

Measurement of coherent $\pi^+\pi^-$ photoproduction on deuteron

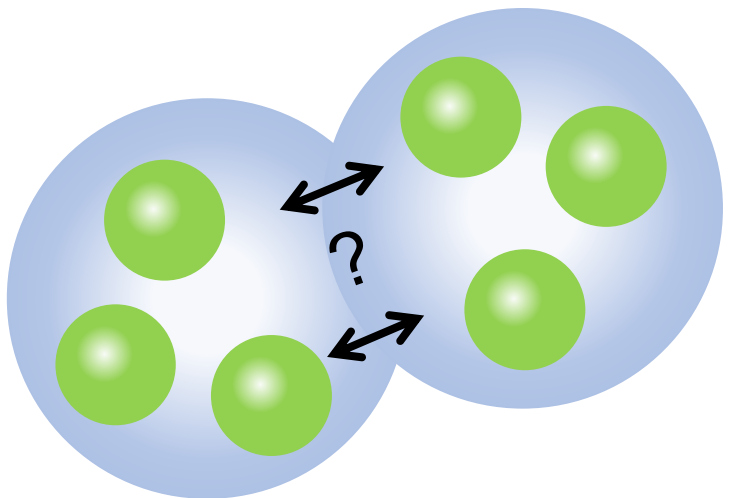
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for theNKS2 Collaboration

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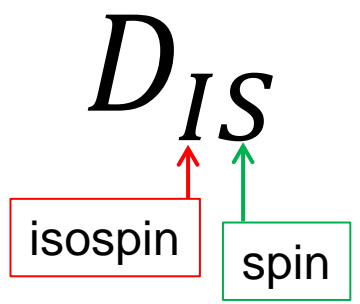
Introduction

- Dibaryon
- D_{12}
- Old measurement of the $\gamma d \rightarrow d\pi^+\pi^-$ reaction
- Goal of this study

What is “dibaryon” ?



Molecule state of 2 baryons?
Compact 6 quark state?



Predicted 2-baryon states without strangeness

D_{IS}	D_{01}	D_{10}	D_{12}	D_{21}	D_{03}	D_{30}
BB	NN	NN	N Δ	N Δ	$\Delta\Delta$	$\Delta\Delta$
Mass formula	A	A	A+6B	A+6B	A+10B	A+10B
Approx. mass	1878	1878	2160	2160	2348	2348

This work

NN bound state
(deuteron)
 3S_1

NN virtual state
(pp, nn, np)
 1S_0

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

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

$$A = 1878 \text{ MeV}$$

$$B = 47 \text{ MeV}$$

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

• Experiment

- B.S. Neganov, L.B. Parfenov, JETP7, 528 (1958).
- $\pi d \rightarrow pp$ scattering PWA: R. Arndt *et al.*, PRC48, 1926 (1993). B.S. Neganov *et al.*, JETP7, 0528 (1958).
- $\pi d \rightarrow \pi d$ 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).

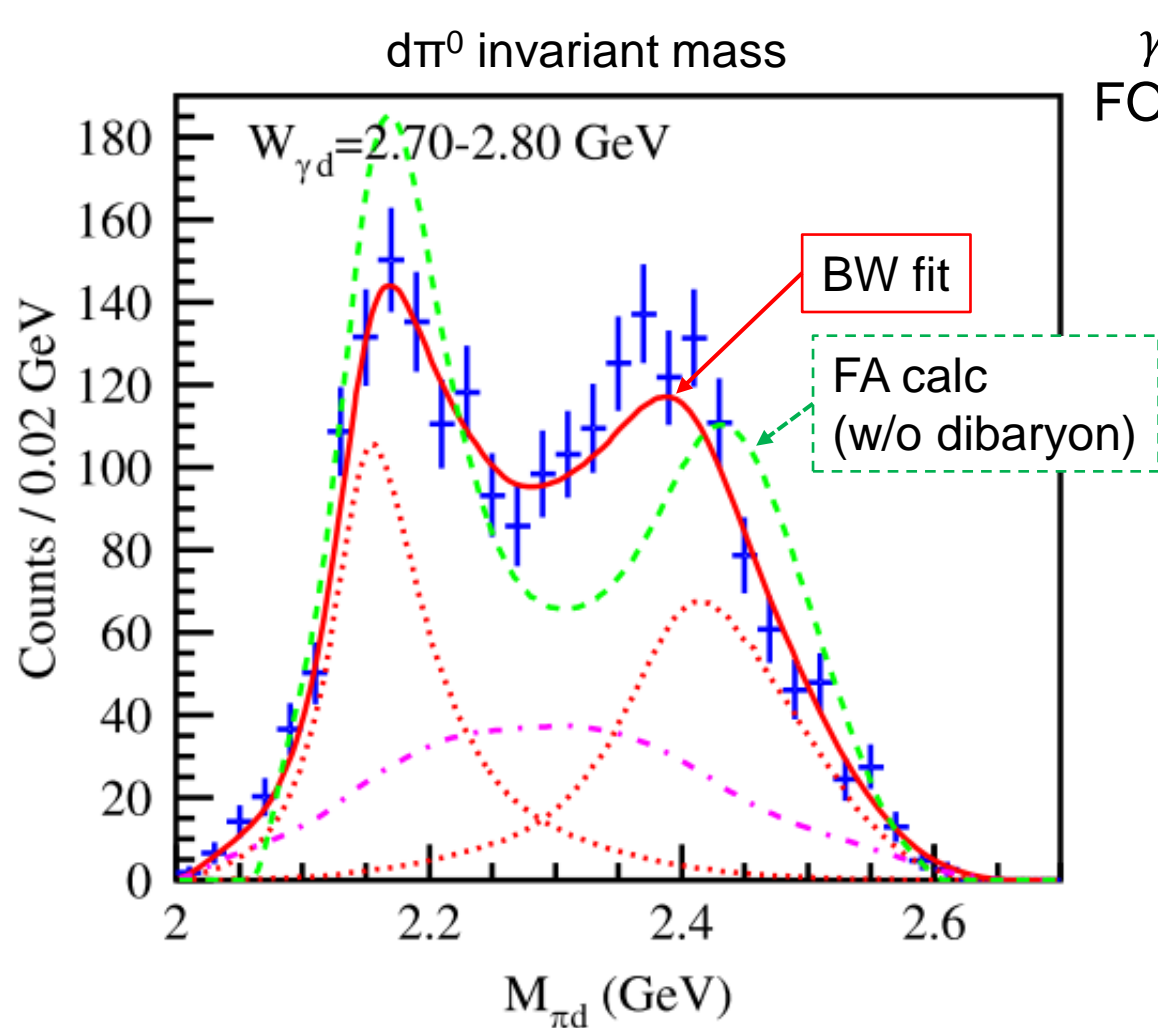
• Theory

- 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. Kukulkin, NPA 946, 117 (2016).

However, dibaryonic interpretation of D_{12} was still questionable.
i.e. kinematical effect or true resonance? (PLB112,17 (1982) etc.)

Recent experimental data of photoproduction

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



$\gamma d \rightarrow d\pi^0\pi^0$
FOREST, ELPH

$M = 2.14 \pm 0.01$ GeV
 $\Gamma = 0.09 \pm 0.01$ GeV
 $J^P = 1^+, 2^+, \text{ or } 3^-$

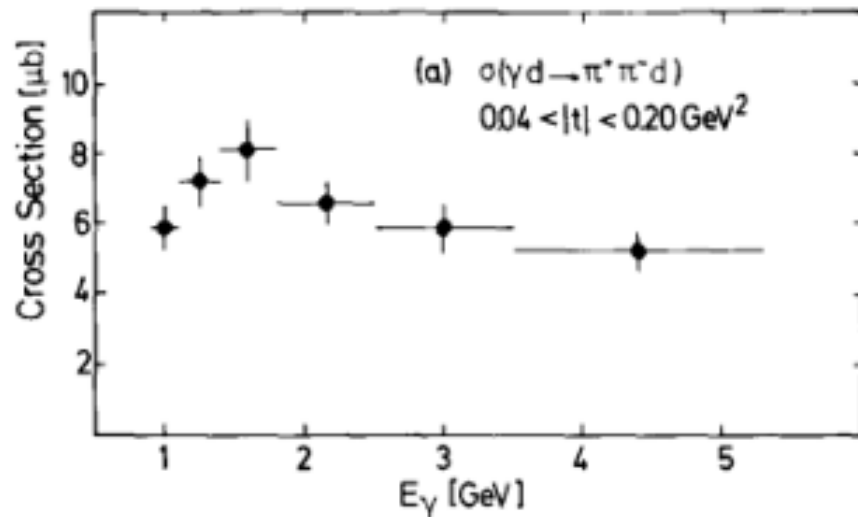
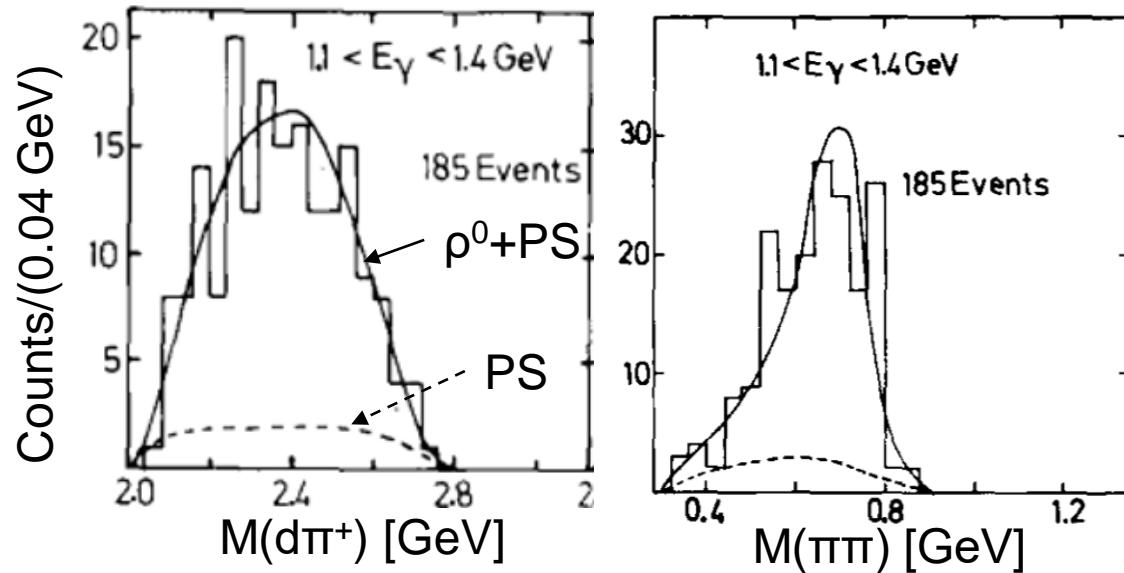
- 3 isoscalar dibaryon, 1 isovector dibaryon
- Isovector dibaryon as a decay product of isoscalar dibaryons

They suggest

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

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

Old measurement of the $\gamma d \rightarrow d\pi^+\pi^-$ reaction



Benz *et al.*, NPB79 (1974) 10.

Old bubble chamber experiment

- Higher E_γ ($1.1 < E_\gamma < 5.3 \text{ GeV}$)
- Limited statistics
- Limited t region ($0.04 < |t| < 0.20 \text{ GeV}^2/c^2$, lower d momentum ($\text{mom}_d \lesssim 0.4 \text{ GeV}/c$))
- **No peak structure in $d\pi$ invariant mass**
 - ρ^0 and PS dist. reproduce the data
- Differential cross section $d\sigma/dt$ of ρ^0 production
- Total cross section $\sim 6\mu\text{b}$ ($E_\gamma \sim 1 \text{ GeV}$)

Experiment

Oct. 2010

- Research Center for ELeCtron PHoton Science (ELPH)
- Neutral Kaon Spectrometer 2 (NKS2)

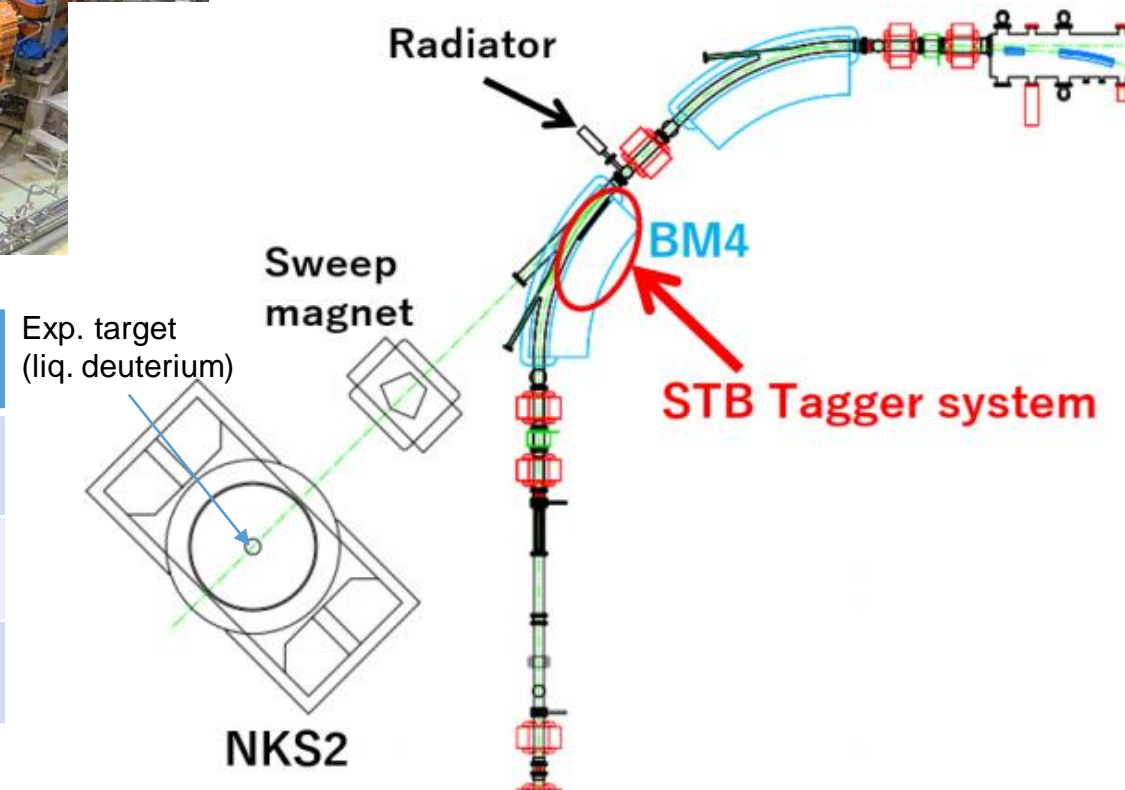
Research Center for ELelectron PHoton Science (ELPH)



- Location: Sendai, Japan
- Electron Synchrotron
 - Internal target system for γ beam [1]

[1] H. Yamazaki *et al.*, Nucl. Instr. and Meth. A 536 (2005) 70.

Experimental condition (2010 NKS2)	
Injection Beam energy	150 MeV
Ring top energy	1.2 GeV
Gamma beam energy	0.78—1.08 GeV

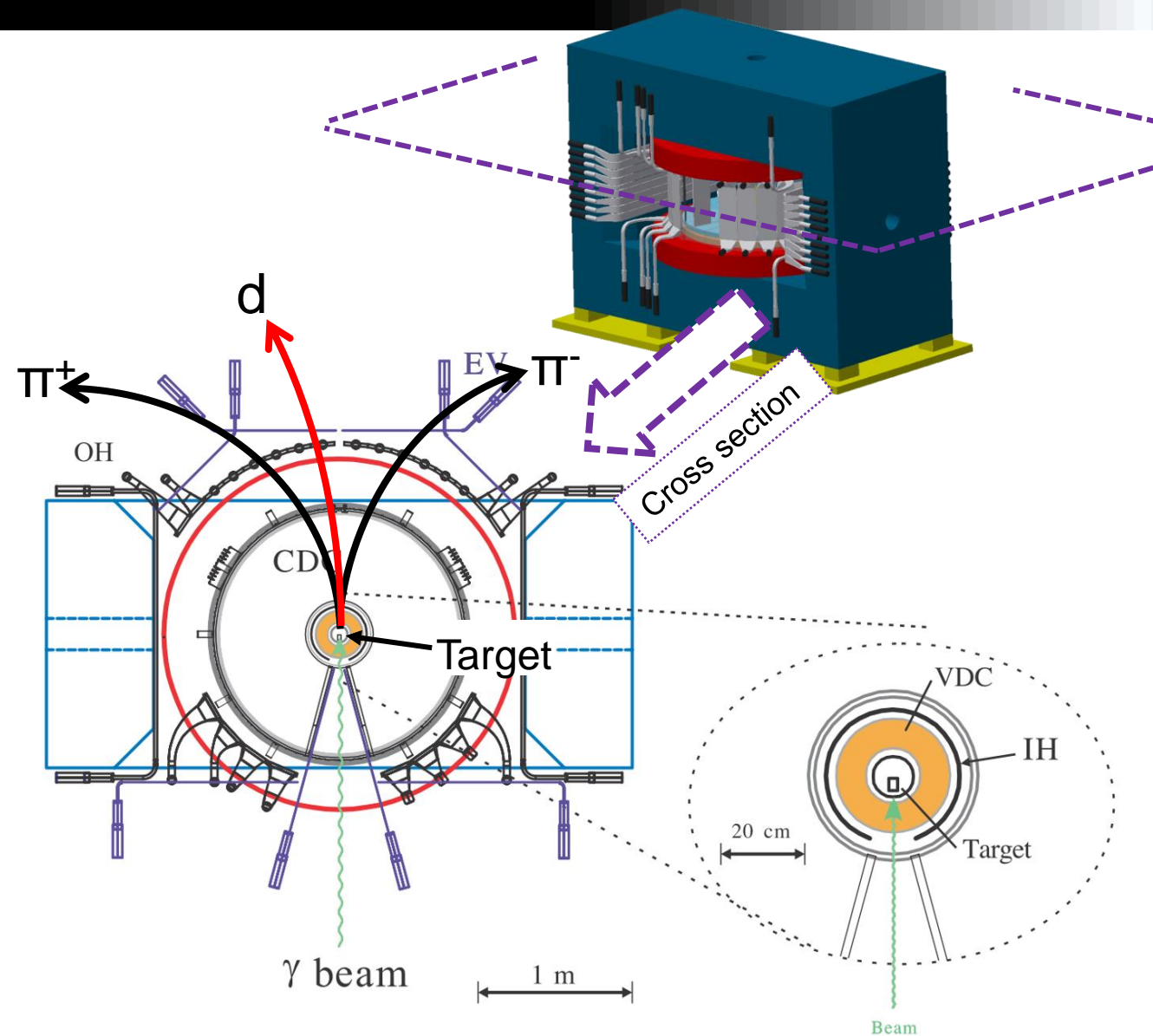


Neutral Kaon Spectrometer 2 (NKS2)

M. Kaneta *et al.*, NIMA886 (2018) 88

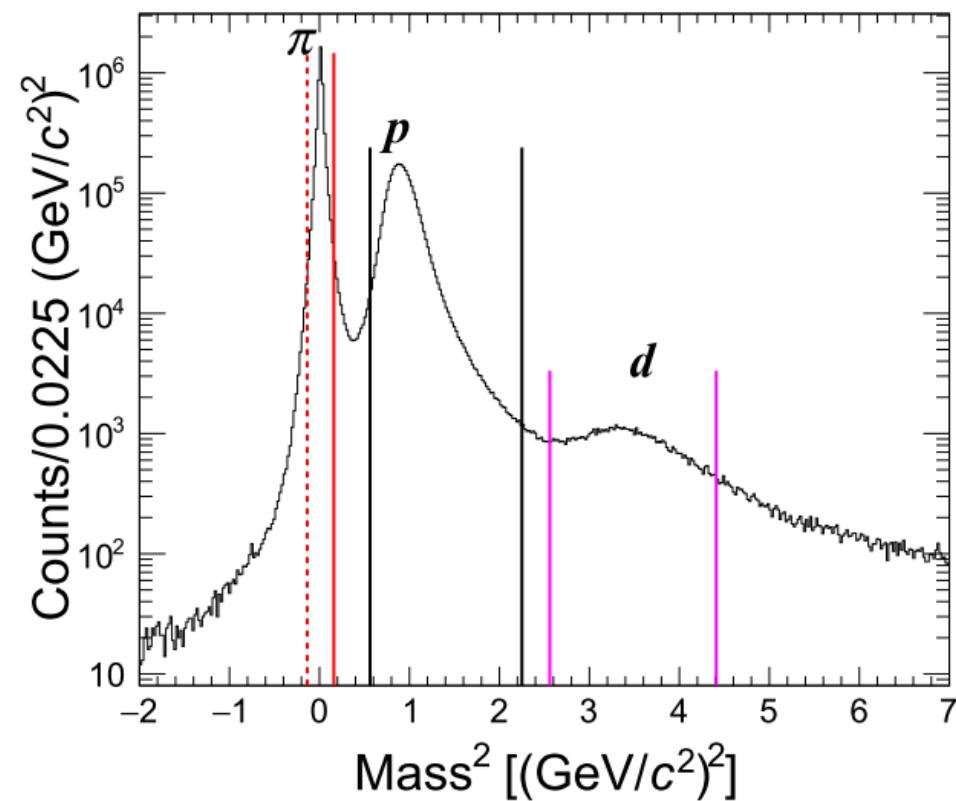
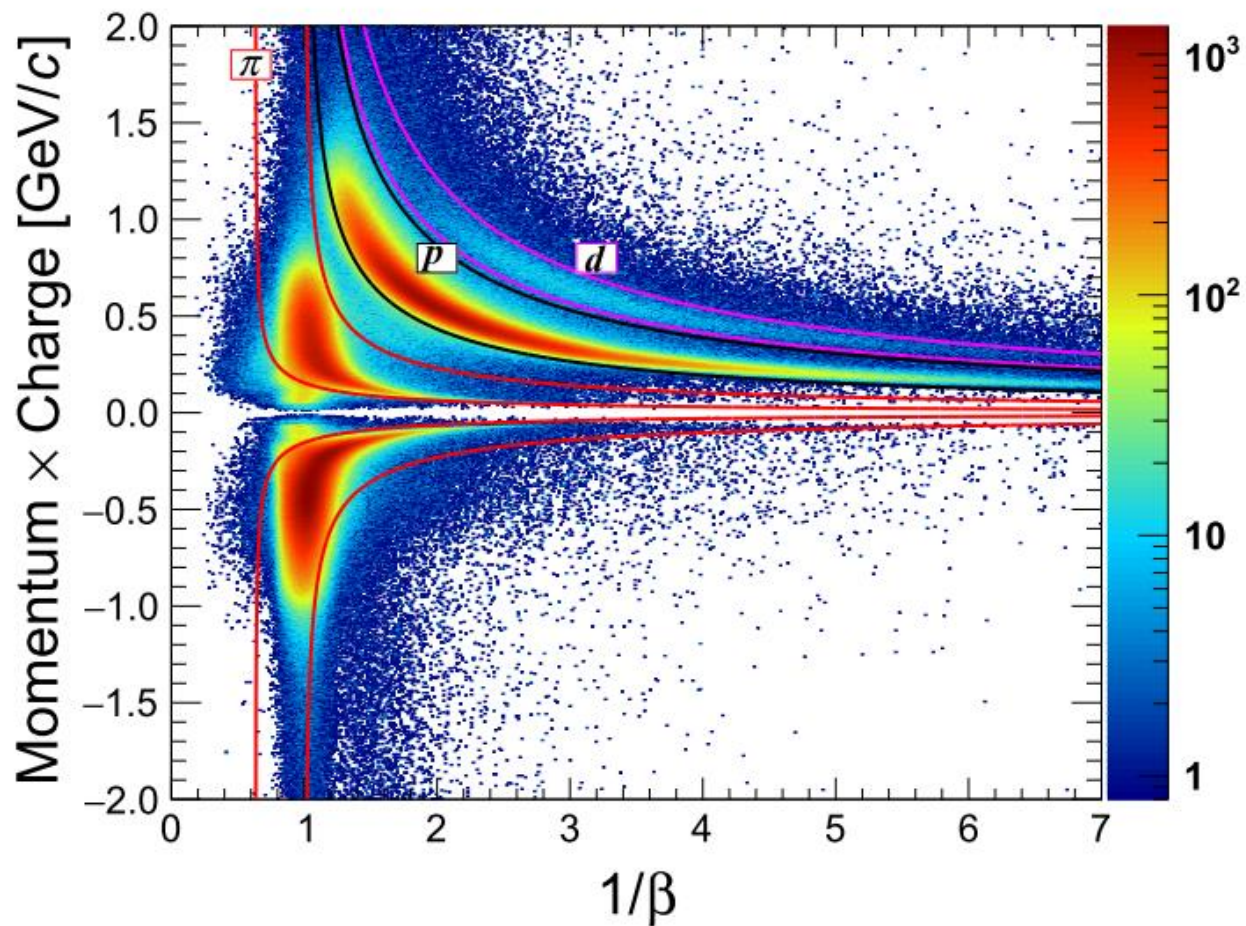
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- $\gamma d \rightarrow d\pi^+\pi^-$
- Data taken in Oct. 2010
- $E_\gamma = 0.78\text{--}1.08$ GeV
- liq. D target (516 mg/cm²)
- $N_\gamma = 3 \times 10^{12}$
- **Dipole magnet** : $B \sim 0.42$ T, $R = 0.8$ m
- Hodoscopes (IH and OH): TOF measurement
- **MWDC's (CDC and VDC)** : Tracking for momentum and vertex finding
- **EV**: e^+e^- rejection
- Geometrical acceptance: ~ 1 π sr

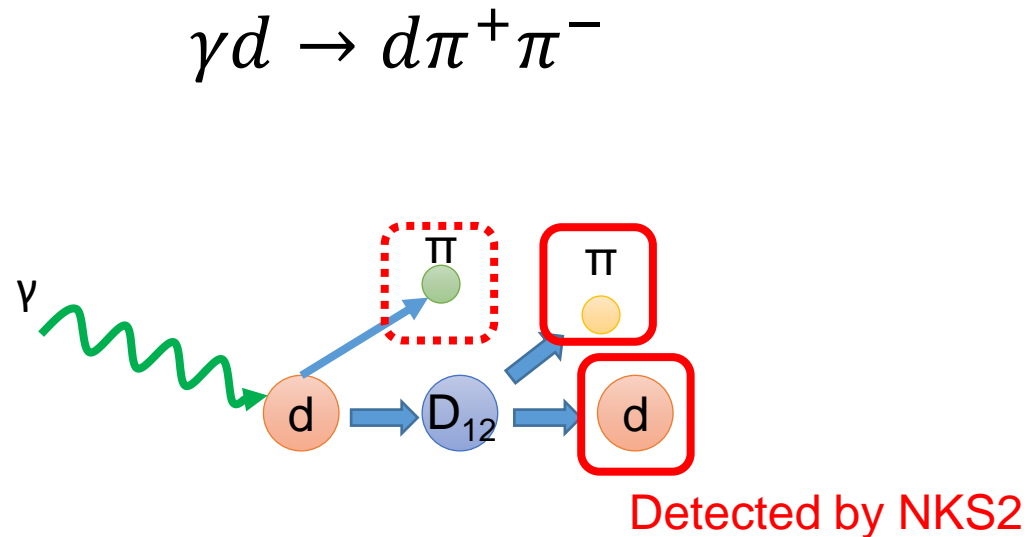


Analysis & Results

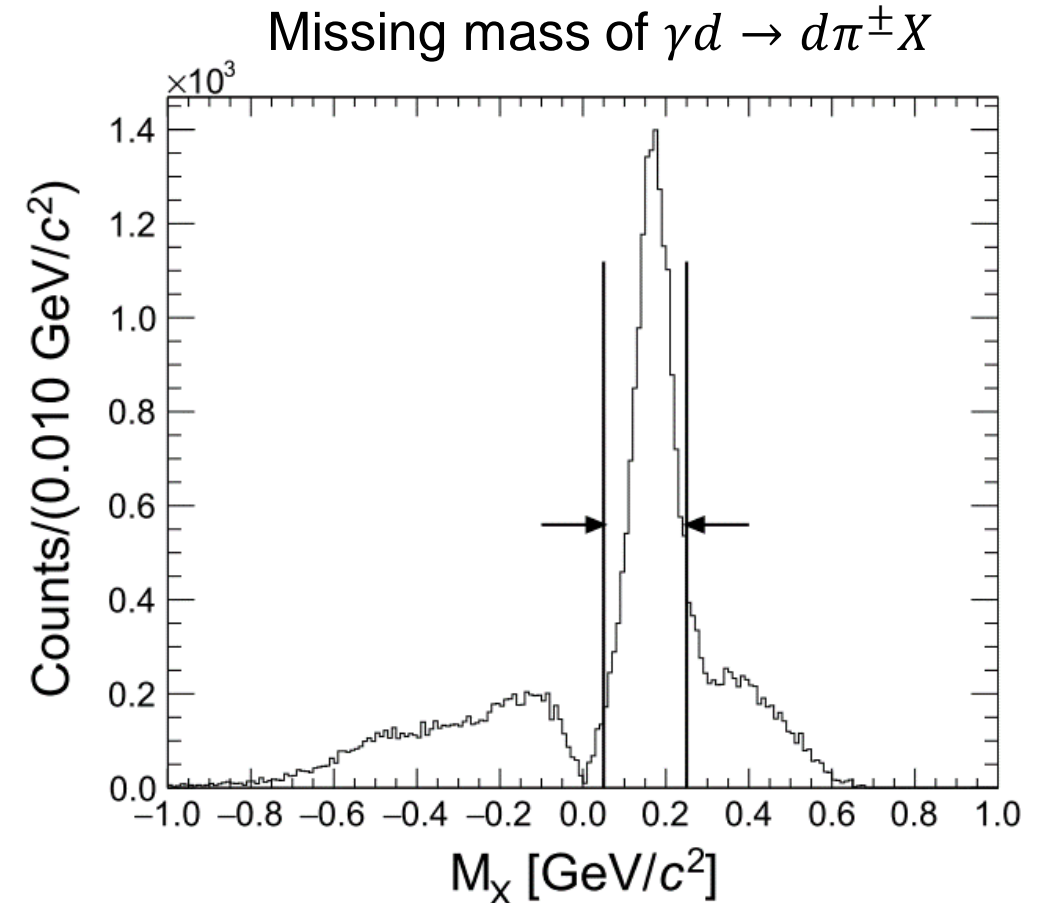
- Selection of the $\gamma \rightarrow d\pi^+\pi^-$ reaction events
- Invariant mass distributions
- Cross sections



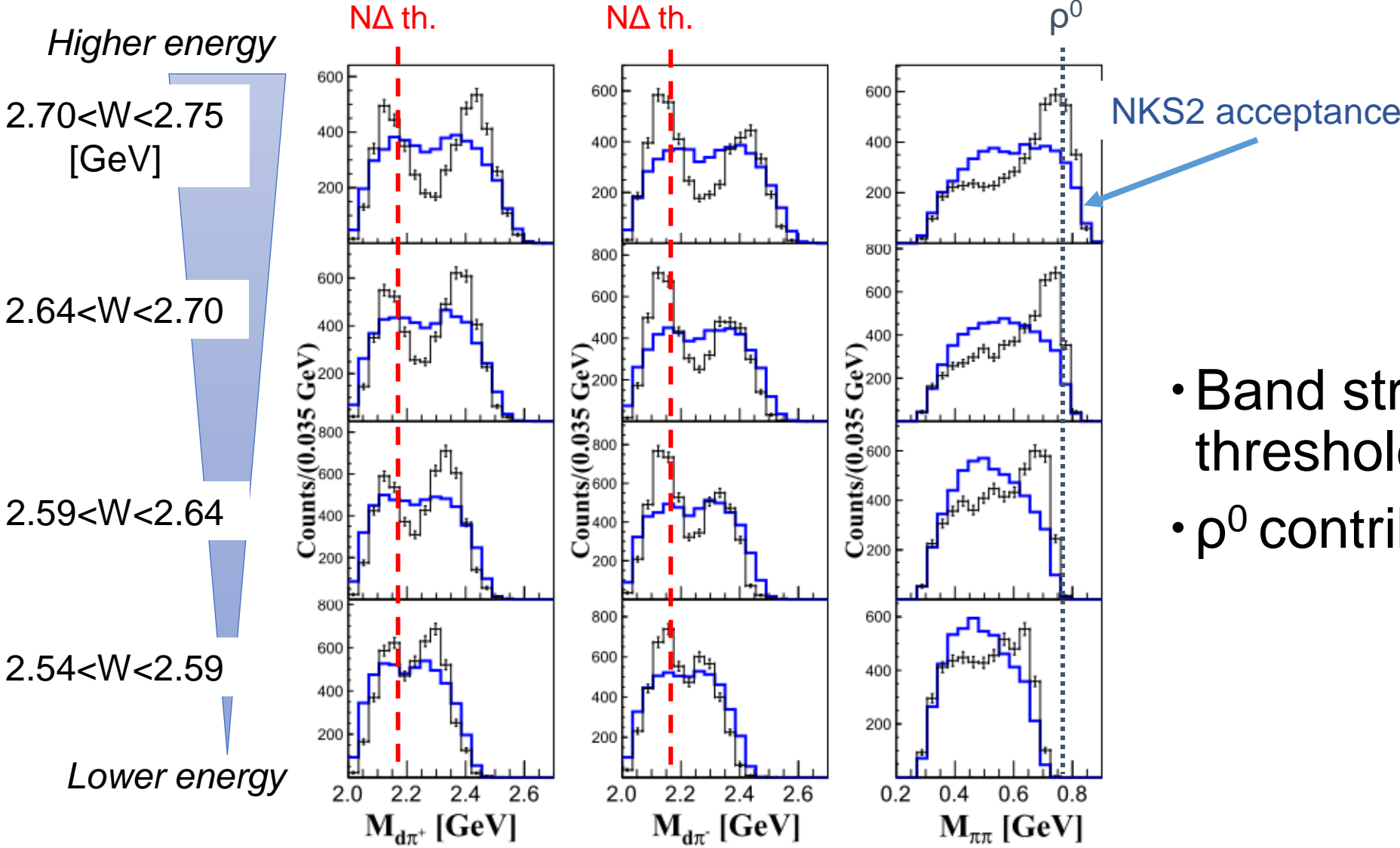
- Momentum and ToF between IH & OH
- Good π , p , d separation



- 2-track analysis
 - Detect 2 charged particles, $d\pi^+$ or $d\pi^-$
 - Missing mass for $\pi^{+/-}$
- 3-track analysis (for consistency check, not shown today)
 - Detect 3 charged particles, $d\pi^+\pi^-$
 - Mom & Energy conservation cut

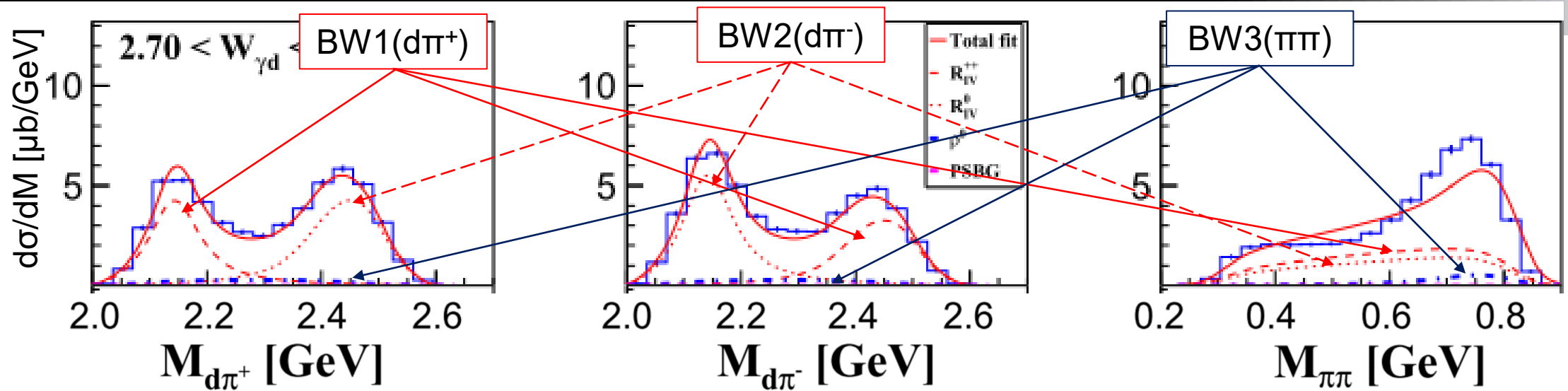


Invariant mass spectra (event counts)



- Band structure below $N\Delta$ threshold in $M_{d\pi}$
- ρ^0 contribution in $M_{\pi\pi} \sim 0.7$

Differential cross sections ($d\sigma/dM$)

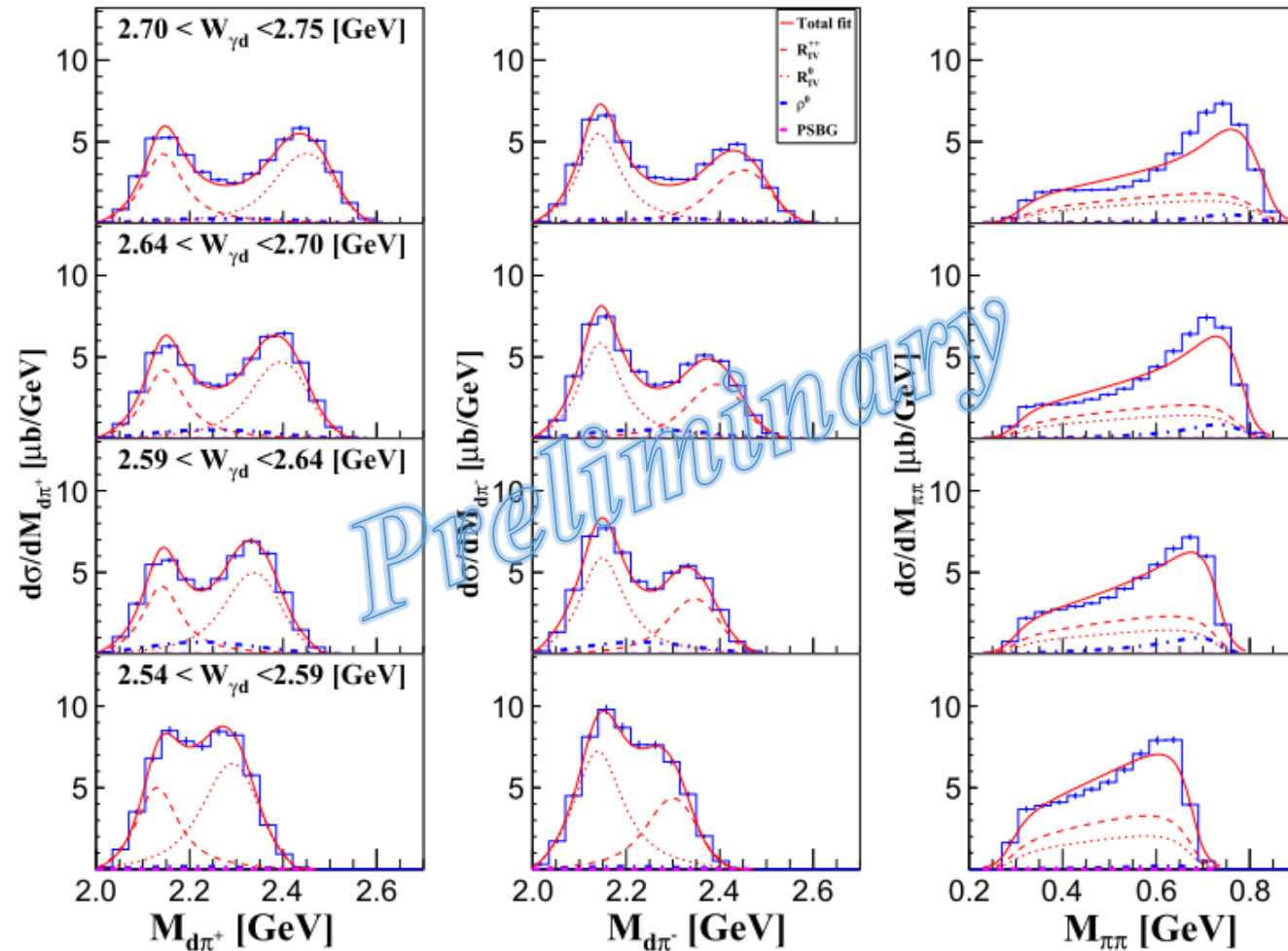


$$N(m_{d\pi^+}) = \int_{m_{\pi\pi}} \int_{m_{d\pi^-}} \left(\left| \alpha A_{M_{++}, \Gamma_{++}}^{R_{IV}^{++}}(m_{d\pi^+}) + \beta A_{M_{0}, \Gamma_{0}}^{R_{IV}^0}(m_{d\pi^-}) + \gamma A_{M_{\rho}, \Gamma_{\rho}}^{\rho}(m_{\pi\pi}) \right|^2 + C \right) V_{PS}(m_{d\pi^+}, m_{d\pi^-}, m_{\pi\pi}) dm_{d\pi^-}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

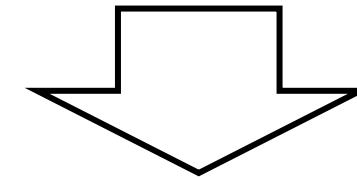
Phase space

- (3 Breit-Wigner + PS background) \otimes Det. Resolution
 - Mass & Width of ρ^0 were fixed at 0.77 and 0.15 GeV

Differential cross sections ($d\sigma/dM$)



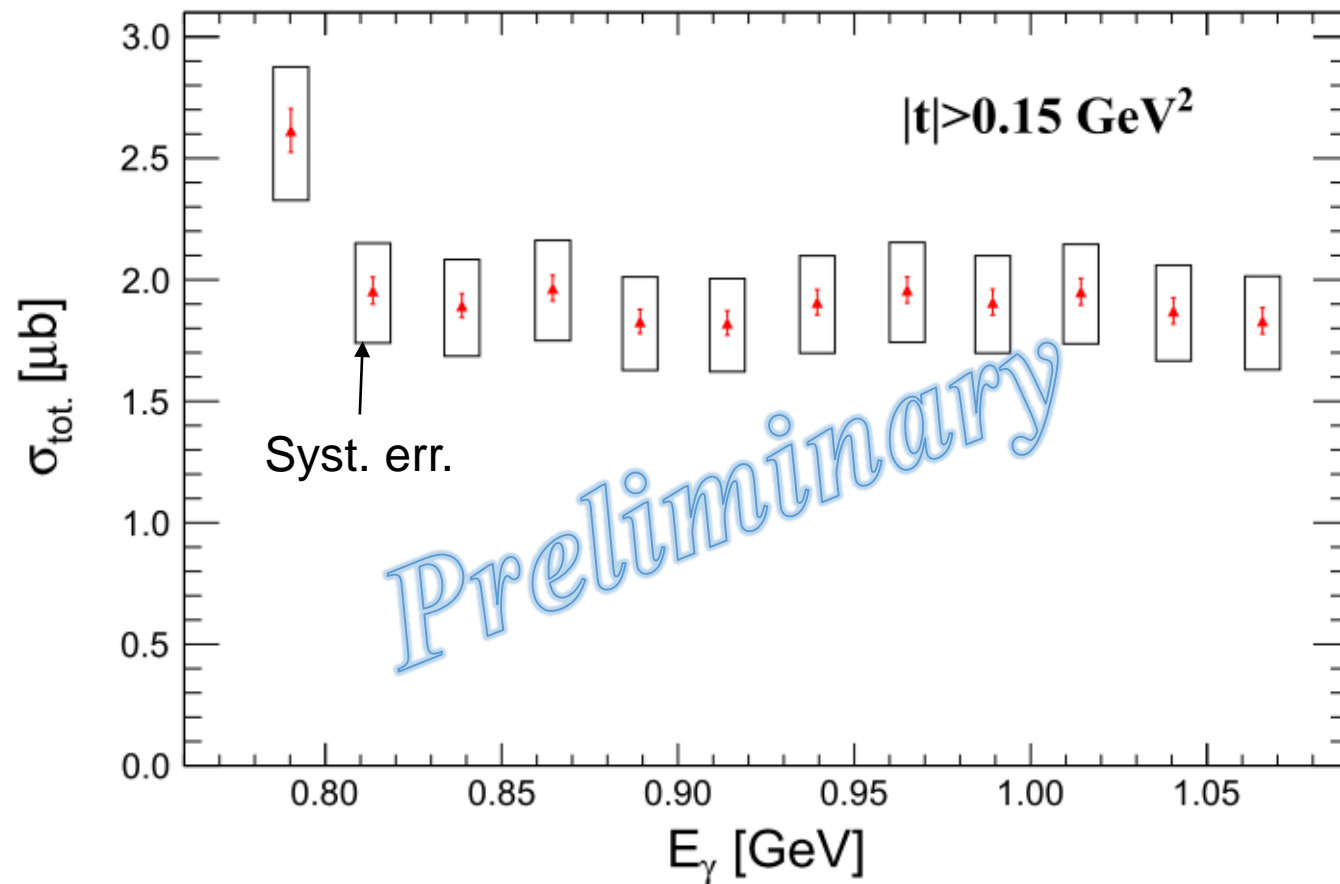
- Weighted average of higher energy points
 - $M=2.133\pm 0.001$ (stat.) ± 0.009 (syst.) GeV
 - $\Gamma=0.103\pm 0.002$ (stat.) ± 0.009 (syst.) GeV
- Systematic errors of fitting
 - standard deviation of the all points
 - ρ^0 free fitting result



Lower than $N\Delta$ threshold (~ 2.17 GeV)
 Narrower than single Δ width (~ 0.12 GeV)

Consistent with D_{12} ($z=+1$) from FOREST
 ($M=2.140\pm 0.011$ GeV, $\Gamma=0.091\pm 0.011$ GeV)

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



- No significant structure

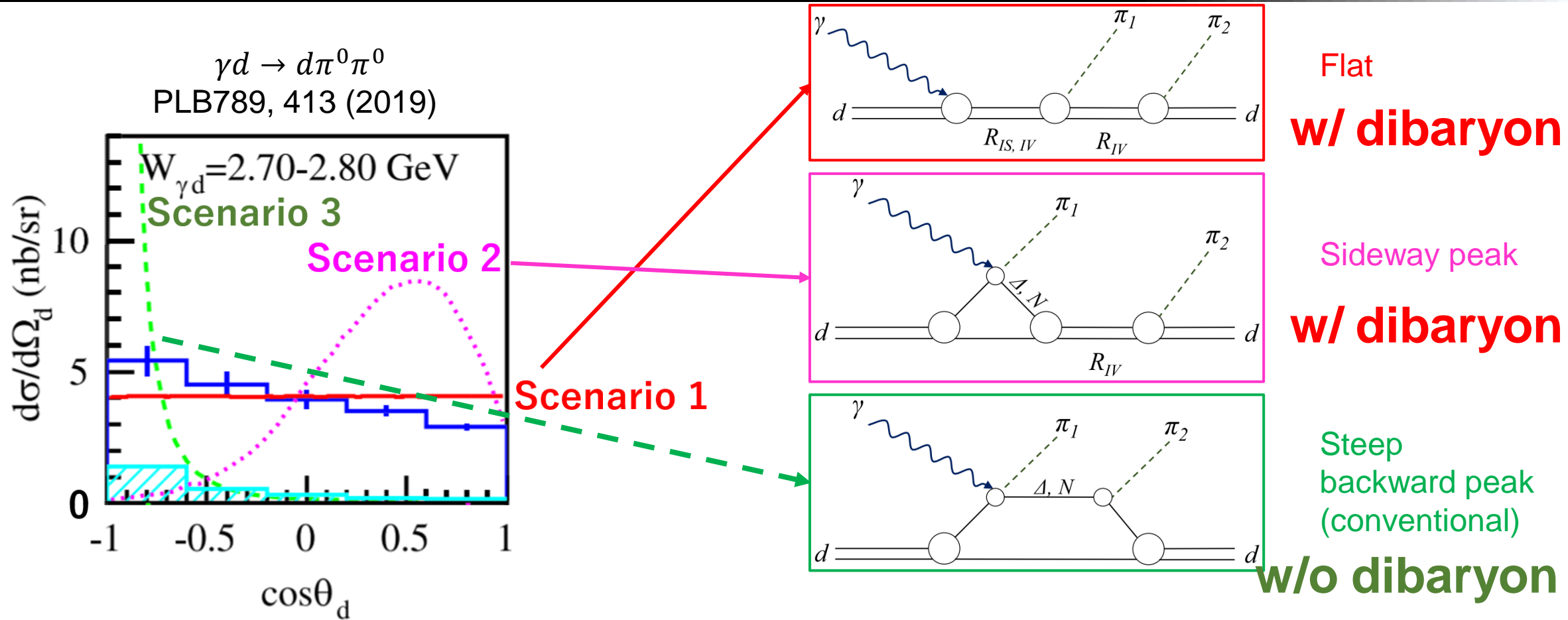
- $\sim 2 \mu\text{b}$
- Syst. error $\sim 8\%$

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

- $|t|=0.15 \text{ GeV}^2/c^2 \Rightarrow p_d \sim 350 \text{ MeV}/c$
 - Out of NKS2 acceptance due to the energy loss

Discussions

- Possible scenarios for 2π production and deuteron emission angle distribution

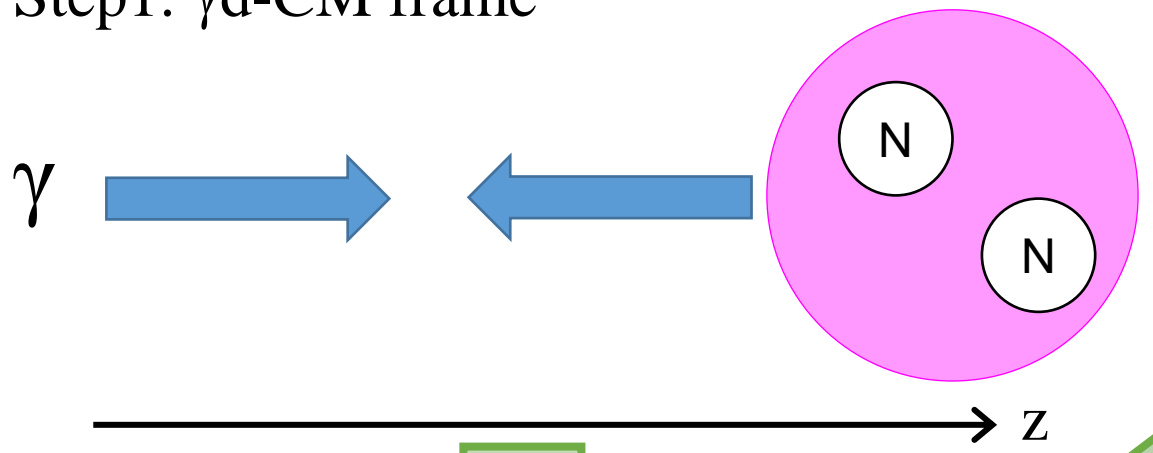


These are separatable by $\cos\theta_d$ (γd CM frame) distribution

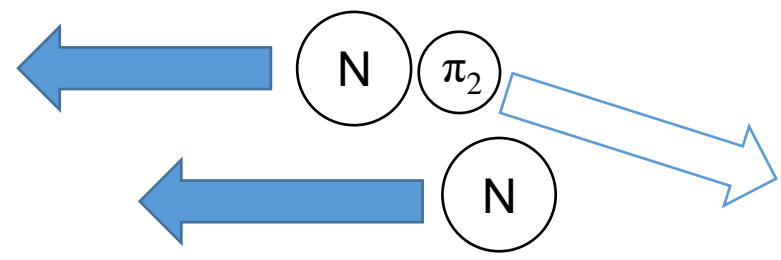
if no isovector dibaryon (conventional), $\cos\theta_d$ strong backward peak

Quasi-free 2π production (Scenario3, Fix calc.)

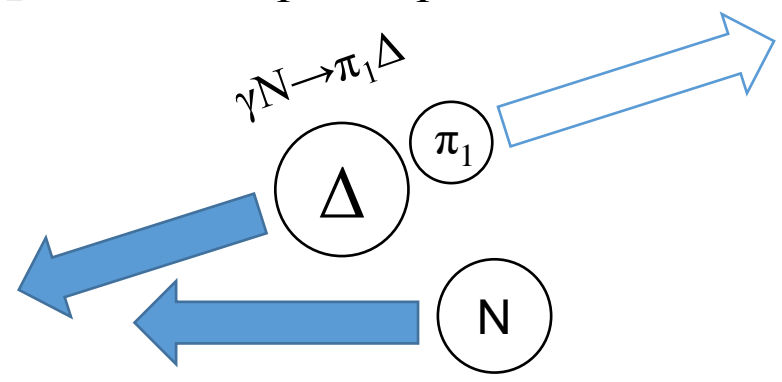
Step1. γ d-CM frame



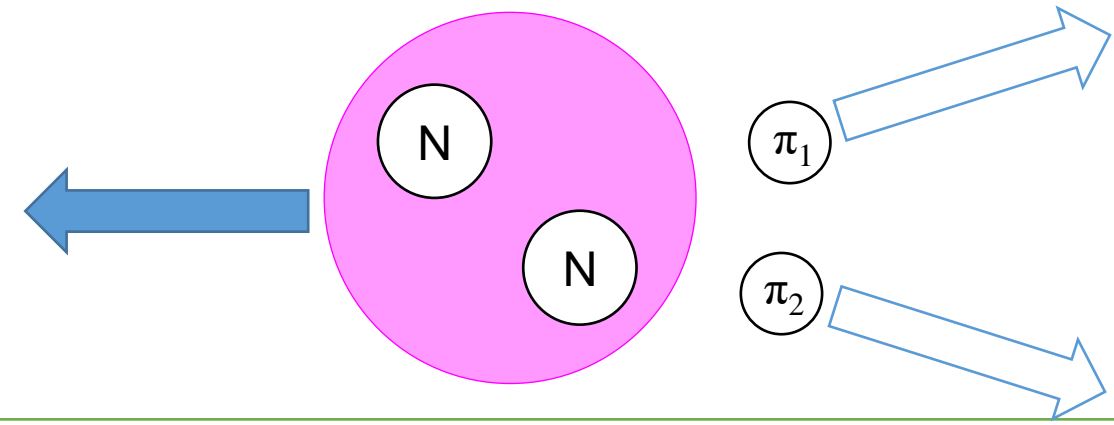
Step3. $\Delta \rightarrow \pi_2 N$, π_2 forward emission

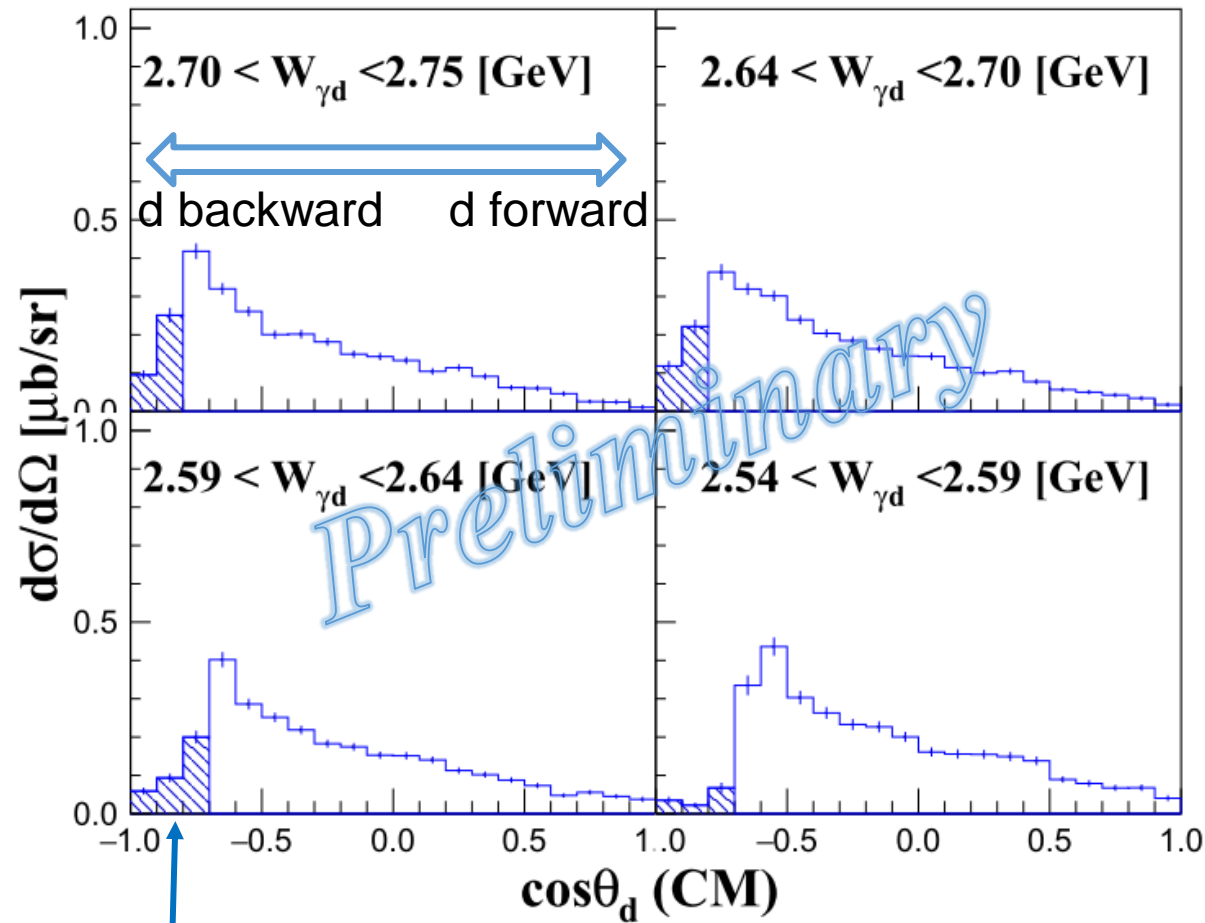


Step2. $\gamma N \rightarrow \pi_1 \Delta$, π_1 forward emission

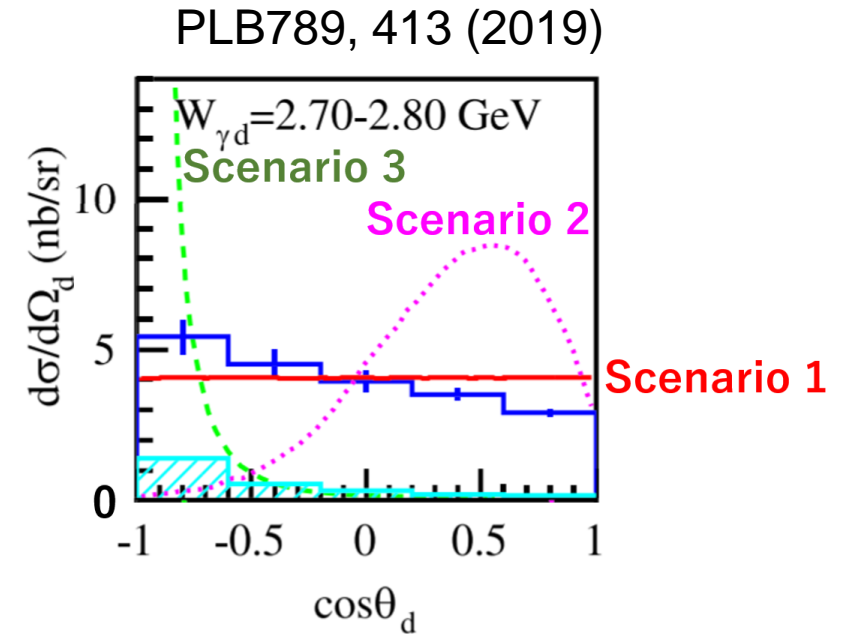


Step4. NN forms deuteron

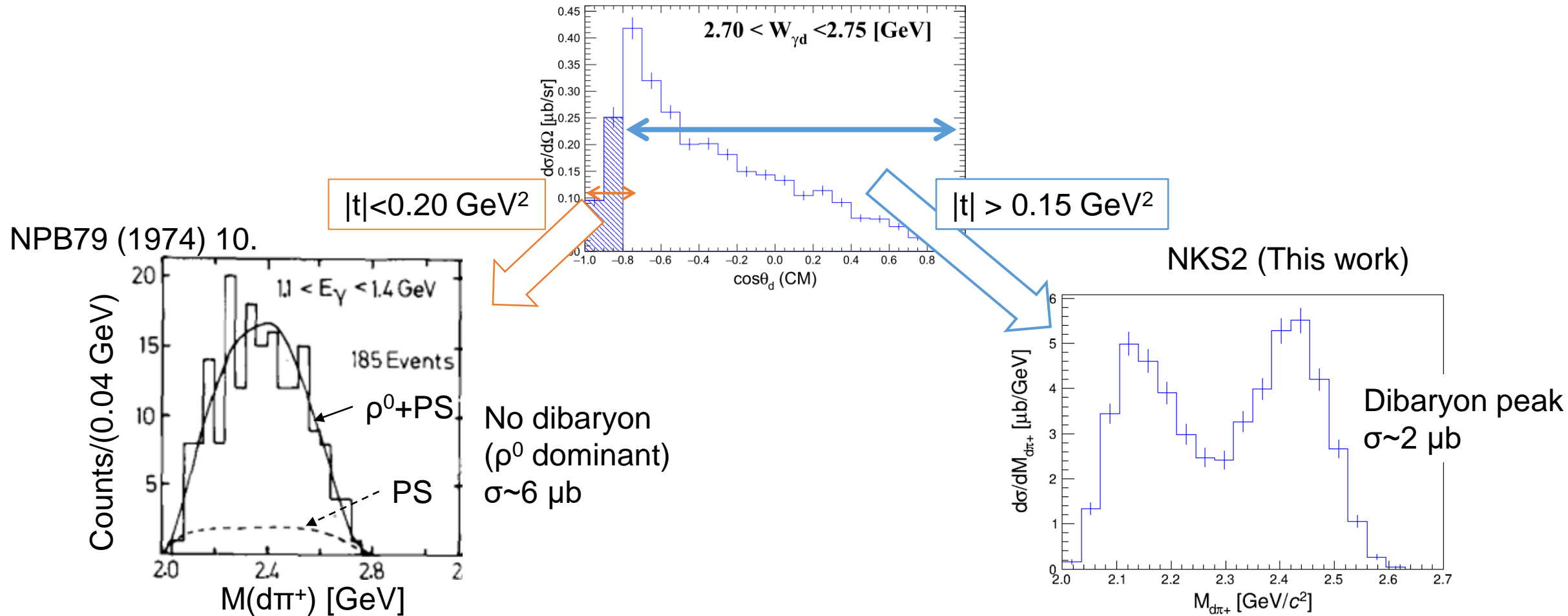




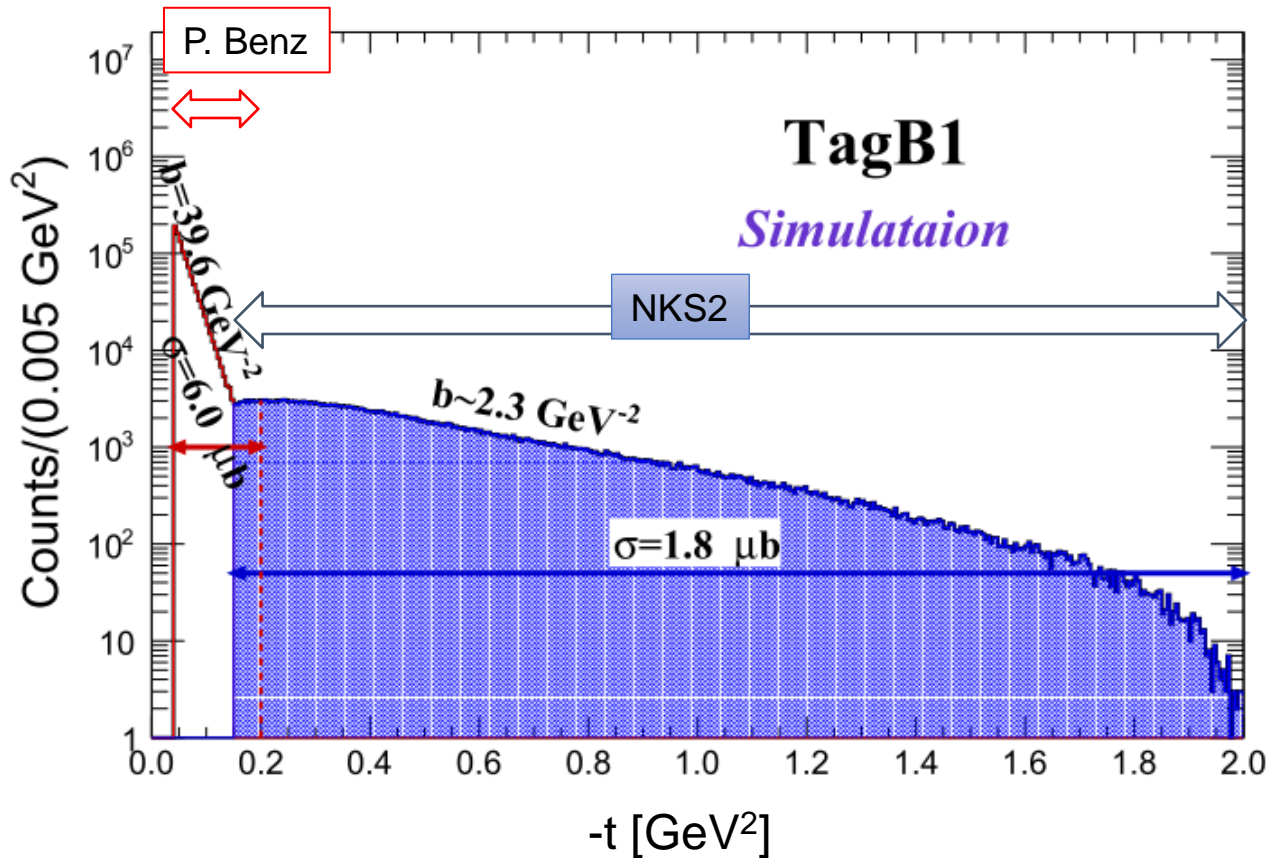
$|t| < 0.15 \text{ GeV}^2$
(almost no sensitivity)



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



Our kinematic region was sensitive to unconventional processes.



- $|t| > 0.15 \text{ GeV}^2$ region: Tuned by NKS2 data
- Boundaries:
 - Connection at $|t| = 0.15 \text{ GeV}^2$
 - $\exp(-b|t|)$ shape in $|t| < 0.15 \text{ GeV}^2$ region
 - $6 \mu\text{b}$ in $0.04 < |t| < 0.20 \text{ GeV}^2$ region
- $b \sim 40 \text{ GeV}^{-2}$ was obtained
 - Same order of ρ^0 production in $1.8 < E_\nu < 2.5 \text{ GeV}$ (NPB79 (1974) 10.)

Our result might observed unconventional process region.

Future prospects

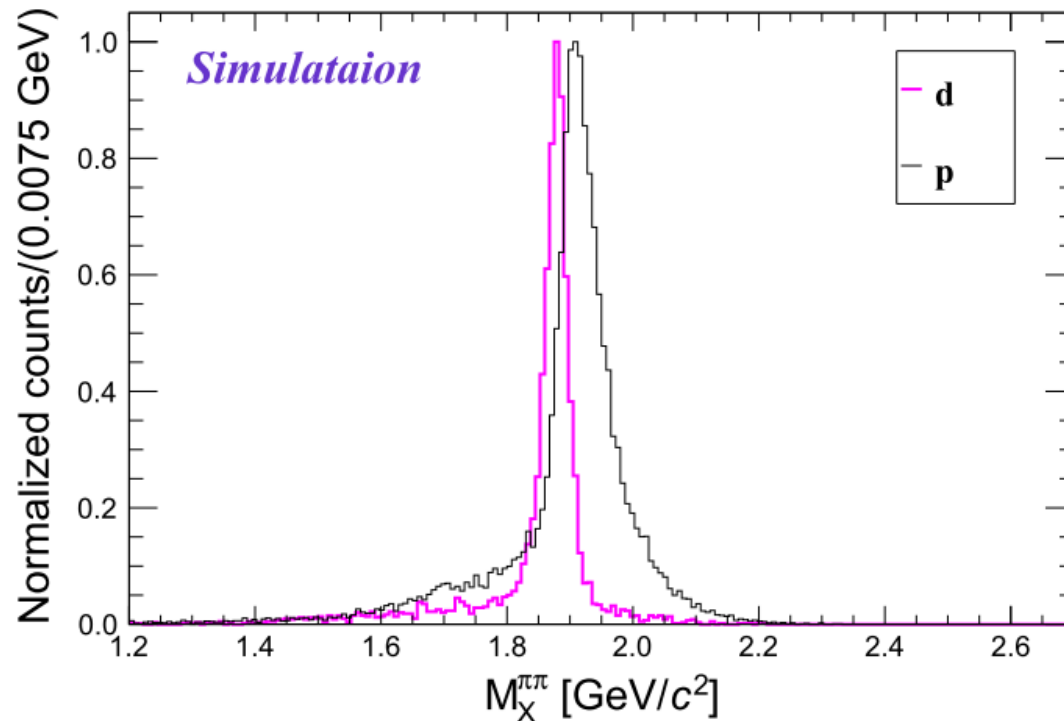
Further analysis of existing data

Further experiment

We have well calibrated data! Why not analyze?

- $\gamma d \rightarrow d\pi^+\pi^-$ in $|t| < 0.15 \text{ GeV}^2$ (low mom. d) region
 - Suppress $\gamma d \rightarrow pn\pi^+\pi^-$ b.g. by Genfit or(and) kinematical fit of VDC
 - ~ 60000 events expected (if $\sigma=6 \text{ } \mu\text{b}$ in this region and efficiencies are same in my analysis)
- $\gamma d \rightarrow d\pi^+\pi^-\pi^0$
 - D_{03} search
 - η 'd nucleus (BE=25 MeV) threshold $E_\gamma \sim 1.15 \text{ GeV}$ (out of range)
- Strangeness production (polarization)
 - $K^0\Lambda$
 - $K^+\Lambda$ (3-track analysis partly done by T. Fujii, [JPS Conf. Proc. 021003](#))

- Missing mass of the $\gamma d \rightarrow \pi^+ \pi^- X$ reaction with simulations of
 - $\gamma d \rightarrow \pi^+ \pi^- \mathbf{d}$
 - $\gamma d \rightarrow \pi^+ \pi^- \mathbf{pn}$ (quasi-free reaction)



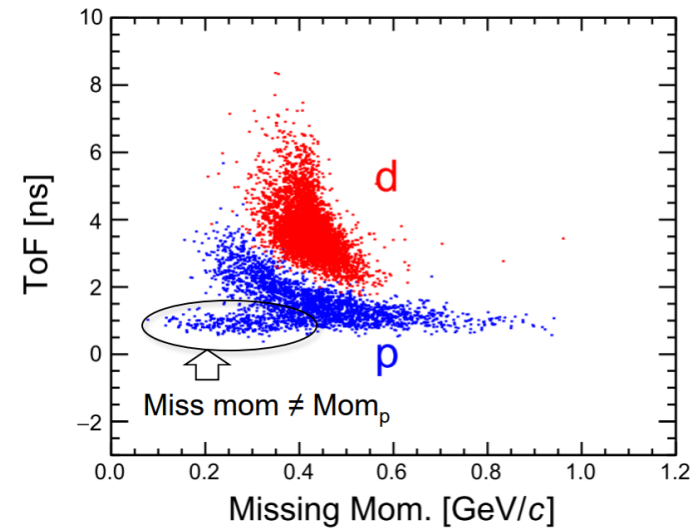
Simulated data of $\gamma d \rightarrow \pi^+ \pi^- \mathbf{d}$ and $\gamma d \rightarrow \pi^+ \pi^- \mathbf{pn}$
 $\gamma d \rightarrow \pi^+ \pi^- \mathbf{d}$: Tuned generator for the acceptance estimation of NKS2
 $\gamma d \rightarrow \pi^+ \pi^- \mathbf{pn}$: Quasi-free 2π production (on-shell proton w/ fermi motion, spherical uniform)

Difficult to discriminate them but...

d/p separation by using ToF between the target & IH

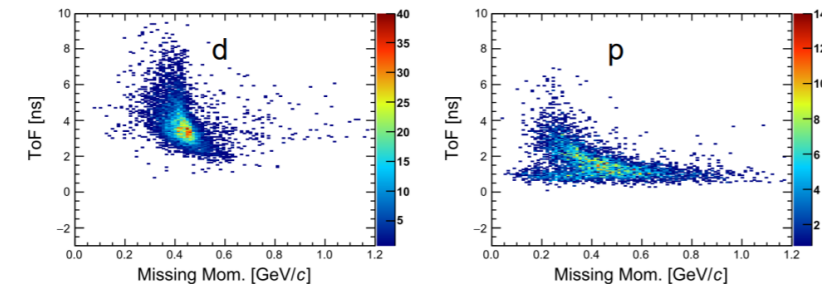
- d (or p) w/ IH (inner hodo.) hit
 - Min. mom_d : $\sim 350 \text{ MeV}/c \Rightarrow \sim 200 \text{ MeV}/c$
- Cross section of the $p\pi^+\pi^-$: ~ 100 times larger
- Other available information
 - Hit pattern of VDC&CDC
 - dE measured by IH
 - Machine learning? Kinematical fit?

Separation of $p\pi\pi$ and $d\pi\pi$



- w/o DC info.

- IH resolution: 200 ps (σ)
- t_0 : time at vertex $\pi^{+/-}$
- ToF: $\text{IH}_d - t_0$
- Missing mom.: $\gamma d \rightarrow \pi^+\pi^-X$
- $p\pi\pi$ simulation: QF $p\pi\pi$ (w/ fermi motion)
- Event selection: $\pi\pi$ vertex, d (or p) w/ IH hit, w/o OH hit



$$\gamma d \rightarrow D_{03} \pi^0 \rightarrow D_{12} \pi^{\pm} \pi^0 \rightarrow d \pi^+ \pi^- \pi^0$$

- Next step of the $\gamma d \rightarrow d \pi^+ \pi^-$ reaction analysis
 - d signal by VDC
 - $\pi^+ \pi^-$ VDC&CDC
 - π^0 missing
- Maybe difficult...

- Planning liquid deuterium target exp.
 - Λn FSI ($\gamma d \rightarrow \Lambda n K^+$)
 - η' 'd nucleus search ($\gamma d \rightarrow [d\eta'] \rightarrow d\eta \rightarrow d\pi^+\pi^-\pi^0$)
- Data w/ higher E_γ (upto 1.25 GeV) would be accumulated automatically!

- The cross section of the $\gamma d \rightarrow d\pi^+\pi^-$ reaction in $|t|>0.15 \text{ GeV}^2/c^2$ region
 - First measurement in this kinematic region
 - E_γ : 0.78—1.08 GeV
 - Total cross section: $\sim 2\mu\text{b}$ (almost flat)
- Isovector resonance structure (R_{IV}) in $d\pi^{+/-}$ invariant mass
 - $M=2.133 \pm 0.001 \text{ (stat.)} \pm 0.009 \text{ (syst.) GeV} < M_N+M_\Delta \sim 2.17 \text{ GeV}$
 - $\Gamma = 0.103 \pm 0.002 \text{ (stat.)} \pm 0.009 \text{ (syst.) GeV} < \Gamma_\Delta \sim 0.12 \text{ GeV}$
 - Consistent with FOREST ($M=2.14 \pm 0.01, \Gamma=0.09 \pm 0.01 \text{ GeV}$)
 - $z=+2, 0$ state of D_{12}
- Room of further analysis & experiments