# Interaction of real and virtual $N\bar{N}$ pairs in $J/\psi$ decays

Sergey Salnikov

Budker Institute of Nuclear Physics
Novosibirsk, Russia

International Conference on Exotic Atoms and Related Topics - EXA2017

September 13, 2017

# Outline

- Motivation.
- Interaction of $N\bar{N}$ pairs produced in $e^+e^-$ annihilation.
- $p\bar{p}$ interaction in the decays $J/\psi \to p\bar{p}\pi^0$ and $J/\psi \to p\bar{p}\eta$.
- $p\bar{p}$ interaction in the decays $J/\psi \to p\bar{p}\omega$, $J/\psi \to p\bar{p}\rho$ and $J/\psi \to p\bar{p}\gamma$.
- Interaction of virtual $N\bar{N}$ pairs in the decay $J/\psi \to \gamma\eta'\pi^+\pi^-$.

# Motivation

- There are several optical potential models describing $N\bar{N}$ interaction at low energies.
- The parameters of the models were obtained by fitting the experimental data for scattering of unpolarized particles.
- The predictions for some spin-dependent observables are essentially different.

# Motivation

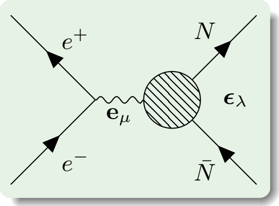
- There are several optical potential models describing $N\bar{N}$ interaction at low energies.
- The parameters of the models were obtained by fitting the experimental data for scattering of unpolarized particles.
- The predictions for some spin-dependent observables are essentially different.

$$\Downarrow$$

**Idea**

Try to include other available experimental data in fitting procedures.

# $N\bar{N}$ production near the threshold




Possible states of $N\bar{N}$ pair: ${}^3S_1$ and ${}^3D_1$, $I = 0, 1$

$$T^I_{\lambda\mu} = \frac{4\pi\alpha}{Q^2} \cdot G^I_s \left\{ \sqrt{2}\, u^I_{1R}(0)(\boldsymbol{e}_\mu \cdot \boldsymbol{\epsilon}^*_\lambda) + u^I_{2R}(0) \left[ (\boldsymbol{e}_\mu \cdot \boldsymbol{\epsilon}^*_\lambda) - 3(\hat{\boldsymbol{p}} \cdot \boldsymbol{e}_\mu)(\hat{\boldsymbol{p}} \cdot \boldsymbol{\epsilon}^*_\lambda) \right] \right\}$$

$$G^I_M = G^I_s \left[ u^I_{1R}(0) + \frac{1}{\sqrt{2}} u^I_{2R}(0) \right], \qquad \frac{2M}{Q} G^I_E = G^I_s \left[ u^I_{1R}(0) - \sqrt{2}\, u^I_{2R}(0) \right]$$

$$\sigma^I = \frac{2\pi\beta\alpha^2}{Q^2} \left| G^I_s \right|^2 \left[ \left| u^I_{1R}(0) \right|^2 + \left| u^I_{2R}(0) \right|^2 \right] \qquad \text{— "elastic" cross section}$$

## $N\bar{N}$ contribution to the total hadronic cross section

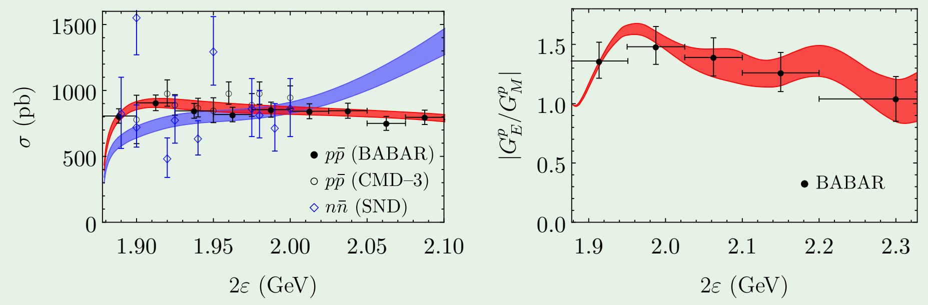
$$\sigma^I_{tot} = -\frac{2\pi\alpha^2}{M^2 Q^2} \left| G^I_s \right|^2 \mathrm{Sp} \left[ \mathrm{Im}\, \mathcal{D}(0, 0|E) \right] \qquad \text{— "total"}$$

- Valid also below the $N\bar{N}$ threshold

# Simple potential model of $N\bar{N}$ interaction

- Only partial waves $^3S_1$ and $^3D_1$ are considered.
- Long-range pion-exchange potential and short-range potential well.
- Experimental data for $N\bar{N}$ scattering (elastic, charge-exchange $p\bar{p} \leftrightarrow n\bar{n}$ and annihilation), $p\bar{p}$ and $n\bar{n}$ production in $e^+e^-$ annihilation, ratio of electromagnetic form factors of the proton $|G_E^p/G_M^p|$ are taken into account.

Cross sections of $e^+e^- \to p\bar{p}$ and $e^+e^- \to n\bar{n}$ and the ratio $|G_E^p/G_M^p|$

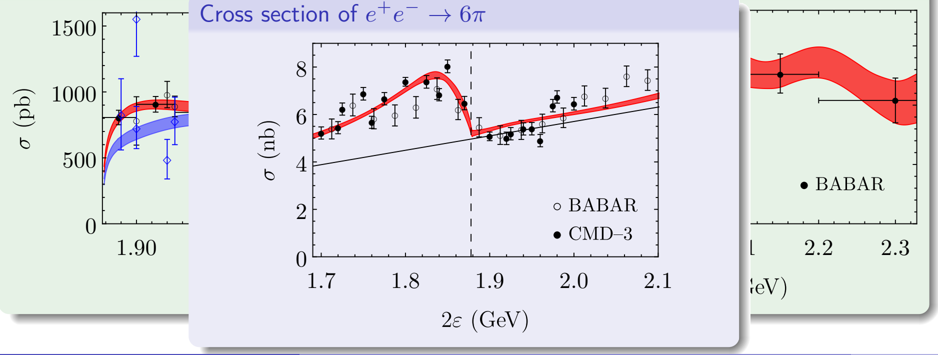


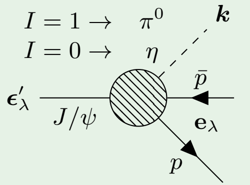
# Simple potential model of $N\bar{N}$ interaction

- Only partial waves $^3S_1$ and $^3D_1$ are considered.
- Long-range pion-exchange potential and short-range potential well.
- Experimental data for $N\bar{N}$ scattering (elastic, charge-exchange $p\bar{p} \leftrightarrow n\bar{n}$ and annihilation), $p\bar{p}$ and $n\bar{n}$ production in $e^+e^-$ annihilation, ratio of electromagnetic form factors of the proton $|G_E^p/G_M^p|$ are taken into account.

Cross sections of $e^+e^- \to p\bar{p}$ and $e^+e^- \to n\bar{n}$ and the ratio $|G_E^p/G_M^p|$

Cross section of $e^+e^- \to 6\pi$






${}^3S_1 - {}^3D_1$ states dominate near the threshold of $p\bar{p}$ production, as in the case of $e^+e^- \to N\bar{N}$

$$T^I_{\lambda\lambda'} = \frac{\mathcal{G}_I}{m_{J/\psi}} \left[\boldsymbol{k} \times \boldsymbol{\epsilon}_{\lambda'}\right] \left(\mathbf{e}_\lambda u^I_1(0) + \frac{u^I_2(0)}{\sqrt{2}} \left[\mathbf{e}_\lambda - 3\hat{\boldsymbol{p}}(\mathbf{e}_\lambda \cdot \hat{\boldsymbol{p}})\right]\right)$$

$p\bar{p}$ invariant mass spectrum: $$\frac{d\Gamma}{dM} = \frac{\mathcal{G}_I^2 p k^3}{2^5\, 3\pi^3 m^4_{J/\psi}} \left(\left|u^I_1(0)\right|^2 + \left|u^I_2(0)\right|^2\right)$$

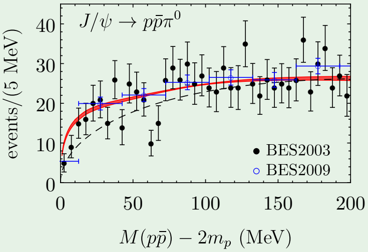
## Angular distributions

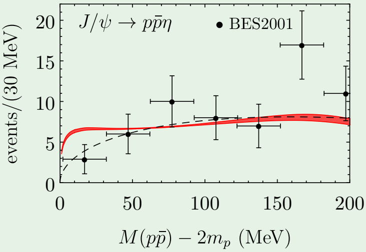
$$\frac{d\Gamma}{dM\, d\Omega_p} = \frac{1}{4\pi}\frac{d\Gamma}{dM}\left[1 + \gamma^I P_2(\cos\vartheta_p)\right], \qquad \frac{d\Gamma}{dM\, d\Omega_{pk}} = \frac{1}{4\pi}\frac{d\Gamma}{dM}\left[1 - 2\gamma^I P_2(\cos\vartheta_{pk})\right]$$

Anisotropy parameter: $$\gamma^I = \frac{1}{4}\frac{\left|u^I_2(0)\right|^2 - 2\sqrt{2}\,\mathrm{Re}\left[u^I_1(0) u^{I*}_2(0)\right]}{\left|u^I_1(0)\right|^2 + \left|u^I_2(0)\right|^2}$$

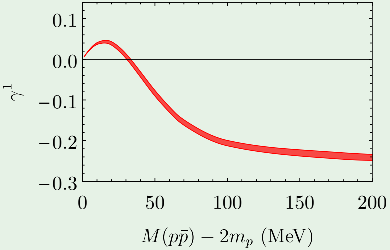
# Spectra of decays $J/\psi \to p\bar{p}\pi^0(\eta)$

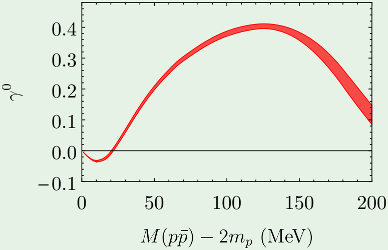
## $p\bar{p}$ invariant mass spectra in $J/\psi$ decays



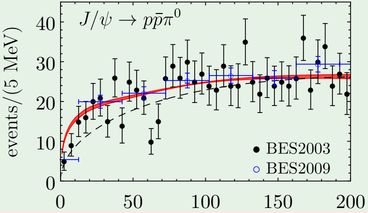

## Anisotropy parameters in $J/\psi$ decays

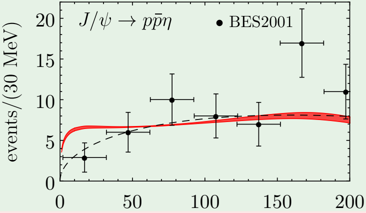


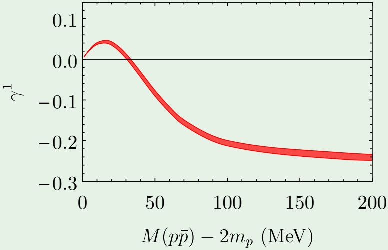
# Spectra of decays $J/\psi \to p\bar{p}\pi^0(\eta)$

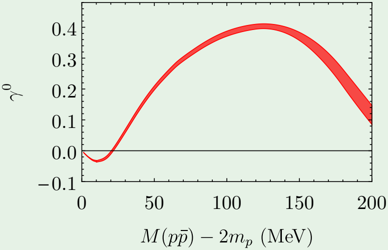
## $p\bar{p}$ invariant mass spectra in $J/\psi$ decays

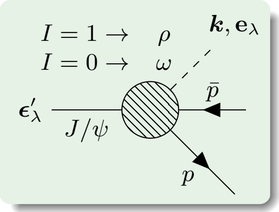



There are no experimental data for the angular distributions in $J/\psi$ decays near the threshold of $p\bar{p}$ production






$^1S_0$ state dominates near the threshold of $p\bar{p}$ production

$$T^I_{\lambda\lambda'} = \frac{\mathcal{G}_I}{m_{J/\psi}} \mathbf{e}_\lambda \left[\boldsymbol{k} \times \boldsymbol{\epsilon}_{\lambda'}\right] \psi^I_R(0)$$

$$\frac{d\Gamma}{dM} = \frac{\mathcal{G}_I^2 p k^3}{2^4\, 3\pi^3 m^4_{J/\psi}} \left|\psi^I_R(0)\right|^2$$

## Simple potential model

- Only partial wave $^1S_0$ is considered.
- The potential is a sum of potentials of isoscalar and isovector exchange

$$V(r) = V_0(r) + V_1(r)\,(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)$$

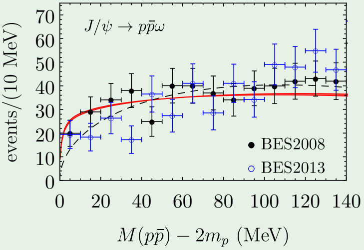
$$V_0(r) = (U_0 - i\,W_0)\,\theta\,(a_0 - r)$$

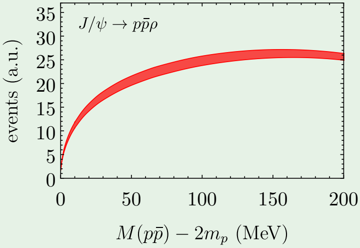
$$V_1(r) = (U_1 - i\,W_1)\,\theta\,(a_1 - r) \quad + \quad 3 f_\pi^2 \frac{e^{-m_\pi r}}{3r} \theta\,(r - a_1)$$

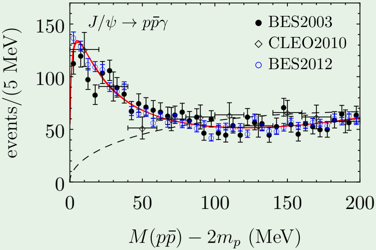
- Experimental data for $N\bar{N}$ scattering (elastic, charge-exchange $p\bar{p} \leftrightarrow n\bar{n}$ and annihilation) and spectra of the $J/\psi$ decays taken into account.

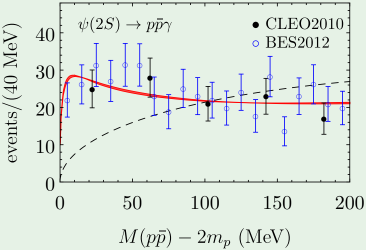
# Spectra of decays $J/\psi \to p\bar{p}\omega(\rho, \gamma)$

## $p\bar{p}$ invariant mass spectra in $J/\psi$ decays

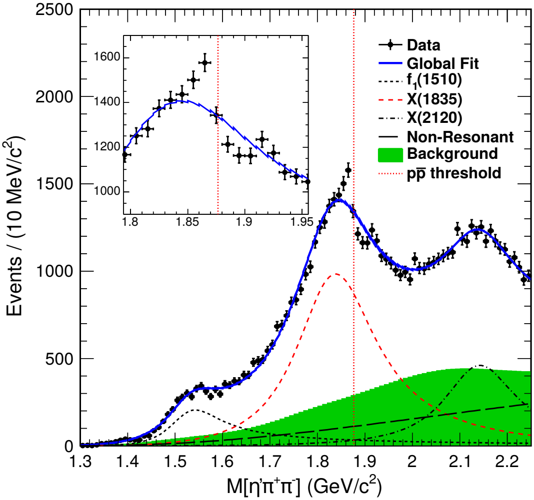


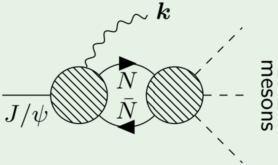



# Decay $J/\psi \to \gamma\eta'\pi^+\pi^-$




M. Ablikim, et al., Phys. Rev. Lett. 117 (2016) 42002

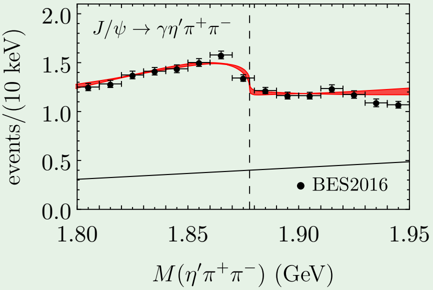
# Decay $J/\psi \to \gamma\eta'\pi^+\pi^-$




$$\frac{d\Gamma_{\rm tot}}{dM} = -\frac{\mathcal{G}_I^2 k^3}{2^4\, 3\pi^3 m_p m_{J/\psi}^4}\,\mathrm{Im}\,\mathcal{D}^I\,(0,\,0|E) \quad = \frac{d\Gamma_{\rm el}}{dM} + \frac{d\Gamma_{\rm inel}}{dM}\,,$$

$$\mathcal{D}^I\,(r,\,r'|E) = -m_p p\left[\theta\,(r'-r)\,\psi_R^I(r)\psi_N^I(r') + \theta\,(r-r')\,\psi_N^I(r)\psi_R^I(r')\right]$$

## $\eta'\pi^+\pi^-$ invariant mass spectrum




The spectrum is approximated by the curve

$$\underbrace{A\cdot\frac{d\Gamma^0_{\rm inel}}{dM}}_{N\bar{N}\ \text{contribution}} + \underbrace{B\cdot M + C}_{\text{other contributions}}$$

$A$ — probability of $N\bar{N} \to \eta'\pi^+\pi^-$

# Conclusion

- The idea: try to use all available experimental data to fit the parameters of the models.
- The $p\bar{p}$ invariant mass spectra in the decays $J/\psi \to p\bar{p}\pi^0$ and $J/\psi \to p\bar{p}\eta$ are described with the help of a simple potential model.
- The predictions for the angular distributions in these decays are obtained. The experimental measurement would be helpful.
- The $p\bar{p}$ invariant mass spectra in the decays $J/\psi \to p\bar{p}\omega$, $J/\psi \to p\bar{p}\gamma$ and $\psi(2S) \to p\bar{p}\gamma$ are described.
- The peak in the spectrum of the decay $J/\psi \to \gamma\eta'\pi^+\pi^-$ is described by $N\bar{N}$ interaction in the intermediate state.

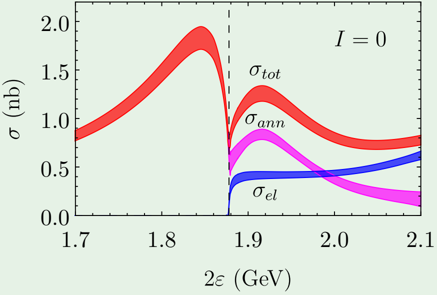
## Publications

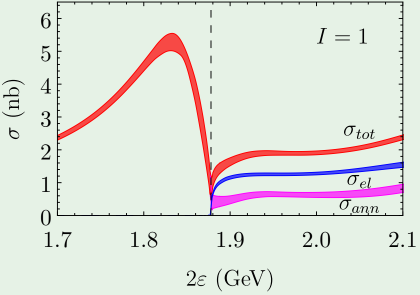

- V.F. Dmitriev, A.I. Milstein, and S.G. Salnikov, Phys. Rev. D 93 (2016) 034033.
- V.F. Dmitriev, A.I. Milstein, and S.G. Salnikov, Phys. Lett. B. 760 (2016) 139.
- A. I. Milstein, and S. G. Salnikov, Nucl. Phys. A. 966 (2017) 54.

Thank you for attention

# $S = 1$

**Total, *elastic* and inelastic $N\bar{N}$ contributions**



# $S = 0$

## Total, *elastic* and inelastic $N\bar{N}$ contributions