Results from low energy e^+e^- facilities of Budker Institute of Nuclear Physics

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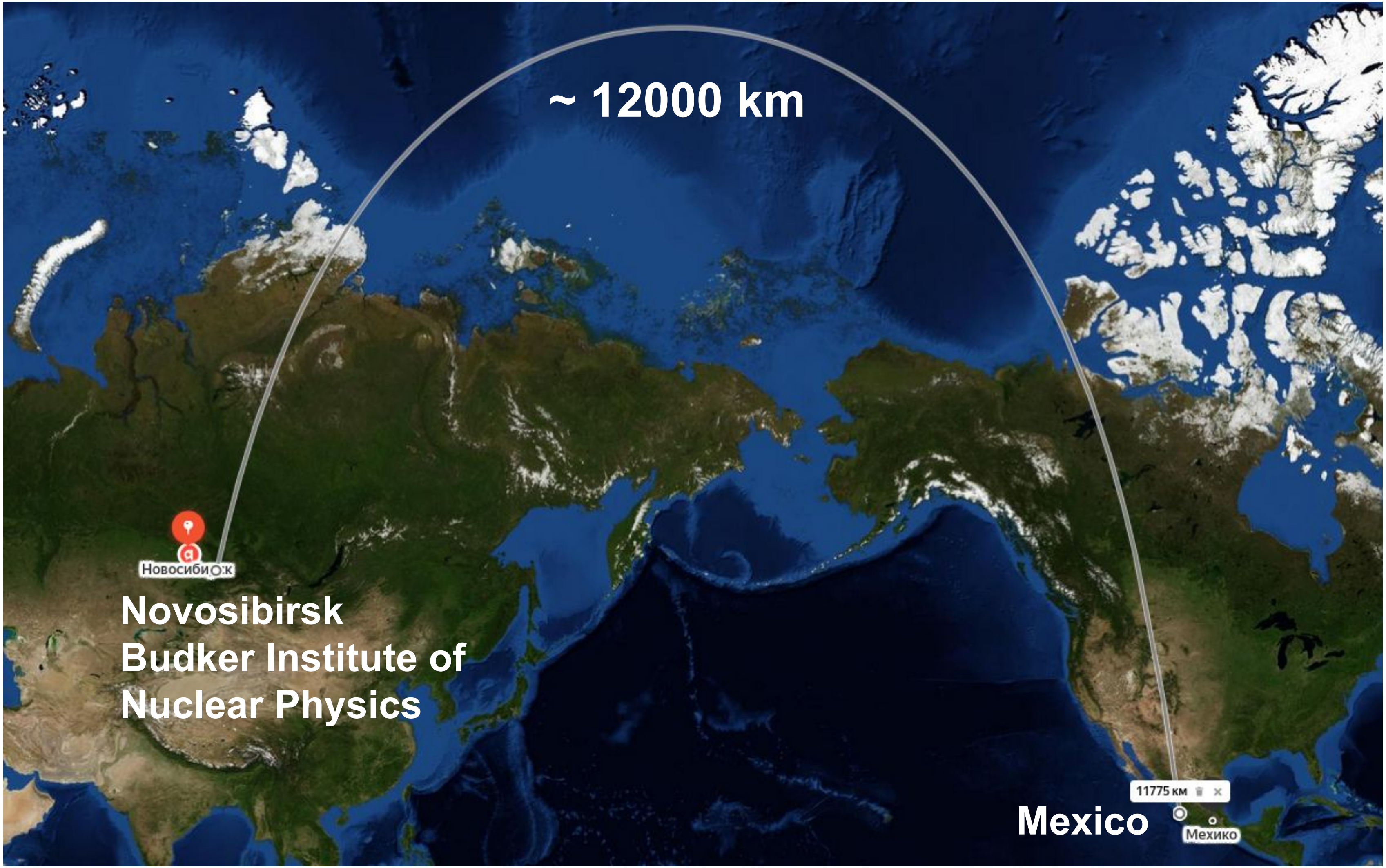
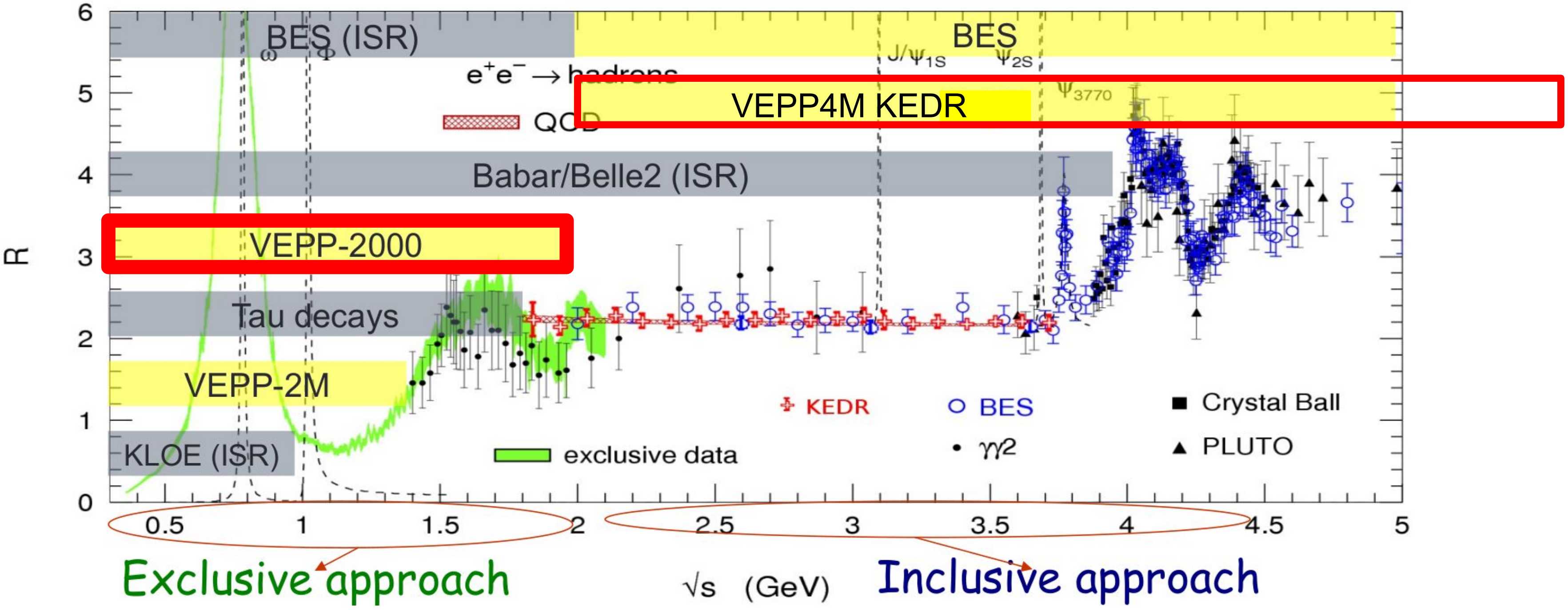

~ 12000 km
Новосибирск
Novosibirsk
Budker Institute of
Nuclear Physics
11775 км
Mexico
Мехико

I was appreciated
to be invited by
Simon Eidelman
to give this talk

Outline

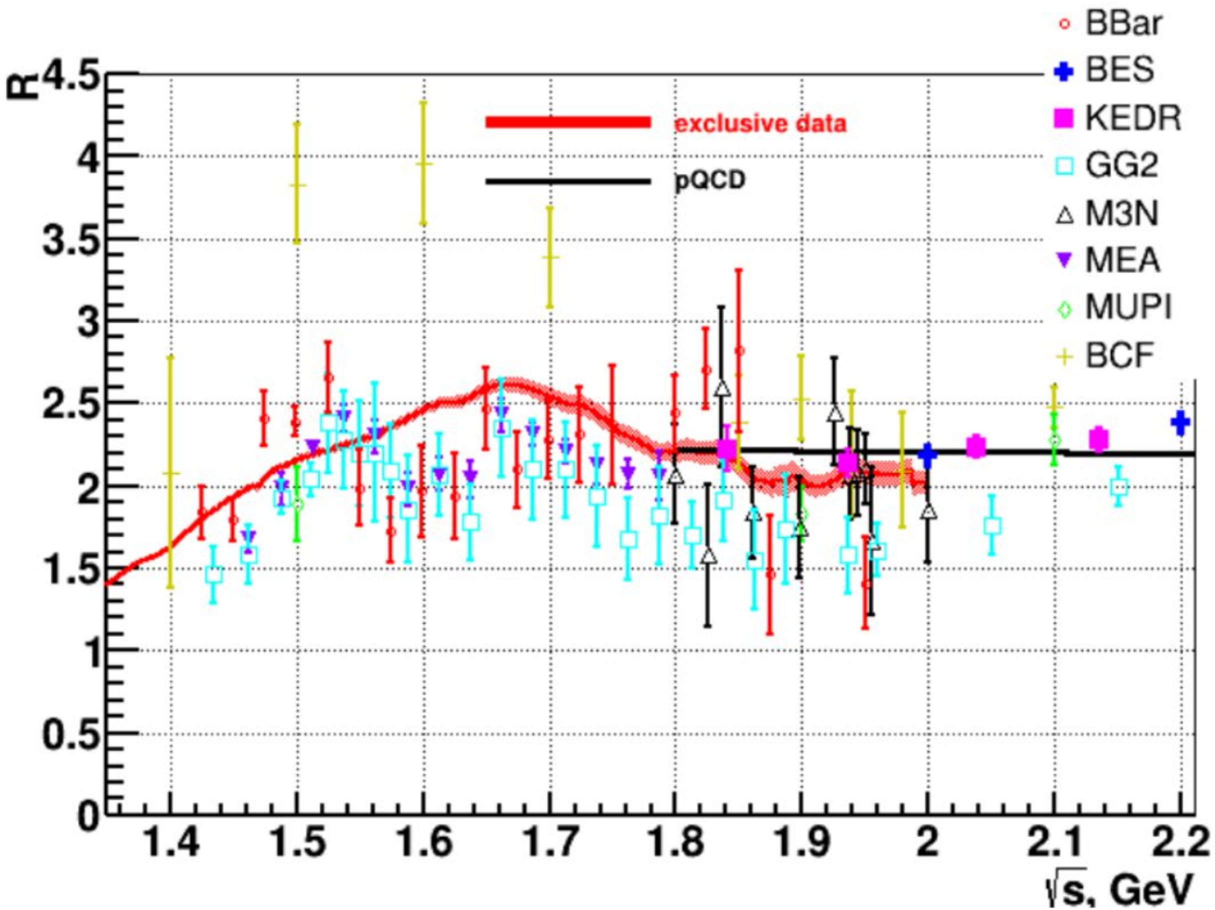
1. Physics program
2. Collider VEPP-2000. Detectors CMD-3 and SND
3. Collider VEPP-4M. Detector KEDR
4. Recent results from the CMD-3
5. Recent results from the SND
   (more detailed overview can be found in **Victor Zhabin**'s talk on the Tuesday session "Hadron decays, production and interactions-2" https://indico.nucleares.unam.mx/event/1541/session/20/contribution/155/material/slides/0.pdf)
6. Recent result from the KEDR
7. Summary

Physics program, R measurement



- VEPP-2000: direct exclusive measurement of σ (e+e- → hadrons). Only one working this days on scanning below 2 GeV with world-best luminosity (1 GeV excluded – where KLOE outperfom everybody).
- BESIII, KEDR – direct scan from 2 GeV to 5 (11) GeV.

Physics program, R measurement



- Indication: the sum of exclusive measurements disagrees with pQCD as well as with inclusive data
- More precise data is needed
- There is still unmeasured exclusive processes, ex., $e^+e^- \to \pi^+\pi^-\pi^0\pi^0\pi^0\pi^0\pi^0$

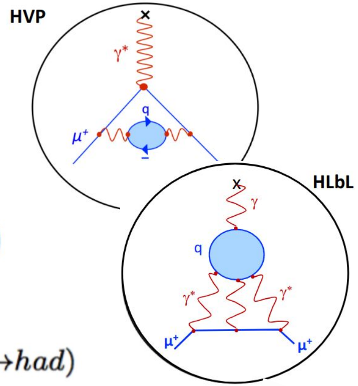
Physics program, anomalous magnetic moment of muon

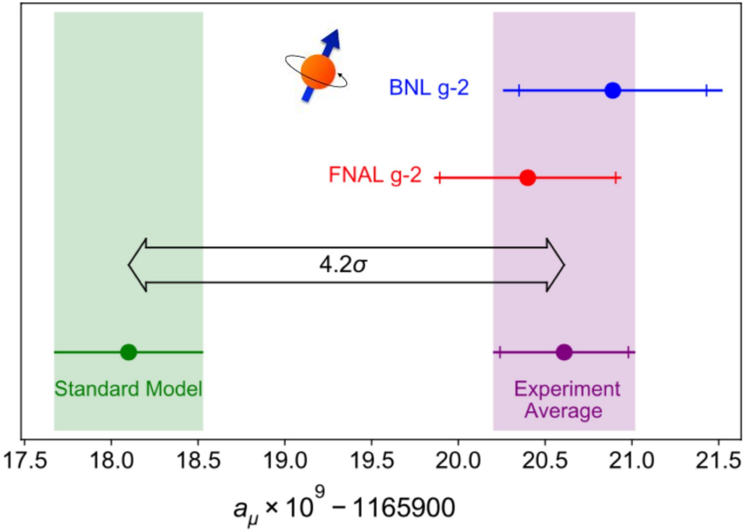
$a_\mu = (g-2)/2 = a_\mu^{QED} + a_\mu^{weak} + a_\mu^{had} = (\,11\,659\,181.0 \pm 4.3\,)\cdot 10^{-10}$

Kinoshita et al.'12
$(\,11\,658\,471.808 \pm 0.015\,)\cdot 10^{-10}$

Czarnecki et al.
$(\,15.4 \pm 0.2\,)\cdot 10^{-10}$

$$\vec{\mu} = g\left(\frac{e}{2m}\right)\vec{S}$$





- Optical theorem and analyticity for HVP:

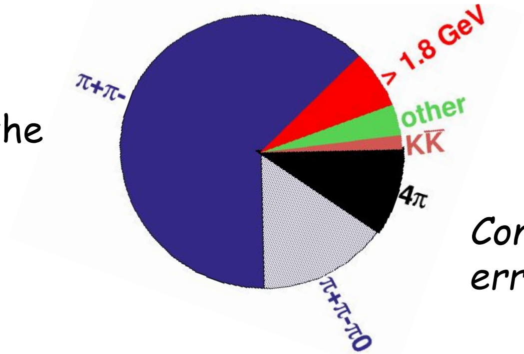
$$\sigma(s)_{(e^+e^-\to had)} = \frac{4\pi}{s}\,\mathrm{Im}\,\Pi_{hadron}(s)$$

$$a_\mu^{HLO} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds\, K(s)\cdot\sigma(s)_{(e^+e^-\to had)}$$

- The main contribution is in resonances in low energy region

$$K(s) = \int_0^1 dx\,\frac{x^2(1-x)}{x^2+(1-x)(s/m^2)} \sim \frac{1}{s}$$

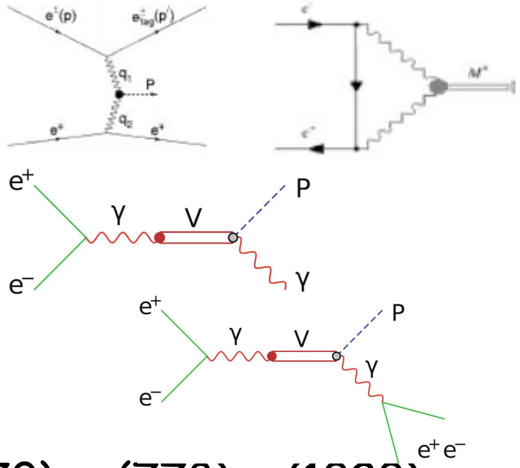
- The enhancement at low energy implies that the $\rho\to\pi^+\pi^-$ resonance is dominating in the dispersion integral (~75%). Current precision at 0.6%.



Contributions to HVP error of a_μ

Physics program

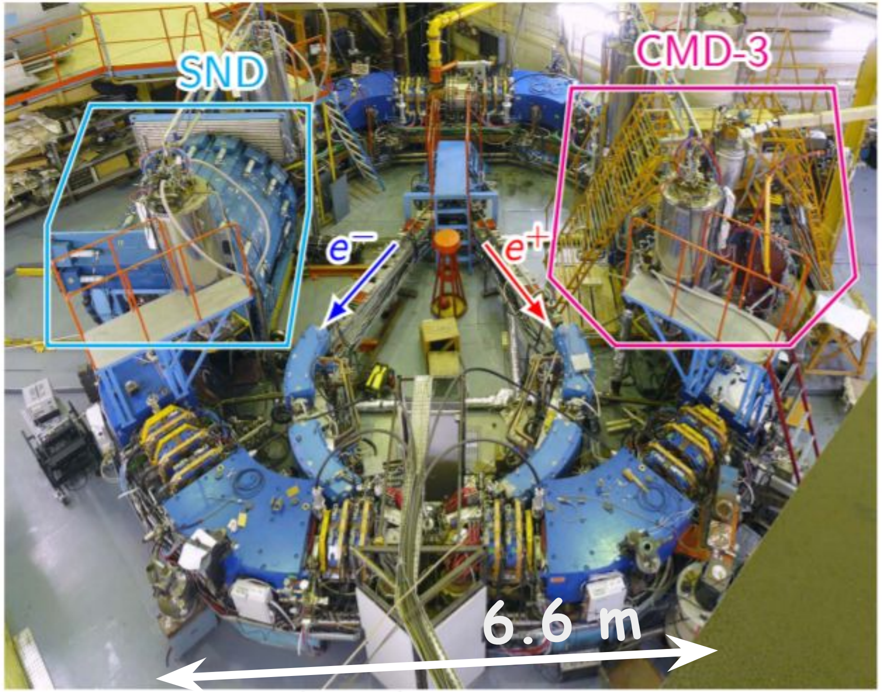
- The measurement of cross sections e^+e^- -> hadrons exclusively (VEPP-2000) and inclusively (VEPP-4M). The total hadronic cross section is calculated as a sum of exclusive cross sections.
- The measurement of two photon cross sections and transition form factors of mesons ($e^+e^- \to X\gamma$, $e^+e^- \to e^+e^- X$, $e^+e^- \to X\gamma \to Xe^+e^-$)
- The study of two photons direct production of C-even resonance ($e^+e^- \to X$).
- Amplitude analysis, a study of internal dynamics of the process of hadronization.
- Measurement of parameters of vector states ($J^{PC} = 1^{--}$) $\rho(770)$, $\omega(778)$, $\varphi(1020)$ and its excited states.
- Rare decays, $\varphi \to \pi^+\pi^-$, $\omega \to \pi^0\mu^+\mu^-$ ….
- Precise measurement of masses of mesons J/ψ, $\psi(2S)$, $\psi(3770)$, D^0, $D^\pm$, $\Upsilon(ns)$ and τ-lepton.
- Precise measurement of total, leptonic and exclusive hadronic widths of charmonium J/ψ, $\psi(2S)$, $\psi(3770)$ and other states.



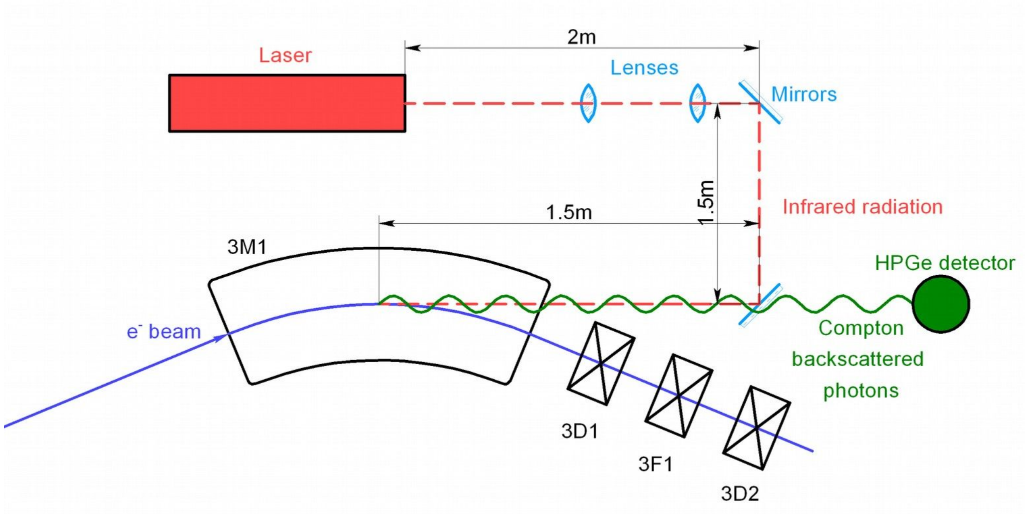
Collider VEPP-2000

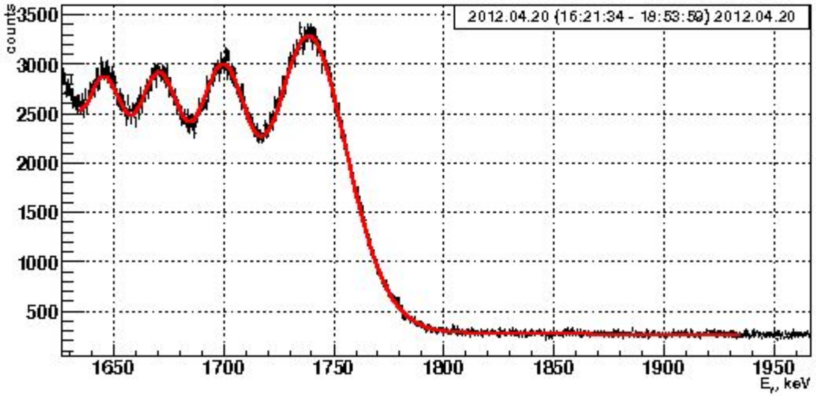
	Parameters at 1 GeV	
	Design	Achieved
Circumference	24.388 m	
Beam energy, MeV	150–1000	160–1005
N of bunches	1×1	
N of particles / bunch	1×10^{11}	0.9×10^{11}
Luminosity, $cm^{-2}s^{-1}$	1×10^{32}	0.5×10^{32}

- Round beams concept
- 13 T solenoids for FF
- E_{beam} controled by Compton back scat. ($\sigma_{\sqrt{s}} = 0.1$ MeV)

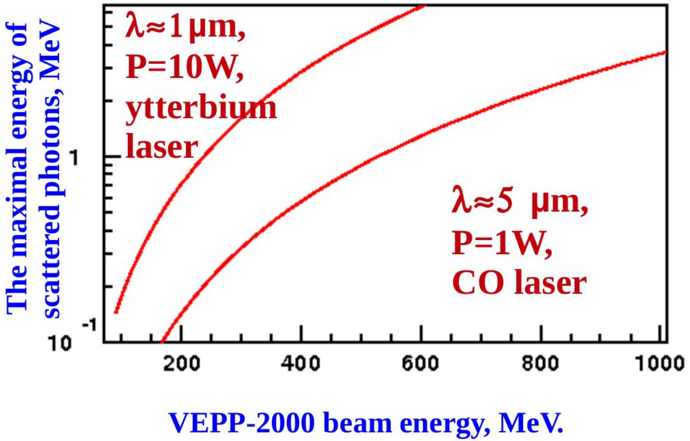


Beam energy measurement system

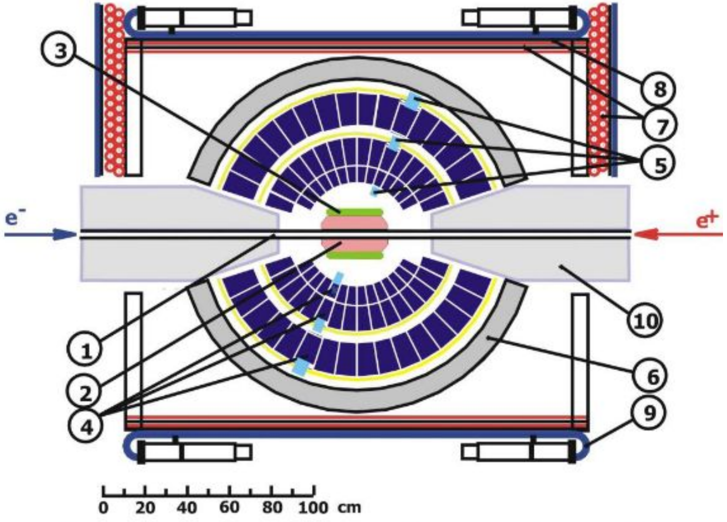




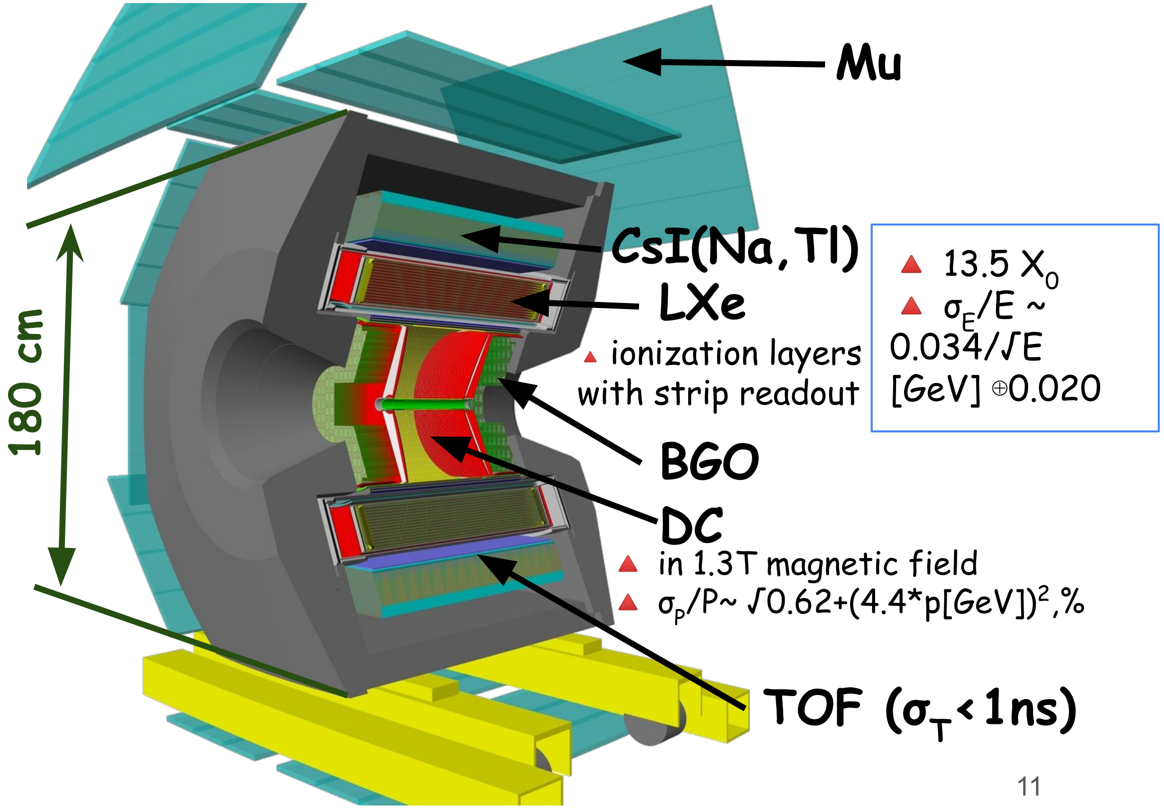
The beam energy is measured using the Compton backscattering of the laser photons on the electron beam. The measurement accuracy is about 30-50 keV.



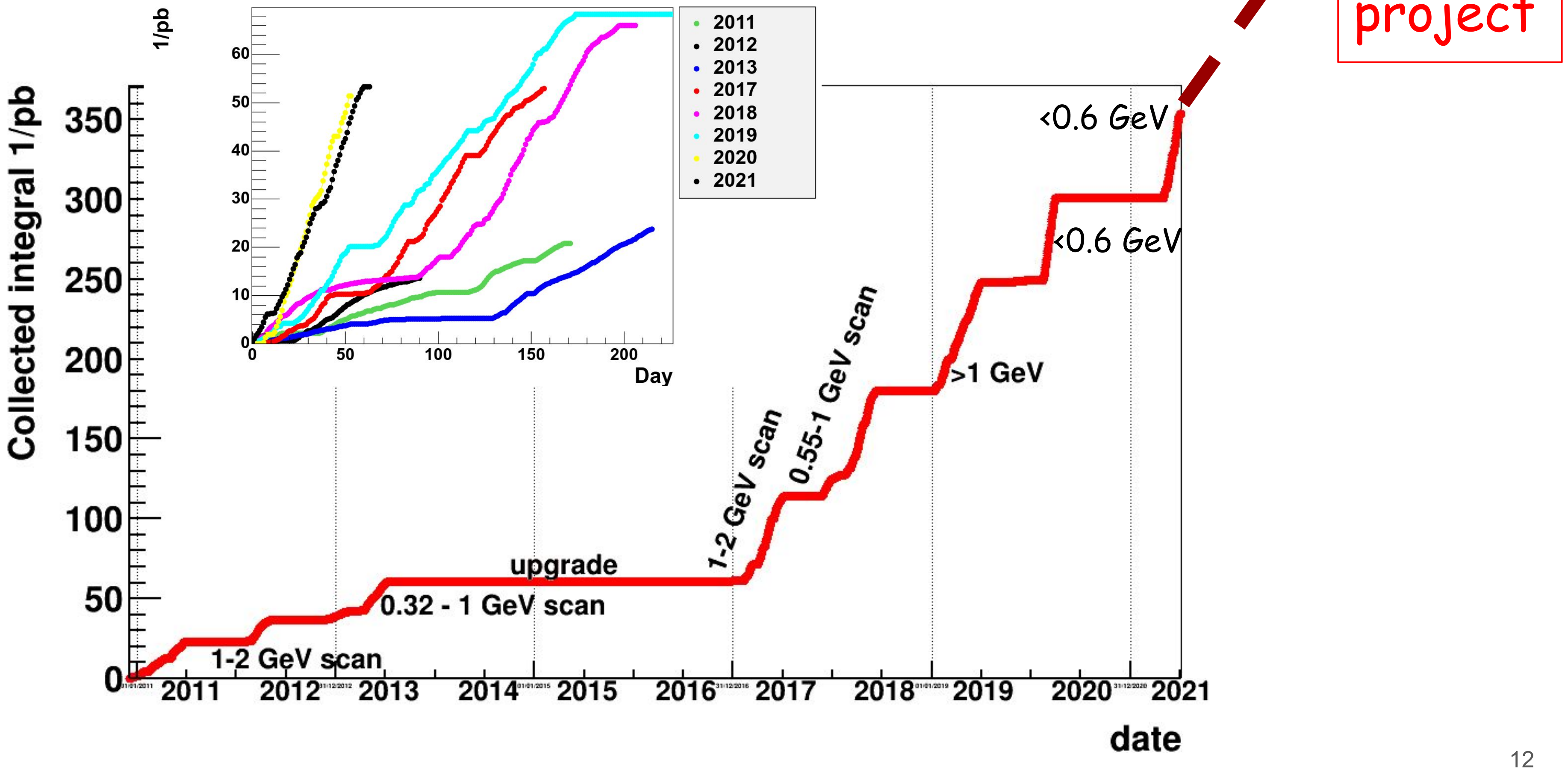
Spherical Neutral Detector (SND) and Cryogenic Magnetic Detector-3 (CMD-3)



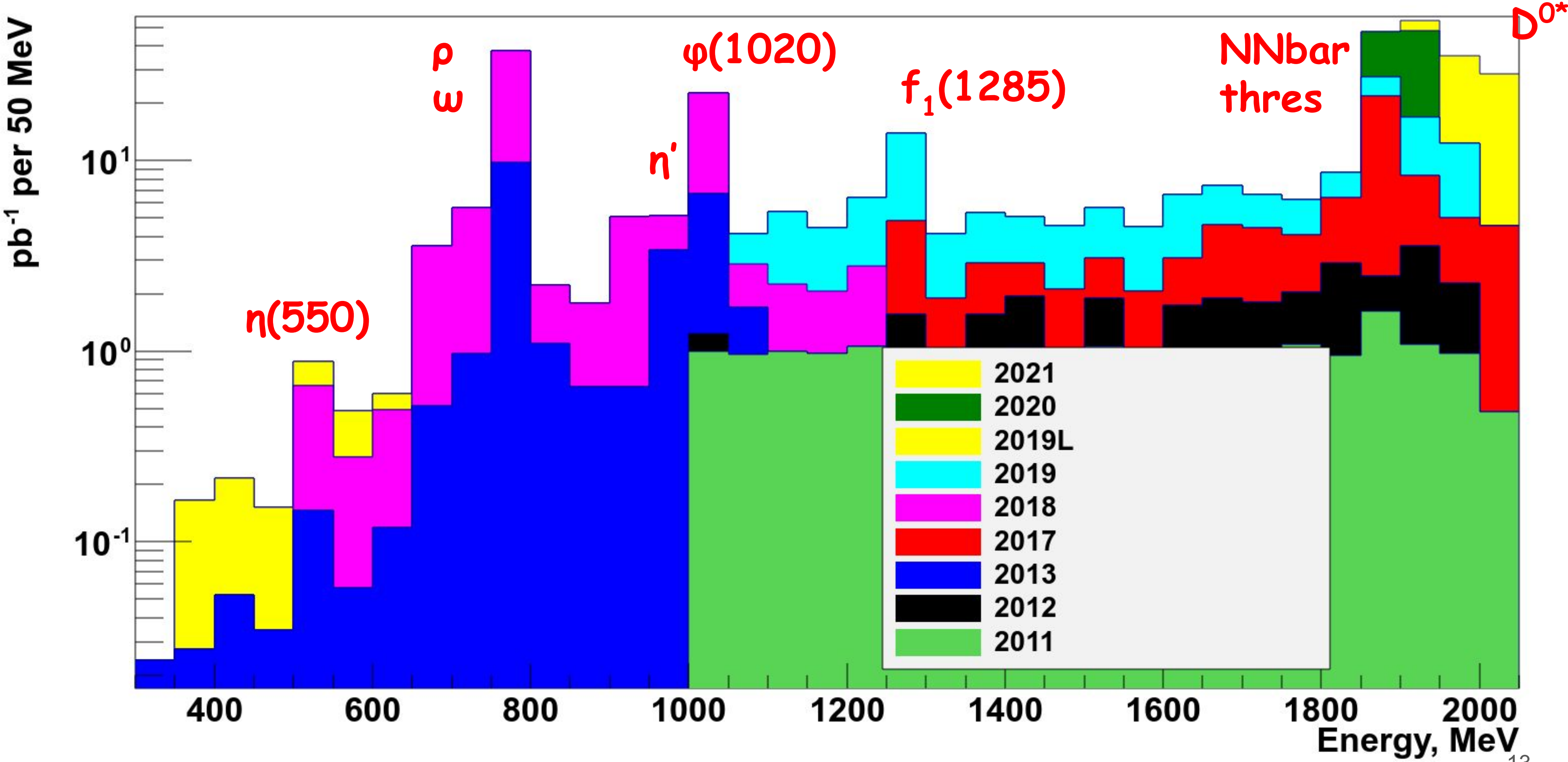
1 – beam pipe, 2 – tracking system, 3 – aerogel Cherenkov counter , 4 – NaI(Tl) crystals, 5 – phototriodes, 6 – iron muon absorber, 7–9 – muon detector, 10 – focusing solenoids.



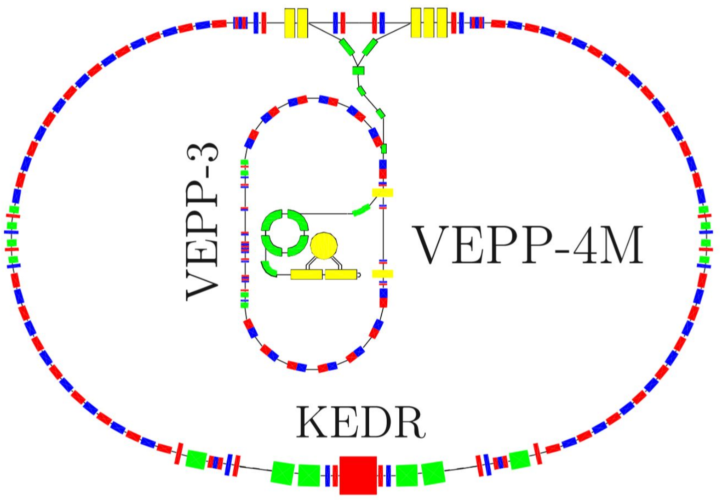
Luminosity collection history



Integrated luminosity collected at VEPP-2000 collider with CMD-3 detector



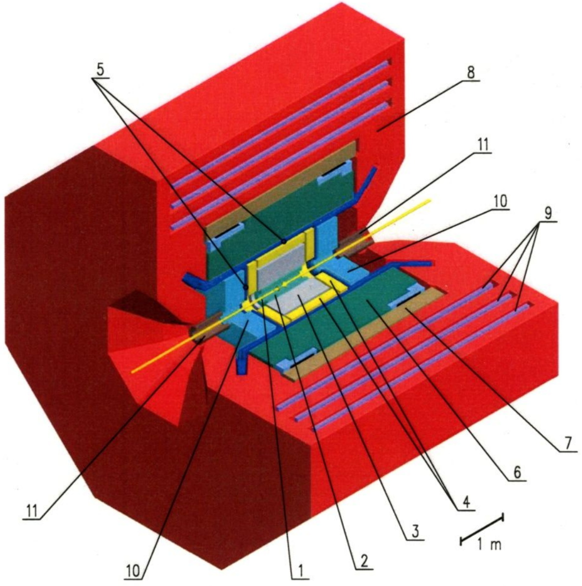
Collider VEPP-4M and KEDR detector



Beam energy	1 - 6 GeV
Number of bunches	2 x 2
Luminosity at 1.5 GeV	$2 \cdot 10^{30}$ cm^{-2} s^{-1}
Luminosity at 5.0 GeV	$2 \cdot 10^{31}$ cm^{-2} s^{-1}

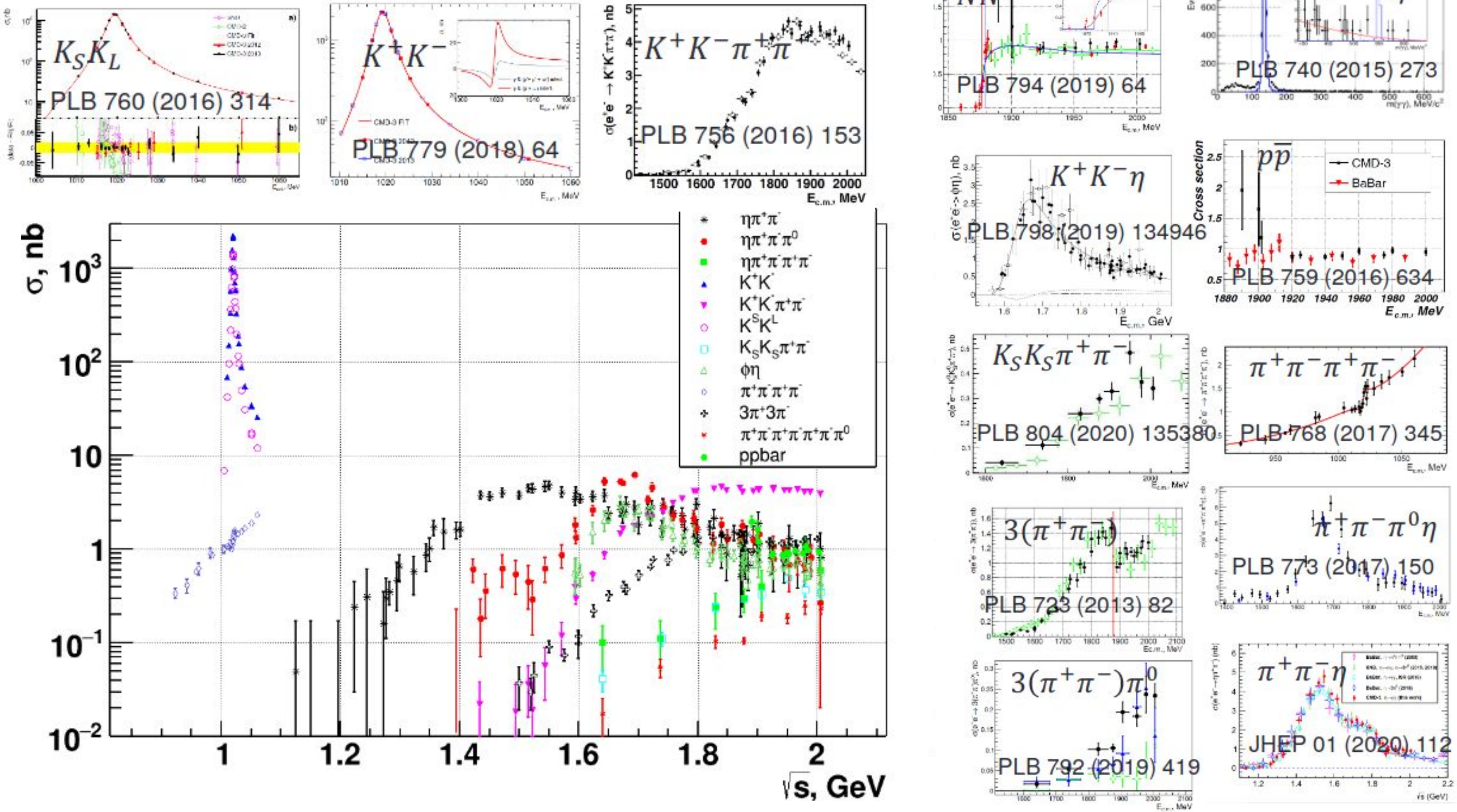
Beam energy measurement:

- Resonant depolarization method
  - Instant measurement accuracy 1 keV
  - Energy interpolation accuracy 10-30 keV
- Infrared light Compton backscattering
  - Monitoring with accuracy 100 keV



1. Vacuum chamber
2. Vertex detector
3. Drift chamber
4. Threshold aerogel counters
5. ToF counters
6. Liquid krypton calorimeter
7. Superconducting coil
8. Magnet yoke
9. Muon tubes
10. CsI calorimeter
11. Compensating s/c solenoid

CMD-3 published results



Measured cross section by CMD-3

Published:

$e^+e^- \to p\bar{p}$	Phys.Lett. B759 (2016) 634-640
$\eta'(958)$	Phys.Lett. B740 (2015) 273-277
$2(\pi^+\pi^-)$	Phys.Lett. B768 (2017) 345-350
$3(\pi^+\pi^-)$	Phys.Lett. B723 (2013) 82-89
$\omega\eta$, $\eta\pi^+\pi^-\pi^0$	Phys.Lett. B773 (2017) 150-158
$3(\pi^+\pi^-)\pi^0$	*Phys.Lett.B 792 (2019) 419-423*
$K_S K_L$	Phys.Lett. B760 (2016) 314-319
K^+K^-	Phys.Lett. B779 (2018) 64-71
$K^+K^-\pi^+\pi^-$	Phys.Lett. B756 (2016) 153-160
$K^+K^-\eta$	*Phys.Lett. B 798 (2019) 134946*
$K_S K_S \pi^+\pi^-$	*Phys.Lett. B804 (2020) 135380*
$\eta\pi^+\pi^-$	*Journal of HEP, 2020, 2020(1), 112*

Near finished result:

$e^+e^- \to \pi^+\pi^-$
D^{0*}
$K_S K^+\pi^-$
$\omega\pi^+\pi^-$

Under active analysis:

$e^+e^- \to \pi^+\pi^-\gamma$,
$\eta\gamma$, $\pi^0\gamma$,
$\pi^+\pi^-\pi^0\pi^0$, $2(\pi^+\pi^-)$,
$2(\pi^+\pi^-)\pi^0$, $2(\pi^+\pi^-\pi^0)$
K^+K^-, KSKL – at higher energies
$K^+K^-\pi^0$, $K_SK_L\pi^0$, $K_SK_L\eta$,
nnbar,
$\pi^0e^+e^-$, ηe^+e^-
.....
...
..

Analysis of a channel takes full person-years:
higher systematic requirement, more effects more years

R(s) at nucleon antinucleon threshold

- VEPP-2000: unique ability for detailed scan of ppbar and nnbar threshold.

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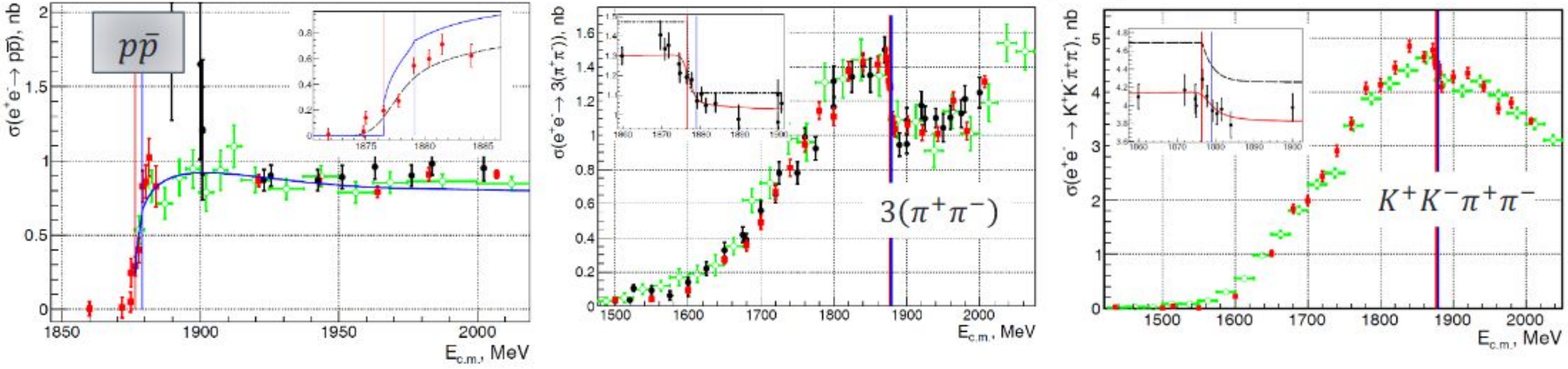
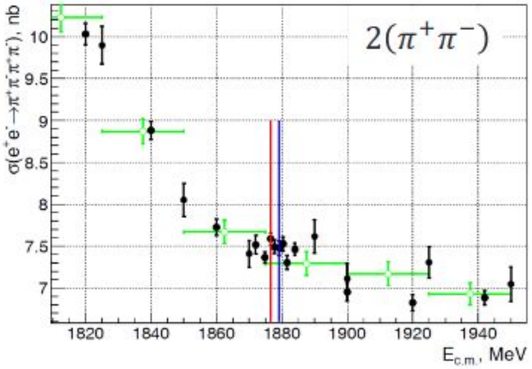


- observed the sharp change of $e^+e^- \to p\bar{p}$, $3(\pi^+\pi^-)$, $K^+K^-\pi^+\pi^-$
- width is ~1 MeV – consistent with energy resolution
- puzzle – why there is no change in $e^+e^- \to 2(\pi^+\pi^-)$?



- We plan to do comprehensive study of this energy range

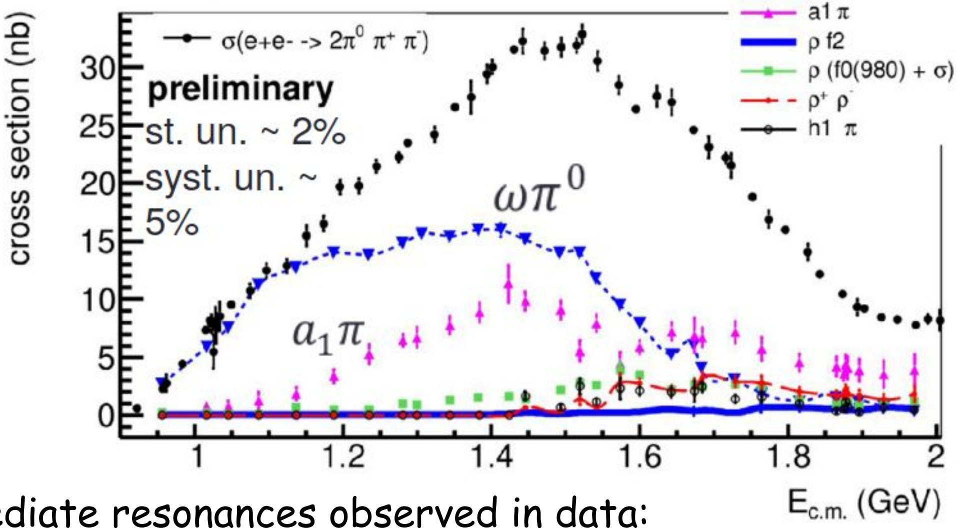
Study of internal dynamics at CMD-3

\ 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!

The study of $e^+e^- \to 4\pi$ at CMD-3

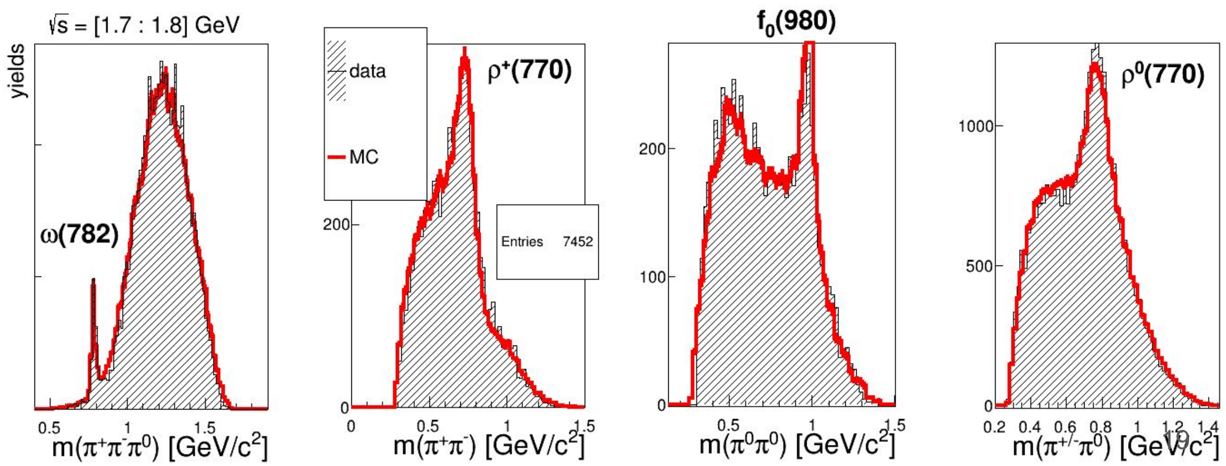
- Simultaneous unbinned amplitude analysis of 150 000 $\pi^+\pi^-\pi^0\pi^0$ events and 250 000 $\pi^+\pi^-\pi^+\pi^-$ events



- 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:



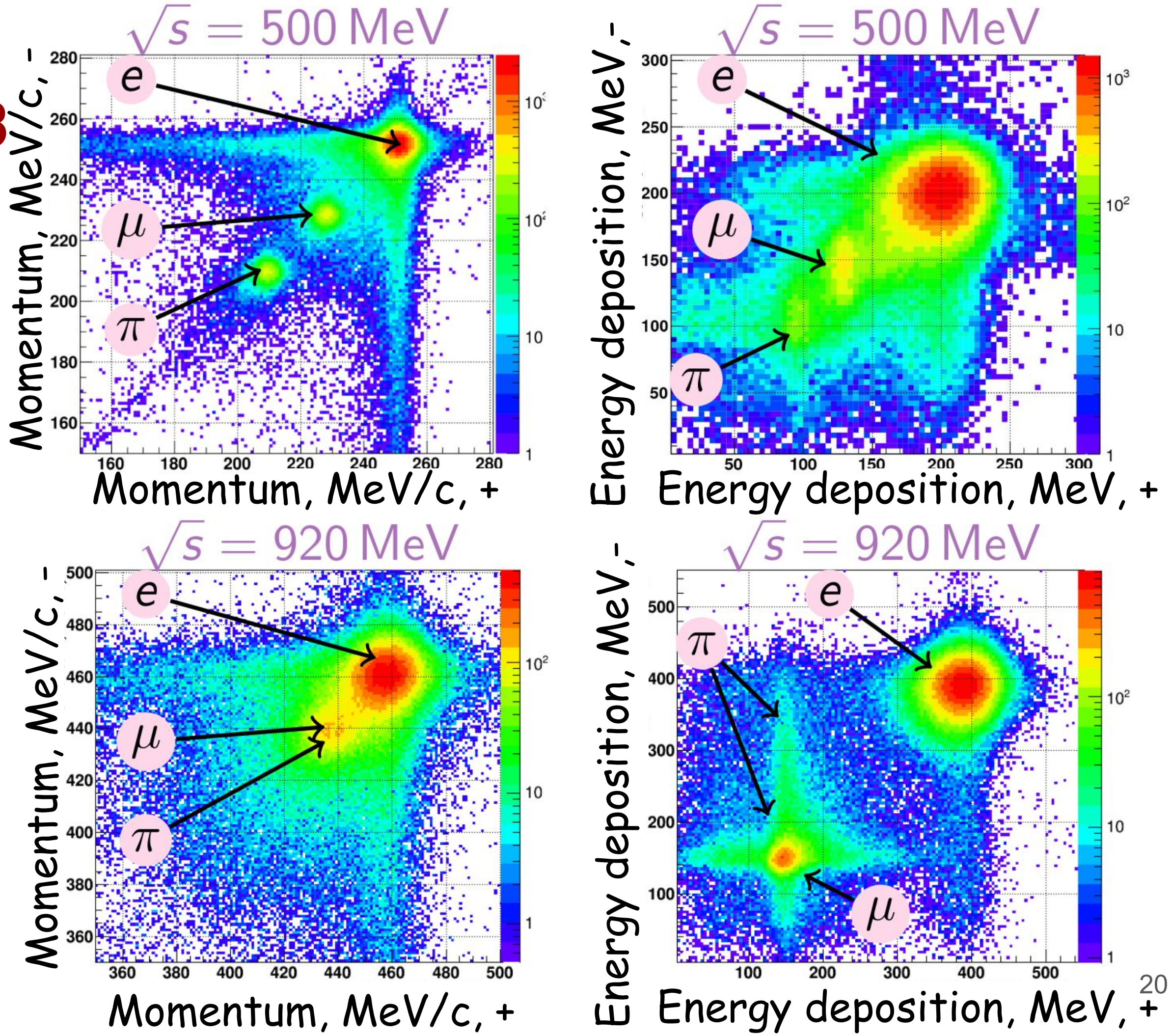
The study of $e^+e^- \to \pi^+\pi^-$ at CMD-3

Analysis strategy

- 2 tracks with $1 \le \theta \le \pi - 1$
- Separation of e/μ/π/cosmic
- Two independent approaches:
  - Separation by momenta
  - Separation by energy depositions

- Binned likelihood minimization:

$$-\ln L = -\sum_{\text{bins}} n_i \ln\Big[\sum_{\substack{X=ee,\\ \mu\mu,\,\pi\pi,\\ \text{bg}}} N_X f_X(p^+, p^-)\Big] + \sum_X N_X$$



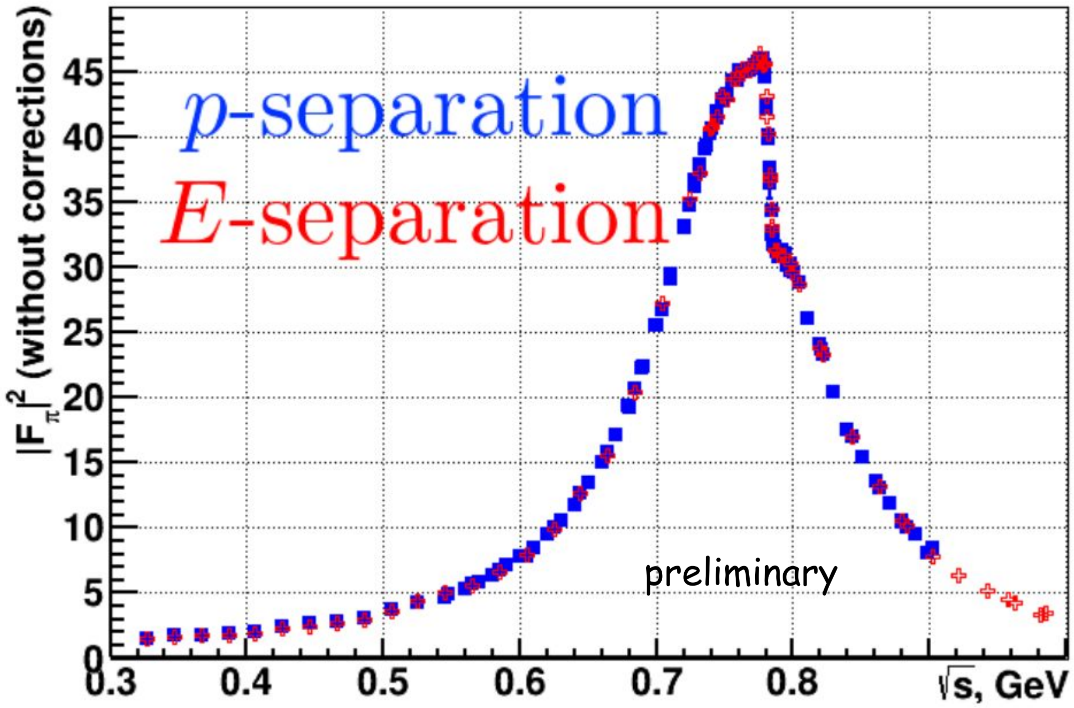
The study of $e^+e^- \to \pi^+\pi^-$ at CMD-3

Separation by **momentum**

- take e^+e^-, $\mu^+\mu^-$, $\pi^+\pi^-$ and $\pi^+\pi^-\pi^0$ PDFs from MC generators smeared by the detector resolution.
- cosmic PDF from data

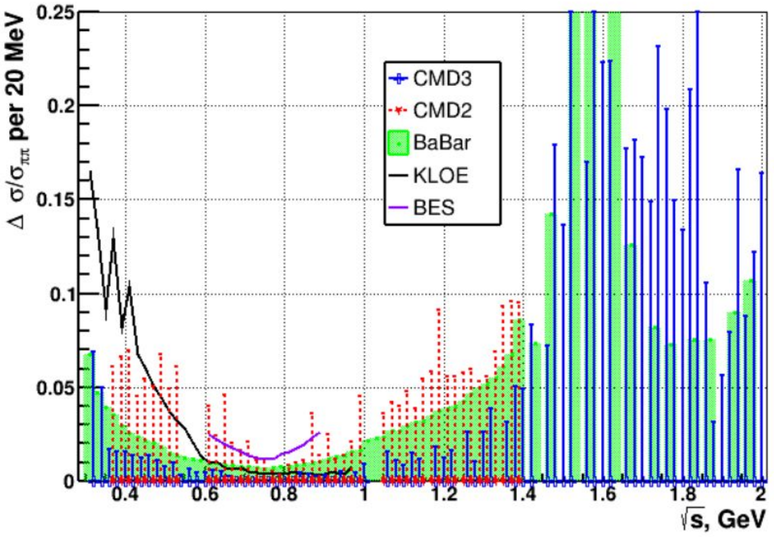
Separation by **energy deposition in LXe**

- No need for PDFs from MC
- Energy deposition includes FSR
- Fit data by analytical functions



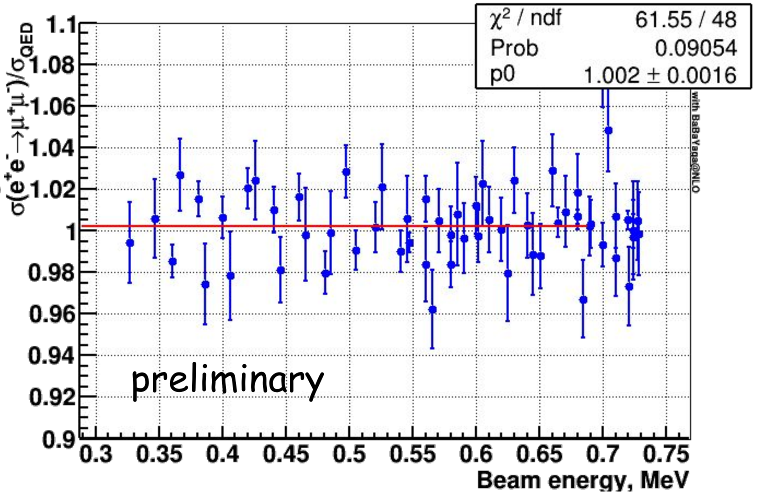
The analysis on its final stages. Additional local consistency checks should be fulfilled. The aim systematic uncertainty is 0.5 %.

The study of $e^+e^- \to \pi^+\pi^-$ at CMD-3

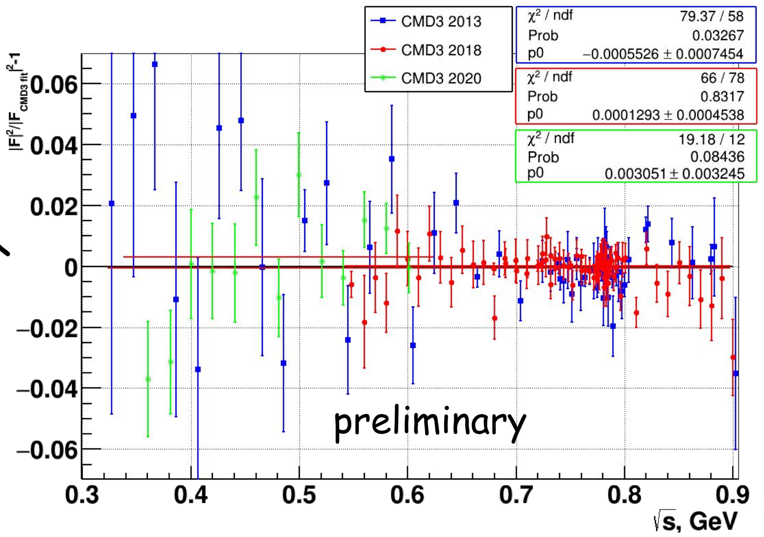


Comparison of statistical uncertainties of cross sections in different experiments

Comparison of $\sigma(e^+e^- \to \mu^+\mu^-)$ with QED

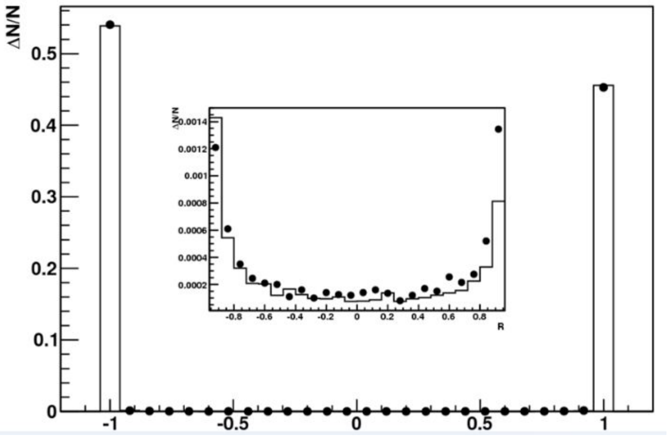


Different seasons comparison

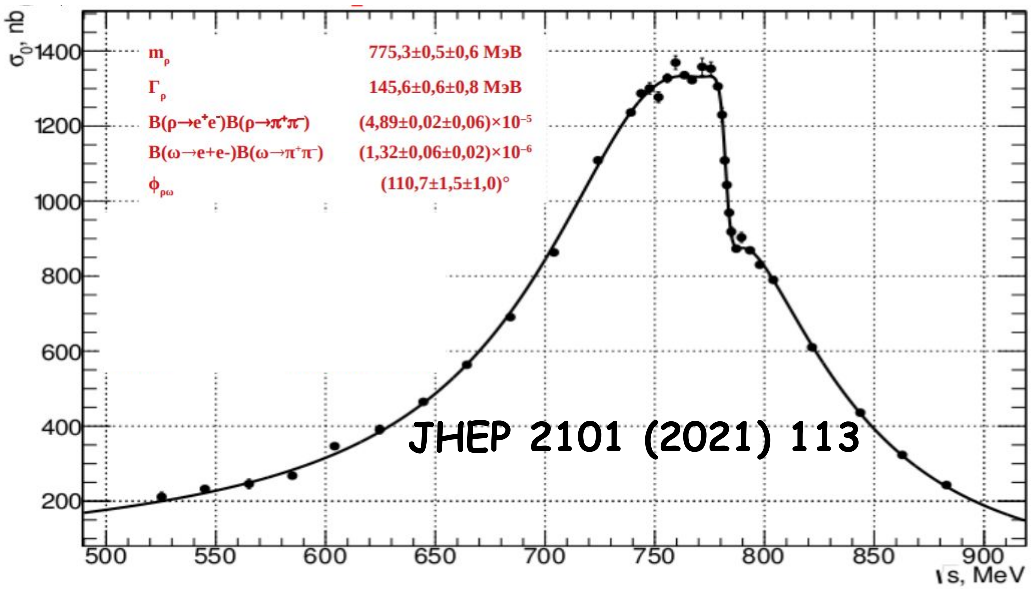


The study of $e^+e^- \to \pi^+\pi^-$ at SND

- The analysis is based on 4.7 pb^{-1} data recorded in 2013 (1/10 full data set in rho-meson region)
- Systematic uncertainty ~ 0.8 %

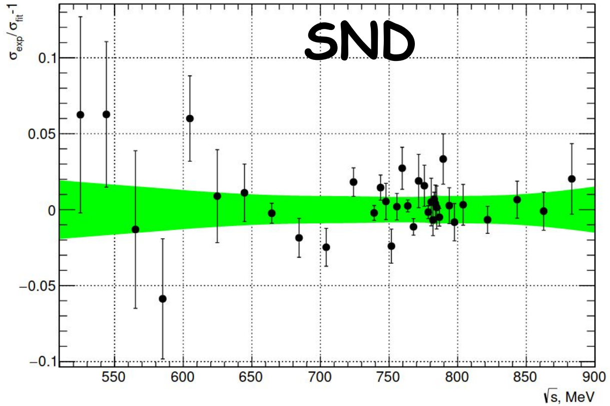


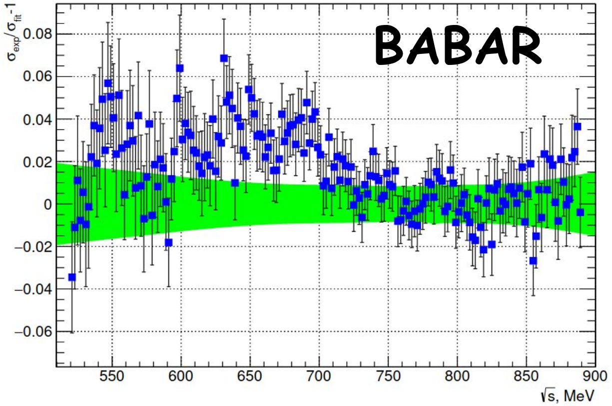
BDT was trained by full information of shower profile in three layer calorimeter



Source	< 0.6 GeV	0.6 - 0.9 GeV
Trigger	0.5	0.5
Selection criteria	0.6	0.6
e/π/μ separation	0.5	0.1
Nucl. interaction	0.2	0.2
Theory	0.2	0.2
Total	**0.9**	**0.8**

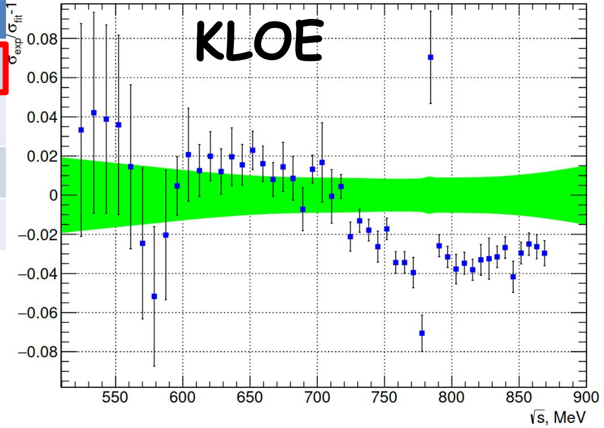
Comparison with the shape of fit

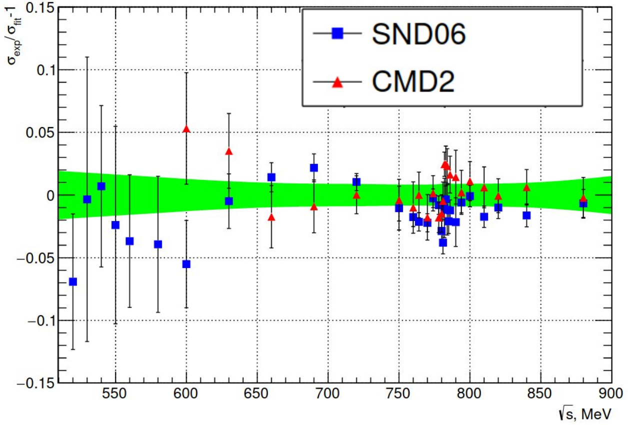




- Contribution to anomalous magnetic moment of muon
  $0.53 < \sqrt{s} < 0.88$ GeV

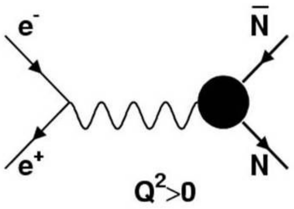
	$a_\mu \times 10^{10}$
SND @ VEPP-2000	409.79 ± 1.44 ± 3.87
SND @ VEPP-2M	406.47 ± 1.74 ± 5.28
BABAR	413.58 ± 2.04 ± 2.29
KLOE	403.39 ± 0.72 ± 2.50





SND result is consistent with BABAR and KLOE

The study of $e^+e^- \to$ nnbar below 2 GeV at SND



- Differential cross section: $$\frac{d\sigma}{d\Omega}=\frac{\alpha^2\beta C}{4s}\left[|G_M(s)|^2(1+\cos^2\theta)+\frac{1}{\tau}|G_E(s)|^2\sin^2\theta\right]$$

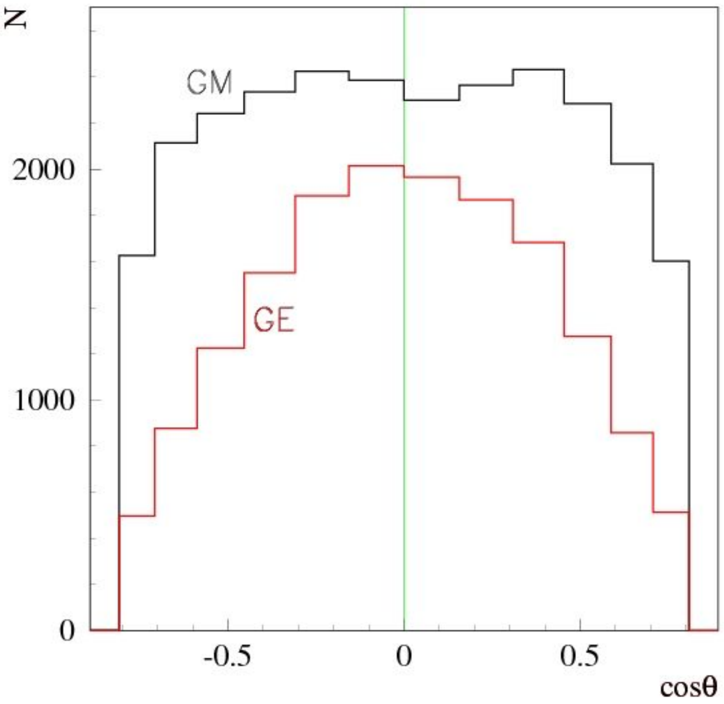
$$\beta=\sqrt{1-4m_N^2/s},\quad \tau=\frac{s}{4m_N^2}$$

- G_E and G_M are electric and magnetic form factors, $|G_E|=|G_M|$ at the reaction threshold

- The total cross section:

$$\sigma_0(s)=\frac{4\pi\alpha^2\beta C}{3s}\left[|G_M(s)|^2+\frac{1}{\tau}|G_E(s)|^2\right]$$

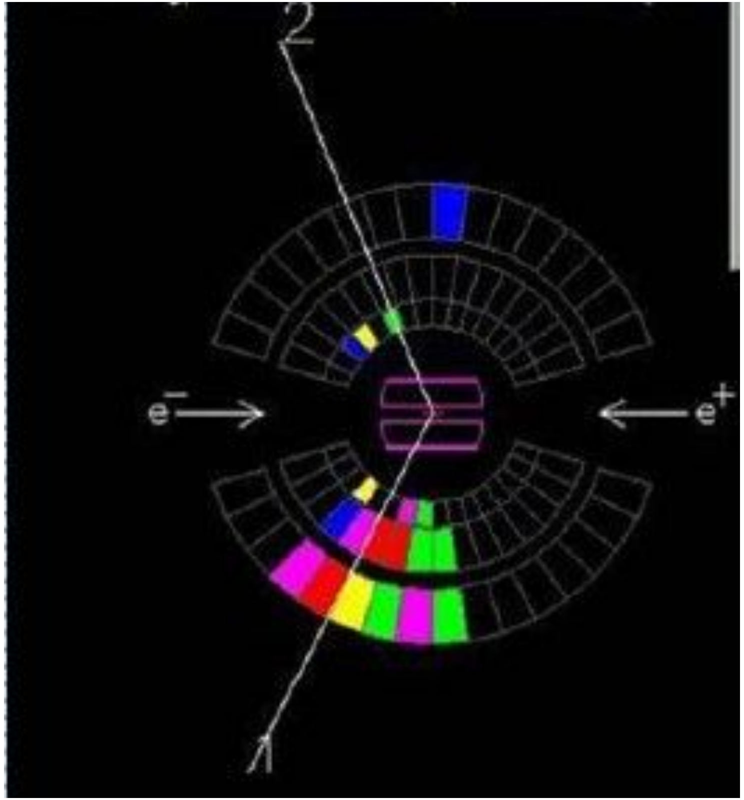
- The $|G_E|/|G_M|$ ratio can be obtained using $\cos\theta$ distribution.



The study of $e^+e^- \to$ nnbar below 2 GeV at SND

Features of the $e^+e^- \to$ nnbar events in SND

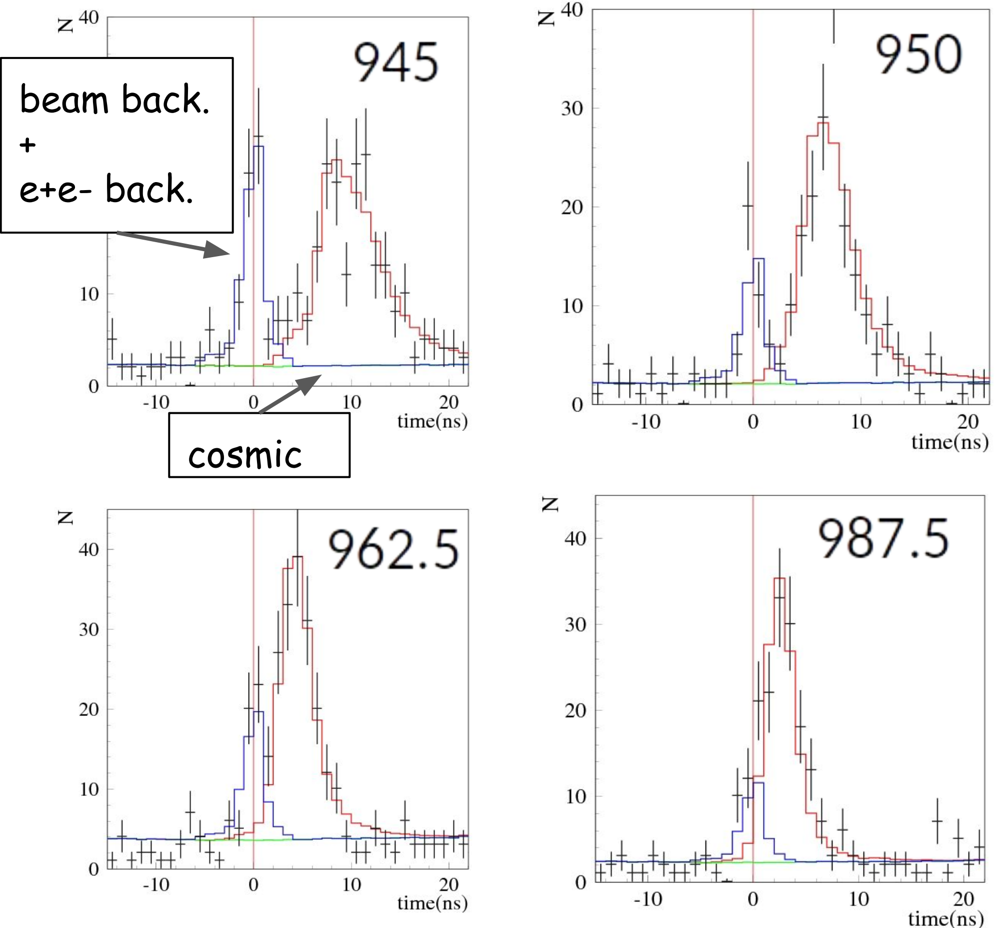
- nucleon is rather slow. This leads to large time-of-flight.
- energy deposition of n is very low and it is not reconstructed.
- antineutron annihilates in calorimeter with large energy deposition.



Main selection requirements:

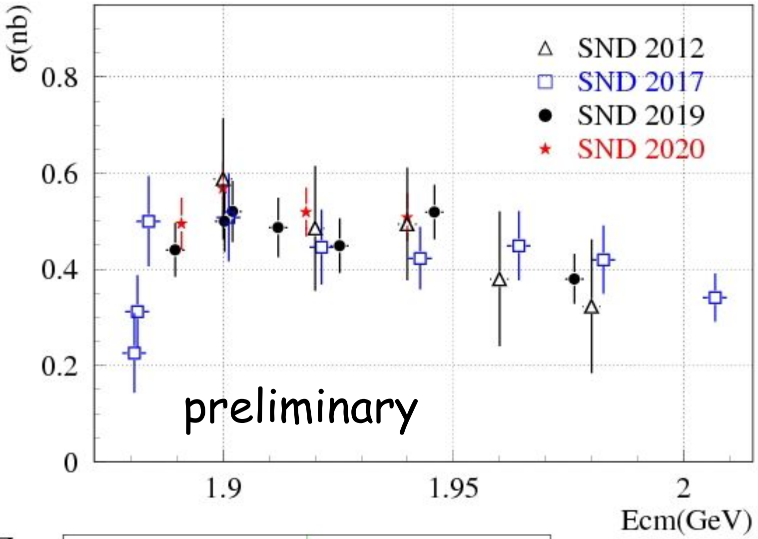
- No charged central tracks
- Muon system veto
- No cosmic tracks in calorimeter
- Large unbalanced momentum in calorimeter (P > 0.4Ebeam)
- EMC energy : Etot > Ebeam

The study of $e^+e^- \to$ nnbar below 2 GeV at SND

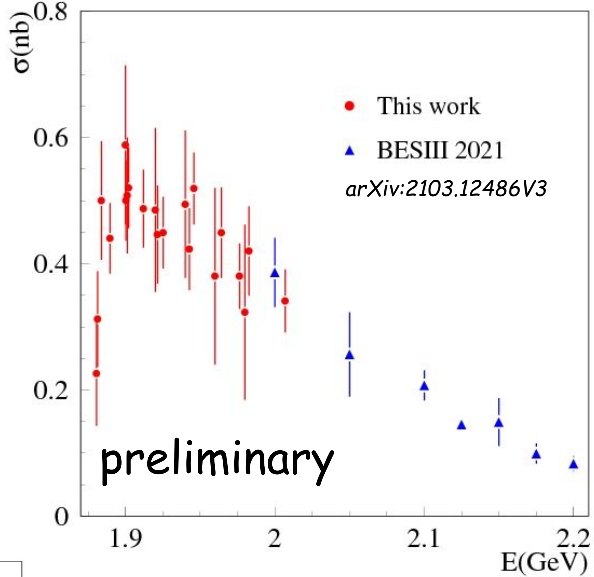


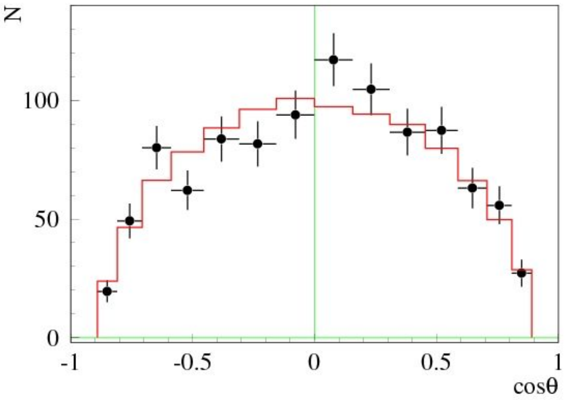
- The number of signal events was obtained by the fit to distribution of event time measurement (calorimeter trigger time before 2017, flash ADC after 2018)
- MC detection efficiency ~ 0.2
- S/N ~ 1
- IL ~ 70 pb^{-1}
- N_{signal} ~ 12000

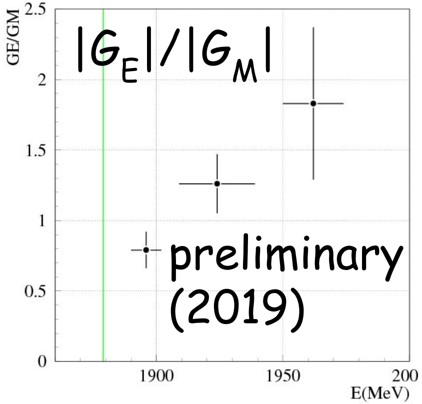
The study of $e^+e^- \rightarrow$ nnbar below 2 GeV at SND



- Different seasons comparison
- Systematic uncertainty ~ 10%



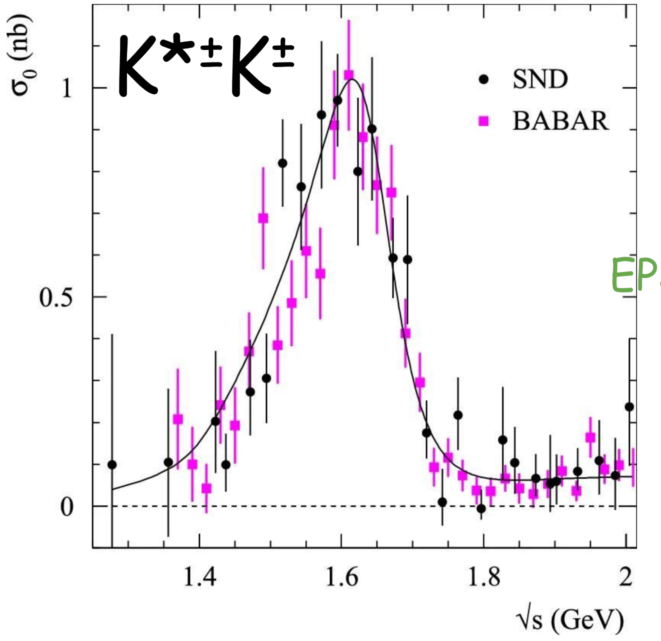




- The average ratio $|G_E|/|G_M|$=1.16+/-0.25 agrees with unity

The study of $e^+e^- \to K+K-\pi^0$ at SND

- The cross sections for the processes $e^+e^- \to K^{*\pm}K^\pm \to K^+K^-\pi^0$ and $e^+e^- \to \varphi\pi^0 \to K^+K^-\pi^0$ are measured separately.



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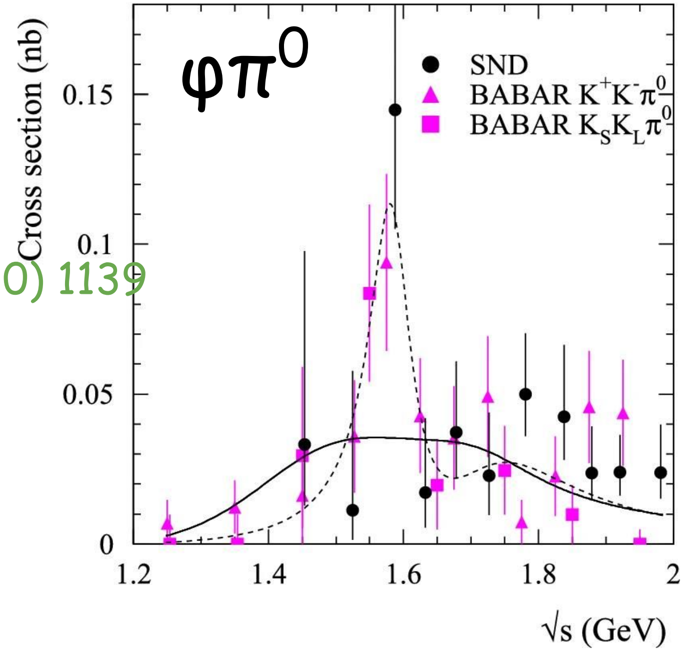
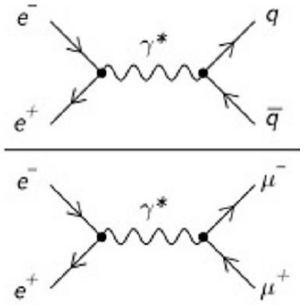


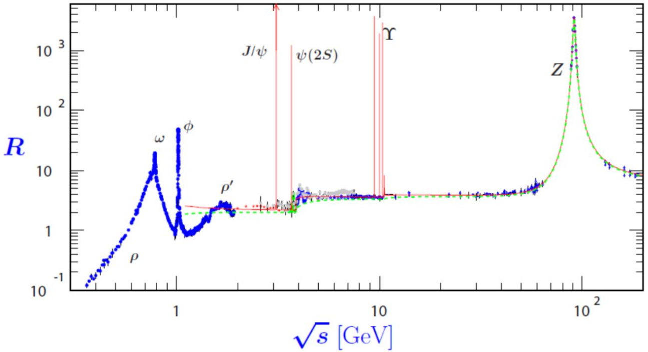
$\varphi(1680)$ gives the main contribution to the $e^+e^- \to K^{*\pm}K^\pm$ cross section

The $e^+e^- \to \varphi(1020)\pi^0$ cross section can not be described by $\rho(1450)$ and $\rho(1700)$. It can be fitted with inclusion of an unknown resonance with m=1585±15 MeV and Γ=75±30 MeV

Precise measurement of R between 1.84 and 3.72 GeV at the KEDR detector

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





In first approximation:

$$R(s) \simeq 3 \sum e_q^2$$

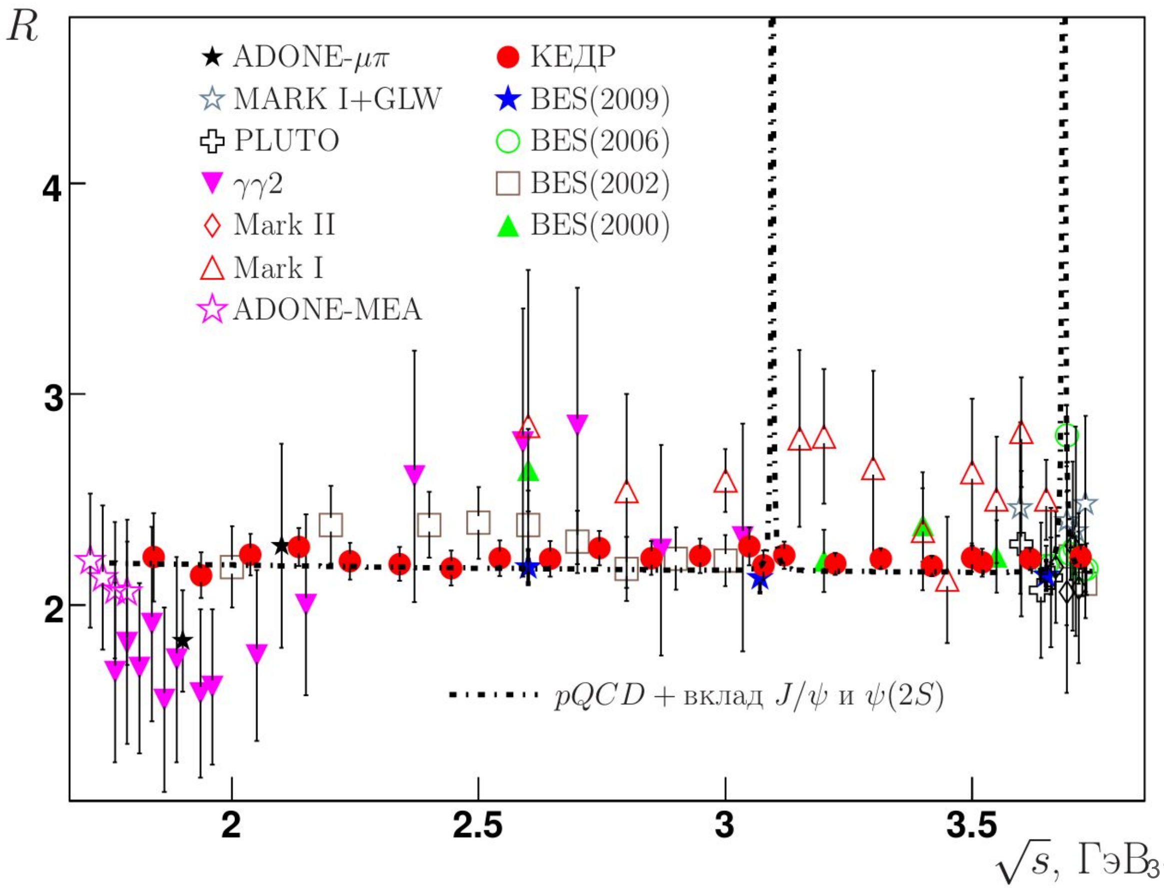
$\sqrt{s}$, GeV	N_{points}	$\int Ldt, pb^{-1}$	Unc., %	Ref.
1.84 - 3.05	13	0.66	≤ 3.9 total (≈2.4 syst.)	V.V. Anashin. Phys.Lett. B 770 (2017) 174
3.08 - 3.72	9	1.3	≤ 2.6 total (≈1.9 syst.)	V.V. Anashin. Phys.Lett. B 788 (2019) 42

$R(s)$ is used to determine:

- $\alpha_s(s)$
- $(g_\mu - 2)/2$
- $\alpha(M_Z^2)$
- m_Q

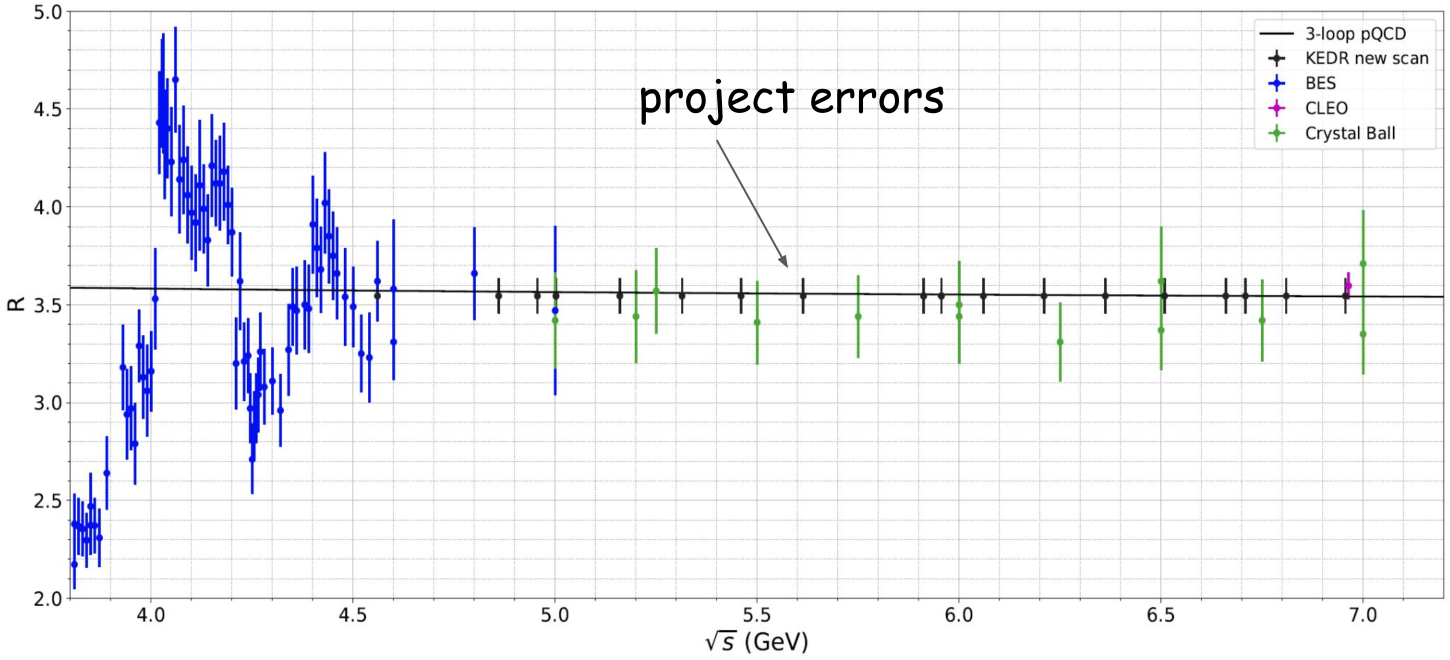
Precise measurement of R between 1.84 and 3.72 GeV at the KEDR detector

- This result provides the most precise information about R in this energy range
- The result is consistent with the pQCD predictions within their errors
- The result allows to reduce light quarks contribution to the uncertainty of c quark mass from 2 MeV down to 1 MeV



Next coming results from the KEDR detector

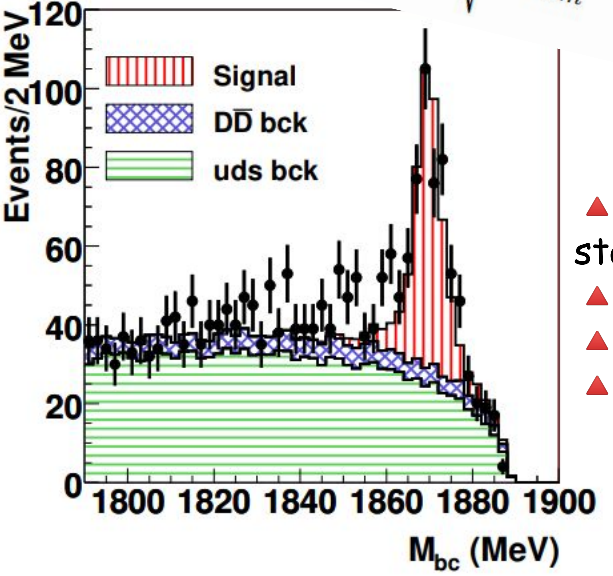
- R measurement between 4.5 and 7.0 GeV
  - Integrated luminosity 13.7 pb^{-1}
  - 17 energy points
  - Expected total uncertainty is about 3 % (systematic uncertainty about 2.5%)

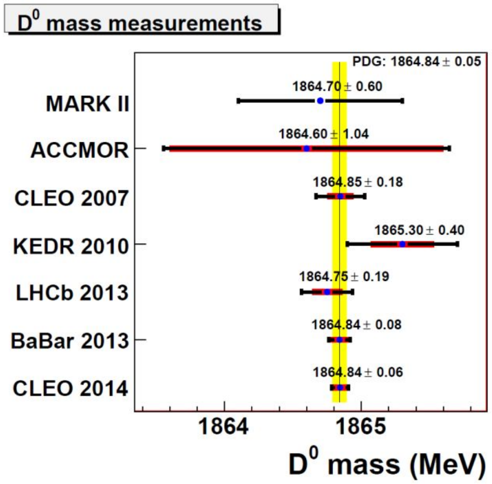


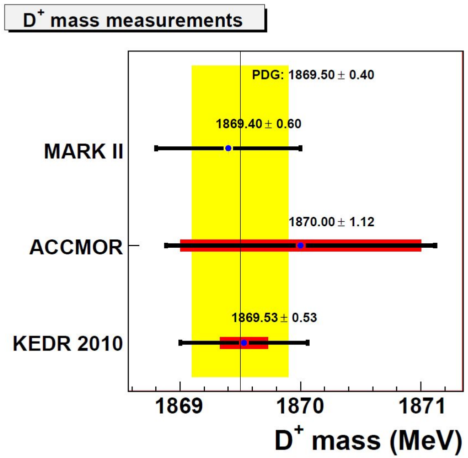
Next coming results from the KEDR detector

- D-mesons masses measurement
  - This knowledge affects understanding of the (X(3872)) nature

$$M_{bc} = \sqrt{E_{beam}^2 - \left(\sum_i \vec{p_i}\right)^2}$$







- New analysis with increased statistics
- Process $e^+e^- \to \psi(3770) \to$ DDbar
- $D^+ \to K^-\pi^+\pi^+$ (Br = 9.38 ± 0.16%)
- $D^0 \to K^-\pi^+$ (Br = 3.95 ± 0.03%)

- M(D+) = 1869.53±0.49±0.20 MeV *(Phys.Lett.B 686 (2010) 84)*

Uncertainties estimate for new analysis with increased statistics:

153 keV *(stat)*

117 keV *(syst.)*

- M(D0) = 1865.300±0.330±0.230 MeV (Phys.Lett.B 686 (2010) 84)

140 keV *(stat)*

110 keV *(syst.)*

Summary

VEPP-2000

- The VEPP-2000 collider delivered about 370 pb^{-1} of integrated luminosity in the energy range 0.32 – 2.01 GeV to the SND and CMD-3 detectors from 2010 to 2021. Today VEPP-2000 is only one working on direct scanning of the region for measurement of exclusive $\sigma(e^+e^- \to hadrons)$.

- The VEPP-2000 results will help to reduce error of the hadronic contribution to vacuum polarisation and it is independent cross-check of ISR data, future Lattice, space-like.

- The $e^+e^- \to \pi^+\pi^-$ and $e^+e^- \to nnbar$ (preliminary) cross sections are measured with systematic uncertainty better then 1% and 10% respectively. Publication of a large number of precise measurements are expected soon.

⇉ We have goal to collect O(1) 1/fb at VEPP-2000 in 5 years, which should provide new precise results on the hadron production.

VEPP-4M

- The most precise measurement of R was made between 1.84 and 3.72 GeV at the KEDR detector.

- Analysis of data in the energy range between 4.56 and 6.96 GeV was started, expected accuracy is less than 3%. New measuring of D-meson masses is ongoing with aim to increase accuracy by 2 times compared to previous measurement back up

Precise measurement of R between 1.84 and 3.72 GeV at the KEDR detector