The BGOOD experiment at ELSA
exotic structures in the light quark sector?

Tom Jude, on behalf of the BGOOD collaboration

Physikalisches Institut, University of Bonn

jude@physik.uni-bonn.de

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:

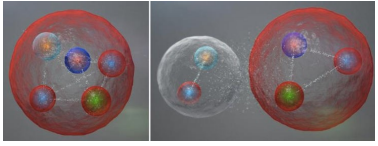
- Wealth of γN data - ELSA, MAMI, GRAAL, CLAS
- Sophisticated PWA, eg Bonn-Gatchina
- Improved understanding of known N^*, but few new states observed

		PDG status in	
state	J^P	2010	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?

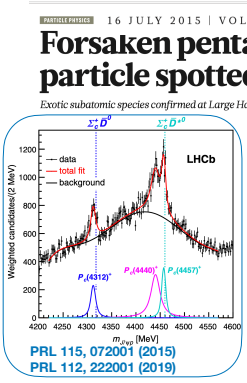
Glozman & Riska, Phys. Rep. 268 (1996) 263,
Garcia-Recio et al., PLB 582 (2004) 49,
Lutz & Kolomeitsev, PLB 585 (2004) 243



Exotic phenomena in the **charmed** sector*

*__Not__ what we study at BGOOD!

Pentaquarks at LHCb



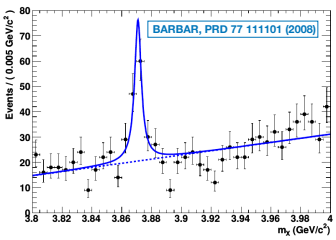
Meson-baryon dynamically generated states?

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

XYZ states in the charmed meson sector

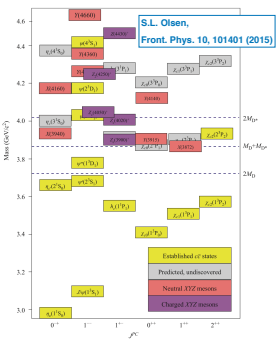
$X(3872) \rightarrow \pi^+\pi^- J/\psi$ - most cited paper from Belle

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!

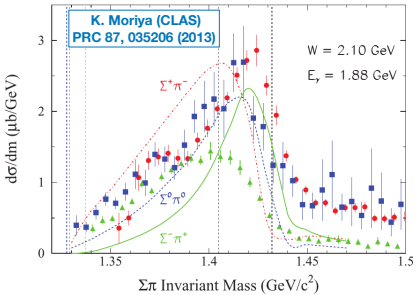
- Considered a $\bar{K}N$ molecule prior to the quark model

  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:



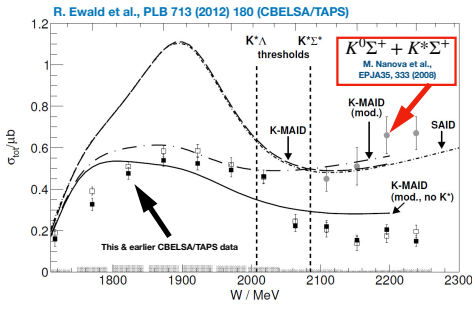
- $\Lambda(1405)$ - dynamically generated by meson-baryon interactions?

  Nacher, Oset, Toki, Ramos, & Meißner, NPA725 (2003)181
  Molina & Döring, PRD 94, 056010 & 079901 (2016)

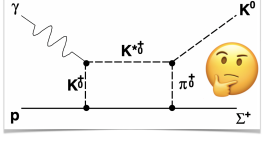
- LQCD: Hall et al., PRL 114 (2015) 132002

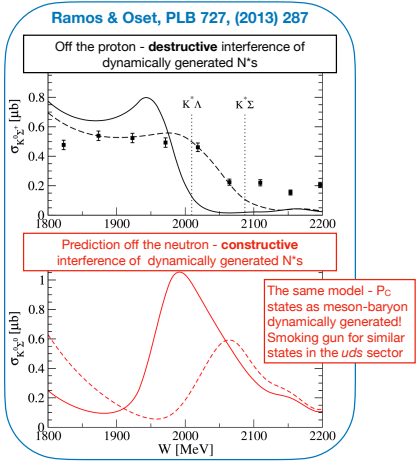
Motivation: Cusp in the $\gamma p \to K^0\Sigma^+$ cross section

Previous CBELSA/TAPS data:



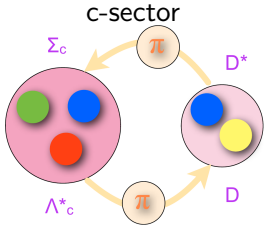
K^{*0} sub-threshold production rescattering to π^0 & K^0?

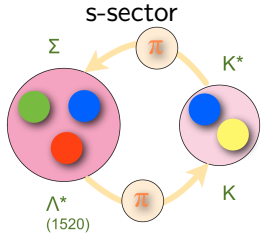




Parallels between charmed & strange sectors?

	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	$D^{*0}\bar{D}^0/D^0\bar{D}^{*0}$	$\Lambda_c^*\bar{D}+\Sigma_c\bar{D}^*$	$K^*\bar{K}/K\bar{K}^*$	$\Lambda^*\bar{K}+\Sigma\bar{K}^*$
Quantum numbers	$J^{PC}=1^{++}$	$J^P=3/2^-$	$J^{PC}=1^{++}$	$J^P=3/2^-$
3-body threshold	$D^0\bar{D}^0\pi^0$	$\Sigma_c^+\bar{D}^0\pi^0$	$K\bar{K}\pi$	$\Sigma\bar{K}\pi^0$
Closed flavour thresh.	$J/\psi\omega$	$\chi_{c1}p$	$\phi f_0(500)$	ϕp





The BGOOD experiment at ELSA

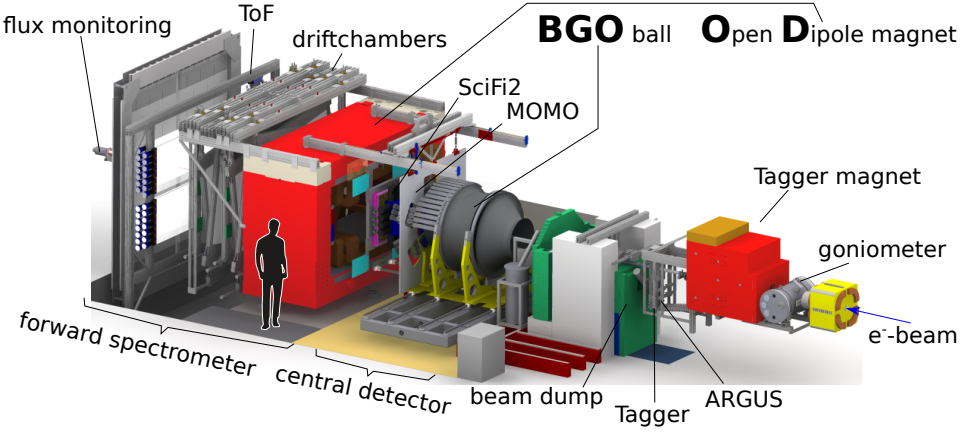
Exotic structures in the light quark sector?

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

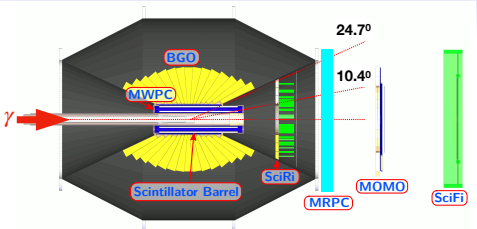
The BGOOD experiment, Eur. Phys. J. A 56:104 (2020)

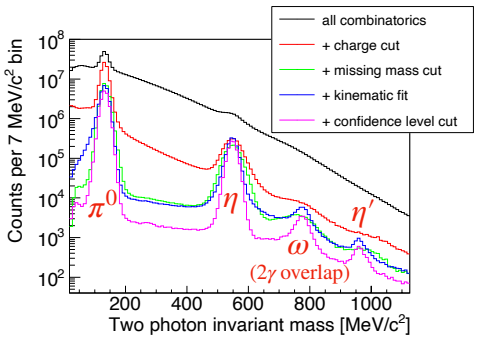
Spokespersons: T.C Jude (Bonn) & P. Levi Sandri (Frascati)

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

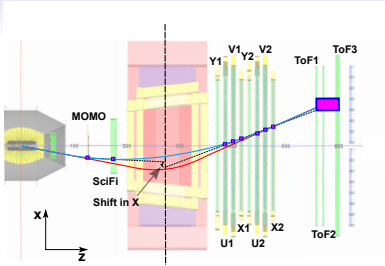


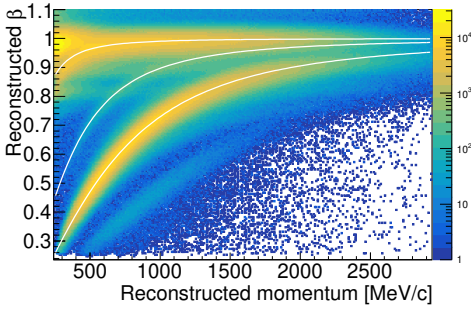
BGOOD central region





BGOOD forward region





The BGOOD experiment at ELSA

Exotic structures in the light quark sector?

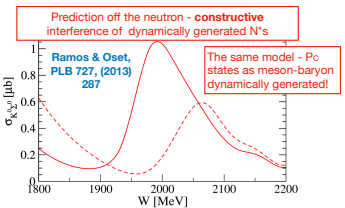
1. Motivation - parallels in the strange & charmed quark sectors?
   The BGOOD experiment at ELSA, Bonn

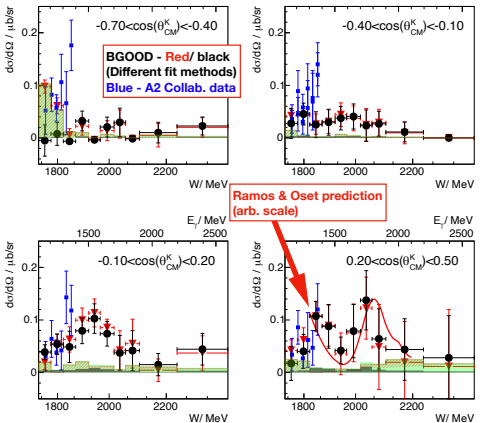
2. Exotic structure in associated strangeness photoproduction?
   - K^0 photoproduction - driven by molecular N^* states?
   - $K^+\Lambda(1405)$ - evidence of triangle singularity mechanism
   - Cusp at forward $K^+\Sigma^0$ photoproduction at the $K\bar{K}p$ threshold

3. Searches for exotic dibaryons at BGOOD

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

K. Kohl, T.C. Jude, et al. arXiv:2108.13319 (2021), accepted for EPJA





- $K^0 \to 2\pi^0$ in the BGO Rugby Ball
- Identify $\Sigma^0 \to \gamma\Lambda$ & angle cut on $\Lambda \to p\pi^-$
- Consistent with model prediction
- More data taken & being analysed
  A. Sonnenschein - PhD thesis (in preparation)

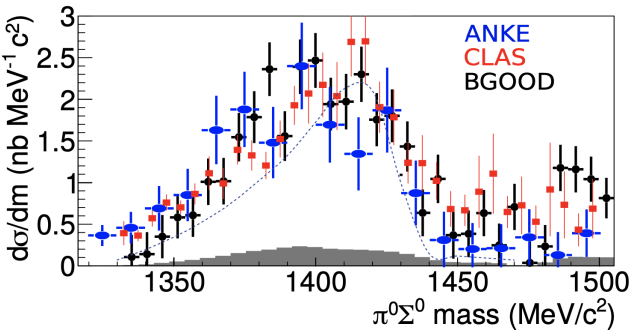
blue squares - Akondi et al. (A2) EPJA 55 11, 202 (2019)

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

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

- $\Lambda(1405) \to \pi^0\Sigma^0$ - Clean identification: $\Sigma(1385) \to \Sigma^0\pi^0$ isospin forbidden
- Full reconstruction: $K^+\Lambda(1405) \to K^+\Sigma^0\pi^0 \to K^+\gamma\Lambda\pi^0 \to K^+3\gamma p\pi^-$

- 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)

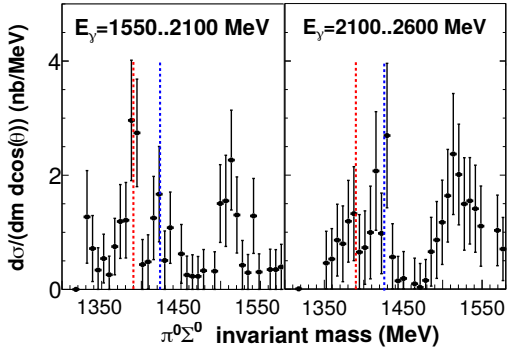


CLAS: Moriya, et al PRC 87, 035206 (2013)
ANKE: Zychor et al, PLB 660, 167 (2008)
Dashed line: Nacher et al, PLB 455, 55 (1999)

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

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 ($\sigma_{\mathrm{Mass}} \sim 13\,\mathrm{MeV/c^2}$, $\cos\theta^K_{\mathrm{CM}} > 0.86$):



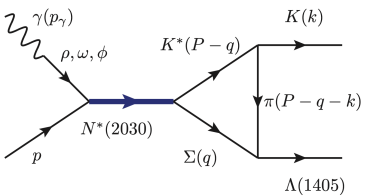
$\gamma p \to K^+\Lambda(1405) \to K^+(\Sigma^0\pi^0)$

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

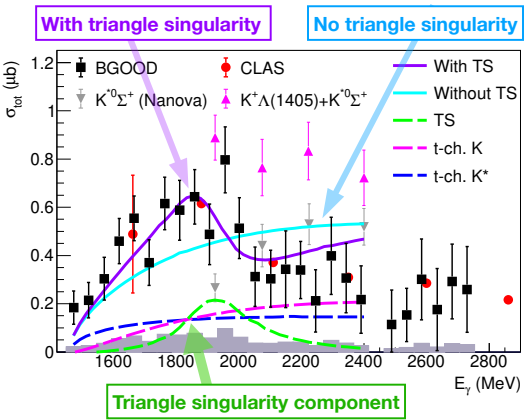
Triangle singularity in $\gamma p \to K^+\Lambda(1405)$

Wang et al. PRC 95, 015205 (2017)

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



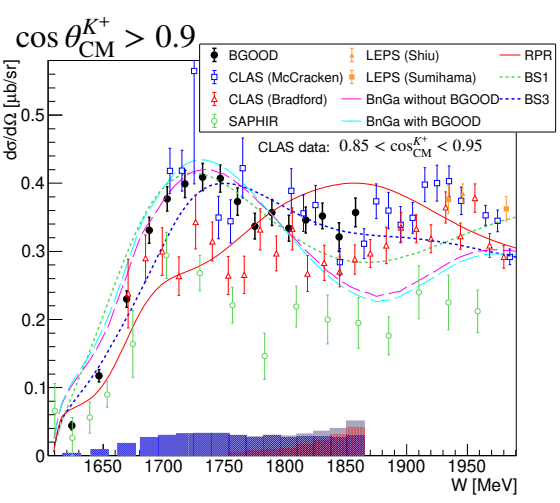
- $N^*(2030)$ close in mass & strong coupling to $K^*\Sigma$
- $K^*\Sigma$ molecular component?

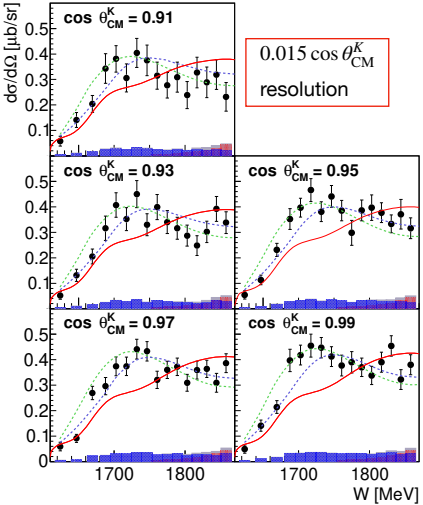


[CLAS: Moriya, PRC 87, 035206 (2013)]
[M. Nanova et al., EPJA 35 (2008) 333]

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

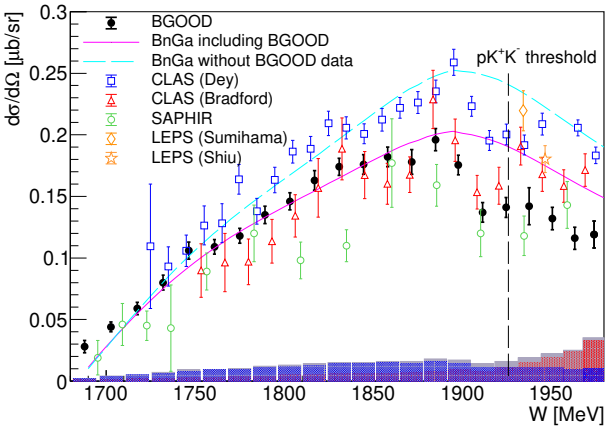
- Low t data - constraint on hypernuclei electroproduction
- Forward angles - sensitive to high spin N^*





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

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

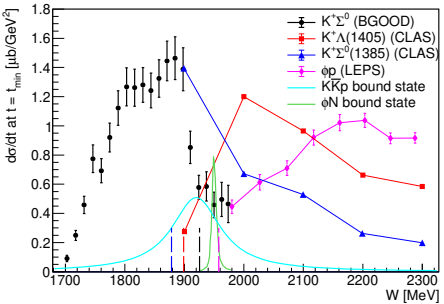


- Cusp regarded as a peak before - PWA have attributed $D_{13}(1895)$, $S_{31}(1900)$, $P_{31}(1910)$ & $P_{13}(1900)$

R. Bradford *et al.* (CLAS), PRC 73, 035202 (2006),
B.Dey *et al.* (CLAS), PRC 82, 025202 (2010),
CLAS data in $\cos\theta^K_{\rm CM}$ 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 $t_{\min}, \cos\theta^K_{\rm CM} = 1$



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

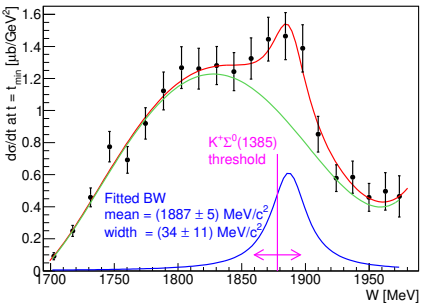
Channel thresholds:

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

Investigating other channels, eg $\gamma n \to K^+\Sigma^-$
J. Groß, PhD analysis, Uni Bonn

$\gamma p \to K^+\Sigma^0$ 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
$\frac{1}{2}^-$	$\Sigma_c\bar{D}$	$P_C(4312)$	Σ^0K^+	$N^*(1535)$?
$\frac{3}{2}^-$	$\Sigma_c^*\bar{D}$	$P_C(4382)$	$\Sigma^0(1385)K^+$	Peak in $K^+\Sigma^0$
$\frac{3}{2}^-$	$\Sigma_c\bar{D}^*$	$P_C(4457)$	Σ^0K^{*+}	Peak/cusp in $K^0\Sigma^{0/+}$ TS in $K^+\Lambda(1405)$
$\frac{1}{2}^-/\frac{5}{2}^-$	$\Sigma_c^*\bar{D}^*$	-	$\Sigma(1385)^0K^{*+}$	-

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

The BGOOD experiment at ELSA

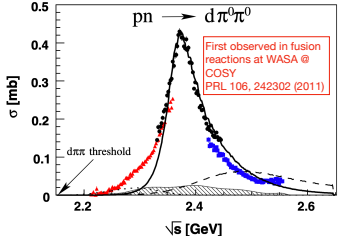
Exotic structures in the light quark sector?

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

Dibaryons - Motivation

Evidence of the $d^*(2380)$

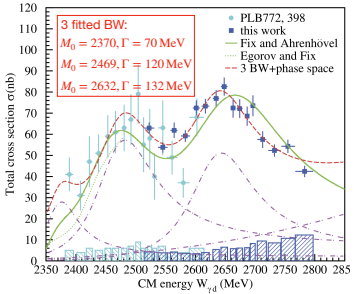
Adlarson et al PRL 106:242302, 2011
Bashkanov et al PRL 102:052301, 2009



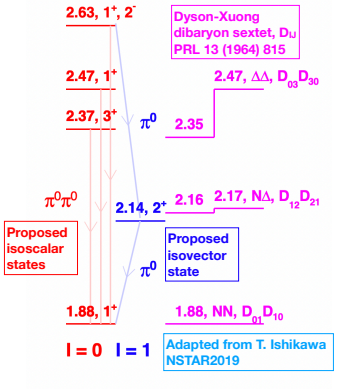
- $(I)J^P = (0)3^+$
- Observed in multiple final states

$\gamma d \to \pi^0\pi^0 d$ at ELPH

Ishikawa et al, PLB 789 (2019) 413 & PLB 772 (2017) 398

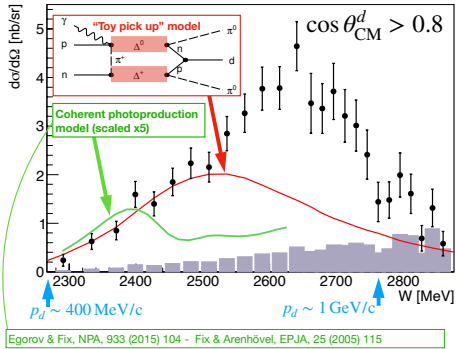


See also, preliminary data: M. Guenther et al (A2), PoS (Hadron 2017)051



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

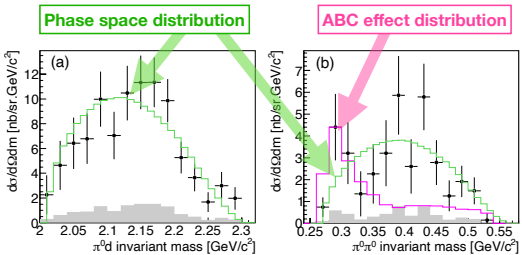
- Coherent reaction - $\gamma d \to \pi^0\pi^0 d$, deuterons in the forward spectrometer
- Not described by coherent production or *Toy pick up model*



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

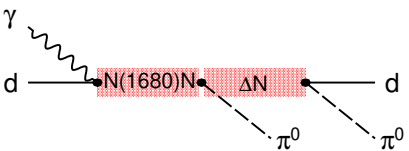
- $\pi^0\pi^0$ invariant mass over the $d^*(2380)$ - Consistent with the ABC effect

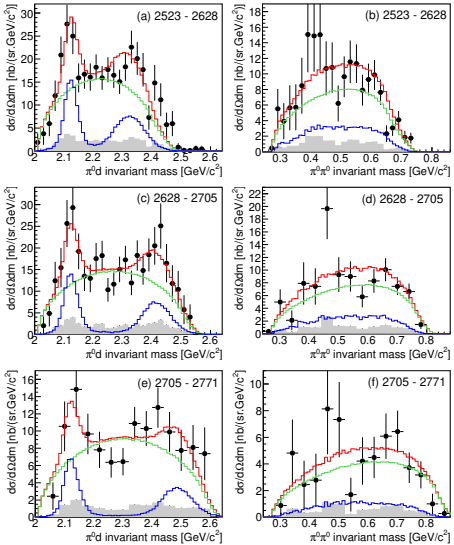
(distribution from P. Adlarson et al. PRC, 86:032201, 2012.)



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

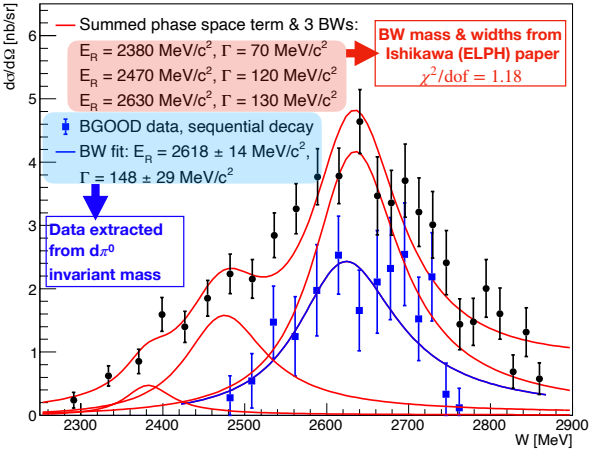
- $\pi^0 d$ & $\pi^0\pi^0$ invariant mass distributions for higher W intervals
- Simulated sequential decay - different masses & widths of the first dibaryon
- Sequential decay + Phase space = sum
- Mass of 2114 MeV/c^2 and width $\sim$ 20 MeV/c^2 (exp. resolution!) proved optimal

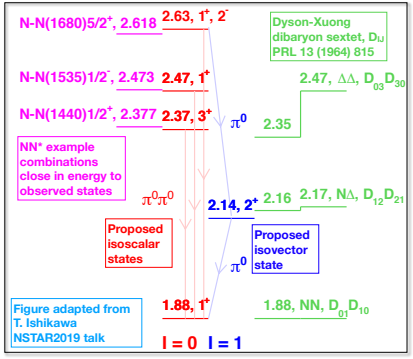




$\gamma d \to \pi^0\pi^0 d$ at BGOOD - Evidence of a dibaryon spectrum?

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



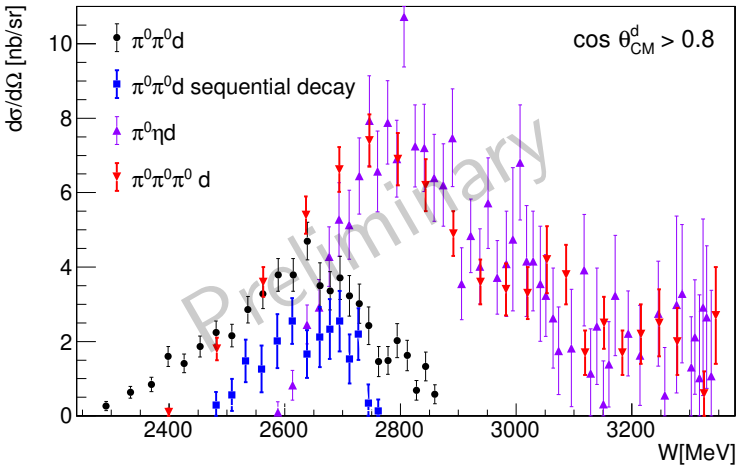


Coherent photoproduction at BGOOD - What's next?

- Other coherent final states - Access to isovector dibaryon candidates?
- $\pi^0\eta d$

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

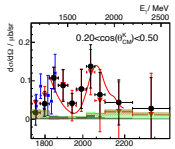
  A. Stirner, Masters thesis (Uni Bonn 2021)

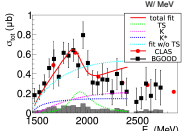


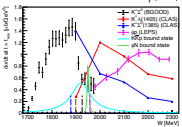
Coherent $\pi^0\eta d$ photoproduction paper in preparation (A. Figueiredo, TCJ, et al.)

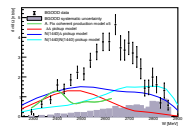
The BGOOD experiment at ELSA - the story so far

- Molecular-like structure in the *uds* sector?
- BGOOD - photoproduction at forward angles & low momentum transfer Eur. Phys. J. A 56:104 (2020)
- $\gamma n \to K^0\Sigma^0$ - dynamically generated meson-baryon resonance contributions? (parallels to P_C states)
  K. Kohl, T.C. Jude, arXiv:2007.08898 (2021), accepted by EPJA
- $\gamma p \to K^+(\Lambda(1405) \to \Sigma^0\pi^0)$ - triangle diagram mechanism?
  G. Scheluchin, T.C Jude et al. Phys. Lett. B 833 (2022) 137375)
- Cusp in $\gamma p \to K^+\Sigma^0$ - at thresholds & bound state predictions
  T.C. Jude et al., Phys. Lett. B 820 (2021) 136559, Eur. Phys. J. A (2021) 57:80
- Coherent $\gamma d \to \pi^0\pi^0 d$ - dibaryons?
  T.C. Jude, et al., Phys. Lett. B 832 (2022) 137277







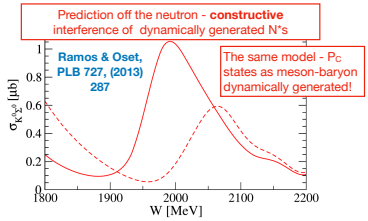


Extra slides

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

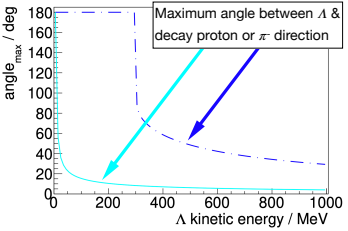
Predicted peak - "smoking gun" for reaction mechanism

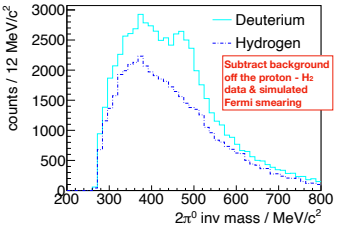


Dynamically generated meson-baryon states? - $\Lambda^* K + \Sigma K^*$

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

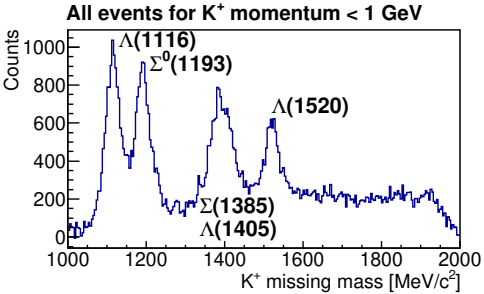
- $K^0 \to 2\pi^0$ in the BGO Rugby Ball
- Identify $\Sigma^0 \to \gamma\Lambda$ & angle cut on $\Lambda \to p\pi^-$

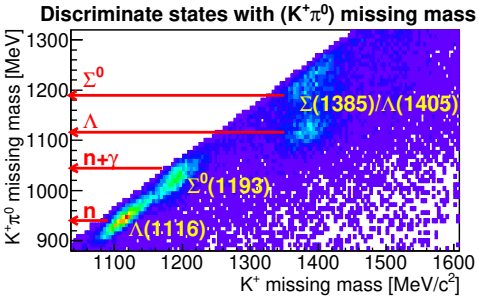




Forward K^+Y analysis

- 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





- Identify Y^* states from $K^+\pi^0$ recoiling mass

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

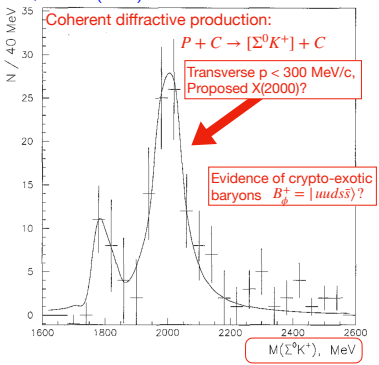
    Gao, Huang, Liu, Ping, Wang & Z. Zhao, PRC, 95:055202, 2017
  - Molecular $K\Sigma$ states, $J^P = 1/2^-$ & $3/2^-$ consistent with $N^*(1875)$ & $N^*(2100)$

    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

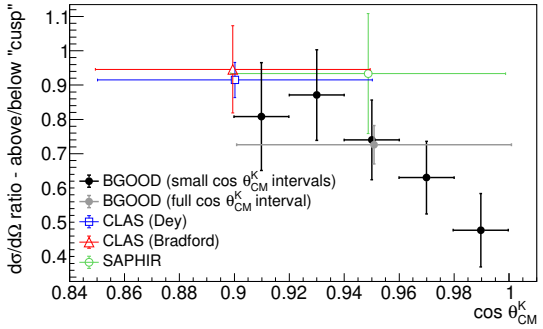
ZPC, 68:585 (1995)

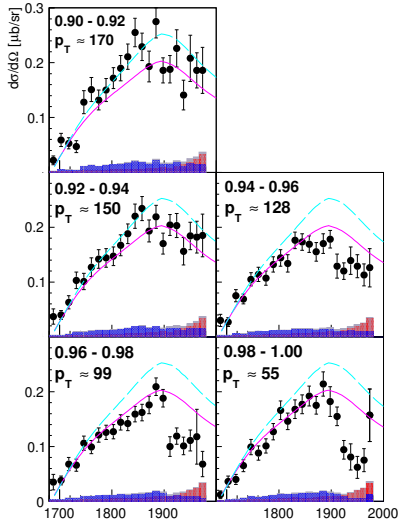


Low transverse p requires forward kinematics in photoproduction!

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

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

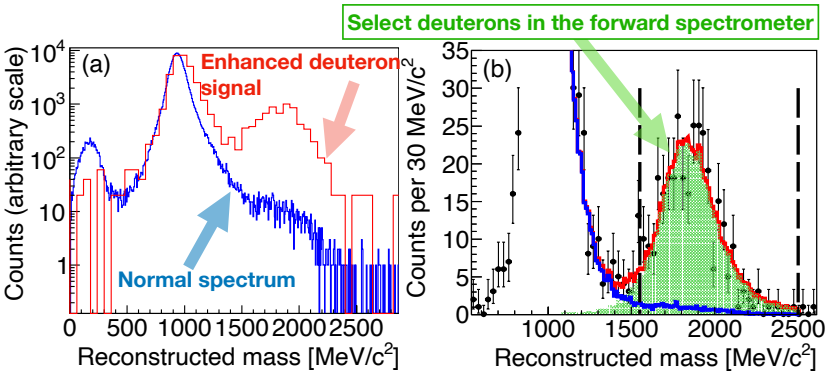




$\gamma d \to \pi^0\pi^0 d$ at BGOOD - analysis steps

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

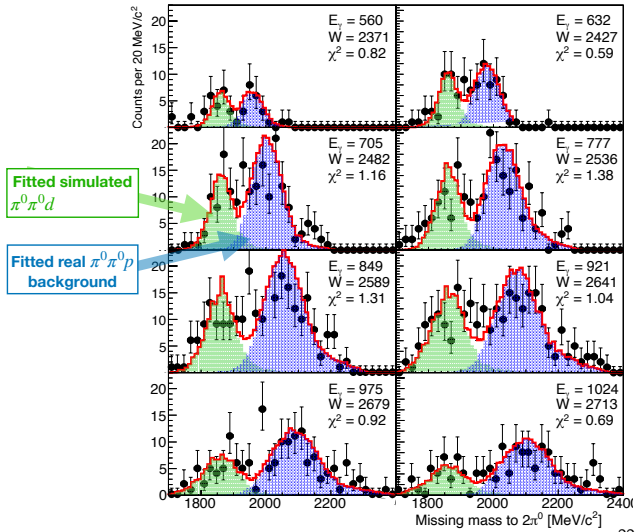
- Coherent reaction - $\gamma d \to \pi^0\pi^0 d$, deuterons in the forward spectrometer
- Unexpected! $p_d > 400\,\mathrm{MeV/c}$ & deuteron Fermi momentum $\sim 80\,\mathrm{MeV/c}$



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

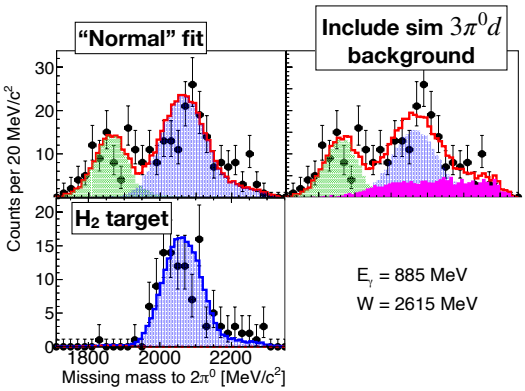
T.C. Jude, et al., Phys. Lett. B 832 (2022) 137277

- 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" ($\gamma d \to \pi^0\pi^0 X$)

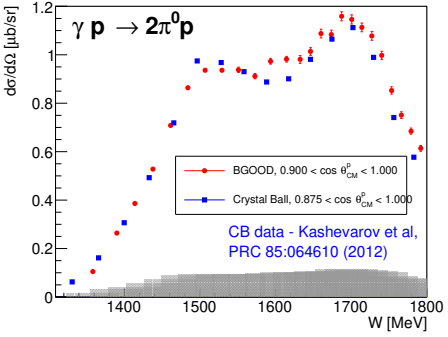


$\gamma d \to \pi^0\pi^0 d$ at BGOOD - systematic uncertainties

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

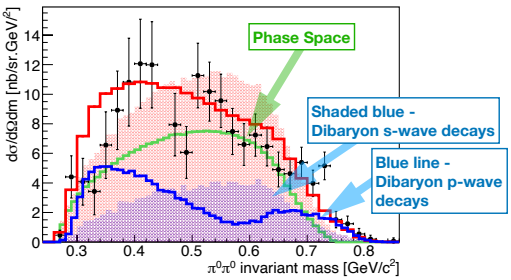


- Good agreement for a "Similar reaction", $\gamma p \to \pi^0\pi^0 p$
- Small difference at $W \sim 1600$ MeV understood - background from $\gamma p \to \eta p$



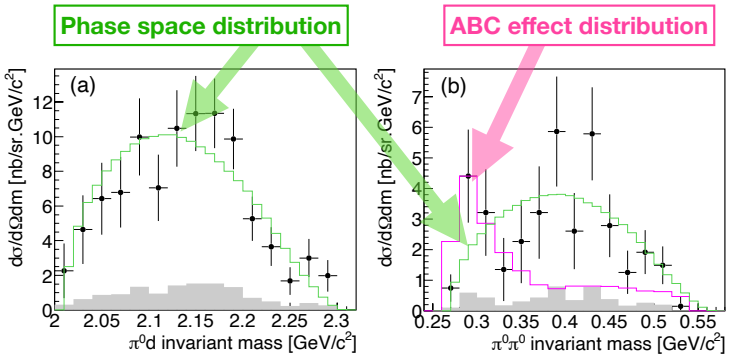
$\gamma d \to \pi^0\pi^0 d$ at BGOOD - Evidence of a dibaryon spectrum?

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

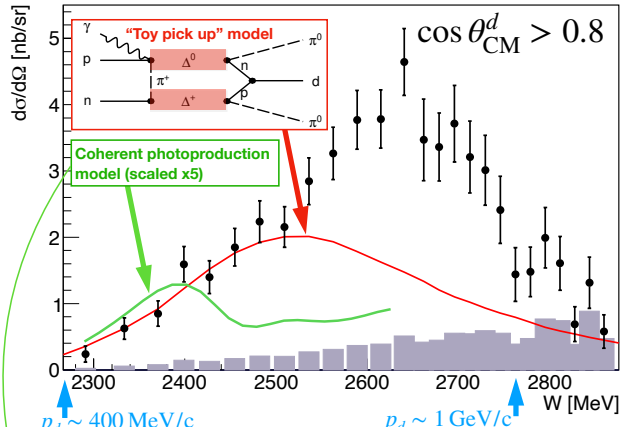


- Differential cross section for $\gamma d \to d^*(2380) \to \pi^0\pi^0 d$: $(22 \pm 6_{\mathrm{stat}} \pm 4_{\mathrm{sys}})$ nb/sr
- Angular dis. well known - cross section extrapolated to $(11.3 \pm 3.2_{\mathrm{stat}} \pm 2.7_{\mathrm{sys}})$ nb

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



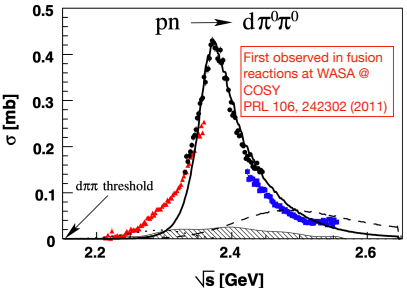
Egorov & Fix, NPA, 933 (2015) 104 - Fix & Arenhövel, EPJA, 25 (2005) 115

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

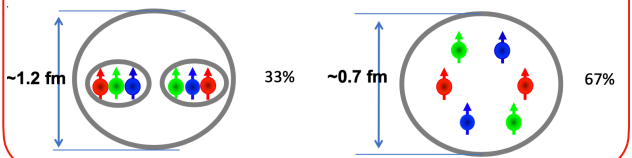
The $d^*(2380)$ dibaryon/hexaquark

Discovery of the $d^*(2380)$



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

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 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