# Exotic Hadrons wth Two Strange Quarks

## $H$-Dibaryon ($uuddss$) and $\phi\phi(s\bar{s}s\bar{s})$

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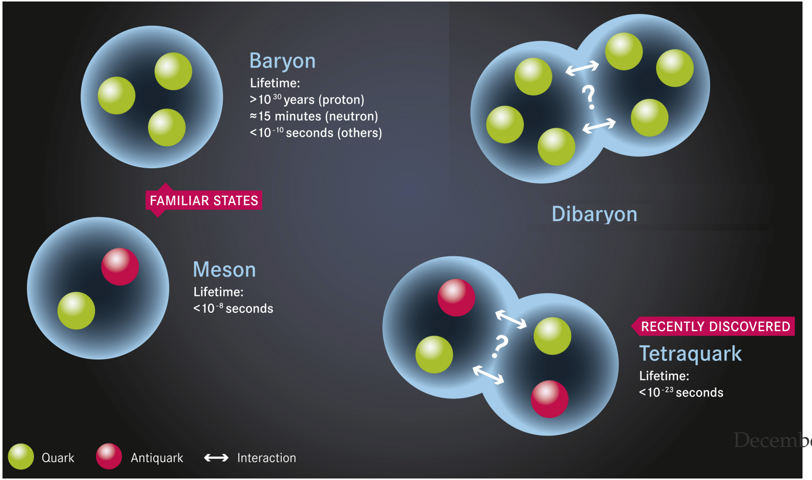
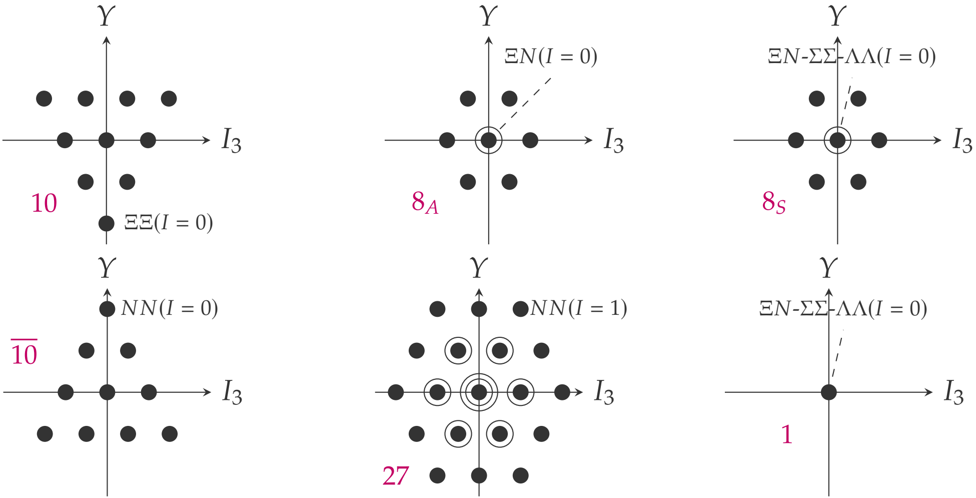
# $H$-Dibaryon

# Toward Drip Line of Multiquark States

- The observation of many multiquark candidates (XYZ, $P_c$) poses a question on the dripline of further multiquark states: hexaquark state.



# Dibaryon Multiplets in SU(3)$_f$



## Effective Hamiltonian

- The QCD color magnetic interaction can be summarized by an effective Hamiltonian acting on the quarks' spin and color indices;

$$\mathcal{H}_{\rm eff} \propto -\sum_{i\neq j} \vec{\lambda}_i \cdot \vec{\lambda}_j \vec{\sigma}_i \cdot \vec{\sigma}_j$$

- For $N$ quarks,

$$\mathcal{H}_{\rm eff} \propto -\sum_{i\neq j}^{N} \{\vec{\lambda}\vec{\sigma}\}_i \cdot \{\vec{\lambda}\vec{\sigma}\}_j = 8N - \frac{1}{2}C_6^N + \frac{4}{3}S_N(S_N+1).$$

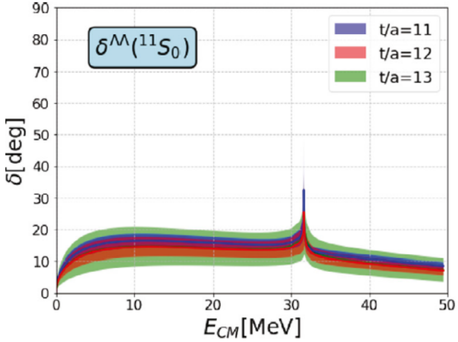
- For 6 quarks, the color-spin interaction energies are

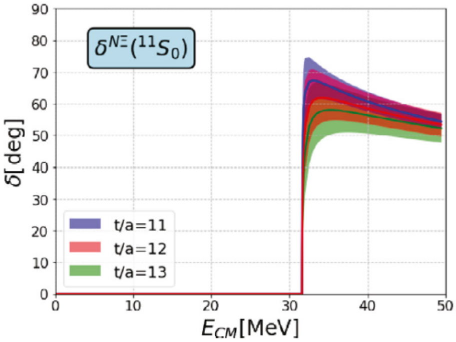
$$\langle\mathcal{H}_{\rm eff}\rangle_1 = -24, \quad \langle\mathcal{H}_{\rm eff}\rangle_8 = -28/3, \quad \langle\mathcal{H}_{\rm eff}\rangle_{\overline{10}} = +8/3, \quad \langle\mathcal{H}_{\rm eff}\rangle_{27} = +3,$$

# 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 ${}^{6}_{\Lambda\Lambda}$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 $H \longrightarrow \Lambda p \pi^-$ and $H \longrightarrow \Lambda\Lambda$ in high-energy
- $e^+e^-$, $pp$ and AA experiments
- 2021 — LQCD calculations point to the mass of the H-dibaryon
- very close to $\Xi N$ 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.

# Recent Lattice QCD Calculation Results




- LQCD calculation result predicts a sharp resonance just above $N\Xi$ threshold with $I = 0$ $^1S_0$ phase shifts at $m_\pi \approx 146$ MeV. [a]
- $\Lambda\Lambda$ correlations in HI collisions indicate a possible virtual state near $N\Xi$ threshold. [b]

[a] K. Sasaki for the HAL Collab., NPA 998 (2020) 121737.
[b] J. Haidenbauer, NPA 981, 1 (2019)

# H-Dibaryon Search at J-PARC : E42

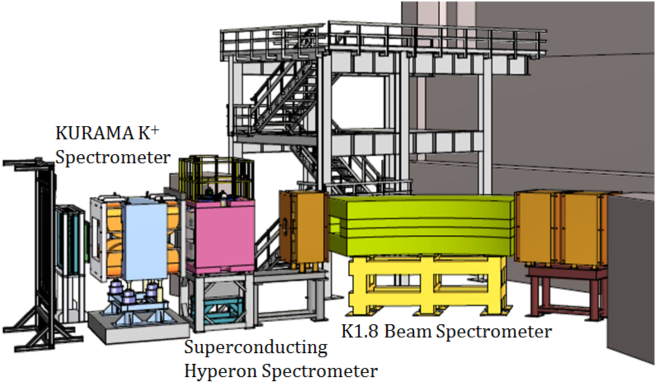
The existence of the H-dibaryon still awaits definitive experimental confirmation or exclusion.

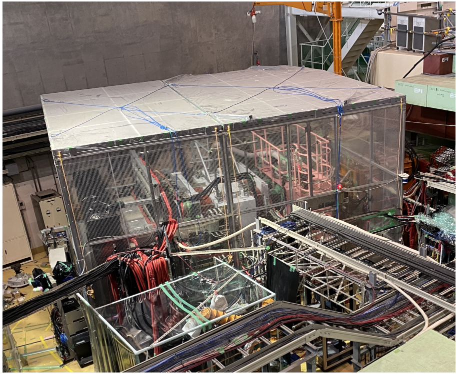
- Weakly-bound : $H \to \Lambda p \pi^-$
- Virtual state : $\Lambda\Lambda$ or $\Xi^- p$ threshold effect
- Resonance : Breit-Wigner peak in $\Lambda\Lambda$ and $\Xi^- p$ masses

## 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

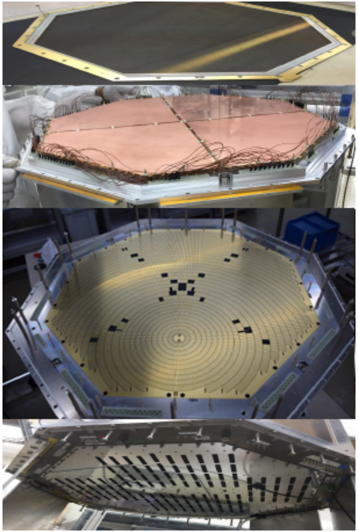
# E42 Detector for the $H$-Dibaryon Search

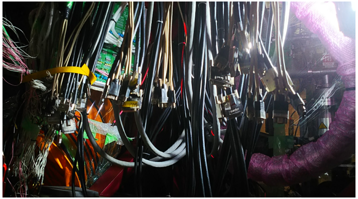


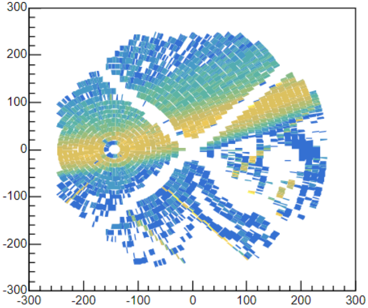



- $(K^-, K^+)$ reaction events are tagged by the K1.8 beam and the KURAMA spectrometers.
- Decays of the $S = -2$ system are reconstructed using the Superconducting Hyperon Spectrometer.

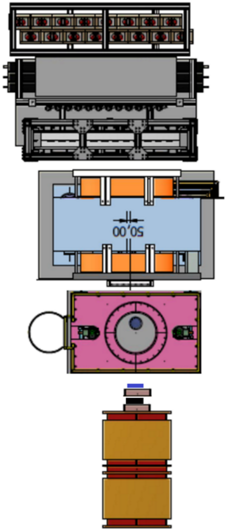
# Hyperon Time Projection Chamber (HypTPC)

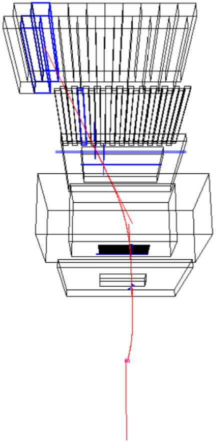


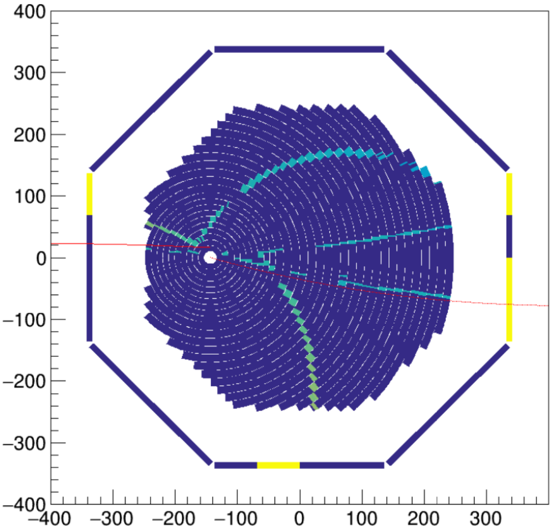




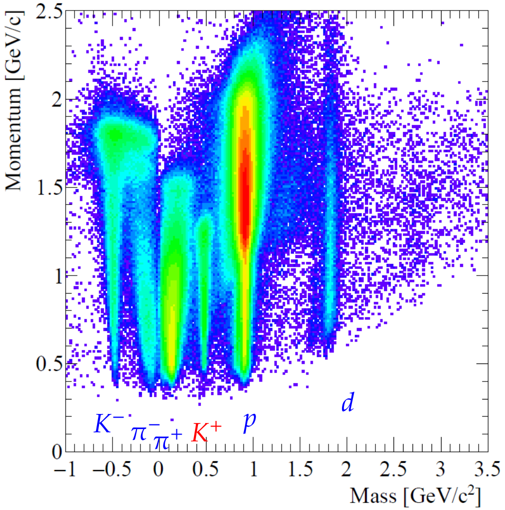
# $^{12}C(K^-, K^+)$ Reaction Event

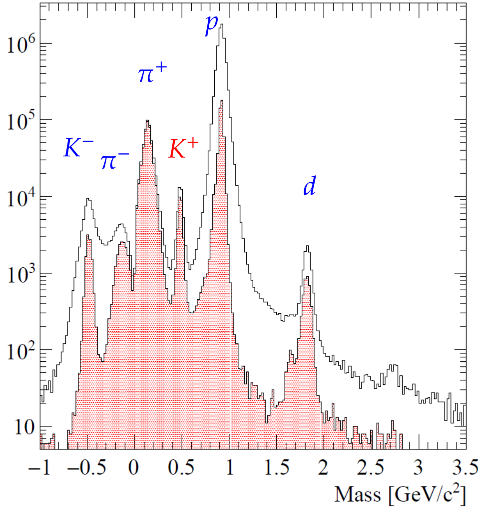




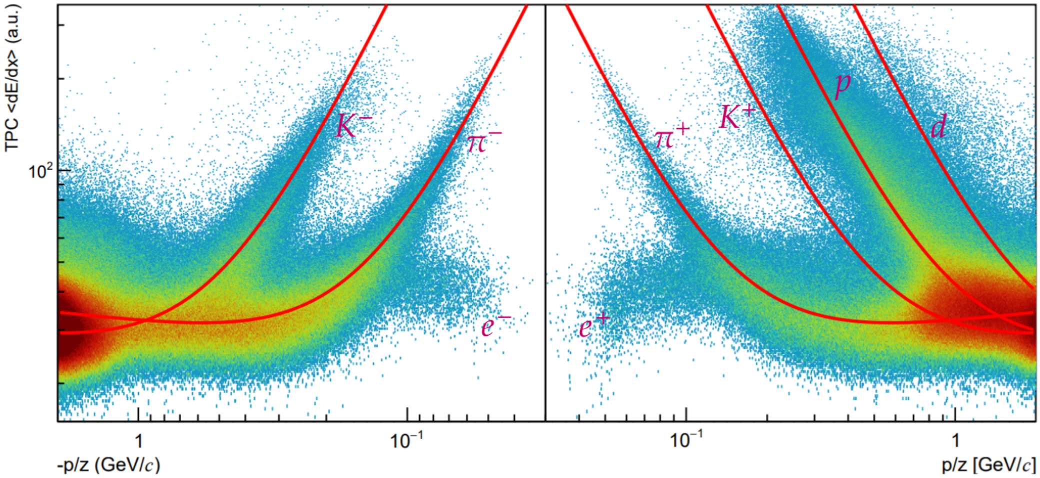


# Scattered Particles at Forward Angles



# Particle Identification with HypTPC



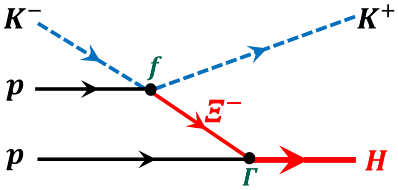
# Elementary processes in $(K^-, K^+)$ reactions

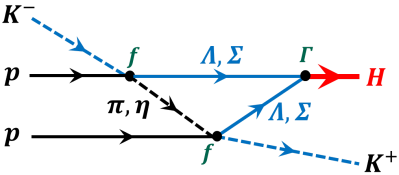
$$K^- p \to K^+ \begin{pmatrix} \Xi^- \\ \Xi(1535)^- \end{pmatrix}$$

$$K^- p \to \begin{pmatrix} \pi \\ \eta \\ \rho \end{pmatrix} \begin{pmatrix} \Lambda \\ \Sigma \\ \Sigma^* \end{pmatrix} ; \begin{pmatrix} \pi \\ \eta \\ \rho \end{pmatrix} N \to K^+ \begin{pmatrix} \Lambda \\ \Sigma \\ \Sigma^* \end{pmatrix}$$

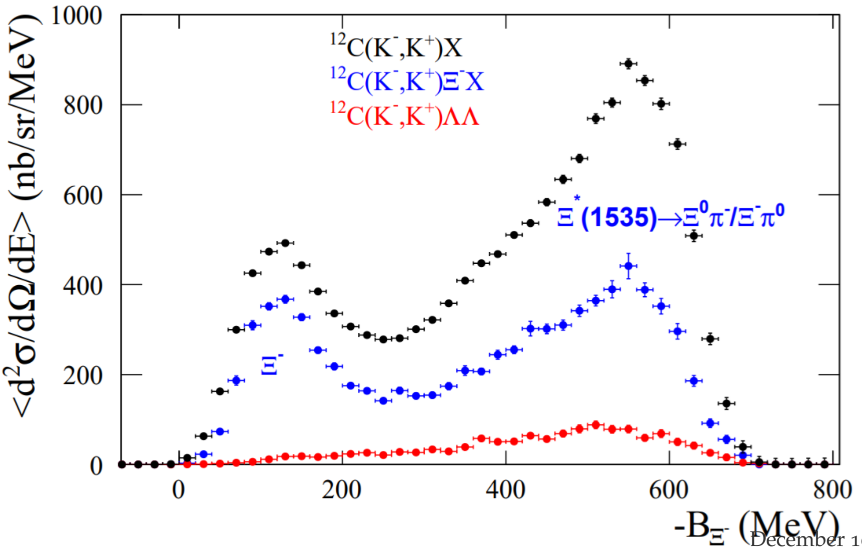
$$K^- p \to K^+ \Xi^- ; \Xi^- p \underbrace{\to}_{\mathbf{H}} \begin{pmatrix} \Lambda\Lambda \\ \Xi^- p \end{pmatrix}$$

$$K^- p \to \begin{pmatrix} \phi \\ a_0 \\ f_0 \end{pmatrix} \Lambda, \quad \text{where } \phi, a_0, f_0 \to K^+ K^-$$

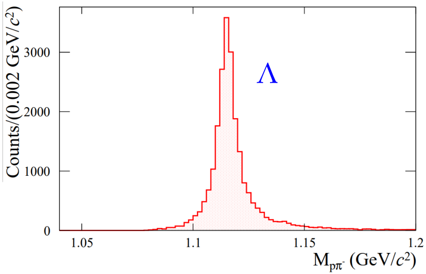


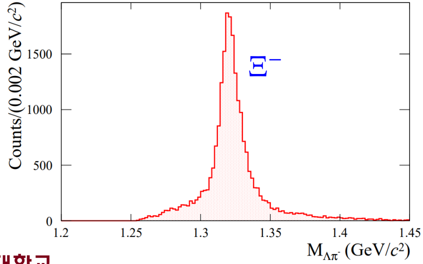



# Binding Energy Spectrum for $^{12}C(K^-, K^+)(\Xi^- + ^{11}B)$

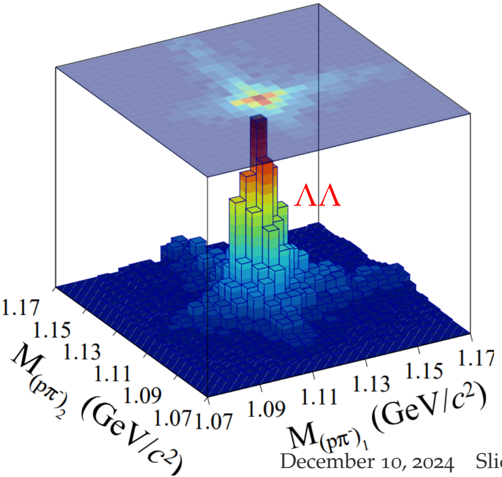


# *H*-Dibaryon Search Experiment (J-PARC E42)

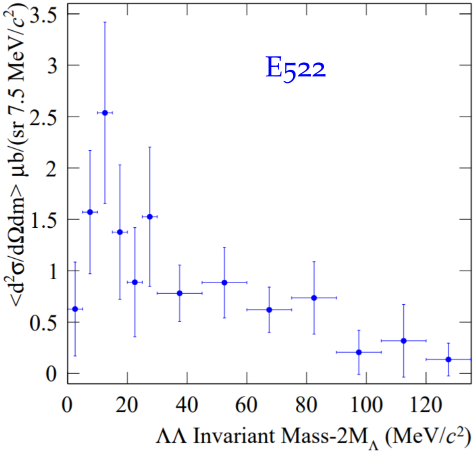


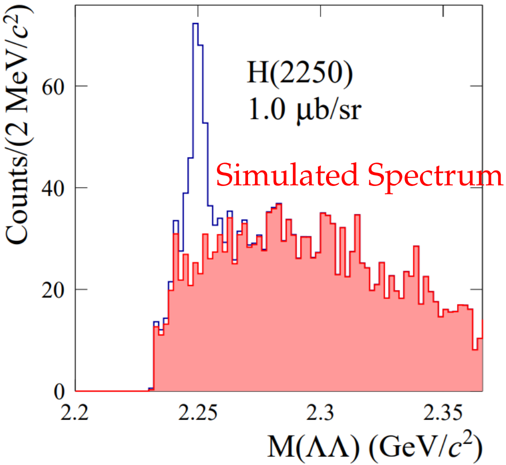




- We are nearing the final step in opening the box.



# *H*-Dibaryon Search Experiment (J-PARC E42)



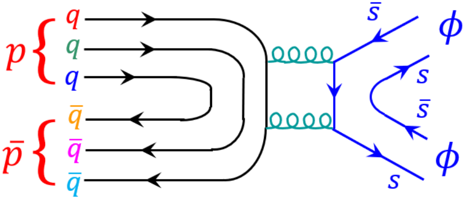



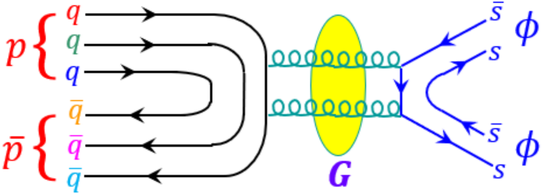

C.J. Yoon *et al.* (KEK-PS E522), Phys. Rev. C 75, 022201(R) (2007).

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

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

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

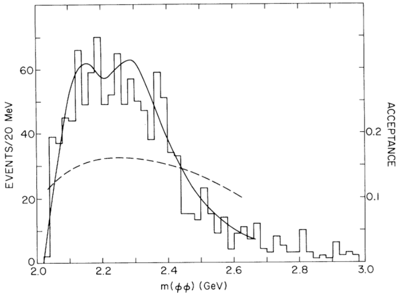



- All three valence quarks in $p$ annihilate with the corresponding three antiquarks in $\bar{p}$ to produce a purely gluonic state from which $\phi\phi$ is formed. This should be OZI-suppressed without an intermediate resonant gluonic state (glueball).

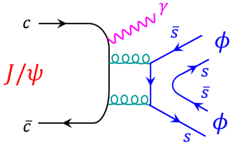
# $\pi^- p \to \phi\phi n$ and $J/\psi \to \gamma\phi\phi$

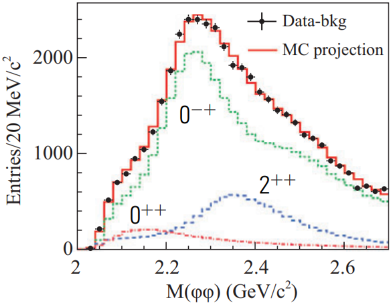
- Based on 1203 events of the reaction $\pi^- p \to \phi\phi n$ at 22 GeV/$c$, a BNL experiment reported an observation of two $2^{++}$ mesons at 2160 and 2320 MeV. [a]




[a] A. Etkin *et al.*, Phys. Rev. Lett. 49, 1620 (1982).

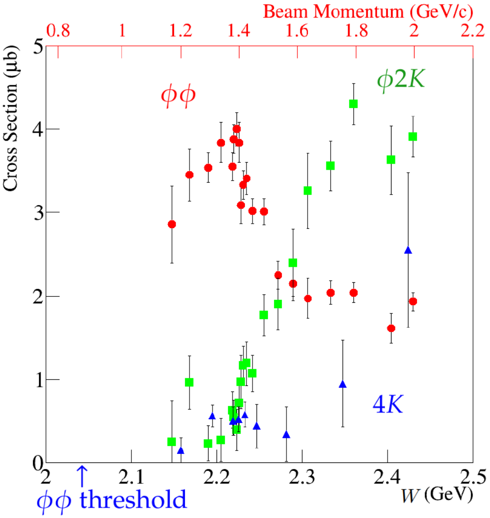
- BESIII reported an observation of $f_0(2100)$, $f_2(2010)$, $f_2(2300)$ and $f_2(2340)$. [a]

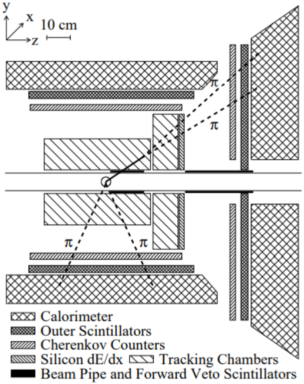



[a] BESIII, Phys. Rev D 93, 112011 (2016).

# $\bar{p}p \to \phi\phi$ (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 $\phi$ meson, due to the actual mixing of the vector meson singlet and octet:[b]

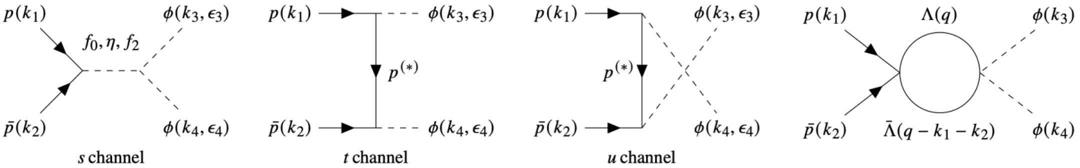
$$\sigma(\bar{p}p \to \phi\phi) = \tan^4\delta \cdot \sigma(\bar{p}p \to \omega\omega) \approx 10\ \text{nb},$$

  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.

[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 $\Theta$ between $(\phi, \omega)$ mesons and the SU(3) states $(\omega_0, \omega_8)$.

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




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

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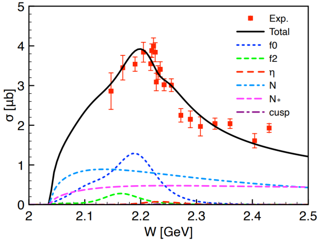
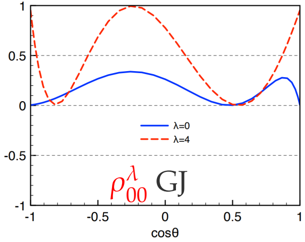
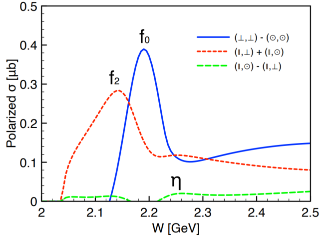
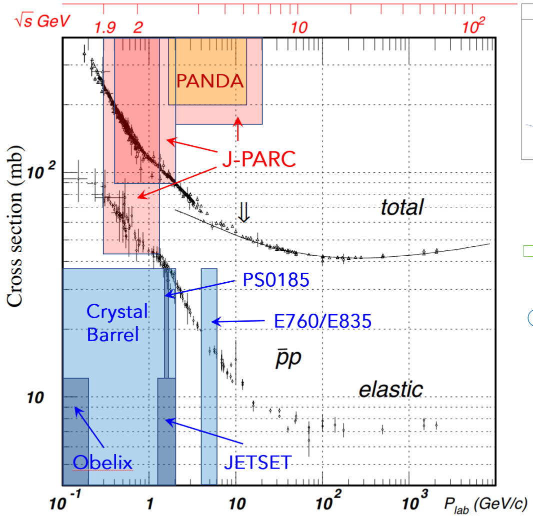
[a] D.Y, Lee, J.K. Ahn, S.i. Nam, arXiv:24xxx submitted to PRD.

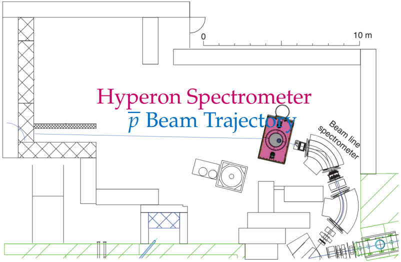


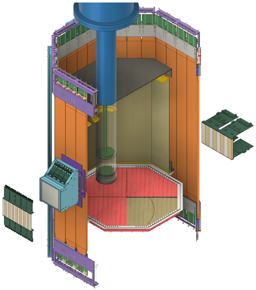



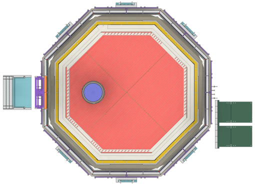



# Antiproton Beam Facilites and Experiments



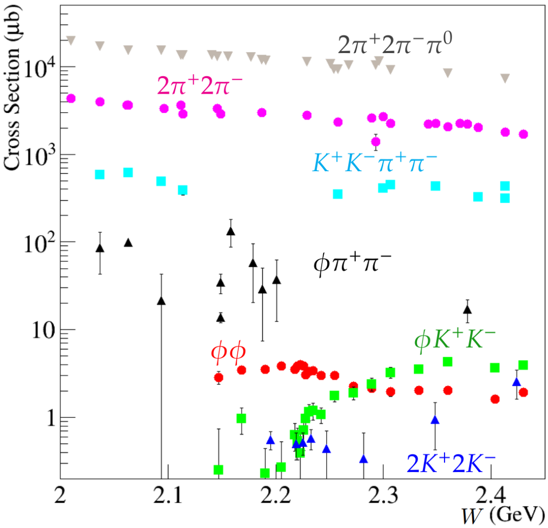





- The J-PARC K1.8BR beamline delivered $2 \times 10^5$ $\overline{p}$ per spill during the 5.2 s duration (40 kHz) in the 50 kW operation and can provide 64 kHz at 80 kW.

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



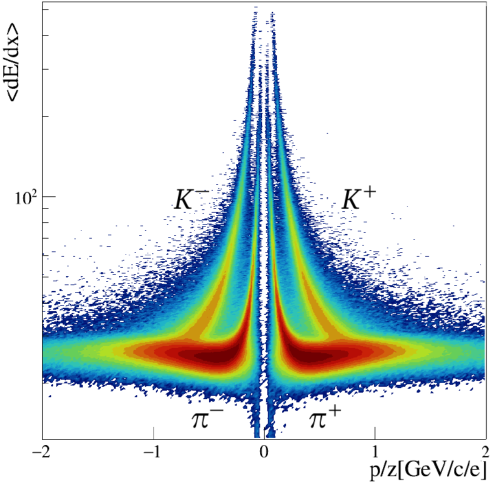

| $\bar{p}p$ Reactions | $p_{\text{thre}}^{\text{lab}}$ (GeV/$c$) |
|---|---|
| $2\pi^+2\pi^-\pi^0$ | 0 |
| $2\pi^+2\pi^-$ | 0 |
| $K^+K^-\pi^+\pi^-$ | 0 |
| $\phi\pi^+\pi^-$ | 0 |
| $2K^+2K^-$ | 0.662 |
| $\phi K^+K^-$ | 0.767 |
| $\phi\phi$ | 0.866 |
| $\bar{p}p\pi^+\pi^-$ | 1.219 |
| $\bar{p}p\phi$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

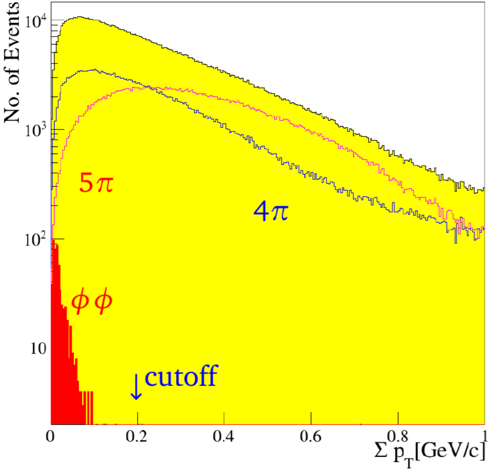
- Multipion production processes dominate $\bar{p}p$ reactions with four charged-particle emission. [a]

[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

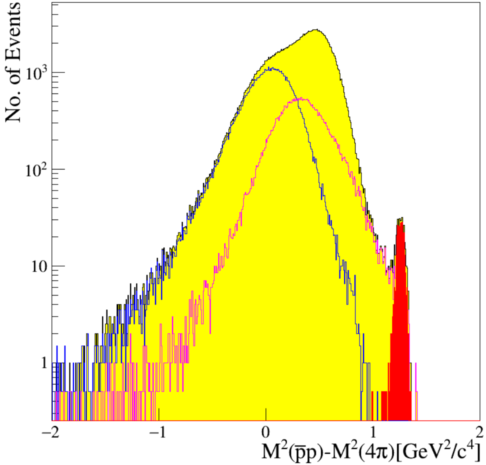
- The $5\pi$ events are then further rejected by requiring transverse momentum balance.

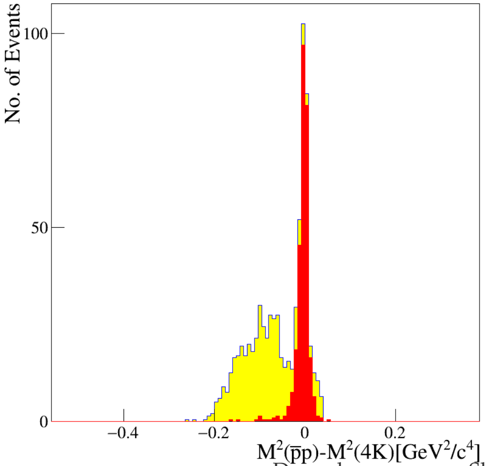


# Event Selection with Energy Balance Contraints

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

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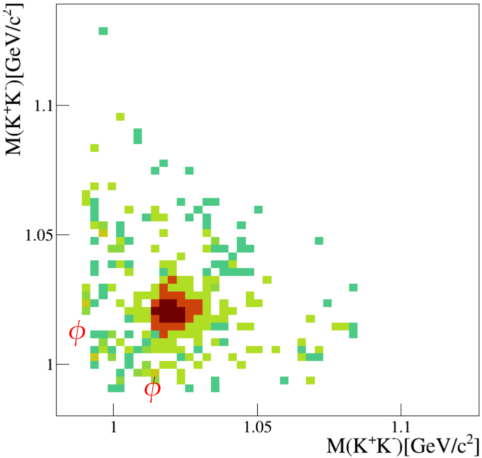
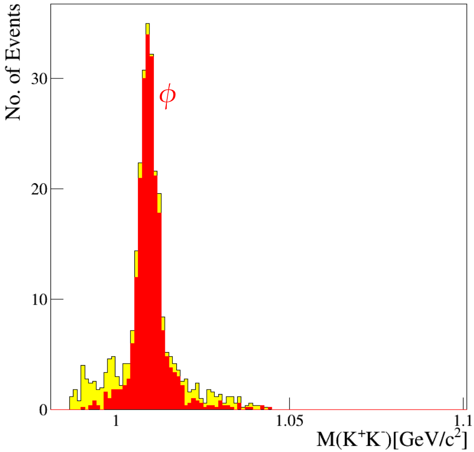
# Reconstructed $\phi\phi$ Events

- 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 $M_\phi$. from $M_\phi$.



# Expected Yield $\bar{p}p \rightarrow \phi\phi$ 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 $\pi/K$ 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

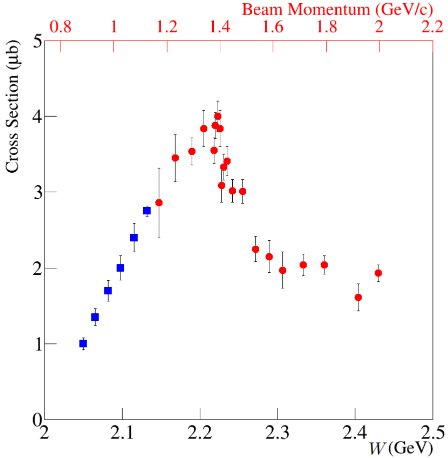
$$N_{2\phi} = 0.046/\text{s} \cdot \varepsilon_{\text{acc}} \cdot \varepsilon_{\text{recon}} \cdot \text{Br}(\phi \rightarrow K^+K^-)^2 \cdot 8.64 \times 10^4\ \text{s/d}$$
$$\approx 5.2 \times 10^2/\text{d}$$

# 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 $\phi$ Production in $\bar{p}p$ 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.