# Измерение сечения $e^+e^- \rightarrow \pi^+\pi^-$ с детектором КМД-3 на коллайдере ВЭПП-2000 и его последствия для проблемы аномального магнитного момента мюона

Иван Борисович Логашенко (ИЯФ СО РАН)

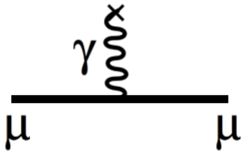
Научная сессия
Объединенного
ученого совета
по физическим
наукам СО РАН

29 ноября 2023

# The basics

**Gyromagnetic ratio $g$** connects magnetic moment $\mu$ and spin $s$

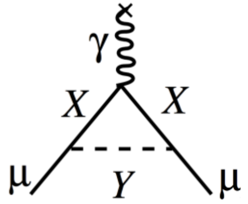
$$\vec{\mu}_S = g\frac{e}{2m}\vec{S}$$



For point-like particle $\boldsymbol{g} = \mathbf{2}$

**Anomalous magnetic moment $a$** arises in higher-orders

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



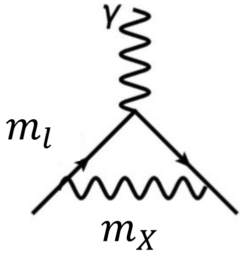
$a_e \approx a_\mu \approx \frac{\alpha}{2\pi} \approx 10^{-3}$ (QED dominated)

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

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

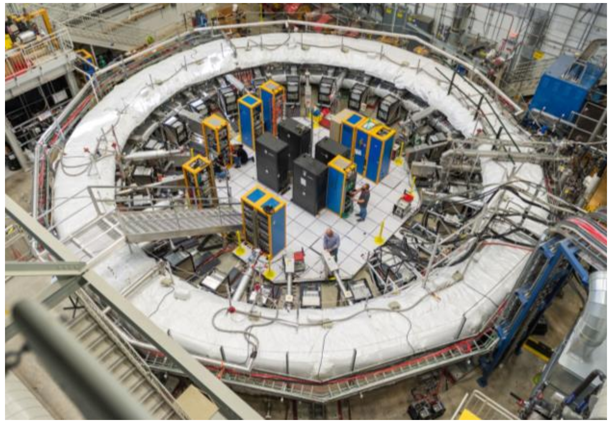
**Why muon?** For massive fields there is natural scaling, which enhances contribution to $a_\mu$ by $(m_\mu/m_e)^2 \sim 43000$ compared to $a_e$

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

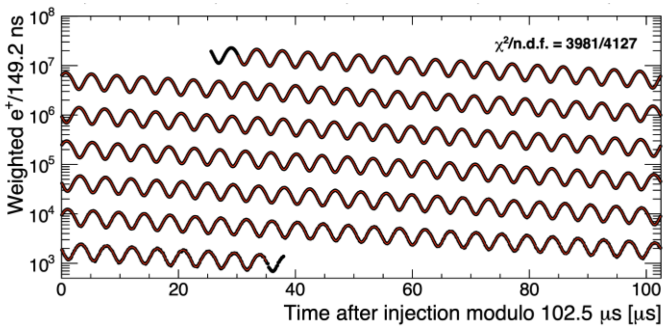


# Generations of $a_\mu$ measurements

**FNAL Run 2-3 (USA)**



Run 3a



$$g_\mu(\text{эксп}) \quad = 0.001\,165\,920\,55\,(24)$$ FNAL2023

$$g_\mu(\text{теория}) = 0.001\,165\,918\,10\,(43)$$ WP2020

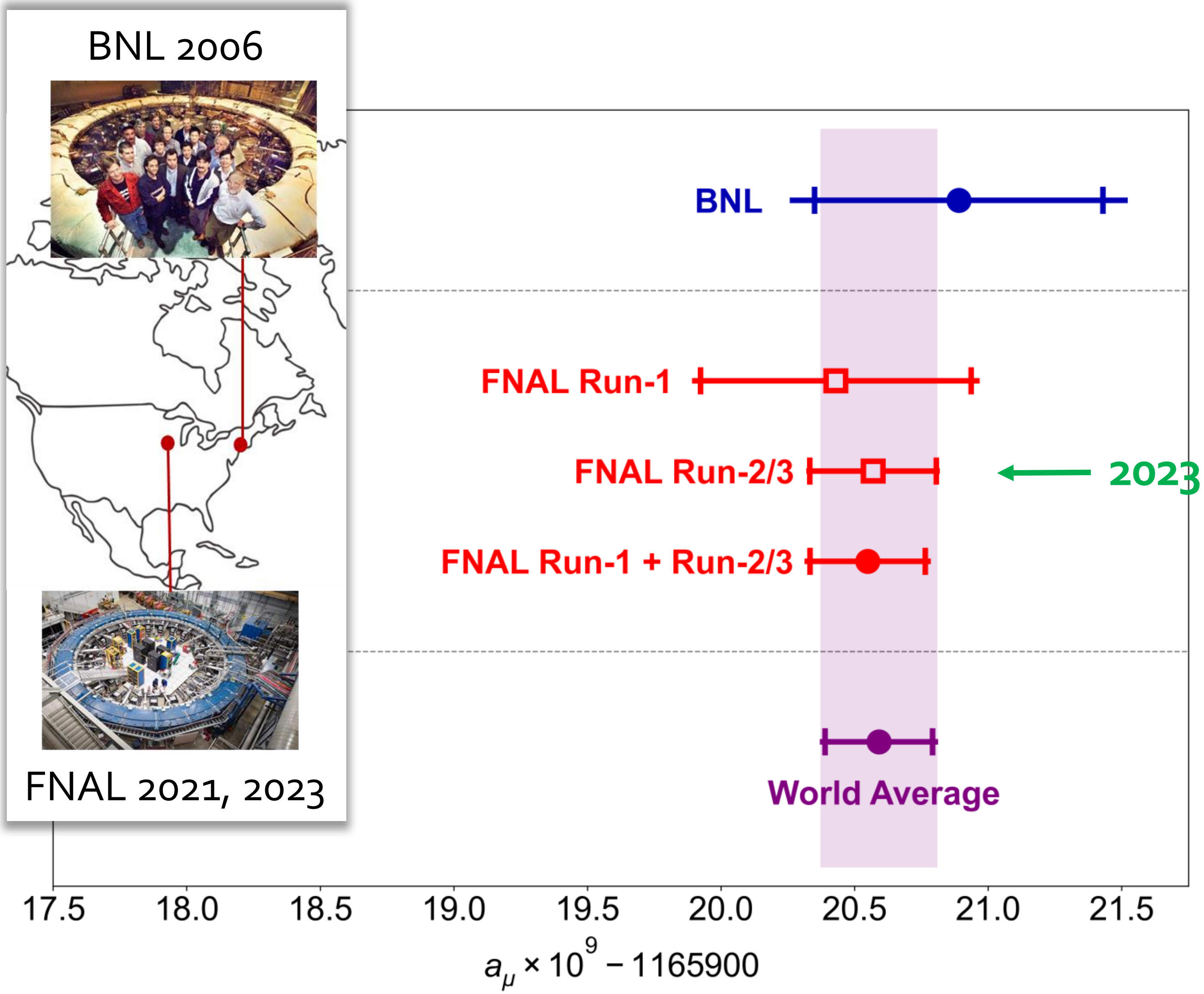
QED

Strong

Weak

Contributions of known interactions

# Muon G-2 2023 result



2023 result

$$a_\mu(\text{Exp}) = 0.00\,116\,592\,059(22) \quad [190\ \text{ppb}]$$

# Experiment vs SM prediction

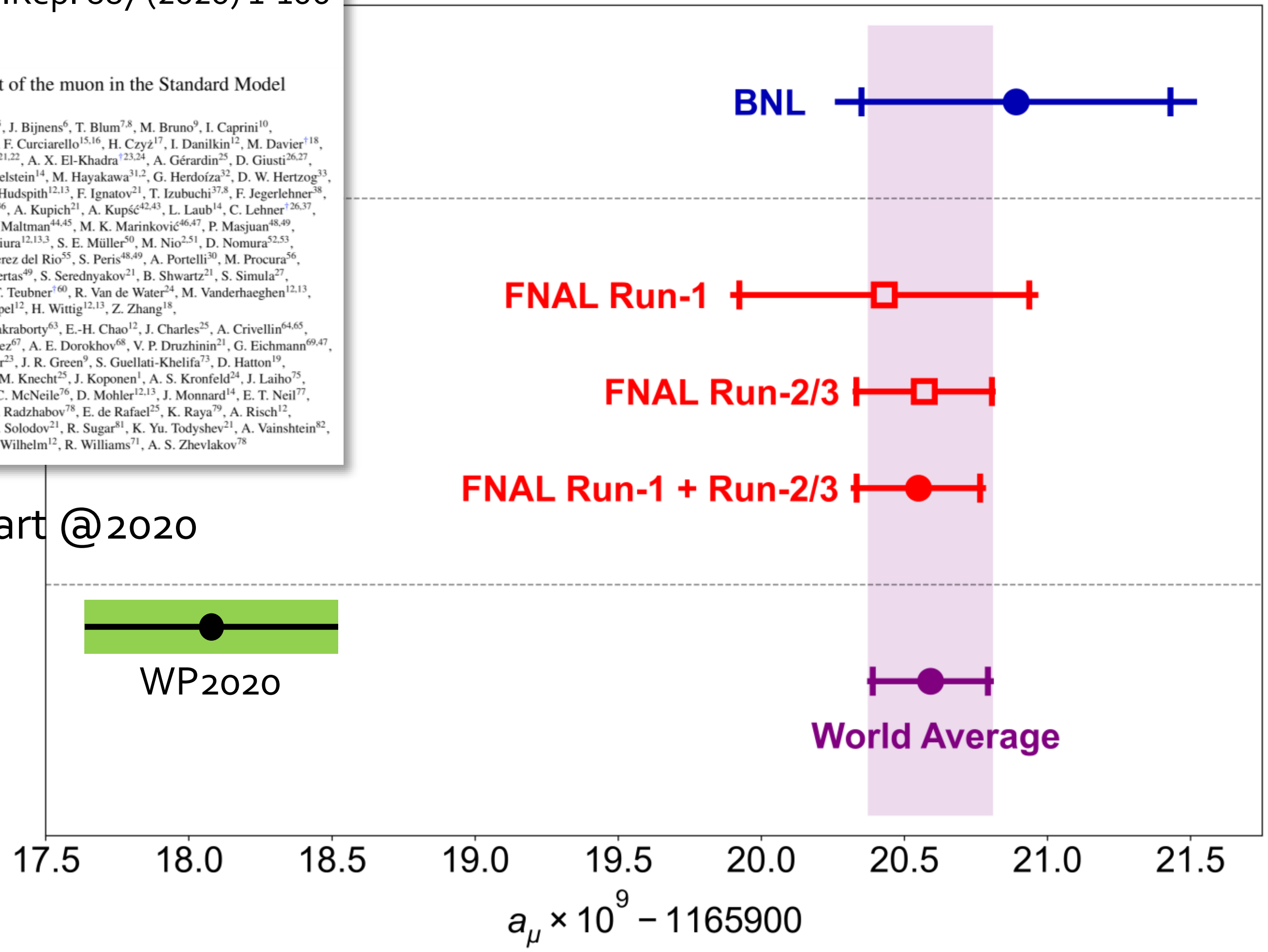
## Muon G-2 Theory Initiative

Consortium of >100 theorists
and experimental physicists
“White paper”, Phys.Rep. 887 (2020) 1-166

### The anomalous magnetic moment of the muon in the Standard Model

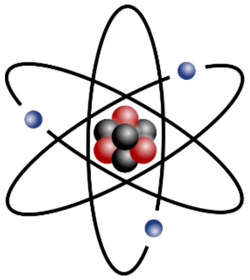
T. Aoyama[1,2,3], N. Asmussen[4], M. Benayoun[5], J. Bijnens[6], T. Blum[7,8], M. Bruno[9], I. Caprini[10], C. M. Carloni Calame[11], M. Cè[9,12,13], G. Colangelo[†14], F. Curciarello[15,16], H. Czyż[17], I. Danilkin[12], M. Davier[†18], C. T. H. Davies[19], M. Della Morte[20], S. I. Eidelman[†21,22], A. X. El-Khadra[†23,24], A. Gérardin[25], D. Giusti[26,27], M. Golterman[28], Steven Gottlieb[29], V. Gülpers[30], F. Hagelstein[14], M. Hayakawa[31,2], G. Herdoíza[32], D. W. Hertzog[33], A. Hoecker[34], M. Hoferichter[†14,35], B.-L. Hoid[36], R. J. Hudspith[12,13], F. Ignatov[21], T. Izubuchi[37,8], F. Jegerlehner[38], L. Jin[7,8], A. Keshavarzi[39], T. Kinoshita[40,41], B. Kubis[36], A. Kupich[21], A. Kupść[42,43], L. Laub[14], C. Lehner[†26,37], L. Lellouch[25], I. Logashenko[21], B. Malaescu[5], K. Maltman[44,45], M. K. Marinković[46,47], P. Masjuan[48,49], A. S. Meyer[37], H. B. Meyer[12,13], T. Mibe[†1], K. Miura[12,13,3], S. E. Müller[50], M. Nio[2,51], D. Nomura[52,53], A. Nyffeler[†12], V. Pascalutsa[12], M. Passera[54], E. Perez del Rio[55], S. Peris[48,49], A. Portelli[30], M. Procura[56], C. F. Redmer[12], B. L. Roberts[†57], P. Sánchez-Puertas[49], S. Serednyakov[21], B. Shwartz[21], S. Simula[27], D. Stöckinger[58], H. Stöckinger-Kim[58], P. Stoffer[59], T. Teubner[†60], R. Van de Water[24], M. Vanderhaeghen[12,13], G. Venanzoni[61], G. von Hippel[12], H. Wittig[12,13], Z. Zhang[18],

M. N. Achasov[21], A. Bashir[62], N. Cardoso[47], B. Chakraborty[63], E.-H. Chao[12], J. Charles[25], A. Crivellin[64,65], O. Deineka[12], A. Denig[12,13], C. DeTar[66], C. A. Dominguez[67], A. E. Dorokhov[68], V. P. Druzhinin[21], G. Eichmann[69,47], M. Fael[70], C. S. Fischer[71], E. Gámiz[72], Z. Gelzer[23], J. R. Green[9], S. Guellati-Khelifa[73], D. Hatton[19], N. Hermansson-Truedsson[14], S. Holz[36], B. Hörz[74], M. Knecht[25], J. Koponen[1], A. S. Kronfeld[24], J. Laiho[75], S. Leupold[42], P. B. Mackenzie[24], W. J. Marciano[37], C. McNeile[76], D. Mohler[12,13], J. Monnard[14], E. T. Neil[77], A. V. Nesterenko[68], K. Ottnad[12], V. Pauk[12], A. E. Radzhabov[78], E. de Rafael[25], K. Raya[79], A. Risch[12], A. Rodríguez-Sánchez[6], P. Roig[80], T. San José[12,13], E. P. Solodov[21], R. Sugar[81], K. Yu. Todyshev[21], A. Vainshtein[82], A. Vaquero Avilés-Casco[66], E. Weil[71], J. Wilhelm[12], R. Williams[71], A. S. Zhevlakov[78]

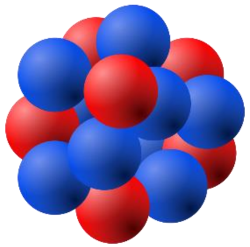


State-of-art @2020

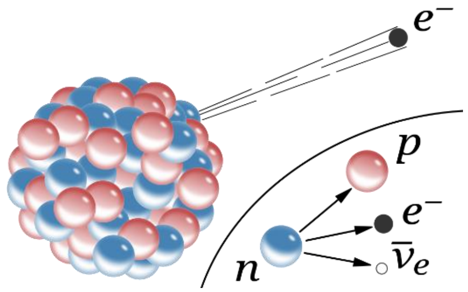
# SM prediction for $a_\mu$



**Electromagnetic interactions**



**Strong interactions**



**Weak interactions**

0.001 165 847 19 (0.1)

0.000 000 069 37 (43)

0.000 000 001 54 (1)

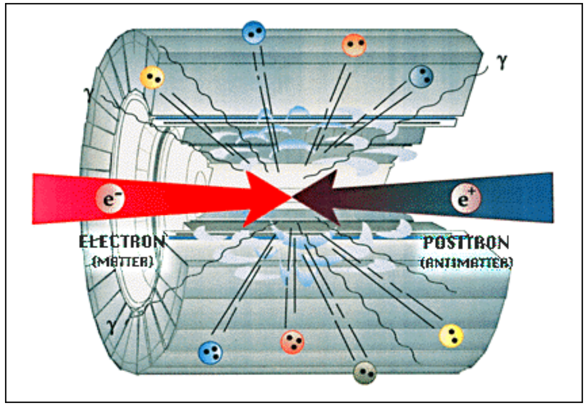
$$a_\mu = 0.001\,165\,918\,10\;(43)$$

The uncertainty is dominated by contribution of strong interactions

# Contribution of exclusive hadronic cross sections to $a_\mu$

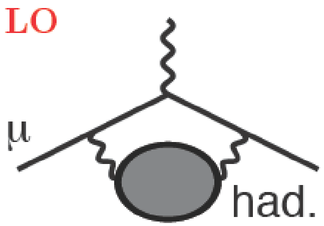
Hadronic contribution can be calculated via dispersion relation, using measured cross section of hadron production in $e^+e^-$ annihilation:

$$a_\mu^{had}(LO) = \frac{1}{4\pi^3}\int \sigma^0(e^+e^- \to X)K_\mu(s)ds$$



In exclusive approach, we calculate $a_\mu$ integral for each final state and sum them:

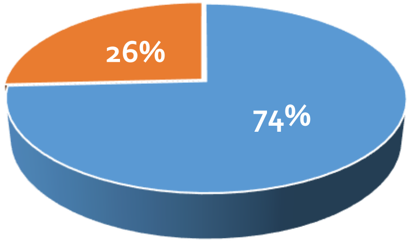
$$a_\mu^{had}(LO) = \sum_{X=\pi^0\gamma,\pi^+\pi^-,\ldots} \frac{1}{4\pi^3}\int \sigma^0(e^+e^- \to X)K_\mu(s)ds$$



$e^+e^- \to \pi^+\pi^-$ gives by far the largest contribution to the integral – about 74%
(and the largest contribution to uncertainty)

$\sigma(e^+e^- \to \pi^+\pi^-)$ required to be measured with <1% precision (→0.1%)

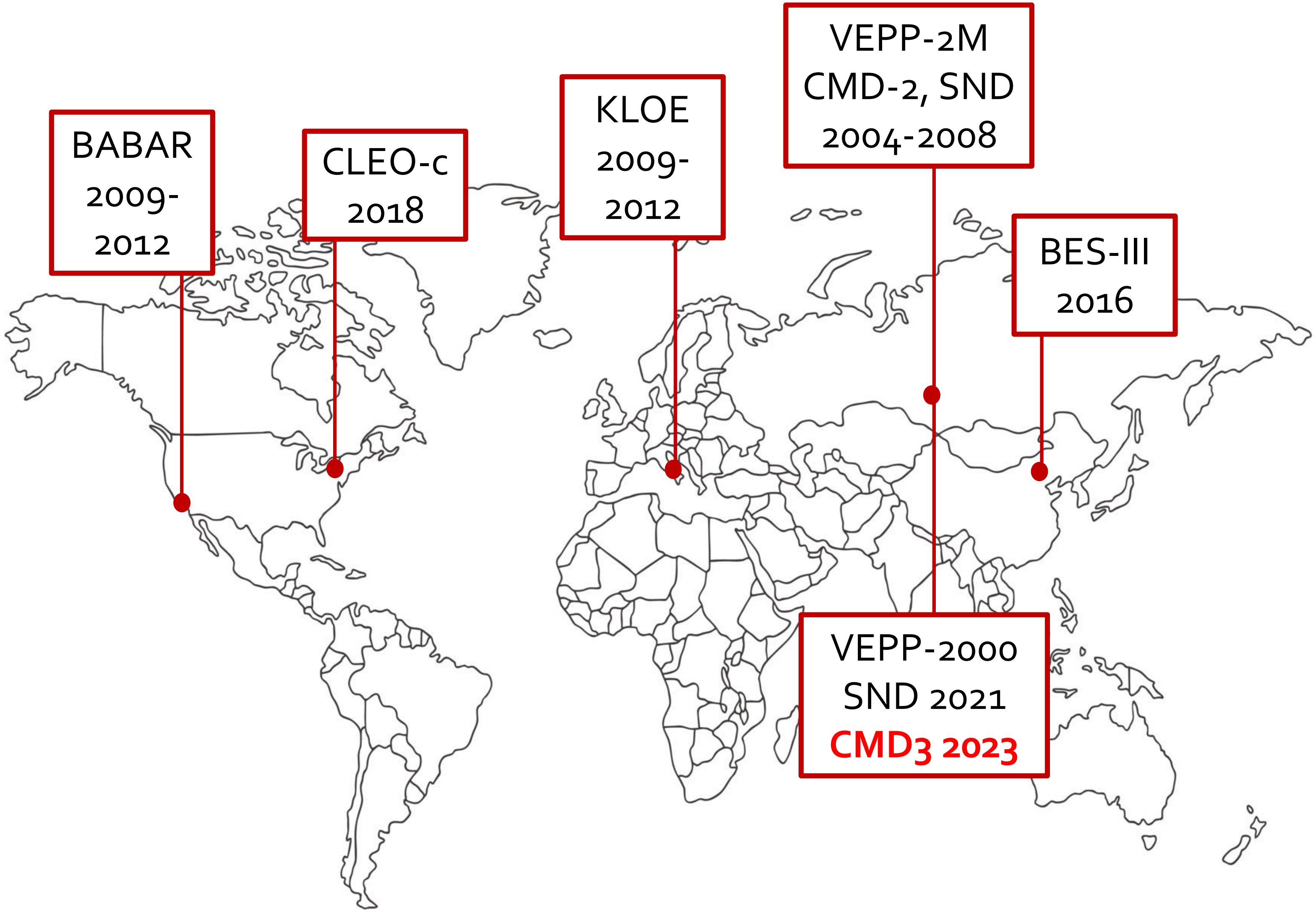
All the rest



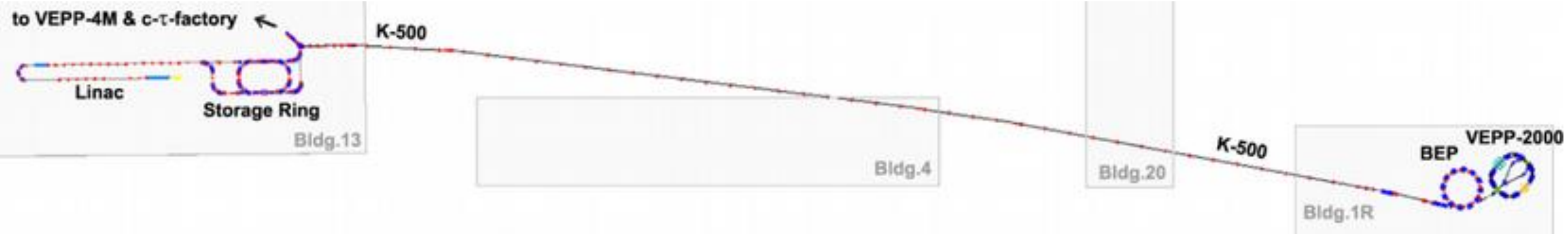
$e^+e^- \to \pi^+\pi^-$

# Measurements of $e^+e^- \to \pi^+\pi^-$

There are several measurements of $\sigma(e^+e^- \to \pi^+\pi^-)$ with sub-percent systematic accuracy

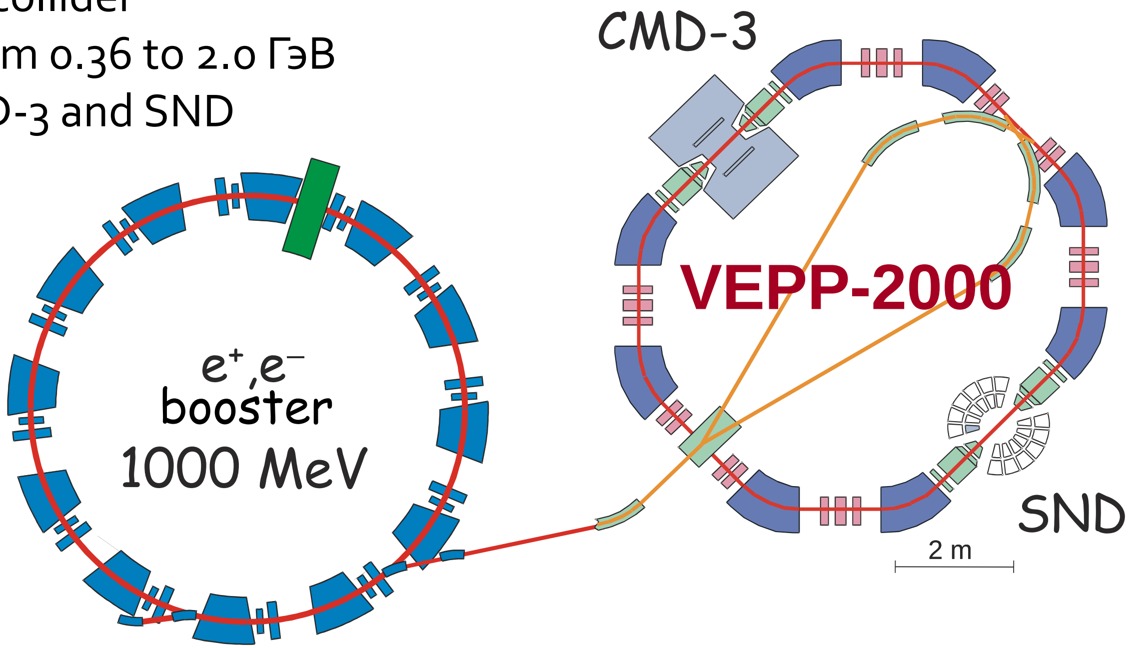


# VEPP-2000 collider



Electron-positron collider
Covers c.m. energy range from 0.36 to 2.0 ГэВ
Two experiments – CMD-3 and SND

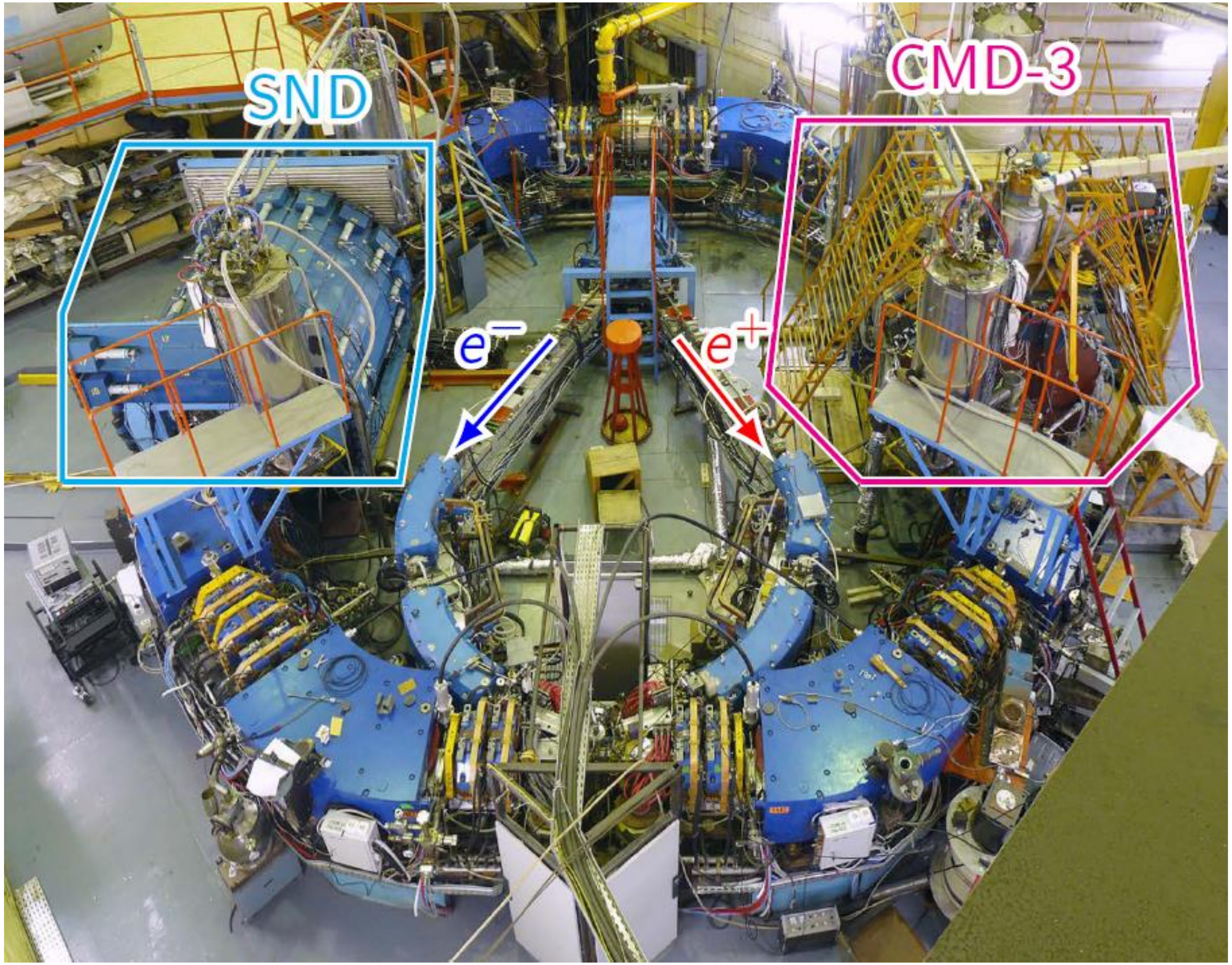
| Design parameters @ 1 GeV | |
|---|---|
| Circumference | 24.388 m |
| Beam energy | 150 ÷ 1000 MeV |
| N of bunches | 1×1 |
| N of particles | $1\times10^{11}$ |
| Betatron tunes | 4.14 / 2.14 |
| Beta* | 8.5 cm |
| BB parameter | 0.1 |
| Luminosity | $1\times10^{32}$ cm$^{-2}$s$^{-1}$ |



“Round beam” optics

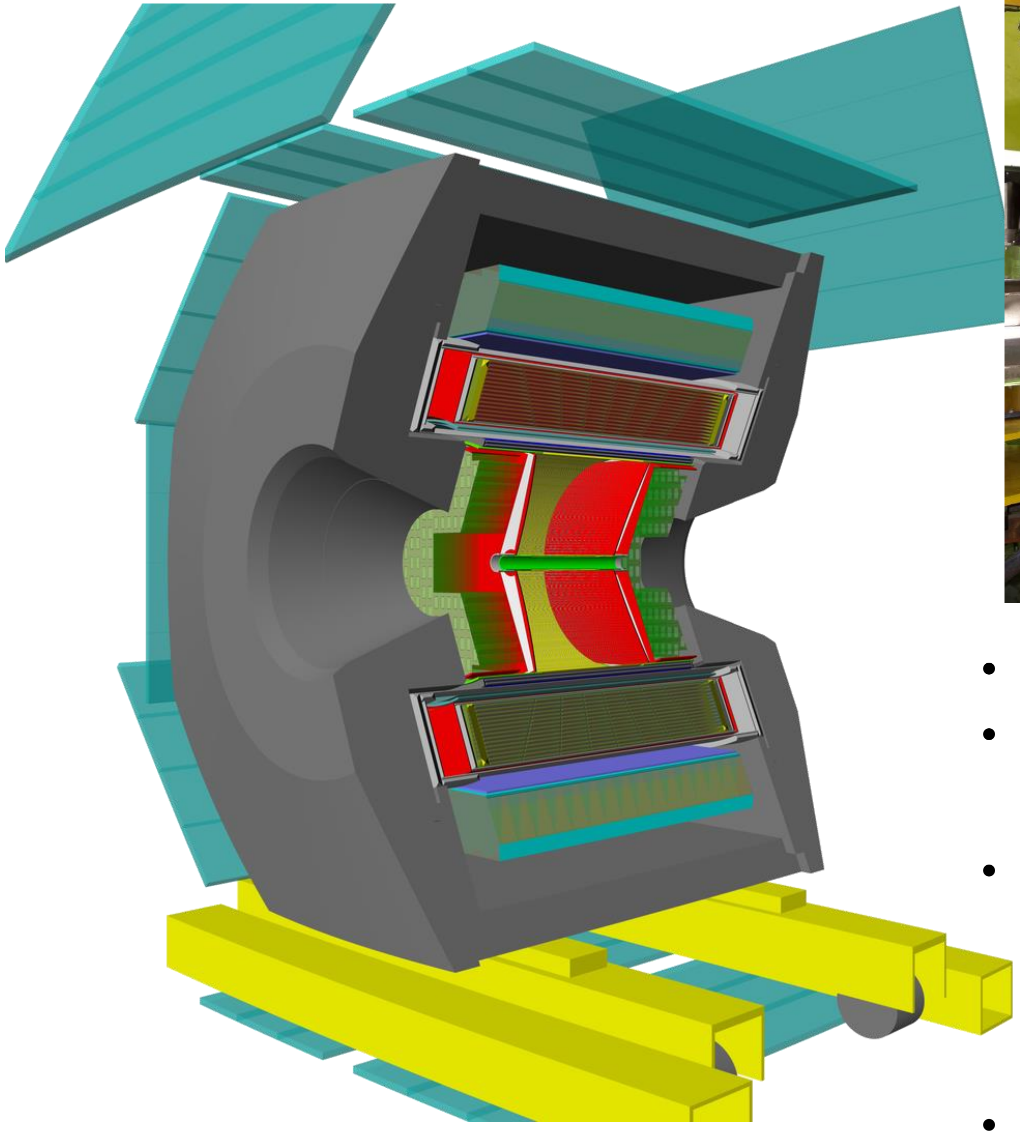
Energy monitoring by Compton backscattering ($\sigma_{\sqrt{s}} \approx 0.1$ MeV)

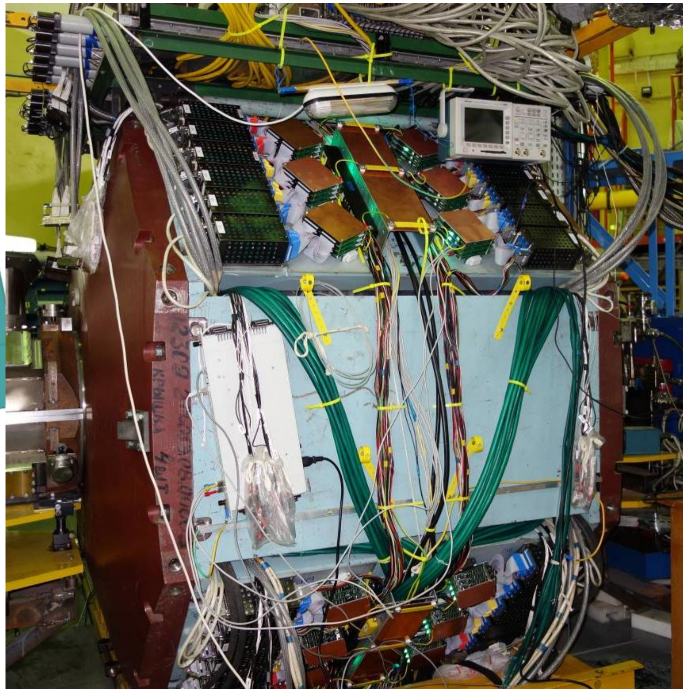
# VEPP-2000



# CMD-3 Detector

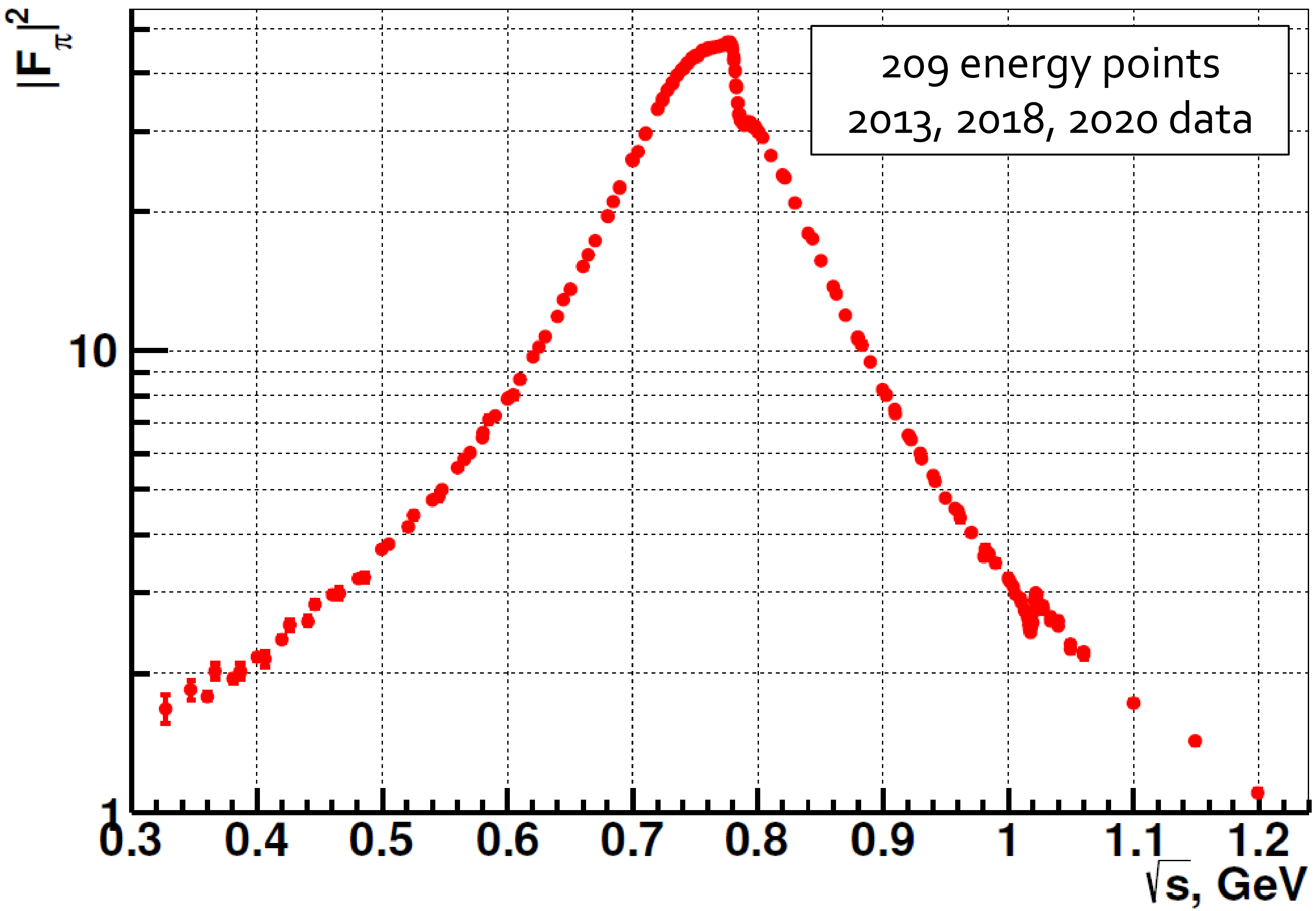
*Cryogenic Magnetic Detector





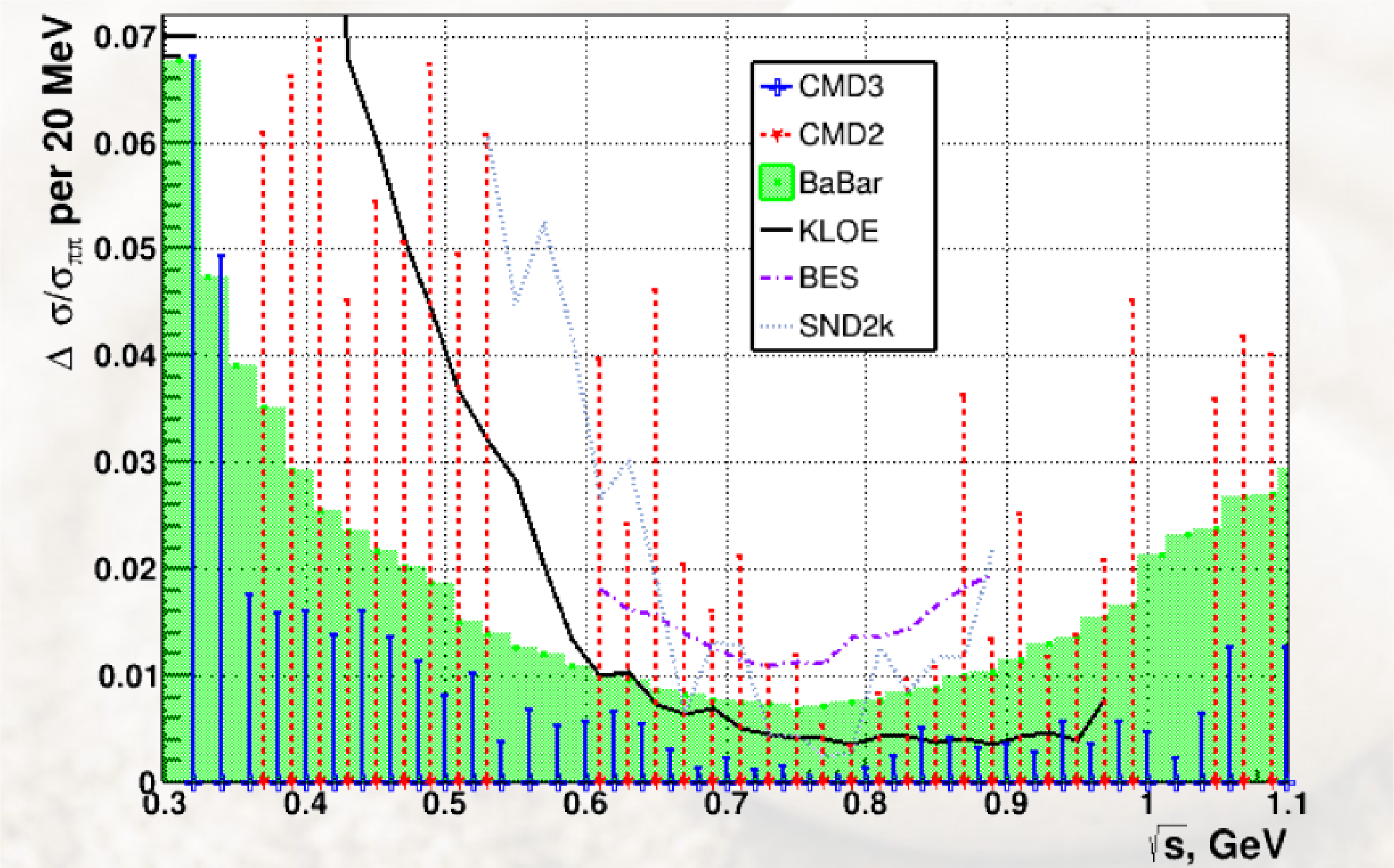
- Magnetic field 1.0-1.3 T
- Drift chamber
  - $\sigma_{R\varphi} \sim 100\ \mu, \sigma_z \sim 2-3$ mm
- EM calorimeter (LXE, CsI, BGO), 13.5 $X_0$
  - $\sigma_E/E \sim 3\% - 10\%$
  - $\sigma_\Theta \sim 5$ mrad
- TOF
- Muon counters

# Measurement of $e^+e^- \to \pi^+\pi^-$ at CMD-3



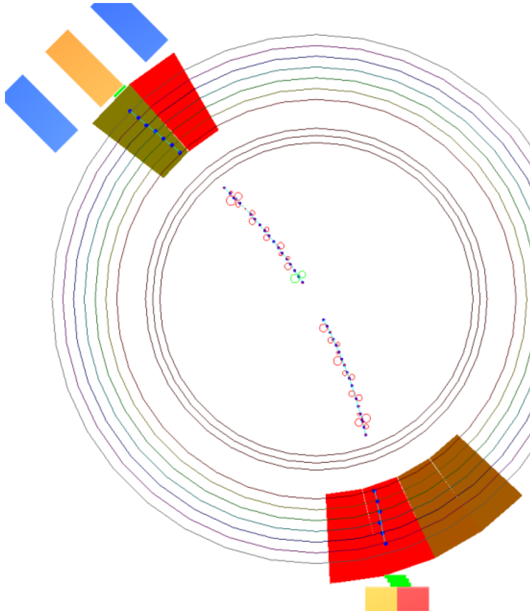
209 energy points
2013, 2018, 2020 data

# Statistical precision of CMD-3 data



based on L = 61.9 $pb^{-1}$ at $\sqrt{s}$ < 1 GeV (+25.7 $pb^{-1}$, 1.0-1.2 GeV)

# Three methods of separation of $e^+e^-, \mu^+\mu^-, \pi^+\pi^-$



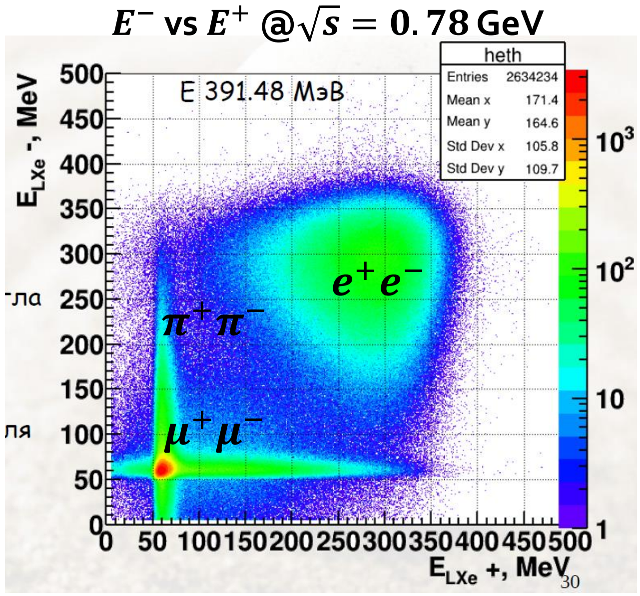
Example of $e^+e^- \to \pi^+\pi^-$ event

Similar events: $e^+e^- \to \mu^+\mu^-$, $e^+e^- \to e^+e^-$

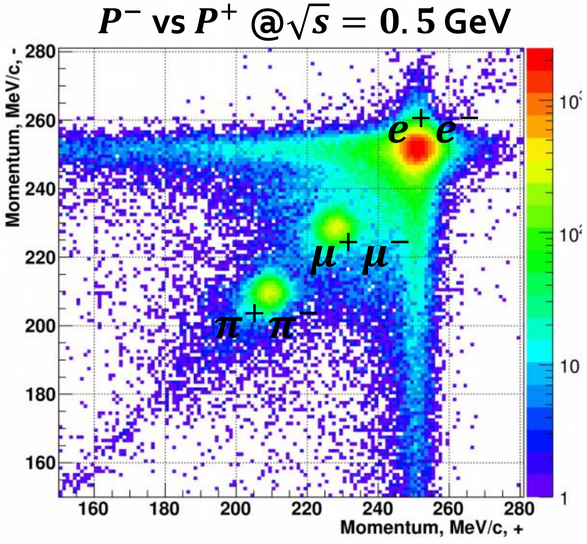
Unique feature of CMD-3:
three independent methods to measure $N_{\pi\pi}/N_{ee}$!

- Energy deposition distribution
- Momentum distribution
- Angular distribution

Agree to 0.2%!

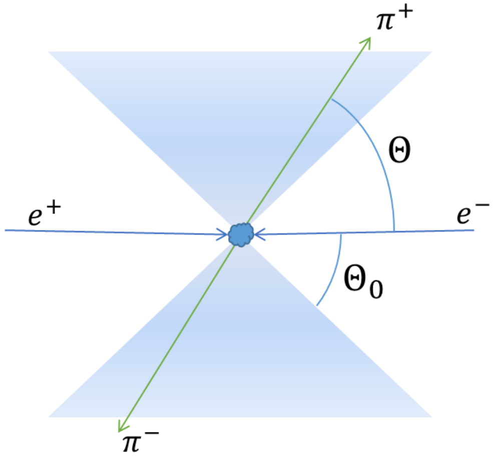


$E^-$ vs $E^+$ @$\sqrt{s} = 0.78$ GeV



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

# Measurement of polar angle

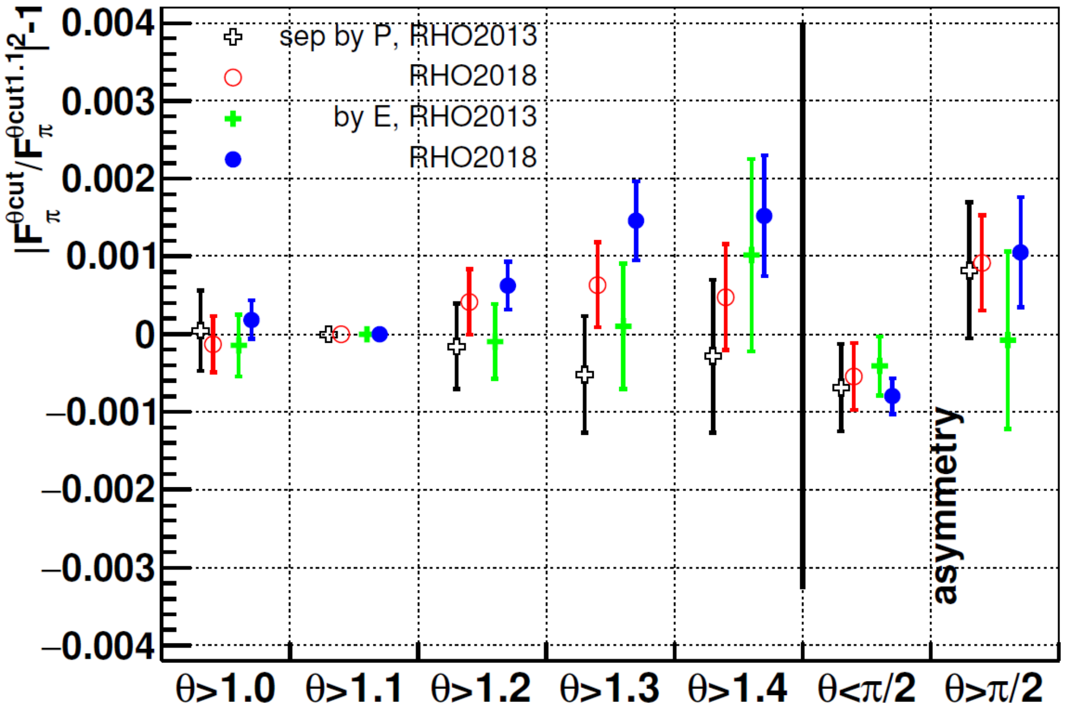


$\Theta$ angle is measured by drift chamber via charge division

Two detector systems with strips readout, LXe calorimeter and Z-chamber, are used for precise calibration and monitoring of DC

We need to precisely know the fiducial volume ($\Theta_0$ cut).

$$|F_\pi|^2 = \left(\frac{N_{\pi\pi}}{N_{ee}} - \Delta_{bg}\right)\cdot\frac{\sigma^0_{ee}\cdot(1+\delta_{ee})\cdot\varepsilon_{ee}}{\sigma^0_{\pi\pi}\cdot(1+\delta_{\pi\pi})\cdot\varepsilon_{\pi\pi}}$$



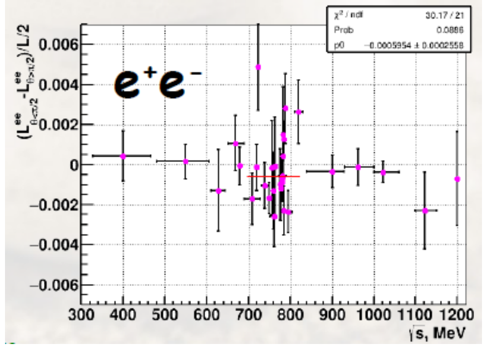
Dependence of result on $\Theta_0$ cut

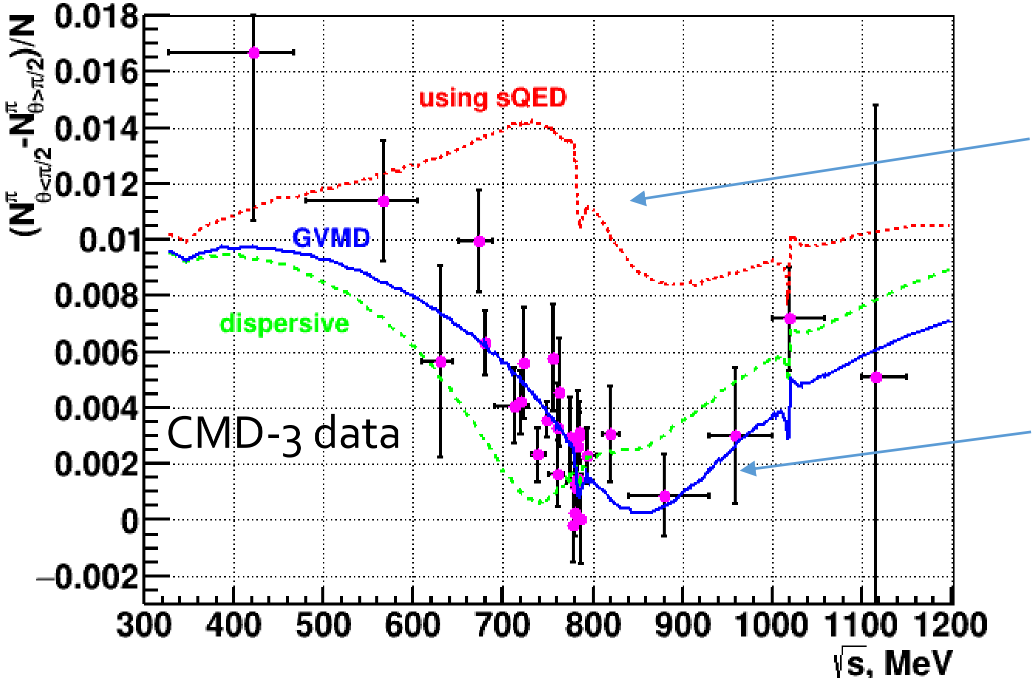
Factor 10 smaller compared to CMD-2, SND2k!

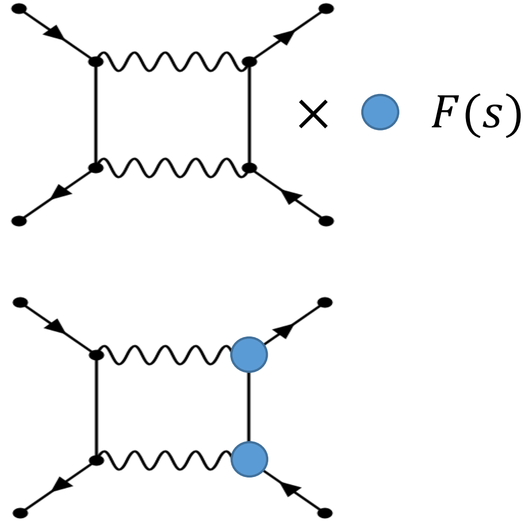
# Charge asymmetry in $e^+e^- \to \pi^+\pi^-$

Charge asymmetry in $e^+\,e^- \to \pi^+\,\pi^-$ is due to interference between ISR/FSR and between one- and two-photon exchange

$$A = \left(N^{\pi}_{\Theta<\pi/2} - N^{\pi}_{\Theta>\pi/2}\right)/N$$







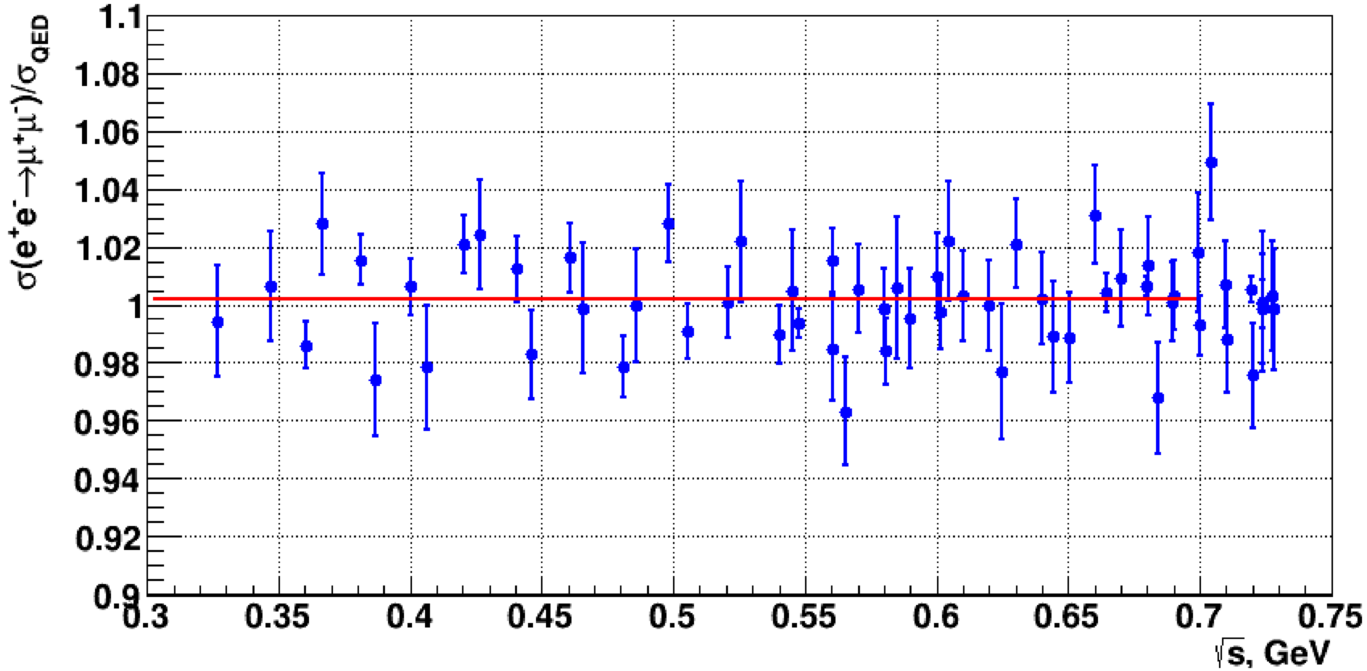
The theoretical model by Lee, Ignatov, PLB 833 (2022) 137283 (GVDM) describes well the CMD-3 data

Recent calculation in dispersive formalism Colangelo et al., JHEP 08 (2022) 295 confirms the effect.

# Measurement of $e^+e^- \to \mu^+\mu^-$

$e^+e^- \to \mu^+\mu^-$ events are identified as a by-product of analysis, which allows to measure $\sigma(e^+e^- \to \mu^+\mu^-)$ and compare it to QED prediction

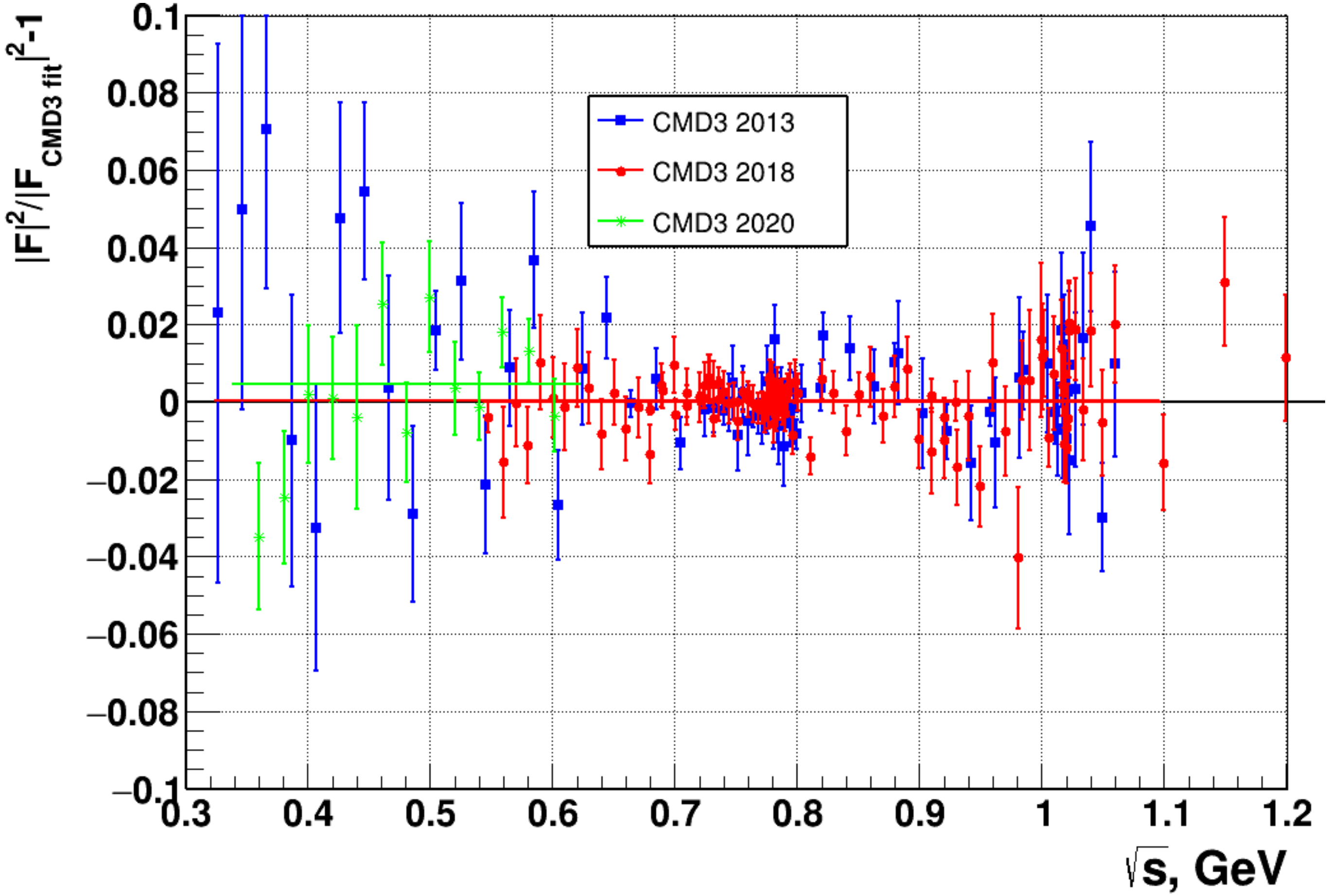
$$\sigma(e^+e^- \to \mu^+\mu^-)_{CMD3}/\sigma(e^+e^- \to \mu^+\mu^-)_{QED}$$



+0.17 ± 0.16 %

Powerful cross-check of $\sigma(e^+e^- \to \pi^+\pi^-)$ measurement! All ingredients are tested: event separation, detection efficiencies, radiative corrections.

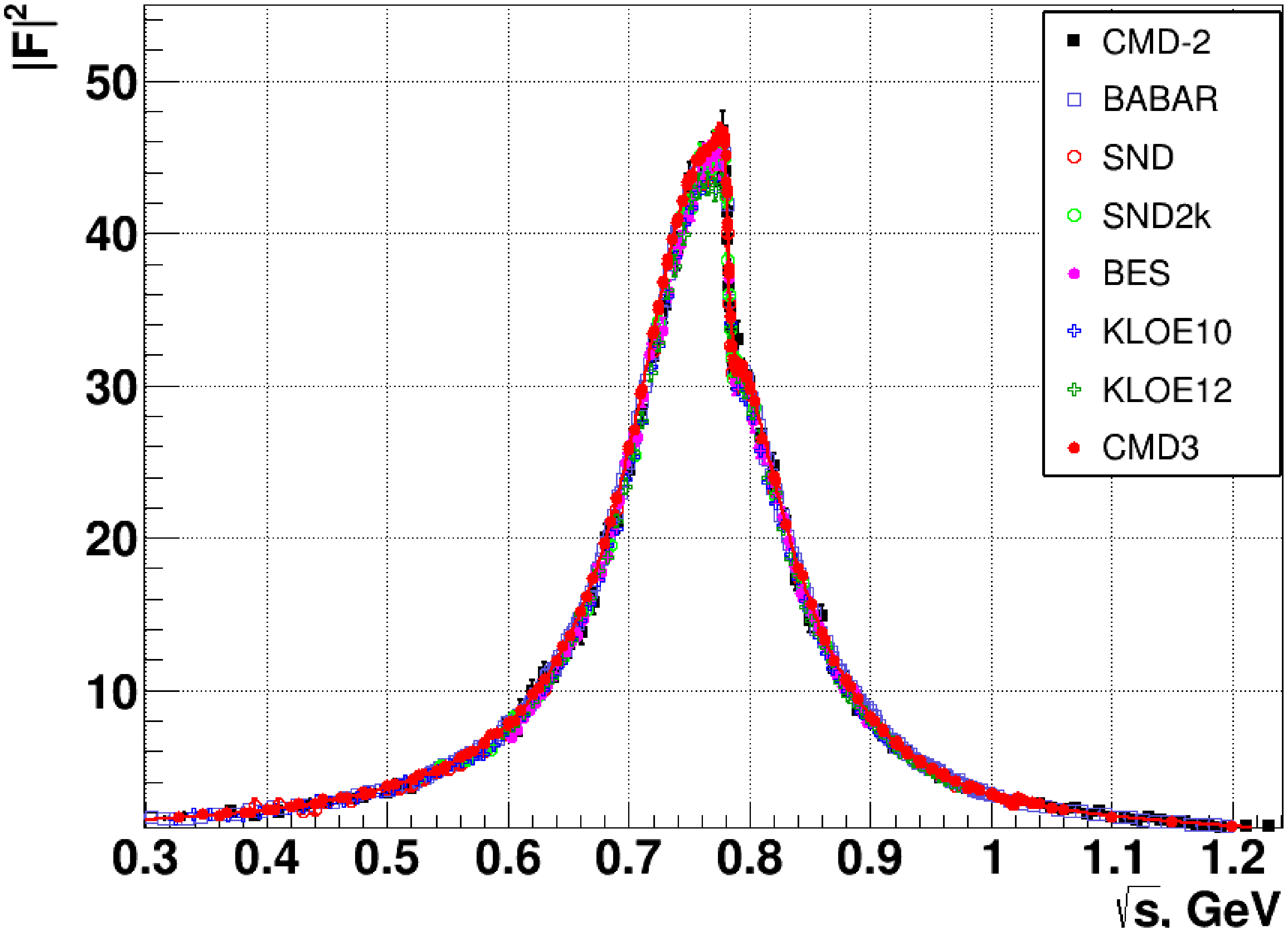
# Comparison of data taking seasons



Results based on 2013, 2018 and 2020 data only agree to ~0.1%!
The detector performance and run conditions were significantly different for these runs.

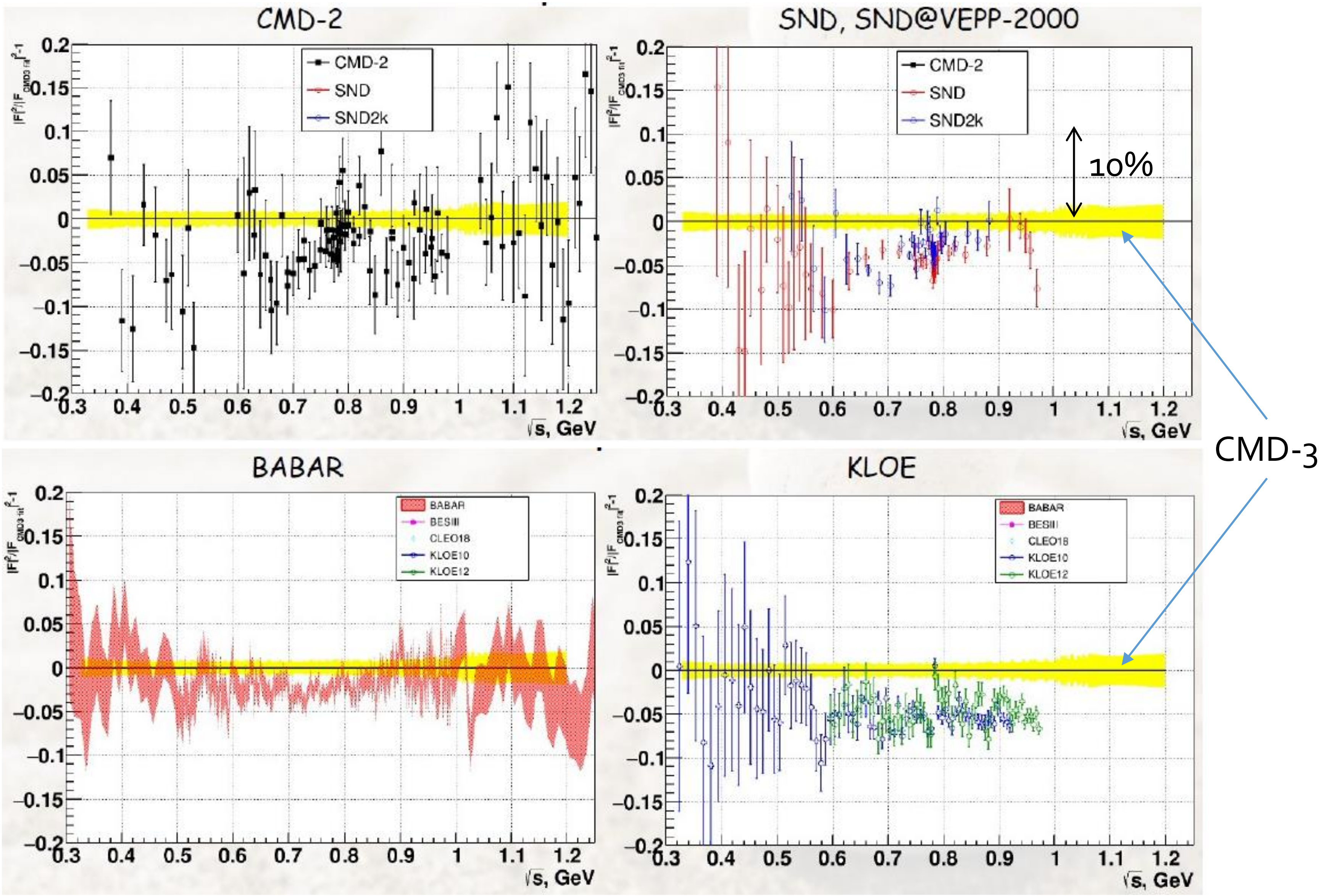
# Comparison to other measurements

At first glance, they looks close to each other…

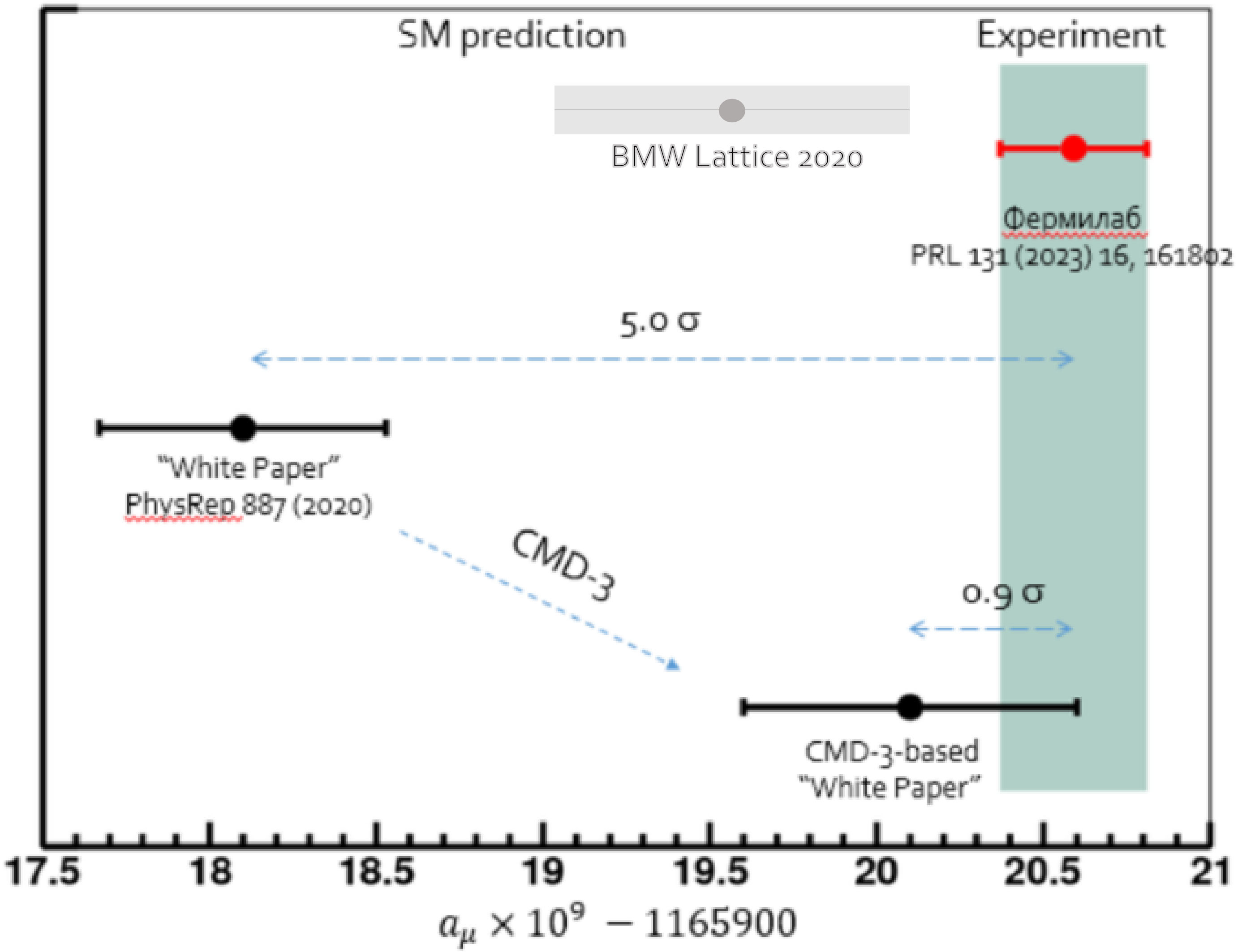


# Comparison to other measurements

CMD-3 is systematically above previous measurements by ~2-5%



# Experiment vs SM prediction



# Результат

- На детекторе КМД-3 измерено сечение $\sigma(e^+e^- \to \pi^+\pi^-)$ в области энергий от 0.32 до 1.2 ГэВ в системе центра масс
  - Лучшая статистическая точность в мире
  - Наиболее детальный анализ систематических ошибок, уникальные методы перекрестных проверок
  - «Побочные» измерения: зарядовая асимметрия в $e^+e^- \to \pi^+\pi^-$, сечение $\sigma(e^+e^- \to \mu^+\mu^-)$, параметры векторных мезонов,…
  - >10 лет работы
- Результат КМД-3 привел к пересмотру устоявшегося мнения о наличии противоречия между измеренной величиной аномального магнитного момента мюона и предсказанием Стандартной модели
- Результат КМД-3 вызвал большой резонанс в сообществе физики элементарных частиц
  - Проведены рабочие совещания, посвященные результату и детальной проверке анализа данных
  - Ведутся новые независимые измерения/обработки данных, которые должны подтвердить/опровергнуть результат КМД-3
- На ВЭПП-2000 мы планируем провести новый цикл измерений с целью повысить точность в 2-3 раза

Публикации (направлены в PRL/PRD):

- 1. F.V.Ignatov et al. (CMD-3 Collaboration) Measurement of the pion formfactor with CMD-3 detector and its implication to the hadronic contribution to muon (g-2) // arXiv:2309.12910 [hep-ex]
- 2. F.V.Ignatov et al. (CMD-3 Collaboration) Measurement of the e^+ e^−→π^+ π^− cross section from threshold to 1.2 GeV with the CMD-3 detector // arXiv:2302.08834 [hep-ex]