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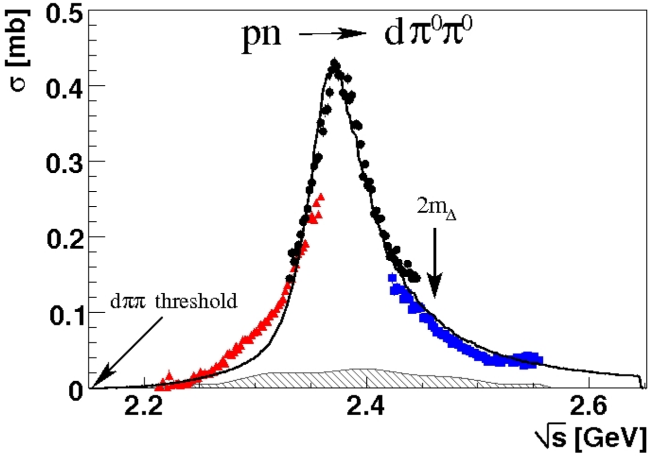

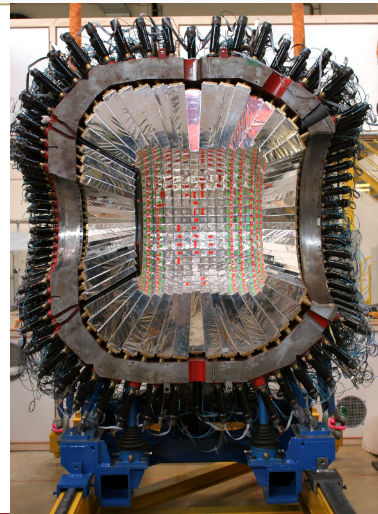

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DFG Deutsche Forschungsgemeinschaft

Dibaryons --- fake or true?

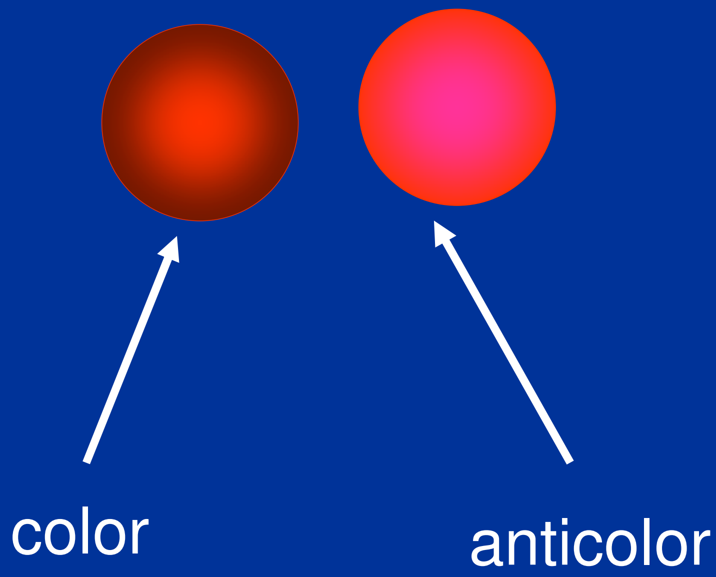
2nd Jagiellonian Symposium on Fundamental and Applied Subatomic Physics

Cracow, June 4 – 9, 2017

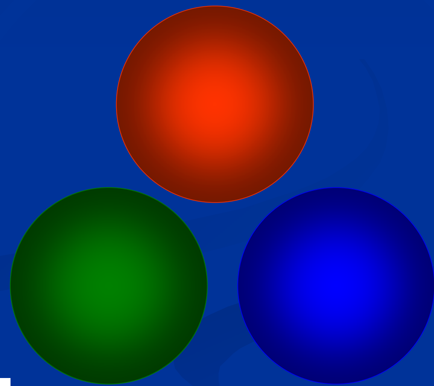
Heinz Clement

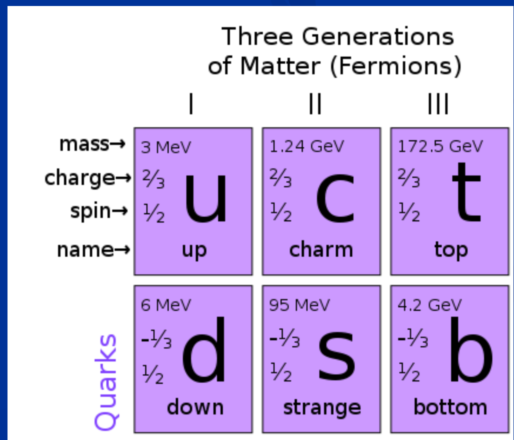
Types of conventional particles/resonances

Meson



Baryon





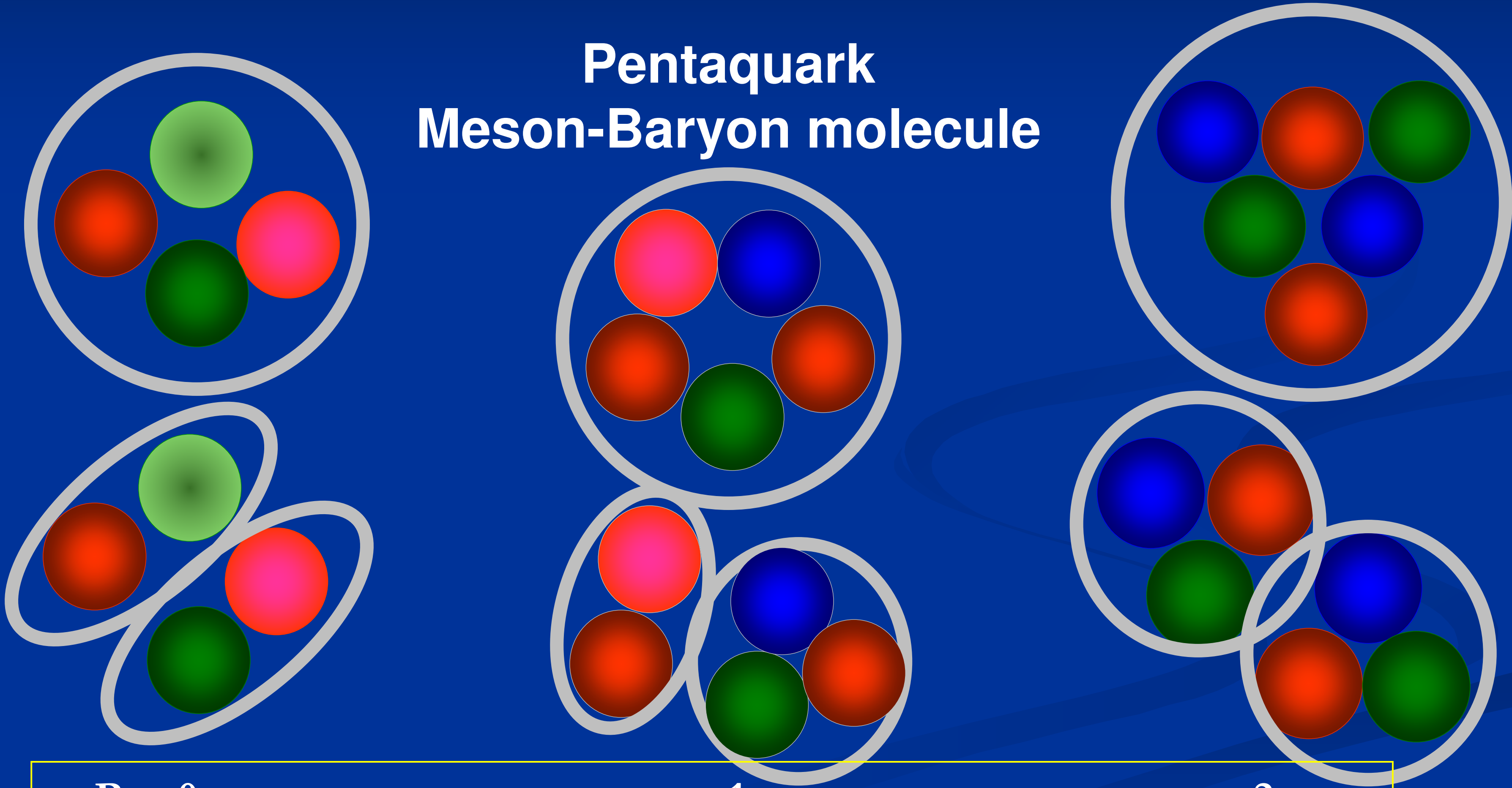
2

Possible further particles

Tetraquark
Meson-Meson molecule

Pentaquark
Meson-Baryon molecule

Hexaquark
Baryon-Baryon molecule



B = 0	1	2

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: hexaquarks (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

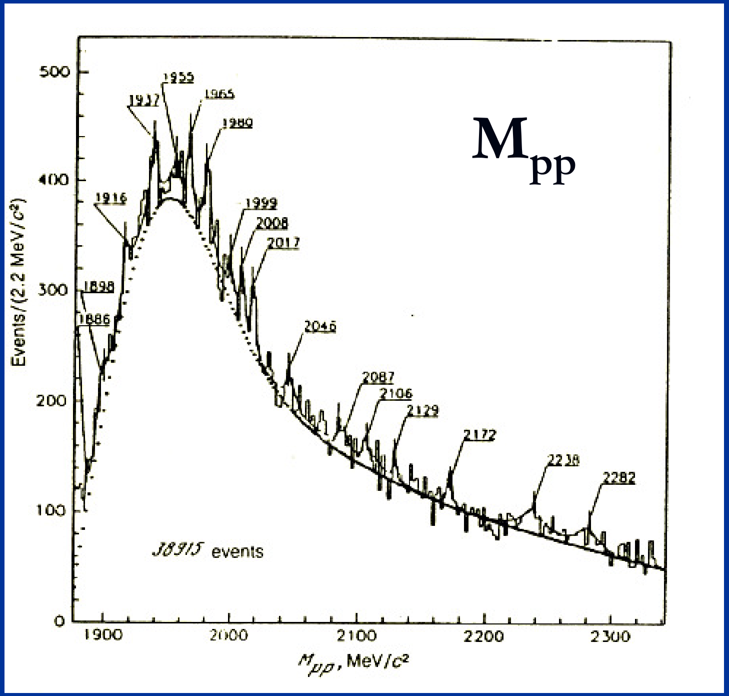
Early Predictions of Dibaryons

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

The Experimental Rush for Dibaryons

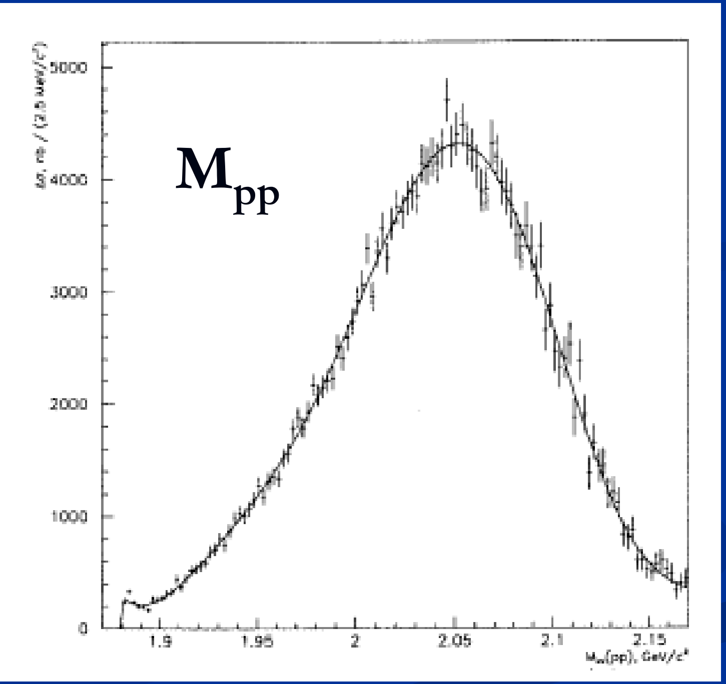
- Low statistics versus high statistics (quality):

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



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

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

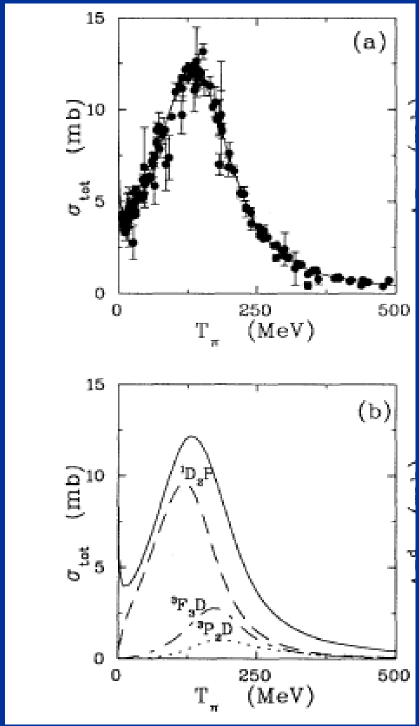


Abramov et al., Z. Phys. C69 (1996) 409

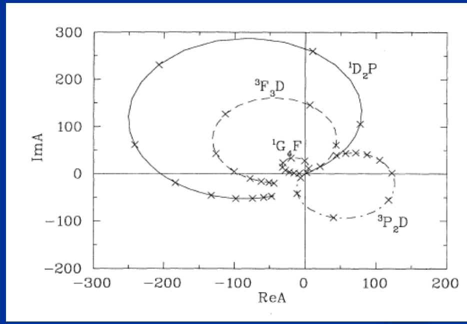
Possibly the only surviver: $^1D_2$ Resonance

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

σ_{tot} ($\pi^+d \rightarrow pp$)



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

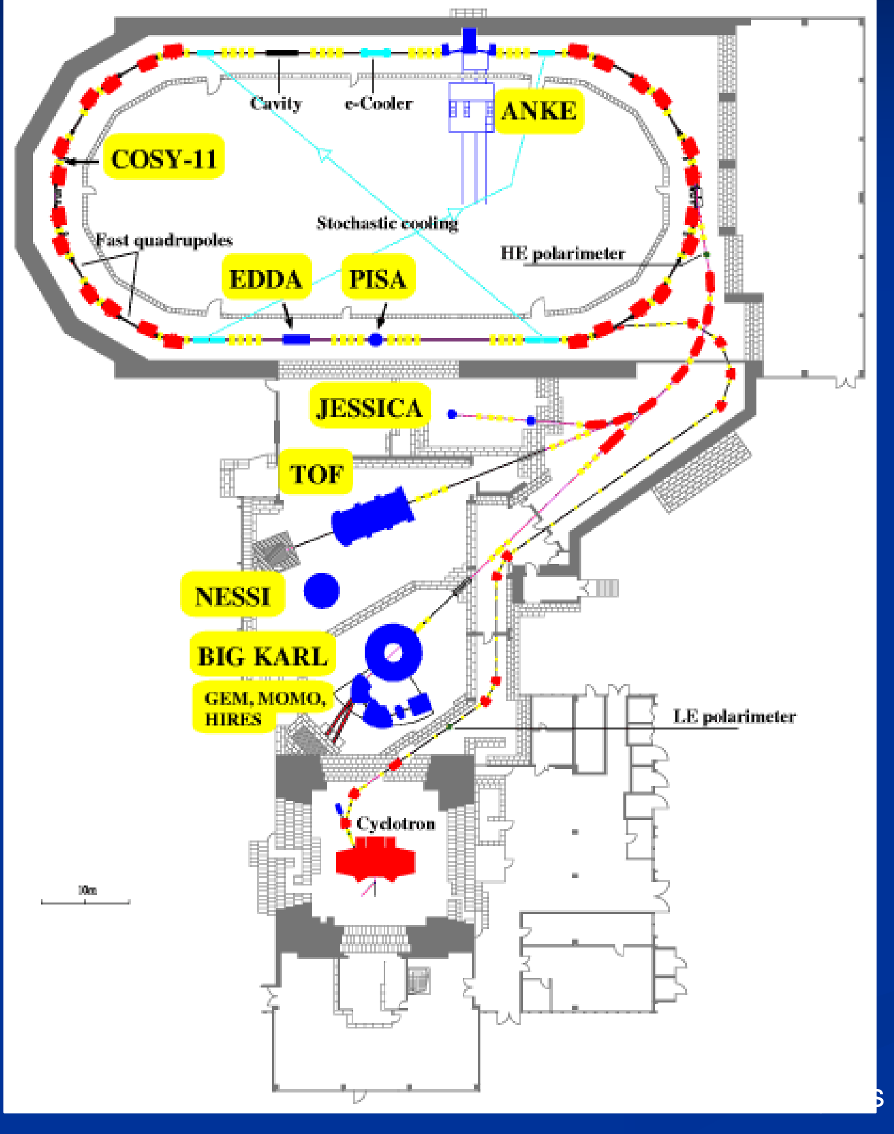
Alternative description: cusp, virtual state, reflection D. Bugg et al.

Conclusion from the Failures in the Dibaryon Rush Era:

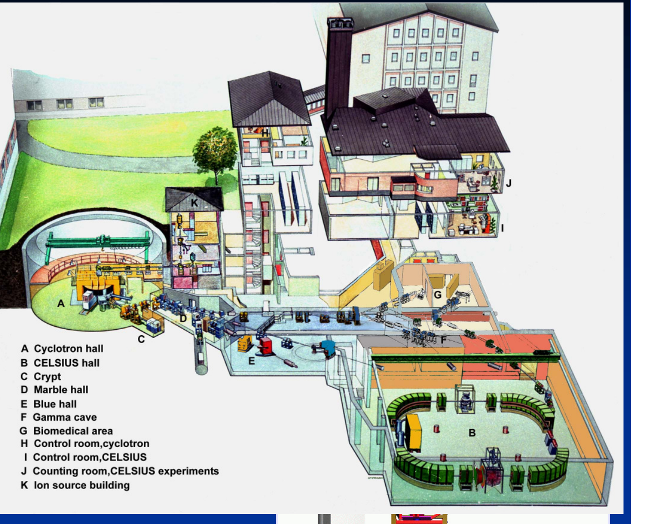
Do Exclusive and kinematically complete measurements

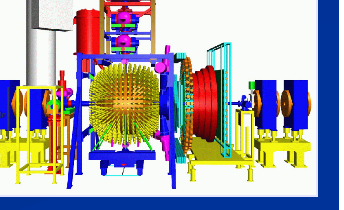
- Our approach:
  - Two-pion production with best suited equipment
    - 4π detector: WASA
    - pellet target: p and d
    - storage ring: CELSIUS $\rightarrow$ COSY
  - The learning phase:
    - pp induced two-pion production
  - Following a trace:
    - the ABC effect in double-pionic fusion
  - The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

WASA at COSY



2005 - 2006

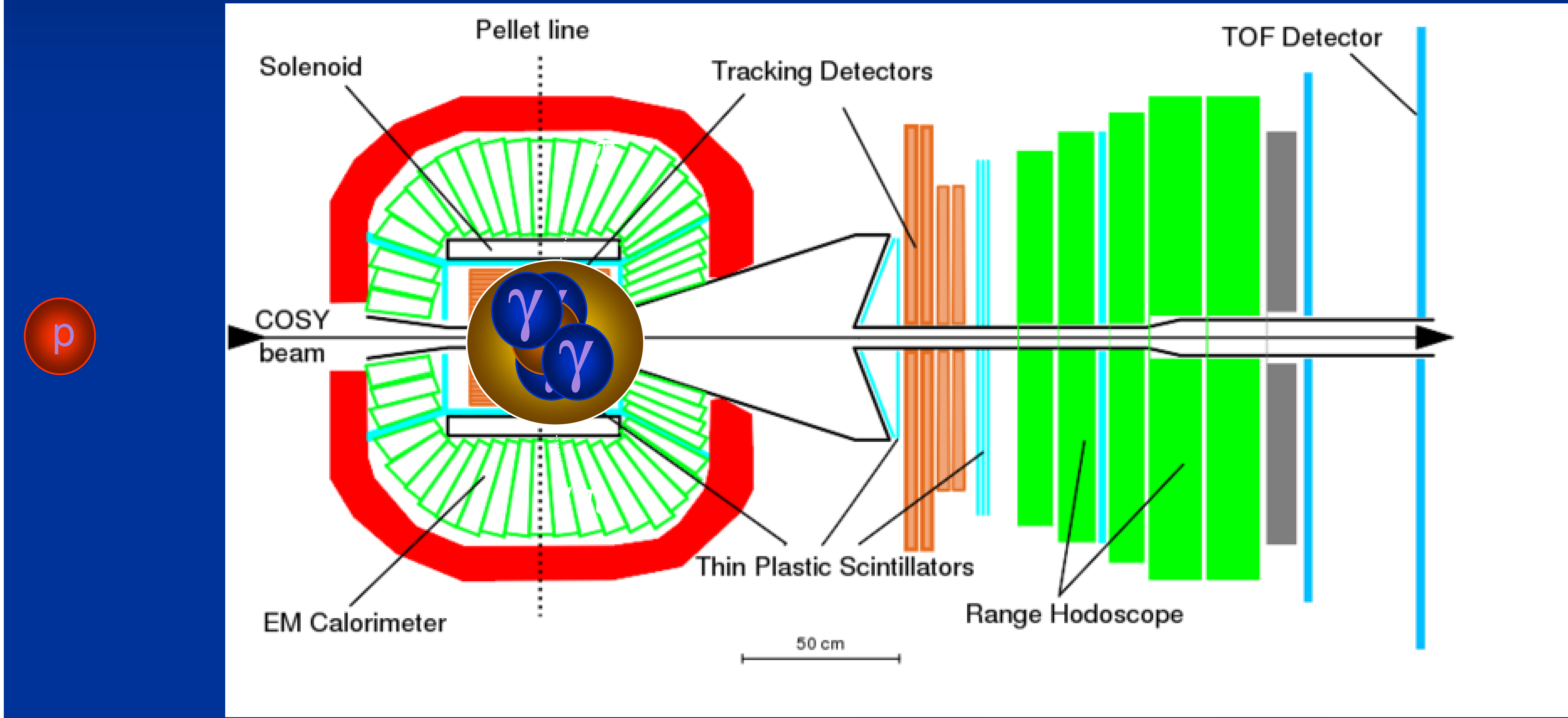




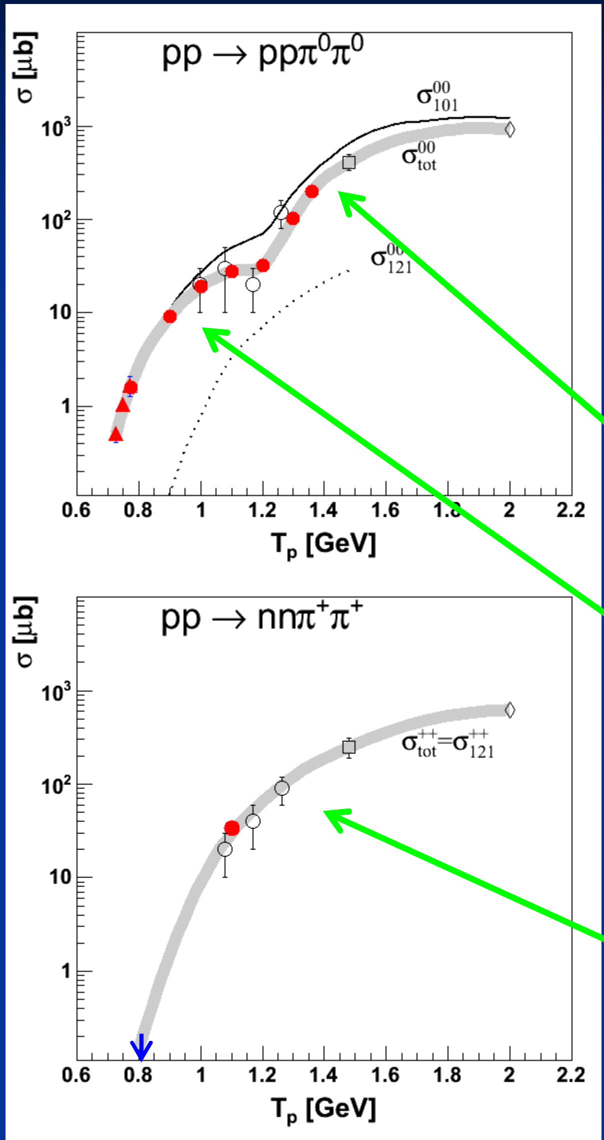
CELSIUS/WASA

WASA 4π Detector

$$pn \rightarrow \textbf{dibaryon} \rightarrow d\pi^0\pi^0$$



Isovector : Total Cross Sections



isospin decomposition

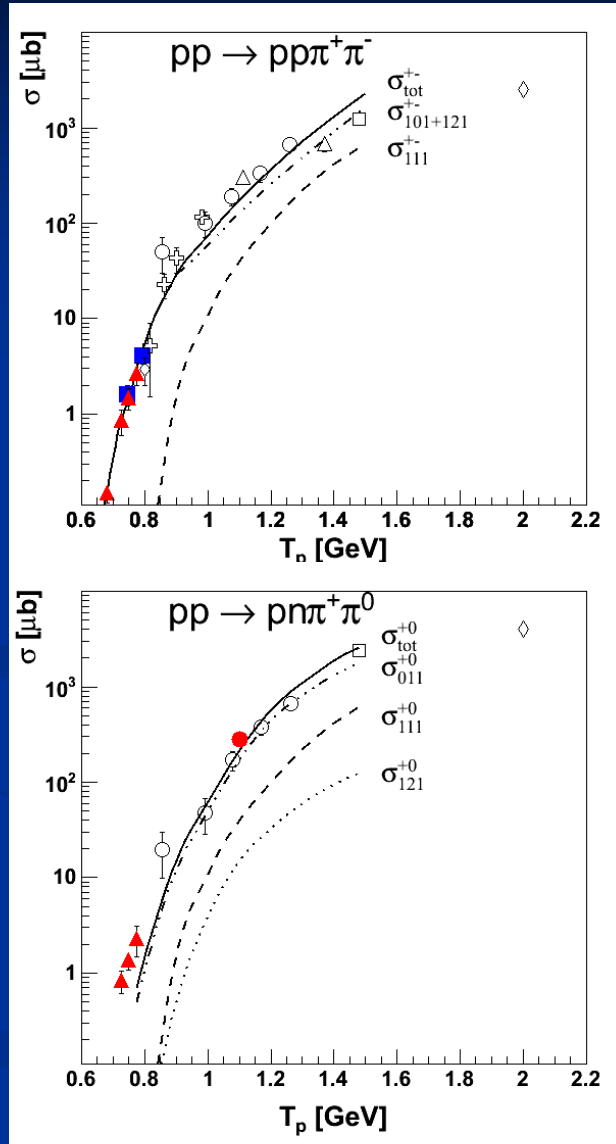
⇒

ΔΔ

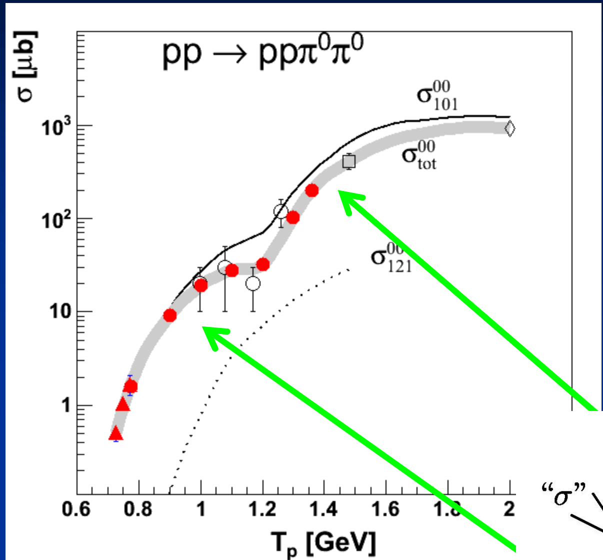
N*(1440)

Δ(1600) (?)

Phys. Lett. B 679 (2009) 30

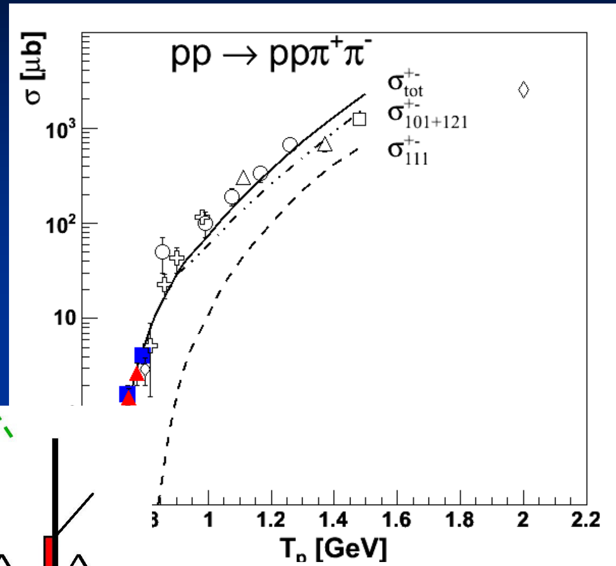


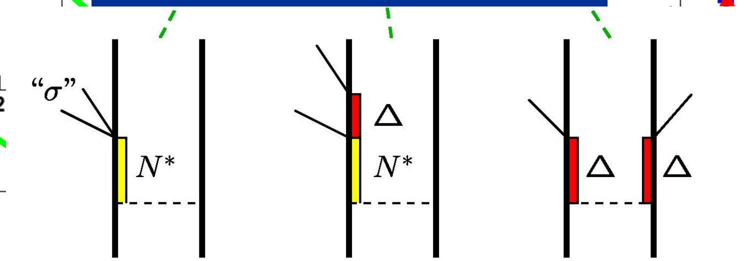
Isovector : Total Cross Sections



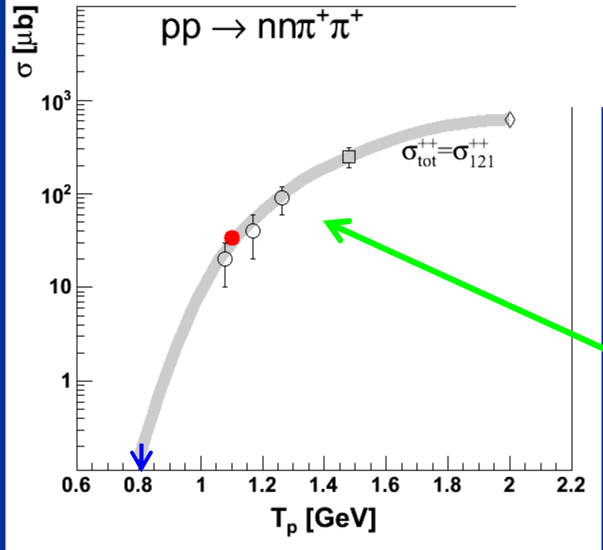
isospin decomposition

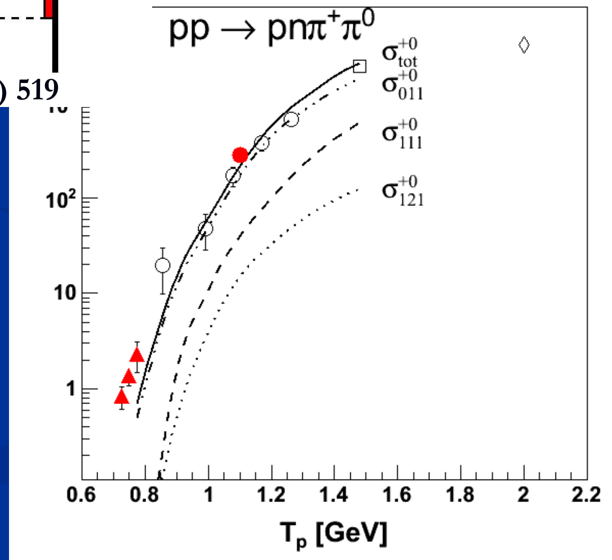
⇒





Alvarez-Ruso, Oset NPA 633 (1998) 519

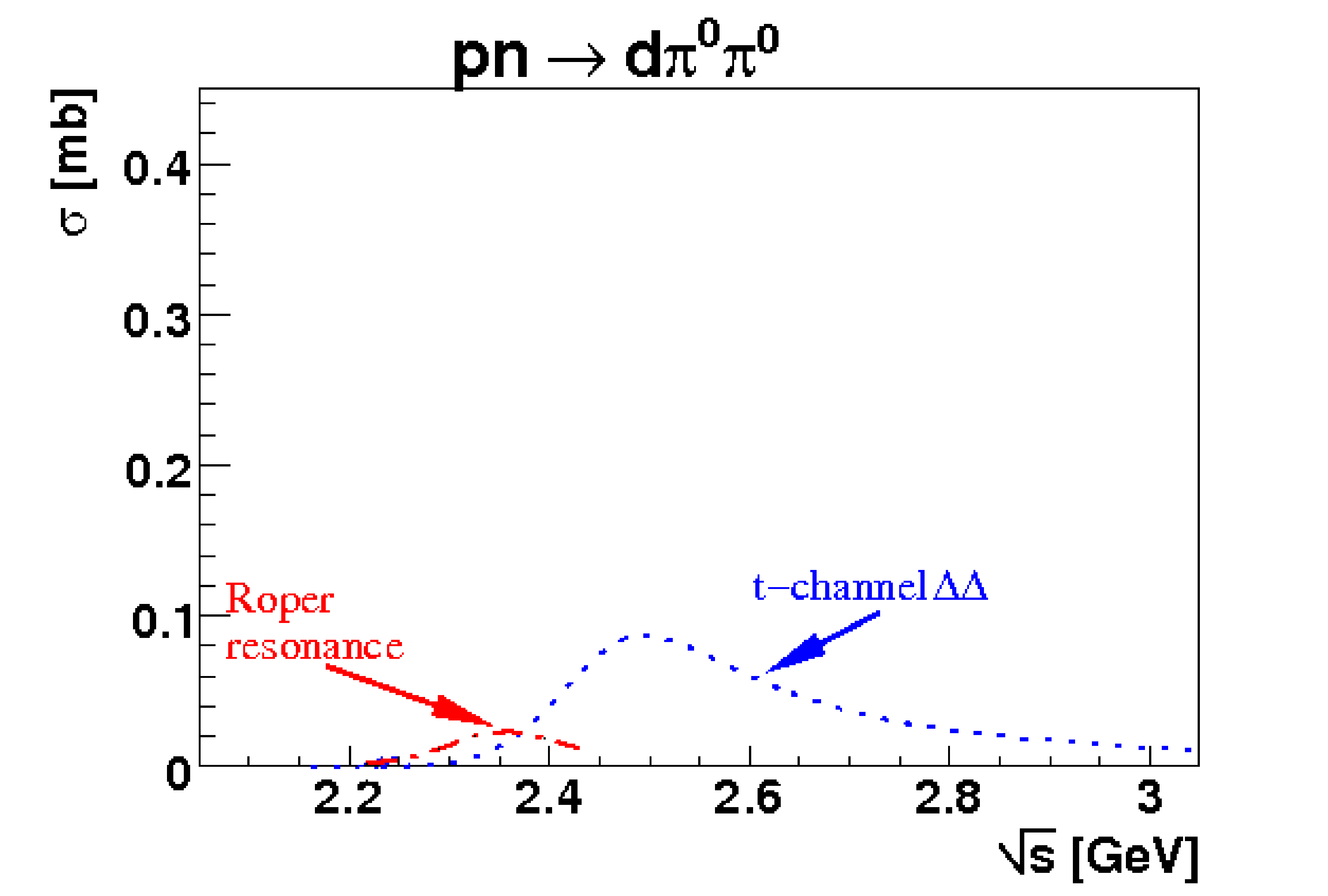




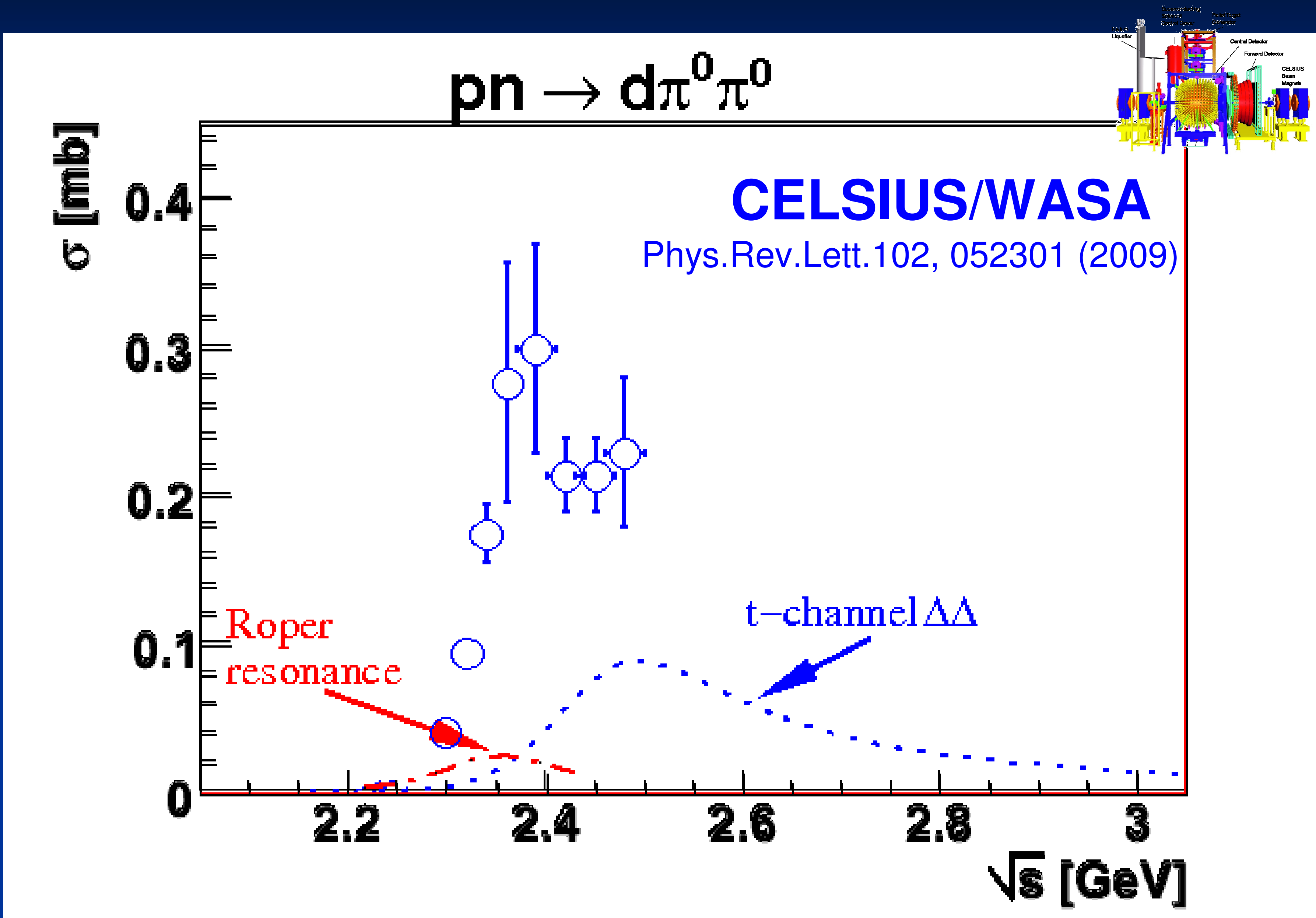
Δ(1600) (?)

Phys. Lett. B 679 (2009) 30

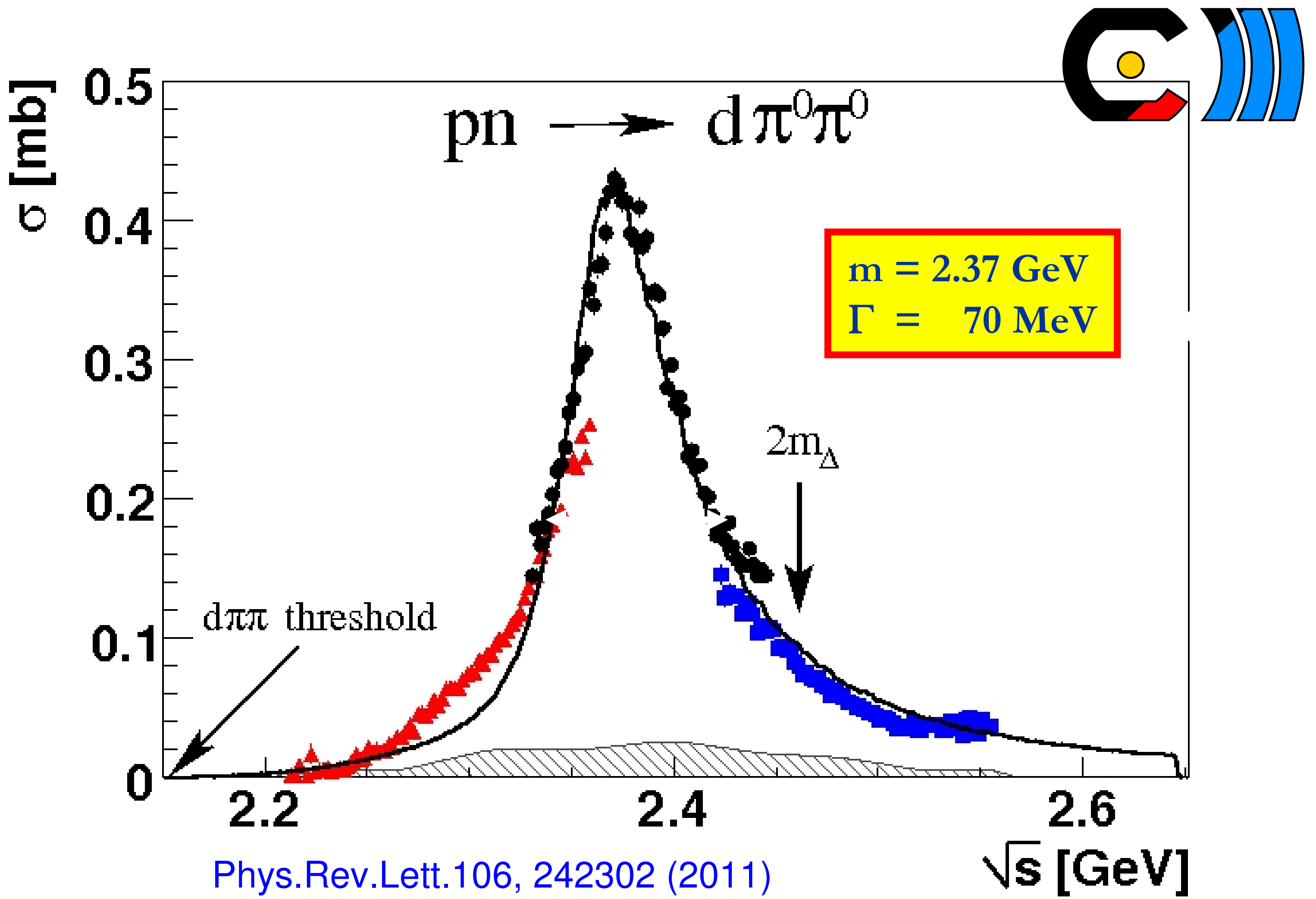
Isoscalar : … this is what we expected!



Isoscalar : … and this is what we found!

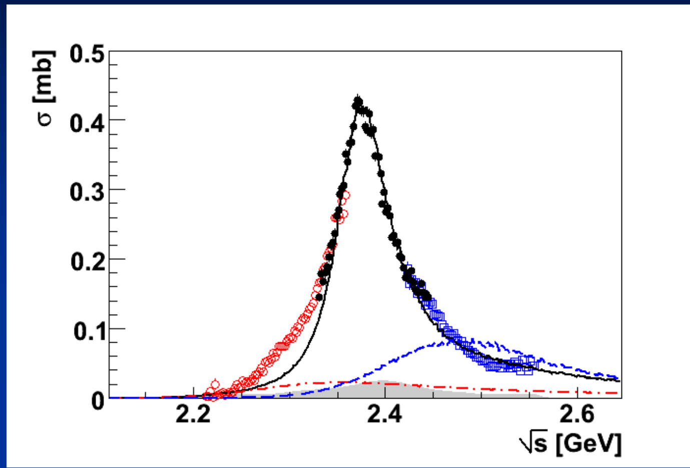


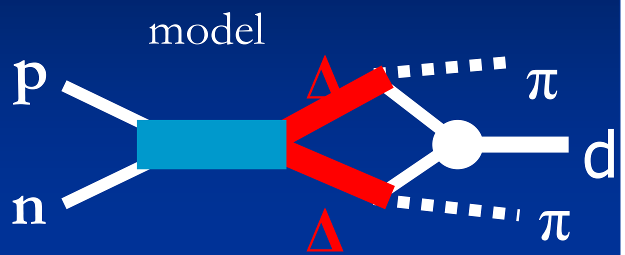
Isoscalar : Results from WASA at COSY



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

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

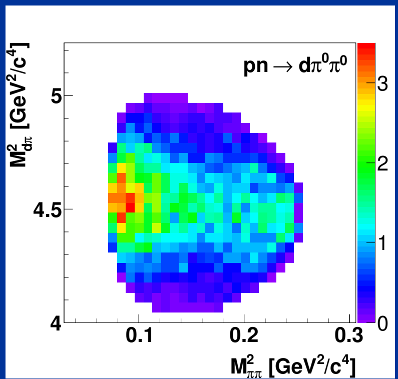


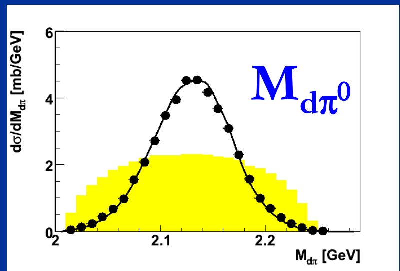


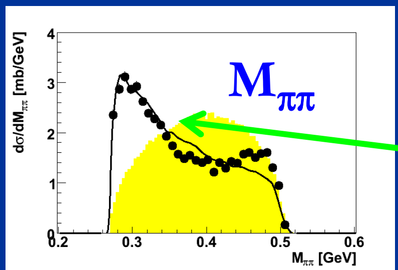
$I\,(J^P) = 0\,(3^+)$

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

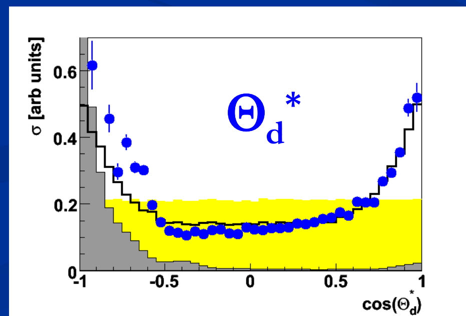
Phys.Rev.Lett.106, 242302 (2011)





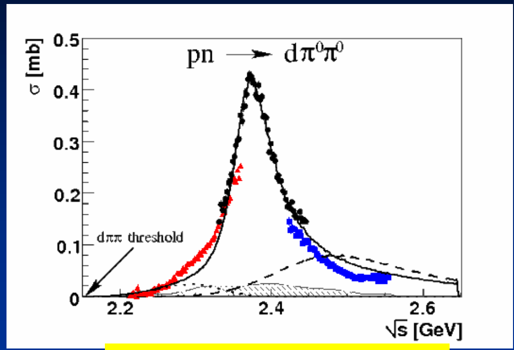


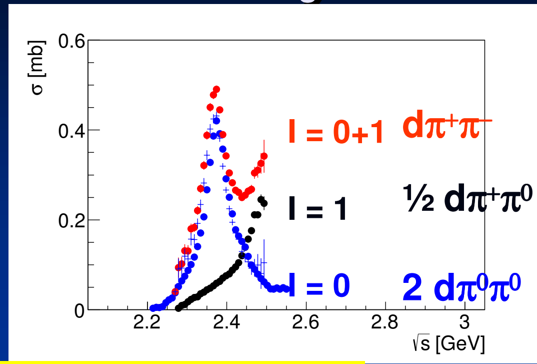
ABC effect



hadronic decays

PRL 106 (2011) 242302





PLB 721 (2013) 229

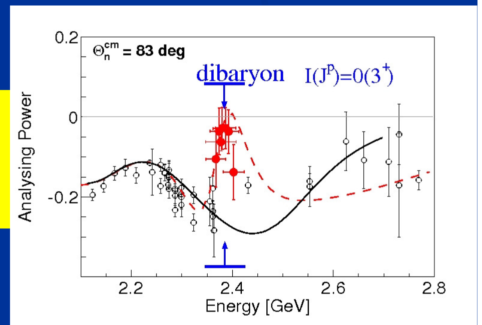
○ ● ● WASA data

$d\pi^0\pi^0$

$d\pi^+\pi^-$

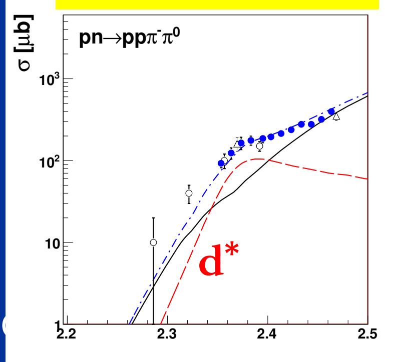
pn → d*(2380)

pn

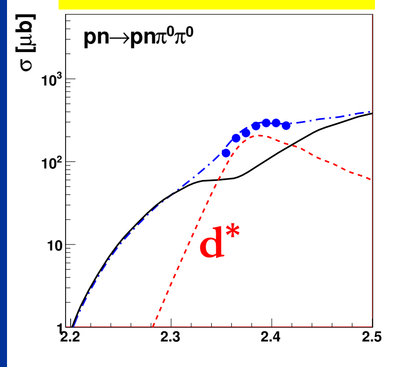


PRL 112 (2014) 202301
PRC 90 (2014) 035204

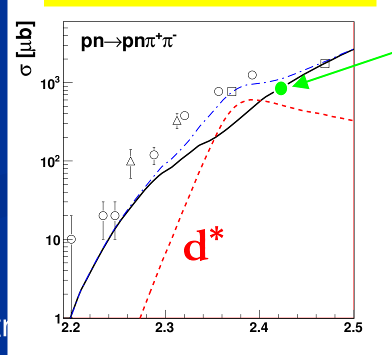
$pp\pi^-\pi^0$



$pn\pi^0\pi^0$



$pn\pi^+\pi^-$



HADES PLB 750 (2015) 184

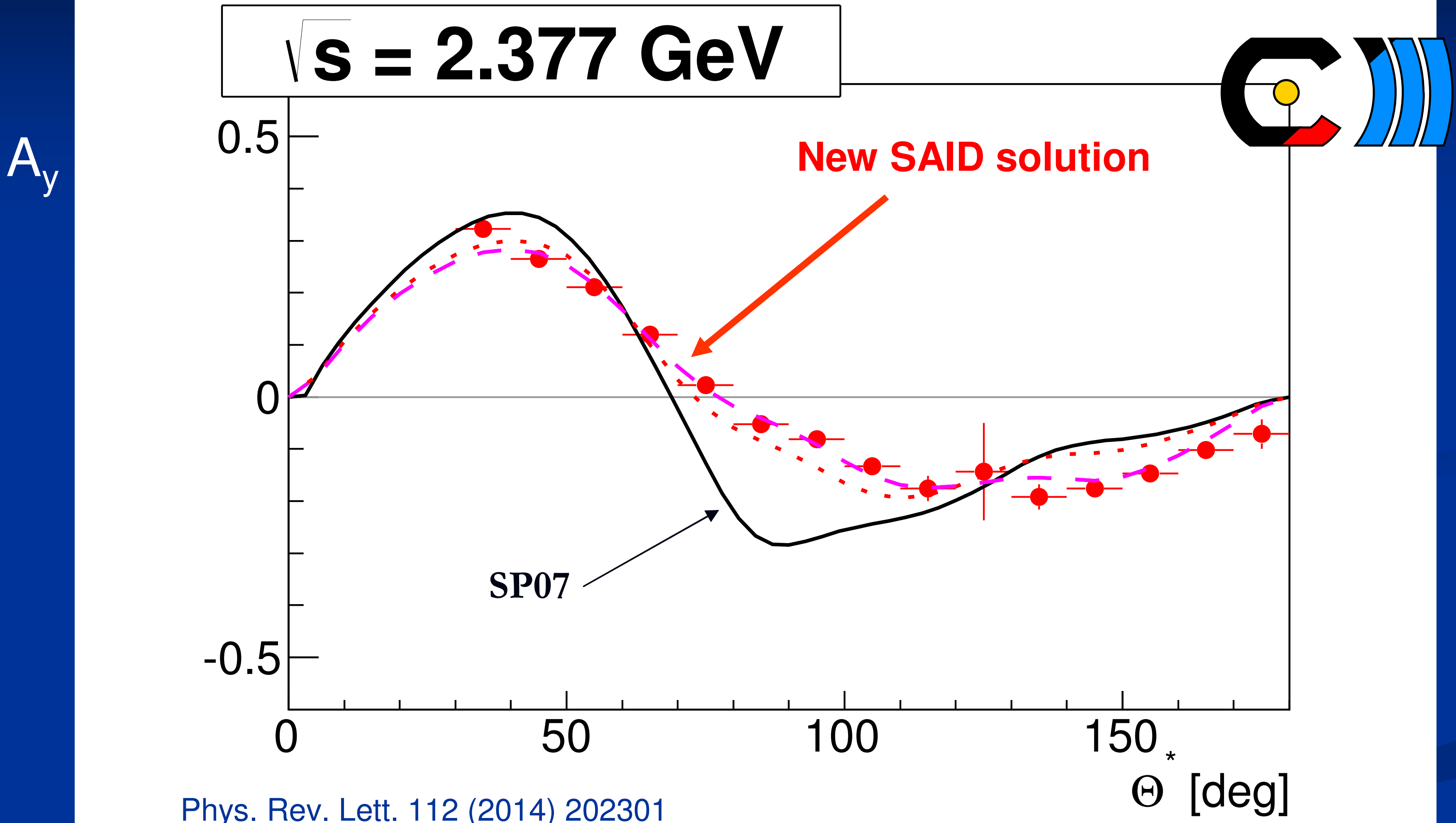
PRC 88 (2013) 055208
PLB 743 (2015) 325
Phys. Scr. T 166 (2015) 014016

→ √s [GeV]

„Experimentum Crucis“ for d^*

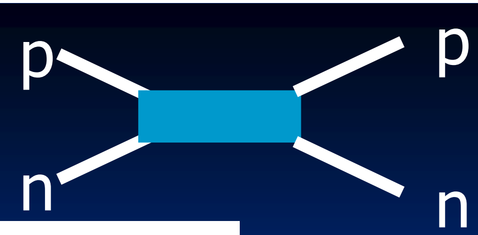
- If d^* a true s-channel resonance
- $\Leftrightarrow$
- then also a resonance in the np system
- $\Leftrightarrow$
- to be sensed in np scattering
- $\Leftrightarrow$
- in particular in the analyzing power
- $\Leftrightarrow$
- resonance effect ~ $P^1{}_3\,(\Theta)$
- i.e. maximal at $\Theta = 90^0$

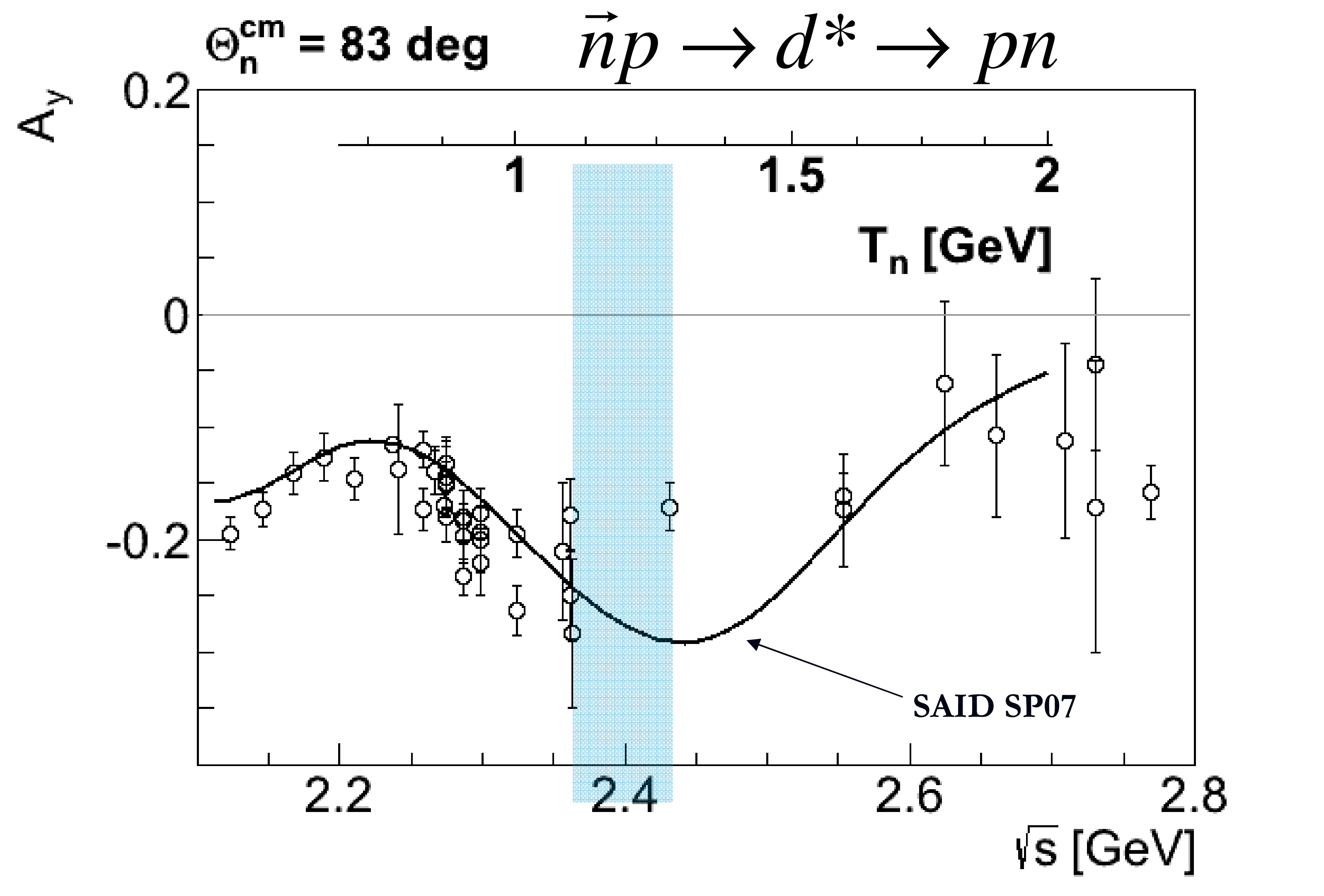
A_y Angular Distribution at Resonance



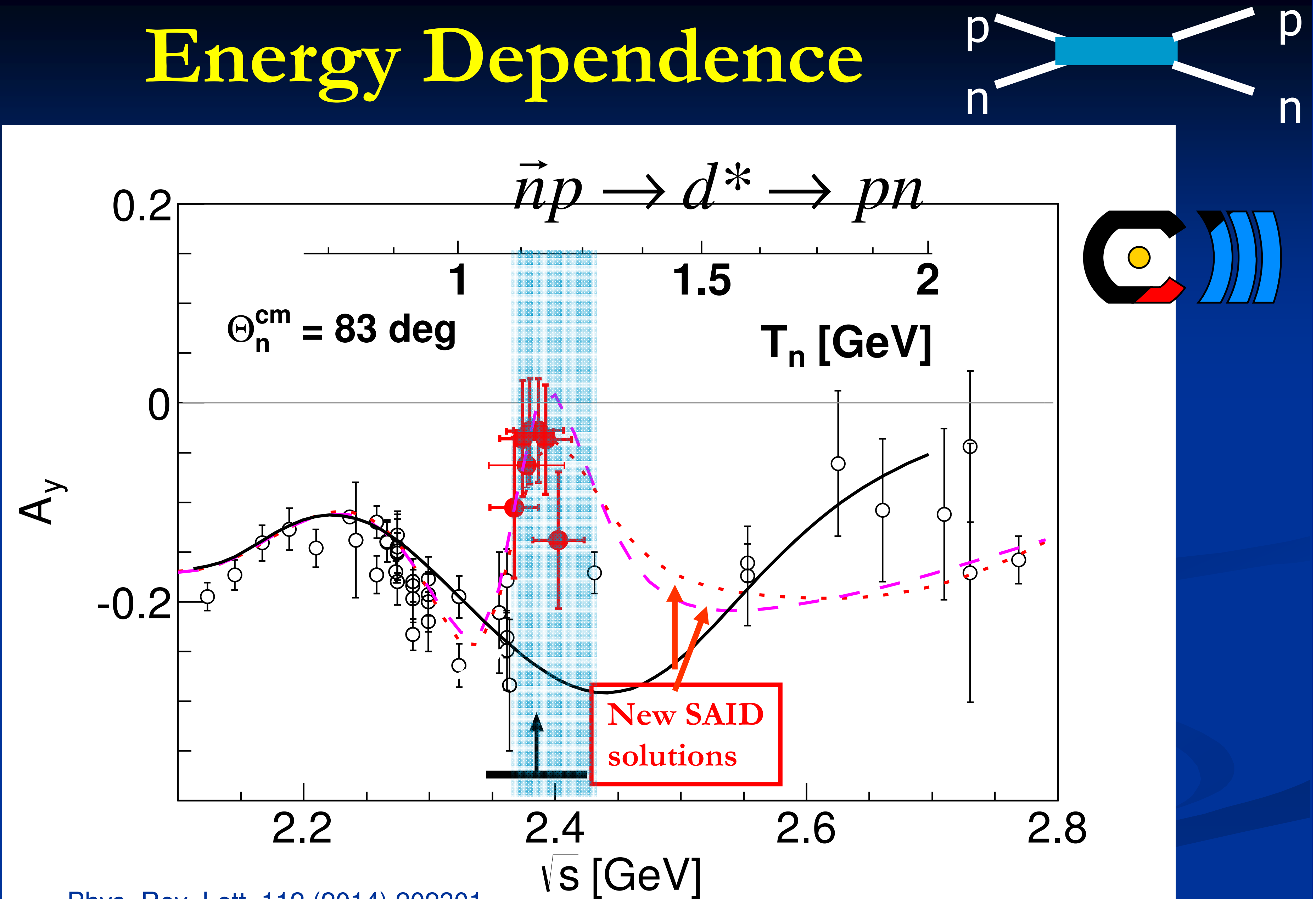
Phys. Rev. Lett. 112 (2014) 202301

Energy Dependence





Energy Dependence

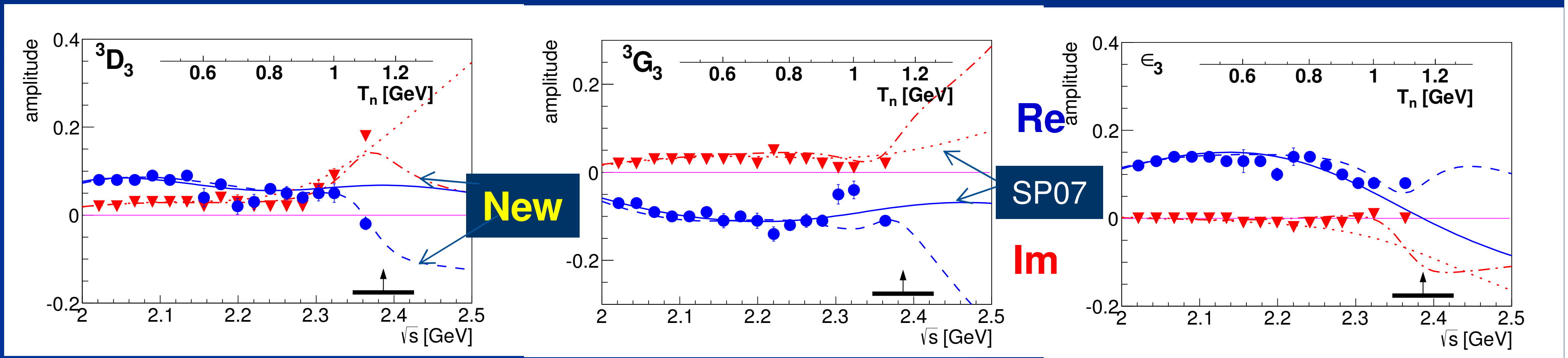


Phys. Rev. Lett. 112 (2014) 202301

SAID Partial-Wave Analysis

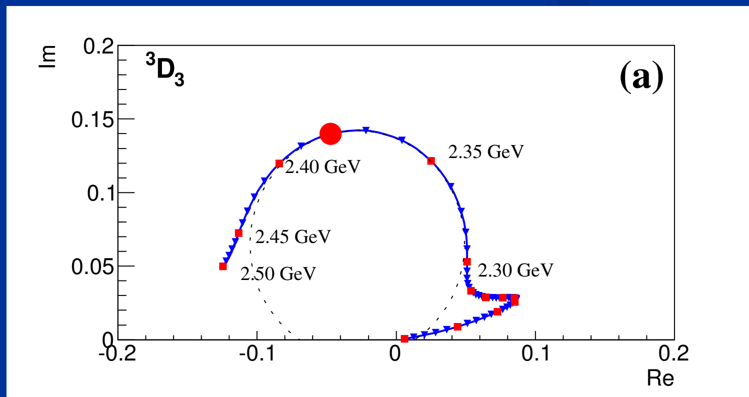
$^3D_3 - {}^3G_3$ Coupled Partial Waves

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

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

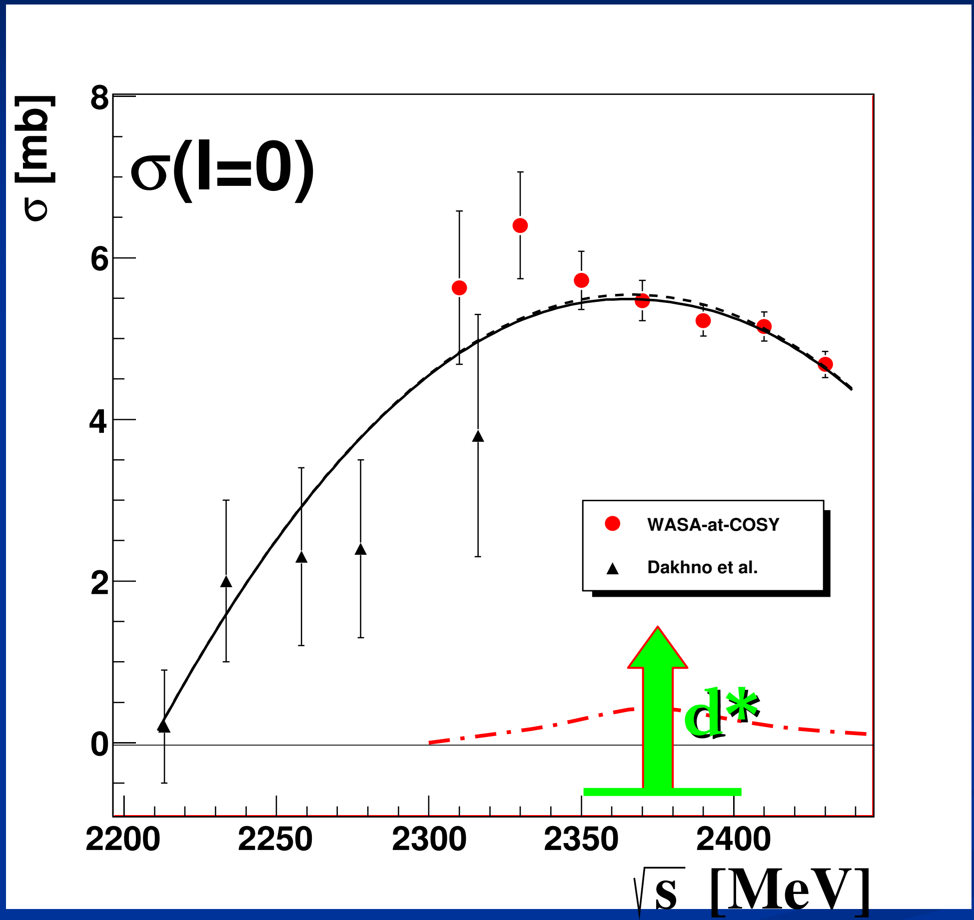
- hadronic decays

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

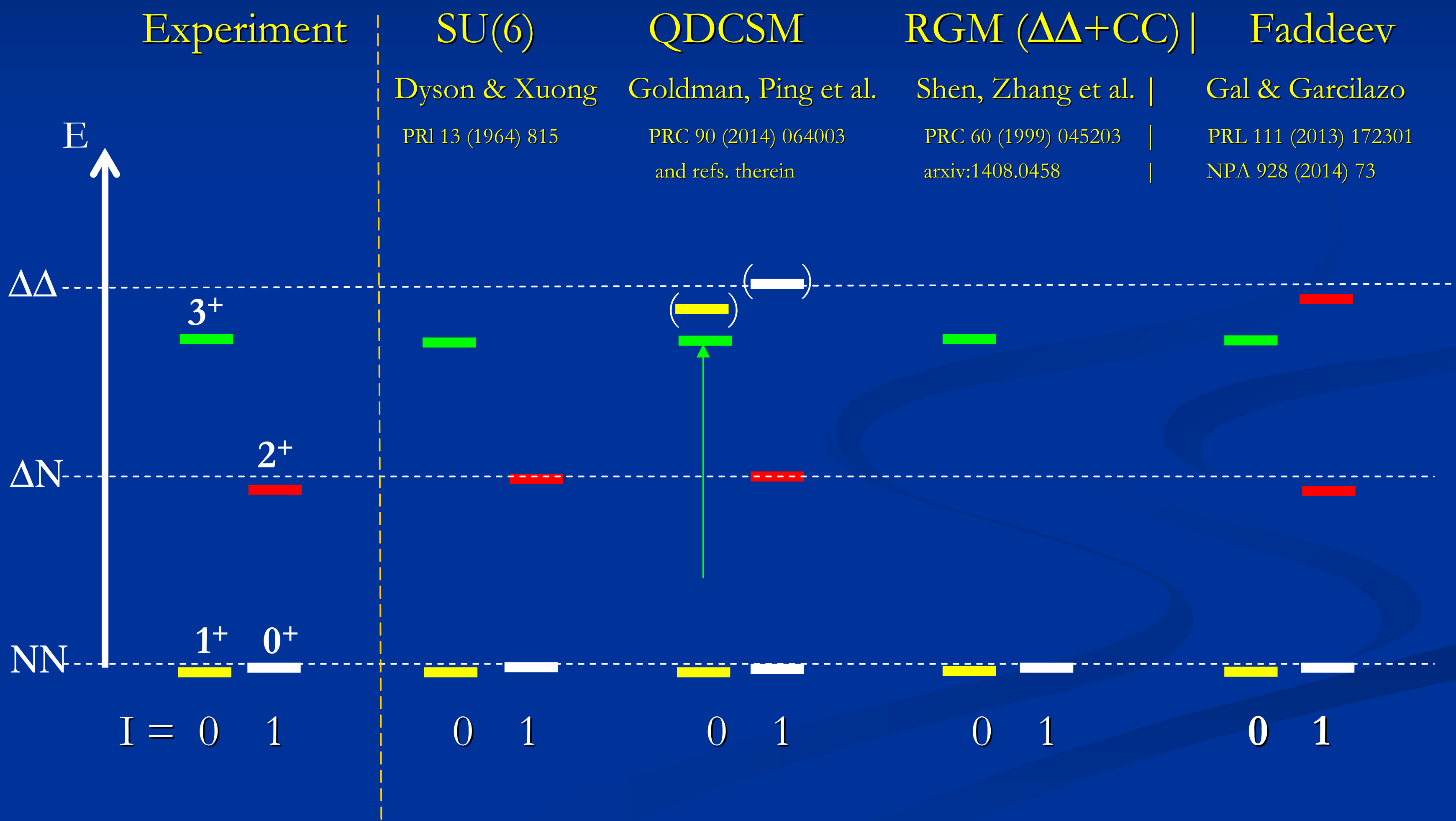
consistent with isospin coupling for a ΔΔ inter-mediate system

Isoscalar Single-Pion Production



arxiv: 1702.07212

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) 69 MeV PRC 91 (2015) 064002

Molecule vs Hexaquark

27

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 0.8 fm
- Faddeev hadr. G&G 1.5 – 2 fm

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

PLB 769 (2017) 436

Rèsumè

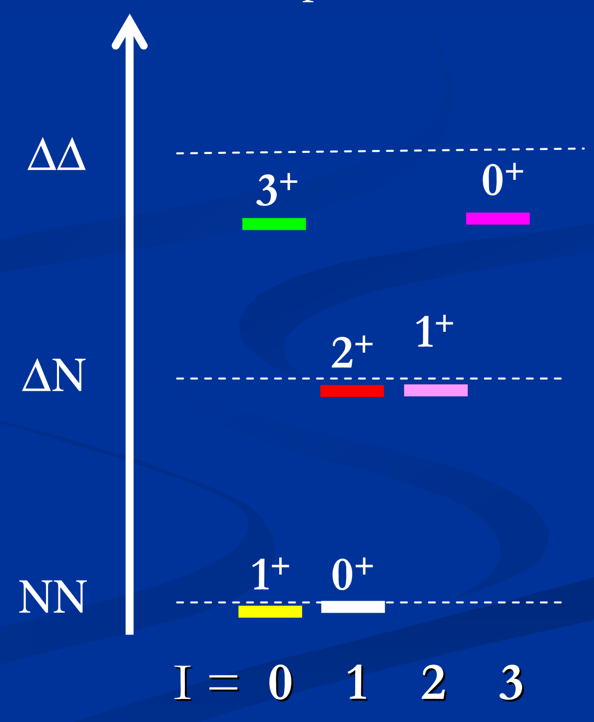
- Non-Strange Two-Baryon Spectrum
  - 3 established states: $^3S_1$ deuteron groundstate
    $^1S_0$ virtual state
    $^1D_2$ resonance (ΔN)
  - 1 new - presumably exotic - state:
    $d^*(2380)$ resonance (ΔΔ)
  - Are there more states?
    - NN-decoupled states with I = 2, 3?
    - Search in pp →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

Zhang, Chen, Shen et al.

Huang, Ping, Wang et al.

Gal & Garcilazo

Dyson's prediction



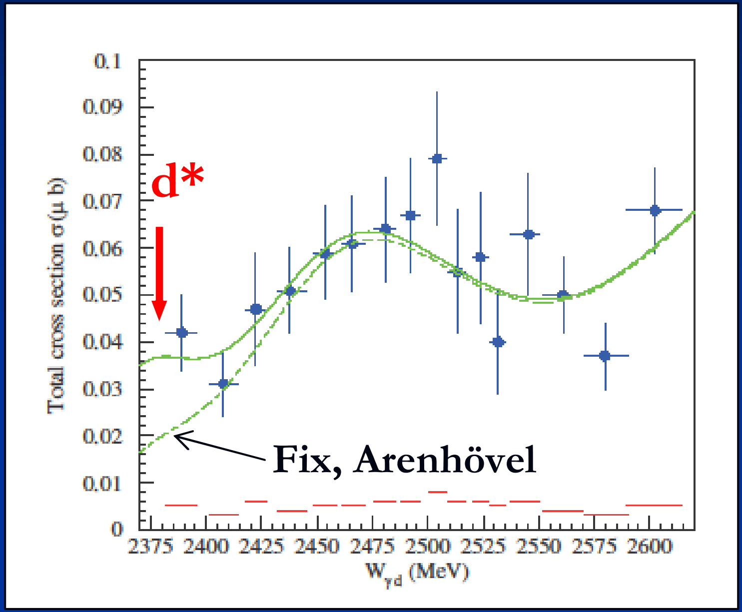
Summary

- d^*(2380) established as a genuine s-channel resonance
- It is the first unambiguously detected non-trivial dibaryon state.
- It could be a compact hexaquark state – but this needs experimental verification.

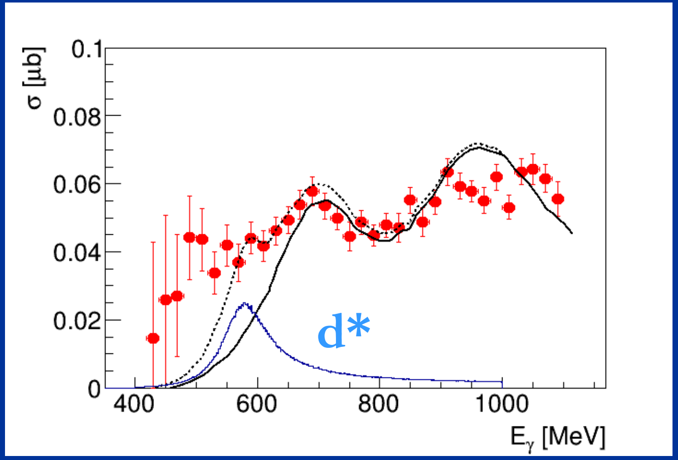
Outlook and Open Problems

- 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 ?? $e^+e^- \rightarrow d\, d^*$ at 4.3 – 4.6 GeV ??
  - KEK, JPARC, LHCb, others ???
- Are there more (exotic) dibaryons?
  - Mirror state of d^* …, strange, charmed dibaryons

γ d $\rightarrow$ d$\pi^0\pi^0$



FOREST@ELPH,
Ishikawa et al., PLB in press
arXiv: 1610.05532 [nucl-ex]



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

Outlook and Open Problems

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