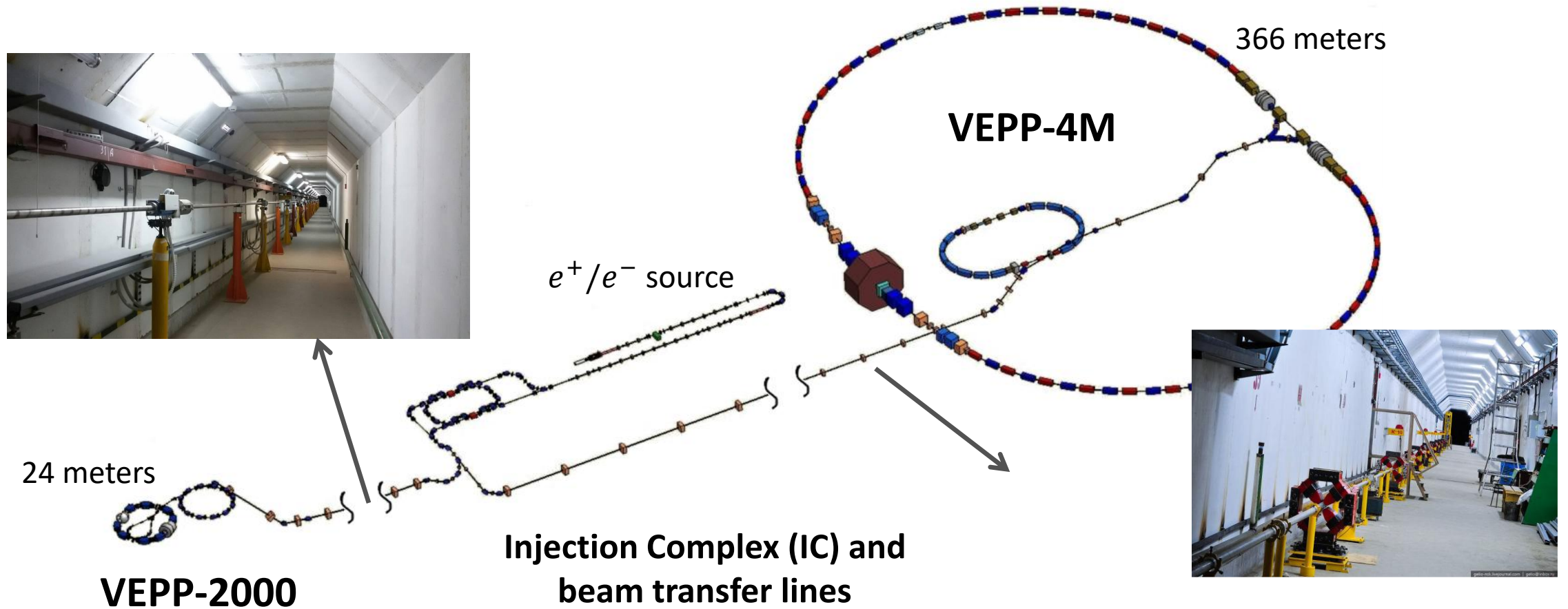


Результаты с коллайдеров ИЯФ СО РАН и проект ВЭПП-6

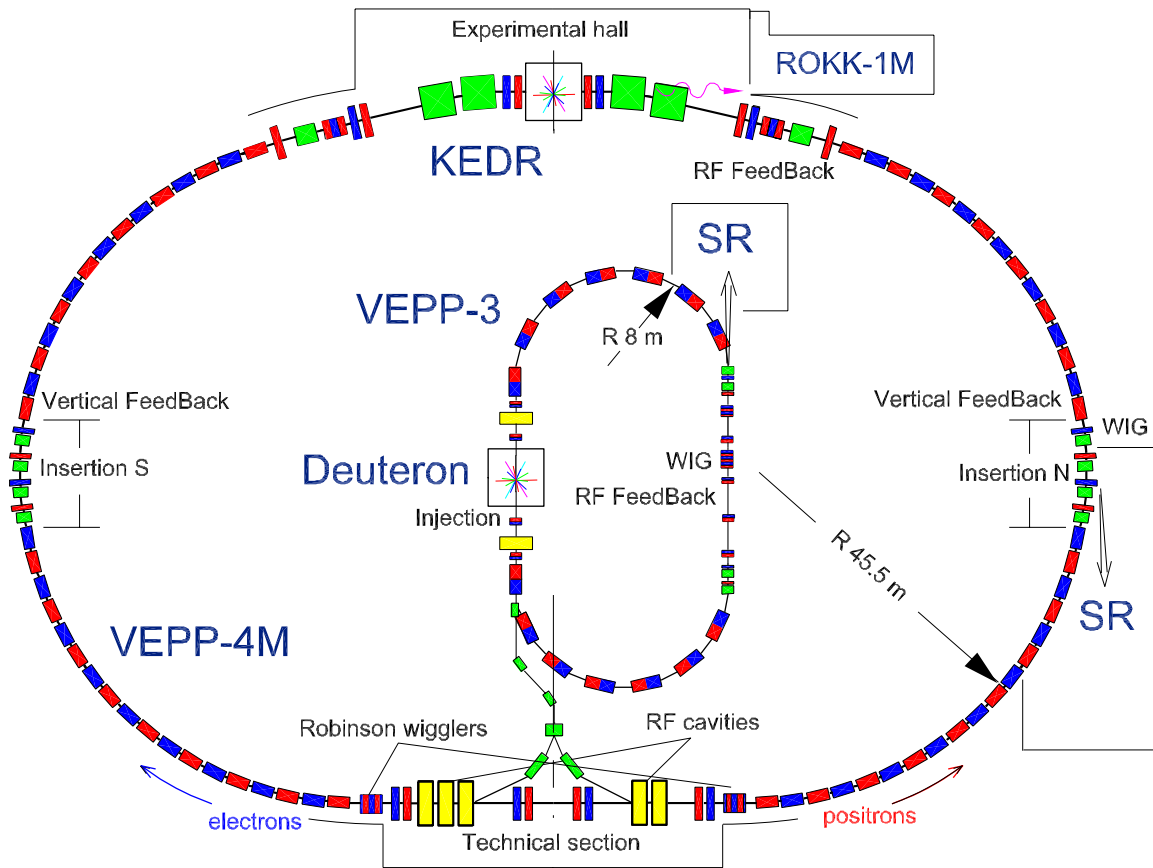
ИВАН ЛОГАШЕНКО

ИЯФ СО РАН (НОВОСИБИРСК)

BINP accelerator complex layout



VEPP-4M and VEPP-3



Beam energy
 $2 \times (0.925-4.7) \text{ GeV}$
 Luminosity
 $\sim 4 \cdot 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$

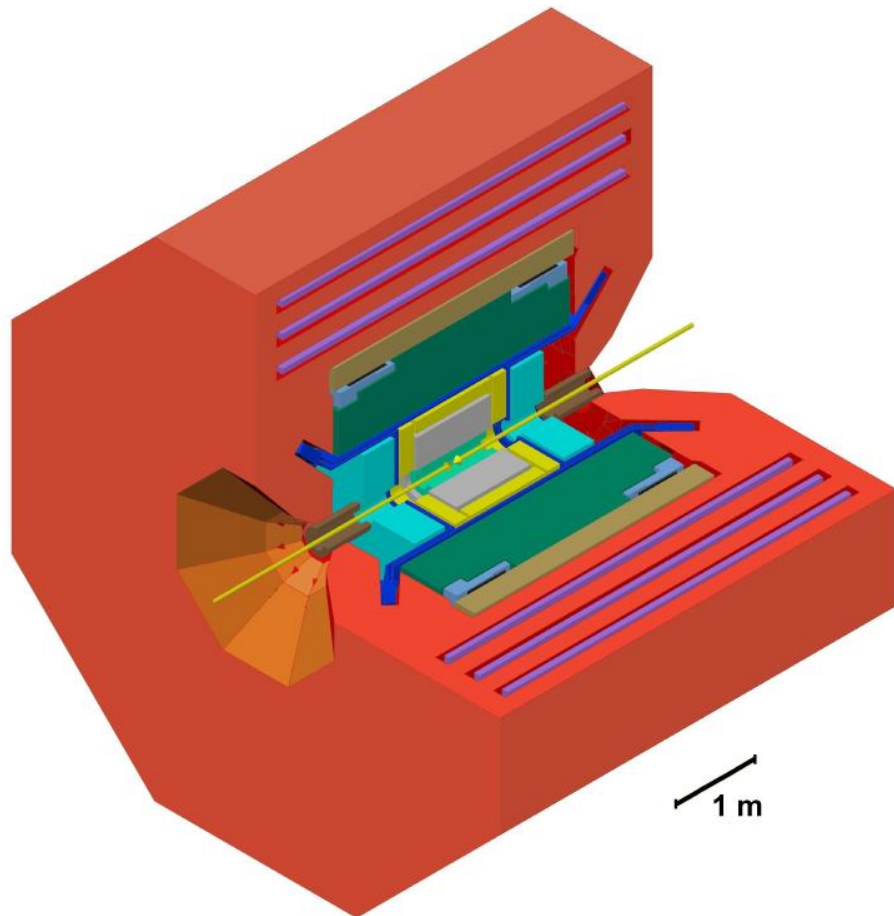
Experimental program:

- e^+e^- HEP with KEDR detector
- SR at VEPP-3 (2 GeV)
- SR at VEPP-4M (2÷4 GeV)
- Nuclear physics at VEPP-3 with Deuteron facility
- Test Beam Facility at VEPP-4M

Energy determination with resonant depolarization technique

- Toushek polarimeter: $\frac{\Delta E}{E} \approx 10^{-6}$ for $E < 2 \text{ GeV}$
- Laser polarimeter: $\frac{\Delta E}{E} \approx 3 \cdot 10^{-6}$ at $E = 4.73 \text{ GeV}$

KEDR detector



- Vertex detector
- Drift chamber
- Aerogel threshold counters
- ToF counters
- Lkr calorimeter
- Superconducting coil
- Yoke
- Muon chambers
- CsI calorimeter
- Compensating solenoid

Key results:

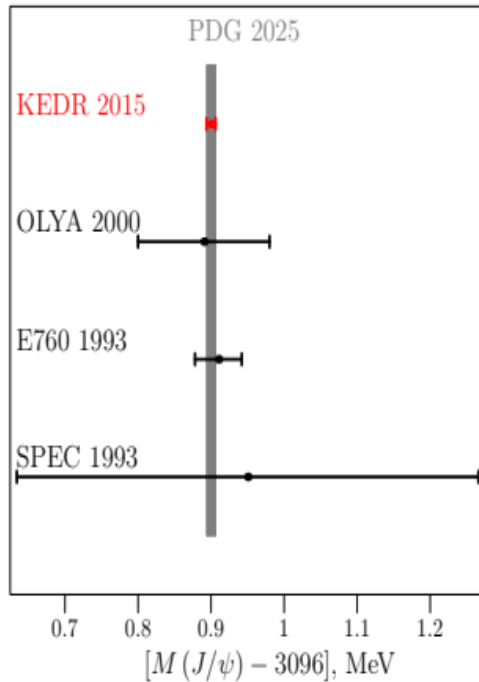
- R ratio (1.84-3.72 GeV, 4.56-6.96 GeV in progress)
- J/ψ , $\psi(2S)$, τ , D masses
- J/ψ , $\psi(2S)$ widths (partial, leptonic,...)

Ongoing experiment:

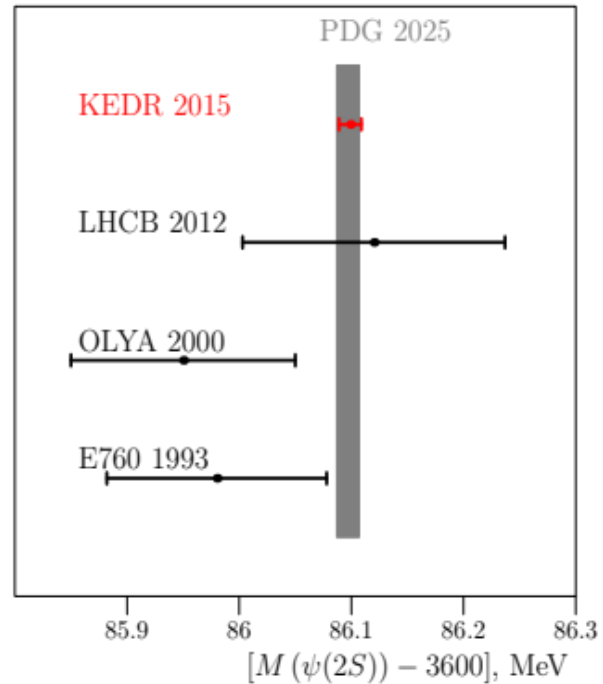
- $\Upsilon(1S)$ mass and leptonic width

KEDR detector results

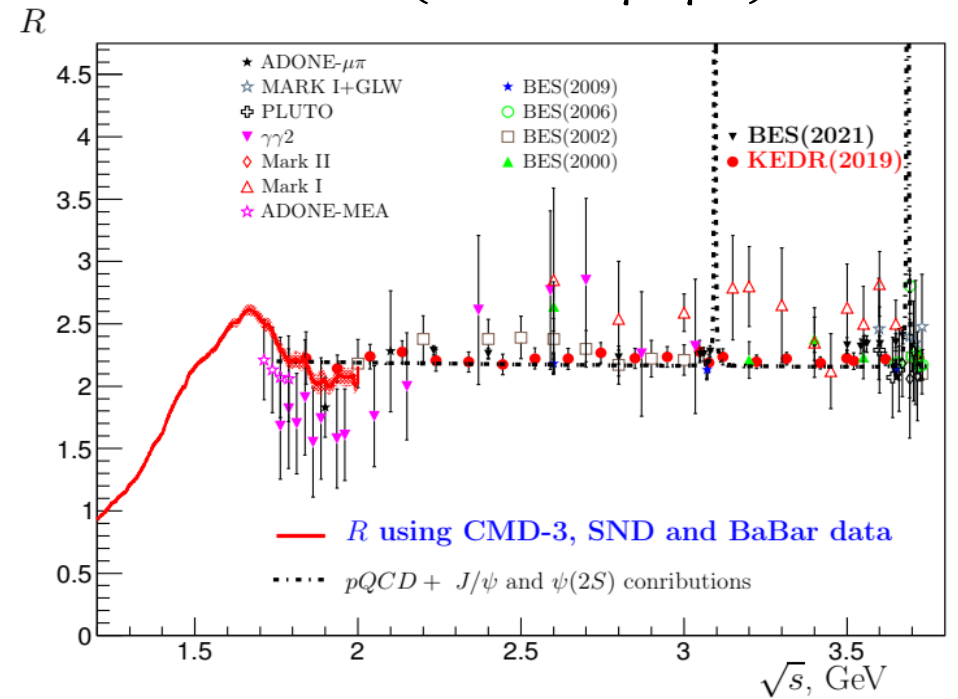
$M(J/\psi)$



$M(\psi(2S))$

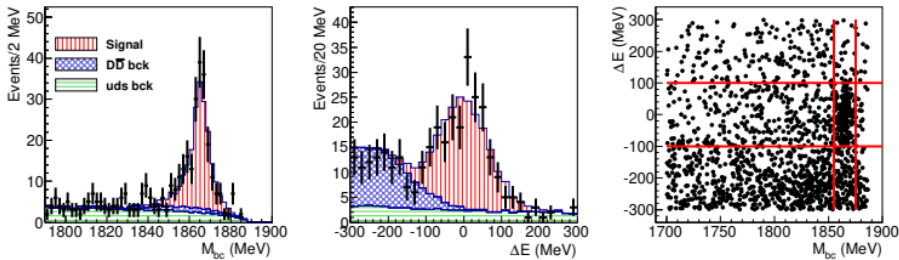


$$R(s) = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$$

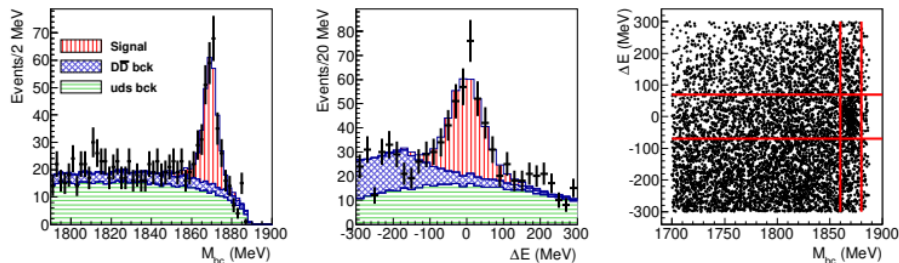


New measurement of D^0 and D^\pm masses

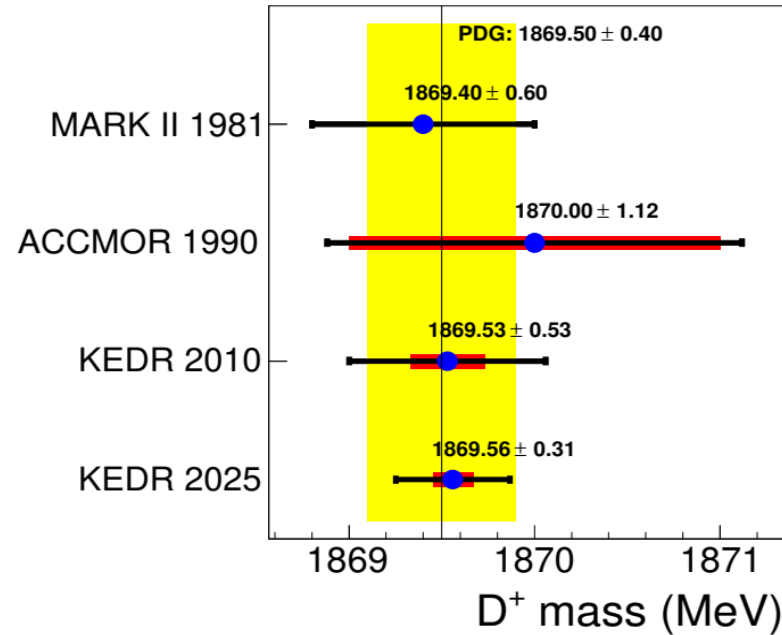
D^0 signal



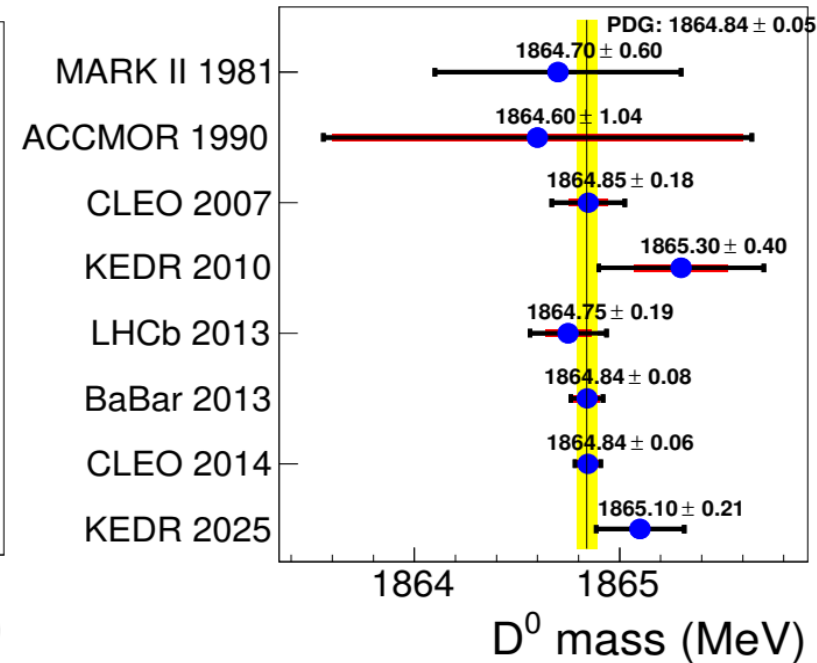
D^\pm signal



D^+ mass measurements

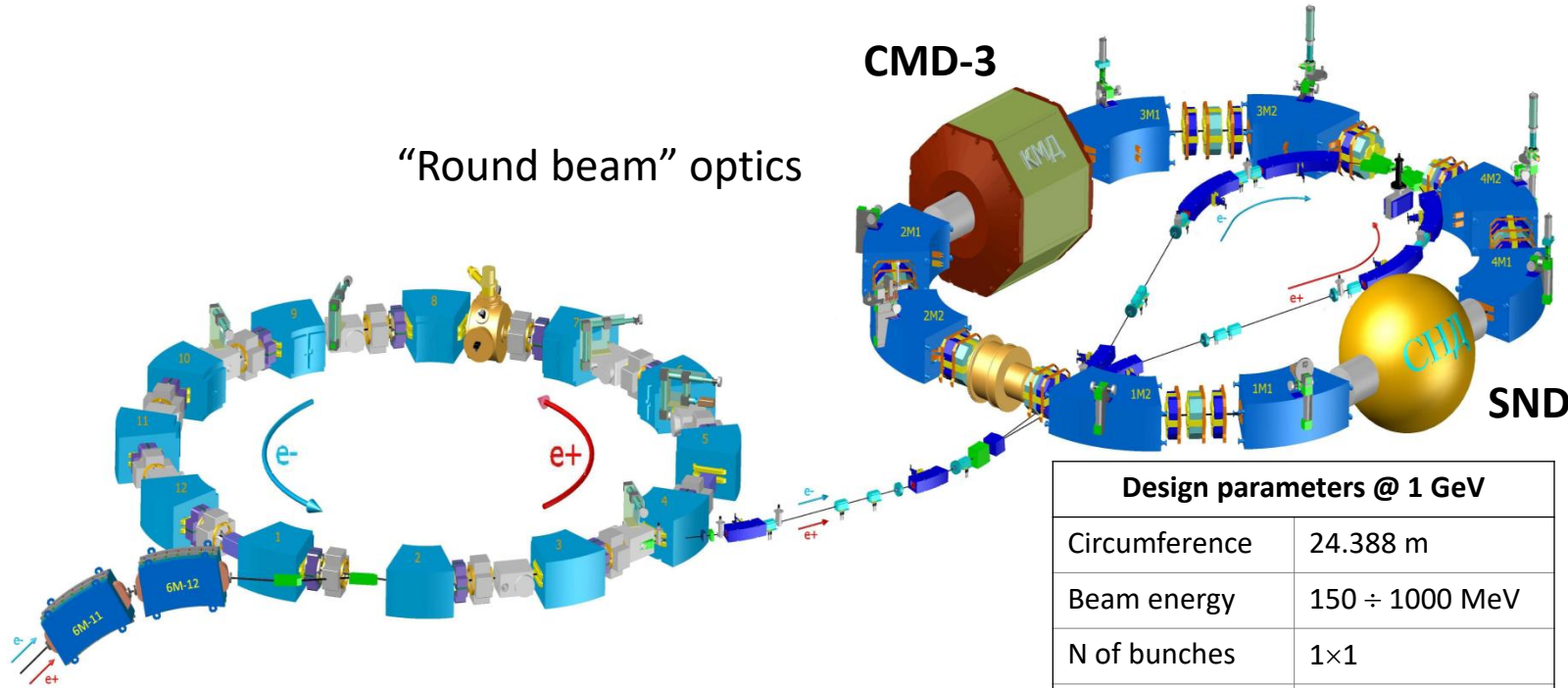


D^0 mass measurements



V.V.Anashin et. al. (KEDR collaboration), JHEP 11 (2025) 001

VEPP-2000



“Round beam” optics

Energy monitoring by Compton backscattering

$$\Delta E_b/E_b = 6 \times 10^{-5}$$

Design parameters @ 1 GeV	
Circumference	24.388 m
Beam energy	150 ÷ 1000 MeV
N of bunches	1×1
N of particles	1×10 ¹¹
Betatron tunes	4.14 / 2.14
Beta*	8.5 cm
Luminosity	1×10 ³² cm ⁻² s ⁻¹

World-highest luminosity below 2 GeV
(except at φ)

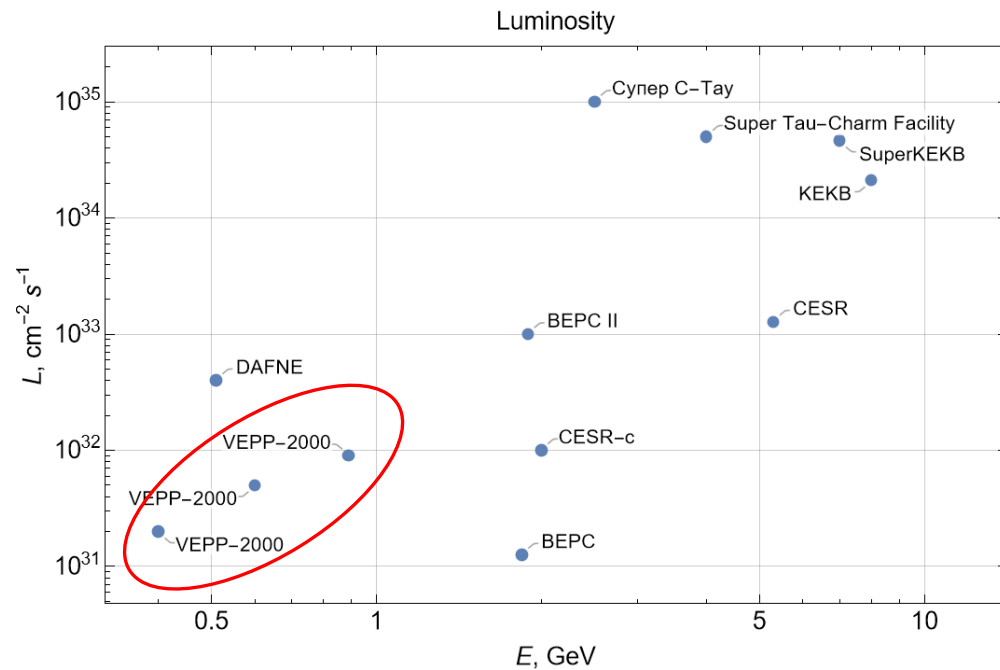
Experimental program:

- Exclusive $e^+e^- \rightarrow hadrons$ at $\sqrt{s} \leq 2.007$ GeV (spectroscopy of uds hadrons, dynamics,...)
- Related to muon (g-2)
- $p\bar{p}, n\bar{n}$ threshold
- Other topics

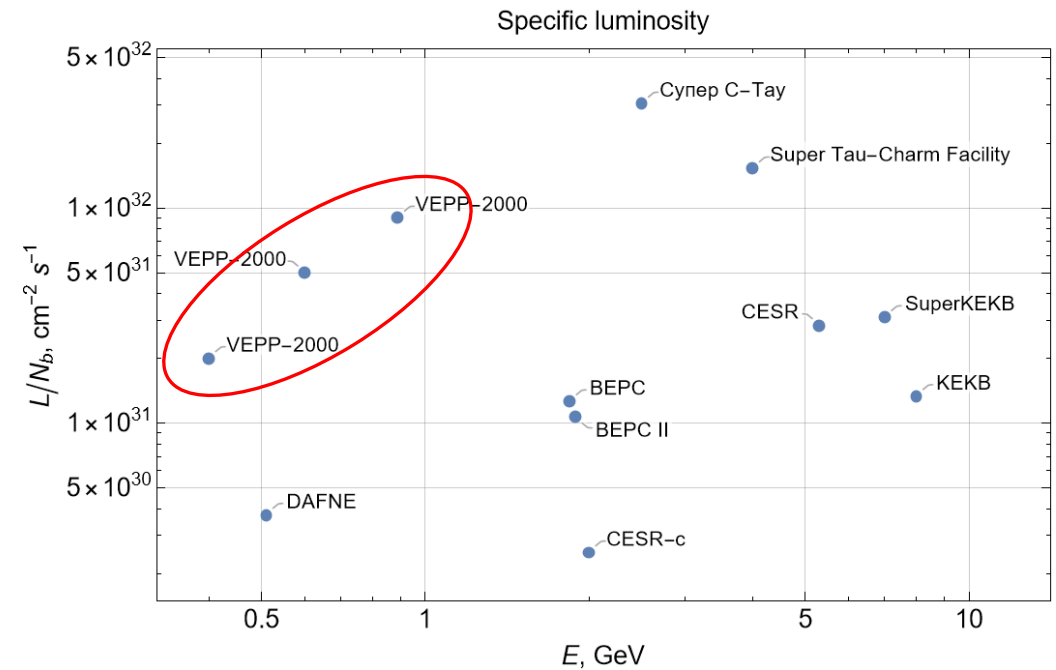
>1 fb⁻¹ collected per detector

VEPP-2000 luminosity

Unique VEPP-2000 optics, “round beams”, allows to suppress beam-beam effects
VEPP-2000 holds world record for single bunch luminosity

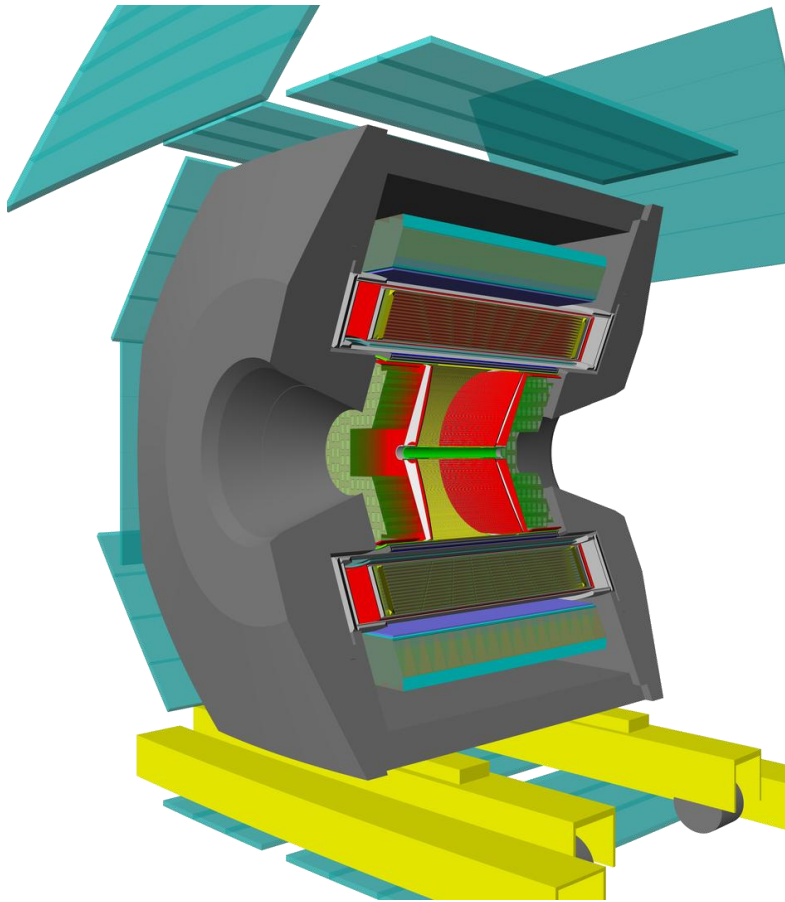


Luminosity of colliders



Per bunch luminosity of colliders

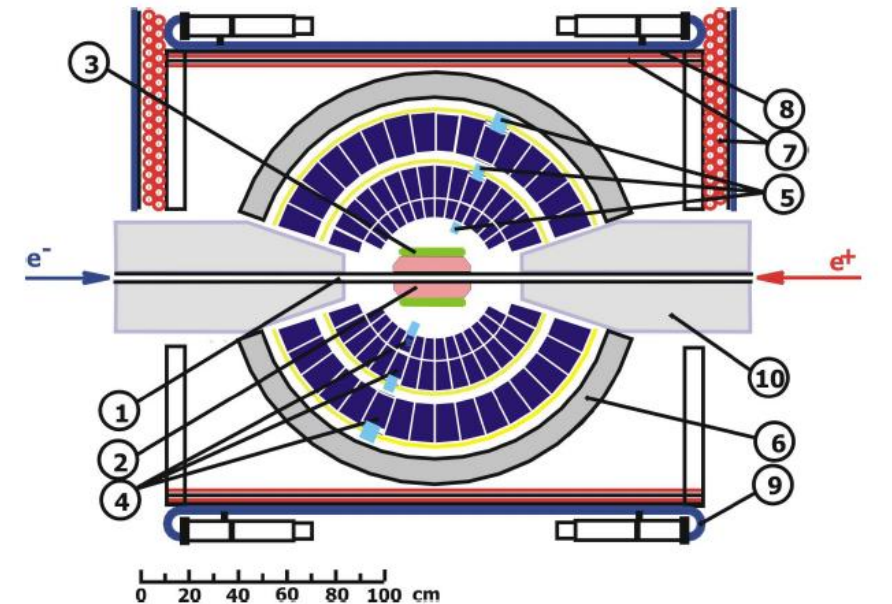
VEPP-2000 detectors



CMD-3 detector

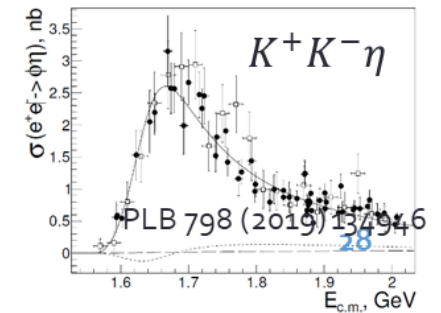
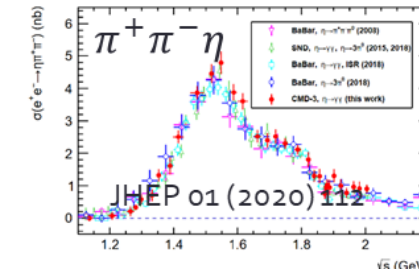
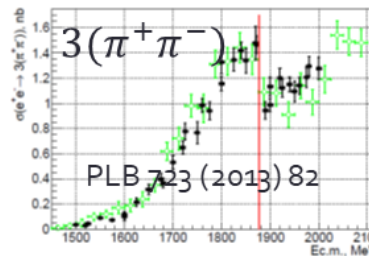
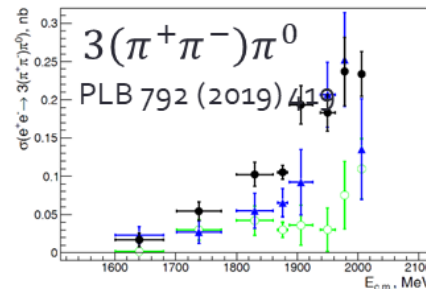
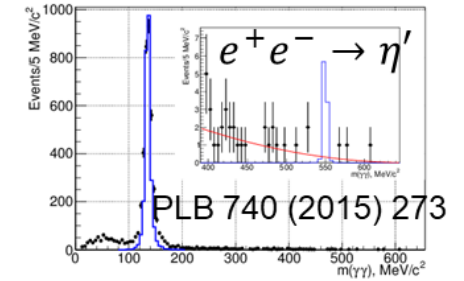
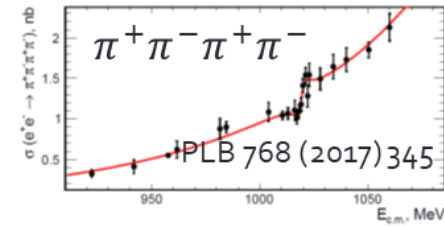
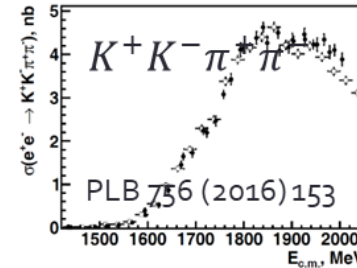
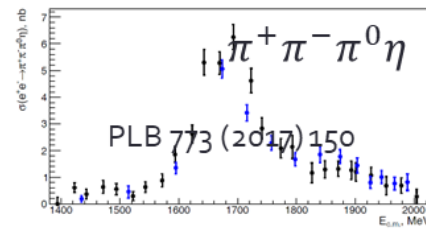
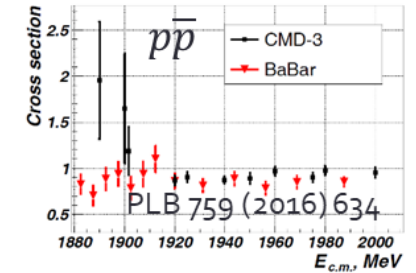
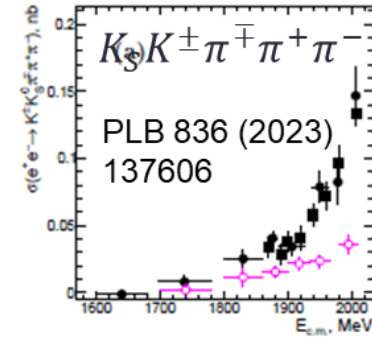
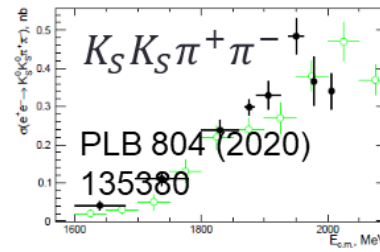
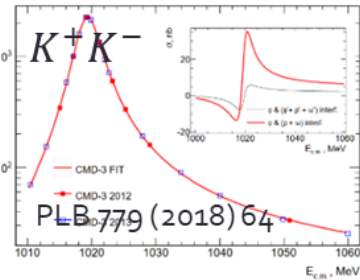
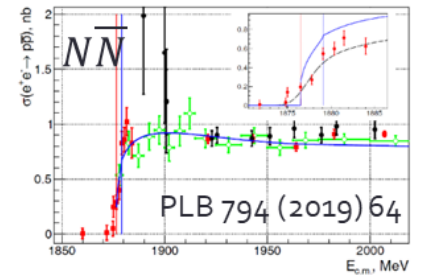
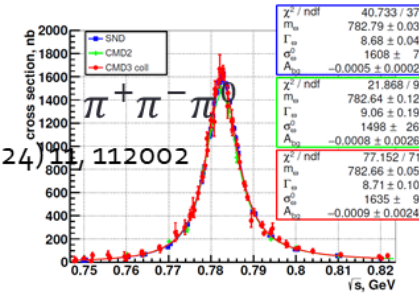
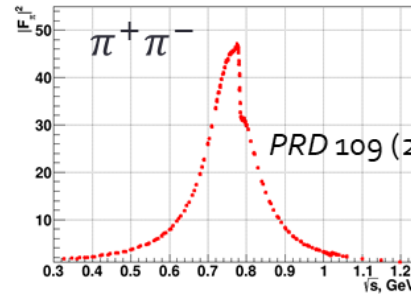
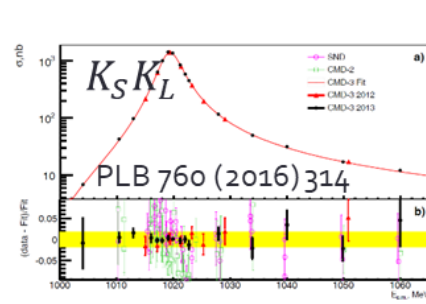
- B field 1.0-1.3 T
- Tracking resolution
 - $\sigma_{R\phi} \sim 100 \mu, \sigma_z \sim 2 - 3 \text{ m}$
- Combined calorimeter (LXE, CsI, BGO), $13.5 X_0$
 - $\sigma_E/E \sim 3\% - 10\%$
 - $\sigma_\Theta \sim 5 \text{ mrad}$
- TOF system
 - $\sigma_t \sim 0.5 \div 1 \text{ ns}$
- Muon counters

SND detector

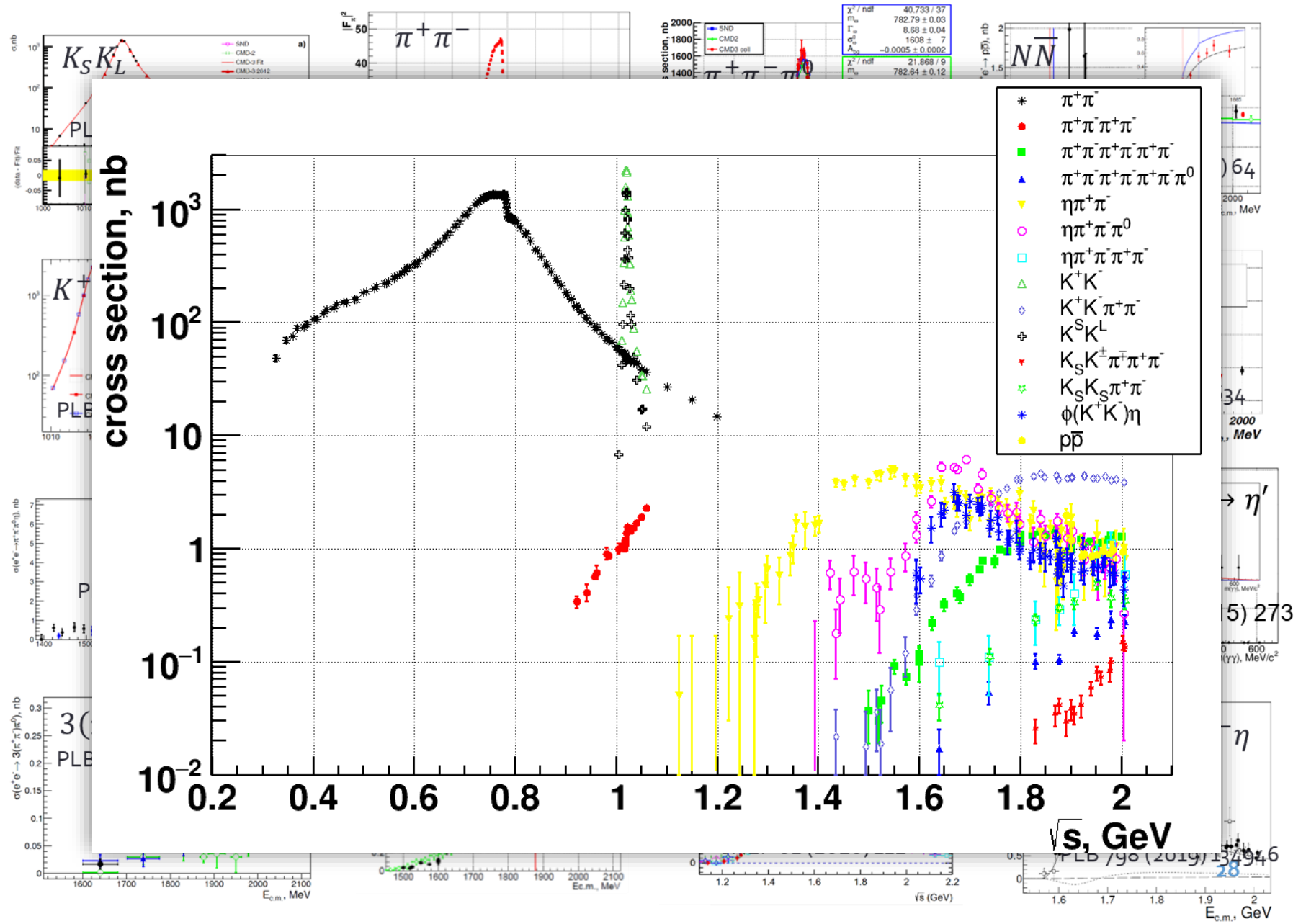


1-beam pipe, **2**-tracking system, **3**- aerogel Cherenkov counter, **4** - NaI(Tl) crystals, **5** - phototriodes, **6** - iron muon absorber, **7-9** - muon detector, **10** - focusing solenoids.

Published CMD-3 results



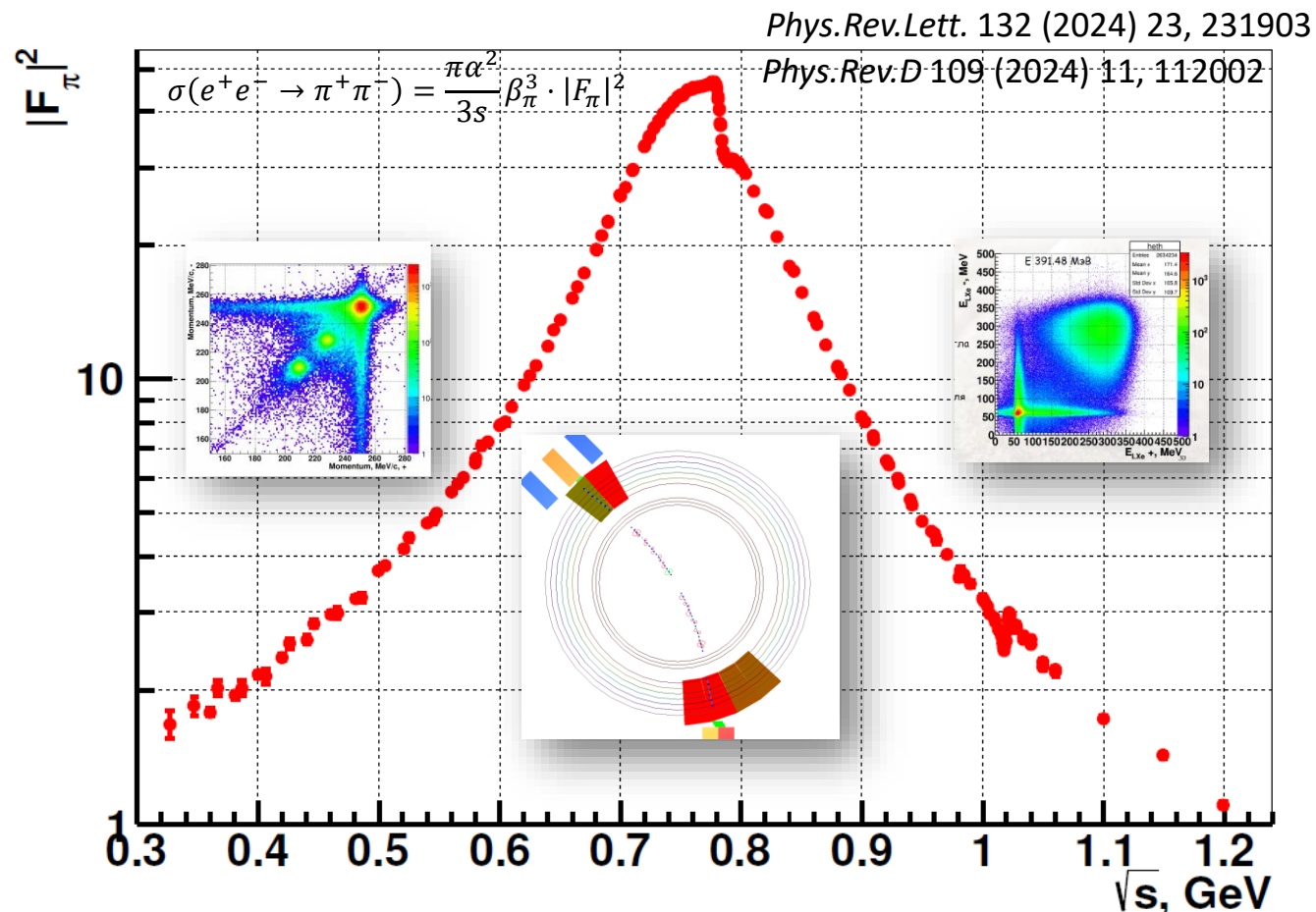
Published CMD-3 results



CMD-3 measurement of $e^+e^- \rightarrow \pi^+\pi^-$

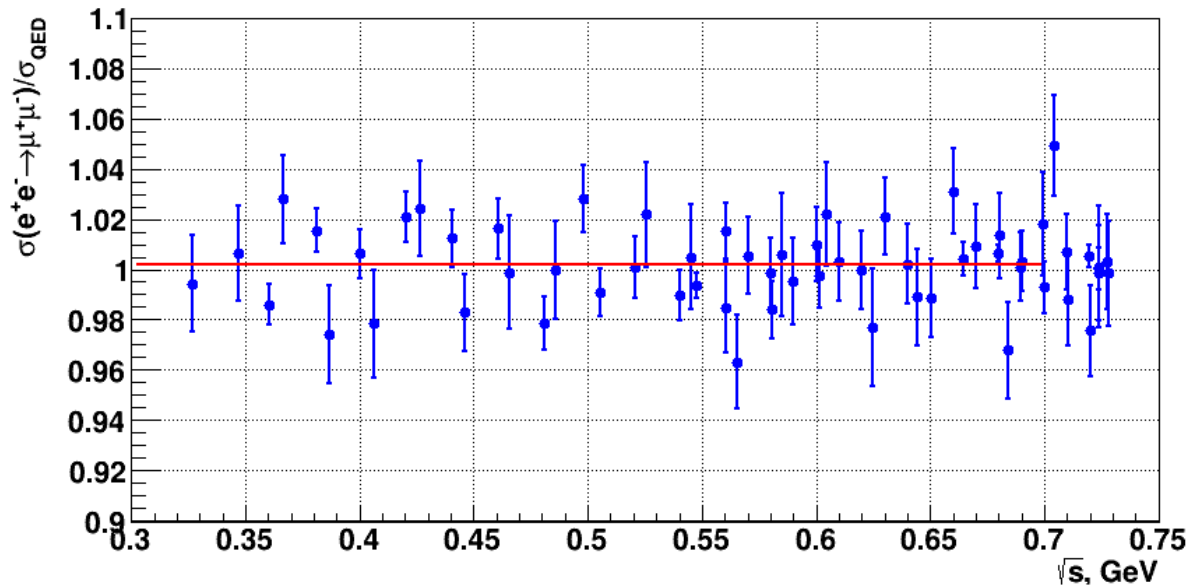
- World-largest statistics
 - 34 000 000 $e^+e^- \rightarrow \pi^+\pi^-$
 - 3 700 000 $e^+e^- \rightarrow \mu^+\mu^-$
 - 44 000 000 $e^+e^- \rightarrow e^+e^-$
 - 209 energy points (2013, 2018, 2020)
- Many built-in cross checks
 - 3 methods for final states identification
 - 2 methods for angle measurement
 - Measurement of $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$
 - Measurement of charge asymmetry
- Very detailed study of potential systematics

Systematic error is **0.7%** at ρ peak



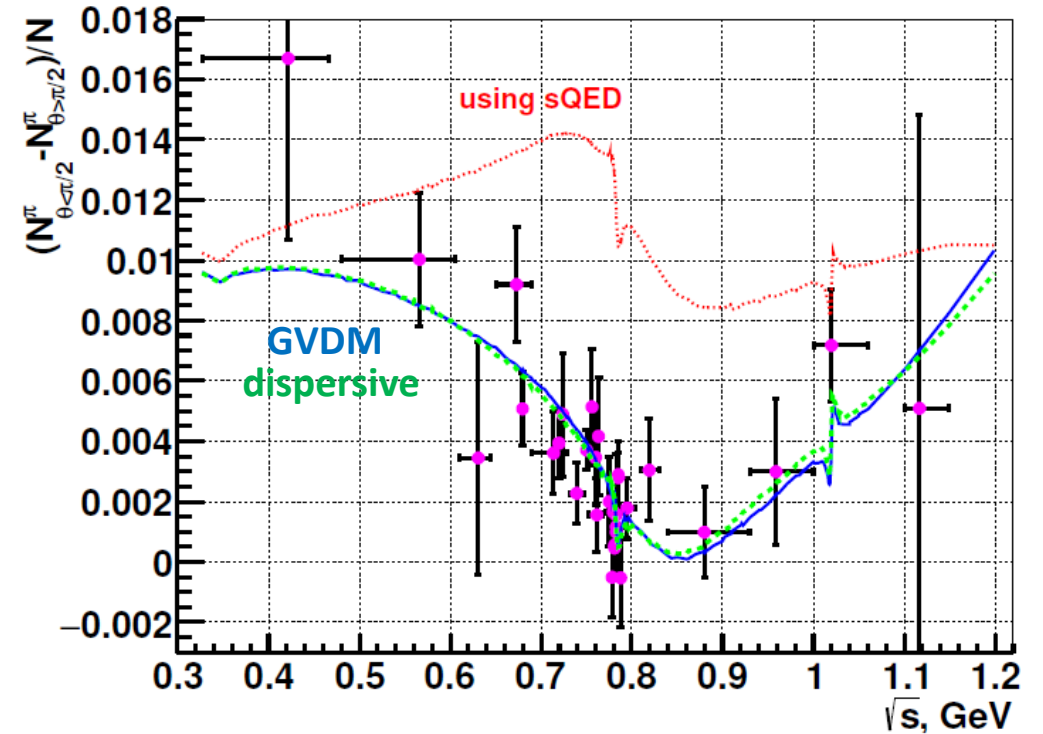
$e^+e^- \rightarrow \pi^+\pi^-$ accompanying measurements

$$\sigma(e^+e^- \rightarrow \mu^+\mu^-)_{CMD3}/\sigma(e^+e^- \rightarrow \mu^+\mu^-)_{QED}$$



$+0.17 \pm 0.16 \%$

Charge asymmetry in $e^+e^- \rightarrow \pi^+\pi^-$

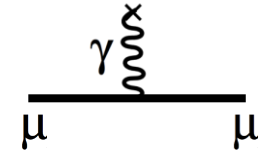


Anomalous magnetic moment of muon

The basics

Gyromagnetic ratio g connects magnetic moment μ and spin s

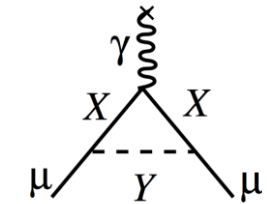
$$\vec{\mu}_s = g \frac{e}{2m} \vec{S}$$



For point-like particle $g = 2$

Anomalous magnetic moment a arises in higher-orders

$$a = (g - 2)/2$$



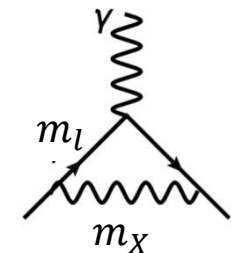
$$a_e \approx a_\mu \approx \frac{\alpha}{2\pi} \approx 10^{-3} \quad (\text{QED dominated})$$

Idea of experiment: by comparing measured value of a with the theory prediction we probe extra contributions to a beyond theory expectations

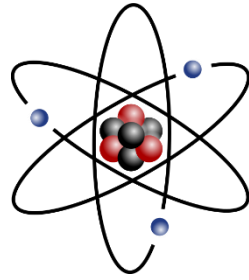
$$a_\mu(\text{strong})/a_\mu(\text{QED}) \approx 6 \times 10^{-5} \quad a_\mu(\text{weak})/a_\mu(\text{QED}) \approx 10^{-6}$$

Why muon? For massive fields there is natural scaling, which enhances contribution to a_μ by $(m_\mu/m_e)^2 \sim 43000$ compared to a_e

$$\Delta a \sim \left(\frac{m_l}{m_X} \right)^2$$

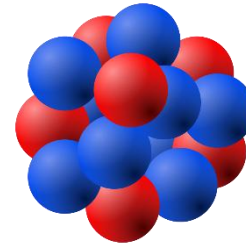


Standard Model prediction for a_μ



Electromagnetic interactions

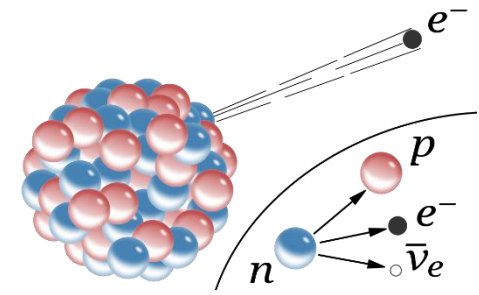
0.001 165 847 19 (0.2)



Strong interactions

???

0.000 000 071 61 (62)



Weak interactions

0.000 000 001 54 (0.4)

Physics Reports 1143 (2025) 1-158

$$a_\mu = 0.001\ 165\ 920\ 33\ (62) \quad \text{WP2025}$$

22 in experiment

The uncertainty is dominated by contribution of strong interactions

Dispersive approach:
$$a_\mu(Had; LO) = \int \sigma_{e^+e^- \rightarrow hadrons}(s) K(s) ds$$

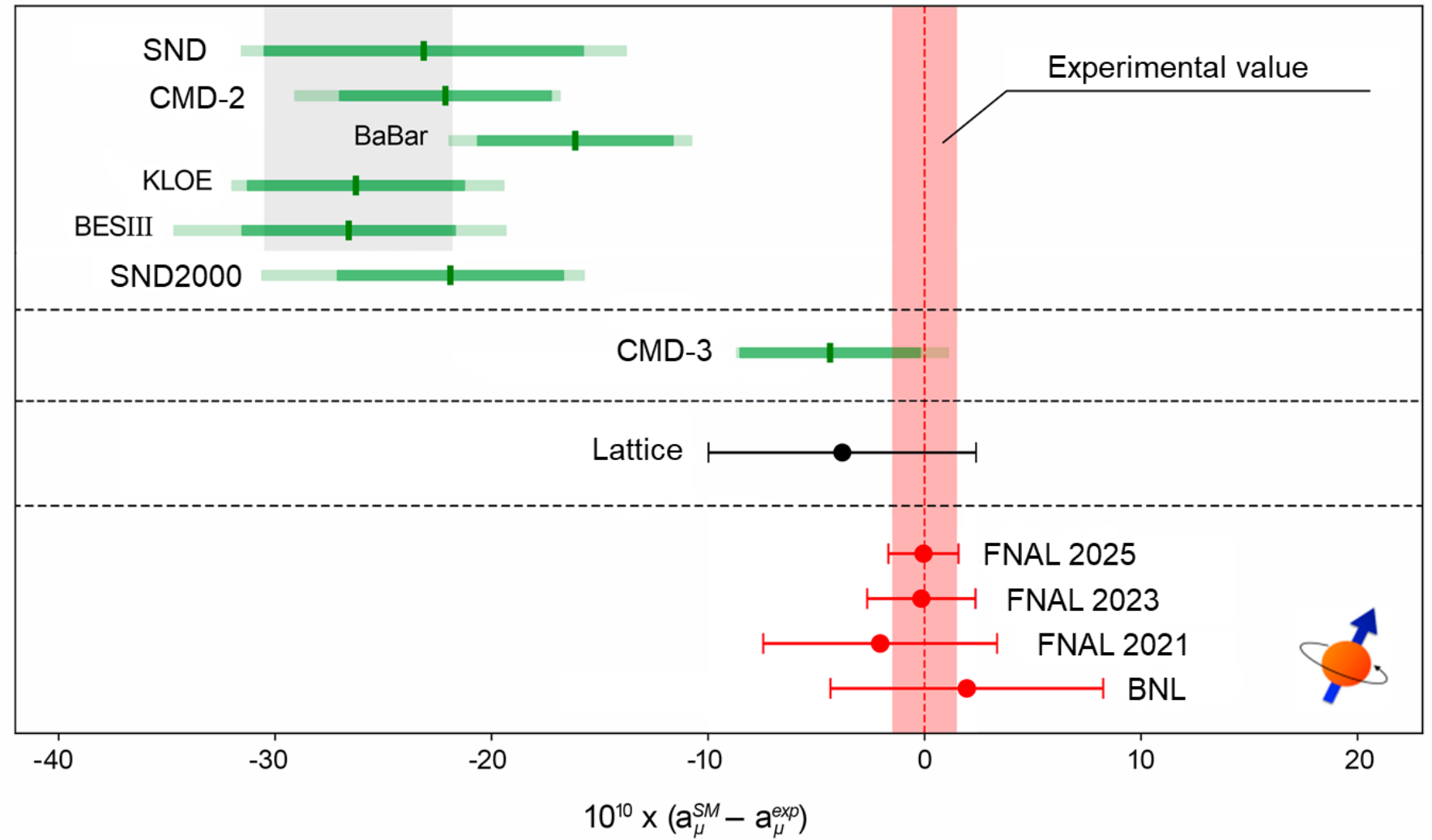
Requires knowledge of $\sigma_{e^+e^- \rightarrow hadrons}(s)$ from the threshold to few GeV

$\sigma(e^+e^- \rightarrow \pi^+\pi^-)$ is responsible for $\frac{3}{4}$ of $a_\mu(Had; LO)$

Difference between a_μ (Standard Model) and a_μ (experiment)

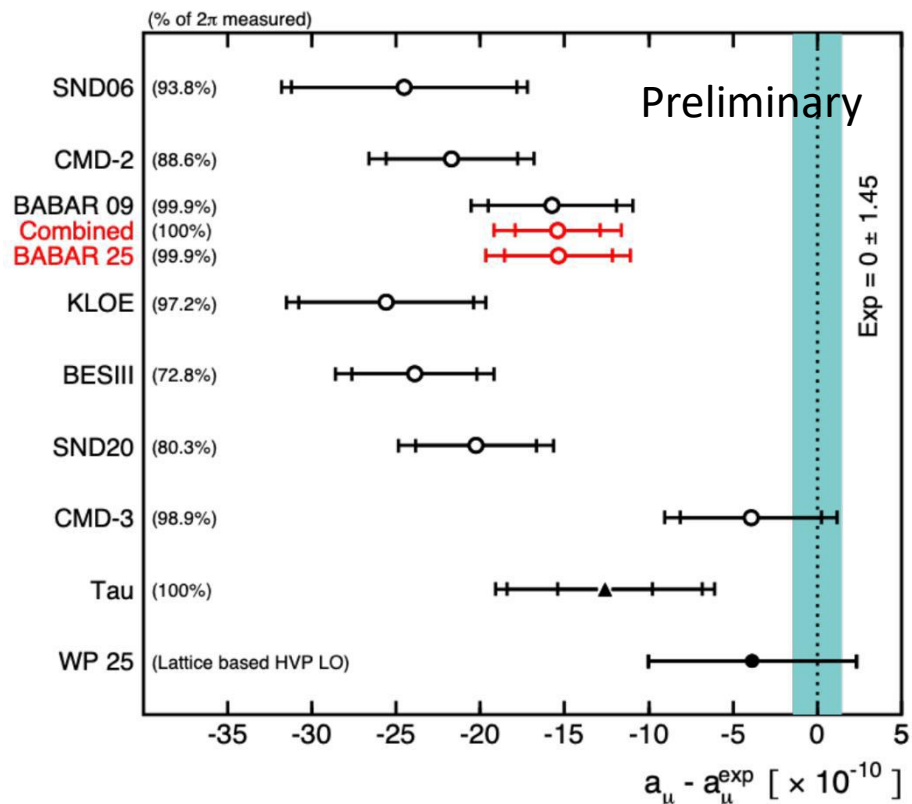
WP 2025

Implications
of CMD-3
result

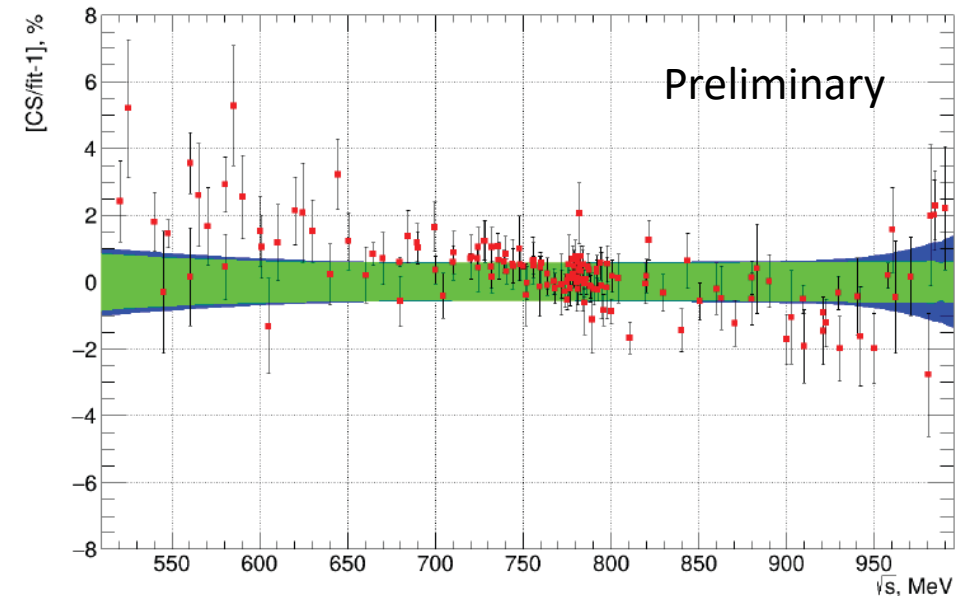


Ongoing measurements of $\sigma(e^+e^- \rightarrow \pi^+\pi^-)$

New BABAR result seems to confirm previous BABAR result



New SND results seems to not contradict CMD-3



Deviation from our fit, green area – systematics, blue one - total uncertainty

$$a_\mu \times 10^{10} = 431.11 \pm 3.52 \text{ vs. CMD-3: } a_\mu \times 10^{10} = 433.62 \pm 3.76$$

$e^+e^- \rightarrow \pi^+\pi^-\pi^0$ @CMD-3

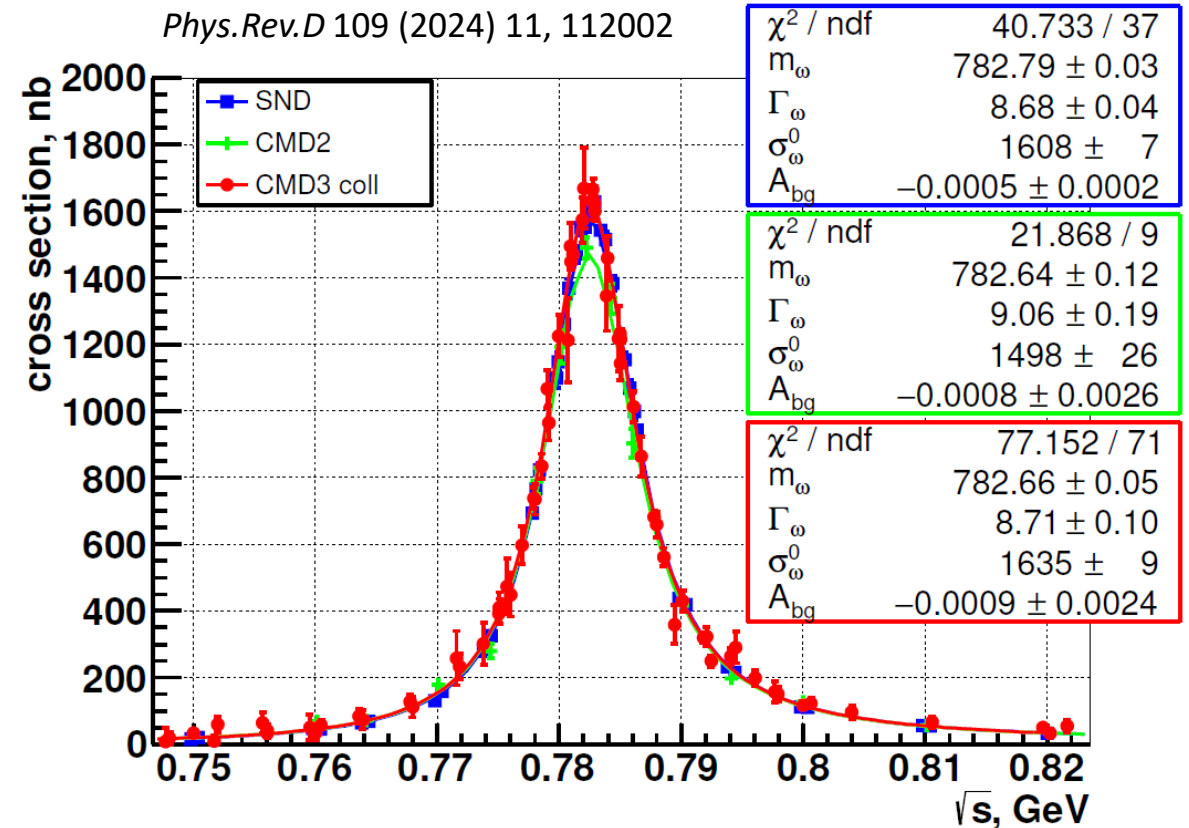
By-product of $e^+e^- \rightarrow \pi^+\pi^-$ analysis

Based on small subset of $e^+e^- \rightarrow \pi^+\pi^-\pi^0$ sample (“collinear” selection cuts, π^0 nearly at rest)

Estimated systematic error is 3.3%

2.2 σ tension with CMD-2 measurement

Dedicated analysis of full $e^+e^- \rightarrow \pi^+\pi^-\pi^0$ is underway



$e^+e^- \rightarrow \pi^+\pi^-\pi^0$ @SND

Данные 2018 года: **66 пб⁻¹ в 102 точках**

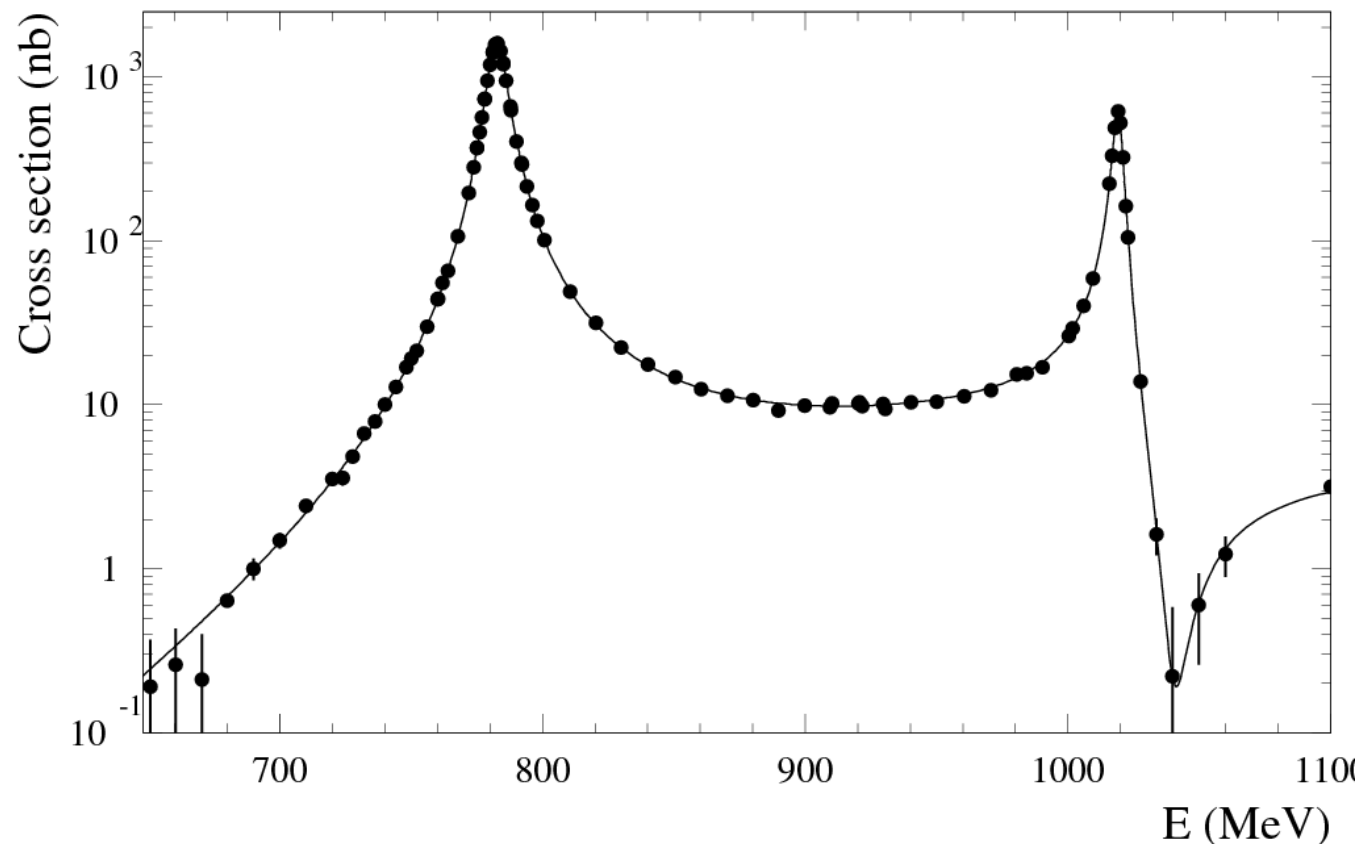
Энергетический диапазон 0.56-1.1 ГэВ:
резонансы ω , ρ и ϕ

Статистика существенно превышает статистику ВЭПП-2М и BABAR

Систематическая ошибка:

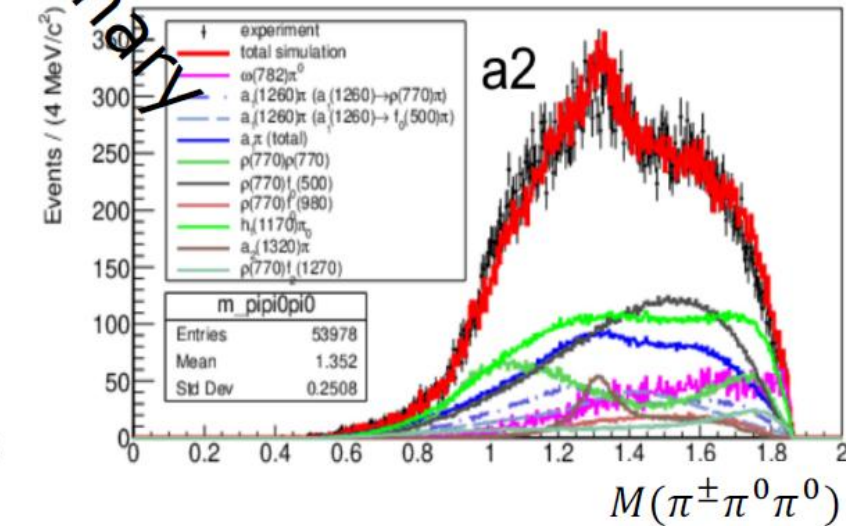
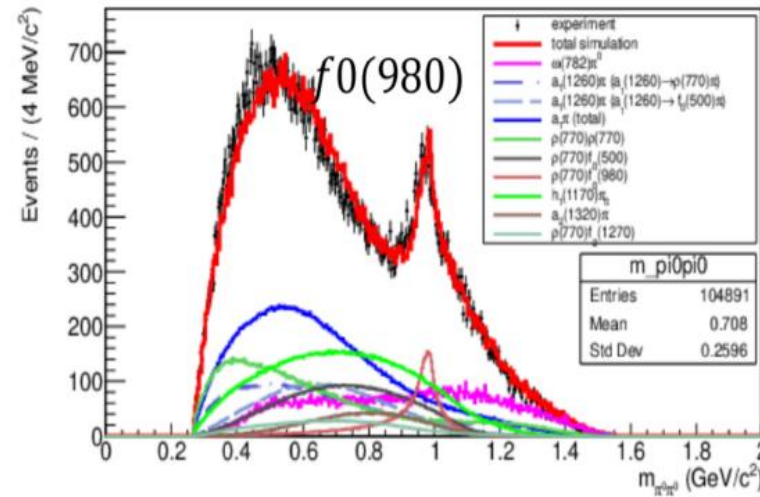
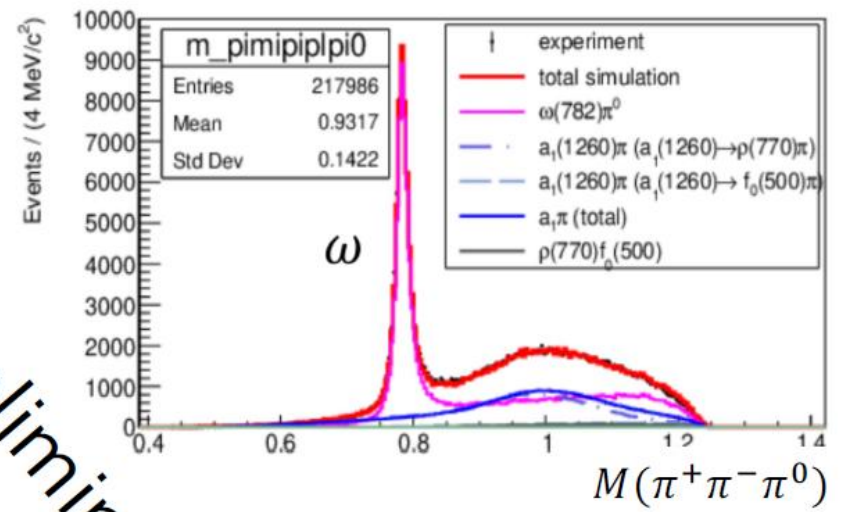
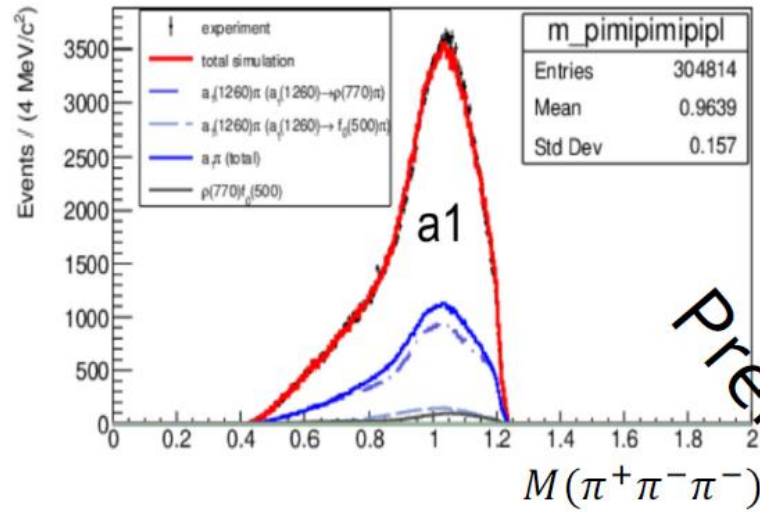
- 0.9% на ω
- 1.2% на ϕ
- 1.5% между ω и ϕ

Submitted



Preliminary results of amplitude analysis for $\pi^+\pi^-\pi^+\pi^-$ and $\pi^+\pi^-\pi^0\pi^0$

@CMD-3



Preliminary

Amplitude analysis allows to study dynamics and to reduce model error

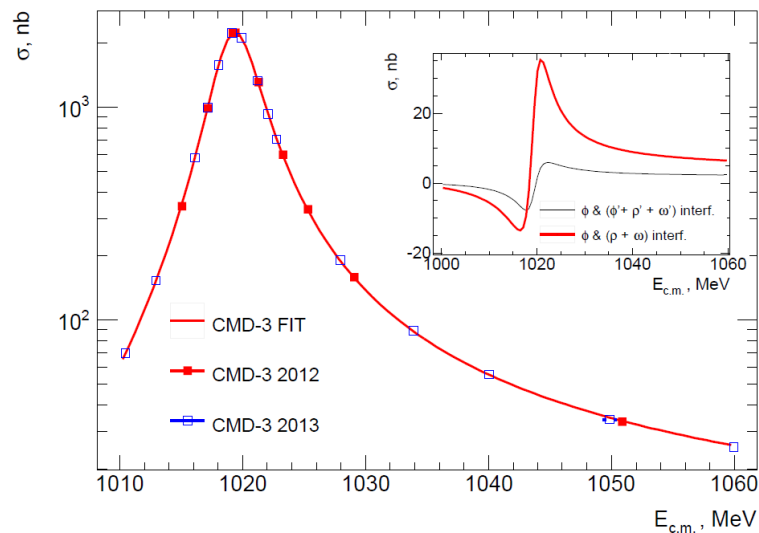
Large statistics required

Amplitude analysis based on full statistics is under way for several channels

$K_S K_L, K^+ K^-$

@CMD-3

$$e^+e^- \rightarrow K^+K^-$$



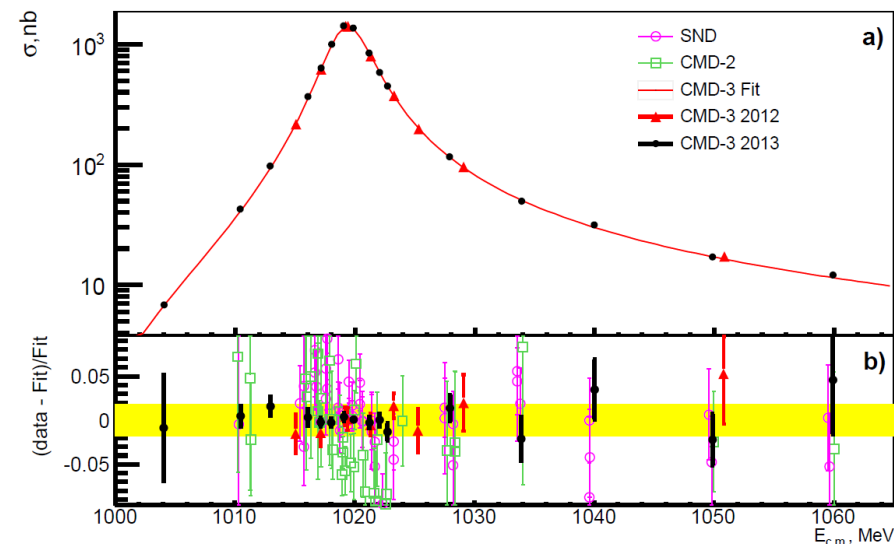
PLB 779 (2018) 64

2.0% systematic error

CMD-3 published $K_S K_L, K^+ K^-$ at $\varphi(1020)$ only

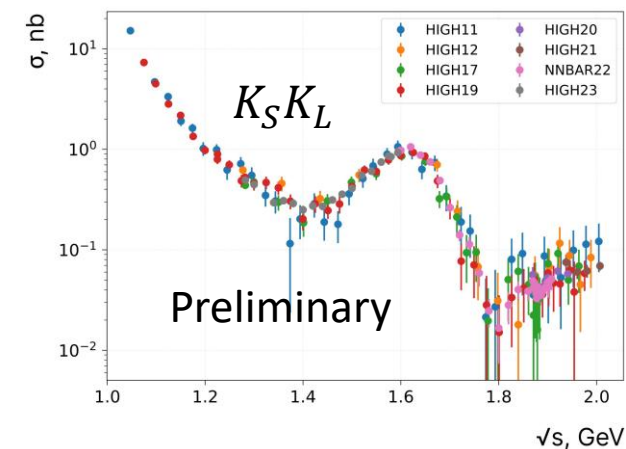
The data analysis at energies above φ is ongoing for both channels

$$e^+e^- \rightarrow K_S K_L$$

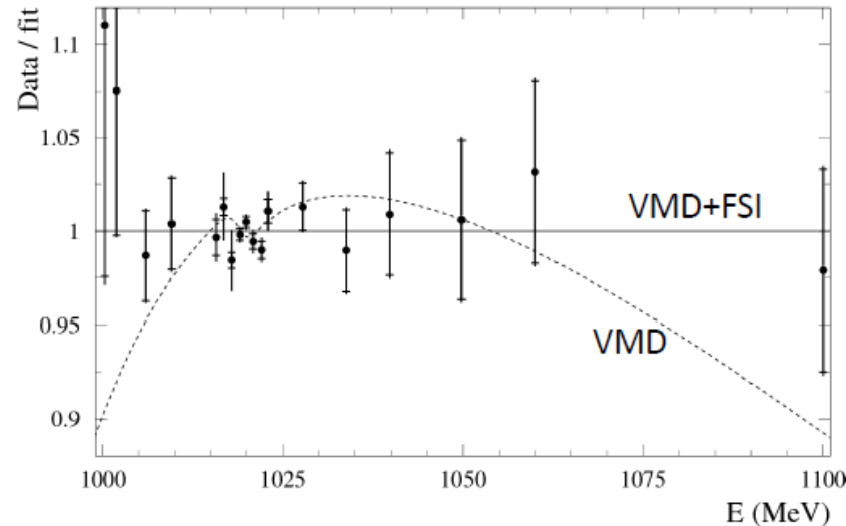
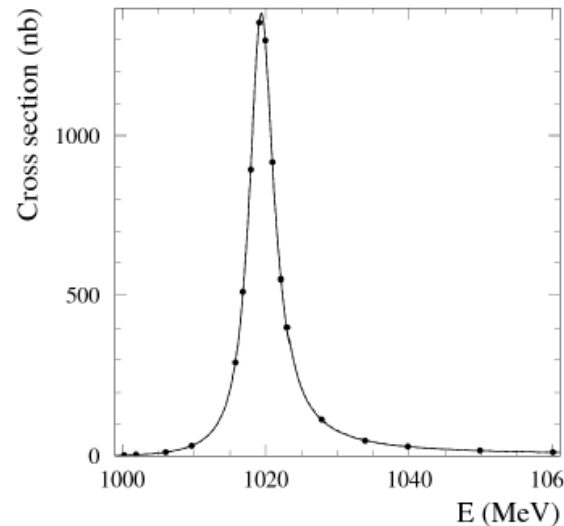


PLB 760 (2016) 314

1.8% systematic error



$e^+e^- \rightarrow K^+K^-$ near φ @SND



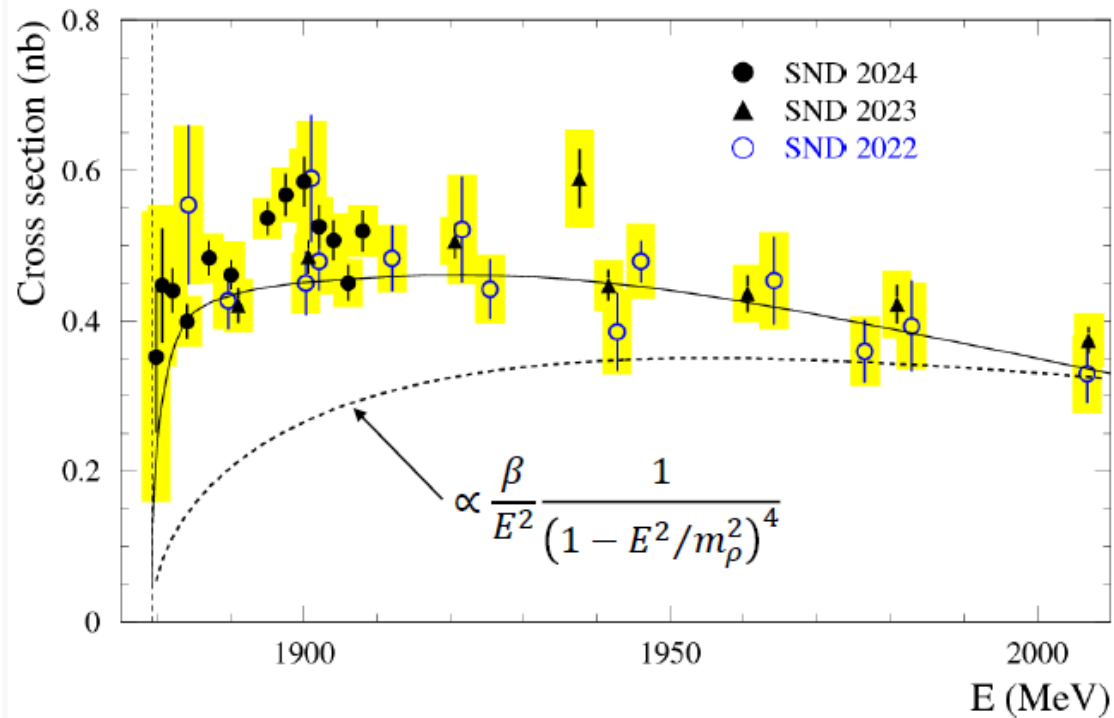
Phys. Rev. D 110, 072001 (2024)

The process $e^+e^- \rightarrow K_S K_L$ is studied in the decay mode $K_S \rightarrow \pi^0 \pi^0 \rightarrow 4\gamma$. In the multiphoton final state, $K_S K_L$ events can be selected with very loose conditions.

Two models are used to describe the cross section: VMD and VMD+FSI. The latter provides significantly better fit quality, $\chi^2/\text{ndf}=13.7/14$ against $23.7/14$ for the pure VMD model. **The FSI significance is 3.2σ .**

The FSI effect was calculated by S.Salnikov and A.Milstein (work in progress). The scale factor to the cross section is 1.16 at $E=1000$ MeV, 1 at $E=m_\phi$, and 0.92 at $E=1100$ MeV

$e^+e^- \rightarrow n\bar{n}$ @SND



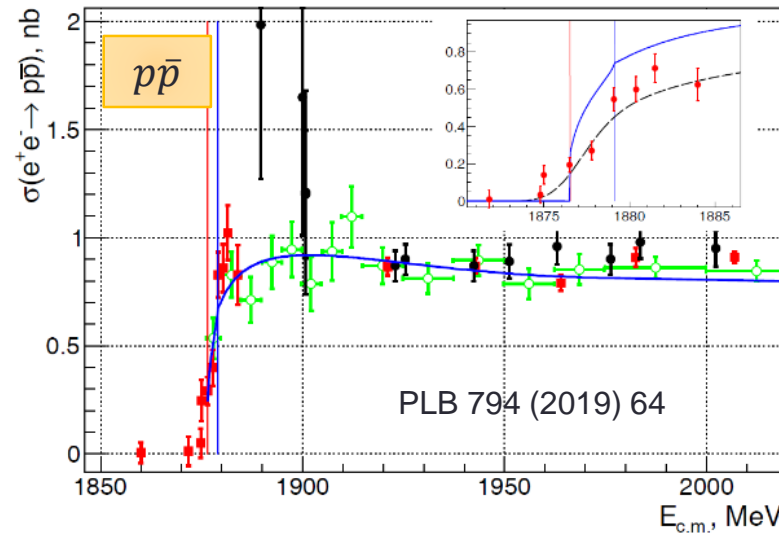
M.N. Achasov *et al*, Eur. Phys. J. C **22**, 761 (2022)
 (2017 and 2019 datasets)
 Phys. Atom. Nucl. **86**, 1165 (2023)
 (2020 and 2021 datasets)
 Phys. Atom. Nucl. (2024) (2022 dataset)

- ✓ The $e^+e^- \rightarrow n\bar{n}$ cross section in the below 2 GeV has been measured with about 5% statistical and 10-15% systematic uncertainty.
- ✓ The cross section is flat and very different from the energy dependence of the S-wave phase space ($\propto \beta$).
- ✓ The difference is explained by the $n\bar{n}$ final state interaction (A.I.Milstein and S.G.Salnikov, Phys. Rev. D **106**, 074012 (2022)), which leads to a large effect.

Hadron production in e^+e^- annihilation at $N\bar{N}$ threshold @CMD-3

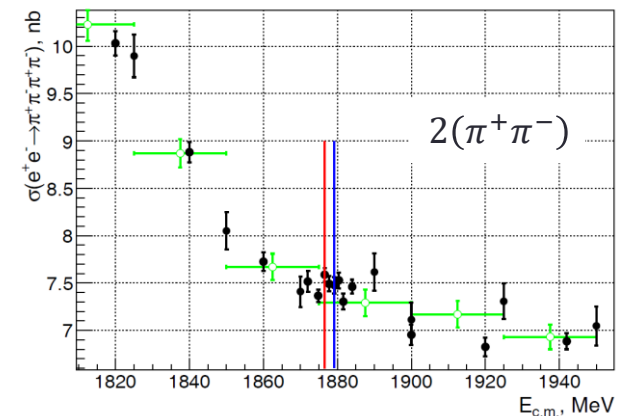
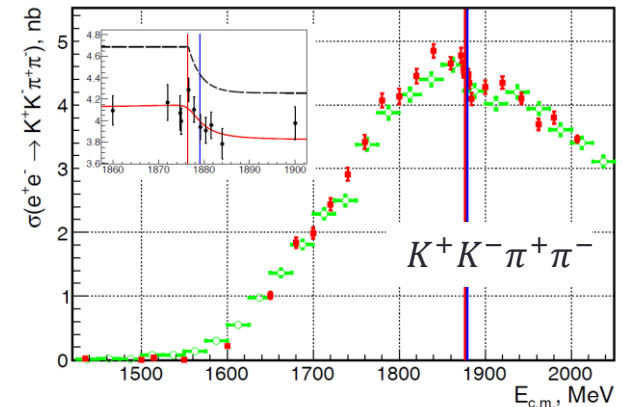
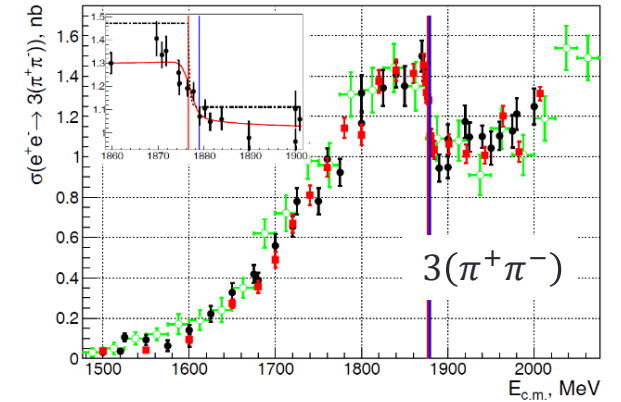
Detailed study of hadronic cross sections near $p\bar{p}$ and $n\bar{n}$ thresholds

2017 data



- sharp change in $e^+e^- \rightarrow p\bar{p}$, $3(\pi^+\pi^-)$, $K^+K^-\pi^+\pi^-$
- width ~ 1 MeV – consistent with energy resolution
- no structure in $e^+e^- \rightarrow 2(\pi^+\pi^-)$?

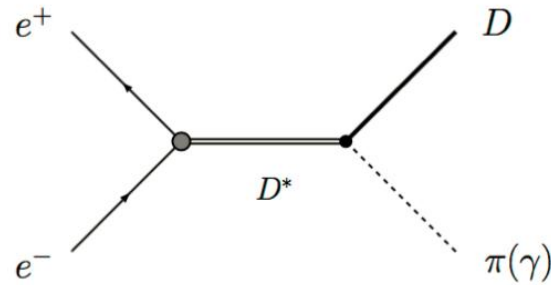
x17 more data collected, finer scan, under analysis: $p\bar{p}$ (including $|G_E/G_M|$), $n\bar{n}$



Search for FCNC process

$$e^+ e^- \rightarrow D^{*0}$$

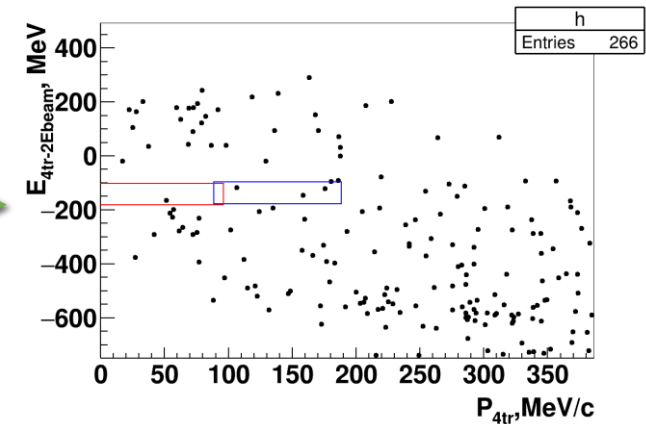
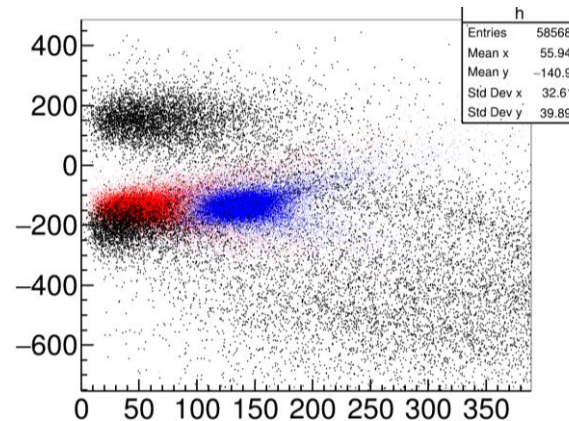
@CMD-3



CMD-3 has collected 25 1/pb at D^{0*}

$$B(D^{0*} \rightarrow e^+ e^-) < 3.7 \cdot 10^{-7}$$

preliminary



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Sensitivity:

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

SM prediction:

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

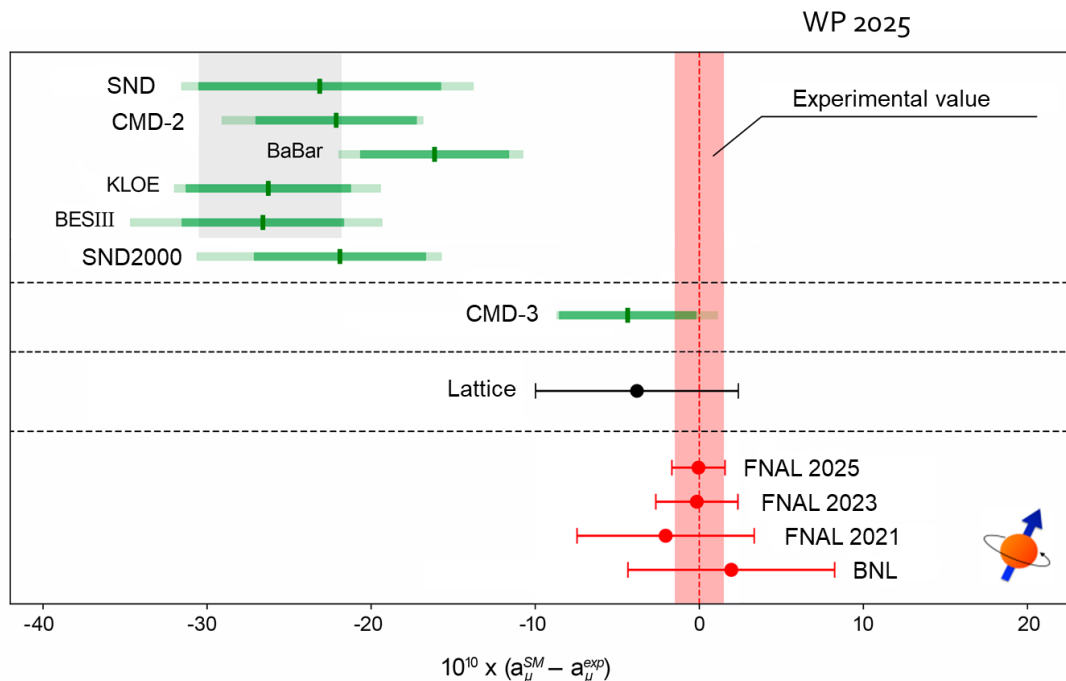
BSM predictions:

$$B_{D^{*} \rightarrow e^+ e^-}^{Z'} < 2.5 \times 10^{-11}$$

Room for several orders of magnitude improvement at STCF and VEPP-6

Next round of experiments at VEPP-2000

Anomalous magnetic moment of muon



SM estimation of a_{μ} based on $\sigma(e^{+}e^{-} \rightarrow hadrons)$ is
~3 times less precise than experimental value

VEPP-2000 energy range is still interesting:

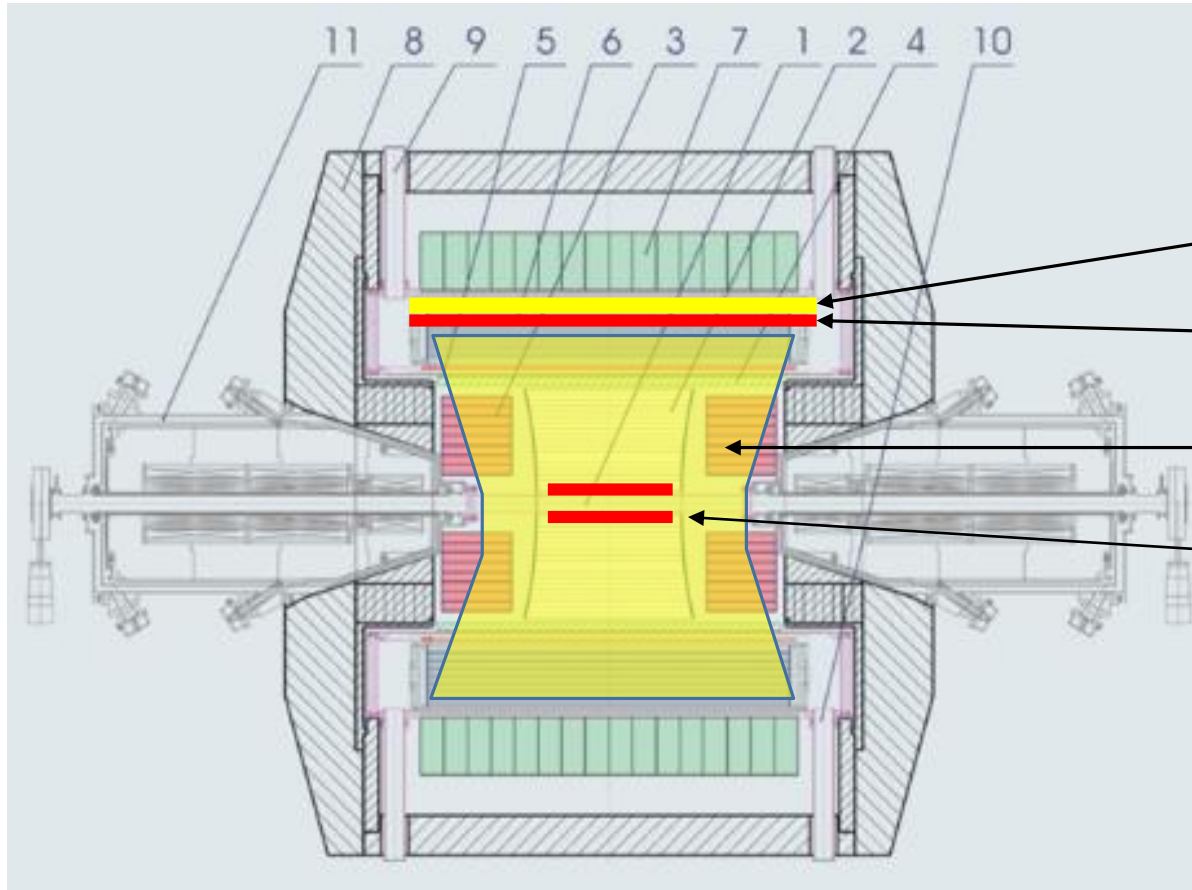
- Need $\sigma(e^{+}e^{-} \rightarrow \pi^{+}\pi^{-})$ with <0.2% precision (as well as other exclusive final states)
- Dynamics of $e^{+}e^{-} \rightarrow hadrons$ (amplitude analysis)
- Rare processes

VEPP-2000 luminosity is still the highest in the world in its energy range. The precision is limited by detectors.

Now working on detector upgrades.

~2030 – start data taking with upgraded detectors

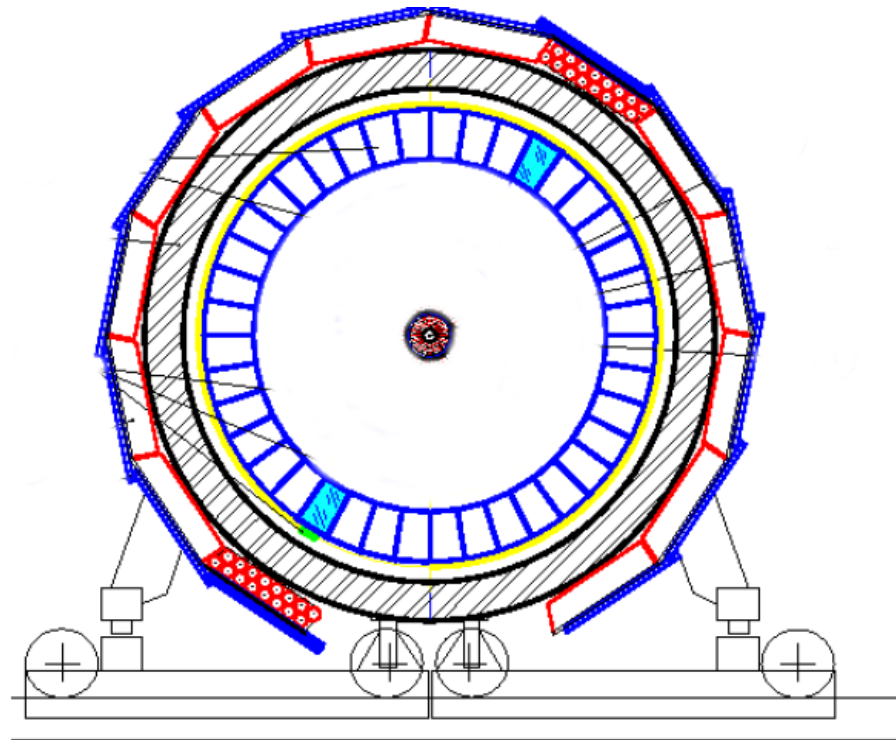
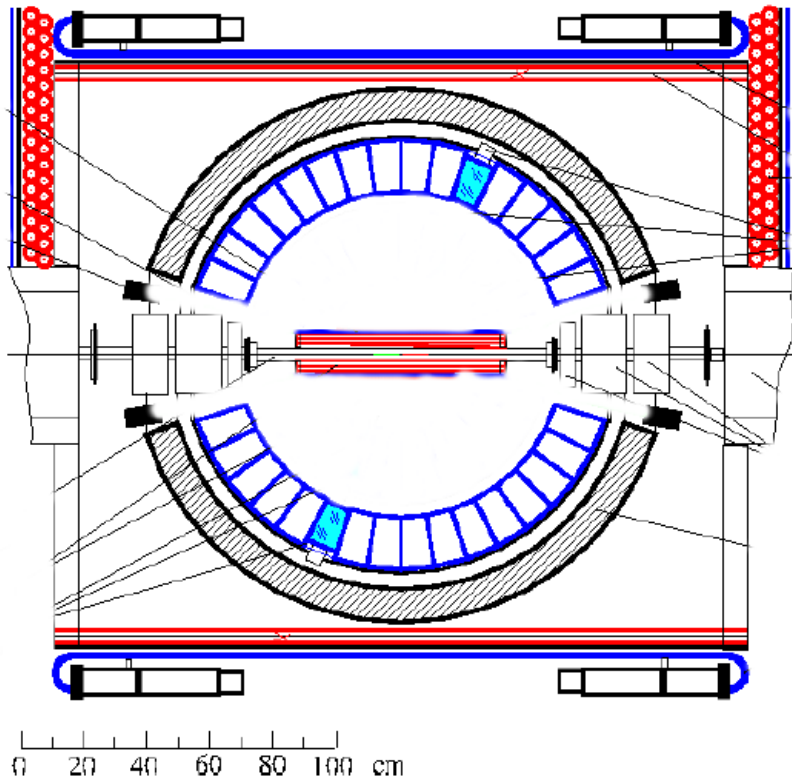
Proposed CMD-3 upgrades



CMD-3 upgrades:

- New SC magnet
- New Z-chamber
- New drift chamber
- New silicon vertex detector
- New electronics

Proposed SND upgrades for $n\bar{n}$



- New drift chamber
- New electronics
- Larger flight distance of neutrons

Dedicated measurement of $|G_E/G_M|$ of neutron

VEPP-6

- e^+e^- collider - J/ψ factory and beyond
 - Beam energy from <0.5 to 1.6 GeV (J/ψ) (2.1 GeV)
 - Luminosity $\mathcal{L} \approx 10^{34} \text{ cm}^{-2} \text{ c}^{-1}$ @ 1.6 GeV
 - Located at BINP (Novosibirsk)
- General purpose detector
- Physics
 - J/ψ decays, physics of light hadrons

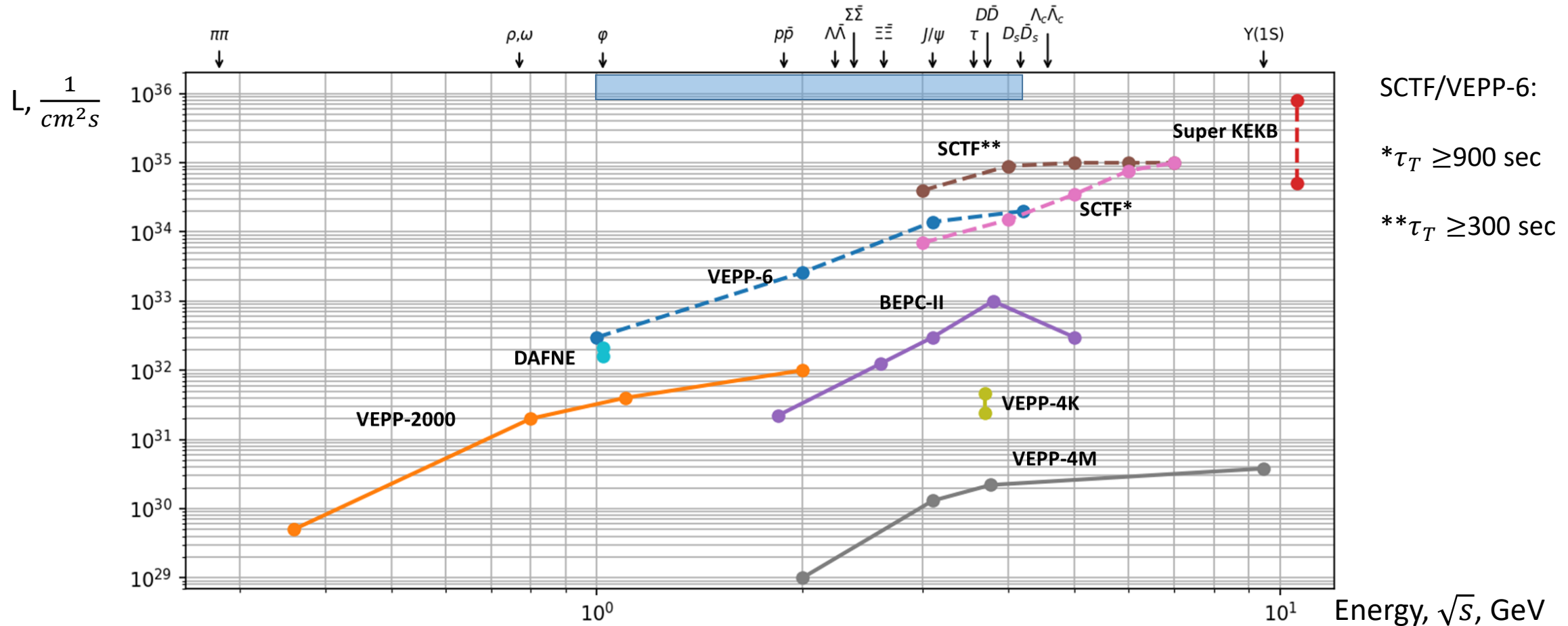
$5 \times 10^{11} J/\psi: 5 \times 10^8 \eta, 3 \times 10^9 \eta', 10^{10} a_2/f_2, 10^9 \Lambda\bar{\Lambda}, \dots$

 - Baryon thresholds
 - Measurement of $e^+e^- \rightarrow \text{hadrons}$, direct/ISR

From A.Bogomyagkov

$E, \text{ MeV}$	500	1000	1550	2100
$\Pi, \text{ m}$			388	
$2\theta, \text{ mrad}$			50	
$\beta_x^*/\beta_y^*, \text{ mm}$			150/3	
$I_{tot}, \text{ A}$	0.26	0.78	1.5	1.5
$\varepsilon_x, \text{ nm}$	55	33	31	31
$T_{Touschek}, \text{ s}$	900	900	1000	2000
$\mathcal{L}, 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$	1.7	25	150	200
	DAΦNE: 2-4	VEPP-2000: 0.9	BEPCII: 3.1	BEPCII: 10

VEPP-6 and other e^+e^- colliders



VEPP-6 physics program

Comprehensive study of strong interaction in the least-known intermediate energy range

- Physics of charmonium ($J/\psi, \psi', h_c, \eta_c, \chi_c, \dots$)
 - Radiative and hadronic decays
 - Spectroscopy of light hadrons
 - XYZ physics with light quarks
 - Search for glueball and hybrids
 - Invisible decays (dark photon etc.)
- Physics of baryons
 - EM form factors (including phase)
 - Final state interactions near thresholds
- $e^+e^- \rightarrow hadrons$
 - Measurement of R
 - Exclusive final states: cross sections, dynamics via amplitude analysis
 - Related to $(g-2), \alpha(s)$, pQCD tests, LQCD validation,...
- Additional possibilities
 - $e^+e^- \rightarrow D^{*0}$
 - $\gamma\gamma \rightarrow hadrons$
 - τ physics
 - $e^+e^- \rightarrow DD, DD\pi, DD^*, \dots$

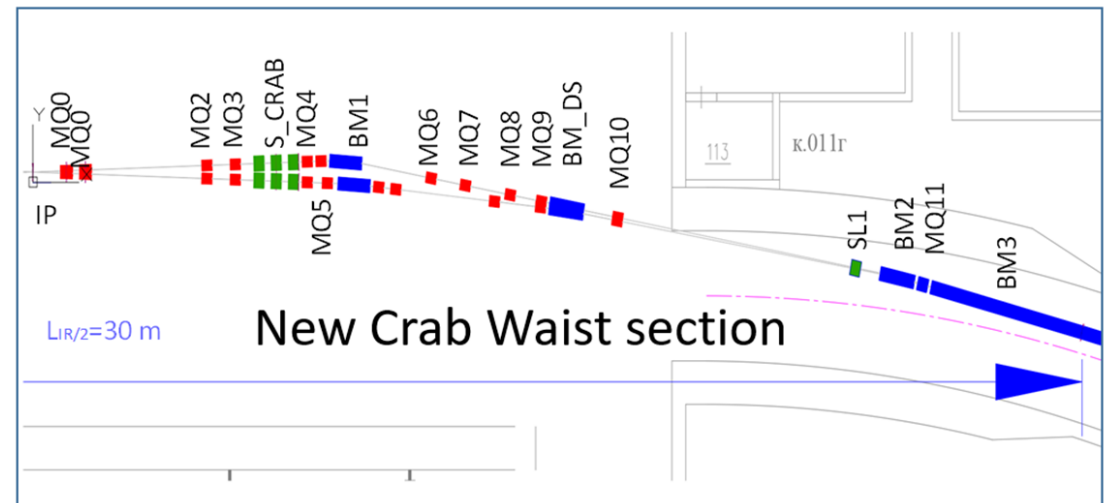
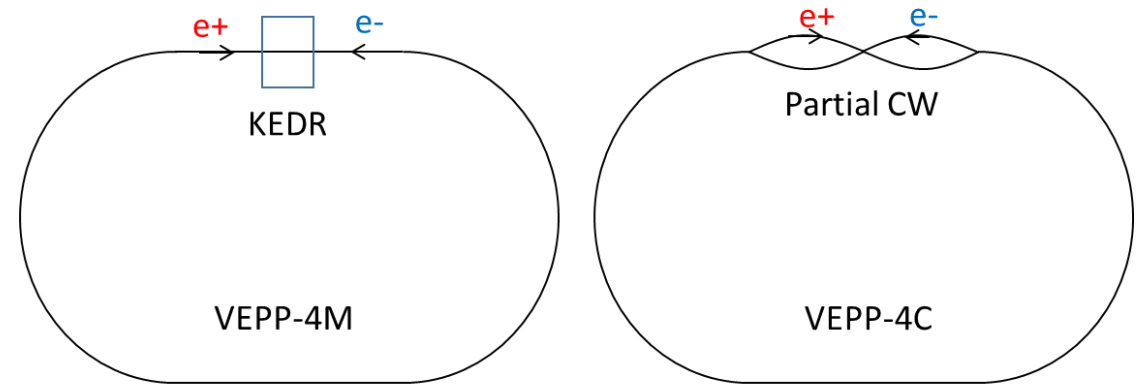
Road to VEPP-6: VEPP-4C, CW test at VEPP-4M

- Idea: use existing VEPP-4M facility and FF installation to perform comprehensive study of crab-waist technique (VEPP-4C)

VEPP-4M straight section is modified.
Electrostatic separation of colliding beams.

20-50x luminosity of VEPP-4M

- What can be tested
final focus elements, nonlinear beam dynamics, beam-beam effects, backgrounds,...
- Beneficial for all future collider projects, including STCF – topic for collaboration

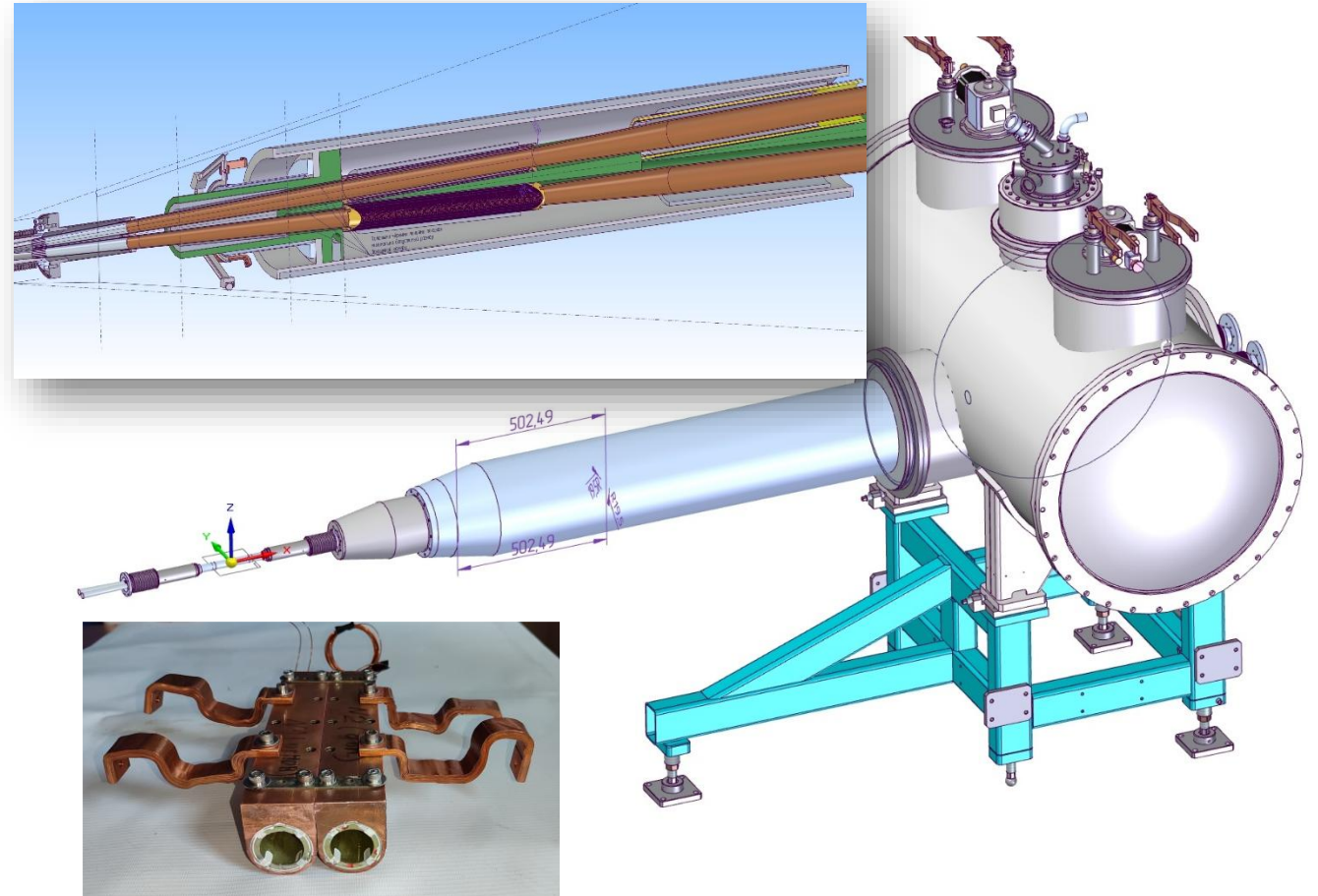


Full-scale test of the final focus

First stage of VEPP-4C is to build full scale prototype of VEPP-6 final focus

- Done: test of CCT lenses for FF
- Under development: technical design of the full FF installation
- Plan to build the full installation and to perform complete set of tests

Designed for VEPP-6, beneficial for STCF and other CW-based projects.



Conclusion

1. VEPP-4M and VEPP-2000 colliders at BINP cover wide energy range from 0.26 GeV to 9.5 GeV. Three detectors, KEDR, CMD-3 and SND are taking data.
2. Experiments at VEPP-2000 collected the world-largest sample of $e^+e^- \rightarrow \text{hadrons}$ data below 2 GeV. Data analysis is under way, many results have been published.
3. VEPP-2000 continues to be the highest luminosity collider in the world at energies below 2 GeV. The new round of experiments is planned after upgrade of detectors, now in progress.
4. VEPP-6 is the flagship collider project at BINP aimed at detailed study of strong interactions of light hadrons and search of new phenomena. Physics program of VEPP-6 is complementary to Super tau-charm and Super-B factories physics program.
5. We plan to use VEPP-4M infrastructure to perform comprehensive study of the crab-waist beams collision technique (VEPP-4C project). It is beneficial for development of all future crab-waist-based colliders.