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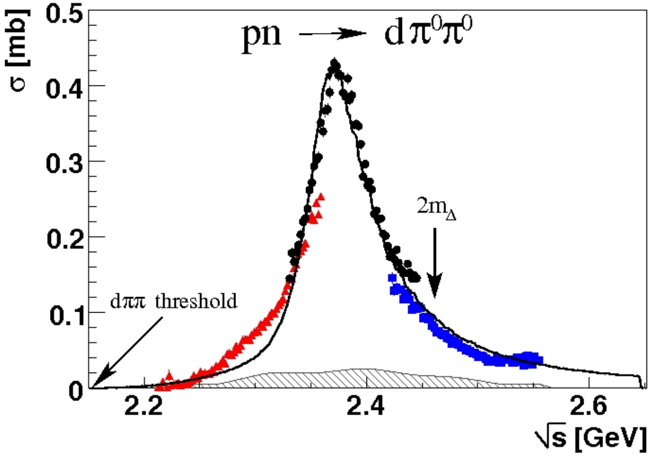
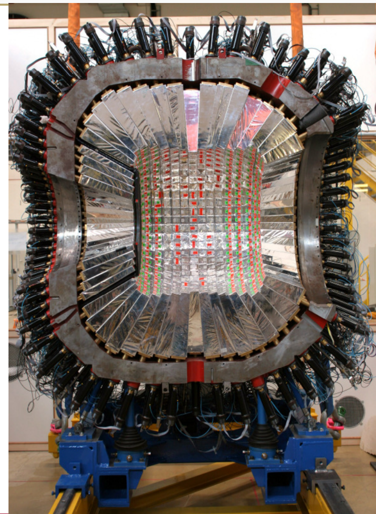
Fachbereich Physik





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Status of Dibaryons: Hexaquarks versus Molecules

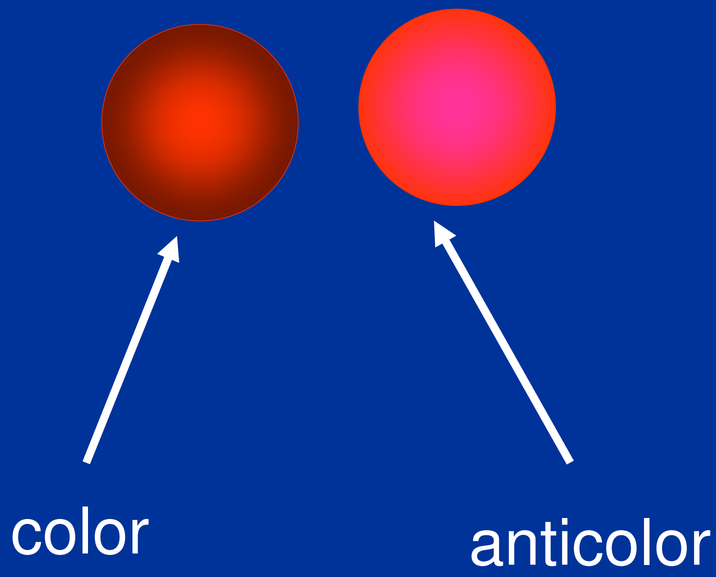
The Strong Interaction: From Quarks and Gluons to Nuclei and Stars

Erice, Sept. 16 – 24, 2018

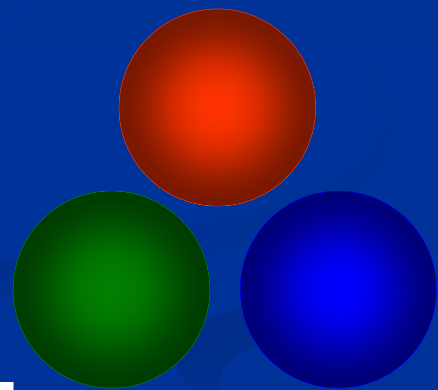
Heinz Clement

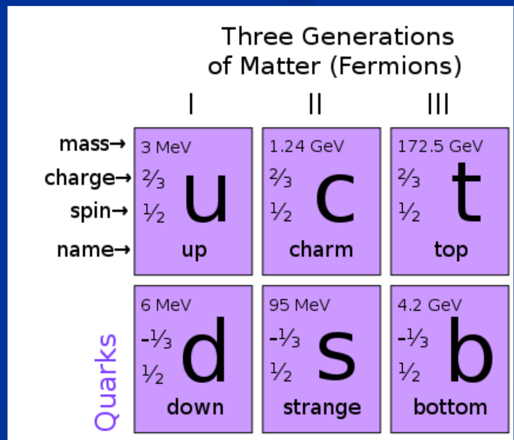
Types of conventional particles/resonances

Meson

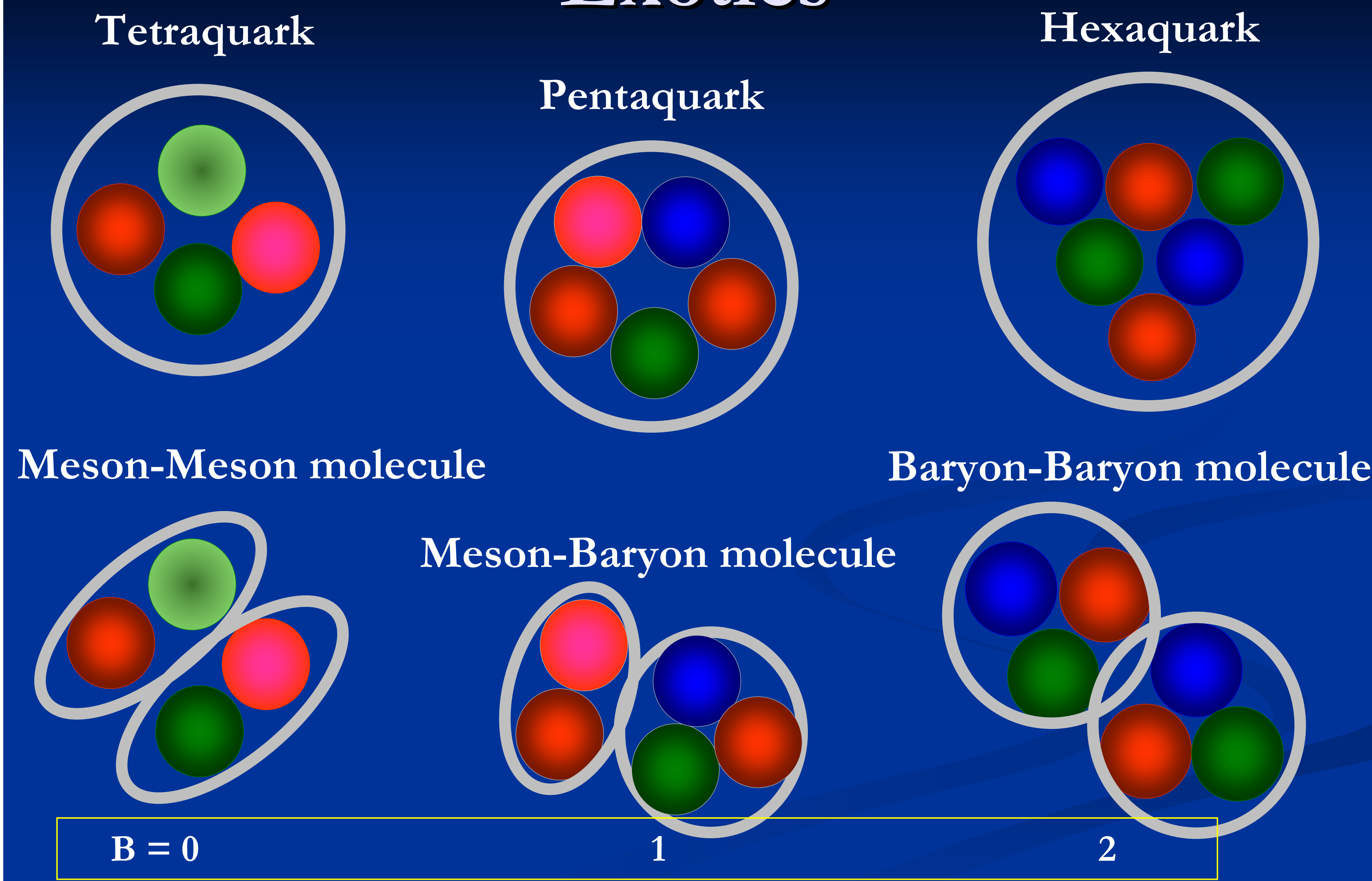


Baryon





Exotics



Dibaryon

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?

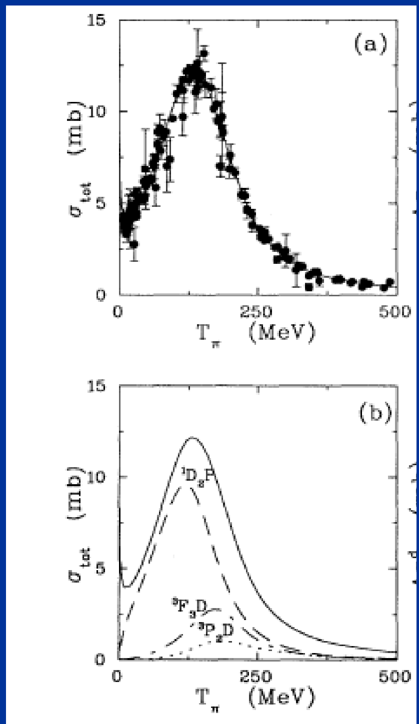
Early Predictions of Dibaryons

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

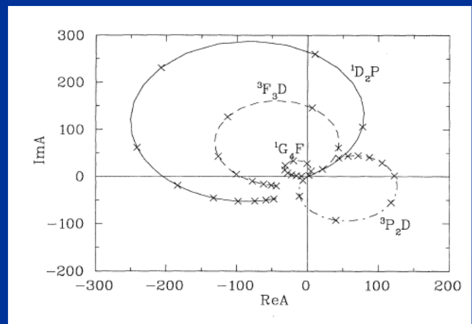
Possibly the only surviver: $^1D_2$ Resonance

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

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

$I (J^P) = 1 (2^+)$
$M \approx 2148$ MeV $= m_\Delta + m_N - 22$ MeV
$\Gamma \approx 126$ MeV $\approx \Gamma_\Delta$

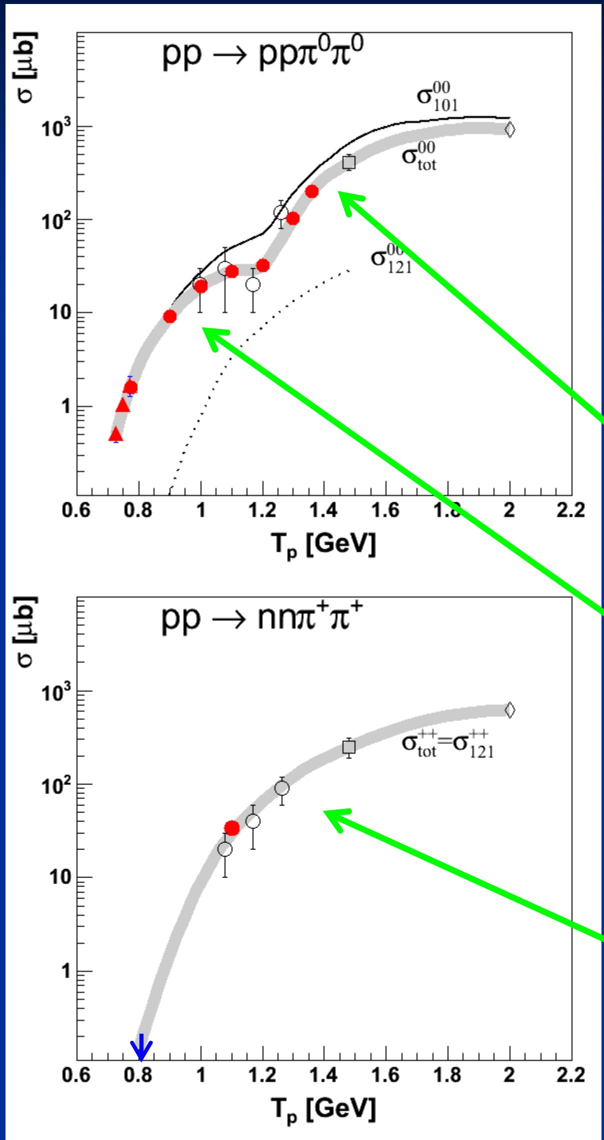
Alternative description: cusp, virtual state, reflection D. Bugg et al.
However, not consistent!!! Kukulin and Platonova PRD 94 (2016) 054039

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

Isovector : Total Cross Sections



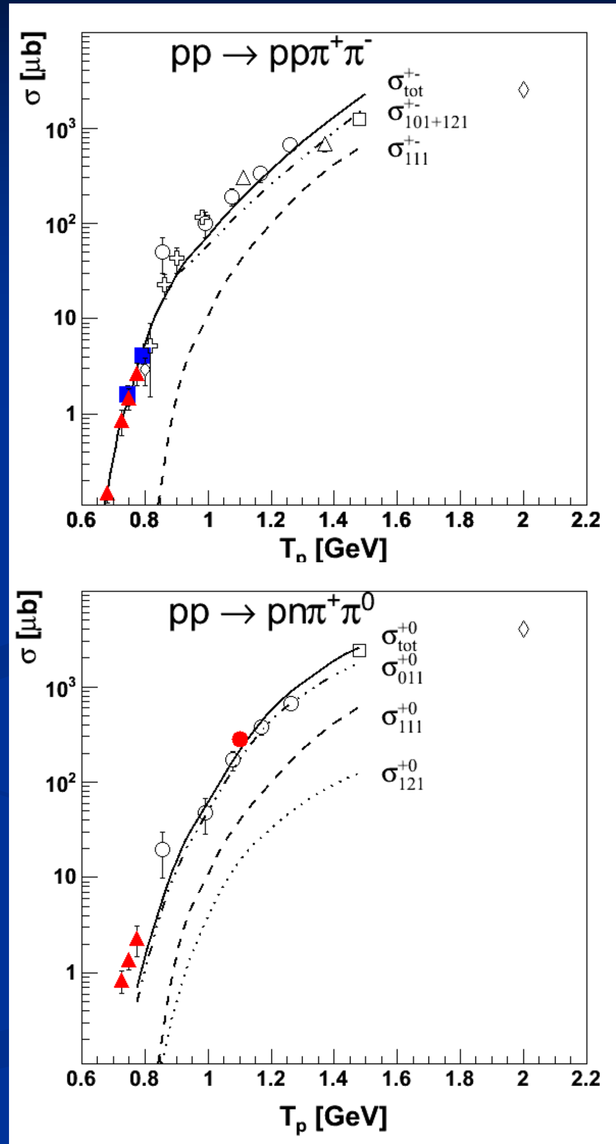
isospin decomposition

⇒

ΔΔ

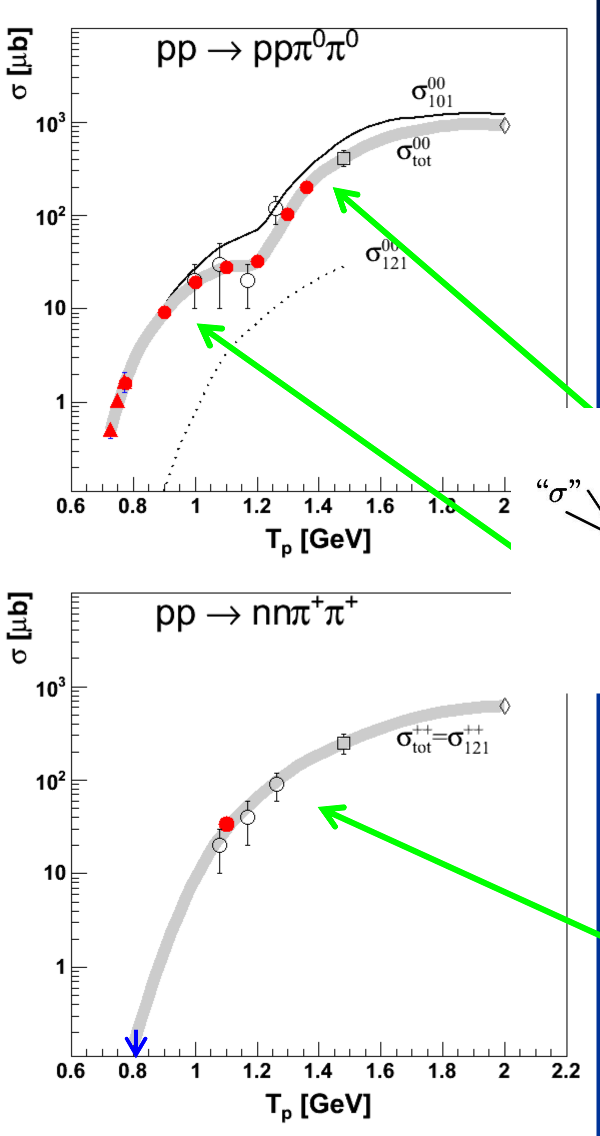
N*(1440)

Δ(1600) (?)



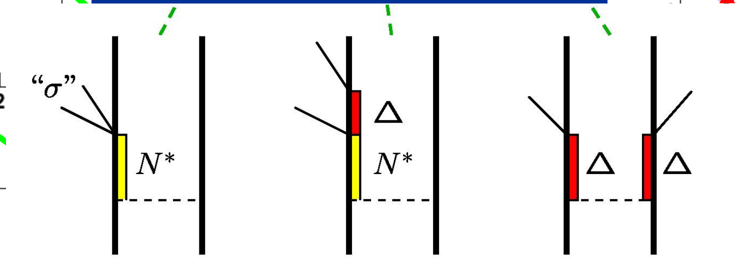
Phys. Lett. B 679 (2009) 30

Isovector : Total Cross Sections

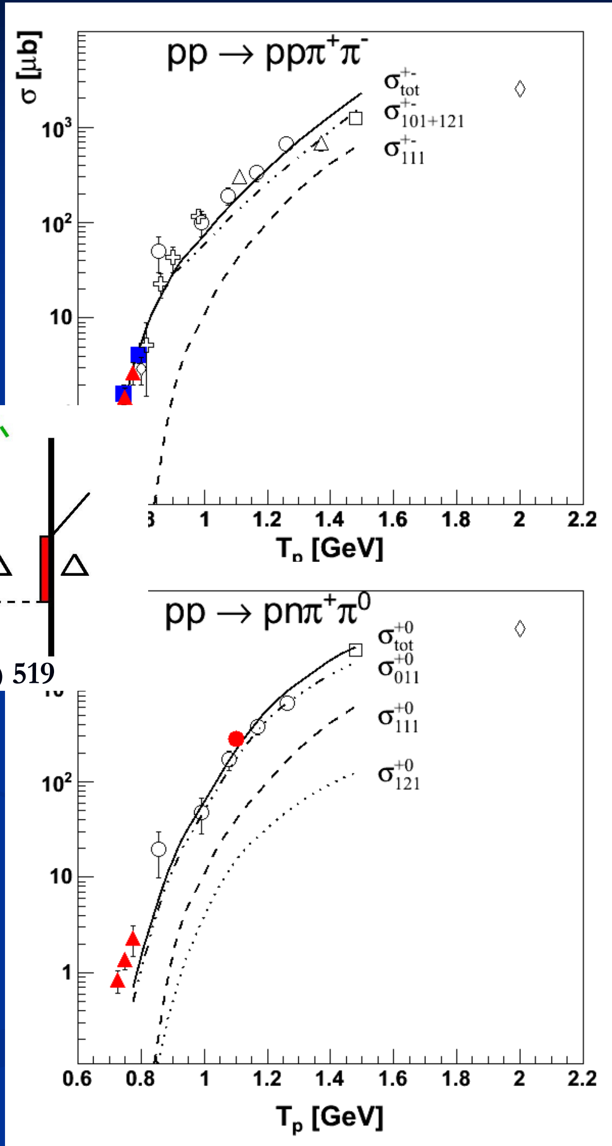


isospin decomposition

⇒



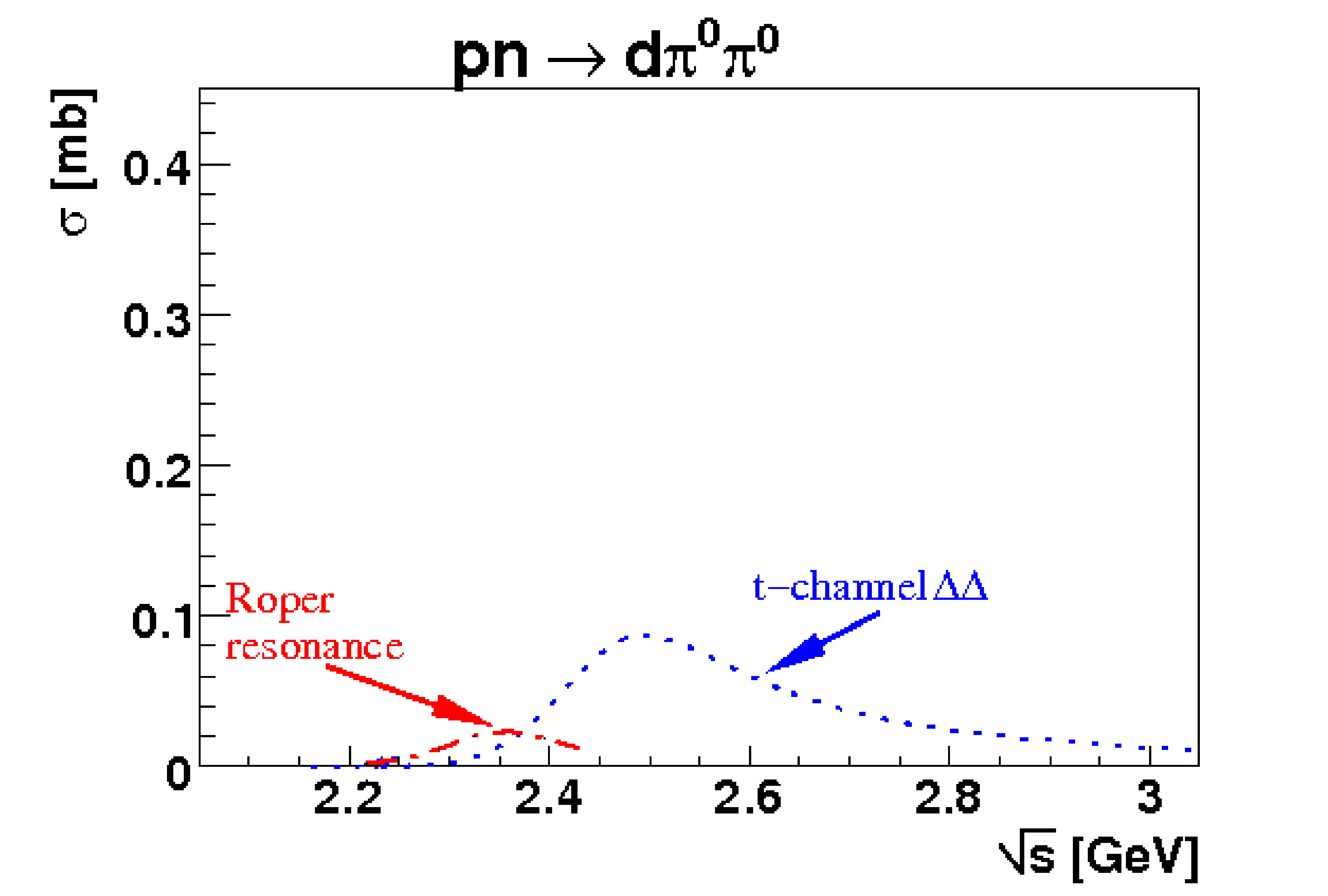
Alvarez-Ruso, Oset NPA 633 (1998) 519



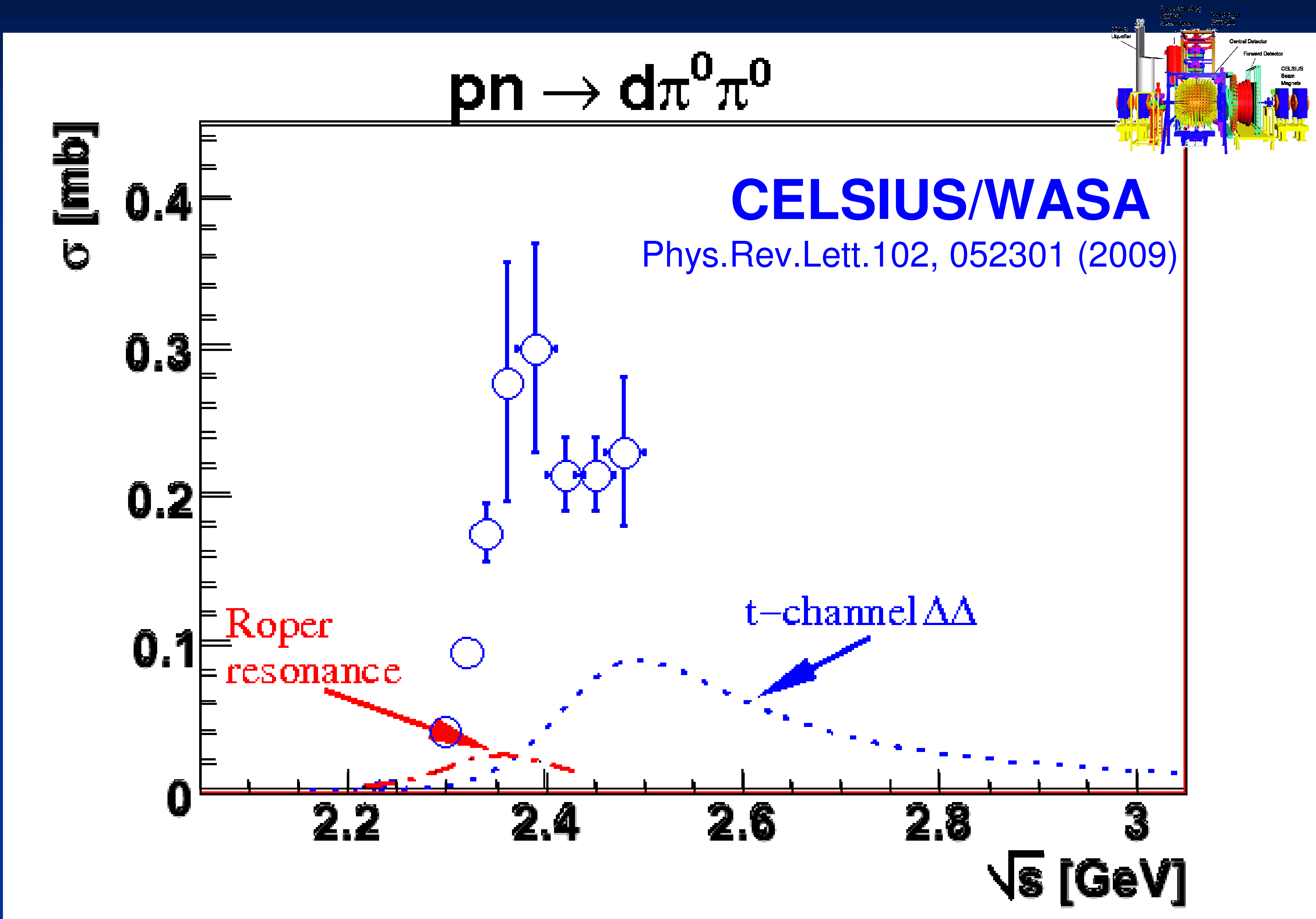
Δ(1600) (?)

Phys. Lett. B 679 (2009) 30

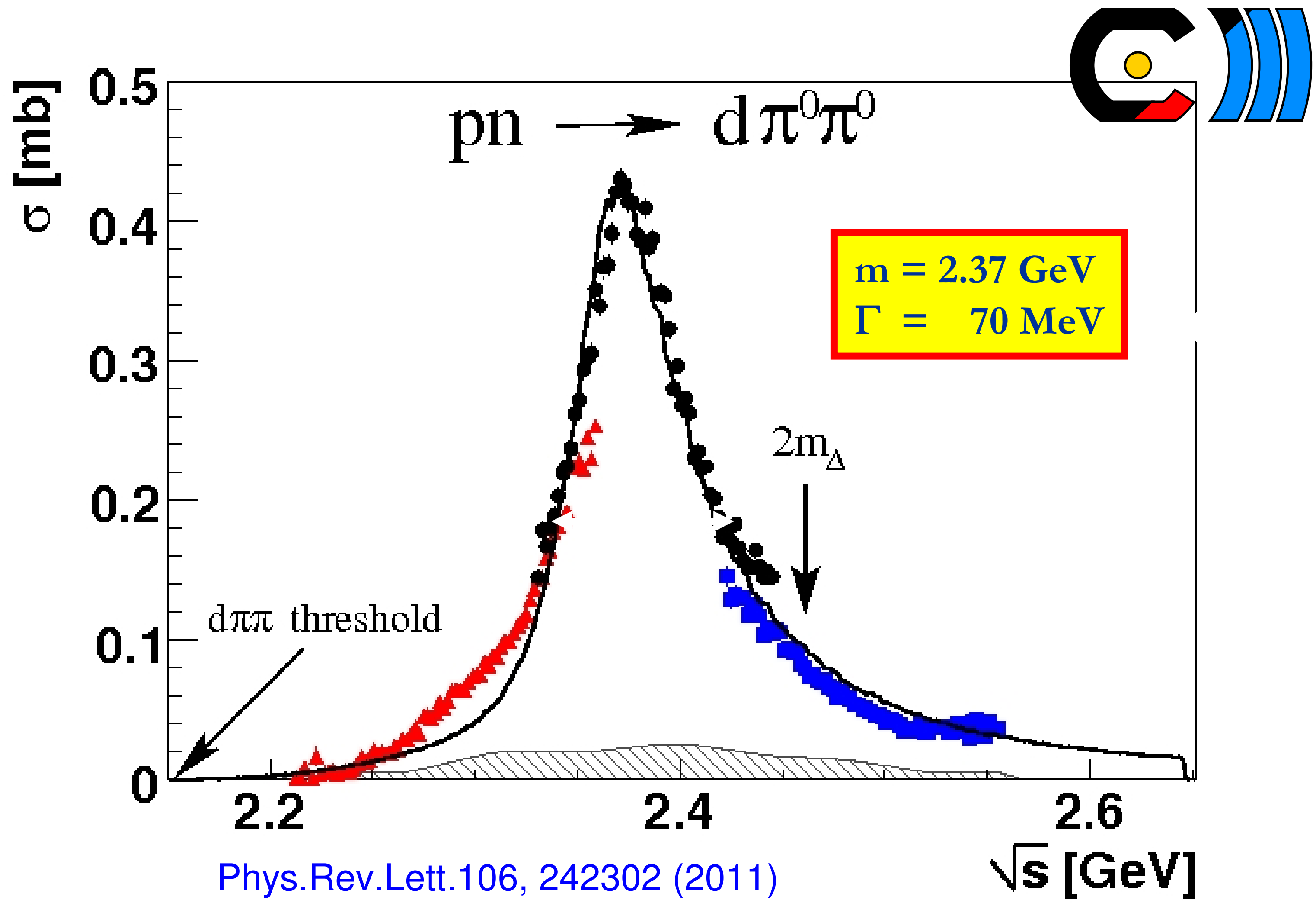
Isoscalar : … this is what we expected!



Isoscalar : … and this is what we found!

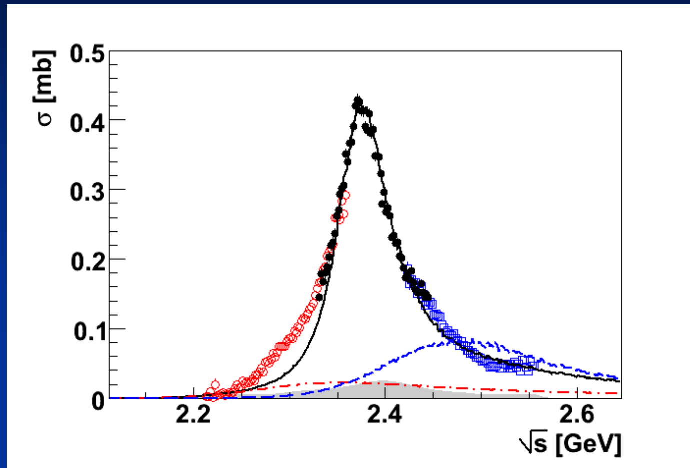


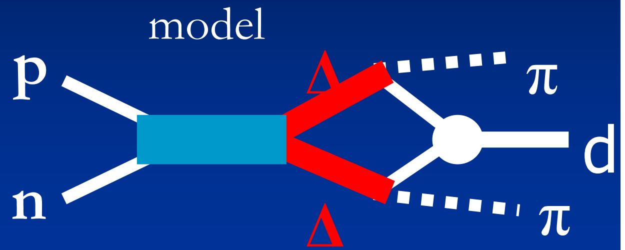
Isoscalar : Results from WASA at COSY



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

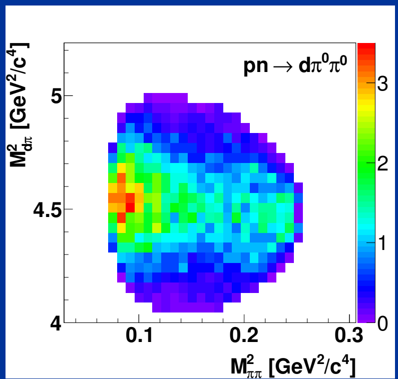
$pn \rightarrow d^* \rightarrow \Delta\Delta \rightarrow d\pi^0\pi^0$

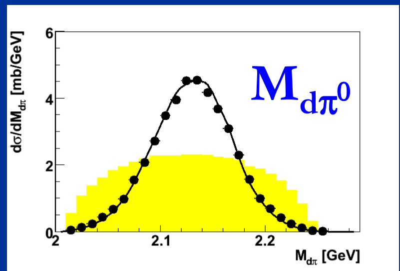




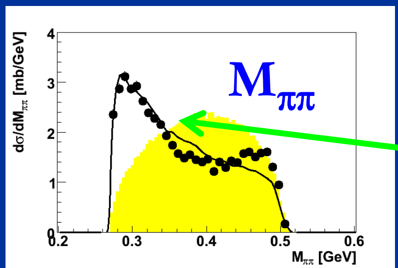
$I(J^P) = 0\,(3^+)$

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

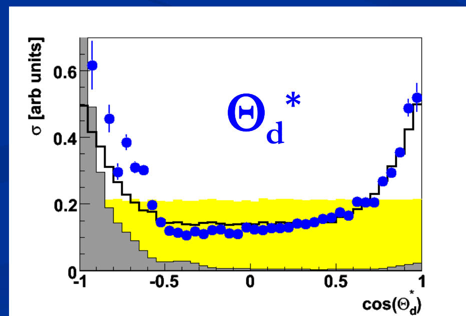




Phys.Rev.Lett.106, 242302 (2011)

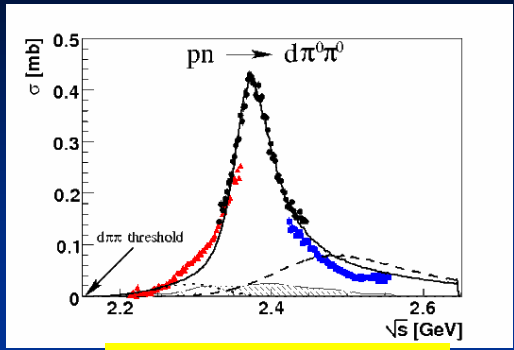


ABC effect

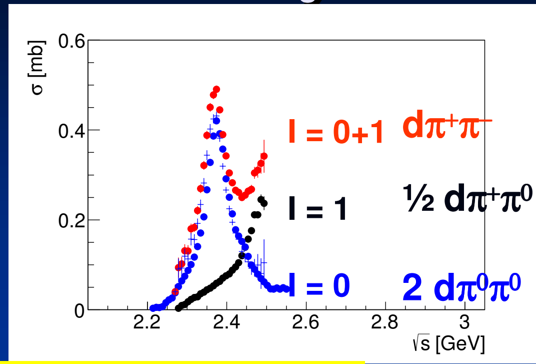


hadronic decays

PRL 106 (2011) 242302



○ ● ● WASA data



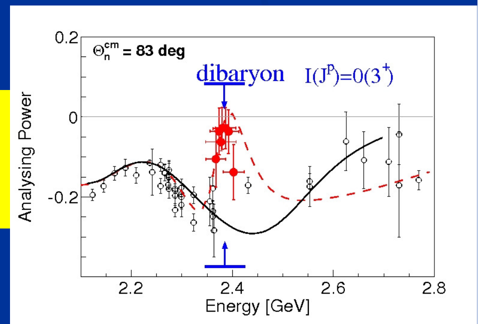
PLB 721 (2013) 229

$d\pi^0\pi^0$

$d\pi^+\pi^-$

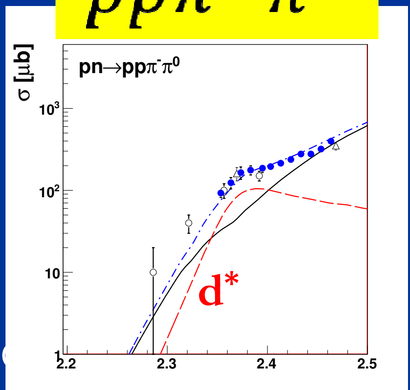
pn → d*(2380)

pn

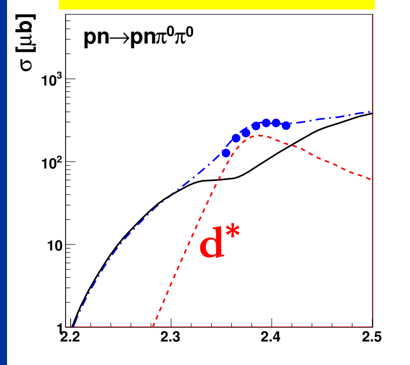


PRL 112 (2014) 202301
PRC 90 (2014) 035204

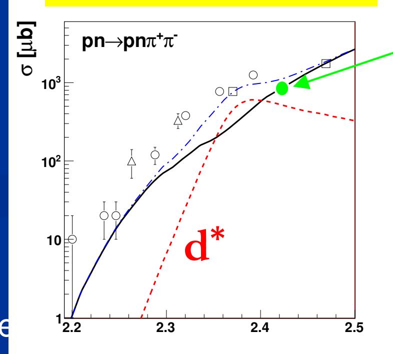
$pp\pi^-\pi^0$



$pn\pi^0\pi^0$



$pn\pi^+\pi^-$



HADES 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

⇔

then also a resonance in the np system

⇔

to be sensed in np scattering

⇔

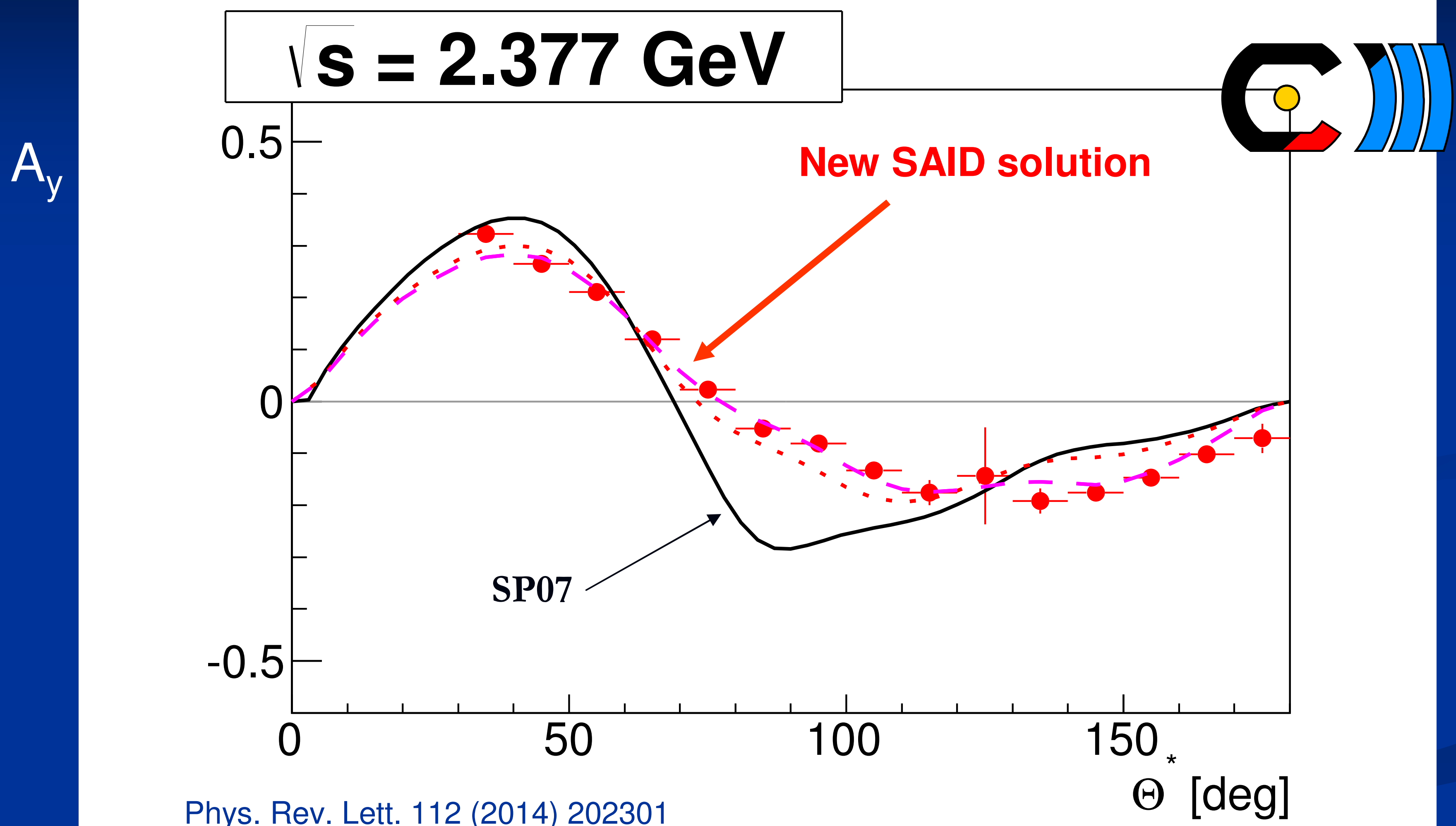
in particular in the analyzing power

⇔

resonance effect ~ $P^1_3(\Theta)$

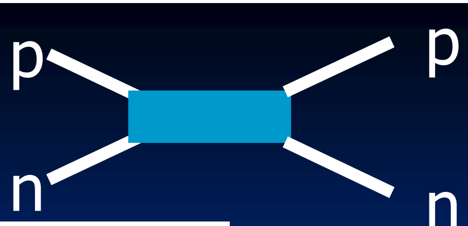
i.e. maximal at $\Theta = 90^0$

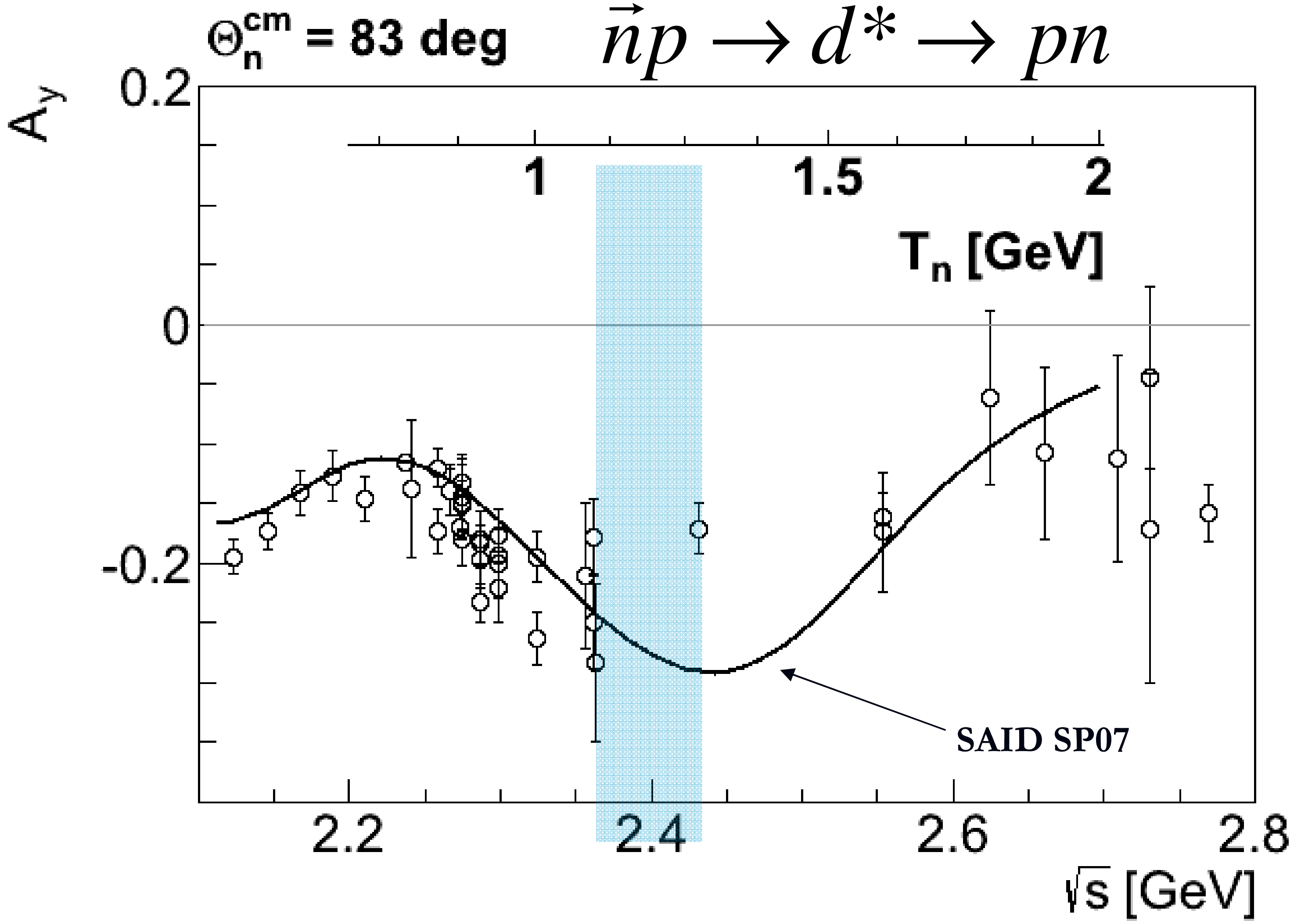
A_y Angular Distribution at Resonance



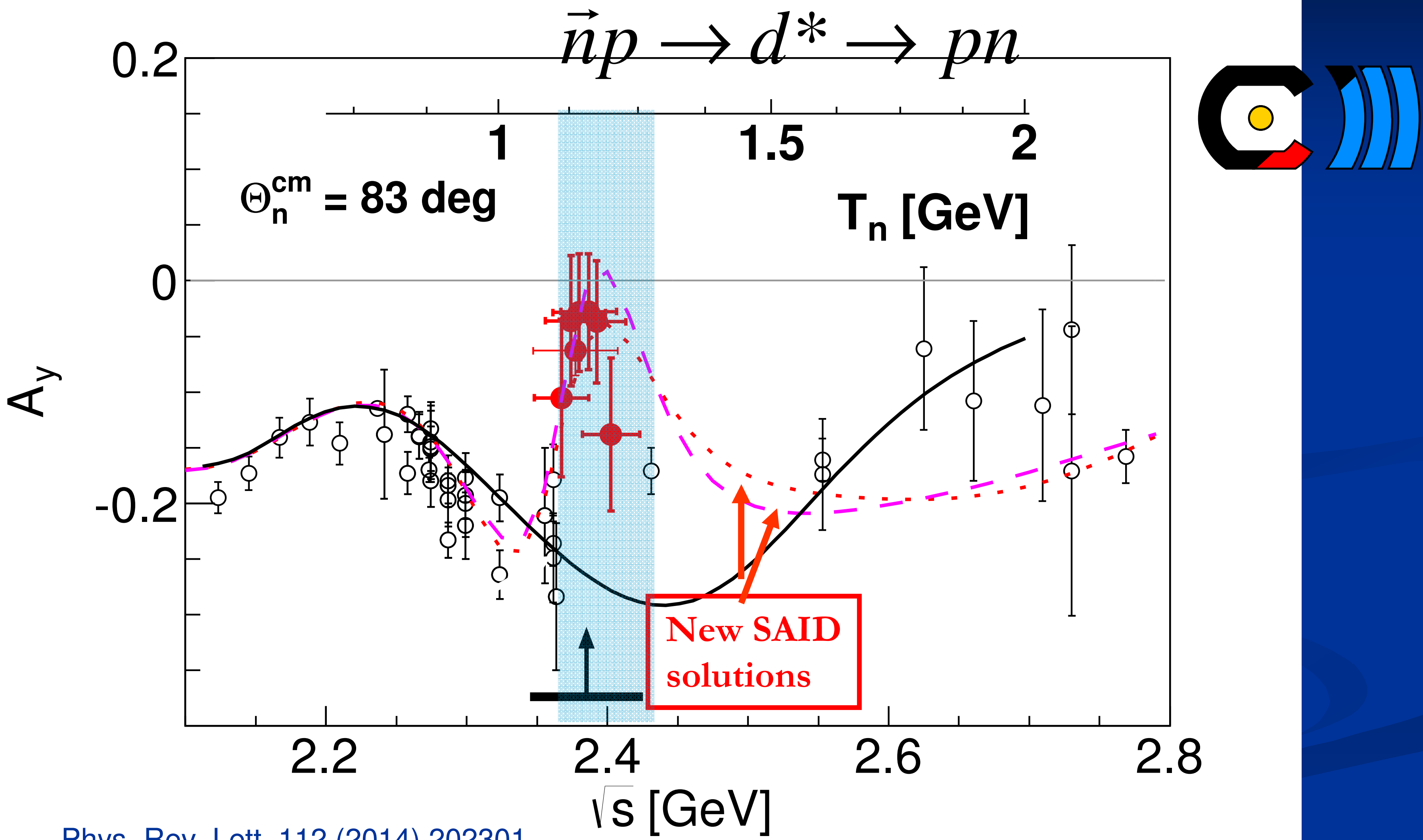
Phys. Rev. Lett. 112 (2014) 202301

Energy Dependence





Energy Dependence

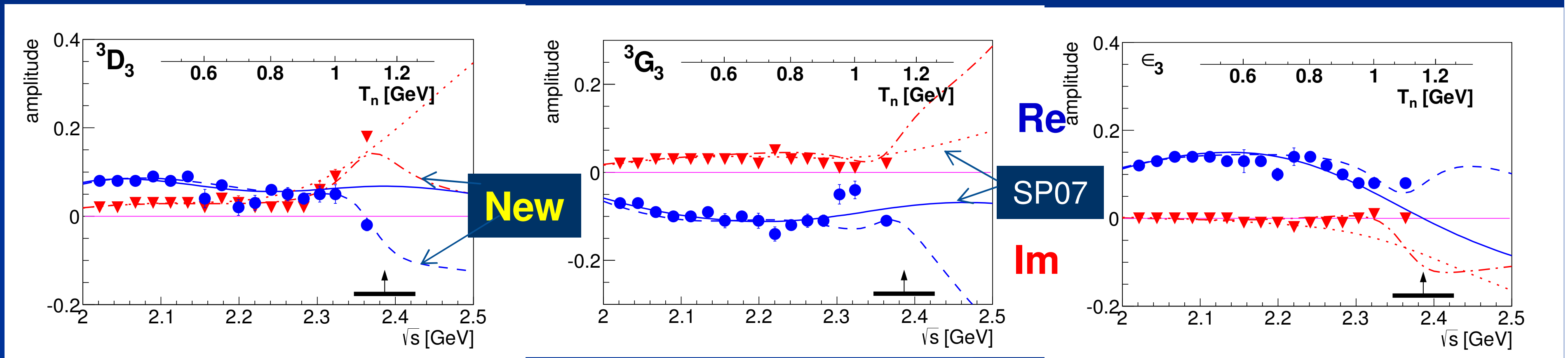


Phys. Rev. Lett. 112 (2014) 202301

SAID Partial-Wave Analysis

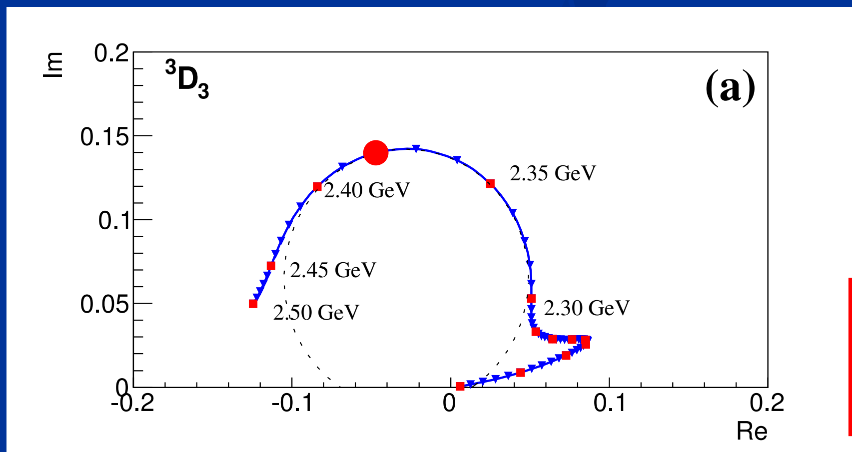
$^3D_3 - {}^3G_3$ Coupled Partial Waves

Phys. Rev. Letters 112 (2014) 202301



Argand diagram:

PRC 90 (2014) 035204

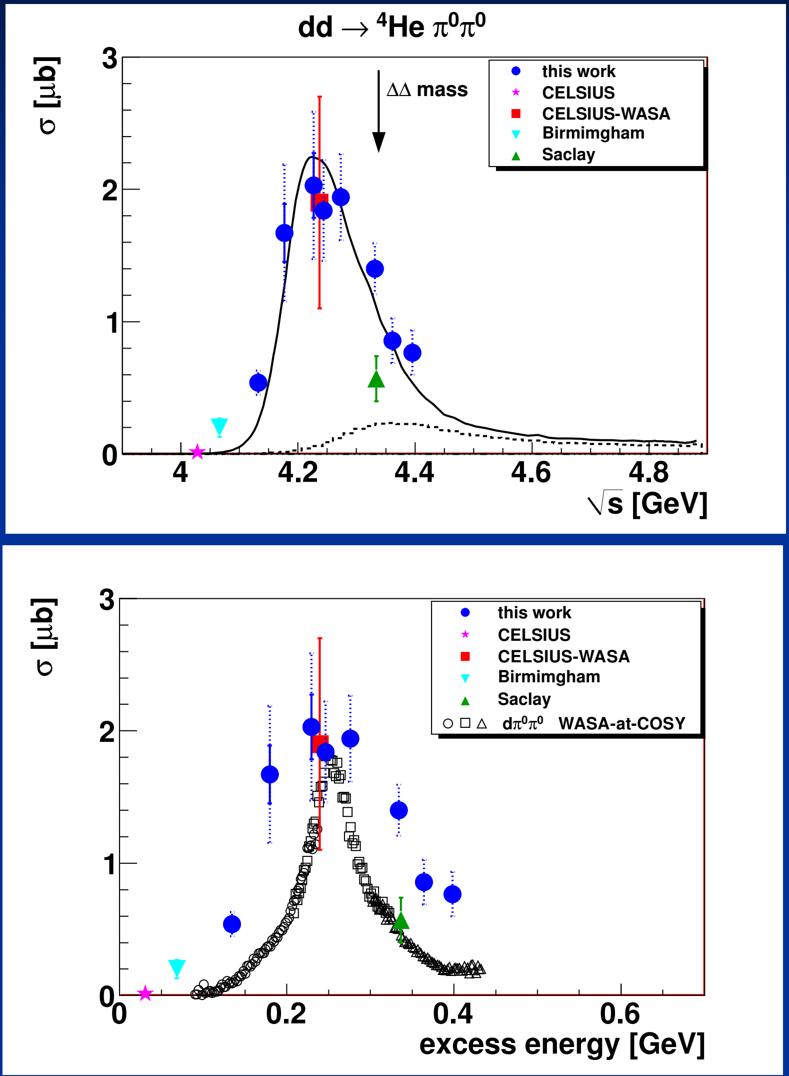


Pole in $^3D_3$ at 2380 ± 10 - i 40 ± 5 MeV

⇔ Genuine Resonance in np System

19

dd → ^{4}He $\pi^0\pi^0$



PRC 86 (2012) 032201(R)

- Energy dependence of total cross section
  - shows resonance structure
  - exactly at the same excess energy as in pn → d$\pi^0\pi^0$
  - is broadened due to Fermi motion and collision damping
- **⇒ d* obviously survives even in nuclear surrounding**

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

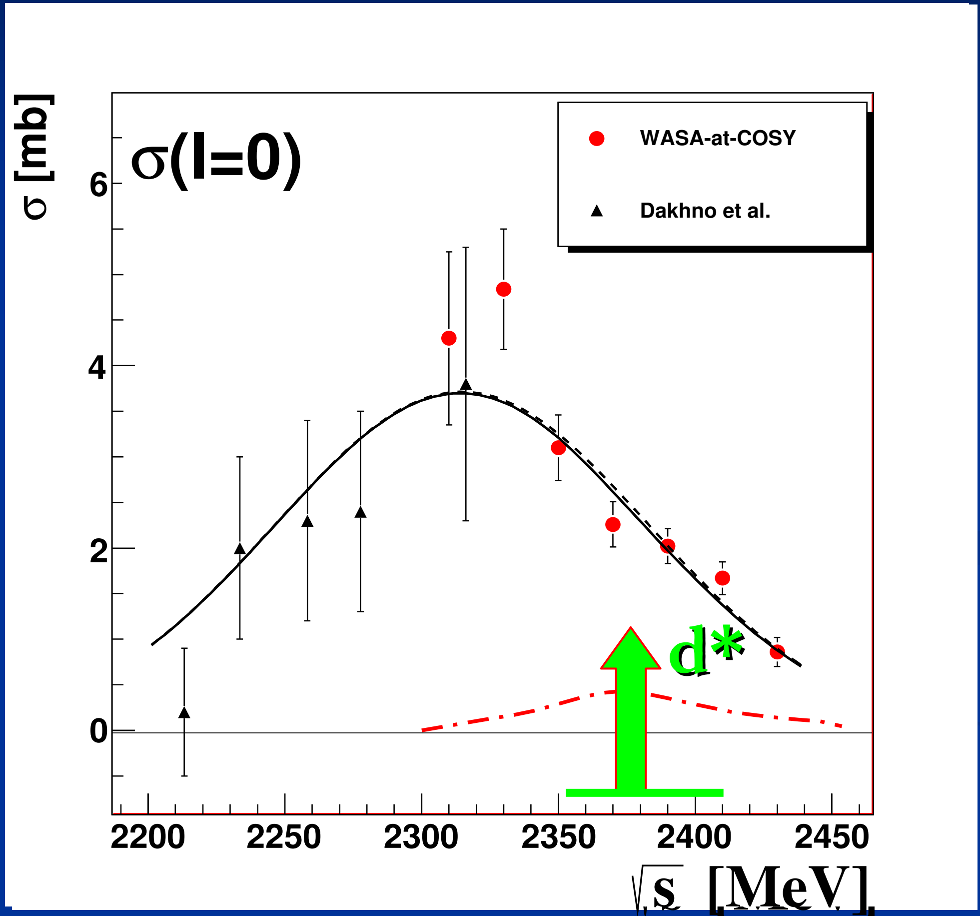
- hadronic decays

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 $\Delta\Delta$ intermediate system

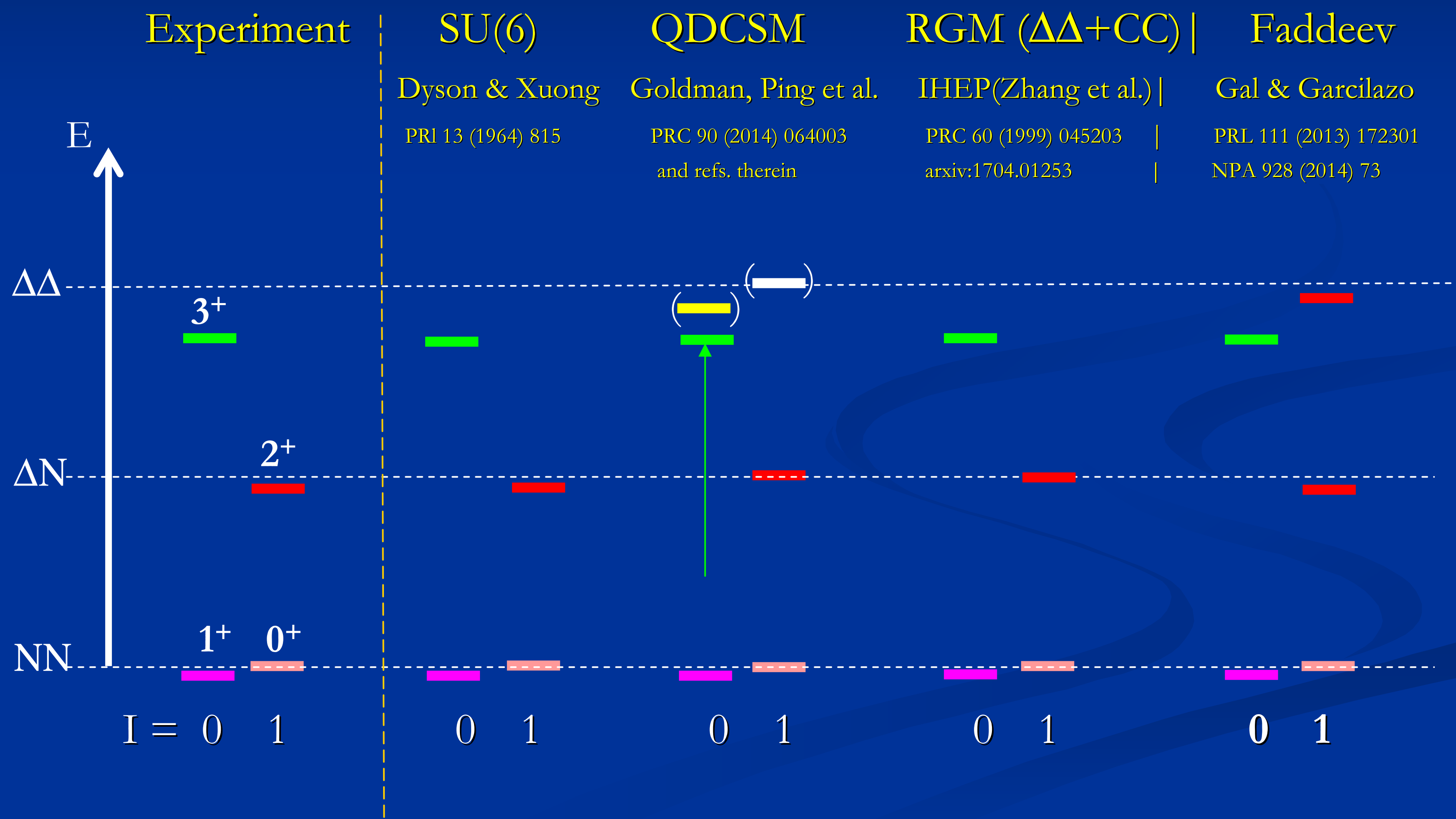
Isoscalar Single-Pion Production



BR < 9%

PLB 774 (2017) 599

Comparison to predictions from Quark and Hadron Models



Width of d*(2380)

- Experiment: **Γ≈ 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) **72** MeV PRC 94 (2016) 014003

Branching via Intermediate State

- $d^* \to \Delta\Delta \to NN\pi\pi$ | $d^* \to {}^1D_2\,\pi \to NN\pi\pi$

IHEP., PRC 94 (2016) 014003 | $NN \leftarrow\!\!|\!\!\rightarrow NN\pi$

Gal. PLB 769 (2017) 436

channel	rel. branching		rel. branching
$d\,\pi^0\pi^0$	1		1
$d\,\pi^+\pi^-$	2		2
$np\pi^0\pi^0$	1		1
$np\pi^+\pi^-$	5/2		5/2
$pp\pi^0\pi^-$	1/2		1/2
np	≈ 0.9	√	0
$(NN\pi)_{I=0}$	≈ 0	√	≈1.3

Identical Isospin Relations

Molecule vs Hexaquark

Size of $d^*(2380)$

- Estimate from uncertainty relation:

$$R \approx \hbar c / \sqrt{2\mu B}$$

$$B_{\Delta\Delta} \approx 80 \text{ MeV} \quad \Rightarrow \quad R \approx 0.5 \text{ fm}$$

- QCD model IHEP 0.8 fm
- QCD model Nangjing (LAMPF) 0.8 fm

} hexaquark

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

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

  PLB 769 (2017) 436

Summary on d*

- $d^*(2380)$ established as a **genuine** s-channel resonance
- It is the first unambiguously detected **non-trivial** dibaryon state.
- Narrow width and decay branchings favor a **compact hexaquark** state.
- LQCD extrapolation by EFT down to pion mass also sees d*(2380) arxiv:1708.08071
- Astrophysical consequences …

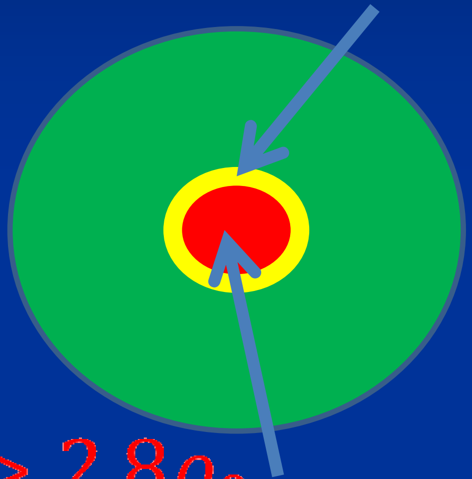
d^* in neutron stars

I. Vidaña, M. Bashkanov, D.P. Watts, A. Pastore, PLB 781 (2018) 112

Urca cooling

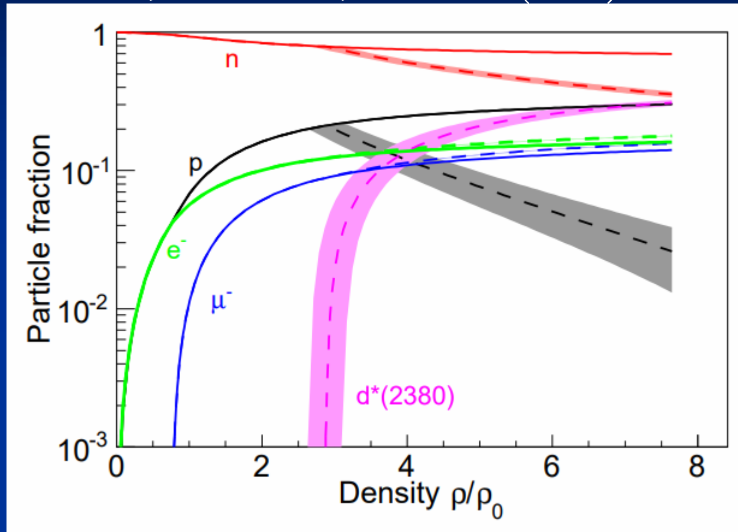
$$d^* \rightarrow nn + e^+ + \nu_e$$

$\rho \sim 2.8\rho_0$



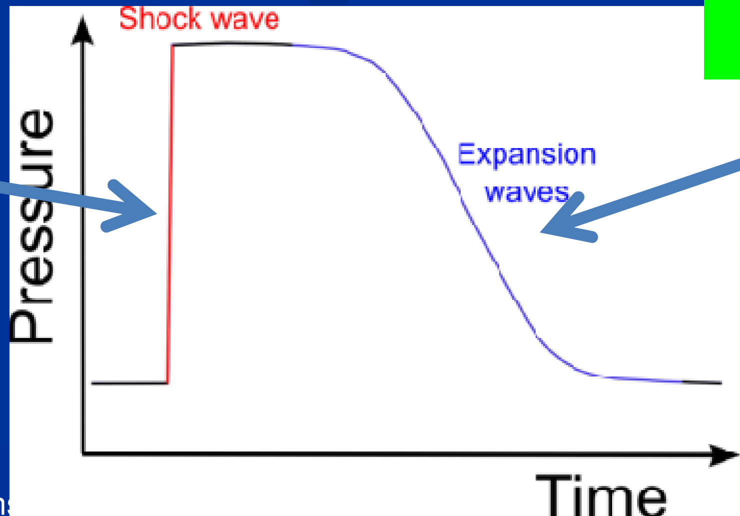
$\rho > 2.8\rho_0$

$$nn \rightarrow d^* + e^- + \bar{\nu}_e$$



Neutron stars mergers

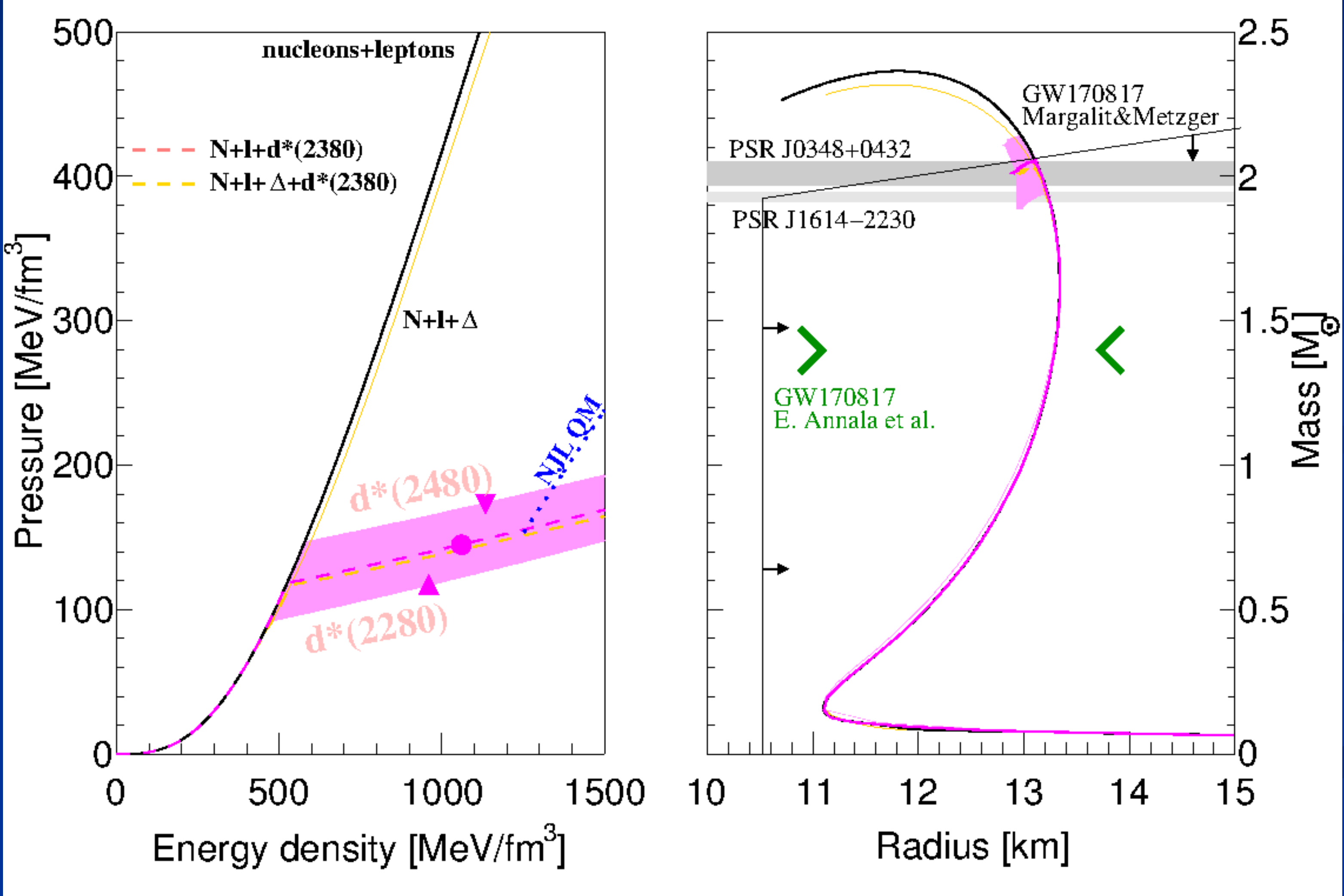
$$d^* \rightarrow pn$$



- Ejecta
- HMNS->black hole
- nucleosynthesis

d* (2380) in neutron stars

I. Vidaña, M. Bashkanov, D.P. Watts, A. Pastore, Phys.Lett. B781 (2018) 112



Rèsumè

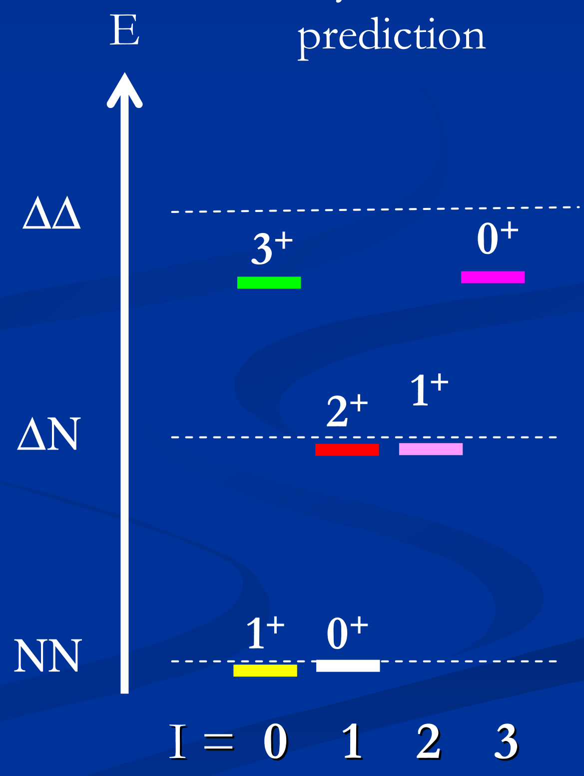
Zhang, Chen, Shen et al.

Huang, Ping, Wang et al.

Gal & Garcilazo

Dyson's prediction

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



Where can D_{21} be seen?

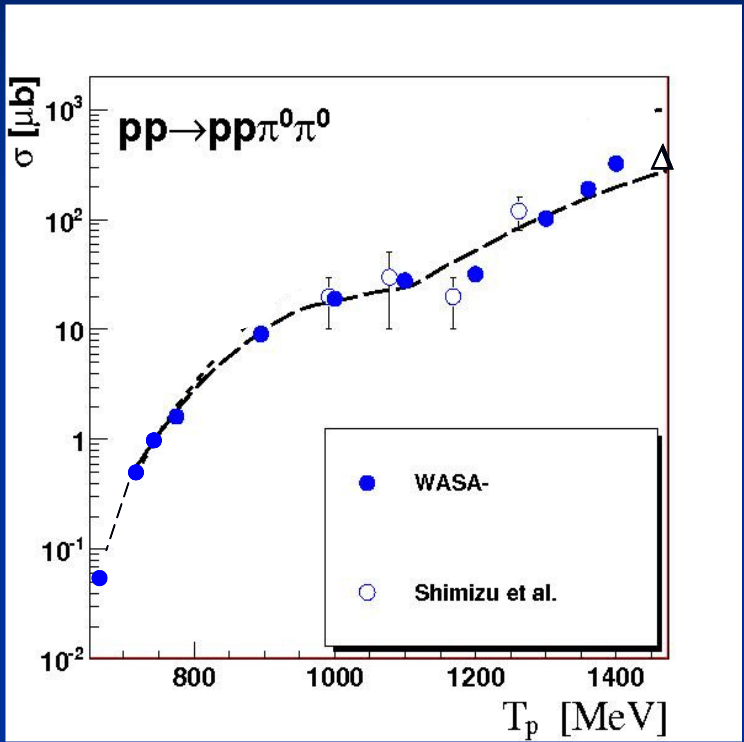
I=2 ⇒ only associated production

$$pp \rightarrow \boxed{pp\pi^+}\,\pi^-$$

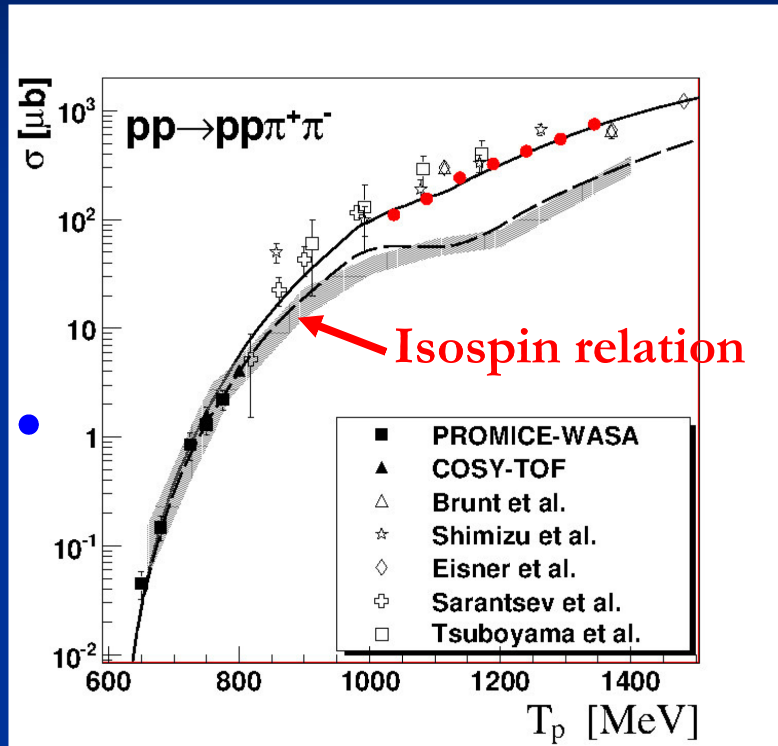
⇓

$$\mathbf{D_{21}}$$

Total cross section



PLB 695 (2011) 115



PRL 121 (2018) 052001

- - - - - - - modified Valencia model (Roper + ΔΔ)

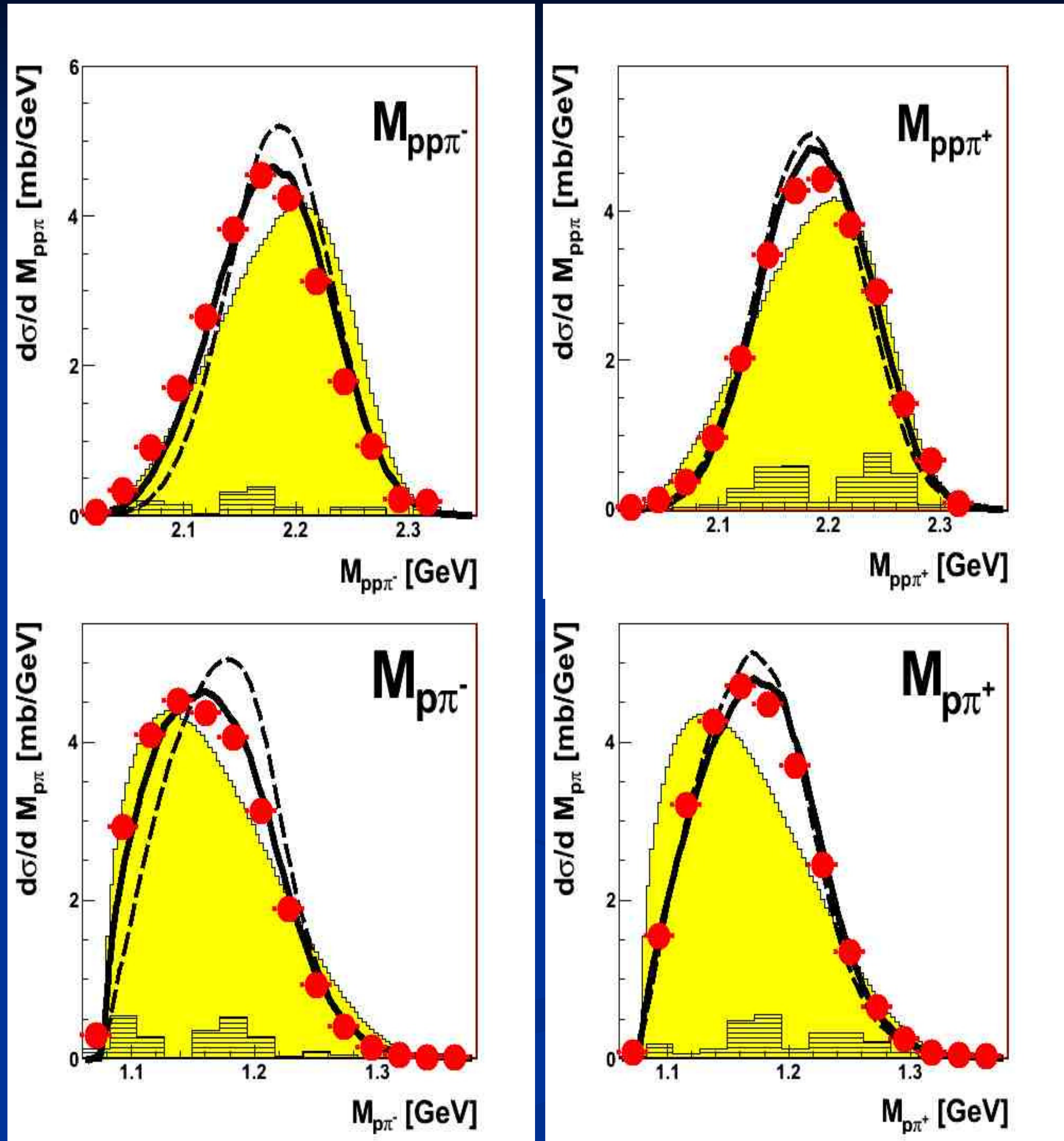
——— modified Valencia model (Roper + ΔΔ) + D_{21}

T_p=1.2 GeV

Invariant Mass Distributions

- - - - - - - -
modified Valencia model

———————
modified Valencia model **+ D_{21}**



N.B.: If ΔΔ dominates :
$M_{p\pi+} = M_{p\pi-}$

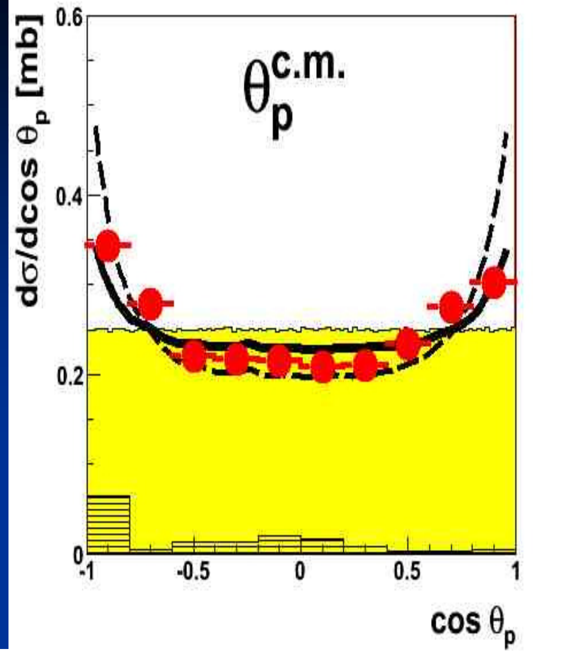
PRL 121 (2018) 052001

Angular distributions

T_p=1.2 GeV

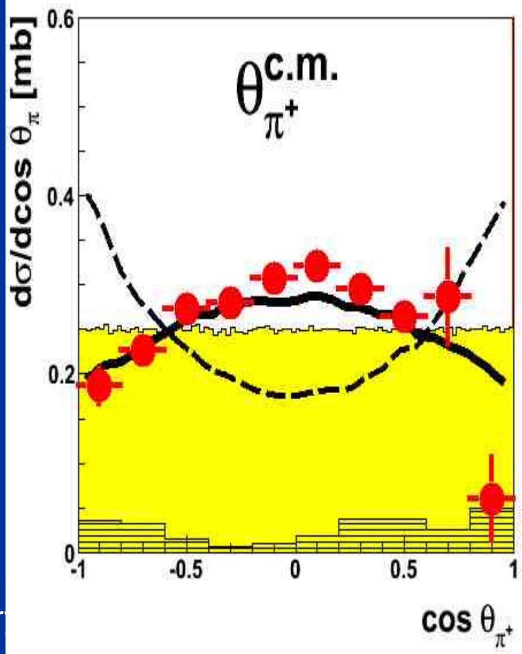
- - - - - - - modified Valencia model

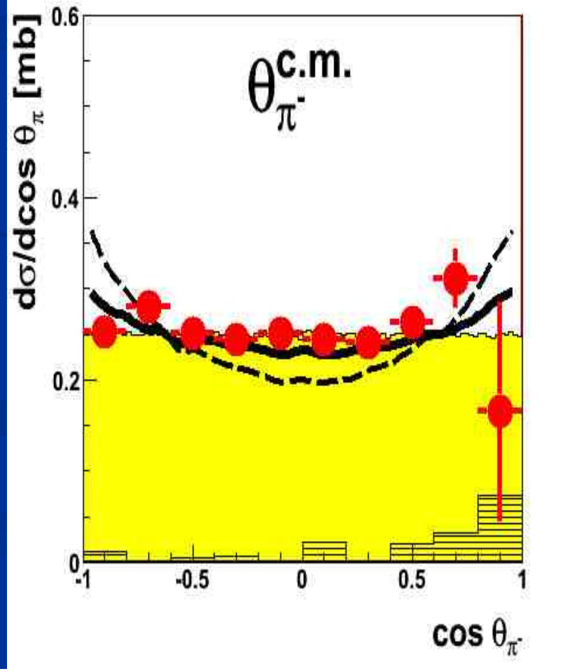
——— modified Valencia model + D_{21}



N.B: If ΔΔ dominates
$\theta_{\pi+} = \theta_{\pi-}$

PRL 121 (2018) 052001





Conclusions on D_{21}

- isospin relations for total cross sections demand the opening of a new isotensor contribution in $pp \to pp\pi^+\pi^-$.

- differential $M_{p\pi-}$ and $\theta_{\pi+}$ distributions show a clear deviation from the modified Valencia model calculations.

- total and differential cross sections agree well with assumption that in the $pp \to pp\pi^+\pi^-$ channel there is an additional production mechanism – the associated production of the isotensor ΔN state $D_{21.}$

- **m = 2140(10) MeV, Γ = 110(10) MeV $\Rightarrow$ same as D_{12} !**

(Molecular) States near ΔN Threshold

	I = 1		I = 2
S-wave:	2^+ $(^1D_2)$	D_{12}	1^+ $(^3P_1)$ D_{21}
P-wave:	0^- $(^3P_0)$	COSY-ANKE	
	2^- $(^3P_2)$	-"- , SAID	
	3^- $(^3F_3)$	SAID (?)	

Where can D_{30} be seen?

I=3 ⇒ only associated production

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

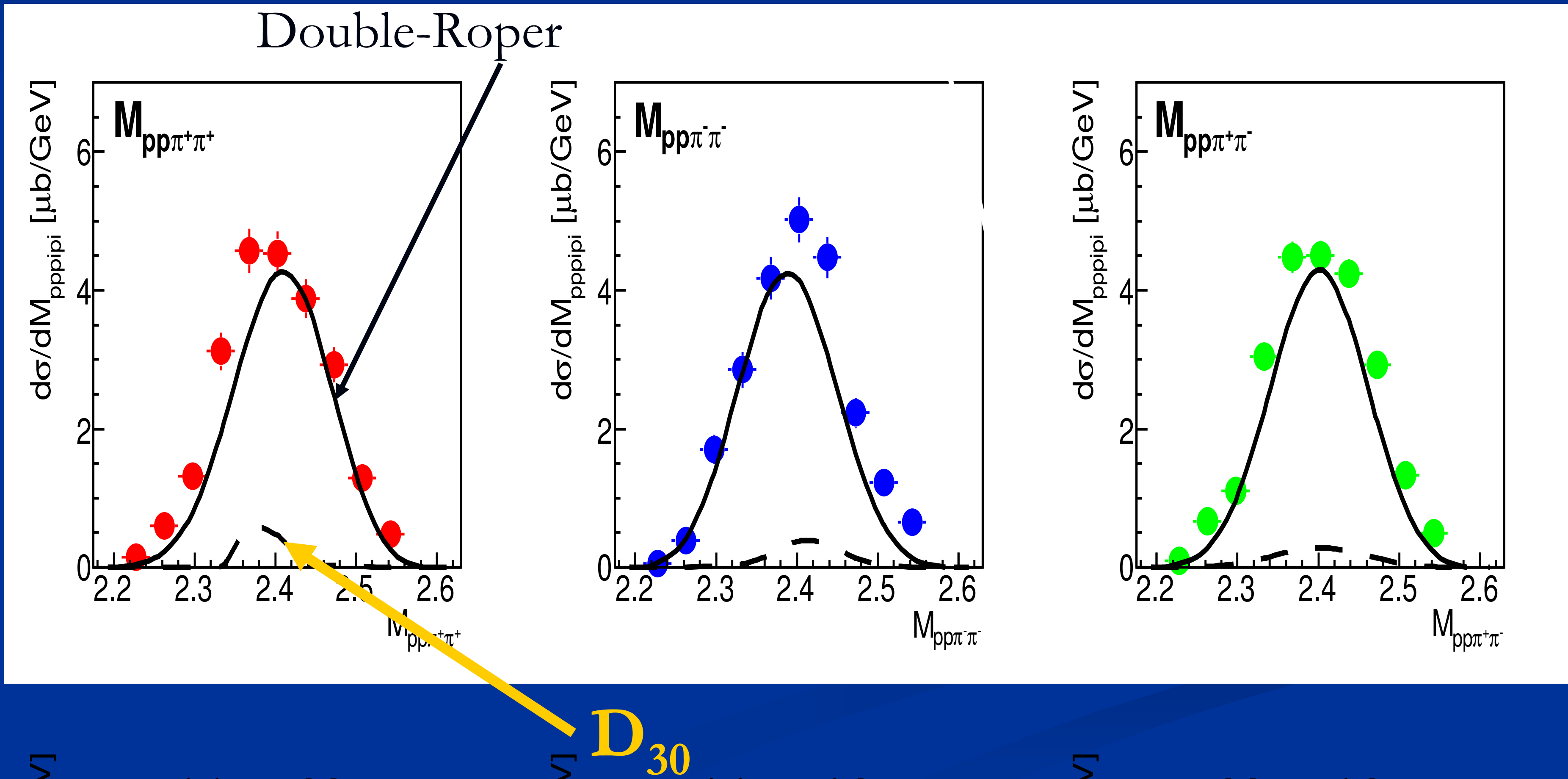
$$\downarrow$$

$$D_{30}$$

$pp \rightarrow D_{30}\, \pi^- \pi^- \rightarrow pp\pi^+\pi^+\pi^-\pi^-$

T_p = 2.541 GeV

Phys.Lett. B762 (2016) 445



D_{30} dibaryon upper limit

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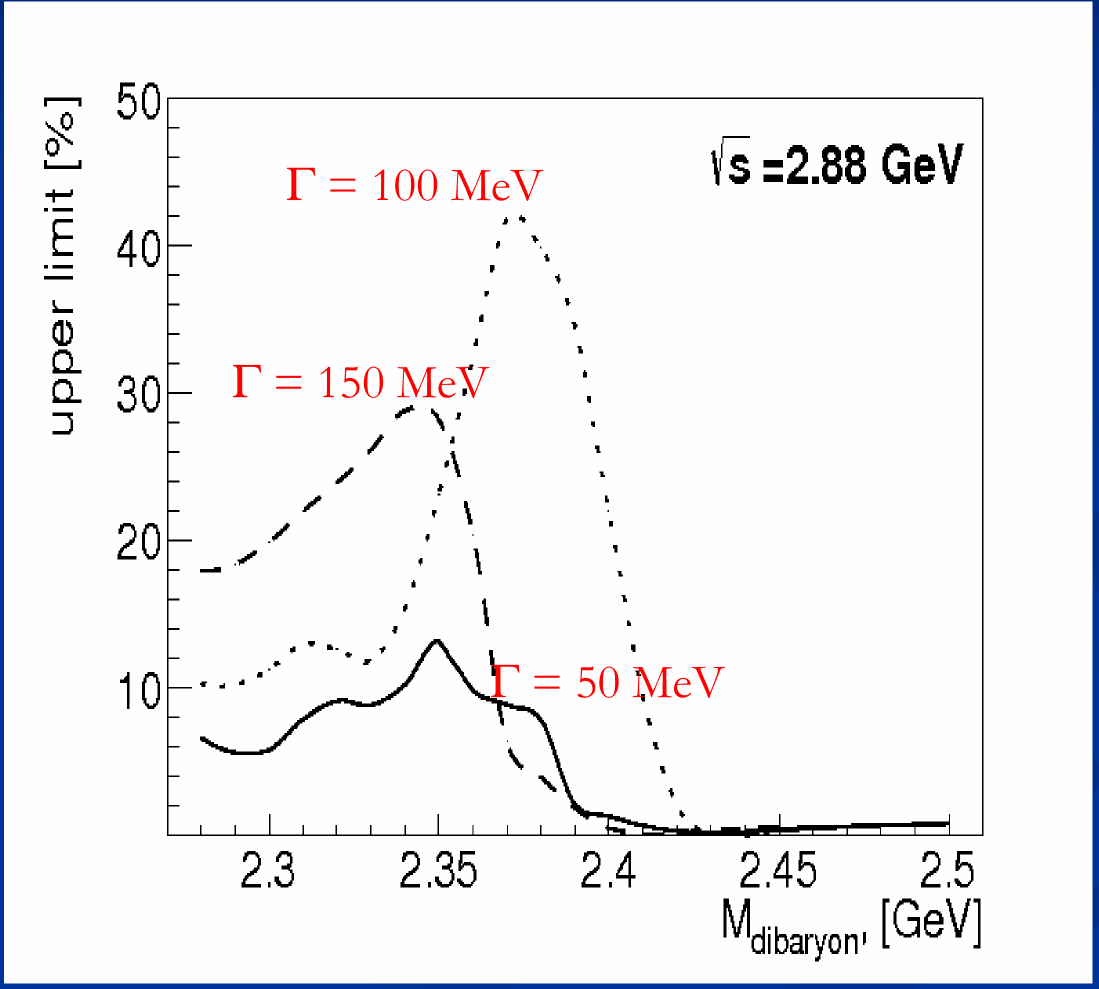


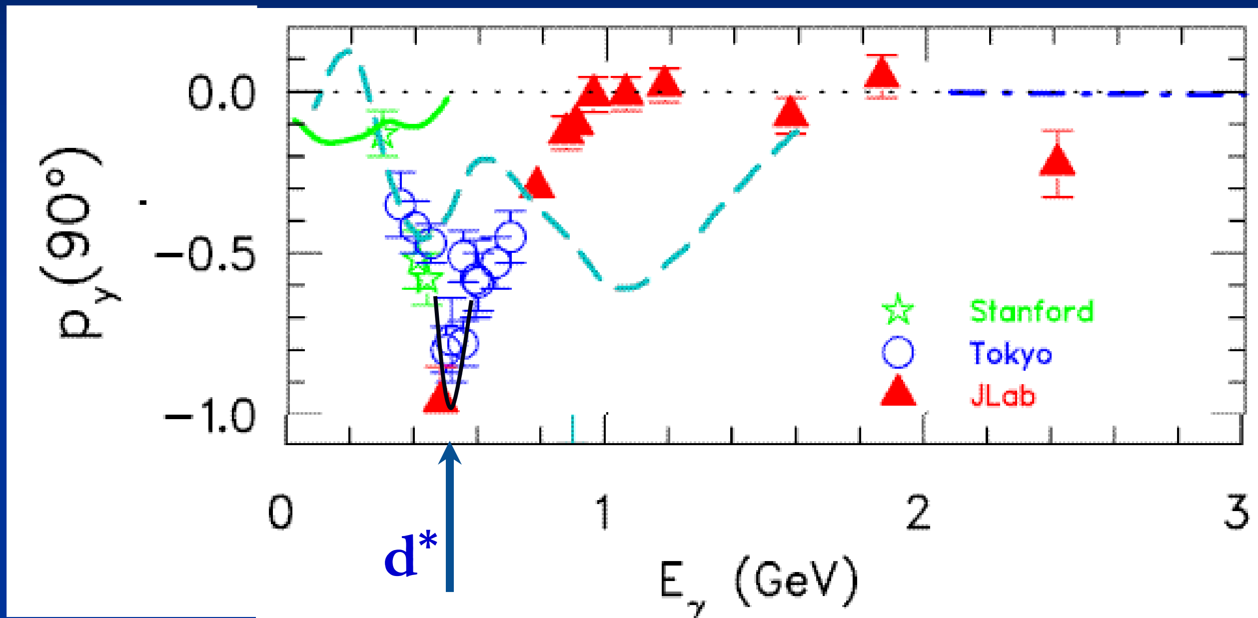
Conclusions on D_{30}

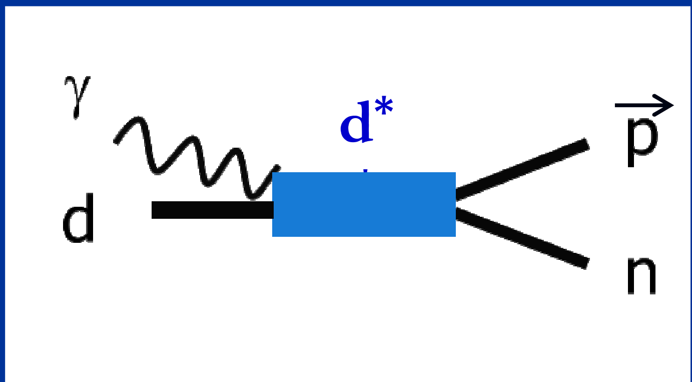
- only upper limit so far
- both background model and data to be improved
- check associated production with d*(2380)

Outlook and Open Problems

- Size of $d^*(2380)$
  - $\Rightarrow$ elm excitation of d^* $\gamma d \rightarrow d^* \rightarrow pn$
  - $ed \rightarrow ed^* \rightarrow ed\pi^0\pi^0$
- Observation at other installations
  - HADES @ GSI: under way, but no 4π
  - IHEP ?? $e^+e^- \rightarrow \bar{d}\, d^*$ at 4.3 – 4.6 GeV ??
  - KEK, JPARC, LHCb, others ???
- Are there more (exotic) dibaryons?
  - D_{30} mirror state of d^*
  - strange, charmed dibaryons??

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



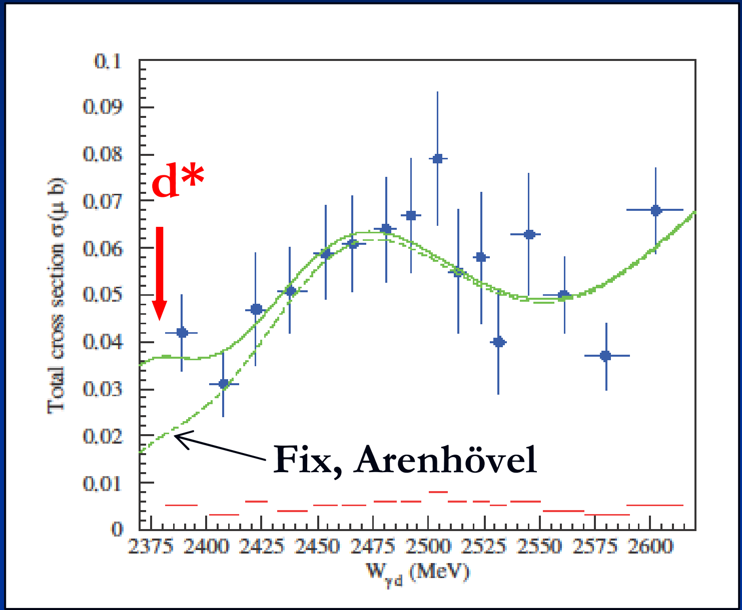


R. Gilman and F. Gross AIP Conf. Proc. 603 (2001) 55
K. Wijesooriya et al., Phys. Rev. Lett. 86 (2001) 2975

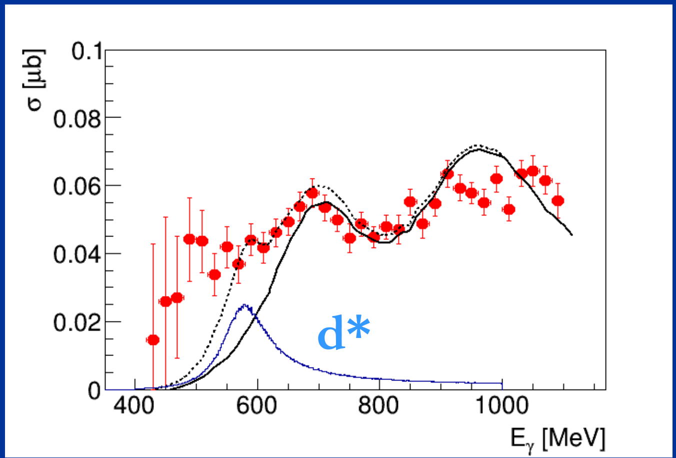
T. Kamae, T. Fujita Phys. Rev. Lett. 38 (1977) 471

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

$\gamma\, d \rightarrow d\pi^0\pi^0$



FOREST@ELPH,
Ishikawa et al., PLB 772 (2017) 398



Crystal Ball @ MAMI
Master Thesis M. Guenther, Basel 2015
PoS (Hadron2017) 051

Outlook and Open Problems

- Size of $d^*(2380)$
  - $\Rightarrow$ elm excitation of d^* $\gamma d \rightarrow d^* \rightarrow pn$
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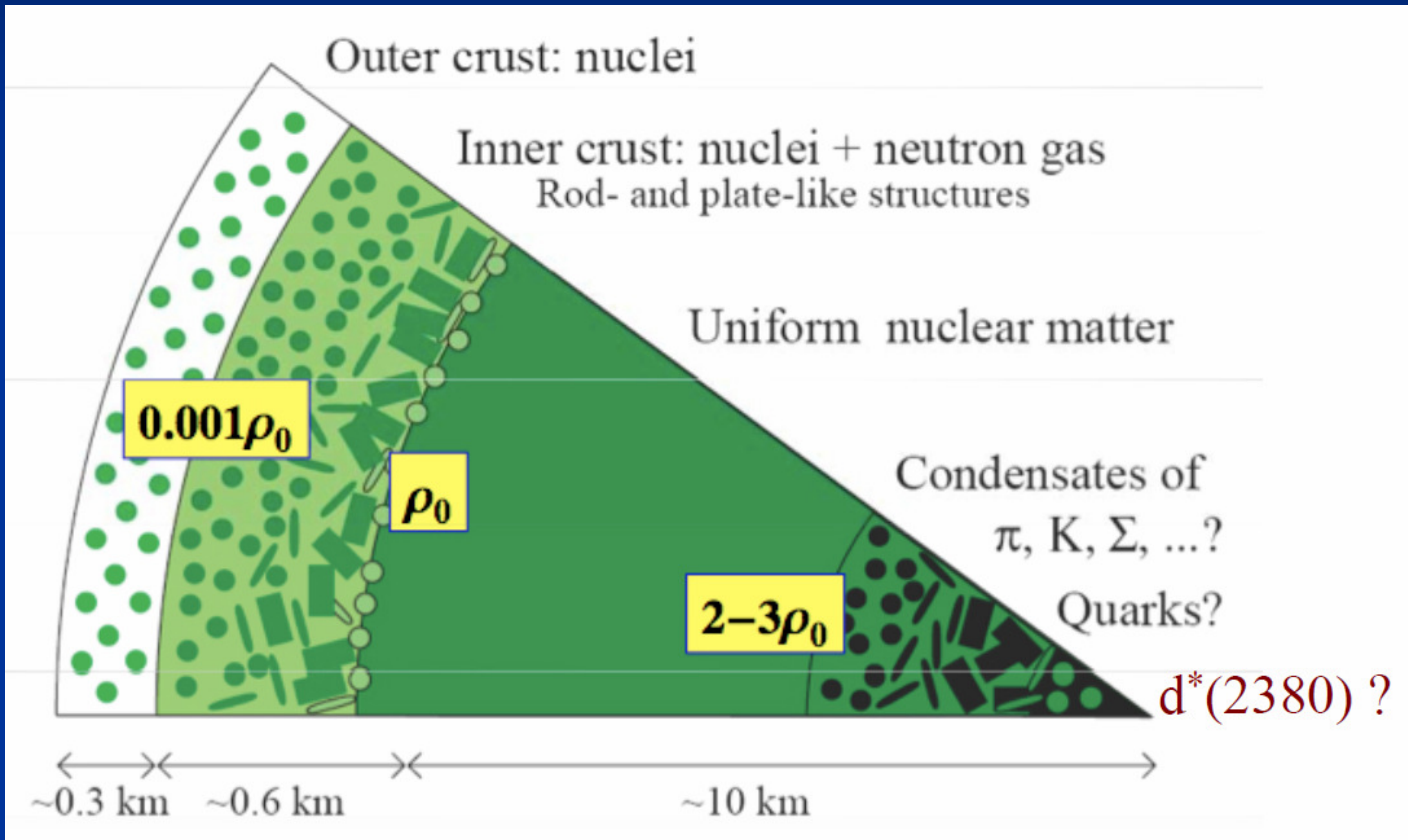
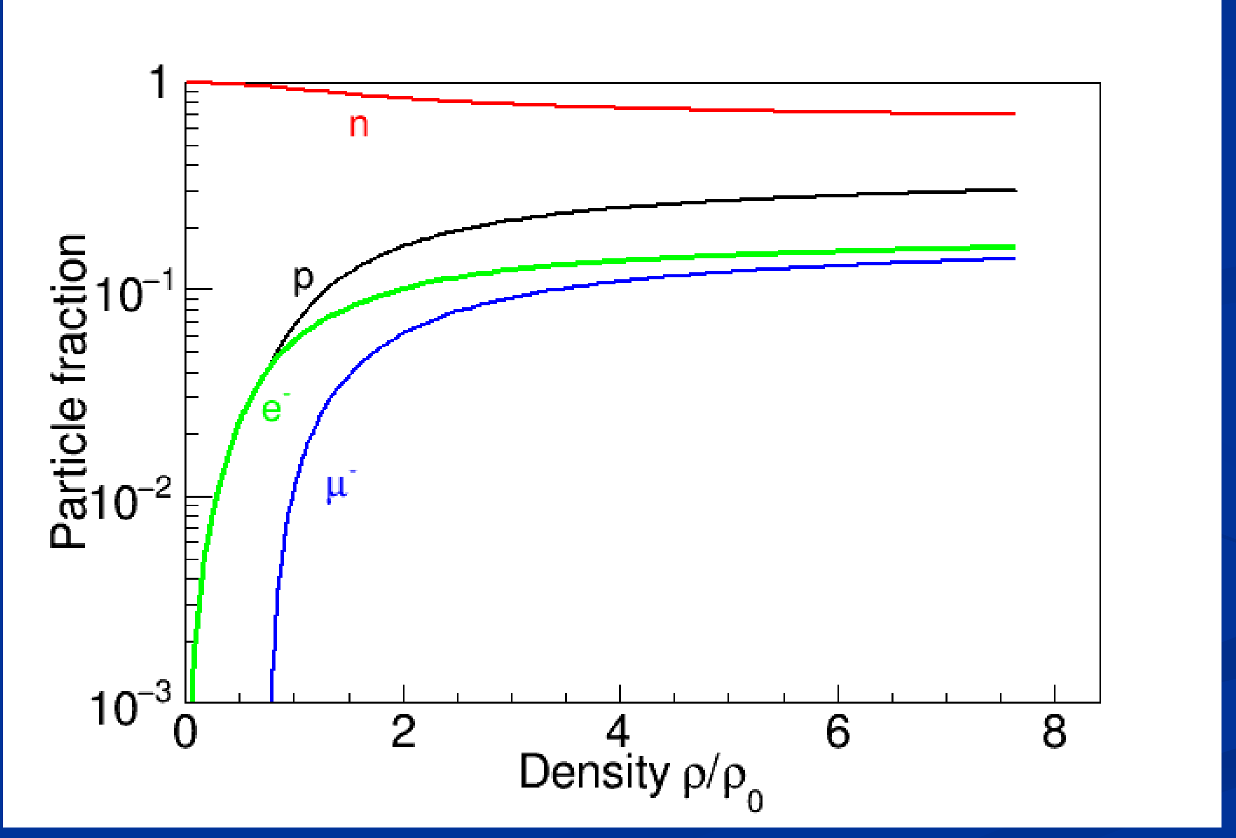
Nuclear matter at high density



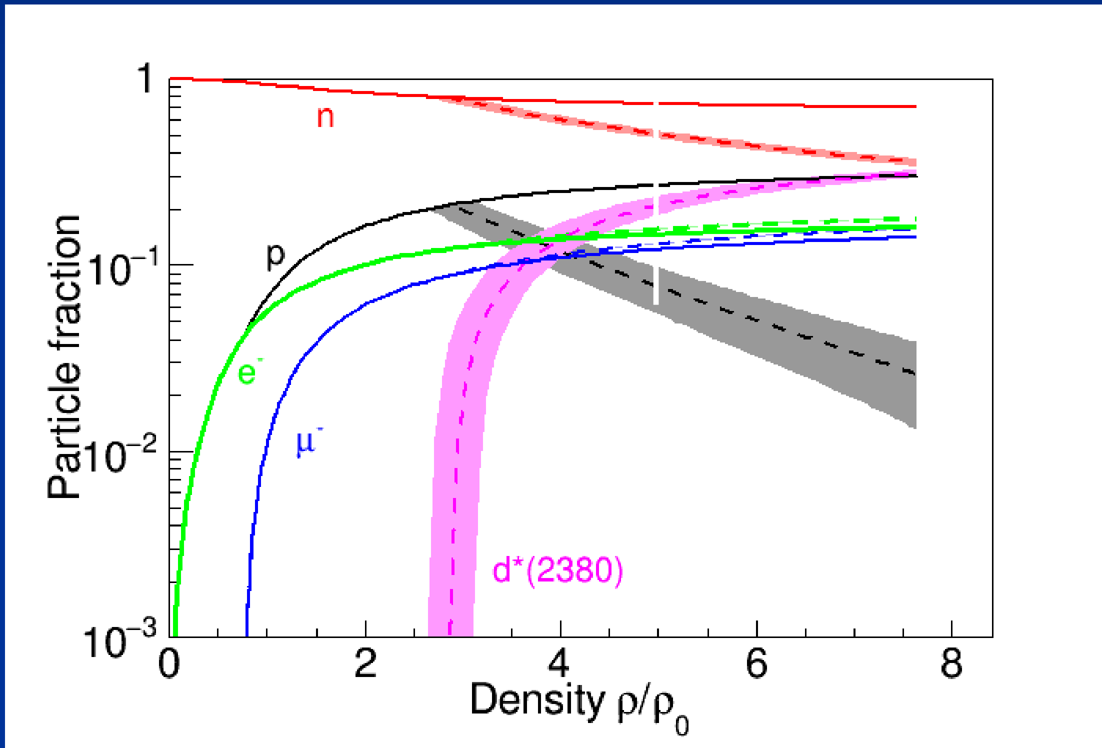
Neutron stars EoS

I. Vidaña, M. Bashkanov, D.P. Watts, A. Pastore
Phys.Lett. B781 (2018) 112



The d*(2380) in neutron stars

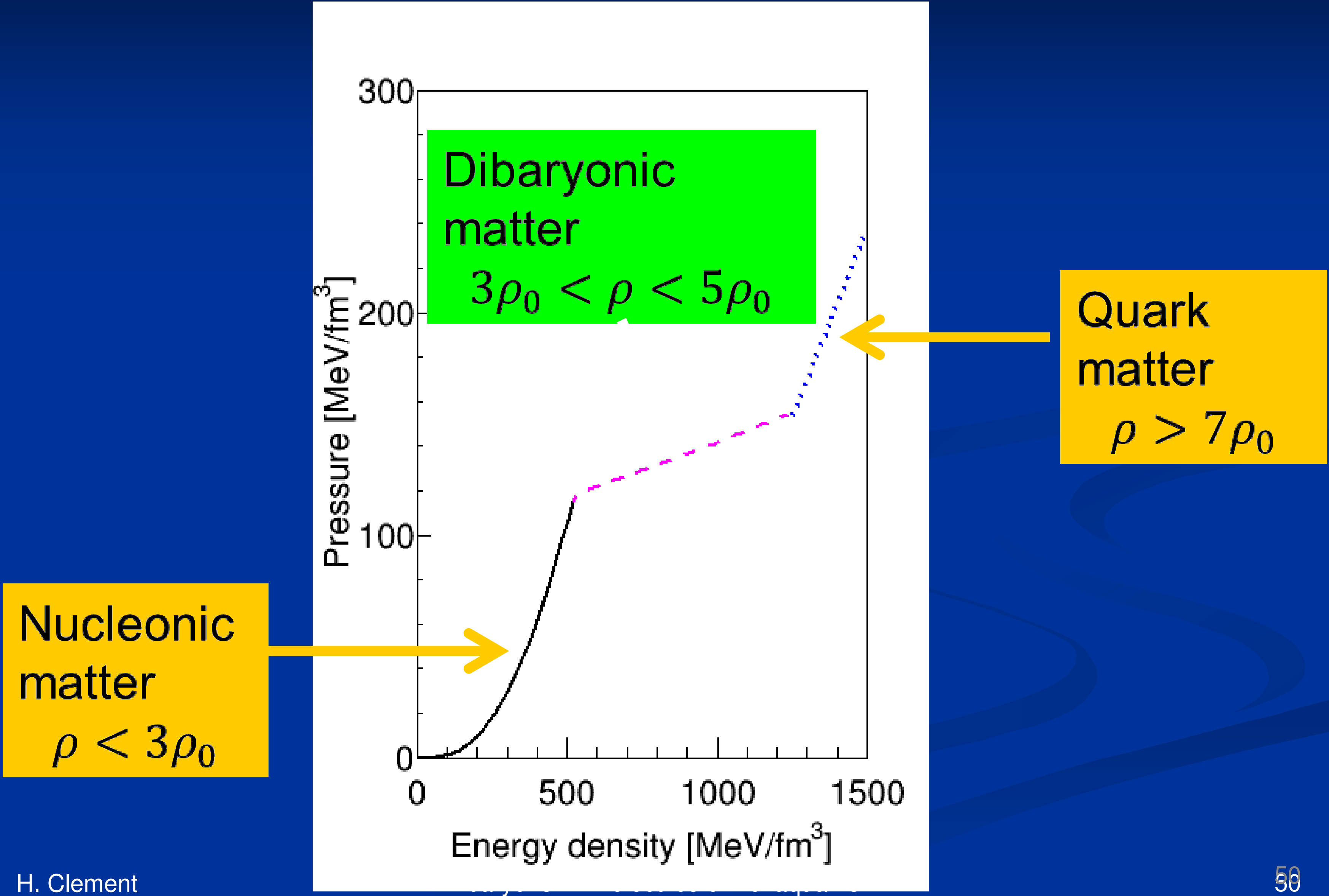
a new degree of freedom?



The Roper resonance = No molecule

I. Vidaña, M. Bashkanov, D.P. Watts, A. Pastore, PLB 781 (2018) 112

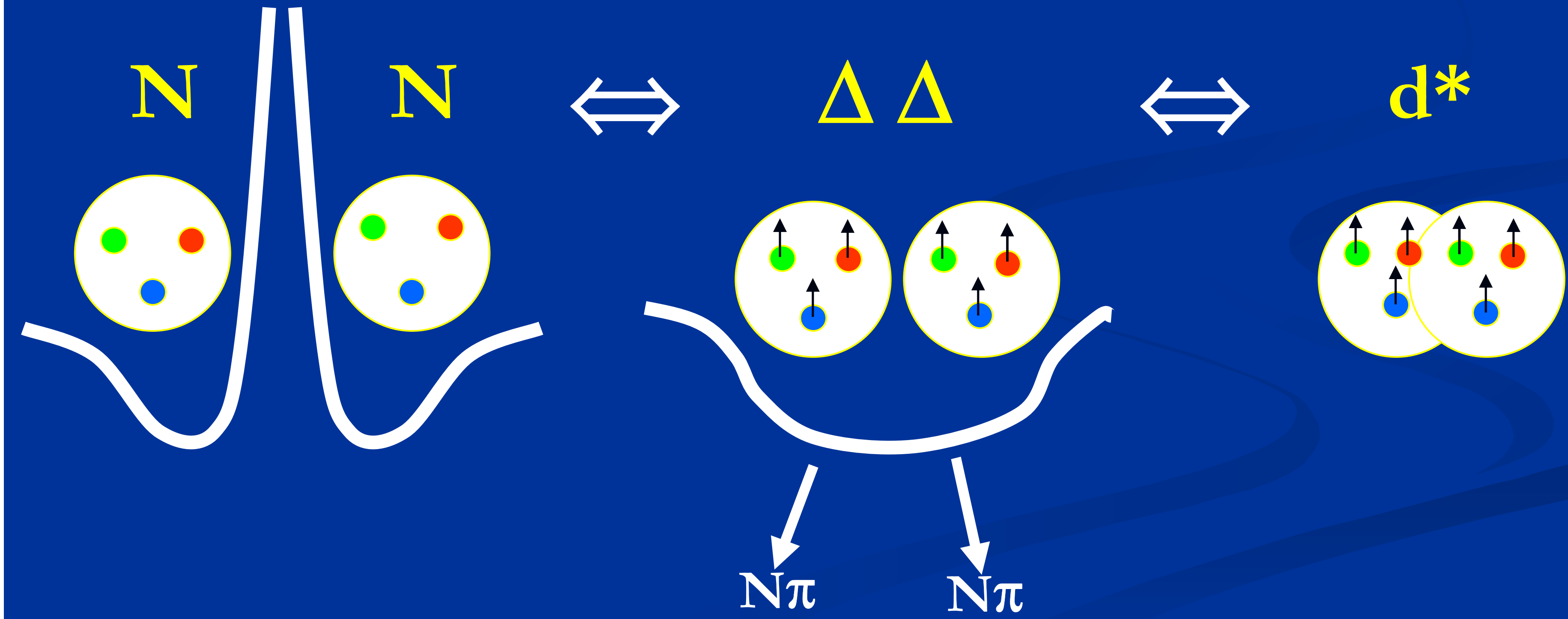
From Nucleons to Quarks



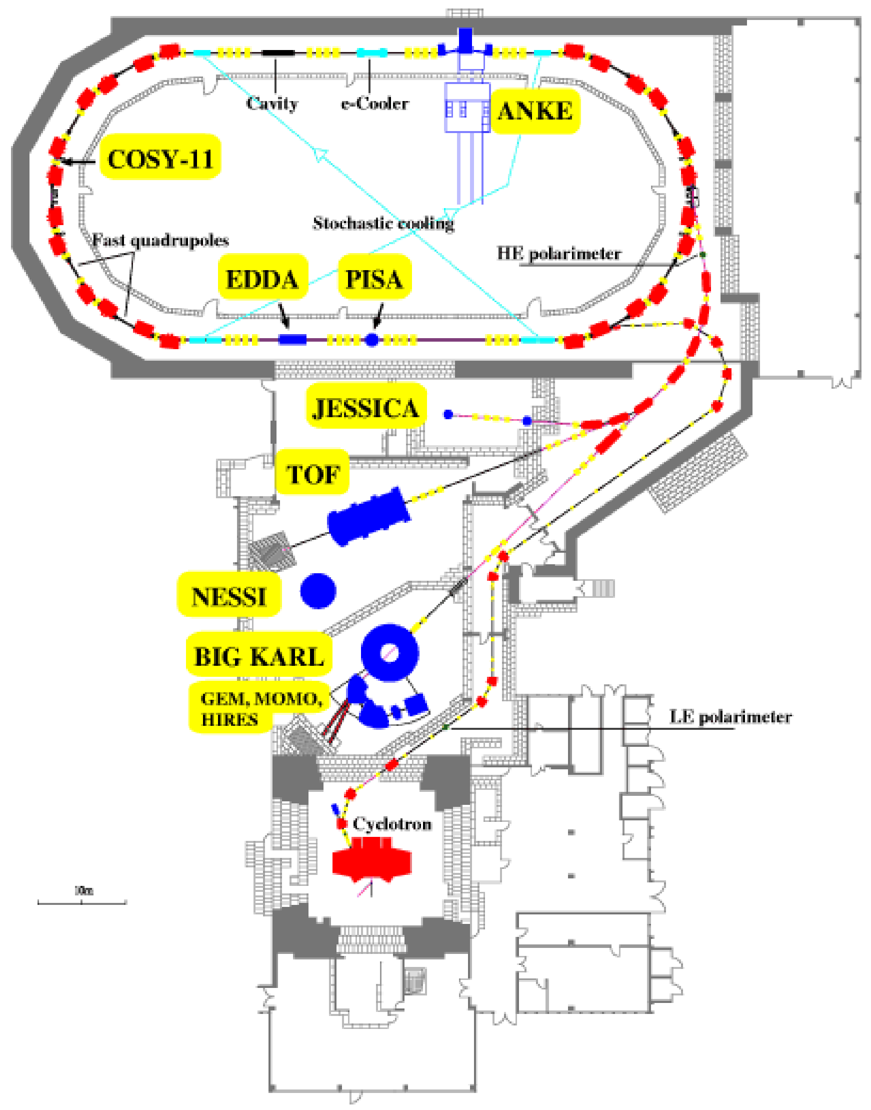
… inevitable dibaryon

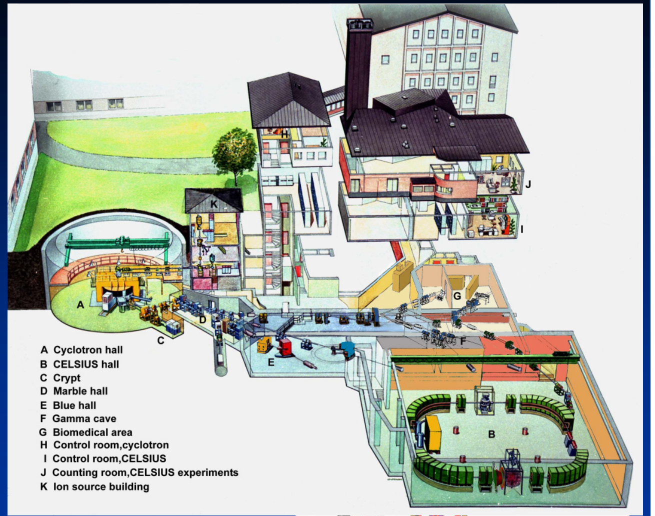
$I(J^P) = 0(3^+)$ state: totally symmetric in space, spin & color
antisymmetric in isospin

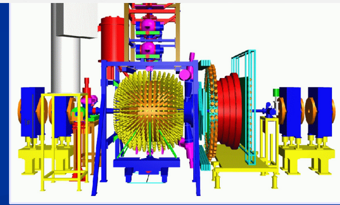
accessed via ΔΔ as doorway ?



WASA at COSY







2005 - 2006

CELSIUS/WASA

WASA 4π Detector

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