Measurement of the hadronic cross sections with the CMD-3 and SND detectors at the VEPP-2000 collider

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(on behalf of the SND and the CMD-3 collaborations)

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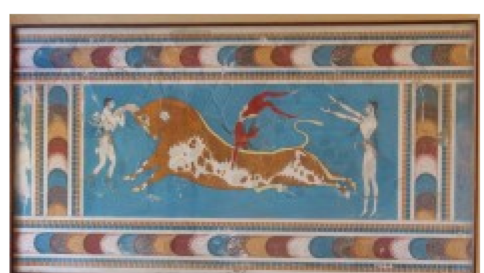
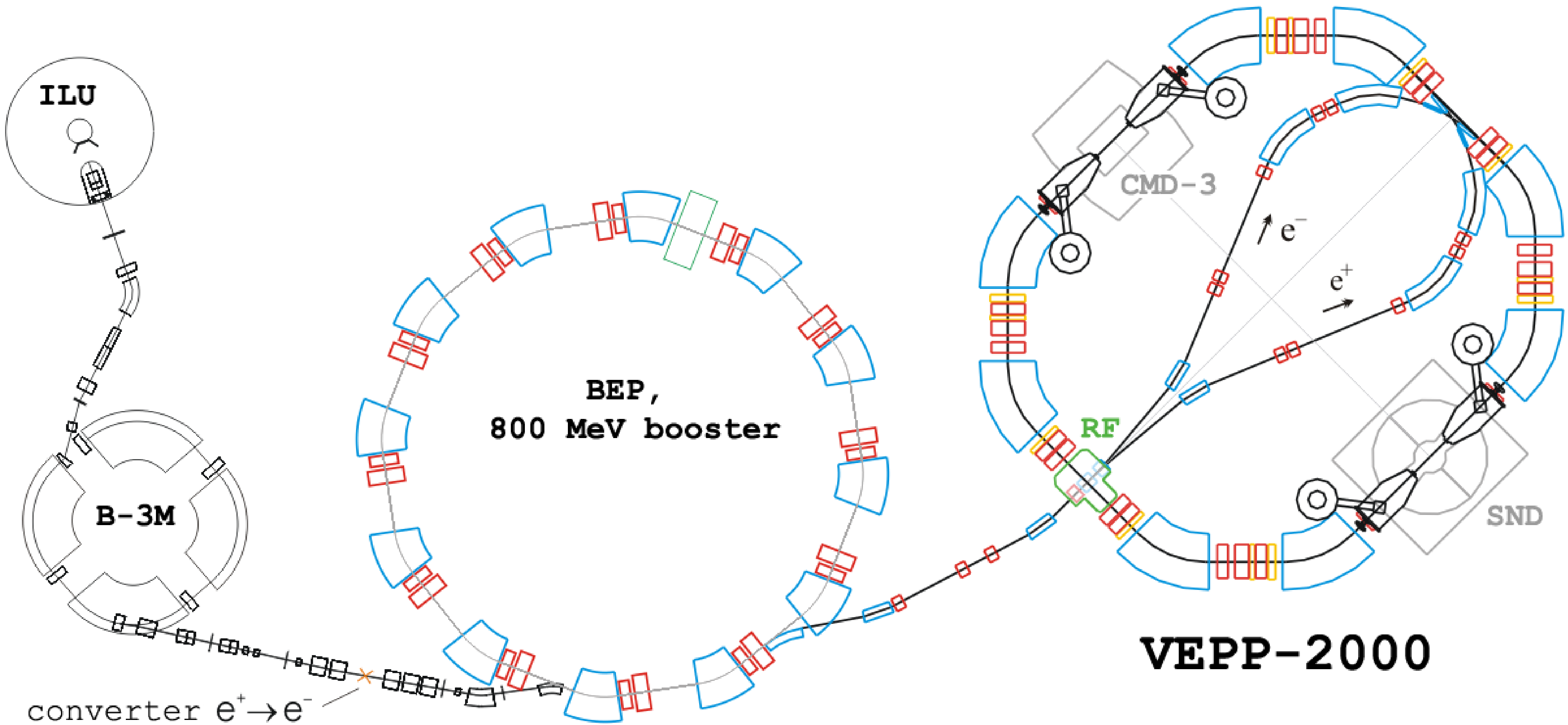
17-29 August 2017



VEPP-2000 e^+e^- collider

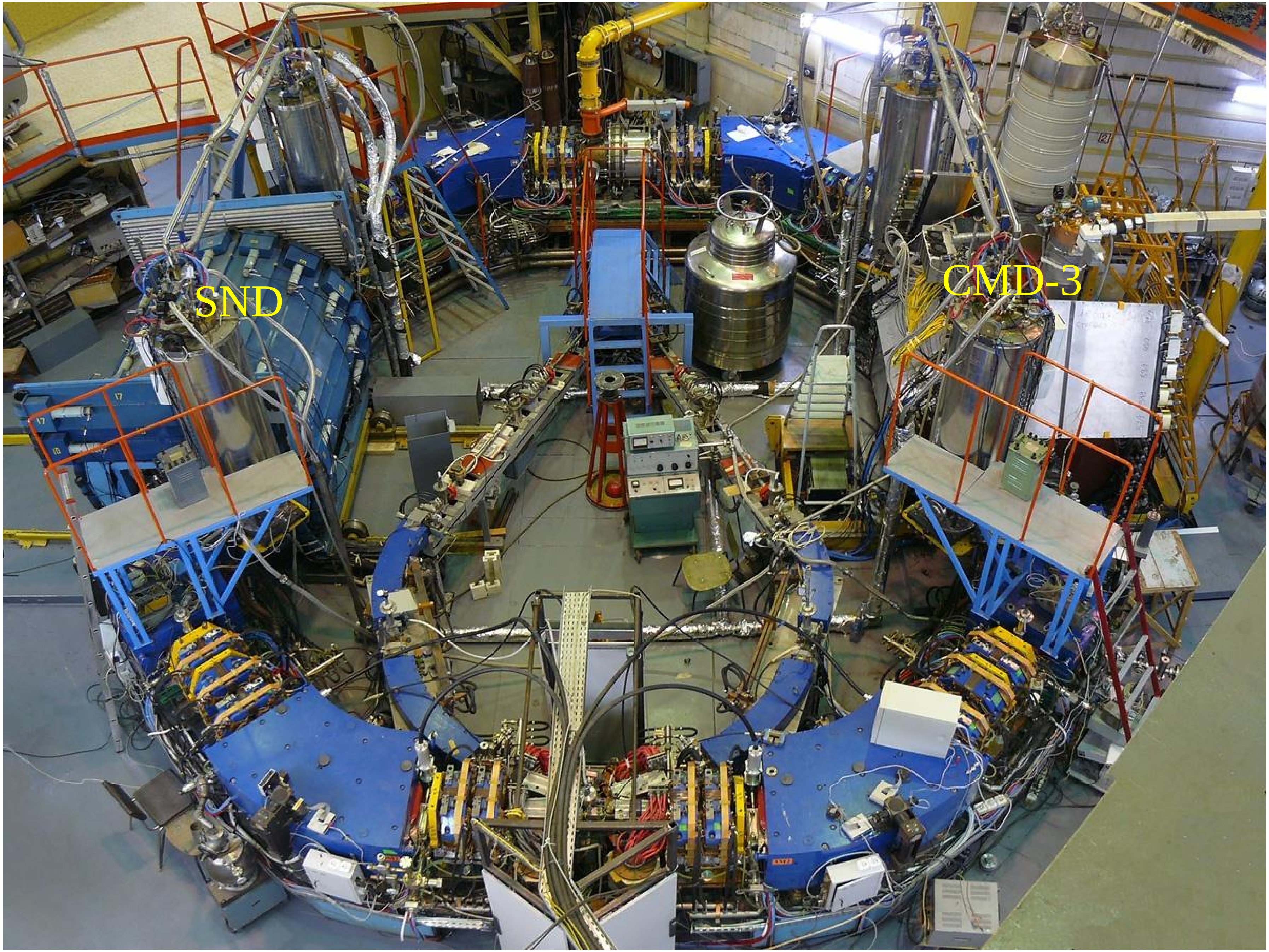


c.m. energy 0.3-2.0 GeV
circumference – 24.4 m
round beam optics

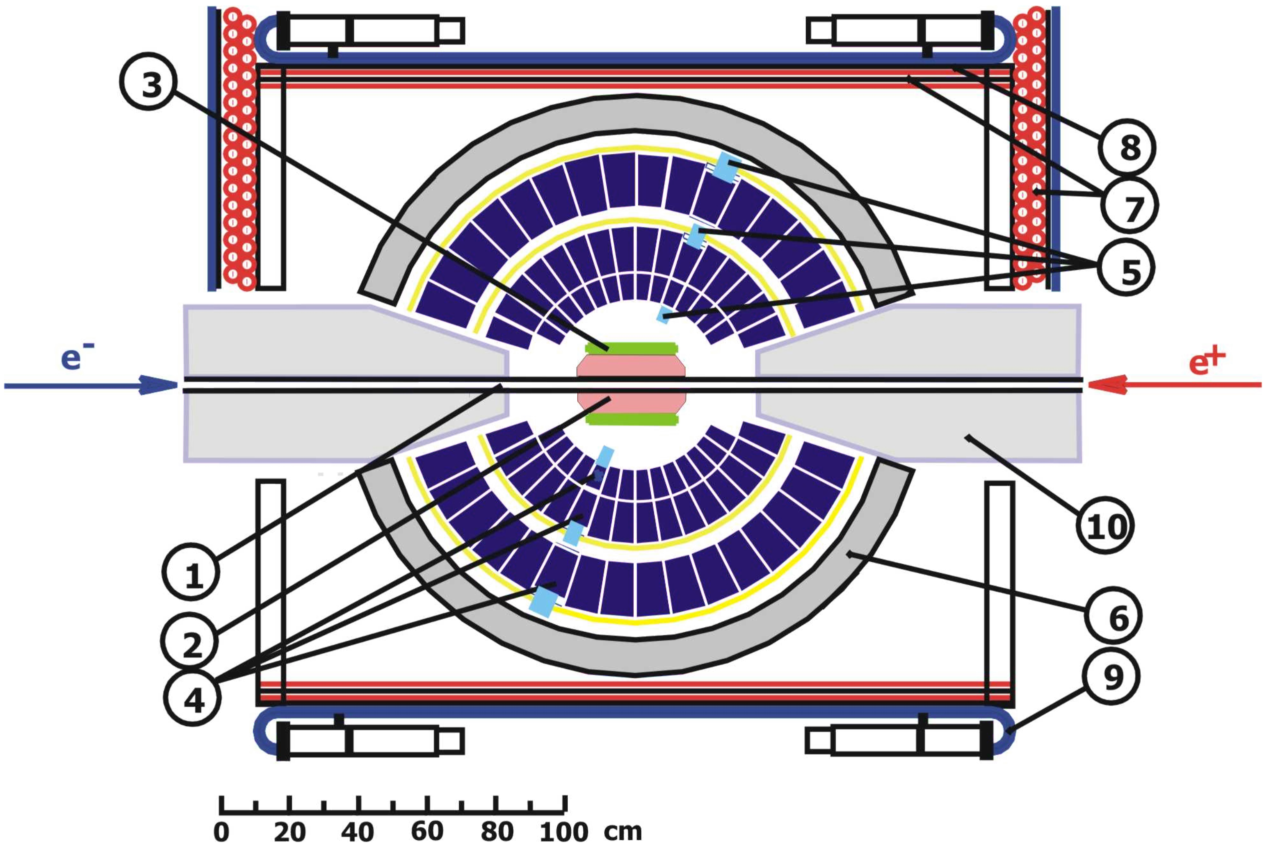
luminosity at 2 GeV:
1×10^{32} cm^{-2} sec^{-1} (project)
2×10^{31} cm^{-2} sec^{-1} (achieved)

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

VEPP-2000



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.

[NIM A449 (2000) 125-139]

Calorimeter

- $13.5X_0, 0.95 \times 4\pi$
- Energy resolution

$$\frac{\sigma_E}{E} = \frac{0.042}{\sqrt[4]{E[GeV]}}$$

- Angular resolution

$$\sigma_\varphi = \frac{0.82^\circ}{\sqrt{E[GeV]}} \oplus 0.63^\circ$$

Tracking system

- 9 layers, $0.94 \times 4\pi$
- Angular resolution

$$\sigma_\varphi = 0.55^\circ, \sigma_\theta = 1.2^\circ$$

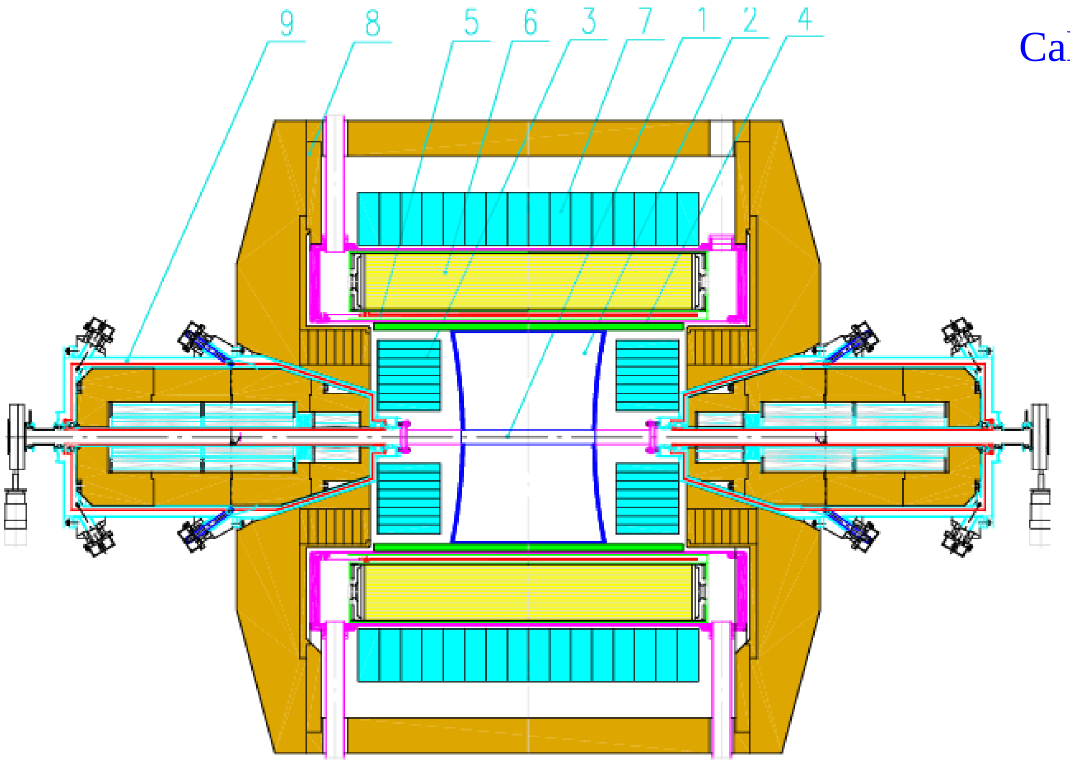
- Vertex position resolution

$$\sigma_R = 0.12cm, \sigma_Z = 0.45cm$$

Aerogel counters

- K/π separation E < 1 GeV

CMD-3 detector

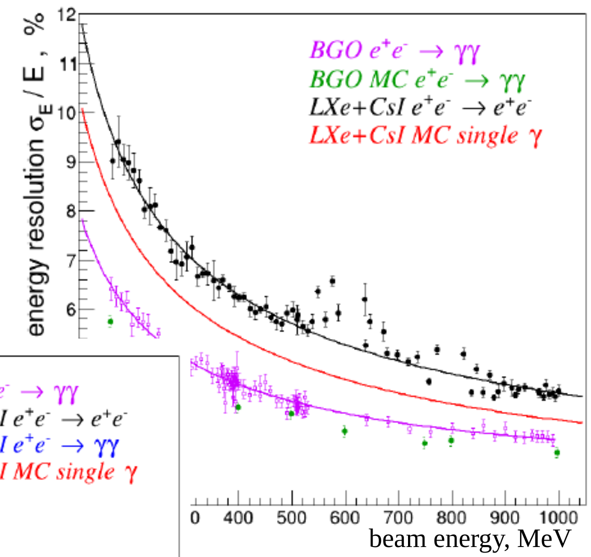


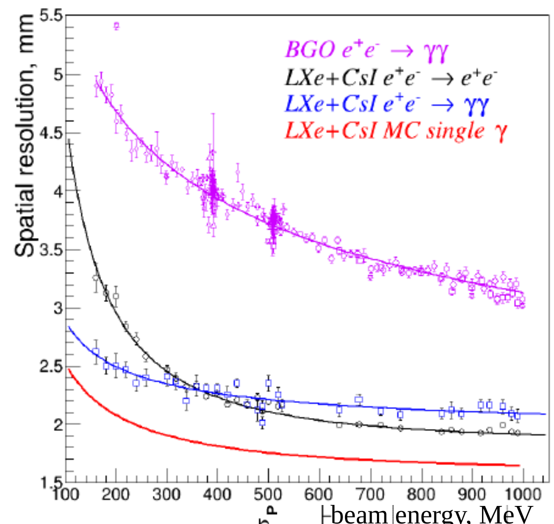
Calorimeter

$13.5X_0$

$\frac{\sigma_E}{E} \sim 3...10\%$

$\sigma_\theta \sim 5\ mrad$



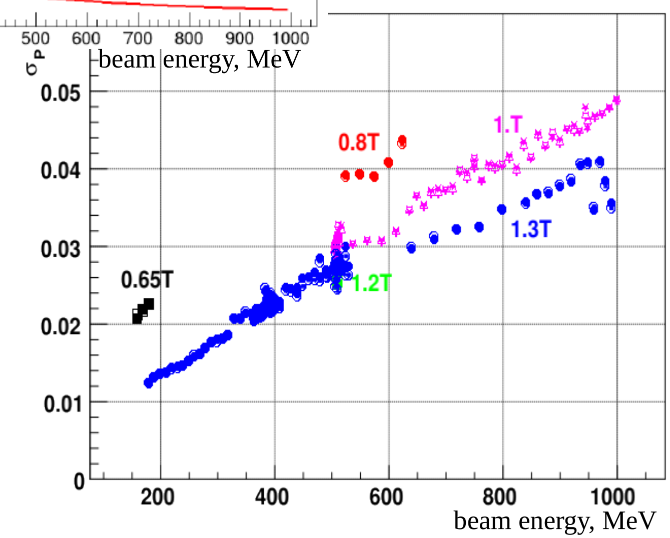


Tracking

1...1.3 T

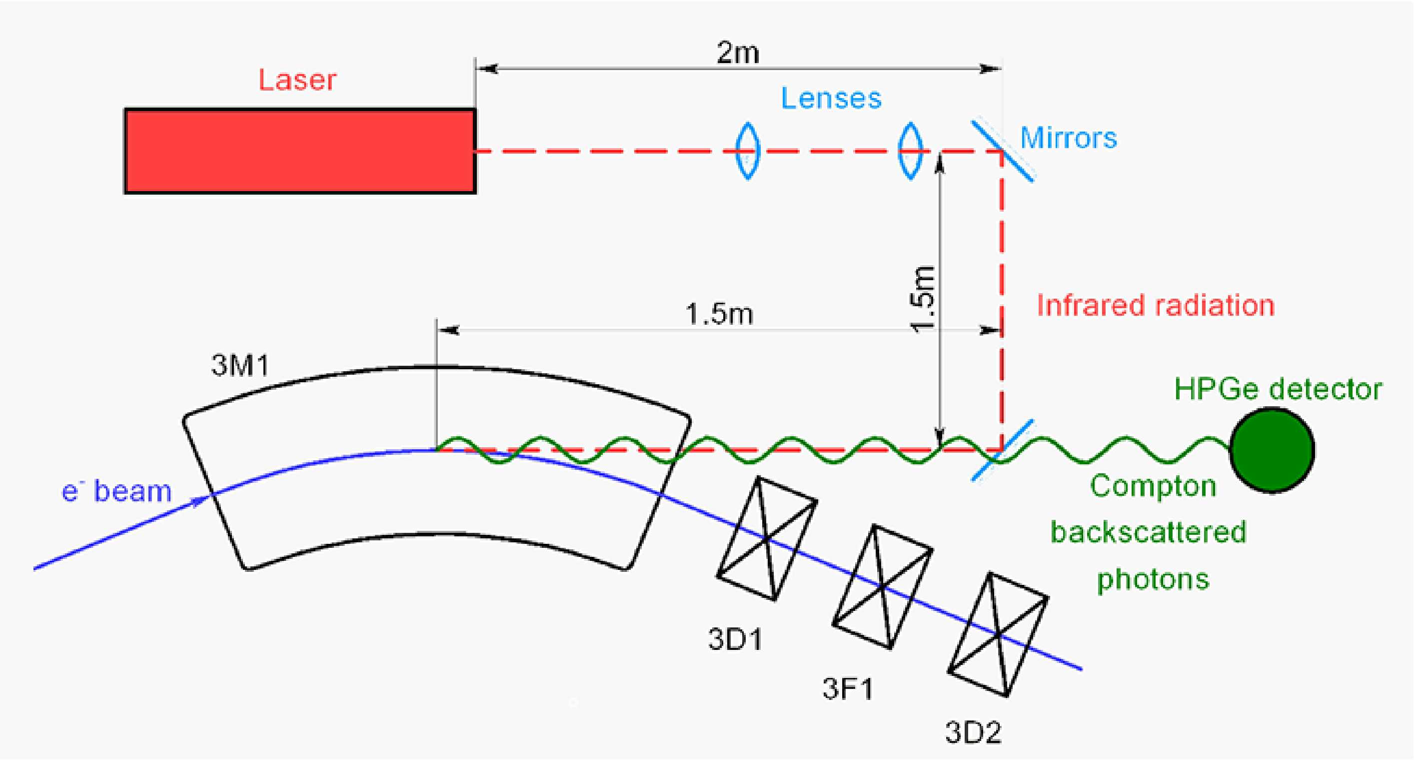
$\sigma_{R\varphi} \sim 100\ \mu$

$\sigma_Z \sim 2...3\ mm$



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

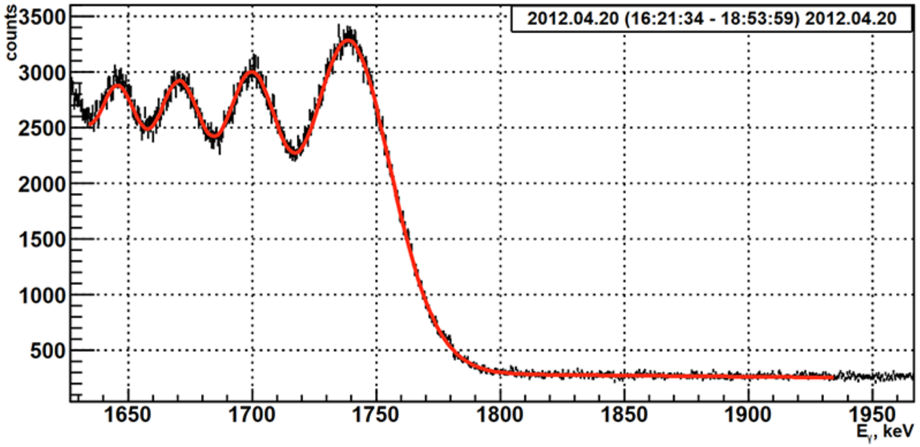
Beam energy measurements: CBS system



Backscattered photons spectrum edge:
parameters B, S, E

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

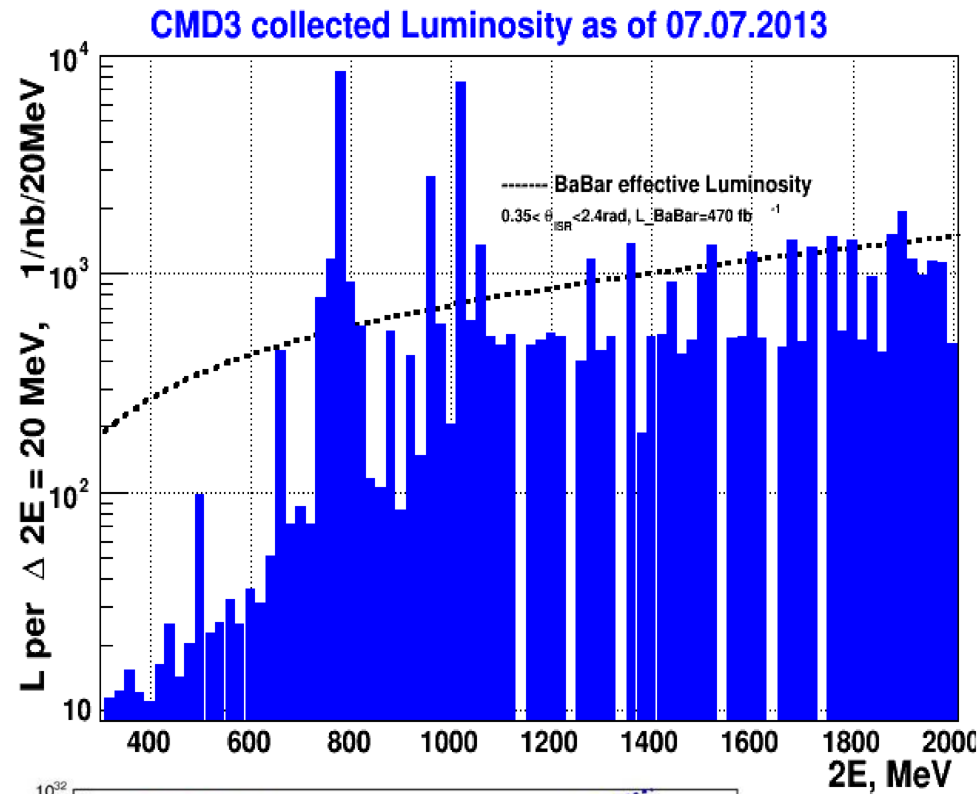
E.V. Abakumova et al., PRL 110 2013 140402

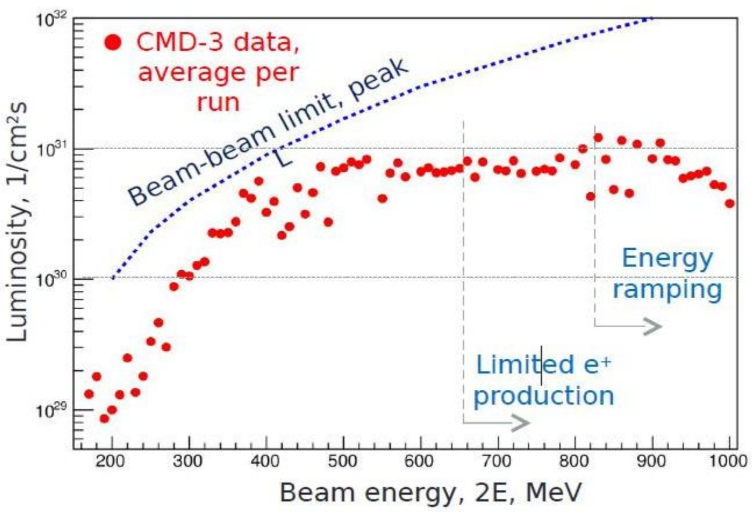


Data collected 2010-2013

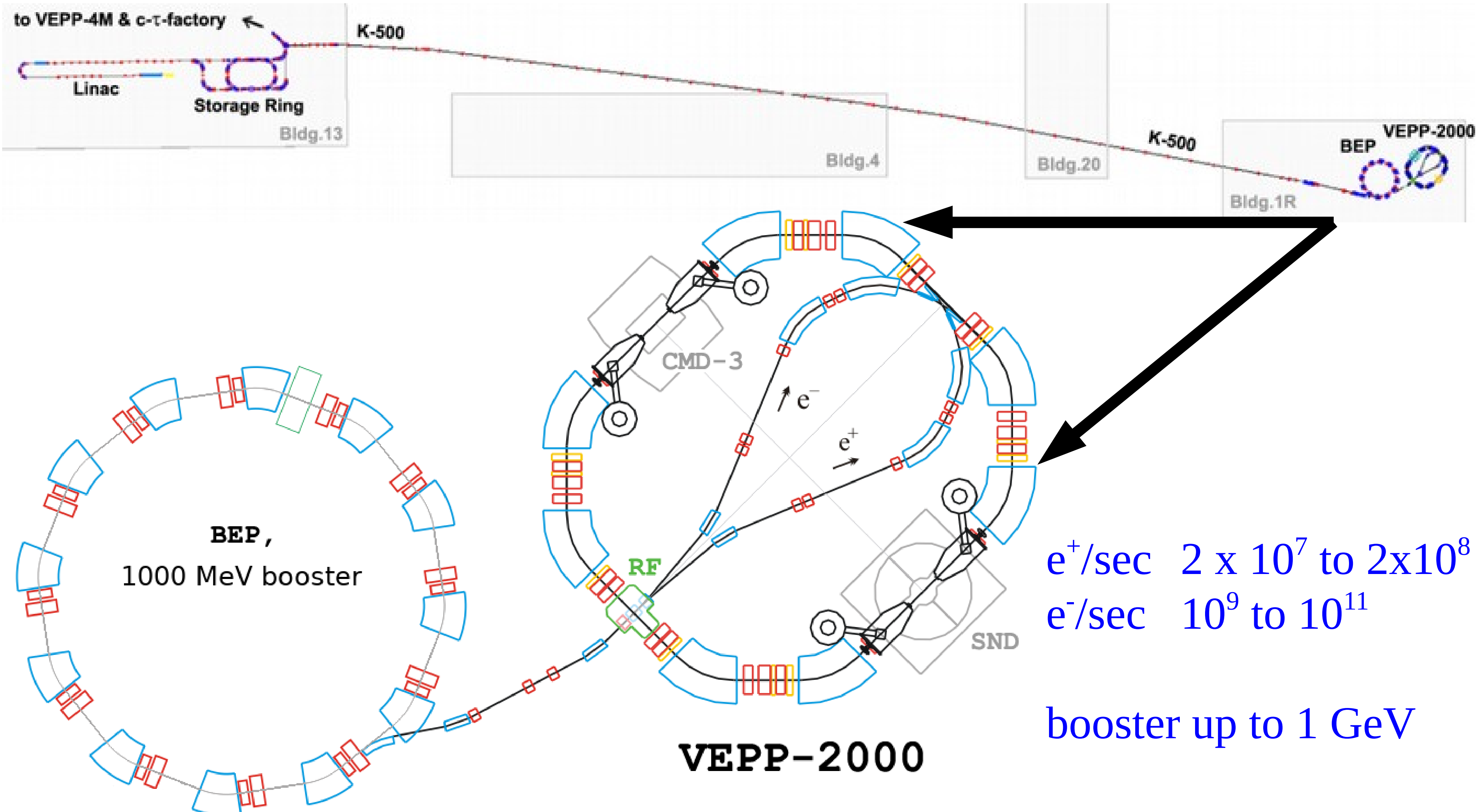
Years	Energy √s (GeV)	L(pb^{-1})
2010-2012	1.05 – 2.0	45
	>1.88	8.8
2013	0.32 – 1.06	22
Total		**67**

Collected L ~ 67 pb^{-1} per detector	
8.3 pb^{-1}	ω-region
9.4 pb^{-1}	below 1 GeV (except ω)
8.4 pb^{-1}	ϕ-region
41 pb^{-1}	above ϕ





Collider upgrade



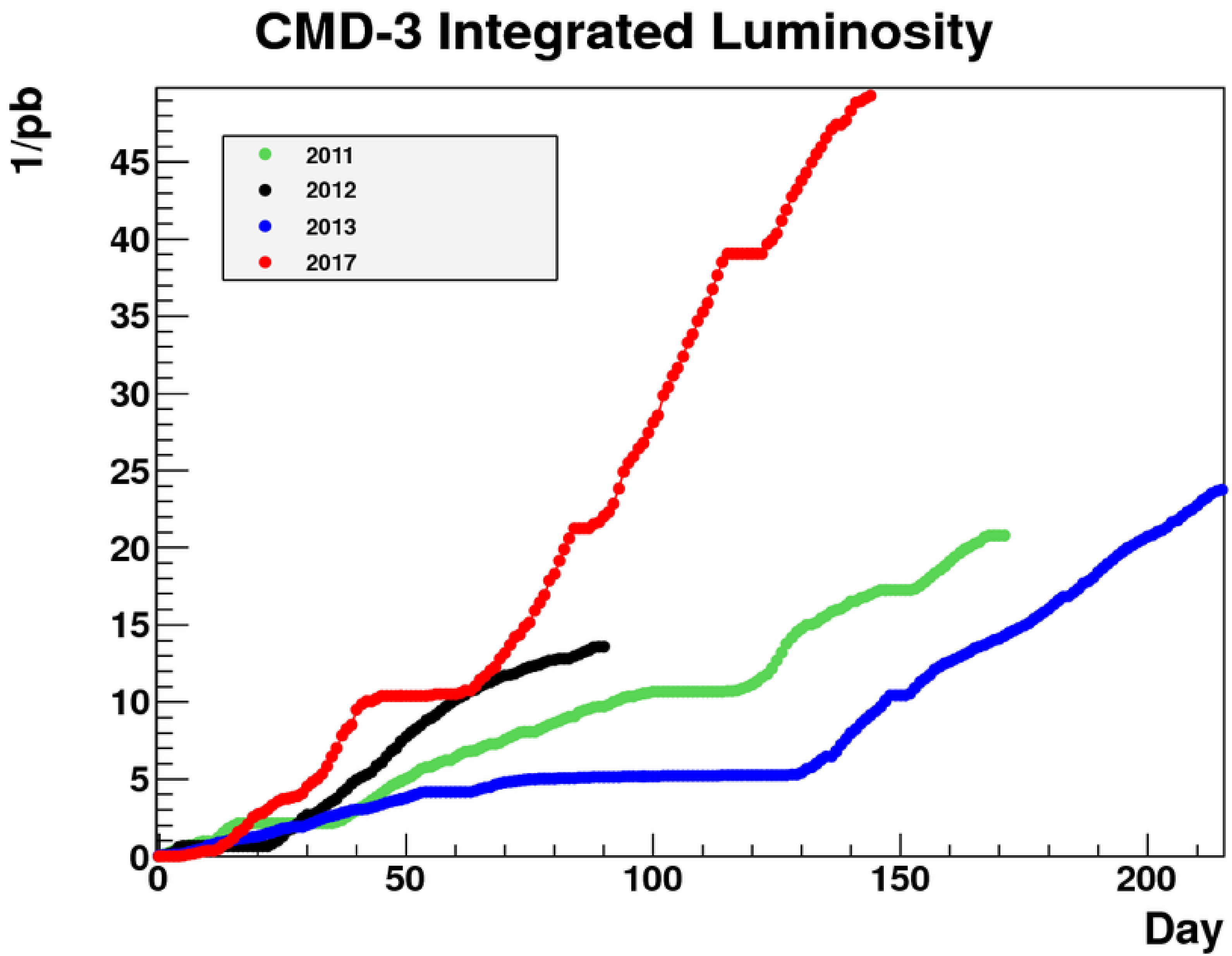
e^+/sec 2 x 10^7 to 2x10^8

e^-/sec 10^9 to 10^{11}

booster up to 1 GeV

started end 2016

Collected data graphs



Physical program

1. Study of dynamics of hadron production, i.e. separation between different intermediate states , for example, $\omega\eta$, $\varphi\eta$, ρa_0 etc. in the reaction $e^+e^- \rightarrow \pi^+\pi^-\pi^0\eta$. This is needed for understanding hadronization mechanisms.
2. Hadron spectroscopy: study of light-vector-meson exitations., in particular, search for their radiative decays.
3. Search for rare and forbidden decays of the ρ, ω, and φ mesons.
4. Study of nucleon-antinucleon pair production, extraction of the proton and neutron electromagnetic formfactors.
5. Two-photon physics, in particular, measurement of the photon-meson transition form factors for π^0, η, $\eta^{/}$.
6. Search for production of C-even resonances: $e^+e^- \rightarrow \eta, \eta^{/}, f_1, f_2, a_2$ …
7. Using radiative return technique as alternative method for measurement of hadronic cross sections.
8. Measurement of exclusive hadronic cross sections below 2 GeV. The goal is to obtain the total cross section for $e^+e^- \rightarrow$ *hadrons*, which used for calculation HVP contribition to the muon (g-2) and the running α_{QED}.
9. Test of high-order QED: $2 \rightarrow 4,5$.
10. etc.

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

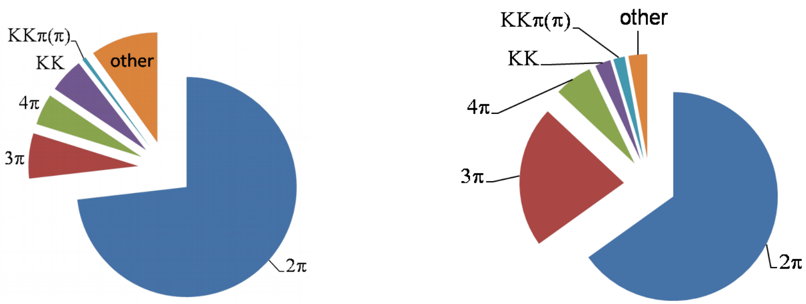
$(g\text{-}2)_\mu$

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

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

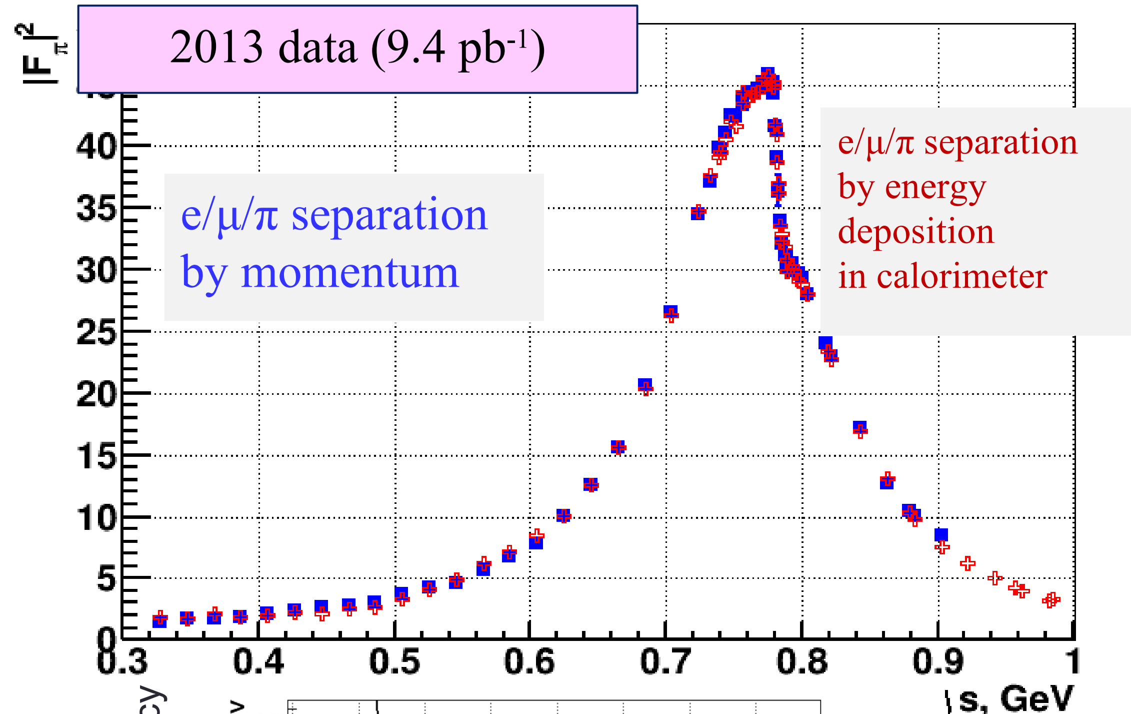
Contribution to the hadronic part of $(g\text{-}2)_\mu$ value from the VEPP-2000 energy region is about 92%:

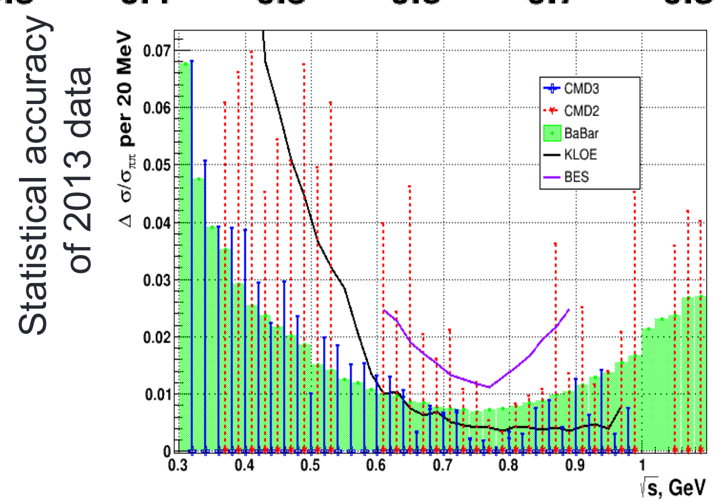
Contribution and squared error fraction:



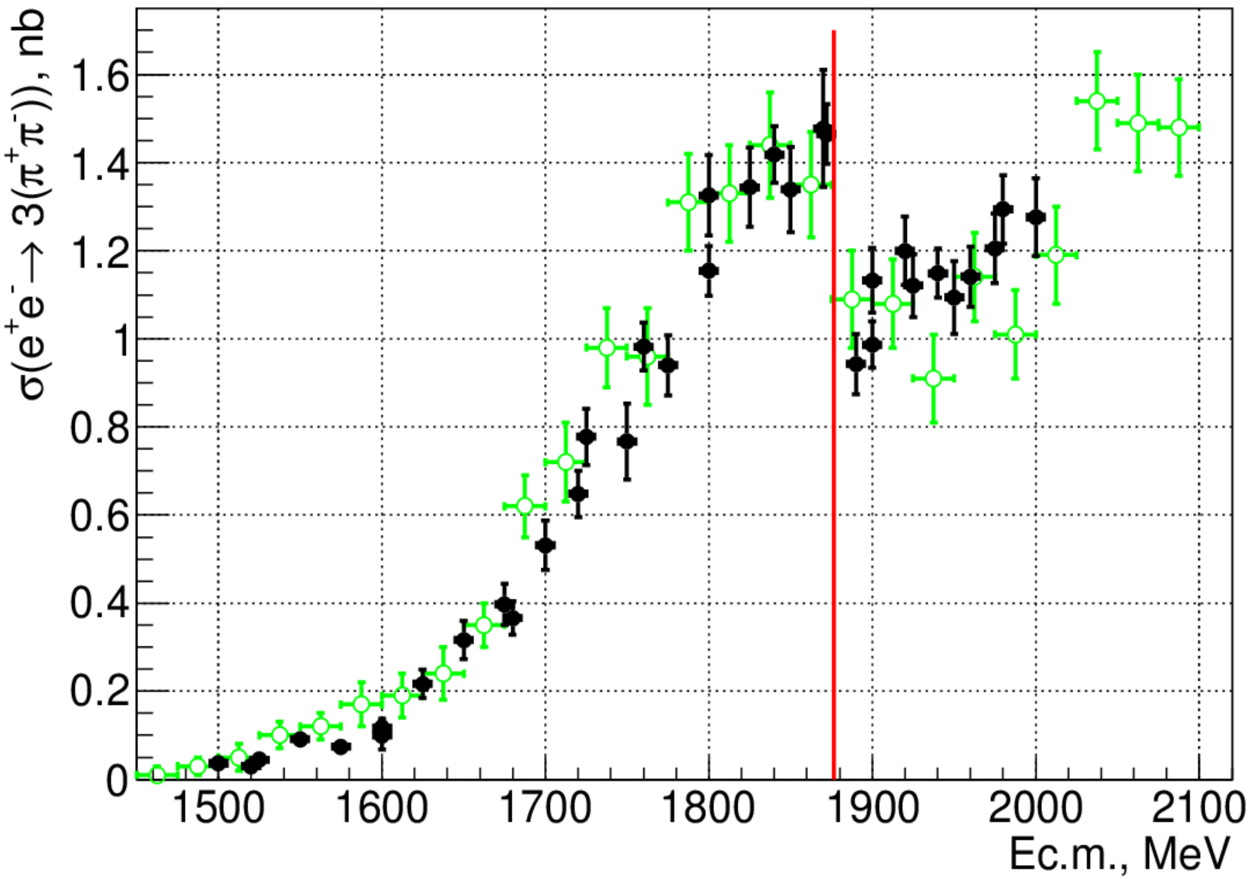
The goal is to reach systematic error under 0.36% (now radiative correction to 0.2-0.4%, e/μ/π separation 0.1-0.5%, 0.3-0.6% pion decay and nuclear interaction).

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





R(s) at $N\bar{N}$ threshold



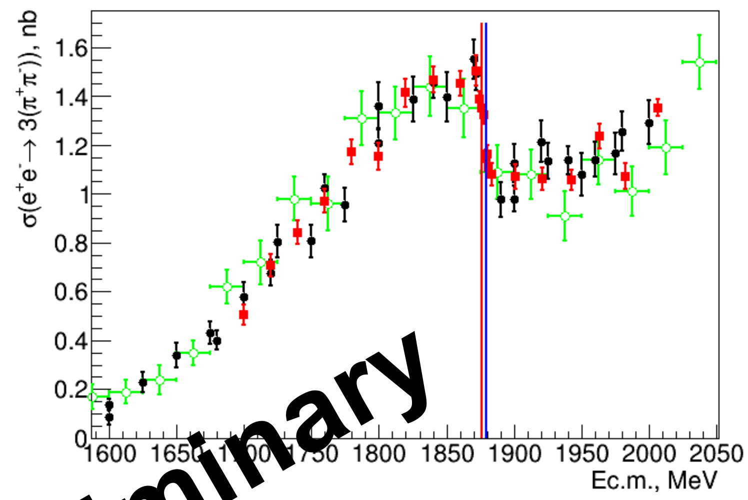
One of first results from CMD-3:

Sudden drop of $3\pi^+3\pi^-$ cross section at $N\bar{N}$ threshold.

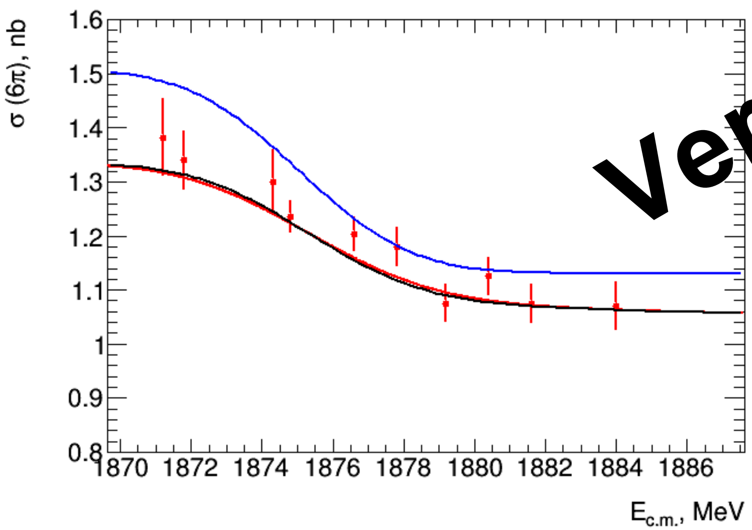
Preliminary studies of dynamics of $3\pi^+3\pi^-$, show also hint of energy dependent dynamics in 1.7-1.9 GeV energy range

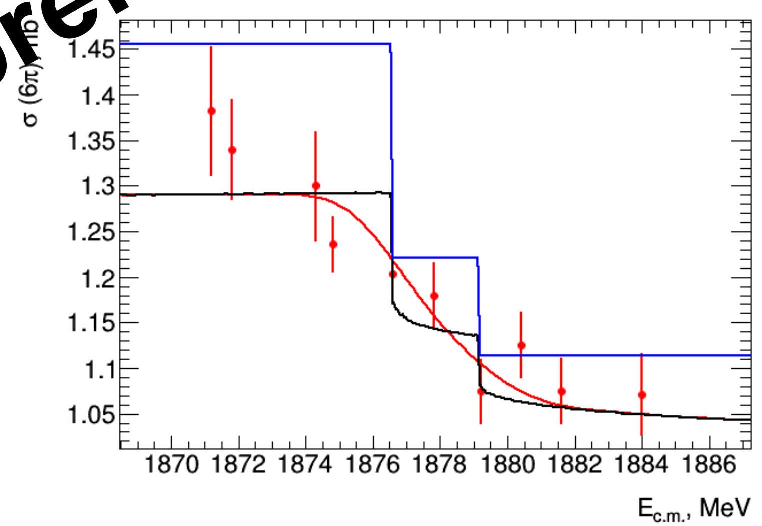
R(s) at $N\bar{N}$ threshold 2017

In 2017, detectors collected ~ 13 pb^{-1} per detector in the narrow energy range around threshold.
Very first look at the (CMD-3) $3\pi^+3\pi^-$ data: the sharp drop in cross sectionis confirmed and can be described either as a single transition with ~2.5 MeV width or as two narrow transitions at $p\bar{p}$ and $n\bar{n}$ thresholds (consistent with only beam energy spread, MeV)



Very preliminary



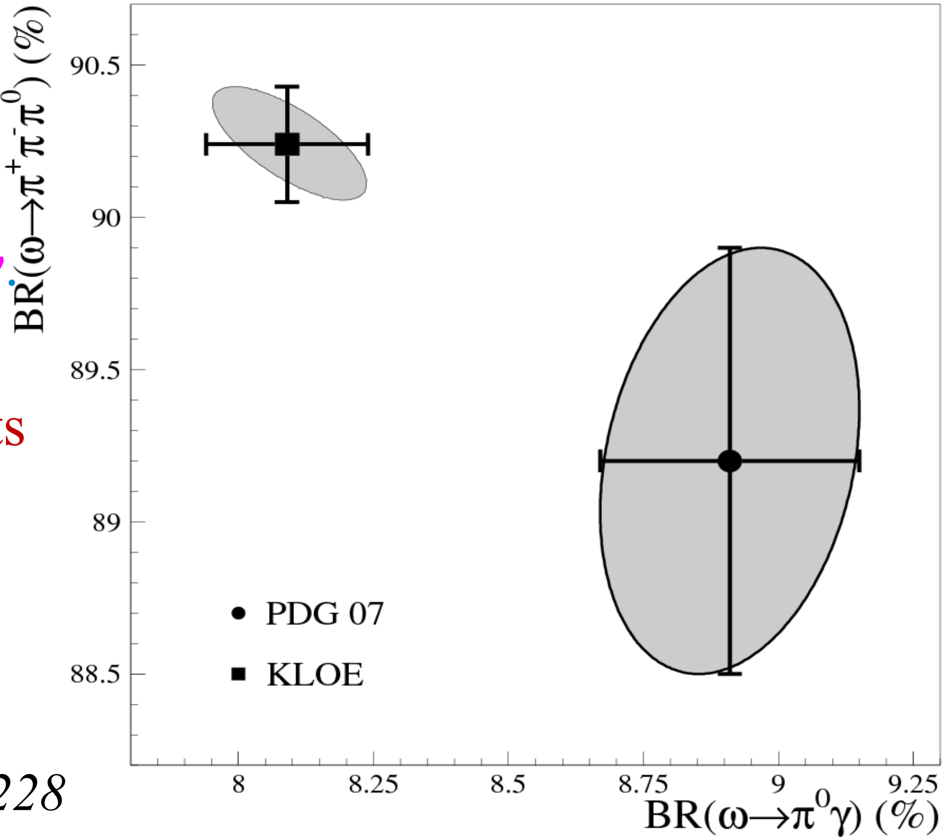


Process $e^+e^- \to \pi^\circ\gamma$

- Third largest cross section (after **2π** and **3π**) below **1 GeV**
- Measurement of the $\pi^\circ\gamma^*\gamma$ transition form factor
- Measurement of the radiative decays $V \to \pi^\circ\gamma$, V= ρ, ω, ϕ, ...
- There is a tension between the **KLOE** measurement of the ratio $\Gamma(\omega\to\pi^\circ\gamma)/\Gamma(\omega\to\pi^+\pi^-\pi^\circ)$ and other measurements of ω-meson parameters:

KLOE have studied the $e^+e^-\to\omega\pi^\circ$ process near the ϕ-meson resonance in two decay modes $\omega\to\pi^+\pi^-\pi^\circ$ and $\omega\to\pi^\circ\gamma$.

The ω-meson parameters obtained through KLOE studies have a large shifts from the previously measurements, especially for $\omega\to\pi^\circ\gamma$ decay.



F. Ambrosino, et. al., Phys. Lett. B 665 (2008) 223-228

$e^+e^- \rightarrow \pi^\circ\gamma$

VEPP-2M and VEPP-2000 data

The process $e^+e^- \rightarrow \gamma\gamma$ is used for normalization.

Common selection criteria for 2γ and 3γ final states:

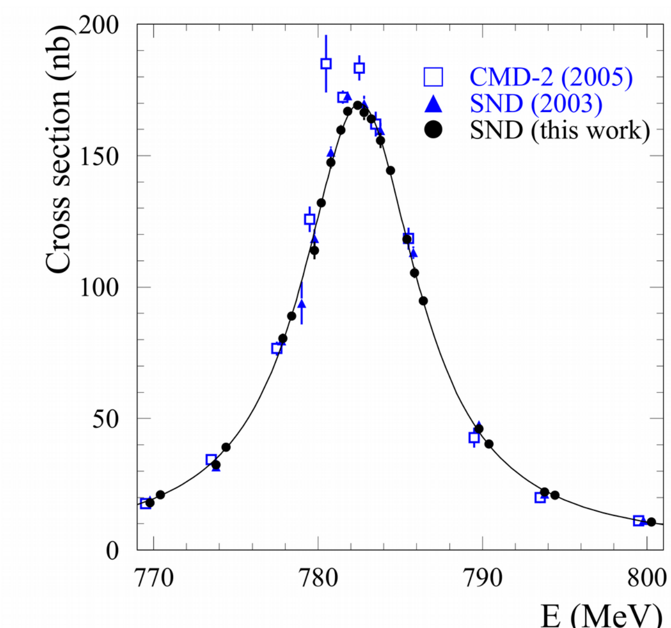
- trigger, no charged tracks, total energy deposition and momentum, muon system veto.

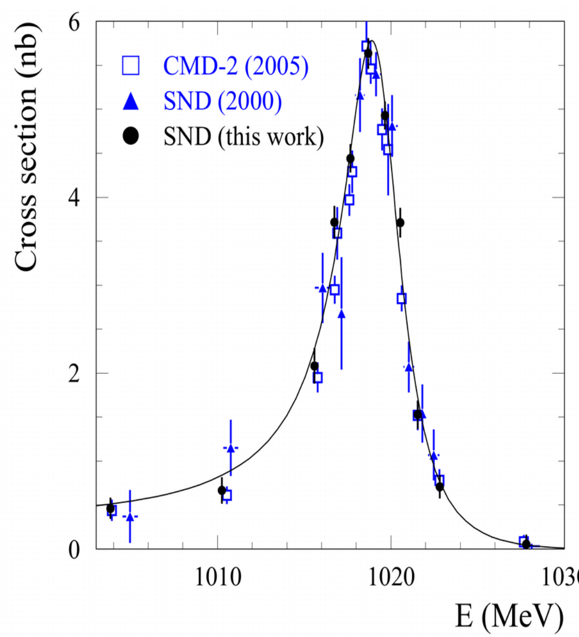
Final selection is **based on 4C kinematic fit:**

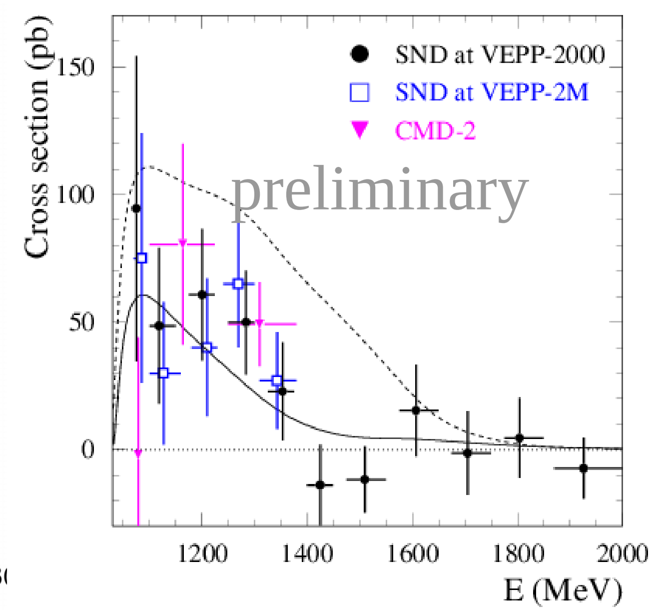
$$\chi^2_{3\gamma} < 30, \quad 36^\circ < \theta_\gamma < 144^\circ, \; 80 < M_{rec} < 190 \text{ MeV},$$

here M_{rec} is the mass recoiling against largest energy photon.

The number of signal events is determined from **the fit of π° in M_{rec} spectrum.**







M.N. Achasov, et. al., Phys. Rev. D 93 092001 (2016)

Results on radiative decays

$$B(\omega \to \pi^0\gamma)B(\omega \to e^+e^-) = (6.336 \pm 0.056 \pm 0.089) \times 10^{-6}$$

Using PDG value for **$B(\omega\to\pi^+\pi^-\pi^\circ)\times B(\omega\to e^+e^-)$** we have obtained **$\Gamma(\omega\to\pi^\circ\gamma)/\Gamma(\omega\to\pi^+\pi^-\pi^\circ)=0.0992\pm0.0023$**,
which is higher than the KLOE value **0.0897 ± 0.0016** by **3.4σ .**

$$B(\rho \to \pi^0\gamma) = (4.20 \pm 0.47 \pm 0.22) \times 10^{-4}$$

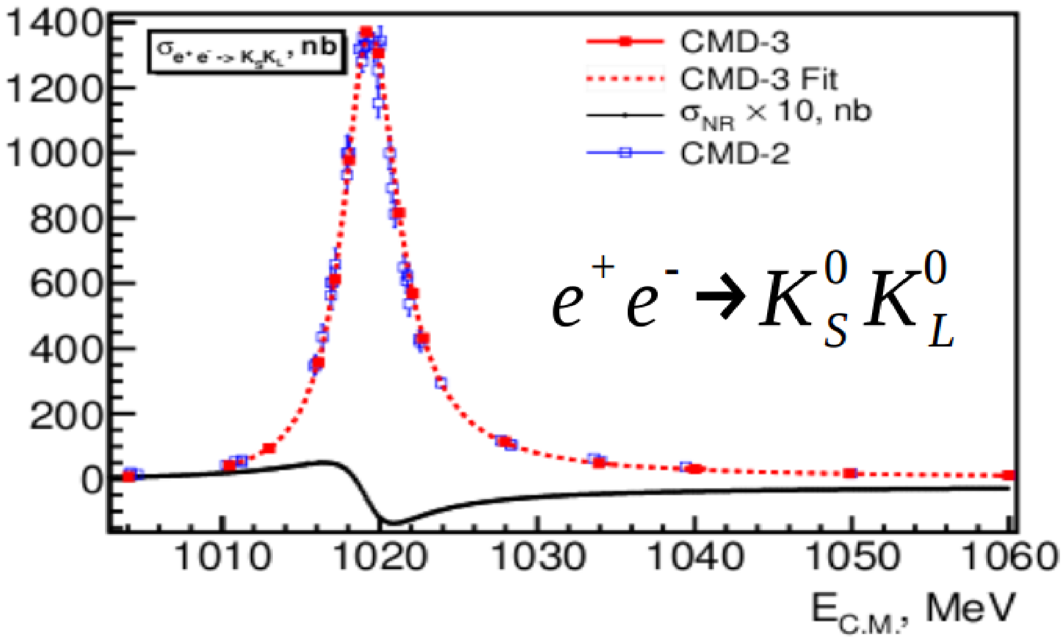
By **1.8σ** lower than the current PDG value **$(6.0\pm0.8)\times10^{-4}$**, but agrees with the branching fraction for the charged mode **$B(\rho^\pm\to\pi^\pm\gamma) = (4.5\pm0.5)\times10^{-4}$.**

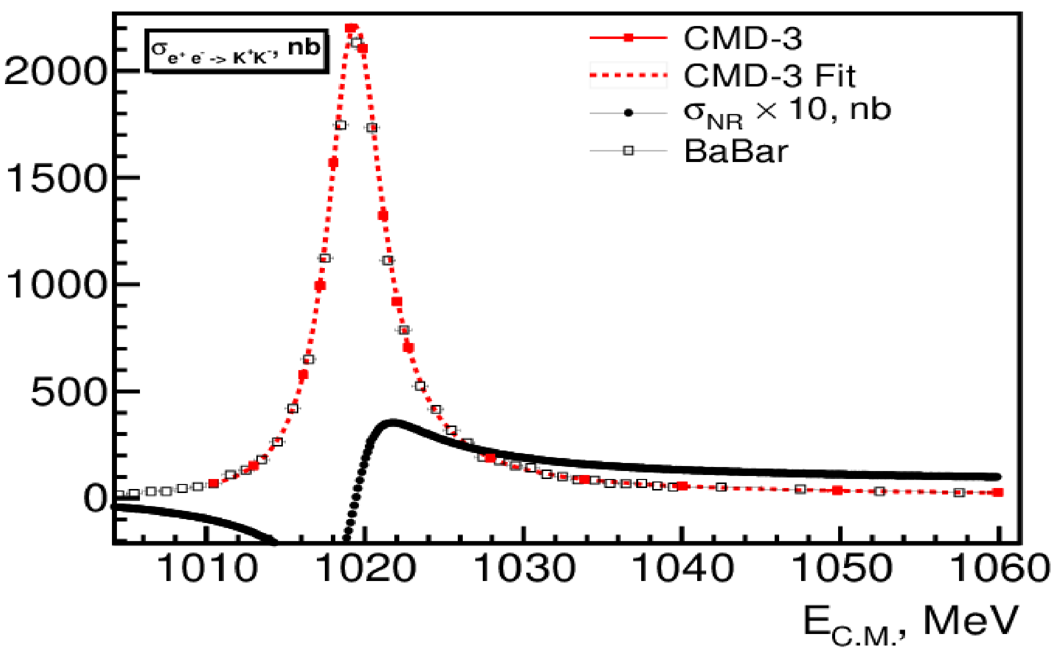
$$B(\phi \to \pi^0\gamma)B(\phi \to e^+e^-) = (3.92^{+0.71}_{-0.40} \pm 0.51) \times 10^{-7}$$

The model uncertainties of the previous measurements (**~8%**) were underestimated. For **ϕ_ϕ** fixed at the value **$(163\pm7)^\circ$** obtained in the VMD fit to **$e^+e^-\to\pi^+\pi^-\pi^\circ$** data

$$B(\phi \to \pi^0\gamma)B(\phi \to e^+e^-) = (4.04 \pm 0.09 \pm 0.19) \times 10^{-7}$$

$K_L K_S$ and K^+K^- at φ(1020)

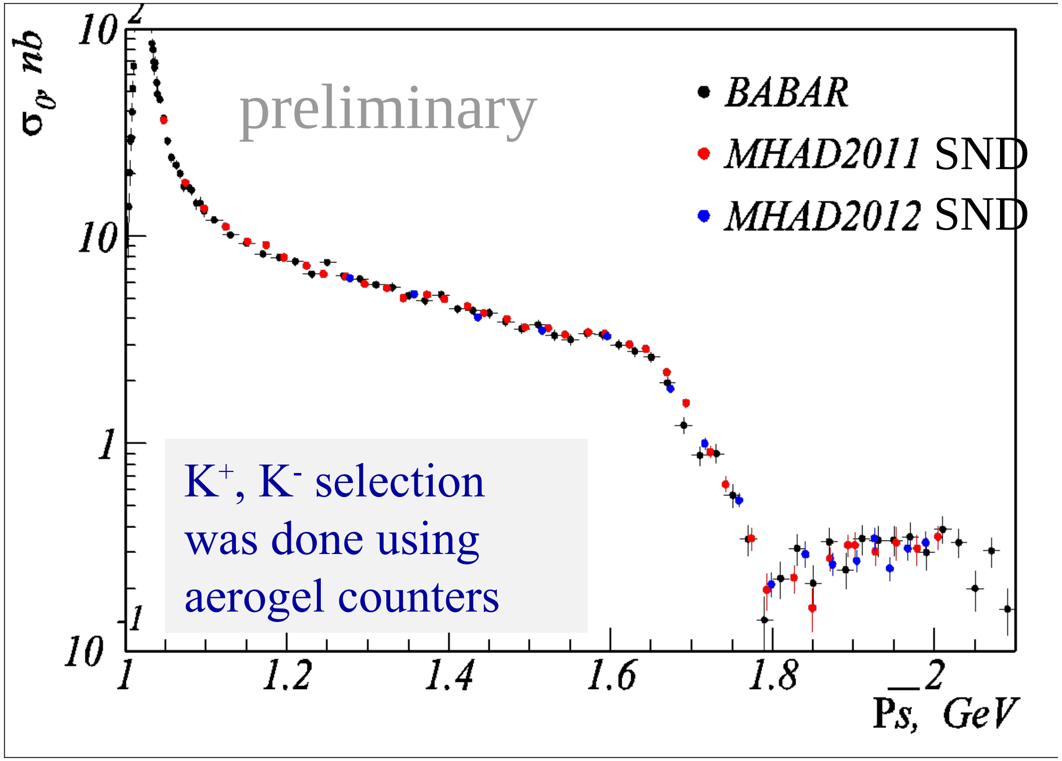


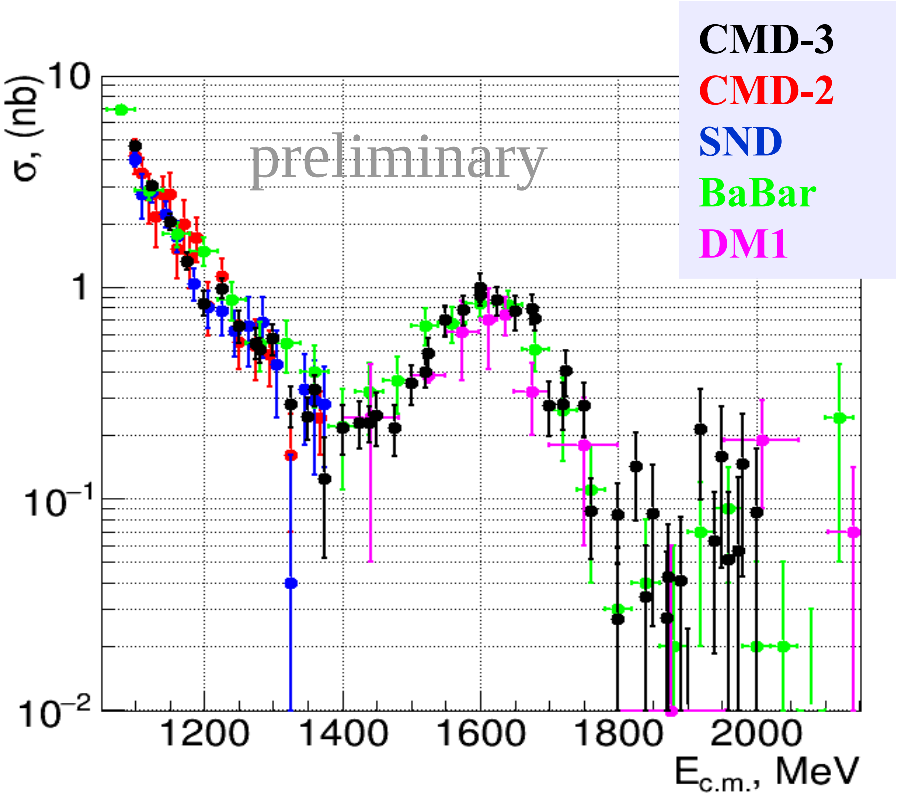


Used luminosity ~ 6 pb^{-1}

Systematic error for $K_L K_S$ is 1.8%

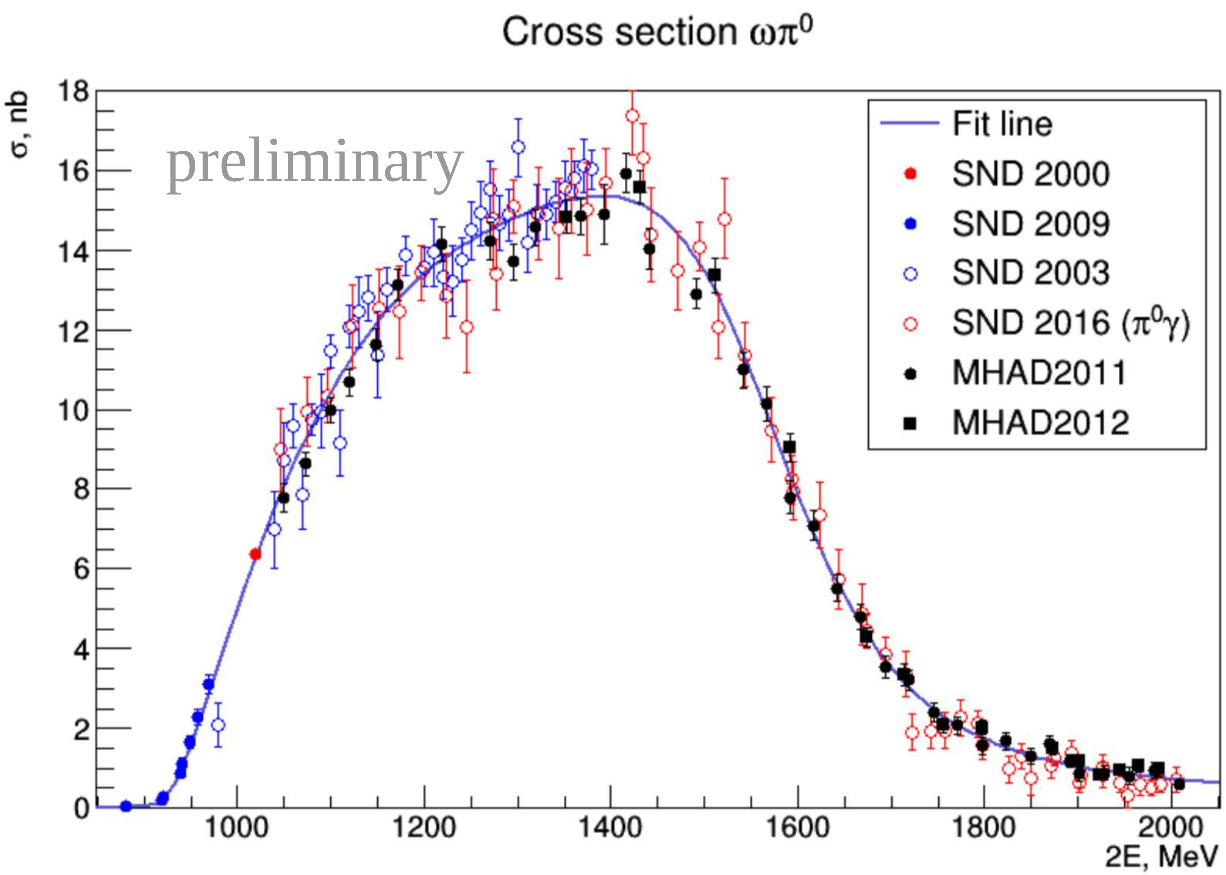
Systematic error for K^+K^- is 2.5% (preliminary)





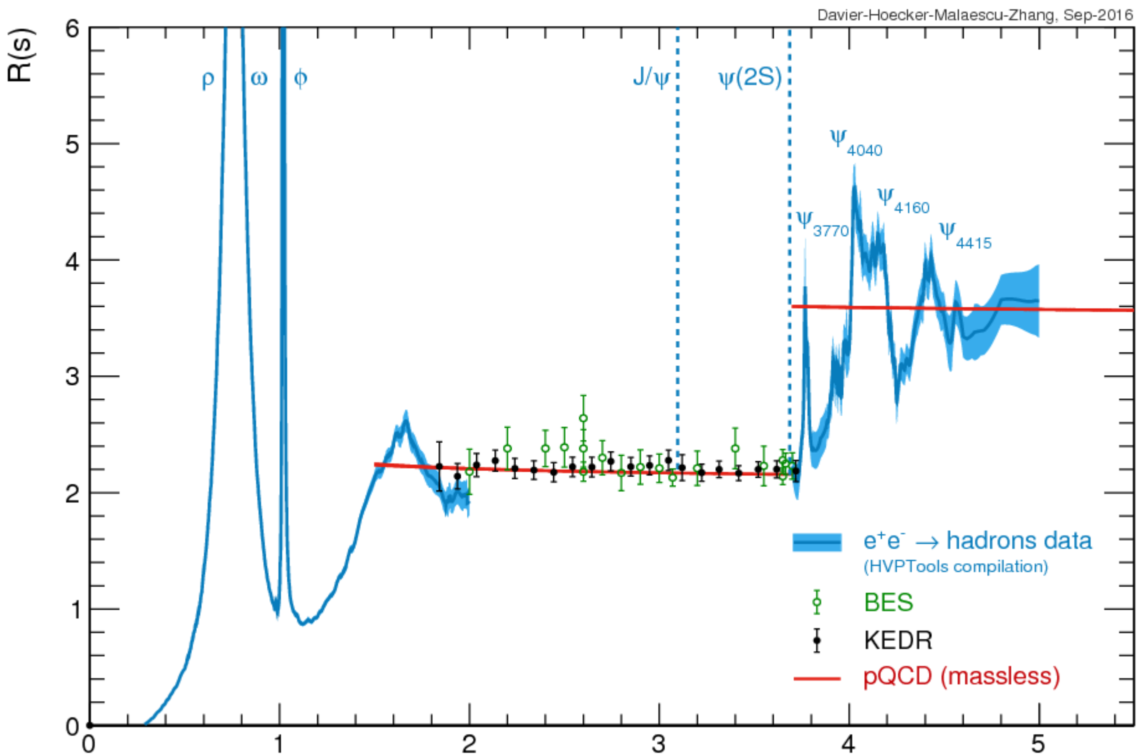
The complex form of these cross sections is due to interference of many excited vector resonances in this energy region

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



- The result is based on the data subset 2011-2012
- Statistical error 2-16% depending from energy
- Systematic error 1-9%

Exclusive vs inclusive measurements



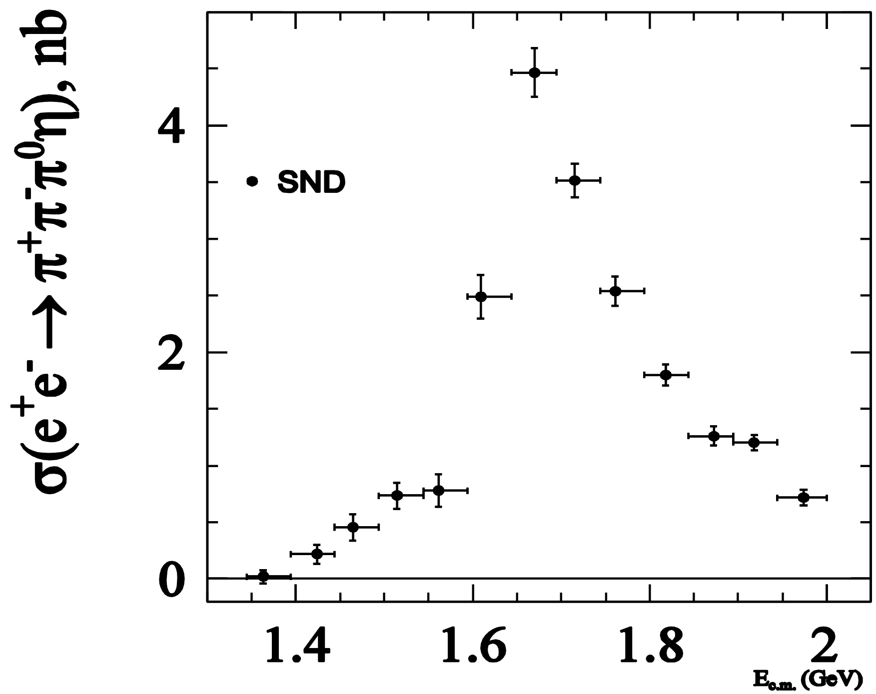
(DHMZ , TAU 2016, arXiv:1612.02743)

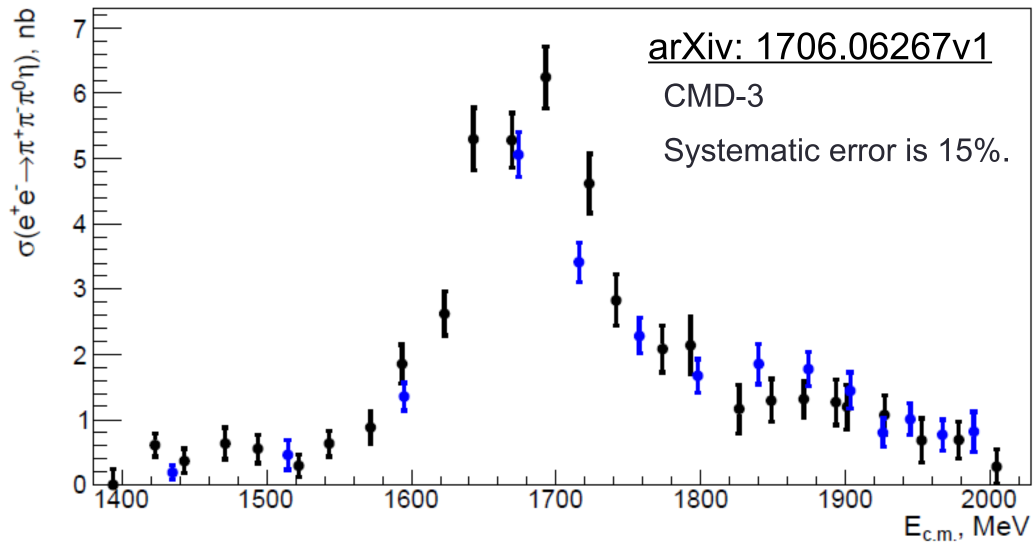
Below **2 GeV** the total hadronic cross section is calculated as a sum of exclusive cross sections.

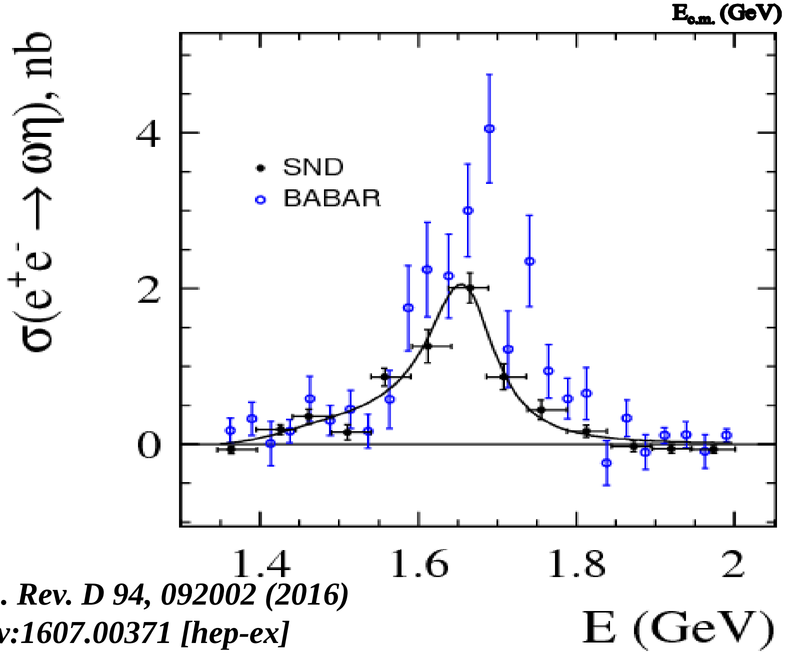
Currently the exclusive and inclusive data below **2 GeV** are in reasonable agreement.

In the energy region 1.5-2.0 GeV exclusive data are incomplete. There are no experimental data on the final states $\pi^+\pi^-\pi^\circ\eta$, $\pi^+\pi^-\eta\eta$, $\pi^+\pi^-\pi^\circ\pi^\circ\pi^\circ$, $\pi^+\pi^-\pi^\circ\pi^\circ\eta$, ...

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





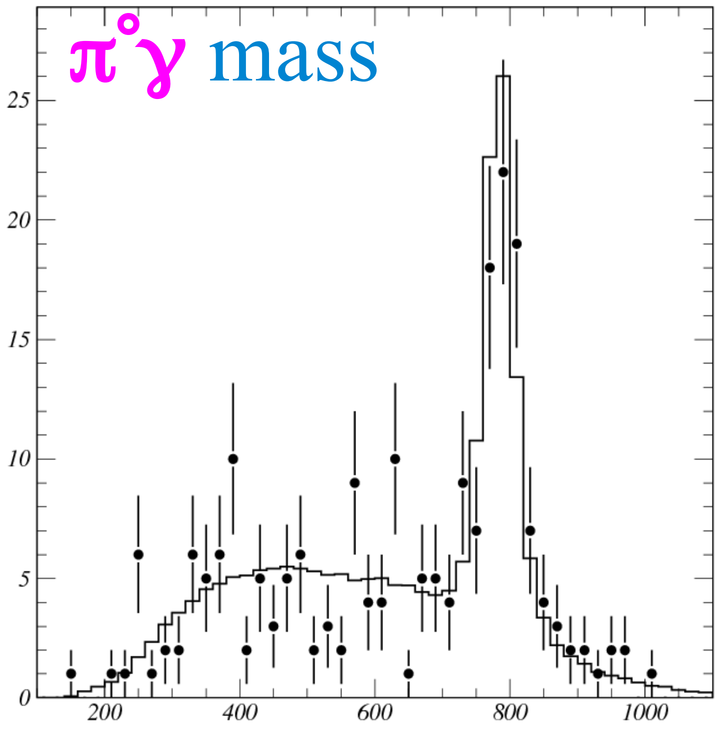


Phys. Rev. D 94, 092002 (2016)
arXiv:1607.00371 [hep-ex]

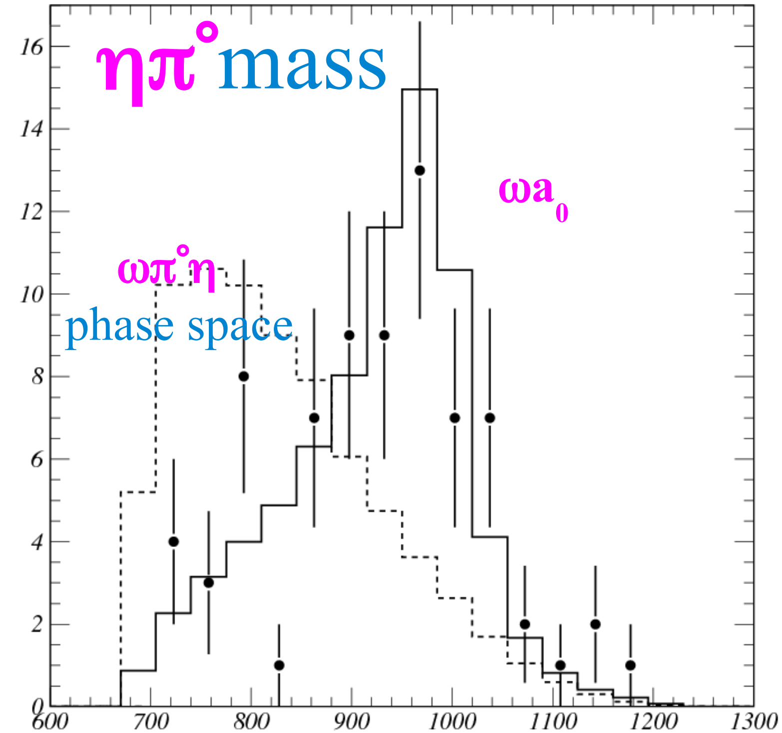
- First measurements of this process.
- The intermediate states are $\omega\eta$, $\phi\eta$, structureless $\pi^+\pi^-\pi^0\eta$ and $a_0(980)\rho$.
- The known $\omega\eta$ and $\phi\eta$ contributions explain about 50-60% of the cross section below **1.8 GeV**.
- Above **1.8 GeV** the dominant reaction mechanism is $a_0(980)\rho$.

- The process $e^+e^-\to\omega\eta$ has been measured separately.
- There is a significant difference between **SND** result and the previous **BABAR** measurement.

Process $e^+e^- \to \omega\pi^\circ\eta$

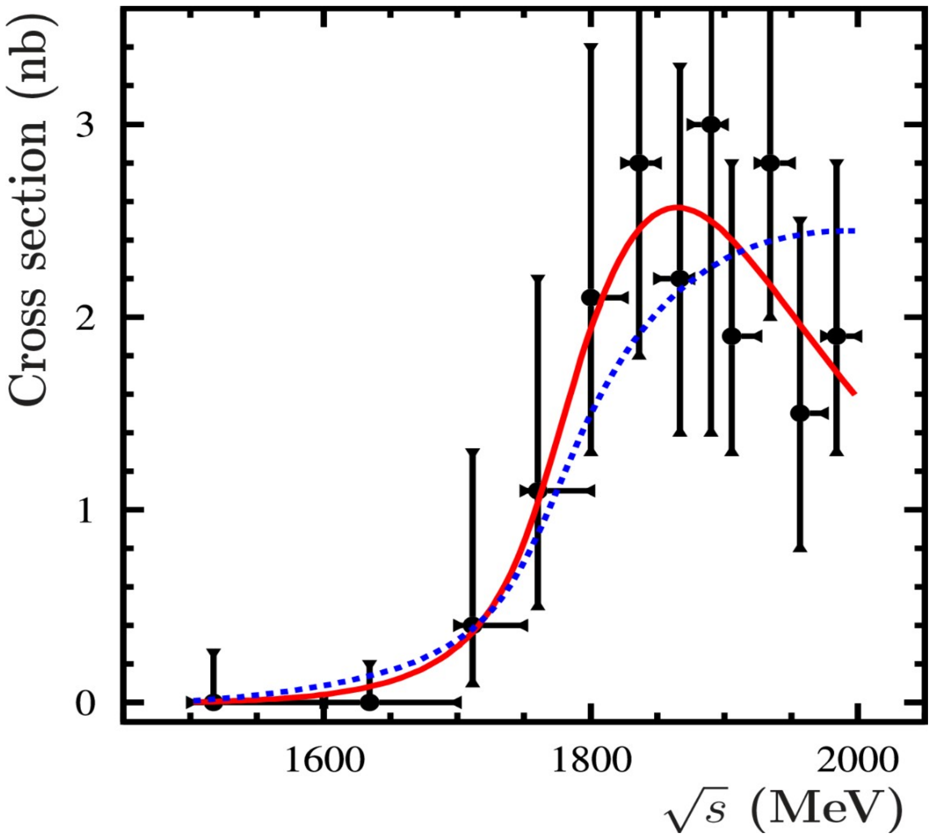


Events of the $e^+e^- \to \pi^\circ\pi^\circ\eta\gamma \to 7\gamma$ process are selected. The dominant intermediate state is $\omega\pi^\circ\eta$. No noticeable $\eta'\gamma$ signal observed.



The $\eta\pi^\circ$ mass spectrum for selected $\omega\pi^\circ\eta$ events is well described by the model of the $\omega a_0(980)$ intermediate state.

$e^+e^- \to \omega\pi^\circ\eta$: cross section



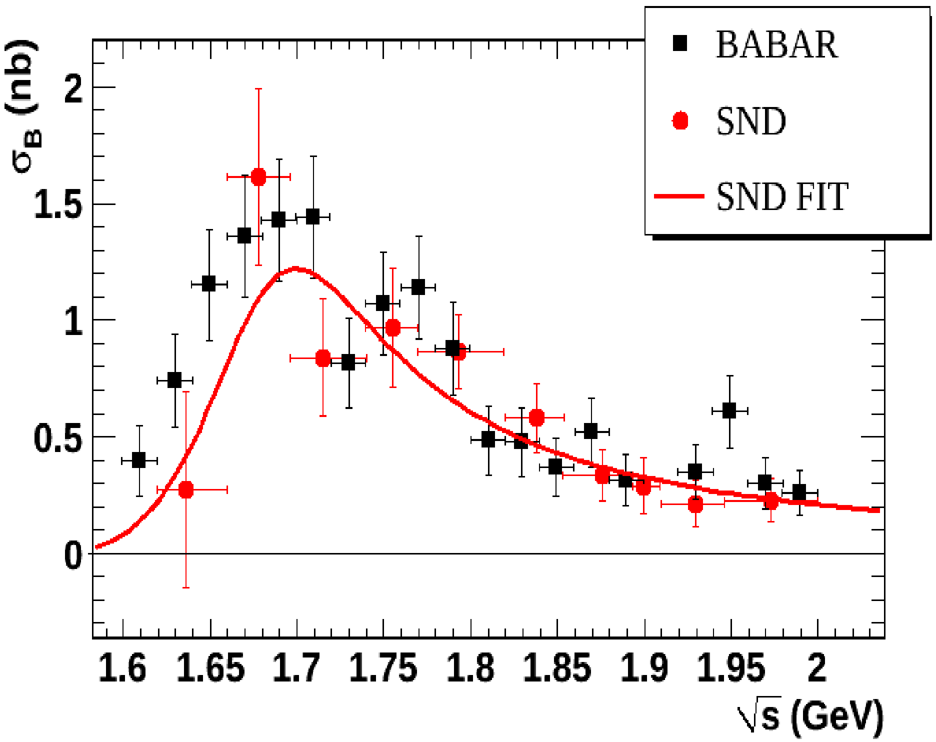
- First measurement of the $e^+e^- \to \omega\pi^\circ\eta$ cross section.
- The cross-section energy dependence is described by a single-resonance model.
- The resonance mass and width are consistent with those for ρ(1700)

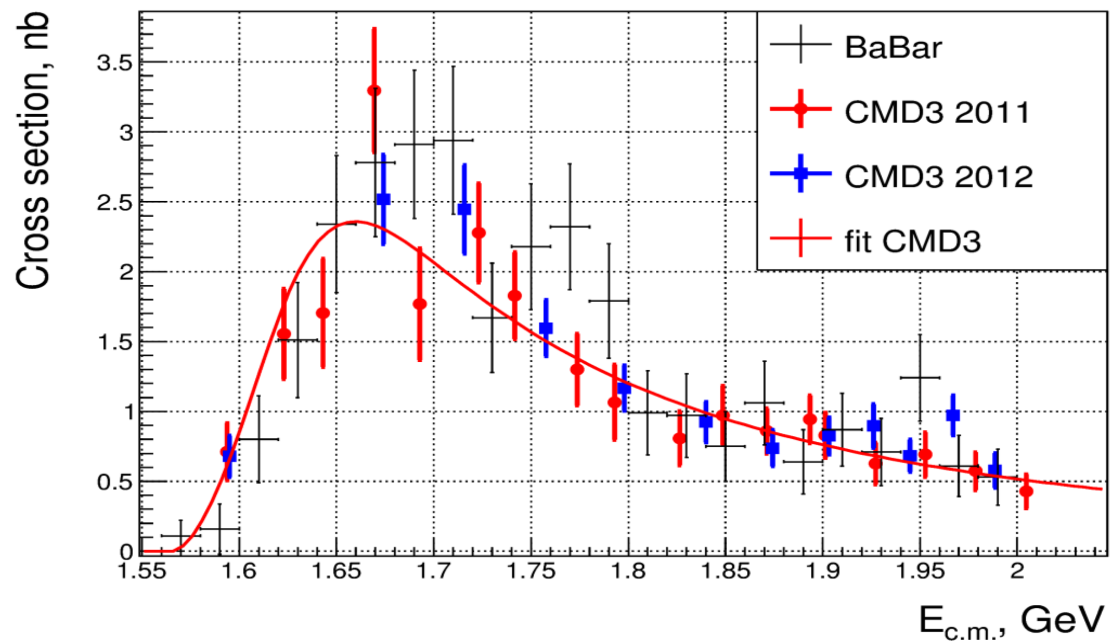
and non-resonant is worse at 1.2σ

Phys. Rev. D 94, 032010 (2016)
arXiv:1606.06481 [hep-ex]

The cross section is about **2.5 nb.**
5% of the total hadronic cross section in the energy region **1.8 – 2.0 GeV**.

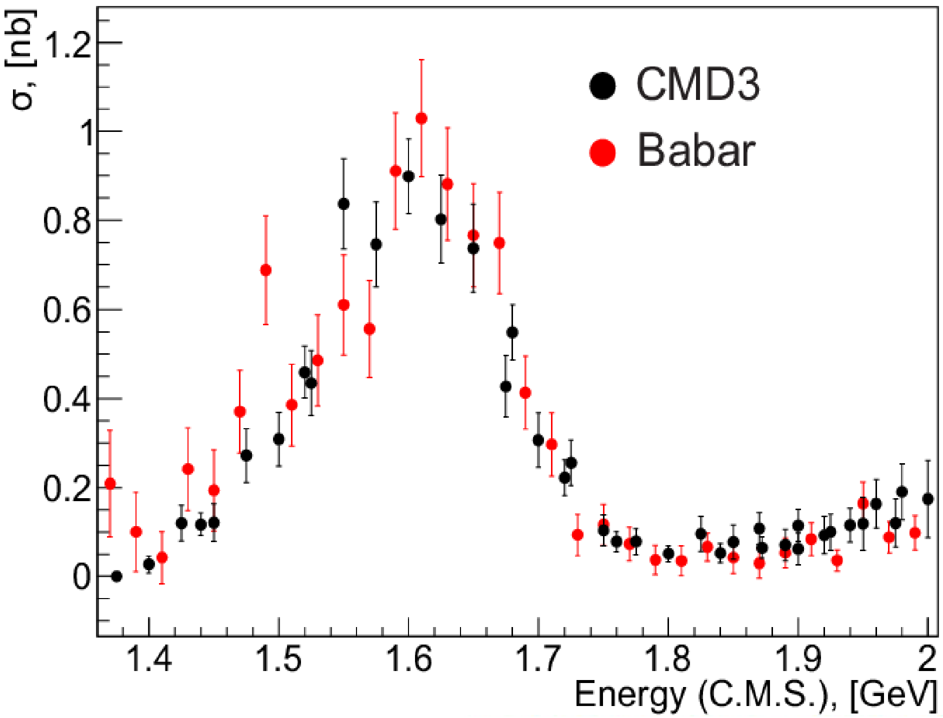
$e^+e^- \to K^+K^-\eta$

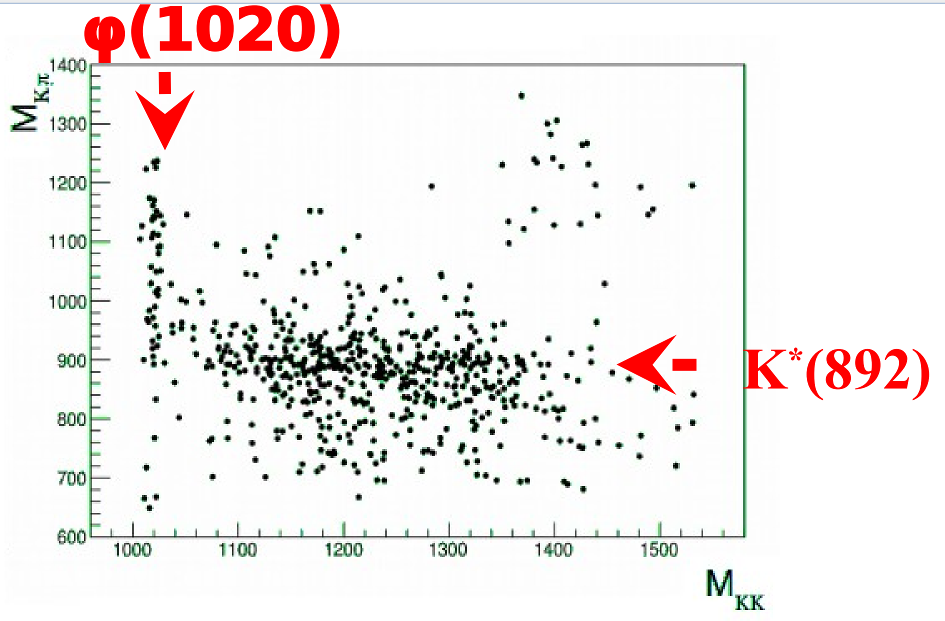




It is assumed that the dominant reaction mechanism is **φ(1680) → φ(1020)η**. This hypothesis is in agreement with the data

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





Analysis is based on the integrated luminosity of 34 pb^{-1}

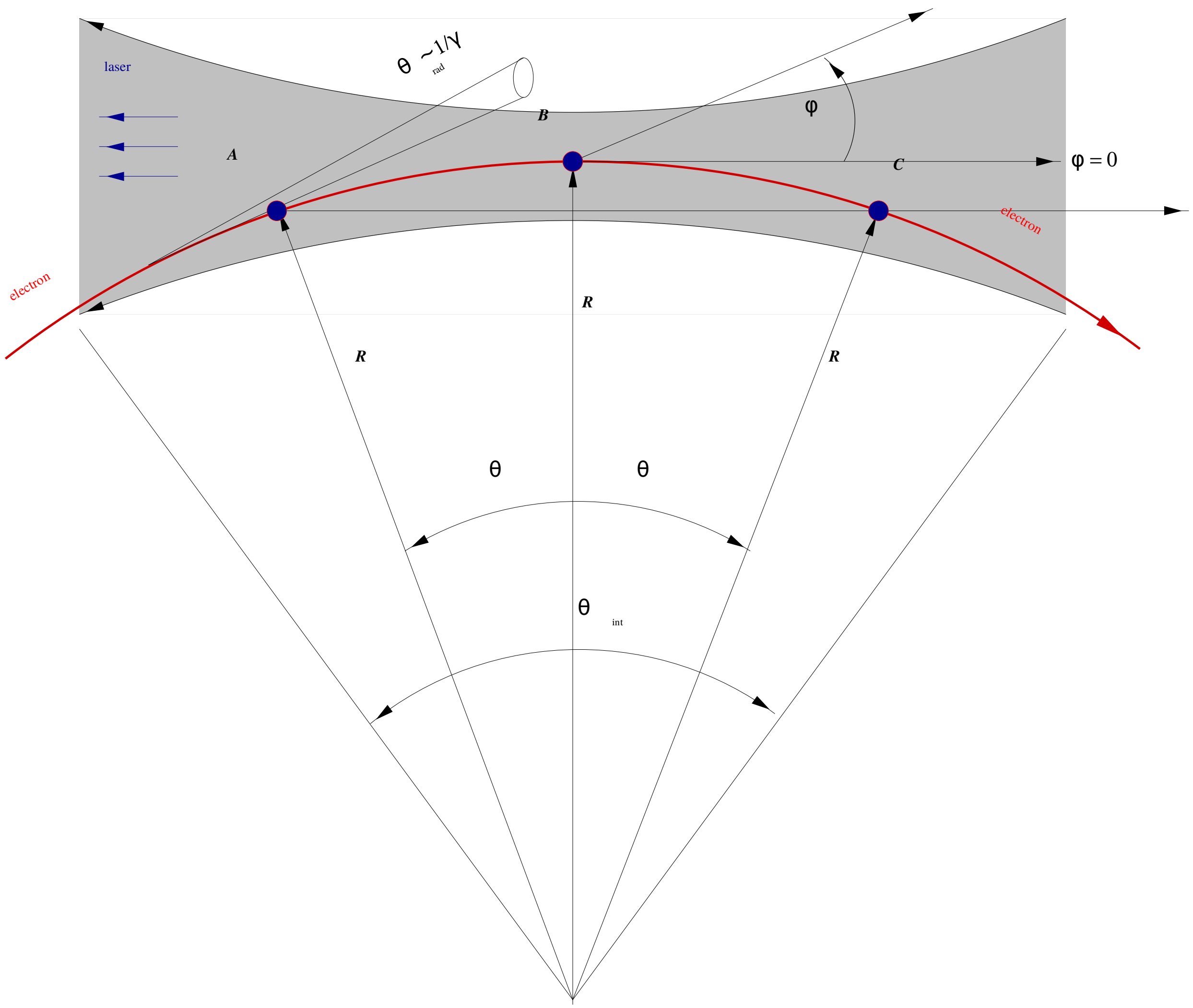
Two intermediate states are clearly seen: $\phi\pi^\circ$ and K*(892)K mechanism. The current systematic uncertainty is estimated as 10%

Conclusions

- During **2010 – 2013** the **SND** detector accumulated **~70 pb^{-1}** of integrated luminosity at the **VEPP-2000** electron-positron collider in the c.m. energy range **0.3 – 2 GeV**.
- Data analysis on hadron production is in progress. The obtained results have comparable or better accuracy than previous measurements.
- For some processes the cross sections have been measured for the first time.
- After **VEPP-2000** upgrade the data taking runs are continued with a goal of **~1 fb^{-1}** of integrated luminosity.

Thank you!

CBS interference illustration



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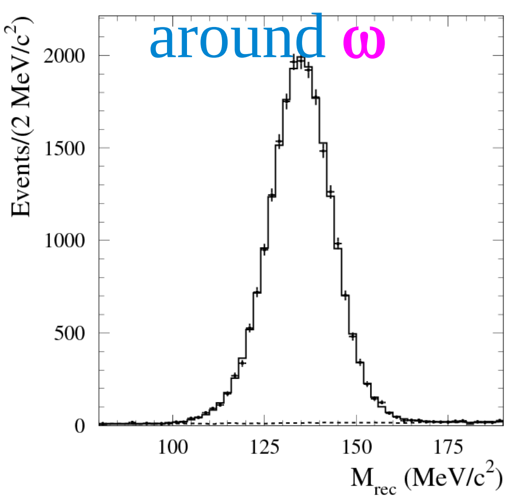
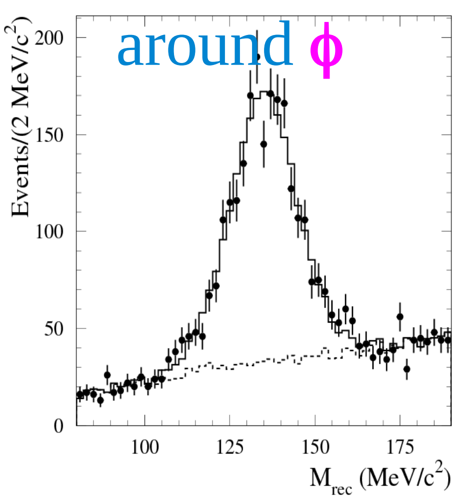
$$\chi^2_{3\gamma} < 30, \quad 36^\circ < \theta_\gamma < 144^\circ, 80 < M_{rec} < 190 \text{ MeV},$$

here M_{rec} is the mass recoiling against largest energy photon.

The number of signal events is determined from **the fit of π° in M_{rec} spectrum.**





below1.4GeV

above1.4GeV

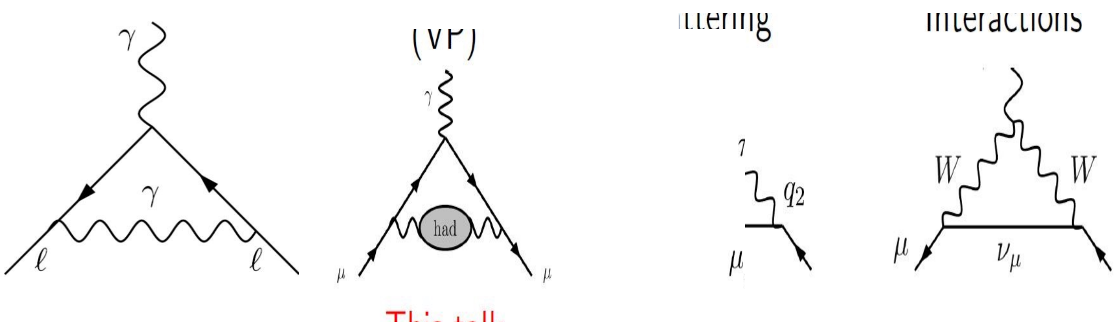
$(g\text{-}2)_\mu/2$ of muon (experiment)

Magnetic moment

$$\vec{\mu} = g\frac{e\hbar}{2mc}\vec{S}$$

✓The Dirac equation predicts g=2 for point-like fermions.
✓Higher order QFT contributions lead to nonzero

$$a=(g-2)/2$$



✓ a_μ is sensitive to New Physics contributions

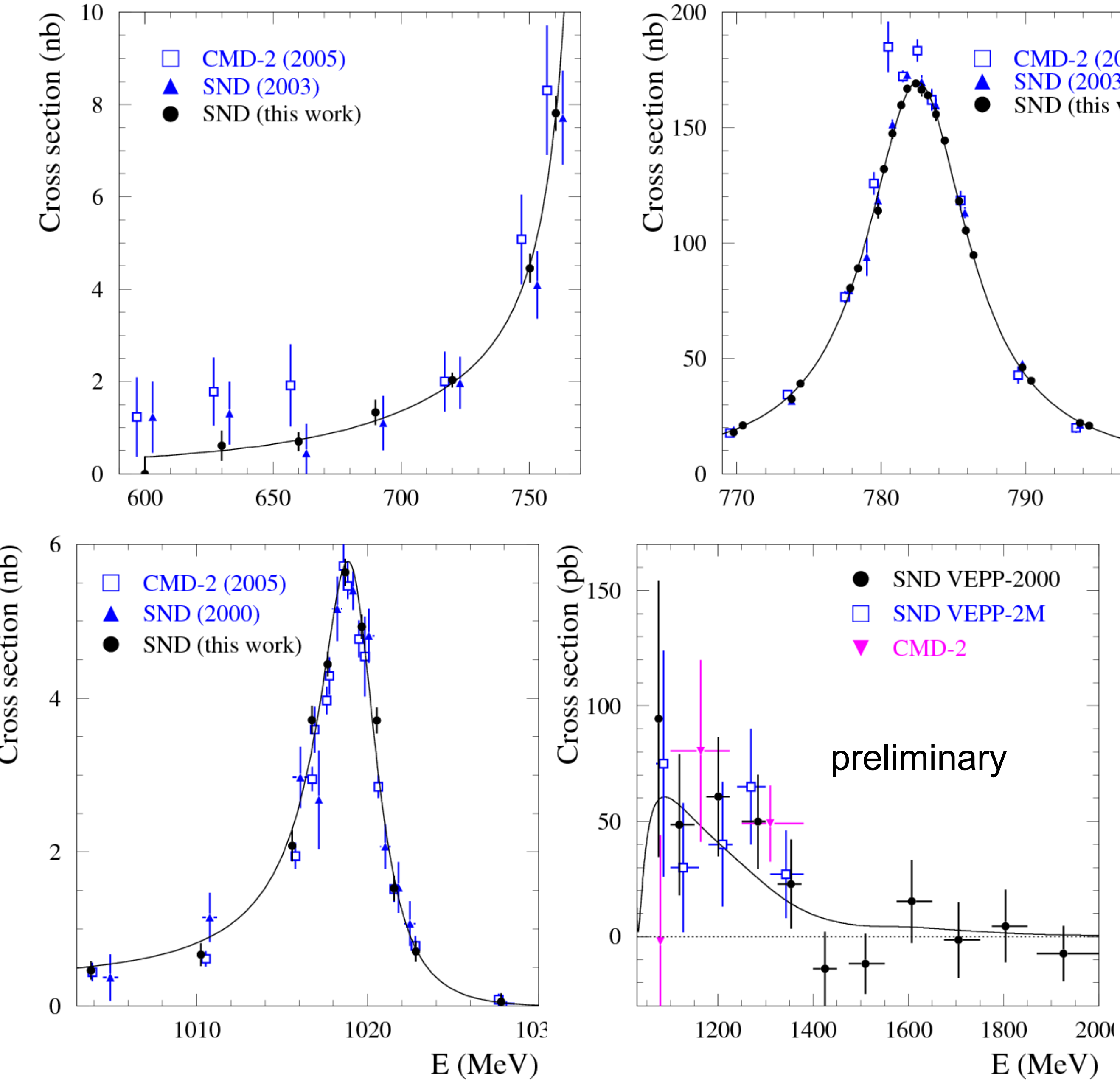
E821@BNL (1997-2001):
G.W. Bennett *et al.*,
Phys. Rev. D **77**, 072003 (2006)
$a_\mu = (11\ 659\ 209.1 \pm 6.3) \times 10^{-10}$ (0.54 ppm)

E989 @ FNAL (2017-…):
F. Gray *et al.*, arXiv: 1510.003
a_μ = … (0.14 ppm)

E34 @ J-PARC (????-…):
T. Mibe *et al.,*
Chin. Phys. C **34** (2010) 745
a_μ = … (0.1 ppm)

Phys. Rev. D 93, 092001 (2016)

$e^+e^- \to \pi^0\gamma$ @ SND



✓ The most precise measurement of the cross section

✓ Systematic uncertainty at the ω peak is 1.4% (1.2% from luminosity and 0.6% due to selection criteria)