Kepler Center for Astro and Particle Physics

Eberhard Karls Universität Tübingen

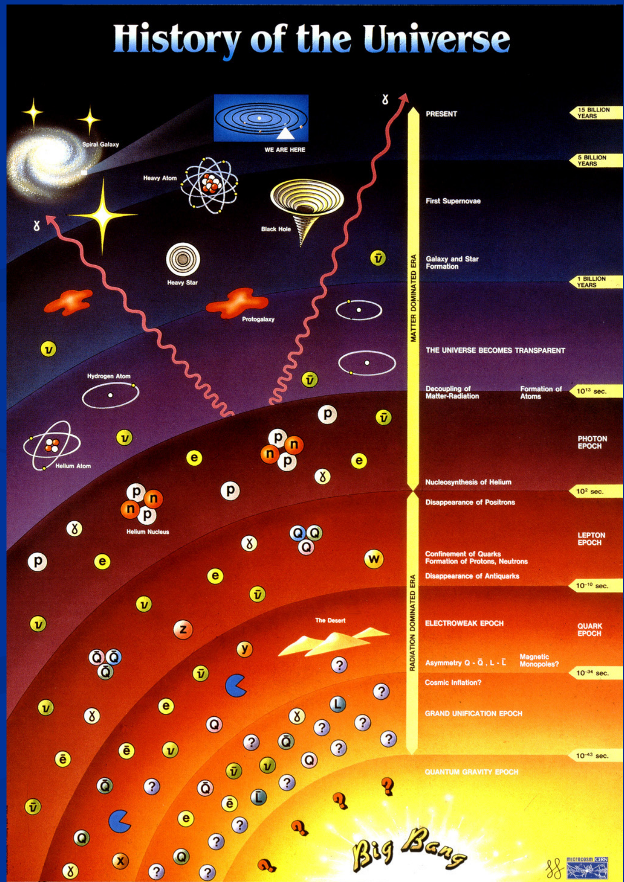
Hadrons

in the Universe and in the Lab

Kepler Colloquium 2008

Heinz Clement

- Primer on Hadrons
- Hadrons in the Universe
  - Early Universe
  - Matured Universe
- Hadrons in the Lab
  - Basic quantities
  - Equation of State - Exotics



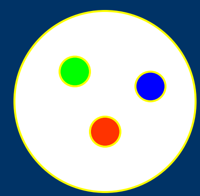
Hadrons

- „colorless“ particles composed of

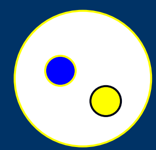
  Quarks (q) and Gluons (g)
- Quarks and Gluons
  - carry Strong Charge: „**Color**“ R, B, G (QCD)
  - are **confined** within interaction range (< 1 fm)

  ⇒

  rearrange into „**colorless**“ objects:



- **Baryons** (qqq, qqq-gg, qqq-$\bar{q}$q, …)
- **Mesons** (q$\bar{q}$, gg, $\bar{q}$q-g, $\bar{q}$q-$\bar{q}$q, …)
- **Exotics** (Dibaryons, …) ???



Quark Family

- „Flavors“

$$\begin{pmatrix} u \\ d \end{pmatrix} \qquad \begin{pmatrix} c \\ s \end{pmatrix} \qquad \begin{pmatrix} t \\ b \end{pmatrix}$$

- „bare“ masses [GeV / c^2]

$$\approx 0.004 \qquad 1.2 \qquad 174$$

$$\approx 0.008 \qquad 0.1 \qquad 4$$

e.g. from $\eta \rightarrow \pi^+\pi^0\pi^-$

provided by „Higgs field“ (weak interaction)

Nucleon
Proton (uud) and Neutron (udd)

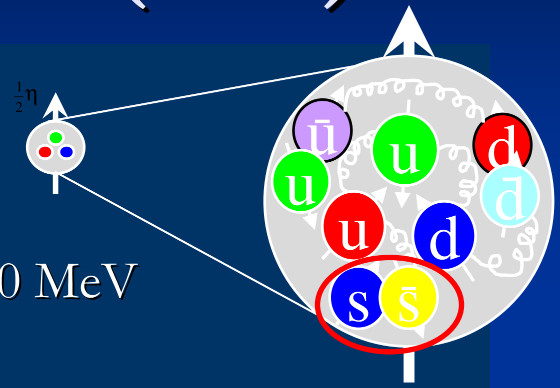
- **„bare“ mass** (without gluons)
  - naiv:
    - sum of bare valence quark (u,d) masses: 10 – 20 MeV
  - better:
    - pion-nucleon sigma term:

      $\sigma_0 = (m_u + m_d)/2 \, \Sigma_{q=u,d,s} \langle N|q\bar{q}|N\rangle/m_q = 36\ (7)\ \text{MeV}$

      from mass differences in baryon octet (see later)
  - still better:
    - Accounting for strange quark content y

      $\Sigma_{\pi N} = \sigma_0 \,/(1\text{-}y) = 64\ (8)\ \text{MeV}$

from πN scattering



Nucleon

- **„real" mass:**

$$m_p = 939 \text{ MeV}$$

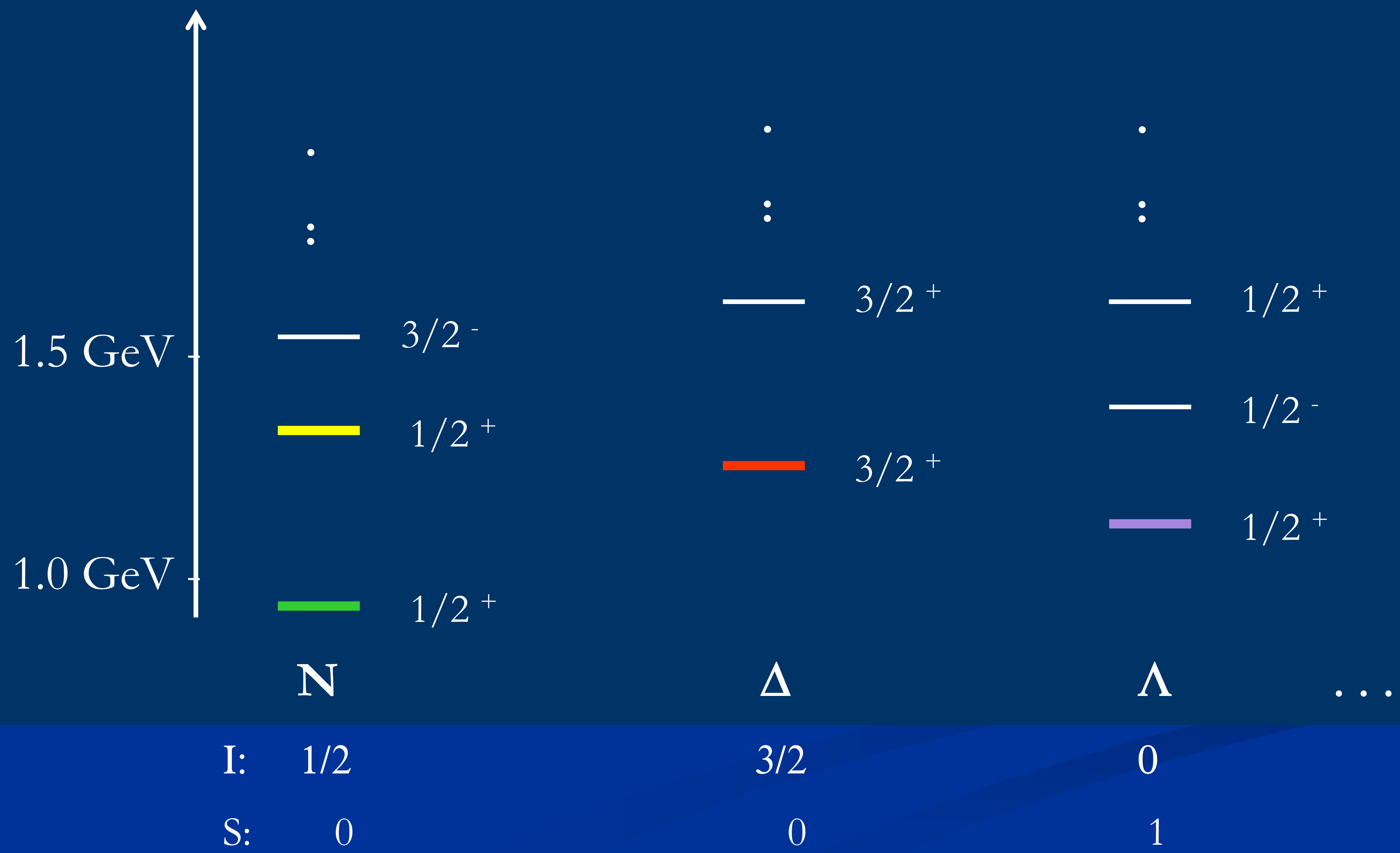
⇒ *most of nucleon's mass made by glue (gluon self interaction) !*

⇒ „dressed or constituent" quarks or

⇒ σ field *(analog to the Higgs field in weak interaction)*

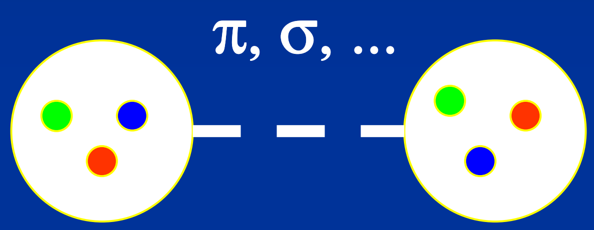
⇒ **σ meson** *(chiral partner of pion, gives binding to nuclei)*

Excitations of the Nucleon

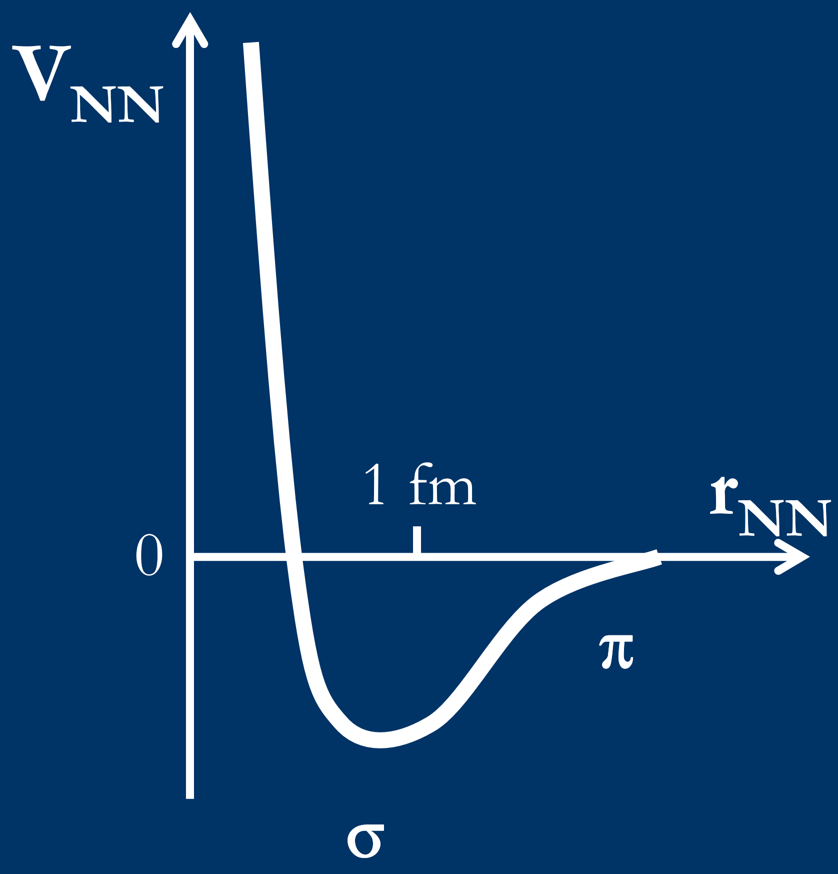


Nucleon – Nucleon Interaction
(Nuclear Force)

- mediated by mesons:



- Boundstates:
  - d, ΛΛ,… ???
- Quasibound states, Resonances ???
  ΔΔ



Hadrons in the Universe

- Early Universe
  - Baryogenesis:
    - Quark-Gluon Plasma → Hadrons

      (LEP, RHIC, LHC, FAIR/GSI)
  - Nucleosynthesis:
    - Formation of light nuclei d, ^{3}H, ^{3}He, ^{4}He, ^{6}Li, ^{7}Li

$$\Leftrightarrow$$

pion-nucleon coupling constant $\mathbf{g_{\pi NN}}$ ✓

Hadrons in the Universe

- Late Universe
  - Star Burning
    - Nuclear reaction cross sections ✓
    - Nuclear structure ✓
  - Burn-out phase (compactification):
    - Equation of state for nuclear matter

      $\Rightarrow$ Herbert Müther, Kepler Colloquium, Nov. 7
      - **What happens at high densities ???**

Hadrons in the Universe

- today's Universe
  - Cosmics
    - GZK cutoff at highest energies

      due to pion production with CBR photons:

$$p + \gamma_{CBR} \rightarrow \Delta \rightarrow p + \pi \quad \checkmark$$

i.e., protons get decelerated

Hadrons in the Universe

- today's Universe
  - Direct Dark Matter Detection:
    - WIMP scattering on nuclei:

$\Leftrightarrow$ *measurement of nuclear recoil*

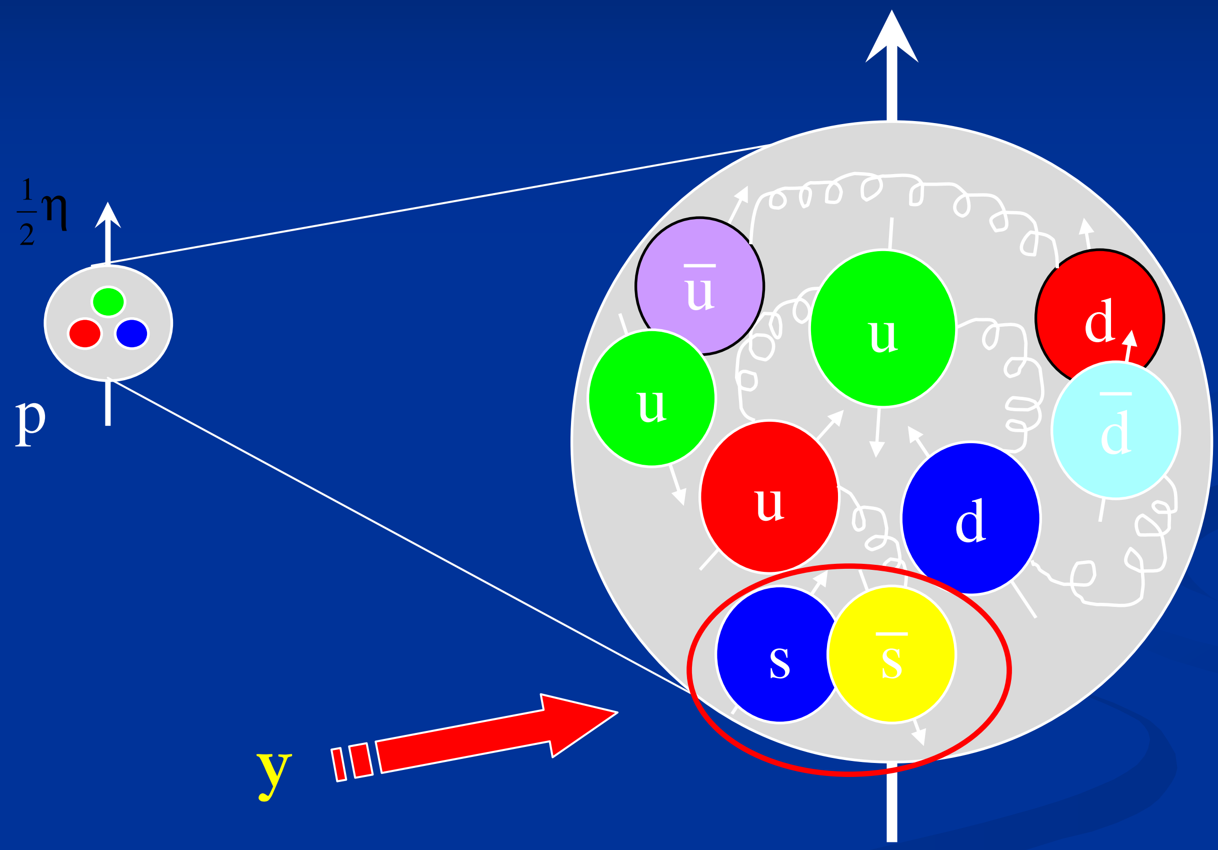
ss content of nucleon

WIMP-nucleus cross section:

$$\sigma_{WIMP} \sim \Sigma_{\pi N}^2 \; |\, const. \; + \; y \, m_s/m_d \,|^2$$

uncertain to 2 orders of magnitude due to $\Sigma_{\pi N}$!!!

Strangeness in the nucleon ?



PHYSICAL REVIEW D **77,** 065026 (2008)

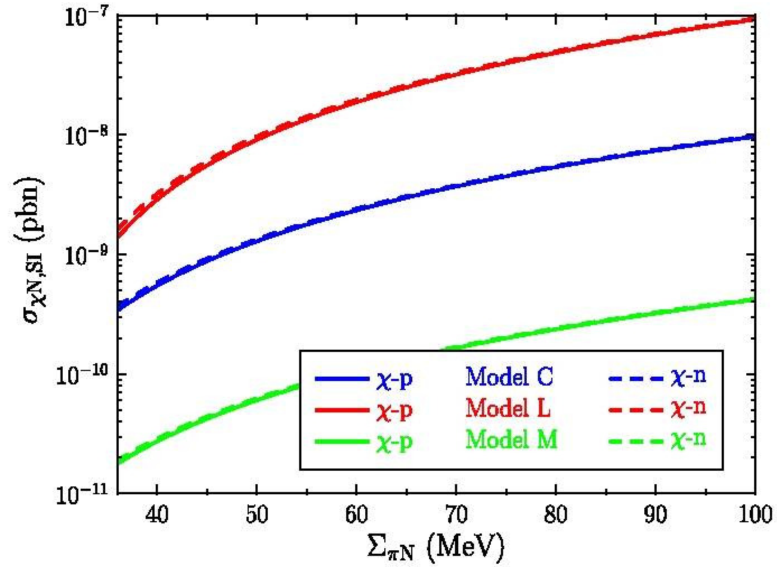
Hadronic uncertainties in the elastic scattering of supersymmetric dark matter

John Ellis,[1,*] Keith A. Olive,[2,†] and Christopher Savage[2,‡]
[1]*TH Division, Physics Department, CERN, 1211 Geneva 23, Switzerland*
[2]*William I. Fine Theoretical Physics Institute, School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota 55455, USA*
(Received 28 January 2008; published 27 March 2008)

We review the uncertainties in the spin-independent and spin-dependent elastic scattering cross sections of supersymmetric dark matter particles on protons and neutrons. We propagate the uncertainties in quark masses and hadronic matrix elements that are related to the π-nucleon σ term and the spin content of the nucleon. By far the largest single uncertainty is that in spin-independent scattering induced by our ignorance of the $\langle N|\bar{q}q|N\rangle$ matrix elements linked to the π-nucleon σ term, which affects the ratio of cross sections on proton and neutron targets as well as their absolute values. This uncertainty is already impacting the interpretations of experimental searches for cold dark matter. *We plead for an experimental campaign to determine better the π-nucleon σ term.* Uncertainties in the spin content of the proton affect significantly, but less strongly, the calculation of rates used in indirect searches.

DOI: 10.1103/PhysRevD.77.065026 PACS numbers: 1

$s\bar{s}$ content of nucleon



y = 0 1/2 2/3

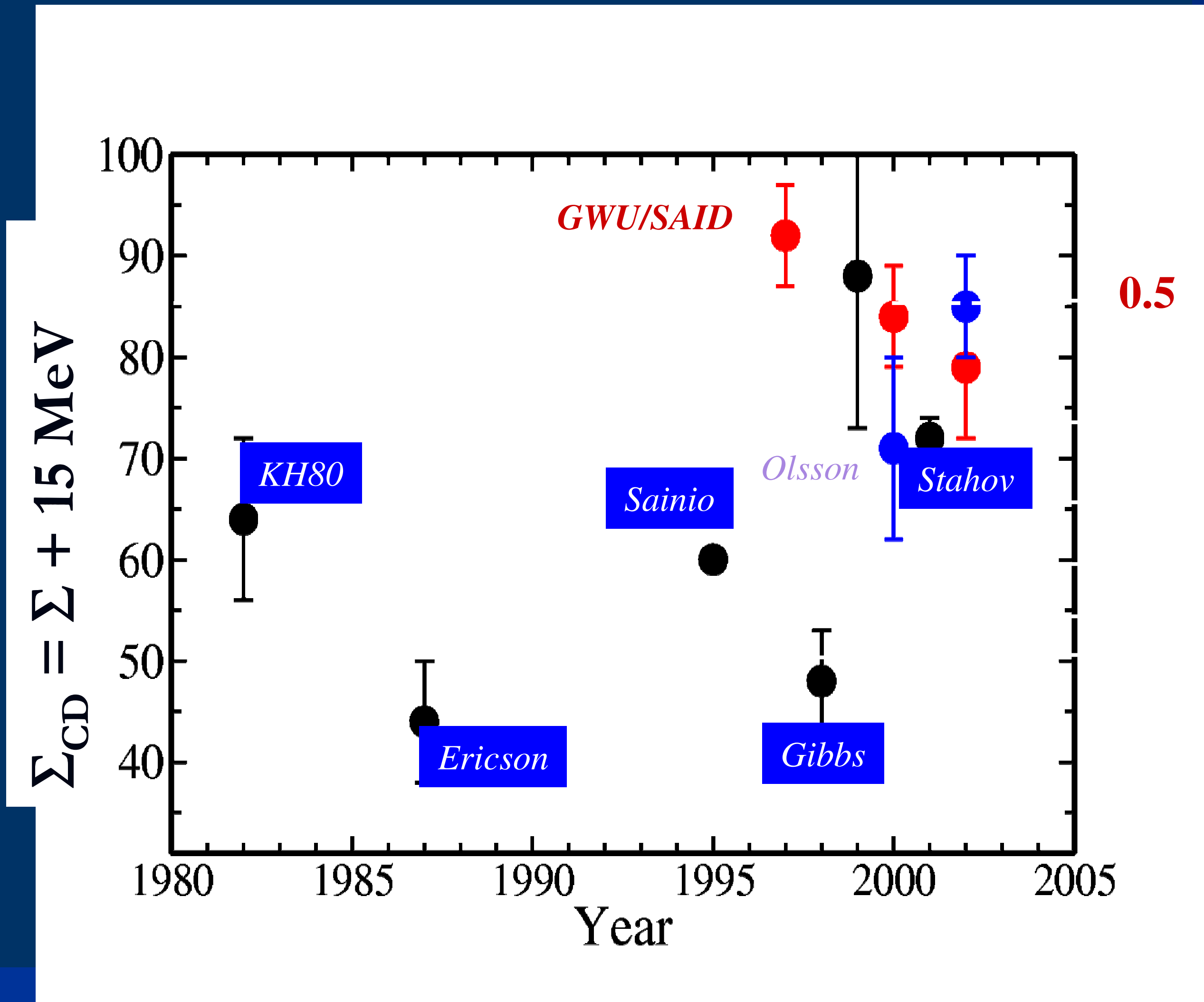
mark models C, L, and M. Note that $\sigma_{\chi p,SI}$ and $\sigma_{\chi n,SI}$ are nearly indistinguishable at the scale used in this plot.

Our πp results tend to prefer small y

Hadrons in the Lab

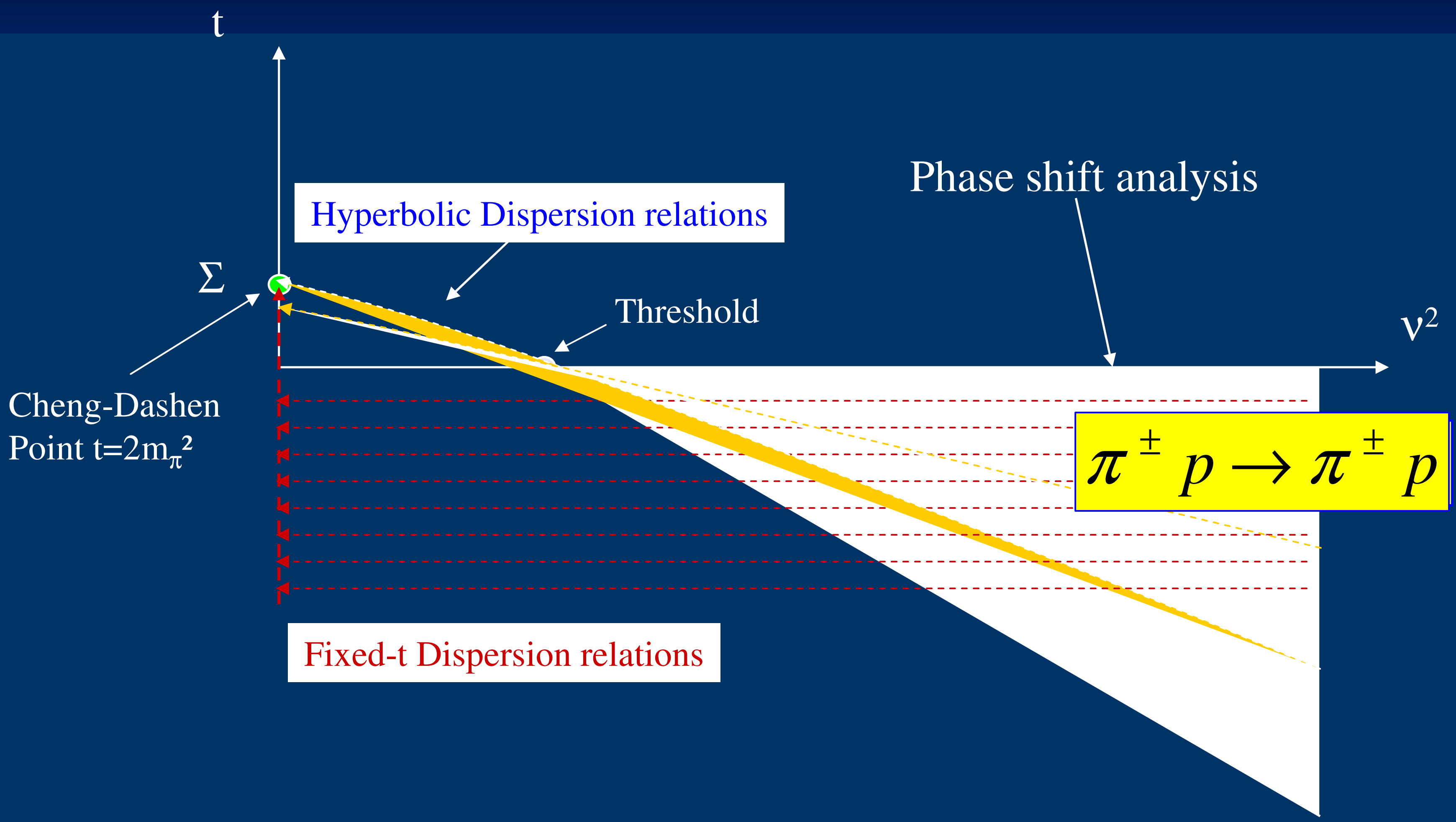
- Pion-Nucleon sigma term:

What do we know?



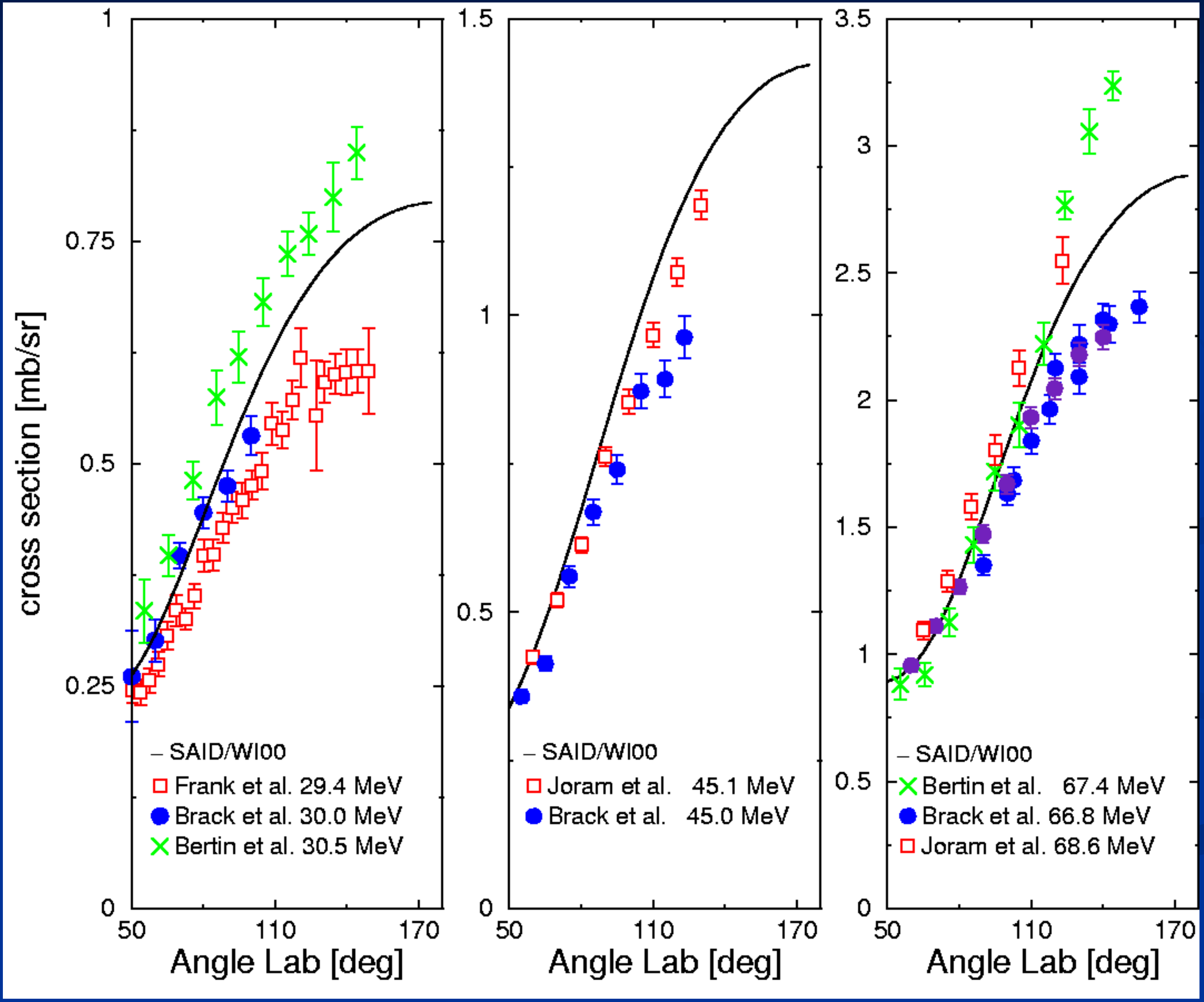
principal problem: Isospin breaking

Extraction of the sigma-term: extrapolation into unphysical region



➢ High sensitivity to data at and close to threshold !

Inconsistencies at energies < 100 MeV



πp Scattering at Low Energies

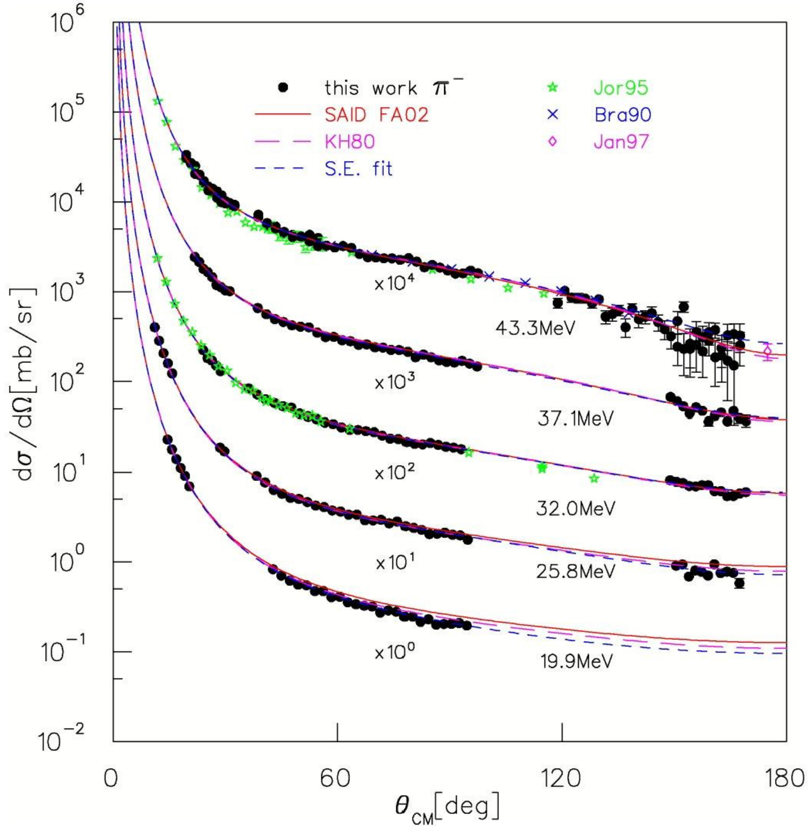


Fig. 2. Results of this experiment for $\pi^- p$ scattering together with phase shift solutions and results from other experiments at closeby energies. Bars denote statistical errors only. The absolute normalisation is uncertain by 5 to 9% (see text).

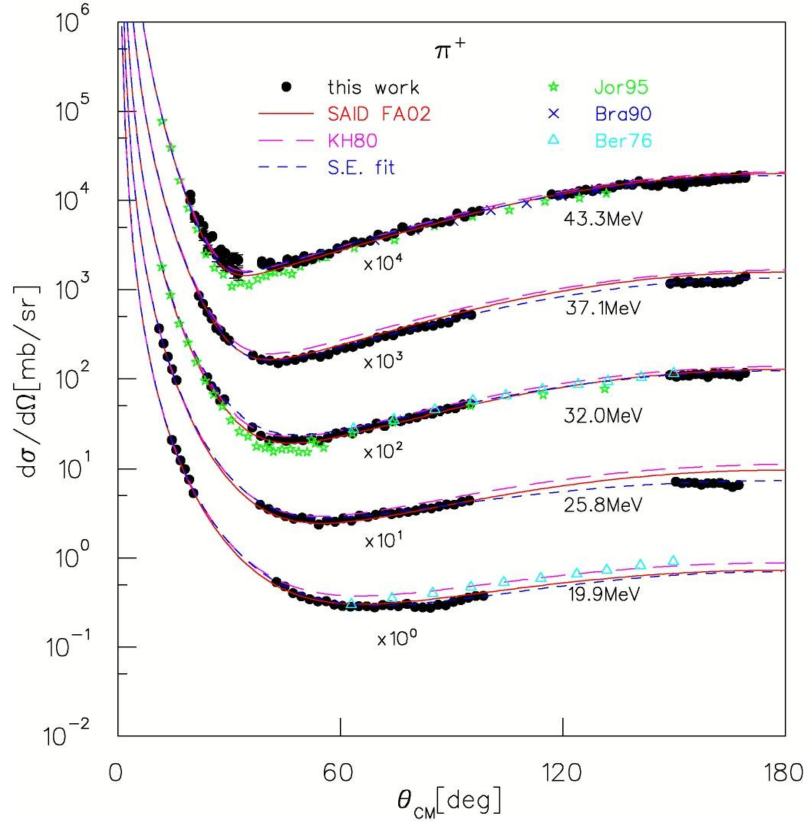


Fig. 3. As Fig. 2, but for $\pi^+ p$ scattering.

Denz et al. , Phys. Lett. B633, 209 (2006)

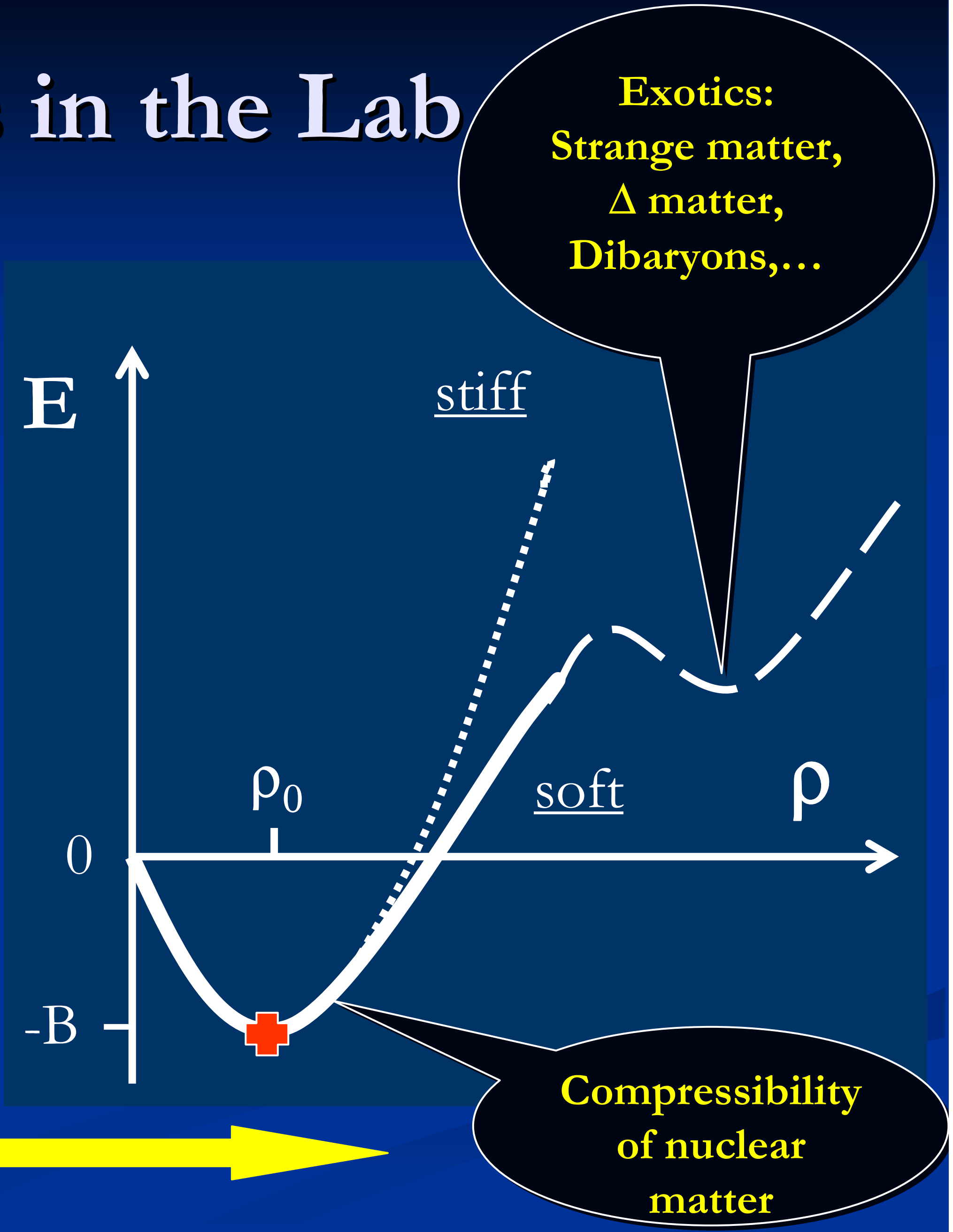
Hadrons in the Lab

- Equation of State for Nuclear Matter

Hadrons in the Lab

- Equation of State
  for Nuclear Matter:

  - Monopole excitation
    of nuclei:
    „Breathing Mode“



Hadrons in the Lab

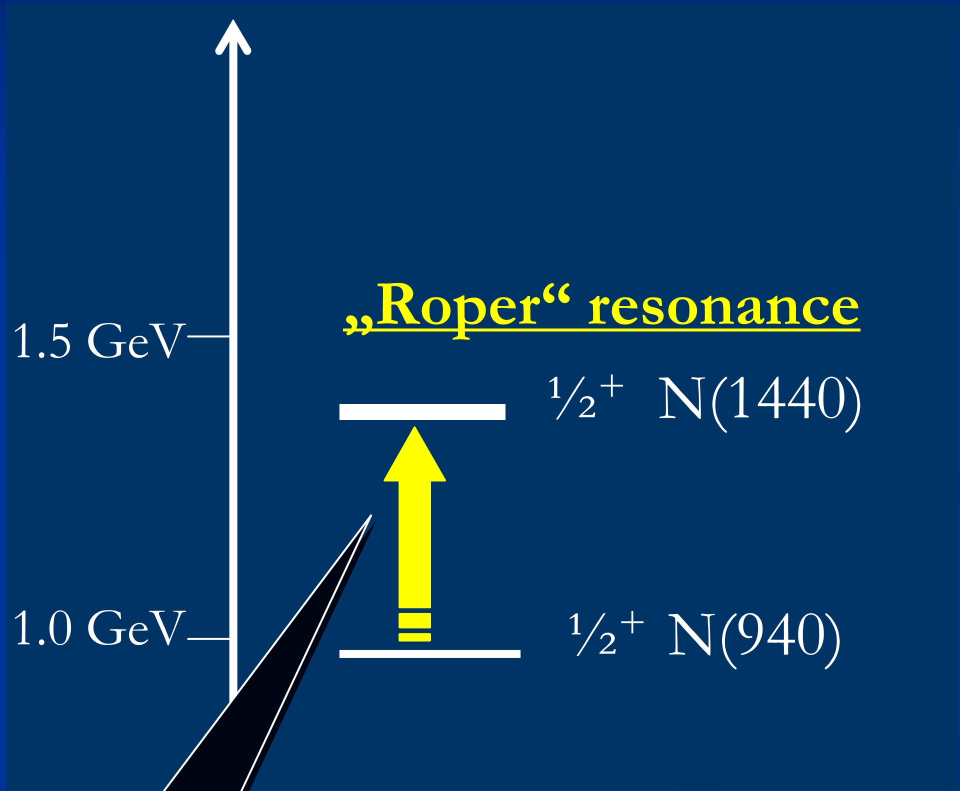
- Equation of State

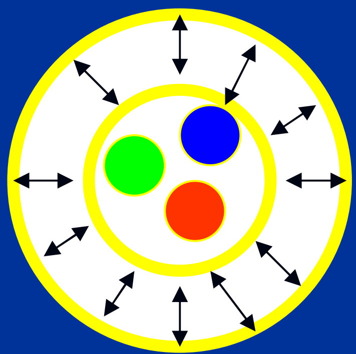
  Compressibility of the nucleon:

  - Monopole excitation

    of the nucleon:

    „Breathing Mode“



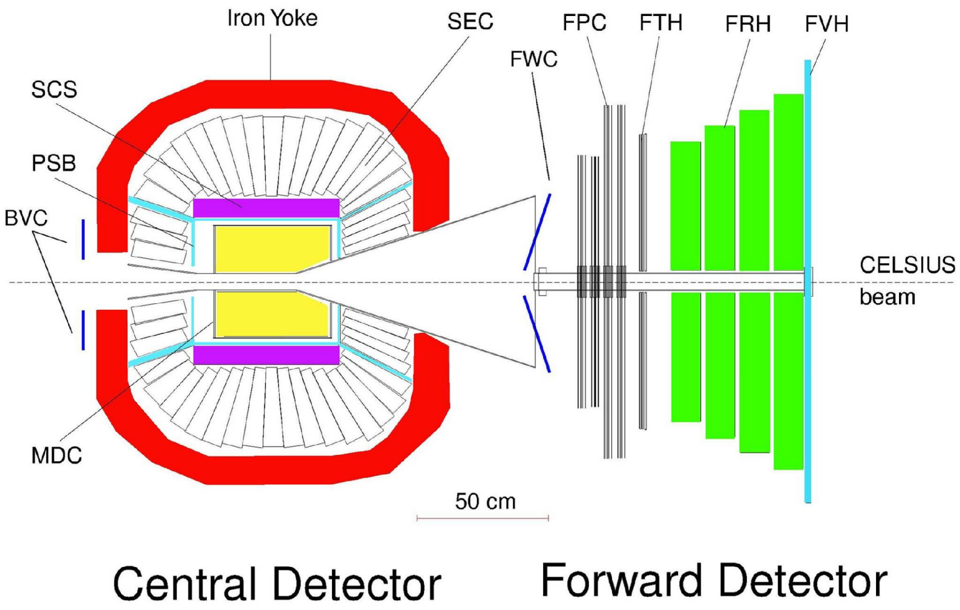


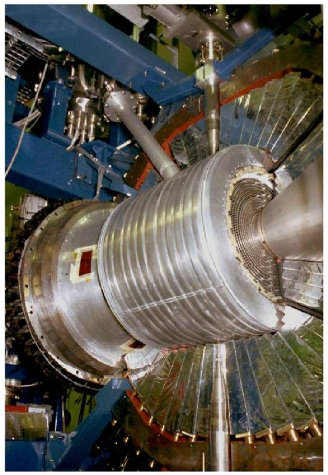
Compressibility of nucleon

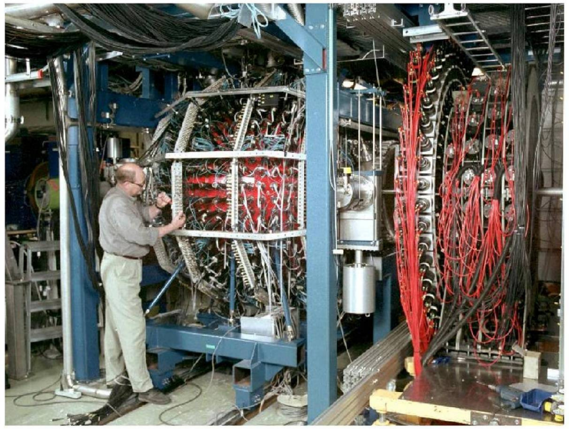
π and ππ Production @ CELSIUS and COSY

- **Δ** **N*(1440)**
- excitations in the **NN** system
- … and in Nuclei

WASA 4π Detector

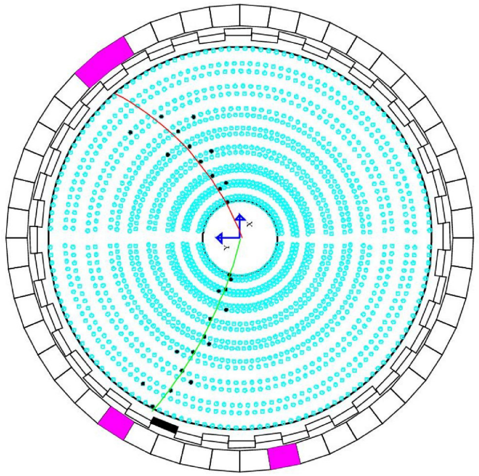






MDC event

$pp \to pp\pi^+\pi^-$



– reconstruction of all particles ⇒ overdetermin

– magnetic fiel

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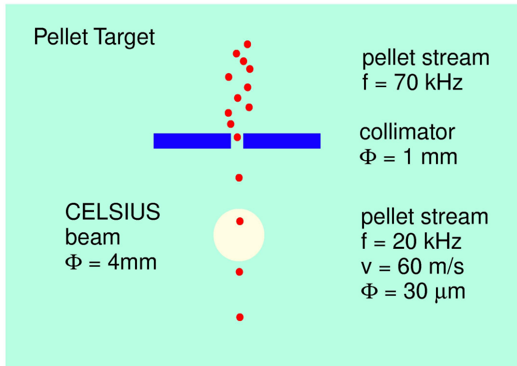
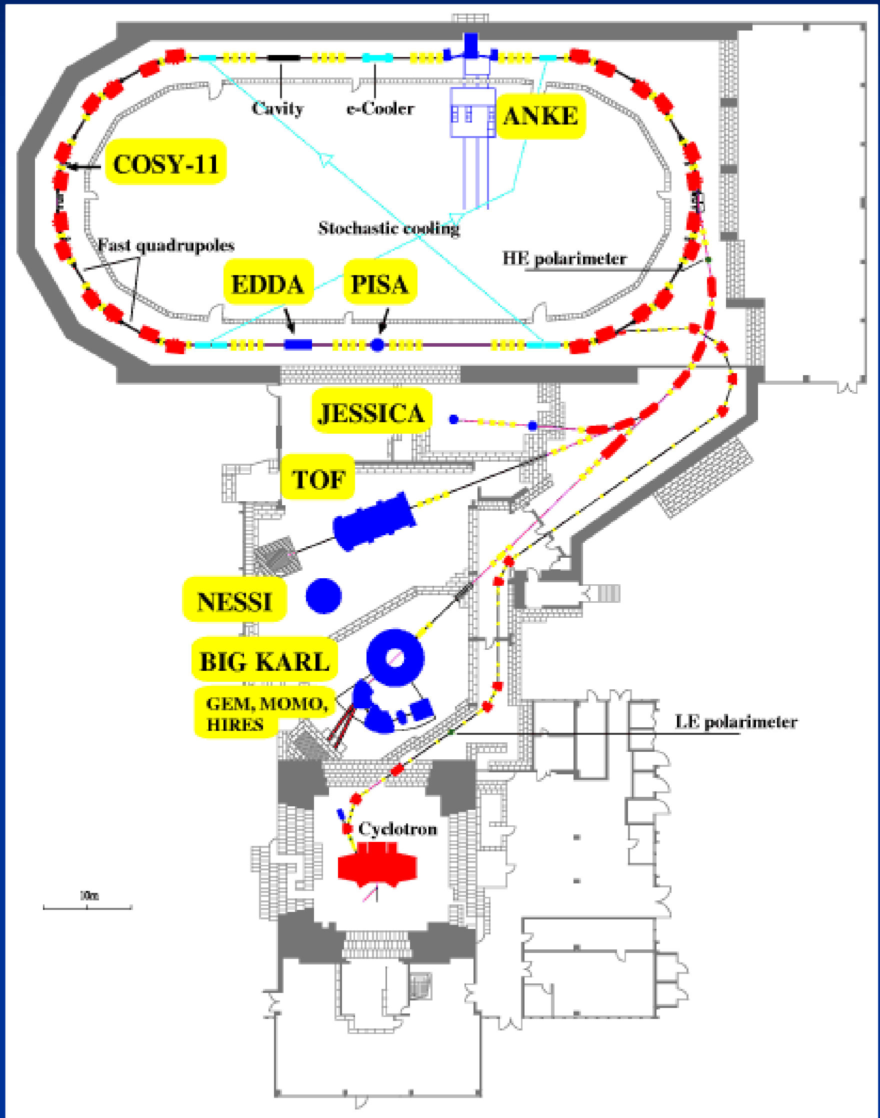
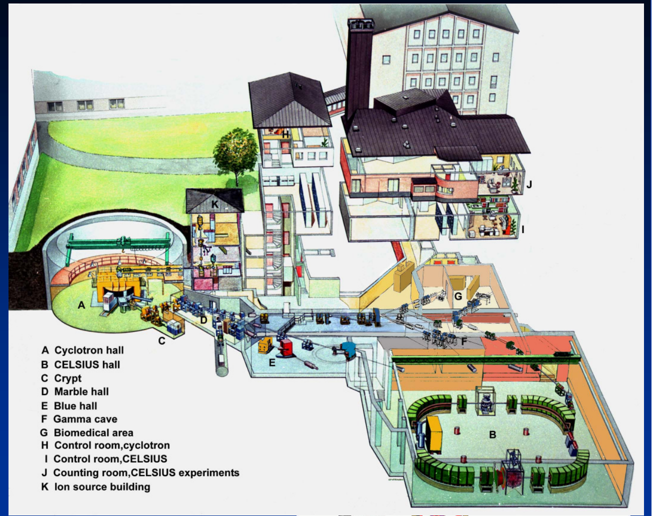
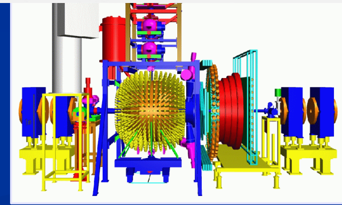
Pellet Target



WASA at COSY







2005 - 2006

CELSIUS-WASA

Dubna -Hamburg -Jülich -
Lodz - Moscow - Novosibirsk -
Stockholm - Tsukuba -
Tübingen - Uppsala - Warsaw

Roper Resonance
$N^*(1440)$

- πN and γN:
  - Roper´s resonance
  - a resonance without seeing it
- **New generation of measurements:**
  - the „narrow“ Roper

Roper´s πN Resonance

VOLUME 12, NUMBER 12 PHYSICAL REVIEW LETTERS 23 MARCH 1964

EVIDENCE FOR A P_{11} PION-NUCLEON RESONANCE AT 556 MeV†

L. David Roper
Lawrence Radiation Laboratory, University of California, Livermore, California
(Received 17 February 1964)

The purpose of this note is to report strong evidence for the existence of a resonance in the P_{11} state of the pion-nucleon system. Previous pion-nucleon resonances were discovered from observations on the qualitative behavior of experimental observables. The resonance suggested in this paper, however, is not associated with conspicuous features in the observables measured so far and has been inferred from a more quantitative analysis.

How to excite the Roper?

- $N \quad \rightarrow \quad N^{*}(1440)$

  $I(J^{P})$: $\quad \tfrac{1}{2}(\tfrac{1}{2})^{+} \rightarrow \tfrac{1}{2}(\tfrac{1}{2})^{+}$

  $\Rightarrow$

  - **scalar-isoscalar excitation: σ**

    or

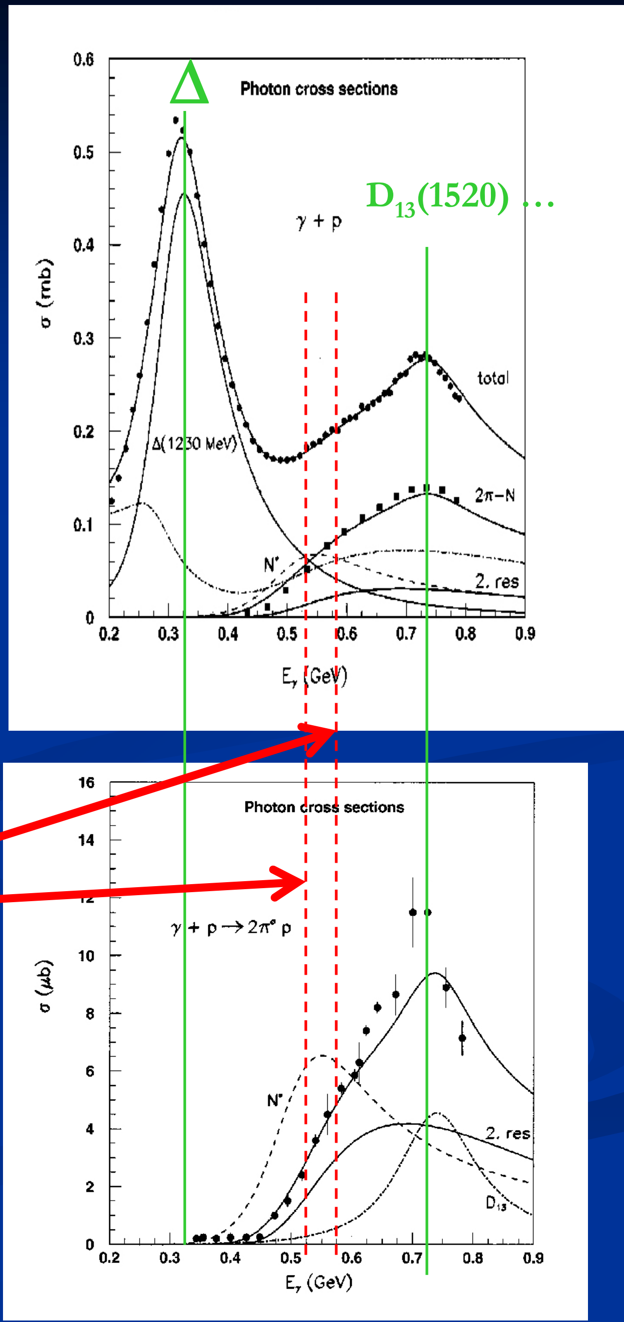
  - **isovector excitation: π, γ (M1), …**

    with spinflip preferred

Where to see?

- γN
  - photo absorption
  - $\gamma p \rightarrow p\, \pi^0\pi^0$

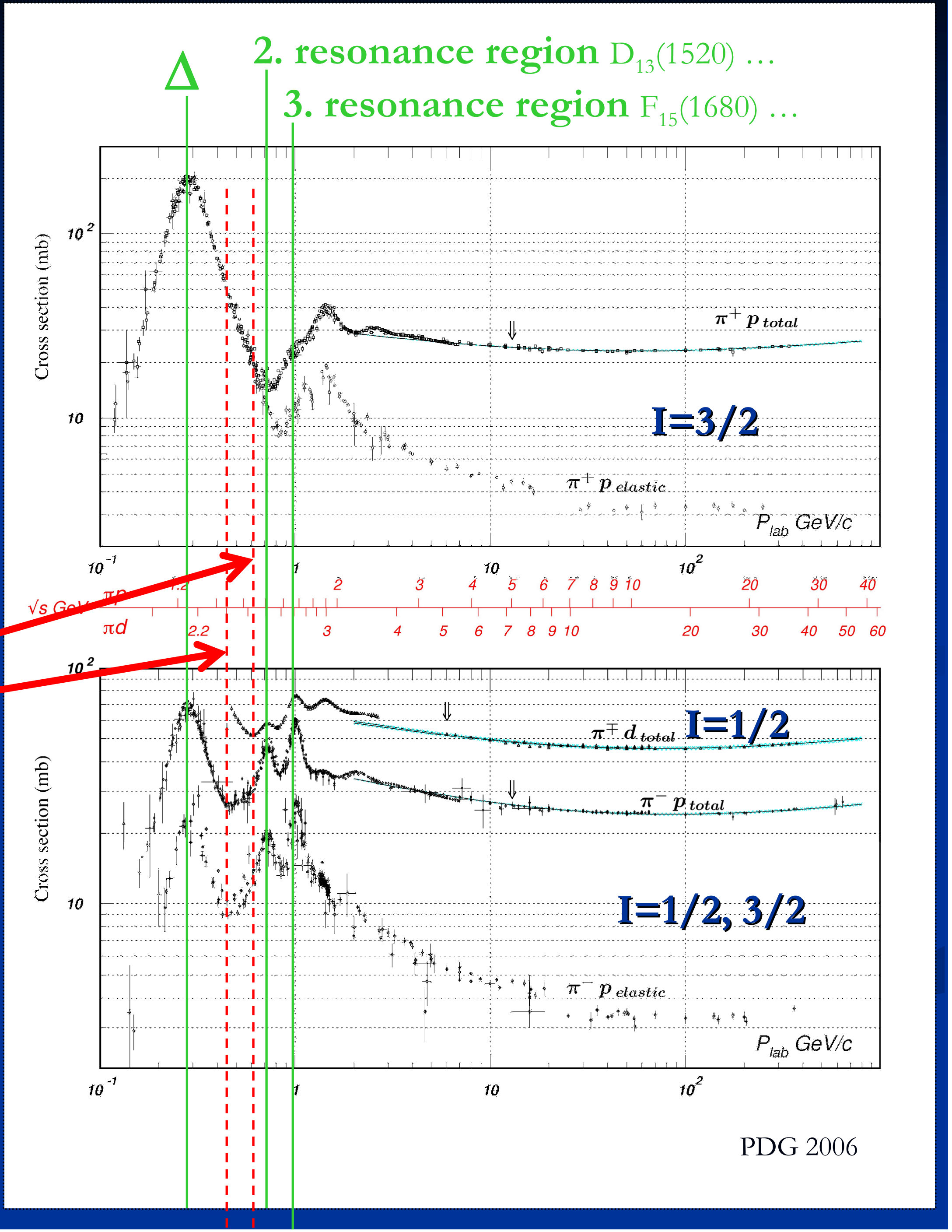
- Where is the Roper?



Morsch and Zupranski, PRC 61, 024002 (1999)

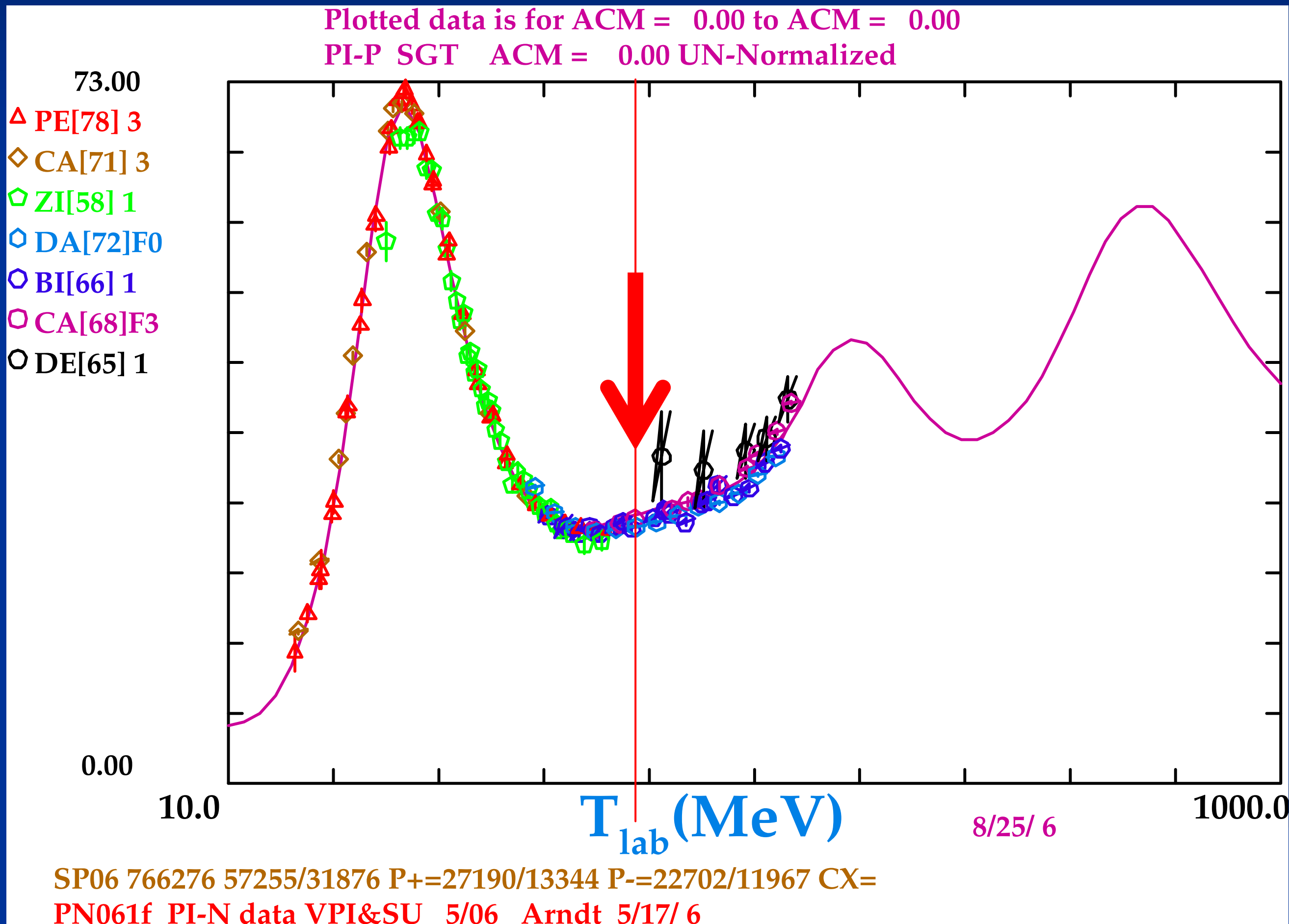
Where to see?

- πN scattering:
- Where is the Roper?



$\pi^- p$ total cross section

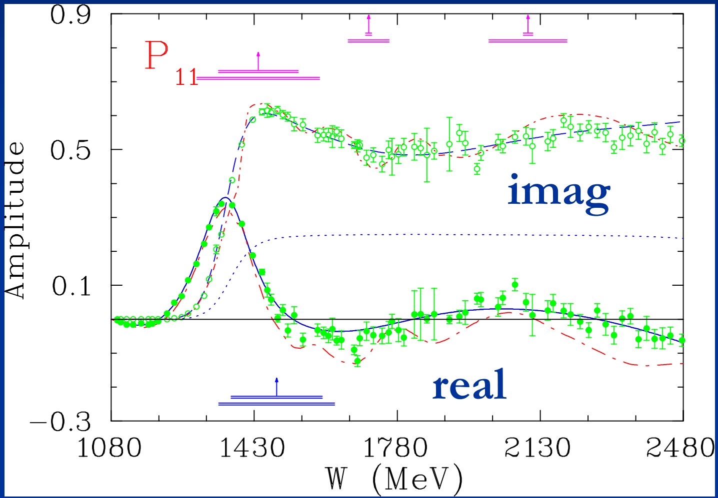
Where is the Roper?

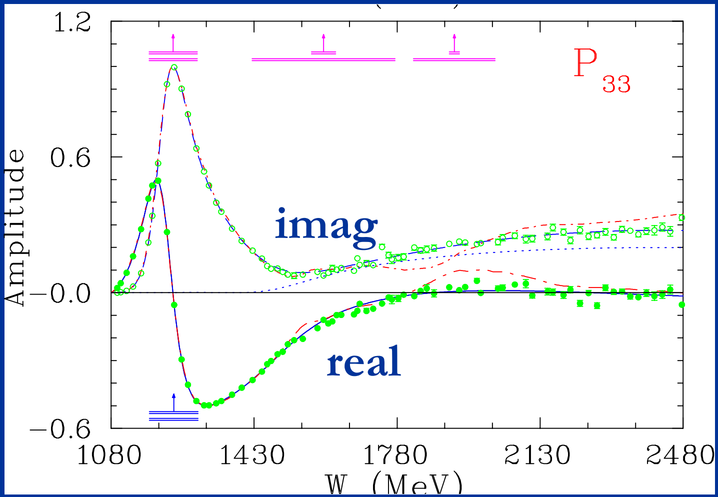


SAID data base

πN partial wave analysis

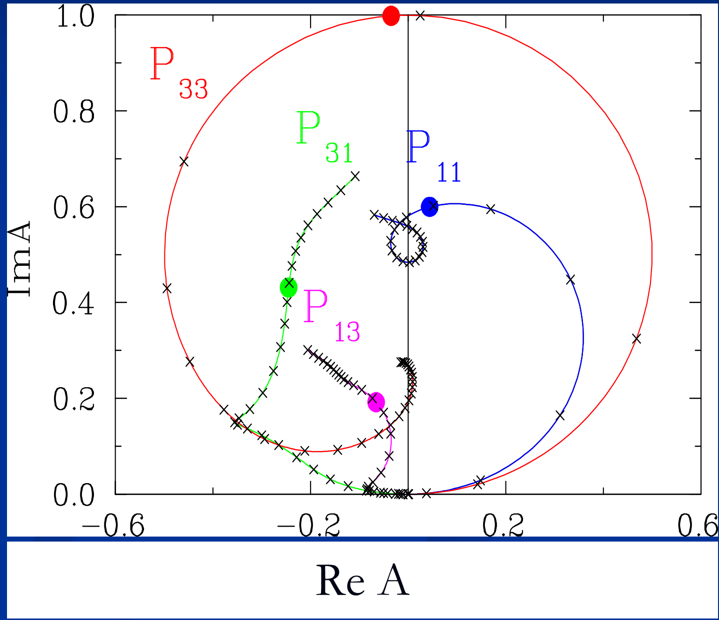
- Partial wave amplitudes





- Argand plot

SAID nucl-th/0605082



here is theRoper :

SAID: M_{pole} = 1357 MeV

Γ_{pole} = 160 MeV

Bonn *(Sarantsev et al.)*: **1371 (2)**

πN + γN **184 (20)**

What does the „Bible“ tell us today?

PDG 2006:

$N(1440)\ P_{11}$ $\quad I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

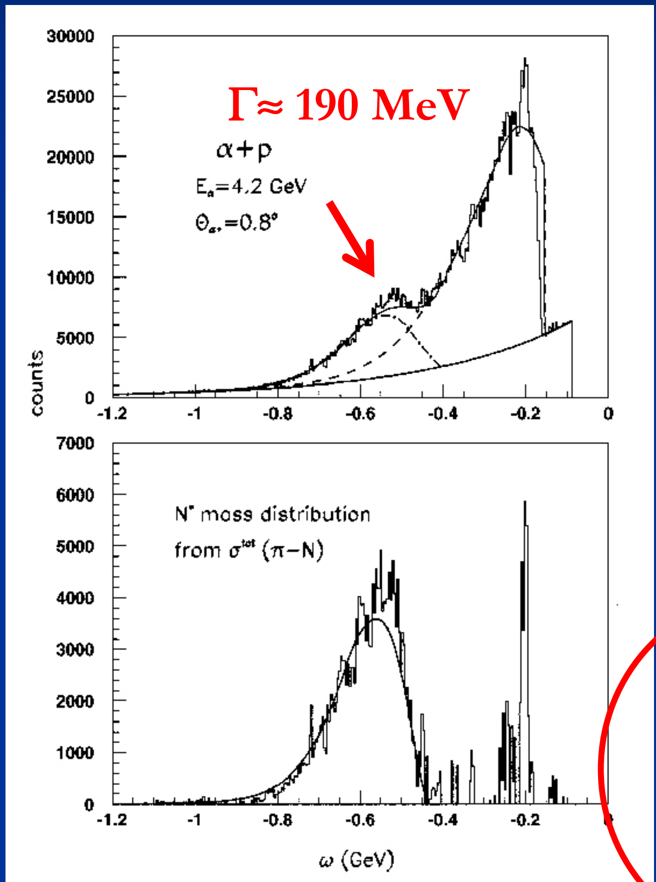
Breit-Wigner mass = 1420 to 1470 (≈ 1440) MeV
Breit-Wigner full width = 200 to 450 (≈ 300) MeV
$p_{beam} = 0.61$ GeV/c $\quad 4\pi\lambda\!\!\!^{-2} = 31.0$ mb
Re(pole position) = 1350 to 1380 (≈ 1365) MeV
−2Im(pole position) = 160 to 220 (≈ 190) MeV

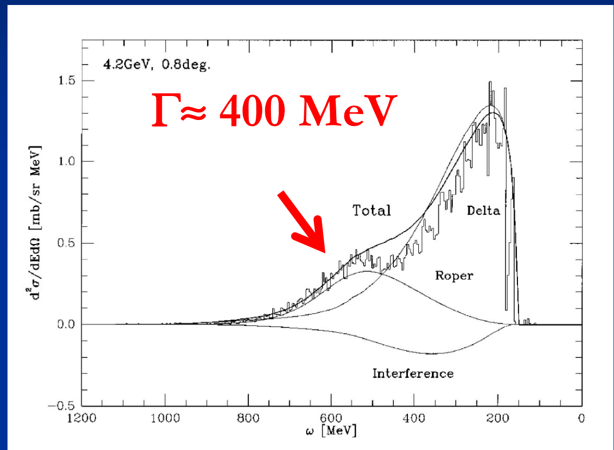
N(1440) DECAY MODES	Fraction (Γ_i/Γ)
$N\pi$	0.55 to 0.75
$N\pi\pi$	30–40 %
$\Delta\pi$	20–30 %
$N\rho$	<8 %
$N(\pi\pi)^{I=0}_{S\text{-wave}}$	5–10 %
$p\gamma$	0.035–0.048 %
$p\gamma$, helicity=1/2	0.035–0.048 %
$n\gamma$	0.009–0.032 %
$n\gamma$, helicity=1/2	0.009–0.032 %

New Generation of Experiments visualizing a „narrow“ Roper (?)

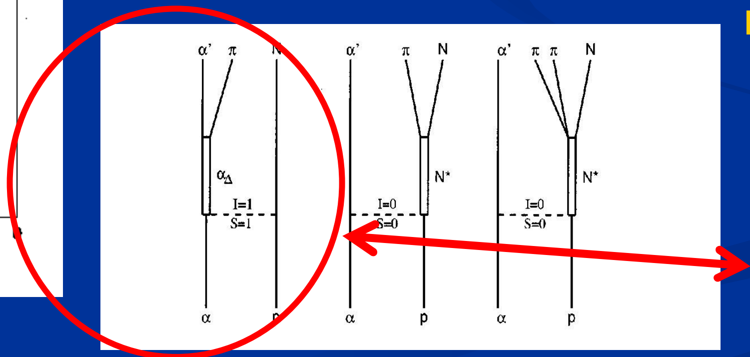
- $\alpha\, p \to \alpha\, X$ @ 4.2 GeV (Saturne)
- $J/\psi \to \bar{N}\, N^*$ and $N\, \bar{N}^*$ (BES)
- $pp \to np\pi^+$ @ 1.1 and 1.3 GeV (WASA)
  $pp \to pp\pi^0\pi^0$ @ 0.65 – 1.36 GeV

New Generation of Experiments:
1. $\alpha\, p \rightarrow \alpha\, X$ (Saclay)





Hirenzaki et al., PRC 53, 277 (1996)



- scalar-isoscalar probe α

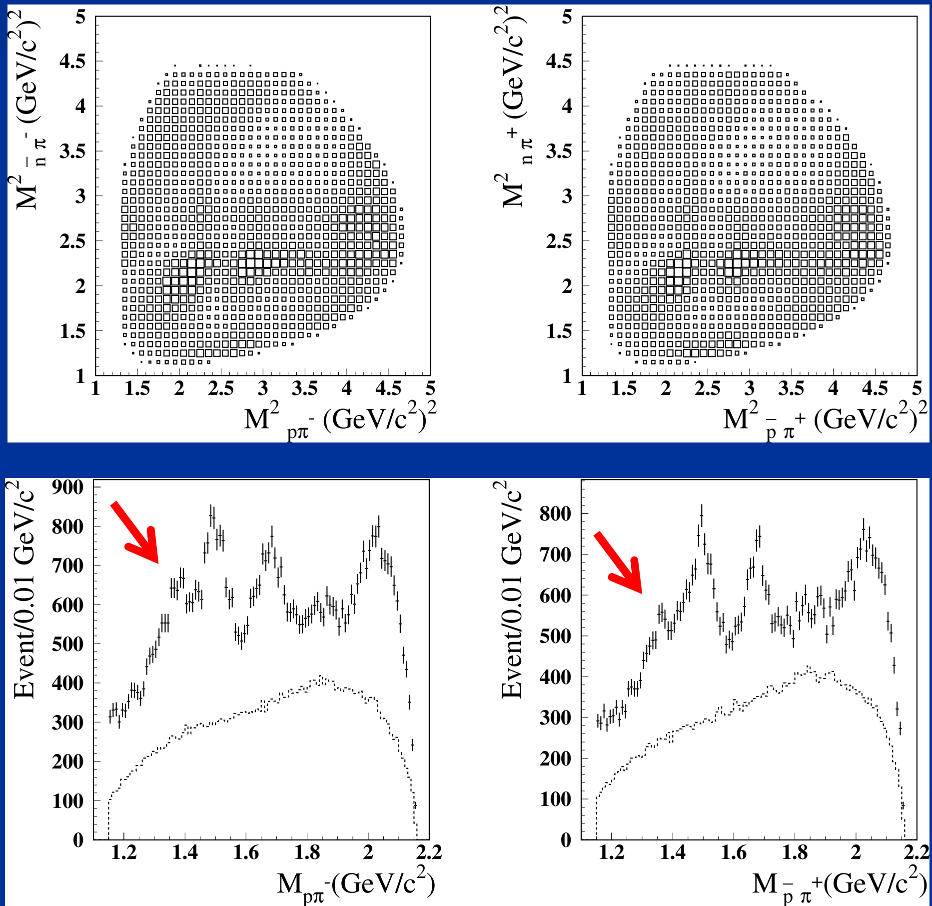
  however:

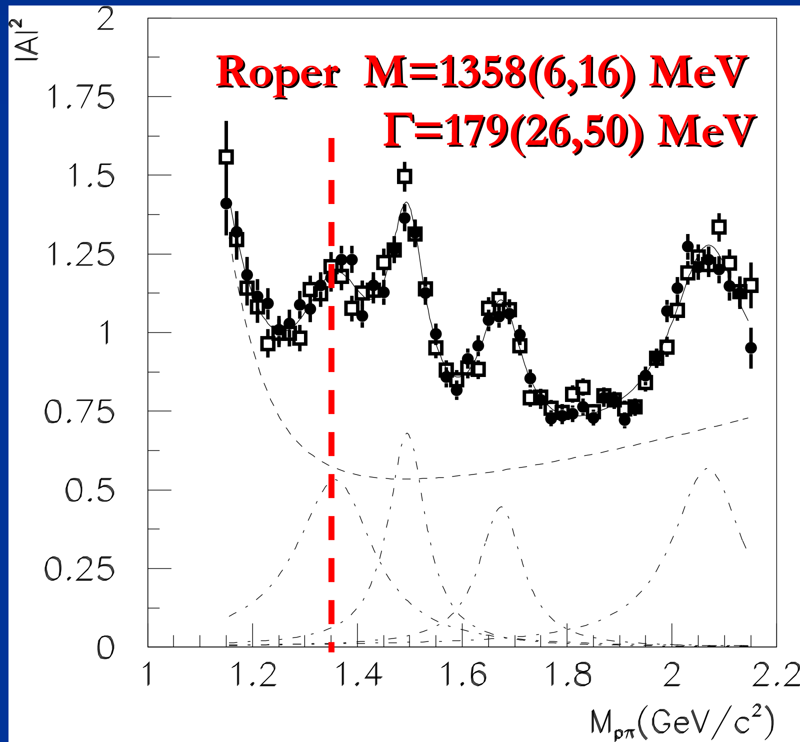
- interfering background from projectile excitation

Morsch et al., PRL 69, 1336 (1992) and PRC 61, 024002 (1999)

New Generation of Experiments:
2. $J/\psi \rightarrow \bar{N} N^*$ and $N \bar{N}^*$ (BES)

$\bar{n}\, p\pi^-$ and $\bar{p}\pi^+ n$ events $\Rightarrow$ I= 1/2 N^* excitations only





Ablikim et al., PRL **97** (2006) 062001
hep-ex/0405030

Decay of Roper

- decay channels: BR(1440) BR(1371)

	PDG 2006	Bonn 2007 *(Sarantsev et al.)*
$N^* \rightarrow N\pi$	0.55 – 0.75	0.61 (2)
$N^* \rightarrow N\pi\pi$	0.30 – 0.40	0.39 (5)
$\rightarrow \Delta\pi \rightarrow N\pi\pi$	0.20 – 0.30	0.18 (2)
$\rightarrow N\rho \rightarrow N(\pi\pi)_{I=L=1}$	< 0.08	
$\rightarrow N\sigma \rightarrow N(\pi\pi)_{I=L=0}$	0.05 – 0.10	0.21 (3)
$N^* \rightarrow \Delta\pi$ / $N^* \rightarrow N\sigma$:	**2 – 6**	**0.9 (2)**

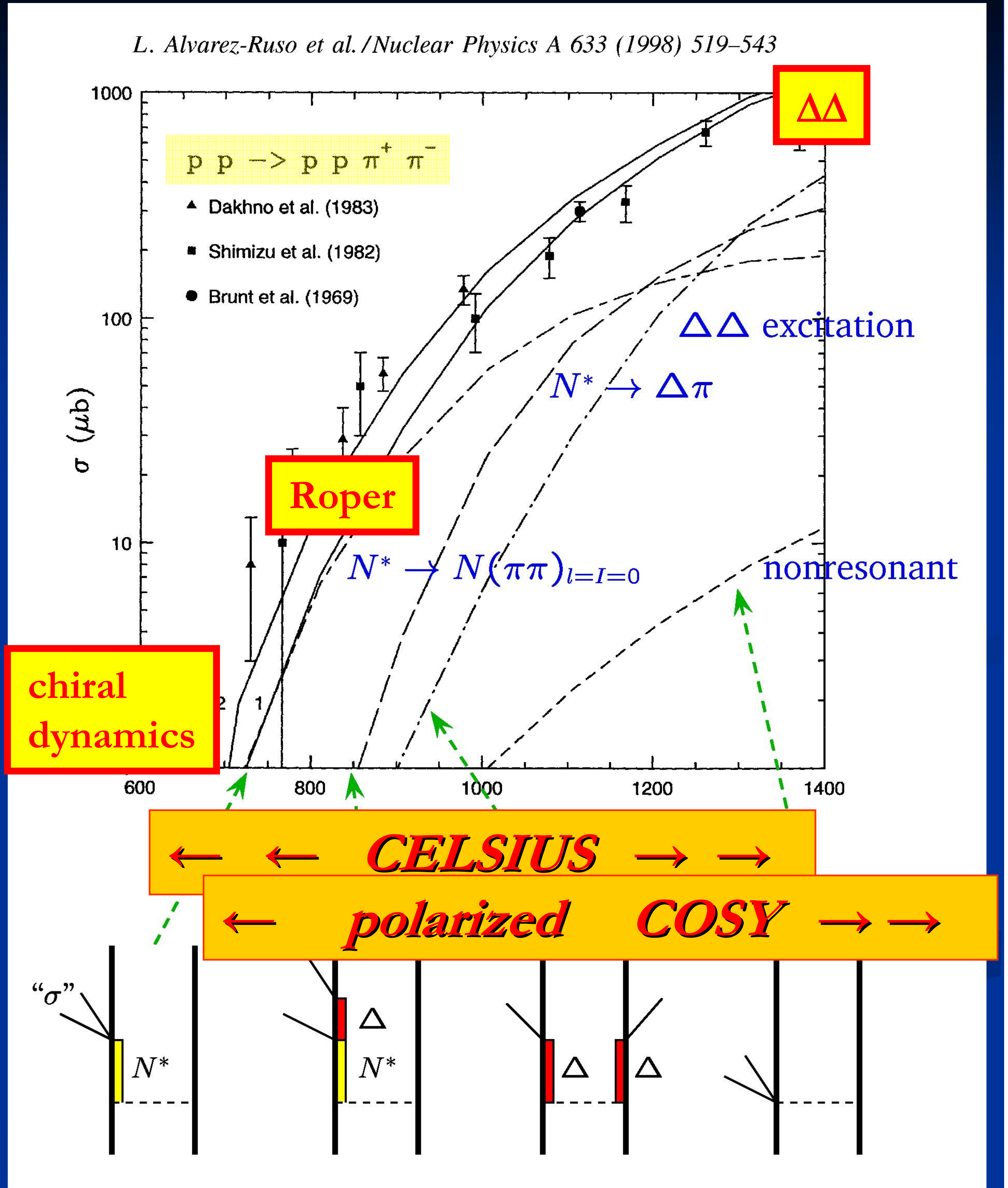
PRC 67 (2003) 052202 *(Pätzold et al)*

- **$N^* \rightarrow N\pi\pi$:** look in $pp \rightarrow pp^* \rightarrow pp\pi\pi$: **1.0 (1)**

ππ production

Status quo ante:

experimental and theoretical situation



PROMICE / WASA

- $T_p = 650 – 775$ MeV

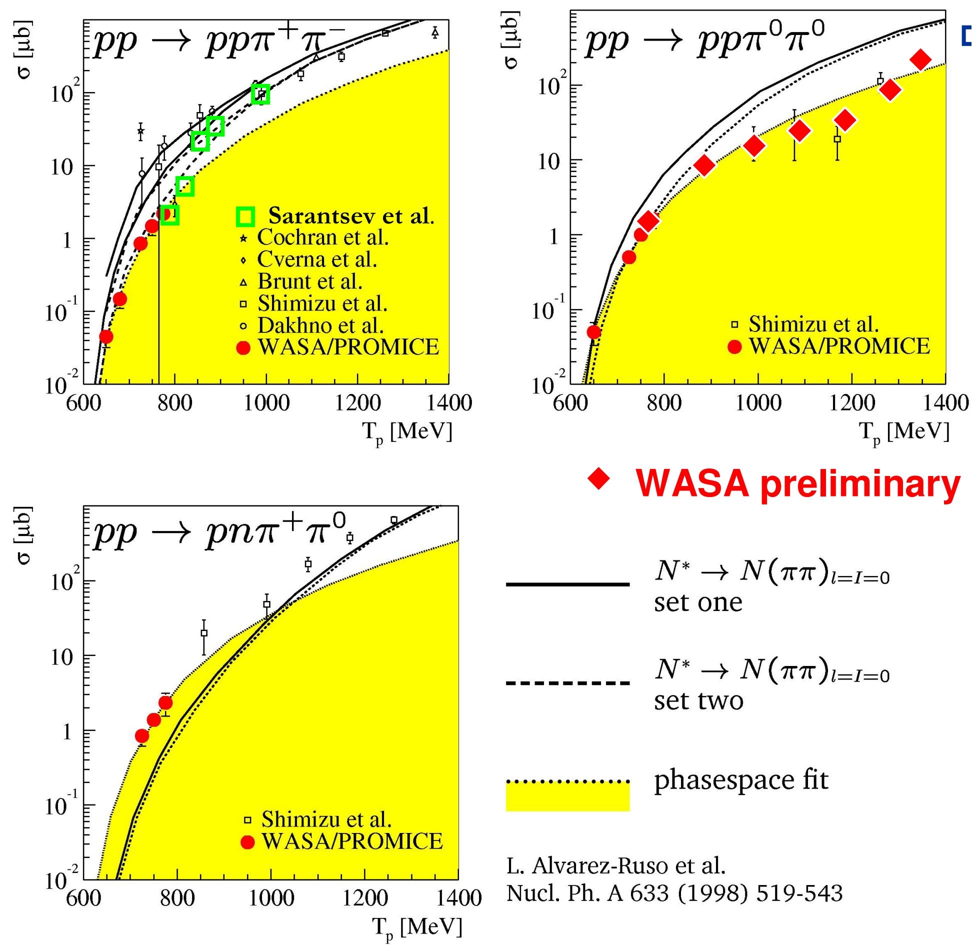
Phys. Rev. Lett. 88 (2002) 192301
Nucl. Phys. A 712 (2002) 75
Phys. Lett. B 550 (2002) 147
Phys. Rev. C 67 (2003) 052202 Rapid Comm.
many conference contributions

WASA

- $T_p = 775 – 1450$ MeV

M. Bashkanov
T. Skorodko

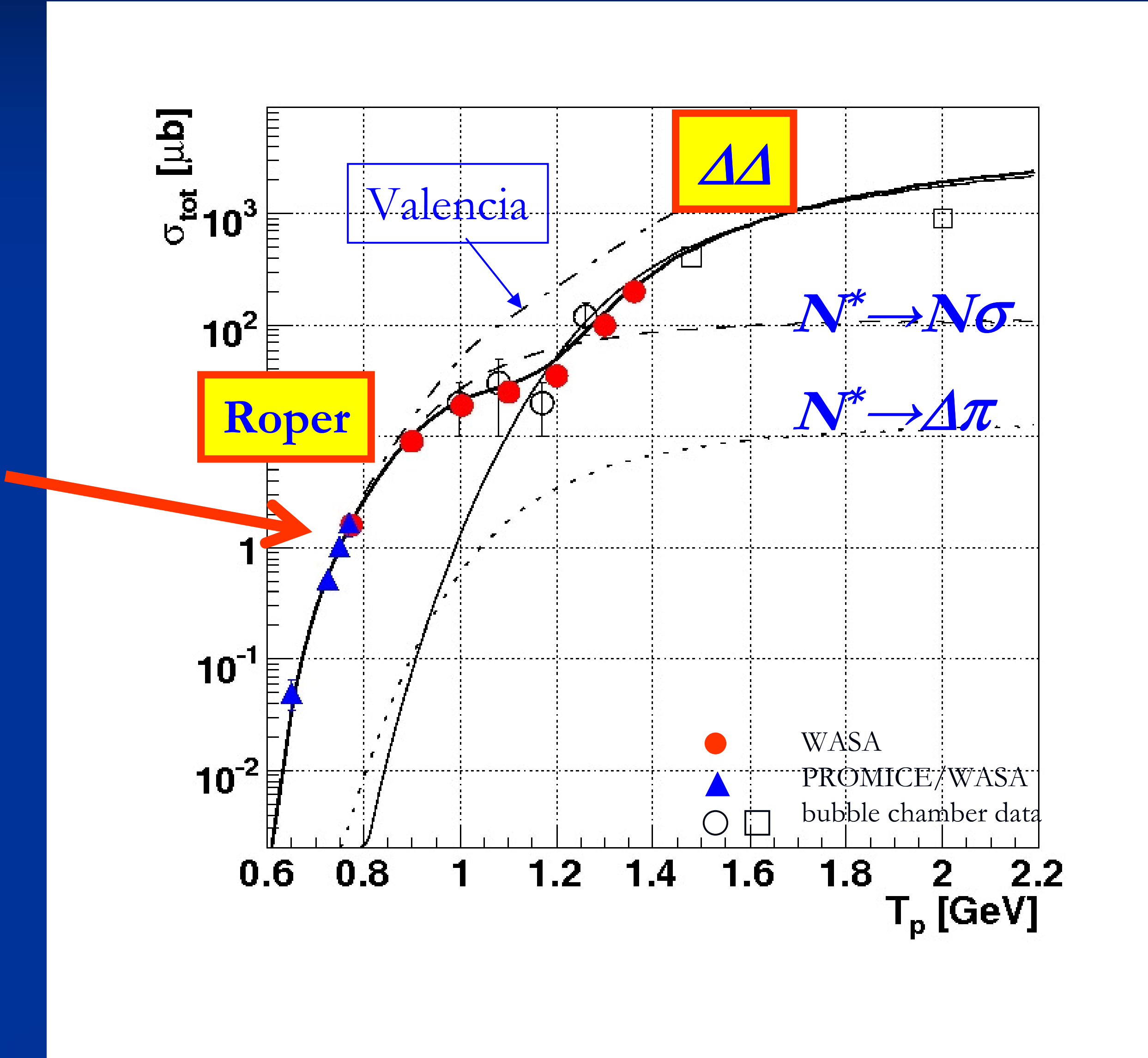
Total Cross Sections



L. Alvarez-Ruso et al.
Nucl. Ph. A 633 (1998) 519-543

ππ Production: $pp \rightarrow pp\pi^0\pi^0$

- Energy dependence of total cross section

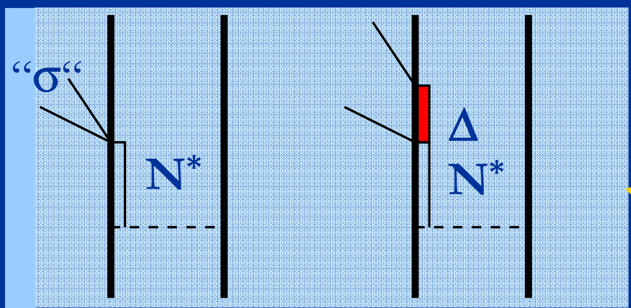


threshold region: $\pi^+\pi^-$

Roper excitation and decay

(conventional analysis)

PRC 67 (2003) 052202

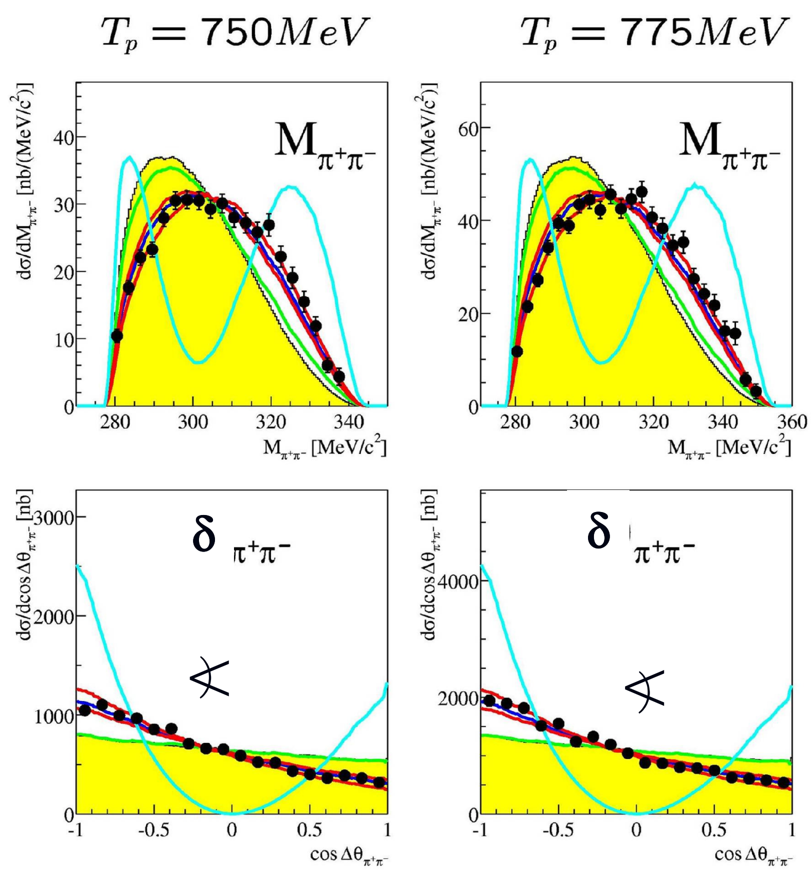


Branching Ratio @ pole: 1440 1350 MeV

$N^* \to \Delta\pi$ / $N^* \to N\sigma$ = 3.4 (3) 0.6 (1)

PDG 4 (2)

$N^*(1440)$ Decays



$N^* \overset{\Delta\pi}{\underset{N\sigma}{\rightrightarrows}} N(\pi\pi)_{l=I=0}$ 0% -20% -25% -33% ∞

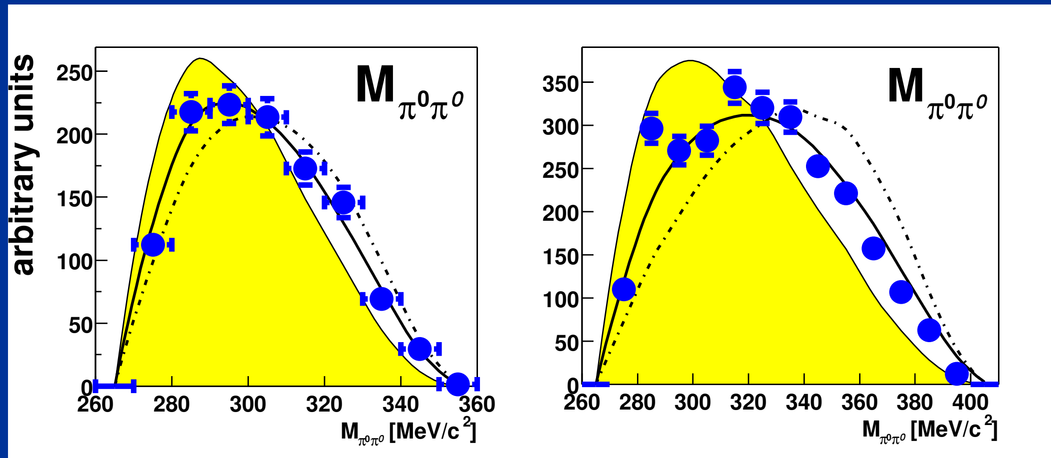
- Interference between both decay channels
- $\sigma \sim |a + b\vec{k_1} \cdot \vec{k_2}|^2$

CELSIUS-WASA

$pp \rightarrow pp\pi^0\pi^0$

$I_{\pi\pi} = 0$

$T_p = 775$ MeV $\quad$ $T_p = 900$ MeV



········	BR($\Delta\pi$/Nσ) = 1 : 2	$I_{\pi\pi} = 0 + 1$
———	BR($\Delta\pi$/Nσ) = 1 : 8	$I_{\pi\pi} = 0$

$\Rightarrow$ $N^* \rightarrow N\pi\pi$

dominantly $N \rightarrow N\sigma$!

(nucl-ex/0612015)

Conclusions (1)

- **Roper Resonance historically:**
  - **Originally found in πN phase shifts of P_{11} partial wave**
    - Interpretation as a Breit-Wigner resonance in πN

$$\Rightarrow \quad \mathbf{M \approx 1440\ MeV,\ \Gamma \approx 400\ MeV}$$

Conclusions (2)

- **Roper resonance now:**

	M	Γ (MeV)
SAID πN partial wave analysis:	1357	160
Bonn *(Sarantsev et al)* $\pi N + \gamma N$	1371(2)	184(20)

- Explicitly seen in:

	M	Γ (MeV)
$\alpha\, p \to \alpha\, X$	1390	190 (?)
$J/\psi \to n\, p\pi^-$	1358	160
$p\, p \to p\, n\pi^+$	1380	150

- **Roper decay** $N^* \to N\, \pi\pi$
  - $pp \to NN\pi\pi \quad \Rightarrow$ dominantly $N^* \to N\, \sigma$

Conclusions (3)

- **Scalar-isoscalar probes (σ exchange) see „narrow" monopole excitation at very low excitation energy :**

breathing mode @ $\omega \approx 400$ MeV !

i.e. only 100 MeV above Δ, the lowest excited state

$\pi\pi$ Production in Nuclei and the **ABC Puzzle**

- a standing problem since nearly 50 years!

- nuclei as isospin filter:

$\pi^0\pi^0$ – system

  - pp → pp $\pi\pi$ — I = 0, ~~1~~, 2
  - pn → d $\pi\pi$ — 0, ~~1~~
  - pd → ^{3}He $\pi\pi$: — 0, ~~1~~
  - dd → ^{4}He $\pi\pi$: — 0

$\left.\begin{array}{l} \text{pn} \\ \text{pd} \\ \text{dd} \end{array}\right\}$ **ABC effect**

ABC effect

(Abashian, Both, Crowe)

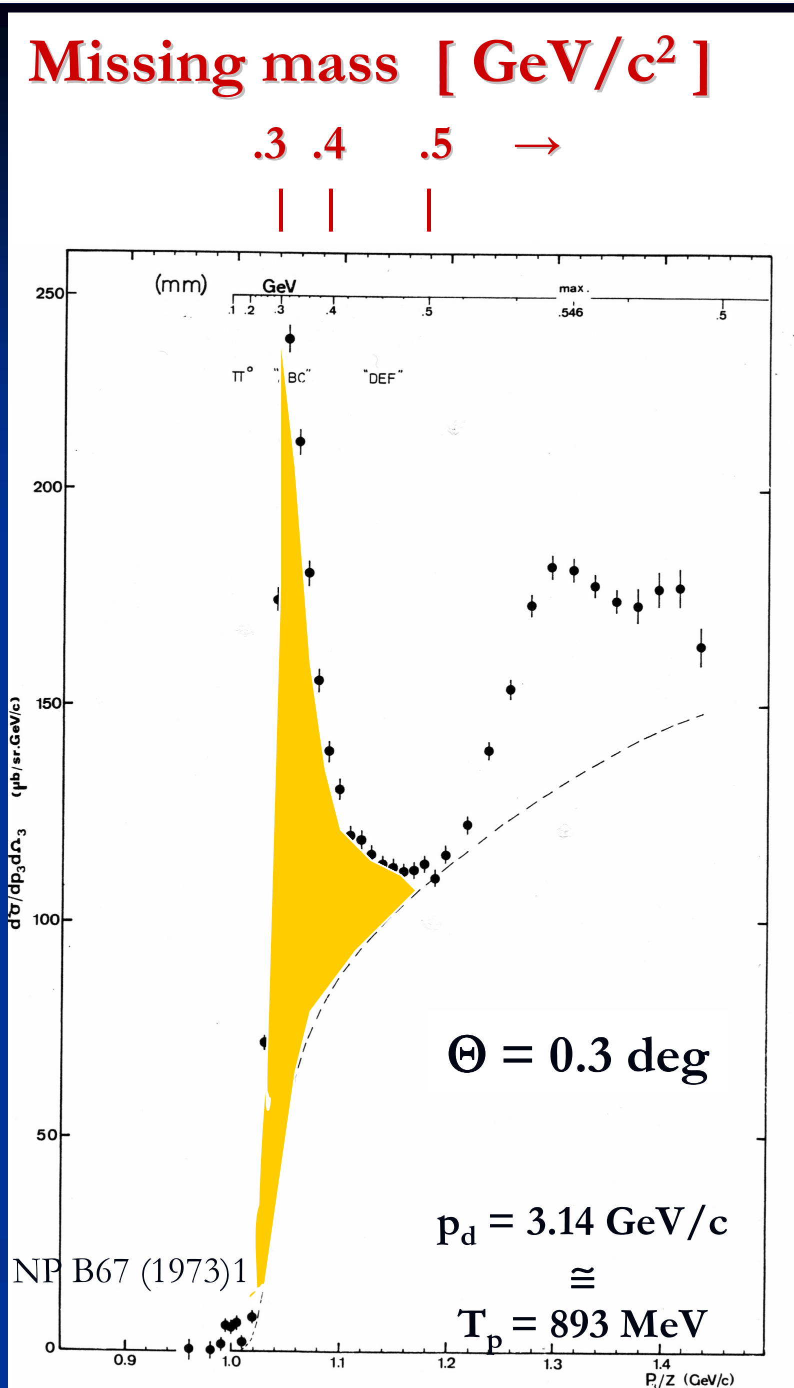
- Inclusive measurements:

  pd → ^{3}He X

Abashian et al.	Berkeley
Banaigs et al.	Saclay

⇒

low-mass enhancement !



First exclusive measurement: @ CELSIUS-WASA

$p\,d \rightarrow {}^3He\ \pi\pi$ @ T_p = 895 MeV

$M_{\pi\pi}$ $M_{^3He\,\pi}$

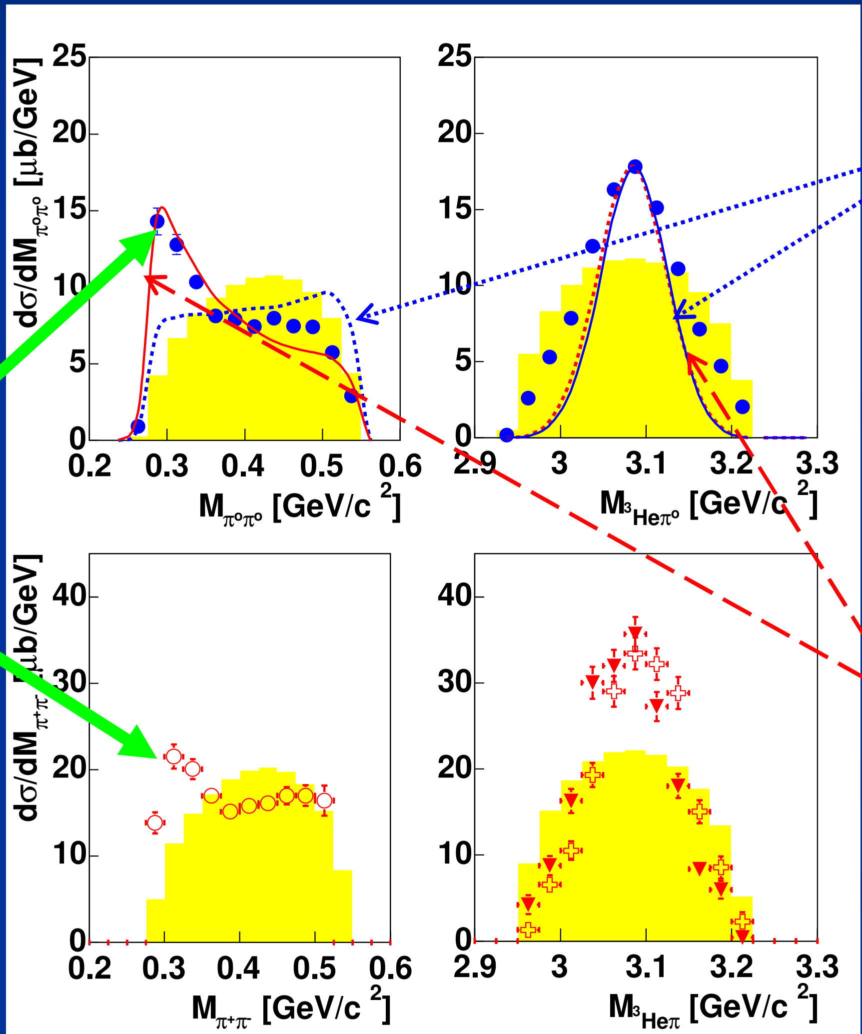
$\pi^0\pi^0$

(I = 0)

ABC

$\pi^+\pi^-$

(I = 0, 1)



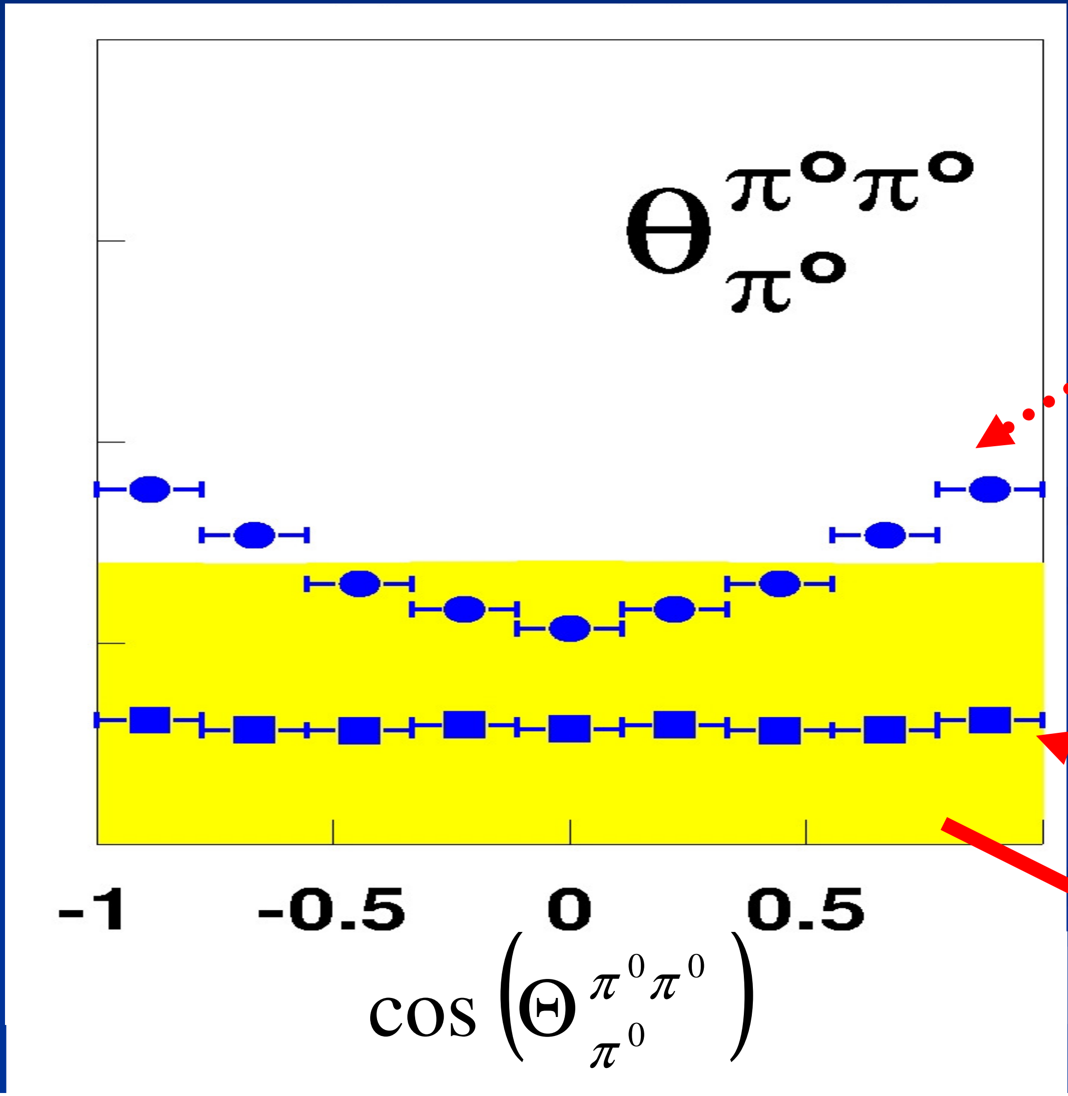
$(\Delta\Delta)_{conventional}$

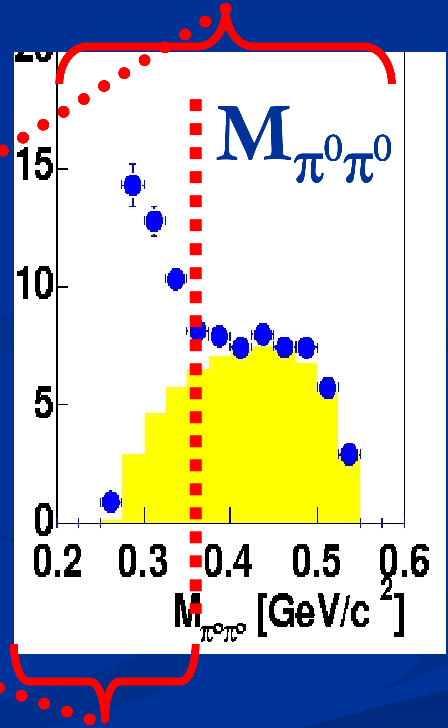
$(\Delta\Delta)_{int}$

Phys. Lett. B637, 223 (2006)

Angular Distribution of Isoscalar Low-Mass Enhancement ?

Phys. Lett. B637, 223 (2006)





scalar – isoscalar !

First exclusive measurement: @ CELSIUS-WASA

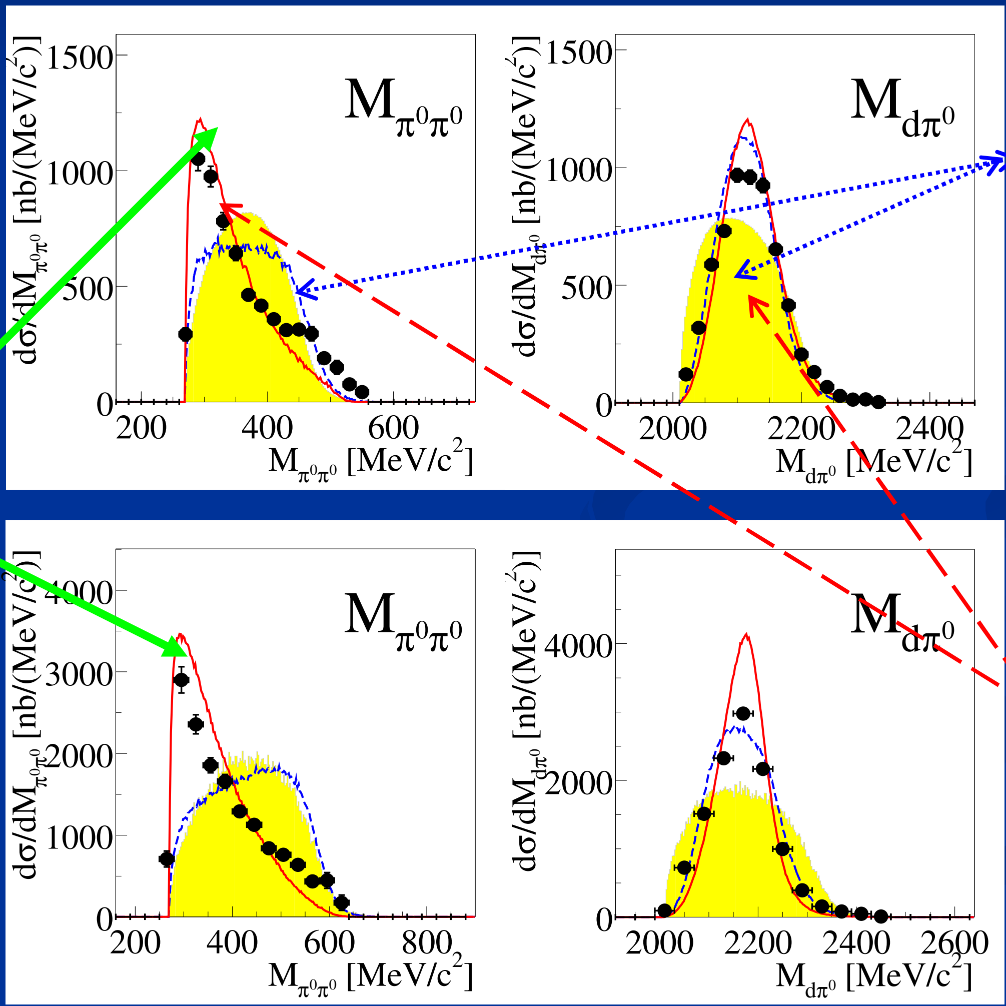
$$p\,d \rightarrow d\,\pi^0\pi^0 + p_{spectator}$$

$M_{\pi\pi}$ $M_{d\pi}$

$T_p = 1.04$ GeV

ABC

$T_p = 1.36$ GeV



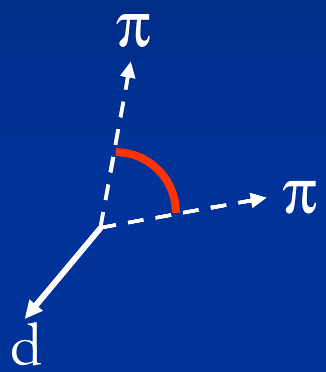
$(\Delta\Delta)_{conventional}$

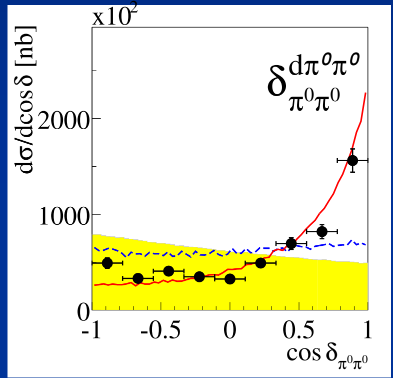
$(\Delta\Delta)_{int}$

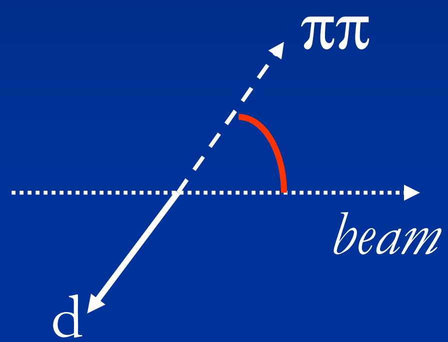
Proc. MESON 06,
Int. J. Mod. Phys.
A22 (2007) 617

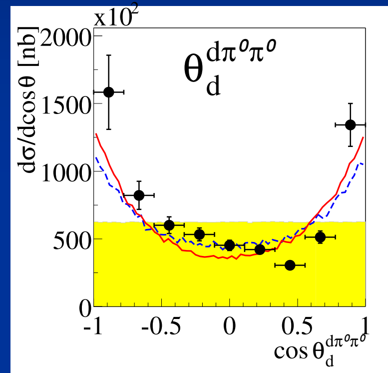
Quasifree $pn \rightarrow d\pi^0\pi^0$ *(bin T_p = 1.0 – 1.04 GeV)*

- Angular distributions: <u>overall cms</u>

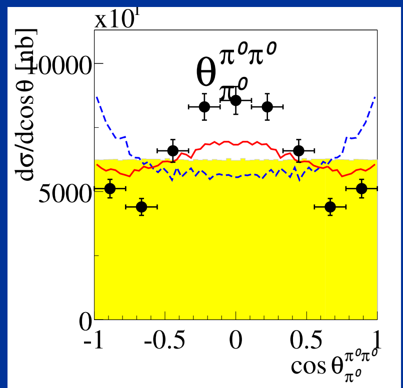


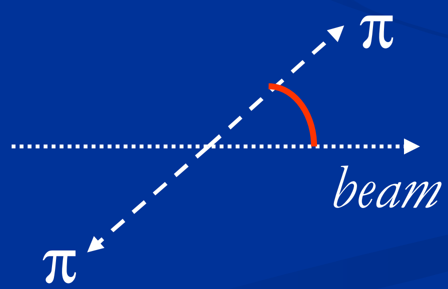


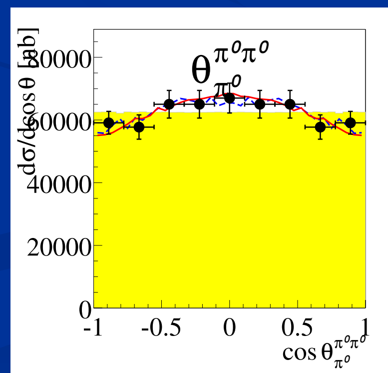




<u>ππ subsystem (Jackson frame)</u>





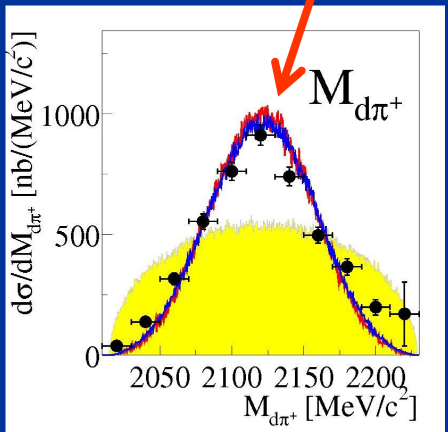


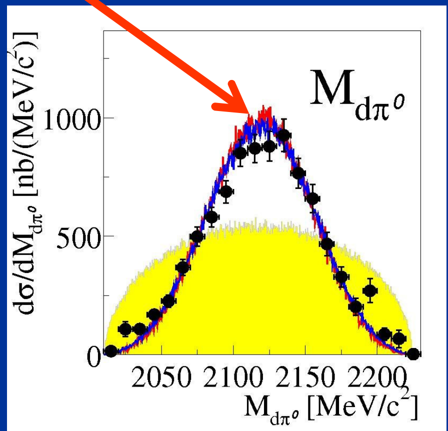
with cut on ABC peak

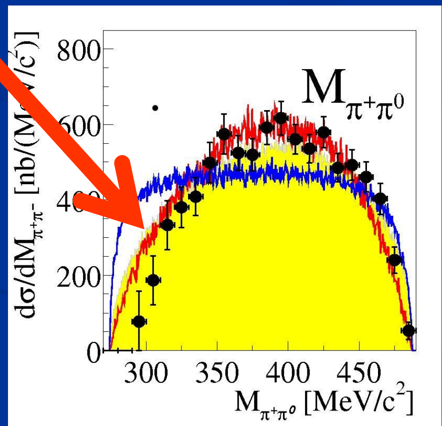
control reaction

$pp \to d\pi^+\pi^0$ @ 1.1 GeV

- I = 1 channel ⇔ **no** ABC !
- despite ΔΔ excitation







ΔΔ $\sigma^*(k_1 \times k_2)$

ΔΔ

Total Cross Sections

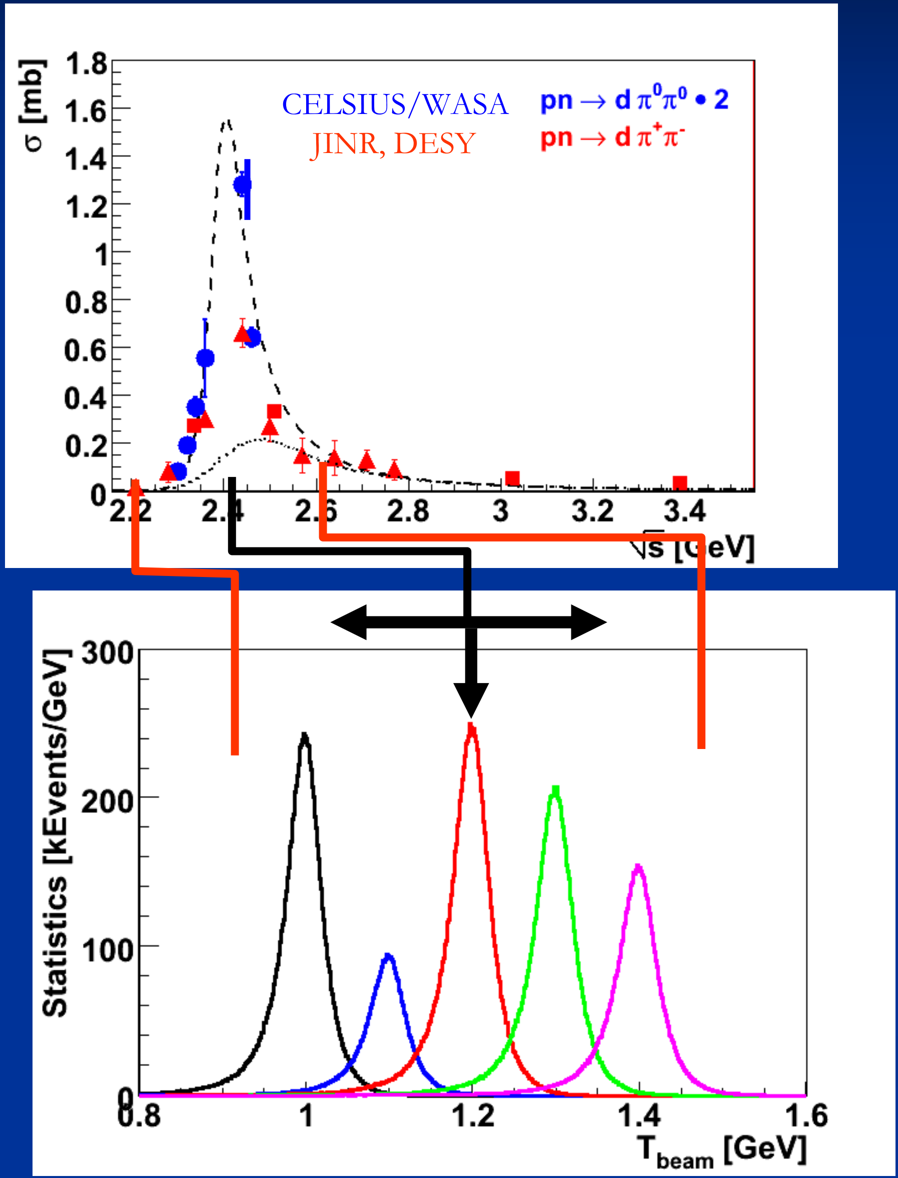
- Isospin relations $\Rightarrow$

	$pn \rightarrow d\pi^+\pi^-$	$pn \rightarrow d\pi^0\pi^0$ $\boxed{\underline{*\ 2}}$
$I = 1$	1/2	----
$I = 0$	2/5	1/5 $\boxed{\underline{*\ 2}}$

$\Big\}\ *\ pp \rightarrow d\pi^+\pi^0$

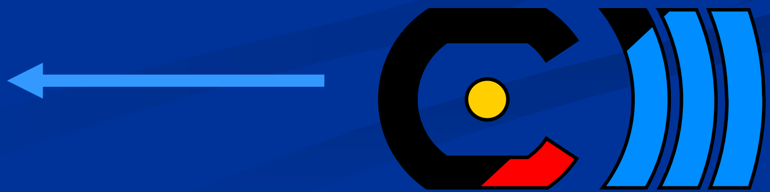
if $\Delta\Delta$ mechanism

WASA@COSY – first data on ABC

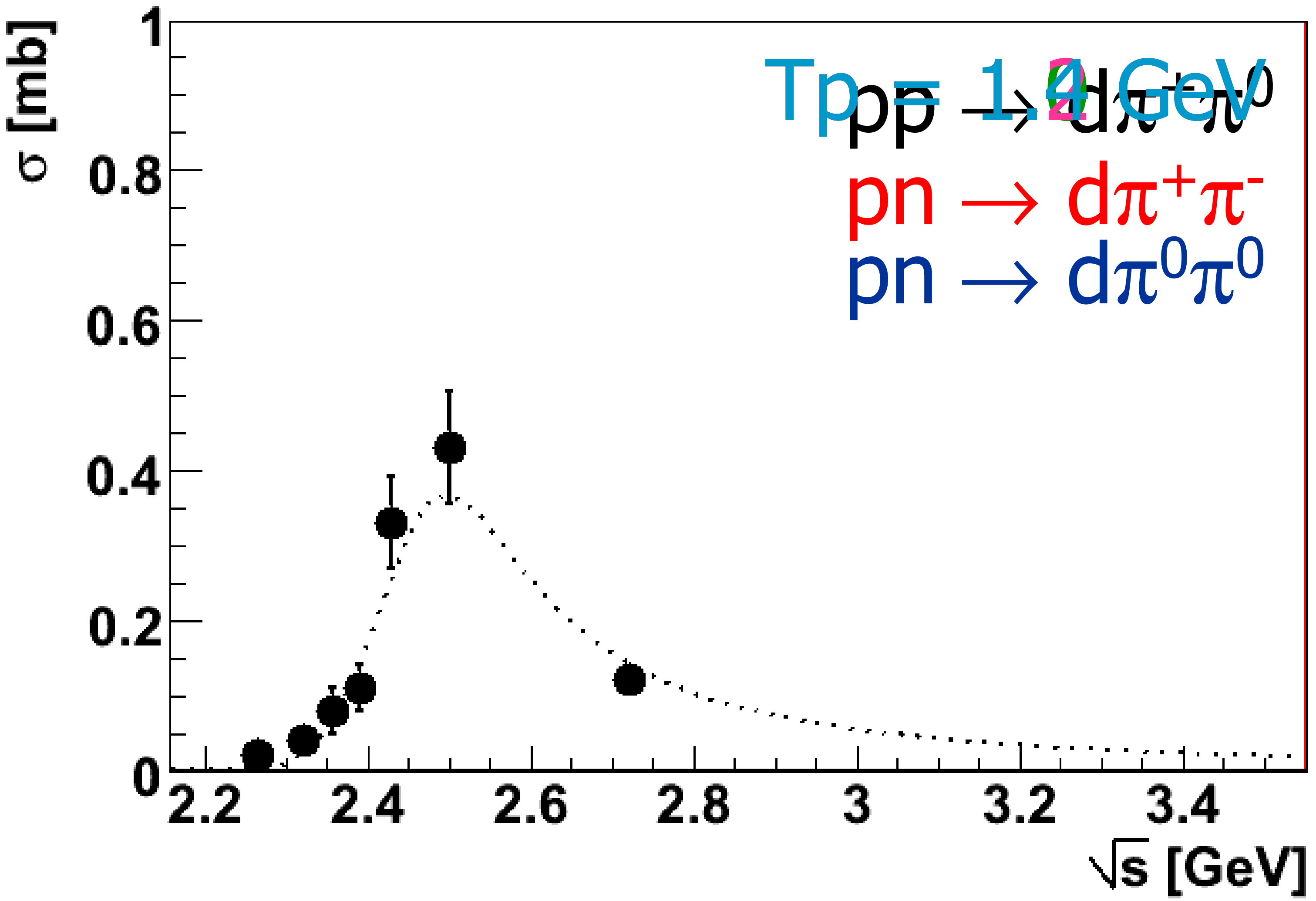


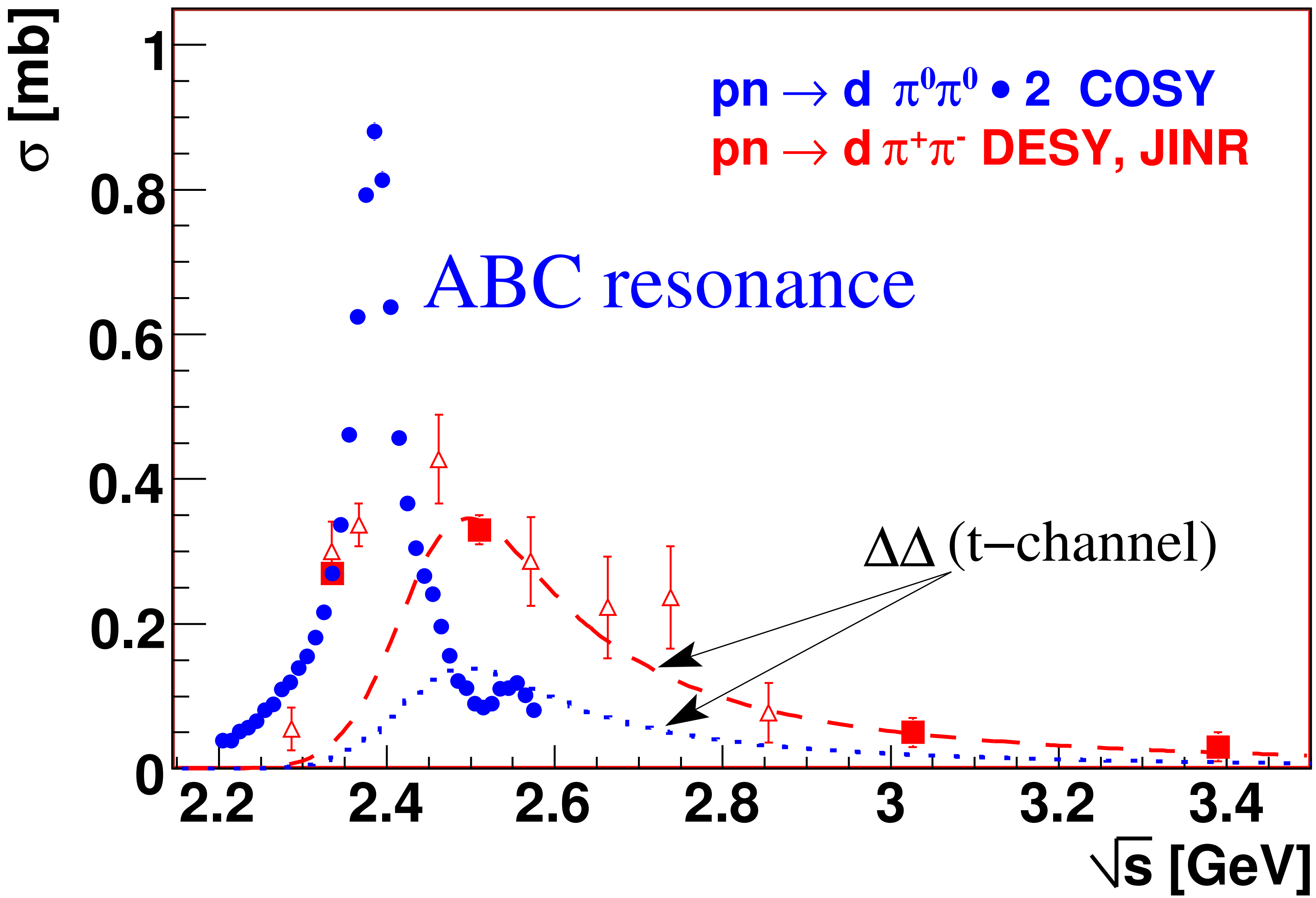
- First preliminary results from January 2008 beamtime
- Quasifree

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



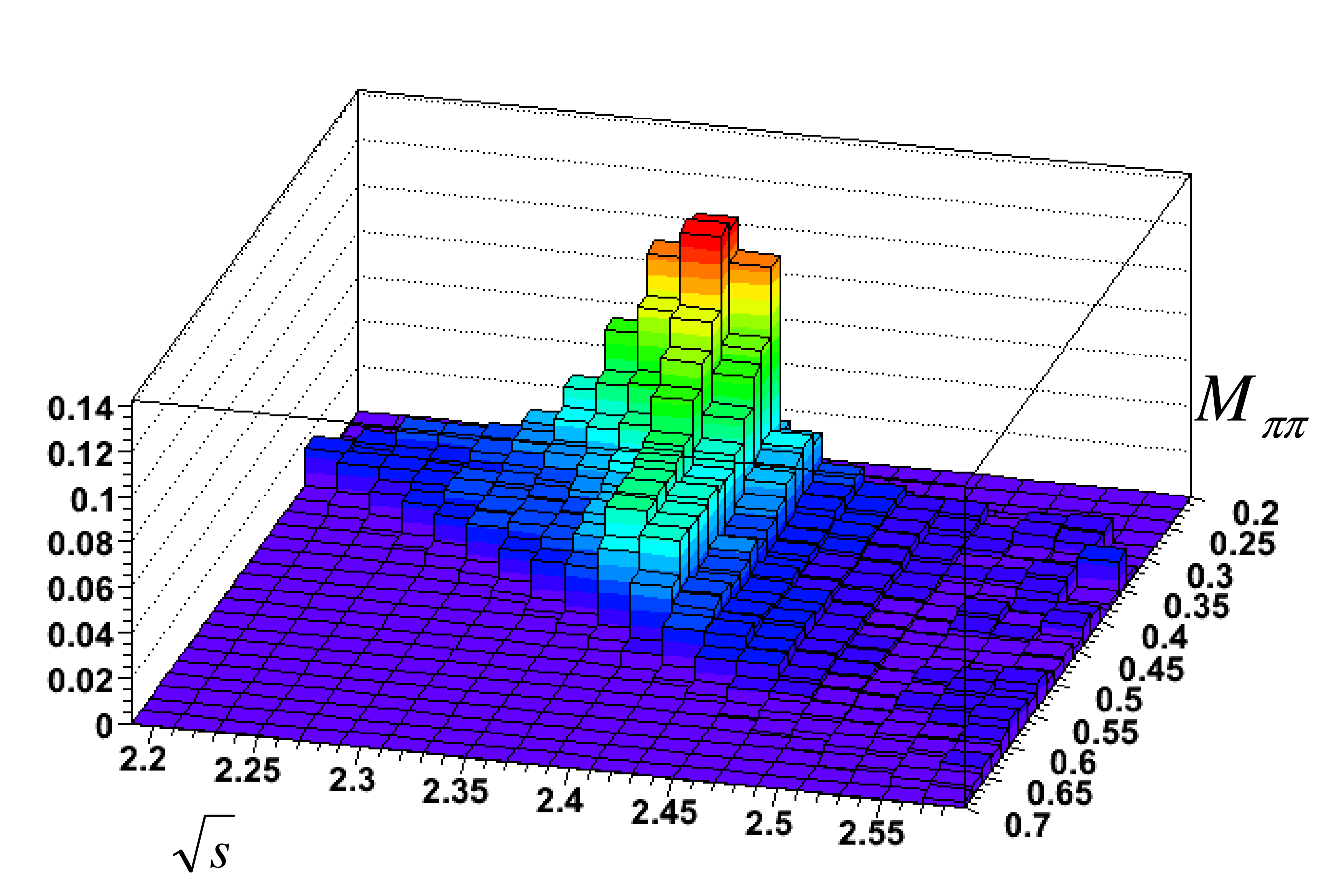
Total xsection





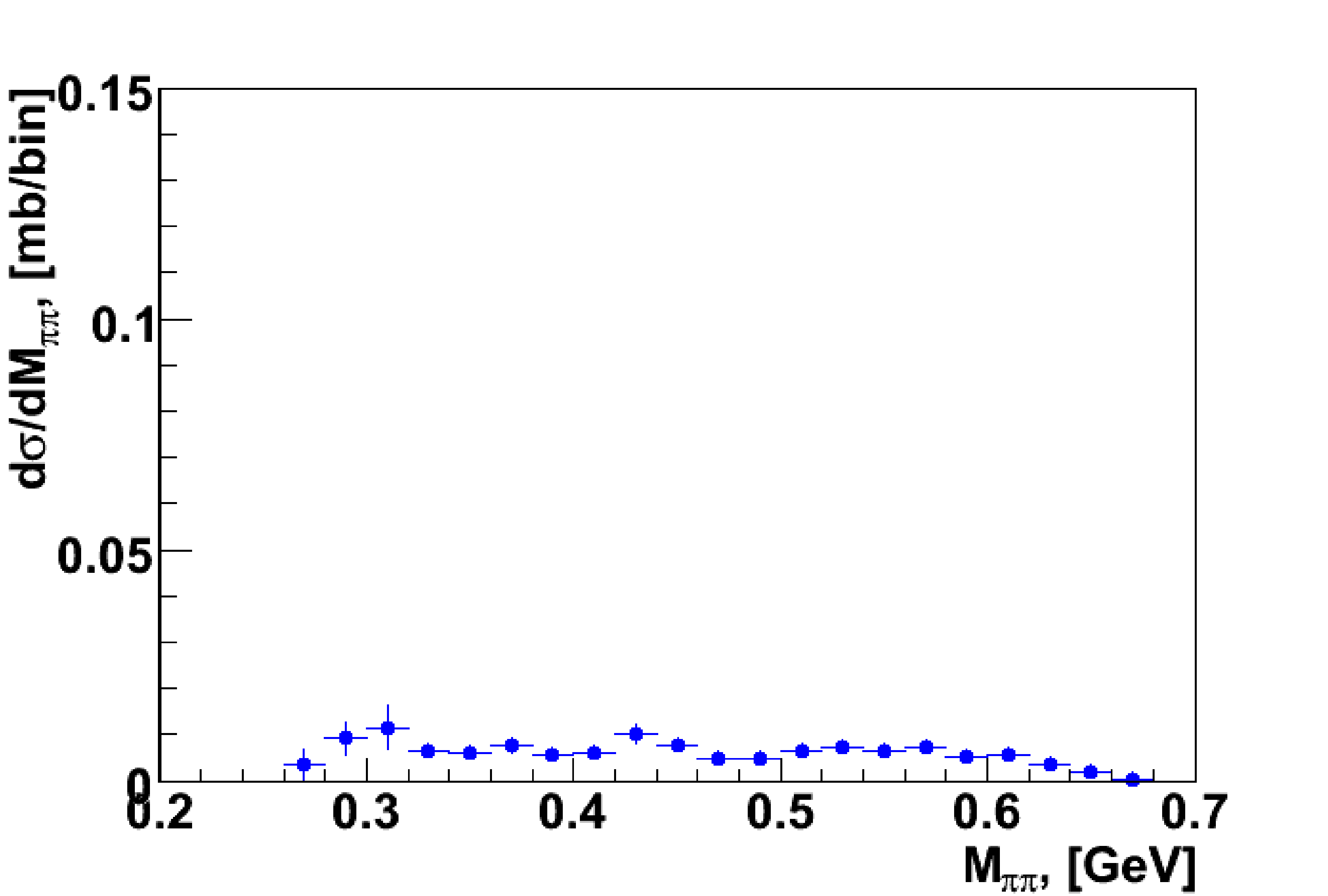
σ [mb]
1
0.8
0.6
0.4
0.2
0
2.2
2.4
2.6
2.8
3
3.2
3.4
√s [GeV]
pn → d π⁰π⁰ • 2 COSY
pn → d π⁺π⁻ DESY, JINR
ABC resonance
ΔΔ (t−channel)

2D x-section



0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
2.2
2.25
2.3
2.35
2.4
2.45
2.5
2.55
$\sqrt{s}$
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.7
$M_{\pi\pi}$

Sliced x-section

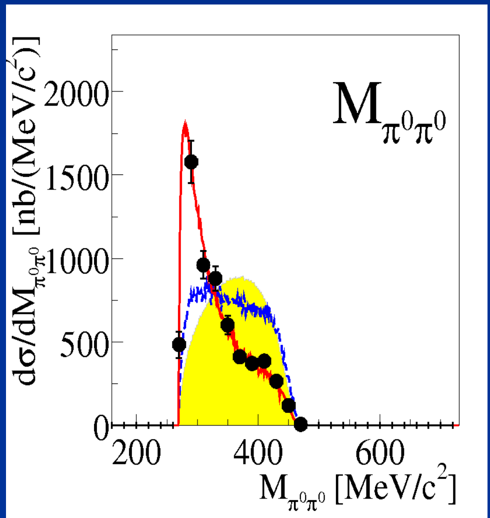


$\Delta\Delta$ System
Conclusions

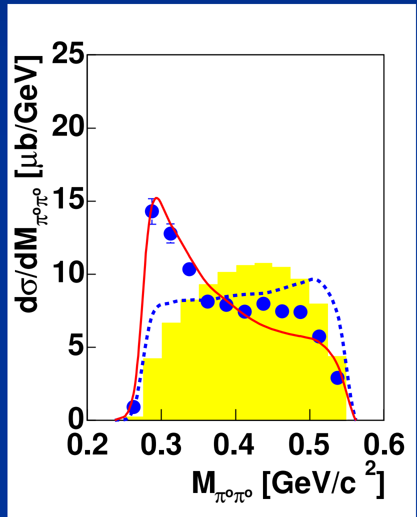
- $\exists$ resonances in $NN \leftrightarrow \Delta\Delta \leftrightarrow d\pi\pi$
  - trivial (?) ones at threshold:
    - $m \approx 2\ m_\Delta$
    - $\Gamma \approx 2\ \Gamma_\Delta$
  - a non-trivial one below threshold: ***$I(J^P) = 0(1^+$ or $3^+)$***
    - $m \approx 2\ m_\Delta$ **- 70 MeV**
    - $\Gamma \approx$ **50 MeV** $<< 2\ \Gamma_\Delta$
    - Δ^+ and Δ^0 in relative s-wave! *(hetero ♂♀)*

$\pi^0\pi^0$ Enhancement Gallery

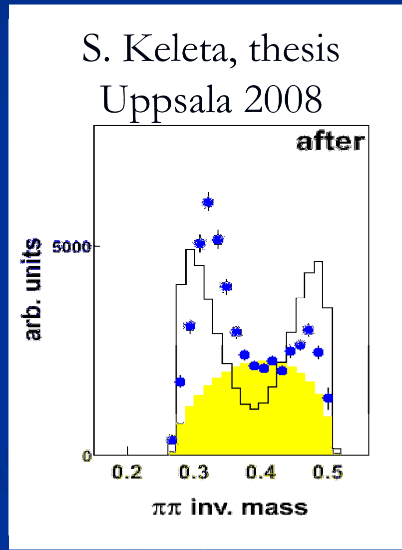
$pn \rightarrow d\,\pi^0\pi^0$
@ 1.0 GeV



$pd \rightarrow {}^3He\,\pi^0\pi^0$
@ 0.9 GeV



$dd \rightarrow {}^4He\,\pi^0\pi^0$
@ 1.0 GeV



heavier nuclei ??

CELSIUS-WASA measurements

WASA@COSY: exclusive measurements over full ΔΔ region!

Summary

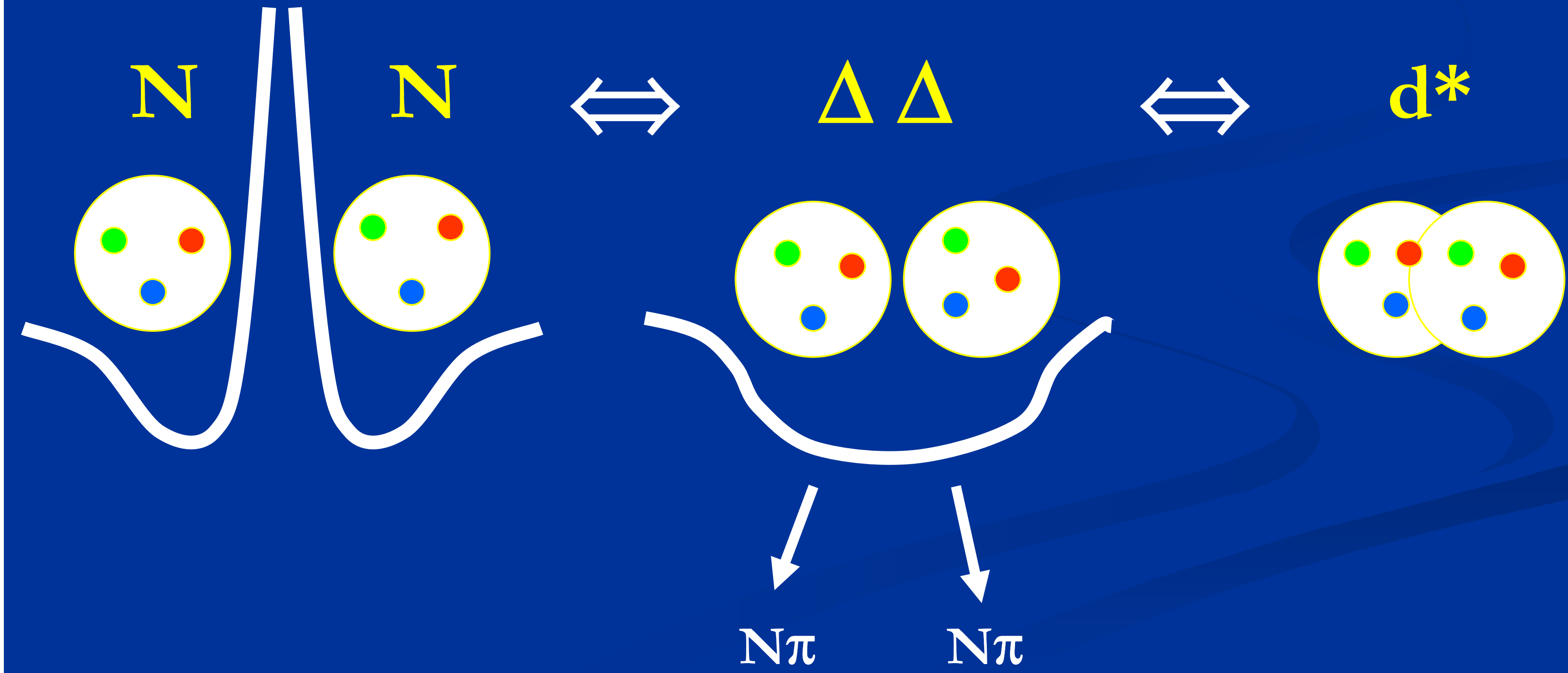
- There is more in the NN system than just the $^3S_1$ boundstate and $^1S_0$ virtual state :

- There are $\Delta\Delta$ states, eigenstates of the NN system,
  in particular the ABC-effect state with $I(J^P) = 0(1^+$ or $3^+)$
  small width and survives even in nuclear medium

$\Rightarrow$ *more than just a $\Delta\Delta$ molecule?*

Summary cont'd

- Is it a genuine dibaryon $I(J^P) = 0(3^+)$ accessed via ΔΔ as doorway ?



Final Summary

- Pion-nucleon sigma term:
  - Strange quark content ?

    $\Leftrightarrow$ dark matter scattering cross section
- Equation of state for nuclear matter:
  - Breathing mode in nuclei $\Rightarrow$ soft
  - Breathing mode in nucleon $\Rightarrow$ soft
  - Exotics: resonances in the dibaryon system

    $\Rightarrow$ new state of matter

    $\Rightarrow$ influence on hot/dense matter?

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