Recent Results and Future Program of the NKS2 Experiment

Masashi Kaneta
Dept. of Phys., Grad. Sch. of Sci., Tohoku Univ.

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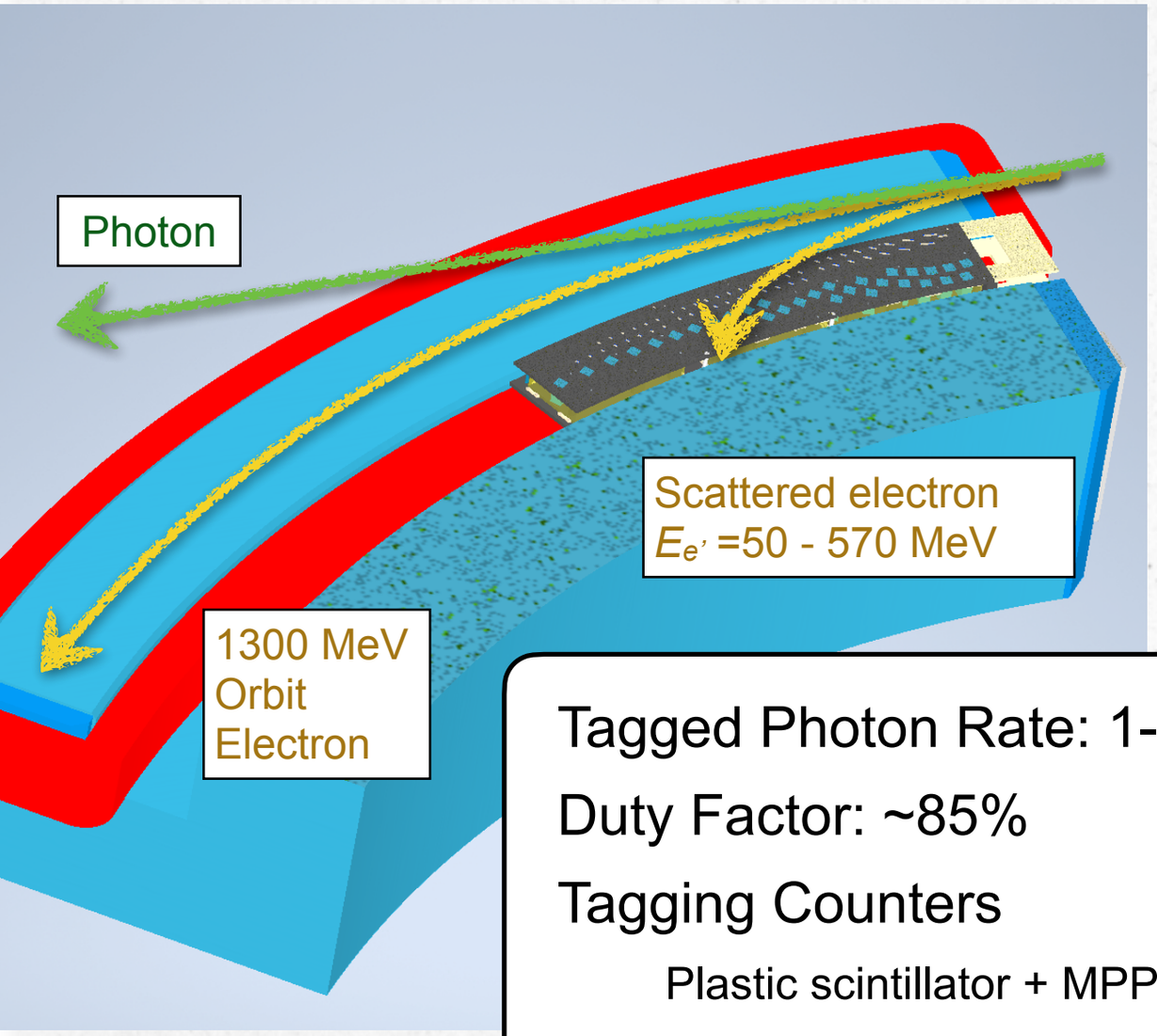
ELPH workshop C003

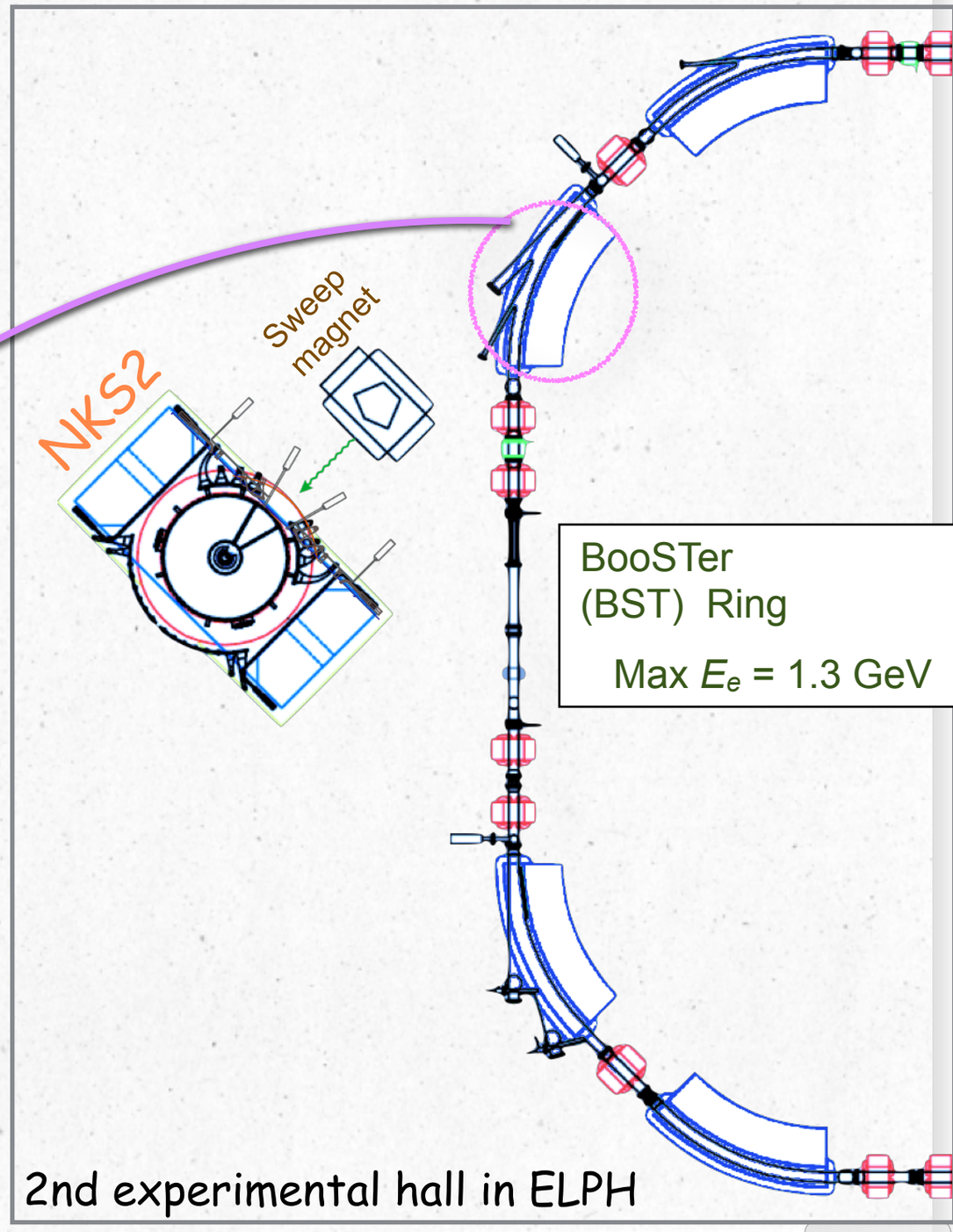
The NKS2 Experiment

- NKS2: Neutral Kaon Spectrometer 2
  - $\gamma + p/d/\mathrm{A}$ reaction
  - Photon tagging system and magnetic spectrometer
  - Liquid hydrogen/deuterium target for p/d
- Physics program
  - Strangeness production in the threshold region of γ+d
  - Di-baryon search in $\gamma + d \rightarrow d + \pi^+ + \pi^-$
  - Search of η'd bound state
  - Λn interaction via FSI in γ+$d \rightarrow K^+$+Λ+n
  - Life time measurement of $^3_\Lambda$H
- Collaboration
  - Tohoku Univ., Tokyo Tech., Tokyo Univ., (Lanzhou Univ.)

Photon Beam Line and NKS2

in Research Center of Electron Photon Science (ELPH), Tohoku Univ.





Tagged Photon Rate: 1-3 MHz

Duty Factor: ~85%

Tagging Counters

Plastic scintillator + MPPC

TagF: Position measurement

TagB: Timing measurement

σ = ~60 ps

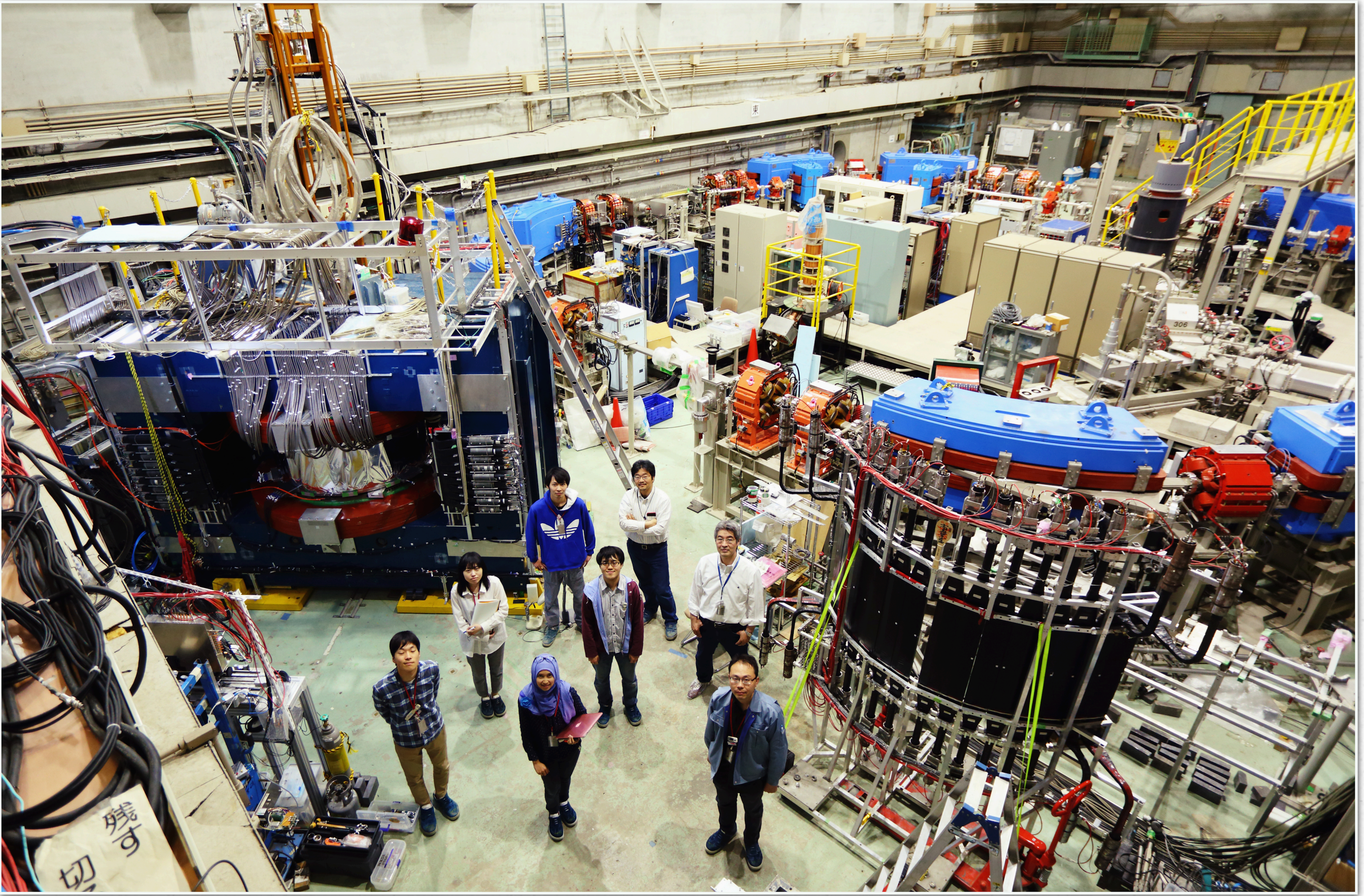
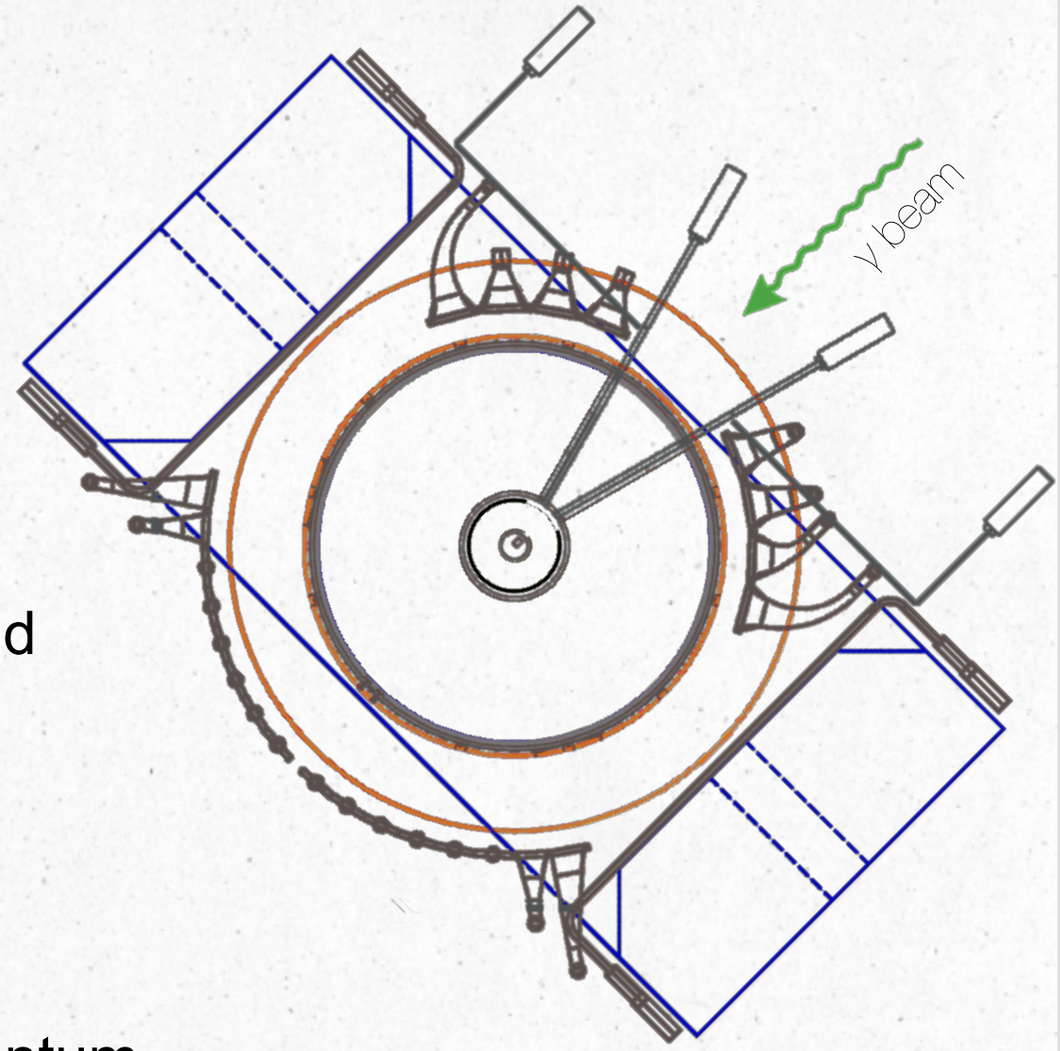


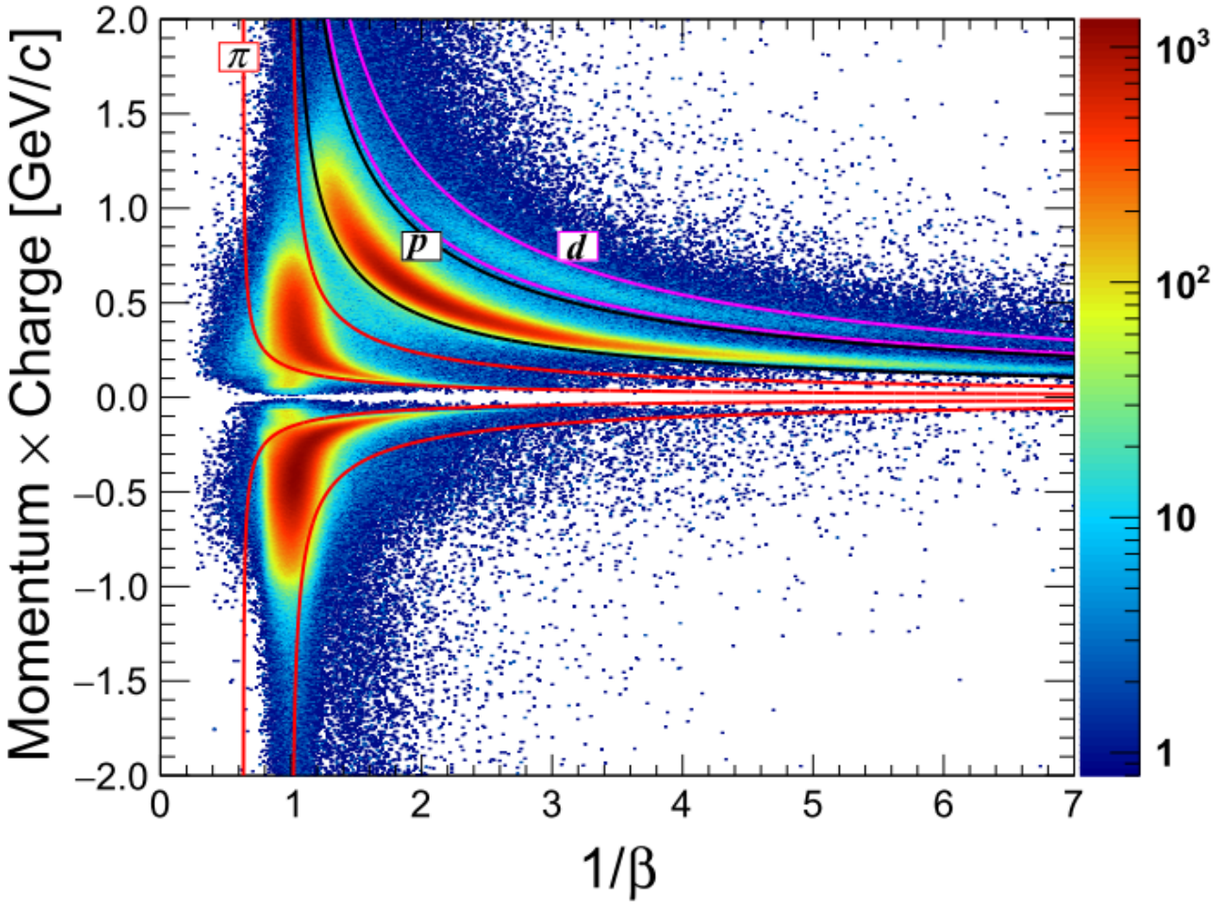
Photo taken in 2016/5

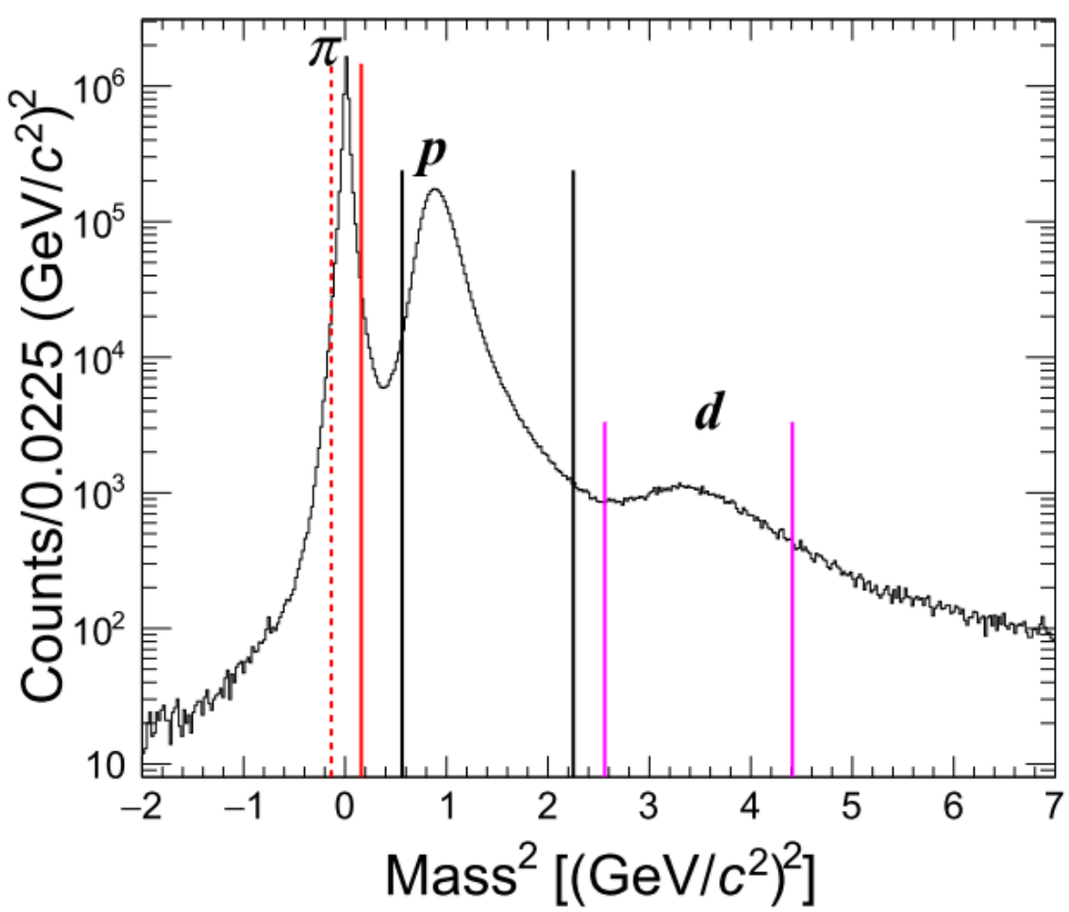
The NKS2 Experiment

- Tagged photon beam
  - E_γ = 0.80-1.25 GeV
- Liquid D_2 or H_2 target
- Magnetic spectrometer
  - Tracker
    - Two drift chambers
    - Charged particle momentum, trajectory, and decay vertex
  - Hodoscopes
    - Plastic scintillator + PMT
    - Time-Of-Flight (TOF)
    - Particle identification combined with momentum
  - Electron Veto
- Acceptance
  - Covering large kinematic region including forward angle



Particle Identification





- TOF and momentum
- Good separation of $\pi/p/d$

Dibaryon Search

Dibaryon

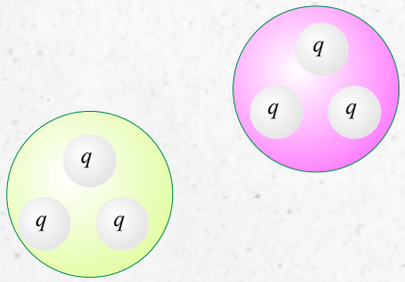
D_{IS} (I: isospin, S: spin)	D_{01}	D_{10}	D_{12}	D_{21}	D_{03}	D_{30}
BB	NN	NN	NΔ	NΔ	ΔΔ	ΔΔ
Mass formula	A	A	A+6B	A+6B	A+10B	A+10B
Approx. mass [MeV]	1878	1878	2160	2160	2348	2348

Deuteron

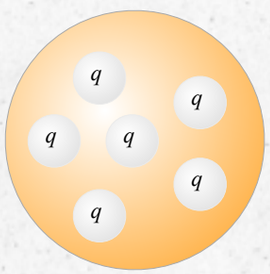
unbound
pp, nn, np

Work of Y. Toyama

WASA/CELSIUS
WASA at COSY
$d^*(2380)$



Molecule state?
Compact 6 quark state?



Mass formula

$$M = A + B\,(\; I(I+1) \; + S(S+1) - 2\;)$$

A: 1878 MeV

B: 47 MeV

F.J. Dyson and N.H. Xuong, PRL 13 (1964) 815

Dibaryon

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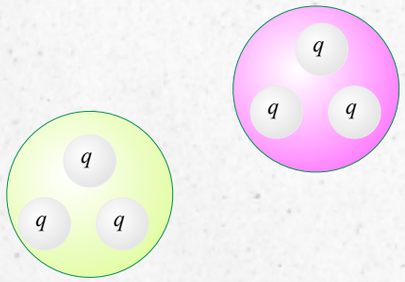

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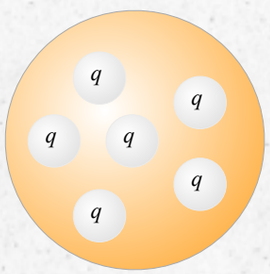

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Past Studies of D_{12}

- Experiment
  - $\pi d \to pp$ scattering PWA
    - R. Arndt et al., PRC48, 1926 (1993). B.S. Neganov et al., JTEP7, 0528 (1958).
  - $\pi d \to \pi d$ scattering PWA
    - R. Arndt et al., PRC50, 1796 (1994).
  - Coupled channel analysis of the reactions above & *pp* scattering
    - C.H. Oh et al., PRC56, 635 (1997).
- Theory
  - Bag model
    - P.J. Mulders, A.T. Aerts, J.J. de Swart, PRD 21, 2653 (1980).
  - Bag model + π cloud correction
    - P.J. Mulders, A.W. Thomas, JPG 9, 1159 (1983).
  - πNN three-body Faddeev
    - A. Gal, H. Garcilazo, NPA 928, 73 (2014).
  - NN scattering including intermediate dibaryon:
    - M.N. Platonova, V.I. Kukulin, NPA 946, 117 (2016).

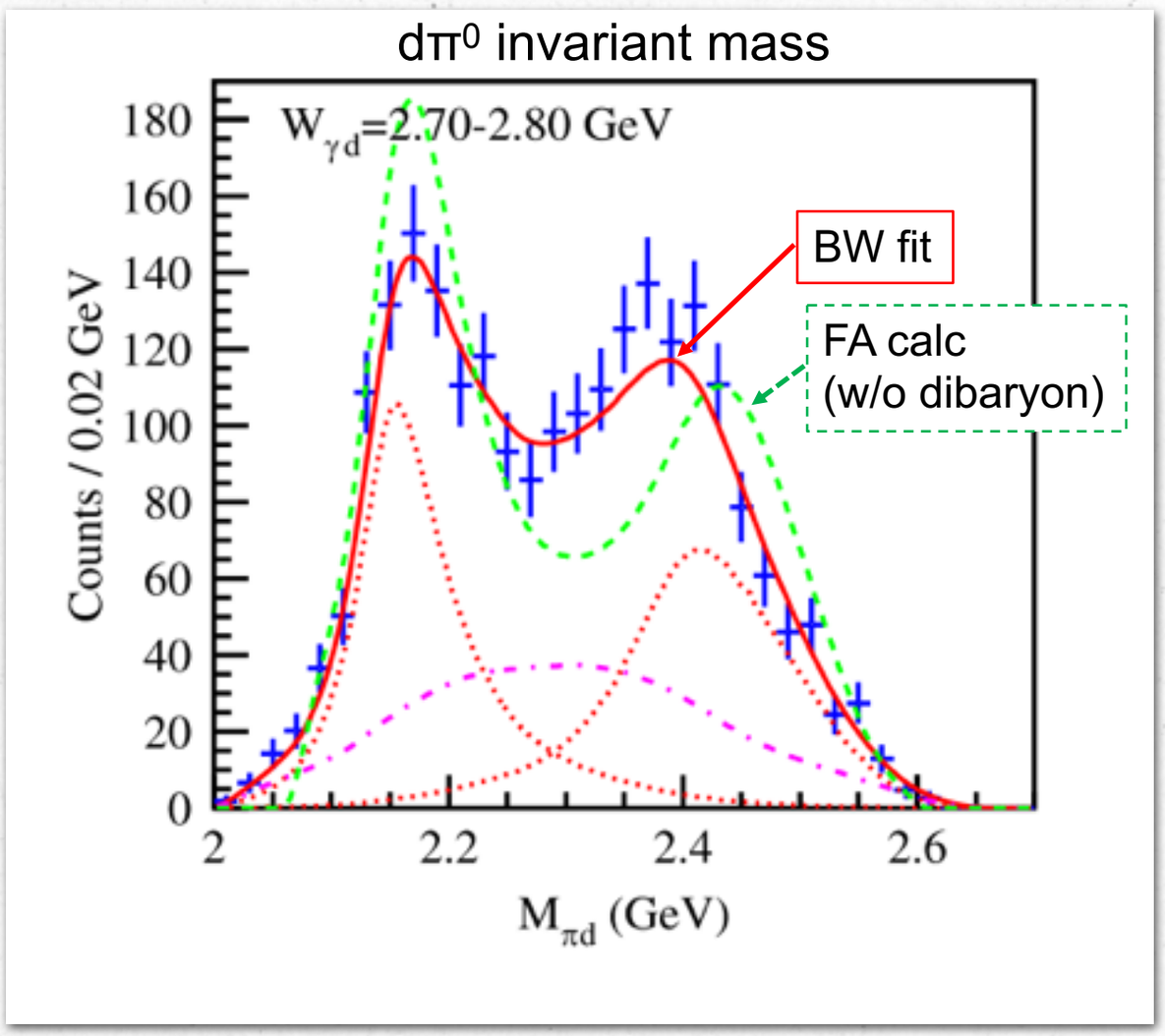
Recent Experimental Data

T. Ishikawa et al., PLB789, 413 (2019)

FOREST, $\gamma d \to d\,\pi^0\,\pi^0$

A B S T R A C T

Coherent double neutral-pion photoproduction on the deuteron, $\gamma d \to \pi^0\pi^0 d$, has been experimentally studied at incident photon energies ranging from 0.75 to 1.15 GeV. The total cross section as a function of the γd center-of-mass energy shows resonance-like behavior, which peaks at approximately 2.47 and 2.63 GeV. The measured angular distribution of deuteron emission is rather flat, which cannot be reproduced by the kinematics of quasi-free $\pi^0\pi^0$ production with deuteron coalescence. In $\pi^0 d$ invariant-mass distributions, a clear peak is observed at 2.14 ± 0.01 GeV/c^2 with a width of 0.09 ± 0.01 GeV/c^2. The spin-parity of this state is restricted to 1^+, 2^+ or 3^- from the angular distributions of the two π^0s. The present work shows strong evidence for the existence of an isovector dibaryon resonance with a mass of 2.14 GeV/c^2. The 2^+ assignment is consistent with the theoretically predicted $\mathcal{D}_{12}$ state, and also with the energy dependence of the πd partial-wave amplitude $^3P_2$ for the $\pi^{\pm} d \to \pi^{\pm} d$ and $\pi^+ d \to pp$ reactions.



They suggest

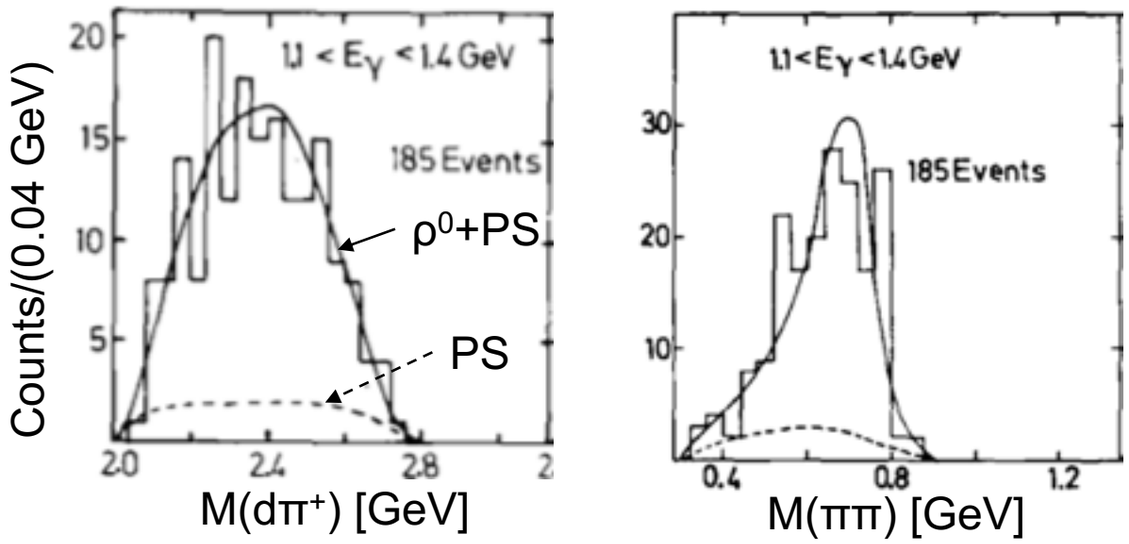
$$\gamma d \to R_{IS} \to D_{12}\pi^0 \to d\pi^0\pi^0$$

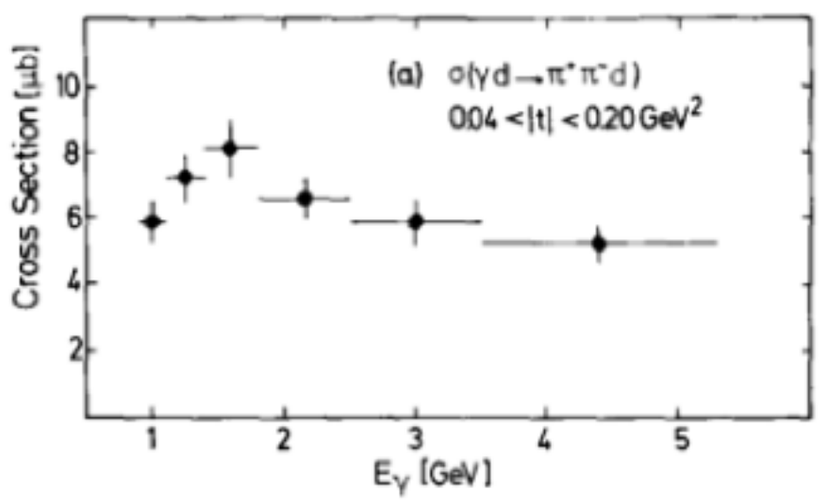
Isoscalar dibaryon

Isovector dibaryon

We are searching for the other charge state ($d\pi^{\pm}$) by the $\gamma d \to d\pi^+\pi^-$

Old Measurement of the $\gamma d \to d\pi^+\pi^-$



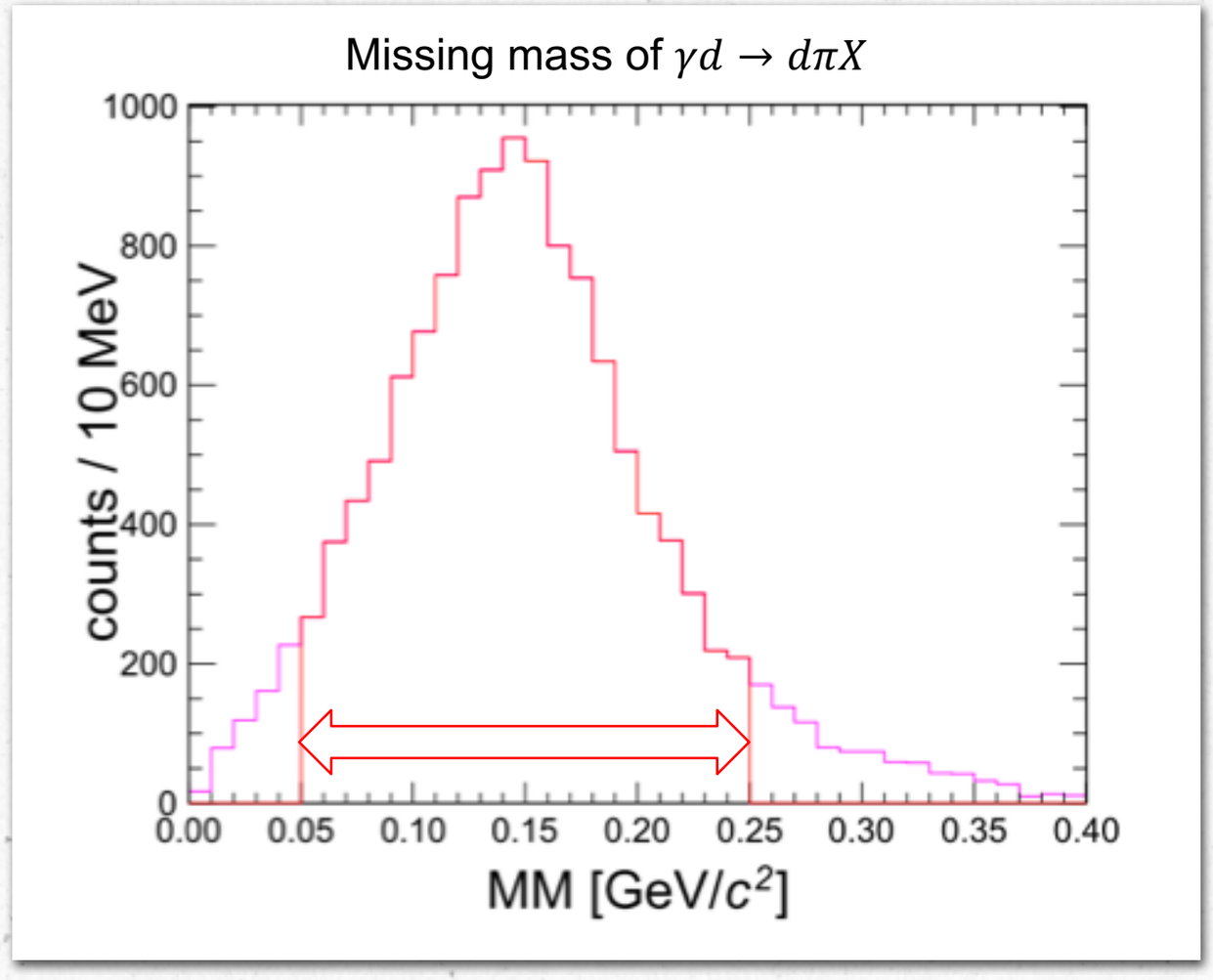


Benz et al., NPB79, 10 (1974)
Buble chamber experiment

- E_γ = 1.1 - 5.3 [GeV]
- ρ and ω production on deuterons
- Limited *t* region
  - $0.04 < |t| < 0.20$ GeV^2
- Low *d* momentum
  - p_d<0.4 GeV/*c*
- No peak structure
  - ρ^0 and phase space can explain the date

Search D_{12} in NKS2

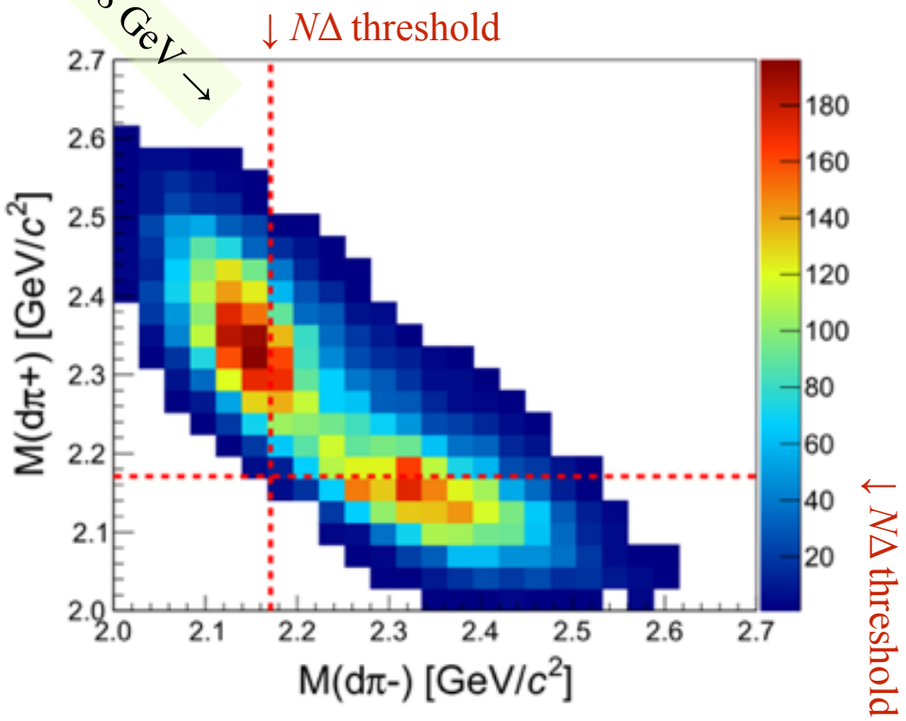
- Data taken in 2010
  - E_γ = 0.78 - 1.08 GeV
- Reaction
  - $\gamma\, d \rightarrow d\, \pi^+\, \pi^-$
    - 2-track analysis
      - Identification of d and π
      - The other π is identified by missing mass
    - 3-track analysis
      - Tried to check consistency
      - Not shown in this talk
- Y. Toyama's work

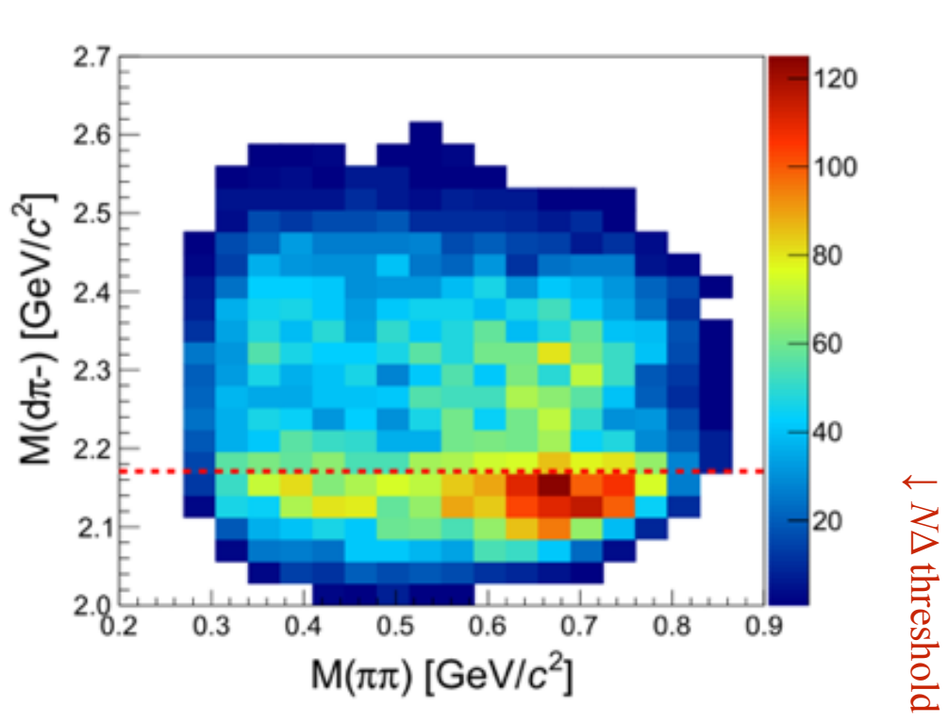


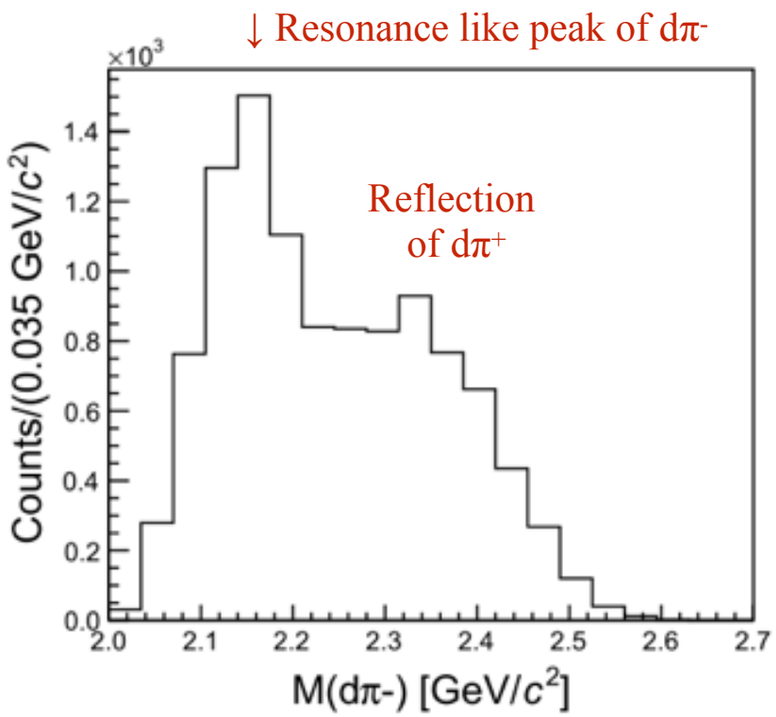
Invariant Mass

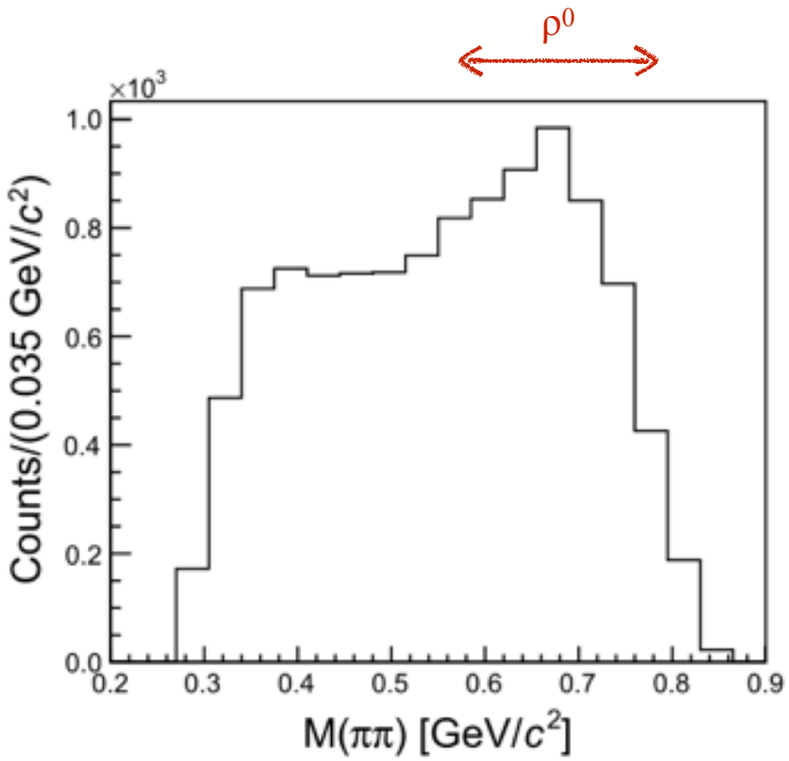
$E_\gamma = 0.78$ GeV →

$E_\gamma = 1.08$ GeV →









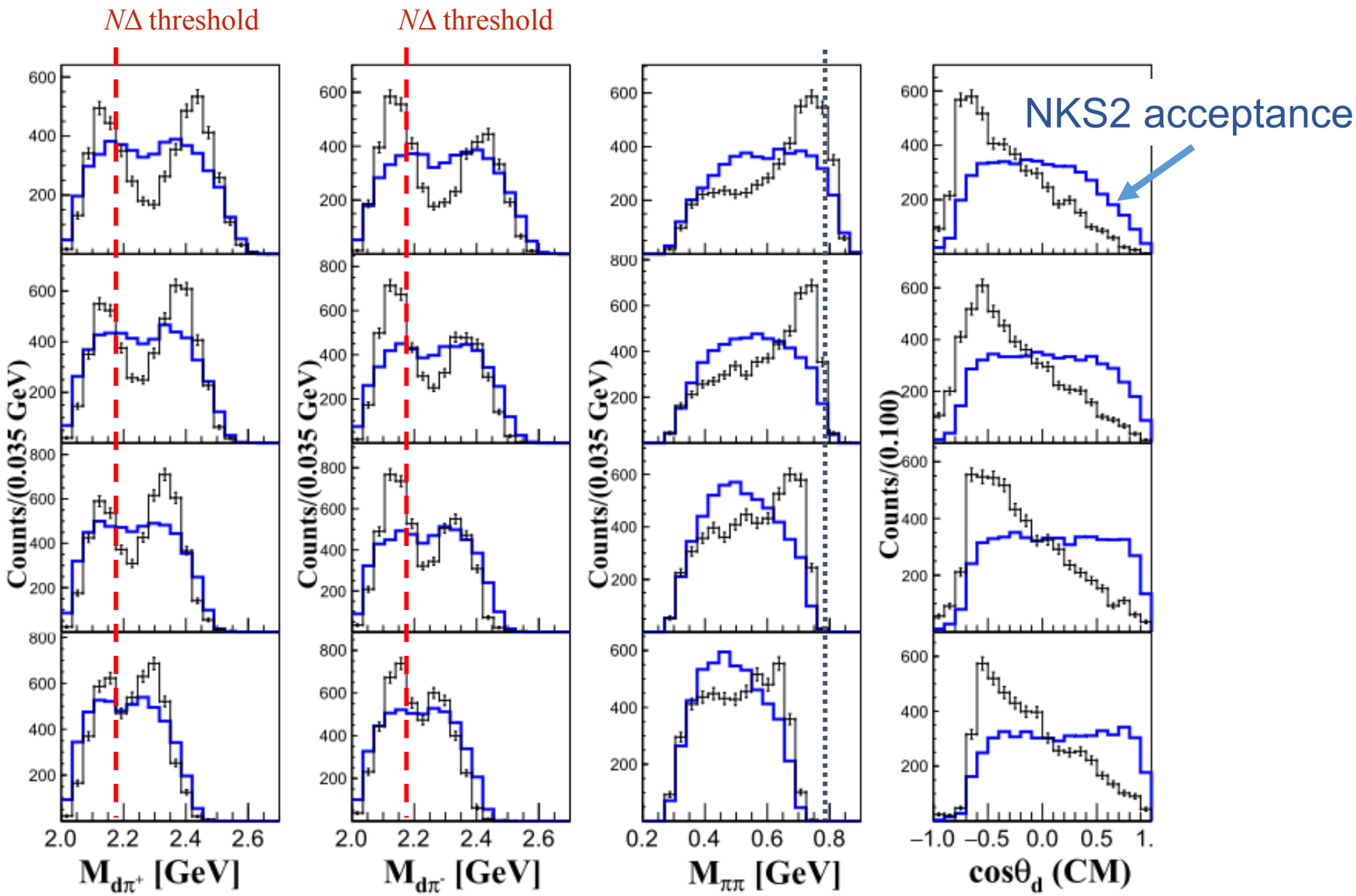
Invariant Mass & cosθ$_d$ Distributions

2.70<W<2.75 [GeV]

2.64<W<2.70

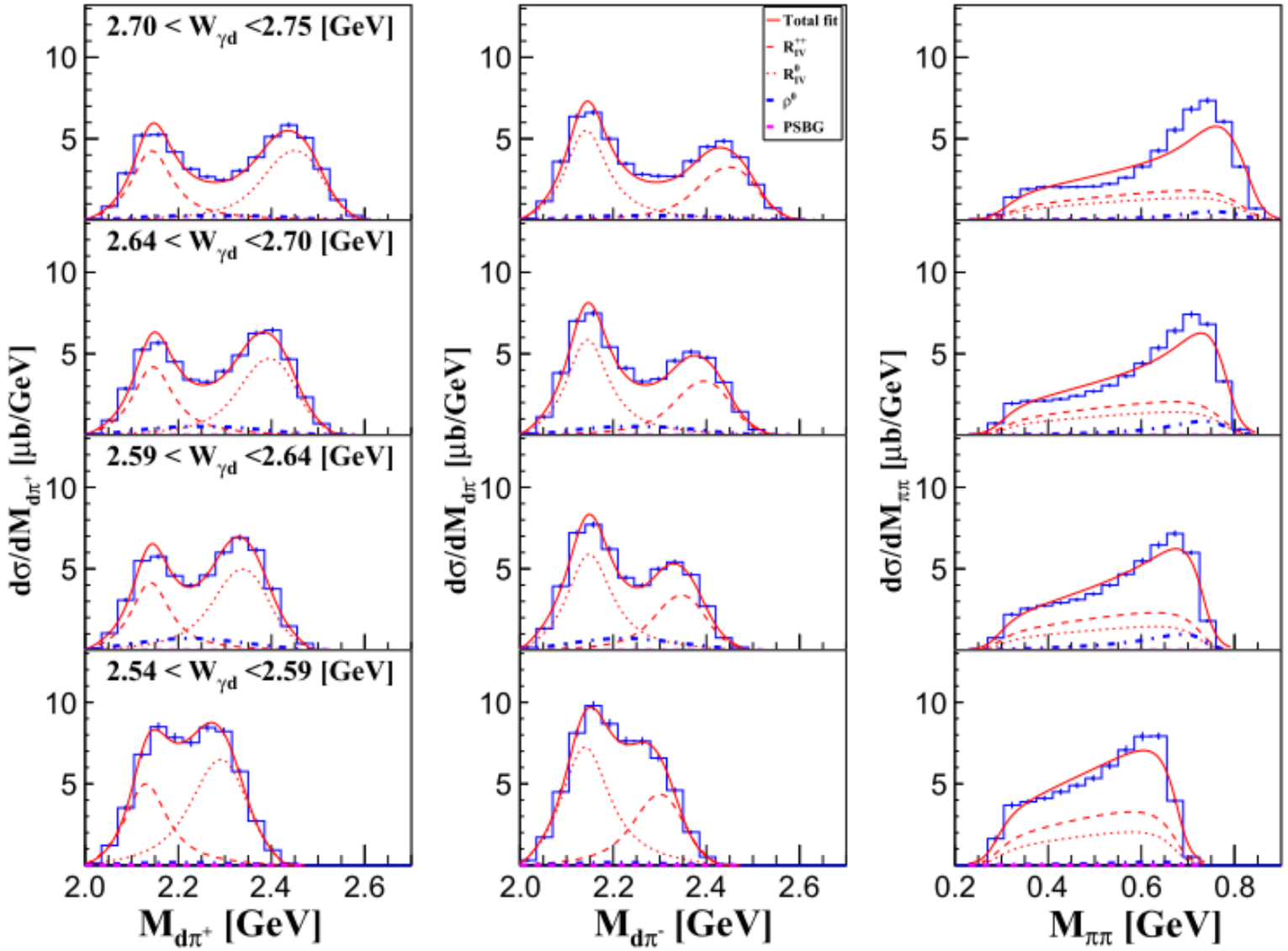
2.59<W<2.64

2.54<W<2.59



- Band structure below *N*Δ threshold in $M_{d\pi}$
- ρ^0 contribution in $M_{\pi\pi}$ ~0.7
- d emitted backward

Differential Cross Sections



$$N(m_{d\pi^+}) = \int_{m_{\pi\pi}} \int_{m_{d\pi^-}} \left(\left| \alpha A^{R^{++}_{IV}}_{M_{++},\Gamma_{++}}(m_{d\pi^+}) + \beta A^{R^{0}_{IV}}_{M_0,\Gamma_0}(m_{d\pi^-}) + \gamma A^{\rho}_{M_\rho,\Gamma_\rho}(m_{\pi\pi}) \right|^2 + C \right) V_{PS}(m_{d\pi^+}, m_{d\pi^-}, m_{\pi\pi})\, dm_{d\pi^-} dm_{\pi\pi}$$

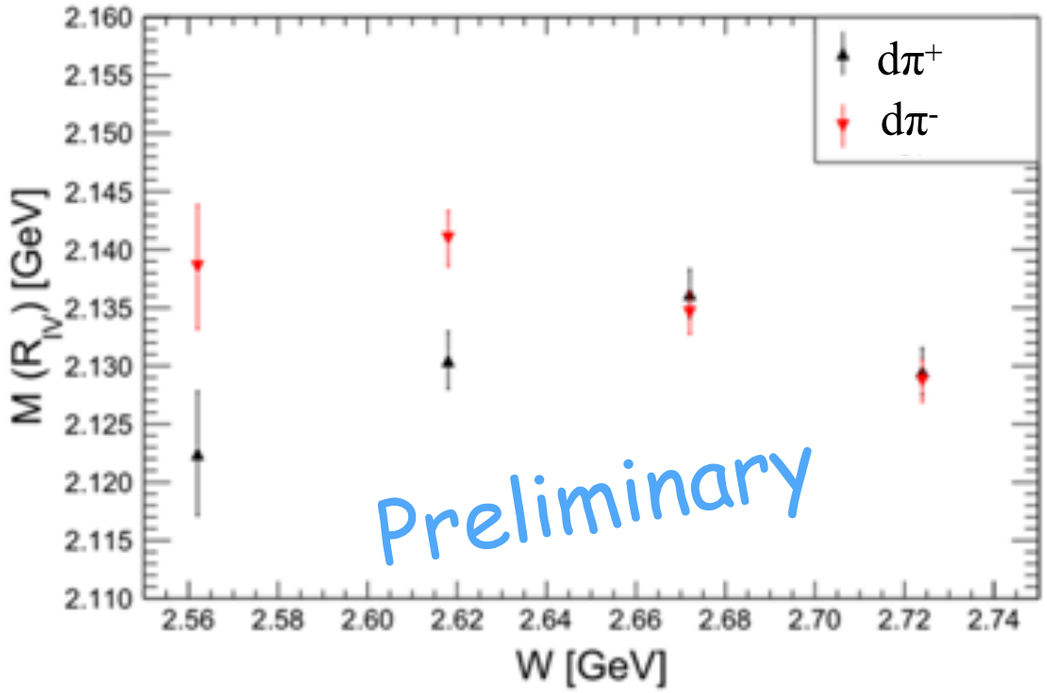
BW1($d\pi^+$) BW2($d\pi^-$) BW3($\pi\pi$)

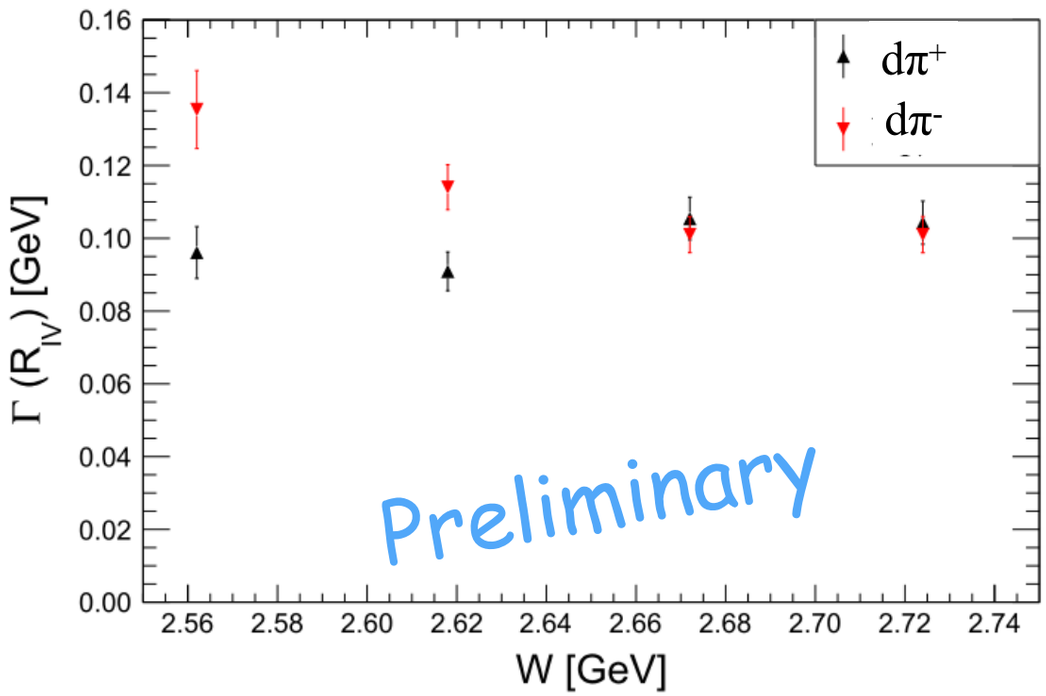
BW: $A_{M,\Gamma}(m) = (M^2 - m^2 + iM\Gamma)^{-1}$

Phase space

- (3 Breit-Wigner + Phase Space background) ⊗Resolution
- Mass & Width of ρ^0 were fixed at 0.77 and 0.15 GeV

Mass & Width of the dπ Resonances





- Weighted average of higher energy points
  - M = 2.133 ± 0.001 (stat.) ± 0.009 (syst.) [GeV]
  - Γ = 0.103 ± 0.002 (stat.) ± 0.009 (syst.) [GeV]
- Systematic errors of fitting
  - Standard deviation of the all points
  - ρ^0 free fitting result

Lower than NΔ threshold (~2.17 GeV)

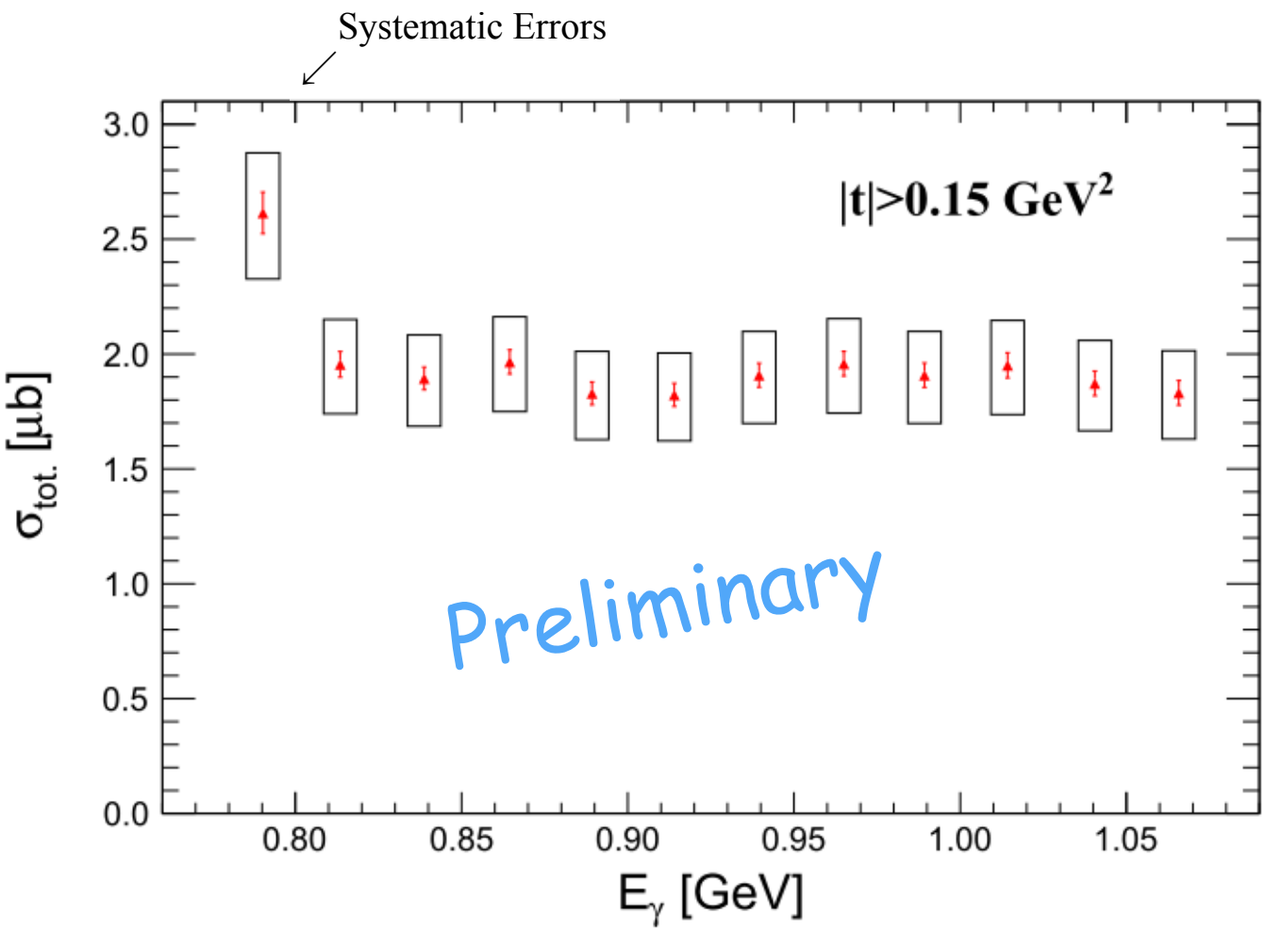
Narrower than single Δ width (~0.12 GeV)

Consistent with D_{12} (z=+1) from FOREST

(M=2.140±0.011 GeV, Γ=0.091±0.011 GeV)

$z = +2$ or 0 states of D_{12}?

Total Cross Section



- No significant structure
  - ~2 μb
  - Syst. error ~8%
- |t|=0.15 GeV²
  ⇒ p_d ~ 350 MeV/c

$$t = (P_\gamma - P_{\pi\pi})^2$$

  - Out of NKS2 acceptance due to the energy loss

Possible Scenarios for 2π Production and cosθ$_d$ Distribution

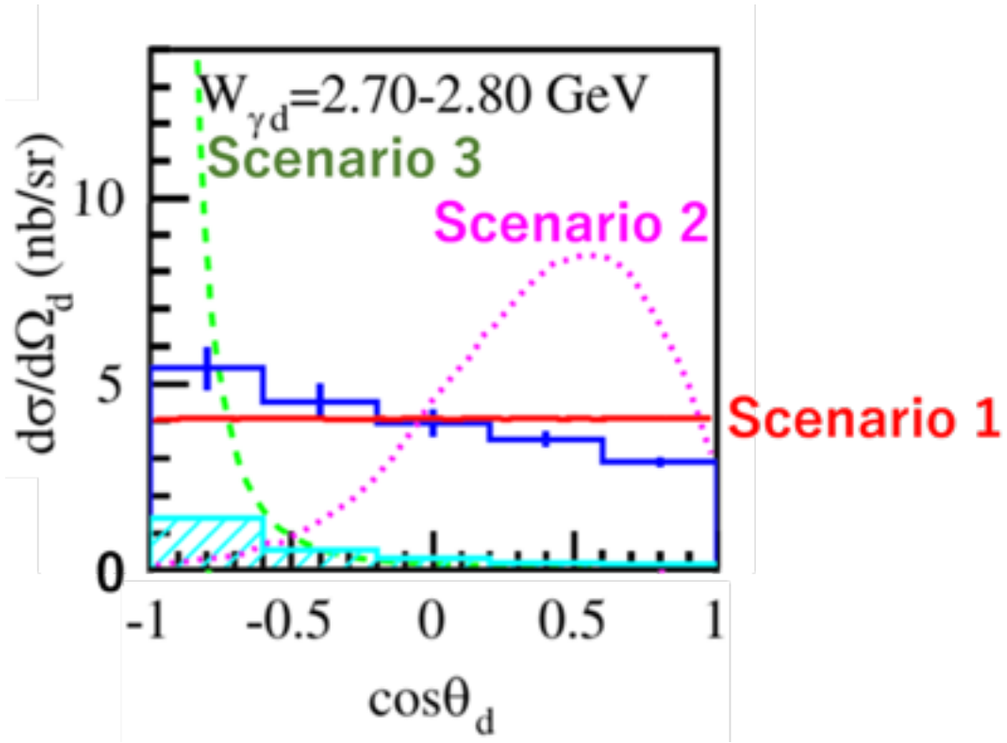
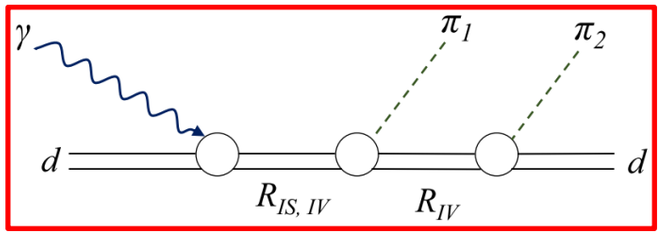
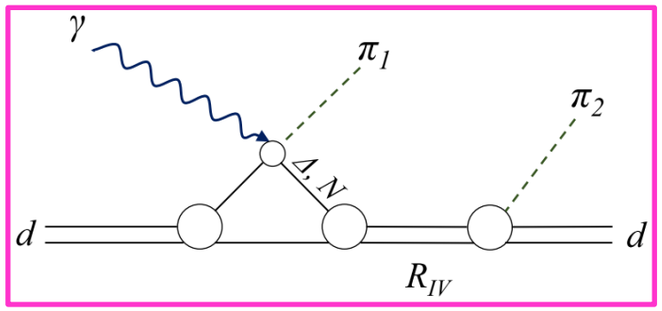


Figure from PLB789, 413 (2019)

Scenario 1

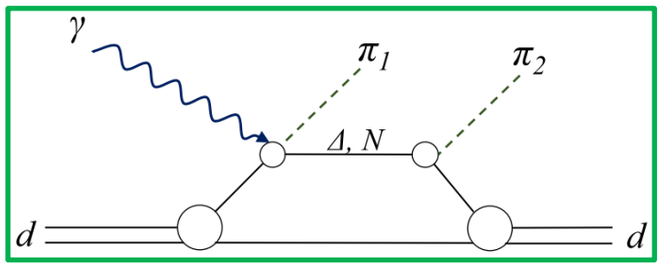


Scenario 2



With dibaryon

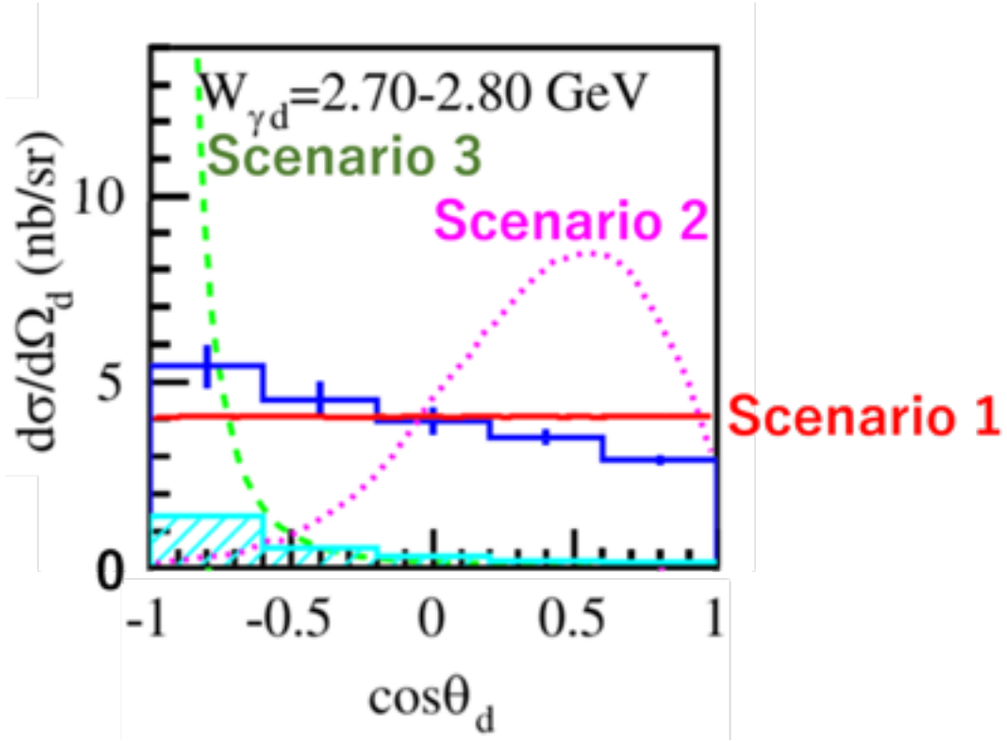
Scenario 3



Without dibaryon

- They can be separated by cosθd (γd CM frame) distribution
- If no isovector dibaryon (conventional), cosθ$_d$ shows strong backward peak

Possible Scenarios for 2π Production and $\cos\theta_d$ Distribution



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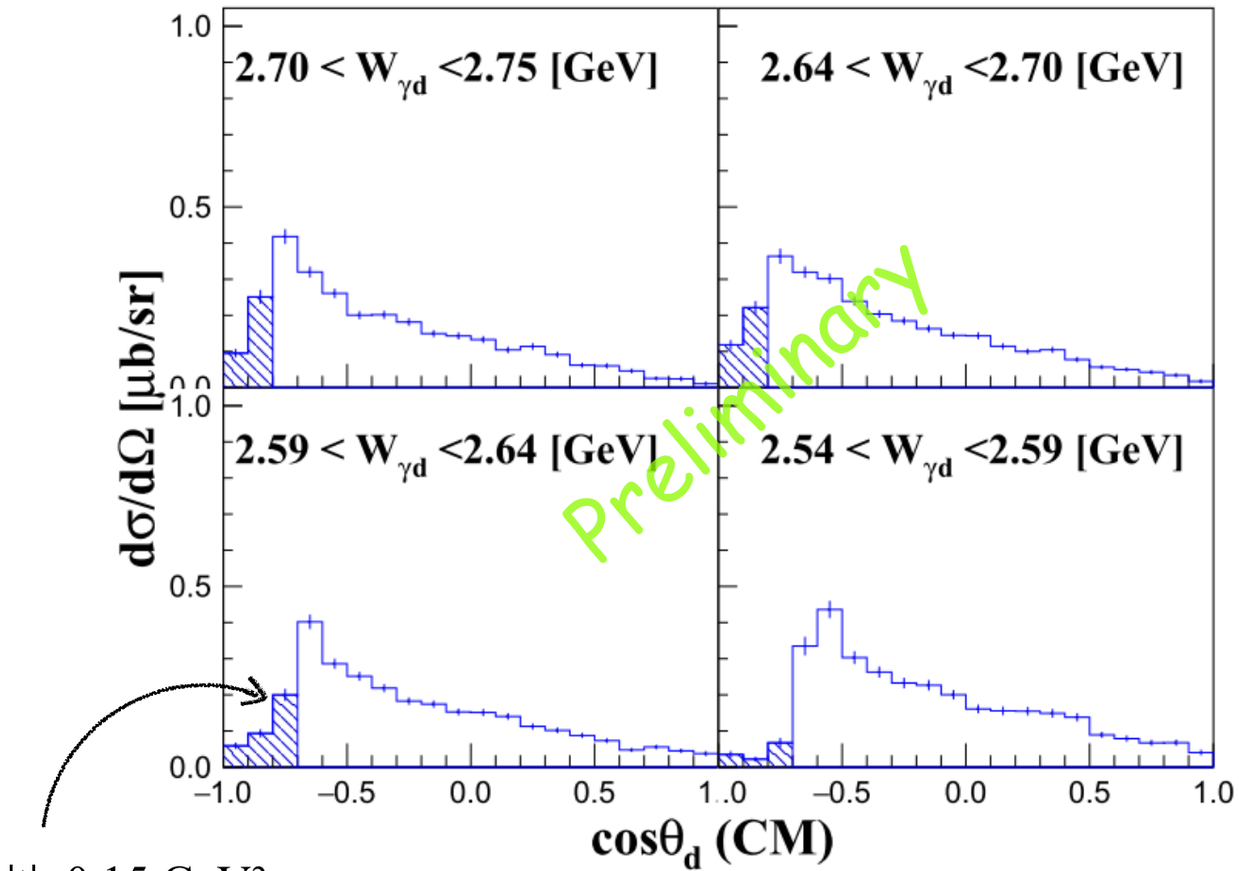

$|t|<0.15$ GeV^2

- Backward enhanced structure in $|t|>0.15$ GeV^2 region
  - But not so steep peak
  - Can not be explained by Scenario 3 only
- $d\sigma/d\Omega > 0.1$ μb/sr in $\cos\theta_d > 0$
  - ⇒ unconventional process (i.e. dibaryon)

To conclude, measurement of lower momentum (< 400 MeV/c) of deuteron is needed

Future Program of Strangeness

An interaction

— Neutral Channel —

How to Measure Λn interaction

- No neutron and no Lambda target
  - Simple scattering experiment is impossible
- Possible experimental approach
  - See an effect of Λn final state interaction in cross-section
- Reactions proposed by theorists
  - $\gamma d \rightarrow K^{+}\Lambda n$
    - H. Yamamura, K. Miyazawa *et al.*, PRC61 (1999) 014001
  - $K^{-}d \rightarrow \Lambda n\gamma$
    - W. R. Gibbs, S.A. Coon, H.K. Han, and B.F. Gibson, PRC61 (2000) 064003
  - $K^{-}d \rightarrow \Lambda n\pi^{0}\,(K^{-}d \rightarrow \Lambda p\pi^{-})$
    - Y. Iizawa, D. Jido, T. Ishikawa, ArXiv:2201.06737 [nucl-th]

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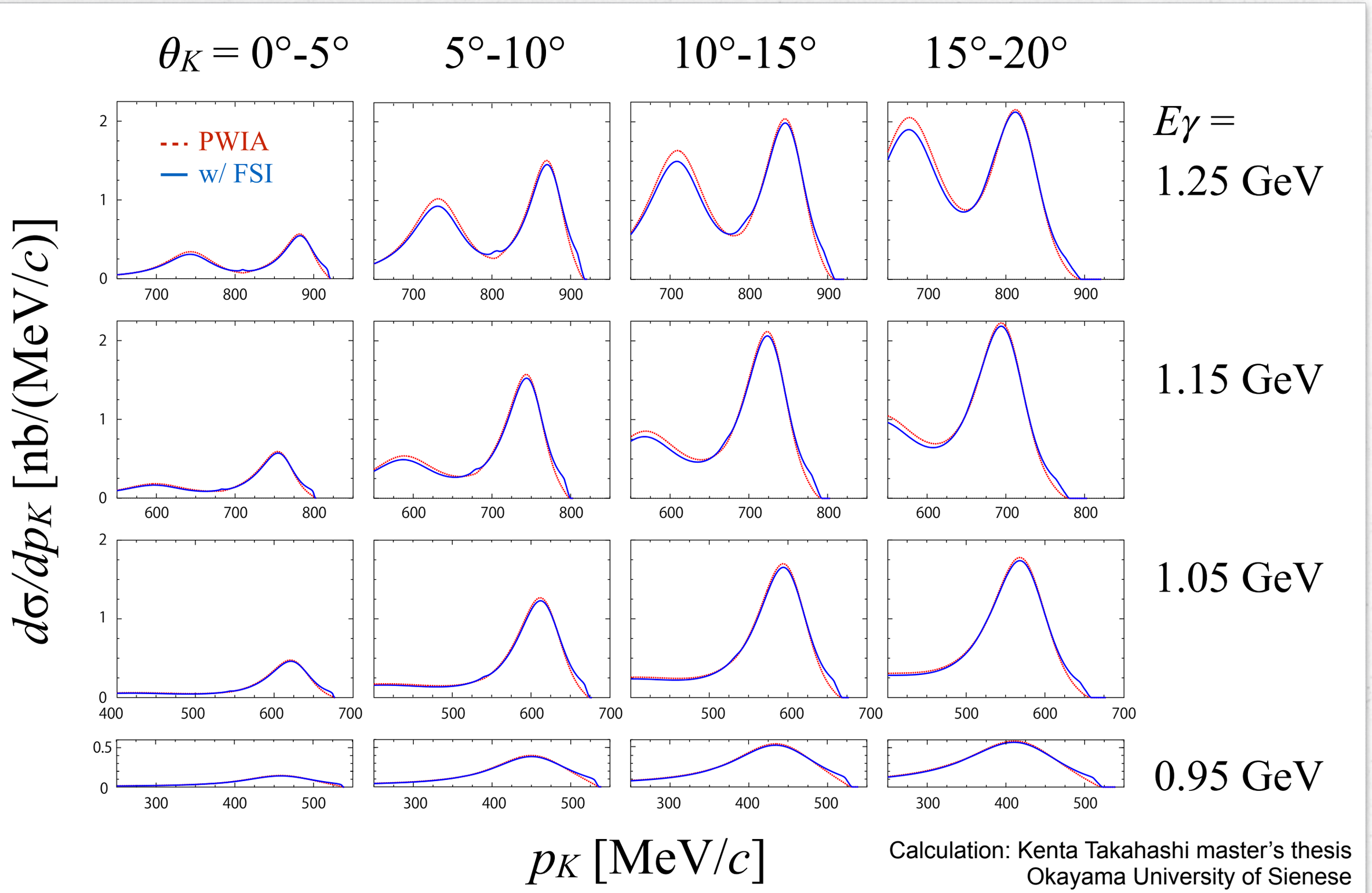
Characteristics of the Reactions by Photon/Hadron Beam

- FSI effects appear at threshold region
  - No resonance decay effects
  - Cross section is small
- Photon beam
  - $\gamma d \rightarrow K^+ \Lambda n$
    - < 1 μb
    - Dominant B.G.: e^+e^- pair production and pion production
  - $K^- d \rightarrow \Lambda n \gamma$
    - ~2x10^{-3} of $K^- d$ total (~several 10 mb) cross section: ~100 μb
    - Using K-stop candidate
    - B.G. photon: $K^- d \rightarrow Y N \pi$, $\pi^- d \rightarrow nn\gamma$
      - Some kinematical cuts are needed to reject B.G.
    - B.G. in photon detector: neutron

FSI Effect in the K^+ Cross-section



Calculation: Kenta Takahashi master's thesis
Okayama University of Sienese

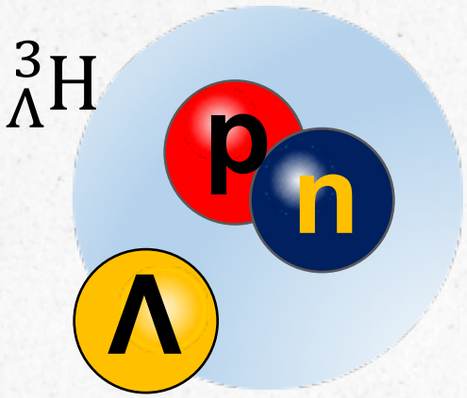
One More Topic:

Lifetime of

Light Hypernuclei

Lifetime of Light Hypernuclei

- ${}^{3}_{\Lambda}$H puzzle

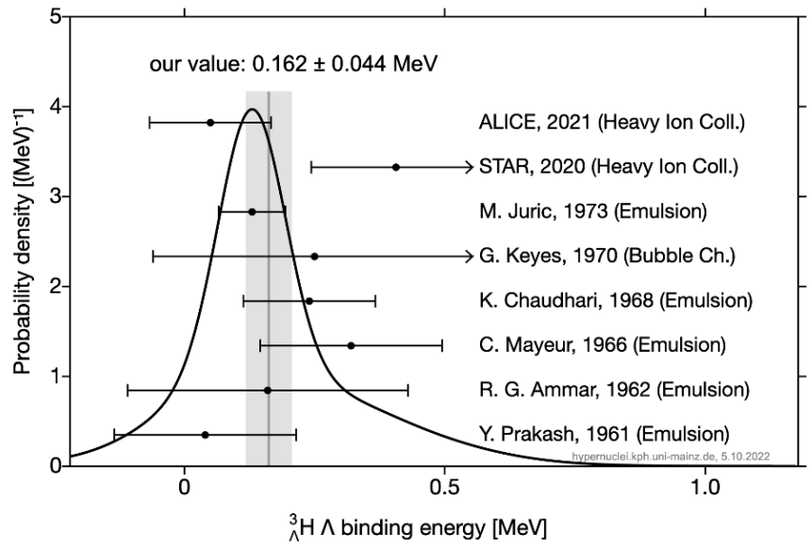


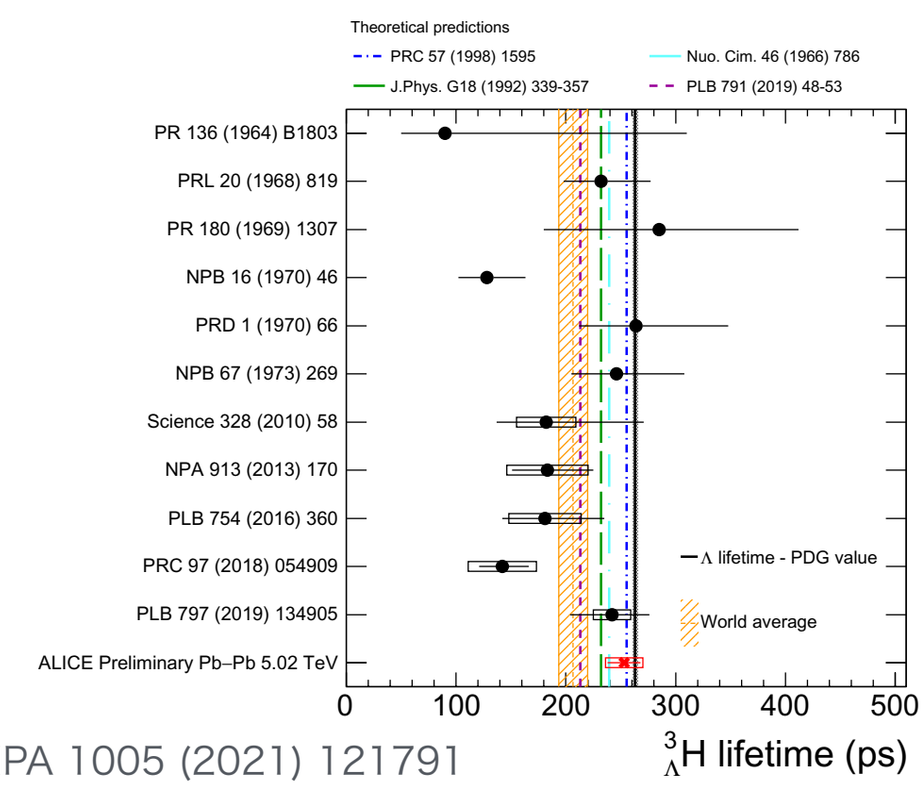
B_Λ~0.16 MeV [1] ($^4_\Lambda$H : B_Λ=2.12 MeV[2])

τ = ~200 ps (τ_Λ =263 ps)

{ Small Λ biding energy
Shorter hypernuclei lifetime than free space Λ

Difficult to explain simultaneously

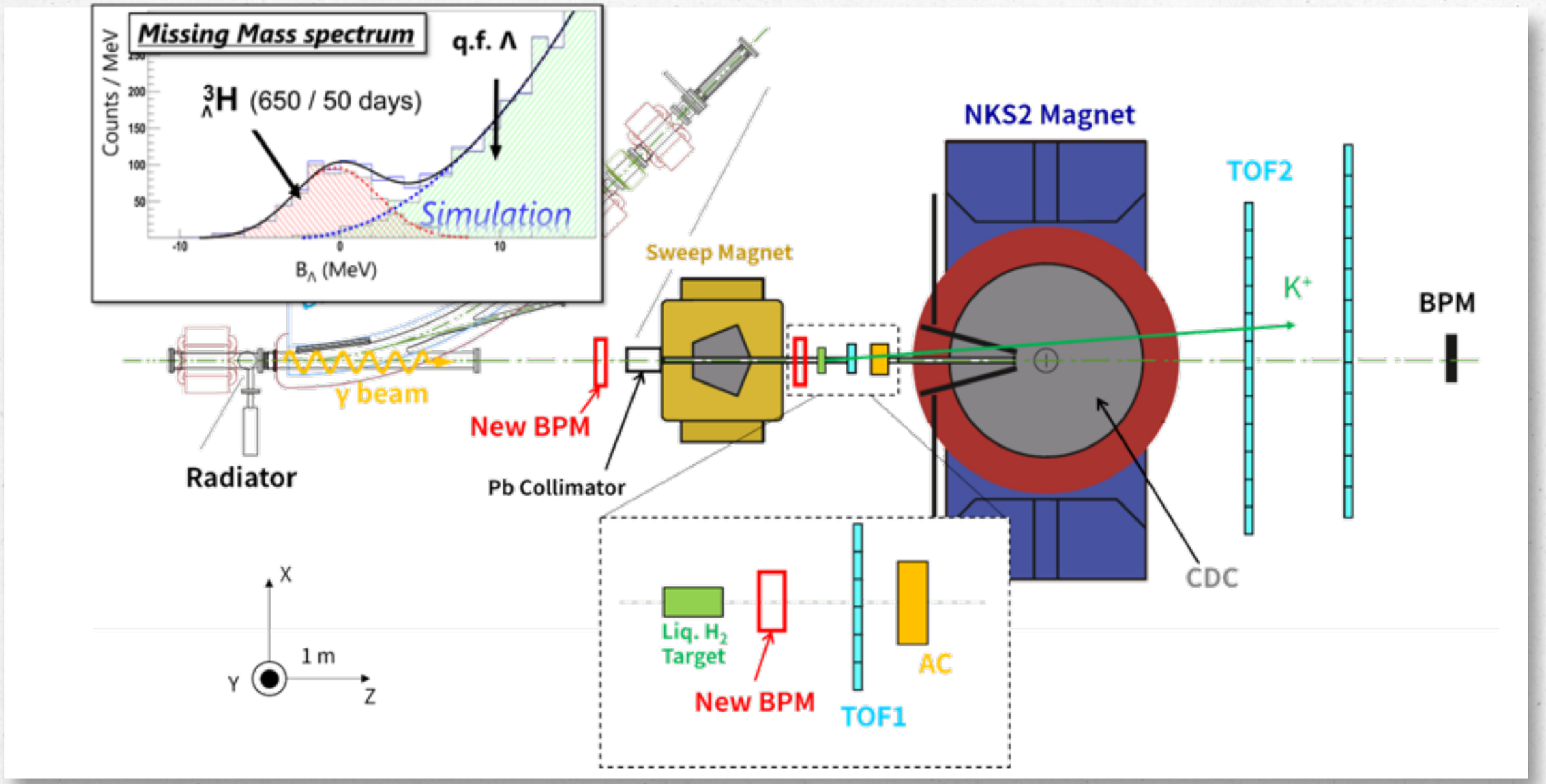




NPA 1005 (2021) 121791

[1] https://hypernuclei.kph.uni-mainz.de/
[2] S.Nagao, Doctoral thesis 2015 Tohoku University,
A.Esser, S.Nagao, F.Schulz *et al*., Phys. Rev. Lett. **114** (2015)222501.

${}^{3}_{\Lambda}$H Lifetime Measurement at ELPH



- K^+ ID with new TOF counters
- π^- decay time with new TOF
- Photon beam course by new beam position monitor

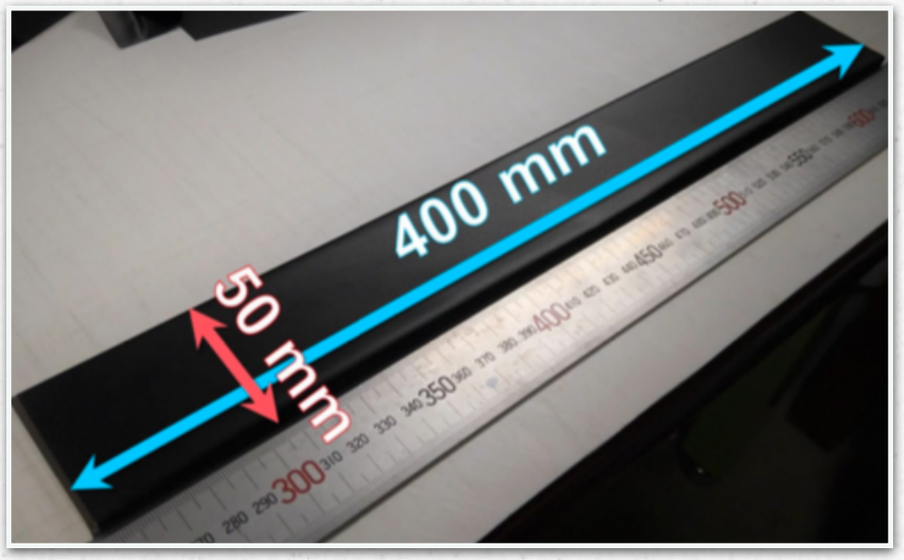
Detector Upgrade Plane and Status of Preparations

Detector Upgrade Plan

- Kaon Identification
  - pi/K/p separation
- Better DAQ efficiency under higher photon beam rate
  - Electron veto on trigger level
  - Beam position monitor
- Replacement of data acquisition system

Preparation Status

- Kaon identification
  - Replacement of Inner/Outer Hodoscopes is on-going
    - Scintillator + SiPM
      - Expected intrinsic time resolution: ~100 ps → TOF resolution: < 150 ps
        - Current TOF resolution: < 270 ps
      - Developed by T. Fuwara and reported by his master's thesis
    - Charger information will be taken as Time-over-threshold by TDC module
    - Outer Hodoscope will be common for FSI and lifetime experiment



Outer hodoscope design
Picture from T.Fujiwara's JPS talk

Preparation Status

- Better DAQ efficiency under higher photon beam rate
  - Rejection of e^+e^- event on the trigger level
- Aerogel Cherenkov Electron Veto Counter
  - Feasibility study is done
    - Aerogel
      - n = 1.01: only electron emits the Cherenkov light in p<1.GeV/c
      - 3 x 4 x 6 cm^3 to locate between two chambers
    - Micro-Channel Plate PMT as photon sensor
      - almost no thermal noise
    - Scintillation light from s reflector (Teflon) is negligible
    - Developed by K. Tachibana and will be summarized on his master's thesis

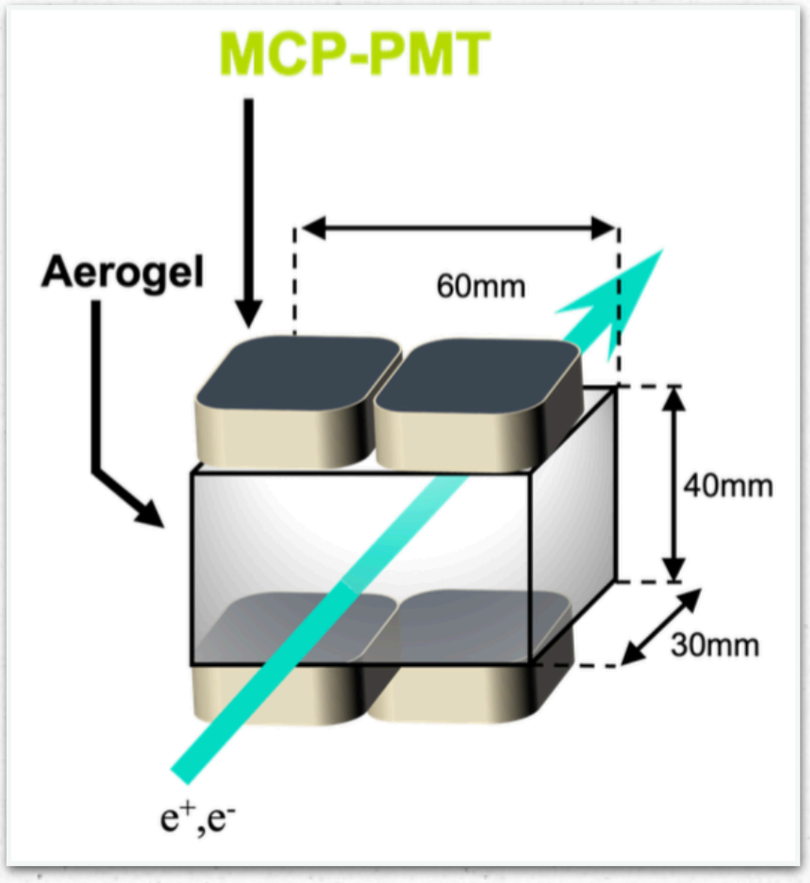


Figure from K. Tachibana's CLUSHIQ2022 talk

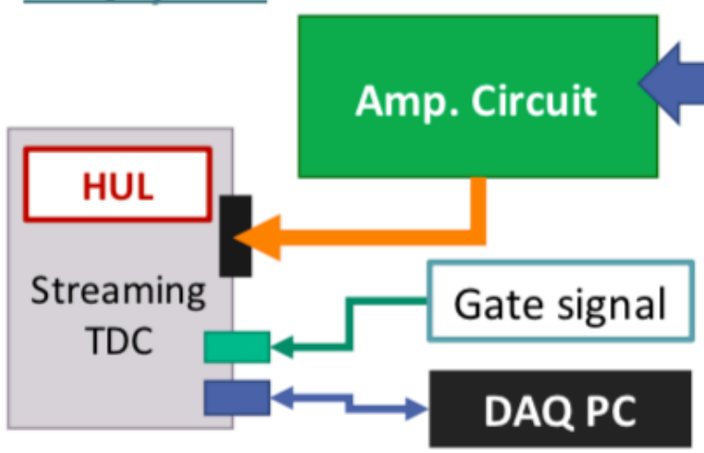
Preparation Status

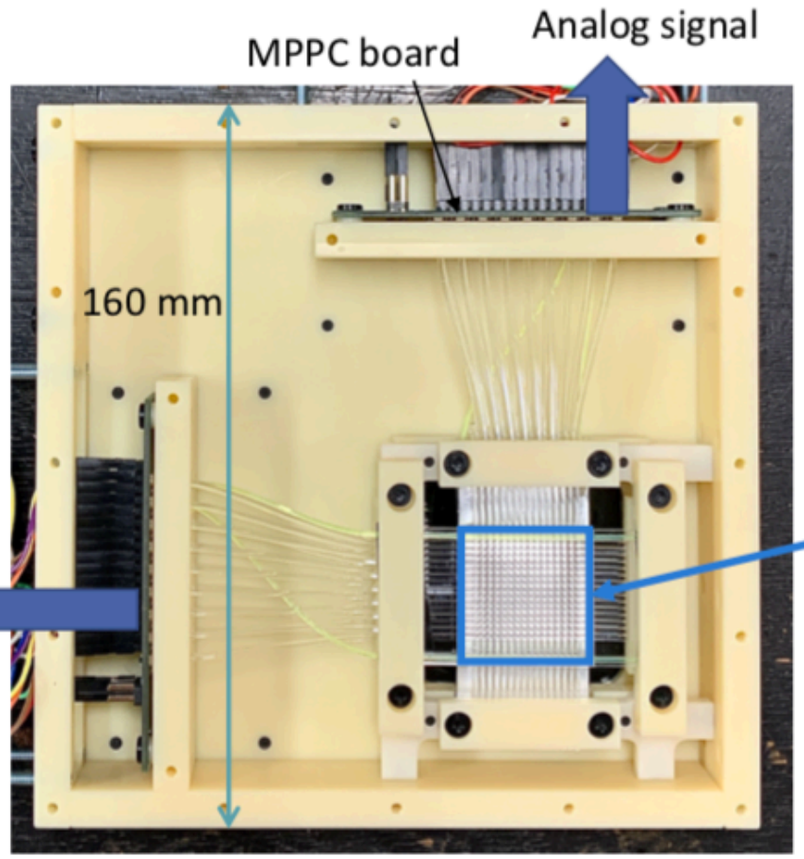
- Beam position monitor
  - Scintillation fiber + SiPM (MPPC)
  - Real time monitoring
  - Developed by R. Kino and will be reported in her master's thesis

Basic Structure

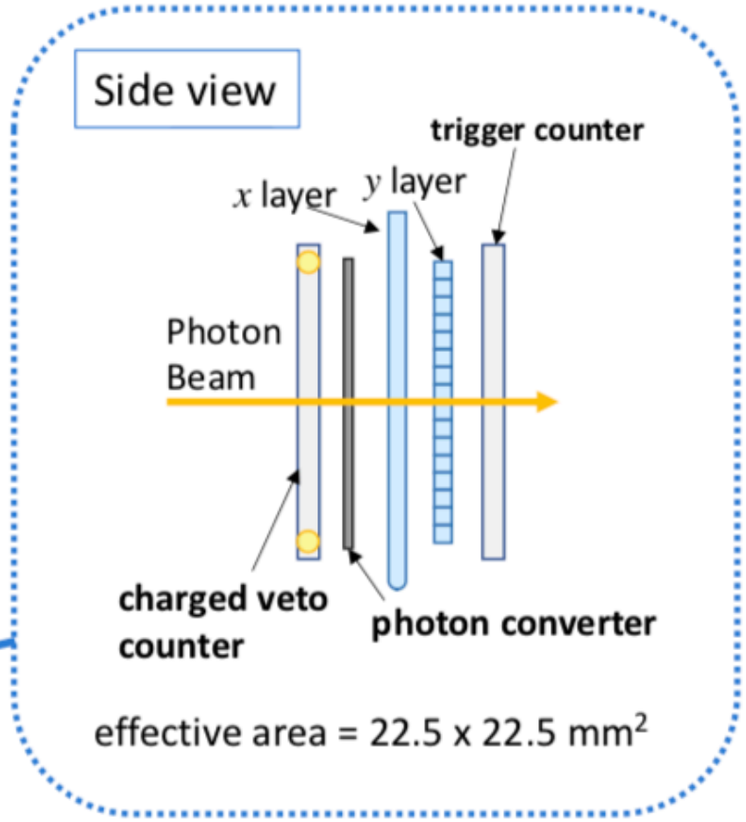
- Scintillation Fibers (ϕ1.5 mm)
  SCSF-78 (Kuraray)
- SiPM
  MPPC S13360-1350PE
  (Hamamatsu Photonics K.K.)
- DAQ: Streaming type TDC
  (Hadron Universal Logic)

DAQ System





Beam Position Monitor



event ID:

$[\,\overline{\text{veto}}\,] \otimes [\,\text{x layer}\,] \otimes [\,\text{y layer}\,] \otimes [\,\text{trig.}\,]$

→ Only photon events can be extracted!

Slide from R. Kino's talk on SNP School 2021

Preparation Status

- Plan of data acquisition system
  - Trigger construction
    - NIM modules to FPGA modules
    - Logic width and delay will be adjusted on the FPGA
  - Wiring in the 2nd experimental hall
    - Current system: logic signals are sending to counting room
    - less delay time (experimental hall ↔ counting room: ~1 μs)
  - No QDC module
    - Energy deposit (Charge) information will be record as logic width (Time-Over-Threshold) by TDC module
    - No decay cable for QDC gate

Summary

- NKS2 experiment at ELPH
  - Photon tagger + magnetic spectrometer
  - Physics topics
    - Strangeness nuclear and hadron physics
- Recent results and future program is introduced
- The upgrade plan for the future program
  - Detector R&D
    - TOF counter
    - Electron veto
    - Beam position monitor
  - DAQ system
    - Discussion is on-going
    - Trial of constructing the tigger by FPGA for Tagger