MEASUREMENT OF HADRONIC CROSS SECTIONS AT CMD-3

Ivan Logashenko

on behalf of the CMD-3 collaboration

Budker Institute of Nuclear Physics
Novosibirsk State University

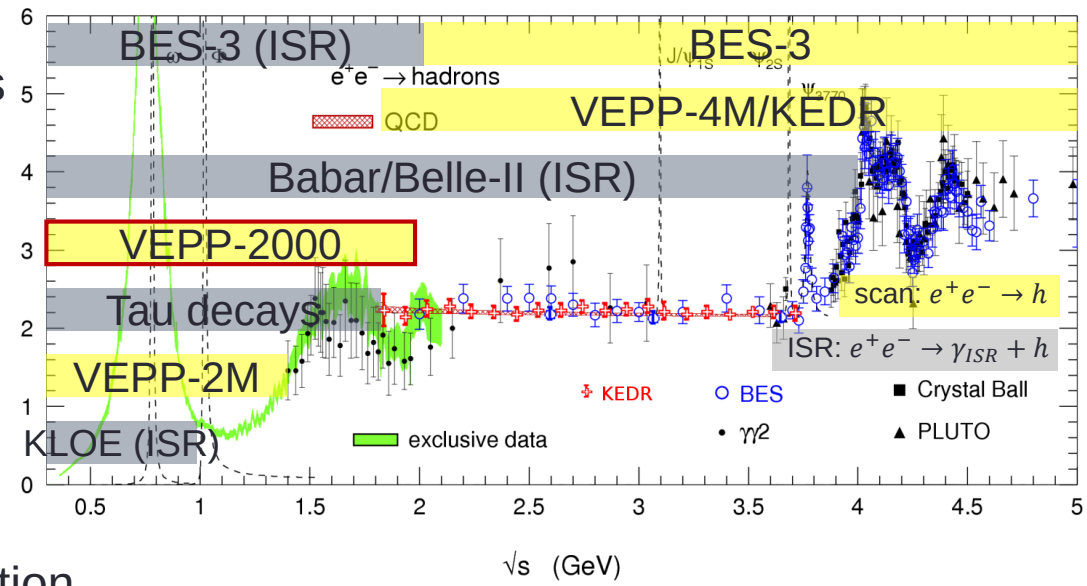
ICHEP 2020, July 28 - August 6, 2020

Introduction

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

$e^+e^- \to hadrons$ at low energies ($\sqrt{s} < 2$ GeV)

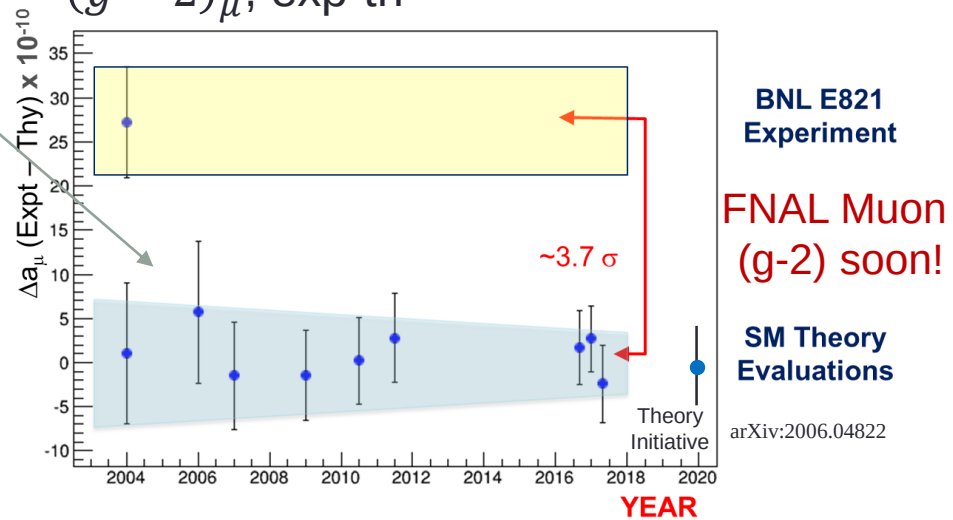
- study of properties of light vector mesons (directly) and other light mesons (in intermediate states)
- understand hadronization in highly non-perturbative regime
- key experimental input for evaluation of hadronic contribution to muon (g-2)



Sources of data:

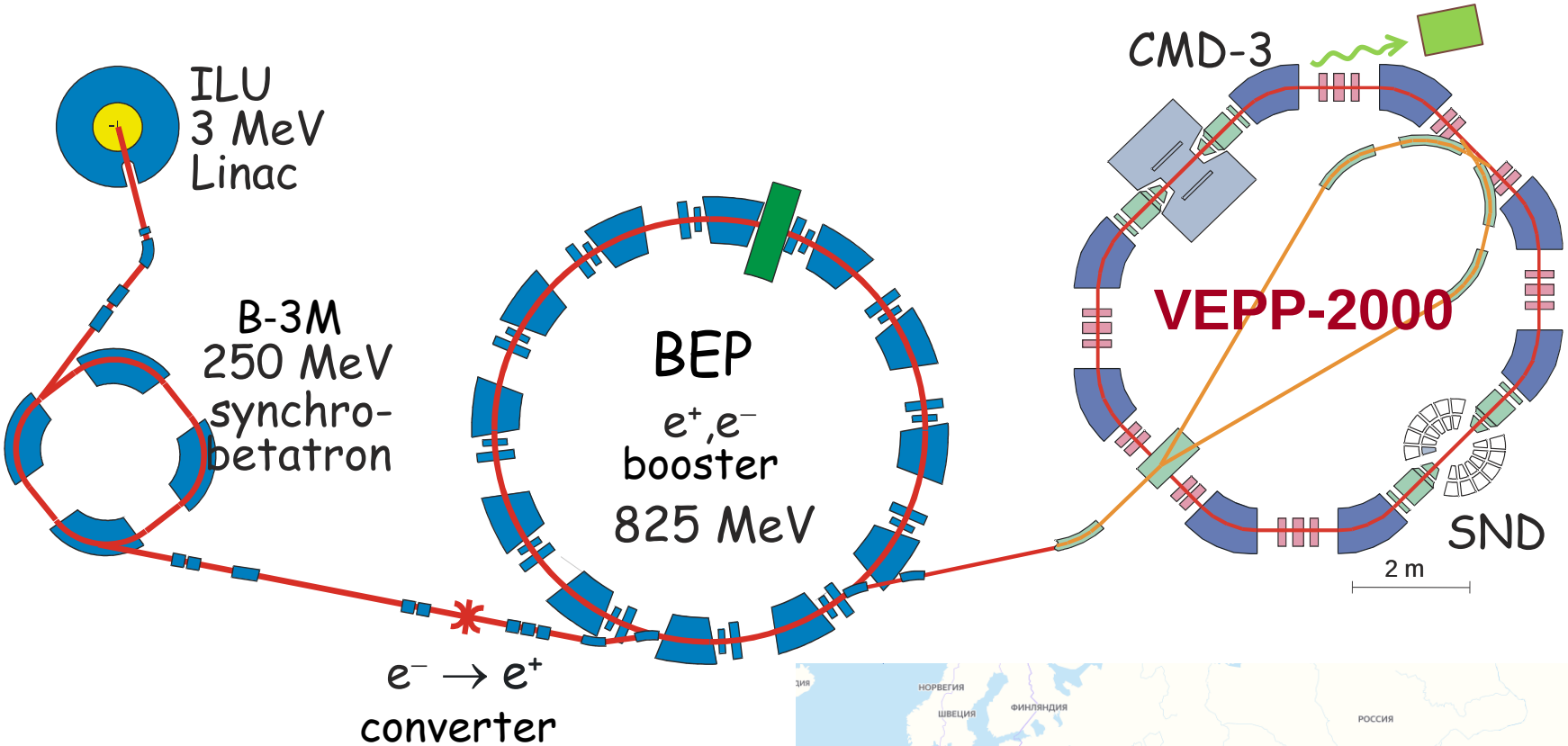
- Novosibirsk: VEPP-2M, VEPP-2000
- Factories: BaBar, KLOE-1/2, Belle-II
- BES-III, KEDR

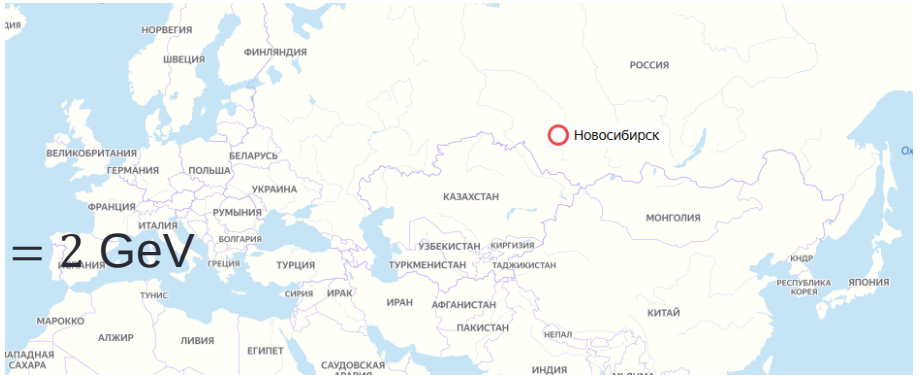
$(g-2)_\mu$, exp-th



VEPP-2000 (2011-2013)

Beam energy by Compton backscattering





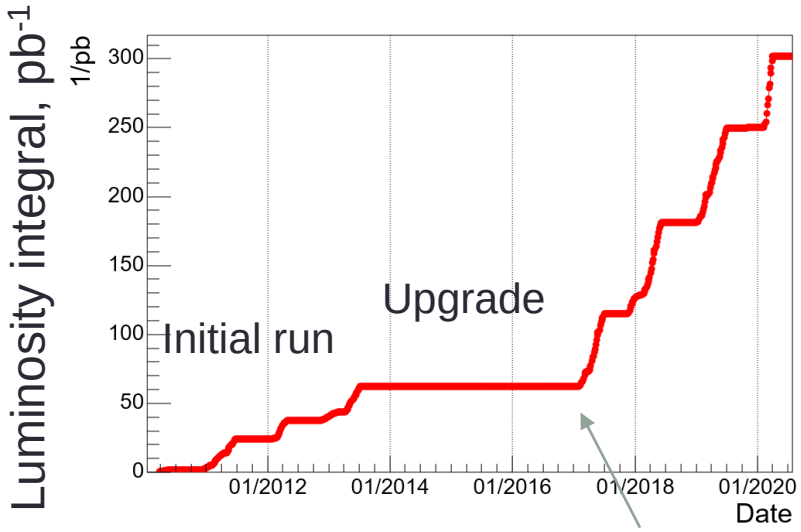
2E = 0.32-2.0 GeV; “round beams”

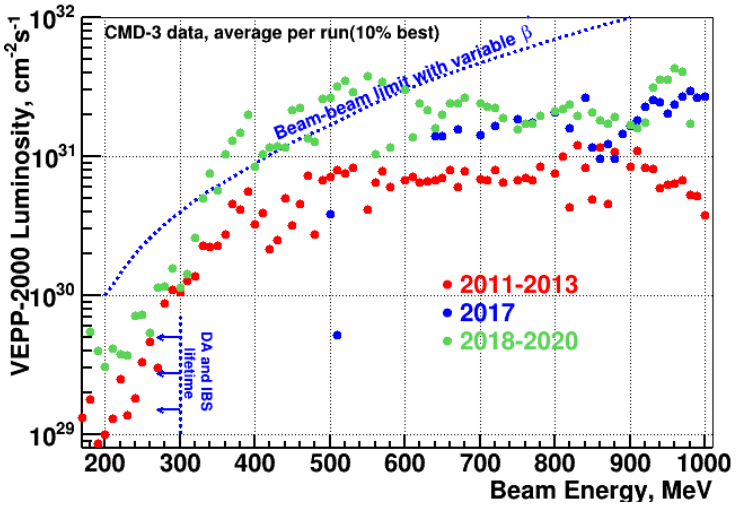
Design luminosity is $L = 10^{32}/cm^2 s$ @ $\sqrt{s} = 2$ GeV

Two detectors, CMD-3 and SND

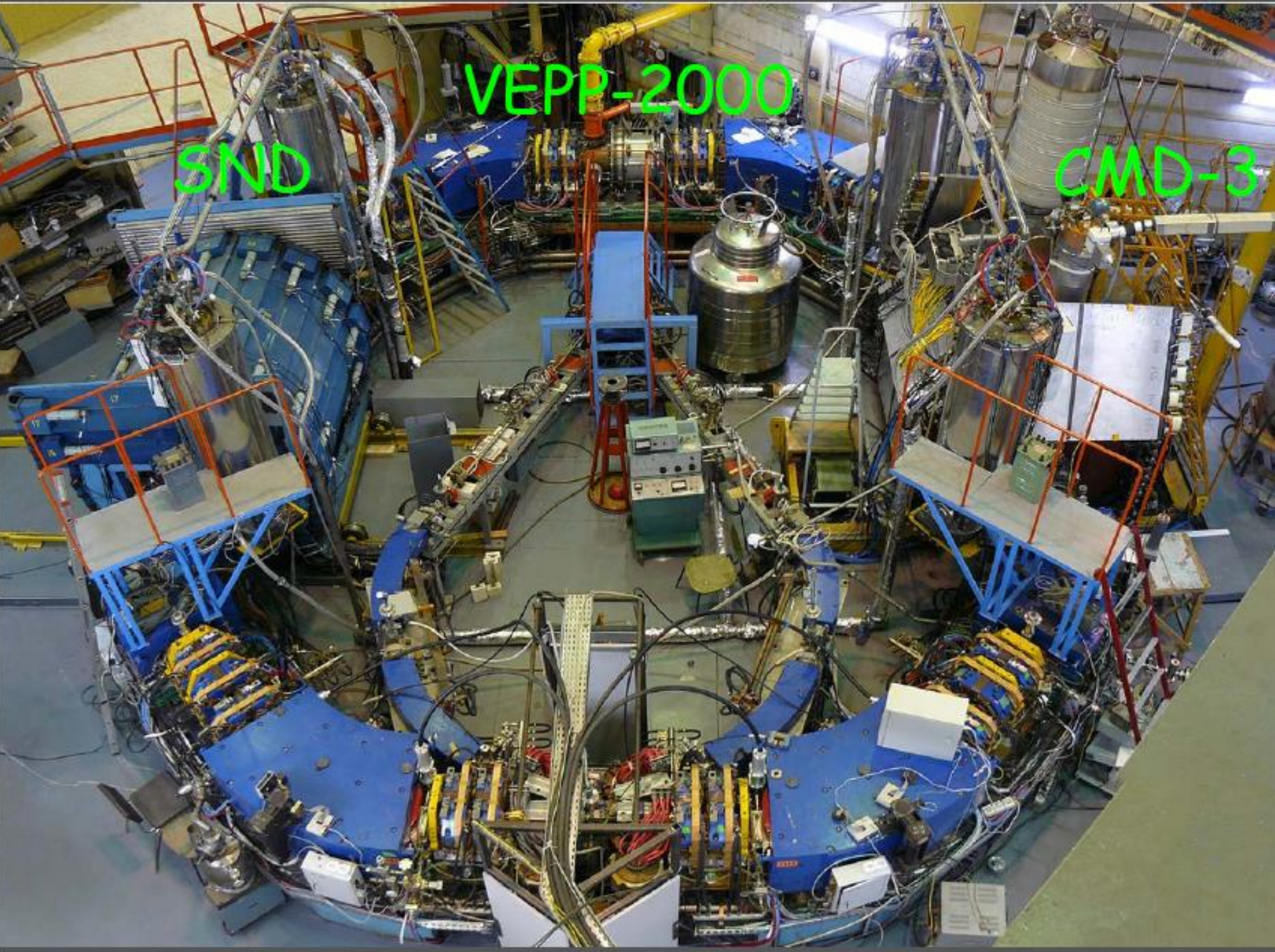
VEPP-2000 after upgrade (2017-2020)

Major upgrade of VEPP-2000 (2013-2016): new positron source

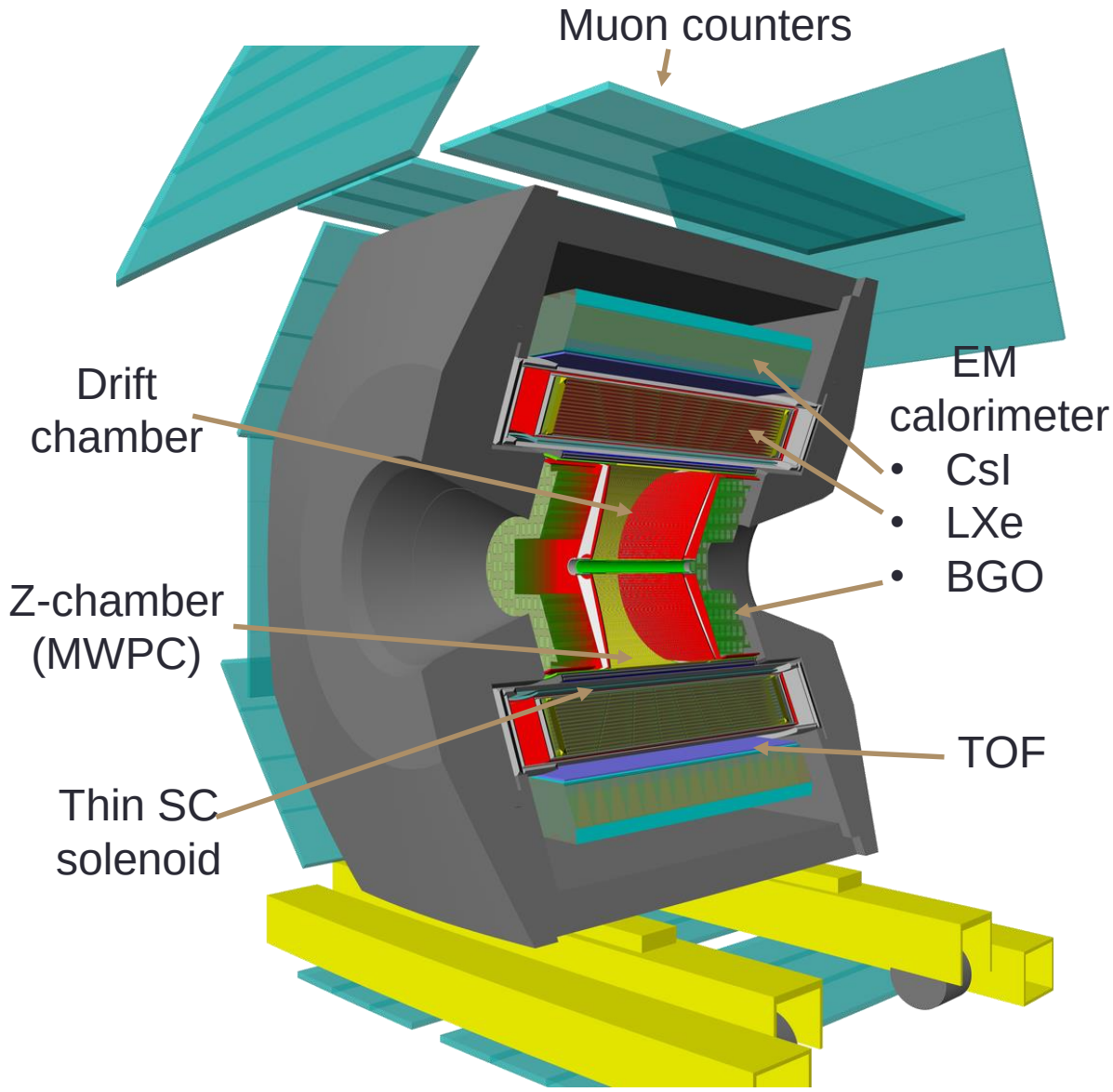


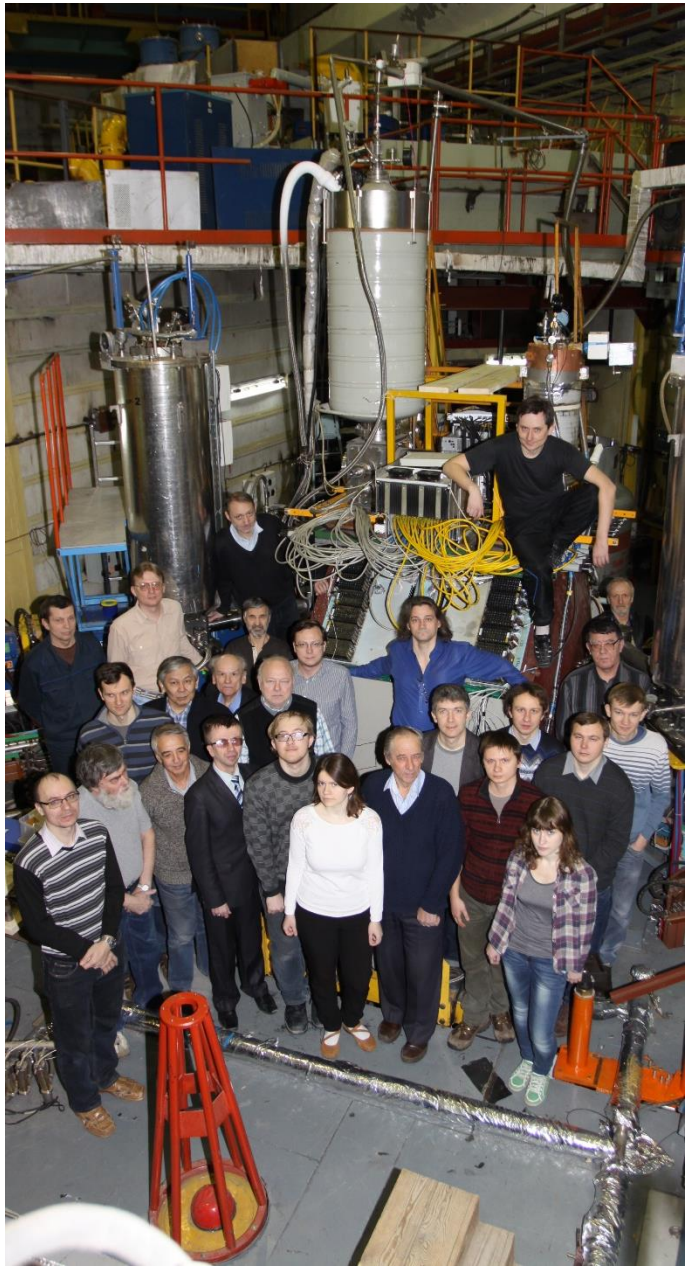


Detectors resumed data taking in 2017


VEPP-2000
SND
CMD-3

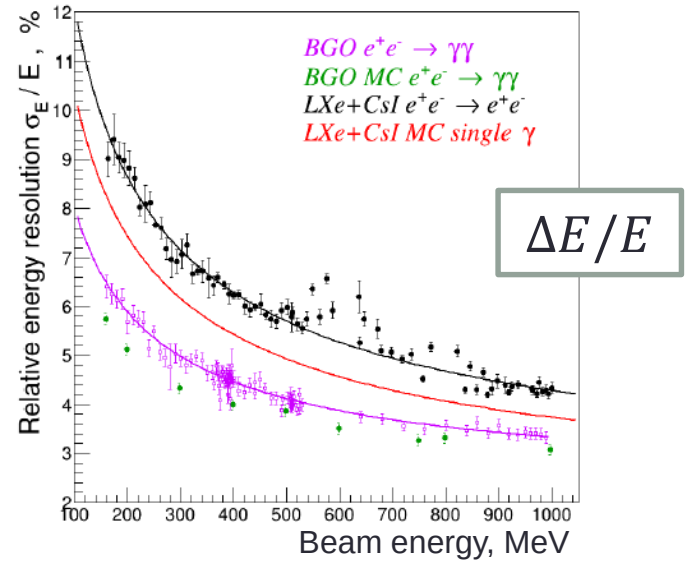
Detector CMD-3

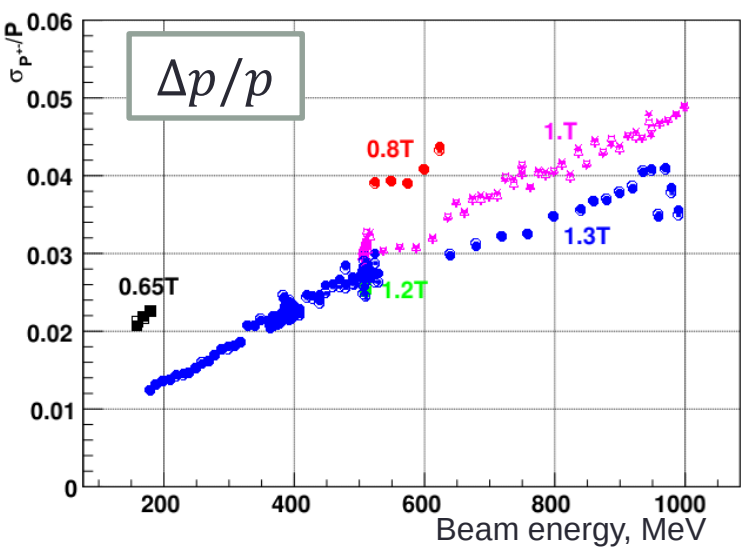


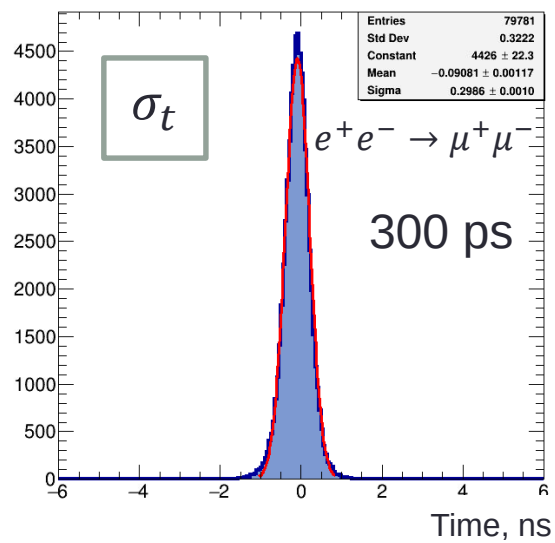


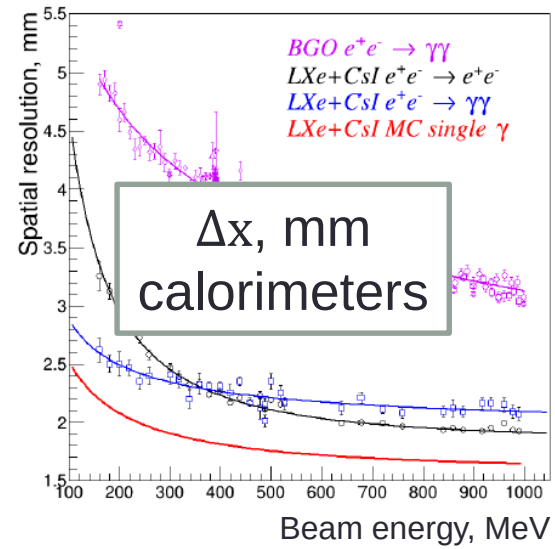
Detector performance

- 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
- TOF: 600 ps per counter

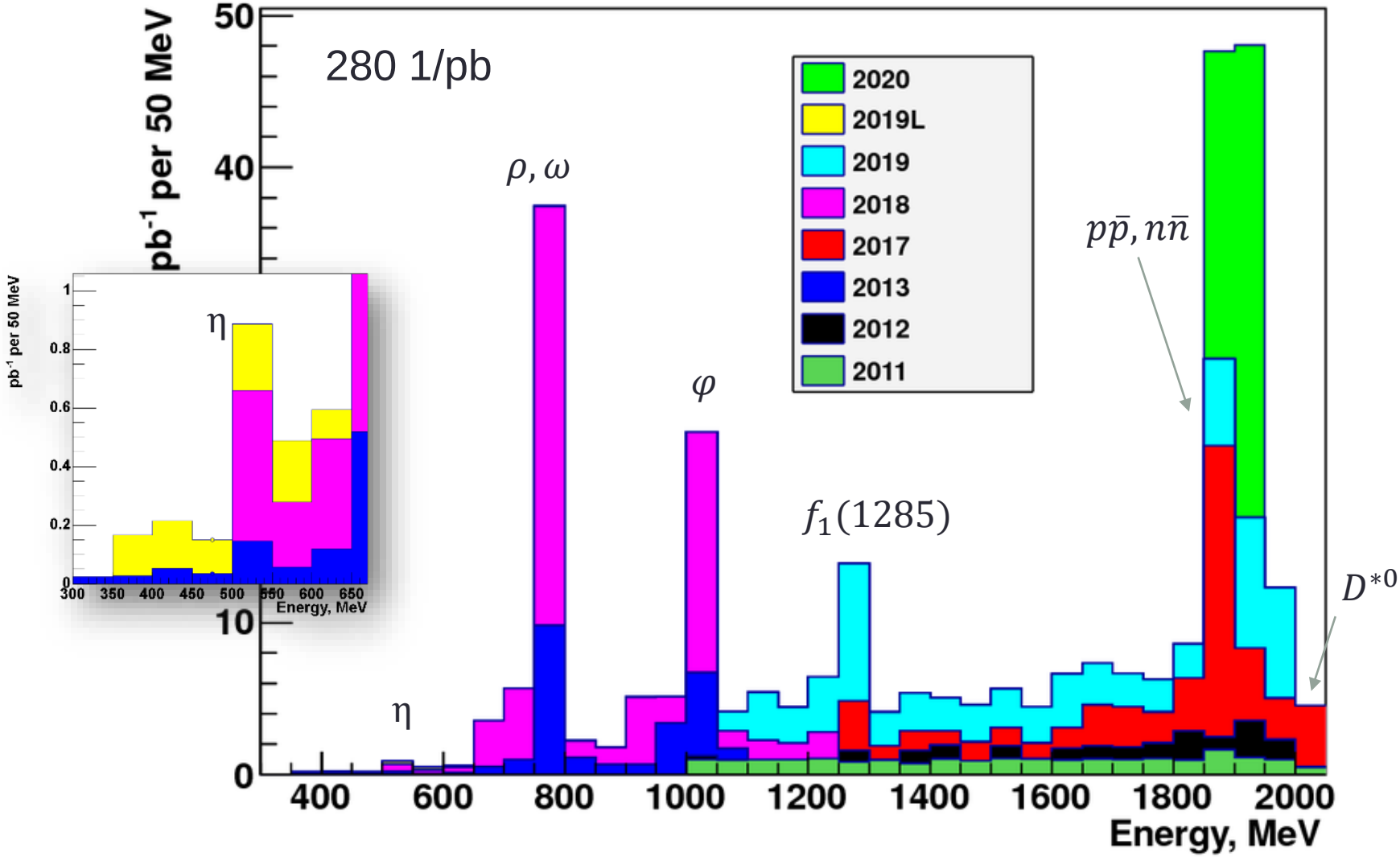








Collected luminosity by energy



Exclusive channels under analysis

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

- 2 charged

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

- 2 charged + γ's

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

- 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

$$e^+e^- \to 3(\pi^+\pi^-), K_SK_S\pi^+\pi^-, K_SK^\pm\pi^\mp\pi^-$$

- γ's only

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

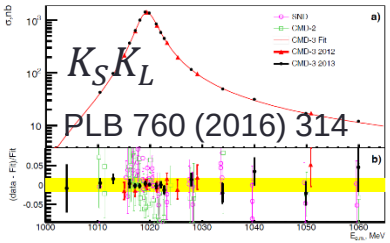
- other

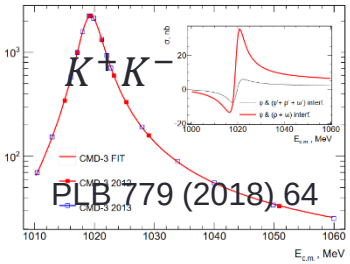
$$e^+e^- \to n\overline{n}, \pi^0e^+e^-, \eta e^+e^-, 3(\pi^+\pi^-)\pi^0$$

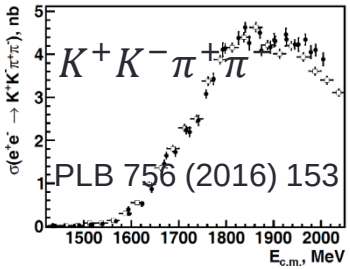
- rare decays

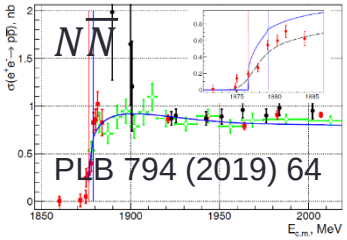
$$e^+e^- \to \eta, \eta', D^{*0}$$

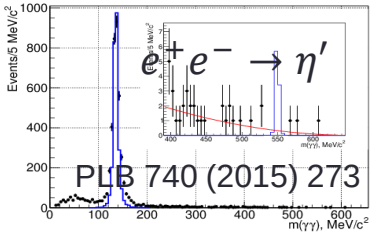
CMD-3 published results

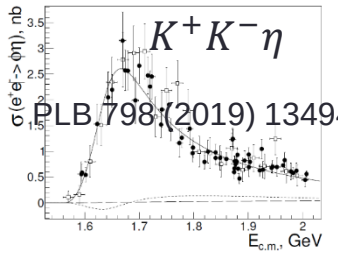


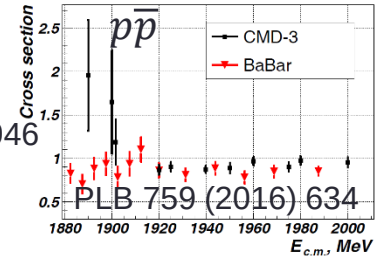


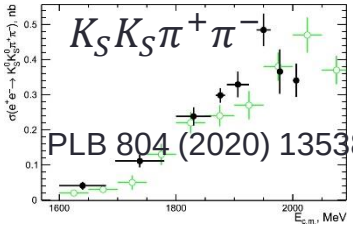


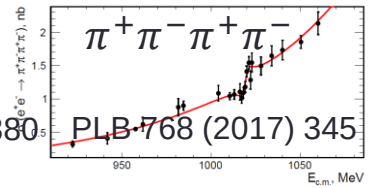


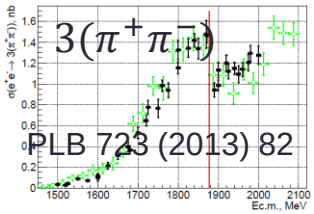


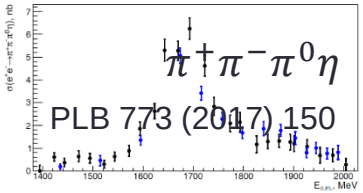


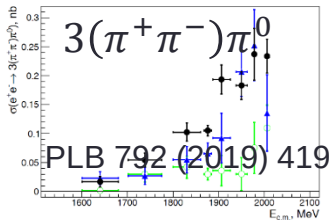


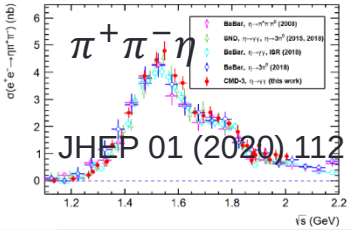


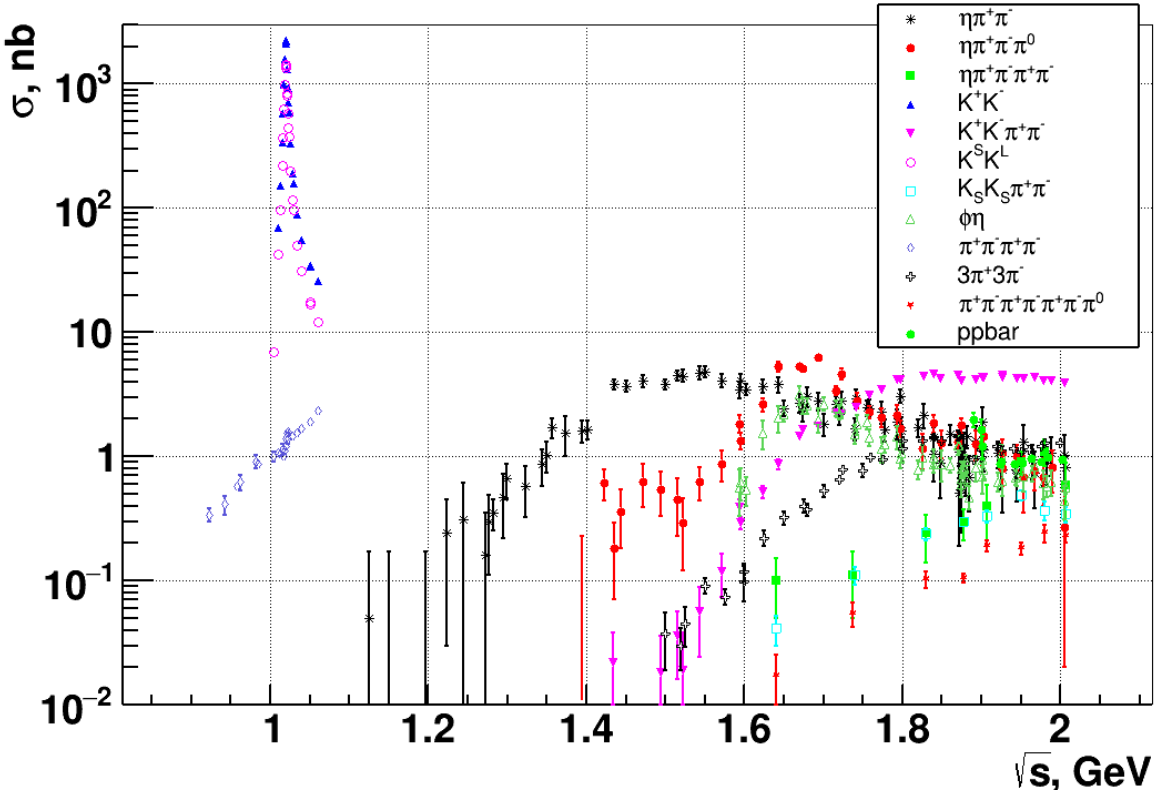






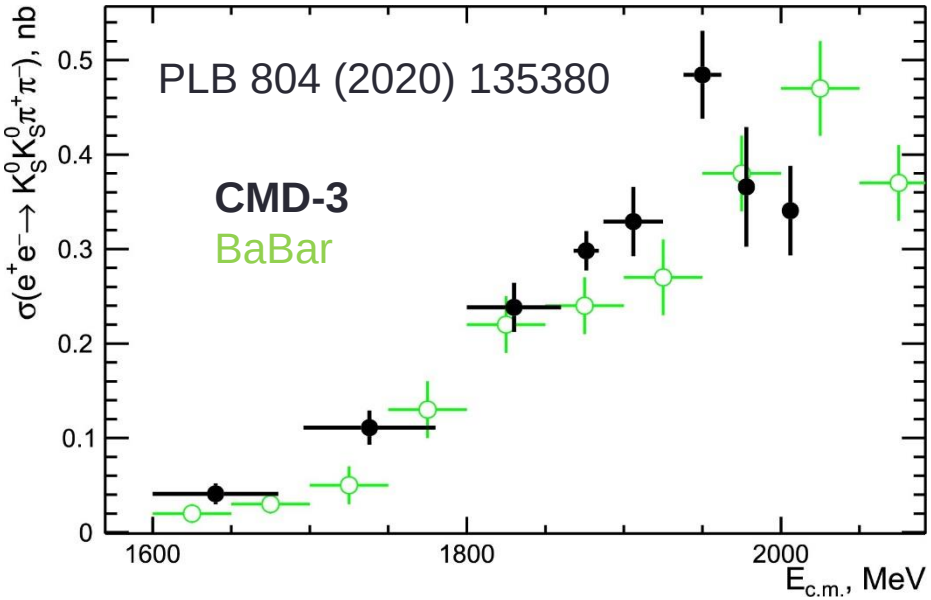






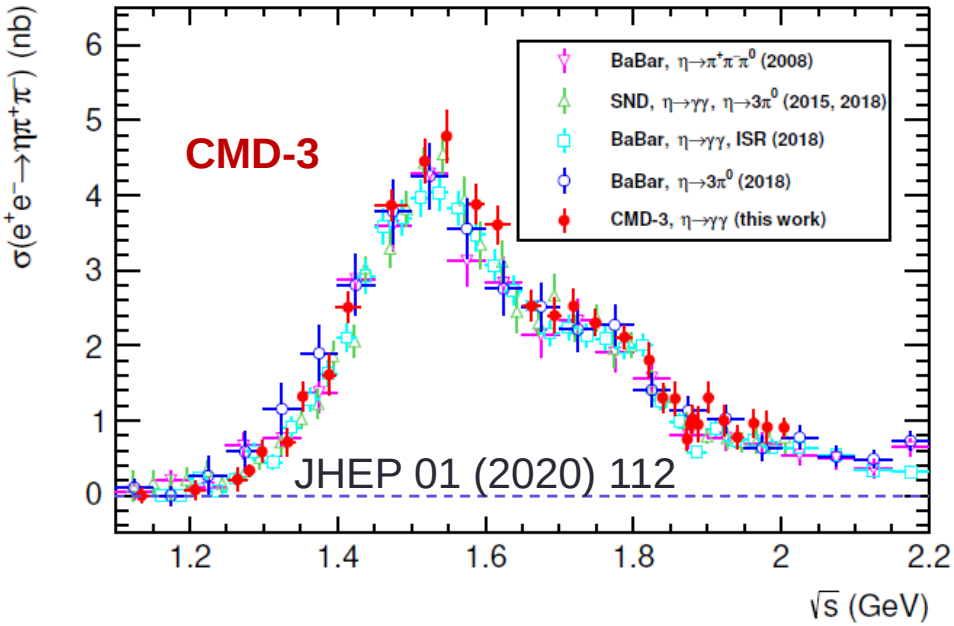
Recent results (2020)

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



- Systematic uncertainty ~10%
- Dominated by $K^*(892)^+K^*(892)^-$, $K_1(1270)K_S^0$ possible

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

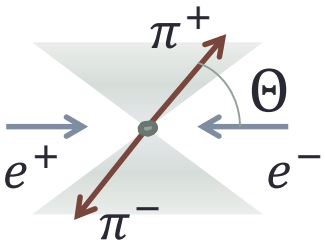


- Systematic uncertainty ~6%
- Dominated by $\eta\rho(770)$
- Line shape described by $\rho(770)$, $\rho(1450)$ and $\rho(1700)$

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

Very simple, but the most challenging channel due to high precision requirement.

- 70% of $a_\mu(had)$
- 0.25% precision required to match FNAL (g-2)
- Several measurements <1%, local discrepancies O(1%)



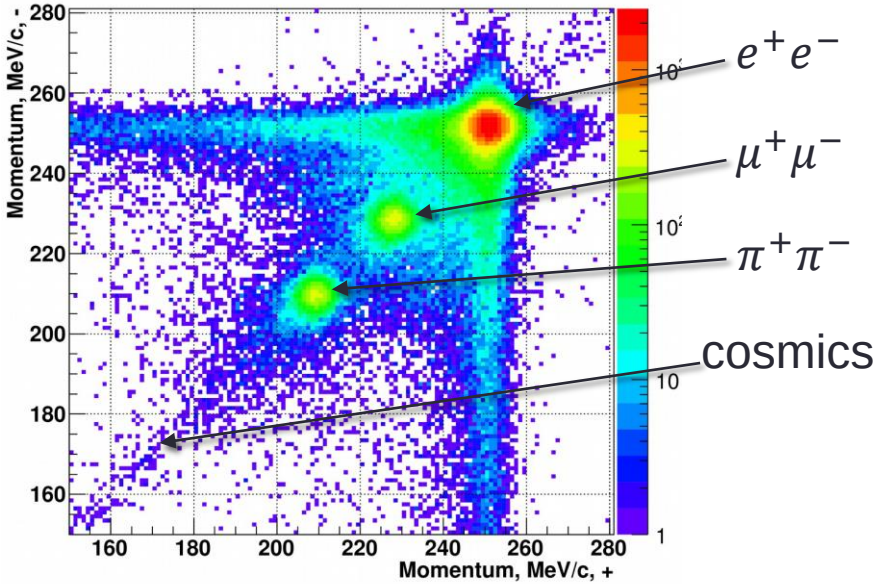
Main background:
$e^+e^- \to e^+e^-, \mu^+\mu^-$

Measurement at CMD-3:

- several scans of the whole energy region below 2 GeV
- detector optimized for this measurement
- $e^+e^-, \mu^+\mu^-, \pi^+\pi^-$ separation either by 2D momentum or by 2D energy deposition (by classifiers are under development) – independent measurements

Goal: ~0.5% systematics

P^- vs P^+ @$\sqrt{s} = 0.5$ GeV



$e^+e^- \to \pi^+\pi^-$: radiative corrections

Measurement of $e^+e^- \to \pi^+\pi^-$ requires high precision calculation of radiative corrections.

We use two high-precision MC generators for $e^+e^- \to e^+e^-$:

- MCGPJ generator (0.2%)

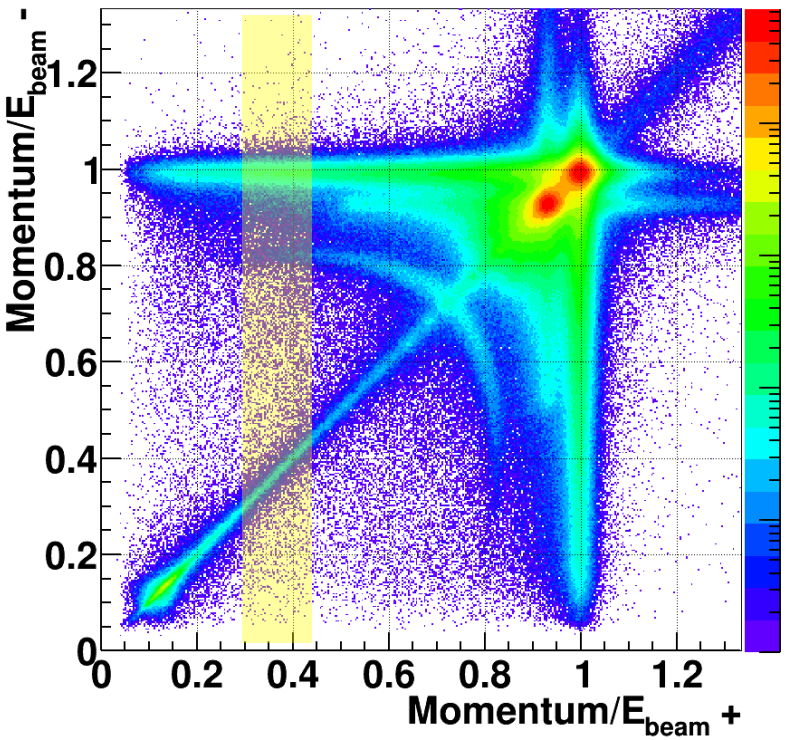
  1 real γ from any particle
  + γ jets along all particles (collinear structure function)

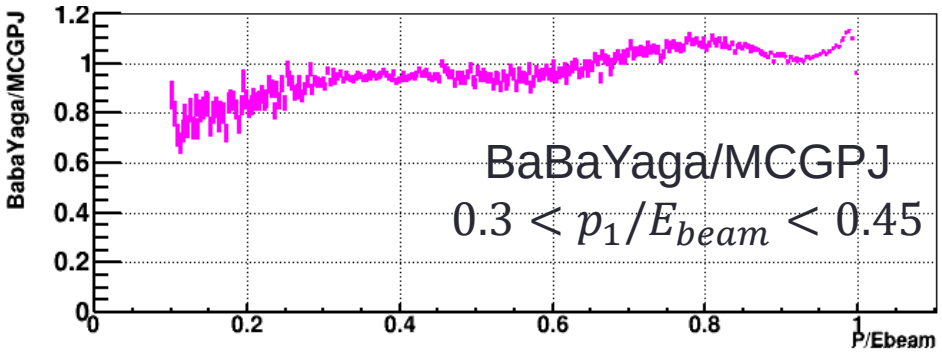
- BaBaYaga@NLO (0.1%)

  Parton shower approach: n γ with angular distribution, accounts for interference with 1γ radiation

Tails of e^+e^- spectra differ by few %, which limits the precision to O(0.1%)

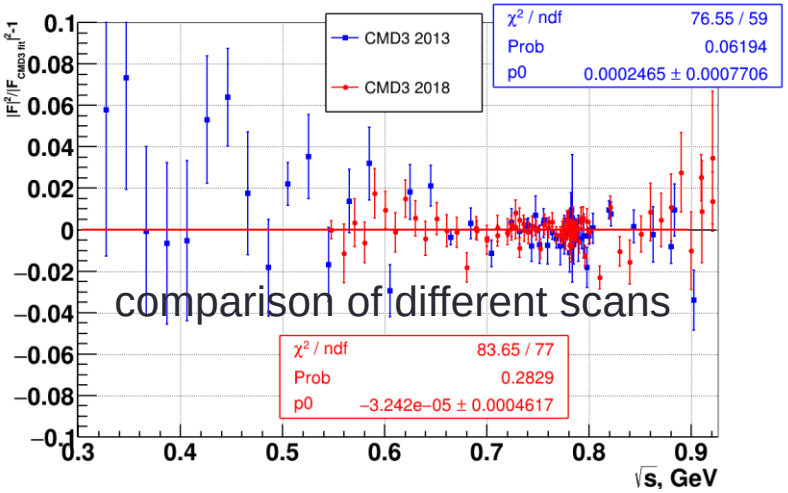
NNLO MC generator for $e^+e^- \to e^+e^-$ is needed for higher precision



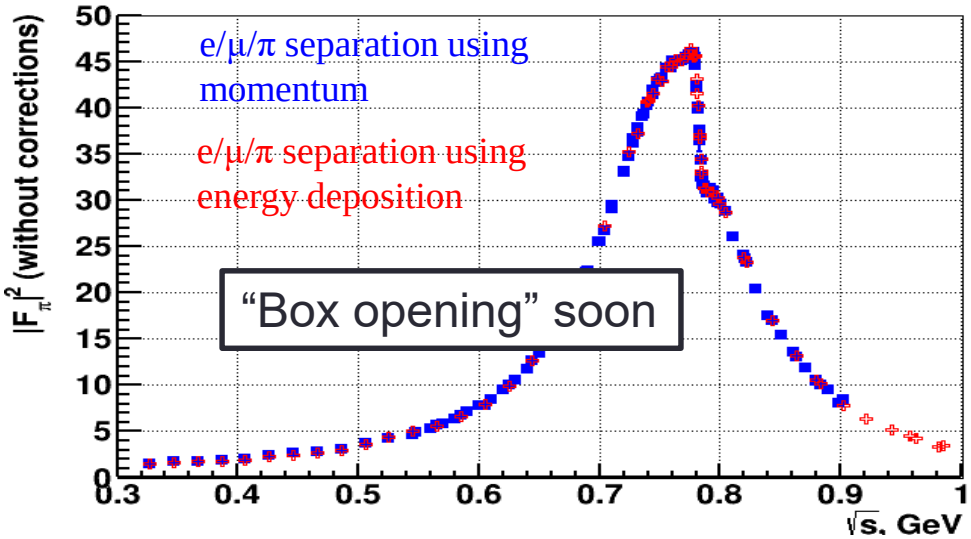


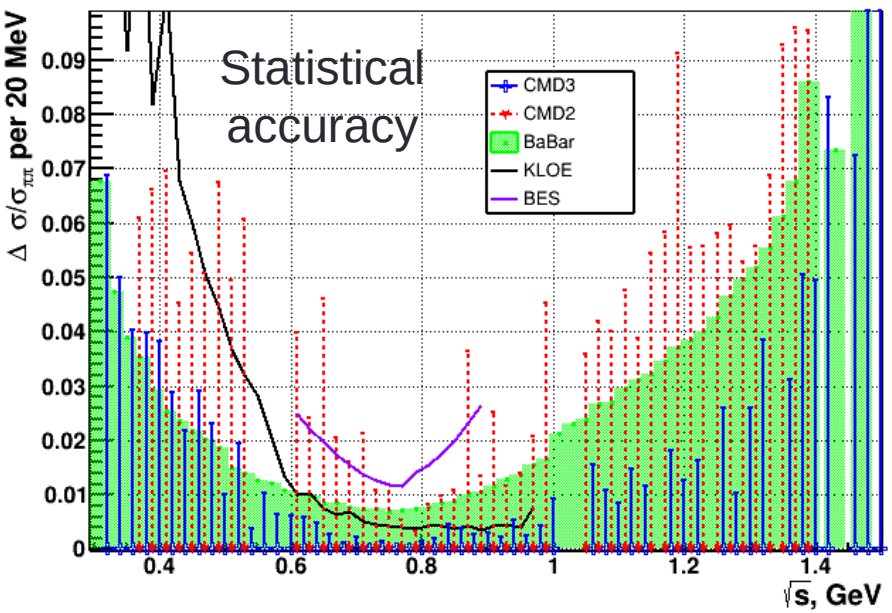
$e^+e^- \to \pi^+\pi^-$: status

$|F_\pi|^2, 2018/2013 - 1$



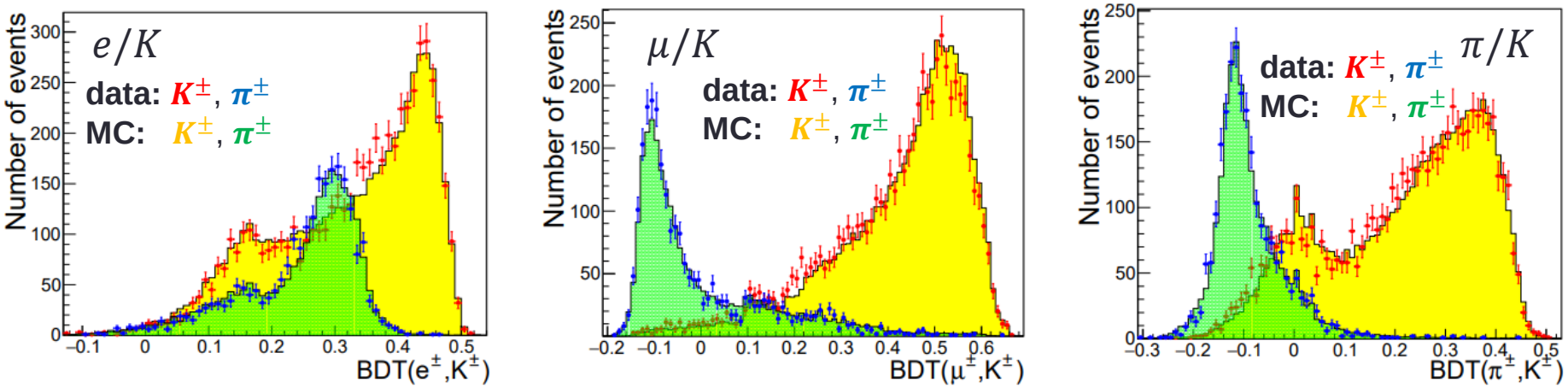
$|F_\pi|^2$, "blinded" (no pion corrections)



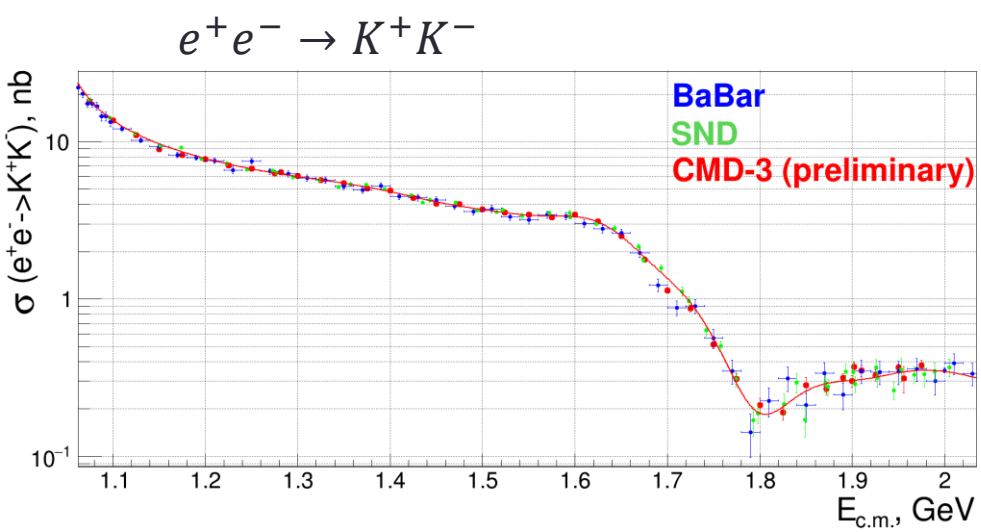


Sources of systematics	
Rad.corr.	0.2%⊗(0-0.4-1.0)%
$e/\mu/\pi$	0.5% - 0.2%(ρ) - 1.0%
Fiducial vol.	0.2%⊗0.3%
Beam energy	0.1%
Nuclear int.	0.1%
Pion decay	0.3% - 0.15%(ρ)
Total	**0.8% - 0.6%(ρ) - 1.0%**

$e^+e^- \to K^+K^-$: particle ID with LXe



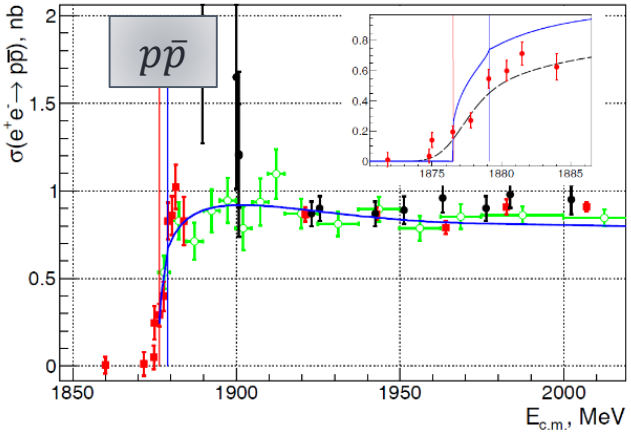
- Measurement of longitudinal shower profile in LXe calorimeter gives particle ID using machine learning (BDT)
- Example: measurement of $e^+e^- \to K^+K^-$ cross section; background from e^+e^- and $\pi^+\pi^-$ is suppressed using LXe PID

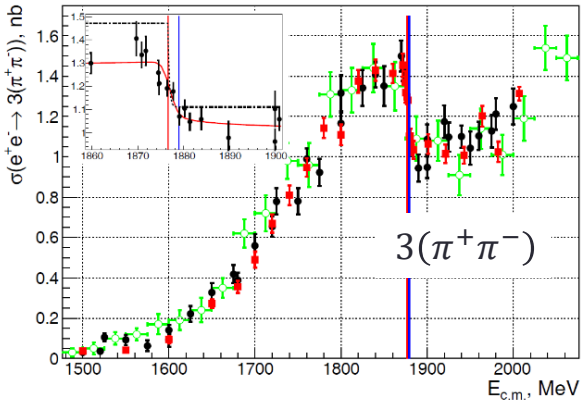


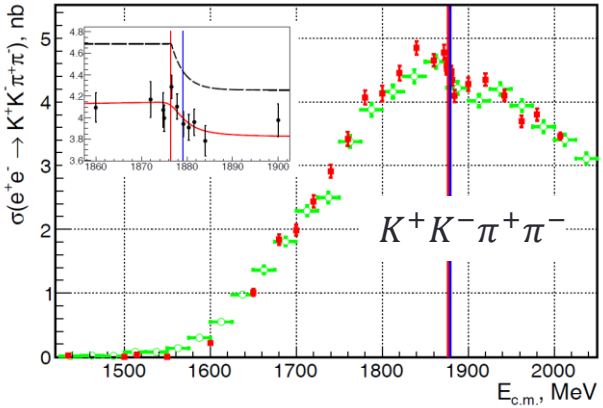
$R(s)$ at $N\bar{N}$ threshold

VEPP-2000: unique ability for detailed scan of $p\bar{p}$ and $n\bar{n}$ threshold.

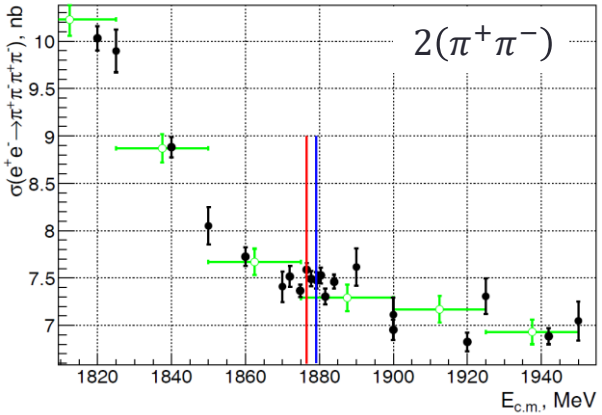
PLB 794 (2019) 64







- observed the sharp change of $e^+e^- \to p\bar{p}$, $3(\pi^+\pi^-)$, $K^+K^-\pi^+\pi^-$
- width is ~1 MeV – consistent with energy resolution
- puzzle – why there is no change in $e^+e^- \to 2(\pi^+\pi^-)$?



We plan to do comprehensive study of this energy range.

Study of internal dynamics

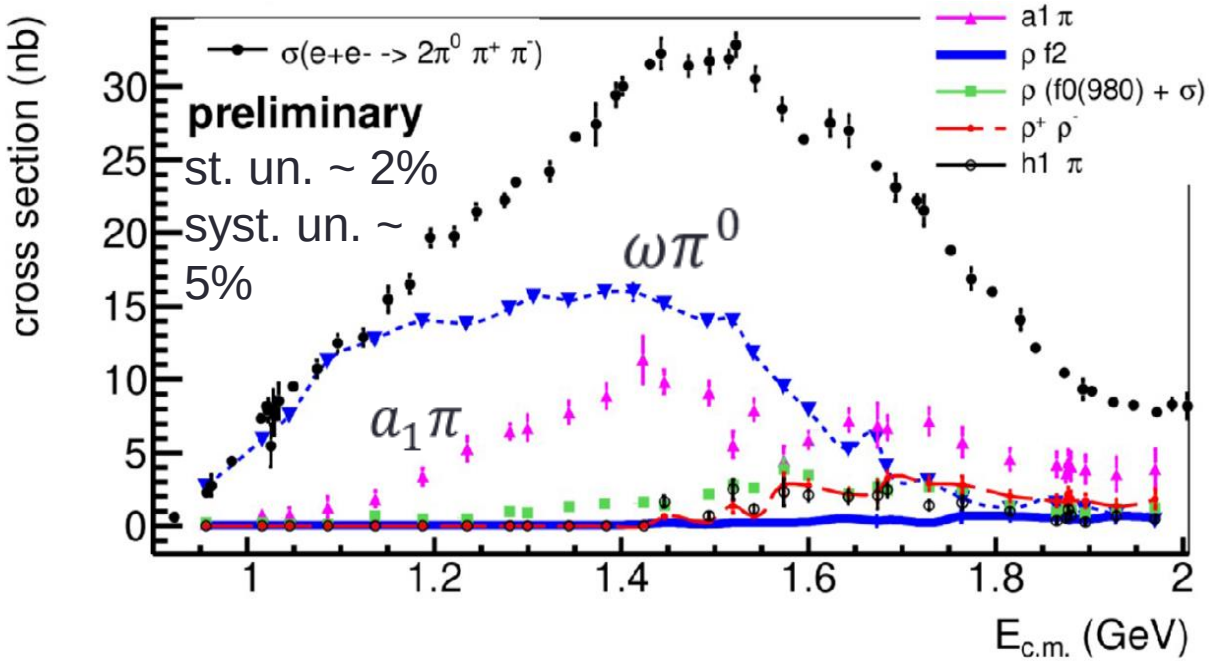
\ intermediate state final state (fs)	1-- ρ',ω',φ'...	1-- ρ(770)	1-- ω(782)	1-- φ(1020)	1- K*(890)	1+ K1(1270)	1++ a1(1260)	1++ f1(1285)	0+ f0(980)	0+ a0(980)	0−+ η, η'(958)
π+π-	fs	fs	fs	fs							
π+π-π0	fs	2π	fs	fs							fs
π+π-π0π0	fs	π±π0, π+π-	π+π-π0				π-π0π0	fs	π0π0		
π+π-π+π-	fs	π+π-					π-π+π-	fs	π+π-		
5π	fs	2π	3π								fs, π+π-π0
6π	fs	π±π0, π+π-					3π				π+π-π0
7π	fs		3π								π+π-π0
8π	fs										
K+K-, KSKL	fs	fs	fs	fs							
2Kπ0, 2Kη	fs			2K	Kπ						
2K2π	fs	2π		2K	Kπ	K2π			2π		
2K3π	fs	2π			Kπ			2Kπ	2K	2K	
nucleon bar nucleon	fs										
πγ, ηγ, η'γ	fs	fs	fs	fs							
πee, ηee, η'ee	fs	fs	fs	fs							
π0π0γ, π0ηγ	fs		π0γ	fs					π0π0	π0η	
π+π-η	fs	fs, 2π		fs				fs			fs
π+π-π0η	fs	π+π-	π+π-π0	π+π-π0						π0η	
μ+μ-π0, μ+μ-η, 4πη, 2π2η	fs										

The table is not comprehensive!

$e^+e^- \to 4\pi$

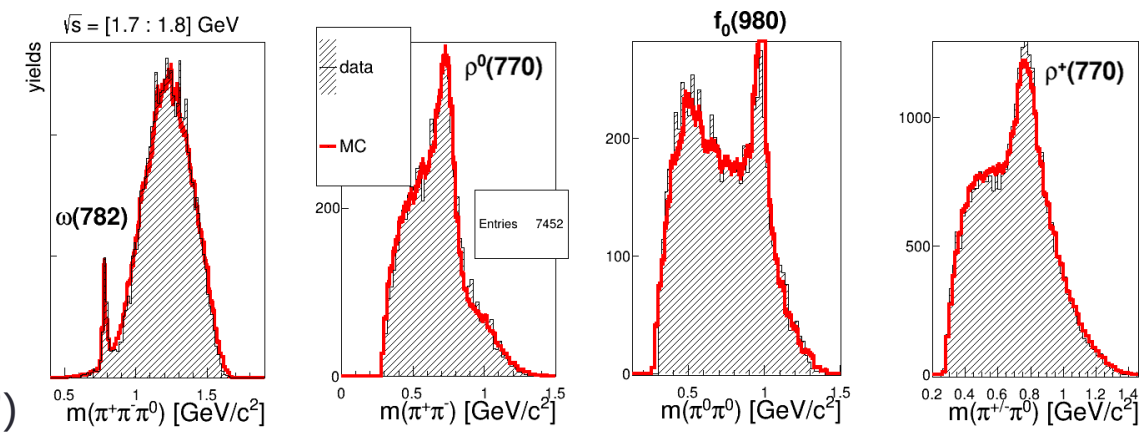
Simultaneous unbinned amplitude analysis of 150 000 $\pi^+\pi^-\pi^0\pi^0$ events and 250 000 $\pi^+\pi^-\pi^+\pi^-$ events.

Amplitudes accounted for in the likelihood function:



- $\omega[1^{--}]\pi^0[0^{++}]$ (only $\pi^+\pi^-2\pi^0$)
- $a_1(1260)[1^+]\pi[0^-]$
- $\rho[1^{--}]f^0/\sigma[0^{++}]$
- $\rho f_2(1270)[2^{++}]$
- $\rho^+\rho^-$ (only $\pi^+\pi^-2\pi^0$)
- $h_1(1170)[1^{+-}]\pi^0$ (only $\pi^+\pi^-2\pi^0$)

Intermediate resonances observed in data:

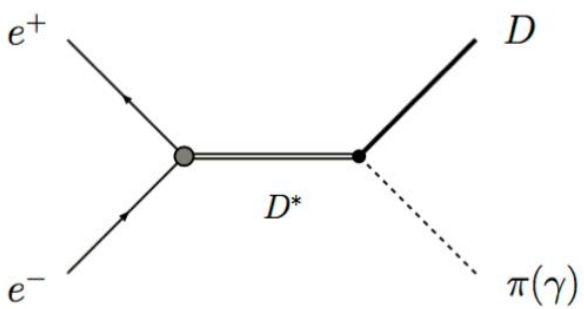


Search for FCNC process: $e^+e^- \to D^{*0}$

A.Khodjamirian, T.Mannel, A.Petrov, JHEP 1511 (2015) 142

$$\sigma(e^+e^- \to D\pi)_{\sqrt{s}\simeq m_{D^*}} \equiv \sigma_{D^*}(s) = \frac{12\pi}{m_{D^*}^2} \mathcal{B}_{D^*\to e^+e^-}\mathcal{B}_{D^*\to D\pi} \frac{m_{D^*}^2\Gamma_0^2}{(s-m_{D^*}^2)^2 + m_{D^*}^2\Gamma_0^2}$$

Search for rare decay $D^{*0} \to e^+e^-$ in inverse process $e^+e^- \to D^{*0}$



Estimated sensitivity:

$$B_{D^*\to e^+e^-} \geq \frac{4\times 10^{-10}}{\varepsilon \int Ldt\ [pb^{-1}]} \times \frac{\sigma_{2E}}{\Gamma_{D^*}\ [60\ keV]}$$

Standard Model:

$$B_{D^*\to e^+e^-} \approx (0.1 \div 7)\times 10^{-19}$$

Example of New Physics contribution:

$$B^{Z'}_{D^*\to e^+e^-} < 2.5\times 10^{-11}$$

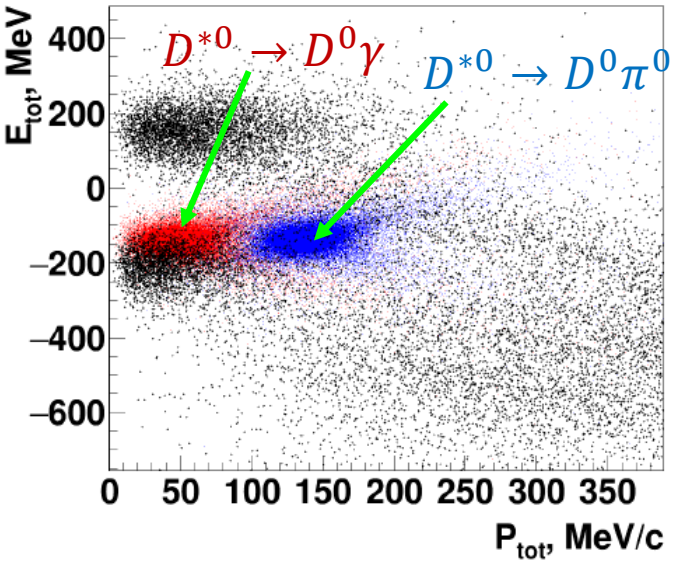
In 2017 CMD-3 collected 4 pb^{-1} at 2007 MeV with $\sigma_{2E} \approx 1.5$ MeV

Search for FCNC process: $e^+e^- \to D^{*0}$

We use
$D^{*0} \to D^0 + \pi^0/\gamma \to K^-\pi^+\pi^-\pi^+ + \pi^0/\gamma$
(branching~8%)

$$B_{D^*\to e^+e^-} \geq \frac{4\times 10^{-10}}{\varepsilon \int Ldt\ [pb^{-1}]} \times \frac{\sigma_{2E}}{\Gamma_{D^*}\ [60\ keV]}$$

~1% ~1/60



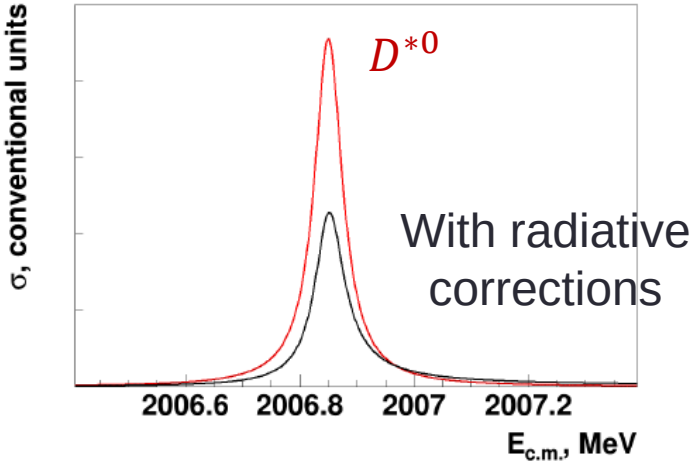
Preliminary CMD-3 result:

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

Estimation for VEPP-2000 (0.1 1/fb): $\sim 10^{-7}$

Estimation for BES-III (1 1/fb): $\sim 10^{-8} - 10^{-9}$

Estimation for proposed Super $c\tau$ factory (100 1/fb): $\sim 10^{-11}$



Summary

- About 280 pb^{-1} were collected with the CMD-3 detector in the whole energy range $0.32 \leq \sqrt{s} \leq 2.0$ GeV, available at VEPP-2000. Overall we plan to collect about 1 fb^{-1}.
- Comprehensive analysis of exclusive modes of $e^+e^- \to hadrons$ is in progress. Results for a number of modes have been published, most recently: $e^+e^- \to K_S K_S \pi^+\pi^-$ and $e^+e^- \to \eta\pi^+\pi^-$.
- For final states with high statistics, e.g. $e^+e^- \to 4\pi$, full internal dynamics is reconstructed
- Measurement of the total cross section has important implications for calculation of the hadronic contribution to muon (g-2).
- There are plans to upgrade detector, in particular, to install endcap tracking counters.