Measurement of the cross-section $e^+e^- \longrightarrow n\bar{n}$ near threshold at SCTF

Alexander Bobrov

BINP SB RAS, NSU

Plan

1. Introduction
2. Method description
3. Simulation
4. Cross section reconstruction
5. Results
6. Summary

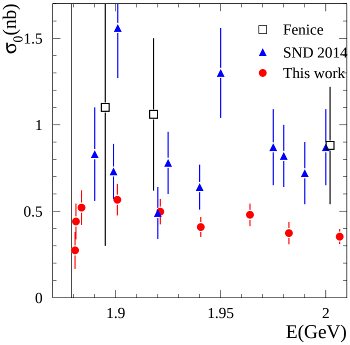
Introduction

Cross sections $e^+e^- \to N\bar{N}$ and partial widths $\frac{d\Gamma}{dm_{N\bar{N}}}$ $N\bar{N}$ system do not tend to 0 at the threshold.

The Sommerfeld-Gamow-Sakharov factor for charged particles $\sigma(s = 4m^2) = \frac{\pi^2\alpha^3}{2m^2}$

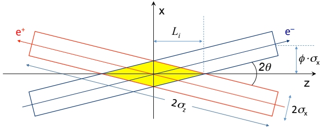
Low energy range, nonperturbative QCD.

Invariant mass resolution σ_W for reactions $e^+e^- \to N\bar{N}$ depends on the beam energy spread $\sigma_W/m_n \propto \delta E_b/E_b$, $\sigma_W \sim$ MeV.



Resent results from SND EPJ Web Conf., 212 (2019) 07007

An idea was suggested by Alexander Bondar: to reconstruct cross-section by studying the angular distribution as a beam energy and beam energy spread function.



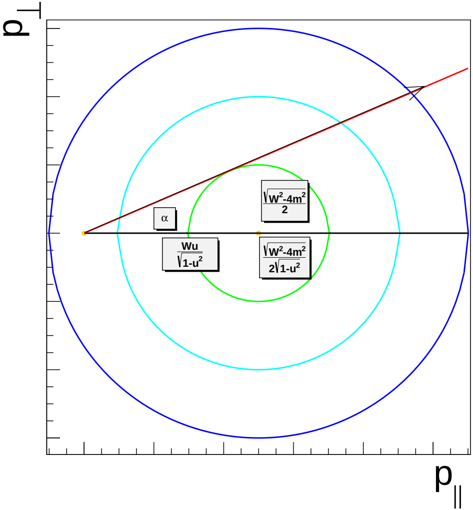
Crab Waist collision scheme
$\Theta \sim 0.05, v_{c.m.s.} = \tan\Theta \sim 0.05$

$$W = \sqrt{(P_0 + \delta P)^2} = W_0 + (P_0; \delta P_{\parallel})/W_0 + (\delta P_{\perp}^2 + \delta P_{\parallel}^2)/2W_0 =$$

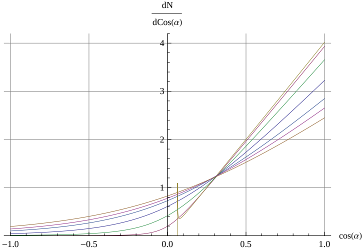
$$W_0 + (P_0; \delta P_{\parallel})/W_0 + O(\delta P^2) \; v_{c.m.s.} = \frac{P_0 + \delta P_{\parallel} + \delta P_{\perp}}{\sqrt{(P_0 + \delta P_{\parallel} + \delta P_{\perp})^2}} = v^0_{c.m.s.} + \frac{\delta P_{\perp}}{W_0}$$

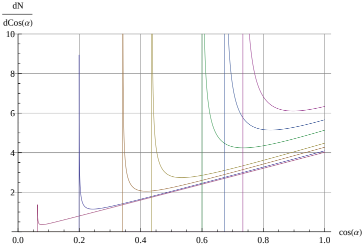
Approximation W invariant mass can vary , but velocity cannnot.
At the threshold all particles have singular angular distribution: $\delta(\vec{n} - \vec{v}/|\vec{v}|)$.

Method description



Two body decay. The ellipse equation shows momentum as a function of angle.





α is the angle between boost direction and antineutron motion direction in the lab. frame.

$\frac{dN}{d\cos\alpha}$ is calculated from Lorenz transformation (see appendix).

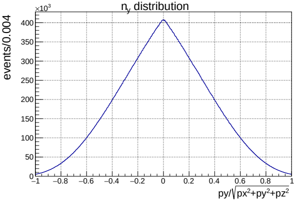
Relation between invariant mass and maximal angle:

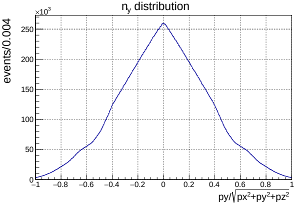
$$W = 2m_n\sqrt{1 + v^2_{c.m.s.}\sin^2\alpha_{max}/(1 - v^2_{c.m.s.})}$$

$$W = 2m_n\sqrt{1 + \sinh^2\psi\sin^2\alpha}$$

$$v_{c.m.s.} = \tanh\psi$$

Method description





If invariant mass W is less than $2m_n/\sqrt{1-v^2_{c.m.s}} = W^\star$ (critical invariant mass), there is maximum angle.

$$W = 2m_n\sqrt{1+\sinh^2\psi\sin^2\alpha}.$$

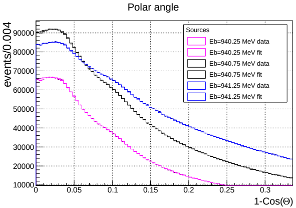
Near threshold

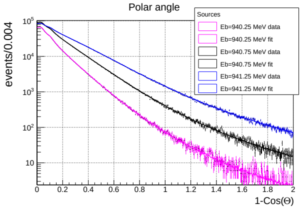
$$W = 2m_n + m_n\sinh^2\psi\sin^2\alpha =$$
$$= 2m_n + m_n\sinh^2\psi\alpha^2$$

Invariant mass resolution due to beam energy spread $\sigma_W = m_n\sinh^2\psi\sigma^2_\alpha(0)$.
$\sigma_\alpha(0)$ angular spread at $\alpha = 0$,
$\sigma_\alpha(0) = \delta p_{c.m.s.}/p_{c.m.s.} \propto \delta E_b/(E_b\sinh\psi)$.
So $\sigma_W \propto m_n(\delta E_b/E_b)^2 \sim$ keV!

Invariant mass resolution due to angular resolution $\sigma_W = m_n\sinh^2\psi\sigma^2_\alpha$
$\sigma_\alpha = 5mm/1m = 1/20$
$\sigma_W \sim m_n(1/20)^2(1/20)^2 \sim 10$ keV.

1. $\delta E_b / E_b = 10^{-3}$
2. angular dispersion 10^{-3} radian
3. Half of the beam intersection angle 0.05 radian
4. neutron antineutron angular distribution is isotropic
5. Beam energy E_b vary from 939.75 to 942.25 MeV, with step 0.25 MeV (threshold $E_b = 940.74$ MeV, $\sigma_W \sim 1.3$ MeV.)
6. Radiative correction is absent
7. Antineutron angle reconstruction is ideal
8. Antineutron/neutron time life is ∞
9. Cross section (1 nb) is simulated by the Heaviside function with step value at the energy threshold, besides cases with hypothetical resonances.





The invariant mass range was divided divided into 11/40 intervals in case of absence/presence of hypothetical resonances.

Coordinate frame: the velocity of the c.m.s. is $(v, 0, 0)$, orbit plane (x,z).

From one data set shape distributions were obtained as a function of W.

Cross section was reconstructed from another data set.

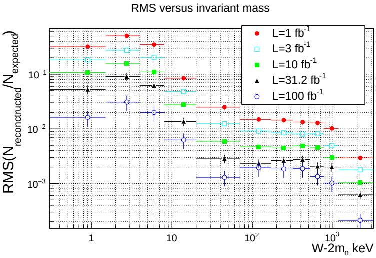
Heaviside step function:

n_y bin size is 0.004 non-uniform dividing for n_z.

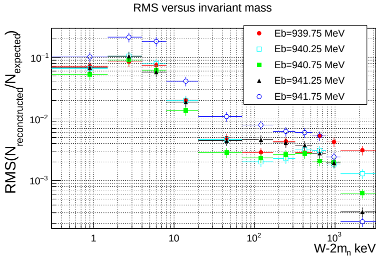
Events with $n_x < 0$ have one bin for all n_z. Two dimensional bilinear fit $(n_y; n_z)$.

Hypothetical resonances:

Two dimensional bilinear fit $(\cos\alpha, E_b)$. $\cos\alpha$ bin size is 0.004.



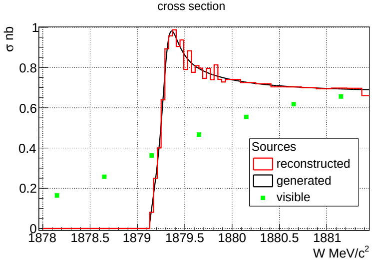
Beam energy is 940.75 MeV, threshold

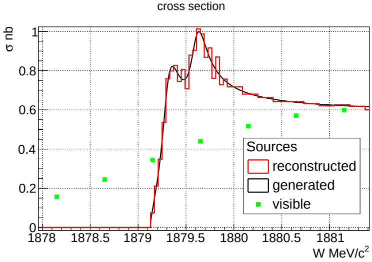


Integrated luminosity is 31.2 fb^{-1}

Cross section (1 nb) is simulated by the Heaviside function with step value at the energy threshold.
There are 50 pseudoexperiments for $1, 3, 10$ fb^{-1}, 16 experiments for 31.2 fb^{-1}, 5 experiments for 100 fb^{-1}.
Relative accuracy varies from ~ 0.1 at keV scale up to $\sim 3 \times 10^{-3}$ at MeV scale, with 30 fb^{-1}!

Results

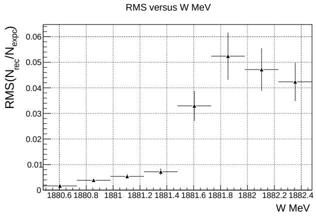




Integrated luminosity 70 fb^{-1}, seven points near threshold. Cross section an increasing up function with resonance(s) $\Gamma = 0.1$ MeV. In visible cross section resonant structure is integrated.

Results

Relation
$W = 2m_n\sqrt{1 + \sinh^2\psi \sin^2\alpha}$
outside range $W \in [2m_n; W^\star)$
becames invalid.
Invariant mass resolution in the region $W > W^\star$ increases by ~ 5 times.



Resolution near critical invariant mass

Important parameters from the accelerator point of view are
$W^\star = 2m_n/\sqrt{1 - v^2_{c.m.s}}$ and $R = (W^\star - 2m_n)/\sigma_W$.
If $R \ll 1$, most of the of events are $W > W^\star$, and relatively good resolution is unavalible for $W < W^\star$ region. In our simulation $R = 1.75$ so this is not an issue.

Summary

1. Modification of the standard method for the cross-section measurement using analysis of the angular distribution in lab. frame has been suggested
2. New approach was tested with MC for $e^+e^- \to n\bar{n}$ process near threshold
3. Energy and angular spreads in beams give much smaller contribution to the invariant mass resolution at the threshold $\frac{\delta W}{W} = Const(\frac{\delta E}{E_b})^2 \sim$ keV which is compared with the standard approach, where $\frac{\delta W}{W} = Const' \frac{\delta E}{E_b} \sim$ MeV
4. Critical invariant mass is $W^\star = 2m/\sqrt{1 - v^2_{c.m.s.}} = 2m_n + (2.34 \div 0.85)$ MeV (our simulation÷SCTF). From accelerator point of view, main parameteres for this approach are $v_{c.m.s.} = 1/20 \div 1/33.3$ and $R = (W^\star - 2m)/\sigma_W = 1.75 \div 0.73$. Could we expand $W^\star, R$?

Summary

Plans

1. Next approximation MC
    1. Antineutron angle reconstruction
    2. Beam energy and beam energy spread measurement
    3. D-wave contribution in angular distribution
    4. Antineutron time reconstruction
    5. Radiative correction
    6. Background
2. Study of the accuracy dependence on the crossing beams angle, beam energies asymmetry

$$\frac{dN}{d\cos\alpha} =$$

$$\begin{cases} \dfrac{\Theta(\cos\alpha - \sqrt{1 - \sinh^2\beta/\sinh^2\psi})(\sinh^2\beta - \sinh^2\psi\sin^2\alpha + \cos^2\alpha\cosh^2\beta}{\cosh^2\psi\sinh\beta(1 - \cos^2\alpha\tanh^2\psi)^2\sqrt{\sinh^2\beta - \sinh^2\psi\sin^2\alpha}} \\ \dfrac{(\sqrt{\sinh^2\beta - \sinh^2\psi\sin^2\alpha} + \cos\alpha\cosh\beta\tanh\psi)^2}{2\cosh^2\psi\sinh\beta(1 - \cos^2\alpha\tanh^2\psi)^2\sqrt{\sinh^2\beta - \sinh^2\psi\sin^2\alpha}} \end{cases}$$

$\frac{dN}{d\cos\alpha}$, α - angle between boost direction and antineutron momentum, β, ψ -pseudorapidities of the c.m.s in lab. frame and antineutron in c.m.s.