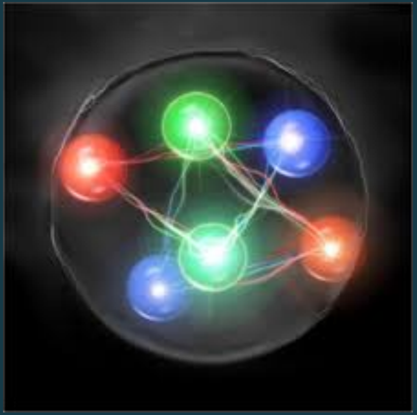
Hexaquark studies in the light quark sector

Dan Watts

UNIVERSITY of York

Main aims of Strong-2020 dibaryon/hexaquark workpackage

- Network the community of hexaquark/dibaryon researchers
- Expand the community
- Engage wider stakeholders (e.g. astrophysics community, PP, ..)
- Feel free to get in touch!



Overview

- d*(2380) – Theoretical studies

  Overview and recent progress
  Potential astrophysics relevance

- d*(2380) - Experimental evidence

  NN scattering
  Photon beam investigations
  (Some of) the future plans

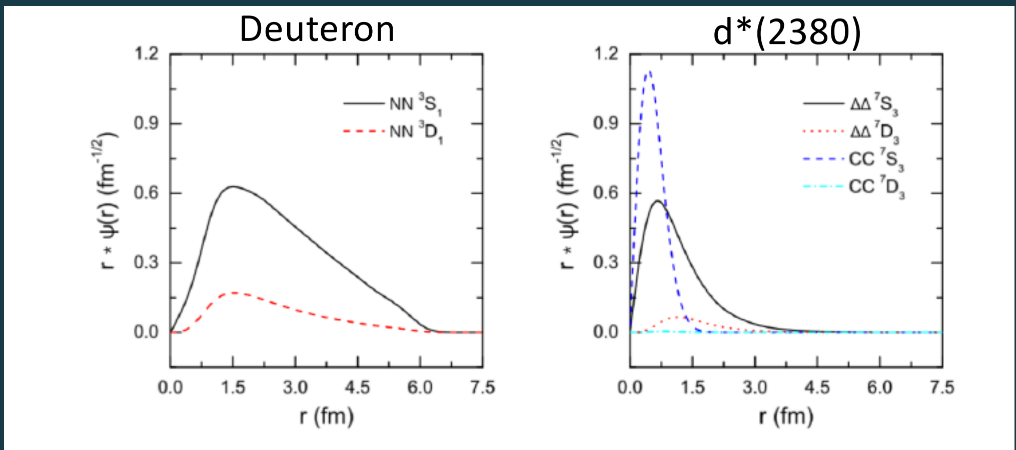
d*(2380) – theoretical studies

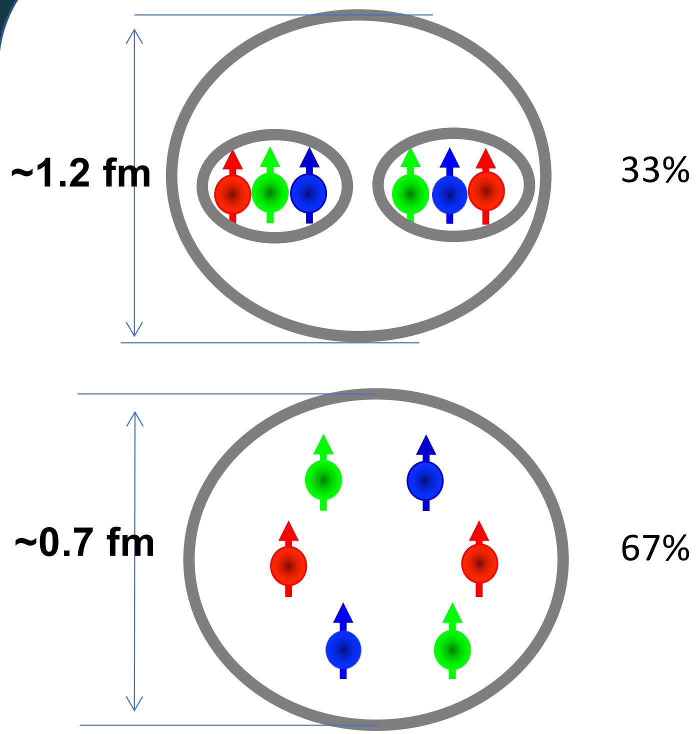
Historical review, see review (H. Clement **Prog.Part.Nucl.Phys. 93 (2017) 195**)

d*(2380) in chiral quark model

Any quark model with confinement and one gluon exchange *inevitably* predicts a 6-quark object with $(I)J^P=(0)3^+$

T Goldman et. al. Phys. Rev. C 39, 1889 (1989)

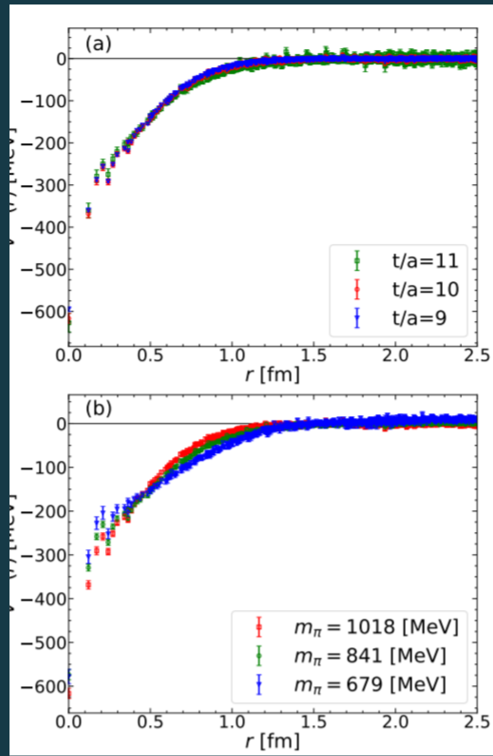




Recent microscopic chiral quark models
ΔΔ + **hidden colour**

F. Huang et al, Chin.Phys. C39 (2015) 7, 071001

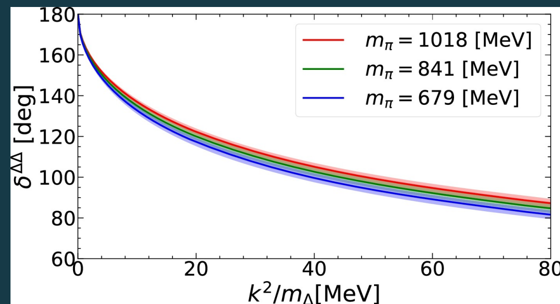
d*(2380) in Lattice QCD – recent progress

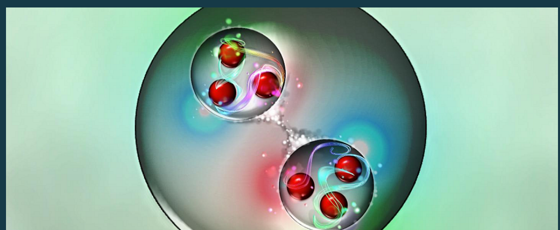


- Lattice QCD (HAL QCD PLB811 (2020) 135935)
- Δ stable (heavy quark masses) i.e. no CC but capture formation mechanism
- Quasi-bound state corresponding to d*(2380) formed

Binding energy below ΔΔ threshold
Size ~0.8-1 fm

- Previous HAL : spin-0 channel supports shallow di-Omega dibaryon state





d*(2380) in ChEFT

Regular Article - Theoretical Physics | Open Access | Published: 12 November 2017

Scattering of decuplet baryons in chiral effective field theory

J. Haidenbauer, S. Petschauer, N. Kaiser, Ulf-G. Meißner & W. Weise

The European Physical Journal C 77, Article number: 760 (2017) | Cite this article

851 Accesses | 19 Citations | 1 Altmetric | Metrics

- Calculation of scattering of octet/decuplet baryons within SU(3) chiral EFT
- Interaction potential - single pseudoscalar-meson (π, η, K) exchange plus four-baryon contact terms (short range – from LQCD)
- Bound d* state plausible – but significant extrapolations (masses) and approximations

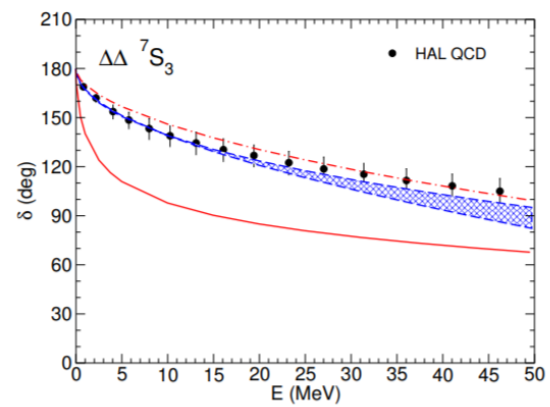


Fig. 5: Prediction for the $\Delta\Delta$ $^7S_3$ phase shift with isospin $I = 0$. The result of the HAL QCD collaboration is taken from ref. [21]. Results of a fit to the lattice simulation is shown by a hatched band, corresponding to cutoff variations between 500 and 700 MeV. The corresponding results for physical masses are shown by solid (700 MeV) and dash-dotted (500 MeV) lines.

d*(2380) - other recent theory developments

- NN scattering phase-shifts & helicities ($^3D_3$–$^3G_3$)
  -> dressed 0(3+) dibaryon + peripheral 1-π exchange

- Fitted resonance parameters compatible with mass and width of the d*(2380)

Physics Letters B 801 (2020) 135146
Contents lists available at ScienceDirect
Physics Letters B
www.elsevier.com/locate/physletb
ELSEVIER

Role of the *d**(2380) dibaryon in *NN* interaction

V.I. Kukulin[a], O.A. Rubtsova[a], M.N. Platonova[a], V.N. Pomerantsev[a,*], H. Clement[b]
[a] Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Leninskie Gory 1/2, 119991 Moscow, Russia
[b] Physikalisches Institut, Universität Tübingen, D-72076 Tübingen, Germany

- Indicates inapplicability of diquark models in light quark sector

Eur. Phys. J. C (2019) 79:538
https://doi.org/10.1140/epjc/s10052-019-7024-9
THE EUROPEAN PHYSICAL JOURNAL C
Letter

A diquark model for the *d(2380) dibaryon resonance?**

Avraham Gal[1,a], Marek Karliner[2,b]
[1] Racah Institute of Physics, The Hebrew University, 91904 Jerusalem, Israel
[2] School of Physics and Astronomy, Tel Aviv University, 69978 Tel Aviv, Israel

d*(2380) - other recent theory developments

- "Hexaquark picture for d*(2380)" : Hungchong, Kim, Oka, PRD 102 (2020) no.7, 074023
  hexaquark picture is promising for d∗(2380) as far as the mass is concerned
- "Nuclear states and spectra in holographic QCD": Hashimoto, Matsuo, Morita JHEP 1912 (2019) 001
  lowest energy states are(J; I) = (1; 0) and (3; 0).
  2^{nd} order correction (parameters fixed to D and d* -> predict H and di-omega
- "QCD sum rule Study of the *d**(2380)": Chen, Cui, Chen, Steele, Zhu PRC91 (2015) no.2, 025204
  Construct *I*(*JP*)=0(3+) six-quark local interpolating currents without derivative operators
  Mass extracted from this analysis is M_{d*}=2.4±0.2 GeV
- "Scattering of nucleons in the classical Skyrme model" : Foster & Manton, NP B899 (2015) 513
  Identify dineutron/diproton and dibaryon short-lived resonance states

d*(2380) in high energy physics (heavy quark sector)

- The opportunity to find d*(2380) in the Υ(nS) decay Phys.Rev. D99 (2019) no.3, 036015
- Selected strong decays of pentaquark State Pc(4312)Pc(4312) in a chiral constituent quark model , Eur.Phys.J. C80 (2020) no.4, 341
- Triply-charmed dibaryon states or two-baryon scattering states from QCD sum rules Phys.Rev. D102 (2020) no.3, 034008

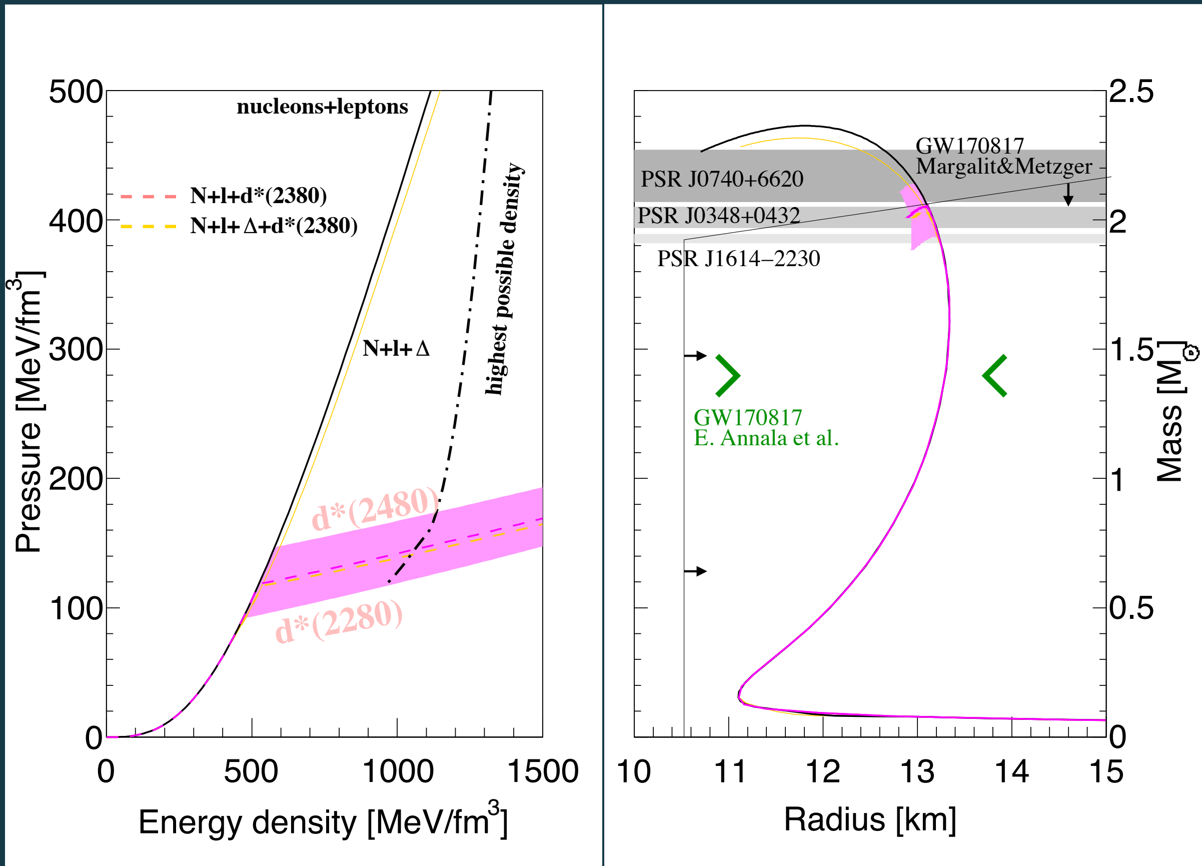
d*(2380): potential impact on astrophysics

The d*(2380) in neutron stars

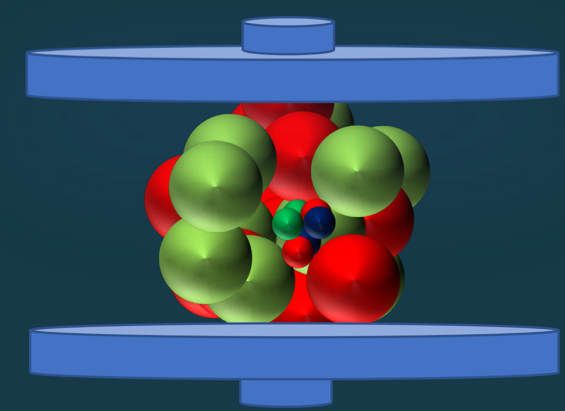

Physics Letters B 781 (2018) 112–116
Contents lists available at ScienceDirect
Physics Letters B
www.elsevier.com/locate/physletb

The *d**(2380) in Neutron Stars — A New Degree of Freedom?

I. Vidaña [a], M. Bashkanov [b,*], D.P. Watts [b], A. Pastore [c]
[a] INFN Sezione di Catania, Dipartimento di Fisica, Università di Catania, Via Santa Sofia 64, 95123 Catania, Italy
[b] School of Physics and Astronomy, University of Edinburgh, James Clerk Maxwell Building, Peter Guthrie Tait Road, Edinburgh EH9 3FD, UK
[c] Department of Physics, University of York, Heslington, York, Y010 5DD, UK



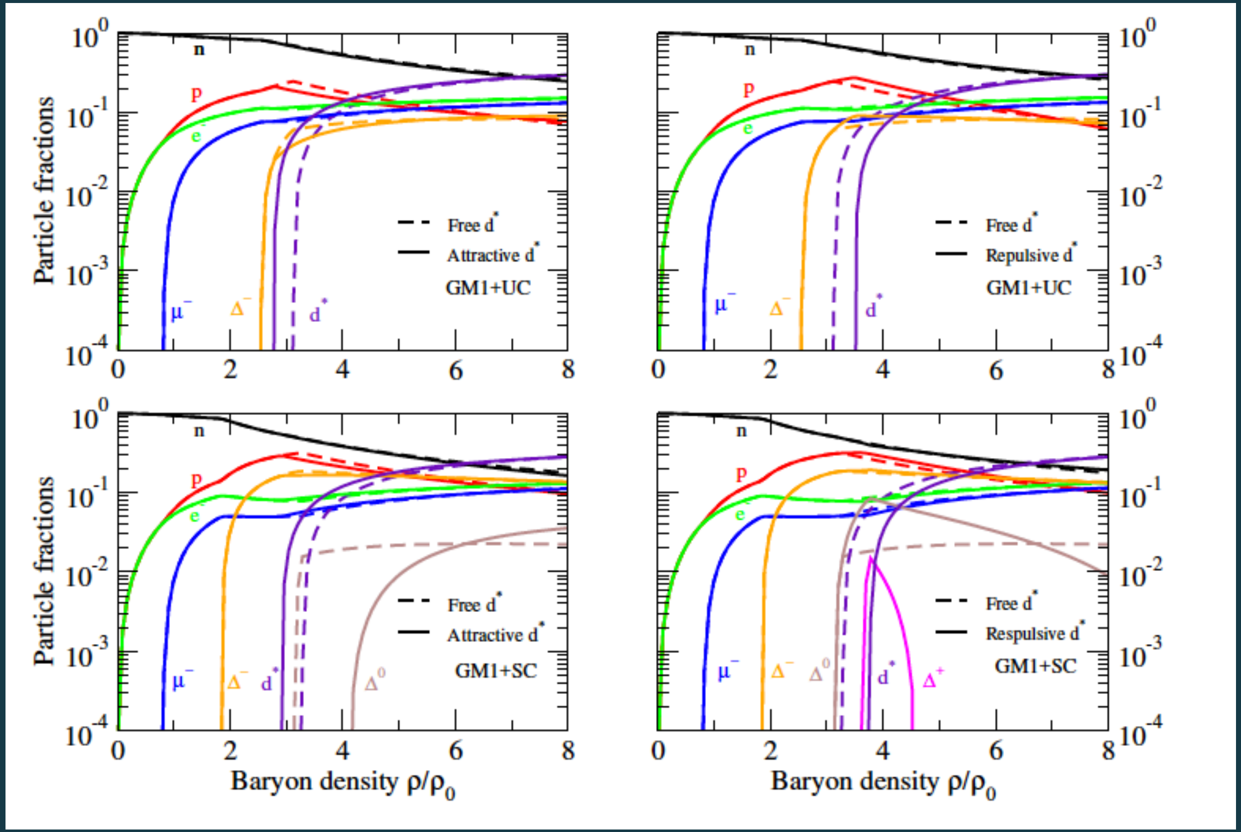
- d* -> forms copiously above $2.5\rho_0$
  ->~20% d* at centre of heavy stars

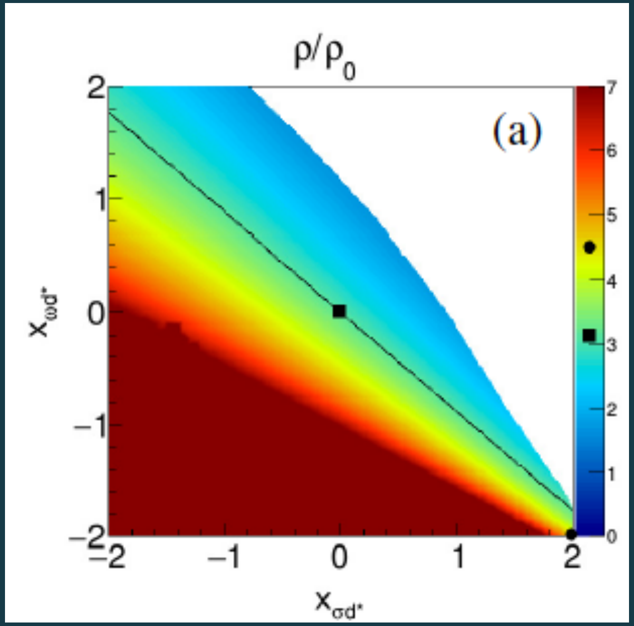


- Star mass limit - around $2.1M_o$

d* in neutron stars- coupling variation

- Standard non-linear Walecka model
- Including additional terms: d^*(2380) other particles through σ- and ω-meson fields





MAMI data under analysis for d* photoproductoin in medium (nuclear targets + nuclear decay tagging)

(Speculative!) Bose-Einstein condensate possibilities

- Assume d* : hexaquark, compact, bosonic, isoscalar form of light quark matter
- Assembly of d* hexaquarks -> Bose-Einstein condensate ?
- Analogous to the Hoyle state of ^{12}C (7.65 MeV)
  (70% BEC + 30% non-BEC -> ^{4}He large isoscalar boson)

Alpha-Particle Condensate Structure of the Hoyle State: where do we stand?

To cite this article: P Schuck *et al* 2017 *J. Phys.: Conf. Ser.* **863** 012005

- Simple “condensate” drop model + Boltzmann for QGP
- Binding energy potentially high (TeV scale)

  -> Constraint from FERMI-LAT data Beck: arxiv. 2003.09283 (2019)
  -> Estimates of DCB breaking **Chan 2020 *ApJ* 898 132**

- More detailed calculations needed..

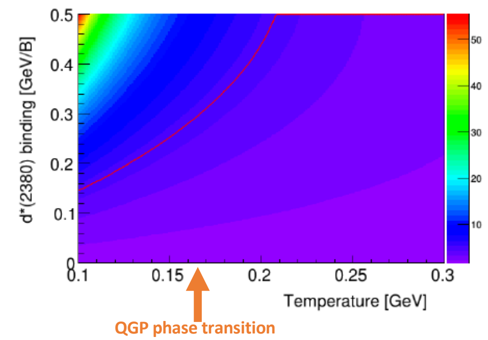


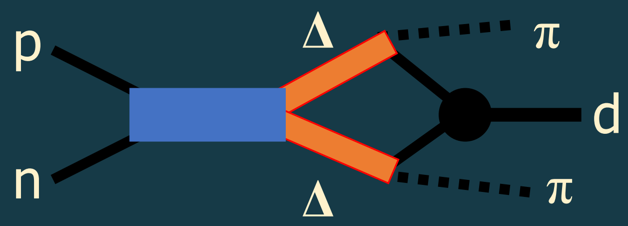
Figure 2. The primordial production of d^*(2380)-BEC (expressed as a ratio to baryon matter) calculated as a function of binding energy and decoupling temperature. The red line shows the loci corresponding to the current experimental determination of the dark matter to matter ratio[33].

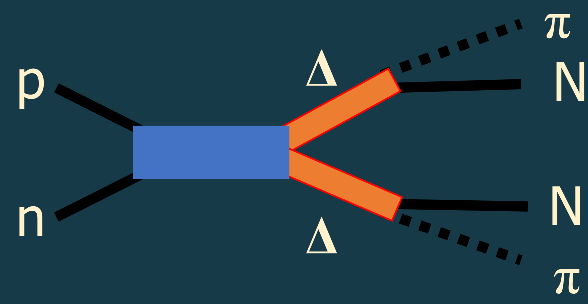
J. Phys. G: Nucl. Part. Phys. **47** 03LT01 (2020)

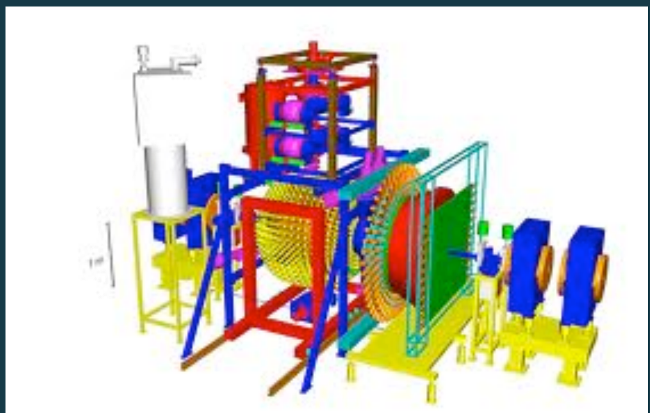
d*(2380) in pn scattering – experimental evidence

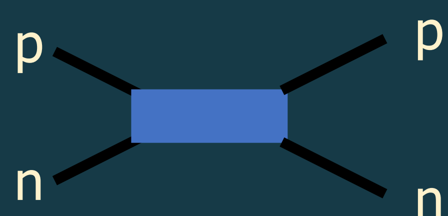
Nucleon scattering with large acceptance

- $pn \rightarrow d^* \rightarrow \Delta\Delta \rightarrow d\pi\pi$
- $pn \rightarrow d^* \rightarrow \Delta\Delta \rightarrow NN\pi\pi$

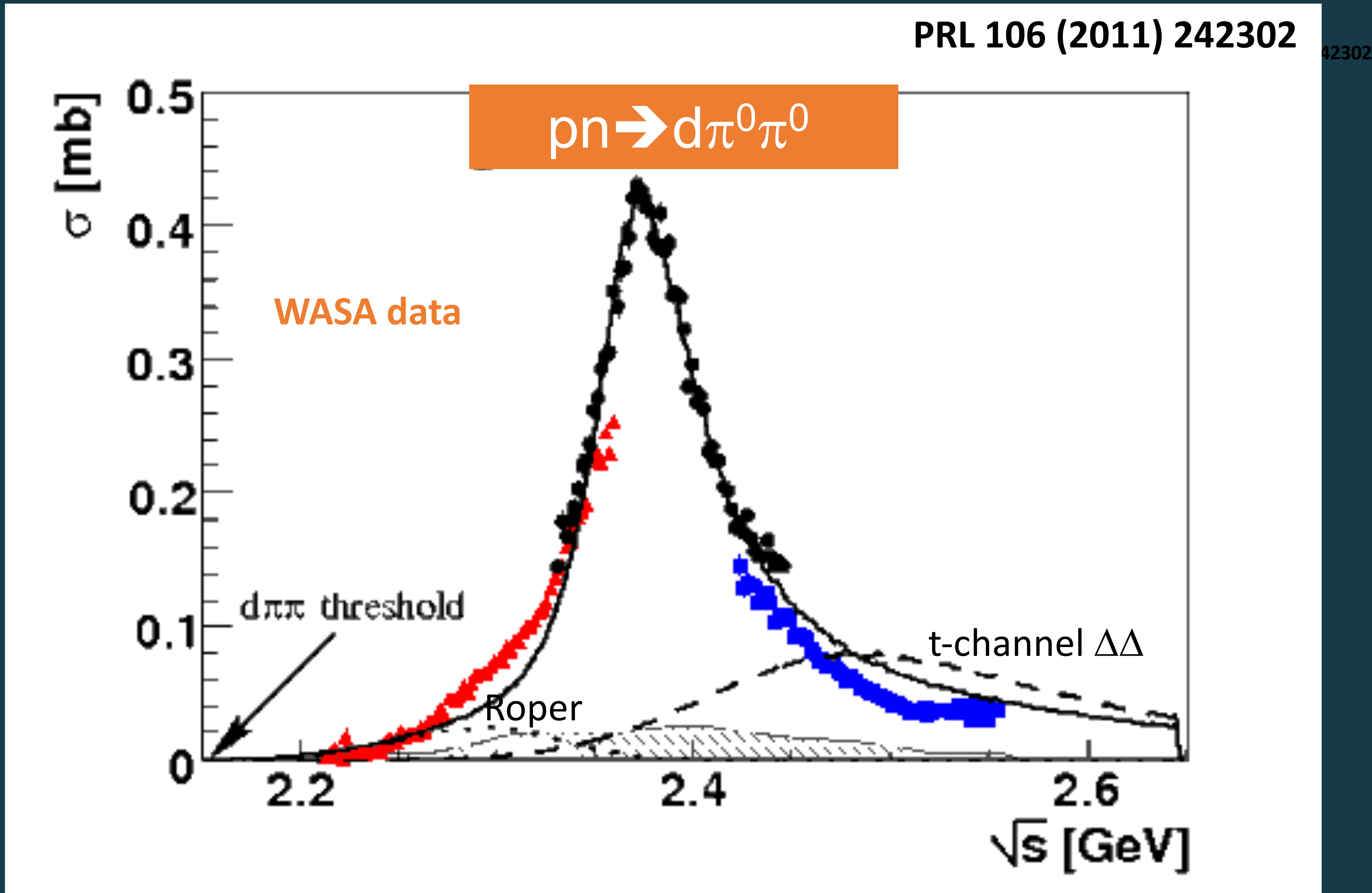






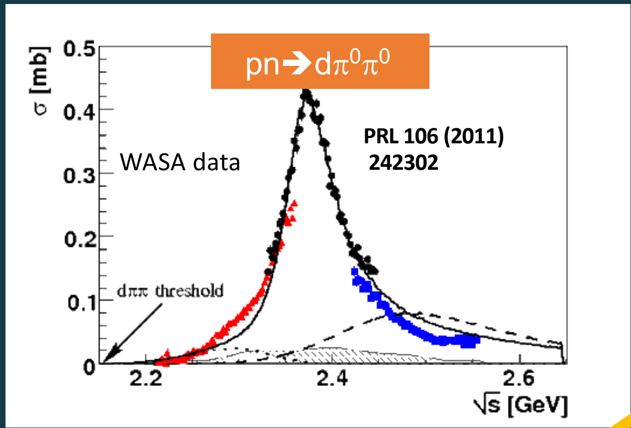


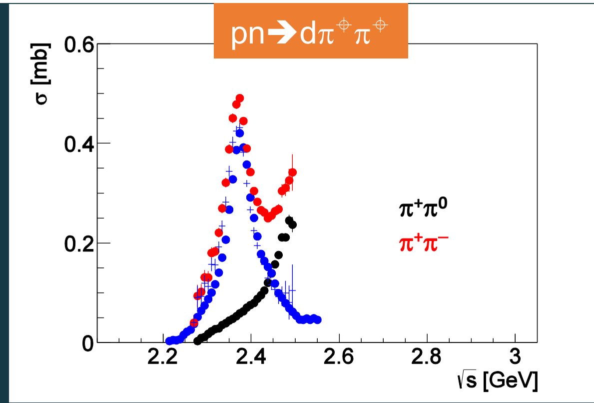
d*(2380) signals



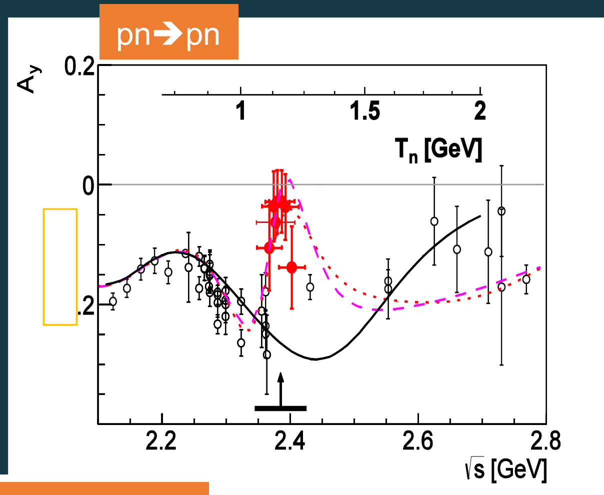
$p + n \rightarrow$ **d*(2380)**

$I(J^P) = 0(3^+)$

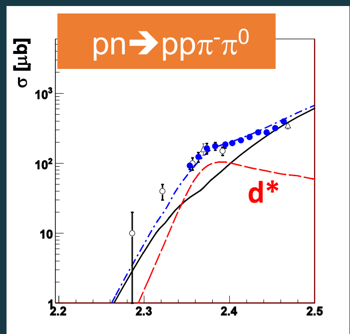


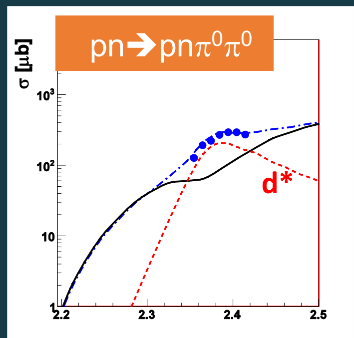


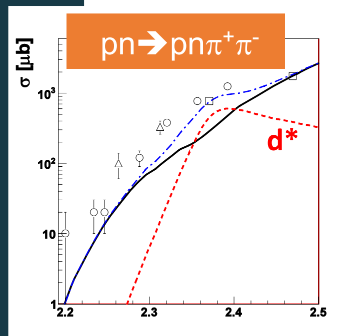
PLB 721 (2013) 229



PRL 112 (2014) 202301
PRC 90, (2014) 035204







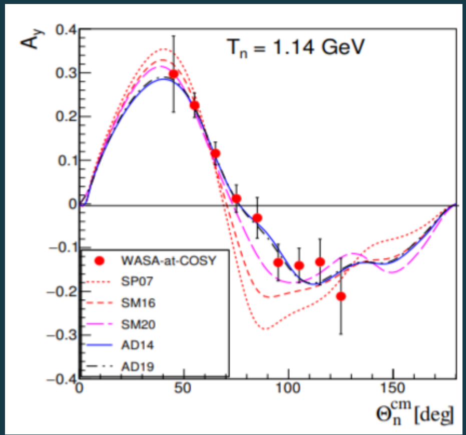
ΔΔ decay ~90%
pn decay ~10%

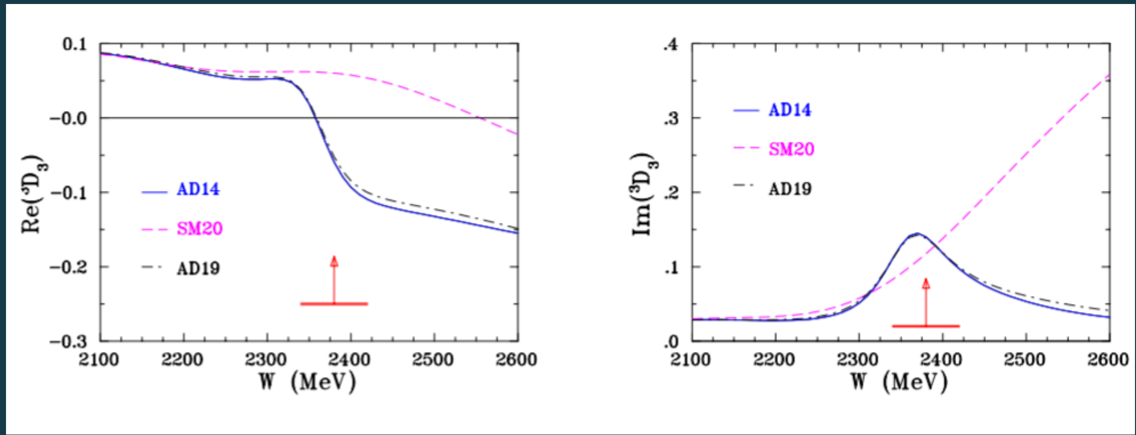
PRC 88 (2013) 055208
PLB 743 (2015) 325

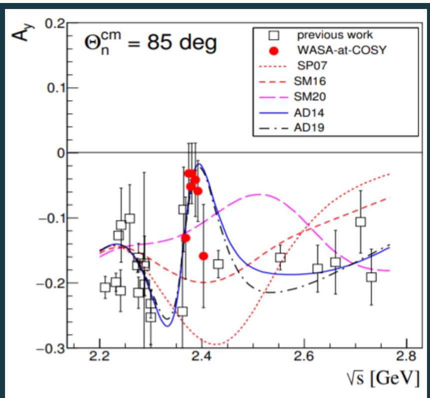
WASA at COSY – polarized pn scattering

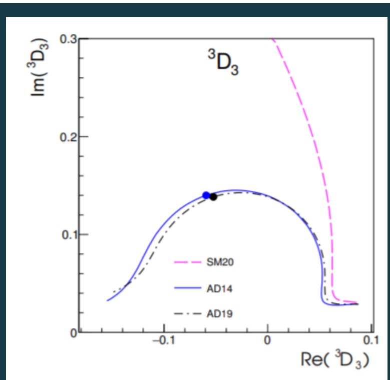
Update of NN phase shifts

WASA-at-COSY PRC102 (2020) no.1, 015204)







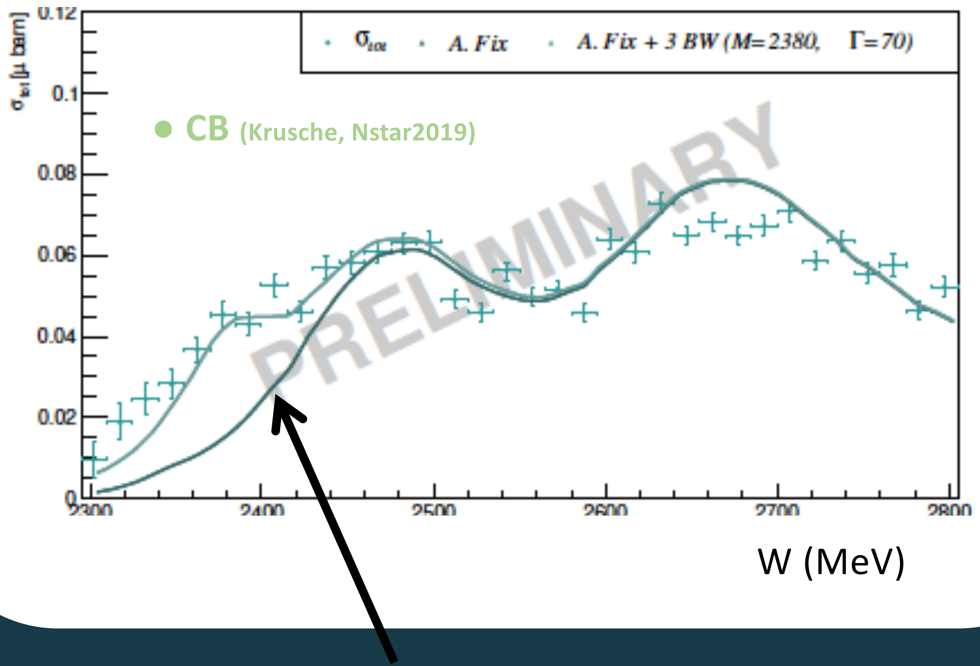


(SM20 solution does not allow d*
== cannot describe the data)

d*(2380) in photoexcitation from deuteron experimental evidence

Photoproduction of d$\pi\pi$ final state

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

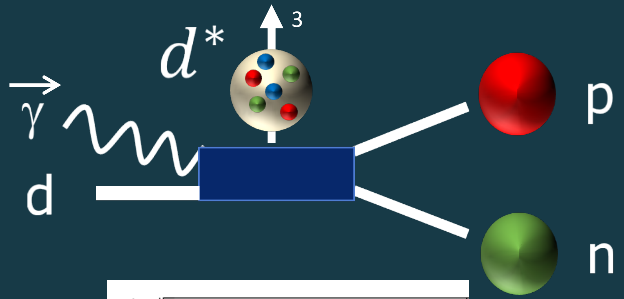


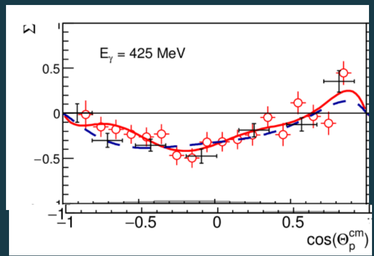
Conventional Background

M. Egorov, A. Fix, Nucl.Phys. A933 (2015) 104-113

- Photoproduction kinematics challenging –> deuteron only detected at forward angles
- Active deuteron target appears necessary

Deuterium photodisintegration (Σ)



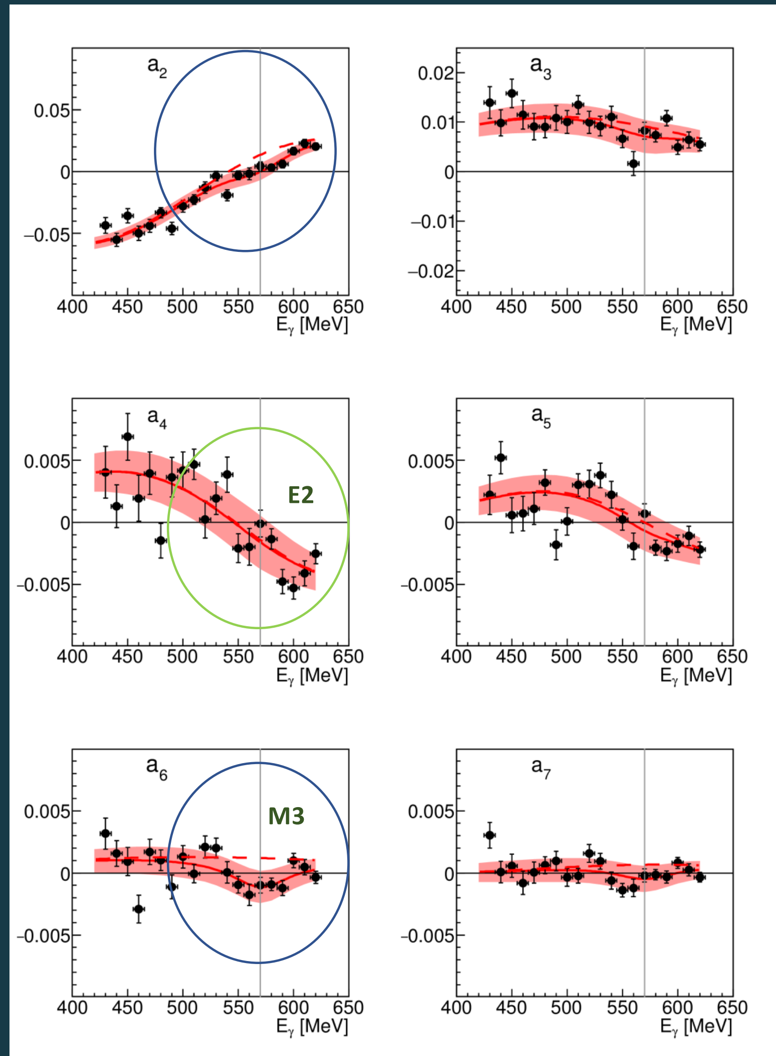


H.Ikeda *et al.*,NPB172,509,(1980)

$$\Sigma \sim \sum_{l=2} a_l P_l^2(cos\Theta)$$

E2 transition ⇒ small
M3 transition ⇒ dominant

Consistent with d*(2380)
as a compact object



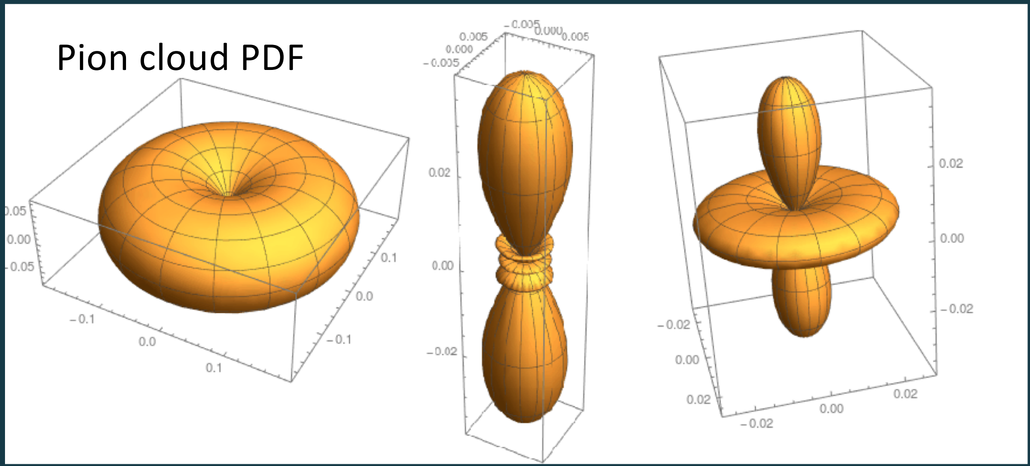
Bashkanov, DPW, Kay, CB@MAMI; PLB789 (2019) 7-12

d* in pion cloud model

- EM properties determined in simple overlapping Δ pion cloud model:

ΔΔ NΔπ NNπ π

Spherical Donut Rugby ball



NΔπ NNππ Sum

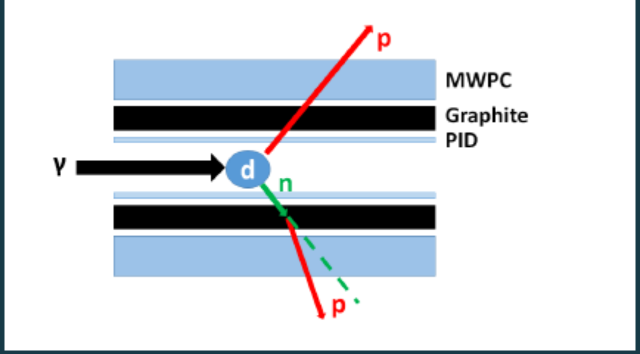
- EQM -> ΔΔ no contribution
  NΔπ , NNππ ~equal contribution but opposite sign -> cancellation

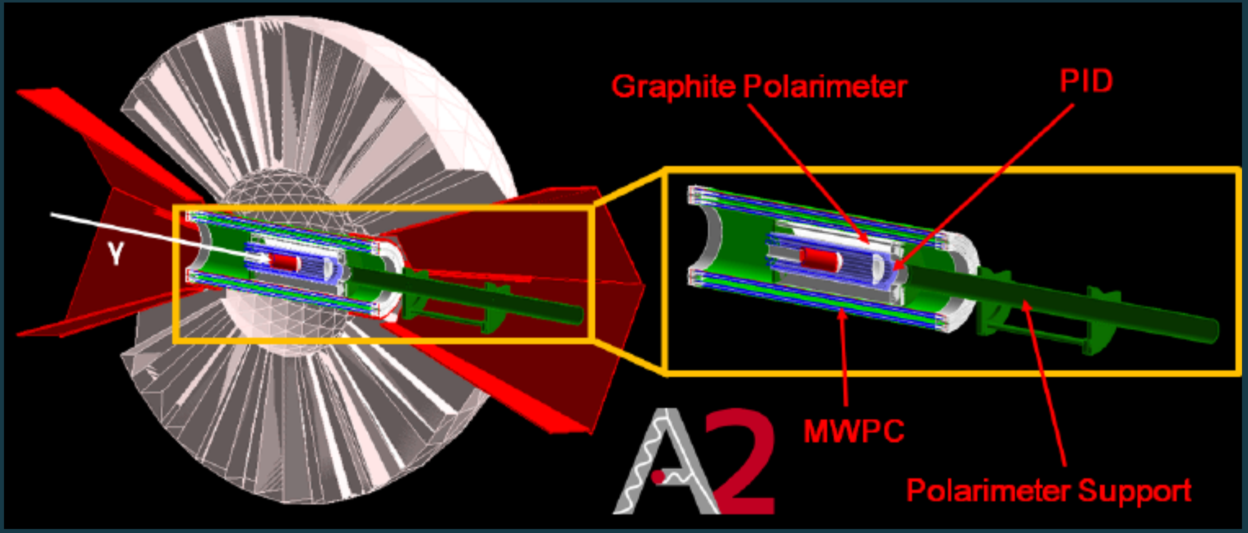
- MOM -> ΔΔ no contribution
  NΔπ , NNππ ~equal contribution but **same** sign

Bashkanov, DPW, Pastore; PRC 100 012201(R) 2019

Nucleon recoil polarization in deuterium photodisintegration

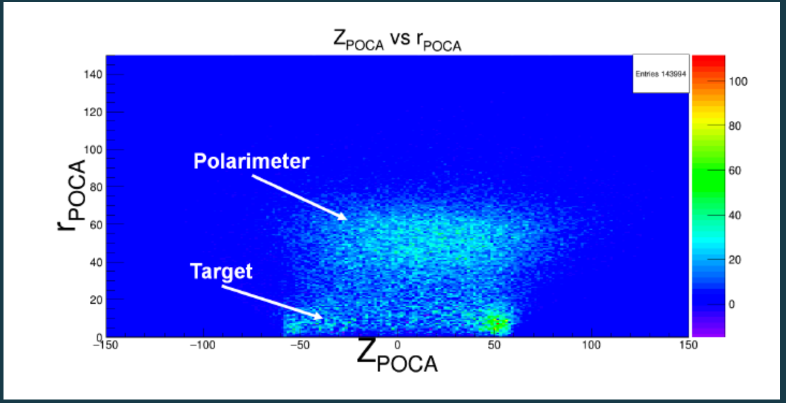
- Analysing material (graphite) placed between PID and MWPC





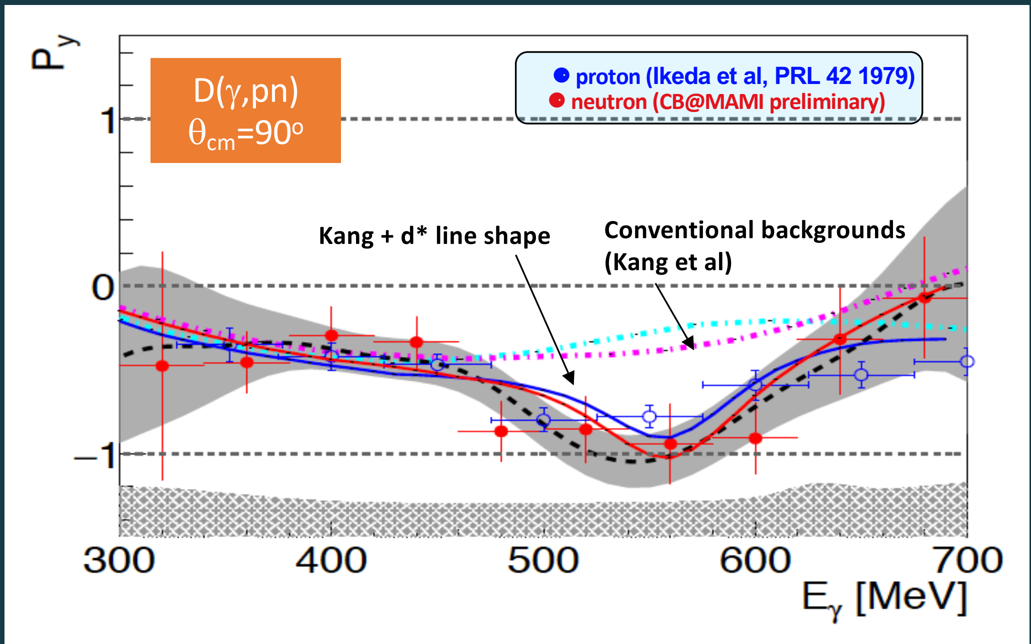
- Polarisation extracted from phi modulation of scatter yield (for a determined azimuthal (theta) range)

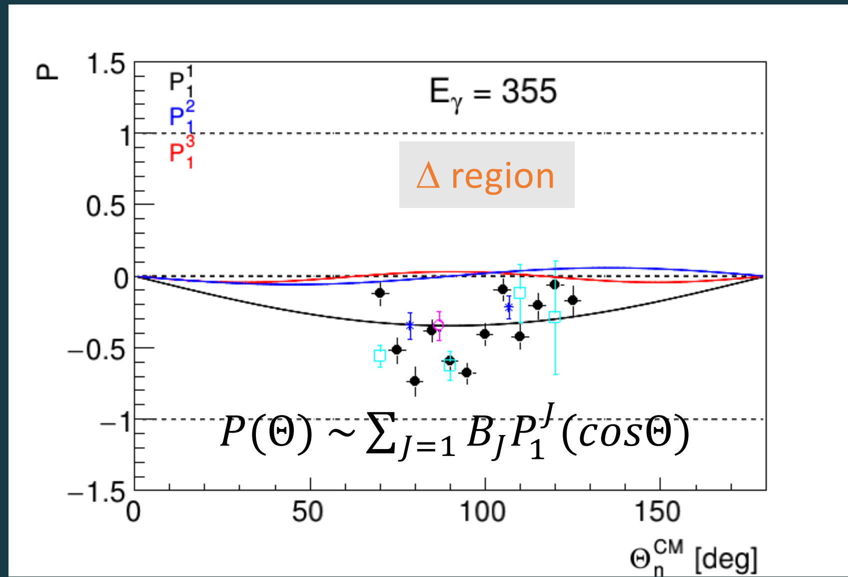
- Proton and neutron polarization measurements possible

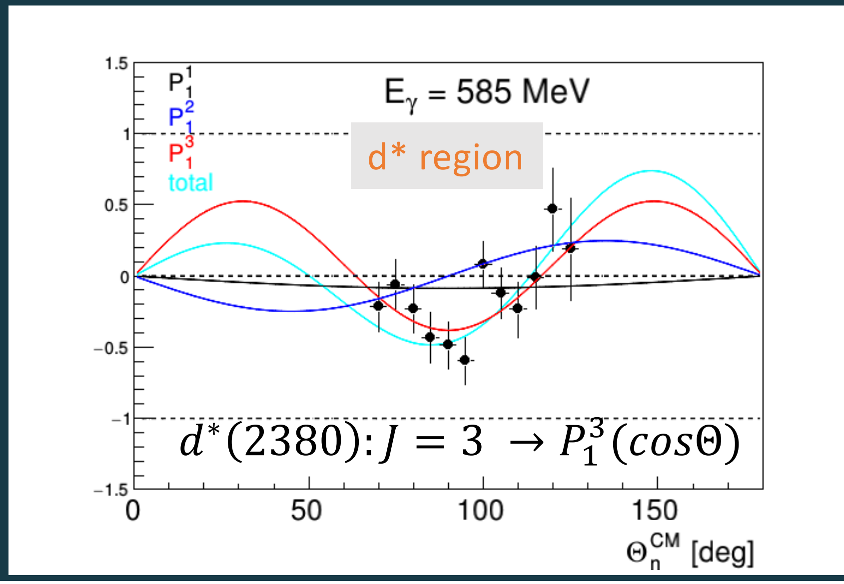


Deuterium photodisintegration (P_y)

- 1st measurement of final state neutron polarisation
  -> ***Both*** p and n highly polarised in region of d*!
- θ_{CM} dependence – consistent with spin 3





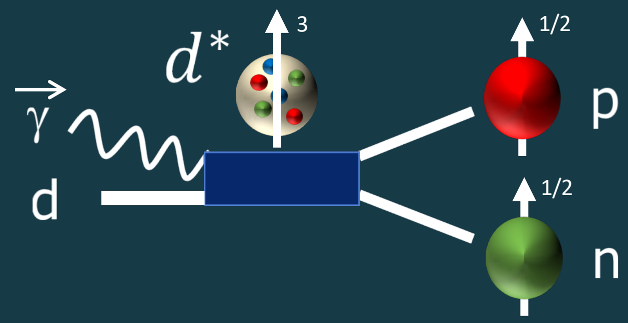


A2

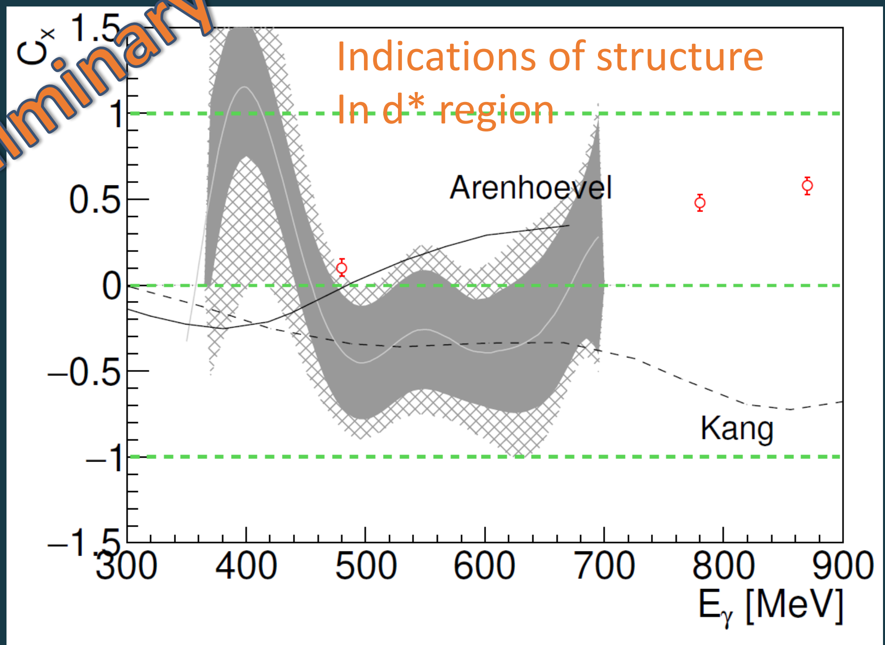
Bashkanov, DPW, CB@MAMI; Phys.Rev.Lett. 124 (2020) no.13, 132001

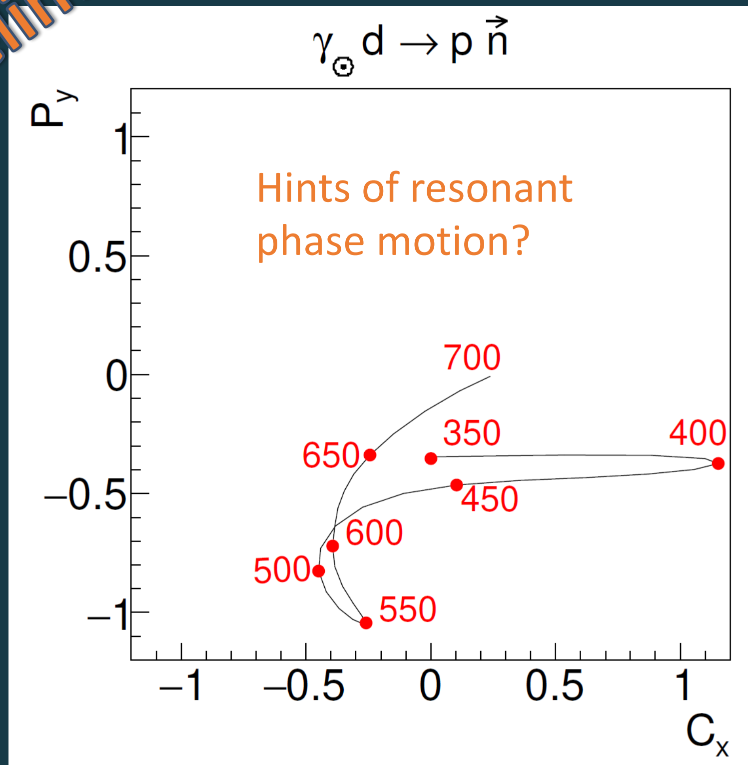
Deuterium photodisintegration (C_x*)

Observable	Structure function	Helicity amplitude combination
p_y	$R_T(y)$	$2\mathrm{Im}\sum_{i=1}^{3}\left[F_{i+}^{*}\,F_{(i+3)-}+F_{i-}\,F_{(i+3)+}^{*}\right]$
T	$R_T(\mathrm{Im}T_{11})$	$2\mathrm{Im}\sum_{i=1}^{2}\sum_{j=0}^{1}\left[F_{(i+3j)+}\,F_{(i+3j+1)+}^{*}+F_{(i+3j)-}\,F_{(i+3j+1)-}^{*}\right]$
Σ	R_{TT}	$2\mathrm{Re}\sum_{i=1}^{3}(-)^{i}\left[-F_{i+}\,F_{(4-i)-}^{*}+F_{(3+i)+}\,F_{(7-i)-}^{*}\right]$
T_1	$R_{TT}(y)$	$2\mathrm{Im}\sum_{i=1}^{3}(-)^{i}\left[-F_{i+}F_{(7-i)+}^{*}+F_{i-}F_{(7-i)-}^{*}\right]$
$C_{x'}$	$R_T(x')$	$2\mathrm{Re}\sum_{i=1}^{3}\left[F_{i+}^{*}\,F_{(i+3)-}+F_{i-}\,F_{(i+3)+}^{*}\right]$
$C_{z'}$	$R_T(z')$	$\sum_{i=1}^{6}\{\lvert F_{i+}\rvert^{2}-\lvert F_{i-}\rvert^{2}\}$
$O_{x'}$	$R_{TT}(x')$	$2\mathrm{Im}\sum_{i=1}^{3}(-)^{i+1}\left[F_{i+}F_{(7-i)+}^{*}+F_{i-}F_{(7-i)-}^{*}\right]$
$O_{z'}$	$R_{TT}(z')$	$2\mathrm{Im}\sum_{i=1}^{3}(-)^{i+1}\left[F_{i+}\,F_{(4-i)-}^{*}+F_{(3+i)+}\,F_{(7-i)-}^{*}\right]$



Preliminary





Bashkanov, DPW, CB@MAMI; in preparation

d*(2380) – future experiments

Observables: D(γ,pn) with polarised target

- Longitudinal target polarisation

$$T_{10}^{c}(-E)\,\frac{d\sigma_0}{d\Omega_p} = \frac{1}{2}\sum_{sm_s}\left(|t_{sm_s 11}|^2 - |t_{sm_s 1-1}|^2\right)$$

Circular γ-polarisation

$$T_{10}^{l}(G)\,\frac{d\sigma_0}{d\Omega_p} = \Im m \sum_{sm_s}\left(t^{*}_{sm_s 11}\, t_{sm_s -11}\right)$$

Linear γ-polarisation

- Transverse target polarisation

$$T_{11}^{0}(-T)\,\frac{d\sigma_0}{d\Omega_p} = \Im m \sum_{sm_s}\left(t^{*}_{sm_s 1-1}\, t_{sm_s 10} + t^{*}_{sm_s 10}\, t_{sm_s 11}\right)$$

Unpolarised

$$T_{11}^{c}(-F)\,\frac{d\sigma_0}{d\Omega_p} = -\Re e \sum_{sm}\left(t^{*}_{sm_s 1-1}\, t_{sm_s 10} + t^{*}_{sm_s 10}\, t_{sm_s 11}\right)$$

Circular γ-polarisation

$$T_{11}^{l}\,\frac{d\sigma_0}{d\Omega_p} = \Im m \sum_{sm_s}\left(t^{*}_{sm_s 1-1}\, t_{sm_s -10}\right)$$

Linear γ-polarisation

$$T_{1-1}^{l}\,\frac{d\sigma_0}{d\Omega_p} = -\Im m \sum_{sm_s}\left(t^{*}_{sm_s 11}\, t_{sm_s -10}\right)$$

Linear γ-polarisation

D(γ,pn): transverse target observables

Photodisintegration of polarized deuterons –
measurement of angular distributions at $E_\gamma = 450$, 550 and 650 MeV

K.H. Althoff, G. Anton, B. Bock[1], D. Bour, R. Dostert[2], P. Erbs, T. Jahnen, O. Kaul[3], E. Kohlgarth, B. Lücking[4], D. Menze, W. Meyer, E.P. Schilling, W.J. Schwille, D. Sundermann[5], W. Thiel, D. Thiesmeyer[6]
Physikalisches Institut der Universität Bonn, Nussallee 12, D-5300 Bonn 1, Federal Republic of Germany

Received 14 February 1989

$$T = \frac{3}{2} \cdot \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_0 + \sigma_-}$$

Significant improvement
In data quality possible
at MAMI
1% s.a. in 10 MeV bins

$$Z = (-2) \cdot \frac{\sigma_+ + \sigma_- - 2\sigma_0}{\sigma_+ + \sigma_0 + \sigma_-}$$

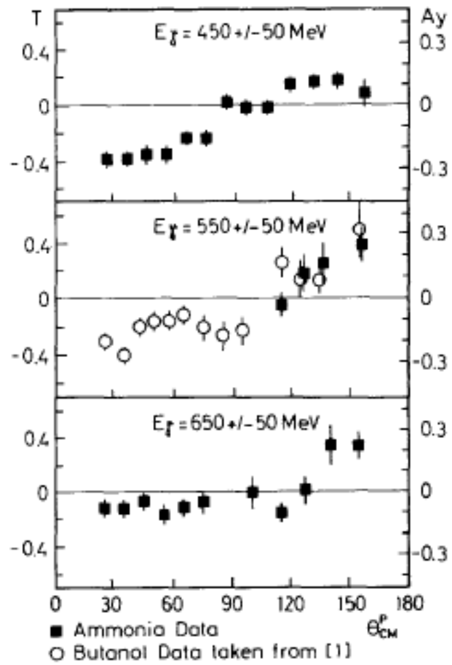


Fig. 4. Target asymmetry vs. proton angle Θ^p_{CM}

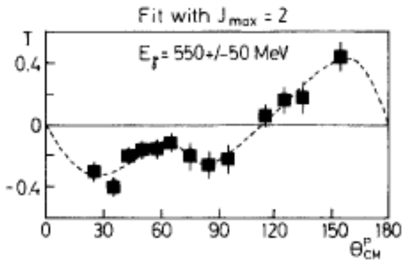


Fig. 6. Angular distribution at 550 MeV fitted with angular momentum $J_{max} = 2$

Taken as contribution of higher multipoles

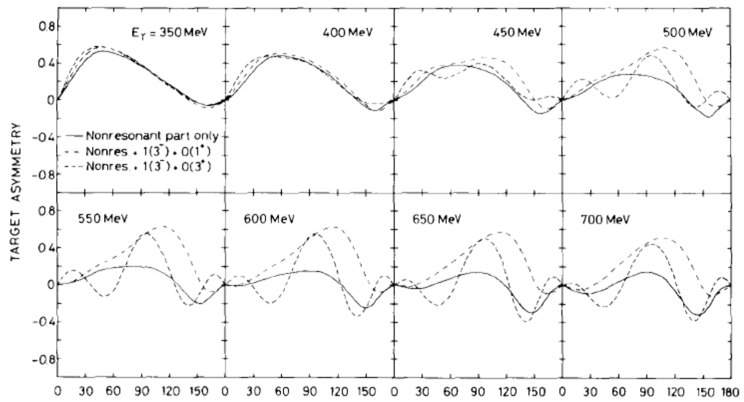
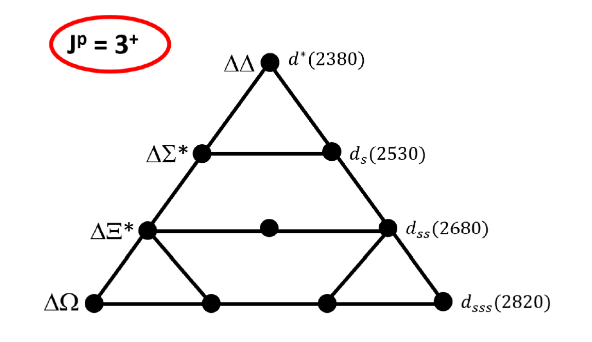


Fig. 11. Polarized target asymmetry defined by $(\sigma_1 - \sigma_{-1})/(\sigma_1 + \sigma_0 + \sigma_{-1})$. The curves are coded as in fig. 4.

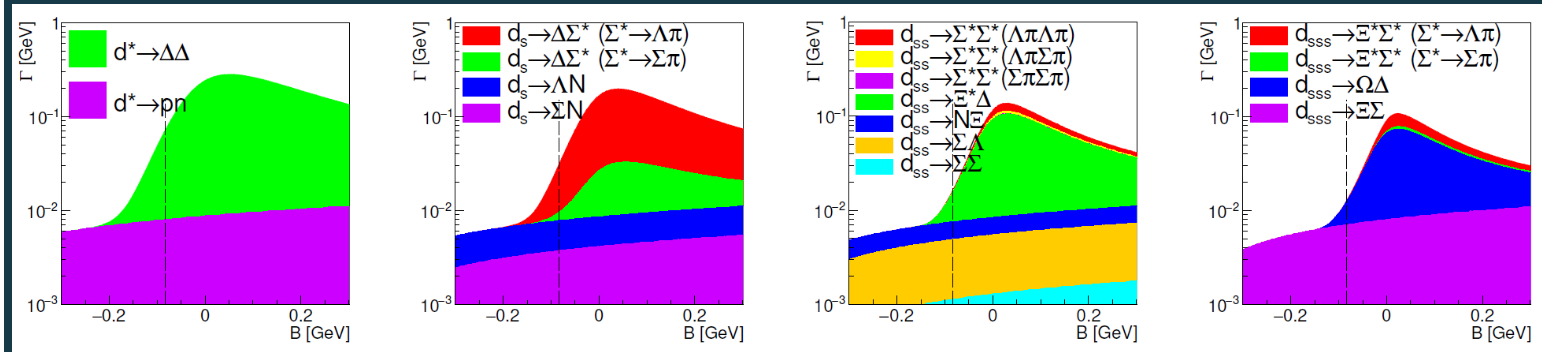
d* antidecuplet - decay widths and branches

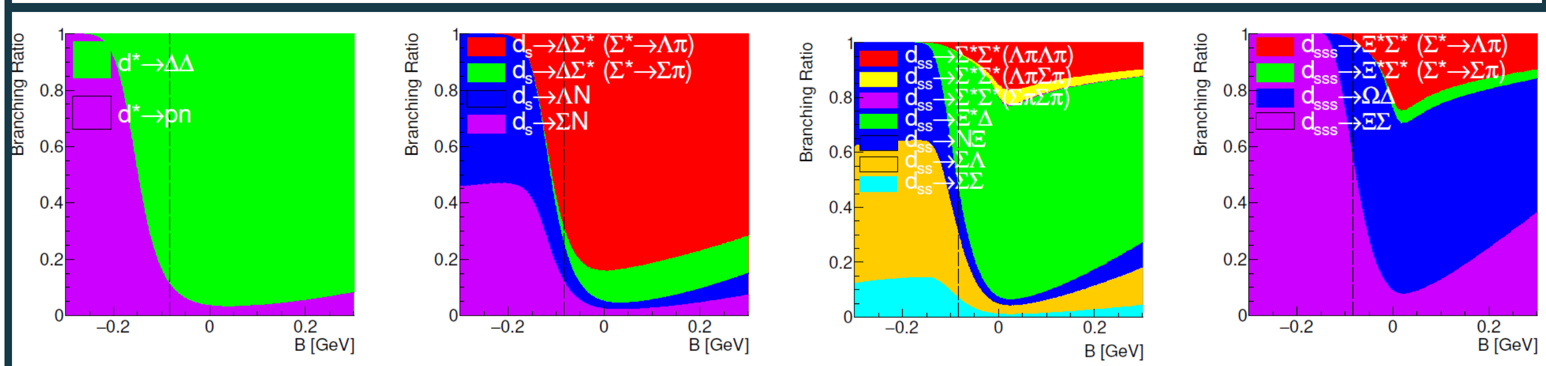
TABLE II. d^* multiplet width results for the $B = -84$ MeV.

d^*			d_s			d_{ss}			d_{sss}		
decay	Γ, [MeV]	BR [%]	decay	Γ, [MeV]	BR [%]	decay	Γ, [MeV]	BR [%]	decay	Γ, [MeV]	BR [%]
$\Delta\Delta$	63	89	$\Delta\Sigma^*(\Sigma^* \to \Lambda\pi)$	21	69	$\Sigma^*\Sigma^*(\Lambda\Lambda\pi\pi)$	0.6	3.8	$\Xi^*\Sigma^*(\Sigma^* \to \Lambda\pi)$	0.34	3
pn	8	11	$\Delta\Sigma^*(\Sigma^* \to \Sigma\pi)$	1.7	6	$\Sigma^*\Sigma^*(\Lambda\Sigma\pi\pi)$	0.05	0.3	$\Xi^*\Sigma^*(\Sigma^* \to \Sigma\pi)$	0.0007	0.05
			$N\Lambda$	4.1	13	$\Sigma^*\Sigma^*(\Sigma\Sigma\pi\pi)$	4.06e-6	0	$\Omega\Delta$	5.2	41
			$N\Sigma$	3.7	12	$\Delta\Xi^*$	7.8	48.9	$\Xi\Sigma$	7.1	56
						$N\Xi$	2.6	16.4			
						$\Sigma\Sigma$	1.1	7.1			
						$\Sigma\Lambda$	3.8	23.5			
total	**71**		total	**30.5**		total	**15.95**		total	**12.6**	



Particle	$8 \oplus 8$	$10 \oplus 10$
d^*	pn	$\Delta\Delta$
d_s	$\frac{1}{\sqrt{2}}(N\Lambda - N\Sigma)$	$\Delta\Sigma^*$
d_{ss}	$\frac{1}{\sqrt{6}}(\sqrt{2}N\Xi - \Sigma\Sigma + \sqrt{3}\Sigma\Lambda)$	$\frac{1}{\sqrt{3}}(\sqrt{2}\Delta\Xi^* + \Sigma^*\Sigma^*)$
d_{sss}	$\Sigma\Xi$	$\frac{1}{\sqrt{2}}(\Delta\Omega - \Sigma^*\Xi^*)$





B – Binding energy relative to decuplet-decuplet pole. Dashed line nominal mass (common binding for all members)

- Decuplet existence and properties -> new info on d* structure
- 10* -> 8⊕8 or 10⊕10
- CLAS12 analysis underway

Model assumptions:
BW width energy dependent
CC independent of strangeness
Decuplet decays - monopole FF Λ=0.16GeV/c

Bashkanov, Clash, Mocanu, Nicol, DPW (UoY)

Summary

- d* theory evolving and developing
- Evidenced in NN scattering; evolving with EM beams
- Potential for impact outside of hadron physics (e.g. astrophysics)
- Welcome to join us !!
- Please get in touch with any suggestions, requests

(Daniel.watts@york.ac.uk)