Measurement of the e+e- $\to \pi^+\pi^-$ cross section below 1.2 GeV with the CMD-3 detector at electron-positron collider VEPP-2000

G.V.Fedotovich

on behalf of the CMD-3 collaboration

Novosibirsk State University
&
Budker Institute of Nuclear Physics,
Novosibirsk, Russia

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Outline

- Motivation
- Collider and detector
- Experiment
- Event separation techniques
- Study systematic corrections
- Cross section calculation and fitting
- Contribution to (g-2)/2 of muon
- Conclusion

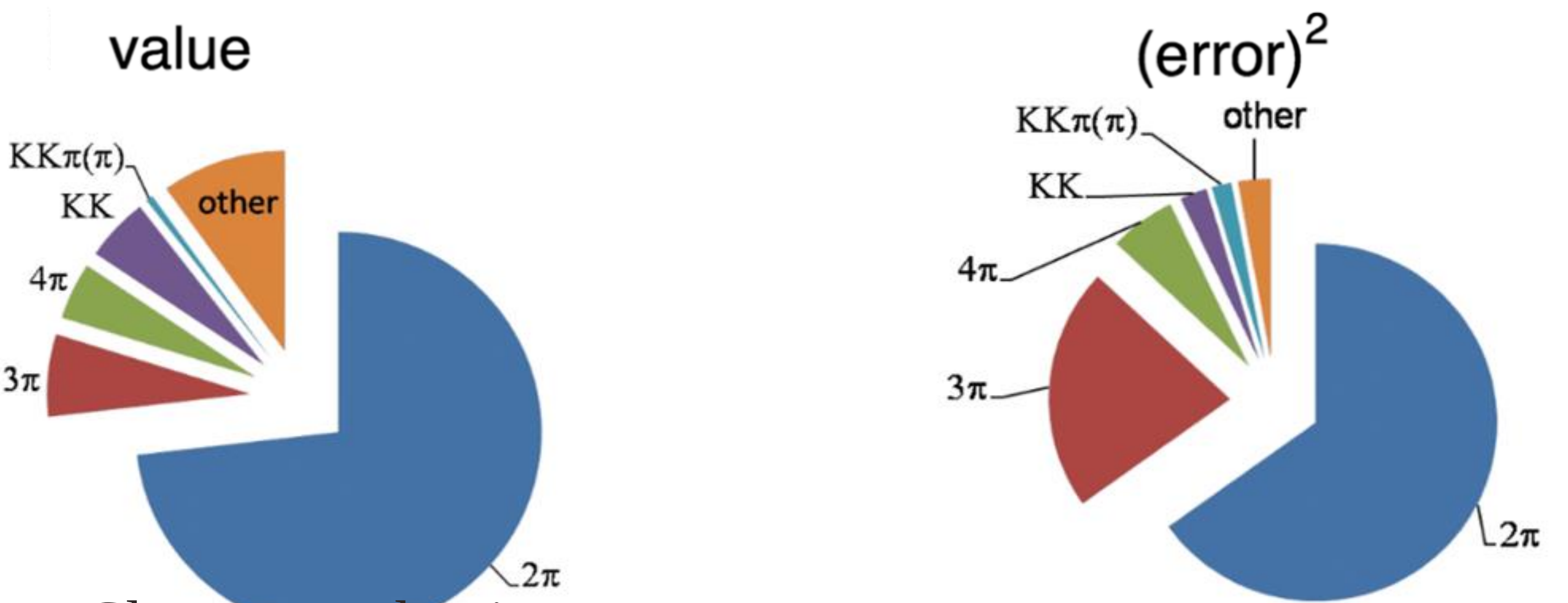
LO-Hadronic contribution to the value $a_\mu^{had'LO}$

(Anomalous Magnetic Moment of muon, AMM)

$a^{\text{had,LO}}{}_{\mu}$ is calculated by integrating the experimental inclusive cross section $\sigma(e^+e^- \to hadrons)$:

$$a^{had;LO}{}_{\mu} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi{}^2}^{\infty} \frac{ds}{s^2} K(s) R(s)$$

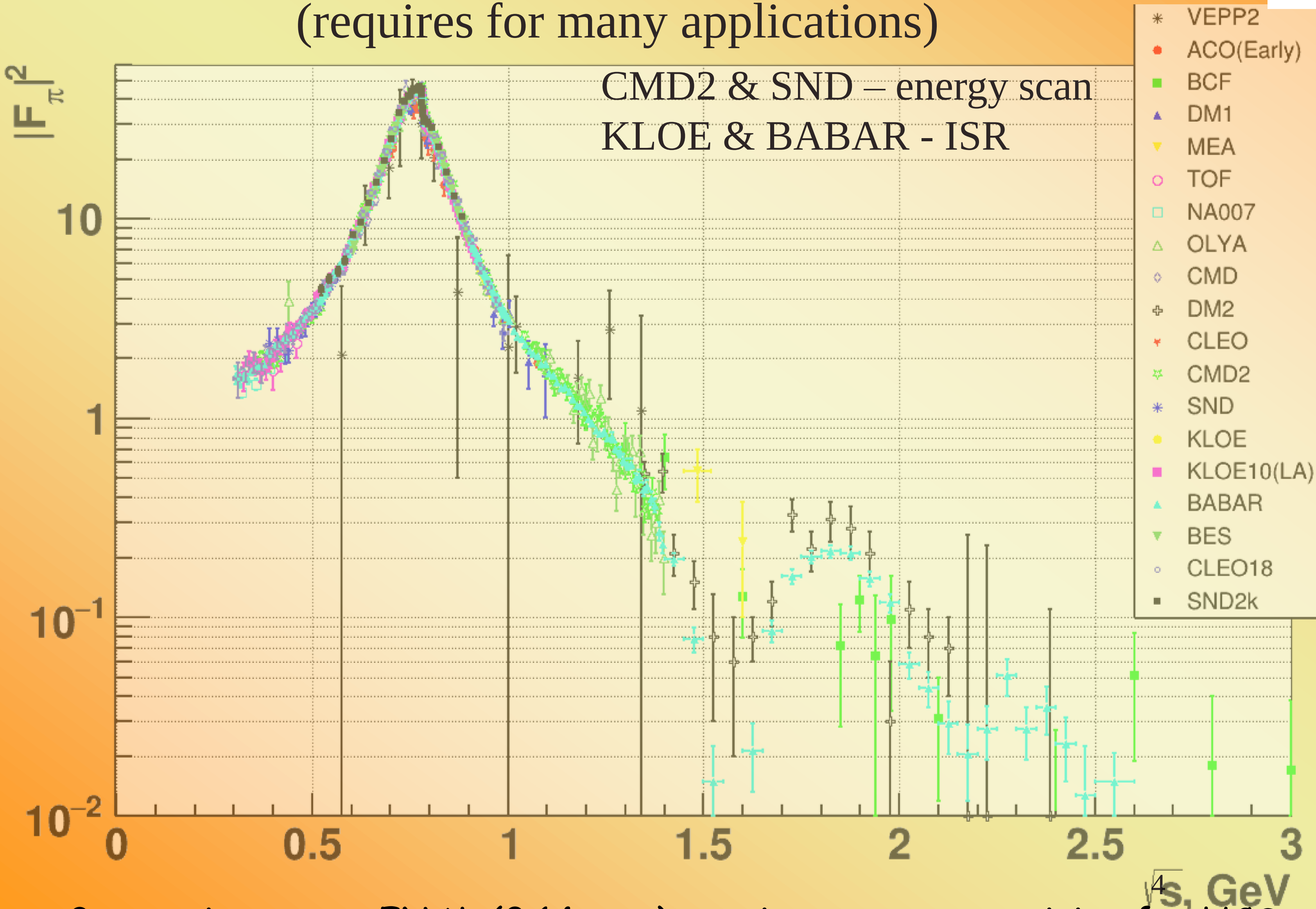
Due to $1/s^2$ weighting the energy range of VEPP-2000 makes a dominant contribution of ~93% to the $a^{had;LO}{}_{\mu}$ and determines ~70% its uncertainty



Clear $\pi+\pi-$ dominance

History study of the $e^+e^- \to \pi^+\pi^-$ process today

Experiments have been going on for over 50 years
(requires for many applications)

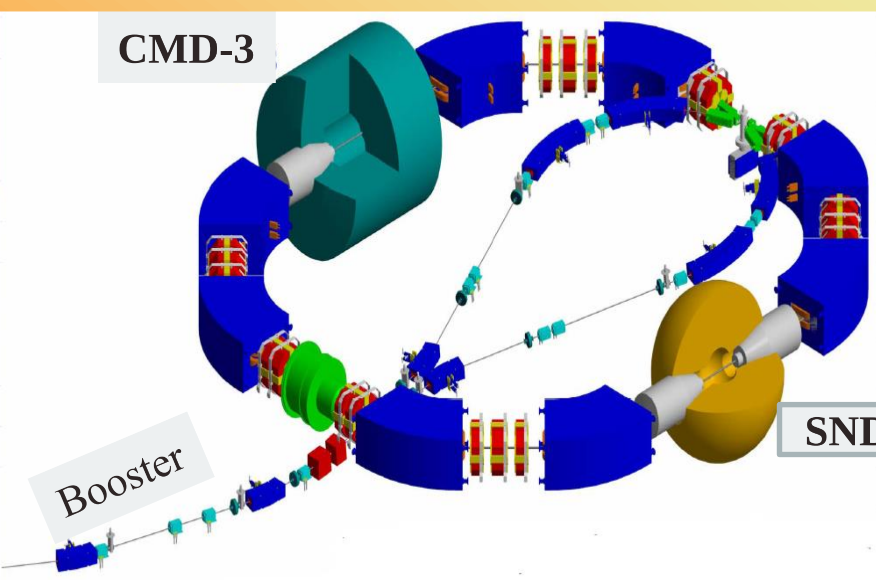


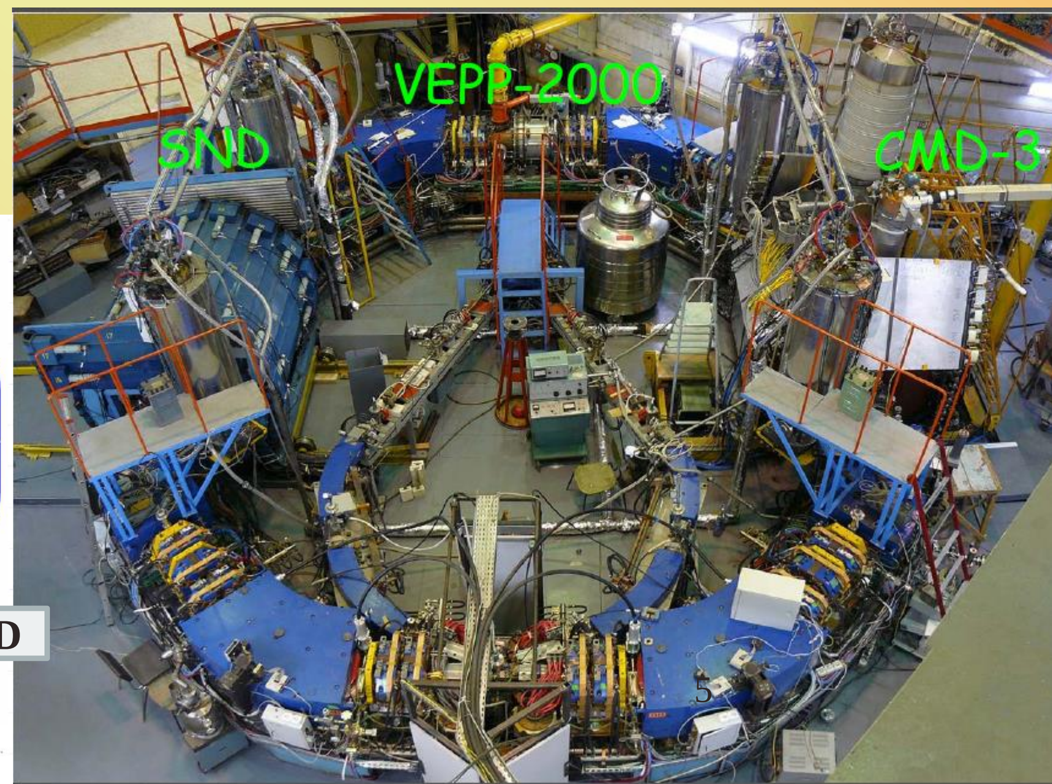
New g-2 experiments at FNAL (0.14 ppm) require average precision for HCS ~ 0.2%

VEPP-2000 collider with two detectors

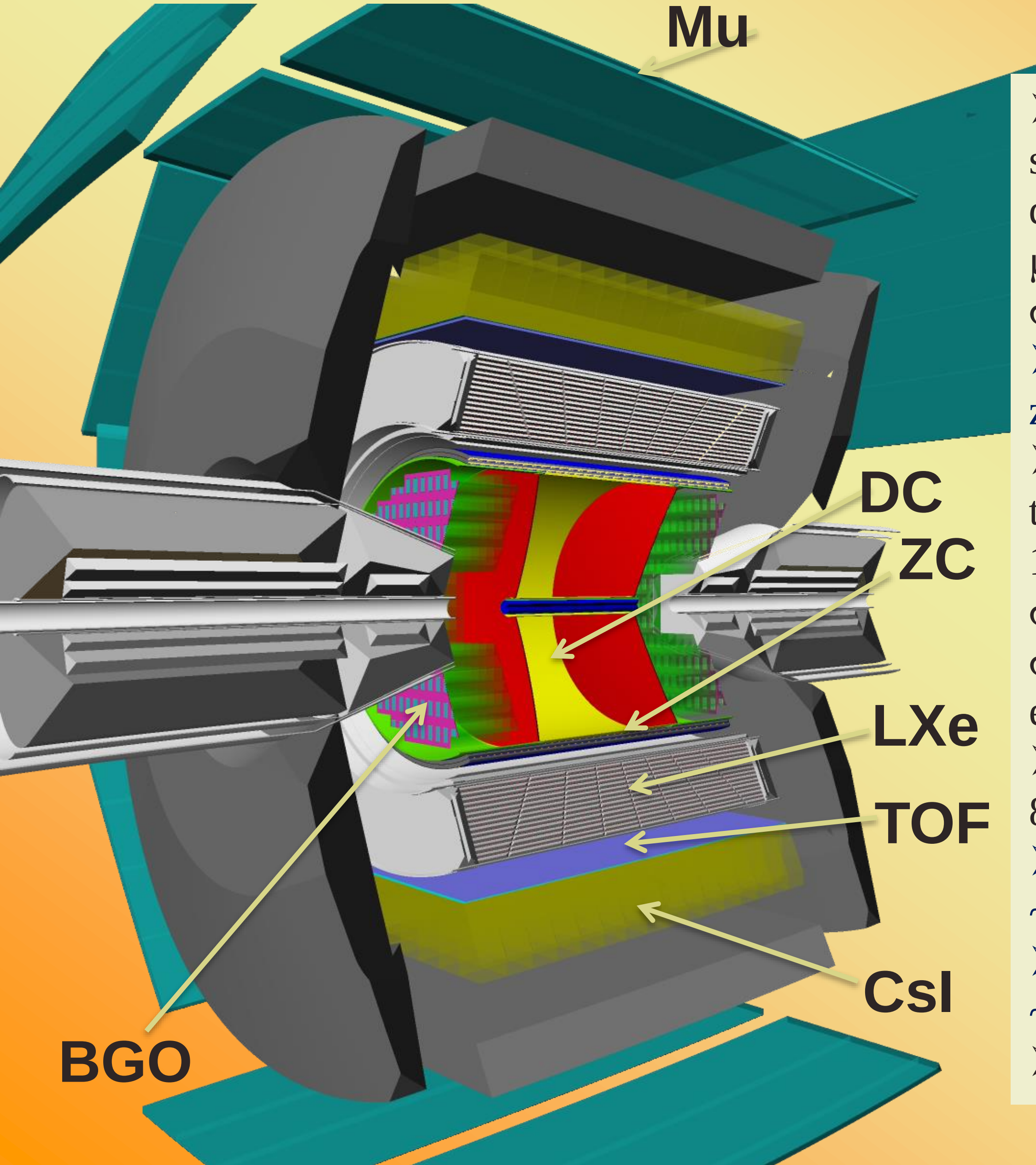
- VEPP-2000 (Novosibirsk, Russia) scans the $\sqrt{s}$ in the range from 0.32 to 2.01 GeV
- Beam energy is monitored by the Compton backscattering laser light system with ~50 keV precision

- Uses “round beams” technique (focusing solenoids with magn. field 13 T)
- Current Luminosity achieved - $7 \times 10^{31}\ \mathrm{cm^{-2}s^{-1}}$ (project ~ $10^{32}\ \mathrm{cm^{-2}s^{-1}}$)
- CMD-3 and SND detectors placed at two beam interaction points opposite to each other.





CMD-3 detector

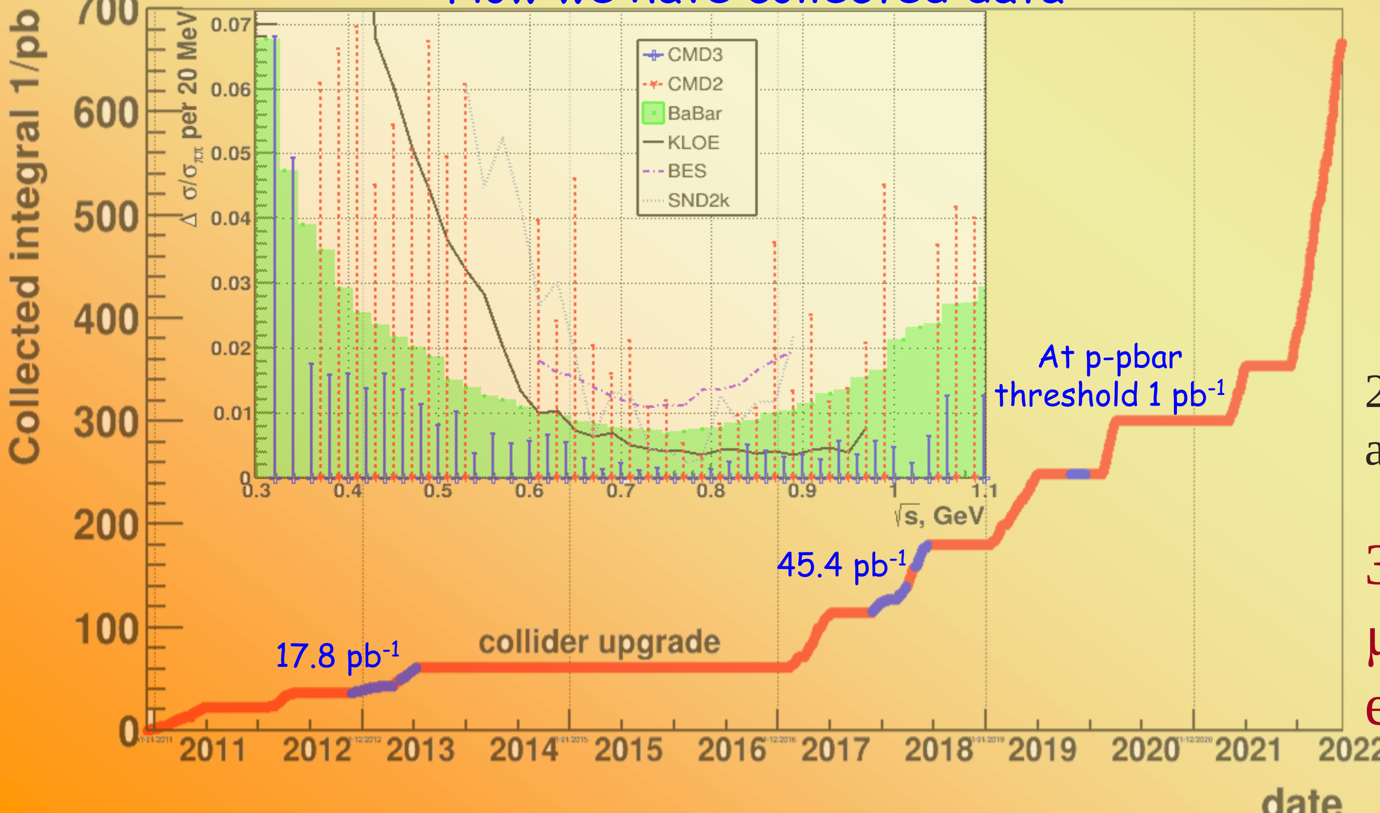


- DC – 1218 hexagonal cells with sensitive wires, W-Re alloy, 15 μ in diameter, spatial resolution ~ $\sigma_{R\varphi}$ ~ 100 μm, σ_Z ~ 2.5mm
  σP/P ~ √0.62+(4.4*p[GeV])2 ,%
- Z-chamber – start FLT, precise z-coordinate ~ 500 μ (detector acceptance)
- LXe calorimeter thickness $5{,}1X_0$, 196 towers & 1286 strips. Spatial resolution 1 – 2 mm, for photon point conversion
  σE /E ~ 0.034/ √E [GeV] ⊕ 0.020 - barrel
  σE /E ~ 0.024/ √E [GeV] ⊕ 0.023 – endcap.
- Calorimeter with CsI crystals (~3,5 t), 8 octants, number of crystals - 1152, $\sim 8X_0$
- TOF – 16 counters, time resolution ~ 0.5 ns mainly for anti neutron detection
- MR system – 8 octants (cosmic veto, ~ 1ns) particle ID
- Magnetic field is about 1.3 T

CMD-3: overview of data taking

- Before upgrade (2011-2013) luminosity at high energies was limited by deficit of positrons and limited energy of the booster
- 2017: new injection complex and booster gave a big improvement in luminosity
- 2018: “Beamshaking” technique was introduced too at low energies, which suppressed beam instabilities (x4 Lum)
- L~750 pb^{-1} per detector collected so far: ~65 pb^{-1} < 1 GeV, ~685 pb^{-1} > 1 GeV

How we have collected data



Three physical runs:
RHO2013
RHO2018
LOW2020

Analysis based on
L = 61.9 pb^{-1} at
2E < 1 GeV, L=25.7 pb^{-1}
at 2E = 1.0 – 1.02 GeV

$34 \cdot 10^6$ π+π-, $3{,}7 \cdot 10^6$ μ+μ- and $44 \cdot 10^6$ e+e- events were selected at 2E < 1 GeV

$e^+e^- \to \pi^+\pi^-$: pion formfactor measurement

The basic idea of the measurement is: events with two back-to-back tracks at the large angle are selected. The selection criteria include cuts on momenta, vertex position along beam axis, average scattering angle, acollinearity angles Δφ and ΔΘ and others.

The selected sample is composed by e+e− → π+π− events, accompanied by e+e− and μ+μ− events and single cosmic muons, miss reconstructed as back-to-back particles originated near IP

- Two charged collinear tracks:

  $|\Delta\phi| < 0.15\text{rad}, |\Delta\theta| < 0.25\text{rad}$

  $Q_1 + Q_2 = 0, |\Delta t| < 20ns$
- Vertex position close to interaction point

  $\rho_{average} < 0.3\text{см}, |Z_{average}| < 5\text{см}$

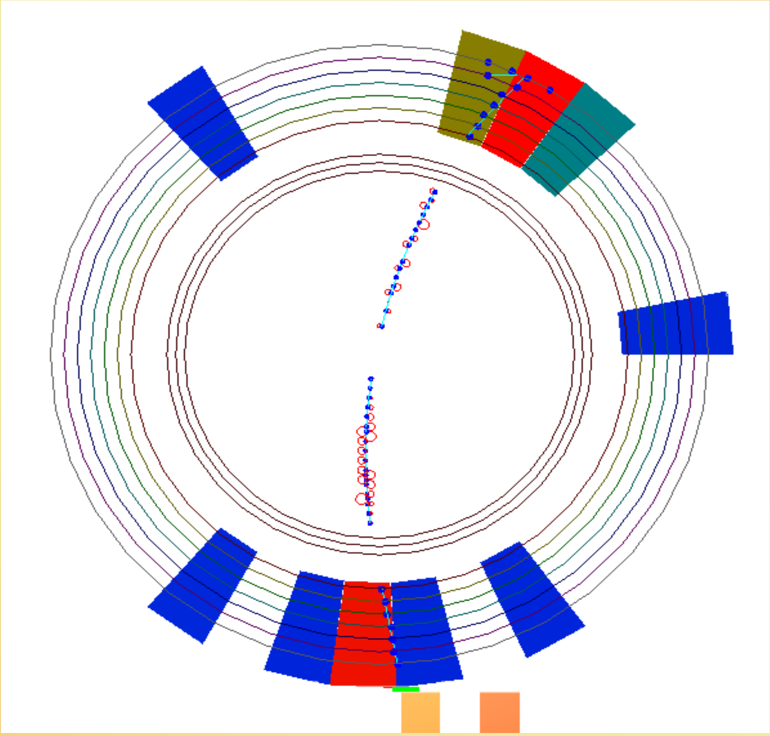
  $|\Delta\rho| < 0.3\text{см}, |\Delta Z| < 5\text{см}$
- Fiducial volume inside good region of the DCH

  $1.1 < (\pi + \theta^+ - \theta^-)/2 < \pi - 1.1\ rad$
- Quality of selected tracks:

  $\chi^2/ndf < 10, \quad N_{hits} \geq 10$
- Filtration of low momentum and cosmic background:

$0.45E_{beam} < p\pm < E_{beam} + 100\ MeV/c,\ p\pm > 1.15p\_(K\pm)$

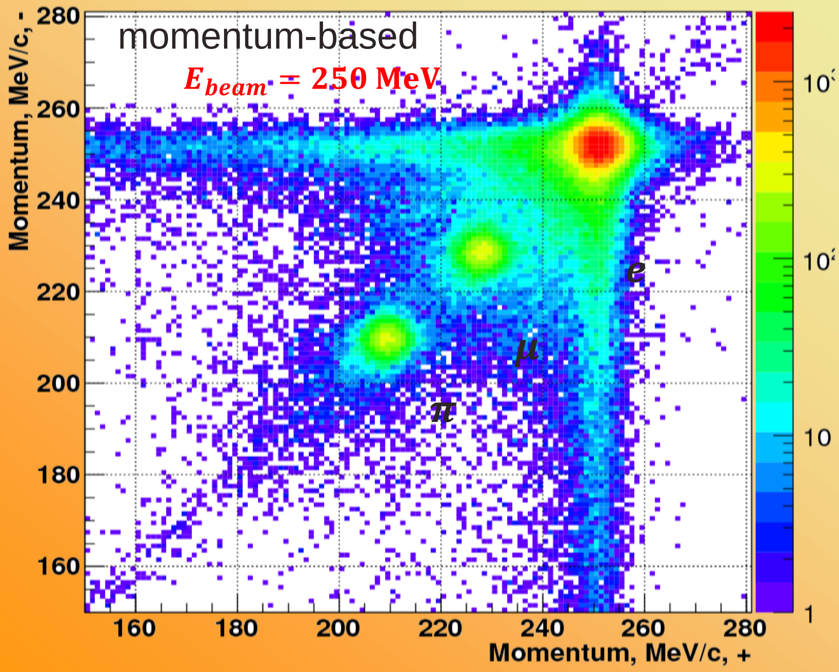
Example of e+e− → π+π− event in CMD-3

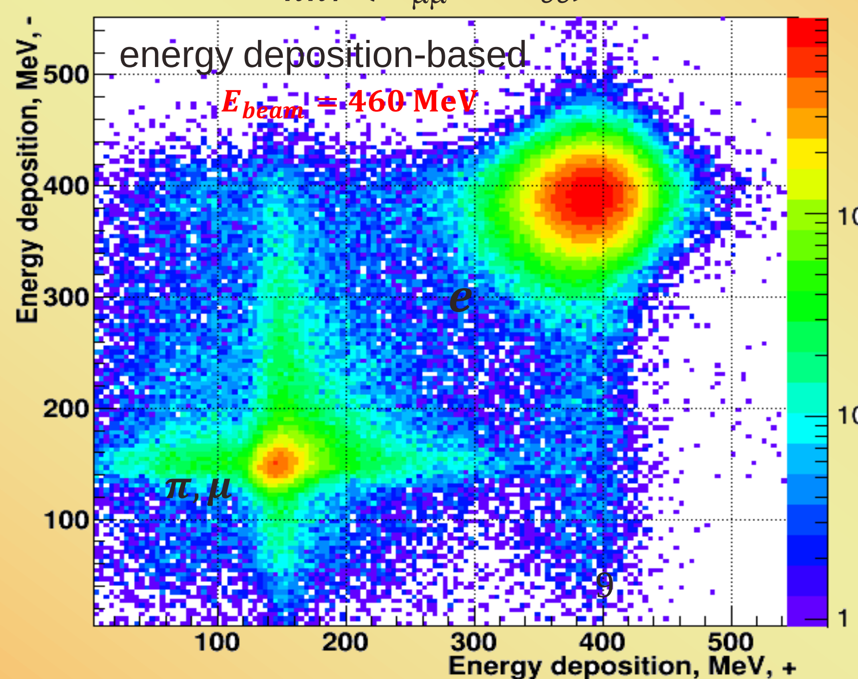


Pion formfactor measurement

- Two pion channel gives the main contribution to the $a^{\mathrm{had,LO}}{}_{\mu}$ (~73%)
- The CMD-3's goal it to measure the $|F_{\pi}|^2$ with 0.4-0.5% systematics uncertainty
- 2013 & 2018 the collected statistics for $\pi^+\pi^-$ a few times larger than in all others experiments taken together
- To control systematics two independent approaches for determination of the number of $\pi^+\pi^-$ events are used: momentum-based and energy deposition-based
- Momentum-based approach works better at low energies (<0.8 GeV) and better the second one at large energies (>0.6 GeV). Using both methods in the middle allows to control systematics

In both cases 2D-likelihood function is constructed to obtain $N_{\pi\pi}/(N_{\mu\mu} + N_{ee})$





Event separation

Separation of $\pi^+\pi^-$, $\mu^+\mu^-$, e^+e^- of final states is based on likelihood minimization of the 2D distributions of momenta of two particles (p+ vs p−) or energy deposition in LXe calorimeter (E+ vs E−).

$$-lnL = -\sum_{events} ln\left[\sum_i N_i f_i(X^+, X^-)\right] + \sum_i N_i$$

where fi(X+, X−) is the probability density functions (PDFs) for e, μ and π

Momentum-based separation:

PDFs are constructed as follows: MC generator spectra are convolved with detector response function (momentum resolution, bremsstrahlung, pion decays). In the whole there were used 36 free parameters in fit per each energy point

Separation based on energy deposition:

PDFs is described by a generic functional form (log-gaus), trained on the data: by tagged electron, cosmic muons and use 57 free parameters in fit

$N_{\pi\pi}/N_{ee}$ – one of the free parameters,

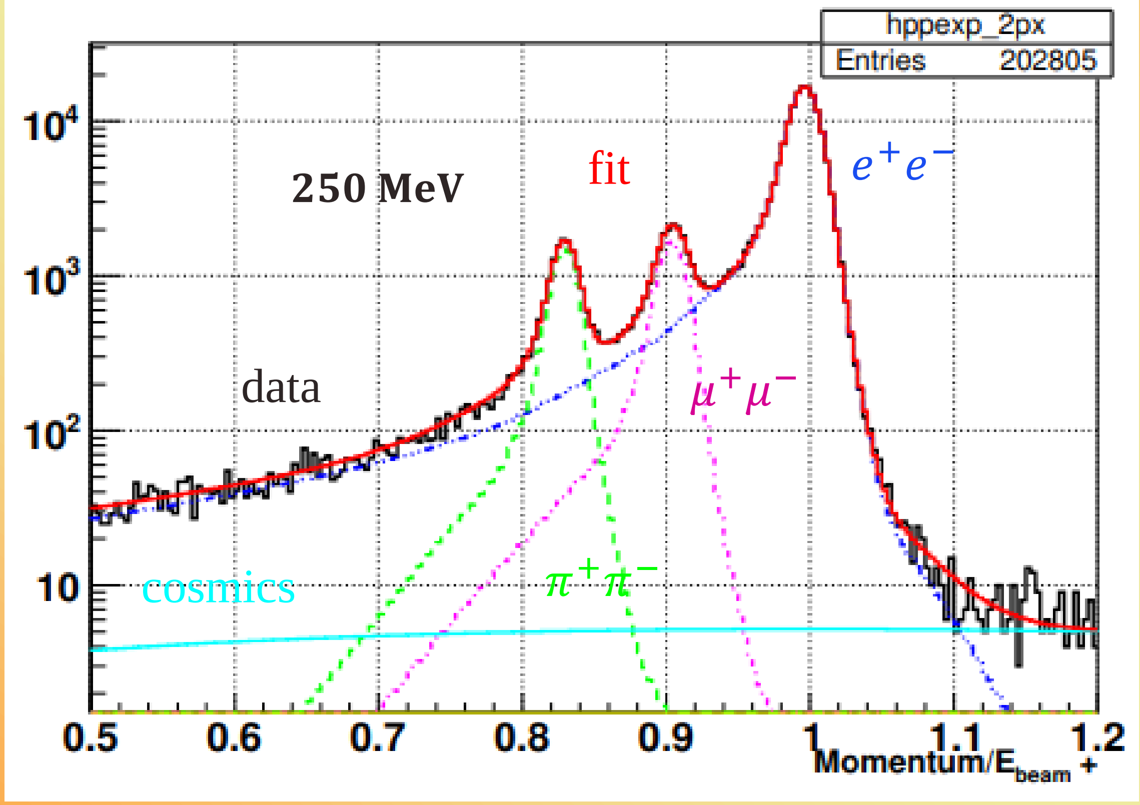
$N_{\mu\mu}/N_{ee}$ – fixed from QED (free at $\sqrt{s}<0.7$ GeV)

Cross-check on full MC confirms consistency between both approaches within 0.2% at ρ energies

Example of PID procedure

The momentum-based procedure, performs better at low energies ($\sqrt{s} \leq 0.9$ GeV) where the difference between momentum pe, pμ and pπ is large enough.

For energy deposition-based procedure the p.d.f.s fi(E+, E−) are constructed purely empirical, with the shape to describe the data.



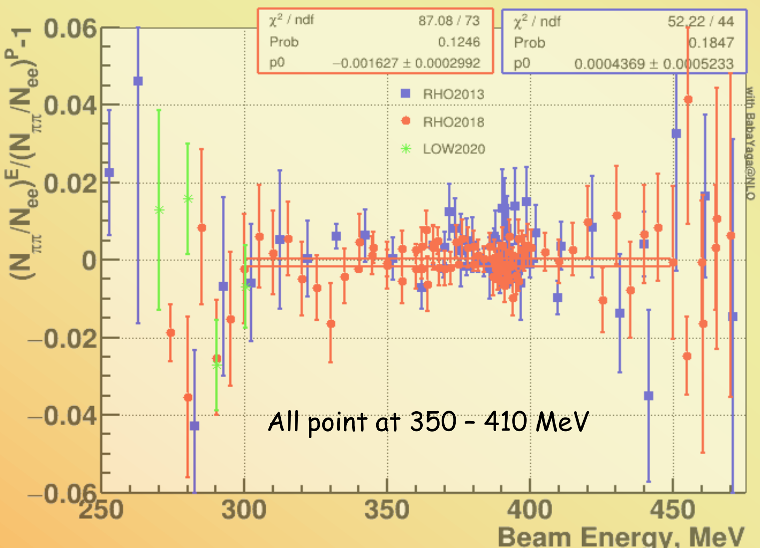
The final ratio Nππ/Nee is obtained as average results of two procedures weighted according to their estimated systematics whereas the ratio Nμμ/Nee is kept fixed to QED prediction.

First test: e/μ/π separation

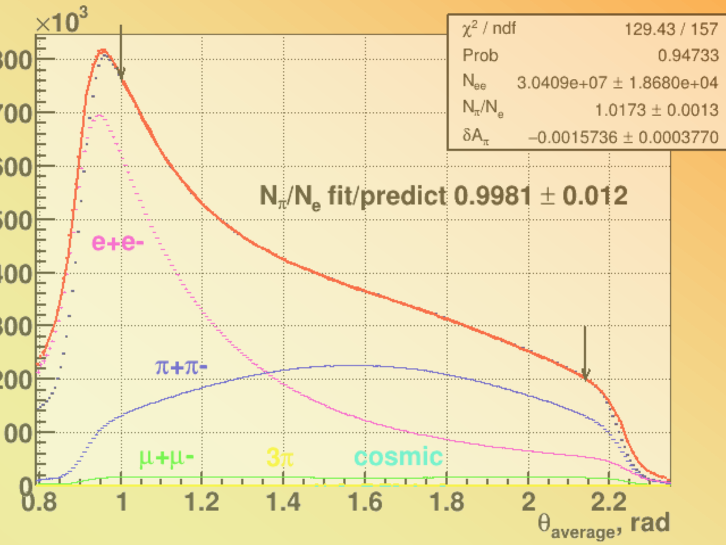
3 methods for $N_{\pi\pi}/N_{ee}$ determination based on independent information:

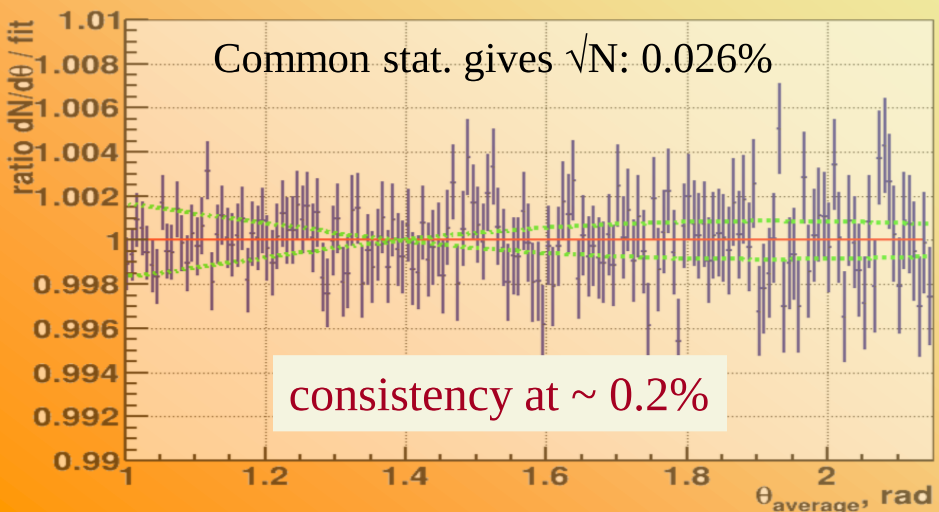
1) Momentum from DCH **2)** Energy deposition in LXe **3)** angles in DCH

E vs P separations



Fit by θ distribution





Common stat. gives √N: 0.026%

consistency at ~ 0.2%

The ratio Nμμ/Nee is fixed to QED
Number of background events is fixed to the result of momentum-based procedure
Nππ/Nee is the free parameter of the fit
Result is: in the most important energy range at the peak and left tail of ρ(770), where all three method were used, showed very good agreement at 0.2% level.

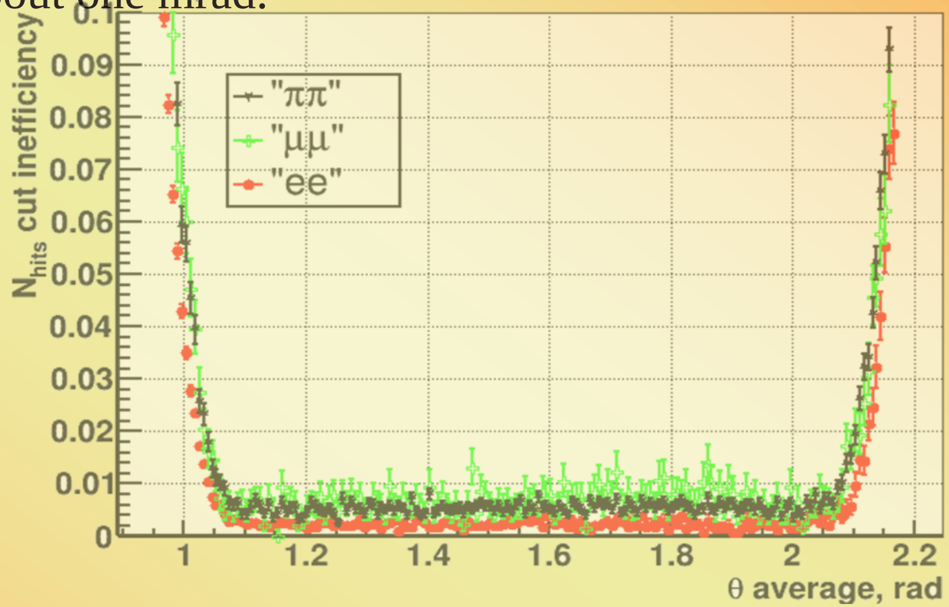
Polar angle systematic study

The some sources of systematics for e/μ/π separation is uncertainty of the fiducial volume (track polar angle in DC), beam energy spread, electron bremsstrahlung loss, pion specific corrections (nuclear interaction with the detector material), radiative corrections, detection and trigger efficiencies and so on.

The cross sections of e/μ/π particles depend significantly on the range of polar angle used in the event selection.

According to simulation to reach the sub-percent precision for the pion form factor, track polar angle Θmin, should be known with precision about one mrad.

- The polar angle is measured by DC using charge division method, but it cannot provide the necessary systematic precision because it depends on the stability of the parameters of electronics which change with time, temperature, external electromagnetic noise and so on.
- Two other detector subsystems provide the precise calibration of the DC wires: Z-chamber, a 2-layer MWPC, and LXe calorimeter, both installed at outer radius of the drift chamber.



- It was shown if we used either Z-chamber or Lxe calorimeter allows us to reach about 2 mrad systematic accuracy for track polar angle Θ.
- As it is seen on graph inefficiencies a bit different for e/μ/π at 0.1% level and must be taken account and inefficiency sharply increase at small polar angle of track in DC

Fit with different θ *selection*

The analysis of detection efficiencies is based on the experimental data and covers inefficiencies of all event selection cuts, trigger, resolution effects and possible reconstructed angle biases and others.

It was established, that one of the largest source of inefficiency comes from the cut on the z coordinate of the vertex (along beam axis) due to the DC length 40 cm. So, particle with $\Theta \approx 1$ rad to cross all wire layers must originate close to center of the DC with $|Zvtx| < 5$ cm whereas the beam size σz varied between 1.3 and 3.0 cm over the years of data taking, leading to up to10% inefficiency.

Dependence on theta cut $\theta_{cut} < \theta^{event} < \pi - \theta_{cut}$

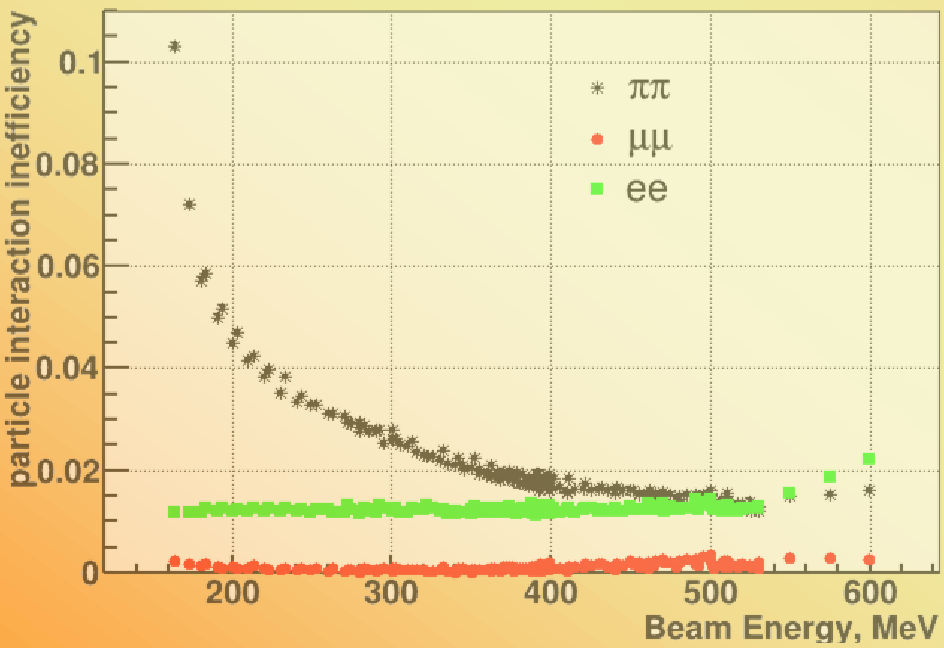
Average at 2E= 0.7-0.82 GeV

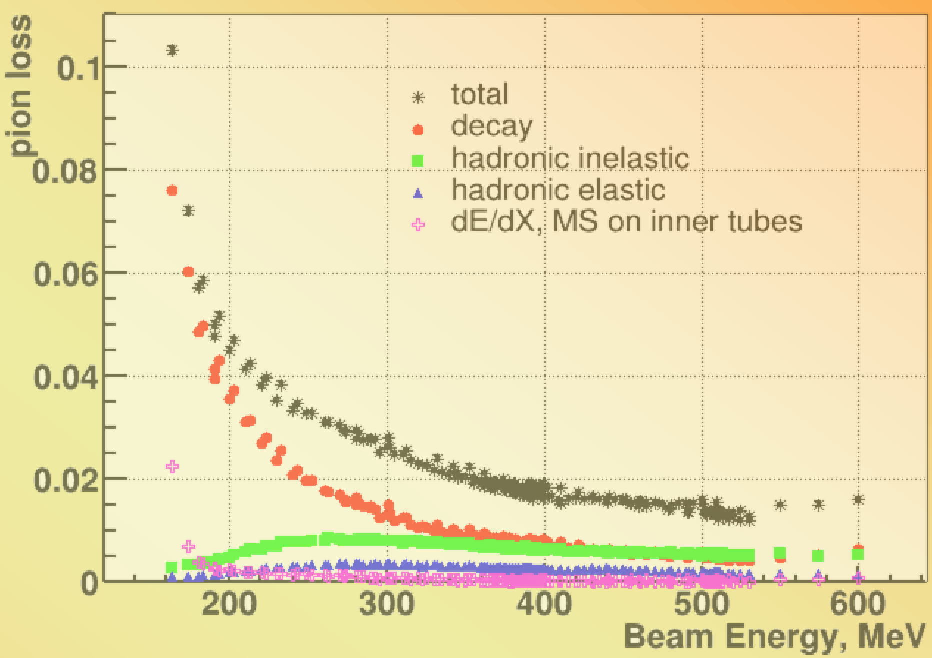
Fortunately, this inefficiency is the same for all final states, thus it cancels out in ratios Nππ/Nee and Nμμ/Nee.

The difference in dE/dx leads to difference in detection efficiencies for e and π in response to cut on number of hit wires along track. The significant drop, up to few percent, was observed at the edge of selected polar angle. After accounting for this inefficiency, no residual effect is observed, which validates the correction.

Systematic study
(particle specific losses)

Bremsstrahlung energy loss, decay in flight, nuclear interaction with materials, multiple scattering on the wall of vacuum tube, … Contribution of these effects are taken from detailed full MC (including detector conditions with time)



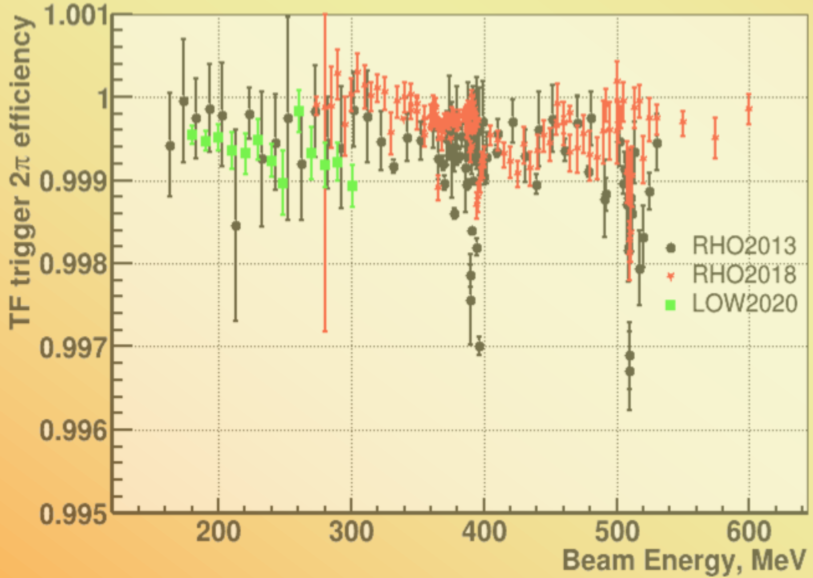


Nuclear interactions mostly on the wall of VEPP-2000 vacuum tube (systematics 0.2%)

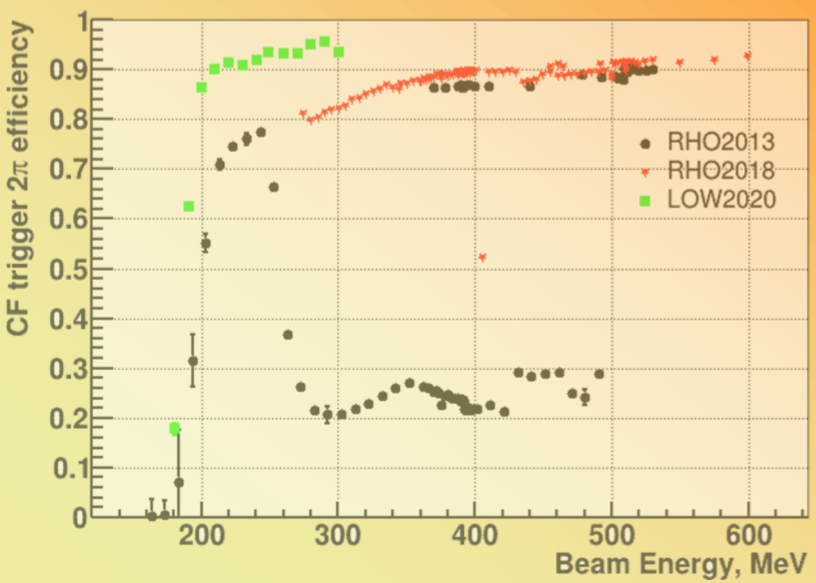
Most dangerous is decay in flight as it depends on detector conditions in time (syst. 0.1-0.2%)

Systematic study
(trigger inefficiency)

Track**F**inder 2π efficiency



Cluster**F**inder 2π efficiency



Having two "independent" first level triggers allows to study an efficiency of certain one by requiring that other presents in an event: $\epsilon_{TF}^{trig} = (N_{TF\&CF}/N_{CF})/(\epsilon_{TF\&CF}^{rec}/\epsilon_{CF}^{rec})$

Trigger efficiencies are evaluated from dependence with polar angle (TF), with energy of two clusters (CF). **Total TF|CF: → ~ >0.9994 for 2π events (and higher for e+e-)**

Out-of-synchronisation trigger issue gives 0.1-0.5% effect to lose both tracks. It leads to trigger systematics 0.05% (<1GeV) – 0.3% (>1GeV) as difference between 2π/e+e-

Systematic study of the radiative corrections

The radiative corrections (RC) calculation are based on two MC generators:

- MCGPJ (Monte Carlo Generator Photon Jets, 0.2% precision) for $e^+e^- \rightarrow e^+e^-/\ \pi^+\pi^-/\mu^+\mu^-$ and BabaYaga (precision 0.1%) for $e^+e^- \rightarrow e^+e^-/\mu^+\mu^-$, when one and more photons are emitted by initial and final electron/positrons with taken into account their interference.
- Two codes use different approximations to describe the emission of multiple photons along the initial or final particles. The careful comparison for $e^+e^- \rightarrow e^+e^-$ process shows that the calculated values of $(1 + \delta_{ee})$ are consistent to better than 0.1%, but the predicted spectra $d\sigma/dp^+dp^-$ differ, leading to systematic shift of results of momentum-based procedure.
- BabaYaga generator predicted momentum spectrum that describes the data well. It was established the difference between two generators due to MCGPJ code based on assumption that photon jets are emitted exactly along parent particle The original version of MCGPJ was modified a bit by taking into account angular distribution of photons in the jet to improve agreement with data.
- By convention, the standard definition of the pion form factor includes the vacuum polarization and the corresponding terms do not need to be additionally taken into account in RC.
- When $\sigma(e^+e^-\rightarrow\pi^+\pi^-)$ is used for the evaluation of hadronic contribution to a_μ, the VP is excluded from cross section and FSR added to the cross section.

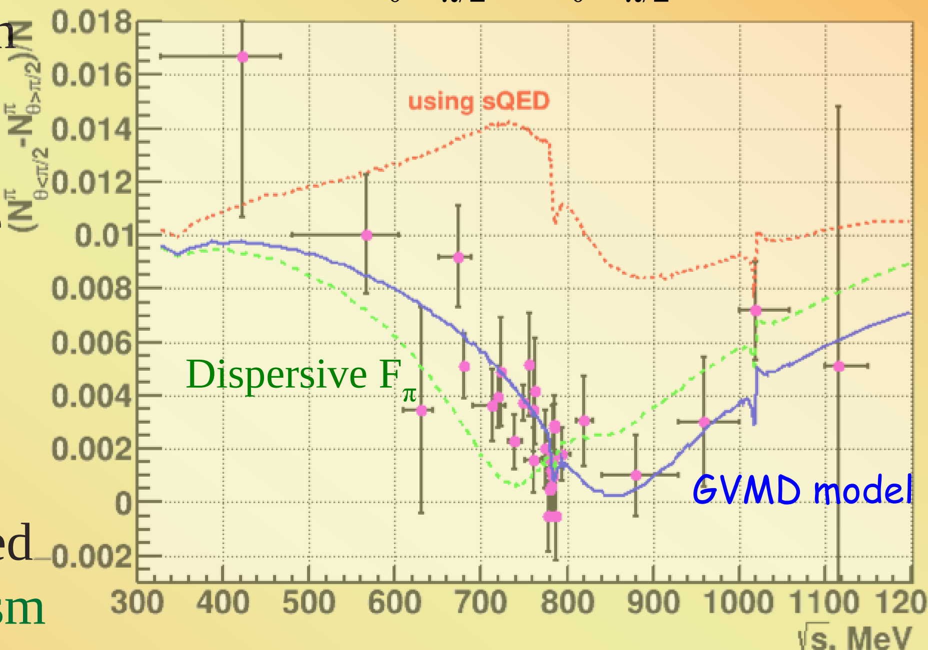
Additional checks
Charge asymmetry in e+e- -> π+π-

Two powerful analysis were done which provide an additional cross check pion form factor measurement.

- **The first one** relates to the forward backward charge asymmetry in $e^+e^- \to \pi^+\pi^-$. Accurate measurement of this effect (value ~ 1%) with respect to much larger asymmetry in $e^+e^- \to e^+e^-$ provides a test of the polar angle accuracy.

$$\delta A = (N_{\theta < \pi/2} - N_{\theta > \pi/2})/N$$

- The energy dependence of the asymmetry observed in CMD-3 disagreed with prediction based on conventional scalar QED (sQED) approach.



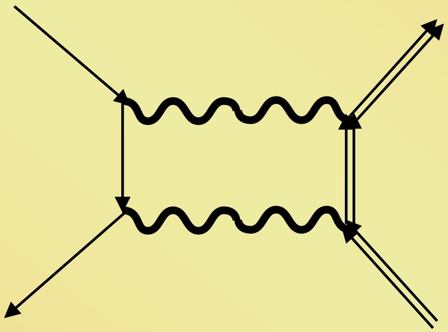
- The generalized vector-meson-dominance (GVMD) model, proposed in [R.Lee et al., Phys.Lett.B 833 (2022) 137283], allowed to overcome this problem and its prediction showed perfect consistent with the CMD-3 observations. The similar result was confirmed by calculation in frame of dispersive formalism (M.Hoferichter et al., JHEP 08 (2022)295). Average relative difference between measured and predicted asymmetry: $\delta A_\pi = (-2.9 \pm 2.3)\cdot 10^{-4}$, $\delta A_e = (-6.0 \pm 2.6)\cdot 10^{-4}$

Conclusion: Ensure our θ angle systematic estimation for $|F_\pi|^2$

sQED assumptions for radiative corrections

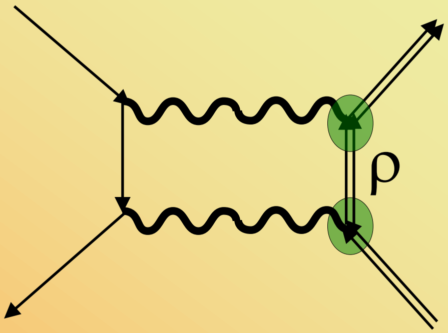
The radiative correction calculations is commonly done in the sQED approach,
It's mean that the calculations are performed without form factor,
then final Amplitude is scaled by $F(q^2)$

Scalar QED approach



$A = sQED*F(s)$

Proper way



$A \sim \int F(q_1)F(q_2)$

Proper way will be to put $F(q^2)$ to each vertex
Roman Lee, this calculation was done with above sQED

Consistency checks

The second test is the measurement of $e^+e^- \to \mu^+\mu^-$ cross section, predicted by QED and was done for momentum-based analysis for $\sqrt{s} < 0.7$ GeV only, where momentum resolution of the tracker allowed to separate muons from other particles.

The number of $\mu^+\mu^-$ pairs is used for cross check QED-prediction ratio:

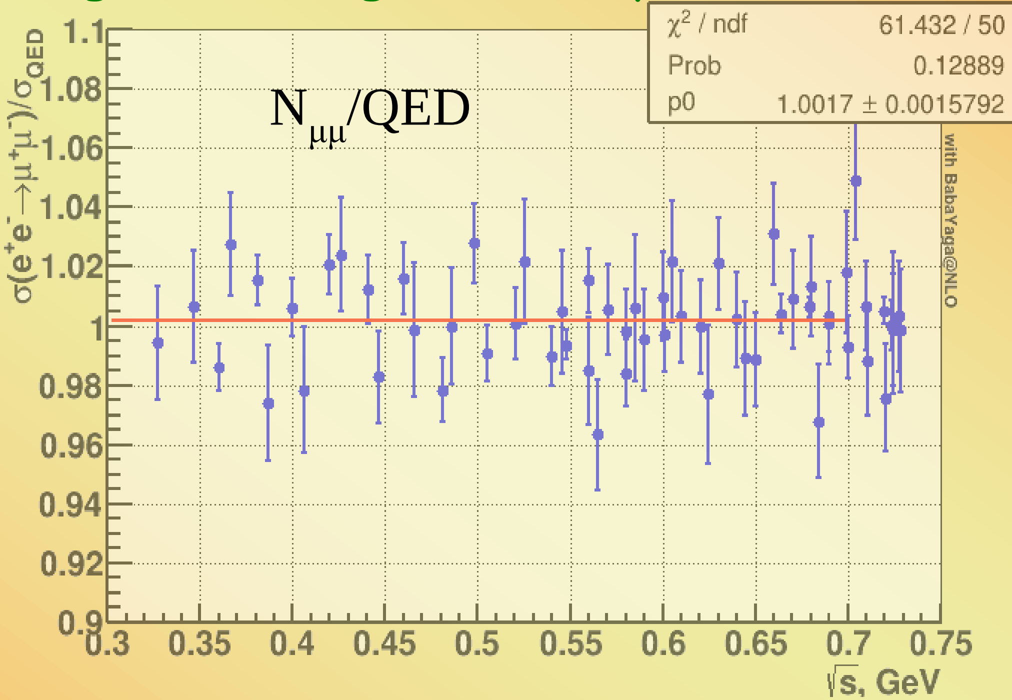
$$N_{\mu+\mu-}/N_{e+e-} = [\sigma^0_{\mu+\mu-}\cdot(1+\delta_{\mu+\mu-})\cdot\varepsilon_{\mu+\mu-}]/[\sigma^0_{e+e-}\cdot(1+\delta_{e+e-})\cdot\varepsilon_{e+e-}]$$

angle/tracking related systematics

The observed average ratio of the measured cross section to the QED prediction is:

1.0017±0.0016

proves the consistency of the most parts of the analysis procedure, including separation procedure, detector effects, evaluation of the RC and etc.



Many others consistency checks were performed too

Summary of systematic study

The estimated systematic error of the pion form factor measurement depends on energy and at the ρ-meson peak, $\sqrt{s} = 0.77$ GeV, is the lowest.

The main sources of the error are listed in Table

Table: Contributions to the systematic error of $|F\pi|^2$

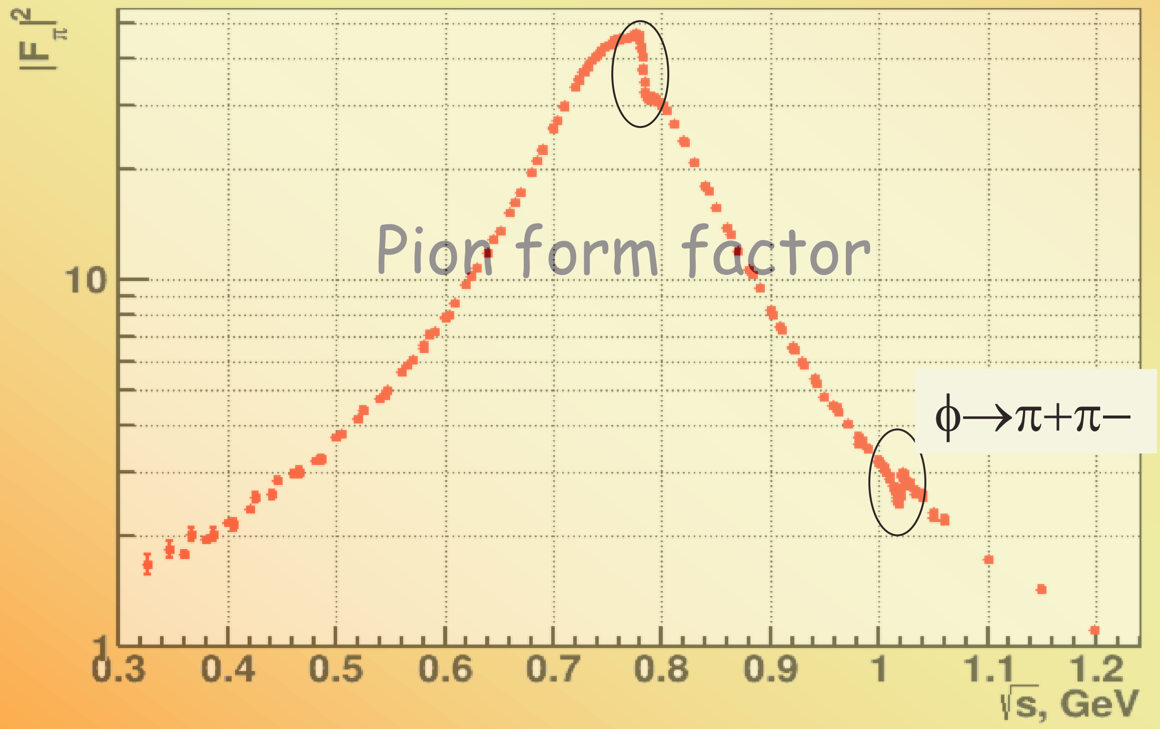
Source	Contribution
Radiative corrections	0.3% (0.2% (2π) $\oplus$ 0.2% (Fπ) $\oplus$ 0.1%)(e+e-)
e/μ/π separation (three procedures)	0.2% (0.5% (low), 0.2% (ρ), 0.6 (φ) %)
Fiducial volume (variation select. cuts)	0.5% / 0.8%
Detector efficiency	0.1%
Beam Energy (by Compton)	0.1% (0.5% at ω, φ -peaks)
Bremsstrahlung loss	0.05%
Pion nuclear interactions	0.2%
Pion decays in flight	0.1%
Total Systematics	0.7% (0.8% at low), 1.6% at φ and higher)

The error rises up to 0.8% toward lower energies due to increased contribution from pion decays in flight and particles separation. The error increase at higher energies, up to 1.6% at $\sqrt{s} = 1.0$ GeV, mainly due of uncertainty of $N_{\mu\mu}/N_{ee}$ ratio

$|F_\pi|^2 = (N_{\pi+\pi-}/N_{e+e-} - \Delta^{bg})\cdot[\sigma^0_{e+e-}\cdot(1+\delta_{e+e-})\cdot\varepsilon_{e+e-}]/[\sigma^0_{\pi+\pi-}\cdot(1+\delta_{\pi+\pi-})\cdot\varepsilon_{\pi+\pi-}]$

Pion form factor fit includes the next contributions:

$$|F_\pi(s)|^2 = \left|\left(\mathrm{BW}_\rho^{GS}(s)\cdot\left(1+\delta_\omega\frac{s}{m_\omega^2}\mathrm{BW}_\omega(s)+\delta_\phi\frac{s}{m_\phi^2}\mathrm{BW}_\phi(s)\right)+ \right.\right.$$
$$\left.\left. + a_{\rho'}\,\mathrm{BW}_{\rho'}^{GS}(s) + a_{\rho''}\,\mathrm{BW}_{\rho''}^{GS}(s) + a_{cont}\right)/(1+a_{\rho'}+a_{\rho''}+a_{cont})\right|^2$$



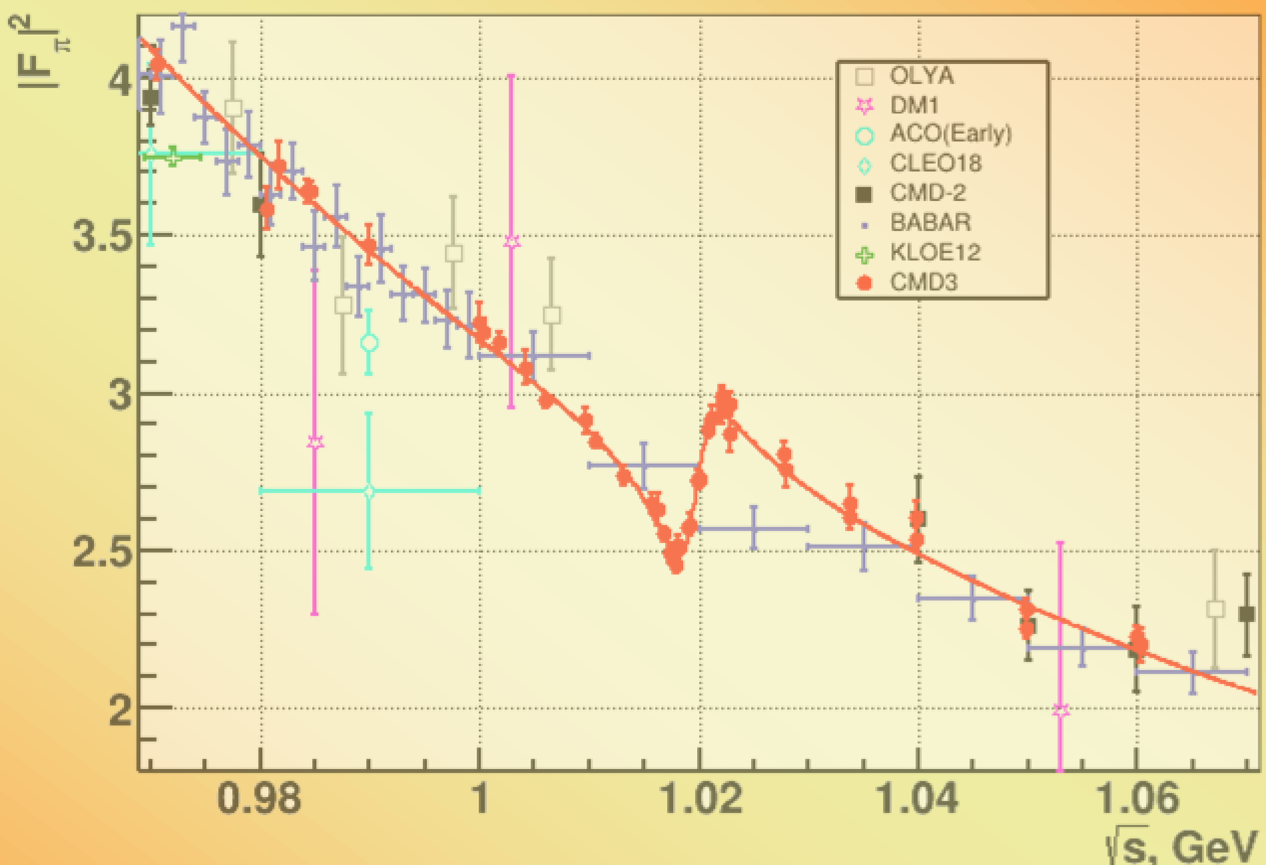
ρ, ρ’, ρ” - by the Gounaris-Sakurai parameterization (GS)

ω, φ - by the constant width relativistic Breit-Wigner

a_{cont} - constant for continuum contribution (partially absorb ρ’, ρ”, ρ”’ , …)

ρ’, ρ” – parameters fixed by combined fit together with CMD-2 and DM2 , √s>1.1 GeV

First direct $|F_\pi|^2$ measurement around φ resonance



CMD3

$\psi_\pi = (-21.3 \pm 2.0 \pm 10.0)°$

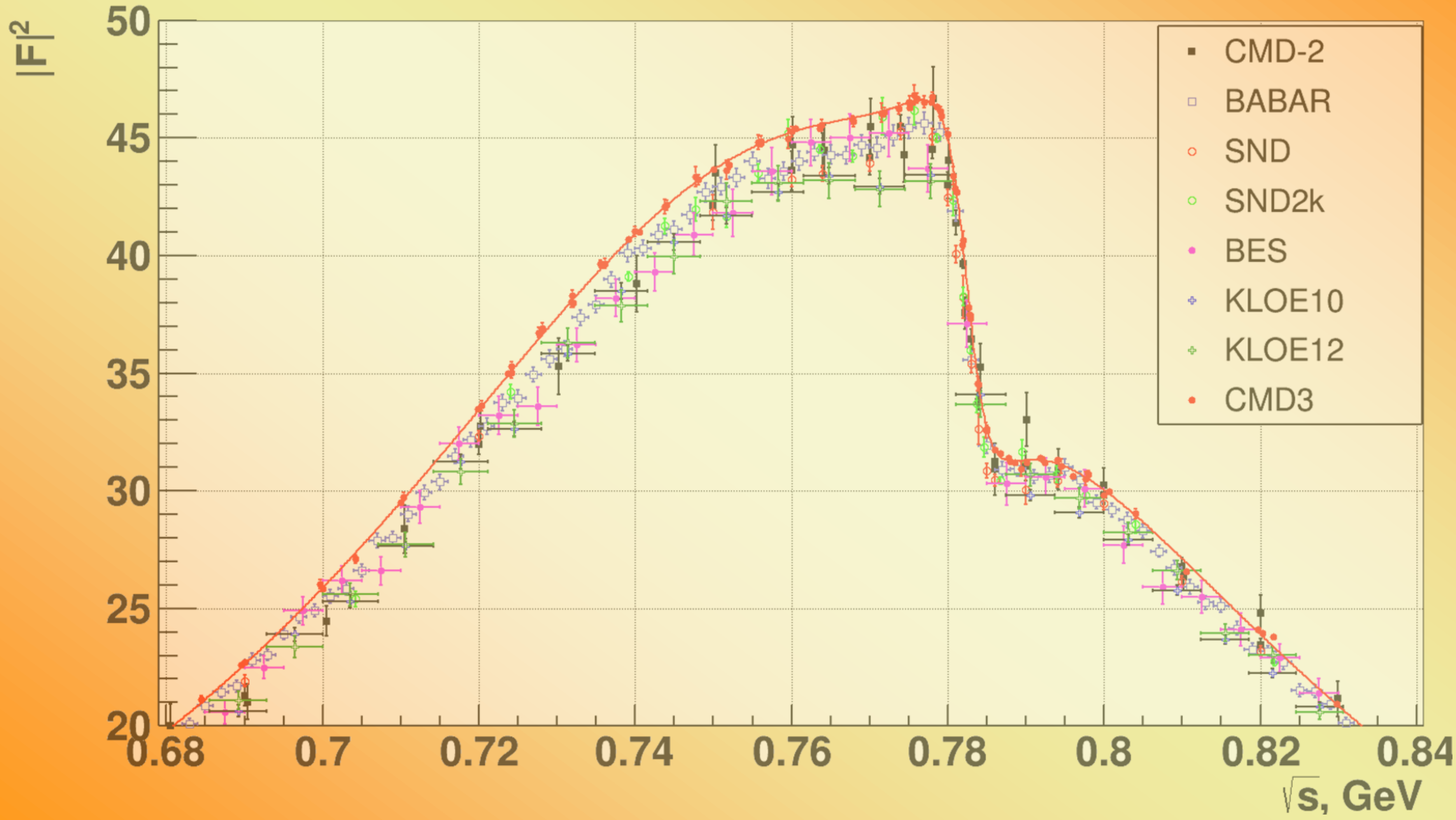
$B(\varphi \to e^+e^-)B(\varphi \to \pi^+\pi^-) =$

$= (3.5 \pm 0.33 \pm 0.24)x10^{-8}$

Previous measurements were based on detected $N_{\pi+\pi-}$ or visible cross-section by OLYA, ND, SND (Phys.Lett.B474:188-193,2000) $\psi_\pi = (-34 \pm 5)°$

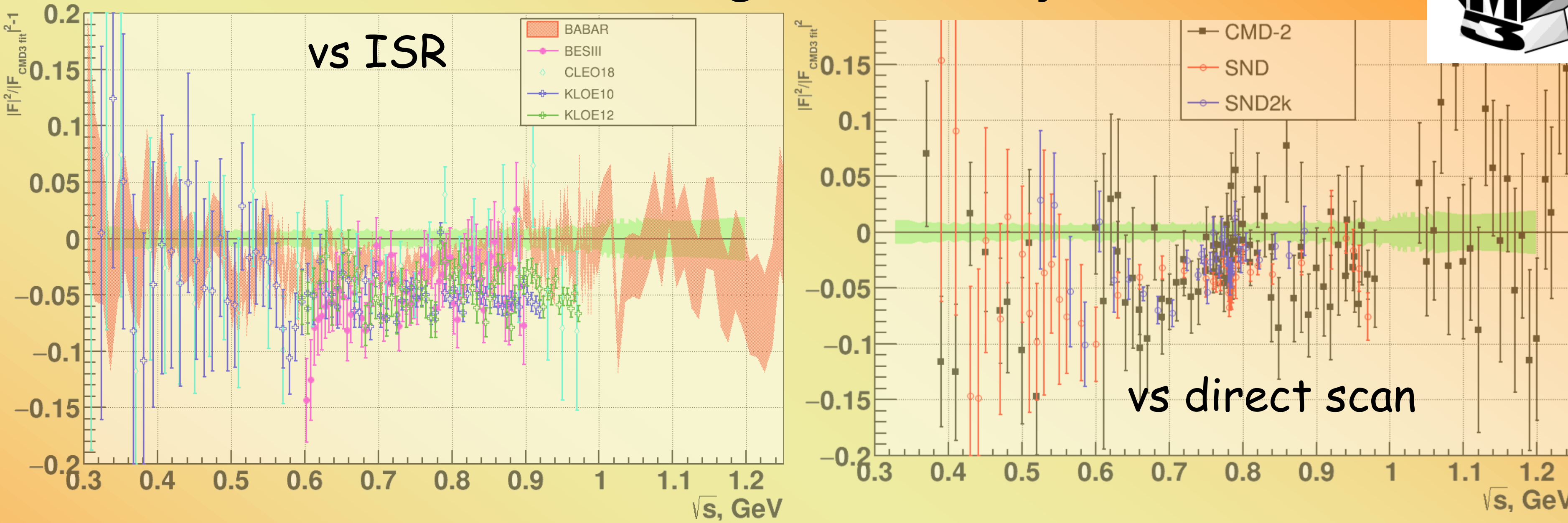
$B(\varphi \to e^+e^-)B(\varphi \to \pi^+\pi^-) = (2.1 \pm 0.4)x10^{-8}$

Pion form factor
CMD3 vs other experiments



CMD3 vs Other experiments

Relative to CMD-3 fit, green band – systematic value



The points are shown relative to the fit of CMD-3 data. The green band around zero reflects the systematic error of our measurement.

The comparison of our measurement with the most precise ISR experiments (BABAR, KLOE) is shown in the left plot. BES and CLEO results are also shown, but have somewhat larger statistical errors.

The comparison with the most precise previous energy scan experiments (CMD-2, SND at the VEPP-2M and SND at the VEPP-2000) is shown in the right plot.

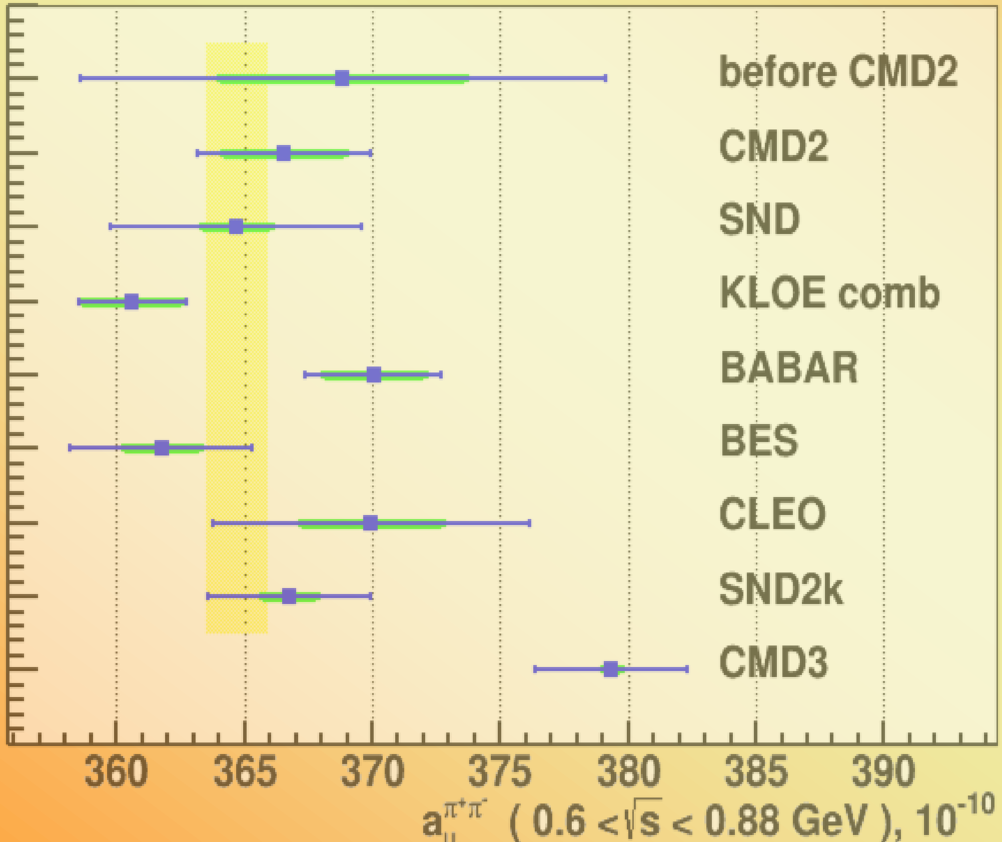
The new CMD3 result generally shows larger pion form factor than previous experiments. The most significant difference, up to 5% is observed at the left slope of ρ-meson ($\sqrt{s} = 0.6 - 0.75$ GeV).

Fit Parameters of Pion Form Factor with PDG

Both errors are statistical
Second error correspond to ρ' , ρ'' fixing

Parameter	value	$M_{\phi,\omega}, \Gamma_{\phi,\omega}$ constrained by PDG's values	PDG(2022) [56]
m_ρ, MeV	$775.41 \pm 0.08 \pm 0.07$	$775.4 \pm 0.07 \pm 0.07$	775.26 ± 0.23
Γ_ρ, MeV	$148.8 \pm 0.16 \pm 0.05$	$148.76 \pm 0.16 \pm 0.06$	147.4 ± 0.8
m_ω, MeV	$782.43 \pm 0.03 \pm 0.01$	$782.44 \pm 0.03 \pm 0.01$	782.66 ± 0.13
Γ_ω, MeV	$8.57 \pm 0.06 \pm 0.01$	$8.59 \pm 0.06 \pm 0.01$	8.68 ± 0.13
$\mathcal{B}_{\omega\to\pi^+\pi^-}\mathcal{B}_{\omega\to e^+e^-}$, 10^{-6}	$1.204 \pm 0.009 \pm 0.003$	$1.204 \pm 0.009 \pm 0.004$	1.28 ± 0.05
$\arg(\delta_\omega)$, rad	$0.167 \pm 0.008 \pm 0.01$	$0.169 \pm 0.008 \pm 0.012$	
m_ϕ, MeV	$1019.761 \pm 0.128 \pm 0.022$	$1019.465 \pm 0.016 \pm 0$	1019.461 ± 0.016
Γ_ϕ, MeV	$4.681 \pm 0.271 \pm 0.058$	$4.25 \pm 0.013 \pm 0$	4.249 ± 0.013
$\mathcal{B}_{\phi\to\pi^+\pi^-}\mathcal{B}_{\phi\to e^+e^-}$, 10^{-8}	$3.65 \pm 0.24 \pm 0.02$	$3.51 \pm 0.22 \pm 0.03$	2.2 ± 0.4
$\arg(\tilde{\delta}_\phi)$, rad	$2.883 \pm 0.052 \pm 0.011$	$2.77 \pm 0.023 \pm 0.006$	
$\lvert a_{cont}\rvert$	$0.0975 \pm 0.0011 \pm 0.0096$	$0.0971 \pm 0.001 \pm 0.0106$	
$\arg(a_{cont})$, rad	$2.337 \pm 0.021 \pm 0.286$	$2.344 \pm 0.02 \pm 0.309$	
χ^2/ndf	212.53 / 195	223.42 / 199	
m'_ρ, MeV	1226.22 ± 24.76		1465 ± 25
Γ'_ρ, MeV	272.97 ± 45.53		$400. \pm 60$
m''_ρ, MeV	1604.66 ± 30.8		1720 ± 20
Γ''_ρ, MeV	249.39 ± 52.24		$250. \pm 100$
$\lvert a'_\rho\rvert$	0.3589 ± 0.0693		
$\lvert a''_\rho\rvert$	0.1042 ± 0.031		
$\arg(a'_\rho)$, rad	-1.831 ± 0.07		
$\arg(a''_\rho)$, rad	3.384 ± 0.234		
χ^2/ndf CMD3+CMD2+DM2	288.87/240 $\chi^2 = 220.08$(CMD3)+25.30(CMD2)+40.10(DM2)+3.39(PDG) ndf= 207+29+20+4 - 12$(\rho, \omega, \phi, cont)$ - 8(ρ', ρ'')		

The π+ π− contribution to $a_\mu^{had,LO}$



	1$a_\mu^{\pi\pi\ ,LO}$, 10^{-10}
before CMD2	368.8 ± 10.3
CMD2	366.5 ± 3.4
SND	364.7 ± 4.9
KLOE	360.6 ± 2.1
BABAR	370.1 ± 2.7
BES	361.8 ± 3.6
CLEO	370.0 ± 6.2
SND2k	366.7 ± 3.2
CMD3	379.3 ± 3.0

$\Delta a_\mu^{\pi\pi}$(CMD3-CMD2) more than 2.5 σ

The contribution π+π− channel to the value $a\mu^{had;\ LO}$, calculated using only CMD-3 measurement, is: $a\mu^{had;LO} = 526(4.2)\times10^{-10}$, which should be compared to $506(3.4)\times10^{-10}$ based on the average of all previous measurements (about 5σ).

It is necessary underline the value of the estimated error, 4.2×10^{-10}, is completely determined by the systematic uncertainty.

Hadronic contribution to $a_\mu^{had;LO}$

Replacing in the complete calculation of $a_\mu^{had;LO}$ the $\pi^+\pi^-$ contribution with our value, we found the resulting SM prediction for the anomalous magnetic moment of muon in a good agreement, within 0.9 standard deviations:

a_μ(exp, FNAL+ BNL) − a_μ(SM based only on CMD-3) = $4.9(5.5)\times10^{-10}$.

Agreement between a_μ(exp) and a_μ(SM) at the current level of precision goes well with no BSM signal found at LHC at energies up to ~1 TeV.

Doing a_μ test with higher precision will allow to go beyond LHC, but it will be possible, if accuracy of the hadronic cross sections measurement will be significantly improved too.

At the moment hadronic contribution continues to be a limiting factor and inconsistency between different experiments gives dominant uncertainty. Difference between world average and CMD3 is about 5 sigma. To understand of the sources of this discrepancy requires both the rethinking of the experimental techniques and related systematic uncertainties.

Exclusive channels of $e^+e^- \to hadrons$

Event signature	Final state (published/submitted, in progress, are waited)
2 charged	$\pi^+\pi^-$ K^+K^- K_SK_L $p\bar{p}$ $\pi^+\pi^-\gamma$
2 charged + γ's	$\pi^+\pi^-\pi^0$ $\pi^+\pi^-2\pi^0$ $\pi^+\pi^-3\pi^0$ $\pi^+\pi^-4\pi^0$ $\pi^+\pi^-\eta$ $\pi^+\pi^-\pi^0\eta$ $\pi^+\pi^-2\pi^0\eta$ $K^+K^-\pi^0$ $K^+K^-2\pi^0$ $K^+K^-\eta$ $K_SK_L\pi^0$ $K_SK_L\eta$ $\eta'(958)$
4 charged	$2\pi^+2\pi^-$ $K^+K^-\pi^+\pi^-$ $K_SK^\pm\pi^\mp$
4 charged + γ's	$2\pi^+2\pi^-\pi^0$ $2\pi^+2\pi^-2\pi^0$ $\pi^+\pi^-\eta$ $\pi^+\pi^-\omega$ $2\pi^+2\pi^-\eta$ $K^+K^-\omega$ $K_SK^\pm\pi^\mp\pi^0$ $D^{*0}(2007)$
6 charged	$3\pi^+3\pi^-$ $K_SK_S\pi^+\pi^-$ KsK±π∓π+π–
6 charged + γ's	$3\pi^+3\pi^-\pi^0$
Fully neutral	$\pi^0\gamma$ $2\pi^0\gamma$ $3\pi^0\gamma$ $\eta\gamma$ $\pi^0\eta\gamma$ $2\pi^0\eta\gamma$
Other	$n\bar{n}$ $\pi^0e^+e^-$ ηe^+e^-

Published/submitted results:

$3\pi^+3\pi^-$: PLB 723 (2013) 82-89

η': PLB 740 (2015) 273-277

$p\bar{p}$: PLB 759 (2016) 634-640

$K^+K^-\pi^+\pi^-$: PLB 756 (2016) 153-160

K^+K^- (at $\phi(1020)$): PLB 779 (2018) 64-71

$2\pi^+2\pi^-$ (near $\phi(1020)$): PLB 768 (2017) 345-350

$\omega\eta, \eta\pi^+\pi^-\pi^0$: PLB 773 (2017) 150-158

K_SK_L (at $\phi(1020)$): PLB 760 (2016) 314-319

$3\pi^+3\pi^-\pi^0$: PLB 792 (2019), 419-423

$K^+K^-\eta$: arXiv:1906.08006, accepted by PLB

$\pi^+\pi^-\eta$: submitted to PLB

Summary

- CMD-3 has taken ~750 pb^{-1} of data in the whole energy range $0.32 \leq \sqrt{s} \leq 2.0$ GeV and is going to take ~ 250 pb^{-1} in the next years
- VEPP-2000 collider is only one working this days on direct scanning below 2 GeV for measurement of exclusive σ (e+e- → hadrons)
- CMD-3 pion form factor measurement is based on full data set at √s < 1 GeV 34 x 10^6 of π+π- events was used in analysis (at √s<1 GeV)
- At the current moment the combine NEW FNAL with BNL result for AMM of muon demonstrates inconsistency between different experiments which give the dominant uncertainty in the calculation of the hadronic contribution within the framework of the SM
- Some upgrade of the CMD-3 detector subsystems are planned (endcap and barrel coordinate counters, new drift chamber and so on)
- Many analyses with hadronic CS have been published. Many others are in progress

Thank you *for attention*!