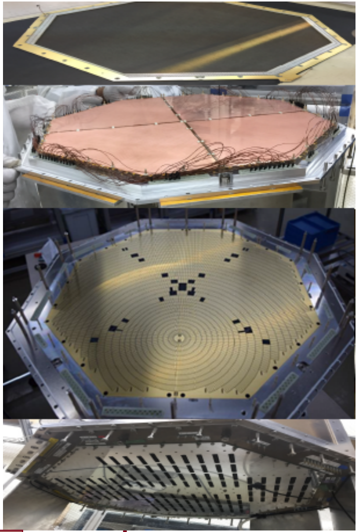
E42 Detector for the H-Dibaryon Search

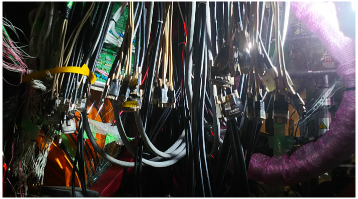


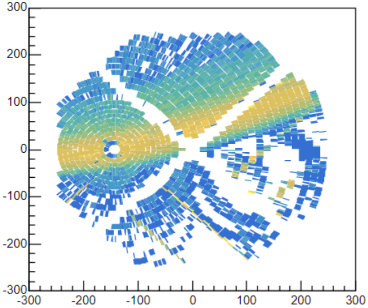


- (K^-, K^+) reaction events are tagged by the K1.8 beam and the KURAMA spectrometers.
- Decays of the $S = -2$ system are reconstructed using the Superconducting Hyperon Spectrometer.

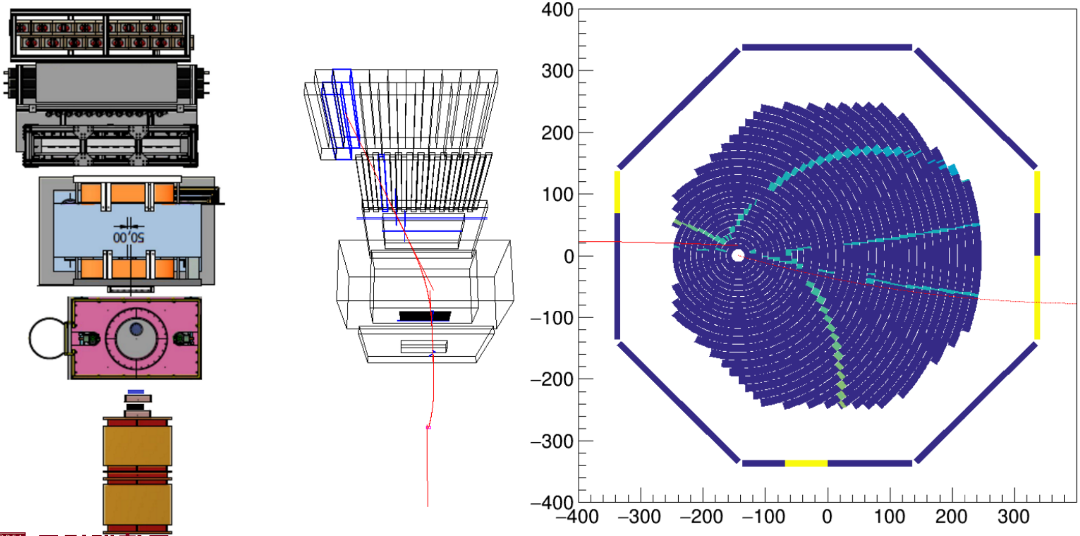
Hyperon Time Projection Chamber (HypTPC)



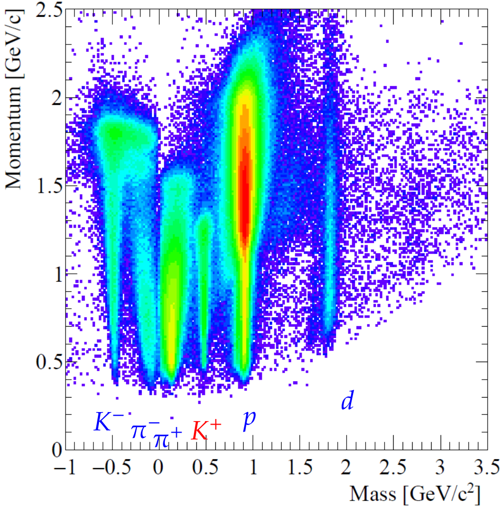


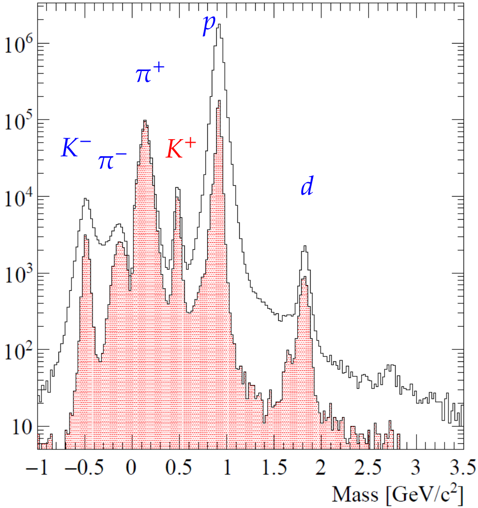


$^{12}C(K^-, K^+)$ Reaction Event



Scattered Particles at Forward Angles





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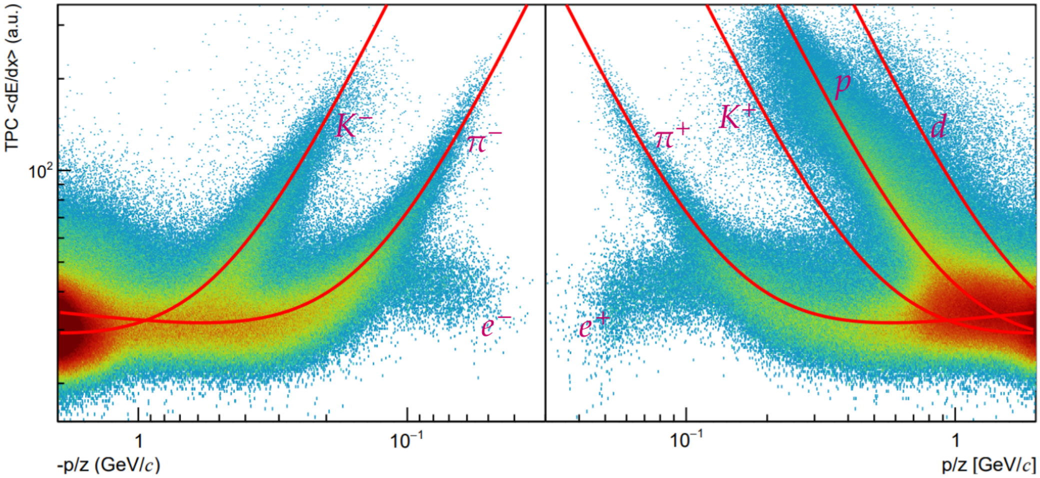
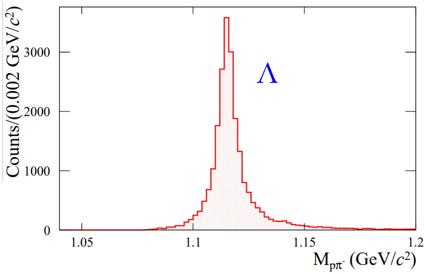
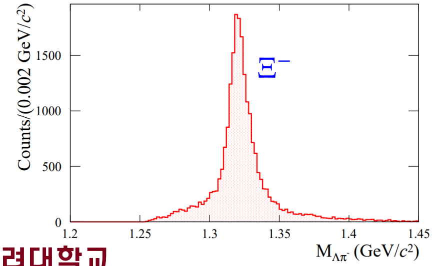
Particle Identification with HypTPC

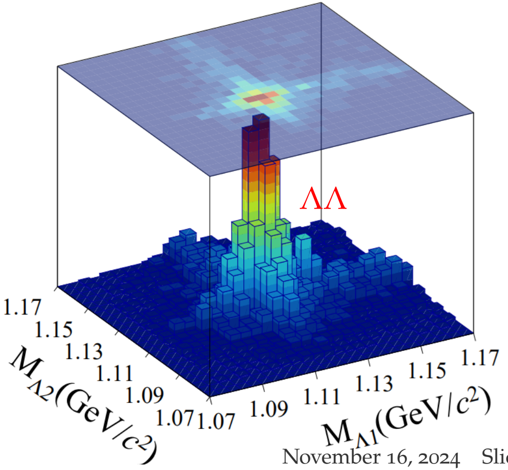


H-Dibaryon Search Experiment (J-PARC E42)





- We are nearing the final step in opening the box.



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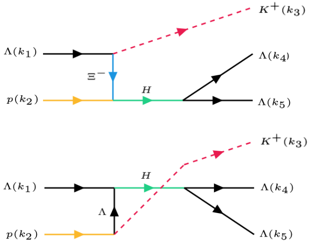
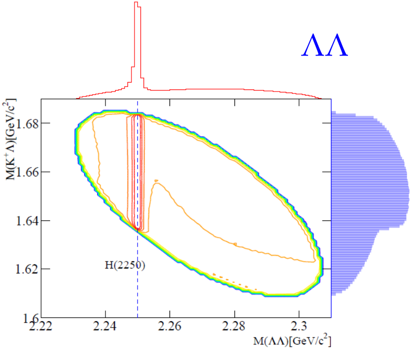
H-Dibaryon in Λp Reaction

- $\Lambda p \to K^+ X$ reaction at 2.83 GeV/c within the effective Lagrangian approach. [a]

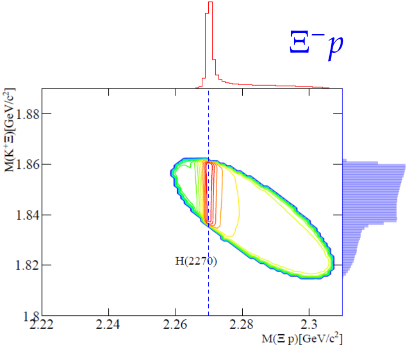
[a] J.K. Ahn and S.-i. Nam, Phys. Rev. D 103, 114022 (2021).



$\Lambda\Lambda$

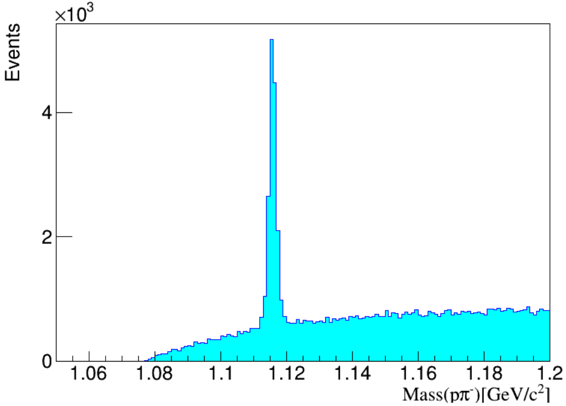


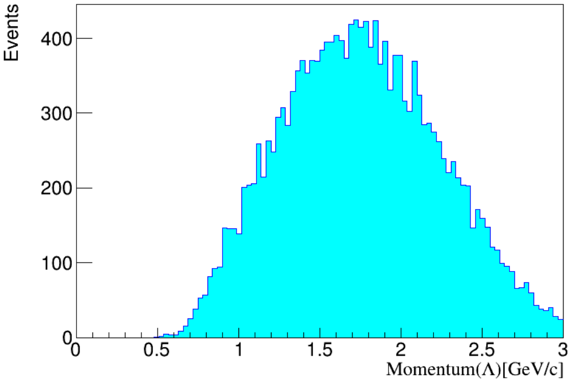
$\Xi^- p$



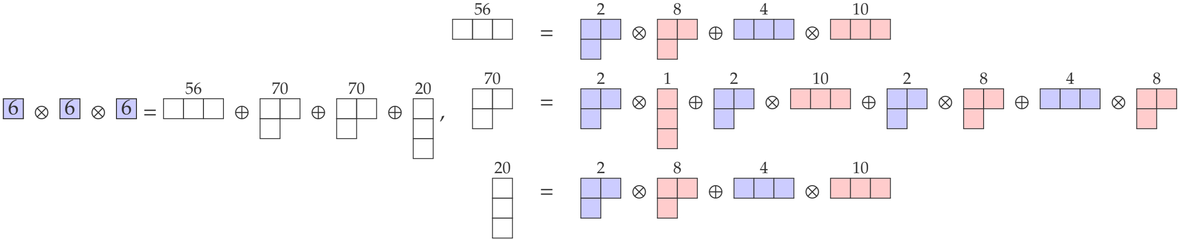
High-momentum Λ Beam from Photoproduction

- LEPS collected approximately 10^5 Λ hyperons in $p\pi^-$ mass at forward angles.
- The Λ momentum range reached 3 GeV/c to make the $\Lambda p \to HK^+$ reaction viable.





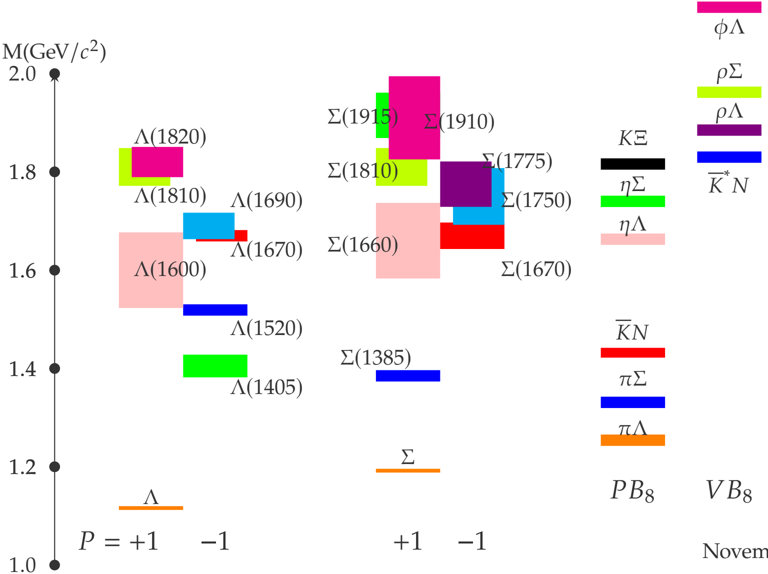
Low-lying Hyperons in the Quark Model



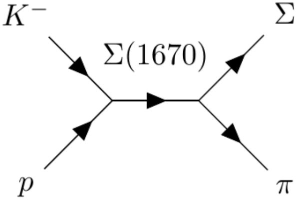
J^p	(D, L_N^P)	Octets			Singlet
$1/2^+$	$(56, 0_0^+)$	$\Lambda(1116)$	$\Sigma(1193)$	$\Xi(1318)$	
$1/2^+$	$(56, 0_2^+)$	$\Lambda(1600)^{***}$	$\Sigma(1660)^{***}$	$\Xi(?)$	
$1/2^-$	$(70, 1_1^-)$	$\Lambda(1670)^{****}$	$\Sigma(1620)^{*}$	$\Xi(1690)$	$\Lambda(1405)$
$3/2^-$	$(70, 1_1^-)$	$\Lambda(1690)^{****}$	$\Sigma(1670)^{****}$	$\Xi(1820)$	$\Lambda(1520)$

J^p	(D, L_N^P)	Decuplets		
$3/2^+$	$(56, 0_0^+)$	$\Sigma(1385)$	$\Xi(1530)$	$\Omega(1672)$

Λ^* and Σ^* Resonances



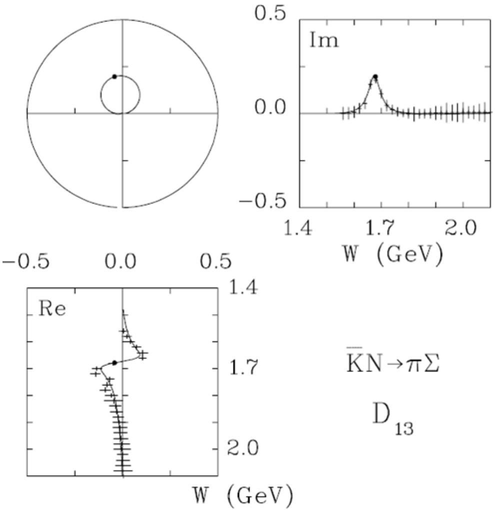
Σ(1670) in Formation Experiments



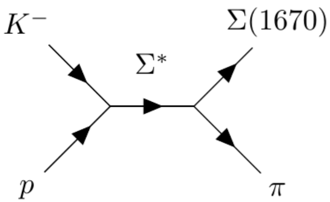
Σ(1670) MASS

DOCUMENT ID		TECN	COMMENT
KOISO	85	DPWA	$K^- p \to \Sigma\pi$
GOPAL	80	DPWA	$\overline{K}N \to \overline{K}N$
ALSTON-...	78	DPWA	$\overline{K}N \to \overline{K}N$
GOPAL	77	DPWA	$\overline{K}N$ multichannel
HEPP	76B	DPWA	$K^- N \to \Sigma\pi$
BAILLON	75	IPWA	$\overline{K}N \to \Lambda\pi$
VANHORN	75	DPWA	$K^- p \to \Lambda\pi^0$
KANE	74	DPWA	$K^- p \to \Sigma\pi$
MARTIN	77	DPWA	$\overline{K}N$ multichannel
DEBELLEFON	76	IPWA	$K^- p \to \Lambda\pi^0$
PONTE	75	DPWA	$K^- p \to \Lambda\pi^0$

- Formation experiments observe one Σ resonance in the 1670 MeV mass region with $J^P = \frac{3}{2}^-$, primarily decaying to $N\bar{K}$, $\Lambda\pi$, and $\Sigma\pi$.



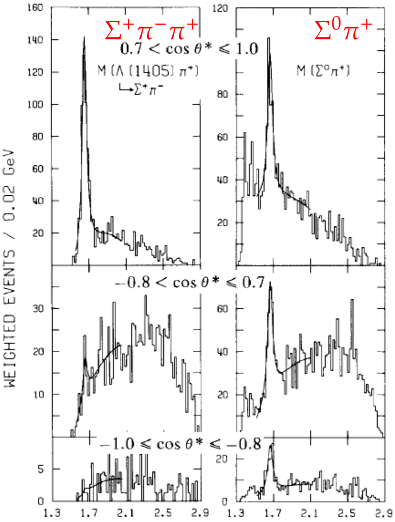
Σ(1670) in Production Experiments



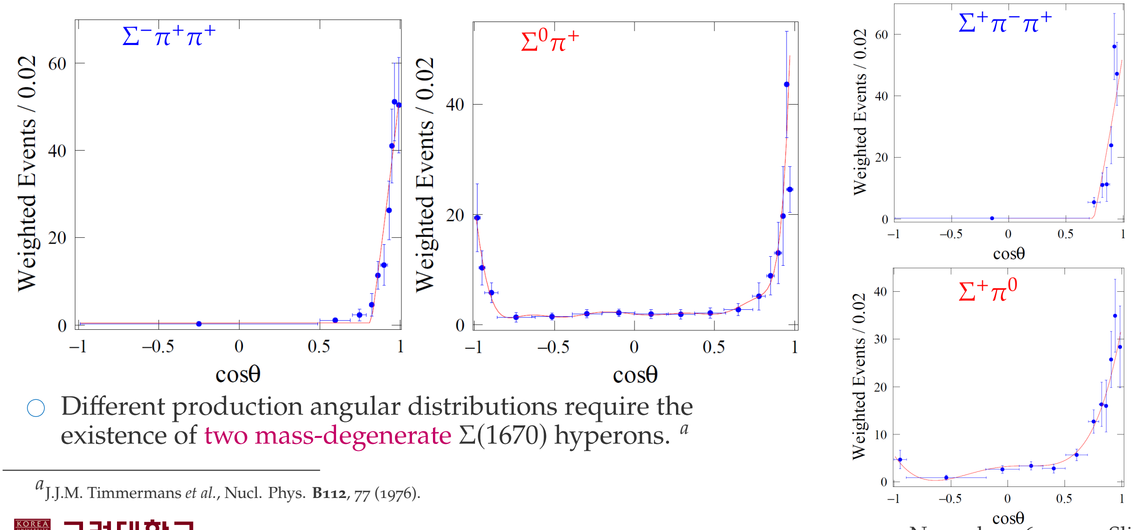
Σ(1670) (PRODUCTION EXPERIMENTS)

DOCUMENT ID		TECN	CHG	COMMENT
[1] CARROLL	76	DPWA		Isospin-1 total σ
[2] HEPP	76	DBC	−	$K^- N$ 1.6–1.75 GeV/c
APSELL	74	HBC		$K^- p$ 2.87 GeV/c
BERTHON	74	HBC	0	Quasi-2-body σ
AGUILAR-...	70B	HBC		$K^- p \to \Sigma\pi\pi$ 4 GeV
AGUILAR-...	70B	HBC		$K^- p \to \Sigma 3\pi$ 4 GeV
ALVAREZ	63	HBC	+	$K^- p$ 1.51 GeV/c
[3] FERRERSORIA	81	OMEG	−	$\pi^- p$ 9,12 GeV/c
TIMMERMANS	76	HBC	+	$K^- p$ 4.2 GeV/c
BUGG	68	CNTR		$K^- p$, d total σ
PRIMER	68	HBC	+	See BARNES 69E
ALEXANDER	62C	HBC	−0	$\pi^- p$ 2–2.2 GeV/c

- Production experiments have found evidence for two Σ resonances in this mass region with similar mass and width. This evidence is based on a difference in the production angular distributions of Σ(1670) decaying to $\Sigma\pi$ and to $\Sigma\pi\pi$.



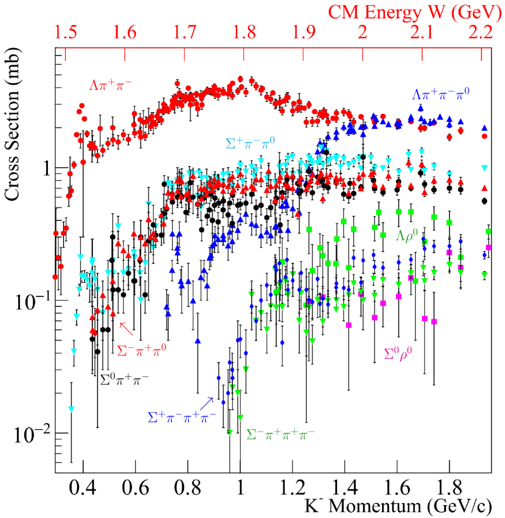
$\Sigma(1670)$ in Production Experiments



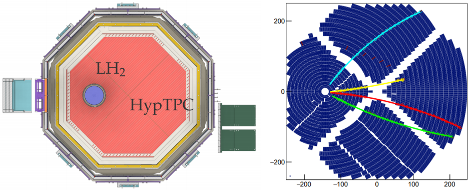
- Different production angular distributions require the existence of two mass-degenerate $\Sigma(1670)$ hyperons. [a]

[a] J.J.M. Timmermans *et al.*, Nucl. Phys. **B112**, 77 (1976).

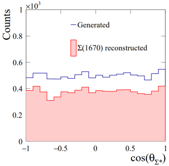
$\Sigma(1670)$ Formation and Production in K^-p Reactions



- High-statistics measurement is required to reconfirm the existence of two $\Sigma(1670)$ resonances and to unveil the nature of these states.
- $K^-p \to \Sigma(1670) \to \Sigma^\pm\pi^\mp, \quad \Sigma^0\pi^+\pi^-$
- $K^-p \to \Sigma(1670)^\pm\pi^\mp \to$ $\Sigma^0\pi^+\pi^-, \quad \Sigma^\pm\pi^\mp\pi^-\pi^+$

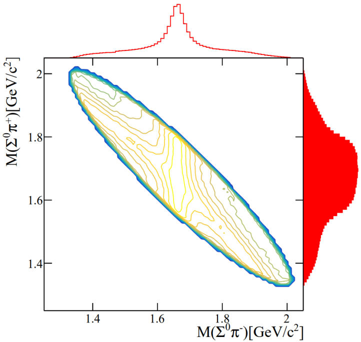


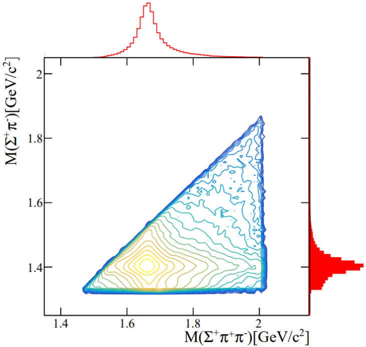
Possible Measurement of Σ(1670) with Hyperon Spectrometer

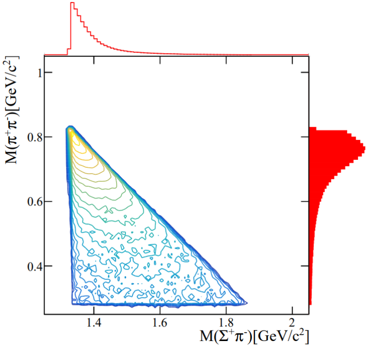


- Partial-wave analysis will unveil the nature of Σ(1670), based on high-statistics datasets from our proposed experiment. [a]

[a] W.S. Jung, B. Kang, J.K. Ahn, and S.Y. Ryu, to be submitted.







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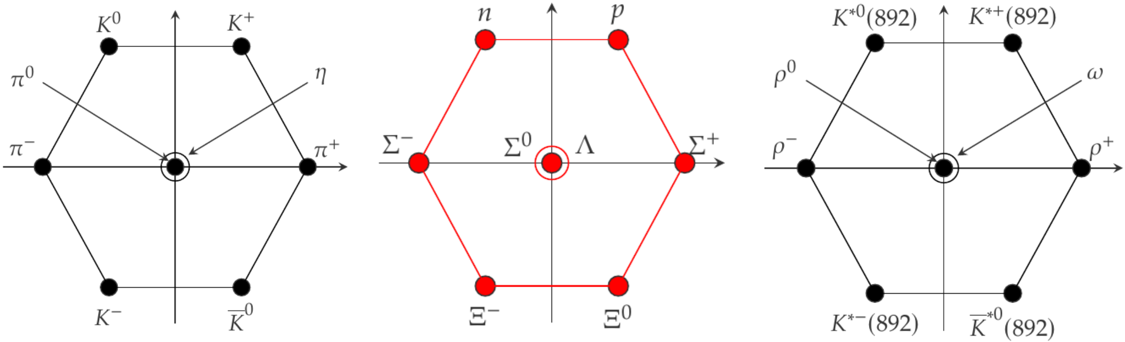
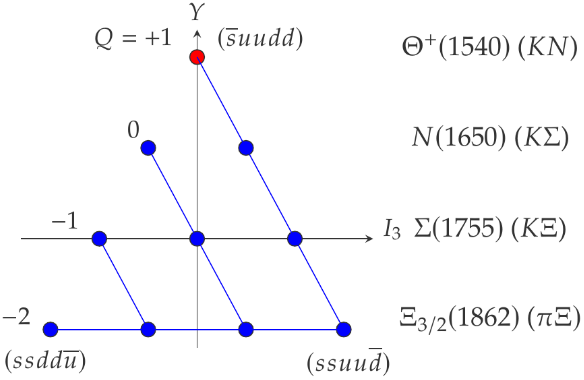
Pentaquark States in $SU(3)_f$ Antidecuplets

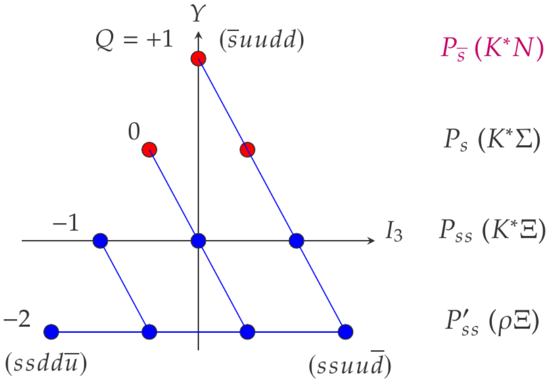


- For meson octet and baryon octet members, one can make the $SU(3)_f$ pentaquark multiplets:

$$8 \otimes 8 = 1 \oplus 8_S \oplus 8_A \oplus 10 \oplus \overline{10} \oplus 27$$

Pentaquark States in $SU(3)_f$ Antidecuplets

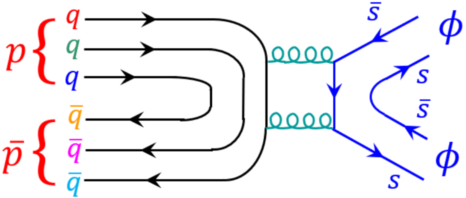


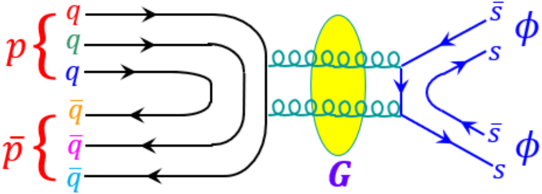


- Observation of new pentaquark states $P_s(K^*\Sigma, \phi N)$ will support the existence of the $P_{\bar{s}}(K^*N)$ state on the top corner of the $\overline{10}$ weight diagram.

$\bar{p}p \to \phi\phi$ Reaction

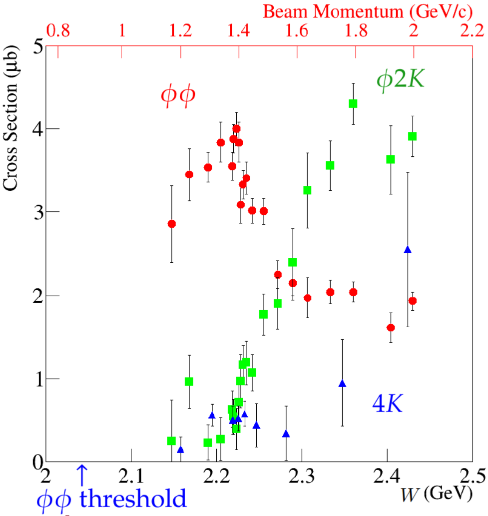
- The reaction $\bar{p}p \to \phi\phi$ may proceed via two gluon emission from $\bar{q}q$ annihilation.

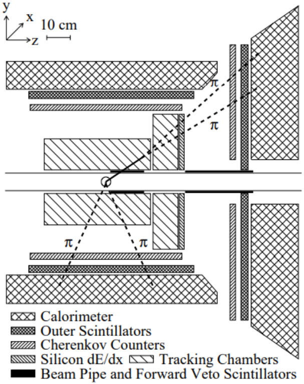




- All three valence quarks in p annihilate with the corresponding three antiquarks in $\bar{p}$ to produce a purely gluonic state from which $\phi\phi$ is formed. This should be OZI-suppressed without an intermediate resonant gluonic state (glueball).

$\bar{p}p \to \phi\phi$ (JETSET)





- JETSET observed unexpectedly large magnitude for $\bar{p}p \to \phi\phi$ cross section [a].

[a] JETSET, Il Nouvo Cimento 107, 2329 (1994); JETSET, Phys. Rev. D 57, 5370 (1998).

Reaction Mechanisms for $\bar{p}p \to \phi\phi$

- A substantial OZI rule violation could be the signal of interesting new physics.
  1. Production of glueballs
  2. Coupling to four quark states involving $\bar{s}s$ such as $\phi(2170)/X(2239)$[a].
  3. Non-strange quark component of the ϕ meson, due to the actual mixing of the vector meson singlet and octet:[b]

$$\sigma(\bar{p}p \to \phi\phi) = \tan^4\delta \cdot \sigma(\bar{p}p \to \omega\omega) \approx 10\ \text{nb},$$

  4. The presence of substantial $\bar{s}s$ content in $\bar{p}p$ wave functions,
  5. Instanton induced interactions between quarks
  6. Hadron production and its rescattering in which each individual transition is OZI-allowed,
  7. Baryon exchange in t- and u- channel diagrams.

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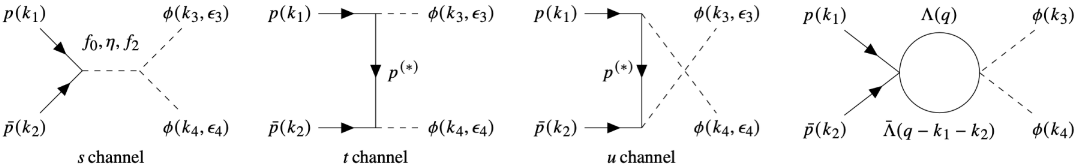
[a] H.-W. Ke and X.-Q. Li, Phys. Rev. D 99, 036014 (2019); Q.-F. Lü et al., Chinese Phys. C 44, 024101 (2020).

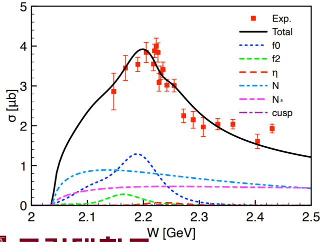
[b] The angle $\delta(= \Theta_i - \Theta)$ denotes the difference between the ideal mixing angle $\Theta_i = 35.3^\circ$ ($\sin\Theta_i = 1/\sqrt{3}$) and the mixing angle Θ between (ϕ, ω) mesons and the SU(3) states (ω_0, ω_8).

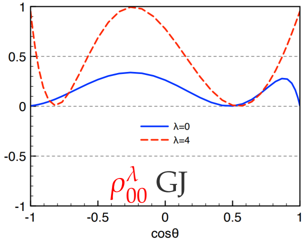
$\bar{p}p \to \phi\phi$ Reaction

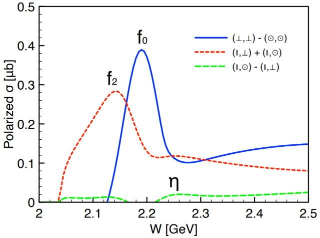


- A new theoretical calculation shows that spin observables (spin-density matrix elements, spin correlation between two ϕ mesons) may pin down the individual process contributions. [a]

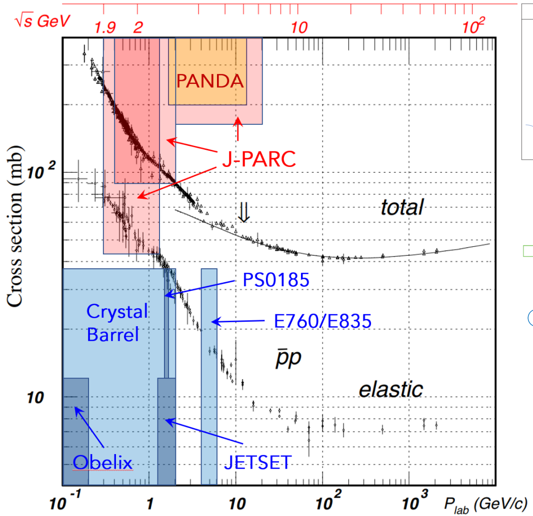
[a] D.Y, Lee, J.K. Ahn, S.i. Nam, arXiv:24xxx submitted to PRD.

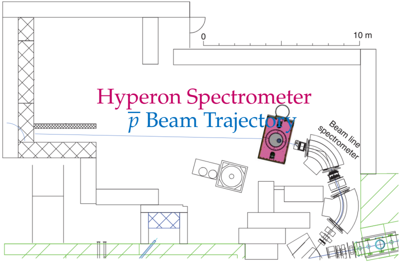


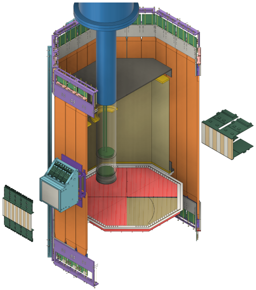


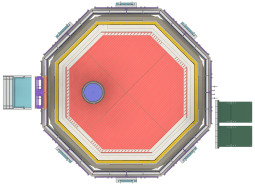


Antiproton Beam Facilites and Experiments



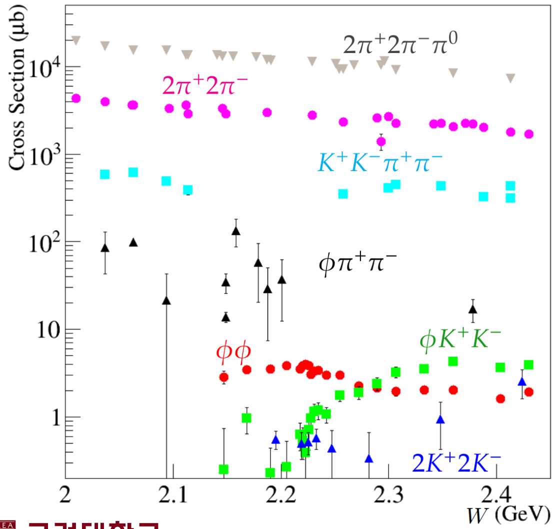






- The J-PARC K1.8BR beamline delivered 2×10^5 $\overline{p}$ per spill during the 5.2 s duration (40 kHz) in the 50 kW operation and can provide 64 kHz at 80 kW.

Background $\bar{p}p \to$ 4-prong Reactions



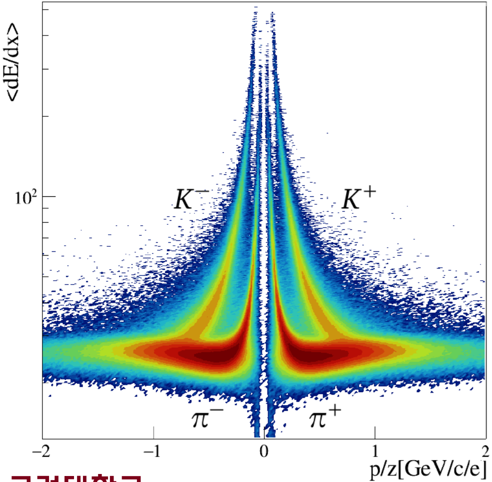
$\bar{p}p$ Reactions	$p^{\text{lab}}_{\text{thre}}$ (GeV/c)
$2\pi^+2\pi^-\pi^0$	0
$2\pi^+2\pi^-$	0
$K^+K^-\pi^+\pi^-$	0
$\phi\pi^+\pi^-$	0
$2K^+2K^-$	0.662
ϕK^+K^-	0.767
$\phi\phi$	0.866
$\bar{p}p\pi^+\pi^-$	1.219
$\bar{p}p\phi$	3.403

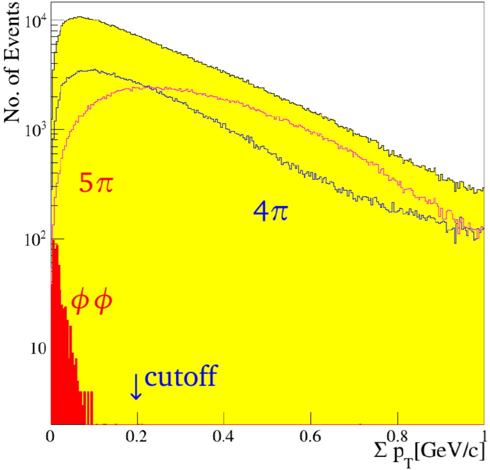
- Multipion production processes dominate $\bar{p}p$ reactions with four charged-particle emission. [a]

[a] V. Flaminio, W.G. Moorhead, D.R.O. Morrison, N. Riviore, CERN-HERA 84-01, 17, April 1984.

Particle ID and Momentum Balance Constraints

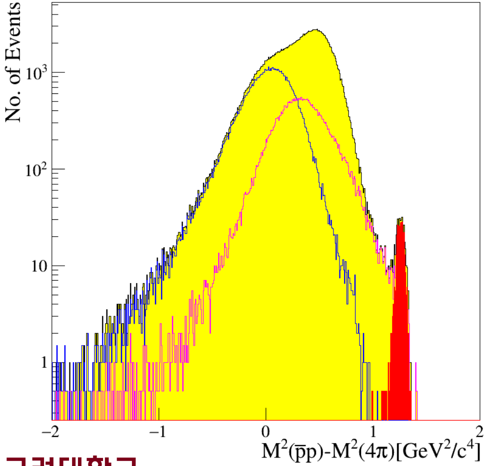
- The 5π events are then further rejected by requiring transverse momentum balance.

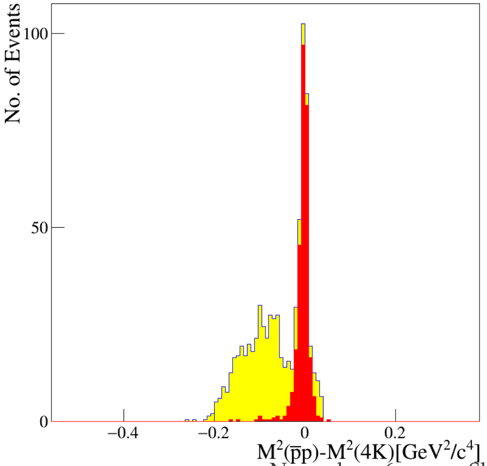




Event Selection with Energy Balance Contraints

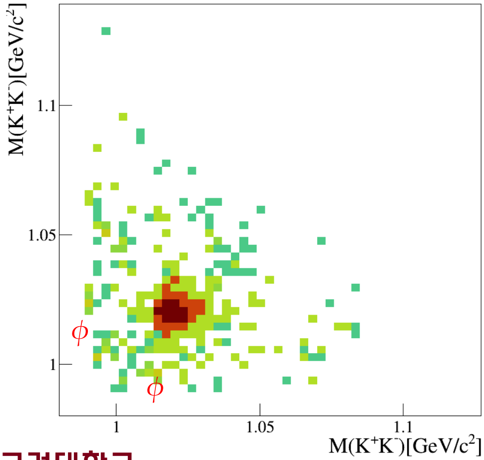
- Energy balance constraints in the center-of-mass energy ($\Delta m^2 = (p_{\bar{p}} + p_p)^2 - (\sum_{i=1}^{4} p_i)^2 = 0$, where p_i denotes a four-momentum of particle i) between the intial and final states.

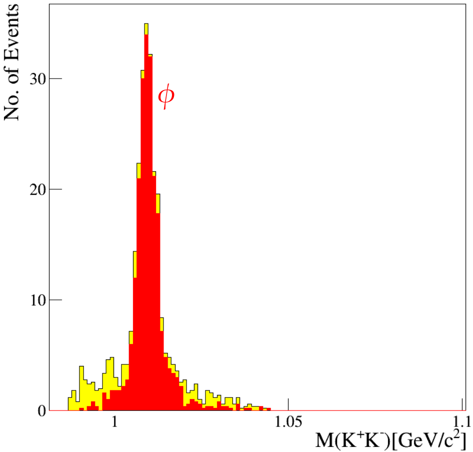




Reconstructed $\phi\phi$ Events

- From two K^+ and two K^- tracks, the correct pair of two oppositely charged kaons is chosen by selecting the pair with a mass closer to M_ϕ. from M_ϕ.





Expected Yield $\overline{p}p \longrightarrow \phi\phi$ Events

- For the 80 kW MR operation the trigger rate is 0.046 Hz.
- Background processes ($2\pi^+2\pi^-,\ 2\pi^+2\pi^-\pi^0$) are largely suppressed by imposing kinematic constraints and ensuring excellent π/K separation of the HypTPC.
- Reconstruction efficiency for the $\phi\phi$ events ($\varepsilon_{\text{recon}} = 0.6$).
- Assuming the accelerator operates constantly 90% of the time ($\varepsilon_{\text{acc}} = 0.9$), the number of $\phi\phi$ events ($\sigma = 3\ \mu\text{b}$) collected in a day is

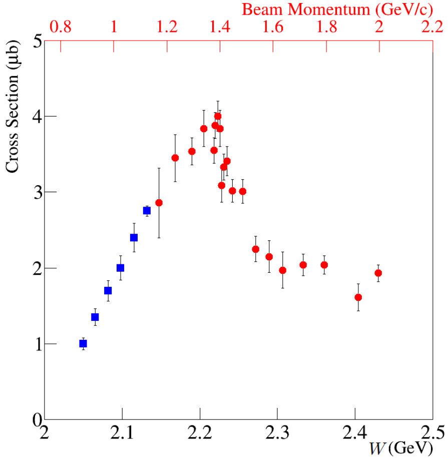
$$N_{2\phi} = 0.046/\text{s} \cdot \varepsilon_{\text{acc}} \cdot \varepsilon_{\text{recon}} \cdot \text{Br}(\phi \longrightarrow K^+K^-)^2 \cdot 8.64 \times 10^4\ \text{s/d}$$
$$\approx 5.2 \times 10^2/\text{d}$$

Beam Time Request (J-PARC P104)

- We are requesting 6.5 days of beam time. Three days will be dedicated to the high-statistics data collection at 1.15 GeV/c to measure spin observables.

The $\phi\phi$ Collaboration

- **Korea University (J.K. Ahn / spokesperson)**
- RCNP/OU, RARIS/Tohoku, RIKEN, GWU, CERN
- KEK, Tohoku, ASRC/JAEA, KNU
- PKNU, Inha, Soongsil, Giessen



Double ϕ Production in $\overline{p}p$ Reactions near Threshold

- The proposed experiment is meant as a feasibility study and independent confirmation of the enhancement of the production cross section near the threshold.
- Detailed studies of the production mechanism are the perspective for future work, both in theory and experiment.