Study of the $\omega \to \pi^0 e^+ e^-$ conversion decay with the CMD-3 detector at VEPP-2000 collider

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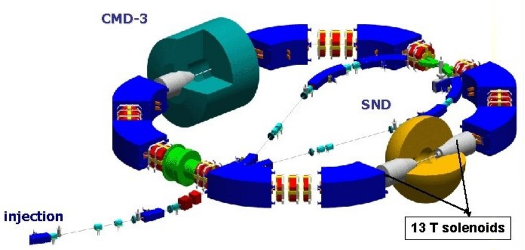
Content

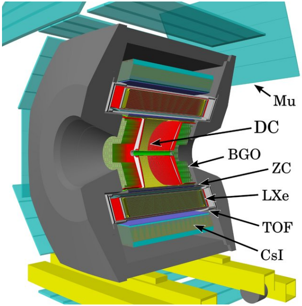
VEPP-2000



The layout of the VEPP-2000 electron-positron collider complex

- Energy from 0.32 GeV to 2 GeV in c.m. reference frame
- Circumference 24.39 m
- Luminosity $(0.6 - 0.7) \cdot 10^{32}$ cm^{-2}s^{-1}
- Two experiments on the collider - CMD-3 and SND

CMD-3



The layout of CMD-3 detector. Mu - muon system; DC - drift chamber; BGO - endcap calorimeter; ZC - Z camera; TOF - time-of-flight system; CsI, LXe – cylindrical calorimeter

- Precision measurements of hadronic cross sections and investigation of exclusive hadron annihilation channels e^+e^- for accurate measurement of $R(s) = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$
  - $R(s)$ is used to calculate the anomalous magnetic moment of the muon
- Study of the properties of vector mesons and their excited states

Introduction

- The process $e^+e^- \to (\omega, \rho) \to \pi^0 e^+ e^-$ in the decay channel $\pi^0 \to \gamma\gamma$
- Motivation to study: accurate knowledge of decay probabilities mesons with the production of dileptons is necessary to study quark-gluon plasma, branching measurement: VMD check.
- The data from CMD-3 detector
- Integral luminosity ~ 10 pb^{-1}

Purpose of the work: Measurement of $\omega \to \pi^0 e^+ e^-$ decay probability

Selections

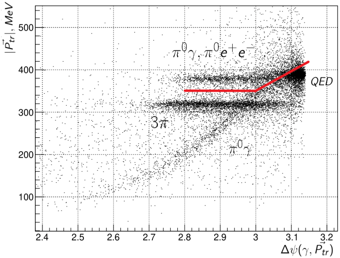
Table: Background processes

Resonant (ρ, ω)	Nonresonant
$\pi^0\pi^+\pi^-$ $\pi^0\gamma$ (Dalitz decay $\pi^0 \to \gamma e^+ e^-$) $\pi^0\gamma$ (Conversion on the meterial before sensitive detector)	Cosmic particles QED events Particles scattered from the beam

- The minimal distance to beams $\rho < 1$ cm
- Z vertex coordinate $|\text{Zvert}| < 8$
- Two "good" tracks (more than 10 triggered wires per track, $P_{tr_{1,2}} > 40\ MeV/c,\ 0.9 < \theta_{1,2} < 0.9,\ Q_{tot} = 0$)
- $N_\gamma \geq 2$ with energy $40\ MeV < E_{\gamma_{1,2}} < 2 \cdot E_{beam}$ and polar angle $0.5 < \theta_\gamma < \pi - 0.5$

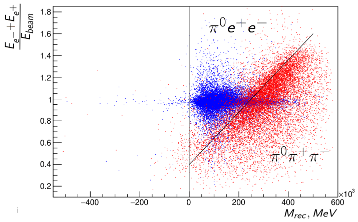
Selections

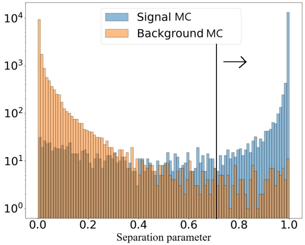
- $M_{inv}(e^+ e^- \gamma_{max_0}) < 1.9 \cdot E_{beam}$
- Noncollinearity of tracks in $R - \phi$ projections $|\pi - |\phi_1 - \phi_2|| > 0.15$
- Spatial angle between average track momentum and each photon is more than 1.5 rad
- The angle between photons is less than 1.6 rad
- Spatial angle between tracks $\Delta\psi < 1$ rad



Dependence of the total momentum of charged particles P_{tr} on the angle between the sum of track momentum and photon of maximum energy γ_0

Selections





Recoil pair mass dependence $M_{rec}^2 = (2E_0)^2 - 4E_0 E_{\pi_0} + m_{\pi_0}^2$ on the sum of track momentum normalized to the beam energy

Distribution on the separation parameter (ξ) for signal events (blue) and for background process with photon conversion (orange) obtained from a neural network (multilayer perceptron)

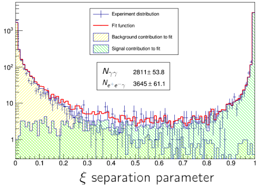
Input model parameters

1. The spatial angle between e^+e^-
2. The spatial angle between e^+e^- after VPP*
3. The VPP χ^2 parameter
4. The total momentum of e^+e^- normalized on the beam energy (E_{beam})
5. Electron transverse momentum normalized on the E_{beam}
6. Positron transverse momentum normalized on the E_{beam}
7. The distance between the interaction point to the vertex
8. The distance between the interaction point to the second geometrically reconstructed vertex**
9. Invariant mass of e^+e^-
10. The polar angle of the total momentum of e^+e^-
11. The azimuths angle of the total momentum of e^+e^-

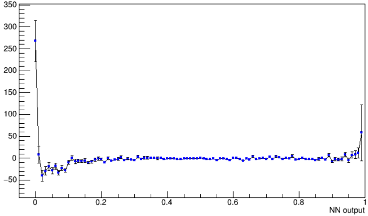
* Together with the standard algorithm, we developed and applied beam-independent tracks and vertex reconstruction algorithm (we call it vertex processing procedure - VPP)

** Since lepton tracks are circles they have two common points. The first one is reconstructed vertex, and the second one is determined from known parameters of tracks.

Suppression of photon conversion events on the detector substance



The fit of separation parameter distribution ξ from experiment (blue) with signal and background shapes obtained from MC (red)

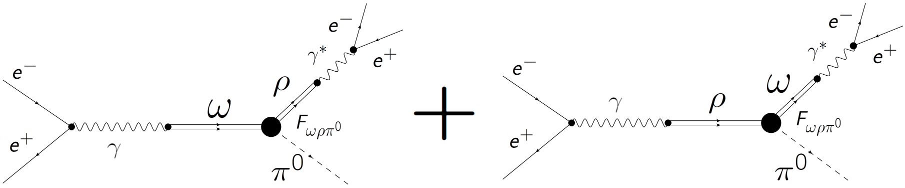


Experimental deviation from MC

Table: The result of calculating the ratio of events $[N_{ee\gamma}/N_{\gamma\gamma}]_{mc}\,/\,[N_{ee\gamma}/N_{\gamma\gamma}]_{exp}$ for all models and energy points

	Calculation efficiency		Systematic error
	680 MeV	750 MeV	
The MP	0.966 ± 0.025	1.020 ± 0.017	2.5 %
The GBDT	0.973 ± 0.025	1.031 ± 0.016	2.6 %
Ensemble	0.968 ± 0.025	1.035 ± 0.016	2.7 %

Born cross-section from VMD



Feynman diagrams contributing to the process $e^+e^- \to (\omega, \rho) \to \pi^0 e^+e^-$ under study.
$F_{\omega\rho\pi^0}$ — transition form factor from ω to π^0

$$\sigma_{\pi^0 e^+ e^-} = \frac{|g_{\gamma\omega} g_{\omega\rho\pi} g_{\rho\gamma}|^2}{4s} \int_{-1}^{1} dcos(\theta_1) \int_0^{2\pi} d\phi_1 \int_0^{2\pi} d\phi_{12} \iint_{\mathcal{D}} d\omega_1 d\omega_2 |L(\overrightarrow{p_1}, \overrightarrow{p_2}, \overrightarrow{p_3})|^2 \cdot$$

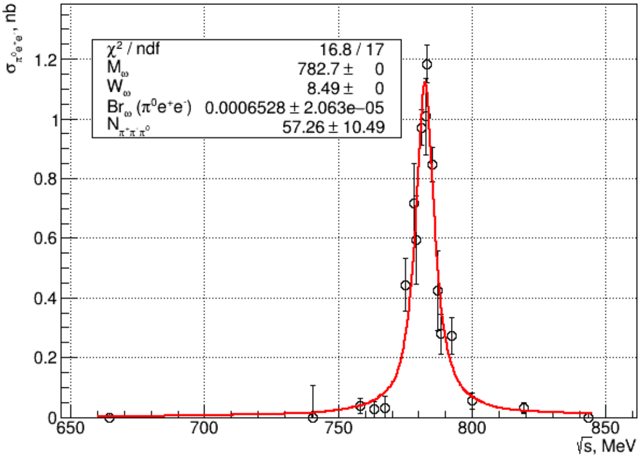
$$\cdot \left| \frac{1}{D_\omega(S) D_\rho(q^2)} + \frac{1}{D_\rho(S) D_\omega(q^2)} \right|^2$$

$$g_{\gamma V} = \left[\frac{3 m_V^3 \Gamma_V Br(V \to e^+e^-)}{4\pi\alpha} \right]^{1/2}$$

$$g_{V\rho\pi} = \left[\frac{4\pi \Gamma_V Br(V \to \rho\pi)}{W_{\rho\pi}(m_V)} \right]^{1/2}$$

$\mathcal{D}$ — Dalitz surface in the energy variables e^- ω_1 and e^+ ω_2, θ_1, ϕ_1 — polar and azimuthal electron angles, ϕ_{12} — plane rotation angle $(\vec{p_1}, \vec{p_2})$, $\vec{p_1}$ and $\vec{p_1}$ are electron and positron momenta, respectively, $D_V(s)$ — meson propagator

Branching $\omega \to \pi^0 e^+ e^-$



Approximation of the Born section $\pi^0 e^+ e^-$: $\sigma_{born} = \frac{N_{sig,i}}{L_i(1+\delta_i)\varepsilon_{det}\varepsilon_{\pi^0}\varepsilon_{\Delta\psi} Br(\pi^0 \to \gamma\gamma)}$

Branching $\omega \to \pi^0 e^+ e^-$

Table: Main contributions to systematic error

Background subtraction	ρ and ω resonance parameters	Conversion suppression	Luminosity	Form factor	3π	Close tracks	Radiation correction
3.6%	2.4%	2%	1.5%	1.2%	0.9%	0.5%	0.5%

Table: Branching of $\omega \to \pi^0 e^+ e^-$ in various experiments

	ND	SND	CMD-2	CMD-3 (preliminary)
$\mathrm{Br}(\omega \to \pi^0 e^+ e^-), 10^{-4}$	5.9 ± 1.9	$7.61 \pm 0.53 \pm 0.64$	$8.19 \pm 0.53 \pm 0.62$	$6.53 \pm 0.21 \pm 0.34$
Integral luminosity, pb^{-1}	-	9.8	3.3	10

Conclusion

- Machine learning models have systematic uncertainties if trained on MC but high efficiency;
- Linear classifications are simpler but require manual feature selection;
- The main contributions to systematic uncertainty was evaluated;
- The relative decay probability is determined:

$$Br(\omega \to \pi^0 e^+ e^-) = (6.53 \pm 0.21(\text{stat.}) \pm 0.34(\text{sys.})) \cdot 10^{-4}.$$

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Thank you for your attention!