XXIV INTERNATIONAL BALDIN SEMINAR ON HIGH ENERGY PHYSICS PROBLEMS

RELATIVISTIC NUCLEAR PHYSICS & QUANTUM CHROMODYNAMICS

RECENT RESULTS FROM THE CMD-3

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on behalf of CMD-3 collaboration

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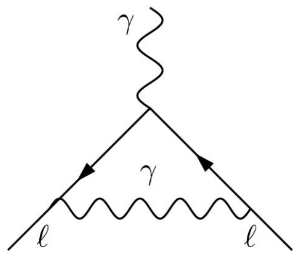
Novosibirsk State University
*THE REAL SCIENCE

(g-2)/2 of muon (theory)

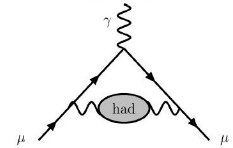
Magnetic moment of Dirac particle:

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

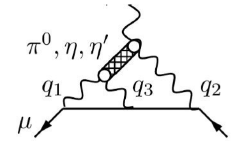
- **Gyromagnetic factor g for**
  - **Point-like fermions: g = 2**
  - **Higher order contributions (QFT): g ≠ 2**
- **Muon anomaly**
  - **$a_\mu = (g-2)_\mu/2$**



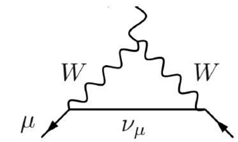
Hadronic Vacuum Polarisation (VP)



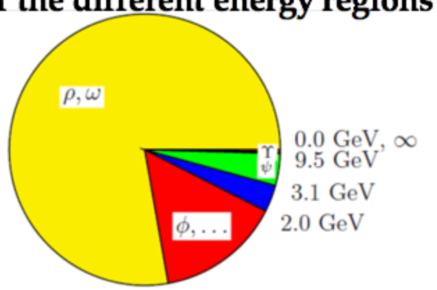
Hadronic light-by-light Scattering



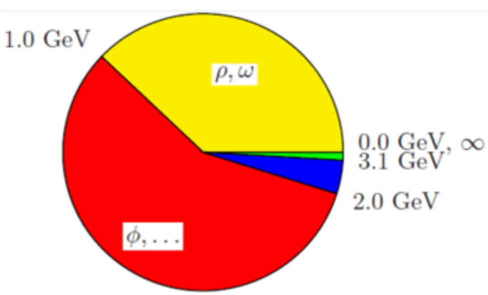
Weak Interactions



Contributions of the different energy regions to:



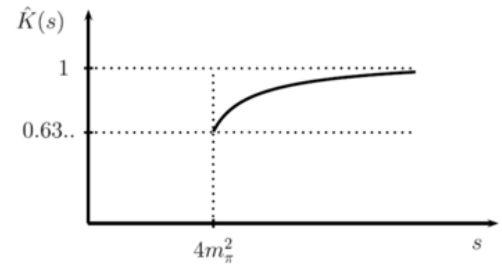
a_μ integral



a_μ uncertainty

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

$$a_\mu^{had} = \frac{\alpha^2}{3\cdot\pi^2}\int_{4m_\pi^2}^{\infty} ds \cdot \frac{K(s)}{s}\cdot R(s)$$



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

$$a_\mu^{\text{theo}} \times 10^{10} = 11\,659\,180.2 \pm 4.9$$

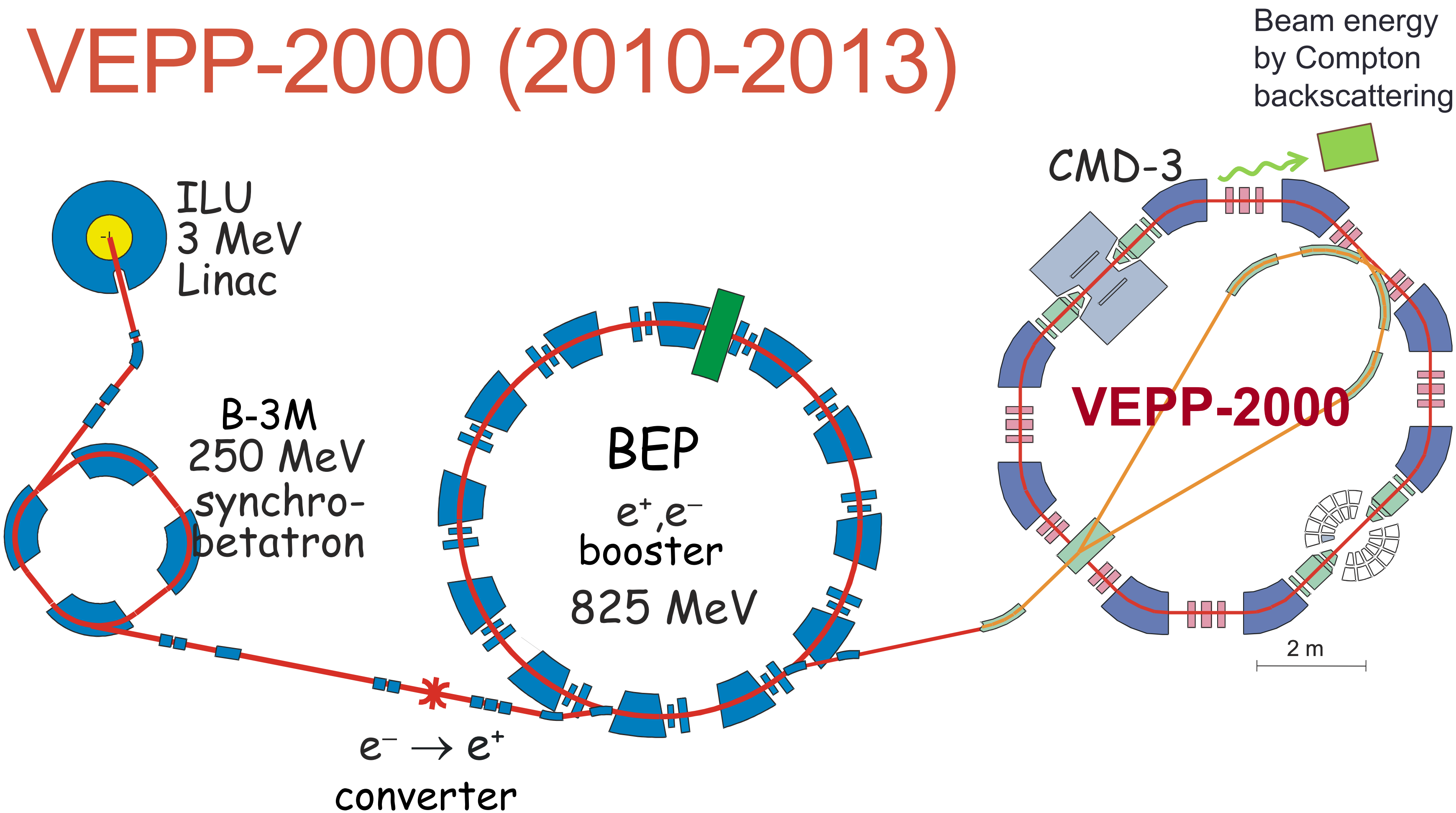
$$a_\mu^{\text{exp}} \times 10^{10} = 11\,659\,208.9 \pm 6.3$$

$$\Delta a_\mu \times 10^{10} = 28.7 \pm 8.0$$

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

(M. Davier et al., EPJC71(2011)1515)

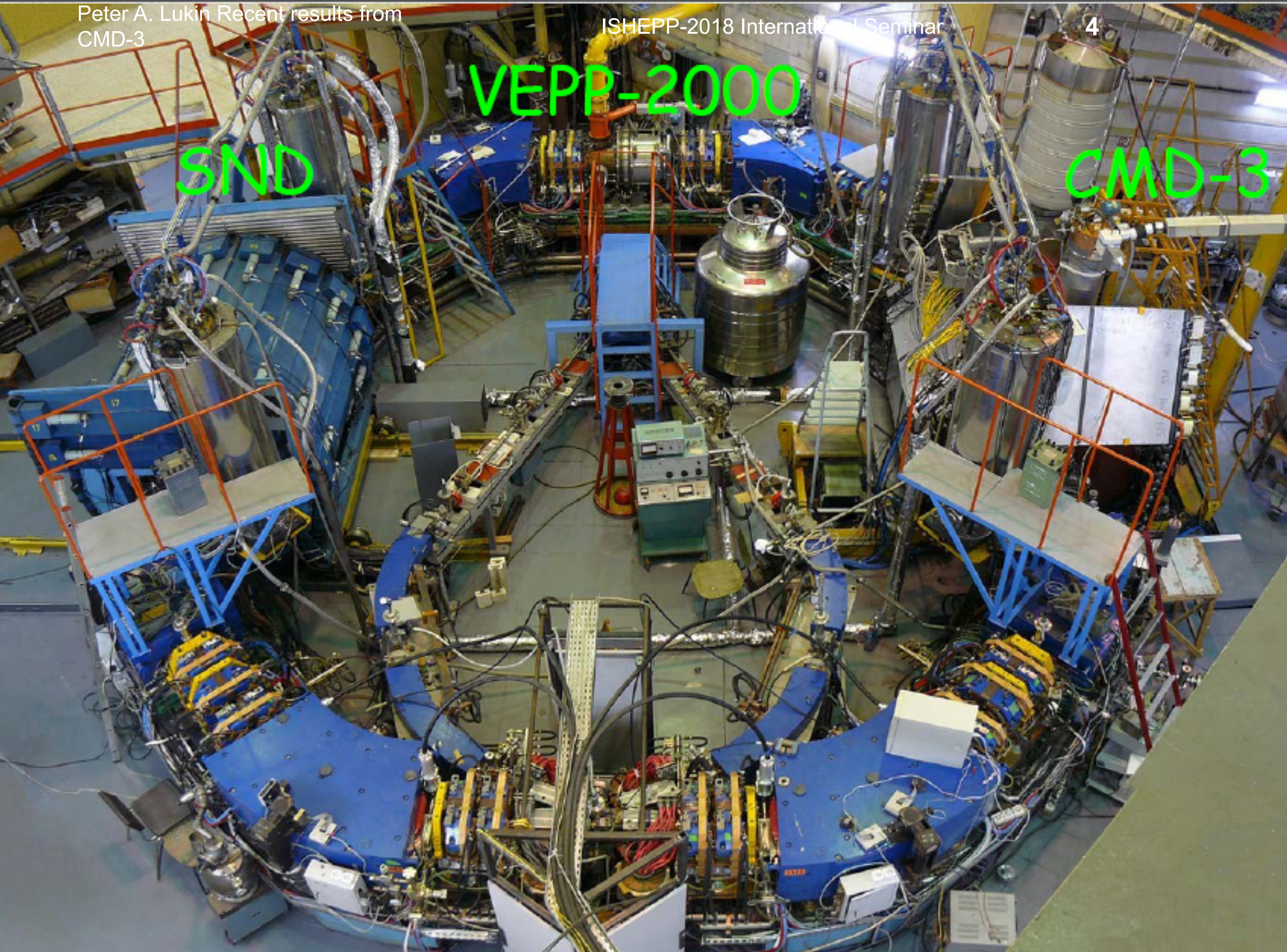
VEPP-2000 (2010-2013)



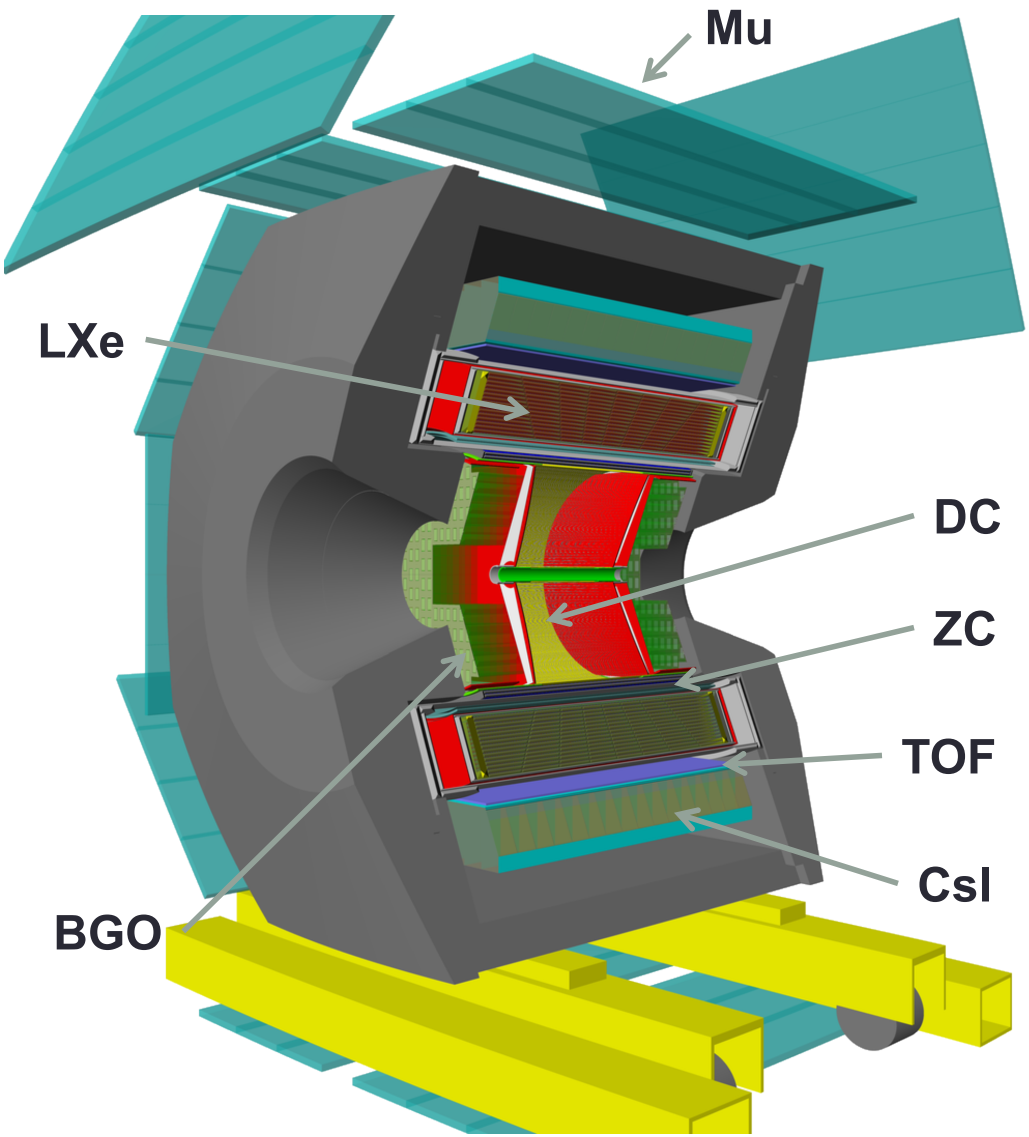
C.m. energy range is 0.32-2.0 GeV; unique optics – “round beams”

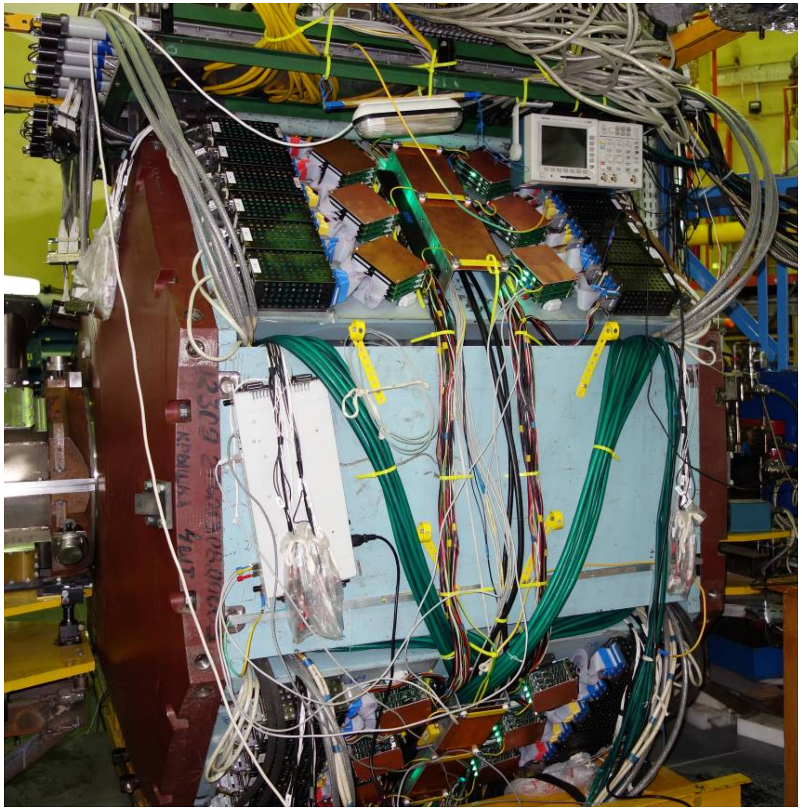
Design luminosity is $L = 10^{32} 1/cm^2 s$ @ $\sqrt{s} = 2$ GeV

Experiments with two detectors, CMD-3 and SND, started by the end of 2010

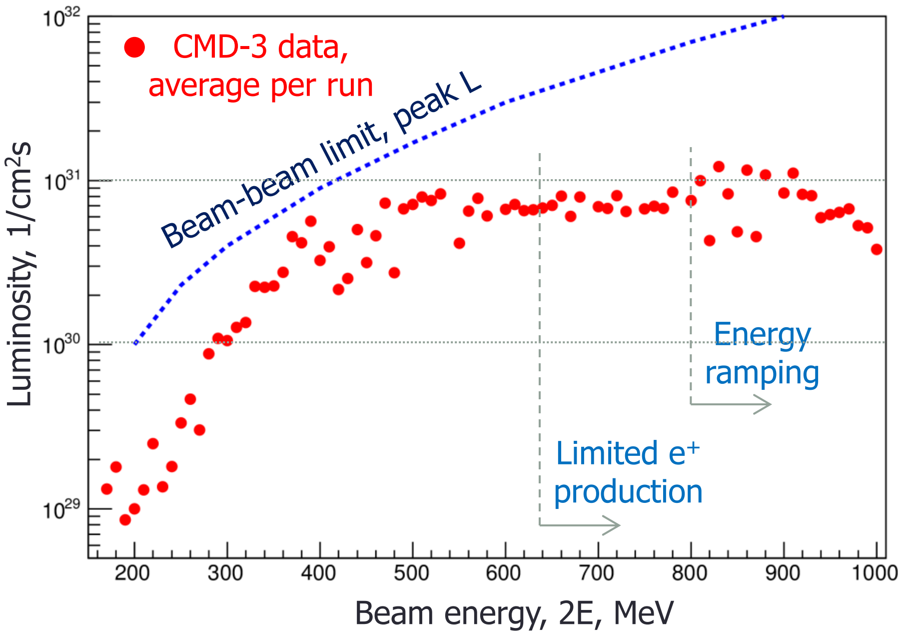

VEPP-2000
SND
CMD-3

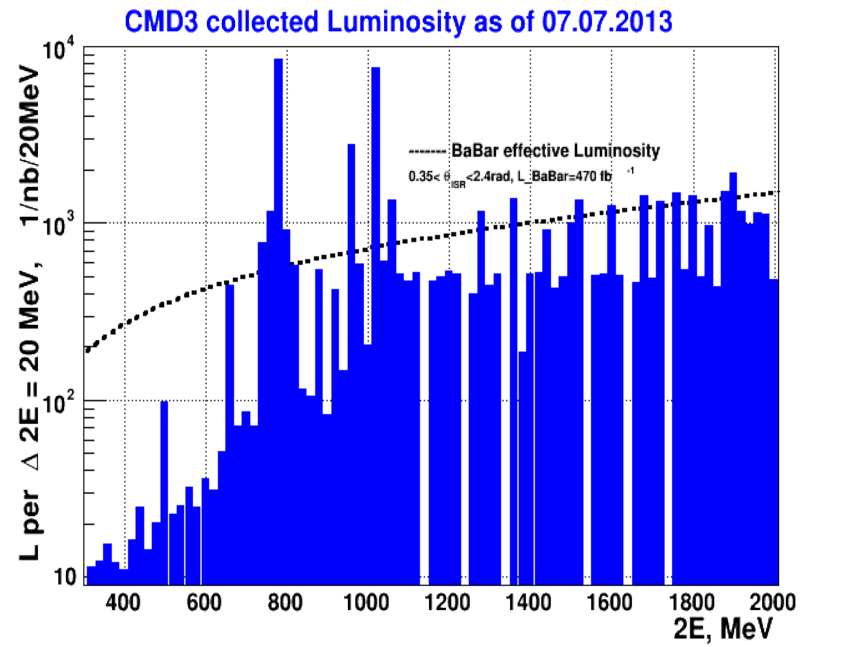
Detector CMD-3





Collected luminosity in 2011-2013





The luminosity was limited by a deficit of positrons and limited energy of the booster.

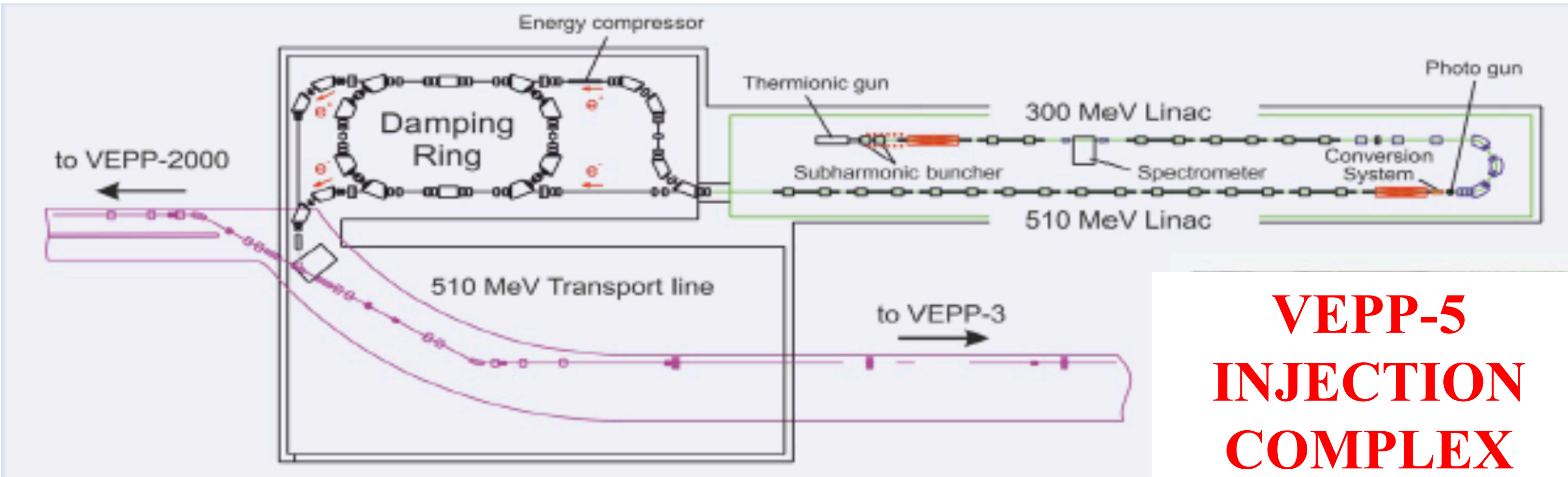
In 2013 we reached 2 × 160 MeV, the smallest energy ever measured at ee colliders

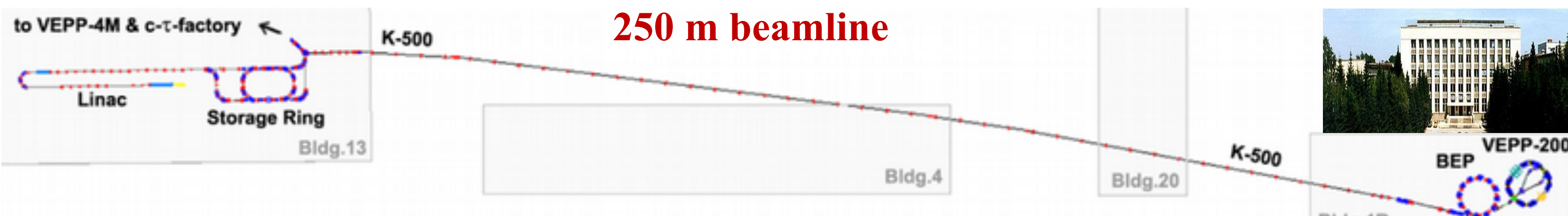
The VEPP-2000 upgrade has started in 2013.

About 60 pb-1 collected per detector

$\omega(782)$	$8.3\ 1/pb$
$2E < 1$ GeV (except ω)	$9.4\ 1/pb$
$\varphi(1019)$	$8.4\ 1/pb$
$2E > 1.04$ GeV	$34.5\ 1/pb$

VEPP-2000 upgrade (2013-2016)





New injection complex

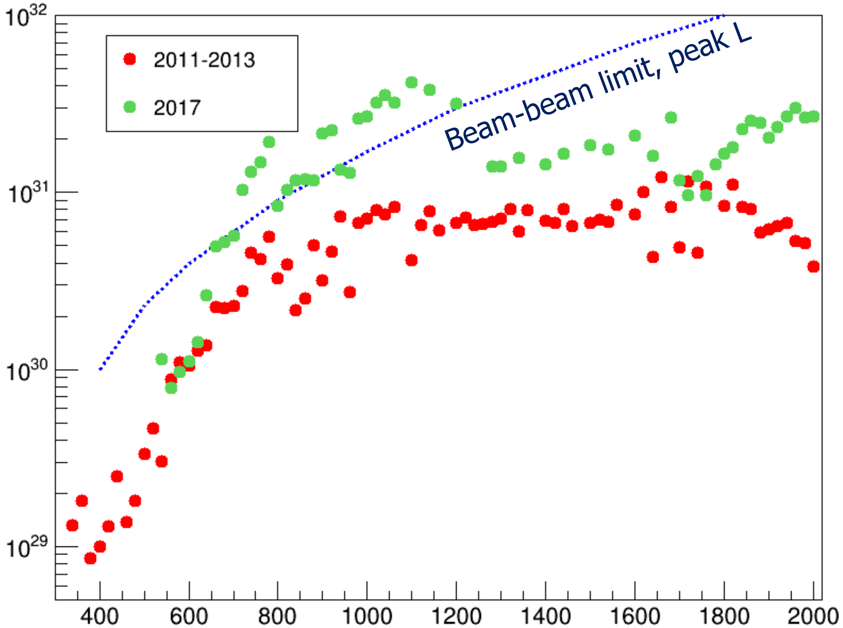
Collider upgrades:
- x10 more intense positron source
- booster up to 1 GeV (match VEPP-2000)

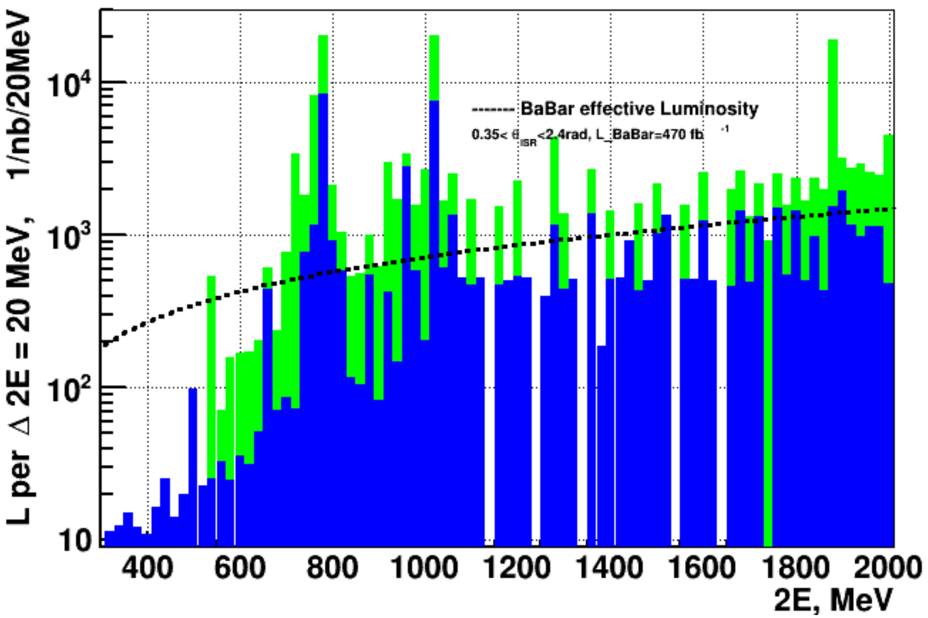
CMD-3 upgrades:
- New electronics for LXe calorimeter
- New TOF system
- DAQ and electronics upgrades

Detectors resumed data taking by the end of 2016

2017 data taking

2017-2018
2011-2013





In 2017: big improvement in luminosity

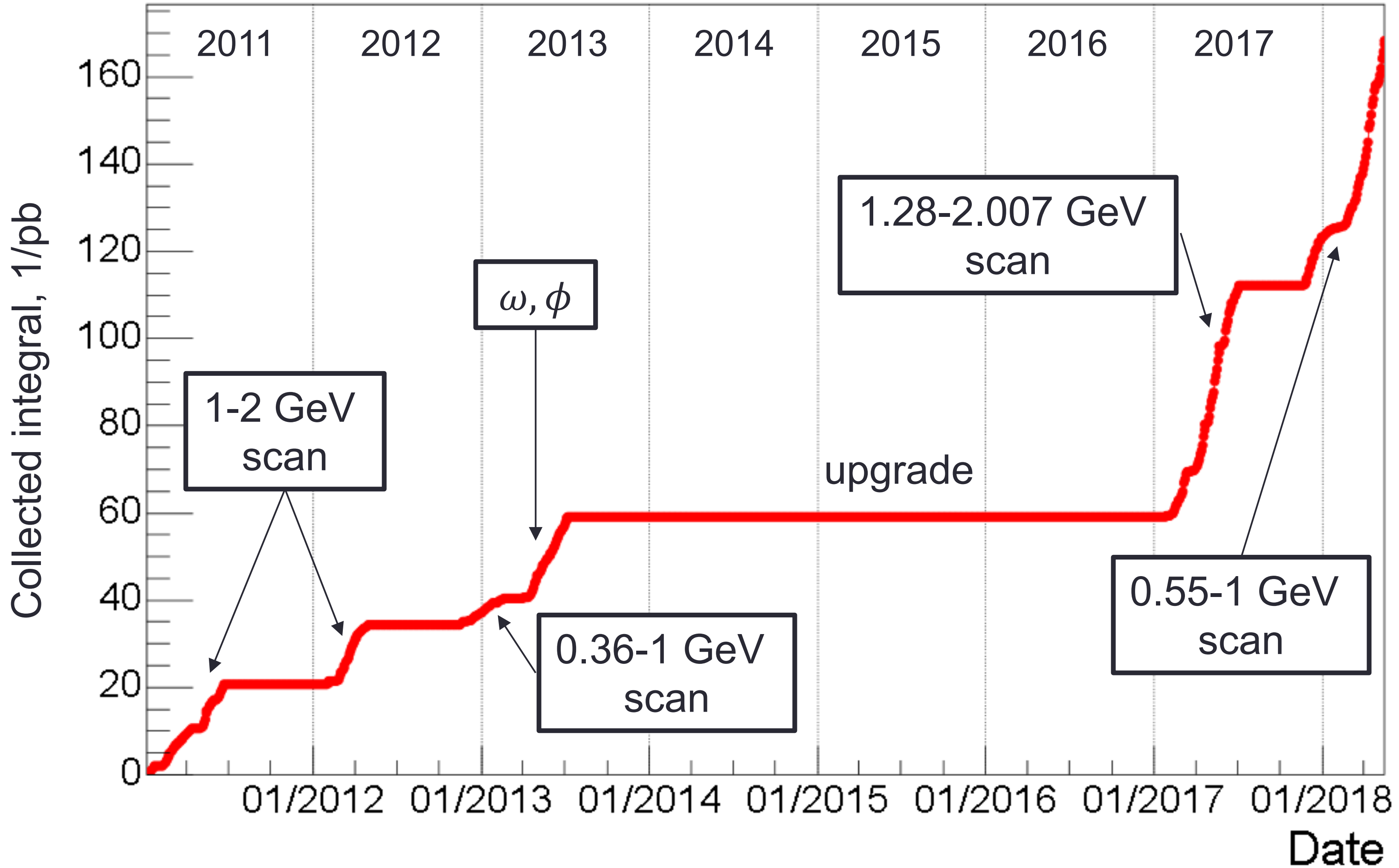
Below 1 GeV: >50 pb^{-1} collected and counting

$0.55 - 1.00$ GeV	$> 50\ 1/pb$

Above 1 GeV: ~50 pb^{-1} collected

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

Overview of CMD-3 data taking runs



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

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

published
in progress

- 2 charged

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

- 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

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

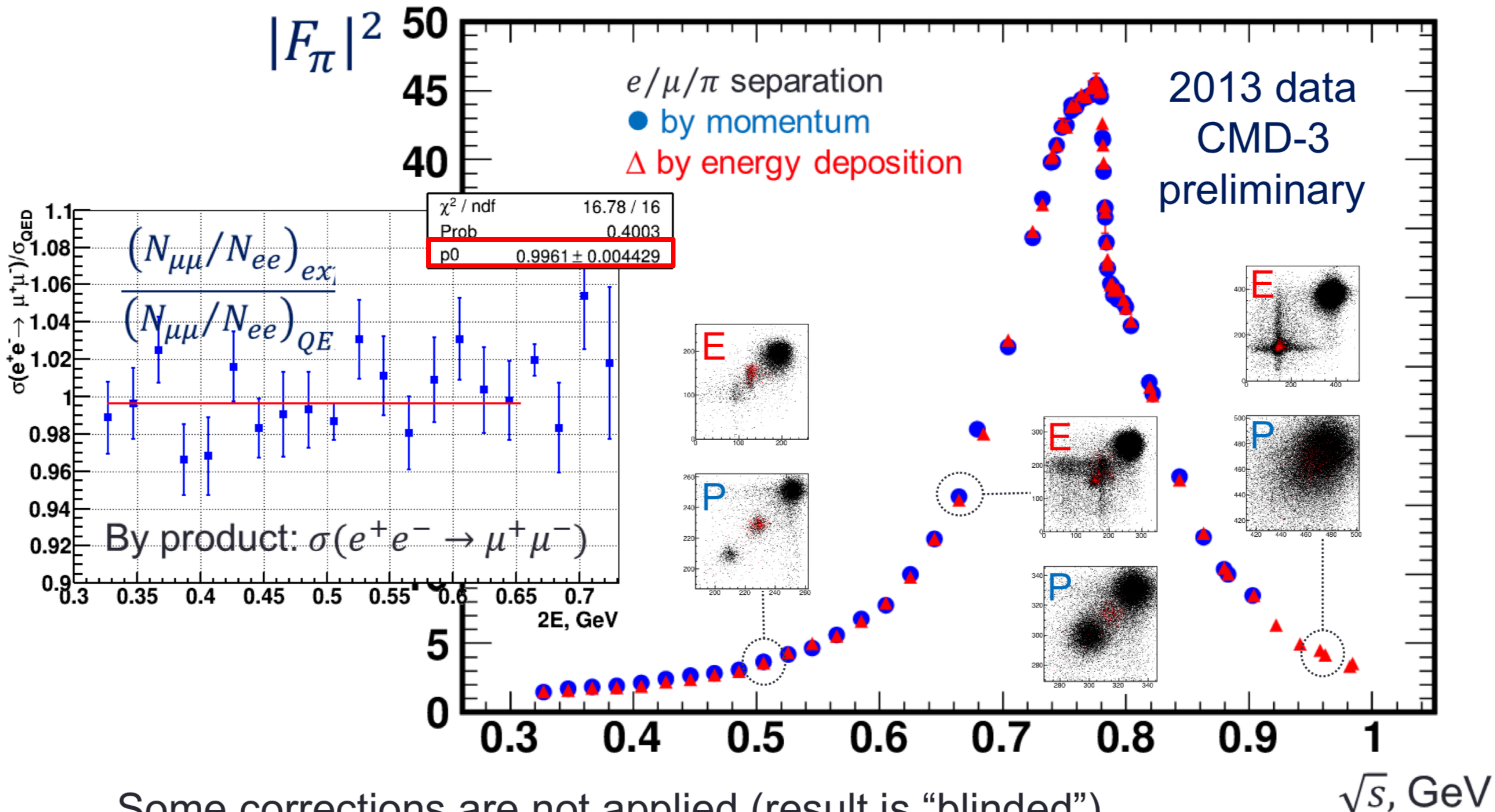
- γ's only

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

- other

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

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

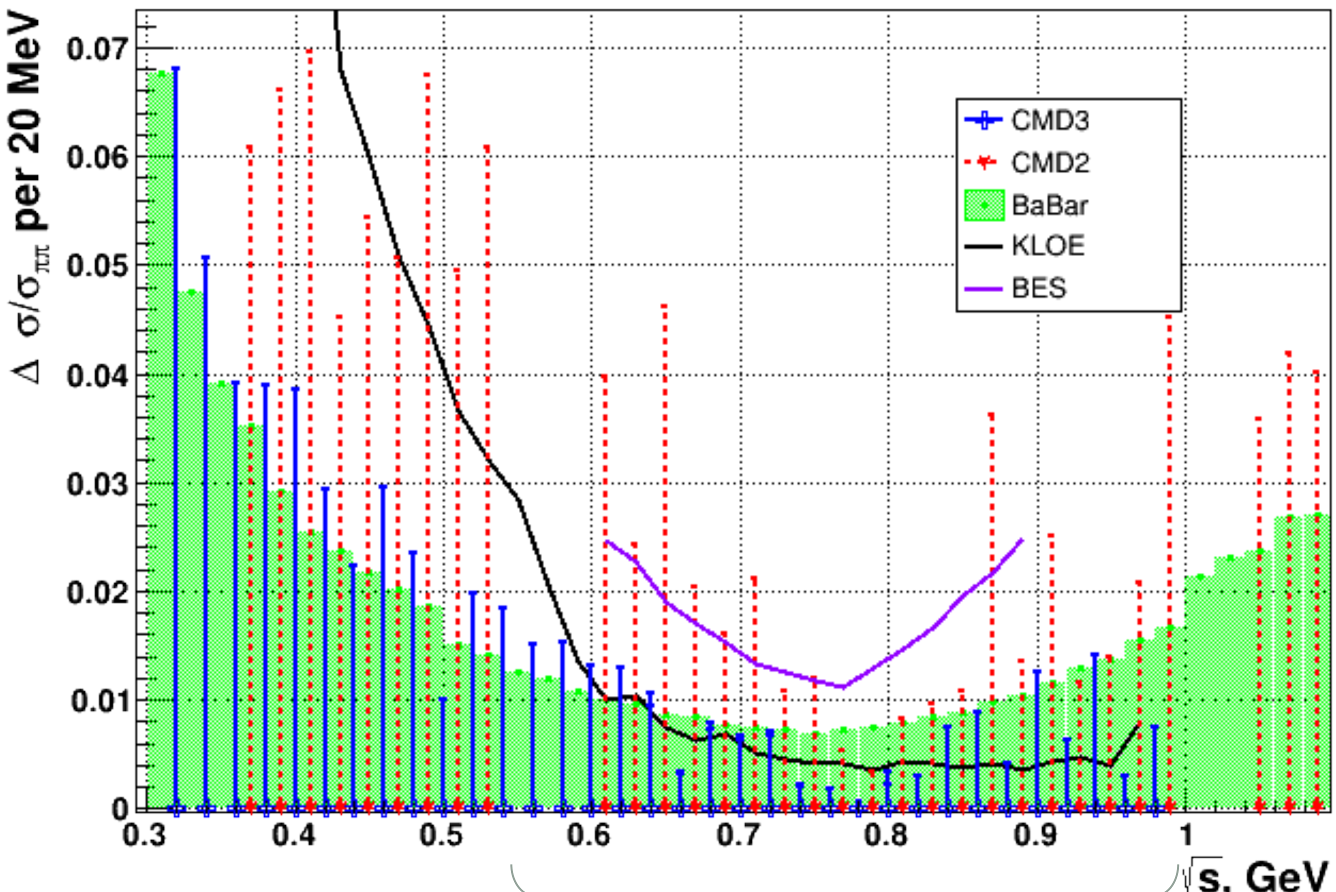


Some corrections are not applied (result is "blinded")

"Open box", when systematics of both methods < 1%
Our goal is to have systematic error at the level ~ 0.33%

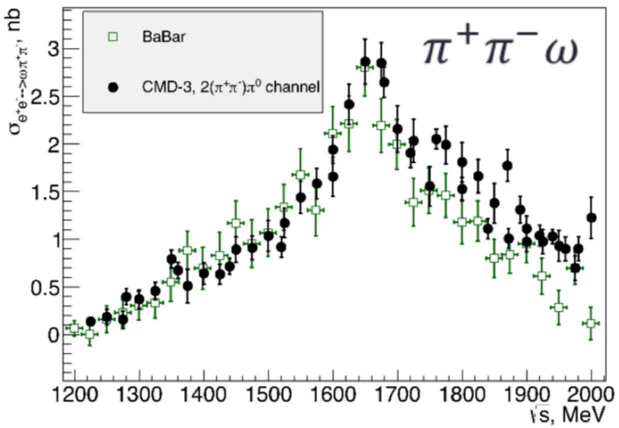
Dominant Channel: $e^+e^- \to \pi^+\pi^-$. Statistics

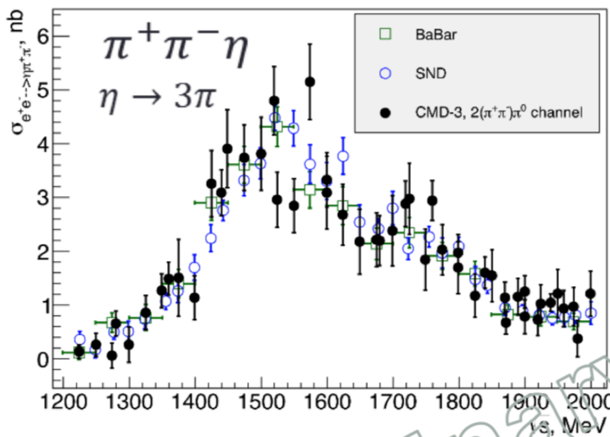
Statistical accuracy $\Delta\sigma/\sigma$ in 20 MeV bins

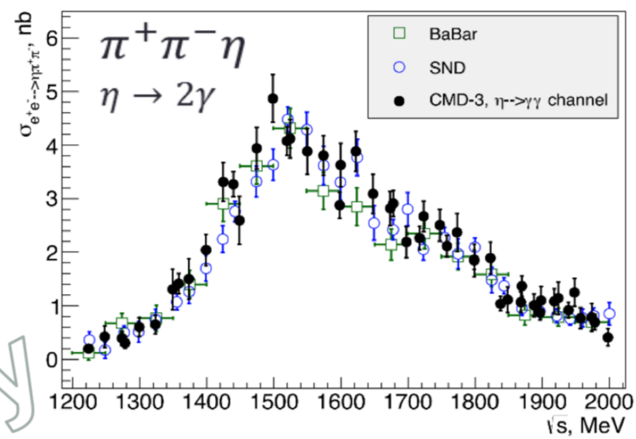


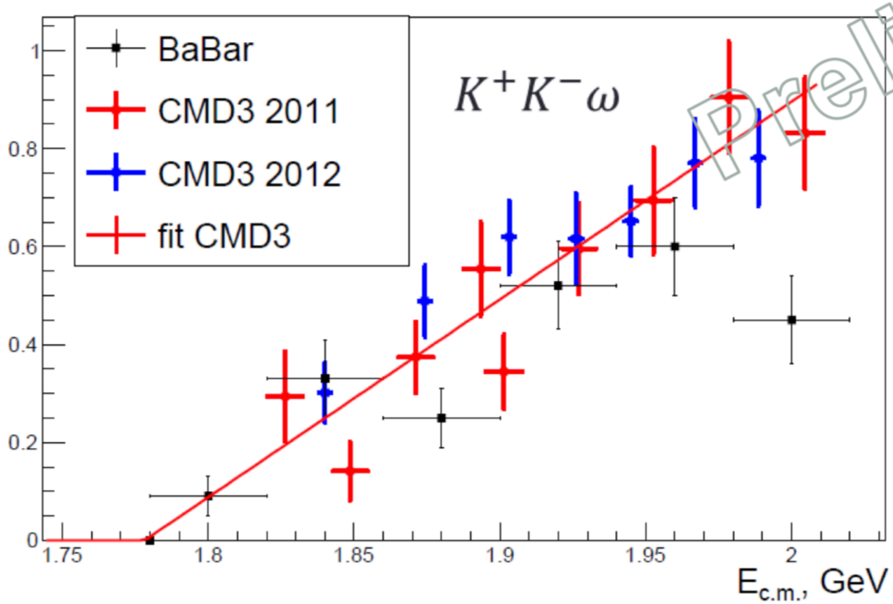
Already collected x2-3 data in 2017-2018

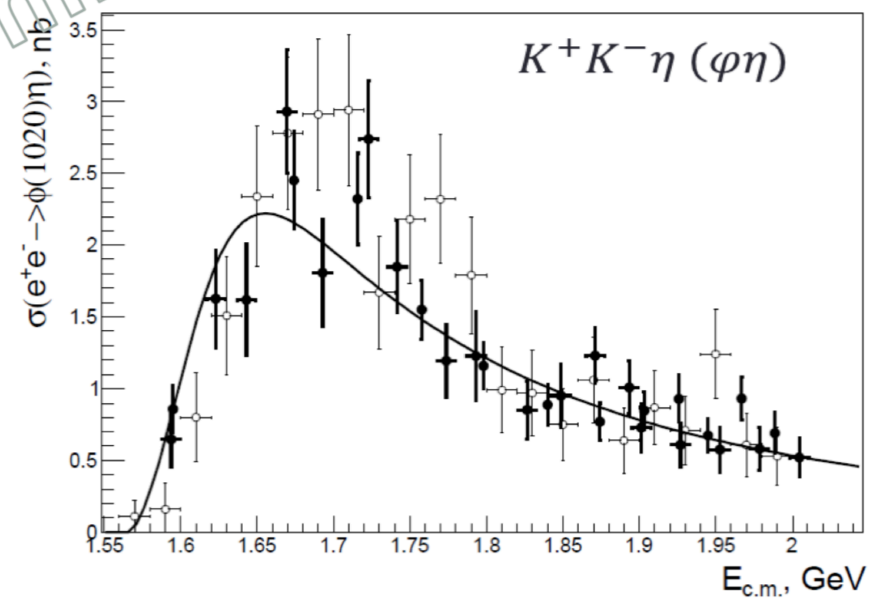
CMD-3 preliminary results from 2011-2013







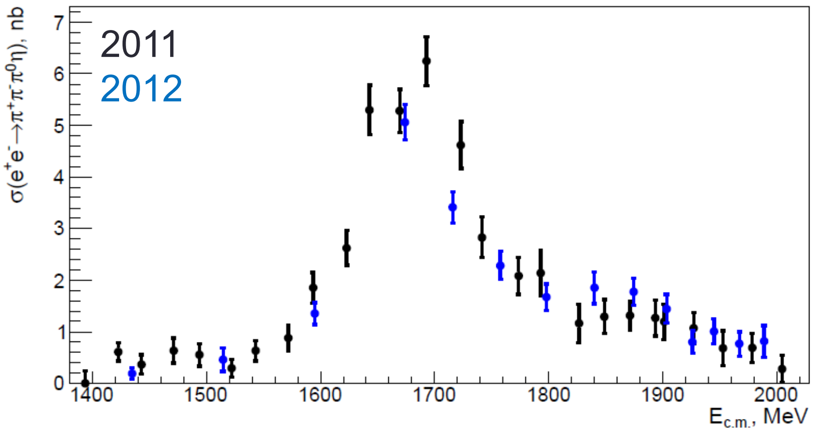


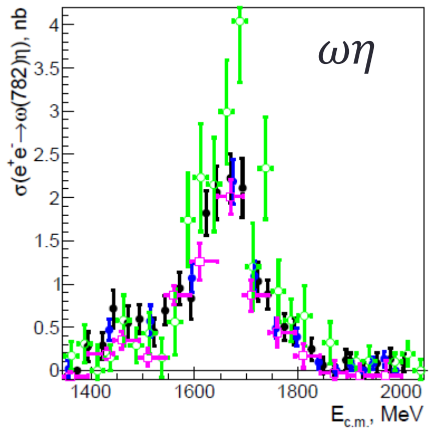


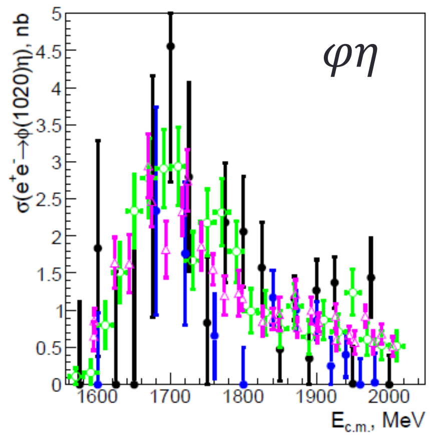
$e^+e^- \to \pi^+\pi^-\pi^0\eta$

First measurement of total $e^+e^- \to \pi^+\pi^-\pi^0\eta$ cross section. Systematic error is 15%.

Phys.Lett. B773 (2017) 150-158



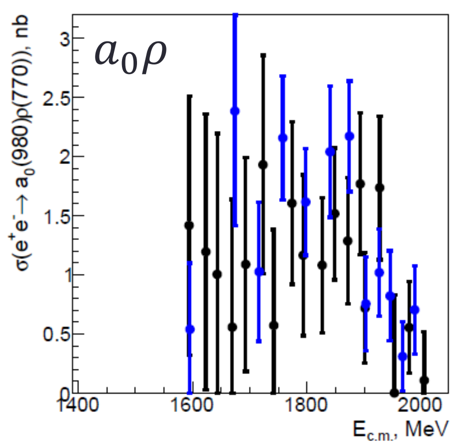


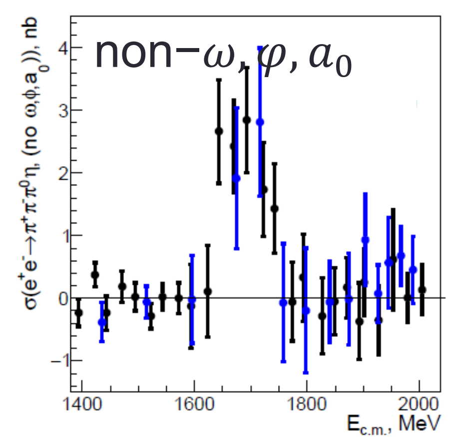


At "low" energies dominated by $e^+e^- \to \omega\eta, \varphi\eta$

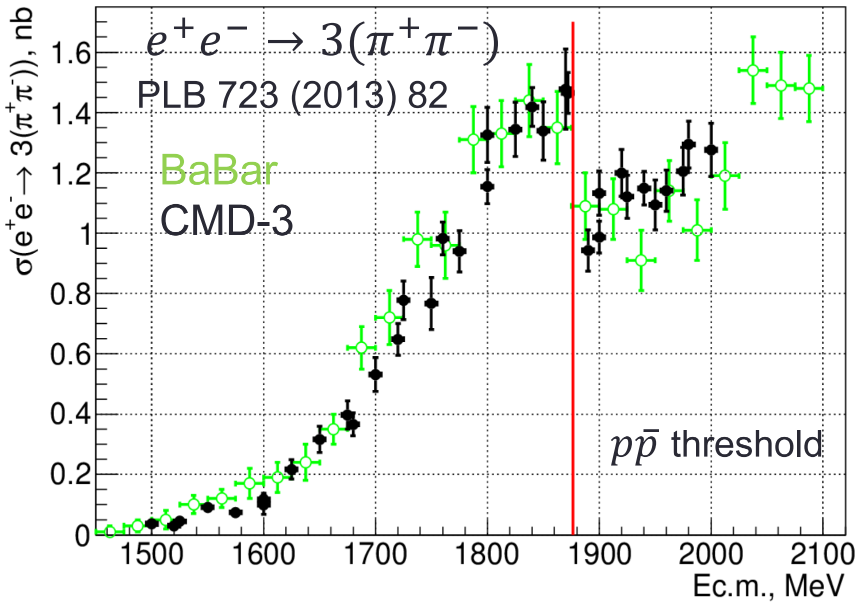
At "high" energies dominated by $e^+e^- \to a_0(980)\rho$

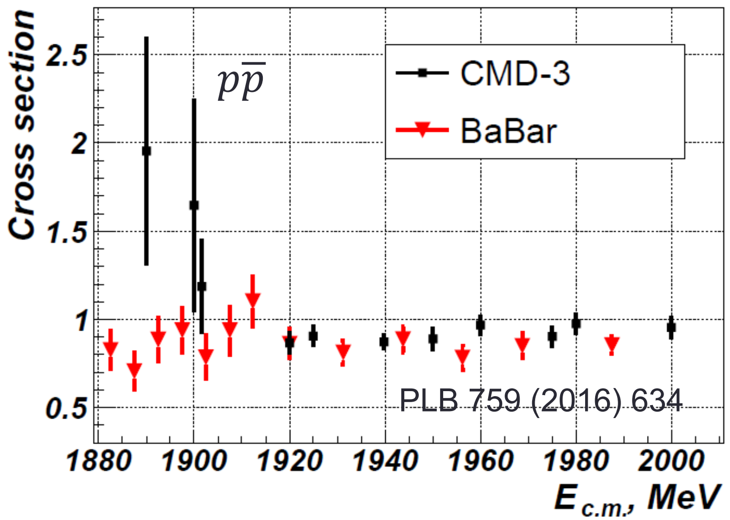
We see non-ω, φ, a_0 contribution
Possible mechanism:
$e^+e^- \to \omega(1650) \to \rho(1450,1700)\pi \to \rho(770)\eta\pi$





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





One of first results from CMD-3:

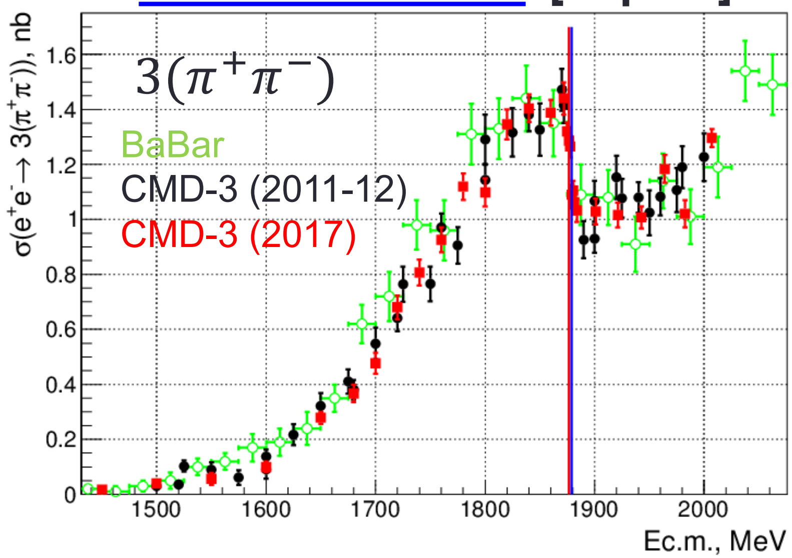
- Sudden drop of $e^+e^- \to 3(\pi^+\pi^-)$ cross section at $N\bar{N}$ threshold
- Confirmed, that $p\bar{p}$ production cross section increases quickly at threshold
- Preliminary studies of dynamics of $e^+e^- \to 3(\pi^+\pi^-)$, hint of energy dependent dynamics in 1.7-1.9 GeV energy range

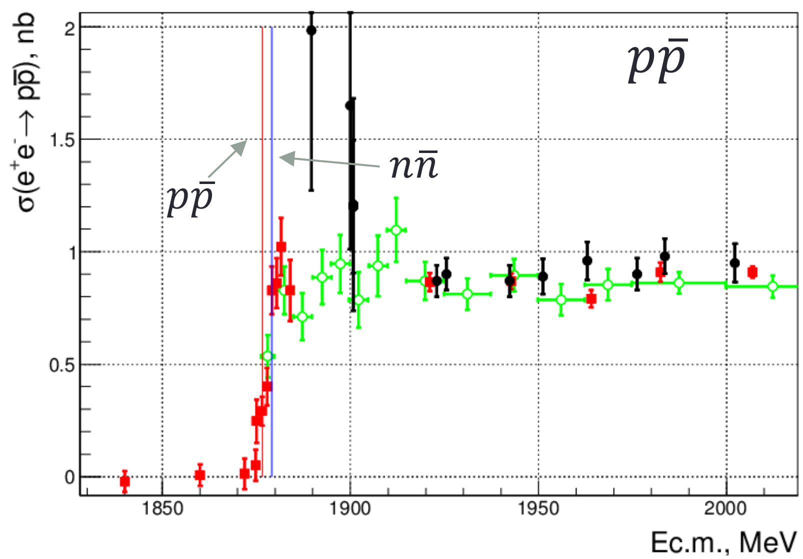
2017: $e^+e^- \to 3(\pi^+\pi^-)$ at $N\bar{N}$ threshold

In 2017, CMD-3 collected 13 1/pb in the narrow energy range around $N\bar{N}$ threshold

- the sharp rise of $e^+e^- \to p\bar{p}$ cross-section is confirmed
- the sharp drop of $e^+e^- \to 3(\pi^+\pi^-)$ cross-section is confirmed
- we see the similar cross-section drop in other channels

arXiv:1808.00145 [hep-ex]





$N\bar{N}$ threshold in $2(\pi^+\pi^-)$ reaction

arXiv:1808.00145 [hep-ex]

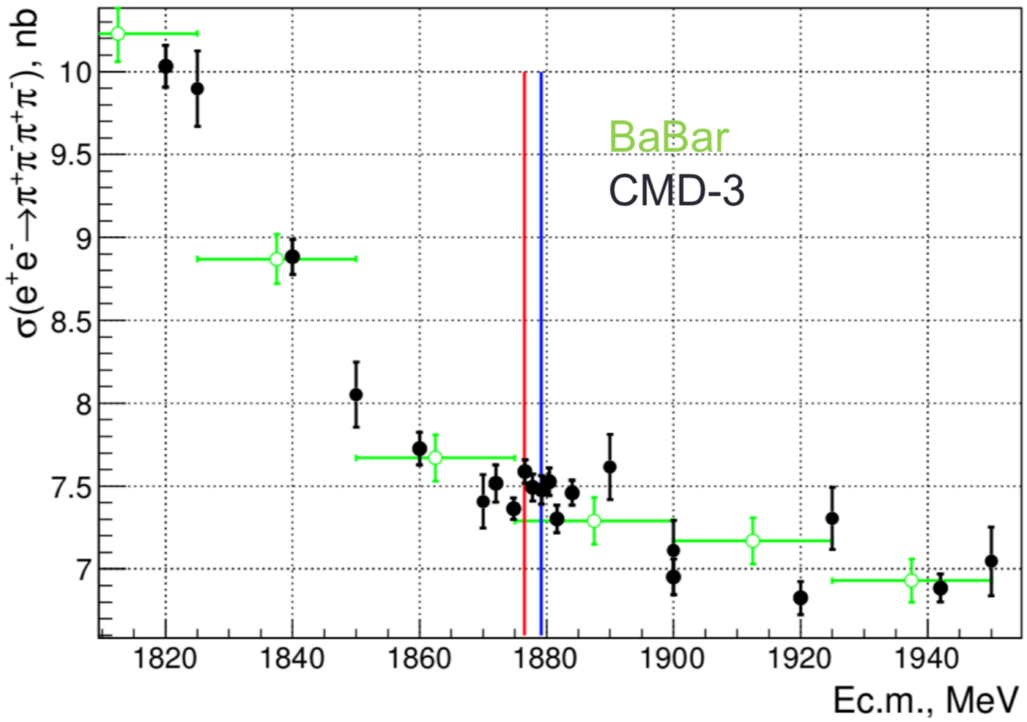


Figure 4: The $e^+e^- \to 2(\pi^+\pi^-)$ cross section measured with the CMD-3 detector. Lines show the $p\bar{p}$ and $n\bar{n}$ thresholds.

We continue search for the NNbar threshold indication in other multi-hadron reactions

Conclusion

- The goal of the CMD-3 experiment at the VEPP-2000 is to provide exclusive measurement of $e^+e^- \to hadrons$ from 0.32 to 2.0 GeV
- In 2011-2013 CMD-3 has collected 60 pb^{-1} in the whole energy range $0.32 \leq \sqrt{s} \leq 2.0$ GeV, available at VEPP-2000.
- In 2013-2016 the collider and the CMD-3 detector have been upgraded and the data taking was resumed in 2017 and > 100 pb^{-1} were collected so far.
- Data analysis of exclusive modes of $e^+e^- \to hadrons$ is in progress. Many results have been published.

Thank You for Your attention!

Stay tuned!

Backup slides

$\sigma(e^+e^- \to hadrons)$ and the hadronic contribution to a_μ

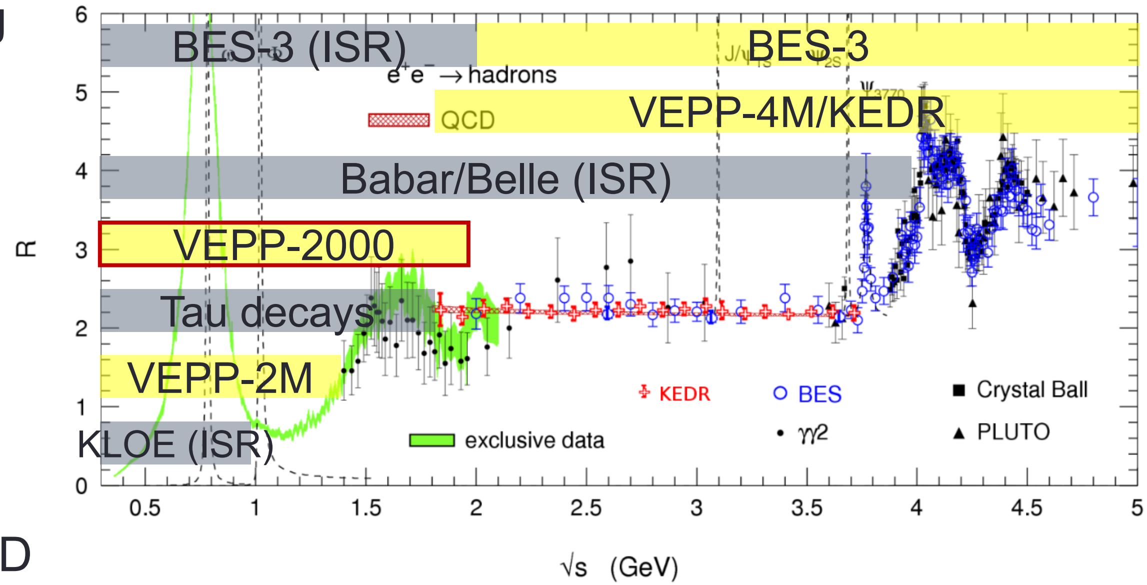
$$R(s) = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

So far, the hadronic contribution to a_μ is calculated by integrating experimental cross-section $\sigma(e^+e^- \to hadrons)$.

Weighting function $\sim 1/s$, therefore lower energies contribute the most.

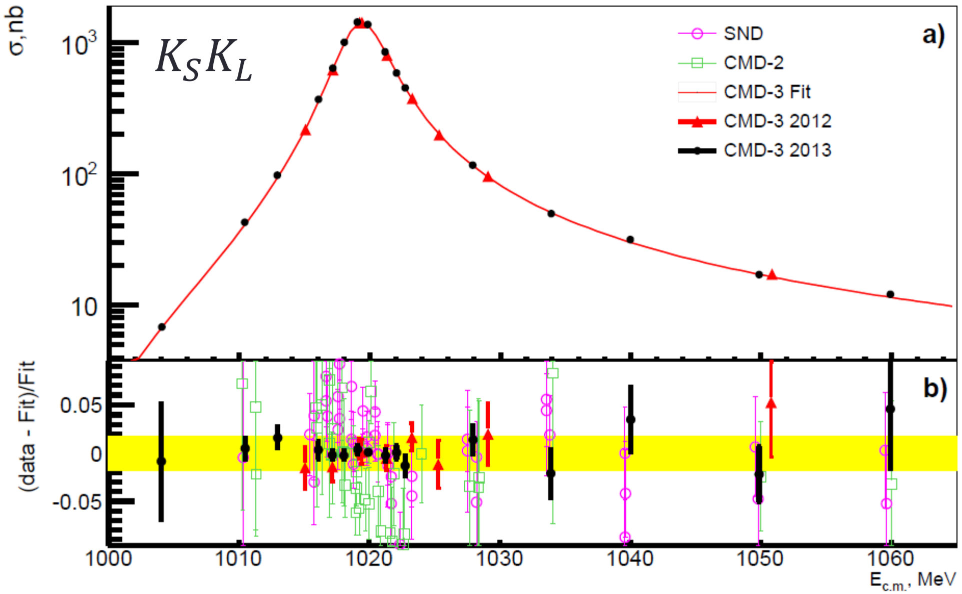
Many sources of data:

- Novosibirsk: CMD-2 and SND (VEPP-2M), CMD-3 and SND (VEPP-2000)
- Factories: Babar, KLOE
- BES-III, KEDR

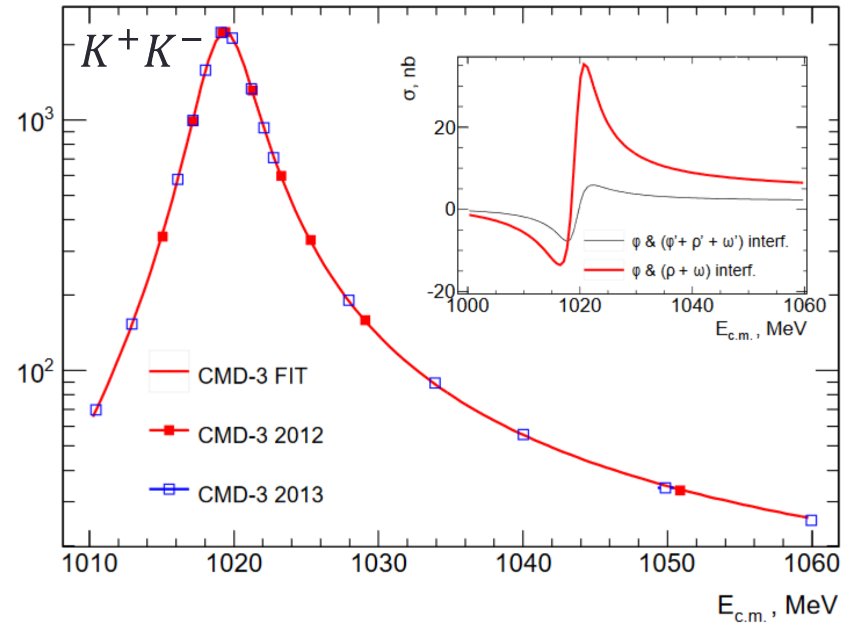


$K_S K_L$ and K^+K^- @$\varphi(1020)$

Phys.Lett. B760 (2016) 314-319



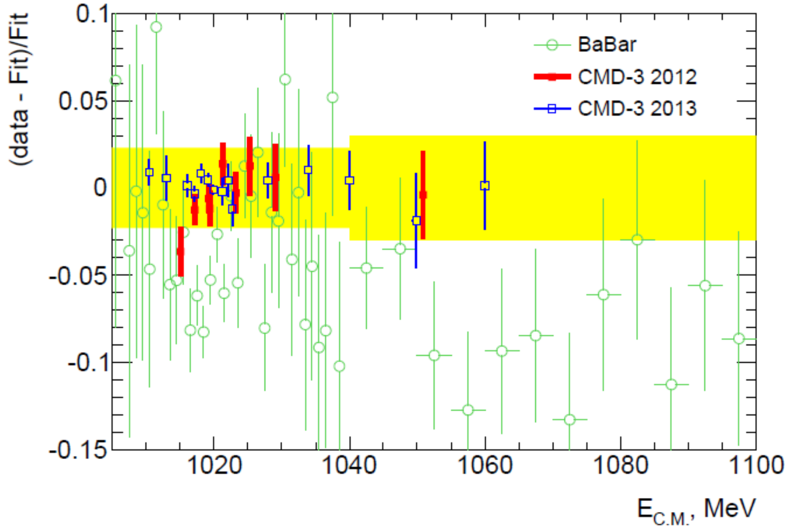
Phys.Lett. B779 (2018) 64-71

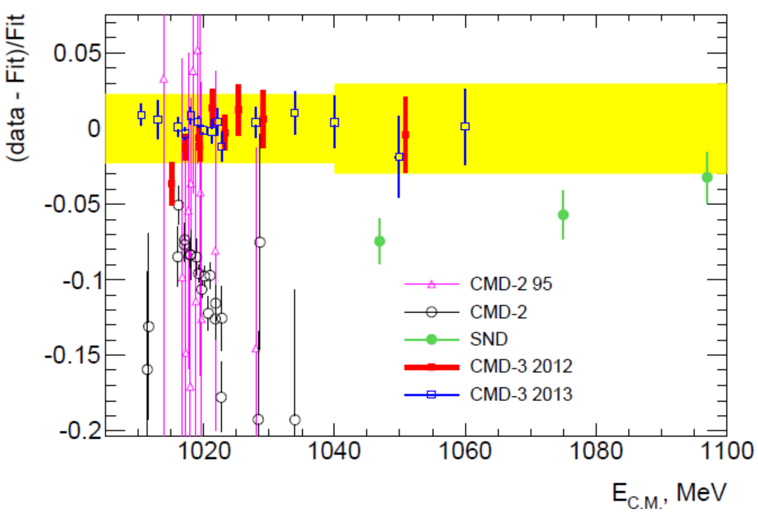


Recent result from CMD-3:

- $K_S K_L$ at φ, systematic precision 1.8%
- K^+K^- at φ, systematic precision 2.0% (2.8%)

K^+K^-: comparison with other measurements





K_SK_L at φ is consistent between different experiments, but there is discrepancy in K^+K^- channel.

New CMD-3 K^+K^- cross-section is above CMD-2 and BaBar, but is consistent with isospin symmetry:

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

- $R_{SND} = 0.92 \pm 0.03(2.6\sigma)$
- $R_{CMD-2} = 0.943 \pm 0.013(4.4\sigma)$
- $R_{BaBar} = 0.972 \pm 0.017(1.5\sigma)$

Possible explanation: CMD-2 trigger correction was underestimated; due to different trigger configuration there is no such correction at CMD-3

$K_S K_L$ and K^+K^-: $\rho - \varphi$ interference

$\rho - \varphi$ interference can be directly observed:

$$R_{c/n} = \sigma(e^+e^- \to K^+K^-)\times\frac{p^3_{K^0}(s)}{p^3_{K^\pm}(s)}\times\frac{1}{Z(s)} - \delta\times\sigma(e^+e^- \to K_S K_L)$$

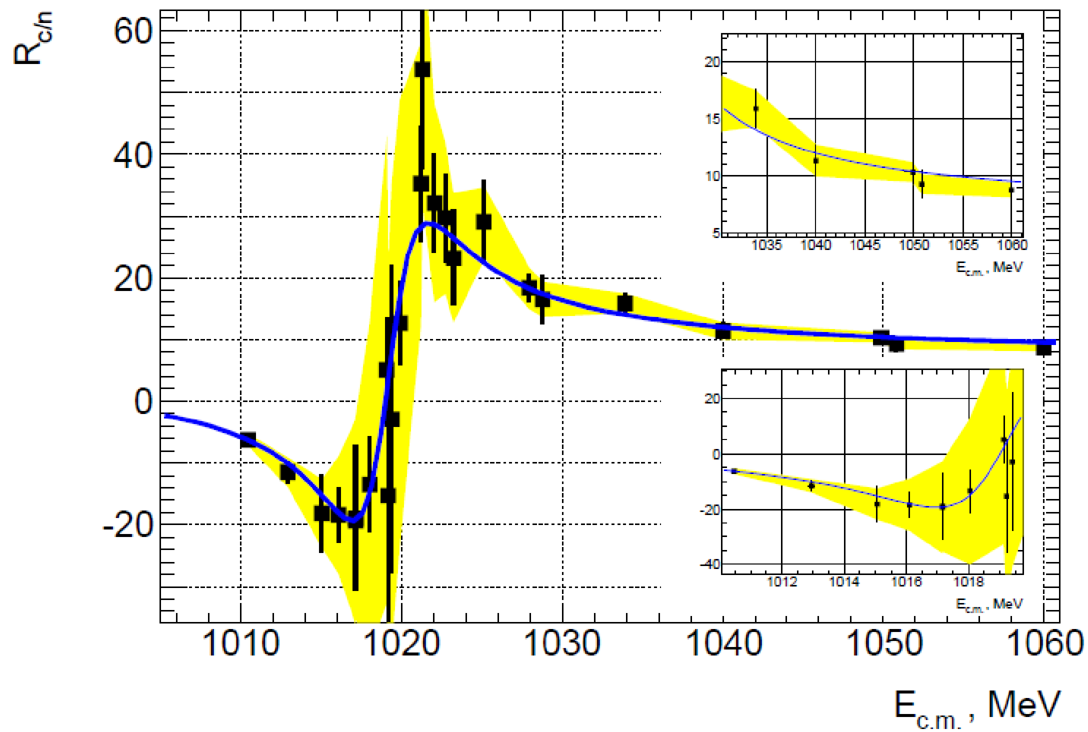
- $r_{\rho,\omega} = 0.91 \pm 0.04$

deviation of SU(3) relations

$$g_{\omega K^+K^-} = g_{\rho K^+K^-} = -g_{\varphi K^+K^-}/\sqrt{2}$$

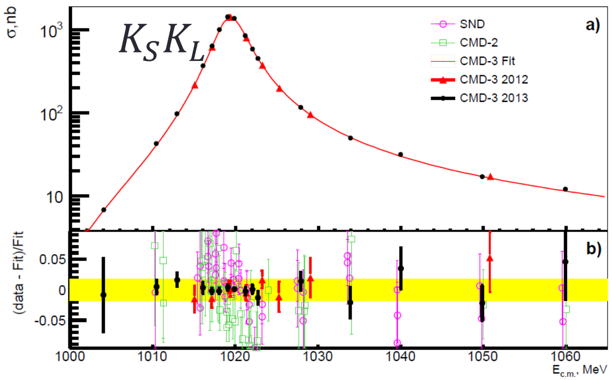
- $\delta = 0.989 \pm 0.003$

test of systematic errors

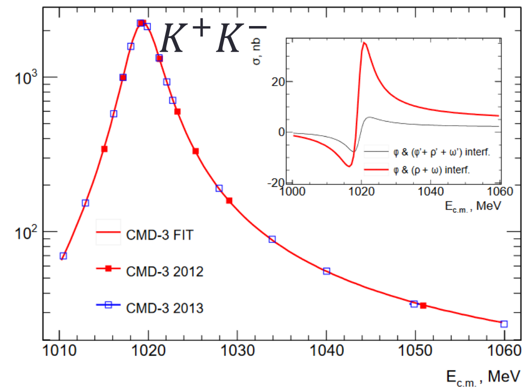


CMD-3 published results from 2011-2013

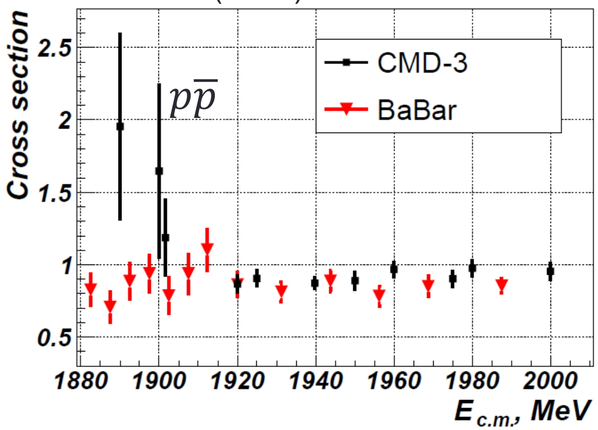
PLB 760 (2016) 314



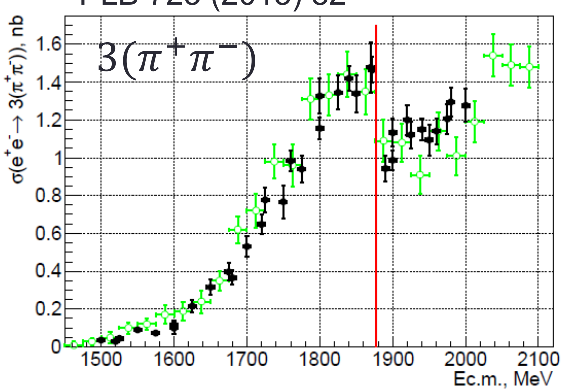
PLB 779 (2018) 64



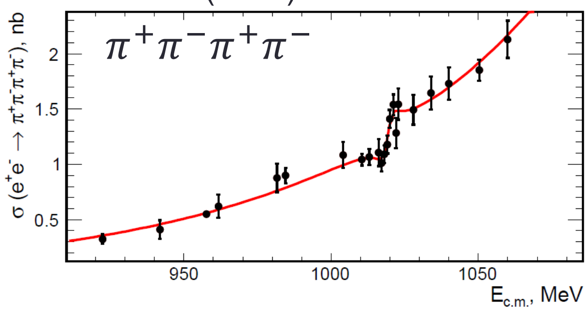
PLB 759 (2016) 634



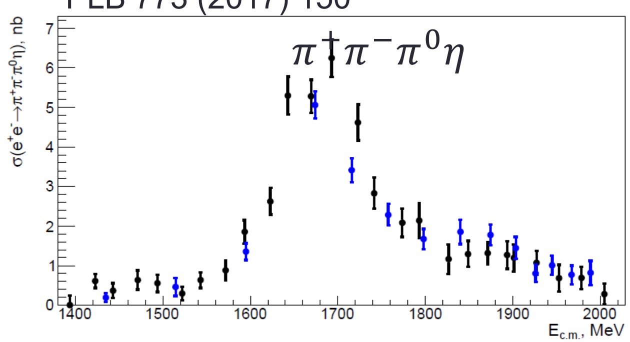
PLB 723 (2013) 82



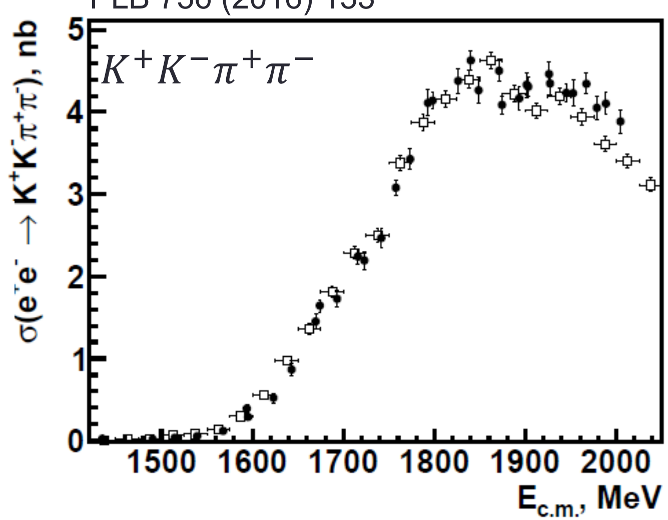
PLB 768 (2017) 345



PLB 773 (2017) 150

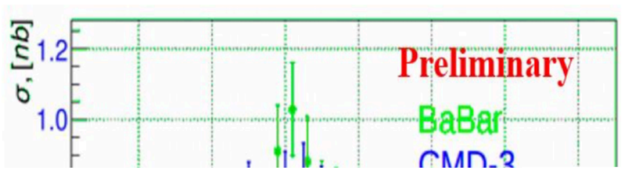


PLB 756 (2016) 153



More CMD-3 preliminary results from 2011-2013

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

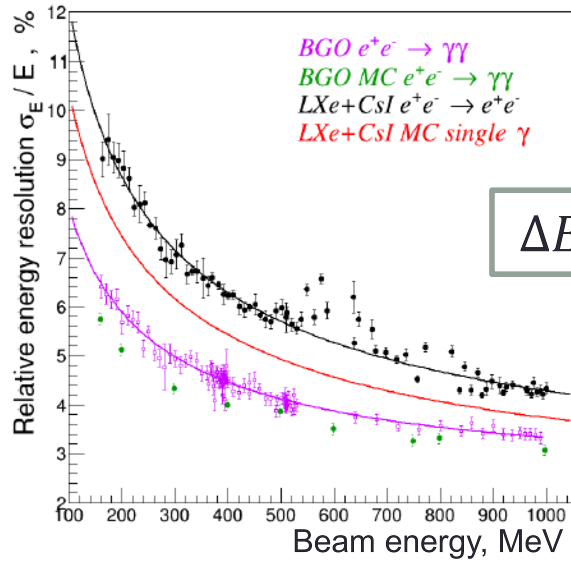


$e^+e^- \to \pi^+\pi^-$: systematics

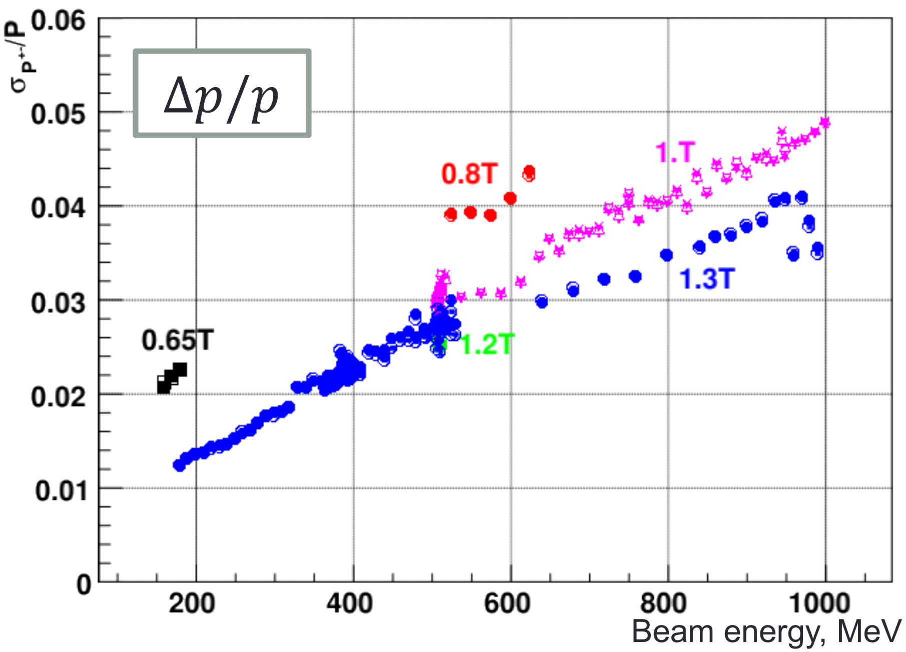
Source	Goal	Current estimation	Comment
Radiative correction	0.2%	0.2% (cross-section) 0.0-0.4% (mom.separation)	To-do: more MCGPJ improvement, comparison to data
Event separation	0.2%	0.1-0.5% (mom.separation) ~1.5% (energy separation)	To-do: improve energy separation
Fiducial volume	0.1%	ok	Two independent subsystems to fix fiducial volume
Beam energy	0.1%	ok	Continuous monitoring via Compton backscattering
Pion corrections (decay, nucl.int.)	0.1%	0.1% - nucl.interations 0.6-0.3% - decays al low energies	To-do: improve reconstruction of decay events
Combined	**0.33%**	**0.4-0.9% (mom.sep.) 1.5% (energy sep.)**	**open box when both <1%**

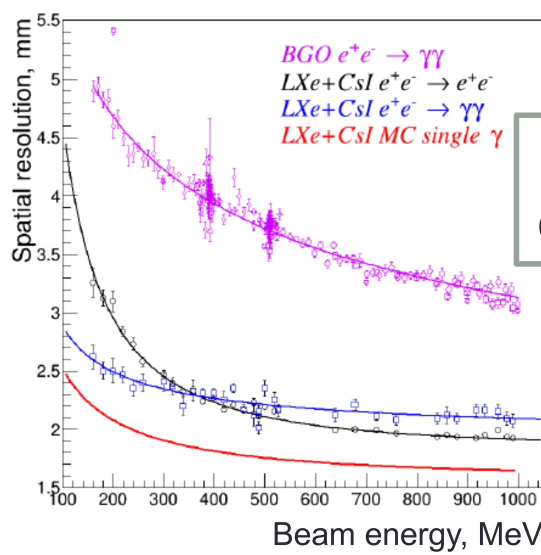
CMD-3 Performance (2011-2013)

- 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



$\Delta E/E$

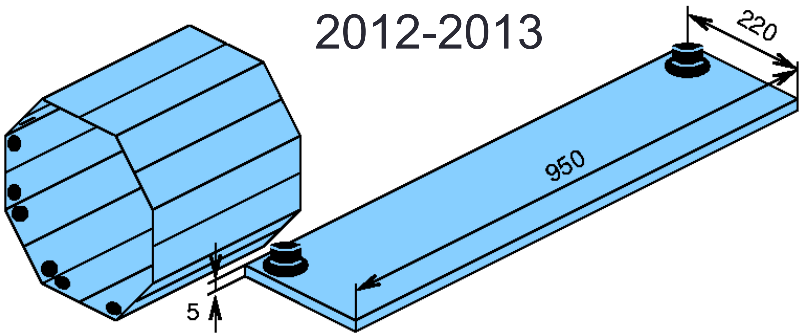




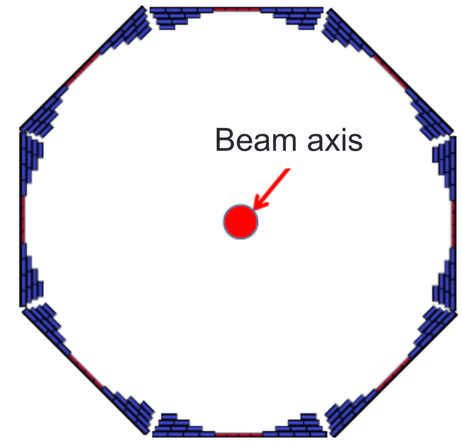
Δx, mm calorimeters

New TOF system

"Old" TOF
2012-2013

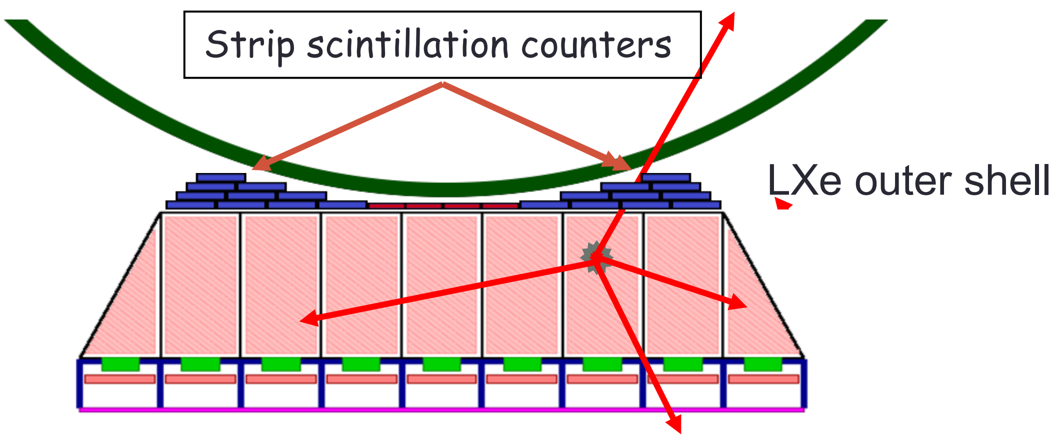


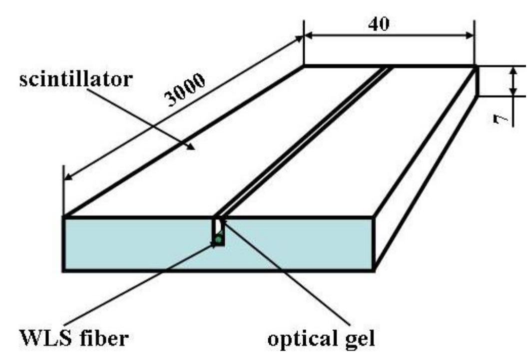
"New" TOF (2017-)



In 2013-2016 the TOF system was completely replaced

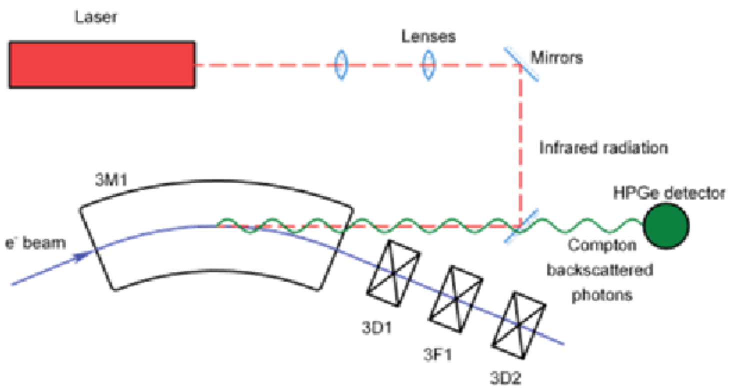
- More granulated (16 counters → 175 counters)
- 0.8 ns resolution per counter

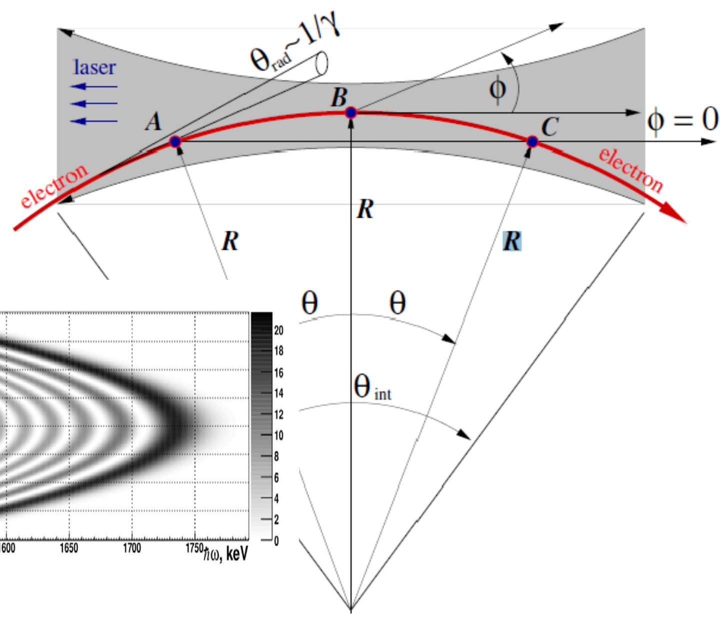


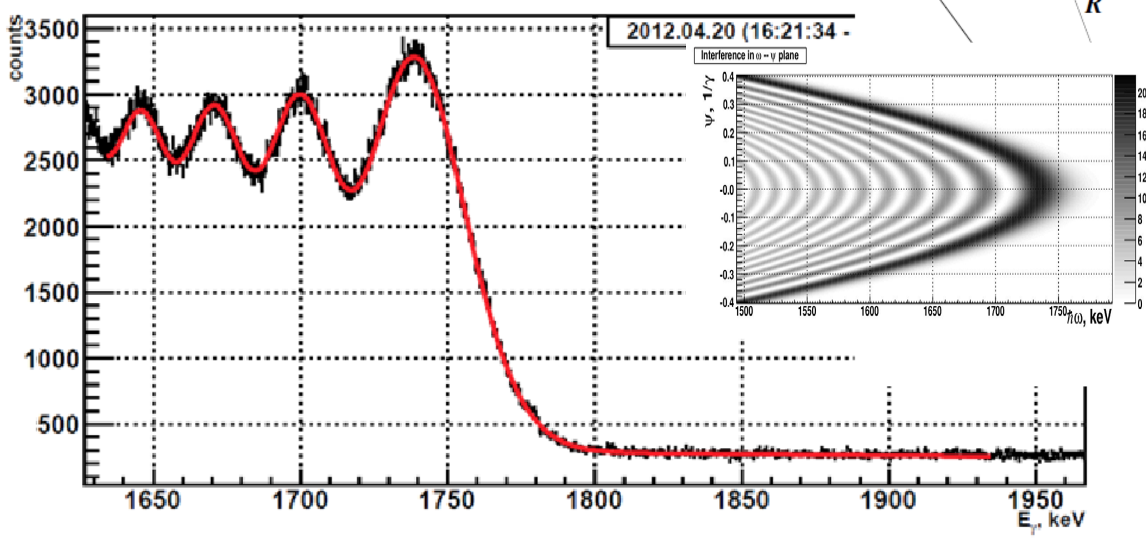


Energy measurement

Starting from 2012, energy is monitored continuously using Compton backscattering





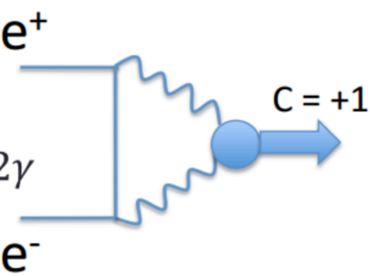


E = 993.662 ± 0.016 MeV

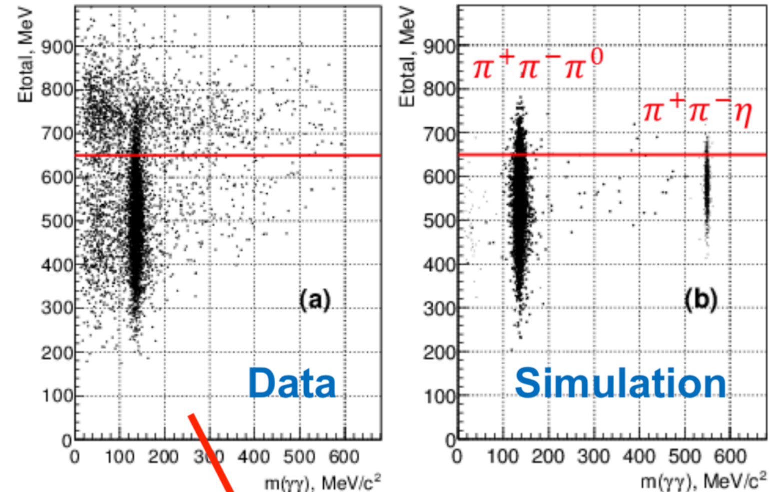
M.N. Achasov et al. arXiv:1211.0103v1 [physics.acc-ph] 1 Nov 2012

Search for e+e- → η'(958)

Phys.Lett. B740 (2015) 273-277



C-even resonances can be produced via 2γ



Theory: assuming real γ

$$B(\eta' \to e^+e^-) = 3.7 \cdot 10^{-11}$$

γ virtuality and transition form factor can enhance it

New limit:

B(η'→e⁺e⁻) < 5.6x10⁻⁹ (90%CL) - SND+CMD-3

Dedicated data taking at $\sqrt{s} = M_{\eta'}$

Continuous beam energy monitoring is crucial