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Observation of a Dibaryon State with WASA at COSY

QCD Exotics 2015
Jinan, June 8 - 12, 2015

Heinz Clement

Two-Baryon Scenario

■ What do we know:

- 3S_1 deuteron groundstate: $I(J^P) = 0 (1^+)$ the only boundstate!
- 1S_0 virtual state (NN FSI): $I(J^P) = 1 (0^+)$ in addition ΔN FSI

■ What would we like to know:

- Are there six-quark bags (genuine dibaryons)?
- Are there in general resonant states (molecular, dynamic) at all?

■ Experimental findings:

- 1D_2 resonance structure at the ΔN threshold:
- 3D_3 resonance much below the $\Delta\Delta$ threshold:

$$I(J^P) = 1 (2^+) \quad ???$$
$$I(J^P) = 0 (3^+)$$



■ Are there more states?

- Theoretical predictions
- Dyson's sextet

Early Predictions on Dibaryons

- 1964 Dyson & Young: 6 non-strange states
- 1975 Jaffe: H-dibaryon (uuddss: $\Lambda\Lambda$)
- Thereafter:
 - multitude of predictions of a vast number of dibaryon states (Nijmegen group,)
 - :
 - LANL theory group (T. Goldman, Fan Wang et al.):
 - The „inevitable dibaryon“: $\Delta\Delta I(J^P) = 0(3^+)$

Dyson & Xuong: Sextet Prediction

VOLUME 13, NUMBER 26

PHYSICAL REVIEW LETTERS

28 DECEMBER 1964

$Y=2$ STATES IN SU(6) THEORY*

Freeman J. Dyson† and Nguyen-Huu Xuong

Department of Physics, University of California, San Diego, La Jolla, California

(Received 30 November 1964)

Two-baryon states.—The SU(6) theory of strongly interacting particles^{1,2} predicts a classification of two-baryon states into multiplets according to the scheme

$$\underline{56} \otimes \underline{56} = \underline{462} \oplus \underline{1050} \oplus \underline{1134} \oplus \underline{490}. \quad (1)$$

We now propose the hypothesis that all low-lying resonant states of the two-baryon system belong to the 490 multiplet.³ This means that six zero-strangeness states shown in Table I should be observed. In all these states odd T goes with even J and vice versa.

Table I. $Y=2$ states with zero strangeness predicted by the 490 multiplet.

Particle	T	J	SU(3) multiplet	Comment	Predicted mass
D_{01}	0	1	<u>10</u> *	Deuteron	A
D_{10}	1	0	<u>27</u>	Deuteron singlet state	A
D_{12}	1	2	<u>27</u>	S -wave $N-N^*$ resonance	$A + 6B$
D_{21}	2	1	<u>35</u>	Charge-3 resonance	$A + 6B$
D_{03}	0	3	<u>10</u> *	S -wave N^*-N^* resonance	$A + 10B$
D_{30}	3	0	<u>28</u>	Charge-4 resonance	$A + 10B$

Dyson & Xuong's Prediction

State	I	J	Asymptotic Configuration	m_{theor} [MeV]	m_{exp} [MeV]	Γ_{exp} [MeV]
D_{01}	0	1	Deuteron	1876	✓ 1876	
D_{10}	1	0	virtual 1S_0	1876	✓ 1878	
D_{12}	1	2	$NN(^4D_2) \leftrightarrow \Delta N \leftrightarrow NN\pi$	2160	(✓) ΔN threshold	
D_{21}	2	1	$\Delta N \leftrightarrow NN\pi$	2160	?	
D_{03}	0	3	$NN(^3D_3) \leftrightarrow \Delta\Delta \leftrightarrow NN\pi\pi$	2350	?	
D_{30}	3	0	$\Delta\Delta \leftrightarrow NN\pi\pi$	2350	?	

... inevitable dibaryon: unique symmetry!

PHYSICAL REVIEW C

VOLUME 39, NUMBER 5

MAY 1989

“Inevitable” nonstrange dibaryon

T. Goldman and K. Maltman*

Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545

G. J. Stephenson, Jr.

Physics Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545

K. E. Schmidt

Courant Institute and Department of Chemistry, New York University, New York, New York 10012

Fan Wang†

Department of Physics, University of California, Los Angeles, California 90024

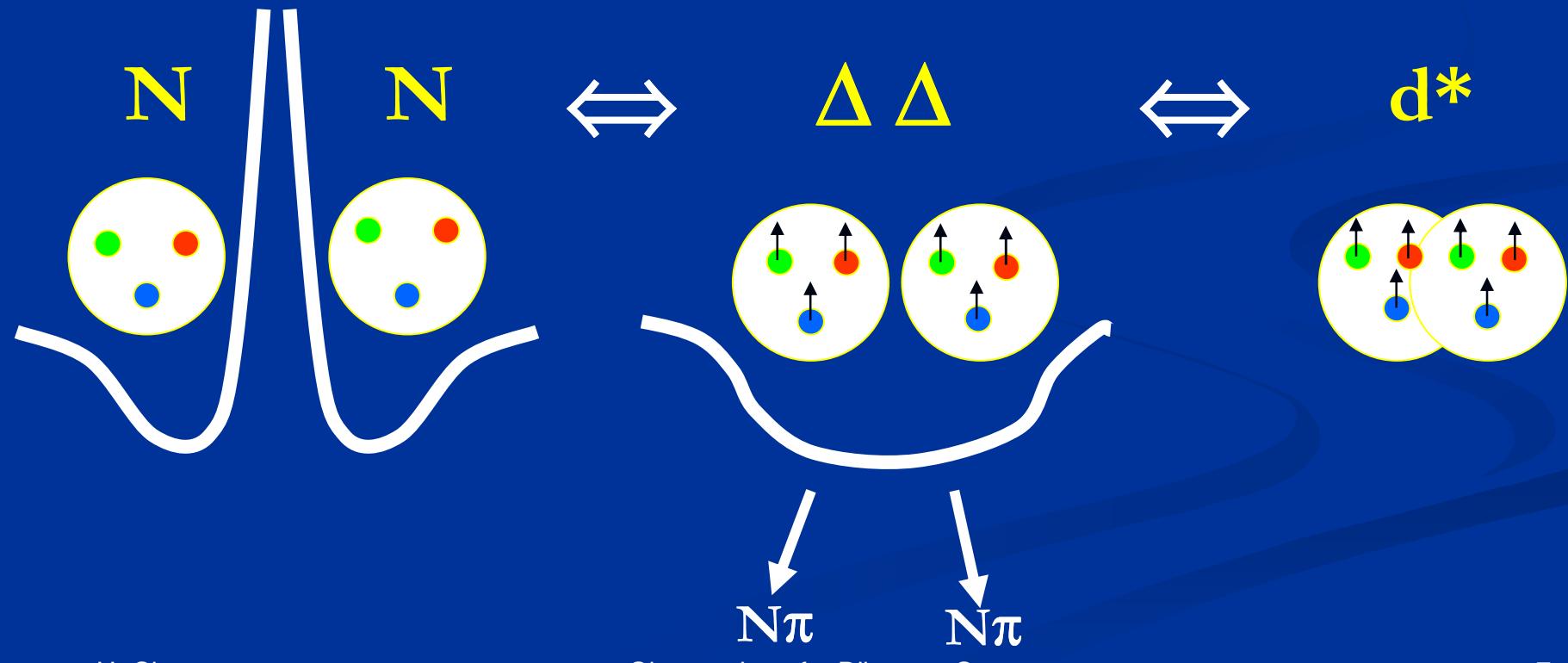
(Received 13 December 1988)

Certain basic features, common to all phenomenological models of hadron structure based on the picture of confinement at large distances and effective one-gluon exchange within the confinement region, necessarily lead to the prediction of the existence of a nonstrange dibaryon resonance with quantum numbers $IJ^P=03^+$, the d^* , independent of more detailed features of the dynamics of any of the models. We discuss the qualitative physics underlying this claim, comment on the probable mass and decay properties of the resulting state, and provide estimates of the expected production cross sections in $np \rightarrow d^*$ and $\pi^\pm d \rightarrow \pi^\pm d^*$.

... inevitable dibaryon



$I(J^P) = 0(3^+)$ state: totally symmetric in space, spin & color
antisymmetric in isospin
accessed via $\Delta\Delta$ as doorway ?



Early Dibaryon Searches

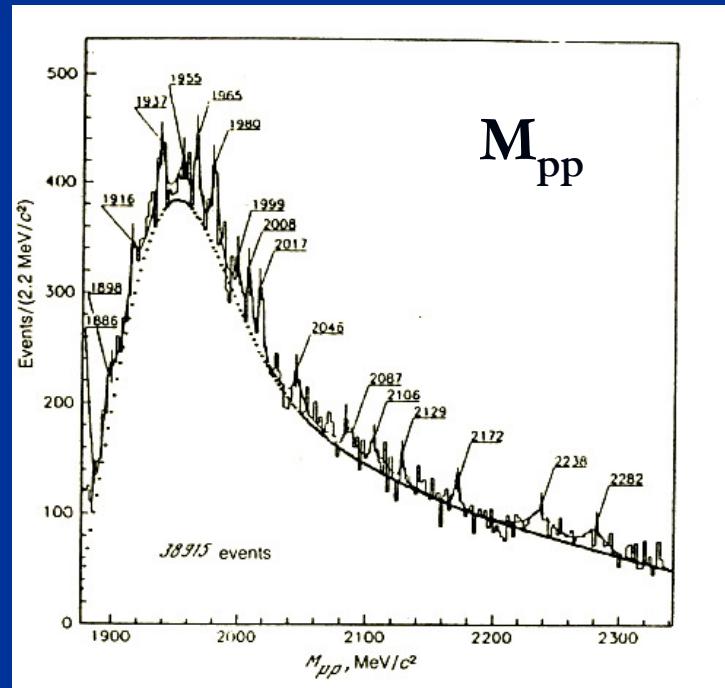
- Before 1964 (quark model):
 - First hints for resonating 1D_2 partial wave from $pp \leftrightarrow d\pi^+$ (Dubna)
- After 1975 (Jaffe's H-dibaryon prediction):
 - Worldwide searches for dibaryons

In the following: only non-strange dibaryons

The Experimental Rush for Dibaryons

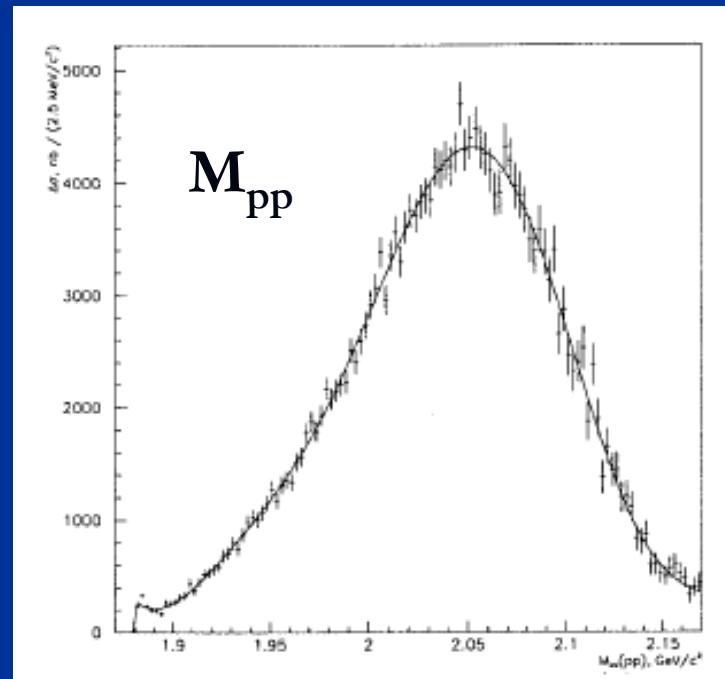
- Low statistics versus high statistics (quality):

$np \rightarrow pp\pi^- + n\pi^0$, bubble chamber



Troyan & Pechenov, Phys. At. Nucl. 56 (1993) 528

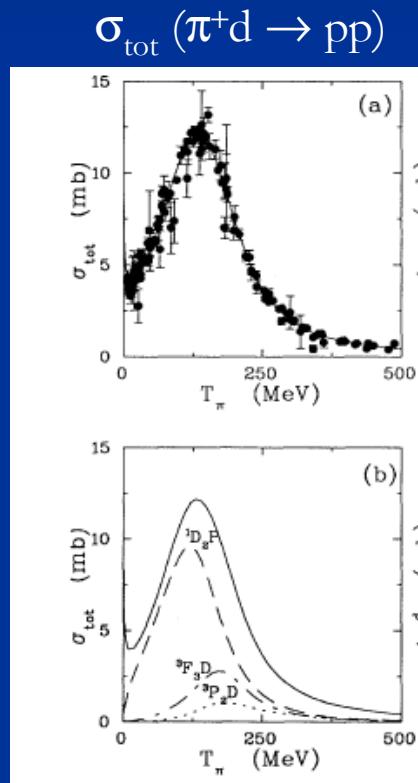
$np \rightarrow pp\pi^-$, magn. spectrometer



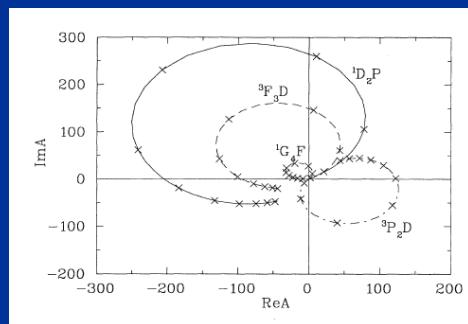
Abramov et al., Z. Phys. C69 (1996) 409

The 1D_2 Resonance

- Best seen in $pp \leftrightarrow d\pi^+$,
- but also in $pp \rightarrow pn\pi^+$ as well as pp and π^+d scattering (phaseshift analyses)



Argand plot



R.A. Arndt et al., PRC 48 (1993) 1926

50 (1994) 1796

56 (1997) 635

N. Hoshizaki, PRC 45 (1992) R1424

Prog. Theor. Phys. 89 (1993) 245

251

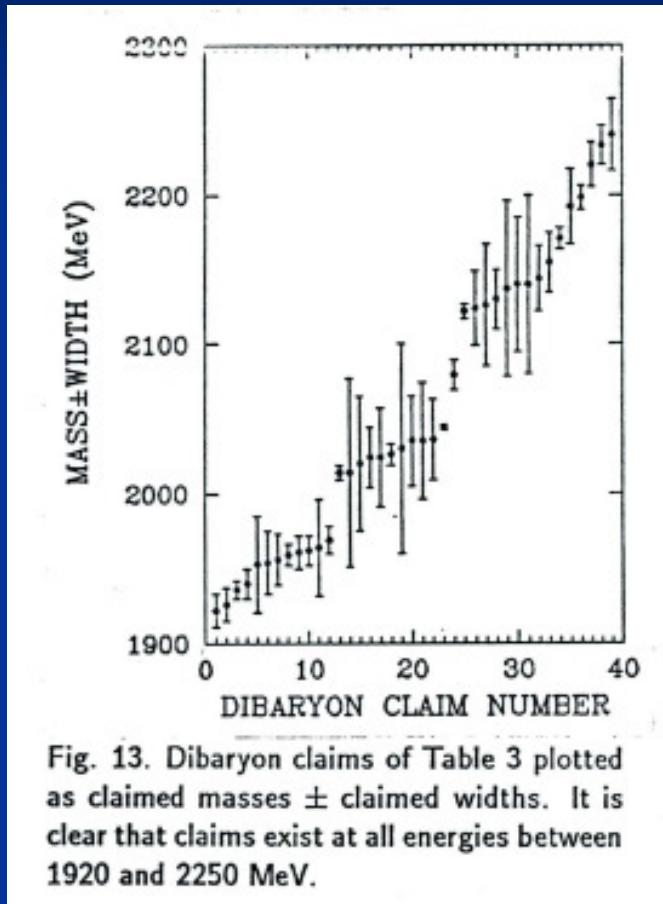
563

569

$I(J^P) = 1(2^+)$
 $M = 2144 \text{ MeV} = m_\Delta + m_N - 26 \text{ MeV}$
 $\Gamma = 110 \text{ MeV} \approx \Gamma_\Delta$

Alternative **dynamic** description: Diss. C.A. Mosbacher, Bonn 1998

One of the Conclusions about this Dibaryon Rush



Kamal Seth (1988)
in
„Dibaryons in
Theory and Practice“

- 1) „Nobody has seen a genuine, gold-(silver-, ... or even un-) plated dibaryon, yet.“
- 2) „The days of Q & D ... are over...
We must do honest hard work, or quit...
We should do exclusive experiments.“

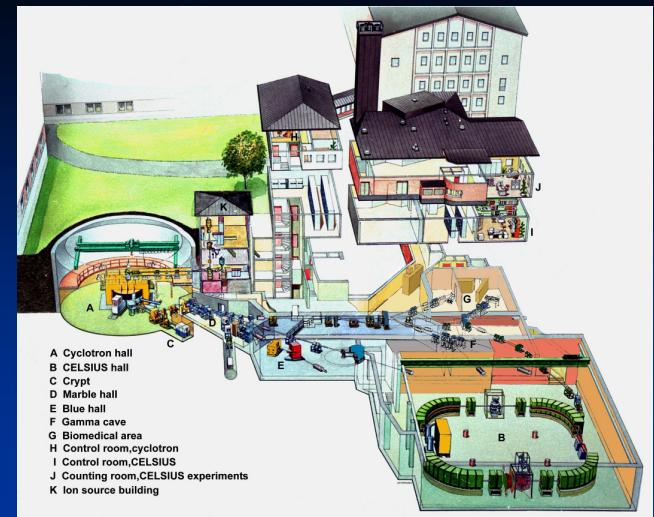
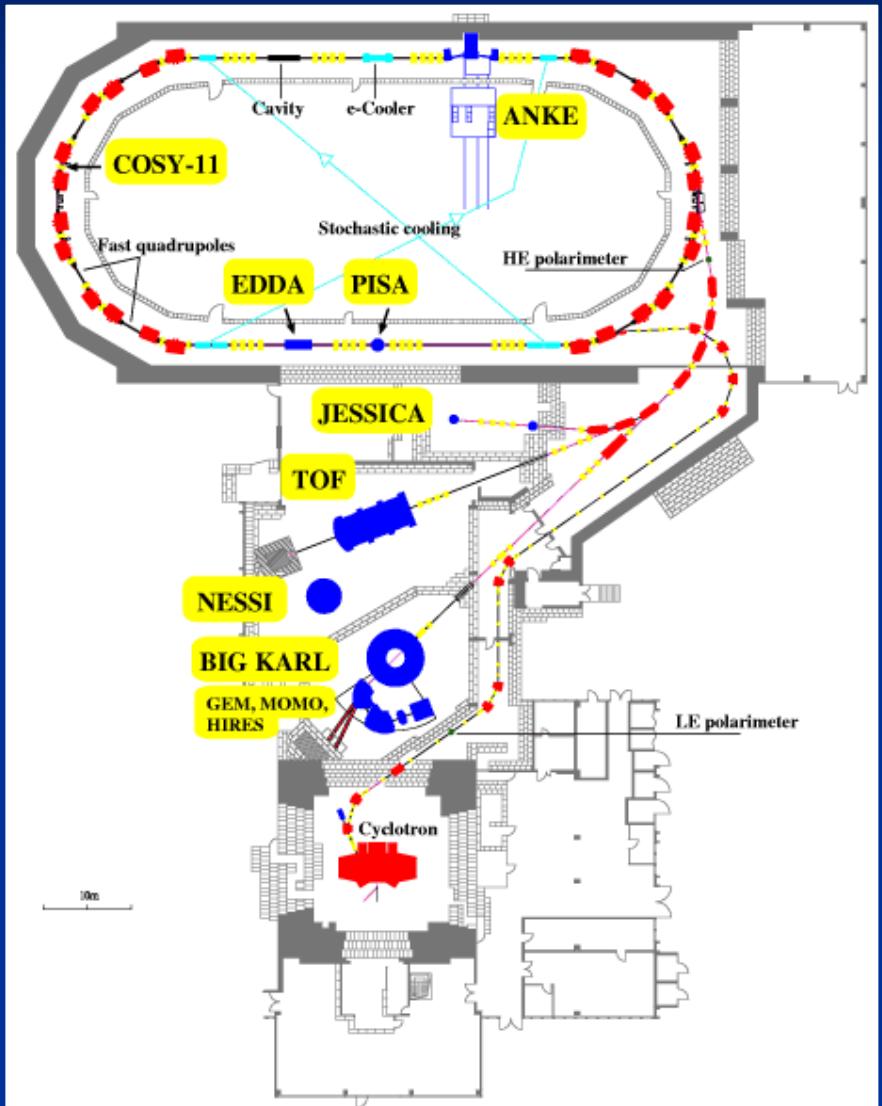
So how to find a Dibaryon?

Exclusive and kinematically complete measurements

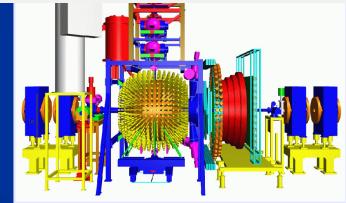
■ Our approach:

- 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 two-pion production

WASA at COSY



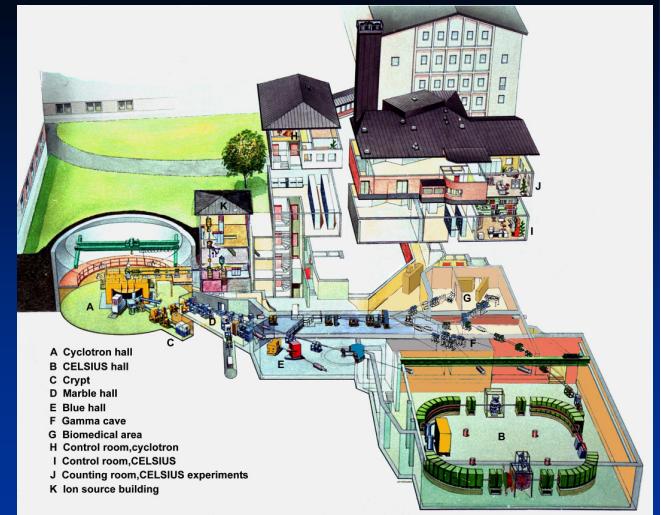
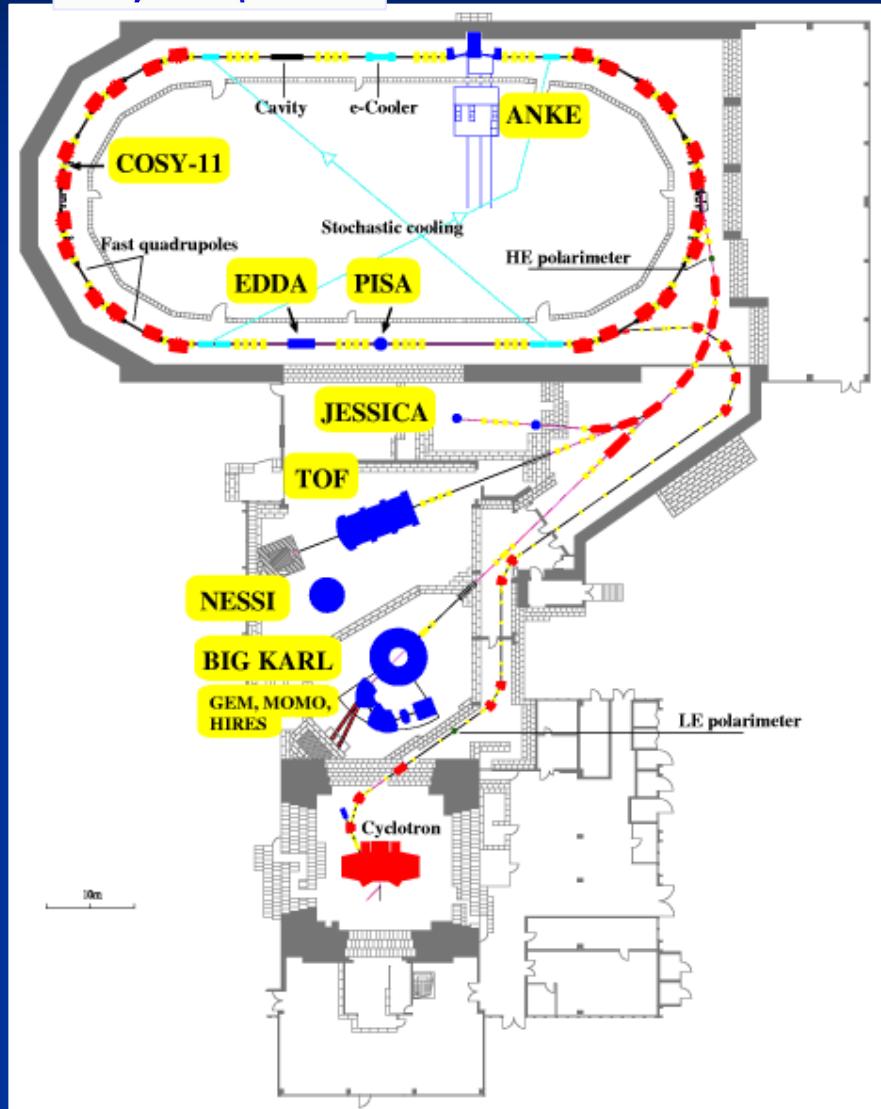
2005 - 2006



CELSIUS/WASA

of a Dibaryon State

WASA at COSY

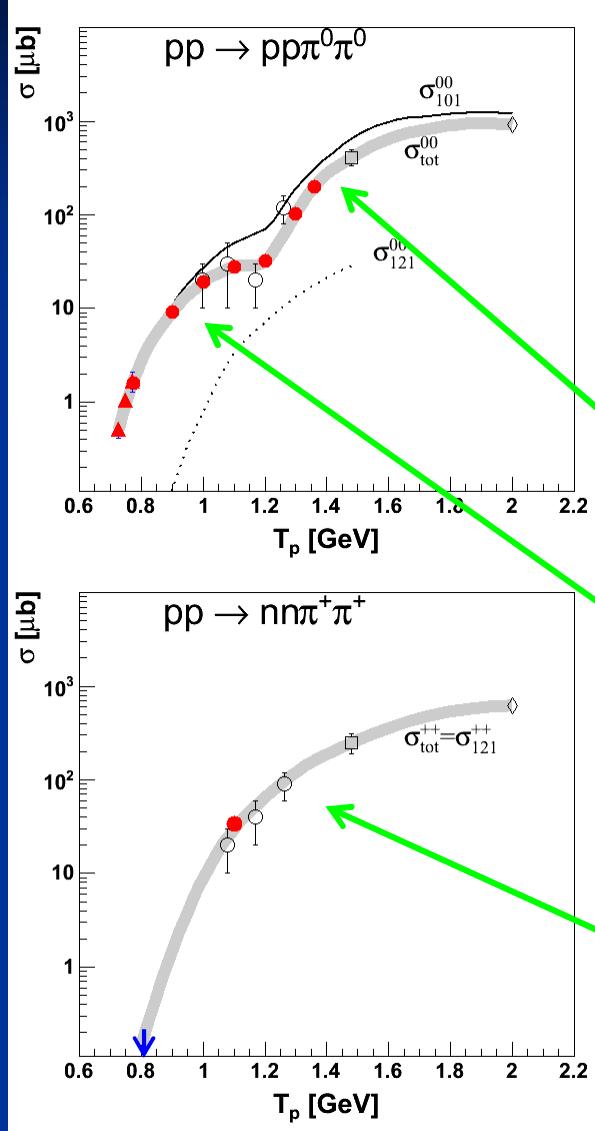
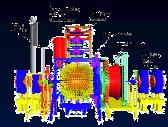


2005 - 2006

CELSIUS/WASA

of a Dibaryon State

Isovector : Total Cross Sections



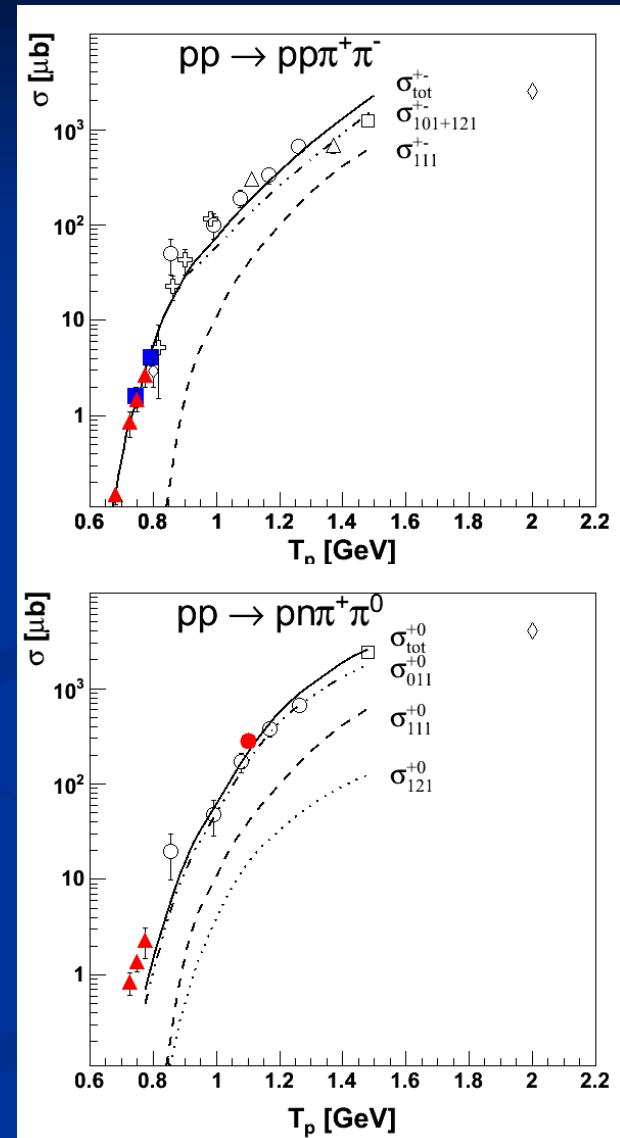
isospin
decomposition



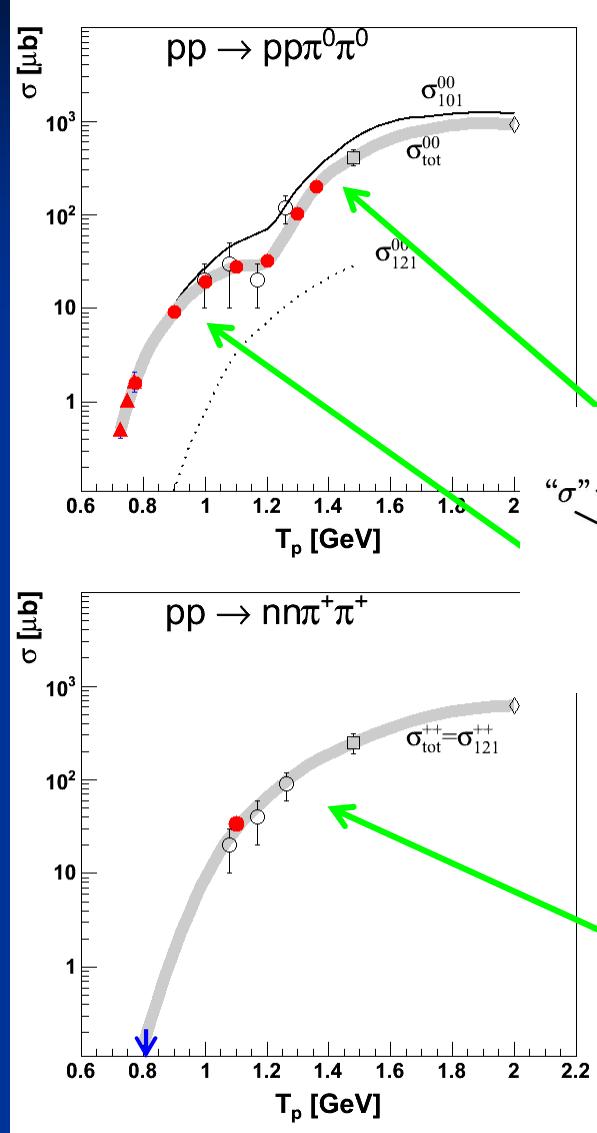
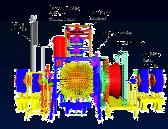
$N^*(1440)$

$\Delta(1600)$ (?)

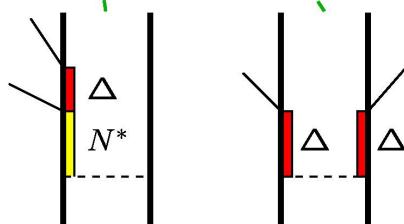
Phys. Lett. B 679 (2009) 30



Isovector : Total Cross Sections

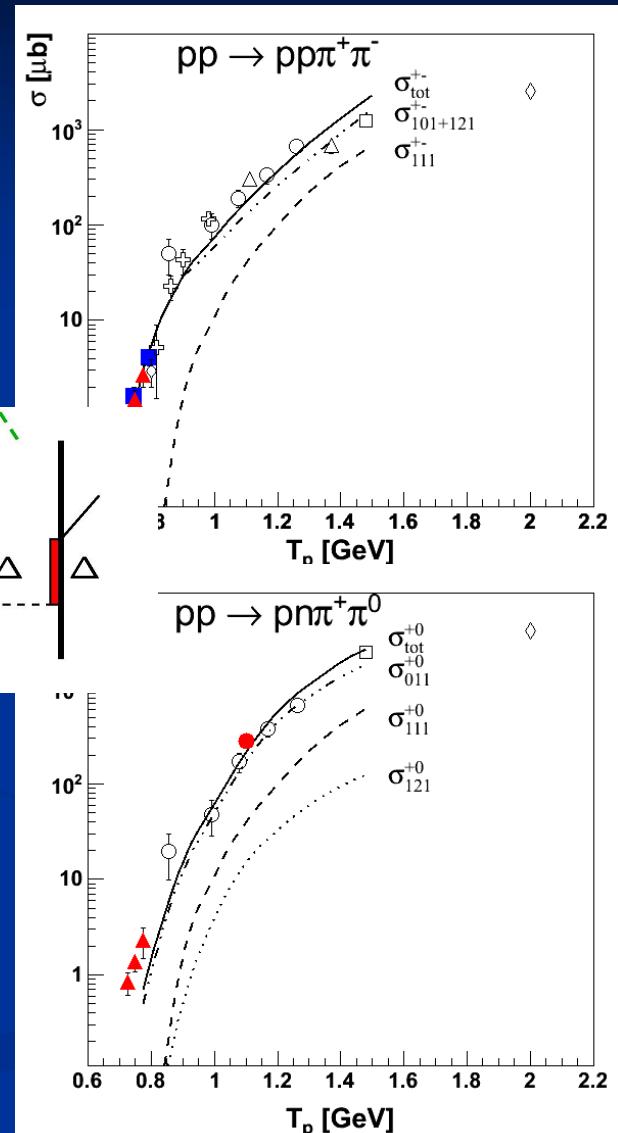


isospin
decomposition

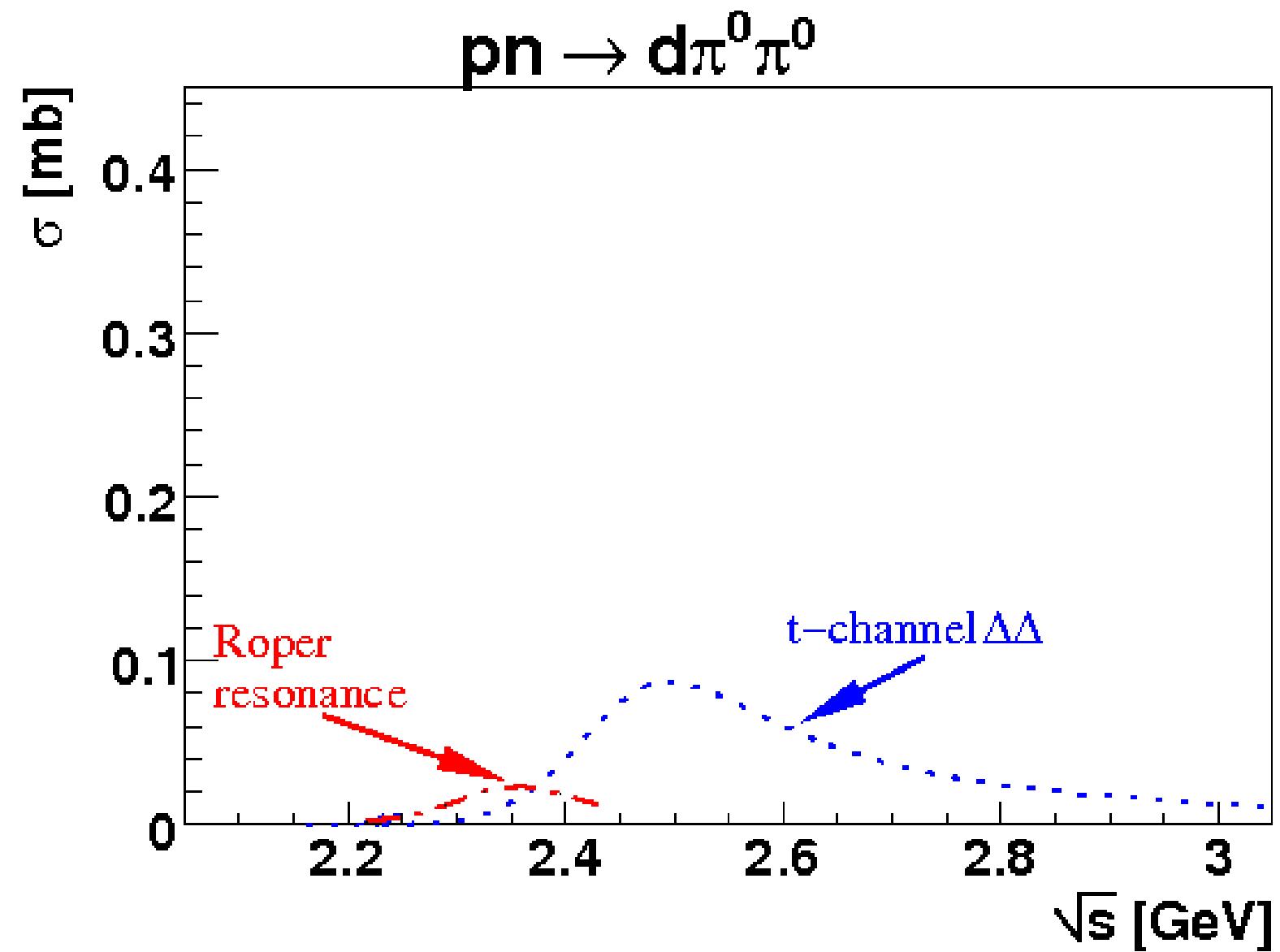


$\Delta(1600)$ (?)

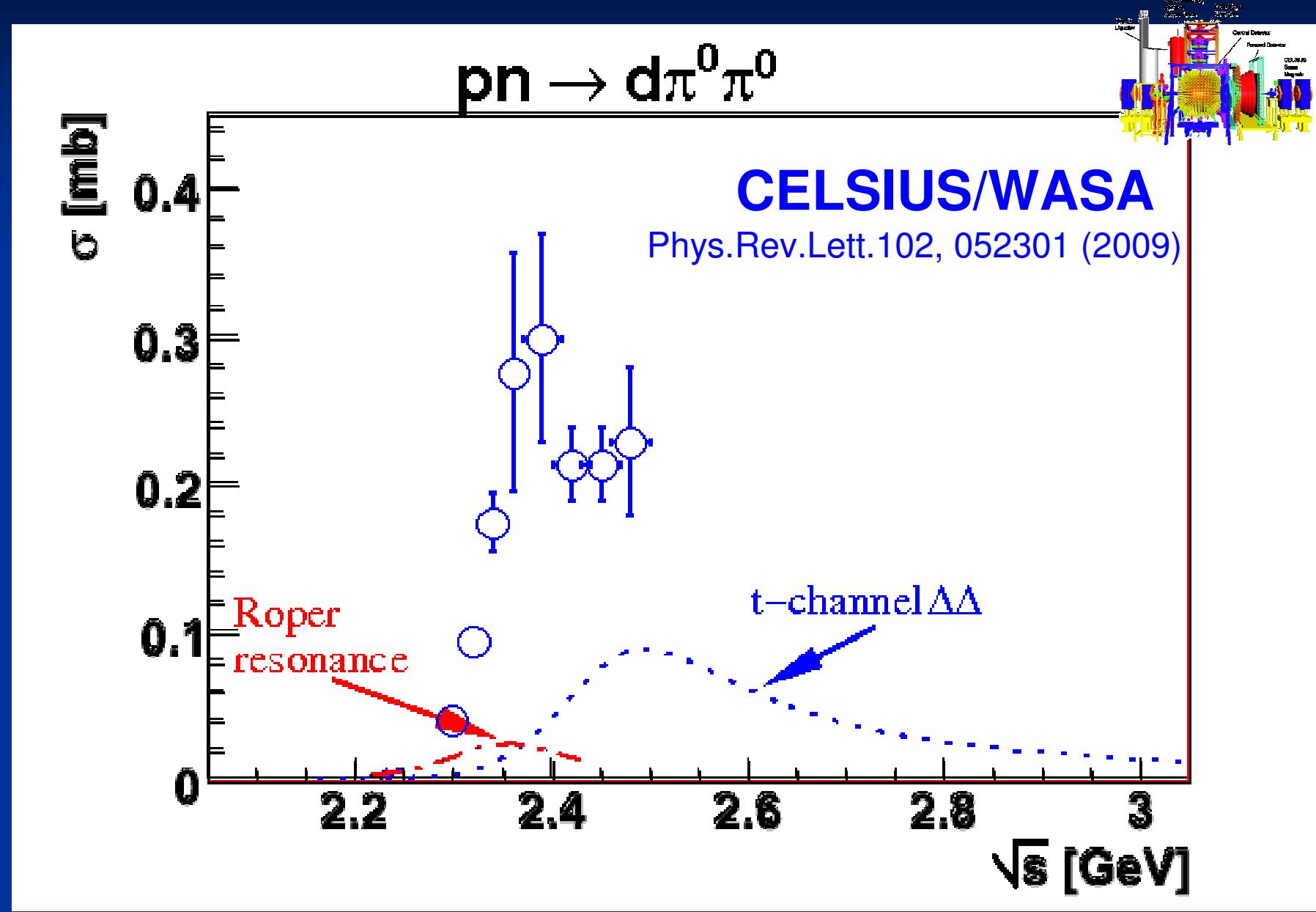
Phys. Lett. B 679 (2009) 30



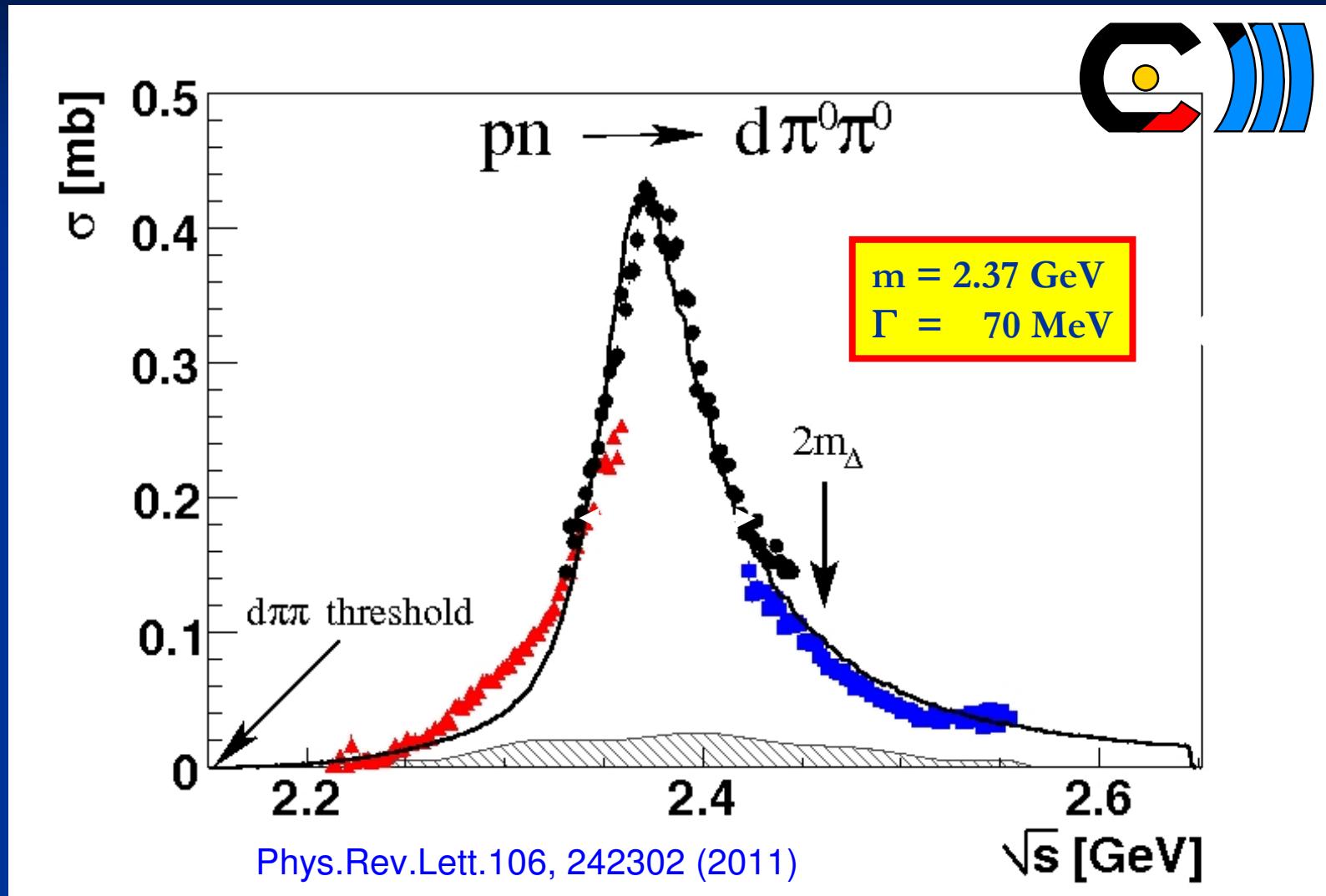
Isoscalar : ... this is what we expected!



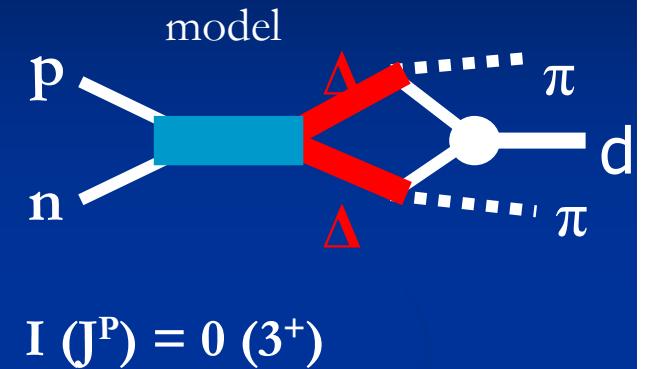
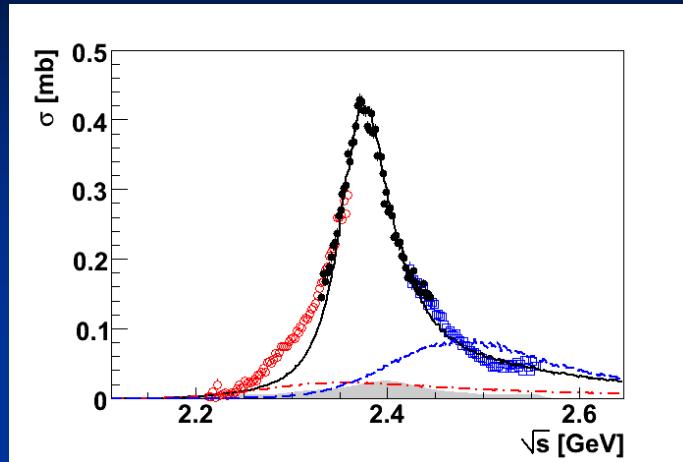
Isoscalar : ... and this is what we found!



Isoscalar : Results from WASA at COSY

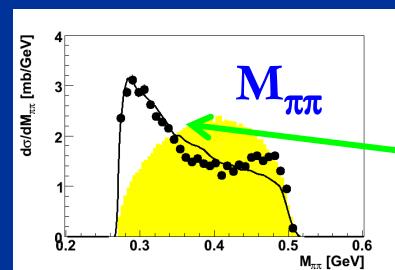
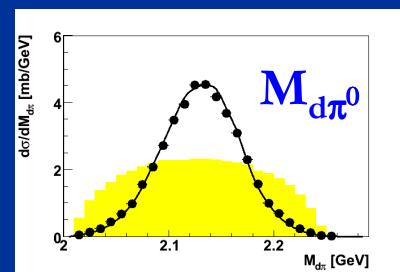
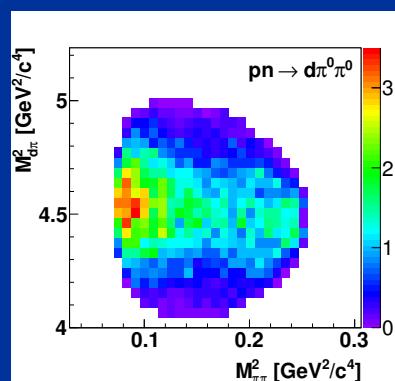


$p\bar{n} \rightarrow d^* \rightarrow \Delta\Delta \rightarrow d\pi^0\pi^0$

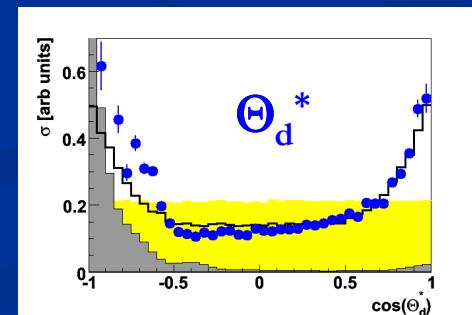


$M, \Gamma, \Gamma_i * \Gamma_f, F(q_{\Delta\Delta})$

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



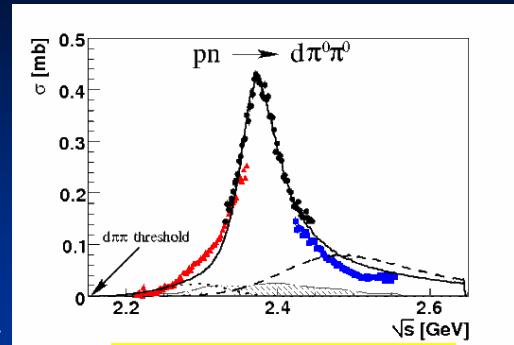
ABC effect



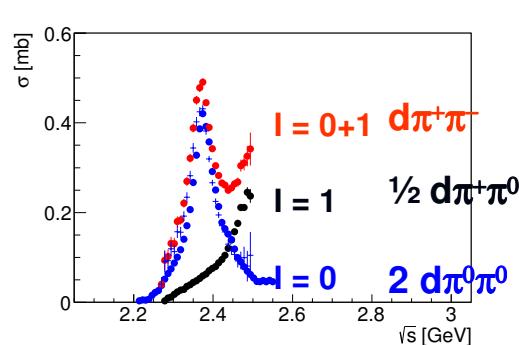
hadronic decays

PRL 106 (2011) 242302

WASA data



PLB 721 (2013) 229



$pn \rightarrow d^*(2380)$

$d\pi^0\pi^0$

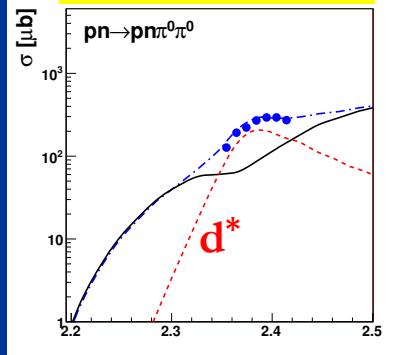
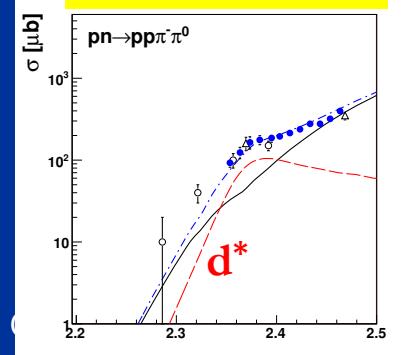
$d\pi^+\pi^-$

$pp\pi^-\pi^0$

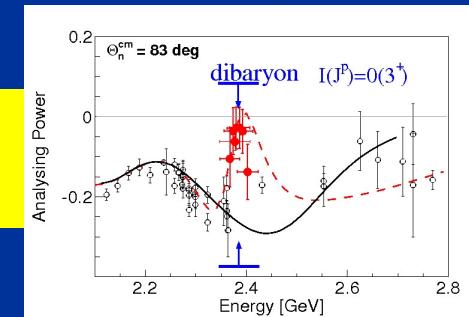
$pn\pi^0\pi^0$

$pn\pi^+\pi^-$

H. O.



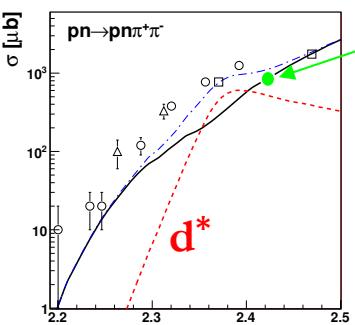
baryo



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

HADES

PRC 88 (2013) 055208
PLB 743 (2015) 325
Proc. STORI 2015



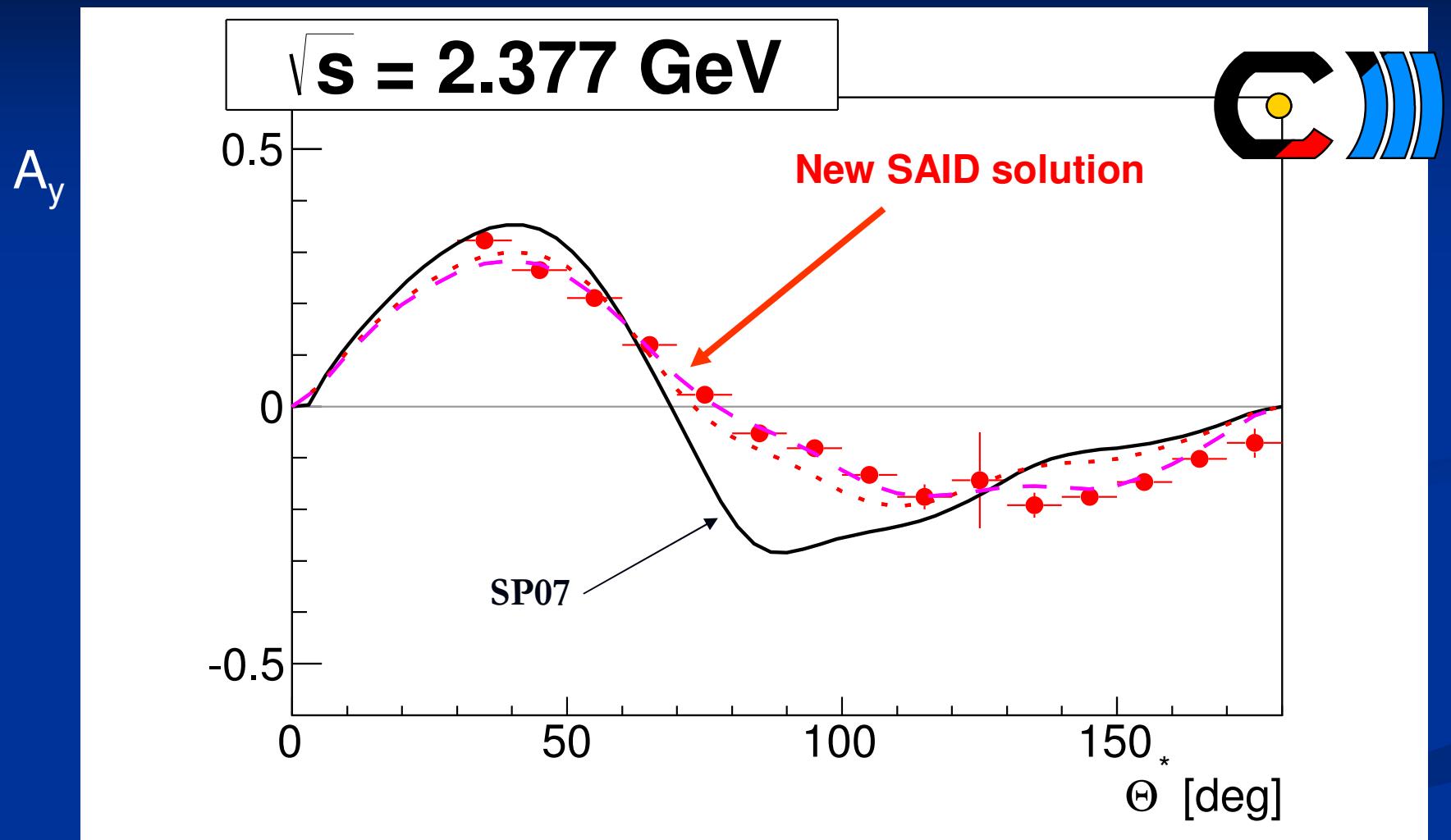
→ \sqrt{s} [GeV]

21

Crucial Experiment for d^*

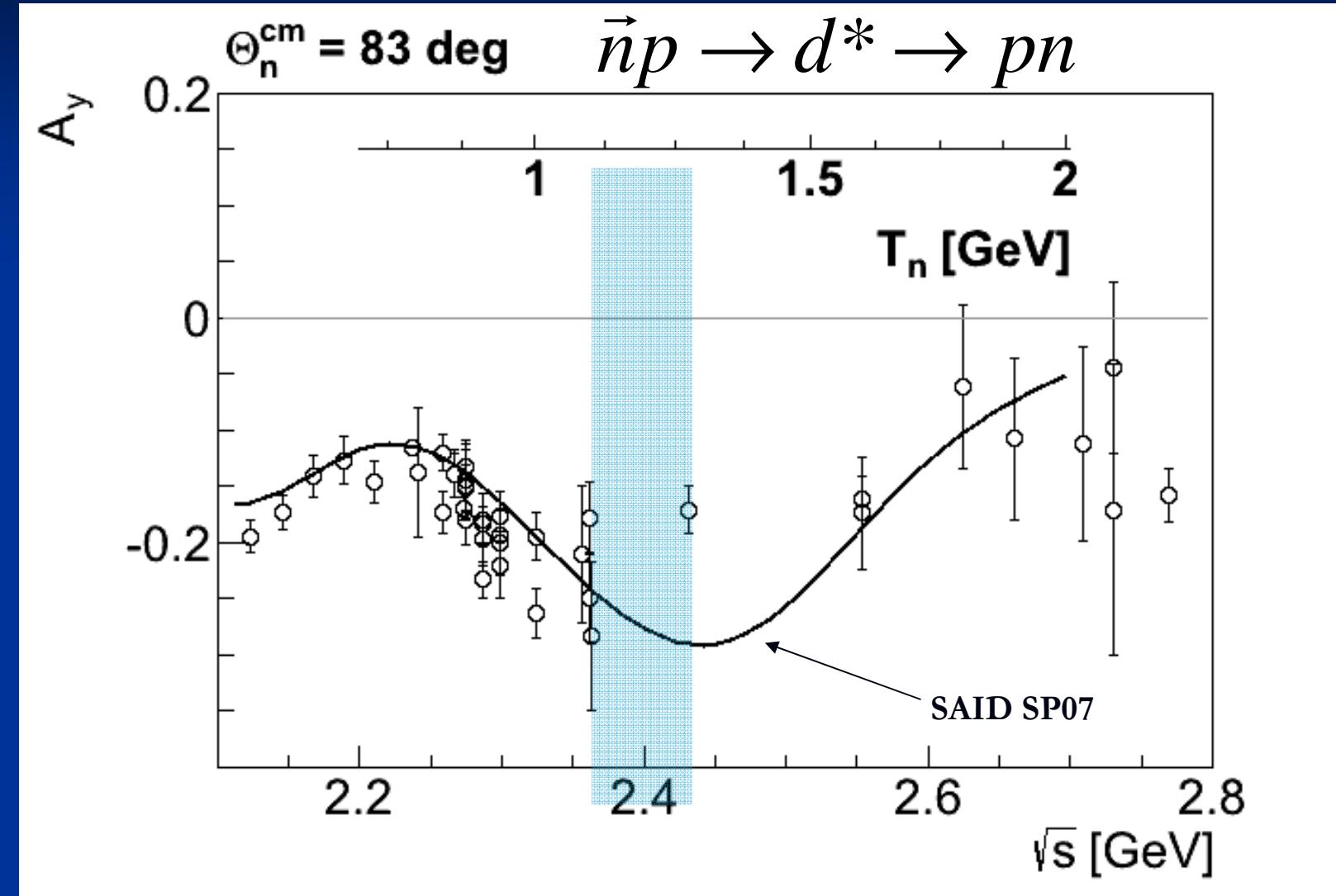
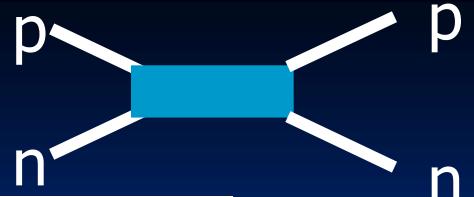
- If d^* a true s-channel resonance
- \Leftrightarrow
- then also a resonance in the np system
- \Leftrightarrow
- to be sensed in np scattering
- \Leftrightarrow
- in particular in the analyzing power
- \Leftrightarrow
- resonance effect $\sim P_3^1(\Theta)$
- i.e. maximal at $\Theta = 90^\circ$

A_y Angular Distribution at Resonance

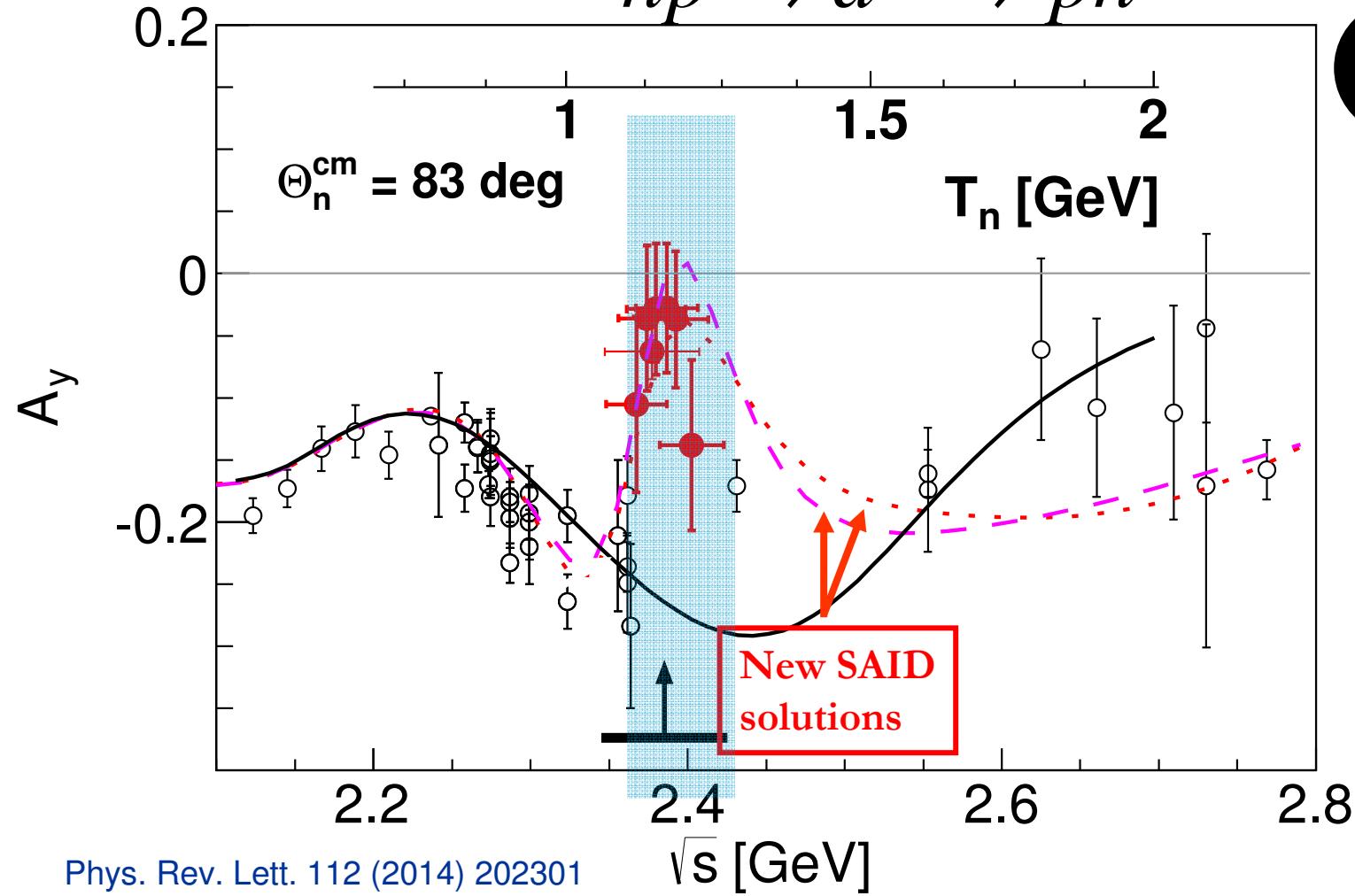


Phys. Rev. Lett. 112 (2014) 202301

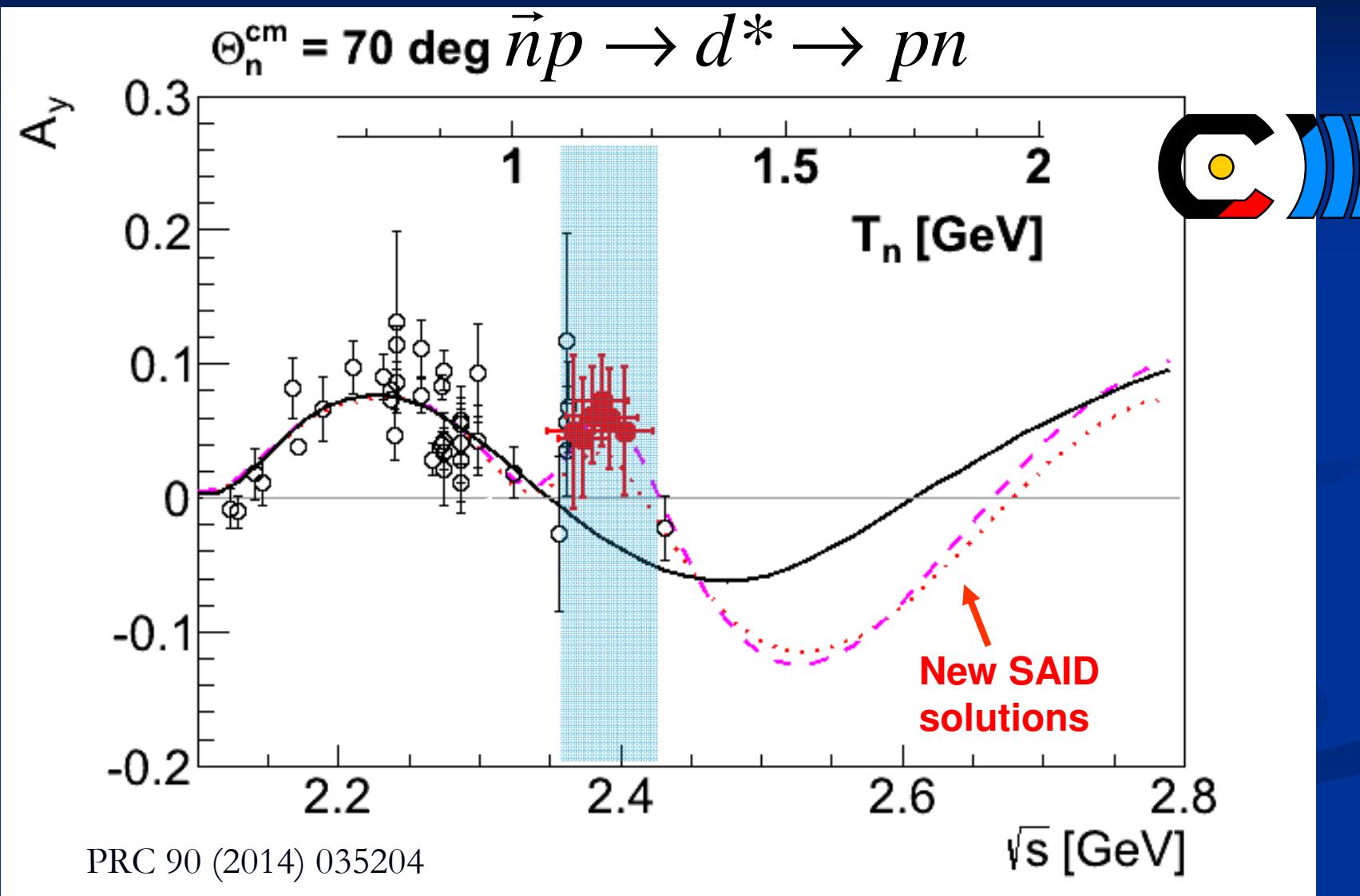
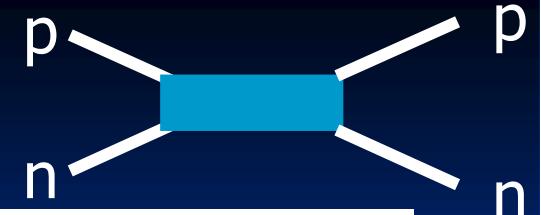
Energy Dependence



Energy Dependence



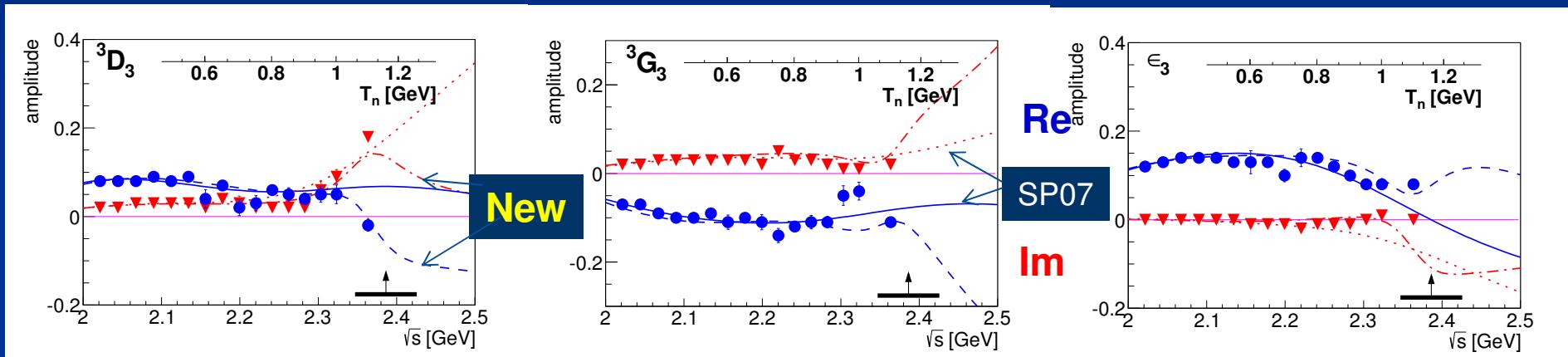
A_y Energy Dependence



SAID Partial-Wave Analysis

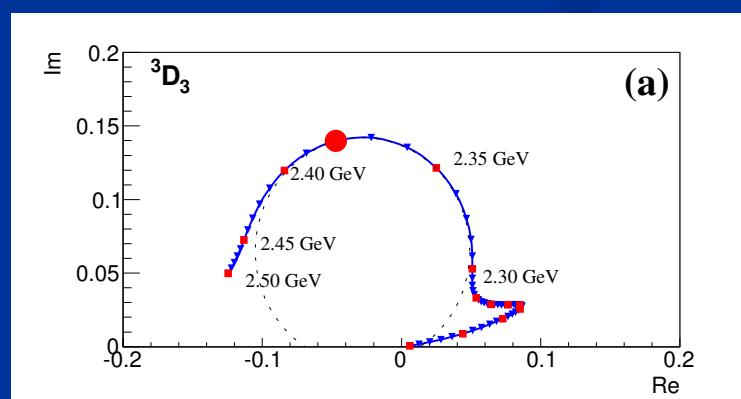
$^3D_3 - ^3G_3$ Coupled Partial Waves

Phys. Rev. Letters 112 (2014) 202301



Argand diagram:

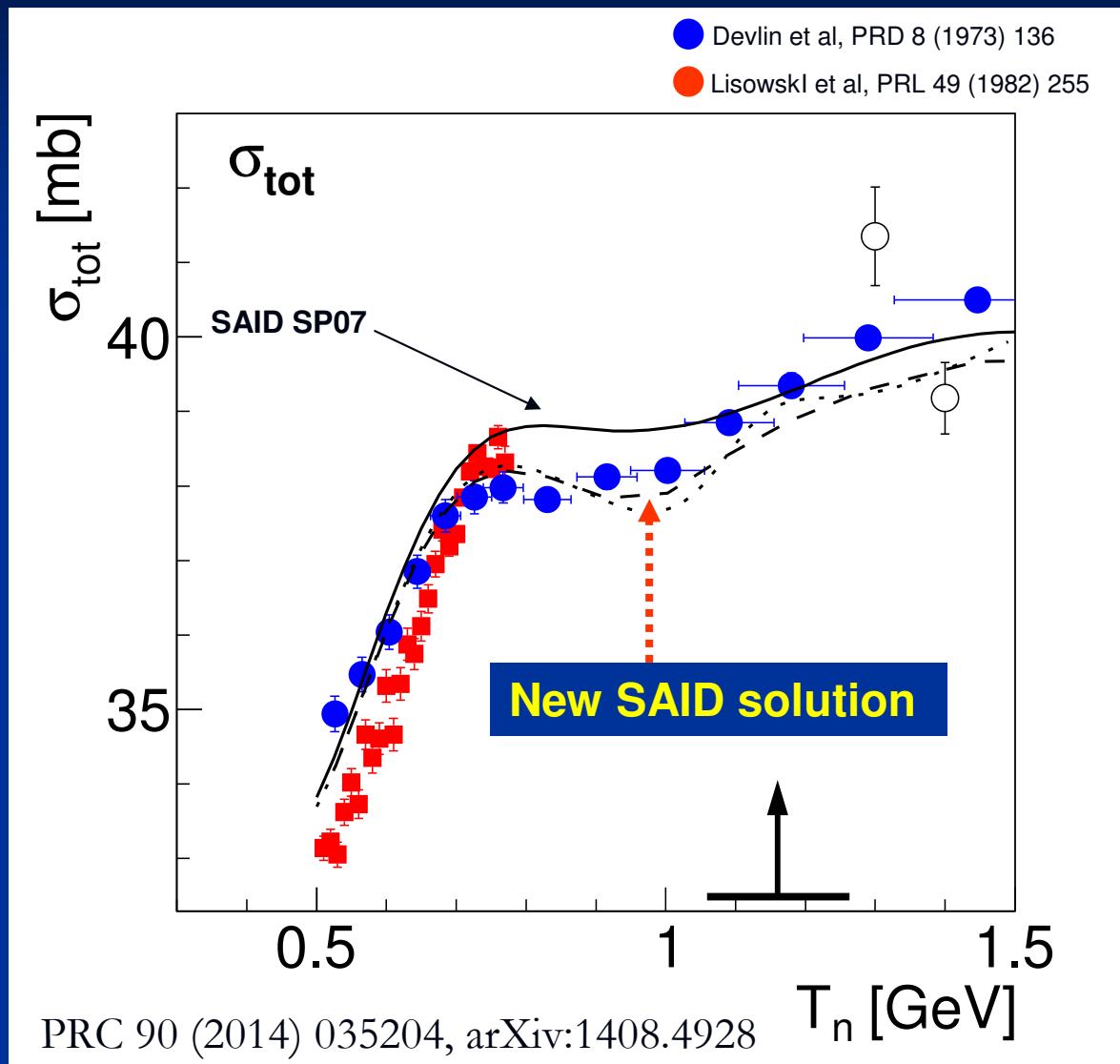
PRC 90 (2014) 035204



Pole in 3D_3 at
 $2380 \pm 10 - i 40 \pm 5$ MeV

↔ Genuine Resonance
in np System

pn Total Cross Section



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

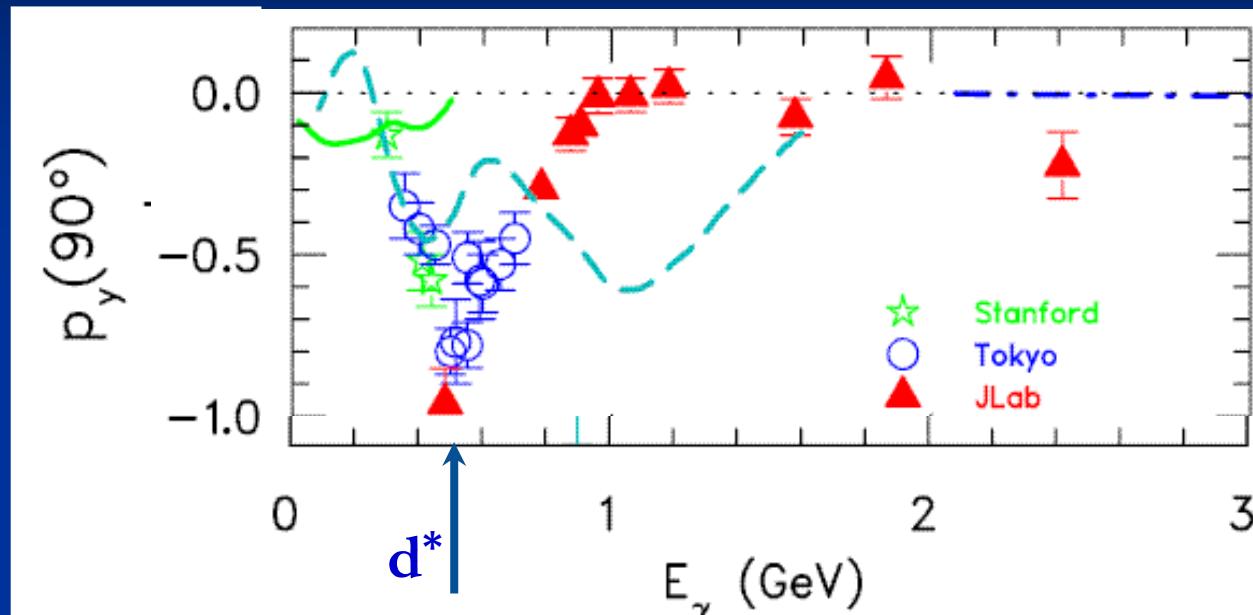
- hadronic decays

arxiv: 1502.07156

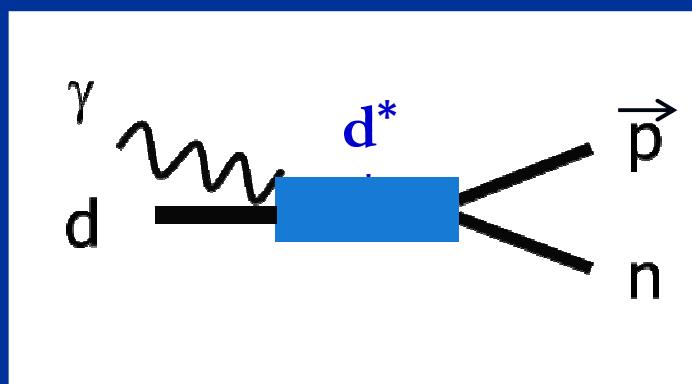
decay channel	branching	derived from
$d \pi^0\pi^0$	$14 \pm 1 \%$	measurement
$d \pi^+\pi^-$	$23 \pm 2 \%$	measurement
$pp\pi^0\pi^-$	$6 \pm 1 \%$	measurement
$nn\pi^+\pi^0$	$6 \pm 1 \%$	isospin mirrored
$np\pi^0\pi^0$	$12 \pm 2 \%$	measurement
$n\bar{p}\pi^+\pi^-$	$30 \pm 4 \%$	measurement, old data + HADES
np	$12 \pm 3 \%$	measurement
$(NN\pi)_{I=0}$	---	estimate: 0%

consistent with
isospin coupling
for a $\Delta\Delta$ intermediate system

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



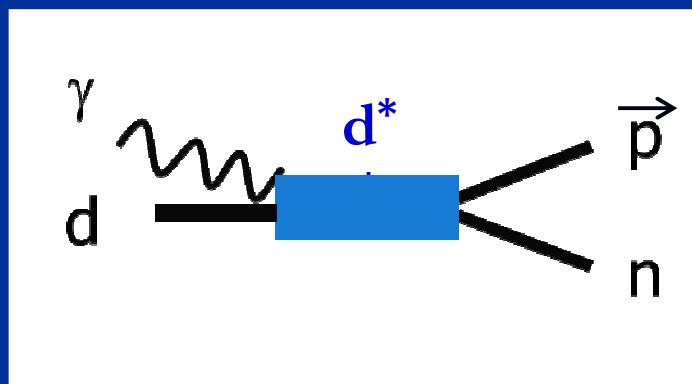
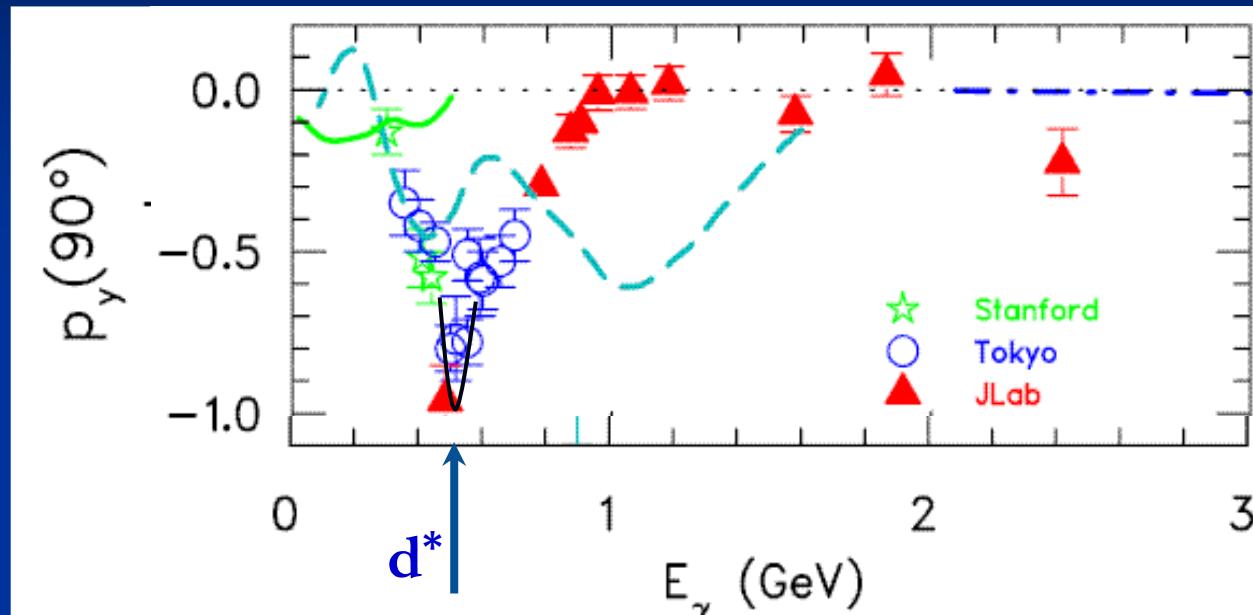
R. Gilman and F. Gross AIP Conf. Proc. 603 (2001) 55
 K. Wijesooriya et al., Phys. Rev. Lett. 86 (2001) 2975



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

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

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

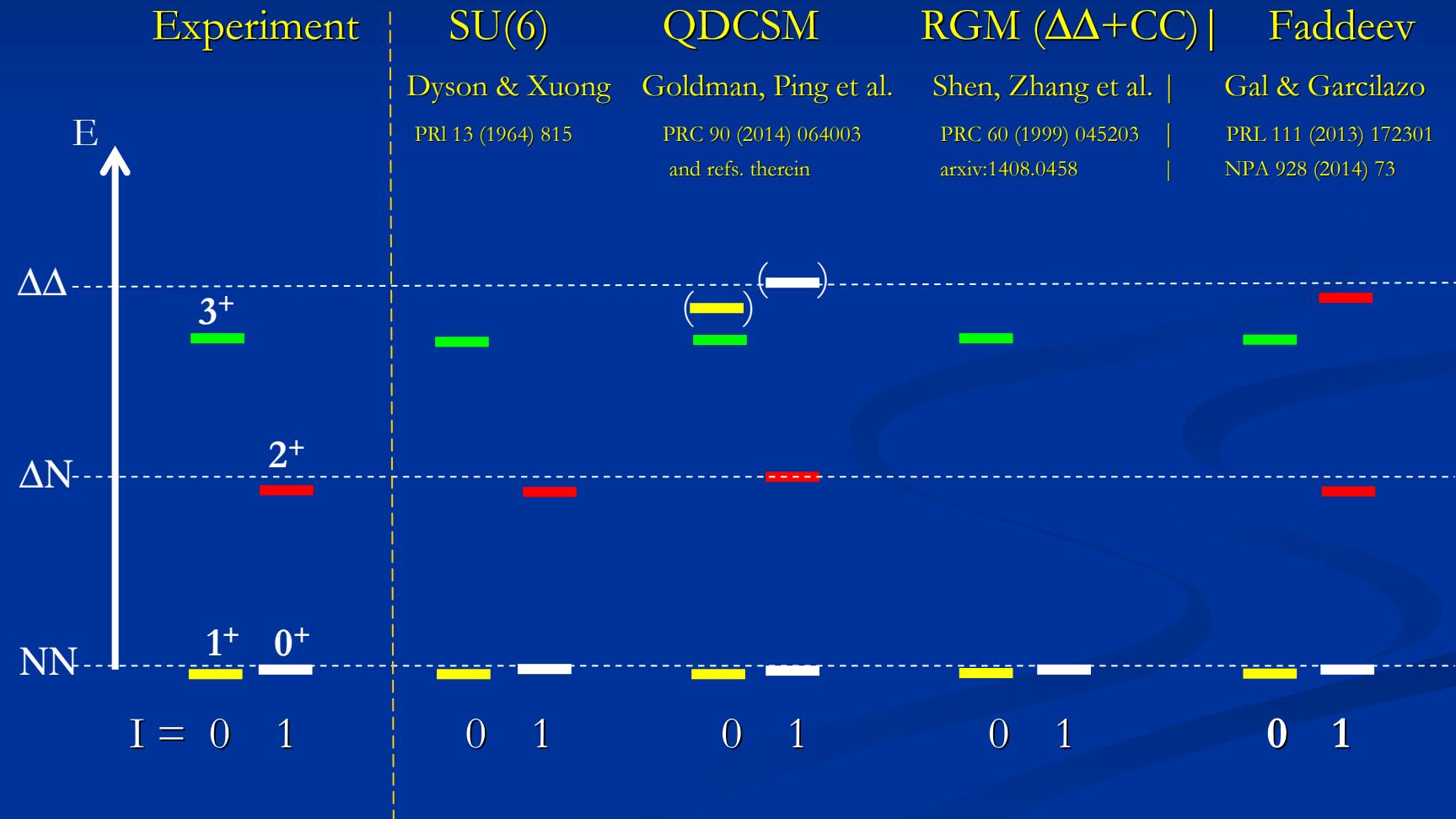
T. Kamae, T. Fujita Phys. Rev. Lett. 38 (1977) 471

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

Dyson & Xuong's Prediction

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D_{10}	1	0	virtual 1S_0	1876	✓ 1878	
D_{12}	1	2	$NN(^4D_2) \leftrightarrow \Delta N \leftrightarrow NN\pi$	2160	✓ 2144	110
D_{21}	2	1	$\Delta N \leftrightarrow NN\pi$	2160	?	?
D_{03}	0	3	$NN(^3D_3) \leftrightarrow \Delta\Delta \leftrightarrow NN\pi\pi$	2350	✓ 2370	70
D_{30}	3	0	$\Delta\Delta \leftrightarrow NN\pi\pi$	2350	?	?

Comparison to predictions from Quark and Hadron Models



Width of $d^*(2380)$

- Experiment: $\Gamma \approx 70$ MeV
 - (t-channel $\Delta\Delta$: ≈ 250 MeV)
- QDCSM: 110 MeV PRC 89 (2014) 034001
- Faddeev: 94 MeV NPA 928 (2014) 73
 - Hidden Color ? PLB 727(2013) 438
- RGM ($\Delta\Delta + CC$) 69 MeV arxiv:1503.02456 and 1505.05395

Conclusions

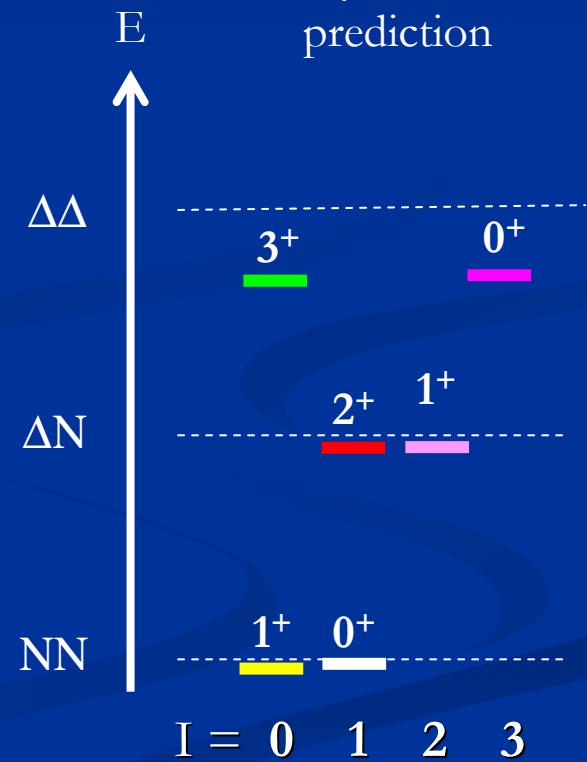
- Non-Strange Two-Baryon Spectrum
 - 3 established states: 3S_1 deuteron groundstate
 1S_0 virtual state
 1D_2 resonance (ΔN)
 - 1 new - presumably exotic - candidate:
 $d^*(2380)$ resonance ($\Delta\Delta$)
 - Are there more states?
 - NN-decoupled states with $I = 2, 3$?
 - Search in $pp \rightarrow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

Zhang, Chen, Shen et al.

Huang, Ping, Wang et al.

Gal & Garcilazo

Dyson's prediction



Outlook: mirror dibaryon



$I(J^P) = 3(0^+)$: totally symmetric in space, isospin & color
antisymmetric in spin
accessed via $\Delta^{++}\Delta^{++}$ as **asymtotic configuration**

