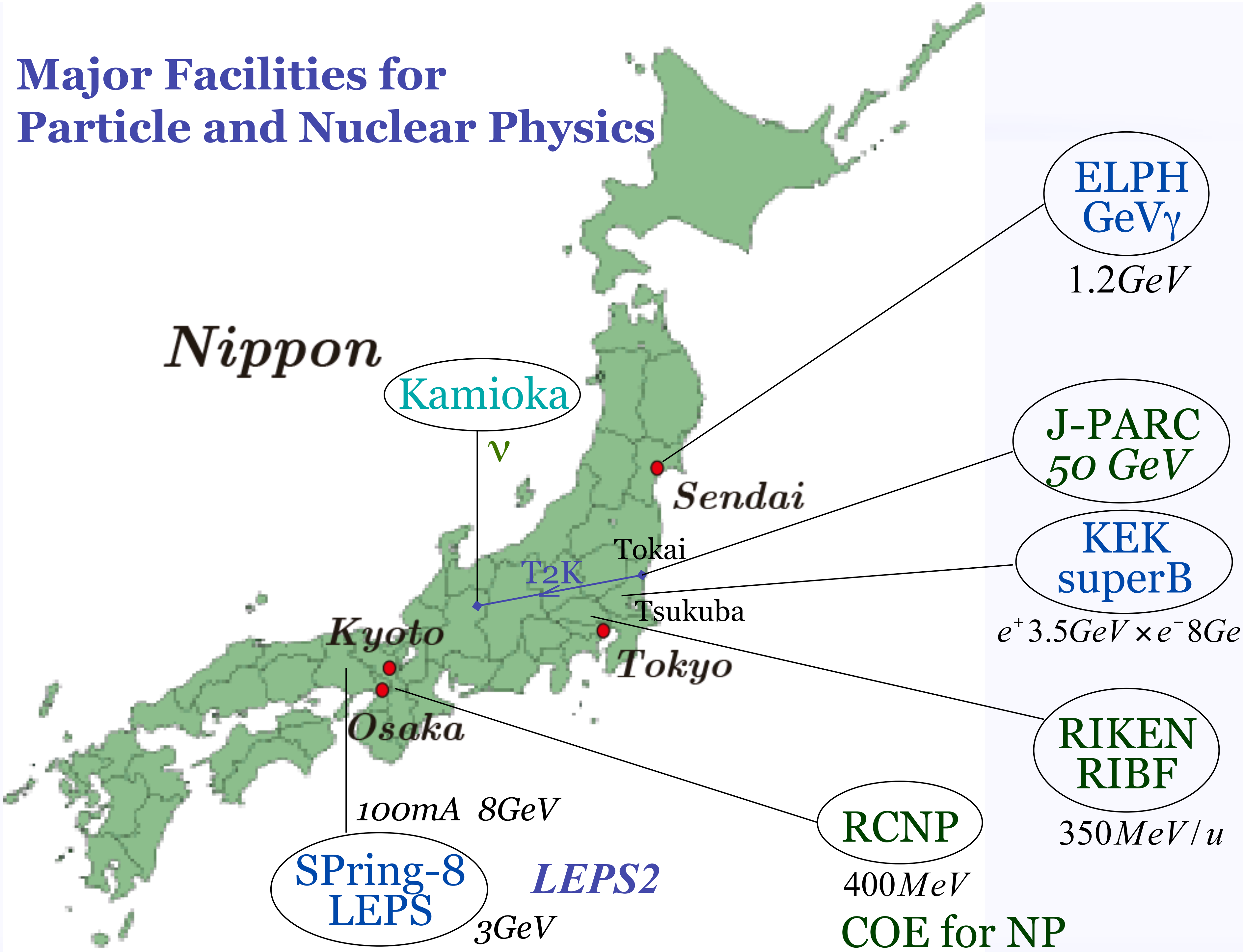
Nov. 22-27, 2010, Tata Institute, Mumbai

Quark Nuclear Physics with a Photon Beam at Elphs Lab

H. Shimizu
Research Center for Electron Photon Science (ELPH)
Tohoku University
Sendai

Major Facilities for Particle and Nuclear Physics



Reorganization of LNS into ELPH

- **LNS was reorganized to be ELPH.**
  Laboratory of Nuclear Science (LNS)
  attached to Faculty of Science

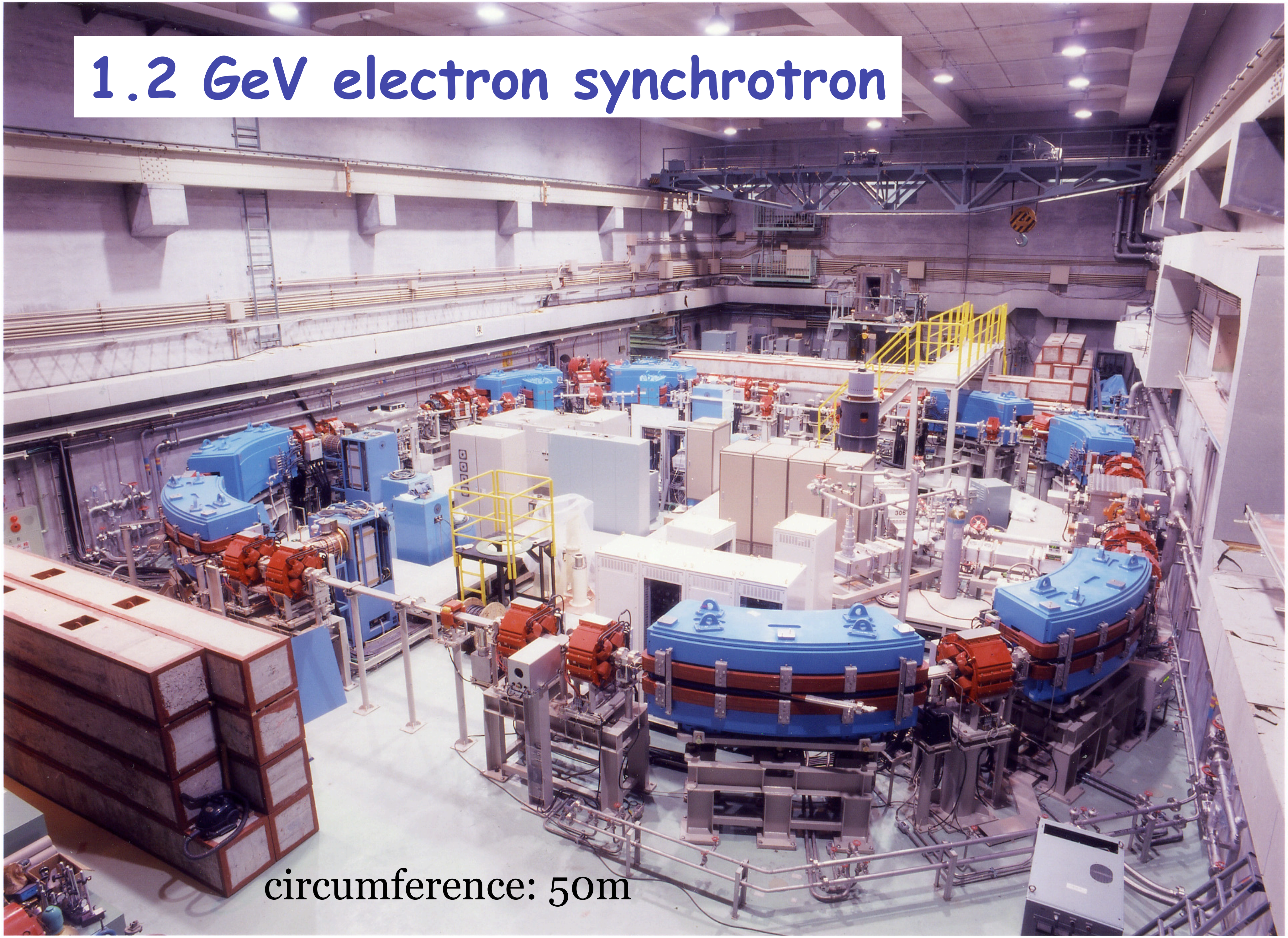
  ↓

  Research Center for
  Electron Photon Science (ELPH, *Elphs Lab*)
  affiliated directly to Tohoku University

- ***Elphs Lab* started operation from Dec.1, 2009.**

- ***Elphs Lab* will be a Joint Usage/Research Center for Electron Photon Science from FY2011.**

1.2 GeV electron synchrotron



circumference: 50m

CONTENTS

Research activities at Elphs Lab

- **Overview**
  - layout of beam lines etc.
- **Quark Nuclear Physics**
  - hadron structure
  - non-perturbative QCD
  - chiral symmetry in the baryon sector
- **Experimental apparatus**
  - penta-quark baryons with hidden strangeness
  - 4π EM calorimeter
  - construction of FOREST
- **Data obtained with FOREST**

Research activities at Elphs Lab

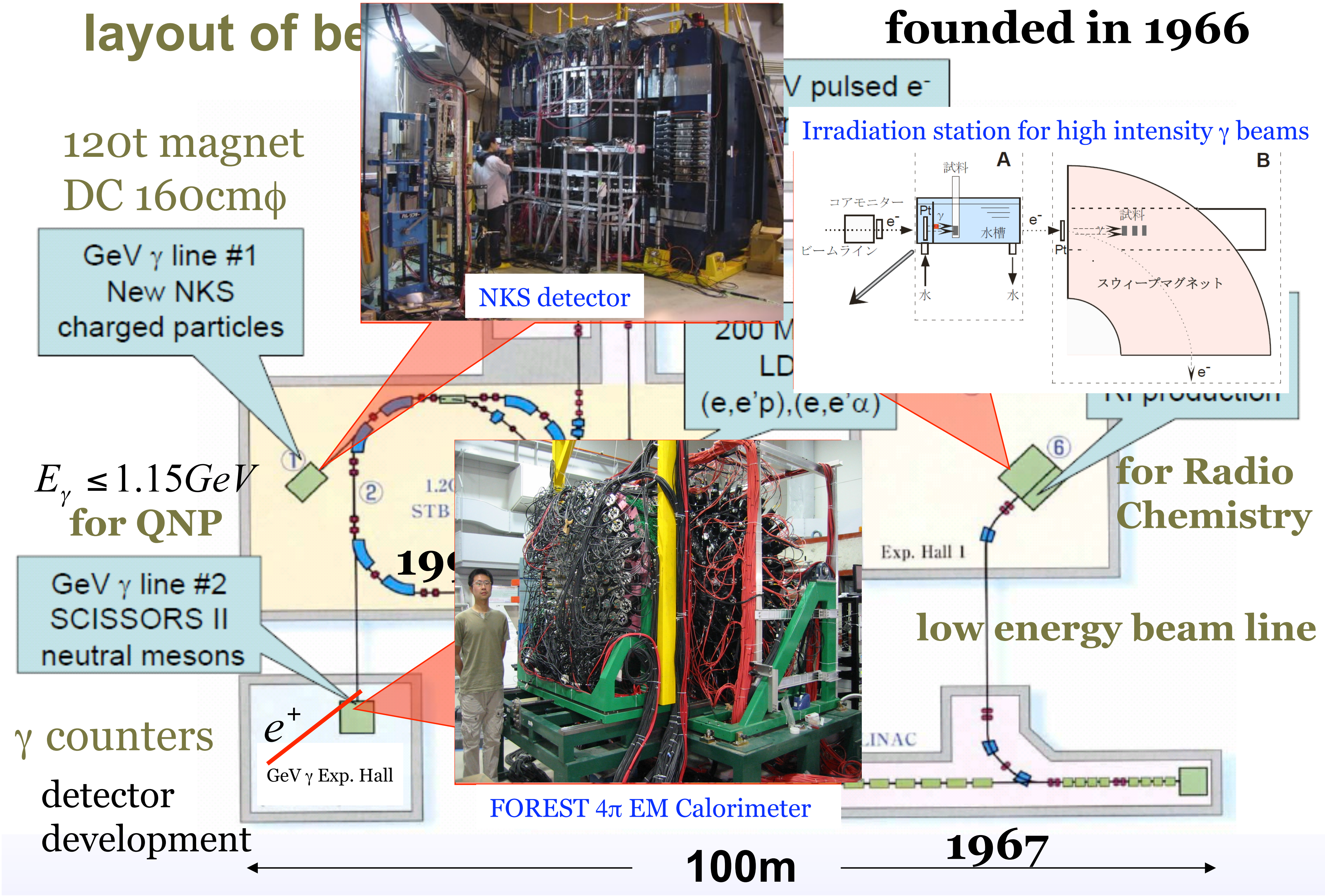
overview

Researches conducted at Elphs Lab

(3 research divisions)

- **Nuclear Physics**
  - **Quark Nuclear Physics**
    - **Penta-quark baryons**
    - **QCD vacuum**
  - **Low Energy Nuclear Physics**
    - **Electron scattering off unstable nuclei**
- **Accelerator Science**
  - **Beam Physics**
    - **Free electron laser**
    - **Super coherent light source**
- **Radio Chemistry**
    - **Radio activity in fullerene**

Experimental apparatus at Elphs Lab, Tohoku U.



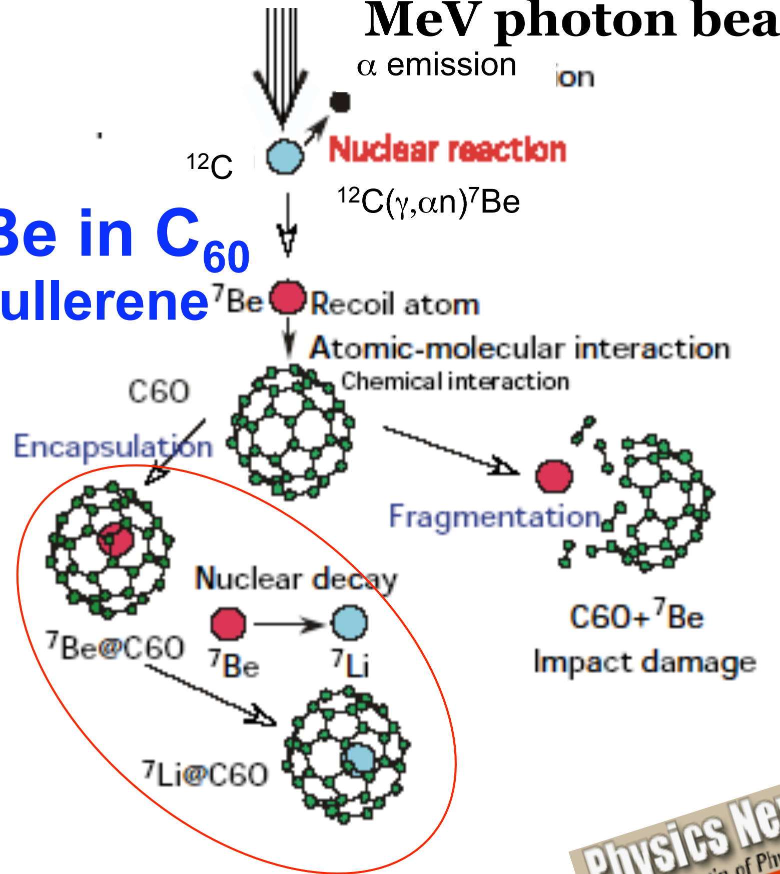
Radio-chemistry @ Elphs Lab

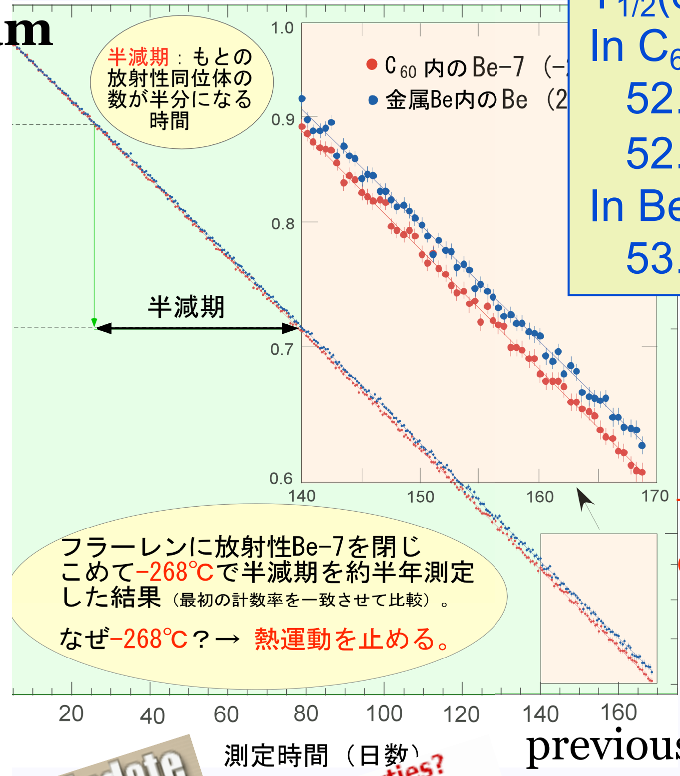
PRL 94 (2004) 112501
PRL 98 (2007) 252501

Discovery of the life time affected by a chemical environment

MeV photon beam

^{7}Be in C_{60} fullerene





$T_{1/2}$(days) of ^{7}Be
In C_{60}
52.68±0.05 (T=290K)
52.47±0.04 (T=5K)
In Be metal
53.12±0.05

~1.4 % change!

the largest change observed up to now

previously observed change ~0.1%

Physics News Update
The AIP Bulletin of Physics News

Can Chemical Environment Affect Nuclear Properties?

A new experiment shows that the decay lifetime of radioactive ... placed inside a carbon-60 molec... when ... seen in a chemically induced ... and one way for it to ... process in whi...

NEWS

Published online: 17September2004; | doi:10.1038/news040913-24

Radioactivity gets fast-forward

Philip Ball

news@nature.com
The best in science journalism

A radioactive element's rate of decay has been speeded up.

Scientists in Japan have persuaded a radioactive material to decay significantly faster than normal.

physicsweb Physics news, jobs and res...

Radioactivity speeds up
21 September 2004

Nuclear physicists in Japan have shown that the electron-capture d... radioactive beryllium-7 can be increased by almost 1% by placing it... carbon-60 "cage". This is the largest change in the decay rate of an... observed. Although the resulting reduction in the radioactive half-l... help with the problem of storing nuclear waste, the cages could be... in medical radiotherapy (T Ohtsuki et al. 2004 Phys. Rev. Lett. 93...

research highlights

Nuclear physics

Accelerated decay

Phys. Rev. Lett. 93, 112501 (2004)

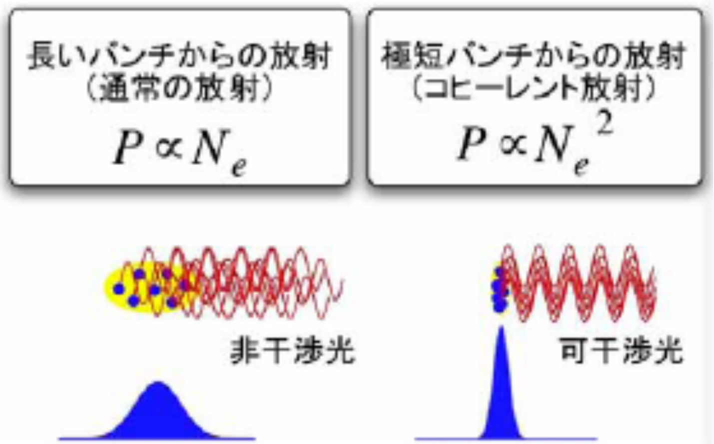
The radioactive decay of beryllium-7 (^{7}Be) speeds up when individual atoms are trapped inside the cage of a fullerene molecule (C_{60}), according to T. Ohtsuki and colleagues. An atom's environment is known to affect its half-life, but the influence of C_{60} on ^{7}Be seems to be the greatest ever recorded — the

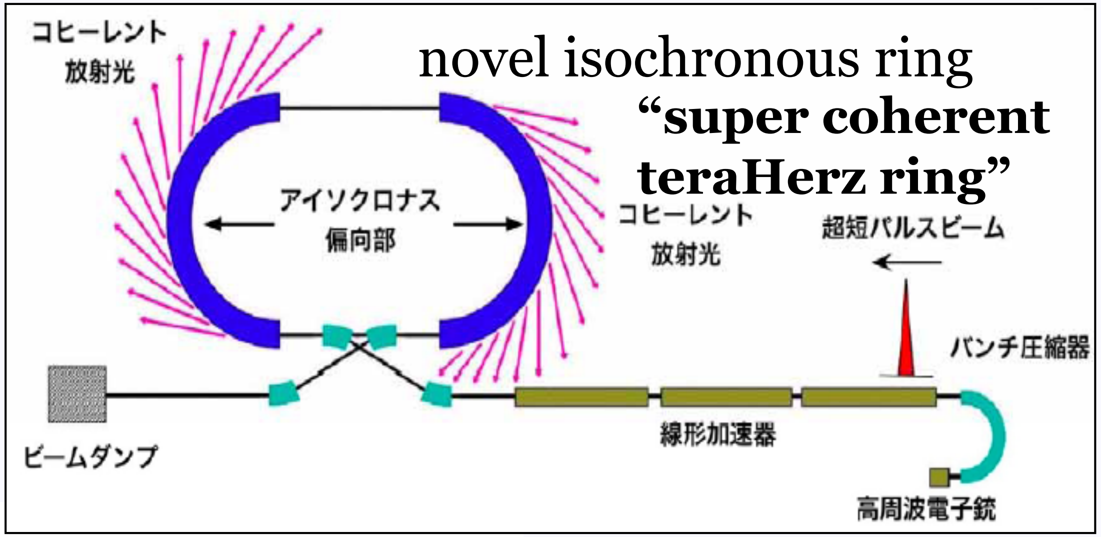
Accelerator science @ Elphs Lab

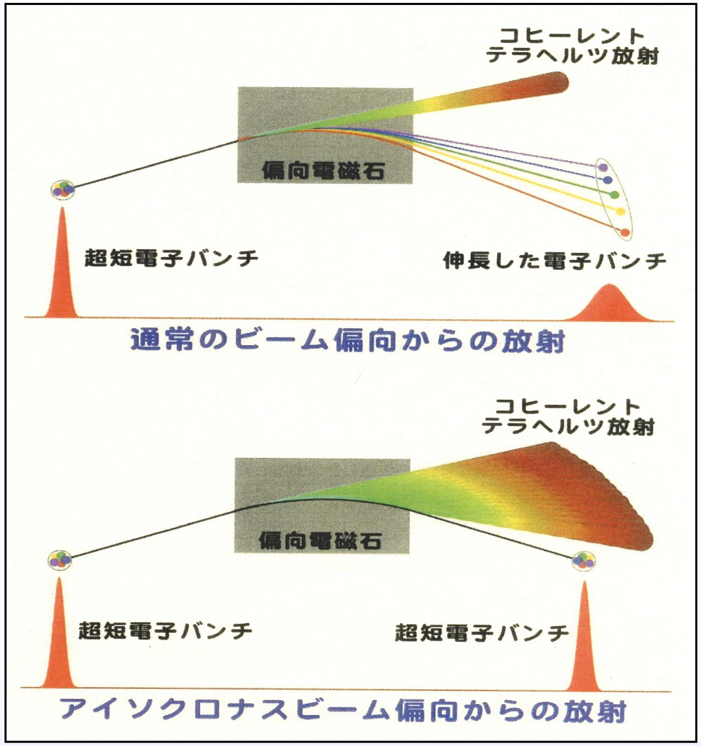
New accelerator principle for a super coherent light source

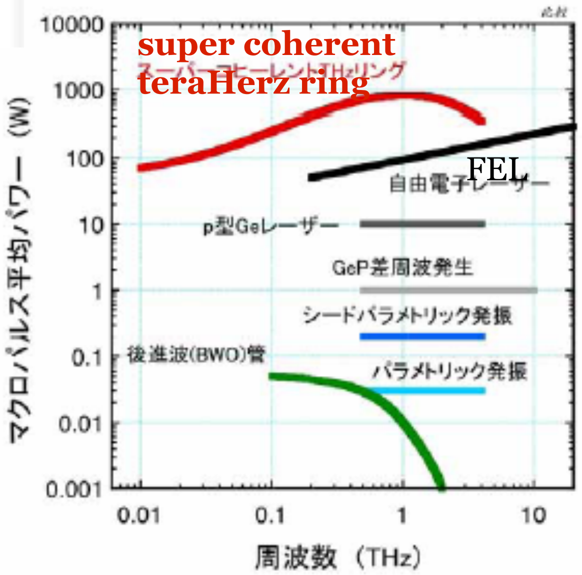
New J. Phys. 8 (2006) 292

coherent radiation









average power
of macro-pulses

the 1st isochronous ring providing extremely high intensity teraHertz lights

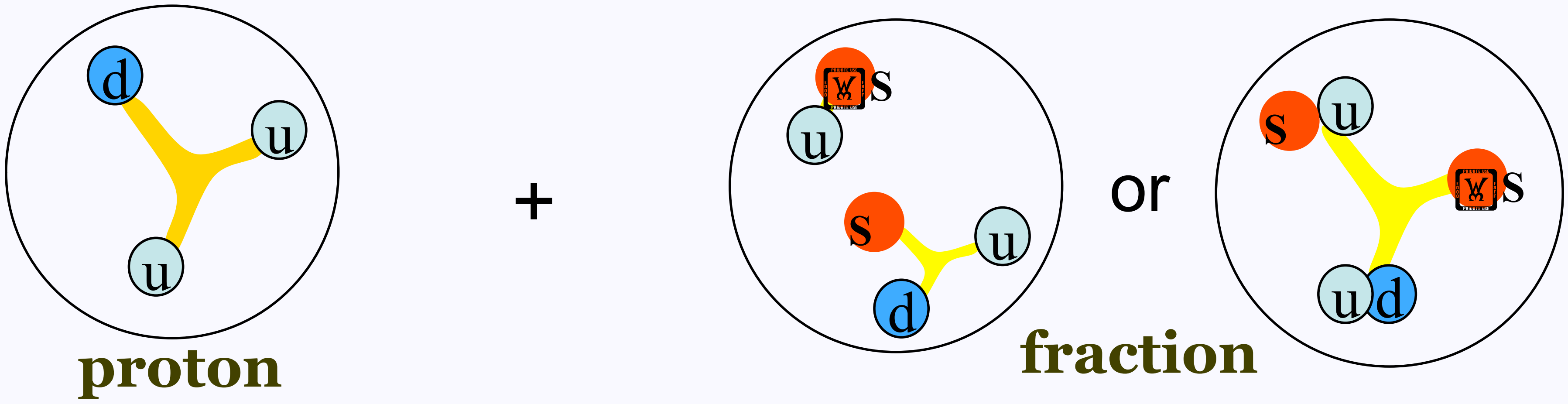
A test ring is now under construction.

Quark Nuclear Physics at Elphs Lab

hadron structure

Quark Nuclear Physics 1

- **Structure of hadrons**



di-quark cluster (5-quark) picture:

$$| p > \sim | uud > + \varepsilon 1 \, | [ud][ud]\bar{d} >$$
$$+ \varepsilon 2 \, | [ud][us]\bar{s} > + \ldots$$

→ **Search for exotic hadrons**

Hadrons realized in color singlets
(color SU(3) scheme)

- **meson** $q\bar{q}$ $u\bar{d} : \pi^+$ $\bar{u}d : \pi^-$

$$3 \otimes \bar{3} = 8 \oplus \underline{1}$$

- **baryon** qqq $uud : p$ $udd : n$

$$3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus \underline{1}$$

QCD allows
exotic hadrons having different configurations

* **meson** $q\bar{q}q\bar{q}$ $c\bar{c}u\bar{u} : X(3872), Z(4430)$

* **baryon** $qqqq\bar{q}$ $uudd\bar{s} : \Theta^+$

color singlet states pentaquark baryons search for

Exotic Hadrons

in these decades

intensive work on

- dibaryons $qqqqqq$
- baryoniums $qq\bar{q}\bar{q}$
- hybrid hadrons $qqqg, q\bar{q}g$
- glueballs gg
- ……

No clear exotics were established before!

narrowness of the width

⇧ the key for identification of exotics ⇦ not have to be narrow (fall-apart decay)

⇧

extra degrees of freedom

Θ^+ came in. S=+1

• pentaquark $uudd\bar{s}$

$\overline{10}$

Search for other members of the anti-decuplet

Quark Nuclear Physics
at Elphs Lab

non-perturbative QCD phenomena

-chiral symmetry-

Quark Nuclear Physics 2

- **Non-perturbative QCD**

  chiral symmetry:

  most fundamental property of QCD

  spontaneously broken

chiral transition

χSB ⇒ a phase transition of the QCD vacuum

QCD-motivated effective theory (NJL)

$$\mathcal{L} = \bar{q}(i\partial\!\!\!/ - m)q + g[(\bar{q}q)^2 + (\bar{q}i\gamma_5\boldsymbol{\tau}q)^2]$$

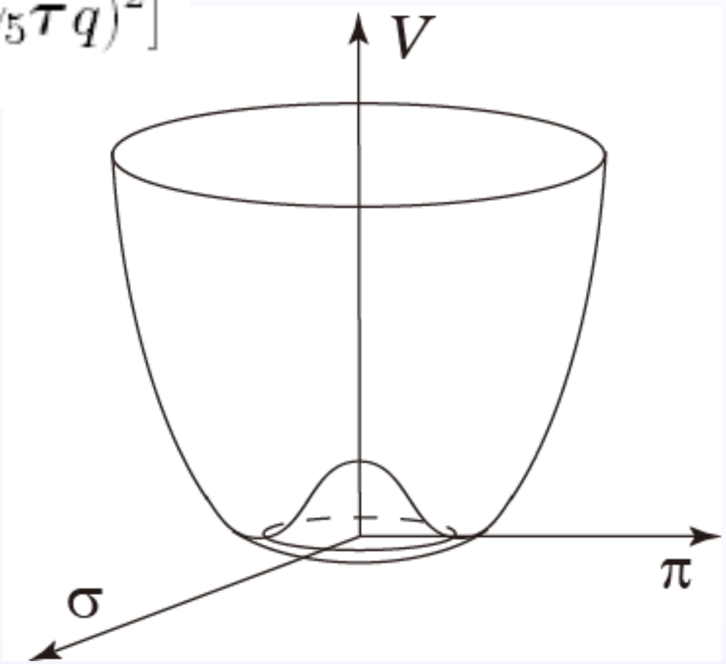
$\sigma \approx \bar{q}q$

amplitude fluctuation of the order parameter $\langle\bar{q}q\rangle$

$\pi \approx \bar{q}i\gamma_5\boldsymbol{\tau}q$

phase fluctuation of $\langle\bar{q}q\rangle$

NG boson of χSB



Nuclear Force (OBEP)

$\mu_\sigma \approx 500 MeV$

$\Gamma_\sigma \approx 500 MeV$

$$Y(x) = \frac{e^{-x}}{x}$$

$$X(x) = \left(1 + \frac{3}{x} + \frac{3}{x^2}\right) Y(x)$$

$$Z(x) = \left(\frac{1}{x} + \frac{1}{x^2}\right) Y(x)$$

$$S_{12} = 3\frac{(\boldsymbol{\sigma}_1 \cdot \boldsymbol{x})(\boldsymbol{\sigma}_2 \cdot \boldsymbol{x})}{x^2} - (\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2)$$

- **scalar meson σ**

$$\mathcal{L}_I = -g_s \bar{\psi} \tau_i \psi \phi_i$$

intermediate range

$$V_s(r) = \frac{\mu_s g_s^2}{4\pi} \left[-\left(1 - \frac{\mu_s^2}{4m^2}\right) Y(\mu_s r) - \frac{\mu_s^2}{2m^2} \boldsymbol{L} \cdot \boldsymbol{S} Z(\mu_s r) \right]$$

state-independent attractive force

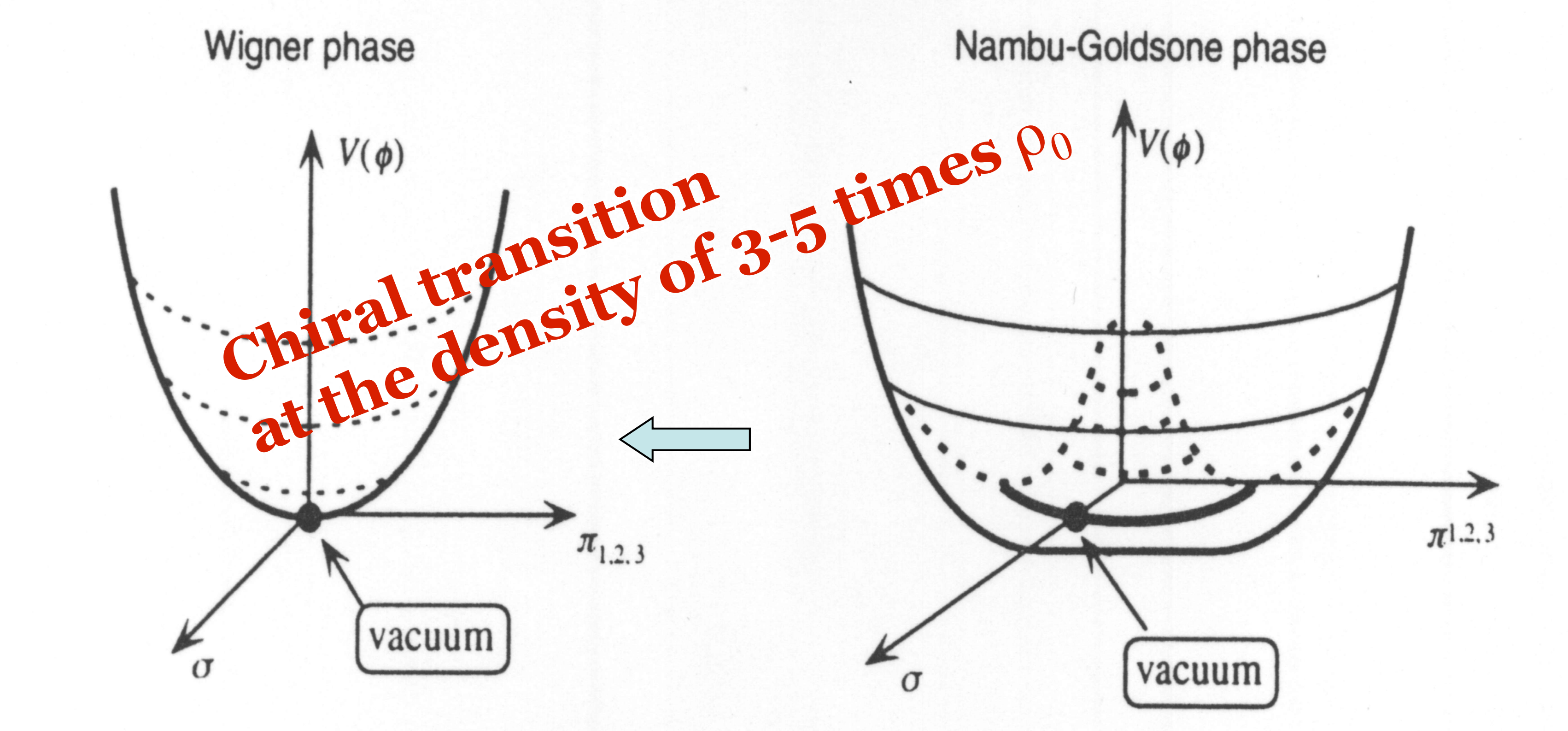
- **pseudoscalar meson π**

$$\mathcal{L}_I = -g_p \bar{\psi}_{p'} i \gamma_5 \psi_p \phi_{ps}$$

strong tensor force

$$V_p(r) = \frac{\mu_p F_p^2}{4\pi} \frac{1}{3} \left[(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2) Y(\mu_p r) + S_{12} X(\mu_p r) \right]$$

Chiral symmetry restoration



χS restoration ⇒ σ and π degenerate in mass: a parity doublet

SSB ⇒ dynamical mass is generated. $M = m - 2g\langle \bar{q}q \rangle$

σ meson : QCD Higgs $\langle \sigma \rangle = \langle \bar{q}q \rangle$

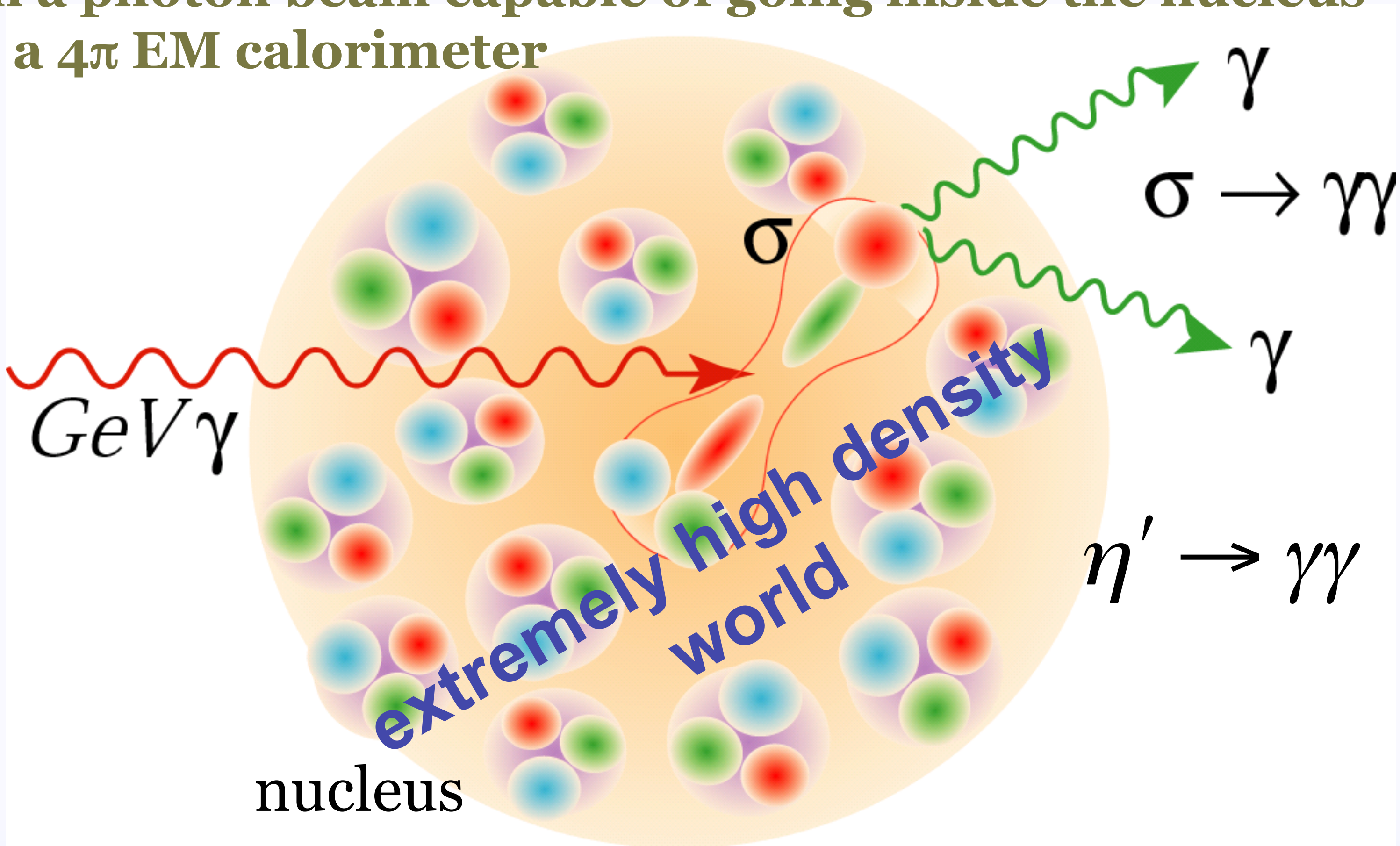
Precursory phenomena are expected even in nuclei.

QCD vacuum

Quark nuclear physics @ Elphs Lab

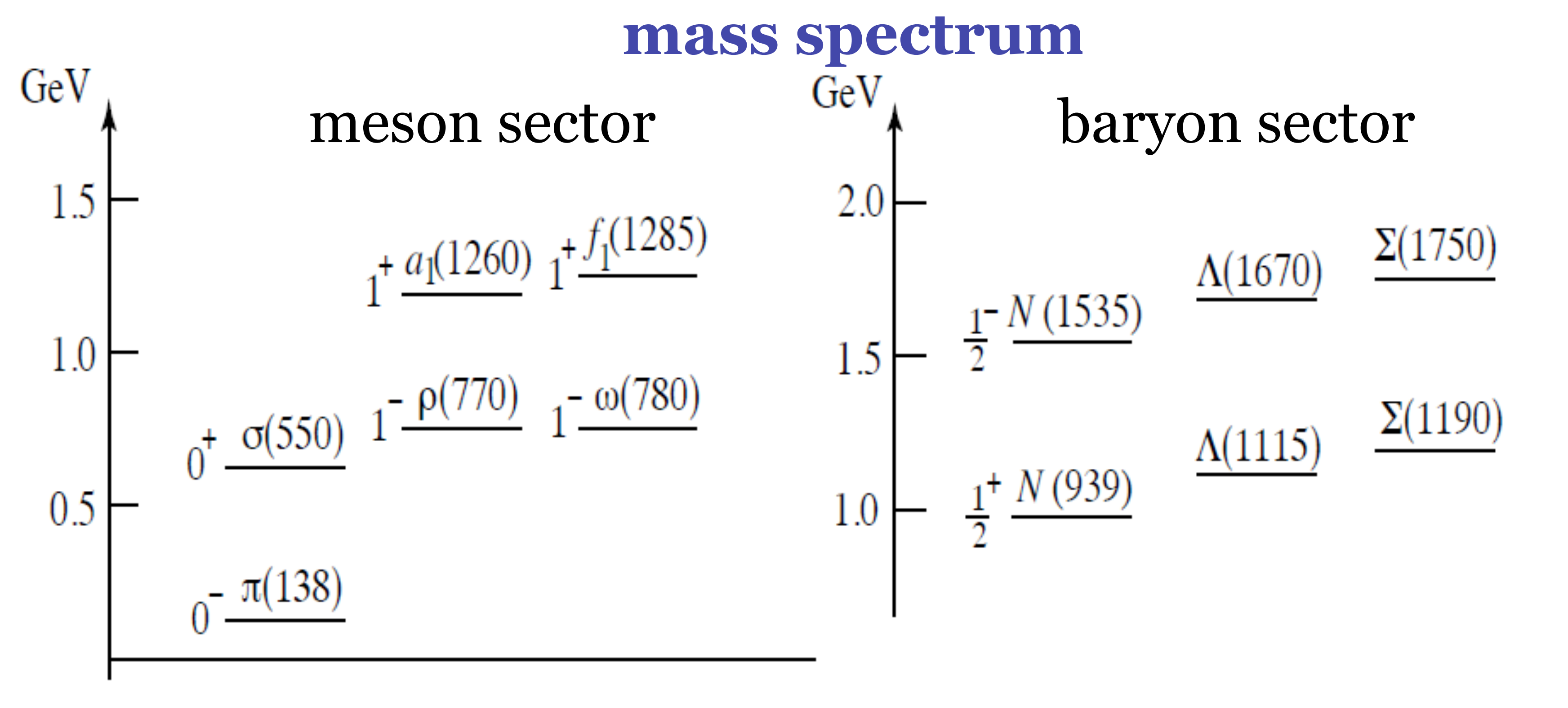
Search for precursory phenomena of the chiral transition in a high density world

- Where is a super high density world?
  : inside the nucleus! $\approx 10^{14} g/cm^3 = 100 Mt/cm^3$
- How?
  : with a photon beam capable of going inside the nucleus and a 4π EM calorimeter



chiral symmetry in the baryon sector

Quark Nuclear Physics 3



- **No parity doublets in our real world!**
- **Existence of parity doublets in the Wigner phase?**
- **Chiral symmetry in the baryon sector?**

2 iso-doublet baryons (χ partners)

- **Lagrangian**

$$\mathcal{L} = (\overline{\psi}_1, \overline{\psi}_2)(i\gamma^\mu\partial_\mu - M)\begin{pmatrix}\psi_1\\ \psi_2\end{pmatrix} \qquad M = \begin{pmatrix}0 & m_0\\ m_0 & 0\end{pmatrix}$$

- **2 kinds of chiral transformations**

  <naïve assignment> $m_0 = 0$

$$\psi_1 \to D_L(\boldsymbol{\alpha})D_R(\boldsymbol{\beta})\psi_1 \simeq \left(1 - i\boldsymbol{\alpha}\cdot\frac{\boldsymbol{\tau}}{2}\right)\psi_{1L} + \left(1 - i\boldsymbol{\beta}\cdot\frac{\boldsymbol{\tau}}{2}\right)\psi_{1R}$$

$$\psi_2 \to D_L(\boldsymbol{\alpha})D_R(\boldsymbol{\beta})\psi_2 \simeq \left(1 - i\boldsymbol{\alpha}\cdot\frac{\boldsymbol{\tau}}{2}\right)\psi_{2L} + \left(1 - i\boldsymbol{\beta}\cdot\frac{\boldsymbol{\tau}}{2}\right)\psi_{2R}$$

  <mirror assignment> $m_0 \neq 0$

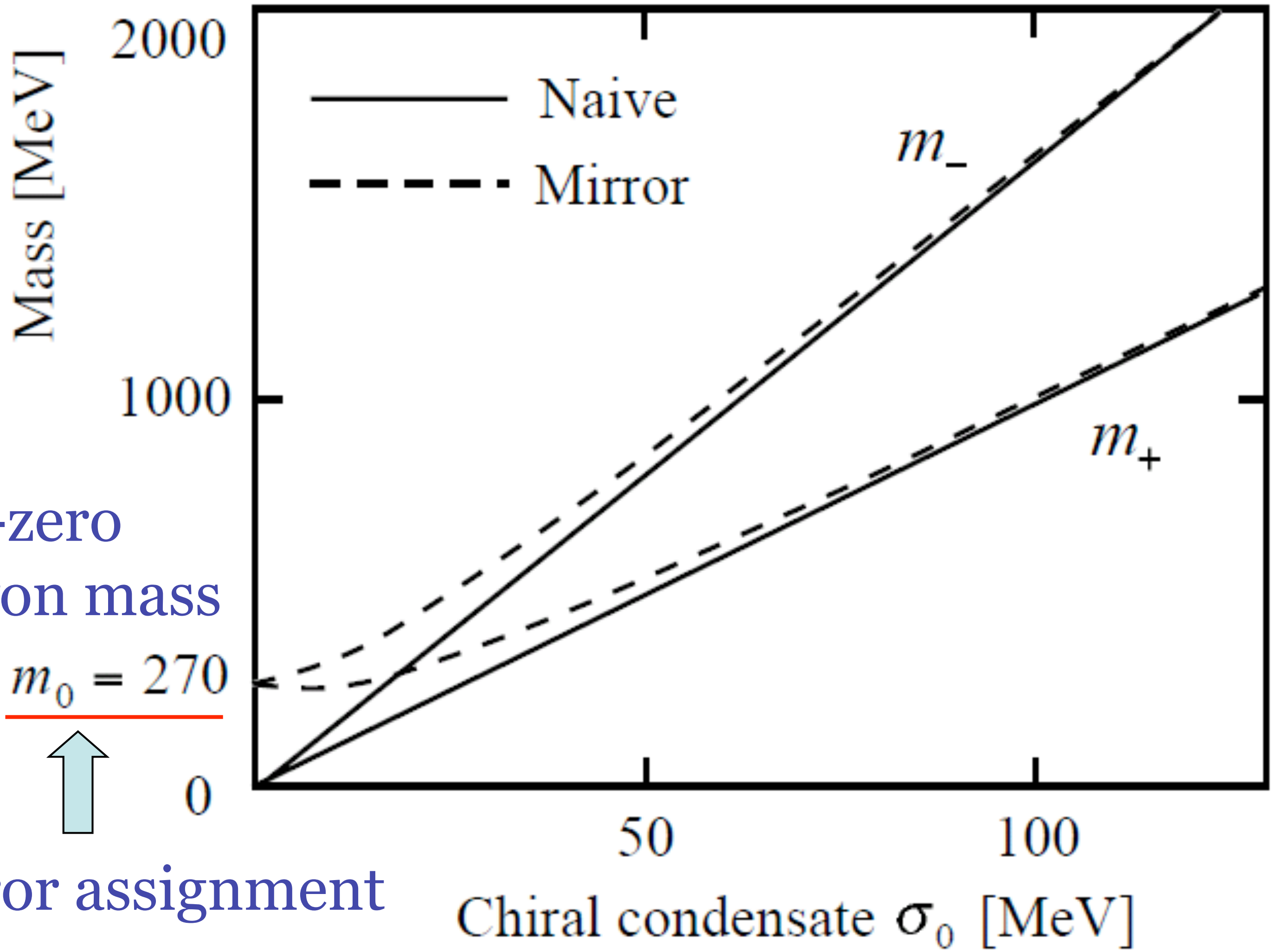
$$\psi_1 \to D_L(\boldsymbol{\alpha})D_R(\boldsymbol{\beta})\psi_1 \simeq \left(1 - i\boldsymbol{\alpha}\cdot\frac{\boldsymbol{\tau}}{2}\right)\psi_{1L} + \left(1 - i\boldsymbol{\beta}\cdot\frac{\boldsymbol{\tau}}{2}\right)\psi_{1R}$$

$$\psi_2 \to D_L(\boldsymbol{\beta})D_R(\boldsymbol{\alpha})\psi_2 \simeq \left(1 - i\boldsymbol{\beta}\cdot\frac{\boldsymbol{\tau}}{2}\right)\psi_{2L} + \left(1 - i\boldsymbol{\alpha}\cdot\frac{\boldsymbol{\tau}}{2}\right)\psi_{2R}$$

Masses of the positive and negative parity nucleons

D. Jido et al., Prog. Theor. Phys. 106 (2001) 873

chiral partners



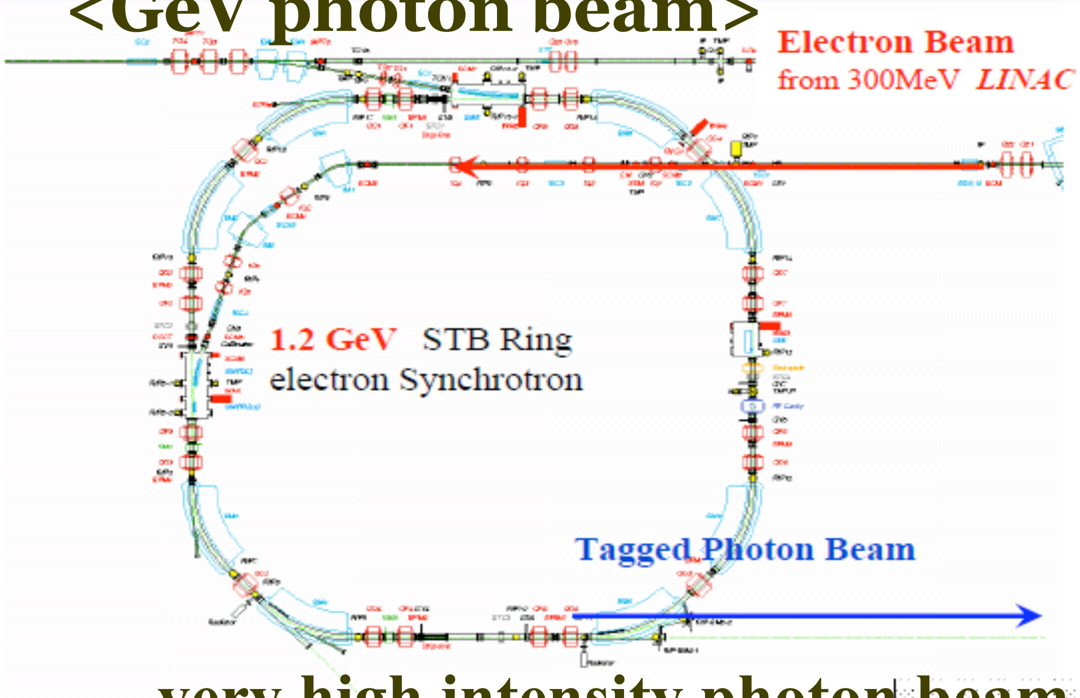
non-zero baryon mass

$m_0 = 270$

mirror assignment

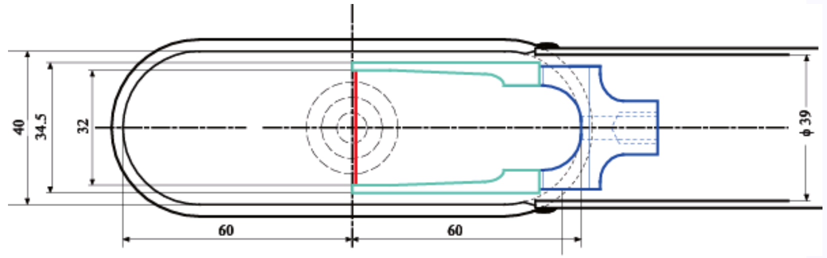
penta-quark baryons with hidden-strangeness

<GeV photon beam>



GeV γ experiments at LNS

internal radiator



carbon fiber 11μmϕ
for Bremsstrahlung photons

very high intensity photon beam

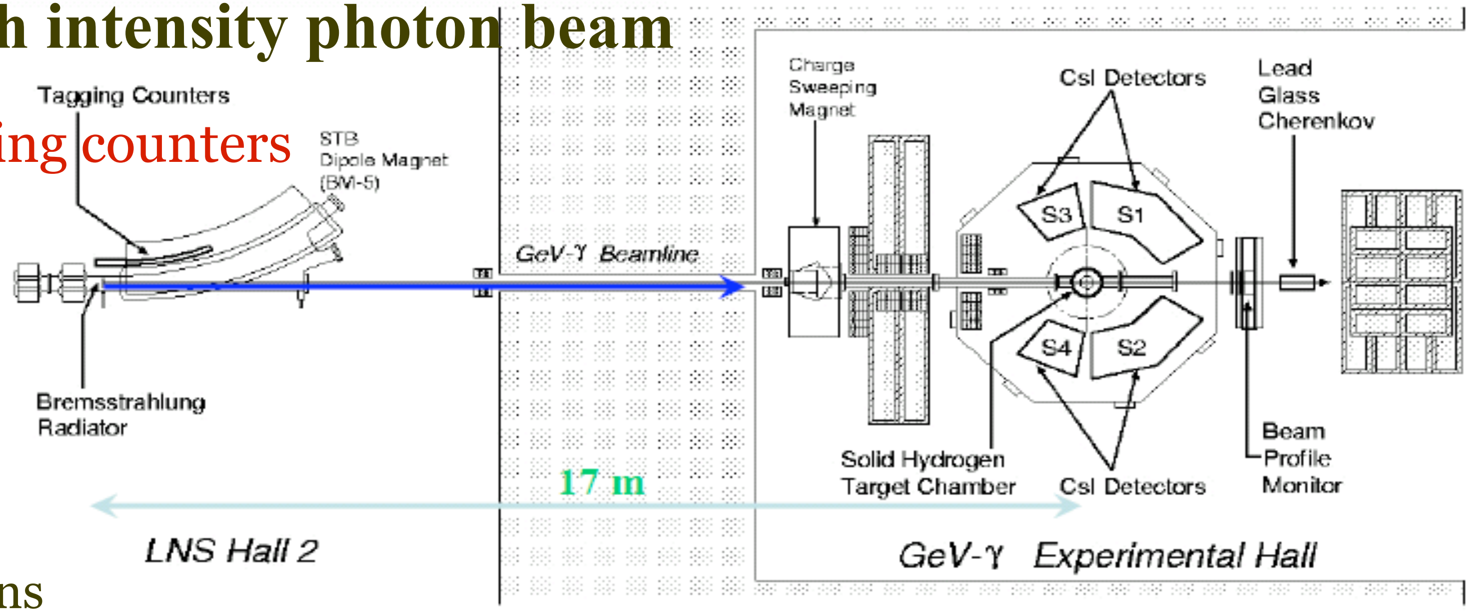


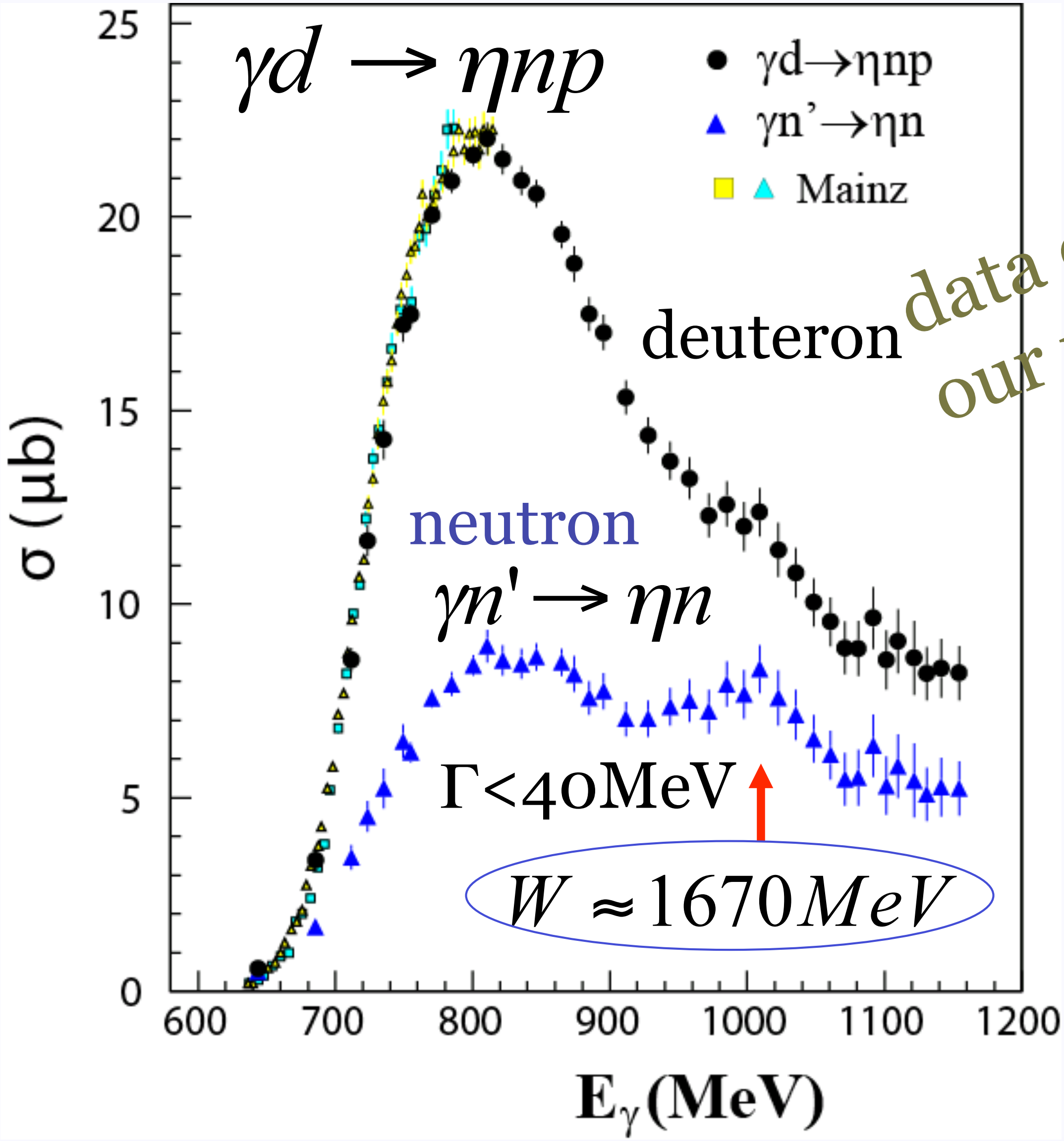
image of
circulating electrons

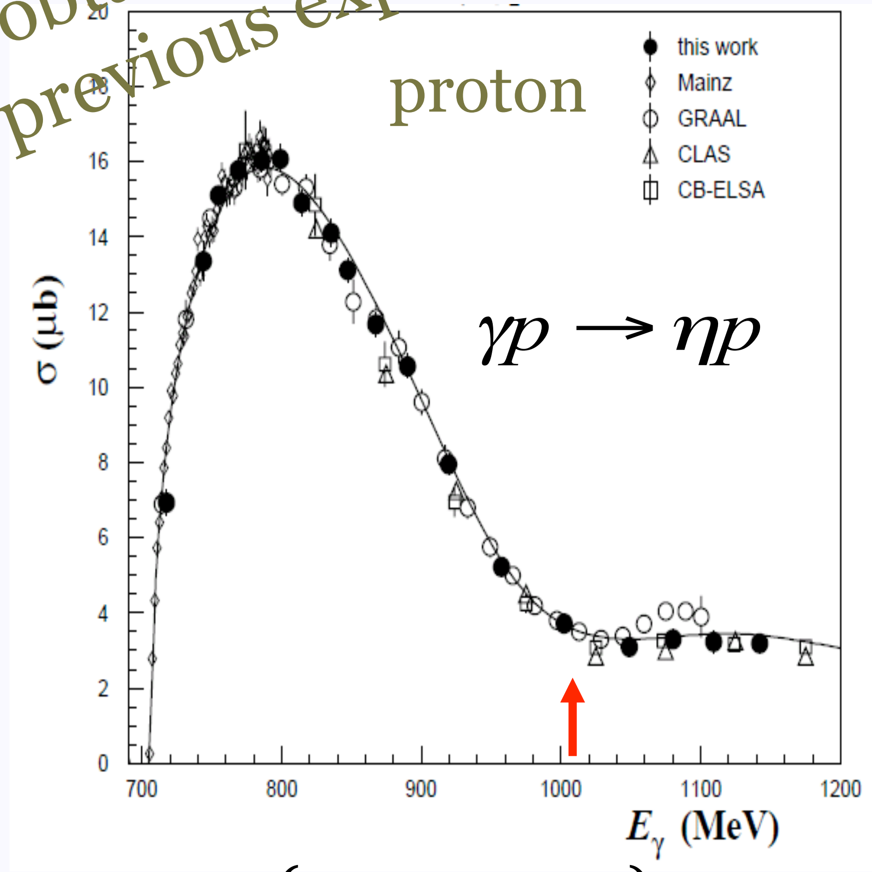
No other labs employ this method for Brems photons.

Single η photoproduction

a candidate for
a member of $\overline{10}$
with hidden-strangeness

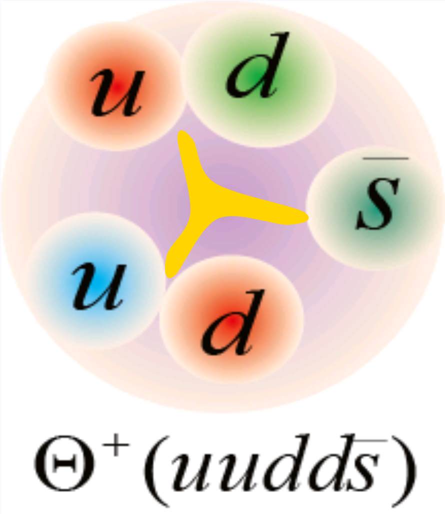
data obtained in
our previous experiments





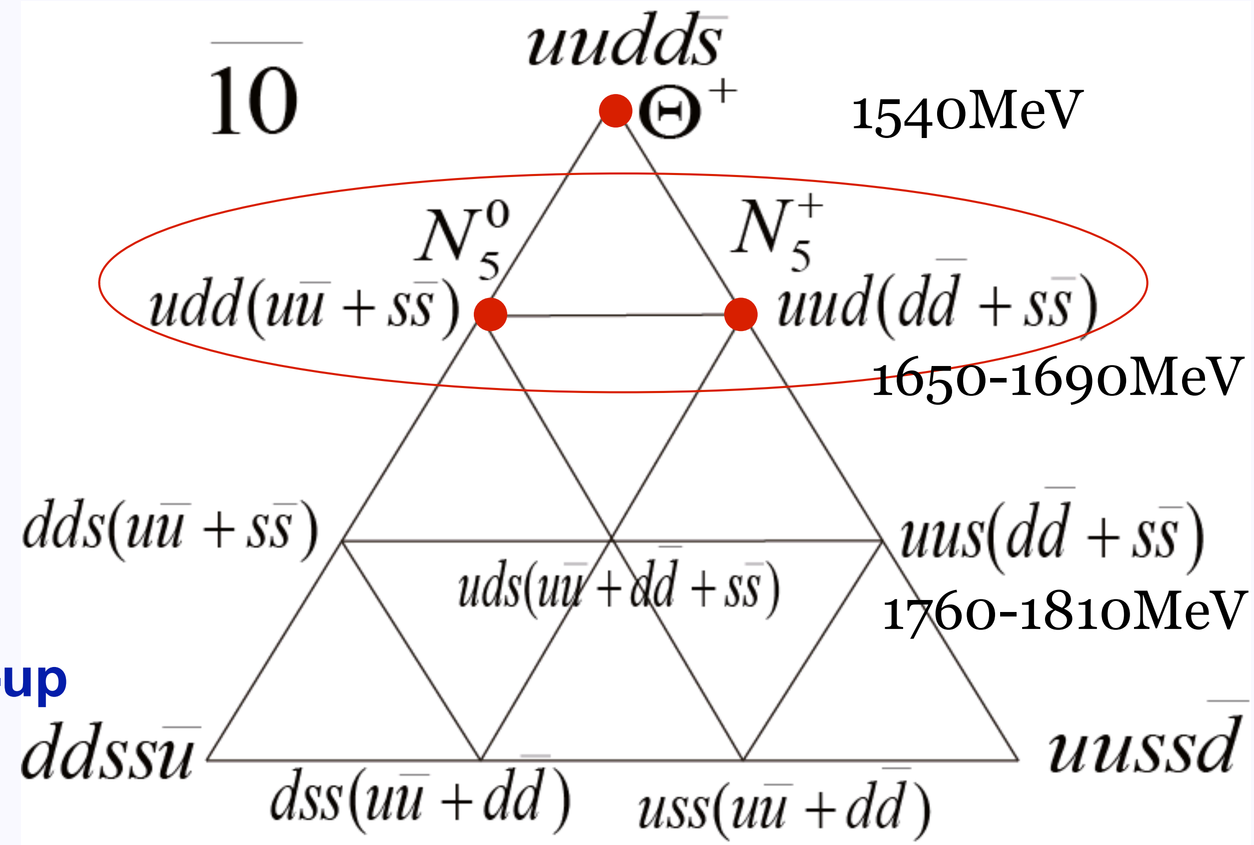
(same setup)

Search for hidden-strange pentaquark baryons



quantum number (S=+1)

impossible to be built-up with any 3q system



anti-decuplet members

Investigation of N*(1670) through η channel

5 year project approved by the Ministry of Education (2017-2012)

U-spin conservation

EM interaction $\not\Rightarrow$ I-spin $\Rightarrow$ U-spin

members of a U-spin multiplet have the same Q.

"pentaquark nucleons" N_5^0 N_5^+

$U-spin$ 1 3/2

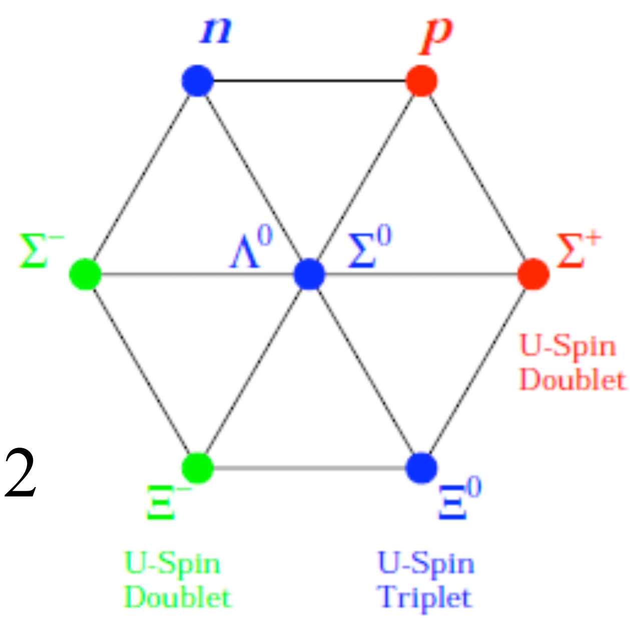
Members of $\overline{10}$ with hidden-strangeness

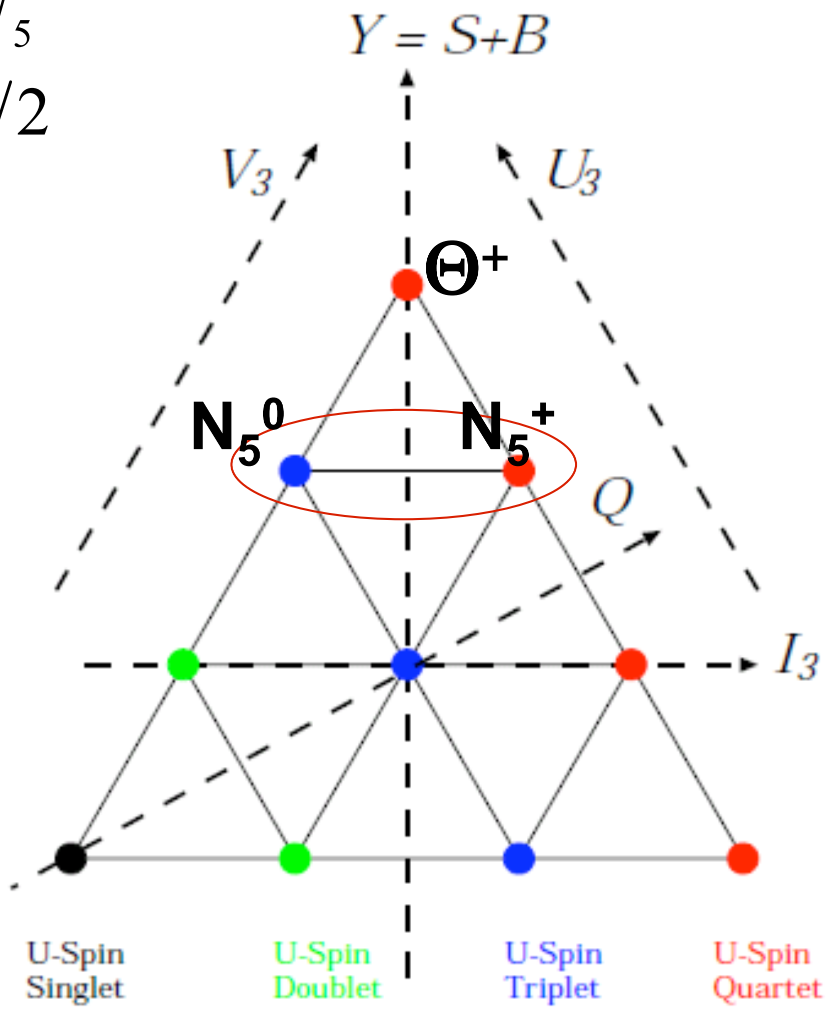
$\gamma + n \rightarrow N_5^0$

$0 \oplus 1 \rightarrow 1$

$\gamma + p \nrightarrow N_5^+$

$0 \oplus 1/2 \nrightarrow 3/2$





Research project

a further study

SPring-8/LEPS: pentaquark $\Theta^+(1540)$

STB ring at ELPH: narrow $N^*(1670)$

aim → **to reveal structure of hadrons**

- to determine the spin and parity of N*(1670)

detection of neutral mesons decaying into photons

$$N^*(1670) \rightarrow \eta n \qquad N^*(1670) \rightarrow \pi^0 n$$

$$\pi^0 \rightarrow \gamma\gamma$$

$$\eta \rightarrow \gamma\gamma$$

→ **4π EM calorimeter FOREST**

- to establish the anti-decuplet scheme experimentally

100 times more statistics!

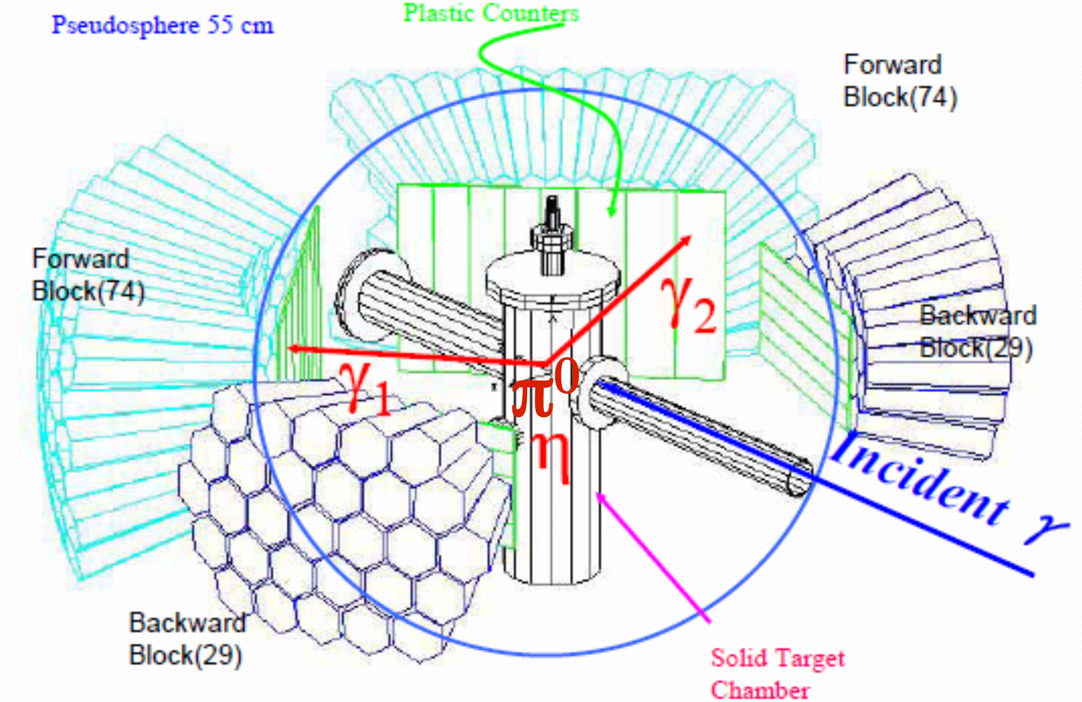
Experimental apparatus

4π EM calorimeter

<Detector>

previous Experimental setup

SCISSORS II :206 pure CsI Crystals
(1.57 str = 12.5% of 4 π)
16.2 X_0 for Forward 148 crystals
13.5 X_0 for Backward 58 crystals



Hydrogen/Deuterium
Solid Target
t = 8 cm (N_T ~4 × 10^{23}/cm^2)

$$\gamma + N \rightarrow \eta + X$$

Identification of η meson
$\Gamma_{\eta-\gamma\gamma}$ = (39.43±0.26)%
→ γγ **Decay Channel**

⇩

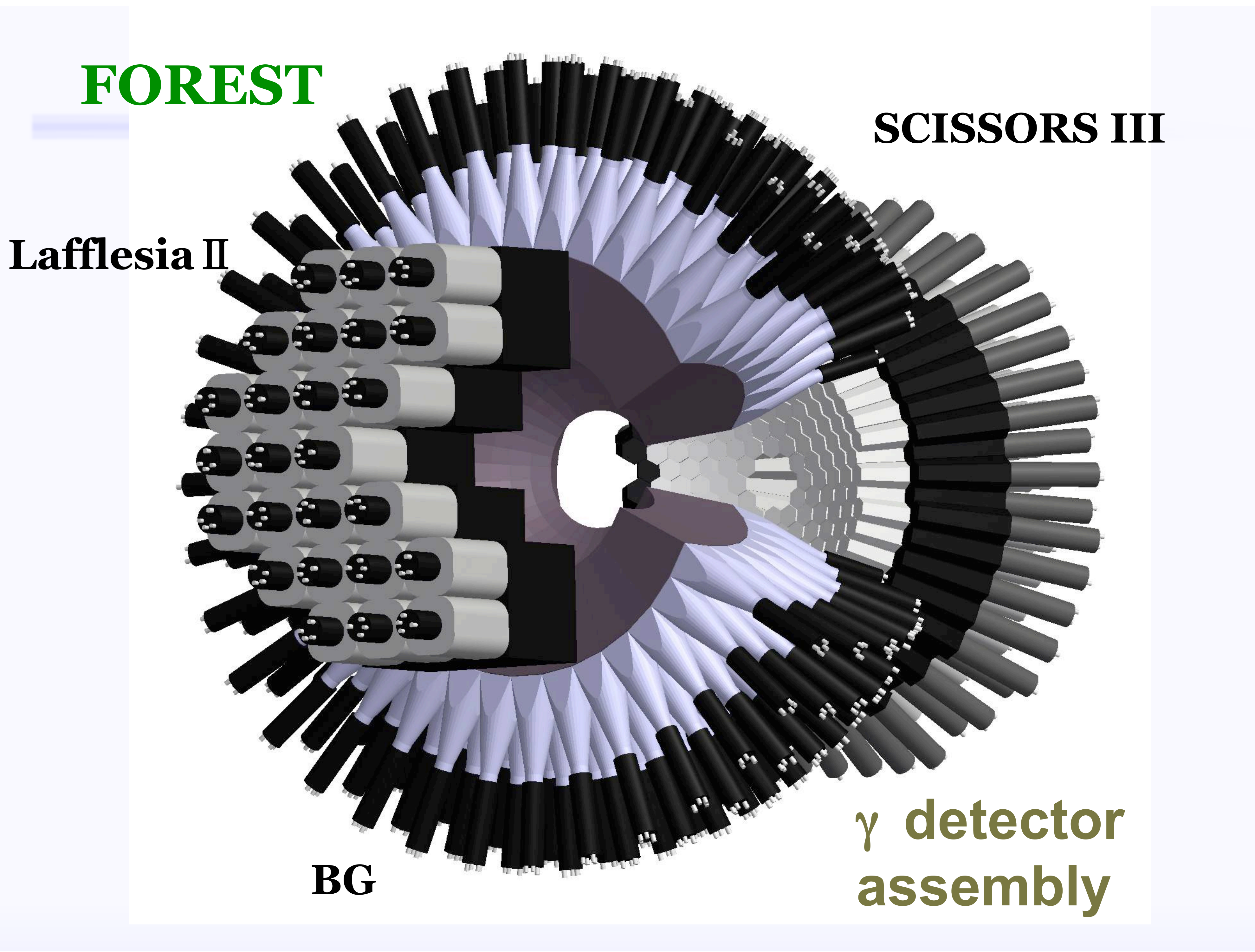
γγ ***Invariant Mass Analysis***

$$M_{\gamma\gamma}^2 = 2E_{\gamma_1}E_{\gamma_2}(1 - \cos\Phi_{\gamma\gamma})$$

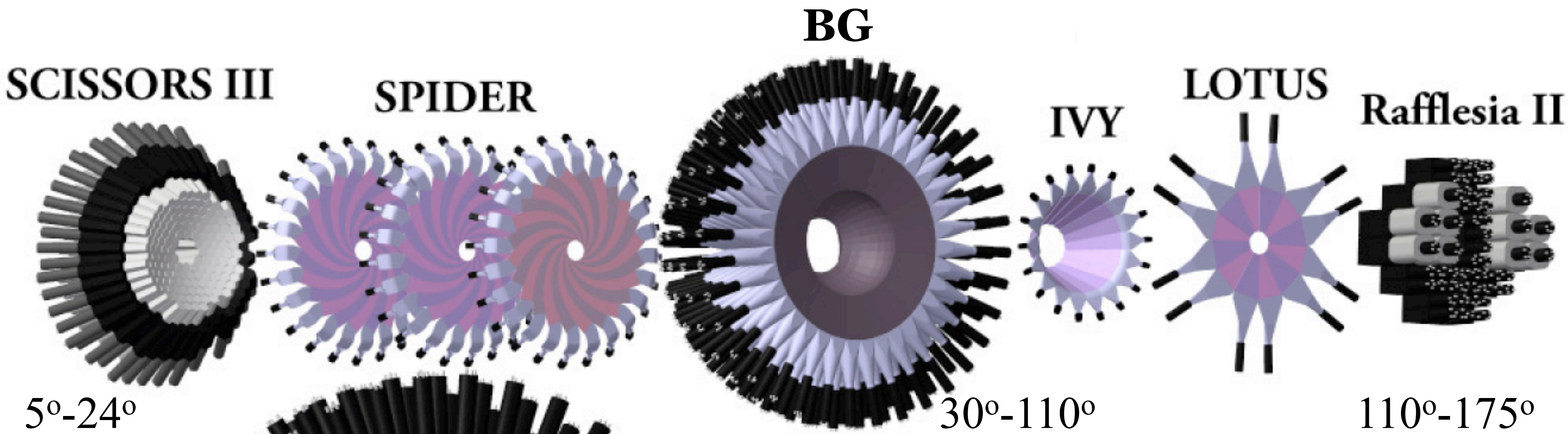
Energy :$E = \Sigma E_i$
Position :$R = \Sigma R_i E_i / \Sigma E_i$

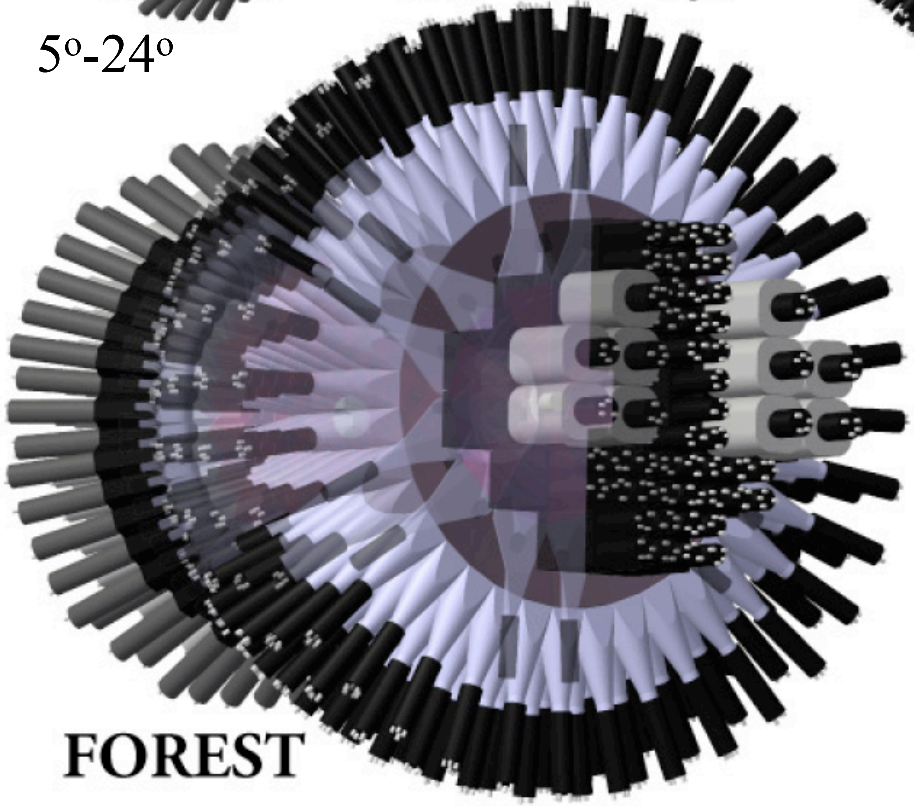
Experimental apparatus

construction of FOREST


FOREST
SCISSORS III
Lafflesia II
BG
γ detector
assembly

EM Calorimeter FOREST assembly of detectors





S3

206 pure CsI crystals

2.3%@1 GeV rearrangement of S2

72 plastic scintillators

BG

252 lead scintillating fibers

7.2%@1 GeV from SPring-8

18 plastic scintillators

Raf

10 SF-5 and 52 SF-6 lead glasses

4.9%@1 GeV from KEK

12 plastic scintillators

Construction of FOREST