EBERHARD KARLS
UNIVERSITÄT
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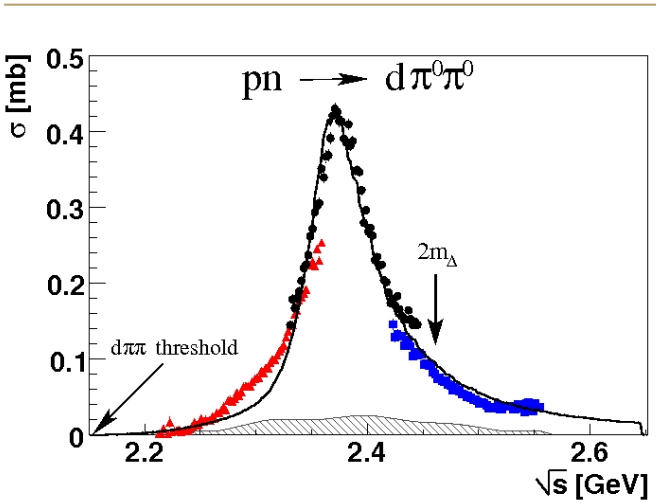
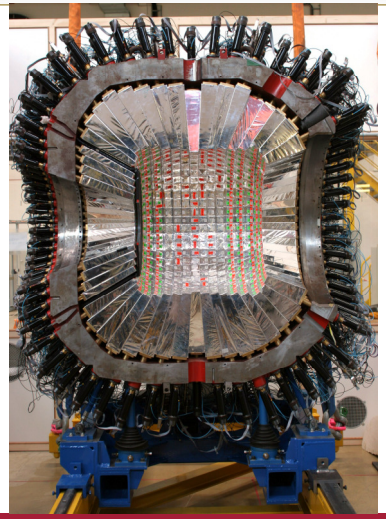
Kepler Center for Astro and Particle Physics

Fachbereich Physik





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The ABC Effect and the Occurrence of a Dibaryon Resonance

MIN 2016

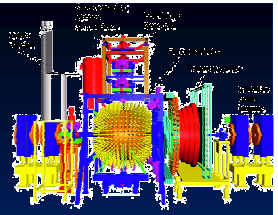
Kyoto July 31 – August 2, 2016

Heinz Clement

The ABC Effect

- … denotes a **low-mass enhancement** in the $M_{\pi\pi}$ spectrum of nuclear two-pion production
- … only shows up in double-pionic **fusion** reactions, if the produced $\pi\pi$-pair is **isoscalar**
- … is named after **A**bashian, **B**ooth and **C**rowe, who were the first to observe this phenomenon in 1960
- … is now found to be **strictly correlated** with the appearance of the **dibaryon resonance d*(2380)**

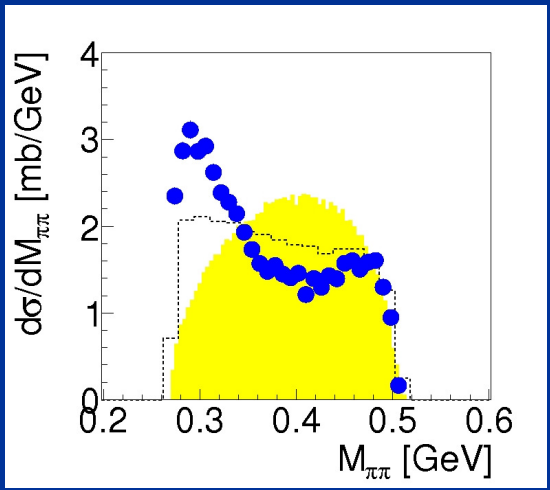
The ABC Gallery



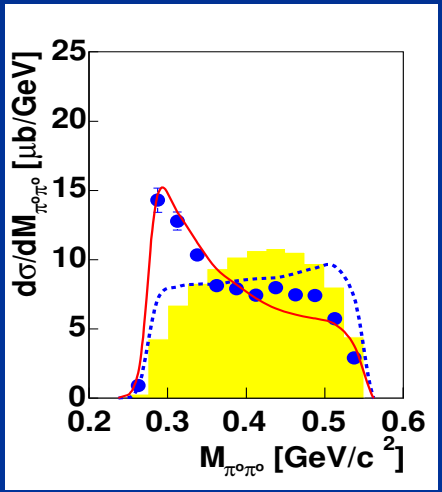
$pn \rightarrow d\,\pi^0\pi^0$ @ 1.1 GeV

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

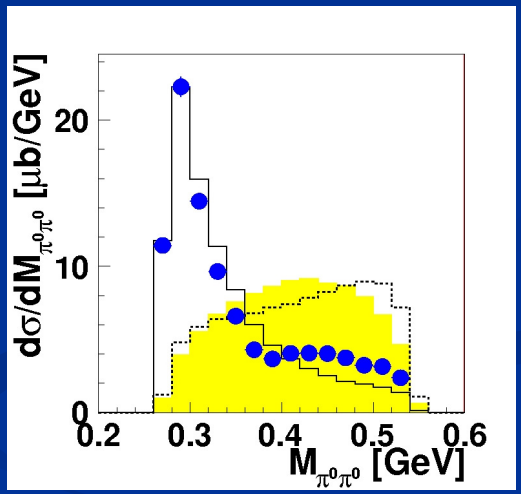
$dd \rightarrow {}^4He\,\pi^0\pi^0$ @ 1.1 GeV



PRL 106 (2011) 202302



PL B 637 (2006) 223

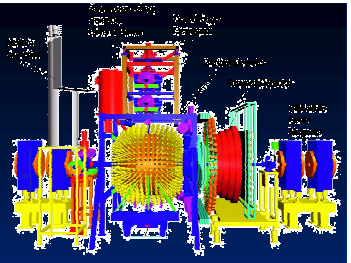


PRC 86 (2012) 032201(R)

heavier nuclei ??

CELSIUS-WASA and WASA-at-COSY measurements

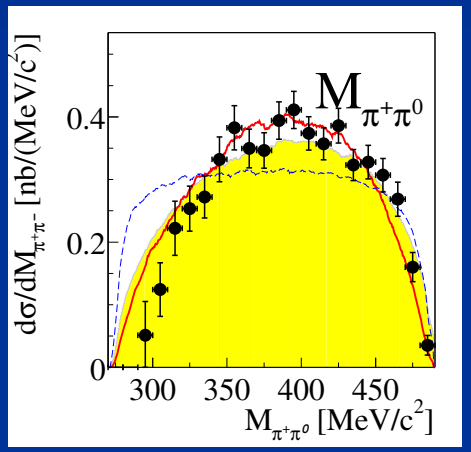
The "no-ABC" Gallery

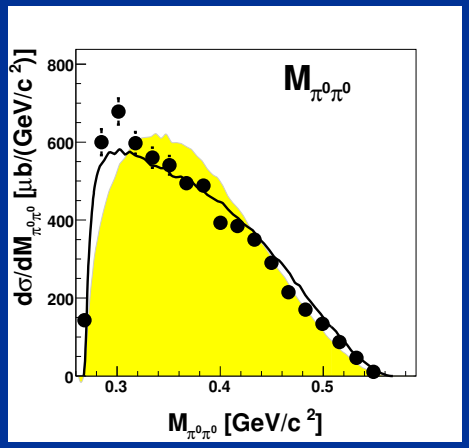


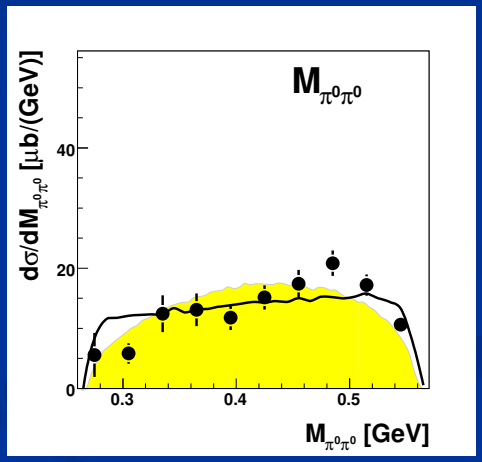
$pp \rightarrow d\,\pi^+\pi^0$ @ 1.1 GeV

$pp \rightarrow pp\,\pi^0\pi^0$ @ 1.3 GeV

$pp \rightarrow$ „^{2}He“ $\pi^0\pi^0$ @ 1.3 GeV



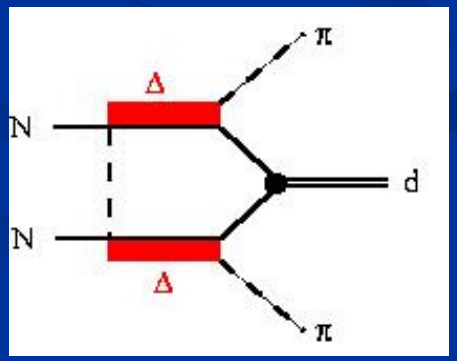




Phys.Lett. **B** 684 (2010) 110

Phys. Lett. **B** 695 (2011) 115

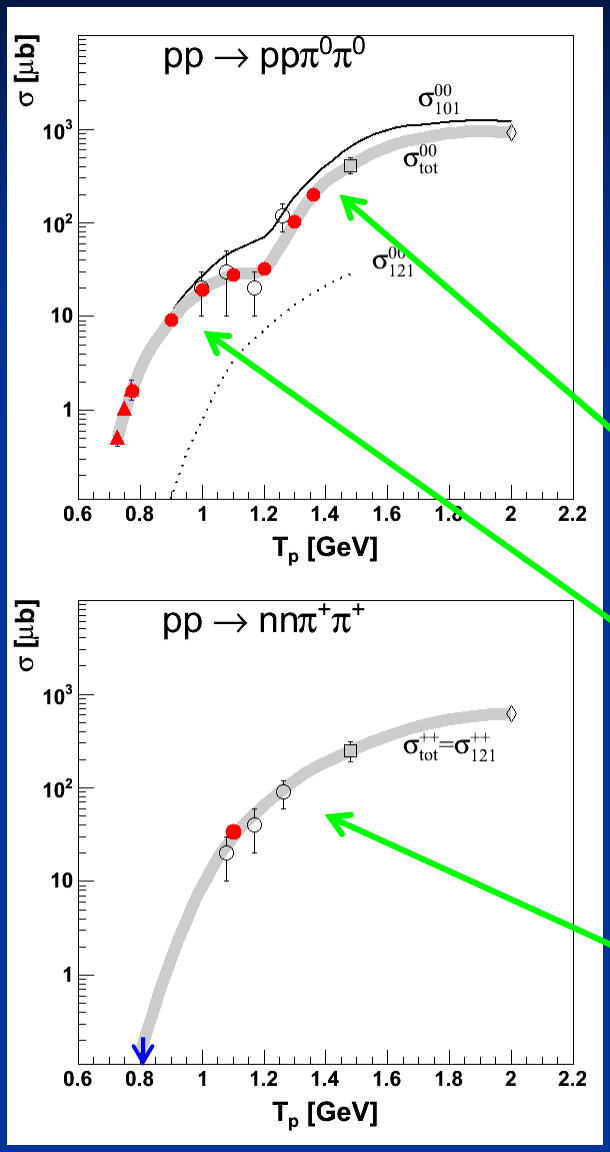
well described by t-channel ΔΔ process



What is the reason for ABC effect?

- Check all observables: exclusive and kinematically complete measurements
- Look on the energy dependence – in particular of total cross section

Isovector : Total Cross Sections



isospin decomposition

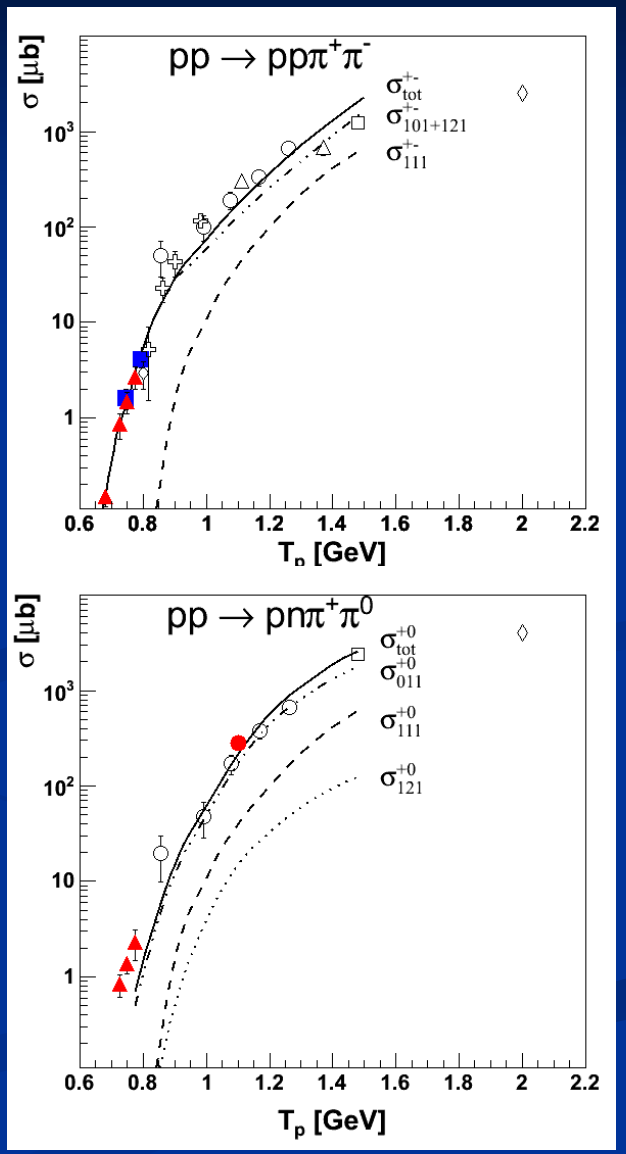
⇒

ΔΔ

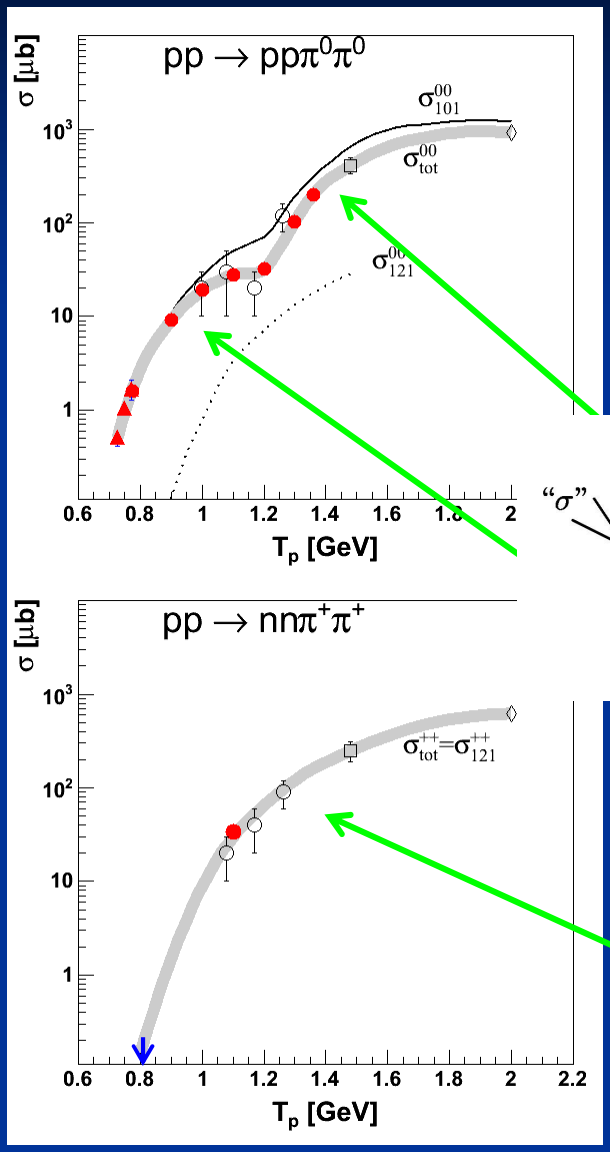
N*(1440)

Δ(1600) (?)

Phys. Lett. B 679 (2009) 30

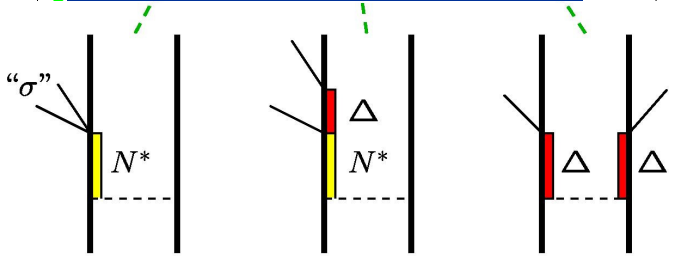


Isovector : Total Cross Sections

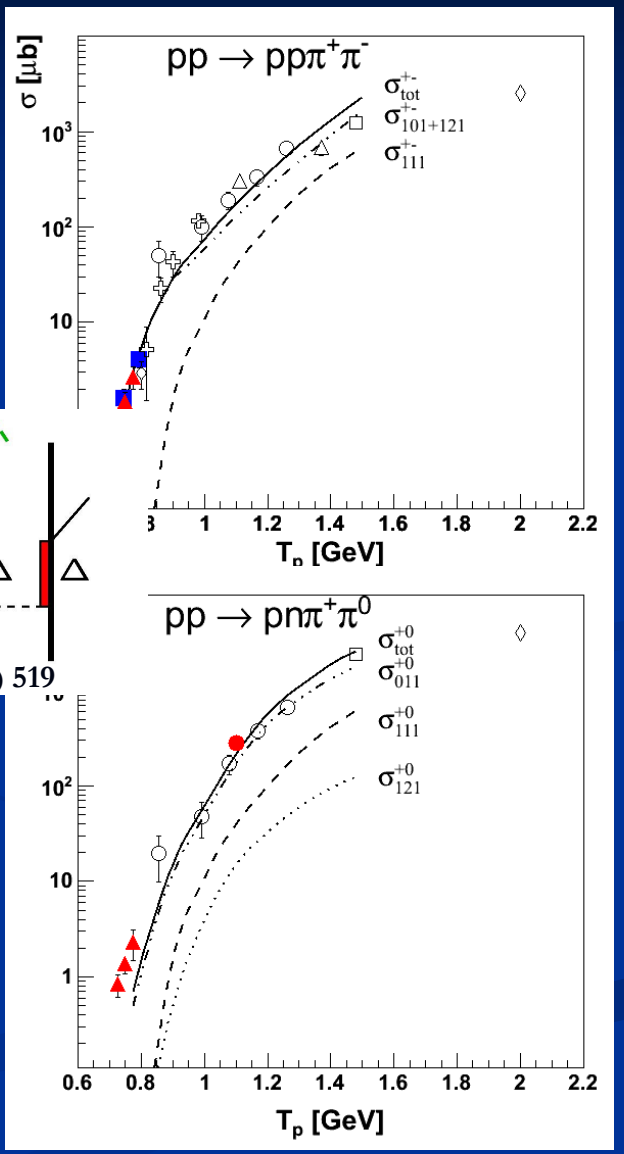


isospin decomposition

⇒



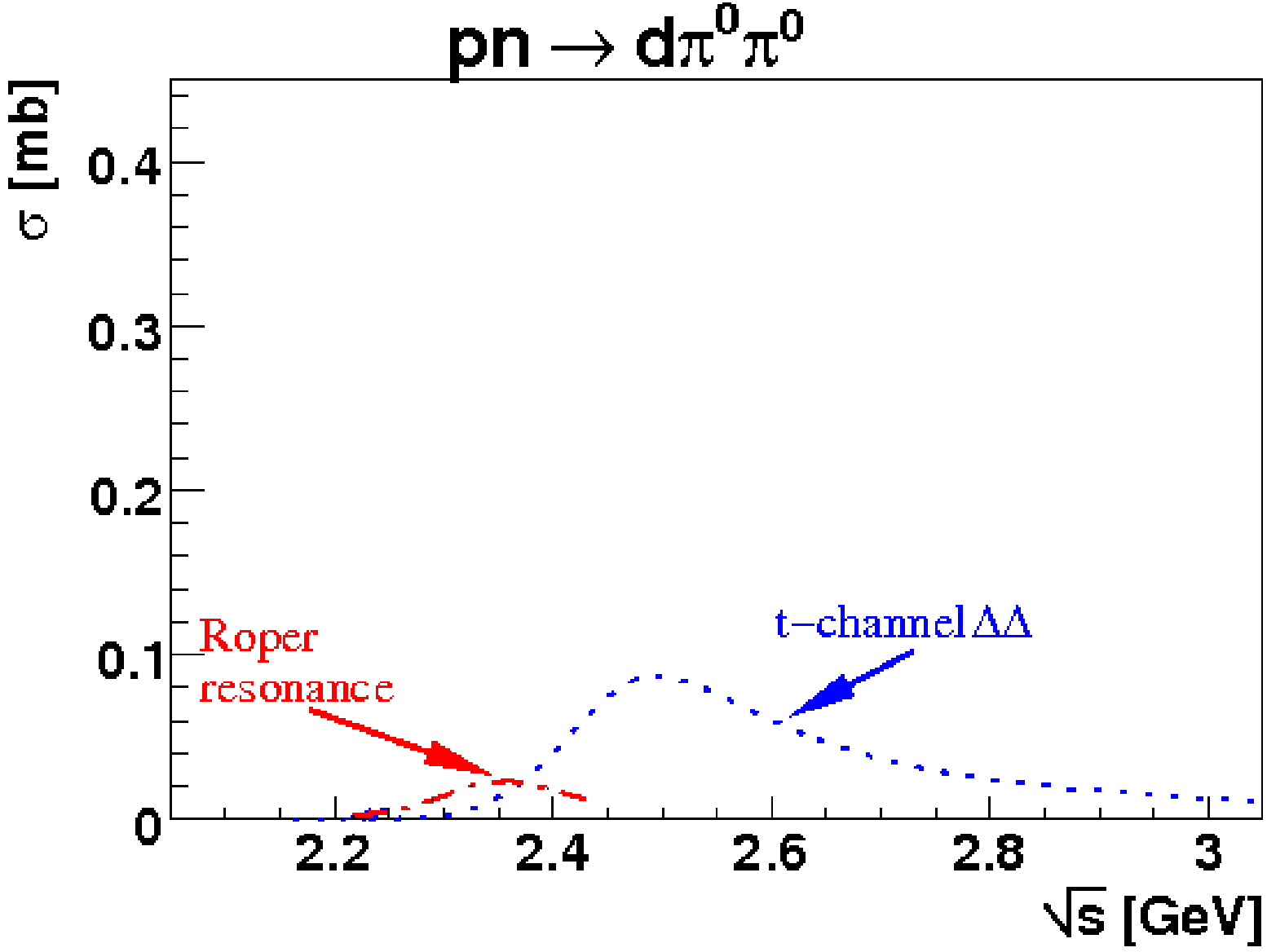
Alvarez-Ruso, Oset NPA 633 (1998) 519



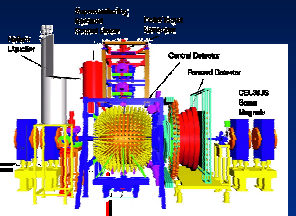
Δ(1600) (?)

Phys. Lett. B 679 (2009) 30

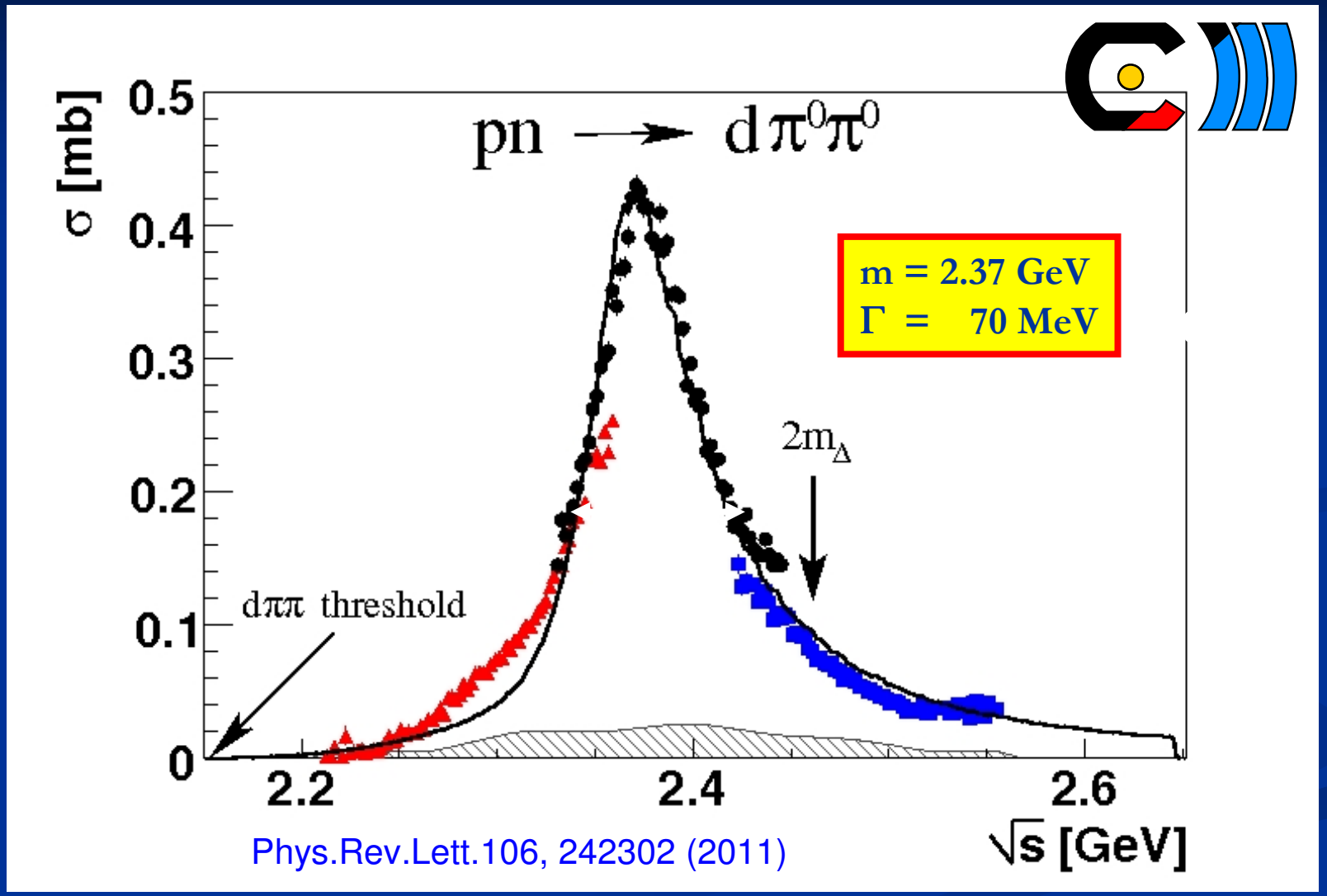
Isoscalar : … this is what we expected!



Isoscalar : … and this is what we found!

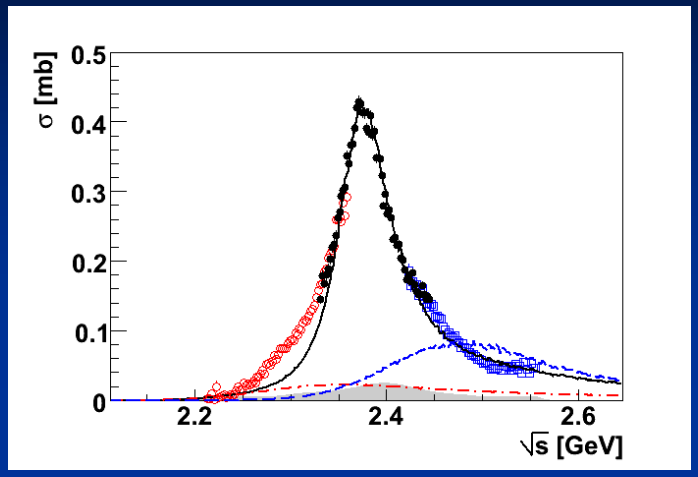


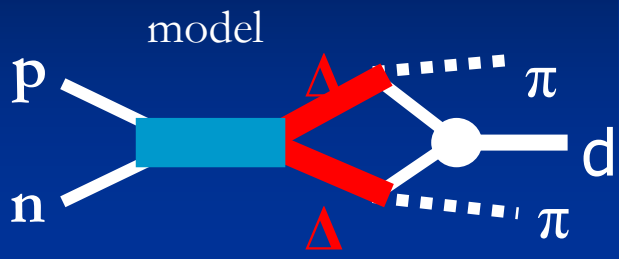
Isoscalar : Results from WASA at COSY



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

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

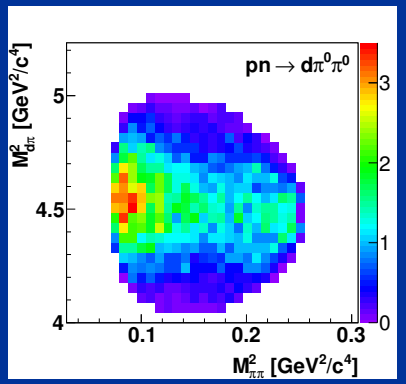


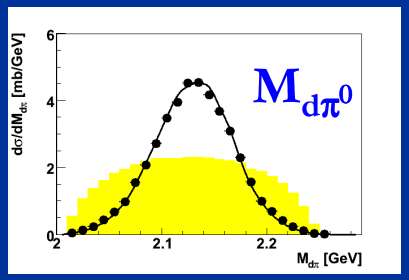


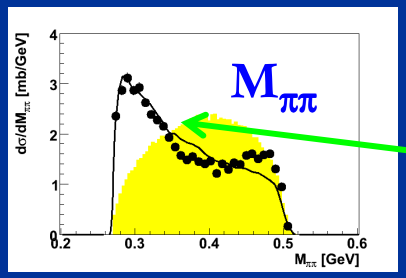
$I(J^P) = 0(3^+)$

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

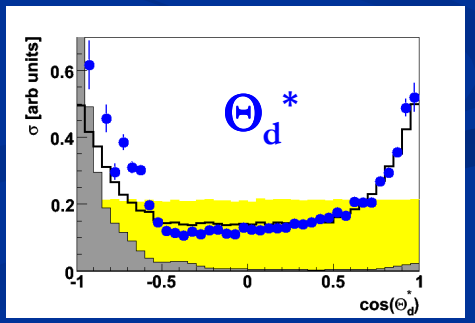
Phys.Rev.Lett.106, 242302 (2011)



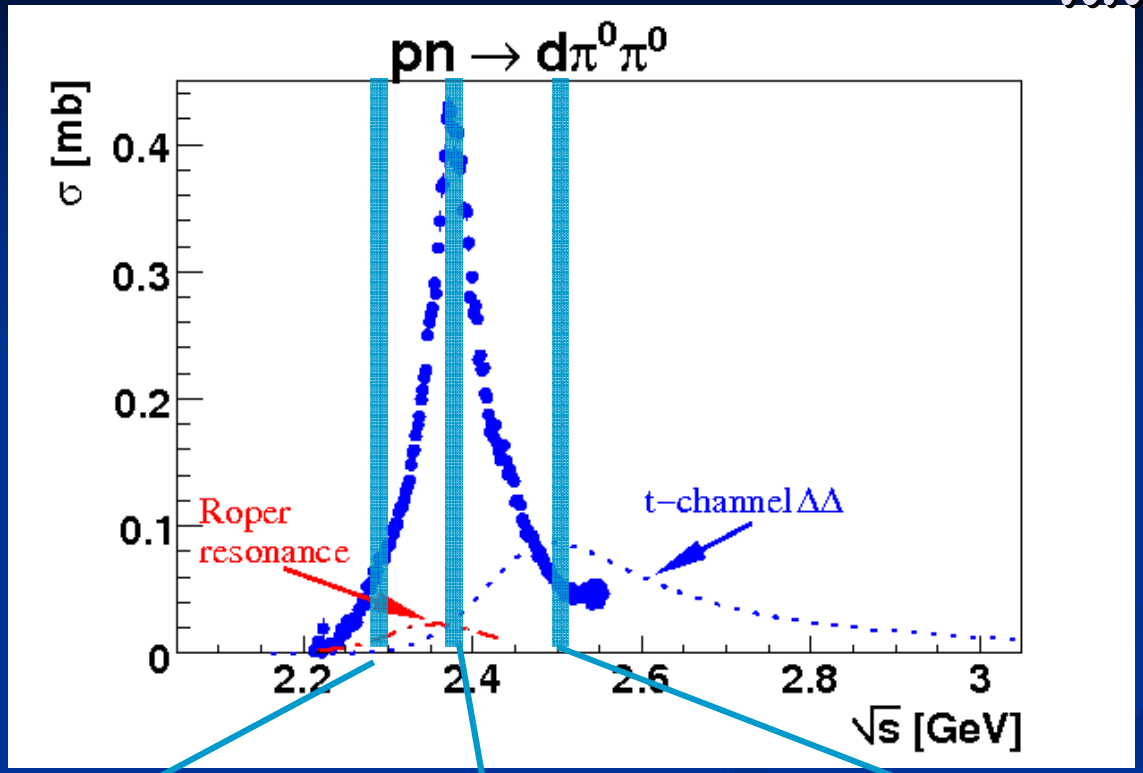




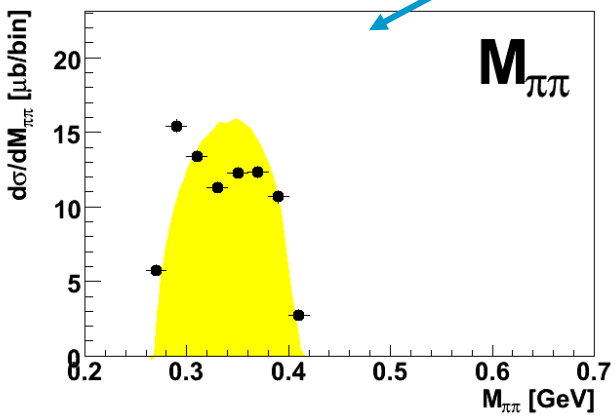
ABC effect

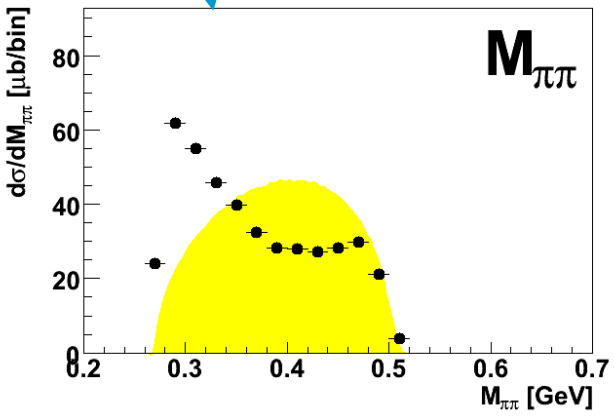


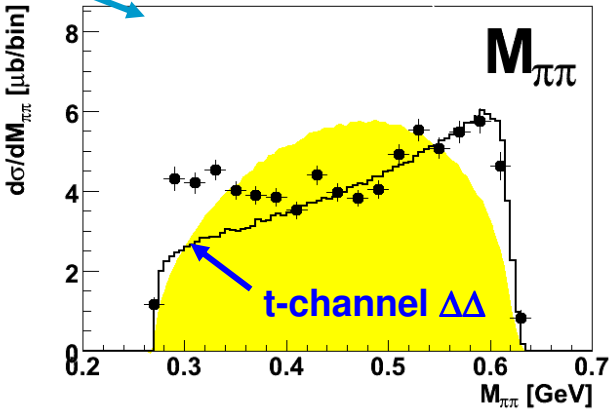
ππ-invariant mass $M_{\pi\pi}$



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







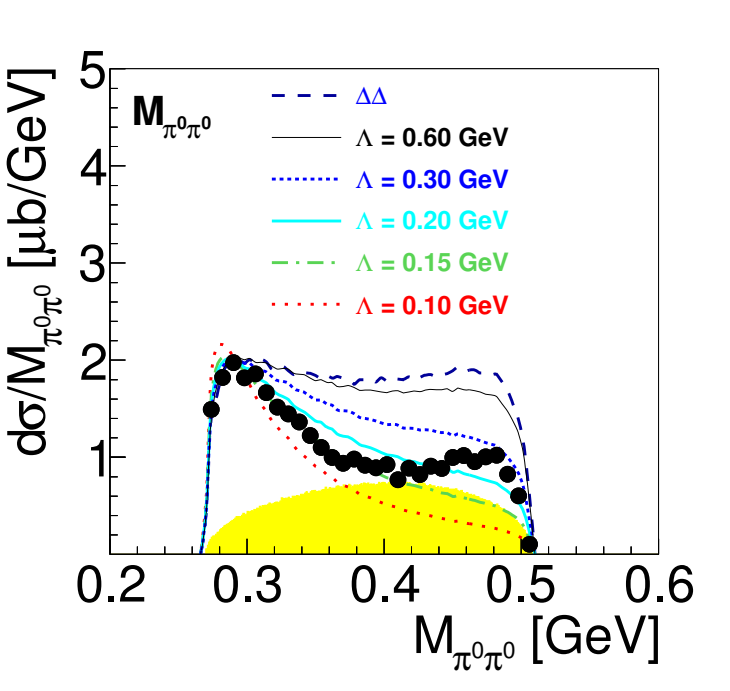
ABC Effect: Mapping of $d^* \rightarrow \Delta\Delta$ on $M_{\pi\pi}$ spectrum

- S-wave decay: $\Gamma_{d^* \rightarrow \Delta\Delta} = \Gamma_0 \, q_{\Delta\Delta} \; \Lambda^2 / (\Lambda^2 + q_{\Delta\Delta}^2)$

- $\underline{q}_{\Delta\Delta} = \underline{p}_{\Delta 1} - \underline{p}_{\Delta 2} = \underline{p}_{N1} + \underline{k}_1 - \underline{p}_{N2} - \underline{k}_2 =$
- $= \underline{q}_{NN} + \underline{q}_{\pi\pi}$

- **Fusion**: $\underline{q}_{NN} = 0$ (neglecting Fermi motion)
- $\Rightarrow \quad q_{\Delta\Delta}^2 = q_{\pi\pi}^2 = M_{\pi\pi}^2 - 4m_\pi^2$

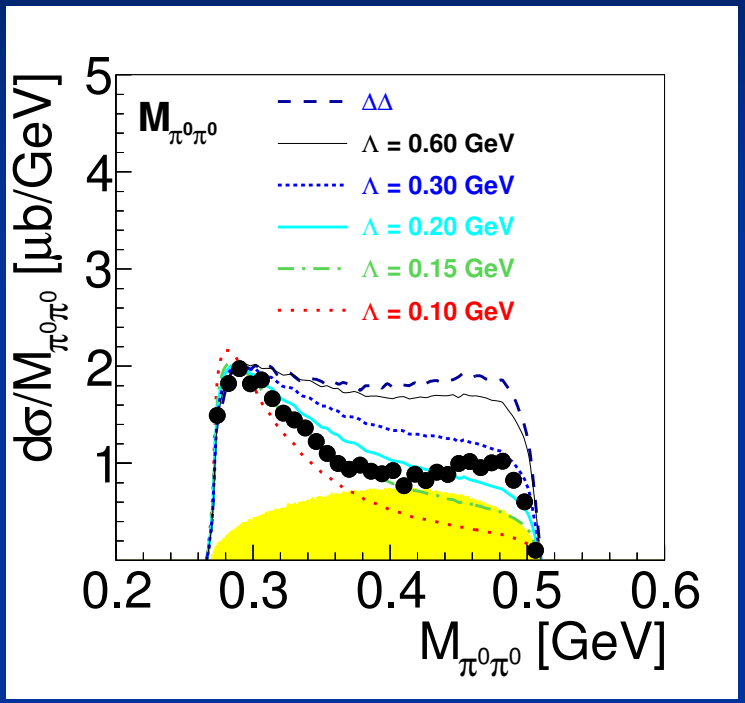
Effect of Vertex Function on $M_{\pi\pi}$ Spectrum



- Variation of cutoff parameter Λ:
- best fit:
- $\Lambda = 0.16$ GeV/c

arXiv:1502.07500

Effect of Vertex Function on $M_{\pi\pi}$ Spectrum

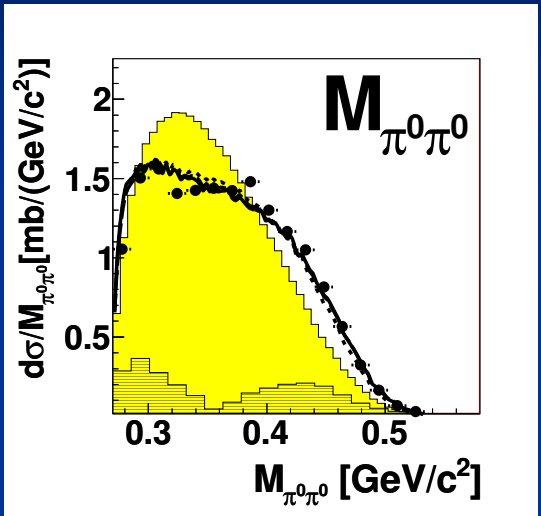


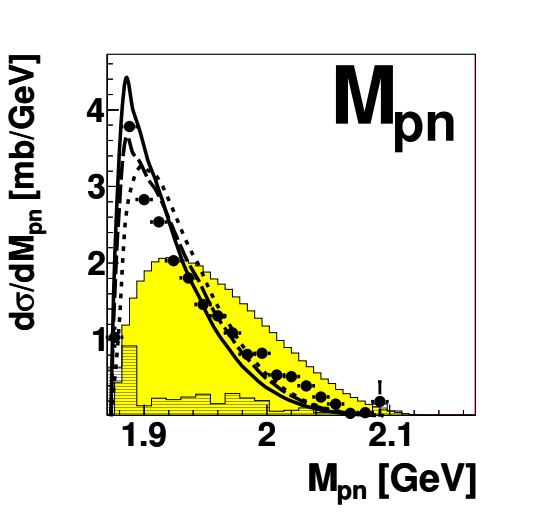
- Variation of cutoff parameter Λ:
- best fit:
- $\Lambda = 0.16$ GeV/c

identical to $\Lambda_{\Delta\to N\pi}$!!!

arXiv:1502.07500

Non-Fusion Two-Pion Production: $np \rightarrow np\pi^0\pi^0$

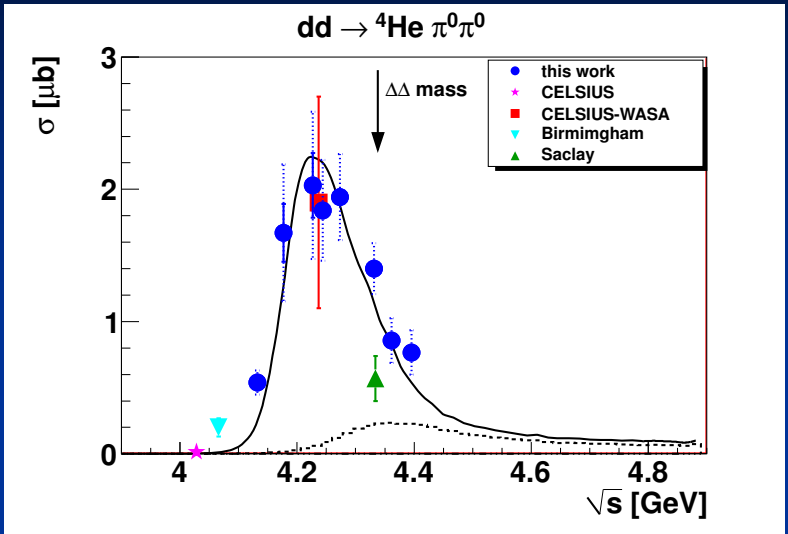


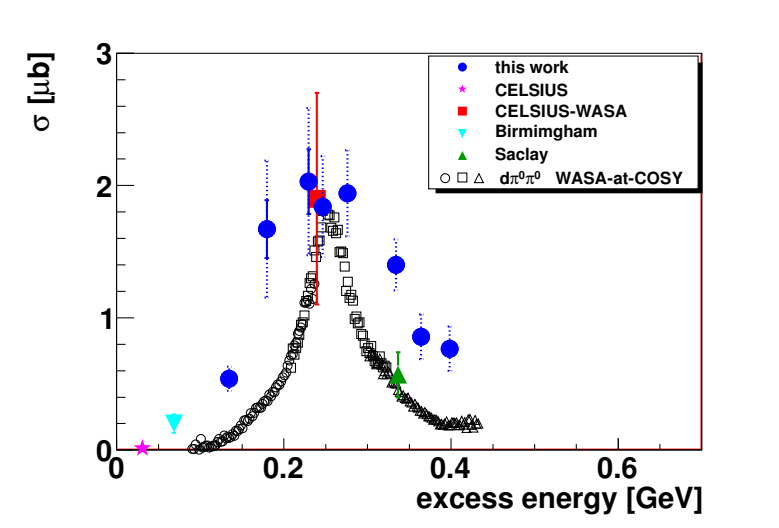


- **No ABC effect !**
- Naturally explained by vertex function:
- **no fusion** $\Rightarrow$ $q_{NN} \neq 0$
- $q_{\Delta\Delta} \approx q_{NN}$
- $\Rightarrow$ enhancement in M_{pn} spectrum

PLB 743 (2015) 325
arXiv:1502.07500

dd → ^{4}He $\pi^0\pi^0$



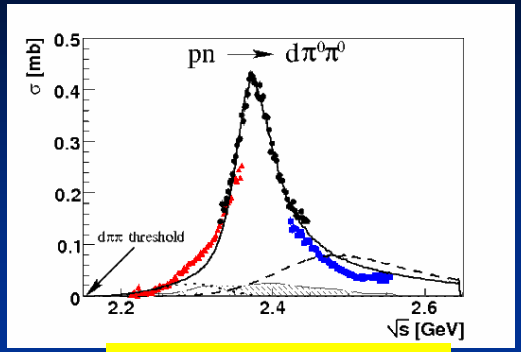


PRC 86 (2012) 032201(R)

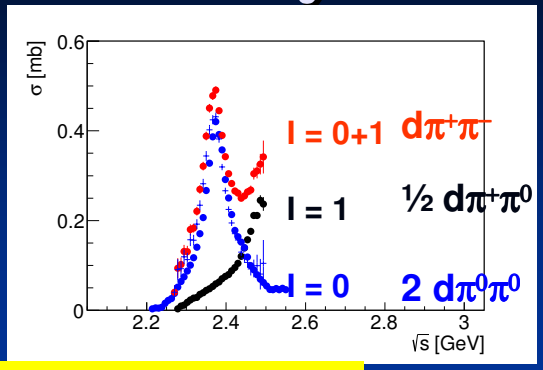
- Energy dependence of total cross section
  - shows resonance structure
  - exactly at the same excess energy as in pn → d$\pi^0\pi^0$
  - is broadened due to Fermi motion and collision damping
- ⇒ **d* obviously survives even in nuclear surrounding**

hadronic decays

PRL 106 (2011) 242302



WASA data

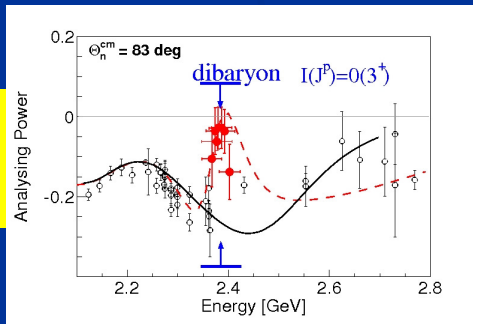


PLB 721 (2013) 229

$d\pi^0\pi^0$ $d\pi^+\pi^-$

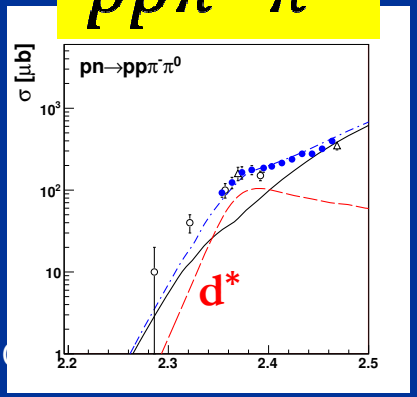
pn → d*(2380)

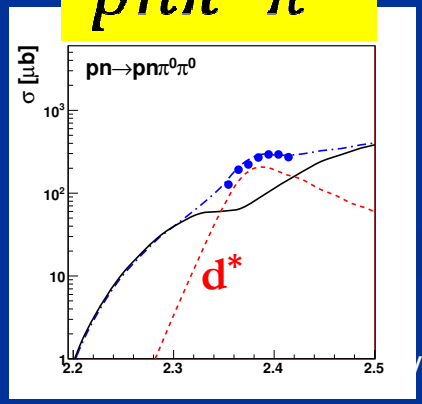
pn

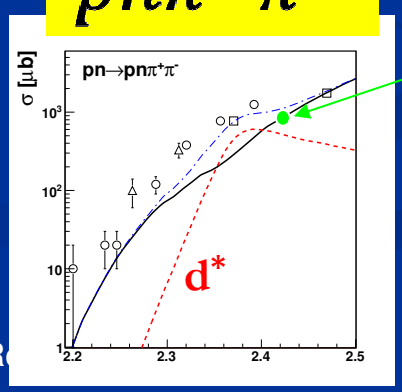


PRL 112 (2014) 202301
PRC 90 (2014) 035204

$pp\pi^-\pi^0$ $pn\pi^0\pi^0$ $pn\pi^+\pi^-$







HADES PLB 750 (2015) 184

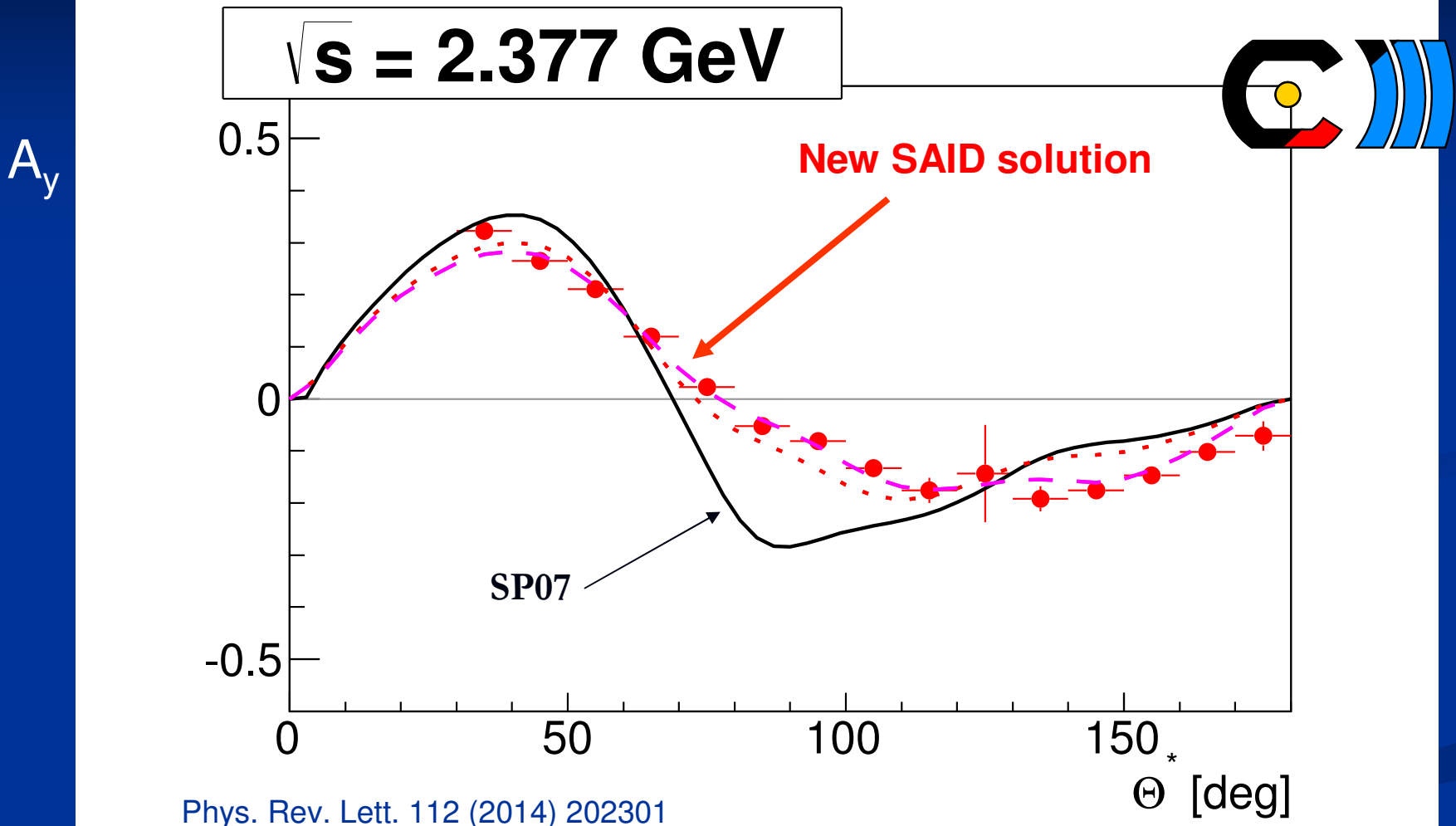
PRC 88 (2013) 055208
PLB 743 (2015) 325
Phys. Scr. T 166 (2015) 014016

→ √s [GeV]

„Experimentum Crucis“ for d*

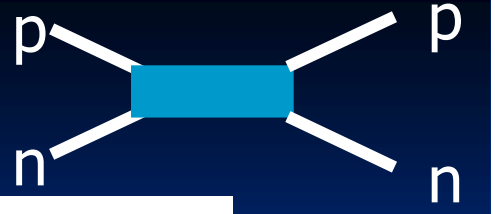
- If d^* a true s-channel resonance
- $\Leftrightarrow$
- then also a resonance in the np system
- $\Leftrightarrow$
- to be sensed in np scattering
- $\Leftrightarrow$
- in particular in the analyzing power
- $\Leftrightarrow$
- resonance effect $\sim P^1{}_3(\Theta)$
- i.e. maximal at $\Theta = 90^0$

A_y Angular Distribution at Resonance

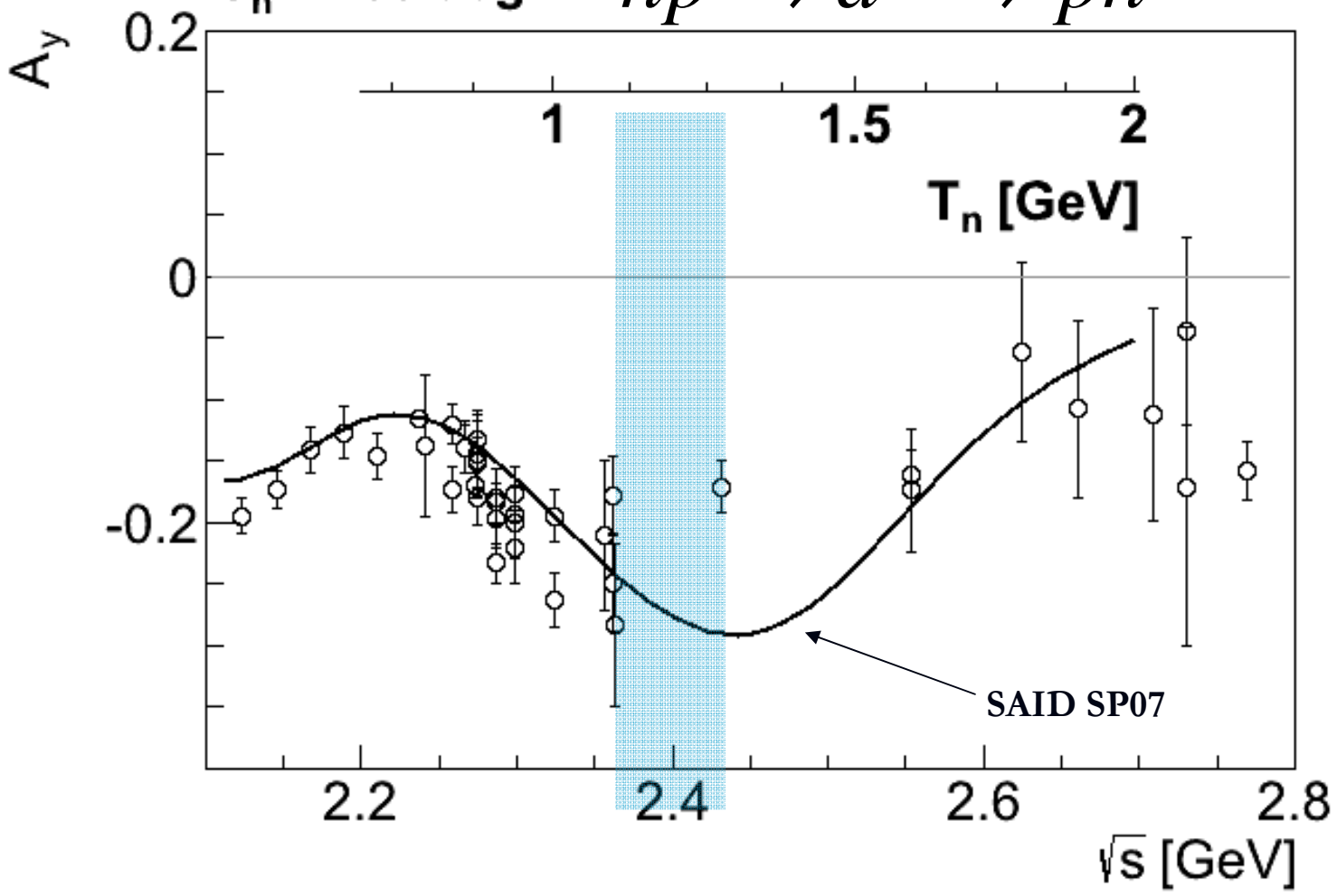


Phys. Rev. Lett. 112 (2014) 202301

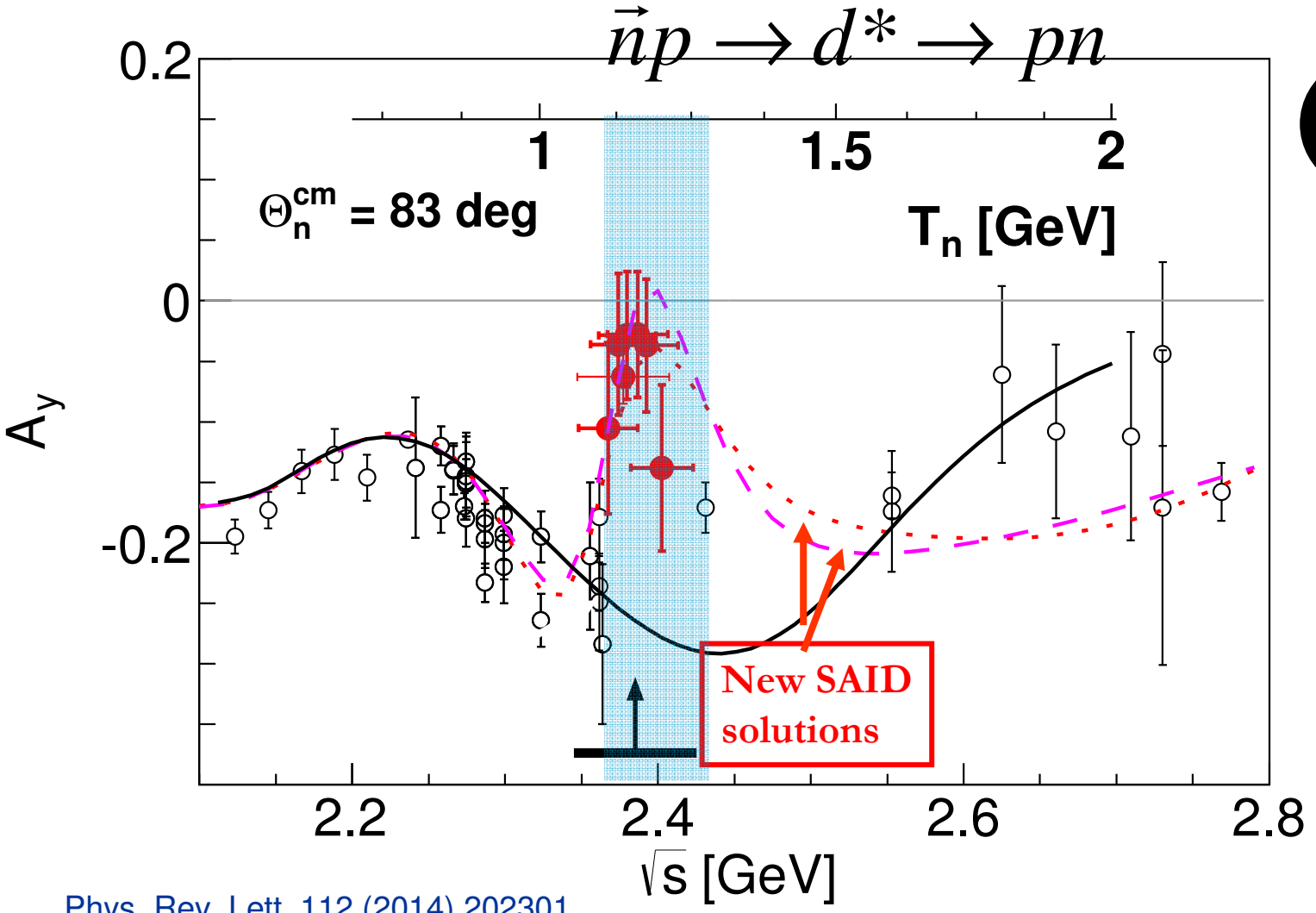
Energy Dependence



$\vec{n}p \rightarrow d^* \rightarrow pn$



Energy Dependence

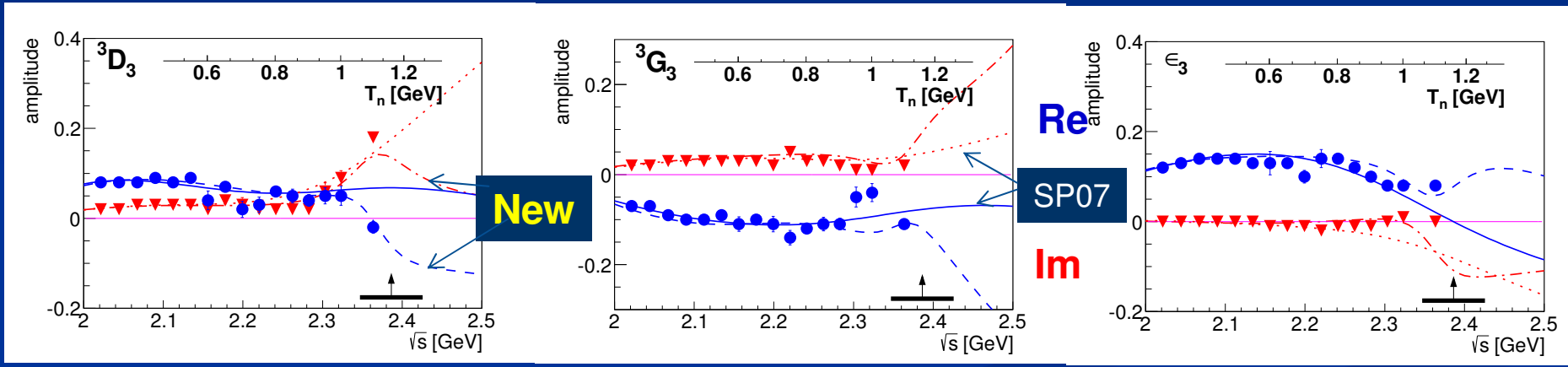


Phys. Rev. Lett. 112 (2014) 202301

SAID Partial-Wave Analysis

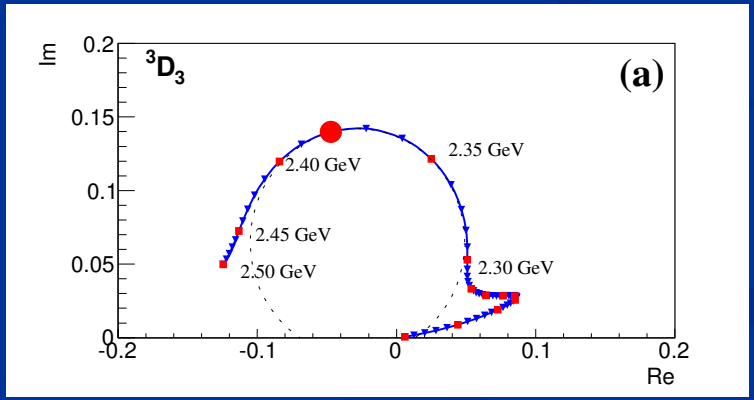
$^3D_3 - {}^3G_3$ Coupled Partial Waves

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 $d^*(2380)$

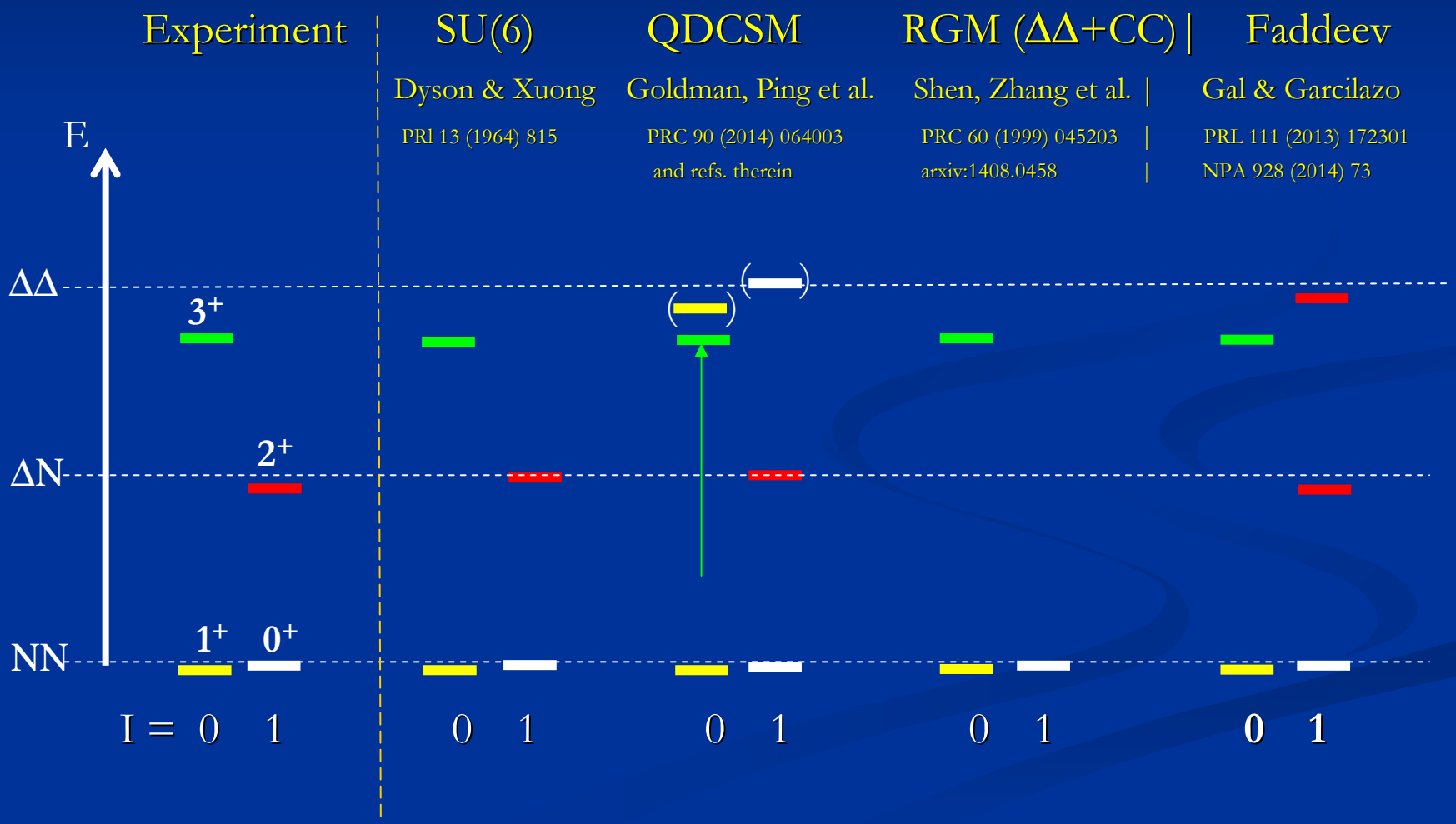
- hadronic decays

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
$(NN\pi)_{I=0}$	---	in progress

consistent with isospin coupling for a ΔΔ inter-mediate system

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) 69 MeV PRC 91 (2015) 064002

Molecule vs Hexaquark

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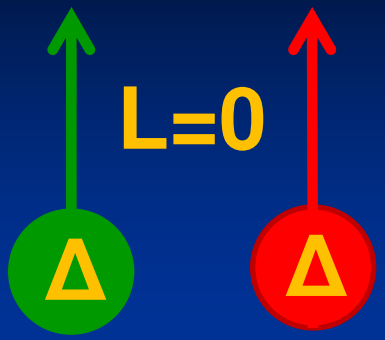
Estimate of Size

- Piccinini (Erice 2015, PRL 103 (2009) 162001)
- $R = \hbar c / \sqrt{2\mu B}$

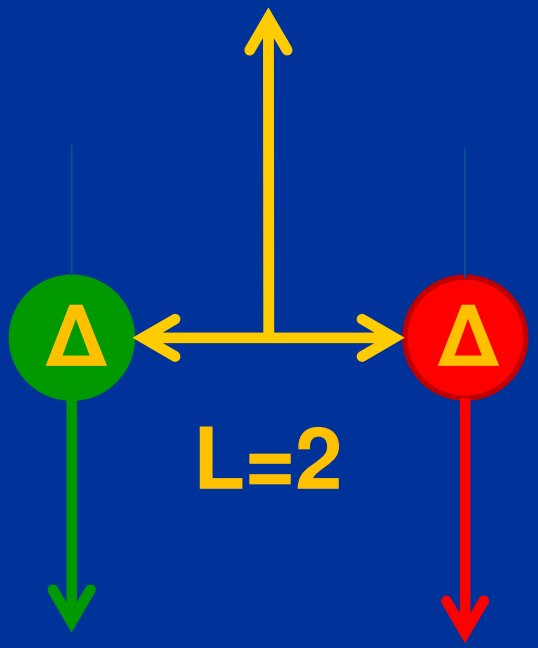
	X(3872)	$d^*(2380)$
	$D - D^*$	$\Delta - \Delta$
	$B = 3$ keV	$B = 80$ MeV
$\Rightarrow$	$R \geq 10$ fm	$R \approx 0.5$ fm

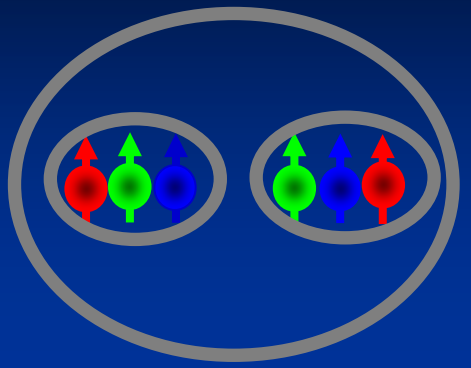
Quark Model

F. Huang et al, arXiv:1408.0458
1505.05395

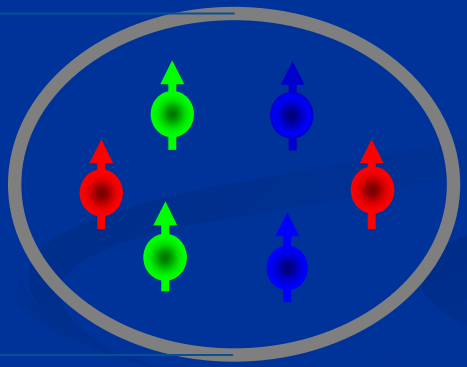


0.8 fm





≈ 33%



≈ 66%

≈15% of ΔΔ configuration

?

Rèsumè

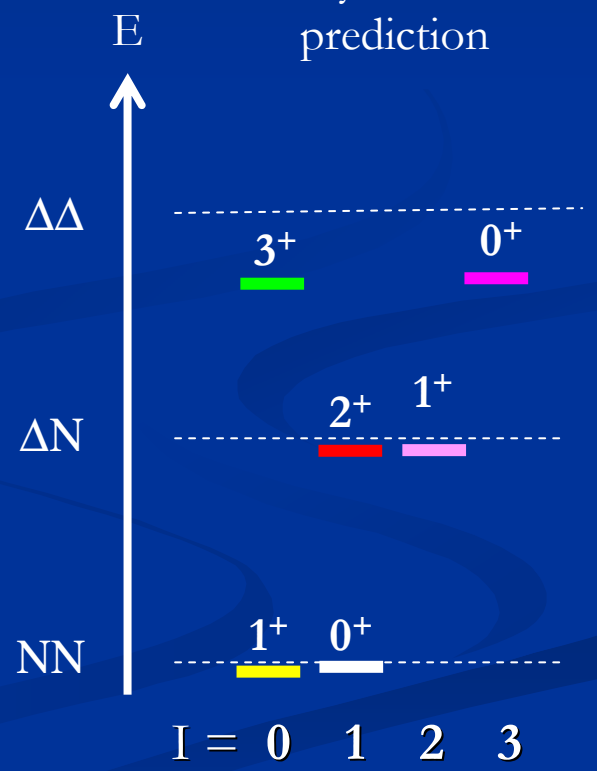
- Non-Strange Two-Baryon Spectrum
  - 3 established states: $^3S_1$ deuteron groundstate
    $^1S_0$ virtual state
    $^1D_2$ resonance (ΔN)
  - 1 new - presumably exotic - state:
    $d^*(2380)$ resonance (ΔΔ)
  - Are there more states?
    - NN-decoupled states with I = 2, 3?
    - Search in pp →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

Zhang, Chen, Shen et al.

Huang, Ping, Wang et al.

Gal & Garcilazo

Dyson's prediction



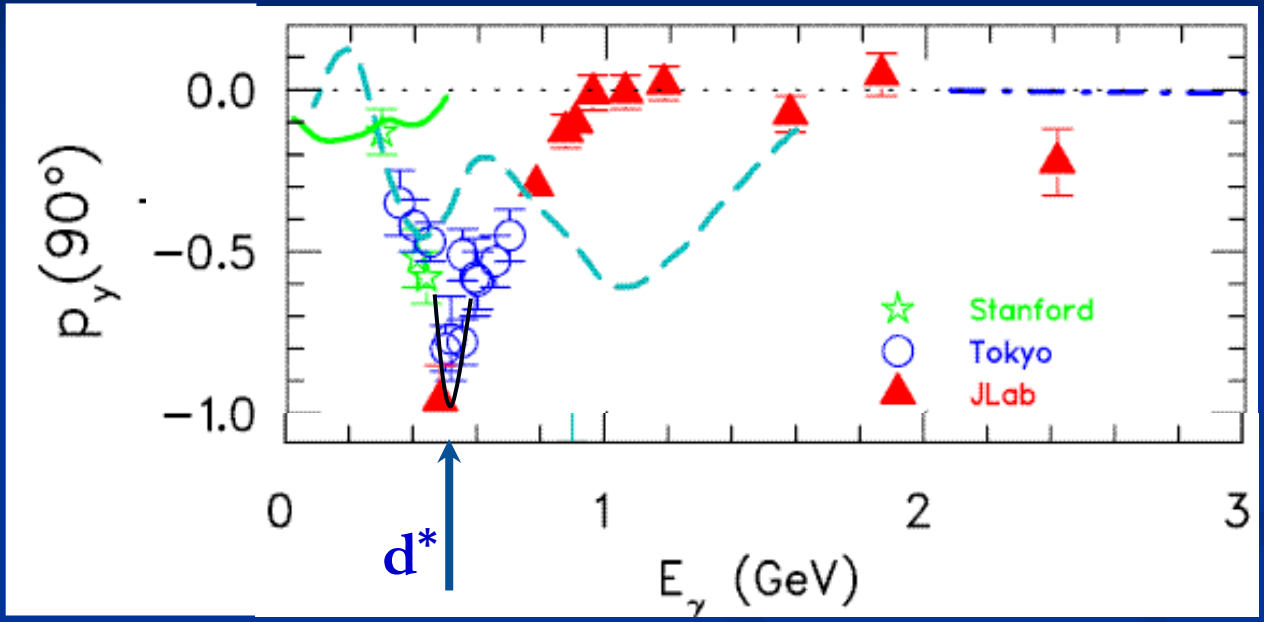
Summary

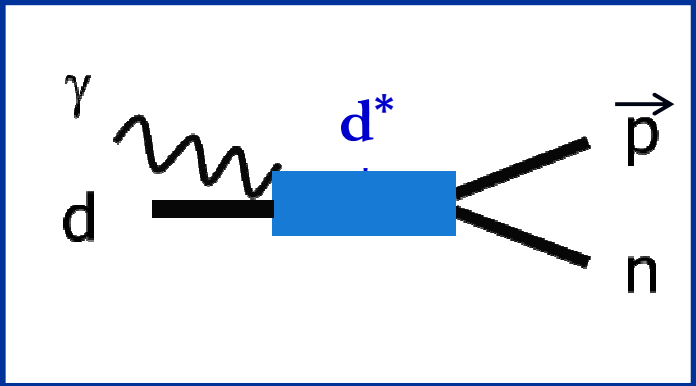
- $d^*(2380)$ established as a genuine s-channel resonance
- It is the first unambiguously detected non-trivial dibaryon state.
- It could be a compact hexaquark state – but this needs experimental verification.
- ABC effect is just a mapping of the $d^* \rightarrow \Delta\Delta$ vertex

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 ??
  - KEK, JPARC, others ???
- Are there more (exotic) dibaryons?
  - Mirror state of d^* …, strange, charmed dibaryons

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





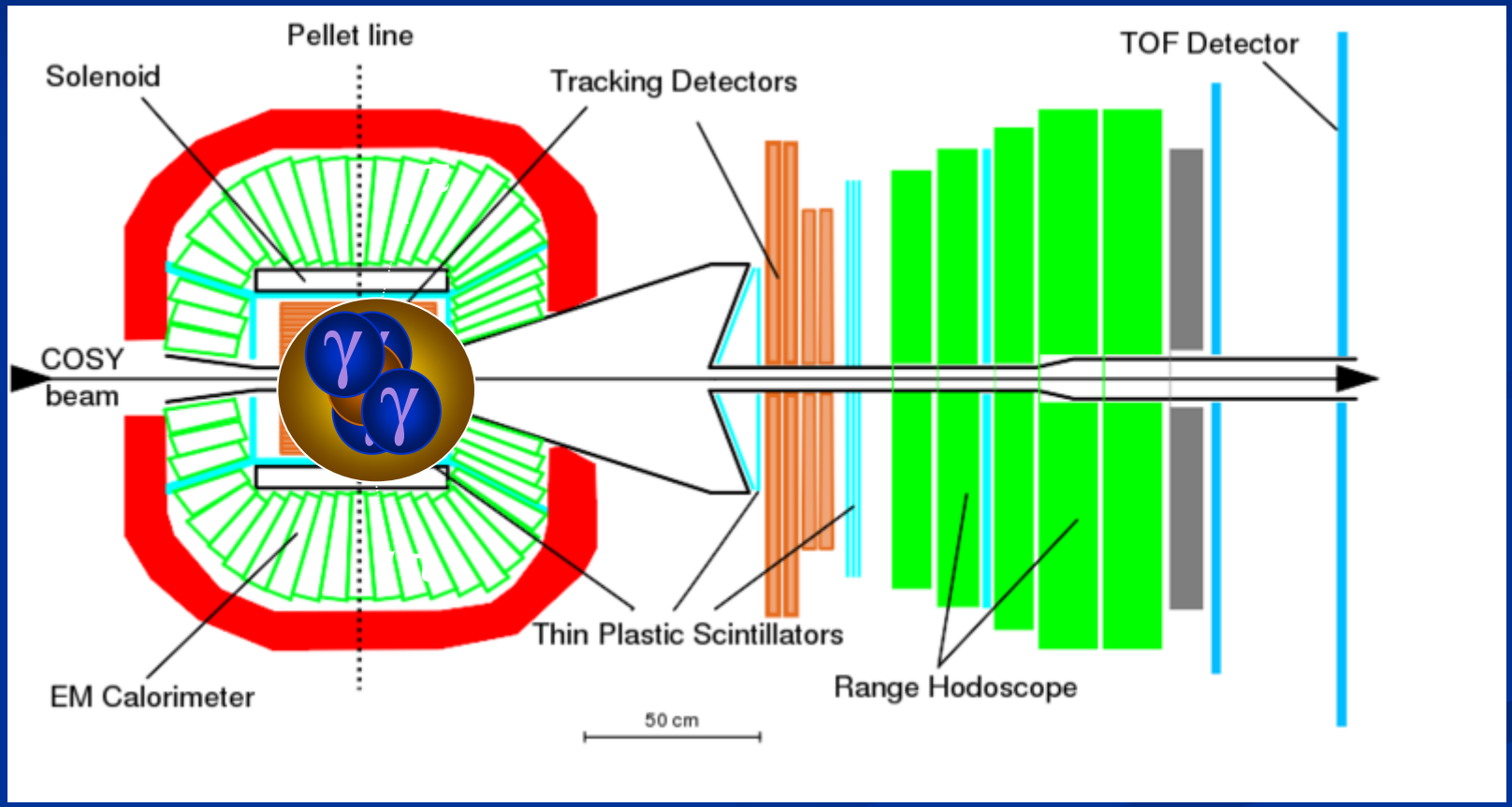
R. Gilman and F. Gross AIP Conf. Proc. 603 (2001) 55
K. Wijesooriya et al., Phys. Rev. Lett. 86 (2001) 2975

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

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

WASA 4π Detector

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



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