# Preliminary results of the $e^+e^- \to \pi^+\pi^-$ analysis with SND at VEPP-2000

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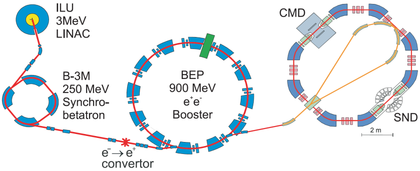
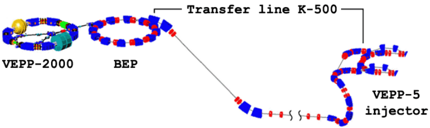
on behalf of SND collaboration

Muon g-2 Theory Initiative workshop
April 15 – 23, 2024

# VEPP-2000 $e^+e^-$ collider



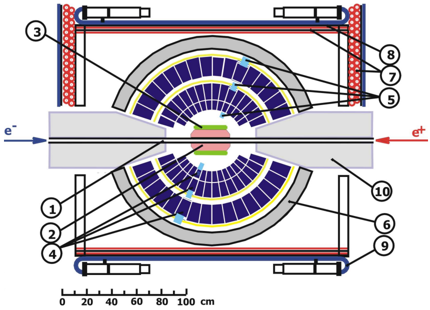




## VEPP-2000 parameters

- c.m. energy E=0.3-2.0 GeV
- Luminosity at E=1.8 GeV
  $10^{32} cm^{-2} sec^{-1}$ (project)
  $6x10^{31} cm^{-2} sec^{-1}$ (achieved)
- Beam energy spread - 0.6 MeV at E=1.8 GeV

- 10 times more intense positron source
- Experiments at upgraded VEPP-2000 were continued in the late 2016

# SND detector

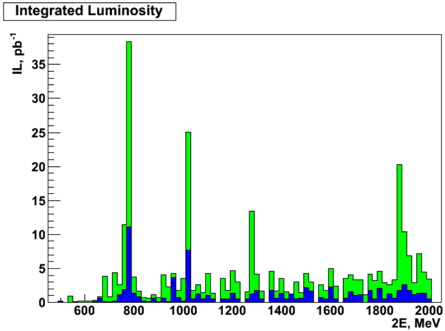



**1**-beam pipe, **2**-tracking system, **3**-aerogel Cherenkov counter , **4** - NaI(Tl) crystals, **5** - phototriodes, **6** - iron muon absorber, **7-9** - muon detector, **10** - focusing solenoids.

**Main physics task of SND is study of all possible processes of $e^+e^-$ annihilation into hadrons below 2 GeV**

- The total hadronic cross section, which is calculated as a sum of exclusive cross sections
- Study of hadronization (dynamics of exclusive processes)
- Study of the light vector mesons
- Production of the C-even resonances

# SND data




## Timeline

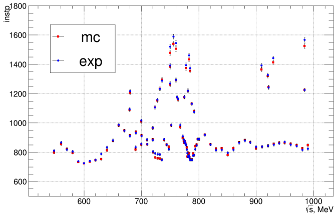
- MHAD2010-MHAD2012 – 48 $pb^{-1}$
- RHO2013 – 32 $pb^{-1}$
- MHAD2017 – 50 $pb^{-1}$
- RHO2018 – 90 $pb^{-1}$
- MHAD2019 – 65 $pb^{-1}$
- RHO2019 – 1 $pb^{-1}$
- MHAD2020 – 45 $pb^{-1}$
- MHAD2021 – 57 $pb^{-1}$
- MHAD2022 – 360 $pb^{-1}$
- MHAD2023 – 223 $pb^{-1}$

Current $e^+e^- \to \pi^+\pi^-$ analysis is based on the statistics, collected in 2017 – 2018 in 100 energy points $\sqrt{s} < 1$ GeV via two energy scans, that corresponds to the $\mathbf{5.6 \times 10^7}$ collinear events, with $\mathbf{2.7 \times 10^7}$ $e^+e^- \to \pi^+\pi^-, \mu^+\mu^-$ and $\mathbf{2.9 \times 10^7}$ $e^+e^- \to e^+e^-$ events.

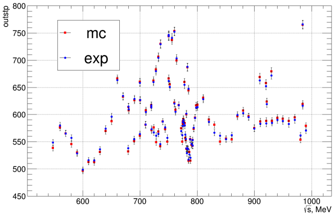
Much higher statistics, comparing to 2013 data (used in 2021 analysis)

# But there are some issues with stability

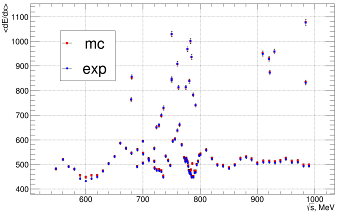
DC gains were adjusted to make MC match Data




inner cathodes




outer cathodes




DC wires

# Event selection ($\sqrt{s} < 900$ МэВ)

1. $N_{ch} \geq 2$ – two or more charged particles are allowed
2. $|\Delta\theta| = |180^\circ - (\theta_1 + \theta_2)| < 14^\circ$ и $|\Delta\varphi| = |180^\circ - |\varphi_1 - \varphi_2|| < 6^\circ$
3. $E_{1,2} > 40$ MeV, here $E_i$ – energy deposition for the $i$–th particle
4. $60^\circ < \theta_0 = (\theta_1 - \theta_2 + 180^\circ) \times 0.5 < 120^\circ$
5. $|r_1| < 1$ cm , $|r_2| < 1$ cm, here $r_i$ – distance between a track of $i$–th particle and the beam axis
6. $|z0_1| < 8$ cm , $|z0_2| < 8$ cm, here $z_i$ – longitudinal coordinate of the vertex
7. Cosmic veto: $veto = 0$

Additional $e^+e^- \to e^+e^-e^+e^-$ background was estimated from MC ( its contribution to $e^+e^- \to \pi^+\pi^-$ is 0.1 – 2 %)

# Event selection without veto ($\sqrt{s} > 900$ МэВ)

1. $N_{ch} \geq 2$ – two or more charged particles are allowed
2. $|\Delta\theta| = |180^\circ - (\theta_1 + \theta_2)| < 14^\circ$ и $|\Delta\varphi| = |180^\circ - |\varphi_1 - \varphi_2|| < 6^\circ$
3. $E_{1,2} > 40$ MeV, here $E_i$ – energy deposition for the $i$–th particle
4. $60^\circ < \theta_0 = (\theta_1 - \theta_2 + 180^\circ) \times 0.5 < 120^\circ$
5. $|r_1| < 0.5$ cm , $|r_2| < 0.5$ cm, here $r_i$ – distance between a track of $i$–th particle and the beam axis
6. $|z0_1| < 10$ cm , $|z0_2| < 10$ cm, $|z0_1 + z0_2|/2 < 8$ cm, here $z_i$ – longitudinal coordinate of the vertex

# Selecting comsic events

1. $N_{ch} \geq 2$ – two or more charged particles are allowed
2. $|\Delta\theta| = |180^\circ - (\theta_1 + \theta_2)| < 14^\circ$ и $|\Delta\varphi| = |180^\circ - |\varphi_1 - \varphi_2|| < 6^\circ$
3. $E_{1,2} > 40$ MeV, here $E_i$ – energy deposition for the $i$–th particle
4. $60^\circ < \theta_0 = (\theta_1 - \theta_2 + 180^\circ) \times 0.5 < 120^\circ$
5. $0.5 < |r_1| < 1$ cm , $0.5 < |r_2| < 1$ cm, here $r_i$ – distance between a track of $i$–th particle and the beam axis
6. $4 < |z0_1| < 10$ cm , $4 < |z0_2| < 10$ cm, here $z_i$ – longitudinal coordinate of the vertex

Using these events one can determine muon veto efficiency (0.92 - 0.98). Latter being used to calculate residual cosmic background.

# Selecting $\omega \to 3\pi$ events

1. $N_{ch} \geq 2$ – two or more charged particles are allowed
2. $N_\gamma \geq 2$
3. $14^\circ < |180^\circ - (\theta_1 + \theta_2)| < 24^\circ$ и $6^\circ < |180^\circ - |\varphi_1 - \varphi_2|| < 14^\circ$
4. $E_{1,2} > 40$ MeV, here $E_i$ – energy deposition for the $i$–th particle
5. $60^\circ < \theta_0 = (\theta_1 - \theta_2 + 180^\circ) \times 0.5 < 120^\circ$
6. $|r_1| < 1$ cm , $|r_2| < 1$ cm, here $r_i$ – distance between a track of $i$–th particle and the beam axis
7. $|z0_1| < 8$ cm , $|z0_2| < 8$ cm, here $z_i$ – longitudinal coordinate of the vertex
8. Cosmic veto: $veto = 0$

Used to estimate number of $\omega \to 3\pi$ events in $\pi^+\pi^-$ sample, their contribution $\approx 0.5$ % at $\sqrt{s} = m_\omega$.

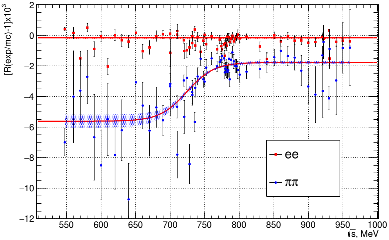
# $e/\pi$ separation

In order to separate events with $e^+e^-$ and $\pi^+\pi^-$ in the final state machine learning methods (based on BDTG) were developed, with input parameters:

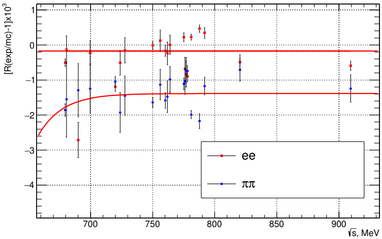
- $^{0}\mathbf{e_j}$ – energy deposition for the $j-$th layer in the central tower
- $^{1}\mathbf{e_j}$ – energy deposition for the $j-$th layer in the towers, next to the central one
- $^{2}\mathbf{e_j}$ – energy deposition for the $j-$th layer outside
- $\mathbf{E_j}$ – full energy deposition for $j-$th layer
- **E** – total energy deposition
- $< \mathbf{dEdx} >$ – dE/dx of a particle in the DC, averaged over layers

Overall $(4 \times 3 + 2) \times 2 = \mathbf{28}$ parameters for the main discriminator.
There is a vertion of discriminator for separate particles.
And one for $\mu/\pi$ separation

In MC ID inefficiency is 0.1-0.15 %. With pseudo-events ee and $2\pi$ being used to estimate correction for ID efficiency




1st scan



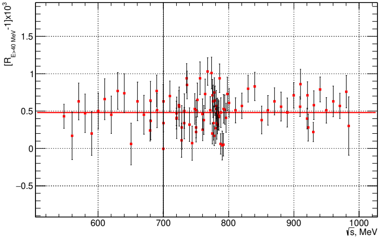

2nd scan

Similar corrections were calculated for $e^+e^- \to \mu^+\mu^-$ events in the first 6 energy points

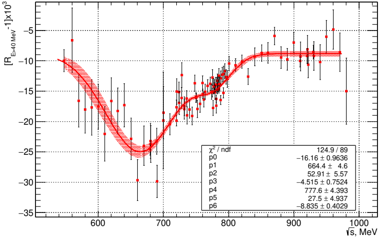
# Changes in the reconstruction algorithm

- Bug in the code (affecting $\Delta\theta$ distribution) was fixed
- Suppression of the wire hits with drift times outside specific range
- There was a bug in parts of code, related to calculation of the drift distance error (changed number of the collinear events)
- It was discovered, that erros for the cuthode strips were overestimated in the reconstruction algorithm, fixing this problem significantly improved $\theta$-resolution
- By altering $\chi^2$ of the tracks we found a way to reduce number of $e^+e^- \to \pi^+\pi^-$ events with one poorly reconstructed track, removing big 'tails' in the $\Delta\theta$ distribution for energy points with a low gain in the DC

Using ee и $2\pi$ events (with some additional cuts*) to calculate efficiency corrections




$e^+e^- \to e^+e^-$ events

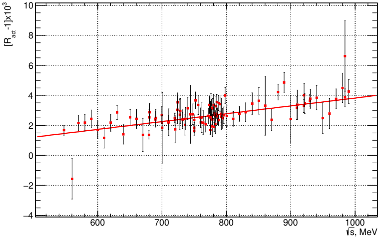



$e^+e^- \to \pi^+\pi^-$ events

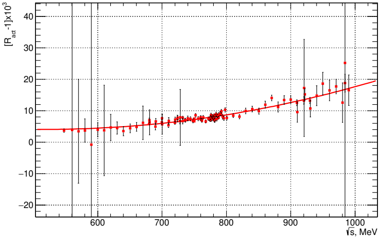
* ACC (not)firing, muon suppression

# Efficiency of the *veto* = 0 cut

Using ee и $2\pi$ events (with some additional cuts* and cosmic background subtraction via fit of the vertex z-coordinate distribution) to calculate efficiency correction




$e^+e^- \to e^+e^-$ events

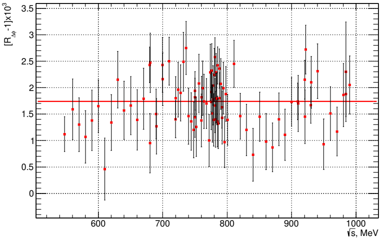



$e^+e^- \to \pi^+\pi^-$ events

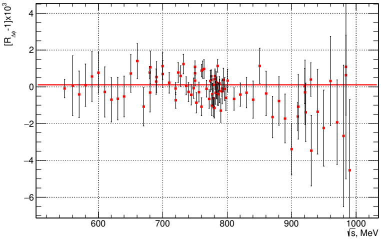
Probability of the muon system firing is higher for MC

* sin($\varphi$)<0.5, ACC (not)firing, muon suppression

Using ee и $2\pi$ events (with some additional cuts*) to calculate efficiency corrections




$e^+e^- \to e^+e^-$ events

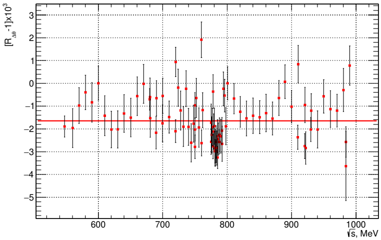



$e^+e^- \to \pi^+\pi^-$ events

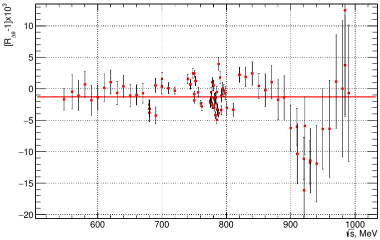
Average deviation from 1 is 0.17%

* ACC (not)firing, muon suppression, $|\Delta\varphi|<12^\circ$, $\omega \to 3\pi$ suppression

Using ee и $2\pi$ events (with some additional cuts*) to calculate efficiency corrections




$e^+e^- \to e^+e^-$ events



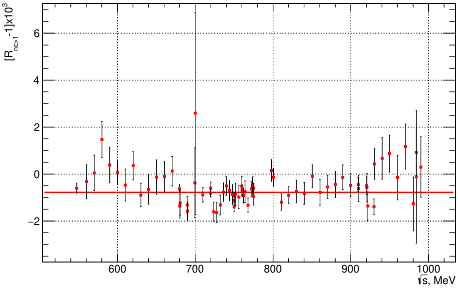

$e^+e^- \to \pi^+\pi^-$ events

For average corrections deviation from 1 is less than 0.2%

* ACC (not)firing, muon suppression, $|\Delta\theta|<24^\circ$, $\omega\to3\pi$ suppression

# Efficiency of the $N_{ch} \geq 2$ cut

Using ee и $2\pi$ events (with some additional cuts*) to calculate efficiency corrections

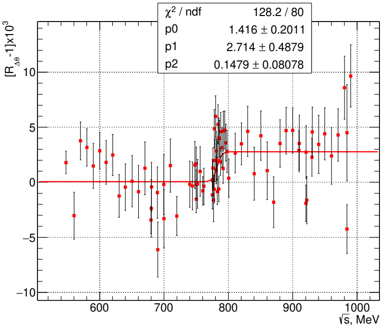



Average ratio of $e^+e^- \to e^+e^-$ and $e^+e^- \to \pi^+\pi^-$ deviates from 1 by 0.08% (for energy points outside $\omega$ range)

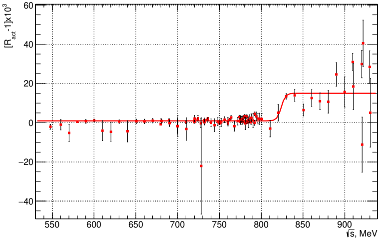
* ACC (not)firing, muon suppression, $e^+e^- \to \gamma\gamma$ background suppression

# Efficiency for $e^+e^- \to \mu^+\mu^-$ events

Using pion suppression one can calculate similar corrections for the $e^+e^- \to \mu^+\mu^-$ events

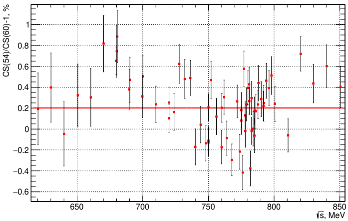



correction for $|\Delta\theta|<14^\circ$ cut
experience 0.3% jump at $\sqrt{s} = m_\omega$

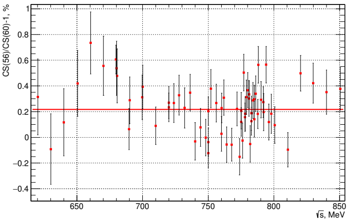



correction for $veto = 0$ cut

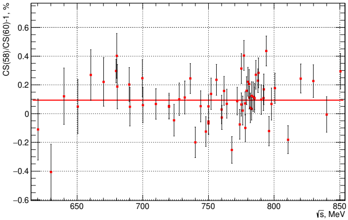
# Ratios of CS with different $\theta_0$ cuts



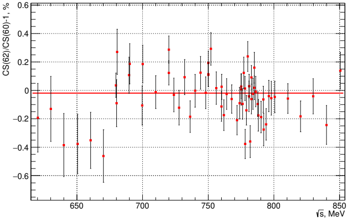

$54^\circ < \theta_0 < 126^\circ$




$56^\circ < \theta_0 < 124^\circ$

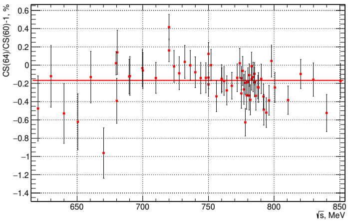



$58^\circ < \theta_0 < 122^\circ$

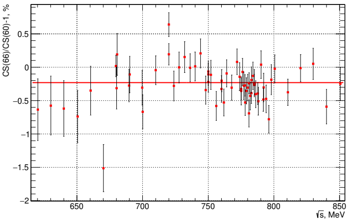



$62^\circ < \theta_0 < 118^\circ$

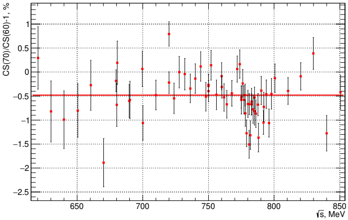
# Ratios of CS with different $\theta_0$ cuts



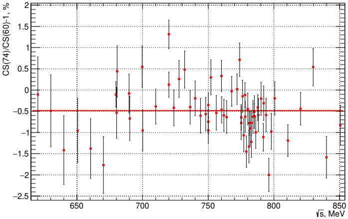

$64^\circ < \theta_0 < 116^\circ$




$66^\circ < \theta_0 < 114^\circ$

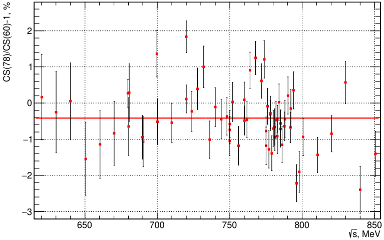



$70^\circ < \theta_0 < 110^\circ$

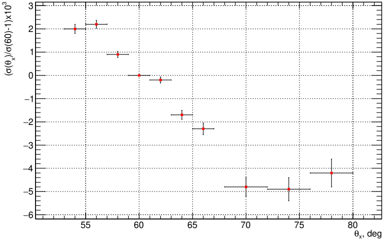



$74^\circ < \theta_0 < 106^\circ$

# Ratios of CS with different $\theta_0$ cuts



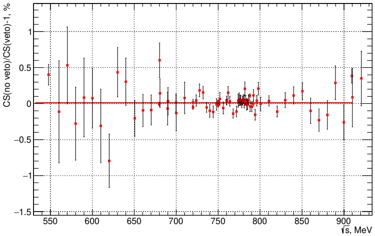

$78^\circ < \theta_0 < 102^\circ$




Averaged correction vs $\theta_x$
$(\theta_x < \theta_0 < 180^\circ - \theta_x)$

Averaged correction plateaued at 1.002 for low $\theta_x$ and 0.995 for high $\theta_x$

Comparing two methods for $\sqrt{s} < 950$ MeV



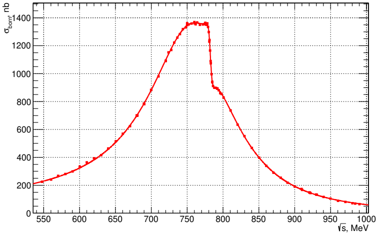

## Subtraction of the cosmic background:

- Muon system veto efficiency being calculated
- Selecting events with $veto > 0$
- From $(z0_1 + z0_2)/2$ distribution fit extracting number of cosmic events with $veto > 0$
- Using this number and veto efficiency to determine overall contribution of the cosmic background (for both types of events)

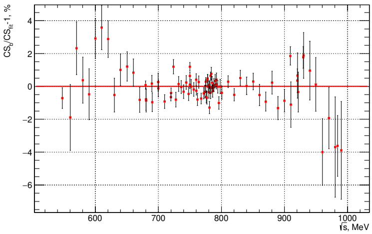
* not exactly

# Systematics

| Source | $\sqrt{s} < 700$ MeV, % | $\sqrt{s} > 700$ MeV, % |
|---|---|---|
| e/$\pi$ | 0.3 | 0.1 |
| $E_i > 40$ MeV | 0.2 | 0.1 |
| rad | 0.2 | |
| nc2 | 0.1 | |
| col | 0.2 | |
| $\theta_0$ | 0.5 | |
| nucl | 0.2 | |
| total | 0.7 | 0.6 |




$e^+e^- \to \pi^+\pi^-$ born cross section




Deviation from fit curve

Main fit results: $M_\rho = 774.7 \pm 0.14$ MeV,
$\Gamma_\rho = 148.69 \pm 0.25$ MeV, $M_\omega = 782.32 \pm 0.07$ MeV,
$\Gamma_\omega = 8.38 \pm 0.14$ MeV, $Br_{\omega\to 2\pi} = 1.53 \pm 0.02$ %,
$\chi^2$/n.d.f. $\approx 2$

# Conclusion + Future plans

- First internally consistent measurents of the $e^+e^- \to \pi^+\pi^-$ cross section with 2018 Data
- First estimates of systematic uncertainties
- To calculate $e^+e^- \to \pi^+\pi^-$ cross section at $\sqrt{s} \leq$600 MeV using 2019 Data with n=1.13 ACC (it allows to suppress $e^+e^- \to \mu^+\mu^-$)
- To reduce a number of tracks, that are poorly reconstructed due to the shifted wire hits in DC
- To construct $\pi\pi$ pseudo-events from $\omega \to 3\pi$ events, in order to calculate efficiency corrections for the ID and $E >$40 MeV cuts at $\sqrt{s} <$ 650 MeV
- To produce more or less final result, and compare it with previous measurements

Thank you for attention !