RESONANCE BEHAVIOUR OF THE REACTIONS $\mathbf{pp} \to \{\mathbf{pp}\}_{\mathbf{s}}\pi^{\mathbf{0}}$ AND $\mathbf{pd} \to \mathbf{pd}\pi\pi$ IN THE GEV REGION

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- **Conventional hadrons:**
  - **Meson:** $q\bar{q}$
  - **Bayron:**qqq
- **QCD allowed other forms:**
  - **Multi-quark state :** ≥ 4 **quarks**
  - **Glueball :gg, ggg,...**
  - **Hybrid:** $q\bar{q}g, qqqg, \ldots$
- **Hadron spectroscopy is a key tool to investigate QCD**

Not unambiguously established yet

What is the nature of two-baryon resonances?

- **Dubna, 1957,** $p +^{12} C \to d + X$ **at 670 MeV,**

D.I. Blokhintsev: fluctons (6q) in nuclei.

- $\Delta(1232)$ **in** $pd \to dp$ **at** $\sim 500 - 600$ **MeV:**

N.S. Craigie, C. Wilkin, (1969) OPE; V.M. Kolybasov, N.Ya. Smorodinskya (1973)
L. Kondratyuk, F. Lev, L.Schevchenko (1979-1982) :
$\boldsymbol{\Delta} + \mathrm{B3}$, **TRIBARIONS (9q)!**

O.Imambekov, Yu.N. U., L.Schevchenko (1988-1989):
Δ**-dominates** $d\sigma/d\Omega$ **but does not solve the** T_{20} **puzzle!** $\Longrightarrow$ **Spin structure of** $NN \to N\Delta$ **is not well known.**

- $\Delta(1232)$ **is against of multiquark exotics**

- **How to suppress the** Δ**-contribution in** pd**- and** pN**-ineractions?**

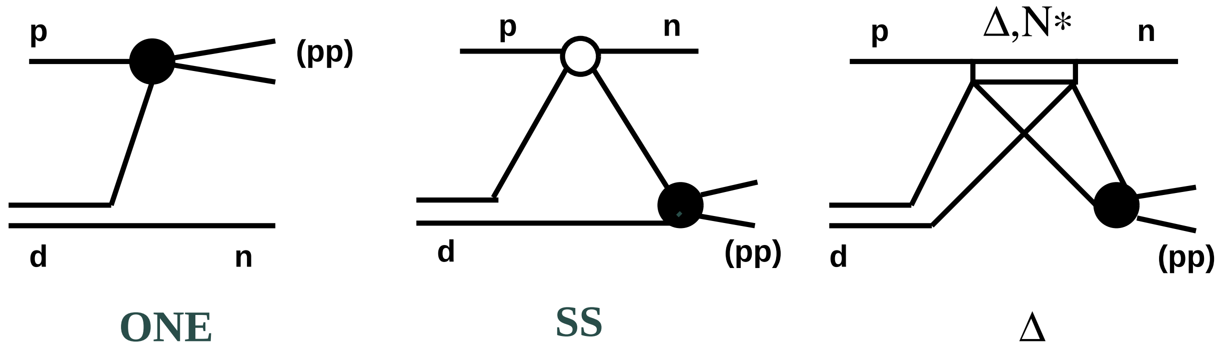
- **Reactions with the $^1S_0$ diproton $\{pp\}_s$ (i.e. $E_{pp} < 3$ MeV) at large Q can give more insight into underlying dynamics due to difference in quantum numbers**

deuteron $\Longrightarrow$ $(^1S_0)$pn singlet deuteron or
$\Longrightarrow$ $(^1S_0)$-diproton, $\{pp\}_s$

1. $\mathbf{pd \to dp \Longrightarrow p\{NN\}_s \to dN}$ **in A(p,Nd)B**
suppression of the Δ- and N^*-excitations as $1:9$

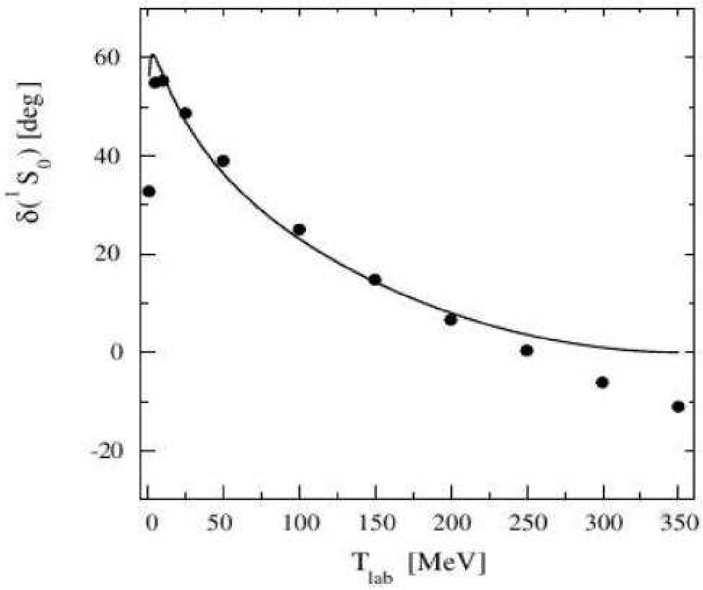
and $\mathbf{pd \to \{pp\}_s n}$

/O.Imambekov , Yu.N.Uzikov, Yad. Fiz. 52 (1990) 1361/



pp(1S0) diproton, E_pp< 3 MeV

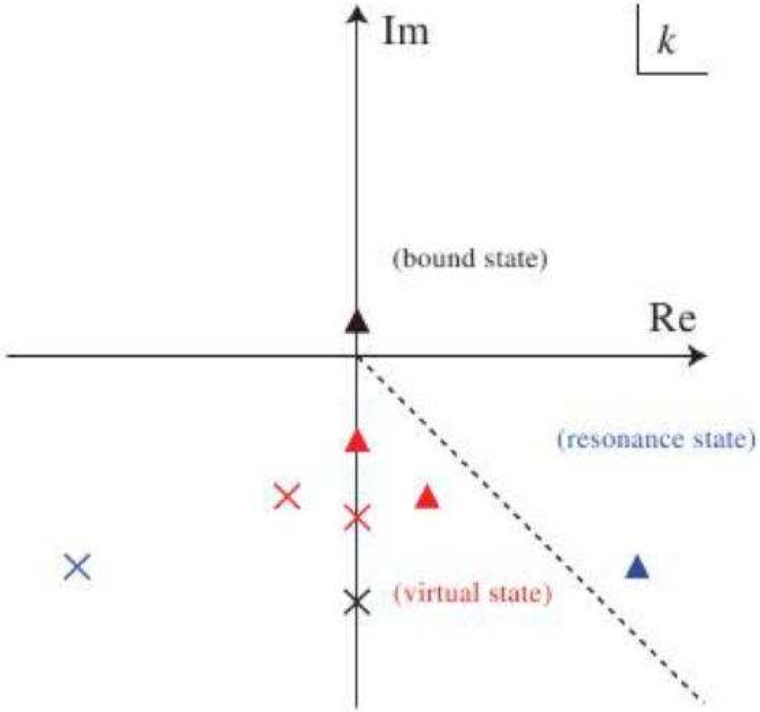
1S0 pp phase shifts



. **3.** The energy dependence of the $^1S_0$ pp phase sl

Anti-bound (virtual) state without width

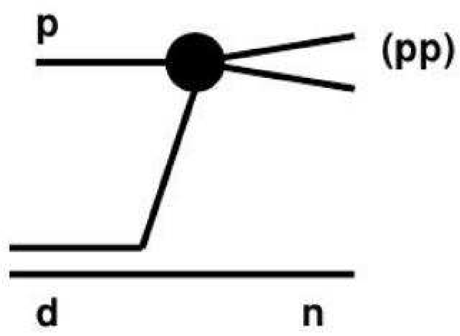
E=-65 keV for the pn (1S0)



1S0 t(q,k) half-off-shell and ONE for the pd->{pp}n

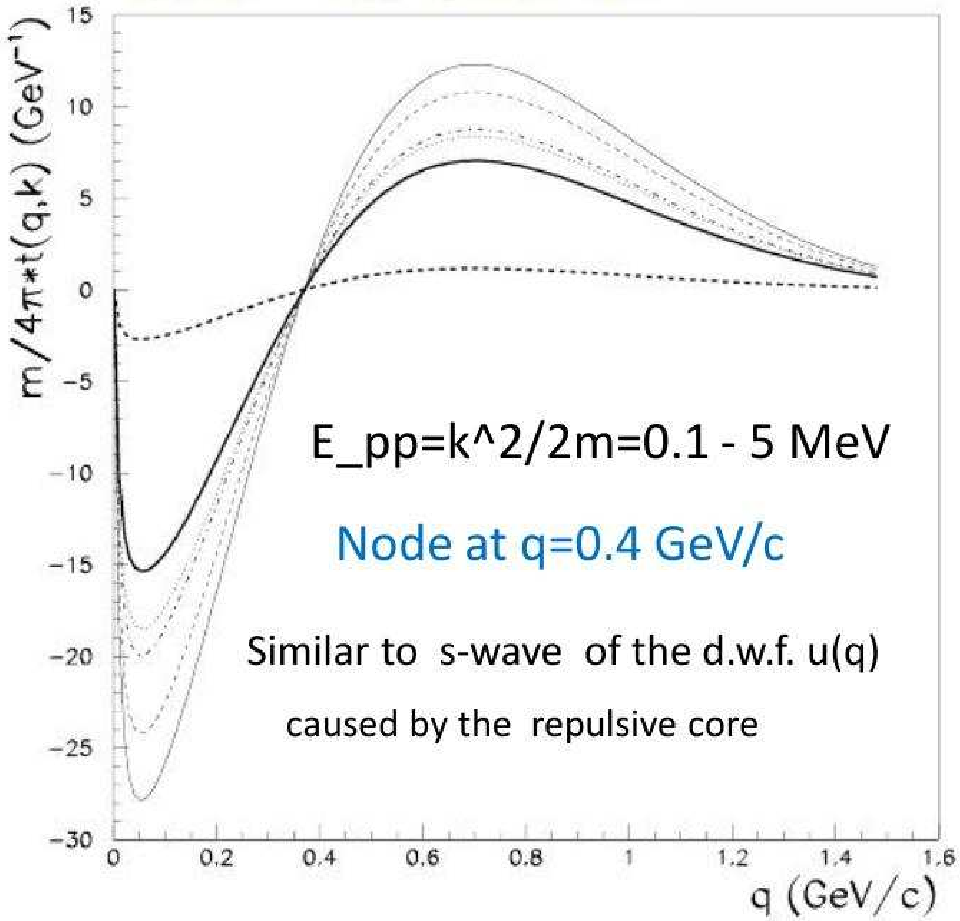
t-matrix of pp($^1S_0$) scattering, $\mathbf{t(q,k)} = <\psi_{\mathbf{k}}^{(-)}(^1\mathbf{S}_0)|\mathbf{V}|\mathbf{q}>$

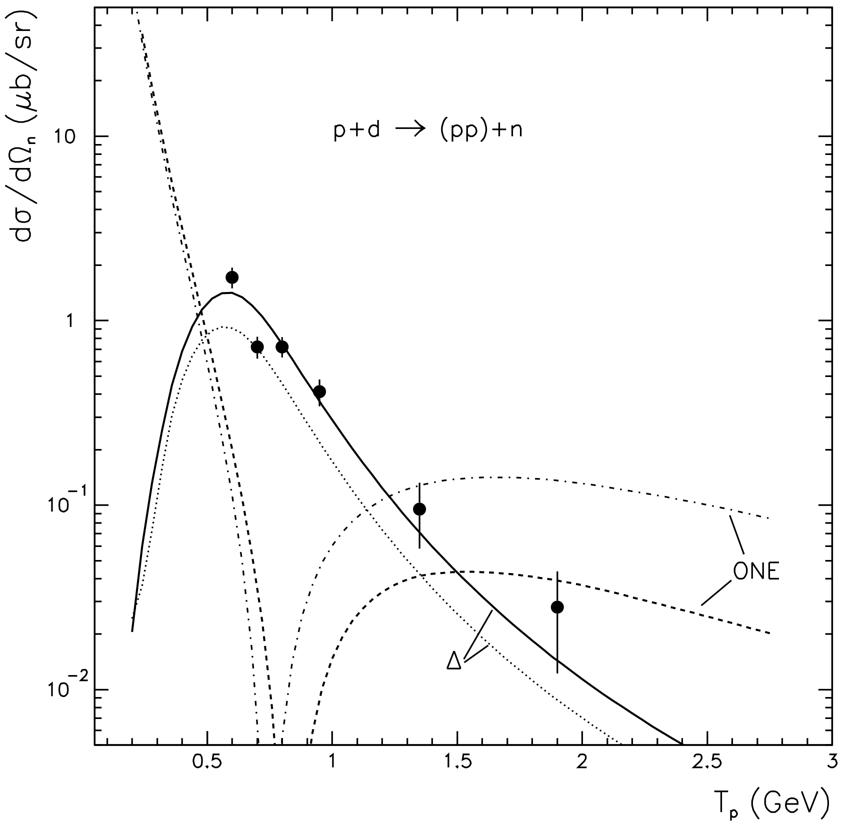
p+d-> (pp)+n

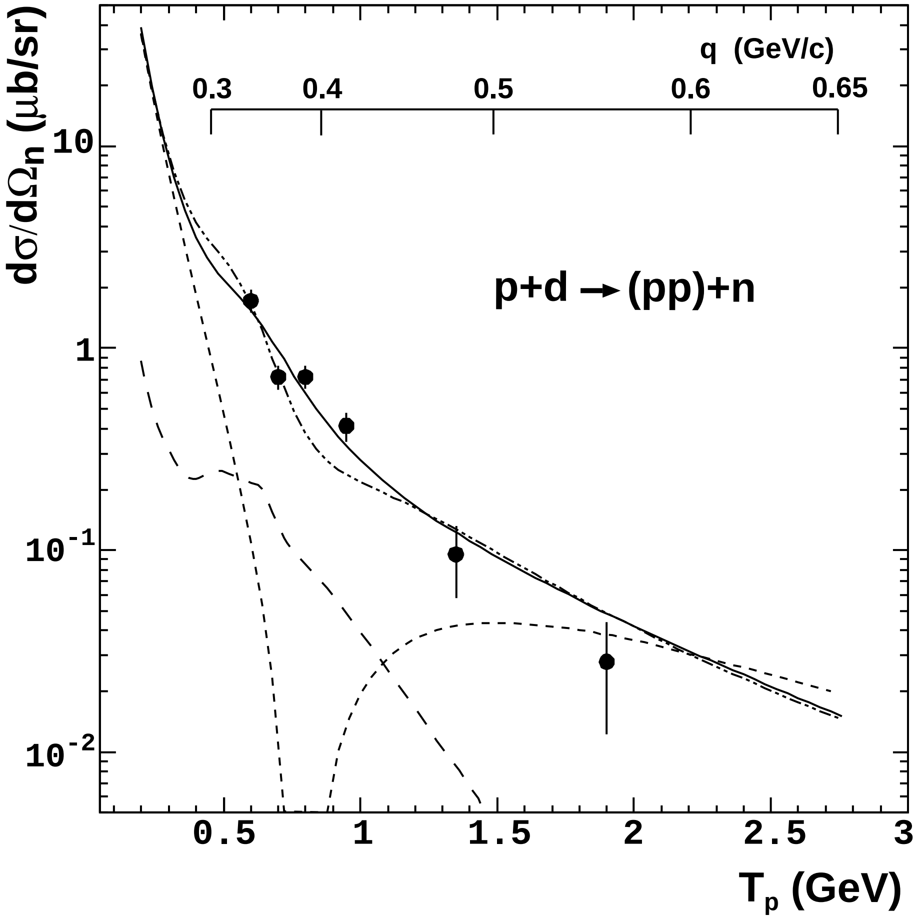


ONE nucleon exchange

d^3k=k^2d2 dΩ K->0







ONE+Δ+SS calculation *(J.Haidenbauer, Yu.Uzikov, Phys.Lett. B562(2003)227)*

When changing hard V_{NN} (RSC, Paris) to the soft V_{NN} (CD Bonn), ONE decreases and Δ-increases providing agreement with the COSY data V. Komarov et al., Phys. Lett. B553 (2003) 179.

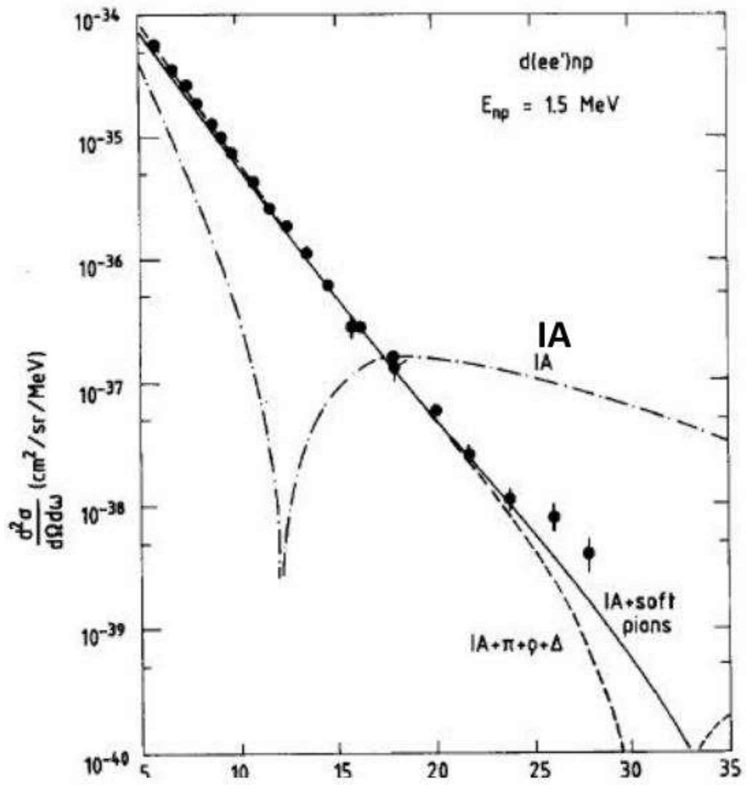
Δ is still large!

The short range V_{NN} is rather soft like for the CD Bonn model, but not the RSC and Paris.

Analogy with MEC in $ed \to e(pn)_s$

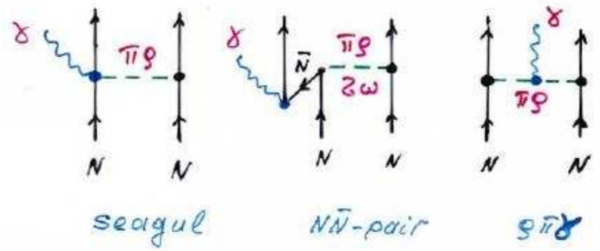
d(e,e')np,

J.-F. Mathiot, Electromagnetic meson-exchange currents at the nucleon mass scale

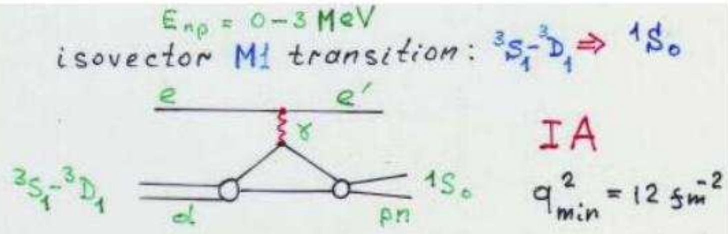


The Node is not observed !

Meson-Exchange currents



See review
J.-F. Mathiot. Phys. Rep. 173



2. $\mathbf{pp} \to \mathbf{d}\pi^+$ & $\mathbf{pp} \to \{\mathbf{pp}\}_\mathbf{s}\pi^\mathbf{0}$

$^1S_0$ **diproton:** $\mathbf{J}^\pi = \mathbf{0}^+,\ \mathbf{T} = \mathbf{1},\ \mathbf{S} = \mathbf{0},\ \mathbf{L} = \mathbf{0}$

deuteron: $\mathbf{J}^\pi = \mathbf{1}^+, \mathbf{T} = \mathbf{0},\ \mathbf{S} = \mathbf{1}, \mathbf{L} = \mathbf{0}, \mathbf{2}$

- $(-\mathbf{1})^{\mathbf{L}+\mathbf{S}+\mathbf{T}} = -\mathbf{1}$ **(Pauli principle)**
- **Spin-parity conservation:**

⋆ $\mathbf{pp} \to \mathbf{d}\pi^+$, **odd and even** L_{pp}, $S = 1$ **and** $S = 0$;

$\Longrightarrow$ $\mathbf{\Delta N}$ **in S-wave (** N^*N**)** $\pi = +1$ -*is allowed*

$\Longrightarrow$ $\Delta(1232)$ **dominates in the** $pp \to d\pi^+$ **at ≈600 MeV**

⋆ $\mathbf{pp} \to \{\mathbf{pp}\}_\mathbf{s}\pi^\mathbf{0}$ **odd** L_{pp}, $S = 1$

$\Longrightarrow$ $\mathbf{\Delta N}$ **in S-wave (or** N^*N**)** $\pi = +1$ - *is vorbidden*

Diproton physics at ANKE-COSY, 2000-2014

$\mathbf{pd} \to \{\mathbf{pp}\}_\mathbf{s}\mathbf{n}$, hard deuteron breakup 0.5 - 2.0 GeV

$\mathbf{pp} \to \{\mathbf{pp}\}_\mathbf{s}\pi^\mathbf{0}$

$\mathbf{pp} \to \{\mathbf{pp}\}_\mathbf{s}\gamma$

$\mathbf{pp} \to \{\mathbf{pp}\}_\mathbf{s}\pi\pi$

$\mathbf{pn} \to \{\mathbf{pp}\}_\mathbf{s}\pi^-$, $T_p = 350$ MeV, the contact d-term for ChPT

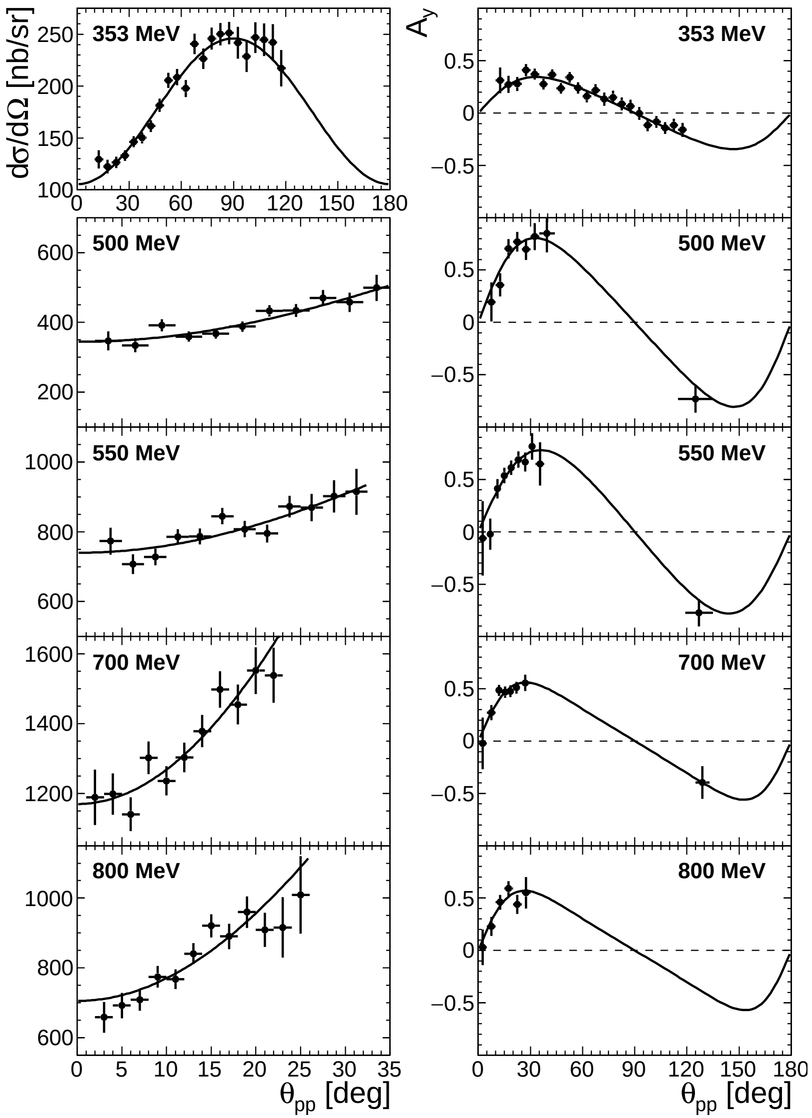
$\mathbf{dp} \to \{\mathbf{pp}\}_\mathbf{s}\mathbf{N}\pi$, $T_d = 1.6 - 2.3$ GeV $\pi N = \Delta$- excitation

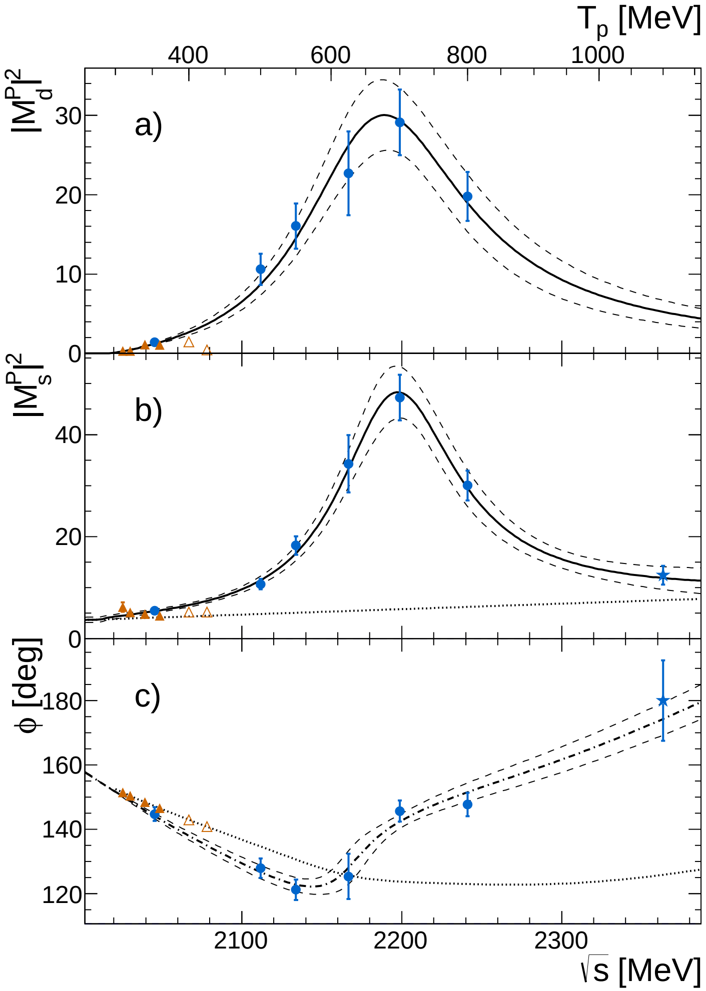
As was shown in CC approach, the resonance sructure in $\mathbf{pp} \to \mathbf{d}\pi^+$ at 500-800 MeV is dominated by the $\Delta(1232)$-isobar excitation (J. Niskanen, NPA(1978), Phys.Lett B141 (1984); C. Furget et al. Nucl.Phys. A655 (1999) 495).

M. Platonova, V. Kukulin, NPA **946** (2016) 117: the Δ mechanism alone is not sufficient, dibaryon resonances were introduced: ^1D_2p (2150 MeV, $\Gamma = 110$MeV), ^3F_3d (2200-2260 MeV $\Gamma = 150$ MeV) to get an agreement (including polarizations, PRD **94** (2016)) with $\mathbf{pp} \to \mathbf{d}\pi^+$.

Thus, it is important to study another channel: $pp \to \{pp\}_s\pi^0$ **at similar kinematics** .

ANKE@COSY $pp \to \{pp\}_s \pi^0$,

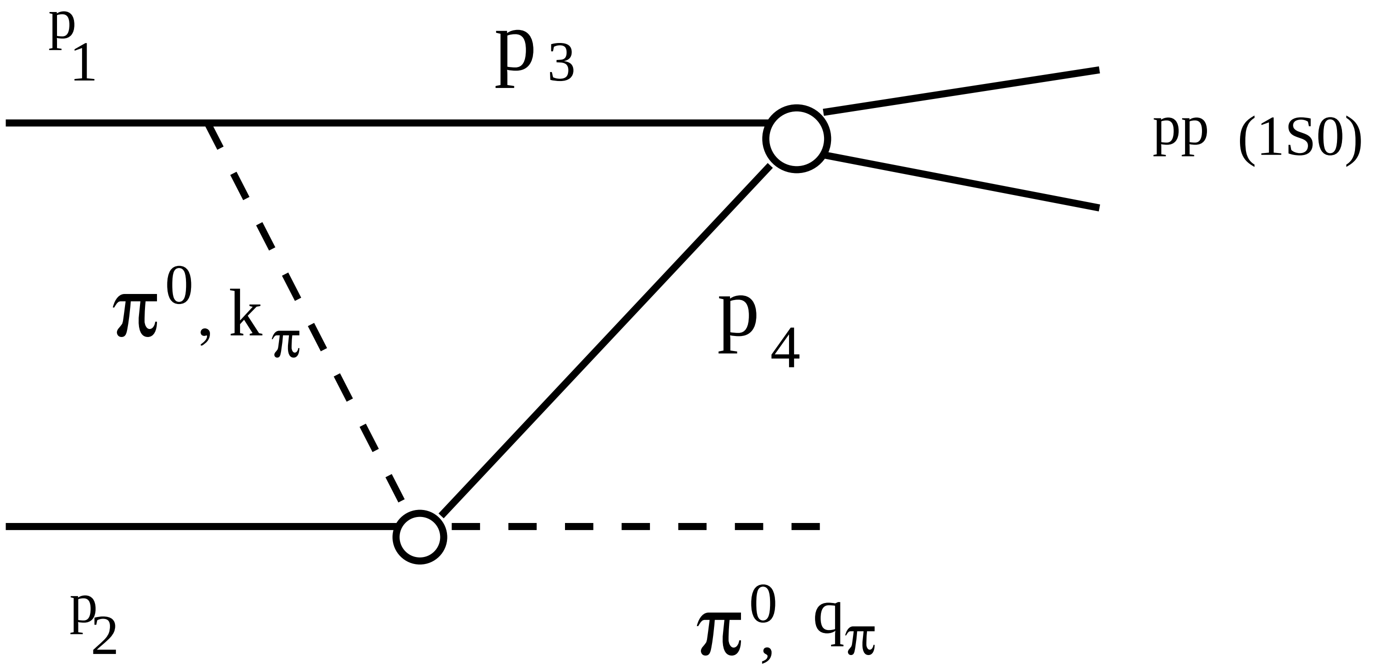




V.Komarov et al. PRC 94 (20016) 052301;

Two $T = 1$ resonances are found with almost equal masses 2205 MeV:
$J^p = 0^-$ ($^3P_0 s$), $J^p = 2^-$ ($^3P_2 d$); $\Gamma_0 = 95 \pm 9$ MeV $\Gamma_2 = 170 \pm 32$ MeV,

The OPE model



$pp \to \{pp\}_s\pi^0$

The $\pi N \to \pi N$ is taken off the loop integral
(similar to Yu.N.U., J. Haidenbauer, C. Wilkin, PRC **75** (2007) 014008)

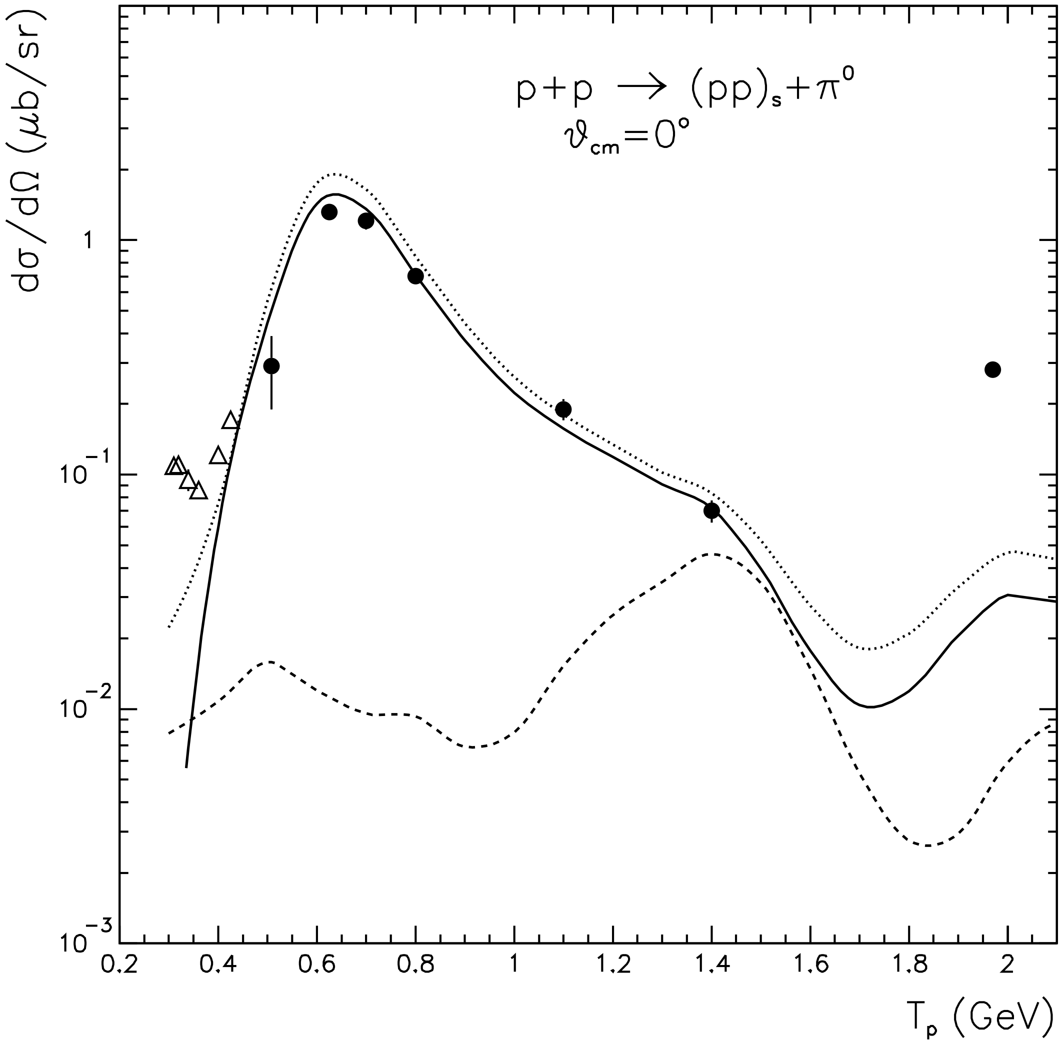
How to exclude Δ from $\pi^0 p \to \pi^0 p$?

$$\mathbf{A}(\pi^{\mathbf{0}}\mathbf{p} \to \pi^{\mathbf{0}}\mathbf{p}) = \frac{\mathbf{1}}{\mathbf{3}}\Big(\mathbf{a}_{\frac{1}{2}} + \mathbf{2a}_{\frac{3}{2}}\Big), \tag{1}$$

$$\mathbf{d}\sigma(\pi^{\mathbf{0}}\mathbf{p} \to \pi^{\mathbf{0}}\mathbf{p}) = \frac{\mathbf{1}}{\mathbf{2}}\Big\{\mathbf{d}\sigma(\pi^{+}\mathbf{p}) + \mathbf{d}\sigma(\pi^{-}\mathbf{p}) - \mathbf{d}\sigma(\pi^{\mathbf{0}}\mathbf{n} \to \pi^{-}\mathbf{p})\Big\}, \tag{2}$$

If the amplitude $a_{\frac{3}{2}}$ is excluded from Eq. (1)

$$\mathbf{d}\widetilde{\sigma}(\pi^{\mathbf{0}}\mathbf{p} \to \pi^{\mathbf{0}}\mathbf{p}) = \frac{\mathbf{1}}{\mathbf{18}}\Big\{\mathbf{3d}\sigma(\pi^{-}\mathbf{p}) - \mathbf{d}\sigma(\pi^{+}\mathbf{p}) + \mathbf{3d}\sigma(\pi^{\mathbf{0}}\mathbf{n} \to \pi^{-}\mathbf{p})\Big\}. \tag{3}$$



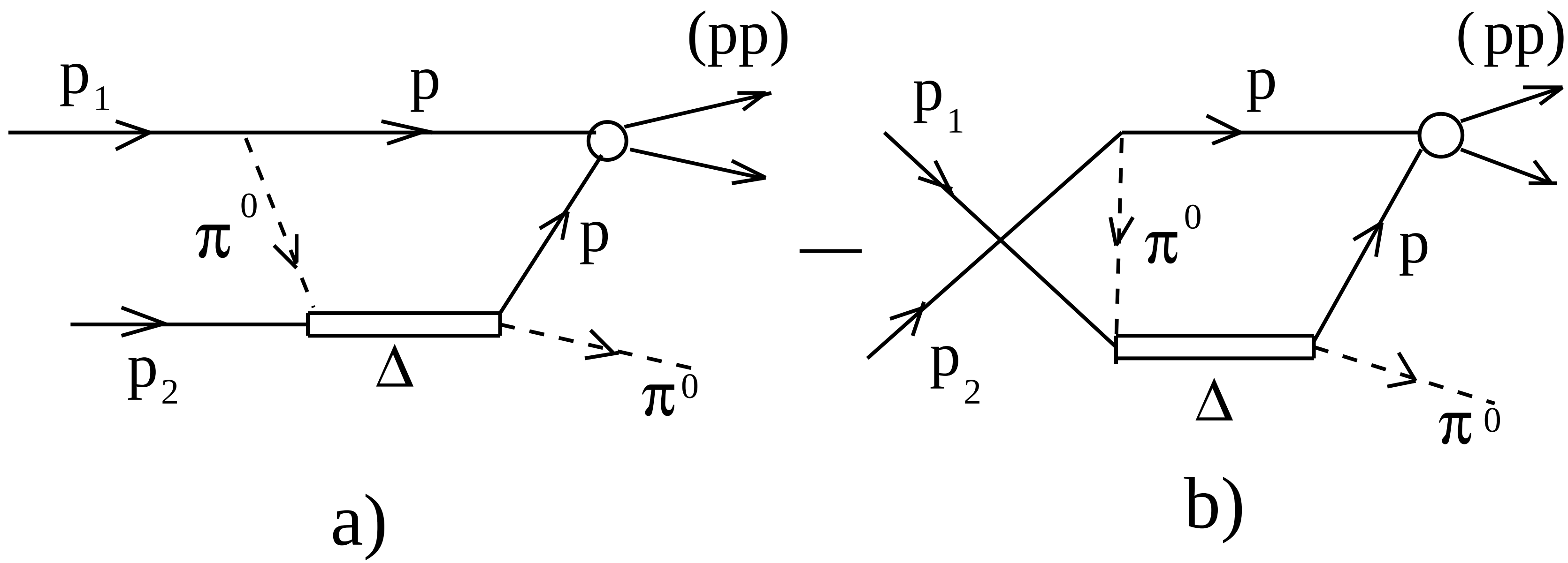
Normalization factor $N = \frac{1}{2.5}$

- • – COSY data at $T_p = 0.8$ GeV , V. Kurbatov et. al, PLB 661 (2008)

OPE: $pp \to \{pp\}_s\pi^0$, $pp \to \{pp\}_s\gamma$

The OPE mechanism does not allow one to take into account the Pauli principle $(-1)^{S+T+L} = -1$ because the direct and exchange diagrams are not involved explicitely.
Even L must be excluded.
An explicite consideration of the Δ-isobar is required.

The BOX-diagram for $pp \to \{pp\}_s\pi^0$ with Δ



$$A^{dir}_{\sigma_1\sigma_2} = -8m_\Delta m_p^2 N_{pp}\left(\frac{f_{\pi NN}}{m_\pi}\right)\left(\frac{f_{\pi N\Delta}}{m_\pi}\right)^2 \frac{2}{3}\frac{i}{\sqrt{2}} G^{dir}_{\sigma_1\sigma_2}\times$$

$$\times \int \frac{F_{\pi NN}(k_\pi^2)}{(m_\pi^2 - k^2_{\pi_a} - i\varepsilon)} \frac{F_{\pi N\Delta}(k_\pi^2)}{(m_\Delta^2 - k^2_{\Delta_a} - im_\Delta\Gamma)} \frac{< \Psi_k^{(-)} \mid V(^1S_0) \mid \mathbf{q} >}{(k^2_{pp} - q^2 + i\varepsilon)} \frac{d^3\vec{q}}{(2\pi)^3} \qquad (4)$$

Yu.N. Uzikov, Izv.RAN, Ser.Fiz. 81 (2017) 815 / Bull. Rus. Ac. Sci: Physics, 81 (2017) 739/

πNN, $\pi N\Delta$-vertices; $\Gamma_\Delta(k)$

$$< \pi N_2|N_1 >= \frac{f_{\pi NN}}{m_\pi}\varphi_1^+(\boldsymbol{\sigma}\mathbf{Q})(\boldsymbol{\tau}\mathbf{\Phi}_\pi)\varphi_2 2m_N,$$

$$< \rho N_2|N_1 >= \frac{f_{\rho NN}}{m_\rho}\varphi_1^+([\boldsymbol{\sigma}\mathbf{Q}]\epsilon_\rho)(\boldsymbol{\tau}\mathbf{\Phi}_\rho)\varphi_2 2m_N,$$

$$< \pi N|\Delta >= \frac{f_{\pi N\Delta}}{m_\pi}(\mathbf{\Psi}_\Delta^+\mathbf{Q}'_\pi)(\mathbf{T}\mathbf{\Phi}_\pi)\varphi\sqrt{2m_N 2m_\Delta},$$

$$< \rho N|\Delta >= \frac{f_{\rho N\Delta}}{m_\rho}([\mathbf{\Psi}_\Delta^+\mathbf{Q}'_\rho]\boldsymbol{\epsilon}_\rho)(\mathbf{T}\mathbf{\Phi}_\rho)\varphi\sqrt{2m_N 2m_\Delta},$$

where

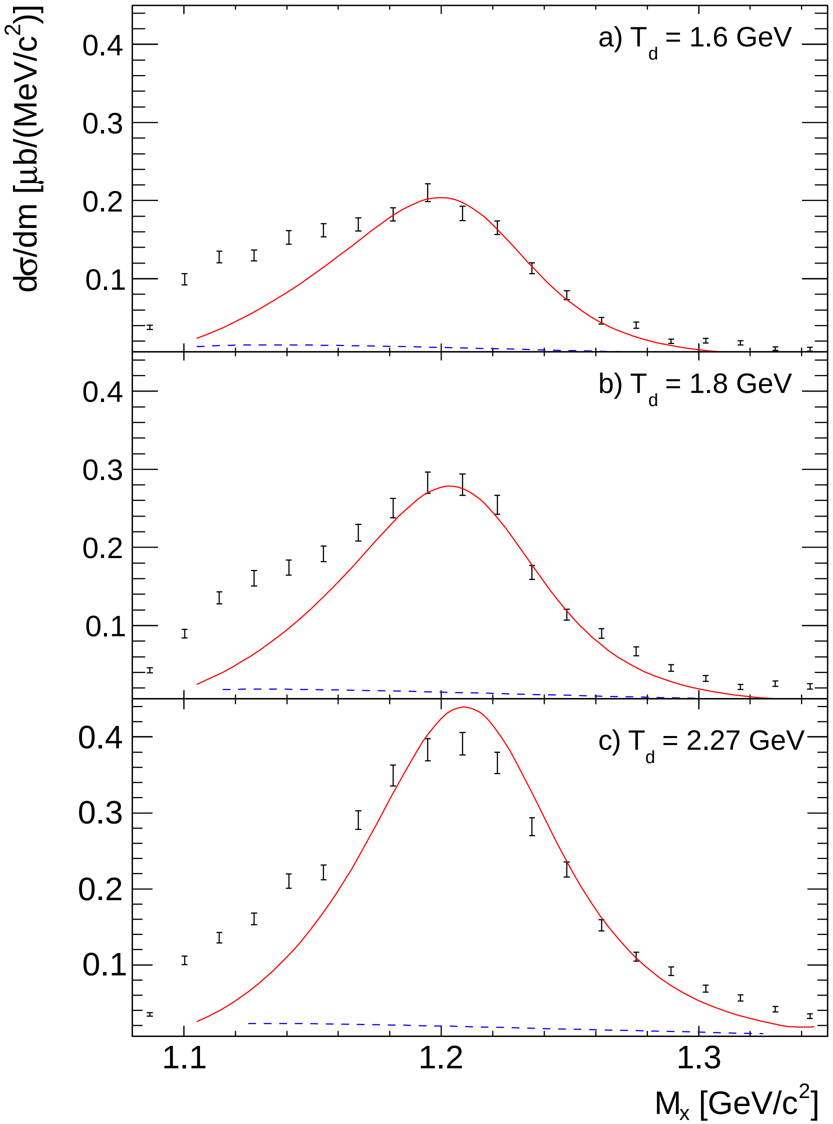
$$f_{\pi NN} = 1.00, f_{\pi N\Delta} = 2.15,$$
$$f_{\rho NN} = 6.20, f_{\rho N\Delta} = 13.33.$$

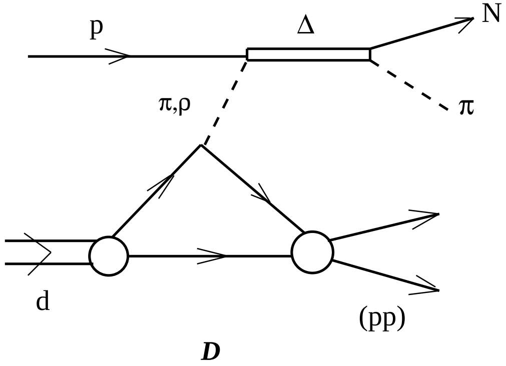
V.F. Dmitriev et al (1987) M.Platonova, V.Kukulin, NPA (2016)

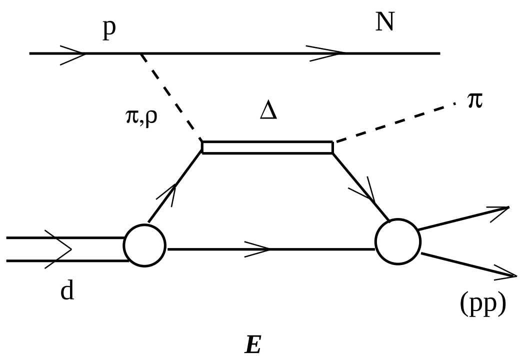
$$\Gamma(k) = \Gamma_0\left(\frac{k_{on}}{k_R}\right)^3\frac{k_R^2+\chi^2}{k_{on}^2+\chi^2}, \qquad \Gamma(k) = \Gamma_0\left(\frac{k_{on}}{k_R}\right)^3\left(\frac{k_R^2+\lambda^2}{k_{on}^2+\lambda^2}\right)^2,$$

$\mathbf{Z} = \frac{\mathbf{k_R^2}+\chi^2}{\mathbf{k_{on}^2}+\chi^2}$, $k_{on} = k(s_\Delta, m^2, m_\pi^2)$; $\chi = 0.18$ GeV, $\lambda = 0.3$ GeV; $\sqrt{Z} \to \pi N\Delta$.

$dp \to \{pp\}_s \pi N$ Yu.N. U., J.Haidenbauer, C. Wilkin, PoS 93 (2015)

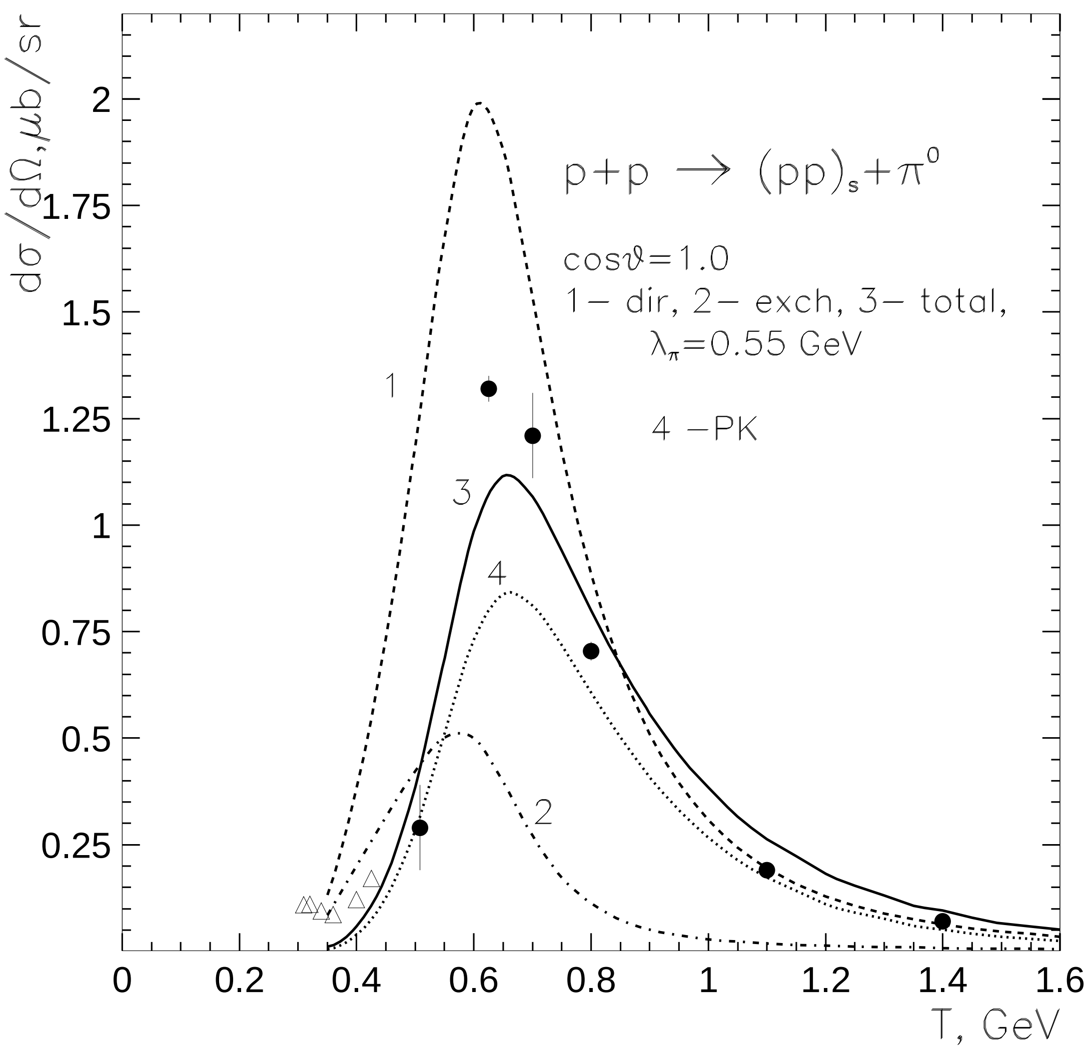






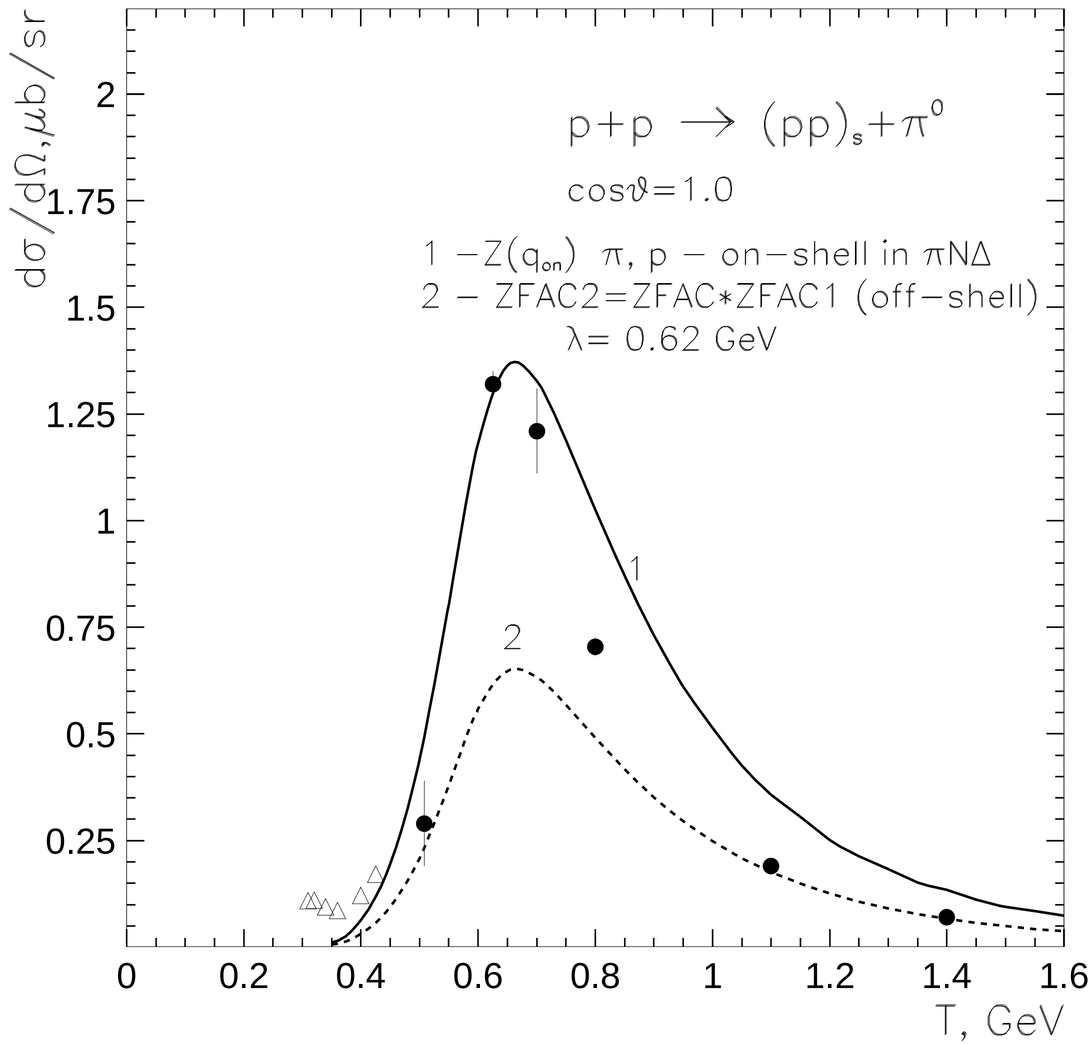
ANKE@COSY data • – D. Mchedlishvili et al., PRL (2013) $\lambda_\pi = 0.5$ GeV, and $\mathbf{T_{22}}$

Z, $\chi = 0.180$ GeV $pp \to \{pp\}_s\pi^0$



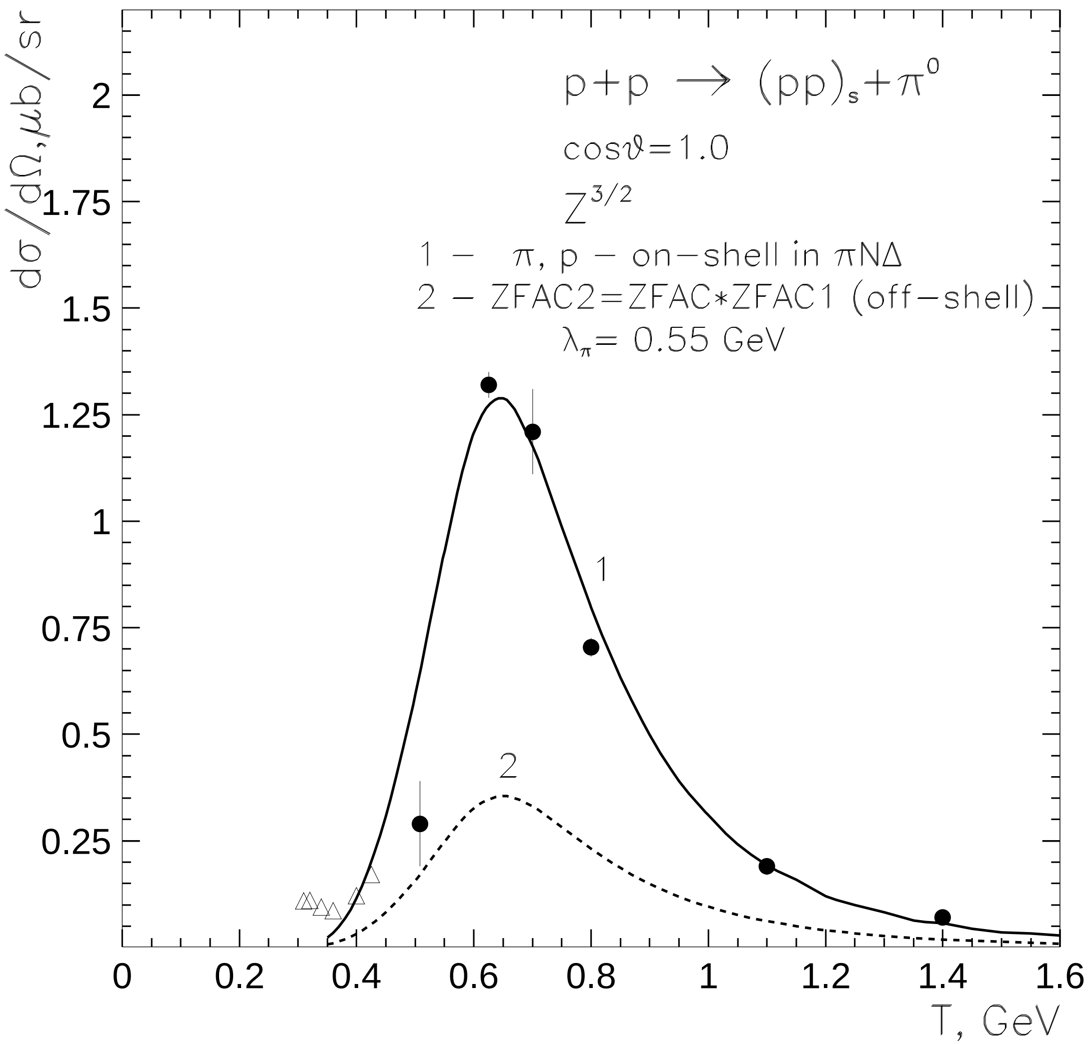
In $\sqrt{Z}$-factor in $\pi N\Delta$ $q = q_{on} = k(s_\Delta, m^2, m_\pi^2)$: 1- direct, 2-exchange, 3- total; 4 – total PK $\Gamma(k) = \Gamma_0\left(\frac{k}{k_R}\right)^3 \frac{k_R^2+\chi^2}{k^2+\chi^2}$ $\chi = 0.180 GeV$, $\lambda_\pi = 0.55$ GeV

Influence of off-shell effects in $\pi N\Delta$-verices via $\sqrt{Z}$



Off-shell $\sqrt{Z}$-factor in $\pi N \Delta -$ vertices diminishes $d\sigma/d\Omega$ (line 2).

$Z^{3/2}, \; pp \to \{pp\}_s \pi^0$



Off-shell $Z^{3/2}$-factor in $\Gamma(k)$ and in $\pi N\Delta-$ vertices improves the shape of $d\sigma/d\Omega$ at $T > 0.6$ GeV but disproves at $T < 0.6$ GeV

Matrix element of $pp \to \{pp\}_s\pi^0$. The PWA expansion.

$$M = \chi^T_{\sigma_2}(2)\frac{i\sigma_y}{\sqrt{2}}\left(A\vec{\sigma}\hat{\vec{p}} + B\vec{\sigma}\hat{\vec{q}}\right)\chi_{\sigma_1}(1) \qquad (5)$$

$\vec{p}$ – the proton momentum, $\vec{q}$ – the pion momentum

$$\frac{d\sigma}{d\Omega} = |A|^2 + |B|^2 + 2ReAB^*\cos\theta, \qquad (6)$$

$$A_y\frac{d\sigma}{d\Omega} = 2ImAB^*\sin\theta;$$

$$M_{\lambda_1=\frac{1}{2},\lambda_2=\frac{1}{2}} = -\frac{1}{\sqrt{2}}(A + B\cos\theta) \equiv \Phi_1,$$

$$M_{\lambda_1=\frac{1}{2},\lambda_2=-\frac{1}{2}} = \frac{1}{\sqrt{2}}B\sin\theta \equiv \Phi_2 \qquad (7)$$

$$M_{\lambda_1\lambda_2} = \sum_J \frac{2J+1}{2}d^J_{\lambda,0}(\theta) < 00; JM|JM; l_\pi 0 >< JM; LS|JM; \lambda_1\lambda_2 > A(^{2S+1}L_J, l_\pi) \equiv$$

$$\equiv \sum_J \frac{2J+1}{2}d^J_{\lambda,0}(\theta)\Phi^{(J)}_{\lambda_1\lambda_2}(E), \qquad (8)$$

$$\Phi^{(J)}_{\lambda_1\lambda_2}(E) = \int_0^\pi M_{\lambda_1\lambda_2}(\theta) d^J_{\lambda,0}(\theta)\sin\theta d\theta. \tag{9}$$

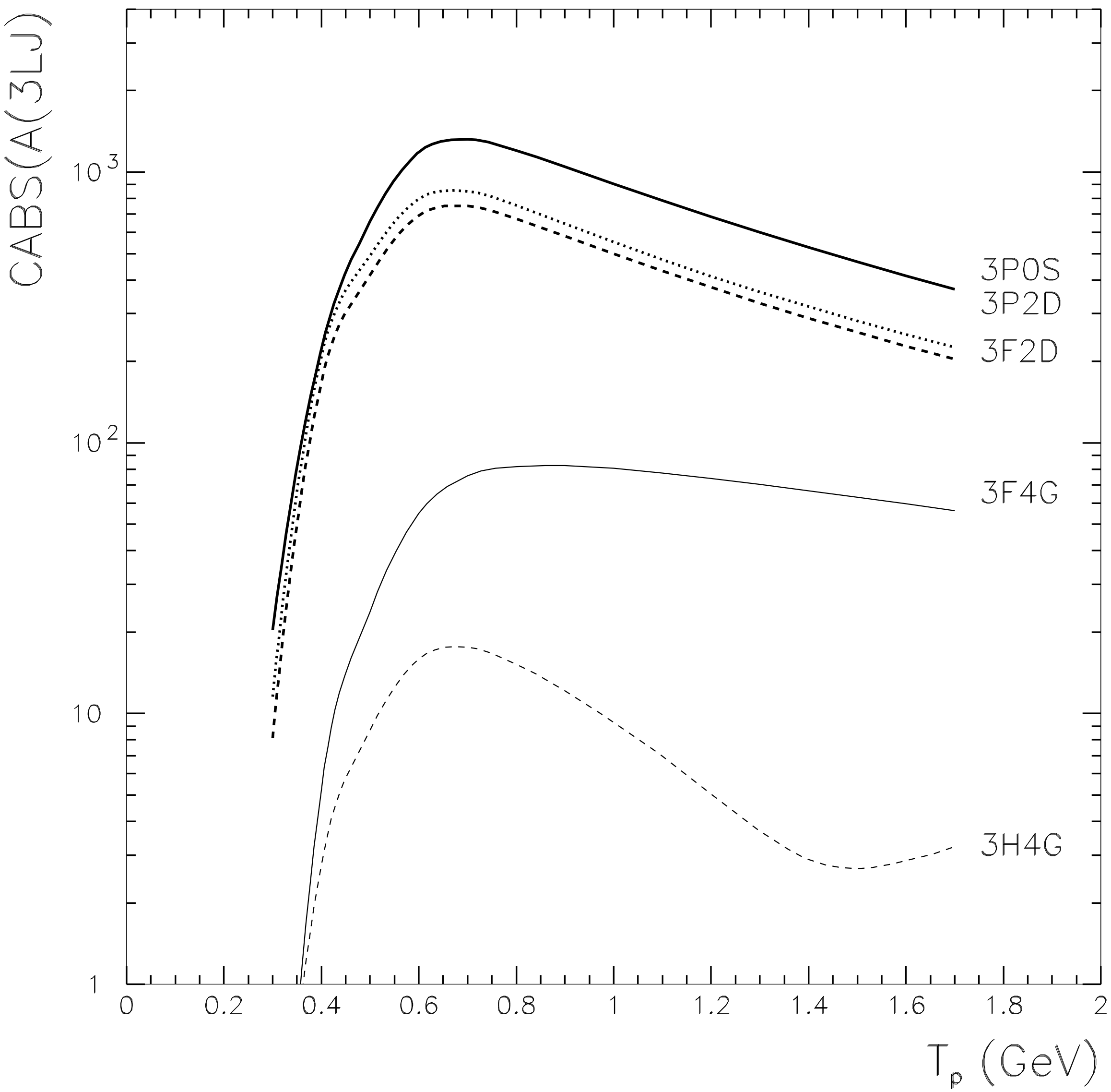
For $J = 0, 2, 4$:

$$\begin{aligned}
A(^3P_0 s) &= -\frac{1}{\sqrt{2}}\Phi_1^{(J=0)}, \\
A(^3P_2 d) &= \frac{1}{\sqrt{5}}\Phi_1^{(J=2)} + \sqrt{\frac{3}{10}}\Phi_2^{(J=2)}, \\
A(^3F_2 d) &= -\sqrt{\frac{3}{10}}\Phi_1^{(J=2)} + \frac{1}{\sqrt{5}}\Phi_2^{(J=2)}, \\
A(^3F_4 g) &= \frac{\sqrt{2}}{3}\Phi_1^{(J=4)} + \frac{1}{3}\sqrt{\frac{5}{2}}\Phi_2^{(J=4)}, \\
A(^3H_4 g) &= -\frac{1}{3}\sqrt{\frac{5}{2}}\Phi_1^{(J=4)} + \frac{\sqrt{2}}{3}\Phi_2^{(J=4)}.
\end{aligned} \tag{10}$$

For $J = 0, 2$ coincides with V.Baru et al. (2014)):

$$\begin{aligned}
A &= M(^3P_0 s) - \frac{1}{3}M(^3P_2 d) + M(^3F_2)\Big(\cos^2\theta - \frac{1}{5}\Big), \\
B &= \Big[M(^3P_2 d) - \frac{2}{5}M(^3F_2 d)\Big]\cos\theta,
\end{aligned} \tag{11}$$

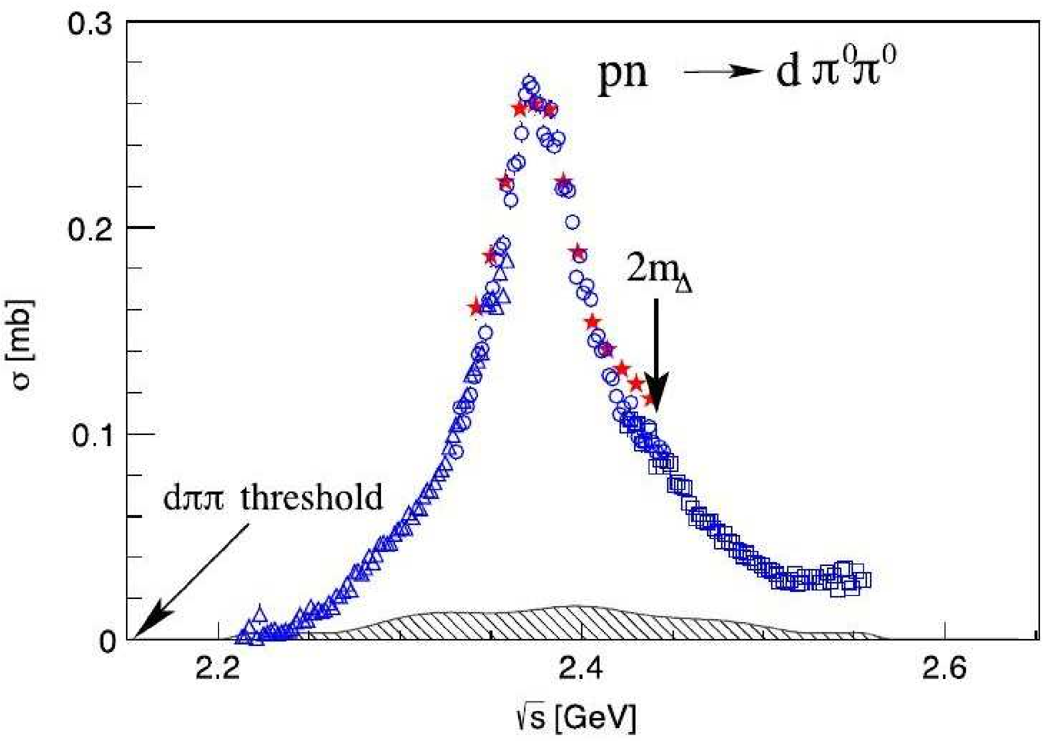
PWA for $pp \to \{pp\}_s\pi^0$ *within the* $\Delta-$ *model: three waves dominate*

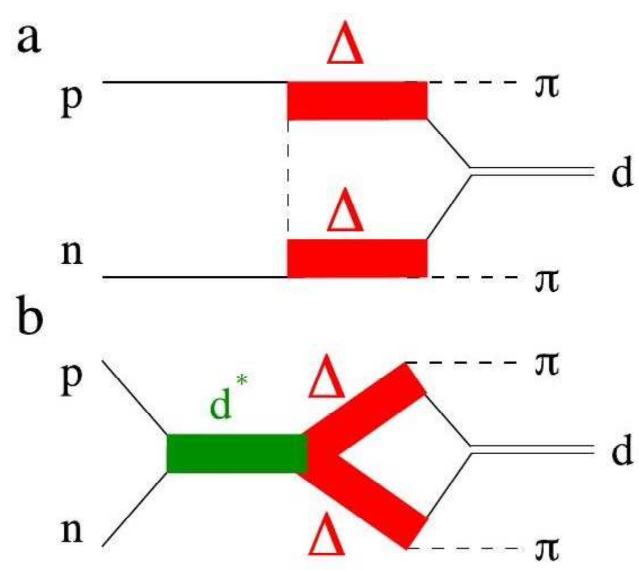


ANKE PWA analysis: ^3P_0s, ^3P_2d are sufficient for $\frac{d\sigma}{d\Omega}$ and $A_y(\theta)$.
The Δ-model: ^3F_2d cannot be neglected.

WASA@COSY $pn \to d\pi^0\pi^0$, $M \approx 2380$ MeV $\Gamma \approx 70$ MeV, $I\,J^\pi = 0\,3^+$

H. Clement / Progress in Particle and Nuclear Physics 93 (2017) 195–242

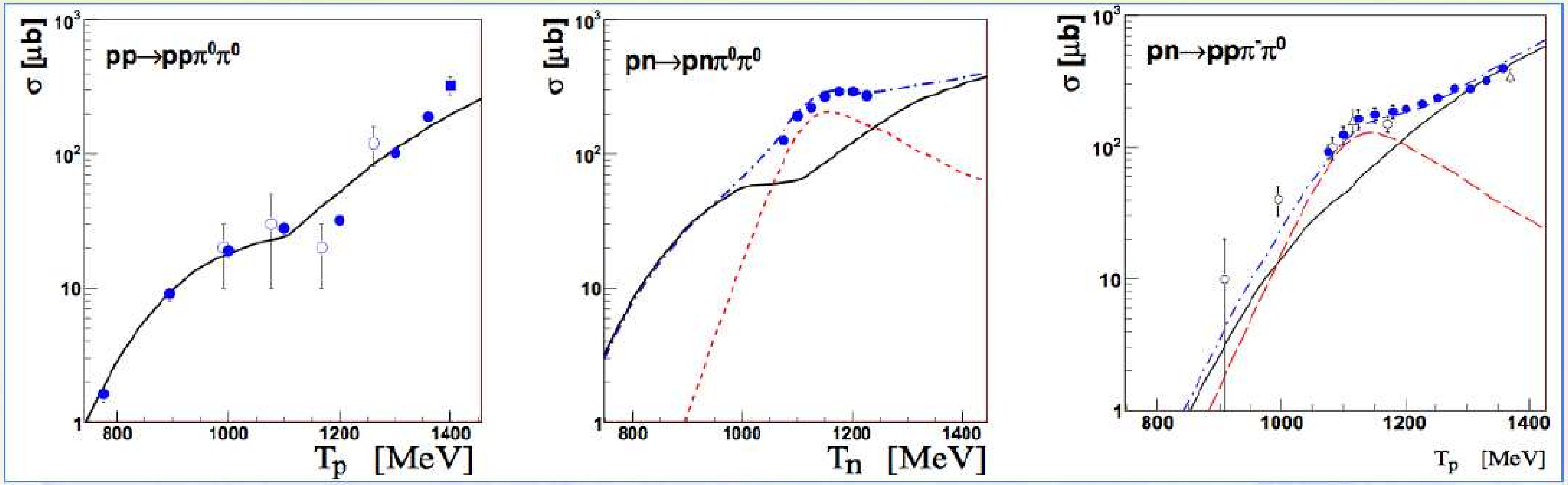


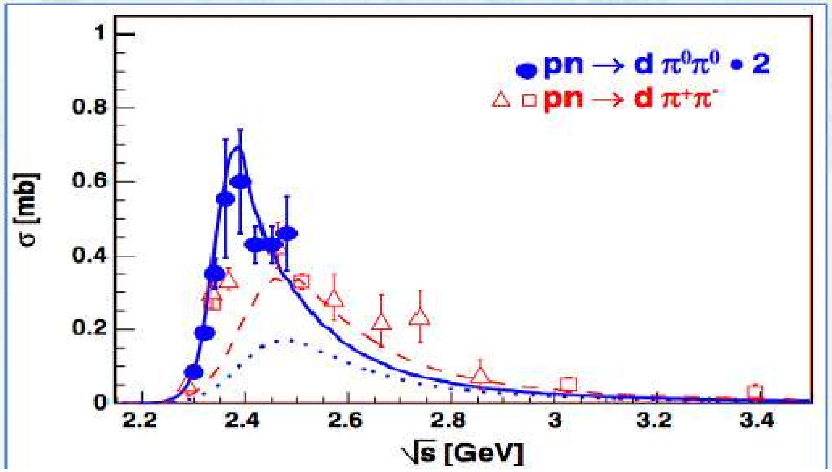


M.Bashkanov et al. PRL 102 (2009) 052301; **several others reactions**
Recent review H. Clement, Prog. Part. Nucl. Phys. 93 (2017) 195

Narrow width: (i) 6q-models, – Y.-B. Dong, et al. (2016) (hidden colour); (ii) hadron picture, $\pi N\Delta$ system – A.Gal, H.Garcilazo, PRL 111 (2013) 172301; $\Delta\Delta$ system – J. Niskanen, PRC 95 (2017) 054002 A. Gal PLB 769 (2017) 436 (see talks on 8 June, and T.Skorodko on 11 June).
New ANKE data on $pd \to pd\pi\pi$ (talk by D.Tsirkov tomorrow)

Signals in other reactions @ COSY





Measured also in fusion reactions to helium isotopes:

$p + d \longrightarrow {}^3He + \pi^0 + \pi^0$

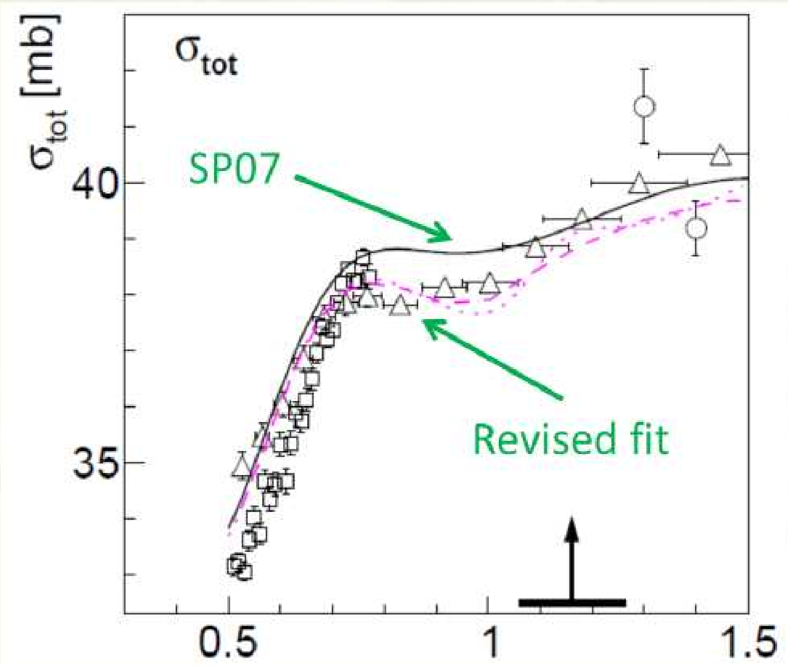
$p + d \longrightarrow {}^3He + \pi^+ + \pi^-$

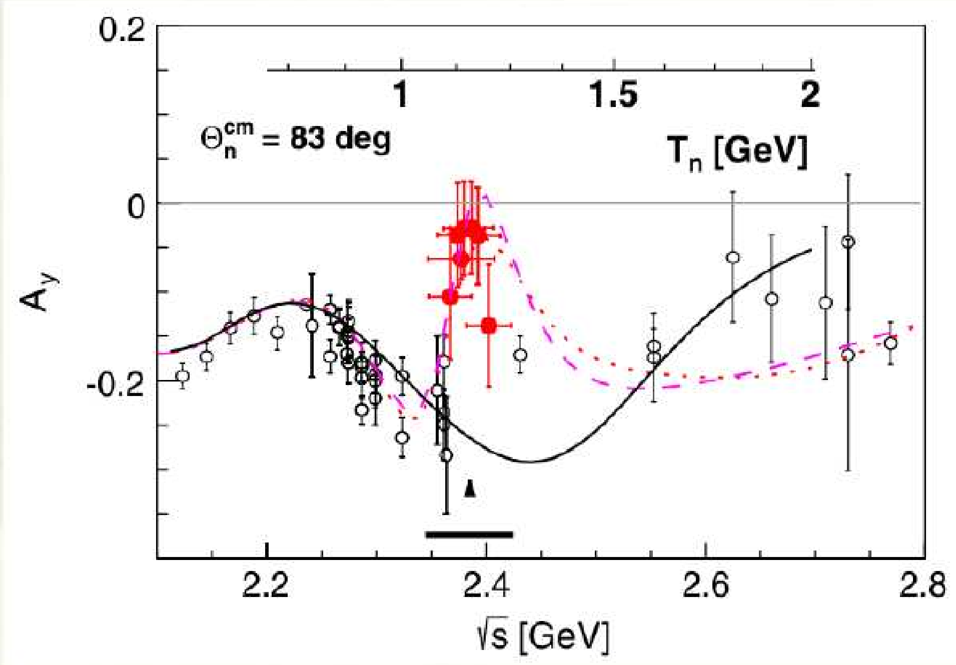
$d + d \longrightarrow {}^4He + \pi^0 + \pi^0$

$d + d \longrightarrow {}^4He + \pi^+ + \pi^-$

Evidence from $\vec{n}p$ scattering

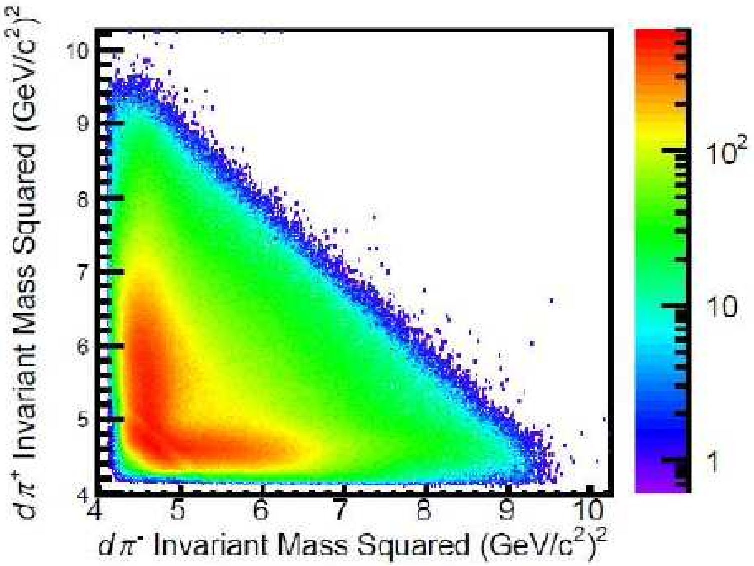
$\vec{d}p \to np + p_{spectator}$ $\quad$ M = (2380±10) - *i* (40±5)

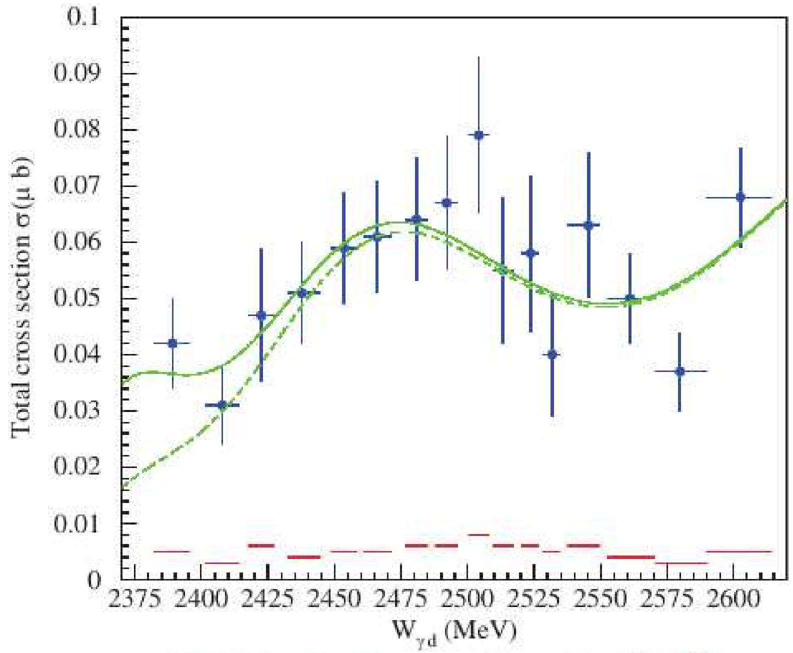




WASA-at-COSY & SAID DAC, PRL112(2014)202301

Dibaryon searches in $\gamma d \to d\pi\pi$





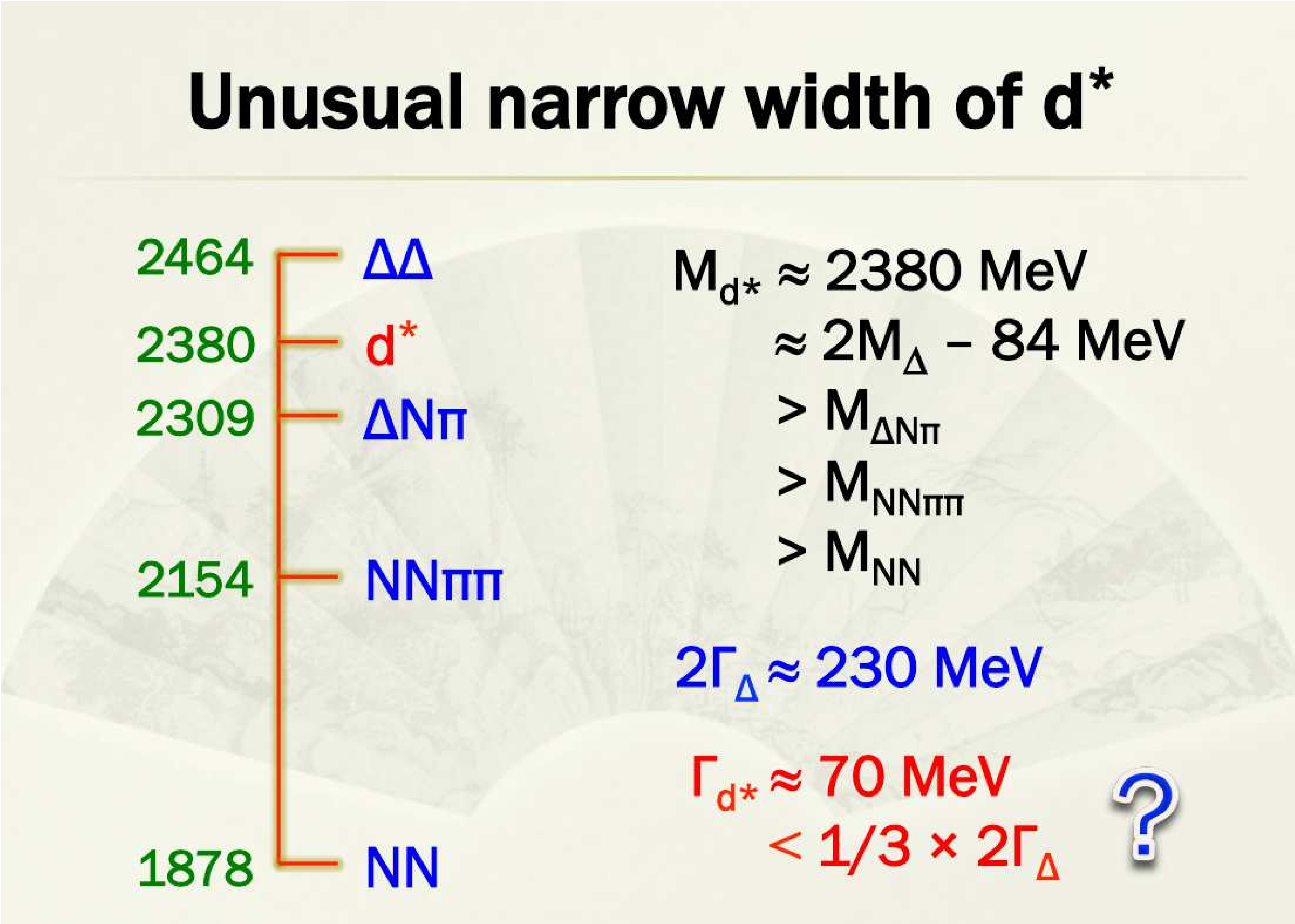
$d\pi^+$ vs. $d\pi^-$ in $\gamma d \to d\pi^+\pi^-$
CLAS prelim. (APS 04/2015)

$\sigma_{tot}(W_{\gamma d})$ in $\gamma d \to d\pi^0\pi^0$
ELPH, PLB 772 (2017) 398
& arXiv:1805.08928

$\mathcal{D}_{12}$ signal? with BW fit
(M,Γ)=(2.12, 0.125) GeV

$\mathcal{D}_{03}$ signal? (2.37, 0.068)
$\mathcal{D}_{12}$ signal? (2.15, 0.110)

See also T.Kamae, T.Fujita, PRL 38 (1977) 468


Unusual narrow width of d*
2464 ΔΔ
2380 d*
2309 ΔNπ
2154 NNππ
1878 NN
$M_{d*} \approx 2380$ MeV
$\approx 2M_\Delta - 84$ MeV
$> M_{\Delta N\pi}$
$> M_{NN\pi\pi}$
$> M_{NN}$
$2\Gamma_\Delta \approx 230$ MeV
$\Gamma_{d*} \approx 70$ MeV
$< 1/3 \times 2\Gamma_\Delta$
?

Hamiltonian of Chiral QM

Total Hamiltonian for 6q systems:

$$H = \sum_{i=1}^{6}\left(m_i + \frac{\vec{P}_i^2}{2m_i}\right) - T_{\rm cm} + \sum_{1=i<j}^{6}\left(V_{ij}^{\rm conf} + V_{ij}^{\rm OGE} + V_{ij}^{\rm ch}\right)$$

Ch. SU(3) QM:

$$V_{ij}^{\rm ch} = \sum_{a=0}^{8} V_{ij}^{\sigma_a} + \sum_{a=0}^{8} V_{ij}^{\pi_a}$$

Ext. Ch. SU(3) QM:

$$V_{ij}^{\rm ch} = \sum_{a=0}^{8} V_{ij}^{\sigma_a} + \sum_{a=0}^{8} V_{ij}^{\pi_a} + \sum_{a=0}^{8} V_{ij}^{\rho_a}$$

Note: OGE almost completely reduced by including VMEs.

CC component

- d^* has a CC fraction of about 2/3

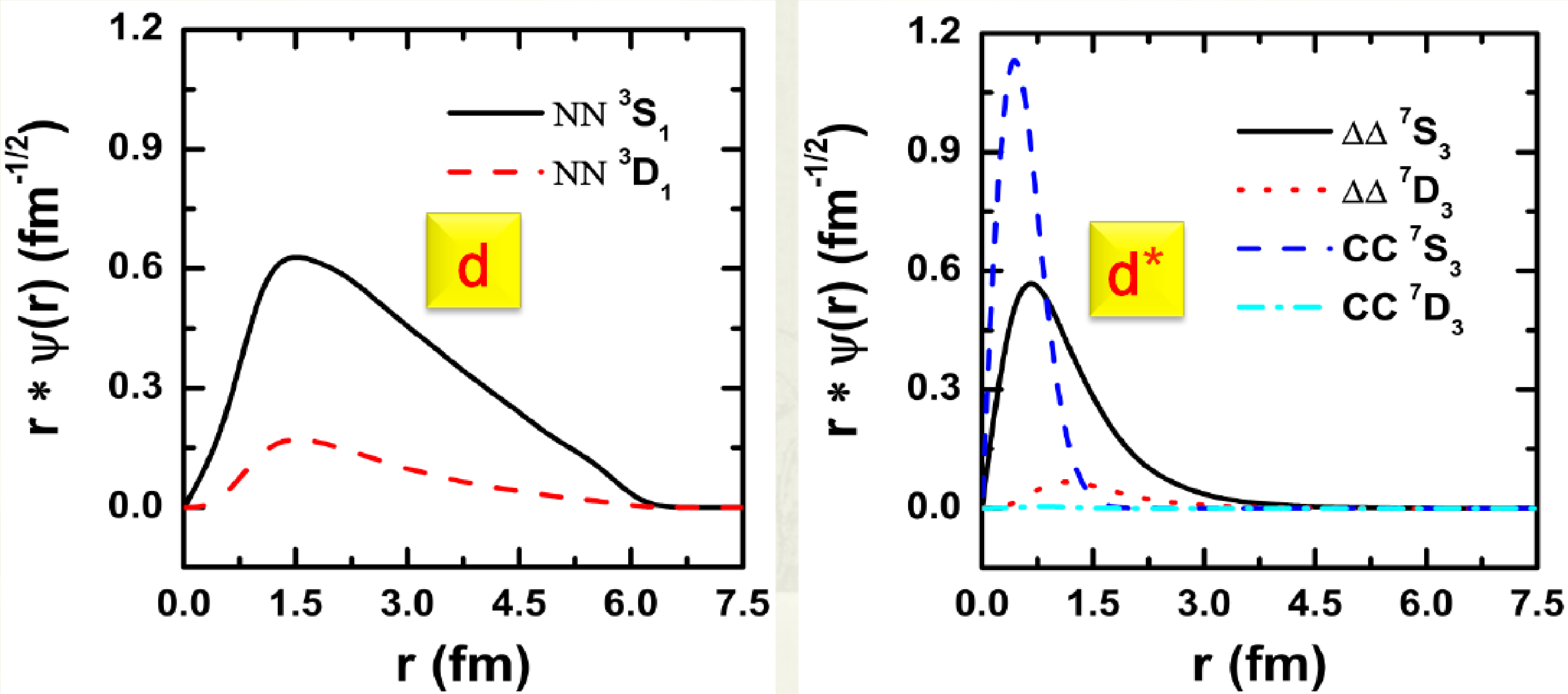
	$\Delta\Delta - CC$ $(L=0,2)$		
	SU(3)	Ext. SU(3) (f/g=0)	Ext. SU(3) (f/g=2/3)
B (MeV)	47.27	83.95	70.25
RMS (fm)	0.88	0.76	0.78
$(\Delta\Delta)_{L=0}$ (%)	33.11	31.22	32.51
$(\Delta\Delta)_{L=2}$ (%)	0.62	0.45	0.51
$(CC)_{L=0}$ (%)	66.25	68.33	66.98
$(CC)_{L=2}$ (%)	0.02	0.00	0.00

- A pure hexaquark state of ΔΔ system has 4/5 CC fraction

$$[6]_{\rm orb}[33]_{IS=03} = \sqrt{\frac{1}{5}}\,|\Delta\Delta\rangle_{IS=03} + \sqrt{\frac{4}{5}}\,|CC\rangle_{IS=03}$$

- d^* is a hexaquark-dominated exotic state!

Relative wave function



Unlike deuteron, d^* is rather narrowly distributed!

Calculated d* mass

Without CC: BE ≈ 29 – 62 MeV

	ΔΔ (L = 0, 2)		
	SU(3)	Ext. SU(3) (f/g=0)	Ext. SU(3) (f/g=2/3)
B (MeV)	28.96	62.28	47.90
RMS (fm)	0.96	0.80	0.84

With CC: BE ≈ 47 – 84 MeV

	ΔΔ – CC (L = 0, 2)		
	SU(3)	Ext. SU(3) (f/g=0)	Ext. SU(3) (f/g=2/3)
B (MeV)	47.27	83.95	70.25
RMS (fm)	0.88	0.76	0.78
$(\Delta\Delta)_{L=0}$ (%)	33.11	31.22	32.51
$(\Delta\Delta)_{L=2}$ (%)	0.62	0.45	0.51
$(CC)_{L=0}$ (%)	66.25	68.33	66.98
$(CC)_{L=2}$ (%)	0.02	0.00	0.00

- d*: a deeply bound & compact ΔΔ-CC state
- Coupling to CC plays a significant role
- Predicted binding energy close to experimental value

$M_{d^*} \approx 2M_\Delta - 84$ MeV

Widths for 2π-decay

	Theor. (MeV)	Expt. (MeV)
$d^* \to d\pi^+\pi^-$	16.8	16.7
$d^* \to d\pi^0\pi^0$	9.2	10.2
$d^* \to pn\pi^+\pi^-$	20.6	21.8
$d^* \to pn\pi^0\pi^0$	9.6	8.7
$d^* \to pp\pi^0\pi^-$	3.5	4.4
$d^* \to nn\pi^0\pi^+$	3.5	4.4
$d^* \to pn$	8.7	8.7
Total	71.9	74.9

Results for single π decay

$$\Gamma_{d^* \to NN\pi} \approx 0.67 \text{ MeV} \qquad \frac{\Gamma_{d^* \to NN\pi}}{\Gamma} \approx 0.9\%$$

The WASA-at-COSY Collaboration / Physics Letters B 774 (2017) 599–607

Exclusive measurements of the quasi-free $pn \to pp\pi^-$ and $pp \to pp\pi^0$ reactions have been performed by means of pd collisions at $T_p = 1.2$ GeV using the WASA detector setup at COSY. Total and differential cross sections have been obtained covering the energy region $T_p = 0.95$–1.3 GeV ($\sqrt{s} = 2.3$–2.46 GeV), which includes the regions of $\Delta(1232)$, $N^*(1440)$ and $d^*(2380)$ resonance excitations. From these measurements the isoscalar single-pion production has been extracted, for which data existed so far only below $T_p = 1$ GeV. We observe a substantial increase of this cross section around 1 GeV, which can be related to the Roper resonance $N^*(1440)$, the strength of which shows up isolated from the Δ resonance in the isoscalar $(N\pi)_{I=0}$ invariant-mass spectrum. No evidence for a decay of the dibaryon resonance $d^*(2380)$ into the isoscalar $(NN\pi)_{I=0}$ channel is found. An upper limit of 180 μb (90% C.L.) corresponding to a branching ratio of 9% has been deduced.

Other explanations in literature

- A. Gal & H. Garcilazo, NPA928(2014)73
  - Dynamically generated ΔNπ 3-body resonance
  - Binding energy: 101 MeV
  - Width: 66 MeV

$B_{exp} \approx 84$ MeV
$\Gamma_{exp} \approx 70$ MeV

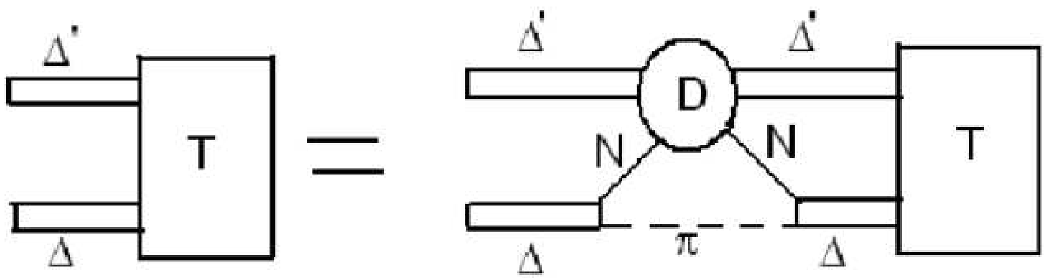
- H.X. Huang, J.L. Ping, & F. Wang, PRC89(2014)034001
  - ΔΔ bound state
  - Binding energy: 71 MeV (ChQM), 107 MeV (QDCSM)
  - Width: 150 MeV (ChQM), 110 MeV (QDCSM)
- H.X. Chen, E.L. Cui, & W. Chen et al., PRC91(2015)025204
  - QCD sum rule analysis
  - Mass: 2.4±0.2 GeV

$\mathcal{D}_{12}(2150)$ $N\Delta$ dibaryon near threshold (2.17 GeV)

- **Long ago established in coupled-channel** $pp(^1D_2) \leftrightarrow \pi^+ d(^3P_2)$ **scattering & reactions. Arndt et al (1987) & Hoshizaki's (1993):** $M \approx 2.15$ **GeV,** $\Gamma \approx 110 - 130$ **MeV.**
- **Nonrelativistic** πNN **Faddeev calculation, Ueda (1982):** $M = 2.12$ **GeV,** $\Gamma = 120$ **MeV.**
- **CLAS** $\gamma d \to d\pi^+\pi^-$ **data [APS 04/2015] suggest** $M_{BW} \approx 2.12$ **GeV,** $\Gamma_{BW} \approx 125$ **MeV.**
- **Our relativistic-kinematics Faddeev calculation gives robust values M≈2.15 GeV, Γ≈120 MeV against variations of** NN **&** πN **input.**

Calculation of $\mathcal{D}_{03}(2380)$ $\Delta\Delta$ dibaryon in terms of π's, N's & Δ's

- Approximate $\pi\pi NN$ problem by $\pi N\Delta'$ problem.
- Separable pair interactions: πN Δ-isobar form factor by fitting $\delta(P_{33})$; $N\Delta'$ $\mathcal{D}_{12}(2150)$-isobar form factor by fitting $NN(^1D_2)$ scattering.
- 3-body S-matrix pole equation reduces to effective $\Delta\Delta'$ diagram:



Width Considerations

- d*(2380) is bound w.r.t. $\Delta\Delta$ by 84 MeV, by 42 MeV on average for each Δ, thereby reducing $\Gamma_\Delta^{\rm free}$=115 MeV to $\Gamma_\Delta^{\rm bound}$=81 MeV.
- However, since none of the Δs is at rest, $s_\Delta^{\rm bound}$ decreases further to $(1232\text{-}42)^2 - P_{\Delta\Delta}^2$, where $P_{\Delta\Delta} \times R_{\Delta\Delta} \geq 3/2$.
- For $R_{\Delta\Delta} \leq 0.8$ fm, $\Gamma_\Delta^{\rm bound} \leq 34$ MeV, so for the $\pi\pi$ decay modes $\Gamma_{\Delta\Delta}^{\rm bound}$=5/3 $\Gamma_\Delta^{\rm bound} \leq 56$ MeV.
- With $R_{\Delta\Delta}$=0.76 fm, as in the Beijing CQM, $\Gamma_{\Delta\Delta}^{\rm bound} \leq 47$ MeV, hence quark-based $\Delta\Delta$ models can't reproduce the LARGE d*(2380) width.
- See also J.A. Niskanen, PRC 95 (2017) 054002.

Kinetic energy vs. Δ width

Centrifugal barrier basically part of kinetic energy. Kinetic energy (relative motion of NΔ) should not contribute to the width of Δ (decay into Nπ).

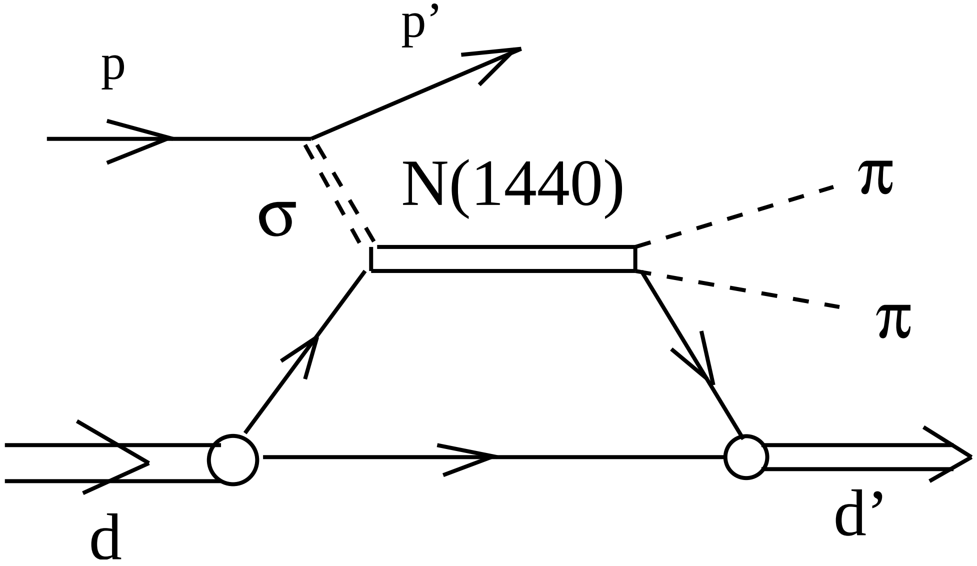
For each relative baryon momentum k this can be calculated and subtracted from the total E to find the energy internal to Δ, available for decay. Pion q from this. The k-momentum distribution can be obtained from the Fourier transform of the NΔ wave function to give

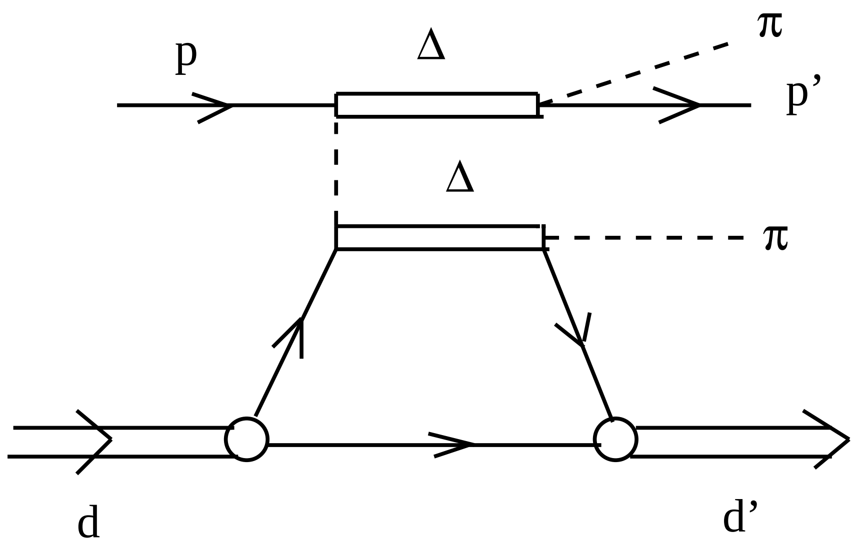
$$\Gamma_3(E) = \frac{2}{\pi} \frac{\int_0^{k_{\max}} |\Psi_{N\Delta}(k)|^2 \Gamma(q) k^2 \, dk}{\int_0^\infty |\Psi_{N\Delta}(r)|^2 r^2 \, dr}$$

Obvious expectation value

ANKE@COSY DATA ON $pd \to d\pi\pi$ REACTION
WERE OBTAINED IN NON QUASI-FREE KINEMATICS
AS A BY PRODUCT OF OUR DEUTERON BREAKUP
PROPOSAL $pd \to \{pp\}_s n$

$pd \to pd\pi\pi$: *Box-diagram with the Roper* $N^*(1440)$ *and* $\Delta\Delta$

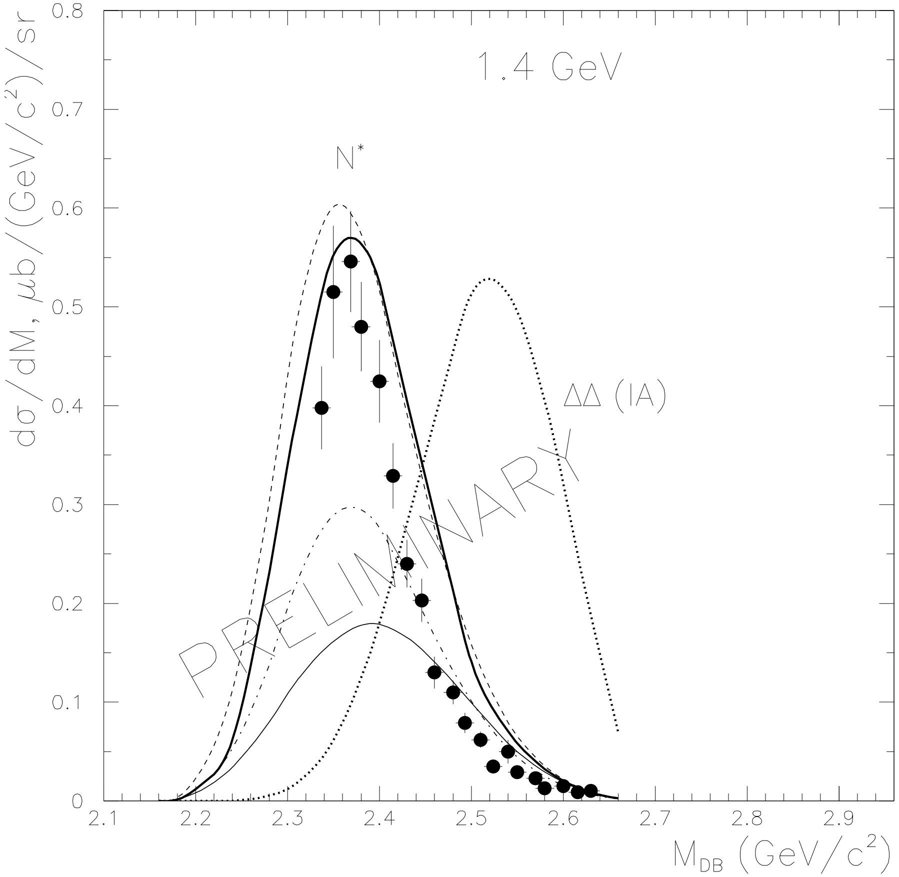




... underestimate the absolute value of the dif. cross section $pd \to pd\pi\pi$ at ANKE@COSY kinematics by two orders of magnitude.

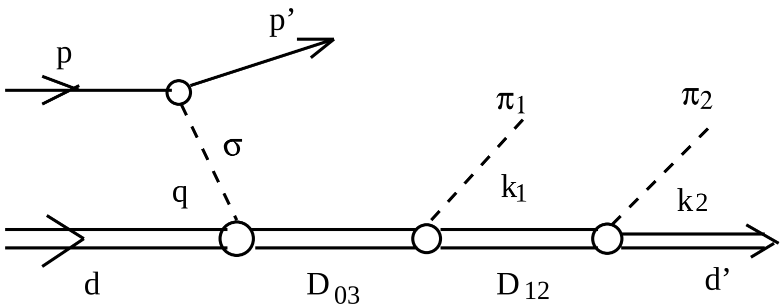
/Yu.N.U., Baldin ISHEPP, 2010, Dubna/

$N^*(1440)$ *and* $\Delta\Delta$ *for* $pd \to pd\pi\pi^0$ *at 1.4GeV*



Roper-resonance
parameters by Skorodjko et al. (dashed-dotted), Zao et al.(dashed), Alvarez-Russo et al. (full line); $\Delta\Delta$(IA).
Yu.N. Uzikov, in: Proc. of Baldin ISHEPP XX "Relativistic Nuclear Physics and Quantum Chromodynamics" (Dubna, October 4-9, 2010).

$pd \to pd\pi\pi$ reaction. Two-resonance model



$\mathbf{\Gamma(D_{03} \to D_{12}\pi) = 6.5}$ **MeV**, $\mathbf{\Gamma(D_{12} \to d\pi) = 10}$ **MeV**, $\mathbf{\Gamma(D_{03} \to d\sigma) = 5}$ **MeV**, $m_\sigma = 0.5$ **GeV**, $\Gamma_\sigma = 0.55$ **GeV.**

$$M_{\lambda_p\lambda_d}^{\lambda'_p\lambda'_d}(pd \to pd\pi\pi) = M_{\lambda_p}^{\lambda'_p}(p \to p'\sigma)\frac{1}{p_\sigma{}^2 - m_\sigma{}^2 + im_\sigma\Gamma_\sigma}M_{\lambda_d}^{\lambda'_d}(\sigma d \to d\pi\pi), \qquad (12)$$

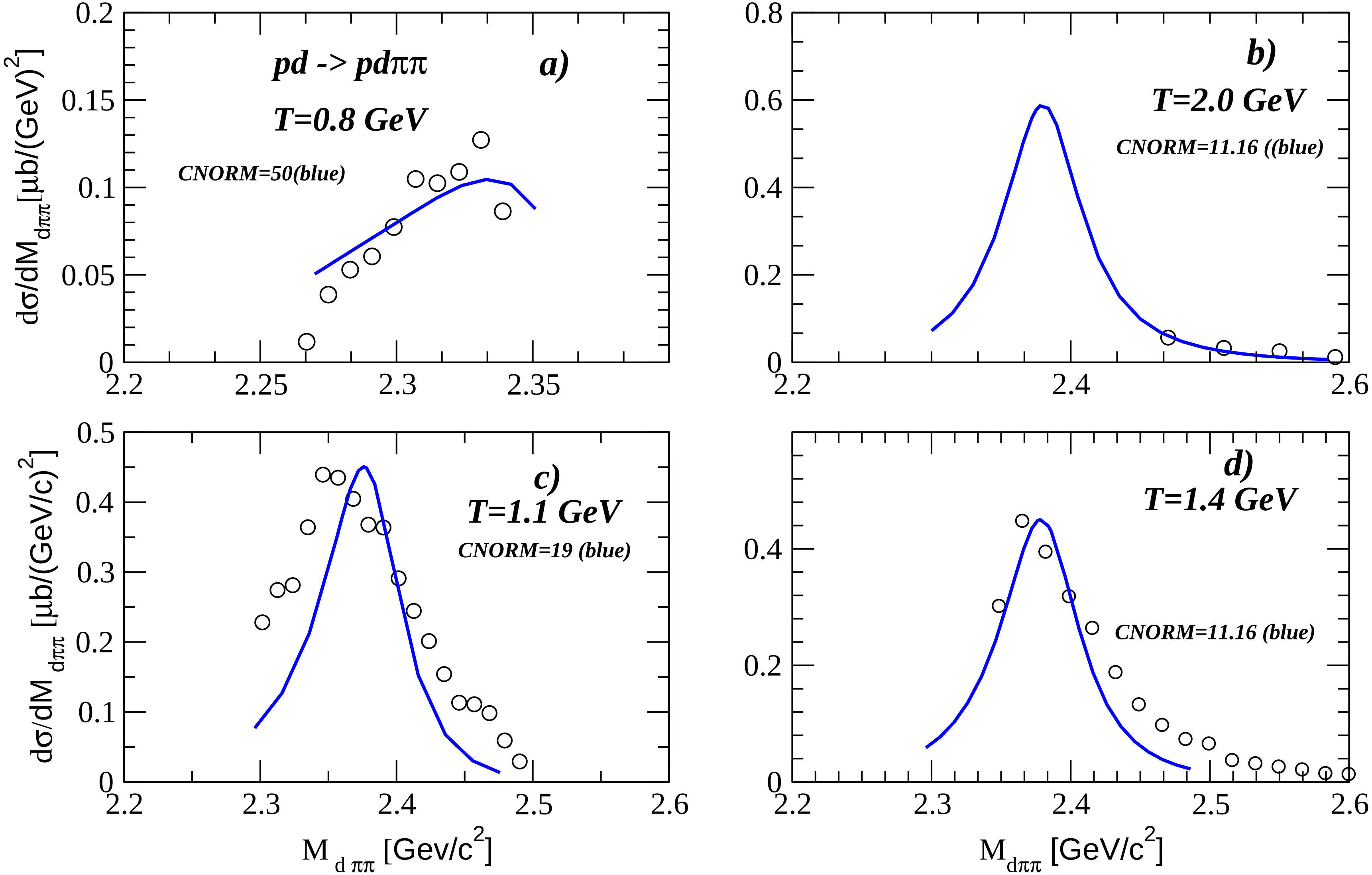
$$M_{\lambda_d}^{\lambda'_d}(\sigma d \to d\pi\pi) = \sum_{\lambda_2,\lambda_3,\mu,m_1,m_2} \frac{F_{D_{03}\to d\sigma}F_{D_{03}\to D_{12}\pi_1}}{P_{D_{03}}^2 - M_{D_{03}}^2 + iM_{D_{03}}\Gamma_{D_{03}}} \frac{F_{D_{12}\to d\pi_2}}{P_{D_{12}}^2 - M_{D_{12}}^2 + iM_{D_{12}}\Gamma_{D_{12}}}$$
$$\times(1\lambda_d 2\mu|3\lambda_3)\mathcal{Y}_{2\mu}(\hat{\mathbf{q}})(2\lambda_2 1m_1|3\lambda_3)\mathcal{Y}_{1m_1}(\hat{\mathbf{k}}_1)(1\lambda'_d 1m_2|2\lambda_2)\mathcal{Y}_{1m_2}(\hat{\mathbf{k}}_2); \qquad (13)$$

$$F_{D_{03}\to d\sigma}(q) = M_{D_{03}}(q)\sqrt{\frac{8\pi\Gamma^{(l=2)}_{D_{03}\to d\sigma}(q)}{q^5}};\ \Gamma^{(l=2)}_{D_{03}\to d\sigma}(q) = \Gamma^{(l=2)}_{D_{03}\to d\sigma}\left(\frac{q}{q_0}\right)^5\left(\frac{q_0^2+\lambda_{d\sigma}^2}{q^2+\lambda_{d\sigma}}\right)^3,$$

$$F_{D_{12}\to d\pi_2}(k_2) = M_{d\pi_2}(k_2)\sqrt{\frac{8\pi\Gamma^{(l=1)}_{D_{12}\to d\pi}(k_2)}{k_2^3}};\ \Gamma^{(l=1)}_{D_{12}\to d\pi}(k_1) = \Gamma^{(l=1)}_{D_{12}\to d\pi}\left(\frac{k_2}{k_{20}}\right)^3\left(\frac{k_{20}^2+\lambda_{d\pi}^2}{k_2^2+\lambda_{d\pi}}\right)^2. \qquad (14)$$

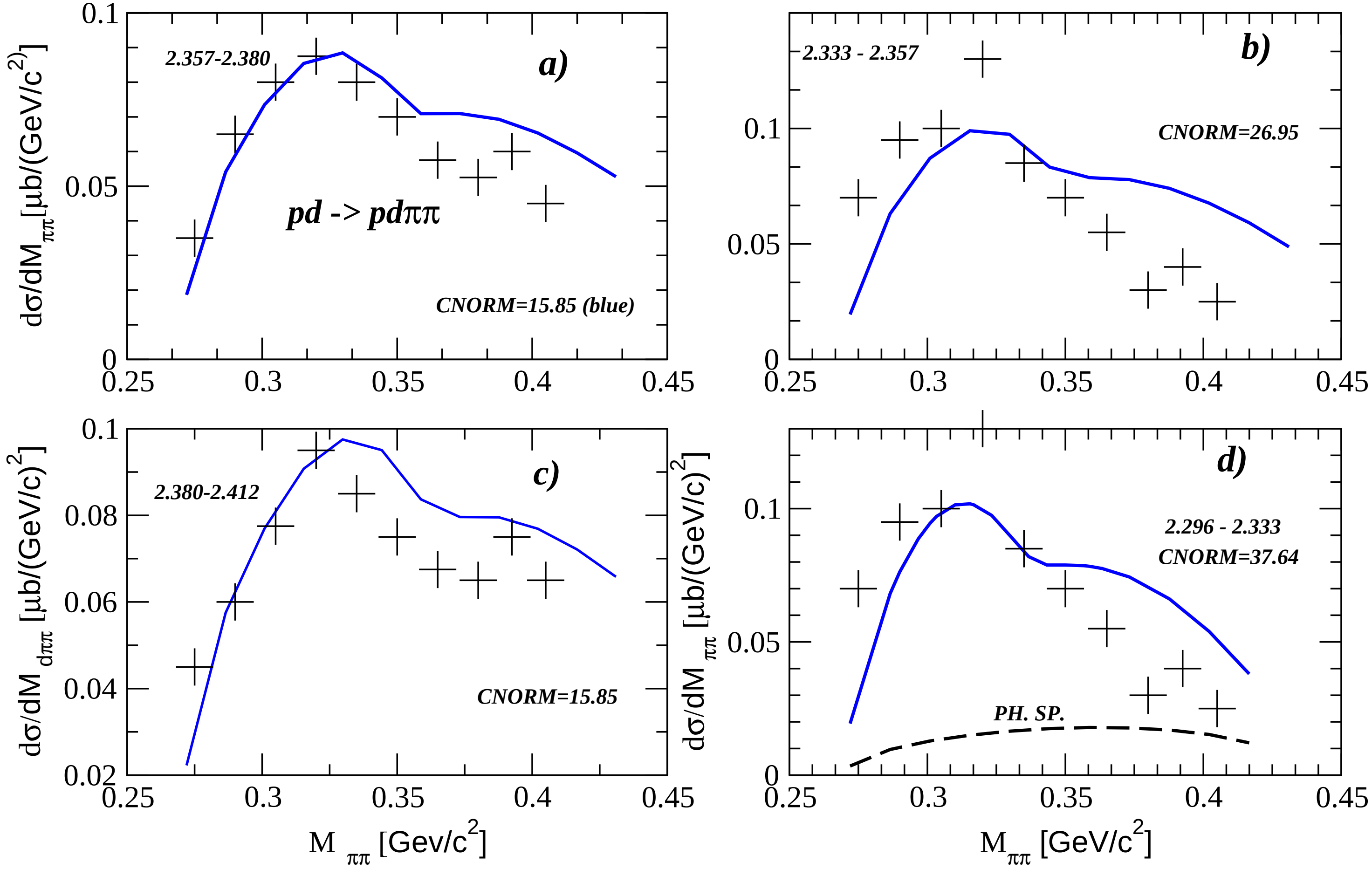
M.N. Platonova, V.I. Kukulin, PRC **87** (2013) 025202; NPA **946** (2016) 117 (whithout their σ-term)

$pd \to pd\pi\pi$ reaction. ANKE@COSY data and two-resonance model



• - V.Komarov et al.(for ANKE collab.) arxiv:1805.01493 [nucl-exp] (see talk by D.Tsirkov)

$pd \to pd\pi\pi$ reaction. $M_{\pi\pi}$ spectra at $T_p = 1.1$ GeV. ABC- effect ?



+ - V.Komarov et al.(for ANKE collab.) arxiv:1805.01493 [nucl-exp]
full lines – two-resonance model.
/Recent review M. Bashkanov, H. Clement, T. Skorodko. NPA 958 (2017) 129/

Conclusion from our calculation

- **Two known resonance structures have been observed by ANKE@COSY at non-usual conditions:**
  - ⋆ **Δ-like resonance in the $pp \to \{pp\}_s\pi^0$ (negative parity);**
  - ⋆ **$D_{03}(2380)$- dibaryon like resonance in $pd \to pd\pi\pi$ at high transferred momentum to the deuteron.**

- **The Δ box-diagram completely fails to explain the angular dependence $d\sigma/d\Omega$ and A_y for $pp \to \{pp\}_s\pi^0$ in contrast to $pp \to d\pi^+$, although reproduces the E-shape of $d\sigma/d\Omega(0^\circ)$. Are there genuine dibaryons here – ${}^3P_0s$, ${}^3P_2d$? ${}^3F_2d$?**

- **Two-resonance (D_{03}, D_{12}) mechanism of the $pd \to pd\pi\pi$ (i) underestimates Γ of peaks, absolute value of $d\sigma$ is not yet determined since $\Gamma(D_{03} \to D_{12}\pi)$, $\Gamma(D_{03} \to d\sigma)$ are not known; (ii) but points out to the ABC effect in the maximum of the $D_{03}(2380)$-peak.**

Nonstrange s-wave dibaryon SU(6) predictions
F.J. Dyson, N.-H. Xuong, PRL 13 (1964) 815

dibaryon	I	S	SU(3)	legend	mass	MESON 2018
$\mathcal{D}_{01}$	0	1	$\overline{10}$	deuteron	A	√
$\mathcal{D}_{10}$	1	0	27	virtual	A	√
$\mathcal{D}_{12}$	1	2	27	$N\Delta$	A+6B	√
$\mathcal{D}_{21}$	2	1	35	$N\Delta$	A+6B	√
$\mathcal{D}_{03}$	0	3	$\overline{10}$	$\Delta\Delta$	A+10B	√
$\mathcal{D}_{30}$	3	0	28	$\Delta\Delta$	A+10B	?

Assuming 'lowest' SU(6) multiplet, 490, within 56×56.

M=A+B[I(I+1)+S(S+1)-2], A=1878 MeV from M(d)≈M(v)

B=47 MeV from $M(\mathcal{D}_{12}) \approx 2160$ MeV observed in $\pi^+ d \to pp$.

Hence, $M(\mathcal{D}_{03}) = M(\mathcal{D}_{30}) \approx 2350$ MeV [$2M(\Delta) \approx 2465$ MeV].

Kamae-Fujita, PRL 38 (1977) 468, 471: proton polarization in $\gamma d \to pn$ supports a dibaryon at M≈2380 MeV.

Where D_{21} can be seen?

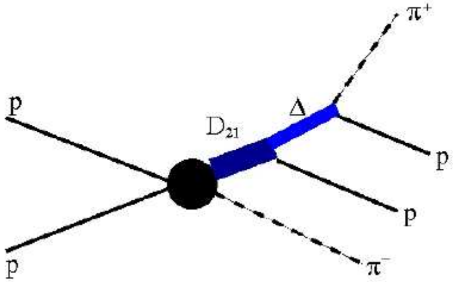
I=2 ⇒ only associated production

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

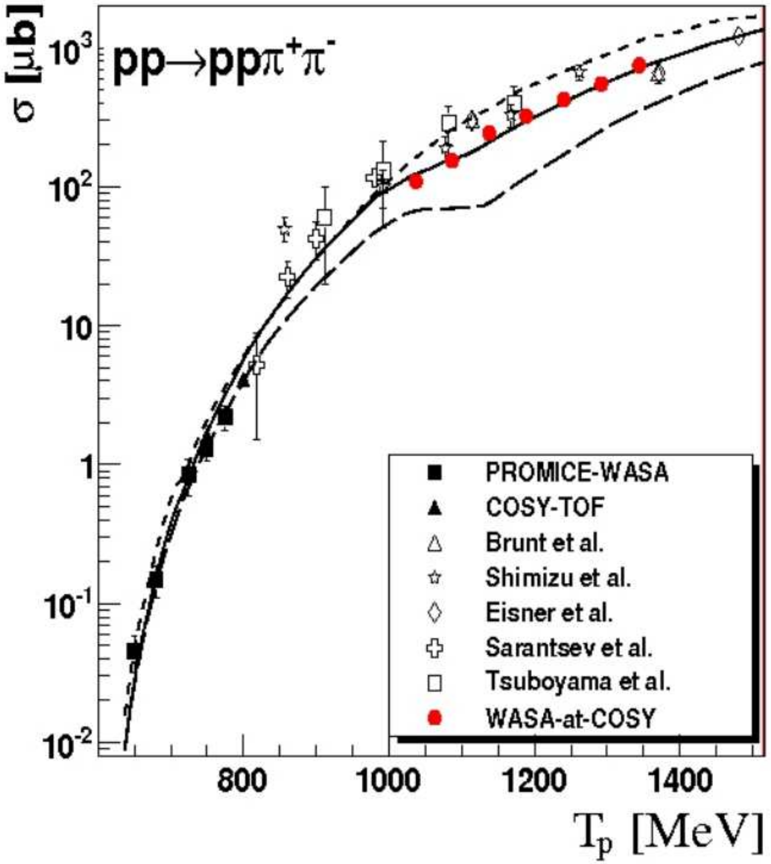
$$D_{21}$$

Results

- - - - - - - - original Valencia model
- - - - - modified Valencia model
——— modified Valencia model + D_{21}



M = 2140 MeV
Γ = 110 MeV



Where D_{30} can be seen?

I=3 $\Rightarrow$ only associated production

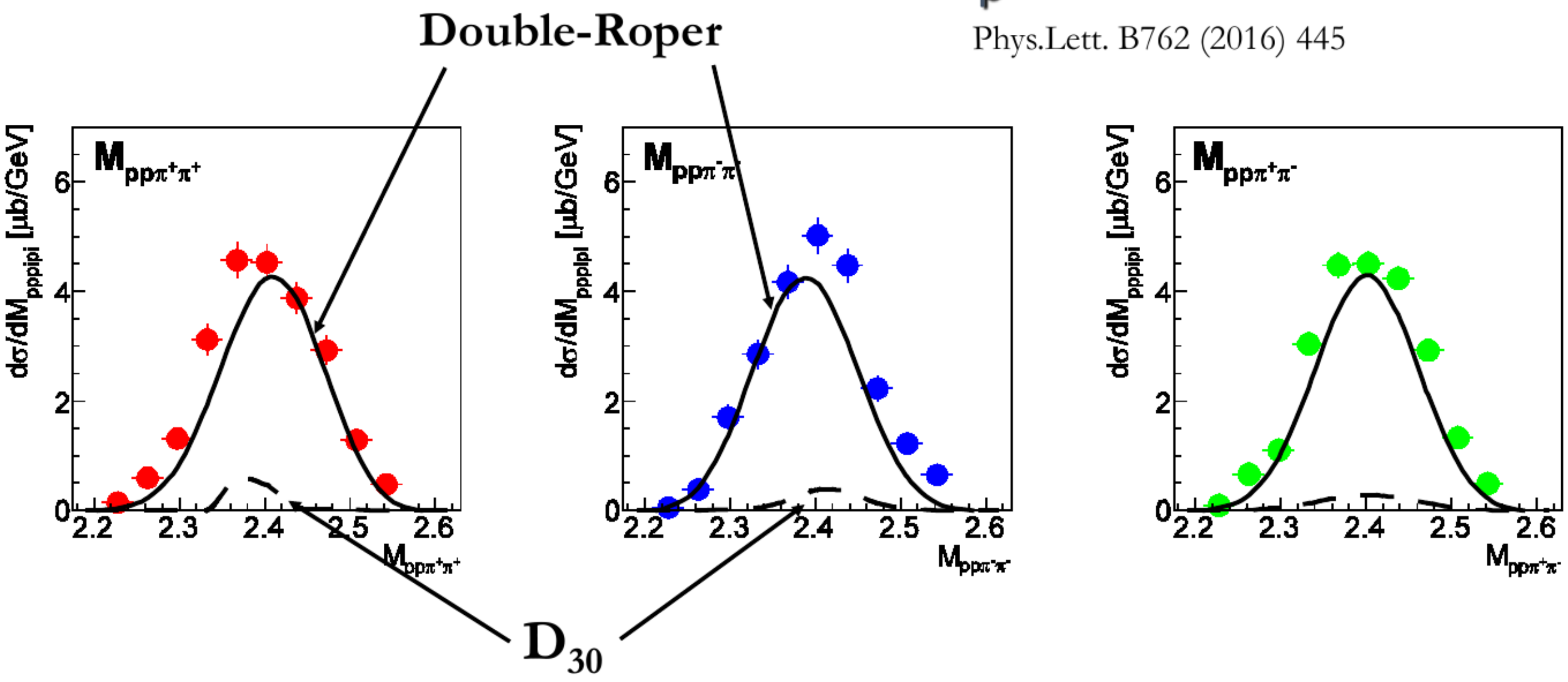
$$pp \to pp\pi^+\pi^+\pi^-\pi^-$$

D_{30}

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

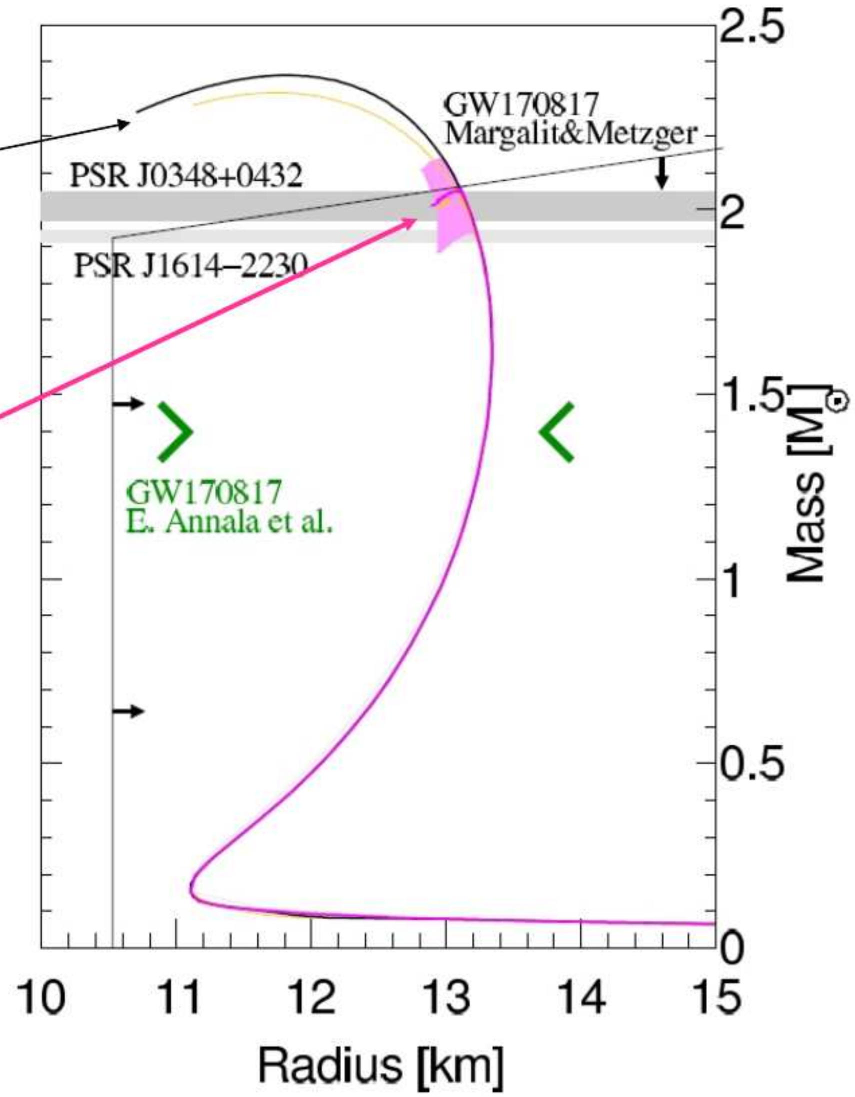
T_p = 2.541 GeV

Phys.Lett. B762 (2016) 445



EoS for nuclear matter

EoS for nuclear matter + d*



d* in neutron stars

Phys. Lett. B781 (2018) 112

Pentaquarks and exotic states

- Quark model allows for states beyond the well established $q\bar{q}$ mesons and qqq baryons
- States such as $qqqq\bar{q}$ (pentaquark), $qq\bar{q}\bar{q}$ (tetraquark) postulated in Gell-Mann's and Zweig's original quark model papers (1964) *Phys.Lett. 8 (1964) 214-215, CERN-TH-412*

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone [4]. Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

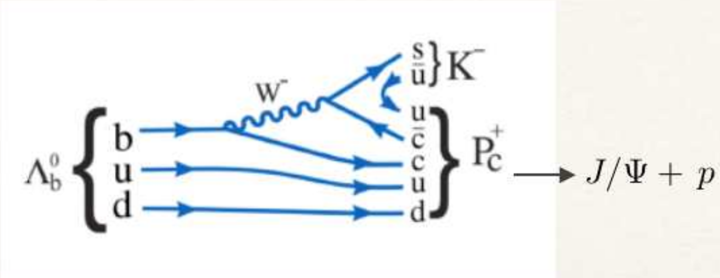
Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means

ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" [6] q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest baryon configuration (qqq) gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\bar{q})$ similarly gives just **1** and **8**.

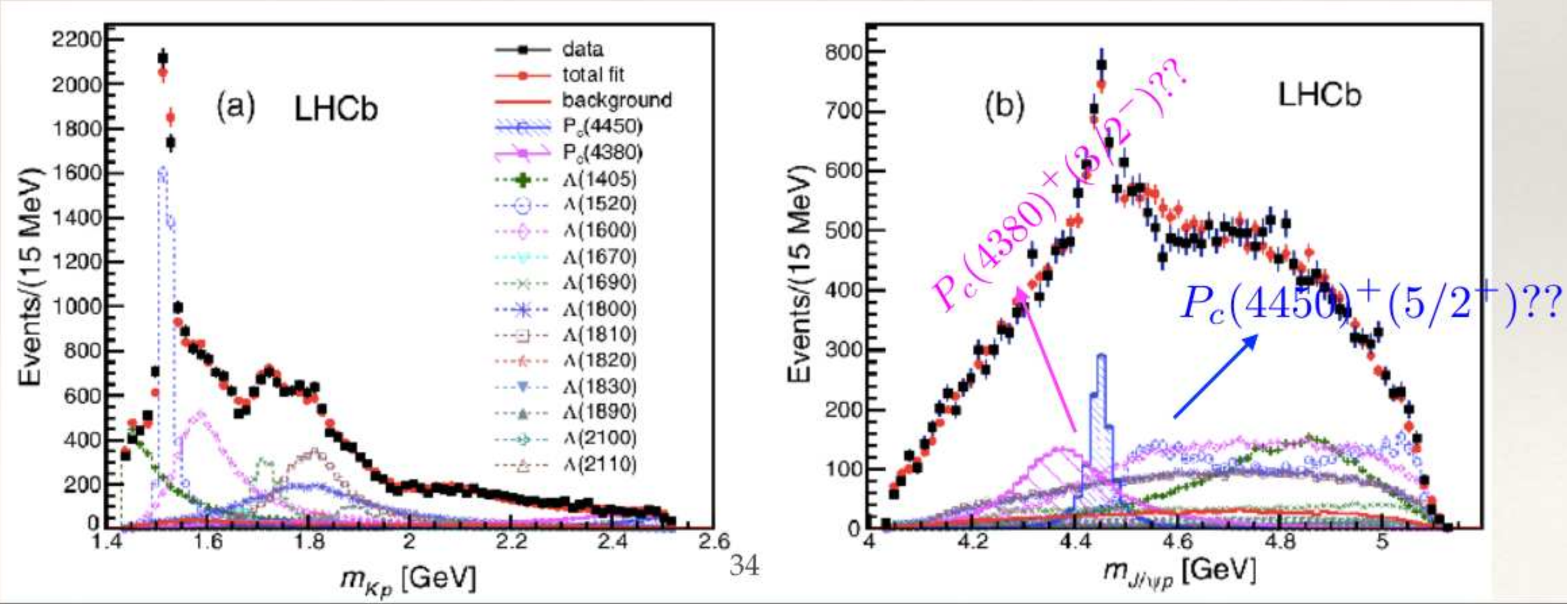
- Now refer to any hadron that does not follow $q\bar{q}/qqq$ as exotic

Pentaquark from LHCb



Partial Wave analysis in m(K-p) and 5 angles including

$\Lambda_b^0 \to J/\psi \Lambda^*, \Lambda^* \to pK^-$ $\Lambda_b^0 \to P_c^+ K^-, P_c^+ \to J/\psi p$



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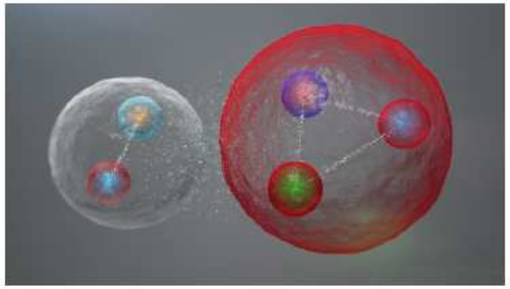
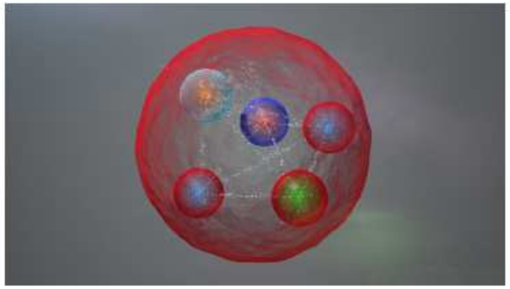
Nature of pentaquarks

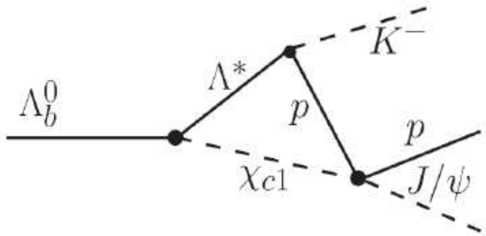
Possible models describing the observed pentaquark states include



Meson-baryon molecules
Phys. Rev. Lett. 115, 122001 (2015)
Phys. Rev. Lett. 115, 172001 (2015)
Phys. Rev. D. 92, 094003 (2015)



Compact tightly-bound pentaquarks
Phys. Lett. B 749, 289 (2015)
Phys. Lett. B 749, 454 (2015)
JHEP 12(2015) 128



Rescattering effects
Phys. Rev. D. 92, 071502 (2015)
Phys. Lett. B 757, 231 (2016)
Phys. Lett. B 751, 59 (2015)
Eur. Phys. J. A 52, 318 (2016)

Many hadrons are proposed to be hadronic molecules

Problem:

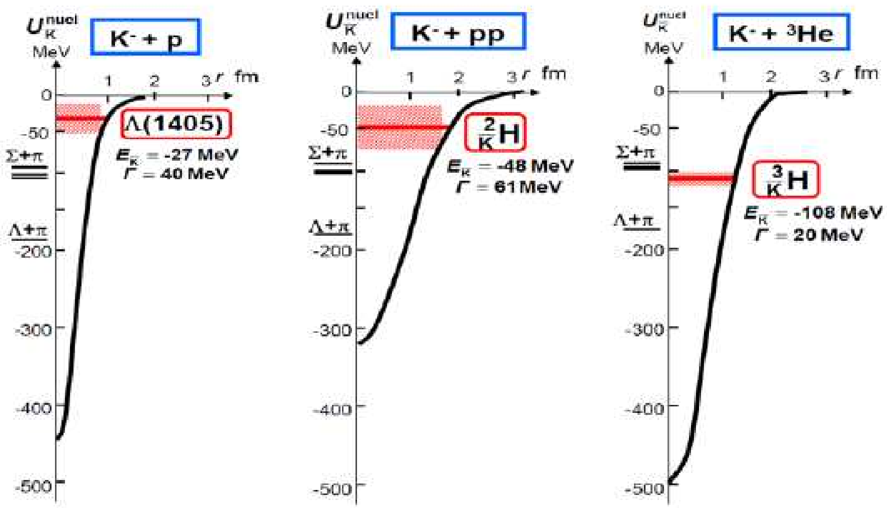
None of them can be clearly distinguished from qqq or $\bar{q}q$ due to tunable ingredients and possible large mixing of various configurations

Solution: **Extension to hidden charm and beauty for baryons**

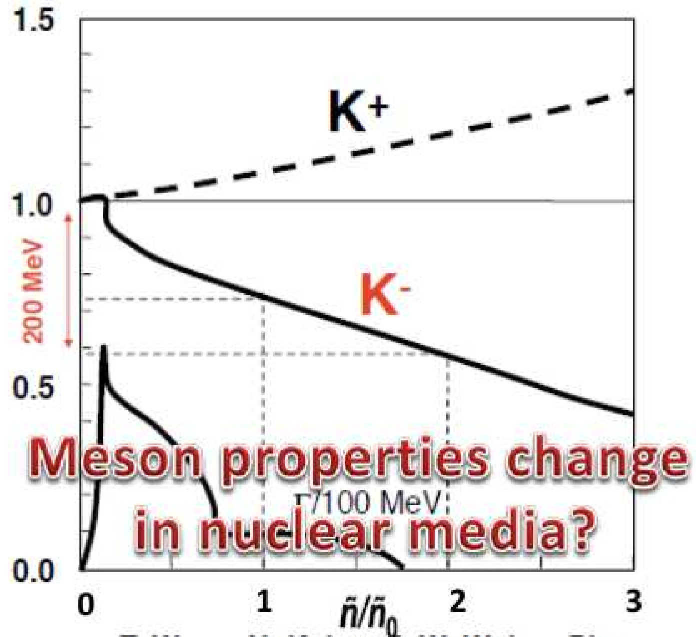
N*(1535)	$\bar{s}suud$	
N*(4260)	$\bar{c}cuud$	J.J.Wu, R.Molina, E.Oset, B.S.Zou. Phys.Rev.Lett. 105 (2010) 232001
N*(11050)	$\bar{b}buud$	J.J.Wu, L.Zhao, B.S.Zou. PLB709(2012)70
Λ*(1405)	$\bar{q}quds$	
Λ*(4210)	$\bar{c}cuds$	J.J.Wu, R.Molina, E.Oset, B.S.Zou. Phys.Rev.Lett. 105 (2010) 232001
Λ*(11020)	$\bar{b}buds$	J.J.Wu, L.Zhao, B.S.Zou. PLB709(2012)70

Kaonic Nuclei

- Bound states of nucleus and anti-kaon
- Predicted as a consequence of **attractive $K^{bar}N$ interaction in I=0**



Y.Akaishi & T.Yamazaki, PLB535, 70(2002).



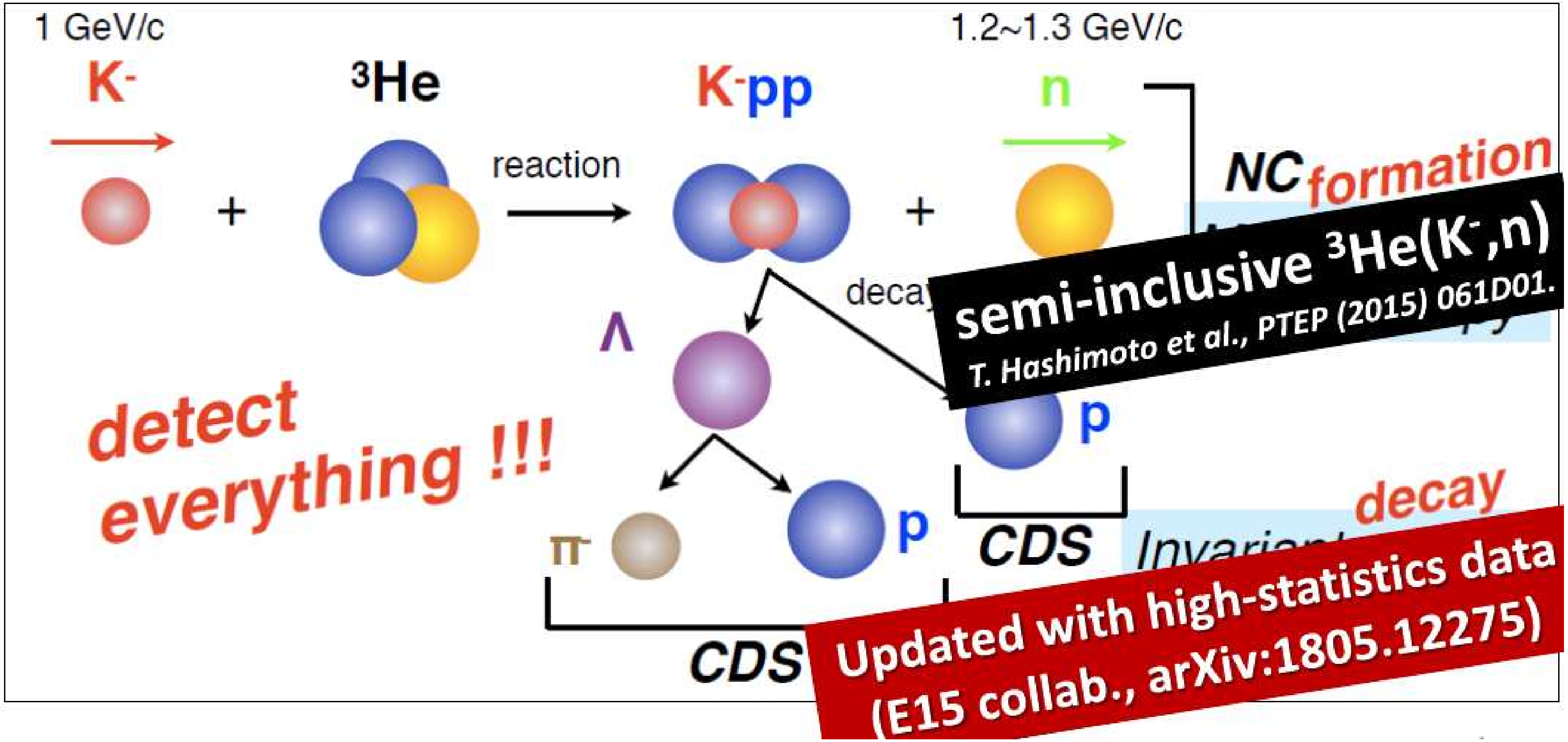
T. Waas, N. Kaiser & W. Weise, Phys. Lett. B379 (1996) 34.

- Will provide new insight on **$K^{bar}N$ interaction** in media

J-PARC E15 Experiment

- ^{3}He(*in-flight* K$^-$,n) reaction @ 1.0 GeV/c

☺ 2NA processes and Y decays can be discriminated kinematically

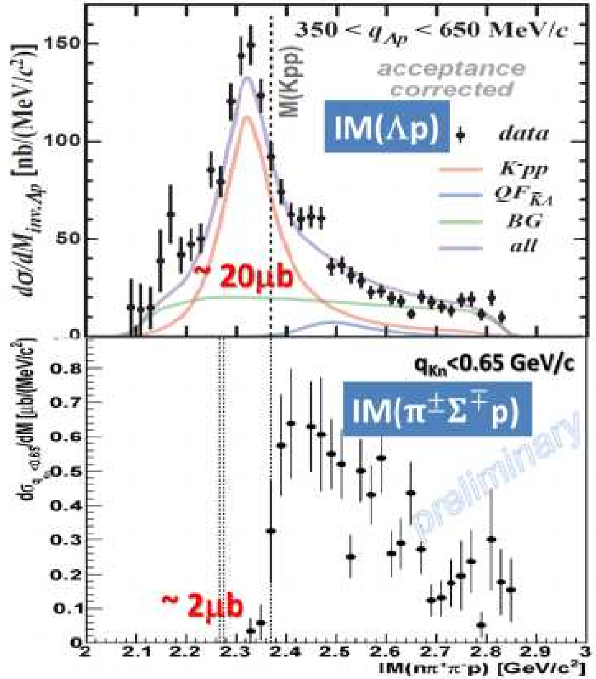


- **We have observed a resonance peak below the K^-pp threshold in $^3He(K^-,\Lambda p)n$, "K^-pp"**
  - Binding energy: ~50 MeV
  - Width: ~100 MeV
  - S-wave form factor: ~400 MeV

  ← E15 collab., arXiv:1805.12275

- **$\Lambda(1405)$ was clearly observed in $\pi^{\pm}\Sigma^{\mp}p$ n_{miss} final state**
  - Large CS of Λ^* compared to "K^-pp" formation

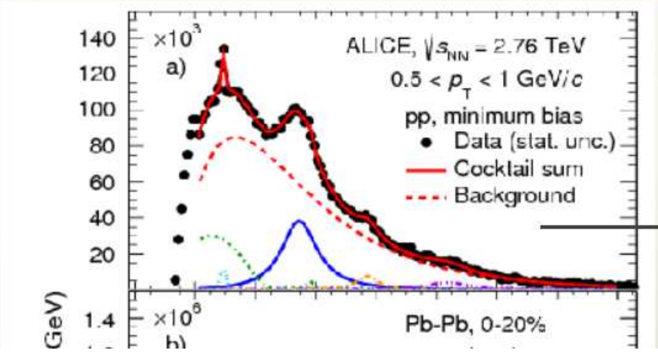
  ← need theoretical feedbacks



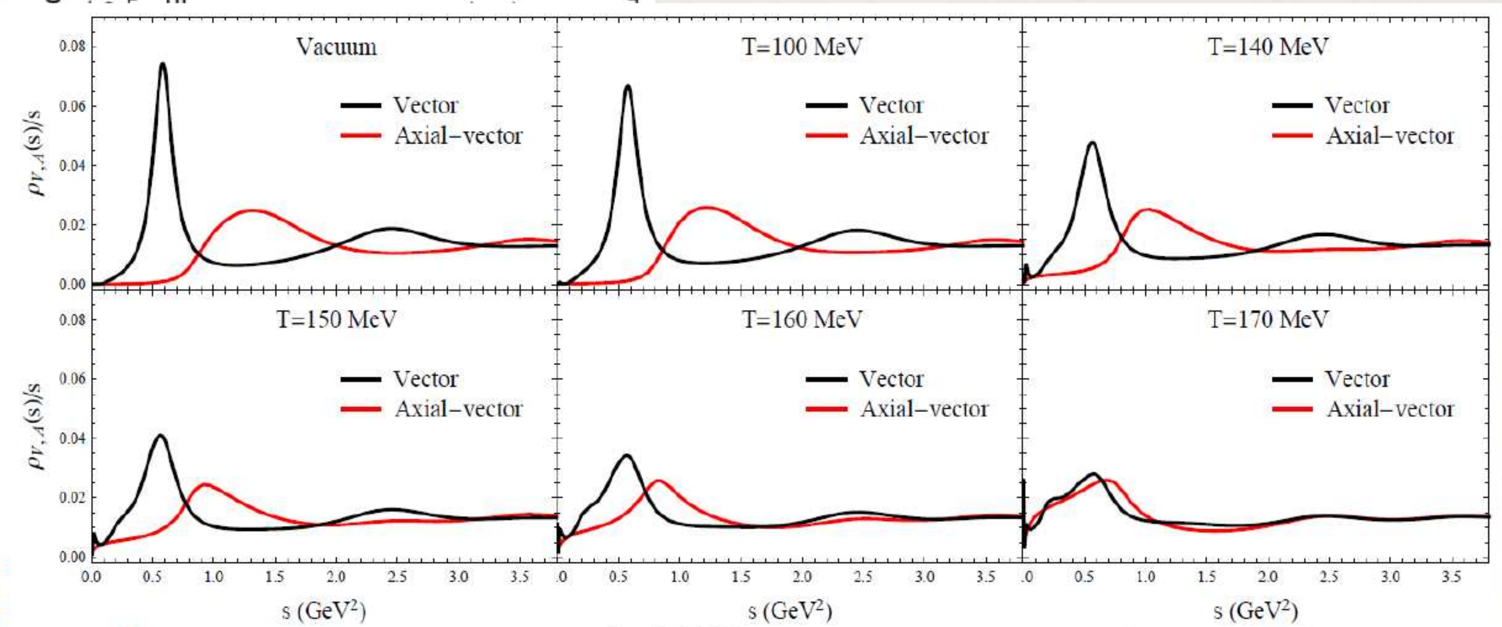
Chiral Symmetry Restoration: a_1?

R. Rapp

ALICE coll. arXiv:1805.04365



6 * 10 7 evts



• Several two-baryon non-strange resonances are well established in pp- and pd-collisions.
• Are observed resonances $d^*(2380)$, $^3P_0$, $^3P_2$ compact densed systems or quasi-molecules?

“Physics of $W^{\pm}$, Z^0 and Higgs boson H at TeV scale (if $M_H > 730$ GeV) would be similar to HADRON physics at GeV scale: resonances, many-particles production... ”

/M.I. Vysotsky, Lectures on electroweak interactions,
M. Fizmatlit, 2011/

THANK YOU FOR ATTENTION!