Review of recent progress in di-baryonic sector

Mikhail Bashkanov

Task 4.1

Six quark systems

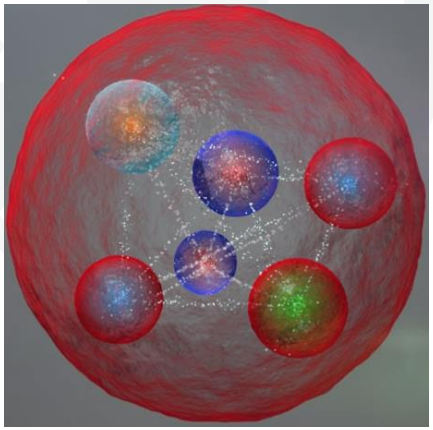
By baryon number:

B=2, $6q$, Dibaryon

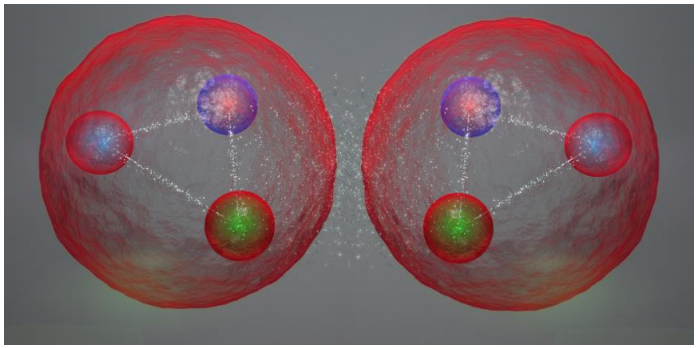
B=0, $3q3\overline{q}$, Baryonium

By internal structure:

Genuine hexaquark



Baryon-baryon molecule



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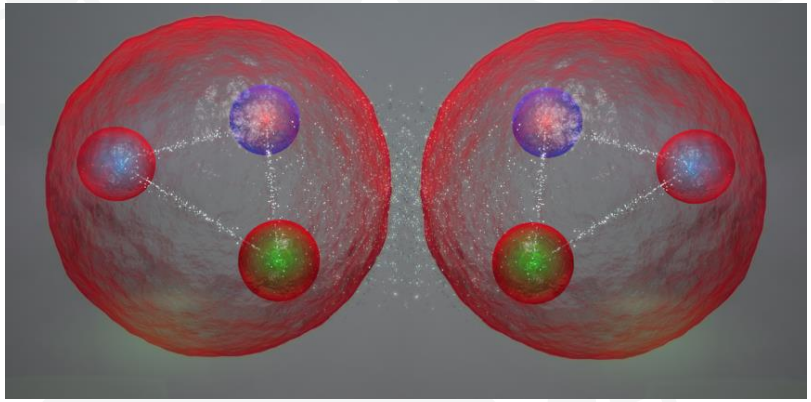
Dibaryons

prehistoric studies

Ancient history

Deuteron – “trivial dibaryon”

proton **neutron**

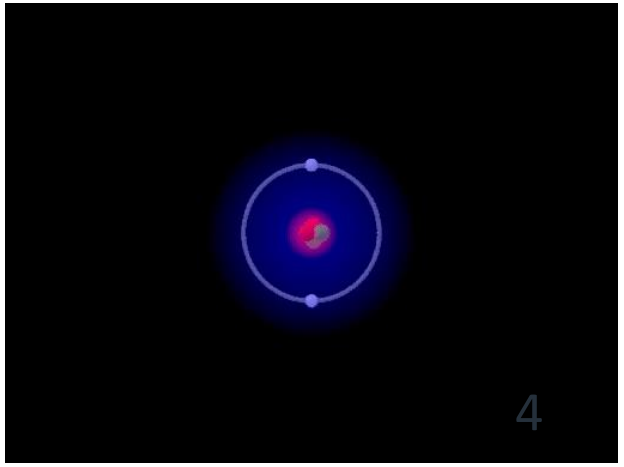


1931 Harold Urey,
Nobel prize 1934

Deuteron phtodisintegration

J. Chadwick, M. Goldhaber
Nature 134, 237, (**1934**)
„Disintegration of the Diplon by γ-Rays“

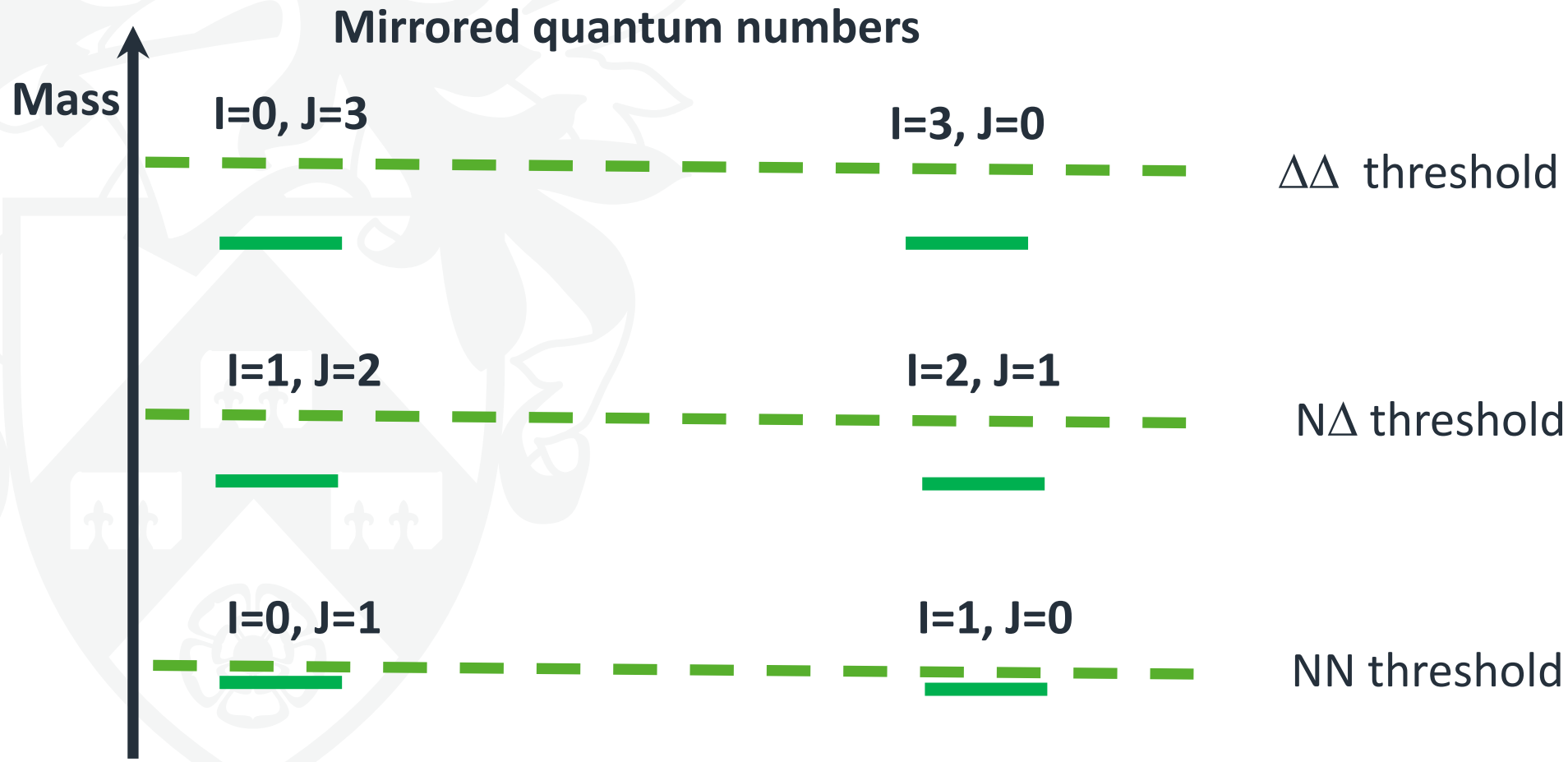
The first search for the excited deuteron



Quark era

Six non-strange dibaryons

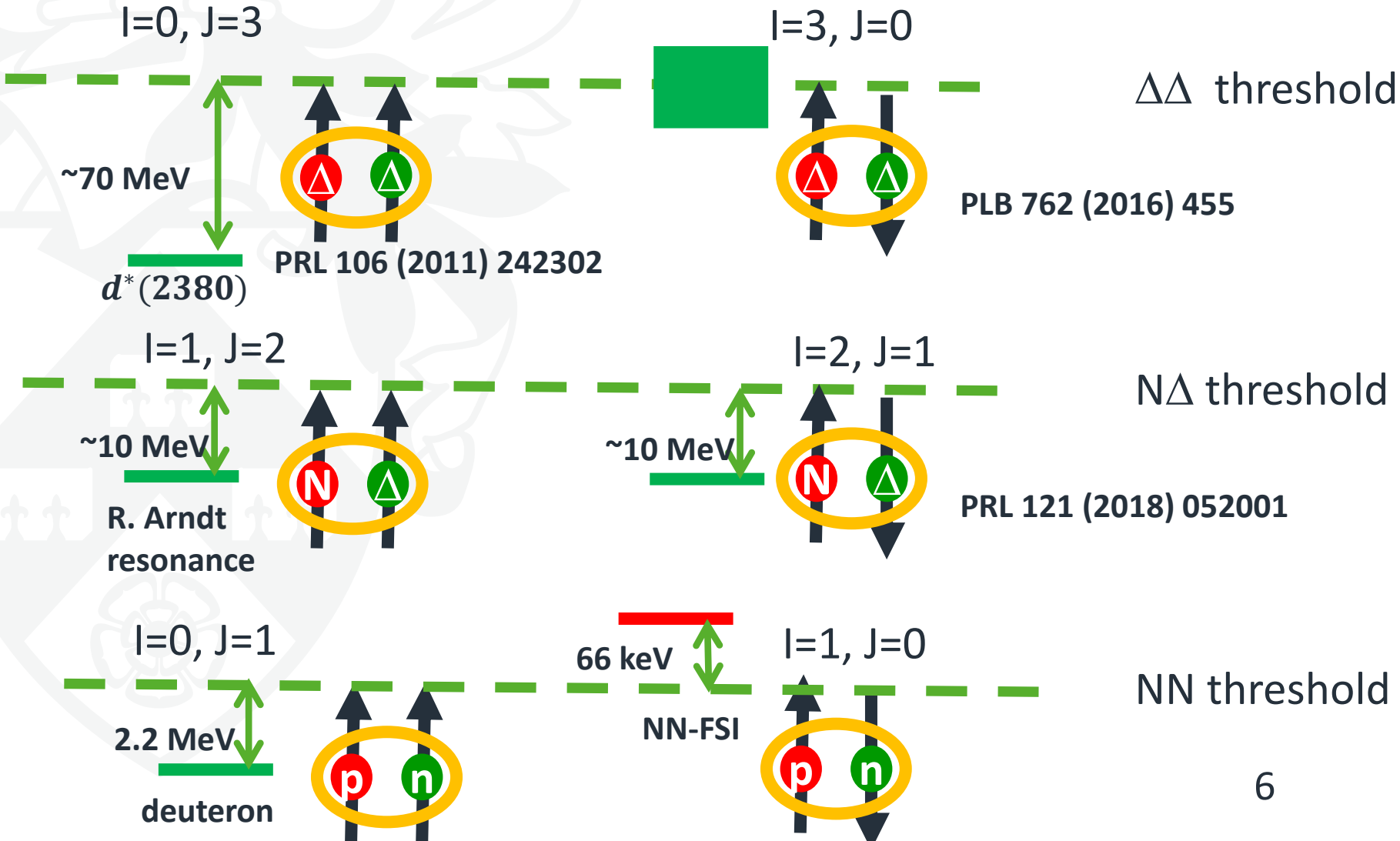
F. J. Dyson, N.-H. Xuong, Phys. Rev. Lett. 13, 815 (**1964**).



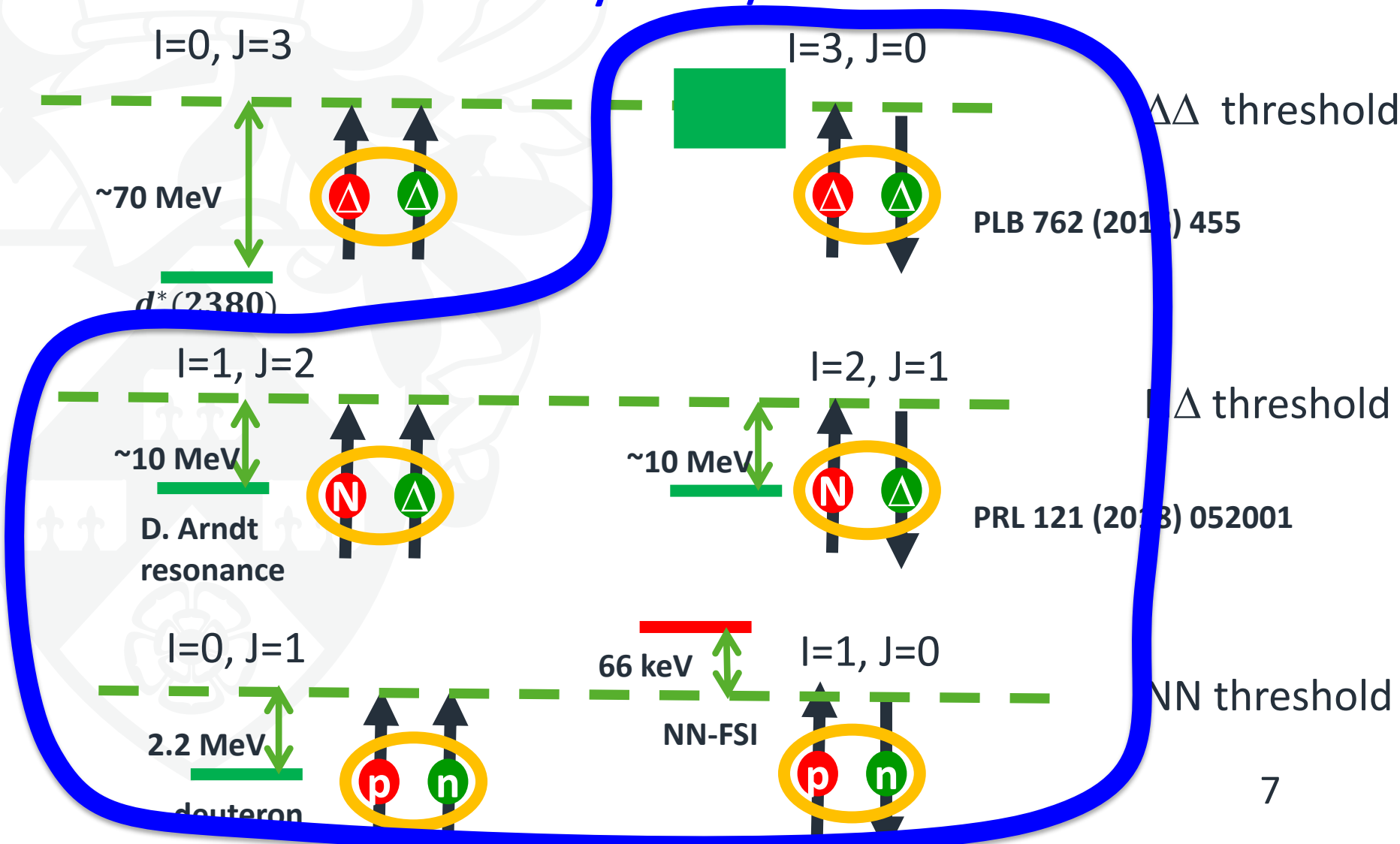
Quark era

Six non-strange dibaryons

F. J. Dyson, N.-H. Xuong, Phys. Rev. Lett. 13, 815 (**1964**).

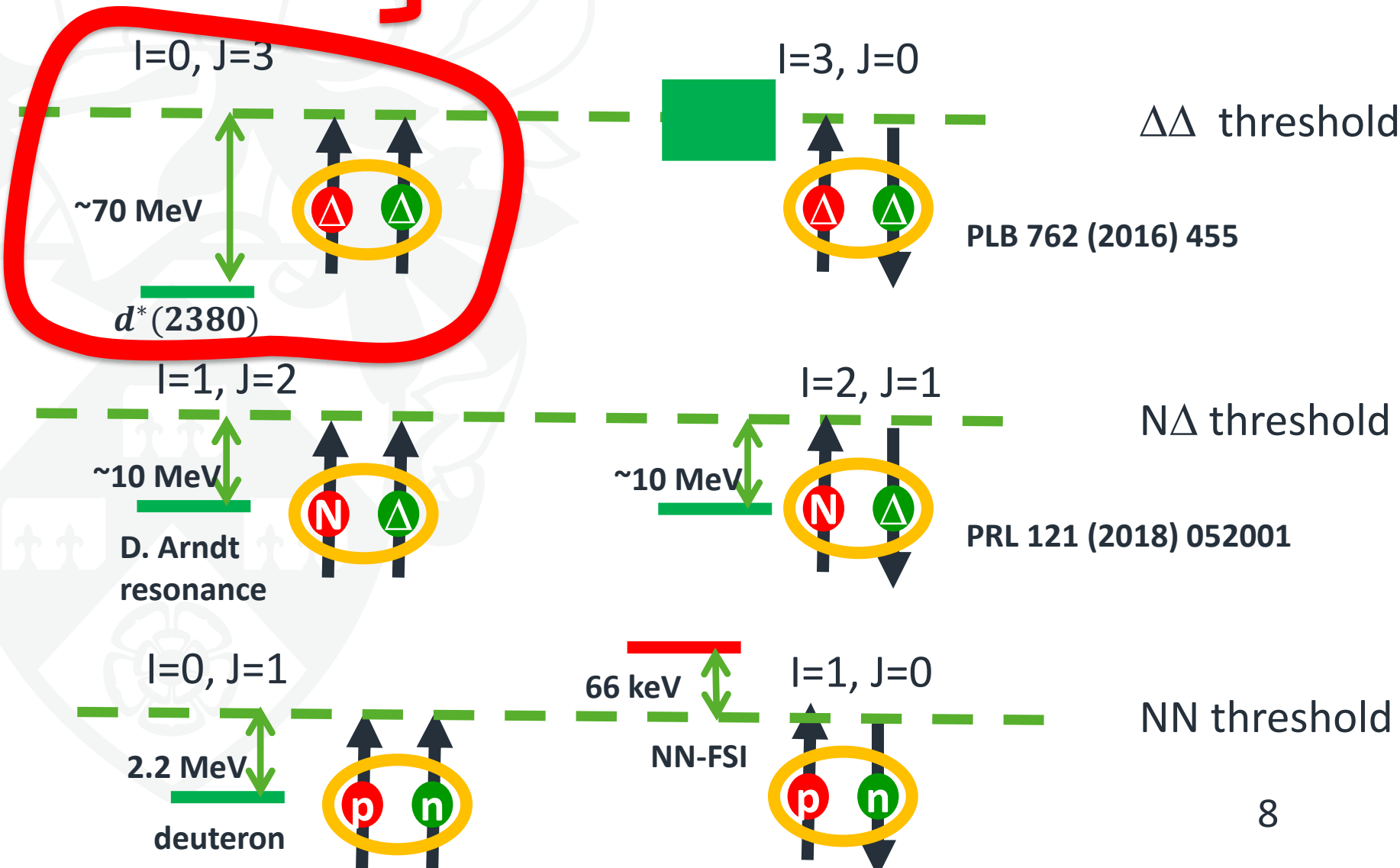


Quark era


Loosely Bound/Unbound == Molecular
I=0, J=3
I=3, J=0
ΔΔ threshold
~70 MeV
PLB 762 (201) 455
d*(2380)
I=1, J=2
I=2, J=1
NΔ threshold
~10 MeV
~10 MeV
D. Arndt
resonance
PRL 121 (201) 052001
I=0, J=1
66 keV
I=1, J=0
NN threshold
2.2 MeV
NN-FSI
deuteron

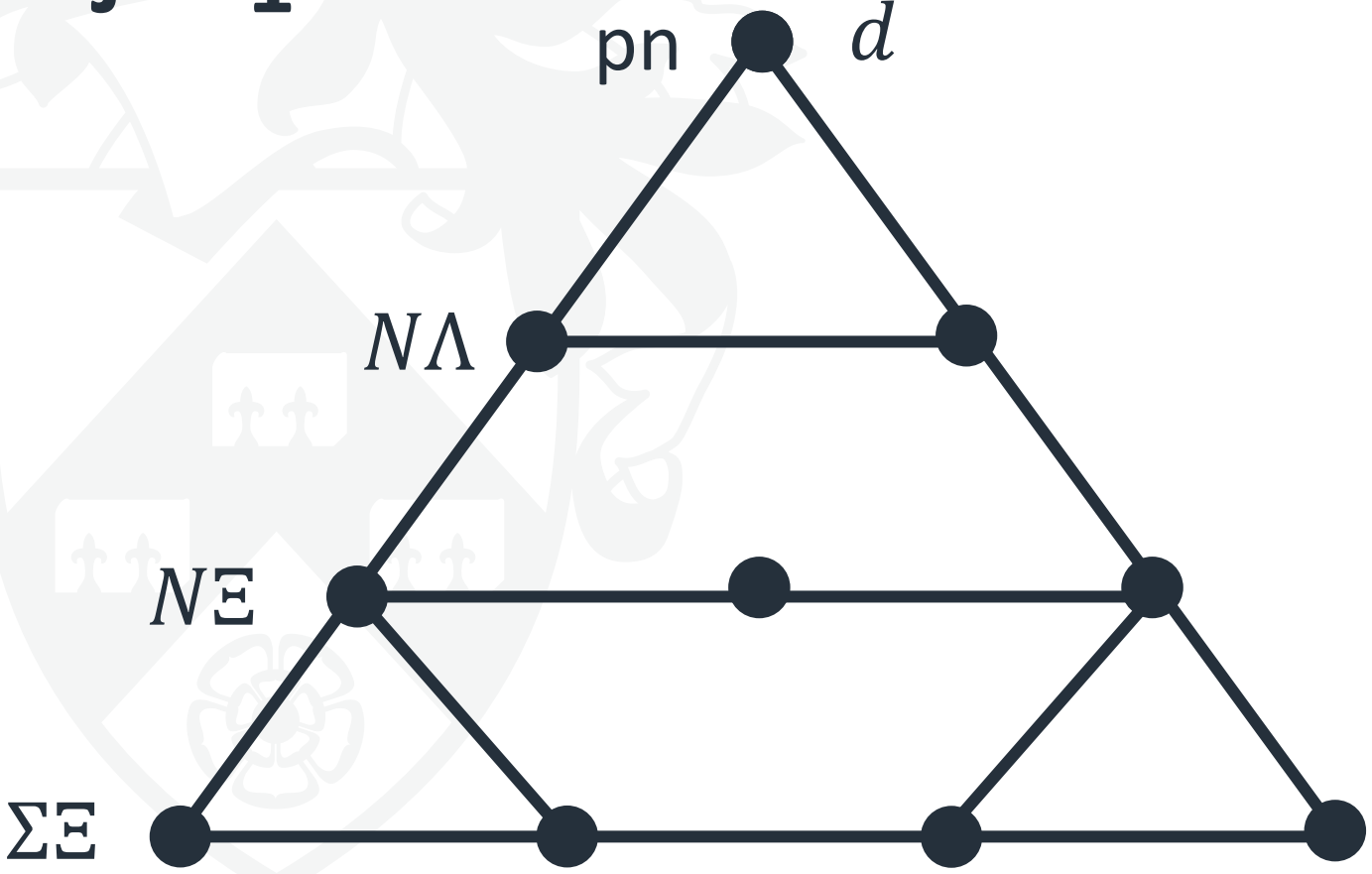
Quark era

Strongly Bound
Far from thresholds
} **potential Hexaquark**

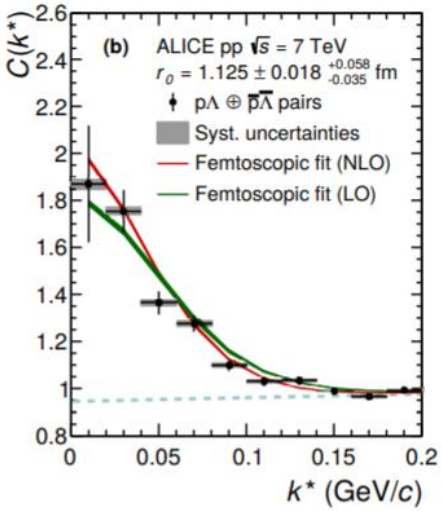


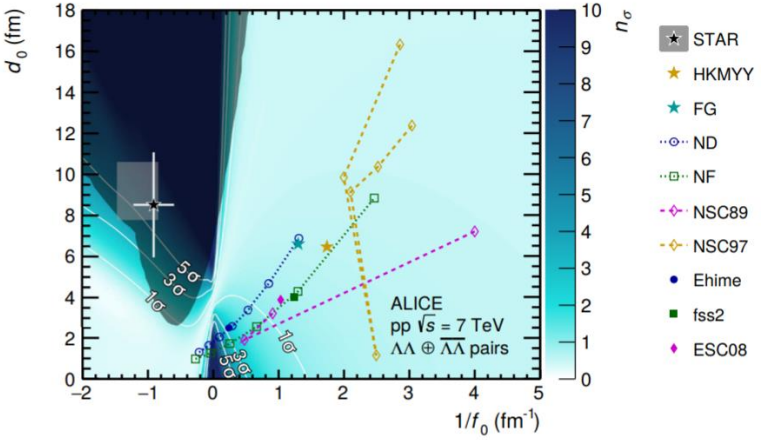
Deuteron SU(3) multiplet

$J^p = 1^+$

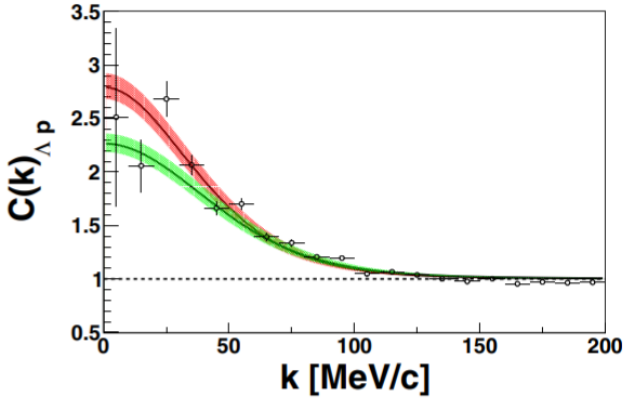


$N\Lambda$ from heavy ions



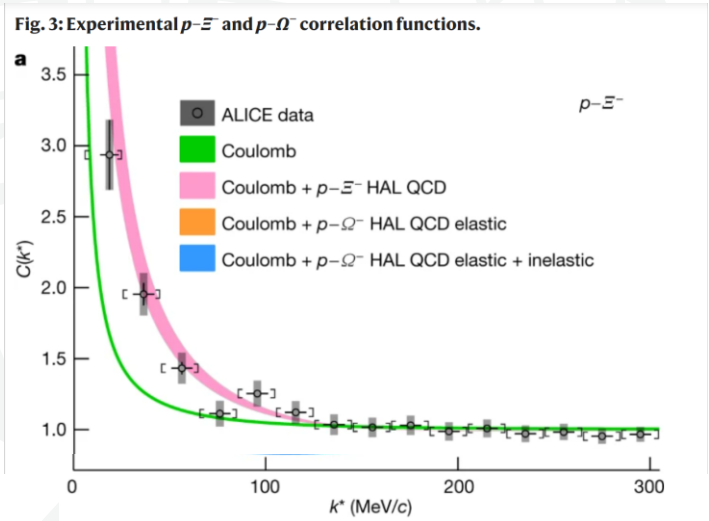


ALICE: PRC **99**, 024001

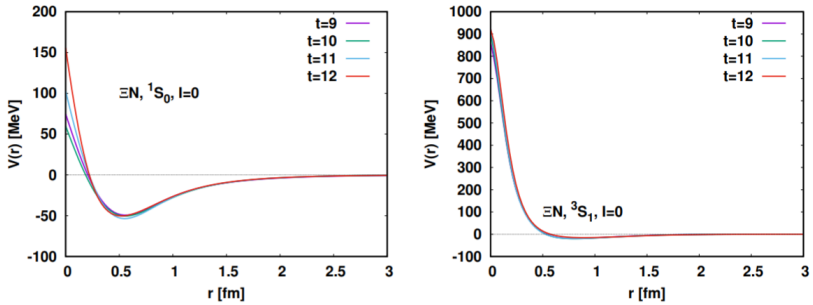


Hades: PRC 94, 025201 (2016)

$p\Xi^-$



ALICE: Nature **588**, 232–238 (2020)



HAL QCD: Nucl.Phys.A 967 (2017) 856

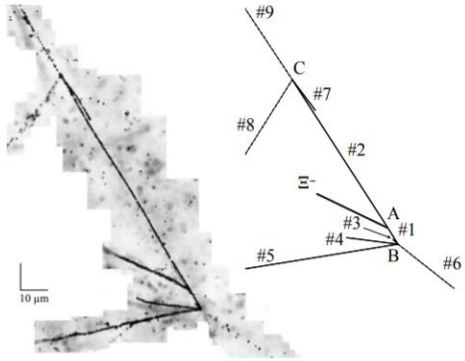


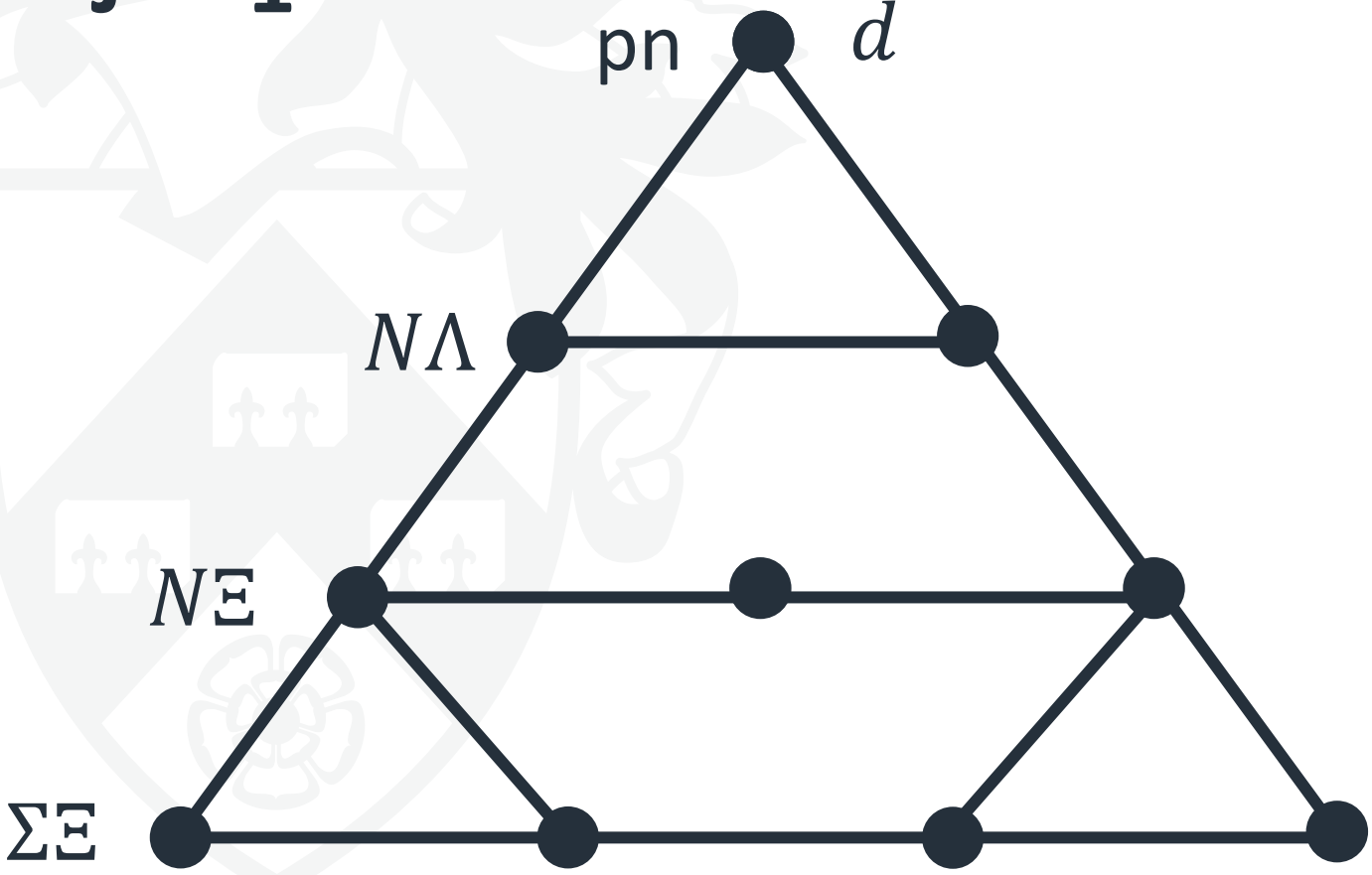
FIG. 1. Superimposed image and schematic drawing of the IBUKI event.

J-PARC: PRL **126**, 062501, 2021

$\Xi^- \, {}^{14}N \rightarrow {}^{10}_{\Lambda}Be\,{}^{5}_{\Lambda}He$

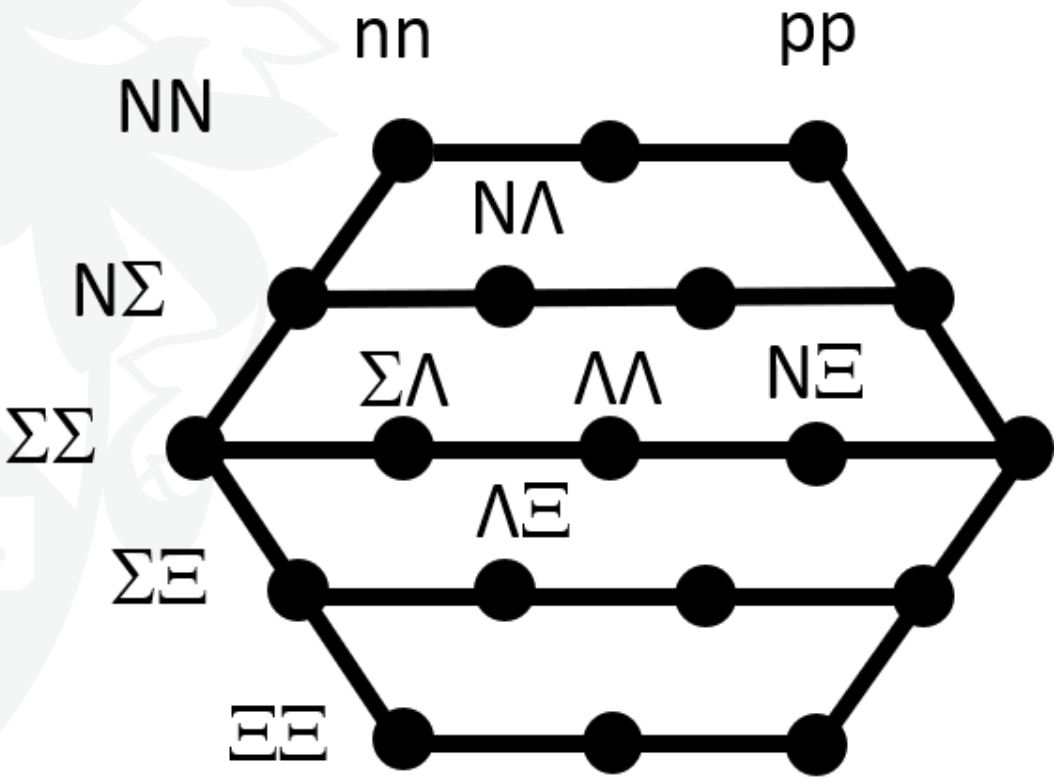
Deuteron SU(3) multiplet

$J^P = 1^+$



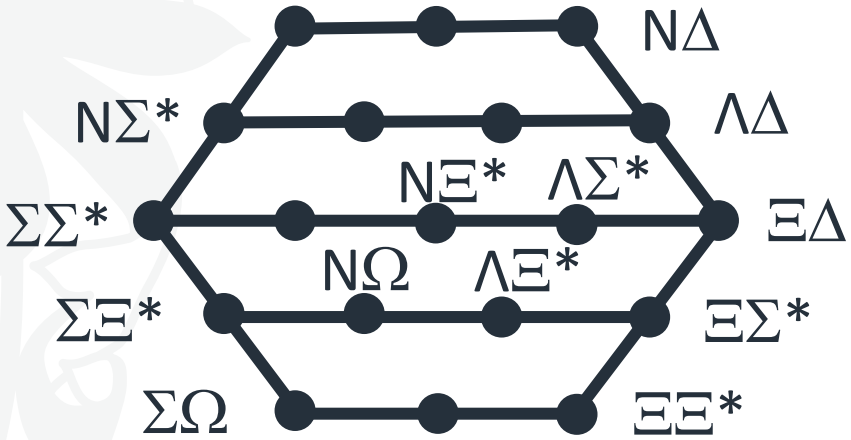
“Demon” Deuteron SU(3) multiplet (27-plet)

$J^p = 0^+$

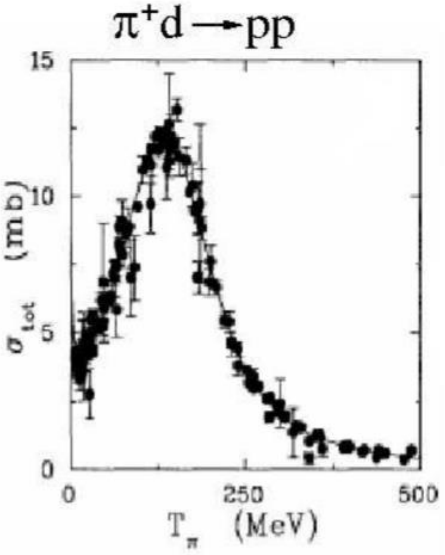


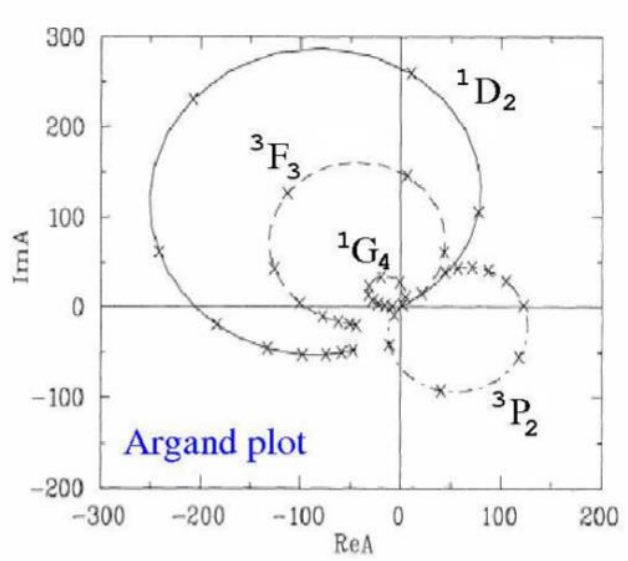
$N\Delta$ multiplet (27-plet)

$J^P = 2^+$



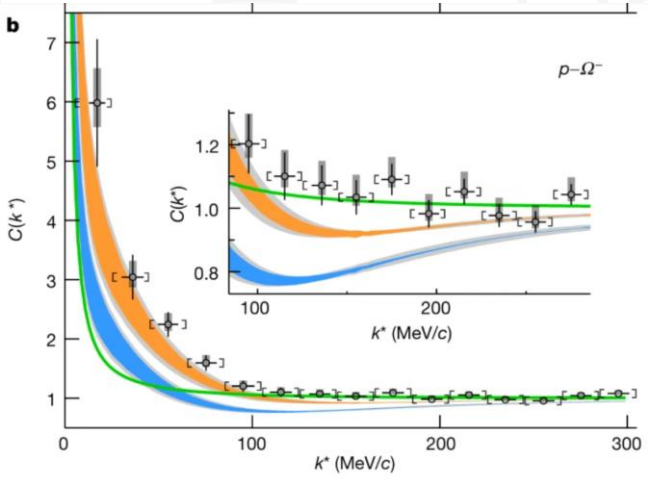
$N\Delta$ R. Arndt resonance

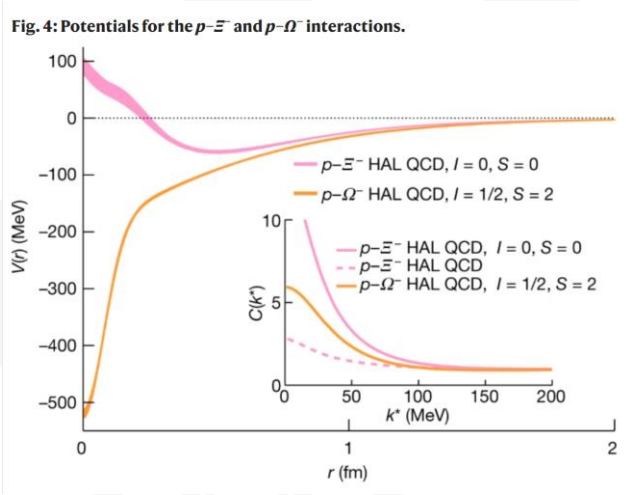


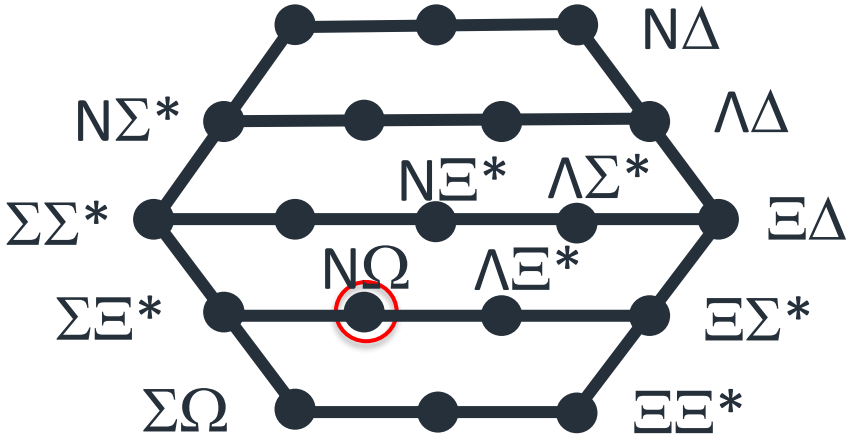


Binding energy ~10 MeV binding energy

$N\Omega$ from heavy ions





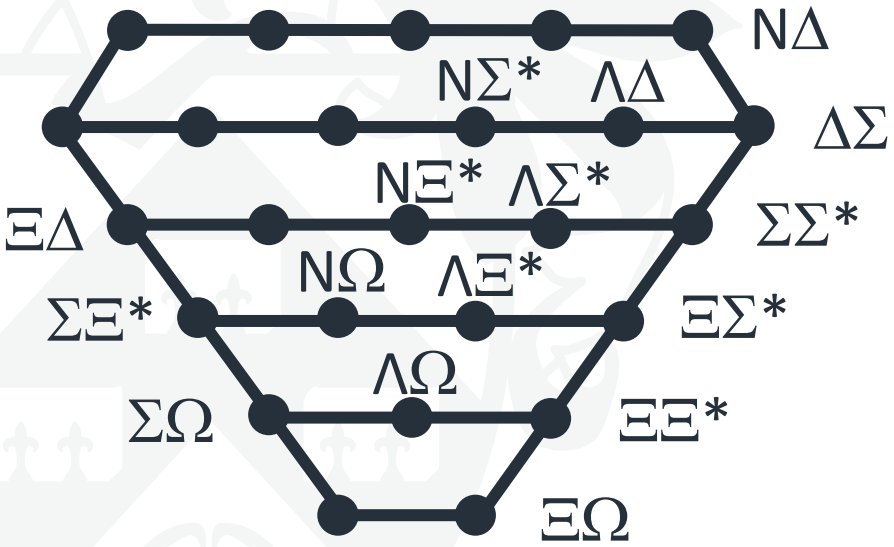


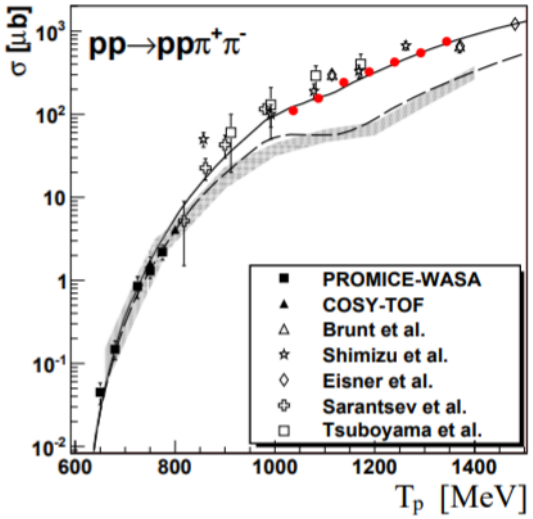
2.5 MeV binding energy (Coulomb+strong)

ALICE: Nature **588**, 232–238 (2020)

$N\Delta$ multiplet (35-plet)

$J^p = 1^+$



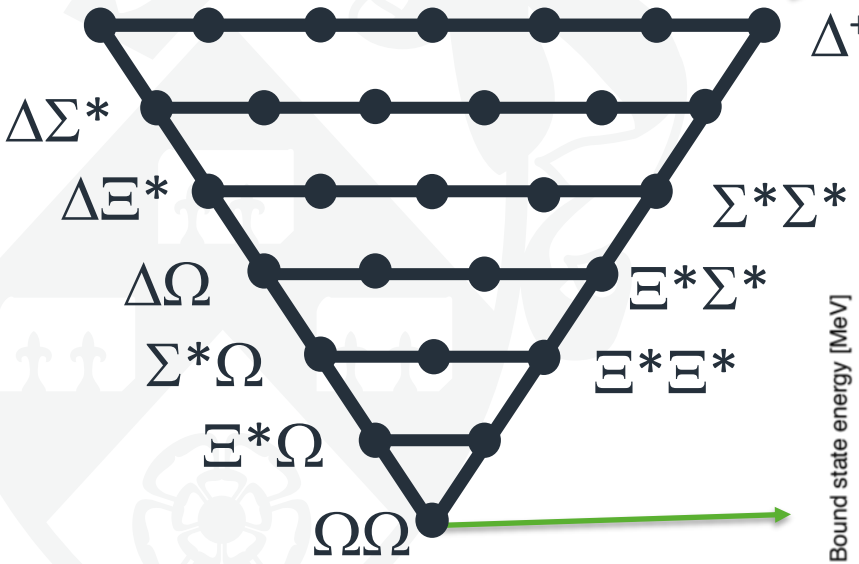


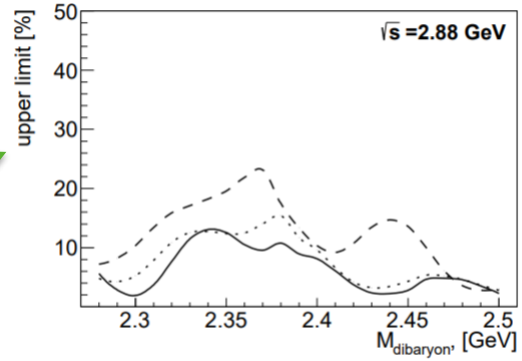
Wasa-at-Cosy: PRL **121**, 2018

Binding energy ~10 MeV binding energy

ΔΔ multiplet (28-plet)

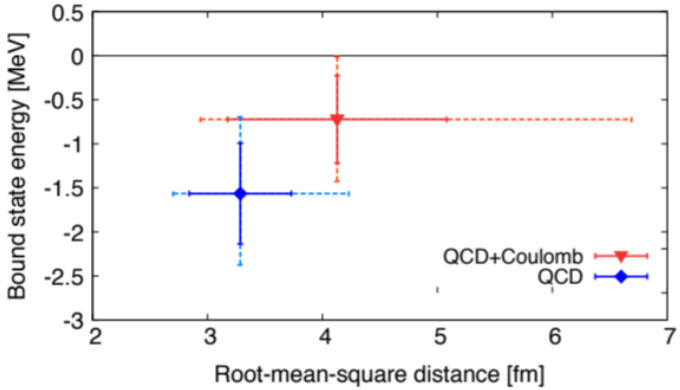
$J^P = 0^+$





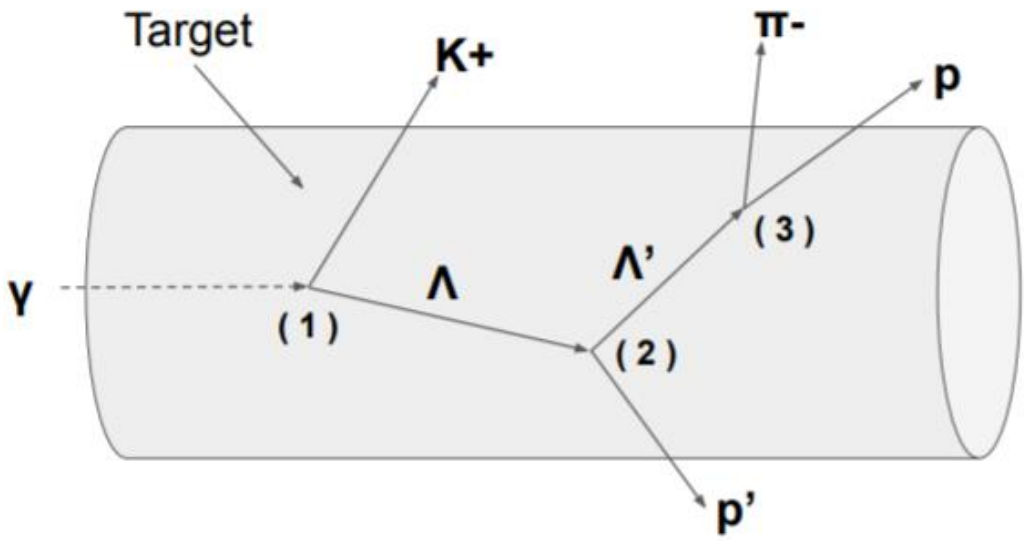
$\Delta^{++}\Delta^{++}$ Wasa-at-Cosy: PLB762, (2016), 455

Either slightly bound or unbound



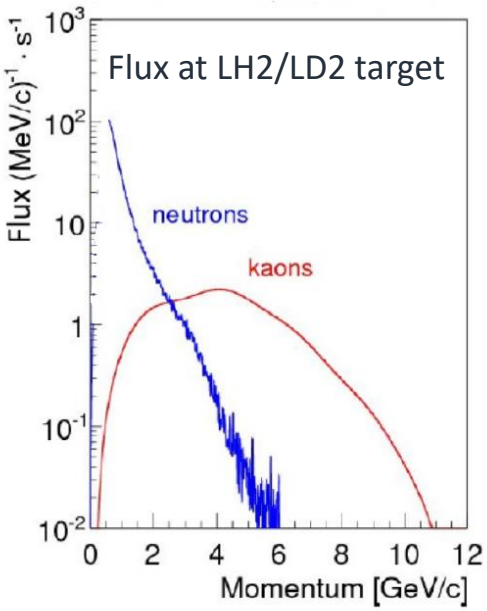
HAL QCD: PRL **120**, 212001, 2018

New methods

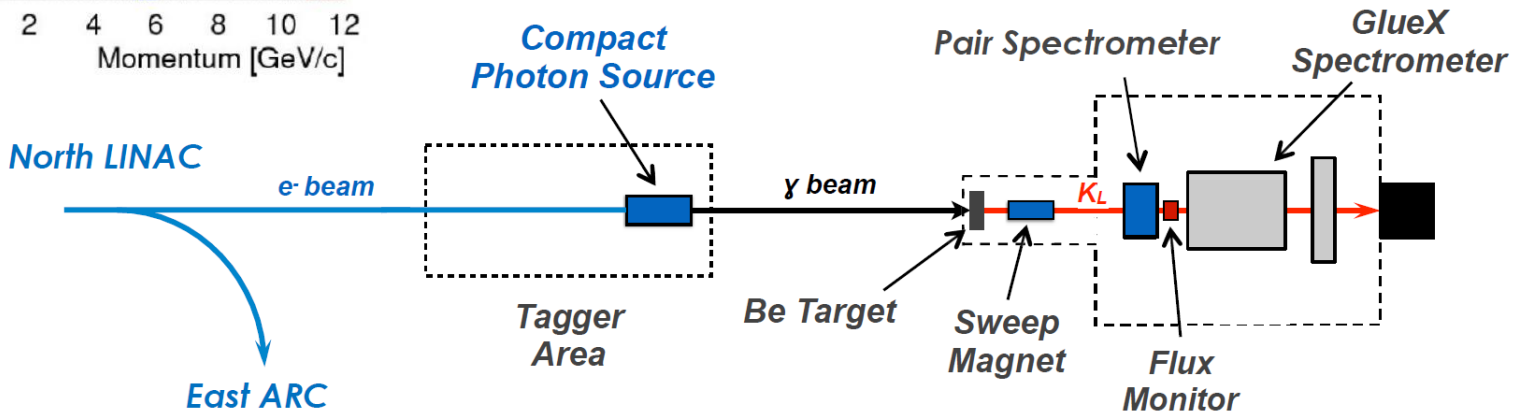


arXiv:2108.03134, see N. Zachariou talk for the details

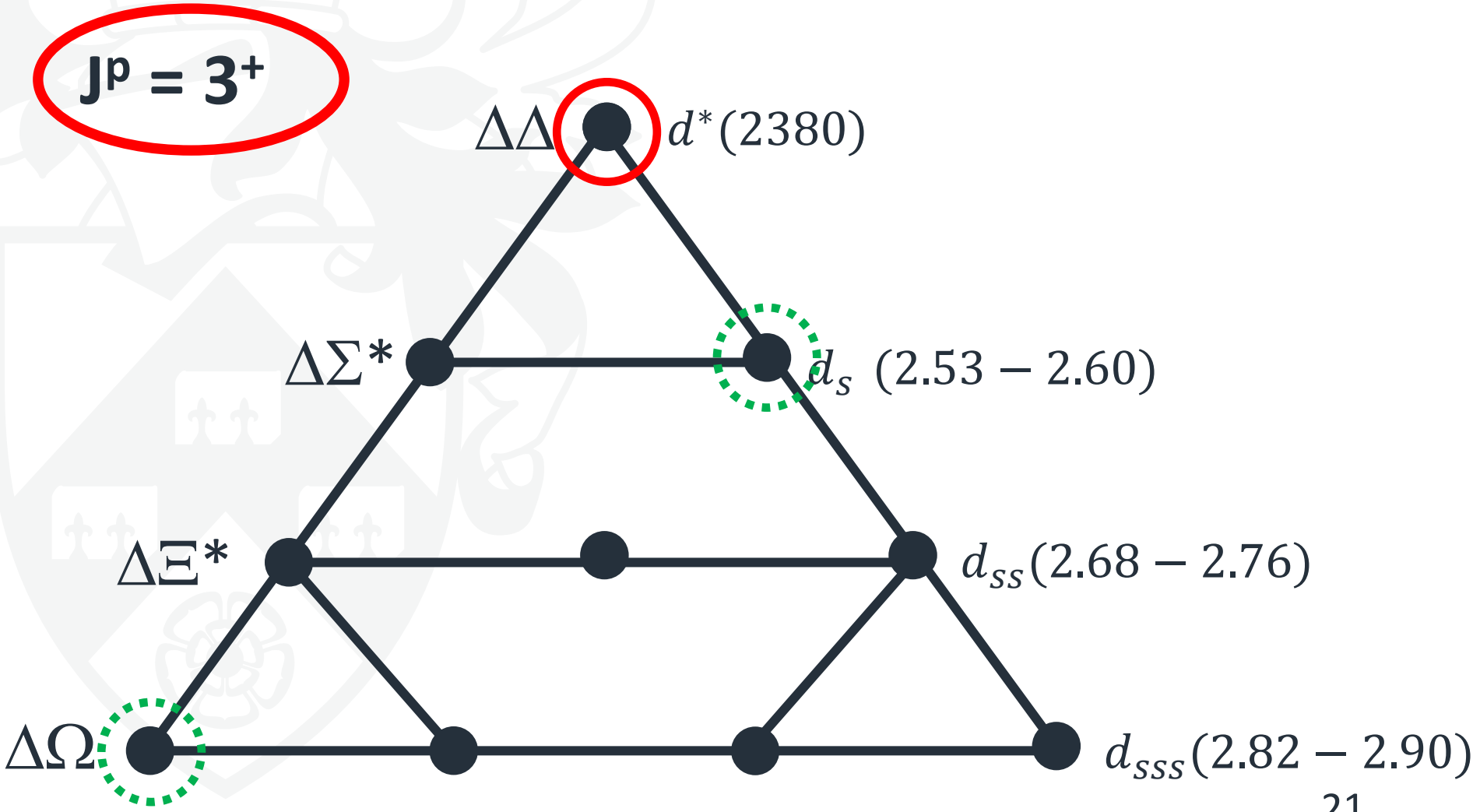
New facilities



Hyperon-Nucleon scattering at KLF
arXiv:2008.08251



$d^*(2380)$ hexaquark SU(3) multiplet



$d^*(2380)$ size

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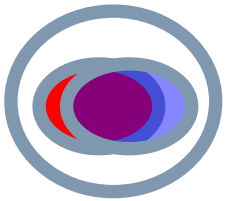
Deuteron

Deltaron



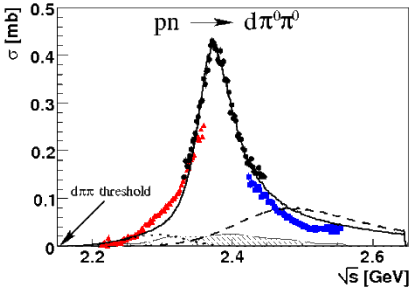
$$\text{size} \sim \frac{1}{\sqrt{mE_B}}$$

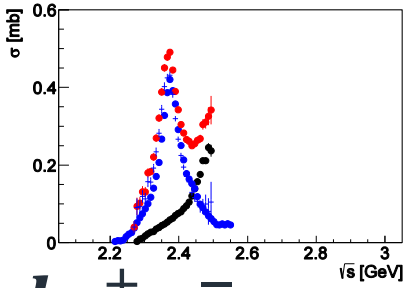
$$\frac{Deltaron}{Deuteron} = \frac{\sqrt{m_N E_{Deuteron}}}{\sqrt{m_\Delta E_{d^*}}} \sim \frac{1}{7}$$

$$R_{deuteron} \sim 2.2\ fm \Rightarrow R_{\Delta\Delta} \sim 0.3\ fm$$

Nearly complete overlap

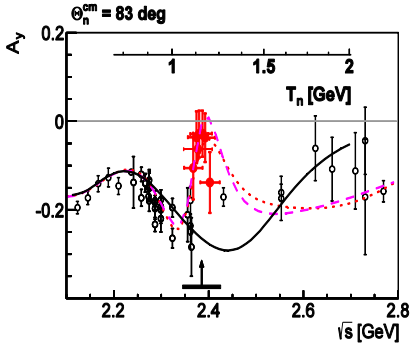
Pathway to discovery



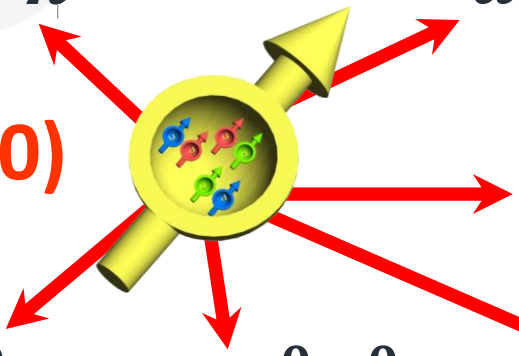


$d\pi^0\pi^0$

$d\pi^+\pi^-$



d*(2380)

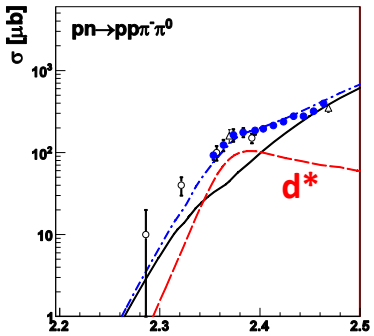


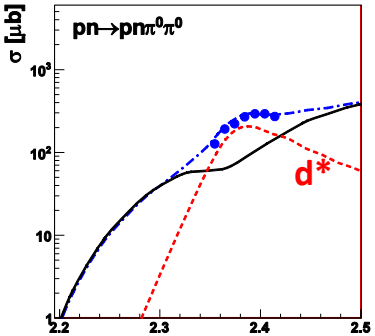
pn

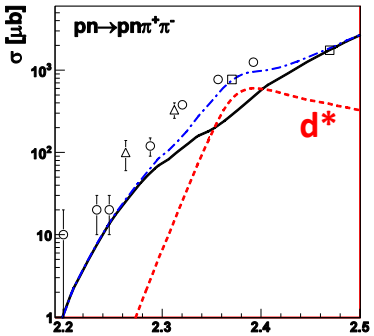
$pp\pi^-\pi^0$

$pn\pi^0\pi^0$

$pn\pi^+\pi^-$







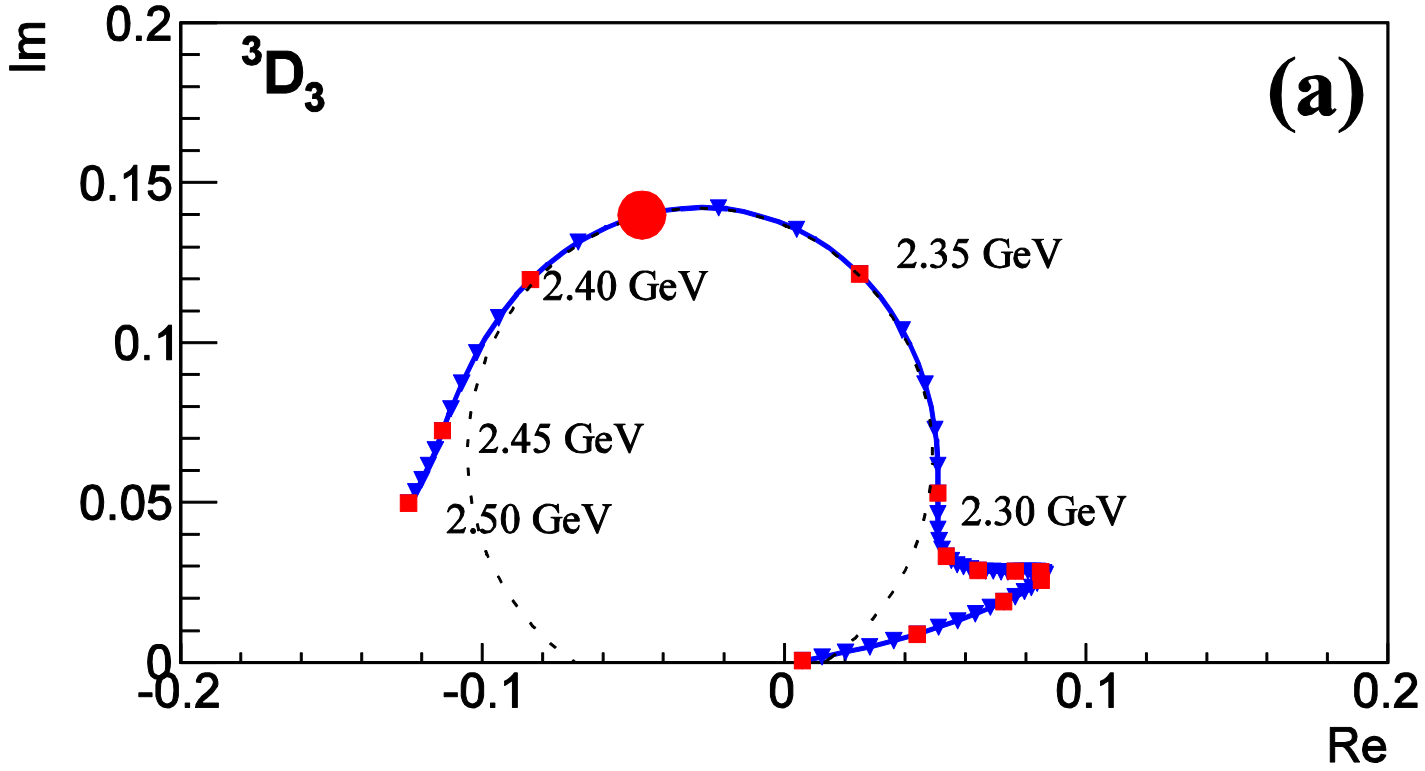
$d^*(2380)$ decay branches

d^* decay channel	Branching ratio, %
pn	12(3)
$d\pi^0\pi^0$	14(1)
$d\pi^+\pi^-$	23(2)
$pn\pi^+\pi^-$	30(5)
$pn\pi^0\pi^0$	12(2)
$pp\pi^0\pi^-$	6(1)
$nn\pi^0\pi^+$	6(1)
$NN\pi$	0(10)

$$\sum \Gamma_i \sim \Gamma_{tot}$$

Eur.Phys.J. A51 (2015) 7, 87

Argand plot



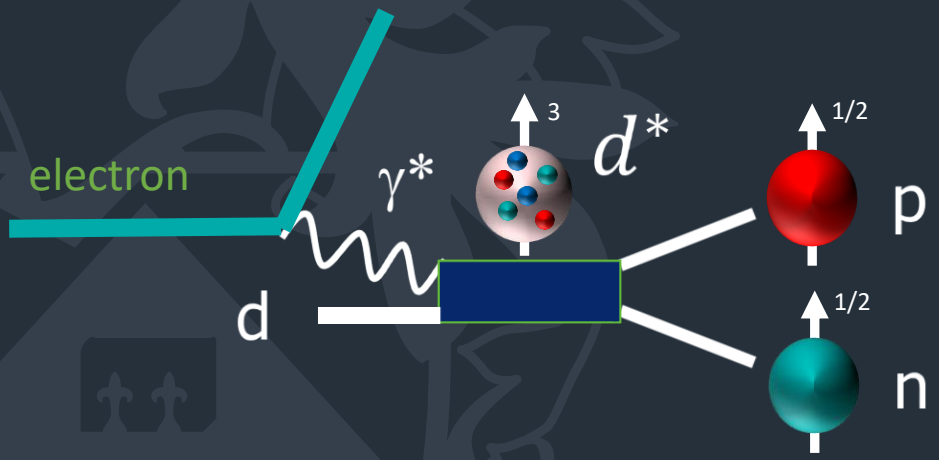
P. Adlarson et al. Phys. Rev. Lett. **112**, 202301, (2014)

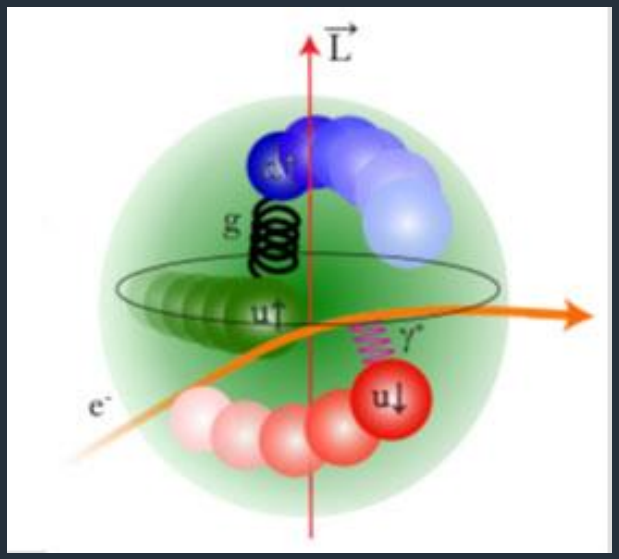
P. Adlarson et al. Phys. Rev. C **90**, 035204 , (2014)

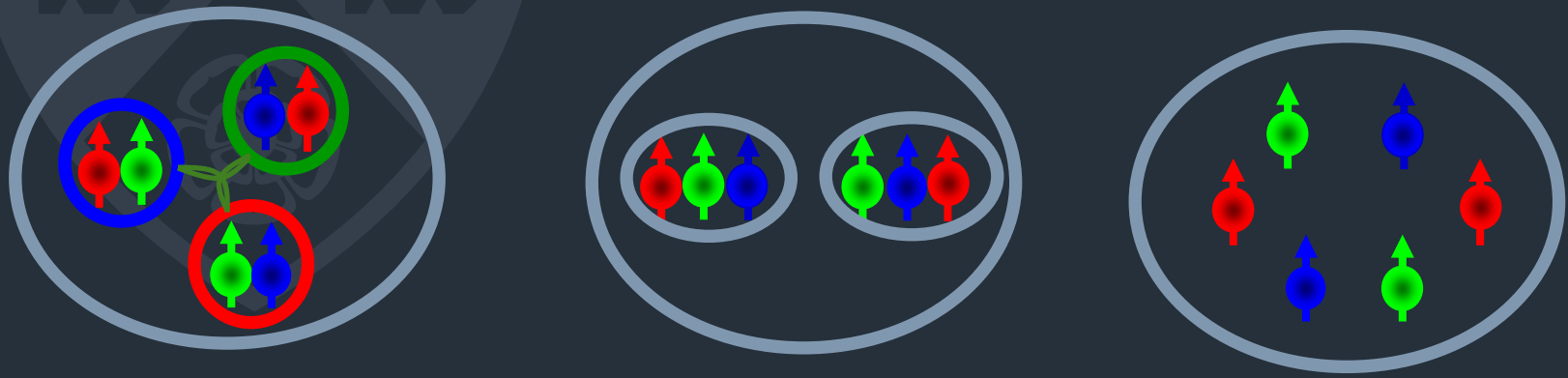
$d^*(2380)$ *internal structure*

EXPERIMENTAL VERIFICATION

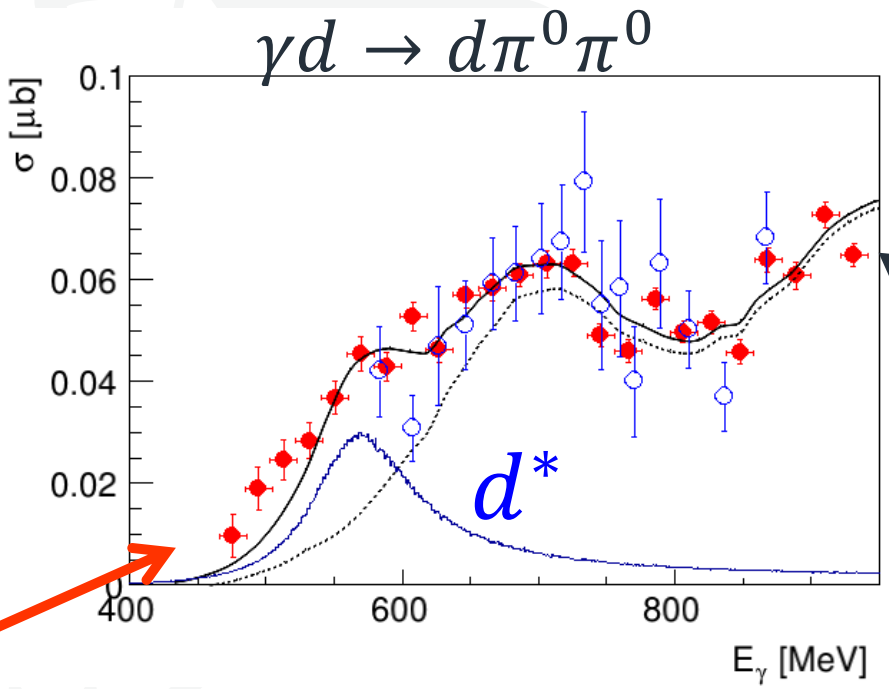
Hexaquark Autopsy







d*(2380) photoproduction



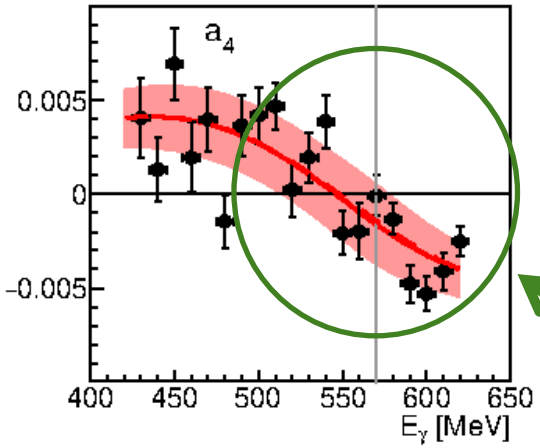
Conventional Background
M. Egorov, A. Fix,
Nucl.Phys. A933 (2015) 104-113

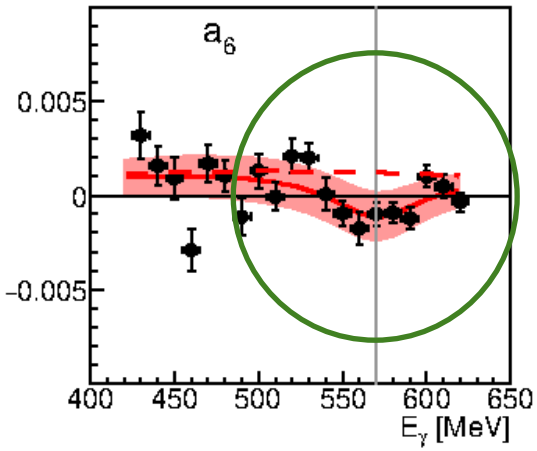
B. Krusche, NStar 2019

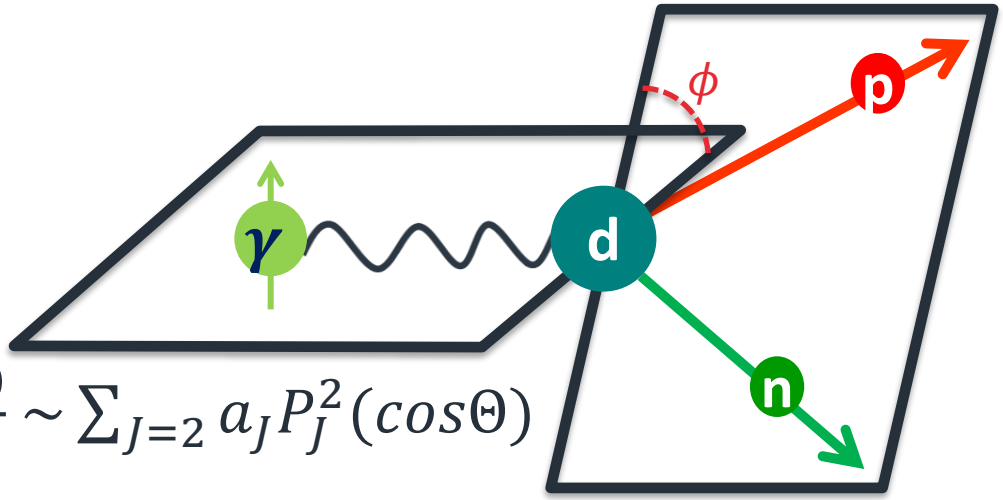
T. Ishikawa et al. Phys.Lett. B772 (2017) 398

BGO-OD, new data soon

Photon beam spin asymmetry







$$\frac{\Sigma(\Theta)\sigma(\Theta)}{\sigma_0} \sim \sum_{J=2} a_J P_J^2(cos\Theta)$$

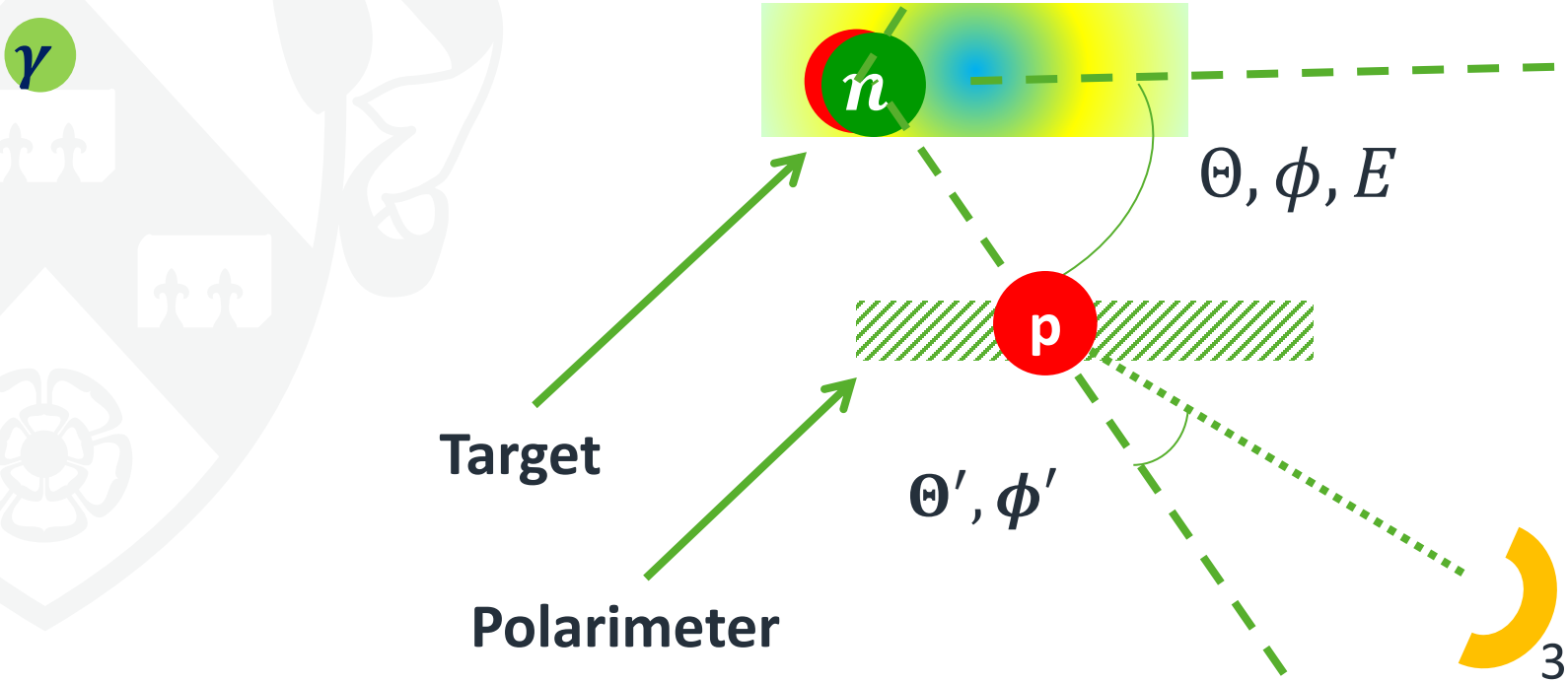
d^* E2 transition likely to be small

d^* M3 transition seems to be preferable

M. Bashkanov et al., Phys. Lett B789, (2019), 7-12

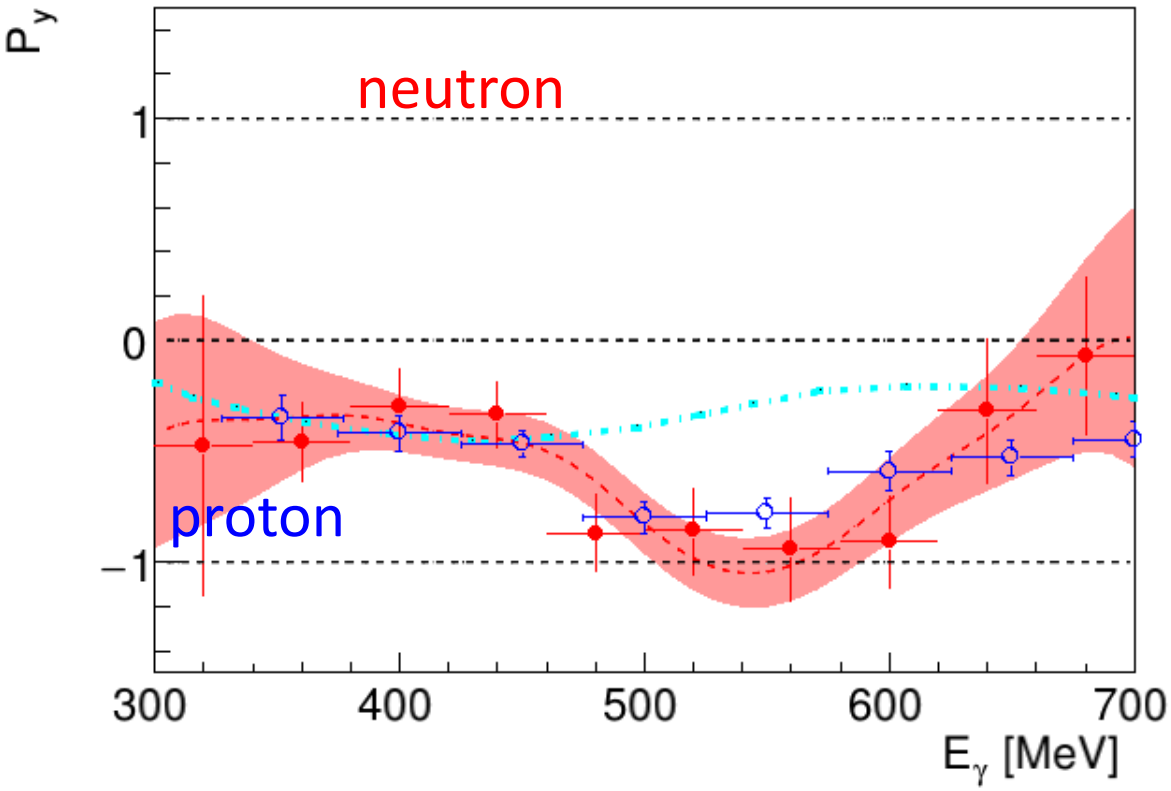
Experimentum crucis

$$\gamma d \rightarrow d^* \rightarrow p\vec{n}$$



Nucleon polarisation at 90°

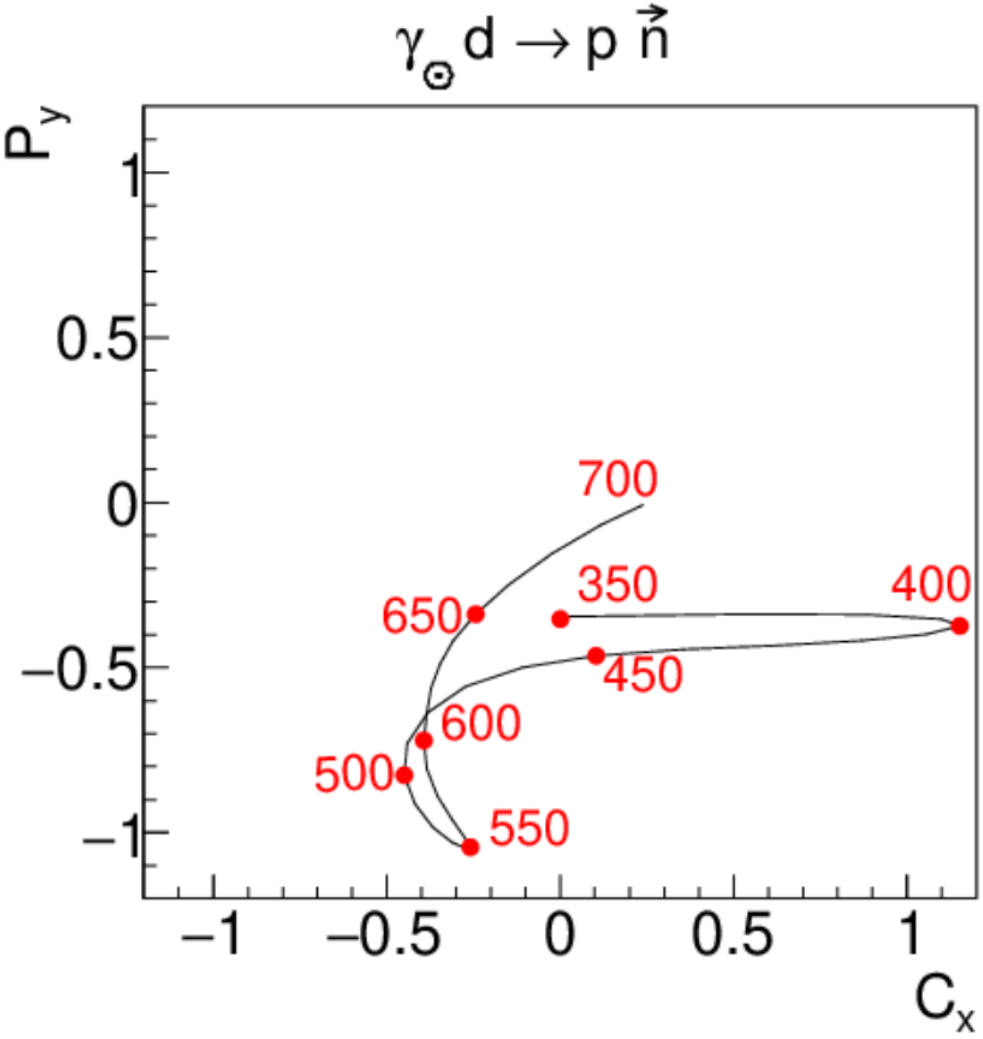
$\gamma d \rightarrow d^* \rightarrow p\vec{n}$ $\gamma d \rightarrow d^* \rightarrow \vec{p}n$



M. Bashkanov et al., PRL 124 (2020) 13

Argand type plots Re vs Im

C_x&P_y at 90 degree



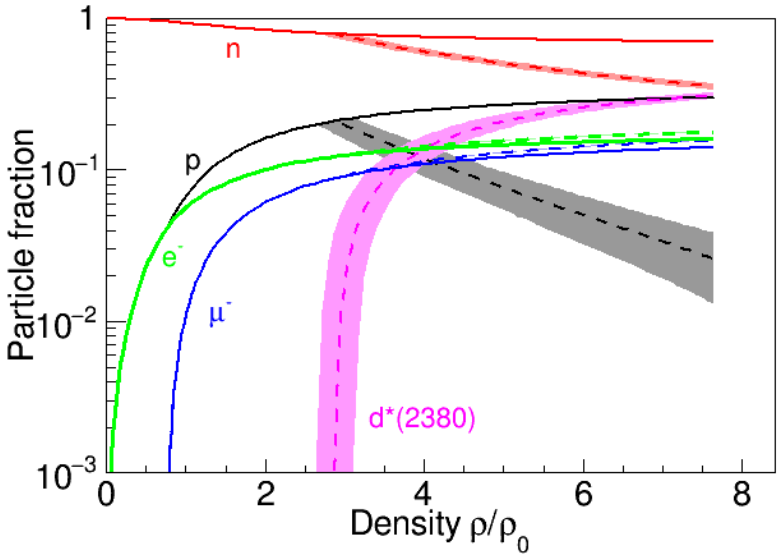
Observable	Structure function	Helicity amplitude combination
p_y	$R_T(y)$	$2\mathrm{Im}\sum_{i=1}^{3}\left[F^*_{i+}\,F_{(i+3)-}+F_{i-}\,F^*_{(i+3)+}\right]$
T	$R_T(\mathrm{Im}T_{11})$	$2\mathrm{Im}\sum_{i=1}^{2}\sum_{j=0}^{1}\left[F_{(i+3j)+}\,F^*_{(i+3j+1)+}+F_{(i+3j)-}\,F^*_{(i+3j+1)-}\right]$
Σ	R_{TT}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

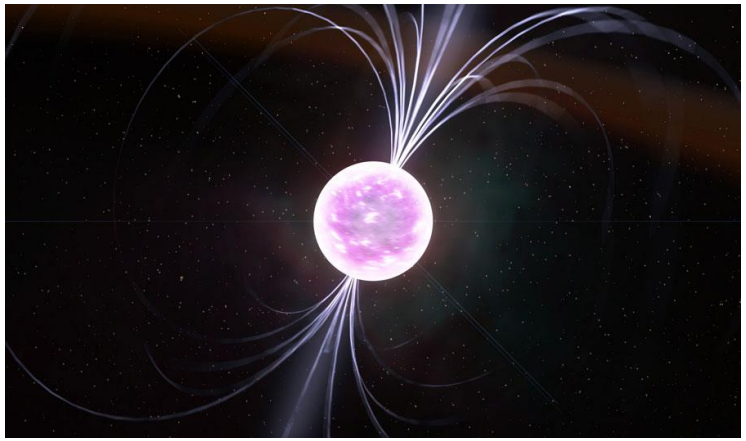
d^* the full experiment

$$\vec{\gamma}\vec{d} \rightarrow d^* \rightarrow \vec{p}\vec{n}$$

Observable	Beam	Target	Recoil	Status
$d\sigma/d\Omega$	unpol	unpol	unpol	Measured
Σ	lin	unpol	unpol	Measured
P_y	unpol	unpol	pol	Measured
C_x	circ	unpol	pol	Prepared for publication
O_x	Lin	unpol	pol	Preselected data
O_z	lin	unpol	pol	
T	unpol	$\perp$	unpol	Measured 2022
E	circ	$\parallel$	unpol	To be analysed
F	circ	$\perp$	unpol	Measured 2022
G	lin	$\parallel$	unpol	To be analysed
T_{11}	lin	$\perp$	unpol	Measured 2022
T_{1-1}	lin	$\perp$	unpol	Measured 2022

Hidden interior





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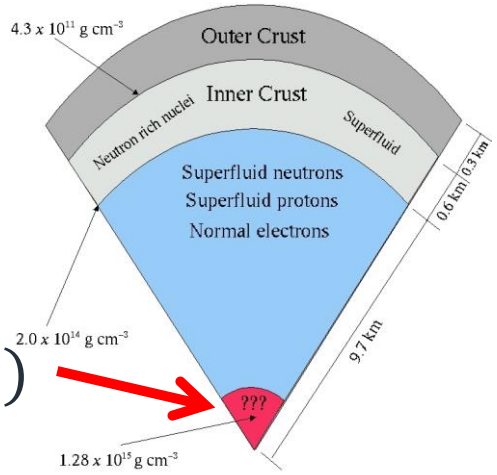
$d^*(2380)$



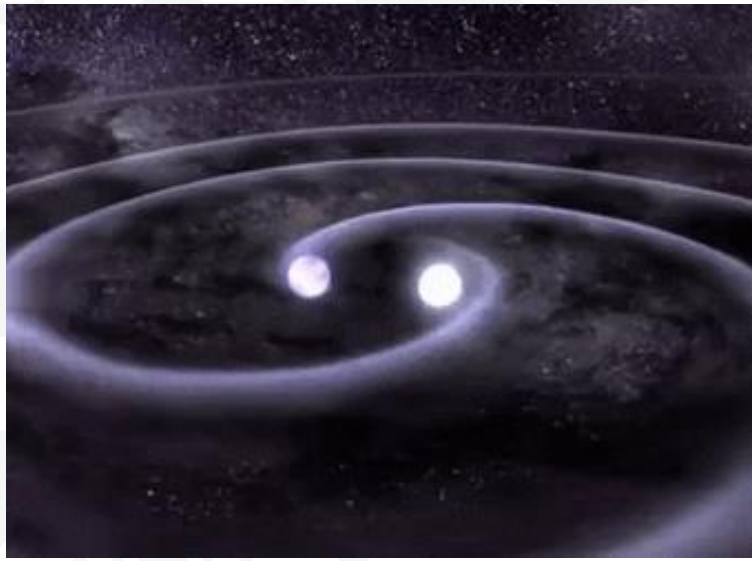
Neutron Star Pizza

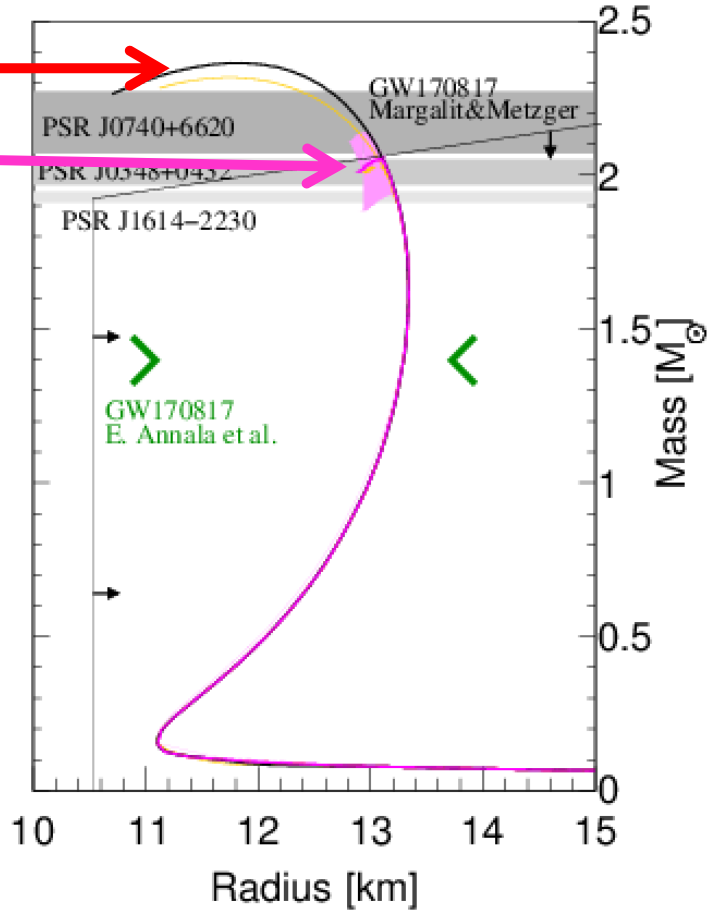
see M. Mocanu poster

Hexaquarks in Neutron Stars

Nuclear Matter

Hexaquark Matter





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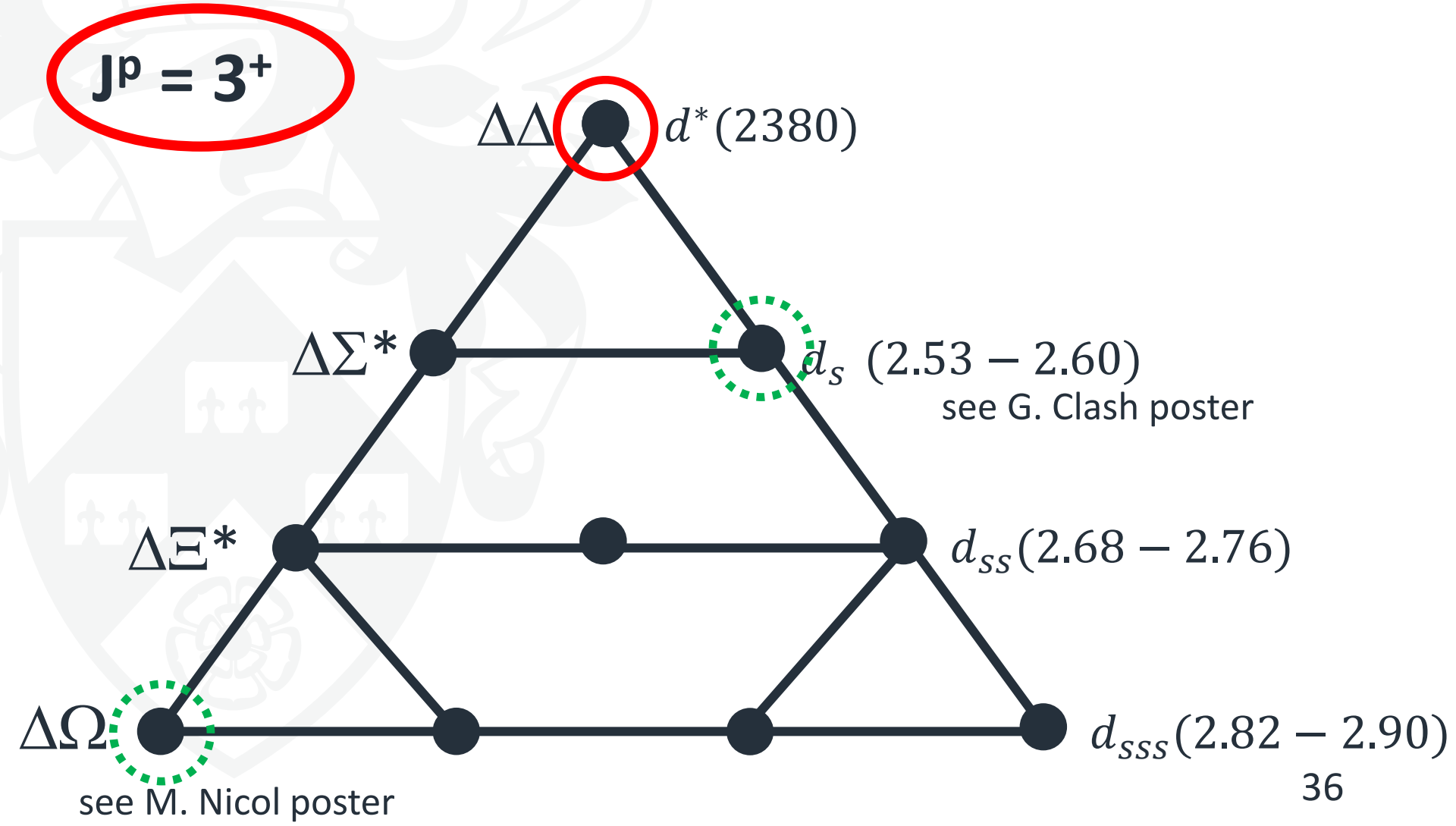
Phys.Lett. B781 (2018) 112-116 Submitted to arXiv: 28.06.2017

$d^*(2380)$ hexaquark SU(3) multiplet



Conclusion

- A lot of new data in dibaryon sector.
  - Heavy ions
  - Photon beams
  - J-PARC
- $d^*(2380)$ multiplet
  - Internal structure
  - $d^*(2380)$ in nuclear medium
  - SU(3) members
  - e-m probes $\rightarrow$ size and structure (A2, ELPH, BGO-OD, CLAS)
- New facilities (KLF)


Thank you