

Evidence of a dibaryon spectrum in coherent $\pi^0\pi^0d$ photoproduction at forward deuteron angles at the BGOOD experiment

Tom Jude, on behalf of the BGOOD collaboration

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Physikalisches Institut, University of Bonn

jude@physik.uni-bonn.de

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grant agreement 824093



Coherent photoproduction at BGOOD

Evidence of a dibaryon spectrum in coherent $\pi^0\pi^0d$ photoproduction

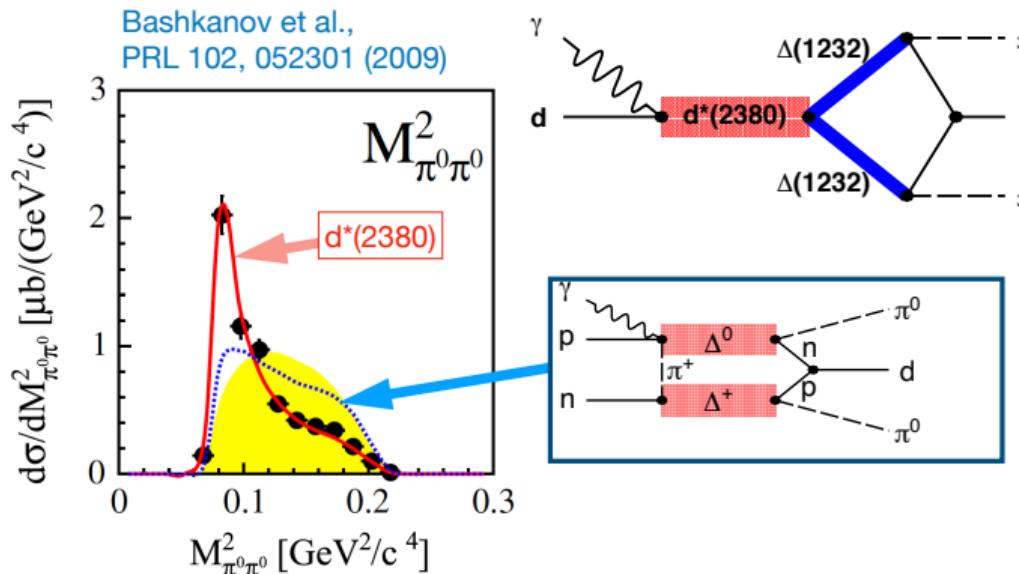
1. Motivation - the $d^*(2380)$, early dibaryon predictions
2. The BGOOD experiment at ELSA, Bonn (Germany)
3. Coherent photoproduction at BGOOD

- $\gamma d \rightarrow \pi^0\pi^0d$ analysis steps
- $\gamma d \rightarrow \pi^0\pi^0d$ results and interpretations
- New preliminary analyses - $\pi^0\eta d$ and $3\pi^0d$



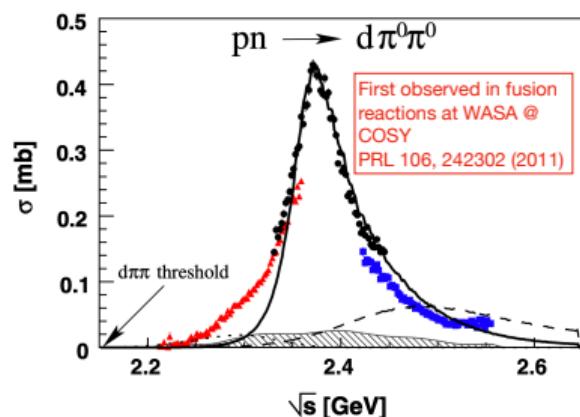
Motivation - the ABC effect

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



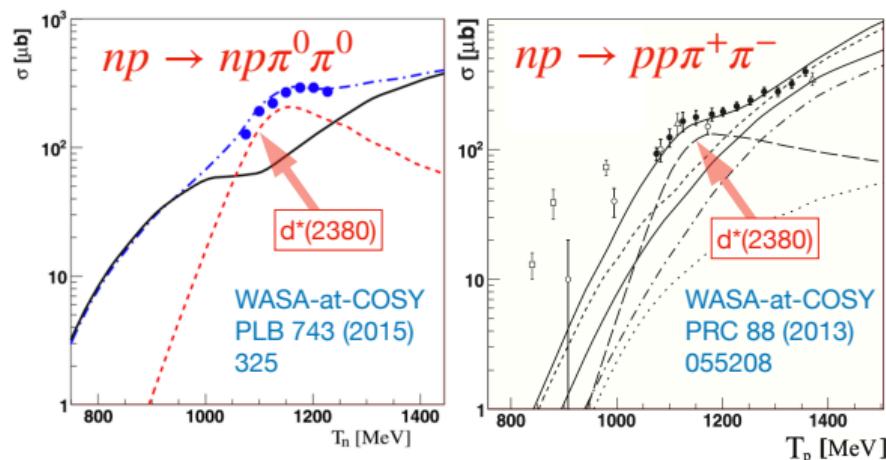
Motivation - the $d^*(2380)$ discovery

Discovery of the $d^*(2380)$ dibaryon



- Width $70 \text{ MeV}/c^2$
- $(I)J^P = (0)3^+$

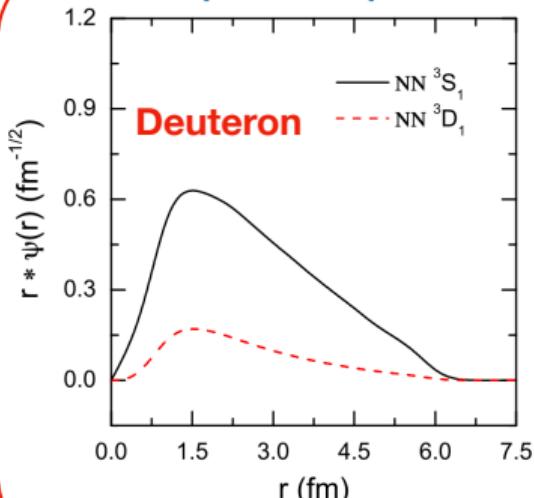
Now observed in multiple final states in pn reactions



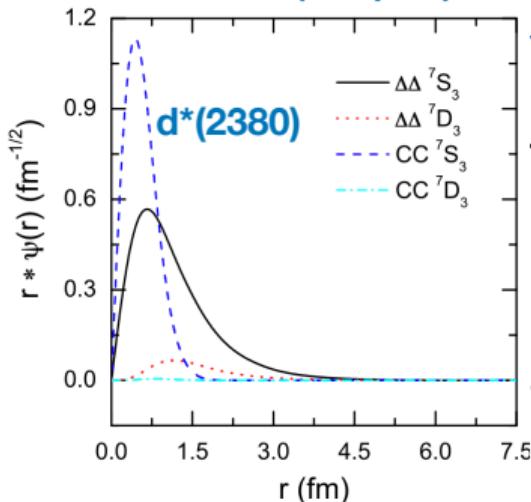
See also: P. Adlarson et al., PLB 721 (2013) 229, P. Adlarson et al. PRL, 112 (2014) 202301, P. Adlarson et al. PRC, 90 (2014) 035204, M. Bashkanov et al. PLB, 789 (2019) 7

Motivation - what is the $d^*(2380)$?

Microscopic chiral quark models: ~2/3 hidden colour (compact) configuration



Huang et al. Chin. Phys. C 7 (2015) 071001



- Compact nature supported by beam asymmetry measurements (Σ) of deuteron photodisintegration by A2 at MAMI [Bashkanov et al. PLB 789 \(2019\) 7](#)

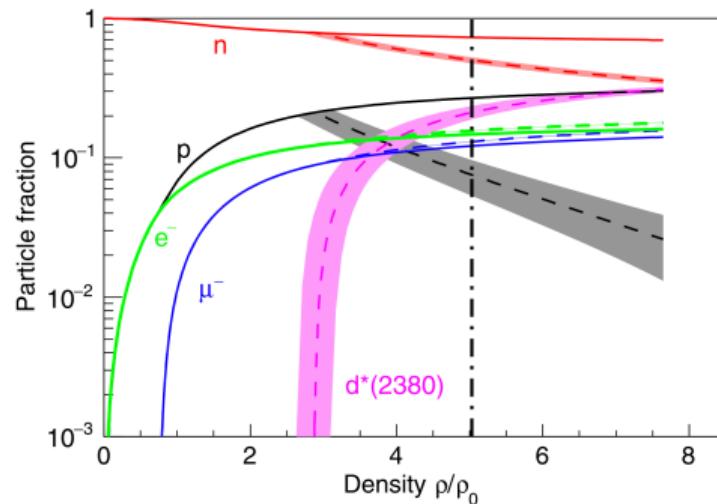
Motivation - $d^*(2380)$ astrophysical implications?

- $d^*(2380)$ in the centre of neutron stars?
Softens the equation of state - mass limits
consistent with observations

Vidana et al, PLB 781 (2018) 112

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

Bashkanov & Watts, J. Phys. G 47 (2020) 03LT01

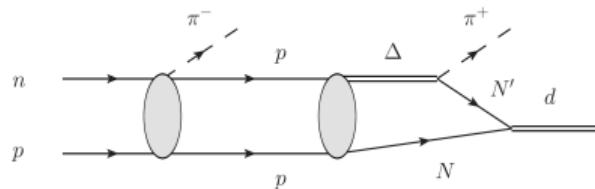


Vidana et al, PLB 781 (2018) 112

Dashed lines - including the $d^*(2380)$
Solid lines - without the $d^*(2380)$

Motivation - early predictions of dibaryons

- Dyson & Xuong: predictions from SU(6) for baryons - 4 dibaryon candidates [PRL 13 \(1964\) 815](#)
- Any quark model with confinement and one gluon exchange inevitably predicts a 6-quark object with $I(J)^P = (0)3^+$
[Goldman et. al. PRC 39, 1889 \(1989\)](#)
- A rich history of searches [H. Clement, Prog. in Part. and Nuc. Phys. 93 \(2017\), 195](#)
- Alternative descriptions describe the $d^*(2380)$ via one pion exchange and “triangle type mechanisms”



Sequential single pion production explaining the dibaryon “ $d^(2380)$ ” peak R. Molina, N. Ikeno, and E. Oset*

Dyson-Xuong
dibaryon sextet, D_{12}
[PRL 13 \(1964\) 815](#)

2.47, $\Delta\Delta$, $D_{03} D_{30}$

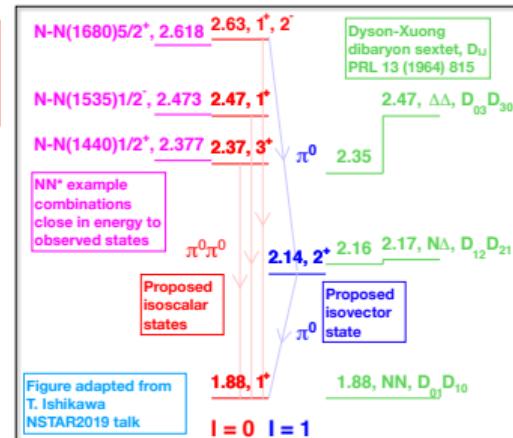
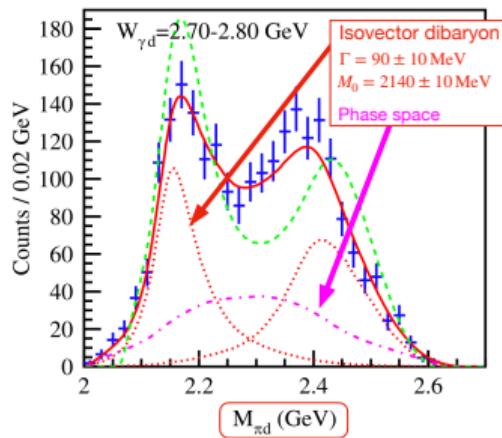
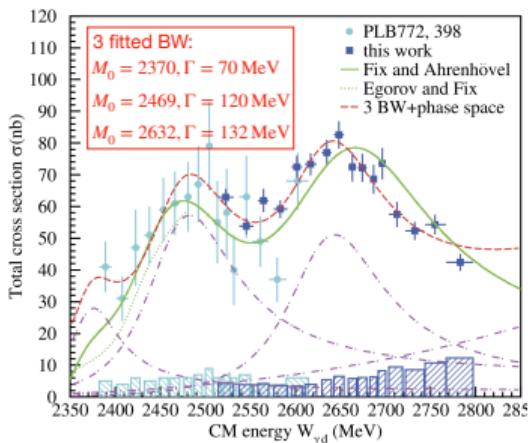
2.35 $d^*(2380)$

2.16 2.17, $N\Delta$, $D_{12} D_{21}$

1.88, NN , $D_{01} D_{10}$ Virtual,
unbound

Coherent photoproduction - previous results from ELPH

- Experimentally challenging - minimal momentum transfer to target deuteron, & large quasi-free background, eg $\gamma p(n) \rightarrow \pi^0 \pi^0 p$
- Advantage - only sensitive to isoscaler ($I = 0$) intermediate states
- Previous data from ELPH Ishikawa et al, PLB 789 (2019) 413 & PLB 772 (2017) 398:



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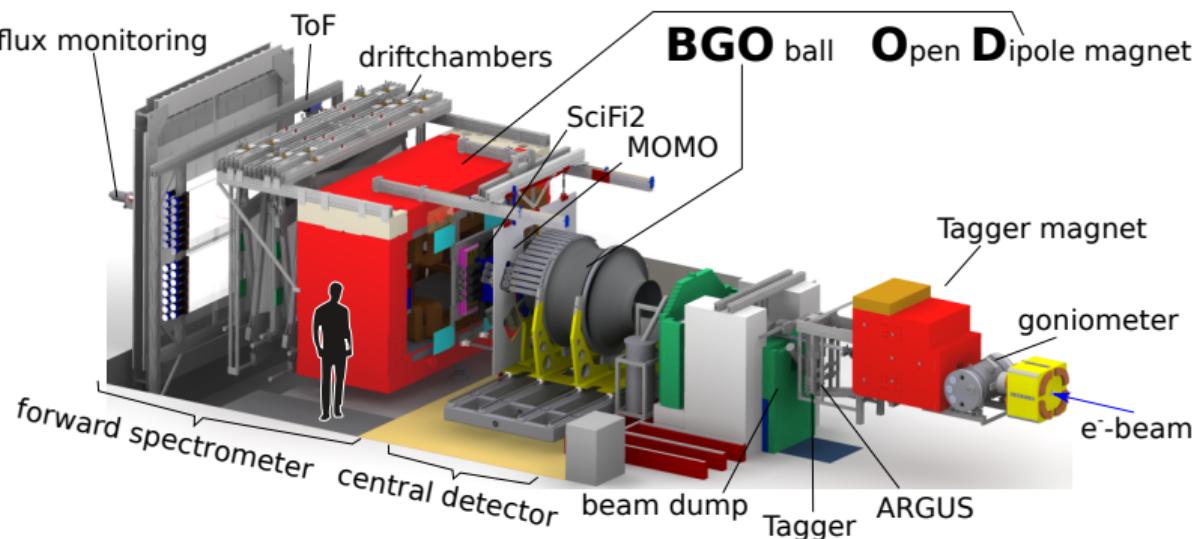
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The BGOOD experiment, Eur. Phys. J. A 56:104 (2020)

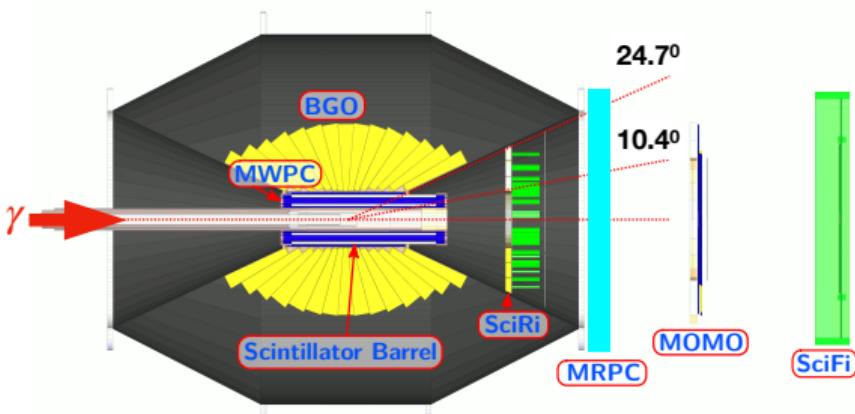
Spokespersons: H. Schmieden (Bonn) & P. Levi Sandri (Frascati)

- ELSA - a 3 stage accelerator - continuous e^- beams up to 3.2 GeV
- BGOOD - BGO calorimeter (central region) & Forward Spectrometer combination
- High momentum resolution, excellent charged & neutral particle ID

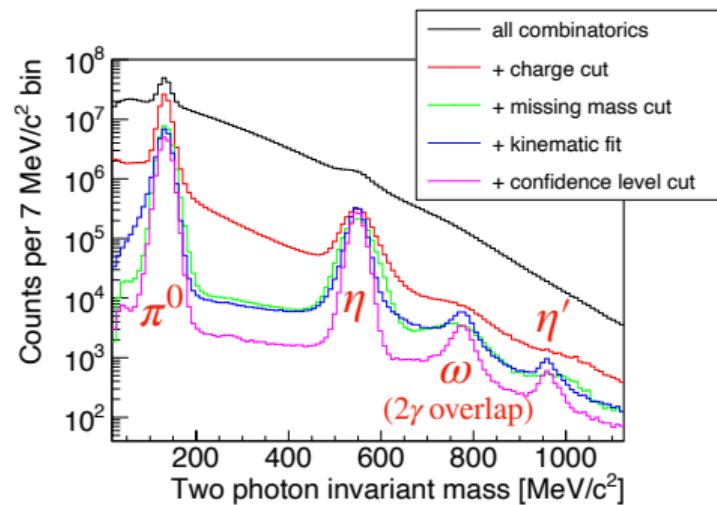


BGOOD - Central region, Eur. Phys. J. A 56:104 (2020)

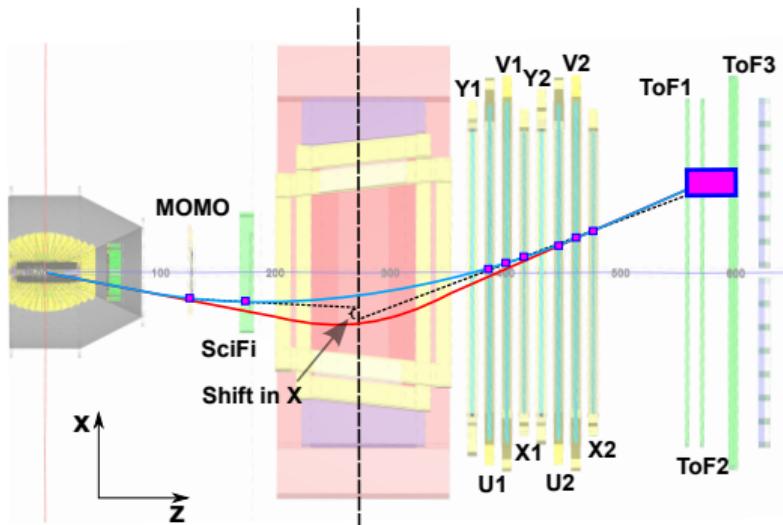
- BGO Rugby Ball (central region)
- Charged & neutral particle ID
- Excellent time resolution (~ 2 ns) per BGO crystal



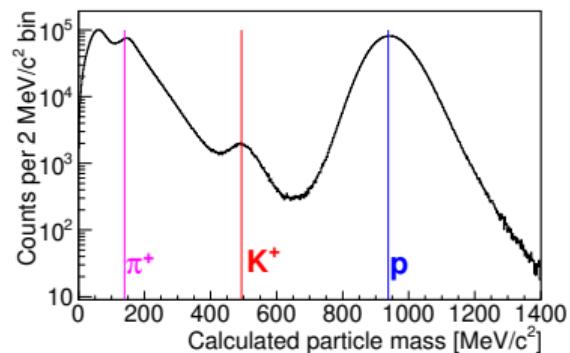
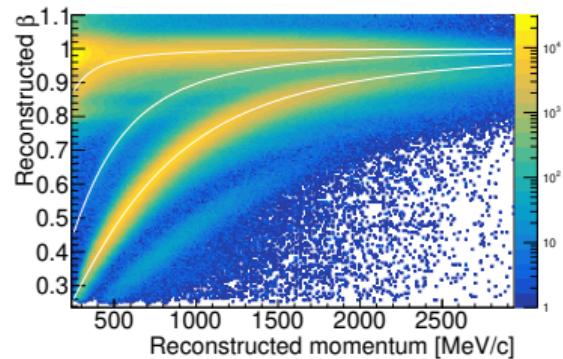
- Clean reconstruction of neutral meson decays:



BGOOD - Forward region, Eur. Phys. J. A 56:104 (2020)



- Charged particle ID & momentum reconstruction
- $1^\circ < \theta_{\text{Lab}} < 12^\circ$, $\Delta\theta_{\text{Lab}} \sim 0.5^\circ$
- $\Delta p/p \sim 3\%$ (at max field strength)



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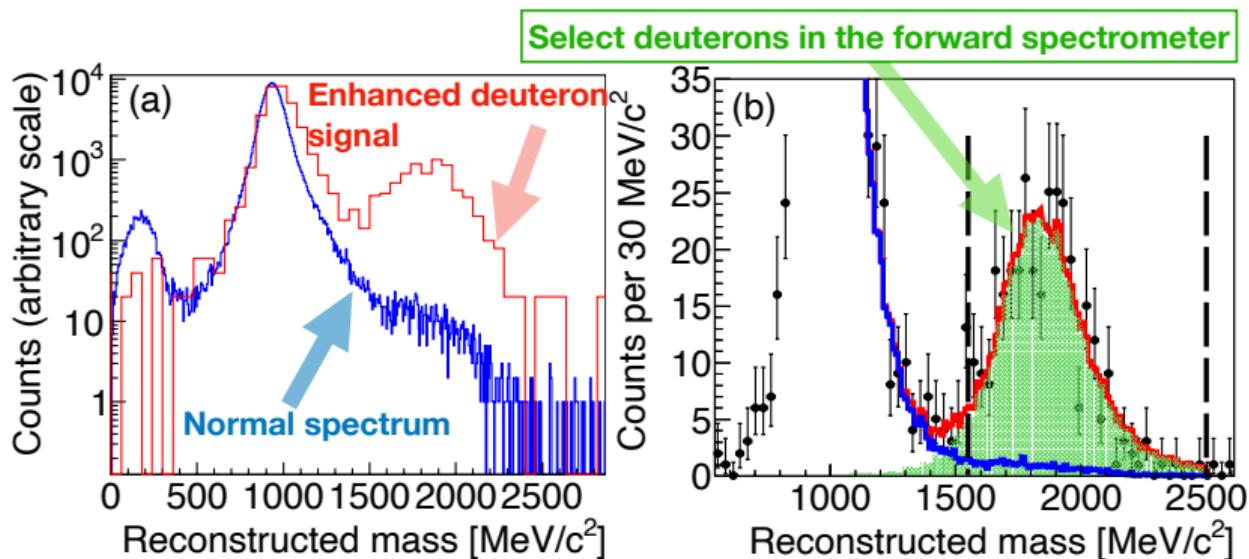
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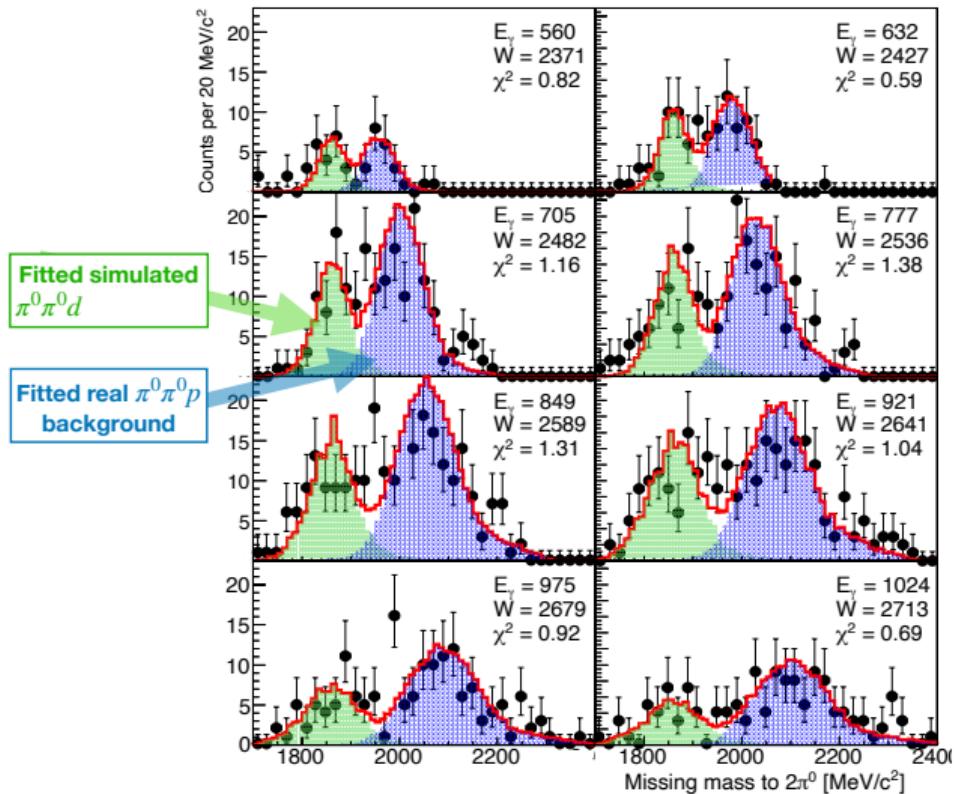
$\gamma d \rightarrow \pi^0\pi^0d$ at BGOOD - analysis steps

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



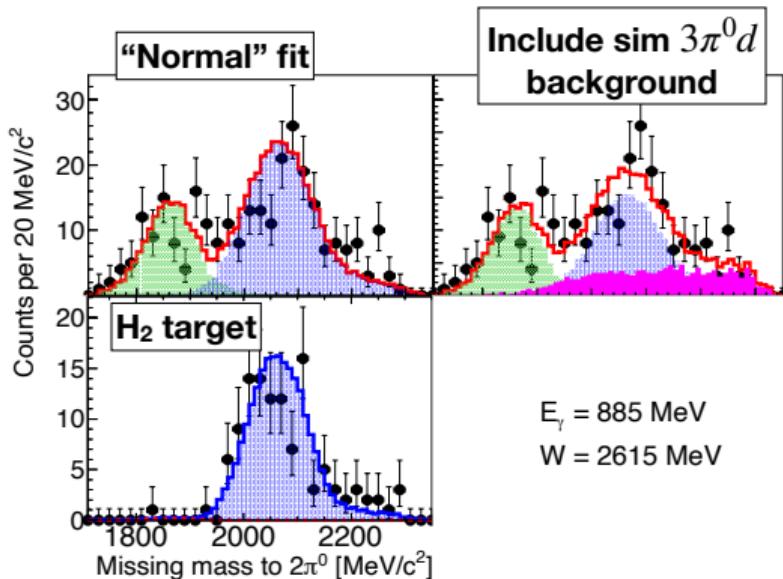
$\gamma d \rightarrow \pi^0\pi^0d$ at BGOOD - analysis steps

- 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” ($\gamma d \rightarrow \pi^0\pi^0X$)

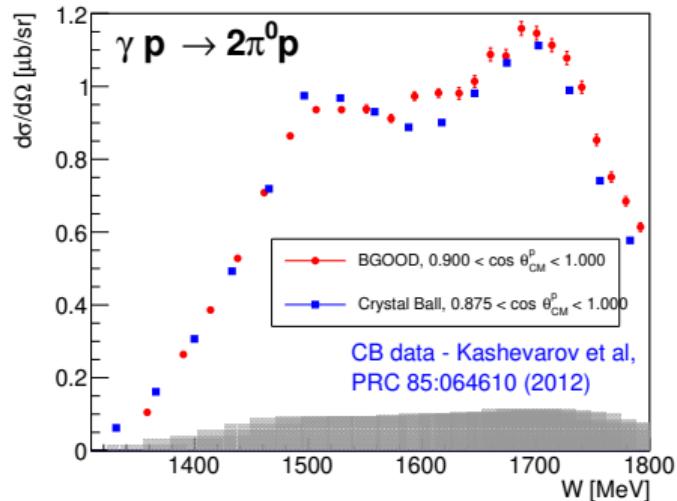


$\gamma d \rightarrow \pi^0\pi^0d$ at BGOOD - systematic uncertainties

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

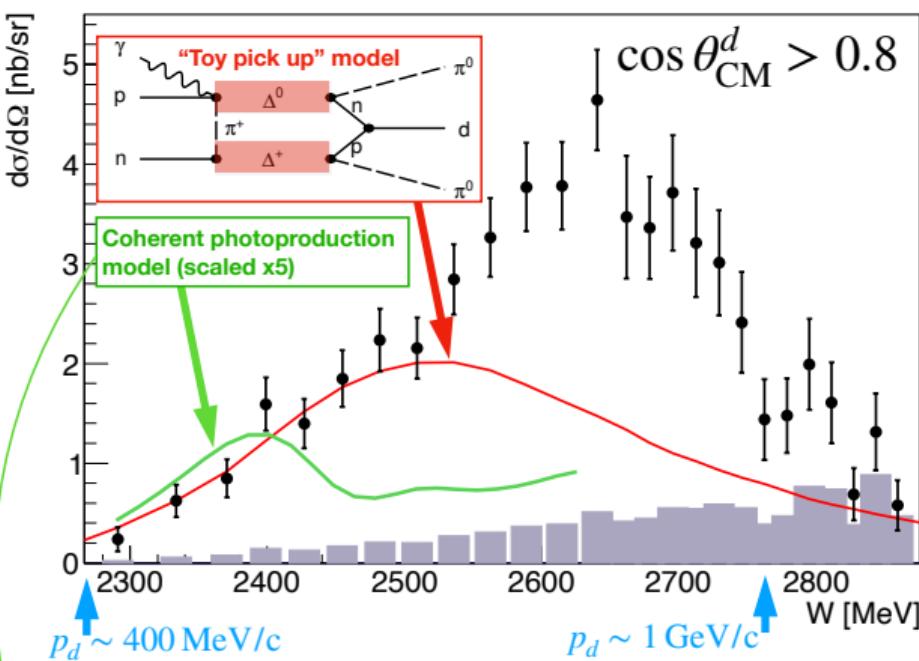


- Good agreement for a “Similar reaction”, $\gamma p \rightarrow \pi^0\pi^0p$
- Small difference at $W \sim 1600$ MeV understood - background from $\gamma p \rightarrow \eta p$



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

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

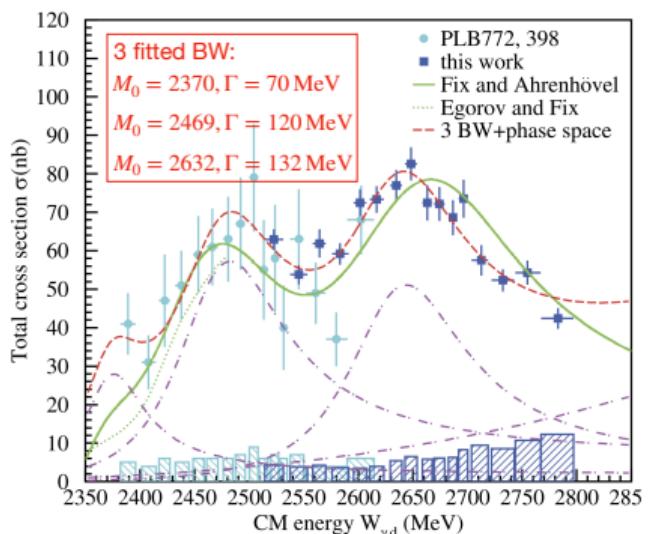
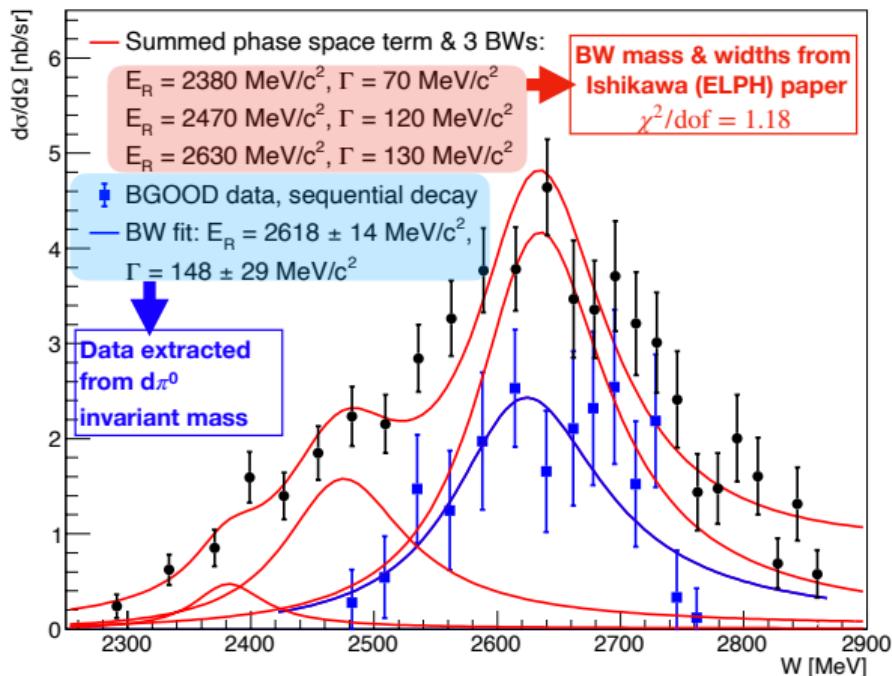


The Toy pick up model

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

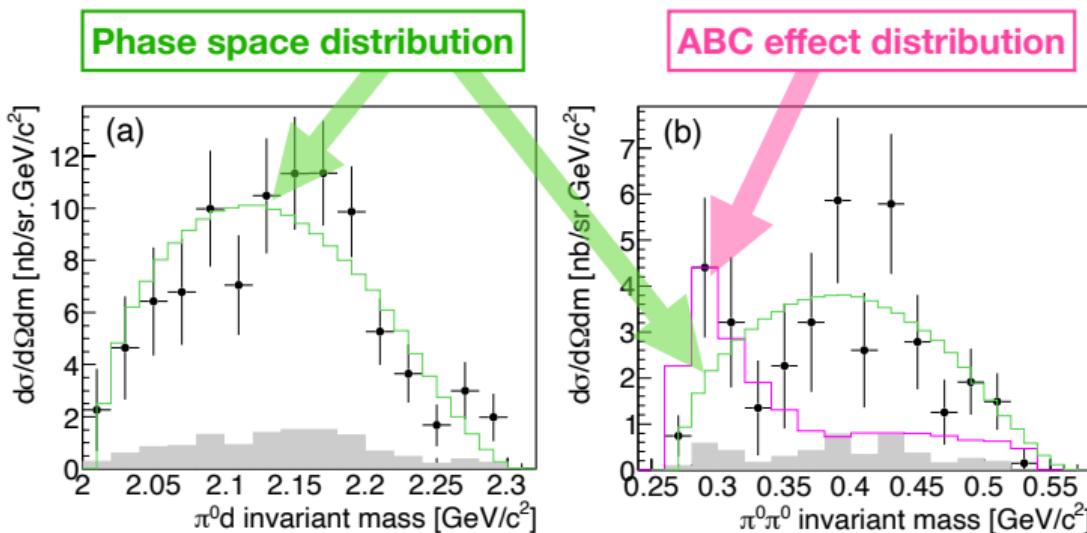
$\gamma d \rightarrow \pi^0 \pi^0 d$ at BGOOD - differential cross section Vs. W

- Differential cross section - Supports dibaryons proposed at ELPH
(Ishikawa et al, PLB 789 (2019) 413, Right hand side figure)



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

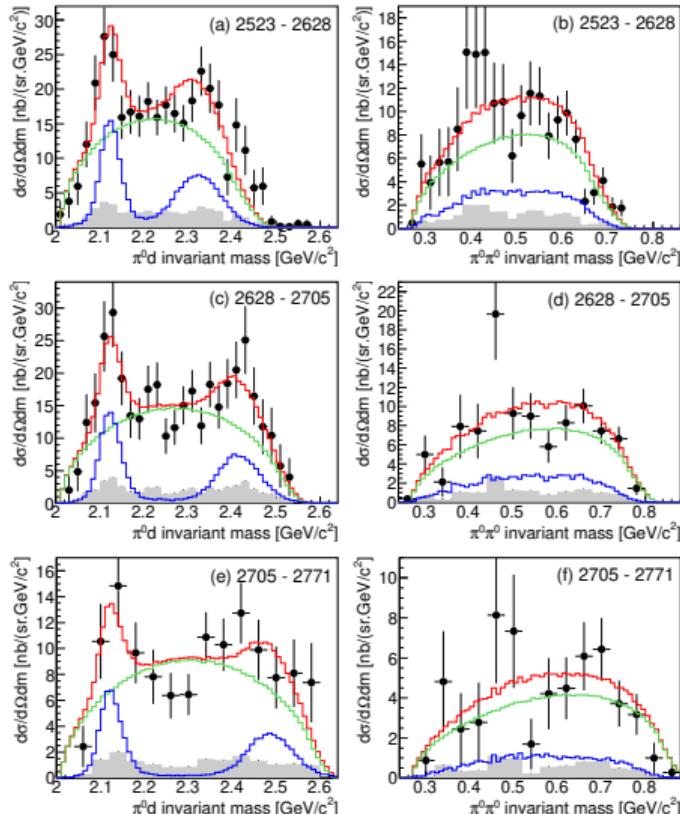
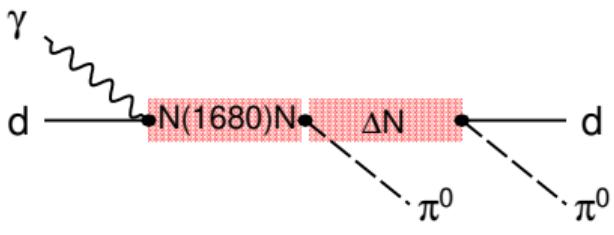
- The $\pi^0 d$ and $\pi^0 \pi^0$ invariant mass distributions over the $d^*(2380)$ range
- Consistent with the ABC effect (distribution from P. Adlarson et al. PRC, 86:032201, 2012.)



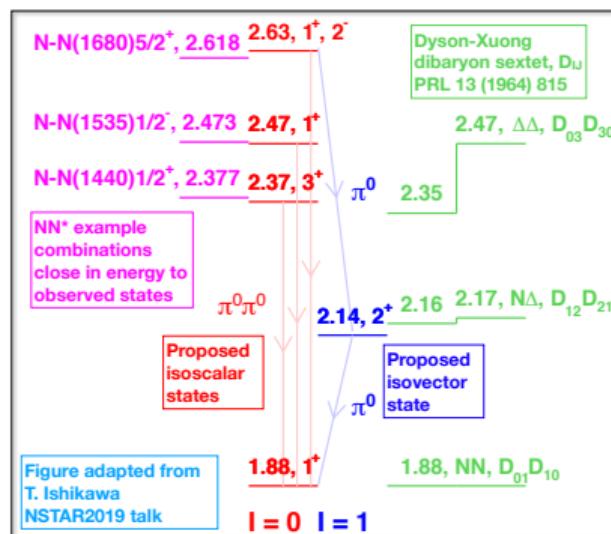
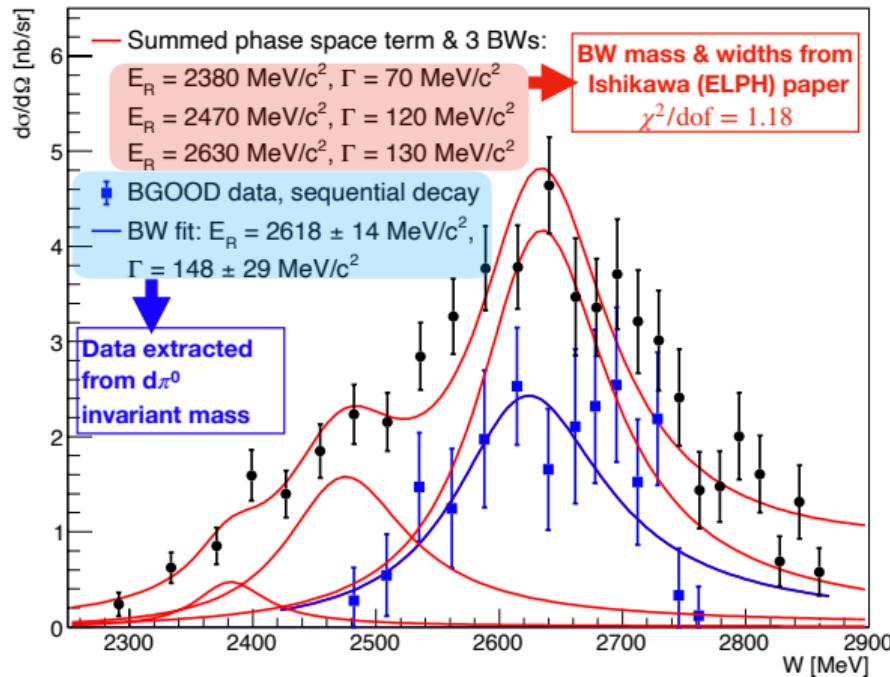
- Differential cross section for $\gamma d \rightarrow d^*(2380) \rightarrow \pi^0 \pi^0 d$: $(22 \pm 6_{\text{stat}} \pm 4_{\text{sys}}) \text{ nb/sr}$
- Angular dis. well known - cross section extrapolated to $(11.3 \pm 3.2_{\text{stat}} \pm 2.7_{\text{sys}}) \text{ nb}$

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

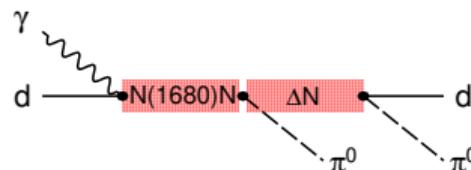
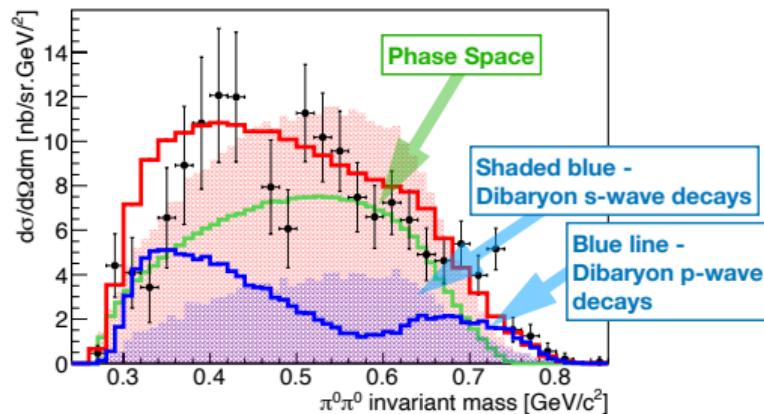


$\gamma d \rightarrow \pi^0 \pi^0 d$ at BGOOD - Evidence of a dibaryon spectrum?



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

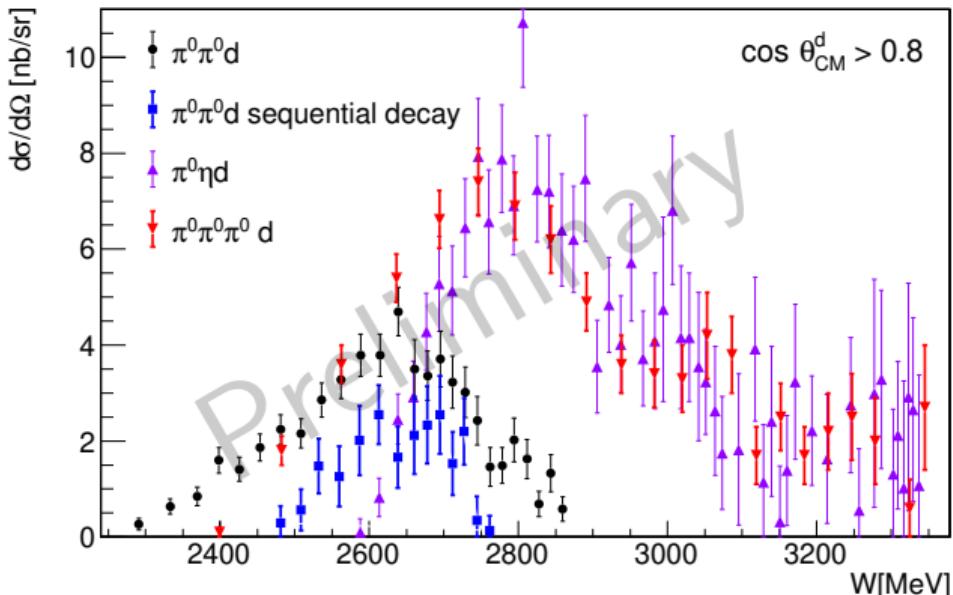
- $\pi^0\pi^0$ invariant mass for $2523 < W < 2738$ MeV
- Propose an $N(1680)5/2^+ N$ dibaryon - large coupling to πN
- Positive parity - consistent with decay with odd relative angular momentum to the $N\Delta \pi^0$ system & the change in spin required of the constituents.



Coherent photoproduction at BGOOD - What's next?

- $\gamma d \rightarrow \pi^0 \pi^0 d$ - x2 data now available & lin. pol. data planned
- Improve mass & W resolutions - kinematic fitting & new forward tracking
A. Figueiredo, Masters project (Uni Bonn)
- Measurements of other coherent final states - Access to isovector dibaryon candidates?

- $\pi^0 \eta d$ L. Lutter, Bachelor thesis (Uni Bonn 2022)
- $3\pi^0 d$ A. Strner, Masters thesis (Uni Bonn 2021)



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

T. C. Jude et al. [BGOOD collaboration], Phys. Lett. **B 832** (2022) 137277

- The strength and shape of the forward going differential cross section hard to reconcile with coherent production models or “pick-up” models
- Isoscalar dibaryon states at 2380, 2470 & 2630 MeV/c²?
- Apparent ABC effect at low W - $d^*(2380)$?
- Peak in the $\pi^0 d$ mass at 2114 MeV/c² - isovector dibaryon?
Narrow width conflicts with ELPH measurement



BGOOD talks at NSTAR 2022

Relevant publications in blue

- *The BGOOD experiment at ELSA - Multi quark structures in the light quark sector*, Katrin Kohl, Tuesday 15:00

G. Scheluchin, T.C. Jude et al. *Photoproduction of $K^+\Lambda(1405) \rightarrow K^+\Sigma^0\pi^0$ extending to forward angles and low momentum transfer* PLB 833 (2022) 137375

K. Kohl, T.C. Jude et al. *Indication of a dynamically generated pentaquark configuration in the $\gamma n \rightarrow K_S^0\Sigma^0$ reaction*, arXiv:2108.13319 (2021), submitted to EPJA

- *Cusp-like structure at forward $K^+\Sigma^0$ photoproduction*,
Johannes Groß, Wed 15:40

T.C. Jude et al., *Observation of a cusp-like structure in the $\gamma p \rightarrow K^+\Sigma^0$ cross section at low momentum transfer*, PLB 820 (2021) 136559

S. Alef et al. *$K^+\Lambda$ photoproduction at forward angles and low momentum transfer*, EPJA 57 (2021) 80

- *Recent results from BGOOD* Rachele Di Salvo, Thursday 11:50

All of the above, plus S. Alef et al. *The BGOOD experimental setup at ELSA*, EPJA 56 (2020) 104



Extra slides

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

Source	% error
π^0 identification ^a	3.5
Beam spot alignment ^b	4.0
Photon flux ^b	4.0
SciFi efficiency ^b	3.0
Track time selection ^b	2.0
ToF wall efficiency ^b	1.5
MOMO efficiency ^b	1.0
Drift chamber efficiency ^b	1.0
Beam energy calibration ^b	1.0
Modelling of hardware triggers ^b	1.0
$\Delta\alpha$ cut ^a	1.0
Forward deuteron mass selection	4.0
Contribution from target walls	1.0
Forward track geometric selection ^b	1.0
Target length ^b	0.8
Summed in quadrature	9.1
Additional systematic uncertainties:	
Fitting to spectra	$100e^{-10.15+0.008E_\gamma}$
Subtraction of background channels ^c	11

^a Determined from the reaction $\gamma p \rightarrow \pi^0 \pi^0 p$

^b Determined previously

^c Only applied in the invariant mass and angle distributions.

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

Detection efficiency:

