FORMATION OF THE $^1\mathbf{S}_0$ DIPROTON IN THE REACTION $\mathbf{pp} \to \{\mathbf{pp}\}_{\mathbf{s}}\pi^{\mathbf{0}}$

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• **Bulk of the data with the deuteron** $AB \to dC$ **at high** Q $(\mathbf{pp} \leftrightarrow \mathbf{d}\pi^+$, $\mathbf{pn} \leftrightarrow \mathbf{d}\gamma$ $\mathbf{pd} \to \mathbf{dp}, \cdots)$ **in the GeV region. Testing ground for NN models**

• **Reactions with the** $^1S_0$ **diproton** $\{pp\}_s$ **can give more insight into underlying dynamics due to difference in quantum numbers** $J_d^\pi = 1^+$, $T_d = 0 \Longrightarrow J_{pp}^\pi = 0^+$, $T_{pp} = 1$

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

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

suppression of the Δ**- and** N^***-excitations as** $1:9$ **inverse channel:** $\mathbf{pd} \to \mathbf{\{pp\}_s n}$

/O.Imambekov , Yu.N.U., In: "Quark-Hadronic Systems" (Dubna,1987); Yad. Fiz. 52 (1990) 1361/

Motivation

$$\pi^-\{\mathbf{pp}\}_\mathbf{s} \to \mathbf{pn} \quad \text{in } ^3He$$ /M.A. Moinster, PRL, 1984/

$$\gamma\{\mathbf{pp}\}_\mathbf{s} \to \mathbf{pp} \quad \text{in } ^3He$$ /J. Laget, NPA,1989/

Δ-contribution is also suppressed as compared to the d channel

- ⋆ Δ mechanism masks short-range NN properties in the d-channel, and these may reveal themselves in the $\{pp\}_s$ channel.
- ⋆ Spin structure of the transition m.e. is much simpler for $\{pp\}_s$

Diproton physics at ANKE-COSY, 1999-2010

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

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

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

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

$\mathbf{pn} \to \{\mathbf{pp}\}_\mathbf{s}\pi^-$ (in progress)

COSY DATA in the Δ-region

$pd \to \{pp\}_s n$ at 0.5-2.0 GeV:

V. Komarov et al., Phys. Lett. B553 (2003) 179;
S.Yaschenko et al., Phys.Rev. Lett. 94 (2005) 072304;
S. Dymov et al., Phys. Rev. C 81 (2010) 044001

$pp \to \{pp\}_s \pi^0$ 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 0.3-0.8 GeV:

V. Komarov et al., Phys.Rev. Lett. 101 (2008) 102501;
D. Tsirkov et al., J.Phys. G:Nucl.Part.Phys. 37 (2010);

Very simple spin structure of the $pp \to \{pp\}_s\pi^\circ$

$$\mathbf{\frac{1}{2}}^+ + \mathbf{\frac{1}{2}}^+ \to \mathbf{0}^+ + \mathbf{0}^-$$

$$F_{fi}^P = \chi_{\sigma_2}^{(T)}(2)\frac{i\sigma_y}{\sqrt{2}}\Big\{A\sigma\cdot\mathbf{l} + B\sigma\cdot\mathbf{m}\Big\}\chi_{\sigma_1}(1), \qquad (1)$$

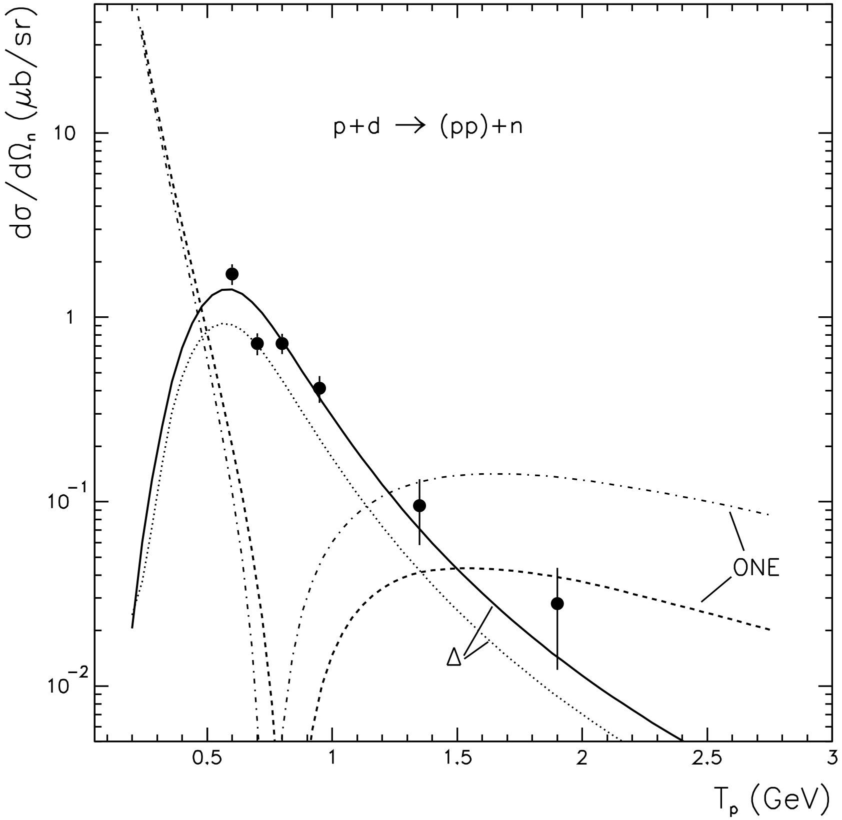
$$d\sigma_0 = \frac{1}{4}(|A|^2+|B|^2),\ A_y^b = A_y^t = -\frac{2Im(A^*B)}{|A|^2+|B|^2},$$

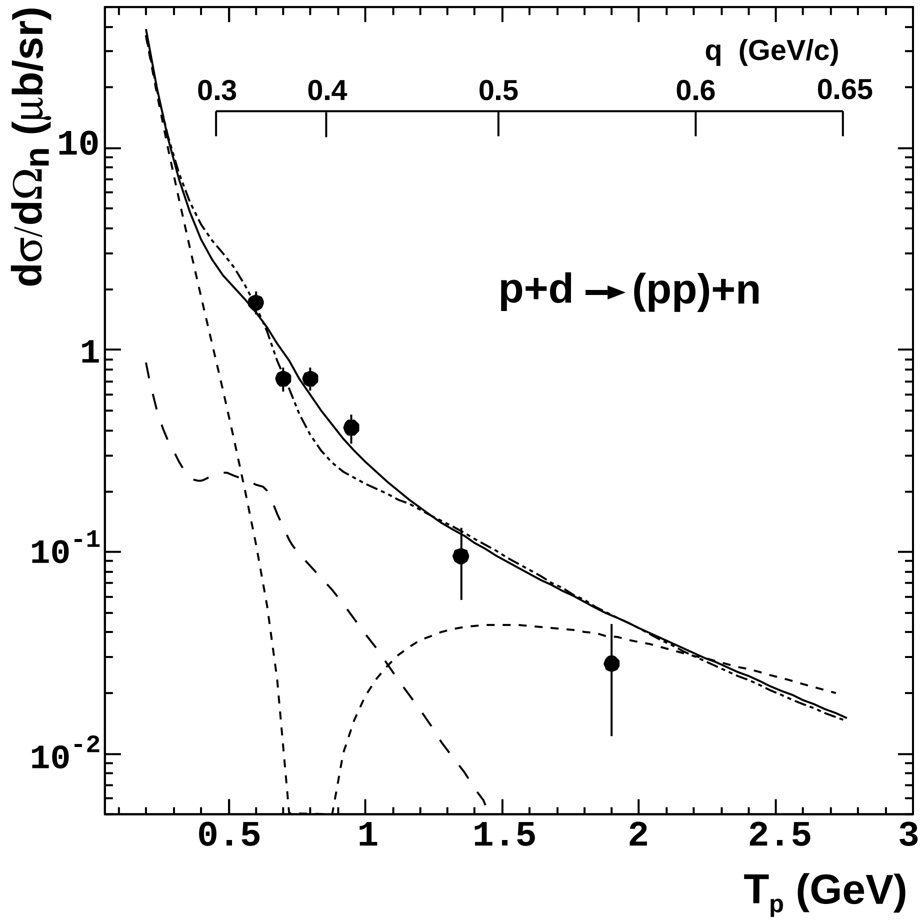
$$C_{x,x} = -C_{z,z} = \frac{|B|^2-|A|^2}{|A|^2+|B|^2},\ C_{y,y} = 1,$$

$$C_{x,z} = C_{z,x} = -\frac{2ReA\,B^*}{|A|^2+|B|^2}, \qquad (2)$$

COMPLETE POLARIZATION EXPERIMENT:
$d\sigma_0$, A_y, $C_{x,z}$, $(C_{x,x})$. **Contact d-term** $NNNN\pi$ **ChEFT**

$pd \to (pp)_s n$





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.
New COSY data confirm this conclusion, PRC 81 (2010)

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

$^1S_0$ **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:**

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

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

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

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

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

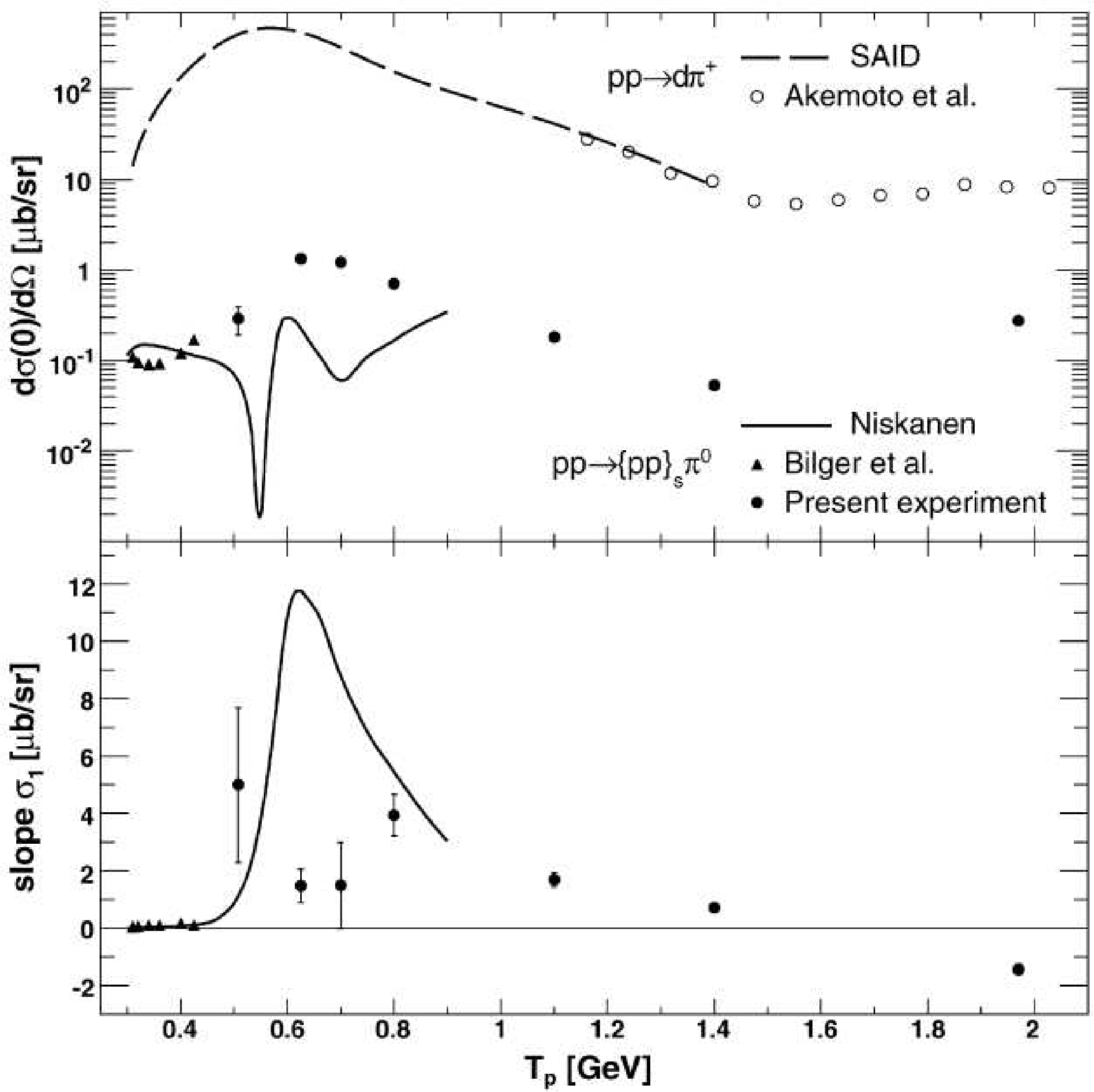
$\mathbf{pp \to pn\pi^+}$ **LAMPF data 800 MeV**

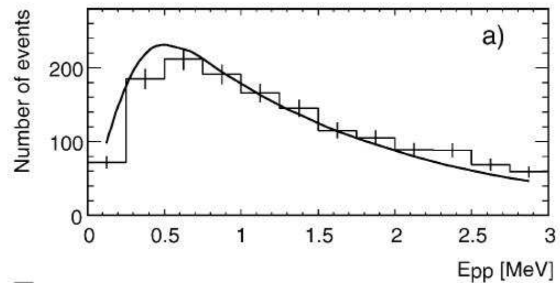
J.Hudomalj-Gabitzch et al. PRC 18 (1978) 2666

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

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

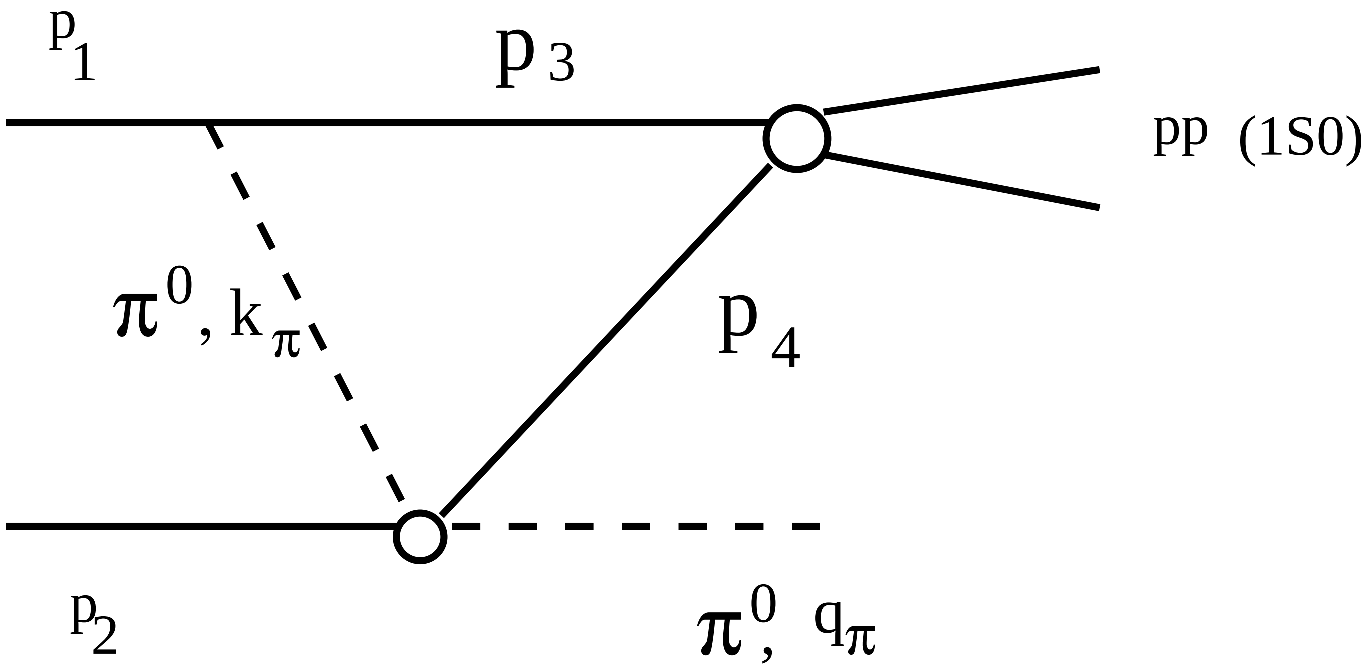
COSY DATA: V.Kurbatov et al., PLB **661** *(2008)22*





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

The OPE model



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

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

$$\mathbf{A^{dir}}(\mathbf{p_1},\sigma_1,\mathbf{p_2},\sigma_2)=\sqrt{3}\frac{\mathbf{f}_{\pi NN}}{\mathbf{m}_\pi}\mathbf{N_{pp}}\mathbf{2m_p}\mathbf{F}_{\pi NN}(\mathbf{k}_\pi^2)\times \tag{3}$$

$$\times\Sigma_{\sigma_3\,\sigma_4\,\mu}(\frac{1}{2}\sigma_3\frac{1}{2}\sigma_4|00)(1\mu\frac{1}{2}\sigma_3|\frac{1}{2}\sigma_1)\mathbf{J}^\mu(\tilde{\mathbf{p}},\gamma)\mathbf{A}_{\sigma_2}^{\sigma_4}(\pi^0\mathbf{p}\to\pi^0\mathbf{p}),$$

where

$$J^\mu(\mathbf{Q})=\int\frac{\mathbf{Q}^\mu\Psi_{\mathbf{k_{pp}}}^{(-)*}(\mathbf{q})}{\mathbf{m}_\pi^2-\mathbf{k}_{\mathbf{pp}}^2-\mathbf{i}\varepsilon}\frac{\mathbf{d^3q}}{(2\pi)^3} \tag{4}$$

$$\mathbf{Q}=\sqrt{\frac{E_1+m_p}{E_3+m_p}}\mathbf{p_3}-\sqrt{\frac{E_3+m_p}{E_1+m_p}}\mathbf{p_1} \tag{5}$$

$$\Psi_k^{(-)*}(\mathbf{q})=(2\pi)^3\delta^{(3)}(\mathbf{q}-\mathbf{k})-\frac{\mathbf{m}<\Psi_{\mathbf{k}}^{(-)}\mid\mathbf{V}(^1\mathbf{S_0})\mid\mathbf{q}>}{\mathbf{q^2}-\mathbf{k^2}-\mathbf{i}\varepsilon} \tag{6}$$

The OPE Formfactor in r-space

$$J^{\mu}(\tilde{p},\gamma) = \sqrt{\frac{E_1+m_p}{2m_p}\frac{m_p}{E_1}}\left\{R^{\mu}F_0(\tilde{p},\gamma) - i\hat{\tilde{p}}^{\mu}\Phi_{10}(\tilde{p},\gamma)\right\}, \quad (7)$$

where

$$\mathbf{F_0}(\tilde{\mathbf{p}},\gamma) = \int_{\mathbf{0}}^{\infty}\mathbf{drrj_0}(\tilde{\mathbf{p}}\mathbf{r})\psi_{\mathbf{k}}^{(-)^*}(\mathbf{r})\exp\left(-\gamma\mathbf{r}\right), \quad (8)$$

$$\mathbf{\Phi_{10}}(\tilde{\mathbf{p}},\gamma) = \mathbf{i}\int_{\mathbf{0}}^{\infty}\mathbf{drj_1}(\tilde{\mathbf{p}}\mathbf{r})\psi_{\mathbf{k}}^{(-)^*}(\mathbf{r})(\mathbf{1}+\gamma\mathbf{r})\exp\left(-\gamma\mathbf{r}\right), \quad (9)$$

$$\psi_{\mathbf{k}}^{(-)}(\mathbf{r}) \to \frac{\mathbf{sin(kr}+\delta)}{\mathbf{kr}}. \quad (10)$$

$$\gamma^2 = \frac{T_1^2}{(E_1/m_p)^2} + \frac{m_\pi^2}{E_1/m_p}, \quad \mathbf{R} = -\mathbf{p}_1\frac{m_p T_1}{(E_1+m_p)E_1}, \quad \tilde{\mathbf{p}} = \frac{\mathbf{p}_1}{E_1/m_p}, \quad (11)$$

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,

$$\frac{\mathbf{d}\sigma}{\mathbf{d}\Omega} = \frac{\mathbf{1}}{(\mathbf{4}\pi)^{\mathbf{5}}} \frac{\mathbf{p_f}}{\mathbf{s_{pp}}\,\mathbf{p_i}} \int_{\mathbf{0}}^{\mathbf{k^{max}}} \mathbf{dk^2} \frac{\mathbf{k}}{\sqrt{\mathbf{m_p^2} + \mathbf{k^2}}} \frac{\mathbf{1}}{\mathbf{2}} \int \mathbf{d\Omega_k} \overline{|\mathbf{A_{fi}}|^{\mathbf{2}}}, \tag{12}$$

$$\frac{d\sigma}{d\Omega}_{\theta}(pp \to \{pp\}_s \pi^0) = \frac{1}{8\pi^2} \frac{p_f}{p_i} \frac{s_{\pi p}}{s_{pp}} \left[\frac{f_{\pi NN}}{m_\pi} N_{pp} m_p F_{\pi NN}(k_\pi^2) \right]^2 \times$$

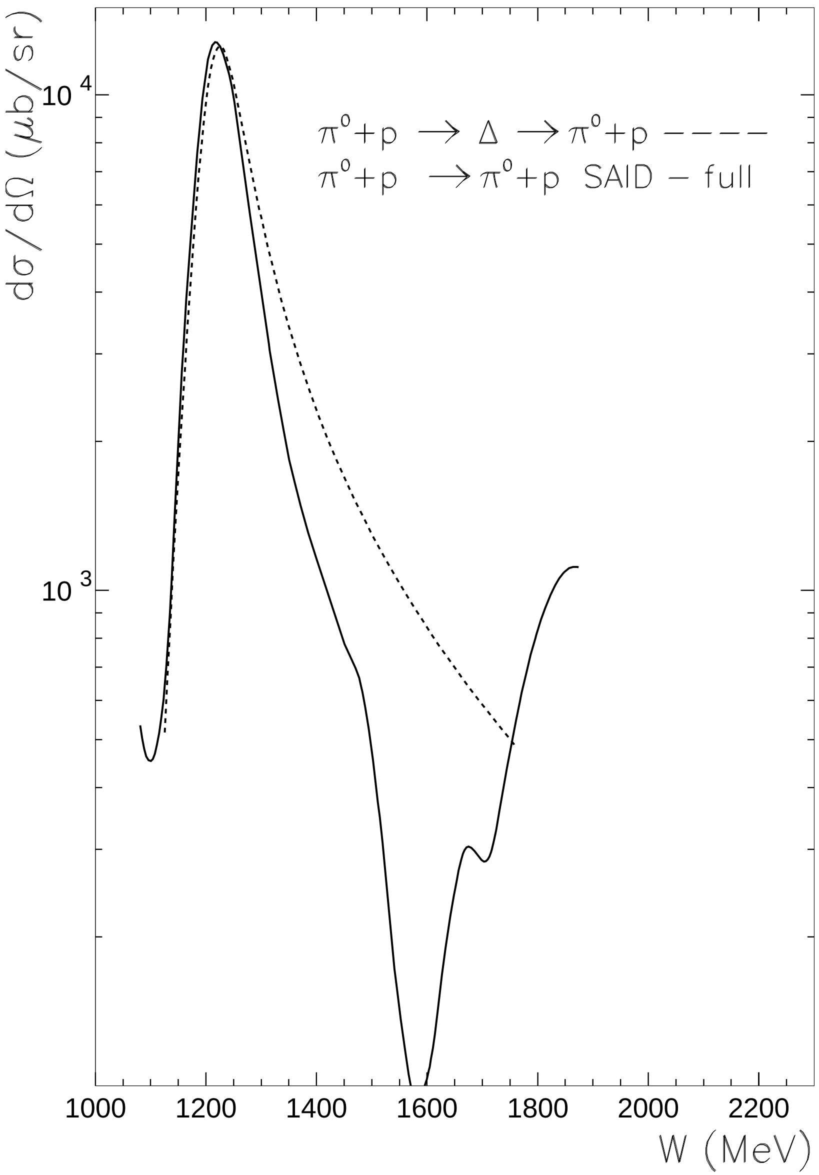
$$\times \int_0^{k^{max}} dk \frac{2k^2}{\sqrt{m_p^2 + k^2}} \left\{ |J^{\mu=0}(Q)|^2 + 2|J^{\mu=1}(Q)|^2 \right\} \frac{d\sigma}{d\Omega}_{\phi}(\pi^0 p \to \pi^0 p) \tag{13}$$

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

$$k_\pi^2 = 2m_p^2 + p_i p_f \cos\theta - \sqrt{m_p^2 + p_i^2}\sqrt{M_{pp}^2 + p_f^2}, \tag{14}$$

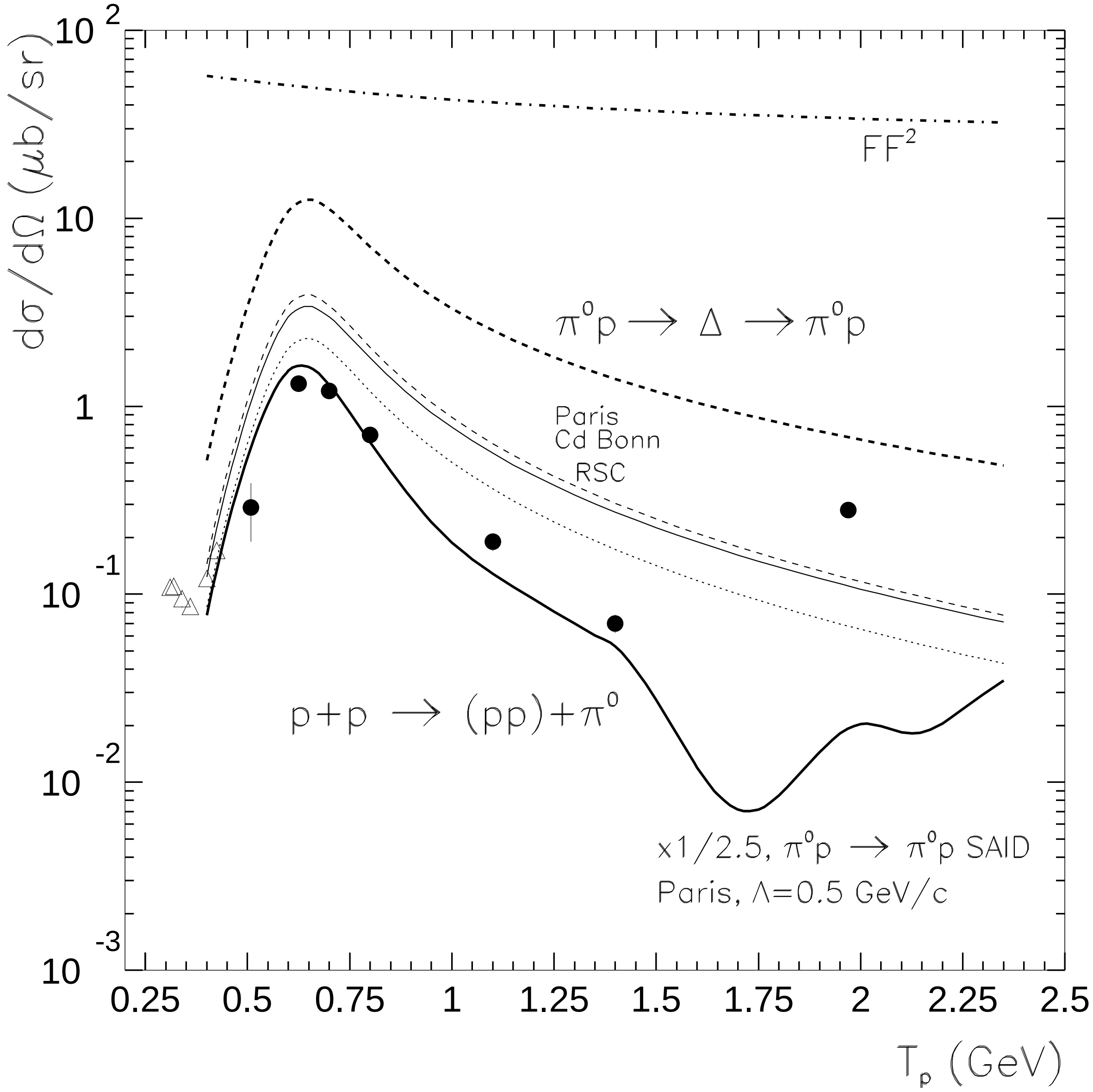
M_{pp} – mass of the diproton. $\Lambda = 0.5$ GeV/c from fit by O.Imambekov, Yu.N.Uzikov Yad.Fiz. (1988) to the $pp \to pn\pi^+$ LAMPF data at 800 MeV in the Δ-region

$\pi^0 p \to \Delta(1232) \to \pi^0 p$



$\pi^0 p \to \pi^0 p$; via Δ mechanism (dashed) and from SAID (full)

The OPE results with $\pi^0 p \to \Delta(1232) \to \pi^0 p$



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

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

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

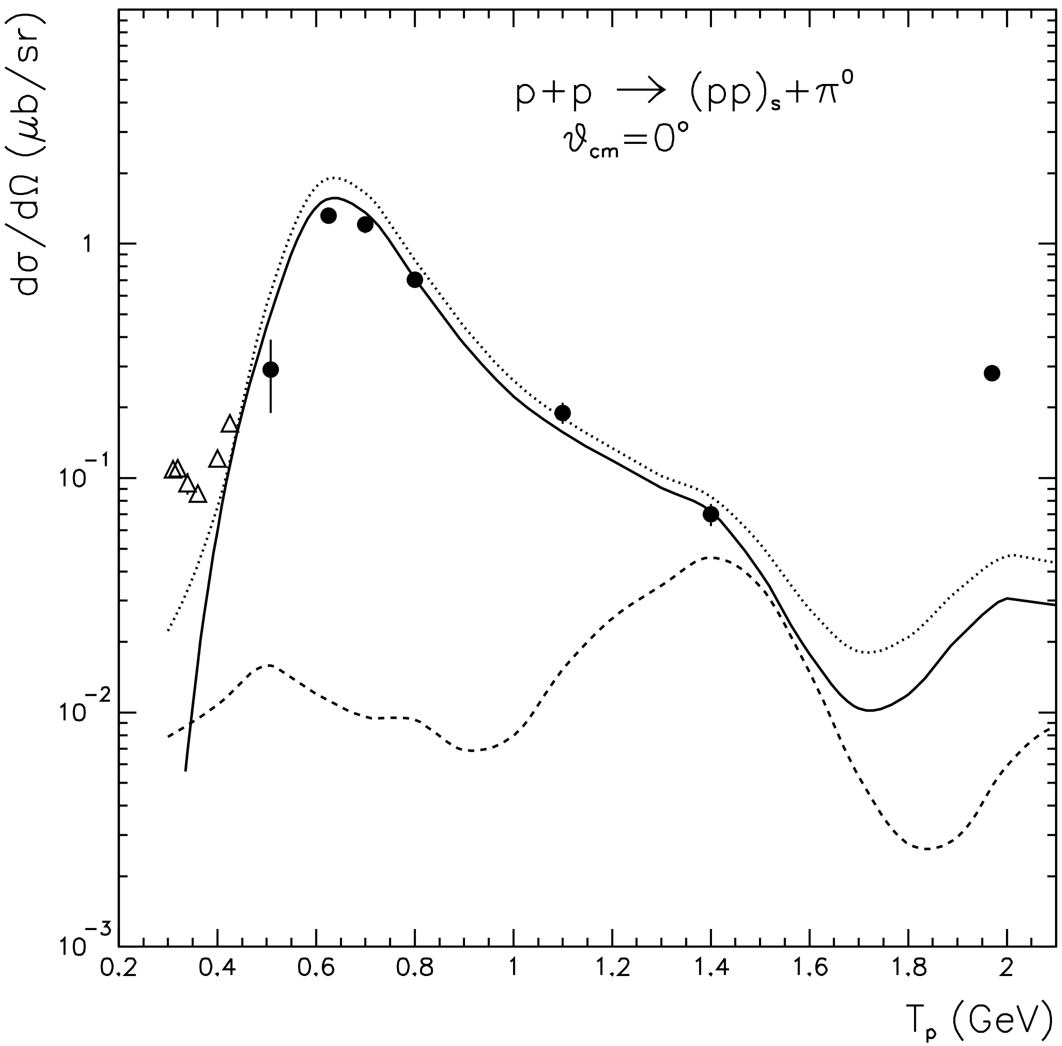
$$\mathbf{A}(\pi^{\mathbf{0}}\mathbf{p} \to \pi^{\mathbf{0}}\mathbf{p}) = \frac{\mathbf{1}}{\mathbf{3}}\Big(\mathbf{a}_{\frac{1}{2}} + \mathbf{2a}_{\frac{3}{2}}\Big), \tag{15}$$

$$\mathbf{d}\sigma(\pi^{\mathbf{0}}\mathbf{p} \to \pi^{\mathbf{0}}\mathbf{p}) = \frac{\mathbf{1}}{\mathbf{2}}\Big\{\mathbf{d}\sigma(\pi^{+}\mathbf{p}) + \mathbf{d}\sigma(\pi^{-}\mathbf{p}) - \mathbf{d}\sigma(\pi^{\mathbf{0}}\mathbf{n} \to \pi^{-}\mathbf{p})\Big\}, \tag{16}$$

If the amplitude $a_{\frac{3}{2}}$ is excluded from Eq. (15)

$$\mathbf{d}\widetilde{\sigma}(\pi^{\mathbf{0}}\mathbf{p} \to \pi^{\mathbf{0}}\mathbf{p}) = \frac{\mathbf{1}}{\mathbf{18}}\Big\{\mathbf{3d}\sigma(\pi^{-}\mathbf{p}) - \mathbf{d}\sigma(\pi^{+}\mathbf{p}) + \mathbf{3d}\sigma(\pi^{\mathbf{0}}\mathbf{n} \to \pi^{-}\mathbf{p})\Big\}. \tag{17}$$

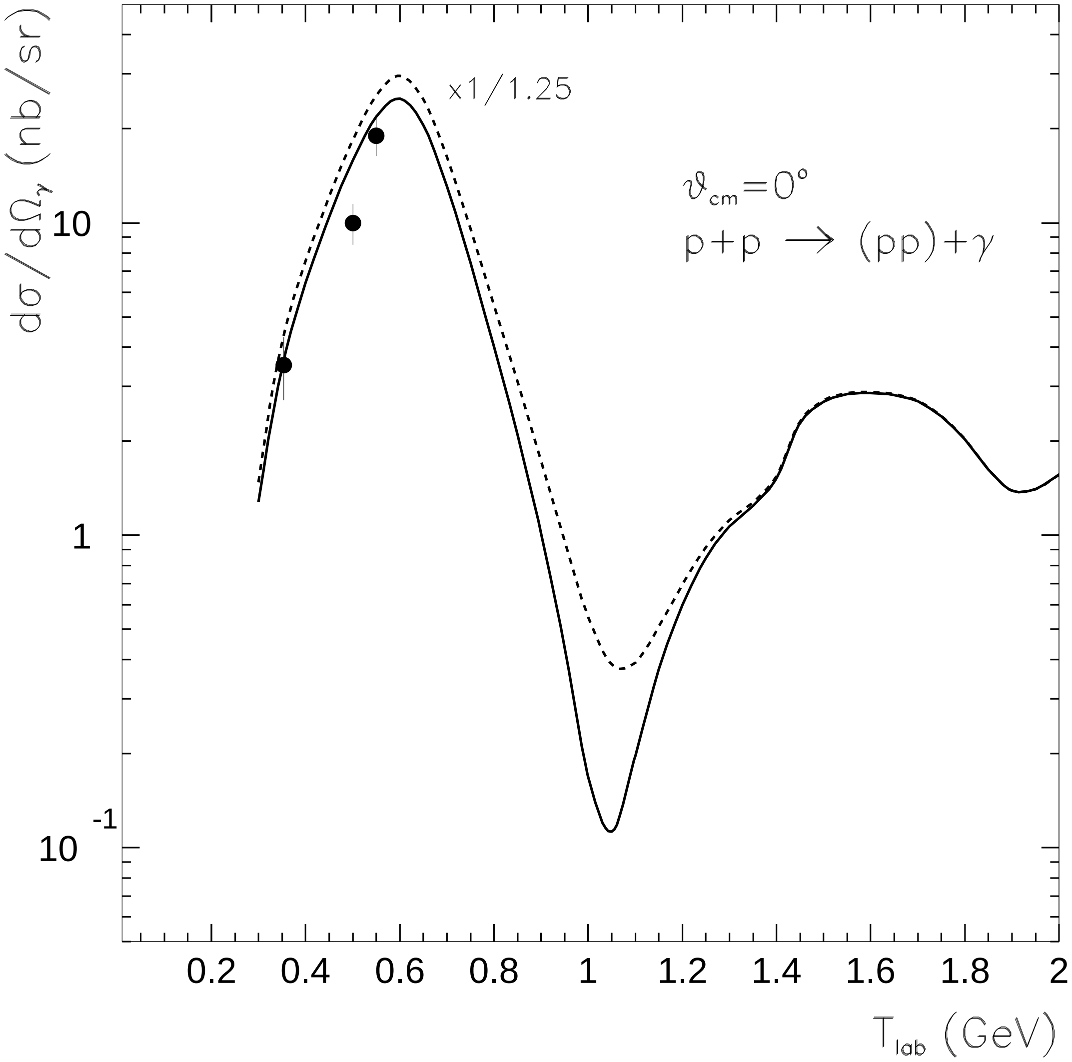
The OPE results with and whithout $\Delta(1232)$



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

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

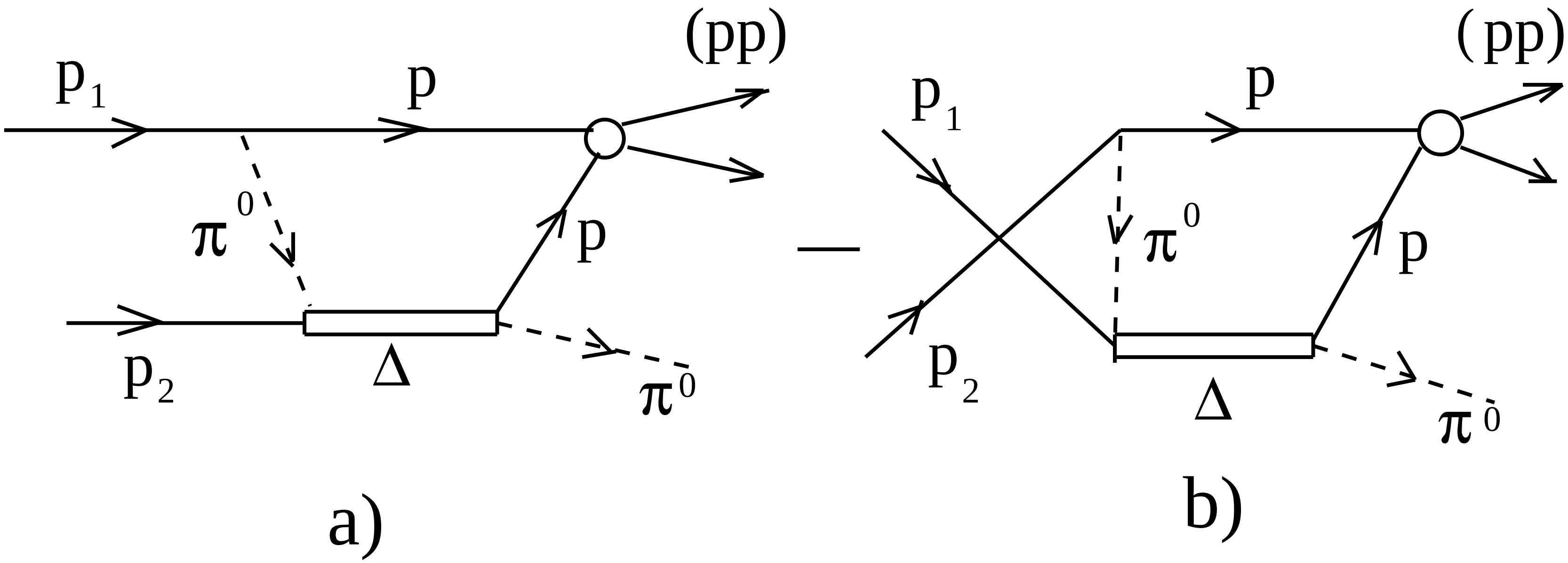
OPE: $pp \to \{pp\}_s\gamma$



V. Komarov et al., PRL (2008)

COSY data • –

The BOX-diagramm with Δ for $p\pi^0 \to p\pi^0$



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

$$\times\int \frac{F_{\pi NN}(k_\pi^2)}{(m_\pi^2 - k_{\pi_a}^2 - i\varepsilon)}\frac{F_{\pi N\Delta}(k_\pi^2)}{(m_\Delta^2 - k_{\Delta_a}^2 - im_\Delta\Gamma)}\frac{<\Psi_k^{(-)} \mid V(^1S_0) \mid \mathbf{q}>}{(k_{pp}^2 - q^2 + i\varepsilon)}\frac{d^3\vec{q}}{(2\pi)^3} \qquad (18)$$

In progress!

Conclusion

- Comparison of d- and $\{pp\}_s$- channels is very instructive.

- The OPE is an initial step of analysis,
explains the shape of $d\sigma/d\Omega(0^\circ)$ for $pp \to \{pp\}_s\pi^0$ and roughly its absolute value at 0.5-1.5 GeV

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

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

- Outlook: explicite Δ consideration + ONE$\Longrightarrow$
$\Longrightarrow A_y$, $C_{x,x}$? $\quad pn \to \{pp\}_s\pi^-$