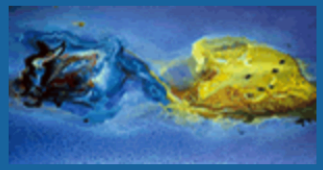


XIIIth Quark Confinement and the Hadron Spectrum

Study of the e^+e^- →hadrons reactions with the CMD-3 detector at the VEPP-2000 collider

Peter A. Lukin

on behalf of the CMD-3 collaboration

Budker Institute of Nuclear Physics

Novosibirsk State University

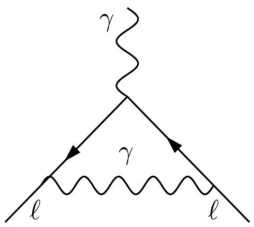
ConfXIII
03.08.2018

Outline

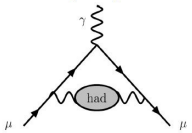
- Motivation
- Collider and detector
- Recent results on hadronic cross sections measurements
- Conclusion

$(g-2)/2$ of muon

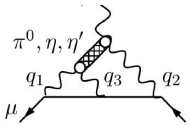
- Magnetic moment of Dirac particle: $\vec{\mu} = g\frac{e\hbar}{2mc}\vec{s}$, gyromagnetic factor g for point-like fermions =2



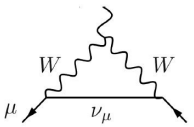
Hadronic Vacuum Polarisation (VP)



Hadronic light-by-light Scattering



Weak Interactions



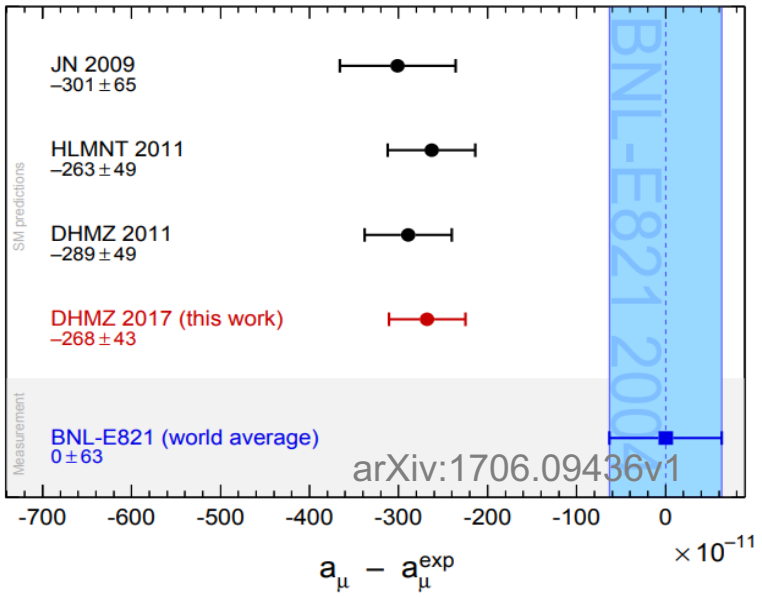
- Higher order contributions make muon magnetic anomaly $a_\mu \equiv (g-2)/2 \neq 0$

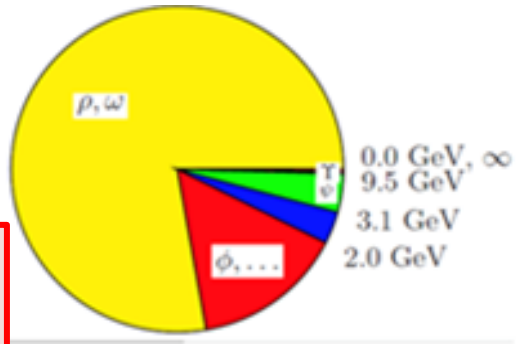
$$\mathbf{a_\mu^{\,theory(SM)} = a_\mu^{\,QED} + a_\mu^{\,had} + a_\mu^{\,weak}}$$

- $a^{\mathrm{had,LO}}{}_\mu$ is calculated by integrating experimental $\sigma(e^+e^- \to hadrons)$

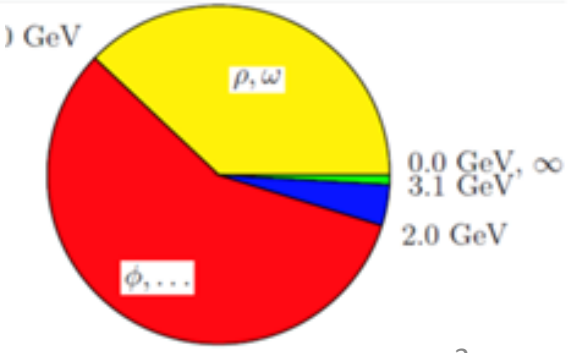
$$a^{had}{}_\mu = \frac{\alpha^2}{3\pi^2}\int_{4m^2{}_\pi}^{\infty} ds\,\frac{K(s)}{s}R(s)$$

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





a_μ integral

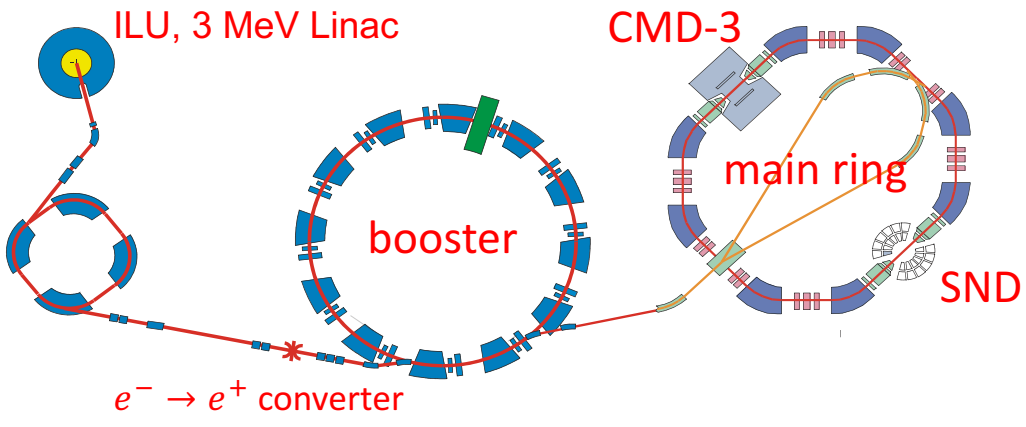


a_μ uncertainty

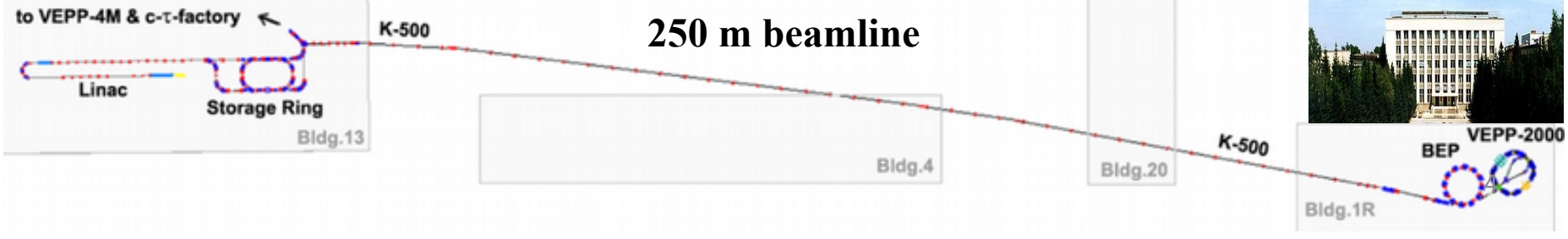
High precision hadronic cross sections measurements in $E_{cm} < 2$ GeV are needed

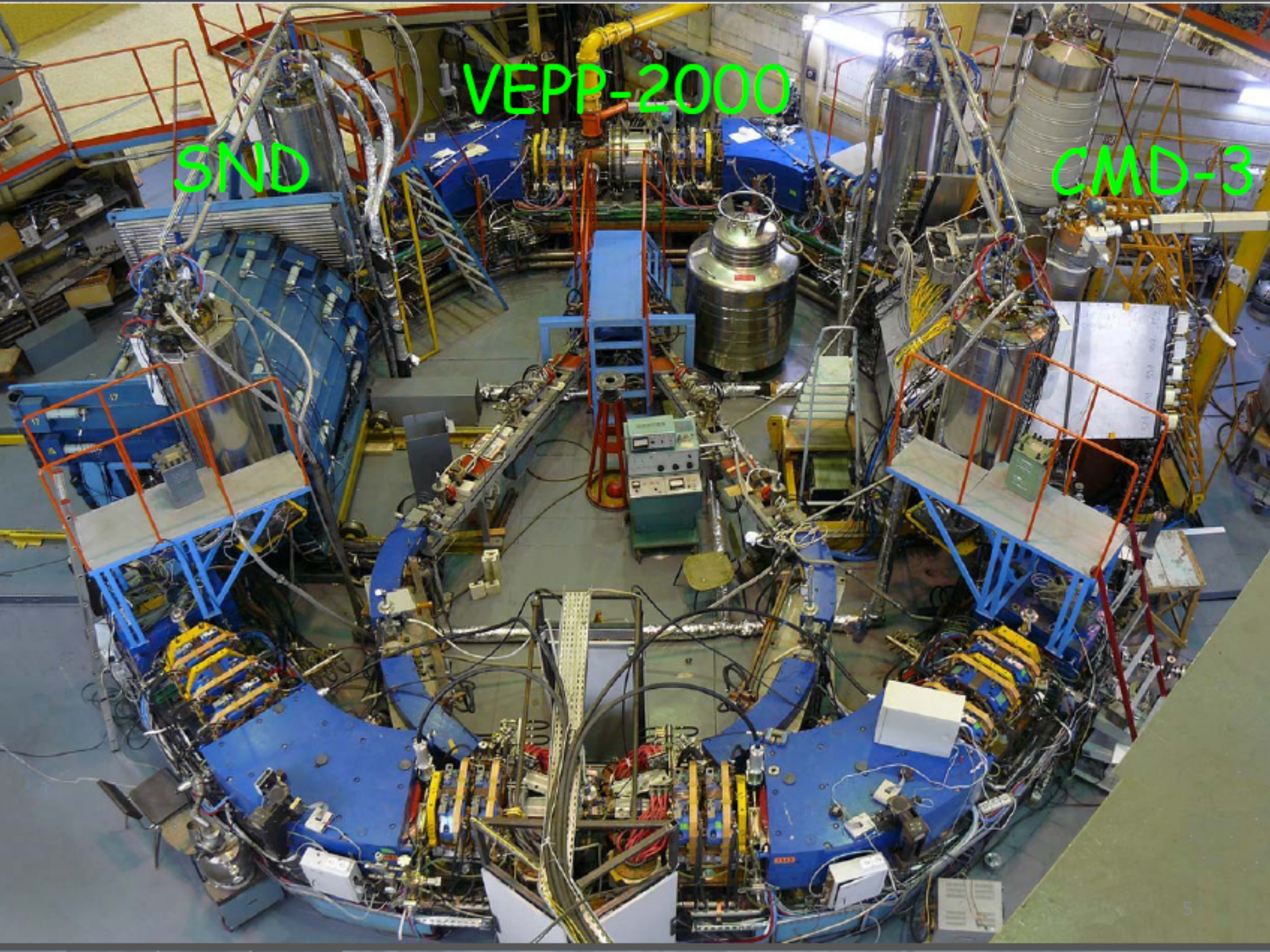
VEPP-2000 collider

- VEPP-2000 scans the $\sqrt{s}$ in the range from 0.32 to 2.01 GeV
- "Round beams" optics (focusing solenoids), design luminosity - $10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ at $\sqrt{s}$= 2.01 GeV (3x$10^{31}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ achieved)
- Beam energy is monitored by the Compton backscattering laser light system with ~50 keV precision
- CMD-3 and SND detectors placed at two beams intersection points

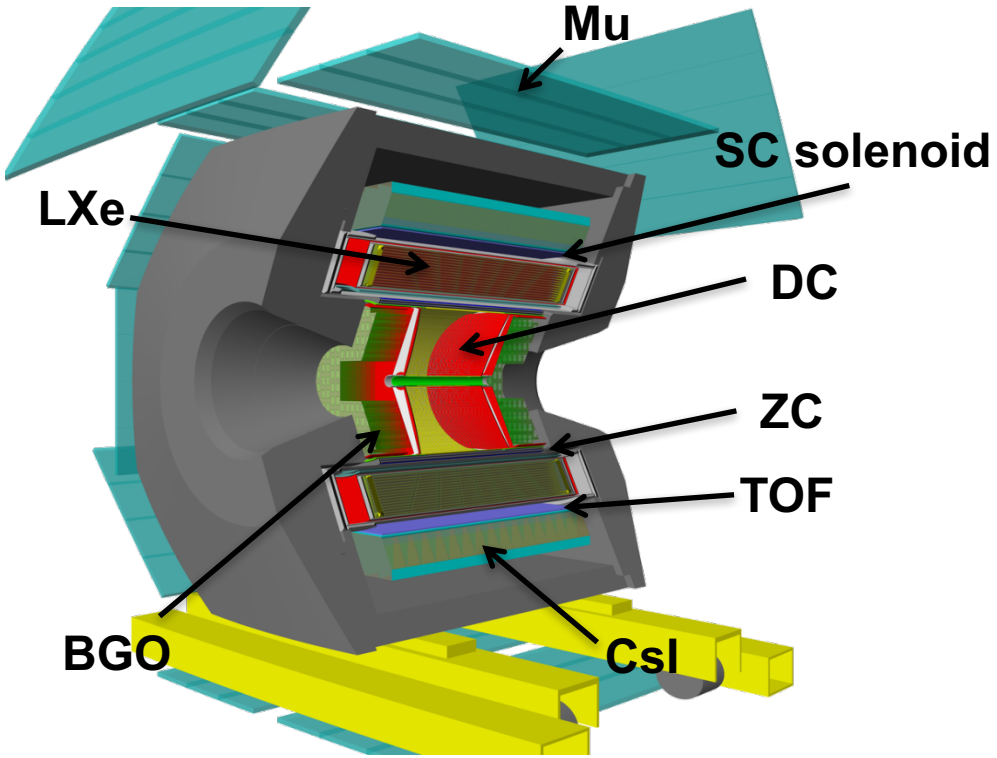


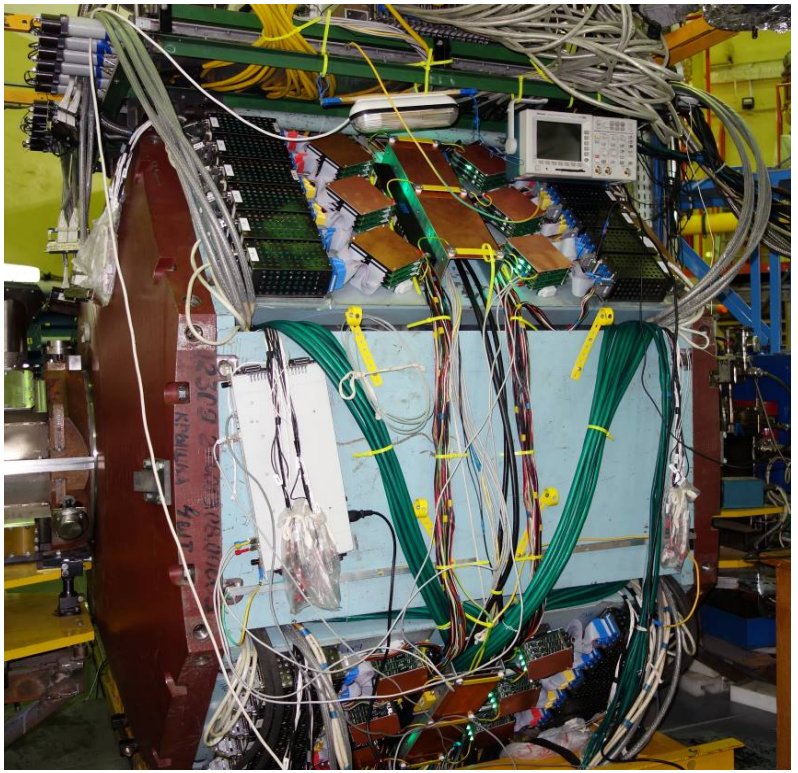
- After upgrade (2013-2016) the new injection complex was commissioned:




VEPP-2000
SND
CMD-3

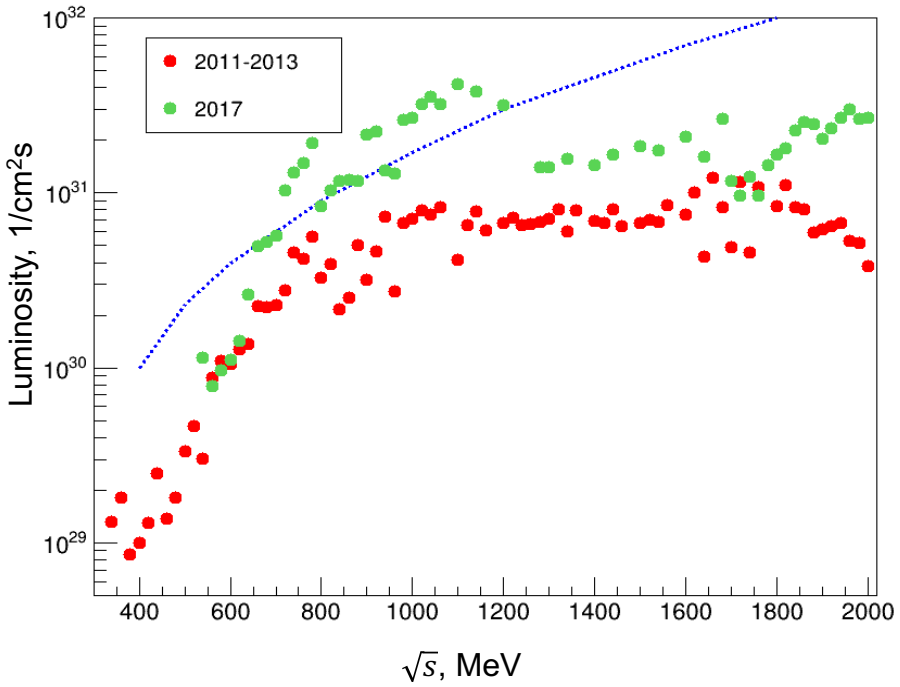
CMD-3 detector & physics program

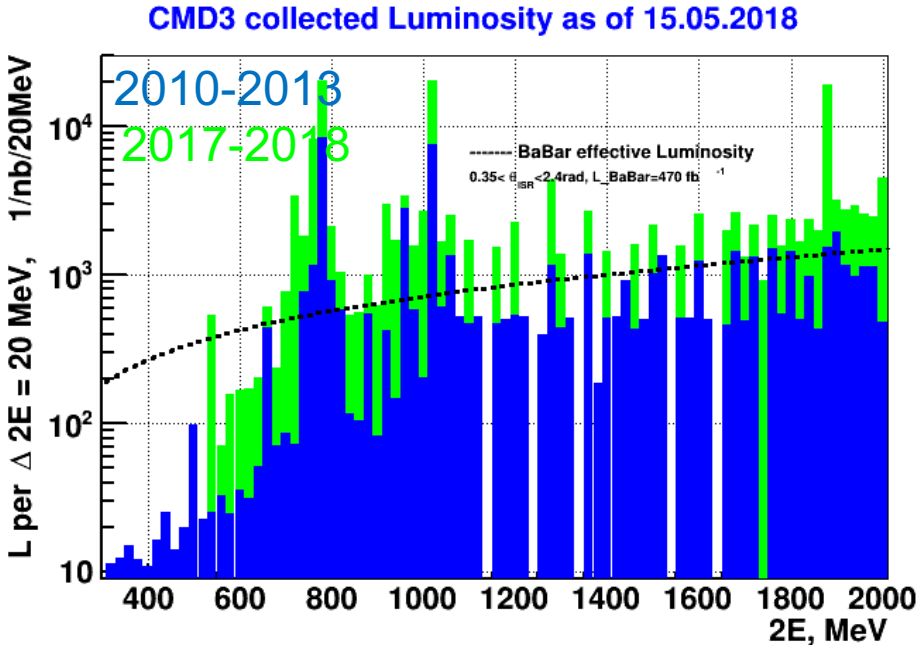




- Precise measurement of $R = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$ to achieve <1% systematic for major channels
- Study of exclusive hadronic channels of e^+e^- annihilation, test isotopic relations
- Study of the "excited" vector mesons: $\rho', \rho'', \omega', \phi'$ ...
- Study of G_E/G_M for nucleons near threshold
- CVC tests: comparison of isovector part of $\sigma(e^+e^- \to hadrons)$ with τ –decay spectra
- Diphoton physics (e.g. η' production)

CMD-3: overview of datataking

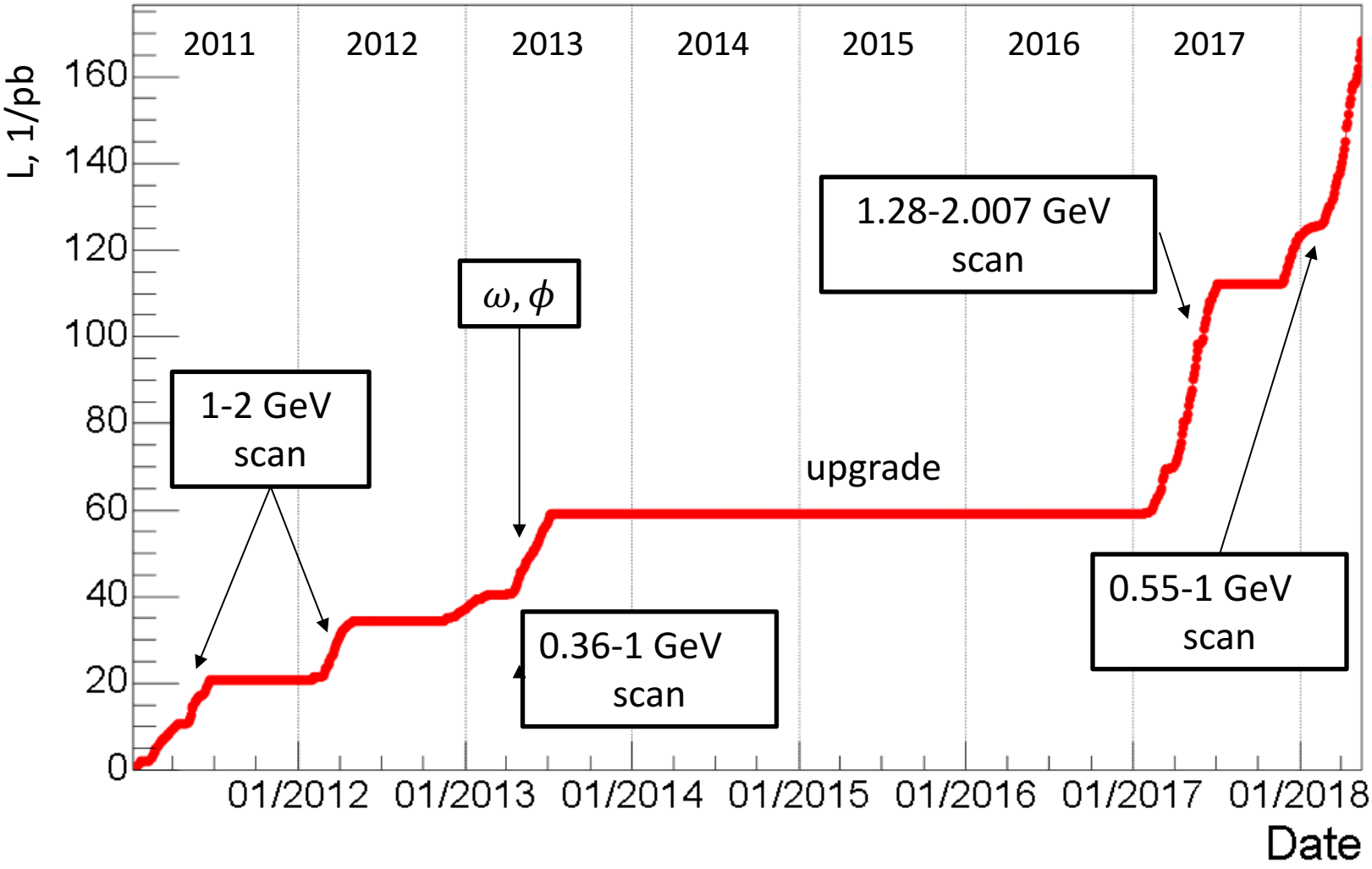




2010-2013 runs	
$\sqrt{s}$ region	L, pb^{-1}
$\omega(782)$	8.3
$\sqrt{s} < 1$ GeV (w/o ω)	9.4
$\phi(1020)$	8.4
$\sqrt{s} > 1.04$ GeV	34.5
Total	60

2017-2018 runs	
$\sqrt{s}$ region	L, pb^{-1}
2.007 GeV ($e^+e^- \to D^{0*}$)	4
$N\bar{N}$ threshold scan	14
Overall $1.28 - 2.007$ GeV	50
$\sqrt{s} < 1.0$ GeV	> 50
Total	~100

CMD-3: overview of datataking



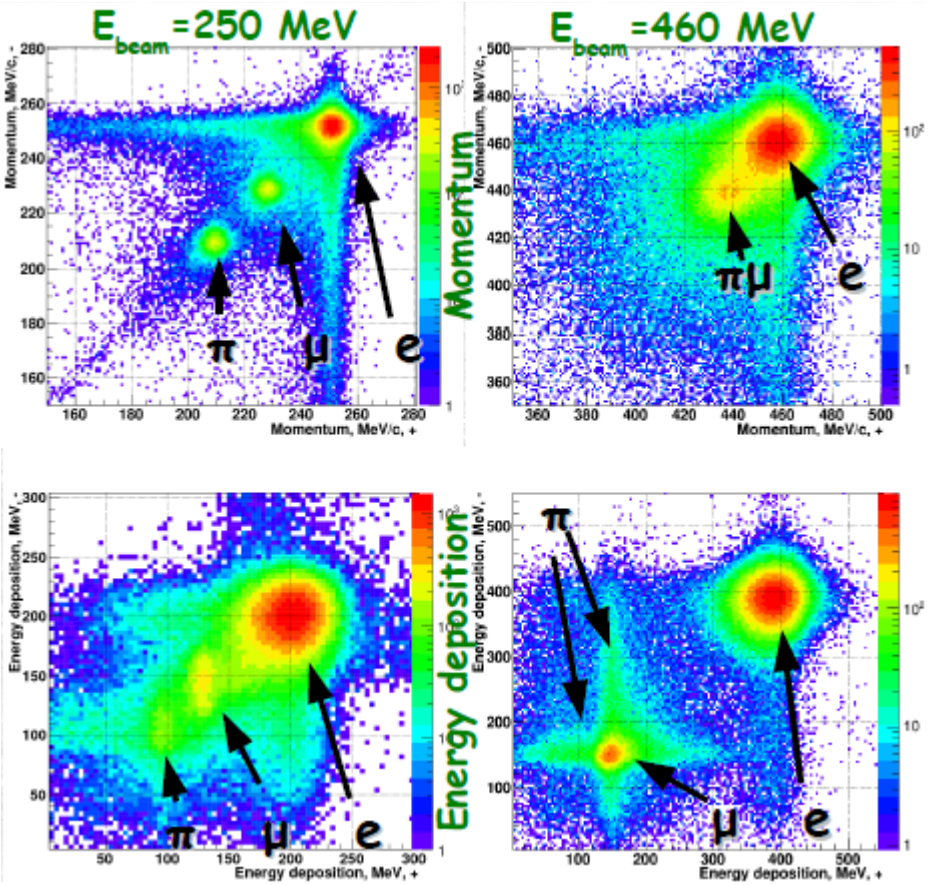
- Data taking will be continued to collect $\sim 1\ \mathrm{fb}^{-1}$ in the next 5-10 years

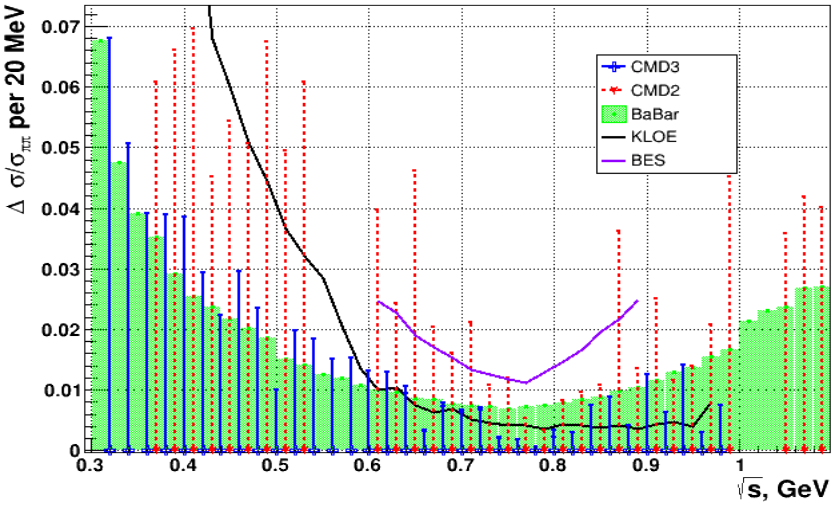
Exclusive $e^+e^- \to hadrons$ channels

Event signature	Final state (published, in progress)
2 charged	$\pi^+\pi^-$ K^+K^- K_SK_L $p\overline{p}$
2 charged + γ's	$\pi^+\pi^-\pi^0$ $\pi^+\pi^-2\pi^0$ $\pi^+\pi^-3\pi^0$ $\pi^+\pi^-4\pi^0$ $\pi^+\pi^-\eta$ $\pi^+\pi^-\pi^0\eta$ $\pi^+\pi^-2\pi^0\eta$ $K^+K^-\pi^0$ $K^+K^-2\pi^0$ $K^+K^-\eta$ $K_SK_L\pi^0$ $K_SK_L\eta$ $\pi^0e^+e^-$ ηe^+e^-
4 charged	$2\pi^+2\pi^-$ $K^+K^-\pi^+\pi^-$ $K_SK^\pm\pi^\mp$
4 charged + γ's	$2\pi^+2\pi^-\pi^0$ $2\pi^+2\pi^-2\pi^0$ $\pi^+\pi^-\eta$ $\pi^+\pi^-\omega$ $2\pi^+2\pi^-\eta$ $K^+K^-\eta$ $K^+K^-\omega$ $K_SK^\pm\pi^\mp\pi^0$
6 charged	$3\pi^+3\pi^-$
6 charged + γ's	$3\pi^+3\pi^-\pi^0$
Fully neutral	$\pi^0\gamma$ $2\pi^0\gamma$ $3\pi^0\gamma$ $\eta\gamma$ $\pi^0\eta\gamma$ $2\pi^0\eta\gamma$ $\eta'(958)$
Other	$n\overline{n}$

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

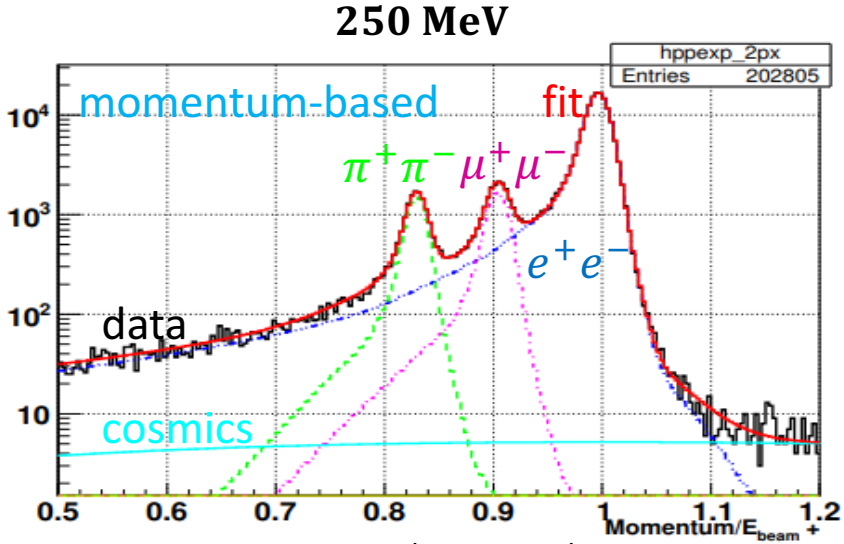
- It is a main contributor to the $a^{\mathrm{had,LO}}_{\mu}$
- The CMD-3's goal it to measure the $|F_\pi|^2$ with $\leq$ 0.35% systematics uncertainty
- To control systematics, two independent approaches for the number of $\pi^+\pi^-$ events determination are used.
- CMD-3's 2011-2013 statistics $\gtrsim$ that provided by BaBar, KLOE and BES, and 2-3 times more data collected in 2017-2018

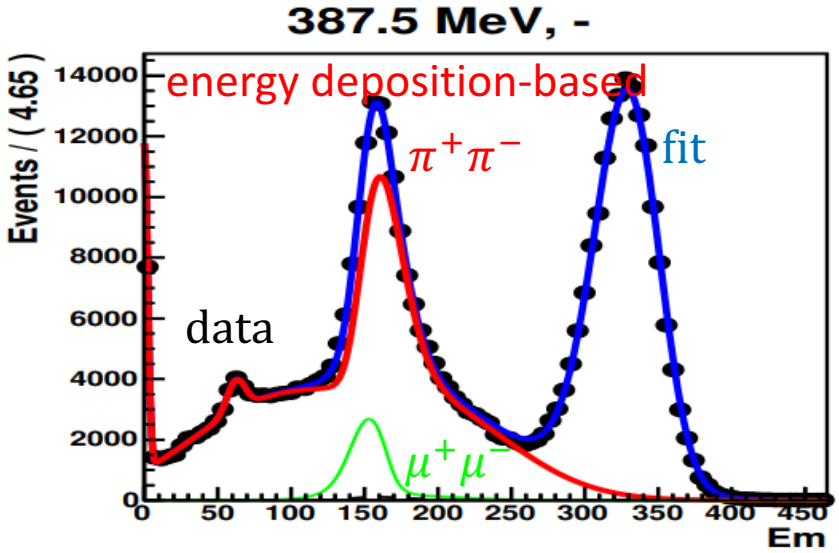




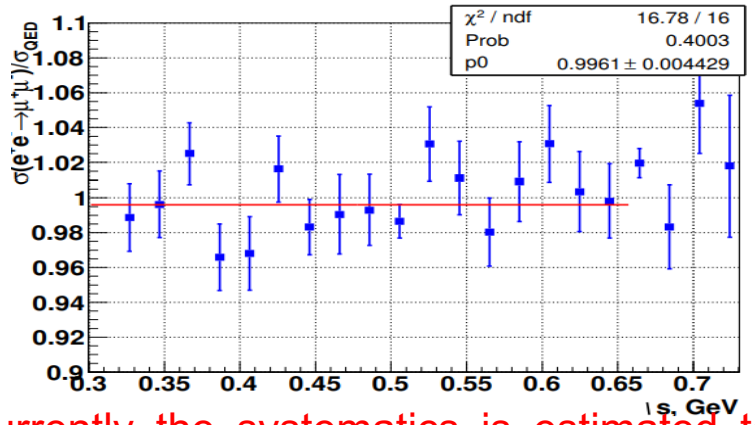
$e^+e^- \to \pi^+\pi^-$: pion formfactor measurement

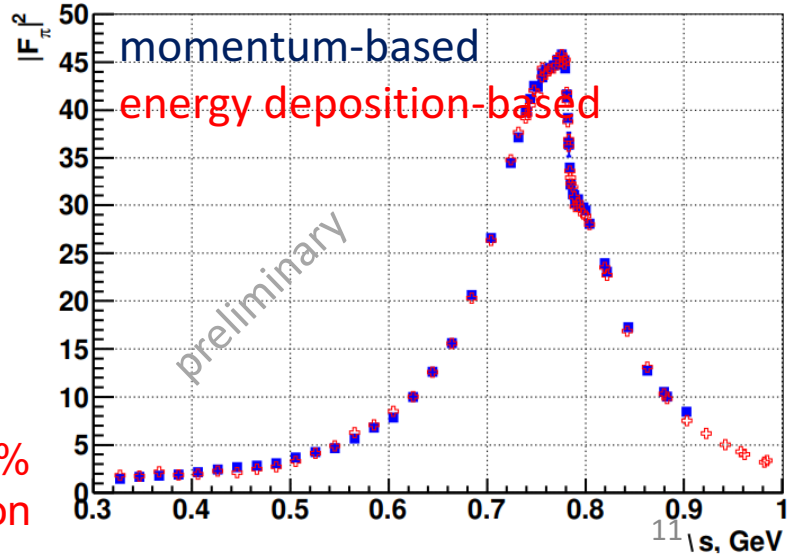
- In both cases 2D-bin-likelyhood function is constructed, its minimization gives $N_{\pi\pi}/N_{ee}$
- The projections of the fitting functions after minimization:





- Additional test - $\sigma(e^+e^- \to \mu^+\mu^-)$ measurement:

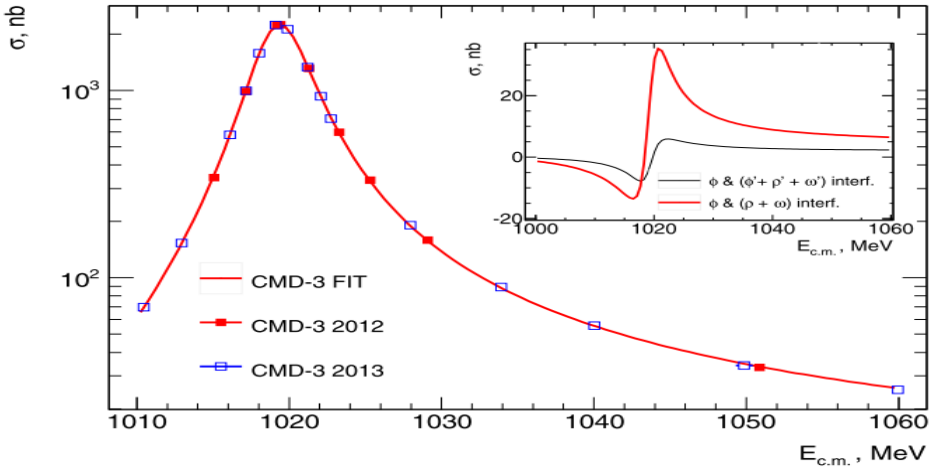




- Currently the systematics is estimated to be 0.4-0.9% (momentum-based) and 1.5% (energy-deposition based), the goal is – 0.35%

$e^+e^- \to K^+K^-$ at ϕ

- The final result published in PLB 779 (2018) 64

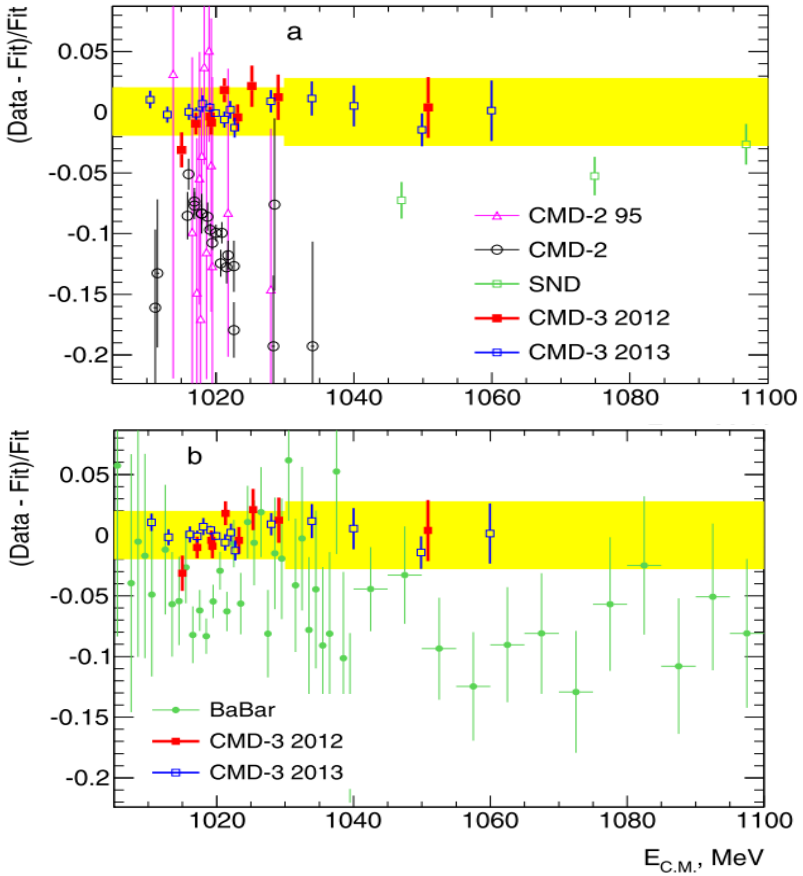


- Systematic precision ~2.0%

- CMD-3 results are above CMD-2 and BaBar, but are consistent with isospin symmetry:

$$R = \frac{g_{\varphi K^+K^-}}{g_{\varphi K_S K_L}\sqrt{Z(m_\varphi)}} = 0.990 \pm 0.017$$

- Comparison with other experiments:

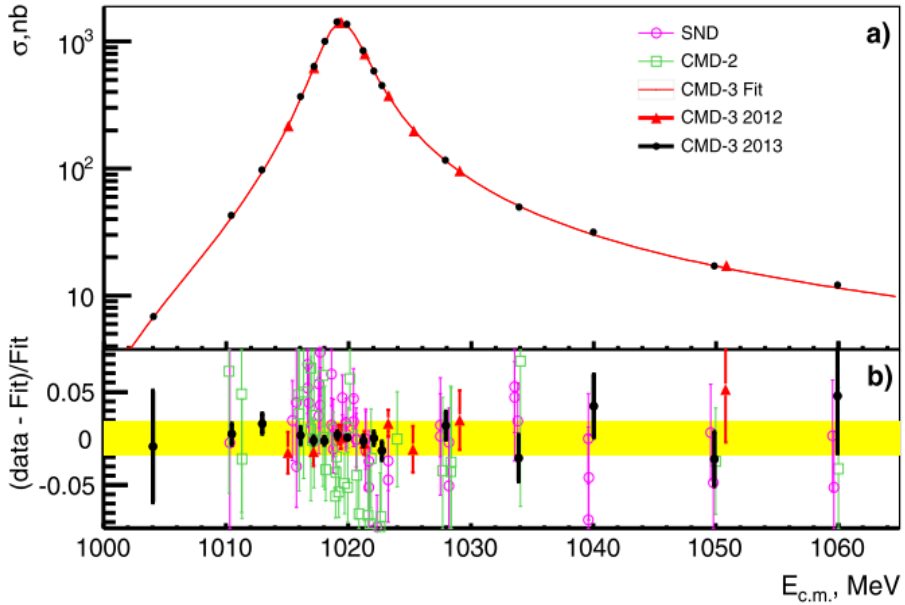


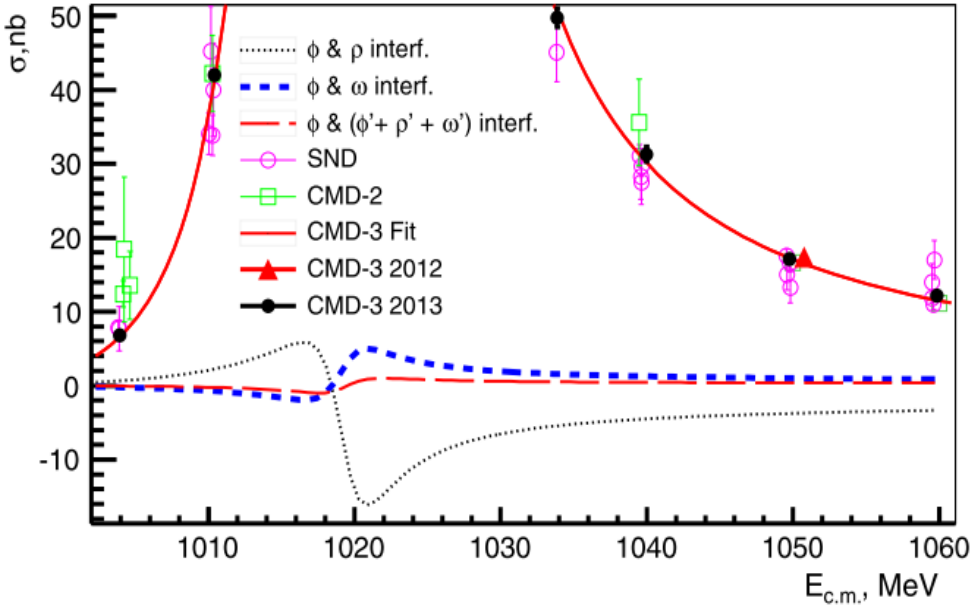
The parameters obtained from a fit of the cross section compared with previous experiments.

Parameter	CMD-3	Other measurements
m_ϕ, MeV	$1019.469 \pm 0.006 \pm 0.060 \pm 0.010$	1019.461 ± 0.019 (PDG2016)
Γ_ϕ, MeV	$4.249 \pm 0.010 \pm 0.005 \pm 0.010$	4.266 ± 0.031 (PDG2016)
$\Gamma_{\phi\to ee}B_{\phi\to K^+K^-}$, keV	$0.669 \pm 0.001 \pm 0.022 \pm 0.005$	0.634 ± 0.008 (BaBar)
$B_{\phi\to ee}B_{\phi\to K^+K^-}$, 10^{-5}	$15.789 \pm 0.033 \pm 0.527 \pm 0.120$	14.24 ± 0.30 (PDG2016)

$e^+e^- \to K_S K_L$ at ϕ

- The final result published in PLB 760 (2016) 314-319
- Systematic precision ~1.8%



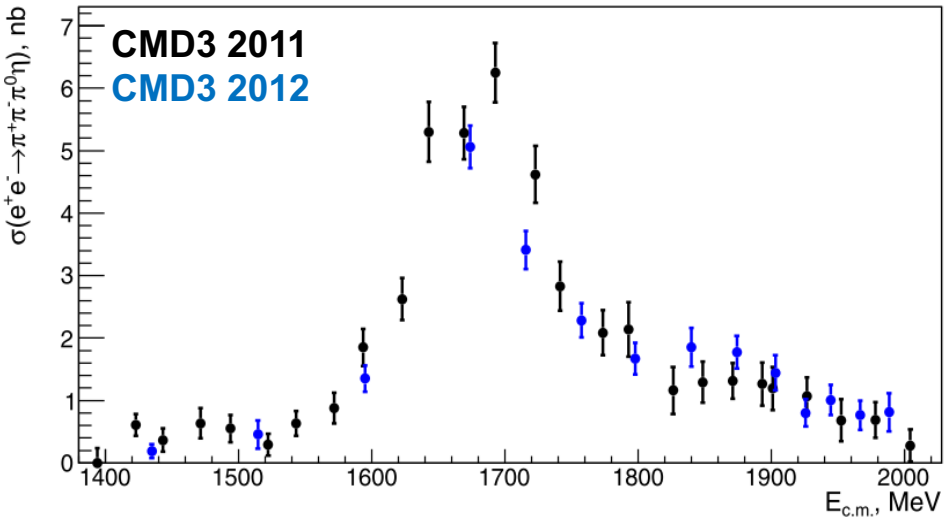


The results of the approximation procedure in comparison with previous experiments.

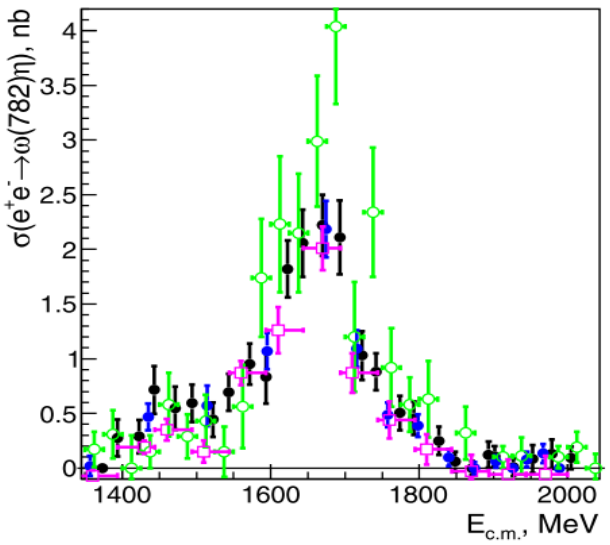
Parameter	CMD-3	Other measurements
m_ϕ, MeV	$1019.457 \pm 0.006 \pm 0.060 \pm 0.010$	1019.461 ± 0.019 (PDG2014)
Γ_ϕ, MeV	$4.240 \pm 0.012 \pm 0.005 \pm 0.010$	4.266 ± 0.031 (PDG2014)
$\Gamma_{\phi\to ee} B_{\phi\to K_S^0 K_L^0}$, keV	$0.428 \pm 0.001 \pm 0.008 \pm 0.005$	0.4200 ± 0.0127 (BaBar)
$B_{\phi\to ee} B_{\phi\to K_S^0 K_L^0}$, 10^{-5}	$10.078 \pm 0.025 \pm 0.188 \pm 0.118$	10.06 ± 0.16 (PDG2014)

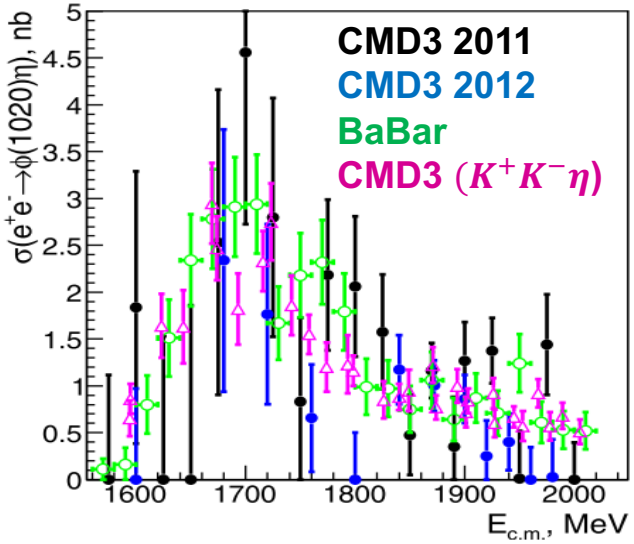
$e^+e^- \to \pi^+\pi^-\pi^0\eta$

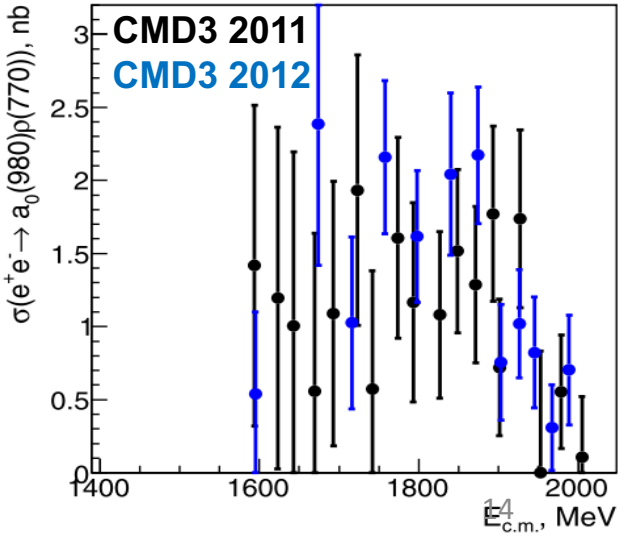
- This is the first measurement of the total $\sigma(e^+e^- \to \pi^+\pi^-\pi^0\eta)$, systematic error is $\sim 15\%$
- The final result published in PLB B773 (2017) 150-158
- The major intermediate mechanisms are $\omega(782)\eta$, $\phi(1020)\eta$ and $a_0(980)\rho(770)$



- The cross sections for particular mechanisms were extracted:



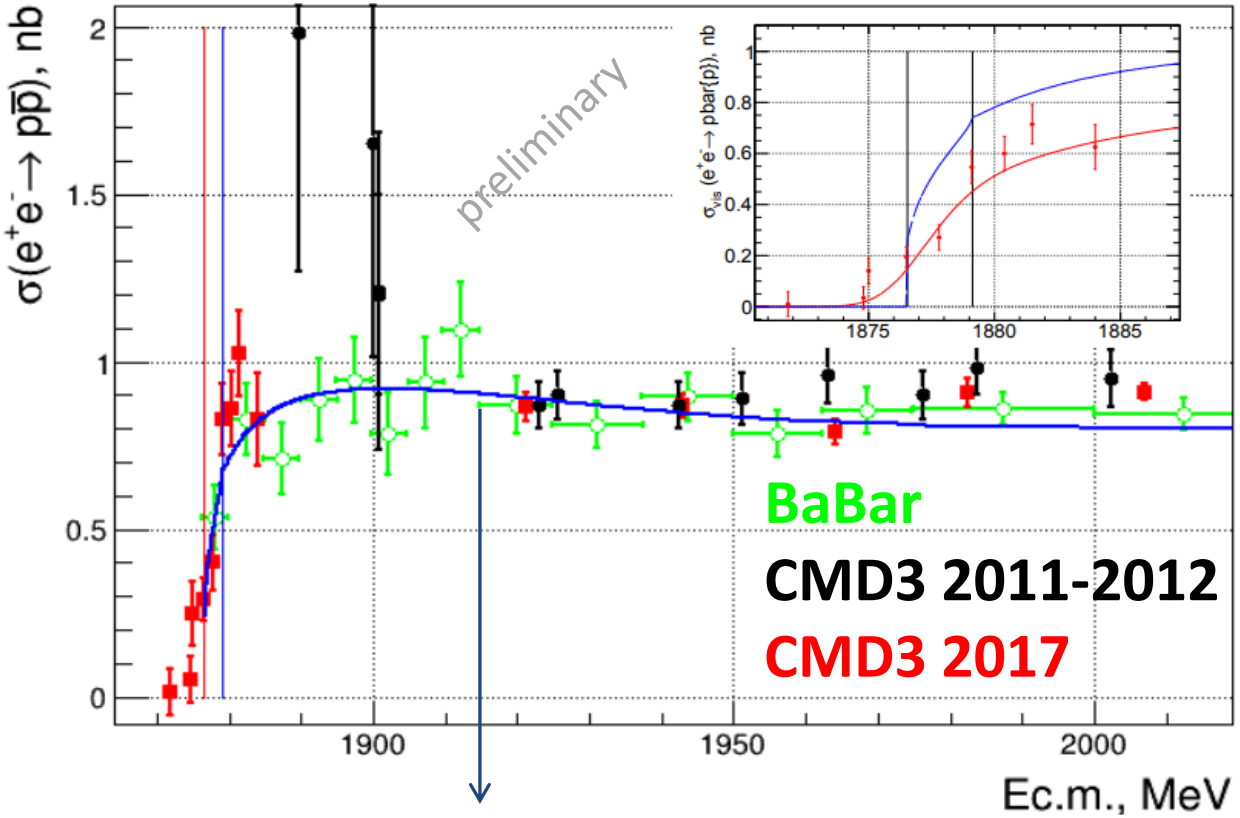




Scanning of $N\bar{N}$ threshold

- The 2011-2012-based results $p\bar{p}$ cross section measurements and the results for $\frac{G_E}{G_M}$ ratio were published (PLB 759 (2016) 634). In 2017 a more thorough threshold scan was performed:

arXiv:1808.00145[hep-ex]

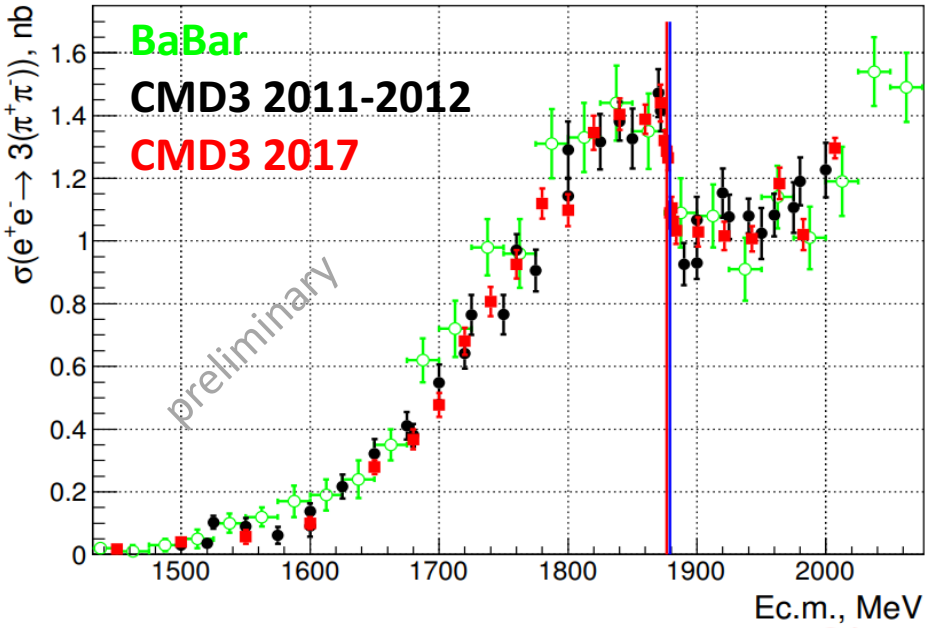


- A solid curve shows the prediction from recent works:

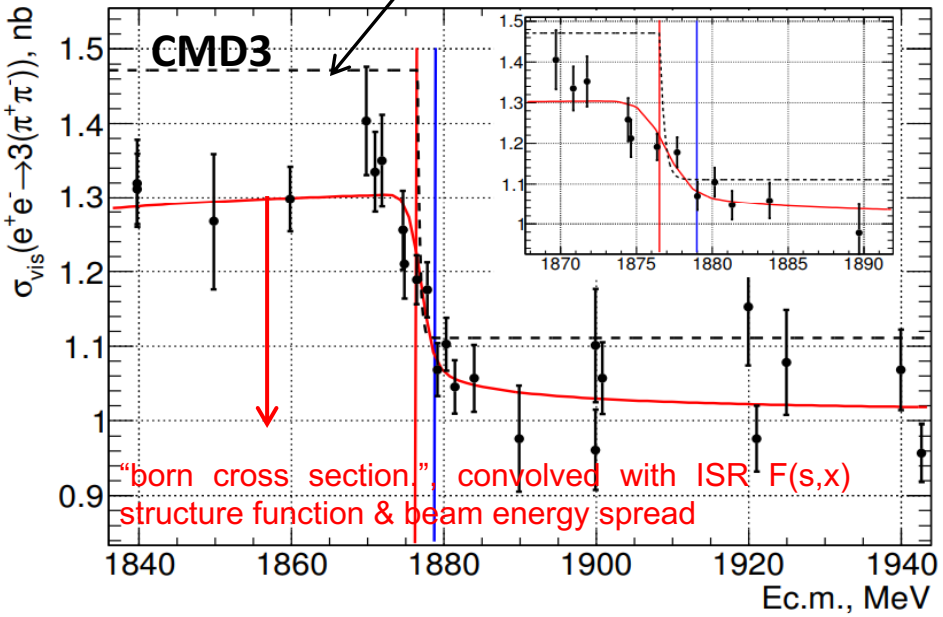
A.I. Milstein and S. G. Salnikov, arXiv:1804.01283v1 [hep-ph]
V. F. 200 Dmitriev, A. I. Milstein and S. G. Salnikov, Phys. Rev. D93, 034033 201 (2016)
A. I. Milstein, S. G. Salnikov, Nucl.Phys. A966, 54 (2017)

$e^+e^- \to 3(\pi^+\pi^-)$ & $N\bar{N}$ threshold

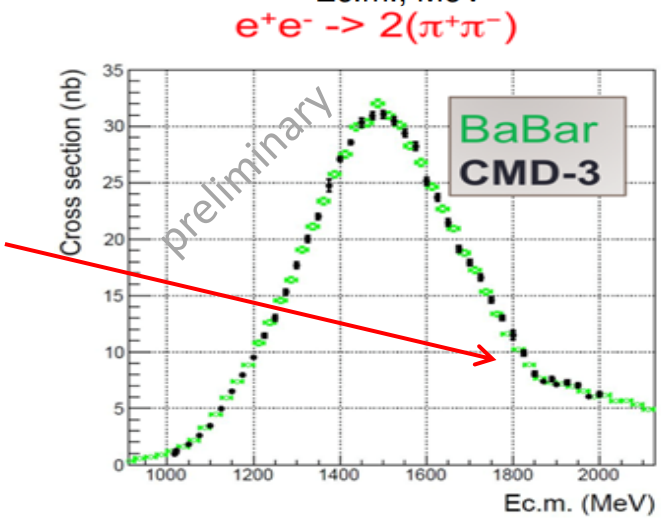
- The 2011-2012-based results were published in PLB 723, 82 197 (2013), new data confirm the drop of the cross section at $N\bar{N}$ threshold

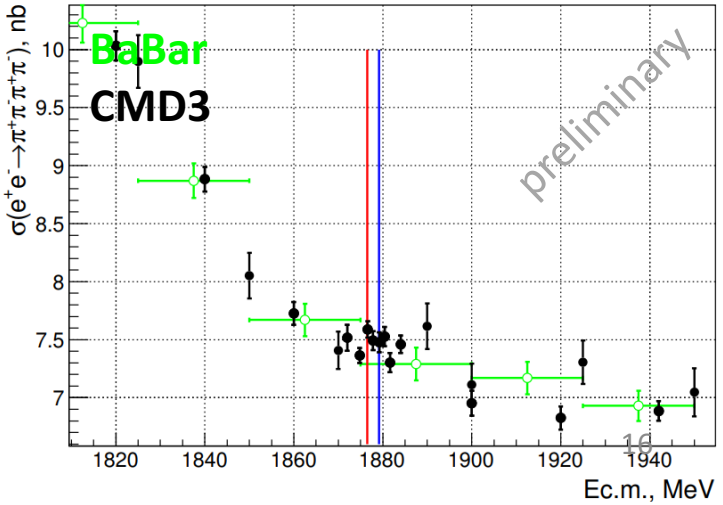


"born cross section" level



- Curious thing: we see no drop in $\sigma(e^+e^- \to 2(\pi^+\pi^-))$

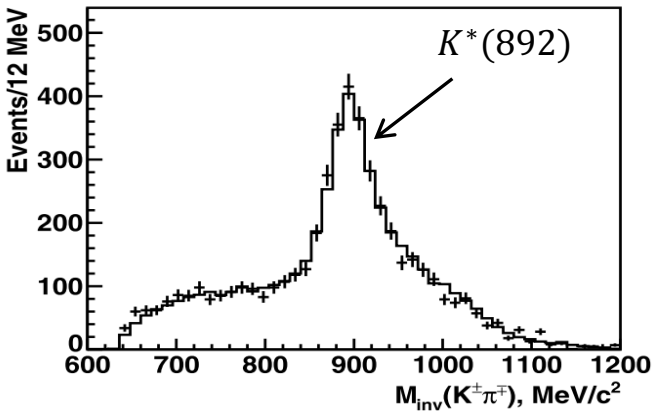


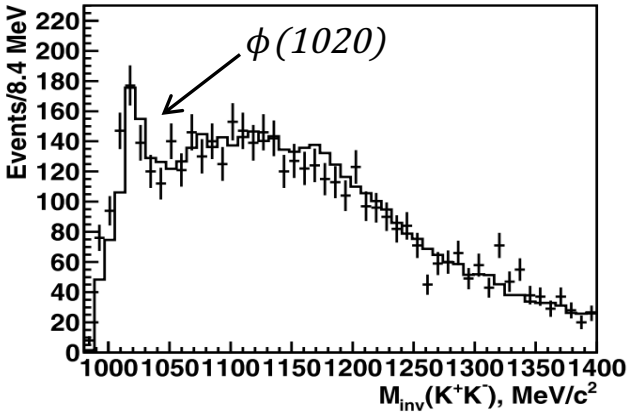


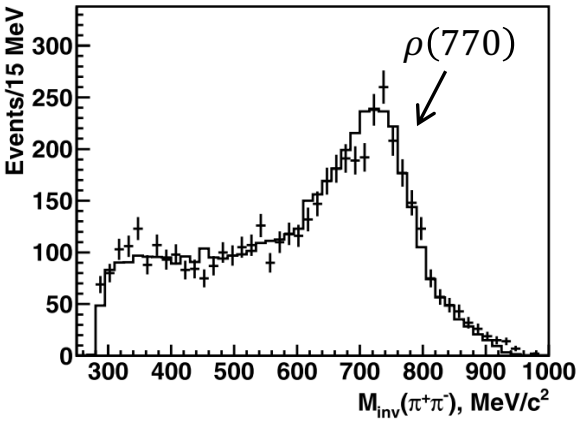
$e^+e^- \to K^+K^-\pi^+\pi^-$ & $N\bar{N}$ threshold

- The major intermediate states were found to be
- $f_0(500)\phi$ & $f_0(980)\phi$,
- $\rho(770)(KK)_{S-wave}$,
- $(K_1(1270,1400)K)_{S-wave} \to (K^*(892)\pi)_{S-wave}K$
- $(K_1(1400)K)_{S-wave} \to (\rho(770)K)_{S-wave}K$

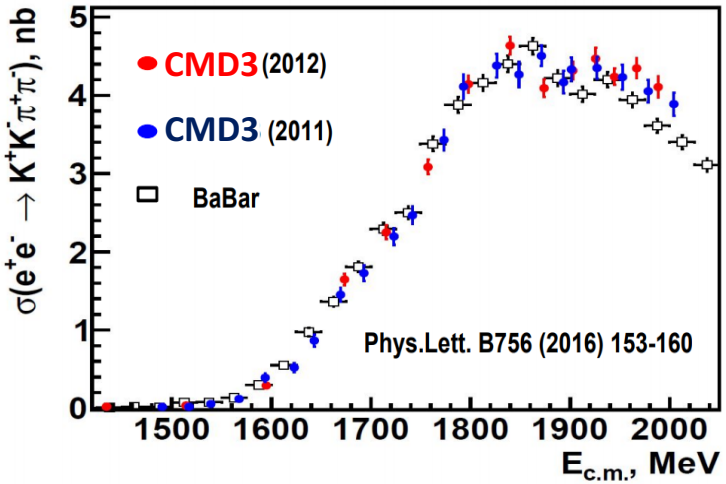
- Their relative amplitudes were found from the unbinned fit of the data:

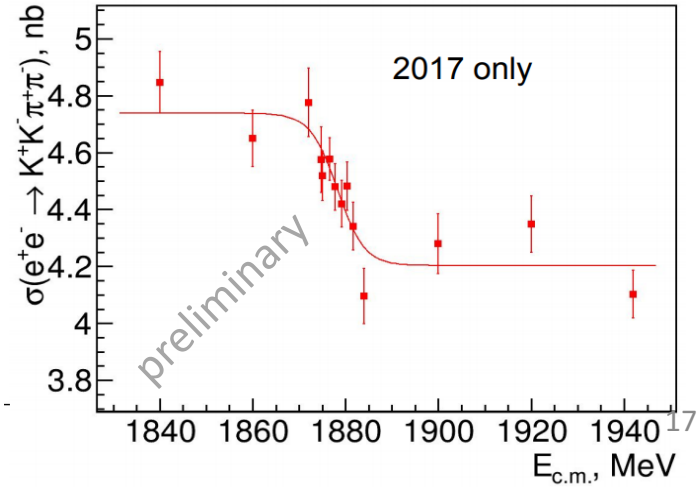






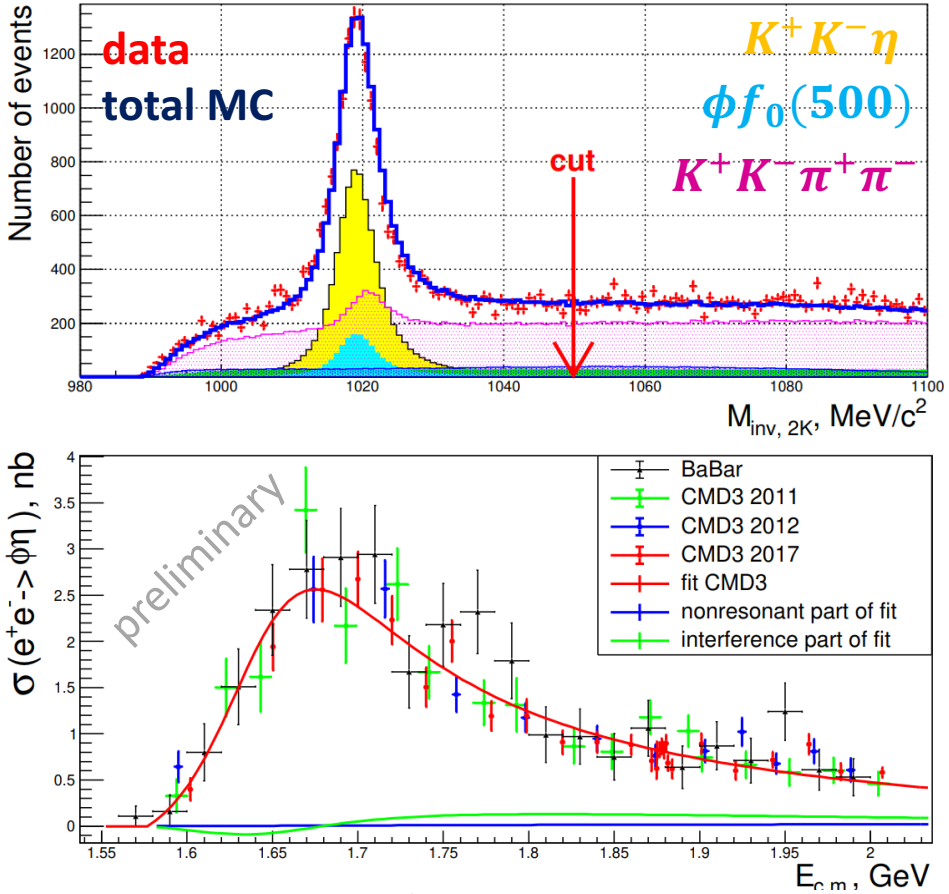
- We see the drop in $\sigma(e^+e^- \to K^+K^-\pi^+\pi^-)$!





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

- The dominant mechanism was found to be $e^+e^- \to \phi(1680) \to \phi\eta$ => the case for $\phi(1680)$ parameters measurement from cross section fitting

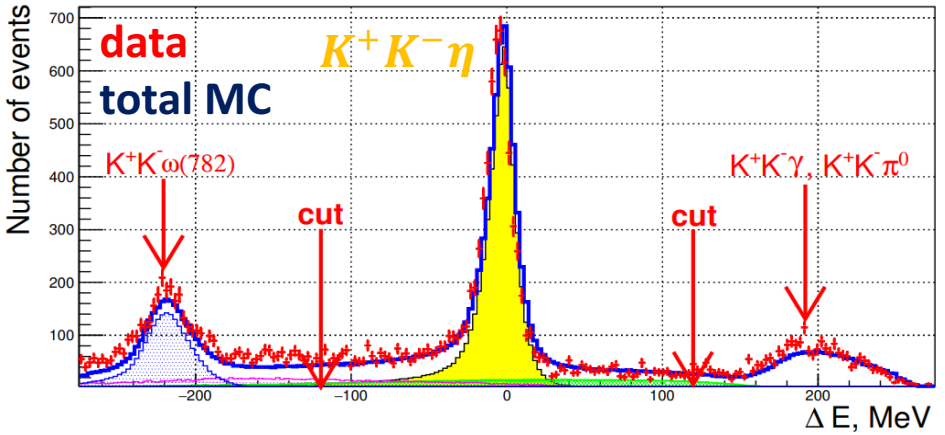


ϕ' parameters from fit

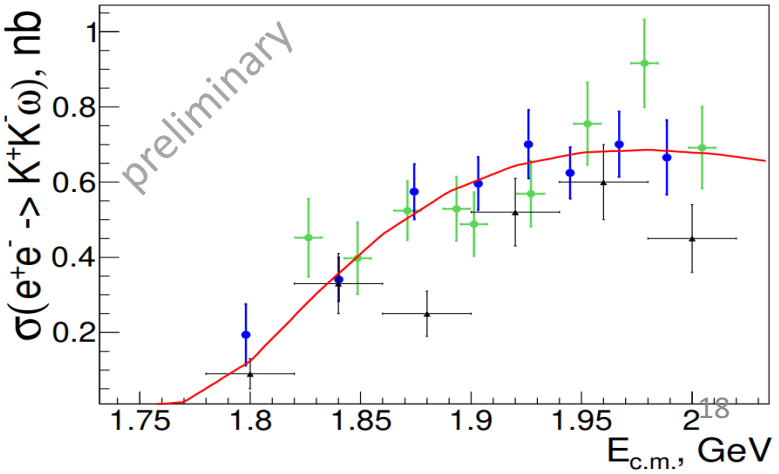
Parameter	Value (CMD-3/BaBar)
χ^2/n.d.f	$91.3/60 = 1.55$ / $184.9/144 = 1.28$
$\Gamma^{\phi'}_{ee}\mathcal{B}(\phi' \to \phi\eta)$,eV	100±11 / 154±32
$m_{\phi'}$,MeV	1682±5 / 1709±19
$\Gamma_{\phi'}$,MeV	199±26 / 325±68

- η was considered as a recoil particle:

$$\Delta E = \sqrt{\vec{p}^2_{K^-} + m^2_K} + \sqrt{\vec{p}^2_{K^+} + m^2_K} + \sqrt{(\vec{p}_{K^-} + \vec{p}_{K^+})^2 + m^2_\eta} - E_{\text{c.m.}}$$



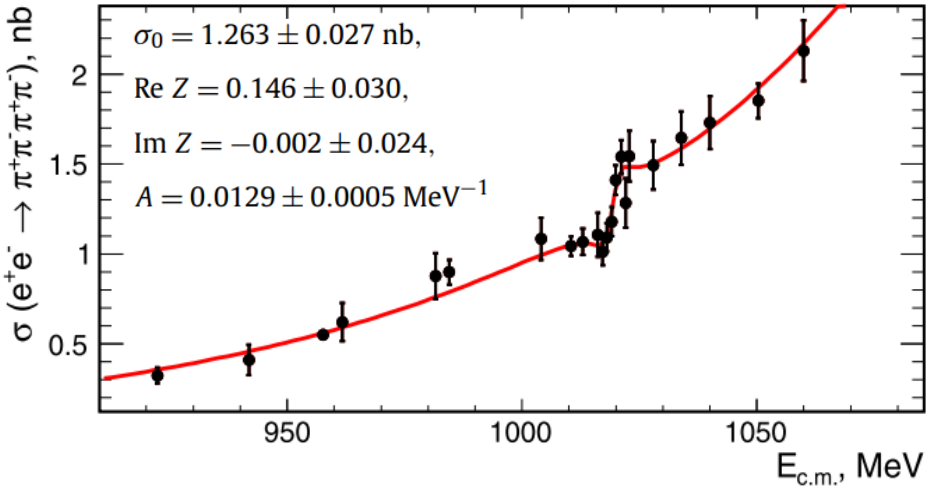
Similarly the $\sigma(e^+e^- \to K^+K^-\omega(782))$ was measured:



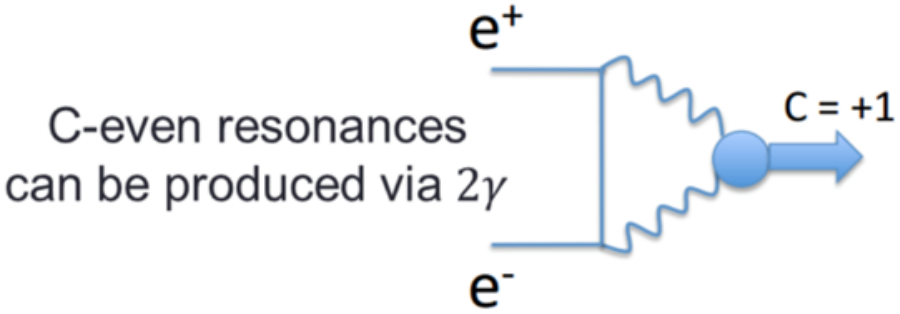
Other results

- Study of $e^+e^- \to 2\pi^+2\pi^-$ in the range (PLB 768 (2017) 345–350)

$$\sigma(E_{c.m.}) = \sigma_0 \cdot f(E_{c.m.}) \cdot \left| 1 - Z \cdot \frac{m_\phi \Gamma_\phi}{m_\phi^2 - E_{c.m.}^2 - iE_{c.m.}\Gamma_\phi} \right|^2 \quad f(E_{c.m.}) = e^{A(E_{c.m.} - m_\phi)}$$



- Search for $e^+e^- \to \eta'(958)$ (PLB 740 (2015) 273–277)

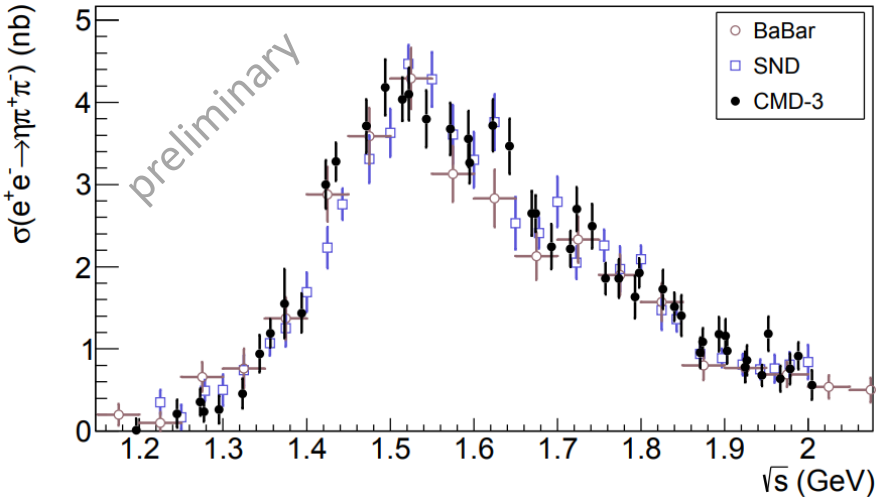


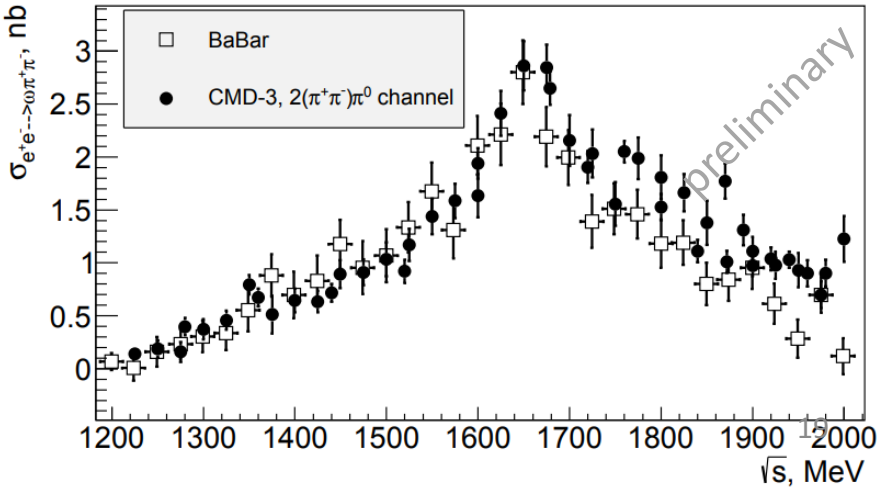
$$Br(\eta' \to e^+e^-) = Br(\eta' \to \gamma\gamma)\frac{\alpha^2}{2\beta}\left(\frac{m_e}{m_{\eta'}}\right)^2\left[\ln\left(\frac{1+\beta}{1-\beta}\right)\right]^2$$

B(η′→e⁺e⁻) < 1.2 10⁻⁸ (90%CL) - CMD-3

B(η′→e⁺e⁻) = 3.7 10⁻¹¹ - Theory

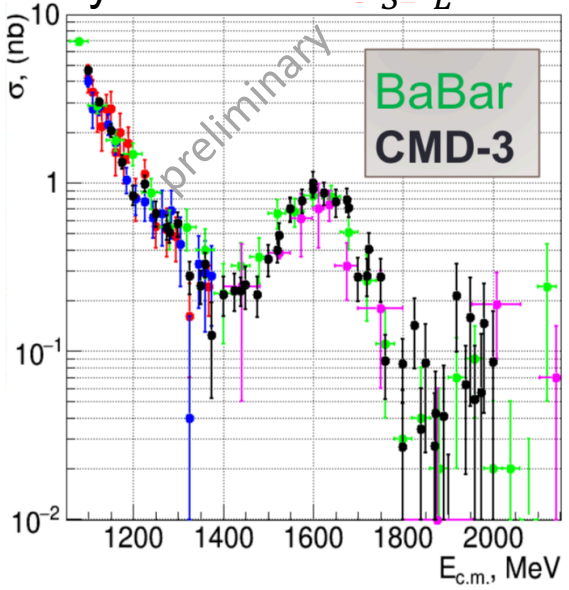
- Measurement of $e^+e^- \to \pi^+\pi^-\eta$ and $\pi^+\pi^-\omega(782)$ cross sections:



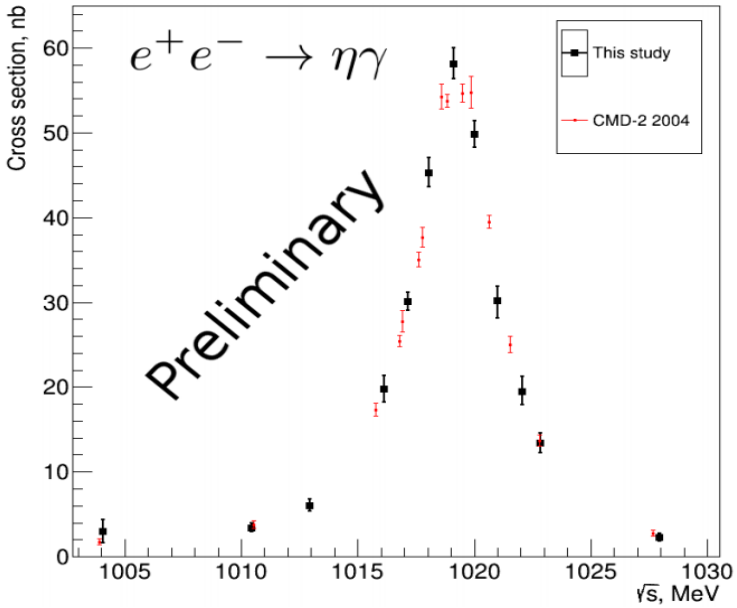


Other results

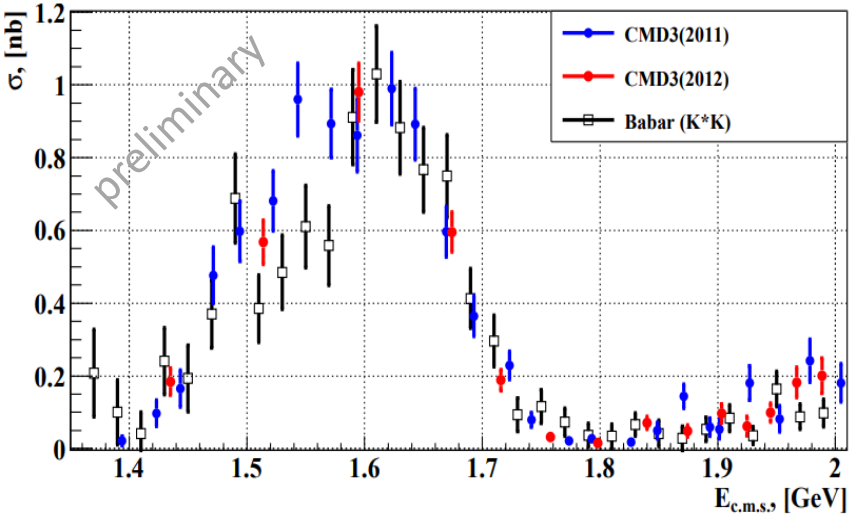
- Study of $e^+e^- \to K_S K_L$ above ϕ



- Study of $e^+e^- \to \pi^0\gamma, \eta\gamma$



- Study of $e^+e^- \to K^+K^-\pi^0$:



Many analysises are in progress…

Conclusion

- CMD-3 has taken ~160 pb^{-1} of data in the whole energy range $0.32 \leq \sqrt{s} \leq 2.0$ GeV and will take ~1fb^{-1} in the next years
- The detector subsystems upgrades are planned (endcap and barrel coordinate counters, possibly a new drift chamber)
- New particle identification technique based on the dE/dx in 14 layers of LXe-calorimeter has been developed, and will be applied in the next seasons for K^+K^-, $K^+K^-\pi^0$, $K^+K^-2\pi^0$, $K_SK^\pm\pi^\mp$ final states analyzes
- This is just a beginning, do not oversleep new interesting results from us!

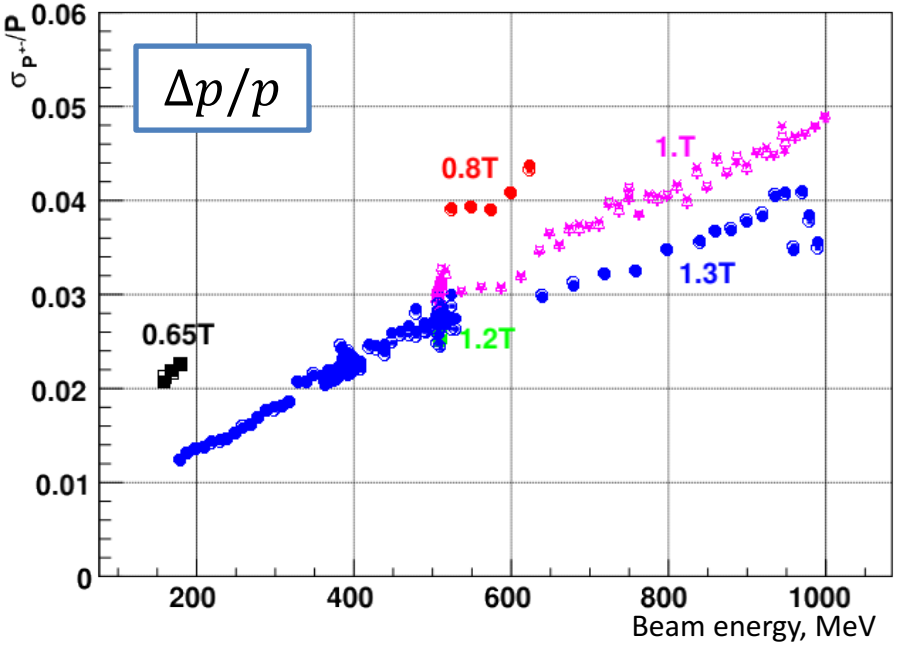
Thank You for Your Attention!

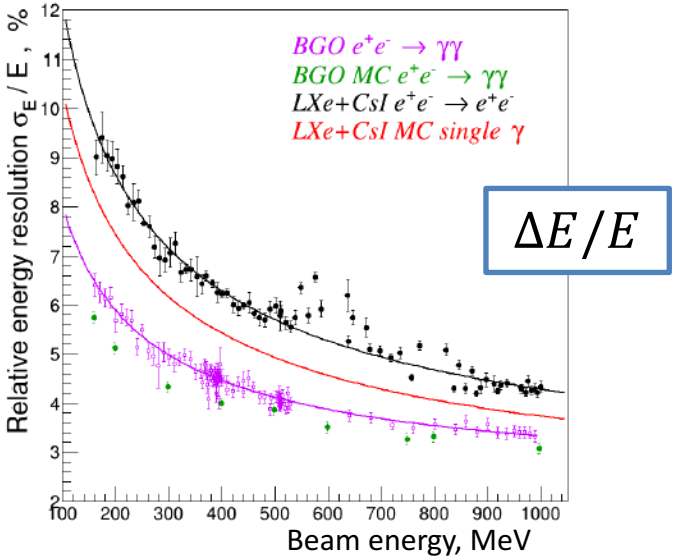
Stay tuned!

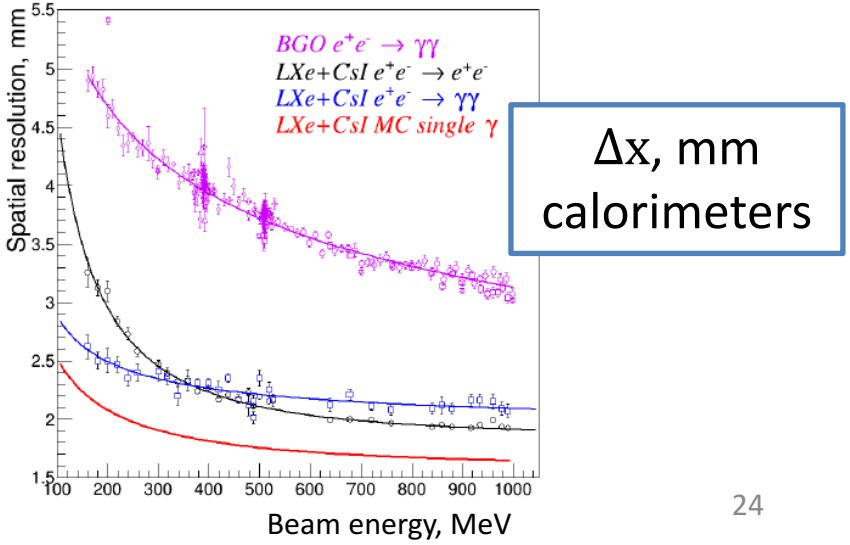
Backup slides

CMD-3 Performance (2011-2013)

- 1.0-1.3 T magnetic field
- Tracking: $\sigma_{R\varphi} \sim 100\ \mu, \sigma_z \sim 2-3$ mm
- Combined EM calorimeter (LXE, CsI, BGO), 13.5 X_0
  - $\sigma_E/E \sim 3\% - 10\%$
  - $\sigma_\Theta \sim 5$ mrad

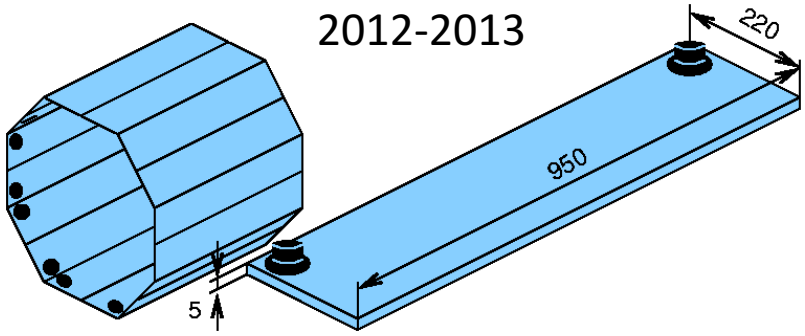




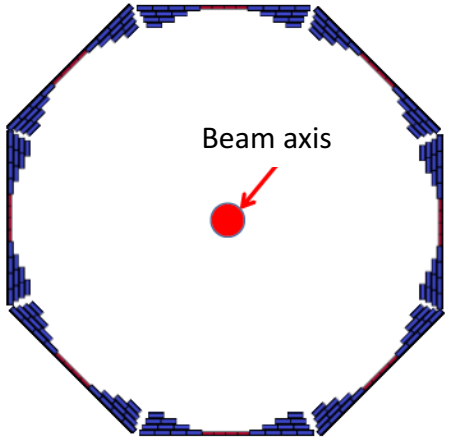


New TOF system

"Old" TOF
2012-2013

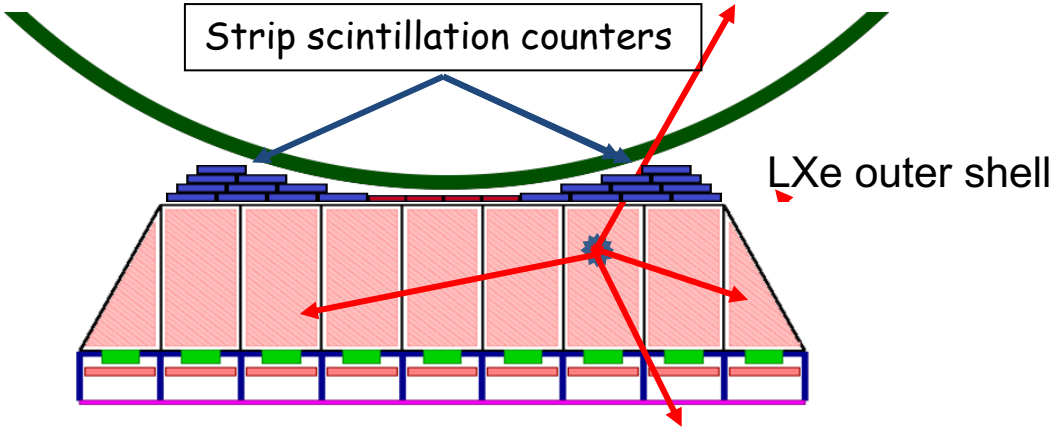


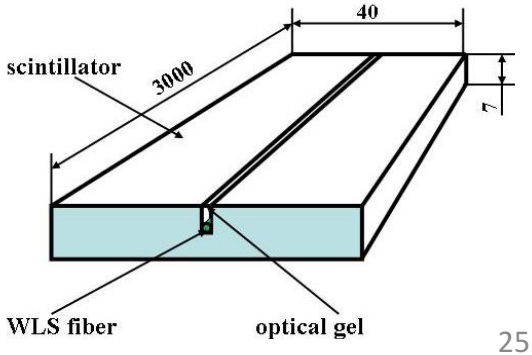
"New" TOF (2017-)



In 2013-2016 the TOF system was completely replaced

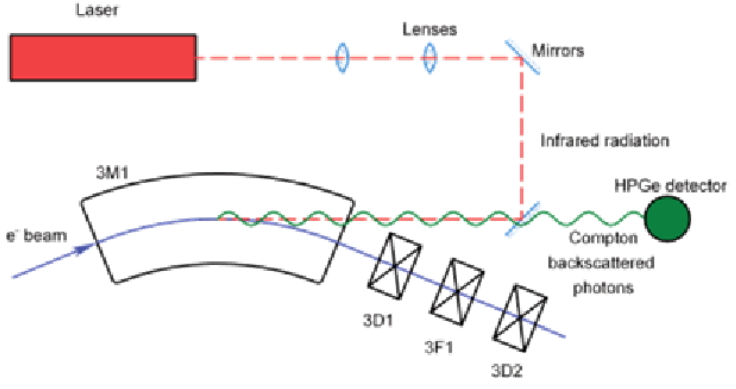
- More granulated (16 counters → 175 counters)
- 0.8 ns resolution per counter

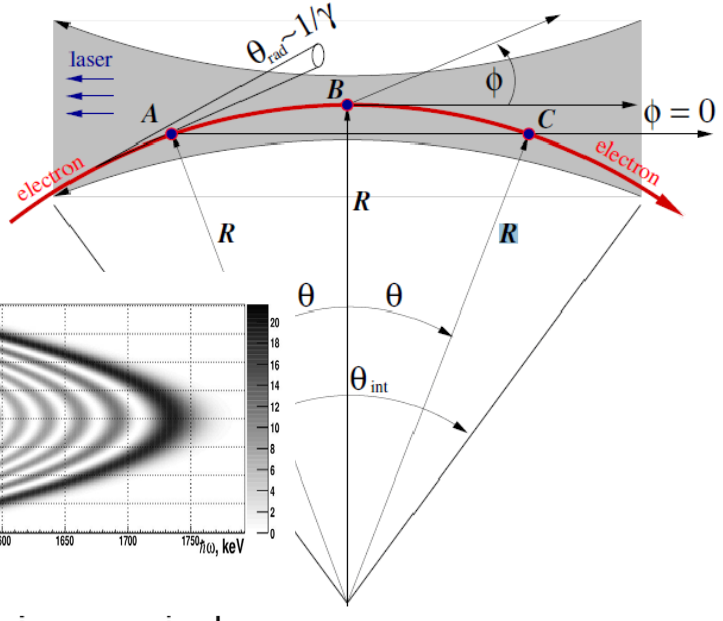


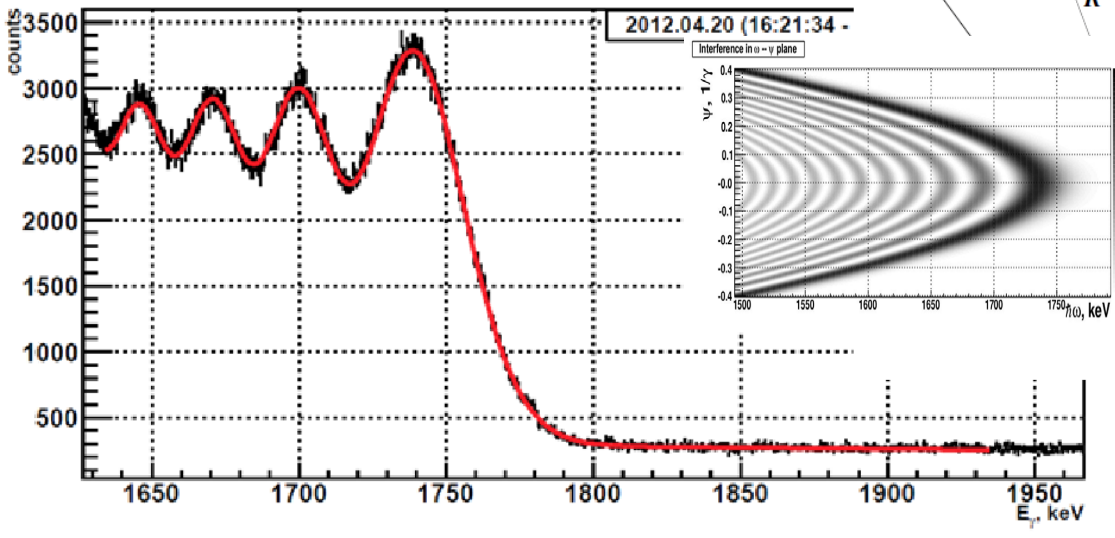


Energy measurement @ VEPP-2000

Starting from 2012, energy is monitored continuously using Compton backscattering



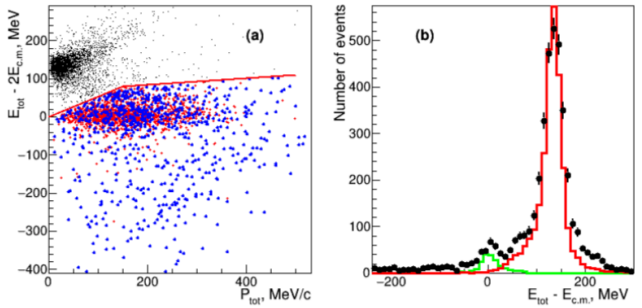


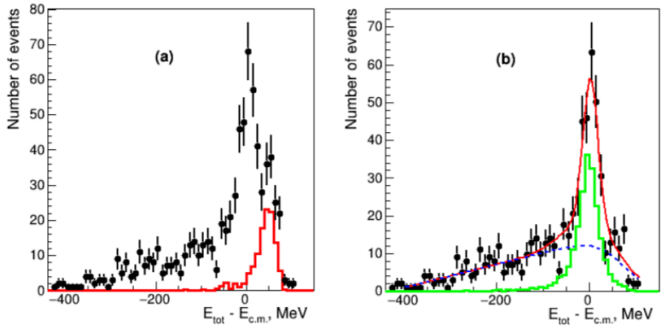


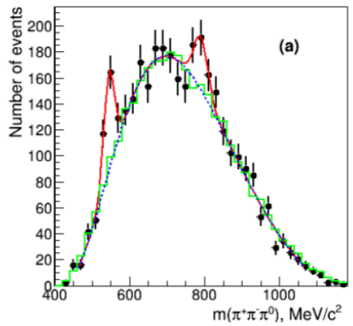
E = 993.662 ± 0.016 MeV

M.N. Achasov et al. arXiv:1211.0103v1 [physics.acc-ph] 1 Nov 2012

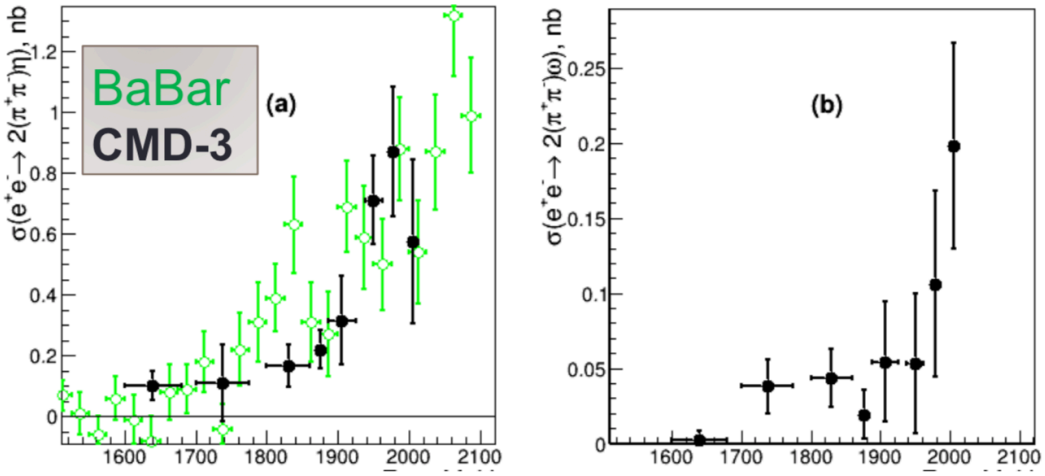
The most hottest result $e^+e^- \to 3(\pi^+\pi^-)\pi^0$







Based on 56 pb^{-1} in 1600-2000 MeV

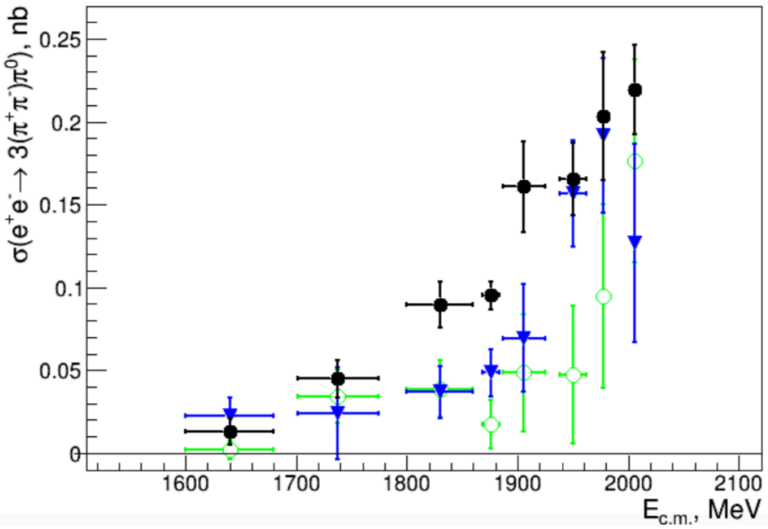


Dominated by

$\omega 4\pi$

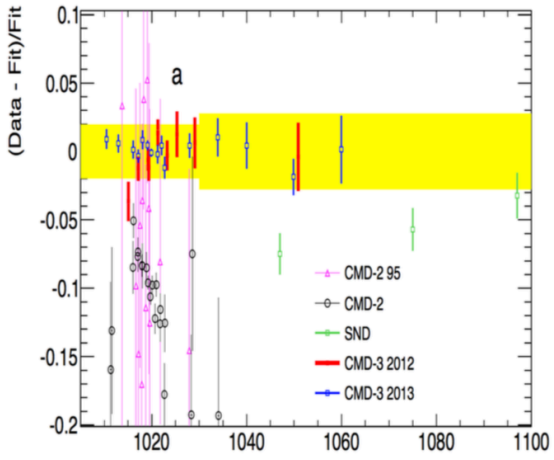
$\eta 4\pi$

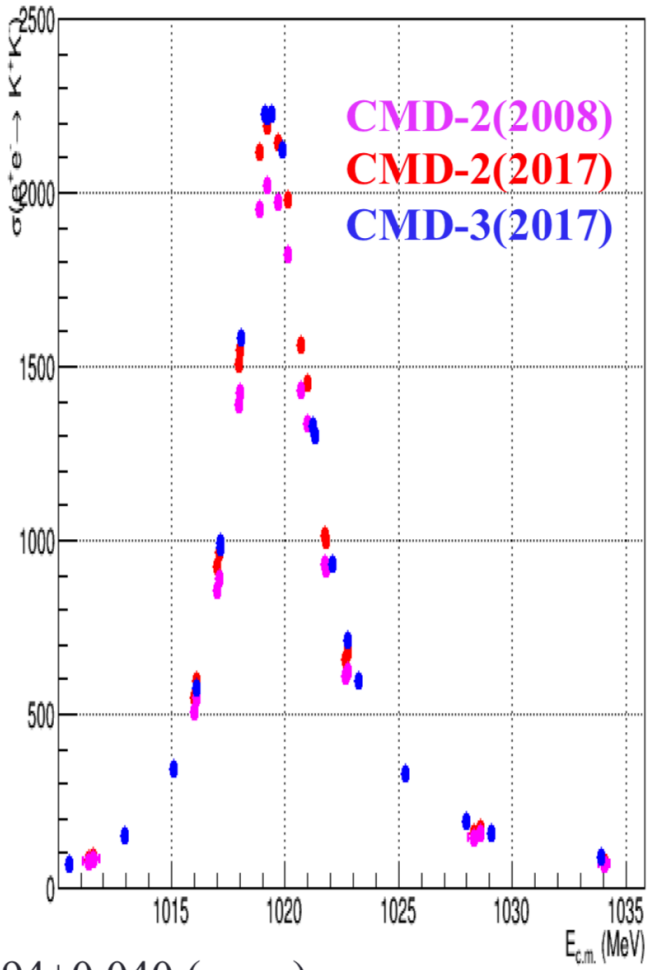
Publications are in preparations



Correction to K^+K^- at ϕ

- We observe large discrepancy between CMD-2 and CMD-3 data.
- CMD-2 has trigger DC+Z-chamber+CsI calorimeter energy deposition – no cross check! Kaons stop in first wall and only decays and interactions provide trigger.
- CMD-3 has only DC hits in trigger, but all information from Z-chamber(the same!) and calorimeter.
- We can directly measure trigger efficiency of CMD-2.
- Corrected data should be published soon





Trigger correction $(1+\delta)_{trig} = 1.094 \pm 0.040$ (сист.)