

J/ ψ production in N-N collisions at threshold

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- Generalities
- np versus pp collisions
 - spin structure
 - polarization phenomena
 - cross section
- Conclusions

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Interest of charmed particle production at threshold

- Threshold physics, similar to π , ϕ , K ... production.
- Large masses: applicability of pQCD for relatively small W (total energy) ?
- General symmetry principles applicable in hot, dense matter?

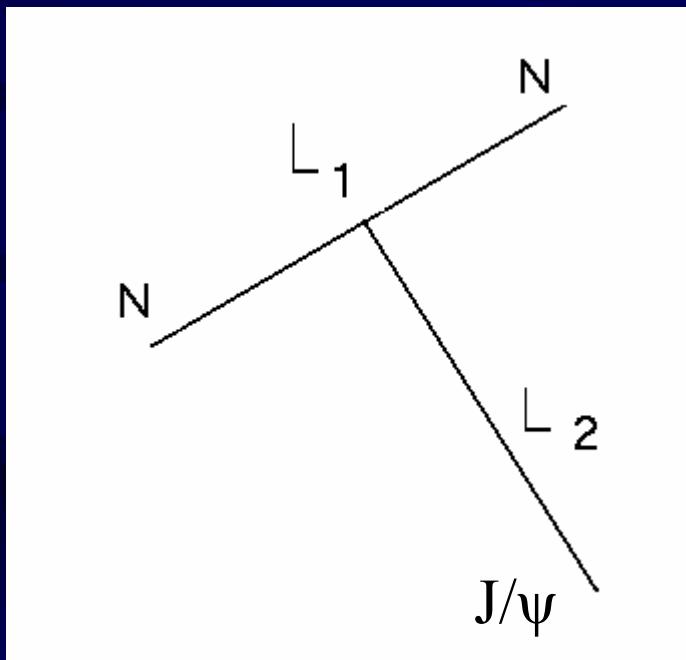
The reaction $N+N \rightarrow N+N+J/\psi$

- Belongs to $N+N \rightarrow N+N+V^0$, with $V^0 = \omega, \phi, J/\psi \dots$
- Near-threshold physics
- Signatures for quark-gluon plasma:
 - J/ψ suppression
 - strangeness excess
- Large isotopic effects
 - $p+p \rightarrow p+p+J/\psi$
 - $n+p \rightarrow n+p+J/\psi$

Definition of threshold region

- $N + N \rightarrow N + N + J/\psi$: all final particles are in relative S-state:

$$L_1 = L_2 = 0$$



The spin structure for pp



$$1/2^+ \ 1/2^+ \rightarrow 1/2^+ \ 1/2^+ \ 1^-$$

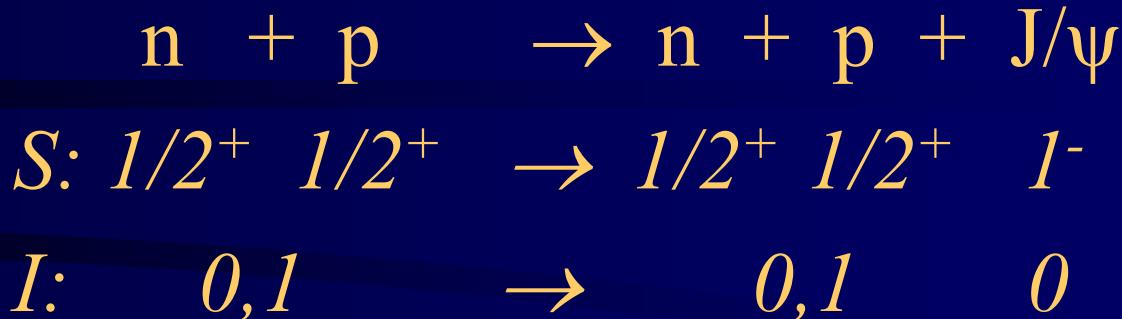


$$L_I = 0 \ S_f = 0 \quad \text{wavy line}$$

$$S_i = 1, \ \ell_i = 1, \rightarrow \mathcal{J}^P = 1^- \rightarrow S_f = 0 \quad L_2 = 0$$

$$\mathcal{M}(pp) = 2f_{10}(\tilde{\chi}_2 \ \sigma_y \ \vec{\sigma} \cdot \vec{U}^* \times \hat{\vec{k}}\chi_1) \ (\chi_4^\dagger \sigma_y \ \tilde{\chi}_3^\dagger)$$

The spin structure for np



$$S_i = 1, \ \ell_i = 1, \rightarrow \mathcal{J}^P = 1^- \rightarrow S_f = 0$$

$I=1: L_1 = 0, S_f = 0$ (as $pp : f_{10}$)

$$S_i = 0, \ \ell_i = 1, \rightarrow \mathcal{J}^P = 1^- \rightarrow S_f = 1$$

$I=0: L_1 = 0, S_f = 1$ (new: f_{01})

$$\begin{aligned}
 \mathcal{M}(np) = & \ f_{10}(\tilde{\chi}_2 \ \sigma_y \ \vec{\sigma} \cdot \vec{U}^* \times \hat{\vec{k}}\chi_1) (\chi_4^\dagger \sigma_y \ \tilde{\chi}_3^\dagger) + \\
 & f_{01}(\tilde{\chi}_2 \ \sigma_y \chi_1)(\chi_4^\dagger \vec{\sigma} \cdot \vec{U}^* \times \hat{\vec{k}}\sigma_y \chi_3^\dagger)
 \end{aligned}$$

The J/ ψ polarization

$$\mathcal{M}(np) = f_{10}(\tilde{\chi}_2 \sigma_y \vec{\sigma} \cdot \vec{U}^* \times \hat{\vec{k}}\chi_1) (\chi_4^\dagger \sigma_y \tilde{\chi}_3^\dagger) + \\ f_{01}(\tilde{\chi}_2 \sigma_y \chi_1) (\chi_4^\dagger \vec{\sigma} \cdot \vec{U}^* \times \hat{\vec{k}}\sigma_y \chi_3^\dagger)$$

The J/ ψ polarization vector U has to be orthogonal to k, therefore the decay products for

$$J/\psi \rightarrow \mu^+ + \mu^-$$

must have a $(1+\cos^2\theta)$ -dependence.

For p+p, n+p, therefore for nucleus-nucleus collisions!

Ratio of cross sections

All observables can be calculated in terms of the two amplitudes

- The ratio of *unpolarized np- and pp-* cross sections

$$\mathcal{R} = \frac{\sigma(np \rightarrow npV^0)}{\sigma(pp \rightarrow ppV^0)} = \frac{1}{2} + \frac{1|f_{01}|^2}{2|f_{10}|^2}$$

Polarized nucleons

- The polarized cross section

$$\frac{d\sigma}{d\omega}(\vec{P}_1, \vec{P}_2) = \left(\frac{d\sigma}{d\omega} \right)_0 \left(1 + \mathcal{A}_1 \vec{P}_1 \cdot \vec{P}_2 + \mathcal{A}_2 \hat{\vec{k}} \cdot \vec{P}_1 \hat{\vec{k}} \cdot \vec{P}_2 \right)$$

- $\vec{p} + \vec{p} \rightarrow p + p + V^0$: $\mathcal{A}_1(pp) = 0$, $\mathcal{A}_2(pp) = 1$.

- $\vec{n} + \vec{p} \rightarrow n + p + V^0$: $\mathcal{A}_1(np) = -\frac{|f_{01}|^2}{|f_{01}|^2 + |f_{10}|^2}$,

$$\mathcal{A}_2(np) = \frac{|f_{10}|^2}{|f_{01}|^2 + |f_{10}|^2}$$

$$-\mathcal{A}_1(np) + \mathcal{A}_2(np) = 1, \quad 0 \leq \mathcal{A}_2(np) \leq 1$$

Polarization observables

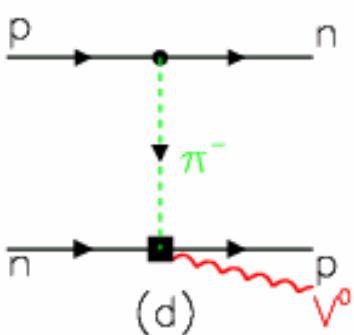
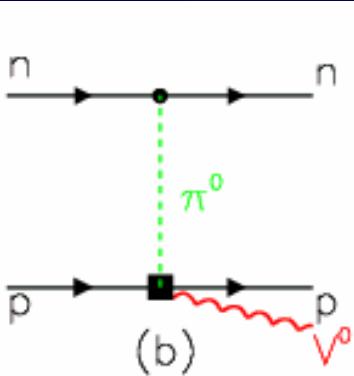
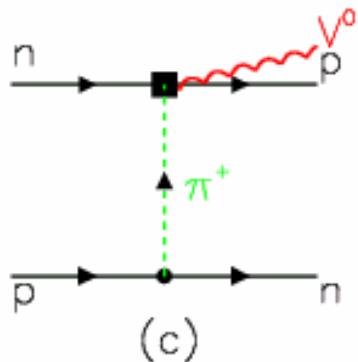
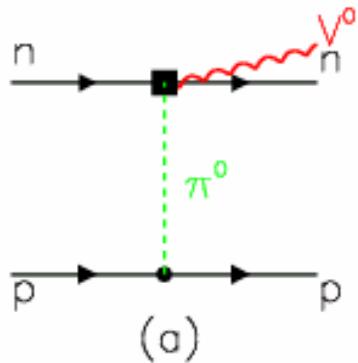
- The polarization transfer

$$\mathcal{P}_f = p_1 \vec{P}_1 + p_2 \hat{\vec{k}} (\hat{\vec{k}} \cdot \vec{P}_1)$$

$$p_1(np) = -p_2(np) = \frac{2\mathcal{R}e f_{01} f_{10}^*}{|f_{01}|^2 + |f_{10}|^2} = \cos \delta \frac{\sqrt{2\mathcal{R}-1}}{\mathcal{R}}$$

$p_1(pp)=p_2(pp)=0$ for $p+p \rightarrow p+p+V^0$

The t-channel dynamics



- Four pion exchange diagrams for $N+N \rightarrow N+N+J/\psi$, as well as for any other meson exchange
- All diagrams are important at threshold

The t-channel dynamics (π , η , σ - exchanges)

	$\pi(f_{01} = -3f_{10})$	$\eta(f_{01} = f_{10})$	$\sigma(f_{01} = -f_{10})$
R	5	1	1
\mathcal{A}_1	$-9/10$	$1/2$	$-1/2$
\mathcal{P}_1	$-3/5$	-1	1

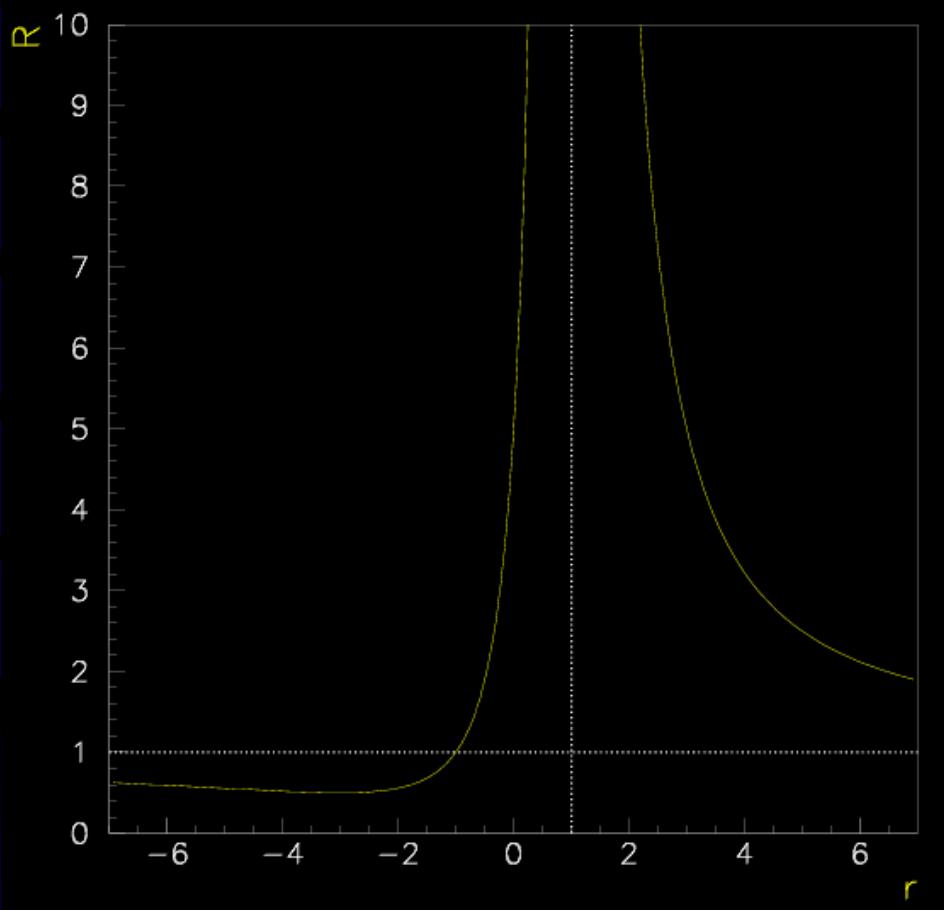
A “realistic model” : $\pi + \eta$ -exchange

$$F_{10}(np) = -A_\pi(1-r)$$

$$F_{01}(np) = -A_\pi(3+r)$$

- The parameter r characterizes the relative role of π and η -exchange in $p+n \rightarrow p+n+J/\psi$.
- Generally r is a complex parameter

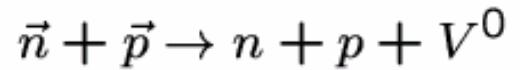
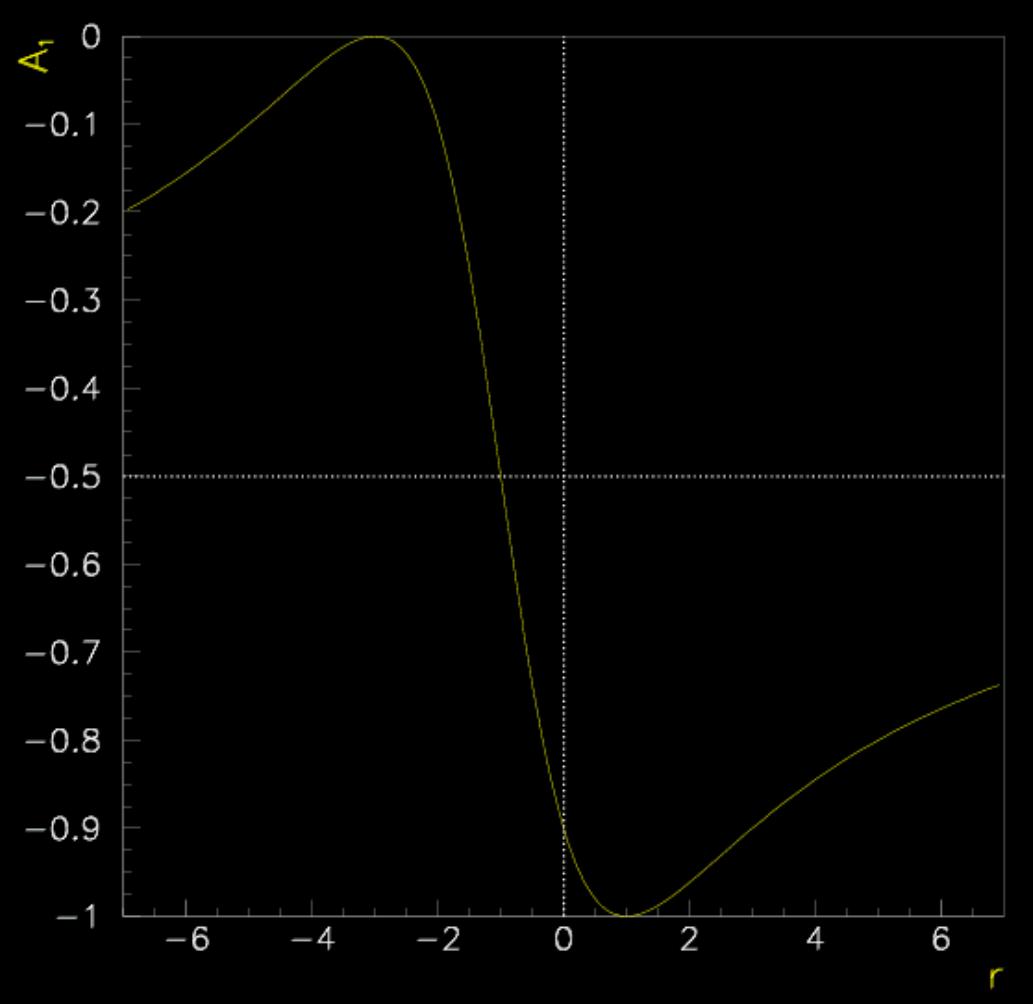
The reaction $N+N \rightarrow N+N+J/\psi$



$$\mathcal{R} = \frac{\sigma(np \rightarrow npV)}{\sigma(pp \rightarrow ppV)} = \frac{5 + 2\Re e r + |r|^2}{|1 - r|^2}$$

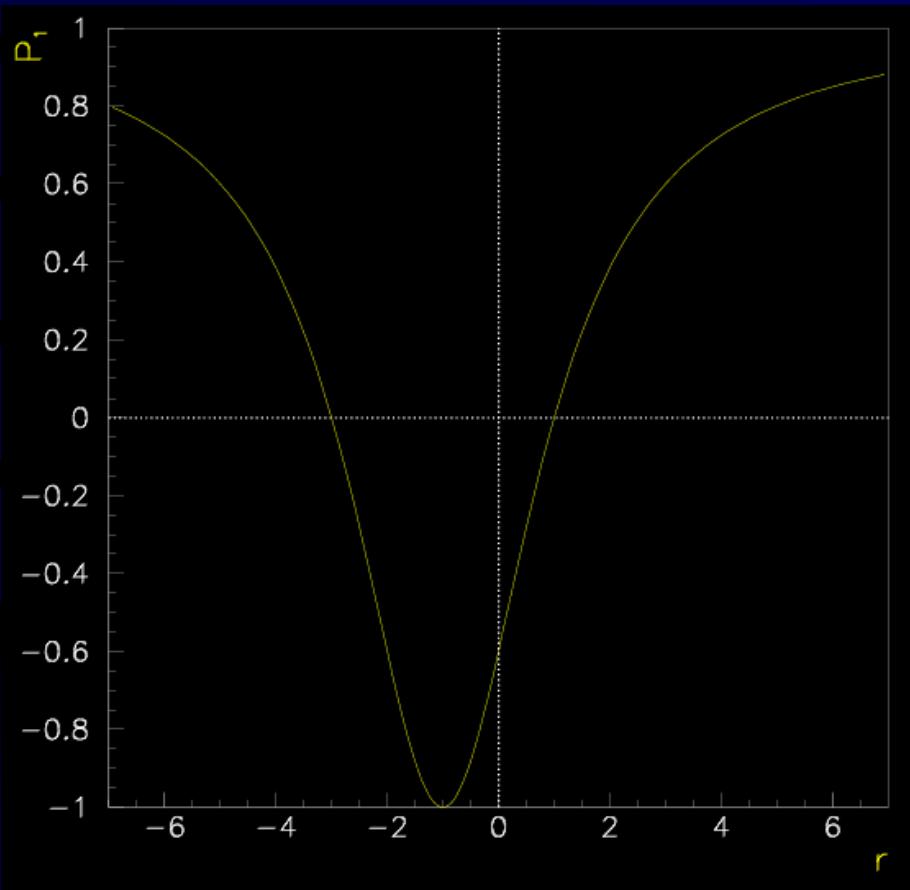
where r is the ratio of $\eta+N \rightarrow N+ V^0$
and $\pi+N \rightarrow N+ V^0$ threshold amplitudes

Correlation polarization coefficient



$$A_1 = -\frac{9 + 6\Re e r + |r|^2}{2(5 + 2\Re e r + |r|^2)}$$

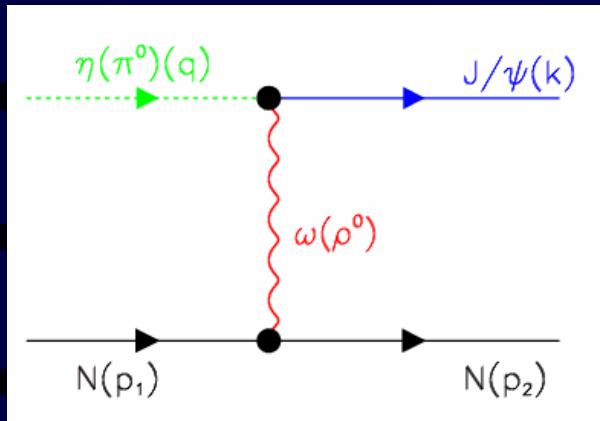
Polarization transfer coefficient



$n + \vec{p} \rightarrow n + \vec{p} + V^0 \rightarrow$ transversal polarization

$$\mathcal{P}_1 = -\frac{3 - 2\Re e r - |r|^2}{5 + 2\Re e r + |r|^2}$$

The reaction $N+N \rightarrow N+N+J/\psi$



$$BR(J/\psi \rightarrow \rho^0 \pi^0) = (4.2 \pm 0.5) \cdot 10^{-3},$$

$$BR(J/\psi \rightarrow \omega \eta) = (1.58 \pm 0.16) \cdot 10^{-3},$$

So, in VDM approach:

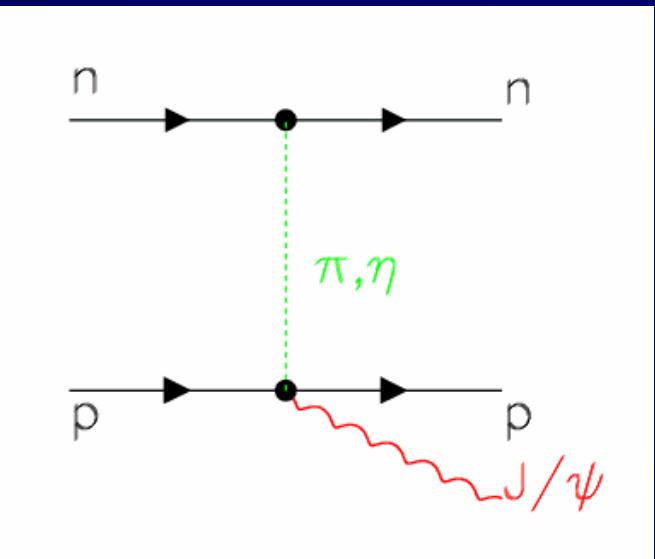
$$r = \frac{g_{\eta NN} (\mu_p + \mu_n)}{g_{\pi NN} (\mu_p - \mu_n)} \frac{g(J/\psi \rightarrow \eta \omega)}{g(J/\psi \rightarrow \pi^0 \rho^0)}$$

$$\simeq \frac{g_{\eta NN}}{g_{\pi NN}} \frac{0.88}{4.8} \sqrt{\frac{\Gamma(J/\psi \rightarrow \eta \omega)}{\Gamma(J/\psi \rightarrow \pi^0 \rho^0)}} \simeq \frac{1}{7} \left| \frac{g_{\eta NN}}{g_{\pi NN}} \right|$$

The reaction $N+N \rightarrow N+N+J/\psi$

$$BR(J/\psi \rightarrow p\bar{p}\eta) = (2.09 \pm 0.18) \cdot 10^{-3},$$

$$BR(J/\psi \rightarrow p\bar{n}\pi^-) = (2.00 \pm 0.10) \cdot 10^{-3},$$



$J/\psi \rightarrow p\bar{p}\eta \leftrightarrow \eta + p \rightarrow p + J/\psi$ (crossed process)

$$r = \frac{g_{\eta NN}}{g_{\pi NN}} \frac{(t - m_\pi^2)}{(t - m_\eta^2)} \left[\frac{BR(J/\psi \rightarrow N\bar{N}\eta)}{BR(J/\psi \rightarrow N\bar{N}\pi^-)} \right]^{1/2} \simeq \frac{g_{\eta NN}}{g_{\pi NN}} < 1$$

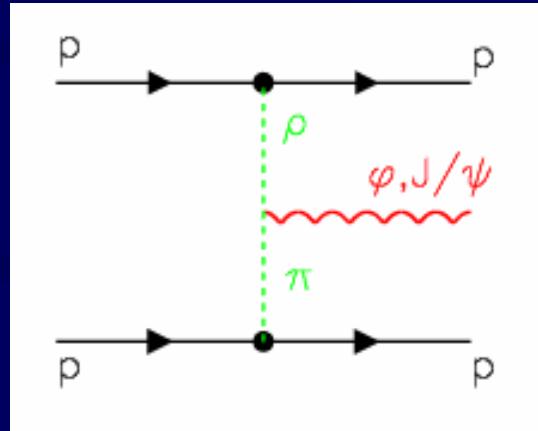
The reaction N+N→N+N+J/ψ

Estimation of cross section

$$R(J/\psi, \phi) = \frac{\sigma(pp \rightarrow ppJ/\psi)}{\sigma(pp \rightarrow pp\phi)} \simeq$$

$$\frac{g^2(J/\psi \rightarrow \pi\rho)}{g^2(\phi \rightarrow \pi\rho)} \left(\frac{t_\phi - m_\pi^2}{t_{J/\psi} - m_\pi^2} \right)^2 \left[\frac{F(t_{J/\psi})}{F(t_\phi)} \right]^2 =$$

$$10^{-5} \left[\frac{F(t_{J/\psi})}{F(t_\phi)} \right]^2$$



$\sigma_{exp}(pp \rightarrow pp\phi) \sim 300 \text{ nb at } p_L = 3.67 \text{ GeV}$
F. Balestra et al., PRC 63, 024004 (2001)

$$F_V(t) = \frac{1}{1 - \frac{t}{\Lambda_V^2}} \text{ with } \Lambda_V \simeq m_V$$

$$\sigma_{th}(pp \rightarrow ppJ/\psi) \simeq 0.03 \text{ nb} \left[\frac{F(t_{J/\psi})}{F(t_\phi)} \right]^2$$

$$\sigma_{exp}(pp \rightarrow ppJ/\psi) \simeq (0.30 \pm 0.09) \text{ nb, } \sqrt{s} = 6.7 \text{ GeV}$$

$$\left[\frac{F(t_{J/\psi})}{F(t_\phi)} \right]^2 \simeq 10!$$

Conclusions

- Spin structure and polarization phenomena for $N+N \rightarrow N+N+ J/\psi$ can be predicted in model independent way.
- Strong isotopic effects.
- Polarization phenomena in np -collisions contain more information than in pp -collisions.
- P-parity in charmed particle sector.