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Kepler Center for Astro and Particle Physics

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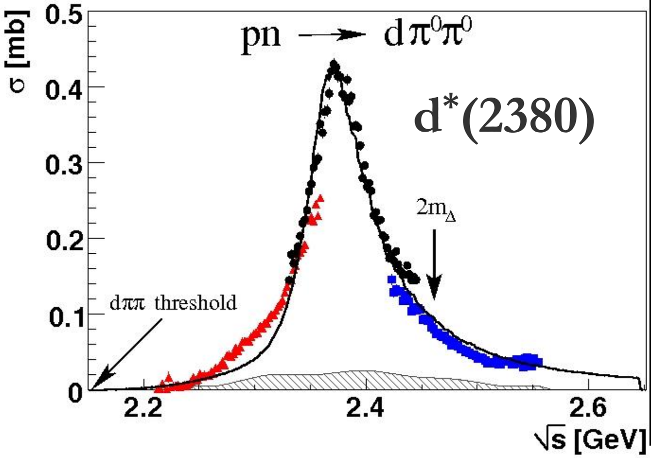

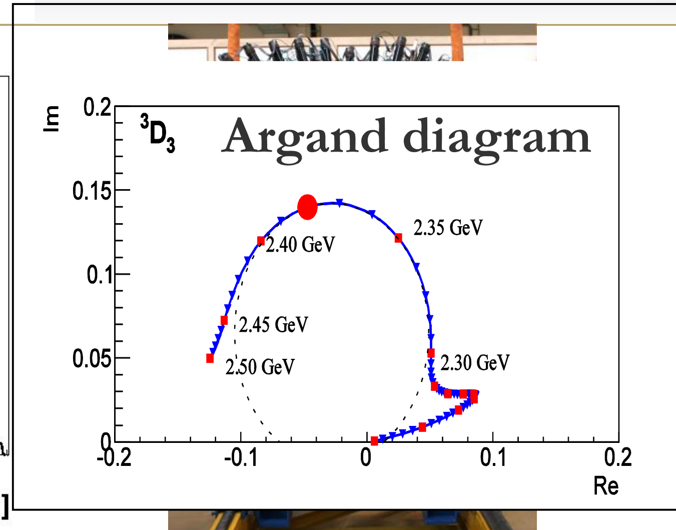

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Dibaryons – Molecule versus Hexaquark

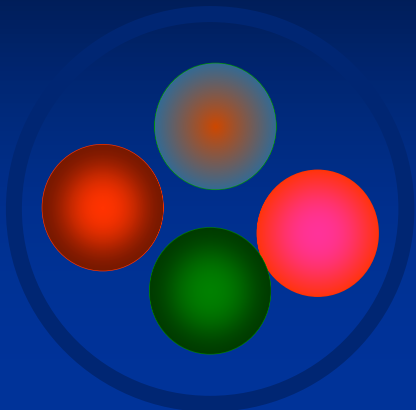
EMMI Workshop

Bologna, Feb. 13 -17, 2023

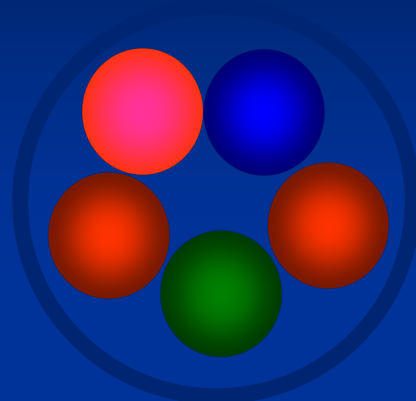
Heinz Clement

Exotics

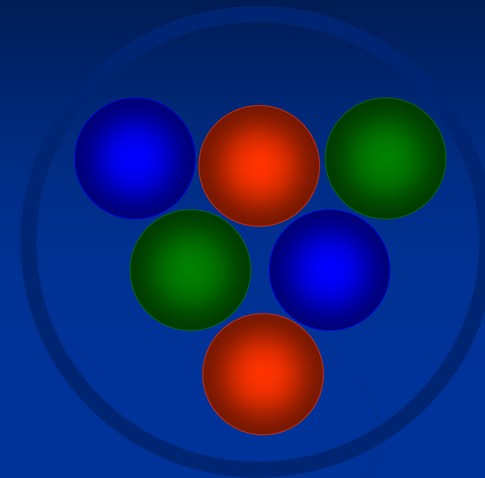
Tetraquark



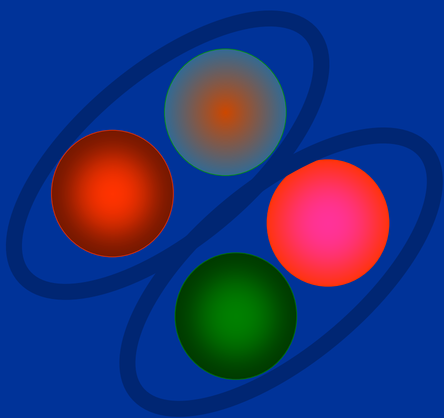
Pentaquark



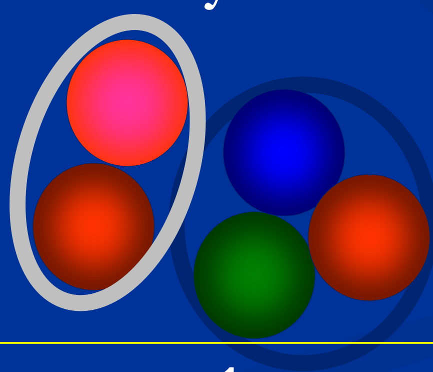
Hexaquark



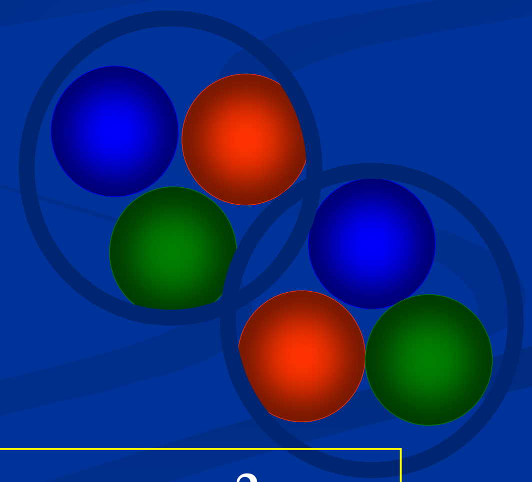
Meson-Meson molecule



Meson-Baryon molecule



Baryon-Baryon molecule



B = 0	1	2

Dibaryon

2

Width of a Resonance

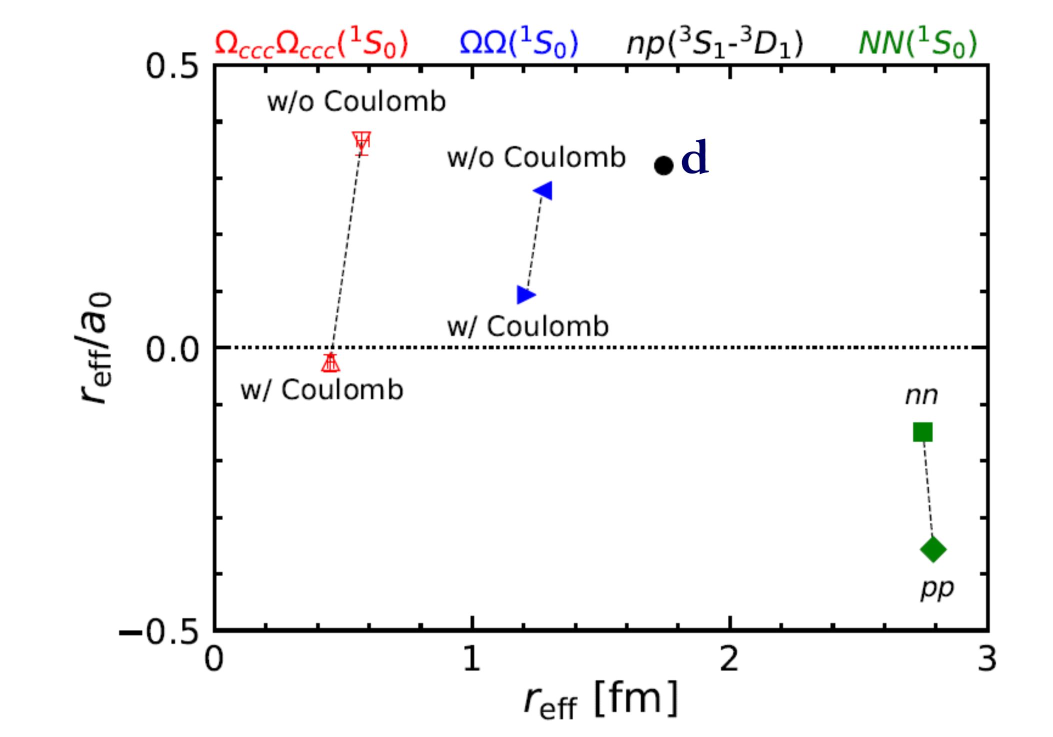
- If width of decay products large, then also resonance width large in general (unflavored sector)

- If width of decay products small, then also the resonance width can be **small (charm and beauty sectors)**
  - Many predictions for a diversity of dibaryon systems,
  - see e.g. Chin. Phys. C 45 (2021) 022001 and many newer ones

a favorite $\Xi_b\Xi_b$??

Flavored Dibaryons

- **LQCD predictions (HAL QCD) :**



PRL 127 (2021) 072003

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 bags: 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?

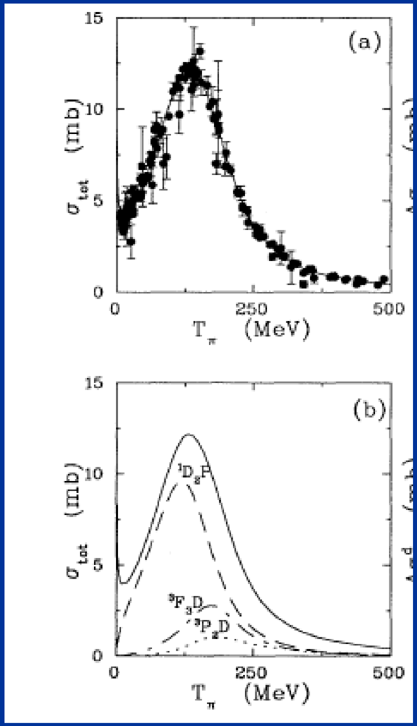
Early Predictions of Dibaryons

- 1964 Dyson & Xoung: 6 non-strange states
- 1975 Jaffe: H-dibaryon (uuddss: ΛΛ)
- Thereafter:
- multitude of predictions of a vast number of dibaryon states (Nijmegen group, ...)
- $\Rightarrow$ **Dibaryon Rush Era:**
- Many experimental claims …
- but **no single one firmly** established finally

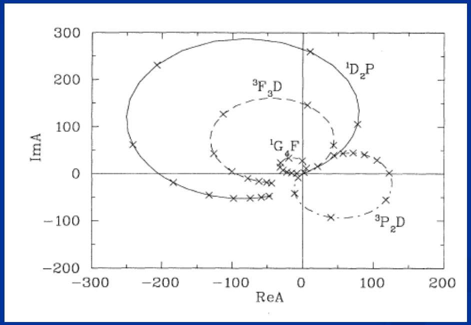
Possibly the only surviver: $^1D_2$ Resonance

- Best seen in pp ↔ $d\pi^+$,
  - but also in pp → $pn\pi^+$ as well as pp and π^+d scattering (phaseshift 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

$I(J^P) = 1\ (2^+)$
$M \approx 2148$ MeV $= m_\Delta + m_N - 22$ MeV
$\Gamma \approx 126$ MeV $\approx \Gamma_\Delta$

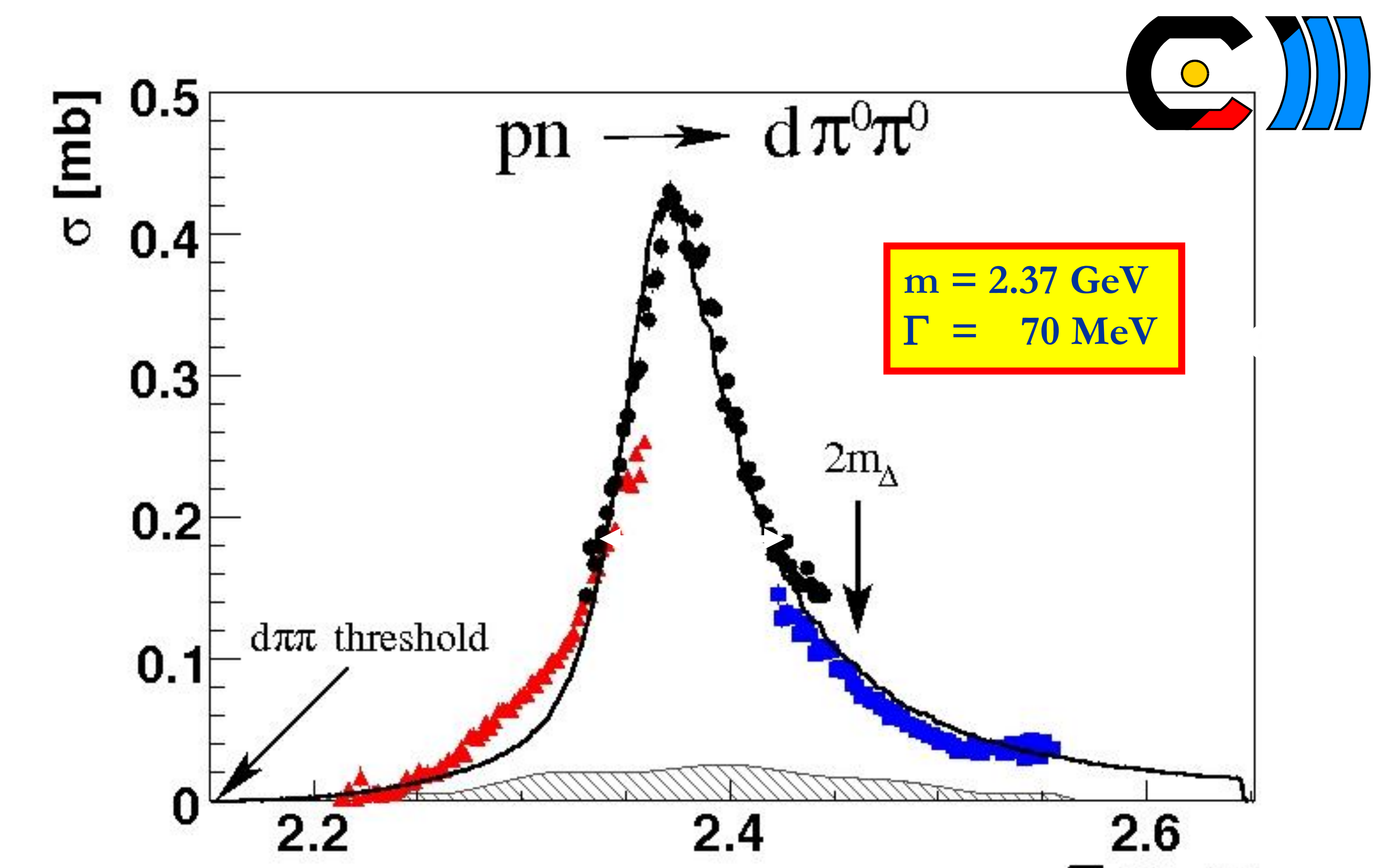
Alternative description: cusp, virtual state, reflection D. Bugg et al.
However, not consistent!!! Kukulin and Platonova PRD 94 (2016) 054039

Conclusion from the Failures in the Dibaryon Rush Era:

Do Exclusive and kinematically complete measurements

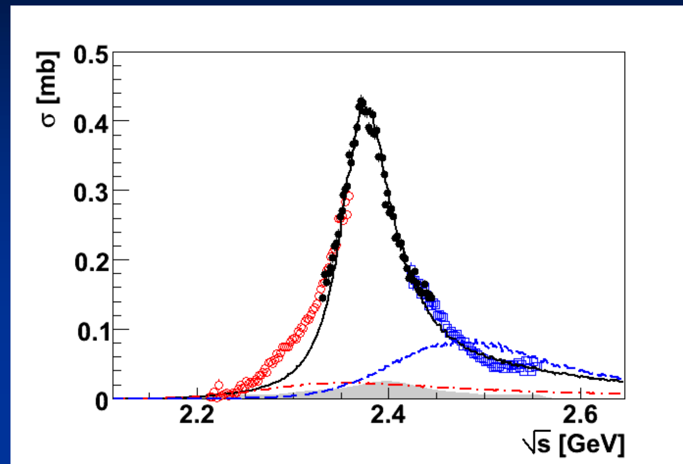
- Our approach:
  - Two-pion production with best suited equipment
    - 4π detector: WASA
    - pellet target: p and d
    - storage ring: CELSIUS → COSY
  - The learning phase:
    - pp induced two-pion production
  - Following a trace:
    - the ABC effect in double-pionic fusion
  - The surprise: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

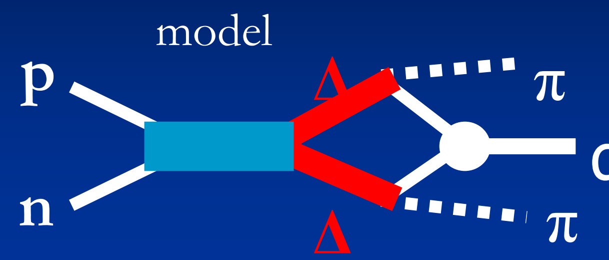
Isoscalar : Results from WASA at COSY



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

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

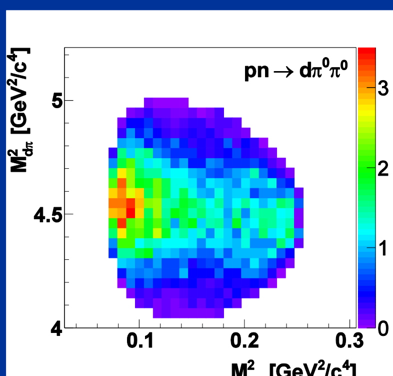


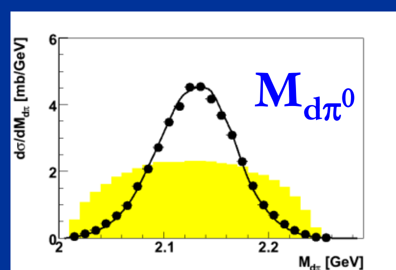


$I\,(J^P) = 0\,(3^+)$

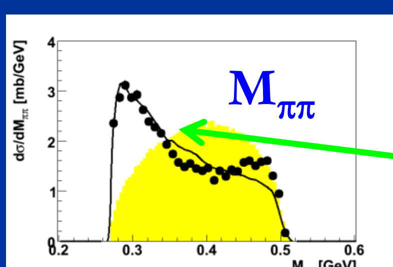
$M, \Gamma, \Gamma_i * \Gamma_f, F(q_{\Delta\Delta})$

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

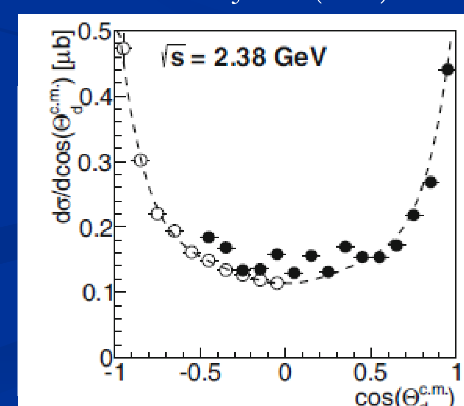




EPJA 52 (2016) 147

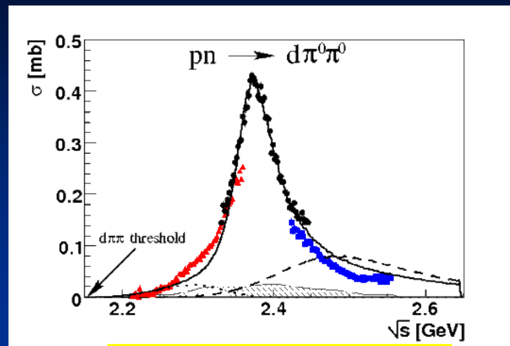


ABC effect

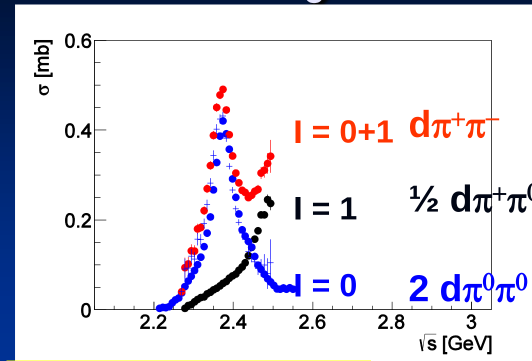


hadronic decays

PRL 106 (2011) 242302



PLB 721 (2013) 229



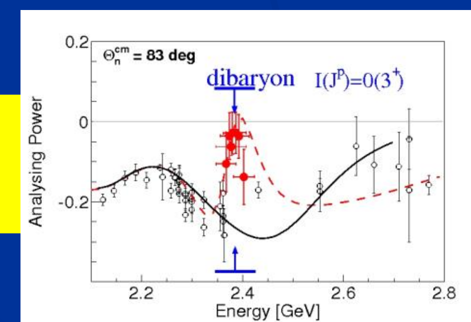
○ ● ● WASA data

$d\pi^0\pi^0$

$d\pi^+\pi^-$

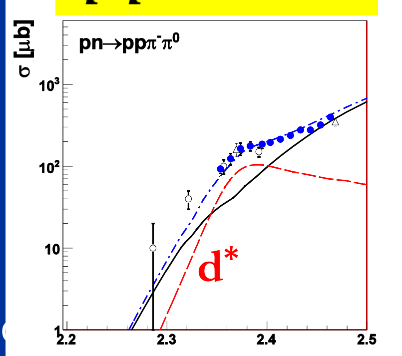
pn → d*(2380)

pn

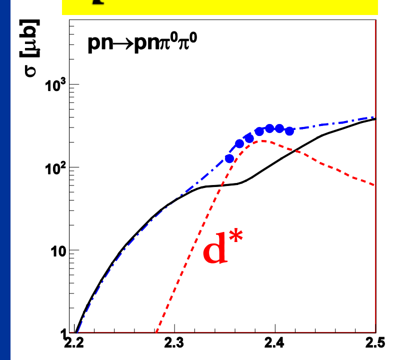


PRL 112 (2014) 202301
PRC 90 (2014) 035204

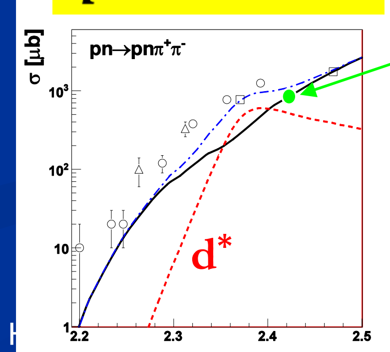
$pp\pi^-\pi^0$



$pn\pi^0\pi^0$



$pn\pi^+\pi^-$



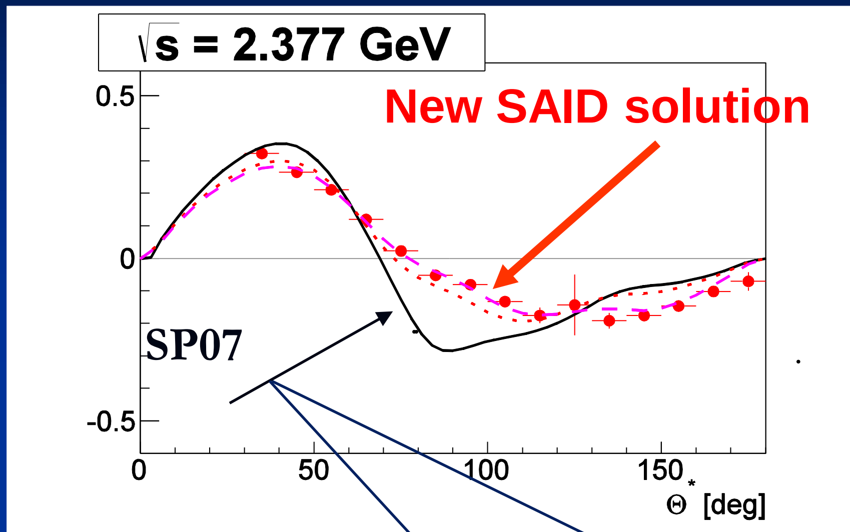
HADES PLB 750 (2015) 184

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

→ √s [GeV]

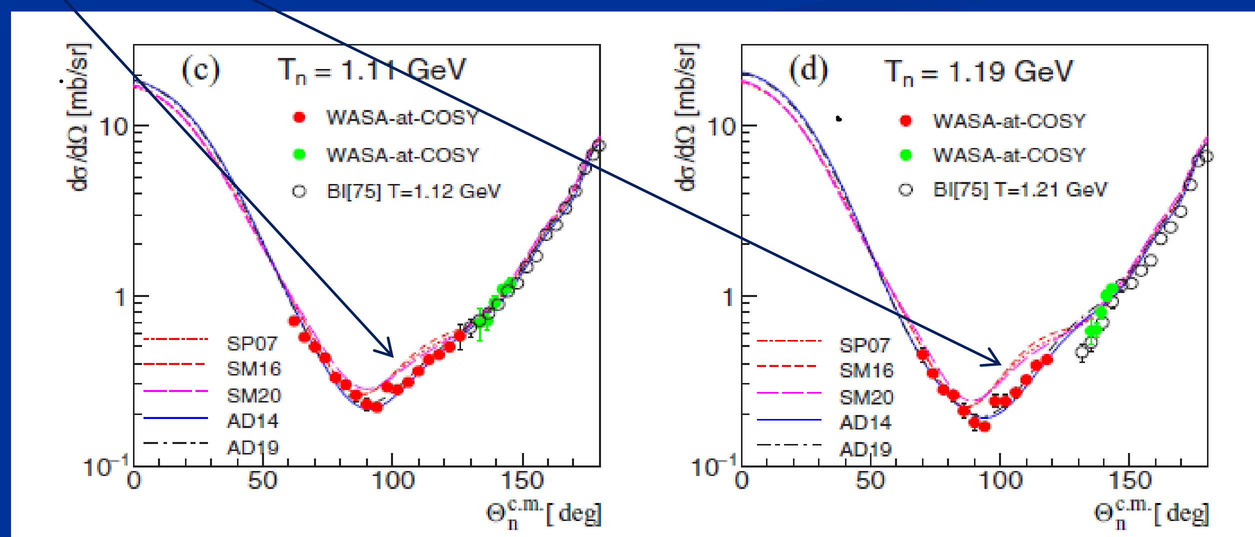
np Elastic: Angular Distributions at Resonance

$A_y(\theta)$



Phys. Rev. Lett. 112 (2014) 202301

$\sigma(\theta)$

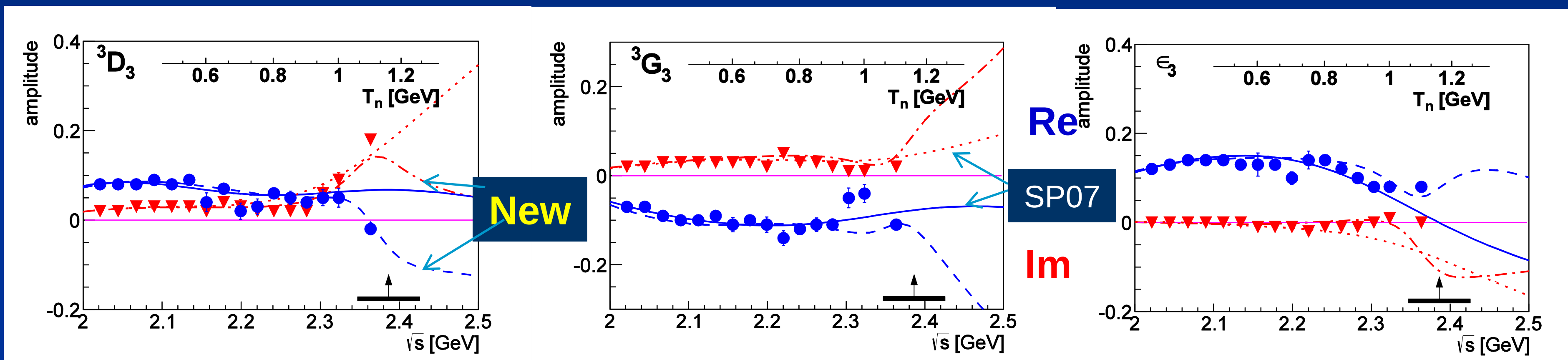


PRC 102 (2020) 015204

SAID Partial-Wave Analysis

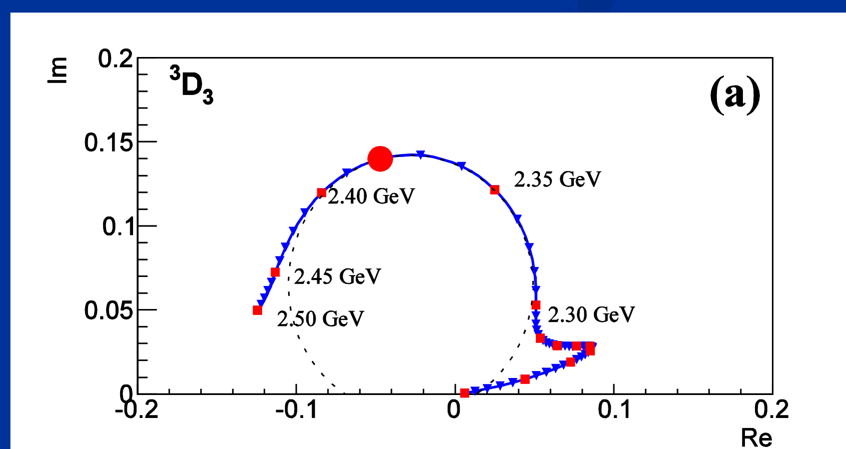
$^3D_3 - {}^3G_3$ Coupled Partial Waves

Phys. Rev. Letters 112 (2014) 202301



Argand diagram:

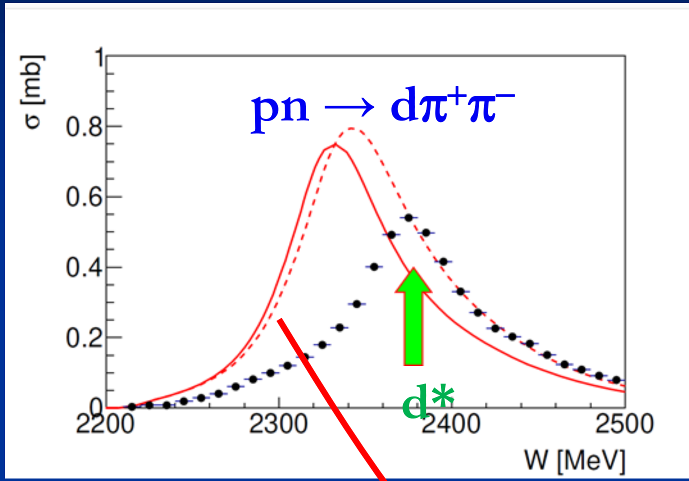
PRC 90 (2014) 035204



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

⇔ Genuine Resonance in np System

Sequential Single-Pion Production



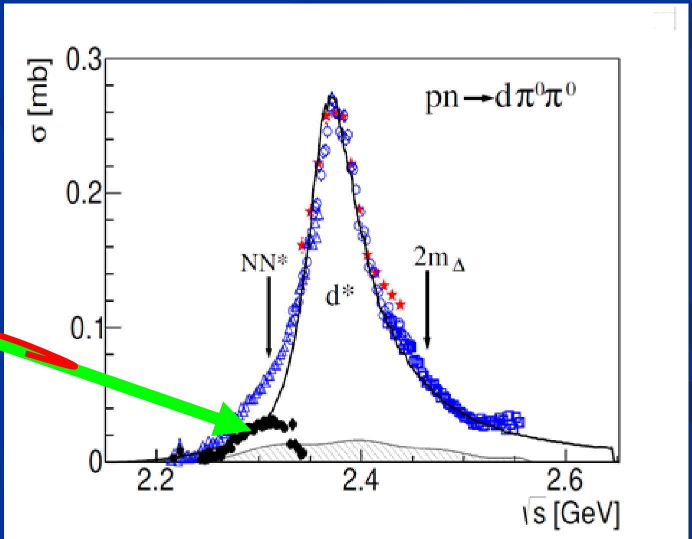
arxiv 2106.0094

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

arxiv 2102.0557

Using proper single-pion data and proper partial waves

PRC 106 (2022) 065204



pn(I=0) → NN* → NΔπ→ dπ⁰π⁰

$J^P = 1^+$ and 1^-

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

- hadronic decays

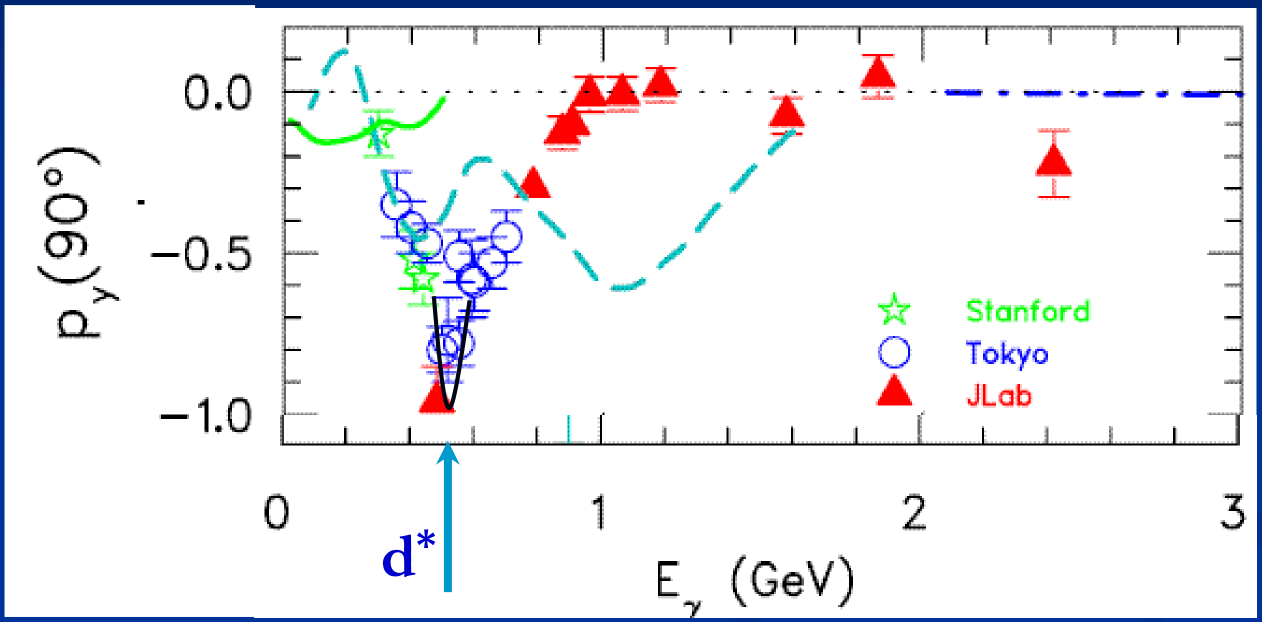
EPJA 51 (2015) 87

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

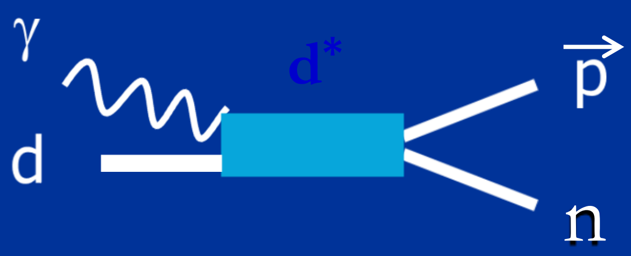
consistent with isospin coupling for a ΔΔ inter-mediate system*

*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

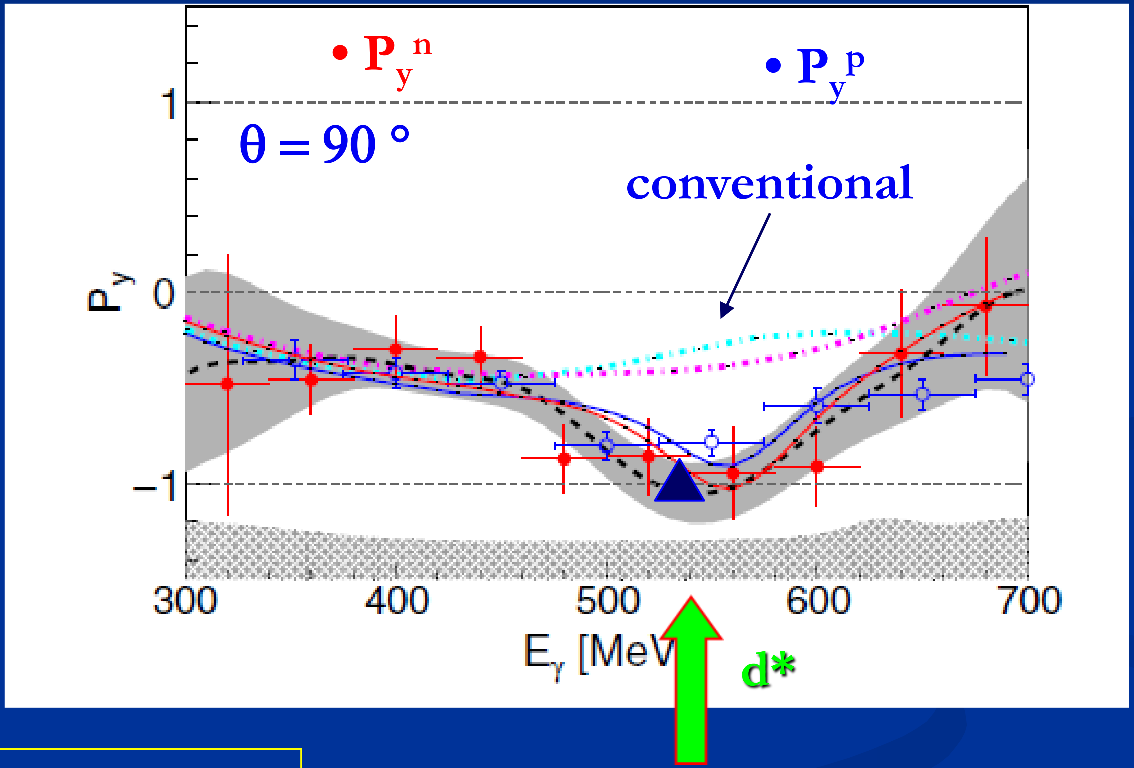
$\gamma d \rightarrow \vec{p} n$
$\rightarrow p \vec{n}$

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

$\longrightarrow$

pn system in S=1

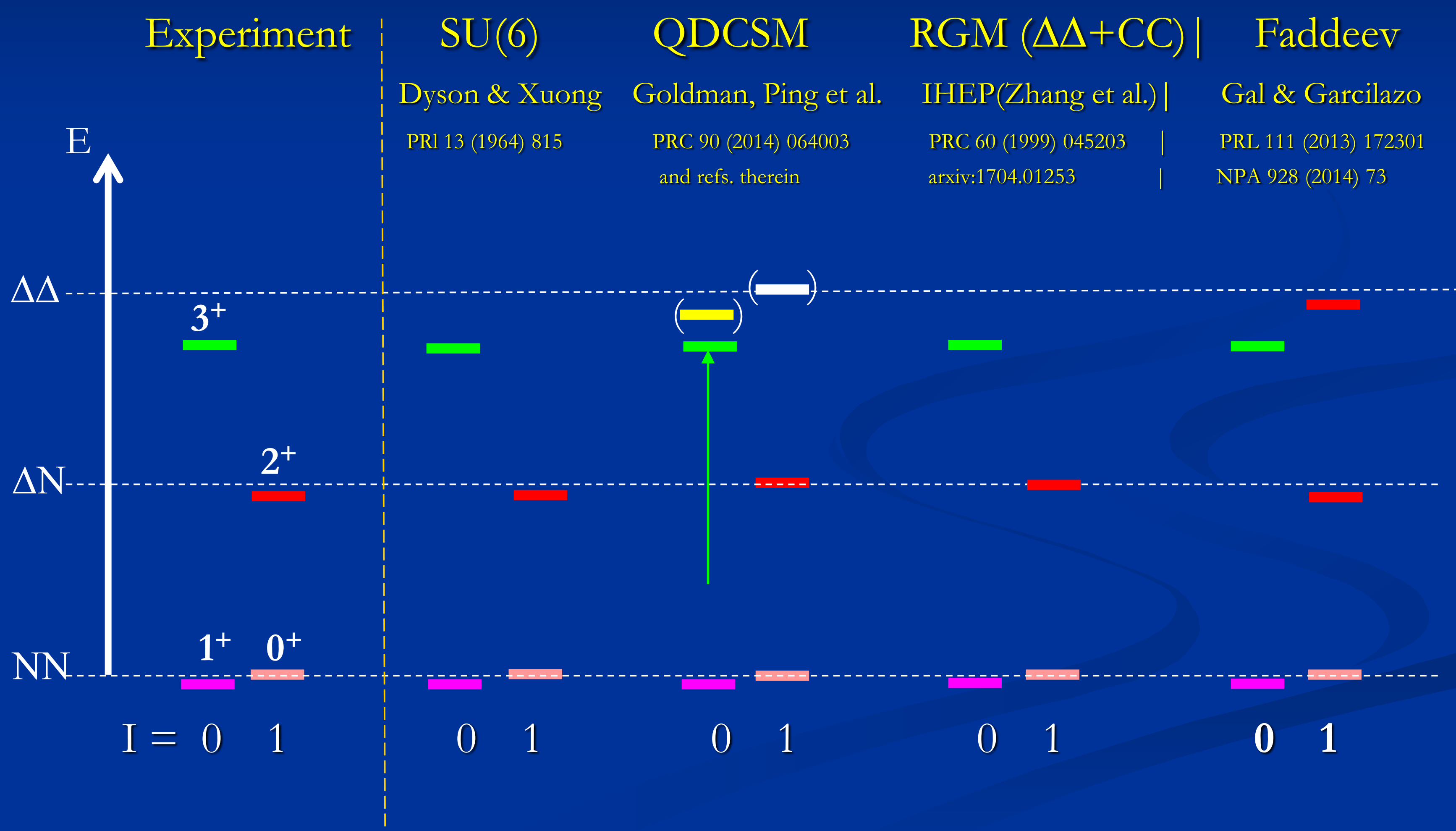
PWA ???



Legendre decomposition of P_y:
P_3^1 gives largest contribution

A2-MAMI, PRL 124 (2020) 132001

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

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

} hexaquark

- Faddeev hadr. G&G 1.5 – 2 fm

molecule

PLB 769 (2017) 436

Branching via Intermediate State

hexaquark		molecule
$d^* \rightarrow \Delta\Delta \rightarrow NN\pi\pi$	|	$d^* \rightarrow {}^1D_2\,\pi \rightarrow NN\pi\pi$
IHEP., PRC 94 (2016) 014003	|	$NN \leftarrow\!\rfloor\!\rightarrow NN\pi$

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

Rèsumè

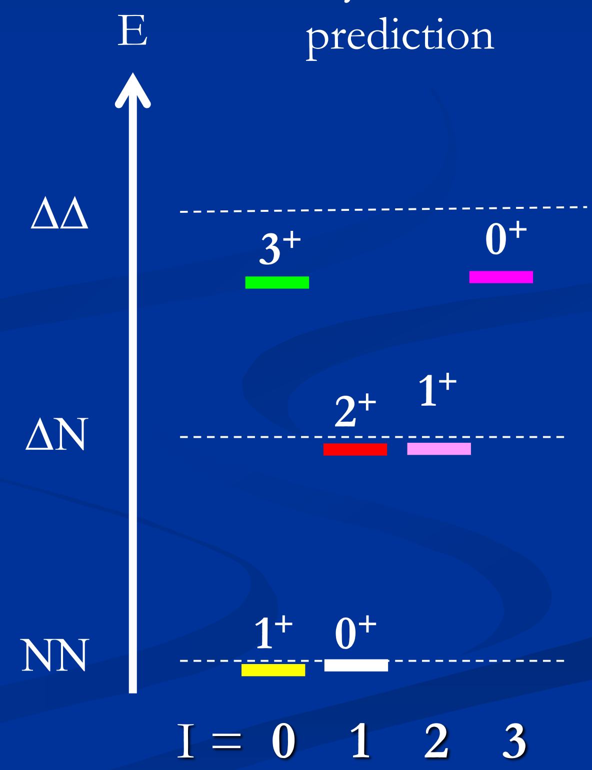
Zhang, Chen, Shen et al.

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 $pp \rightarrow pp\pi^+ \; \pi^-$ √
      and in $pp \rightarrow pp\pi^+\pi^+ \; \pi^-\pi^-$

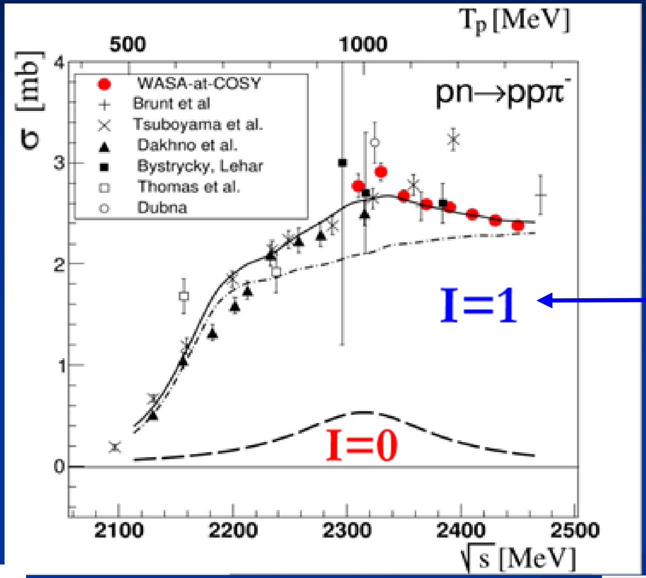


(Molecular) States near ΔN Threshold

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

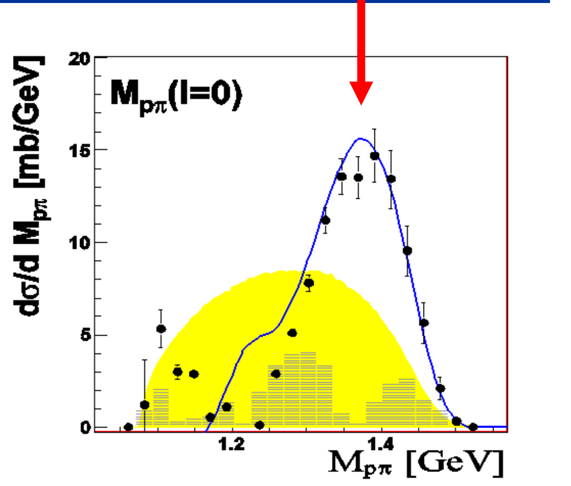
Isoscalar Single-Pion Production: N*N

PRC 106 (2022) 065204

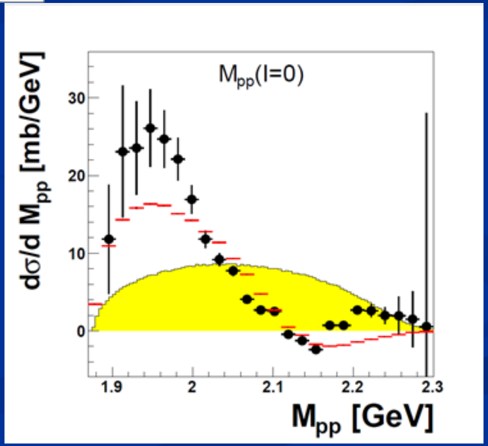


½ σ(pp → ppπ^0)

Roper



PLB 774 (2017) 599



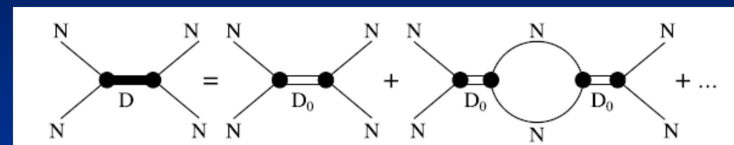
(Molecular) States near NN* Threshold

	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

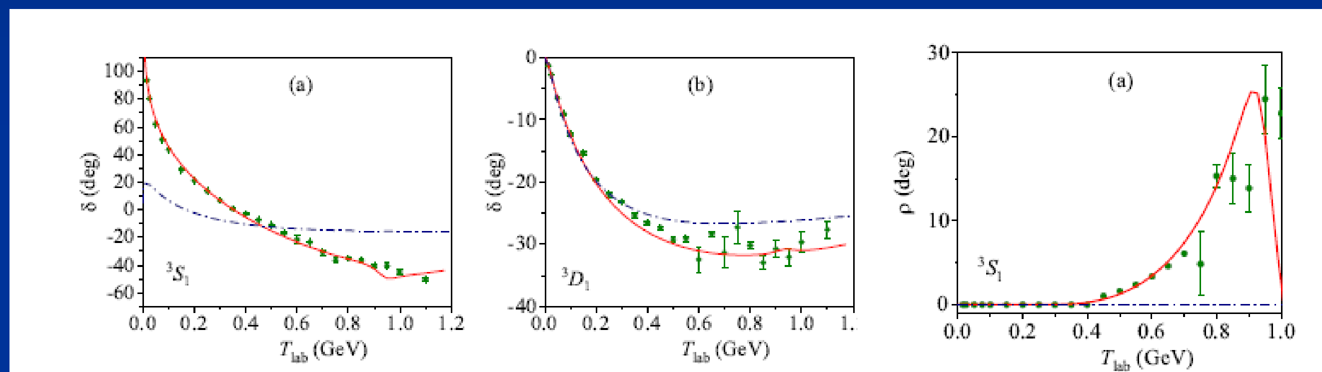
NN-interaction with intermediate dibaryon formation

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



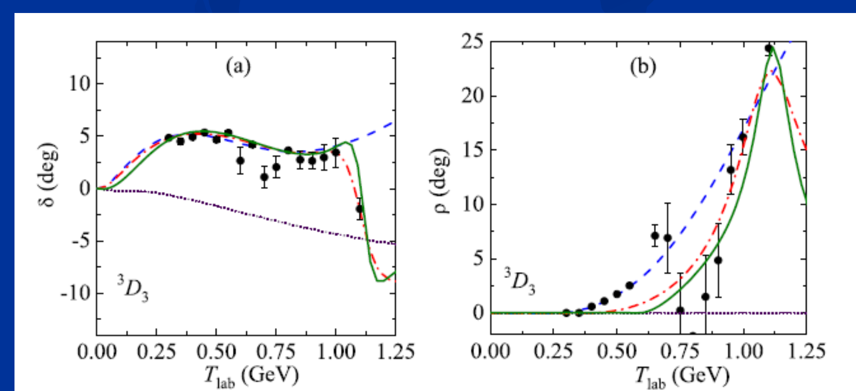
$^3S_1 - ^3D_1$

EPJA 56 (2020) 229



$^3D_3$

PLB 801 (2020) 135146

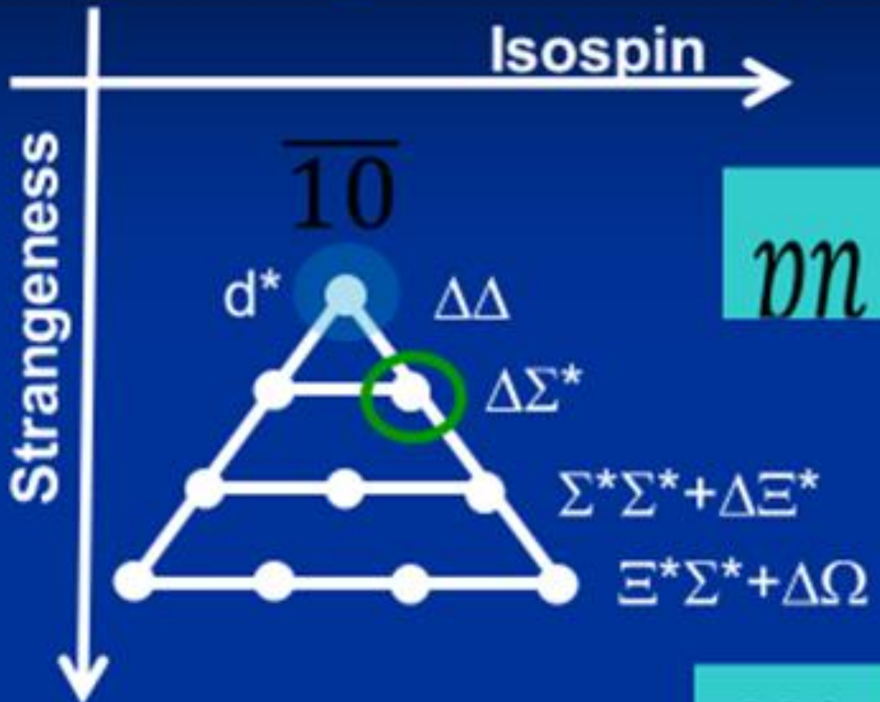


Outlook and Open Problems

- Size of $d^*(2380)$
  - $\Rightarrow$ elm excitation of d^* $\quad ed \rightarrow ed^* \rightarrow ed\pi^0\pi^0$
- Observation at other installations
  - HADES @ GSI: but no full 4π
  - IHEP ?? $\quad e^+e^- \rightarrow \bar{d}\, d^*$ at 4.3 – 4.6 GeV ??
  - KEK, JPARC, LHCb, others ???
- Astrophysical relevance? (M. Bashkanov, York)
- Are there more (exotic) dibaryons?
  - D_{30} mirror state of d^*
  - strange, charmed and beautiful dibaryons??

Strange Dibaryon

M. Bashkanov, York



$pn \to d\pi\pi$ → pn

$pn \to d\pi\pi$ → $\Delta\Delta \to NN\pi\pi$

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

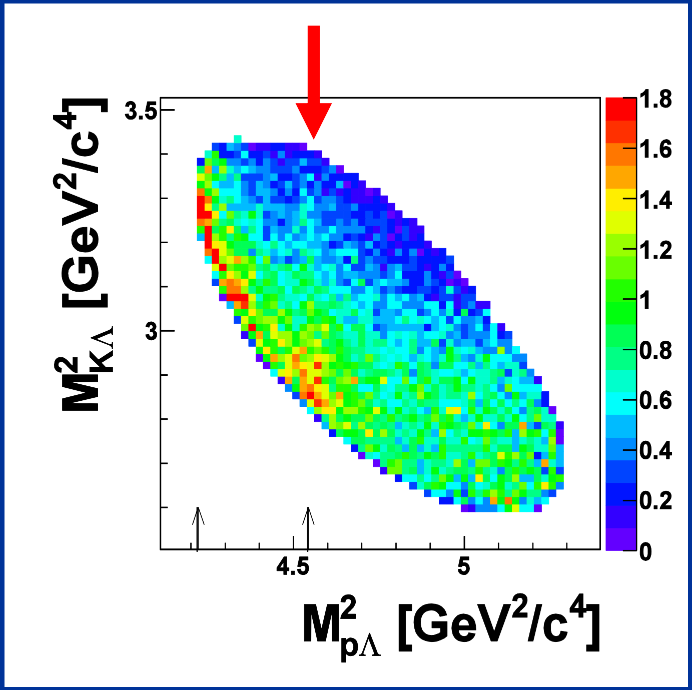
$d_s^*(2530\text{-}2600)$ → $\Delta\Sigma^* \to (N\pi)(\Lambda\pi) \to NN\pi\pi\pi$

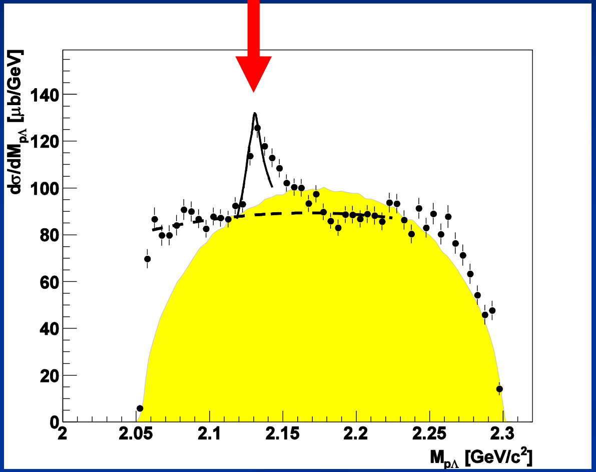
$pp \to K^+ p \Lambda$

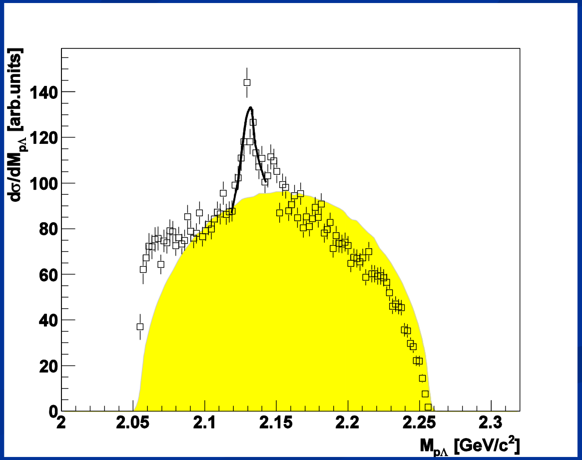
- COSY-TOF

NΣ cusp

NΣ threshold

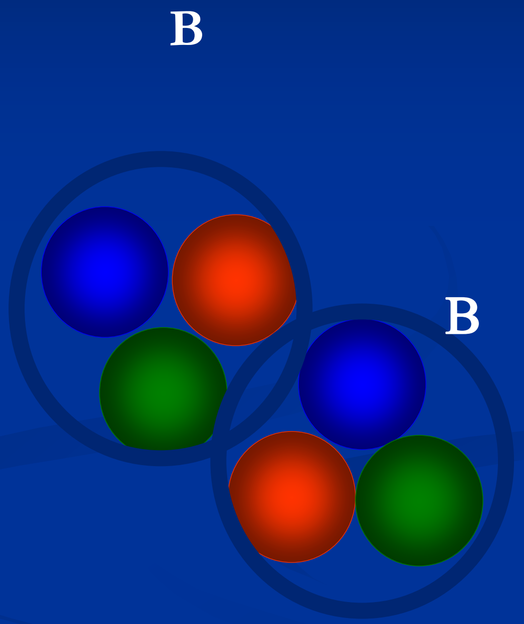






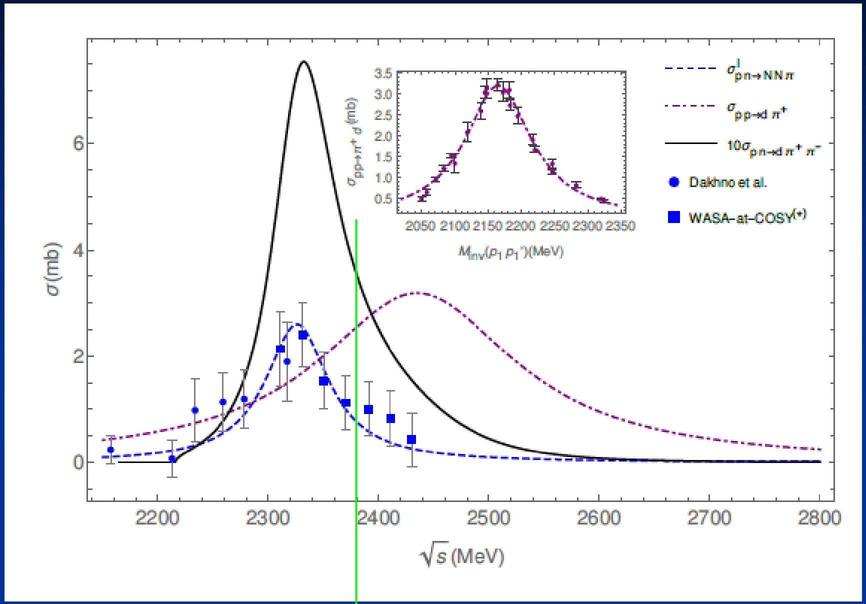
EPJA 49 (2013) 41

… still much to do



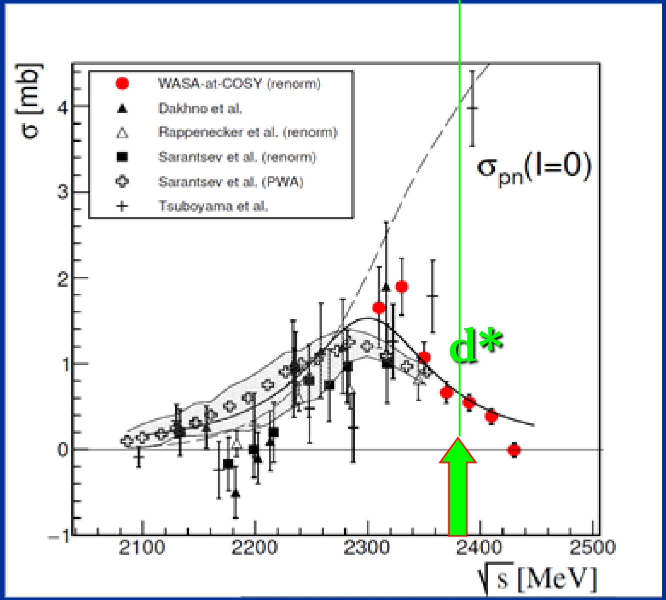
Backup Slides

Sequential Single-Pion Production



Oset et al., arXiv: 2102.05575

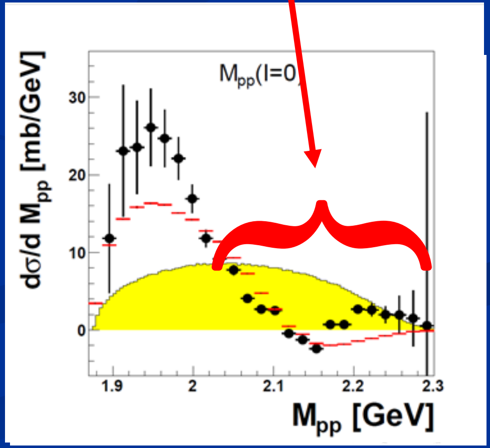
pn (I=0) → {NN} π (I=0)
→ {dπ } π (I=0)



PWA: pn($^3D_3$) → pp($^1D_2$)π^- ≤ 10%

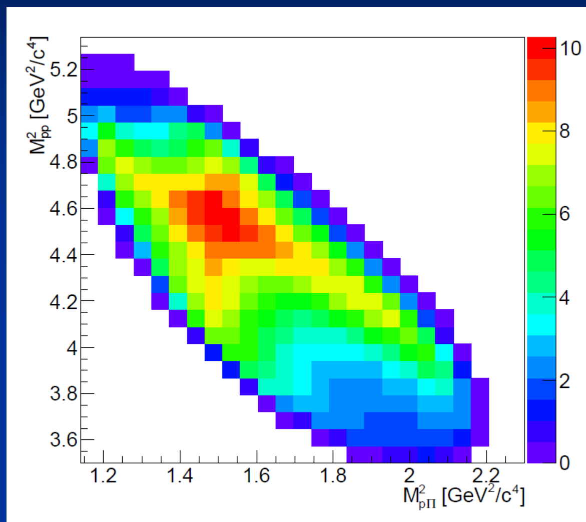
Phys. At. Nucl. 85 (2022) 459

pn (I=0) → NNπ (I=0)

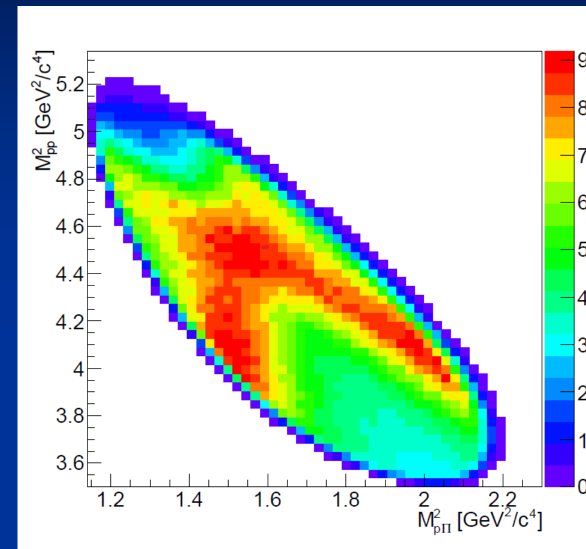


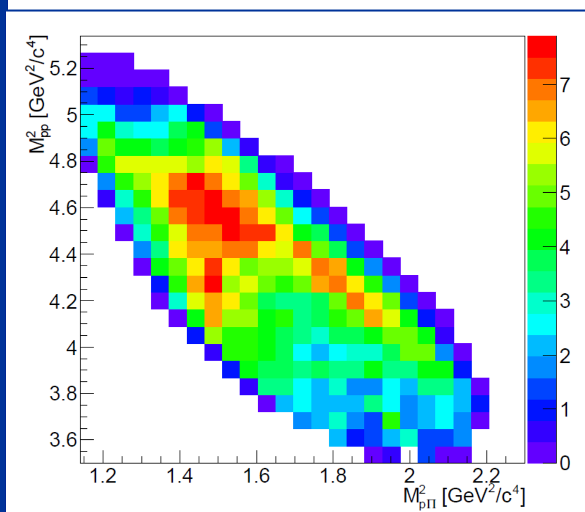
PLB 774 (2017) 599
PLB 806 (2020) 135555
PRC 106 (2022) 065204

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

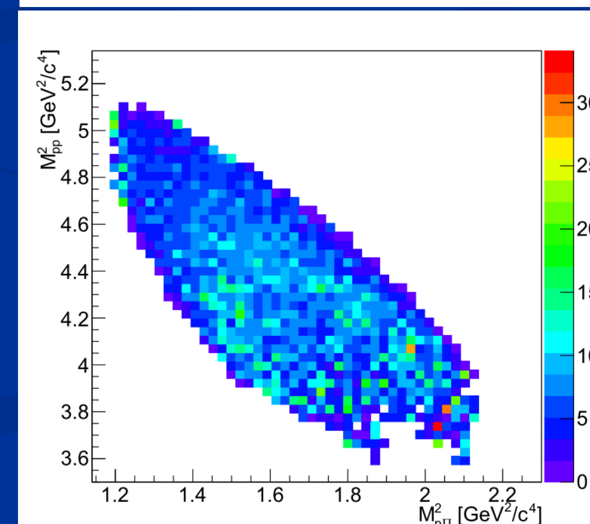


MC





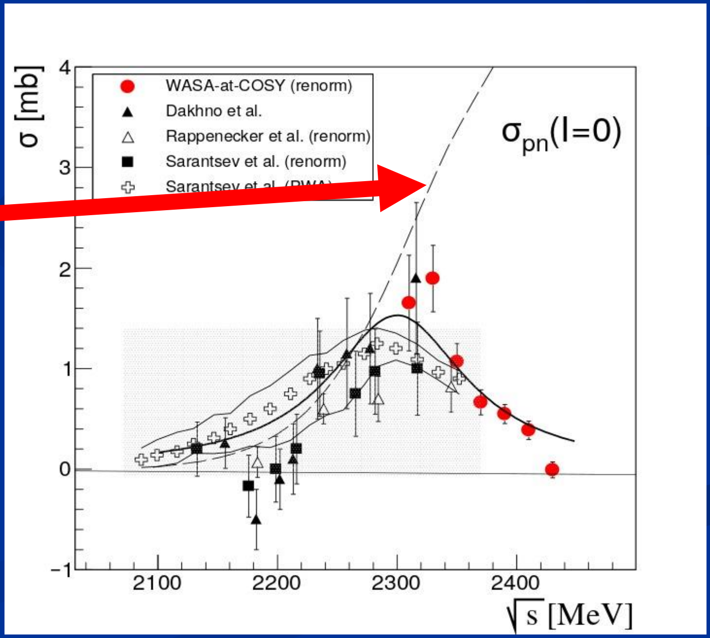
Data



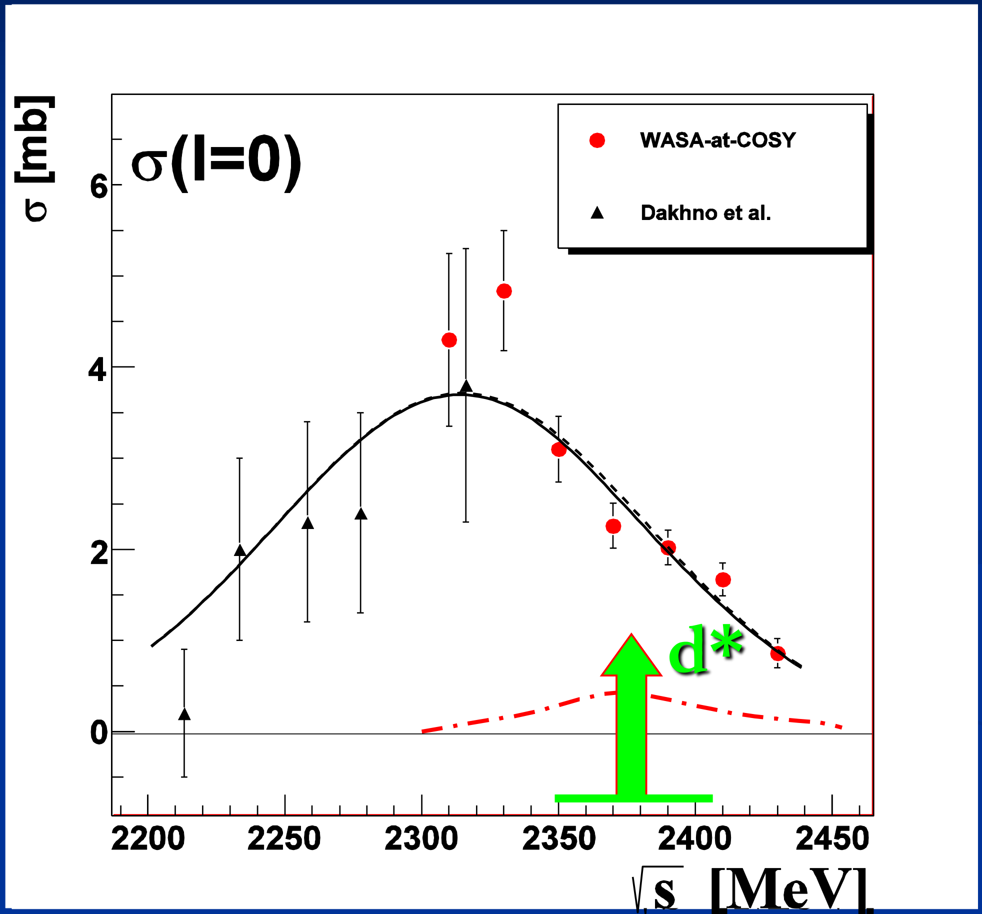
States near NN*(1440) Threshold?

- Isoscalar Single Pion Production:
- $\sigma_{NN \to NN\pi}(I=0) = 3/2(2\sigma_{np \to pp\pi^-} - \sigma_{pp \to pp\pi^0})$
- *Expect rising cross section,*
- *but falls off beyond 2.3 GeV*

PRC 106 (2022) 065204



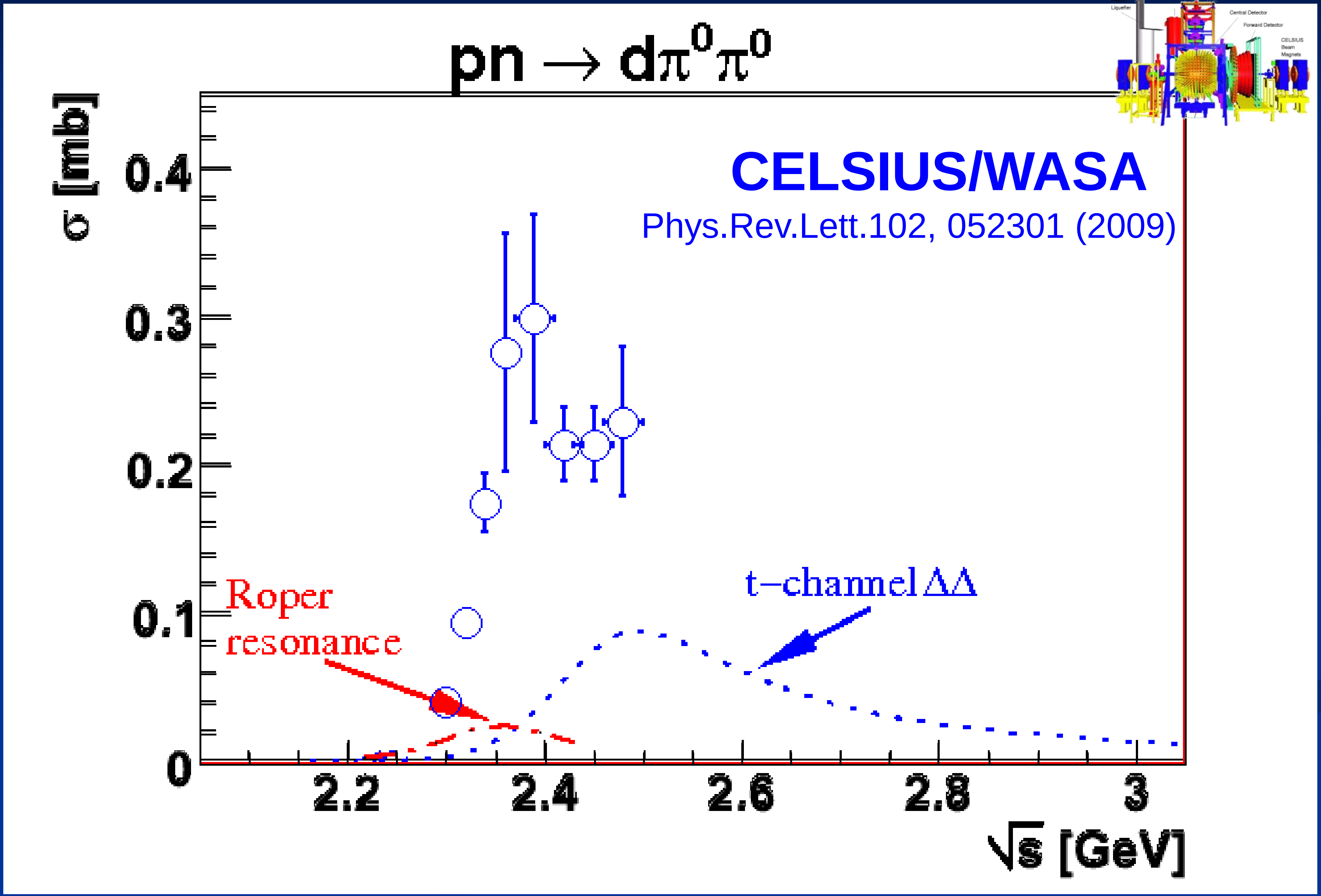
Isoscalar Single-Pion Production



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

PLB 774 (2017) 599

Isoscalar : … and this is what we found!



„Experimentum Crucis" for d^*

If d^* a true s-channel resonance

⇔

then also a resonance in the np system

⇔

to be sensed in np scattering

⇔

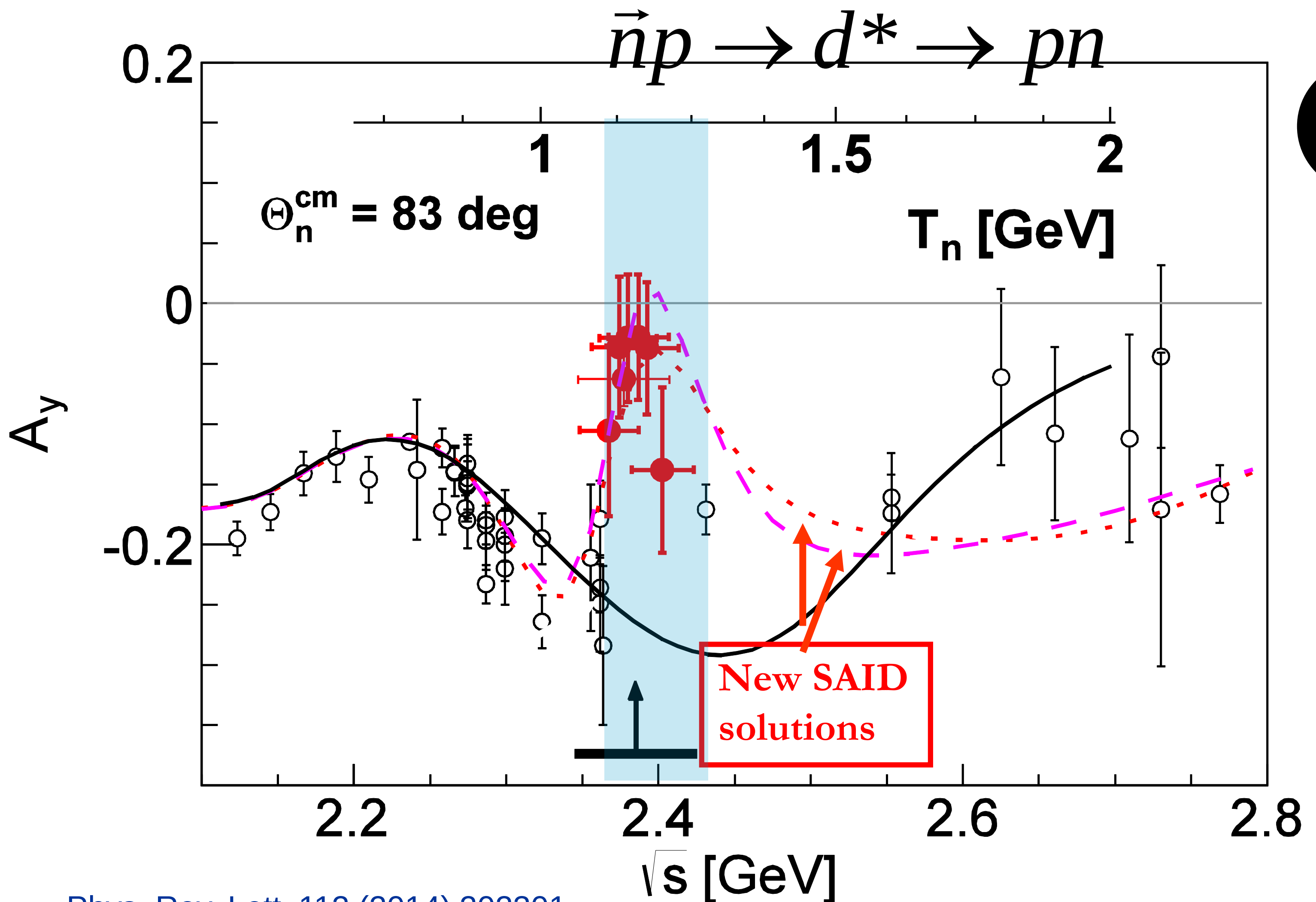
in particular in the analyzing power

⇔

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

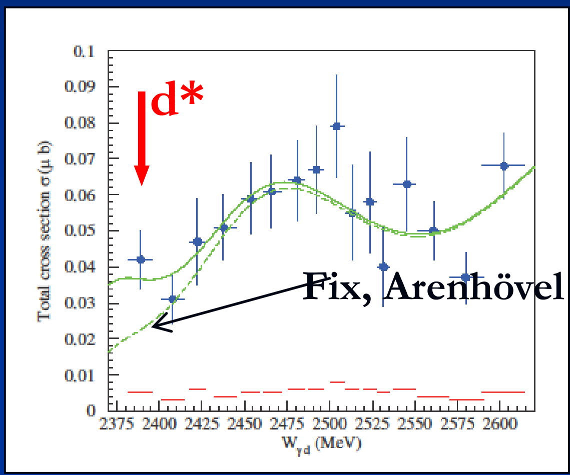
i.e. maximal at $\Theta = 90^0$

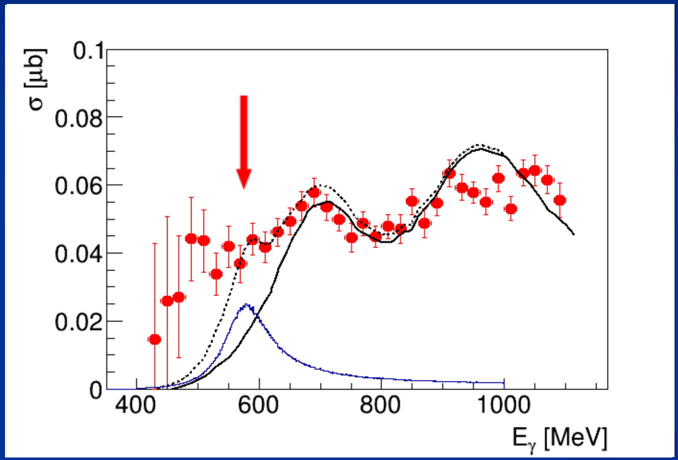
Energy Dependence

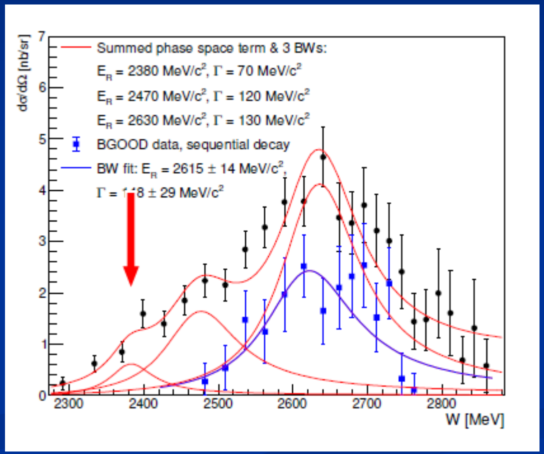


Phys. Rev. Lett. 112 (2014) 202301

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







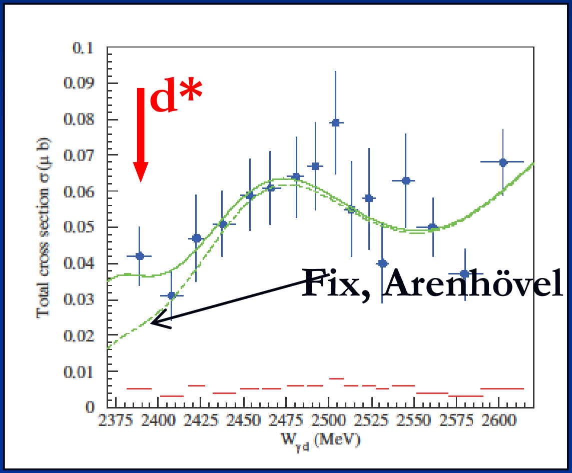
FOREST@ELPH,
PLB 772 (2017) 398

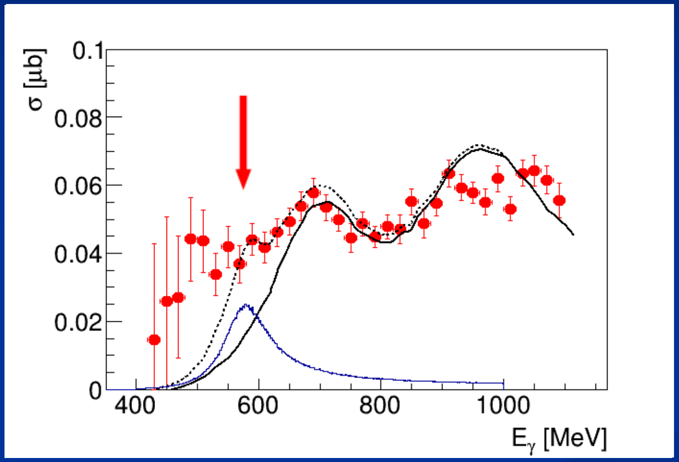
Crystal Ball @ MAMI
PoS (Hadron2017) 051

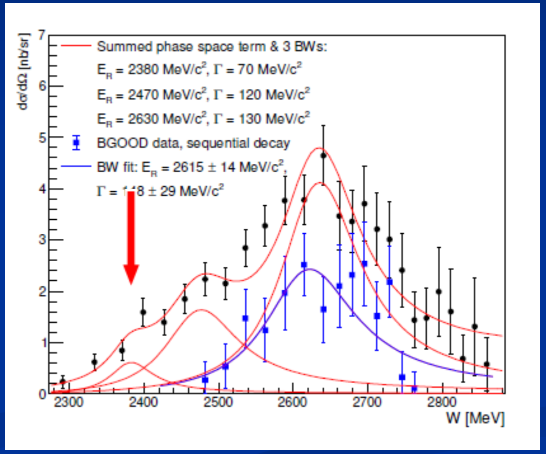
BGOOD@ELSA
arXiv: 2202.08594

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

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







FOREST@ELPH,
PLB 772 (2017) 398

Crystal Ball @ MAMI
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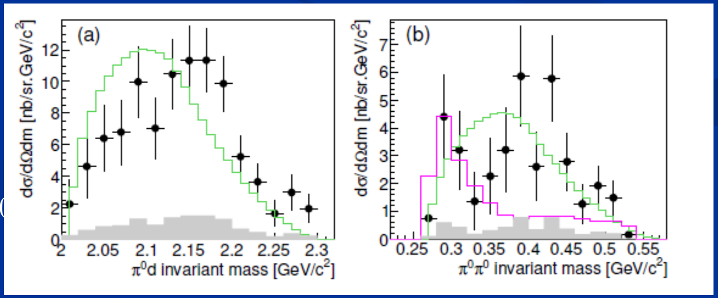


Theoretical prediction: $\sigma \approx 1 - 2$ nb IJMP A34 (2019) 195010

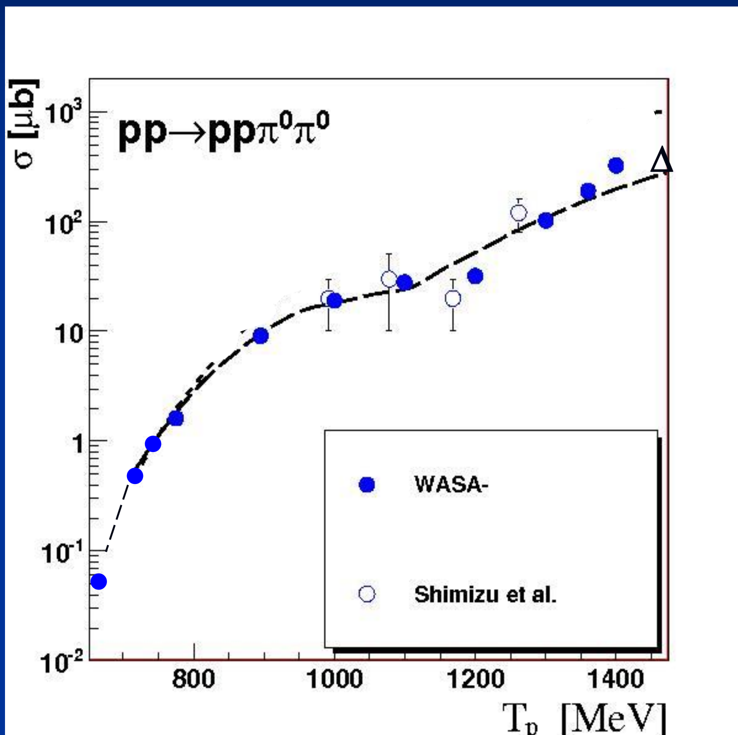
Where can D_{21} be seen?

I=2 $\Rightarrow$ only associated production

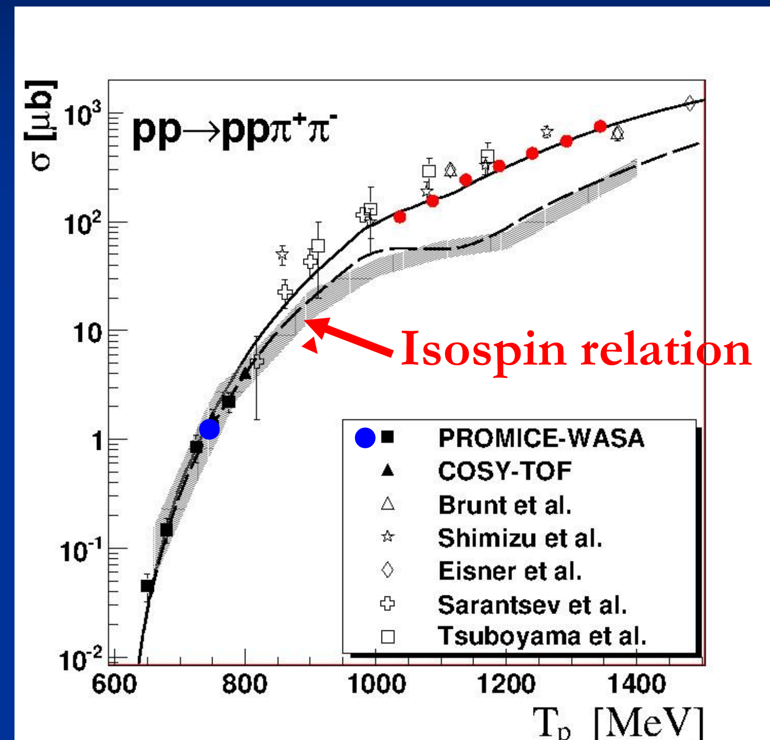
$$pp \rightarrow pp\pi^{+}\pi^{-}$$

$$D_{21}$$

Total cross section



PLB 695 (2011) 115

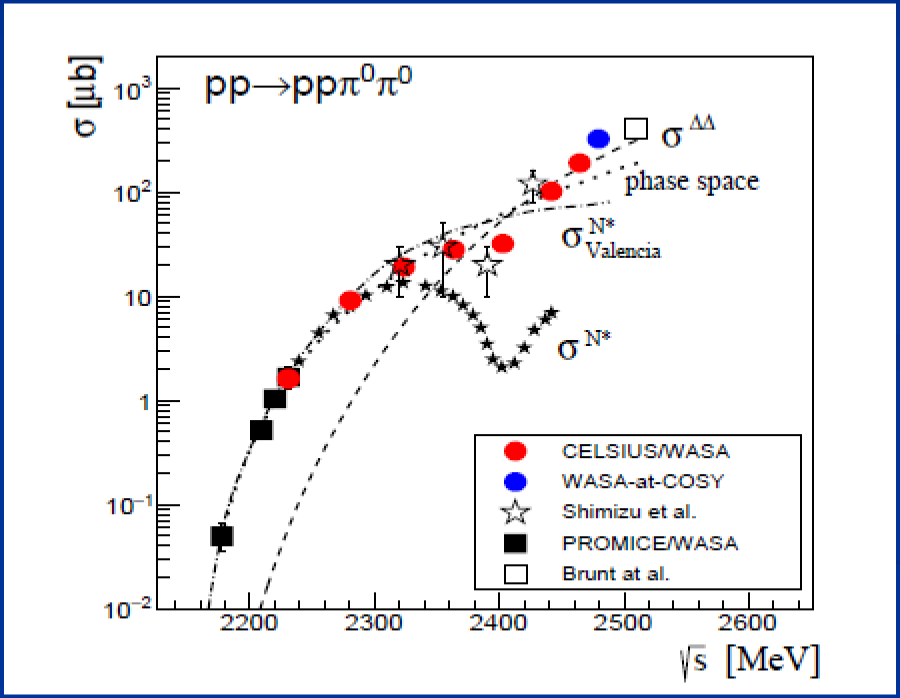


PRL 121 (2018) 052001

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

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

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



EPJA 56 (2020) 229

… inevitable dibaryon

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

accessed via **ΔΔ** as **doorway** ?