Measurement of hadronic cross sections at CMD-3

Vyacheslav Ivanov

on behalf of the CMD-3 collaboration

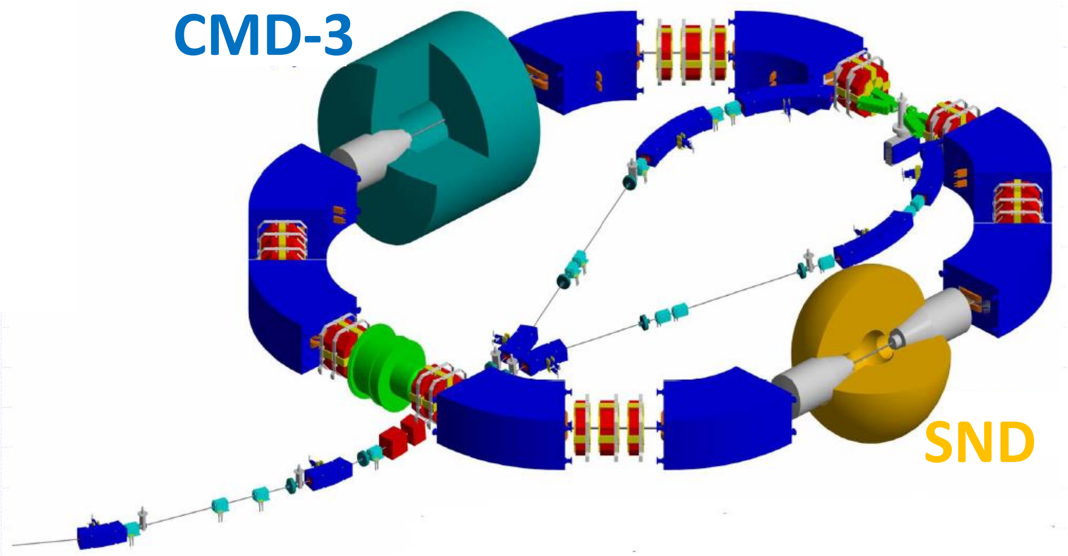
Novosibirsk State University & Budker Institute of Nuclear Physics

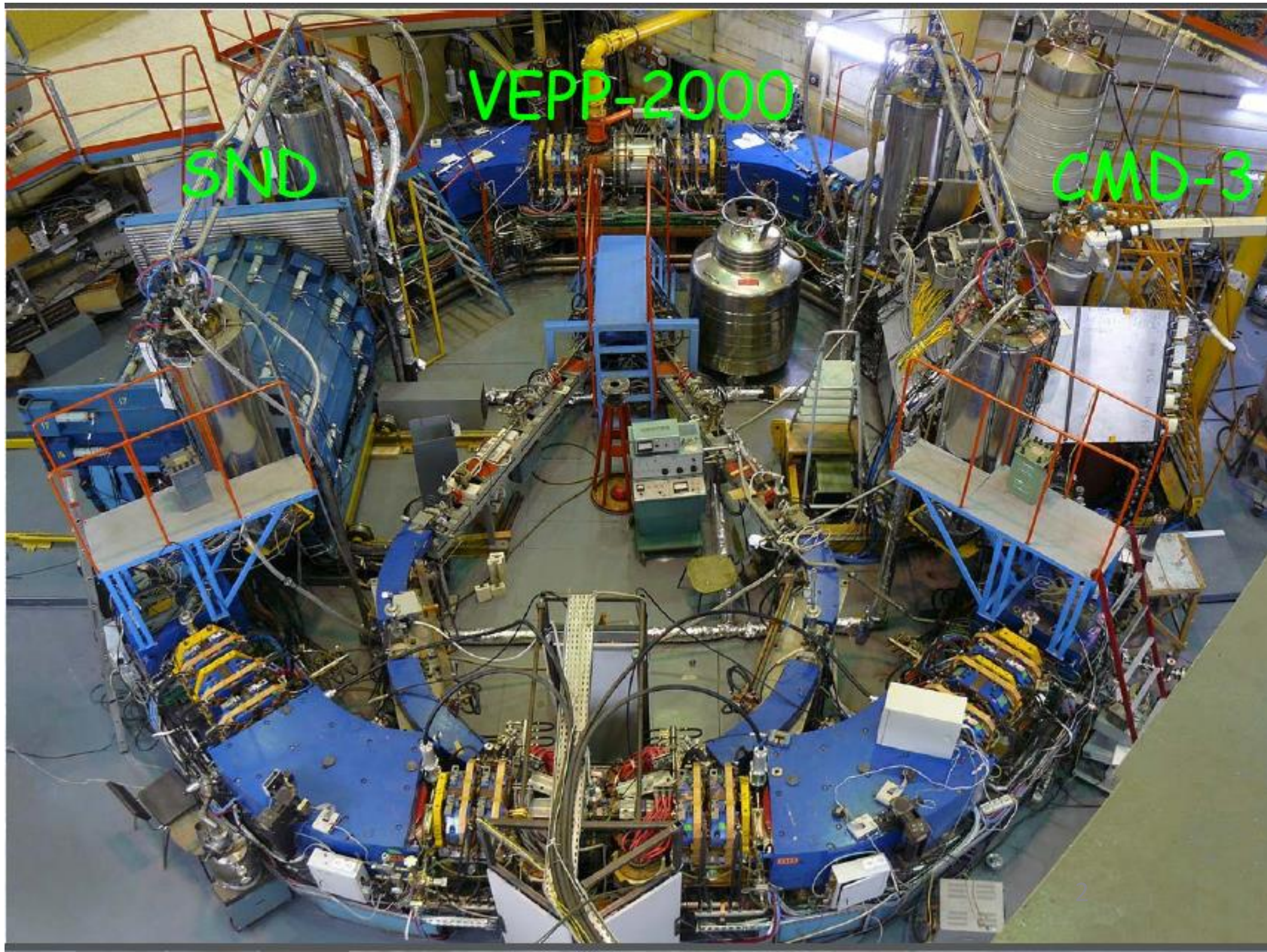
EPS-HEP 2019

12.07.2019

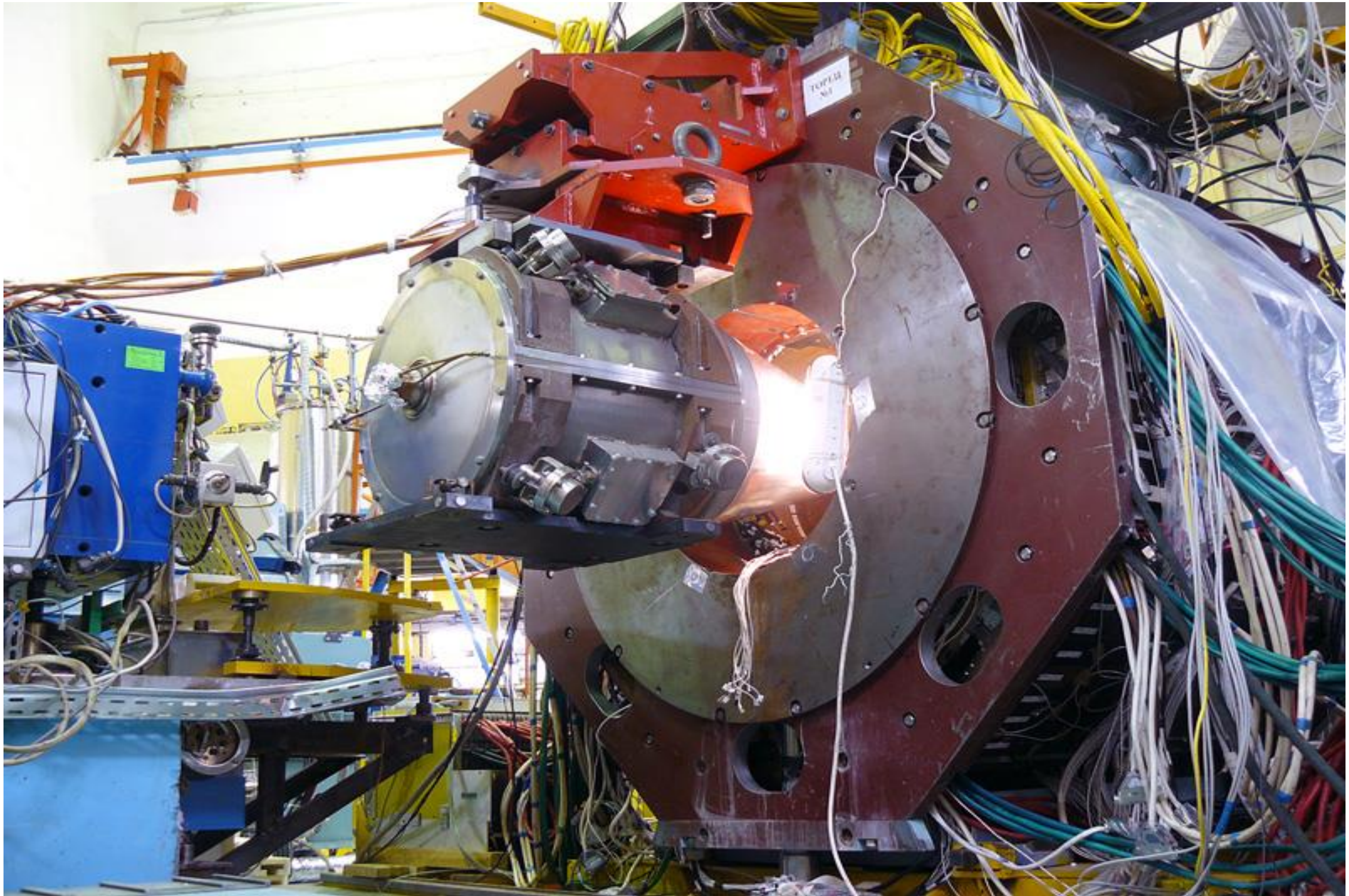
VEPP-2000 collider

- 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)
- Maximum luminosity achieved - $4 \times 10^{31}\ \mathrm{cm^{-2}s^{-1}}$
- CMD-3 and SND detectors placed at two beam interaction points

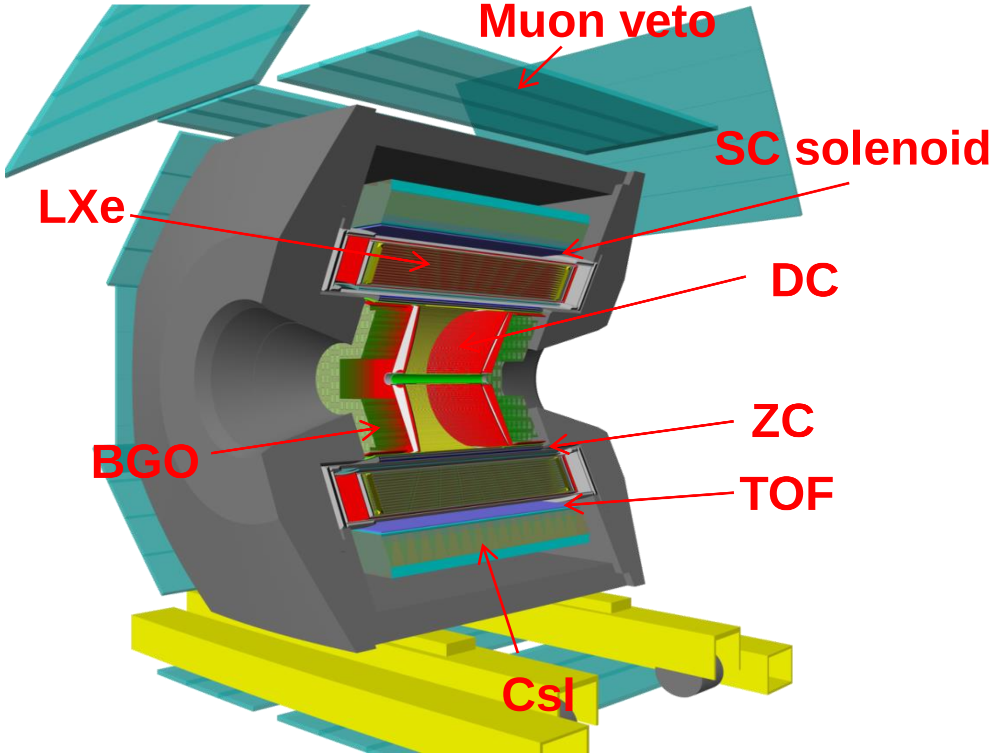


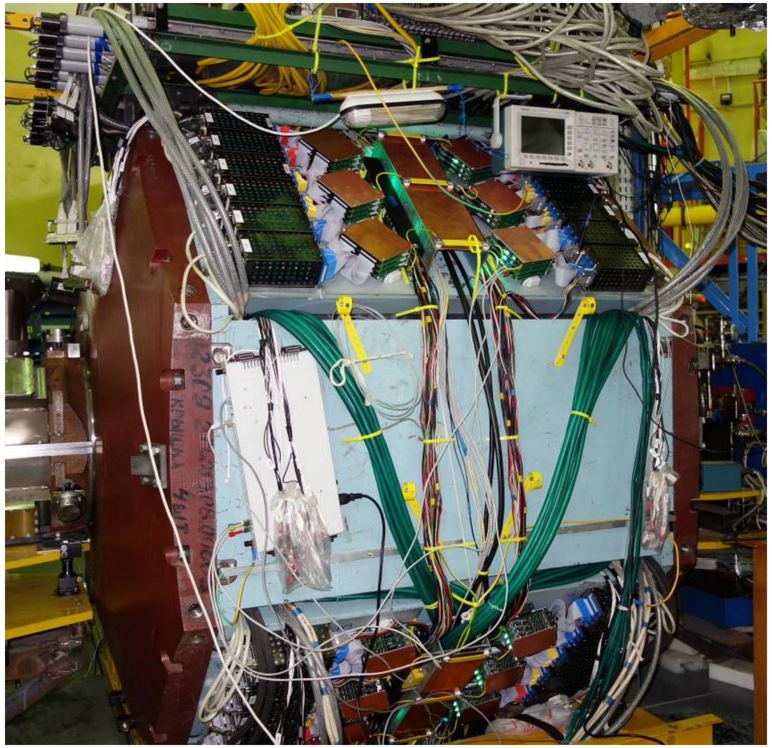


CMD-3 detector



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 the exclusive hadronic channels of e^+e^- annihilation, test of the isotopic relations
- Study of the “excited” vector mesons: $\rho', \rho'', \omega', \phi'$ …
- Study of G_E/G_M for nucleons and behavior of hadronic cross sections near $N\bar{N}$ threshold
- CVC tests: comparison of isovector part of $\sigma(e^+e^- \to hadrons)$ with τ −decay spectra
- Two-photon physics (e.g. η production)

In this talk I’m focusing on the recent results of the study of exclusive hadronic final states

$g - 2$ of muon puzzle

- Magnetic moment of Dirac particle:

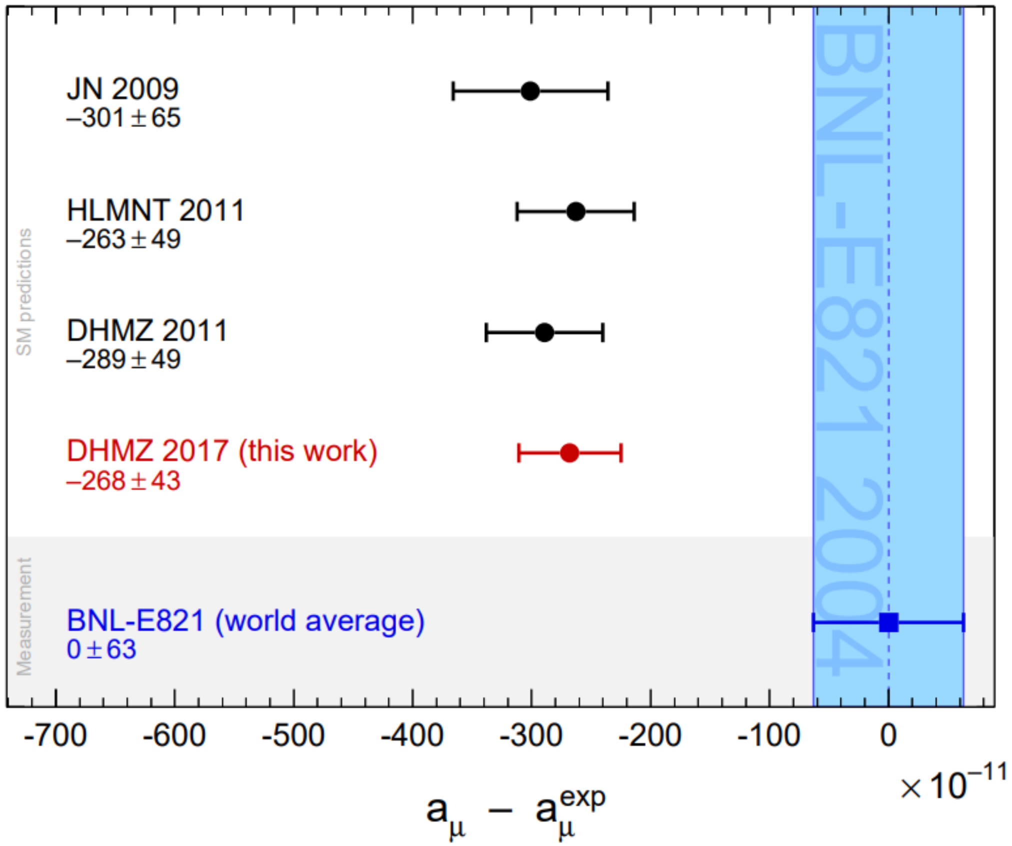
$$\overrightarrow{\mu_\mu} = g_\mu \frac{q_\mu}{2m_\mu}\vec{s}, \qquad g_\mu = 2(1 + a_\mu)$$

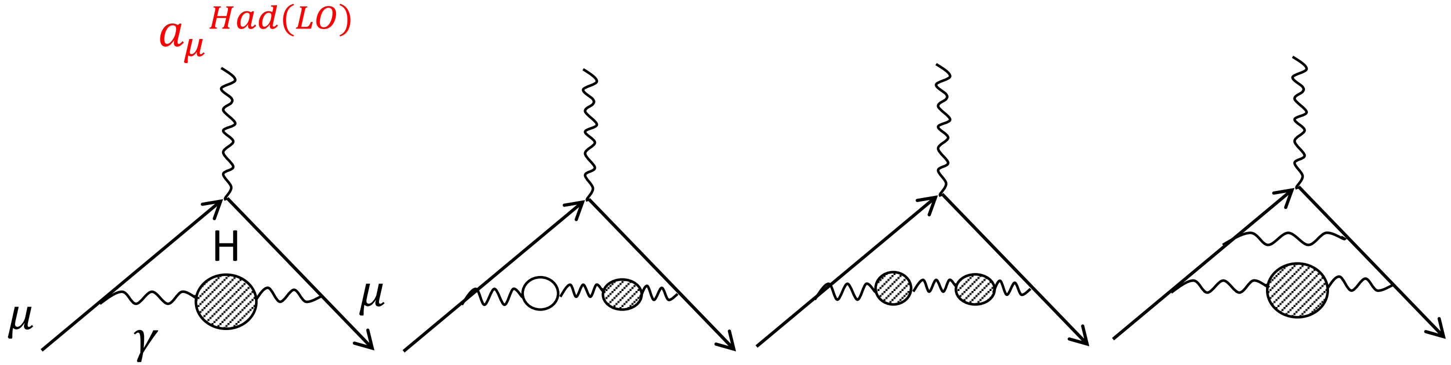
Dirac (↑ 1) Anomaly (↑ a_μ)

- There is ~3.5 σ discrepancy between experimentally measured and SM prediction for a_μ

$$a_\mu{}^{SM} = a_\mu{}^{QED} + a_\mu{}^{Had} + a_\mu{}^{Weak}$$

$$a_\mu{}^{Had} = a_\mu{}^{Had(LO)} + a_\mu{}^{Had(NLO)} + a_\mu{}^{Had(LBL)}$$



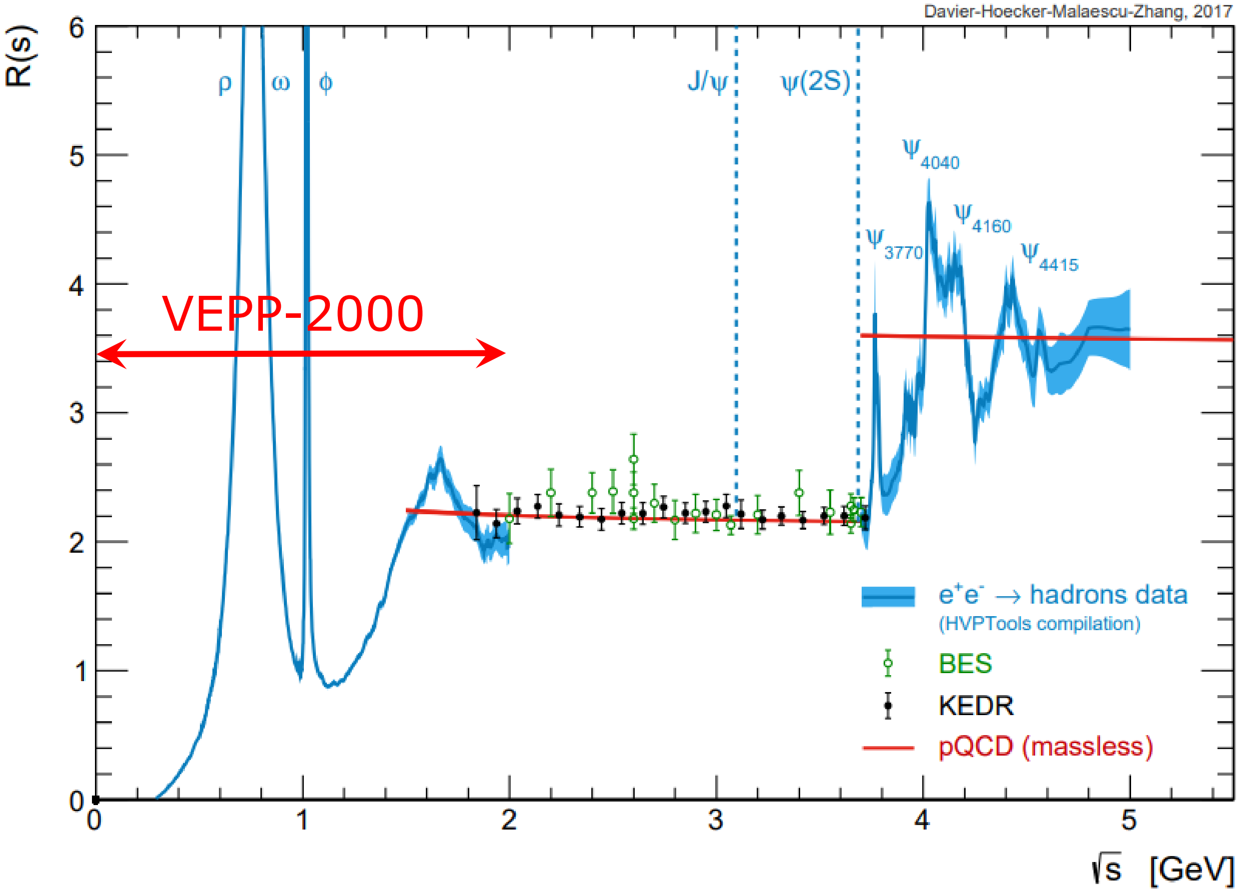


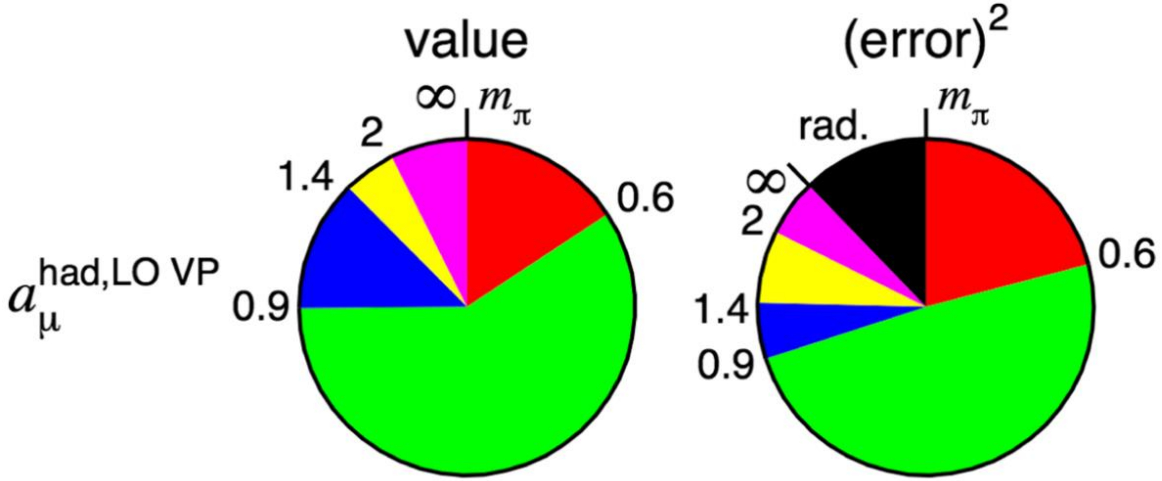
LO-Hadronic contribution to a_μ

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

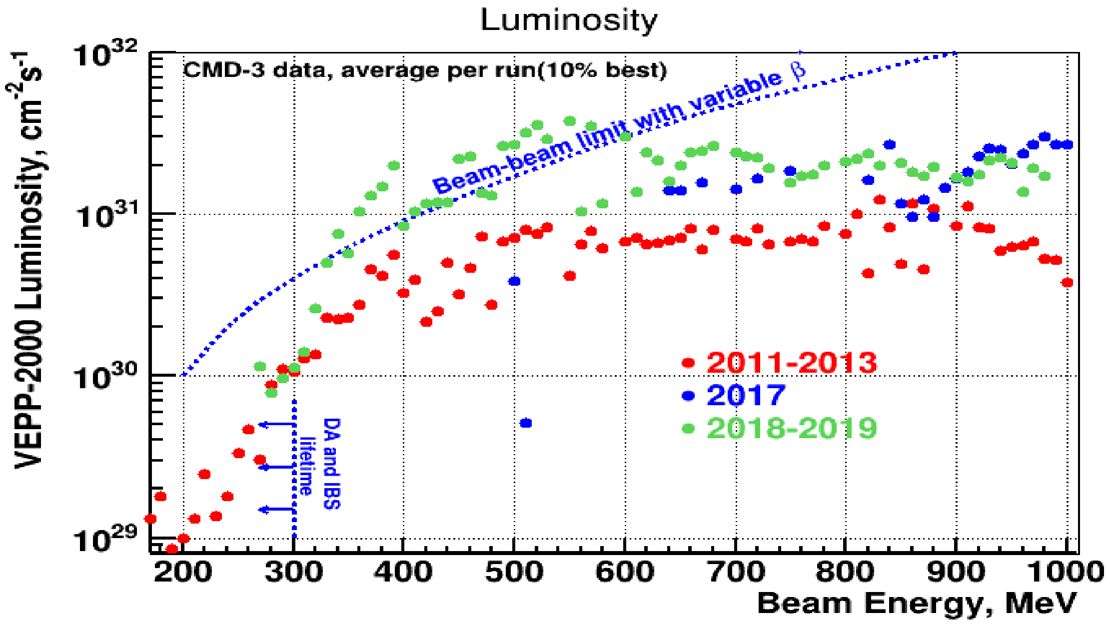
$$a^{had;LO}_\mu = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} \frac{ds}{s^2} K(s) R(s)$$

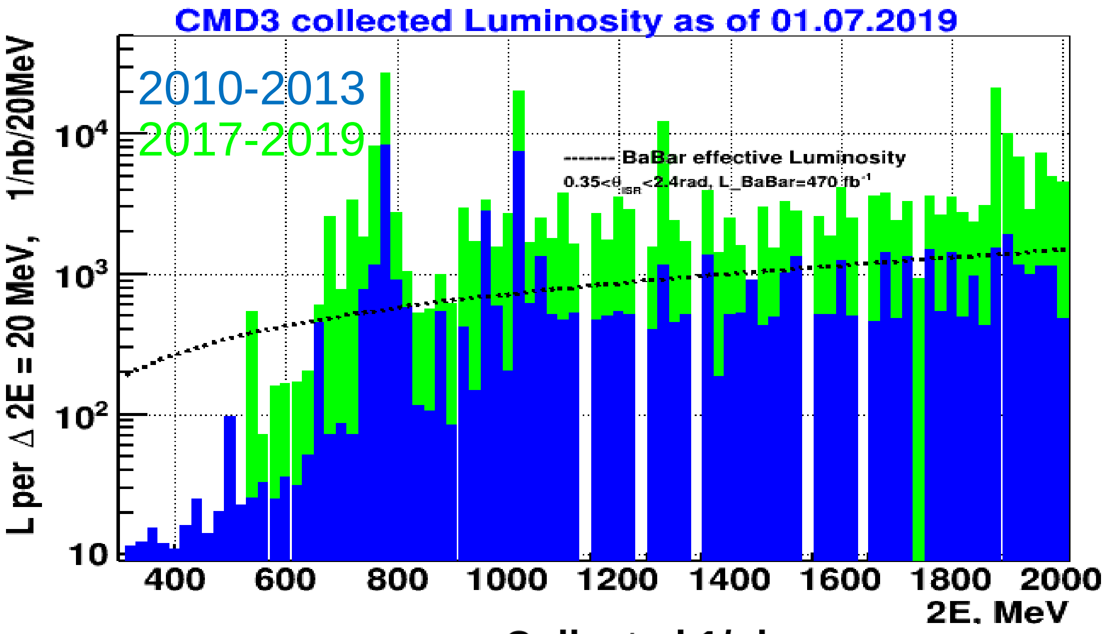
- Due to $1/s^2$ weighting the energy range of VEPP-2000 makes a dominant contribution of ~93% to the $a^{had;LO}_\mu$ and ~70% to its uncertainty





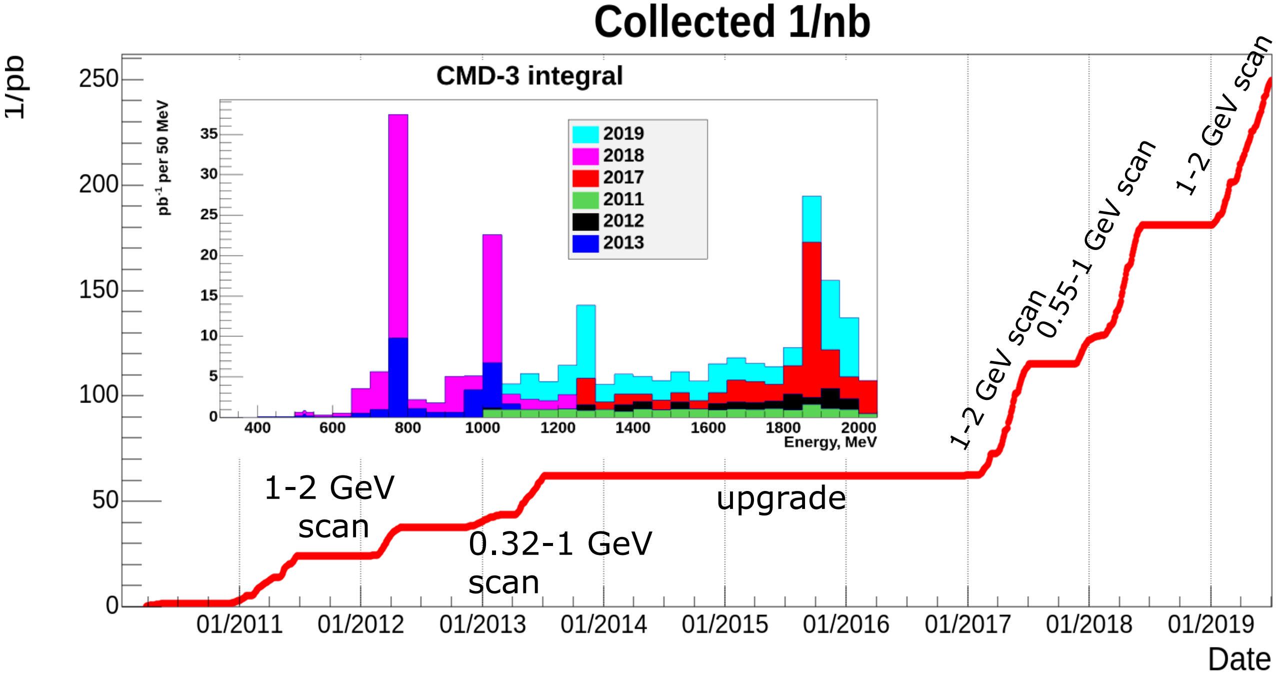
CMD-3: overview of data taking





- Before upgrade (2011-2013) the luminosity at high energies was limited by a deficit of positrons and limited energy of the booster
- 2017: new injection complex and booster gave a big improvement in luminosity at high energy, still way to go
- 2018: "Beamshaking" technique was introduced, which suppresses beam instabilities (x4 Lum)
- $L\sim250\,\mathrm{pb}^{-1}$ per detector collected so far:

  ~65 pb^{-1} < 1 GeV, ~185 pb^{-1} > 1 GeV



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

Event signature	Final state (published/submitted, in progress)
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	$3\pi^+3\pi^-$ $K_SK_S\pi^+\pi^-$
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 760 (2016) 314-319

$2\pi^+2\pi^-$ (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 779 (2018) 64-71

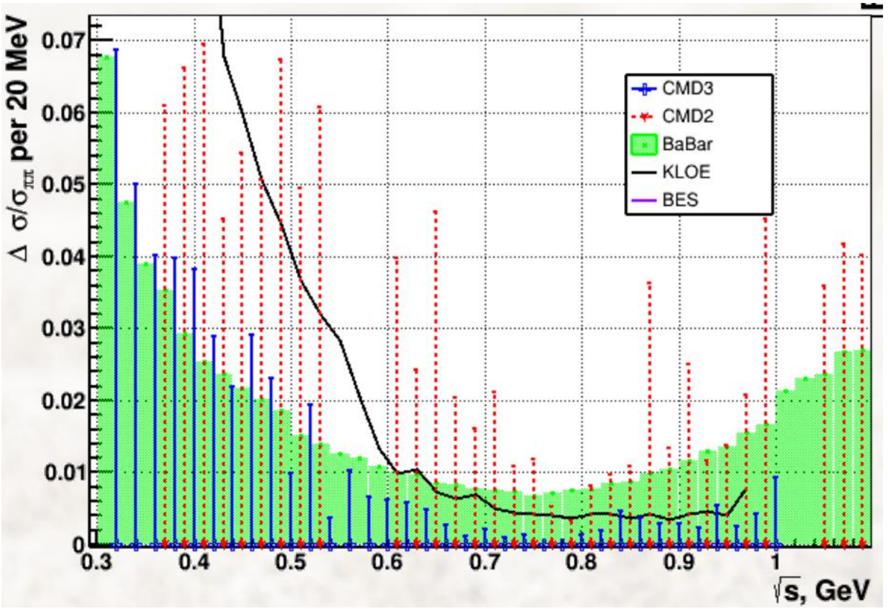
$3\pi^+3\pi^-\pi^0$: PLB 792 (2019), 419-423

$K^+K^-\eta$: arXiv:1906.08006, submitted to PLB

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

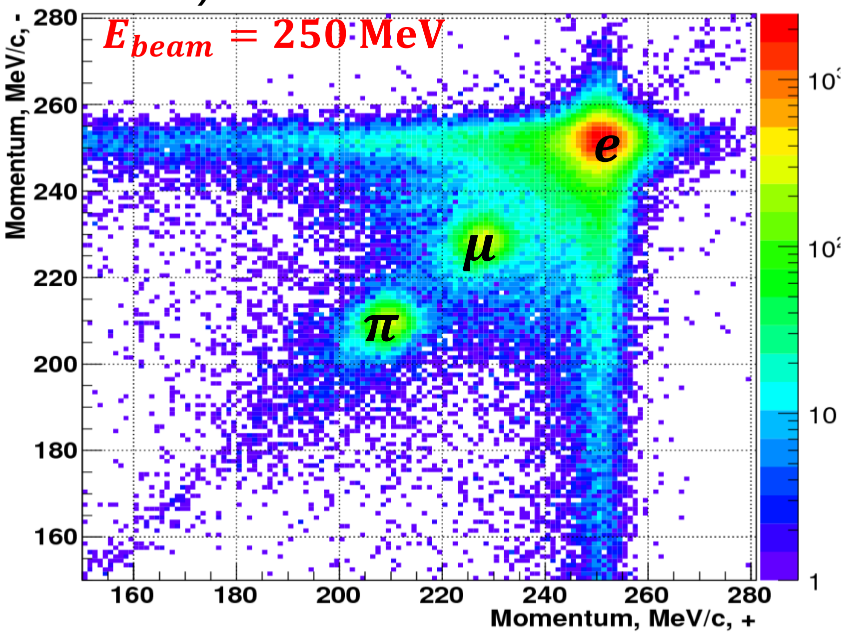
- It is a main contributor to the $a^{\mathrm{had,LO}}_{\mu}$ (~73%)
- The CMD-3's goal it to measure the $|F_\pi|^2$ with 0.4-0.5% systematics uncertainty
- CMD-3's 2013 & 2018 statistics for $\pi^+\pi^-$ a few times larger than in other experiments
- To control systematics, two independent approaches for determination of the number of $\pi^+\pi^-$ events are used:

momentum-based and energy deposition-based

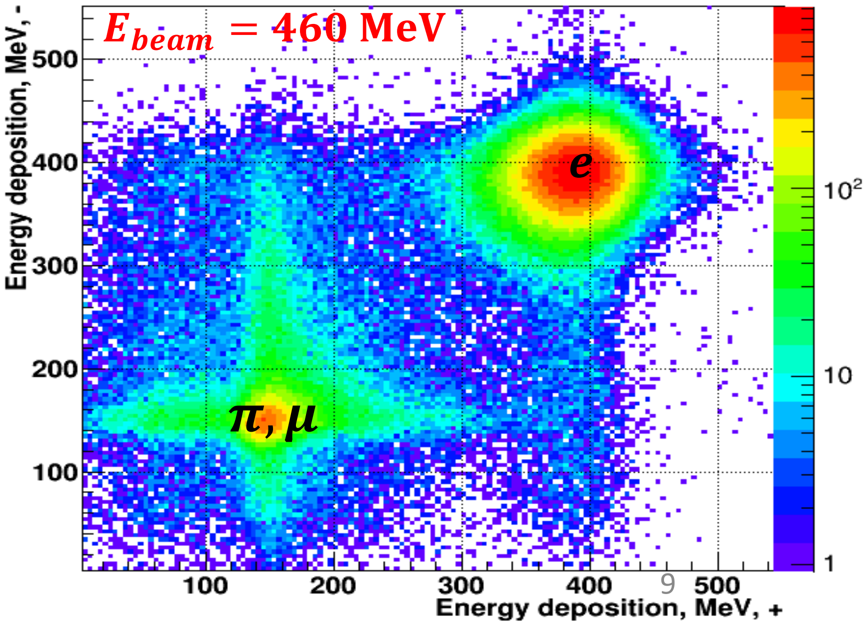


- Momentum-based approach works better at low c.m. energies (<0.8 GeV), energy-based – at large energies (>0.6 GeV). Using both methods in the middle allows to control systematics
- In both cases 2D-likelihood function is constructed, its minimization gives $N_{\pi\pi}/N_{ee}$

1) momentum-based

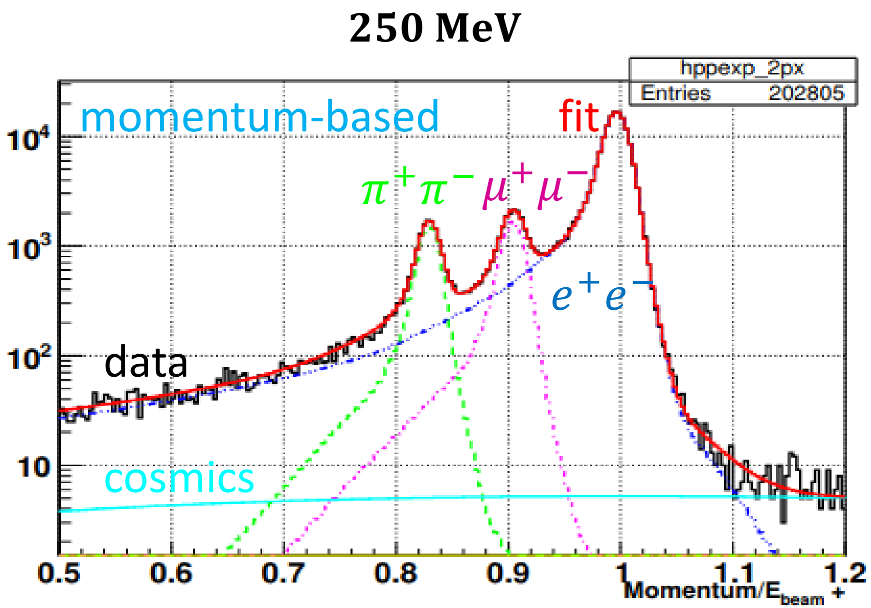


2) energy deposition-based



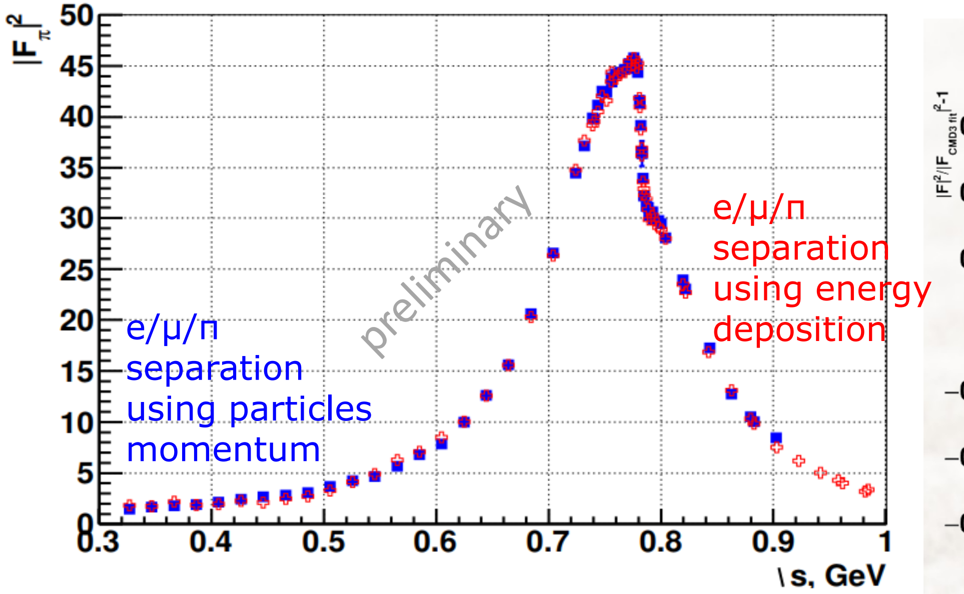
$e^+e^- \to \pi^+\pi^-$: pion formfactor measurement

- The projection of the fitting functions after minimization:

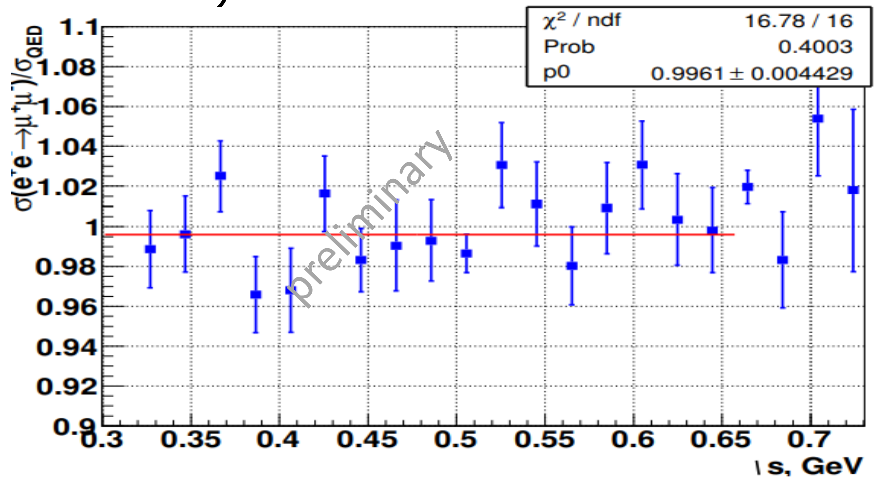


The list of sources of systematics:

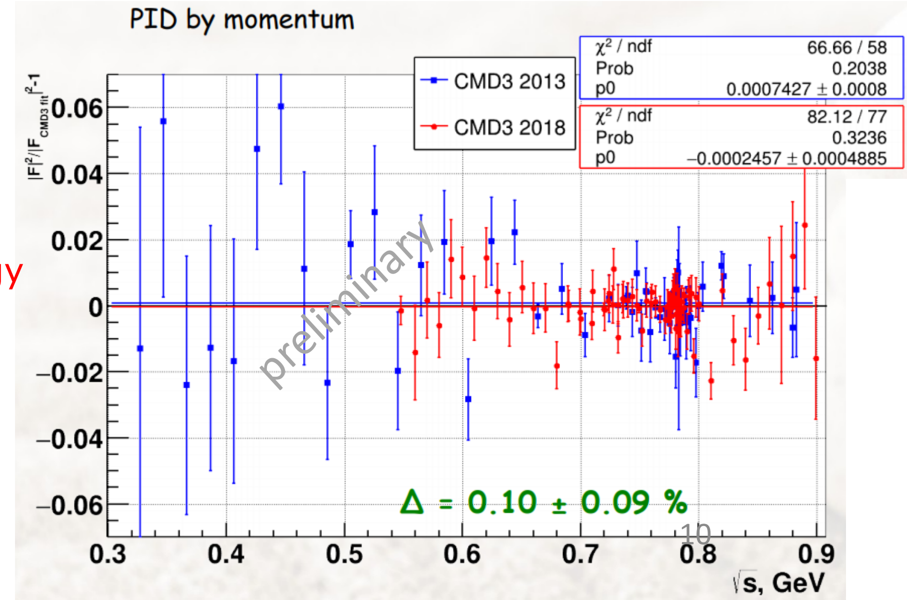
- Radiative corrections
- e/μ/π separation
- Uncertainty of fiducial volume
- Beam energy
- Electron bremsstrahlung loss
- Pion specific corrections
- Currently the systematics is estimated to be 0.6-0.9% (momentum-based)



- Additional test – $\sigma(e^+e^- \to \mu^+\mu^-)$ measurement (compatible with QED at ~0.25%):



- The results of 2013 and 2018 are consistent within ~0.1%:



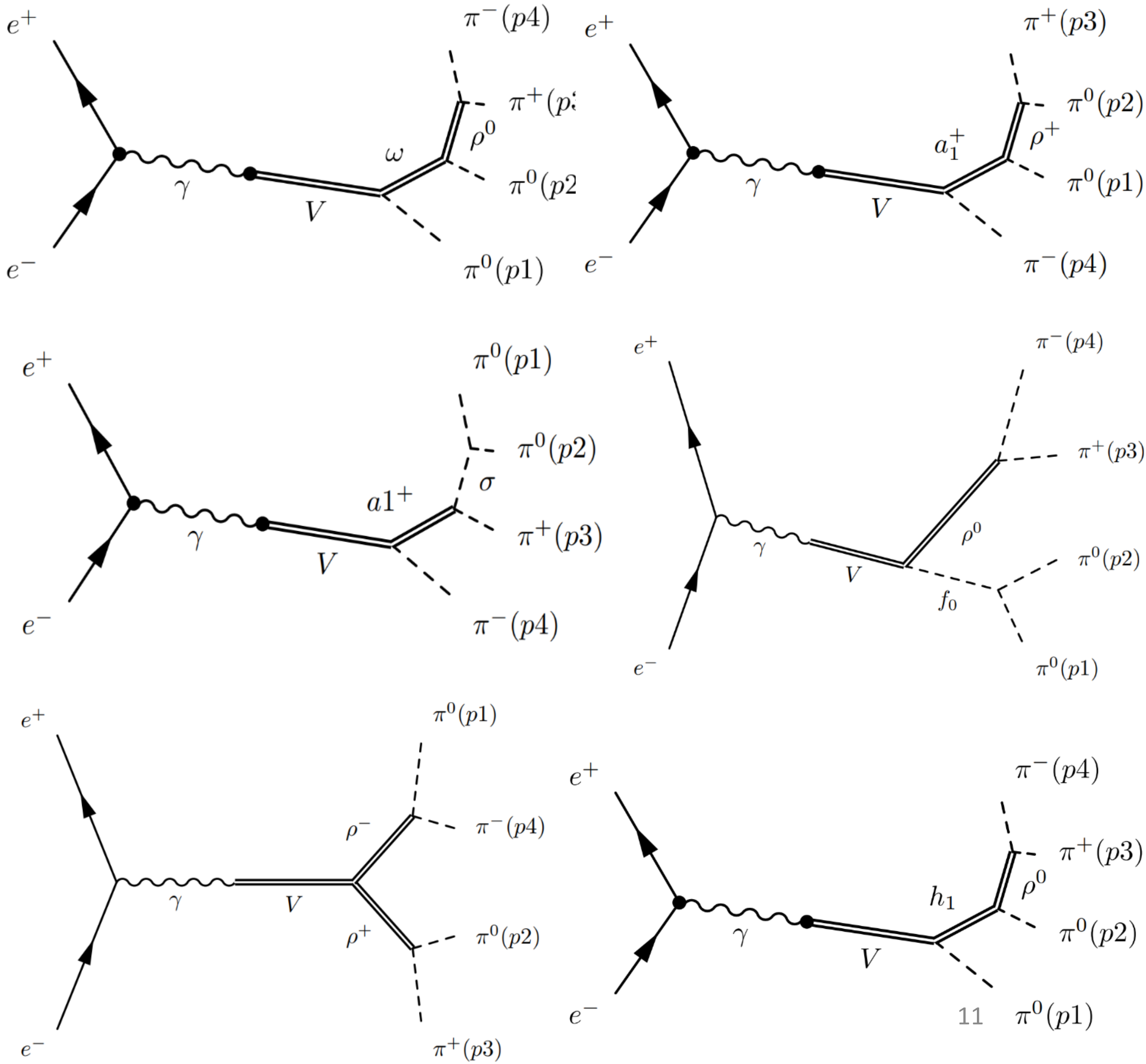
Study of $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$ process

- Process has very complicated production dynamics

- Since the detection efficiency strongly depends on the dynamics, the simultaneous unbinned fit of $\pi^+\pi^-\pi^0\pi^0$ and isotopically-related $\pi^+\pi^-\pi^+\pi^-$ final states is performed

- 64000 $\pi^+\pi^-\pi^0\pi^0$ events were selected in a 5C-kinematic fit (energy-momentum conservation + π^0 mass for one pair of photons)

- 72000 $\pi^+\pi^-\pi^+\pi^-$ events were selected in a 4C-kinematic fit (energy-momentum conservation)



Study of $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$ process

- The effective lagrangians are used to calculate the amplitudes

$$L(\omega\rho\pi) = g_{\omega\rho\pi} \cdot \epsilon_{\mu\nu\rho\sigma} \cdot \delta^{ab} \cdot \omega_\mu \cdot d_\nu \pi^{\star a} \cdot (d_\rho \rho_\sigma^{\star b} - d_\sigma \rho_\rho^{\star b}),$$

$$L(a_1\rho\pi) = g_{a_1\rho\pi} \cdot \epsilon^{abc} \cdot a_{1\mu}^a \cdot d_\nu \pi^{\star b} \cdot (d_\mu \rho_\nu^{\star c} - d_\nu \rho_\mu^{\star c}),$$

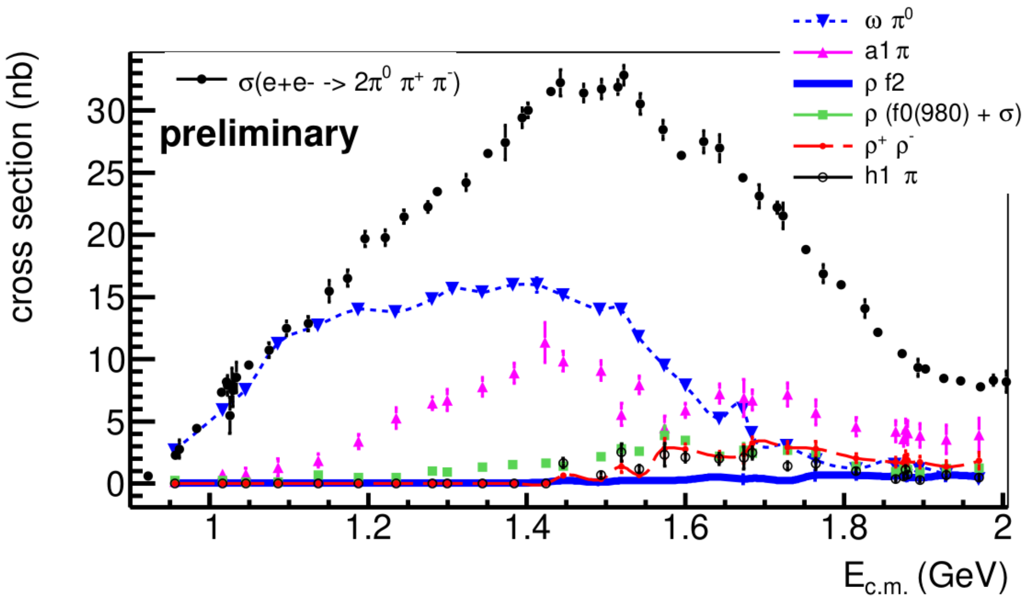
$$L(a_1\sigma\pi) = g_{a_1\sigma\pi} \cdot \delta^{ab} \cdot (d_\mu a_{1\nu}^a - d_\nu a_{1\mu}^a) \cdot d_\mu \phi^\star(\sigma) \cdot d_\nu \phi^{\star b}(\pi),$$

$$L(\rho' \rho f_0) = g_{\rho'\rho f_0} \cdot \delta^{ab} \cdot (d_\mu \rho_\nu^{'a} - d_\nu \rho_\mu^{'a})(d_\mu \rho_\nu^{\star b} - d_\nu \rho_\mu^{\star b}) \cdot \phi_{f0}^\star,$$

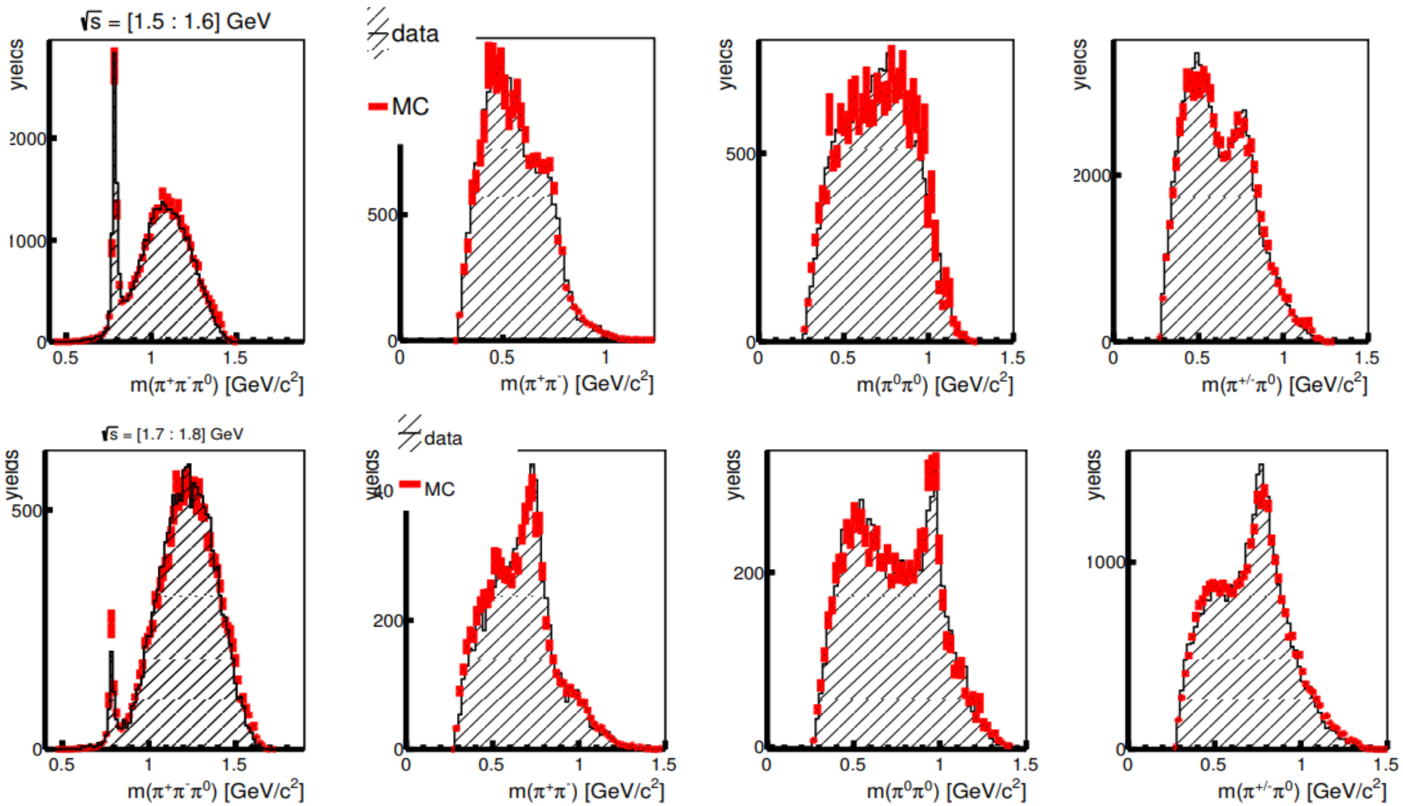
$$L(\rho'\rho^+\rho^-) = g_{\rho'\rho^+\rho^-} \cdot \epsilon^{abc}(d_\mu \rho_\nu^{'a} - d_\nu \rho_\mu^{'a}) \cdot (d_\alpha \rho_\nu^{\star b} - d_\nu \rho_\alpha^{\star b}) \cdot (d_\mu \rho_\alpha^{\star c} - d_\alpha \rho_\mu^{\star c})$$

$$L(\rho' h_1 \pi^0) = g_{\rho' h_1 \pi^0} \cdot \delta^{ab}(d_\mu \rho_\nu^{'a} - d_\nu \rho_\mu^{'a}) \cdot (d_\mu h_{1\nu}^{\star b} - d_\nu h_{1\mu}^{\star b})\phi_\pi^\star,$$

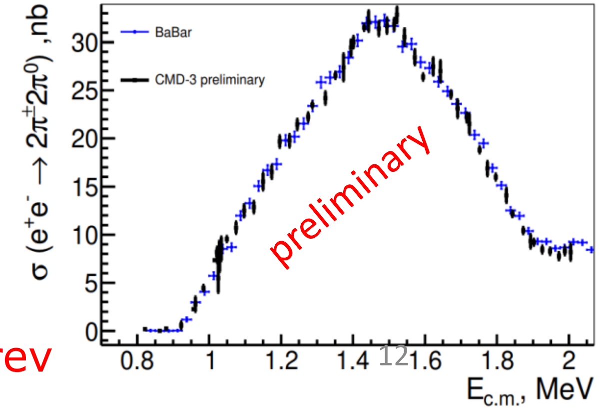
- From the unbinned fit the relative amplitudes of the different mechanisms were determined:



- After the fit simulation shows reasonable agreement with data:



- $\omega(782)\pi^0$ and $a_1\pi$ dominate in the process, but other mechanisms are also statistically significant
- The total cross section was measured:



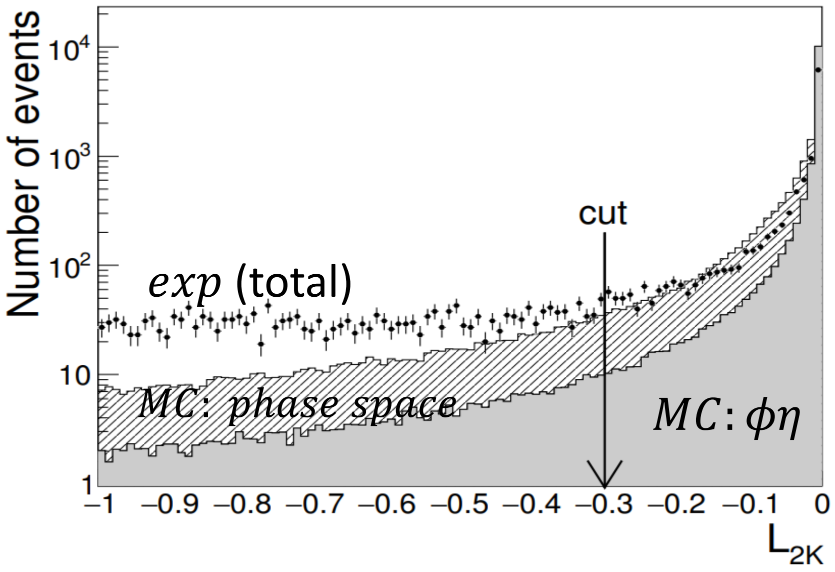
- For more details see poster by E. Kozyrev

Study of $e^+e^- \to K^+K^-\eta$ process

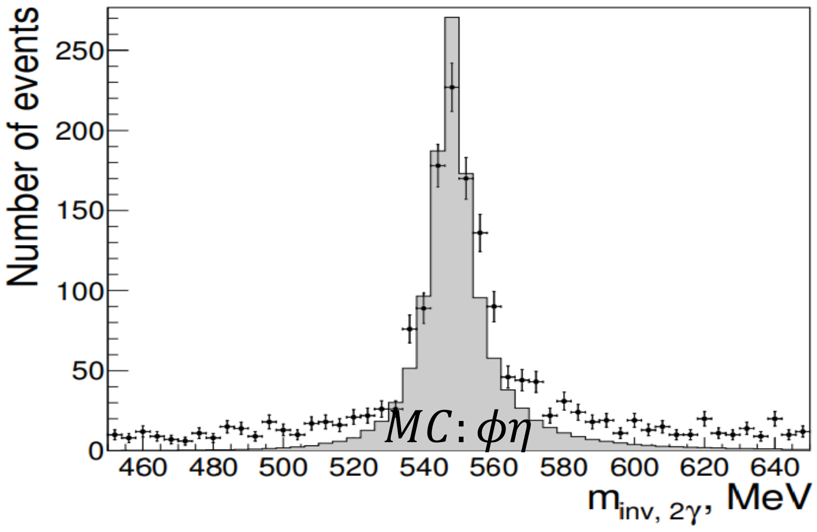
- The selection of kaons is performed using the log-likelihood function, based on the measured dE/dx in the DC

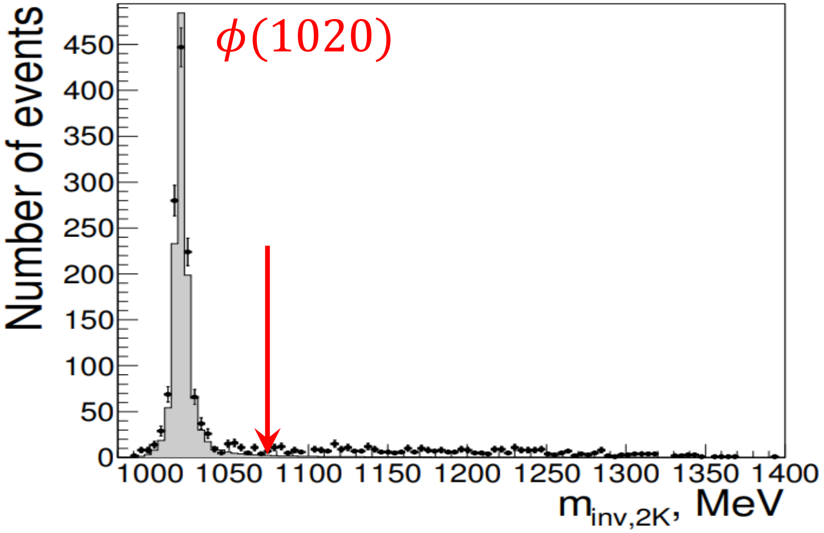
$$L_{2\mathrm{K}} = \sum_{i=1}^{2} \ln\left(\frac{f_K(p_i,(dE/dx)_i)}{f_K(p_i,(dE/dx)_i) + f_\pi(p_i,(dE/dx)_i)}\right)$$

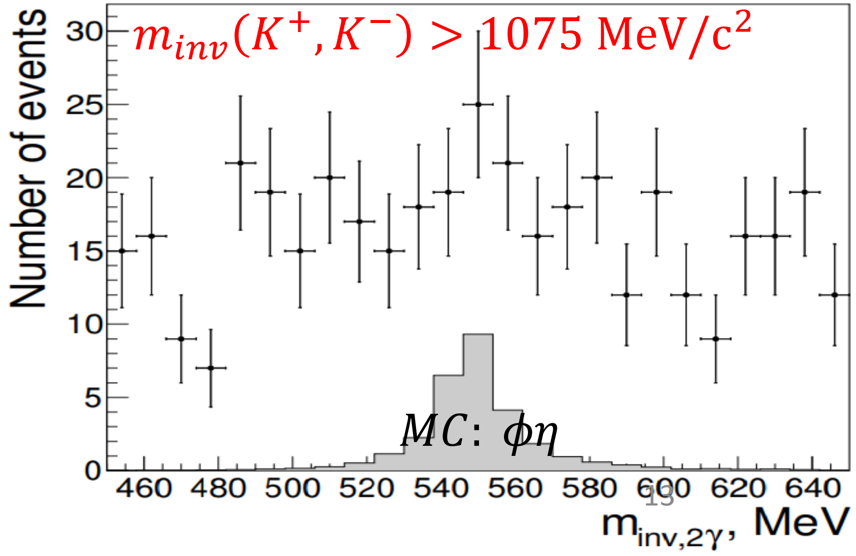
- Event selection: 4C-kinematic fit with all pairs of photons in the event



- No evidence of NON-$\phi\eta$ events with $m_{inv}(K^+,K^-) > 1075\ \mathrm{MeV/c^2}$ (only $\phi\eta$ is seen):





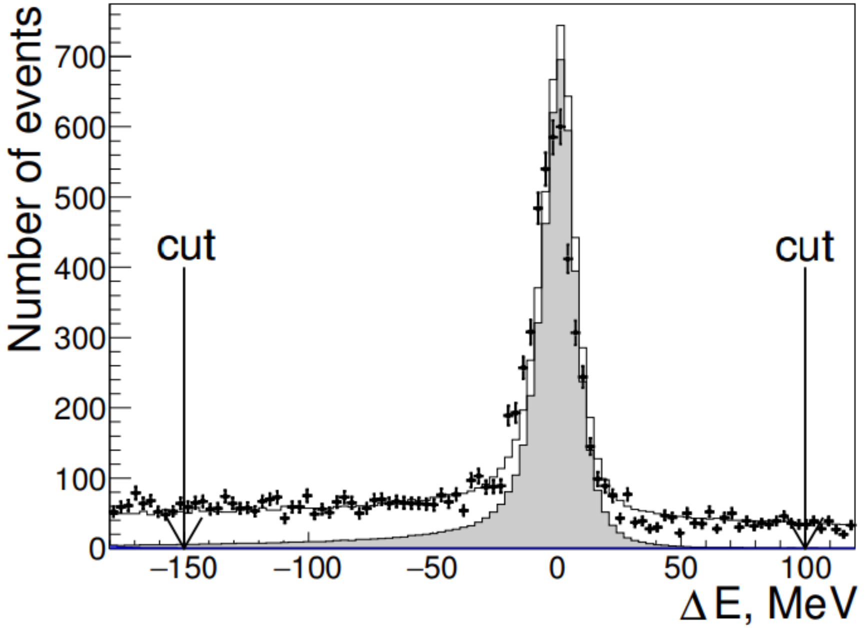


Study of $e^+e^- \to K^+K^-\eta$ process

- Signal/background separation is done by fitting the energy disbalance distribution:

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

- From the cross section fitting the $\phi'(1680)$ parameters were determined with the best precision at the moment



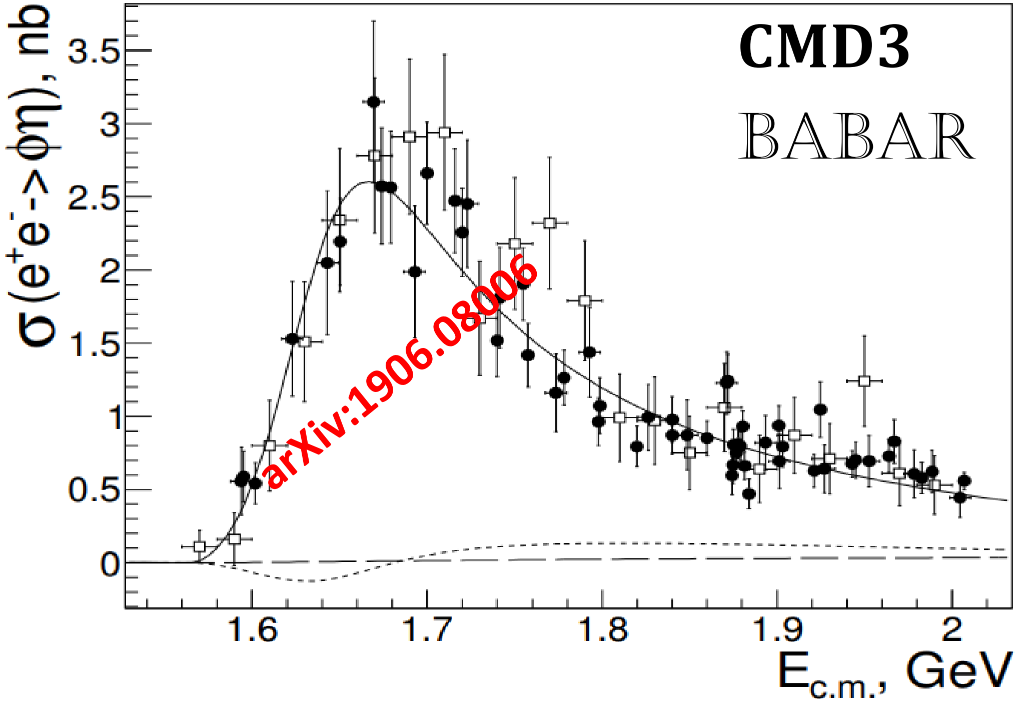


Table 4: Results of the $e^+e^- \to \phi\eta$ cross section approximation.

Parametrization using	$\Gamma^{\phi'}_{ee}\mathcal{B}^{\phi'}_{\phi\eta}$	$\mathcal{B}^{\phi'}_{e^+e^-}\mathcal{B}^{\phi'}_{\phi\eta}$
Parameter	Value	
χ^2/n.d.f	93.8/79≈1.19	
$\Gamma^{\phi'}_{ee}\mathcal{B}^{\phi'}_{\phi\eta}$, eV	$94\pm13_{\rm stat}\pm15_{\rm syst}$	–
$\mathcal{B}^{\phi'}_{e^+e^-}\mathcal{B}^{\phi'}_{\phi\eta}$	–	$0.53\pm0.06_{\rm stat}\pm0.09_{\rm syst}$
$m_{\phi'}$, MeV	$1667\pm5_{\rm stat}\pm11_{\rm syst}$	
$\Gamma_{\phi'}$, MeV	$176\pm23_{\rm stat}\pm38_{\rm syst}$	
$a_{\rm n.r.}$, MeV	$1.1\pm0.6_{\rm stat}$	
$\Psi_{\rm n.r.}$	$0.14\pm0.67_{\rm stat}$	

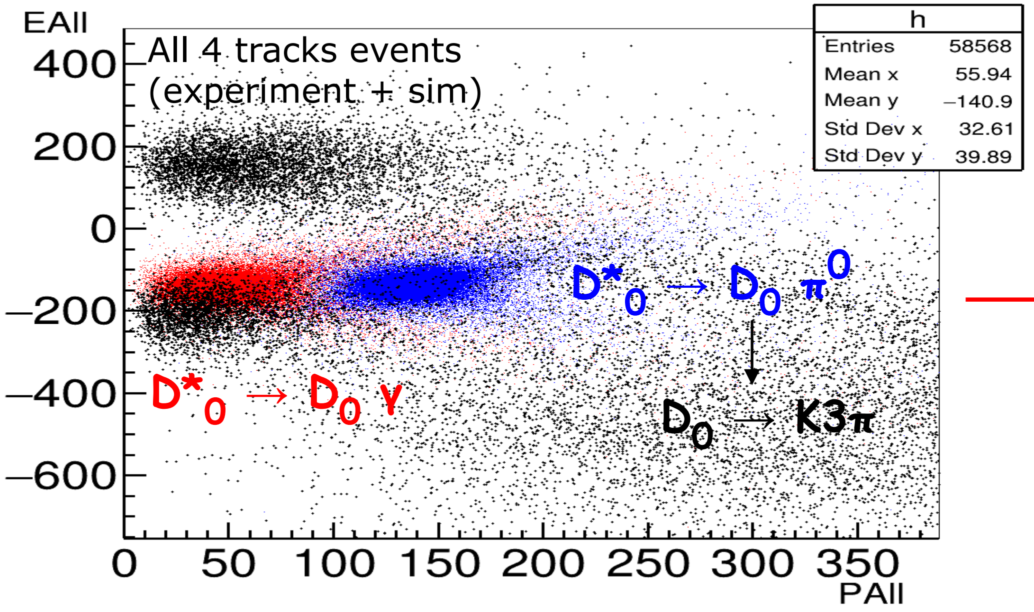
Searching for $e^+e^- \to D^{*0}$ (2007)

- We are trying to probe also charm-physics
- Motivation: A. Khodjamirian et al, JHEP11(2015)142

SM: $\mathcal{B}(D^* \to e^+e^-) \geq 5 \times 10^{-19}$

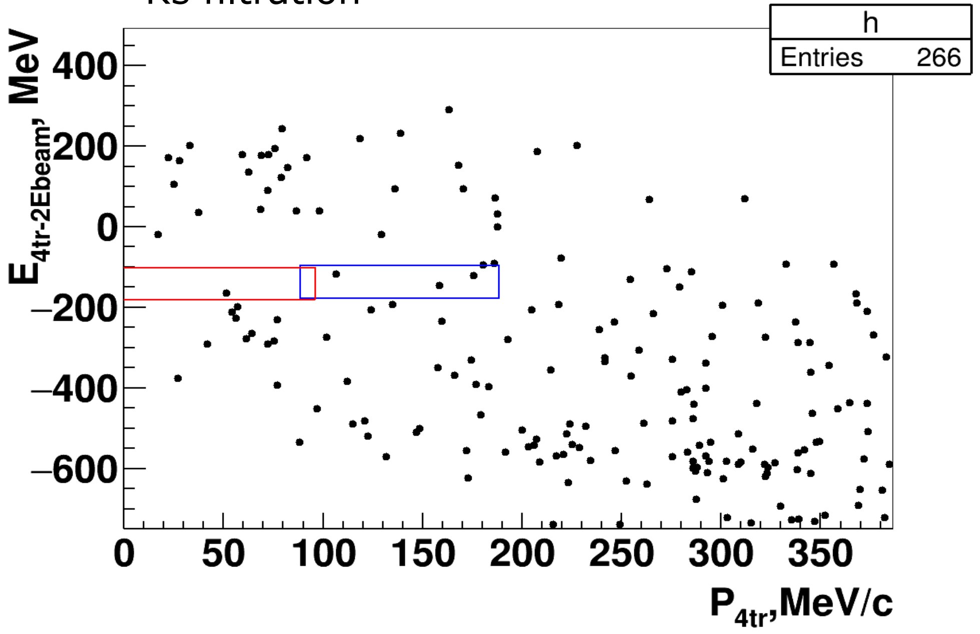
New Physics with Z' : $\mathcal{B}(D^* \to e^+e^-) < 2.5 \times 10^{-11}$

- VEPP-2000 collected 3.4 pb^{-1} at 2007 MeV:



After filtration (1./500 bkg suppression):

- Likelihood of K3π (dE/dx,p)
- Ks filtration



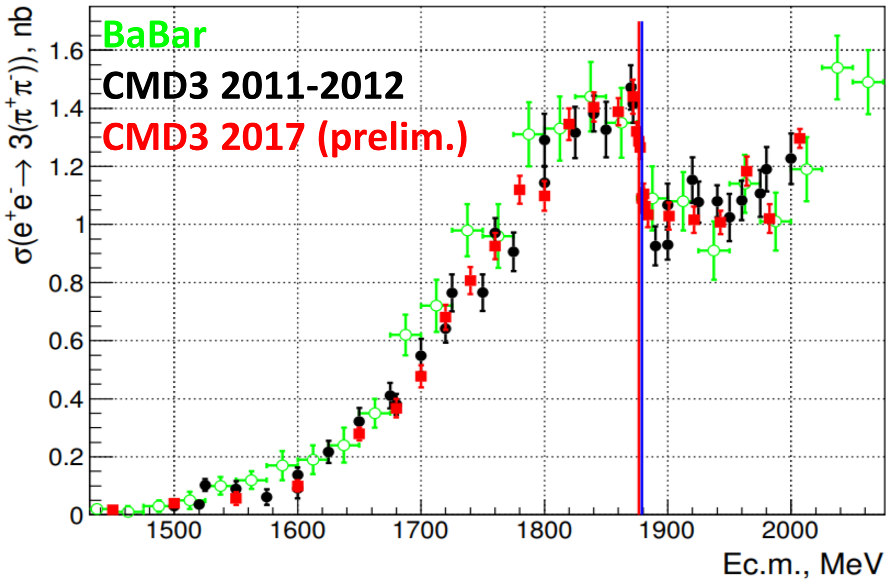
- First time UL measurement:

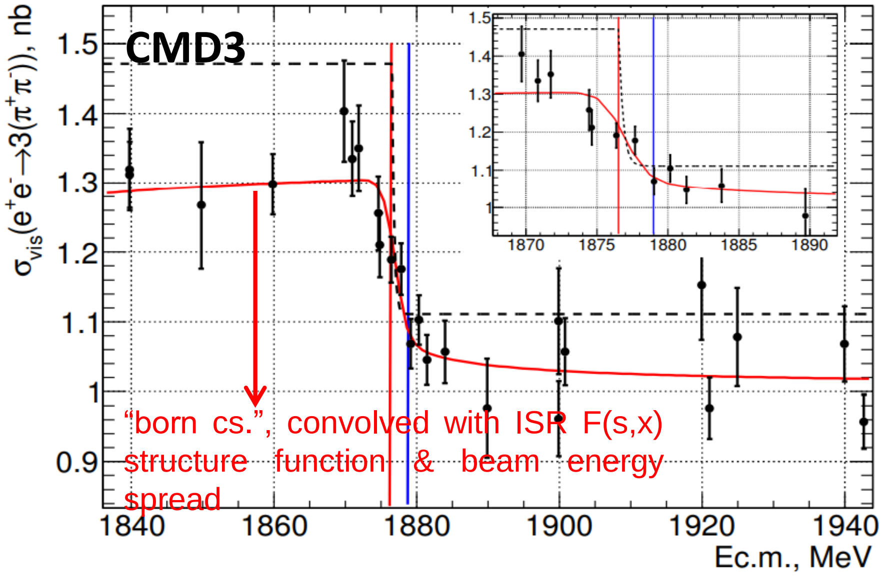
$D^{*0} \to D^0\gamma$: $\mathcal{B}(D^* \to e^+e^-) < 5.2 \times 10^{-6}$ (90% CL)

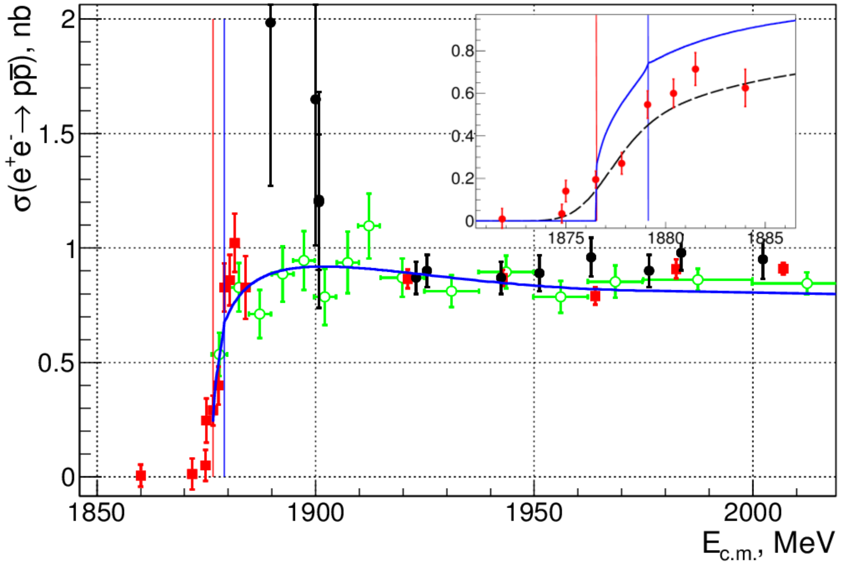
$D^{*0} \to D^0\pi^0$: $\mathcal{B}(D^* \to e^+e^-) < 1.7 \times 10^{-6}$ (90% CL)

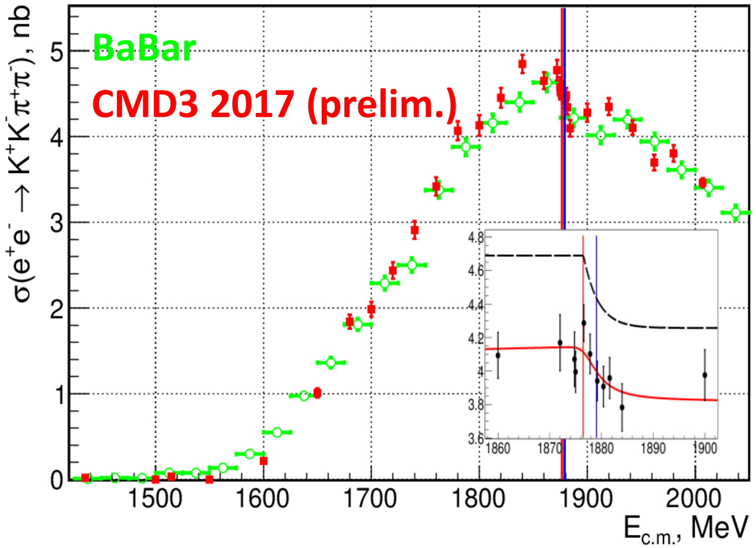
Multihadron production @ $N\bar{N}$ threshold

- In 2017 we did the detailed scan of $N\bar{N}$ threshold region with the step 0.8 MeV (~beam energy spread)
- Several dip structures with ~ 1 MeV width are seen in multihadron production! (see details in PLB 794 (2019) 64-68)
- Effect can be described via optical nucleon-antinucleon potentials ("Milstein-Salnikov" parametrization, see Nuc. Phys. A 977 (2018) 60-68)



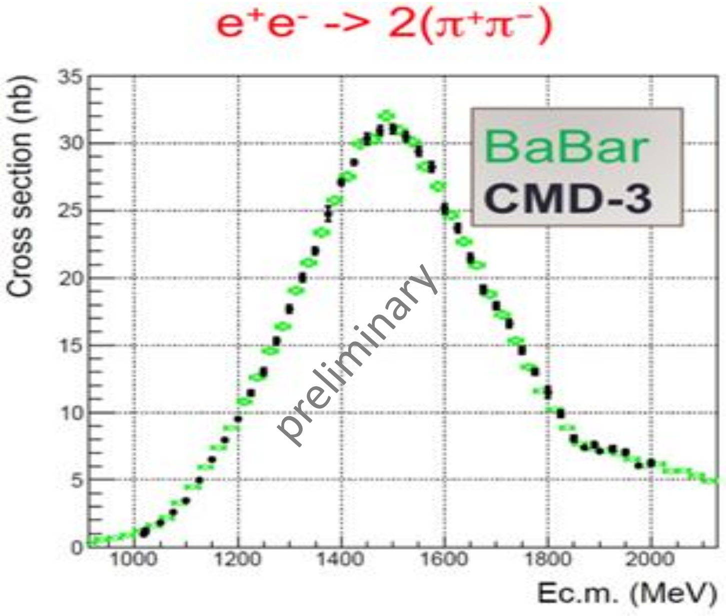






Multihadron production @ $N\bar{N}$ threshold

- Hovewer, some questions still remain: why no “dip” structure in $e^+e^- \to 2\pi^+2\pi^-$, $\pi^+\pi^-4\pi^0$?



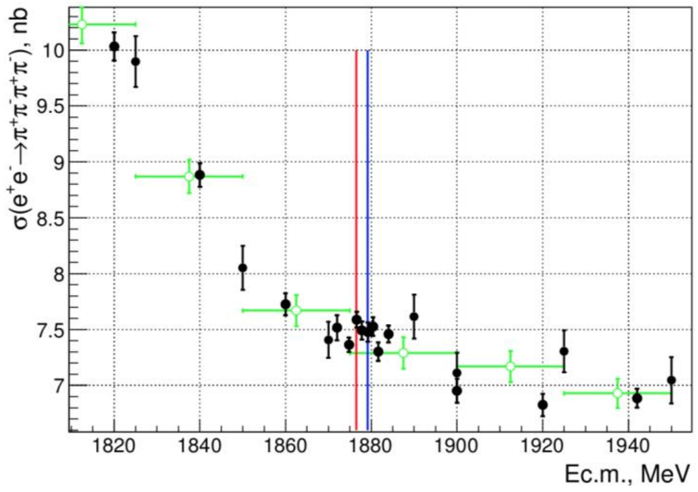
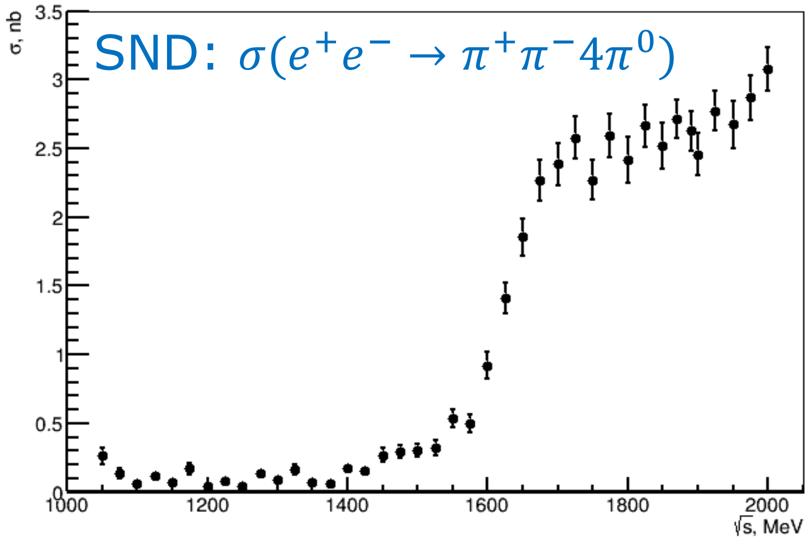
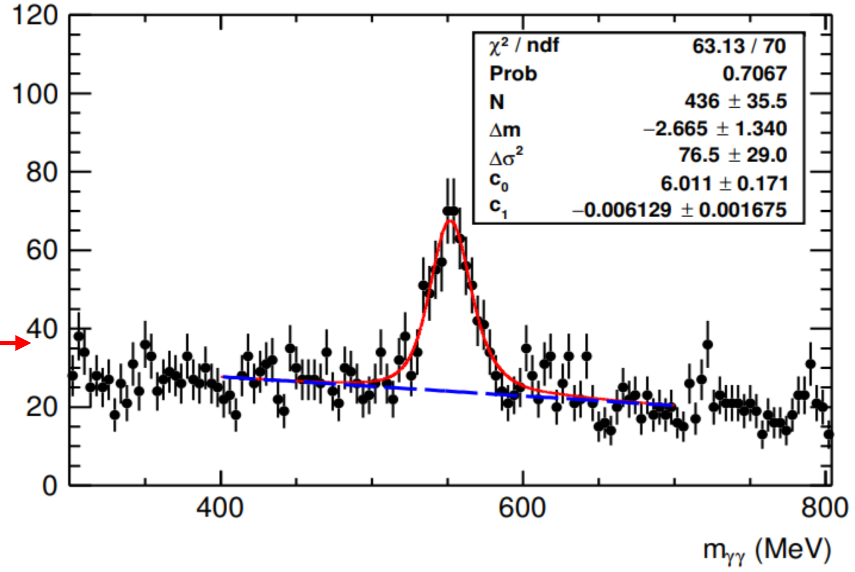


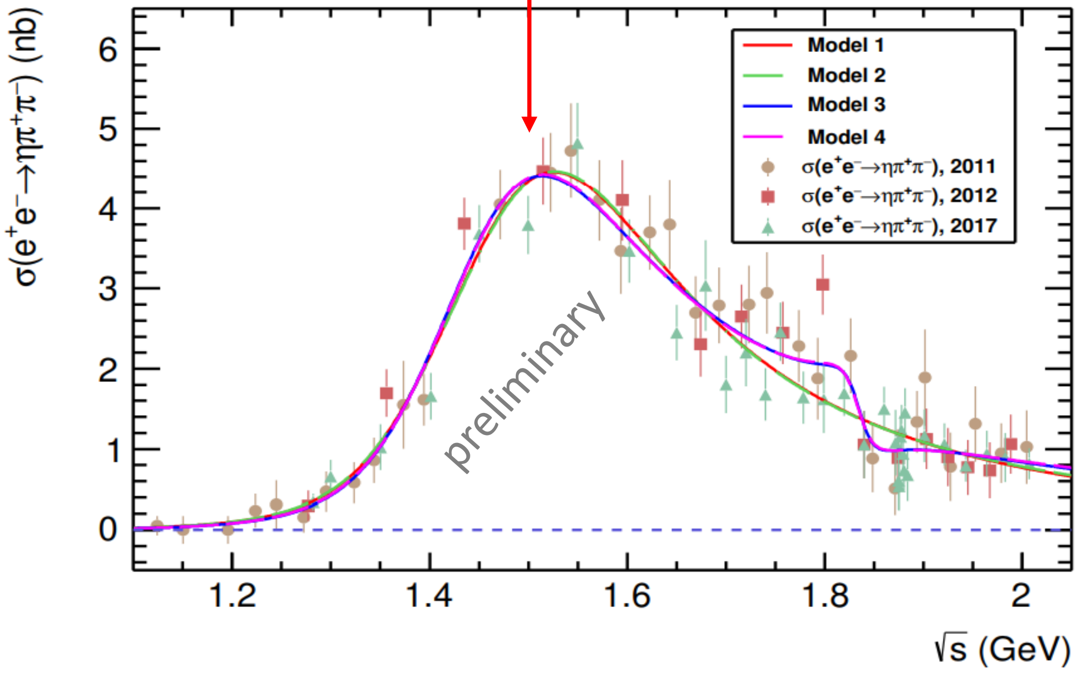
Figure 4: The $e^+e^- \to 2(\pi^+\pi^-)$ cross section measured with the CMD-3 detector. Lines show the $p\bar{p}$ and $n\bar{n}$ thresholds.

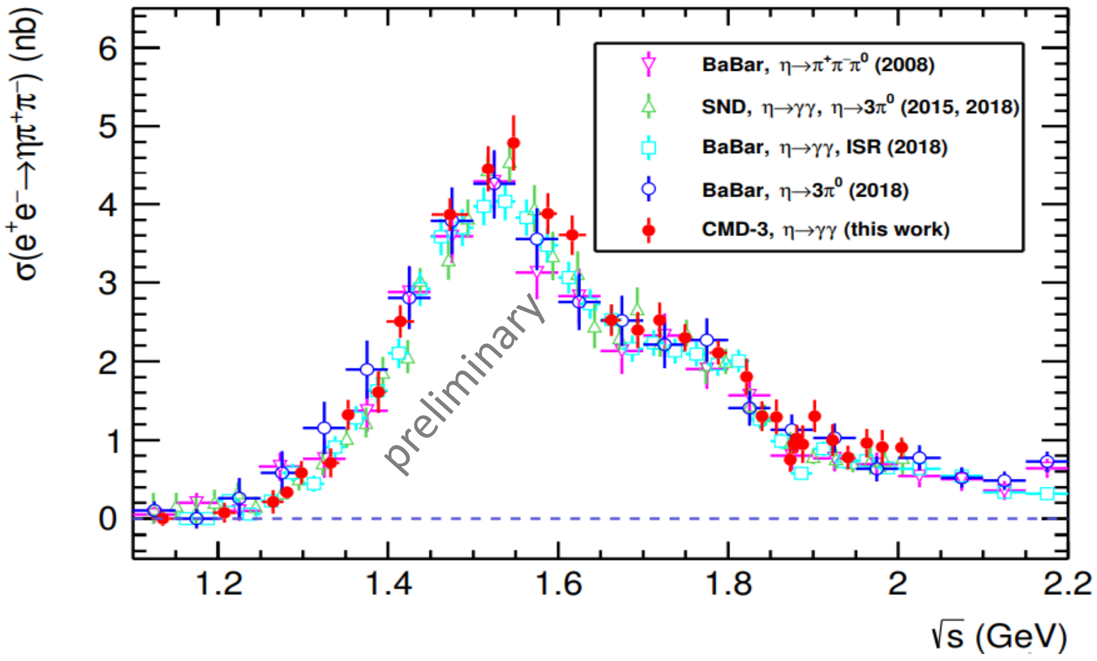


Study of $e^+e^- \to \pi^+\pi^-\eta$ process

- Event selection ($\eta \to \gamma\gamma$): 4C-kinematic fit (energy-momentum conservation)
- $e^+e^- \to \rho(770)\eta$ mechanism dominates
- Signal/background separation using $m(\gamma\gamma)$ distribution
- Cross section is fitted with $\rho(770), \rho(1450)$ and $\rho(1700)$ intermediate resonances

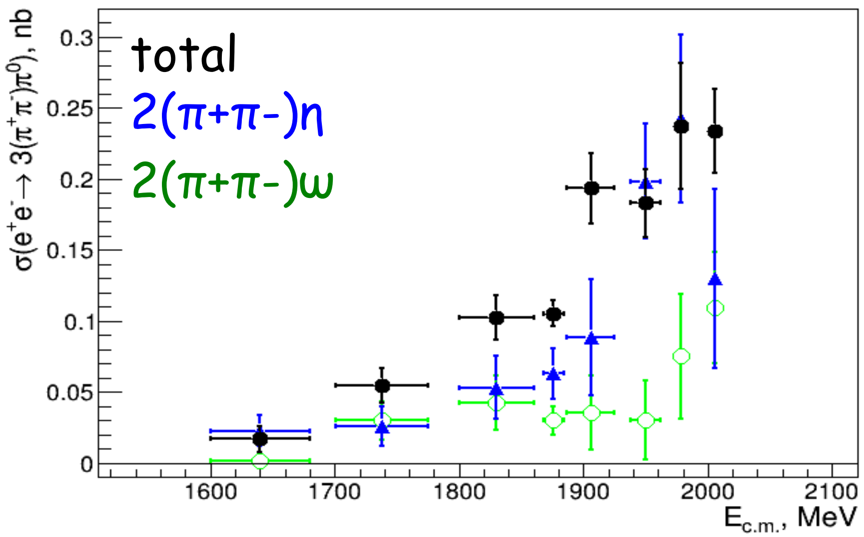




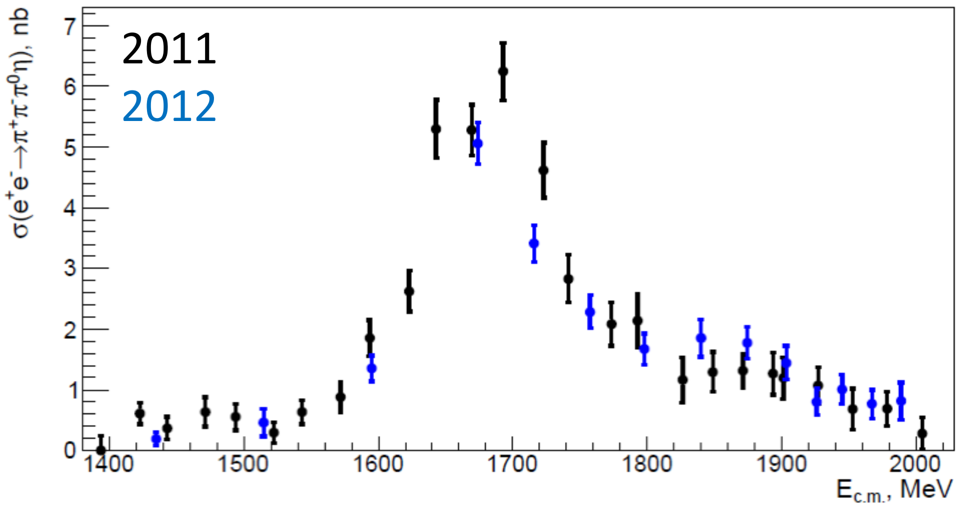


Other published result

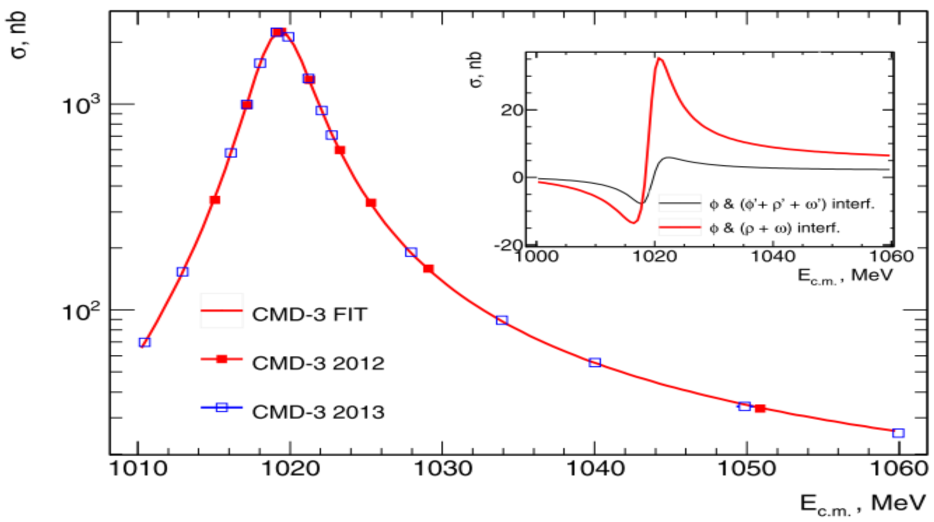
- $e^+e^- \to 3(\pi^+\pi^-)\pi^0$: PLB 792 (2019), 419-423



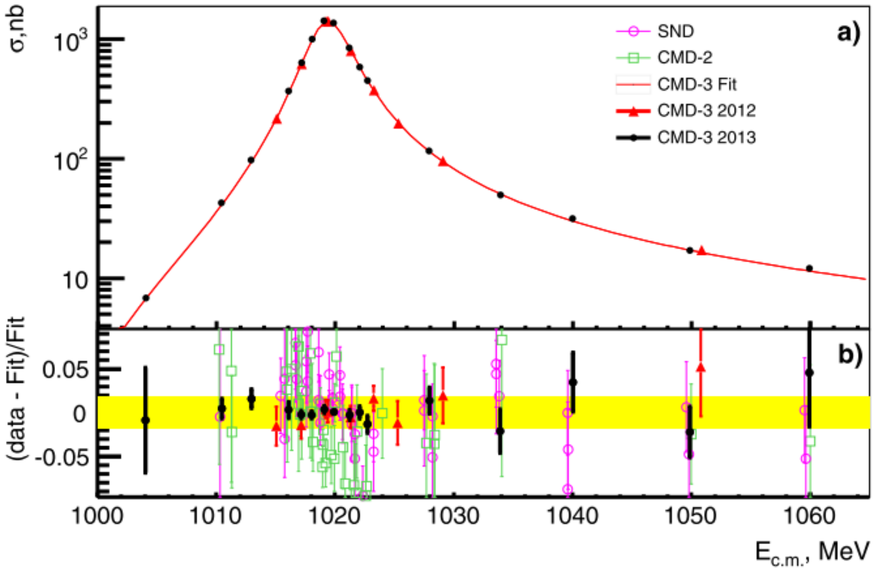
- $e^+e^- \to \pi^+\pi^-\pi^0\eta$: PLB 773 (2017) 150-158



- $e^+e^- \to K^+K^-$ **at** ϕ: PLB 779 (2018) 64

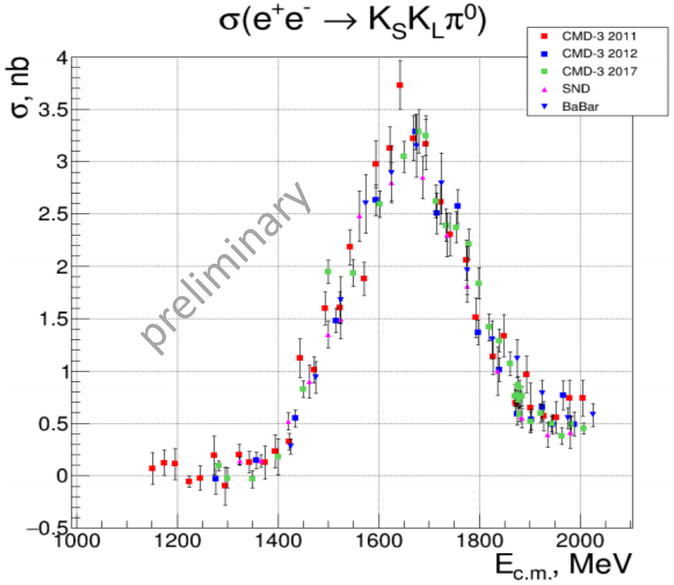


- $e^+e^- \to K_SK_L$ **at** ϕ: PLB 760 (2016) 314-319

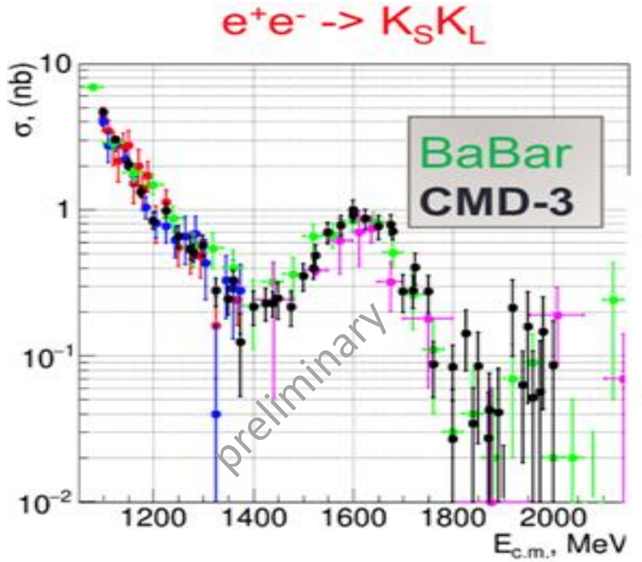


Other preliminary result

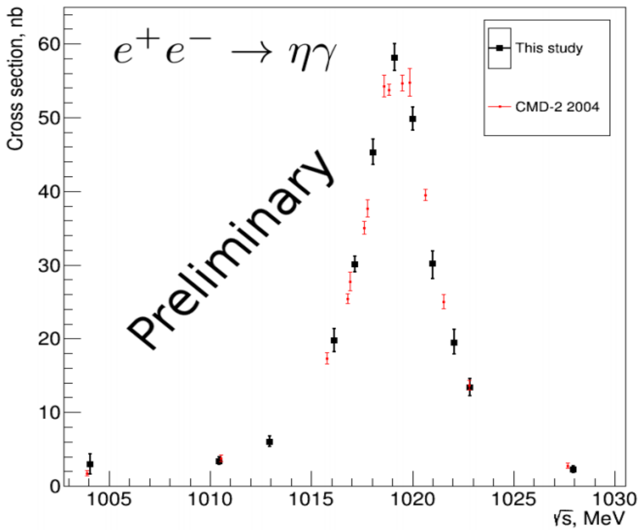
- Study of $e^+e^- \to K_S K_L \pi^0$:



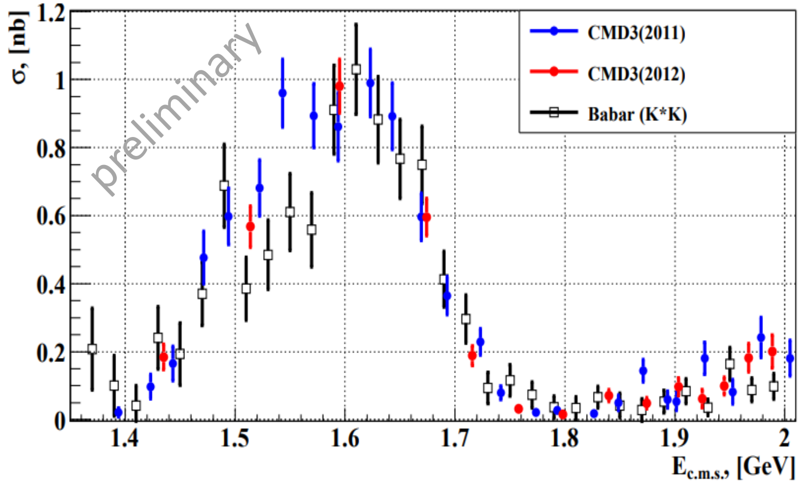
- Study of $e^+e^- \to K_S K_L$ above ϕ



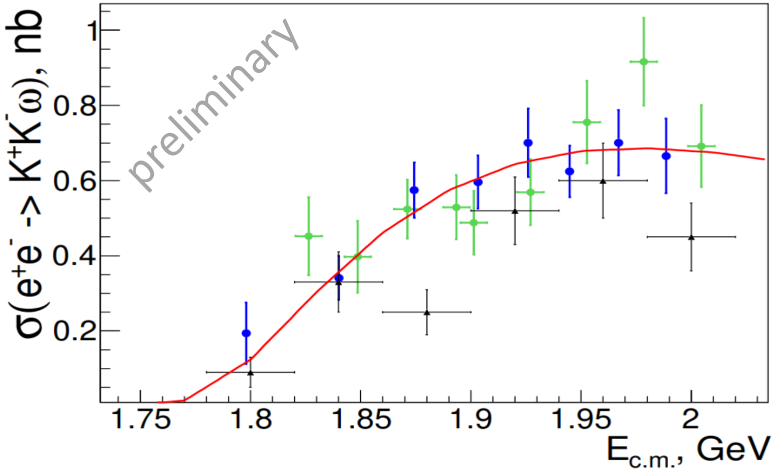
- Study of $e^+e^- \to \pi^0\gamma, \eta\gamma$



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



- Study of $e^+e^- \to K^+K^-\omega(782)$:



Conclusions

- CMD-3 has taken ~250 pb^{-1} of data in the whole energy range $0.32 \leq \sqrt{s} \leq 2.0$ GeV and is going to take ~$1\mathrm{fb}^{-1}$ in the next ~5 years

- Some upgrade of detector subsystems are planned (endcap and barrel coordinate counters, new drift chamber)

- Many analyses have been published. Many others are in progress

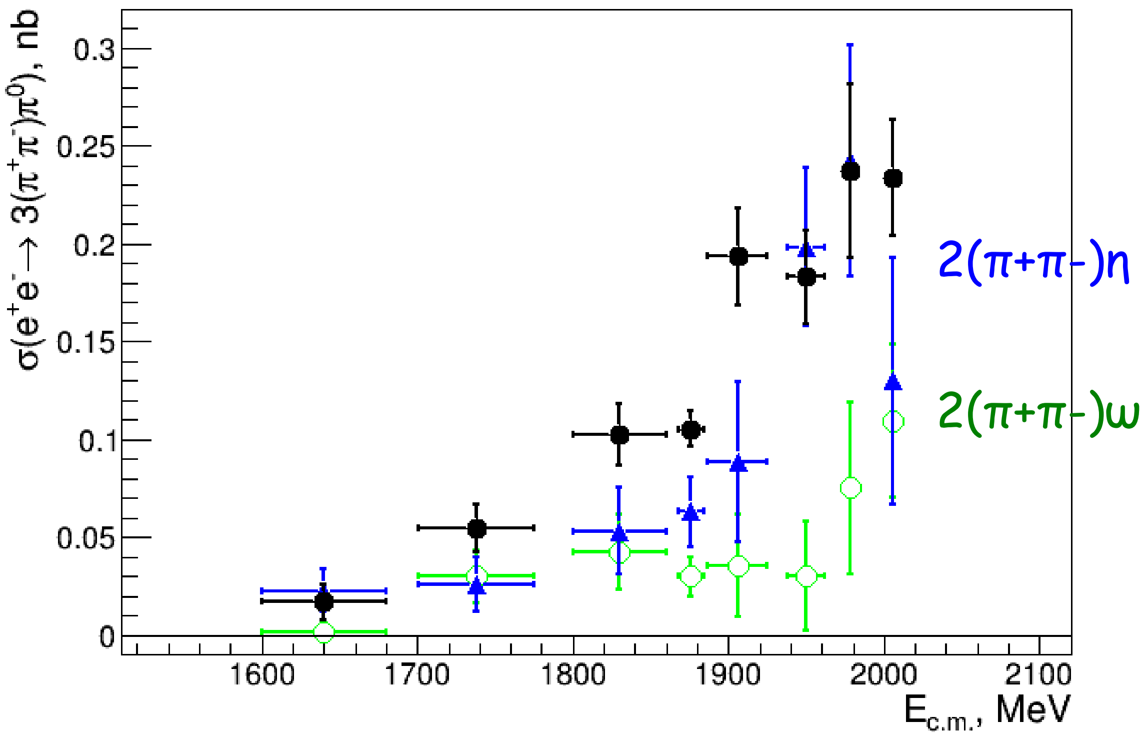
Thank you!

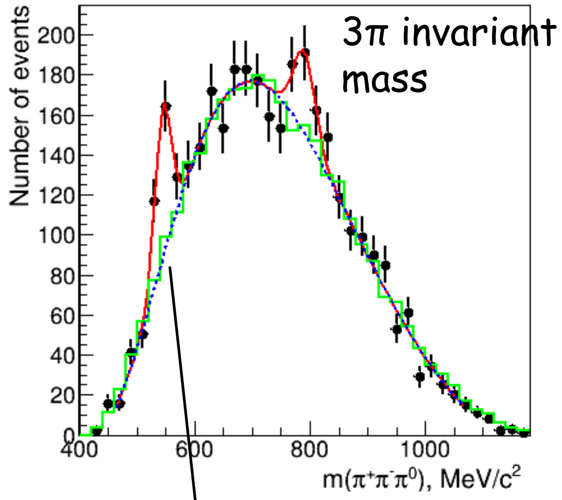
BACKUP

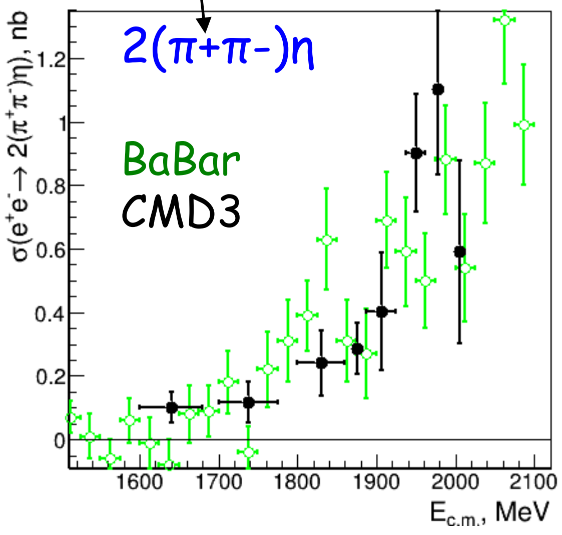
$e^+e^- \to 3(\pi^+\pi^-)\pi^0$ from CMD-3

First time measurement of total cross-section

$4\pi\eta$,$4\pi\omega$ dominated







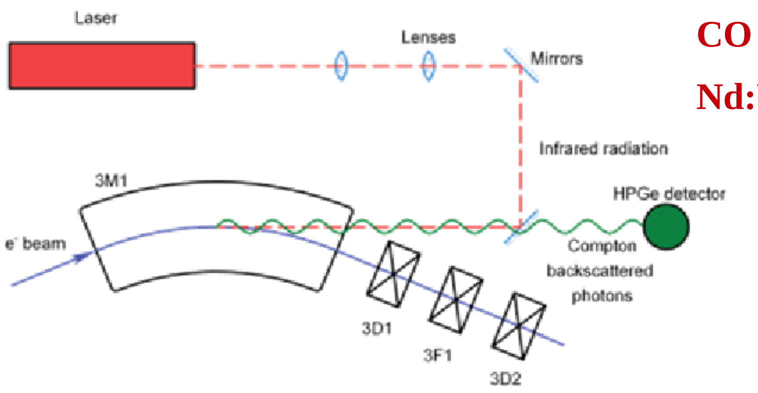
~1% of R(s) at 2 GeV

Phys. Lett. B792, 419 (2019)

It is the first measurement of the 7pi production

Energy measurement

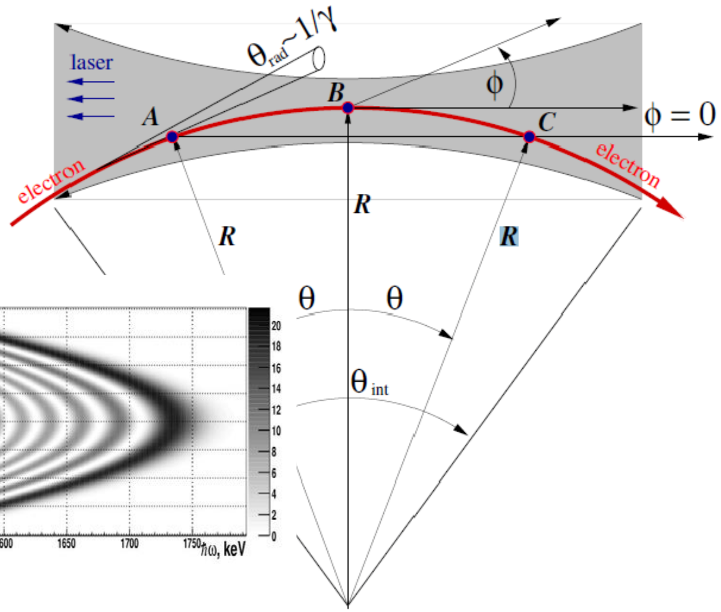
Starting from 2012, beam energy and energy spread are monitored continuously using Compton backscattering system with about 30 keV uncertainty

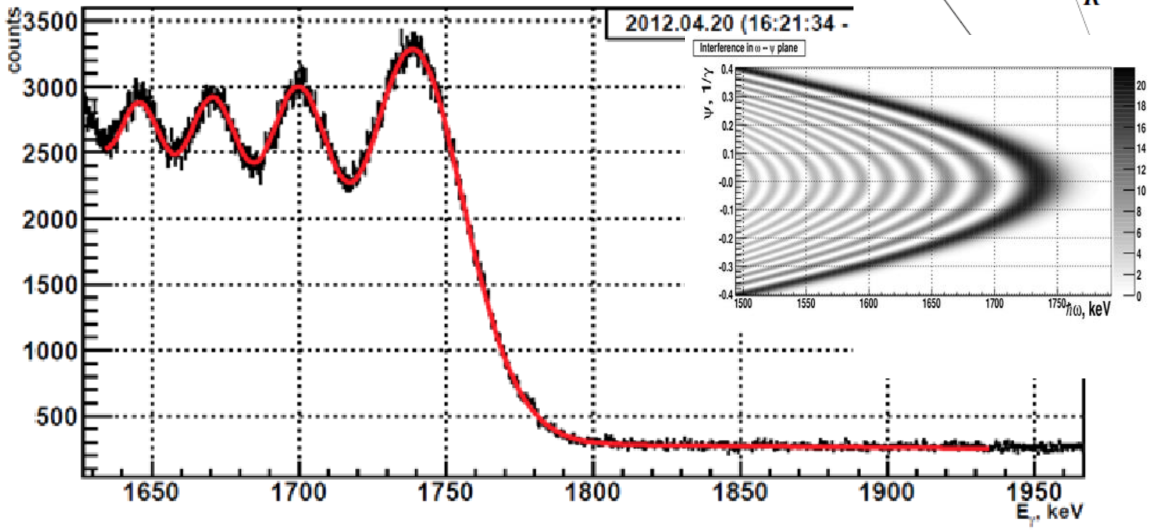


Two sources of photons are used: **ytterbium** and **CO lasers**.

CO (5 nm) at the energy above **500 MeV**,

Nd:YAG (1 nm) at the energy below **500 MeV**.





E = 993.662 ± 0.016 MeV

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