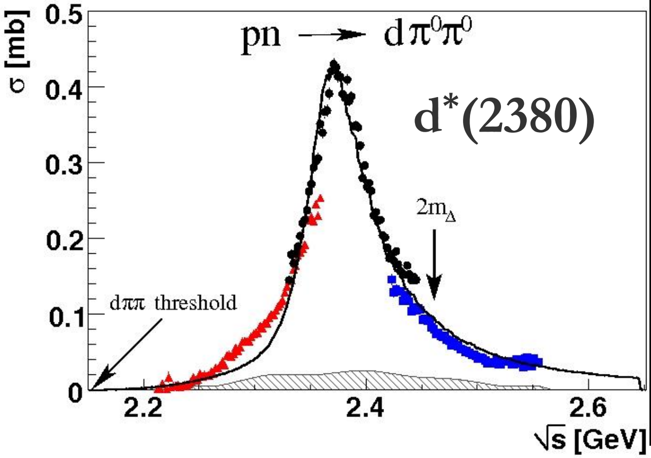
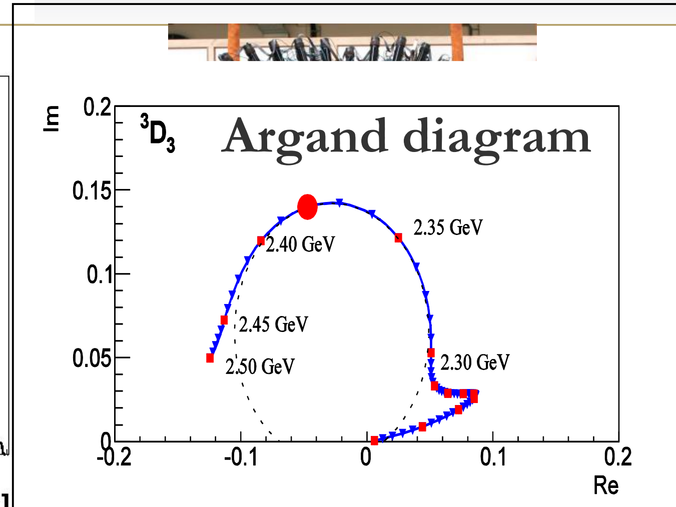
EBERHARD KARLS UNIVERSITÄT TÜBINGEN

Kepler Center for Astro and Particle Physics

Fachbereich Physik





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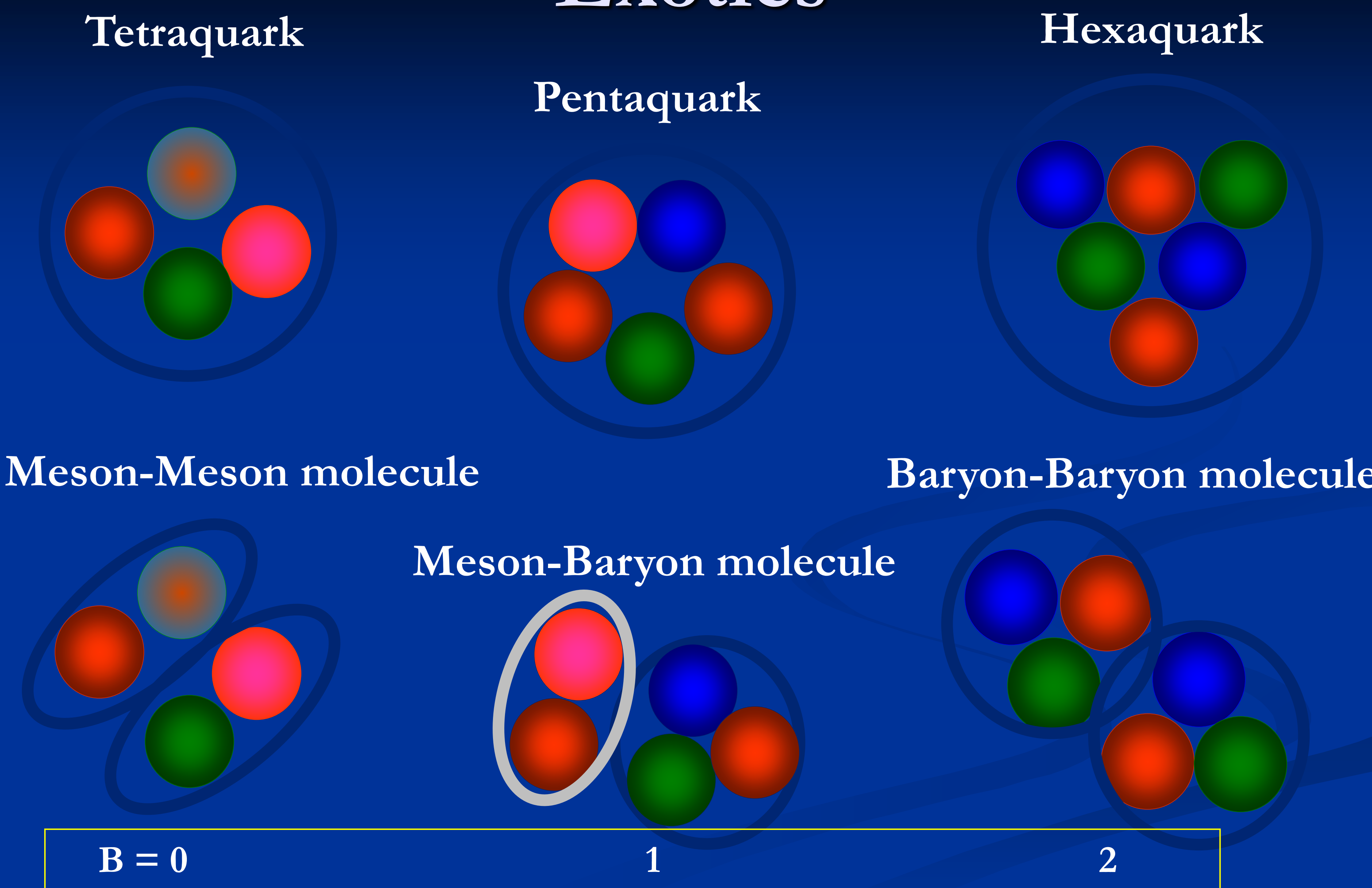
Dibaryonic Excitations – near Thresholds and Below

NSTAR 2024
York, June 17 - 21, 2024

Heinz Clement

Exotics



Dibaryon

Width of a Resonance

- If width of decay products large, then also resonance width large in general (unflavored sector)

- If width of decay products small, then also the resonance width can be **small (charm and beauty sectors)**
  → in particular **near thresholds**, where the decay phase space is small

Charm and beauty sectors:
large number of near-threshold states detected!

→ reinvestigate near-threshold phenomena in **unflavored** sector, though resonances are broad, since decay products already broad

Two-Baryon Scenario

- What do we know so far:
  - $^3S_1$ deuteron groundstate: **$I\,(J^P) = 0\,(1^+)$** **the only boundstate so far!**
  - $^1S_0$ virtual state (NN FSI): **$I\,(J^P) = 1\,(0^+)$** **in addition ΛN FSI**
- What would we like to know:
  - Are there six-quark states: hexaquarks (genuine dibaryons)?
  - Are there in general resonant states (molecular, dynamic) at all?
- Experimental findings:
  - $^1D_2$ resonance structure near the ΔN threshold: **$I\,(J^P) = 1\,(2^+)$**
  - $^3D_3$ resonance much below the ΔΔ threshold: **$I\,(J^P) = 0\,(3^+)$**
- Are there more states?
  - In unflavored or flavored sectors?

Early Predictions of Dibaryons

- 1964 Dyson & Xoung: 6 non-strange states, 5 found
- 1975 Jaffe: H-dibaryon (uuddss: ΛΛ): **not** found so far

  very recently, G. Farrar: dark matter candidate, if deeply bound.

  → *talk by Fumiya Oula , Monday 14:25*
- Thereafter in the seventies and eighties

  multitude of predictions of a vast number of states

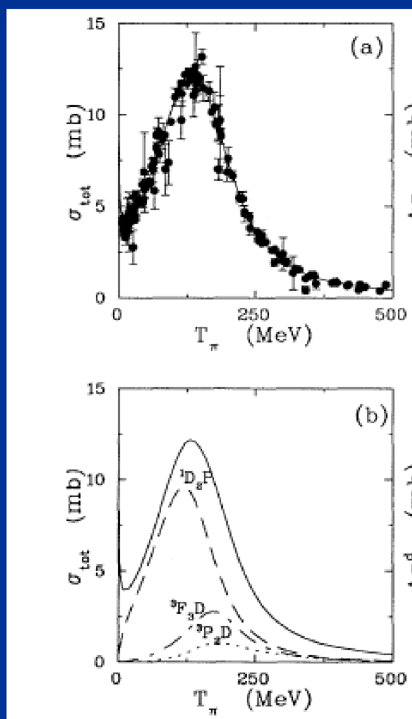
  ⇒ **Dibaryon Rush Era:**

many experimental claims … but **no single one firmly** established finally

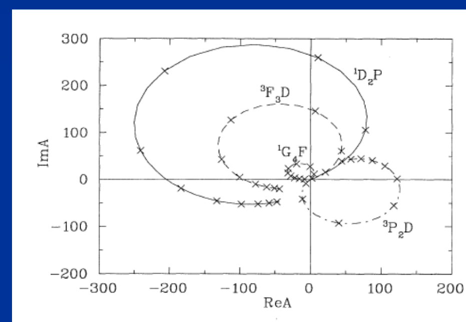
$^1D_2$ Resonance near NΔ Threshold

- Best seen in pp ↔ dπ$^+$,
  - but also in pp → pnπ$^+$ as well as pp and π$^+$d scattering (partial-wave analyses)

σ_{tot} (π$^+$d → pp)



Argand plot



R.A. Arndt et al., PRD 35 (1987) 128
PRC 48 (1993) 1926
50 (1994) 1796
56 (1997) 635
N. Hoshizaki, PRC 45 (1992) R1424
Prog. Theor. Phys. 89 (1993) 245
251
563
569

I (J^P) = 1 (2^+)
M ≈ 2148 MeV = $m_\Delta + m_N$ – 22 MeV
Γ ≈ 126 MeV ≈ Γ_Δ

Alternative descriptions: cusp, virtual state, reflection, triangle singularity
However, not consistent!!! Kukulin and Platonova PRD 94 (2016) 054039

(Molecular) States near ΔN Threshold

	I = 1	I = 2
S-wave:	2^+ $(^1D_2)$ D_{12}	1^+ $(^3P_1)$ D_{21} WASA PRL 121 (2018) 052001
P-wave:	0^- $(^3P_0)$ COSY-ANKE	
	2^- $(^3P_2)$ -"- , SAID	
	3^- $(^3F_3)$ SAID (?)	

Where can D_{21} be seen?

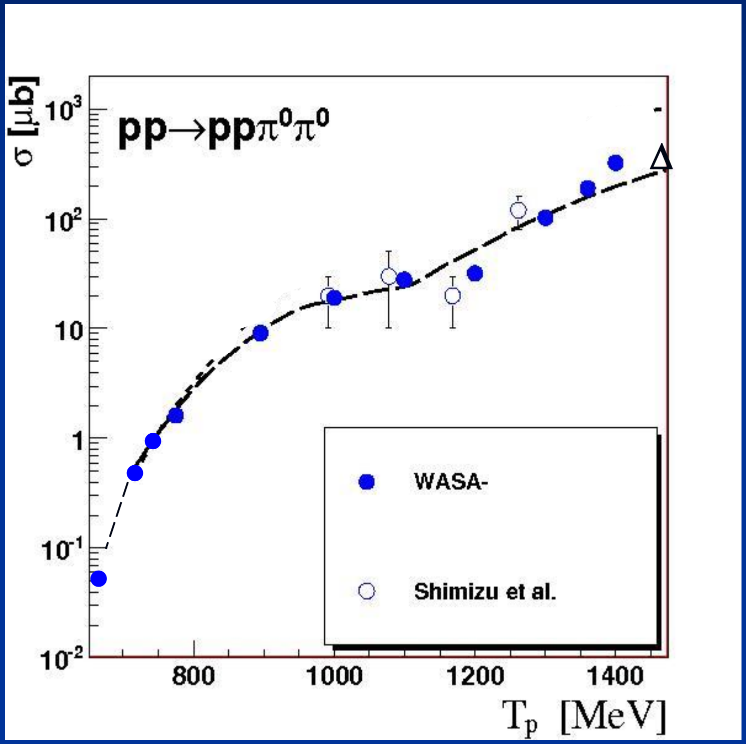
I=2 ⇒ only associated production

$$pp \rightarrow \boxed{pp\pi^+}\,\pi^-$$

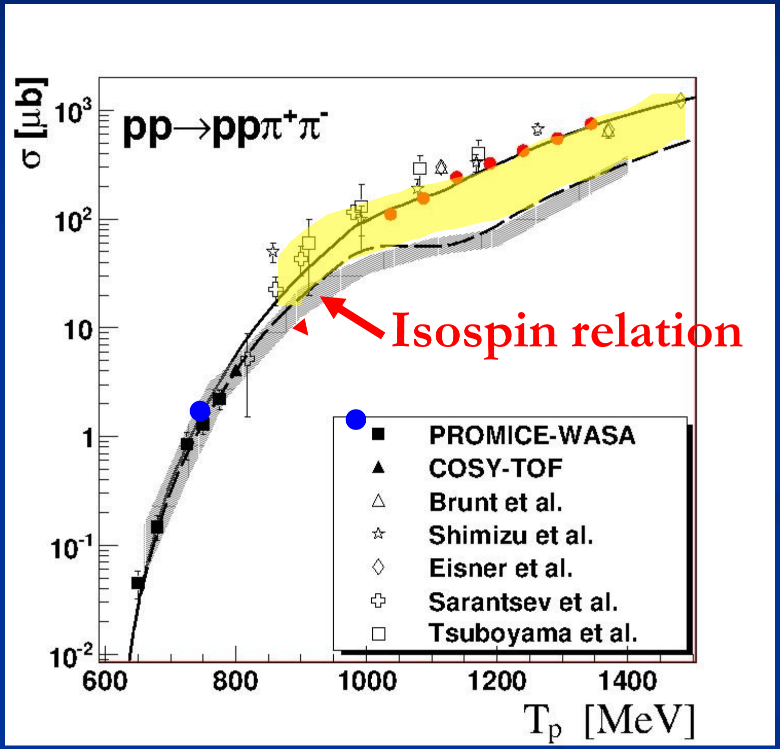
⇓

D_{21}

Total cross section



PLB 695 (2011) 115



PRL 121 (2018) 052001

- - - - - - - modified Valencia model (Roper + ΔΔ)

——— modified Valencia model (Roper + ΔΔ) + D_{21}

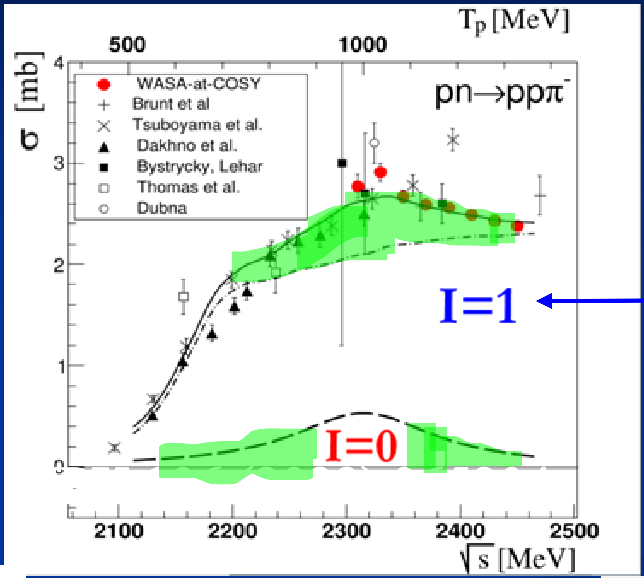
(Molecular) States near NN*(1440) Threshold

	I = 0 PRC 106 (2022) 065204	I = 1 EPJA 56 (2020) 229
S-wave:	1^+ $(^3S_1)$	0^+ $(^1S_0)$??
P-wave:	1^- $(^1P_1)$	

PWA: Sarantsev et al., EPJA 43 (2010) 11

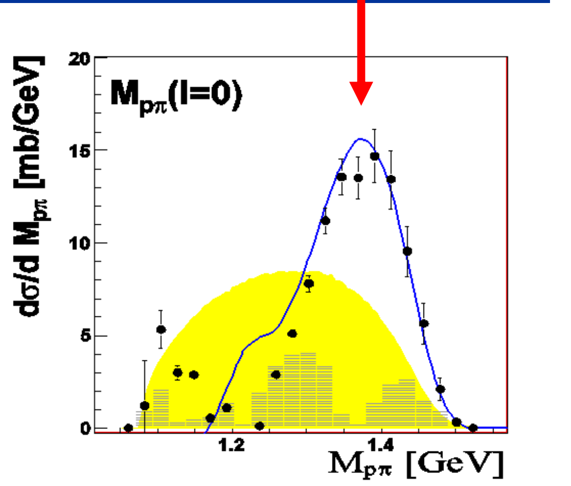
Isoscalar Single-Pion Production: N*N

PRC 106 (2022) 065204

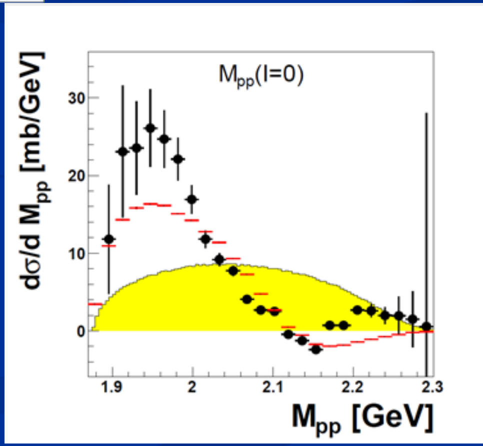


½ σ(pp → ppπ^0)

Roper



pp($^1S_0$)



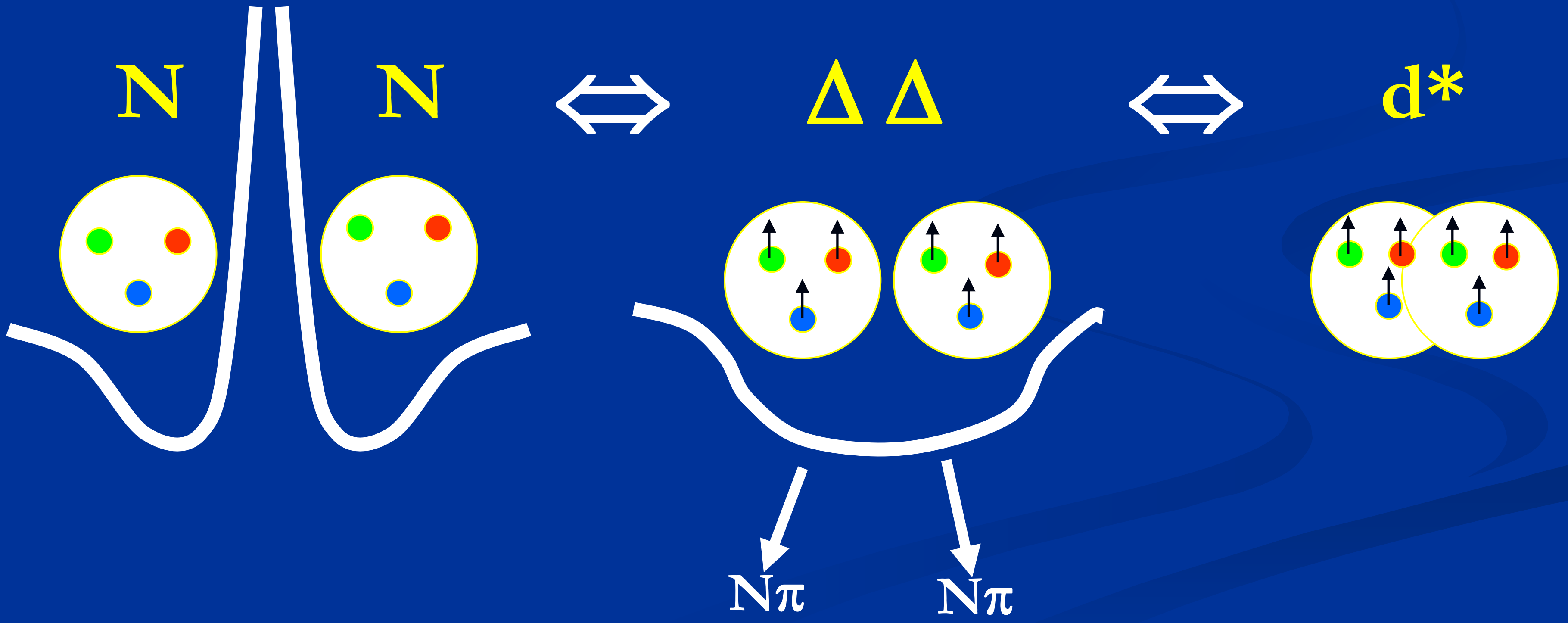
PLB 774 (2017) 599

… inevitable dibaryon

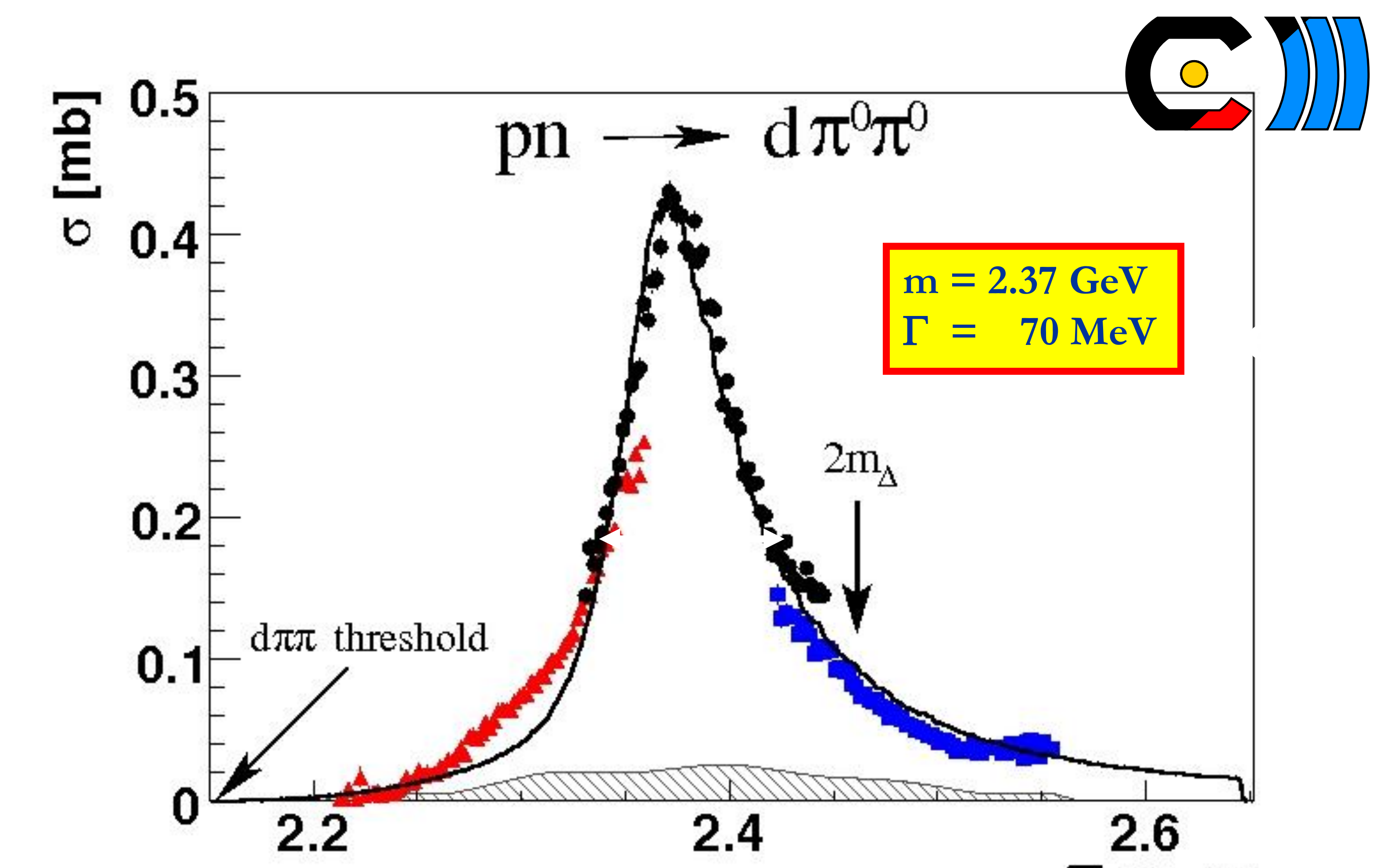
$I(J^P) = 0(3^+)$ state: totally symmetric in space, spin & color

antisymmetric in isospin

accessed via ΔΔ as doorway ?

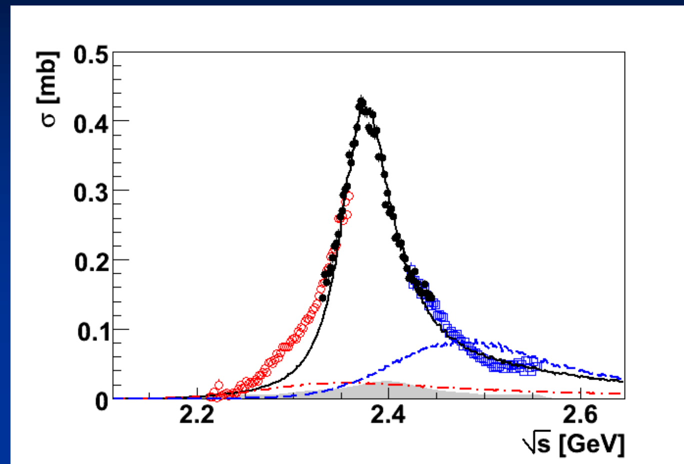


Isoscalar : Results from WASA at COSY

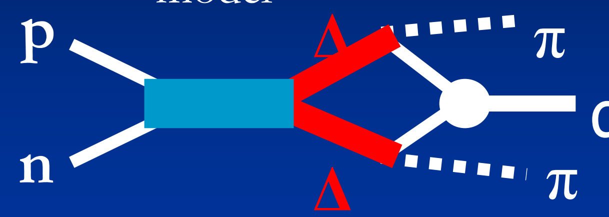


Phys.Rev.Lett.106, 242302 (2011)

$pn \rightarrow d^* \rightarrow \Delta\Delta \rightarrow d\pi^0\pi^0$



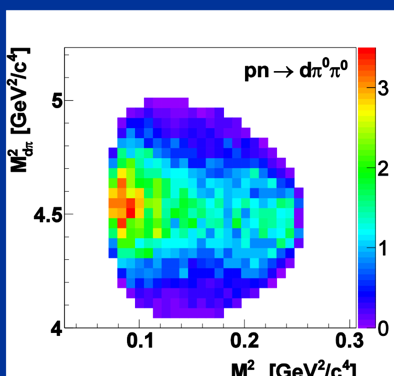
model

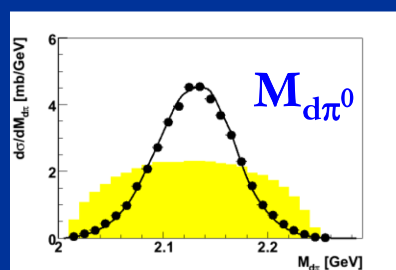


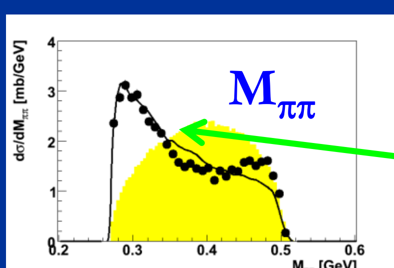
$I\,(J^P) = 0\,(3^+)$

$M, \Gamma, \Gamma_i * \Gamma_f, F(q_{\Delta\Delta})$

Phys.Rev.Lett.106, 242302 (2011)

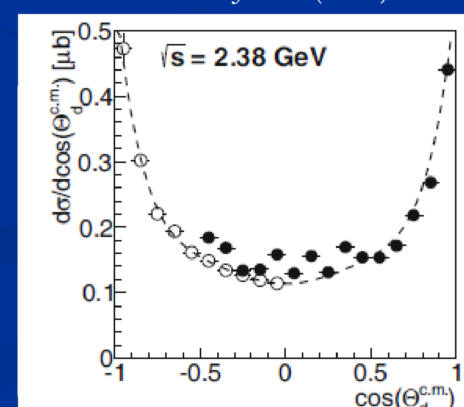






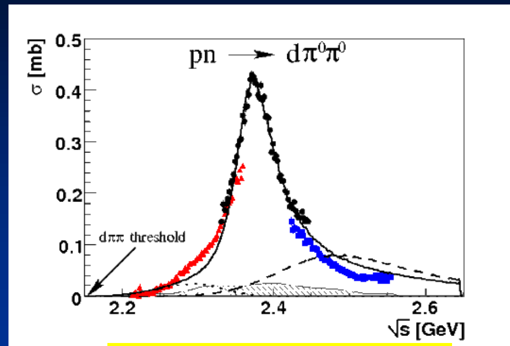
ABC effect

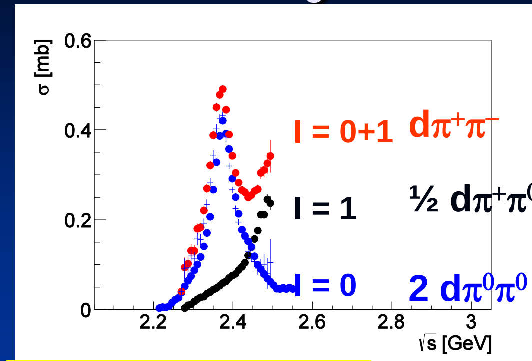
EPJA 52 (2016) 147



hadronic decays

PRL 106 (2011) 242302





PLB 721 (2013) 229

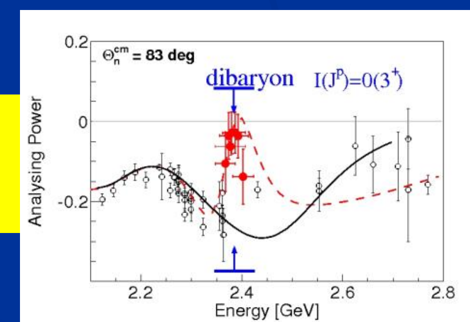
○ ● ● WASA data

$d\pi^0\pi^0$

$d\pi^+\pi^-$

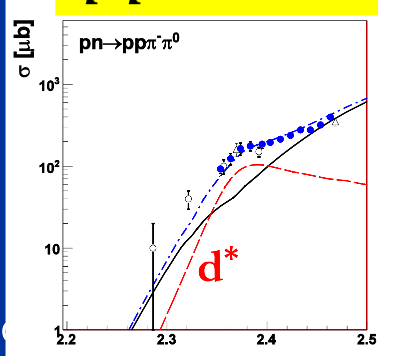
pn → d*(2380)

pn

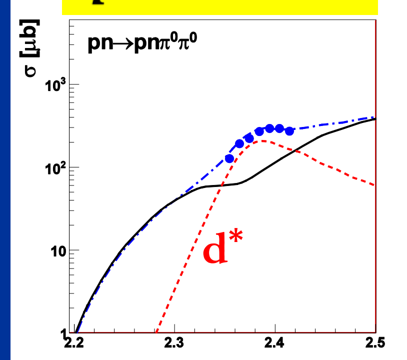


PRL 112 (2014) 202301
PRC 90 (2014) 035204

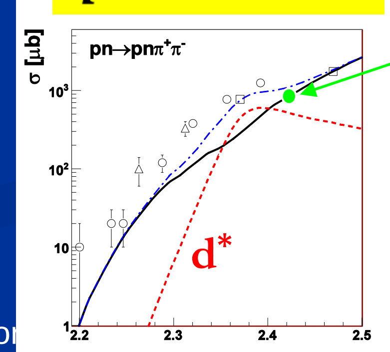
$pp\pi^-\pi^0$



$pn\pi^0\pi^0$



$pn\pi^+\pi^-$



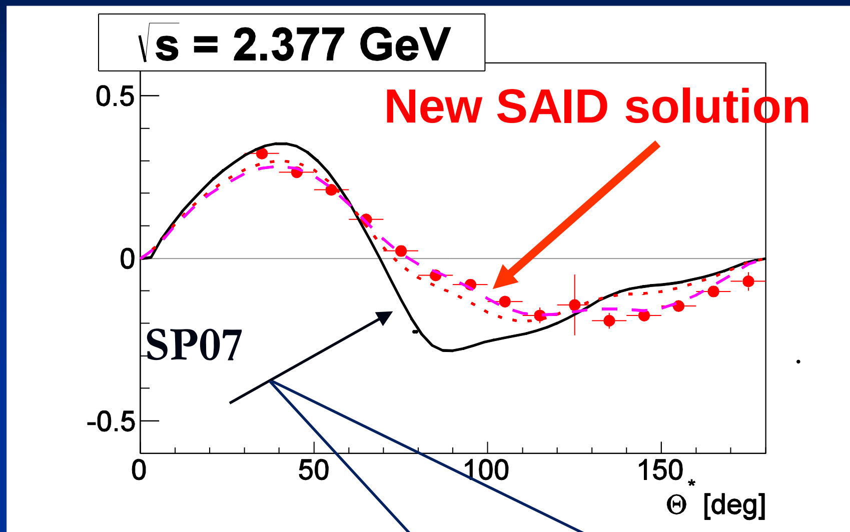
HADES PLB 750 (2015) 184

PRC 88 (2013) 055208
PLB 743 (2015) 325
Phys. Scr. T 166 (2015) 014016

→ √s [GeV]

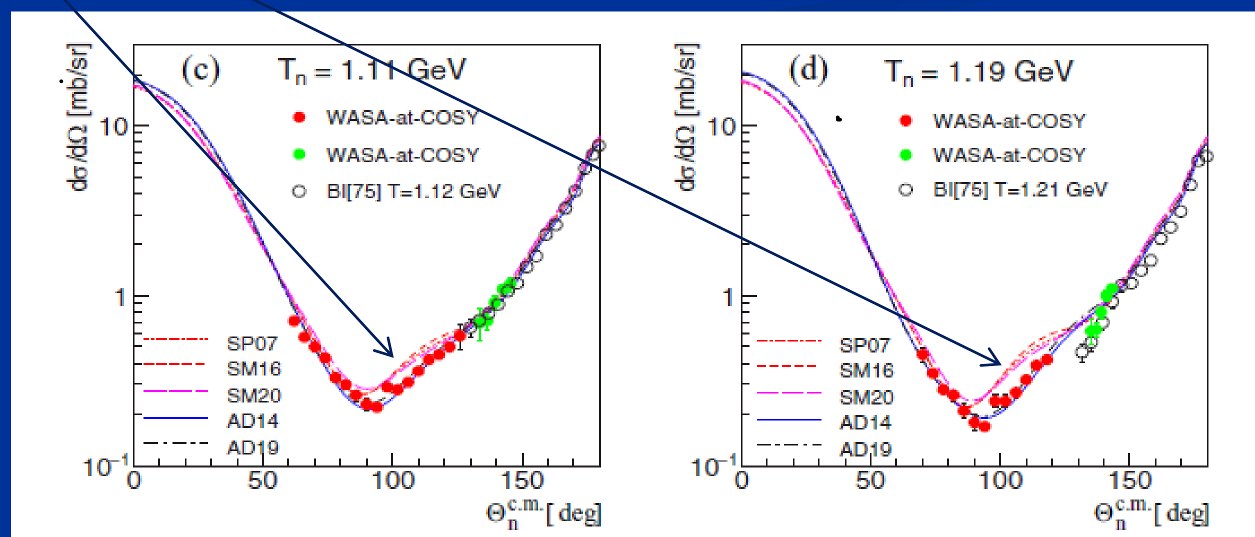
np Elastic: Angular Distributions at Resonance

$A_y(\theta)$



Phys. Rev. Lett. 112 (2014) 202301

$\sigma(\theta)$

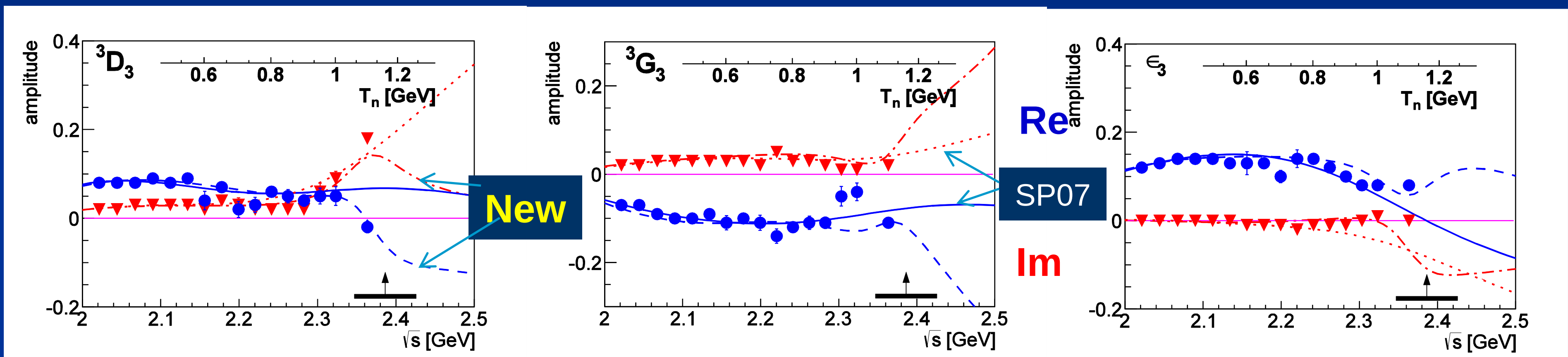


PRC 102 (2020) 015204

SAID Partial-Wave Analysis

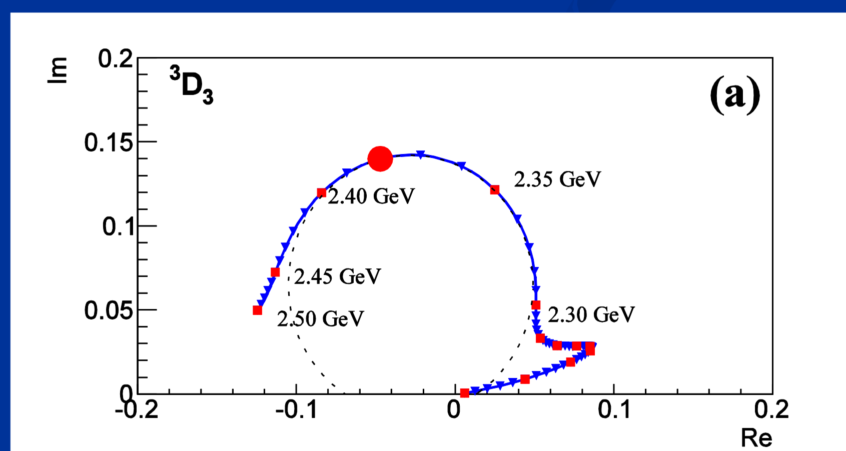
$^3D_3 - {}^3G_3$ Coupled Partial Waves

Phys. Rev. Letters 112 (2014) 202301



Argand diagram:

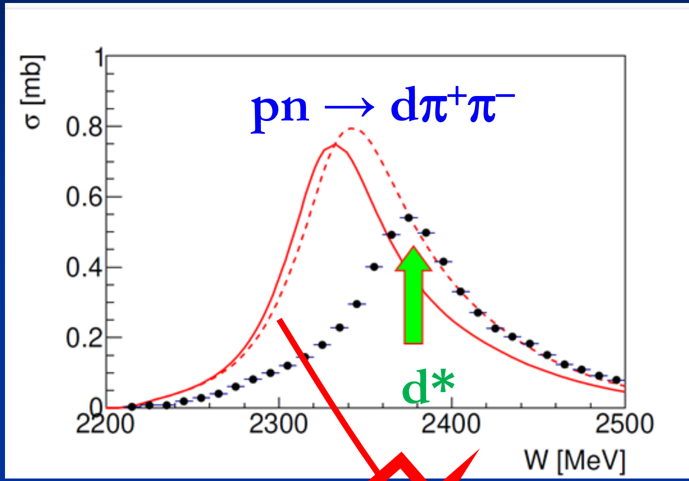
PRC 90 (2014) 035204



Pole in $^3D_3$ at 2380±10 - i 40±5 MeV

⇔ Genuine Resonance in np System

Alternative: Sequential Single-Pion Production



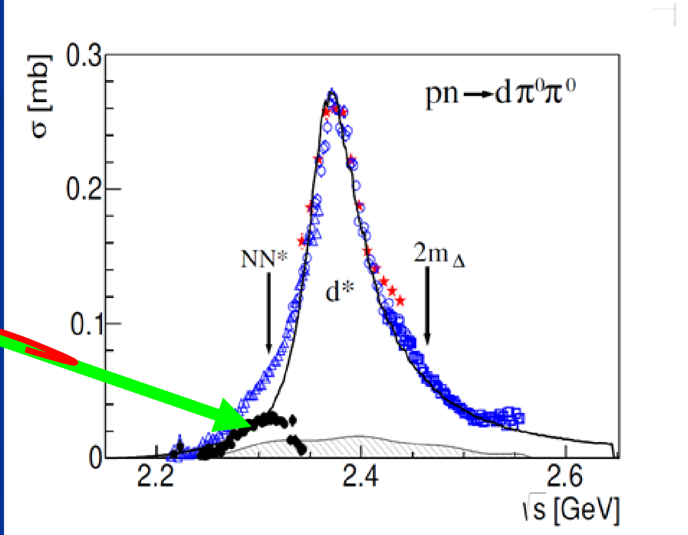
NPA 1037 (2023) 122698

$$pn\ (I=0) \to \{NN\}\ \pi\ \ (I=0)$$
$$\to \{d\pi\}\ \pi\ \ (I=0)$$

Chin. Phys. C 47 (2023) 041001

… is not an explanation for d*(2380), but …

PRC 106 (2022) 065204



Using proper single-pion data
and proper partial waves

$$pn(I=0) \to NN^* \to N\Delta\pi \to d\pi^0\pi^0$$

$$J^P = 1^+ \text{ and } 1^-$$

NPA 1037 (2023) 122698

Branching Ratios for the Decay of $d^*(2380)$

- hadronic decays

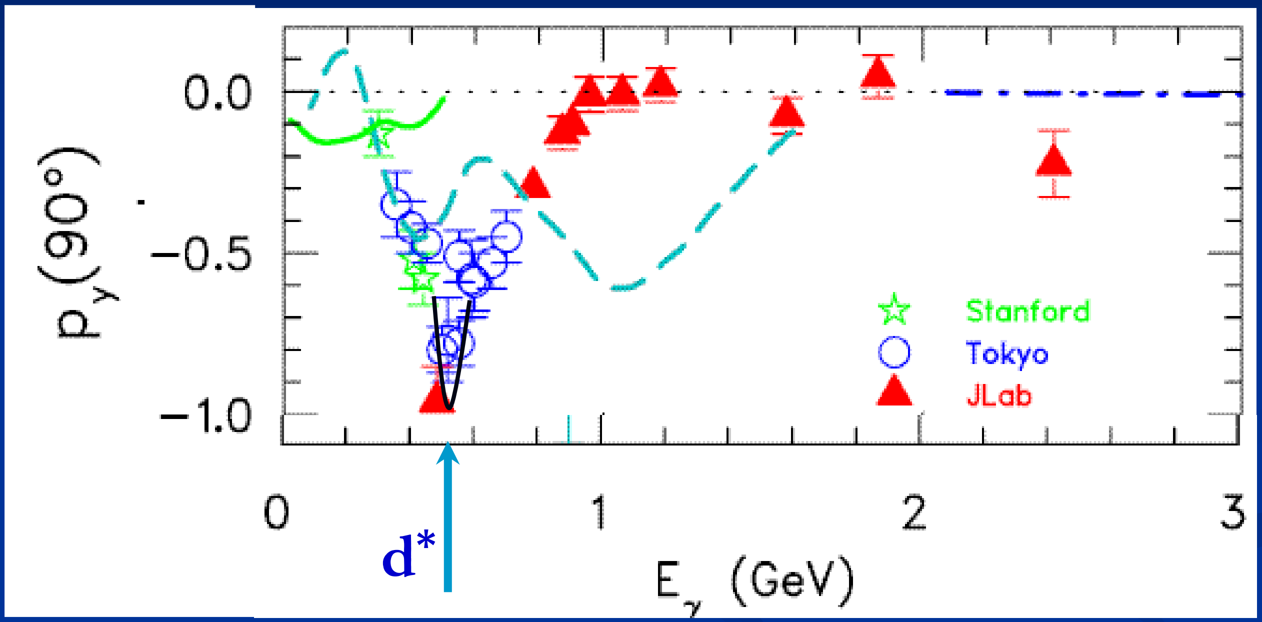
EPJA 51 (2015) 87

decay channel	branching	derived from
$d\ \pi^0\pi^0$	14 ± 1 %	measurement
$d\ \pi^+\pi^-$	23 ± 2 %	measurement
$pp\pi^0\pi^-$	6 ± 1 %	measurement
$nn\pi^+\pi^0$	6 ± 1 %	isospin mirrored
$np\pi^0\pi^0$	12 ± 2 %	measurement
$np\pi^+\pi^-$	30 ± 4 %	measurement (old data + HADES)
np	12 ± 3 %	measurement
$(NN\pi)_{I=0}$	< 5 % (90% C.L.)	measurement

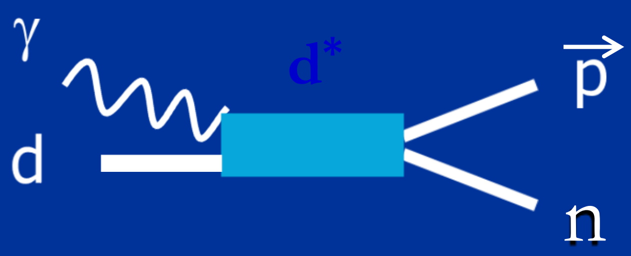
consistent with isospin coupling for a ΔΔ intermediate system*

*see also Fäldt & Wilkin, PLB 701 (2011) 619, Albaladejo & Oset, PRC 88(2003) 014006

Further hints: $\gamma d \rightarrow \vec{p} n$



R. Gilman and F. Gross AIP Conf. Proc. 603 (2001) 55
K. Wijesooriya et al., Phys. Rev. Lett. 86 (2001) 2975



T. Kamae, T. Fujita Phys. Rev. Lett. 38 (1977) 471

H. Ikeda et al., Phys. Rev. Lett. 42 (1979) 1321

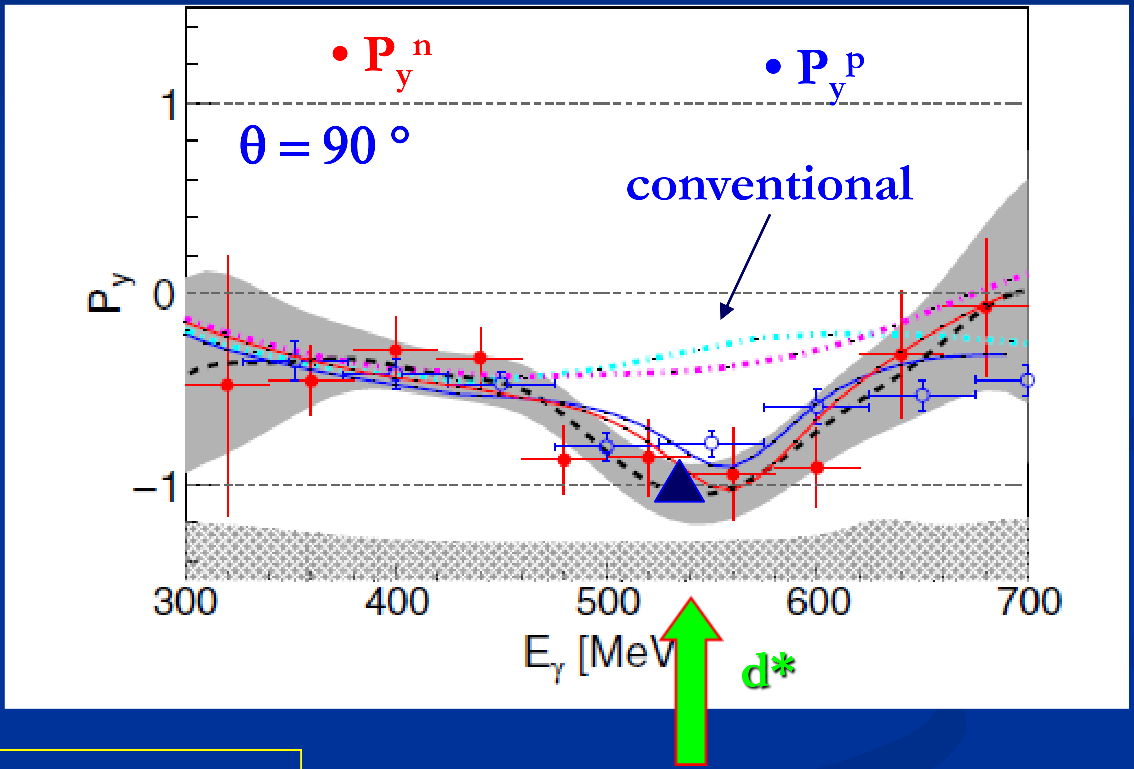
$\gamma d \rightarrow \vec{p}n$
$\rightarrow p\vec{n}$

$P_y^p = P_y^n = -1$

$\longrightarrow$

pn system in S=1

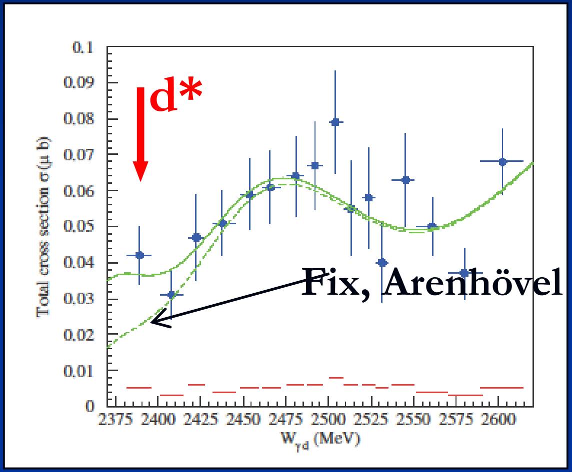
PWA ???



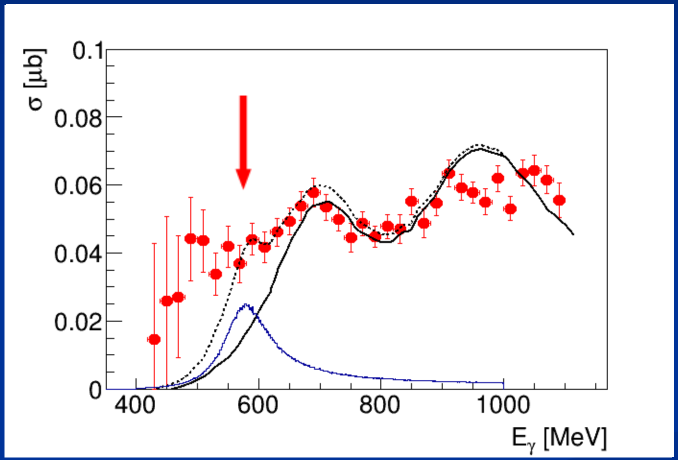
Legendre decomposition of P_y:
P_3^1 gives largest contribution

A2-MAMI, PRL 124 (2020) 132001

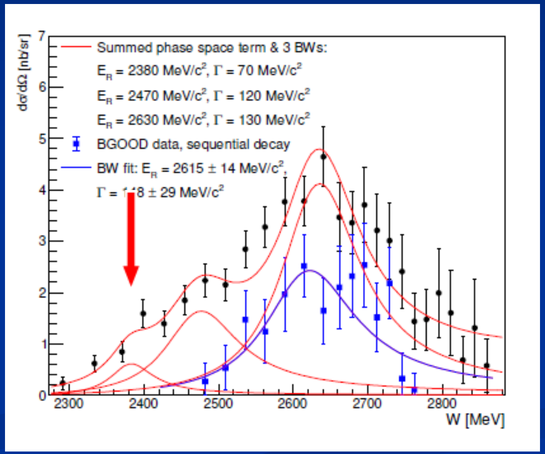
$\gamma\, d \rightarrow d\pi^0\pi^0$



FOREST@ELPH,
PLB 772 (2017) 398



Crystal Ball @ MAMI
PoS (Hadron2017) 051

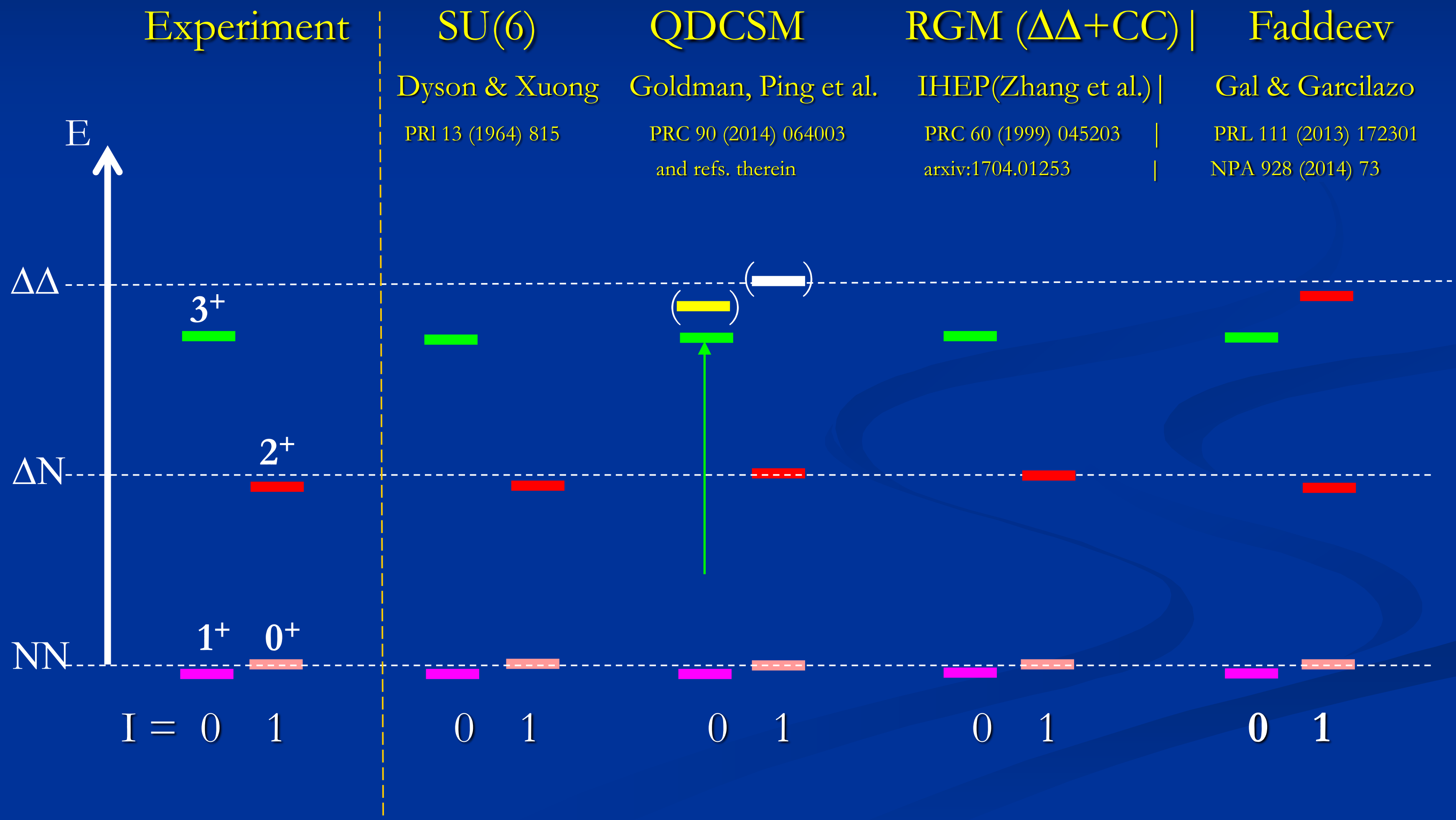


BGOOD@ELSA
PLB 832 (2022) 137277

→ talk by Thomas Jude, Wednesday 9:30

Theoretical prediction: $\sigma \approx 1 - 2$ nb IJMP A34 (2019) 1950100

Comparison to predictions from Quark and Hadron Models



Width of d*(2380)

- Experiment: **$\Gamma \approx$ 70 MeV**
  - (t-channel ΔΔ: ≈ 250 MeV)
- QDCSM: 110 MeV PRC 89 (2014) 034001
- Faddeev: (94 + 10) MeV NPA 928 (2014) 73
  - Hidden Color ? PLB 727(2013) 438
- RGM (ΔΔ + CC) **72** MeV PRC 94 (2016) 014003

See Yubing Dong, next to next talk

Molecule vs Hexaquark

Size of d*(2380)

- Estimate from uncertainty relation:

  $R \approx \hbar c \,/\, \sqrt{2\mu B}$

  $B_{\Delta\Delta} \approx 80$ MeV $\Rightarrow$ $R \approx 0.5$ fm

- QCD model IHEP 0.8 fm
- QCD model Nangjing (LAMPF) 0.8 fm
- LQCD (HAL QCD) 0.8 – 1 fm

  PLB 811 (2020) 135935

agrees with branching ⇩ } hexaquark

- Faddeev hadr. G&G 1.5 – 2 fm **molecule**

  PLB 769 (2017) 436

Rèsumè

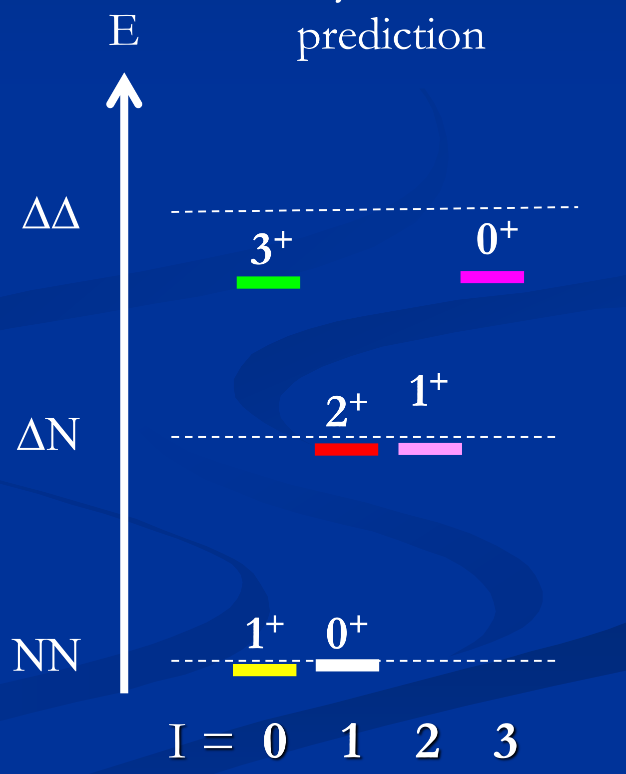
Zhang, Chen, Shen, Dong et al.

Huang, Ping, Wang et al.

Gal & Garcilazo

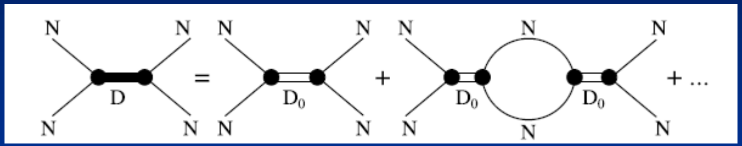
Dyson's prediction

- Non-Strange Two-Baryon Spectrum
  - 3 established states: $^3S_1$ deuteron groundstate
    $^1S_0$ virtual state
    $^1D_2$ resonance (ΔN)
  - 1 new - **presumably exotic** - state:
    $d^*(2380)$ resonance ($\Delta\Delta$)
  - Are there more states?
    - NN-decoupled states with I = 2, 3?
    - Search in $pp \to pp\pi^+ \pi^-$ √
      and in $pp \to pp\pi^+\pi^+ \pi^-\pi^-$???



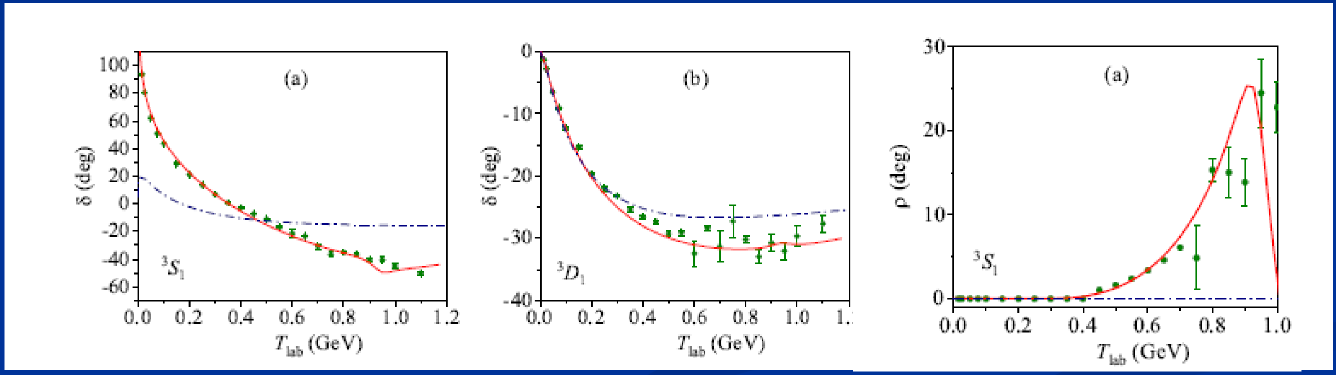
NN-interaction with intermediate dibaryon formation

- Kukulin†, Platonova et al.
  - π–exchange +



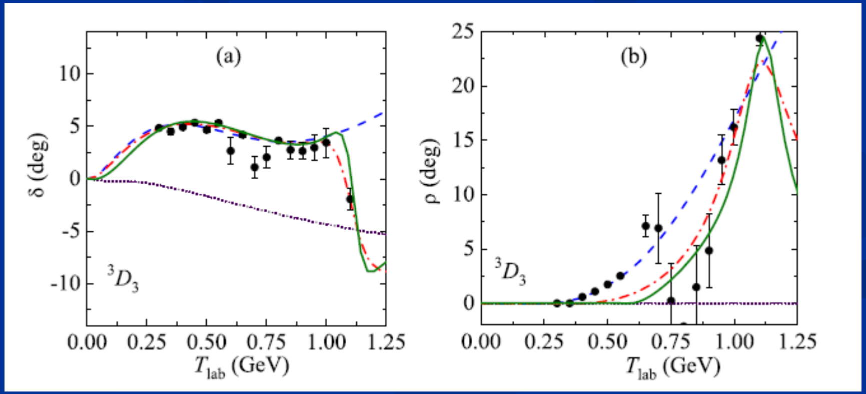
$^3S_1 - {}^3D_1$

EPJA 56 (2020) 229



$^3D_3$

PLB 801 (2020) 135146



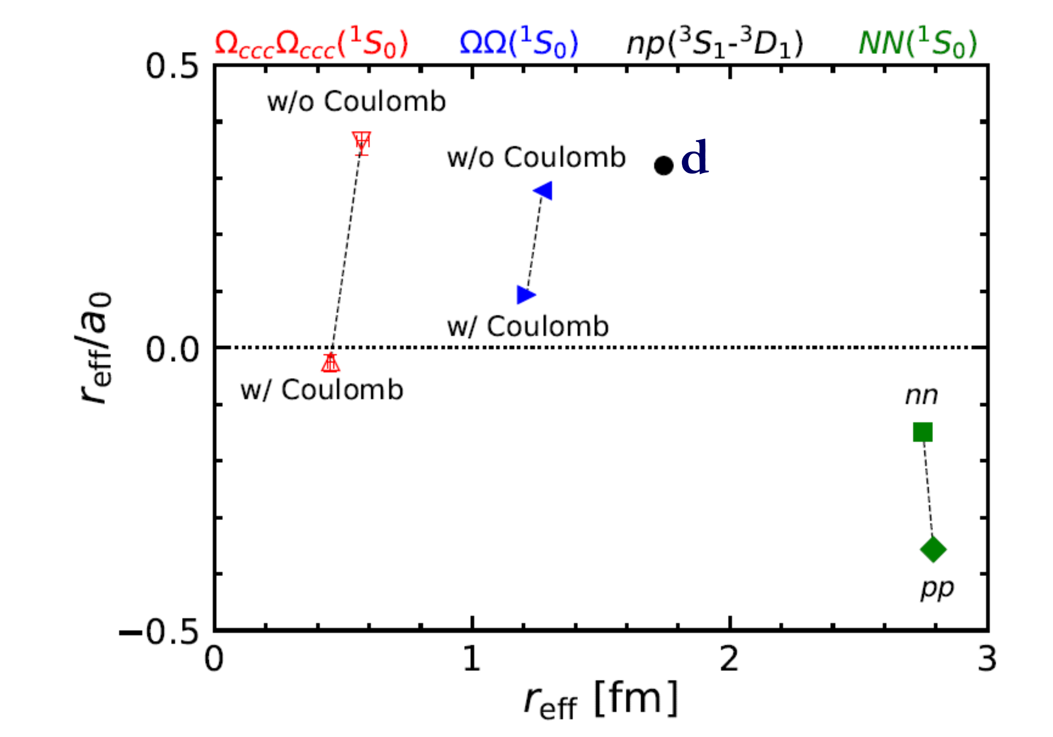
Outlook and Open Problems

- Size of $d^*(2380)$
  - $\Rightarrow$ elm excitation of d^* $ed \rightarrow ed^* \rightarrow ed\pi^0\pi^0$
- Observation at other installations
  - IHEP ?? $e^+e^- \rightarrow \bar{d}\, d^*$ at 4.3 – 4.6 GeV ??
  - KEK, JPARC, LHCb, others ???
- Astrophysical relevance? (M. Bashkanov et al., York)

  neutron stars, dark matter
- Are there more (exotic) dibaryons?
  - D_{30} mirror state of d^*
  - ***strange, charmed and beautiful dibaryons??***

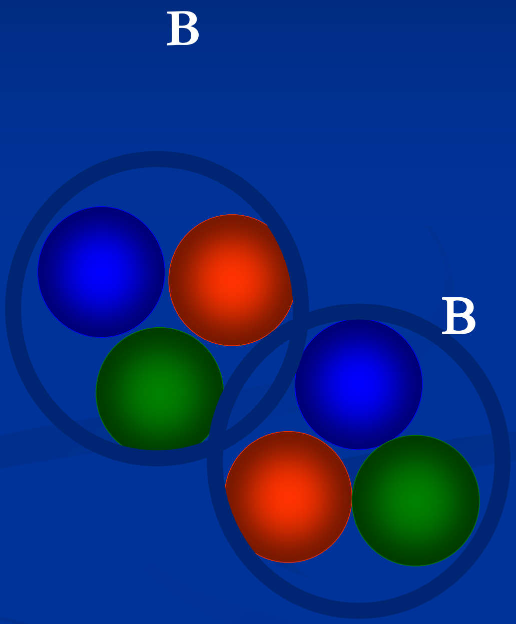
Flavored Dibaryons

- LQCD predictions (HAL QCD) :



PRL 127 (2021) 072003

- … still much to do

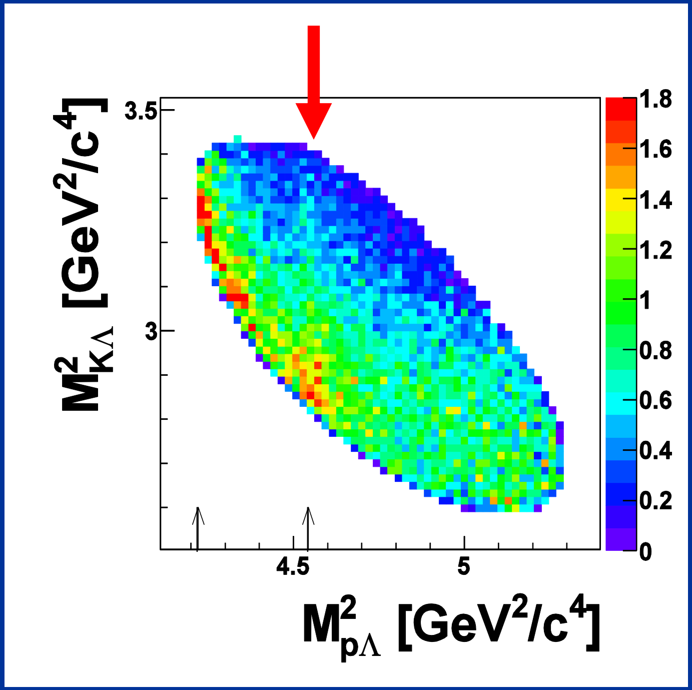


Backup Slides

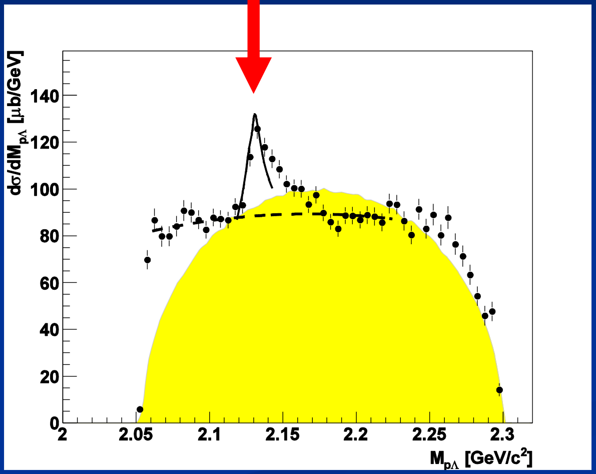
$pp \to K^+ p\Lambda$

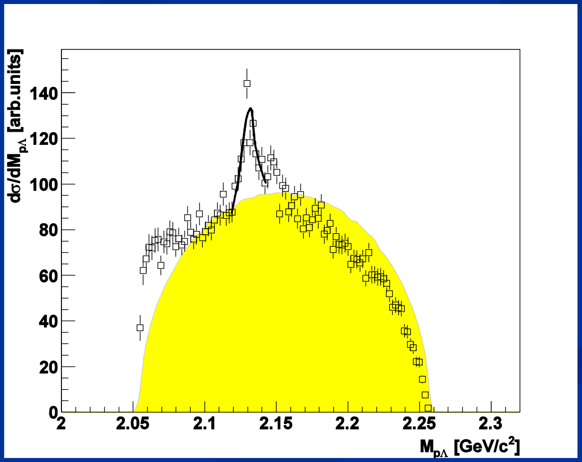
- COSY-TOF

NΣ threshold



NΣ cusp





EPJA 49 (2013) 41

Conclusion from the Failures in the Dibaryon Rush Era:

Do Exclusive and kinematically complete measurements

- Our approach:
  - Two-pion production with best suited equipment
    - 4π detector: WASA
    - pellet target: p and d
    - storage ring: CELSIUS $\rightarrow$ COSY
  - The learning phase:
    - pp induced two-pion production
  - Following a trace:
    - the ABC effect in double-pionic fusion
  - The surprise:
    - a narrow resonance in pn induced **isoscalar** two-pion production

Branching via Intermediate State

hexaquark | **molecule**

- $d^* \to \Delta\Delta \to NN\pi\pi$ | $d^* \to {}^1D_2\,\pi \to NN\pi\pi$

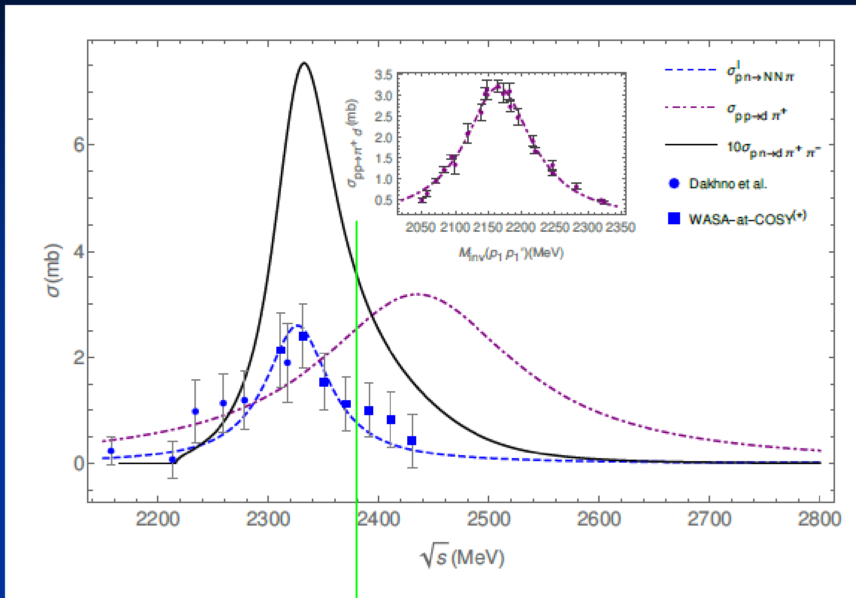
IHEP., PRC 94 (2016) 014003 | $NN \leftarrow \to NN\pi$

Gal. PLB 769 (2017) 436

channel	rel. branching	rel. branching
$d\,\pi^0\pi^0$	1	1
$d\,\pi^+\pi^-$	2	2
$np\pi^0\pi^0$	1	1
$np\pi^+\pi^-$	5/2	5/2
$pp\pi^0\pi^-$	1/2	1/2
np	≈ 0.9 √	0
$(NN\pi)_{I=0}$	≈ 0 √	≈1.3

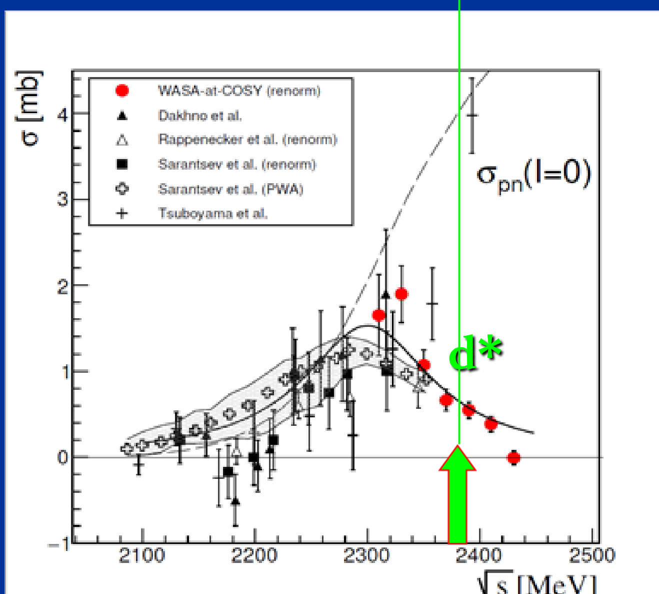
Identical Isospin Relations

Sequential Single-Pion Production



Oset et al., arXiv: 2102.05575
Chin. Phys. C 47 (2023) 041001

pn (I=0) → {NN} π (I=0)
→ {dπ } π (I=0)

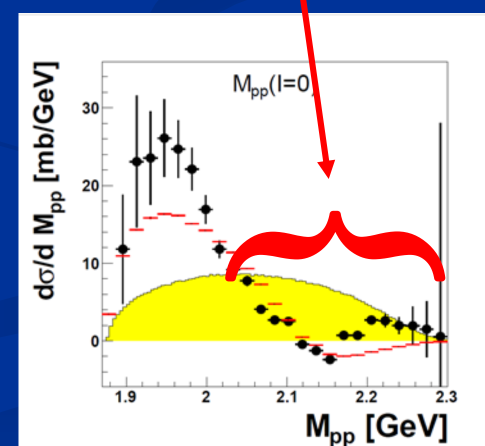


PWA: $pn(^3D_3) \to pp(^1D_2)\pi^- \leq 10\%$

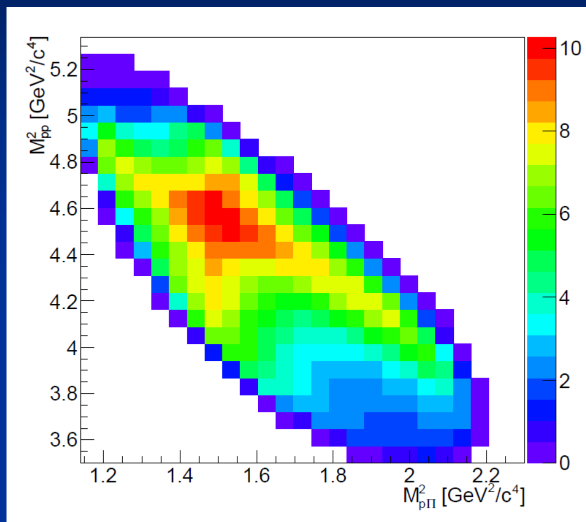
Phys. At. Nucl. 85 (2022) 459

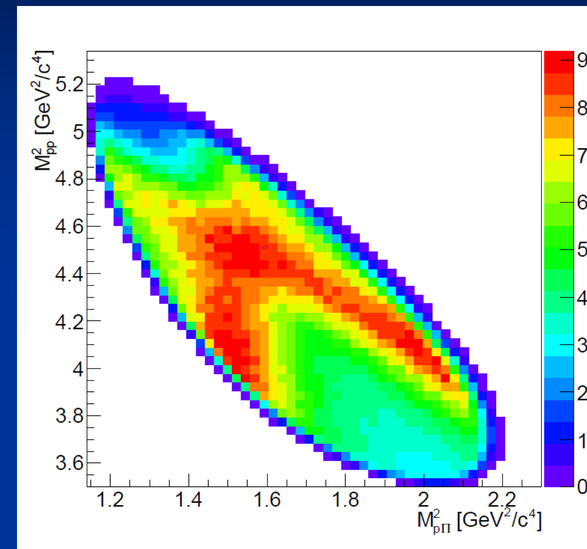
pn (I=0) → NNπ (I=0)

PLB 774 (2017) 599
PLB 806 (2020) 135555
PRC 106 (2022) 065204

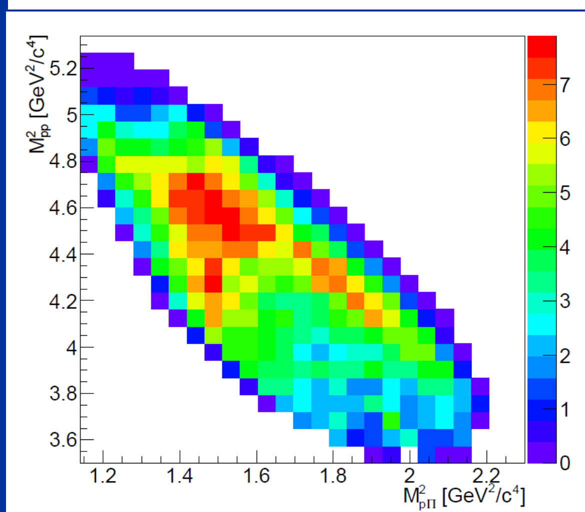


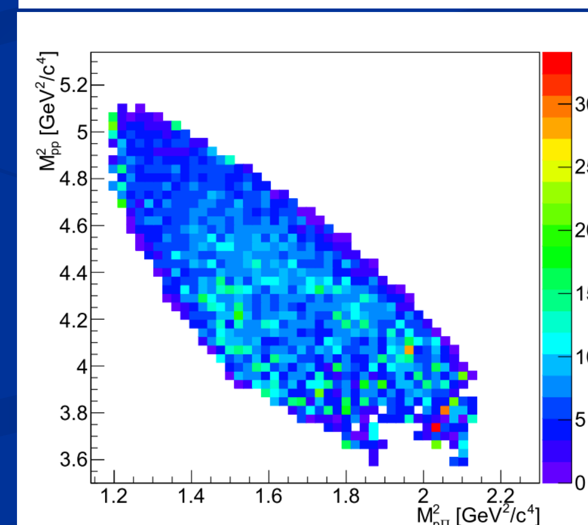
$pp \to pp\pi^0$ $pn \to pp\pi^-$





MC



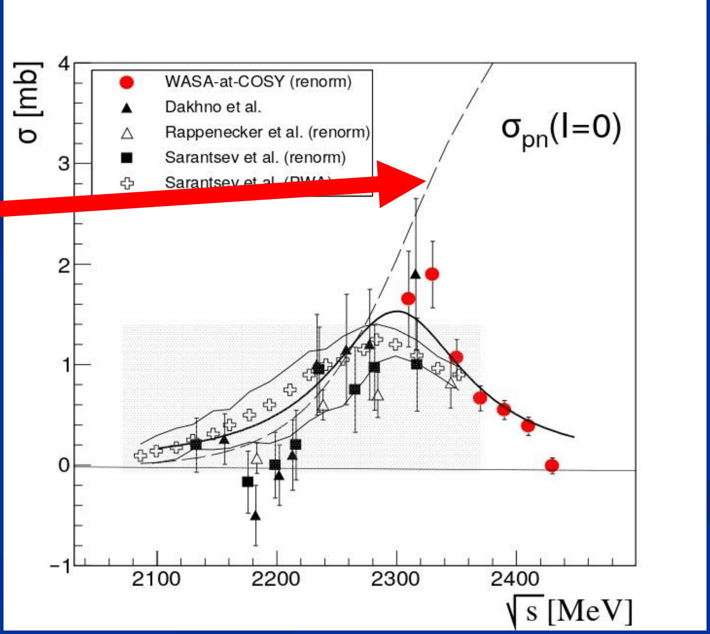


Data

States near NN*(1440) Threshold?

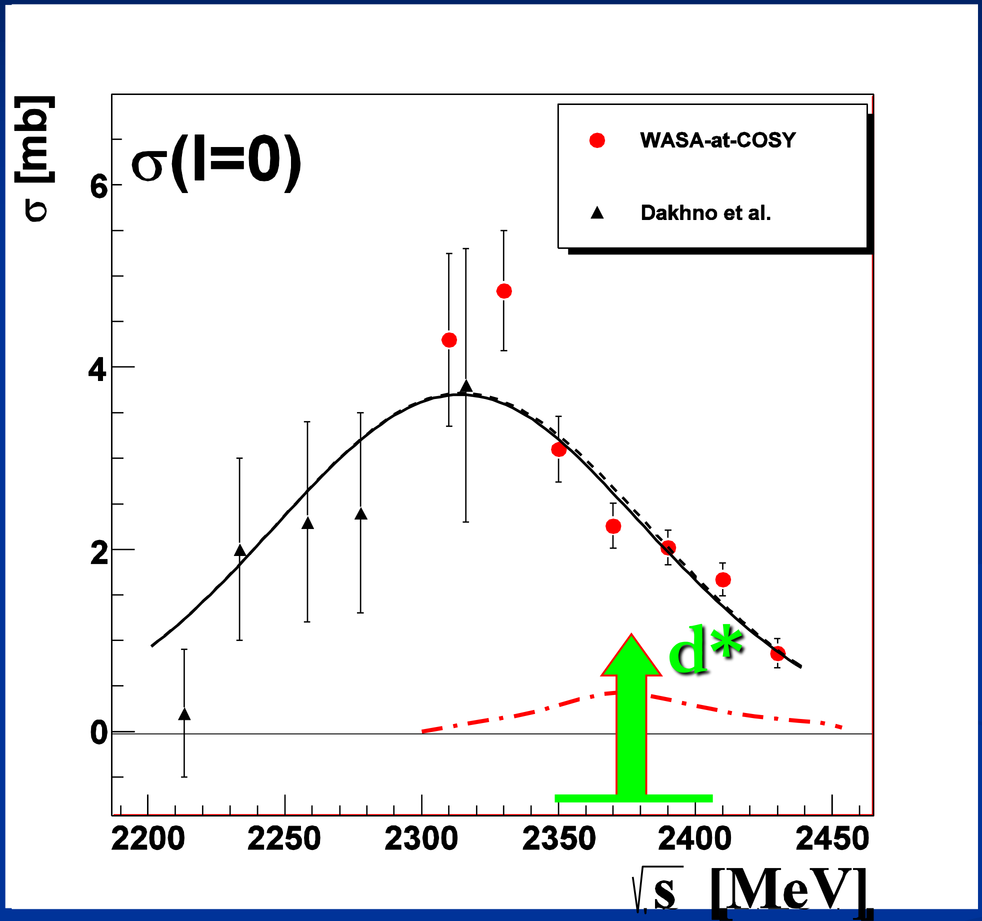
- Isoscalar Single Pion Production:
- $\sigma_{NN \rightarrow NN\pi}(I{=}0) = 3/2(2\sigma_{np \rightarrow pp\pi^-} - \sigma_{pp \rightarrow pp\pi^0})$

- *Expect rising cross section,*
- *but falls off beyond 2.3 GeV*



PRC 106 (2022) 065204

Isoscalar Single-Pion Production



BR < 5%
(90% C.L.)

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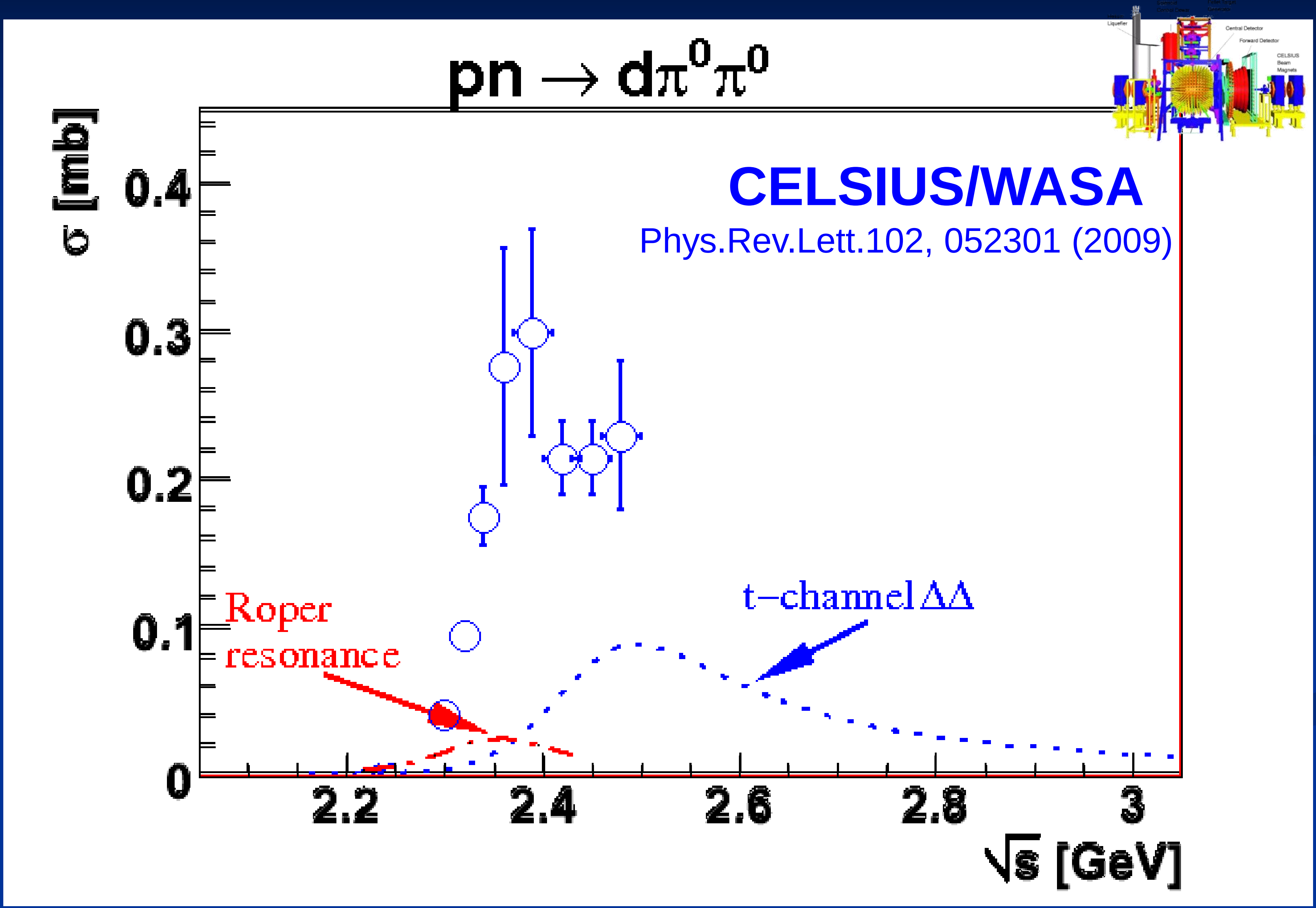
Isoscalar : … and this is what we found!



„Experimentum Crucis" for d^*

If d^* a true s-channel resonance

$\Leftrightarrow$

then also a resonance in the np system

$\Leftrightarrow$

to be sensed in np scattering

$\Leftrightarrow$

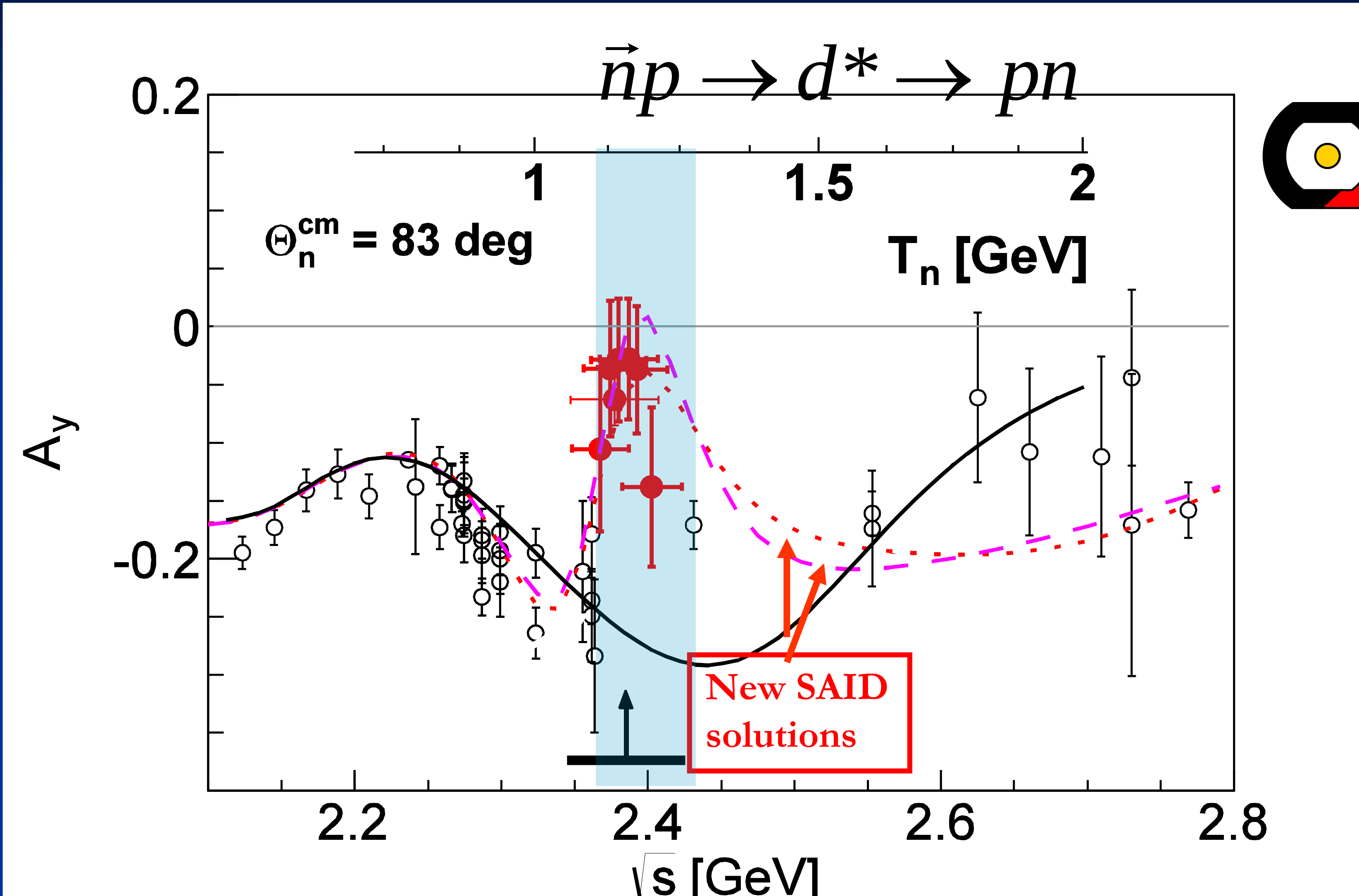
in particular in the analyzing power

$\Leftrightarrow$

resonance effect $\sim P^1_3(\Theta)$

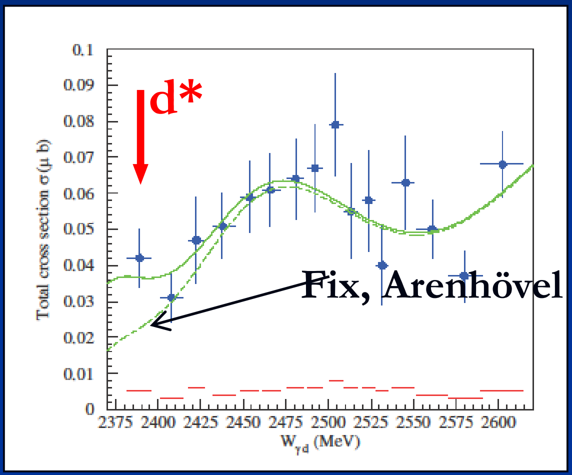
i.e. maximal at $\Theta = 90^0$

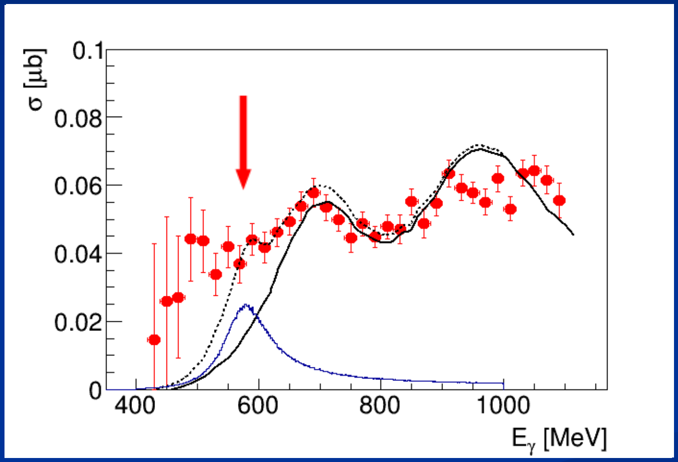
Energy Dependence

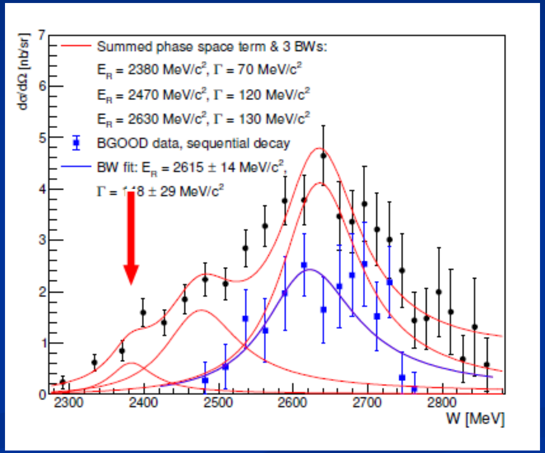


Phys. Rev. Lett. 112 (2014) 202301

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



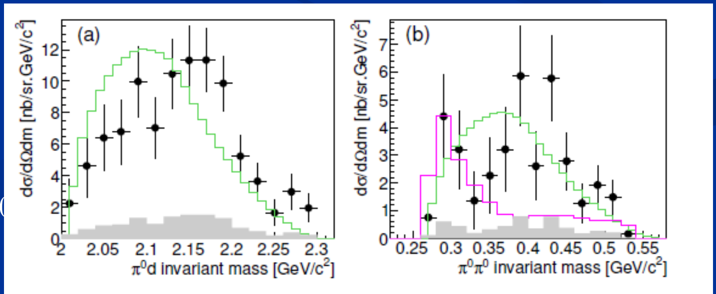




FOREST@ELPH, PLB 772 (2017) 398

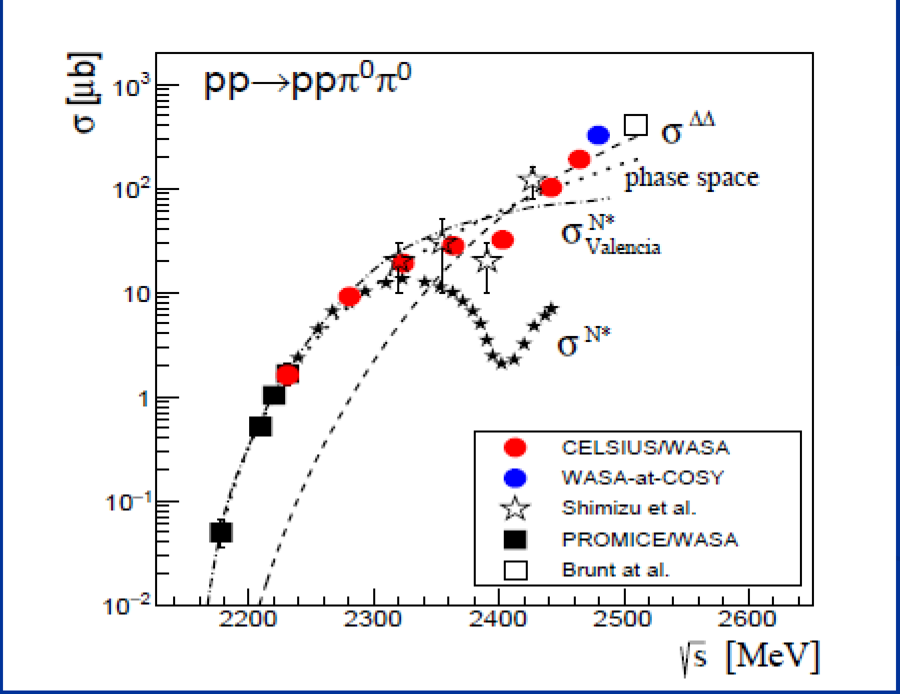
Crystal Ball @ MAMI
PoS (Hadron2017) 051

BGOOD@ELSA
arXiv: 2202.08594



Theoretical prediction: $\sigma \approx 1 - 2$ nb IJMP A34 (2019) 195010

$I(J^P) = 1(0^+)$?



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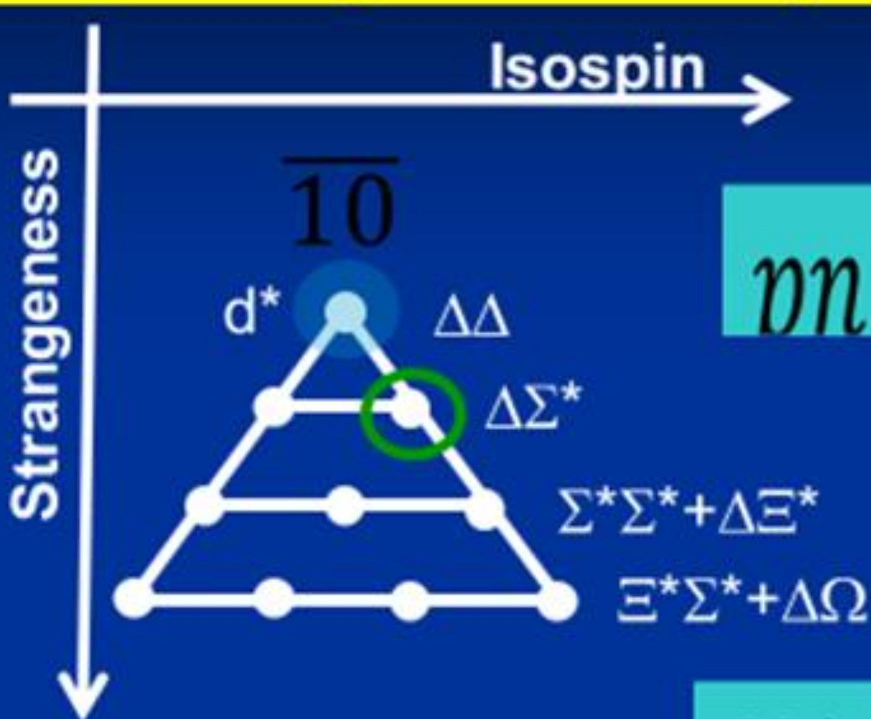
Strange Dibaryon

M. Bashkanov, York



$pn \rightarrow d\pi\pi$

→ pn

→ $\Delta\Delta \rightarrow NN\pi\pi$

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

→ $N\Lambda$

→ $\Delta\Sigma^* \rightarrow (N\pi)(\Lambda\pi) \rightarrow NN\pi\pi\pi$