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Study of e+e- annihilation to hadrons at the VEPP-2000 collider

On the behalf of CMD3 and SND Collaborations

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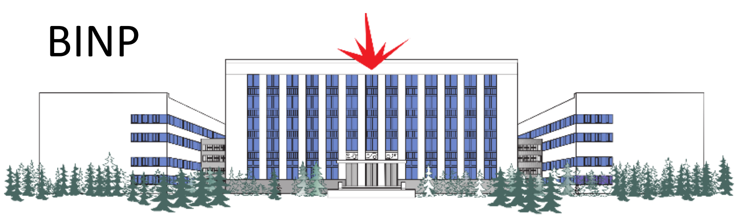
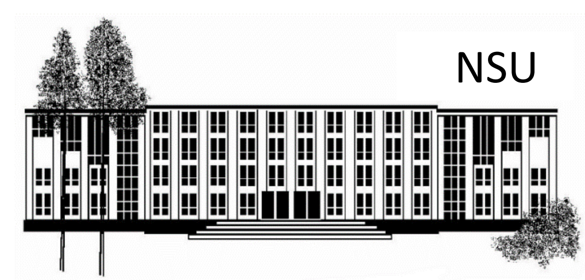
BINP





Introductory comments

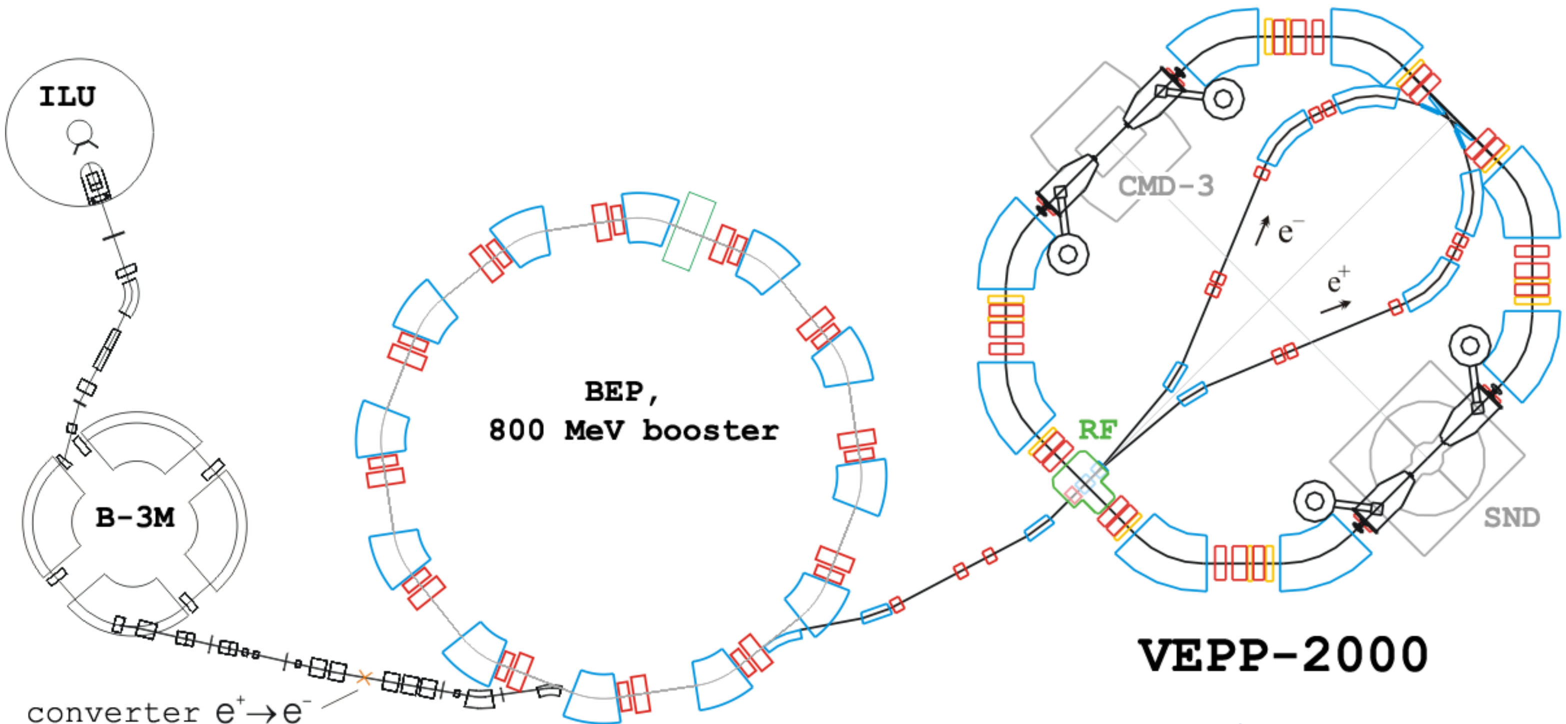
The main goal of experiments at VEPP-2000:

- *a measurement of the total and exclusive cross sections of* $e^+e^- \rightarrow hadrons$ *with high precision*
- *a study of spectroscopy of light vector mesons and their excitations*
- *investigation of mesons with various* J^{PC}
- *production of* $p\bar{p}$ *and* $n\bar{n}$ *pairs near threshold*
- *two-photon physics*
- *searches for various exotics*

Implications of high-precision measurements of low energy cross sections:

- *muon anomalous magnetic moment,* a_μ
- *the running* α
- $m_{u(d)}$ *and quark/gluon condensates from QCD sum rules*
- *tests of CVC by comparing* e^+e^- *and* τ

VEPP-2000 e^+e^- complex (before upgrade)

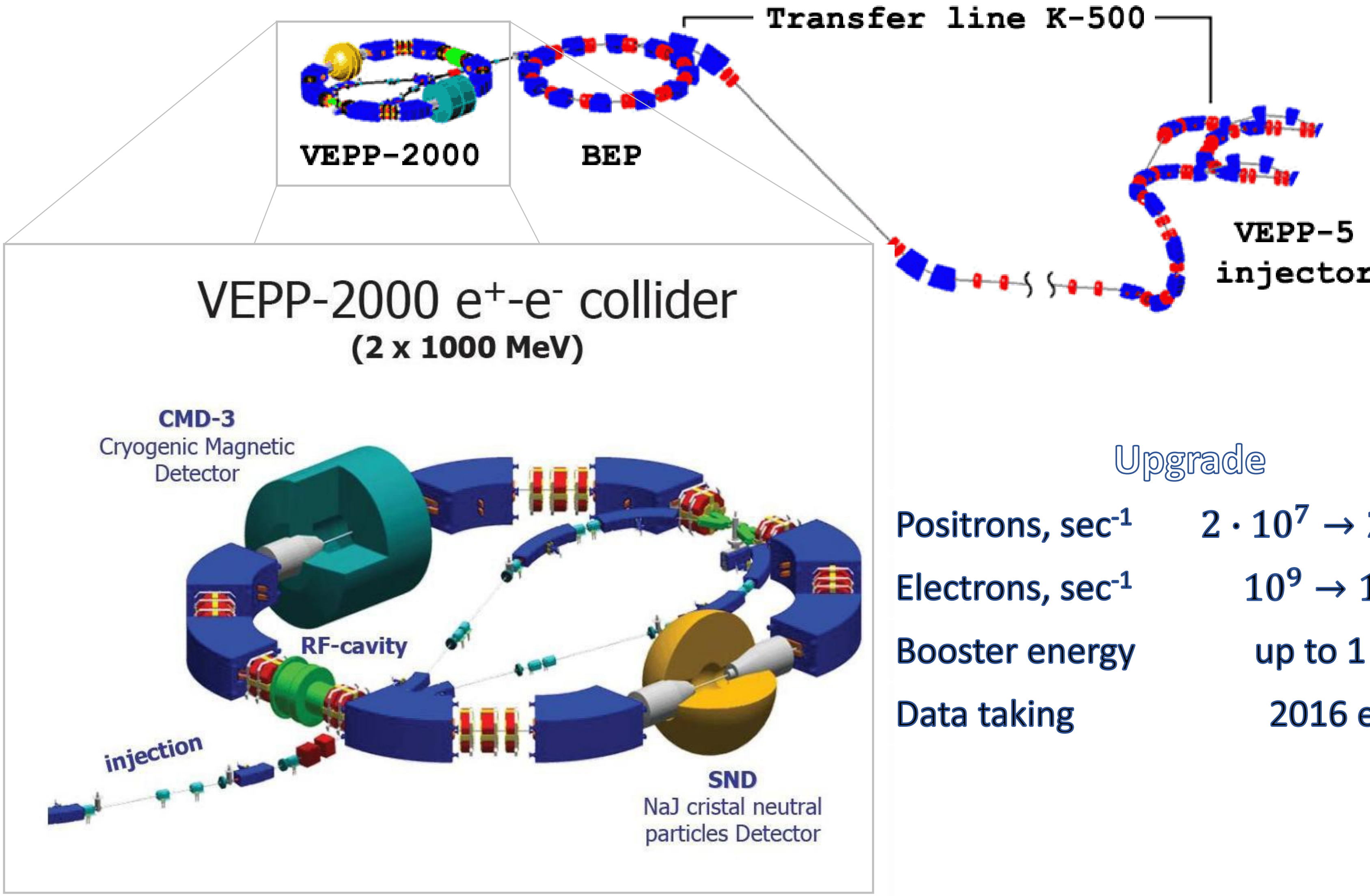


VEPP-2000 main parameters

Energy $\sqrt{s}$, GeV	0.3 – 2.0
Circumference, m	24.4
Beam optics	round
Positron source	converter $e^-\rightarrow e^+$
Luminosity (at 2 GeV), $cm^{-2}\ sec^{-1}$	1×10^{32} (project) 2×10^{31} (achieved)

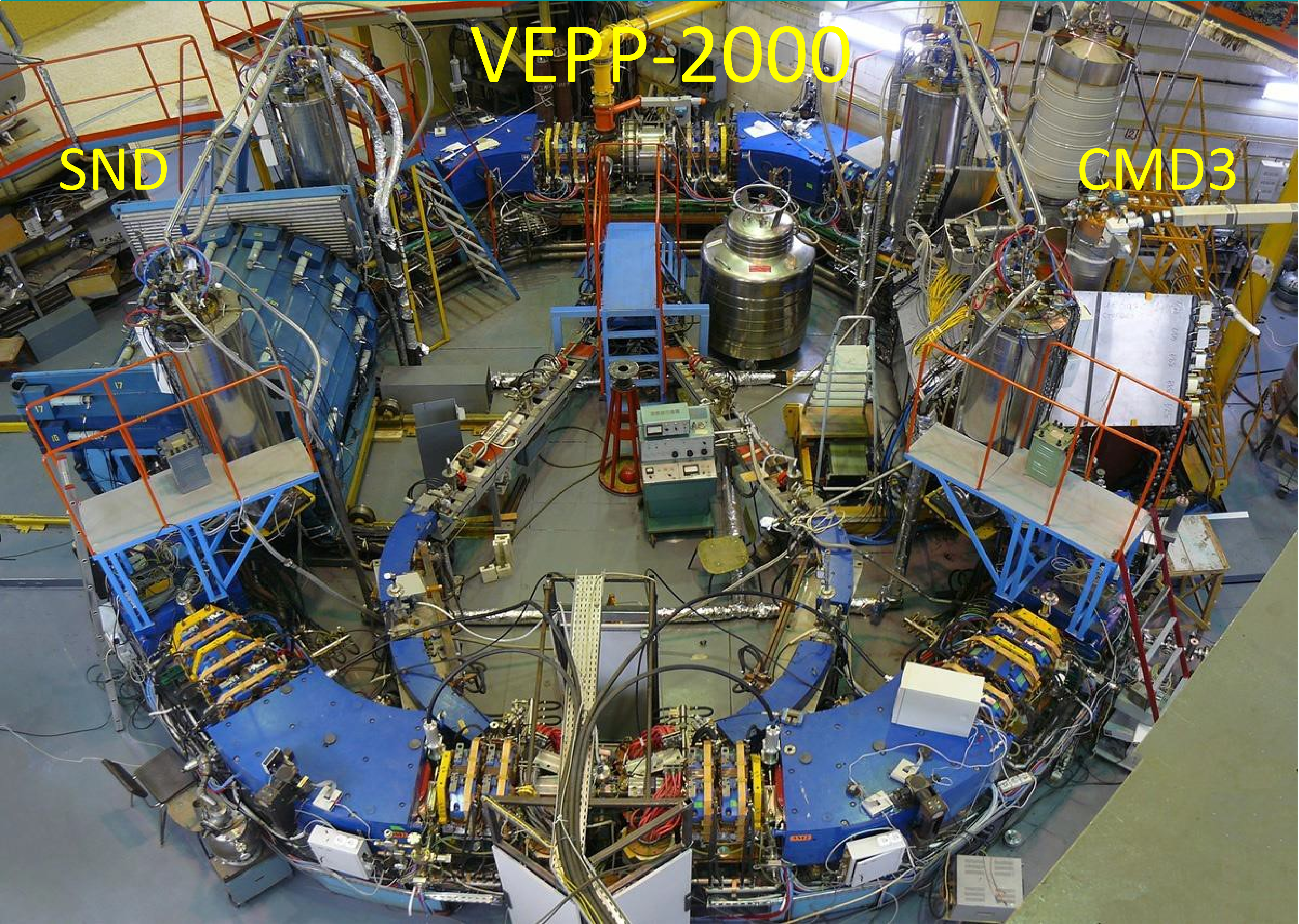
During 2010-2013 the luminosity was limited by shortage of positrons

VEPP-2000 e^+e^- complex (after upgrade)

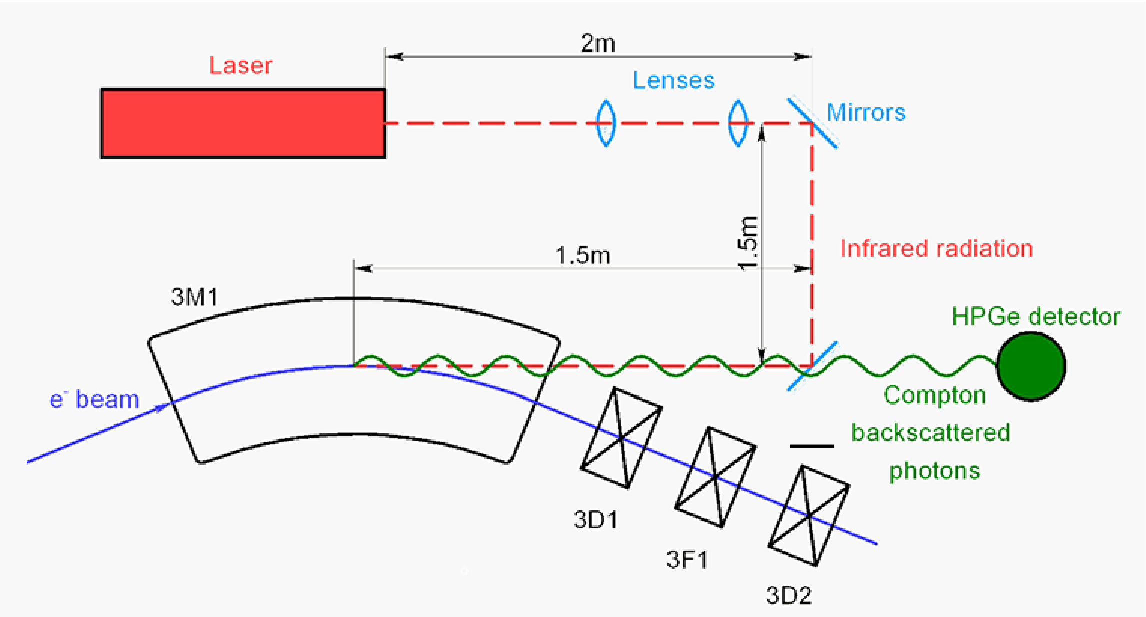


Upgrade

Positrons, sec^{-1}	$2 \cdot 10^7 \rightarrow 2 \cdot 10^8$
Electrons, sec^{-1}	$10^9 \rightarrow 10^{11}$
Booster energy	up to 1 GeV
Data taking	2016 end


VEPP-2000
SND
CMD3

Beam energy measurements: CBS system

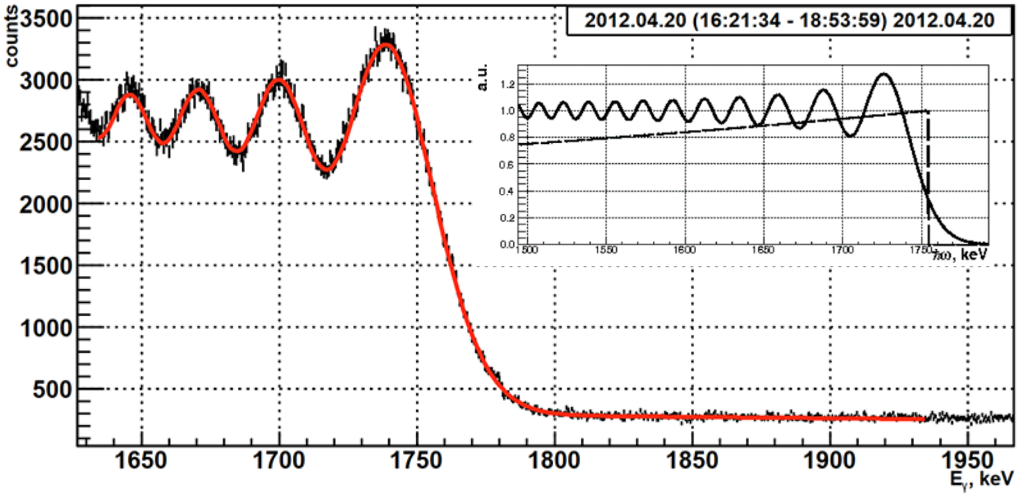


The systematic error of the beam energy determination is tested by comparison with a measurement using the resonance depolarization method:

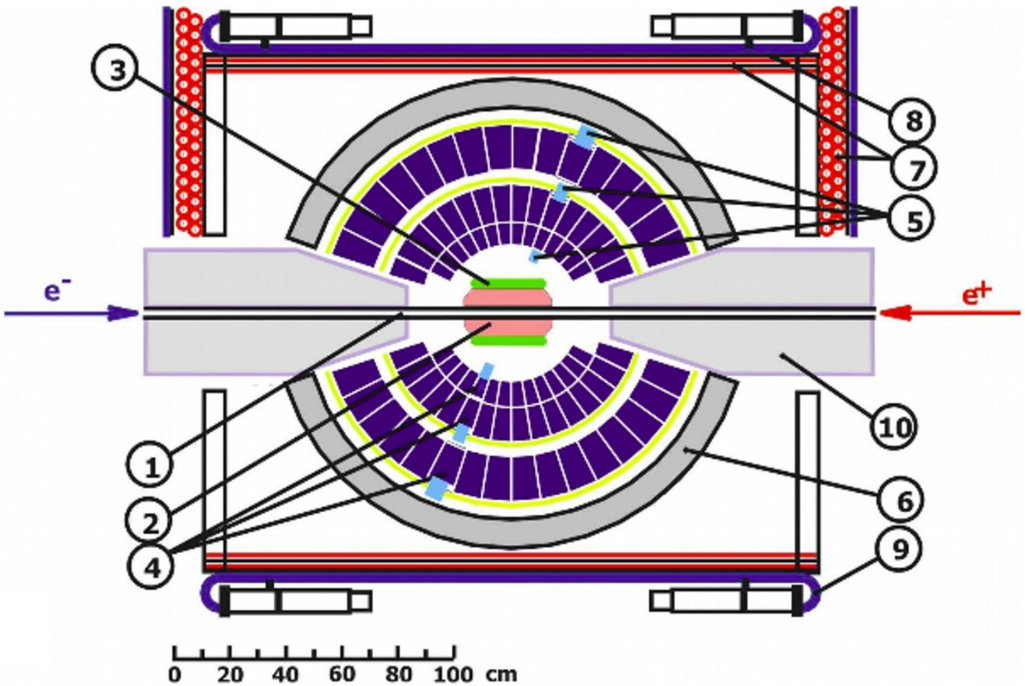
$$\frac{\Delta E}{E} \leq 5 \cdot 10^{-5}$$

The high accuracy of collider beam energy determination is crucial for a lot of physical studies. For example, in order to measure the cross section of the process $e^+e^- \to \pi^+\pi^-$ with accuracy better than 1%.

E = 993.662 ± 0.016 MeV



*S*pherical *N*eutral *D*etector



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.

Calorimeter

Thickness	$13.5\ X_0$
Acceptance	$0.95 \times 4\pi$
Energy resolution	$\frac{\sigma_E}{E} = \frac{0.042}{\sqrt[4]{E[GeV]}}$
Angular resolution	$\sigma_{\phi,\theta} = \frac{0.82^{\circ}}{\sqrt[4]{E[GeV]}} \oplus 0.63^{\circ}$

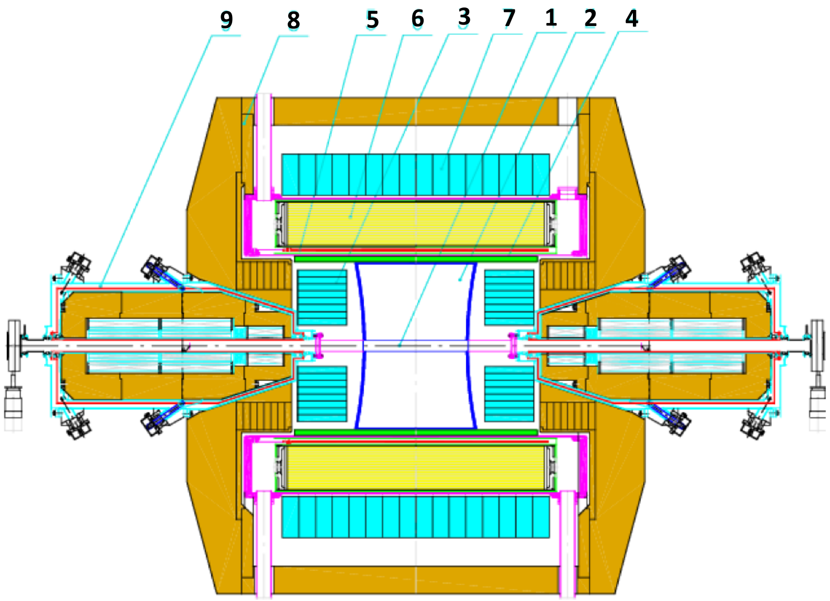
Tracking system

Acceptance (9 layers)	$0.94 \times 4\pi$
Angular resolution	$\sigma_\phi = 0.55^{\circ}, \sigma_\theta = 1.2^{\circ}$
Vertex resolution	$\sigma_R = 0.12cm, \sigma_Z = 0.45cm$

Aerogel counters

K/π separation	E < 1 GeV

Cryogenic Magnetic Detector 3

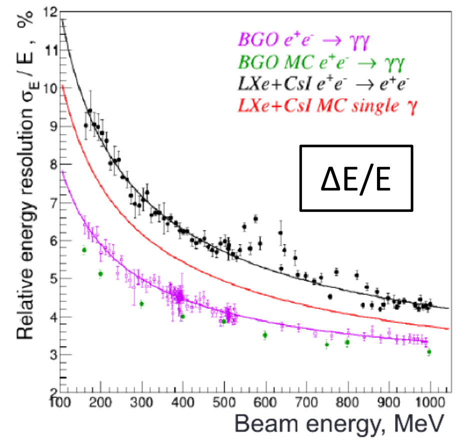


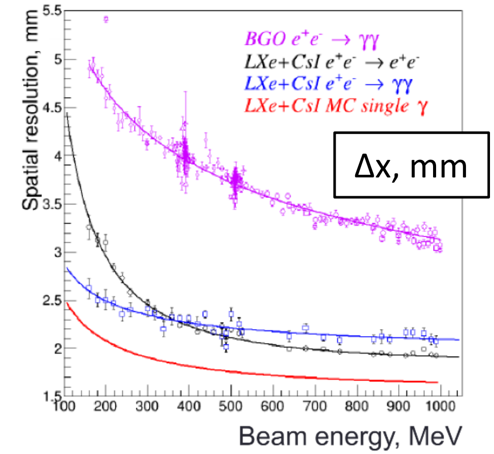
1 – *vacuum chamber*, 2 – *drift chamber*, 3 – *electromagnetic calorimeter BGO*, 4 – *Z-chamber*, 5 – *CMD SC solenoid*, 6 – *electromagnetic calorimeter LXe*, 7 – *electromagnetic calorimeter CsI*, 8 – *yoke*, 9 – *VEPP-2000 solenoid*

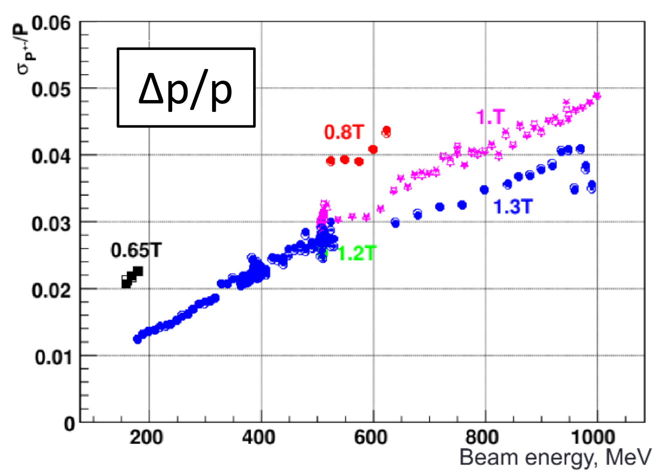
Calorimeter performance (LXE, CsI, BGO):

$1.0-1.3\ T$ $13.5\ X_0$

$\sigma_E/E \sim 3\% - 10\%$ $\sigma_\Theta \sim 5$ mrad







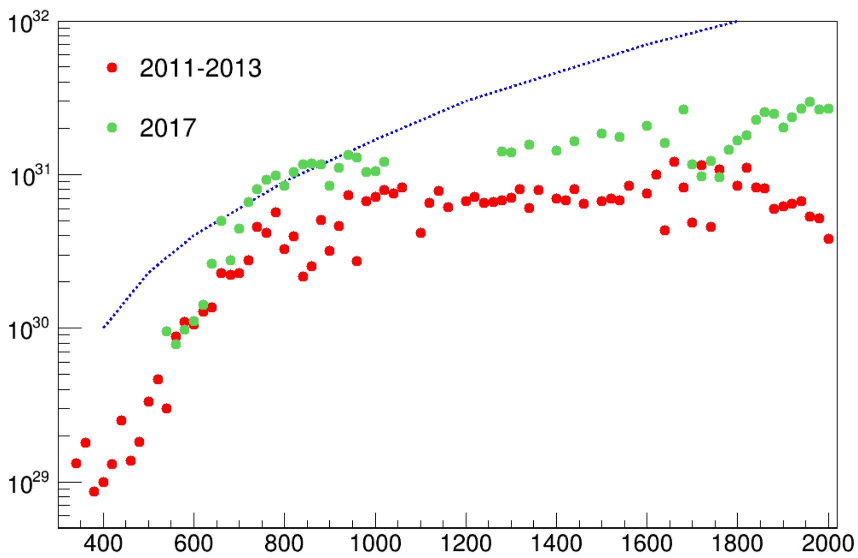
Tracking performance:

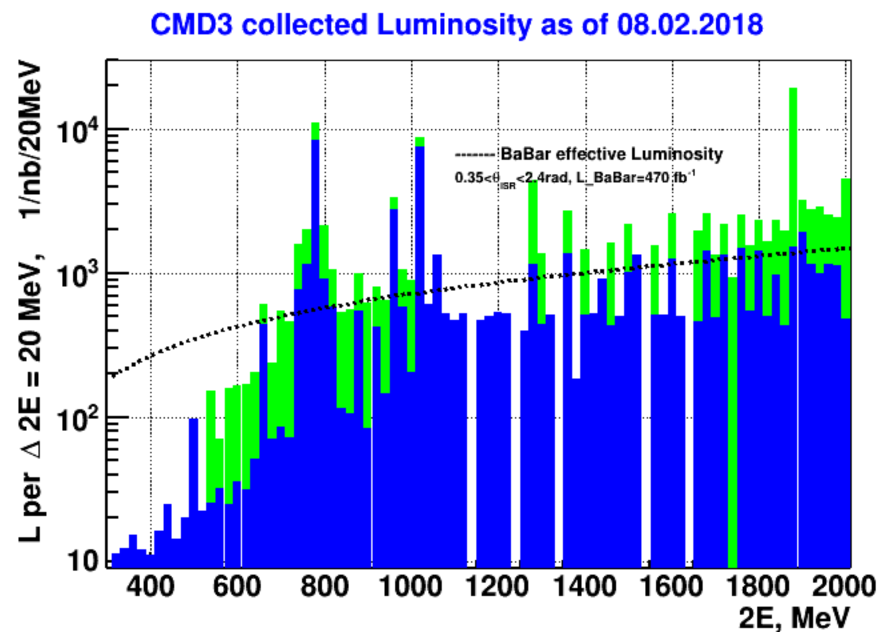
$1.0-1.3\ T$

$\sigma_{R\phi} = 100\ \mu$

$\sigma_Z = 2-3mm$

Luminosity. Data taking





2010-2013

ω-region	8.3 pb^{-1}
Below 1 GeV (except ω)	9.4 pb^{-1}
ϕ-region	8.4 pb^{-1}
Above ϕ	41 pb^{-1}
Overall	67 pb^{-1}

2017-2018

$e^+e^- \rightarrow D^{0*}$ (2.007 GeV)	4 pb^{-1}
$p\bar{p}$ and $n\bar{n}$ threshold	14 pb^{-1}
Overall:	
1.28 – 2.007 GeV	50 pb^{-1}
0.55 – 1.00 GeV	20 pb^{-1}

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

At VEPP-2000 we do exclusive measurement of $\sigma(e^+e^- \to hadrons)$

- **2 charged**

$$e^+e^- \to \pi^+\pi^-,\ K^+K^-,\ K_SK_L,\ \ p\bar{p}$$

- **2 charged + γ's**

$$e^+e^- \to \pi^+\pi^-\pi^0,\ \pi^+\pi^-\eta,\ K^+K^-\pi^0,\ K^+K^-\eta,\ K_SK_L\pi^0,\ \pi^+\pi^-\pi^0\eta,$$
$$\pi^+\pi^-\pi^0\pi^0,\ \pi^+\pi^-\pi^0\pi^0\pi^0,\ \pi^+\pi^-\pi^0\pi^0\pi^0\pi^0$$

- **4 charged**

$$e^+e^- \to \pi^+\pi^-\pi^+\pi^-,\ K^+K^-\pi^+\pi^-,\ K_SK^*$$

- **4 charged + γ's**

$$e^+e^- \to \pi^+\pi^-\pi^+\pi^-\pi^0,\ \pi^+\pi^-\eta,\ \pi^+\pi^-\omega,$$
$$\pi^+\pi^-\pi^+\pi^-\pi^0\pi^0,\ \ K^+K^-\eta,\ K^+K^-\omega$$

- **6 charged**

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

- **γ's only**

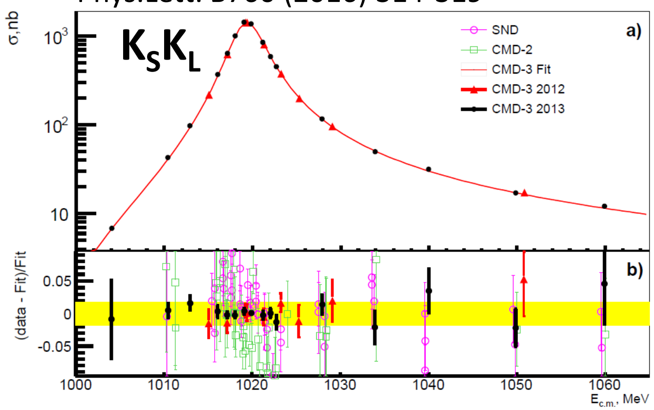
$$e^+e^- \to \pi^0\gamma,.\eta\gamma,\ \pi^0\pi^0\gamma,\ \pi^0\eta\gamma,\ \pi^0\pi^0\pi^0\gamma,\ \ \pi^0\pi^0\eta\gamma,\ K_SK_L,\ K_SK_L\pi^0$$

- **Other**

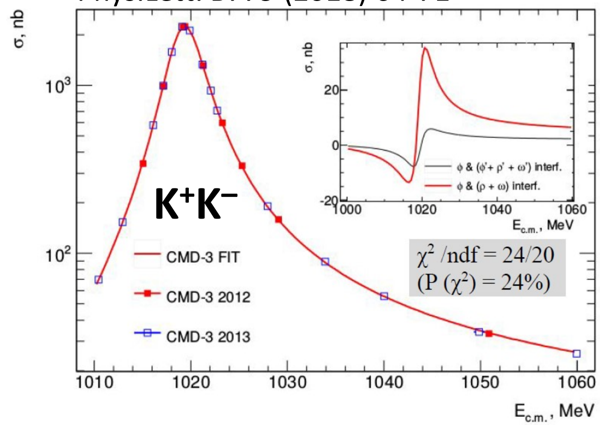
$$e^+e^- \to n\bar{n},\ \ \pi^0e^+e^-,\ \eta e^+e^-,\ \eta'$$

CMD-3 published results from 2011-2013

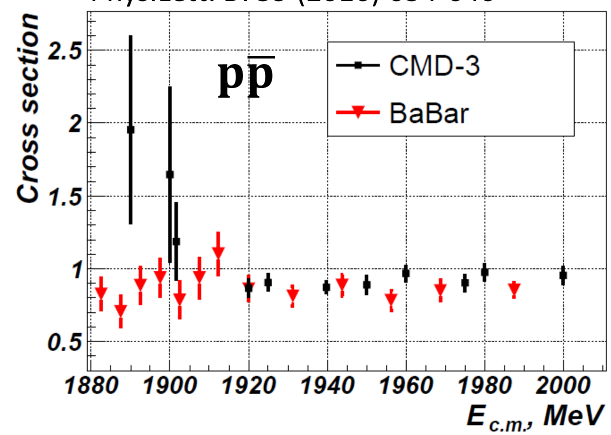
Phys.Lett. B760 (2016) 314-319



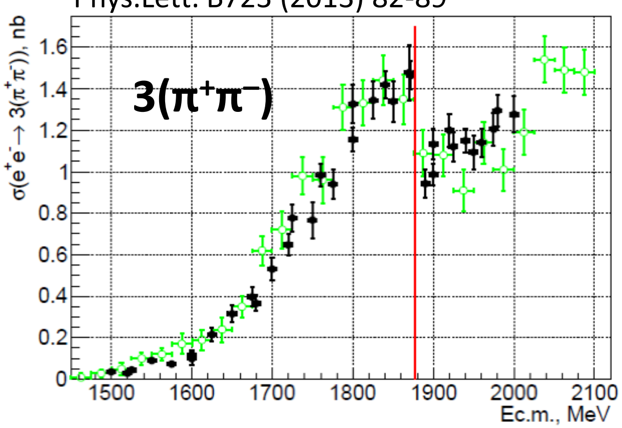
Phys.Lett. B779 (2018) 64-71



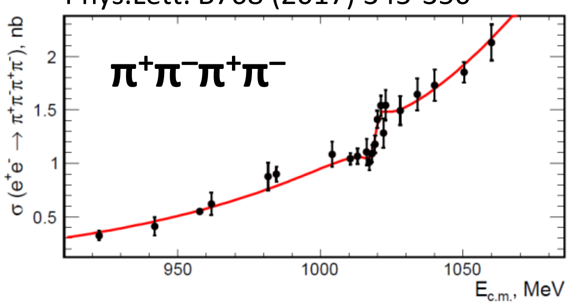
Phys.Lett. B759 (2016) 634-640



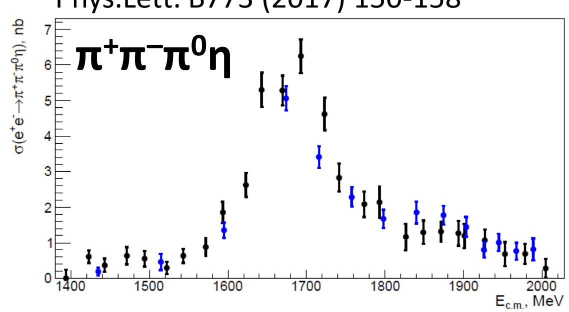
Phys.Lett. B723 (2013) 82-89



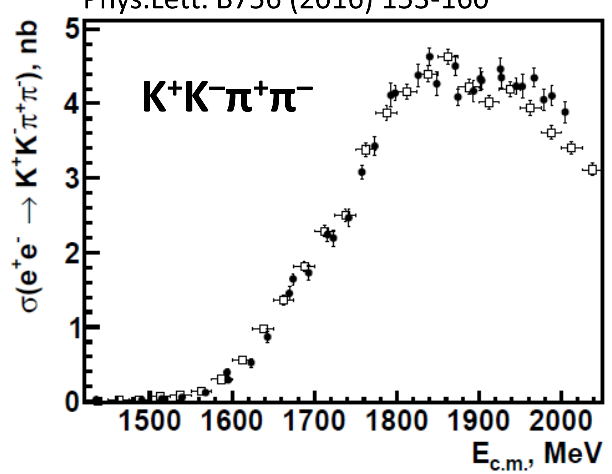
Phys.Lett. B768 (2017) 345-350



Phys.Lett. B773 (2017) 150-158

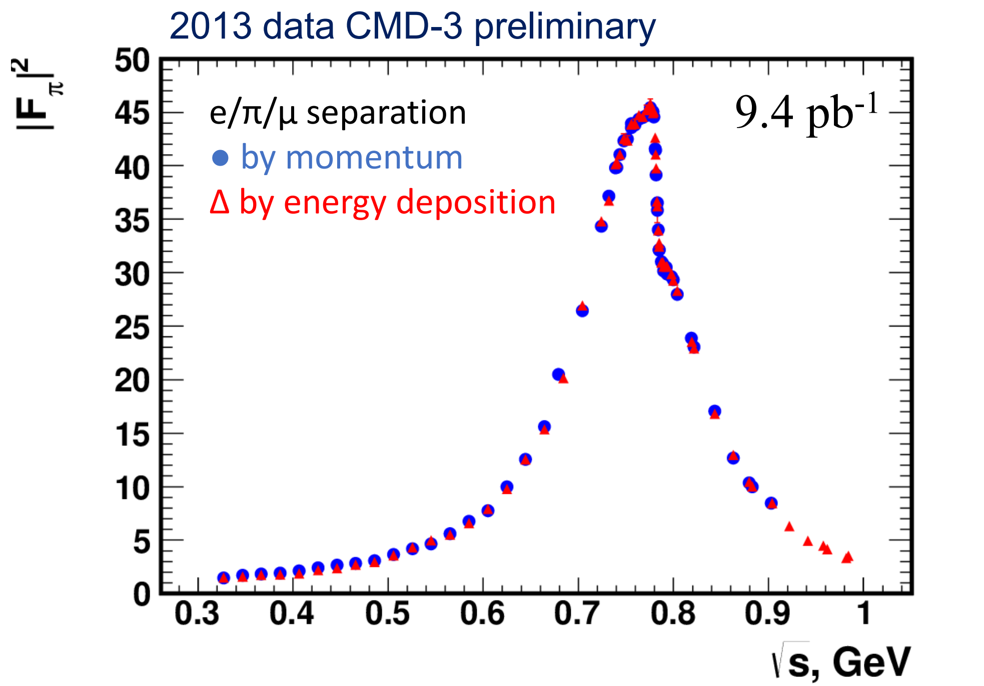


Phys.Lett. B756 (2016) 153-160



Dominant channel $e^+e^- \to \pi^+\pi^-$

Source	Goal	Current estimation
Radiative Correction	0.2%	0.2% (cross-section) 0.0-0.4% (mom.sep.)
Event separation	0.2%	0.1-0.5% (mom. sep.) ~1.5% (energy sep.)
Fiducial volume	0.1%	ok
Beam energy	0.1%	ok
Pion corrections (decay, nucl.int.)	0.1%	0.1% -nucl. int. 0.6-0.3% decays at low energies
Combined	0.33%	0.4-0.9% (mom.sep.) 1.5% (energy sep.)



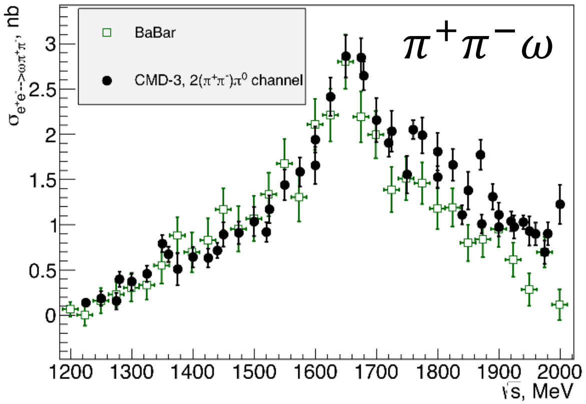
$$a_\mu^{EXP} - a_\mu^{MC} = 3.6\sigma$$

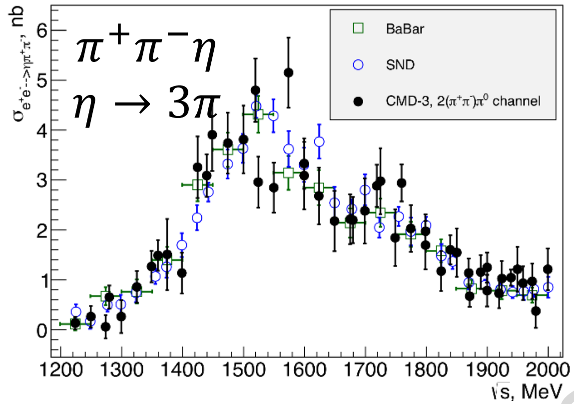
$$a_\mu^{had,LO-VP} = \frac{\alpha^2 m_\mu^2}{9\pi^2} \int_{m_\pi^2}^{\infty} ds \frac{\hat{K}(s)}{s^2} R(s)$$

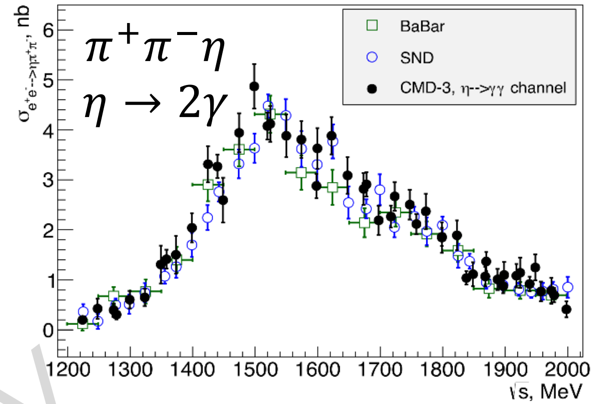
Contribution to the hadronic part of $(g\text{-}2)_\mu$ value from the VEPP-2000 energy region is about 92%

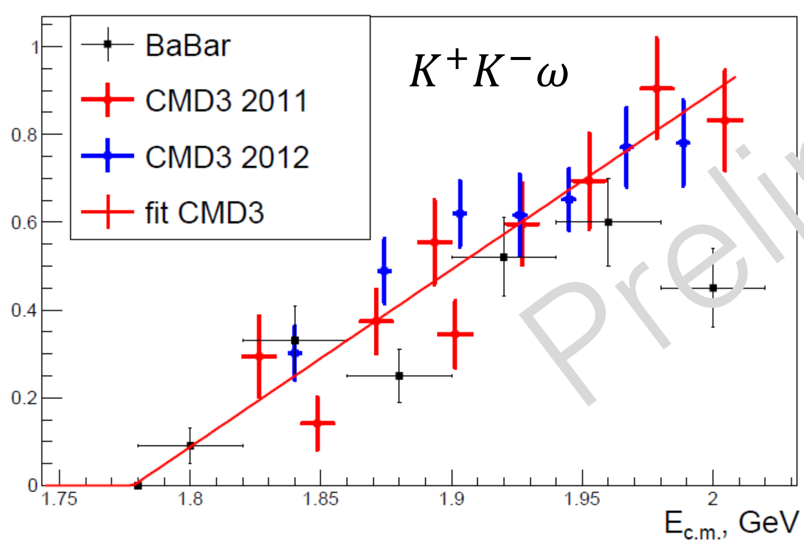
$$R(s) = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

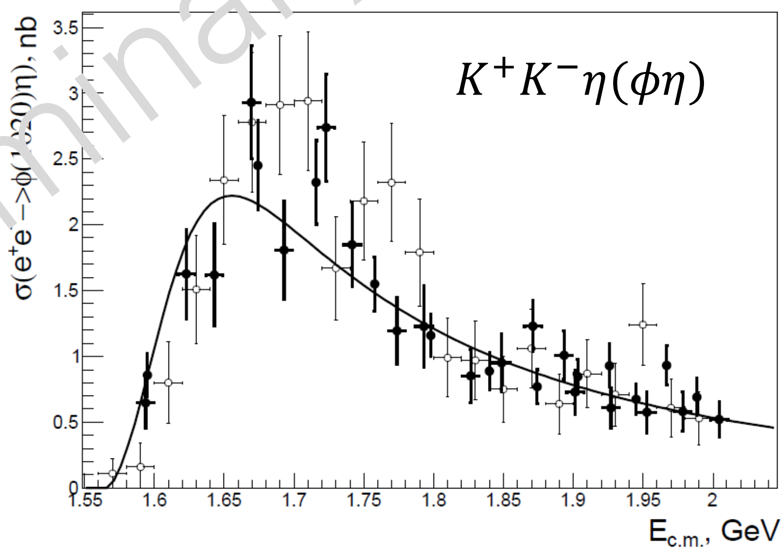
CMD-3 preliminary: $\pi^+\pi^-(\omega,\eta)$, $K^+K^-(\omega,\eta)$











Detailed review in next presentation by Gennady Fedotovich

Overview of SND results

Published

$e^+e^- \to K^+K^-\eta$	Phys. of Atomic Nuclei (2018)
$e^+e^- \to \eta\pi^+\pi^-$	Phys.Rev. D97 (2018) no.1
$e^+e^- \to K_S K_L \pi^0$	Phys.Rev. D97 (2018) no.3
$e^+e^- \to \omega\pi^0 \to \pi^0\pi^0\gamma$	Phys.Rev. D94 (2016) no.11
$e^+e^- \to K^+K^-$	Phys.Rev. D94 (2016) no.11
$e^+e^- \to \omega\eta$	Phys.Rev. D94 (2016) no.9
$e^+e^- \to \omega\eta\pi^0$	Phys.Rev. D94 (2016) no.3
$e^+e^- \to \pi^0\gamma$	Phys.Rev. D93 (2016) no.9
$e^+e^- \to \pi^+\pi^-\pi^0$	JETP 121 (2015) no.1
$\eta \to e^+e^-$	JETP Lett. 102 (2015) no.5
$\eta' \to e^+e^-$	Phys.Rev. D91 (2015)
$e^+e^- \to \eta\pi^+\pi^-$	Phys.Rev. D91 (2015) no.5
$e^+e^- \to n\bar{n}$	Phys.Rev. D90 (2014) no.11
$e^+e^- \to \eta\gamma$	Phys.Rev. D90 (2014) no.3
$e^+e^- \to \omega\pi^0 \to \pi^0\pi^0\gamma$	Phys.Rev. D88 (2013) no.5

In process

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

$e^+e^- \to n\bar{n}$

$\eta \to e^+e^-$

$e^+e^- \to \eta\pi^0\pi^+\pi^-$

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

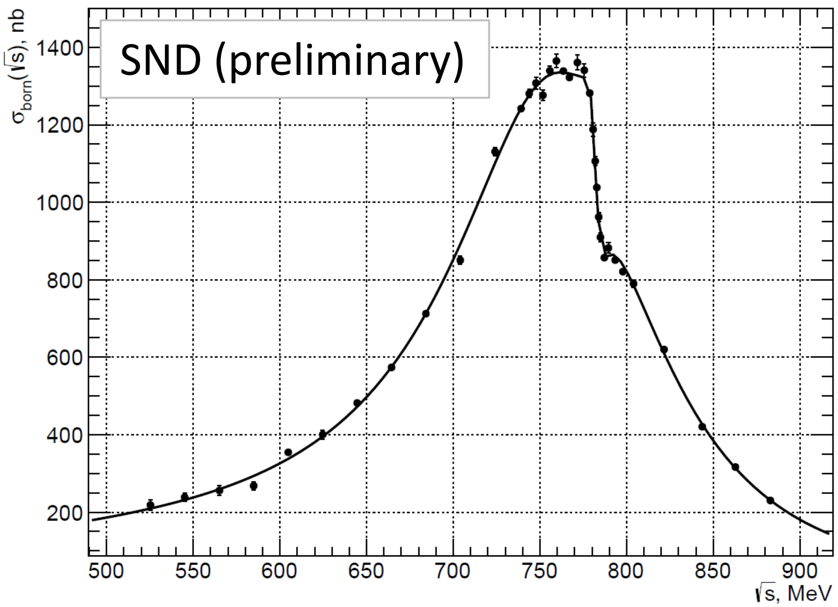
$e^+e^- \to K^+K^-\pi^0$

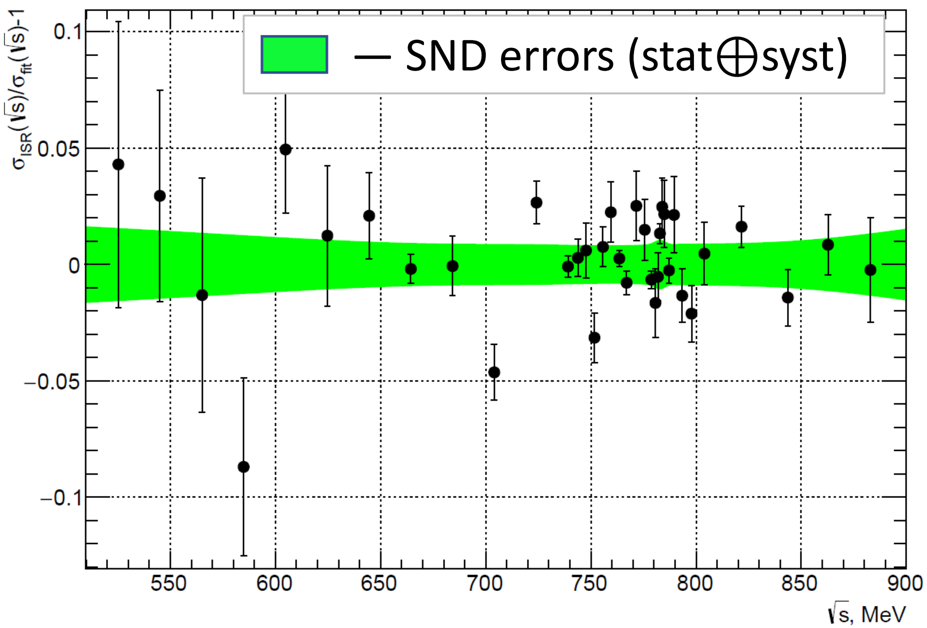
$e^+e^- \to \omega\pi^0\pi^0$

$e^+e^- \to 6\pi$

etc

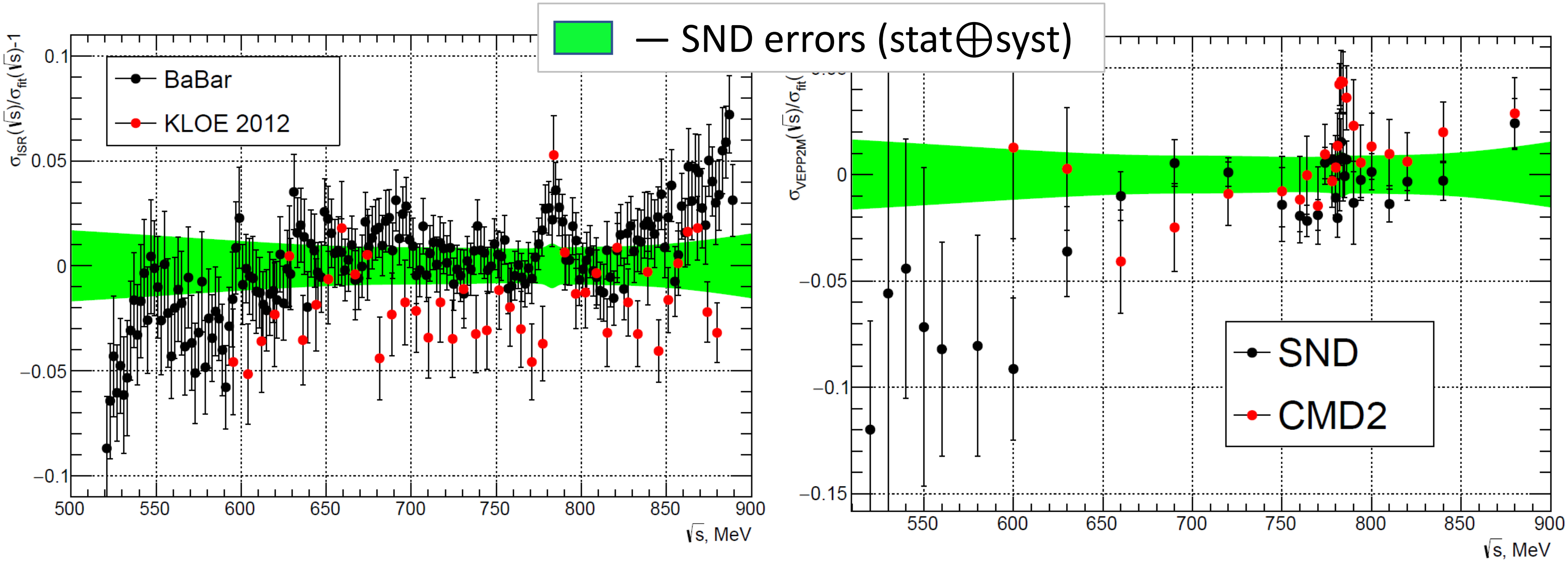
$e^+e^- \rightarrow \pi^+\pi^-$(preliminary)





Parameters	SND & VEPP2000	SND & VEPP2M
m_ρ, MeV	775.925 ± 0.5 ± 0.78	774.6 ± 0.4 ± 0.5
Γ_ρ, MeV	145.686 ± 0.65 ± 1.56	146.1 ± 0.8 ± 1.5
$\sigma(\rho \rightarrow \pi^+\pi^-)$, nb	1188.54 ± 4.6 ± 9.5	1193 ± 7 ± 16
$\sigma(\omega \rightarrow \pi^+\pi^-)$, nb	32.44 ± 1.3 ± 0.3	29.3 ± 1.4 ± 1.0
$\phi_{\rho\omega}$, degree	112.63 ± 1.41	113.7 ± 1.3 ± 2.0
$B_{\rho\rightarrow e^+e^-} \times B_{\rho\rightarrow e^+e^-}$	$(4.892 \pm 0.0154 \pm 0.0391) \times 10^{-5}$	$(4.876 \pm 0.02 \pm 0.06) \times 10^{-5}$
$B_{\omega\rightarrow e^+e^-} \times B_{\omega\rightarrow e^+e^-}$	$(1.358 \pm 0.056 \pm 0.011) \times 10^{-5}$	$(1.225 \pm 0.06 \pm 0.04) \times 10^{-5}$

$e^+e^- \to \pi^+\pi^-$ (preliminary)



$$a_\mu = \left(\frac{\alpha\, m_\mu}{3\,\pi}\right)^2 \int_{s_{min}}^{s_{max}} ds \frac{\hat{K}(s)}{s^2} R(s)$$

$$R(s) = \frac{\sigma_{\pi\pi}^{bare}}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

SND & VEPP2000:

$$a_\mu(524 < \sqrt{s} < 885\ MeV) = (414.48 \pm 1.04 \pm 3.49) \times 10^{-10}$$

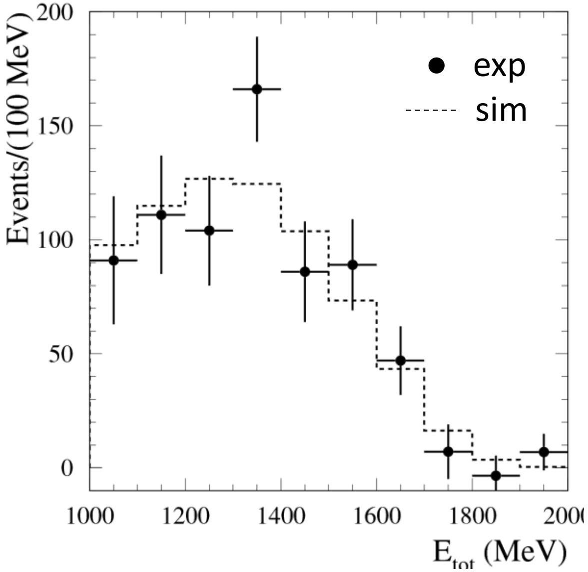
SND & VEPP2M:

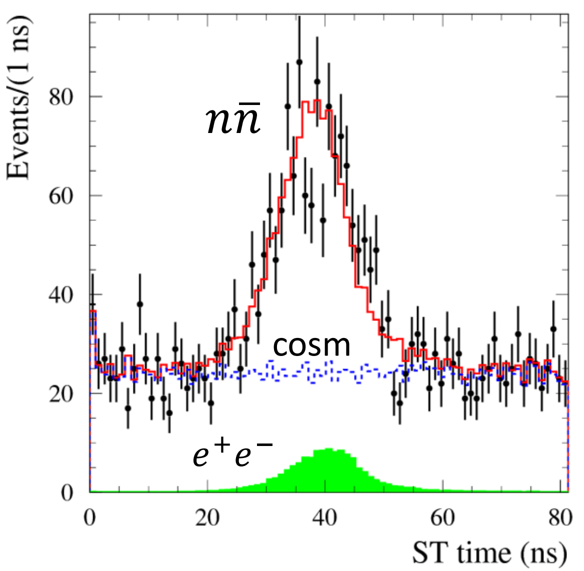
$$(408.88 \pm 1.30 \pm 5.31) \times 10^{-10}$$

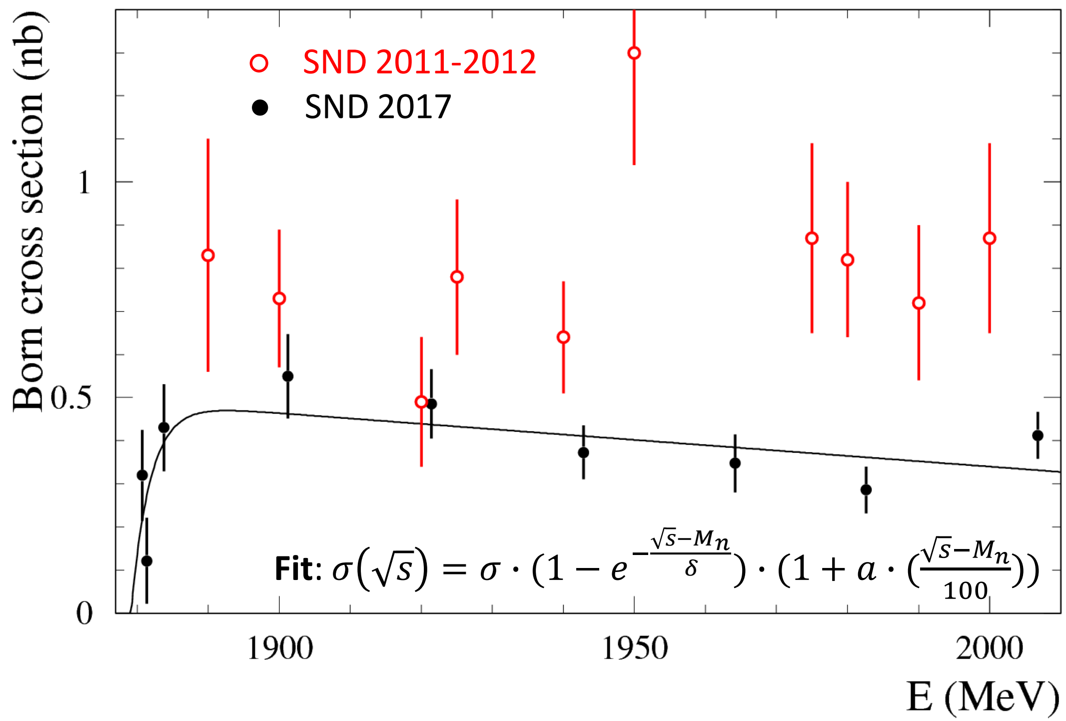
BABAR:

$$(414.93 \pm 0.34 \pm 2.07) \times 10^{-10}$$

$e^+e^- \to n\bar{n}$(2017,preliminary)







The difference:

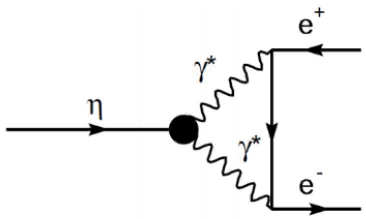
-- incorrect $n\bar{n}$ simulation

-- beam background

-- cosmic background

Systematic uncertainty ~20%, mainly due to MC

$\eta \to e^+e^-$ (preliminary)



$\Gamma_\eta = 1.31 \pm 0.05\ keV$

$\frac{\Gamma(P \to l^+l^-)}{\Gamma(P \to \gamma\gamma)} \sim \alpha^2 \left(\frac{m_l}{m_P}\right)^2$

sensitive to contributions beyond the Standard Model

Unitary limit predictions:

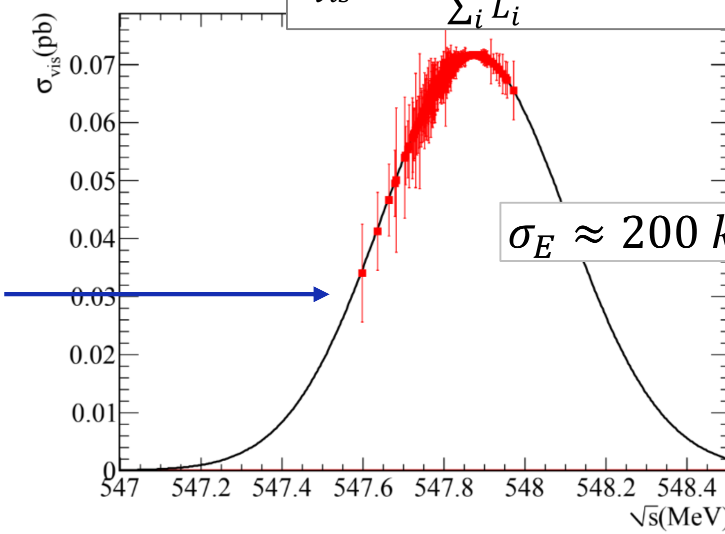
$$\sigma_0 = \frac{4\pi}{E^2}\mathcal{B}(\eta \to e^+e^-)\frac{m_\eta^2\Gamma_\eta^2}{(m_\eta^2 - E^2)^2 + m_\eta^2\Gamma_\eta^2}$$

$$\sigma(s) = \int_0^{x_{max}} W(x,s)\sigma_0(s(1-x))dx$$

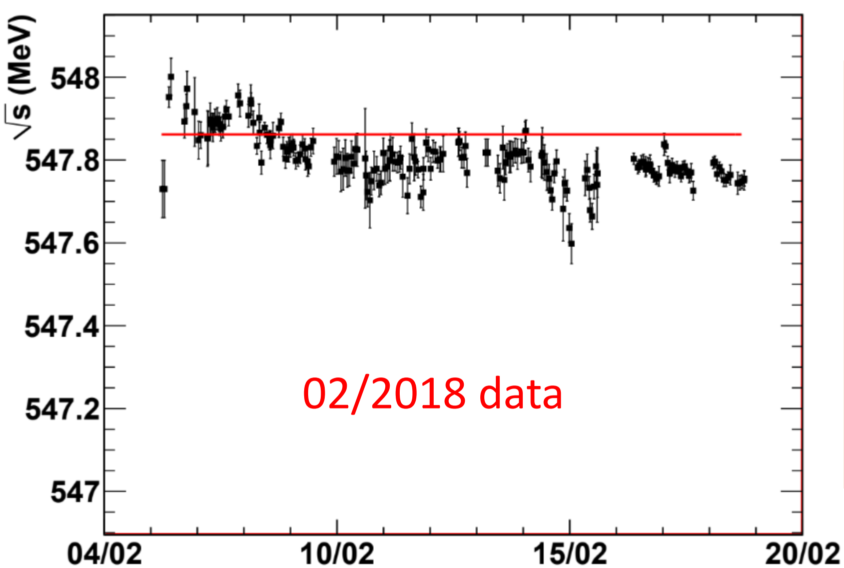
$$\sigma_{exp}(E_0) = \frac{1}{\sqrt{2\pi}\sigma_E}\int_{-\infty}^{+\infty} e^{-\frac{(E-E_0)^2}{2\sigma_E^2}}\sigma(E)dE$$

$\mathcal{B}^{UL}(\eta \to e^+e^-) = 1.78 \times 10^{-9}$

$$\sigma_{vis}^{UL} = \frac{\sum_i L_i\sigma(E_i)}{\sum_i L_i} = 64 \pm 11\ fb$$



$\sigma_E \approx 200\ keV$



Improved by a factor of 3!

Experimental study :

statistics: 654 nb^{-1}

channel: $\eta \to \pi^0\pi^0\pi^0 \to 6\gamma$

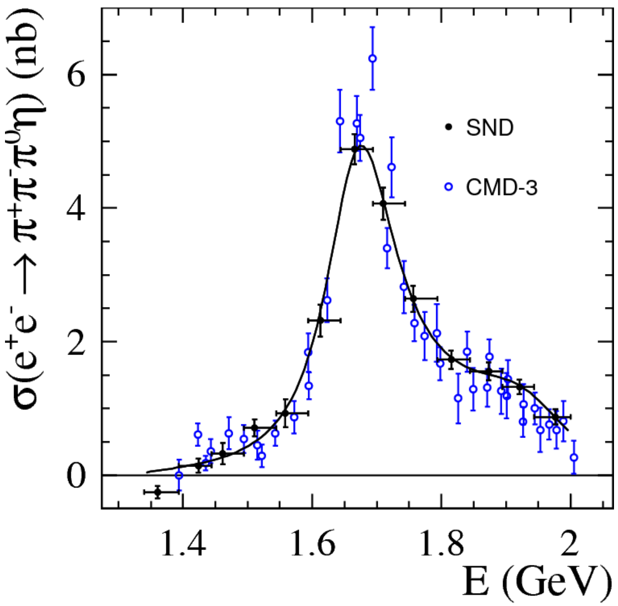
selected events: 0

$\sigma_{vis} < 25\ pb$

SND: $\mathcal{B}(\eta \to e^+e^-) < 7 \times 10^{-7}$ **(90% CL)**

HADES: $\mathcal{B}(\eta \to e^+e^-) < 2.3 \times 10^{-6}$

$e^+e^- \to \pi^+\pi^-\pi^0\eta$ (preliminary)



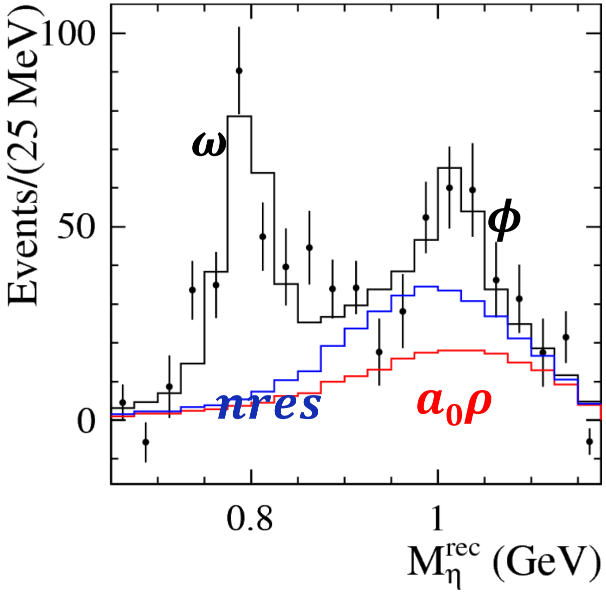
Cross section:

~ 6% of hadr. cross sect. at 1.7 GeV

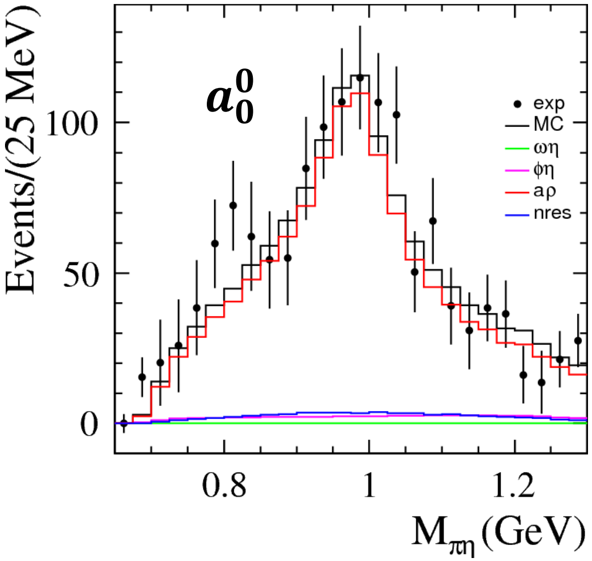
Intermediate states:

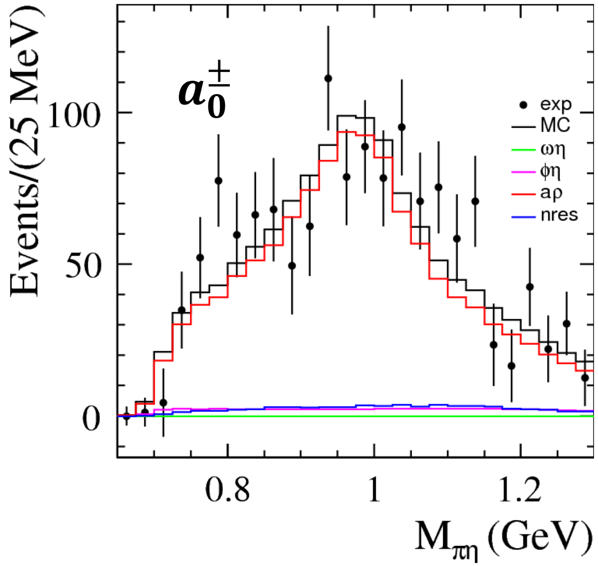
below 1.8 GeV: $\omega\eta$, $\phi\eta$, $a_0\rho$

and structureless $\pi^+\pi^-\pi^0\eta$

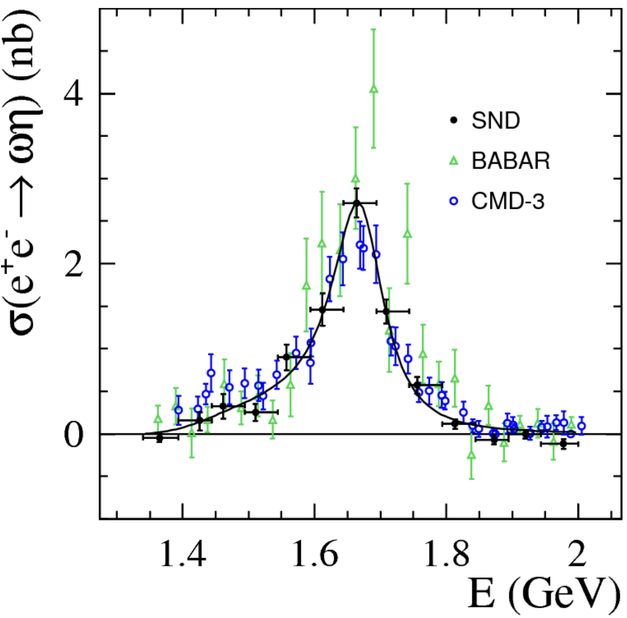


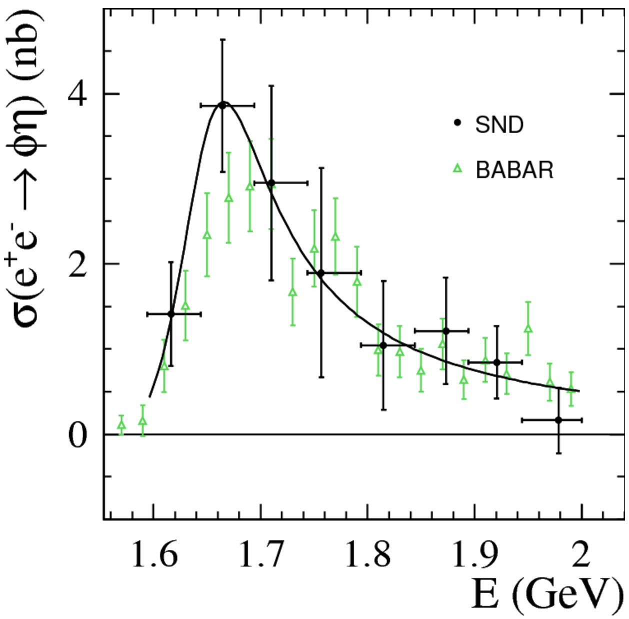
Above 1.8 GeV the dominant reaction mechanism is $a_0\rho$

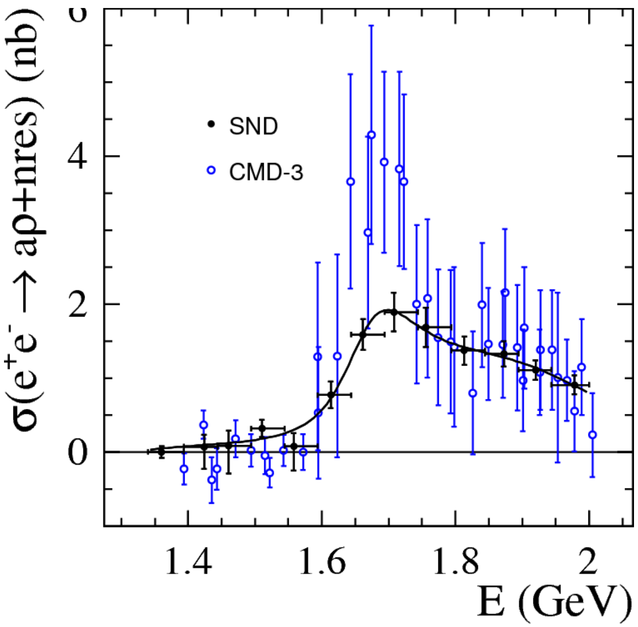


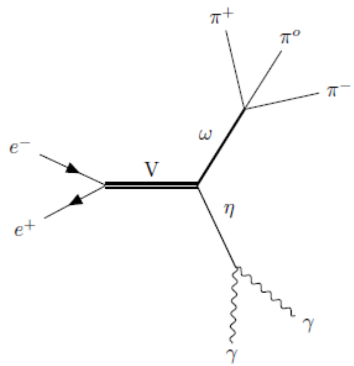


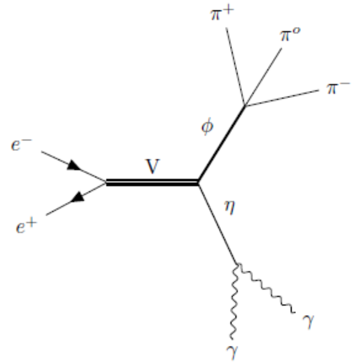
$e^+e^- \to \pi^+\pi^-\pi^0\eta$

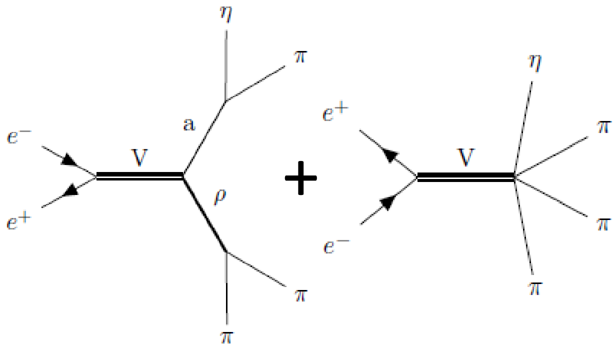




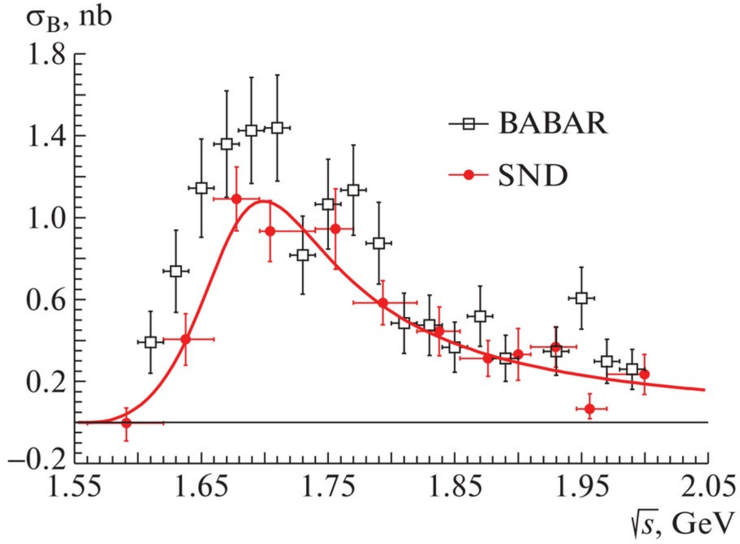






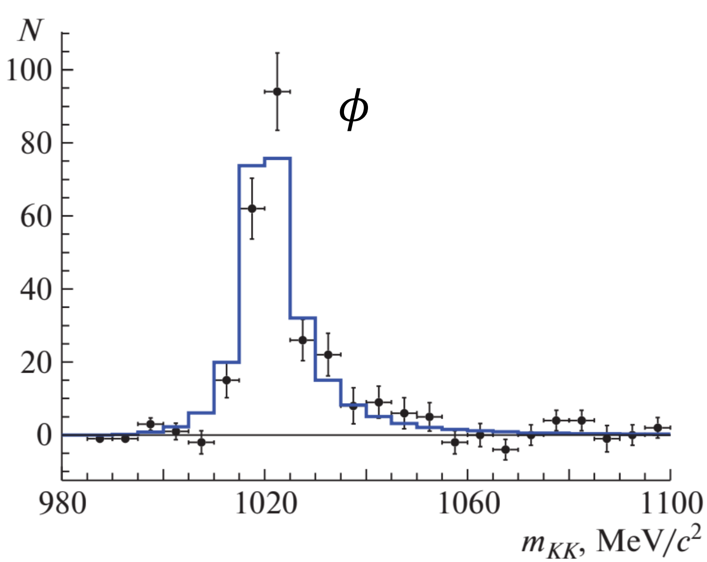


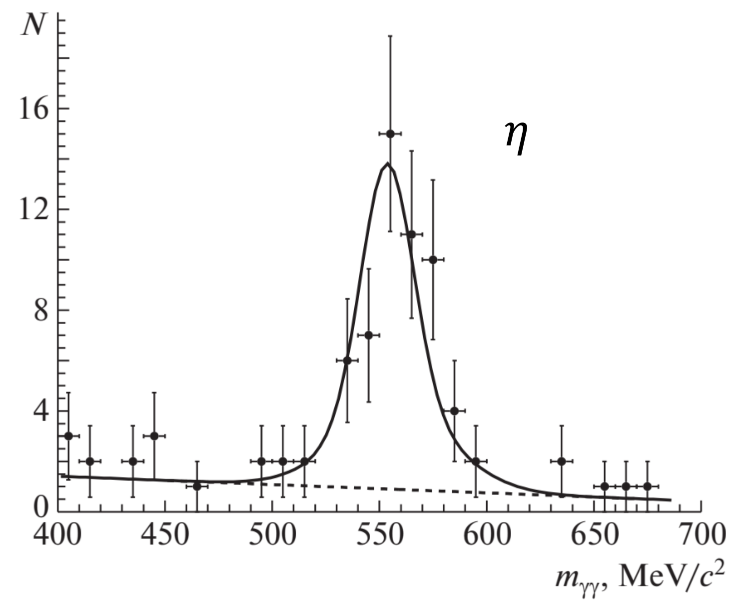
$e^+e^- \to \eta K^+K^-$ (in print)



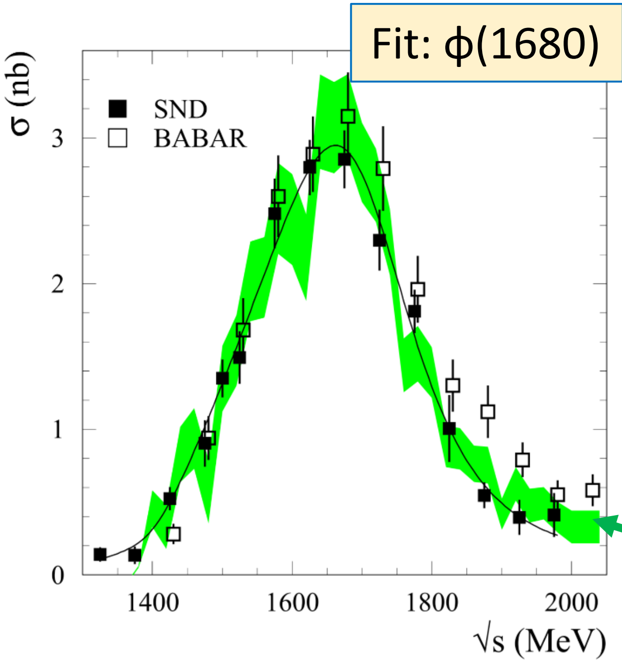
SND cross section of $e^+e^- \to \eta K^+K^-$:

- agrees with the most precise BABAR measurement
- has a comparable accuracy
- dominated by the transition through the ηϕ
- the energy dependence is determined by the ϕ(1680)
- ~ 1% of $e^+e^- \to hadrons$ at 1.7 GeV





$e^+e^- \rightarrow K_S K_L \pi^0$



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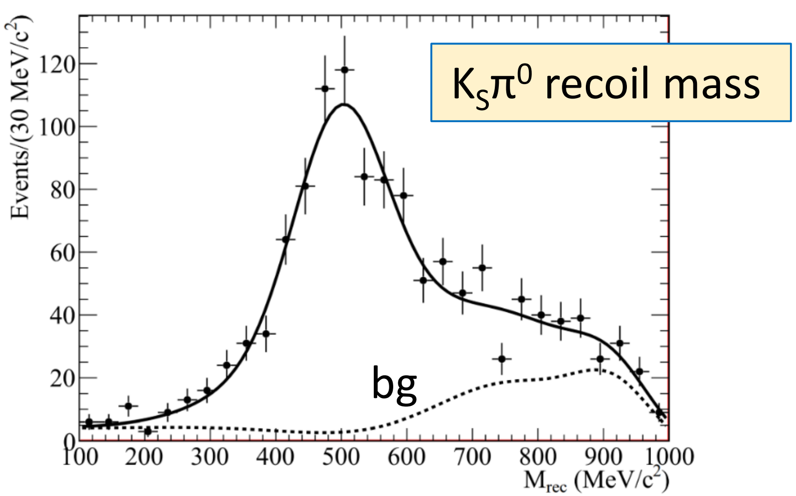
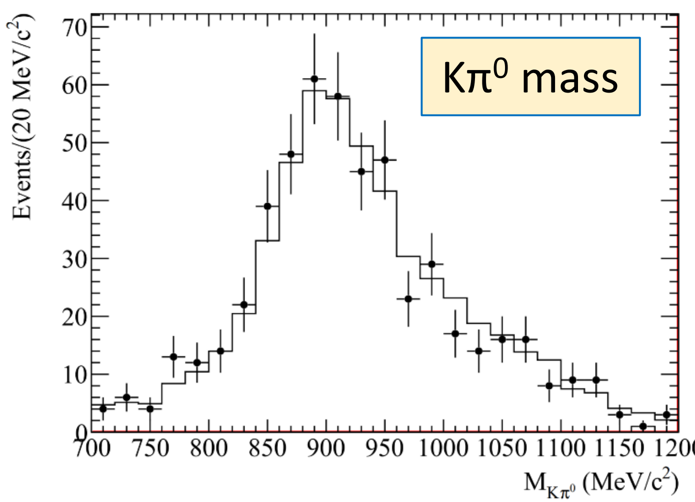
$\underline{e^+e^- \rightarrow K_S K_L \pi^0}$:

- is one of three modes of the process $e^+e^- \rightarrow KK\pi$
- is important for spectroscopy of $s\bar{s}$ vector states
- the systematic uncertainty of the SND data is 12–13%
- cross section ~ 4% of $e^+e^- \rightarrow hadrons$ at 1.7 GeV

Green band corresponds to predictions from isospin relations between KK* channels

$$\sigma(e^+e^- \rightarrow K_S K_L \pi^0) = \sigma(e^+e^- \rightarrow K_S K^{\mp}\pi^{\pm}) - \sigma(e^+e^- \rightarrow K^+K^-\pi^0) + \mathrm{Br}(\phi \rightarrow K_S K_L)\sigma(e^+e^- \rightarrow \phi\pi^0)$$





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

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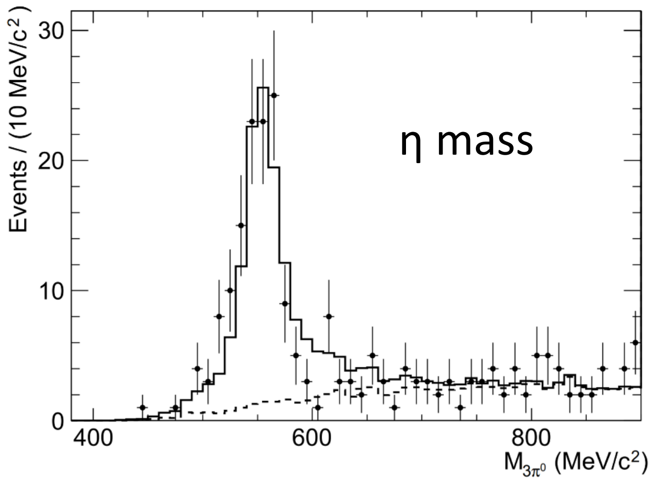
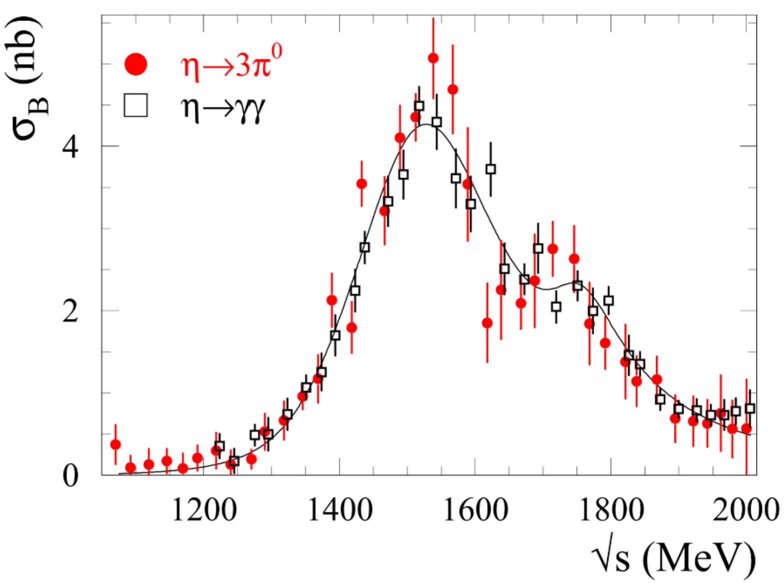
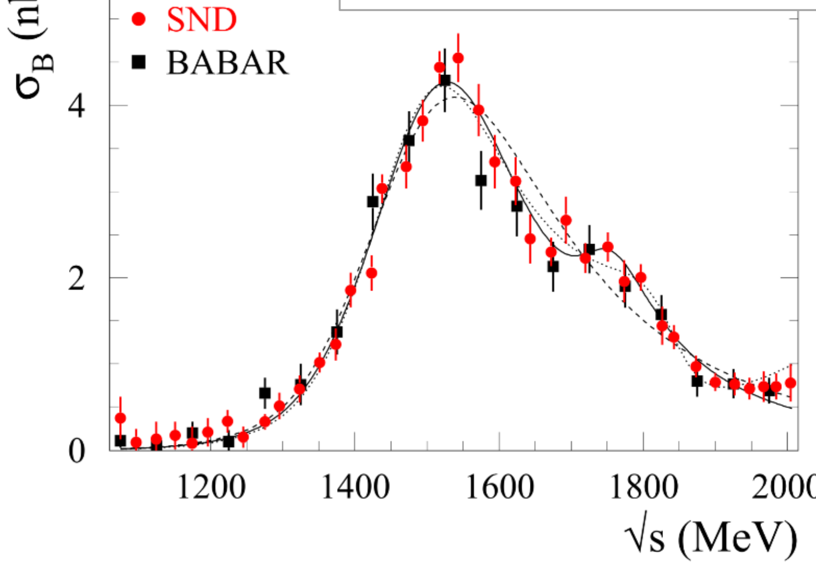


$\boldsymbol{e^+e^- \to \pi^+\pi^-\eta}$:

- cross sections in two η modes are consistent
- proceeding mainly via the ρη Intermediate state
- is important for the spectroscopy of the excited ρ-like states
- gives a sizable contribution to the total hadronic cross section at the center-of-mass (c.m.) energy region s=1.4−1.8GeV



Fit models:
1. ρ(770) - ρ(1450) - ρ(1700)
2. ρ(770) - ρ(1450) + ρ(1700) + ρ(2150)



Conclusions

- The goal of two experiments CMD-3 and SND at VEPP2000 is to provide exclusive measurement of e+e- -> hadrons reactions in the energy range 0.32 – 2.0 GeV
- In 2011-2013 both detectors have collected about 60 pb^{-1} each in the whole 0.32 – 2.0 GeV energy range, available at VEPP2000
- During 2014-2016 machine and detectors have been upgraded and at the end of 2016 detectors resumed data taking
- In 2017 both detectors have collected 50 pb^{-1} in 5 months with c.m. energy scan from 1.68 to 2.0 GeV. At the end of 2017, beginning of 2018 - 25 pb^{-1} have been collected in 0.55-1.0 GeV
- Many analyses have been published. Many more are in the line.