RESONANCE BEHAVIOUR OF THE PION PRODUCTION IN THE REACTION $\mathbf{pp \to \{pp\}_s \pi^0}$

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- **Dubna** $p +^{12} C \to d + X$ **at 670 MeV (M.G. Mescheryakov et al.,1957)**

  D.I. Blokhintsev(1957): 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) :
$\mathbf{\Delta + B3}$ **Tribarions!**

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

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

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

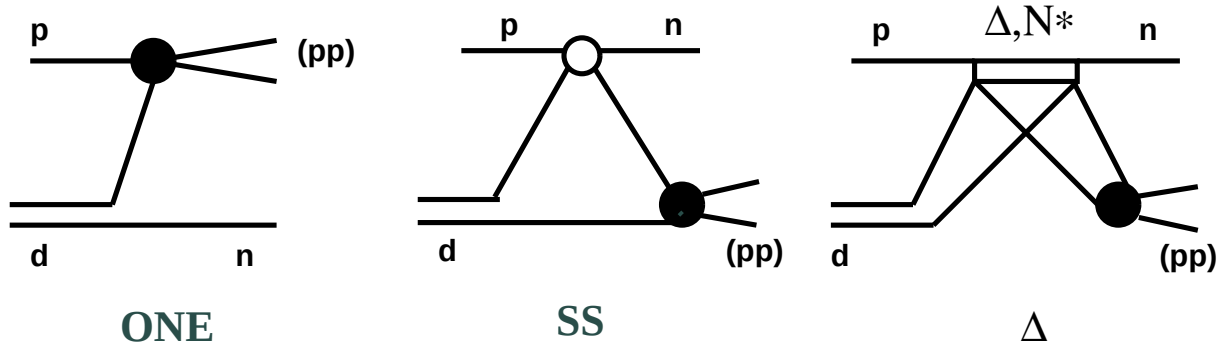
• **Reactions with the $^1S_0$ diproton $\{pp\}_s$ (i.e. $E_{pp} < 3$ MeV) at large Q can give more insight into underlying dynamics due to difference in quantum numbers $J^\pi_d = 1^+$, $T_d = 0 \Longrightarrow$ $J^\pi_{pp} = 0^+$, $T_{pp} = 1$**

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

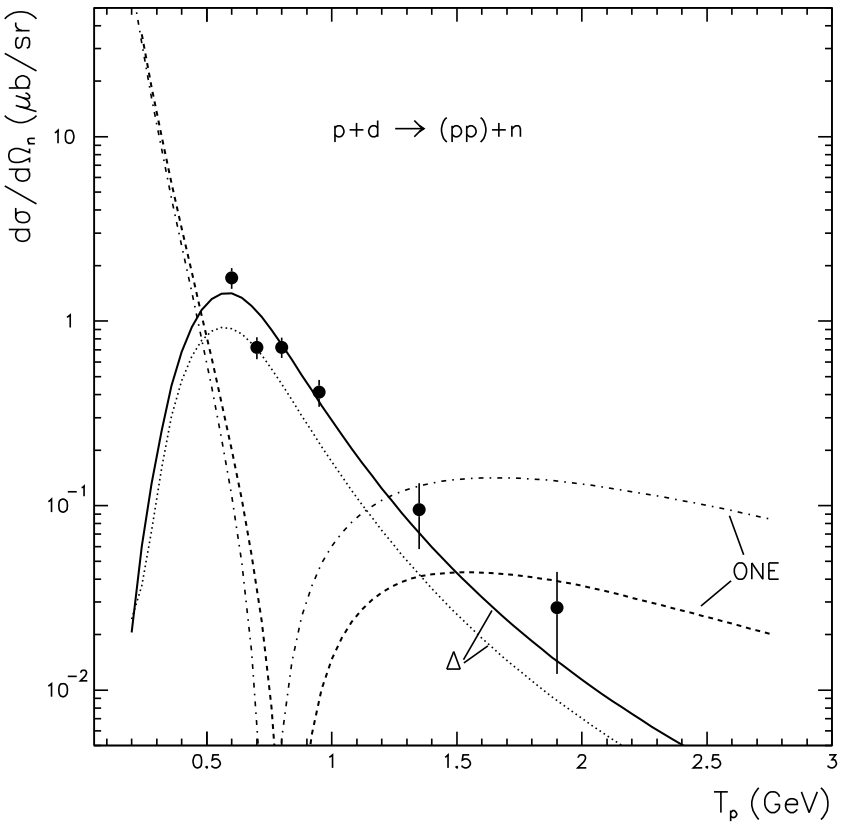
1. $\mathrm{pd} \to \mathrm{dp} \Longrightarrow \mathrm{p\{NN\}_s} \to \mathrm{dN}$ in A(p,Nd)B
suppression of the Δ- and N^*-excitations as $1:9$

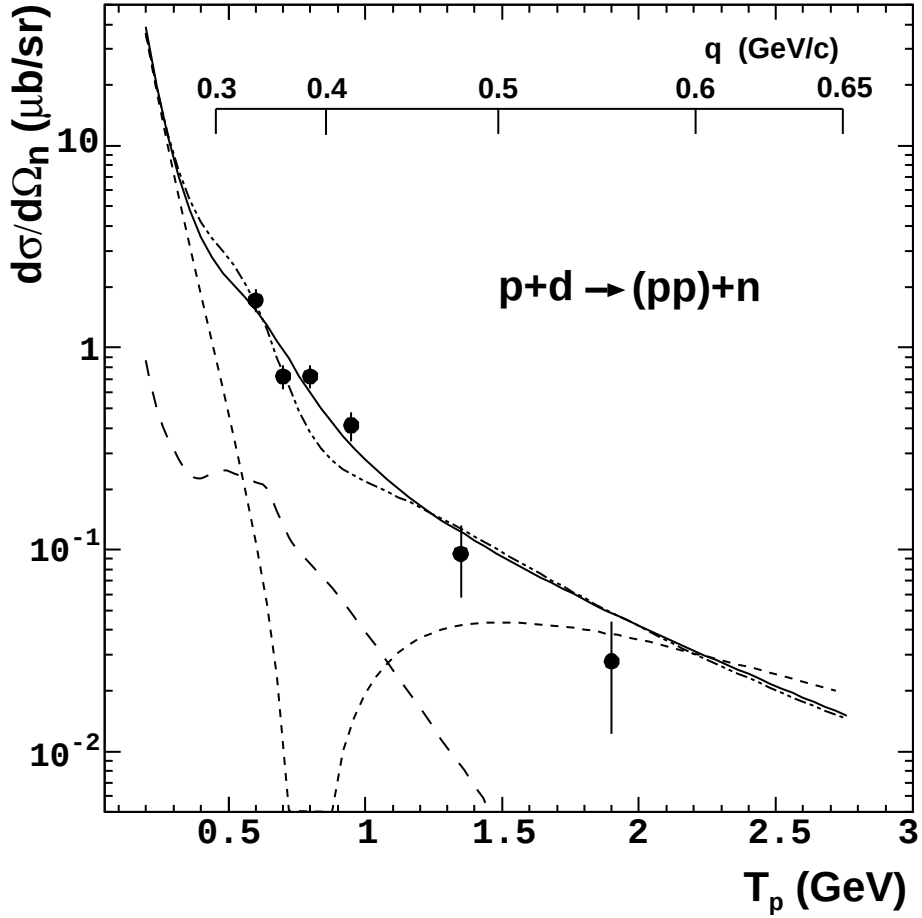
and $\mathrm{pd} \to \mathrm{\{pp\}_s n}$

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



ANKE@COSY $pd \to (pp)_s n$





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.

Diproton physics at ANKE-COSY, 1999-2016

$\mathbf{pd} \to \{\mathbf{pp}\}_\mathbf{s}\mathbf{n}$ 0.5 - 2.0 GeV

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

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

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

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

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

It is assumed that the resonance sructure in $\mathbf{pp} \to \mathbf{d}\pi^+$ at 500-800 MeV is dominated by the $\Delta(1232)$-isobar excitation (J. Niskanen , Phys.Lett B141 (1984) 301; C. Furget et al. Nucl.Phys. A655 (1999) 495).

Remarkable resonance structure is observed in total cross section $pn \to d\pi^0\pi^0$, $D_{T=0,J=3}$(2380), $\Gamma = 70$ MeV (WASA@COSY M.Bashkanov et al. PRL 102(2009) 052301. This obseravtion stimulates to re-consider others resonance-like reactions.

So, new analysis by M.Platonova, V. Kukulin NPA (2016) shows that the Δ mechanism is not sufficient for $\mathbf{pp} \to \mathbf{d}\pi^+$and, therefore, some 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 too PRD94(2016)).

Thus, it is interesting to study another channel:$pp \to \{pp\}_s\pi^0$ **at similar kinematics but with the diproton** $\{pp\}_s$.

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

$^1S_0$ **diproton:** $\mathbf{J^\pi = 0^+, T = 1, S = 0, L = 0}$
deuteron: $\mathbf{J^\pi = 1^+, T = 0, S = 1, L = 0, 2}$

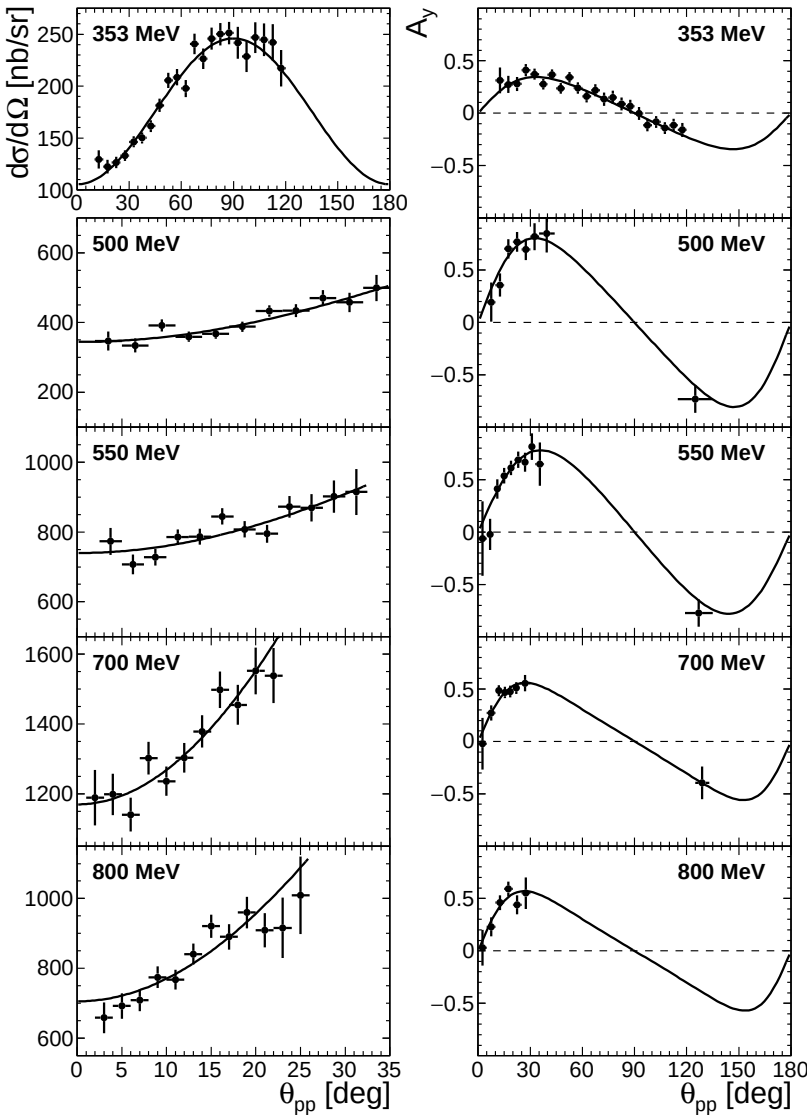
- $(-1)^{\mathbf{L+S+T}} = -1$ **(Pauli principle)**
- **Spin-parity conservation:**

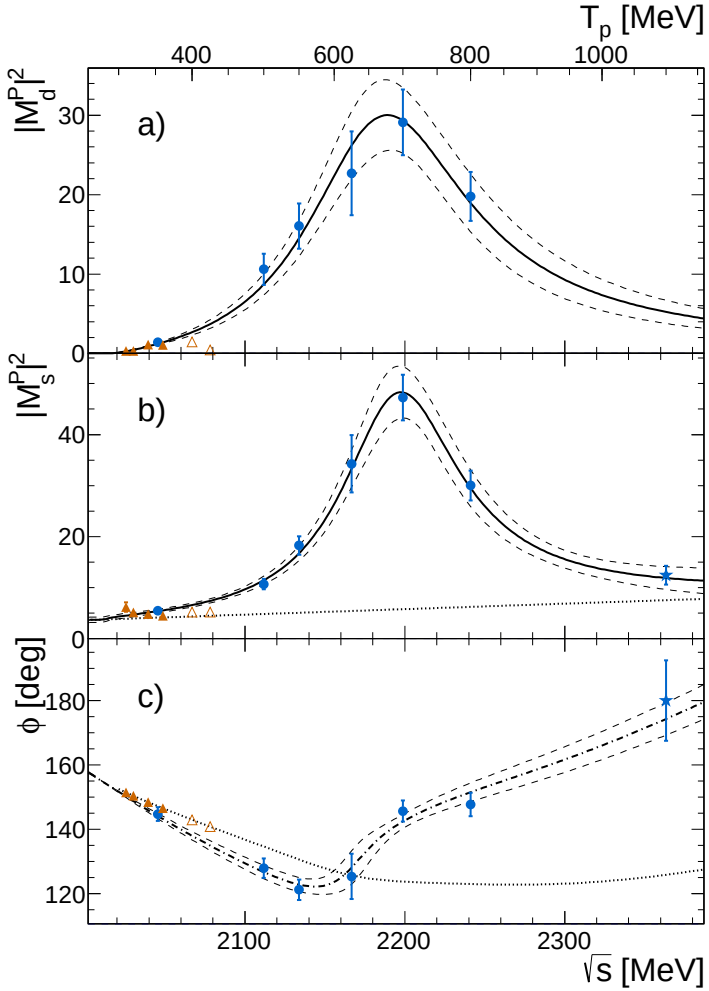
  $\star$ $\mathbf{pp \to \{pp\}_s\pi^0}$ $\mathbf{L - odd(L = 1, 3, \ldots)T = 1, S = 1;}$
  $\Longrightarrow$ $\mathbf{\Delta N}$ **in S-wave (or** N^*N**)** $\pi = +1$ - *vorbidden*

  $\star$ $\mathbf{pp \to d\pi^+}$ **L-odd and even,** $T = 1$, $S = 1$ **and** $S = 0$**;**
  $\Longrightarrow$ $\mathbf{\Delta N}$ **in S-wave (** N^*N**)** $\pi = +1$ -*not vorbidden*
  $\Longrightarrow$ $\Delta(1232)$ **dominates in the** $pp \to d\pi^+$ **at ≈600 MeV**

  And what is the Δ**-contribution in** $\mathbf{pp \to \{pp\}_s\pi^0}$**?**

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





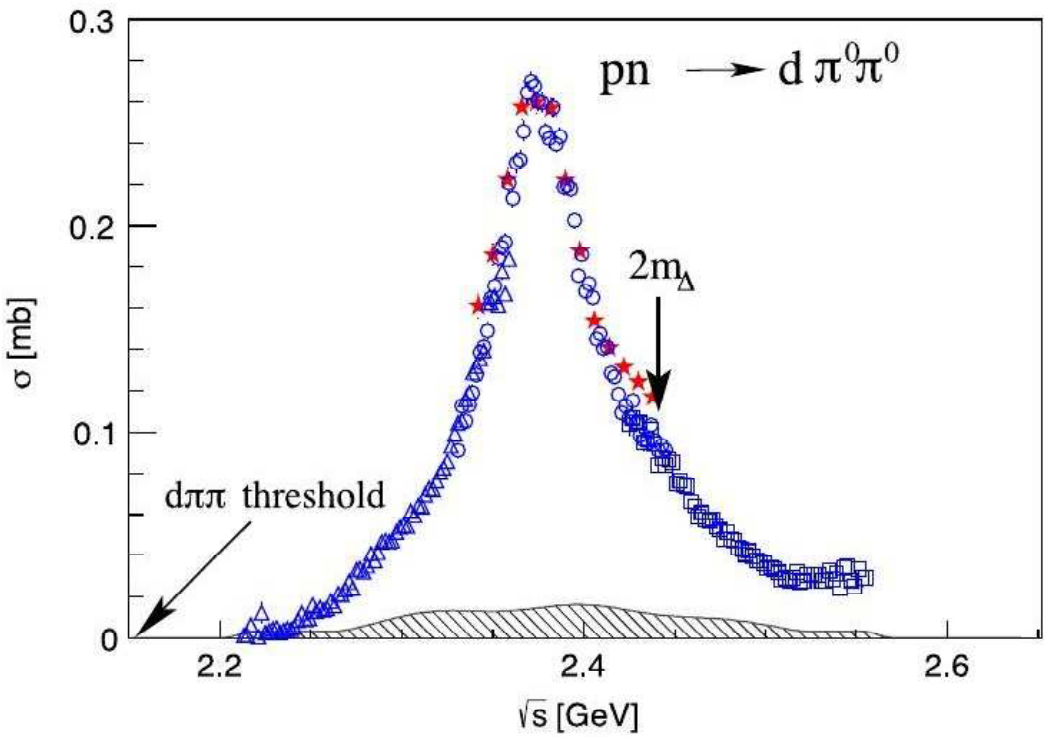
V.Komarov et al. PRC 94 (20016) 052301;

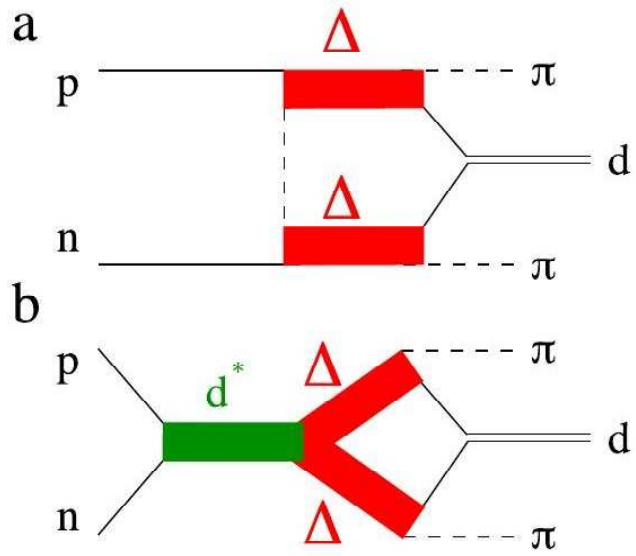
Two $T = 1$ resonances are found with almost equal masses 2205 MeV:

$J^p = 0^-$ **(^3P_0s),** $J^p = 2^-$ **(^3P_2d);** $\Gamma_0 = 95 \pm 9$ **MeV** $\Gamma_2 = 170 \pm 32$ **MeV,**

WASA@COSY $pn \to d\pi^0\pi^0$, $\Gamma = 70$ MeV

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, "On the History of Dibaryons and their final Discovery", Prog. Part. Nucl. Phys. 93 (2017) 195

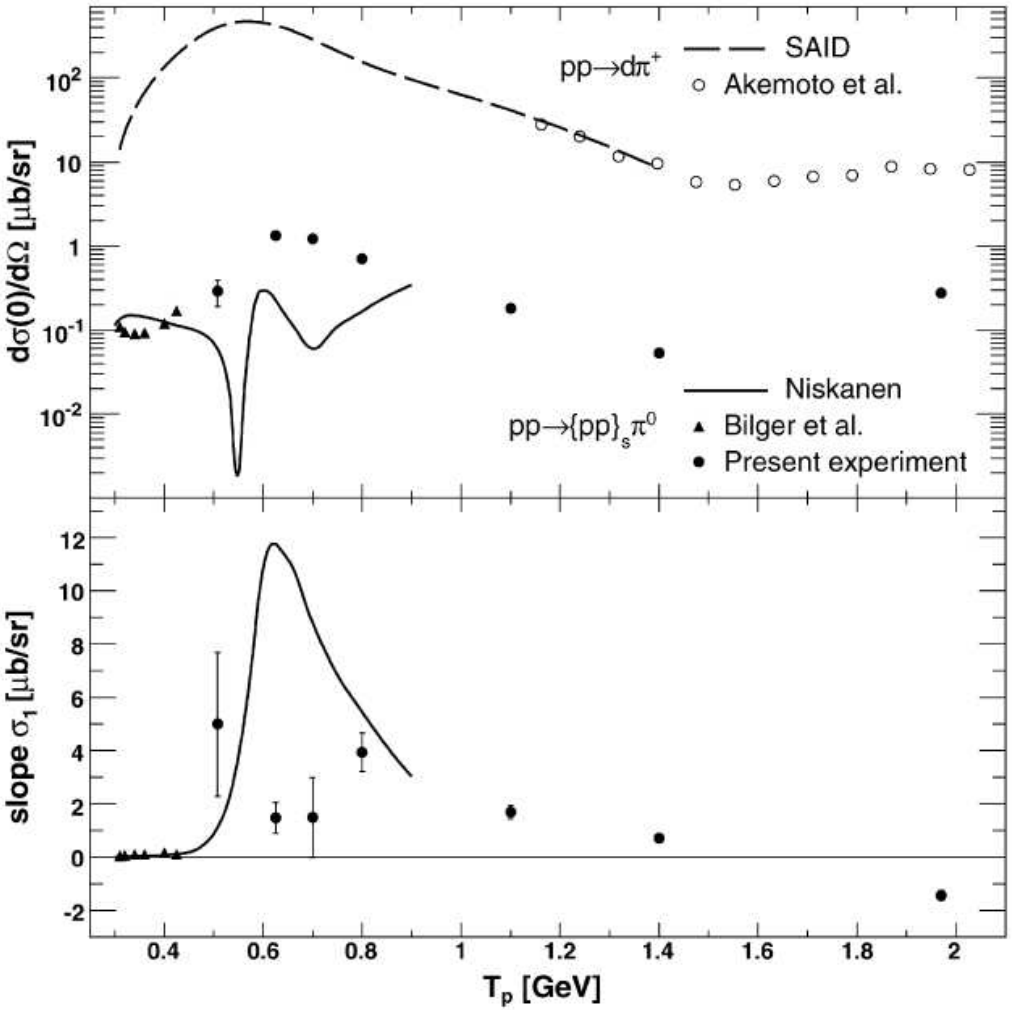
$d(2380)$ **in neutron stars – I.Vidana et al. Arxiv:1706.09701 [nucl-th]**

$\pi N\Delta$ **system – A.Gal, H.Garcilazo, PRL 111 (2013) 172301;**

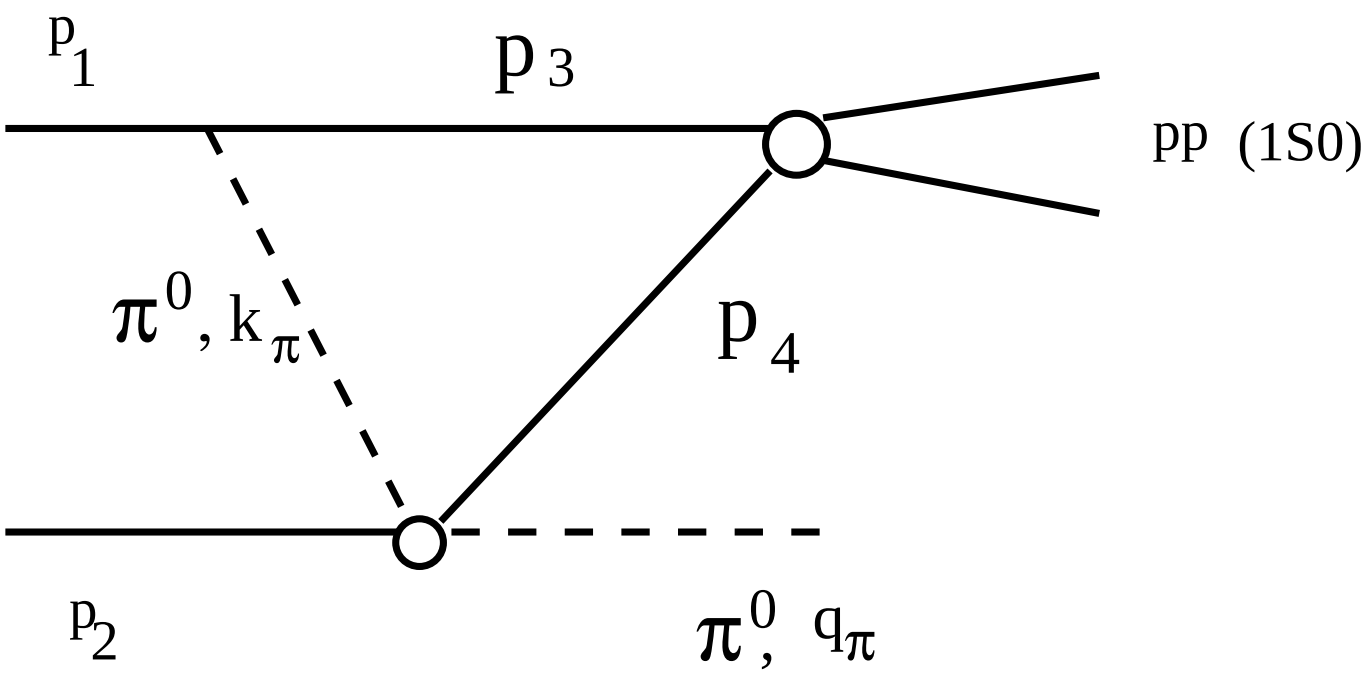
6q-models – see talk by Y.-B. Dong at this conference;

coupled channel, ordinary $\Delta\Delta$ system – J. Niskanen, PRC 95 (2017) 054002

COSY DATA $\mathbf{pp \to \{pp\}_s\pi^0}$*: V.Kurbatov et al., PLB* **661** *(2008)22*



theory: J.Niskanen, PLB 642 (2006) 34 /full lines/



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

The OPE is similar to that for $pd \to \{pp\}_s n$
/Yu.N.U., J. Haidenbauer, C. Wilkin, PRC **75** (2007) 014008/

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

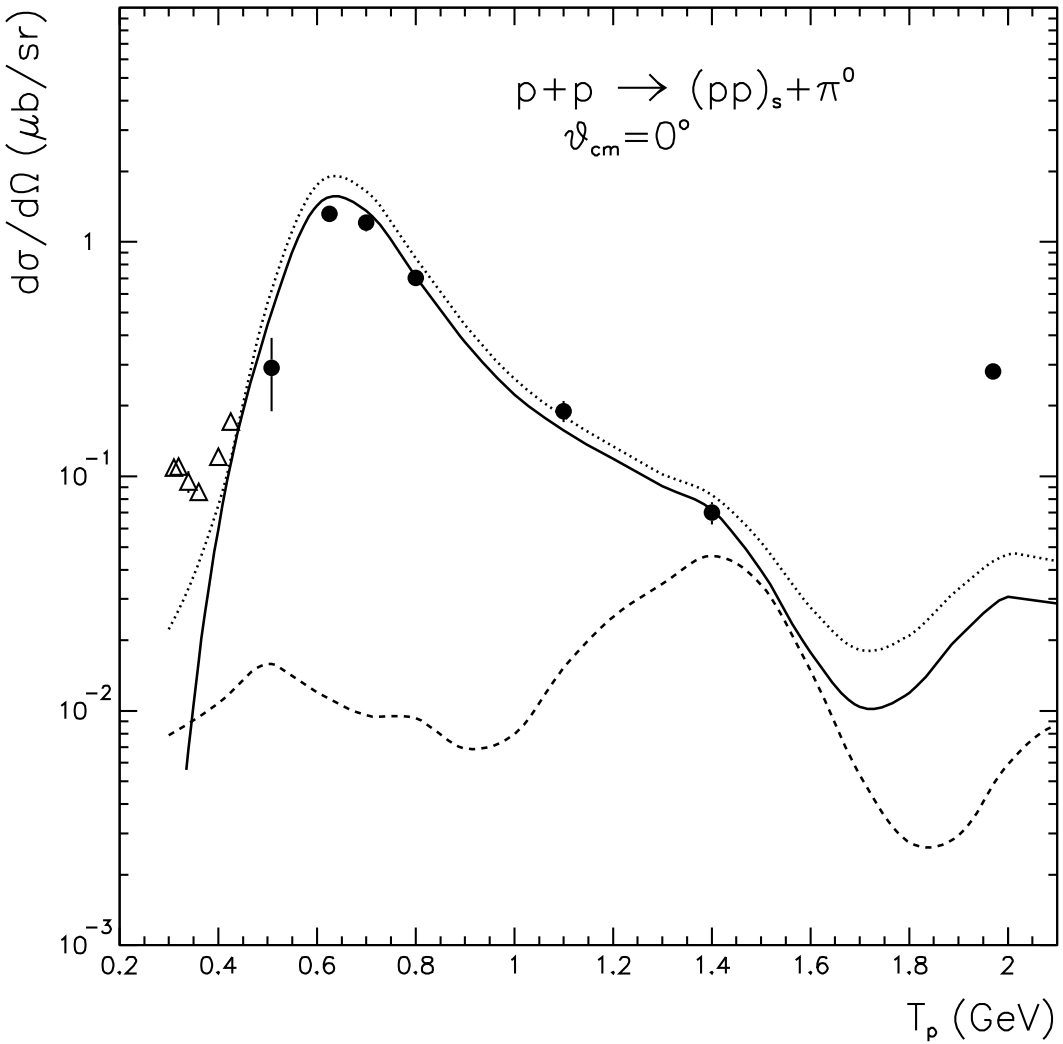
$$\mathbf{A}(\pi^{\mathbf{0}}\mathbf{p} \to \pi^{\mathbf{0}}\mathbf{p}) = \frac{\mathbf{1}}{\mathbf{3}}\Big(\mathbf{a}_{\frac{\mathbf{1}}{\mathbf{2}}} + \mathbf{2}\mathbf{a}_{\frac{\mathbf{3}}{\mathbf{2}}}\Big), \tag{1}$$

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

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

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

$pp \to \{pp\}_s\pi^0$: The OPE results with and whithout $\Delta(1232)$



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

COSY data: • – V.Kurbatov et. al PLB 661 (2008) 33

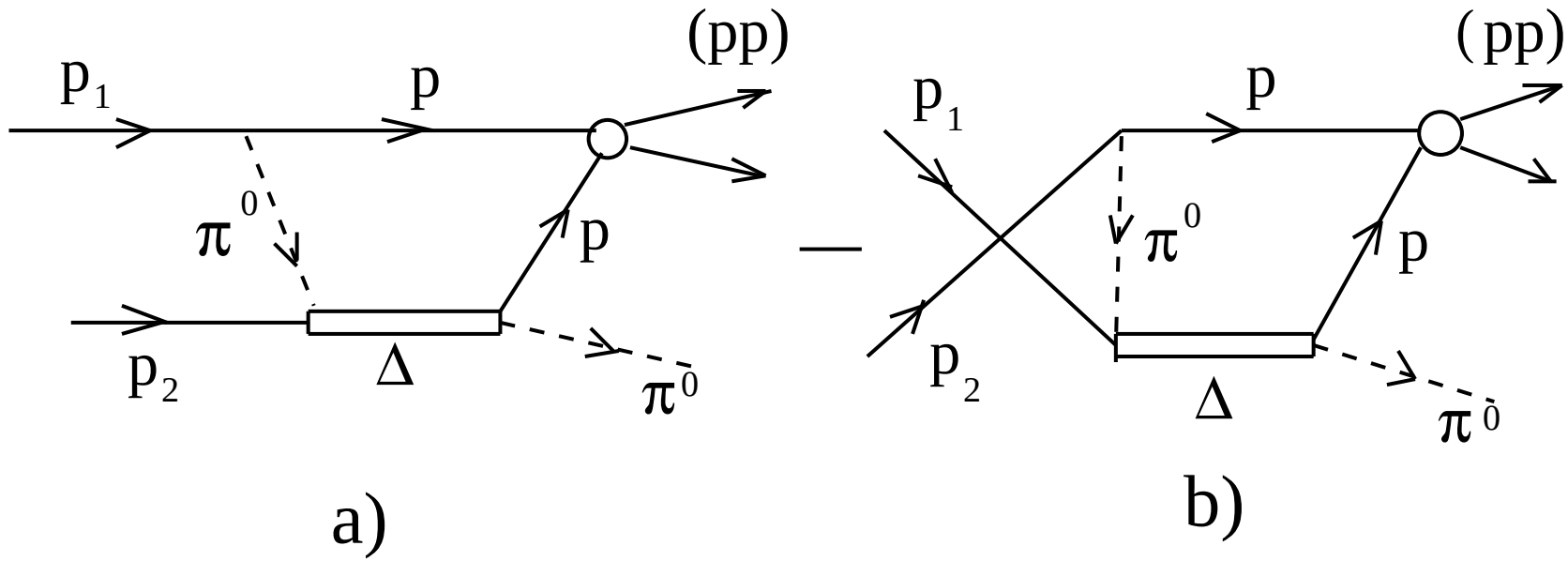
OPE: $pp \to \{pp\}_s\pi^0$, $pp \to \{pp\}_s\gamma$

OPE approximation 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-diagramm with Δ for $p\pi^0 \to p\pi^0$



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

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

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

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

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

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

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

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

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; $\sqrt{Z} \to \pi N\Delta$.

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

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

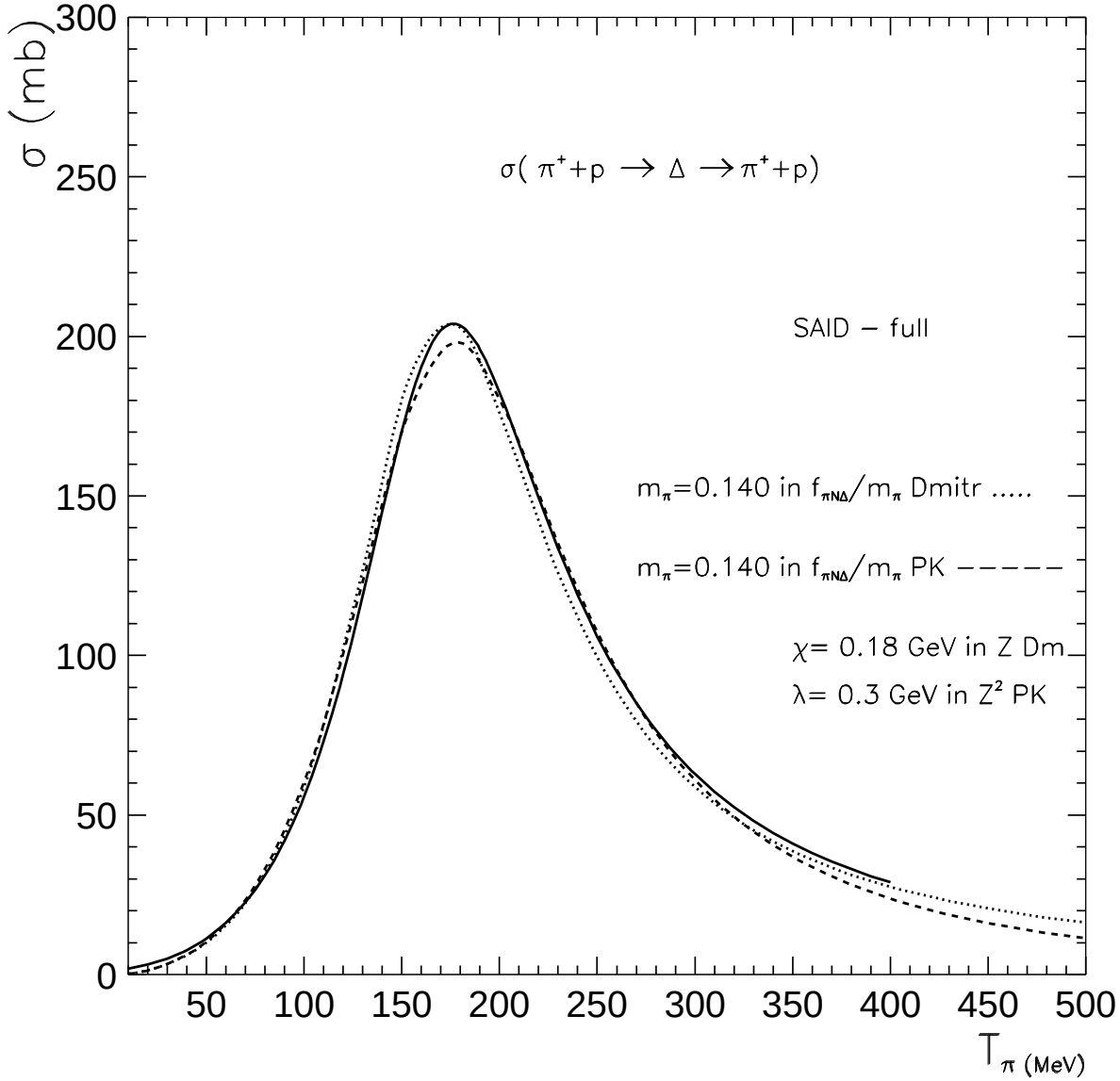
$\vec{p}$ – the proton momentum, $\vec{q}$ – the pion momentum

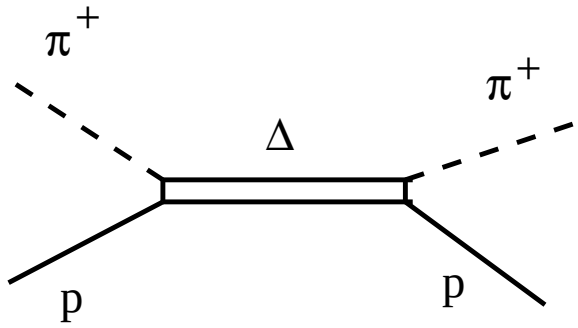
$$\frac{d\sigma}{d\Omega} = |A|^2 + |B|^2 + 2ReAB^*\cos\theta, \tag{6}$$
$$A_y\frac{d\sigma}{d\Omega} = 2ImAB^*\sin\theta;$$

$$M_{\lambda_1=\frac{1}{2},\lambda_2=\frac{1}{2}} = -\frac{1}{\sqrt{2}}(A + B\cos\theta) \equiv \Phi_1,$$
$$M_{\lambda_1=\frac{1}{2},\lambda_2=-\frac{1}{2}} = \frac{1}{\sqrt{2}}B\sin\theta \equiv \Phi_2 \tag{7}$$

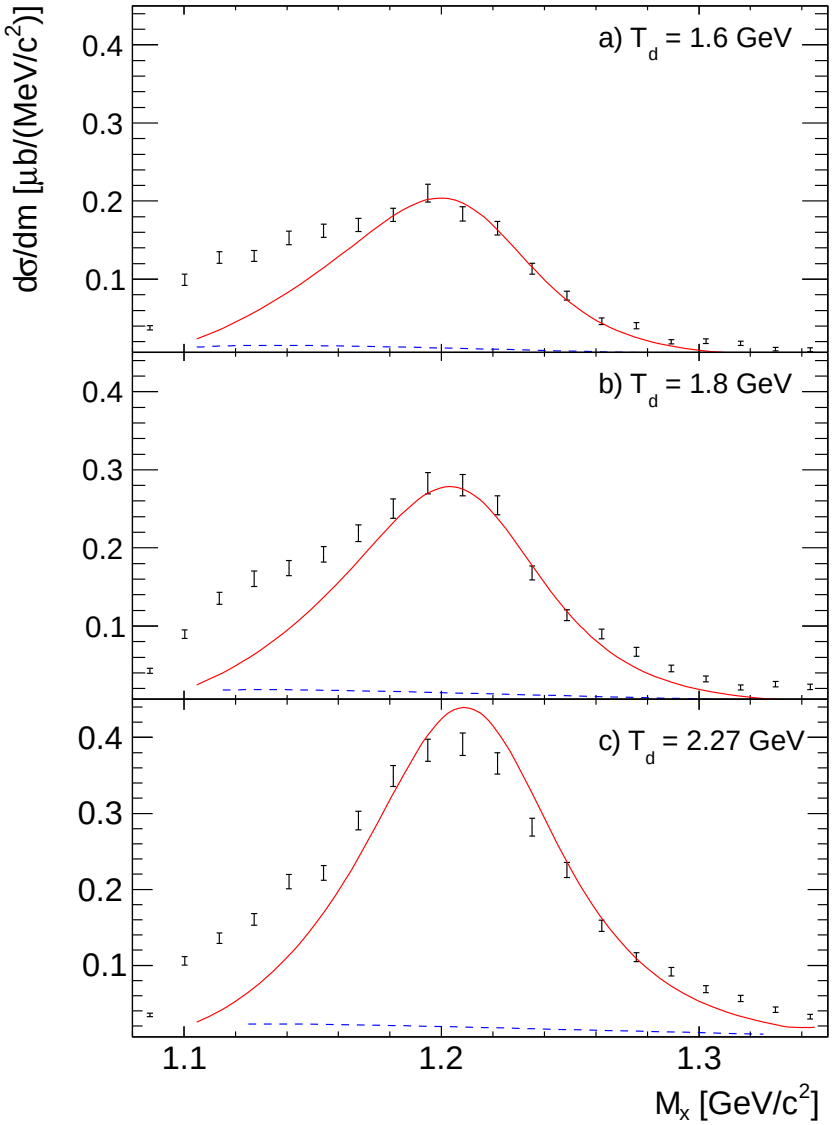
$$M_{\lambda_1\lambda_2} = \sum_J \frac{2J+1}{2}d^J_{\lambda,0}(\theta) < 00; JM|JM; l_\pi 0 >< JM; LS|JM; \lambda_1\lambda_2 > A(^{2S+1}L_J, l_\pi) \equiv$$
$$\equiv \sum_J \frac{2J+1}{2}d^J_{\lambda,0}(\theta)\Phi^{(J)}_{\lambda_1\lambda_2}(E), \tag{8}$$

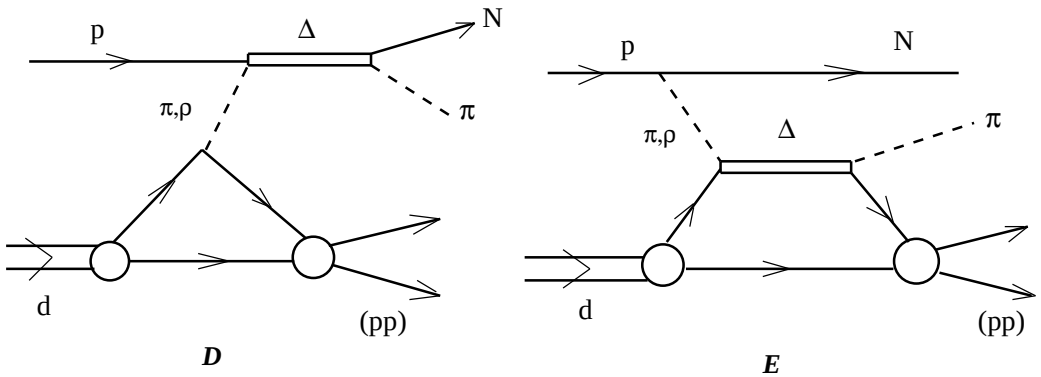
$\pi^+ p \to \pi^+ p$


σ (mb)
300
250
200
150
100
50
0
50
100
150
200
250
300
350
400
450
500
T_π (MeV)
σ(π⁺+p → Δ → π⁺+p)
SAID – full
m_π=0.140 in f_πNΔ/m_π Dmitr .....
m_π=0.140 in f_πNΔ/m_π PK -----
χ= 0.18 GeV in Z Dm
λ= 0.3 GeV in Z² PK


π+
π+
Δ
p
p

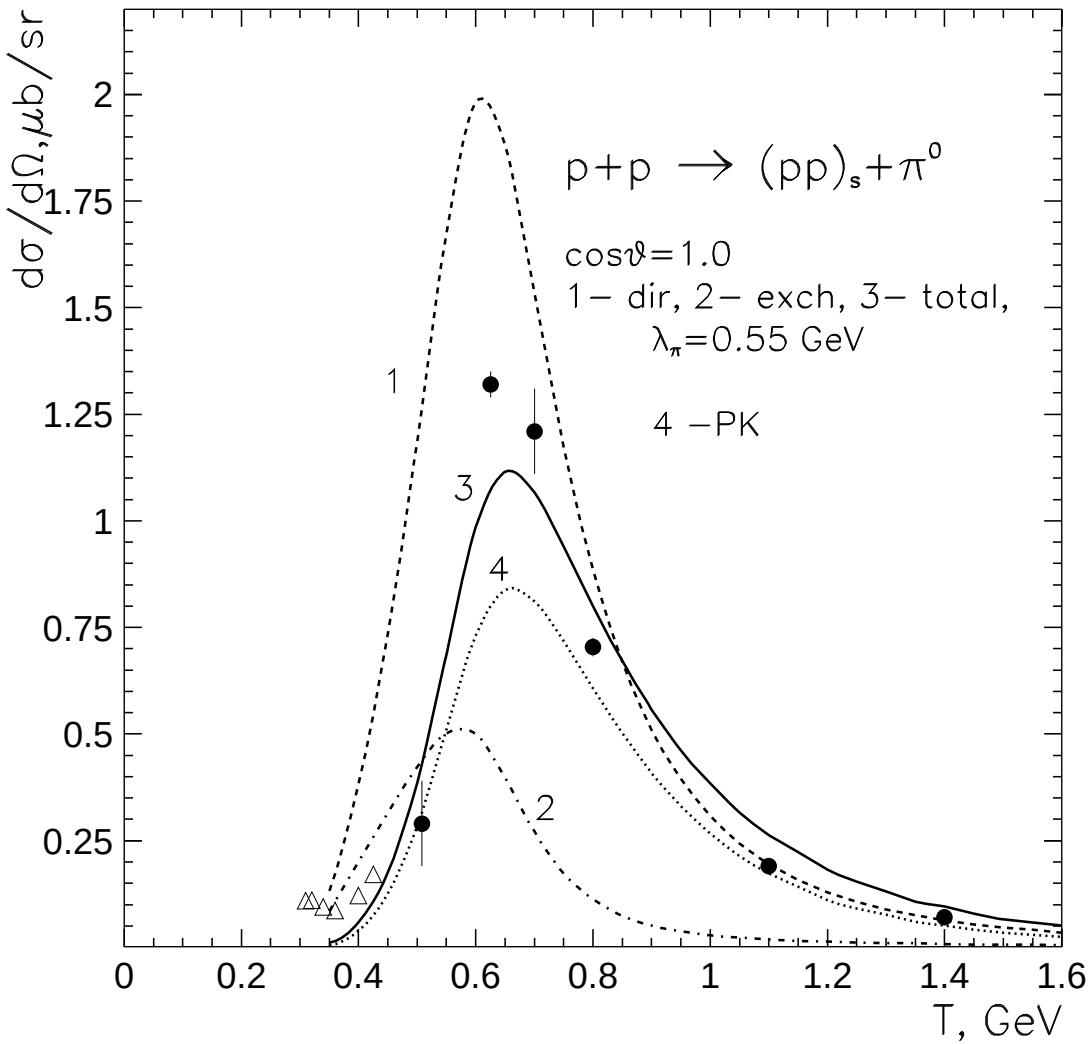
$dp \to \{pp\}_s \pi N$ Yu.N. U., J.Haidenbauer, C. Wilkin, PoS 93 (2015)





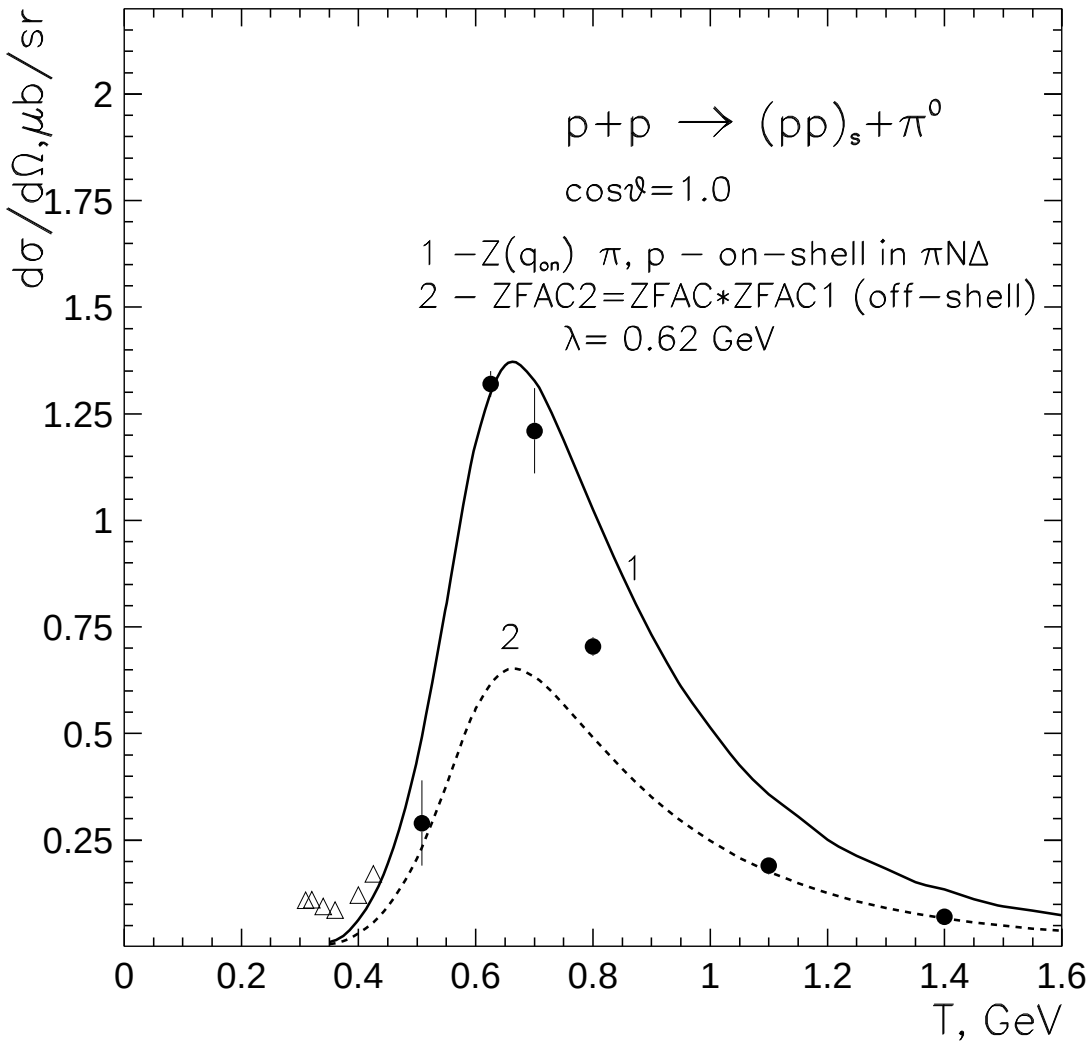
ANKE@COSY data • – D. Mchedlishvili et al., PRL (2013) $\lambda_\pi = 0.5$ GeV, and $\mathbf{T_{22}}$

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



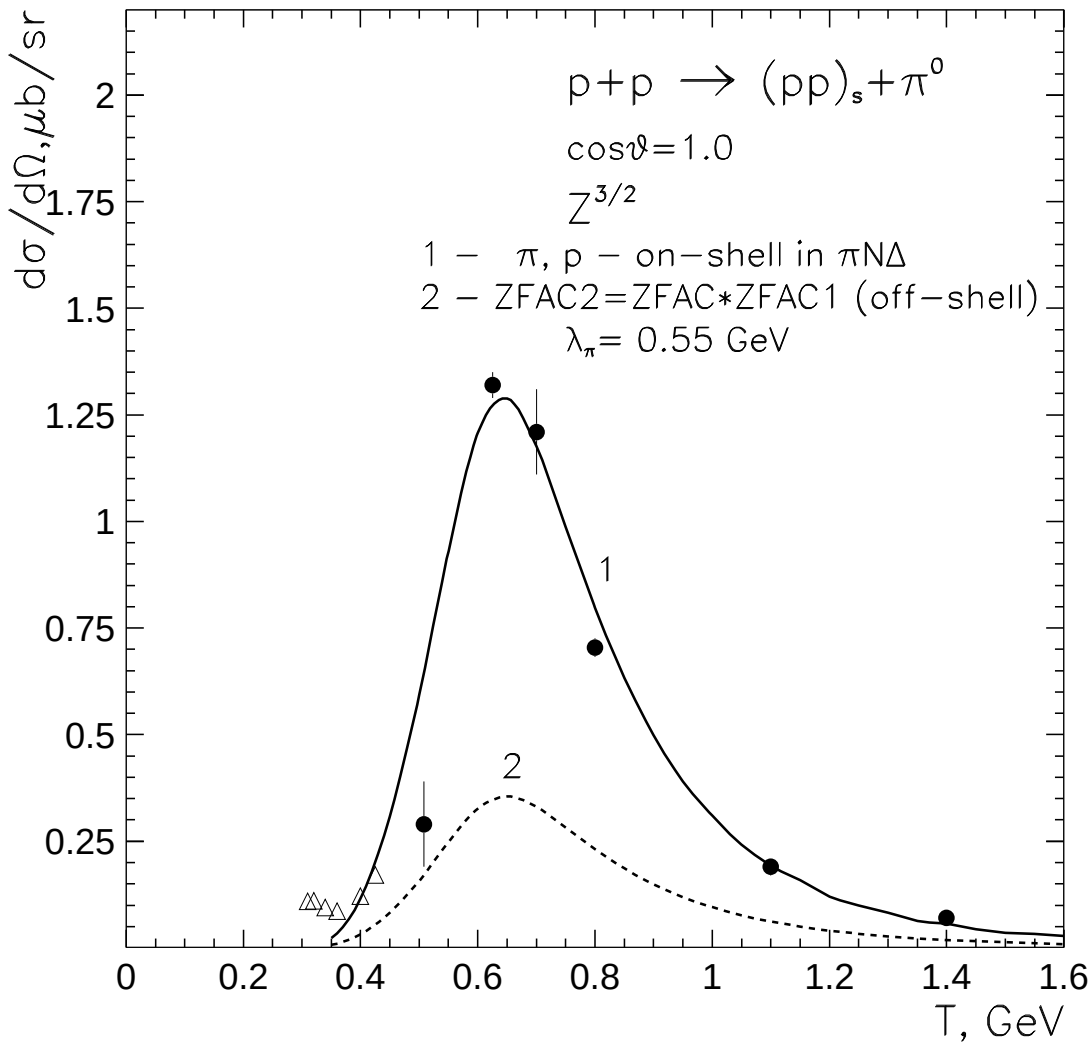
In $\sqrt{Z}$-factor in $\pi N\Delta$ $q = q_{on} = k(s_\Delta, m^2, m_\pi^2)$: 1- direct, 2-exchange, 3- total; 4 – total PK $\Gamma(k) = \Gamma_0 \left(\frac{k}{k_R}\right)^3 \frac{k_R^2+\chi^2}{k^2+\chi^2}$ $\chi = 0.180 GeV$, $\lambda_\pi = 0.55$ GeV

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



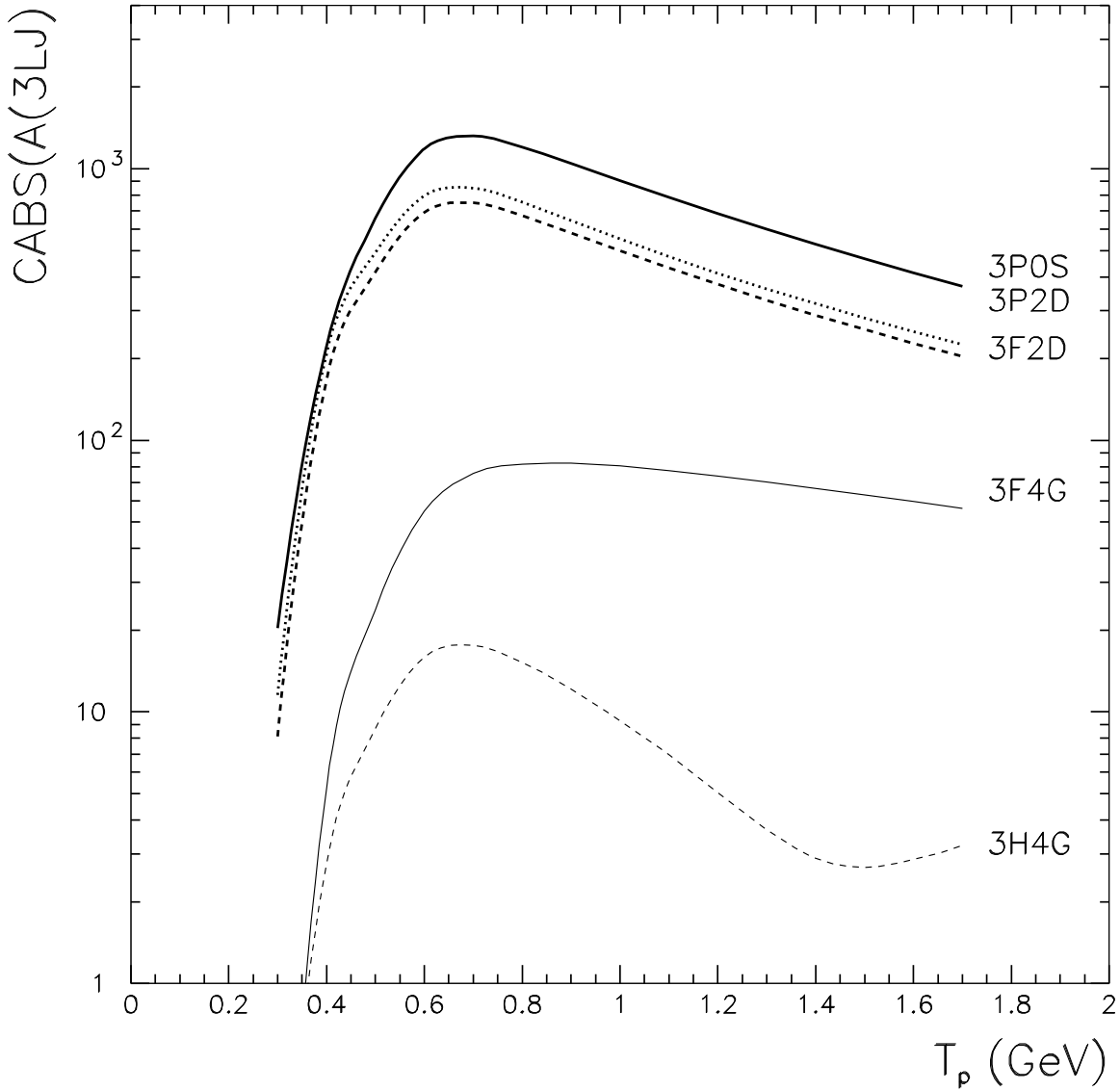
Off-shell $\sqrt{Z}$-factor in $\pi N\Delta-$ vertices diminishes $d\sigma/d\Omega$ (line 2).

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



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

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



V.Komarov et al. PRC 93 (2016)065206: ^3P_0s, ^3P_2d are sufficient for $\frac{d\sigma}{d\Omega}$ and $A_y(\theta)$.
The Δ-model: ^3F_2d is also important.

Summary & Outlook

- **Joint study of the d- and $\{\mathrm{pp}\}_\mathrm{s}$- channels is instructive.**

- **Δ is suppressed in the $\{\mathrm{pp}\}_\mathrm{s}$- channel by spin-parity and isospin conservation but is still very important.**

- **The box-diagram with Δ in $\mathrm{pp} \to \{\mathrm{pp}\}_\mathrm{s}\pi^0$ allows one to some extent explain E-dependence of $d\sigma/d\Omega(0^\circ)$ as in $pp \to d\pi^+$, but completely fails with angular dependence and $A_y(\theta)$.**

- **Is the observed resonance structure caused solely by the Δ-isobar or by specific $\Delta - N$ interaction?**
Dibaryons contrtibution? ($^3P_0 s$, $^3P_2 d$?)

Work is in progress with $\mathrm{pp} \to \{\mathrm{pp}\}_\mathrm{s}\pi^0$...

THANK YOU!