DYNAMICS OF $^1S_0$ DIPROTON FORMATION IN THE REACTIONS $pp \to \{pp\}_s\pi^0$ AND $pp \to \{pp\}_s\gamma$

Yu.N. Uzikov

Joint Institute for Nuclear Research, DLNP, Dubna

$\mathbf{pp} \leftrightarrow \mathbf{d}\pi^{+}$, $\quad \mathbf{pn} \leftrightarrow \mathbf{d}\gamma$ **in the GeV region**

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

/H.Machner, talk on this conf./

$\mathbf{pd} \to \mathbf{dp} \Longrightarrow \mathbf{p\{NN\}_s \to dN}$ **in A(p,Nd)B**

suppression of the Δ**- and** N^***-excitations as** $1:9$

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inverse channel: $\mathbf{pd} \to \mathbf{\{pp\}_s n}$

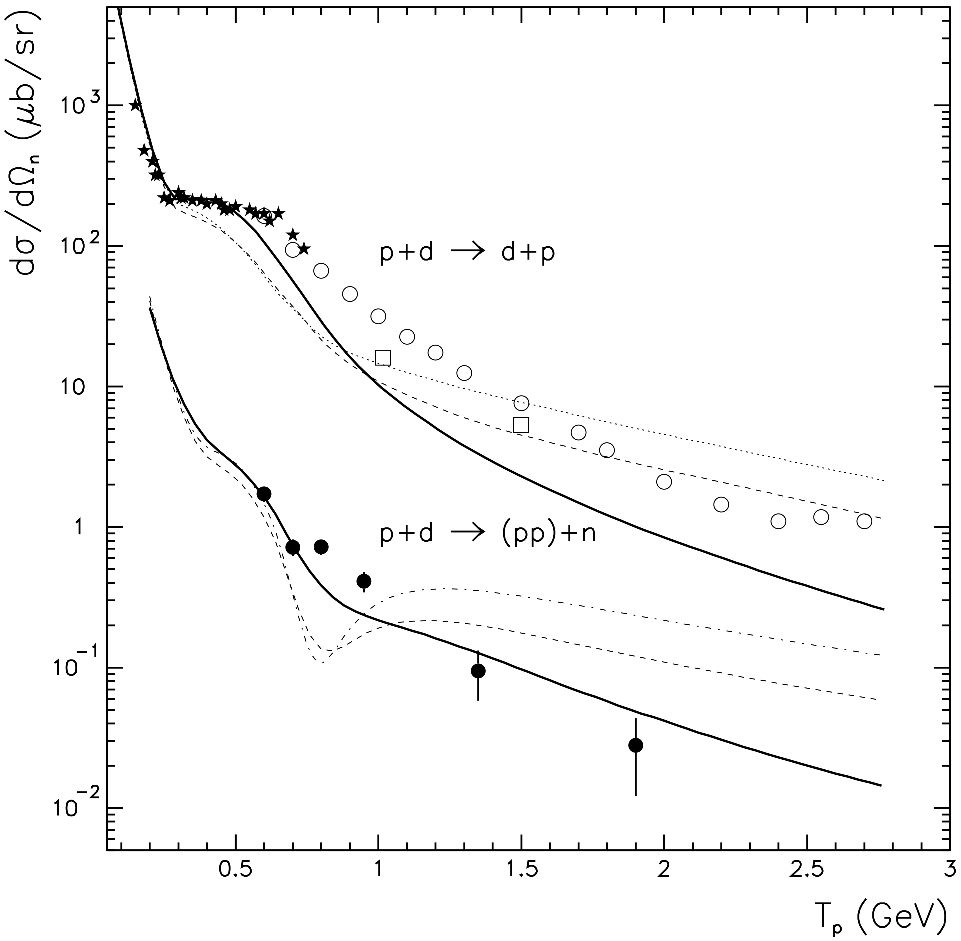
/O.Imambekov , YU.N.U., Yad.Fiz. 1987; 1990/

$\pi^{-}\mathbf{\{pp\}_s} \to \mathbf{pn}$ **in** ^3He **/M.A. Moinster, PRL, 1984/**

$\gamma\mathbf{\{pp\}_s} \to \mathbf{pp}$ **in** ^3He **/J. Laget, NPA,1989/**

COSY DATA, 2003-2008

$pd \rightarrow (pp)_s n$



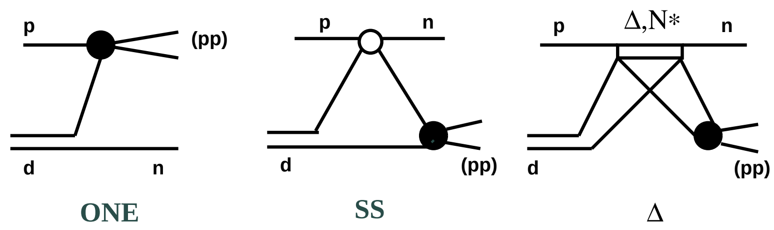


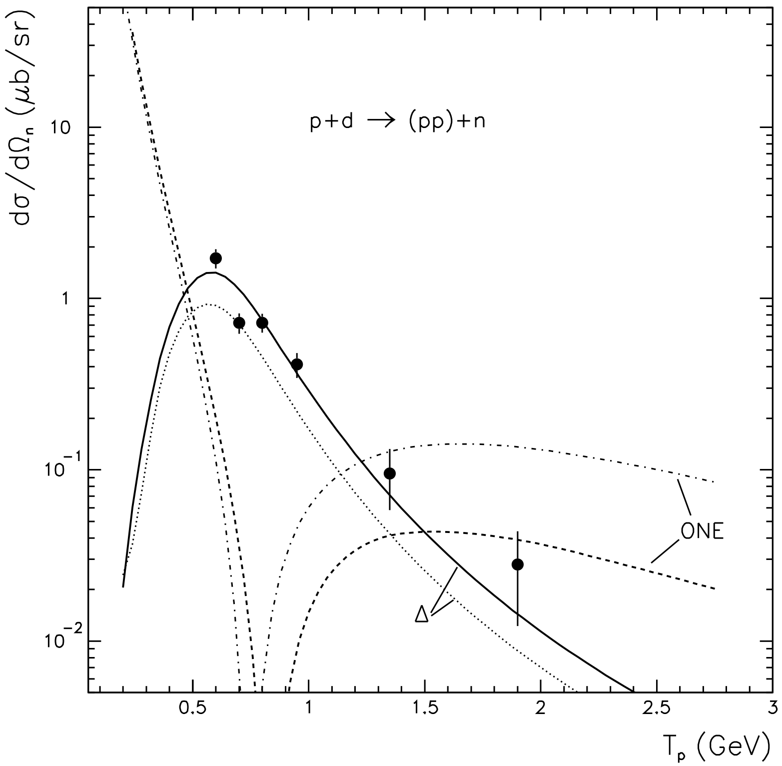
Figure 1: $pd \rightarrow dp$ and $pd \rightarrow (pp)_s n$

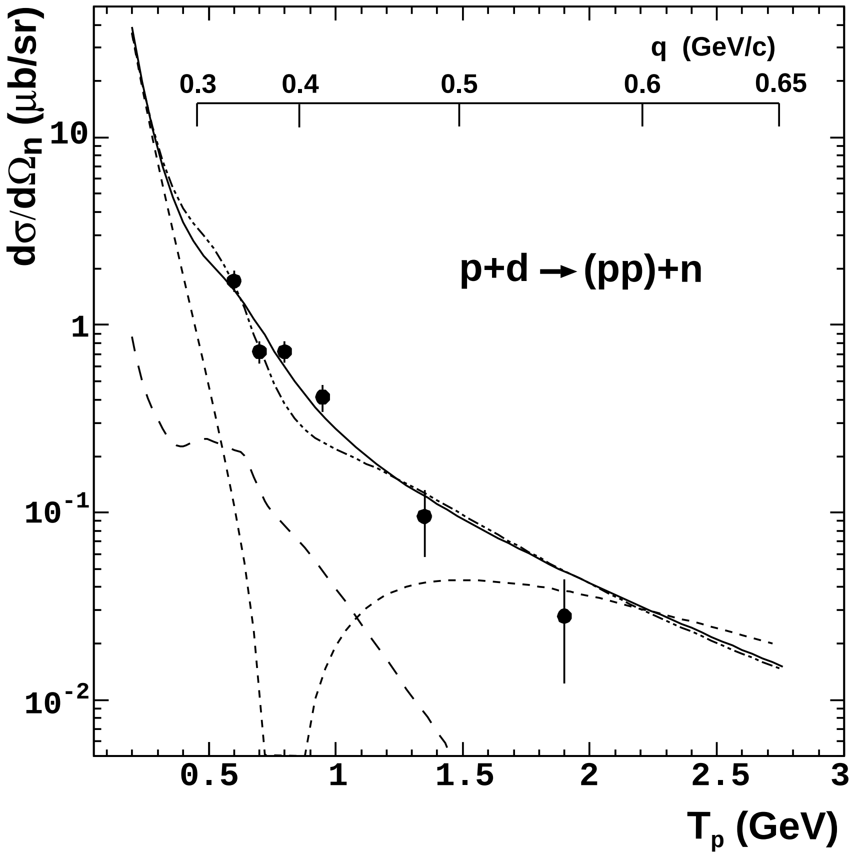
ONE+Δ+SS model: **RSC (dasded-dotted), Paris (dashed), CdBonn (full).**

J.Haidenbauer and Yu.N.U., Phys. Lett. B562 (2003) 227;

COSY data – V.Komarov et.al. Phys. Lett. B553 (2003) 179.

$pd \to (pp)_s n$





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

Allowed transitions in $\mathbf{pp} \to \mathbf{d}\pi^+$ & $\mathbf{pp} \to \{\mathbf{pp}\}_\mathbf{s}\pi^\mathbf{0}$

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

$^1S_0$ **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:**

$\star$ $\mathbf{pp} \to \{\mathbf{pp}\}_\mathbf{s}\pi^\mathbf{0}$ $\mathbf{L} - \mathbf{odd}(\mathbf{L} = \mathbf{1}, \mathbf{3}, \ldots)\mathbf{T} = \mathbf{1},\ \mathbf{S} = \mathbf{1}$

$\Longrightarrow$ **ΔN in S-wave (or N^*N)** $\pi = +1$ - *vorbidden*

$\star$ $\mathbf{pp} \to \mathbf{d}\pi^+$ **L-odd and even,** $T = 1,\ S = 1$ **and** $S = 0$

$\Longrightarrow$ **ΔN in S-wave (N^*N)** $\pi = +1$ -*not vorbidden*

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

$\mathbf{pp} \to \mathbf{pn}\pi^+$ **LAMPF data 800 MeV**

J.Hudomalj-Gabitzch et al. PRC 18 (1978) 2666

singlet-to-triplet $\xi <$ **few % in** $pp \to \{pn\}_{s,t}\pi^+$

Yu.N.U, C.Wilkin, PLB 551 (2001)191

2. $\gamma \mathbf{d} \to \mathbf{pn}$ **and** $\gamma \{\mathbf{pp}\}_\mathbf{s} \to \mathbf{pp}$

Magnetic transition $M1$ dominates $\gamma \mathrm{d} \to \mathrm{pn}$ via $\Delta(1232)$, but is forbidden in $\gamma \{pp\}_s \to pp$.

3. **$\triangle$ mechanism masks short-range NN properties in the d-channel,**

but these may reveal themselves in the $\{pp\}_s$ channel.

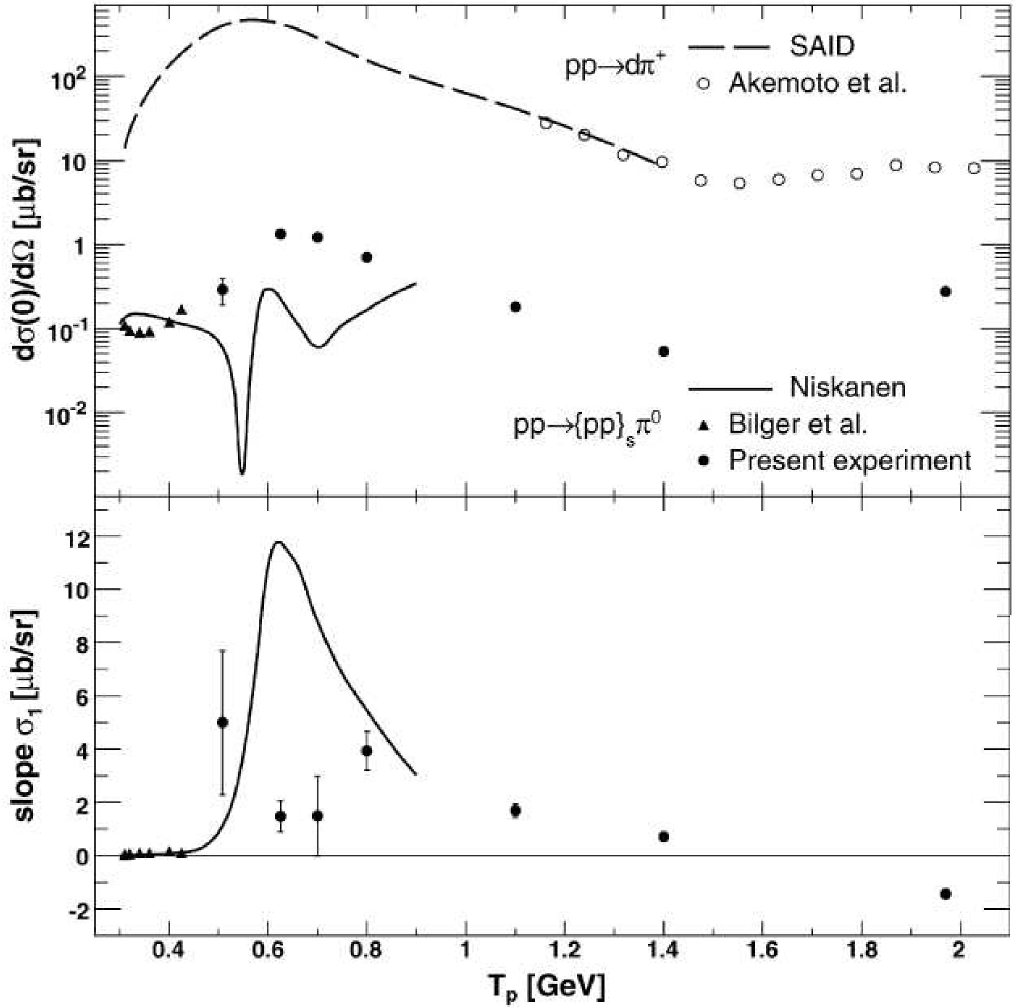
4. COSY DATA on $pp \to \{pp\}_s\pi^0$ at 0.5-2.0 GeV:

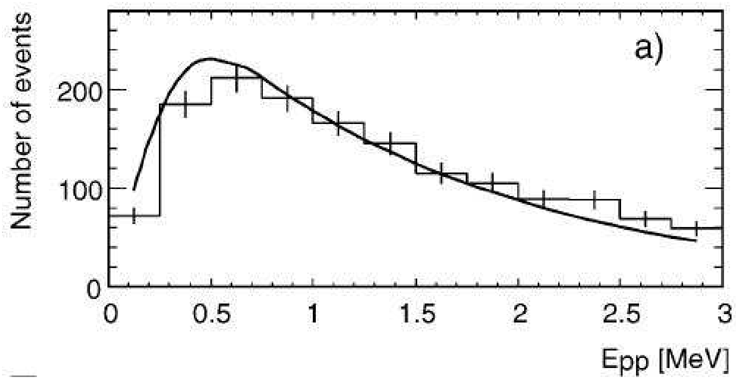
S. Dymov et al., Phys. Lett. B 635 (2006) 270.
V. Kurbatov et al., Phys. Lett. B 661 (2008) 22.

$pp \to \{pp\}_s\gamma$ at 0.3-0.55 GeV:

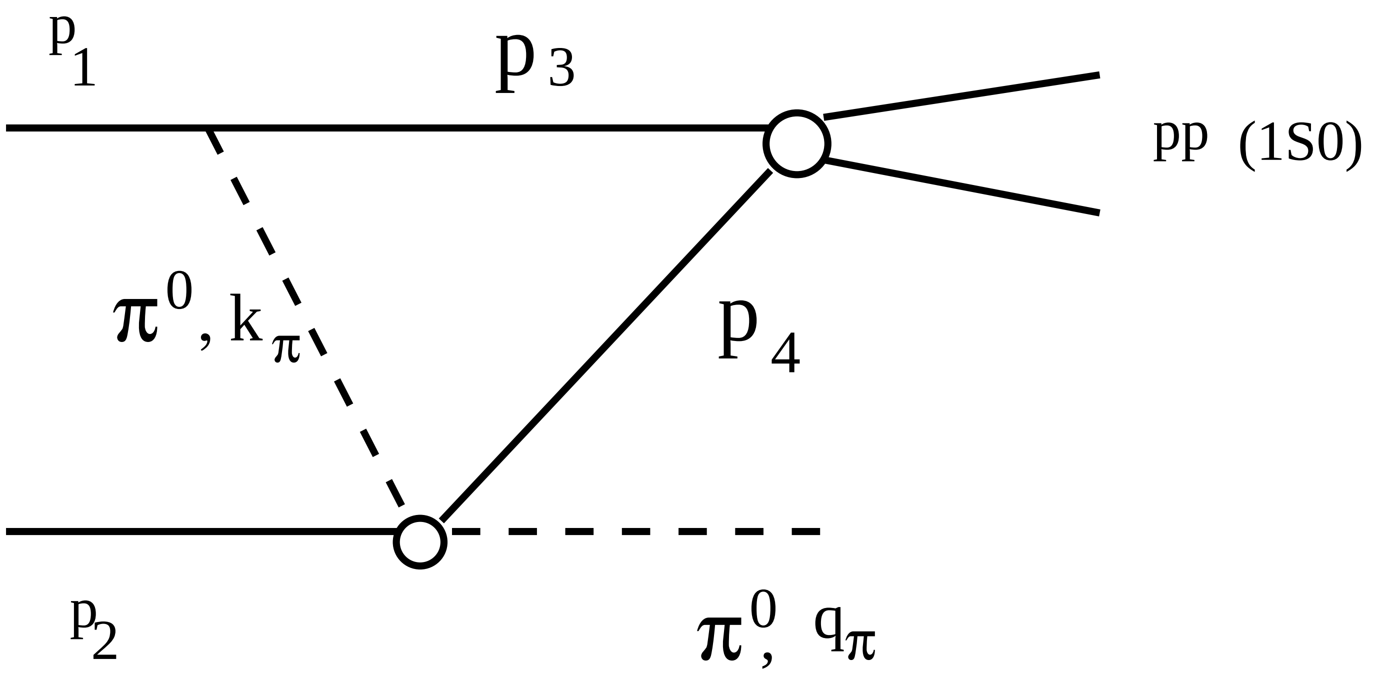
V. Komarov et al., PRL (2008) (in press);
arXiv:0806.0648 [nucl-ex]

COSY DATA: V.Kurbatov et al., PLB **661** *(2008)22*





$pp \to \{pp\}_s\pi^0$, **theory: J.Niskanen, PLB 642 (2006) 34 /full lines/**



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

See OPE for $pd \longrightarrow \{pp\}_s n$ from Yu.N.U., J. Haidenbauer, C. Wilkin, PRC **75** (2007) 014008

$$\mathbf{A}^{\mathbf{dir}}(\mathbf{p_1},\sigma_\mathbf{1},\mathbf{p_2},\sigma_\mathbf{2}) = \frac{\mathbf{f}_{\pi\mathbf{NN}}}{\mathbf{m}_\pi}\mathbf{N_{pp}2m_pF}_{\pi\mathbf{NN}}(\mathbf{k}_\pi^\mathbf{2}) \times \tag{1}$$

$$\times\mathbf{\Sigma}_{\sigma_\mathbf{3}\,\sigma_\mathbf{4}\,\mu}(\frac{\mathbf{1}}{\mathbf{2}}\sigma_\mathbf{3}\frac{\mathbf{1}}{\mathbf{2}}\sigma_\mathbf{4}|\mathbf{00})(\mathbf{1}\mu\frac{\mathbf{1}}{\mathbf{2}}\sigma_\mathbf{3}|\frac{\mathbf{1}}{\mathbf{2}}\sigma_\mathbf{1})\mathbf{J}^\mu(\tilde{\mathbf{p}},\gamma)\mathbf{A}_{\sigma_\mathbf{2}}^{\sigma_\mathbf{4}}(\pi^\mathbf{0}\mathbf{p}\to\pi^\mathbf{0}\mathbf{p}),$$

$$J^\mu(\tilde{p},\gamma) = \sqrt{\frac{E_1+m_p}{2m_p}\frac{m_p}{E_1}}\Big\{R^\mu F_0(\tilde{p},\gamma) - i\hat{\tilde{p}}^\mu\Phi_{10}(\tilde{p},\gamma)\Big\}, \tag{2}$$

where

$$\mathbf{F_0}(\tilde{\mathbf{p}},\gamma) = \int_\mathbf{0}^\infty \mathbf{drrj_0}(\tilde{\mathbf{p}}\mathbf{r})\psi_\mathbf{k}^{(-)^*}(\mathbf{r})\exp(-\gamma\mathbf{r}), \tag{3}$$

$$\mathbf{\Phi_{10}}(\tilde{\mathbf{p}},\gamma) = \mathbf{i}\int_\mathbf{0}^\infty \mathbf{drj_1}(\tilde{\mathbf{p}}\mathbf{r})\psi_\mathbf{k}^{(-)^*}(\mathbf{r})(\mathbf{1}+\gamma\mathbf{r})\exp(-\gamma\mathbf{r}), \tag{4}$$

$$\psi_{\mathbf{k}}^{(-)}(\mathbf{r}) \to \frac{\sin(\mathbf{kr}+\delta)}{\mathbf{kr}}. \qquad (5)$$

$$\gamma^2 = \frac{T_1^2}{(E_1/m_p)^2} + \frac{m_\pi^2}{E_1/m_p}, \quad \mathbf{R} = -\mathbf{p}_1\frac{m_p T_1}{(E_1+m_p)E_1}, \quad \tilde{\mathbf{p}} = \frac{\mathbf{p}_1}{E_1/m_p}, \qquad (6)$$

where E_1, $\mathbf{p}_1$ and $T_1 = E_1 - m_p$ are the total energy, 3-momentum and kinetic energy of the initial proton p_1,

$$\frac{\mathbf{d}\sigma}{\mathbf{d}\Omega} = \frac{\mathbf{1}}{(\mathbf{4}\pi)^{\mathbf{5}}}\frac{\mathbf{p_f}}{\mathbf{s_{pp}\,p_i}}\int_{\mathbf{0}}^{\mathbf{k^{max}}}\mathbf{dk^2}\frac{\mathbf{k}}{\sqrt{\mathbf{m_p^2}+\mathbf{k^2}}}\frac{\mathbf{1}}{\mathbf{2}}\int \mathbf{d}\Omega_{\mathbf{k}}\overline{|\mathbf{A_{fi}}|^{\mathbf{2}}}, \qquad (7)$$

$$\frac{d\sigma}{d\Omega_\theta}(pp \to \{pp\}_s\pi^0) = \frac{1}{24\pi^2}\frac{p_f}{p_i}\frac{s_{\pi p}}{s_{pp}}\left[\frac{f_{\pi NN}}{m_\pi}N_{pp}m_p F_{\pi NN}(k_\pi^2)\right]^2 \times$$

$$\times \int_0^{k^{max}} dk \frac{2k^2}{\sqrt{m_p^2+k^2}}\left\{2|J^{\mu=0}(\tilde{p},\delta)|^2 + |J^{\mu=1}(\tilde{p},\delta)|^2\right\}$$

$$\times \frac{d\sigma}{d\Omega_\phi}(\pi^0 p \to \pi^0 p). \quad (8)$$

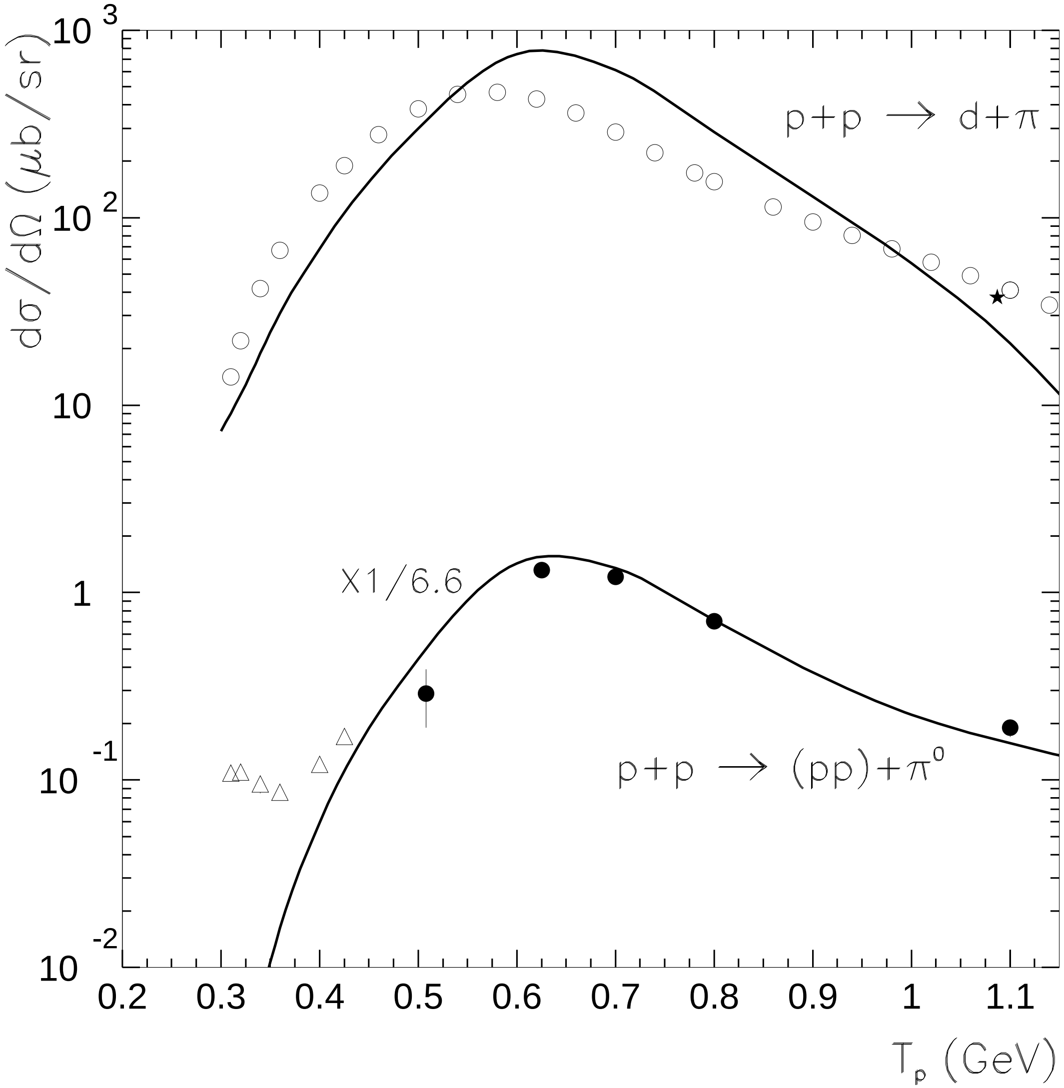
$$f^2{}_{\pi NN}/4\pi = 0.0796, \quad F_{\pi NN}(k^2{}_\pi) = \frac{\Lambda^2 - m^2{}_\pi}{\Lambda^2 - k^2{}_\pi}$$

$$k_\pi^2 = 2m_p^2 + p_i p_f \cos\theta - \sqrt{m_p^2+p_i^2}\sqrt{M_{pp}^2+p_f^2}, \quad (9)$$

M_{pp} – mass of the diproton.

$\Lambda = 0.65$ GeV/c from fit by Yu.N. U, O.Imambekov, Yad.Fiz. (1988) to the $pp \to pn\pi^+$ LAMPF data at 800 MeV in the Δ-region

The OPE results: $pp \to d\pi^+$ *and* $pp \to \{pp\}_s\pi^0$



ONE is important for $pp \to d\pi^+$, but not for $pp \to \{pp\}_s\pi^0$ due to s-wave node; not included

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

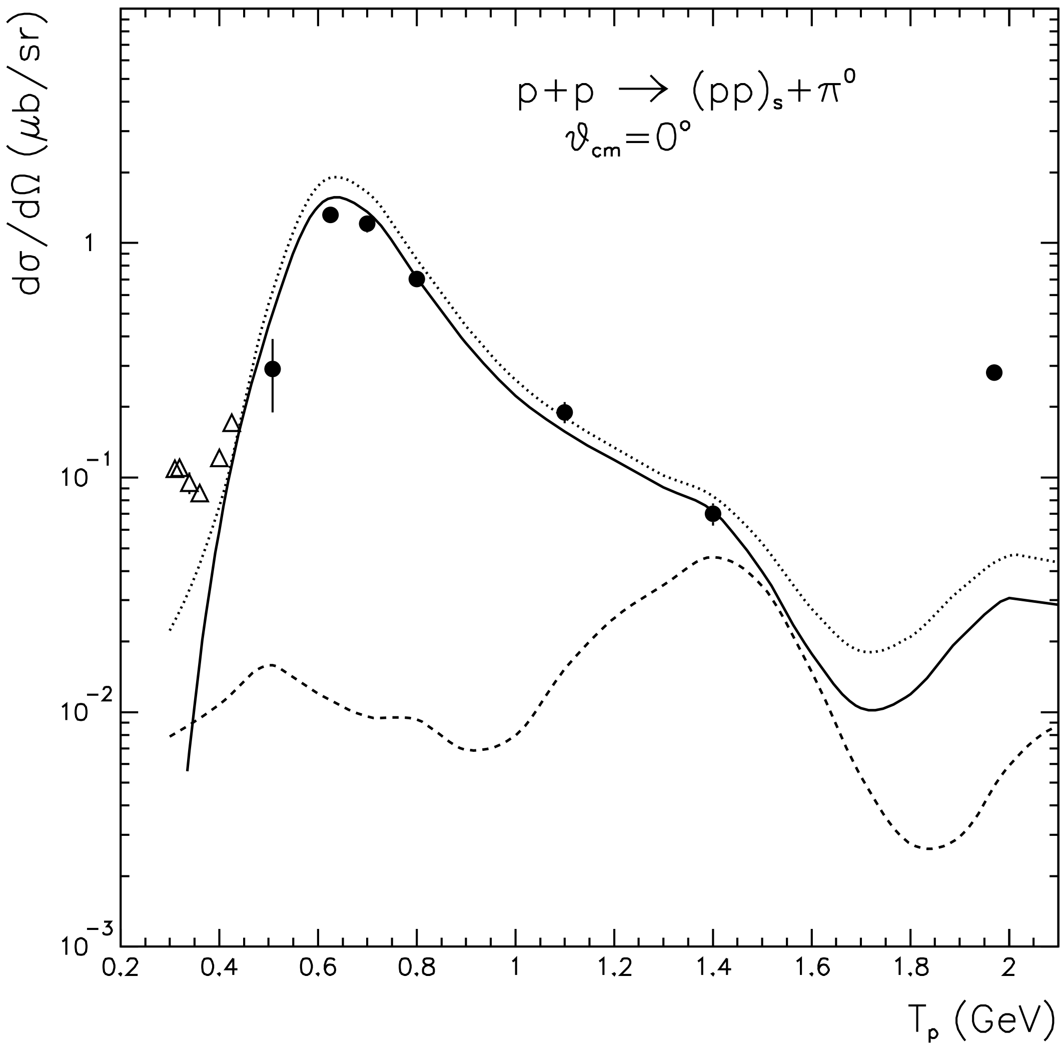
$$\mathbf{A}(\pi^{\mathbf{0}}\mathbf{p} \to \pi^{\mathbf{0}}\mathbf{p}) = \frac{\mathbf{1}}{\mathbf{3}}\Big(\mathbf{a}_{\frac{1}{2}} + \mathbf{2a}_{\frac{3}{2}}\Big), \tag{10}$$

$$\mathbf{d}\sigma(\pi^{\mathbf{0}}\mathbf{p} \to \pi^{\mathbf{0}}\mathbf{p}) = \frac{\mathbf{1}}{\mathbf{2}}\Big\{\mathbf{d}\sigma(\pi^{+}\mathbf{p}) + \mathbf{d}\sigma(\pi^{-}\mathbf{p}) - \mathbf{d}\sigma(\pi^{\mathbf{0}}\mathbf{n} \to \pi^{-}\mathbf{p})\Big\}, \tag{11}$$

If the amplitude $a_{\frac{3}{2}}$ is excluded from Eq. (10)

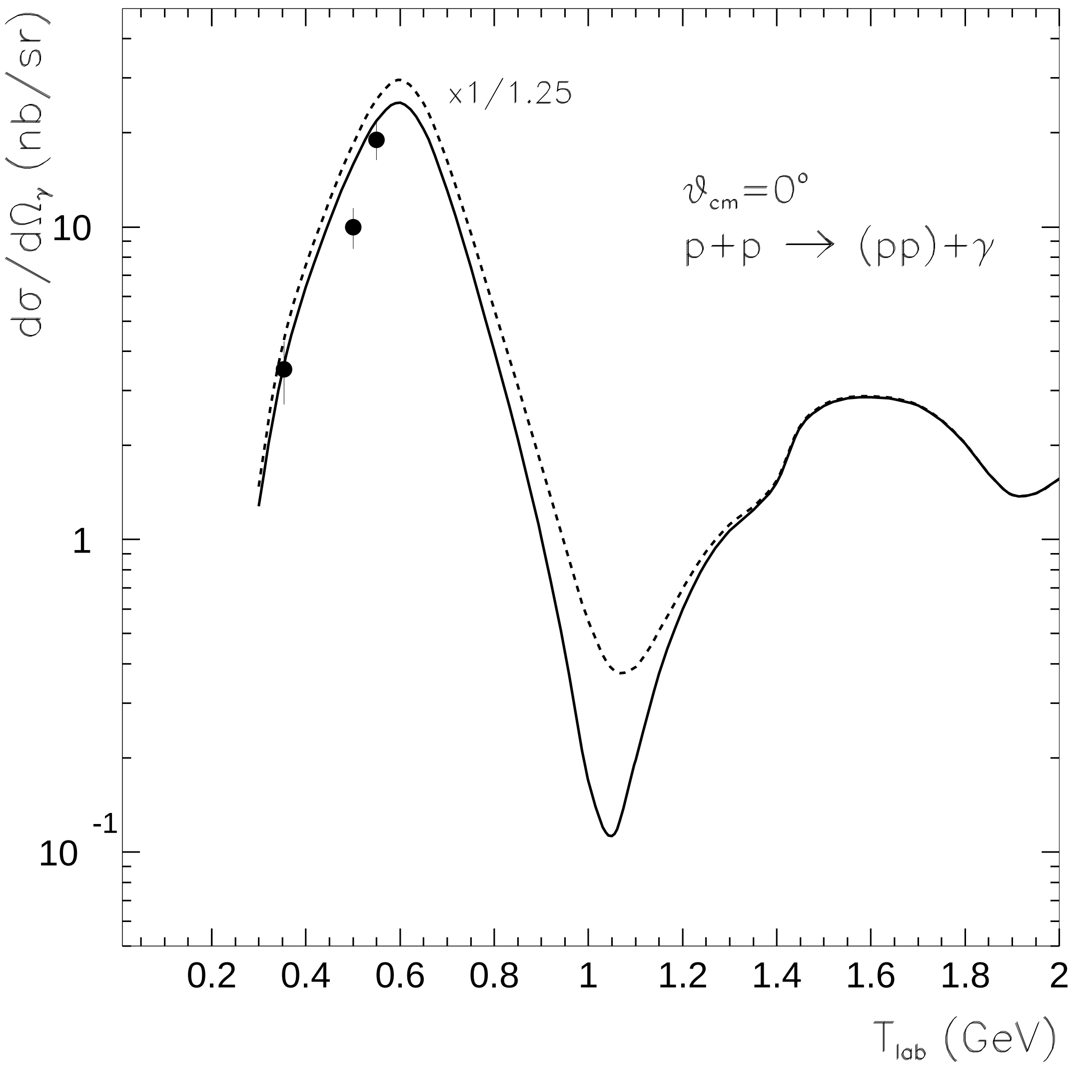
$$\mathbf{d}\widetilde{\sigma}(\pi^{\mathbf{0}}\mathbf{p} \to \pi^{\mathbf{0}}\mathbf{p}) = \frac{\mathbf{1}}{\mathbf{18}}\Big\{\mathbf{3d}\sigma(\pi^{-}\mathbf{p}) - \mathbf{d}\sigma(\pi^{+}\mathbf{p}) + \mathbf{3d}\sigma(\pi^{\mathbf{0}}\mathbf{n} \to \pi^{-}\mathbf{p})\Big\}. \tag{12}$$

The OPE results with and whithout $\Delta(1232)$



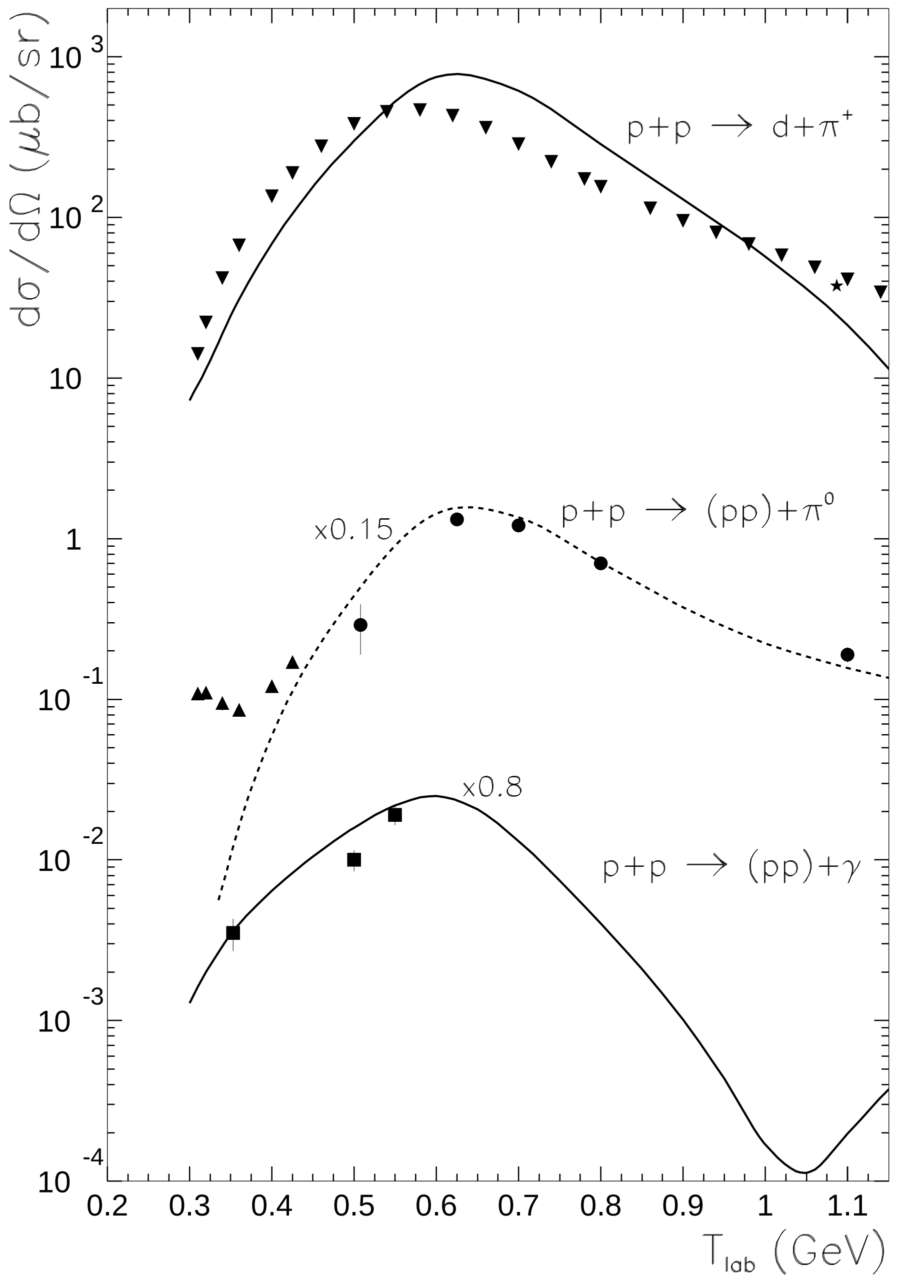
$pp \rightarrow \{pp\}_s\pi^0$; COSY data: • – V.Kurbatov et. al PLB 661 (2008) 33

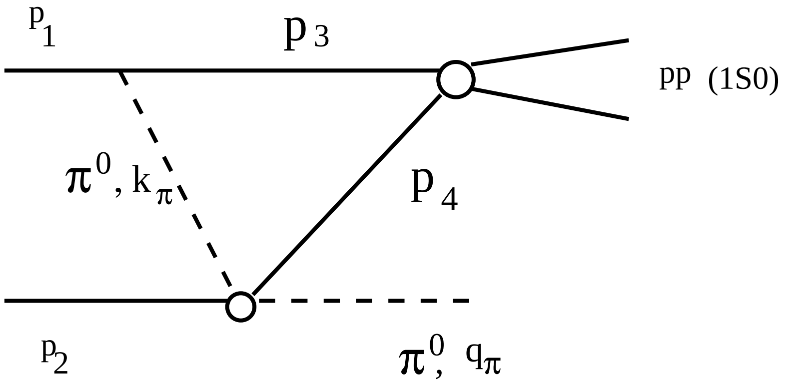
OPE: $pp \to \{pp\}_s\gamma$



COSY data • – V. Komarov et al., PRL (2008) (in press)/arXiv:0806.0648 [nucl-ex]/

The OPE results: $pp \to d\pi^+$, $pp \to \{pp\}_s\pi^0$, $pp \to \{pp\}_s\gamma$





Conclusion

- **Comparison of d- and $\{\mathrm{pp}\}_\mathrm{s}$- channels is very instructive.**

- **The OPE is a first step of analysis,**
explains the shape of $d\sigma/d\Omega(0^\circ)$ for $\mathrm{pp} \to \{\mathrm{pp}\}_\mathrm{s}\pi^0$ and roughly absolute value for $\mathrm{pp} \to \{\mathrm{pp}\}_\mathrm{s}\gamma$ (&$\mathrm{pp} \to \mathrm{d}\pi^+$) at 0.3-1.0 GeV

- **$\Delta(1232)$ contribution is still very important in the $\mathrm{pp} \to \{\mathrm{pp}\}_\mathrm{s}\pi^0$ and in $\mathrm{pp} \to \{\mathrm{pp}\}_\mathrm{s}\gamma$ in spite of strong suppression by spin-parity conservation.**

- **A similar $\Delta-$ dominance was found in $\mathrm{pd} \to \{\mathrm{pp}\}_\mathrm{s}\mathrm{n}$ at 0.5-1 GeV within ONE+Δ+SS & OPE models (softness of NN?).**

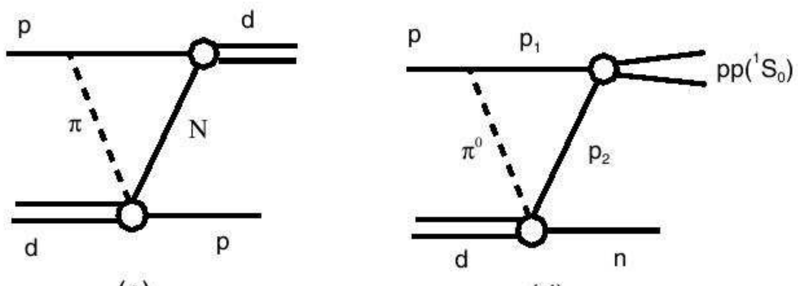
- **Outlook: explicite Δ consideration + ONE$\Longrightarrow$**
$\Longrightarrow$ short-range NN-behaviour; A_y, $C_{x,x}$?
$pn \to \{pp\}_s\pi^-$, $pp \to \{pp\}_s\gamma$ measurements at 0.5 - 2 GeV

$$R_{II} \approx \frac{2}{27}\frac{k_{\max}^3}{6\pi^2 m}\frac{\left|\Phi_{\bar{k}}^{pp}(p_{II}, \delta_{II})\right|^2}{\left|\Phi_{10}^{d}(\tilde{p}, \tilde{\delta})\right|^2}, \tag{33}$$

where $\overline{k} = \sqrt{2m\overline{E}_{pp}}$. In the derivation of R_{II} we have neglected the contribution of the deuteron D-state component and the form factor F_L, which are, however, included in the numerical evaluations.

The origins of the different terms in Eq. (33) are easy to understand. To obtain Eq. (31) from (22) one needs to make the following replacements: (i) $\psi_{\mathbf{k}}^{(-)}(\mathbf{r}) \to \varphi_d(\mathbf{r})/\sqrt{m}$; (ii) multiply by the ratio of the isospin and combinatorial factors $9/(N_{pp}^2/2) = 9/2$; (iii) multiply by the spin factor of three; (iv) multiply by the factor $4\pi^2$, which arises from the difference between three- and two-body phase spaces; (v) divide by the factor

$$\int_0^{k_{\max}} \frac{k^2}{\sqrt{m^2+k^2}}\mathrm{d}k \approx \frac{k_{\max}^3}{3m}. \tag{34}$$



(c) (d)

Yu.N.U, J.Haidenabuer, C.Wilkin, PRC **75** (2007) 014008