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

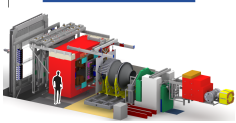
Tom Jude, on behalf of the BGOOD collaboration

Physikalisches Institut
University of Bonn

jude@physik.uni-bonn.de

June, 2022

Supported by the DFG PN 388979758 & 405882627 & the EU Horizon 2020 research and innovation programme, grant agreement no. 824093



Status of N^* spectroscopy

Constituent quark models Vs. experiment

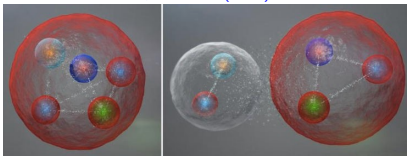
- General agreement of N^* and Δ spectra, however the "Missing resonance problem" persists
- Cannot also describe the parity ordering of lowest states, despite:
  - Wealth of γN data - ELSA, MAMI, GRAAL & CLAS
  - Sophisticated PWA, eg Bonn-Gatchina
  - Much improved understanding of known resonances, 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?

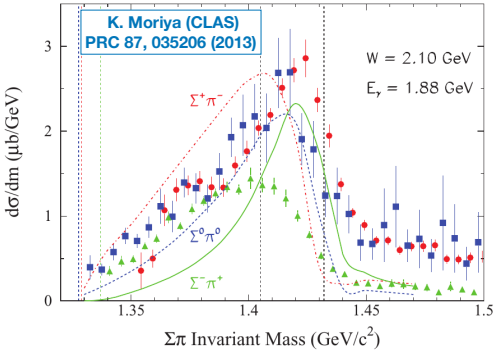
Glozman & Riska, Phys. Rep. 268 (1996) 263,
Garcia-Recio et al., PLB 582 (2004) 49,
Lutz & Kolomeitsev, PLB 585 (2004) 243



Structure of the $\Lambda(1405)$

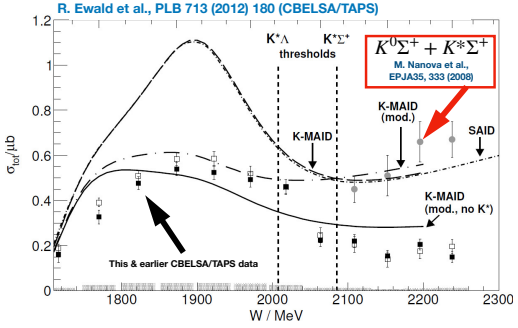
- Well established since the 1960's - considered a $\bar{K}N$ molecule prior to the quark model

  Dalitz & Tuan, PRL 2 (1959) 425
- PDG until 2016 - a 3-quark state - now a $\bar{K}N$ molecule most probable
- Difficult to reconcile within a CQM:
  - Mass too low compared to $N^*(1535)$
  - Large spin orbit splitting to $\Lambda(1520)$
- Lies between the $\pi\Sigma$ & $\bar{K}N$ thresholds

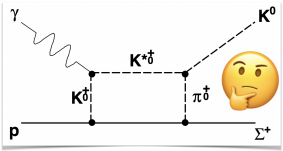


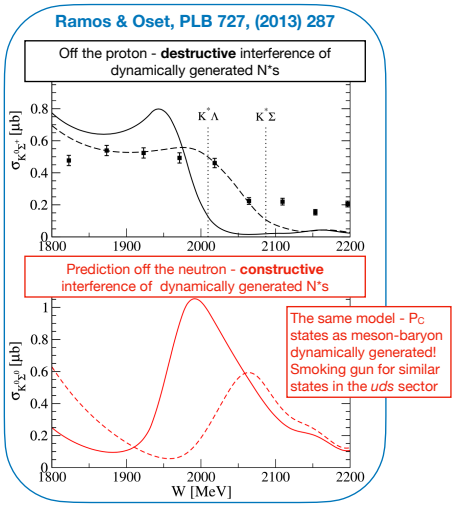
- $\Lambda(1405)$ - dynamically generated by meson-baryon interactions? Nacher, Oset, Toki, Ramos, & Meißner, NPA725 (2003)181
- LQCD: Hall et al., PRL 114 (2015) 132002
- UχPT: Molina & Döring, PRD 94, 056010 & 079901 (2016)

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



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



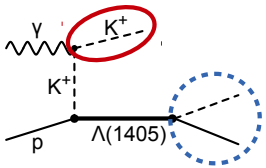


Parallels between charmed & strange sectors

	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

BGOOD at the ELSA facility, Bonn:

- Photoproduction in the *uds* sector
- Charged particle identification at extremely forward angles - reaction dynamics at very low momentum exchange



The BGOOD experiment

Eur. Phys. J. A 56:104 (2020)

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

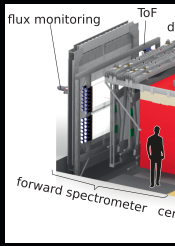
- Located at ELSA (Uni Bonn) - A 3 stage e^- accelerator - continuous beams up to 3.2 GeV
- BGO calorimeter (central region) & Forward Spectrometer combination
- High momentum resolution, excellent charged & neutral particle ID

The European Physical Journal volume 56 · number 4 · april · 2020

EPJ A

Recognized by European Physical Society

Hadrons and Nuclei

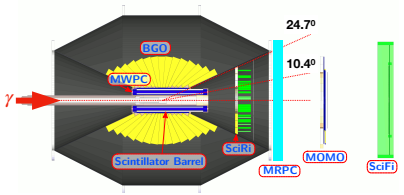


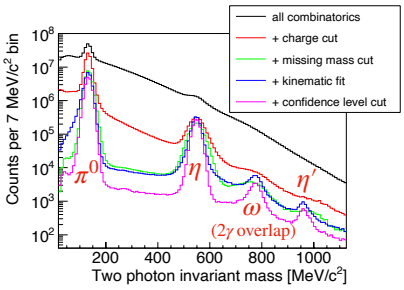
Overview of the BGOOD (BGOball Open Dipole magnet) experiment at the Elsa Facility dedicated to study meson photo-production

From: T. C. Jude and P. Levi Sandri et al. on "The BGOOD experimental setup at ELSA"

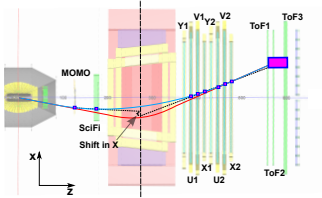
The BGOOD experiment, Eur. Phys. J. A 56:104 (2020)

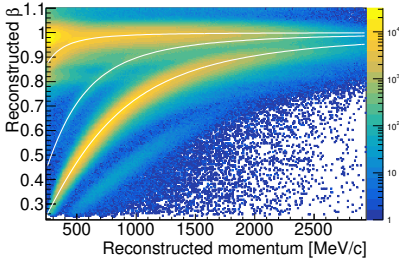
The central region





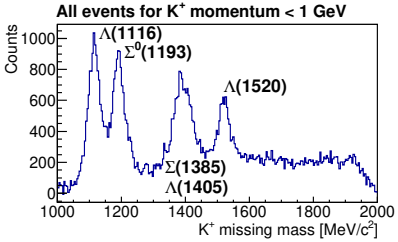
The forward region

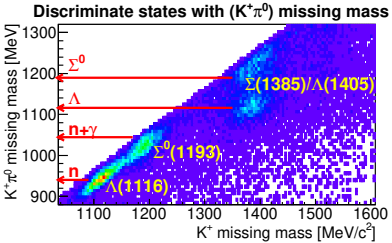




Analysis example - mass recoiling from forward K^+

- The study of Y^* states in an extremely low momentum transfer region

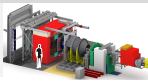




Identify Y^* states from $K^+\pi^0$ recoiling mass

- $K^+\Lambda \rightarrow K^+\pi^0 n$ (Missing neutron mass from $K^+\pi^0$ system)
- $K^+\Lambda(1405) \rightarrow K^+\pi^0\Sigma^0$ (Missing Σ^0 mass from $K^+\pi^0$ system)
- $K^+\Sigma(1385) \rightarrow K^+\pi^0\Lambda$ (Missing Λ mass from $K^+\pi^0$ system)

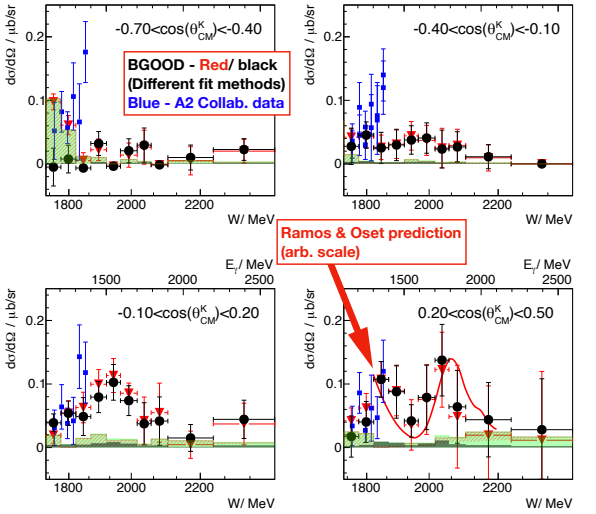
$\gamma n \rightarrow K^0\Sigma^0$ K. Kohl PhD thesis, arXiv:2108.13319 (2021) (submitted to EPJA)



- Peak predicted - "smoking gun" for reaction mechanism - Equivalent model that predicted the P_C states as dynamically generated

  A. Ramos and E. Oset, PLB 727, (2013) 287

- identified via $K^0 \rightarrow 2\pi^0$ & $\Sigma^0 \rightarrow \gamma(\Lambda \rightarrow p\pi^-)$
- Consistent with model prediction - more statistics required for definitive statement
- More data now available

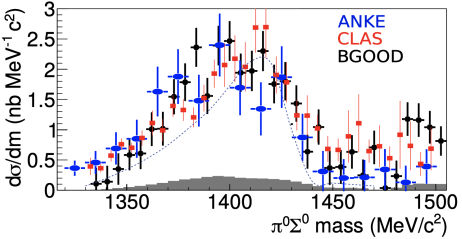


Model prediction - Ramos & Oset, PLB 727, 287 (2013)
Squares - Akondi et al. (A2) EPJA 55 11, 202 (2019),

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

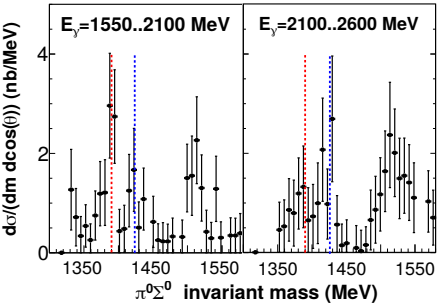
G. Scheluchin PhD thesis, arXiv:2007.08898 (2021), submitted to PLB

- Line shape - good agreement with previous data



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

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



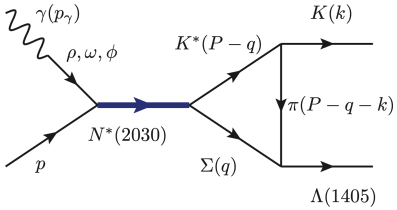
$\gamma p \to K^+\Lambda(1405) \to K^+(\Sigma^0\pi^0)$

G. Scheluchin PhD thesis, arXiv:2007.08898 (2021), submitted to PLB

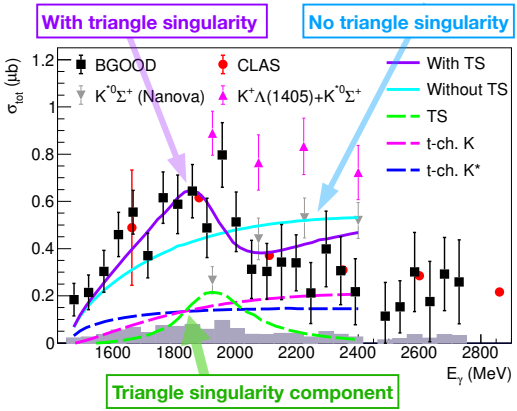
Triangle singularity in $\gamma p \to K^+\Lambda(1405)$

Wang et al. PRC 95, 015205 (2017)

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



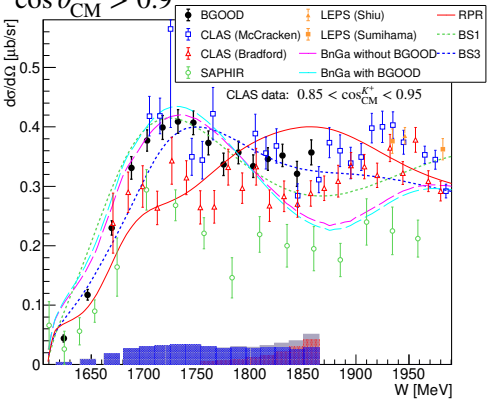
- $N^*(2030)$ close in mass & strong coupling to $K^*\Sigma$
- $K^*\Sigma$ molecular component?



[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

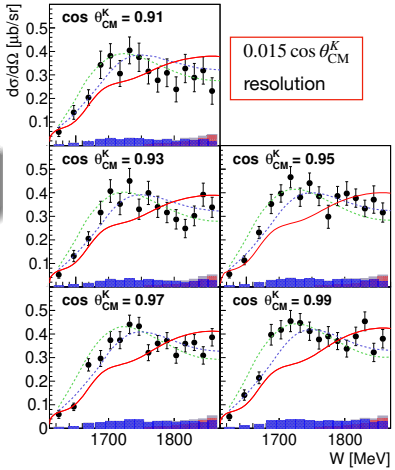
- Low t data - constraint on hypernuclei electroproduction
- Forward angles - sensitive to high spin N^*



CLAS data:

$0.85 < \cos\theta^{K^+}_{\rm CM} < 0.95$

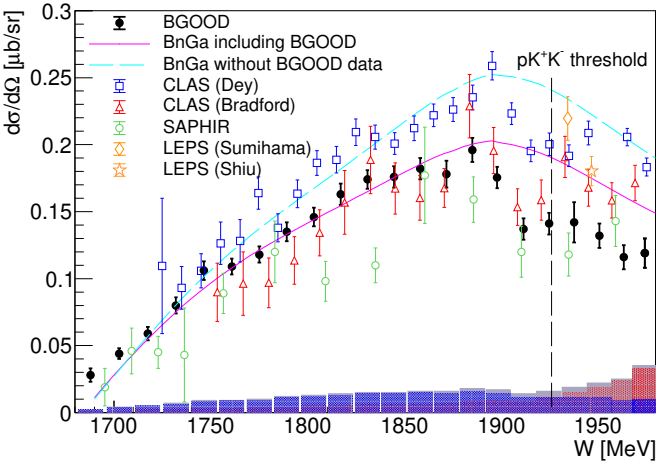
BnGa: EPJA 50:74 (2014)
RPR: Skoupil & Bydžovský, PRC, 100:035202 (2019)
BS1 & BS3: Skoupil & Bydžovský, PRC, 97:025202 (2018)
Bradford, PRC 73:035202 (2006)
McCracken, PRC 81:025201 (2010)
SAPHIR, EPJA 19:251 (2004)
LEPS: PRC 73:035214 (2006) & 97:015208 (2018)



$0.015 \cos\theta^{K}_{\rm CM}$ resolution

$\gamma p \to K^+\Sigma^0$ 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

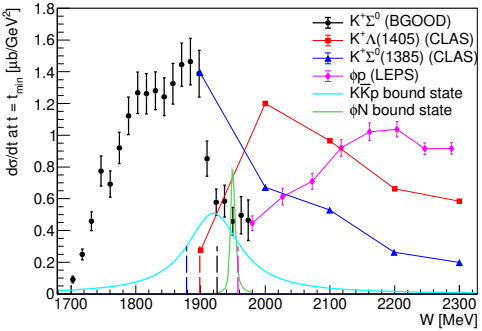


- Cusp regarded as a peak before - PWA have attributed $D_{13}(1895)$, $S_{31}(1900)$, $P_{31}(1910)$ & $P_{13}(1900)$

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} & $\cos\theta^K_{\mathrm{CM}} = 1$



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....

- at predicted $K\bar{K}p$ and ϕp bound states
- 20 MeV above predicted bound $\Sigma(1385)K$ state

Channel thresholds:

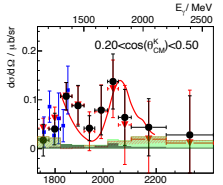
- A "smooth" transition between $K^+\Sigma^0$ & $p\phi$
- Similar behaviour of $K^+\Sigma^0(1385)$

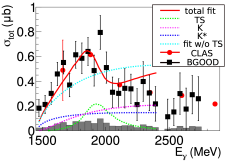
Evidence that the Jülich-Bonn dynamical coupled-channel analysis can describe the "cusp"

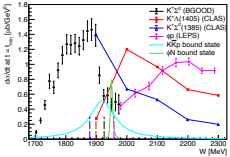
D. Rönchen, priv. comm. 2022

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)
  arXiv:2108.13319 (2021), submitted to EPJA
- $\gamma p \to K^+(\Lambda(1405) \to \Sigma^0\pi^0)$ - triangle diagram mechanism?
  arXiv:2007.08898 (2021), submitted to PLB
- Cusp in $\gamma p \to K^+\Sigma^0$ - at thresholds & bound state predictions
  PLB 820 (2021) 136559
- Forward $\gamma p \to K^+\Lambda$ Eur. Phys. J. A (2021) 57:80







The BGOOD experiment at ELSA - What is next?

Exotic structures in the light quark sector?

- More data this year
- Aerogel Cherenkov - forward K^+/π^+ separation
- Higher statistics study in the strangeness sector
  - $K^0\Sigma$ channels & different $\Lambda(1405)$ decay modes
  - $K^+\Sigma^-$ J. Groß, PhD analysis, Uni Bonn
  - $K^*\Sigma$ A. Figueiredo, Bachelor thesis 2020, & L. Bauchage, Bachelor thesis 2022, Uni Bonn

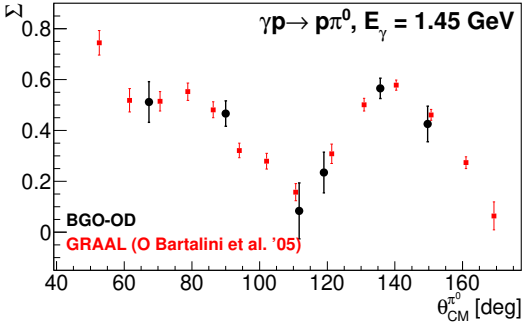
In the non-strange sector...

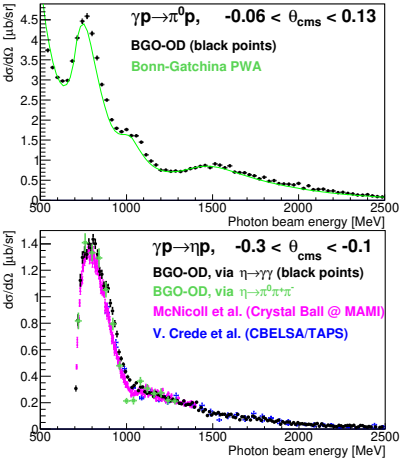
- "Dibaryon" searches in coherent reactions
  - $\gamma d \to 2\pi^0 d$ TJ, arXiv:2202.08594, submitted to PLB
  - $\gamma d \to 3\pi^0 d$ A. Stirner, Masters thesis 2021, Uni Bonn
  - $\gamma d \to \pi^0\eta d$ L. Lutter, bachelor thesis & TJ, Proof of principle tests
- η' near threshold S. Alef, PhD thesis 2021, Uni Bonn
- $\gamma p \to \pi^0\eta$: a_0 & a_2 studies at low p transfer A. Sonnenschein, Masters thesis 2021, Uni Bonn

Extra slides

BGOOD - Central region

- Accurate neutral meson photoproduction cross sections
- γ flux well understood ($\sim 4\%$)
- BGOOD - both neutral & mixed charged identification
- Well understood degree of linear polarisation

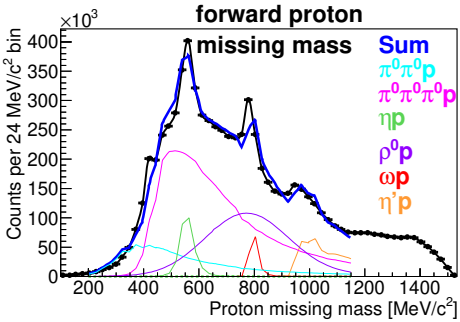


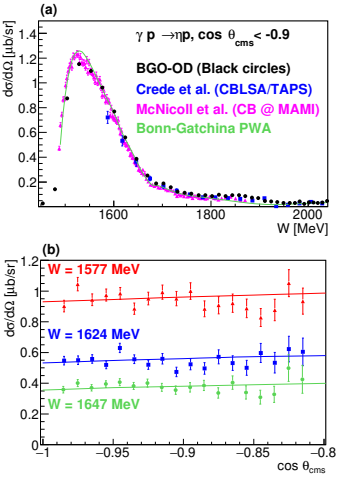


Bartalini *et al.*, EPJA **26**, 399 (2005), BnGa: Anisovich *et al.*, EPJA **25**, 427 (2005), McNicoll *et al.*, PRC **82** 035208 (2010), Crede *et al.*, PRC **80**, 055202 (2009)

BGOOD - Forward region

- Accurate knowledge of detector & trigger efficiencies, momentum & β resolution
- Right: $\gamma p \to \eta p$ (proton in F.S) - excellent agreement with existing data

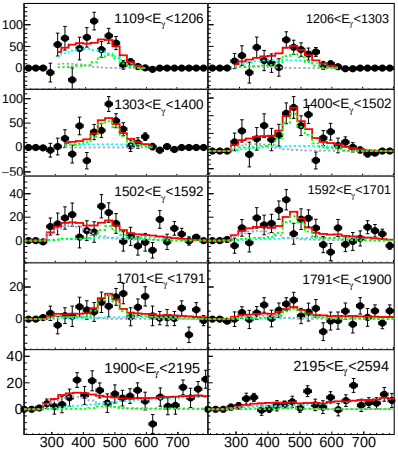




BnGa: Anisovich *et al.*, EPJA **25**, 427 (2005), McNicoll *et al.*, PRC **82** 035208 (2010), Crede *et al.*, PRC **80**, 055202 (2009)

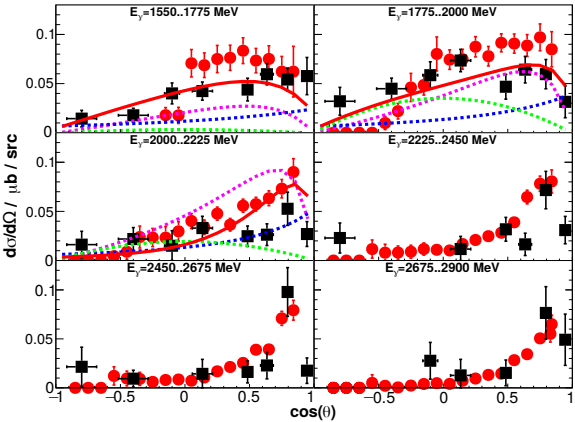
$\gamma n(p) \rightarrow K^0\Sigma^0$ K. Kohl PhD thesis, paper in preparation

- Fit signal & background off the neutron ($3\pi^0 n$ & ηn)
- 2 fit methods - sim or real BG data with relaxed reaction selection constraints



$\gamma p \to K^+\Lambda(1405)$ G. Scheluchin PhD thesis, paper in preparation

- Differential cross section for $\gamma p \to K^+\Lambda(1405) \to \Sigma^0\pi^0$

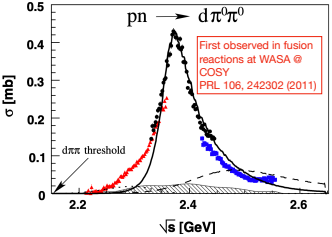


Black points: BGOOD
Red points: CLAS
Solid Red: Total fit
Dotted cyan: fit without Triangle diagram
Dotted green: Triangle diagram contribution
Dotted blue: K^* t-channel exchange
Dotted magenta: K t-channel

Fits from Wang et al. PRC 95, 015205 (2017)

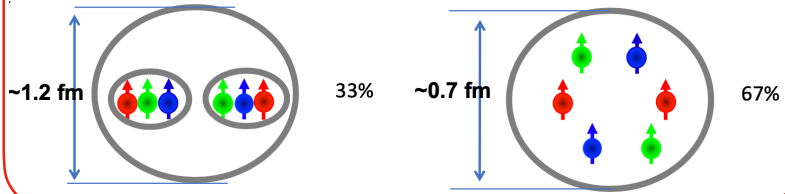
Dibaryons - Motivation

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



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

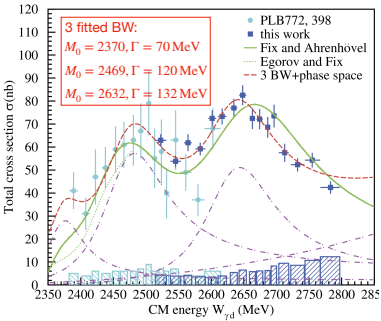
Microscopic chiral quark models: 2/3 hidden colour (compact) configuration, Huang et al. Chin. Phys. C 7 (2015) 071001

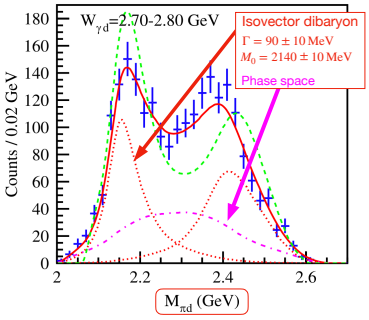


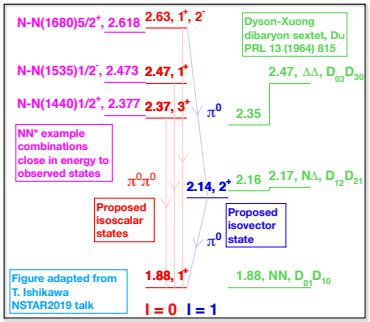
- Calculations of $d^*(2380)$ in the centre of neutron stars - Vidana et al, PLB 781 (2018) 112
- Dark matter candidate - $d^*(2380)$ BEC formed in the early universe Bashkanov & Watts, J. Phys. G 47 (2020) 03LT01

Exotic dibaryon searches at BGOOD - Motivation

- Coherent photoproduction, $\gamma d \to \pi^0\pi^0 d^*(2380)$ challenging - minimal momentum transfer to target deuteron, & large quasi-free background
- Previous data from ELPH Ishikawa et al, PLB 789 (2019) 413:

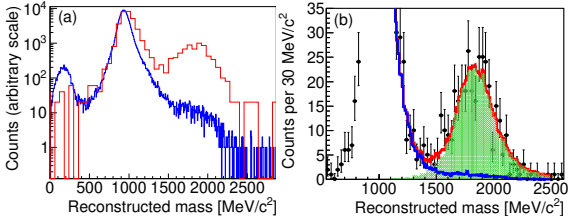






- Dyson & Xuong: predictions from SU(6) for baryons - 4 dibaryon candidates PRL 13 (1964) 815
- Gal & Garcilazo: 3-body calculations - $N\Delta$ & $\Delta\Delta$ resonances in good agreement NPA928 (2014) 73

Exotic dibaryon searches at BGOOD

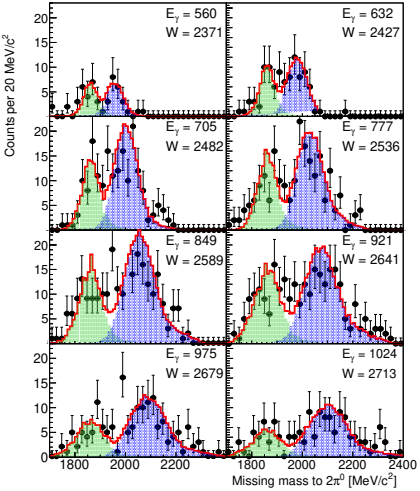


Fit to $2\pi^0$ missing mass spectra (after forward deuteron ID))

$\gamma d \to \pi^0\pi^0 d$ (simulated)

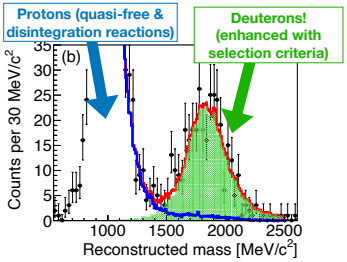
Fitted quasi-free $\gamma p \to \pi^0\pi^0 p$ BG

Total fit



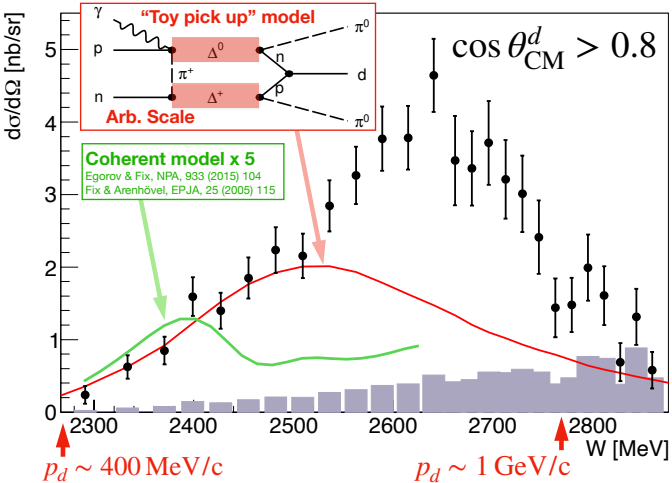
Dibaryons at BGOOD TJ, arXiv:2202.08594, submitted to PLB

Coherent reaction - $\gamma d \to \pi^0\pi^0 d$, deuterons in the forward spectrometer!

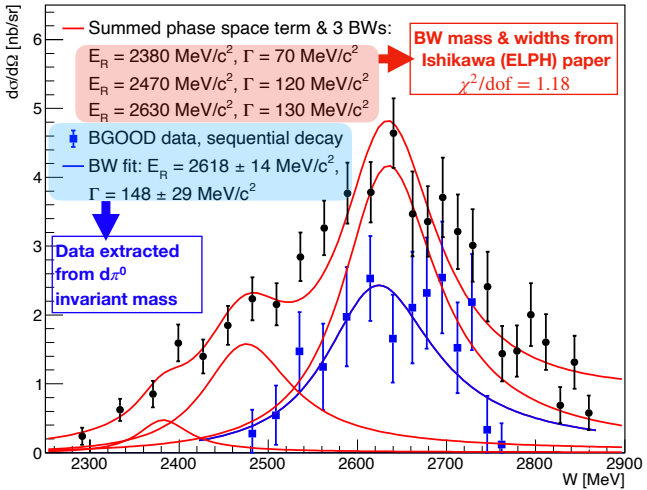


Completely unexpected!

- $p_d > 400\,\mathrm{MeV/c}$
- Deuteron Fermi momentum $\sim 80\,\mathrm{MeV/c}$

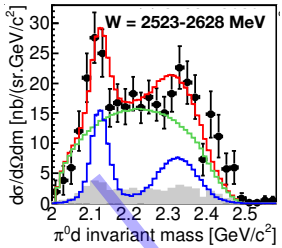


Dibaryons at BGOOD TJ, arXiv:2202.08594, submitted to PLB

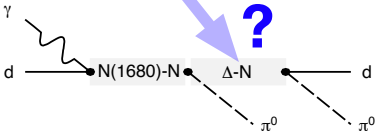


Blue- dibaryon sequential decay

Green - phase space



$E_R \sim 2114\,\mathrm{MeV/c^2}, \Gamma \lessapprox 20\,\mathrm{MeV/c^2}$



The Electron Stretcher Accelerator (ELSA)

A 3 stage e^- accelerator - continuous electron beams up to 3.2 GeV

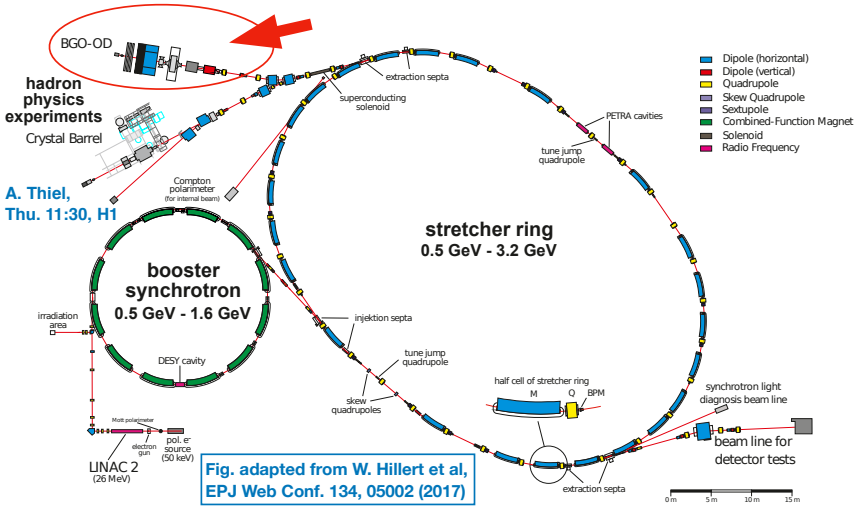


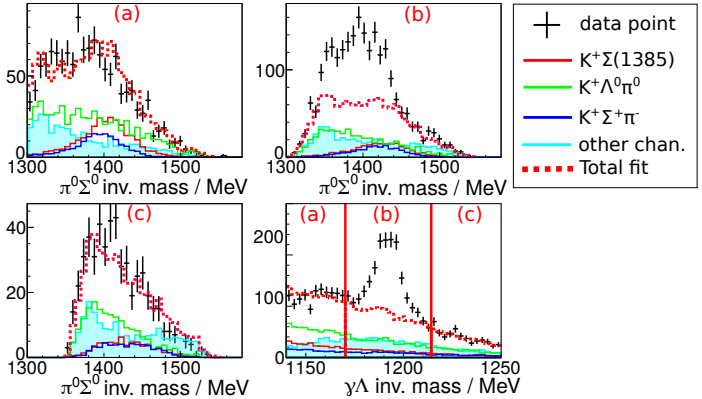
Fig. adapted from W. Hillert et al, EPJ Web Conf. 134, 05002 (2017)

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

G. Scheluchin PhD thesis, arXiv:2007.08898 (2021), submitted to PLB

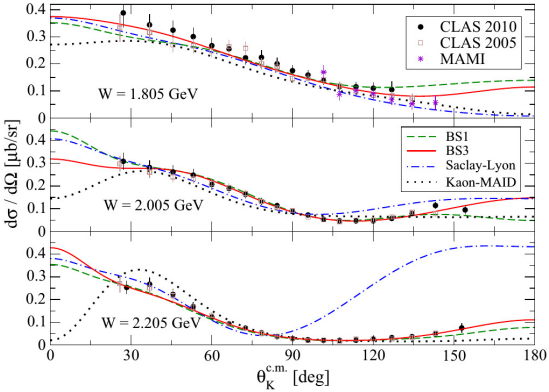
- Line shape & differential cross section for $\gamma p \to K^+(\Lambda(1405) \to \Sigma^0\pi^0)$
- $\gamma p \to K^+(\Lambda(1405) \to \Sigma^0\pi^0) \to K^+(\Lambda\gamma)(\gamma\gamma) \to K^+(p\pi^-\gamma)(\gamma\gamma)$

- Full reconstruction & kinematic fit
- 2D fit to signal & background:
- Other channels (cyan line):
  $\eta\pi p$,
  $K^0\Sigma^+$,
  $K^+\Sigma^0$,
  $\pi^0\pi^+\pi^- p$



Forward $\gamma p \to K^+\Lambda$ - motivation

Not only Y^* states at forward angles important - photoproduction of ground state hyperons at low t virtually unconstrained by data



- BGOOD - high $\cos^{K}_{\mathrm{CM}}$ resolution at forward angles - sensitive to high-spin intermediate states
- low t photoproduction - crucial constraint for hypernuclei electroproduction!

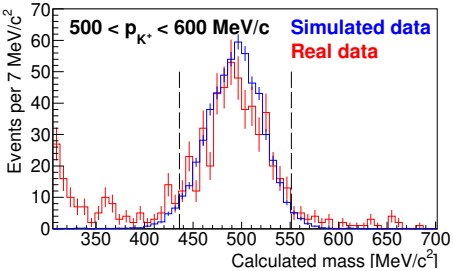
Additional models (not shown):

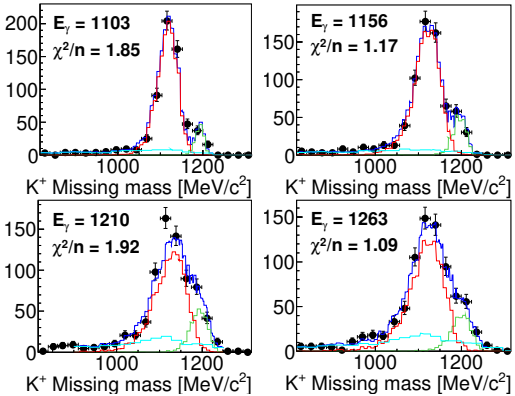
Jülich-Bonn, D. Rönchen, M., Döring, U.G. Meißner, EPJA (2018) 54
BnGa PWA, E. Klempt, A. Sarantsev, U. Thoma, V. Nikonov

D. Skoupil, P. Bydzovsky, PRC 97, 025202 (2018) (& refs. therein)

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

- Identify $\Lambda \rightarrow \pi^0 n$ with low energy deposition the BGO Rugby Ball
- Reconstructed forward K^+ mass:

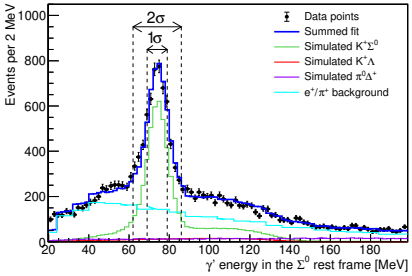




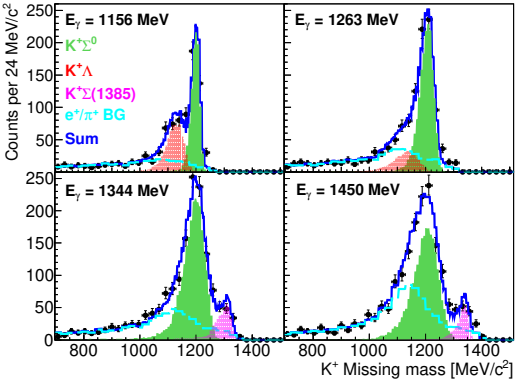
K^+ missing mass fitted with:
Simulated $K^+\Lambda$ and $K^+\Sigma^0$, Background from e^+ & π^+

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

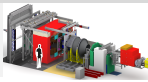
- After identifying forward K^+, boost all γ in the BGO into the Σ^0 rest frame
- 74 MeV decay energy, select 1σ or 2σ events:



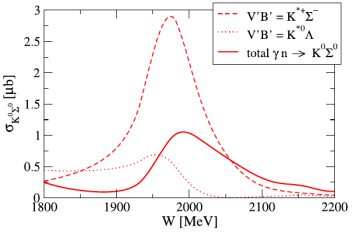
- Missing mass recoiling from forward K^+ after Σ^0 decay photon identification



$\gamma n \to K^0\Sigma^0$ K. Kohl, PhD thesis, arXiv:2108.13319 (2021) (submitted to EPJA)

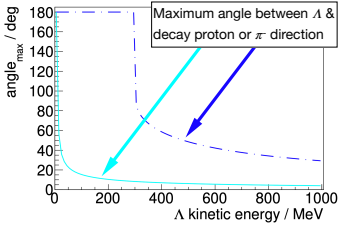


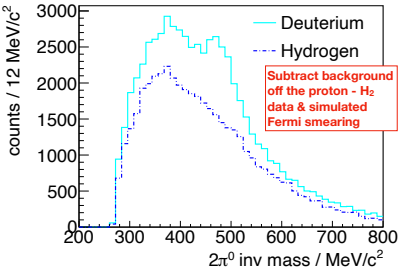
- Peak predicted - "smoking gun" for reaction mechanism
  A. Ramos and E. Oset, PLB 727, (2013) 287
- Equivalent model that predicted the P_C states as dynamically generated



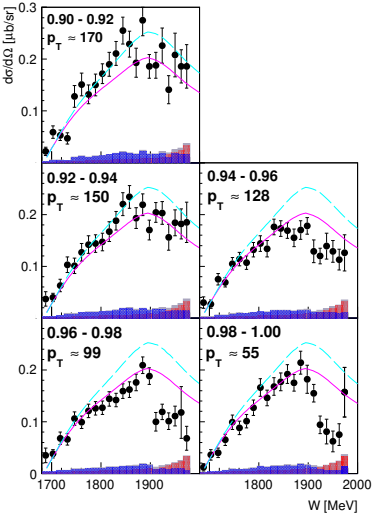
$\gamma n \to K^0\Sigma^0$ at BGOOD

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

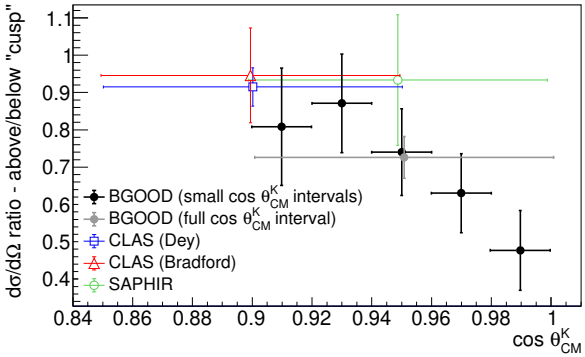




$\gamma p \to K^+\Sigma^0$ T.C. Jude et al., Phys. Lett. B 820 (2021) 136559



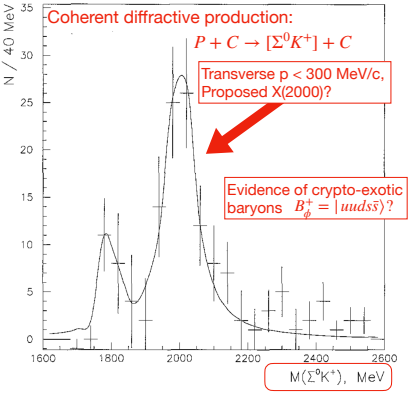
- Cusp increases quickly with $\cos\theta^K_{\mathrm{CM}}$ and K^+ transverse momentum (p_T) (labelled left, inset)
- Consistent with the "extent of cusp" seen at CLAS:



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

- Limited data at forward K^+ angles
- $W \sim 1900\,\text{MeV}$ at the K^+K^-p threshold, 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!

Exotic phenomena in the **charmed** sector*

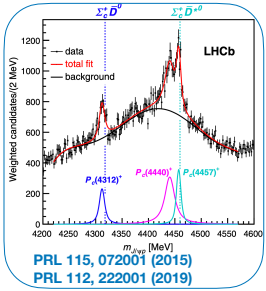
***Not** what we study at BGOOD!

Pentaquark candidates 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.



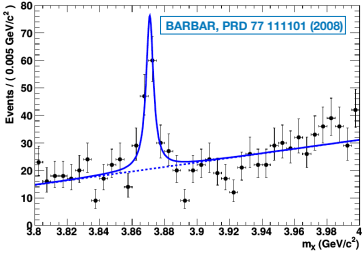
PRL 115, 072001 (2015)
PRL 112, 222001 (2019)

Meson-baryon dynamically generated states?

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

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)