The study of unconventional baryon structure in the light quark sector with the BGOOD experiment

Tom Jude, on behalf of the BGOOD collaboration

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NSTAR2024, York
19th July 2024

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

Status of N^* spectroscopy

Constituent quark models vs. experiment

- *Missing resonances* & parity ordering problems of lowest states persists, despite:

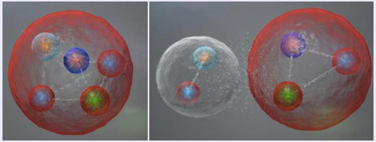
- Wealth of γN data - ELSA, MAMI, GRAAL, CLAS
- Sophisticated PWA, eg Bonn-Gatchina
- Improved understanding of known N^*, but few new states observed

state	J^P	PDG status in 2010	PDG status in 2020(Nγ)
N(1860)	$5/2^+$	*	*
N(1875)	$3/2^-$		**
N(1880)	$1/2^+$		**
N(1895)	$1/2^-$		****
N(1900)	$3/2^+$	****	****
N(1990)	$7/2^+$	**	**
N(2000)	$5/2^+$	**	**
N(2060)	$5/2^-$		***
N(2100)	$1/2^+$	*	**
N(2120)	$3/2^-$		***
N(2190)	$7/2^-$	****	**
N(2220)	$9/2^+$	****	**
N(2250)	$9/2^-$	****	**

Relevant degrees of freedom?

- 3 quark states only?
- Molecule-like states, meson-baryon degrees of freedom?

Glozman & Riska, Phys. Rep. 268 (1996) 263,
Garcia-Recio et al., PLB 582 (2004) 49,
Lutz & Kolomeitsev, PLB 585 (2004) 243



Exotic phenomena in the **charmed** sector*

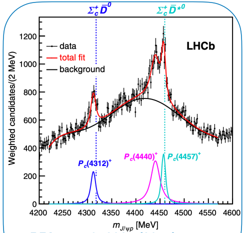
*__Not__ what we study at BGOOD!

Pentaquarks at LHCb

PARTICLE PHYSICS 16 JULY 2015 | VOL 523 | NATURE | 267

Forsaken pentaquark particle spotted at CERN

Exotic subatomic species confirmed at Large Hadron Collider after earlier false sightings.



PRL 115, 072001 (2015)
PRL 112, 222001 (2019)

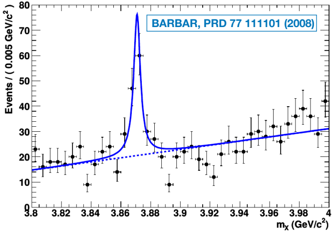
Meson-baryon dynamically generated states?

eg Wu, Molina, Oset, & Zou, PRL 105, 232001 (2010)

XYZ states in the charmed meson sector

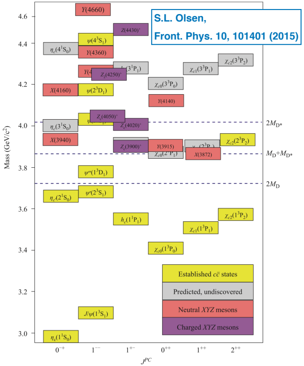
$X(3872) \rightarrow \pi^+\pi^- J/\psi$ - most cited paper from Belle

PRL91, 262001 (2003)



$X(3872)$ - molecular $D^0\bar{D}^{0*}$?

eg, Törnqvist, PLB 590, 209 (2004)

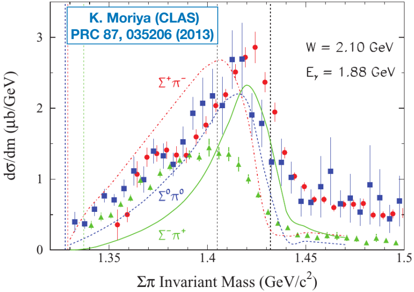


Motivation: Structure of the $\Lambda(1405)$

Back to the *uds* sector accessible at BGOOD!

- Considered a $\bar{K}N$ molecule prior to the quark model
  Dalitz & Tuan, PRL 2 (1959) 425
- Lies between the $\pi\Sigma$ & $\bar{K}N$ thresholds
- Difficult to reconcile within a CQM:
  - Mass too low compared to $N^*(1535)$
  - Large spin orbit splitting to $\Lambda(1520)$

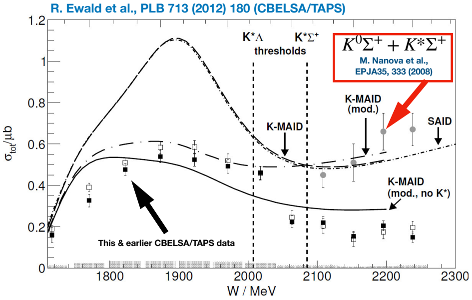
Previous CLAS data:

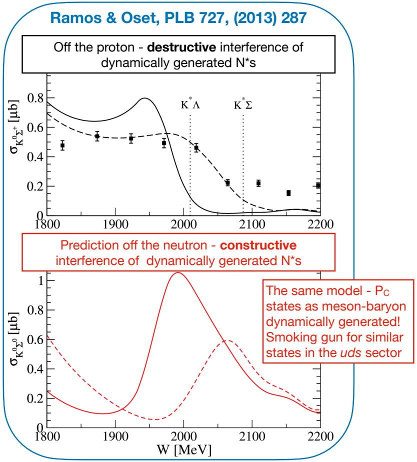


- $\Lambda(1405)$ - dynamically generated by meson-baryon interactions?
  Nacher, Oset, Toki, Ramos, & Meißner, NPA725 (2003)181
  Molina & Döring, PRD 94, 056010 & 079901 (2016)
- LQCD: Hall et al., PRL 114 (2015) 132002

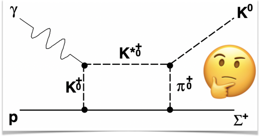
Motivation: Cusp in the $\gamma p \to K^0\Sigma^+$ cross section

Previous CBELSA/TAPS data:





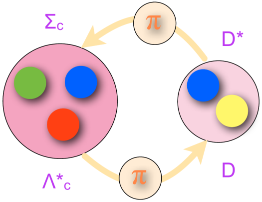
K^{*0} sub-threshold production rescattering to π^0 & K^0?



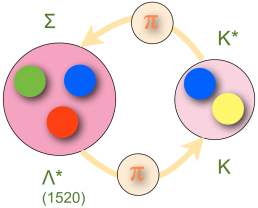
Parallels between charmed & strange sectors?

	Charmed-sector		Strange-sector	
	Meson	Baryons	Meson	Baryons
State(s)	$X(3872)$	$P_c^*(4380/4457)$	$f_1(1285)$	$N^*(2030/2080)$
π exchange transition	$D^{*0}\bar{D}^0/D^0\bar{D}^{*0}$	$\Lambda_c^*\bar{D}+\Sigma_c\bar{D}^*$	$K^*\bar{K}/K\bar{K}^*$	$\Lambda^*K+\Sigma K^*$
Quantum numbers	$J^{PC}=1^{++}$	$J^P=3/2^-$	$J^{PC}=1^{++}$	$J^P=3/2^-$
3-body threshold	$D^0\bar{D}^0\pi^0$	$\Sigma_c^+\bar{D}^0\pi^0$	$K\bar{K}\pi$	$\Sigma K\pi^0$
Closed flavour thresh.	$J/\psi\omega$	$\chi_{c1}p$	$\phi f_0(500)$	ϕp

c-sector



s-sector



The study of unconventional baryon structure in the light quark sector with the BGOOD experiment

1. Motivation - parallels in the strange & charmed quark sectors?

2. The BGOOD experiment at ELSA, Bonn

3. Exotic structure in associated strangeness photoproduction?

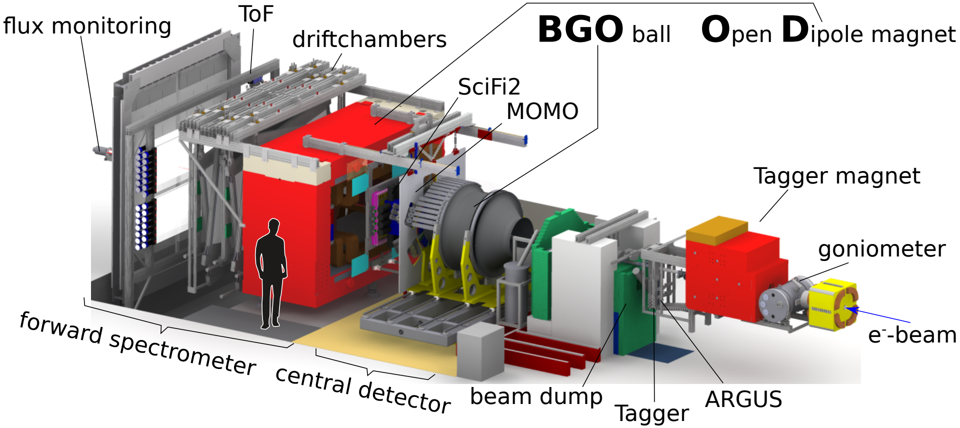
   - K^0 photoproduction - driven by molecular N^* states?
   - $K^+\Lambda(1405)$ - evidence of triangle singularity mechanism
   - Cusp at forward $K^+\Sigma^0$ photoproduction at the $K\bar{K}p$ threshold

4. Searches for exotic dibaryons at BGOOD

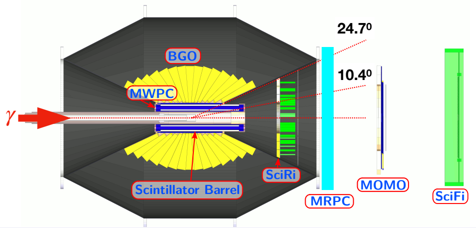
The BGOOD experiment, Eur. Phys. J. A 56:104 (2020)

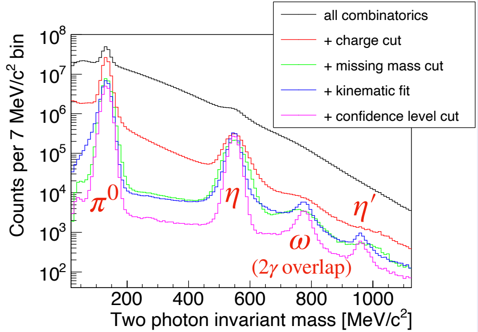
Spokespersons: T.C Jude (Bonn) & P. Levi Sandri (Frascati)

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

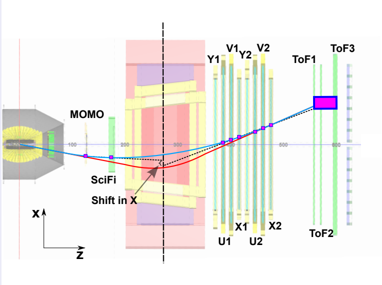


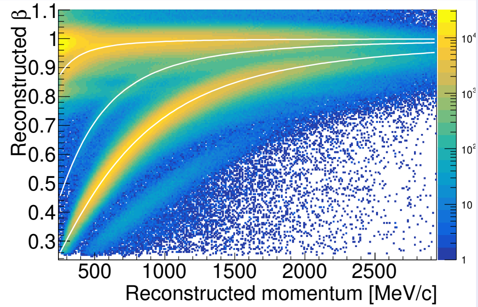
BGOOD central region





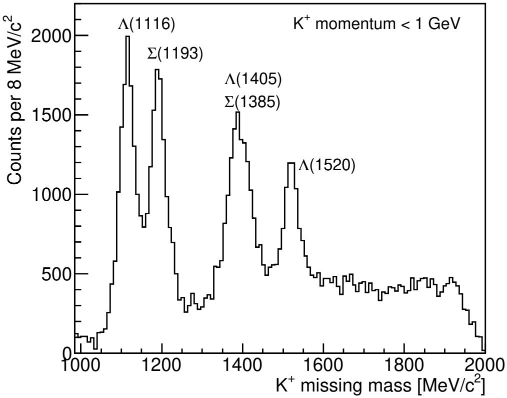
BGOOD forward region

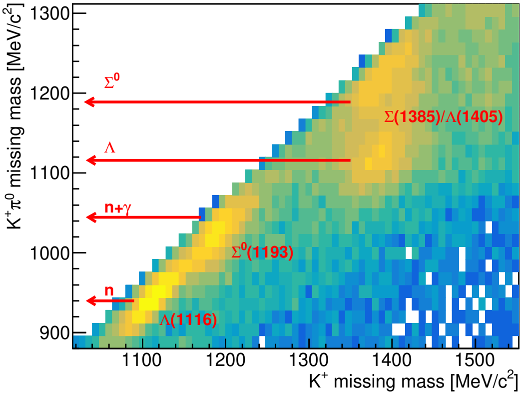




Forward K^+Y identification

- K^+ identified in the Forward Spectrometer, $\cos\theta^K_{\mathrm{CM}} > 0.9$
- The study of Y^* states in an extremely low momentum transfer region





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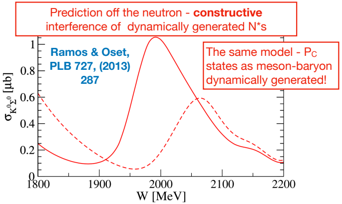
3. Searches for exotic dibaryons at BGOOD

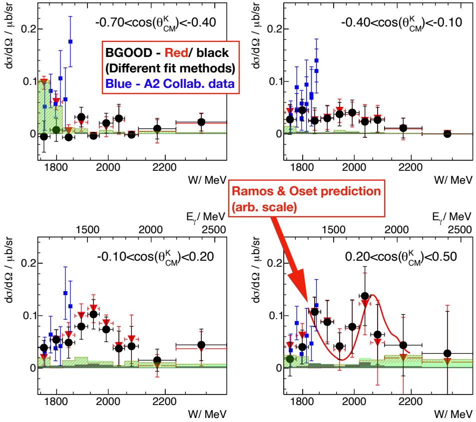
BGOOD

Strange pentaquarks driving the reaction $\gamma n \to K^0\Sigma^0$?

K. Kohl, T.C. Jude, et al., EPJA 59 (2023) 254



- $K^0 \to 2\pi^0$ in the BGO Rugby Ball
- Identify $\Sigma^0 \to \gamma\Lambda$ & angle cut on $\Lambda \to p\pi^-$
- Consistent with model prediction
- Further data & new analysis methods being implemented



blue squares - Akondi et al. (A2) EPJA 55 11, 202 (2019)

$\gamma p \to K^+\Lambda(1405) \to K^+(\Sigma^0\pi^0)$

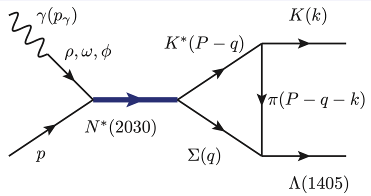
G. Scheluchin, T.C Jude et al. Phys. Lett. B 833 (2022) 137375

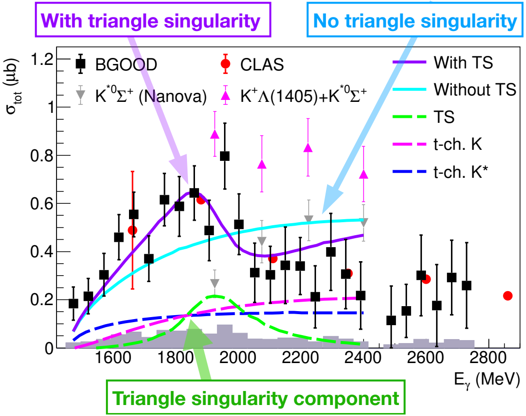
- $K^+\Lambda(1405) \to K^+\Sigma^0\pi^0 \to K^+\gamma\Lambda\pi^0 \to K^+3\gamma p\pi^-$ & kinematic fit

Triangle singularity in $\gamma p \to K^+\Lambda(1405)$

Wang et al. PRC 95, 015205 (2017)

- $N^*(2030)$ proposed for cusp in $K^0\Sigma^+$

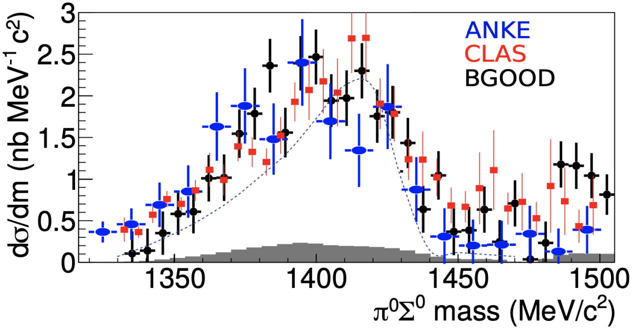




$\gamma p \to K^+\Lambda(1405) \to K^+(\Sigma^0\pi^0)$

G. Scheluchin, T.C Jude et al. Phys. Lett. B 833 (2022) 137375

- Line shape - 2 peak structure at 1395 & 1425 MeV/c^2?
- Close to the $\Lambda(1405)$ proposed 2-pole structure
  Oller & Meißner, PLB 500, 263 (2001)

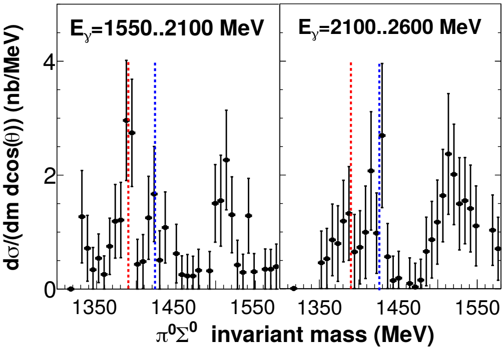


CLAS: Moriya, et al PRC 87, 035206 (2013)
ANKE: Zychor et al, PLB 660, 167 (2008)
Dashed line: Nacher et al, PLB 455, 55 (1999)

$\gamma p \rightarrow K^+\Lambda(1405) \rightarrow K^+(\Sigma^0\pi^0)$

G. Scheluchin, T.C Jude et al. Phys. Lett. B 833 (2022) 137375

- Cross section of "poles" appears to change at forward angles
- K^+ in the forward spectrometer ($\sigma_{\text{Mass}} \sim 13\,\text{MeV/c}^2$, $\cos\theta^K_{\text{CM}} > 0.86$):

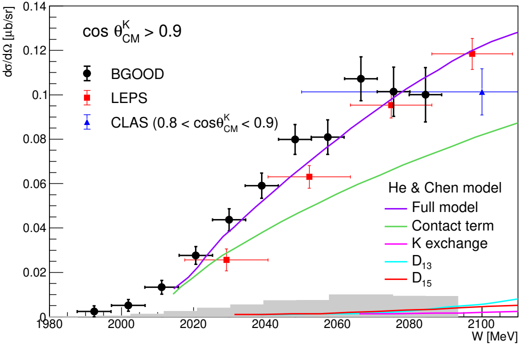


Further data being analysed & $K^+(\Lambda(1405) \rightarrow \Sigma^+\pi^-)$ studies also underway

Forward $\gamma p \to K^+\Lambda(1520)$ differential cross section

E. Rosanowski, T.C Jude et al. arXiv:2406.01121 (To be submitted to EPJA)

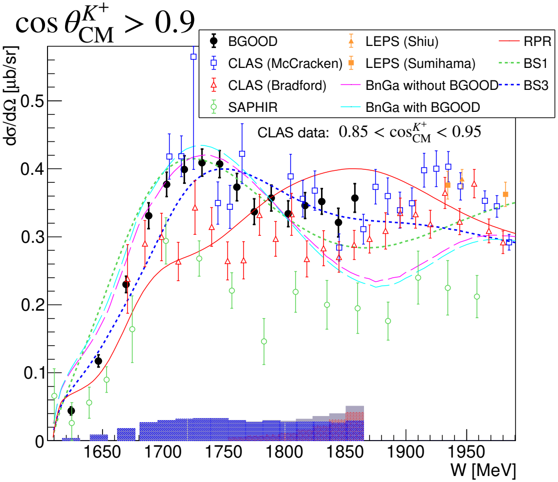
- Forward $K^+\Lambda(1520)$ photoproduction
- First precision data at forward angles near threshold

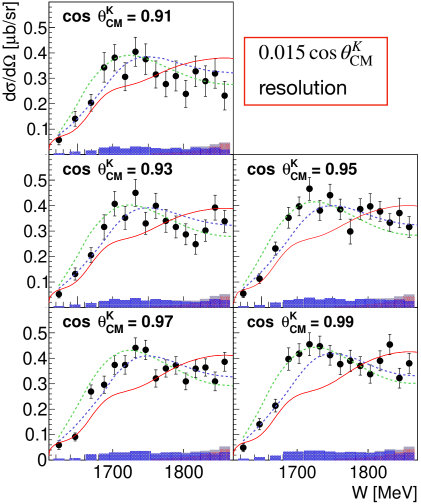


J. He and X.-R. Chen. PRC, 86(035204), 2012.
H. Kohri, et al. (LEPS). PRL., 104:172001, 2010.
U. Shrestha et al. (CLAS). PRC, 103:025206, 2021.

Forward $\gamma p \rightarrow K^+\Lambda$, Eur. Phys. J. A (2021) 57:80

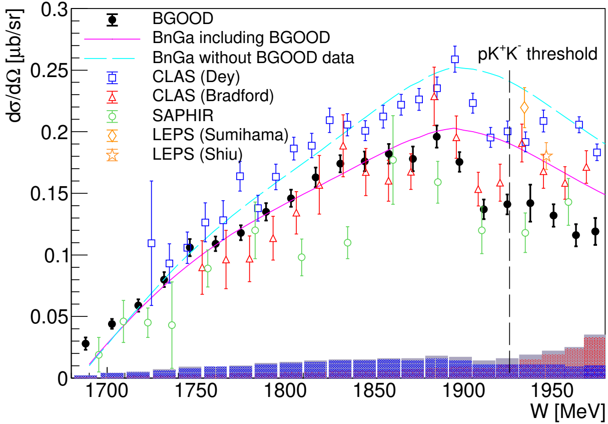
- Low t data - constraint on hypernuclei electroproduction
- Forward angles - sensitive to high spin N^*





$\gamma p \to K^+\Sigma^0$ T.C. Jude et al., Phys. Lett. B 820 (2021) 136559

- Highest statistics to date for $\cos\theta^K_{\mathrm{CM}} > 0.9$ (CLAS data in $\cos\theta^K_{\mathrm{CM}}$ 0.85 to 0.95)
- Resolve discrepancies in world data set & reveals "cusp" at $W \sim 1900\,\mathrm{MeV}$

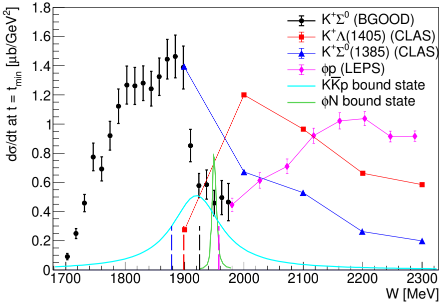


- Cusp regarded as a peak before - PWA have attributed $D_{13}(1895)$, $S_{31}(1900)$, $P_{31}(1910)$ & $P_{13}(1900)$

R. Bradford *et al.* (CLAS), PRC 73, 035202 (2006), B.Dey *et al.* (CLAS), PRC 82, 025202 (2010), CLAS data in $\cos\theta^K_{\mathrm{CM}}$ 0.85 to 0.95 interval, K.H. Glander *et al.* (SAPHIR), EPJA 19, 251 (2004), BnGa PWA - without BGOOD/with BGOOD

$\gamma p \to K^+\Sigma^0$ T.C. Jude et al., Phys. Lett. B 820 (2021) 136559

Data extrapolated to t_{min}, $\cos\theta^K_{\mathrm{CM}} = 1$



CLAS data extrapolated from: K. Moriya. PhD thesis, Carnegie Mellon University, 2010. https://www.jlab.org/Hall-B/general/thesis/Moriya thesis.pdf.
LEPS: Mibe et al. PRL.95:182001,2005.
$K\bar{K}p$ bound state: Mart et al., EPJA, 41:361, 2009.
ϕN bound state: Gao, et al, PRC, 95:055202, 2017.

The Cusp is....

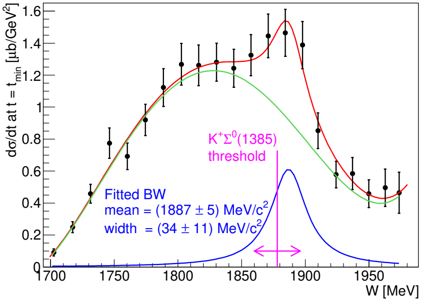
- in the same kinematic regime to the $X(2000)$ proposed by SPHINX
- at predicted $K\bar{K}p$ and ϕp bound states
- 20 MeV above predicted bound $\Sigma(1385)K$ state

Channel thresholds:

- A "smooth" transition between $K^+\Sigma^0$ & $p\phi$
- Similar behaviour of $K^+\Sigma^0(1385)$

$\gamma p \to K^+\Sigma^0$ T.C. Jude et al., Phys. Lett. B 820 (2021) 136559

- A bound $K^+\Sigma(1385)$ system? interesting parallels to proposed P_C states
- Peak-like structure on a smooth background?



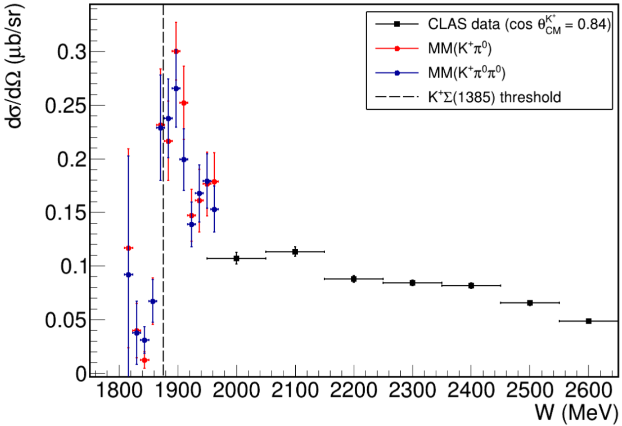
J^P	C-sector Threshold	C-sector State	S-sector Threshold	S-sector Evidence
$\frac{1}{2}^-$	$\Sigma_c \bar{D}$	$P_C(4312)$	$\Sigma^0 K^+$	$N^*(1535)$?
$\frac{3}{2}^-$	$\Sigma_c^* \bar{D}$	$P_C(4382)$	$\Sigma^0(1385)K^+$	Peak in $K^+\Sigma^0$
$\frac{3}{2}^-$	$\Sigma_c \bar{D}^*$	$P_C(4457)$	$\Sigma^0 K^{*+}$	Peak/cusp in $K^0\Sigma^{0/+}$ TS in $K^+\Lambda(1405)$
$\frac{1}{2}^- / \frac{5}{2}^-$	$\Sigma_c^* \bar{D}^*$	-	$\Sigma(1385)^0 K^{*+}$	-

Proposed P_C states - Du *et al*, PRL 124, 072001 (2020)

$K^+\Sigma^0(1385)$ photoproduction

M. Jena Masters thesis (Uni Bonn 2024), data considered preliminary

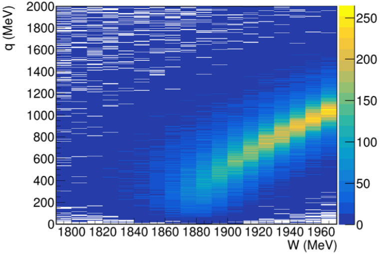
- Differential cross section for $\cos\theta^K_{\mathrm{CM}} > 0.9$
- To avoid $\Lambda(1405)$ background - fitted to missing mass from $K^+\pi^0$ & $K^+\pi^0\pi^0$ systems
- First data from threshold
- large peak at $W \approx 1900\,\mathrm{MeV}$



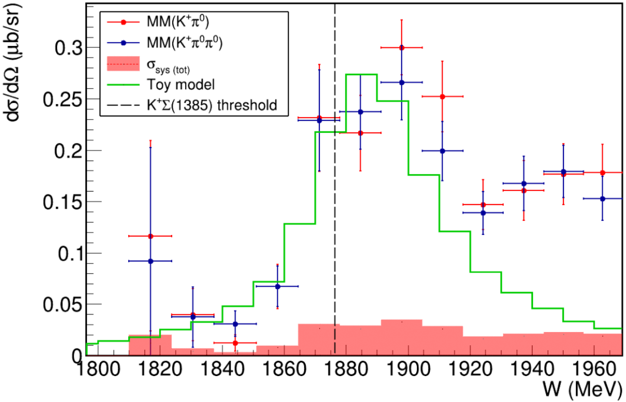
$K^+\Sigma^0(1385)$ photoproduction

M. Jena Masters thesis (Uni Bonn 2024), data considered preliminary

- Origin of peak - momentum dependent π rescattering?
- Relative $K^+ - \Sigma(1385)$ momentum:



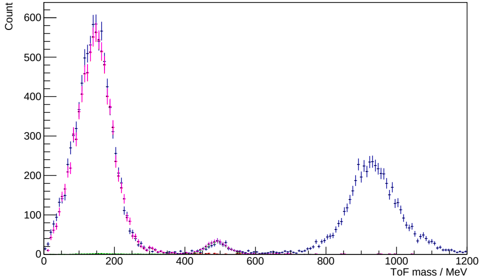
- Assume $\frac{d\sigma}{d\Omega} \propto \frac{1}{(m_\pi^2 + q^2)^2}$



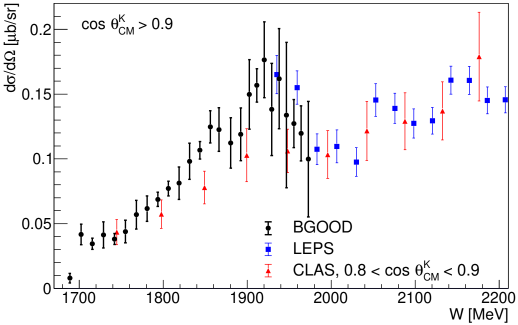
$K^+\Sigma^-$ photoproduction

J. Groß PhD thesis in preparation, data considered preliminary

- Fit to forward particle measured mass - K^+ yield from deuterium target data.
- Subtract normalised yield from hydrogen data



- First data from threshold for $\cos\theta^K_{\mathrm{CM}} > 0.9$
- Interesting structure around $W \sim 1920\,\mathrm{MeV}$?



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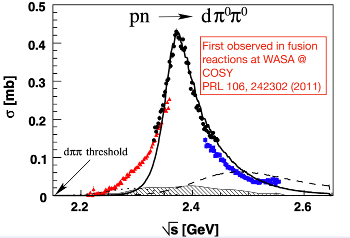
Dibaryons - Motivation

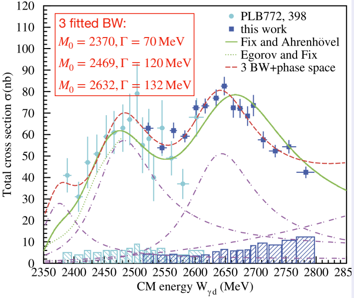
Evidence of the $d^*(2380)$

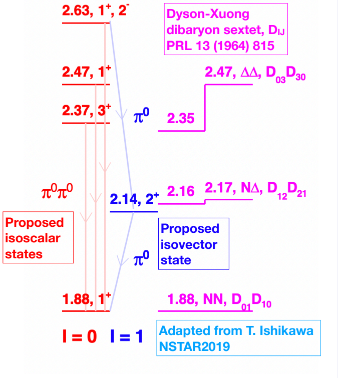
Adlarson et al PRL 106:242302, 2011
Bashkanov et al PRL 102:052301, 2009



- $(I)J^P = (0)3^+$
- Observed in multiple final states

$\gamma d \to \pi^0\pi^0 d$ at ELPH PLB 789 (2019) 413 & PLB 772 (2017) 398

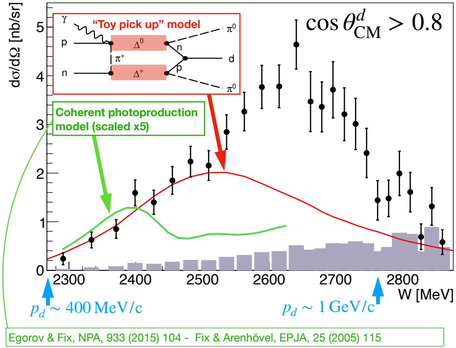




See also, preliminary data: M. Guenther et al (A2), PoS (Hadron 2017)051

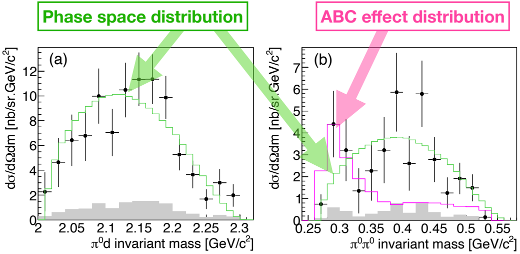
Evidence of dibaryons at BGOOD T.C. Jude, et al., Phys. Lett. B 832 (2022) 137277

- Coherent reaction - $\gamma d \to \pi^0\pi^0 d$, deuterons in the forward spectrometer
- Not described by coherent production or *Toy pick up model*



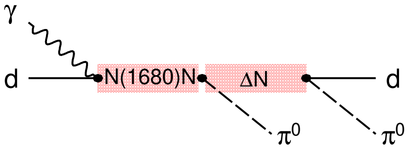
- $\pi^0\pi^0$ invariant mass over the $d^*(2380)$ - Consistent with the ABC effect

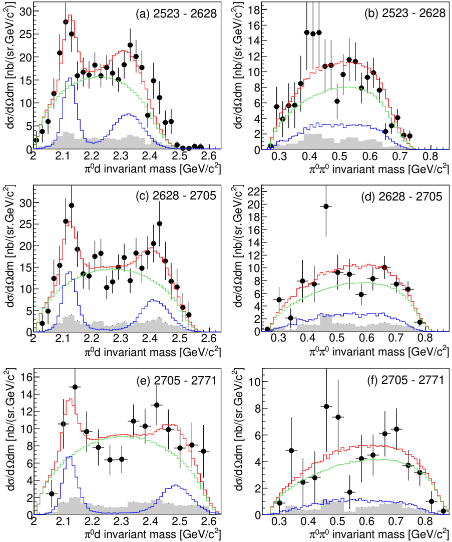
(distribution from P. Adlarson et al. PRC, 86:032201, 2012.)



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

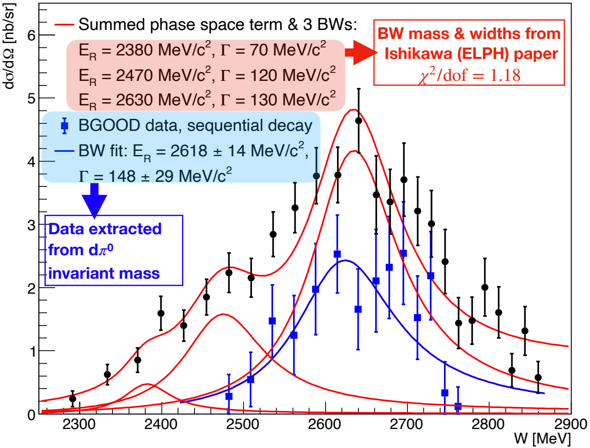
- $\pi^0 d$ & $\pi^0\pi^0$ invariant mass distributions for higher W intervals
- Simulated sequential decay - different masses & widths of the first dibaryon
- Sequential decay + Phase space = sum
- Mass of 2114 MeV/c^2 and width $\sim$ 20 MeV/c^2 (exp. resolution!) proved optimal

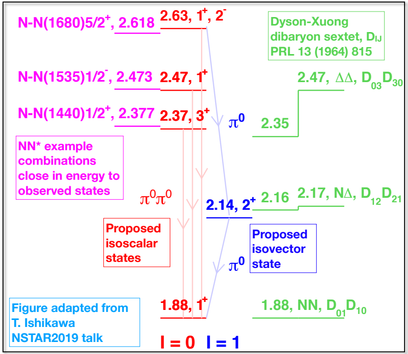




$\gamma d \to \pi^0\pi^0 d$ at BGOOD - Evidence of a dibaryon spectrum?

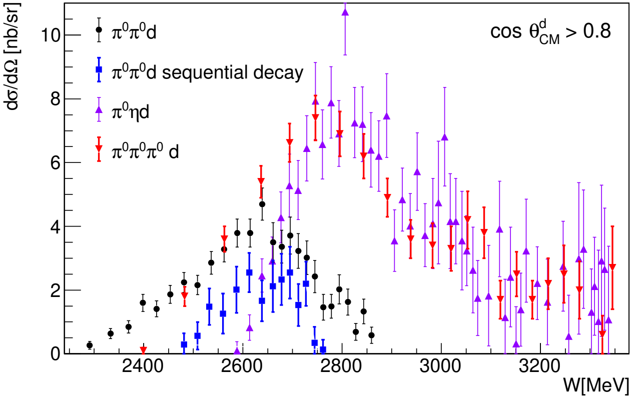
- Supports dibaryons states proposed at ELPH Ishikawa et al, PLB 789 (2019) 413





- Other coherent final states - Access to isovector dibaryon candidates?
- Differential cross section for all channels orders of magnitude higher than expected:
    - $2\pi^0 d$
    - $3\pi^0 d$
    - $\pi^0 \eta d$

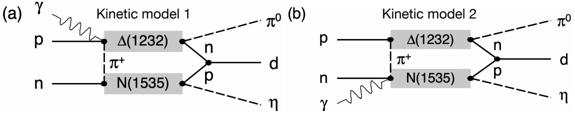
Preliminary $3\pi^0 d$ analysis:

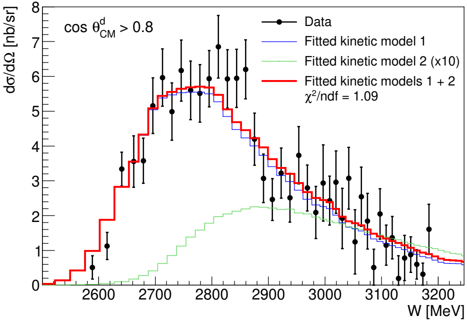


Coherent $\pi^0\eta d$ photoproduction at BGOOD

A. Figueiredo, T. C. Jude , et al. arXiv:2405.09392, submitted to PLB

- Distribution agrees well with models of pion re-scattering





- Similar strength of coherent channels could be explained by similar decay branching ratios::
  - $N(1535) \to \pi N$, $\Gamma_i/\Gamma = 32 - 53\,\%$
  - $N(1535) \to \pi\pi N$, $\Gamma_i/\Gamma = 4 - 31\,\%$
  - $N(1535) \to \pi\eta N$, $\Gamma_i/\Gamma = 30 - 55\,\%$

The BGOOD experiment at ELSA - the story so far

- Molecular-like structure in the *uds* sector?
- BGOOD - photoproduction at forward angles & low momentum transfer

  Eur. Phys. J. A 56:104 (2020)
- $\gamma n \rightarrow K^0\Sigma^0$ - dynamically generated meson-baryon resonance contributions? (parallels to P_C states) K. Kohl, T.C. Jude, et al., EPJA 59 (2023) 254
- $\gamma p \rightarrow K^+(\Lambda(1405) \rightarrow \Sigma^0\pi^0)$ - triangle diagram mechanism?

  G. Scheluchin, T.C Jude et al. Phys. Lett. B 833 (2022) 137375)
- Cusp in $\gamma p \rightarrow K^+\Sigma^0$ - at thresholds & bound state predictions

  T.C. Jude et al., Phys. Lett. B 820 (2021) 136559, Eur. Phys. J. A (2021) 57:80
- Unaccounted reaction mechanisms in coherent $\pi^0\pi^0 d$ and $\pi^0\eta d$ - dibaryons or pion rescattering terms?

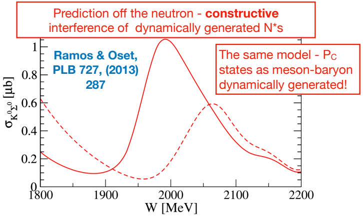
  T.C. Jude, et al., Phys. Lett. B 832 (2022) 137277, A.J. Clara Figueiredo, T.C. Jude, arXiv:2405.09392

Extra slides

Strange pentaquarks driving the reaction $\gamma n \to K^0\Sigma^0$?

K. Kohl, T.C. Jude et al. arXiv:2108.13319, accepted for EPJA

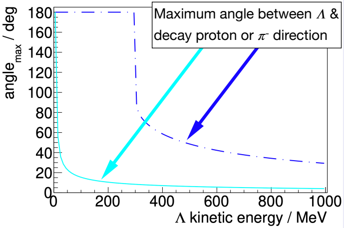
Predicted peak - "smoking gun" for reaction mechanism

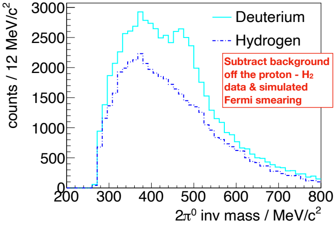


Dynamically generated meson-baryon states? - $\Lambda^* K + \Sigma K^*$

$\gamma n \to K^0\Sigma^0$ at BGOOD

- $K^0 \to 2\pi^0$ in the BGO Rugby Ball
- Identify $\Sigma^0 \to \gamma\Lambda$ & angle cut on $\Lambda \to p\pi^-$





Forward $\gamma p \to K^+\Sigma^0$ - Motivation

- Limited data at forward K^+ angles
- At the K^+K^-p threshold (1900 MeV), many predictions:
  - ϕN bound systems

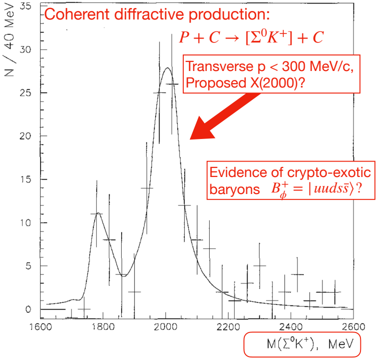
    Gao, Huang, Liu, Ping, Wang & Z. Zhao, PRC, 95:055202, 2017
  - Molecular $K\Sigma$ states, $J^P = 1/2^-$ & $3/2^-$ consistent with $N^*(1875)$ & $N^*(2100)$

    Huang, Zhu & Ping, PRD 97:094019, 2018.
  - A 3-hadron $K\bar{K}N$ molecule with $a_0(980)N$ & $f_0(980)N$ components

    Martínez Torre, Khemchandani, Meißner & Oset, EPJA 41:361, 2009.

Previous SPHINX data

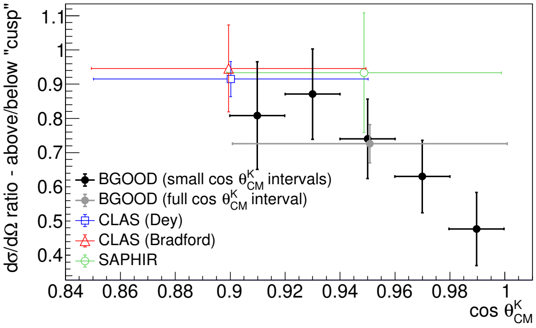
ZPC, 68:585 (1995)

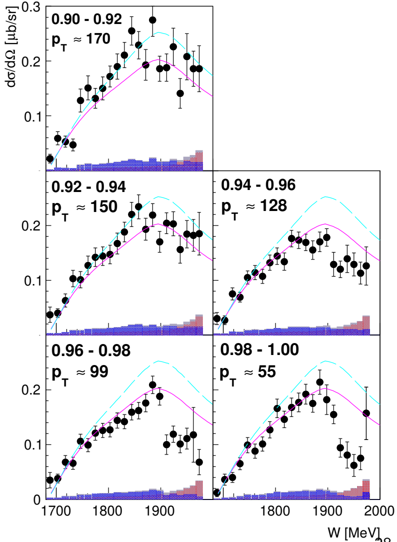


Low transverse p requires forward kinematics in photoproduction!

$\gamma p \to K^+\Sigma^0$ T.C. Jude et al., Phys. Lett. B 820 (2021) 136559

- Cusp increases quickly with $\cos\theta^K_{\rm CM}$ and K^+ transverse momentum (p_T)
- Consistent with the "extent of cusp" seen at CLAS:

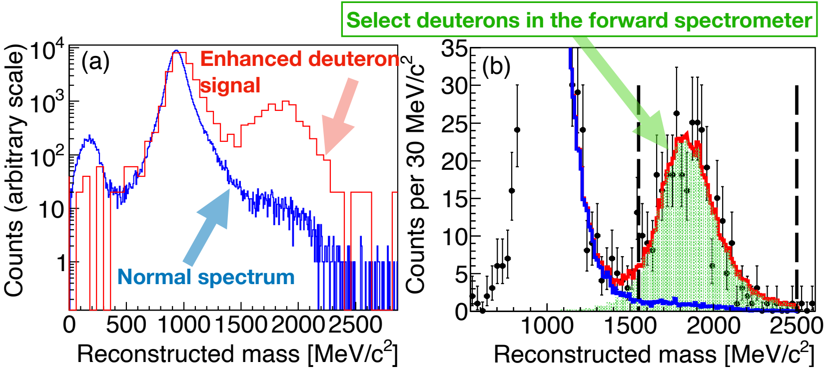




$\gamma d \to \pi^0 \pi^0 d$ at BGOOD - analysis steps

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

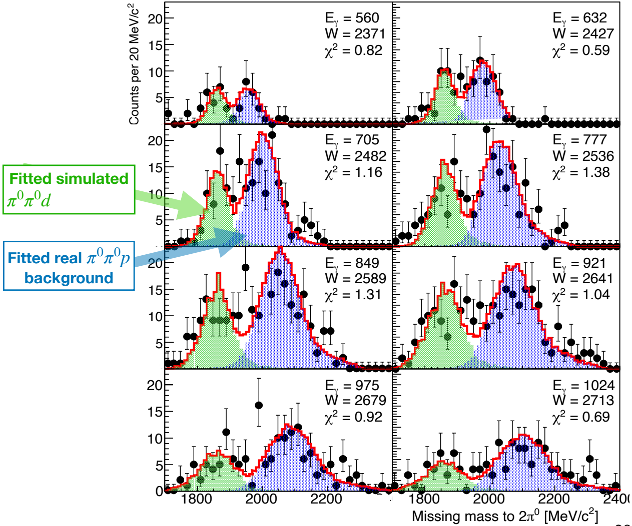
- Coherent reaction - $\gamma d \to \pi^0 \pi^0 d$, deuterons in the forward spectrometer
- Unexpected! $p_d > 400\,\text{MeV/c}$ & deuteron Fermi momentum $\sim 80\,\text{MeV/c}$



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

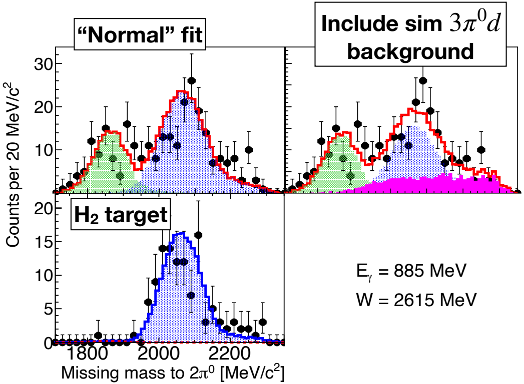
T.C. Jude, et al., Phys. Lett. B 832 (2022) 137277

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

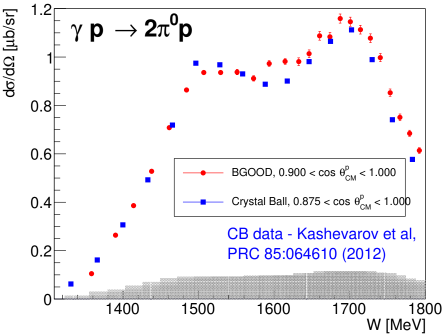


$\gamma d \to \pi^0\pi^0 d$ at BGOOD - systematic uncertainties

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

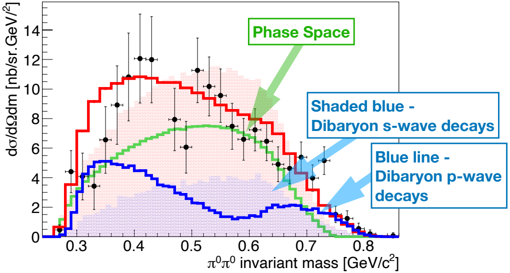


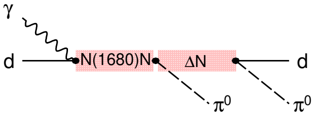
- Good agreement for a "Similar reaction", $\gamma p \to \pi^0\pi^0 p$
- Small difference at $W \sim 1600\,\text{MeV}$ understood - background from $\gamma p \to \eta p$



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

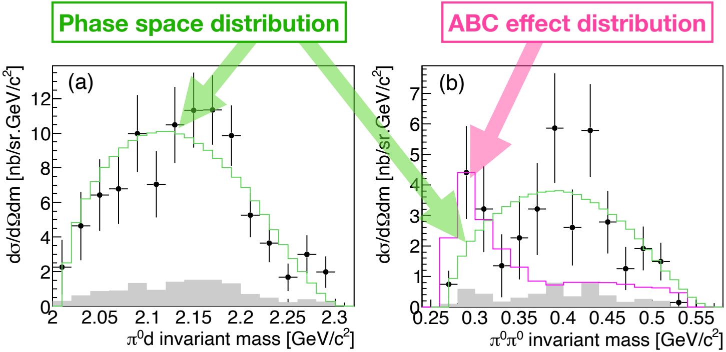
- $\pi^0\pi^0$ invariant mass for $2523 < W < 2738\,\mathrm{MeV}$
- Propose an $N(1680)5/2^+N$ dibaryon - large coupling to πN
- Positive parity - consistent with decay with odd relative angular momentum to the $N\Delta\ \pi^0$ system & the change in spin required of the constituents.





$\gamma d \to \pi^0\pi^0 d$ 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.)

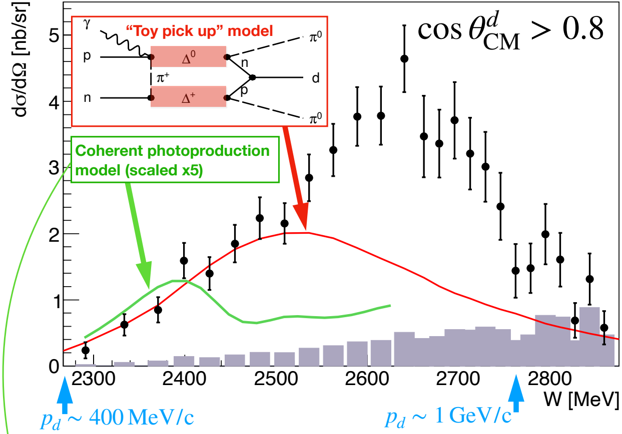


- Differential cross section for $\gamma d \to d^*(2380) \to \pi^0\pi^0 d$: $(22 \pm 6_{\rm stat} \pm 4_{\rm sys})$ nb/sr
- Angular dis. well known - cross section extrapolated to $(11.3 \pm 3.2_{\rm stat} \pm 2.7_{\rm sys})$ nb

$\gamma d \to \pi^0\pi^0 d$ 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"



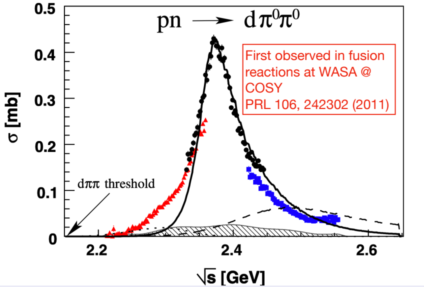
Egorov & Fix, NPA, 933 (2015) 104 - Fix & Arenhövel, EPJA, 25 (2005) 115

The Toy pick up model

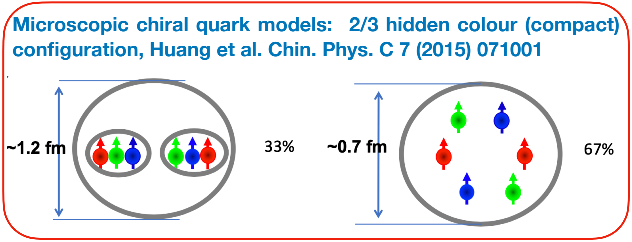
- Arbitrary scale
- On-shell momentum & energy conservation
- Nucleons coalesce to form the deuteron if their relative momentum is sufficiently small

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

Discovery of the $d^*(2380)$



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



- Compact nature supported by beam asymmetry measurements of deuteron photodisintegration

  Bashkanov et al. PLB 789 (2019) 7

- $d^*(2380)$ in the centre of neutron stars (EoS)? Dark matter candidate?

  Vidana et al., PLB 781 (2018) 112, Bashkanov & Watts, JPG 47 (2020) 03LT01