

Coherent meson photoproduction off the deuteron at forward angles at BGOOD

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Exotic multi-quark states and baryon spectroscopy workshop

27th June 2024

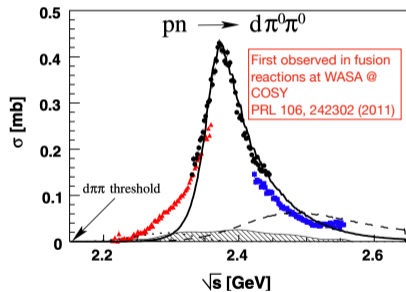
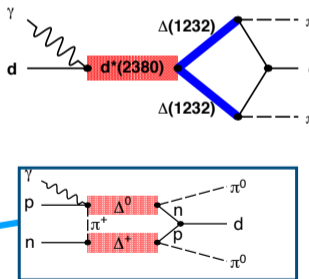
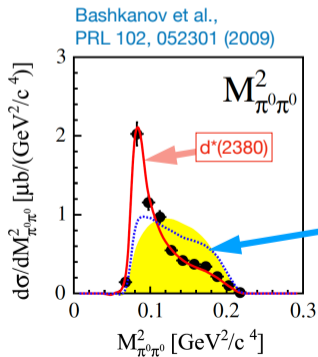
Supported by the DFG PN 388979758 & 405882627 & the EU Horizon 2020 research & innovation programme, grant agreement 824093



The $d^*(2380)$ dibaryon/hexaquark

The ABC effect

- A low mass enhancement in the $\pi\pi$ invariant mass - first observed in the 1960s (double pionic fusion of deuteron and proton to ^3He) Booth, Abashian, & Crowe, PRL. 7, 35 (1961)
- Described when including the $d^*(2380)$:

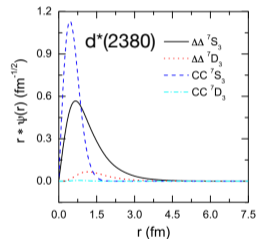
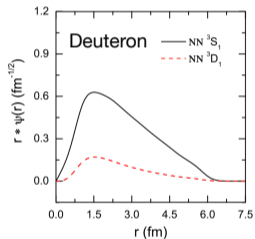
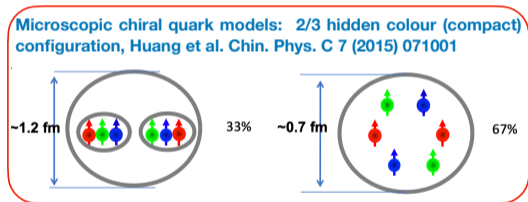


- $(1)J^P = (0)3^+$
- Now observed in multiple final states in pn reactions

The $d^*(2380)$ dibaryon/hexaquark candidate

- Chiral quark models - predict a colour compact configuration

Huang et al. Chin Phys. C 7 (2015) 07001



- Compact nature supported by beam asymmetry measurements of deuteron photodisintegration Bashkanov et al. PLB 789 (2019) 7

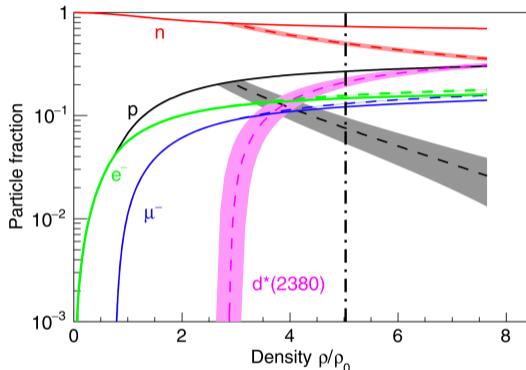
The $d^*(2380)$ dibaryon/hexaquark

- Soften the equation of state of neutron stars - a solution to the *Hyperon puzzle*?

Vidana et al., PLB 781 (2018) 112

- Calculated particle fractions within neutron star interiors with/without $d^*(2380)$ (dashed/solid lines)

Vidana et al., PLB 781 (2018) 112



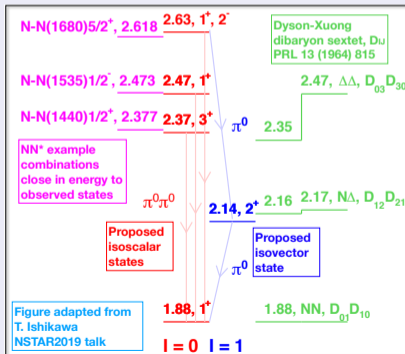
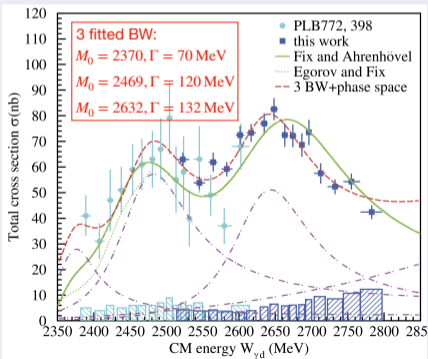
- Dark matter candidate? $d^*(2380)$ BEC formed in the early universe

Bashkanov & Watts, JPG 47 (2020) 03LT01

A spectrum of dibaryons?

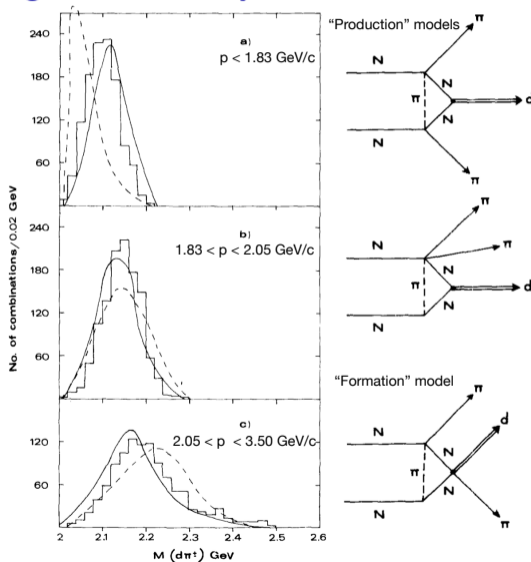
- SU(6) for baryons - 4 dibaryon candidates Dyson & Xuong PRL 13 (1964) 815
- 3-body calculations - $N\Delta$ & $\Delta\Delta$ resonances in good agreement Gal & Garcilazo NPA928 (2014) 73
- Alternative descriptions via OPE & triangle type mech. eg, Molina, Ikeno, Oset, arXiv:2102.05575 (2021)

$\gamma d \rightarrow \pi^0 \pi^0 d$ data from ELPH Ishikawa et al, PLB 789 (2019) 413



Alternatively - π exchange & no dibaryons

- One example of (many) One π Exchange (OPE) model description
I. Bar-Nir et al. , NPB 54 (1973)
- $np \rightarrow \pi^+ \pi^- d$ measured at DESY
- The $\pi^+ d$ invariant mass OPE models, no intermediate dibaryons



Coherent meson photoproduction off the deuteron at forward angles at BGOOD

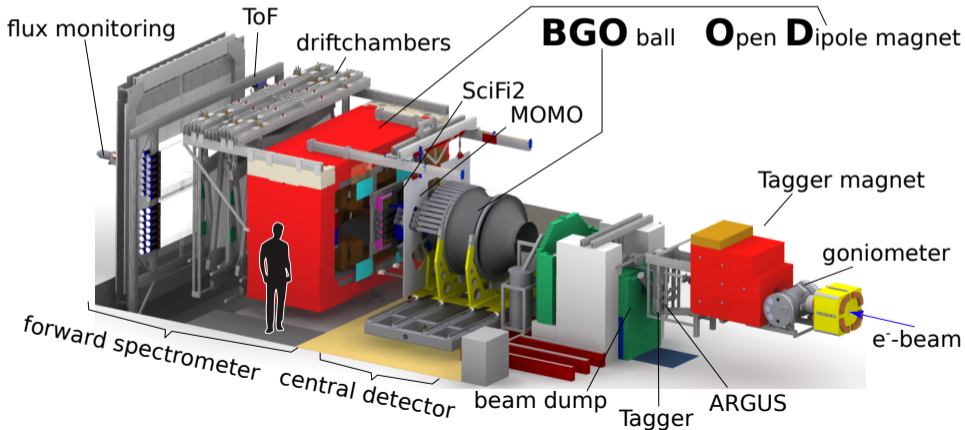
1. Motivation - dibaryon formation or OPE?
2. Studies with the BGOOD experiment at ELSA:
 - Coherent $\pi^0\pi^0d$ photoproduction
 - Coherent $\pi^0\eta d$ photoproduction
 - Coherent $\pi^0\pi^0\pi^0d$ photoproduction



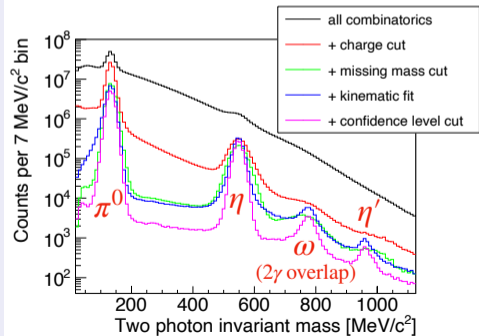
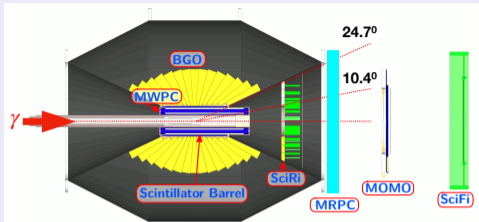
The BGOOD experiment, Eur. Phys. J. A 56:104 (2020)

Spokespersons: T.C Jude (Bonn) & P. Levi Sandri (Frascati)

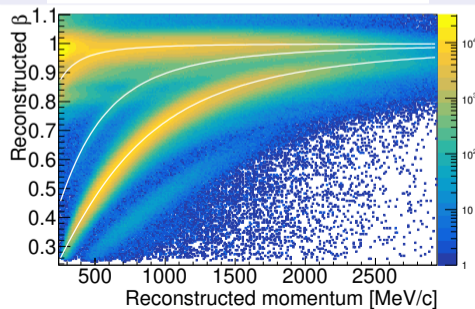
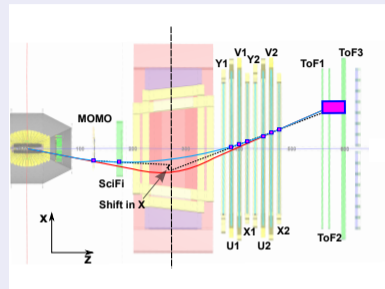
- ELSA - a 3 stage accelerator - continuous e^- beams up to 3.2 GeV
- BGOOD - BGO calorimeter (central region) & Forward Spectrometer combination



BGOOD central region



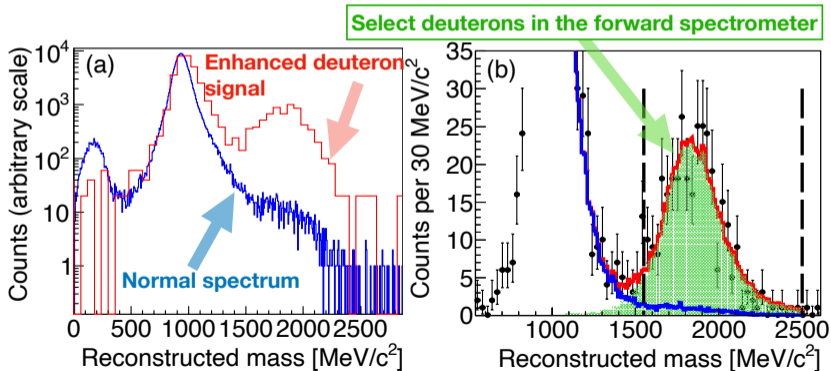
BGOOD forward region



$\gamma d \rightarrow \pi^0 \pi^0 d$ at BGOOD - analysis steps

T.C. Jude, et al., Phys. Lett. B 832 (2022) 137277

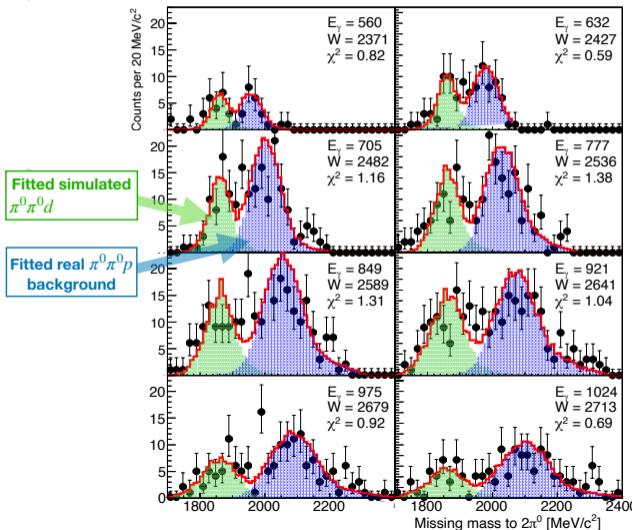
- Coherent reaction - $\gamma d \rightarrow \pi^0 \pi^0 d$, deuterons in the forward spectrometer
- Unexpected! $p_d > 400$ MeV/c & deuteron Fermi momentum ~ 80 MeV/c



$\gamma d \rightarrow \pi^0 \pi^0 d$ at BGOOD - analysis steps

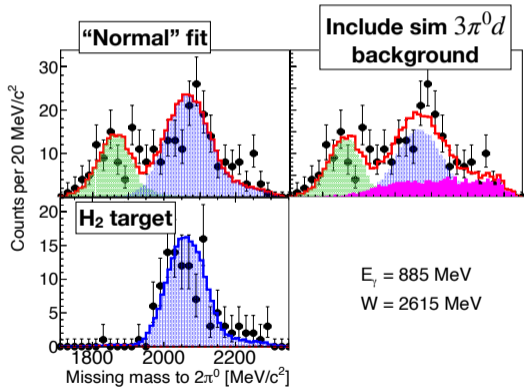
T.C. Jude, et al., Phys. Lett. B 832 (2022) 137277

- Forward deuterons
- $\pi^0 \rightarrow \gamma\gamma$ in the BGO Rugby Ball
- Reconstructed - measured deuteron direction $< 7.5^\circ$
- Fit to the “ $2\pi^0$ Missing mass” ($\gamma d \rightarrow \pi^0 \pi^0 X$)

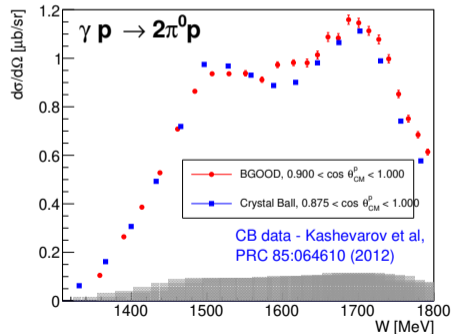


$\gamma d \rightarrow \pi^0 \pi^0 d$ at BGOOD - systematic uncertainties

- Systematic studies using hydrogen data & fitting with other background channels



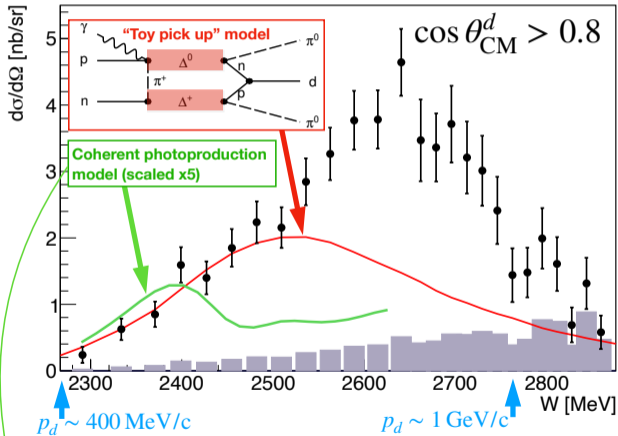
- Good agreement for a “Similar reaction”, $\gamma p \rightarrow \pi^0 \pi^0 p$
- Small difference at $W \sim 1600$ MeV understood - background from $\gamma p \rightarrow \eta p$



$\gamma d \rightarrow \pi^0 \pi^0 d$ at BGOOD - differential cross section Vs. W

T.C. Jude, et al., Phys. Lett. B 832 (2022) 137277

- Not described by coherent photoproduction model or “Toy pick up model”



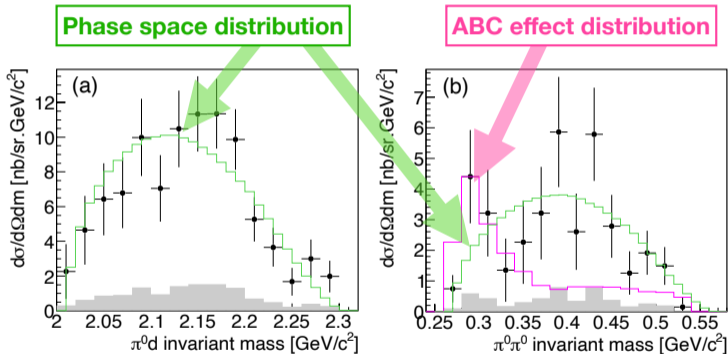
Egorov & Fix, NPA, 933 (2015) 104 - Fix & Arenhövel, EPJA, 25 (2005) 115

The Toy pick up model

- Arbitrary scale
- On-shell momentum & energy conservation
- Nucleons coalesce to form the deuteron if their relative momentum is sufficiently small

$\gamma d \rightarrow \pi^0 \pi^0 d$ at BGOOD - invariant mass distributions

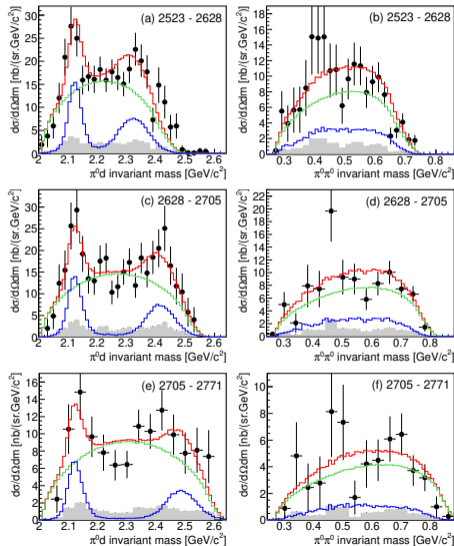
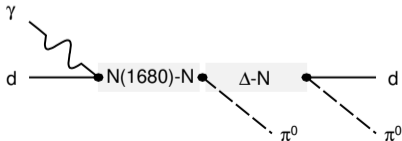
- The $\pi^0 d$ and $\pi^0 \pi^0$ invariant mass distributions over the $d^*(2380)$ range
- Consistent with the ABC effect (distribution from P. Adlarson et al. PRC, 86:032201, 2012.)



- Differential cross section for $\gamma d \rightarrow d^*(2380) \rightarrow \pi^0 \pi^0 d$: $(22 \pm 6_{\text{stat}} \pm 4_{\text{sys}}) \text{ nb}/\text{sr}$
- Angular dis. well known - cross section extrapolated to $(11.3 \pm 3.2_{\text{stat}} \pm 2.7_{\text{sys}}) \text{ nb}$

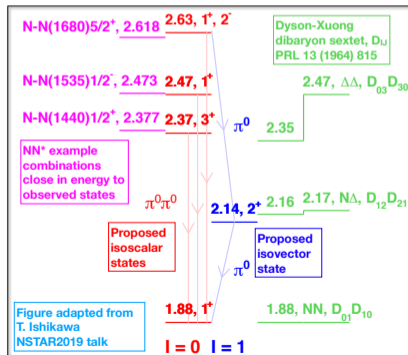
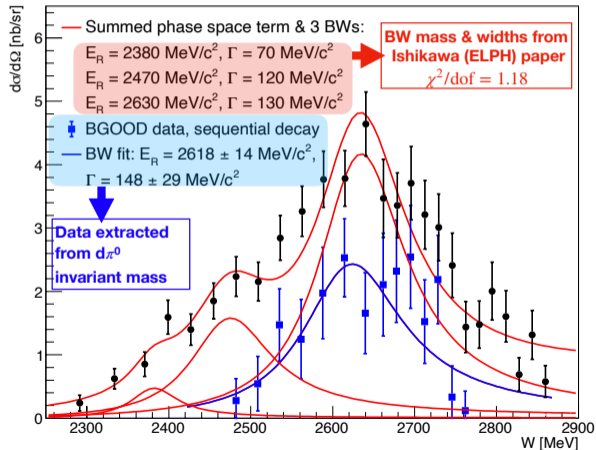
$\gamma d \rightarrow \pi^0 \pi^0 d$ at BGOOD - Invariant mass distributions

- $\pi^0 d$ & $\pi^0 \pi^0$ invariant mass distributions for higher W intervals
- Simulated sequential decay - different masses & widths of the first dibaryon
- Sequential decay + Phase space = sum
- Mass of 2114 MeV/c² and width ~ 20 MeV/c² (exp. resolution!) proved optimal



$\gamma d \rightarrow \pi^0 \pi^0 d$ at BGOOD - Evidence of a dibaryon spectrum?

- Supports dibaryons states proposed at ELPH Ishikawa et al, PLB 789 (2019) 413



Coherent meson photoproduction off the deuteron at forward angles at BGOOD

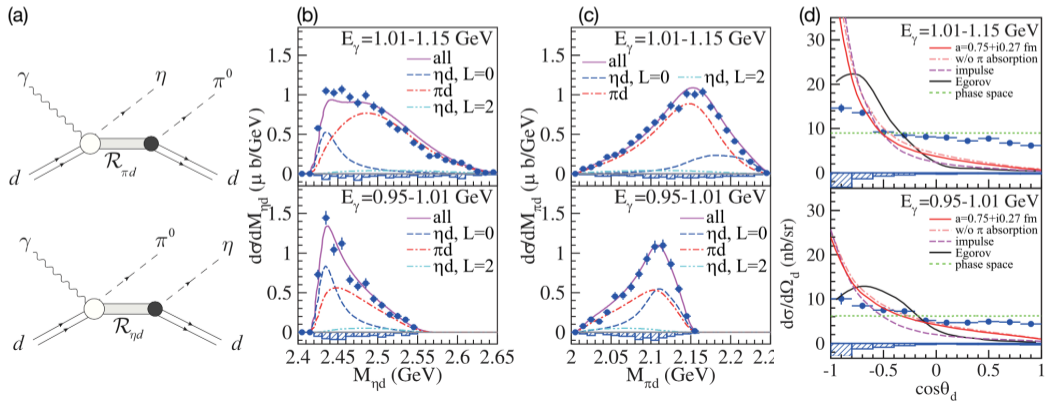
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$\gamma d \rightarrow \pi^0 \eta d$ at ELPH

T. Ishikawa et al., Phys. Rev. C 105, 045201 (2022), Phys. Rev. C 104, L052201 (2021)

- Phenomenological analysis including diagrams in (a)
- invariant mass distributions support a bound/virtual ηd state
- Angular distribution not described by models [Torres, Kemchandani and Oset, PRC 107, 025202 \(2023\)](#)



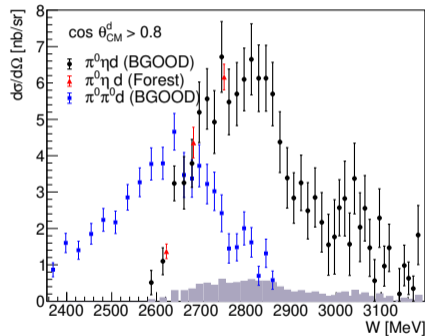
$\gamma d \rightarrow \pi^0 \eta d$ at BGOOD

A.J. Clara Figueiredo, T.C. Jude, arXiv:2405.09392 (2024), to be submitted to PLB

- Excellent agreement with previous ELPH data (red points)

T. Ishikawa et al., PRC 105, 045201 (2022), Phys. Rev. C 104, L052201 (2021)

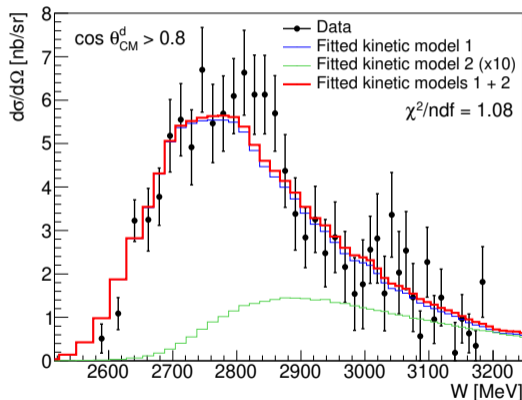
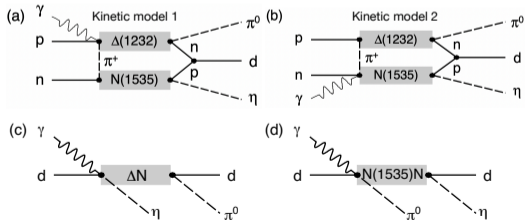
- Unexpectedly large differential cross section, not described by models including $\gamma N \rightarrow \Delta(1700)\frac{3}{2}^- \rightarrow N(1535)\frac{1}{2}^- \pi^0 \rightarrow \pi^0 \eta N$
- Similar mechanism to $\pi^0 \pi^0 d$?



$\gamma d \rightarrow \pi^0 \eta d$ at BGOOD

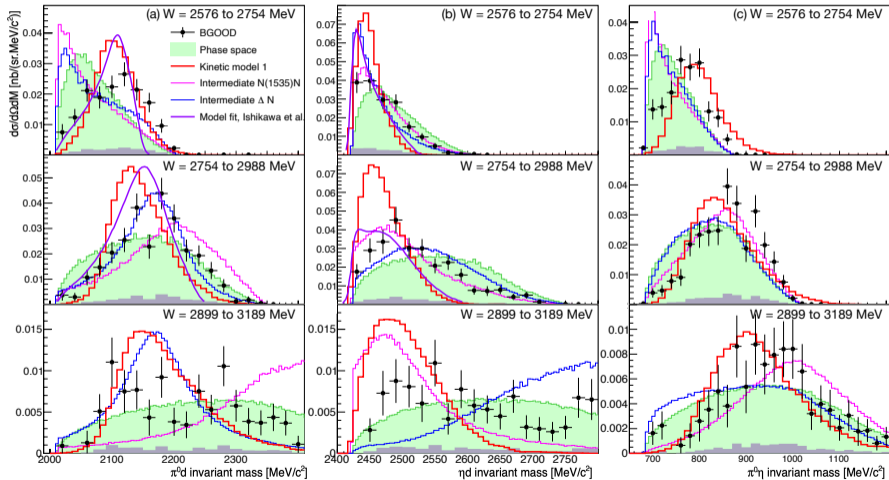
A.J. Clara Figueiredo, T.C. Jude, arXiv:2405.09392 (2024), to be submitted to PLB

- Propose “Toy models” based on diagrams (a) and (b)
- On shell kinematics, final proton & neutron coalesce to deuteron under low relative momentum



$\gamma d \rightarrow \pi^0 \eta d$ at BGOOD - invariant mass distributions

A.J. Clara Figueiredo, T.C. Jude, arXiv:2405.09392 (2024), to be submitted to PLB



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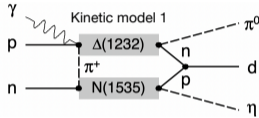
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 - Coherent $\pi^0\pi^0\pi^0d$ photoproduction



$\gamma d \rightarrow \pi^0 \pi^0 \pi^0 d$ at BGOOD

Preliminary, A. Stirner, Masters thesis (Uni Bonn 2021), R. Volk, Master thesis in preparation

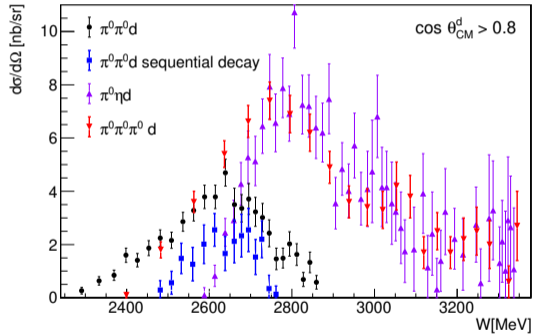
- Similar mechanism to model? -



- Could be naturally explained by similar decay branching ratios:

- $N(1535) \rightarrow \pi N$, $\Gamma_i/\Gamma = 32 - 53\%$
- $N(1535) \rightarrow \pi\pi N$, $\Gamma_i/\Gamma = 4 - 31\%$
- $N(1535) \rightarrow \pi\eta N$, $\Gamma_i/\Gamma = 30 - 55\%$

- Does this discount dibaryon formation?



The BGOOD experiment at ELSA - the story so far

- Unaccounted reaction mechanisms in coherent $\pi^0\pi^0d$ and $\pi^0\eta d$ - dibaryons or pion rescattering terms?

T.C. Jude, et al., Phys. Lett. B 832 (2022) 137277, A.J. Clara Figueiredo, T.C. Jude, arXiv:2405.09392

Extra slides



$\gamma d \rightarrow \pi^0 \pi^0 d$ at BGOOD - Evidence of a dibaryon spectrum?

- $\pi^0 \pi^0$ invariant mass for $2523 < W < 2738$ MeV
- Propose an $N(1680)5/2^+ N$ dibaryon - large coupling to πN
- Positive parity - consistent with decay with odd relative angular momentum to the $N\Delta \pi^0$ system & the change in spin required of the constituents.

