Current status and results of the experiments with CMD-3 detector at VEPP-2000

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First, I would like to to remember and pay tribute to our colleague and friend, Simon Eidelman, passed away this summer, who was very active member of the CMD-2 and CMD-3 collaborations and contributed a lot to the physics results of these experiments.
Simon attended many Workshops on Tau Lepton Physics and was a member of IAC for many years.

TAU 2010

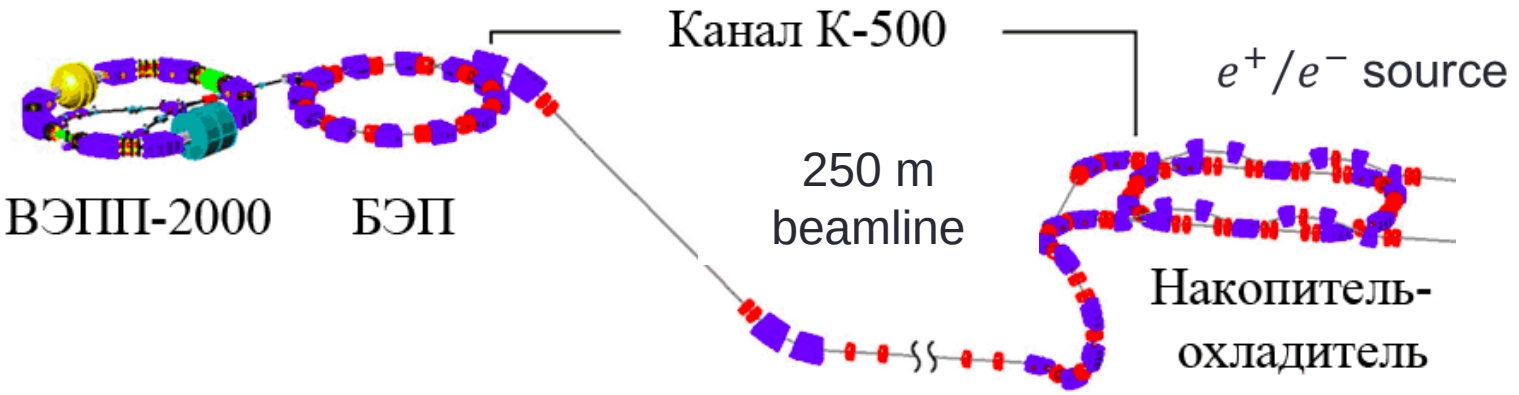
Content

- Main goals of experiments
- VEPP 2000 e^+e^- collider and CMD-3 detector
- Precision measurements of $e^+e^- \to \pi^+\pi^-$ cross section
- Study of the multi-pion processes
- Study of the processes with kaons
- Hadronic cross section near $N\overline{N}$ production threshold
- Conclusion

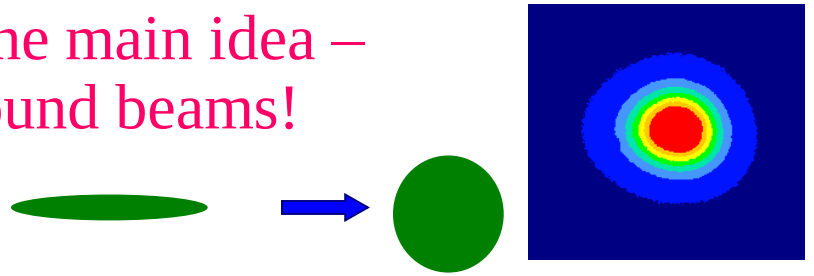
Motivations for precise hadronic cross section measurements

- Tests of perturbative QCD
  - QCD sum rules, quark masses, quark and gluon condensates
  - Higher order QCD corrections - Λ_{QCD}, $\alpha(s)$
- Hadronic corrections to fundamental parameters:
  - Running fine structure constant - $\alpha(M_Z^2)$
  - Anomalous magnetic moment of the muon
- measurement of parameters of light vector mesons ρ, ω, ϕ, ρ’, ρ’’, …..
- Search of and study of the exotic resonance states (X, Y, Z, …)
- Study of the final states dynamics and test of theoretical models
- comparison with spectral functions of the hadronic tau decays via CVC
- Study of nucleon-antinucleon pair production – nucleon ectromagnetic form factors, search for NNbar resonances, ..

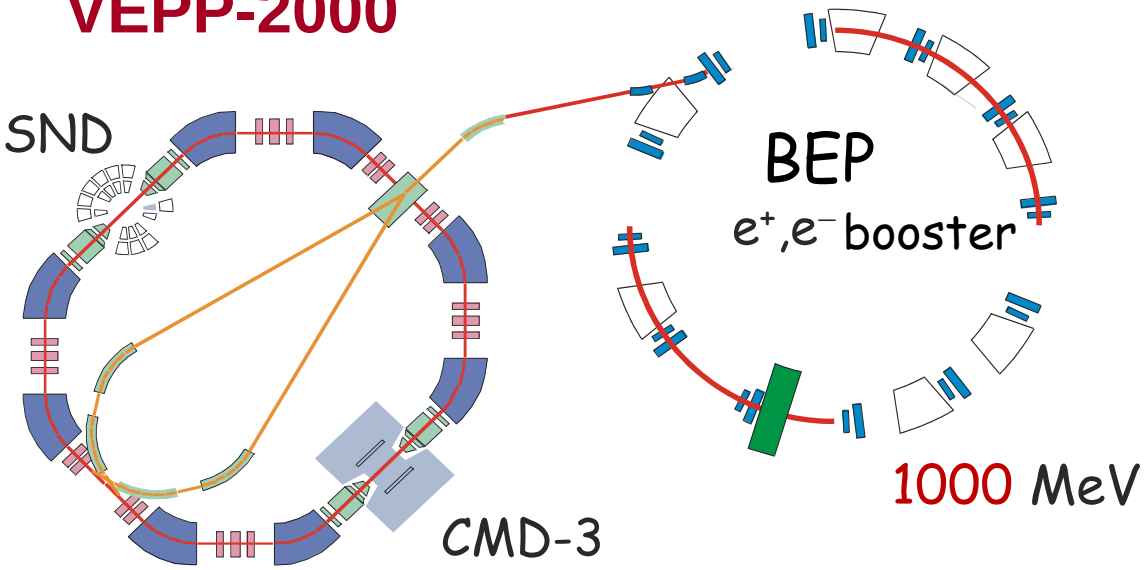
VEPP-2000 after upgrade (from 2017)



The main idea – round beams!

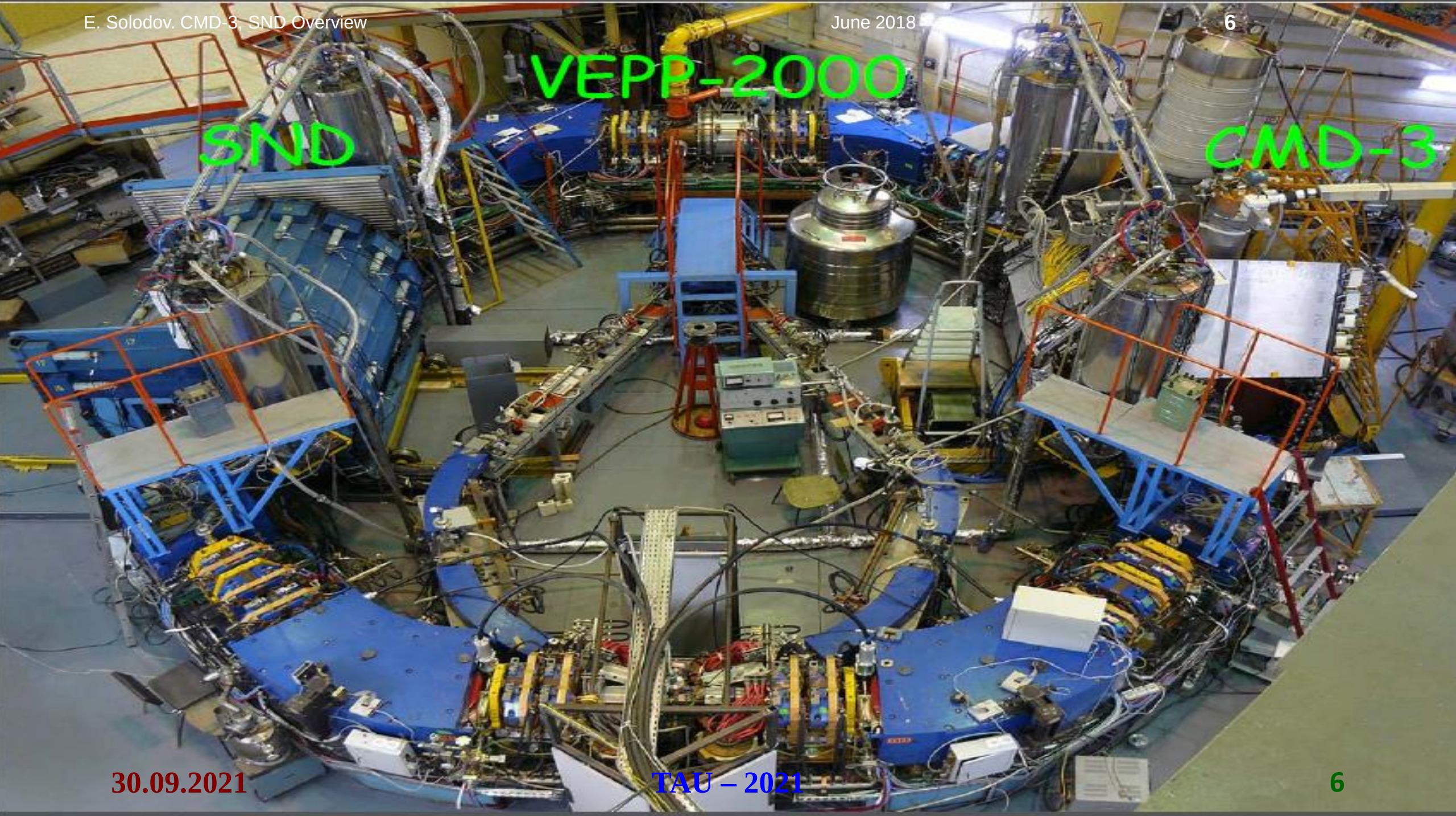


VEPP-2000



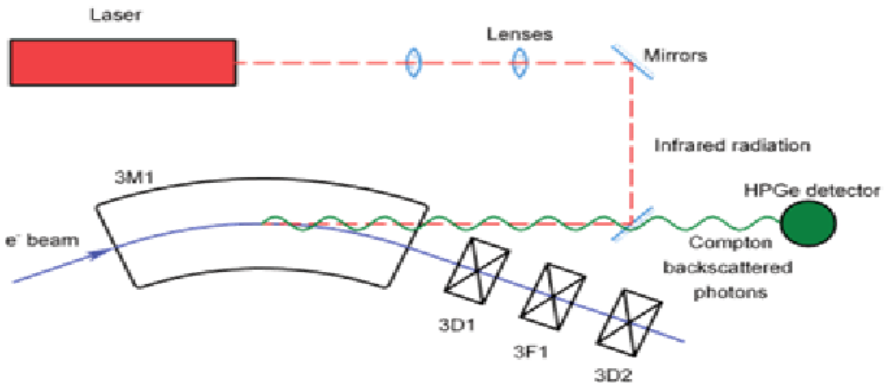
VEPP-2M & VEPP-2000 parameters

	VEPP-2M	VEPP-2000	
E (MeV)	510	510	900
П (cm)	1788	2235	2235
$\mathcal{I}^+, \mathcal{I}^-$ (mA)	40	34	200
$\varepsilon \cdot 10^5$ (cm · rad)	3	0.5	1.6
β_x (cm)	40	6.3	6.3
β_z (cm)	5	6.3	6.3
ξ_x	0.016	0.075	0.075
ξ_z	0.050	0.075	0.075
$\mathcal{L}(\mathrm{cm}^{-2}\mathrm{s}^{-1})$	$3 \cdot 10^{30}$	$1 \cdot 10^{31}$	$1 \cdot 10^{32}$

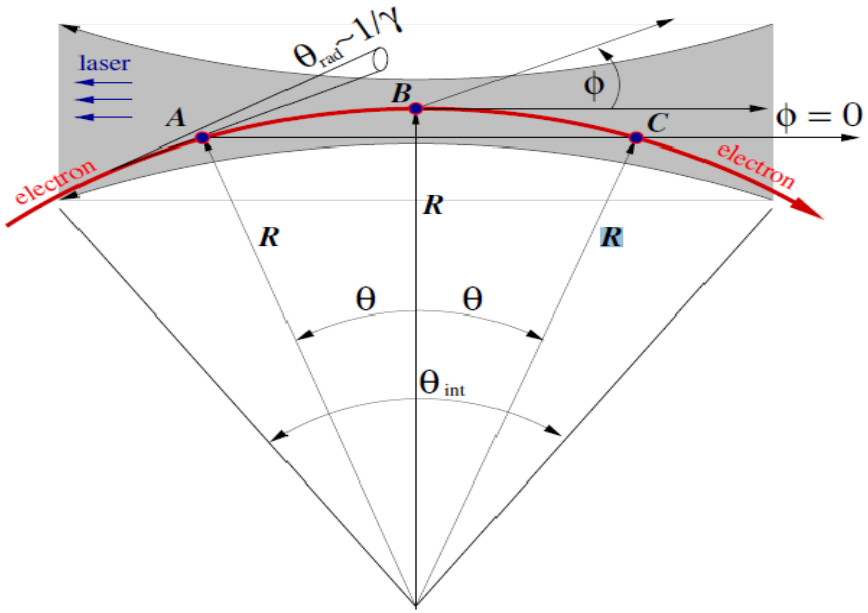

VEPP-2000
SND
CMD-3

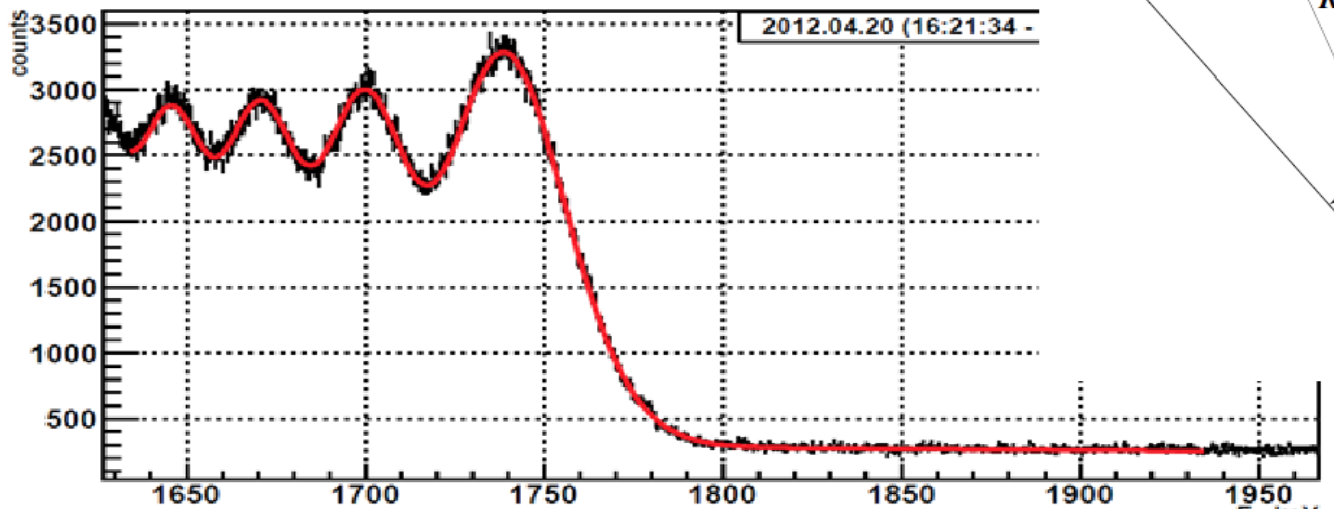
Beam energy measurement

Starting from 2012, energy is monitored continuously using compton backscattering techneques



Radiation coming from A and C points under angle φ = 0 is interferenced



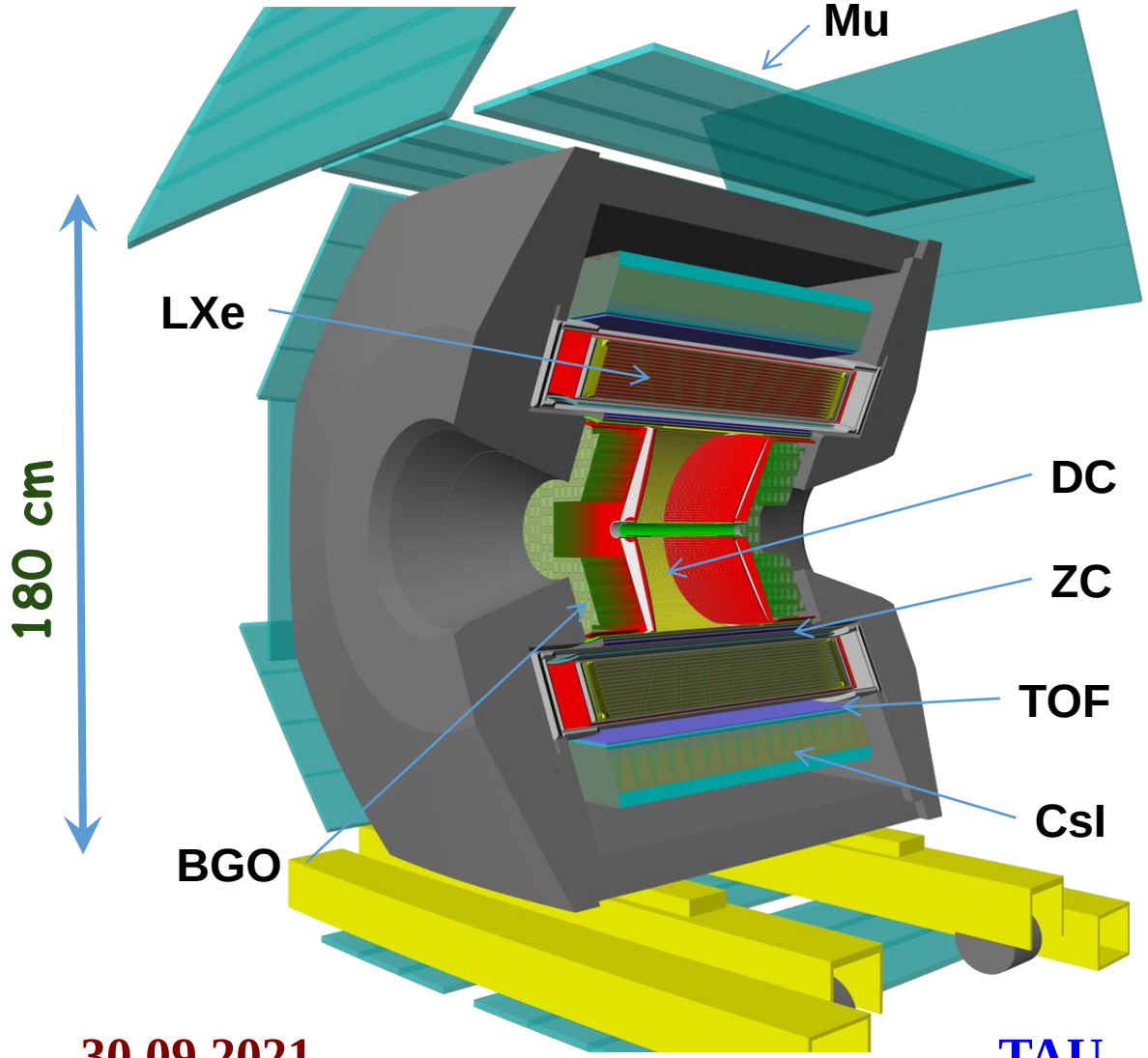


E = 993.662 ± 0.016 МэВ

E.V. Abakumova et al., Phys. Rev. Lett. 110 (2013) 14, 140402,
E.V. Abakumova et al.,Nucl.Instrum.Meth. A744 (2014) 35-40

CMD-3 - detector

Compact multipurpose detector comprising magnetic spectrometry with high resolution calorimetry



Magnetic field: 1.3T

Track reconstruction:

$\sigma_{\rho\varphi} \approx 100$ μm,

$\sigma_z \sim 2 - 3$ mm

$\sigma_p/p \approx \sqrt{(4.4p[GeV])^2 + 0.62\%}$

Combined EM-calorimeter:

Barrel: 5.3 X_0 LXe + 8.1X_0 CsI = 13.5 X_0

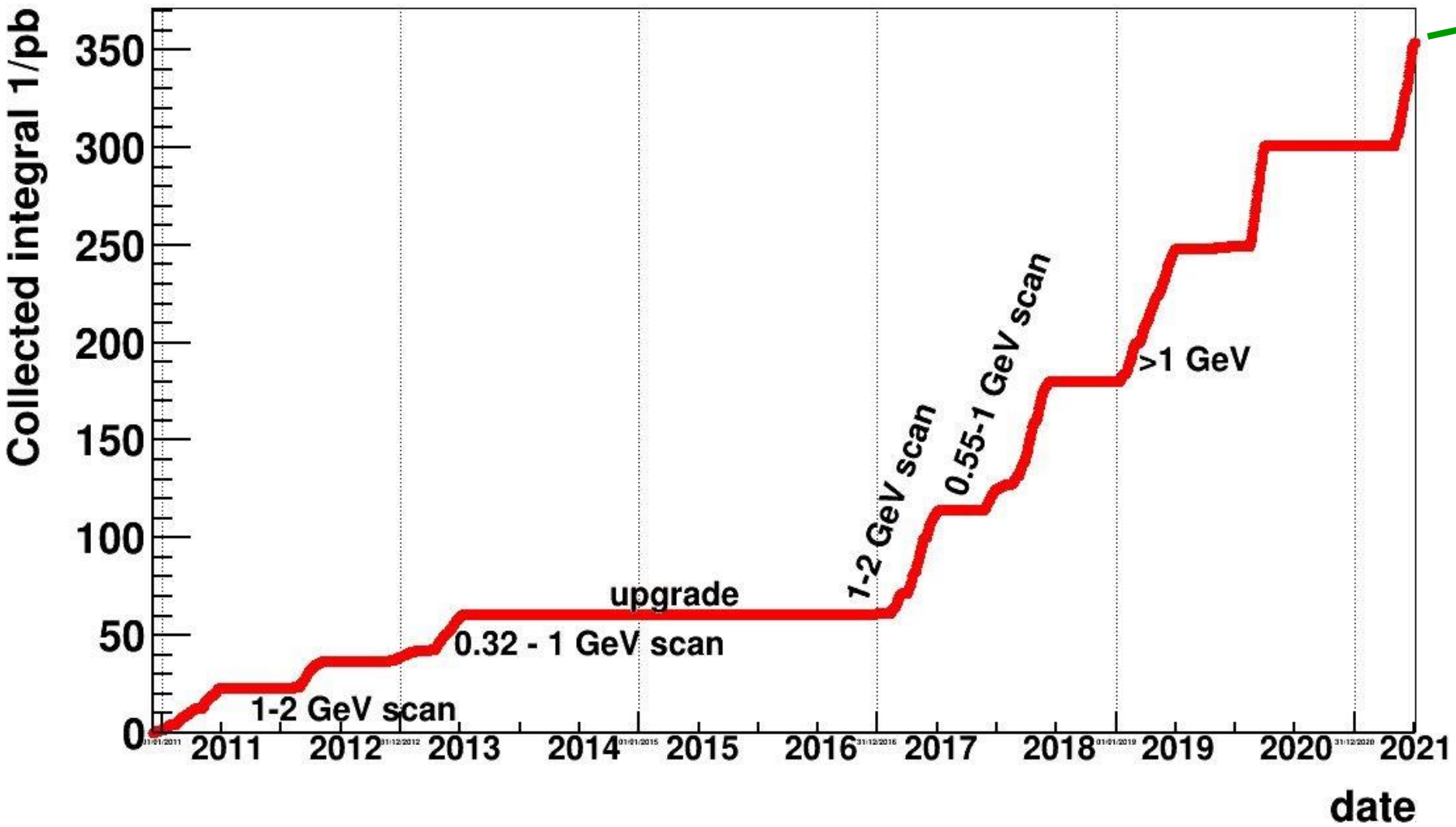
$\sigma_E/E \approx (3.4/\sqrt{E[GeV]} \oplus 2)\%$

$\sigma_\omega \approx 5$ mrad

End caps: BGO (14.4 X_0)

TOF: $\sigma_t \approx 1$ ns

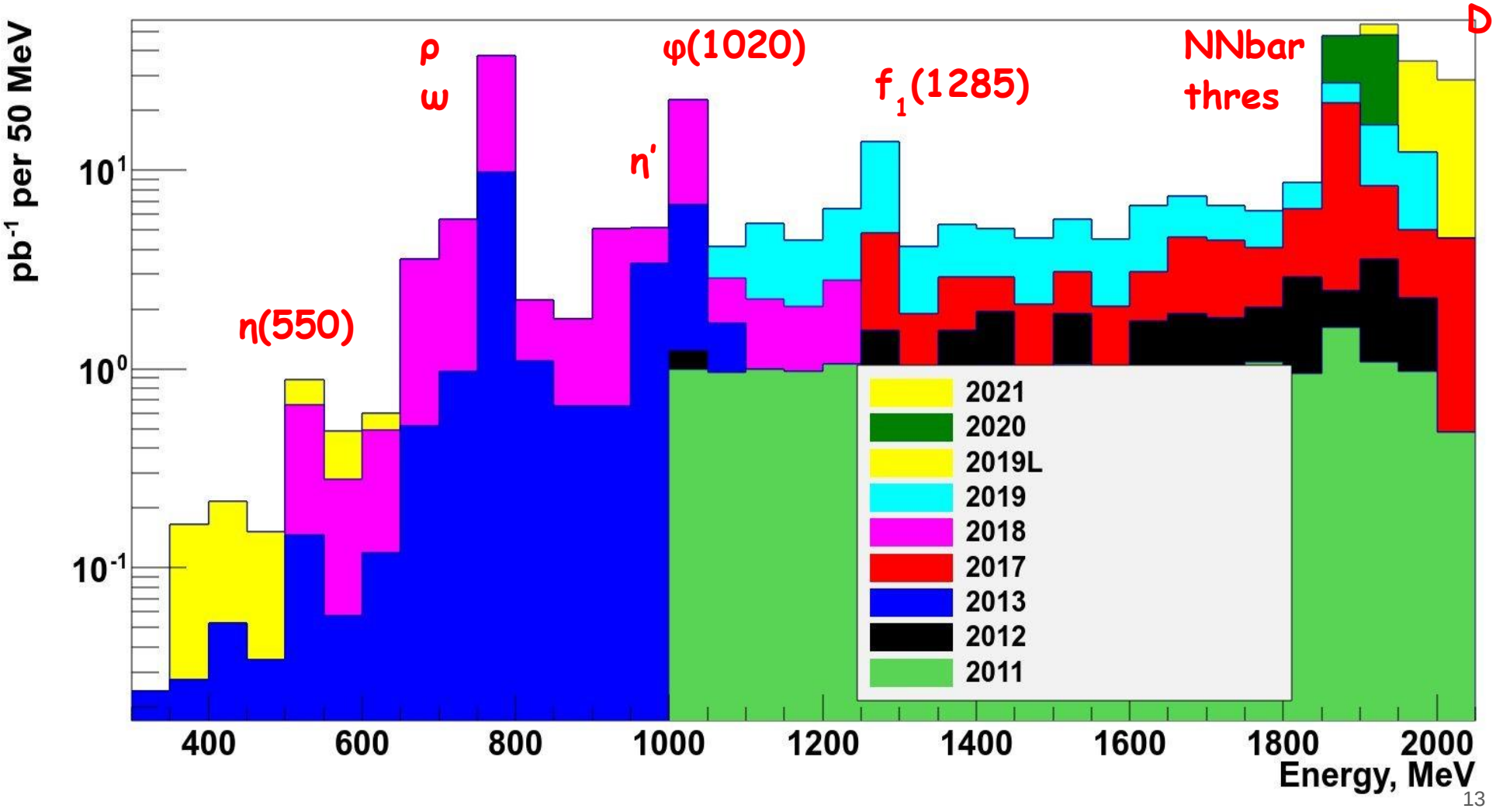
Data collection process



1 fb^{-1} project

Achieved peak luminosity is 0.5×10^{32} $cm^{-2}s^{-1}$

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



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CMD-3 results and analyses ongoing

Published

$3(\pi^+\pi^-)$	PLB 723 (2013) 82
$e^+e^- \to \eta'(958)$	PLB 740 (2015) 273
$p\bar{p}$	PLB 759 (2016) 634
$K^+K^-\pi^+\pi^-$	PLB 756 (2016) 153
K_SK_L	PLB 760 (2016) 314
K^+K^-	PLB 779 (2018) 64
$\pi^+\pi^-\,\pi^+\pi^-$	PLB 768 (2017) 345
$\omega\eta$, $\pi^+\pi^-\,\pi^0\eta$	PLB 773 (2017) 150
$3(\pi^+\pi^-)\pi^0$	PLB 792 (2019) 419
$K^+K^-\eta$	PLB 798 (2019) 134946
$\eta\pi^+\pi^-$	Journal of HEP, 2020, 2020(1), 112

Analyses ongoing

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

$\pi^+\pi^-\,\omega$

$e^+e^- \to D0^*$

$K_SK^+\pi^-$

$2(\pi^+\pi^-)\pi^0$, $2(\pi^+\pi^-\,\pi^0)$

$\pi^+\pi^-\,\eta(3\pi, 2\gamma)$

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

$K^+K^-\,\pi^0$, $K_SK_L\pi^0$, $K_SK_L\eta$

K^+K^-, K_SK_L

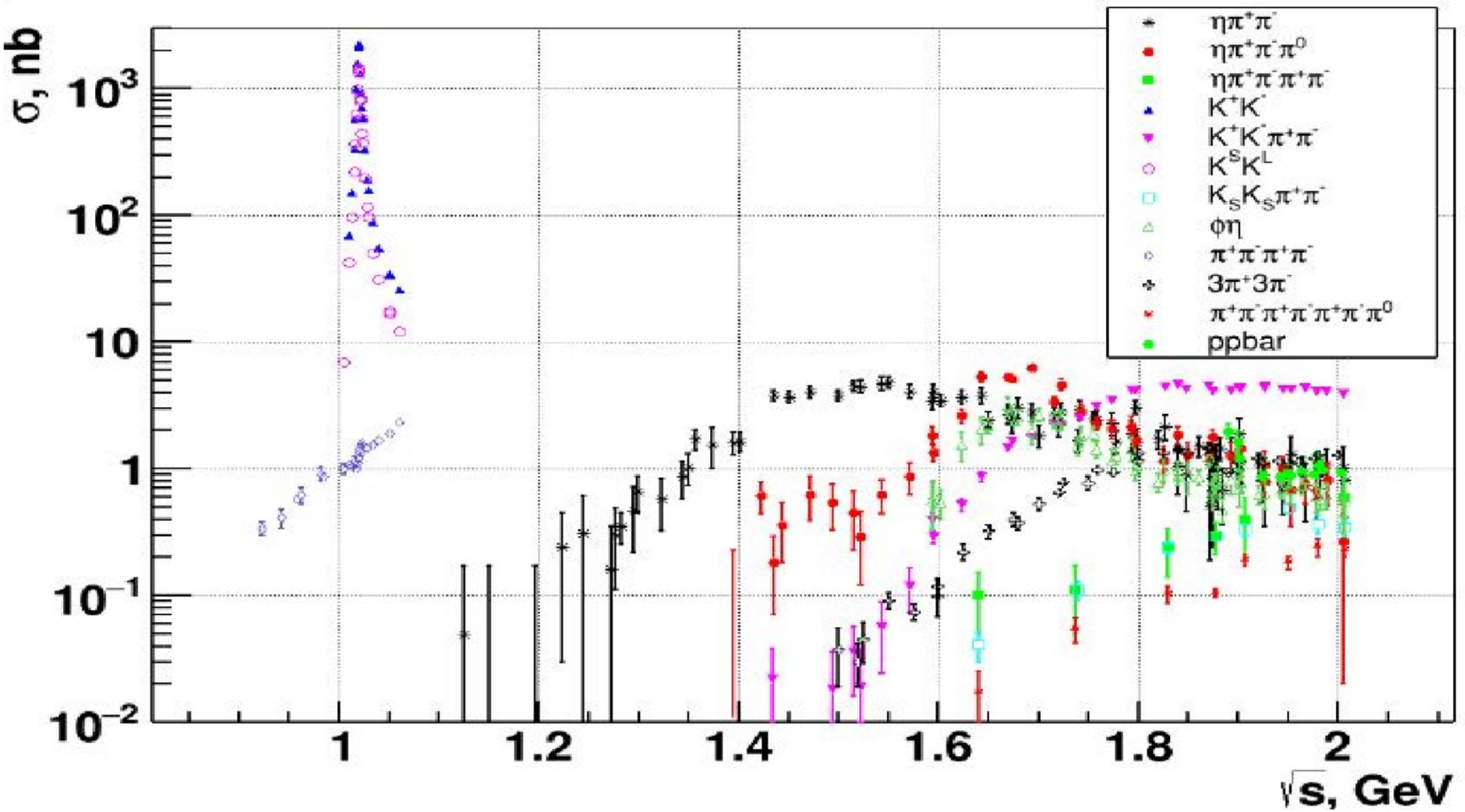
$\pi^+\pi^-\pi^0\pi^0$, $2(\pi^+\pi^-)$

$n\bar{n}$

$\eta\gamma$, $\pi^0\gamma$,

$\omega \to \pi^0\,e^+e^-$, ηe^+e^-

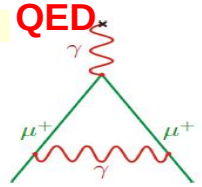
CMD-3 published results



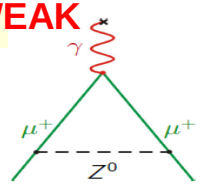
Muon anomaly, $a_\mu=(g-2)_\mu/2$: SM calculations and experiment

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

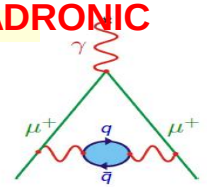
QED



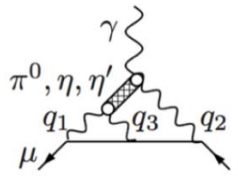
WEAK



HADRONIC



LbL



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

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

Contribution	Value ×1011	References
QED	116 584 718.931(104)	Refs. [33,34]
Electroweak	153.6(1.0)	Refs. [35,36]
HVP (e+e−, LO + NLO + NNLO)	6845(40)	Refs. [2–8]
HLbL (pheno + lattice + NLO)	92(18)	Refs. [18–32]
Total SM Value Section	116 591 810(43)	Refs. [2–8,18–24,31–36]
Exp. (E821) - SM	279(76)	

The table is from:
"The anomalous magnetic moment of the muon in the Standard Model", T. Aoyama et al., Physics Reports 887 (2020) 1–166

CMD-3 at VEPP- 2000

Since new experiments at FNAL and JPARC expect to improve the accuracy of muon (g-2) by factor 3, we need in a precision of the hadronic cross section at the level of 0.3%

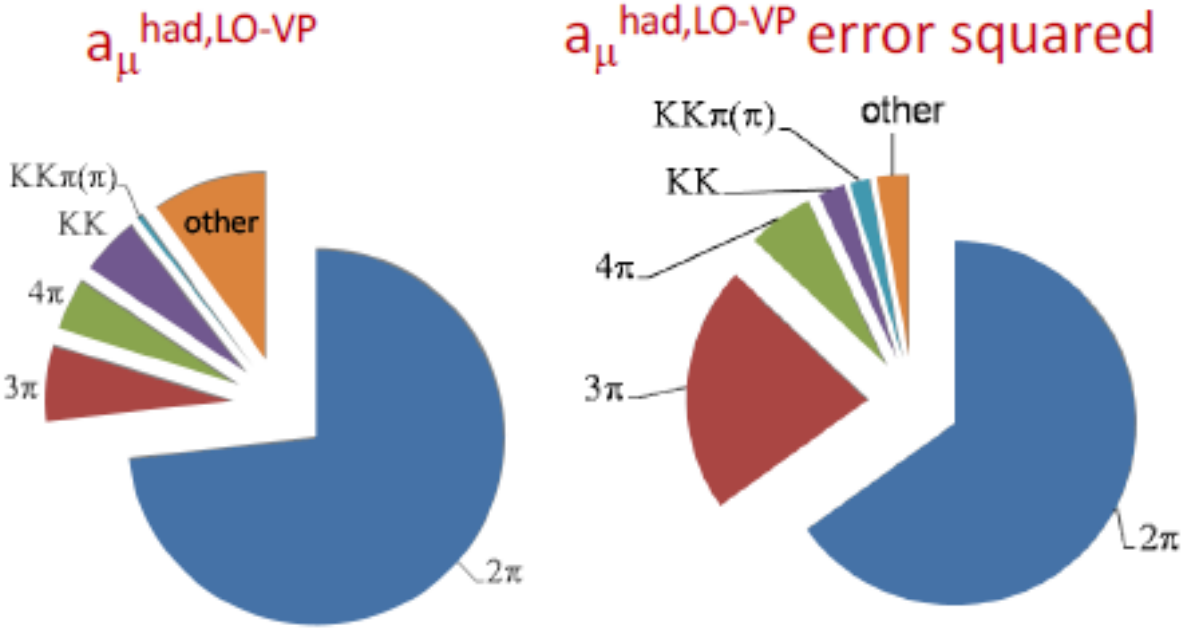
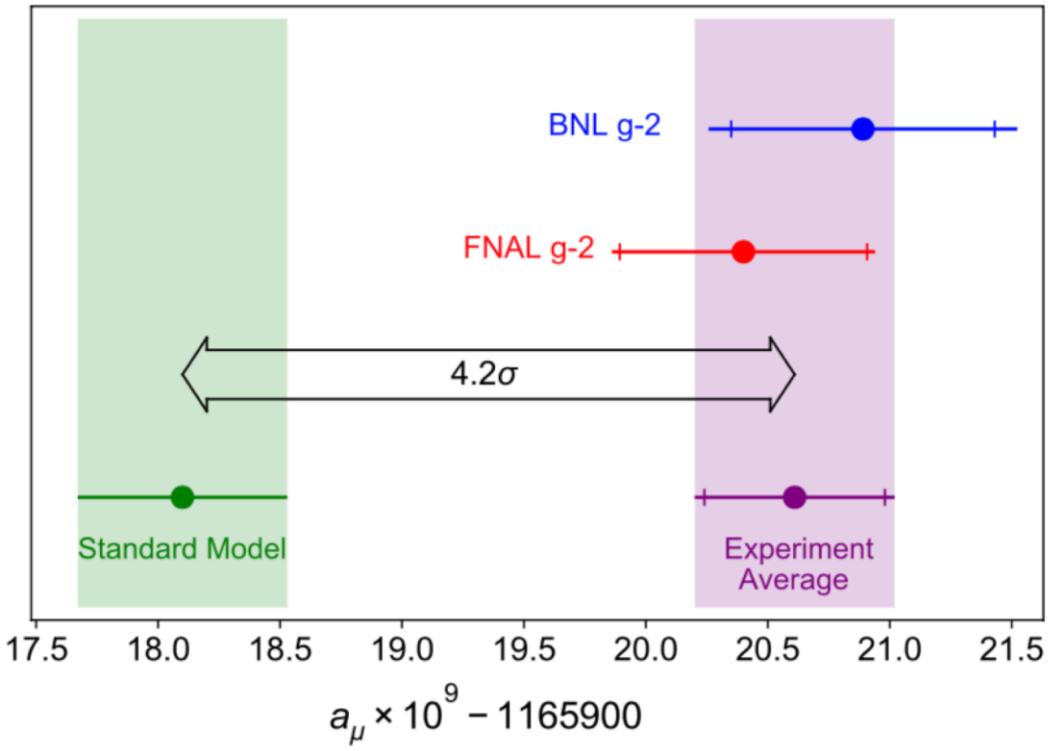
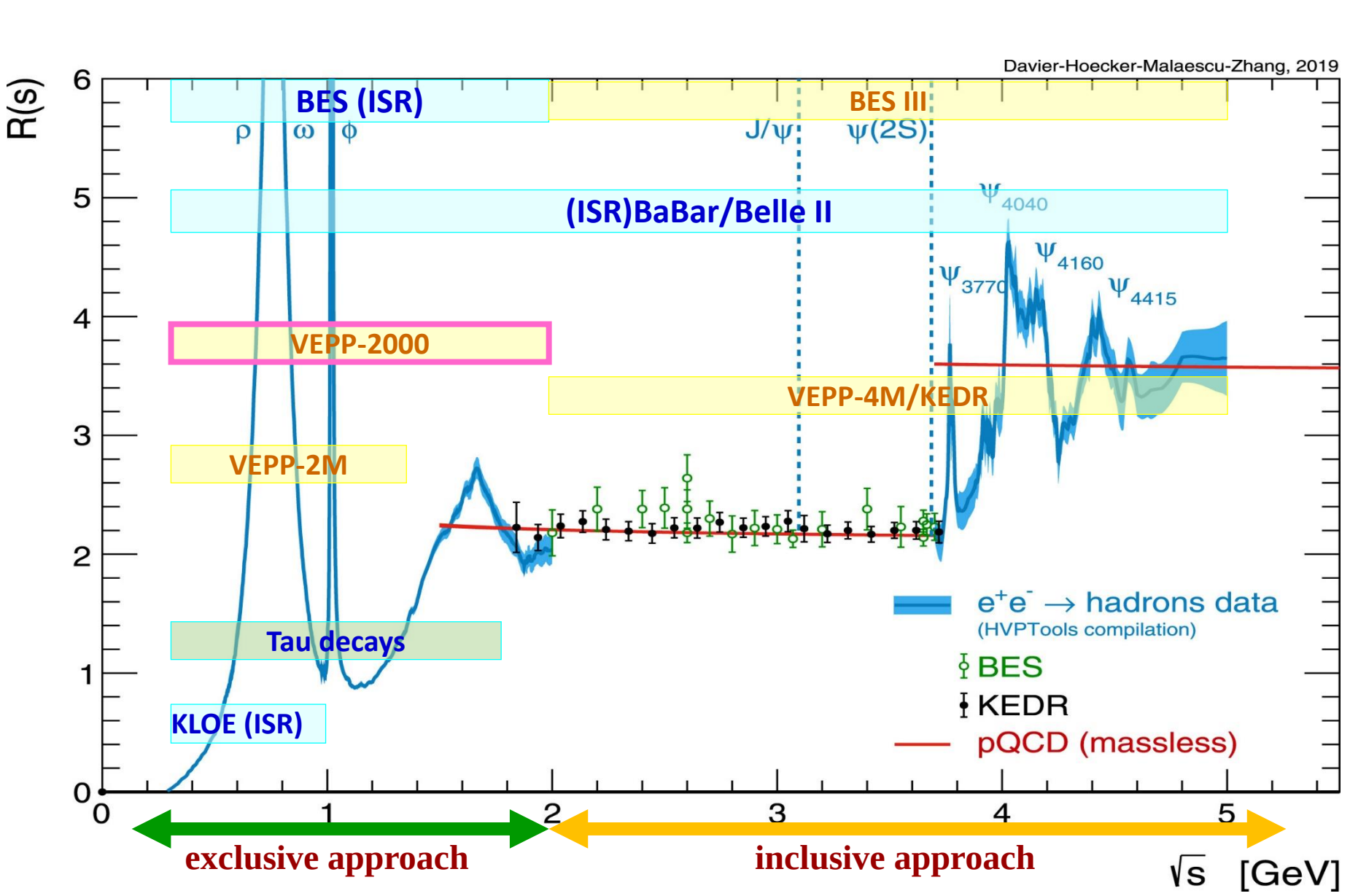


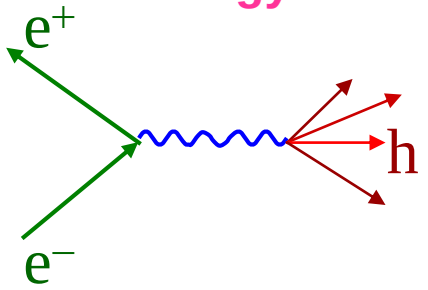
Fig. from Phys. Rev. Lett. 126 (2021) 141801 [arXiv:2104.03281]



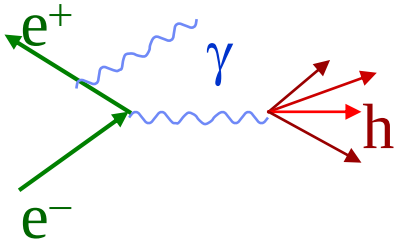
R measurement – exclusive vs inclusive



Energy Scan



ISR



The figure is from:
"The anomalous magnetic moment of the muon in the Standard Model", T. Aoyama et al., Physics Reports 887 (2020) 1–166.

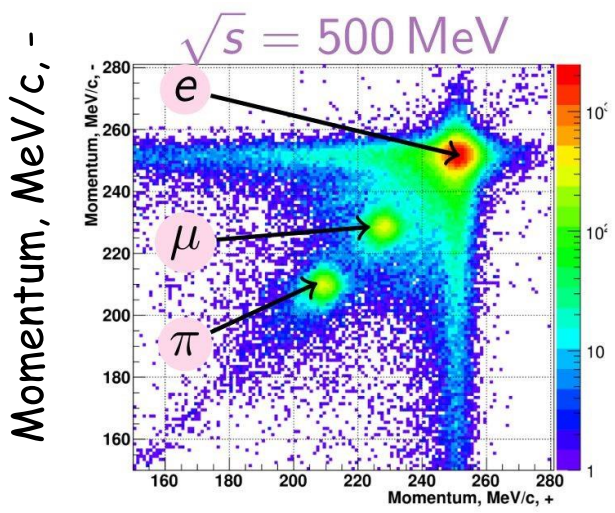
Dominant channel $e^+e^- \to \pi^+\pi^-$ (below - Φ -meson)

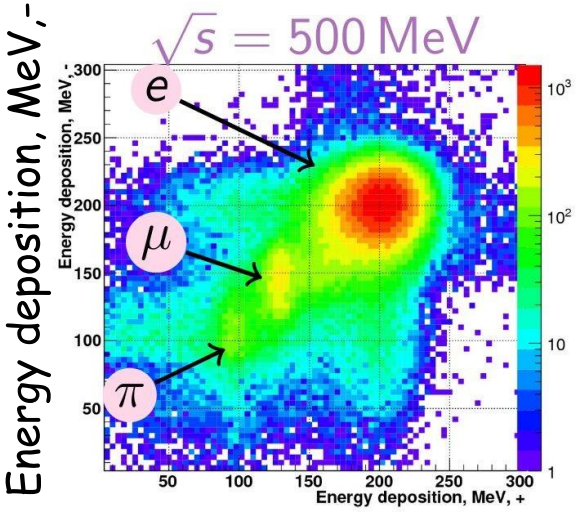
Two charge tracks collinear back-to-back events are selected, $1 \le \theta \le \pi - 1$

Separation of $e^+e^- \to e^+e^-$, $\pi^+\pi^-$, $\mu^+\mu^-$ cosmic events by two independent approaches: particle momenta and energy deposition in the calorimeter

Binned likelihood minimization:

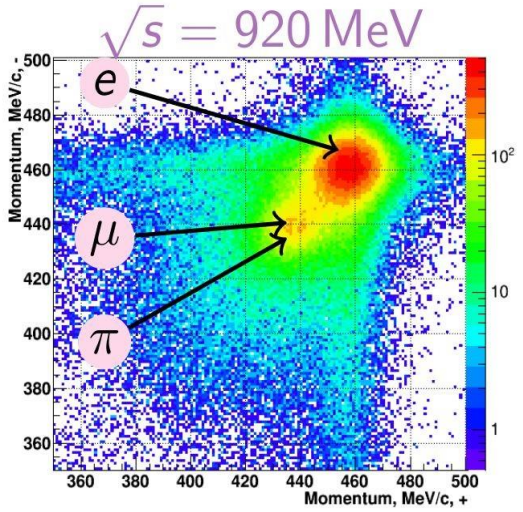
$$-\ln L = -\sum_{\text{bins}} n_i \ln\Big[\sum_{\substack{X=ee,\\ \mu\mu,\ \pi\pi,\\ \text{bg}}} N_X f_X(p^+, p^-)\Big] + \sum_X N_X$$

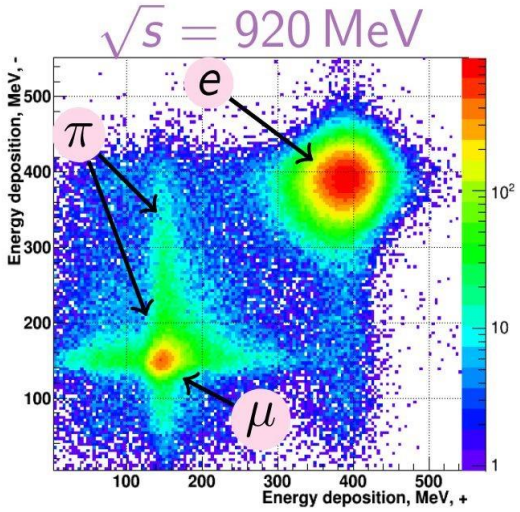




Momentum, MeV/c, +

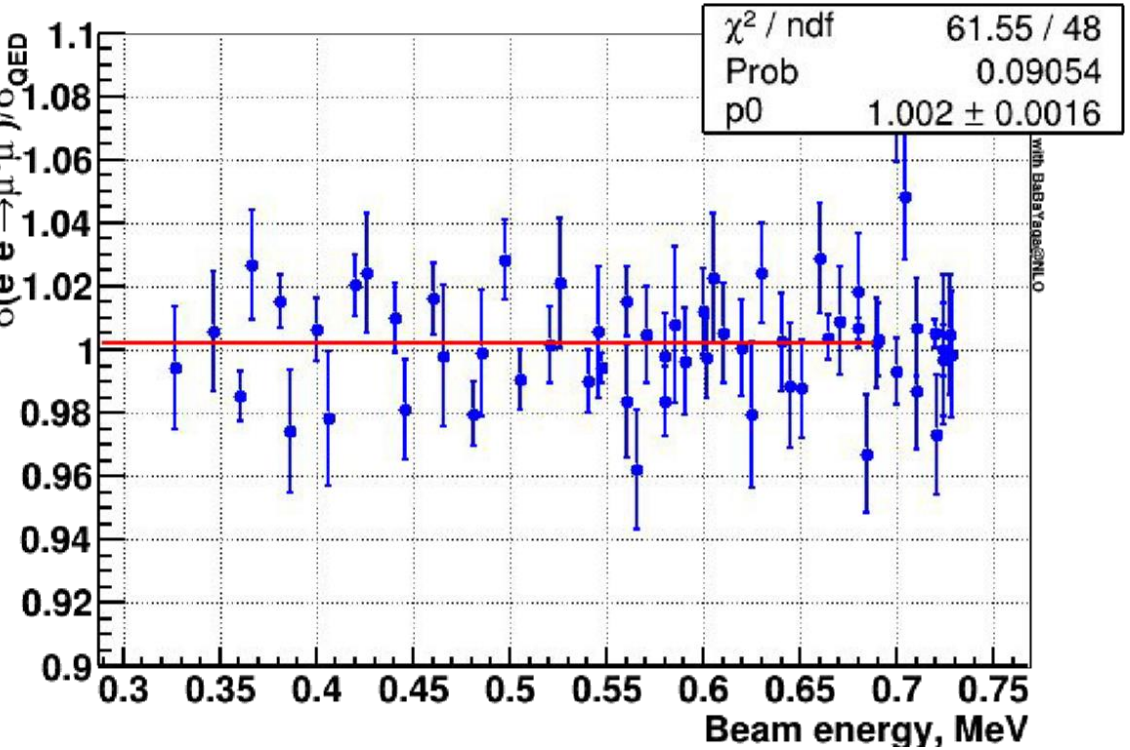
Energy deposition, MeV, +



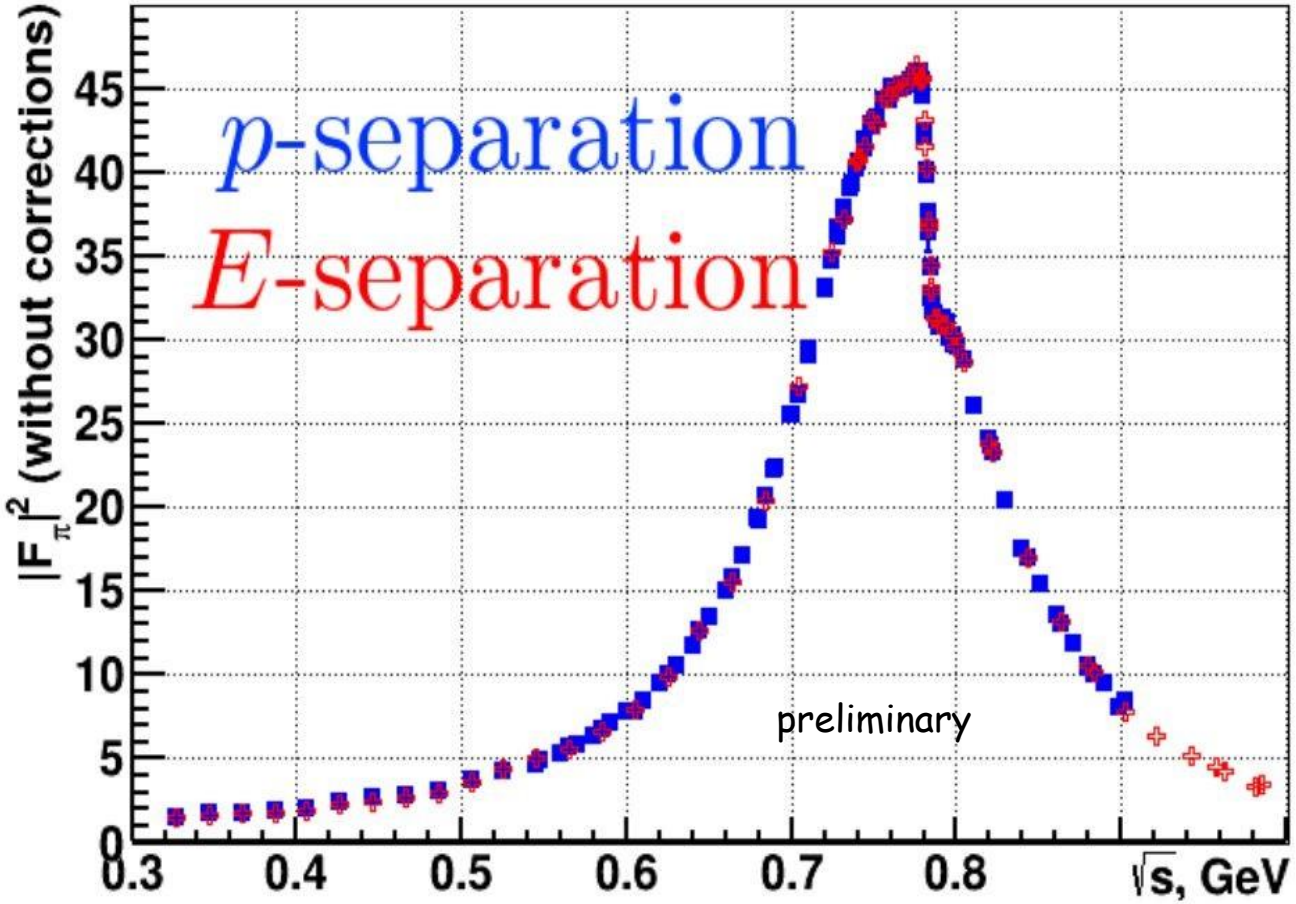


The study of $e^+e^- \to \pi^+\pi^-$ at CMD-3

Comparison of σ(**e+e- →**
μ+μ-) with QED

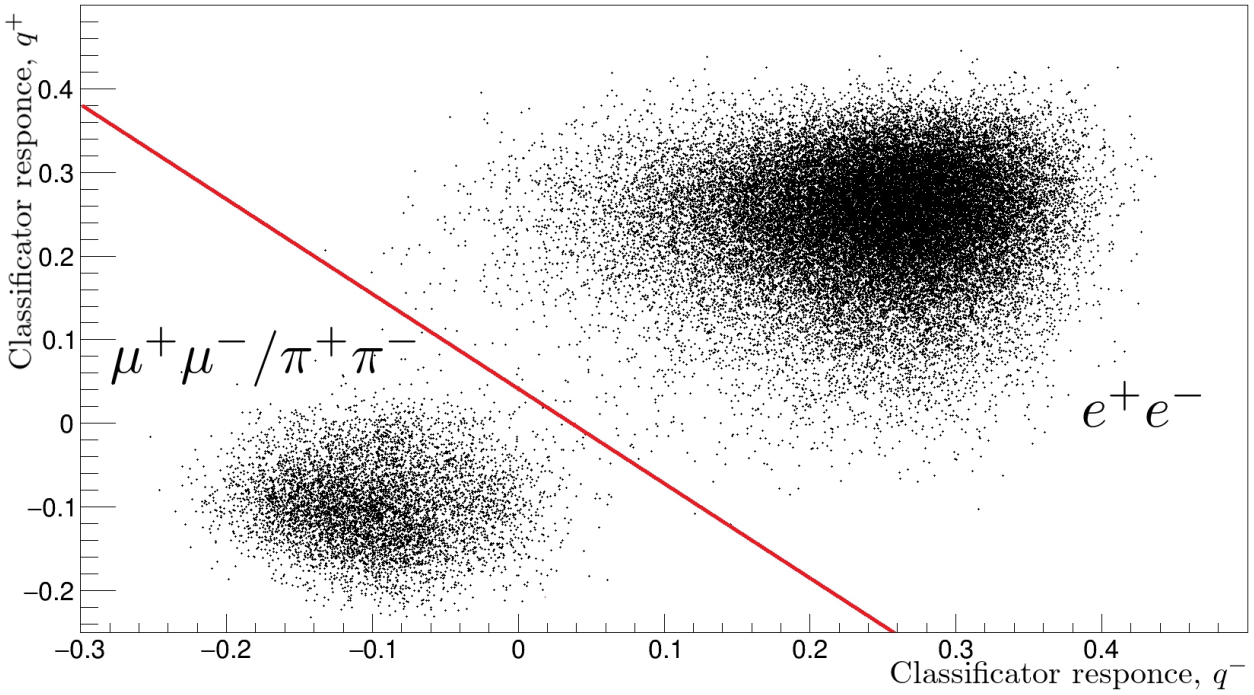


$$|F|^2 = \frac{N_{\pi\pi}}{N_{ee}} \frac{\sigma^B_{ee}(1+\delta_{ee})\varepsilon_{ee}}{\sigma^B_{\pi\pi}(1+\delta_{\pi\pi})\varepsilon_{\pi\pi}}$$

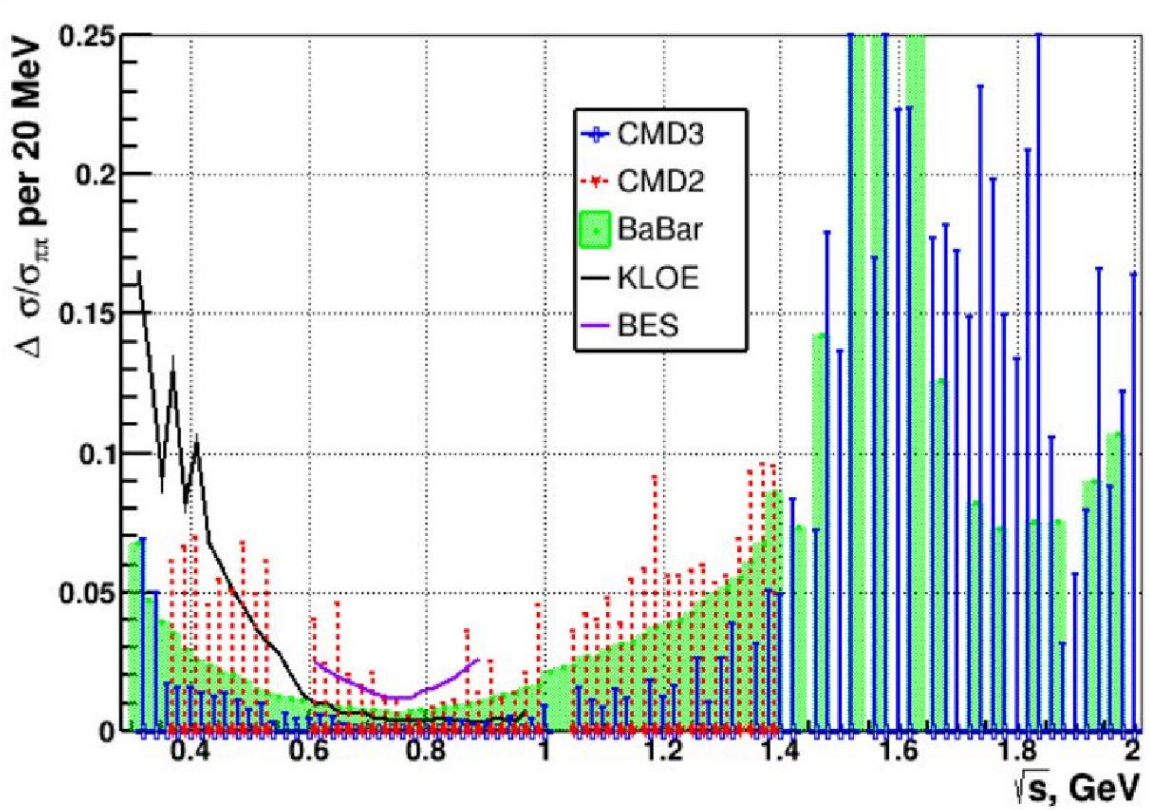


The analysis on of this process in the energy range below 1 GeV is at its final stages. Additional local consistency checks should be fulfilled. The aim systematic uncertainty is 0.5 %.

$e^+e^- \to \pi^+\pi^-$ above 1 GeV



Comparison of the statistical uncertainties

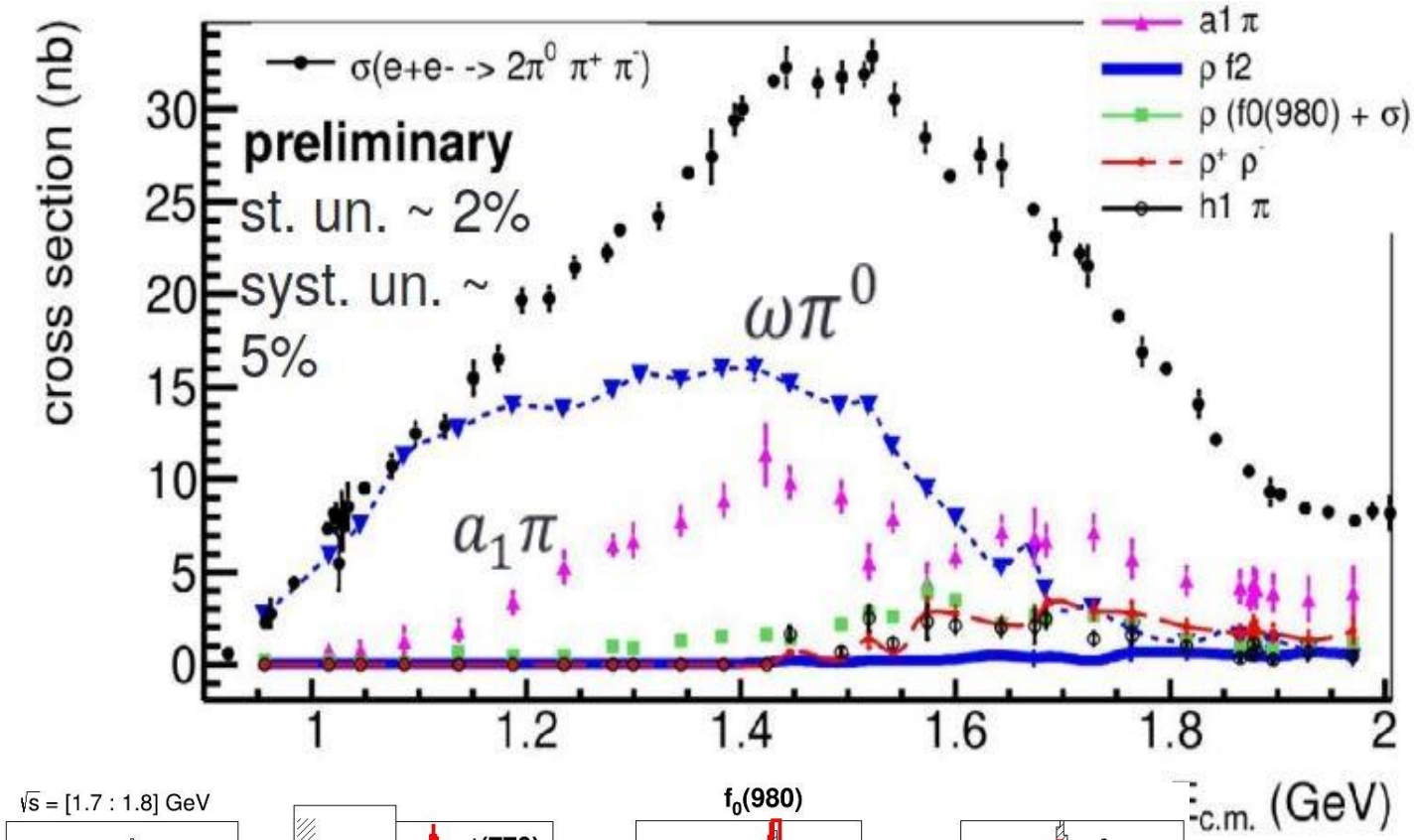


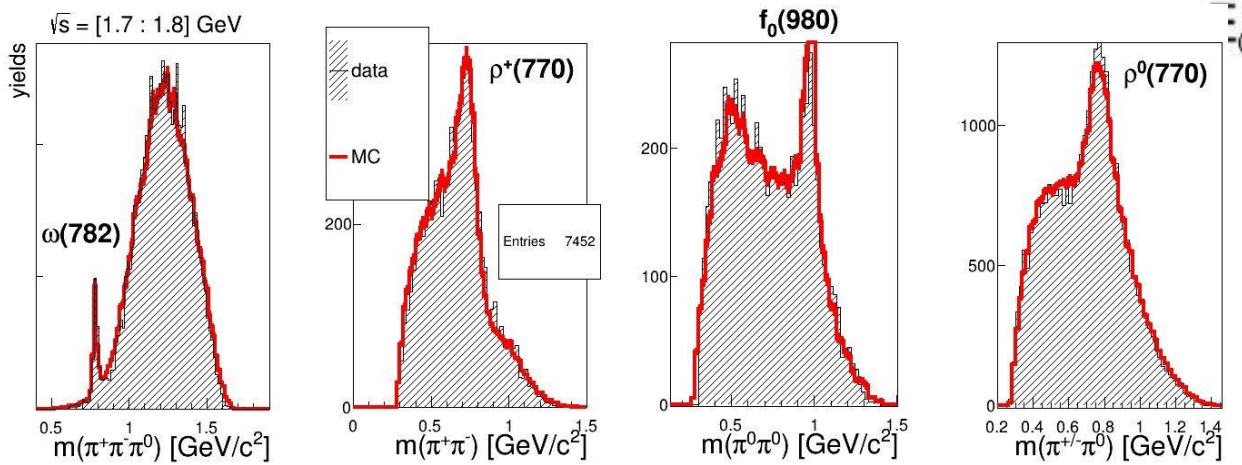
Study of the dynamics of multipion (4π) final states

The study of $\mathbf{e^+e^-} \to 4\pi$ 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

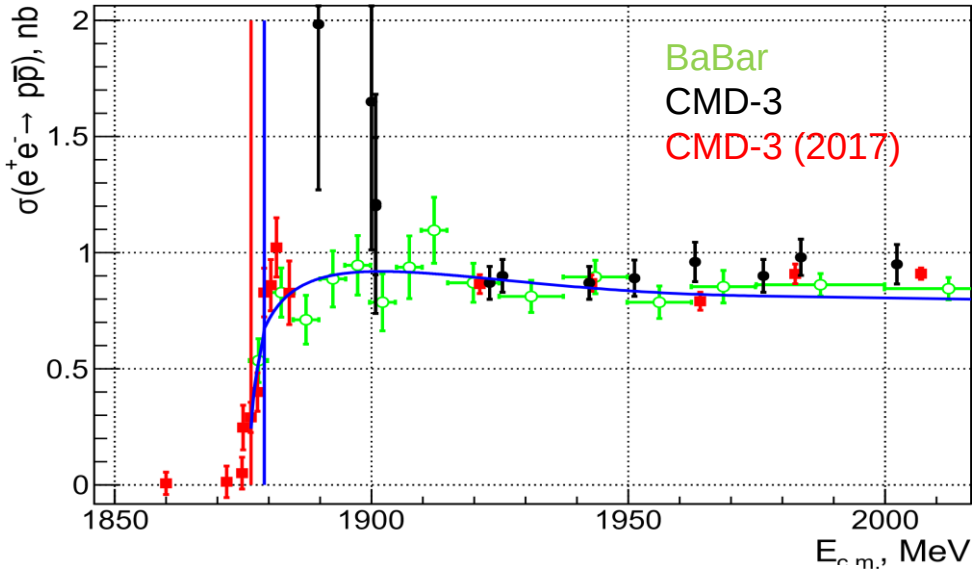
Amplitudes accounted for in the likelihood function:

- $\omega[1^{--}]\pi^0[0^{++}]$ (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 $\pi^+\pi^-2\pi^0$)

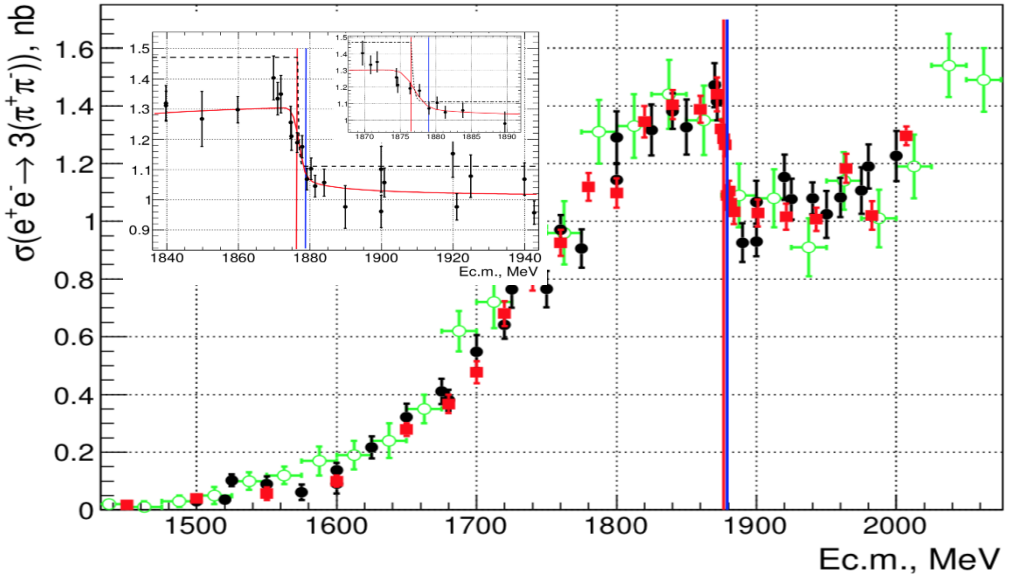


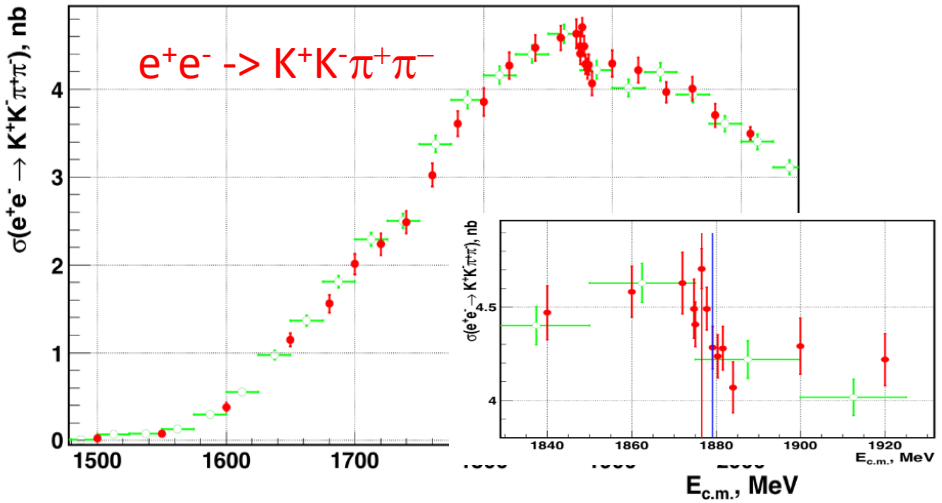


$e^+e^- \to$ at $N\bar{N}$ threshold

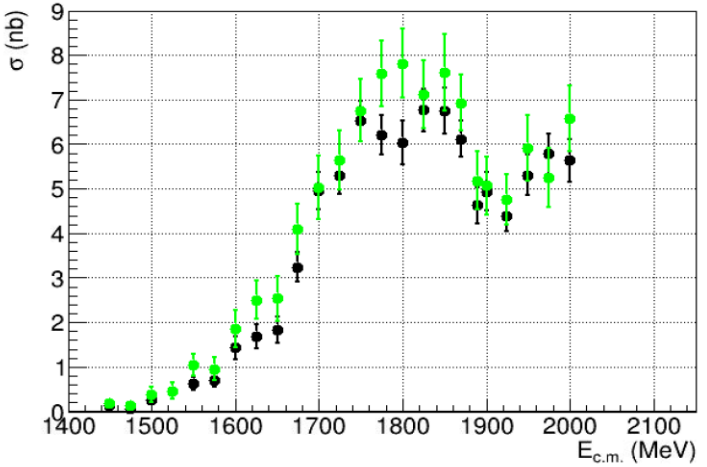


$e^+e^- \to 3(\pi^+\pi^-)$



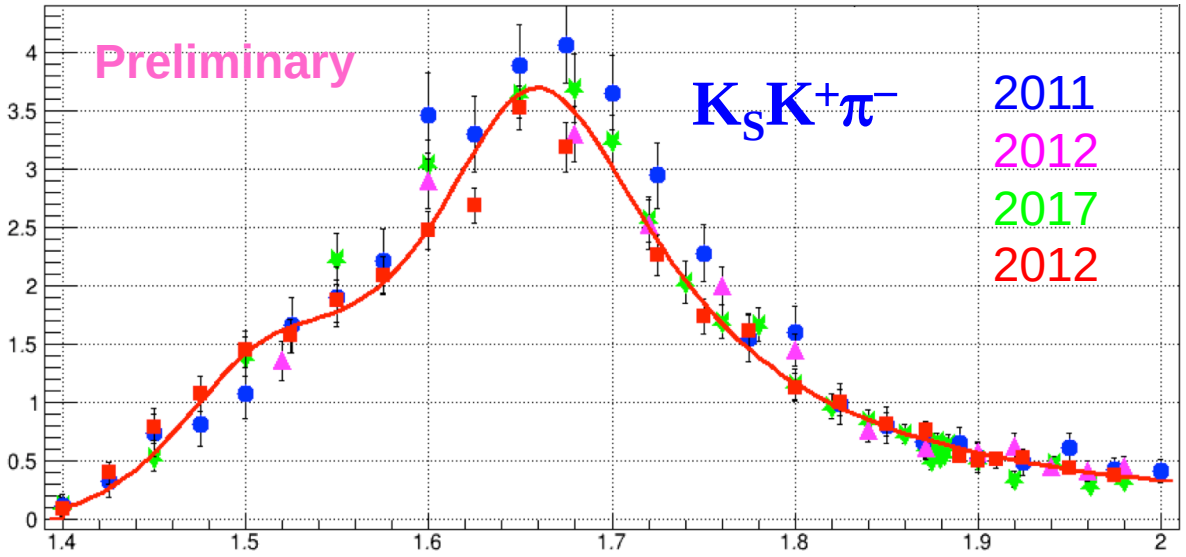


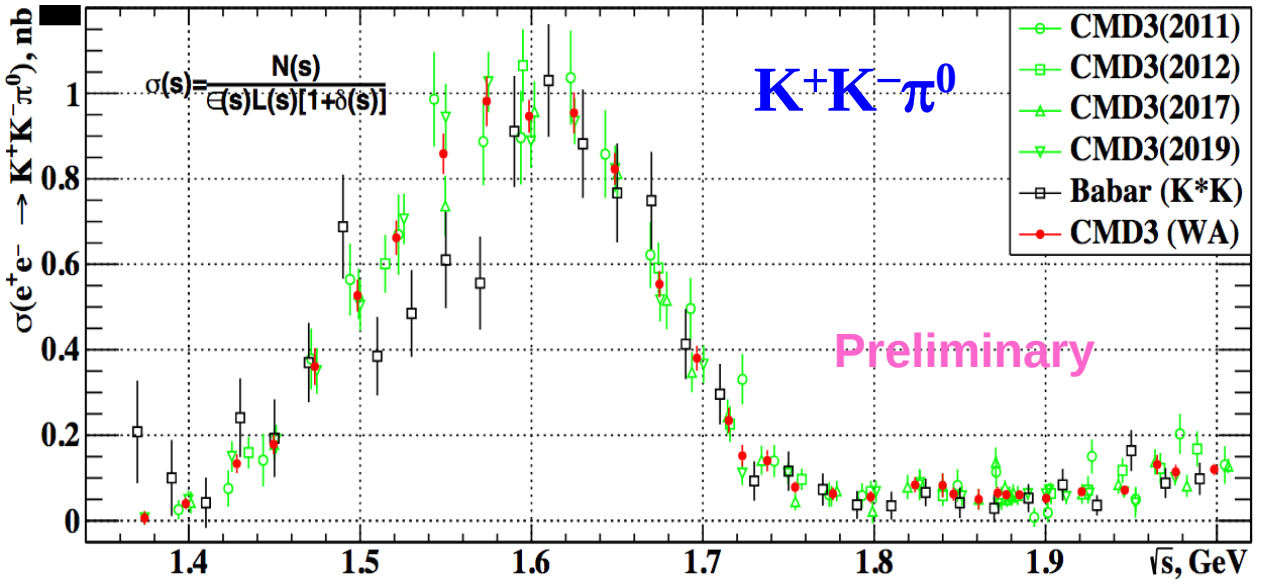
$e^+e^- \to 2(\pi^+\pi^-\pi^0)$

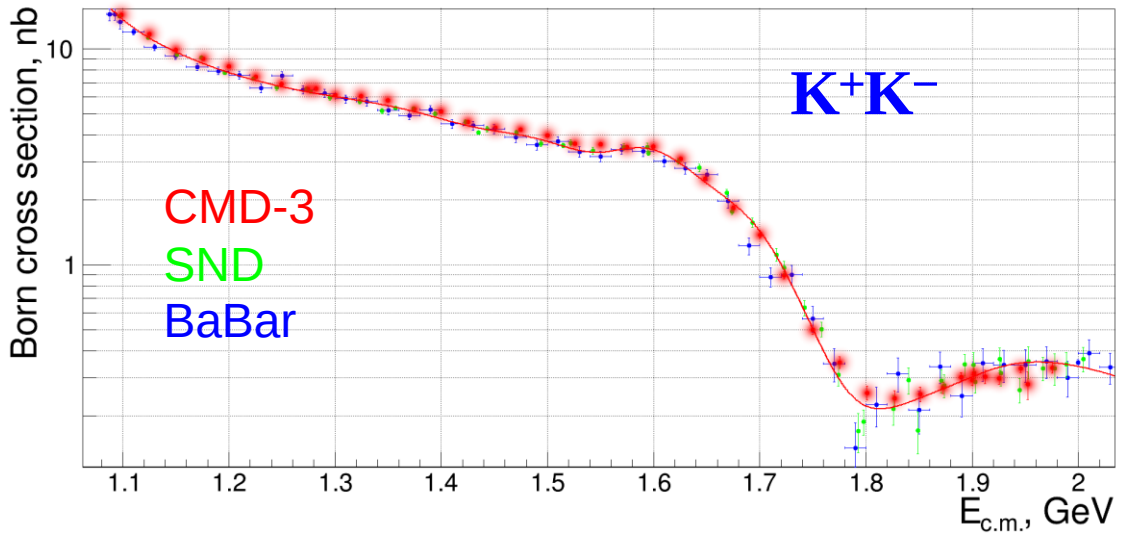


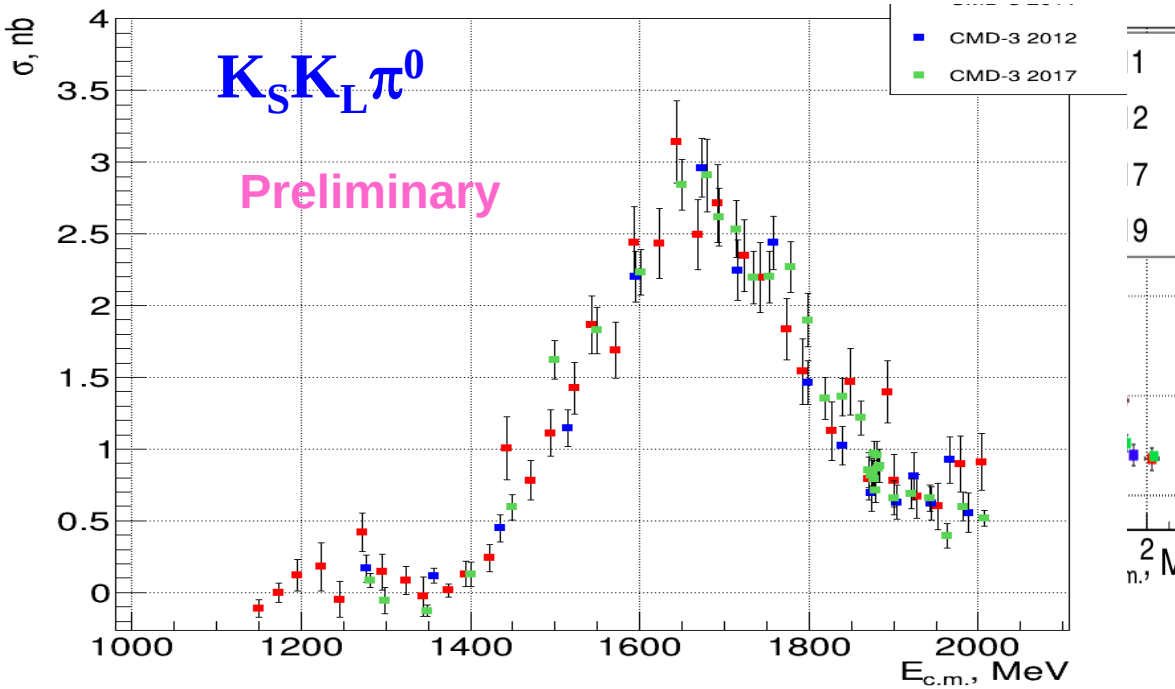
We do not see such structure in e^+e^- -> $2(\pi+\pi-)$

Final states with kaons









Upgrade plans

Z-discs

2 layers of RWELL

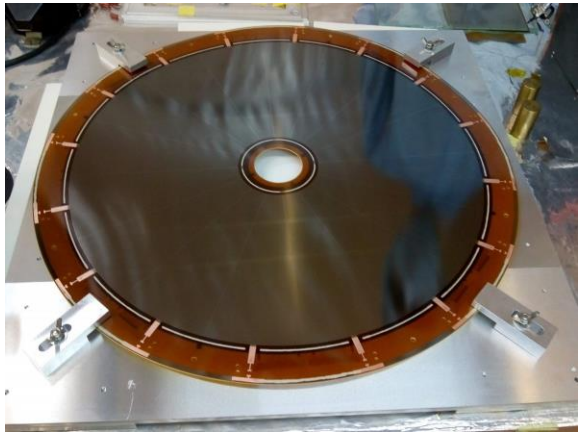
$\sigma_r \sim$ 0.6mm

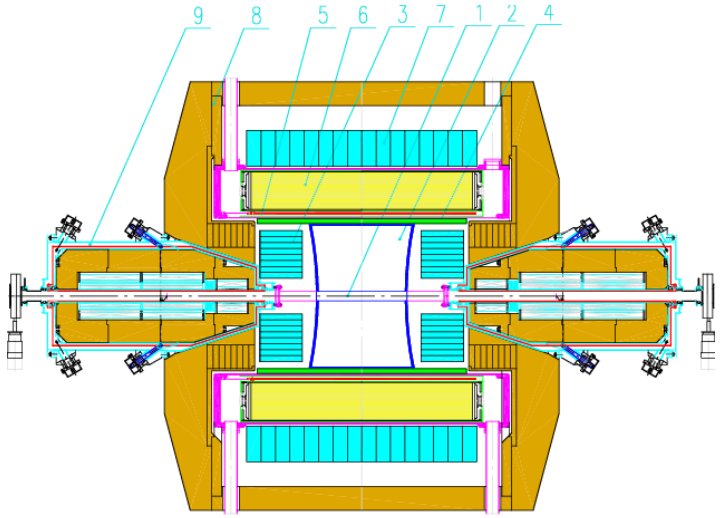
$\sigma_{r\varphi} \sim$ 1.2mm

First disc is ready

Read-out electronics is under test.

Installation 2023-2024





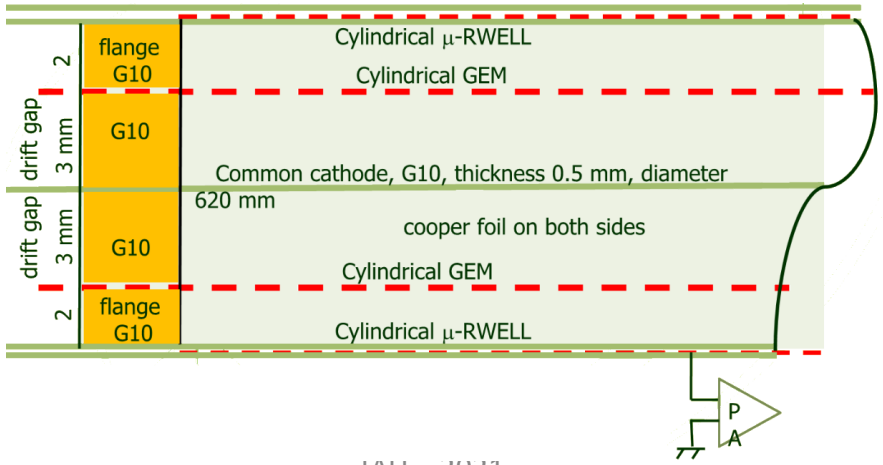
Z-chamber

2 layers of cyl. RWELL

Conceptual design is ready

Strip pitch 1.5mm

$\sigma_z \sim$ 0.4mm

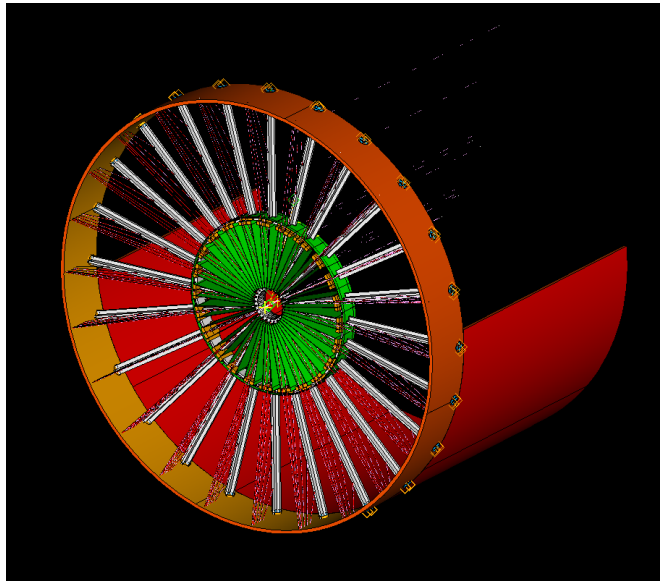


DC chamber

INFN design mechanics inspired by MEG

BINP develop ASIC for cluster counting and wires

Work on the prototype probably start in 2022-2023



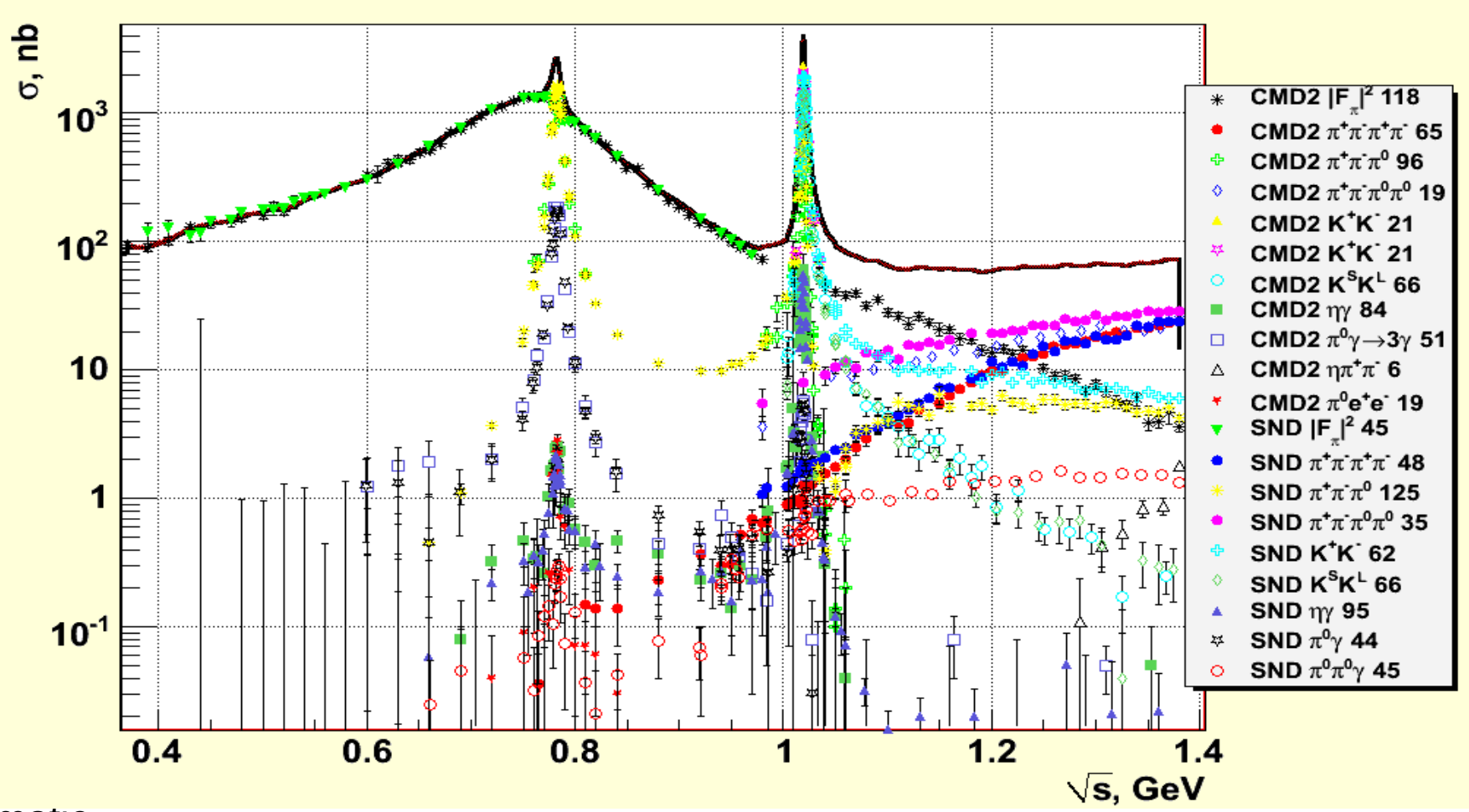
Conclusion

- The goal of two experiments CMD-3 and SND at VEPP2000 is to provide exclusive measurement of $e^+e^- \to$ hadrons reactions with high precision in the energy range 0.32 – 2.0 GeV
- CMD-3 has collected 320 pb^{-1} in the whole energy range 0.32 – 2.007 GeV, available at VEPP-2000, and is on the way to 1 fb^{-1}.
- Since At present a discrepancy between experiment and SM in the muon (g-2) is, probably, the largest among observed, the ultimately precise measurements of the hadronic cross section are crucial. Present target of CMD-3 is to achieve the relative systematic precision of 0.5% in $e^+e^- \to \pi^+\pi^-$ below 1 GeV.
- Data analysis of exclusive modes of is in progress. Many results have been published.
- Detector upgrade is under development: the first step is end-cap coordinate system installation in summer of 2023.

Back up

With $L \approx 10^{30}\ cm^{-2}s^{-1}$ VEPP-2M was pre- ϕ - factory from 1974 to 2000

$$\int Ldt \approx 70\,pb^{-1}$$



Since new experiments at FNAL and JPARC expect to improve the accuracy of muon (g-2) by factor 3, we need in a precision of the hadronic cross section at the level of 0.3%

Systematic error:	~0.6-0.7%	1.0%	0.6%	1.5%	1.5 -- 3.5 %
Total error:	~ 6 -- 1%	1.5%	1--2%	2.0%	2.5 -- 3.5 %

Error of R(s)