Exotic Hadron Spectroscopy with Photon and Hadron Beams

Searching for multiquark and glueball states

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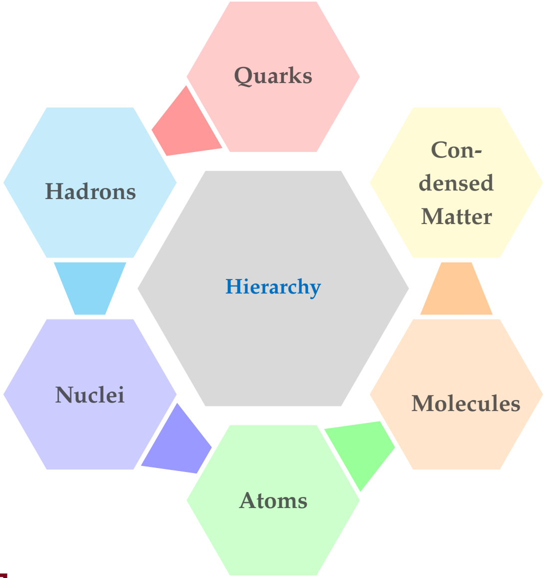
Outline

- Multiquarks and Molecular States (involving Light Quarks)
- Pentaquarks
- Dibaryons
- Glueballs

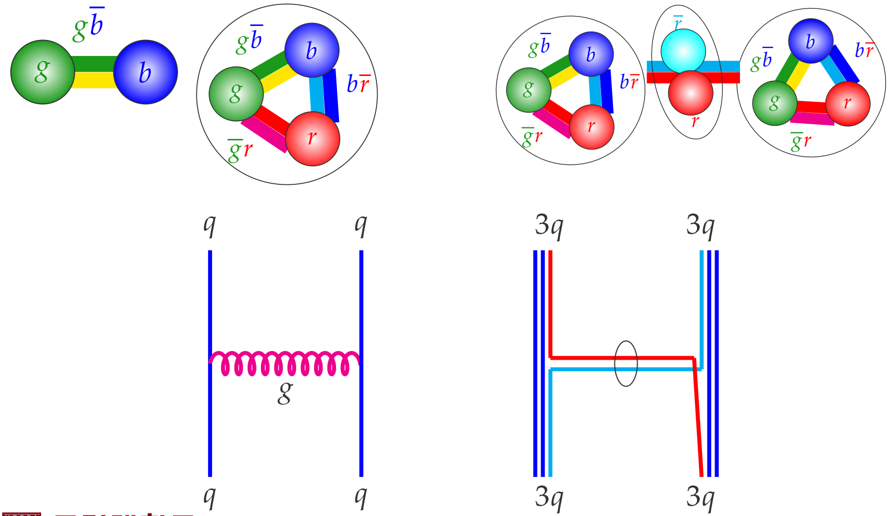
Multiquarks and Molecular States

The (Clustered) Structure of Matter



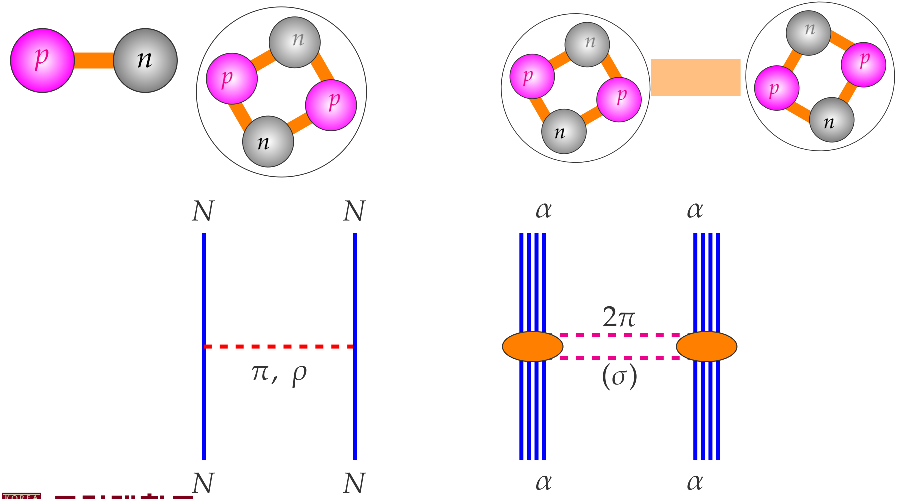
Quarks and Hadrons

- Color force saturation binds quarks as a form of colorless hadrons.

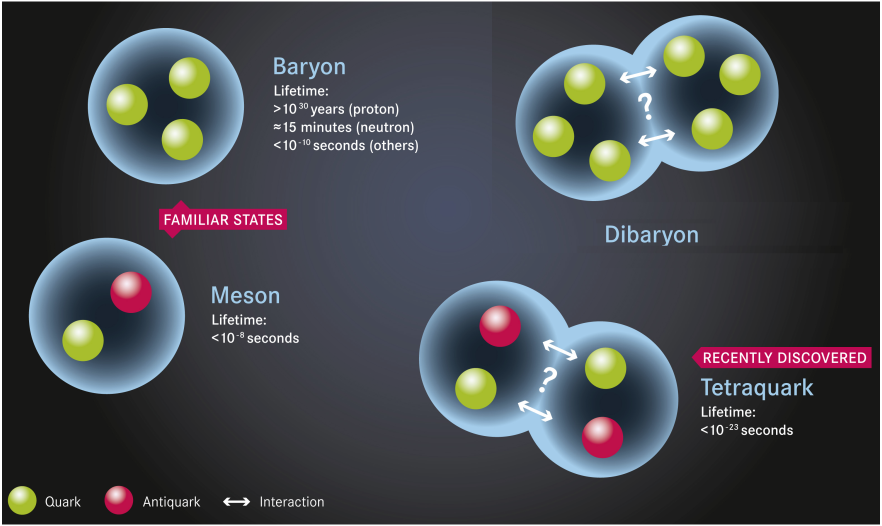


Nucleons and α Cluster

- Spin-Isospin force saturation binds nucleons as a form of scalar α clusters.

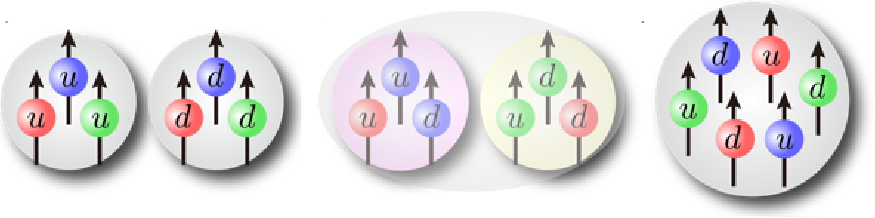


Quark Bound States



Dibaryon and Hexaquark States

- Bound state (color singlet) with two Δ baryons
- Bound state (color singlet) with two color octet baryons (each individual cluster cannot exist)
- Bound state (color singlet) with six independent quarks



Baryons in the Quark Model

- If we combine the spin and the flavor degrees of freedom to an SU(6) spin-flavor symmetry, each quark can be in one of the six different states: $u\uparrow, u\downarrow, d\uparrow, d\downarrow, s\uparrow, s\downarrow$.

- For baryons, one can make the following direct product:

$$\boxed{6} \otimes \boxed{6} \otimes \boxed{6} = \underset{56}{\square\square\square} \oplus \underset{70}{\square\square \atop \square} \oplus \underset{70}{\square\square \atop \square} \oplus \underset{20}{\square \atop {\square \atop \square}},$$

- It is possible to decompose the multiplets into their SU(2) ⊗ SU(3) content.

$$56 = 2 \otimes 8 \oplus 4 \otimes 10$$

$$70 = 2 \otimes 1 \oplus 2 \otimes 10 \oplus 2 \otimes 8 \oplus 4 \otimes 8$$

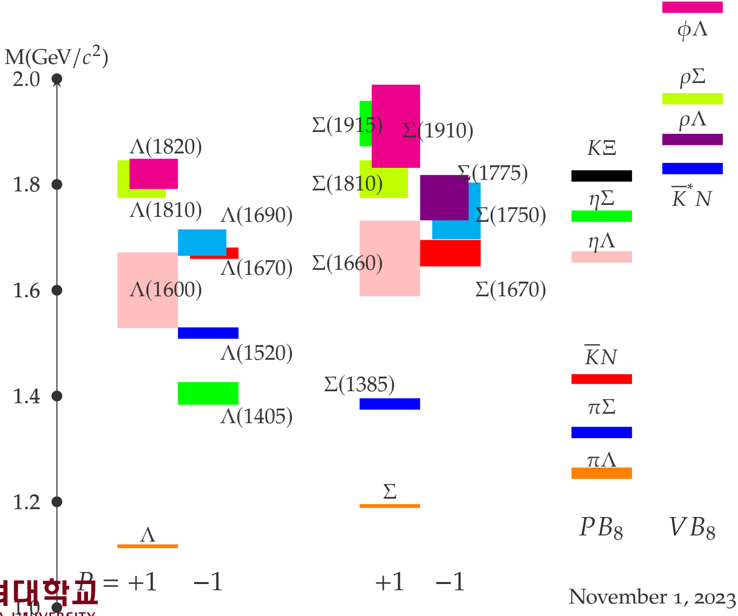
$$20 = 2 \otimes 8 \oplus 4 \otimes 10$$

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



Toward Drip Line of Multiquark States

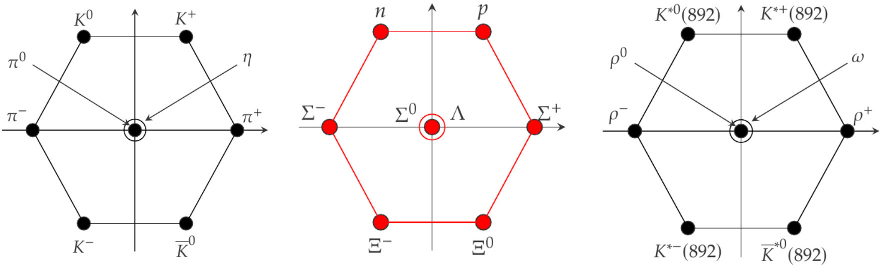
Multiquark States

- An exotic hadron is a state that cannot be classified in terms of standard qqq or $q\overline{q}$ configurations according to $\mathrm{SU}_f(3)$ irreducible representations: multiquark states ($qq\overline{q}\overline{q}$, $qqqq\overline{q}$, $6q$, and so on).

- The existence of multiquark hadrons is now firmly established in the meson sector: tetraquark states such as XYZ states.
- Recently, the LHCb collaboration claims on the observation of three hidden-charm pentaquark P_c states.
- The observation of such many multiquark candidates poses a question on the dripline of further multiquark states: hexaquark state.

PENTAQUARKS

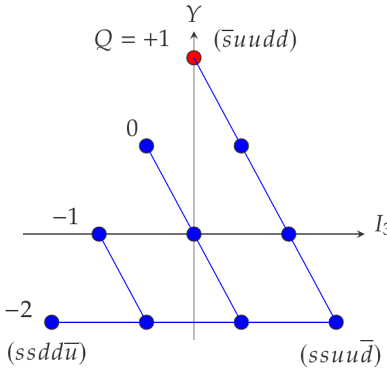
Pentaquark States in $SU(3)_f$ Antidecuplets



- 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



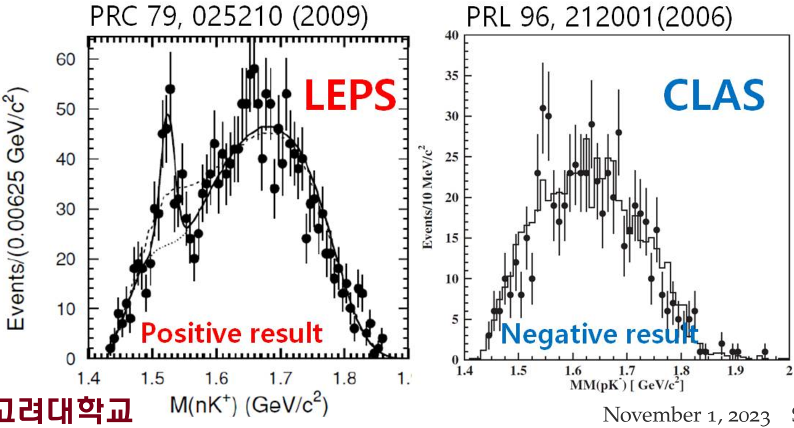
- In the chiral quark soliton model [a], the Θ^+ is a member of the $\overline{10}$ multiplet.

[a] D. Diakonov, V. Petrov, and M.V. Polyakov, Z. Phys. A **359**, 305 (1997).

- The mass splitting between the members was predicted to be 180 MeV multiplied by their strangeness unit difference. This model prediction highlighted the low-mass and narrow width of the $\Theta^+(1540)$ and its spin-parity of $J^p = 1/2^+$ given as a rotating soliton.

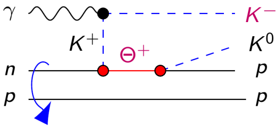
Θ^+ Searches

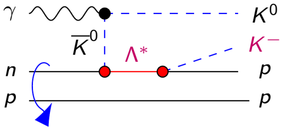
- The $\Theta^+(uudd\bar{s})$ has been once firmly established by many experiments.
- A high-statistics photoproduction JLab experiment found no evidence of the Θ^+ and other higher-statistics results have done likewise. Irrefutable evidence?

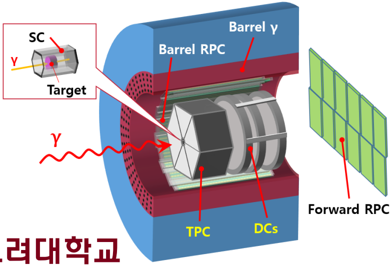


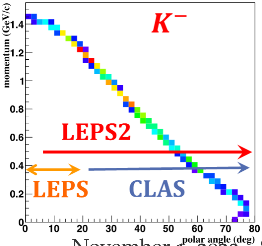
Θ^+ Search at LEPS2

- LEPS2/SPring-8 looks for the Θ^+ via $\gamma d \to K^- K^0 pp$ reaction, followed by $\Theta^+ \to K^0 p$; $K^0(K_S) \to \pi^+\pi^-$.
- All final state particles can be reconstructed using LEPS2 detector, which facilitate a wider angular coverage for K^- detection.





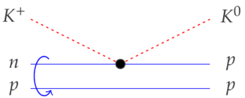


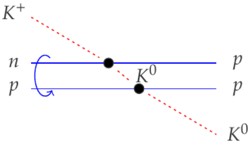


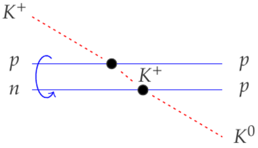
Θ^+ Formation in $K^+d \to K^0pp$ Reactions

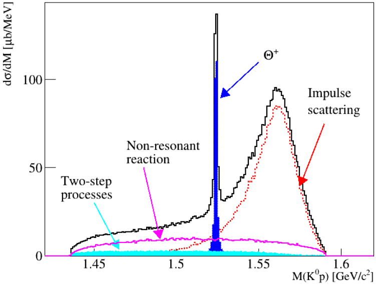
- Direct Θ^+ formation in the $K^+d \to K^0pp$ reaction at 0.5 GeV$/c$ [a]

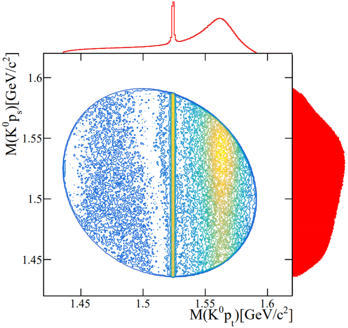
[a] J.K. Ahn and S.H. Kim, JKPS (2023).



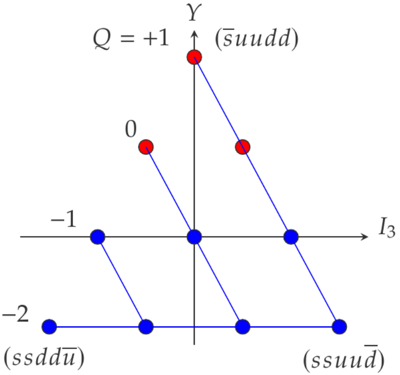








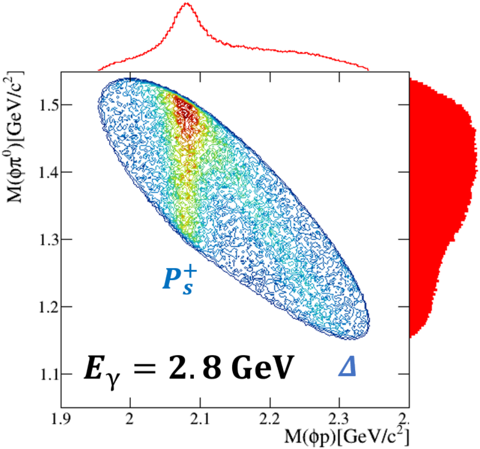
Pentaquark States in $SU(3)_f$ Antidecuplets



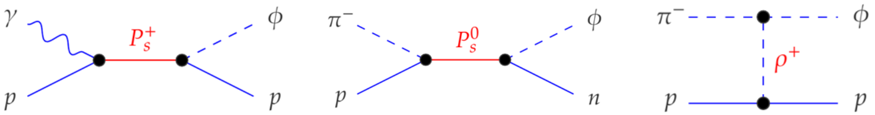
- Exotic N^* states (P_s) can sit in the isospin doublet places in the new $\overline{10}$ multiplet.
- If we assume a similar mass splitting between $P_{\bar{s}}$ and P_s states, $P_{\bar{s}}$ has a mass of 1.91 GeV [a], which can be searched for in photoproduction.

[a] G.S. Yang and S.-i. Nam in progress

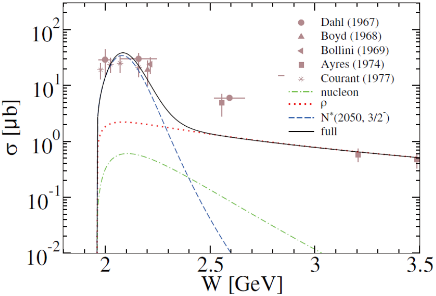
- Photoproduction of P_s with pion involves $\gamma p \to \pi^0 p$ (P_s^+) and $\gamma p \to \phi\pi^+ n$ (P_s^0) reactions.
- A simple event generator simulates $K^+K^-p\pi^0$ and $K^+K^-n\pi^+$ reactions involving ϕ, Δ, K^*, and P_s resonances.
- Exotic meson $\rho(1570)$ $J^{PC} = 1^{--}$, earlier referred to as $C(1480)$, could contribute to the $\gamma p \to \phi\pi N$ reactions (not included in the present simulation).



P_s Search via Pion-induced Reactions

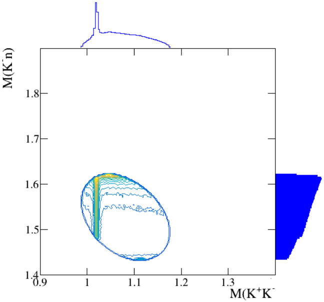


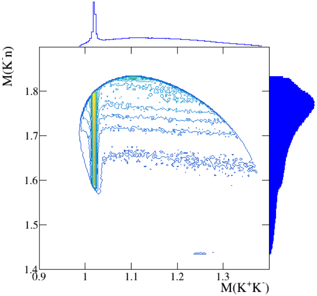
- While t-channel dominates in $\gamma p \to \phi p$, s channel dominates in $\pi^- p \to \phi n$.
- The $\pi^- p$ reaction probes a P_s^0, an I-doublet member with P_s^+.
- Theoretical calculation supports an s-channel dominance below 2.2 GeV/c (Sangho Kim).

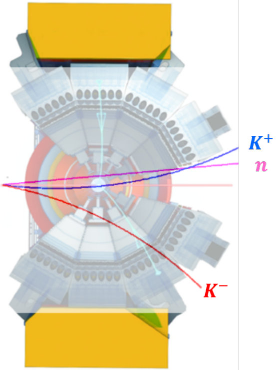


$\pi^- p \to \phi n$ at J-PARC

- Only ϕ and $\Sigma(1775)$ are included in $\pi^- p \to K^+ K^- n$ reaction.
- J-PARC P95 detector will detect two charged kaons and reconstruct a neutron by a missing-mass technique.







Dibaryons

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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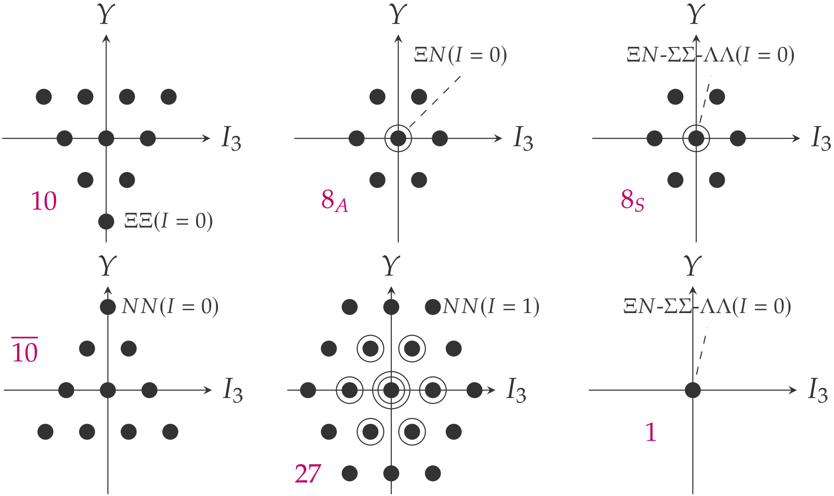
(Received 1 November 1976)

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.

Dibaryon Multiplets in $SU(3)_f$



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 $H \to \Lambda p \pi^-$ and $H \to \Lambda\Lambda$
- in high-energy e^+e^-, pp and AA experiments
- 2021 — LQCD calculations point to the mass 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 about to see what we would see in the E42 dataset.

H-Dibaryon Search at J-PARC : E42

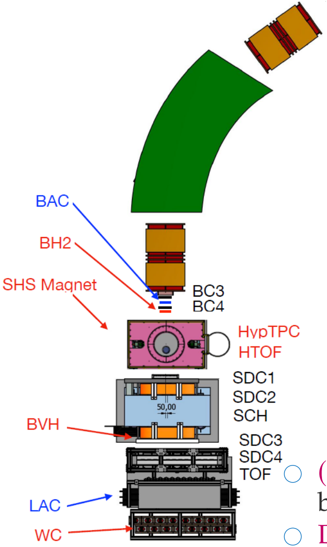
The existence of the H-dibaryon still awaits definitive experimental confirmation or exclusion.

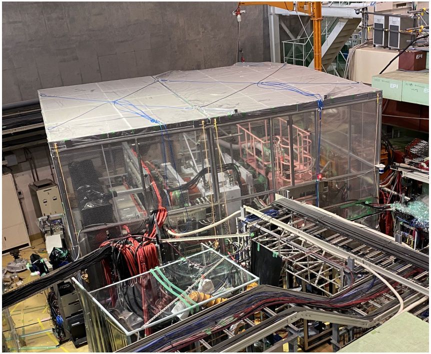
- Weakly-bound : $H \longrightarrow \Lambda p \pi^-$
- Virtual state : $\Lambda\Lambda$ or $\Xi^- p$ threshold effect
- Resonance : Breit-Wigner peak in $\Lambda\Lambda$ and $\Xi^- p$ masses

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

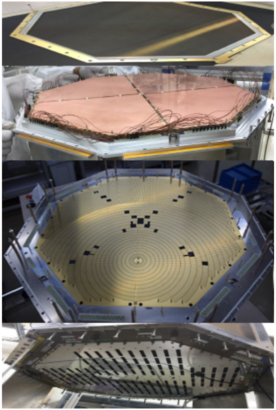
E42 Detector for the H-Dibaryon Search

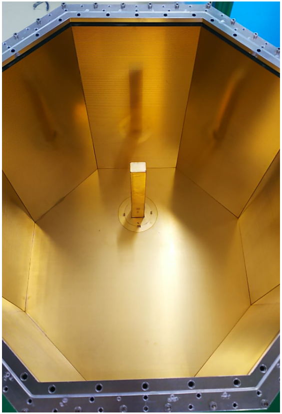


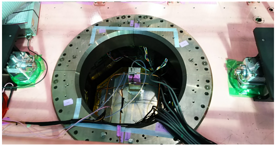


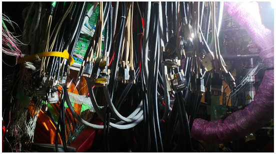
- (K^-, K^+) reaction events are tagged by the K1.8 beam line and the KURAMA spectrometers.
- Decays of the $S = -2$ system are reconstructed using the Superconducting Hyperon Spectrometer.

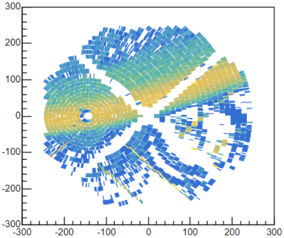
Hyperon Time Projection Chamber (HypTPC)











- The HypTPC operation was relatively stable except two events stopping the E42 run shortly.
- Event display for 0.4 GeV/c π^+ beam tracks accumulated in the calibration run.

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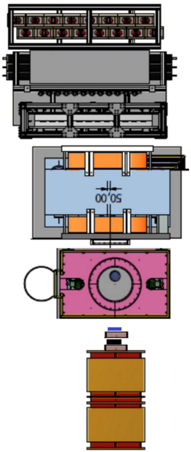
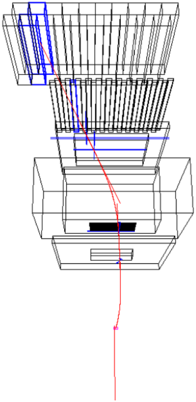
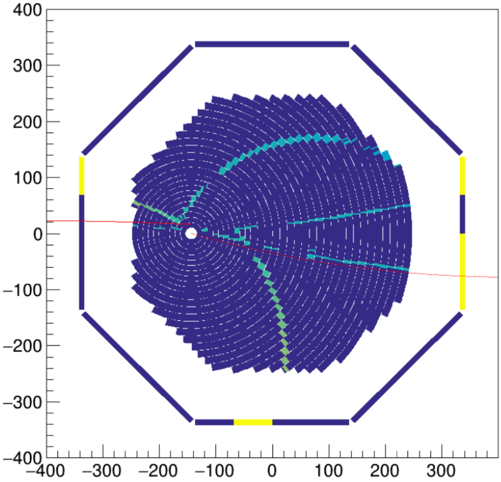
$^{12}C(K^-, K^+)$ Reaction Event



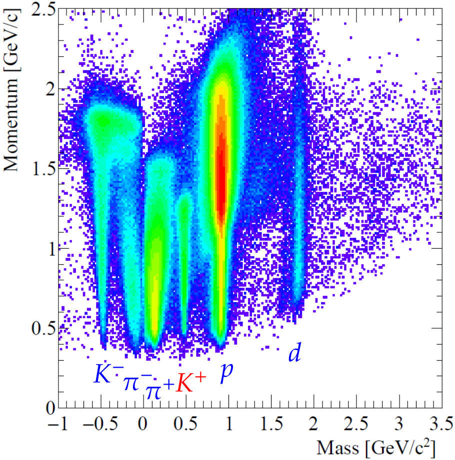


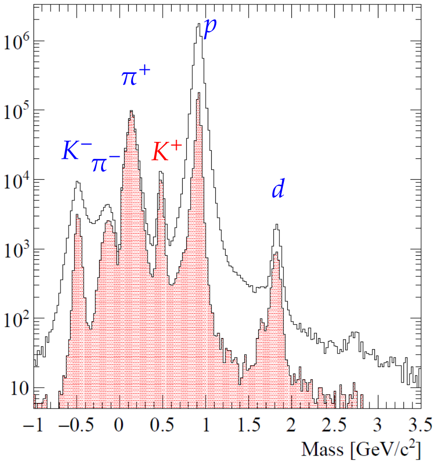


- Reconstructed K^- beam and outgoing K^+ tracks share the vertex at the diamond target position.
- Two Vs are seen in the HypTPC and four decay particles hit the HTOF.

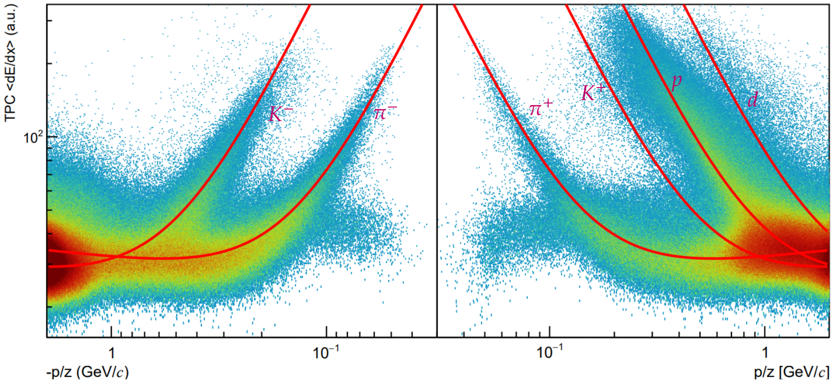
Scattered Particles at Forward Angles

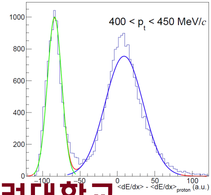
- We reconstructed the masses and momenta for scattered particles successfully with the forward K^+ spectrometer.





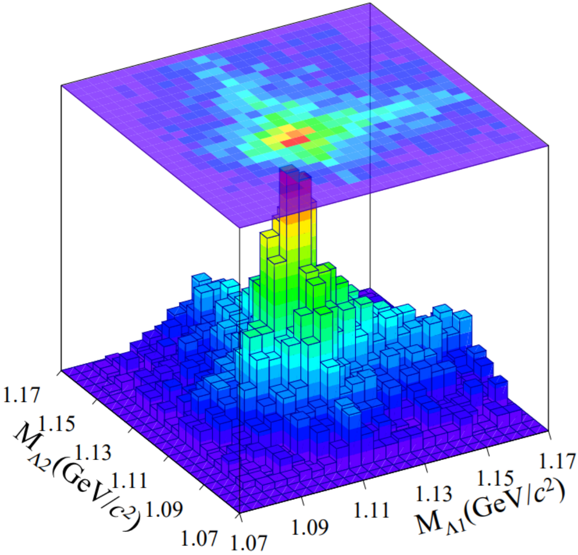
Particle Identification with HypTPC





- $\langle dE/dx \rangle_{20\%\ \text{truncated}}$ vs p/z for reconstructed HypTPC tracks in the diamond target dataset (C(K^-, K^+)X reactions).
- $\sigma_{dE/dx}/\langle dE/dx \rangle \sim$ 20% for the range $0.40 < p_T < 0.45$ GeV/c.

$\Lambda\Lambda$ Production in the (K^-, K^+) Reactions



Simulated $\Lambda\Lambda$ and $\Xi^- p$ Mass Spectra

- Simulated invariant-mass spectra for $H(2250) \longrightarrow \Lambda\Lambda$ [a] and $H(2265) \longrightarrow \Xi^- p$ decays. [b]

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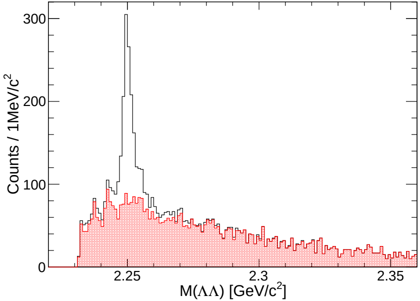
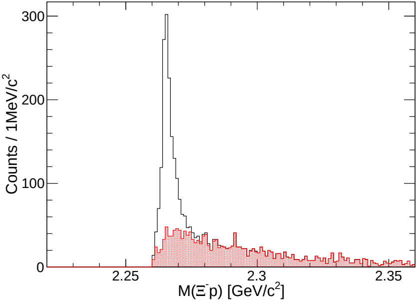
[a] Simulation on two-step processes is based on INC calculation by Y. Nara, A. Ohnishi, T. Harada and A. Engel, Nucl. Phys. A614 (1997) 433.

[b]



Simulated $\Lambda\Lambda$ Spectrum for $H(2250)$ assuming $d\sigma/d\Omega = 1.0\ \mu$b/sr.

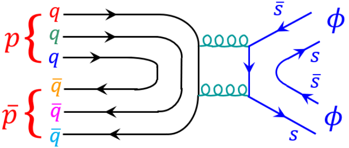


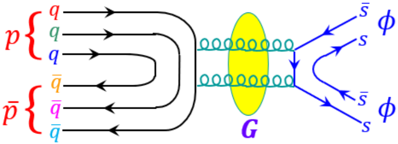
Simulated $\Xi^- p$ Spectrum for $H(2265)$ assuming $d\sigma/d\Omega = 1.0\ \mu$b/sr.

GLUEBALLS

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

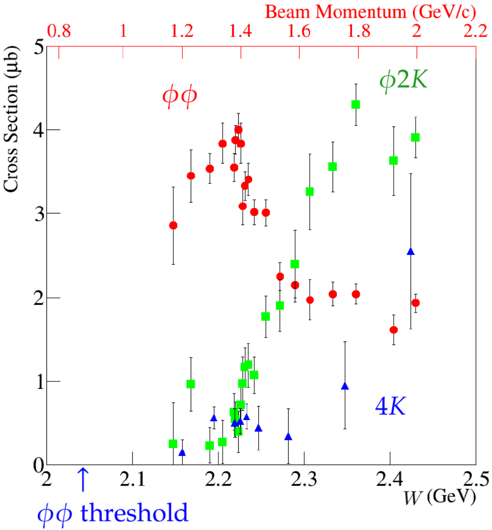
- The reaction $\overline{p}p \to \phi\phi$ may proceed via two gluon emission from $\overline{q}q$ annihilation.

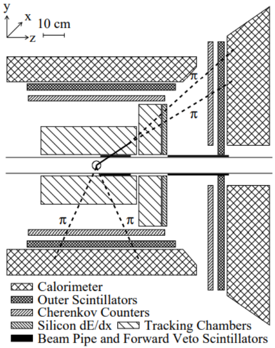




- All three valence quarks in p annihilate with the corresponding three antiquarks in $\overline{p}$ to produce a purely gluonic state from which $\phi\phi$ is formed. This should be OZI-suppressed without an intermediate resonant gluonic state (glueball).

$\bar{p}p \to \phi\phi$ (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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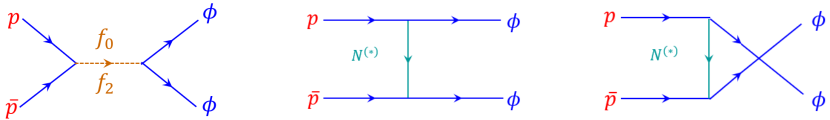
[a] H.-W. Ke and X.-Q. Li, Phys. Rev. D 99, 036014 (2019); Q.-F. Lü et al., Chinese Phys. C 44, 024101 (2020).

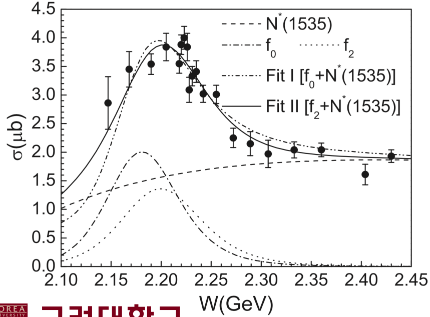
[b] The angle $\delta(= \Theta_i - \Theta)$ denotes the difference between the ideal mixing angle $\Theta_i = 35.3°$ $(\sin\Theta_i = 1/\sqrt{3})$ and the mixing angle Θ between (ϕ, ω) mesons and the SU(3) states (ω_0, ω_8).

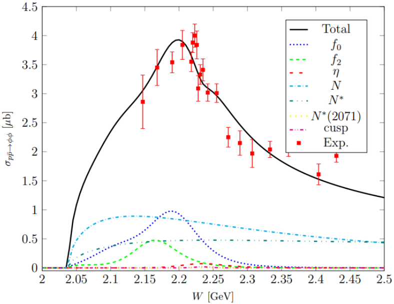
$\bar{p}p \to \phi\phi$ Reaction



- Theoretical calculations describe the JETSET results within an effective Lagrangian approach. [a]

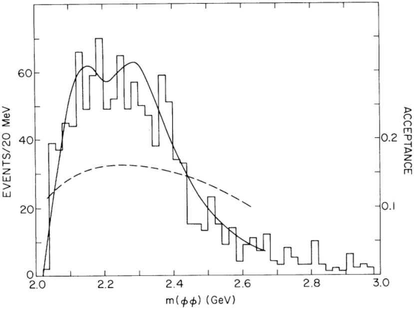
[a] J.-J. Xie, L.-S. Geng, X.-R. Chen, Phys. Rev. C 90, 048201 (2014); D.Y, Lee, J.K. Ahn, S.i. Nam, to be submitted in PRC.





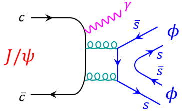
$\pi^- p \to \phi\phi n$ and $J/\psi \to \gamma\phi\phi$

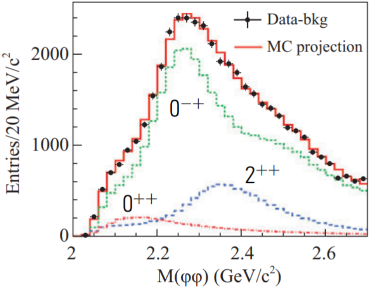
- Based on 1203 events of the reaction $\pi^- p \to \phi\phi n$ at 22 GeV$/c$, a BNL experiment reported an observation of two 2^{++} mesons at 2160 and 2320 MeV. [a]



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

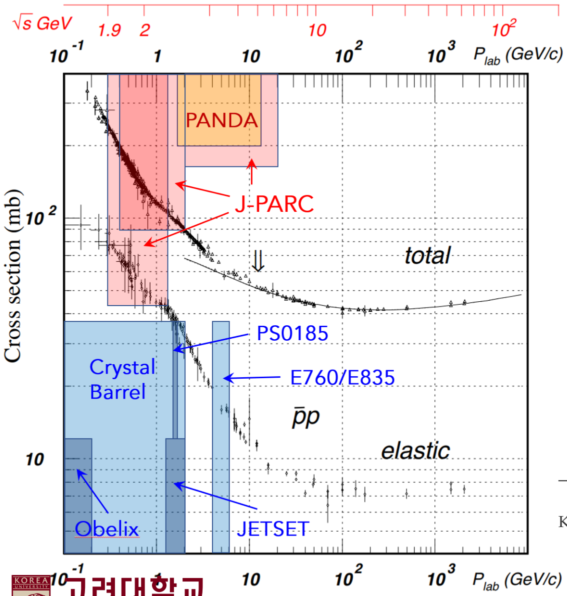
- BESIII reported an observation of $f_0(2100)$, $f_2(2010)$, $f_2(2300)$ and $f_2(2340)$. [a]





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

$\bar{p}p$ Cross Sections and Experiments



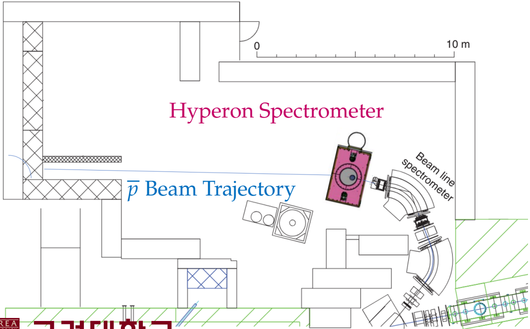
- PANDA awaits the construction of HESR, which could start in early 2030's.
- J-PARC provides antiproton beams from 0.3 GeV/c to 20 GeV/c.
- J-PARC K1.8BR beam line delivered 2×10^5 $\bar{p}$ per spill (5.2 s) during the 50kW operation [1].

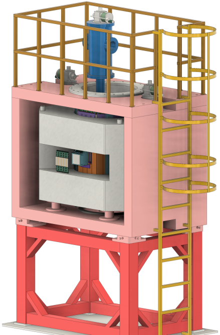
[a] T. Hashimoto *et al.*, Beam measurement at K1.8BR, June 2023.

K1.8BR Beamline and Hyperon Spectrometer

- The K1.8BR beamline delivered 2×10^5 $\overline{p}$ per spill during the 5.2 s duration (40 kHz) in the 50 kW operation.[a]
- The $\overline{p}$ beam intensity can be scaled to 64 kHz at 80 kW.
- The background π^- beam intensity is roughly double that of the $\overline{p}$ beam, resulting in a total beam intensity of 180 kHz or 720k/spill.

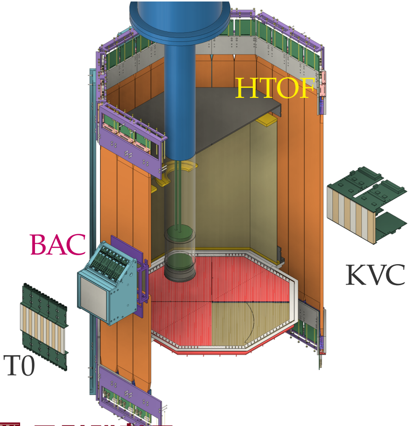
[a] T. Hashimoto *et al.*, Beam profile measurement at K1.8BR, June 2023.

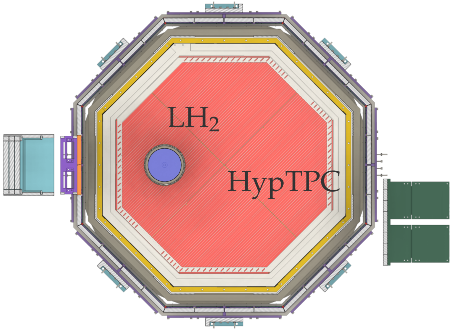




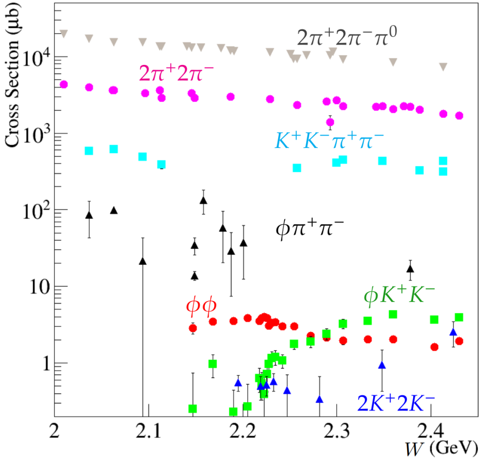
HypTPC and Trigger Counters

- The BAC will reject unwanted beam particles such as π^- and μ^-.
- The beam will enter the HypTPC and may interact with a proton within a liquid hydrogen target located inside the HypTPC.





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



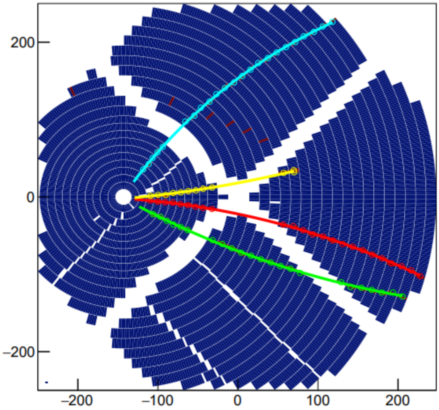
$\bar{p}p$ Reactions	$p^{\rm lab}_{\rm thre}$ (GeV/c)
$2\pi^+2\pi^-\pi^0$	0
$2\pi^+2\pi^-$	0
$K^+K^-\pi^+\pi^-$	0
$\phi\pi^+\pi^-$	0
$2K^+2K^-$	0.662
ϕK^+K^-	0.767
$\phi\phi$	0.866
$\bar{p}p\pi^+\pi^-$	1.219
$\bar{p}p\phi$	3.403

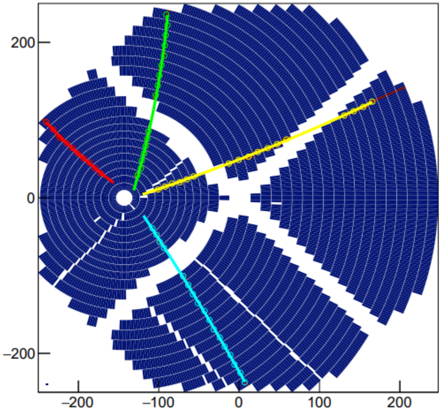
- Multipion production processes dominate $\bar{p}p$ reactions with four charged-particle emission. [a]

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

Simulated Events for $\bar{p}p \to \phi\phi$ and $2\pi^+2\pi^-$

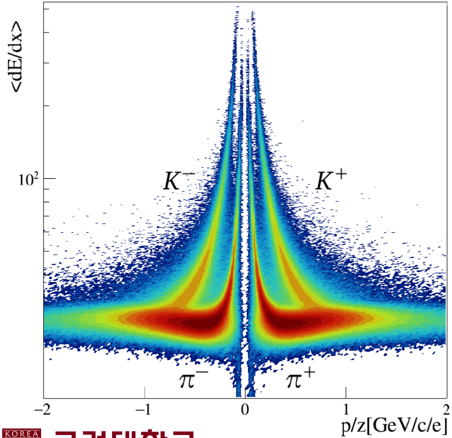
- HypTPC event displays for $\bar{p}p \to \phi\phi$ and $2\pi^+2\pi^-$ reactions.
- All charged tracks are assumed to share the same vertex at the target.

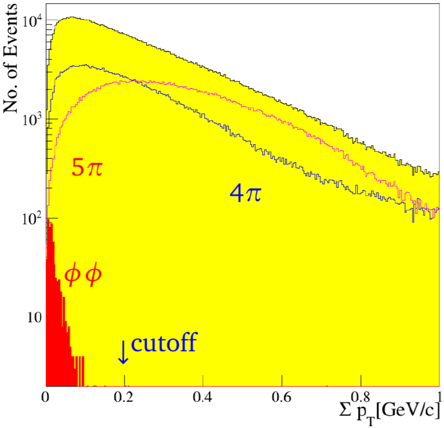




Particle ID and Momentum Balance Constraints

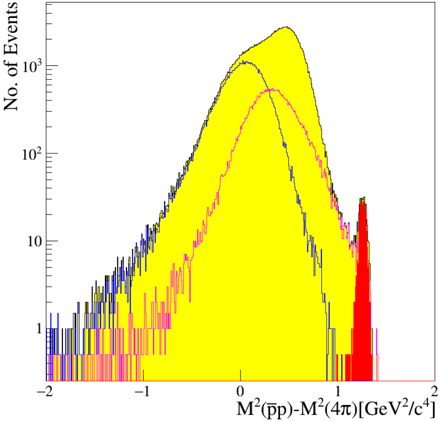
- This energy-loss information assists in identifing particles based on the particle identification function $(dE/dx|_{\text{meas}} - dE/dx|_K)^2/\sigma_K^2$.
- The 5π events are then further rejected by requiring transverse momentum balance.

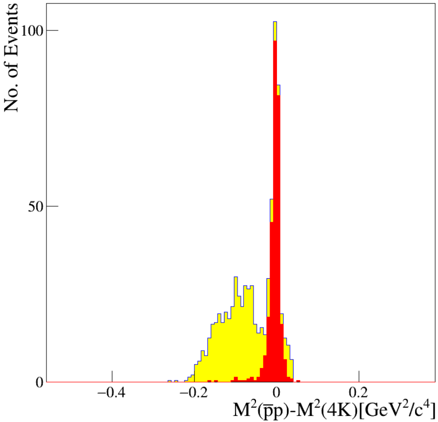




Event Selection with Energy Balance Contraints

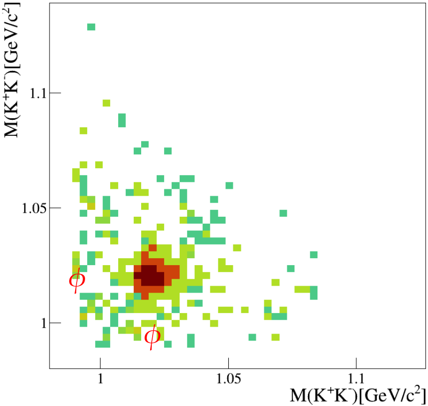
- Energy balance constraints in the center-of-mass energy ($\Delta m^2 = (p_{\bar{p}} + p_p)^2 - (\sum_{i=1}^{4} p_i)^2 = 0$, where p_i denotes a four-momentum of particle i) between the intial and final states.

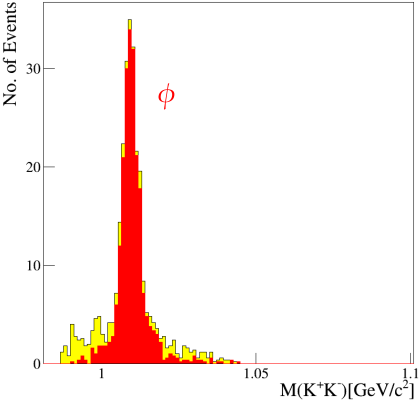




Reconstructed $\phi\phi$ Events

- 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.
- Background events involving pions are located on a parablic curvature away from M_ϕ.





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

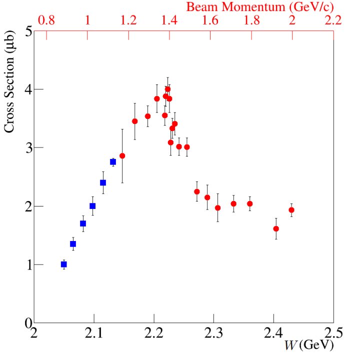
- For the 80 kW MR operation the trigger rate is 0.046 Hz.
- Background processes ($2\pi^+2\pi^-,\ 2\pi^+2\pi^-\pi^0$) are largely suppressed by imposing kinematic constraints and ensuring excellent π/K separation of the HypTPC.
- Reconstruction efficiency for the $\phi\phi$ events ($\varepsilon_{\text{recon}} = 0.6$).
- 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

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

Beam Time Request

- 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 remaining 3 days will be allocated to measuring the reaction at other five momentum settings, allowing the statistical uncertainties within the range of 5%–10%.

Beam switch	0.1 days
Trigger study	0.4 days
0.90 GeV/c	1.0 days (~ 200 events)
0.95 GeV/c	0.5 days (~ 150 events)
1.00 GeV/c	0.5 days (~ 200 events)
1.05 GeV/c	0.5 days (~ 250 events)
1.10 GeV/c	0.5 days (~ 300 events)
1.15 GeV/c	3.0 days (~ 1500 events)



Double ϕ 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.