Searching for the d* in photoreactions on transversely polarized deuterons

Dan Watts

Mikhail Baskanov, Michael Ostrick, …

UNIVERSITY *of York*

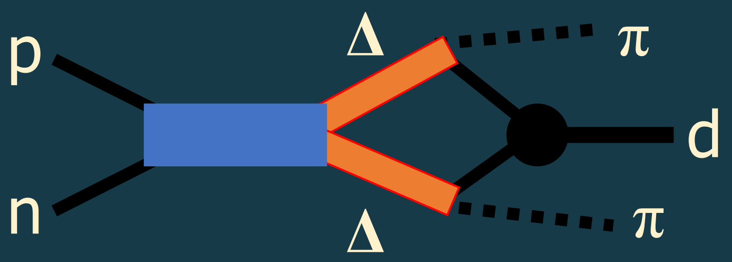
Overview

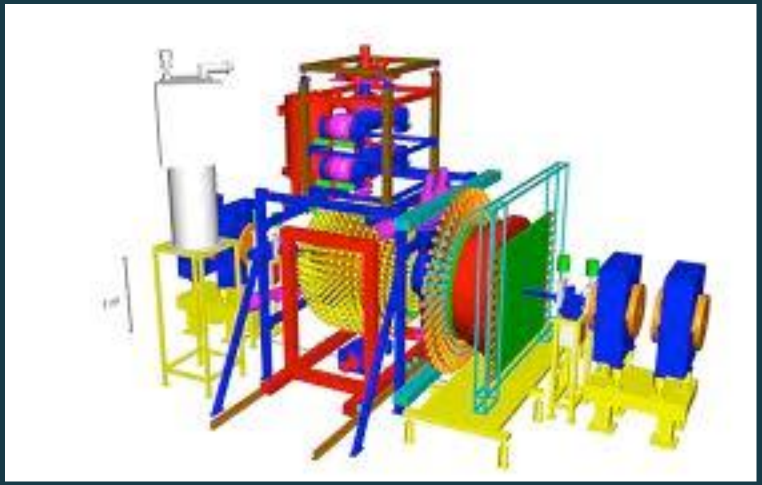
- Evidence from pn scattering
- EM properties – recent MAMI results
- d* theory
- Potential added impact: Neutron stars, DM candidate
- Opportunities with nucleon polarisation observables

The d*(2380) in pn scattering

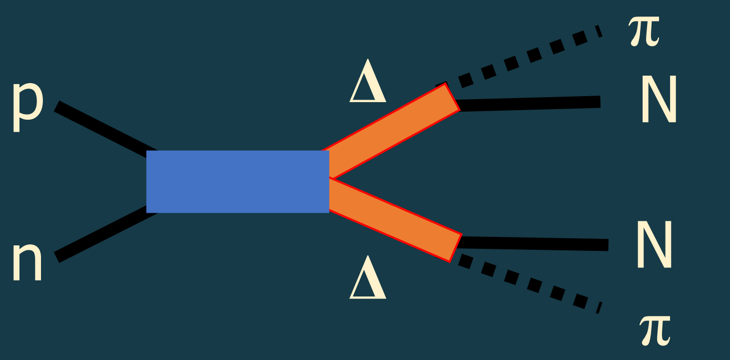
Nucleon scattering with large acceptance

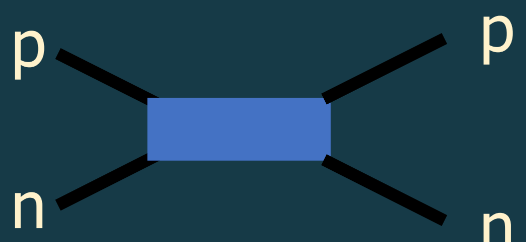
- $pn \rightarrow d^* \rightarrow \Delta\Delta \rightarrow d\pi\pi$



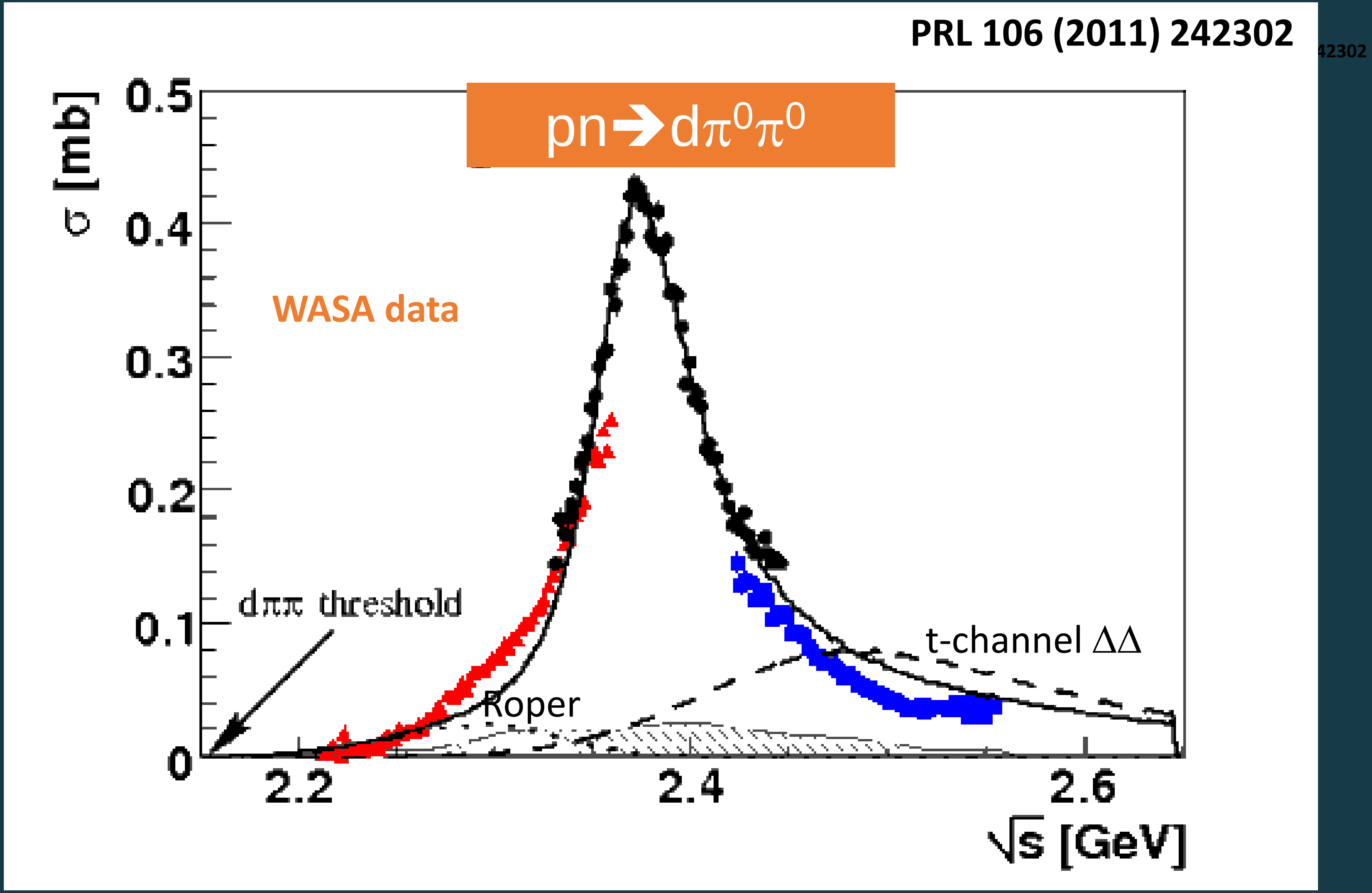


- $pn \rightarrow d^* \rightarrow \Delta\Delta \rightarrow NN\pi\pi$

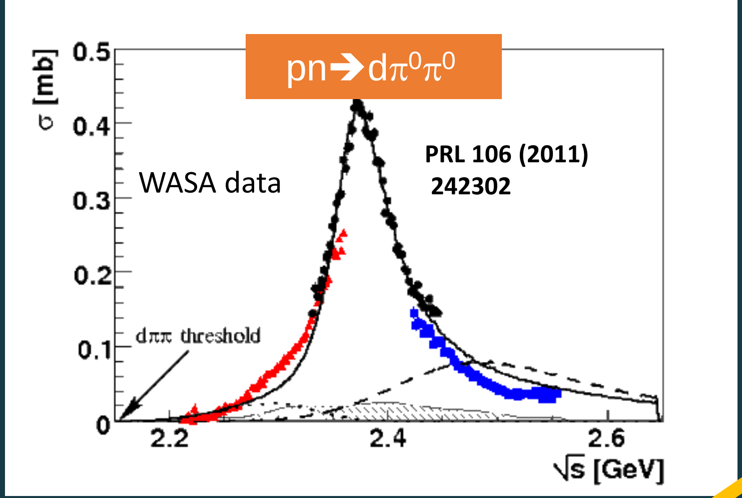


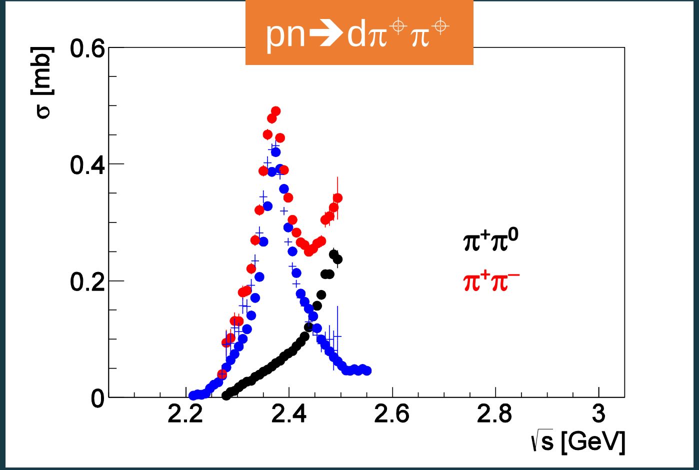


d*(2380) signals



PRL 106 (2011) 242302

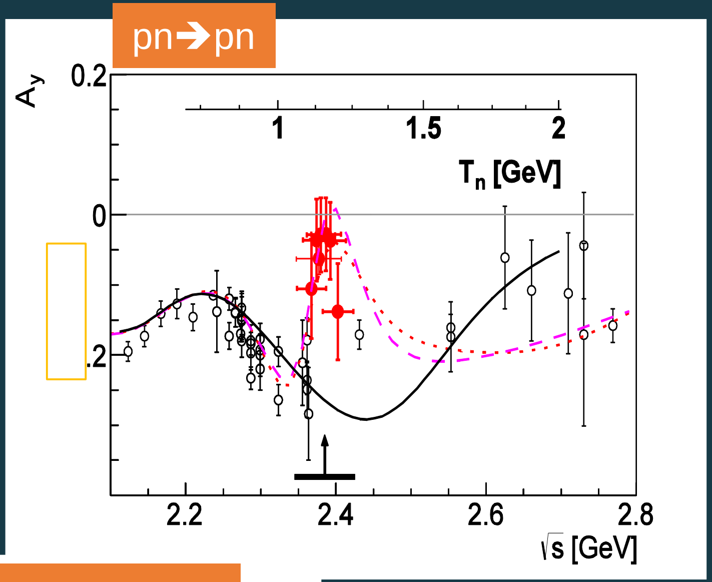




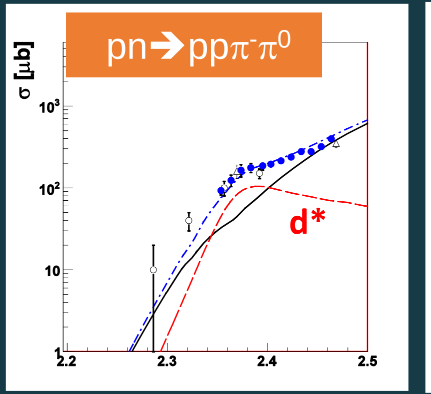
PLB 721 (2013) 229

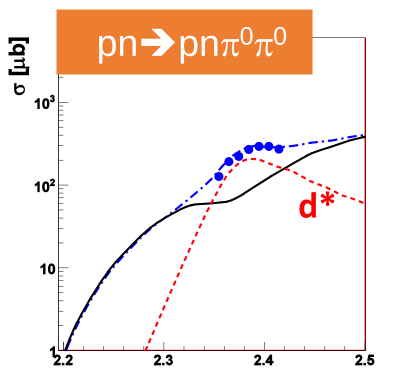
$p + n \rightarrow$ **d*(2380)**

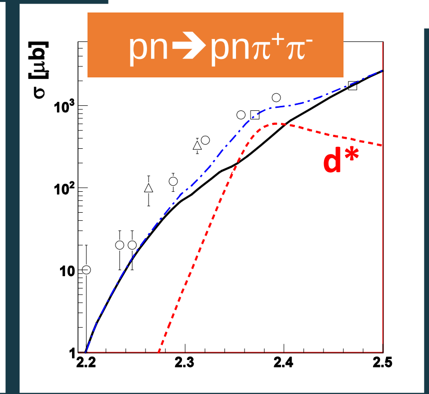
$I(J^p) = 0(3^+)$



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







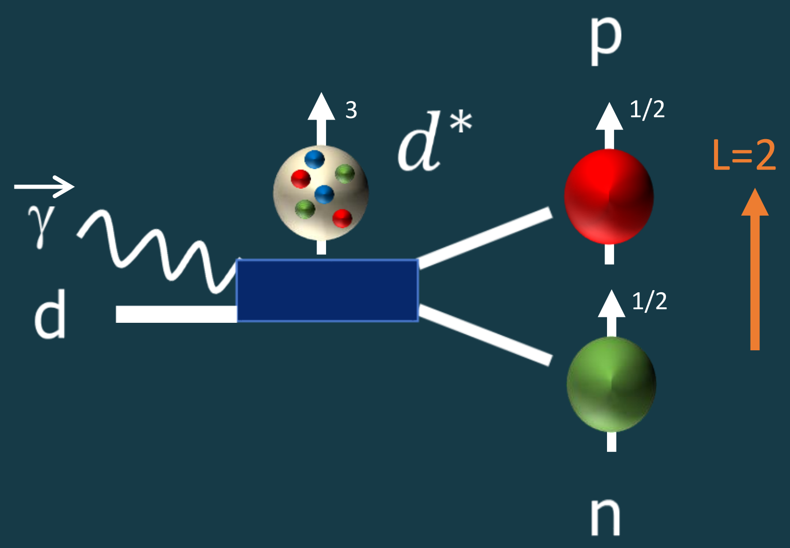
PRC 88 (2013) 055208
PLB 743 (2015) 325

ΔΔ decay ~90%
pn decay ~10%

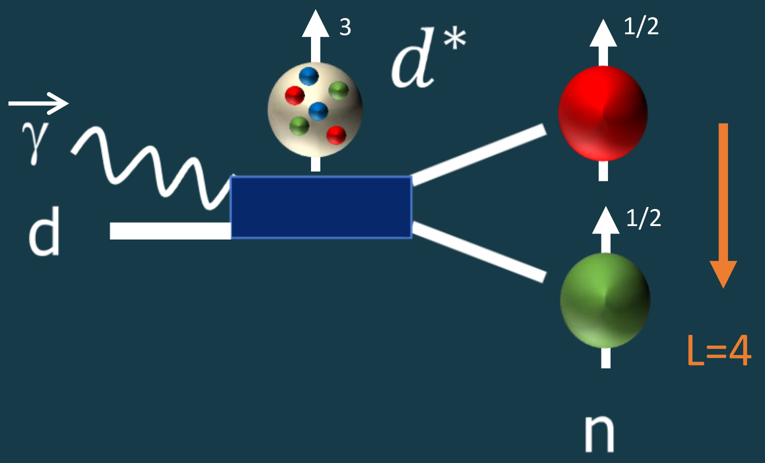
d* decays to pn

- High partial waves in decay to a proton-neutron final state (J=3)

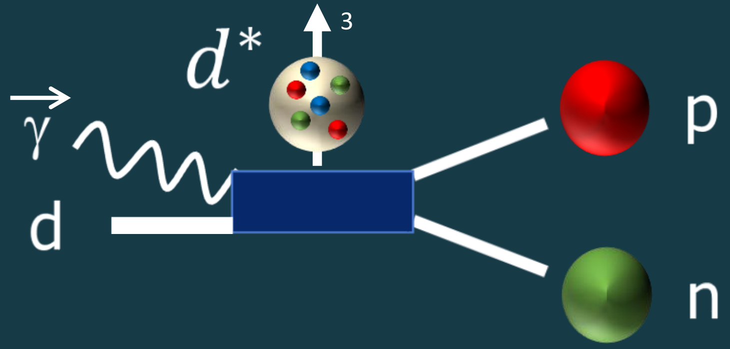
90% of cases this is via the $^3D_3$ partial wave
(L = 2, nucleon spins and L all aligned)



10% of cases via the $^3G_3$ partial wave
(L = 4, nucleon spins aligned, spin and L anti-aligned).



Deuterium photodisintegration (Σ)



- First detailed measurement in region of d*
- Good agreement with sparse existing data
- Almost complete acceptance – amenable to (truncated) PWA

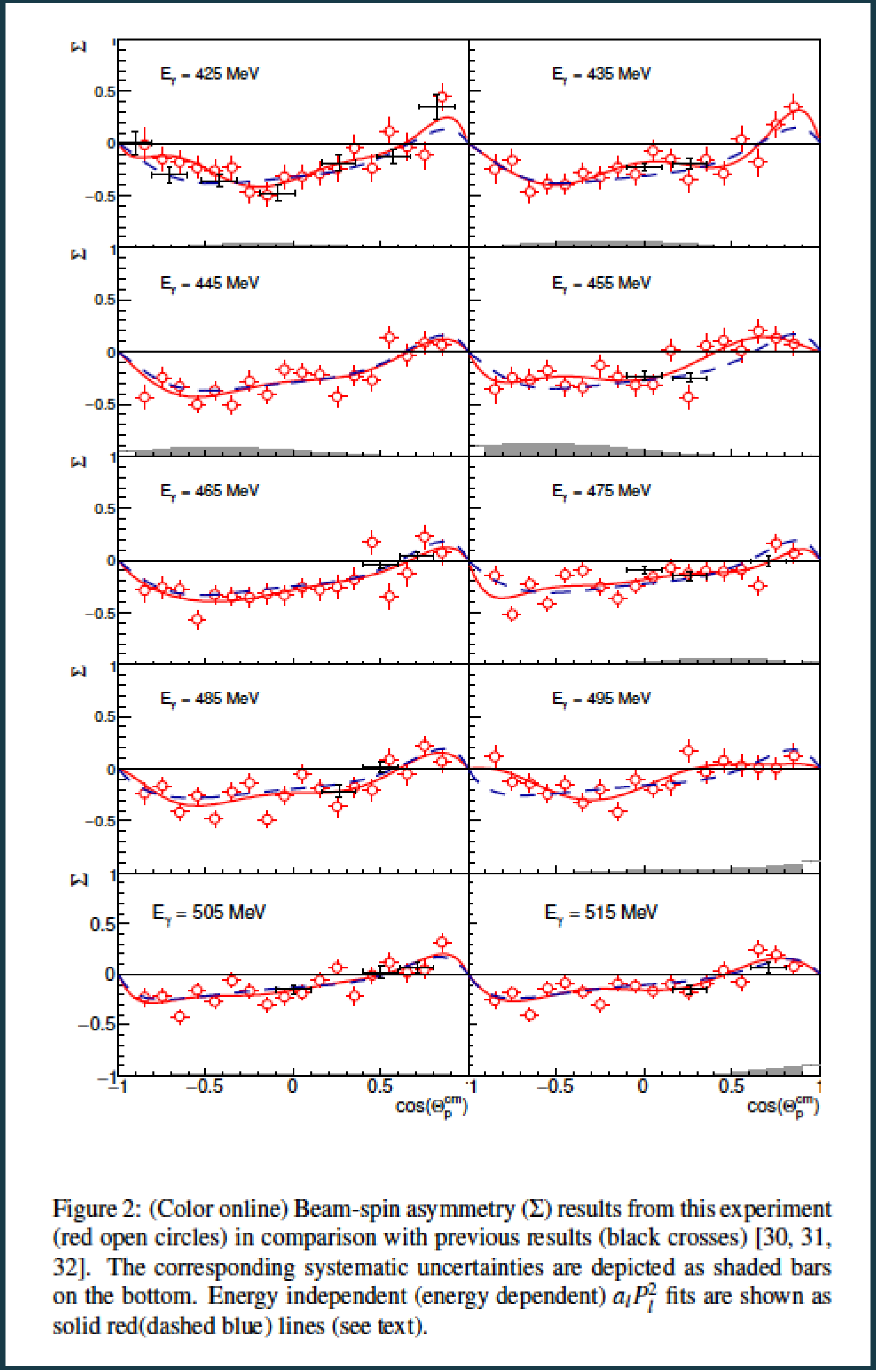


Figure 2: (Color online) Beam-spin asymmetry (Σ) results from this experiment (red open circles) in comparison with previous results (black crosses) [30, 31, 32]. The corresponding systematic uncertainties are depicted as shaded bars on the bottom. Energy independent (energy dependent) $a_l P_l^2$ fits are shown as solid red(dashed blue) lines (see text).

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

Σ decomposition

$$\sigma_1 = \Sigma(\Theta, E_\gamma) \cdot \sigma(\Theta, E_\gamma)$$

$$\frac{\sigma_1}{\sigma_{\text{tot}}} = \sum_{l=2}^{7} a_l P_l^2 .$$

Discrete gaussian sampling method
3 gaussians centroids 420,520,620 width 100 MeV

2 methods: Single energy & energy dependent (smooth functions for a_l)

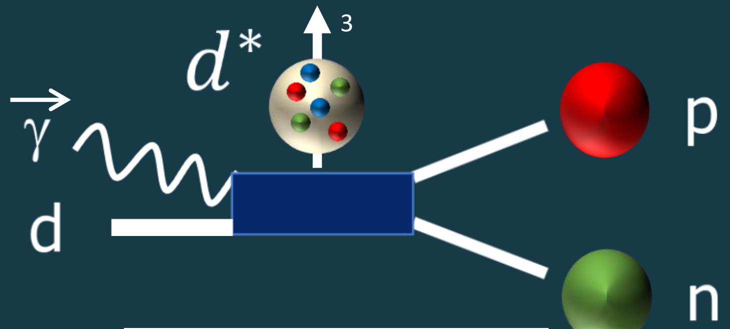
Additional term: BW, mass 2380 MeV, width=70 MeV, arbitrary strength

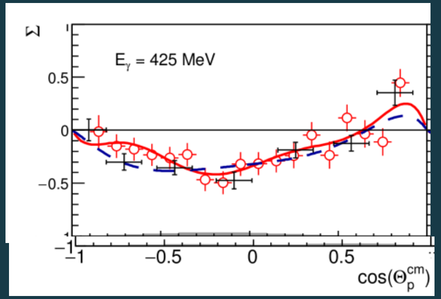
$$\begin{aligned} a_6 &\sim d_1 |{}^3G_3(M3)|^2 + \cdots \\ &+ d_i |{}^3D_3(M3)||{}^3G_3(M3)| cos\delta_i + \cdots \\ &+ d_j |{}^3D_3(E2)||{}^{2S+1}L \geq 4_J(E4)| cos\delta_j + \cdot\cdot \end{aligned}$$

Pure M3 should manifest in a_6 but not a_4

Pure E2 should manifest in a_4 but not a_6
(E2 may contribute in a_6 only with interference with higher multipoles E4 or higher

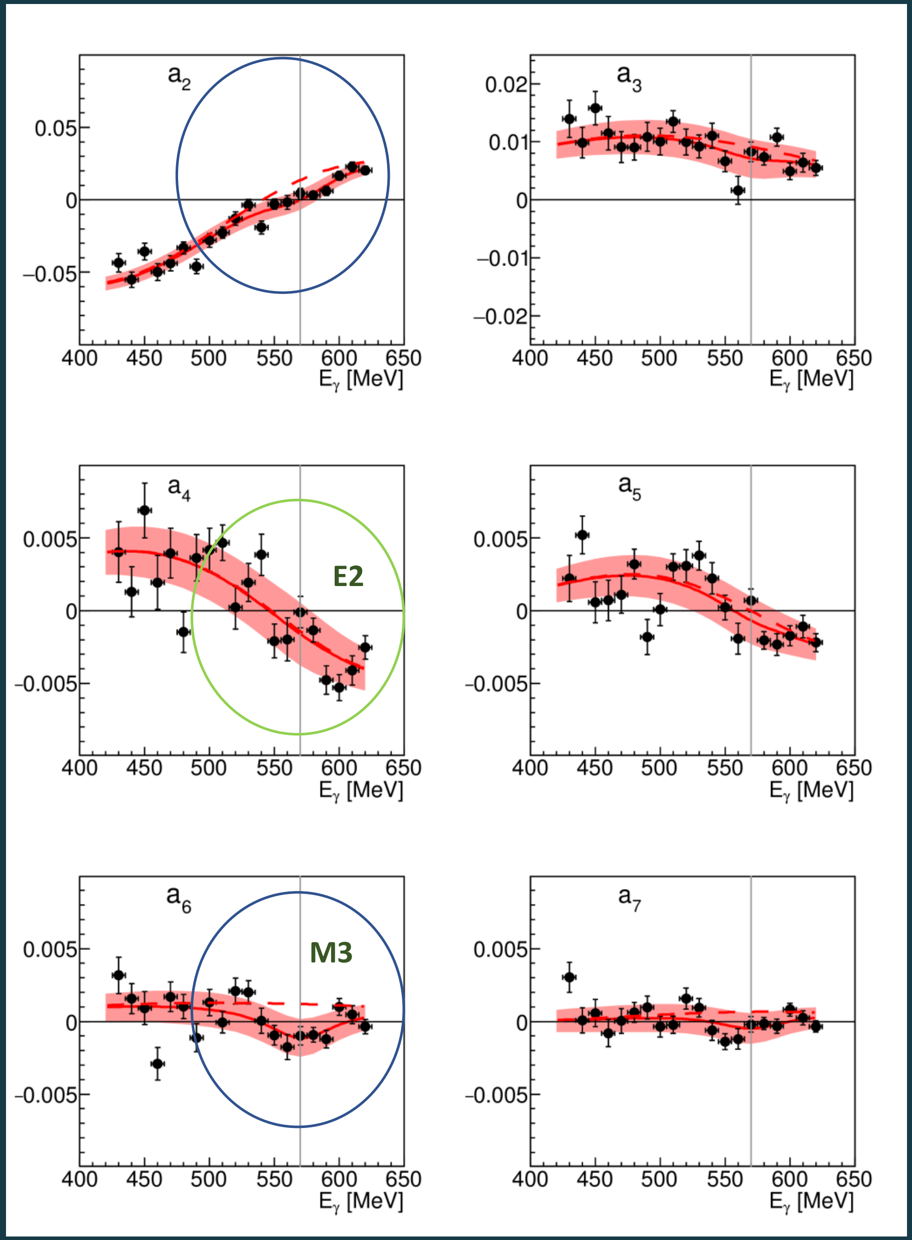
Deuterium photodisintegration (Σ)





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

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



$$\underbrace{\begin{array}{l}\text{E2 transition} \Rightarrow \text{small} \\ \text{M3 transition} \Rightarrow \text{dominant}\end{array}}$$

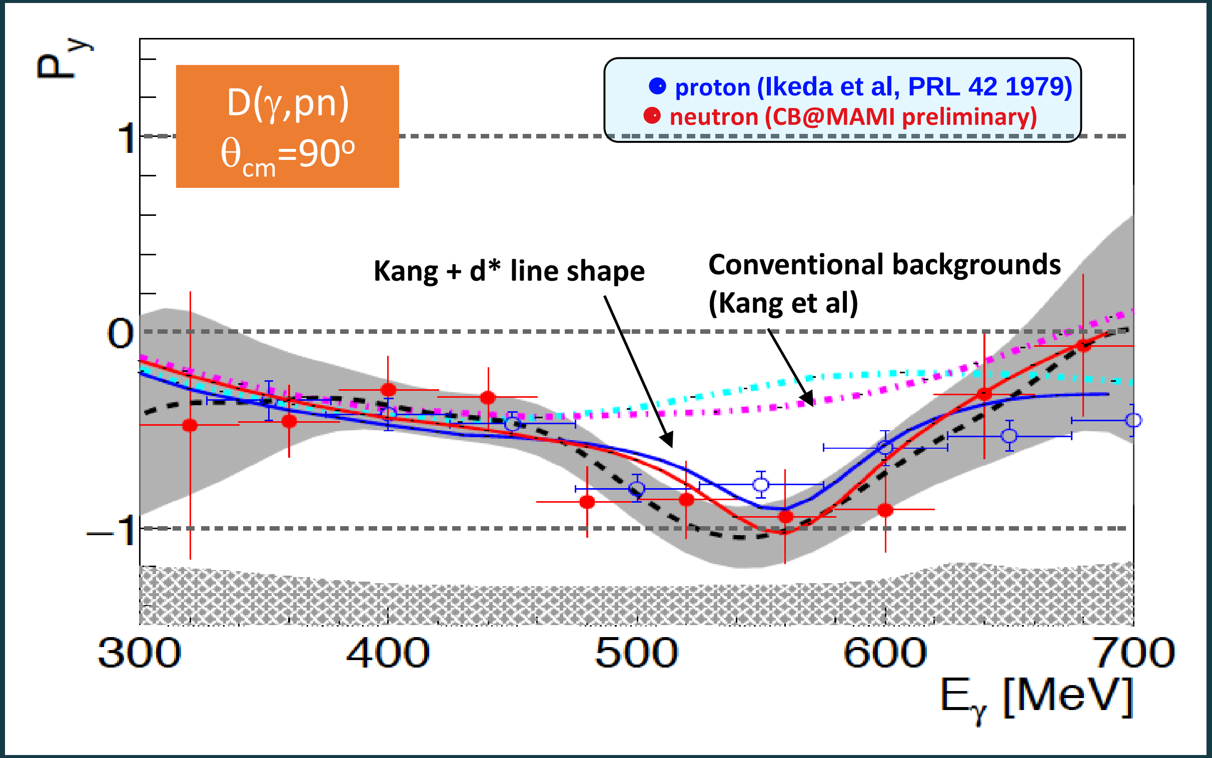
Consistent with $\mathbf{d^*(2380)}$
as a compact object

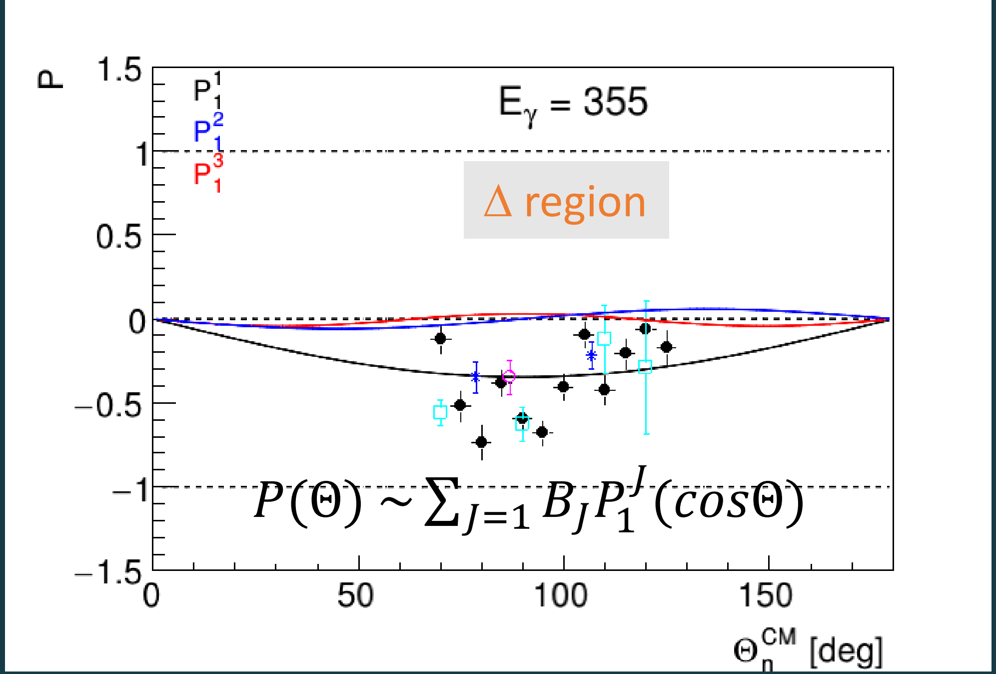
Bashkanov, Watts, Kay, CB@MAMI; PLB789 (2019) 7-12

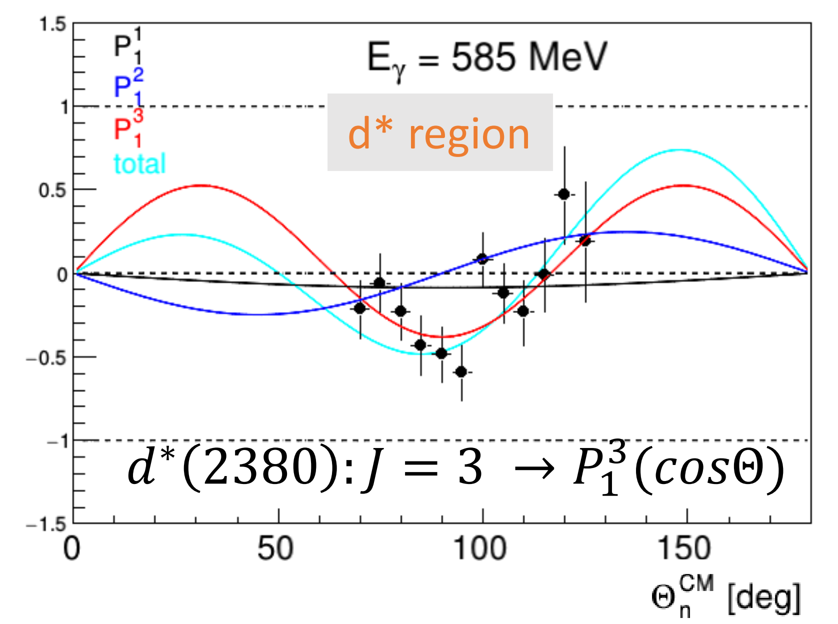
Deuterium photodisintegration (P_y)

- 1st measurement of final state neutron polarisation
  -> ***Both*** p and n highly polarised in region of d*!

- θ_{CM} dependence – consistent with spin 3







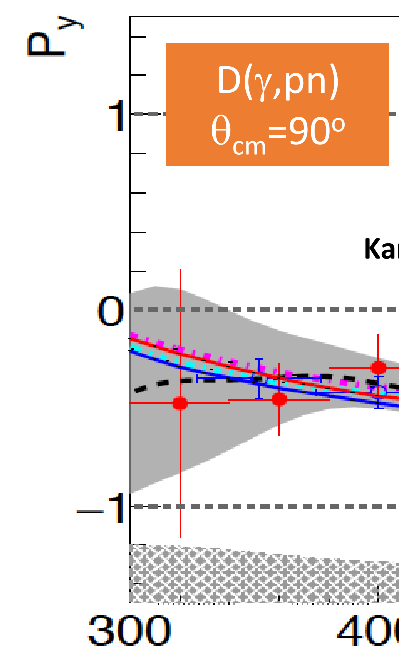
Bashkanov, DPW, Kay, CB@MAMI; PRL under review

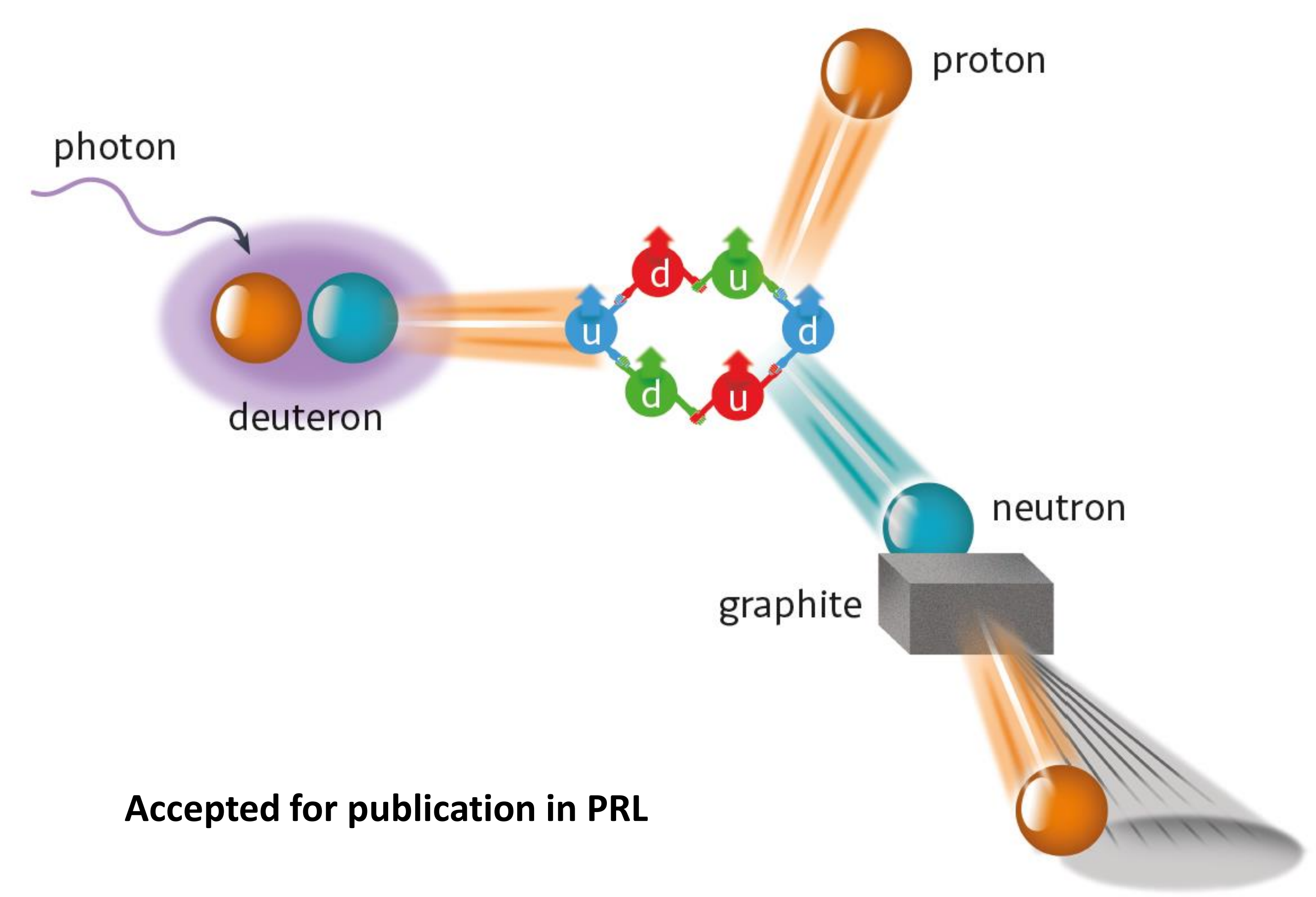
Deuterium photodisintegration (P_y)

- 1st measuremen

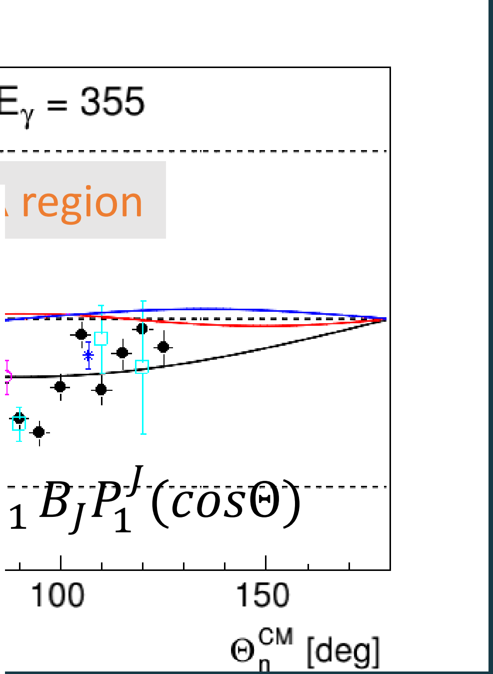
  -> ***Both*** p and n

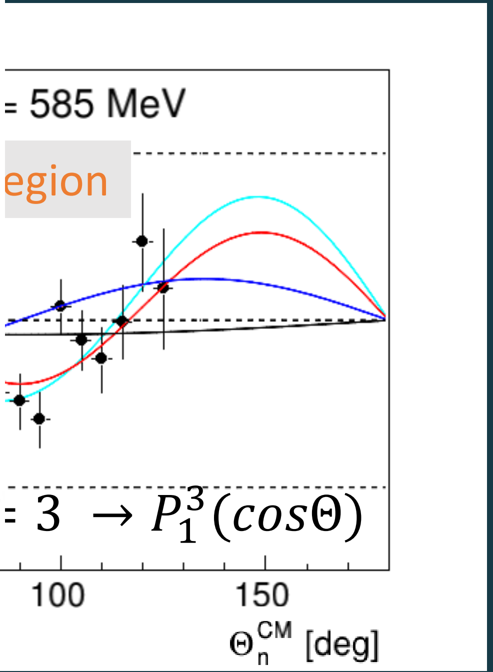
- θ_{CM} dependenc





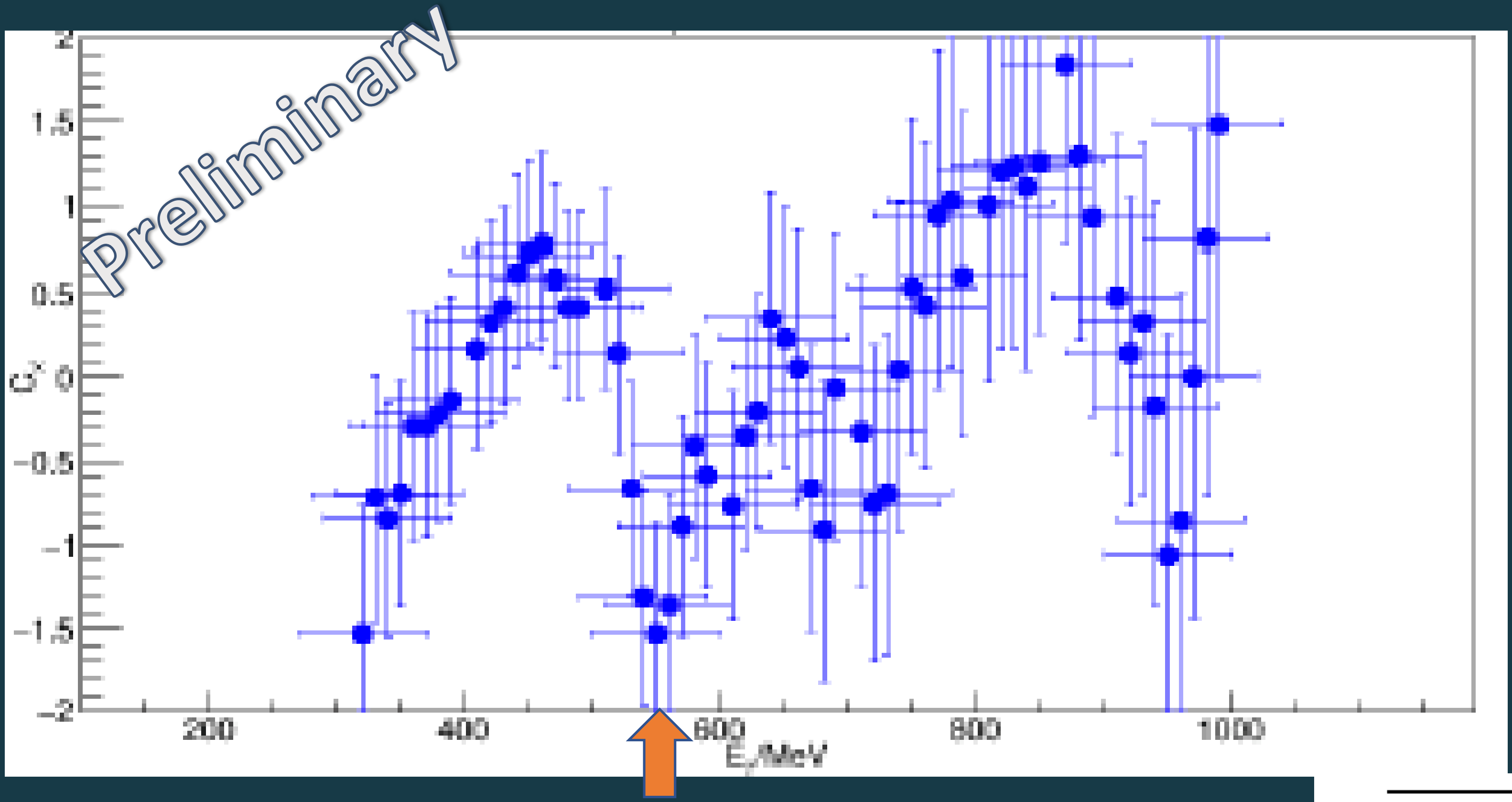
Accepted for publication in PRL





Bashkanov, Watts, Kay, CB@MAMI; PRL

C_x* for neutron final state



Combination of Cx* and P

-> real and imaginary parts of same amplitude combination

- Indications of strong **polarisation *transfer*** in region of d*
- Caveat: approx. (n,p) analyzing power used in analysis

Previous (proton) data

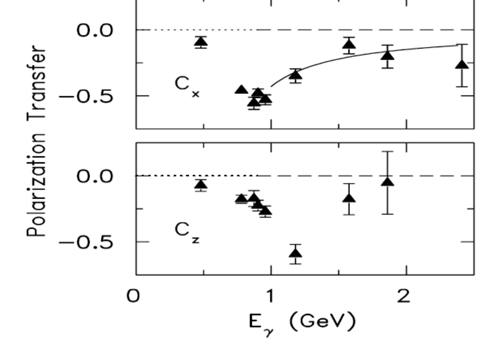
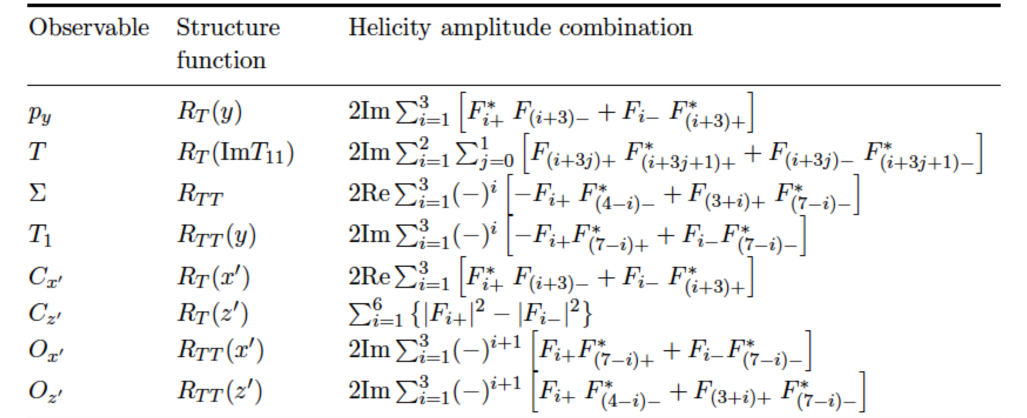


Figure 4: Polarization transfers C_x and C_z at $\theta_{cm} = 90°$. Only statistical uncertainties are shown. The curve is described in the text.

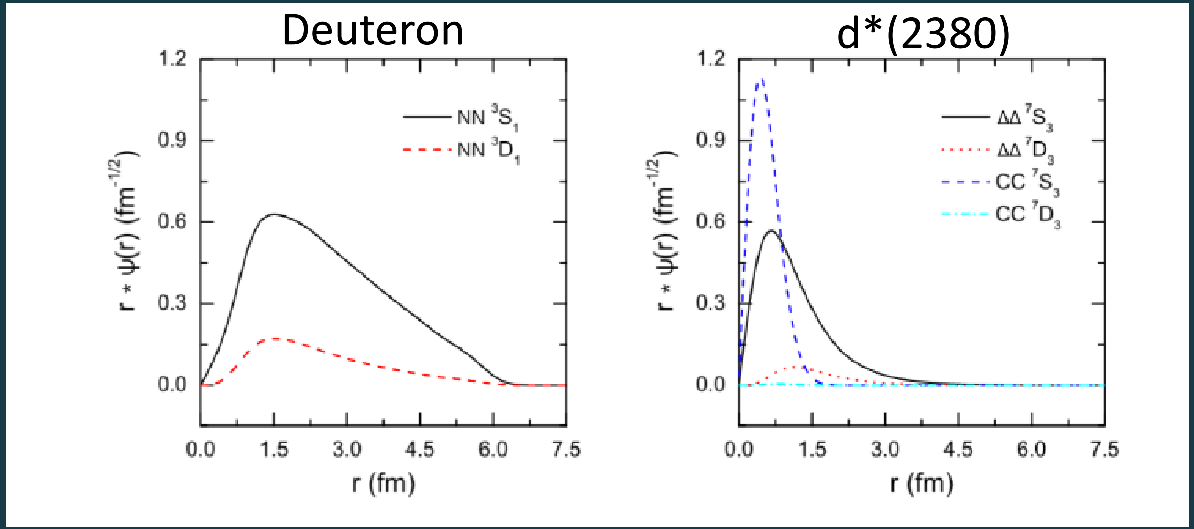


Observable	Structure function	Helicity amplitude combination
p_y	$R_T(y)$	$2\mathrm{Im}\sum_{i=1}^{3}\left[F_{i+}^{*}\,F_{(i+3)-}+F_{i-}\,F_{(i+3)+}^{*}\right]$
T	$R_T(\mathrm{Im}T_{11})$	$2\mathrm{Im}\sum_{i=1}^{2}\sum_{j=0}^{1}\left[F_{(i+3j)+}\,F_{(i+3j+1)+}^{*}+F_{(i+3j)-}\,F_{(i+3j+1)-}^{*}\right]$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

The d*(2380) in models

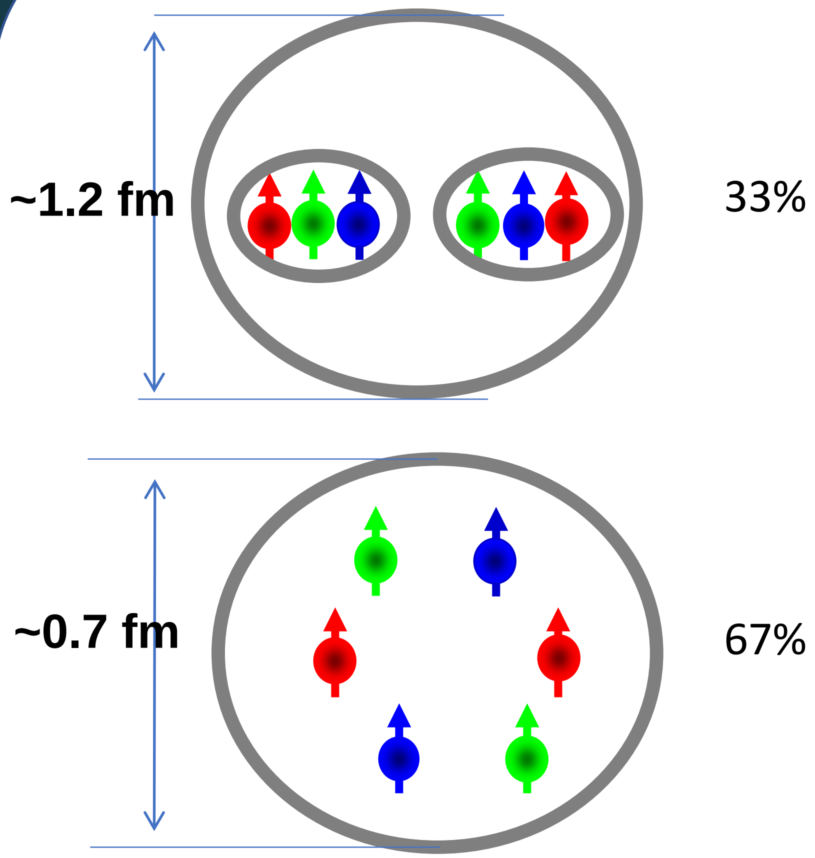
Any quark model with confinement and one gluon exchange *inevitably* predicts a 6-quark object with (I)J^P=(0)3^+

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



Deuteron

d*(2380)



Recent microscopic chiral quark models

$\Delta\Delta$ + **hidden colour**

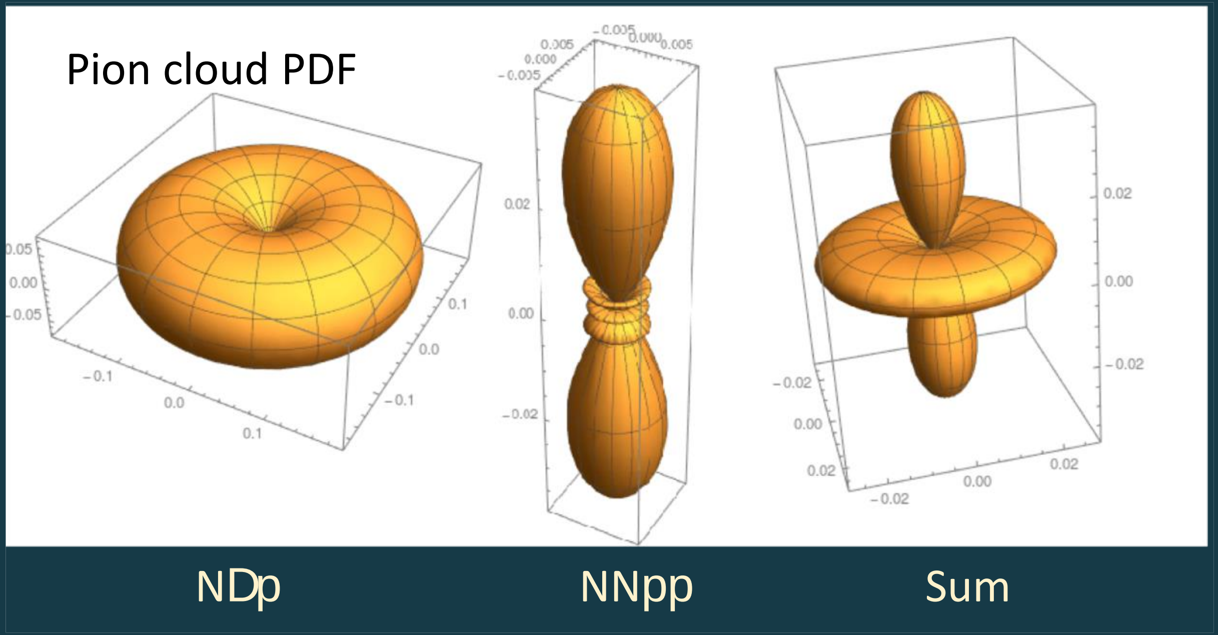
F. Huang et al, Chin.Phys. C39 (2015) 7, 071001

d* in pion cloud model

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

$\Delta\Delta$ $N\Delta\pi$ $NN\pi\pi$

Spherical Donut Rugby ball



- EQM -> $\Delta\Delta$ no contribution
  $N\Delta\pi$, $NN\pi\pi$ ~equal contribution but opposite sign -> cancellation

- MOM -> $\Delta\Delta$ no contribution
  $N\Delta\pi$, $NN\pi\pi$ ~equal contribution but **same** sign

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

The d*(2380) in neutron stars

Physics Letters B 781 (2018) 112–116

Contents lists available at ScienceDirect

Physics Letters B

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

I. Vidaña [a], M. Bashkanov [b,*], D.P. Watts [b], A. Pastore [c]

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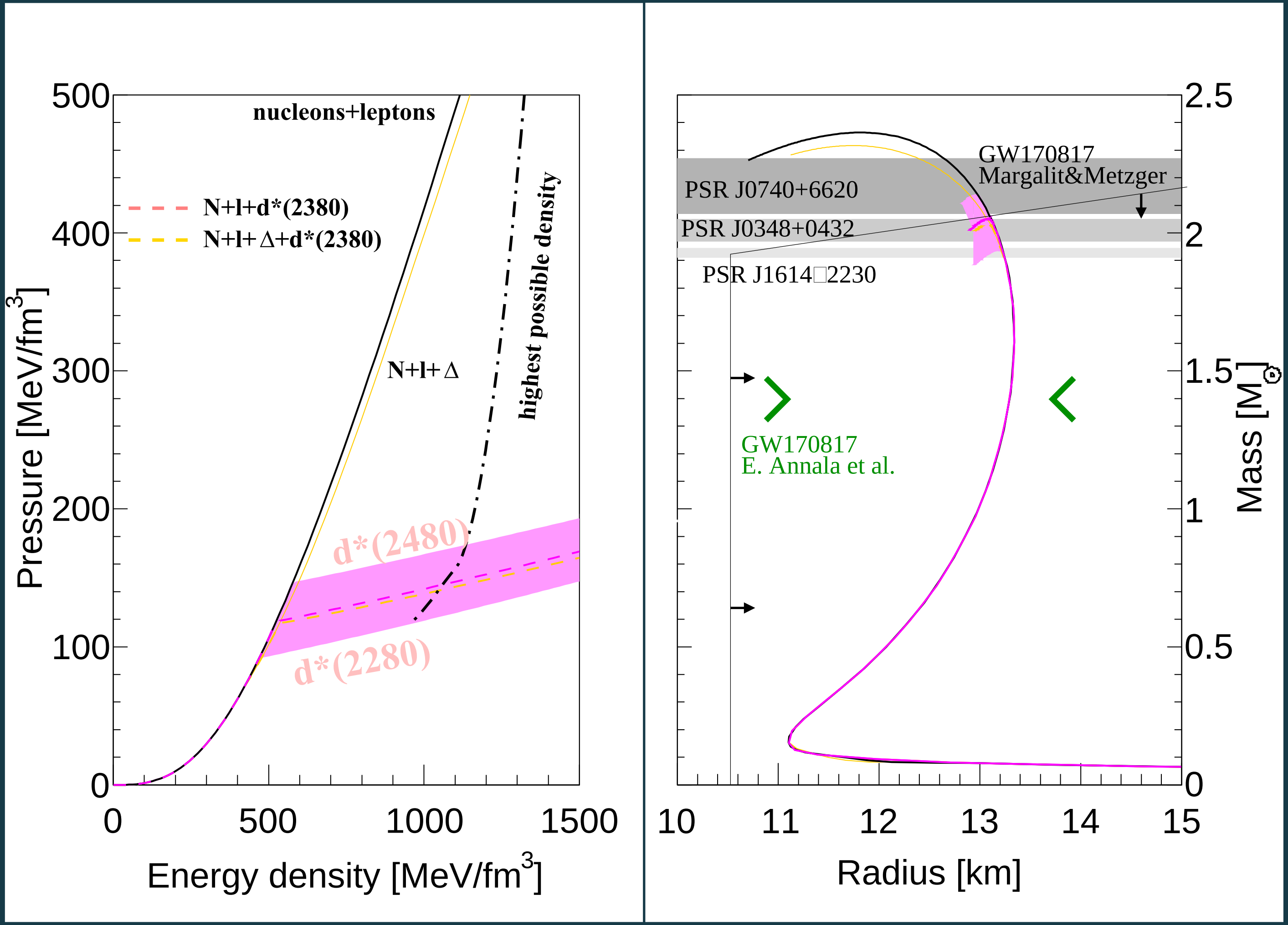
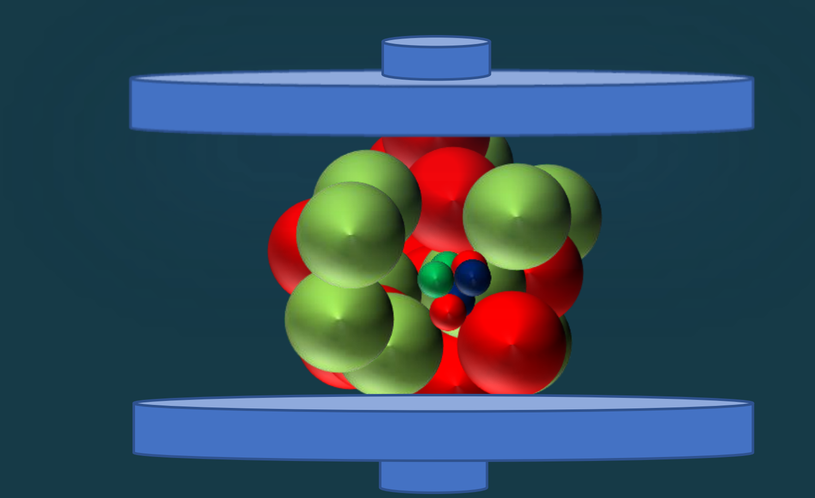
[b] School of Physics and Astronomy, University of Edinburgh, James Clerk Maxwell Building, Peter Guthrie Tait Road, Edinburgh EH9 3FD, UK
[c] Department of Physics, University of York, Heslington, York, Y010 5DD, UK



- d* -> forms copiously above 2.5ρ$_0$

  ->~20% d* at centre of heavy stars



- Star mass limit - around 2.1M$_o$

- d* in medium an important topic

More d*(2380) in neutron stars

Neutron star matter equation of state including *d-hexaquark degrees of freedom**

A. Mantziris[1,2], A. Pastore[1], I. Vidaña[3], D. P. Watts[1], M. Bashkanov[1], and A. M. Romero[1]

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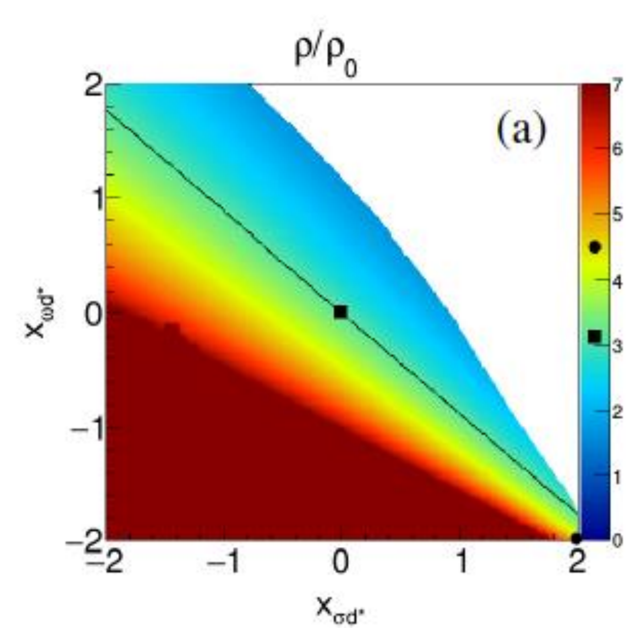
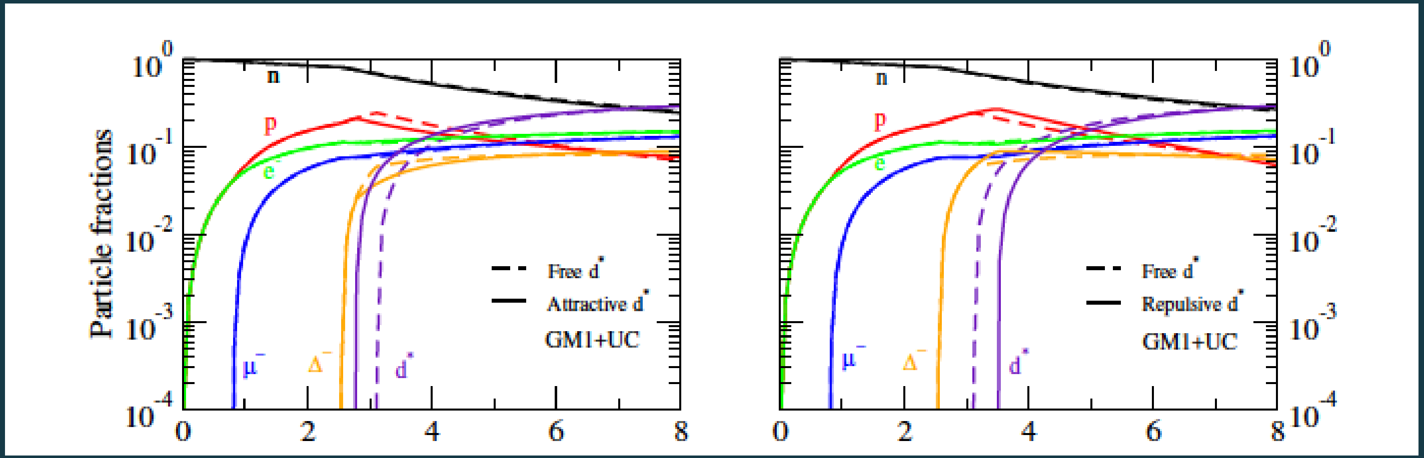
[3] INFN Sezione di Catania, Dipartimento di Fisica "Ettore Majorana", Università di Catania, Via Santa Sofia 64, I-95123 Catania, Italy



- Non-linear Walecka model to describe d*- N interaction via σ,ω
  -> vary the couplings

d* in medium (nuclei) crucial -> Mihai's thesis

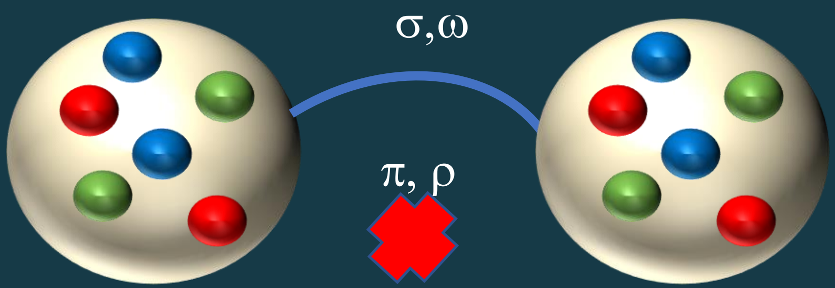


A&A, under review
arxiv:2002.06571

The d*(2380) hexaquark and dark matter

Many body d*(2380) systems

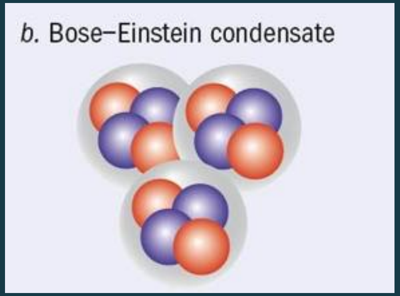
- d* hexaquark - a new compact, bosonic and isoscalar form of light quark matter



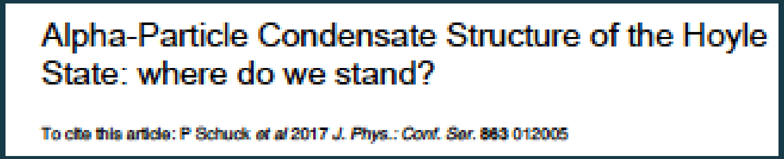
- Its a boson - can the d* form a Bose-Einstein condensate ?

The Hoyle state – a condensate of alpha

- The Hoyle state of ^{12}C (7.65 MeV) - crucial in nucleosynthesis
- α is also an isoscalar, bosonic object
  -> analogous to the d* (but much larger)
- The Hoyle state properties reproduced remarkably well assuming it is a dilute Bose-Einstein condensate of 3 alpha particles.



70% condensed state with 30% of time scattered out from interactions


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

The d* condensate ?

- The Binding Energy of a condensate can be calculated as a function of d* multiplicity
- Account for different scaling of binding and Coulomb terms (common wavefunction for all particles). Surface term not relevant for condensate – linear chain configuration

-> Vary volume coefficient (reflecting the d*-d* interaction potential) over physical ranges

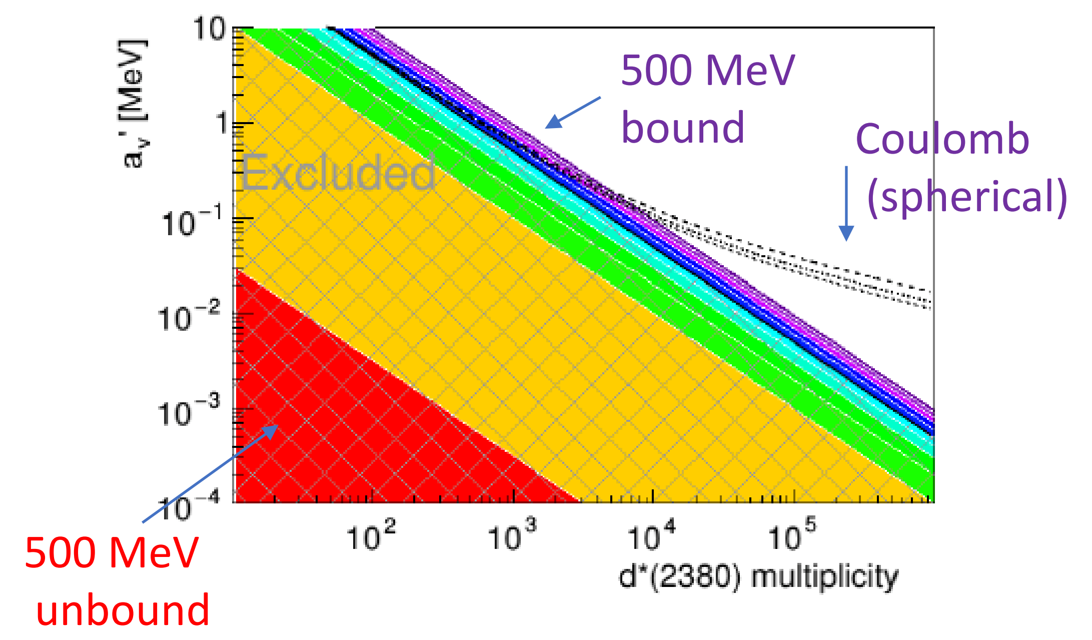
Standard nuclei

$$B_{LD}/A = a_v - a_s \cdot \frac{1}{A^{1/3}} - a_c \cdot \frac{Z(Z-1)}{A^{4/3}}$$

d* condensate

$$B/D = a'_v \cdot (D-1) - a'_c \cdot \frac{(D-1)}{D}; \quad a'_c[MeV] = 0.064 \cdot \frac{\rho}{\rho_0}$$

Bashkanov, Watts – JPhysG Letters 47, 3, 03LT01, (2020)



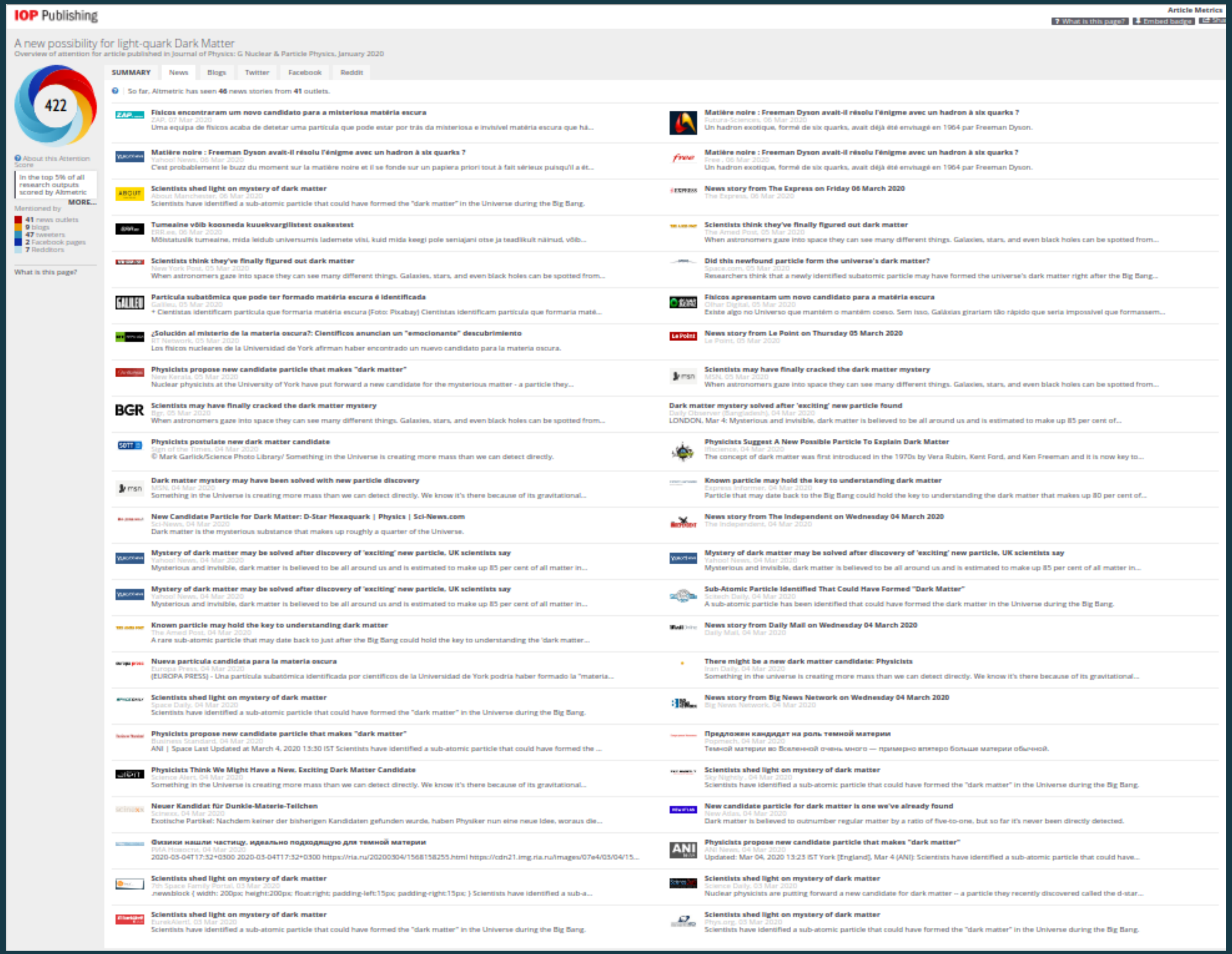
500 MeV bound

Coulomb (spherical)

500 MeV unbound

A new possibility for light-quark Dark matter

- The Independent, Daily Mail, Daily Express, Newsweek…. 40+ newspapers an journals all over the globe.
- 12k downloads a day, 15k+ downloads total.



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C'est probablement le buzz du moment sur la matière noire et il se fonde sur un papiera priori tout à fait sérieux puisqu'il a ét...

Scientists shed light on mystery of dark matter
About Manchester, 06 Mar 2020
Scientists have identified a sub-atomic particle that could have formed the "dark matter" in the Universe during the Big Bang.

Tumeaine võib koosneda kuuekvargilistest osakestest
ERR.ee, 06 Mar 2020
Mõistatuslik tumeaine, mida leidub universumis lademete viisi, kuid mida keegi pole seniajani otse ja teadlikult näinud, võib...

Scientists think they've finally figured out dark matter
New York Post, 05 Mar 2020
When astronomers gaze into space they can see many different things. Galaxies, stars, and even black holes can be spotted from...

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Galileu, 05 Mar 2020
+ Cientistas identificam partícula que formaria matéria escura (Foto: Pixabay) Cientistas identificam partícula que formaria maté...

¿Solución al misterio de la materia oscura?: Científicos anuncian un "emocionante" descubrimiento
RT Network, 05 Mar 2020
Los físicos nucleares de la Universidad de York afirman haber encontrado un nuevo candidato para la materia oscura.

Physicists propose new candidate particle that makes "dark matter"
New Kerala, 05 Mar 2020
Nuclear physicists at the University of York have put forward a new candidate for the mysterious matter - a particle they...

Scientists may have finally cracked the dark matter mystery
Bgr, 05 Mar 2020
When astronomers gaze into space they can see many different things. Galaxies, stars, and even black holes can be spotted from...

Physicists postulate new dark matter candidate
Sign of the Times, 04 Mar 2020
© Mark Garlick/Science Photo Library/ Something in the Universe is creating more mass than we can detect directly.

Dark matter mystery may have been solved with new particle discovery
MSN, 04 Mar 2020
Something in the Universe is creating more mass than we can detect directly. We know it's there because of its gravitational...

New Candidate Particle for Dark Matter: D-Star Hexaquark | Physics | Sci-News.com
Sci-News, 04 Mar 2020
Dark matter is the mysterious substance that makes up roughly a quarter of the Universe.

Mystery of dark matter may be solved after discovery of 'exciting' new particle, UK scientists say
Yahoo! News, 04 Mar 2020
Mysterious and invisible, dark matter is believed to be all around us and is estimated to make up 85 per cent of all matter in...

Mystery of dark matter may be solved after discovery of 'exciting' new particle, UK scientists say
Yahoo! News, 04 Mar 2020
Mysterious and invisible, dark matter is believed to be all around us and is estimated to make up 85 per cent of all matter in...

Known particle may hold the key to understanding dark matter
The Amed Post, 04 Mar 2020
A rare sub-atomic particle that may date back to just after the Big Bang could hold the key to understanding the 'dark matter...

Nueva partícula candidata para la materia oscura
Europa Press, 04 Mar 2020
(EUROPA PRESS) - Una partícula subatómica identificada por científicos de la Universidad de York podría haber formado la "materia...

Scientists shed light on mystery of dark matter
Space Daily, 04 Mar 2020
Scientists have identified a sub-atomic particle that could have formed the "dark matter" in the Universe during the Big Bang.

Physicists propose new candidate particle that makes "dark matter"
Business Standard, 04 Mar 2020
ANI | Space Last Updated at March 4, 2020 13:30 IST Scientists have identified a sub-atomic particle that could have formed the ...

Physicists Think We Might Have a New, Exciting Dark Matter Candidate
Science Alert, 04 Mar 2020
Something in the Universe is creating more mass than we can detect directly. We know it's there because of its gravitational...

Neuer Kandidat für Dunkle-Materie-Teilchen
Scinexx, 04 Mar 2020
Exotische Partikel: Nachdem keiner der bisherigen Kandidaten gefunden wurde, haben Physiker nun eine neue Idee, woraus die...

Физики нашли частицу, идеально подходящую для темной материи
РИА Новости, 04 Mar 2020
2020-03-04T17:32+0300 2020-03-04T17:32+0300 https://ria.ru/20200304/1568158255.html https://cdn21.img.ria.ru/images/07e4/03/04/15...

Scientists shed light on mystery of dark matter
7th Space Family Portal, 03 Mar 2020
.newsblock { width: 200px; height:200px; float:right; padding-left:15px; padding-right:15px; } Scientists have identified a sub-a...

Scientists shed light on mystery of dark matter
EurekAlert!, 03 Mar 2020
Scientists have identified a sub-atomic particle that could have formed the "dark matter" in the Universe during the Big Bang.

Matière noire : Freeman Dyson avait-il résolu l'énigme avec un hadron à six quarks ?
Futura-Sciences, 06 Mar 2020
Un hadron exotique, formé de six quarks, avait déjà été envisagé en 1964 par Freeman Dyson.

Matière noire : Freeman Dyson avait-il résolu l'énigme avec un hadron à six quarks ?
Free , 06 Mar 2020
Un hadron exotique, formé de six quarks, avait déjà été envisagé en 1964 par Freeman Dyson.

News story from The Express on Friday 06 March 2020
The Express, 06 Mar 2020

Scientists think they've finally figured out dark matter
The Amed Post, 05 Mar 2020
When astronomers gaze into space they can see many different things. Galaxies, stars, and even black holes can be spotted from...

Did this newfound particle form the universe's dark matter?
Space.com, 05 Mar 2020
Researchers think that a newly identified subatomic particle may have formed the universe's dark matter right after the Big Bang...

Fisicos apresentam um novo candidato para a matéria escura
Olhar Digital, 05 Mar 2020
Existe algo no Universo que mantém o mantém coeso. Sem isso, Galáxias girariam tão rápido que seria impossível que formassem...

News story from Le Point on Thursday 05 March 2020
Le Point, 05 Mar 2020

Scientists may have finally cracked the dark matter mystery
MSN, 05 Mar 2020
When astronomers gaze into space they can see many different things. Galaxies, stars, and even black holes can be spotted from...

Dark matter mystery solved after 'exciting' new particle found
Daily Observer (Bangladesh), 04 Mar 2020
LONDON, Mar 4: Mysterious and invisible, dark matter is believed to be all around us and is estimated to make up 85 per cent of...

Physicists Suggest A New Possible Particle To Explain Dark Matter
Iflscience, 04 Mar 2020
The concept of dark matter was first introduced in the 1970s by Vera Rubin, Kent Ford, and Ken Freeman and it is now key to...

Known particle may hold the key to understanding dark matter
Express Informer, 04 Mar 2020
Particle that may date back to the Big Bang could hold the key to understanding the dark matter that makes up 80 per cent of...

News story from The Independent on Wednesday 04 March 2020
The Independent, 04 Mar 2020

Mystery of dark matter may be solved after discovery of 'exciting' new particle, UK scientists say
Yahoo! News, 04 Mar 2020
Mysterious and invisible, dark matter is believed to be all around us and is estimated to make up 85 per cent of all matter in...

Sub-Atomic Particle Identified That Could Have Formed "Dark Matter"
Scitech Daily, 04 Mar 2020
A sub-atomic particle has been identified that could have formed the dark matter in the Universe during the Big Bang.

News story from Daily Mail on Wednesday 04 March 2020
Daily Mail, 04 Mar 2020

There might be a new dark matter candidate: Physicists
Iran Daily, 04 Mar 2020
Something in the universe is creating more mass than we can detect directly. We know it's there because of its gravitational...

News story from Big News Network on Wednesday 04 March 2020
Big News Network, 04 Mar 2020

Предложен кандидат на роль темной материи
Popmech, 04 Mar 2020
Темной материи во Вселенной очень много — примерно впятеро больше материи обычной.

Scientists shed light on mystery of dark matter
Sky Nightly , 04 Mar 2020
Scientists have identified a sub-atomic particle that could have formed the "dark matter" in the Universe during the Big Bang.

New candidate particle for dark matter is one we've already found
New Atlas, 04 Mar 2020
Dark matter is believed to outnumber regular matter by a ratio of five-to-one, but so far it's never been directly detected.

Physicists propose new candidate particle that makes "dark matter"
ANI News, 04 Mar 2020
Updated: Mar 04, 2020 13:23 IST York [England], Mar 4 (ANI): Scientists have identified a sub-atomic particle that could have...

Scientists shed light on mystery of dark matter
Science Daily, 03 Mar 2020
Nuclear physicists are putting forward a new candidate for dark matter -- a particle they recently discovered called the d-star...

Scientists shed light on mystery of dark matter
Phys.org, 03 Mar 2020
Scientists have identified a sub-atomic particle that could have formed the "dark matter" in the Universe during the Big Bang.

Bashkanov, Watts – JPhysG Letters 47, 3, 03LT01, (2020)

The proposed programme with polarised deuteron targets

Possible beam-target D(γ,pn) observables

- Longitudinal target polarisation

$$T^c_{10}(-E)\,\frac{d\sigma_0}{d\Omega_p} = \frac{1}{2}\sum_{sm_s}\left(|t_{sm_s11}|^2 - |t_{sm_s1-1}|^2\right)$$

Circular γ-polarisation

$$T^l_{10}(G)\,\frac{d\sigma_0}{d\Omega_p} = \Im m\sum_{sm_s}\left(t^*_{sm_s11}\,t_{sm_s-11}\right)$$

Linear γ-polarisation

- Transverse target polarisation

$$T^0_{11}(-T)\,\frac{d\sigma_0}{d\Omega_p} = \Im m\sum_{sm_s}\left(t^*_{sm_s1-1}\,t_{sm_s10} + t^*_{sm_s10}\,t_{sm_s11}\right)$$

Unpolarised

$$T^c_{11}(-F)\,\frac{d\sigma_0}{d\Omega_p} = -\Re e\sum_{sm}\left(t^*_{sm_s1-1}\,t_{sm_s10} + t^*_{sm_s10}\,t_{sm_s11}\right)$$

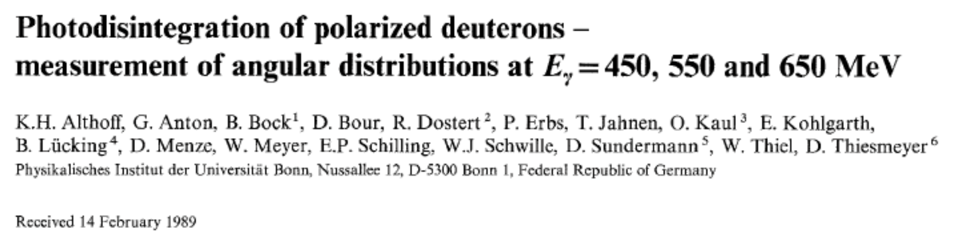
Circular γ-polarisation

$$T^l_{11}\,\frac{d\sigma_0}{d\Omega_p} = \Im m\sum_{sm_s}\left(t^*_{sm_s1-1}\,t_{sm_s-10}\right)$$

Linear γ-polarisation

$$T^l_{1-1}\,\frac{d\sigma_0}{d\Omega_p} = -\Im m\sum_{sm_s}\left(t^*_{sm_s11}\,t_{sm_s-10}\right)$$

Linear γ-polarisation



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

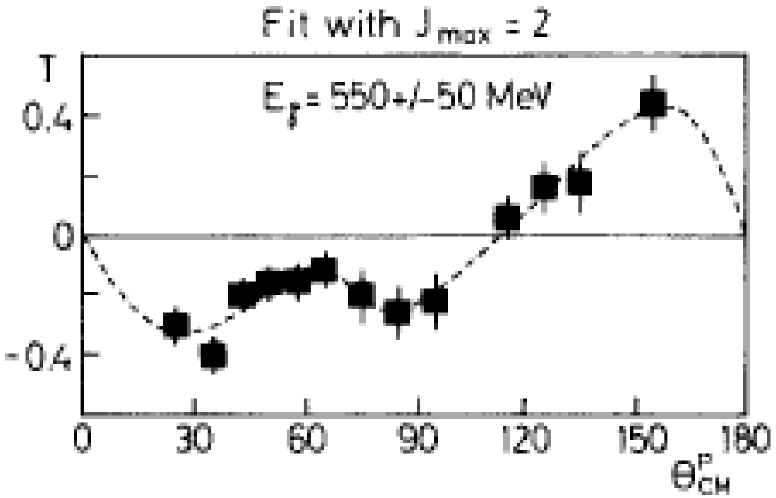


Fig. 6. Angular distribution at 550 MeV fitted with angular momentum $J_{\max} = 2$

Taken as contribution of higher multipoles!

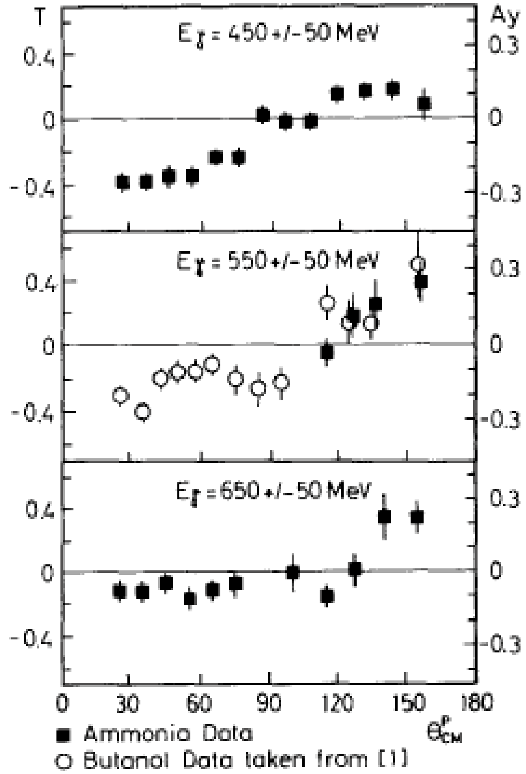
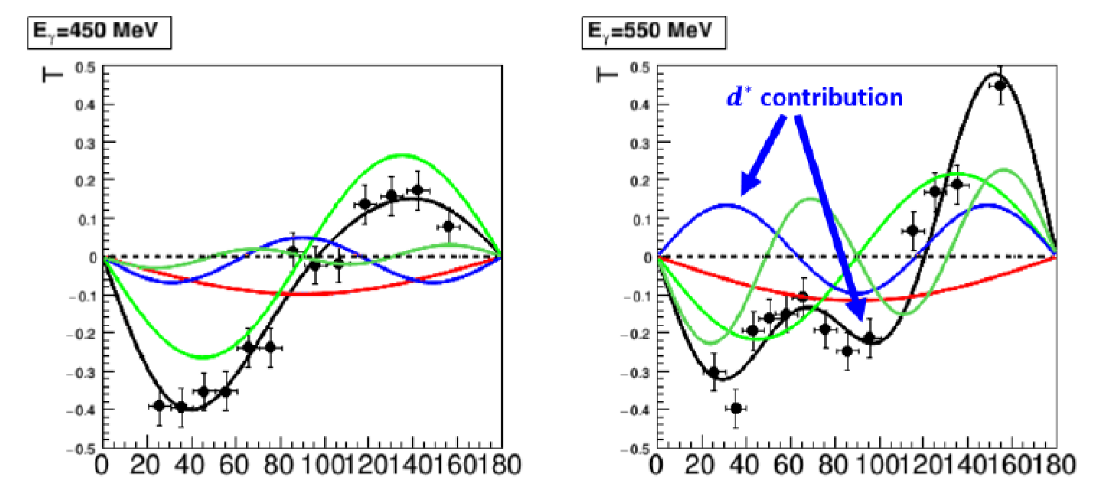


Fig. 4. Target asymmetry vs. proton angle Θ^p_{CM}

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

Significant improvement
In data quality possible
at MAMI

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



Expected sensitivity

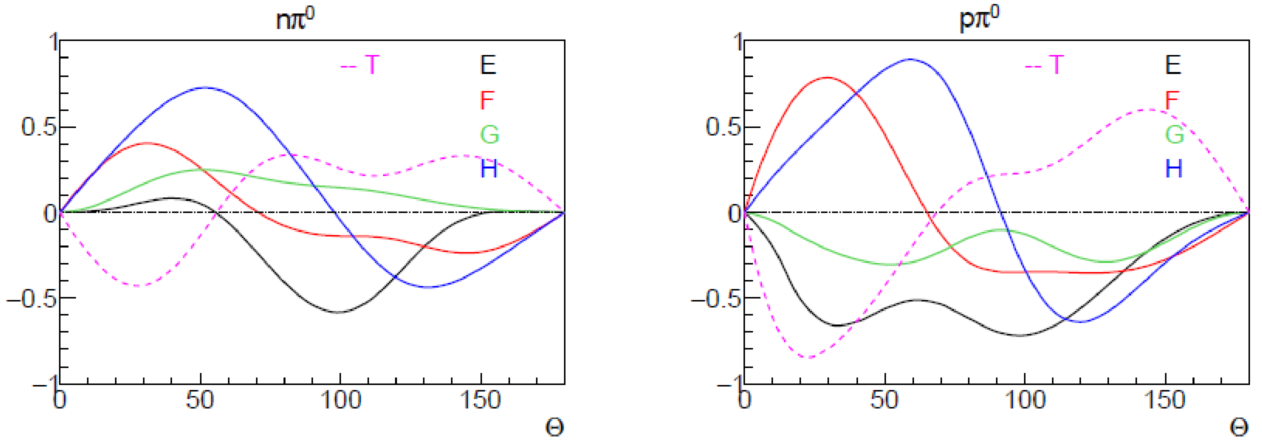
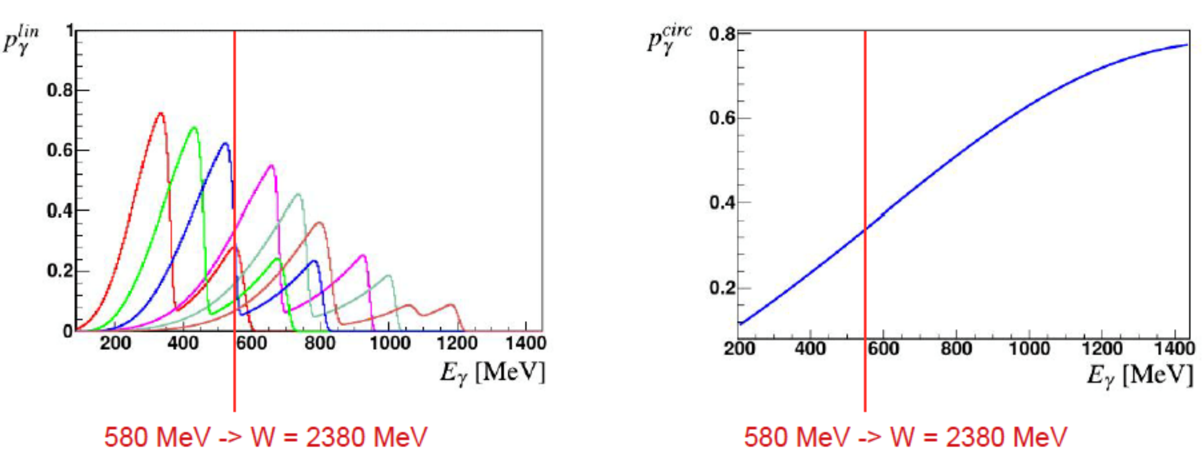


Figure 6: MAID predictions for photoexcitation of the $N^*(1680)$ (along with background from Born terms only). The predictions of various single- and double-polarisation observables for the $n\pi^0$ reaction (left) and $p\pi^0$ reaction (right) are shown. Photon energy = 1035 MeV (W=1680 MeV).

Mainz MAID: $N^*(1680)\ \frac{5}{2}^+$ - same multipoles (E2,M3) as d*

Count rate estimate

- Measure all 4 transverse target asymmetries



580 MeV -> W = 2380 MeV

580 MeV -> W = 2380 MeV

- Stat accuracy $\delta A \sim 0.01$ for ±15 MeV bin
  in d* region, $P_T \sim 0.7$, $P_\gamma \sim 0.4$
  -> requires ~100k events bin^{-1} (good angular binning required)

$$N_{tot} = \frac{1}{P_T^2 \cdot P_\gamma^2 \cdot \delta A^2}$$

Event rate = Beam intensity x tag eff x Number nuclei x efficiency x cross section
= 1 s^{-1}

Beam time ~ 7 weeks

Required beamtime

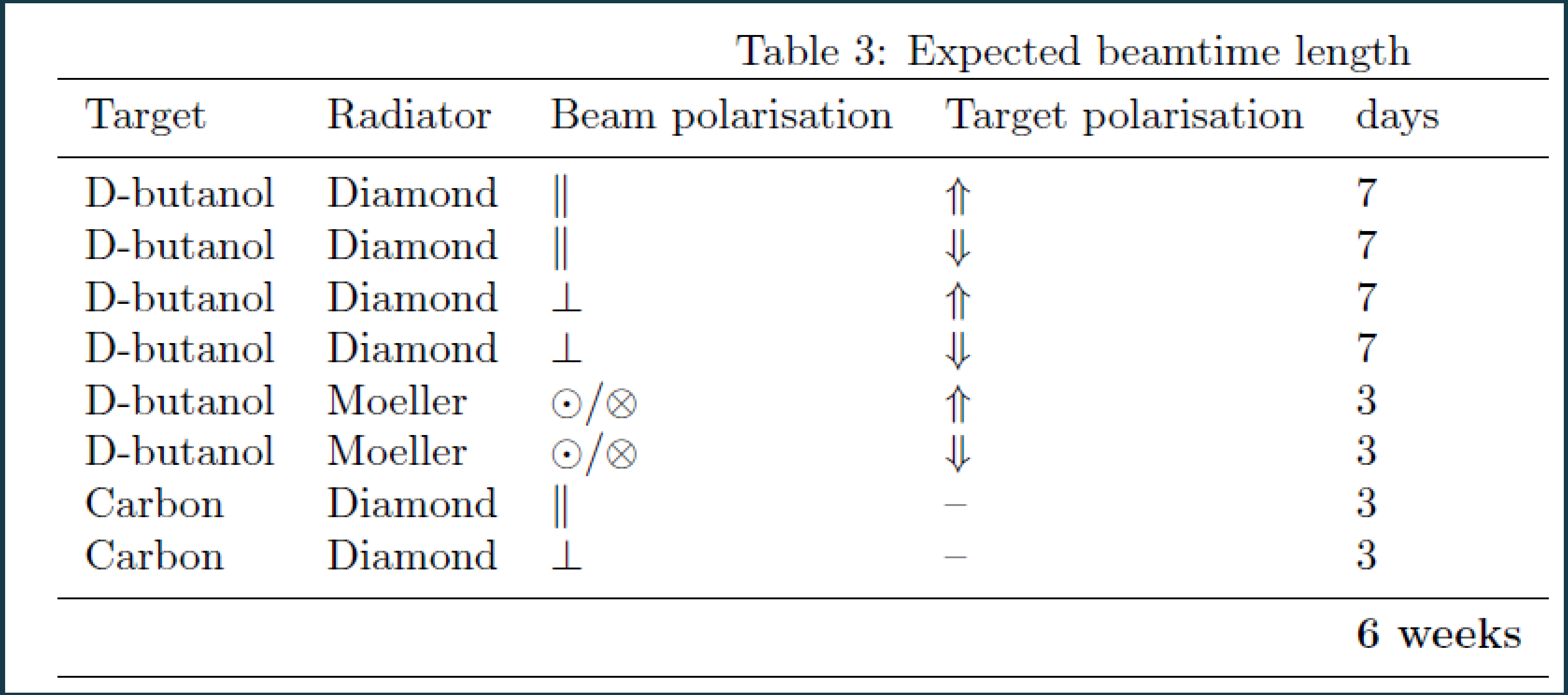


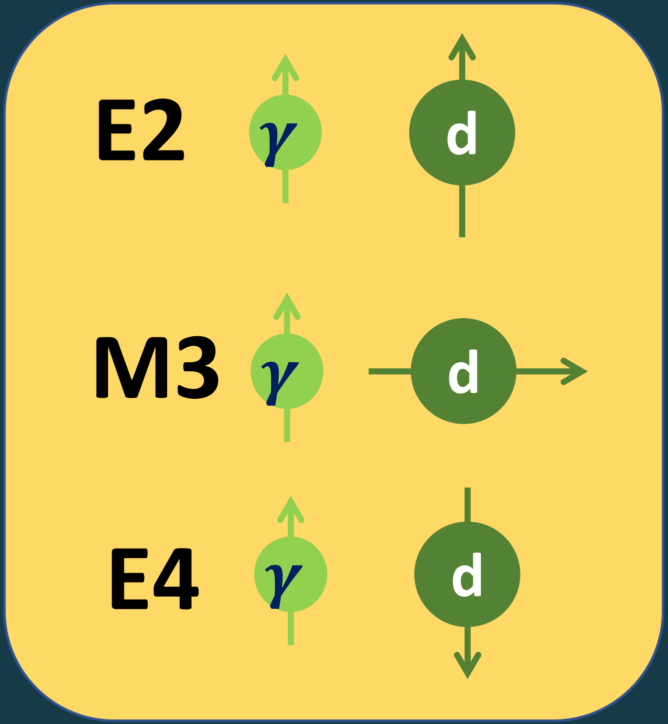
Table 3: Expected beamtime length

Target	Radiator	Beam polarisation	Target polarisation	days
D-butanol	Diamond	$\parallel$	$\Uparrow$	7
D-butanol	Diamond	$\parallel$	$\Downarrow$	7
D-butanol	Diamond	$\perp$	$\Uparrow$	7
D-butanol	Diamond	$\perp$	$\Downarrow$	7
D-butanol	Moeller	$\odot/\otimes$	$\Uparrow$	3
D-butanol	Moeller	$\odot/\otimes$	$\Downarrow$	3
Carbon	Diamond	$\parallel$	–	3
Carbon	Diamond	$\perp$	–	3
				6 weeks

+ 1 week to setup/maintain the target

What will we learn?

- Clean separation of the d*(2380) from background channels
  - Precise knowledge of the d* photo coupling
- d* can be excited in E2, M3 or E4 transitions
  - E2 ↔ Electric Quadrupole moment
  - M3 ↔ Magnetic Octupole moment
  - E4 ↔ Electric Hexadecapole moment

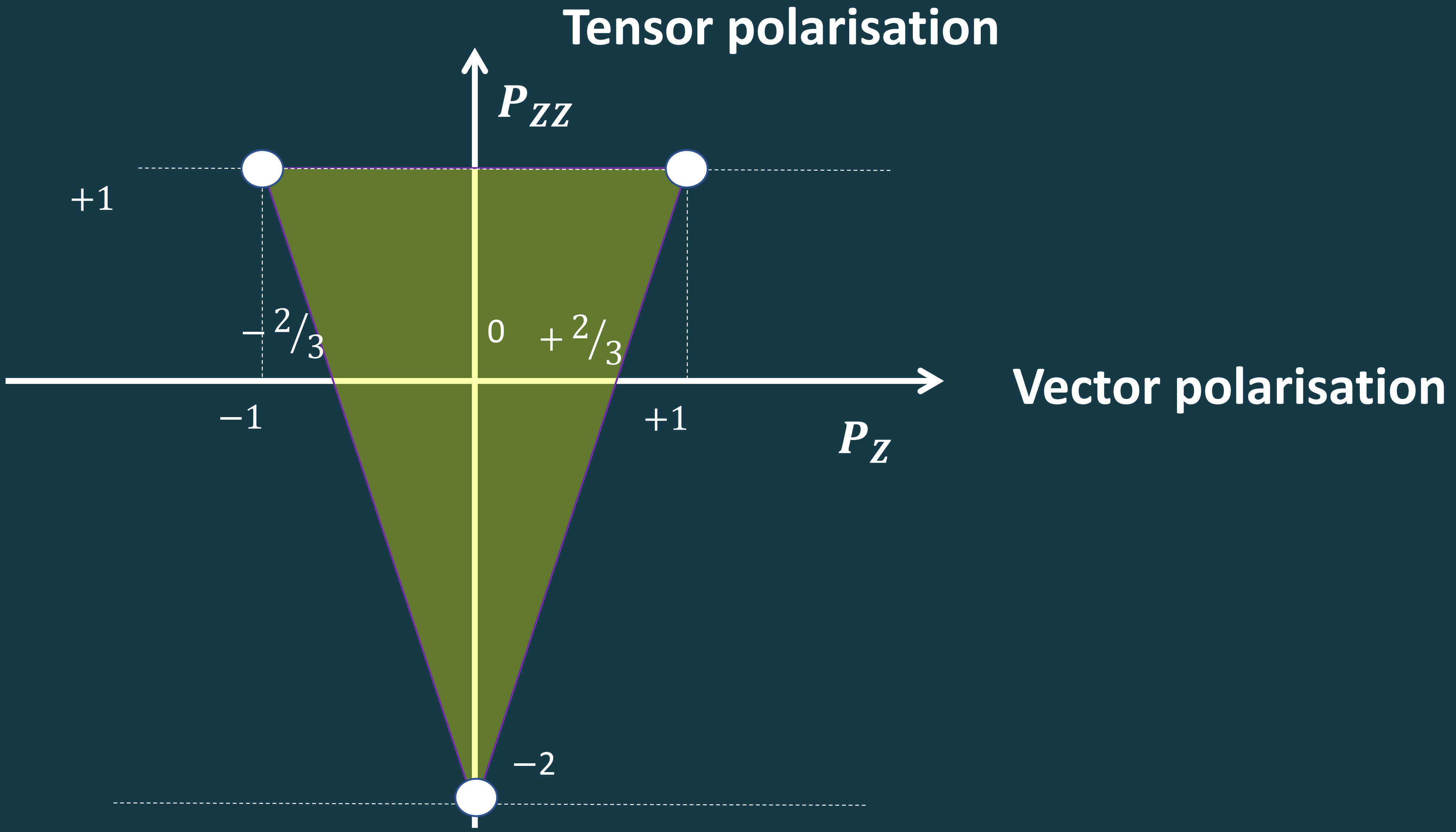


Size and structure of the d*

Summary

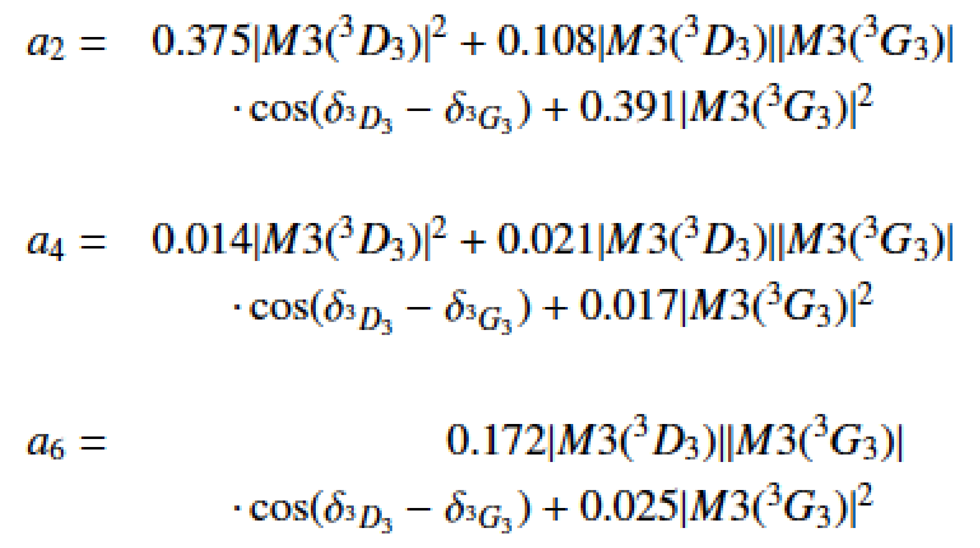
- MAMI can lead the way in providing key data to elucidate the d*(2380) with EM probes
- Important ramifications for hadron physics - potentially for astrophysics
- Campaign with polarized deuteron target would provide T and a trio of beam-target observables

Deuteron polarisation



Extracted (approximate!) d* cross section from σ and Σ

Coefficients: **assuming M3 dominance !**



$$a_2 = 0.375|M3({}^3D_3)|^2 + 0.108|M3({}^3D_3)||M3({}^3G_3)| \cdot \cos(\delta_{{}^3D_3} - \delta_{{}^3G_3}) + 0.391|M3({}^3G_3)|^2$$

$$a_4 = 0.014|M3({}^3D_3)|^2 + 0.021|M3({}^3D_3)||M3({}^3G_3)| \cdot \cos(\delta_{{}^3D_3} - \delta_{{}^3G_3}) + 0.017|M3({}^3G_3)|^2$$

$$a_6 = 0.172|M3({}^3D_3)||M3({}^3G_3)| \cdot \cos(\delta_{{}^3D_3} - \delta_{{}^3G_3}) + 0.025|M3({}^3G_3)|^2$$

-> Use extracted even coefficients to estimate d* contribution

-> 4.6 +-1%

Similar order as suggested by structure in γ + D -> $d\pi^0\pi^0$

(d* coefficients only contribute to odd coefficients via Interference with other partial waves -> therefore assumed small)

Primordial production at the quark hadron phase transition

- DM/matter ratio calculated in general terms assuming Boltzmann distribution in QGP
  arxiv.org/abs/1805.03723

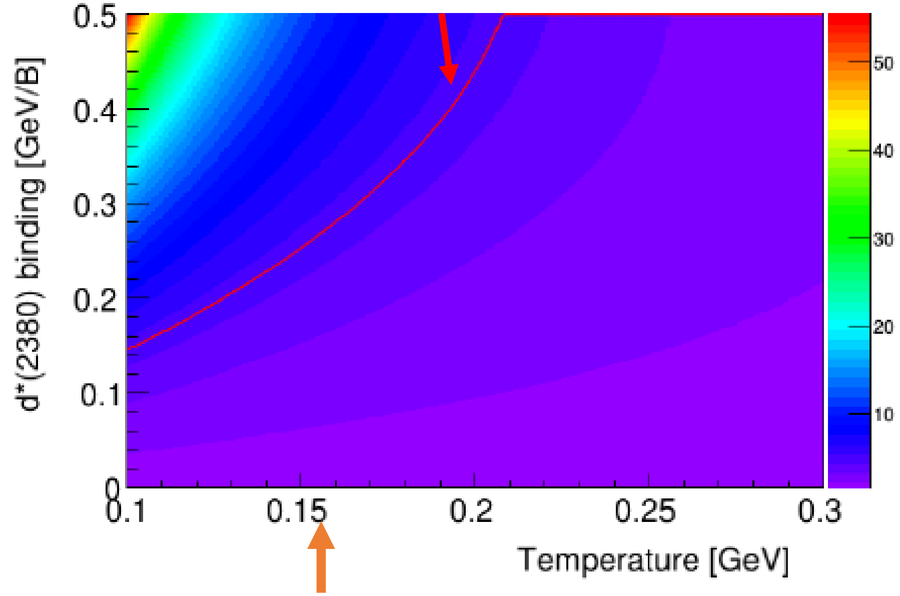
$$\Omega_{DM}/\Omega_{baryon} = \frac{7}{4} M_N \left(1 - \frac{y_D}{M_N}\right)^{3/2} e^{\frac{M_N y_D}{T}}$$

y_D - d* binding energy (units of nucleon mass)
T - temperature

At QGP phase transition (0.16 GeV) a
BE~300 MeV would produce measured DM ratio.

Achievable with d* condensate multiplicity >~1000

d* condensate to matter ratio = 5.3



QGP phase transition

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].

Bashkanov, Watts – JPhysG Letters 47, 3, 03LT01, (2020)

Signatures of d* condensates

- ○ The (charged) chain condensates would attract electrons to become neutral objects (DFT calculations for linear chain configuration in progress)
- ○ Breakup of a condensate “nucleus” would produce a characteristic decay spectrum

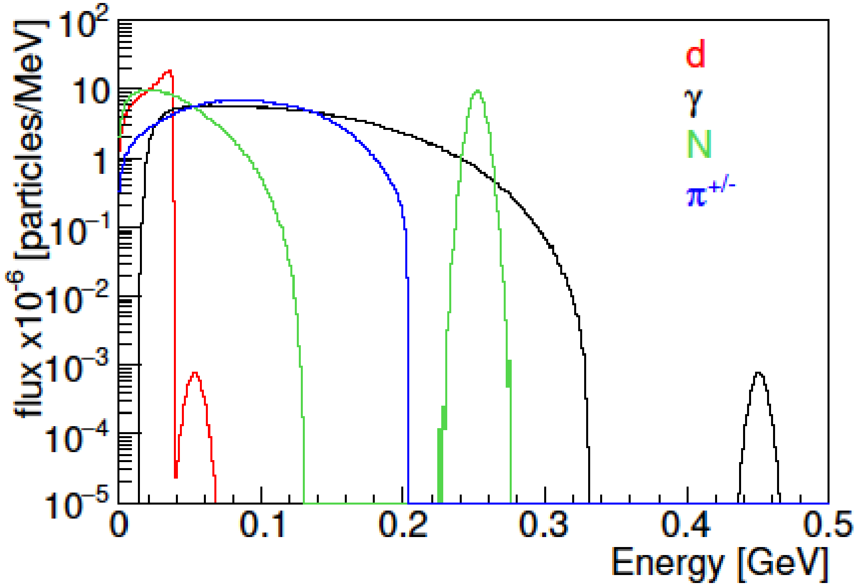
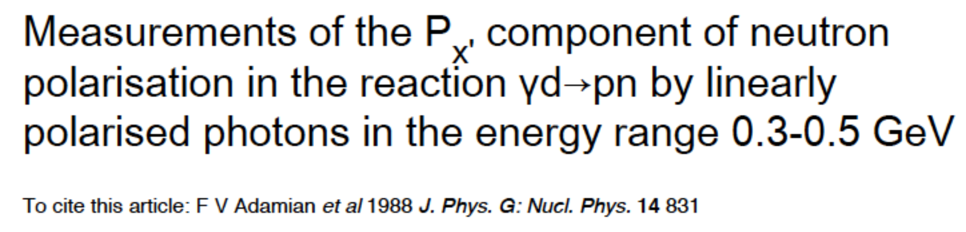
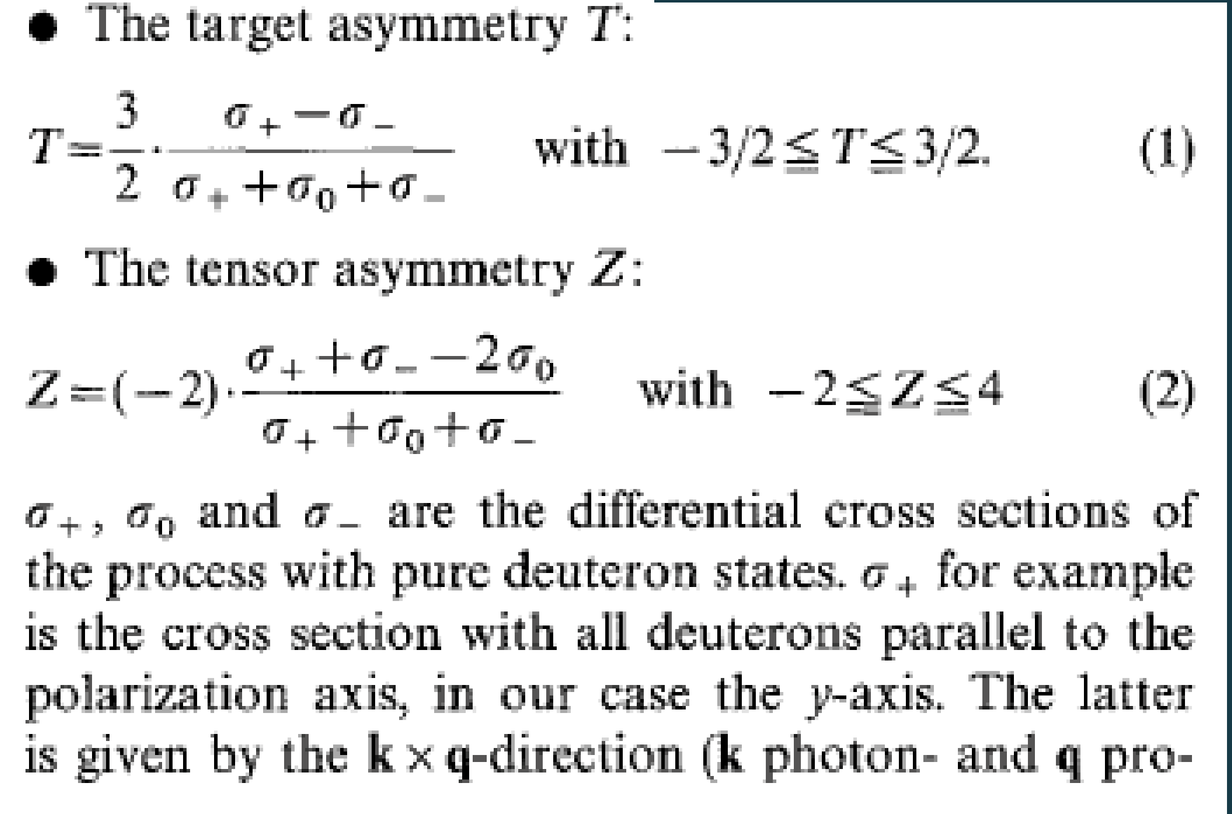


Figure 3. The d^*(2380)-BEC decay spectrum, presented as a flux per d^*(2380), per MeV of kinetic energy. The flux is separated into the contributions from gamma(black), nucleons(green), deuterons(red) and charged pions(blue).



Measurements of the $P_{x'}$ component of neutron polarisation in the reaction γd→pn by linearly polarised photons in the energy range 0.3-0.5 GeV

To cite this article: F V Adamian *et al* 1988 *J. Phys. G: Nucl. Phys.* **14** 831



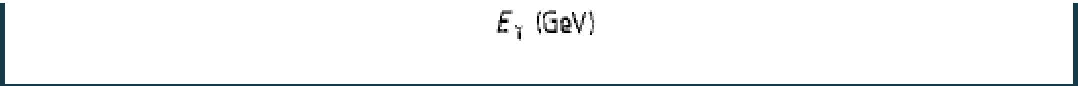
- The target asymmetry T:

$$T=\frac{3}{2}\cdot\frac{\sigma_+-\sigma_-}{\sigma_++\sigma_0+\sigma_-} \quad \text{with} \quad -3/2\leqq T\leqq 3/2. \tag{1}$$

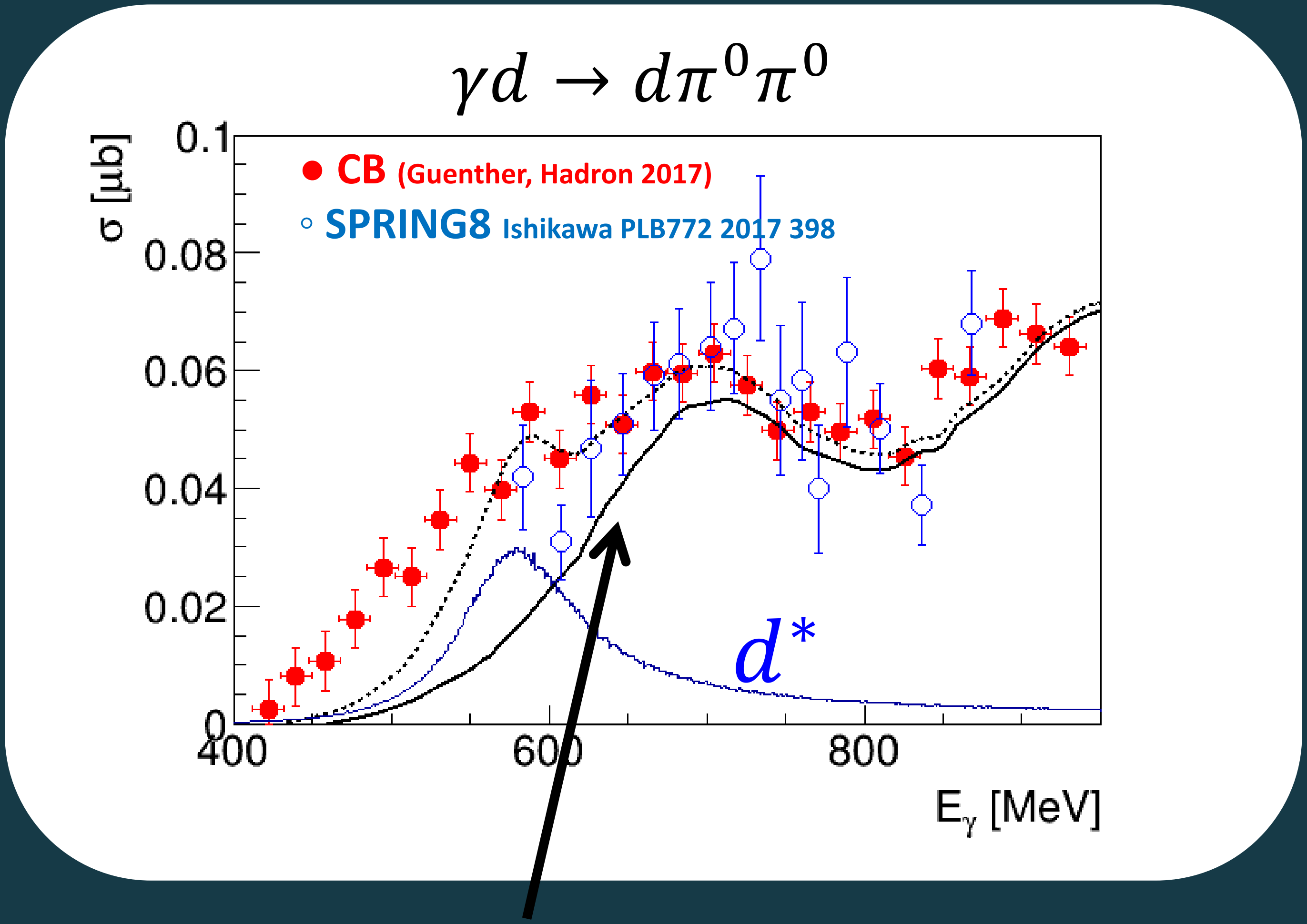
- The tensor asymmetry Z:

$$Z=(-2)\cdot\frac{\sigma_++\sigma_--2\sigma_0}{\sigma_++\sigma_0+\sigma_-} \quad \text{with} \quad -2\leqq Z\leqq 4 \tag{2}$$

σ_+, σ_0 and σ_- are the differential cross sections of the process with pure deuteron states. σ_+ for example is the cross section with all deuterons parallel to the polarization axis, in our case the y-axis. The latter is given by the $\mathbf{k}\times\mathbf{q}$-direction ($\mathbf{k}$ photon- and $\mathbf{q}$ pro-



Photoproduction of d$\pi\pi$ final state



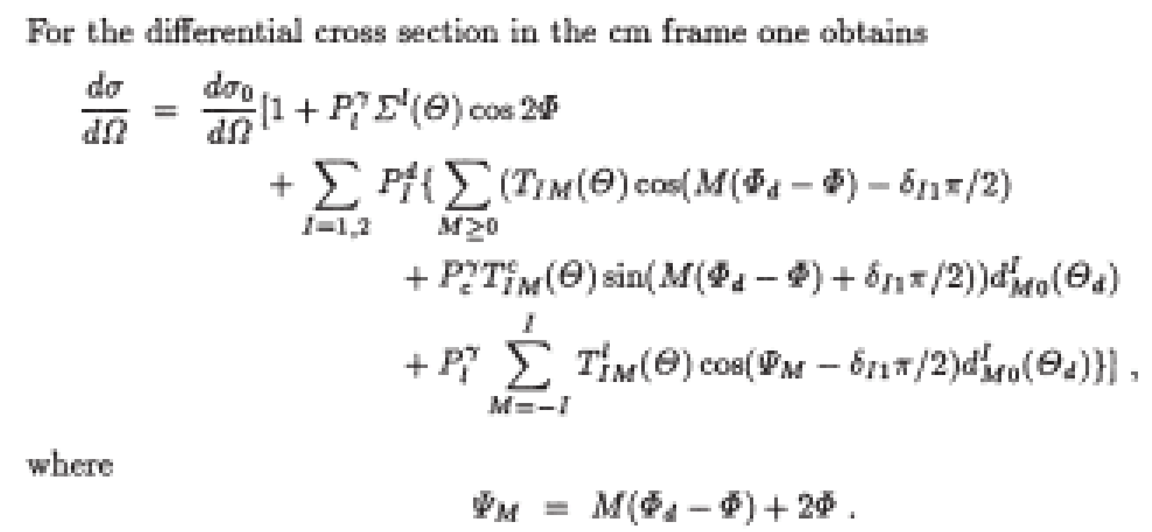
Conventional Background
M. Egorov, A. Fix, Nucl.Phys. A933 (2015) 104-113

- Photoproduction kinematics challenging –> deuteron only detected at forward angles
- Active deuteron target prototype under construction

See talk of B Krusche

Polarization observables - disintegration

12 amplitudes – 23 independent observables

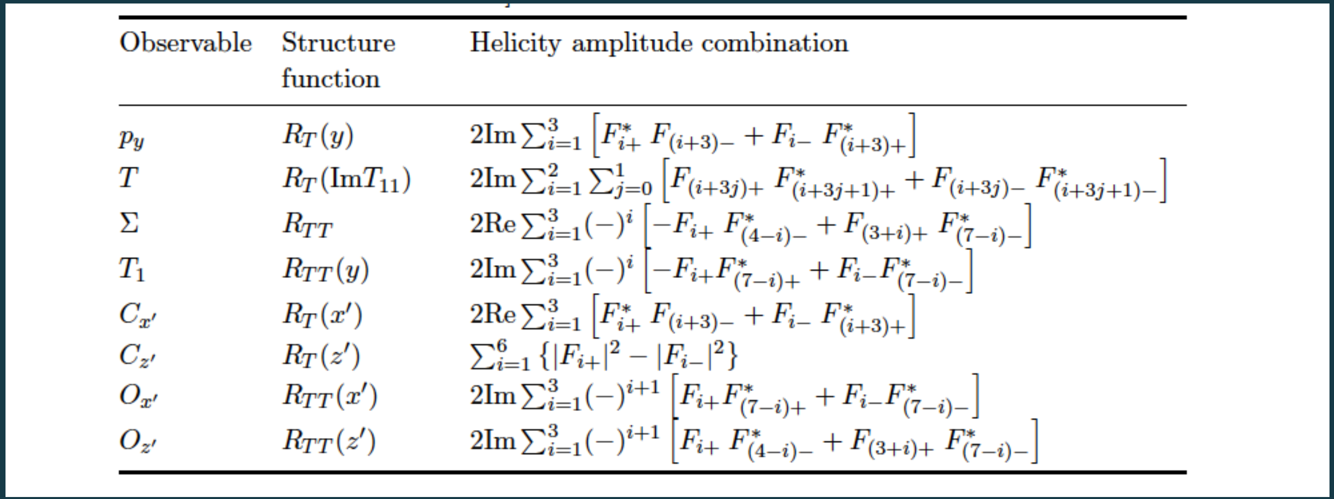


For the differential cross section in the cm frame one obtains

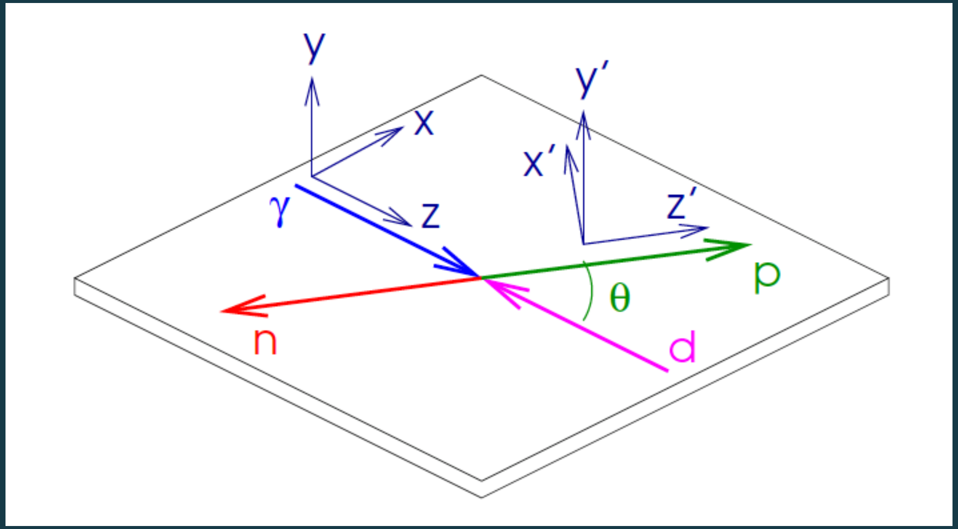
$$\begin{aligned}\frac{d\sigma}{d\Omega} &= \frac{d\sigma_0}{d\Omega}[1 + P_l^\gamma \Sigma^l(\Theta)\cos 2\Phi \\ &\quad + \sum_{I=1,2} P_I^d \{ \sum_{M\geq 0} (T_{IM}(\Theta)\cos(M(\Phi_d - \Phi) - \delta_{I1}\pi/2) \\ &\qquad + P_c^\gamma T_{IM}^c(\Theta)\sin(M(\Phi_d - \Phi) + \delta_{I1}\pi/2))d_{M0}^I(\Theta_d) \\ &\qquad + P_l^\gamma \sum_{M=-I}^{I} T_{IM}^l(\Theta)\cos(\Psi_M - \delta_{I1}\pi/2)d_{M0}^I(\Theta_d)\}] \,,\end{aligned}$$

where

$$\Psi_M = M(\Phi_d - \Phi) + 2\Phi \,.$$

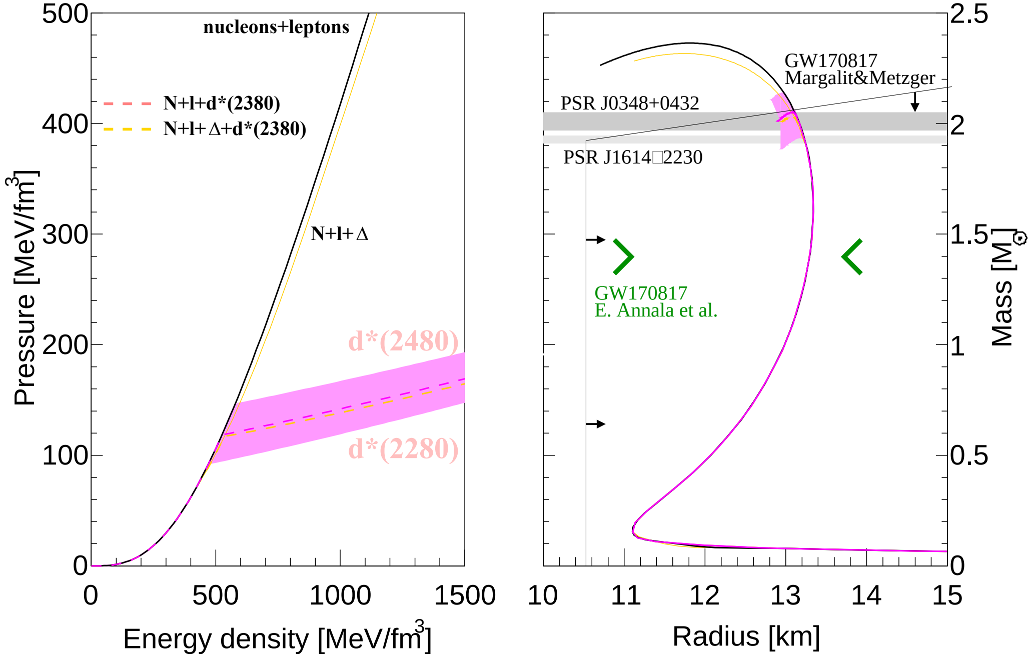


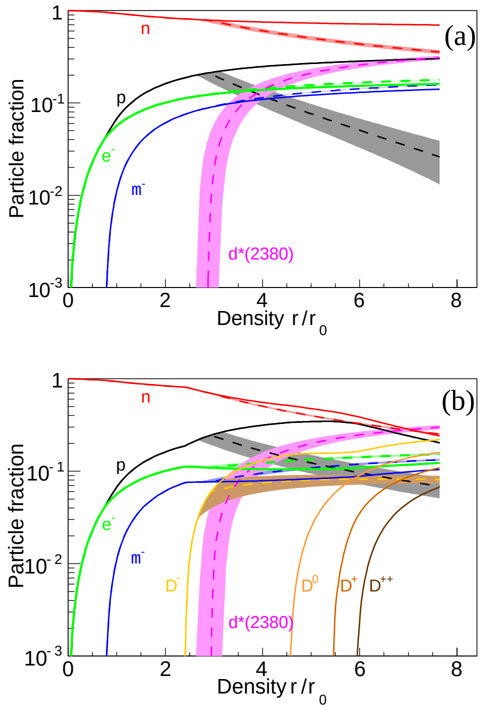
Observable	Structure function	Helicity amplitude combination
p_y	$R_T(y)$	$2\mathrm{Im}\sum_{i=1}^{3}\left[F_{i+}^{*}\,F_{(i+3)-} + F_{i-}\,F_{(i+3)+}^{*}\right]$
T	$R_T(\mathrm{Im}T_{11})$	$2\mathrm{Im}\sum_{i=1}^{2}\sum_{j=0}^{1}\left[F_{(i+3j)+}\,F_{(i+3j+1)+}^{*} + F_{(i+3j)-}\,F_{(i+3j+1)-}^{*}\right]$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



The density frontier – heavy stars and mergers

- d*(2380) may have very significant effect on heavy neutron stars and the physics of mergers. (Vidal, Bashkanov, DPW, Pastore)





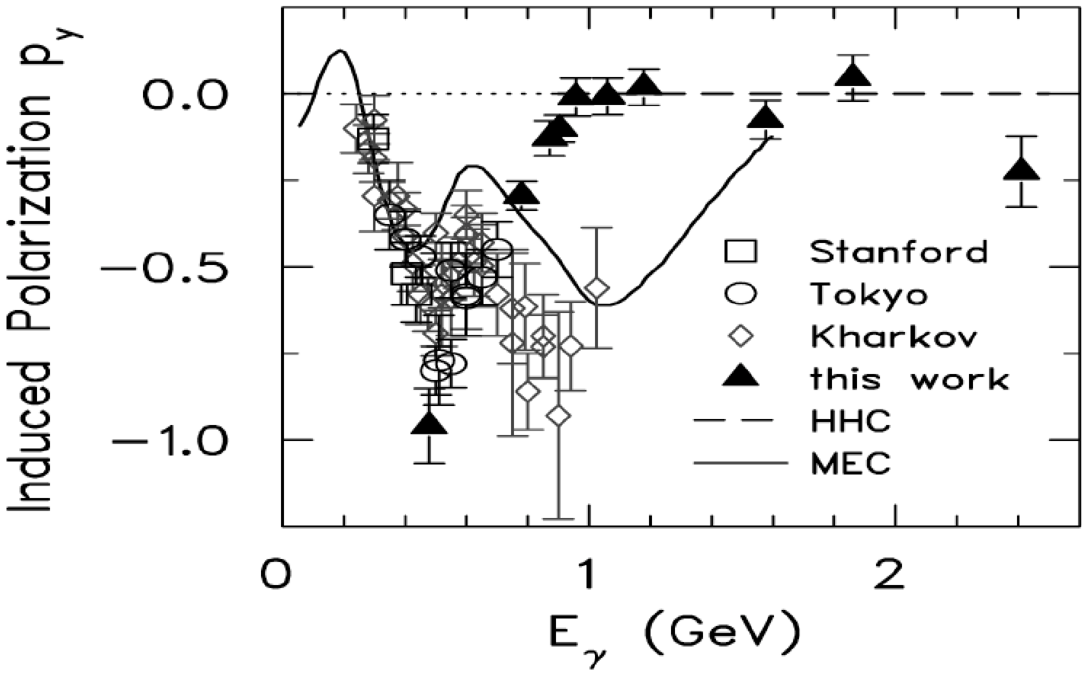


Figure 3: Induced polarization p_y in deuteron photodisintegration at $\theta_{cm} = 90°$. Only statistical uncertainties are shown. The curves are described in the text.

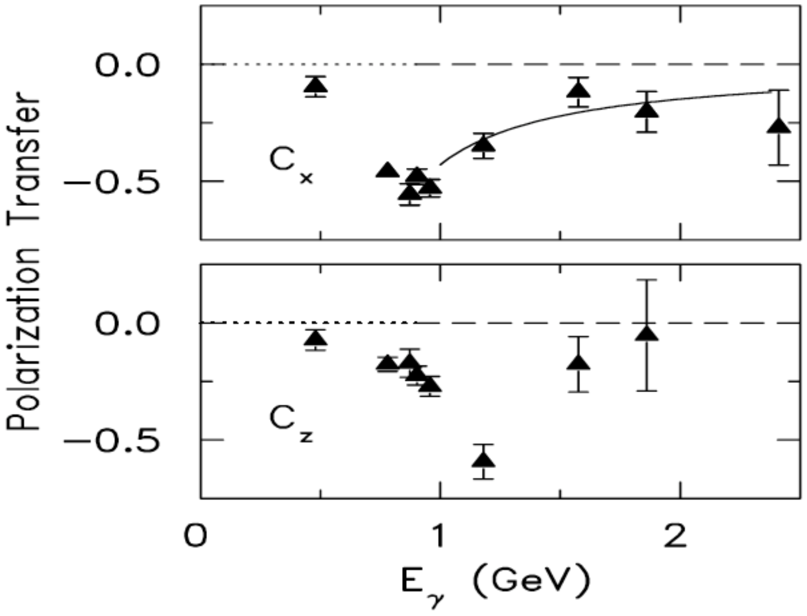


Figure 4: Polarization transfers C_x and C_z at $\theta_{cm} = 90°$. Only statistical uncertainties are shown. The curve is described in the text.

$d^*(2380)$ multipole expansion

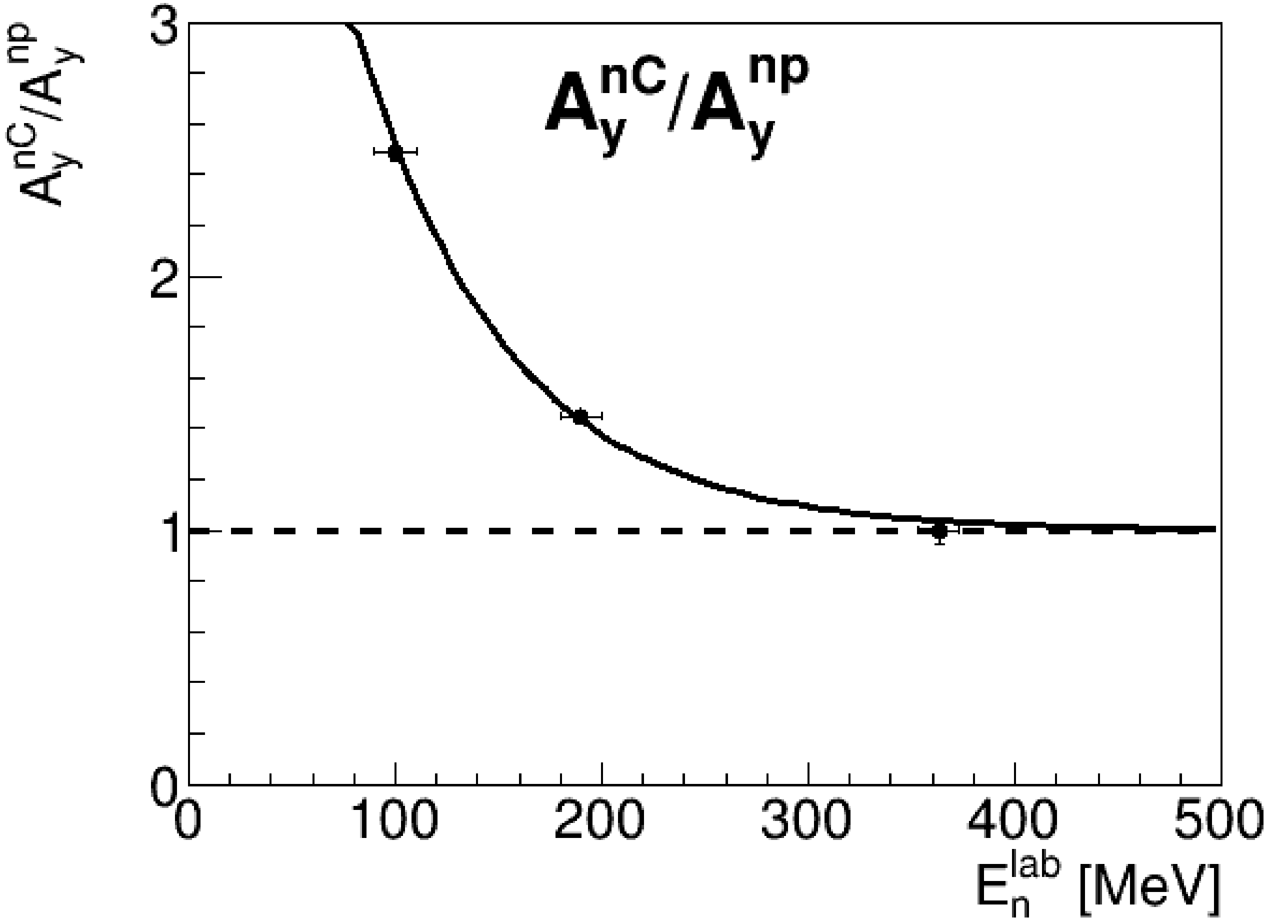
$$\frac{M3}{E2} \sim \frac{\langle\Omega\rangle_{\mathrm{d}\to d^*}}{\langle Q\rangle_{\mathrm{d}\to d^*}} \sim \frac{\langle Q\rangle_{\mathrm{d}\to d^*}\mu_{\mathrm{d}\to d^*}}{\langle Q\rangle_{\mathrm{d}\to d^*}} \sim M_d\omega_\gamma^2\mu_{\mathrm{d}\to d^*}$$

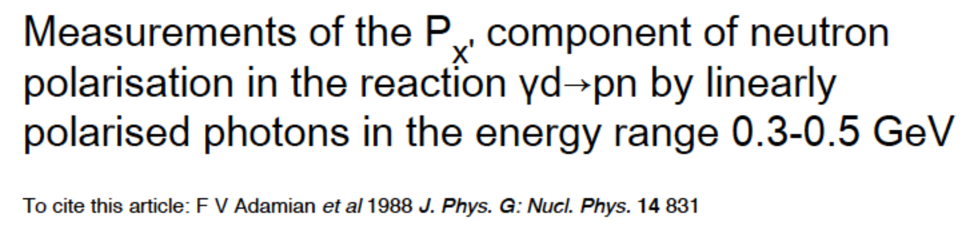
If $\mu_{\mathrm{d}\to d^*}$ is large the $d \to d^*$ M3 transition might be dominant

$$\mu_{d^*} \sim 7.6\mu_N$$

Yubing Dong, Pengnian Shen, Zongye Zhang Phys.Rev. D 97, (2018), no.11, 114002

Neutron A_y on Carbon





Measurements of the $P_{x'}$ component of neutron polarisation in the reaction γd→pn by linearly polarised photons in the energy range 0.3-0.5 GeV

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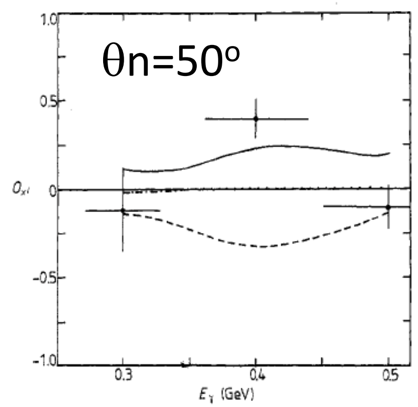
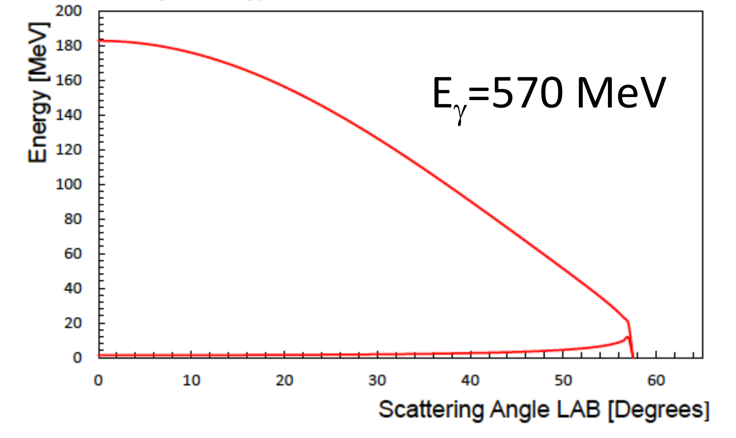


Active deuteron target?

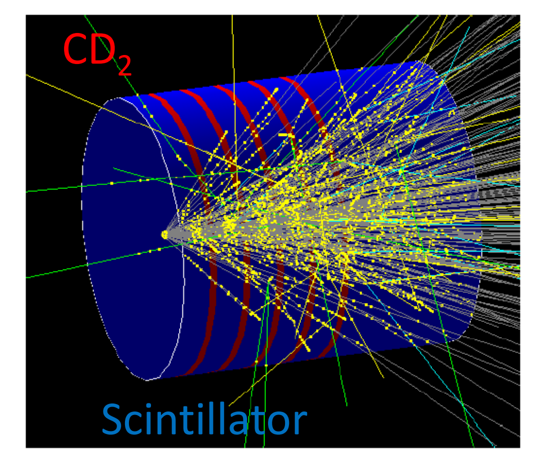


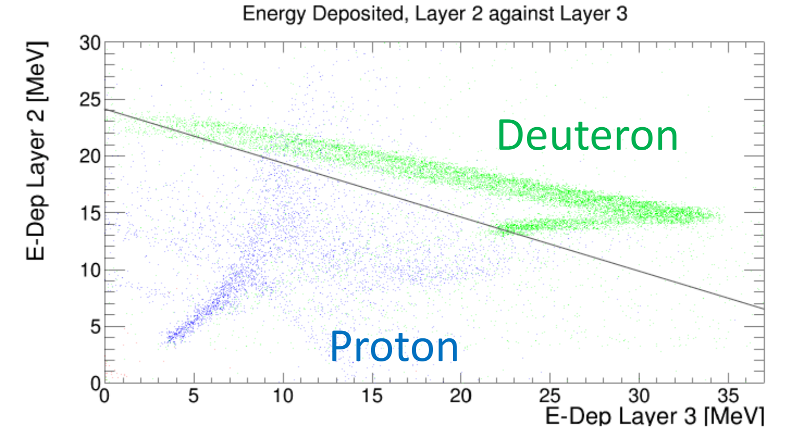
Detecting recoil deuteron in photoproduction of d$\pi\pi$ challenging
-> e.g stops in cryogenic target for much of phase space

Active target prototype developed at UoY

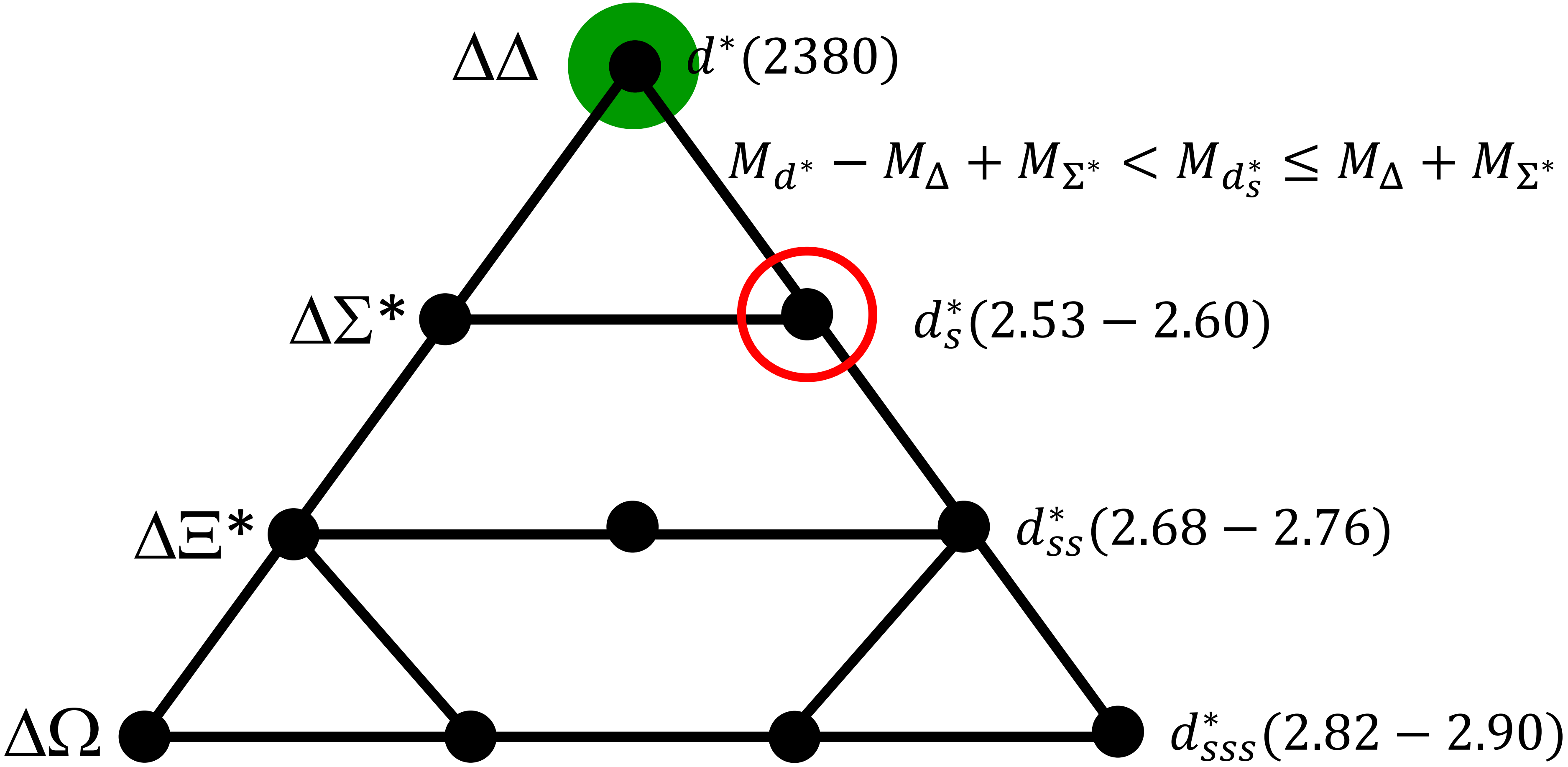
Scintillator pixels interleaved with CD2 target material

Tagging and separation of low energy Deuteron/spectator proton feasible
-> G4 simulation





d*(2380) SU(3) multiplet



ΔΔ $d^*(2380)$

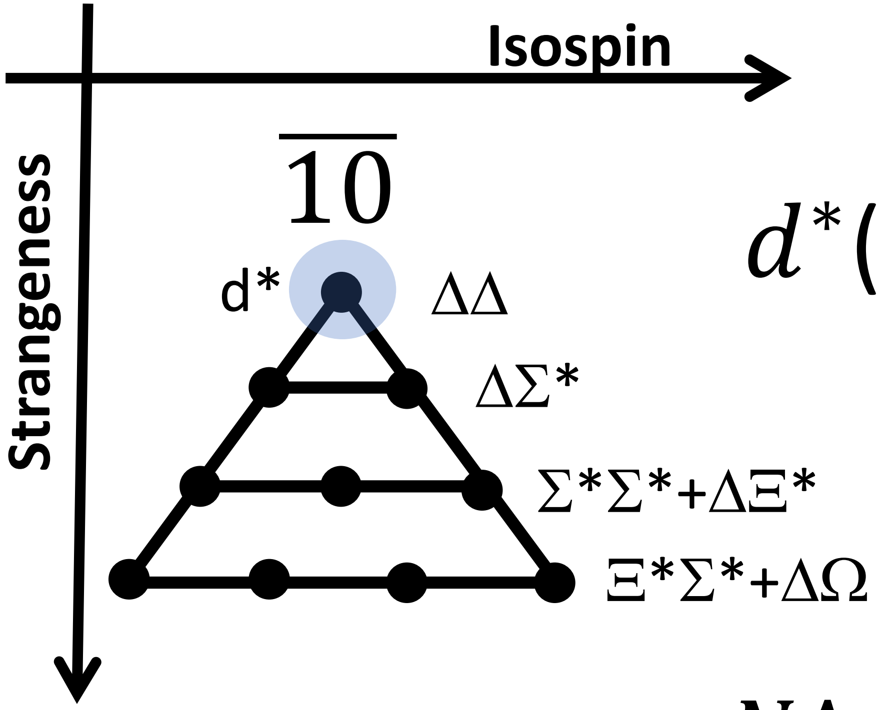
$M_{d^*} - M_\Delta + M_{\Sigma^*} < M_{d_s^*} \leq M_\Delta + M_{\Sigma^*}$

ΔΣ* $d_s^*(2.53 - 2.60)$

ΔΞ* $d_{ss}^*(2.68 - 2.76)$

ΔΩ $d_{sss}^*(2.82 - 2.90)$

Strange Dibaryon decays



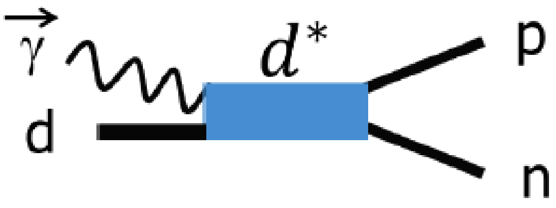
$d^*(2380) \rightarrow pn$

$d^*(2380) \rightarrow \Delta\Delta \rightarrow NN\pi\pi$

$d_s^*(2530\text{-}2600) \rightarrow N\Lambda$

$d_s^*(2530\text{-}2600) \rightarrow \Delta\Sigma^* \rightarrow (N\pi)(\Lambda\pi) \rightarrow NN\pi\pi\pi$

E2 transition (2^+)
M3 transition (3^+)
E4 transition (4^+)



$^3D_3$ **&** $^3G_3$

90% **10%**

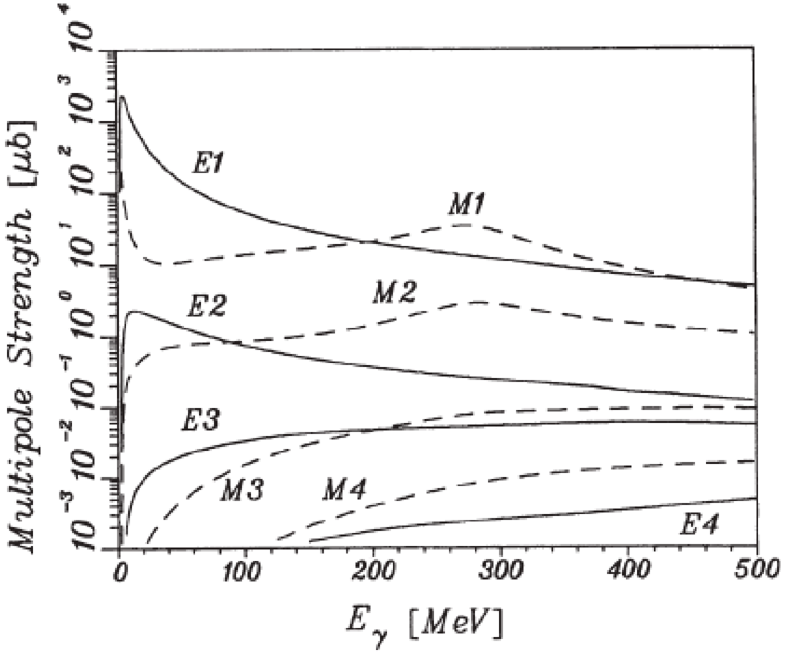
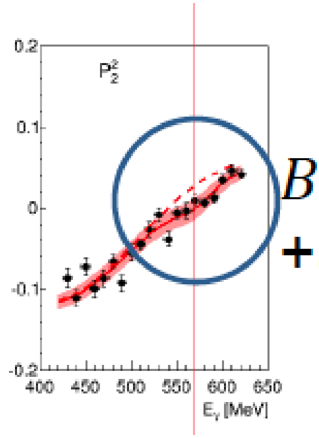


Fig. 7.1.3: Multipole strengths up to $L = 4$ contributing to the total cross section with inclusion of MEC, IC and RC for the Bonn r-space potential.

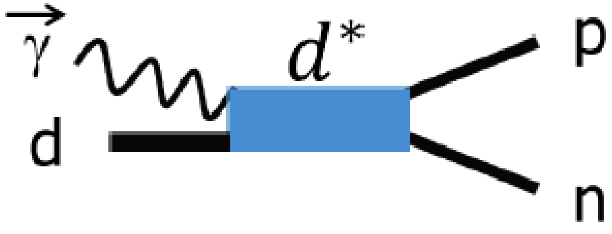
$$\frac{\sigma_\perp - \sigma_\parallel}{\sigma_\perp + \sigma_\parallel} = P_\gamma \boldsymbol{\Sigma} cos2\phi$$

H. Arenhoevel, M. Sanzone “Photodisintegration of the deuteron”

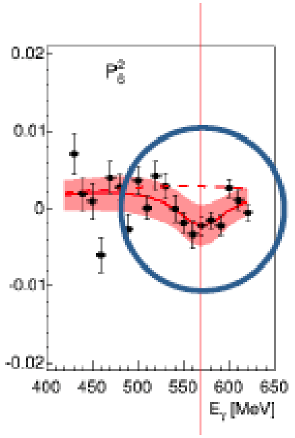
$$\frac{\Sigma(\Theta)\sigma(\Theta)}{\sigma_0} \sim \sum\nolimits_{J=2} B_J P_J^2(cos\Theta)$$



$$B_2 \sim c_1|{}^3D_3(E2)|^2 + c_2|{}^3D_3(M3)|^2 + c_3|{}^3G_3(E2)|^2 + c_4|{}^3G_3(M3)|^2 + \cdots$$

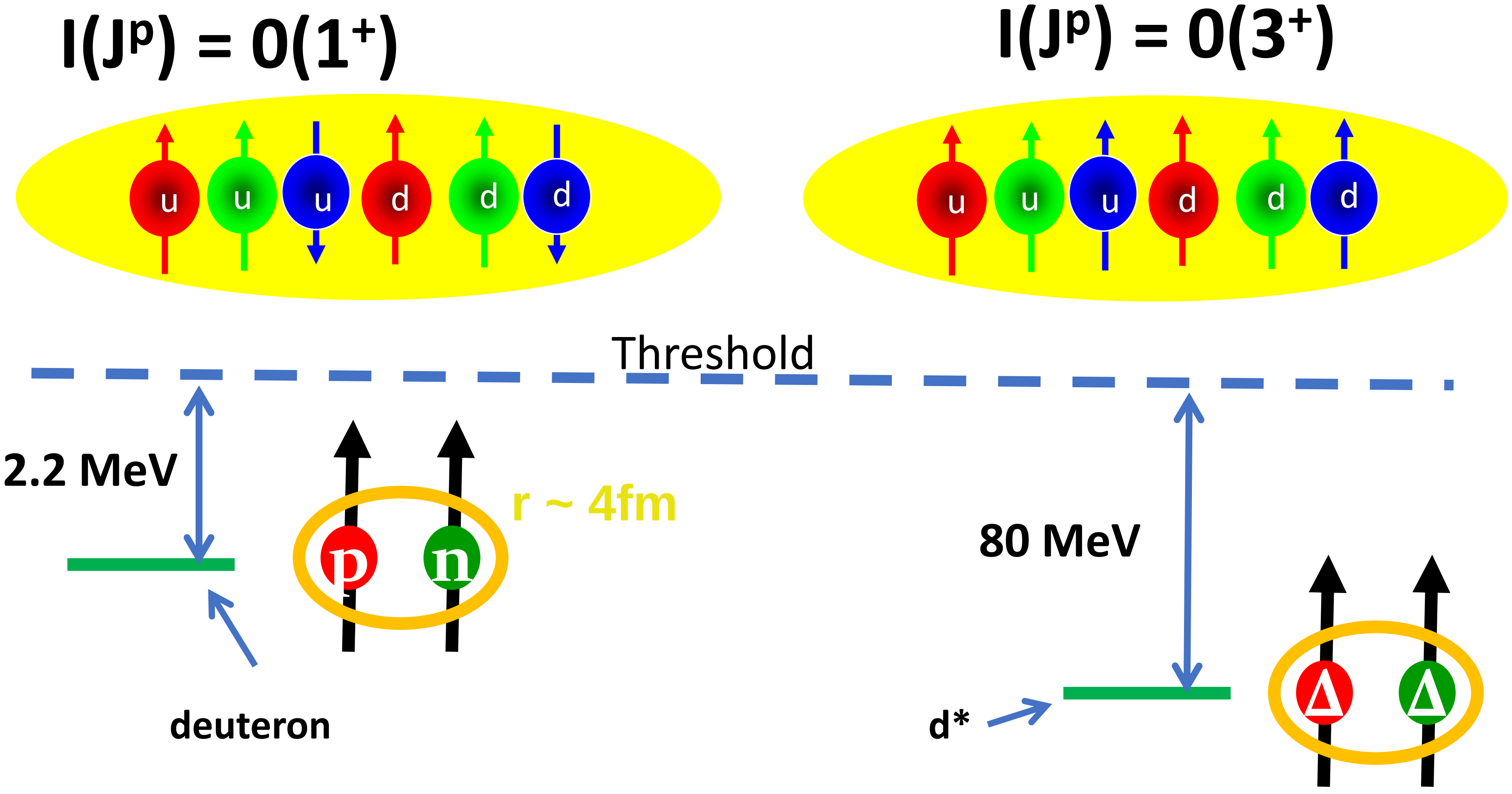


Magnetic M3 transition
might be sizable



$$B_6 \sim d_1|{}^3G_3(M3)|^2 + \cdots$$
$$+d_i|{}^3D_3(M3)||{}^3G_3(M3)|cos\delta_i + \cdots$$
$$+d_j|{}^3D_3(E2)||{}^{2S+1}L \geq 4_J(E4)|cos\delta_j + \cdots$$

What is the d* - Deltaron hypothesis



$I(J^p) = 0(1^+)$

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

Threshold

2.2 MeV

r ~ 4fm

80 MeV

deuteron

d*

But width of d* is 70 MeV – width(ΔΔ)~240 MeV?

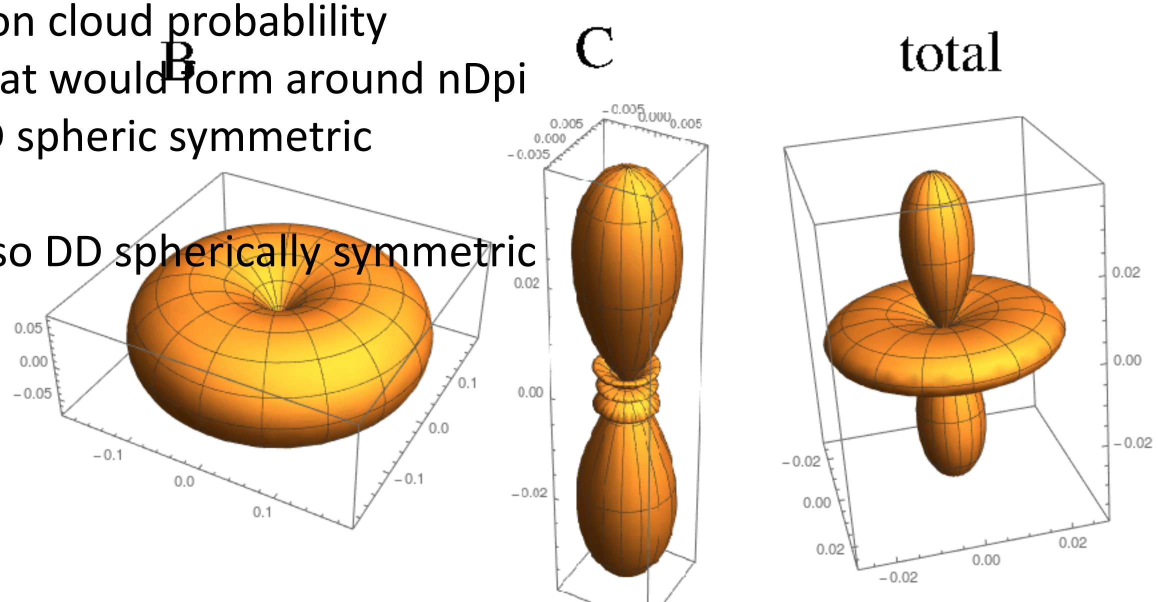
r ~ 1.2fm

& strong decay open (NNππ, NΔπ) ?

d* shape

Pion cloud probablility
That would form around nDpi
nD spheric symmetric

Also DD spherically symmetric



Ndpi
+0.73QD+

Nnpipi
-0.52QD+

Sum

- Estimates made using simple pion cloud model.
- d* made from 2D spend part of time as nucleon plus pion – pure quark DD component, NNpp component and NDpi components
- Enables estimate M3/E2 ratios and ind. strengths
- Indicates d* is spherical (electrical quadropole deformation small)
- However magnectic octupole deformation may be large (don't cancel)
- Octopole moment is quadropole x magnetic dipole
- For 2 cases magnetic dipole moment of oppostite sign (D0npi+ mag moment neut -2mu_b p = 3mu_b
- Nnpi - Dpipi like (but more compact deuteron)NN is like deuteron therefre magnetic moment +1Mu_b. The plot is a Y30 shape octupole.
- More polarization observables (long poalrised target with transeverse beam or transverse target circular beam) , Ox, may help to experimentally determine these ratios M3/E2. This ratio is proportional to mag dipole moment of d* (cancellation)
- M3 prop octupole d* E2 quadropolle d*
- E2 photin spin up target L=1 in same direction 1- + 1+. 1- intrinsic spin 1- from angular givees 2+
- 2+ from E2 plus 1 from deut must be aligned t give 3+
- E4 1-L=1 in same direction gives 4+ E4 transition. 4+E4 and deuteron spin now in OPPOSite direction to get 3+
- Even if d* is not compact the E2 is small because of cancellations. But in this model it is small. Radii of above similar in size to single delta
- Label arbritary units probability density. Prefactors for use in calculation. Product of wavefuncrion with isospin factors.
- Uadropole deformation of delat from pion cloud only, but on lattic shown comes from quarks and has similar size starting rom just quarks.
- Doorwaay d* excited from d-wave of deuteron. Predictions give huge quadropole transition. Real cross section lot smaller. Therefore maybe not d-wave, maybe from 6q compinsnt. 3oom. If 6q get 0.15% so this might be it. 6q still deformed has cloud like nucleon and delta.