

Partial Restoration of Chiral Symmetry at Finite Baryon Density

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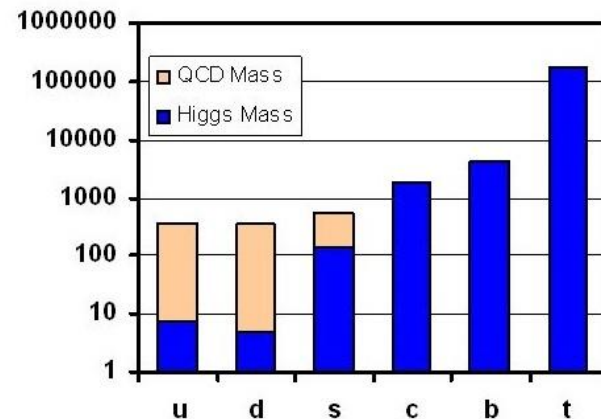
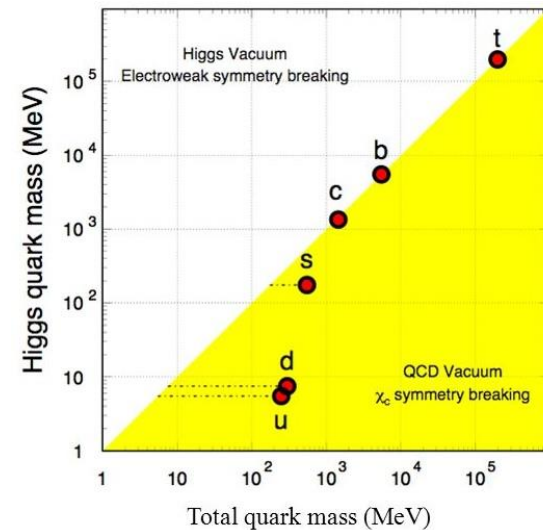
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Introduction

Origin of Quark Mass

- $M_N (\sim 938 \text{ MeV}) \gg m_q (\sim 10 \text{ MeV})$
- Higgs mechanism gives quarks only the current mass
- $\sim 98\%$ of the constituent mass (of u and d quarks) is generated dynamically in the QCD confined potential
- QCD chiral symmetry breaking is responsible for the origin of mass in the universe



Chiral Partners in Flavor SU(3)

- If flavor SU(3) is exact, the vector mesons and axial-vector mesons in the flavor octet representation are chiral partners, while the flavor singlet vector and axial vector mesons are not chiral partners
- In the real world, flavor SU(3) is significantly broken, which makes mixing of octet and singlet

$$\left\{ \begin{array}{l} \omega_o = \frac{1}{\sqrt{3}} (\bar{u}u + \bar{d}d + \bar{s}s) \\ \omega_o = \frac{1}{\sqrt{6}} (\bar{u}u + \bar{d}d - 2\bar{s}s) \end{array} \right. \quad m_3 \gg m_1, m_2 \quad \rightarrow \quad \left\{ \begin{array}{l} \omega = \frac{1}{\sqrt{2}} (\bar{u}u + \bar{d}d) \\ \phi = (\bar{s}s) \end{array} \right.$$

Chiral Partners

- Two pairs of chiral partners in the octet representation of SU(3)

vector ($J^\pi = 1^-$)
 1^+)

axial-vector ($J^\pi =$

$\rho(770)$

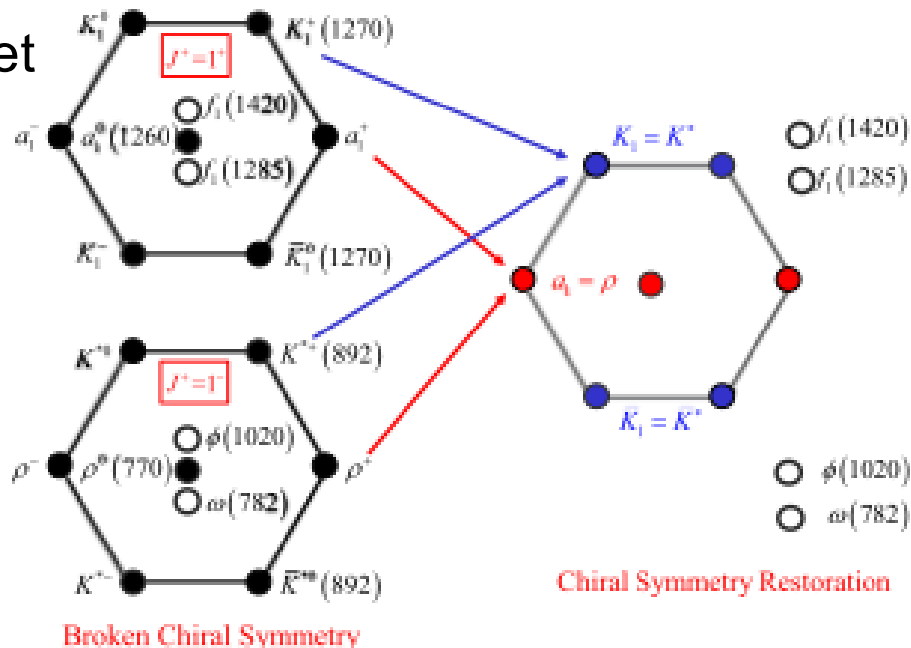
\leftrightarrow

$a_1(1260)$

$K^*(892)$

\leftrightarrow

$K_1(1270)$



Why Chiral Partners?

- The individual meson masses could behave differently depending on whether the hadron is in nuclear matter or at finite temperature, while **the mass difference between chiral partners will only depend on the chiral order parameter and be universal**
- The difference between the vector and axial-vector correlation functions in the open strange channel is also an order parameter of chiral symmetry

How to produce K^* and K_1

- Proton and/or heavy ion beams
- Secondary Kaon beams

With Proton Beams

With Proton Beams

Pros:

- Smaller disturbance expected from phase space limitation

Cons:

- large particle multiplicity per event to be handled
- smaller S/N ratio due to combinatorial
- elaborated (expensive) detector system
- efficient and powerful trigger system

JAM2 setup parameters

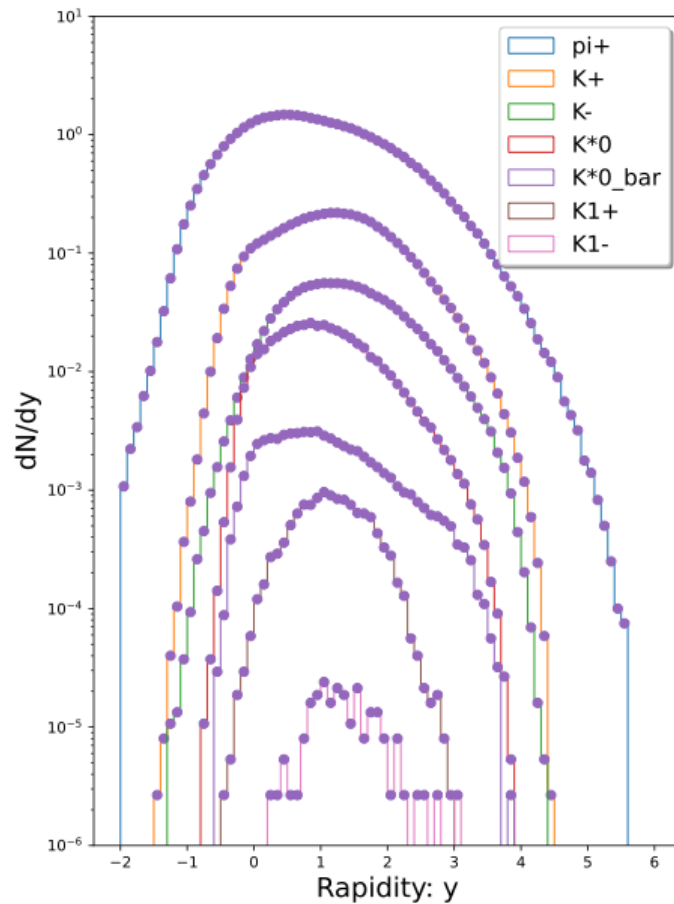
- JAM2: a Monte-Carlo event generator for high-energy nuclear collisions, based on the transport models (by Yasushi Nara et al.)

In this works:

- Cascade Mode with no mean field
- p+Au,
- Elab(proton) ~ 30 GeV/c
- Minimum bias

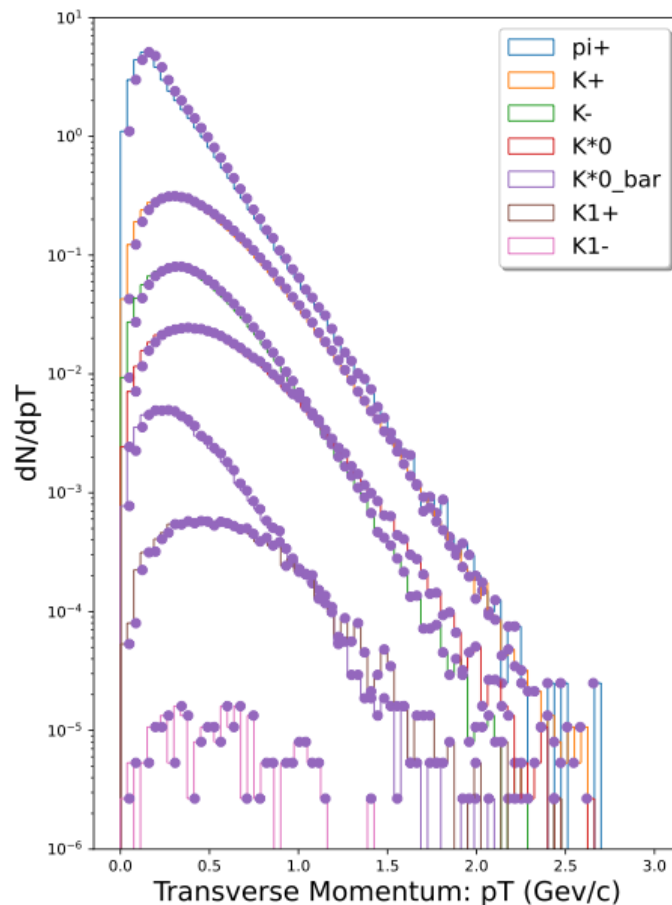
dN/dy

<u>Species</u>	<u>Multiplicity/event</u>
π^+	3.93
K^+	0.497
K^-	0.120
$K^*(892)^+$	0.0435
$\overline{K^*(892)^0}$	0.00639
$K_1(1270)^+$	0.00125
$K_1(1270)^-$	0.0000237



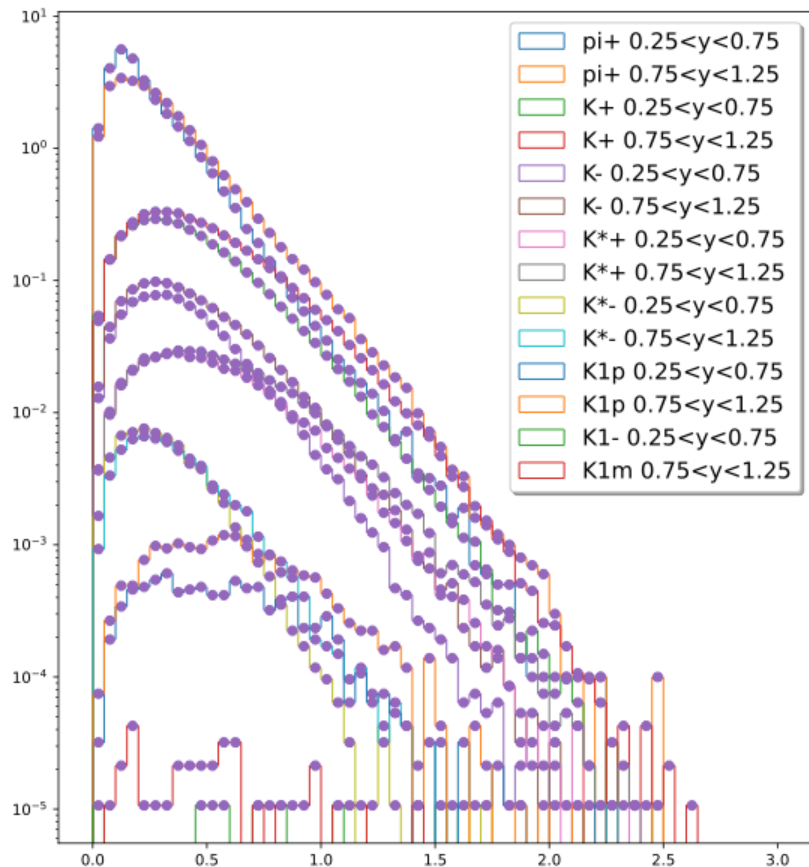
dN/dp_T

- dN/dp_T for π^+ , K^+ , K^- , $K^*(892)^0$, $\overline{K^*(892)^0}$, $K_1(1270)^+$, $K_1(1270)^-$
- dN/dp_T becomes fatter with increase of mass
- Slopes of particles is less steep than that of anti-particles
 - difference clearly seen in $K^*(892)^0$ and $\overline{K^*(892)^0}$



dN/dp_T

- $\frac{dN}{dp_T}$ for π^+ , K^+ , K^- , $K^*(892)^0$, $\overline{K^*(892)^0}$, $K_1(1270)^+$, $K_1(1270)^-$
- In the two rapidity regions:
 - $0.25 < y < 0.75$
 - $0.75 < y < 1.25$
- Slope is less steep in higher rapidity, although difference is small



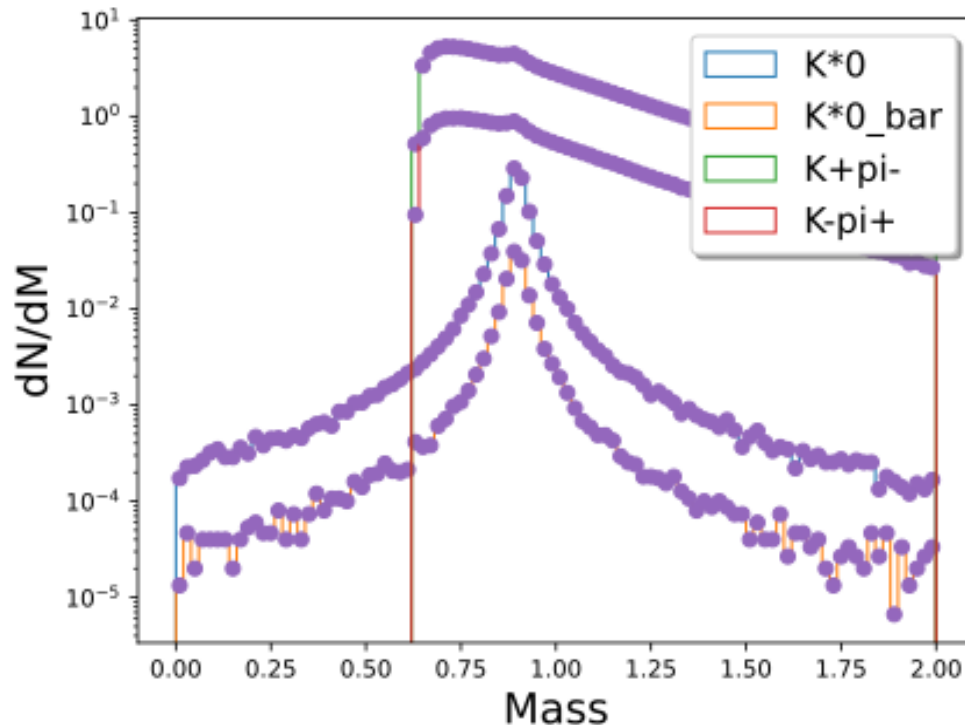
K^* , \overline{K}^* Combinatorial Background

- In this study, only charged hadrons are handled; neutral pions and gammas are not detected $\rightarrow K^{*0}$ and \overline{K}^{*0} are considered:

$$K^{*0} \rightarrow K^+ + \pi^- \quad (\text{BR} \sim 50\%)$$

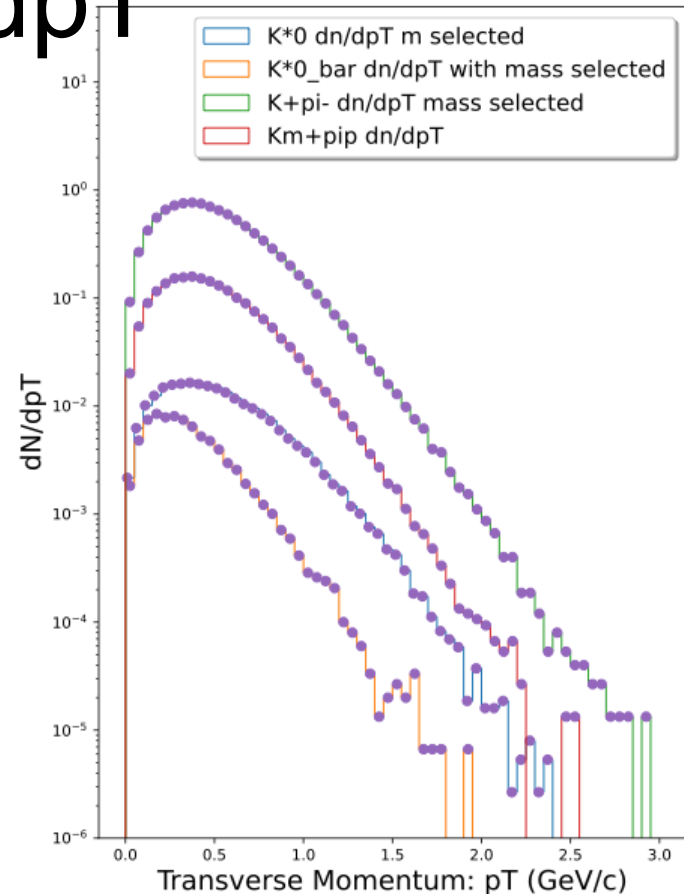
$$\overline{K}^{*0} \rightarrow K^- + \pi^+ \quad (\text{BR} \sim 50\%)$$

- S/N is not great, but seems to be manageable with enough statistics



K^* , \overline{K}^* and comb2 dN/dp_T

- dN/dp_T of K^{*0} is less steep than that of $(K^+ + \pi^-)$
- dN/dp_T of \overline{K}^{*0} turnover comes at smaller p_T than that of $(K^- + \pi^+)$



K_1^+ , K_1^- , and Combinatorials

- In this study, only charged hadrons are handled; neutral pions and gammas are not detected $\rightarrow K_1^+$ and K_1^- are considered:

$$K_1^+ \rightarrow K^+ + \rho^0 (\rightarrow \pi^+ + \pi^-) \quad (\text{BR } 38\% / 2)$$

$$\rightarrow K^0 + \rho^+ (\rightarrow \pi^+ + \pi^0) \quad (\text{BR } 38\% / 2)$$

$$K_1^+ \rightarrow K^{*0} (\rightarrow K^+ + \pi^-) + \pi^+ \quad (\text{BR } 21\% / 4)$$

$$\rightarrow K^{*0} (\rightarrow K^0 + \pi^0) + \pi^+ \quad (\text{BR } 21\% / 4)$$

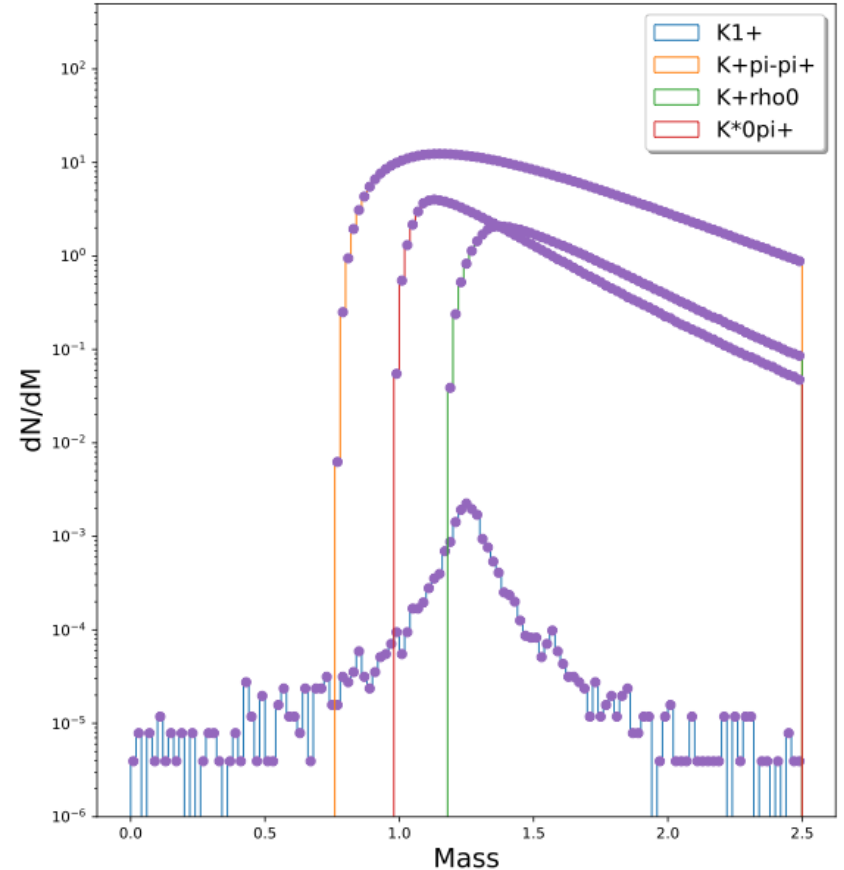
$$\rightarrow K^{*+} (\rightarrow K^+ + \pi^0) + \pi^0 \quad (\text{BR } 21\% / 4)$$

$$\rightarrow K^{*+} (\rightarrow K^0 + \pi^+) + \pi^0 \quad (\text{BR } 21\% / 4)$$

K_1^+ and Comb.

Three combinatorial calculations

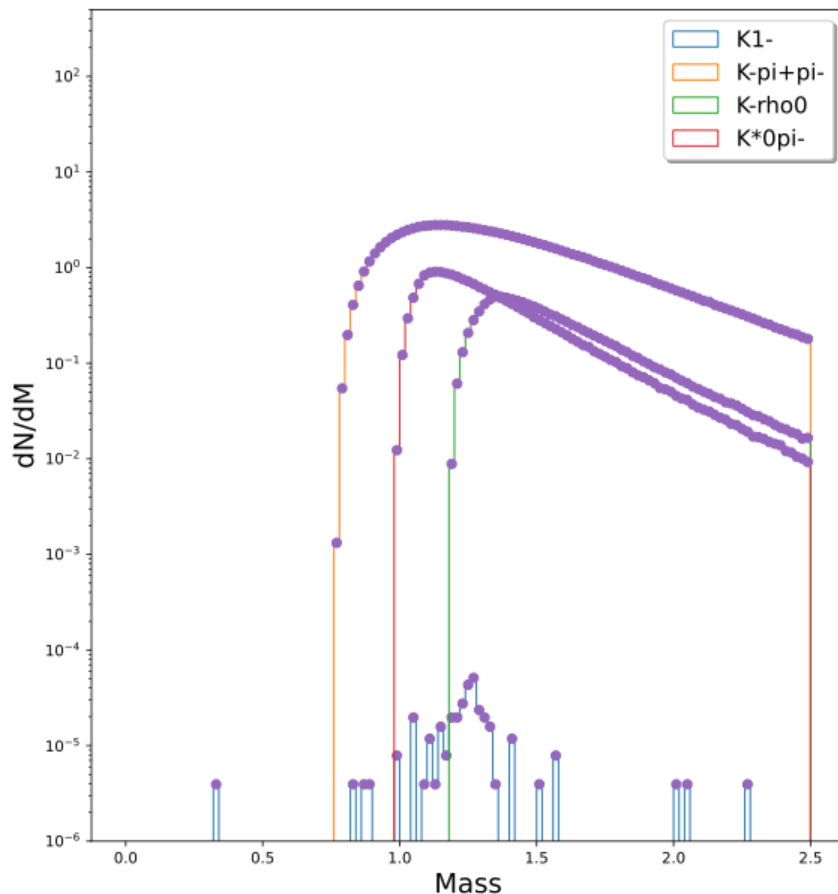
- $K^+ + \pi^- + \pi^+$ total
- $K^+ + \rho^0 (\rightarrow \pi^+ + \pi^-)$
 - cut at $M(\pi^+ + \pi^-)$
 - $M(\rho^0) - \Gamma(\rho^0) < M(\pi^+ + \pi^-) < M(\rho^0) + \Gamma(\rho^0)$
- $K_1^+ \rightarrow K^{*0} (\rightarrow K^+ + \pi^-) + \pi^+$
 - **cut at $M(K^+ + \pi^-)$**
 - $M(K^{*0}) - \Gamma(K^{*0}) < M(K^+ + \pi^-) < M(K^{*0}) + \Gamma(K^{*0})$



K_1^- and Comb.

Three combinatorial calculations

- $K_1^- \rightarrow K^- + \pi^+ + \pi^-$ total
- $K_1^- \rightarrow K^- + \rho^0 (\rightarrow \pi^+ + \pi^-)$
 - cut at $M(\pi^+ + \pi^-)$
 - $M(\rho^0) - \Gamma(\rho^0) < M(\pi^+ + \pi^-) < M(\rho^0) + \Gamma(\rho^0)$
- $K_1^- \rightarrow \overline{K^{*0}} (\rightarrow K^- + \pi^+) + \pi^-$
 - **cut at $M(K^- + \pi^+)$**
 - $M(\overline{K^{*0}}) - \Gamma(\overline{K^{*0}}) < M(K^- + \pi^+) < M(\overline{K^{*0}}) + \Gamma(\overline{K^{*0}})$



Homework

- Combinatorial backgrounds in case of proton beams are very severe, in particular, for K_1^\pm

Homework: How to reduce the combinatorial backgrounds from pions

- Lighter targets such as C and Si (Al)
- Lower energy

With Kaon Beams

Using Kaon Beams

Pros:

- large cross section
- not large particle multiplicity per event to be handled
 - advantage in the S/N ratio
 - detection system may be simpler
 - simpler trigger logic

Cons:

- Limited kinematical phase space → possible effect on the meson mass spectra (which I need to learn better...)
- Need beam line with good Kaon separator

Kinematics for K^* and K_1 Production

Secondary Kaon beams with proton target: $K + p \rightarrow K_X + p$

- 4-momentum conservation:

$$P(K) + P(p^{in}) = P(K_X) + P(p^{out})$$
$$s = \left(P(K) + P(p^{in})\right)^2 = \left(P(K_X) + P(p^{out})\right)^2$$

- At production threshold, K_X and p^{out} stay together at CMS: $s = (m_{K_X} + m_p)^2$
- At laboratory frame: $s = (E_K^{Lab} + m_p)^2 - (p_K^{Lab})^2 = m_K^2 + m_p^2 + 2E_K m_p$

$$E_K^{Lab} = \frac{(m_{K_X} + m_p)^2 - m_K^2 - m_p^2}{2m_p} \quad \rightarrow \quad p_K^{Lab} = \sqrt{(E_K^{Lab})^2 - m_K^2}$$

- velocity of K_X at threshold: $\beta_X = \frac{p_K^{Lab}}{E_K^{Lab} + m_p}$

Threshold to produce K^* and K_1

$$E_K^{Lab} = \frac{(m_{K_X} + m_p)^2 - m_K^2 - m_p^2}{2m_p} \quad p_K^{Lab} = \sqrt{(E_K^{Lab})^2 - m_K^2} \quad \beta_X = \frac{p_K^{Lab}}{E_K^{Lab} + m_p}$$

- $K + p \rightarrow K^*(892) + p$

$$m_{K^*} = 0.89167, \quad m_K = 0.493677, \quad m_p = 0.938272,$$

$$E_K^{Lab} = 1.185(\text{GeV}) \quad p_K^{Lab} = 1.078 (\text{GeV}/c) \quad \beta_X = 0.507$$

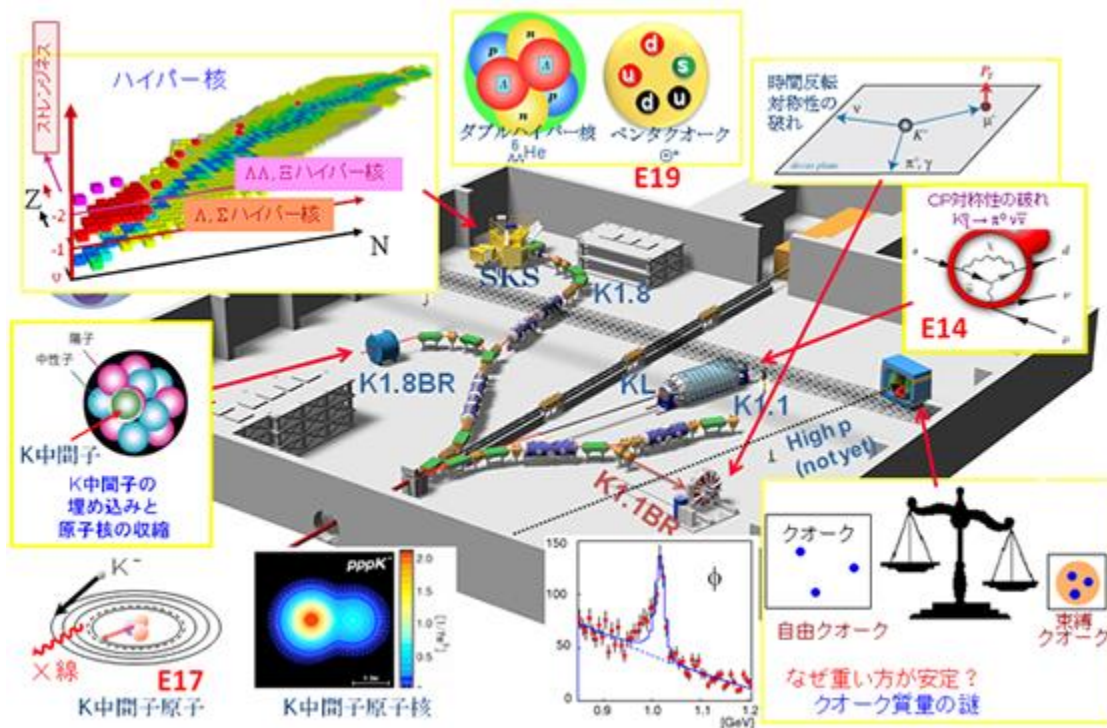
- $K + p \rightarrow K_1(1270) + p$

$$m_{K_1} = 1.270, \quad m_K = 0.493677, \quad m_p = 0.938272,$$

$$E_K^{Lab} = 2.000(\text{GeV}) \quad p_K^{Lab} = 1.938 (\text{GeV}/c) \quad \beta_X = 0.660$$

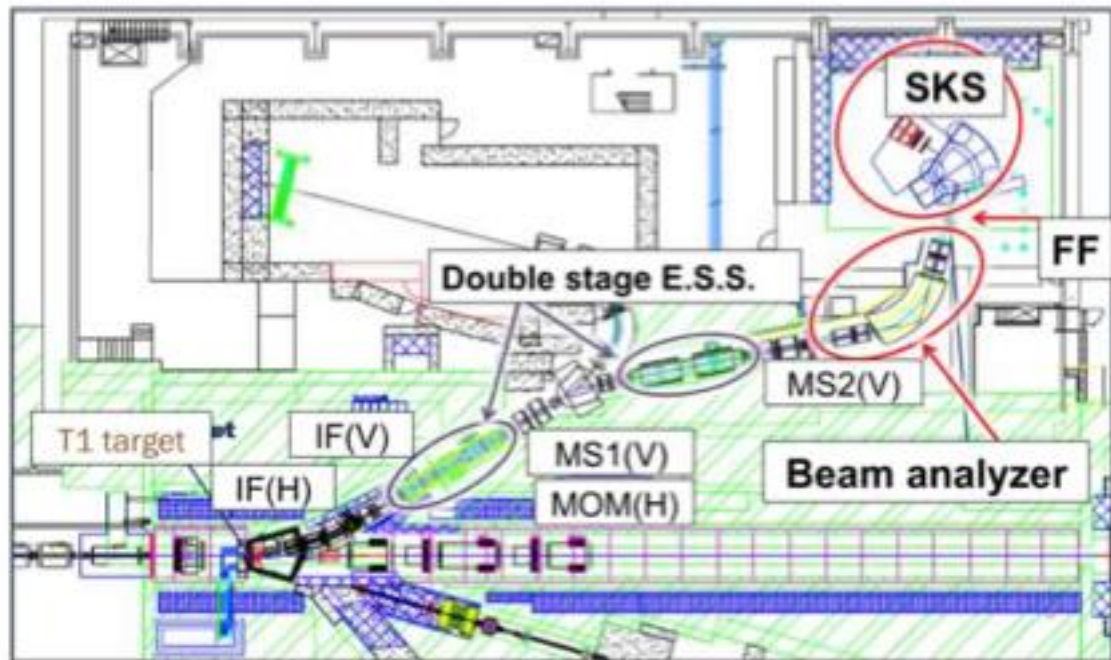
Beam Lines at J-PARC

- High momentum beam line
- Beam lines for charged Kaons; K1.8, K1.8BR, K1.1, K1.1BR
- K1.8: separated beams up to 2 GeV/c
- We need to have a Kaon beamline with higher momentum → **J-PARC K-10 proposal**



Key Specifications of the K1.8 Beam Line

- 30 GeV, 9 μA (2.0×10^{14} ppp)
- Length 45.97 m
- Acceptance 1.4 msr %
- Momentum: up to 2.0 GeV/c
- Electrostatic separators: 750 kV/10 cm, 6 m \times 2
- K^- intensity @FF 1.8 GeV/c: 1.4×10^6 ppp
- $\text{K}^-/(\pi^- + \mu^-)$ @ FF: 3.5
- $X_{\text{rms}}/Y_{\text{rms}}$ size @ FF: 19.8/3.2 mrr



Specifications for an Experiment Setup

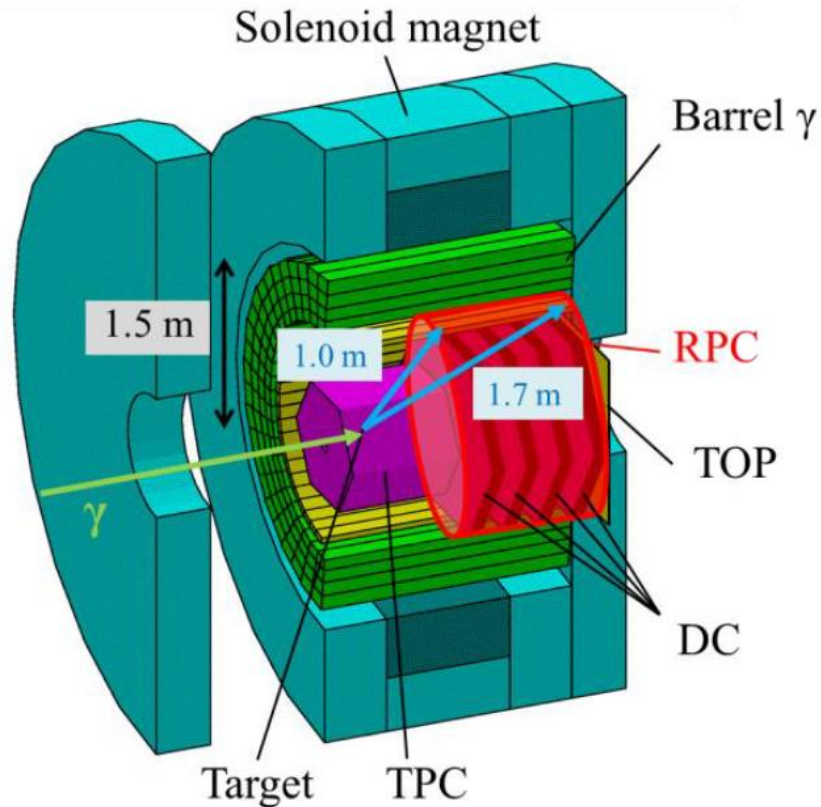
- Large azimuthal aperture in $0 < \text{rapidity} < 1$, $p_T < 1.5 \text{ GeV}/c$
- Tracking, with moderate resolution, e.g. $\delta p/p \sim 0.01p$ (in GeV/c)
- Particle Identification capability for p, K, π
 - dE/dx , TOF, Aerogel Cherenkov Counter
- Vertex counter (SSD) -- distributed target for less scattering
- Multiplicity counter, for fast event selection and trigger
- Possibility of **streaming readout** can be considered

Two types of detector setup to start with:

- **Dipole type, or solenoid type**

Model Solenoid Detector Setup

- LEPS2 large charged particle spectrometer
 - located in the BL31LEP laser-electron photon (LEP) beamline in the Spring8
 - The magnet had been used in the kaon rare decay experiment (E949) at the Brookhaven National Laboratory
 - It has a large bore of 2.22-m length and 2.96-m diameter.
- This spectrometer setup can be a solenoid model setup to start with



Summary and Outlook

Summary and Outlook

Summary:

- Possibilities of experimental study of partial restoration of chiral symmetry were discussed for the two cases; with p+A collisions and with secondary Kaon beams.

Outlook:

- Homework: evaluations of p+A collisions
- Learn more on the Kaon induced reactions
- Hope is that a new Kaon facility and experiment(s) are moving forward in the near future