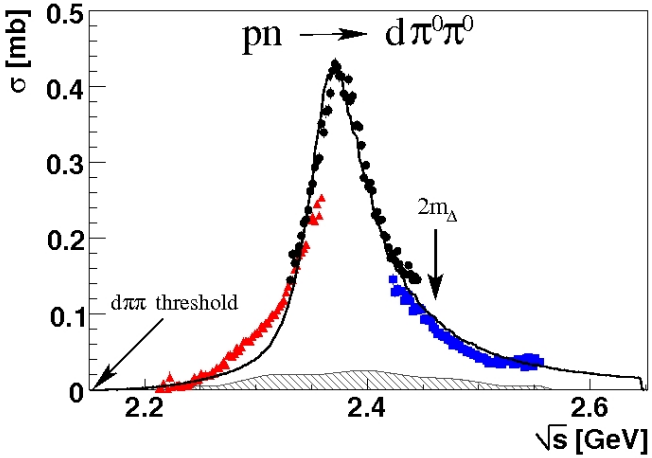
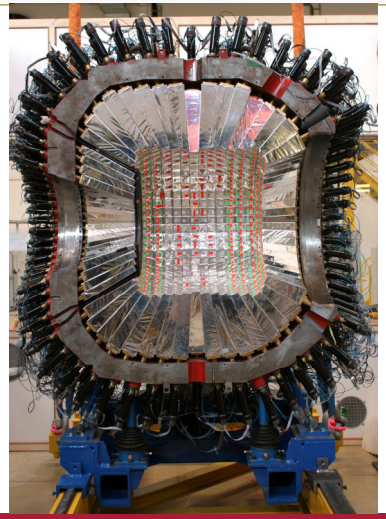
EBERHARD KARLS UNIVERSITÄT TÜBINGEN

Kepler Center for Astro and Particle Physics

Fachbereich Physik





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DFG Deutsche Forschungsgemeinschaft

Dibaryons from WASA-at-COSY

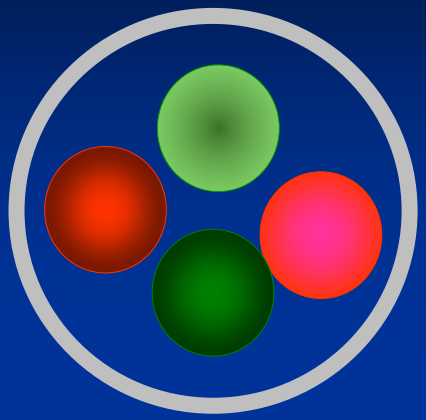
WASA at GSI/FAIR

GSI, November 27 - 28, 2017

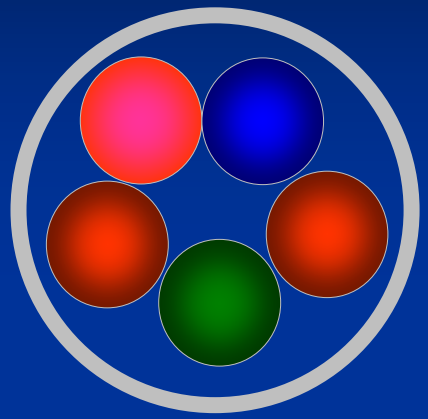
Heinz Clement

Exotics

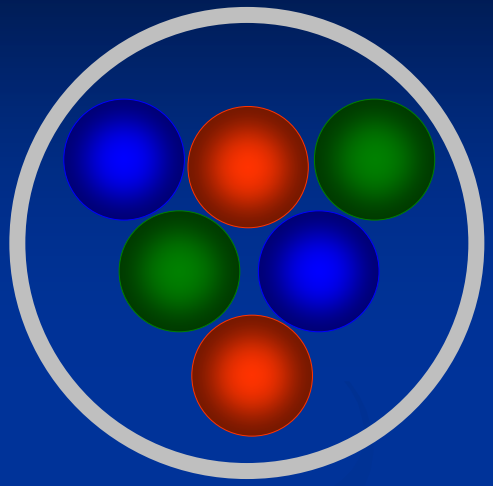
Tetraquark



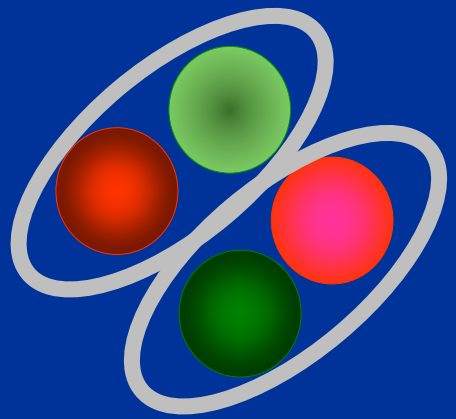
Pentaquark



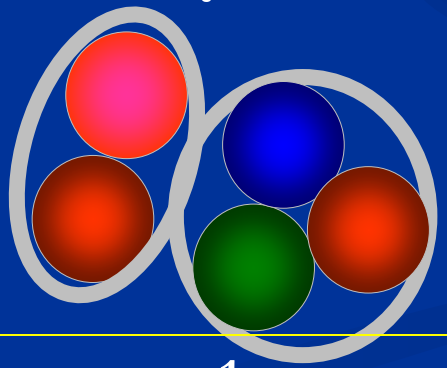
Hexaquark



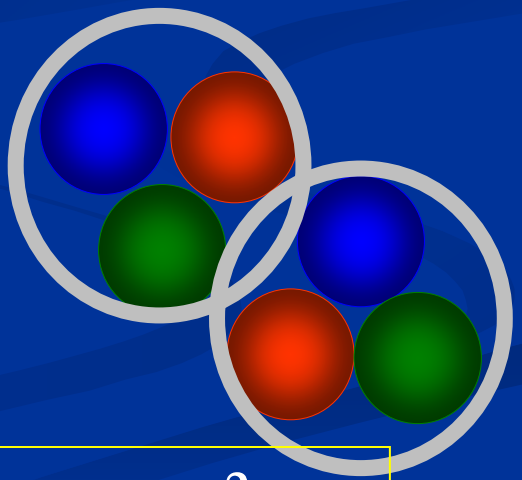
Meson-Meson molecule



Meson-Baryon molecule



Baryon-Baryon molecule



B = 0	1	2

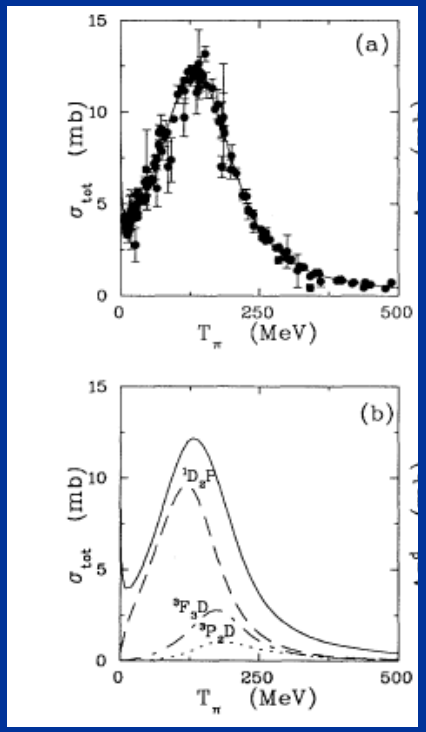
Early Predictions of Dibaryons

- 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, ...)
- ⇒ **Dibaryon Rush Era:**
- Many experimental claims …
- but **no single one** established finally

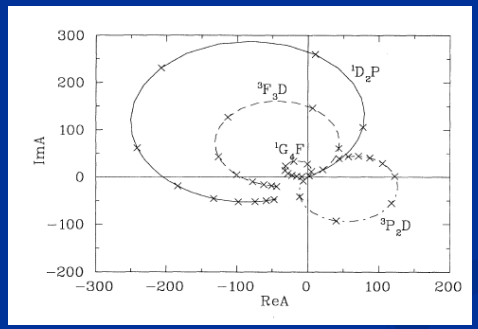
Possibly the only surviver: $^1D_2$ Resonance

- Best seen in pp ↔ dπ^+,
  - but also in pp → pnπ^+ 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 ≈ 2148 MeV = $m_\Delta + m_N$ – 22 MeV
Γ ≈ 126 MeV ≈ Γ_Δ

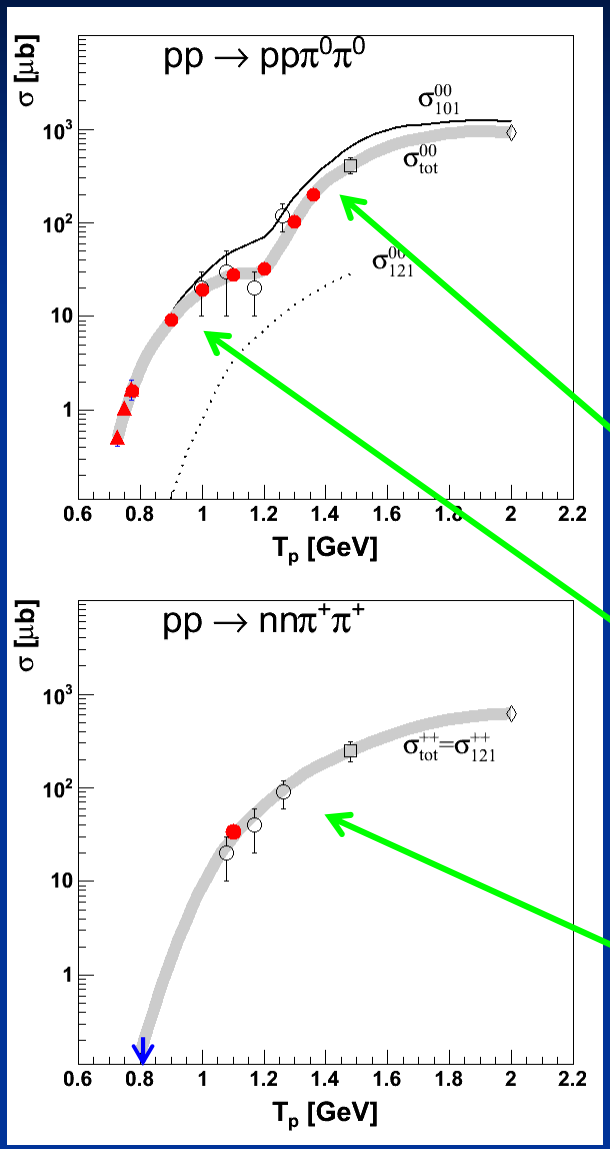
Alternative description: cusp, virtual state, reflection D. Bugg et al.

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 two-pion production

Isovector : Total Cross Sections



isospin decomposition

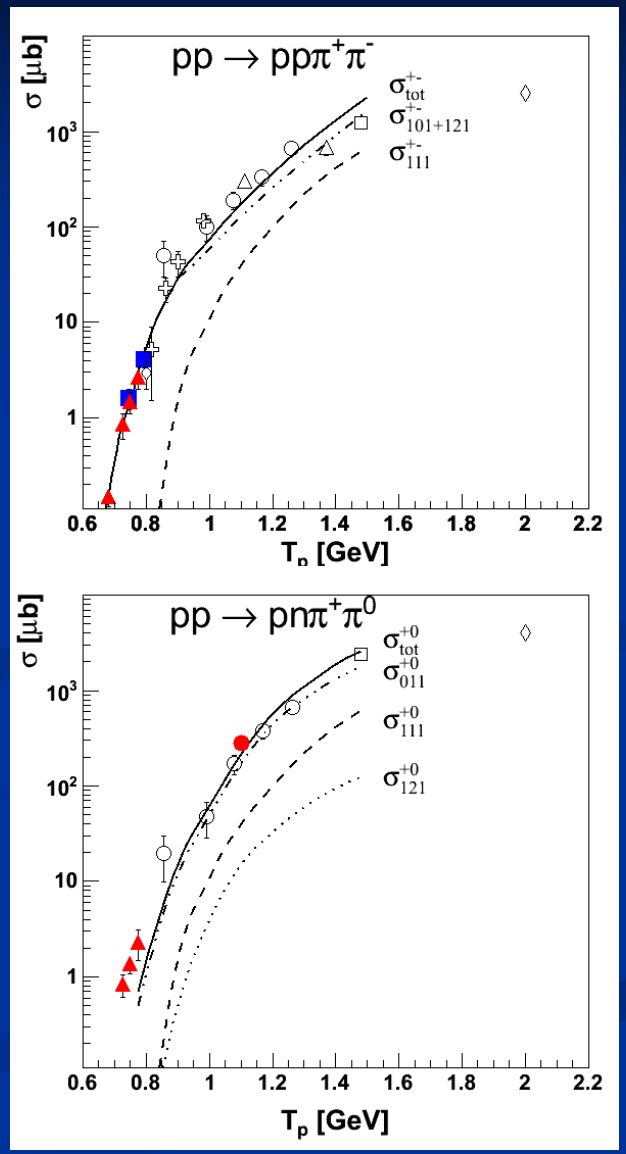
⇒

ΔΔ

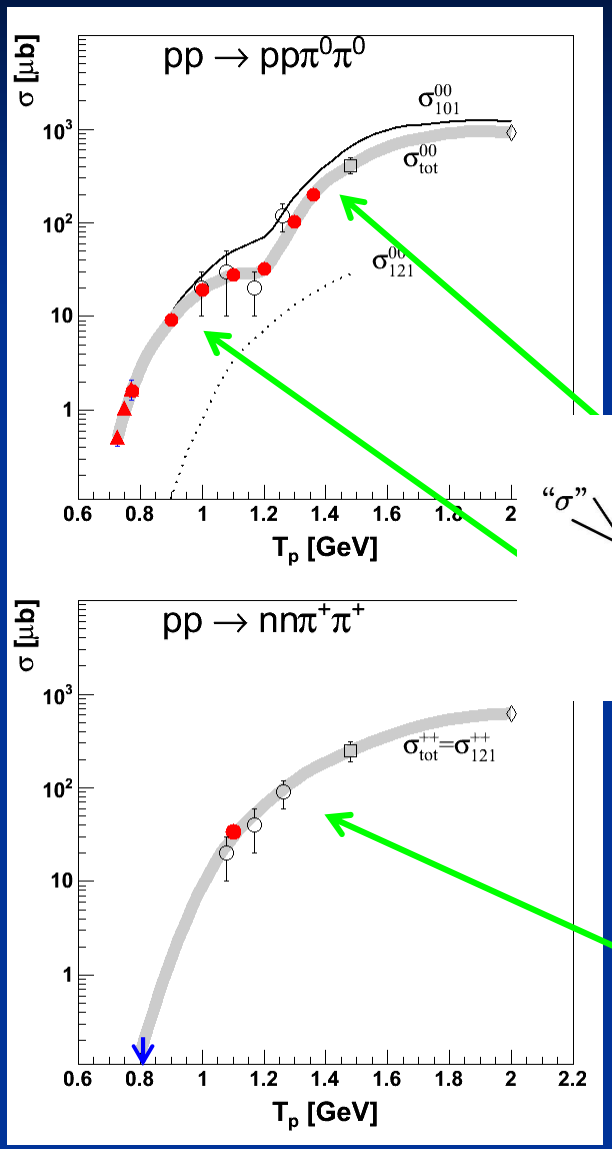
N*(1440)

Δ(1600) (?)

Phys. Lett. B 679 (2009) 30

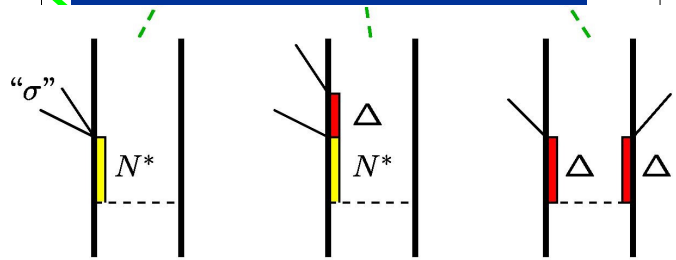


Isovector : Total Cross Sections

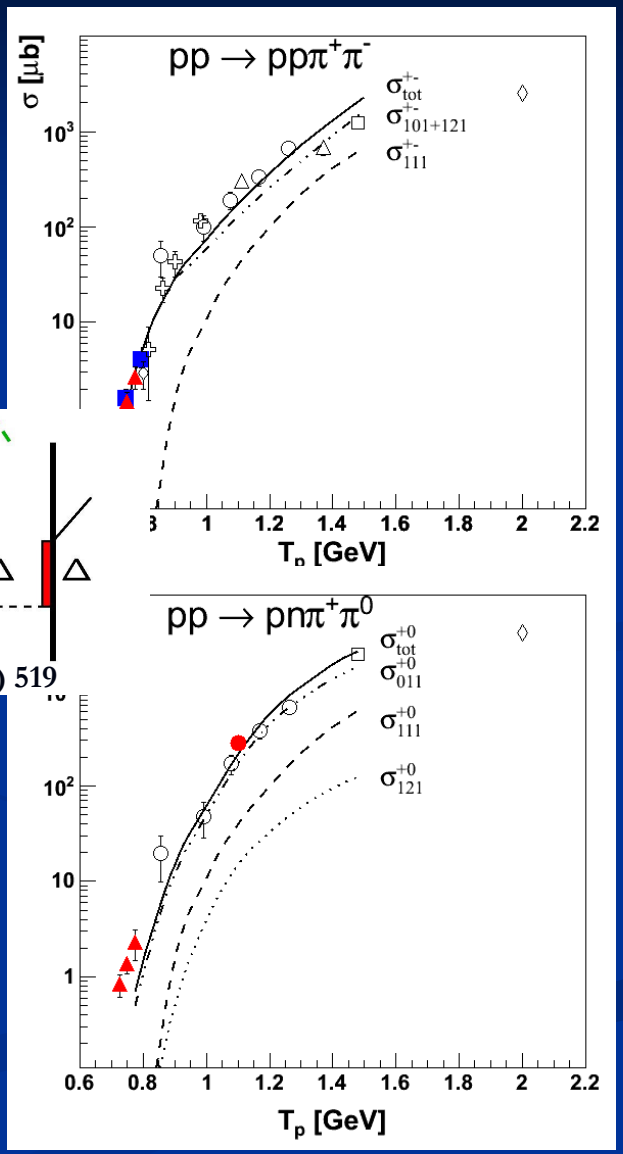


isospin decomposition

⇒



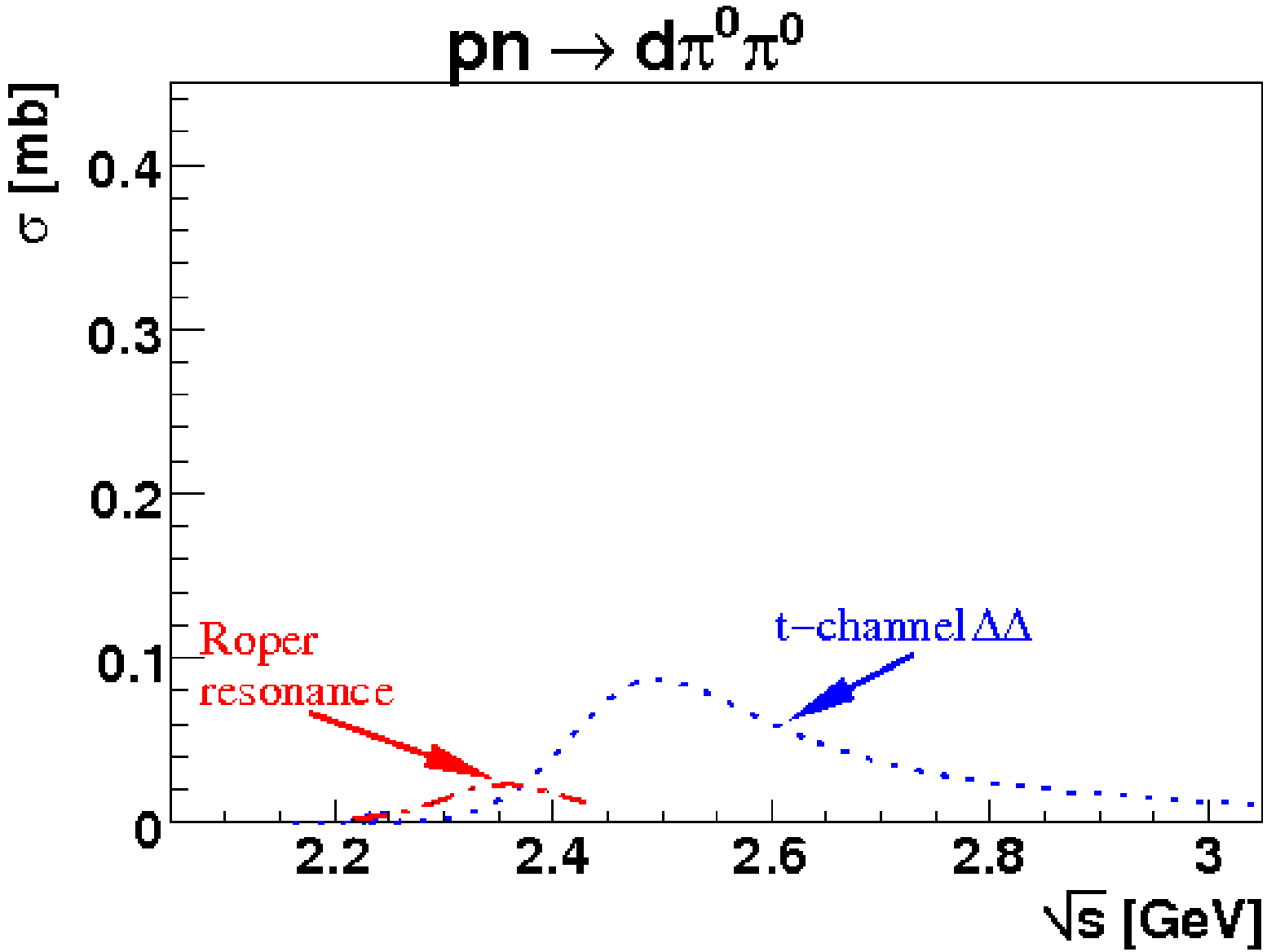
Alvarez-Ruso, Oset NPA 633 (1998) 519



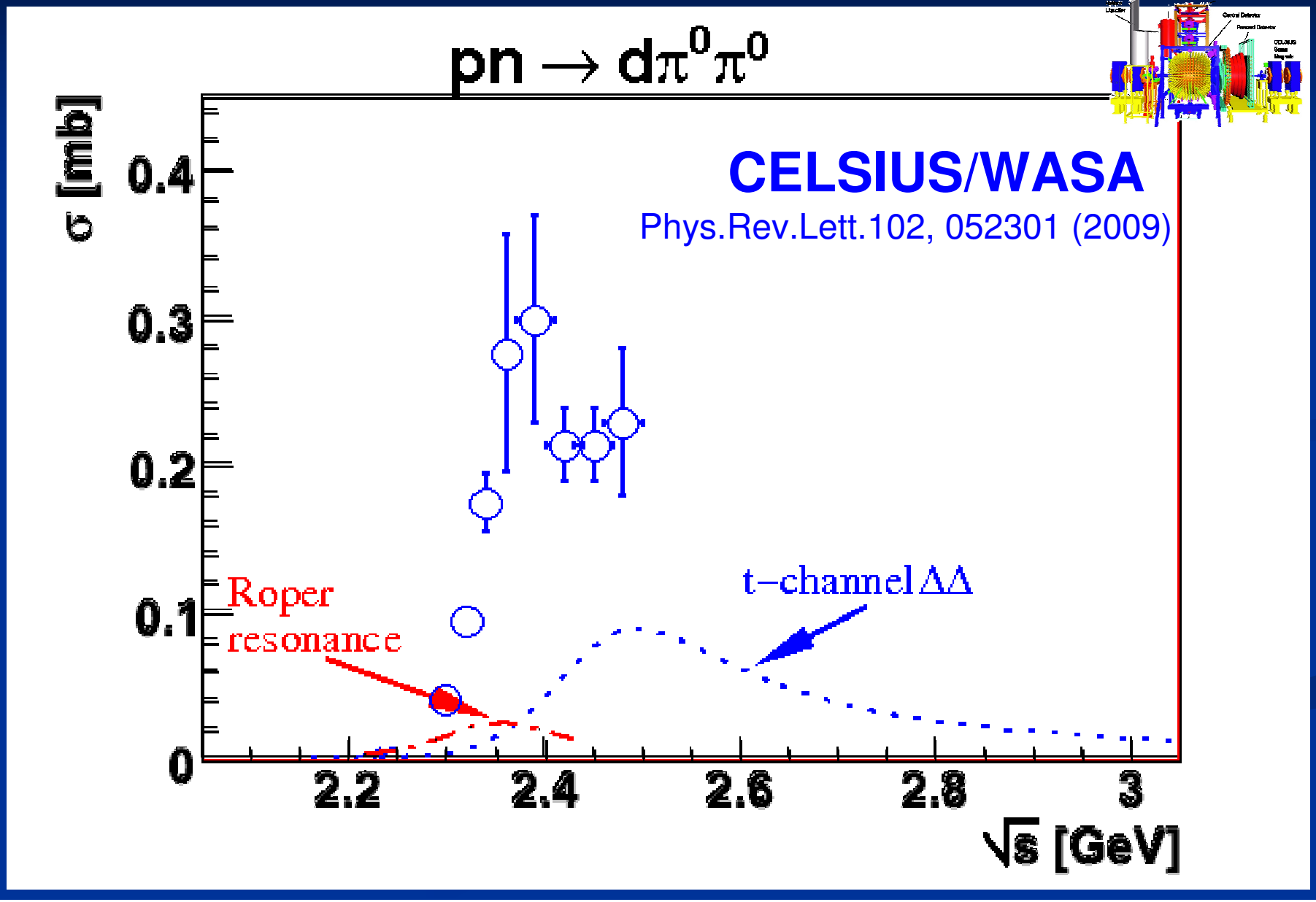
Δ(1600) (?)

Phys. Lett. B 679 (2009) 30

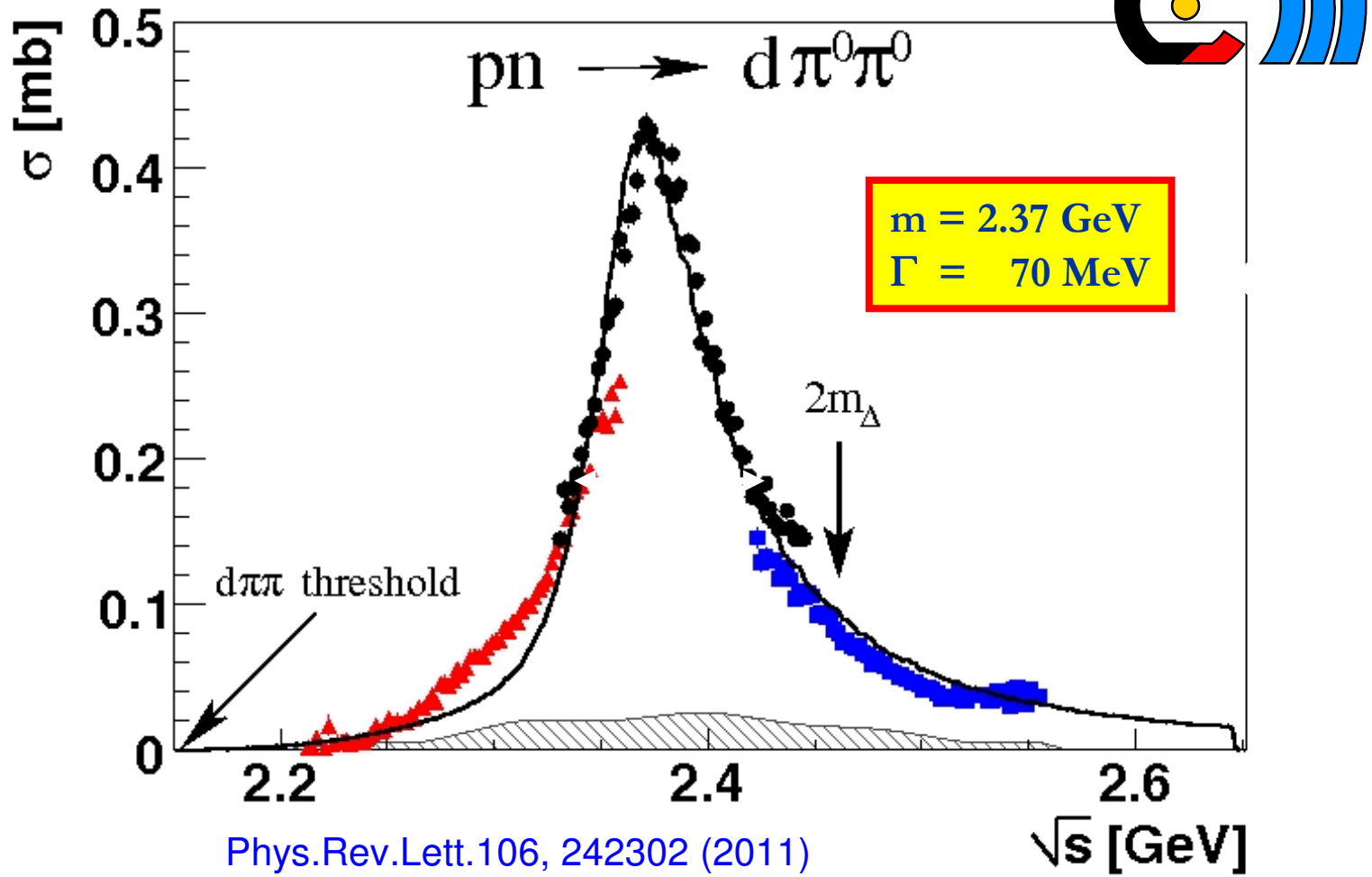
Isoscalar : … this is what we expected!



Isoscalar : … and this is what we found!

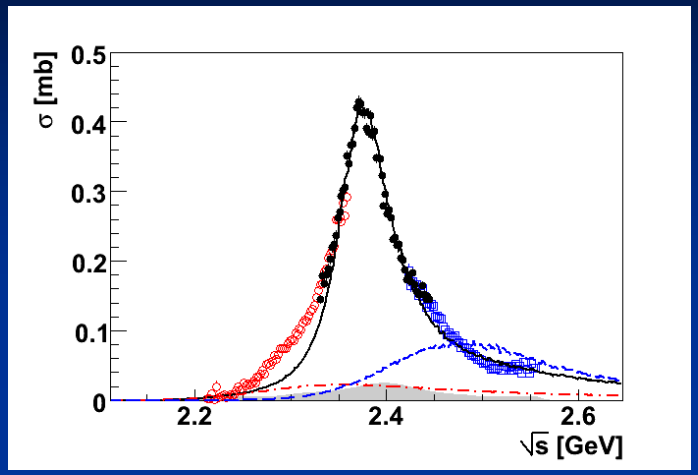


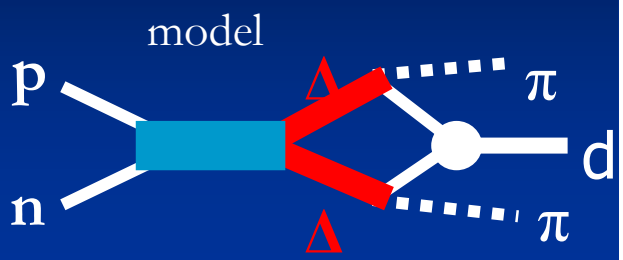
Isoscalar : Results from WASA at COSY



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

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

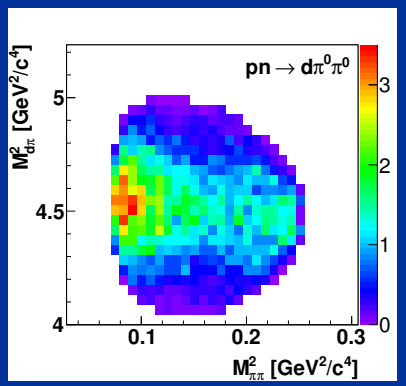


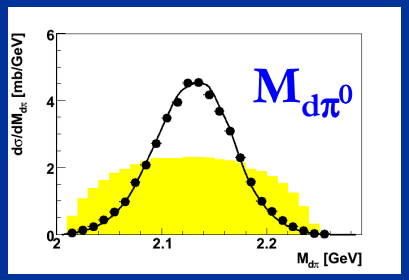


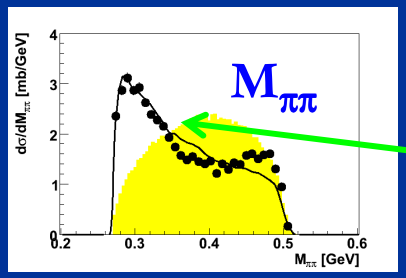
$I\ (J^P) = 0\ (3^+)$

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

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

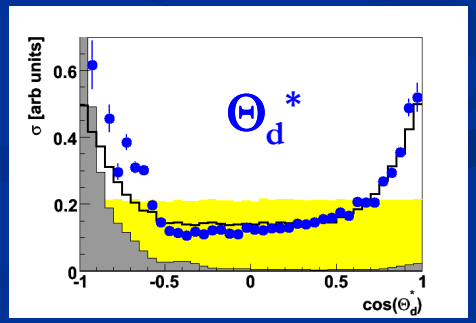






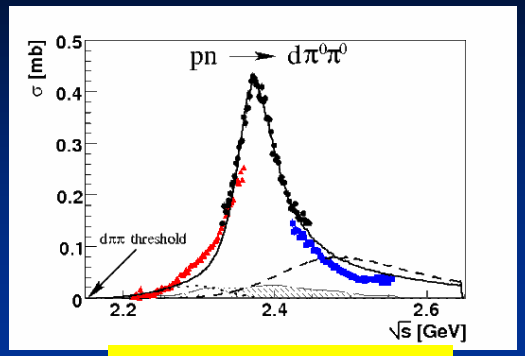
ABC effect

NPA 958 (2017) 129

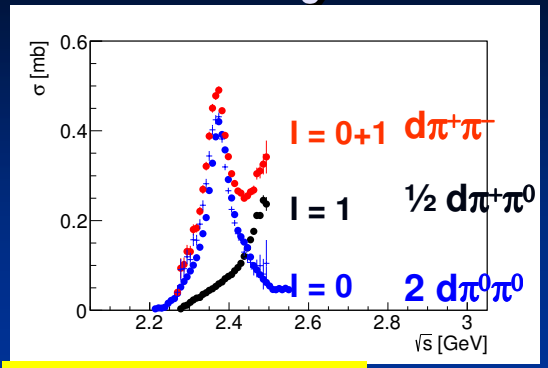


hadronic decays

PRL 106 (2011) 242302



WASA data



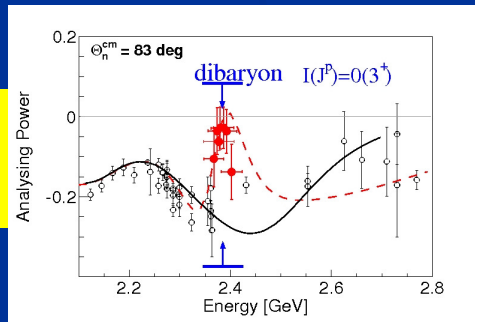
PLB 721 (2013) 229

$d\pi^0\pi^0$

$d\pi^+\pi^-$

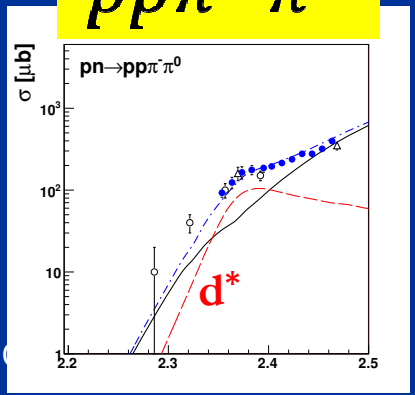
pn → d*(2380)

pn

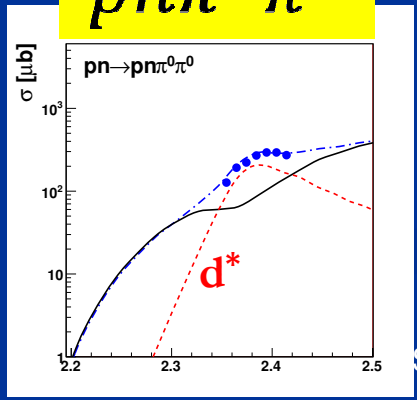


PRL 112 (2014) 202301
PRC 90 (2014) 035204

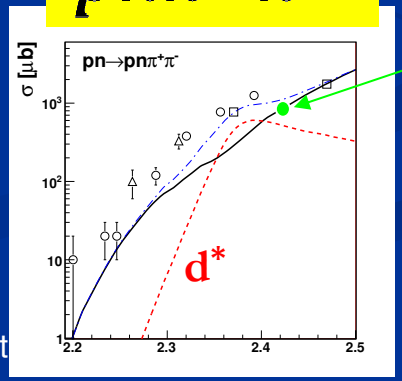
$pp\pi^-\pi^0$



$pn\pi^0\pi^0$



$pn\pi^+\pi^-$



HADES PLB 750 (2015) 184

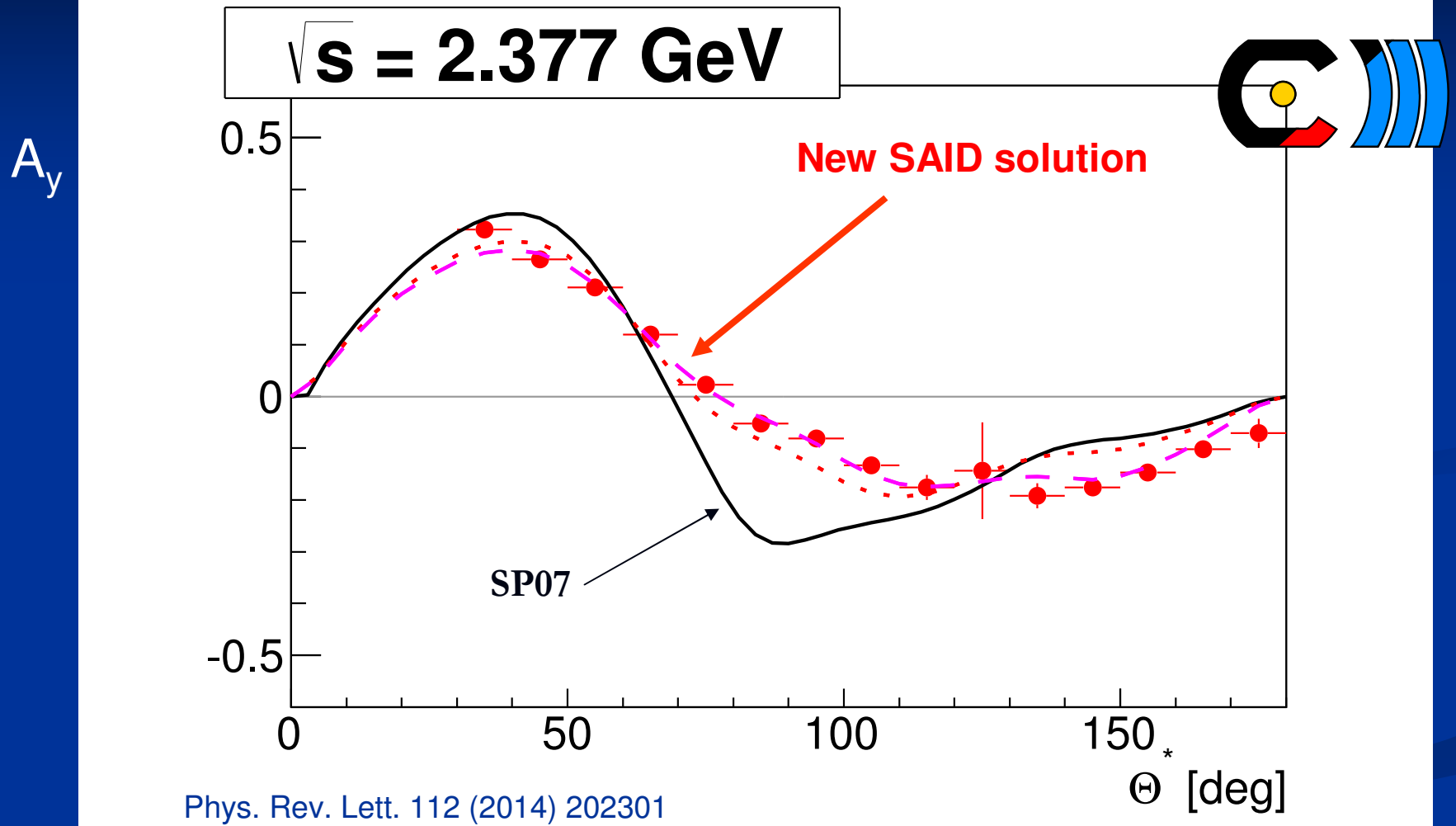
PRC 88 (2013) 055208
PLB 743 (2015) 325
Phys. Scr. T 166 (2015) 014016

→ √s [GeV]

„Experimentum Crucis“ for d*

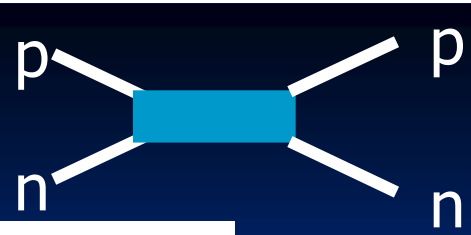
- If d^* a true s-channel resonance
- $\Leftrightarrow$
- then also a resonance in the np system
- $\Leftrightarrow$
- to be sensed in np scattering
- $\Leftrightarrow$
- in particular in the analyzing power
- $\Leftrightarrow$
- resonance effect $\sim P^1_3(\Theta)$
- i.e. maximal at $\Theta = 90^0$

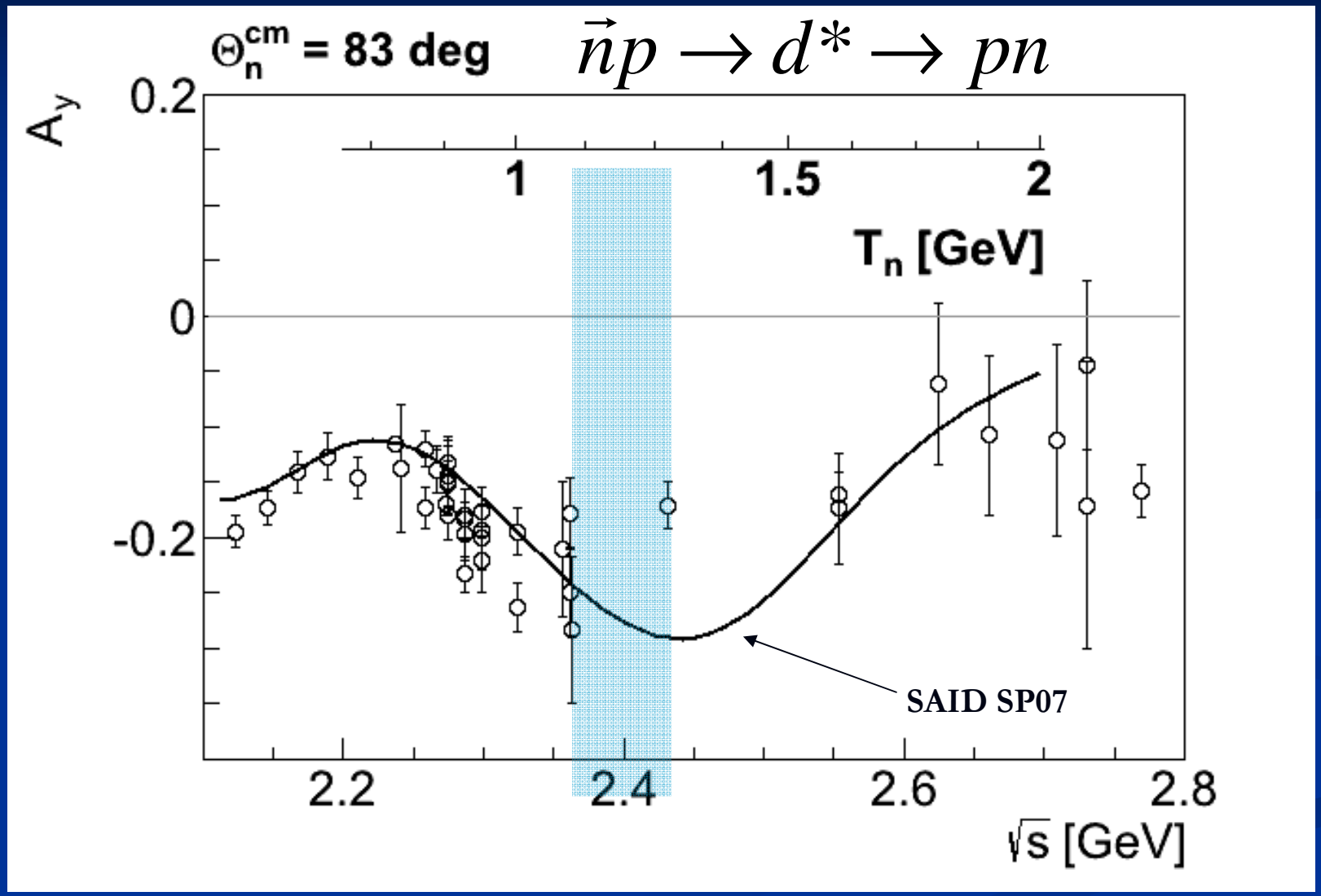
A_y Angular Distribution at Resonance



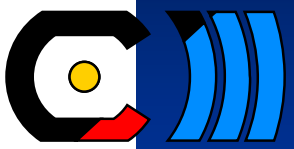
Phys. Rev. Lett. 112 (2014) 202301

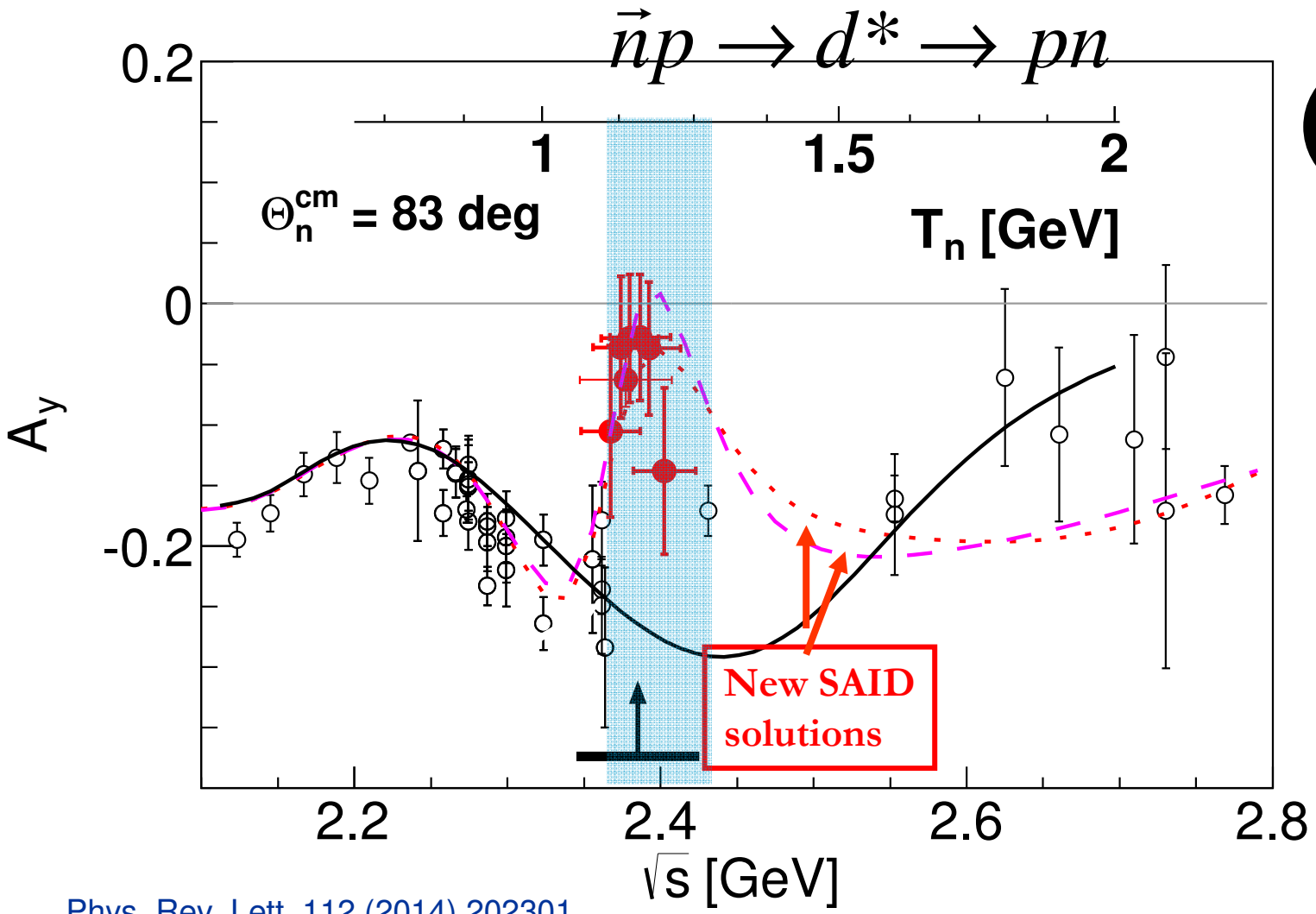
Energy Dependence





Energy Dependence



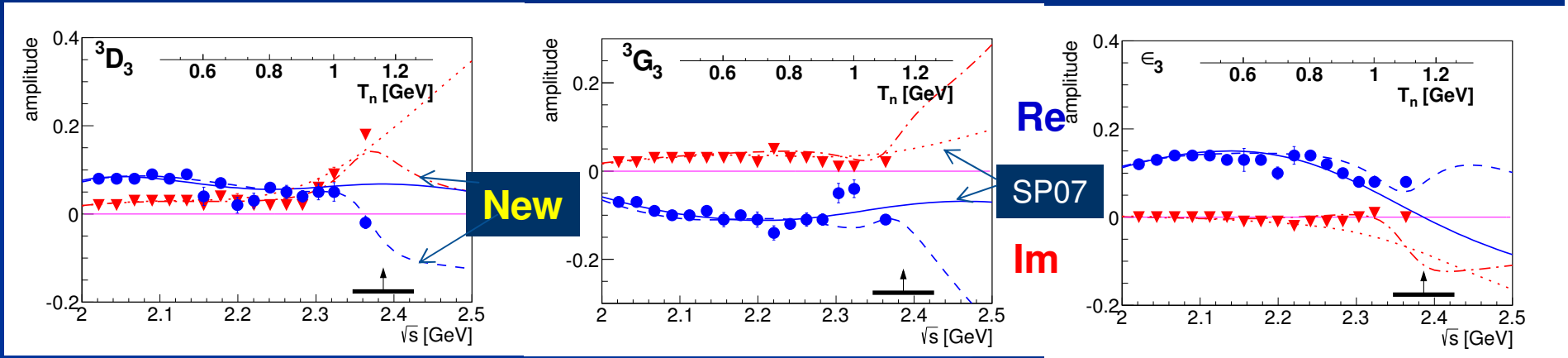


Phys. Rev. Lett. 112 (2014) 202301

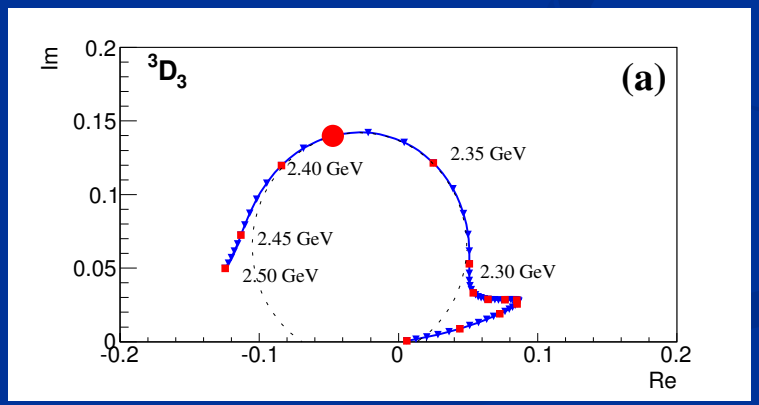
SAID Partial-Wave Analysis

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

Phys. Rev. Letters 112 (2014) 202301



Argand diagram:

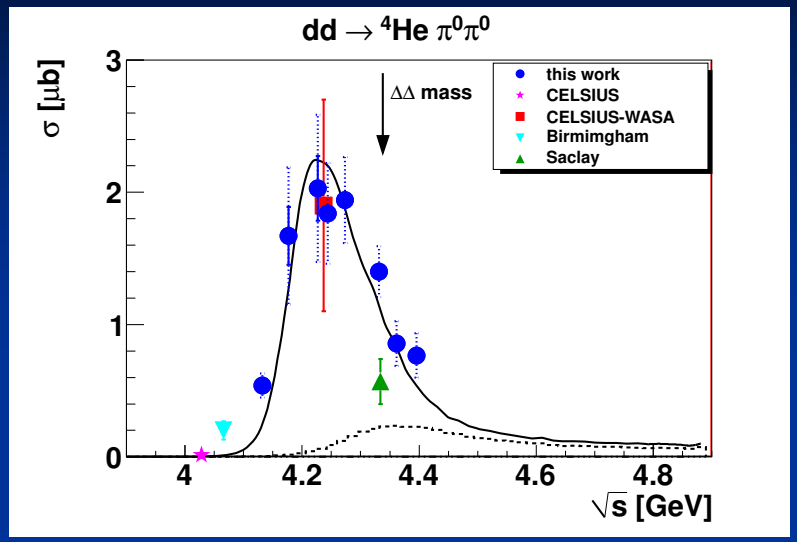


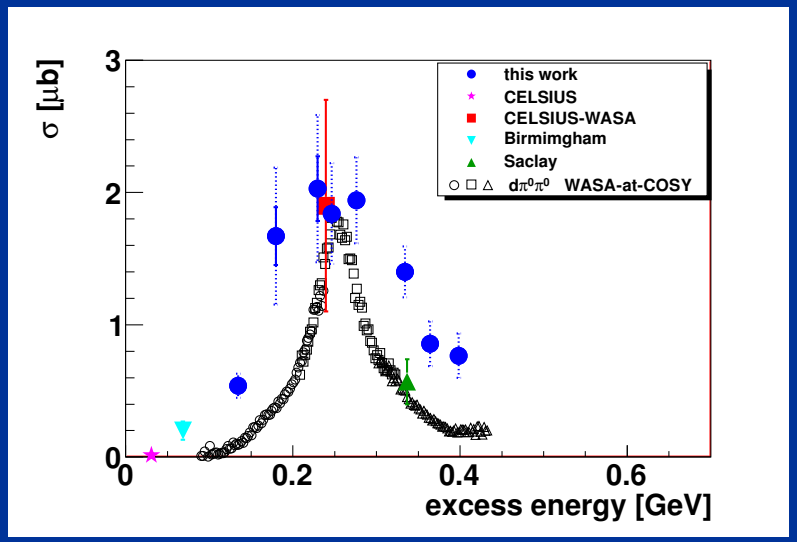
PRC 90 (2014) 035204

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

⇔ Genuine Resonance in np System

$dd \rightarrow {}^4He\ \pi^0\pi^0$





PRC 86 (2012) 032201(R)

- Energy dependence of total cross section
  - shows resonance structure
  - exactly at the same excess energy as in $pn \rightarrow d\pi^0\pi^0$
  - is broadened due to Fermi motion and collision damping
- **$\Rightarrow$ d^* obviously survives even in nuclear surrounding**

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

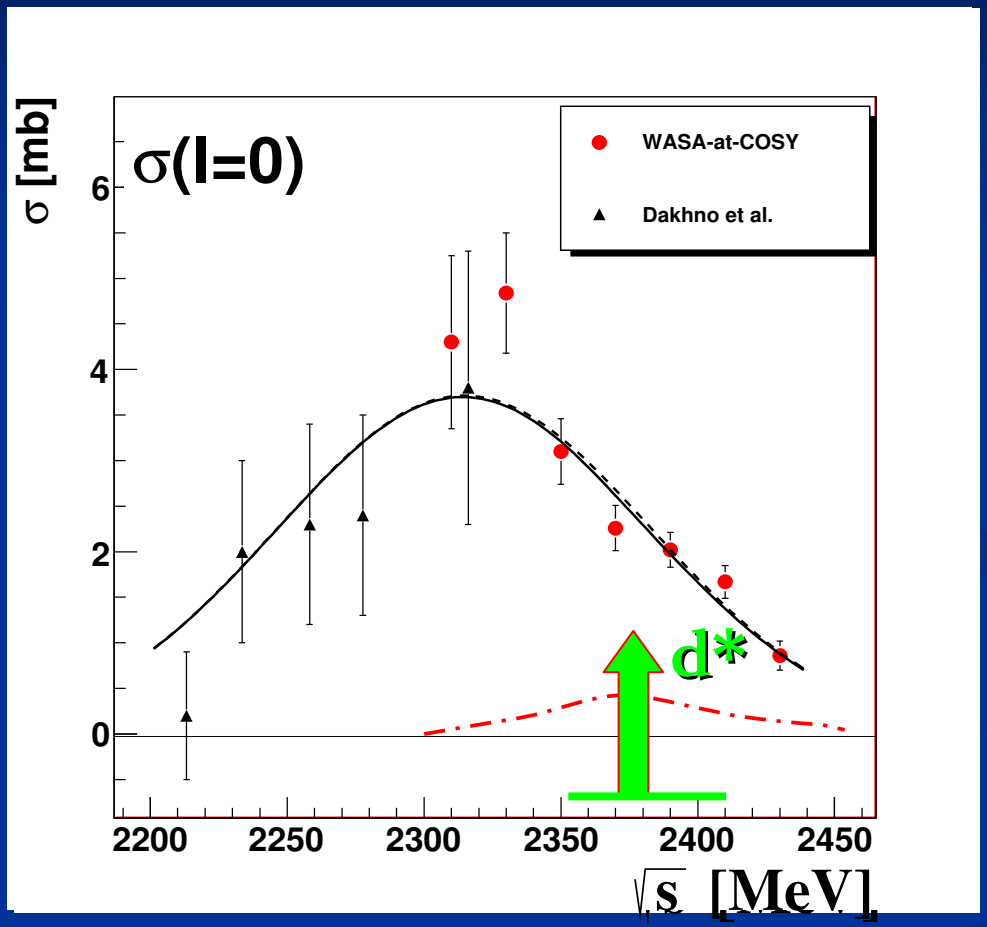
- hadronic decays

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
$(NN\pi)_{I=0}$	< 9 %	measurement

consistent with isospin coupling for a $\Delta\Delta$ inter-mediate system

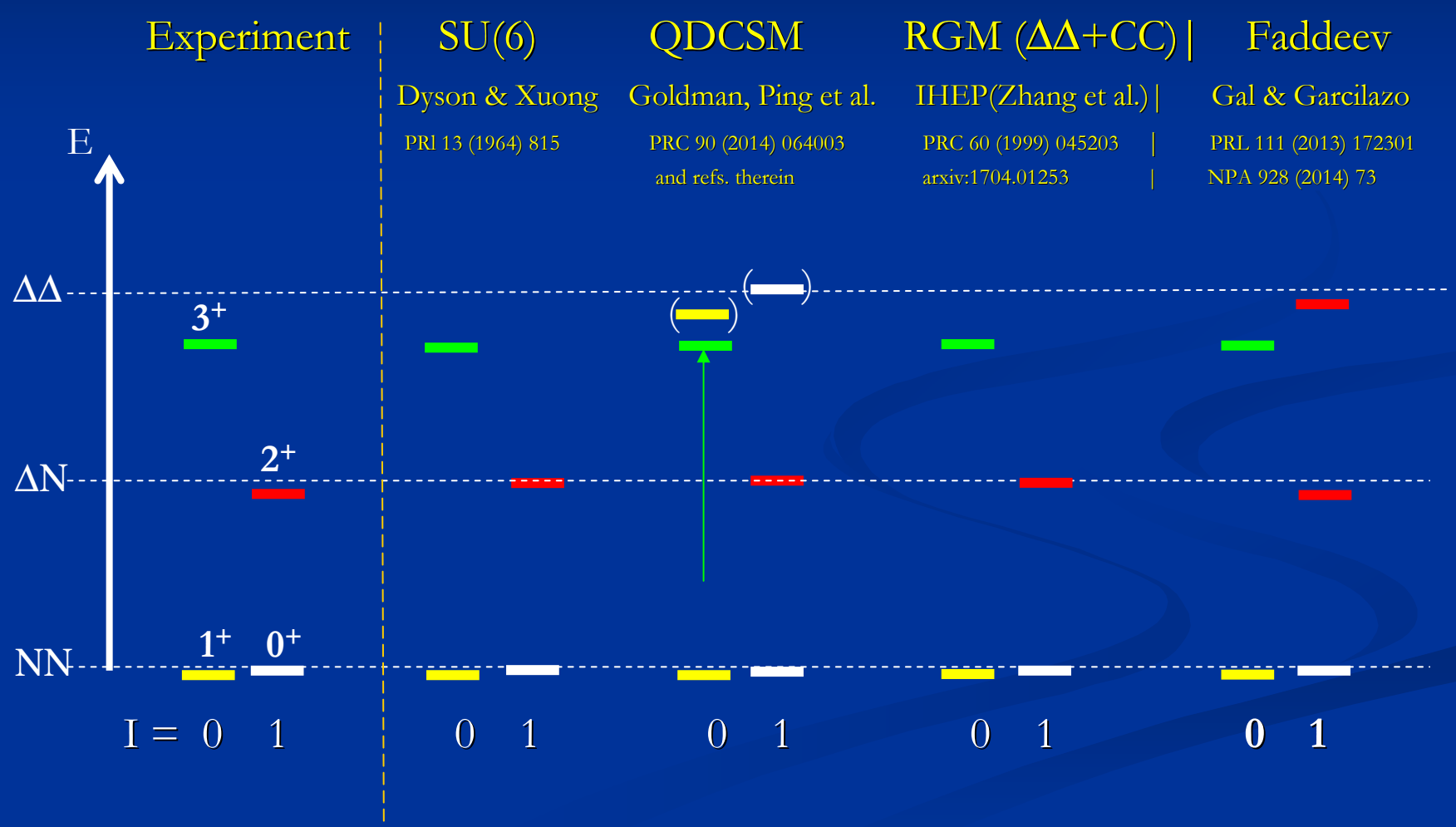
Isoscalar Single-Pion Production



BR < 9%

PLB 774 (2017) 599

Comparison to predictions from Quark and Hadron Models



Width of d*(2380)

- Experiment: **Γ≈ 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

- Faddeev hadr. G&G 1.5 – 2 fm (fails on BRs)

- A. Gal: compact hexaquark surrounded by $D_{12}\pi$ cloud

  PLB 769 (2017) 436

Rèsumè

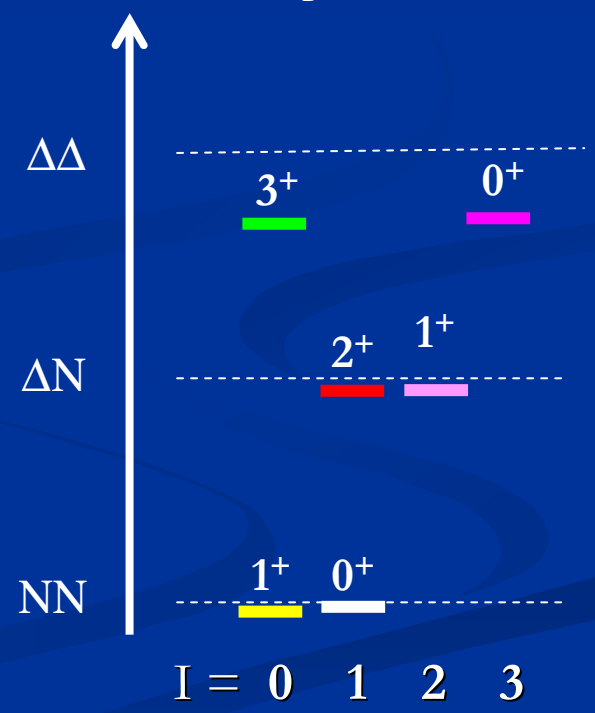
- Non-Strange Two-Baryon Spectrum
  - 3 established states: $^3S_1$ deuteron groundstate
    $^1S_0$ virtual state
    $^1D_2$ resonance (ΔN)
  - 1 new - presumably exotic - state:
    $d^*(2380)$ resonance ($\Delta\Delta$)
  - Are there more states?
    - NN-decoupled states with I = 2, 3?
    - Search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

Zhang, Chen, Shen et al.

Huang, Ping, Wang et al.

Gal & Garcilazo

Dyson's prediction



(Molecular) States near ΔN Threshold

	I = 1	I = 2
S-wave:	2^+ ($^1D_2$)	1^+ ($^3P_1$) (?)
P-wave:	0^- ($^3P_0$) COSY-ANKE	
	2^- ($^3P_2$) -"- , SAID	
	3^- ($^3F_3$) SAID (?)	

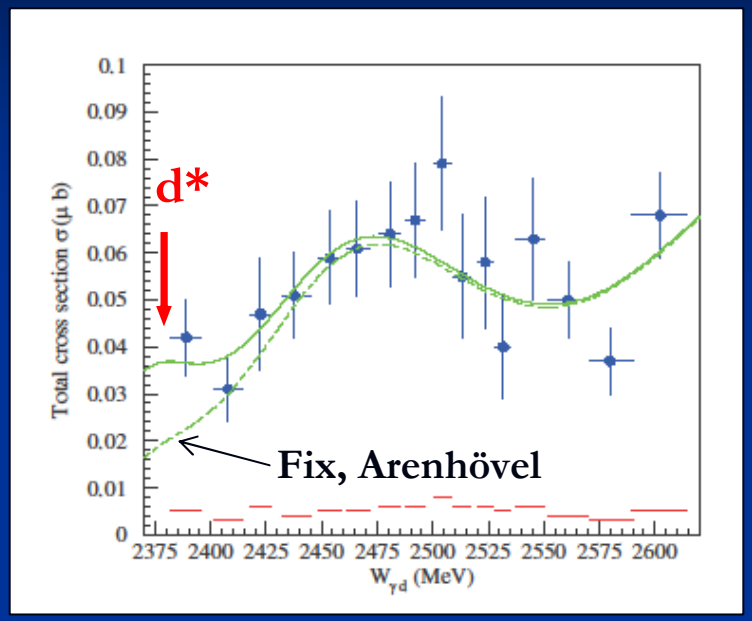
Summary on d*

- $d^*(2380)$ established as a genuine s-channel resonance
- It is the first unambiguously detected non-trivial dibaryon state.
- Narrow width and decay branchings favor a compact hexaquark state – but this needs further experimental verification.
- LQCD extrapolation by EFT to correct pion mass also sees d*(2380) arxiv:1708.08071

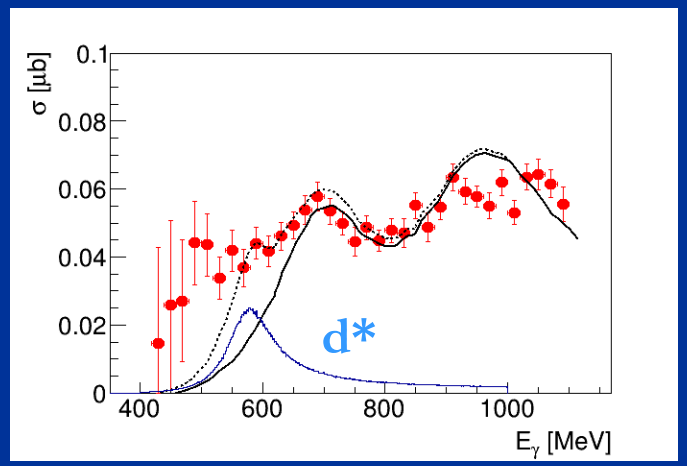
Outlook and Open Problems

- Size of $d^*(2380)$
  - $\Rightarrow$ elm excitation of d^* $\quad \gamma d \rightarrow d^* \rightarrow pn$
  - $\quad ed \rightarrow ed^* \rightarrow ed\pi^0\pi^0$
- Observation at other installations
  - HADES @ GSI: under way, but no 4π
  - WASA@GSI/FAIR : $d + {}^{14}N \rightarrow {}^{16}O\ \pi^0\pi^0$
  - KEK, JPARC, LHCb, IHEP, others ???
- Are there more (exotic) dibaryons?
  - Isotensor dibaryon D_{21} in $pp \rightarrow pp\pi^+\pi^-$?
  - Mirror state of d^* …, strange, charmed dibaryons

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



FOREST@ELPH,
Ishikawa et al., PLB 772 (2017) 398



Crystal Ball @ MAMI
Master Thesis M. Guenther, Basel 2015

Outlook and Open Problems

- Size of $d^*(2380)$
  - $\Rightarrow$ elm excitation of d^* $\quad \gamma d \rightarrow d^* \rightarrow pn$
  - $\quad ed \rightarrow ed^* \rightarrow ed\pi^0\pi^0$
- Observation at other installations
  - HADES @ GSI: under way, but no 4π
  - WASA@GSI/FAIR : $d + {}^{14}N \rightarrow {}^{16}O\ \pi^0\pi^0$
  - KEK, JPARC, LHCb, IHEP, others ???
- Are there more (exotic) dibaryons?
  - Isotensor dibaryon D_{21} in $pp \rightarrow pp\pi^+\pi^-$?
  - Mirror state of d^* …, strange, charmed dibaryons