MASS MODIFICATIONS OF VECTOR MESONS IN A FINITE DENSITY MATTER

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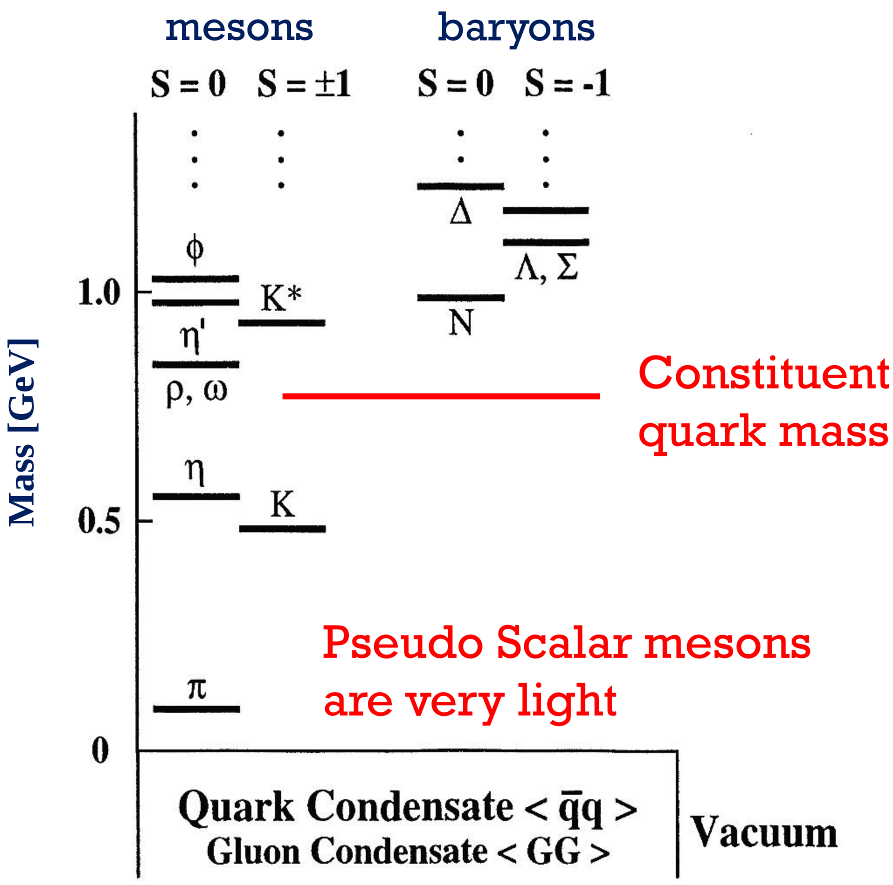
Contents

- Introduction
- Experiment at J-PARC
- Summary

HADRONS MASS AND "QCD VACUUM"

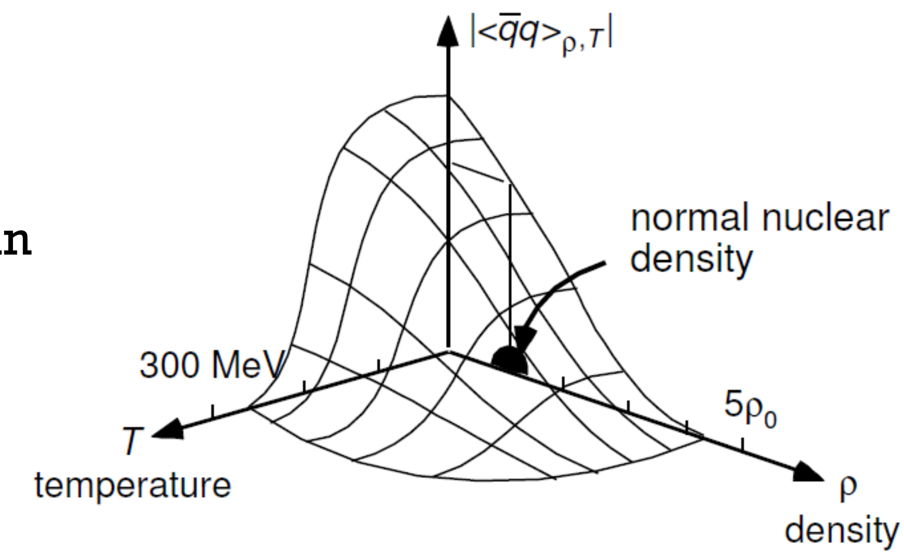
- Mass levels of hadrons can be understood as the excitation energy levels from the vacuum
- The mass of the π meson is very small. It can be understood as a result of spontaneous breaking of chiral symmetry in the vacuum
- Hadron properties should be determined by the vacuum properties
- Thus, we need to study characteristics of "QCD vacuum" to study hadron mass



"QCD VACUUM" AND CONDENSATES

- One of the important properties of "QCD vacuum" is amount of anti-quark quark condensations
  - $\langle\bar{\psi}\psi\rangle$: Expectation value of the vacuum
  - Order parameter of chiral symmetry
- The amount of the condensation in "QCD vacuum" depends on temperature and density of the matter
- However, anti-quark quark condensations itself are not observable
  - Realistic observable should be figured out

W. Weise, Nucl. Phys. A553(1993)59c



VECTOR MESON MASS AND $\langle \bar{q} q \rangle$

P. Gubler and K. Ohtani, Phys. Rev. D **90**, 094002 (2014).

Vector meson mass spectra can be connected with anti-quark quark condensate

Two point correlation functions after the Borel transformation:

$$G_{OPE}(M^2) = \int_0^\infty \exp(-\frac{s}{M^2})\rho(s)ds$$

Spectral Function

QCD sum rule for ϕ meson channel:

$$G_{OPE}(M^2) = \frac{1}{4\pi^2}(1+\frac{\alpha_s}{\pi}) - \frac{1}{M^2}\frac{6m_s^2}{4\pi^2} + \frac{1}{M^4}(2m_s\langle \bar{s}s\rangle_{\rho_N} + \frac{1}{12}\langle\frac{\alpha_s}{\pi}G^2\rangle_{\rho_N}) - \frac{1}{M^6}\frac{112\pi}{81}\alpha_s\langle\bar{s}s\bar{s}s\rangle_{\rho_N} + \frac{1}{M^4}A_2^s M_N \rho - \frac{1}{M^6}\frac{5}{3}A_4^s M_N^3 \rho + \cdots$$

Mass spectra should be measured experimentally

Strangeness content of the nucleon

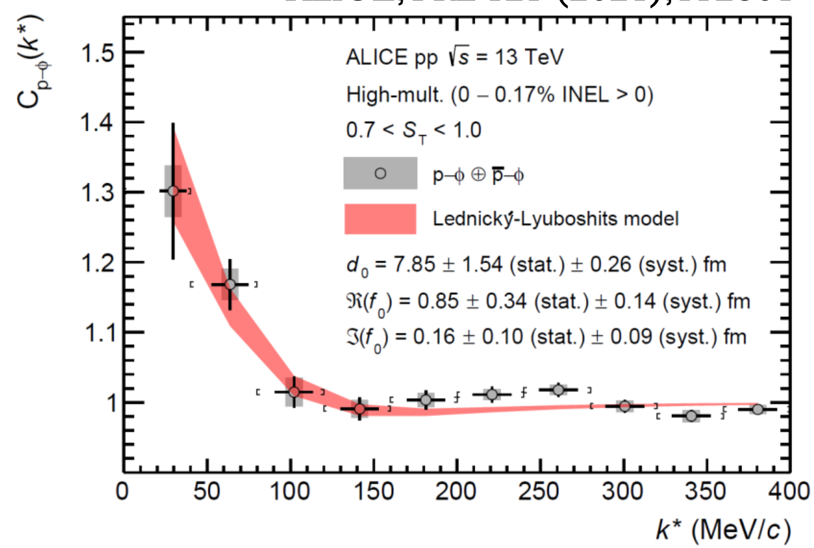
ΦN interactions and mass

- Mass of ϕ meson in a QCD medium can be studied in terms of ϕN interactions
- ALICE shows the attractive strong interaction between a proton and a ϕ meson using two-particle correlations measurements
  - Consistent with LEPS results (W.C. Chang *et al.*, PLB658(2008), 209)
  - Significantly larger than CLAS results (I. I. Strakovsky *et al.*, PRC101(2020), 045201)

- The result suggest a large mass modification of ϕ meson

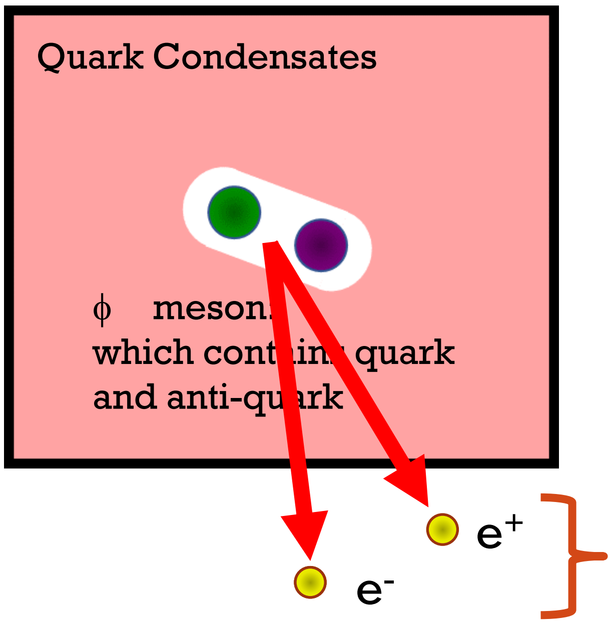
- <u>We are preparing a new experiment to measure mass spectra of vector mesons in nucleus at J-PARC</u>

ALICE, PRL 127 (2021),172301

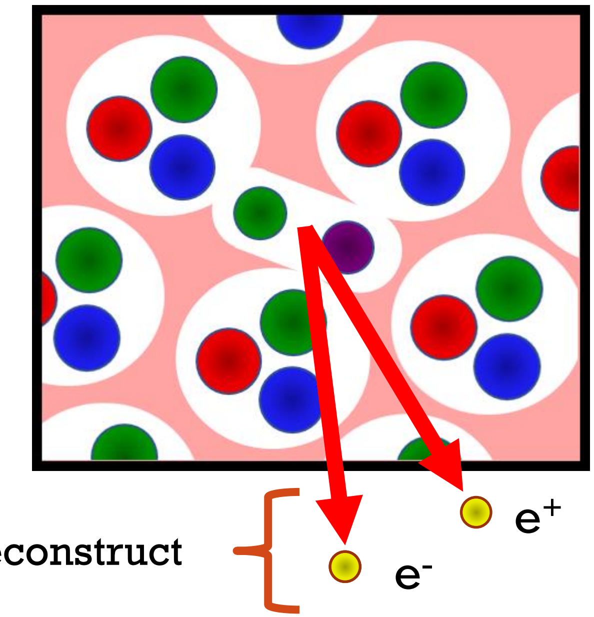


METHOD OF THE EXPERIMENT

Vacuum



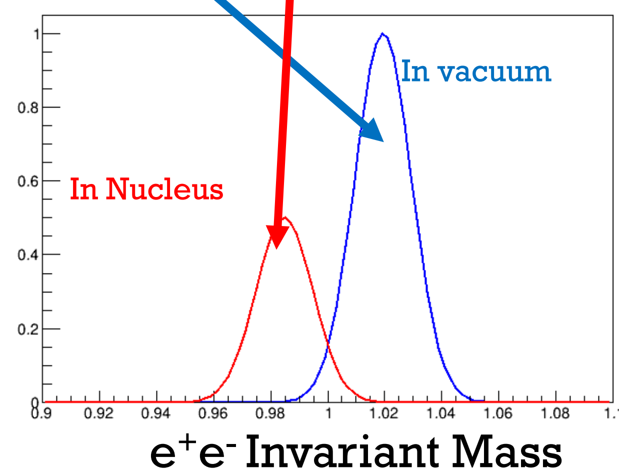
Nucleus (Finite Density)



Change of quark condensates and modifications of mass spectrum

Reconstruct

Reconstruct



Spectral Change:

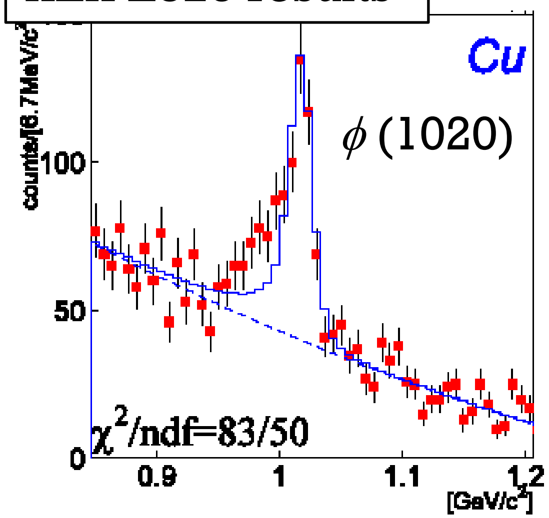
Change of quark condensate

Even in nucleus, changes of condensates can be expected

NEW EXPERIMENT

- A prior experiment is performed at KEK-PS
  - The experiment shows yield excess in e+e- invariant mass and it can be understood as mass modifications of ϕ mesons
- At J-PARC, upgrades of the KEK-PS E325 experiment are being carried out

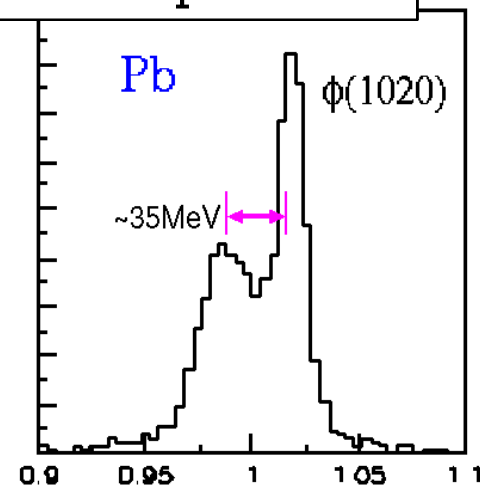
KEK E325 results



e^+e^- invariant mass

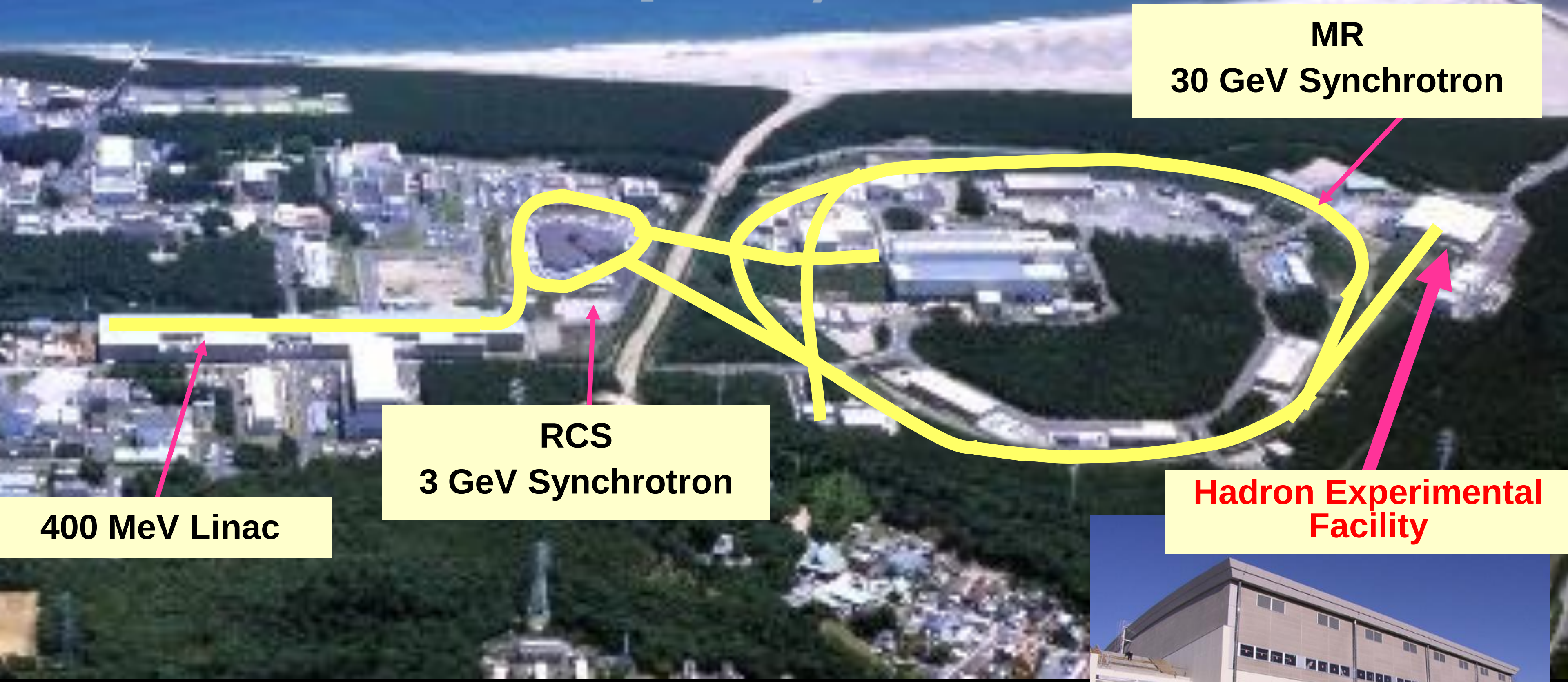
High Statistics
Better
Resolution

J-PARC expectation

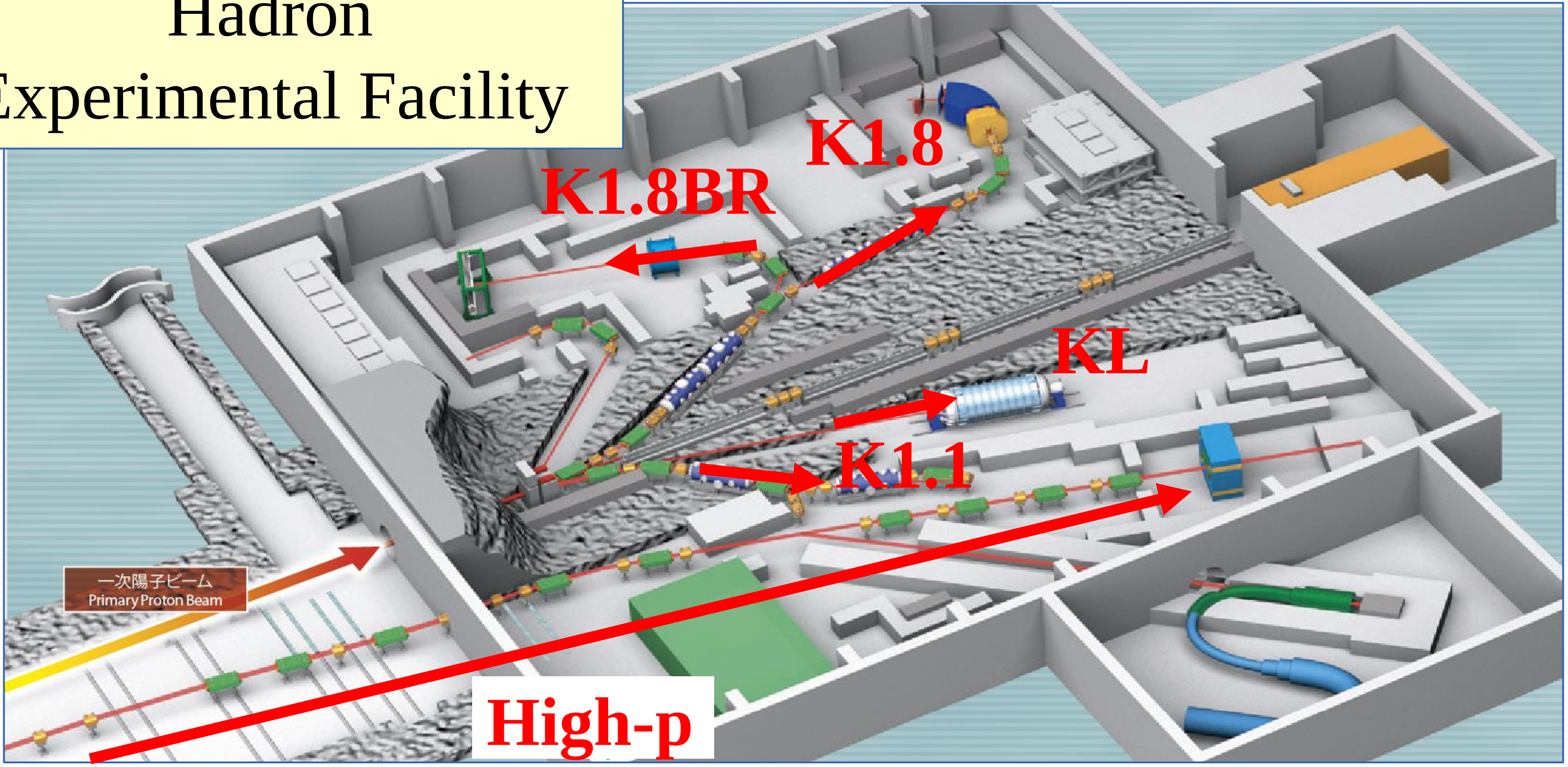


e^+e^- invariant mass

J-PARC (Japan Proton Accelerator Research Complex)



Hadron Experimental Facility



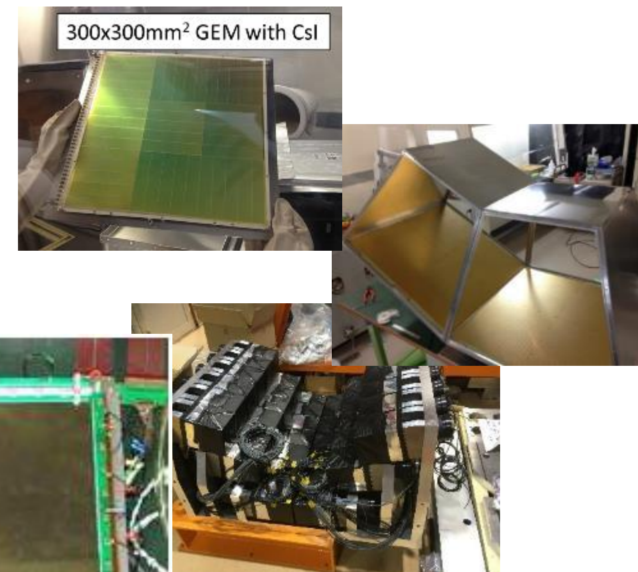
Name	Species	Energy	Intensity
K1.8	$\pi^{\pm}$, $K^{\pm}$	< 2.0 GeV/c	~10^5 Hz for K^+
K1.8BR	$\pi^{\pm}$, $K^{\pm}$	< 1.0 GeV/c	~ 10^4 Hz for K^+
K1.1	$\pi^{\pm}$, $K^{\pm}$	< 1.1 GeV/c	~ 10^4 Hz for K^+

New Beamline

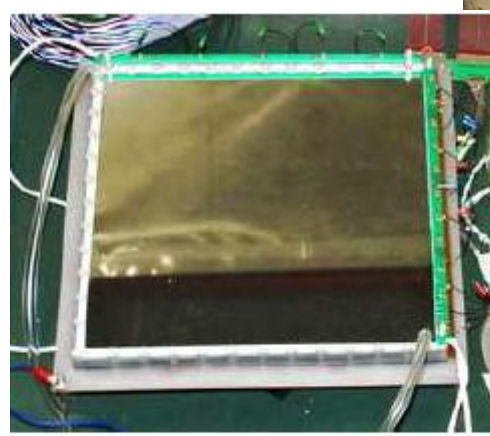
Name	Species	Energy	Intensity
High-p	proton	30GeV	~ 10^{10} Hz
	Unseparated	< 20GeV/c	~ 10^8 Hz

J-PARC E16 EXPERIMENT

- Measurements of e^+e^- pair invariant mass spectra in nucleus
- 10 times larger statistics compared to the KEK experiment
  - 10^{10} protons per spill (10 times higher than KEK)
  - Counting rate: 5 kHz/mm^2 (maximum)
- Two times better resolution than KEK
  - Larger magnetic field
  - Better Position resolution (~100 μm)

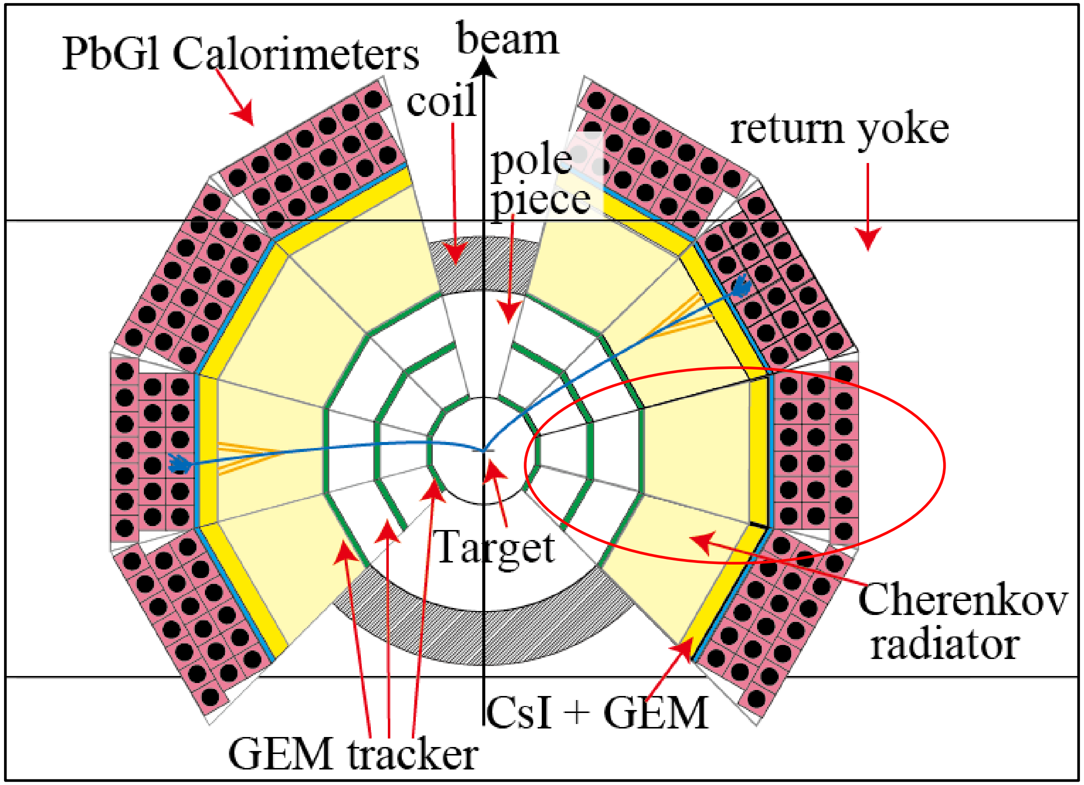


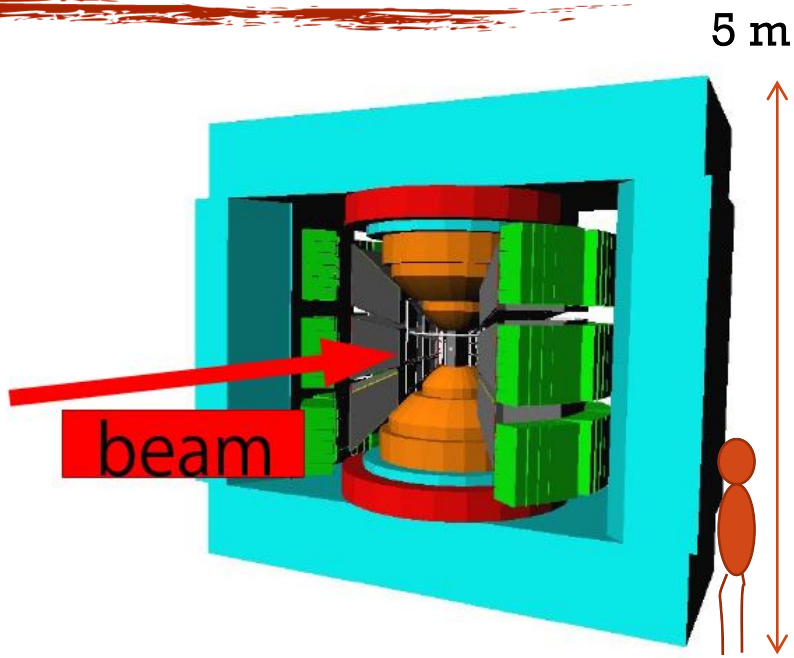
Electron ID

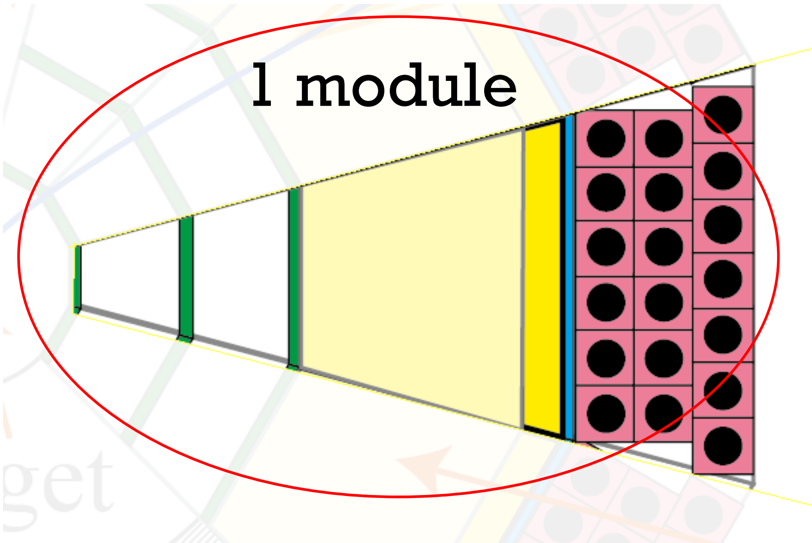


GEM Tracker

SPECTROMETER



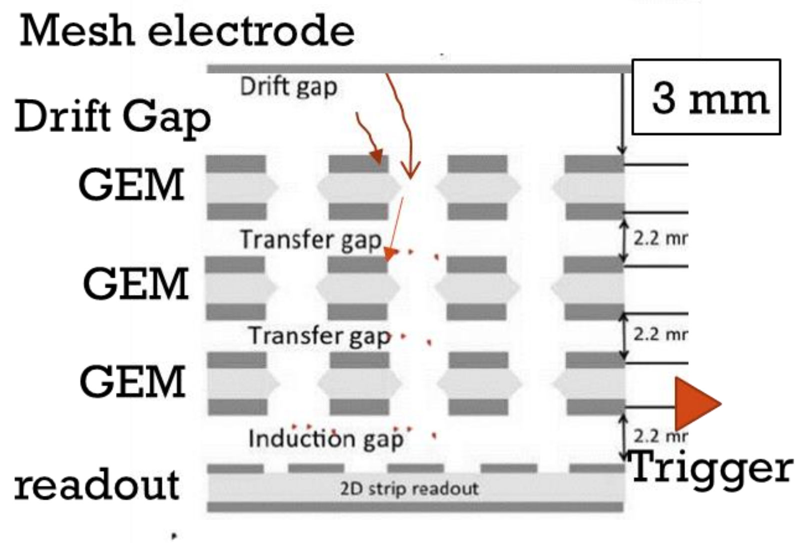


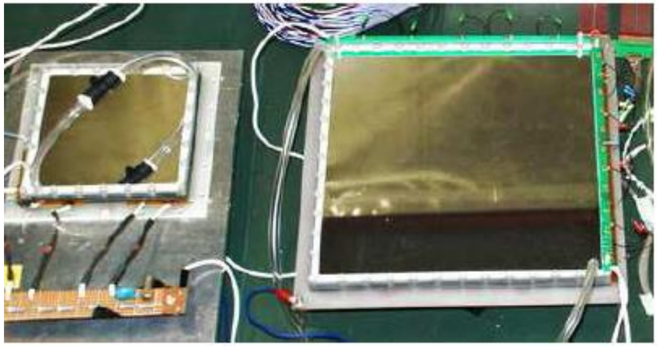


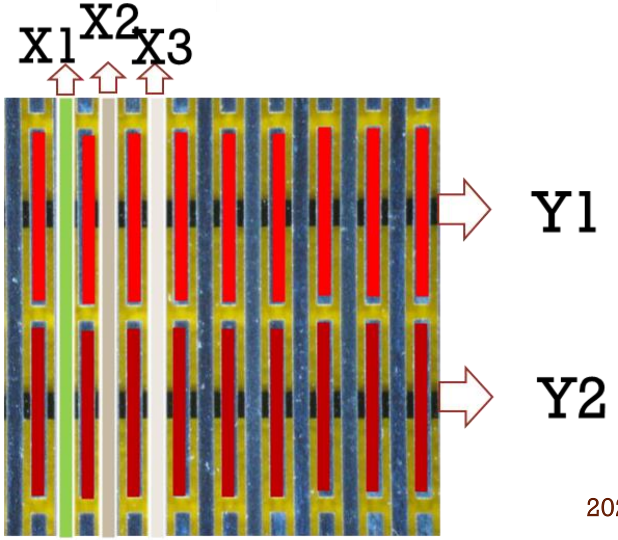
SSD : Tracking , GTR : Tracking
HBD : eID (Cherenkov)
LG : eID (Calorimeter)
26 modules in total. 8 for the 1st physics run.

GEM TRACKER (GTR)

- Ionization electrons in the drift gap are collected and amplified by GEMs.
- Charge collected on to 2D strip readout.
  - X: 350um pitch
    - Sensitive to bending direction.
    - 100 um resolution required.
  - Y: 1400um pitch





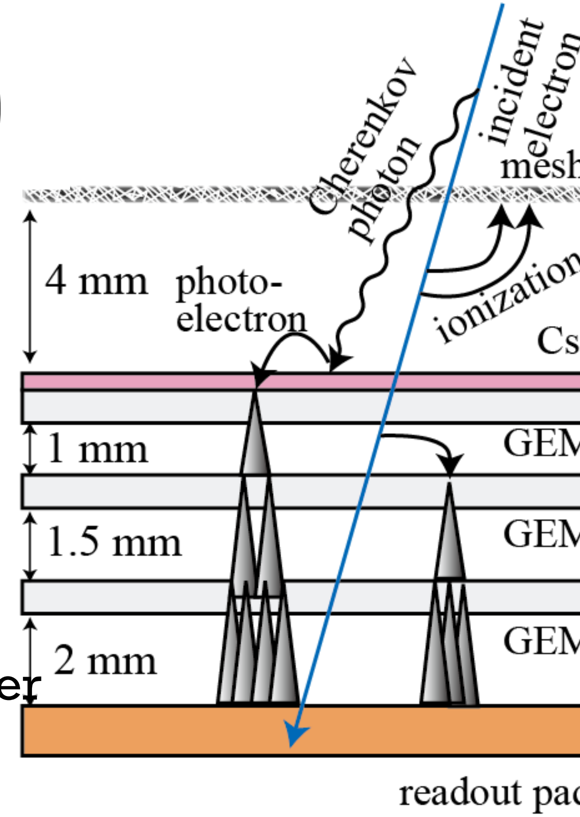


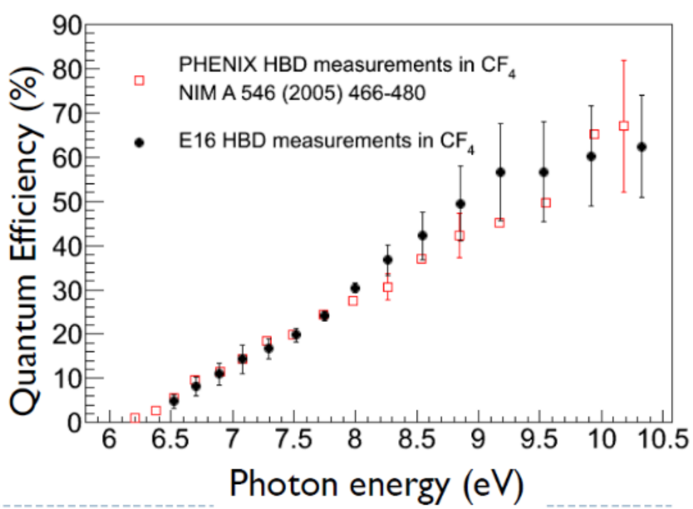
HBD (HADRON BLIND DETECTOR)

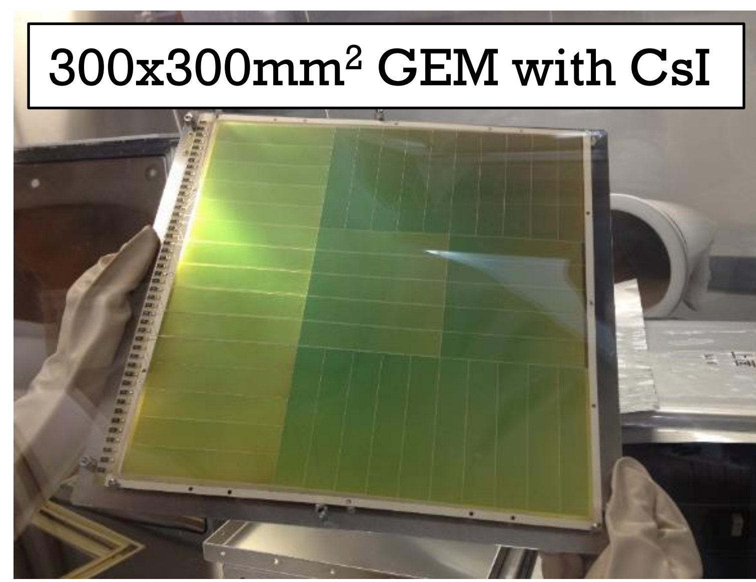
- Based on PHENIX HBD.
- CF4 serves as radiator and amplification gas
  - Radiator 50 cm. / p.e. ~ 11

- Gas Electron Multiplier (**GEM**) for amplification
- **CsI** is evaporated on top GEM
  - Photocathode (> ~6eV)

Trigger





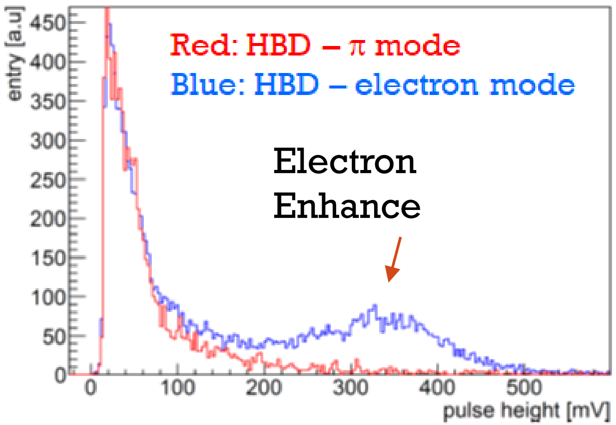


STATUS OF THE EXPERIMENT

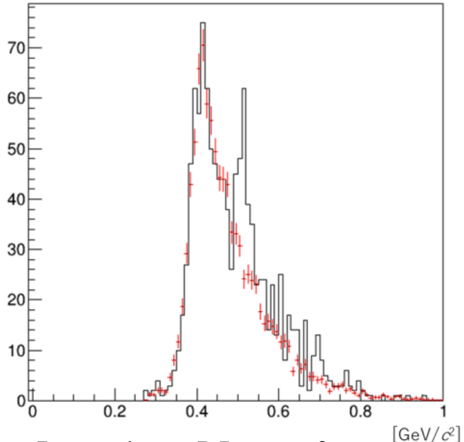
- First beam: May 24, 2020.
- Commissioning runs: June 2020 and June 2021
  - All detectors, triggers, and DAQ worked well
  - Detector performance in commissioning data
- In the next year, we will improve beam conditions and take physics data

Photo of Spectrometer

Pulse Hight @ Lead Glass



Momentum Reconstruction



Invariant Mass of $\pi^+\pi^-$

SUMMARY

- Origin of hadron mass is one of the important topics in hadron physics study to understand our world. Hadron mass is dynamically generated by a spontaneous breaking of chiral symmetry in the medium and closely related with properties of QCD medium
- We are preparing a new experiment to study mass spectra of vector mesons in nucleus, since mass spectra of the vector mesons can be modified due to a finite density effects
- We took pilot data and evaluate detector performance. Detectors work well. We are planning to take physics data in the early next year.

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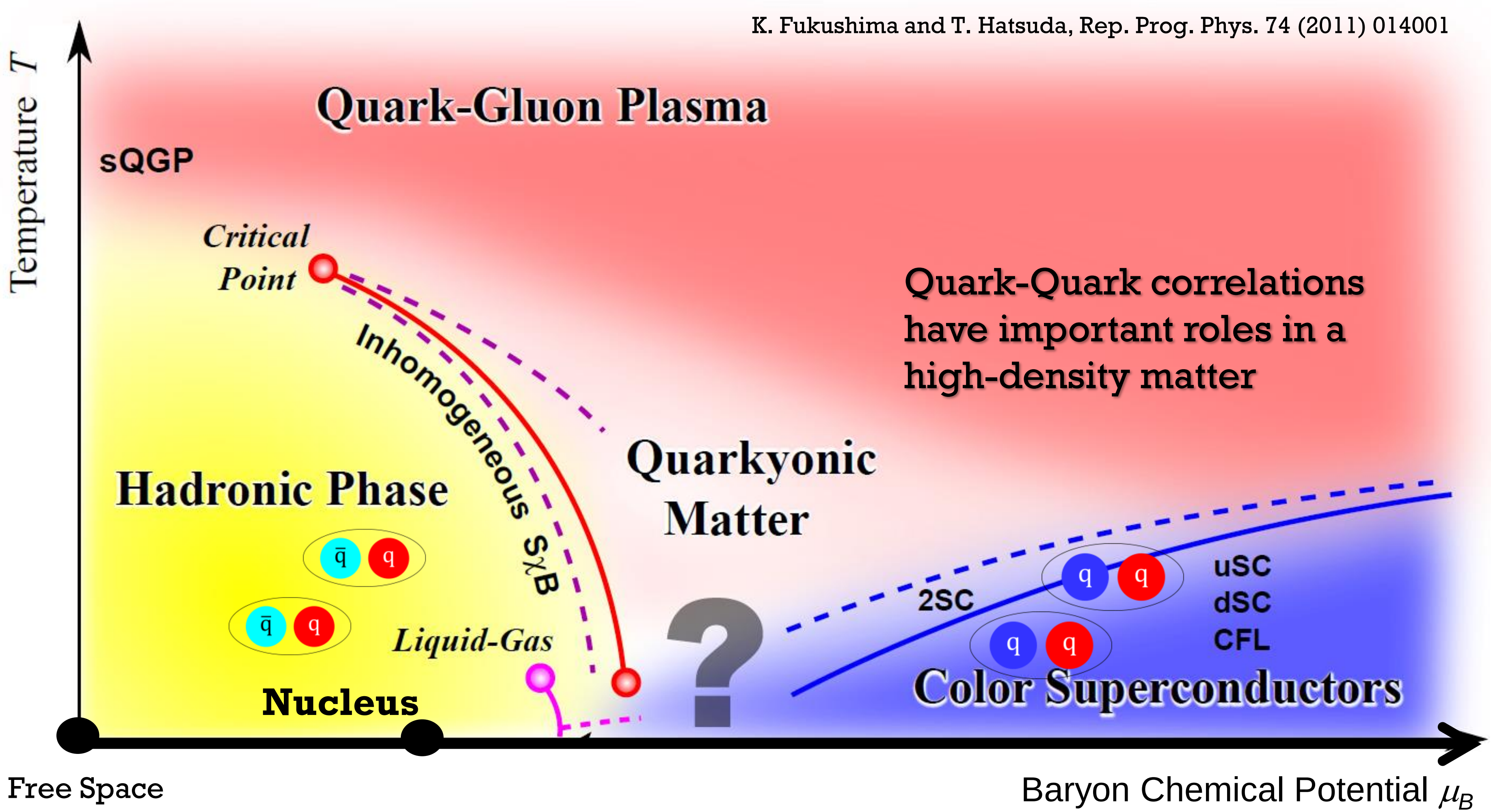
BACK UP

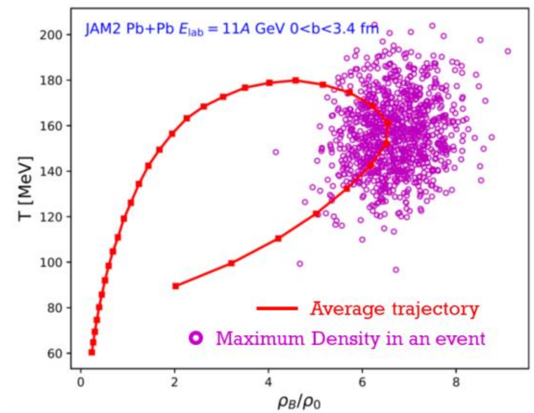
FUTURE: STUDY OF HIGH-DENSITY MATTER



J-PARC Heavy Ion Project

- Main Physics topics
  - QCD phase structure in high density region
  - Study of strangeness systems and hyperon interactions
- Heavy Ion Beam specifications
  - Beam Energy: $\sqrt{S_{NN}} \sim 2 - 5$ GeV
  - Species: Up to Uranium
  - Maximum Beam Intensity: 10^{11} Hz

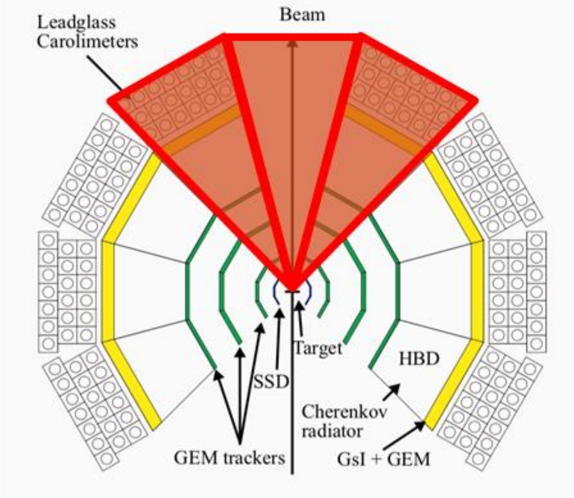
JAM2 Calculation by Y. Nara:
https://gitlab.com/transportmodel/jam2



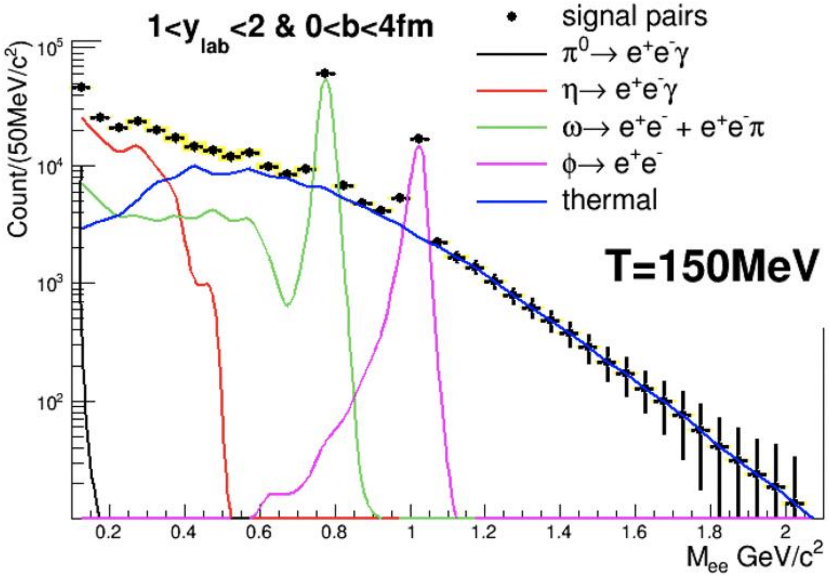
Calculated Temperature and Density

MEASUREMENTS OF ELECTRON PAIRS IN HI

- Di-electron measurements in heavy-ion collisions with spectrometer upgrades
- 10^8 beam/spill, IR rate ~ 50 kHz with 0.035 mm Au target (~0.1% int. length)
- First Proposal is submitted to J-PARC Program Advisory Committee

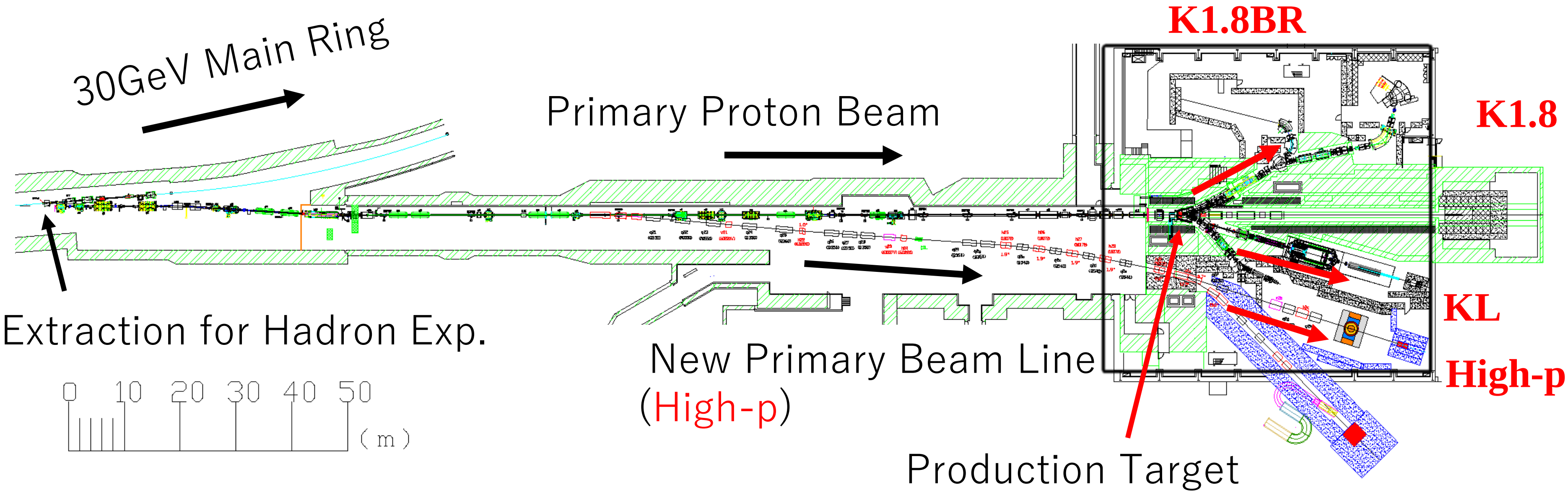


Detector Upgrade
in the forward region



Expected e^+e^- mass spectra

HADRON EXPERIMENTAL FACILITY



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K1.8BR	$\pi^{\pm}, K^{\pm}$	< 1.0 GeV/c	~ 10^4 Hz for K^+
KL	K_L	2.0 GeV/c (Ave.)	~ 10^7 Hz for K^0

New Beamline

High-p	primary	30GeV	~ 10^{10} Hz
	Unseparated	< 20GeV/c	~ 10^8 Hz

HADRON PHSYICS

Understand our world based on quarks and its interactions

Quark：

Current mass (a few MeV/c^2) (Higgs Mechanism)

Colored Quarks are confined

Interaction: Quantum-Chromo-Dynamics

Proton (Hadron)：

Mass of **940**MeV/c^2

Has Constituent quarks inside

Interaction: Hadron interactions

Naïve understandings

Color confinement

Spontaneous breaking of chiral symmetry and Dynamical mass generations

the presence of π, K, η as NG bosons

What we want to know?

How is hadron mass generated?

What are effective degree of freedom inside hadrons?

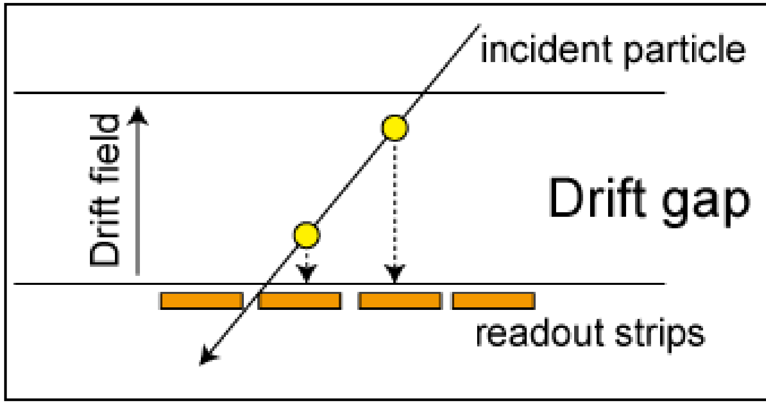
How are hadron interactions understood from quarks?

Silicon Strip Detector

- Run0
  - Existing 6 SSDs used for another J-PARC experiment.
    - ATLAS sensor
    - Sensitive area: 61 mm x 62mm
    - Strip pitch 80 um. (1D)
    - Timing Resolution 4ns
    - It has large unwanted frame.
    - The readout ASIC is APV-25
- Run1
  - Starting collaboration with FAIR-CBM
    - CBM developed sensor
    - Sensitive area: 60 mm x 60 mm
    - Strip pitch 50um (Double sides)
    - Almost no frame
    - The readout ASIC is a CBM special chip
      - Developed for the streaming DAQ, however it can be used for a triggered DAQ

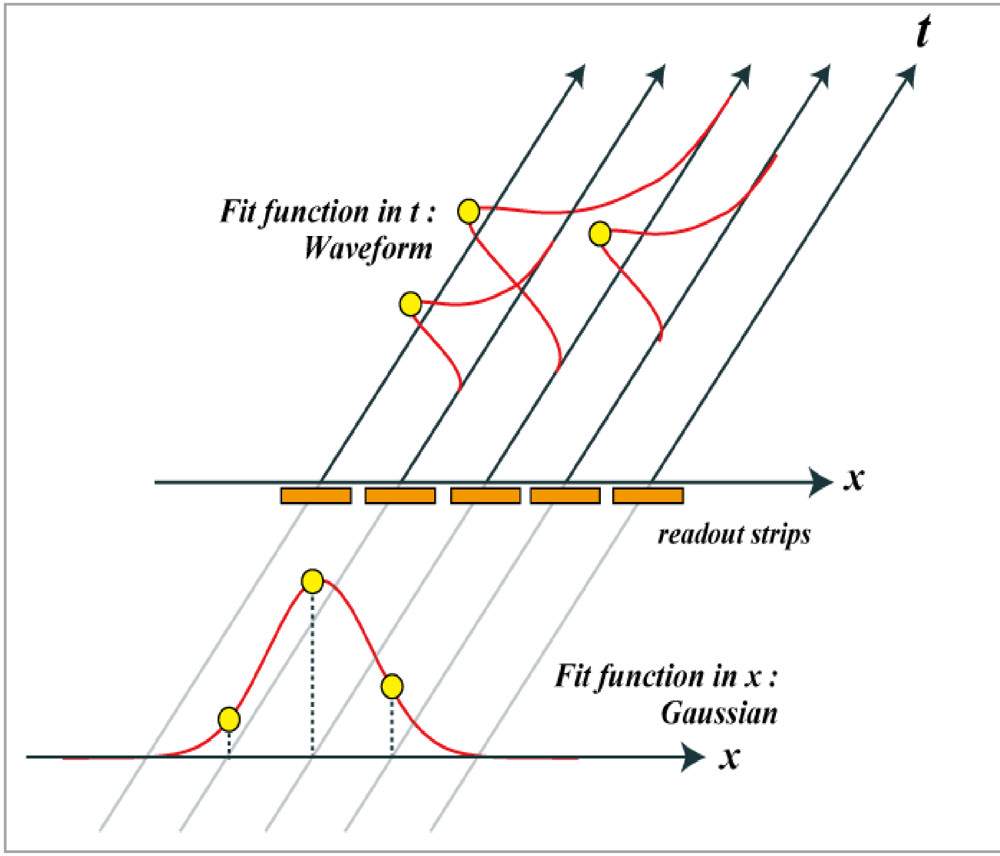
GTR Performance

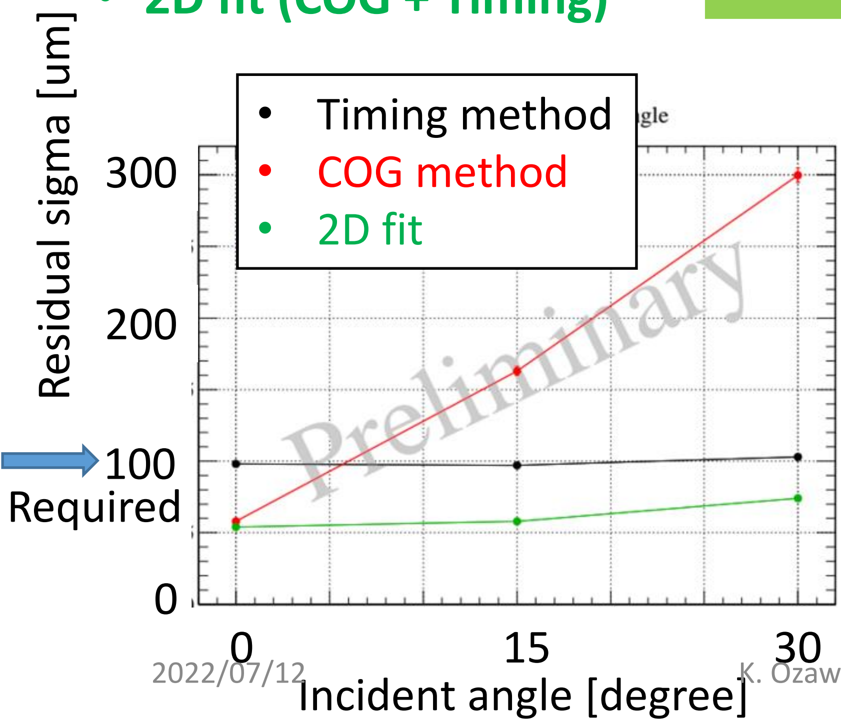
- Center Of Gravity (COG) Method
  - Ordinal analysis method
  - ~ 60 μm @ 0 degree of incident angle
  - Worse results for inclined tracks



- Timing method
  - Distance in drift field dir. Can be obtained using flight time like mini-TPC
  - ~ 100 μm for all tracks

- **2D fit (COG + Timing)**





LG (Lead Glass Calorimeter)

- Reuse from TOPAZ
  - ~300 at the 1st stage.
  - ~1000 in total
  - We have all we need.
- Expected Rejection Power
  - ~25 offline (energy dep. th.)
  - ~10 online (fixed th.)

We've got all we need.