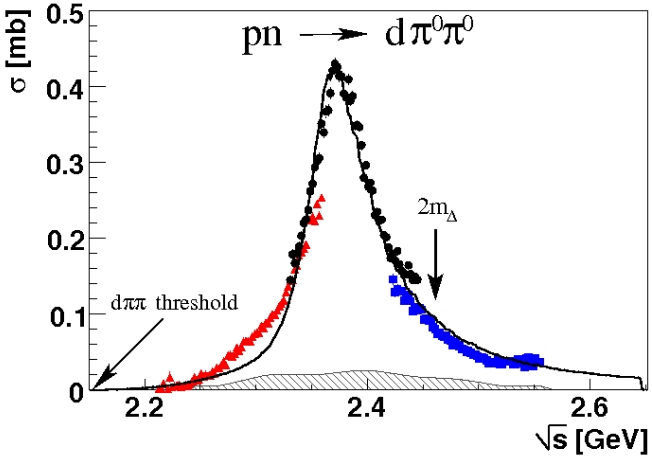
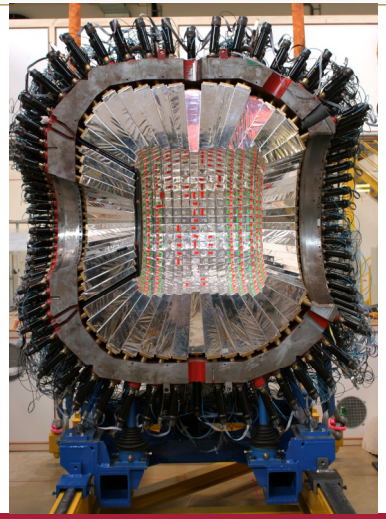
EBERHARD KARLS UNIVERSITÄT TÜBINGEN

Kepler Center for Astro and Particle Physics

Fachbereich Physik





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DFG Deutsche Forschungsgemeinschaft

d*(2380) – Observation of a Dibaryon (Hexaquark) Resonance

Erice School

Sep 16 - 24, 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:
  - $^1D_2$ resonance structure at 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?
  - Theoretical predictions
  - Dyson's sextet

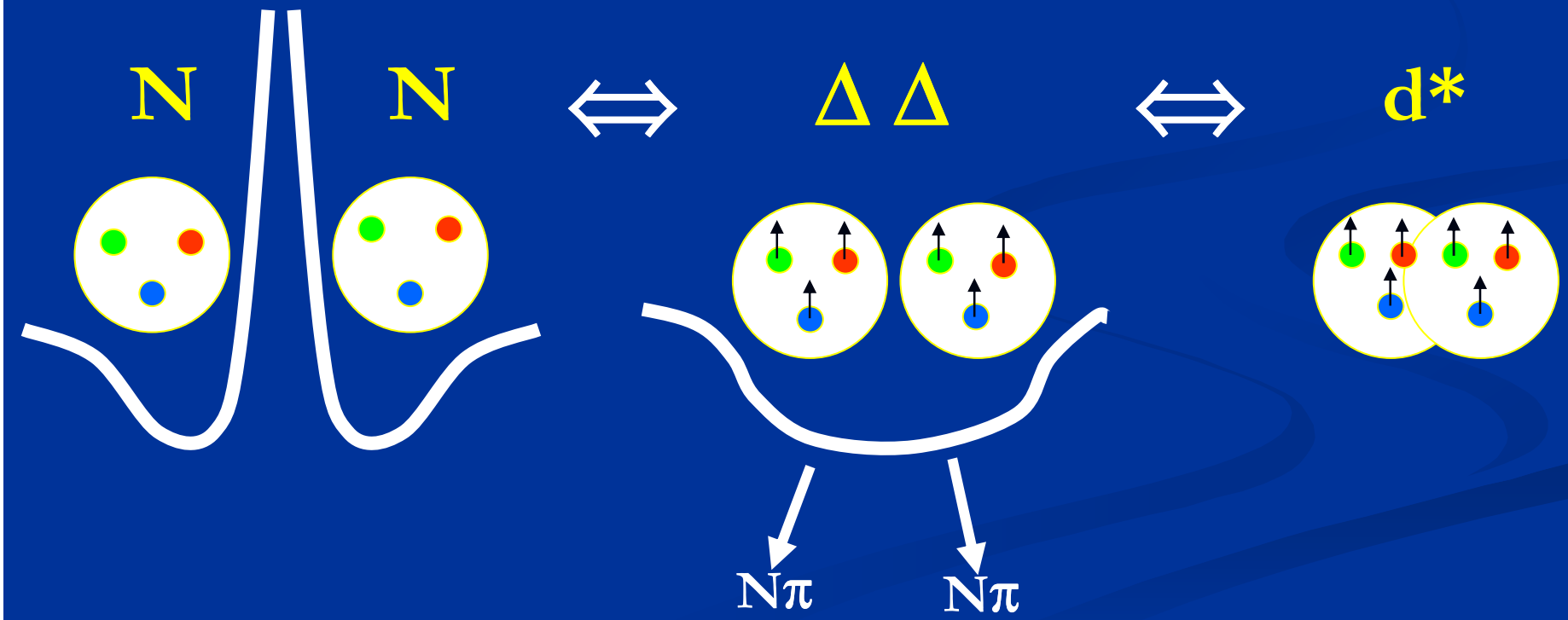
Early Predictions on Dibaryons

- 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, ...)
- ⋮
-
  - LANL theory group (T. Goldman, Fan Wang et al.):
    - The „inevitable dibaryon“: ΔΔ $I(J^P) = 0(3^+)$

… 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

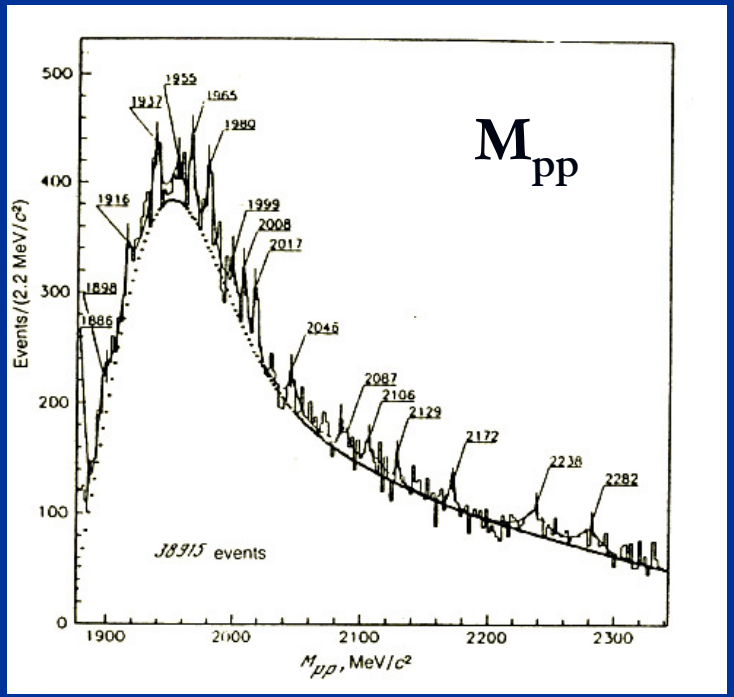
- Before 1964 (quark model):
  - First hints for resonating $^1D_2$ partial wave from $pp \leftrightarrow d\pi^+$ (Dubna)
- After 1975 (Jaffe's H-dibaryon prediction):
  - Worldwide searches for dibaryons

In the following: only non-strange dibaryons

The Experimental Rush for Dibaryons

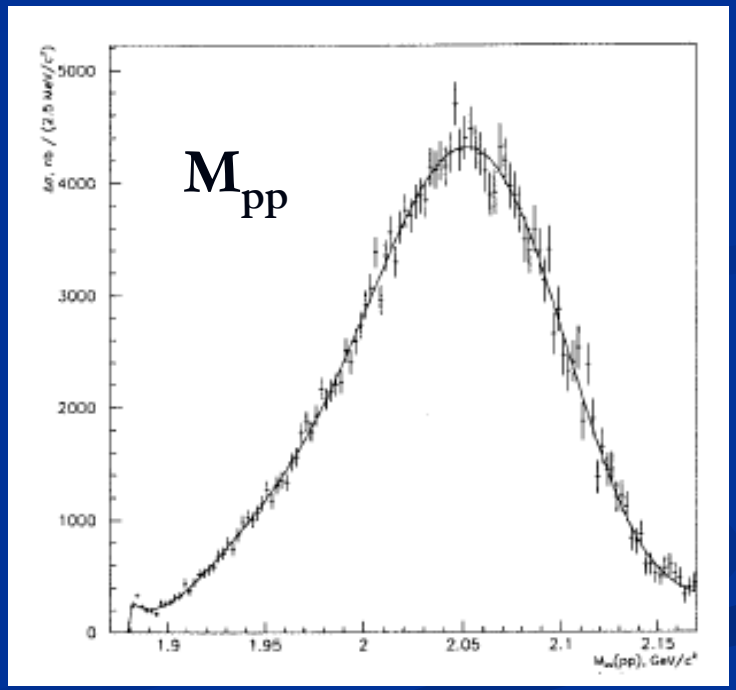
- Low statistics versus high statistics (quality):

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



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

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

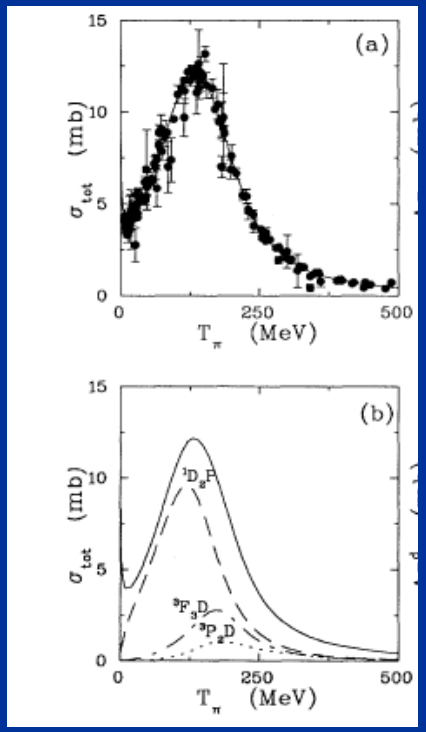


Abramov et al., Z. Phys. C69 (1996) 409

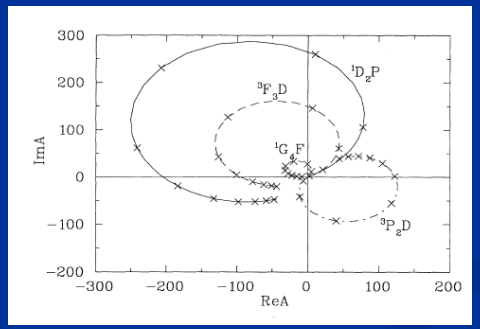
Possibly the only surviver: $^1D_2$ Resonance

- 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., 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 MeV = $m_\Delta + m_N$ – 26 MeV
Γ = 110 MeV ≈ Γ_Δ

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

One of the Conclusions about this Dibaryon Rush

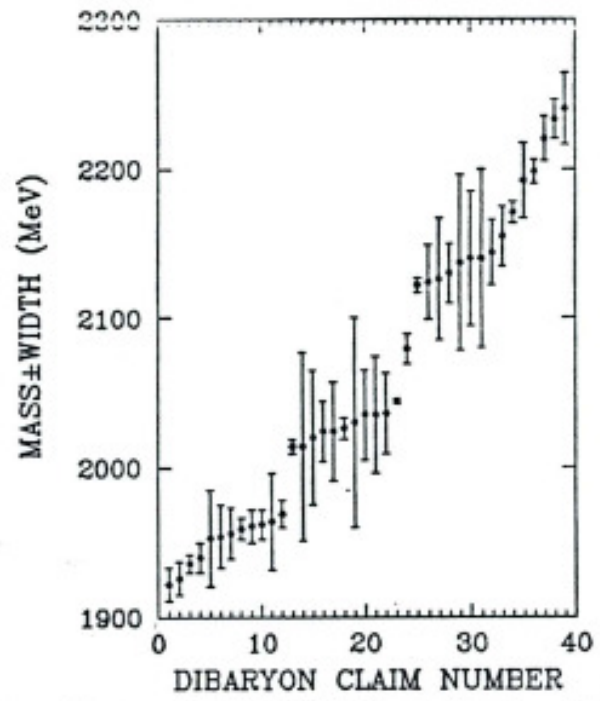


Fig. 13. Dibaryon claims of Table 3 plotted as claimed masses ± claimed widths. It is clear that claims exist at all energies between 1920 and 2250 MeV.

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

1) **„Nobody has seen a genuine, gold- (silver-, ... or even un-) plated dibaryon, yet.“**

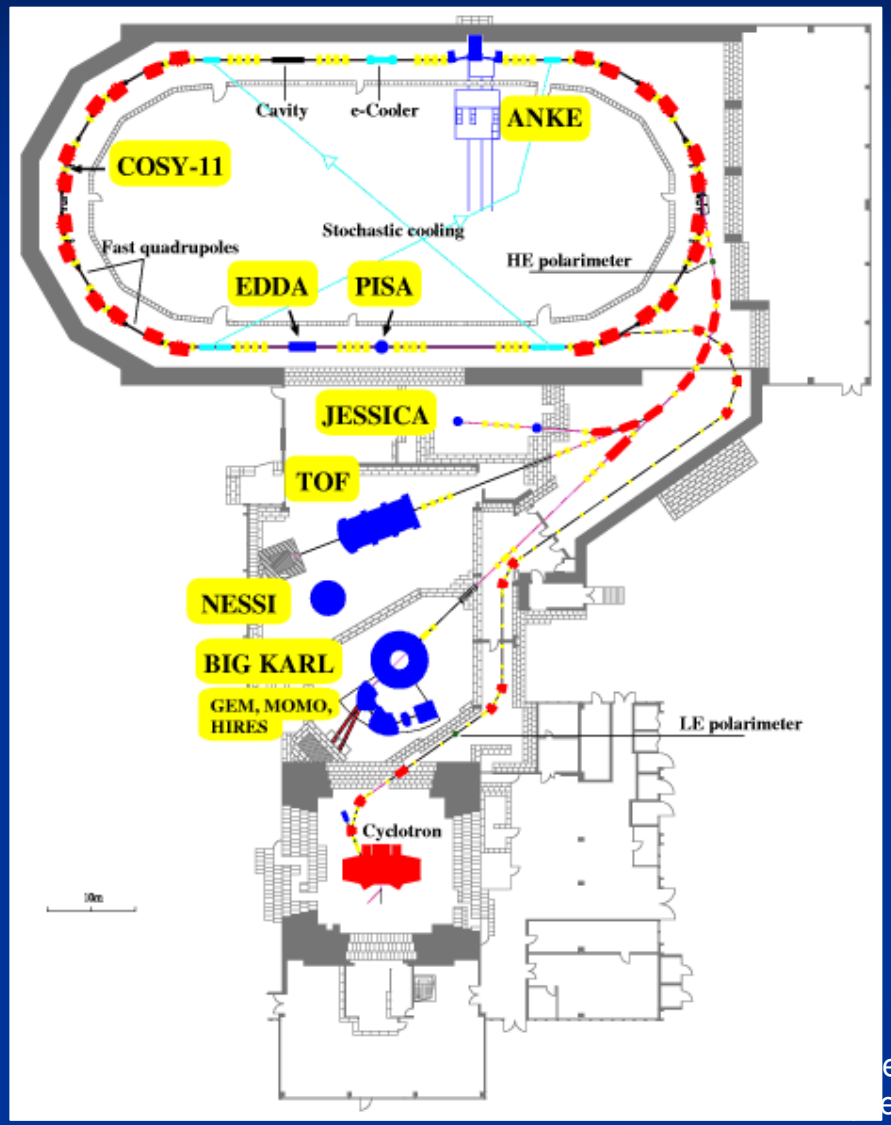
2) **„ The days of Q & D ... are over... We must do honest hard work, or quit... We should do exclusive experiments.“**

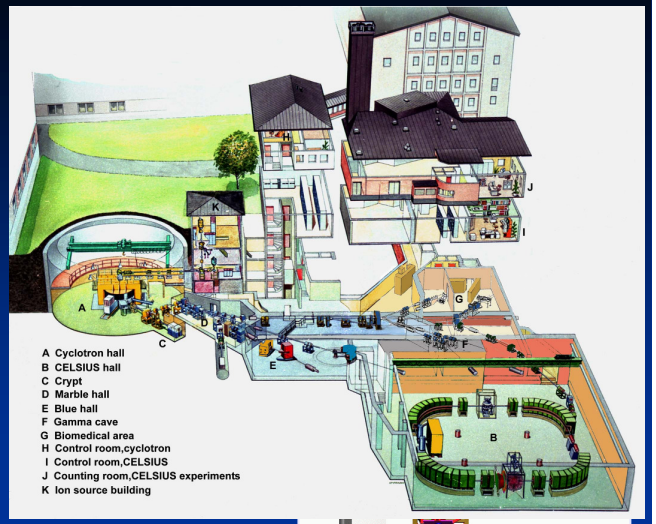
So how to find a Dibaryon?

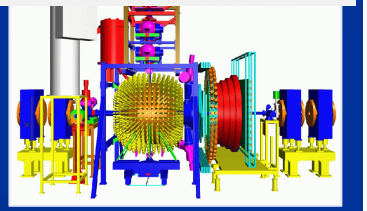
Exclusive and kinematically complete measurements

- 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



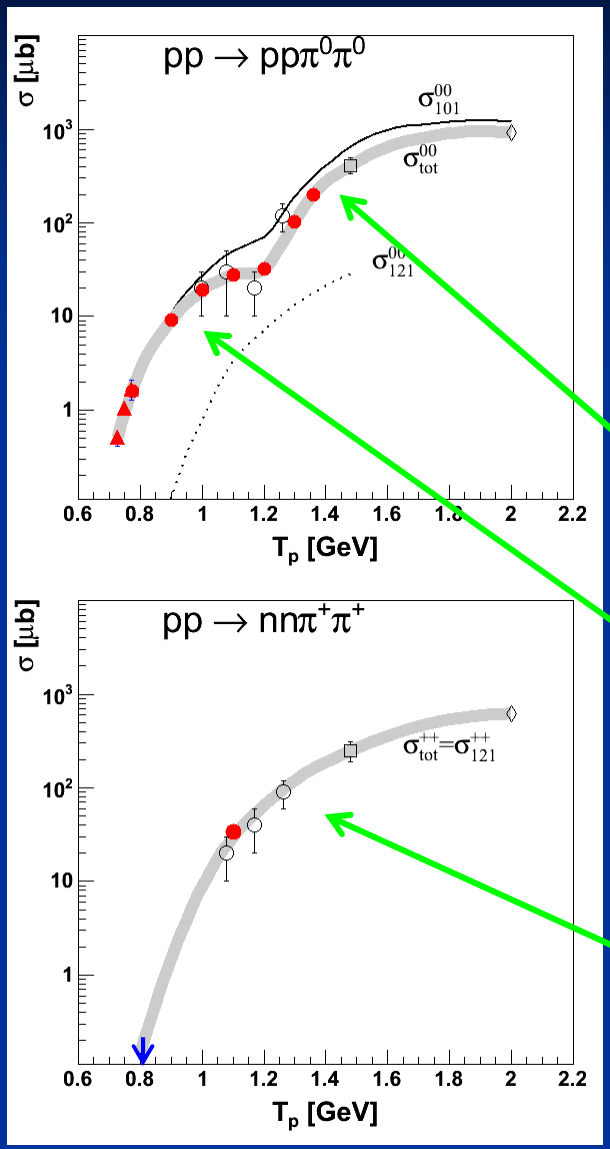




2005 - 2006

CELSIUS/WASA

Isovector : Total Cross Sections



isospin decomposition

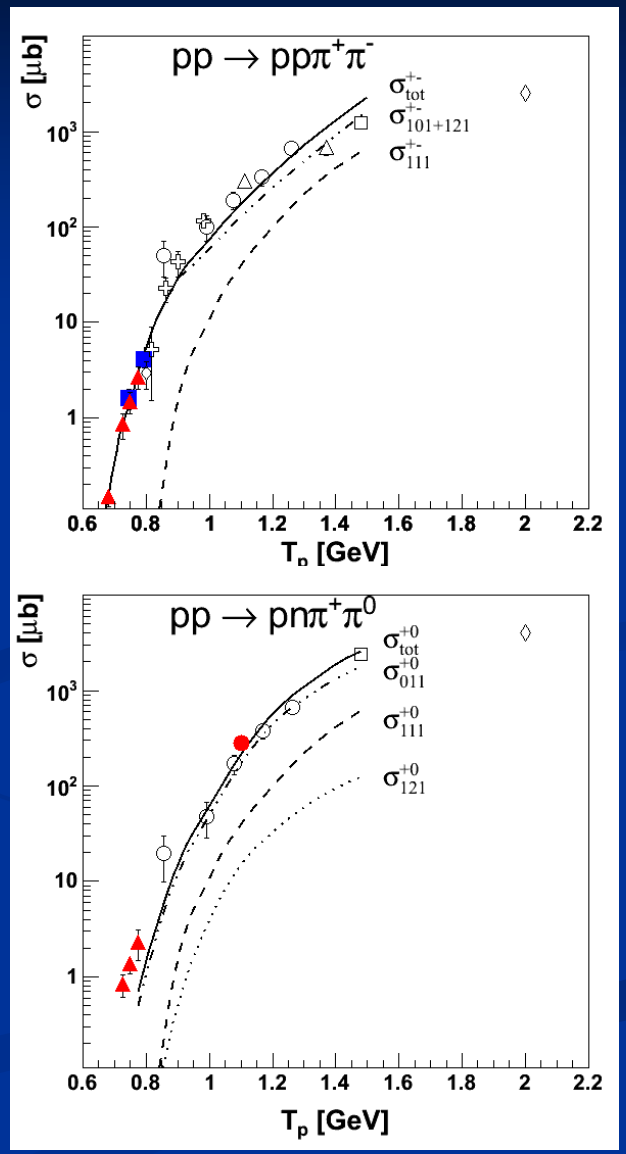
⇒

ΔΔ

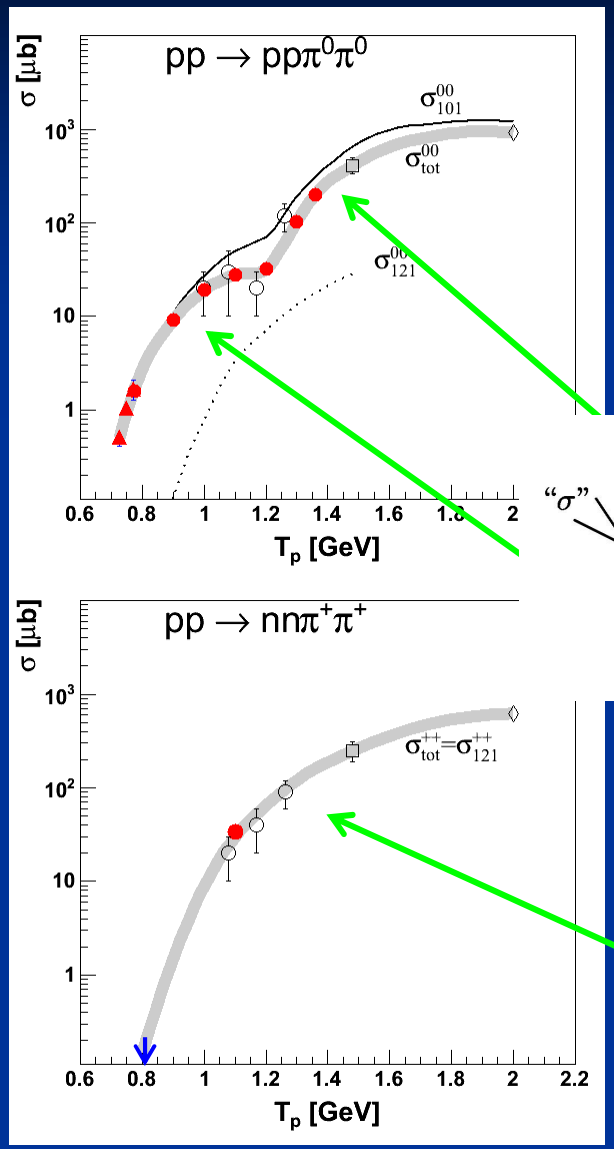
N*(1440)

Δ(1600) (?)

Phys. Lett. B 679 (2009) 30

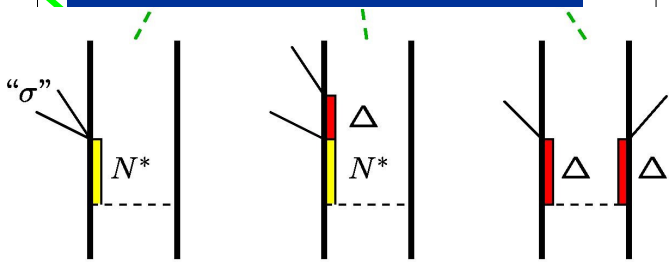


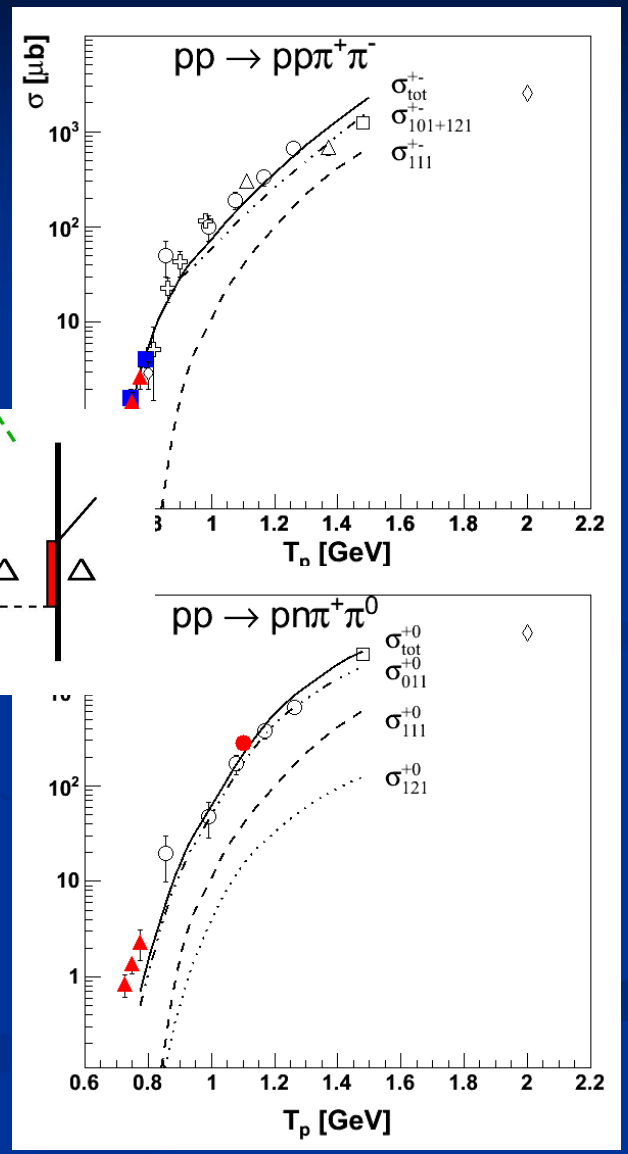
Isovector : Total Cross Sections



isospin decomposition

⇒

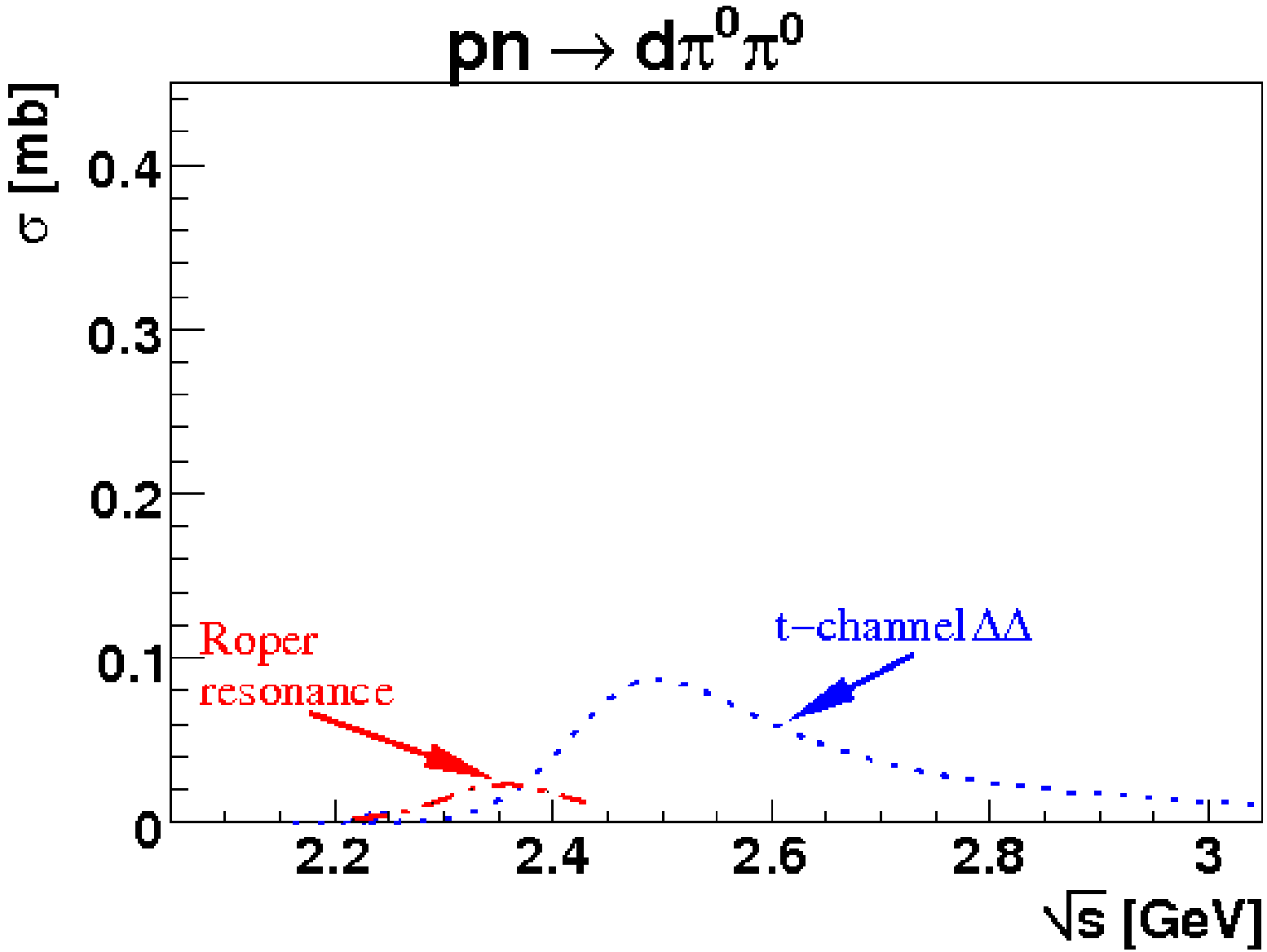




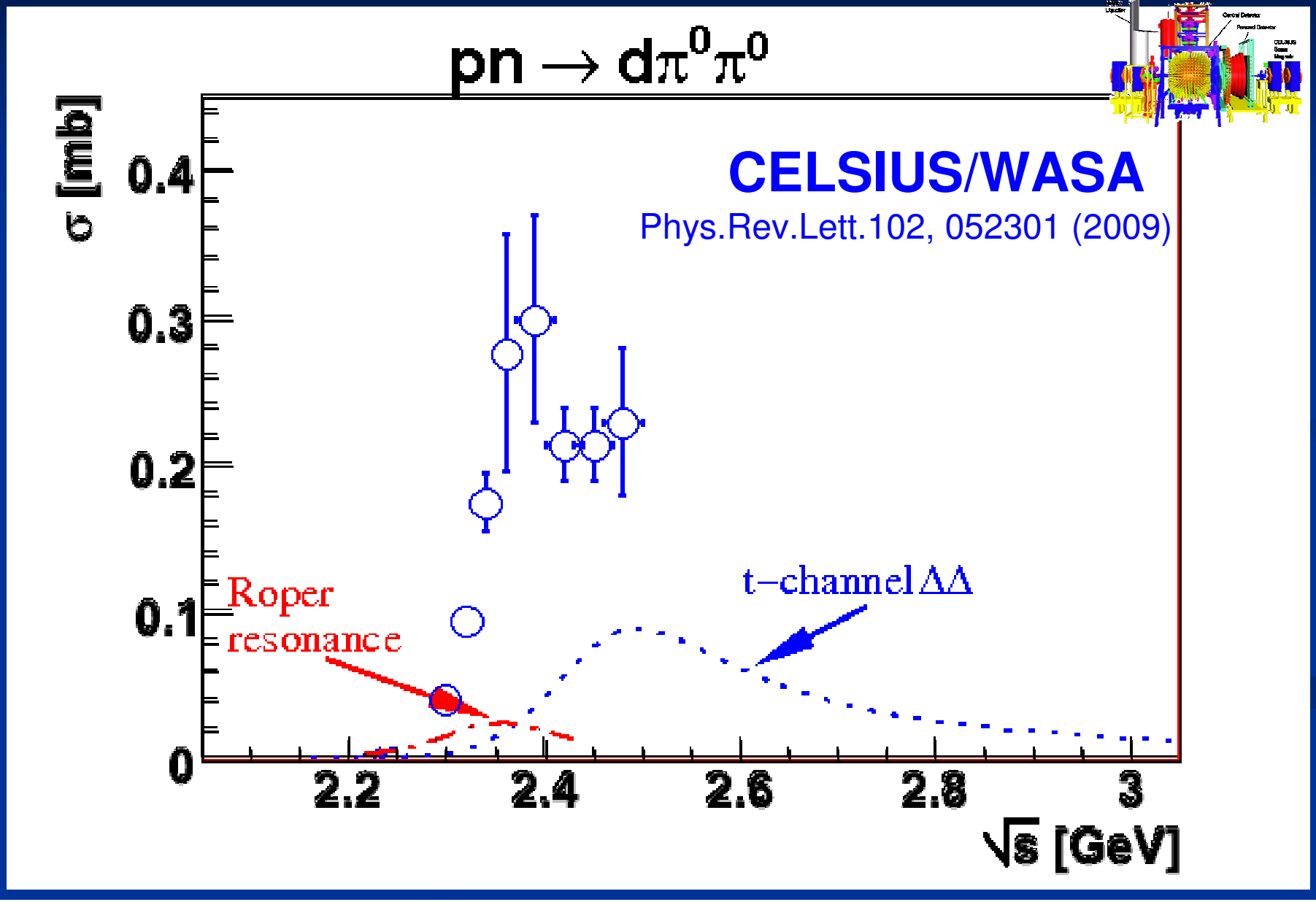
Δ(1600) (?)

Phys. Lett. B 679 (2009) 30

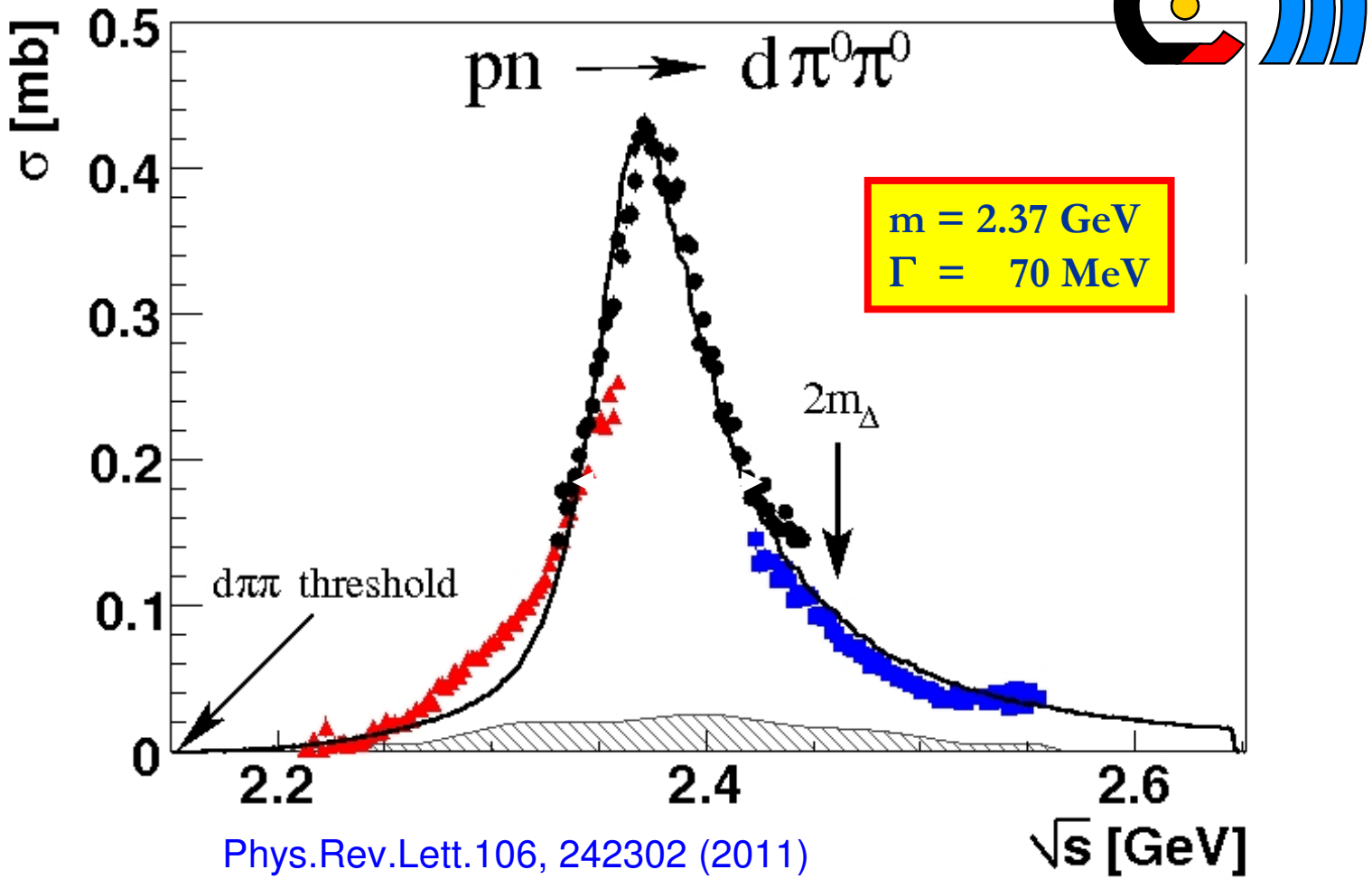
Isoscalar : … this is what we expected!



Isoscalar : … and this is what we found!

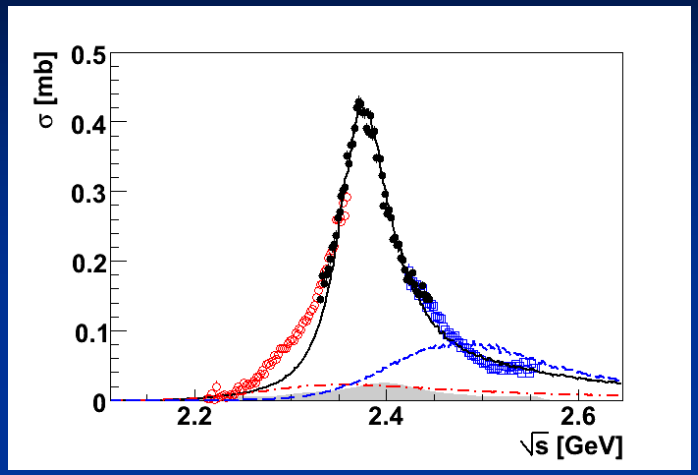


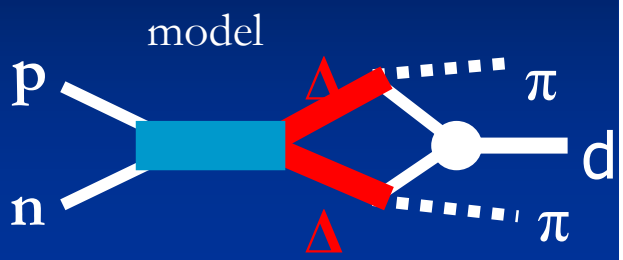
Isoscalar : Results from WASA at COSY



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

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

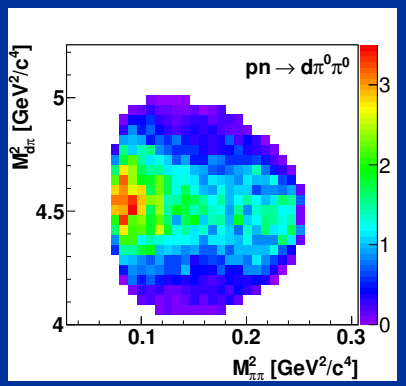


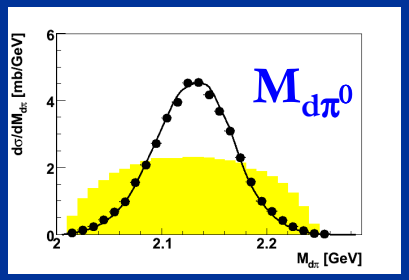


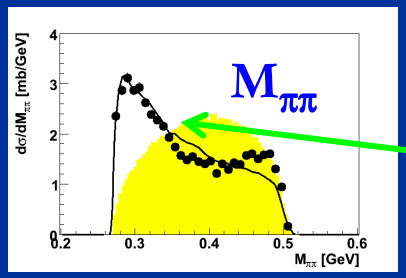
$I\ (J^P) = 0\ (3^+)$

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

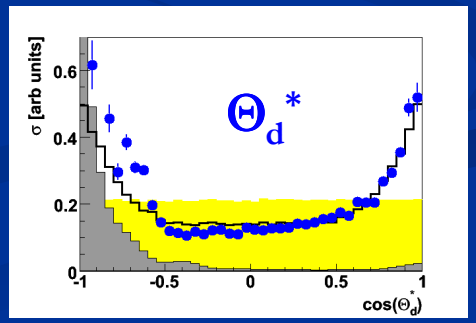
Phys.Rev.Lett.106, 242302 (2011)





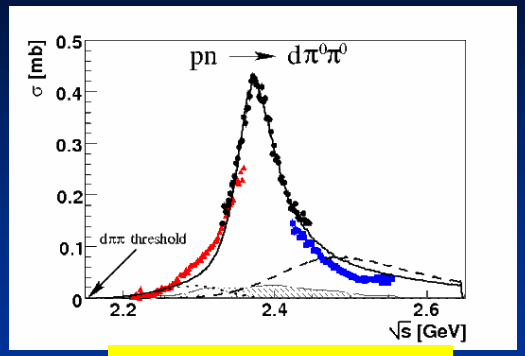


ABC effect

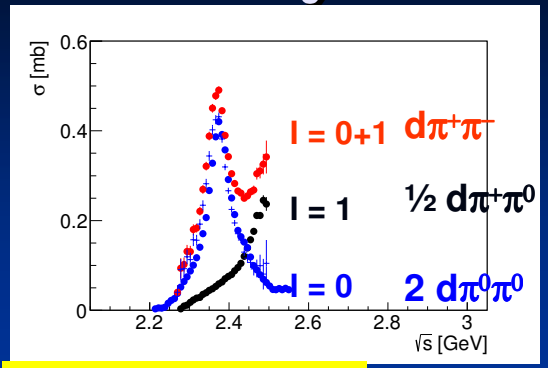


hadronic decays

PRL 106 (2011) 242302



○ ● ● WASA data



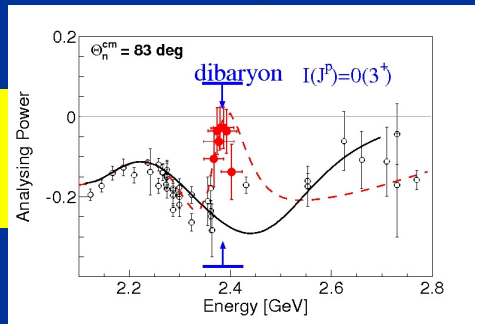
PLB 721 (2013) 229

$d\pi^0\pi^0$

$d\pi^+\pi^-$

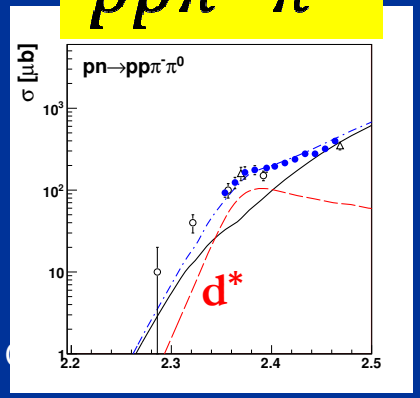
pn → d*(2380)

pn

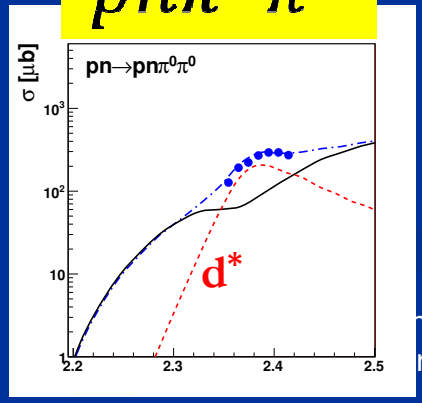


PRL 112 (2014) 202301
PRC 90 (2014) 035204

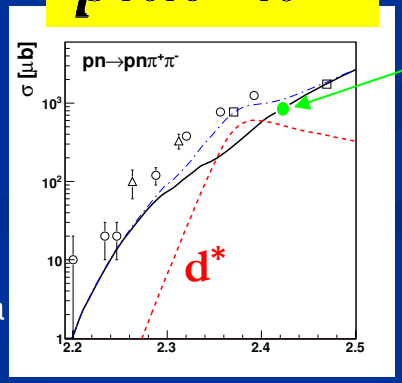
$pp\pi^-\pi^0$



$pn\pi^0\pi^0$



$pn\pi^+\pi^-$



HADES

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

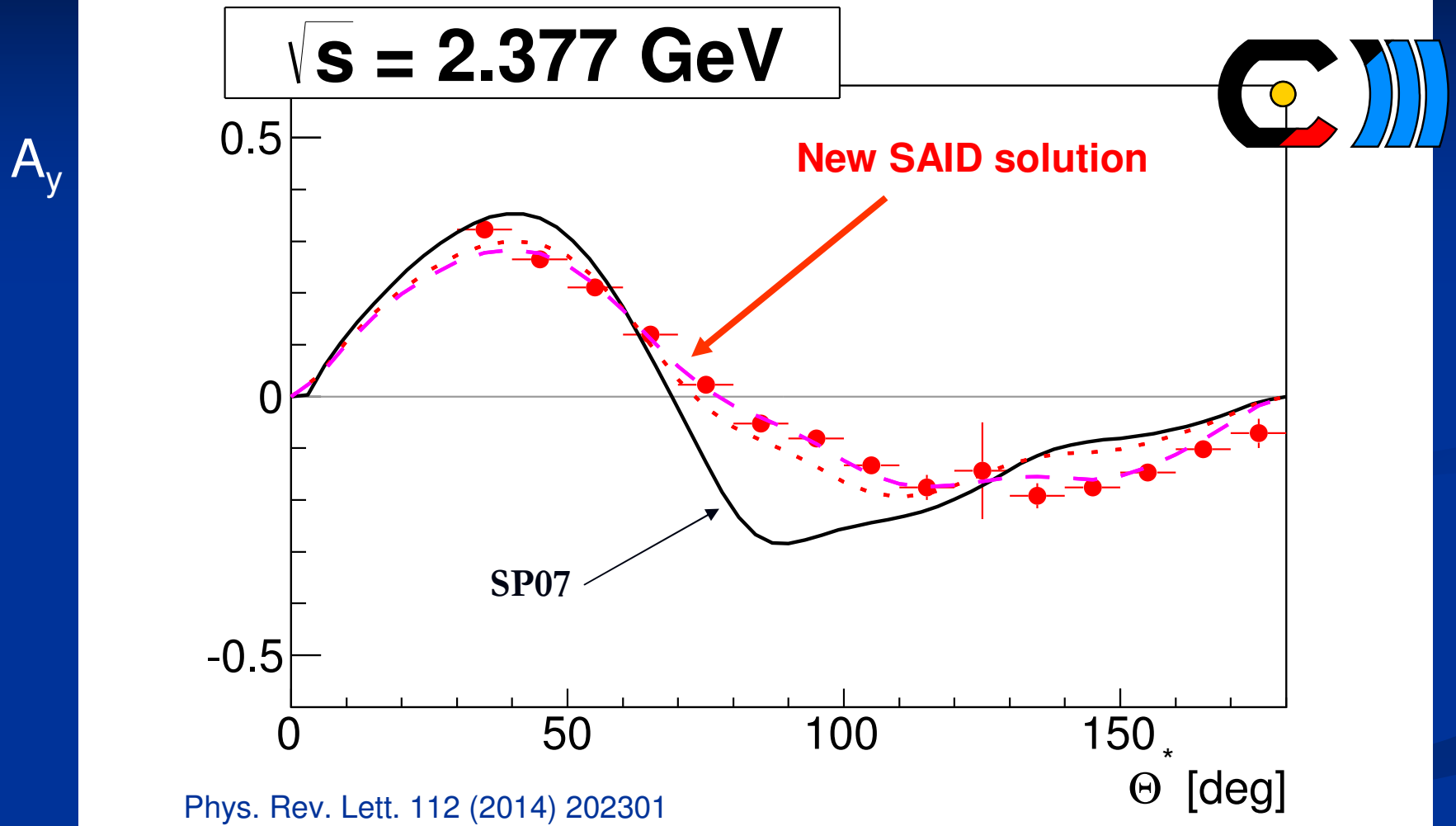
H. (… n of a … rk)

→ √s [GeV]

Crucial Experiment for d*

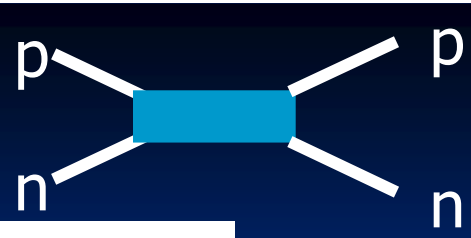
- If d^* a true s-channel resonance
- $\Leftrightarrow$
- then also a resonance in the np system
- $\Leftrightarrow$
- to be sensed in np scattering
- $\Leftrightarrow$
- in particular in the analyzing power
- $\Leftrightarrow$
- resonance effect $\sim P^1_3(\Theta)$
- i.e. maximal at $\Theta = 90^0$

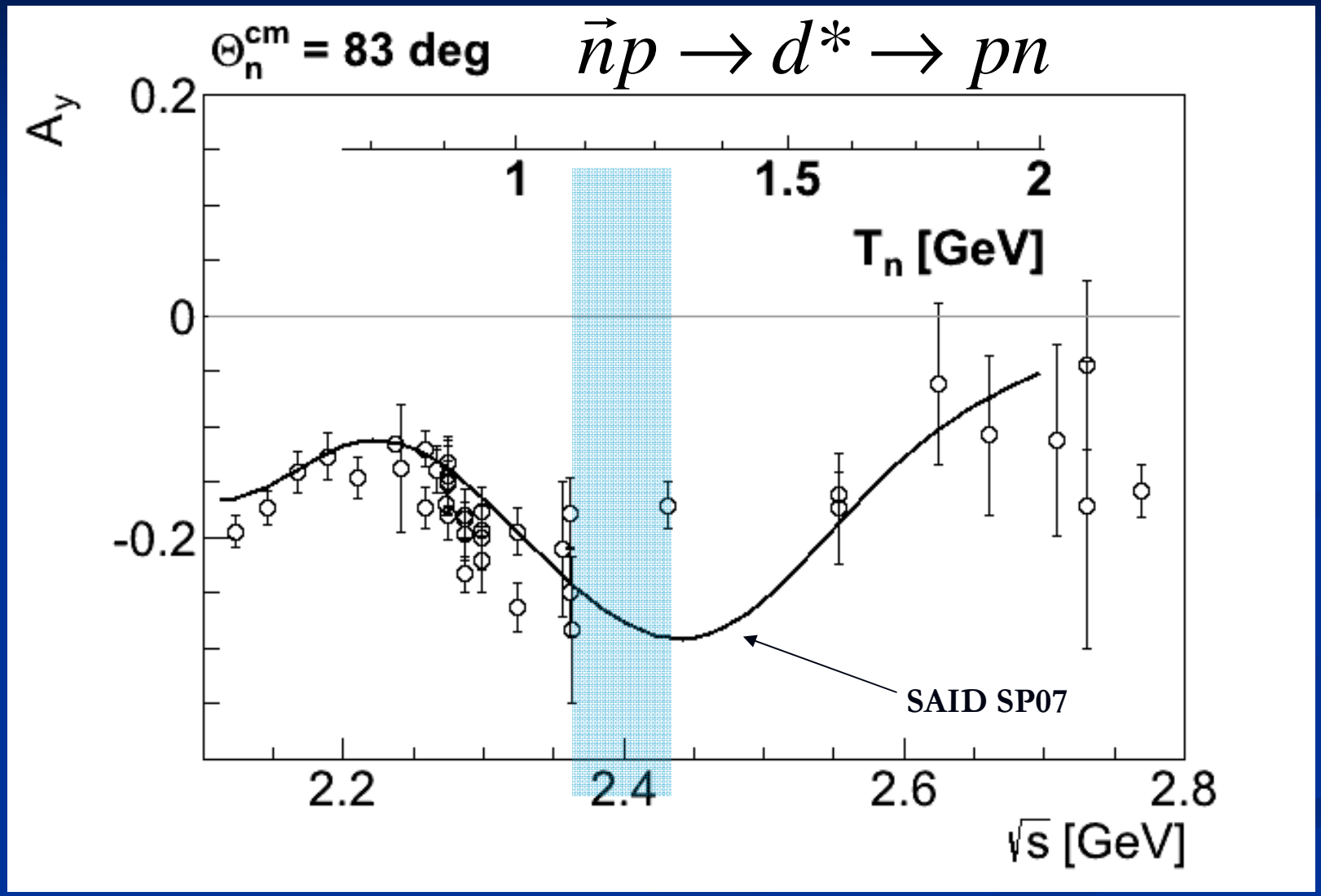
A_y Angular Distribution at Resonance



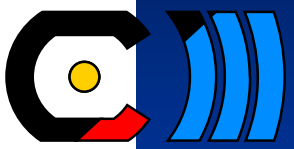
Phys. Rev. Lett. 112 (2014) 202301

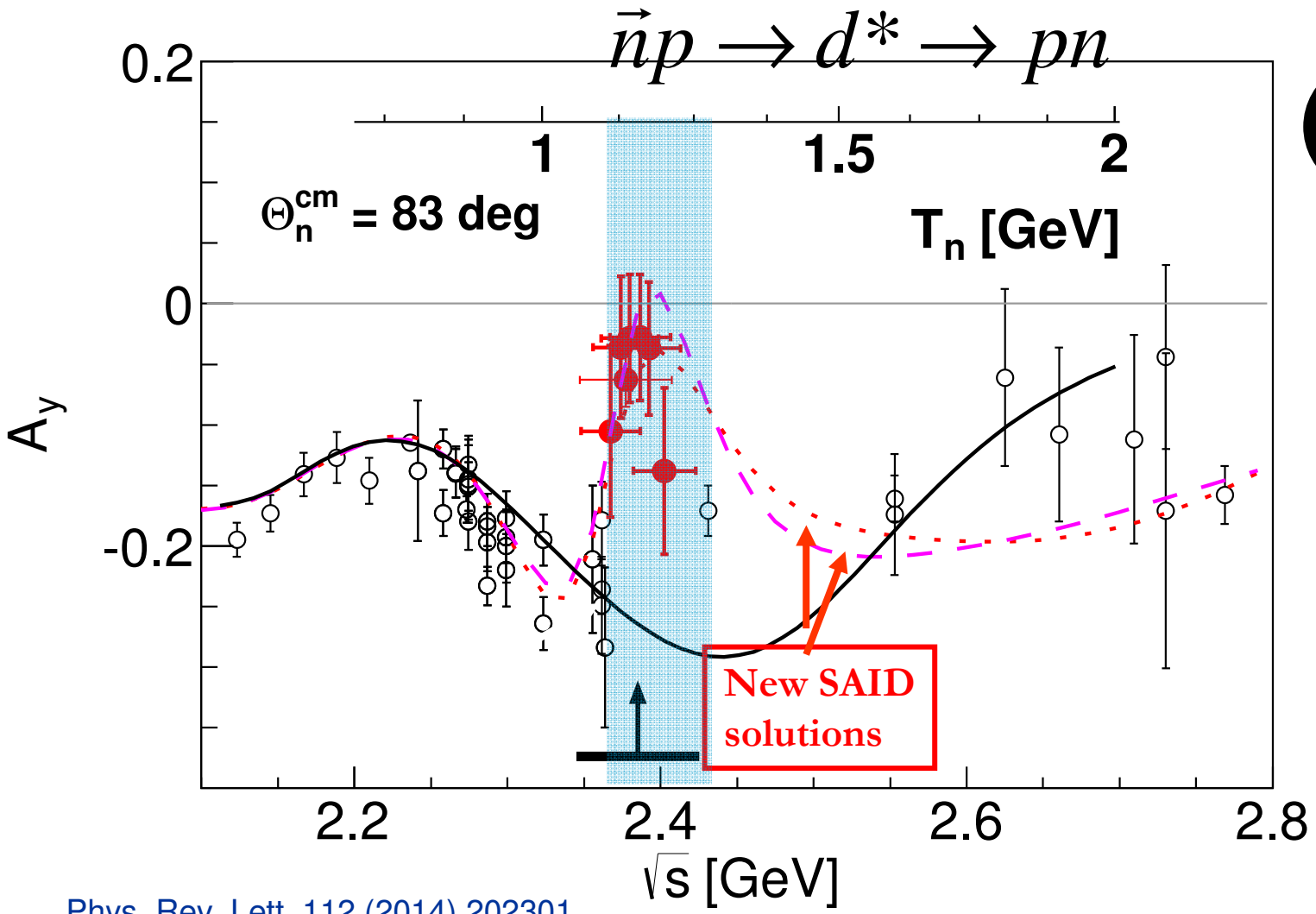
Energy Dependence





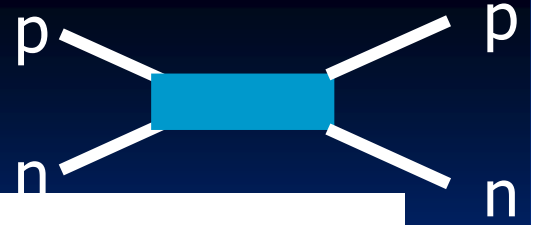
Energy Dependence

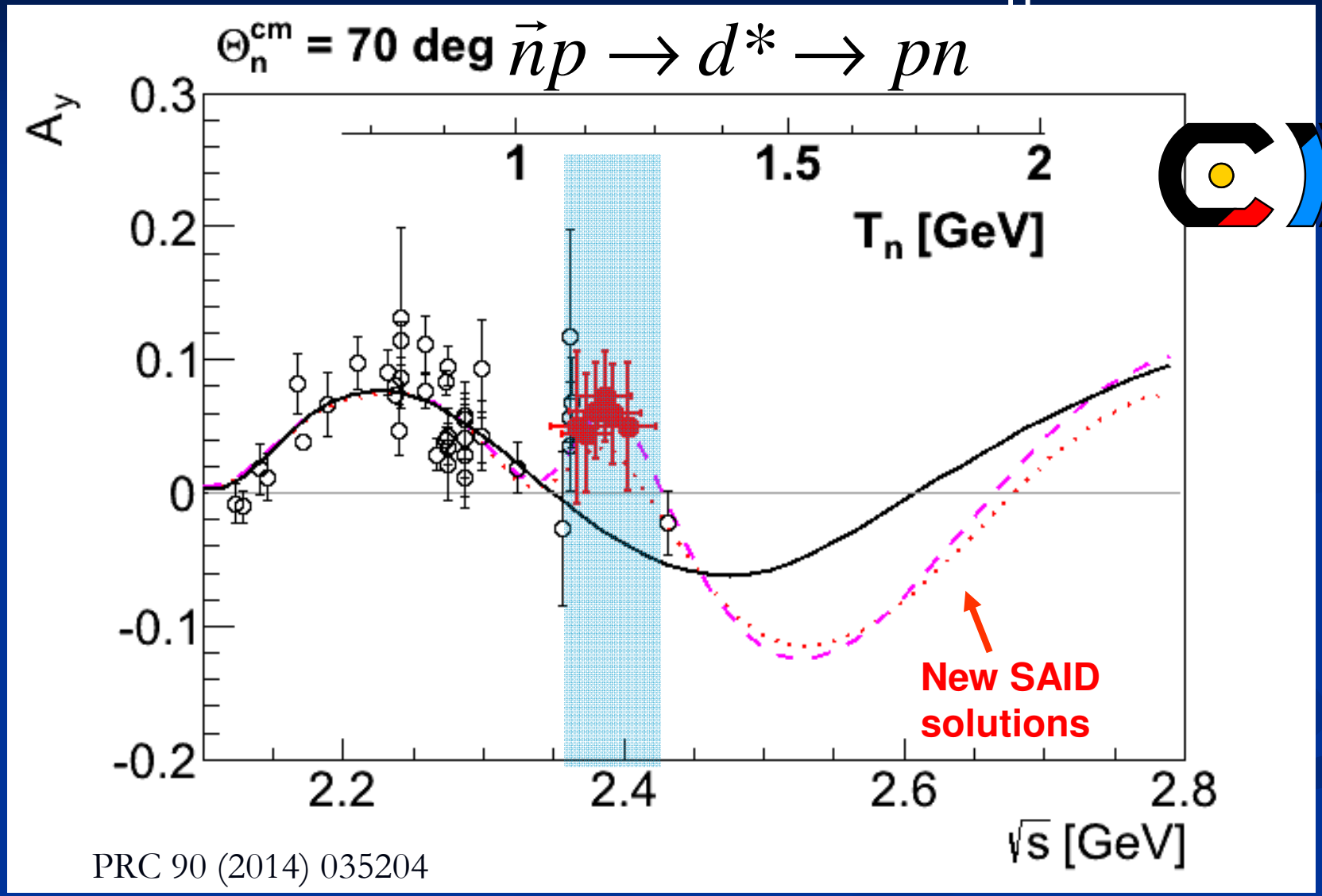




Phys. Rev. Lett. 112 (2014) 202301

A_y Energy Dependence



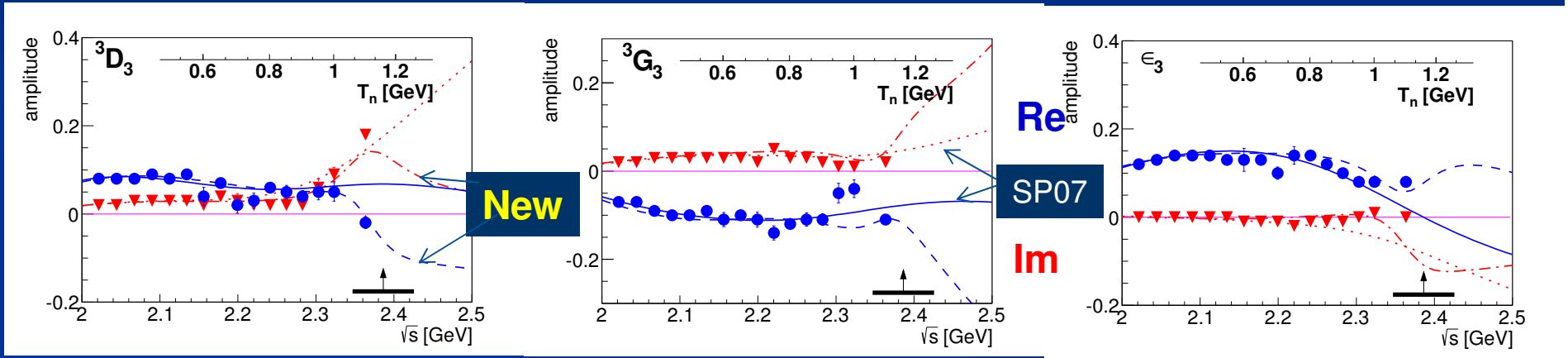


PRC 90 (2014) 035204

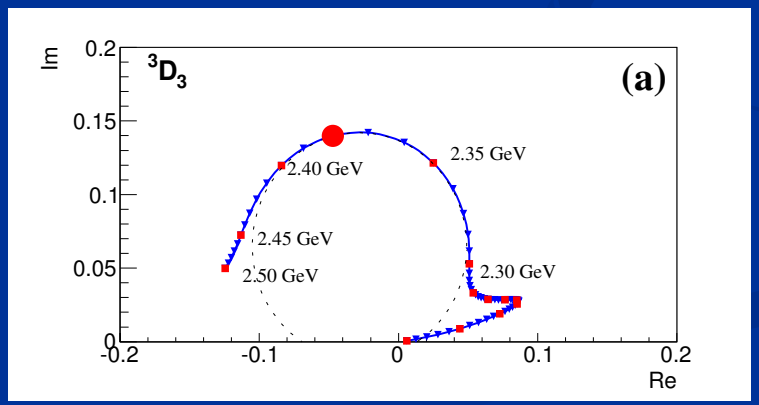
SAID Partial-Wave Analysis

$^3D_3 - {}^3G_3$ 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

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

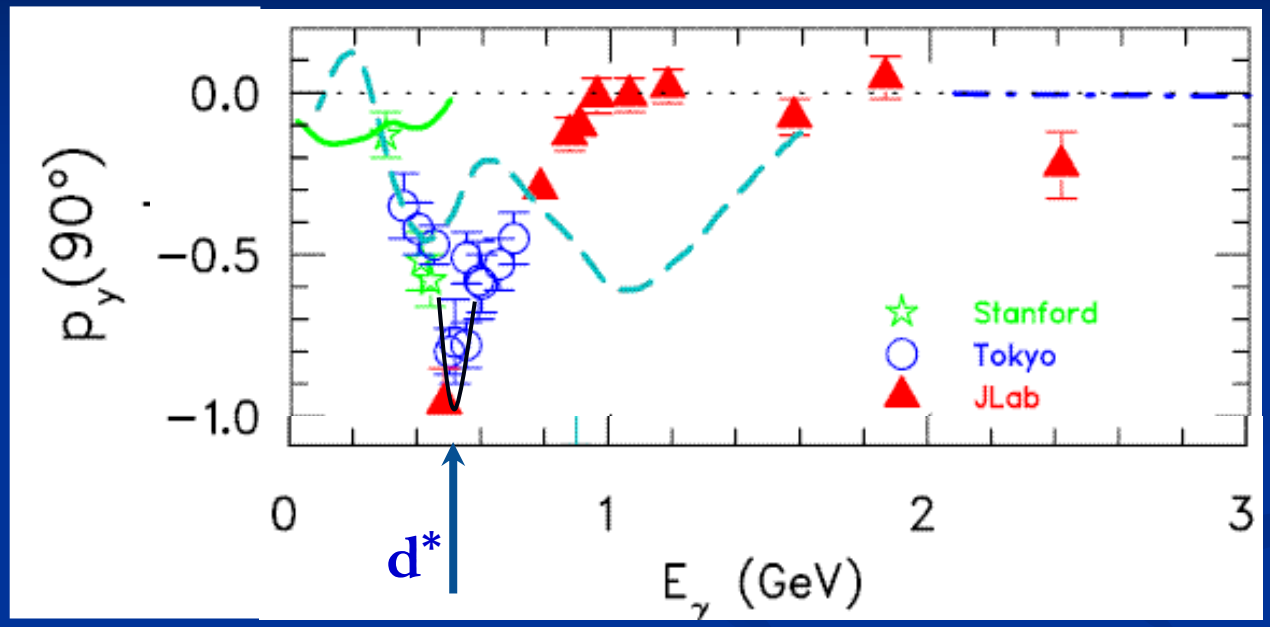
- hadronic decays

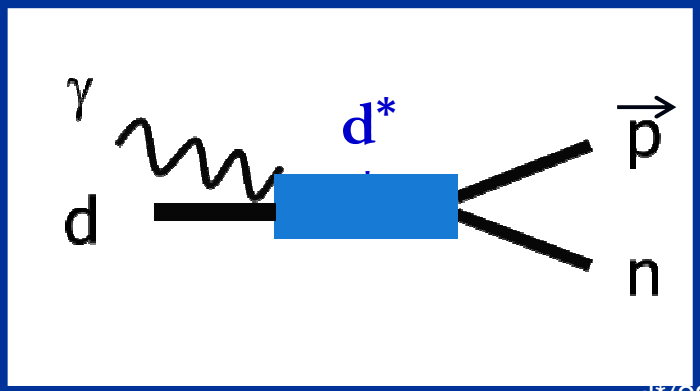
EPJA 51 (2015) 87

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
$(NN\pi)_{I=0}$	---	estimate: 0%

consistent with isospin coupling for a ΔΔ inter-mediate system

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



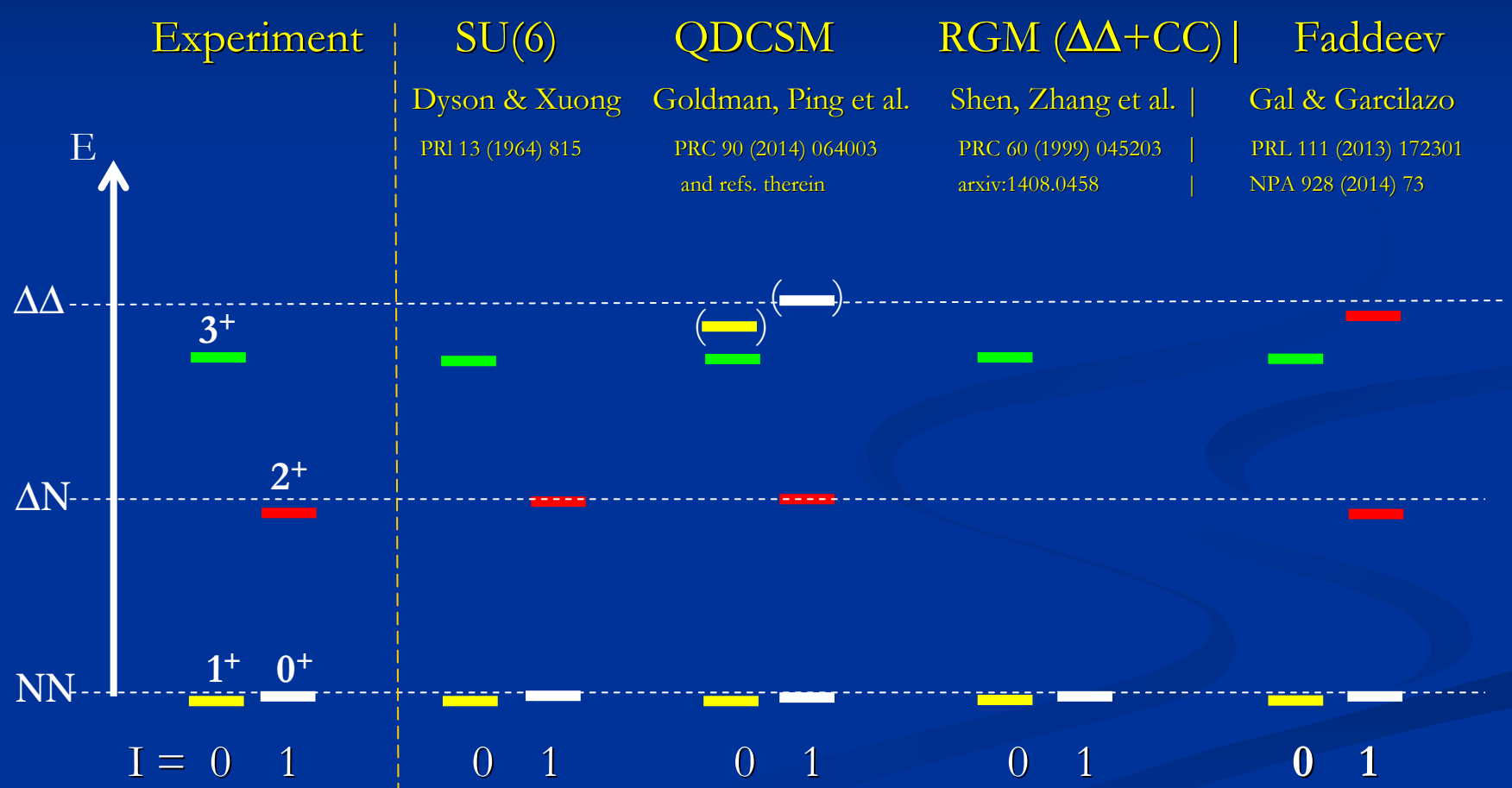


R. Gilman and F. Gross AIP Conf. Proc. 603 (2001) 55
K. Wijesooriya et al., Phys. Rev. Lett. 86 (2001) 2975

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

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

Comparison to predictions from Quark and Hadron Models

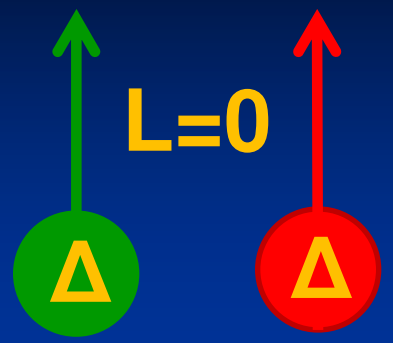


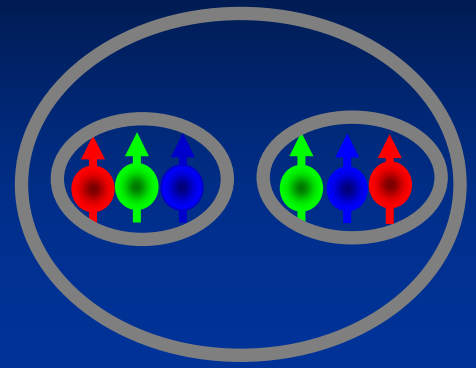
Width of d*(2380)

- 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 PRC 91 (2015) 064002

Molecule vs Hexaquark

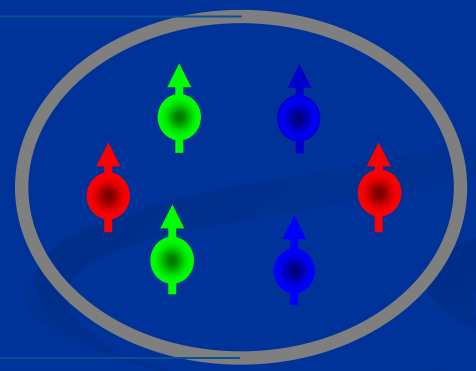
F. Huang et al, arXiv:1408.0458
1505.05395



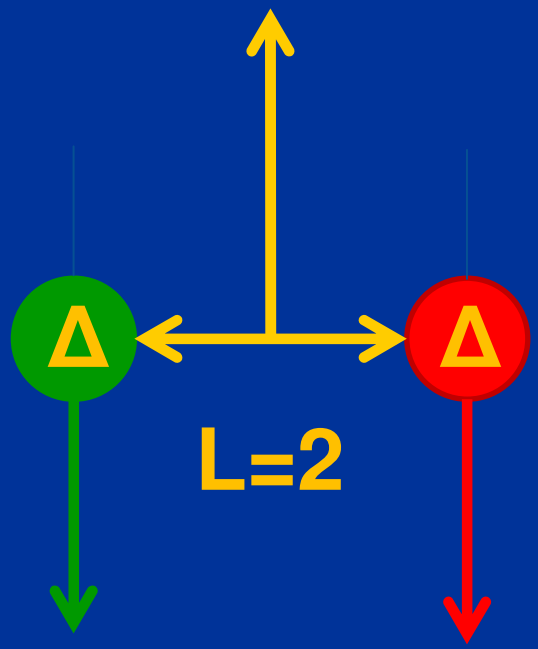


≈ 33%

0.8 fm



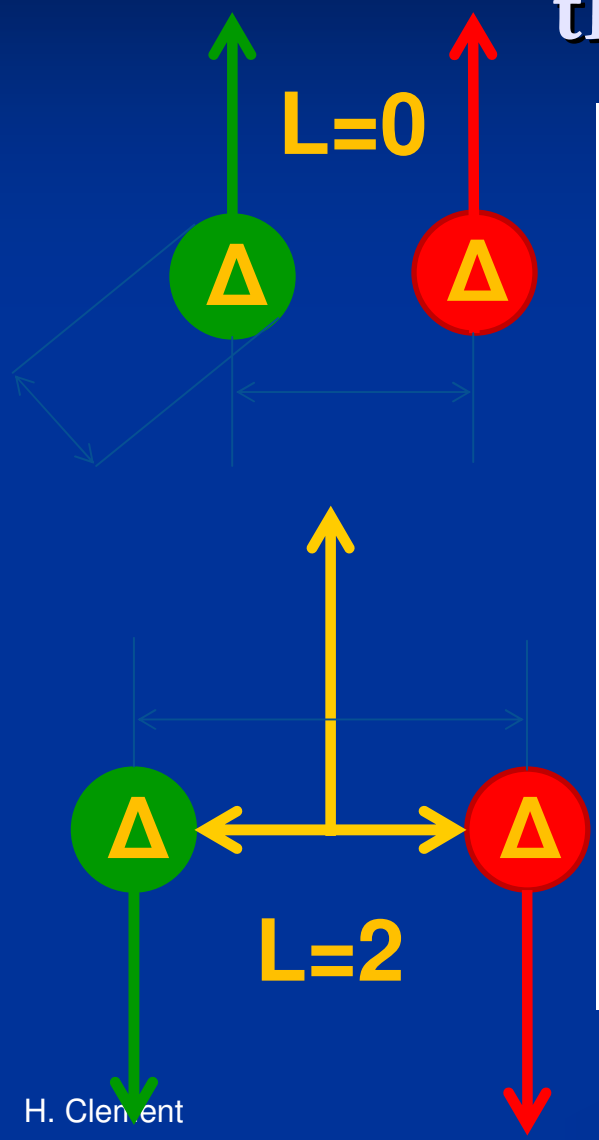
≈ 66%

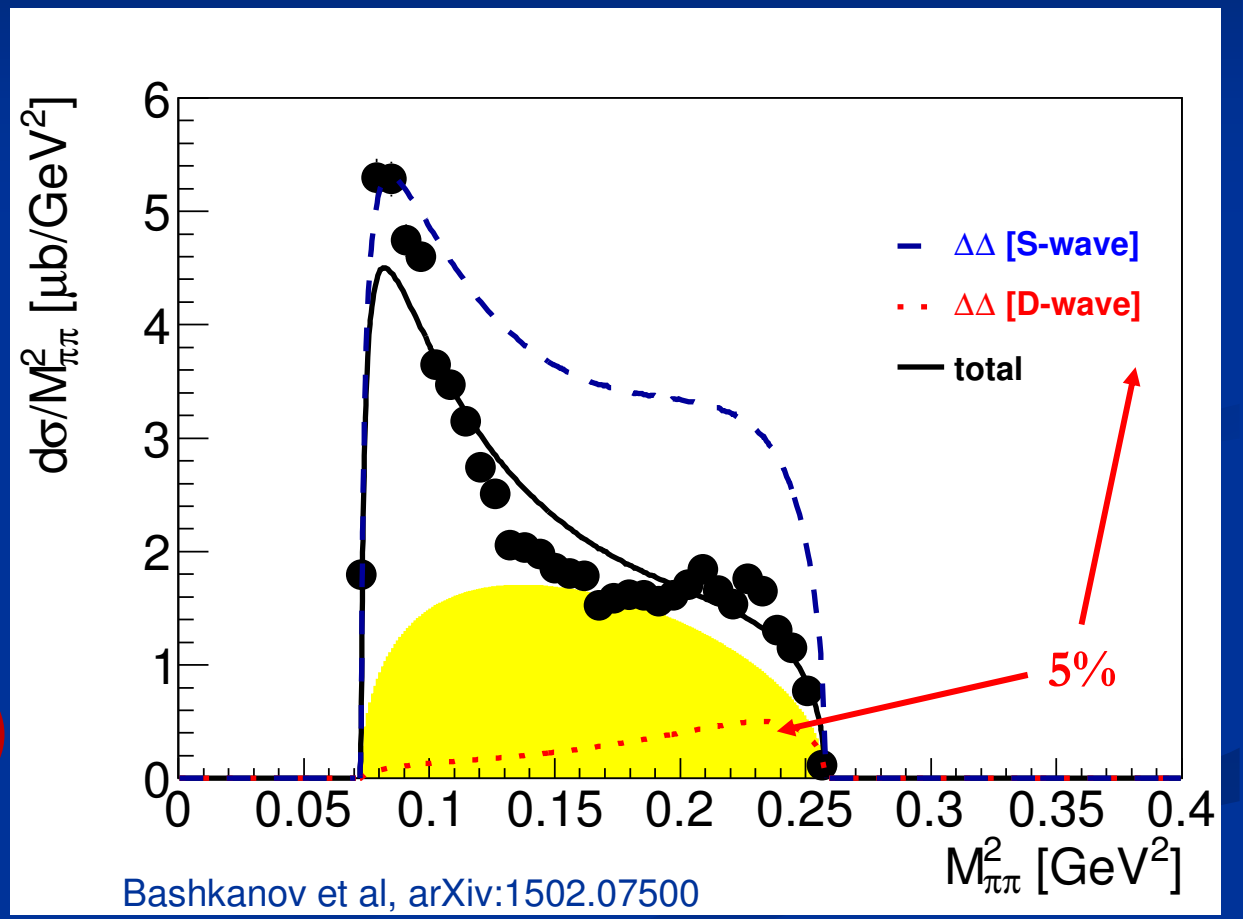


≈ 5% of ΔΔ configuration

?

d*(2380) internal structure and the ABC effect





Bashkanov et al, arXiv:1502.07500

Conclusions

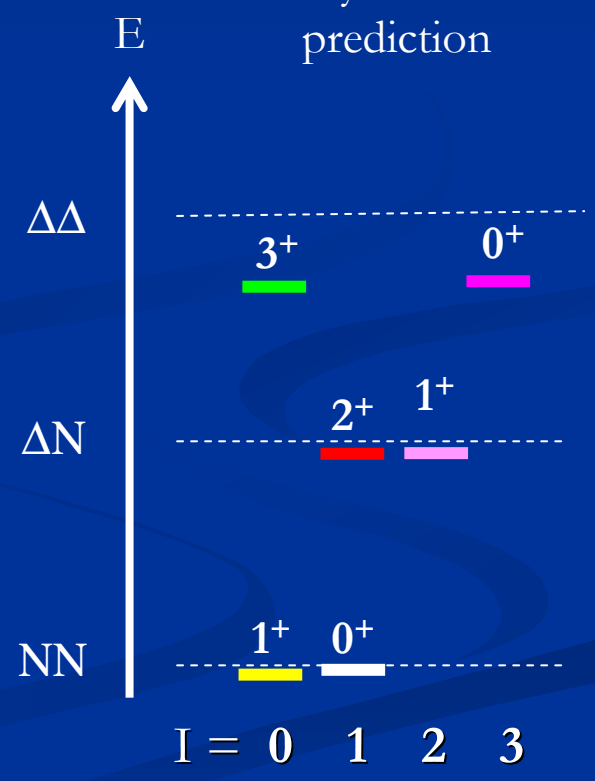
- Non-Strange Two-Baryon Spectrum
  - 3 established states: $^3S_1$ deuteron groundstate
    $^1S_0$ virtual state
    $^1D_2$ resonance (ΔN)
  - 1 new - presumably exotic - state:
    $d^*(2380)$ resonance ($\Delta\Delta$)
  - Are there more states?
    - NN-decoupled states with I = 2, 3?
    - Search in $pp \rightarrow pp\pi^+\ \pi^-$
      and in $pp \rightarrow pp\pi^+\pi^+\ \pi^-\pi^-$
- 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^* $\quad \gamma d \rightarrow d^* \rightarrow pn$
  - $\rightarrow d\pi^0\pi^0$
- Observation at other installations
  - HADES @ GSI: under way, but no 4π and no neutrals
  - IHEP ?? $\quad e^+e^- \rightarrow d\,\bar{d}^*$ 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