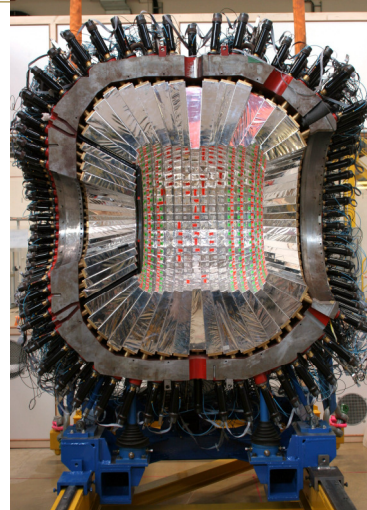
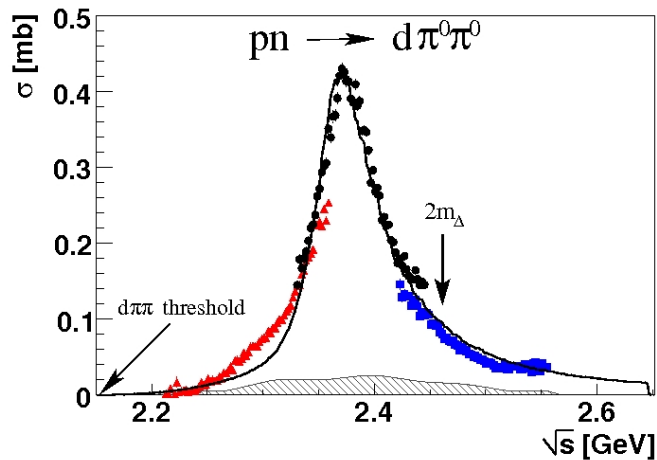




Dibaryon Production at COSY

*EMMI Workshop:
Anti-matter, hyper-matter and exotica production at the LHC
CERN, July 20 -22, 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 ΛN 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:

- $^1\bar{D}_2$ resonance structure at the ΔN threshold:
- $^3\bar{D}_3$ resonance much below the $\Delta\Delta$ threshold:

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



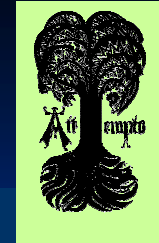
■ Are there more states?

- Theoretical predictions
- Dyson's sextet

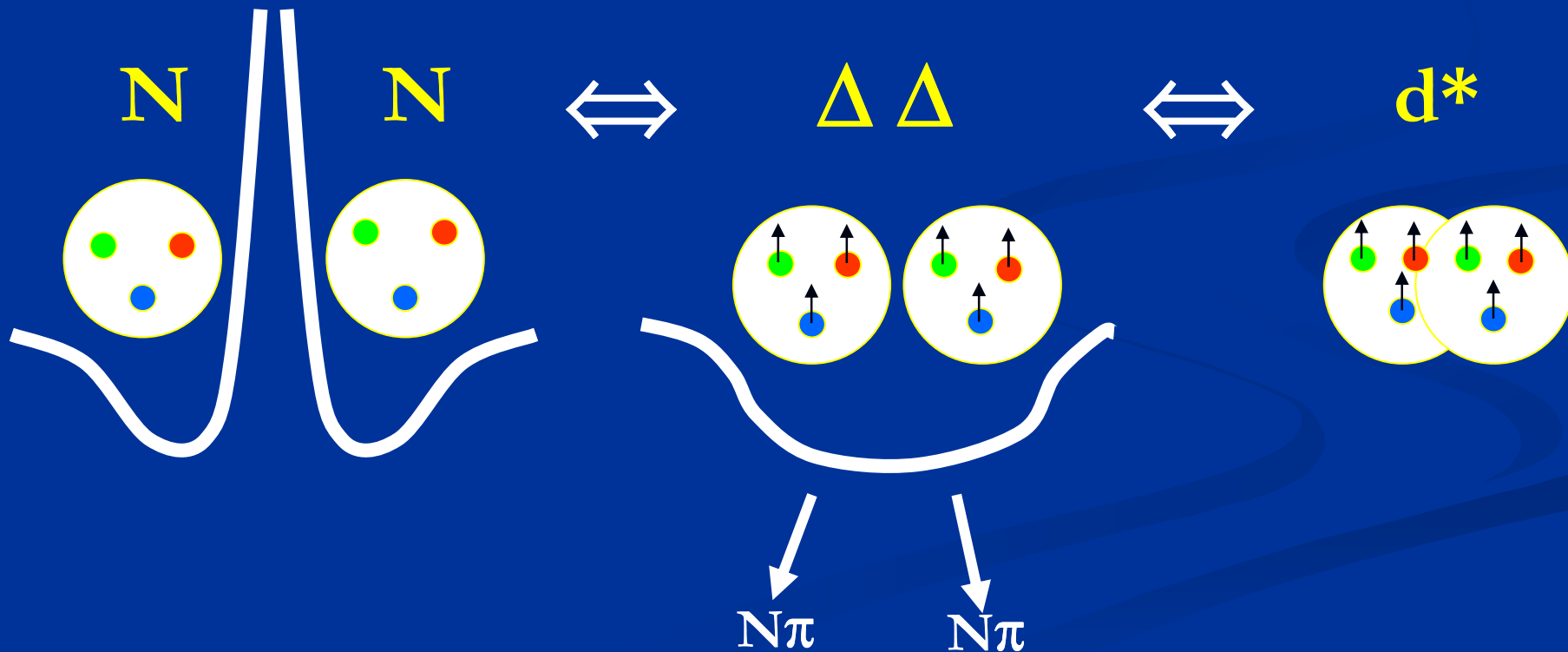
Early Predictions on Dibaryons

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

... 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

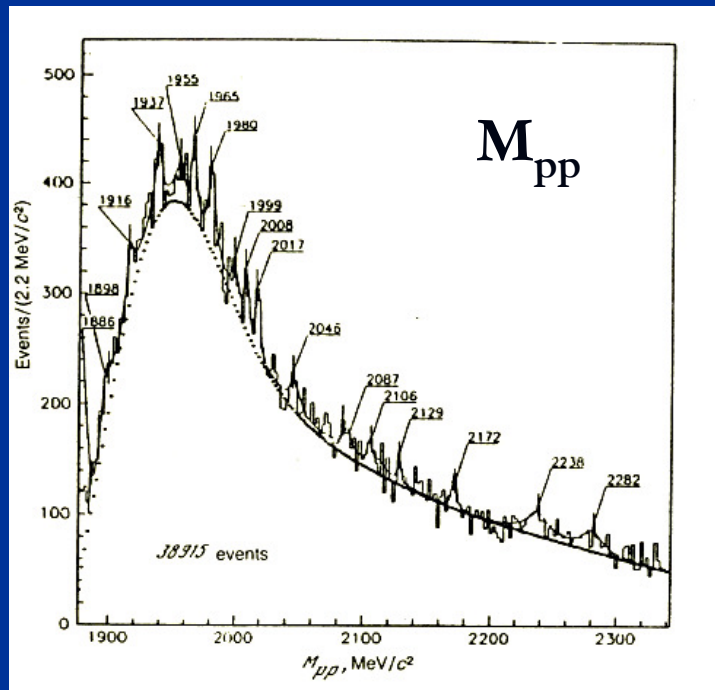
- Before 1964 (quark model):
 - First hints for resonating 1D_2 partial wave from $pp \leftrightarrow d\pi^+$ (Dubna)
- After 1975 (Jaffe's H-dibaryon prediction):
 - Worldwide searches for dibaryons

In the following: only non-strange dibaryons

The Experimental Rush for Dibaryons

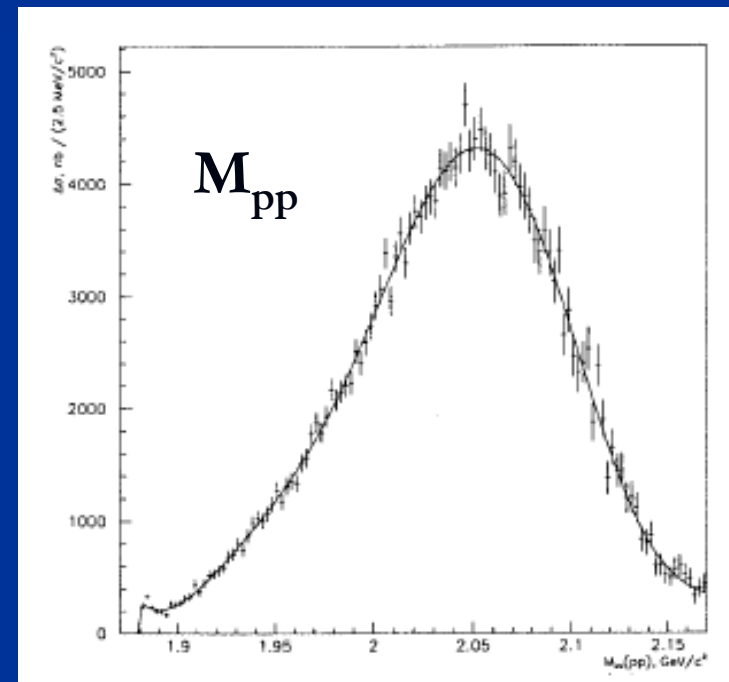
- Low statistics versus high statistics (quality):

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



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

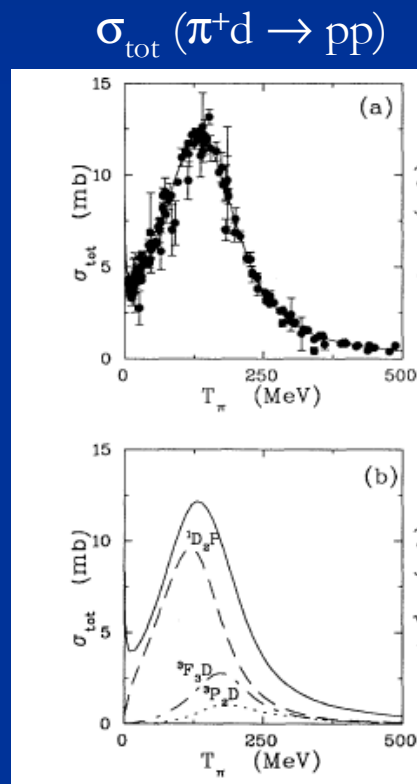
$np \rightarrow pp\pi^-$, magn. spectrometer



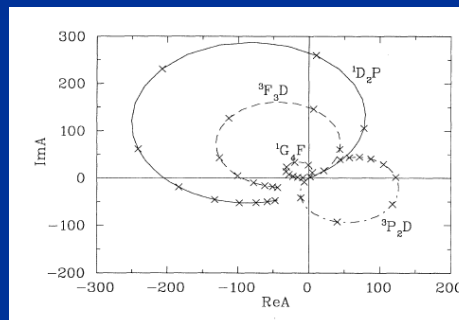
Abramov et al., Z. Phys. C69 (1996) 409

Possibly the only survivor: 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

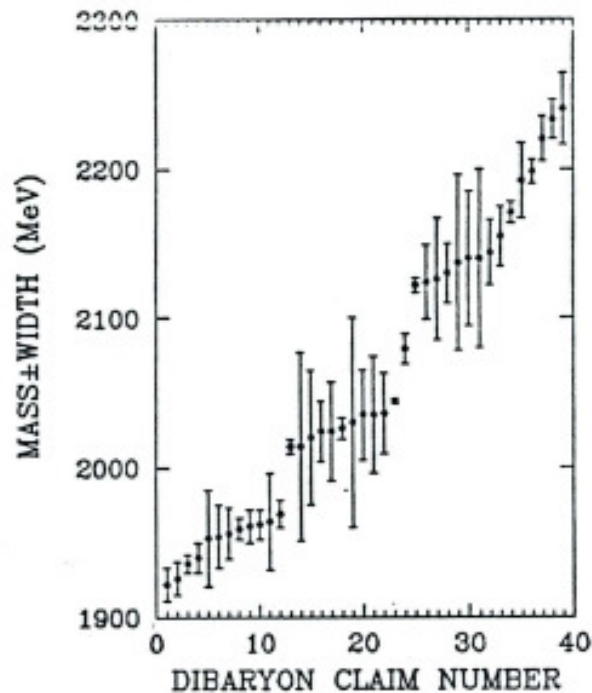


Fig. 13. Dibaryon claims of Table 3 plotted as claimed masses $\pm$ claimed widths. It is clear that claims exist at all energies between 1920 and 2250 MeV.

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

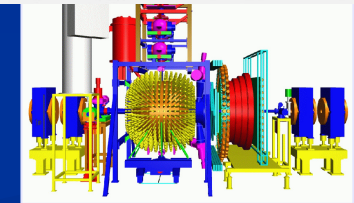
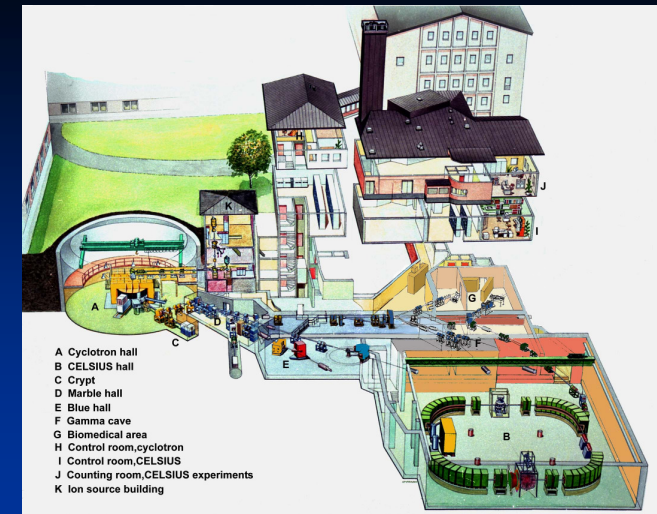
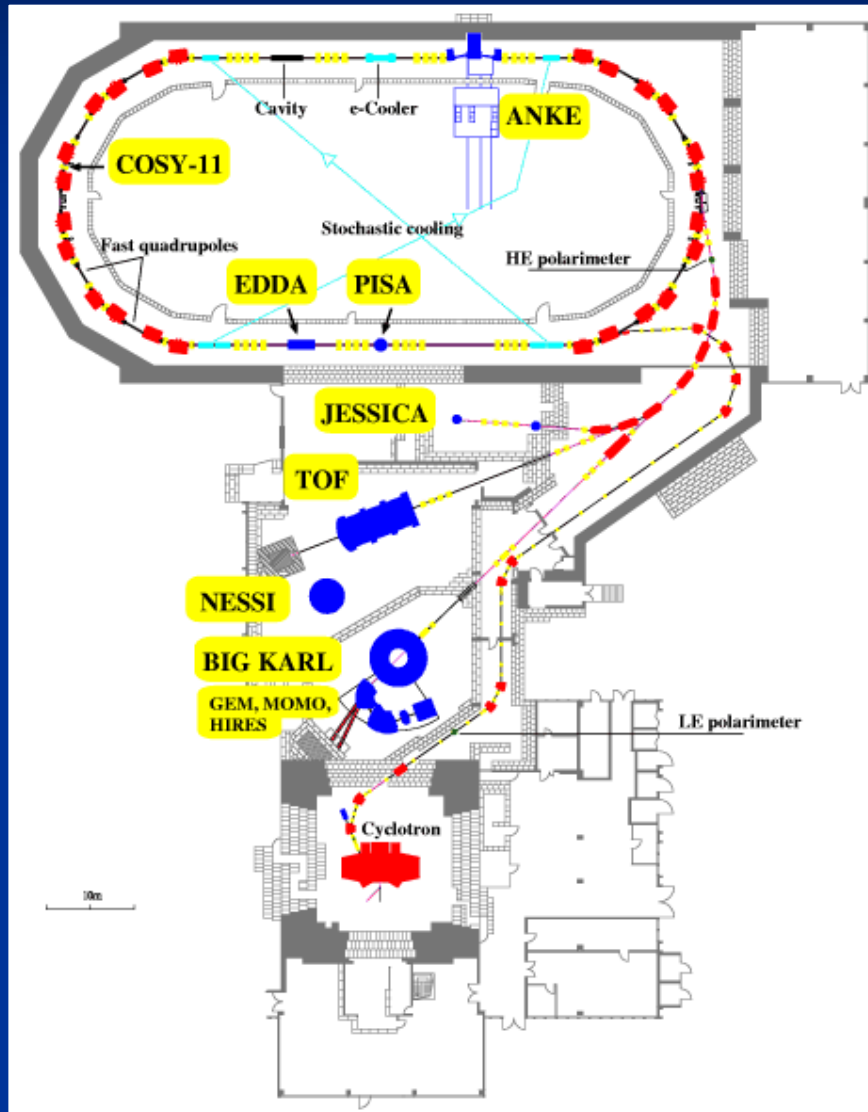
- 1) „Nobody has seen a genuine, gold-
(silver-, ... or even un-) plated
dibaryon, **yet**.“
- 2) „The days of Q & D ... are over...
We must do honest hard work, or quit...
We should do exclusive experiments.“

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 $\rightarrow$ 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

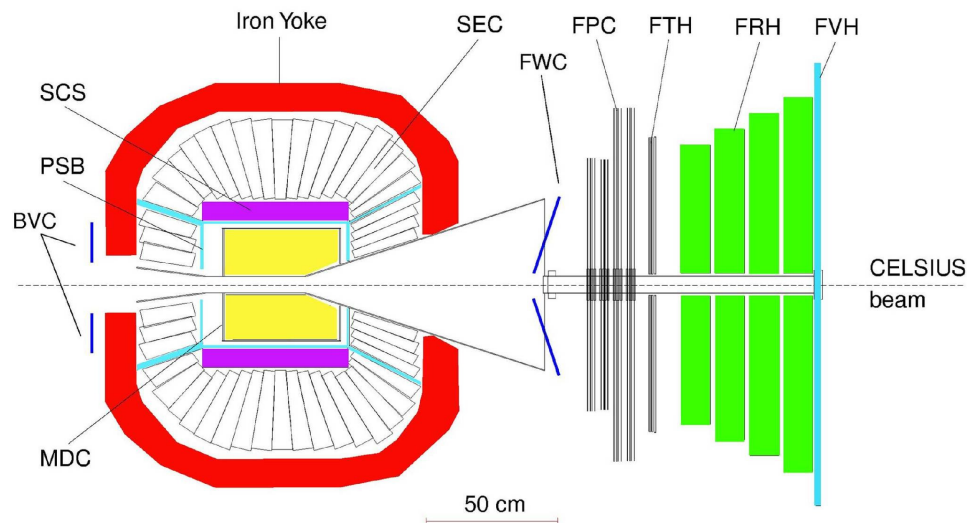
WASA at COSY



2005 - 2006

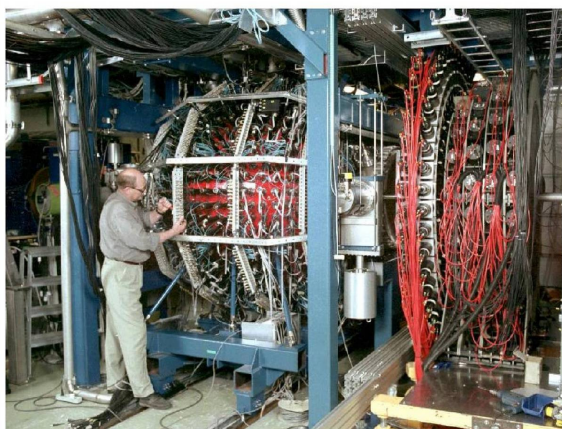
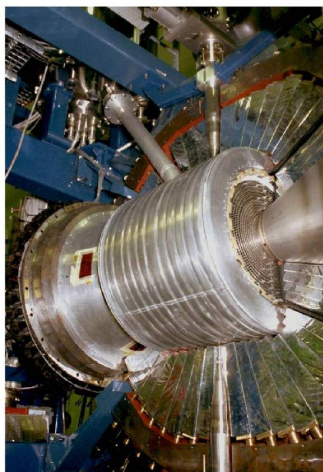
CELSIUS/WASA

WASA 4 π Detector



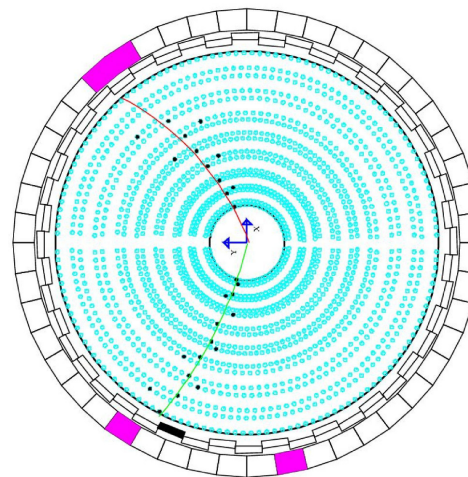
Central Detector

Forward Detector



MDC event

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



- reconstruction of all particles $\Rightarrow$ overdetermined
- magnetic field

Θ resolution

2 deg.

2 deg.

deg.

deg.

5deg

Pellet Target

Pellet Target

pellet stream
 $f = 70$ kHz

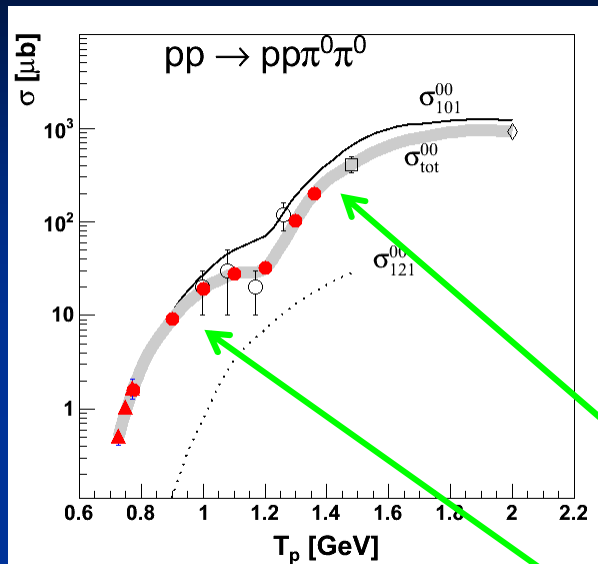
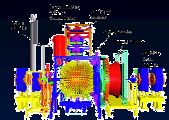
collimator
 $\Phi = 1$ mm

CELSIUS
beam
 $\Phi = 4$ mm

pellet stream
 $f = 20$ kHz
 $v = 60$ m/s
 $\Phi = 30$ μ m

n at COSY

Isovector: Total Cross Sections



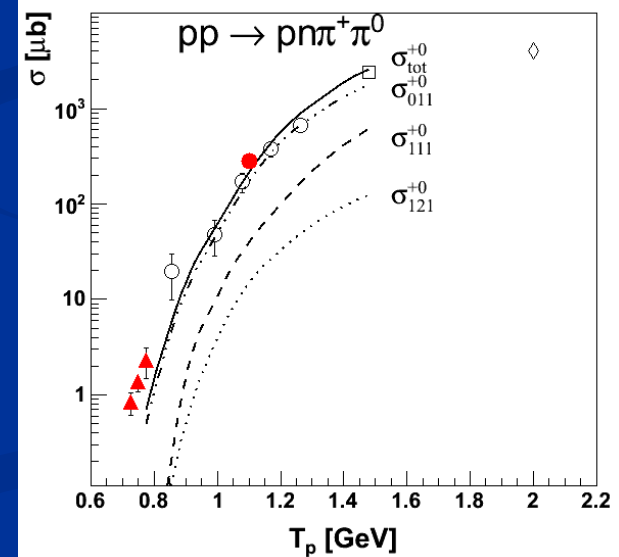
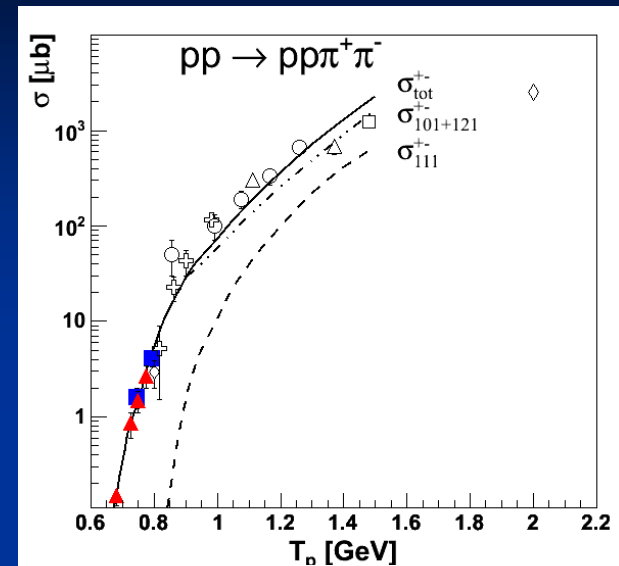
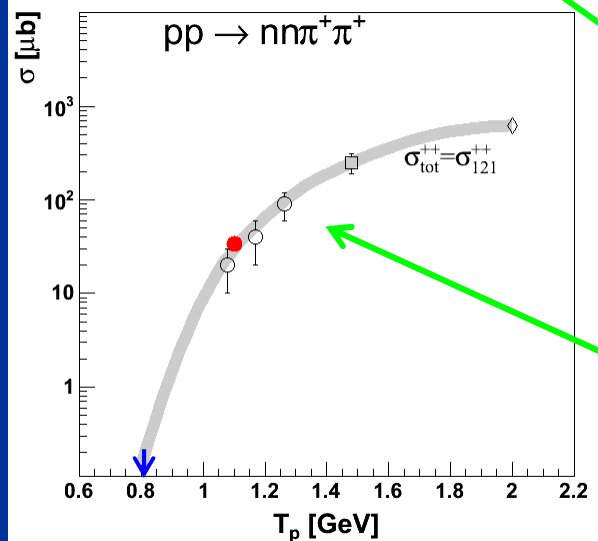
isospin
decomposition



$\Delta\Delta$

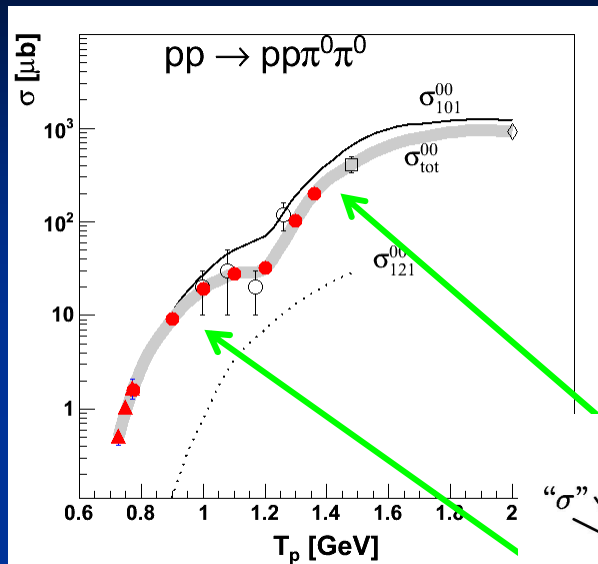
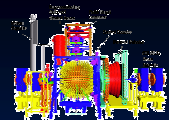
$N^*(1440)$

$\Delta(1600)$ (?)

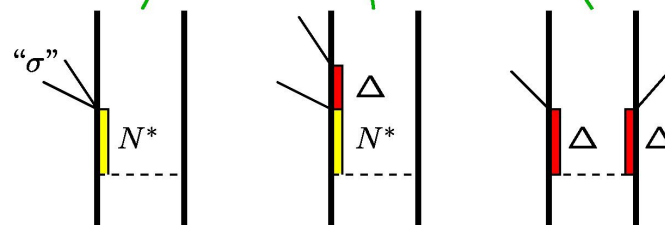
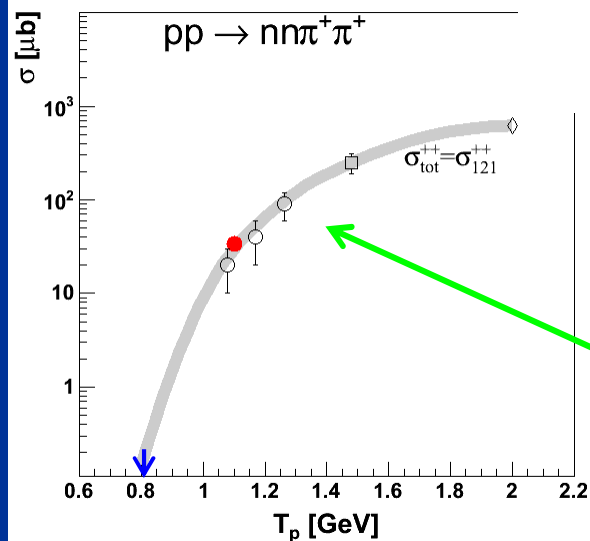
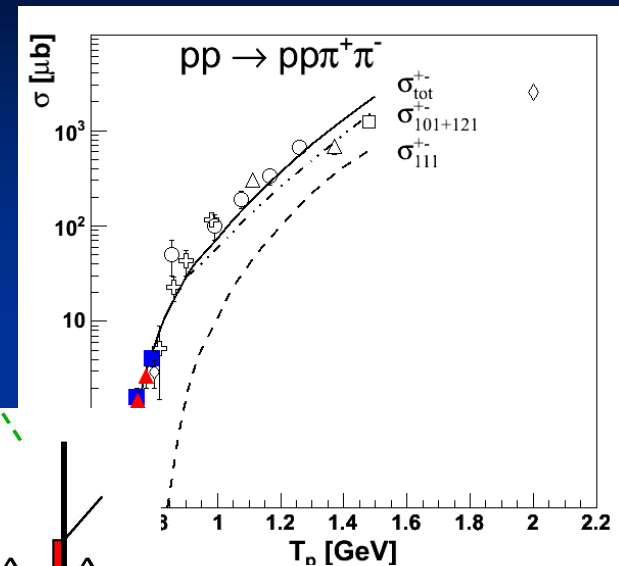


Phys. Lett. B 679 (2009) 30

Isovector : Total Cross Sections

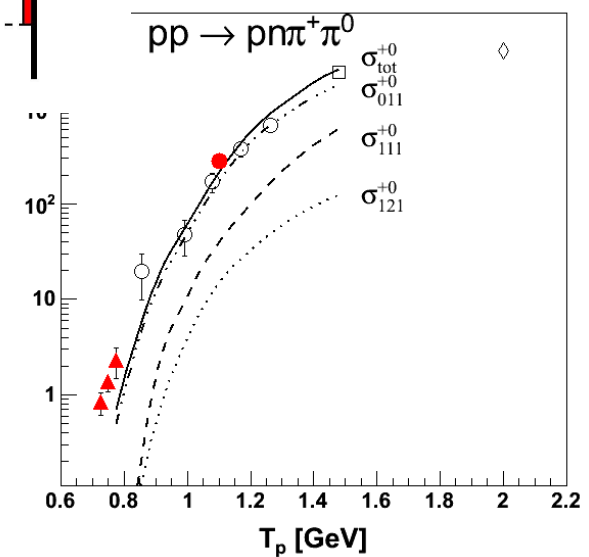


isospin
decomposition

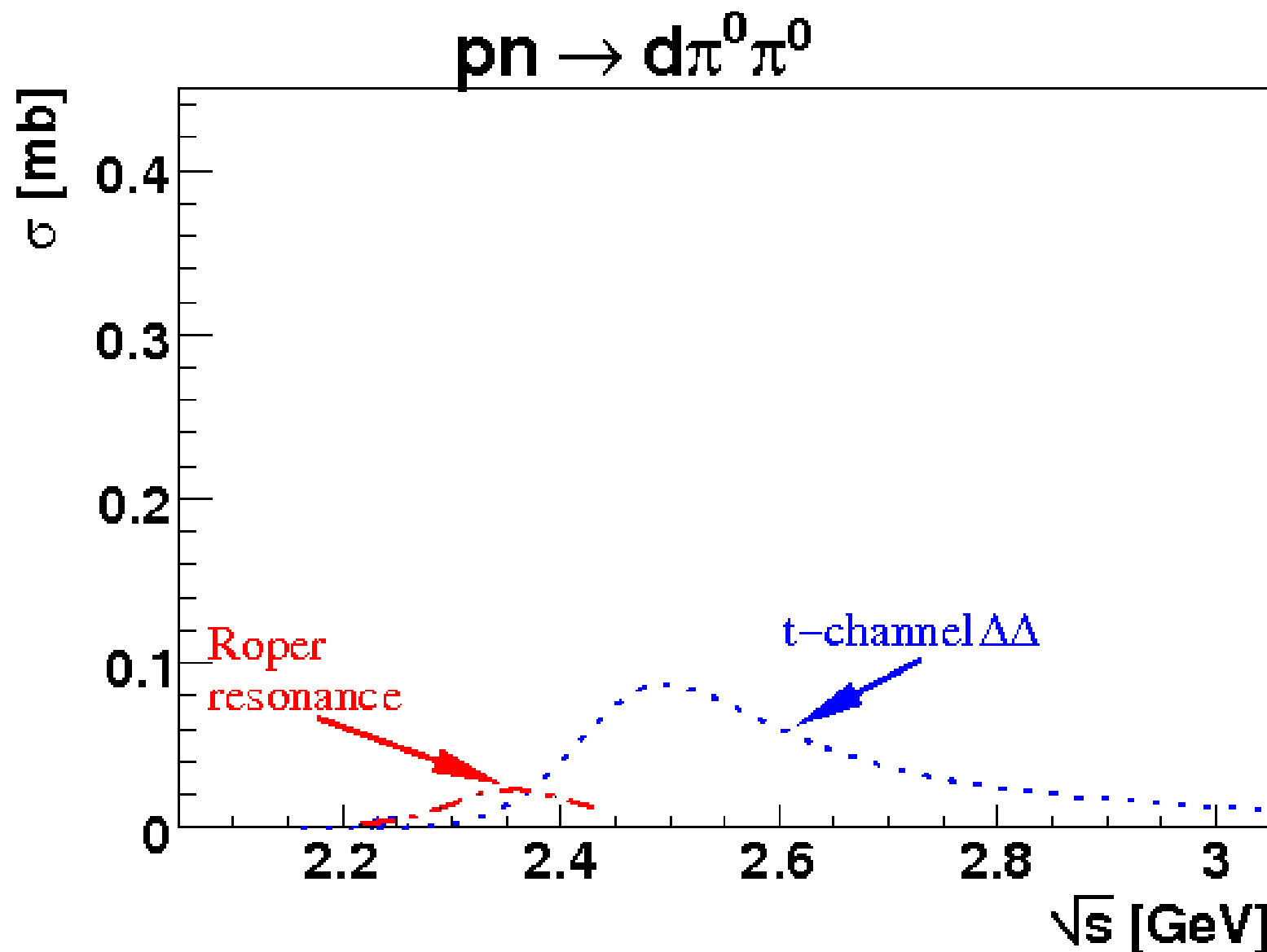


$\Delta(1600)$ (?)

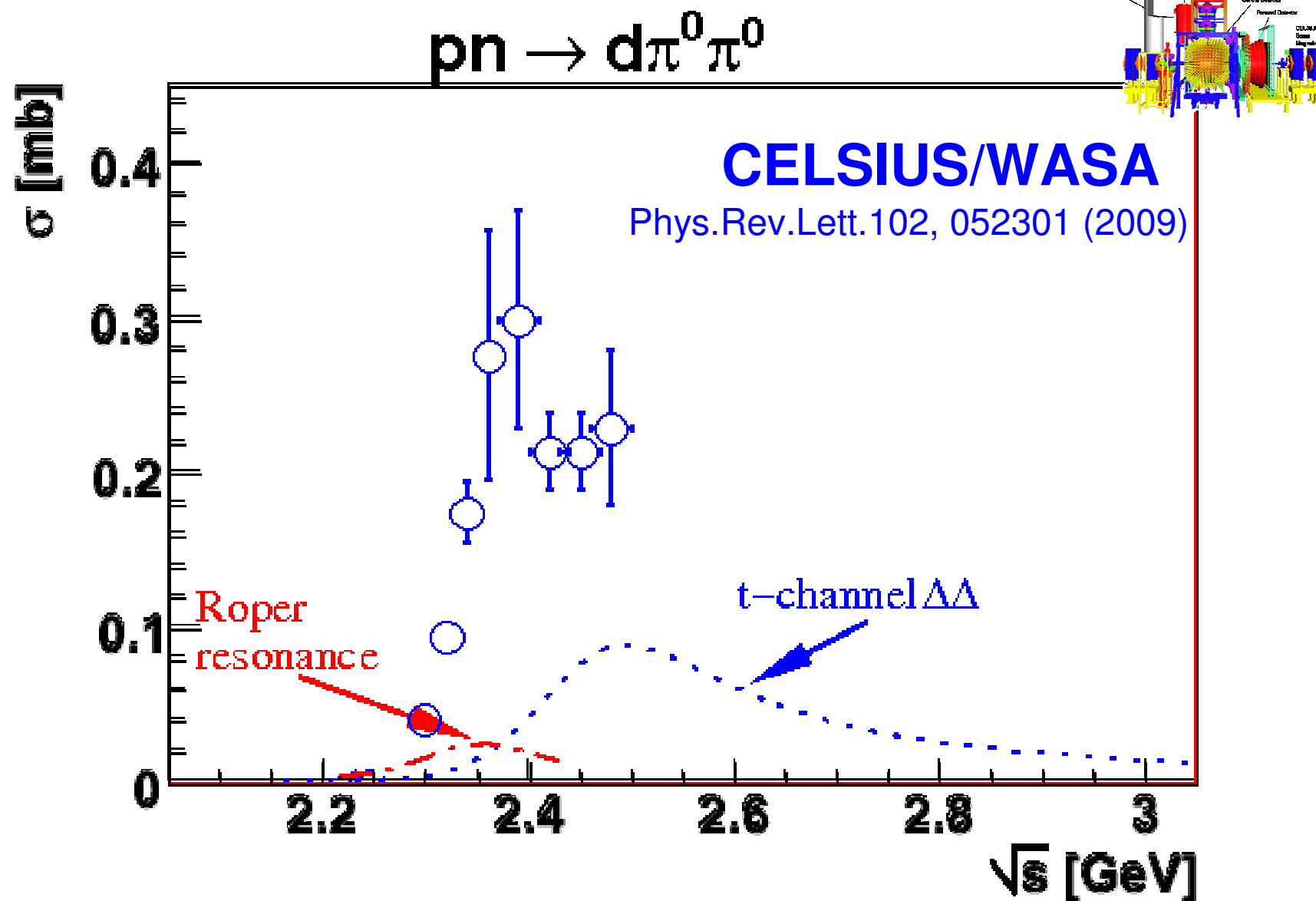
Phys. Lett. B 679 (2009) 30



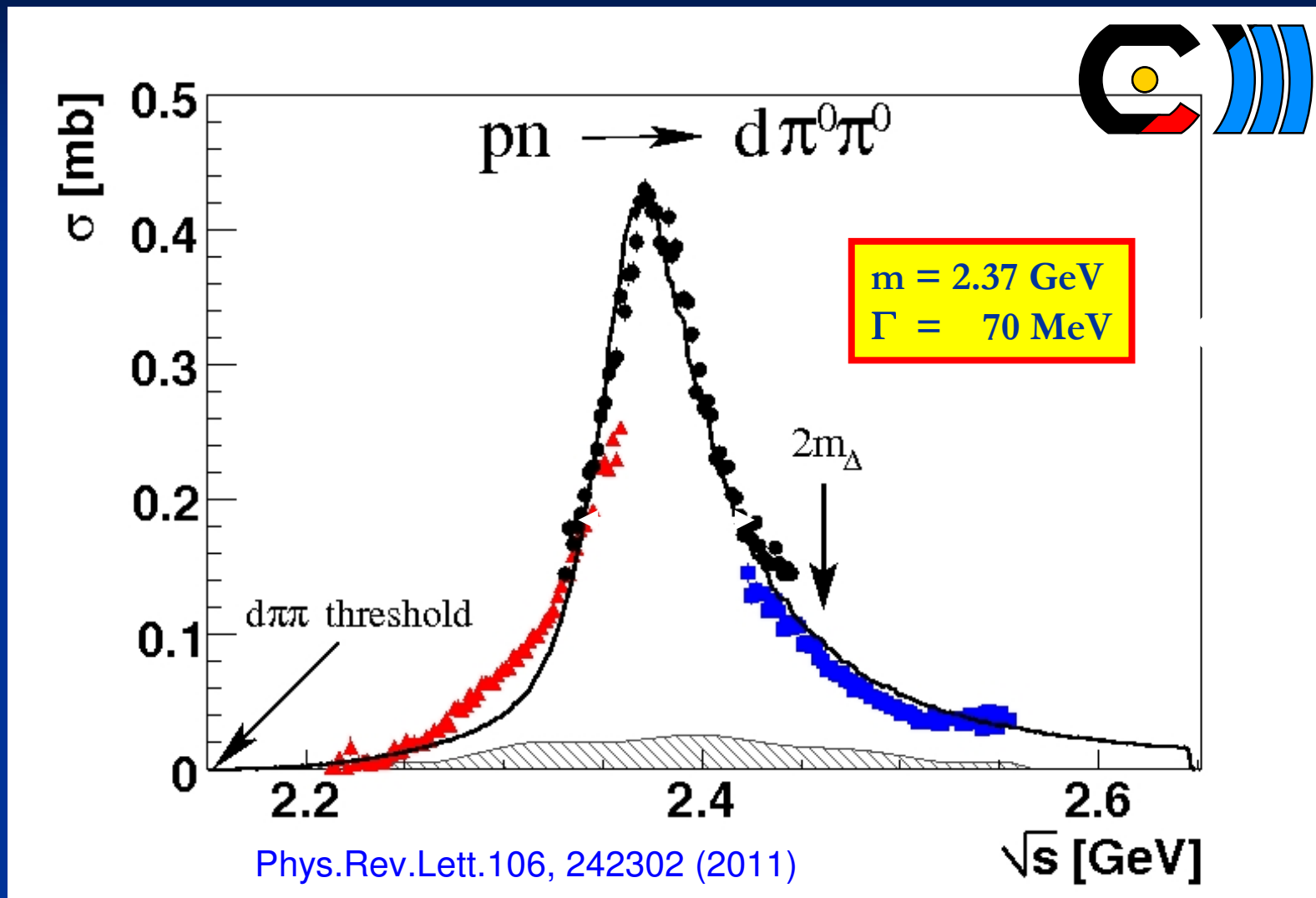
Isoscalar : ... this is what we expected!

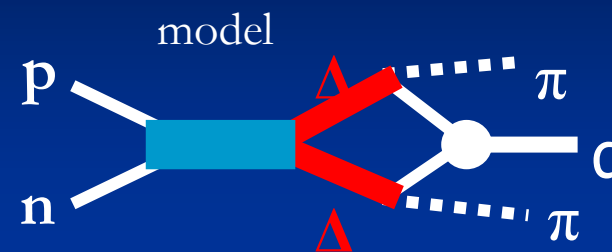
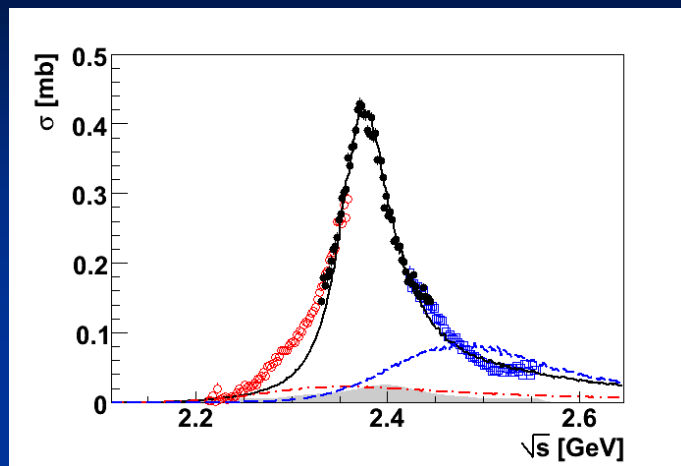


Isoscalar : ... and this is what we found!



Isoscalar : Results from WASA at COSY

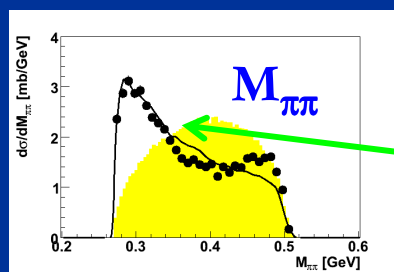
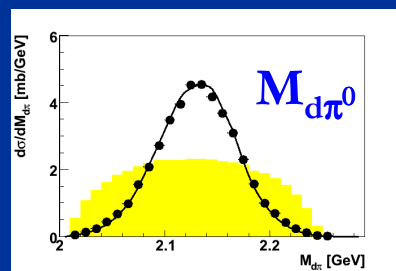
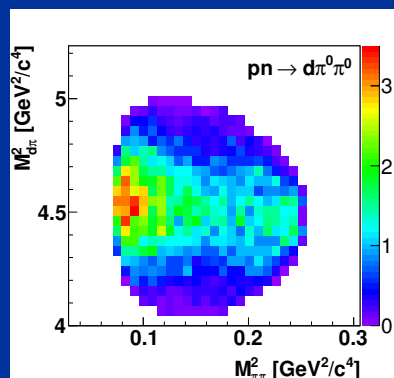




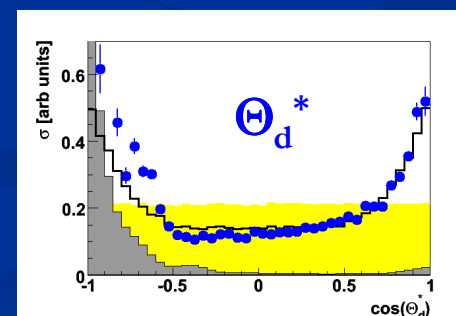
$$I (J^P) = 0 (3^+)$$

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

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



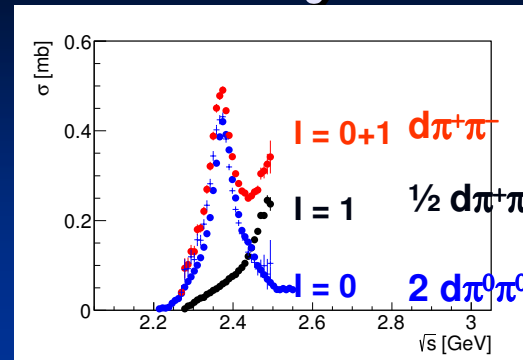
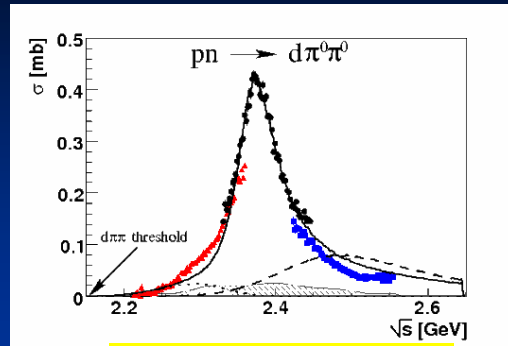
ABC effect



hadronic decays

PRL 106 (2011) 242302

● ● ● WASA data



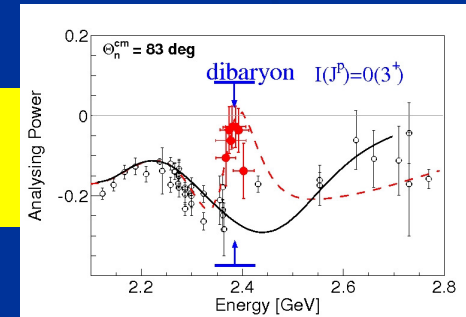
PLB 721 (2013) 229

$d\pi^0\pi^0$

$d\pi^+\pi^-$

$pn \rightarrow d^*(2380)$

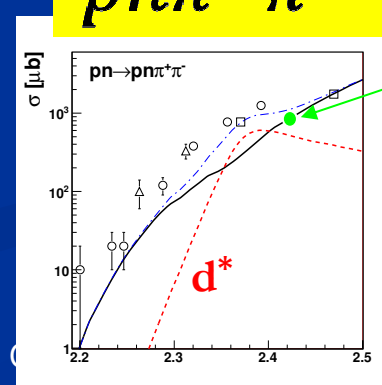
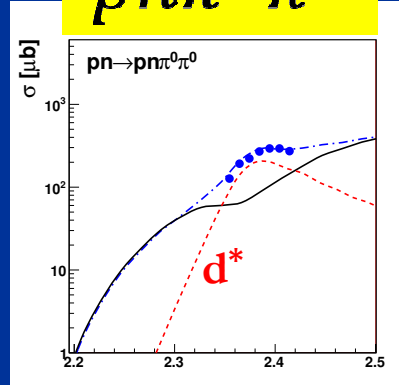
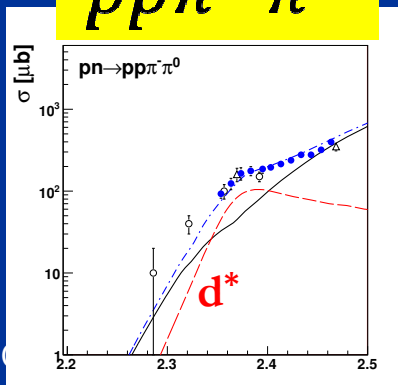
pn



$pp\pi^-\pi^0$

$pn\pi^0\pi^0$

$pn\pi^+\pi^-$



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

HADES

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

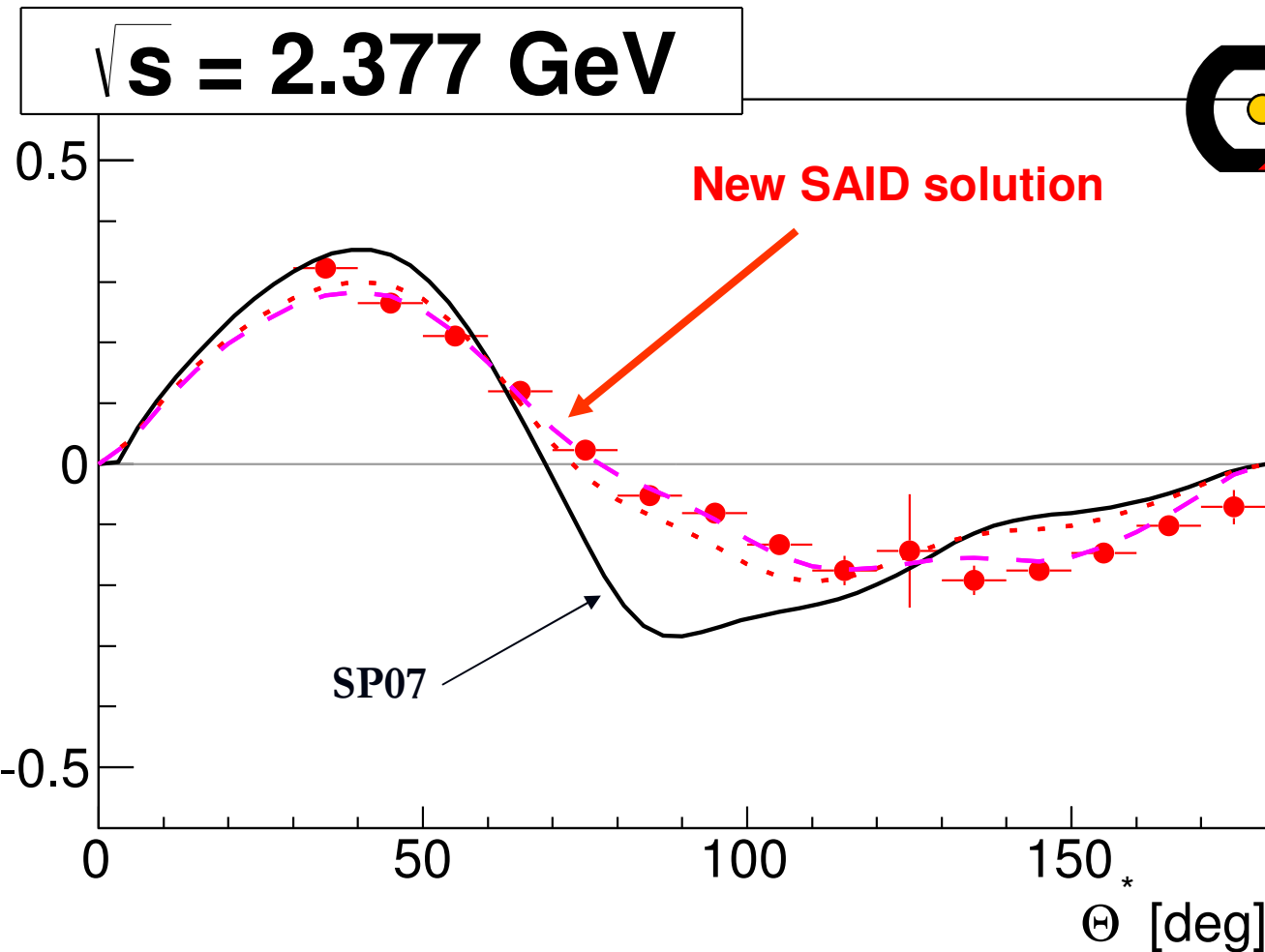
$\rightarrow \sqrt{s}$ [GeV]

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 $\Theta = 90^\circ$

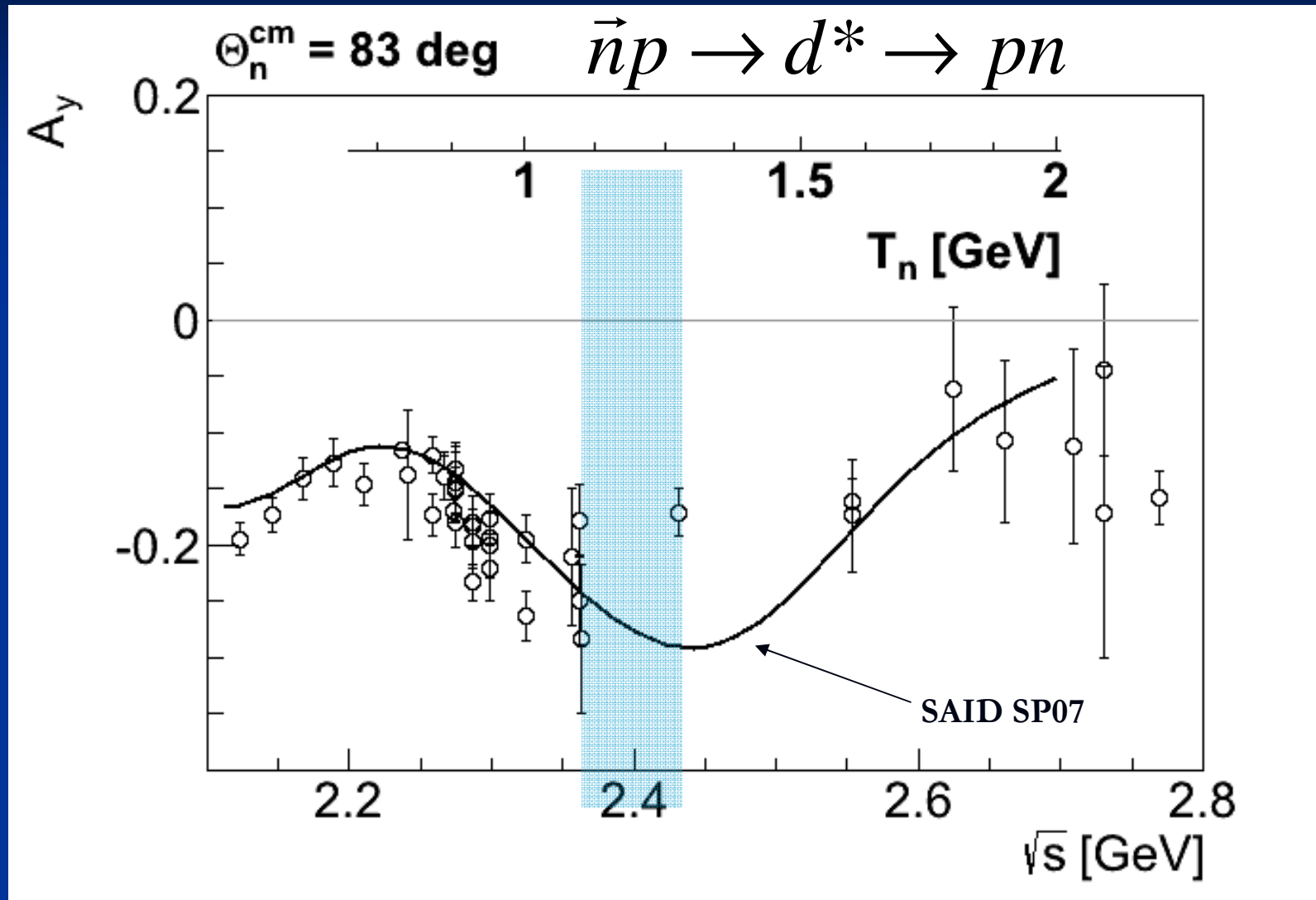
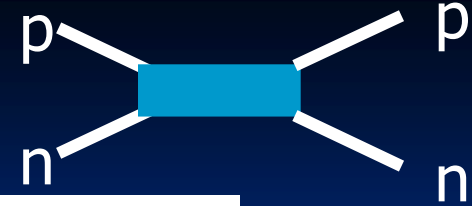
A_y Angular Distribution at Resonance

A_y

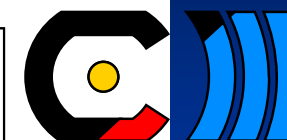
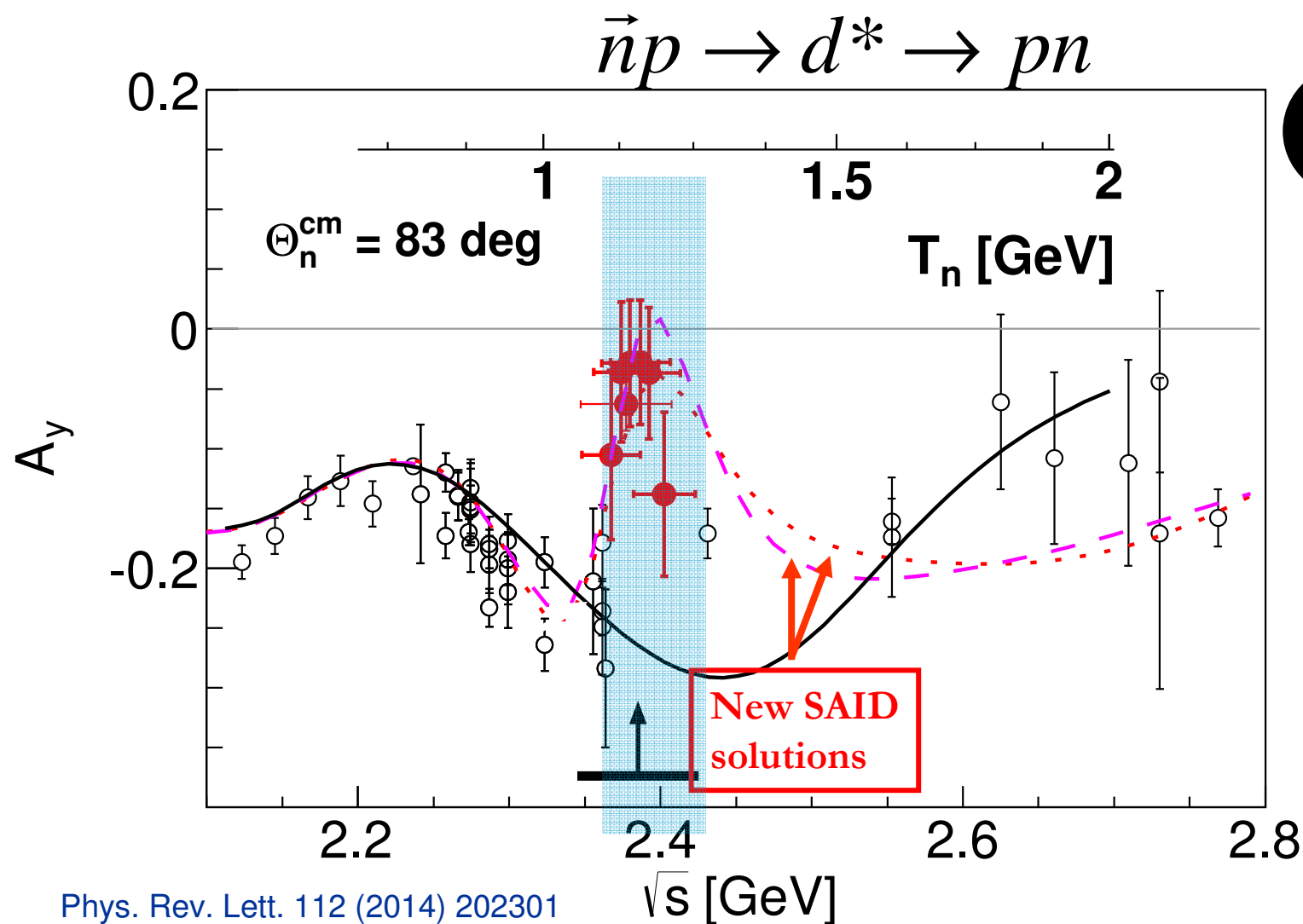


Phys. Rev. Lett. 112 (2014) 202301

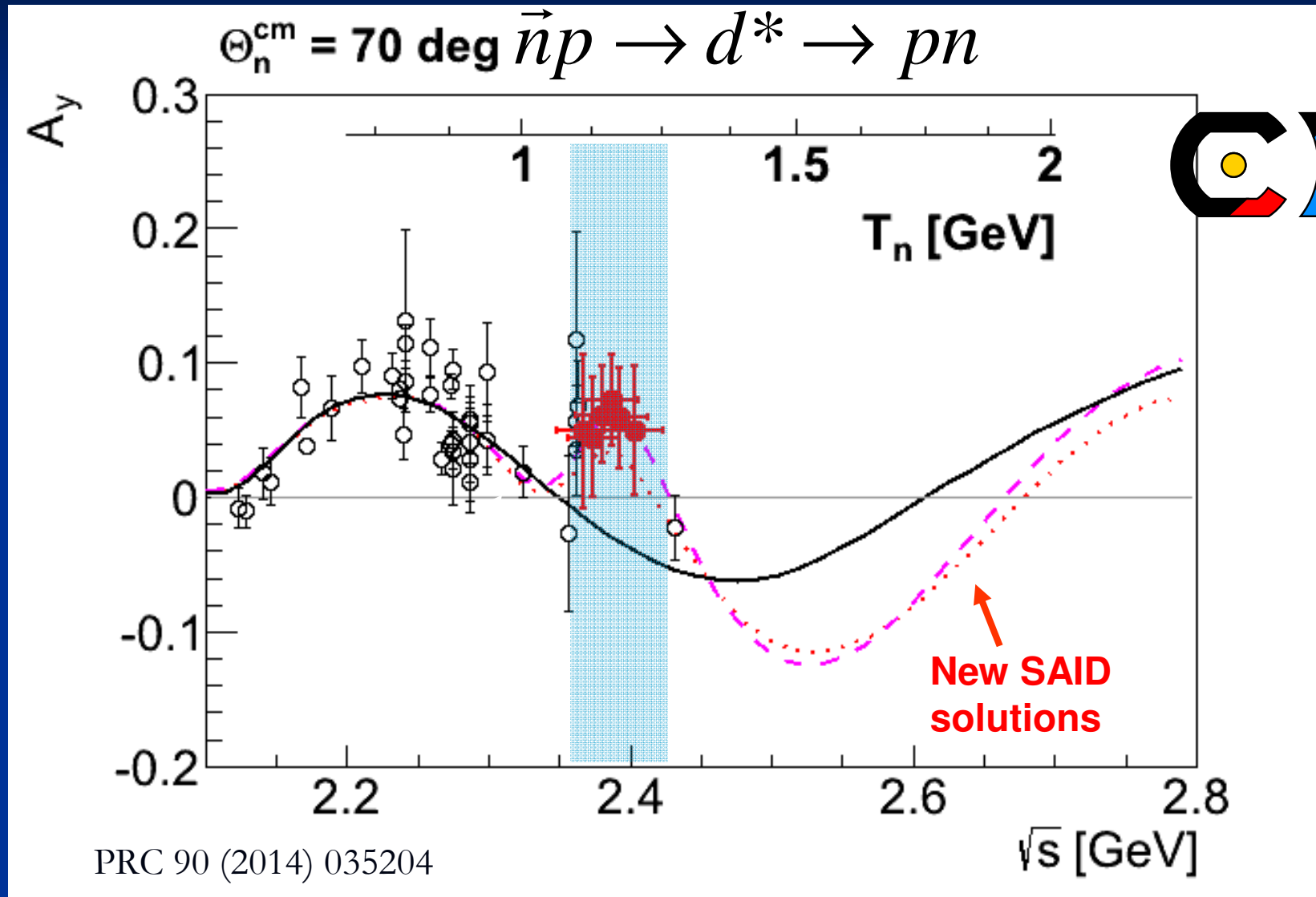
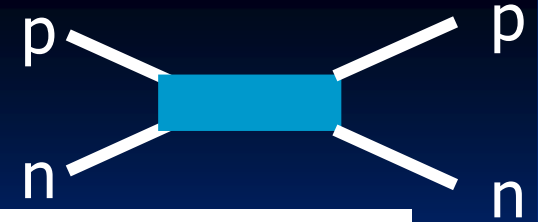
Energy Dependence



Energy Dependence



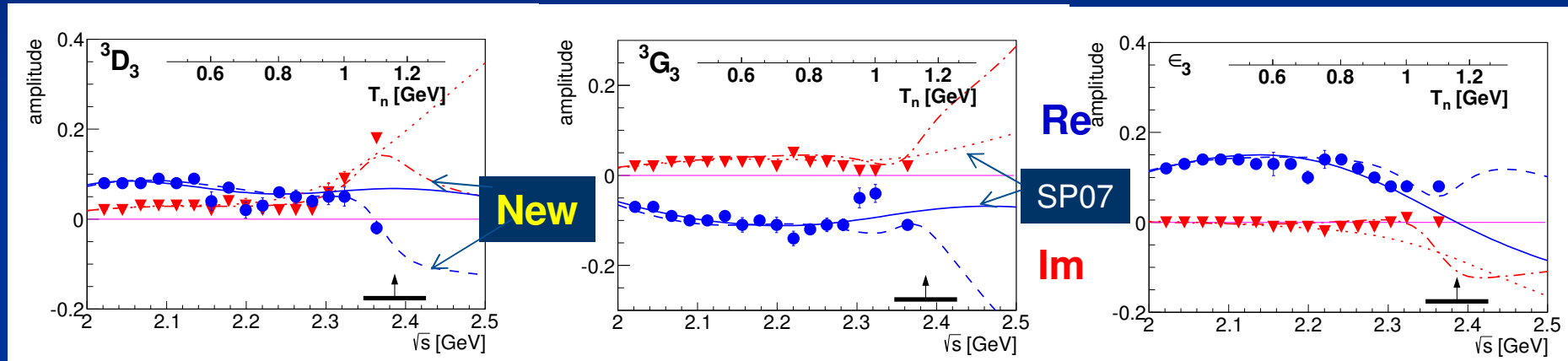
A_y Energy Dependence



SAID Partial-Wave Analysis

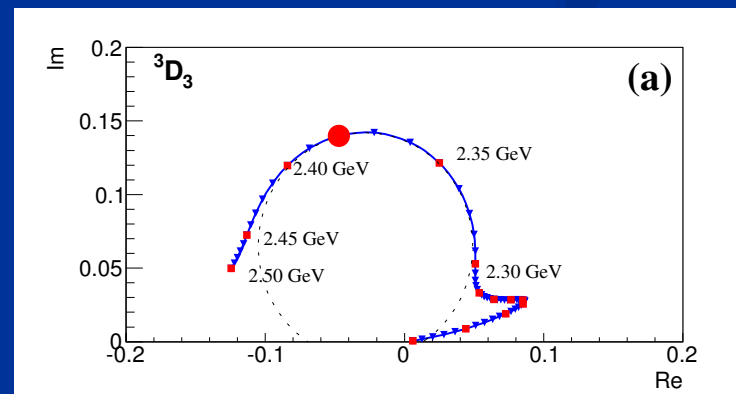
$^3D_3 - ^3G_3$ Coupled Partial Waves

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

$\Leftrightarrow$ Genuine Resonance
in np System

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

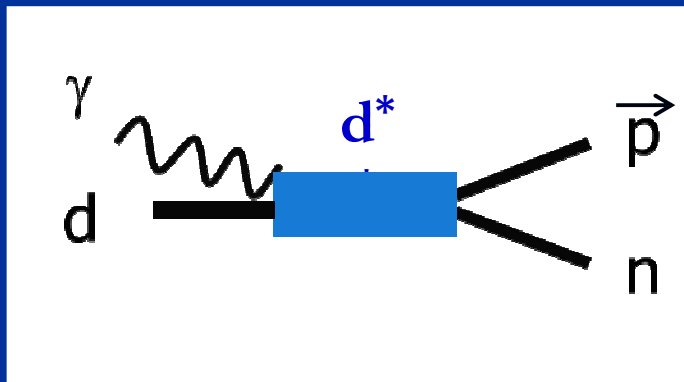
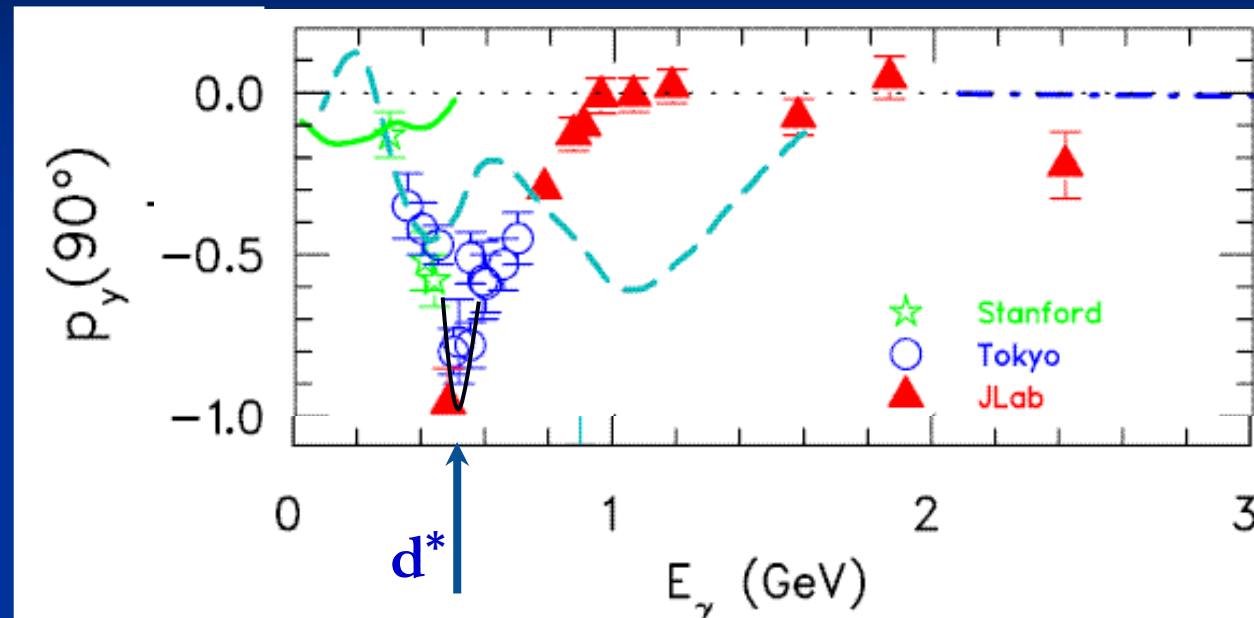
■ hadronic decays

EPJA 51 (2015) 87

decay channel	branching	derived from
$d \pi^0 \pi^0$	$14 \pm 1 \%$	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
$np \pi^+ \pi^-$	$30 \pm 4 \%$	measurement, old data + HADES
np	$12 \pm 3 \%$	measurement
$(NN\pi)_{I=0}$	---	estimate: 0%

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

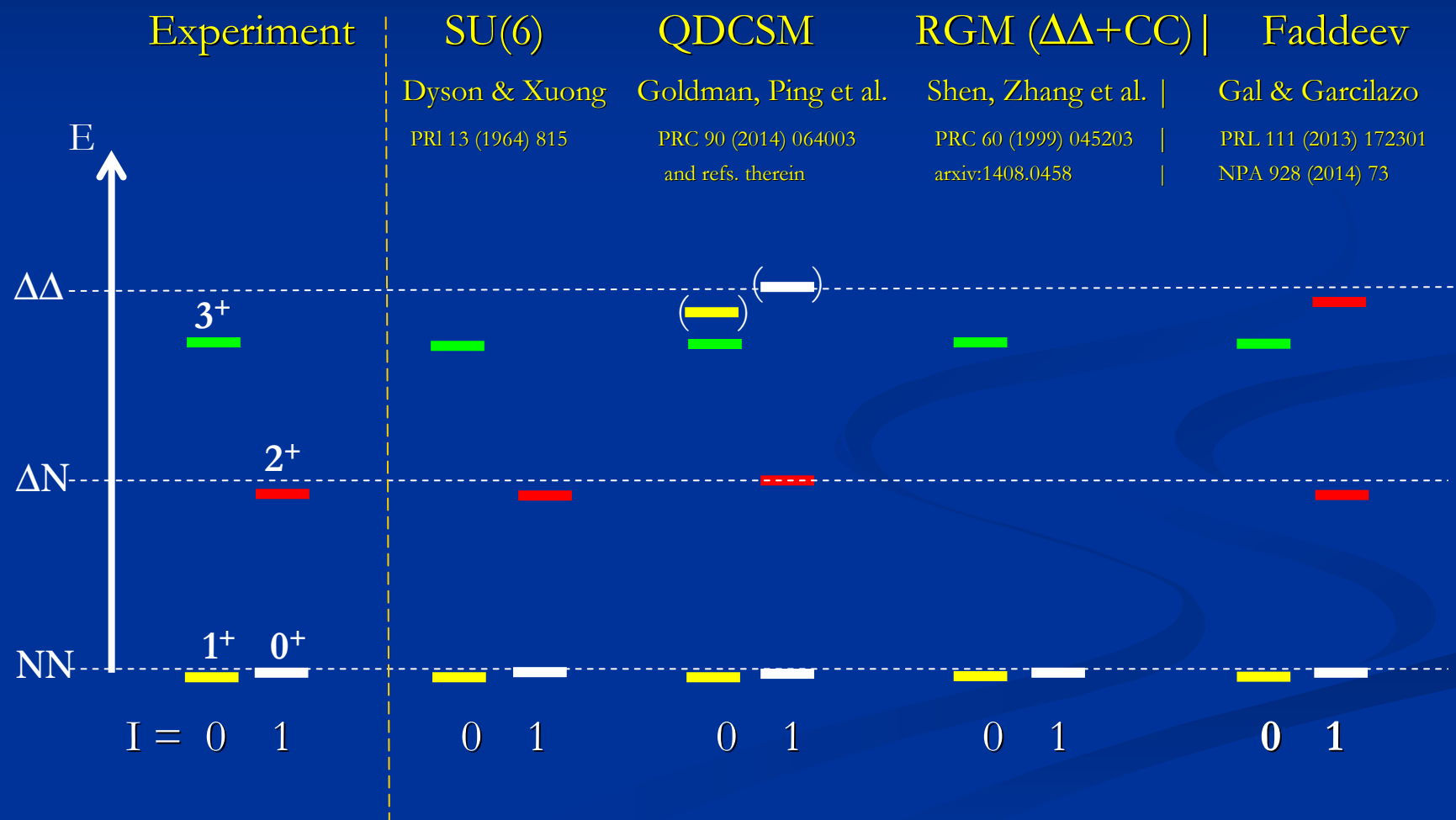
T. Kamae, T. Fujita Phys. Rev. Lett. 38 (1977) 471

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

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	$NN(^1D_2) \leftrightarrow \Delta N \leftrightarrow NN\pi$	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	?	?

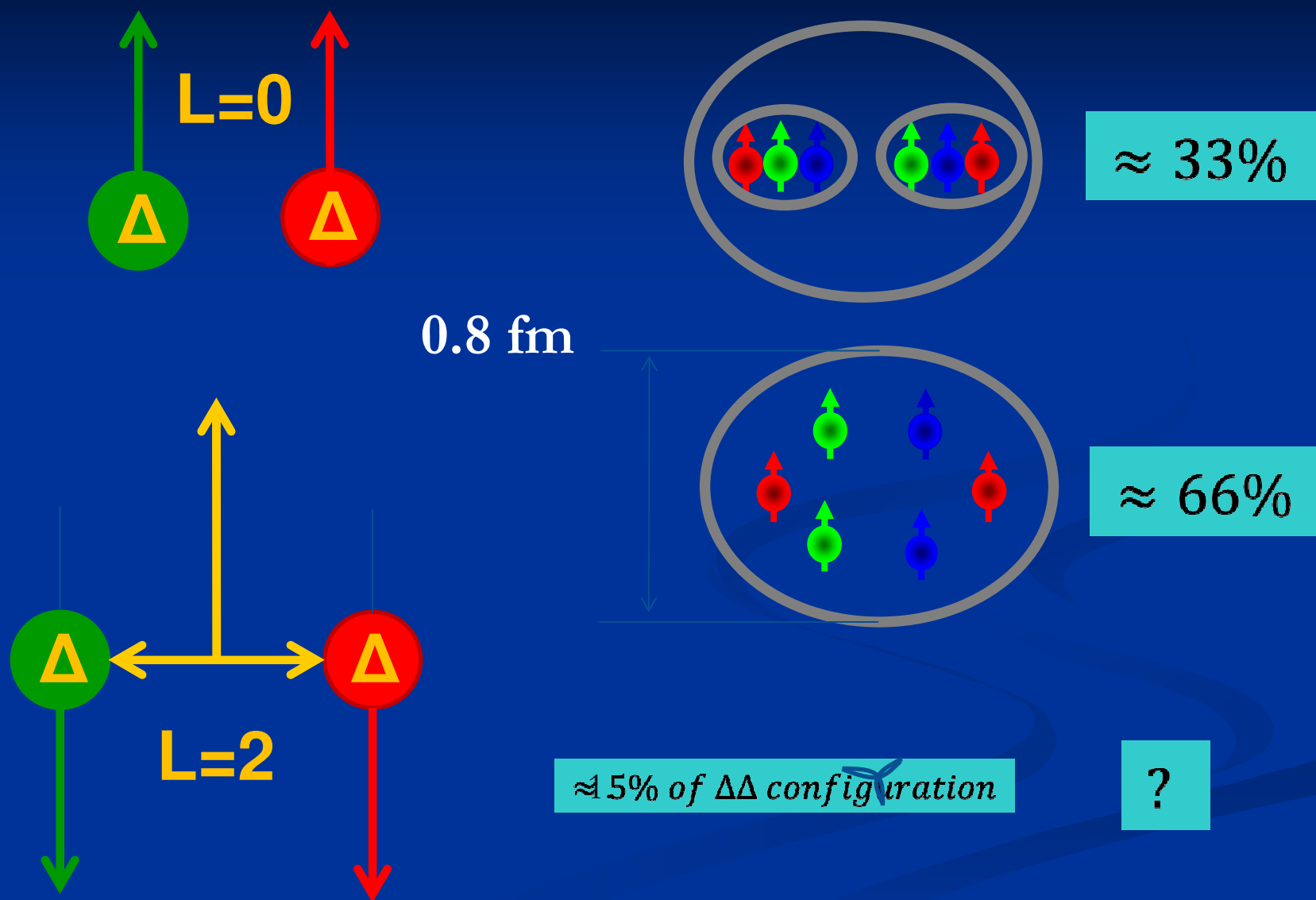
Comparison to predictions from Quark and Hadron Models



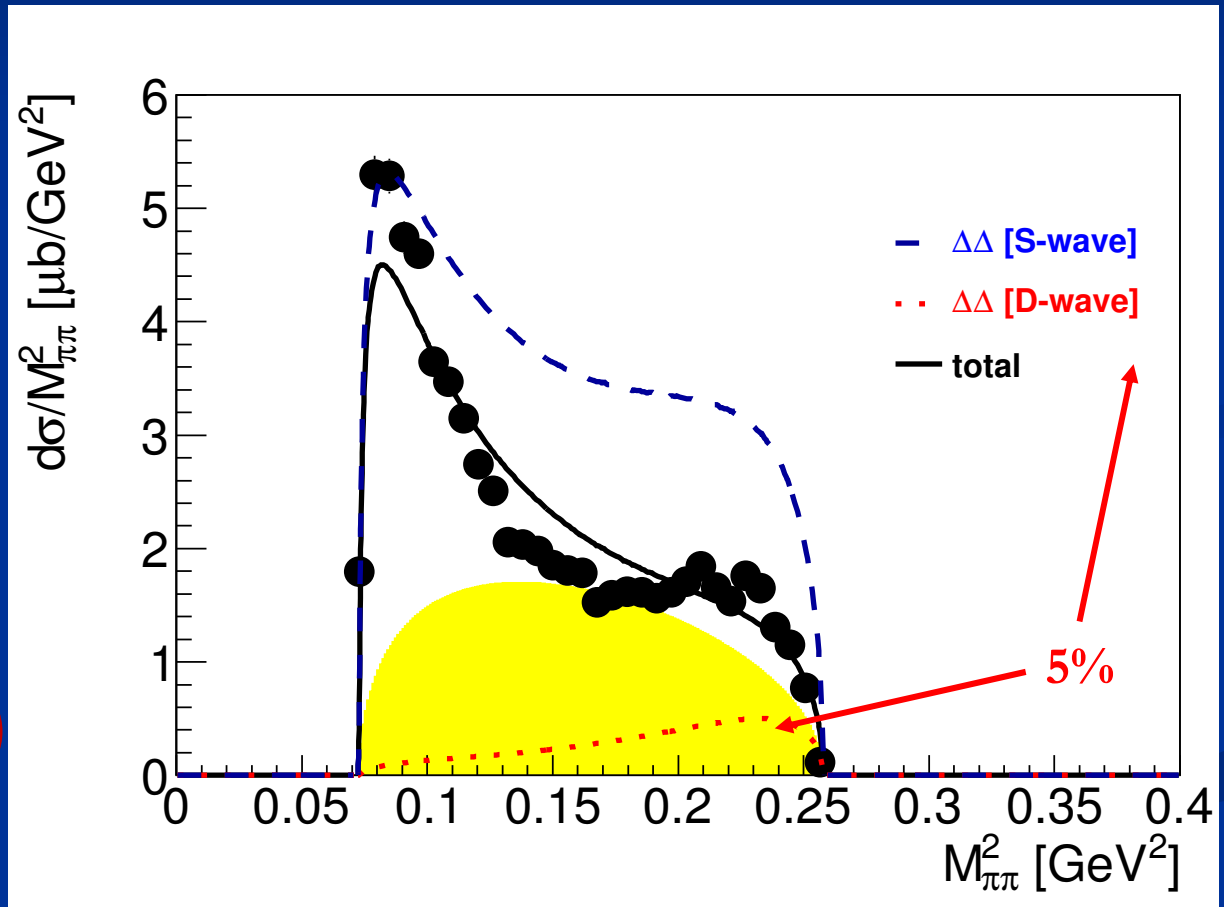
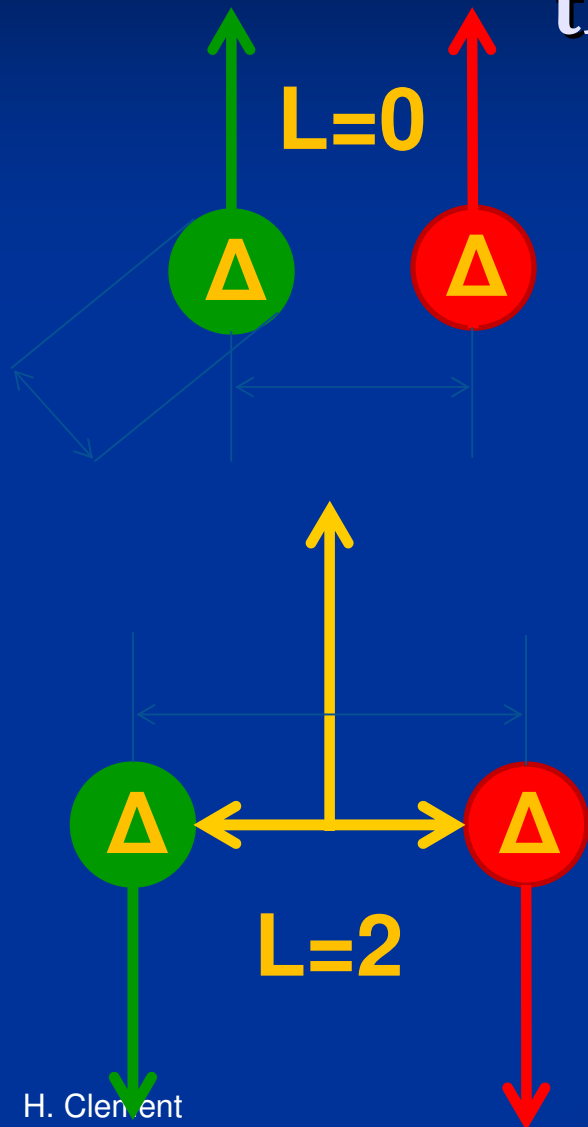
Width of $d^*(2380)$

- Experiment: $\Gamma \approx 70 \text{ MeV}$
 - (t-channel $\Delta\Delta$: $\approx 250 \text{ MeV}$)
- QDCSM: 110 MeV PRC 89 (2014) 034001
- Faddeev: 94 MeV NPA 928 (2014) 73
- Hidden Color? $\text{PLB } 727(2013) \text{ } 438$
- RGM ($\Delta\Delta + \text{CC}$) 69 MeV PRC 91 (2015) 064002

Molecule vs Hexaquark



$d^*(2380)$ internal structure and the ABC effect



Bashkanov et al, arXiv:1502.07500

Dibaryon Production at COSY

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

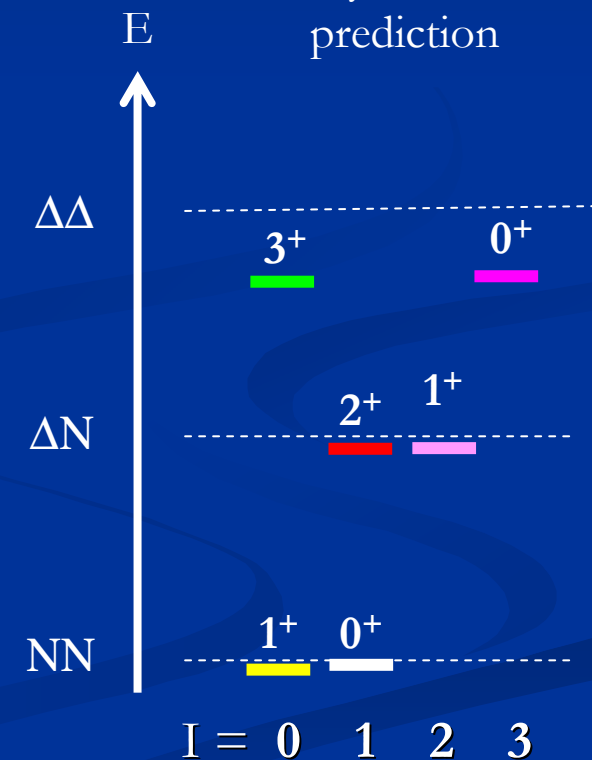
■ Strange, charmed ... Di-Baryons?

Zhang, Chen, Shen et al.

Huang, Ping, Wang et al.

Gal & Garcilazo

Dyson's
prediction



Outlook and Open Problems

■ Size of $d^*(2380)$

- $\Rightarrow$ elm excitation of d^* $\gamma d \rightarrow d^* \rightarrow pn$
- $\rightarrow d\pi^0\pi^0$

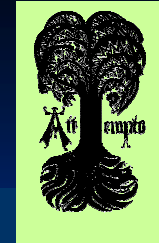
■ Observation at other installations

- HADES @ GSI: under way, but no 4π and no neutrals
- IHEP ?? $e^+e^- \rightarrow d \bar{d}^*$ at 4.3 – 4.6 GeV ??

■ Are there more (exotic) dibaryons?

- Mirror state of d^* ..., strange, charmed dibaryons

Outlook: mirror dibaryon



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

