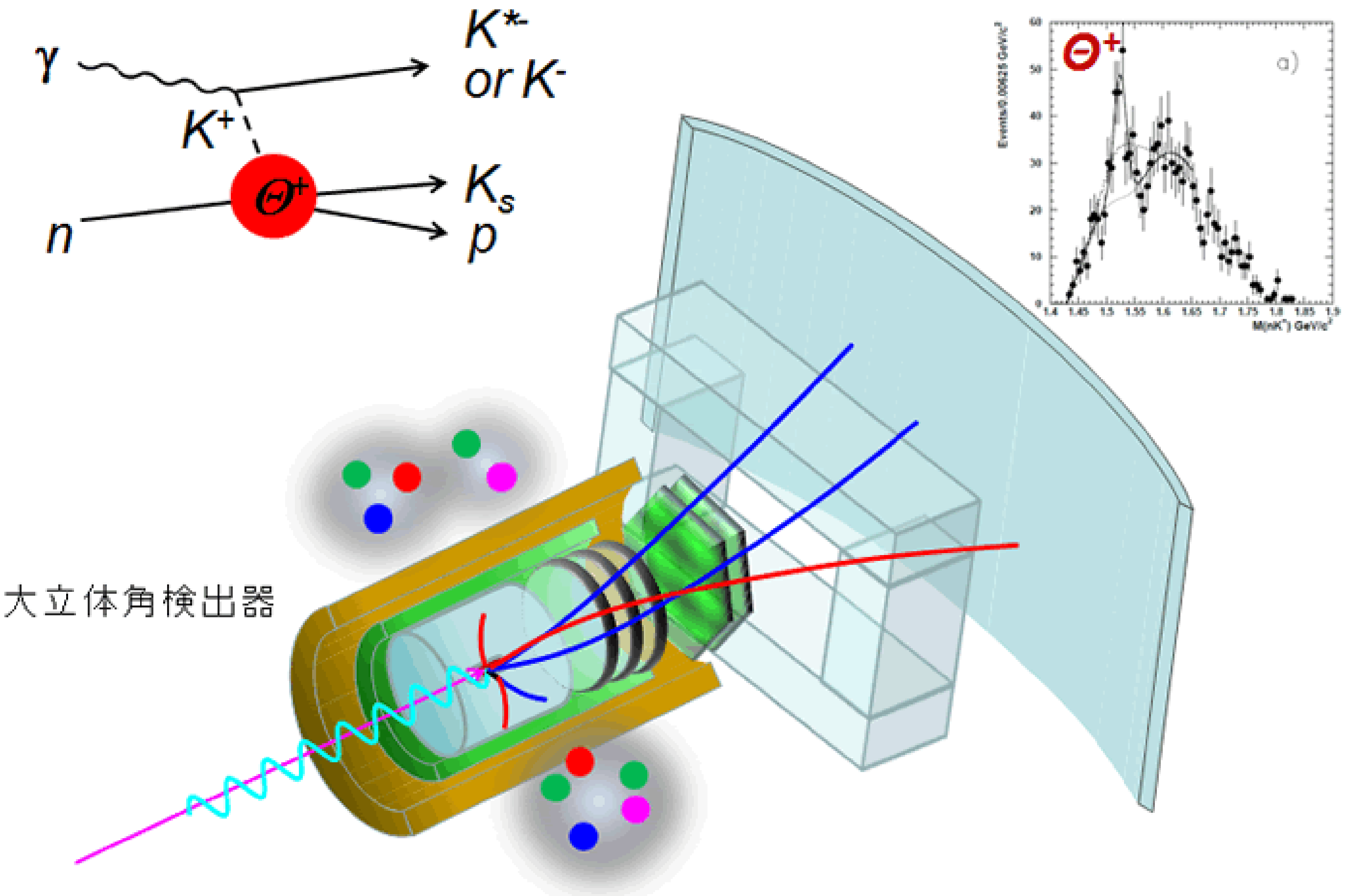
From LEPS to LEPS2
for the exotic hadron (baryon) study

RCNP　M. Yosoi

- 計画研究B01
- What is exotic ? ($qqqq\bar{q}$ or $qqq+q\bar{q}$ ……)
- LEPS results for Θ^+ and $\Lambda(1405)$
- LEPS2 project

レーザー電子光ビームを用いたペンタクォークの研究

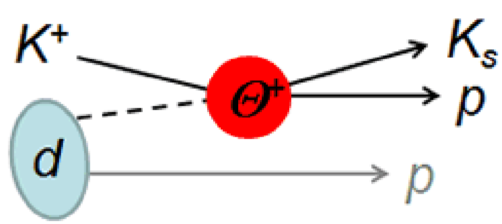


Photon beam (≒neutral vector meson)

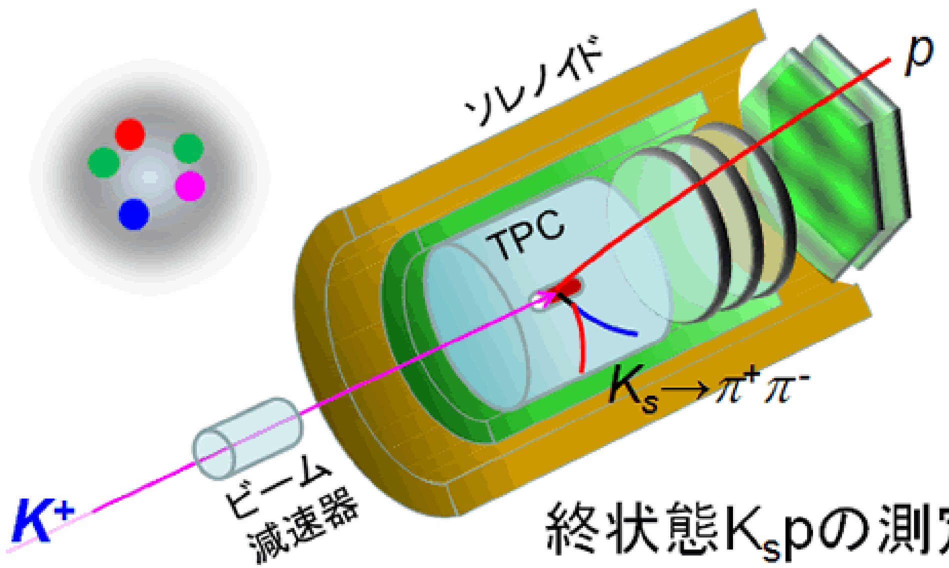
merit: polarization observables

demerit: low interaction rate

K中間子ビームを用いたペンタクォークの研究



$K^+n \rightarrow \Theta^+ \rightarrow K_s p$
共鳴散乱測定(J-PARC LOI)
による共鳴幅とスピンパリティの決定



終状態$K_s p$の測定

$K^{\pm}$, $\pi^{\pm}$ beam (charged pseudoscalar meson)
high interaction rate, high resolution

What is 'exotic' ?

Baryon resonances in the mean field approach

(Diakonov arXiiv:0812.3418 [hep-pn])

Dirac Hamiltonian for quarks in a baryon:

$$H = \gamma^0 (i\gamma^i \partial_i + \sigma(\mathbf{x}) + i\gamma^5 \pi(\mathbf{x}) + \gamma^\mu V_\mu(\mathbf{x}) + \gamma^\mu \gamma^5 A_\mu(\mathbf{x}) + \cdots) = H_s + H_{ud}$$

$$[H_s, \mathbf{J}] = 0, \ [H_{ud}, \mathbf{K}(= \mathbf{T} + \mathbf{J})] = 0$$

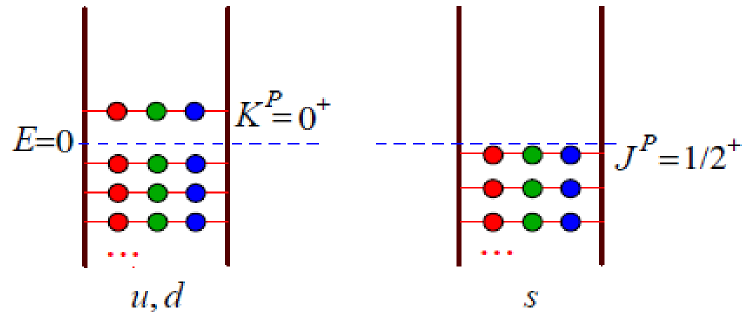


FIG. 1: Filled quark levels for the ground-state baryon $N(940, \frac{1}{2}^+)$. The two lightest baryon multiplets $(\mathbf{8}, \frac{1}{2}^+)$ and $(\mathbf{10}, \frac{3}{2}^+)$ are rotational excitations of the same filling scheme.

Simultaneous ordinary and isospin space rotation: *N* → *Δ*

SU(3) flavor rotation: → octet, decuplet

What is ‘exotic’ ?

A particle-hole excitation for different single particle orbits.

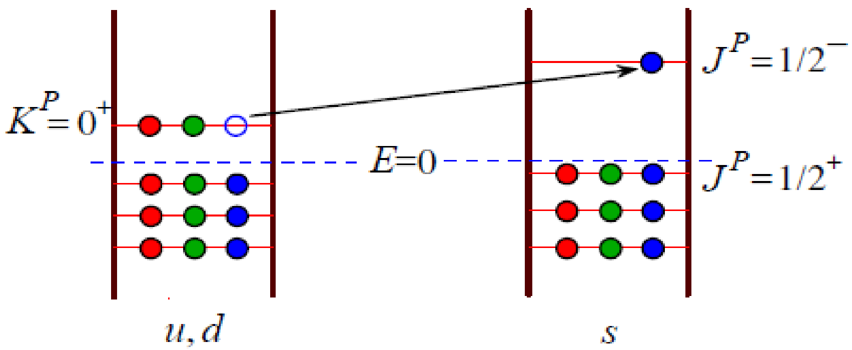


FIG. 2: $\Lambda(1405, \frac{1}{2}^-)$

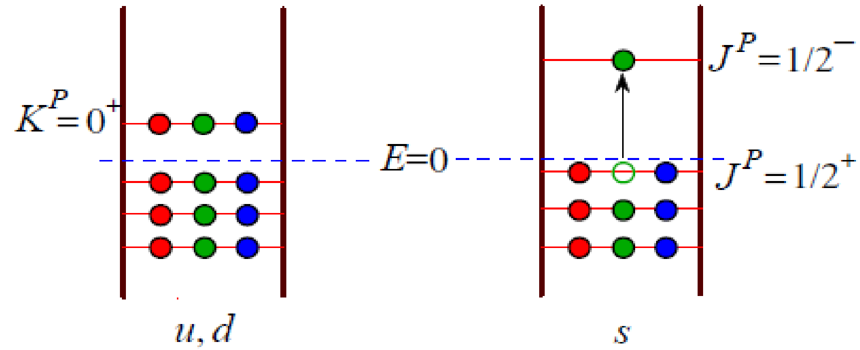


FIG. 3: $N(1535, \frac{1}{2}^-)$

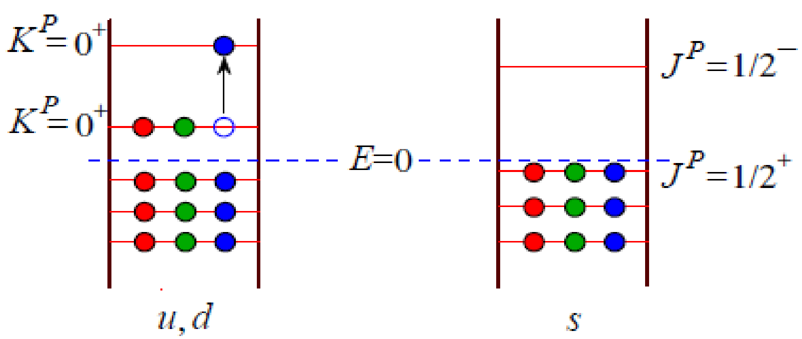


FIG. 4: $N(1440, \frac{1}{2}^+)$

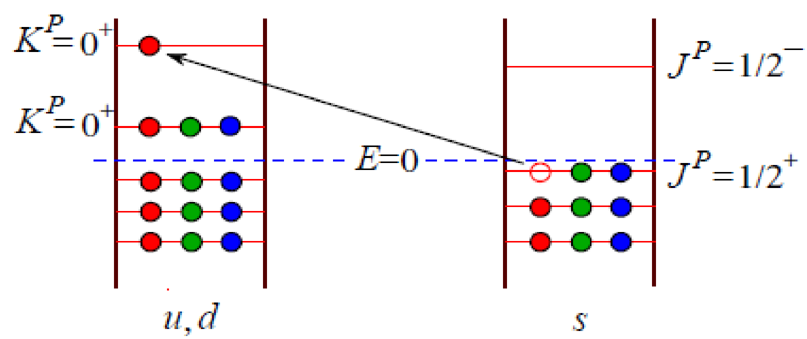
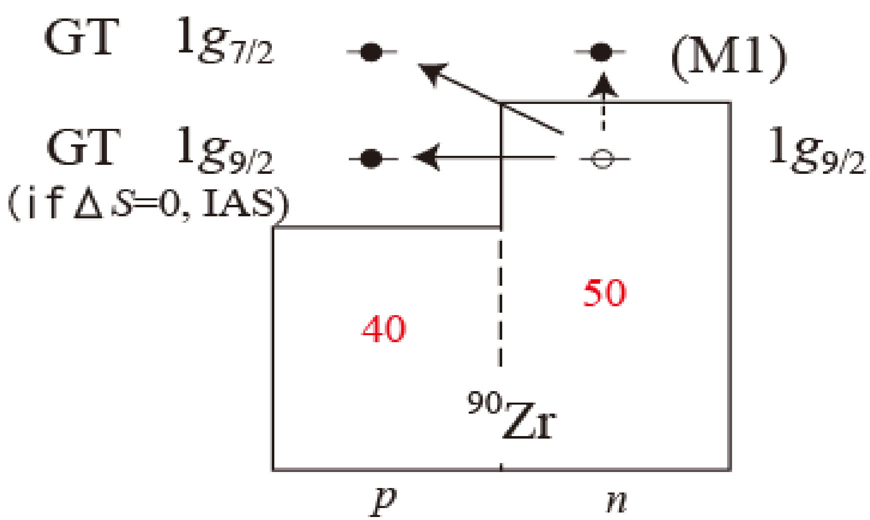


FIG. 5: $\Theta^+(\frac{1}{2}^+)$

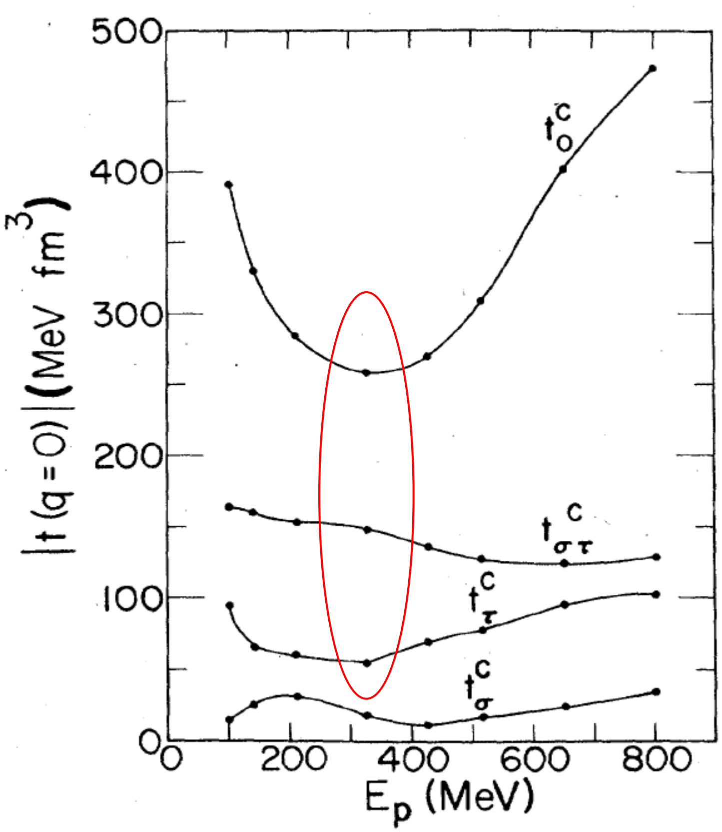
m_ΘP1440+1535-1405 = 1570 MeV

Nuclear Gamow-Teller transitions
(ΔL=0, ΔS=ΔT=1)

[e.g., 90Zr (0^+) → 90Nb (1^+)]

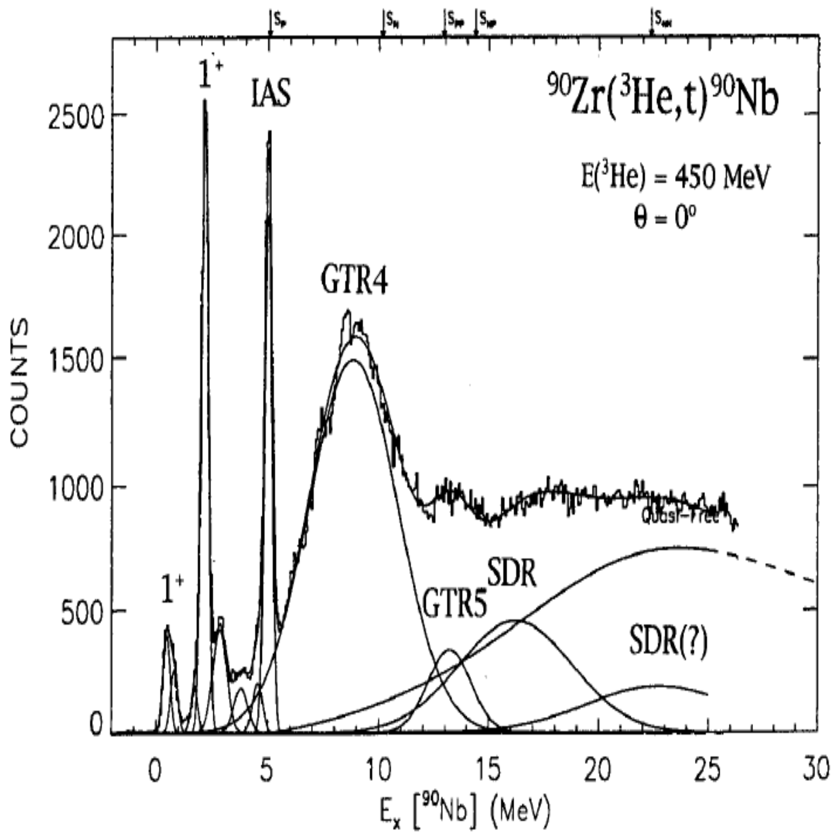


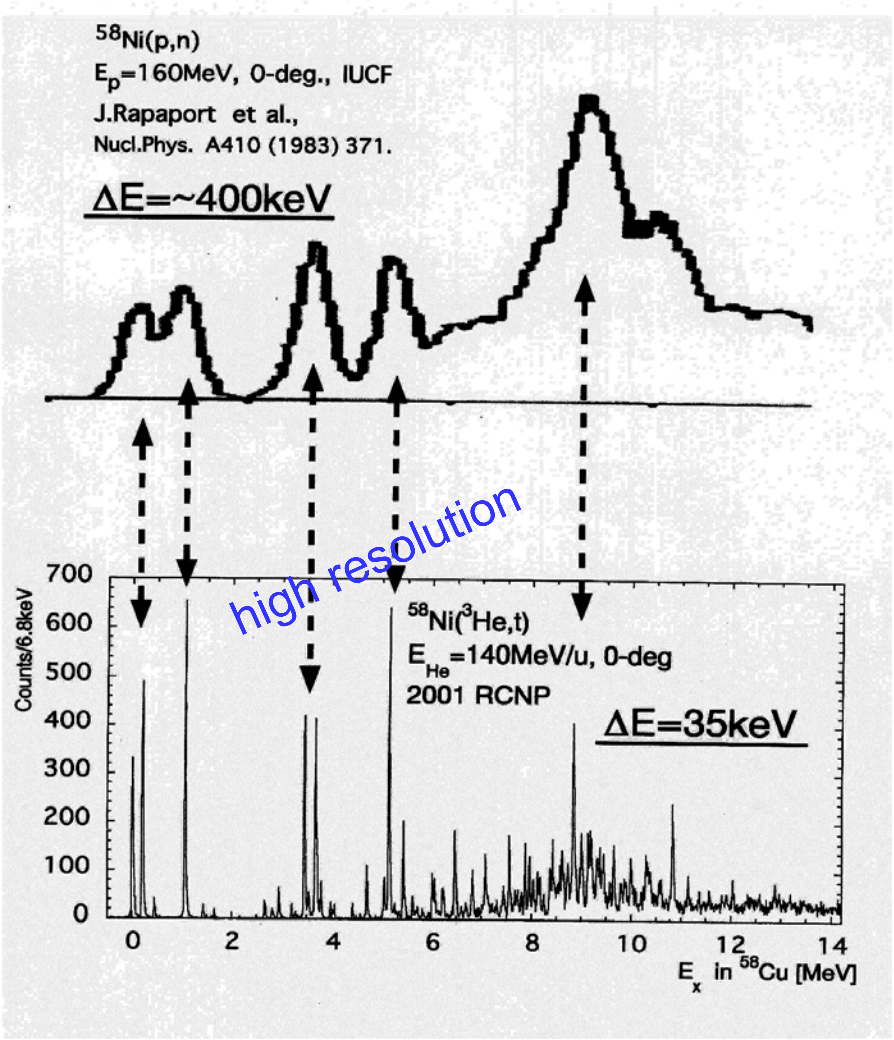
Energy dependence of
NN t-matrix
(PRC24,1073(1981))



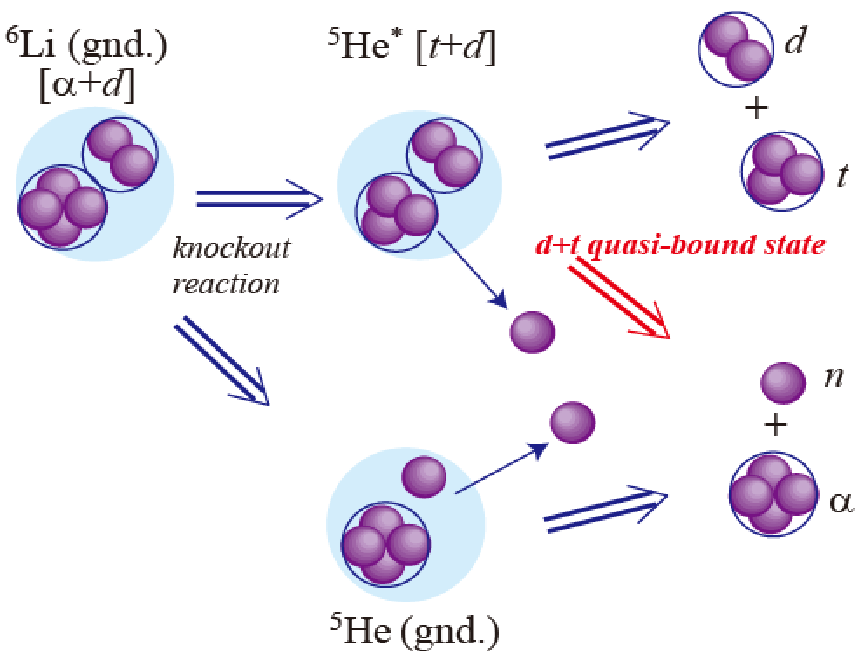
Reaction: (*p*,*n*), (3He,*t*), …
Energy: relatively large $V_{\sigma\tau}$
Angle: very forward

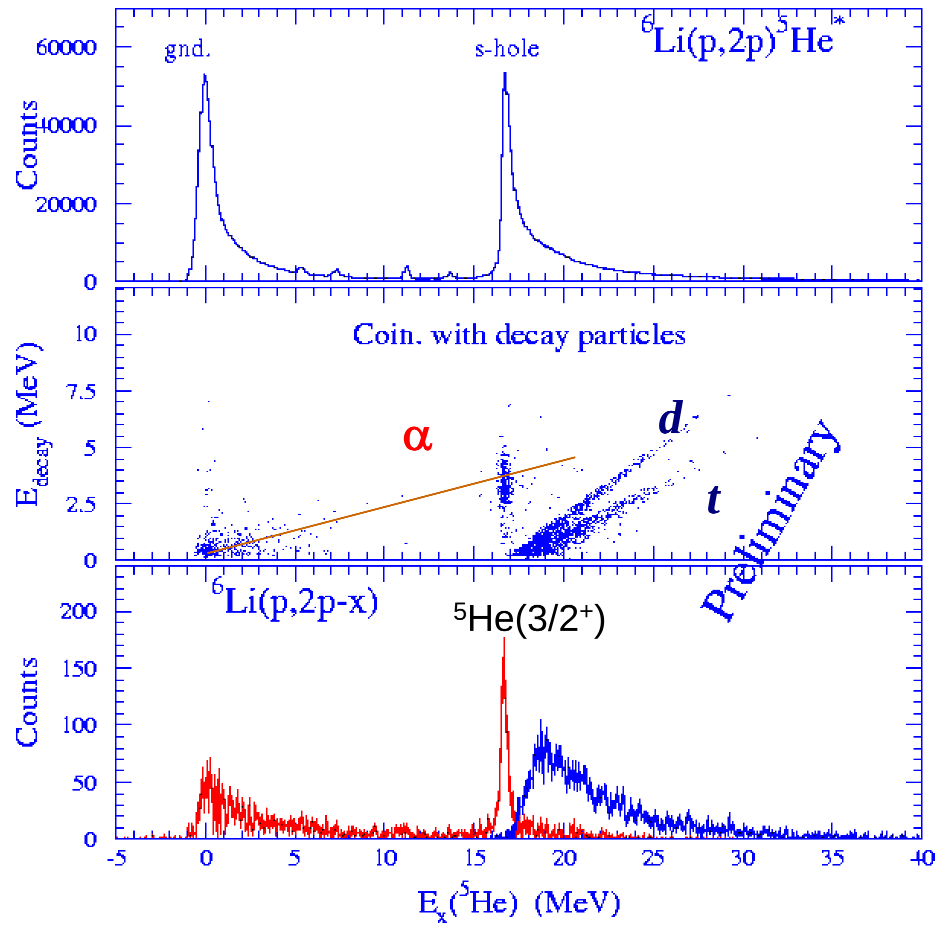
Nuclear Gamow-Teller transitions





Quasi-bound *d+t* cluster state
(^{6}Li(*p*,2*p*)^{5}He* coincidence with decay particles)



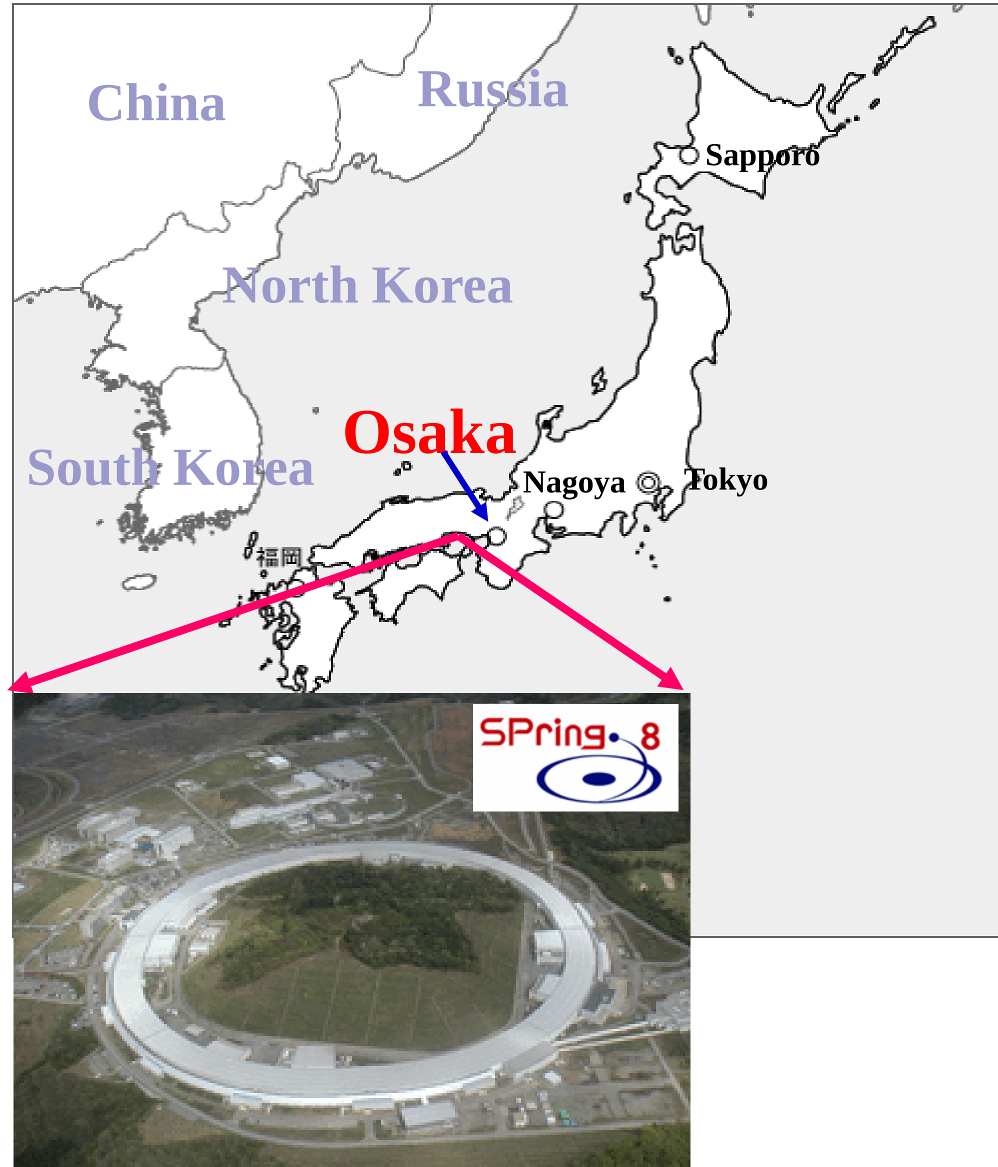


Ground states of nucleon 5-body system are unbound.

LEPS results for Θ^+ and $\Lambda(1405)$

Super Photon ring – 8 GeV

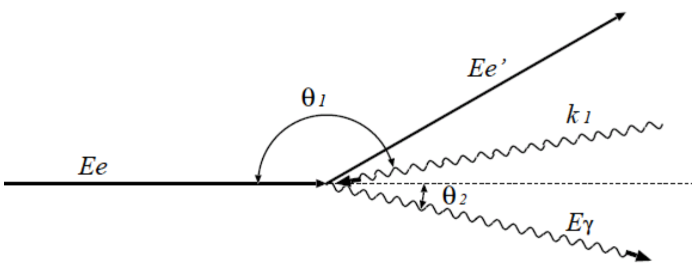
- 8 GeV electron beam
- Diameter ≈457 m
- RF 508 MHz
- One-bunch is spread within $\sigma = 12$ psec.
- Beam Current = 100 mA
- Top-up injection

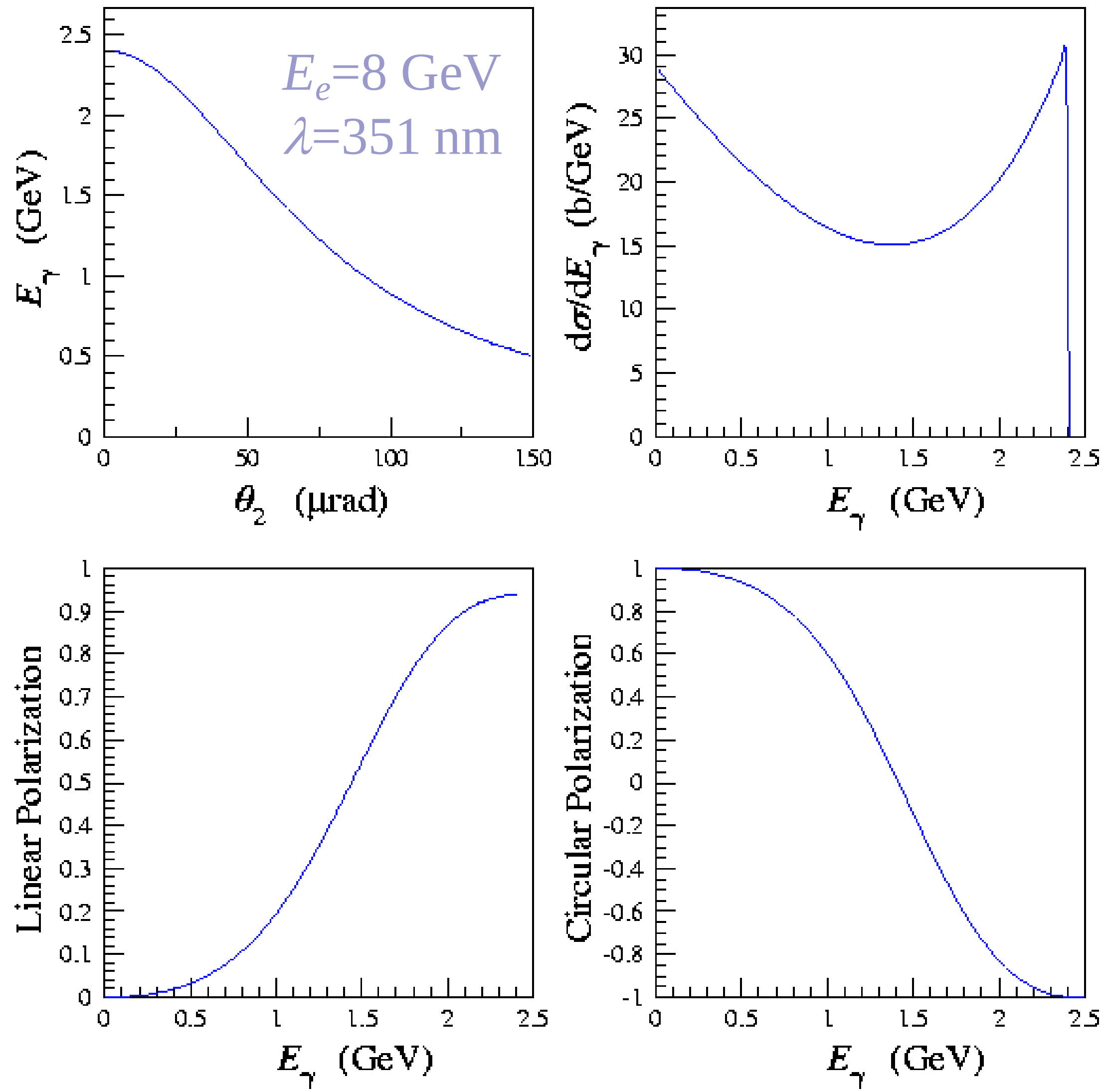


Osaka – SPring-8: about 120 km,
One and half an hour highway drive.

Characteristics of BCS photons

(BCS:Backward Compton Scattering)



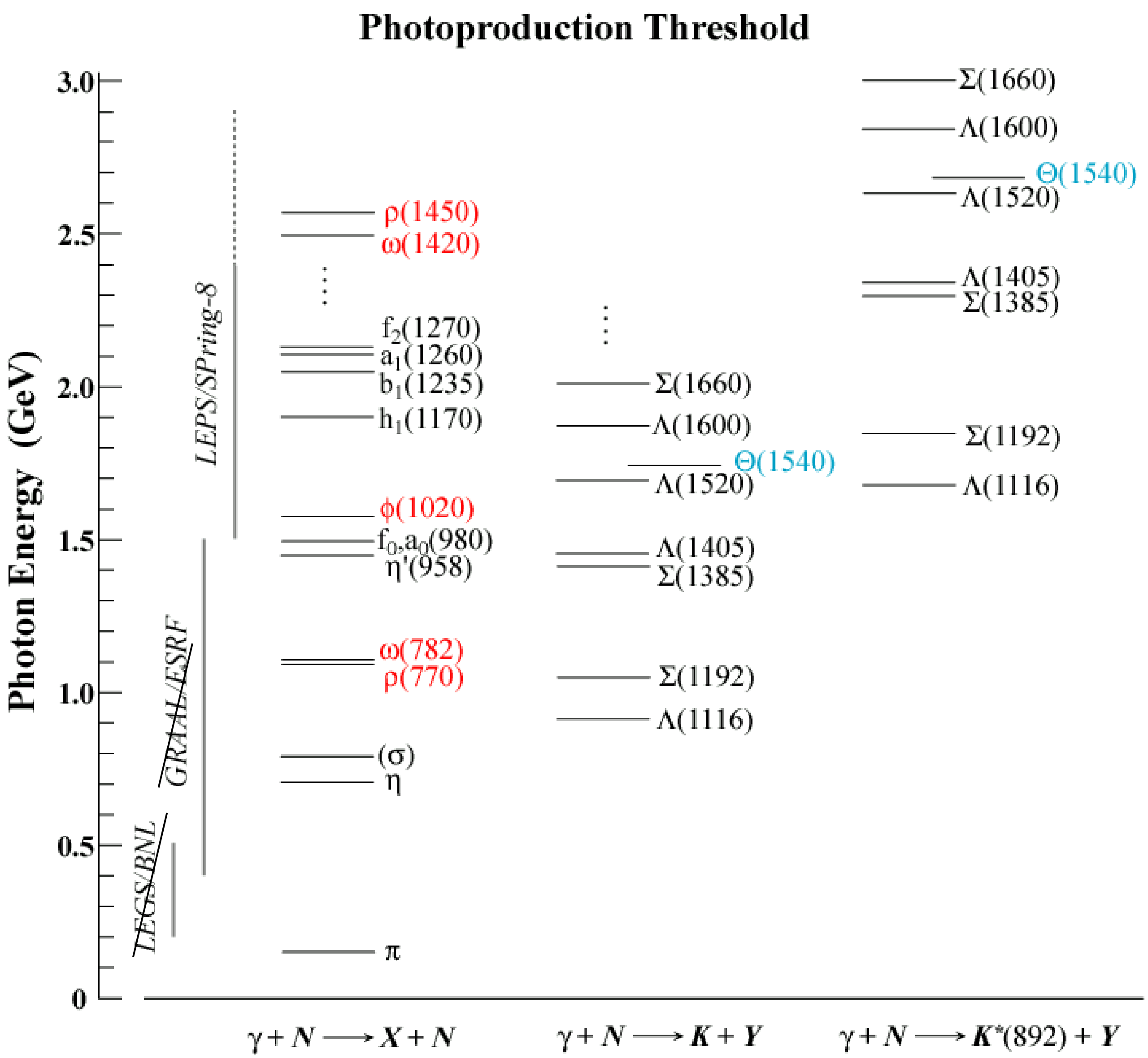


- rather flat energy distribution with small spreading

  (Unlike the Bremsstrahlung, where low energy photons are dominated, ~1/E_γ)

- high linear- or circular- polarization
- photon energy can be tagged by recoil electron

With LEPS, what can be aimed at ?



Threshold region of $\phi(s\bar{s})$ meson and hyperon resonances

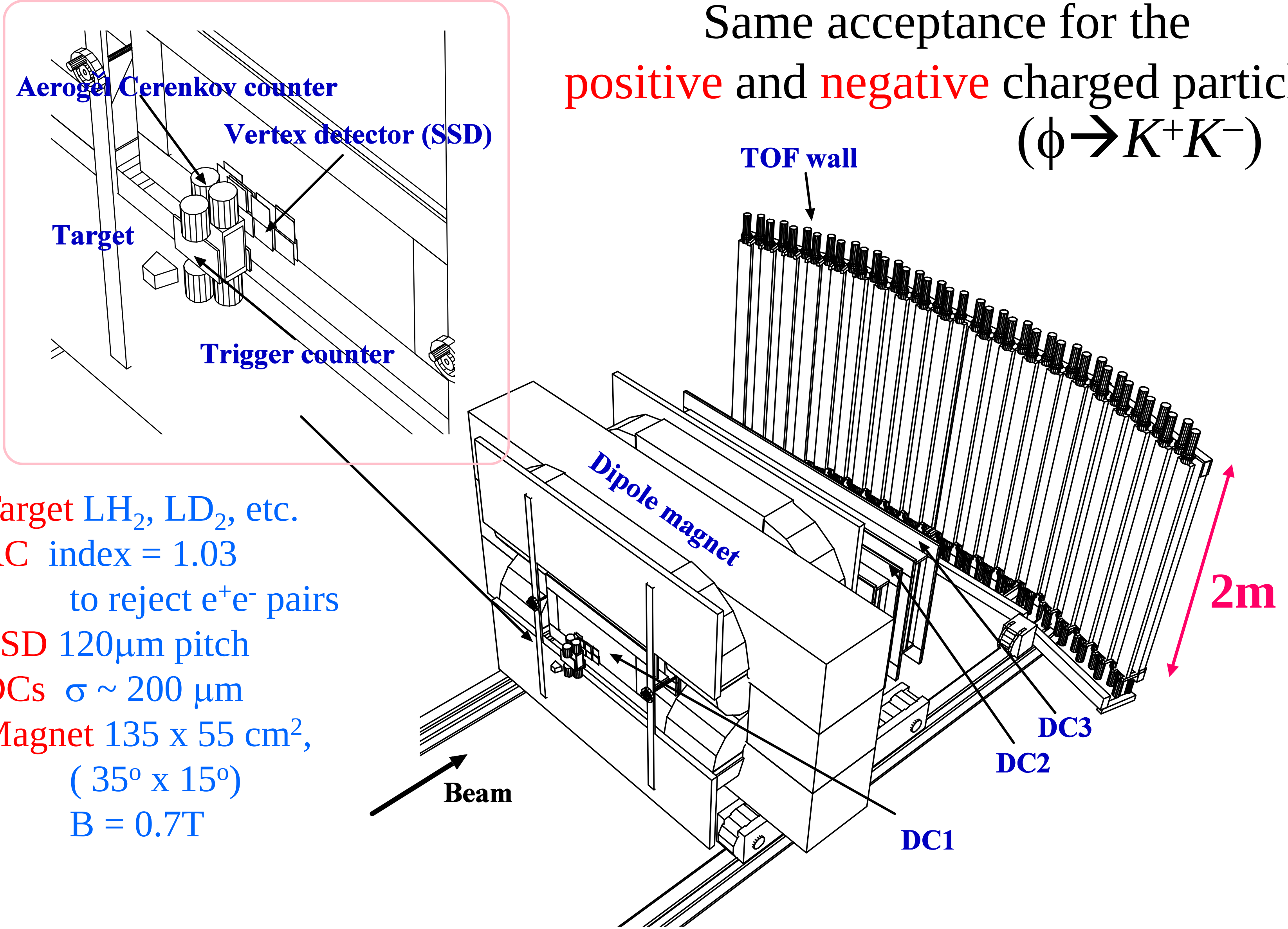
Key words :

1. **Forward angle measurement including 0 deg.**
2. **Polarization observables**
3. **Strangeness**

LEPS forward spectrometer

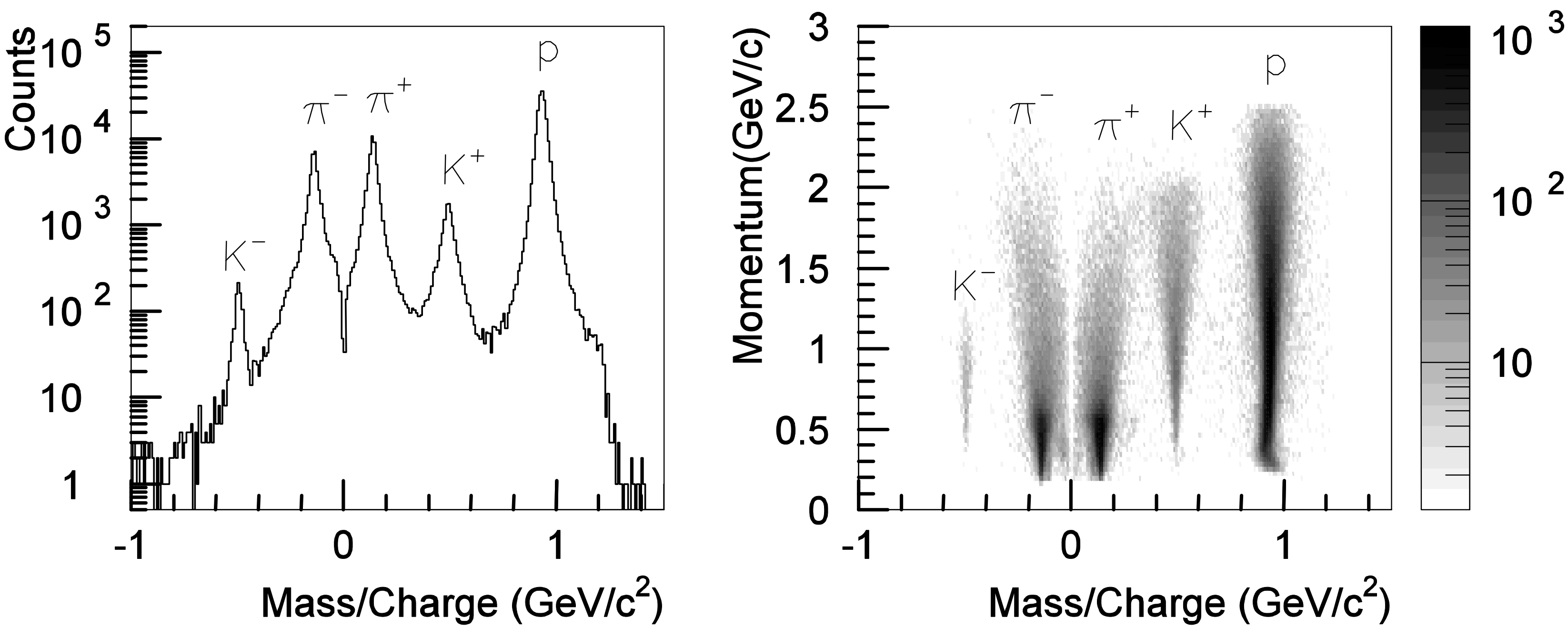
Same acceptance for the positive and negative charged particles ($\phi \rightarrow K^+K^-$)

- Target LH_2, LD_2, etc.
- AC index = 1.03 to reject e^+e^- pairs
- SSD 120μm pitch
- DCs $\sigma \sim 200$ μm
- Magnet 135 x 55 cm^2, (35^o x 15^o) B = 0.7T



Particle identification

Reconstructed mass spectra

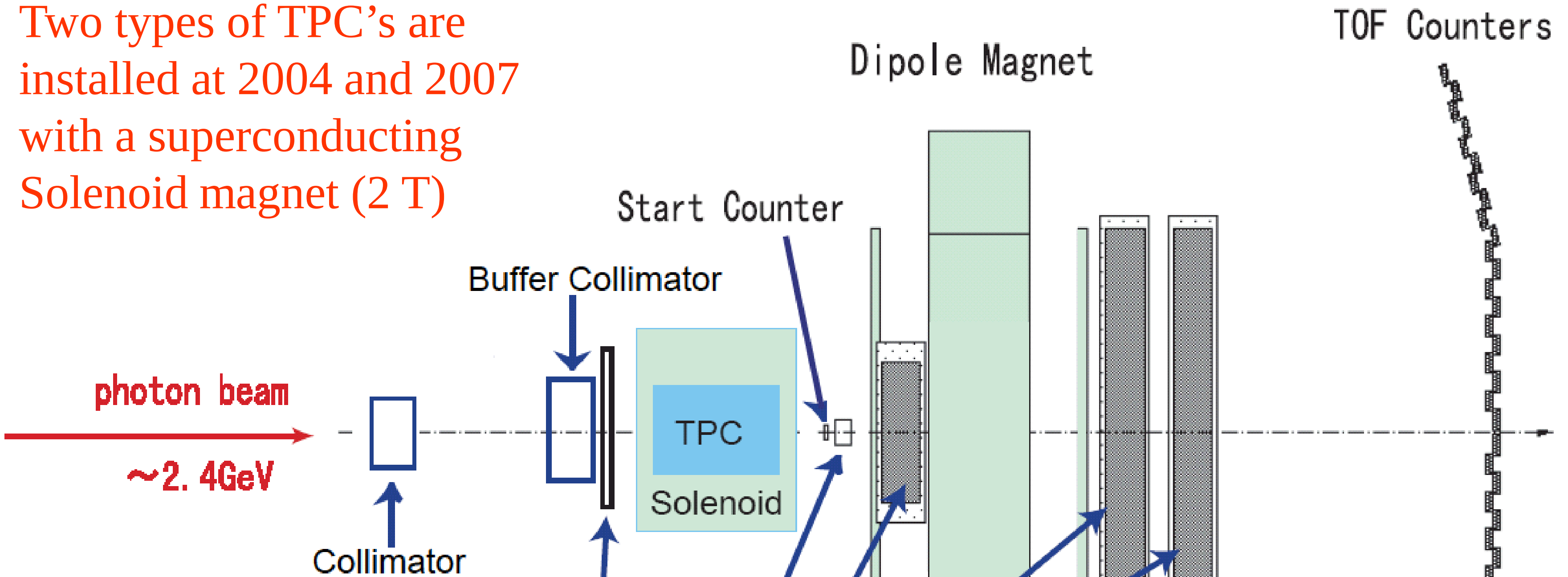


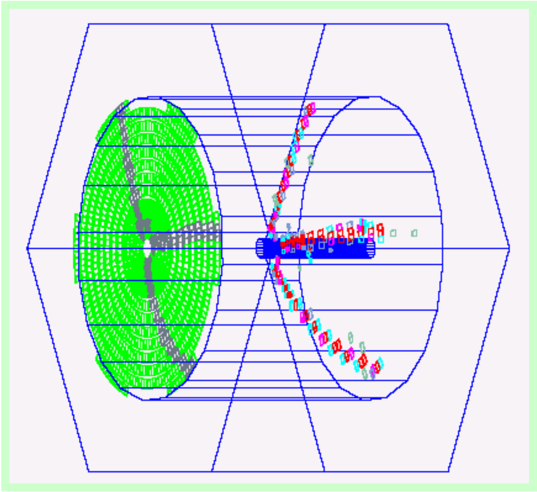
- TOF : RF signal - TOF wall, Δt = 120 ps
- Momentum : SSD, DCs, Tracking

  Δp ~ 6 MeV/c for 1 GeV/c K

Experimental setup with TPC

Two types of TPC's are installed at 2004 and 2007 with a superconducting Solenoid magnet (2 T)





Measure both production and decay simultaneously !

LEPS experiments (2000 – 2009)

year	2000	2001	2002	2003	2004
photon beam		Linearly Polarized E_γ < 2.4 GeV			
target	BL construction & Comissioning	LH2 (short), nuclear targets	LH2, LD2 (long)	nuclear targets	nuclear targets
detector		Forward LEPS spectrometer		Gamma detector Tagger (SSD→ScFi)	Fwd spectrometer + TPC-I

year	2005	2006	2007	2008	2009
photon beam	LP E_γ < 3 GeV	LP E_γ < 2.4 GeV (8W Paladin x2)	LP E_γ < 3 GeV	LP E_γ < 2.4 GeV (test 16W Paladin)	LP E_γ < 3 GeV
target		LD2, LH2 (long)		new target system for TPC (LH2, LD2, LHe)	LH2 (long)
detector		Forward LEPS spectrometer		Fwd spectrometer + TPC-II	Fwd

development of polarized HD target

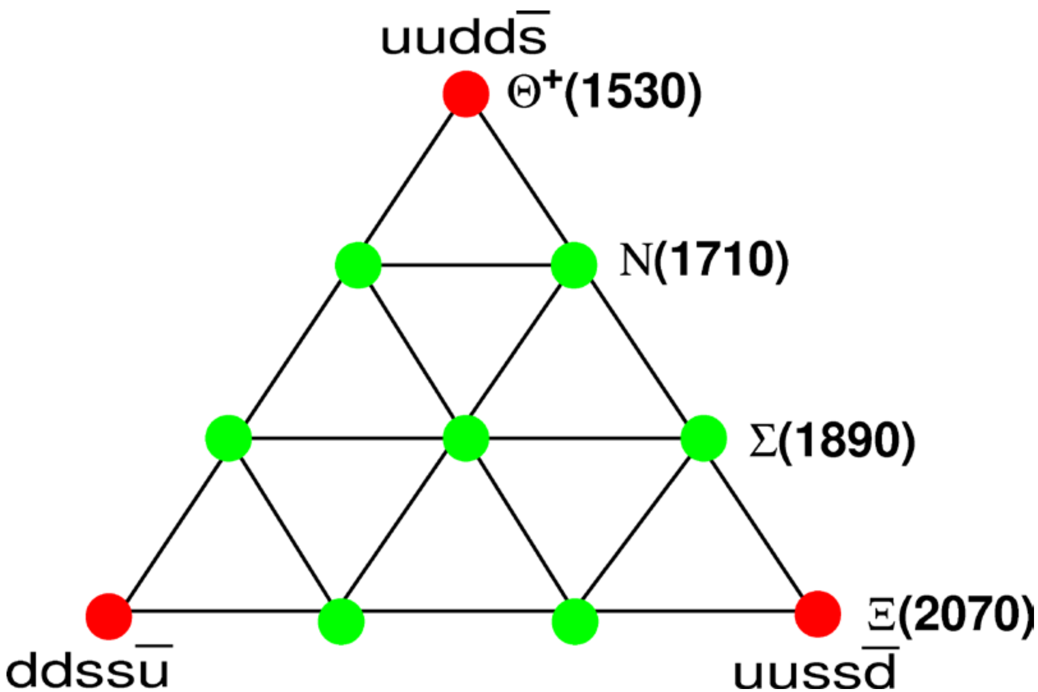
Θ^+ search

- **Minimum quark content : 5 quarks** $uudd\,\bar{s}$
- **Quantum numbers of "Exotic" pentaquarks : not 3-quark**

Theoretical Prediction of Θ^+

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

(Chiral Soliton Model)



M = [1890-180*Y] MeV

- **Exotic: S = +1**
- **Low mass: 1530 MeV**
- **Narrow width: ~ 15 MeV**
- **J^π=1/2$^+$**

First ovservation of Θ^+ from LEPS

$\gamma' n' \to \Theta^+ K^- \to K^+ K^- n$

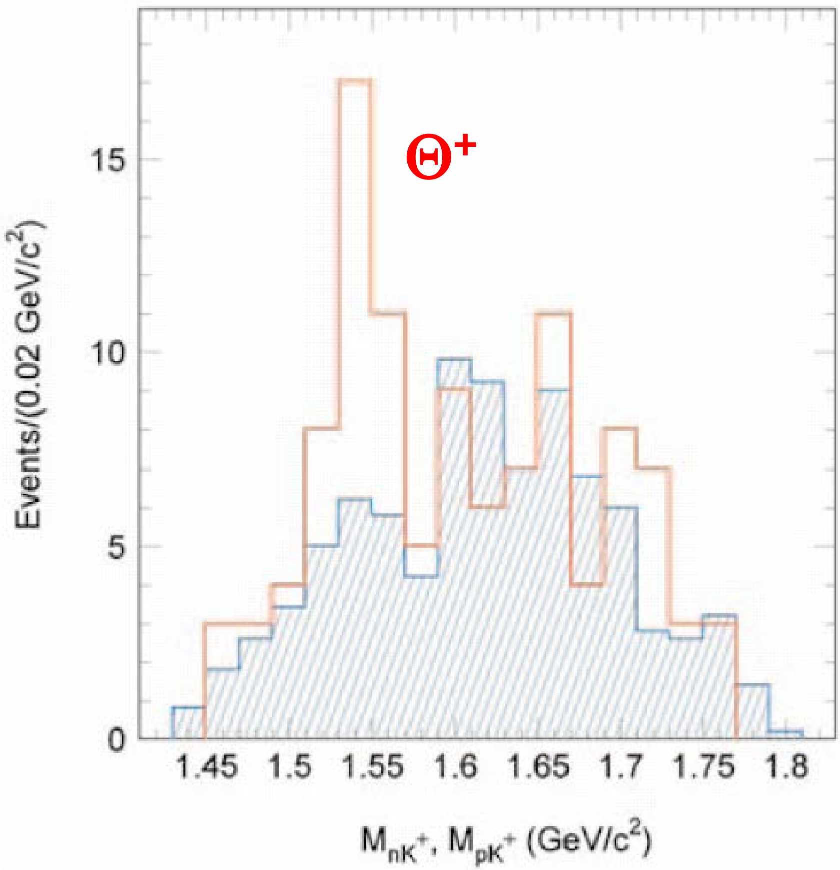
M = 1.54±0.01 GeV
Γ < 25 MeV
Gaussian significance 4.6σ

Target: neutron in Carbon nucleus

Background level is estimated by a fit in a mass region above 1.59 GeV.

Assumption:

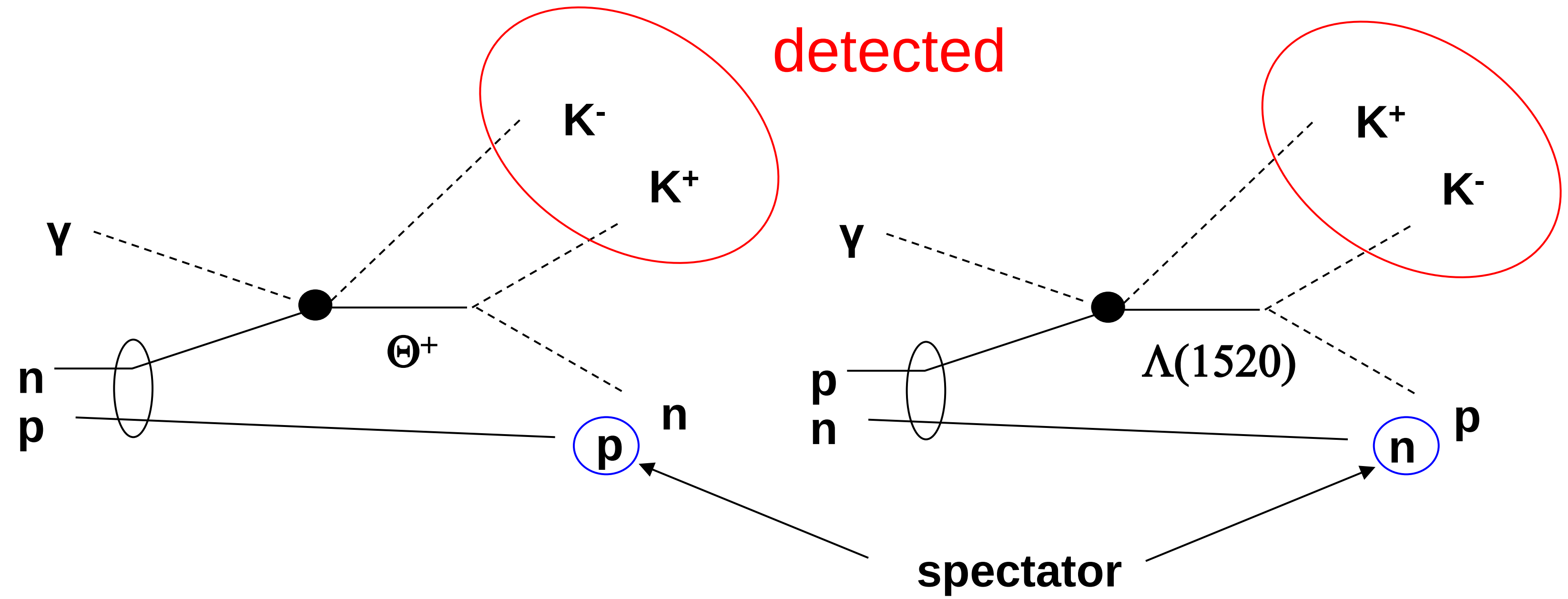
- **Background** is from non-resonant K^+K^- production off the neutron/nucleus
- … is nearly identical to non-resonant K^+K^- production off the proton



T. Nakano et al., PRL91, 012002

Θ^+ analysis in LD_2 run

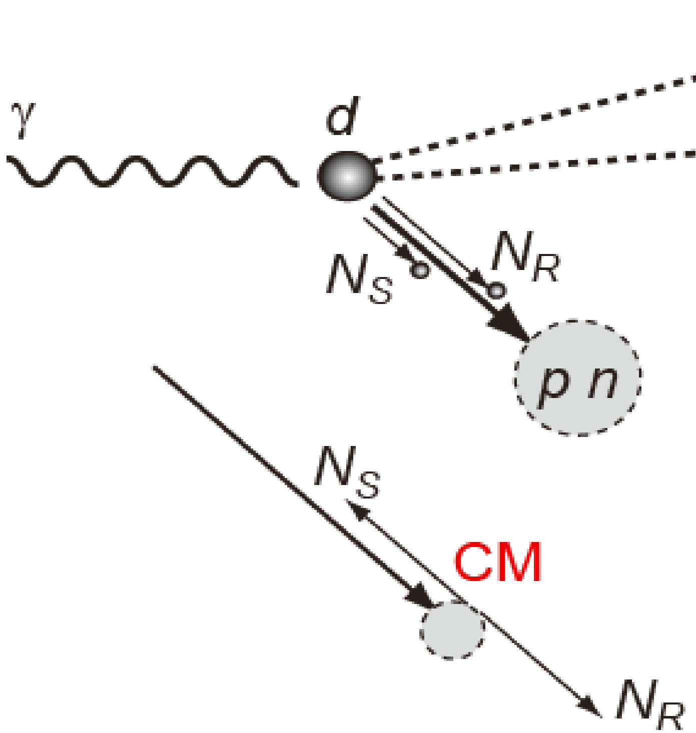
Quasi-free production of Θ^+ and $\Lambda(1520)$

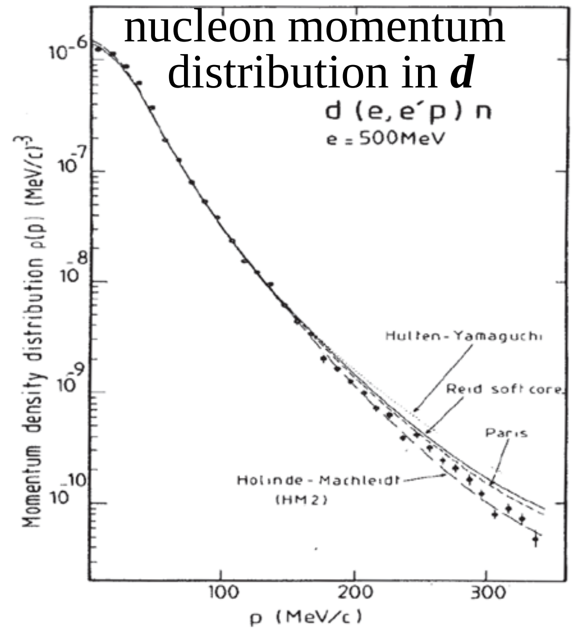


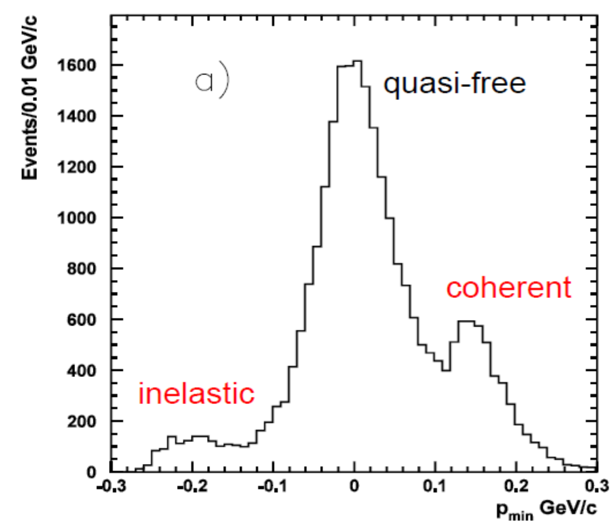
- Both reactions are quasi-free processes.
- Fermi-motion should be corrected.
- Existence of a spectator nucleon characterize both reactions. → $p(N_S)$<~100 MeV/c

Data were taken in 2002-2003 (published in PRC79,025210(2009))
and in 2006-2007 (high statistics, still under analysis)

Minimum Momentum Spectator Approximation







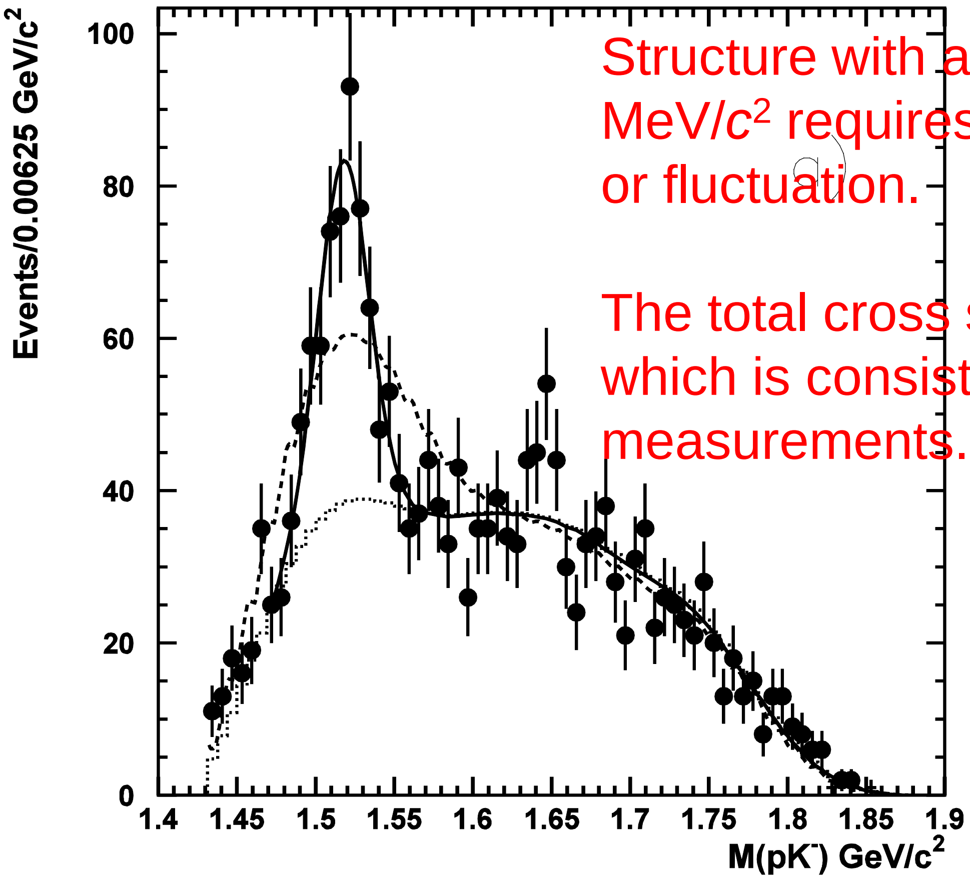
4-momentum of γ, d, K^+, K^-

→ missing energy and momentum of the *pn* system

→ calculate the possible minimum momentum of N_S

Results of Λ(1520) analysis

pK⁻ invariant mass with MMSA: Fermi motion effect corrected.



Structure with a width less than 30 MeV/c^2 requires a physics process or fluctuation.

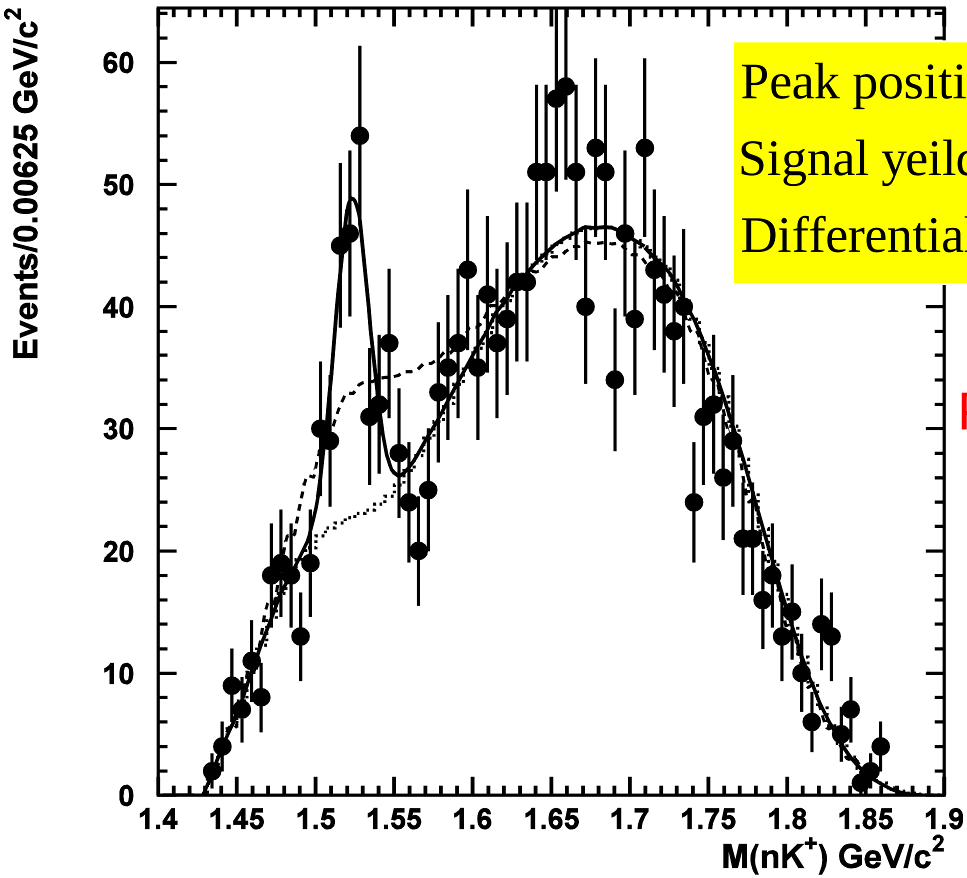
The total cross section is ~1 μb, which is consistent with the LAMP2 measurements.

$\Delta(-2\ln L)$ =55.1 for Δndf=2 ⟶ 7.1σ

$$\mathrm{Prob}(7.1\sigma) = 1.2 \times 10^{-10}$$

Results of Θ^+ analysis

nK⁺ invariant mass with MMSA: Fermi motion effect corrected.



Peak position: 1.527 ± 0.002 GeV/c^2

Signal yeild: 116 ± 21 events

Differential cross-section: 12 ± 2 nb/sr

PRC **79,** 025210 (2009)

"The narrow peak appears only after Fermi motion correction."

$\Delta(-2\ln L) = 31.1$ for $\Delta ndf = 2$ $\longrightarrow$ 5.2σ $\quad \mathrm{Prob}(5.2\sigma) = 2 \times 10^{-7}$

Θ^+ summary

- We observed a 5-σ peak in the Fermi-motion corrected nK^+ invariant mass at 1.527 GeV/c^2

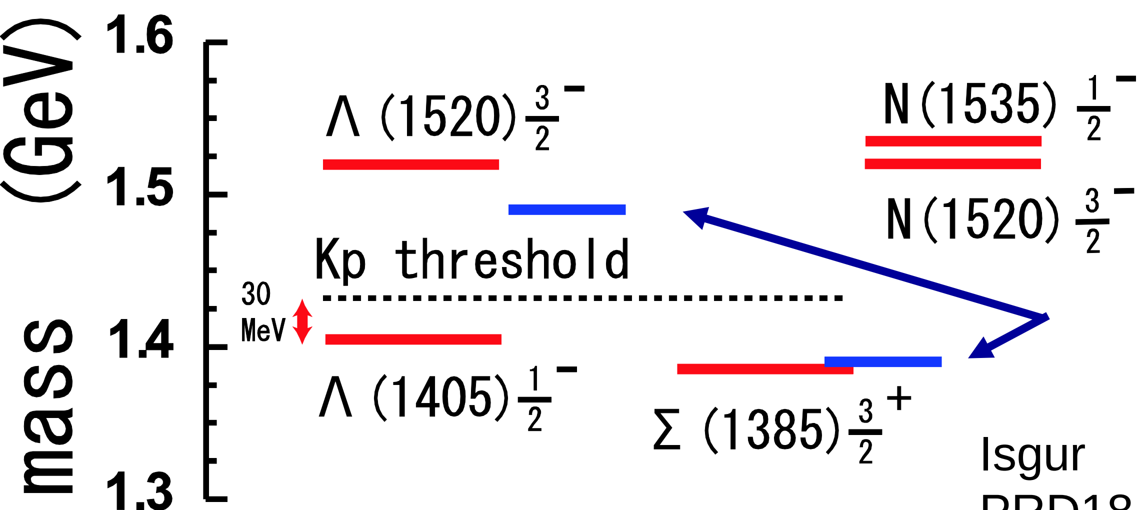
- New data set with 3-times more statistics was taken. Blind analysis is under way to check the validity of the peak.

- A new experiment with a TPC was carried out in 2008-2009: wider angle coverage and Θ^+ reconstruction in pK_s decay mode. (But PI and momentum resolutions are not good.)

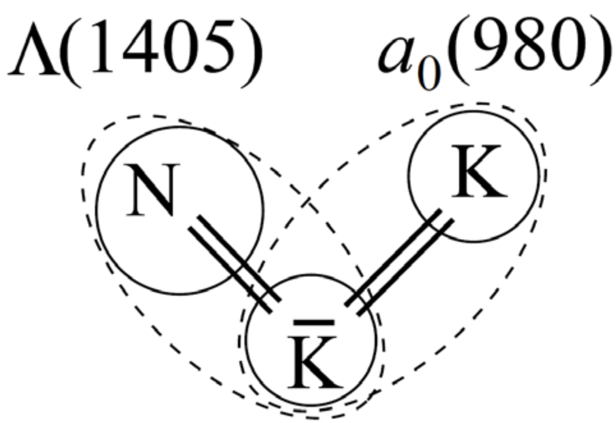
→ LEPS2 and J-PARC (formation)

Study of Λ(1405)

- **3 quark or meson-baryon molecule or 4q-qbar pentaquark?**
  qq LS force is too small to explain the mass of Λ(1405).
  meson-baryon molecule has been suggested. 1-pole or 2-pole ?
- **Low energy K-bar N interaction**
  Kaonic nucleus, Kaon condensation in the neutron star
- **K-bar K N molecular state?**



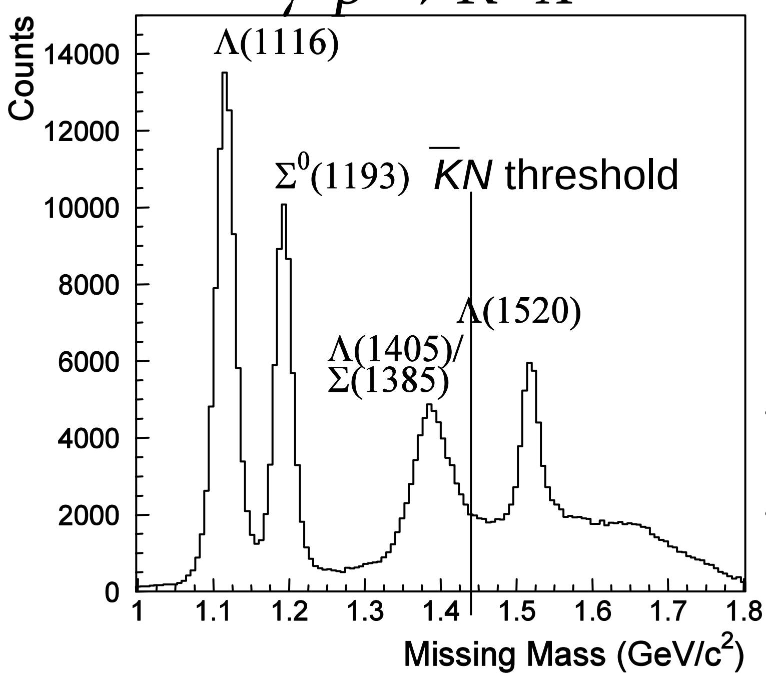
Isgur
PRD18



Jido and En'yo
PRC78

$\Lambda(1405)$ photoproduction at LEPS

$$\gamma\, p \to K^+ X$$



missing mass spectrum can not separate $\Lambda(1405)$ and $\Sigma(1385)$

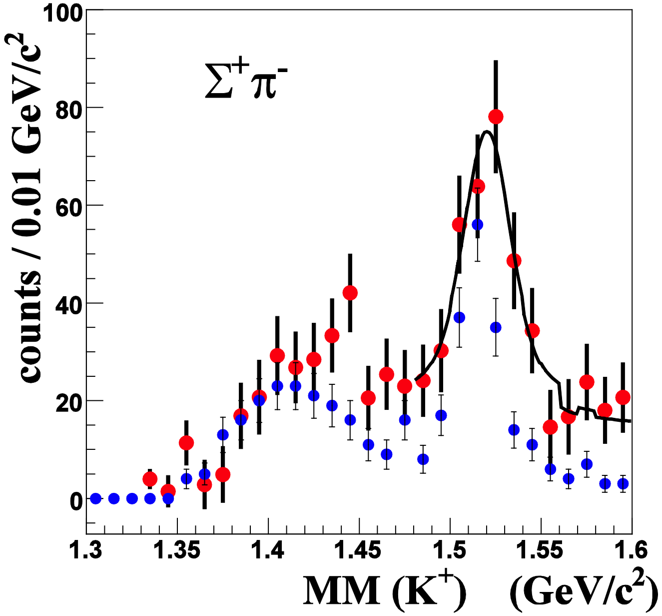
→ detect decay products and distinguish two resonances

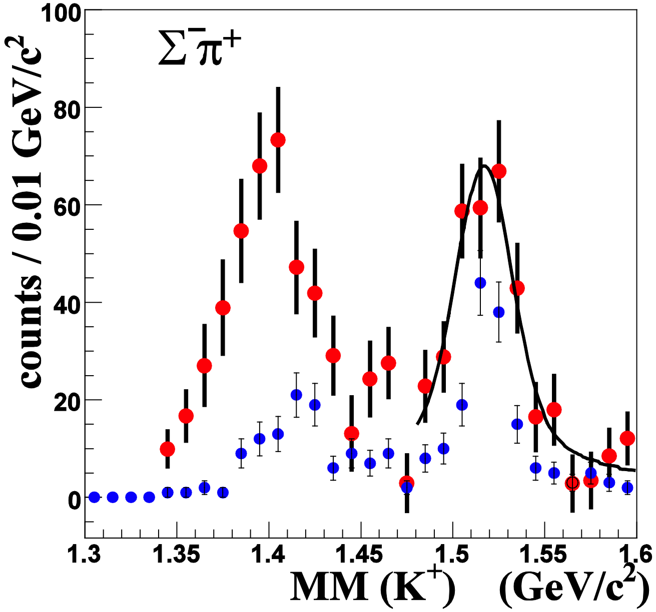
$$\gamma\, p \to K^+\Lambda(1405) \to K^+\Sigma^{\pm}\pi^{\mp} \to K^+ n\pi^+\pi^-$$

$$\gamma\, p \to K^+\Sigma(1385)^0 \to K^+\Lambda\pi^0 \to K^+ p\pi^-\pi^0$$

- line-shape of $\Lambda(1405)$ in $p(\gamma, K^+ \pi^+)$, $p(\gamma, K^+ \pi^-)$ reactions
  J.K.Ahn et al. NPA 721,715c(2003) (Fwd only)
  Interference of $\Sigma\pi$ scattering amplitude
- **Differential cross section of $\Lambda(1405)$ production**
  M.Niiyama et al. PRC78,035202(2008) （Fwd + TPC)
  Enhancement of cross section near threshold.

Lineshape of Λ(1405)





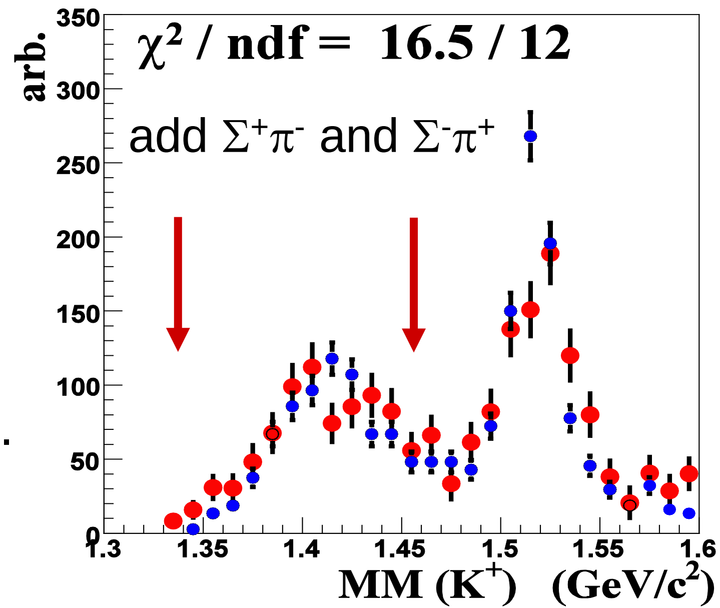
● $\pi^\pm$ in TPC

● $\pi^\pm$ in Fwd

$$\sigma_{\Sigma^+\pi^-} = \frac{1}{2}|T^{(1)}|^2 + \frac{1}{3}|T^{(0)}|^2 + \frac{2}{\sqrt{6}}\mathrm{Re}(T^{(0)}T^1)$$

$$\sigma_{\Sigma^-\pi^+} = \frac{1}{2}|T^{(1)}|^2 + \frac{1}{3}|T^{(0)}|^2 - \frac{2}{\sqrt{6}}\mathrm{Re}(T^{(0)}T^1)$$

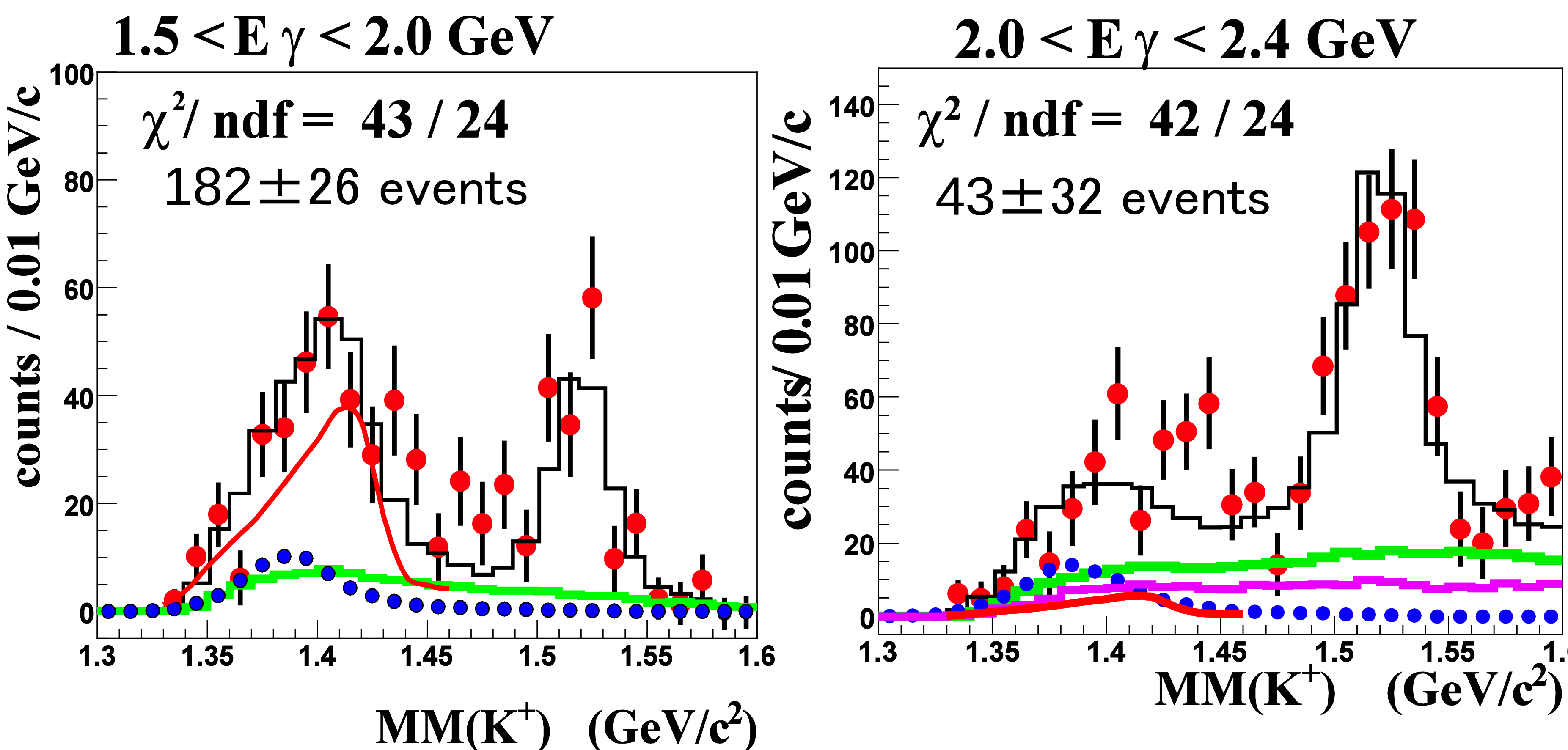
The interference term depends on π decay angle.



Spectrum of Λ(1405) in 2 Eγ bins [CH_2-C]

- data
- Σ(1385) ($\Lambda\pi^0$ mode)
- Σπ phase space
- K*(892)Σ^+
- theoretical model

Λ*/Σ* = 0.54 ± 0.17 (1.5<Eγ<2.0)
0.074 ± 0.076(2<Eγ<2.4)



Absolute value of the differential cross section

Using the ratio of Λ(1405)/Σ(1385) ,
the absolute value is obtained from LH2 data.

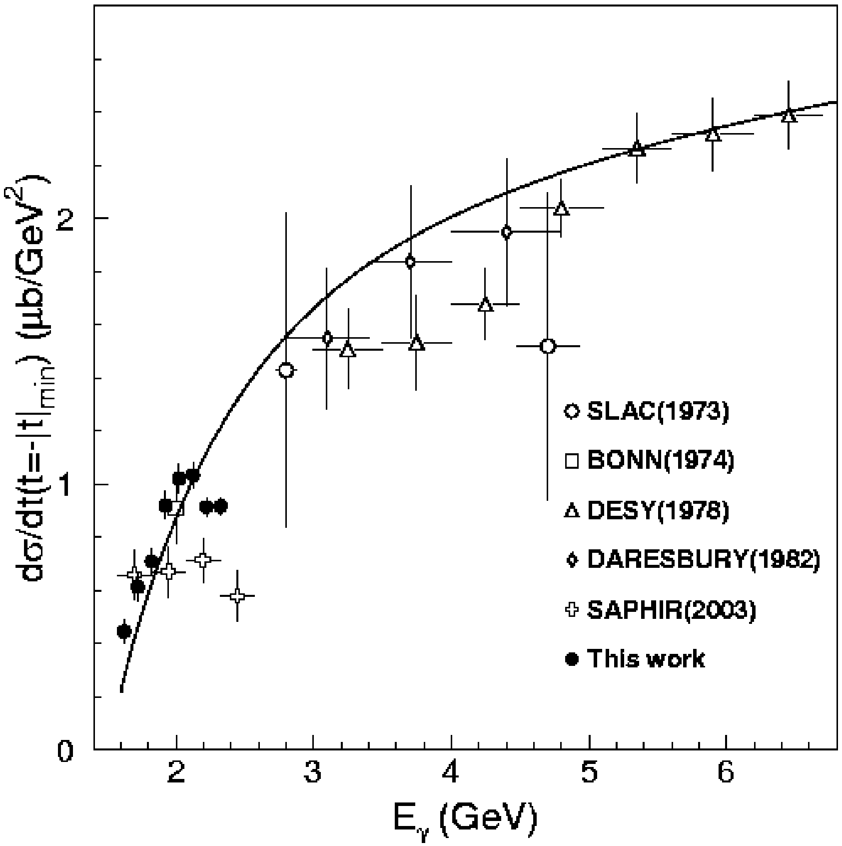
$0.8 < \cos\theta_{kCM} < 1$

	$1.5 < E_\gamma < 2.0$ GeV	$2.0 < E_\gamma < 2.4$ GeV
	$d\sigma/d(\cos\theta)$ [μb]	$d\sigma/d(\cos\theta)$ [μb]
$\Lambda^*(1405)$	$0.43 \pm 0.088^{+0.034}_{-0.14}$	< 0.17 with 95 % C.L.
$\Sigma^{*0}(1385)$	$0.80 \pm 0.092^{+0.062}_{-0.27}$	$0.87 \pm 0.064^{+0.13}_{-0.067}$

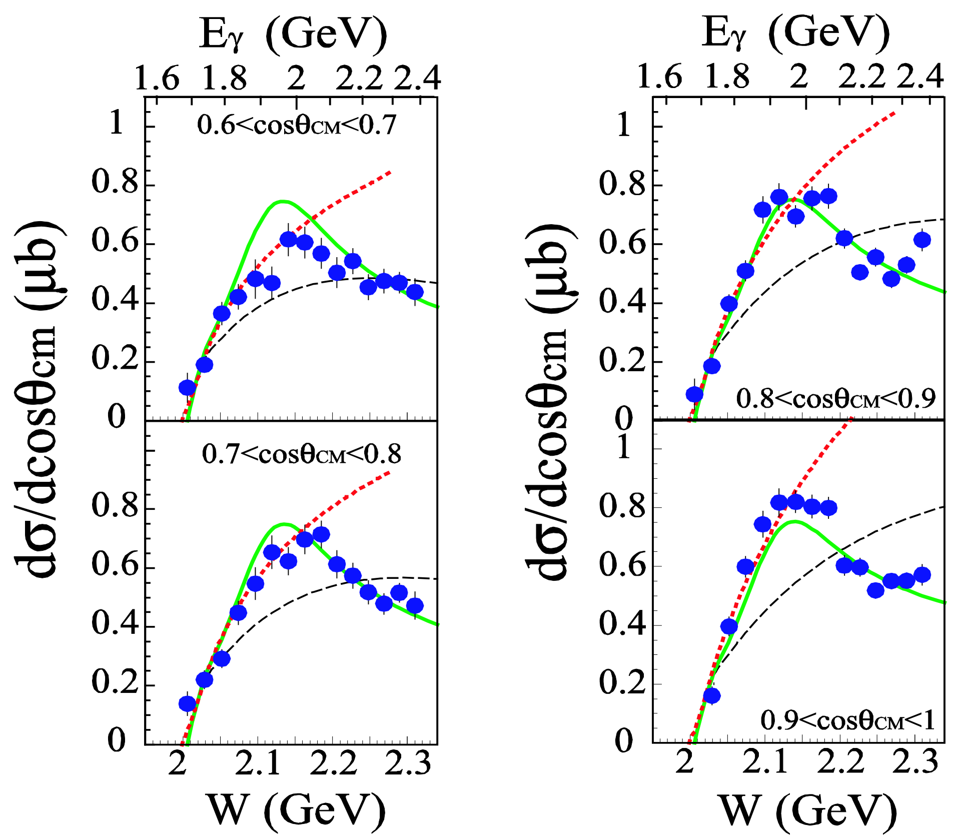
- Strong enhancement of Λ(1405) production near threshold.
  Exotic mechanism may contribute Λ(1405) production.
- on going analysis for LH2 data in 2007-2008
  - obtain moer precise differential cross section
  - photon beam asymmetry
  - $p(\gamma,K^{*+})\Lambda(1405)$

Bump structures around 2 GeV in other reactions

$\gamma\ p \rightarrow \phi\ p$



$\gamma\ p \rightarrow K^+\Lambda(1520)$



T. Mibe et al. PRL95,182001 (2005)

H. Kohri et al. arXiv: 0906.0197 (2009)

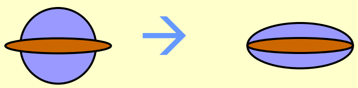
LEPS2 project

LEPS new beam line (LEPS2)

- Beam upgrade:

Intensity --- High power laser, Multi laser(x4)

--- Laser elliptic focus



$2x10^6$ → 10^7 /sec for 2.4 GeV

$2x10^5$ → 10^6 /sec for 3 GeV

Energy --- Laser with short λ ,

(re-injected Soft X-ray+BCS (2nd stage), → up to ~7.5 GeV

- Detector upgrade: (reaction process & decay process)

Scale & Flexibility --- General-purpose large 4π detector → outside of the building

Coincidence measurement of charged particles and neutral particles (photons) ← BNL/E949 detector

DAQ --- High speed for the minimum bias trigger

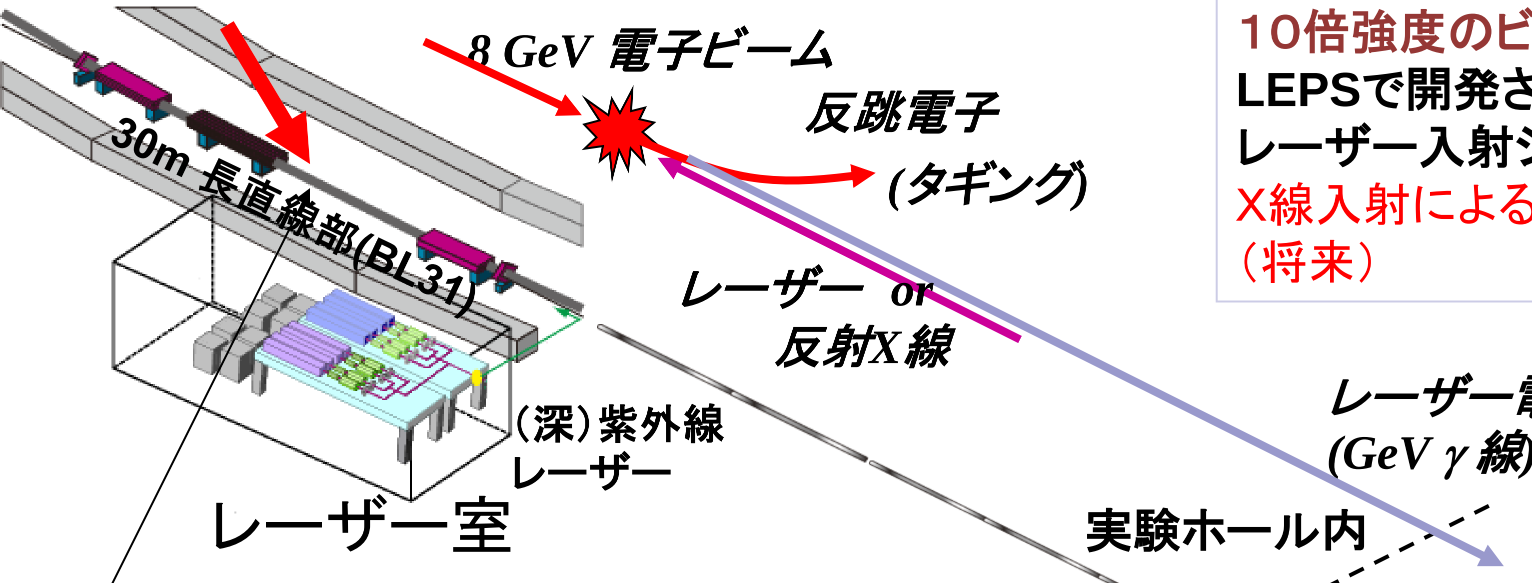
- Physics: Multi-quark (>3)

Workshop on LEPS2 (2005/7, 2007/1)

statistics, acceptance, momentum and PI resolution, neutral particle detection (especially at large angle)

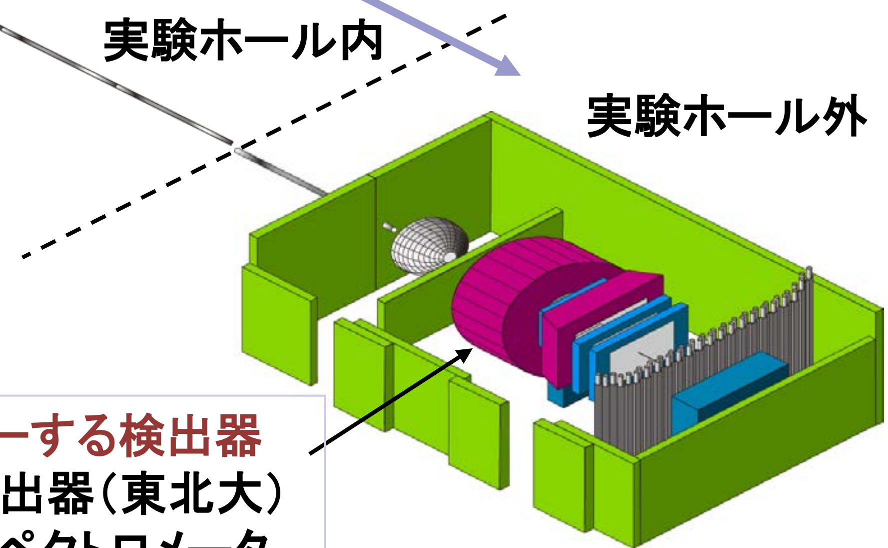
Schematic view of the LEPS2 facility

逆コンプトン散乱



10倍強度のビーム
LEPSで開発されたパラレル・
レーザー入射システム
X線入射による高エネルギー化
（将来）

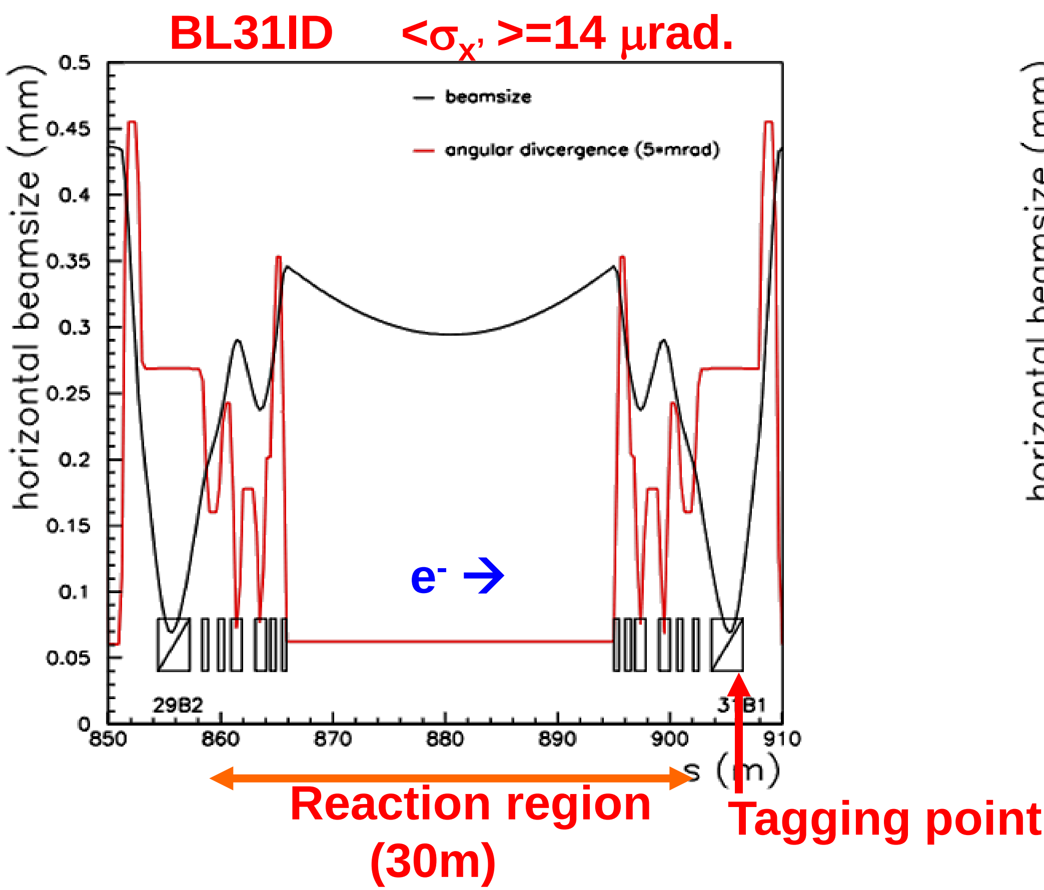
最良エミッタンス（平行ビーム）
→ レーザー電子光が広がらない

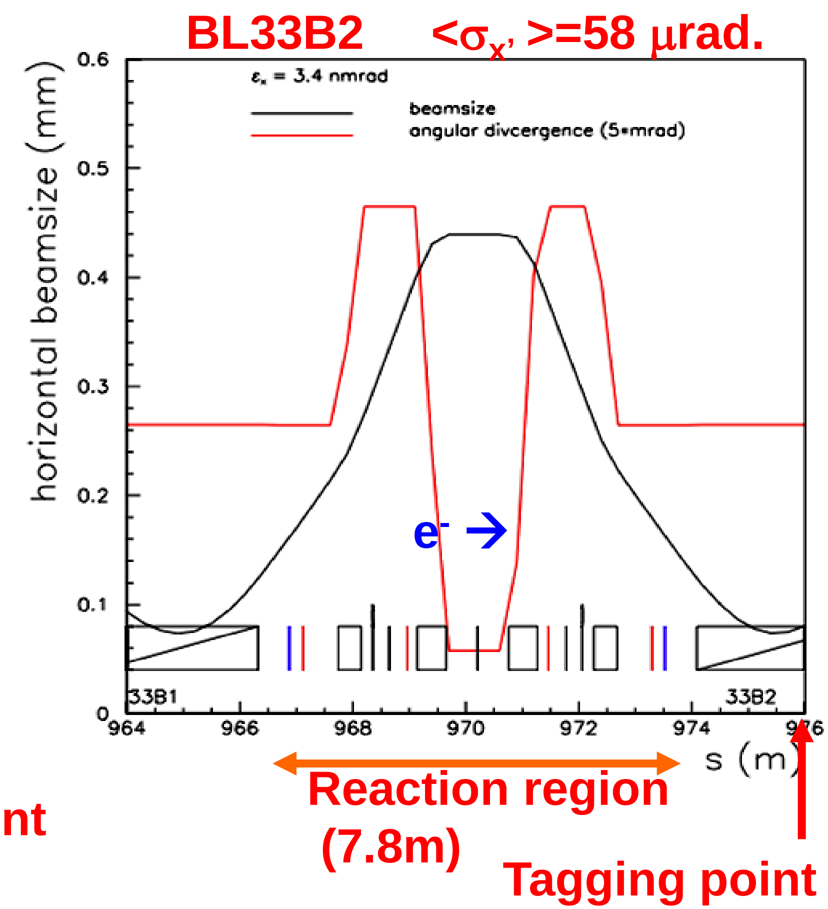


・米国BNL(E949)の400トン
スペクトロメーター有効利用
・阪大ブランドの高速データ
収集回路の開発
・LEPSでの膨大なノウハウ
の蓄積

全方向をカバーする検出器
4πガンマ線検出器（東北大）
崩壊解析用スペクトロメータ
反応同定用スペクトロメータ
高速データ収集システム

Divergence of LEP beam

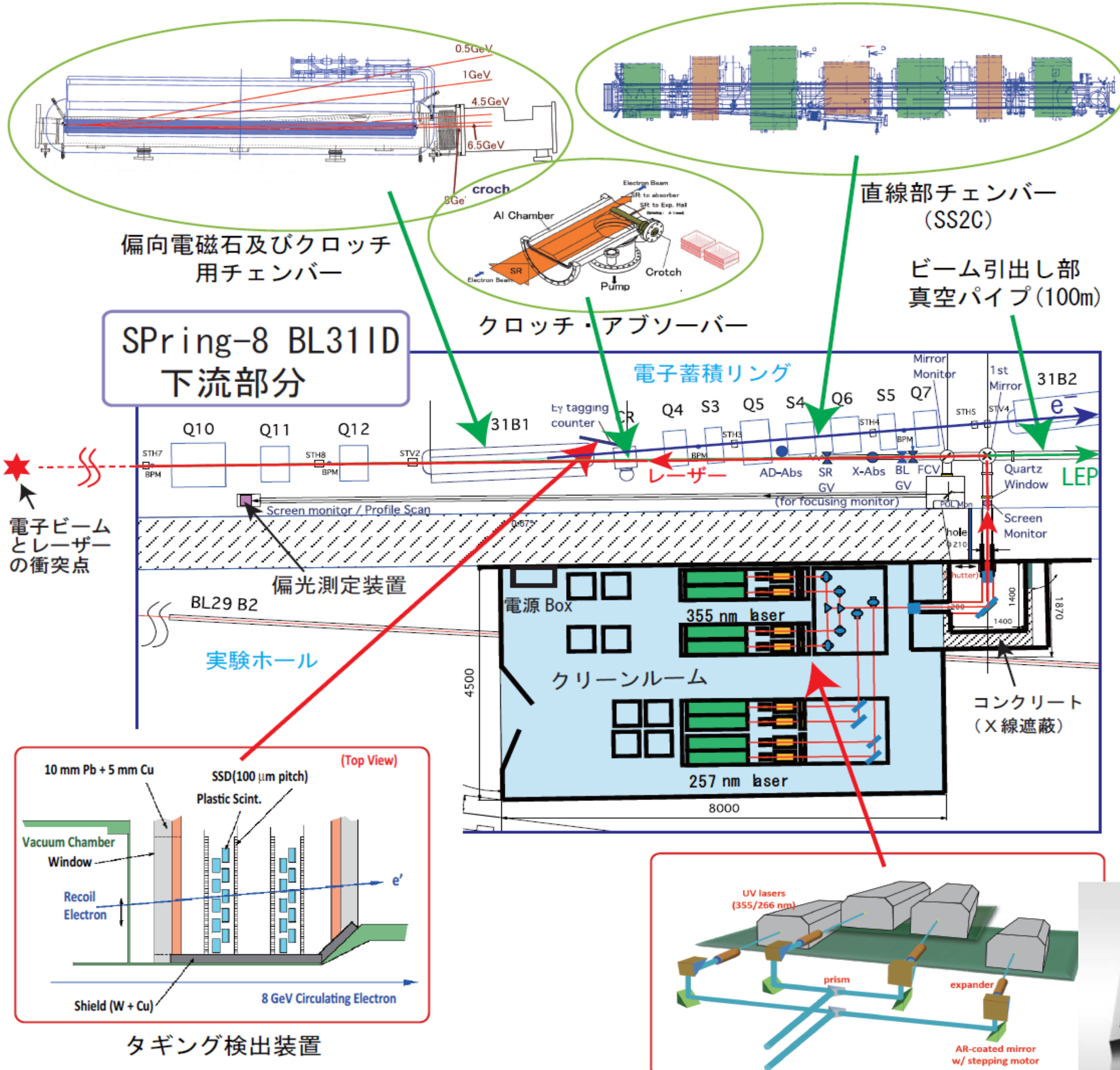




Better divergence → Better tagging resolution

Smaller beam size at the target

LEPS2ビームライン及び測定装置の構成

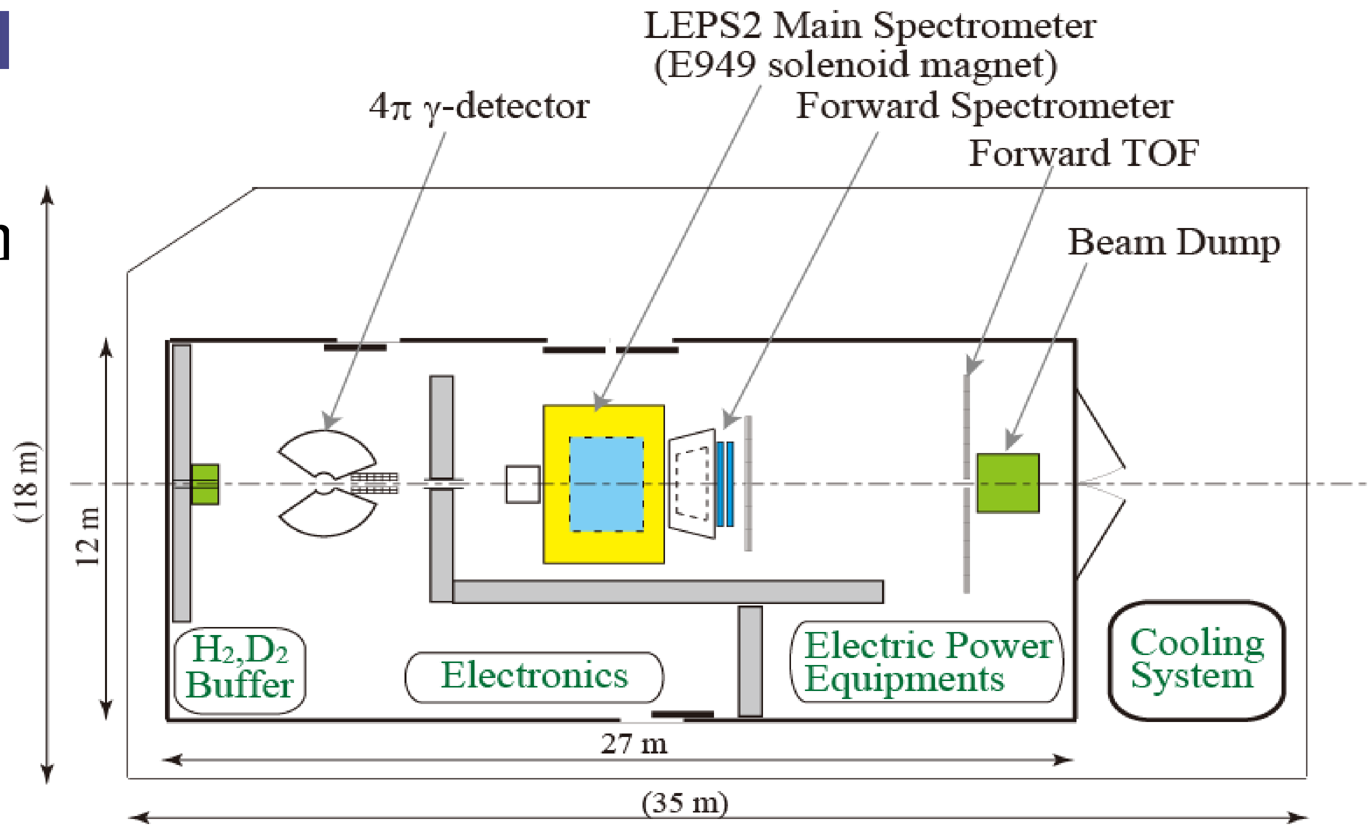


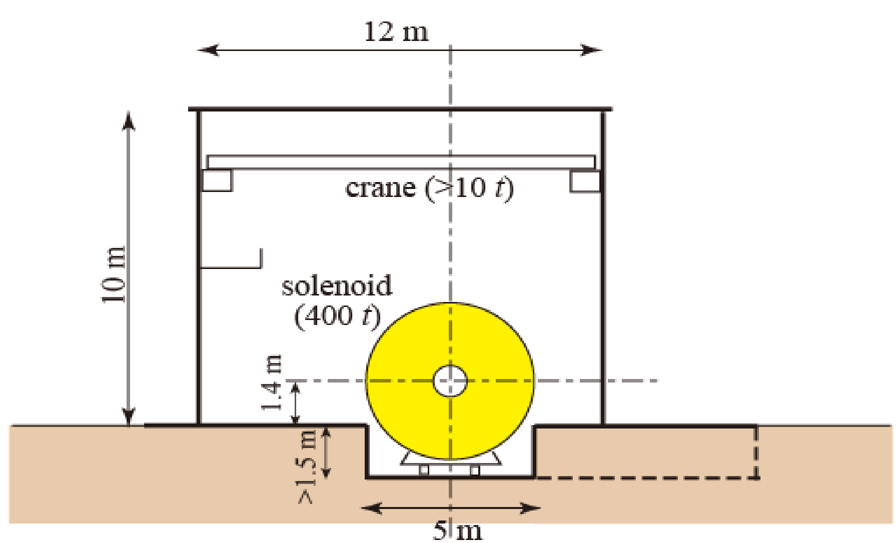
タギング検出装置

レーザー入射システム

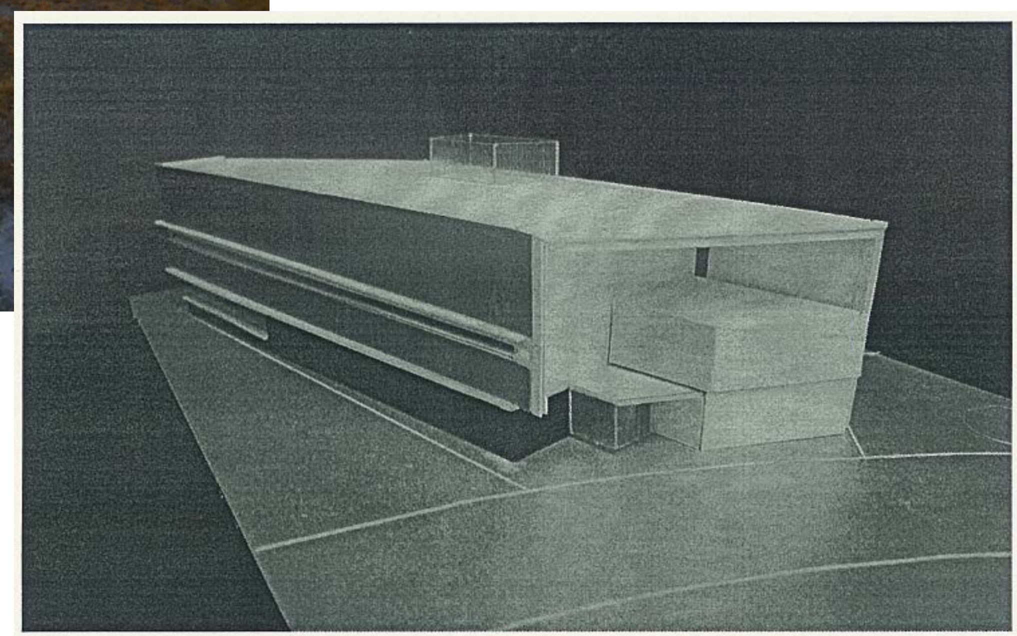
SONY MS
new deep UV laser

LEPS2 Experimen building

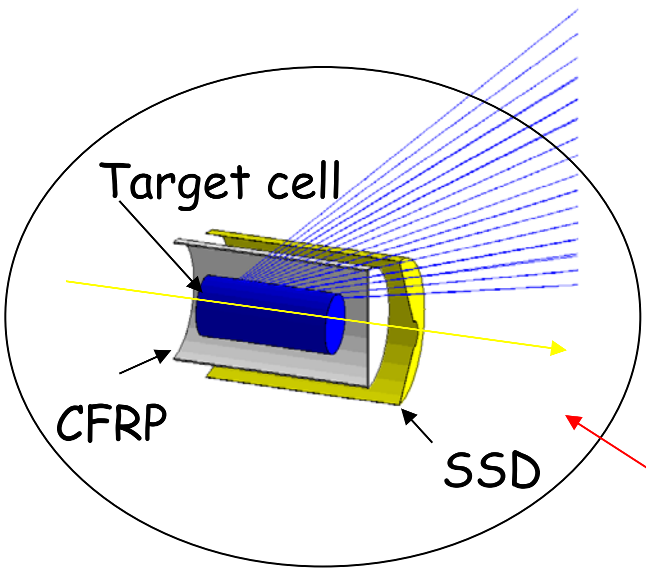


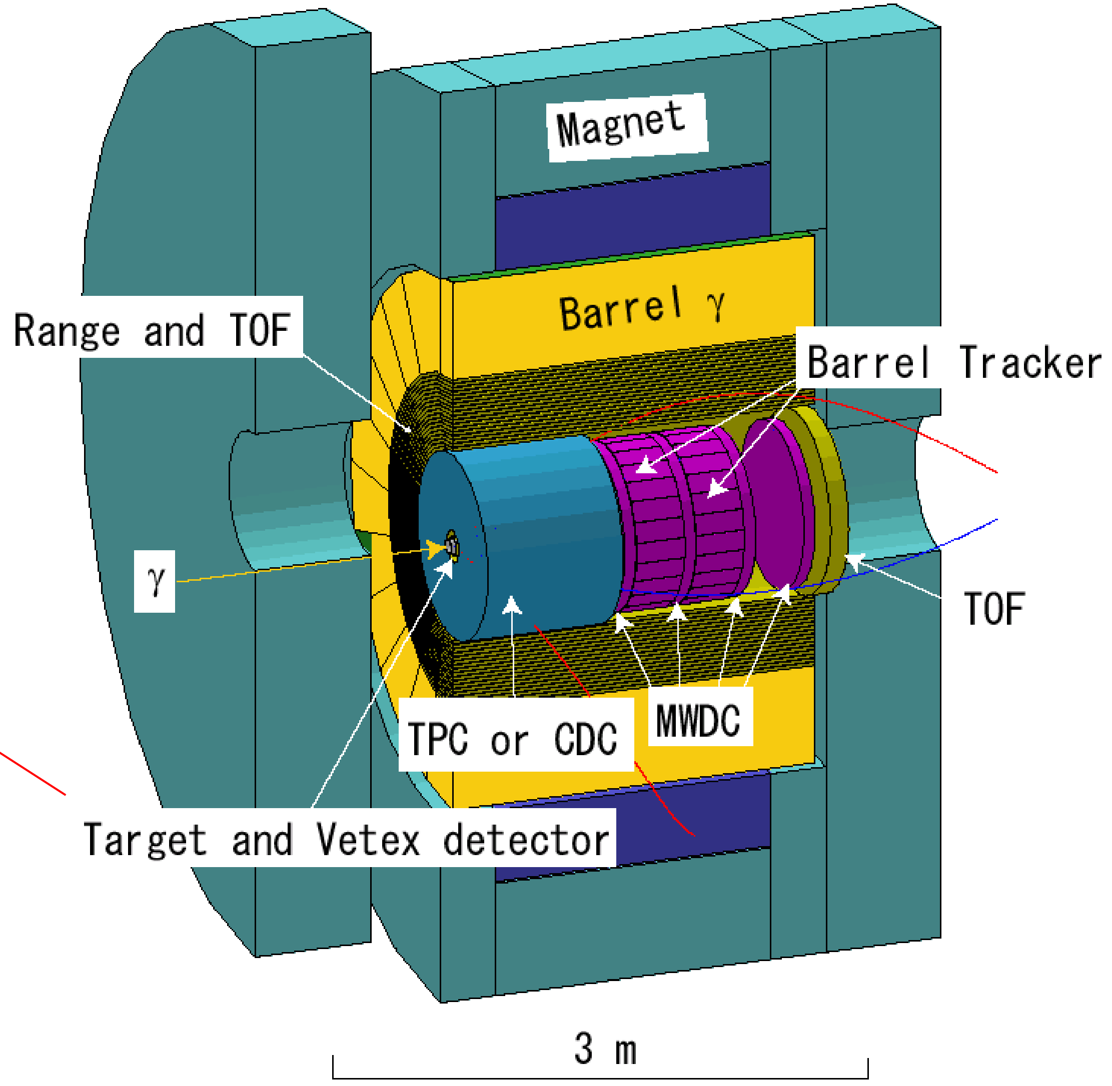


（参考:BL33XU実験棟）

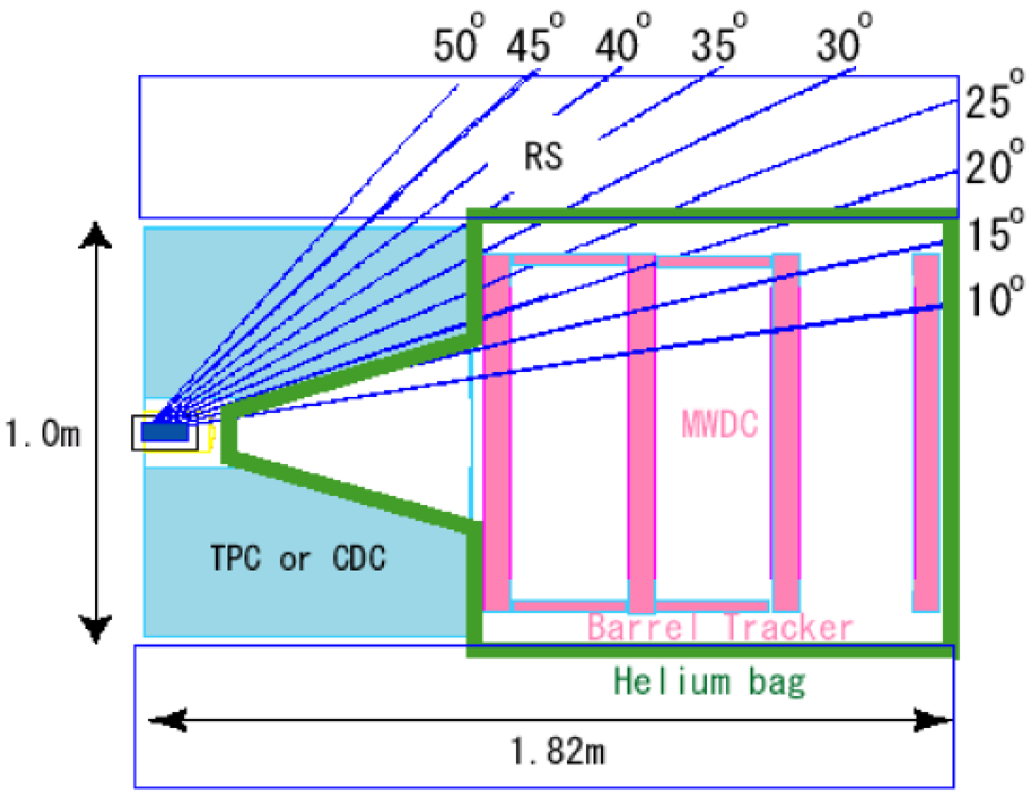


Detector Setup





Tracking system



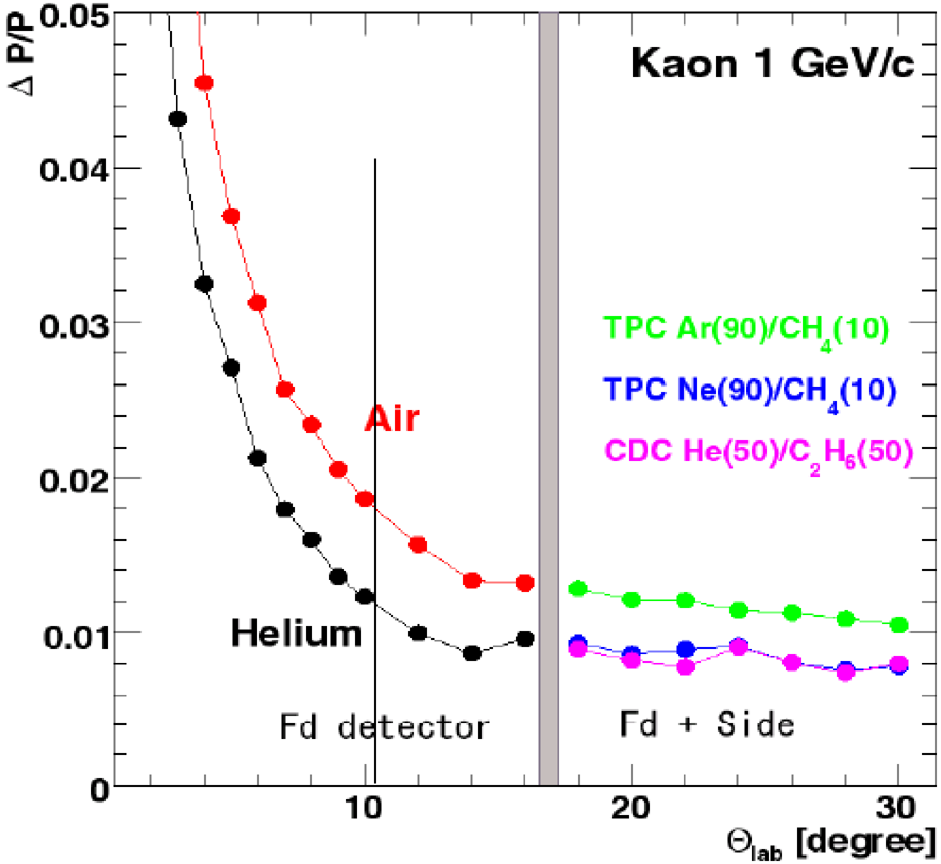
- Side way tracker (TPC)
  R = 500 mm (24-26 layer),
  $\sigma_{r\phi}$ =150um, σ_z =2mm,

- Forward MWDC chamber(450mm)
  ^{4}He+Ethane (X/X_0 = 1.1x10^{-3})
  6 plane (x,x', u(45) u'(-45), y y')
  σ_{xy} =**150um,**

- Barrel tracker
  Cathode strip + Anode wire
  $\sigma_{r\phi}$ = 250um, σ_z = 2-3 mm

- SSD (Cylindrical+ Disk)
  Double side strip sensor
  σ=35um,
  ΔZ< 1 mm at $\theta > 20^0$

ΔP/P at forward region



- $2^o < \theta < 17^o$

  Vertex + Fd MWDC

  No SW tracker

  At 10 degree

  ΔP/P = 1.3% (He4 gas)

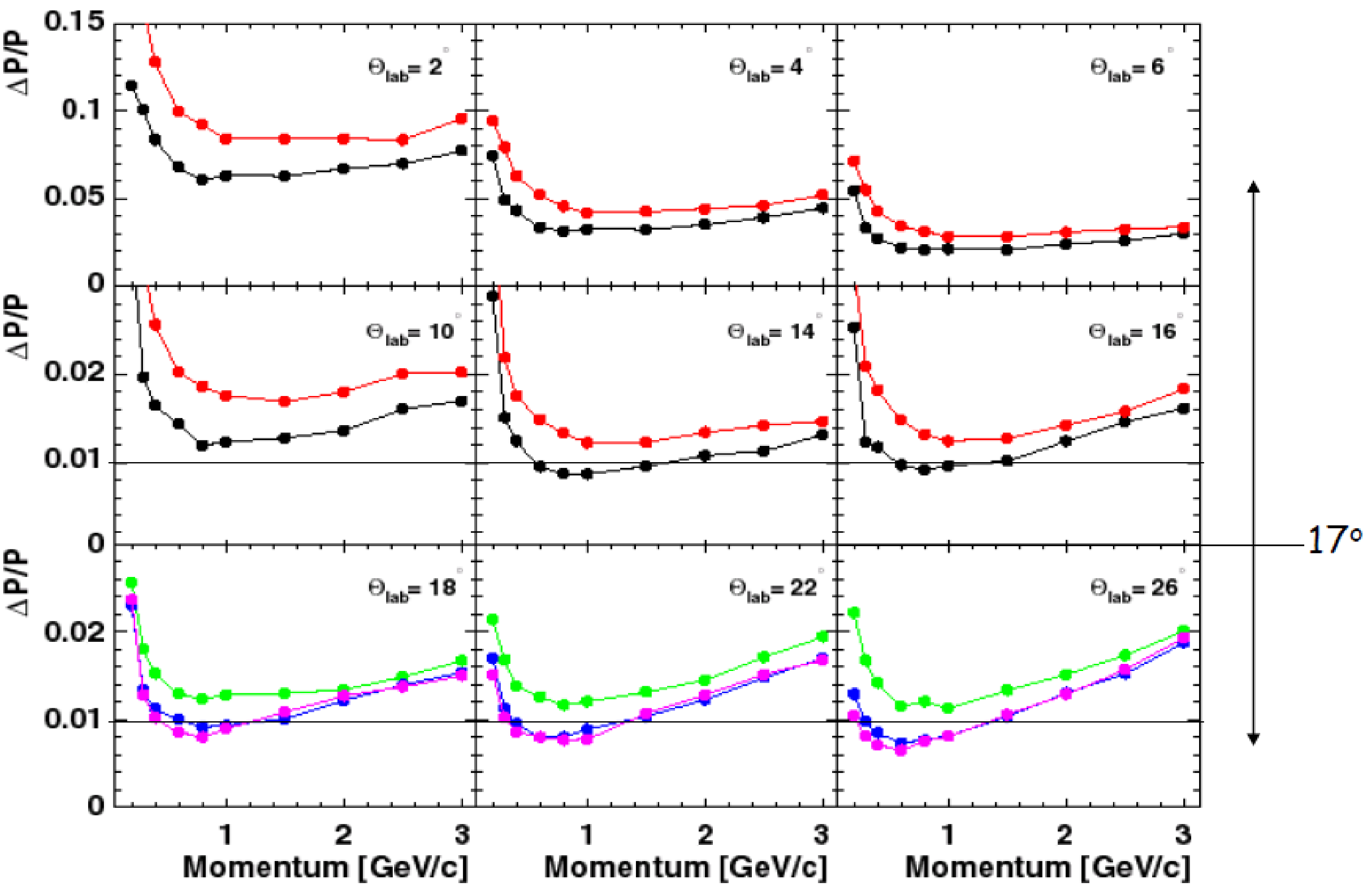
  1.9% (Air)

- $\theta > 17^o$

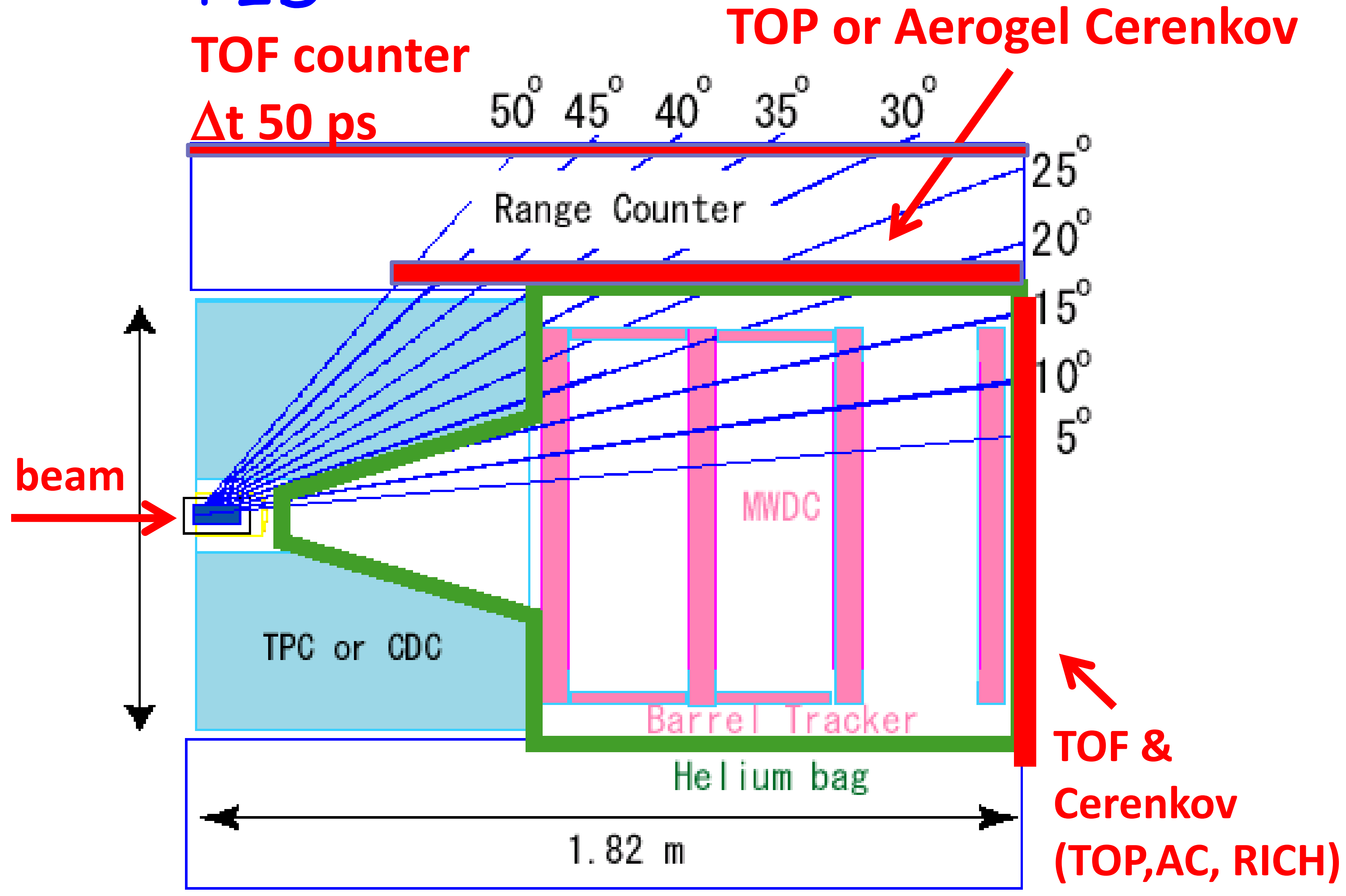
  MS effect in SW tracker

  TPC ⇒ Ar/CH_4 or Ne/CH_4

Momentum dep. of ΔP/P



PID


TOF counter
Δt 50 ps
TOP or Aerogel Cerenkov
50° 45° 40° 35° 30°
25°
20°
15°
10°
5°
Range Counter
beam
MWDC
TPC or CDC
Barrel Tracker
Helium bag
1.82 m
TOF &
Cerenkov
(TOP,AC, RICH)

Penta-quark Θ^+

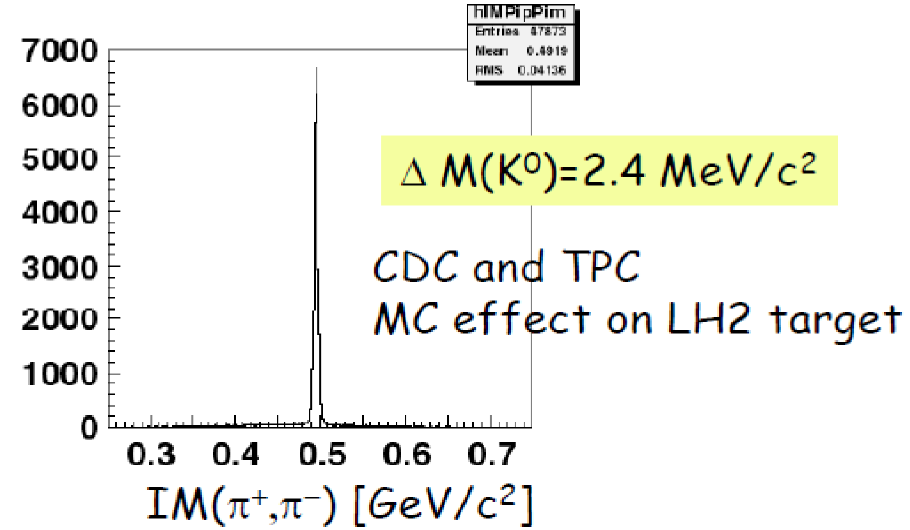
Strangeness tagging

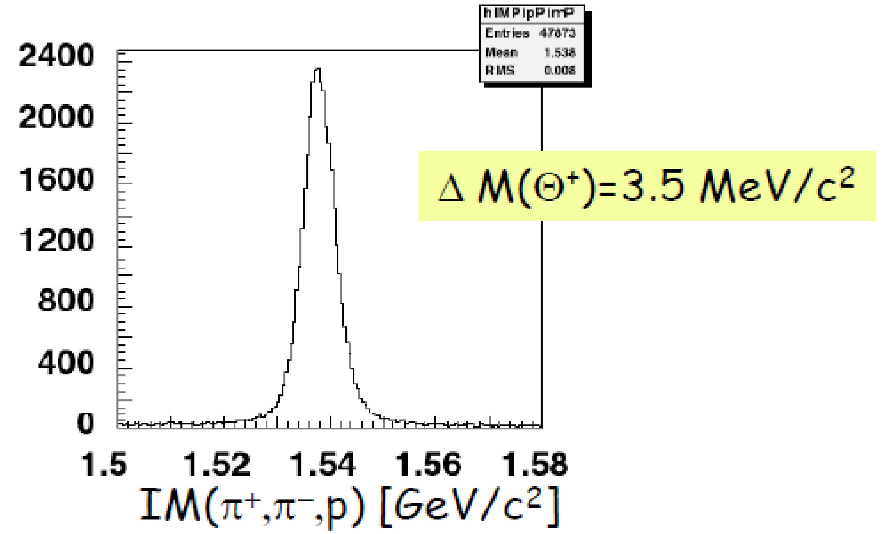
$$\gamma + n \rightarrow K^- + \Theta^+$$

$$\rightarrow p \ K^0$$

$$\rightarrow \pi^+ \pi^-$$

Invariant Mass measureme



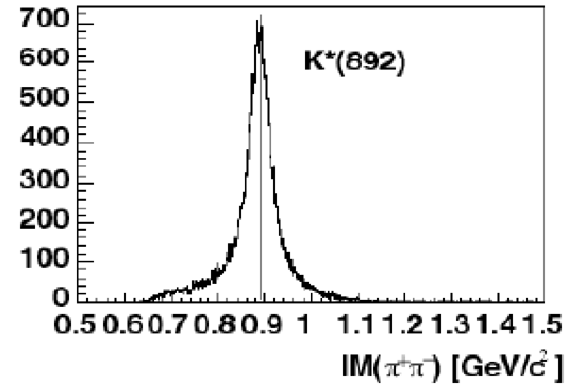


$\gamma p \rightarrow K^* \Lambda(1405)$

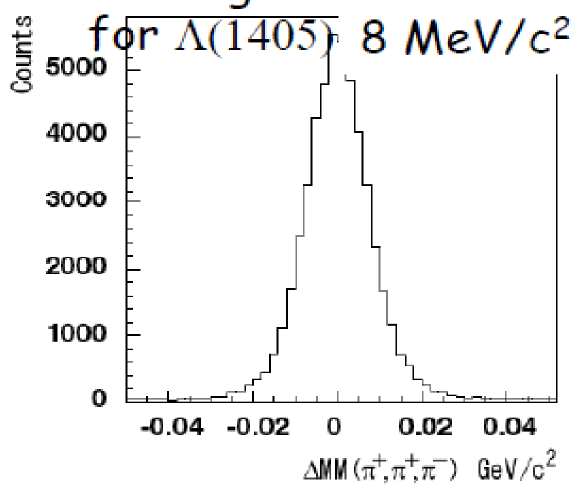
$$\gamma + p \rightarrow K^{*+} + \Lambda(1405)$$

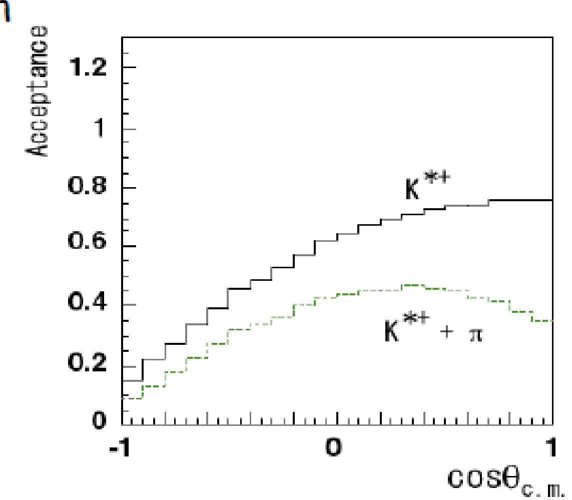
$K^{*+} \rightarrow K^0 \pi^+$, $K^0 \rightarrow \pi^+ \pi^-$

$\Lambda(1405) \rightarrow \Sigma^+ \pi^-$, $\Sigma^+ \rightarrow n \pi^+$



Missing mass resolution for $\Lambda(1405)$ 8 MeV/c^2

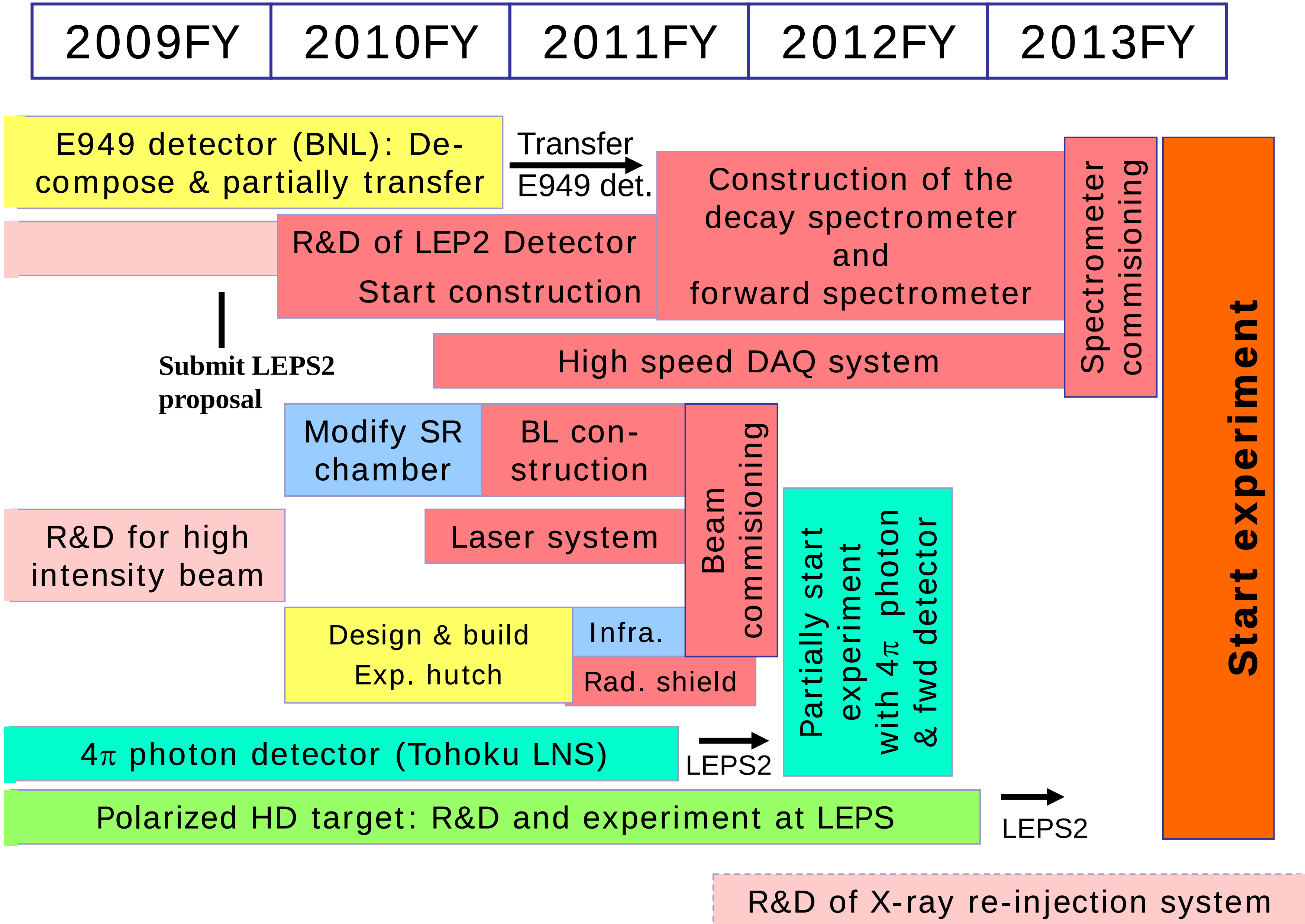




予算 (全体　~1000 Myen)

- H22年度施設整備費補助金　（RCNP）　　□ Myen
  「LEPS2ビームライン及び測定装置」
- 科研費新学術領域「新ハドロン」
  計画研究B01（代表者　野海）　　　　~240 Myen/5年
  　(レーザー、検出器）
- 実験棟建設費（理研？）　　　　　　□ Myen
  （18m × 35m (630mm^2) → 12m ×27m(324mm^2)　1/2縮小案）
- E949検出器&磁石　移設費　　　　　□ Myen
  （RCNPサブアトミック科学推進事業　or　阪大学内措置）
- H23年度以降概算要求（サブアトミック科学推進事業）
  (□ Myen×？年)

LEPS2 Schedule

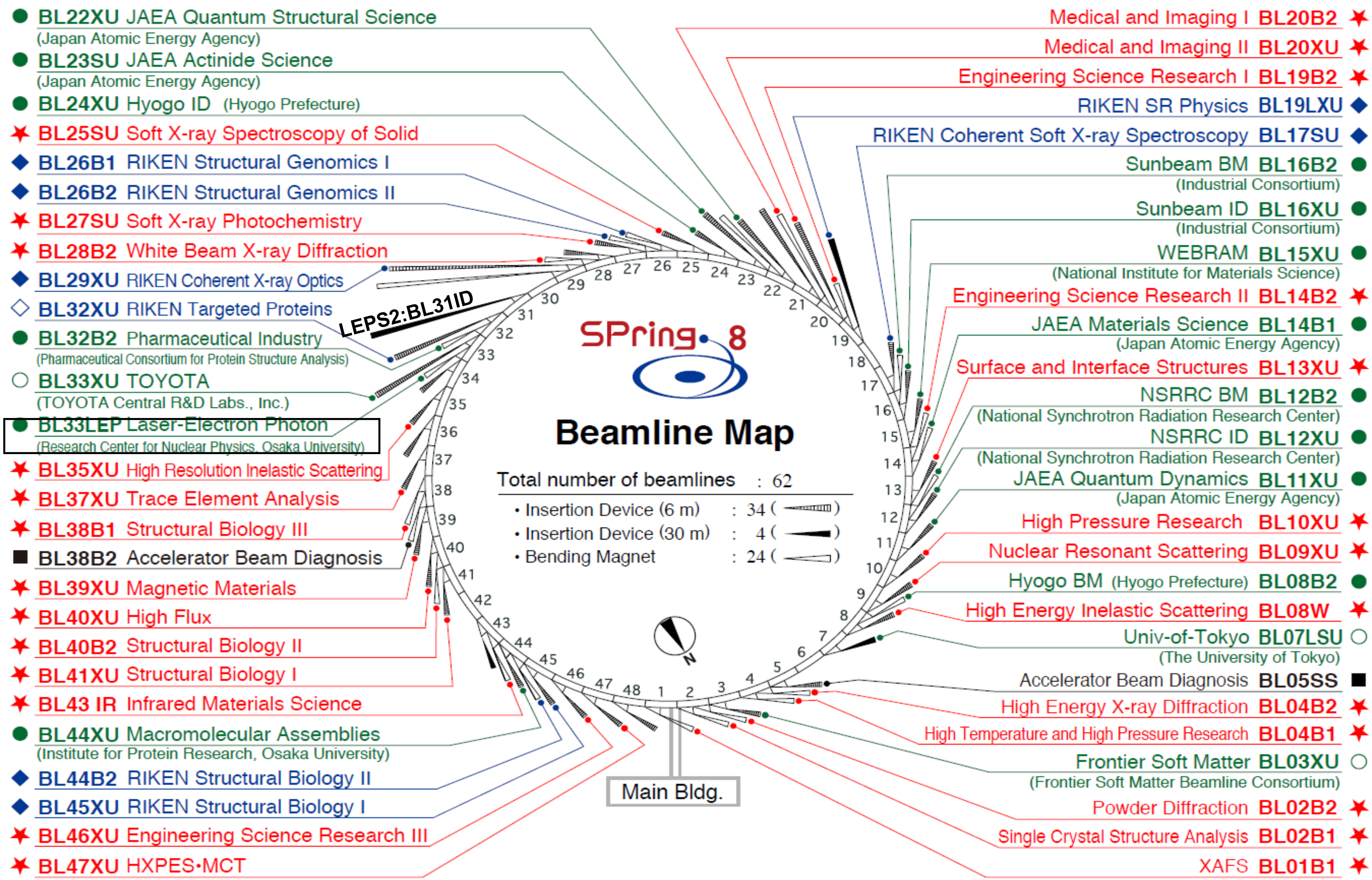


Backup

Status of the LEPS2 project

- 2005.6: Discussion for the LEPS2 beamline was started.
- 2005.7: First workshop was held at RCNP
  → Both physics and technical issues.
- 2005.12: Basic agreement for the movement of the E949 detector was made with BNL and associated laboratories.
- Numerical consideration for getting the high energy γ beam by re-injection of X-ray has been performed. → Need R&D for the mirror.
- Test of the LRNB method for the high intensity LEP
  → The same intensity as the normal Gauss beam
- 2006.4:Test of the two laser injection → succeed !
- Disassembling work for E949 detector
- Discuss detector design, modification of beamline etc.
- 2007.1: Second workshop @RCNP
- 2008.1: Change the plan of the laser injection place.
- 2008.11: Loan agreement for the E949 detector
- LOI to Spring-8: 2006.12 Hearing → Approved. BL31 was assigned.
- Budget request: 2008,2009 from RCNP → X
- Kakenhi "Exotic Hadron" approved (2009-), Budget request 2010 ○?

Beam line map of Spring-8



LEPS2 LOI was approved: BL31 was assigned for LEPS2.

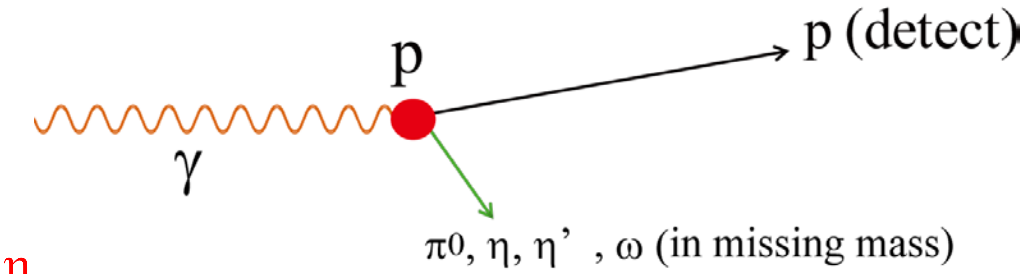
Other

$\gamma p \rightarrow p\,\pi\,\pi$

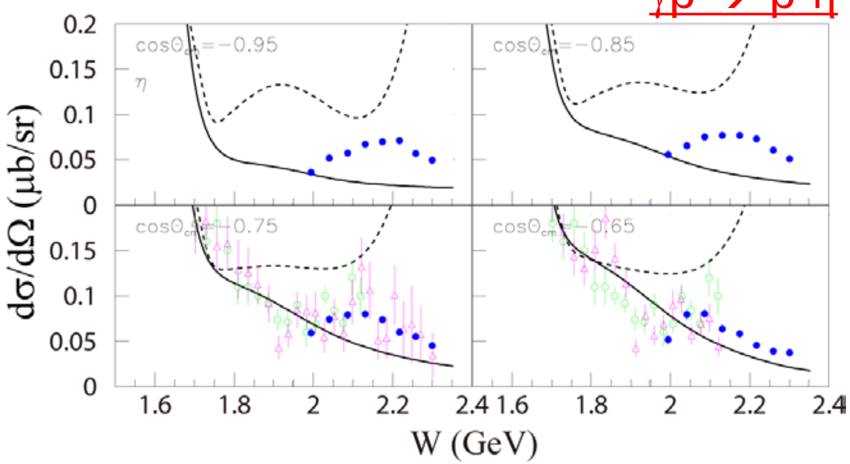
$\gamma p \rightarrow p\,\pi\,\pi\,\pi$

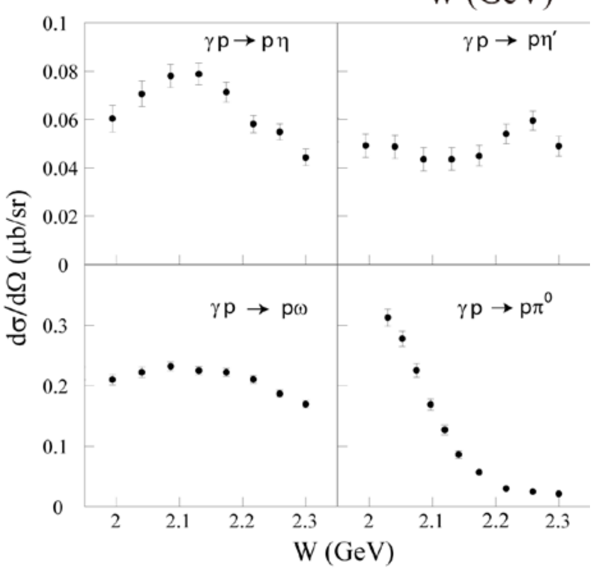
$\gamma p \rightarrow p\,\pi\,\pi\,\pi\,\pi$

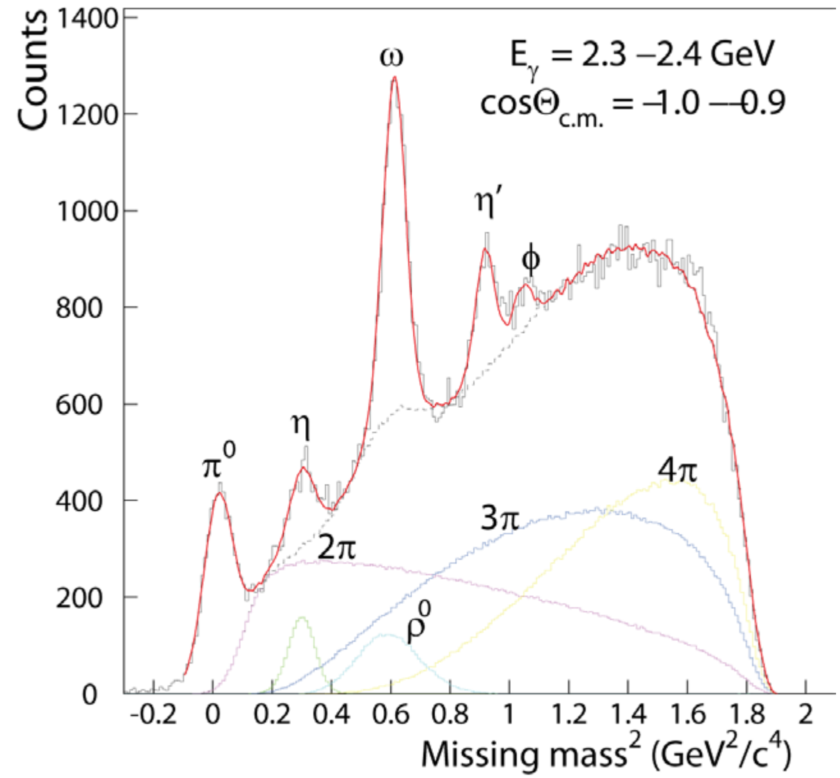
$\gamma p \rightarrow p\,\pi^0/\eta/\eta'/\omega$



$\gamma p \rightarrow p\,\eta$



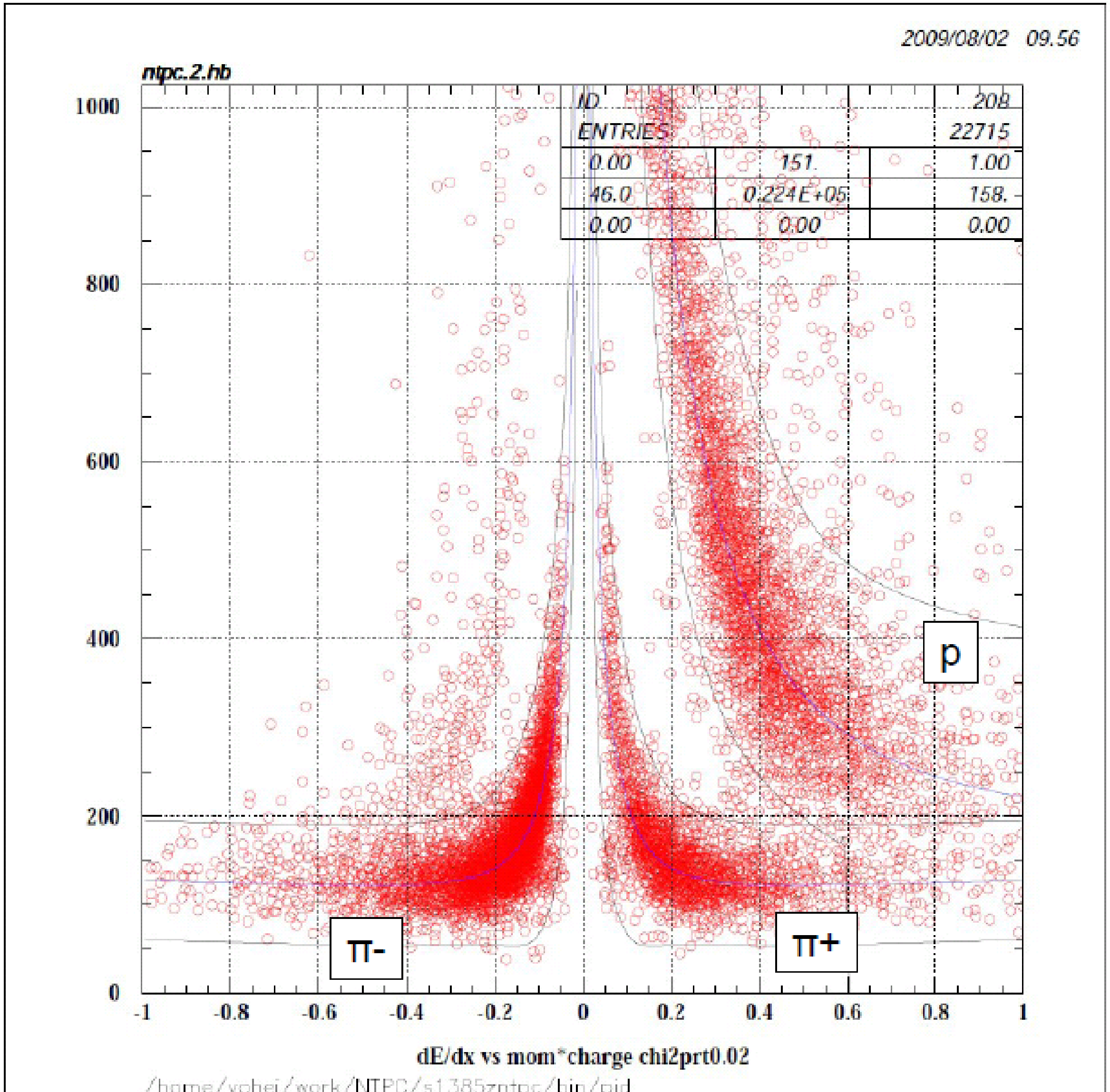




M. Sumihama et al. to be published in PRC.

PID in TPC

Analysis for 2008A(3 GeV) run



forward K+ event

dE/dx
= Average of peak PAD

by Nakatsugawa

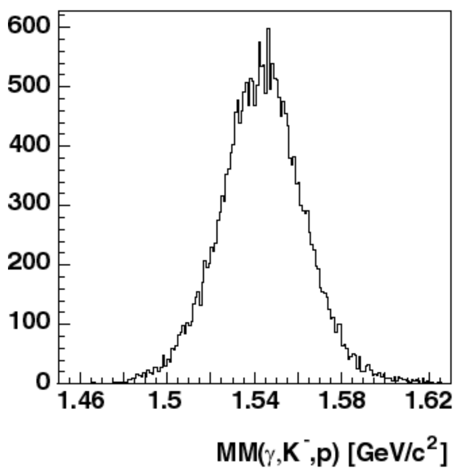
$\gamma\, d \to \Lambda(1520)\Theta^+$

$\gamma d \to \Lambda(1520)\ \Theta^+$

$\hookrightarrow K^- p$

Missing Mass

$\Delta M(\Theta^+) = 17\ MeV/c^2$

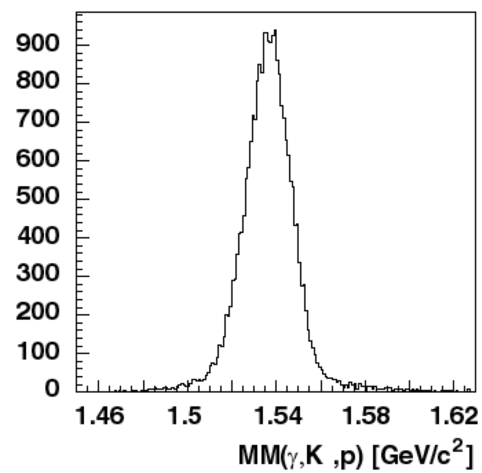


$\gamma d \to \Lambda(1520)\ \Theta^+$

$\hookrightarrow K^- p \quad \hookrightarrow K^+ n$

+ Kinematical fit

$\Delta M(\Theta^+) = 10\ MeV/c^2$

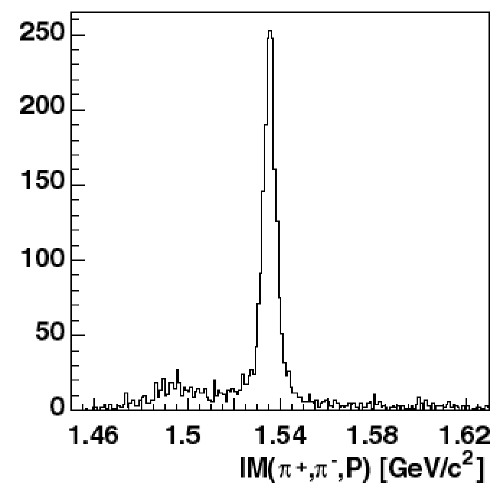


$\gamma d \to \Lambda(1520)\ \Theta^+$

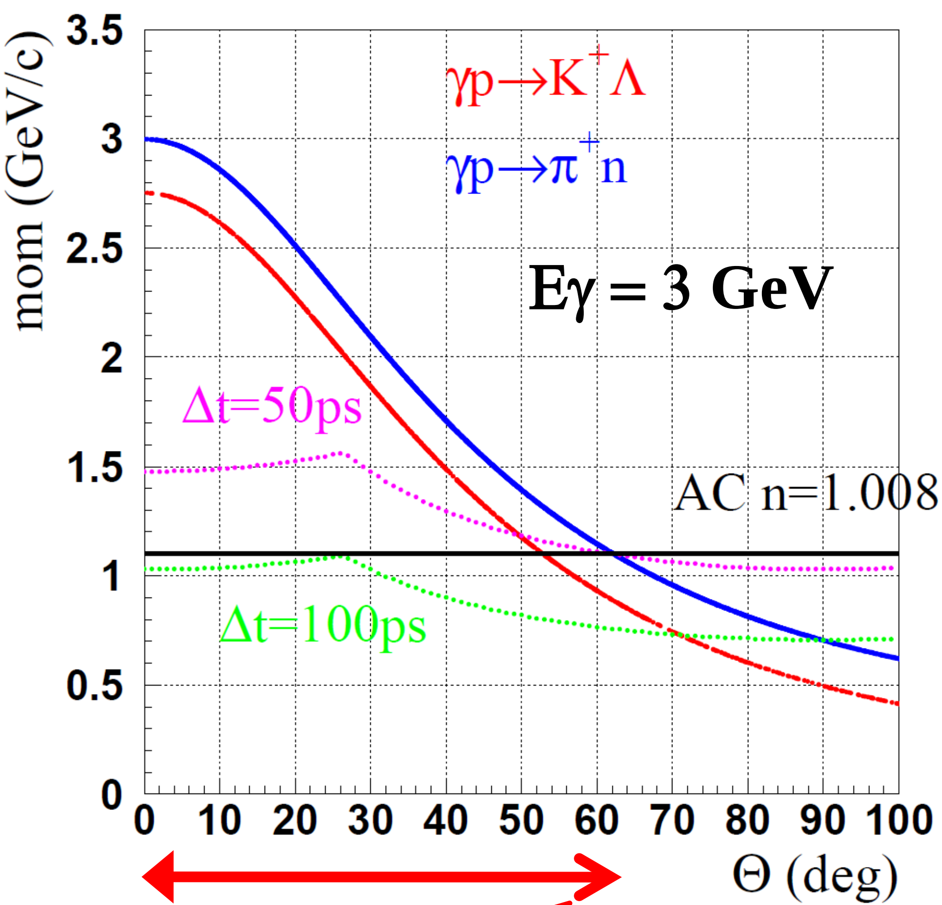
$\hookrightarrow K^- p \quad \hookrightarrow K_s\, p$

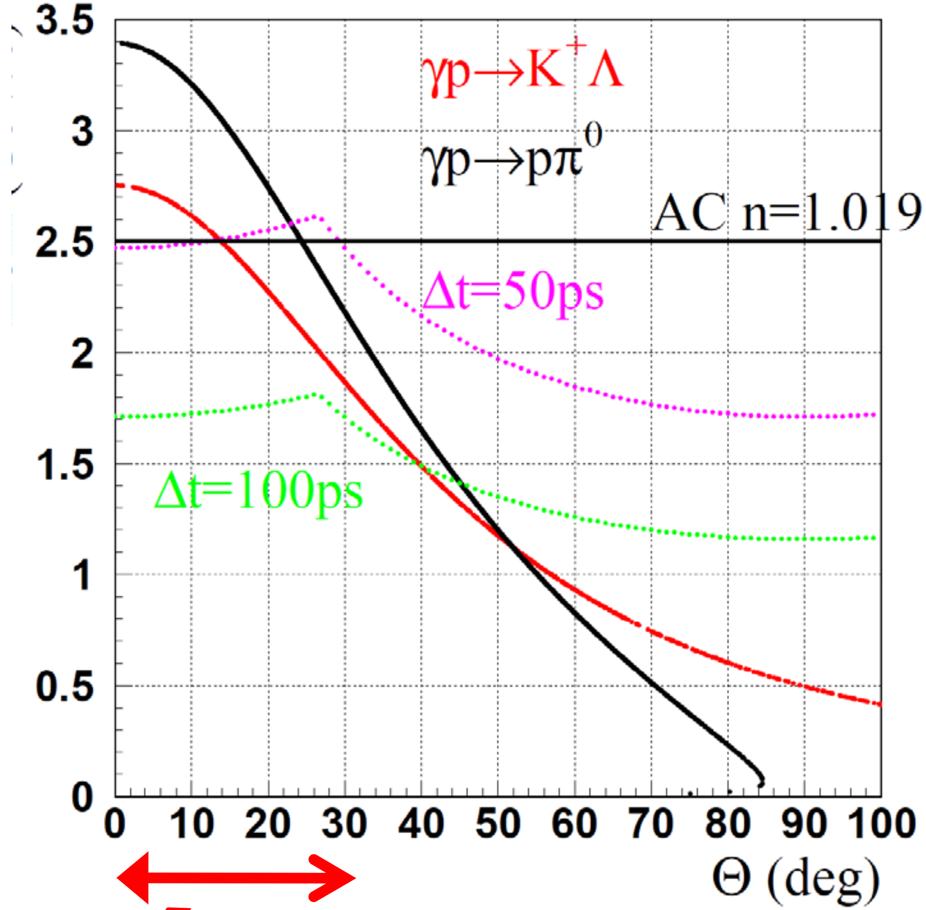
Invariant Mass

$\Delta M(\Theta^+) = 3\ MeV/c^2$



K/π/p separation by TOF counter





Cerenkov counter is necessary