Hadron Physics Experiments with Laser Compton Backscattering Photon Beams at LEPS and LEPS2

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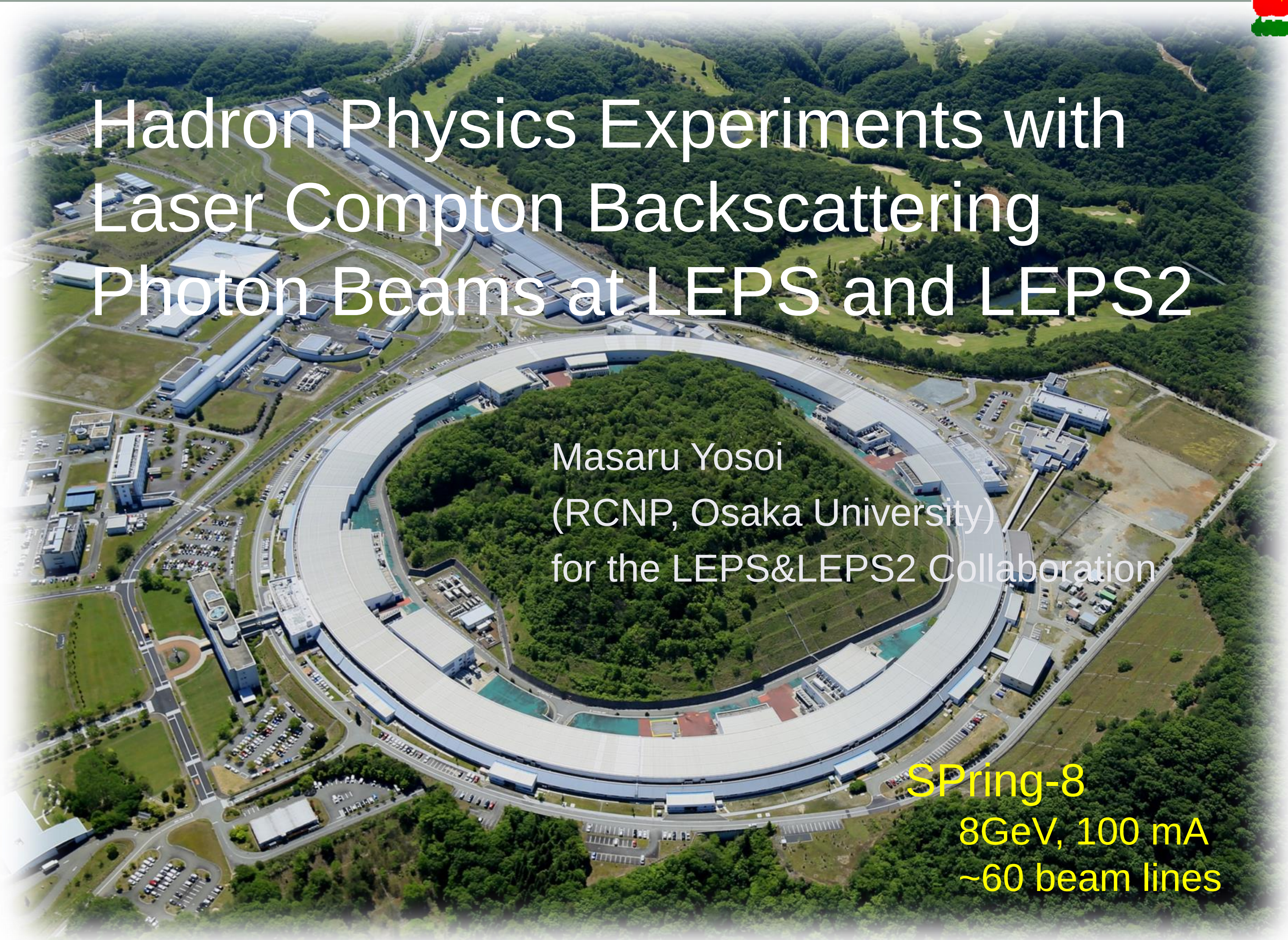
for the LEPS&LEPS2 Collaboration



June 10th, 2021 @ NP2020

Outline

Introduction (hadron physics with GeV photon beams)

Upgrade of laser-electron photon beam

- Synchronizing the timing of pulse laser with electron beam bunches

New results of LEPS2/BGOegg experiments

- η' mesons in nuclei

Experiments with the LEPS2 Solenoid Spectrometer

- Study of exotic hadrons and the present status

Summary

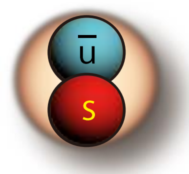
What are hadrons ?

- Hadrons are subject to the strong interaction and consist of quarks with color charges (RGB). (Anti-quarks have anti-colors)
- Quarks have flavors (u, d, s, c, b, t).
- Each hadron should be color singlet (i.e., quarks are confined!)

Baryons (qqq)

proton

Mesons $(q\bar{q})$



K^-

- QCD (Quantum Chromo-Dynamics) is the basic equation of strong interaction, but it can not be directory solved at low energy due to its non-perturbative behavior.

Problems in hadron physics

- Quark model has explained existing mesons and baryons well, but many predicted nucleon resonances are still missing.

  "missing resonances"

- QCD does not prohibit a hadron consisting of more than 3 quarks.

  "Does exotic hadrons ($qq\overline{qq}$, $qqqq\overline{q}$, ……) exist?"

  New forms of hadrons may give a breakthrough of understanding "confinement"

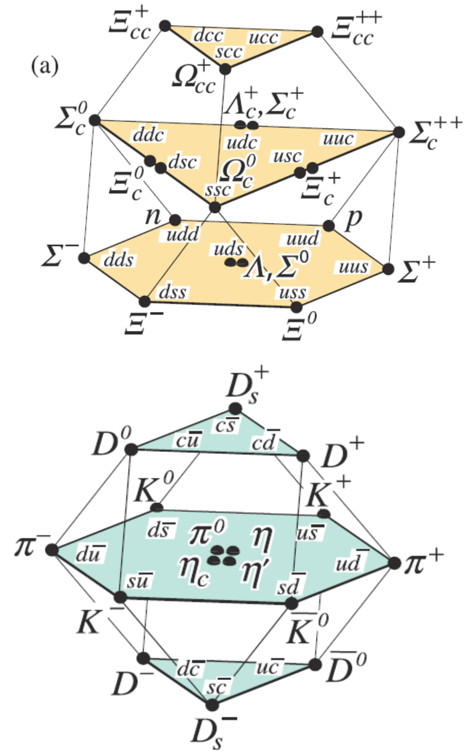
- Bare quark masses are very light, but hadron masses are heavy.

  (m_u, m_d < 5 MeV → $m_{\mathrm{proton}}(uud)$=938 MeV)

  "what is the origin of hadron mass ?"

  Nambu suggested it is due to the spontaneous chiral symmetry breaking. (quark condensate $\langle 0|\overline{q}q|0\rangle \neq 0$)

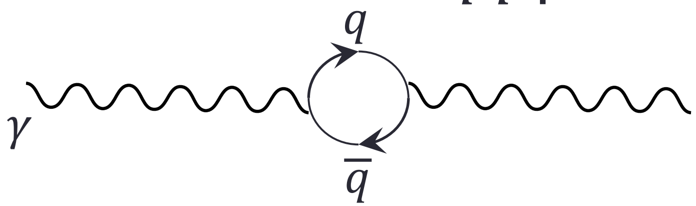
  But experimentally it has not been confirmed.



(from PDG)

Why using GeV photons

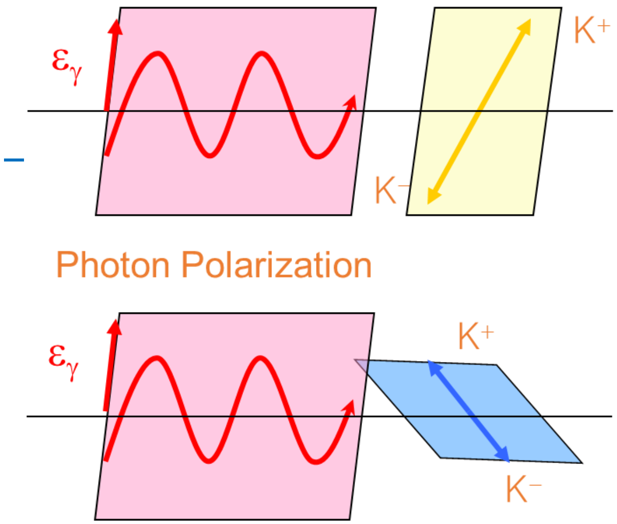
- Typical hadron size: ~1 fm → $E_\gamma \gtrsim 1$ GeV
- Photon can act as a virtual $q\bar{q}$ probe in high energy



- Photon has spin 1. Spin observables can help to understand the reaction mechanism. (Parity filter, etc.)

$\vec{\gamma}p \to \phi p$

$\phi \to K^+K^-$

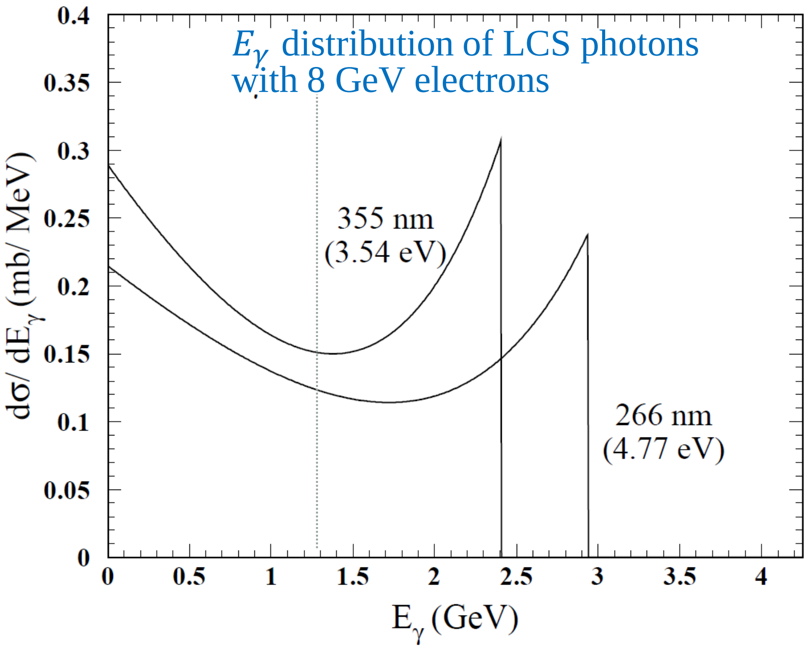


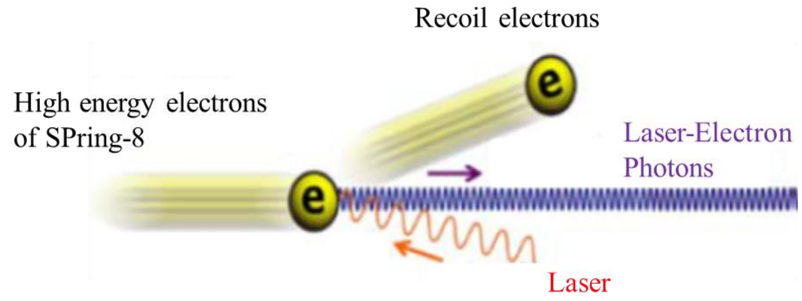
Decay Plane // $\vec{\gamma}$
natural parity exchange $(-1)^J$
(Pomeron, 0^+ glueball,
Scalar mesons)

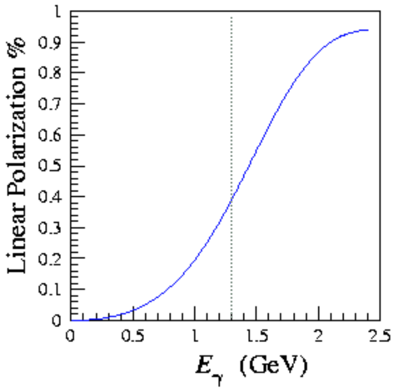
Decay Plane $\perp \vec{\gamma}$
unnatural parity exchange $-(-1)^J$
(Pseudoscalar mesons π,η)

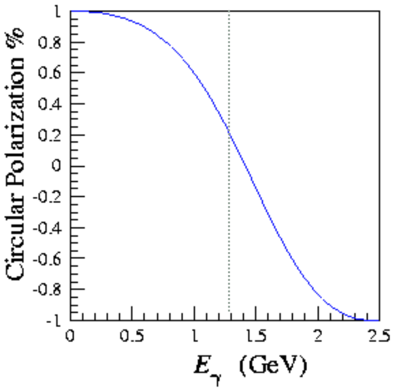
Comlementary to charged hadron beams like $\pi^\pm, K^\pm$

Photon beam by Laser Compton Scattering at SPring-8 (Laser-Electron Photon)





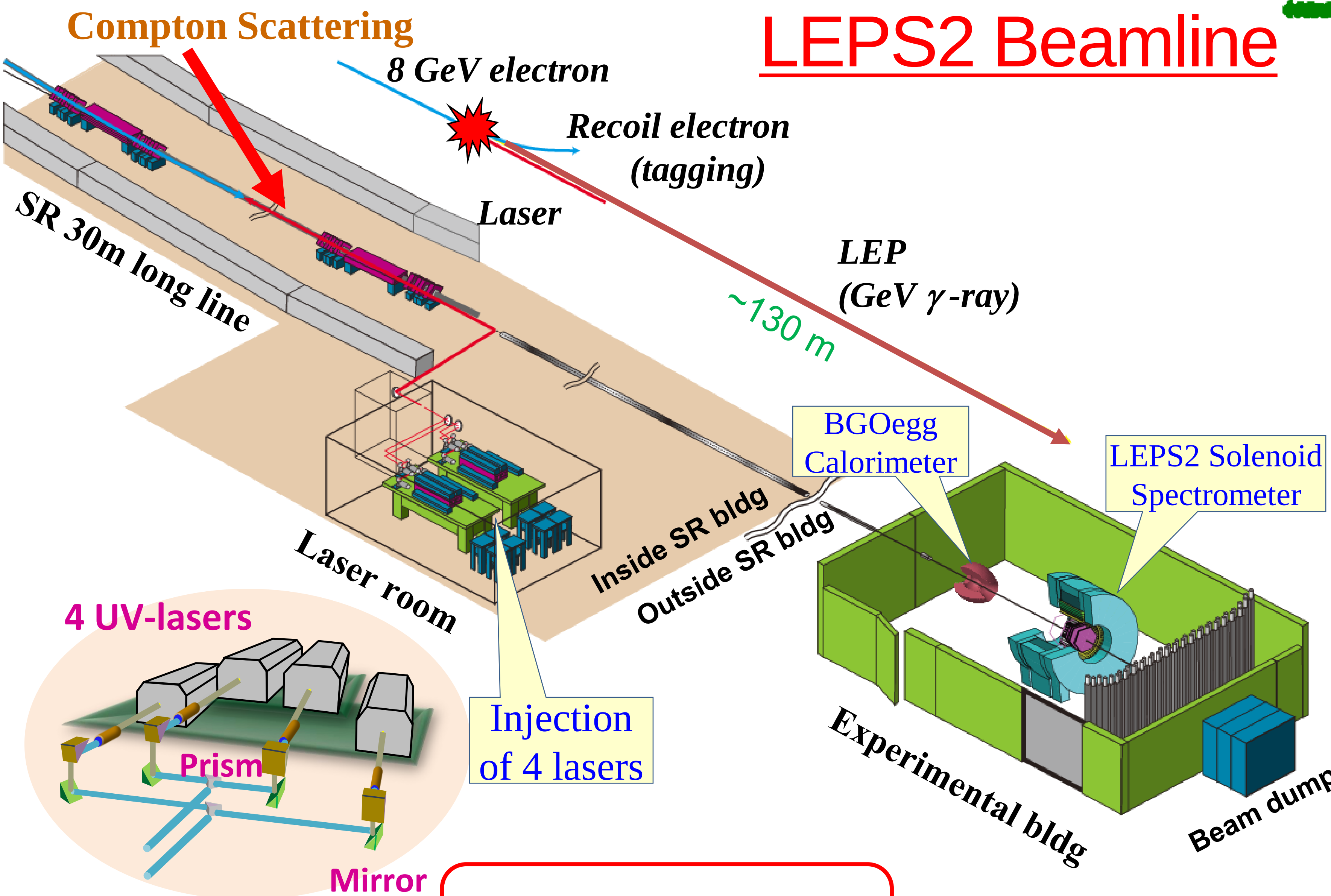




- small amount of low E_γ photons

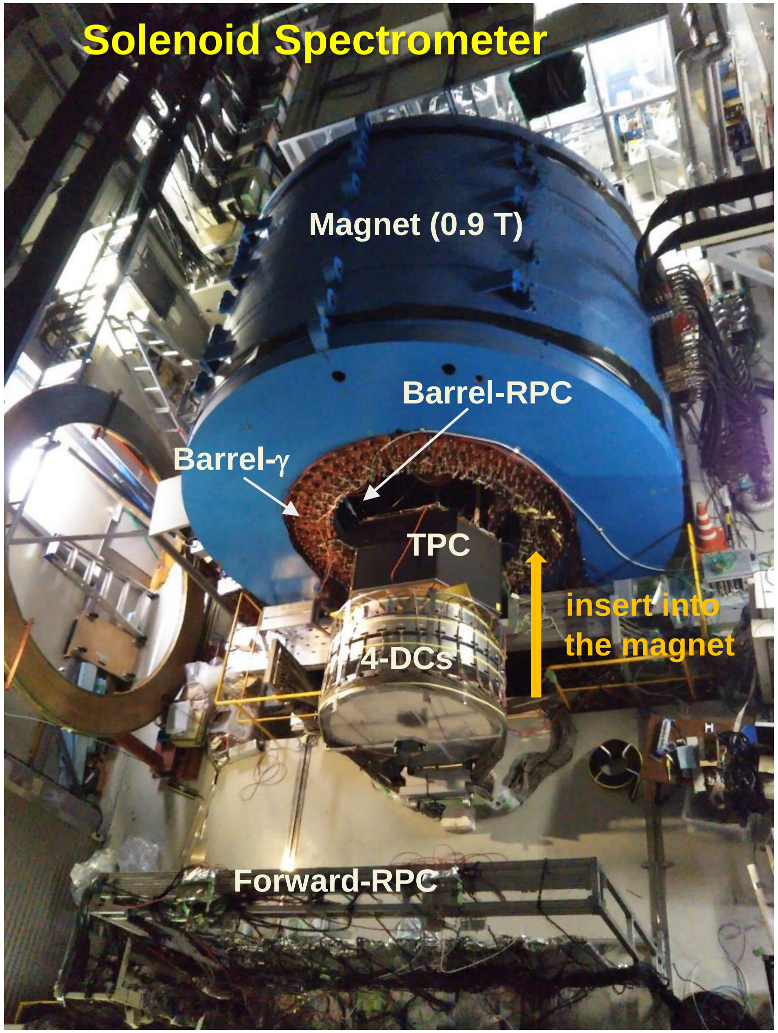
  ($\propto 1/E_\gamma$ for Bremsstrahlung photons)
- high linear (circular) polarization in a wide energy region
- each photon energy (>1.3 GeV) is tagged by detecting the recoil electron

LEPS2 Beamline

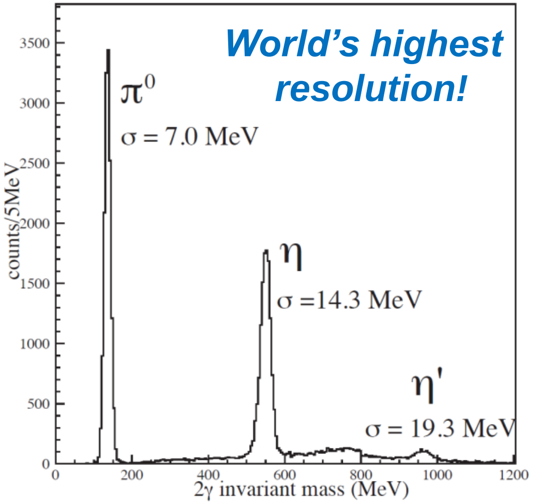


Intensify beam,
Cover large solid angle

Two large acceptance detectors at LEPS2

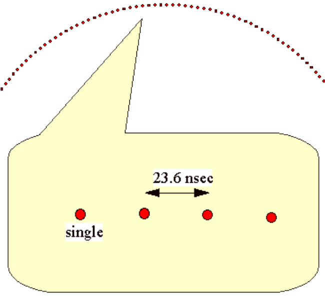


2γ invariant mass spectrum

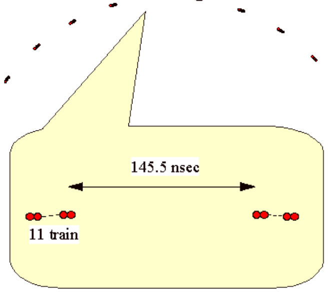


☆ LEP beam by Synchronizing the timing of pulse laser with electron beam bunches

Various several bunch modes in the SPring-8 operation

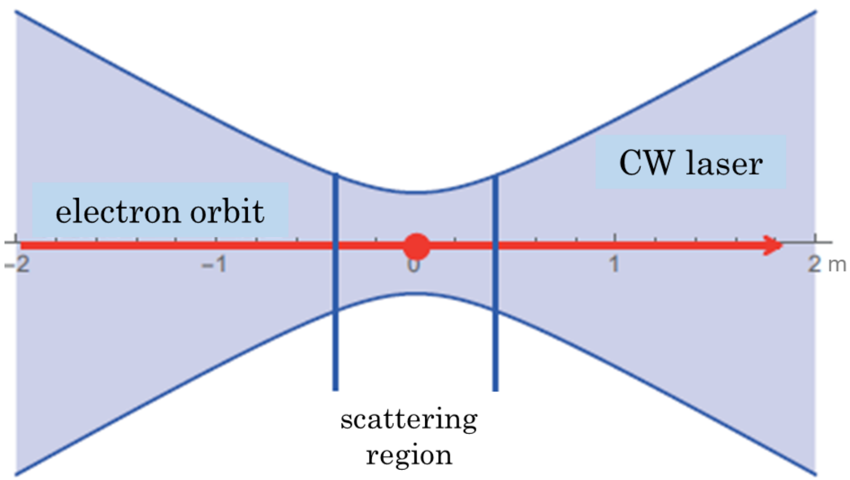


A-mode
203 bunches

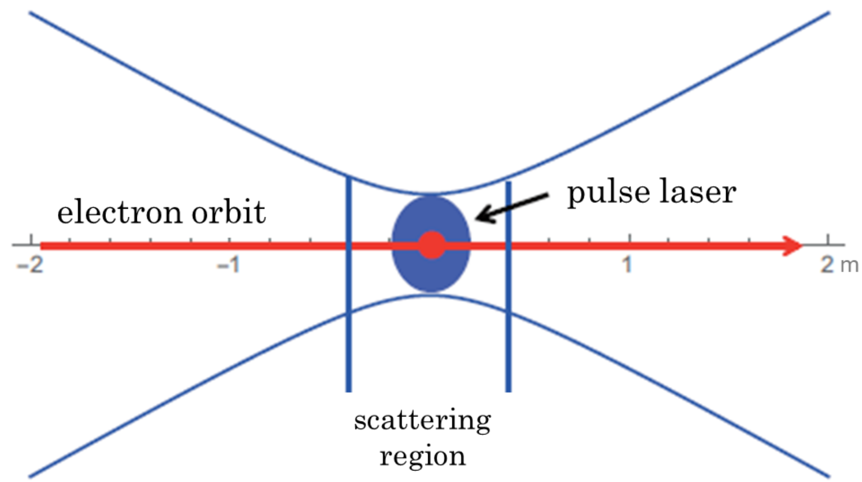


C-mode
11 bunche train x 29

By reducing blank hits
→ Increase the LEP Intensity with lower power output
→ Suppress fast deterioration of optical components

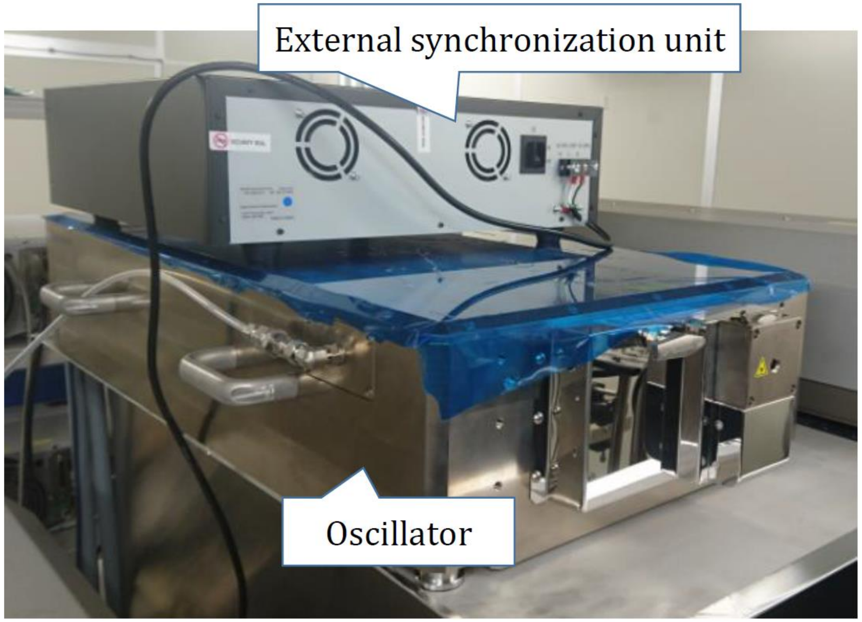


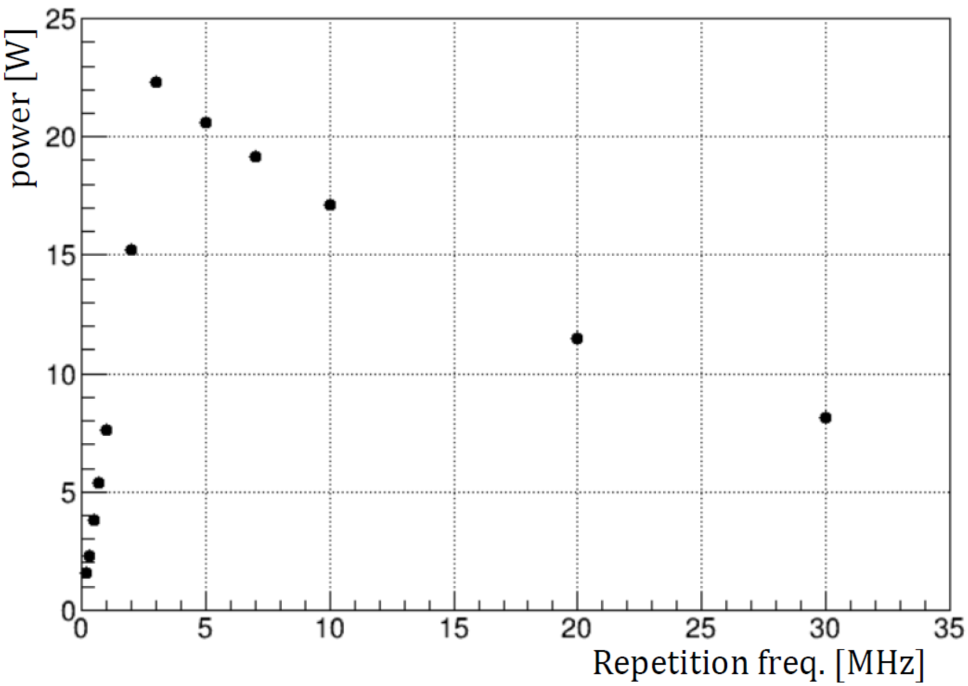
Compton scattering with a conventional CW laser



Compton scattering with a synchronized pulse laser

Pulse Laser

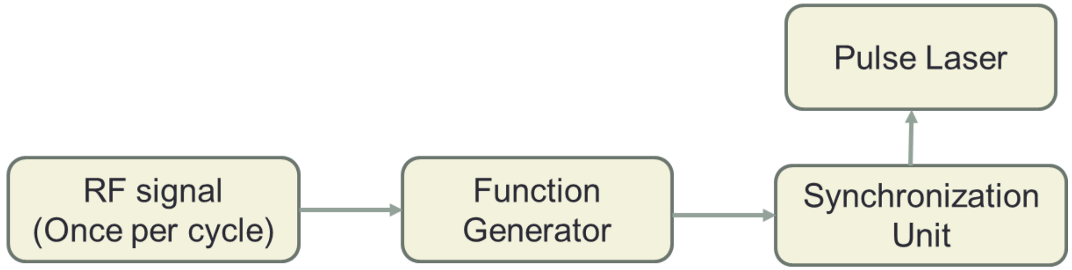




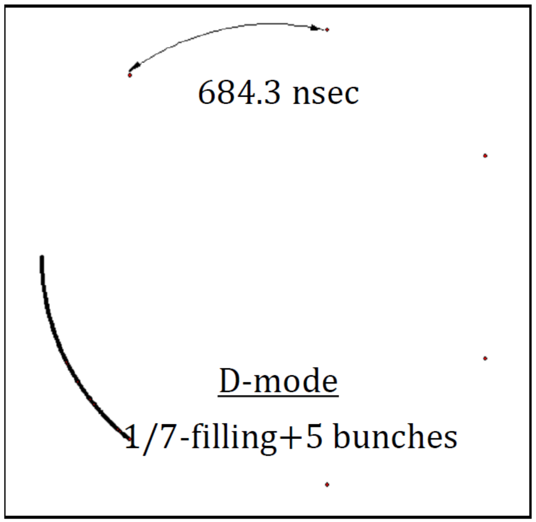
- Product: LDH-V1611-PoD(Spectronix Inc.)
- Wavelength: 355 nm
- Pulse width: <15 ps
- Power: >20W (depends on the repetition frequency)

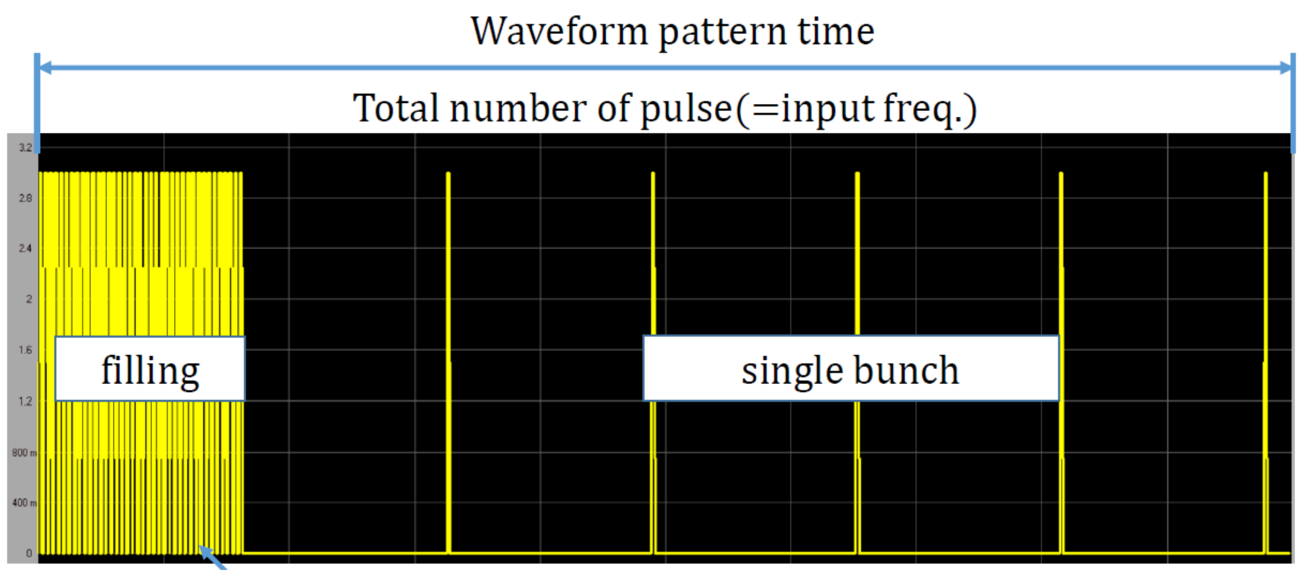
An external synchronization unit controls laser irradiation

R&D results



Example





- Obtain 2~4 times higher LEP beam intensity compared with the asynchronous operation, by optimizing the power, frequency, and irradiation pattern for each filling mode.
- A 258 nm deep-UV pulse laser will be tested in this year.

☆ η' mesons in nuclei

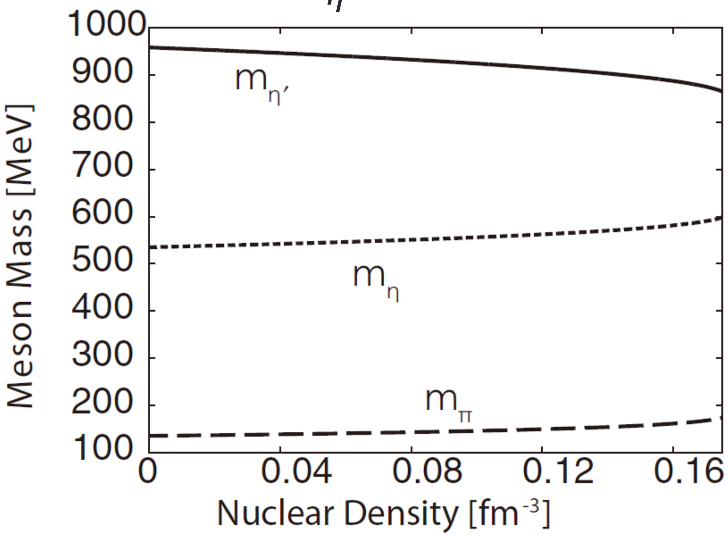
- Change of hadron properties in the finite density
  → hint of the origin of mass, because the chiral symmetry breaking is partially restored

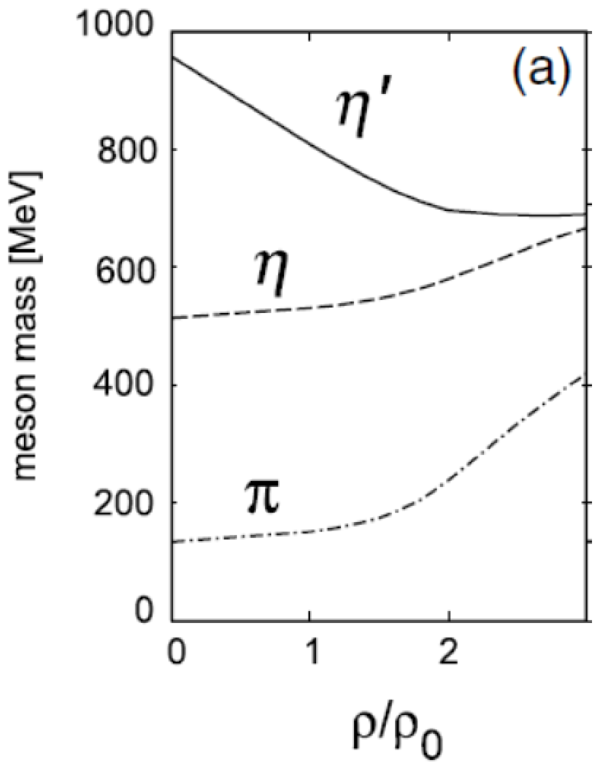
A large mass reduction of η'(958) in nuclei was predicted by theoretical models.

(reduce the $U_A(1)$ quantum anormaly effect)

Phys. Rev. C88, 064906 (2013)

$\Delta m_{\eta'} \approx -80$ MeV



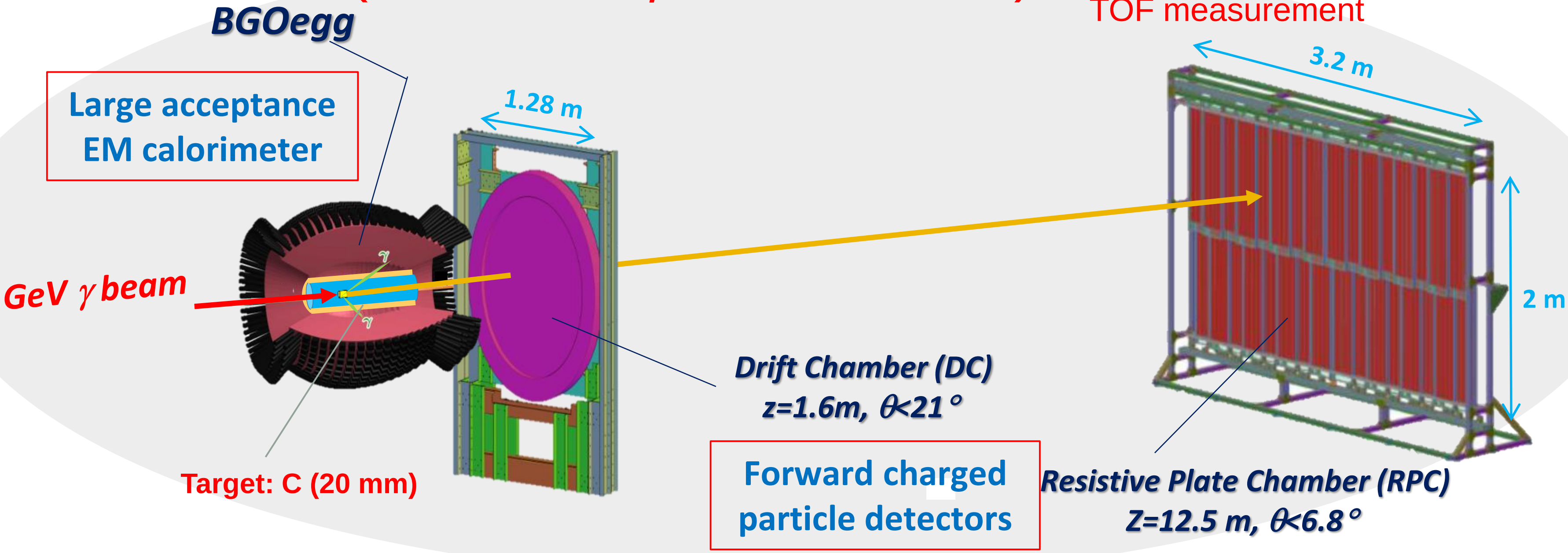


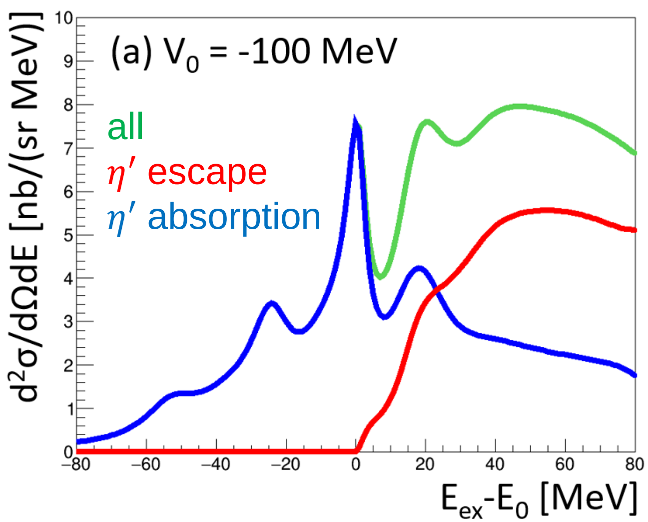
Phys. Rev. C74, 045203 (2006)

$\Delta m_{\eta'} \approx -150$ MeV

Such a large shift brings an attractive potential, and may allow the formation of bound η'-nuclei !

BGOegg experiment for $^{12}C\,(\gamma, p)\,\eta' \otimes {}^{11}B$ reaction
(search for η' bound nuclei)





- η' absorption

$$\gamma + {}^{12}\mathrm{C} \rightarrow p_f + \eta' \otimes {}^{11}\mathrm{B}$$
$$\hookrightarrow \eta' + p \rightarrow \eta + p_s$$

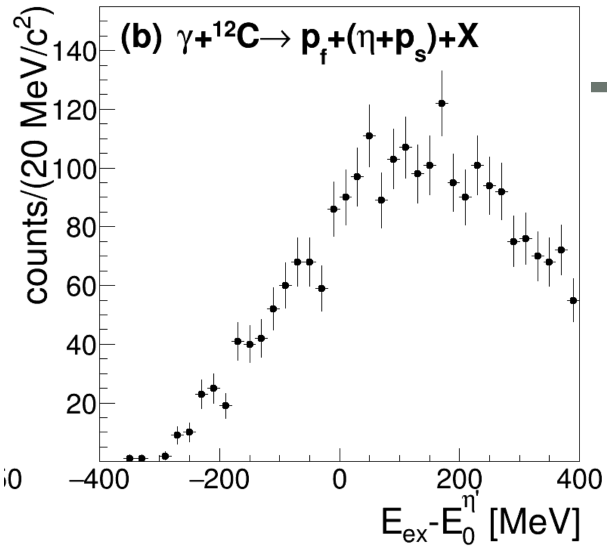
- η' escape

$$\gamma + {}^{12}\mathrm{C} \rightarrow p_f + \eta' + {}^{11}\mathrm{B}$$

○ :TOF-RPC ○ :BGOegg ($\eta \rightarrow 2\gamma, \eta' \rightarrow 2\gamma$)

Results

N. Tomida et al., Phys. Rev. Lett. 124 (2020) 202501

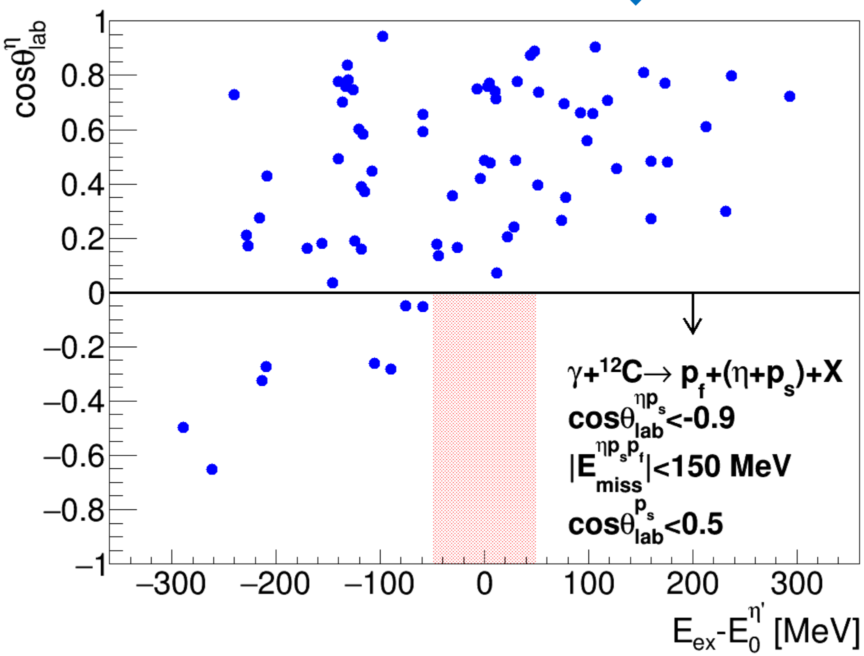


large backgrounds by primary η productions

- $\gamma + {}^{12}\mathrm{C} \rightarrow p_f + \eta + X$
- $\gamma + {}^{12}\mathrm{C} \rightarrow p_f + \eta + \pi + X$

kinematical cuts for BG reduction

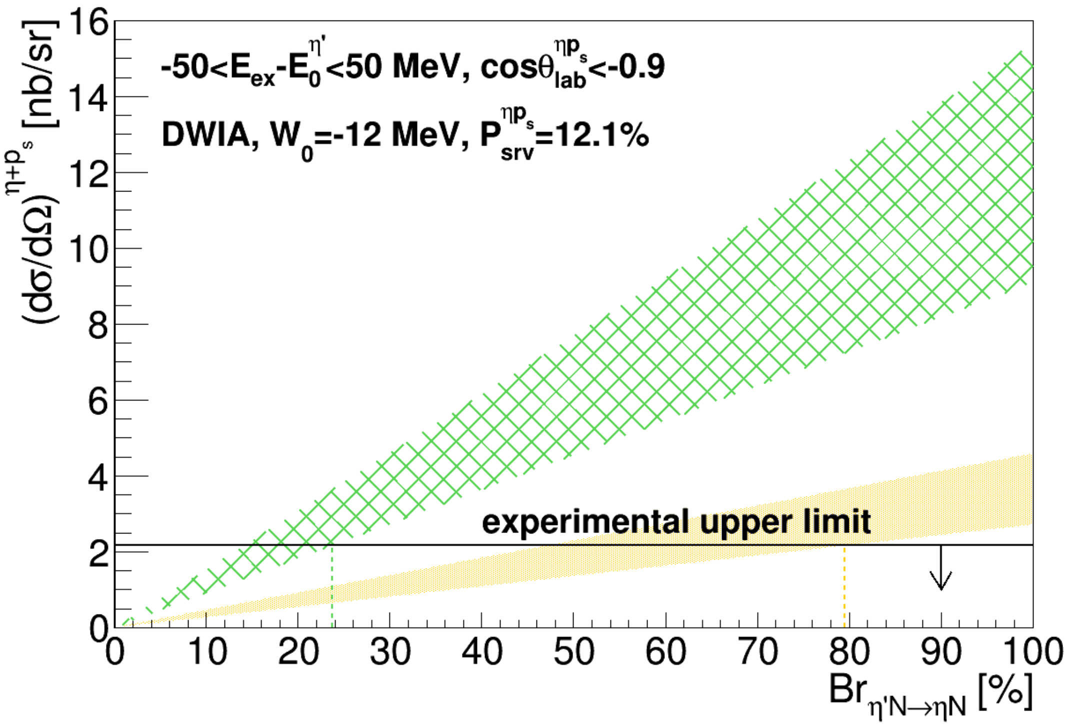
- back-to-back ηp_s
- no additional particle
- remove forward η/p_s



No events in the signal search region

Upper limit of $d\sigma/d\Omega$ for η' bound nuclei with $\eta' p \rightarrow \eta p$ absorption:
2.2 nb/sr（90% C.L.）

Comparison with DWIA calculation



DWIA V_0=-100 MeV

DWIA V_0=-20 MeV

- small branching ratio of $\eta' N \rightarrow \eta N$

  or/and

- shallow attractive potential

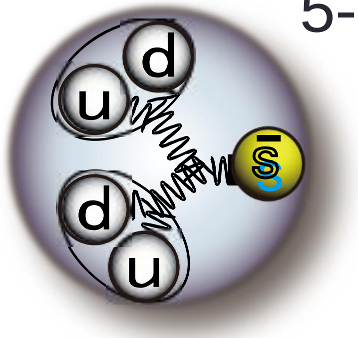
⇔ Expectation : $Br_{\eta' N \text{->} \eta N}$ > 40%

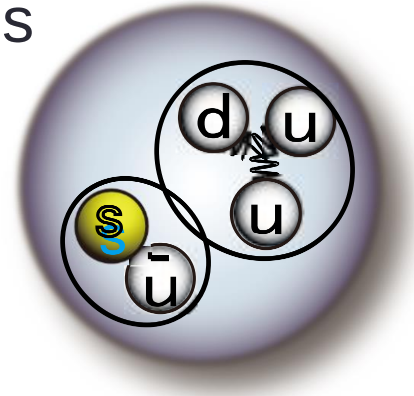
⇔ NJL model : V_0 = -150 MeV

Linear sigma model = -80 MeV

☆Study of exotic hadrons

5-quark baryons





(True) Pentaquark

Compact, di-quark correlation?

Meson-baryon molecular state

e.g.) $\Lambda(1405) \Leftrightarrow \bar{K}N$ molecule?

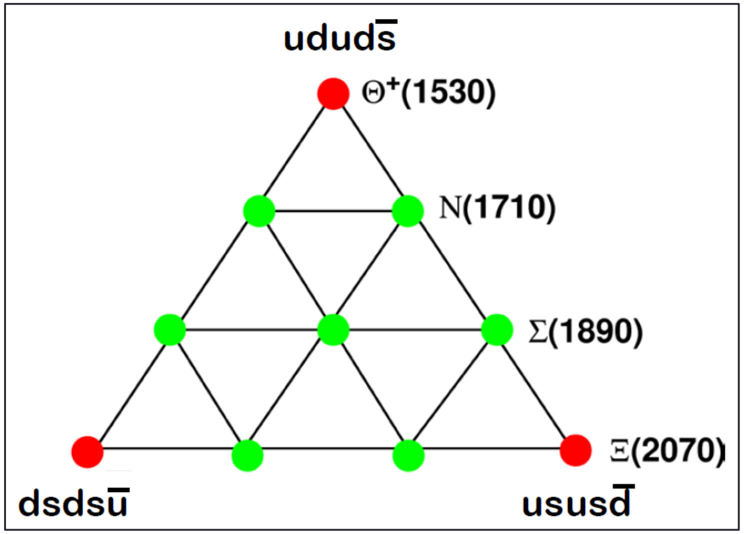
Pentaquark Θ^+

Theoretical model prediction

Z. Phys. A359, 305(1997)

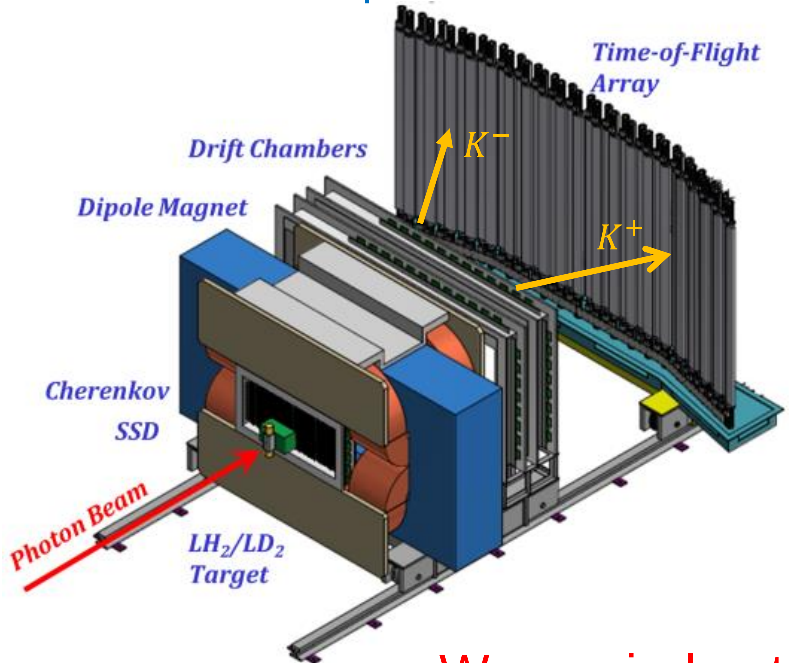
- Strangeness=+1, charge=+1
  minimal quark contents: $udud\bar{s}$
- Light mass: $M(\Theta^+) = 1.53$ GeV
- Small width: $\Gamma < 1$ MeV [theor.+exp.]

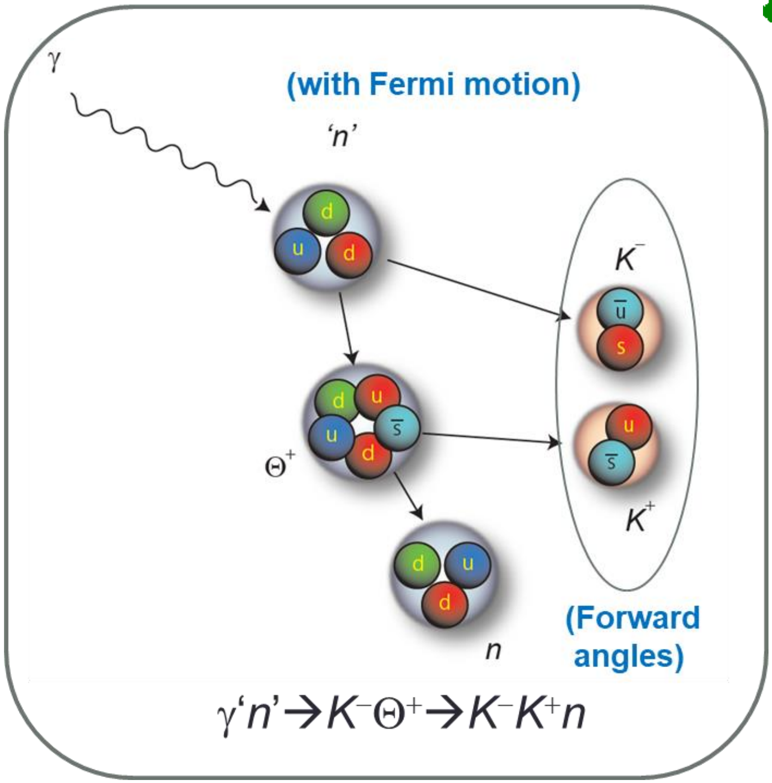
Anti-decaplet baryons with u, d, s quarks



Θ^+ search at LEPS

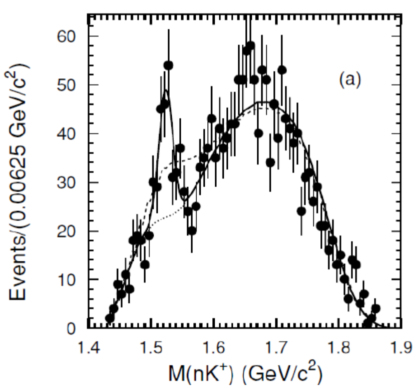
LEPS forward spectrometer





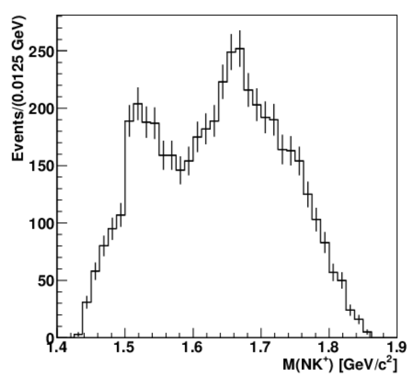
We carried out 3 series of LD_2 runs

PRC 79, 025210(2009)



Increase statistics →

Few Body Syst., 54,1245(2013)

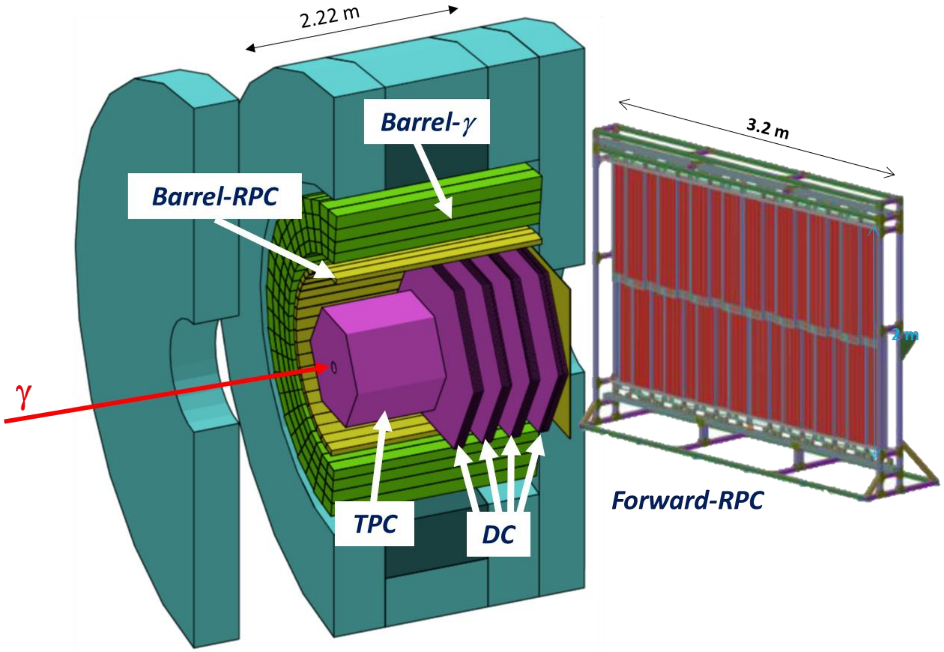


Increase statistics →

reduce BG from spectator protons

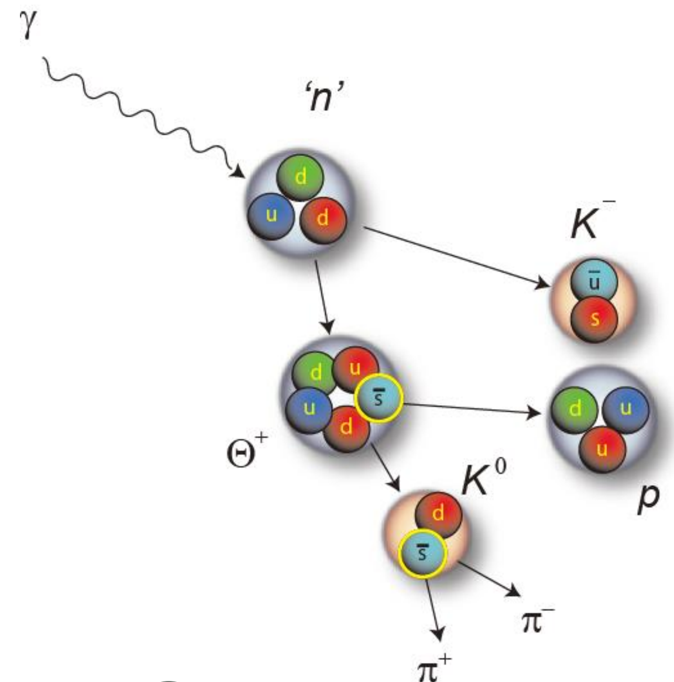
The final results Including the 3rd runs will be open soon.

Θ^+ search at LEPS2



LEPS2 solenoid spectrometer

Multi-purpose large acceptance detector for fixed target exp.



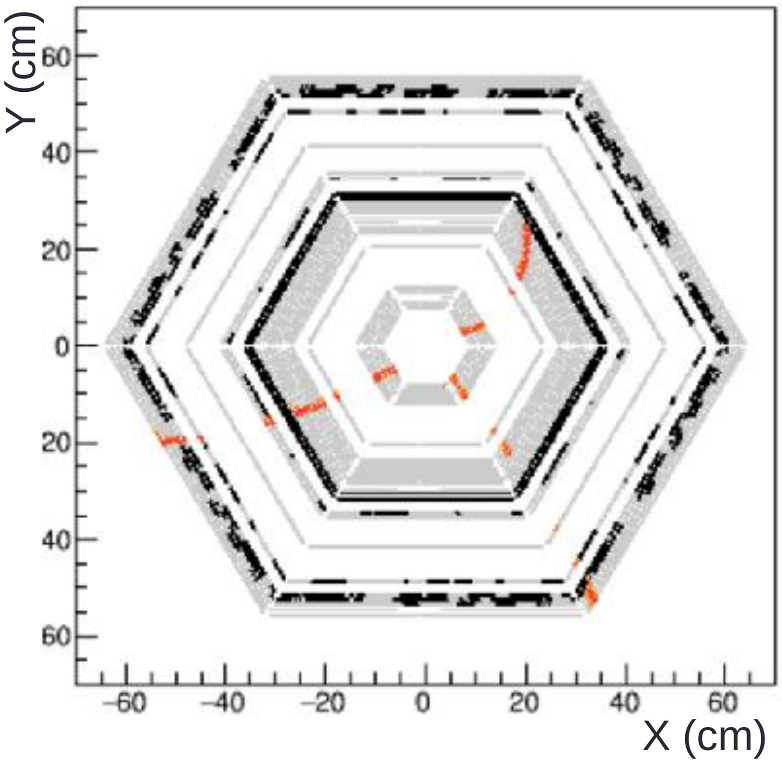
$$\gamma +' n' \rightarrow K^- + \Theta^+$$
$$\hookrightarrow p + K^0{}_S$$
$$\hookrightarrow \pi^+ + \pi^-$$

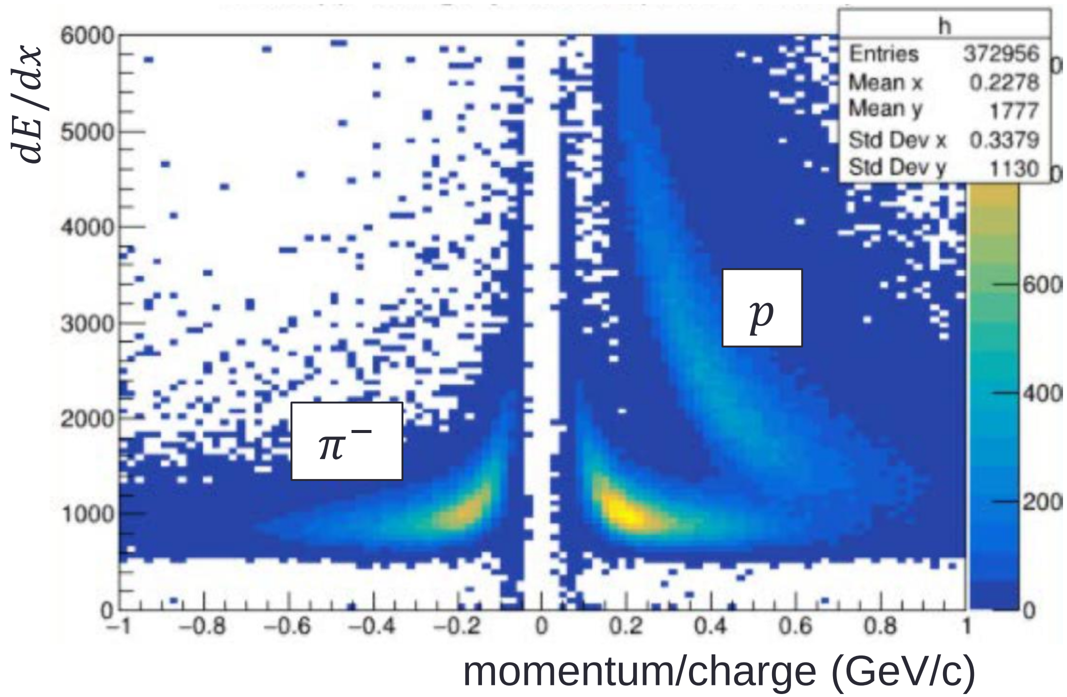
- ***No Fermi motion correction***
- ***No ϕ and non-resonant K^+K^- background***

Mass resolution of Θ^+: ~6 MeV (~11 MeV at LEPS)

Commissioning of Solenoid Spectrometer

TPC event display





Physics run will start from this autumn.

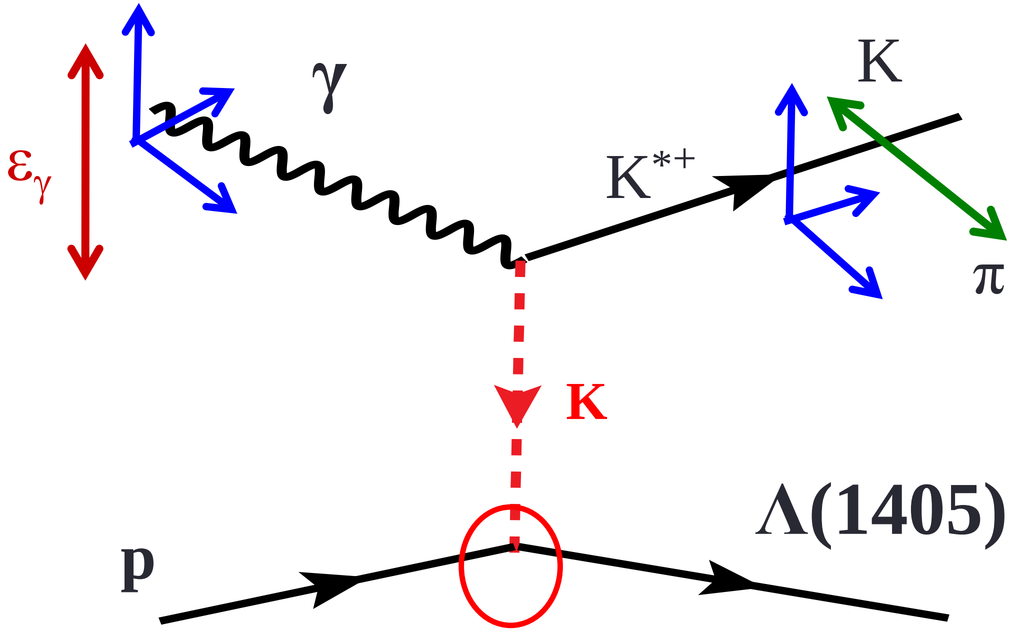
Λ(1405) with K*(892) photoproduction

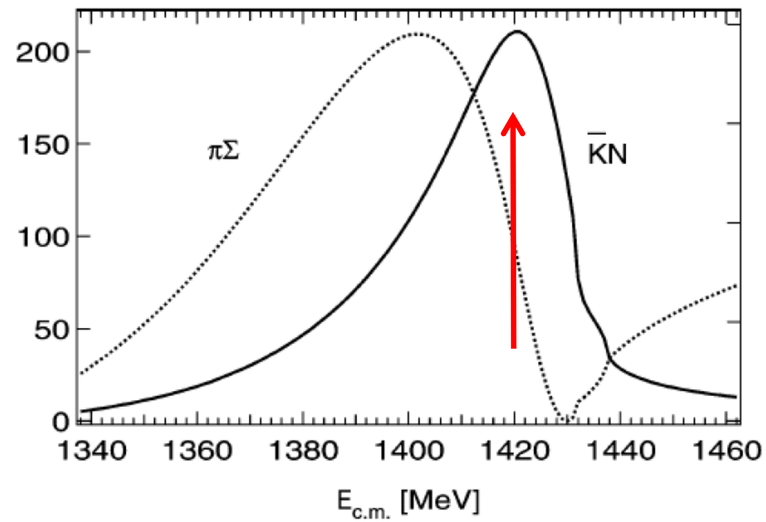
(need high E_γ with DUV lasers)

$$\gamma + p \rightarrow K^{*+} + \Lambda(1405)$$

$$K^{*+} \rightarrow K^0 + \pi^+ \rightarrow \pi^+ + \pi^- + \pi^+$$

Meson-baryon molecule with two poles ?





Nucl. Phys. A 725, 181

Parity filter with linearly polarized photon

$\varepsilon_\gamma \perp K\pi$ → unnatural parity exchange (K)

$\varepsilon_\gamma \parallel K\pi$ → natural parity exchange (K*, κ)

Measure difference of line shape → determine both pole positions.

☆Summary

- LCS photon beams with a few GeV energies have been used for the study of hadron physics in two beamline (LEPS and LEPS2) at SPring-8.
  (LEPS closed once due to contract expiration in 2020.)

- LEPS2/BGOegg experiment
  - η' bound nuclei were searched in the $^{12}C(\gamma, p)$ reaction with simultaneous detection of decay products

  → Large attractive potential ($|V_0| \geq 100$ MeV) is not favored

- LEPS2/Solenoid spectrometer
  - Commissioning run is on going.
  - Physics data taking for $\Theta^+, \Lambda(1405)$, etc. will start soon.

Thank you very much !

BACKUP

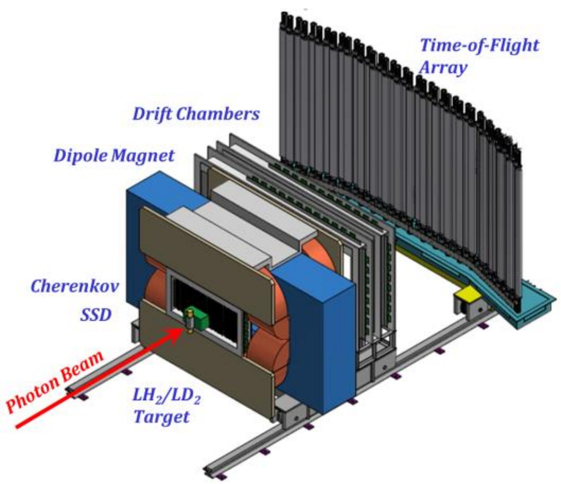
Features of LEPS and LEPS2

	LEPS (2000~2020)	LEPS2 (2013~)	
Tagged photon energy	**1.5 GeV< E_γ<2.4 GeV (UV laser) <2.9 GeV (DUV laser)**	**1.3 GeV< E_γ<2.4 GeV (UV laser) <2.9 GeV (DUV laser)**	
Photon beam intensity	2-Laser Injection **~2×10^6 cps (UV laser) (~2×10^5 cps (DUV laser))**	Max. 4-Laser Injection **<10^7 cps (UV laser) (<10^6 cps (DUV laser))**	
Equipment	LEPS Forward Spectrometer	BGOegg EM Calorimeter	Solenoid Spectrometer

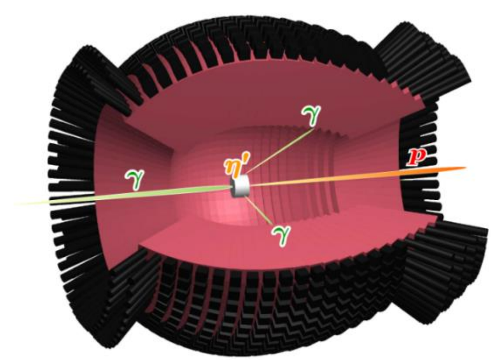
~40 papers w/o including proceedings were published

Some results of 1st Physics run has been opened.

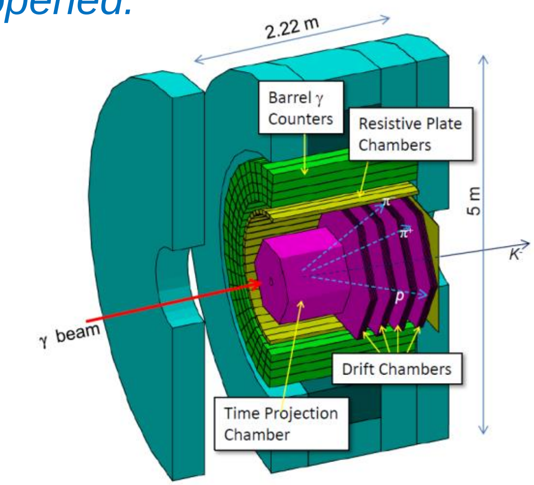
Performing a commissioning run



LEPS spectrometer



BGOegg calorimeter



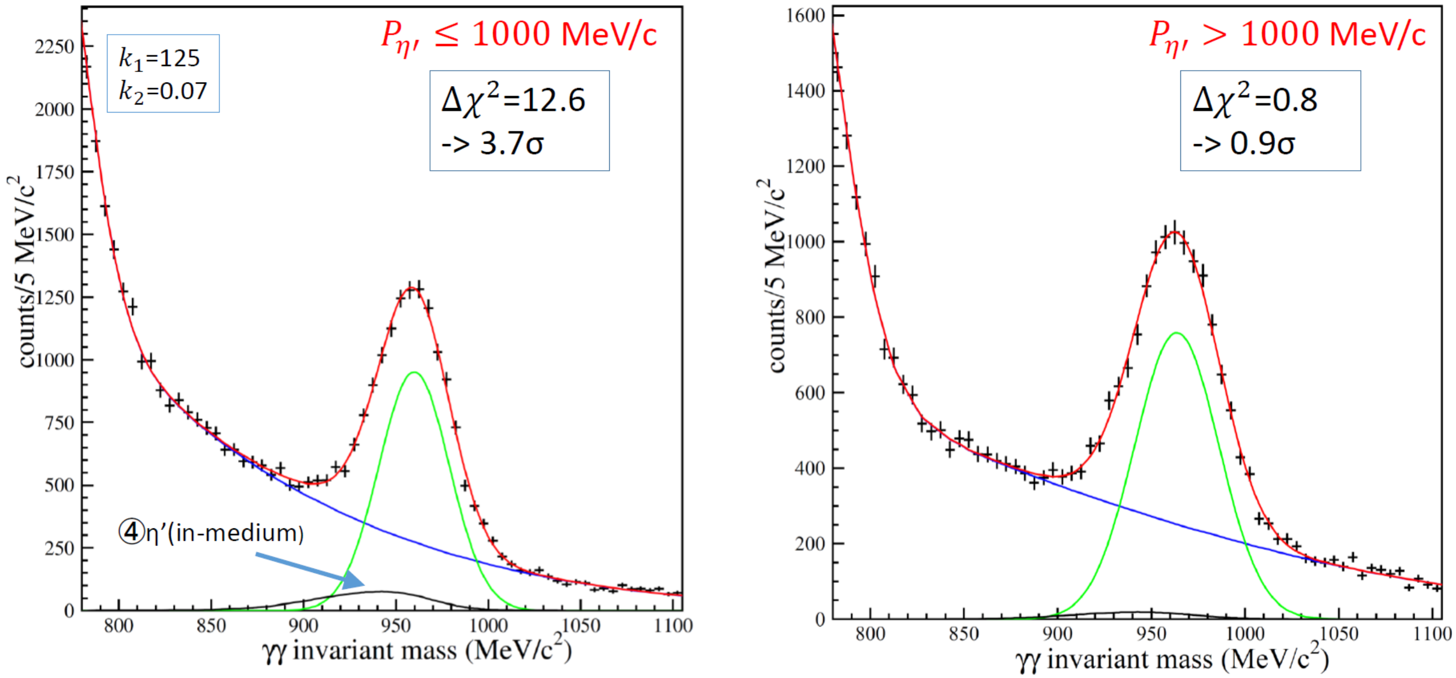
Solenoid spectrometer

Alternative analysis on η' mass

- Direct measurement of η' mass spectrum with $M(\gamma\gamma)$ distribution

→ *Contribution of decays inside a nucleus may appear in the lower tail*

Y. Matsumura, phD thesis (2021)



Some enhancements over the MC-based signal+BG function is seen in the line-shape analysis for low momentum η'

To make it more clear, larger size of nuclei are suitable

→ We are planning to take data with copper target in the next BGOegg exp.