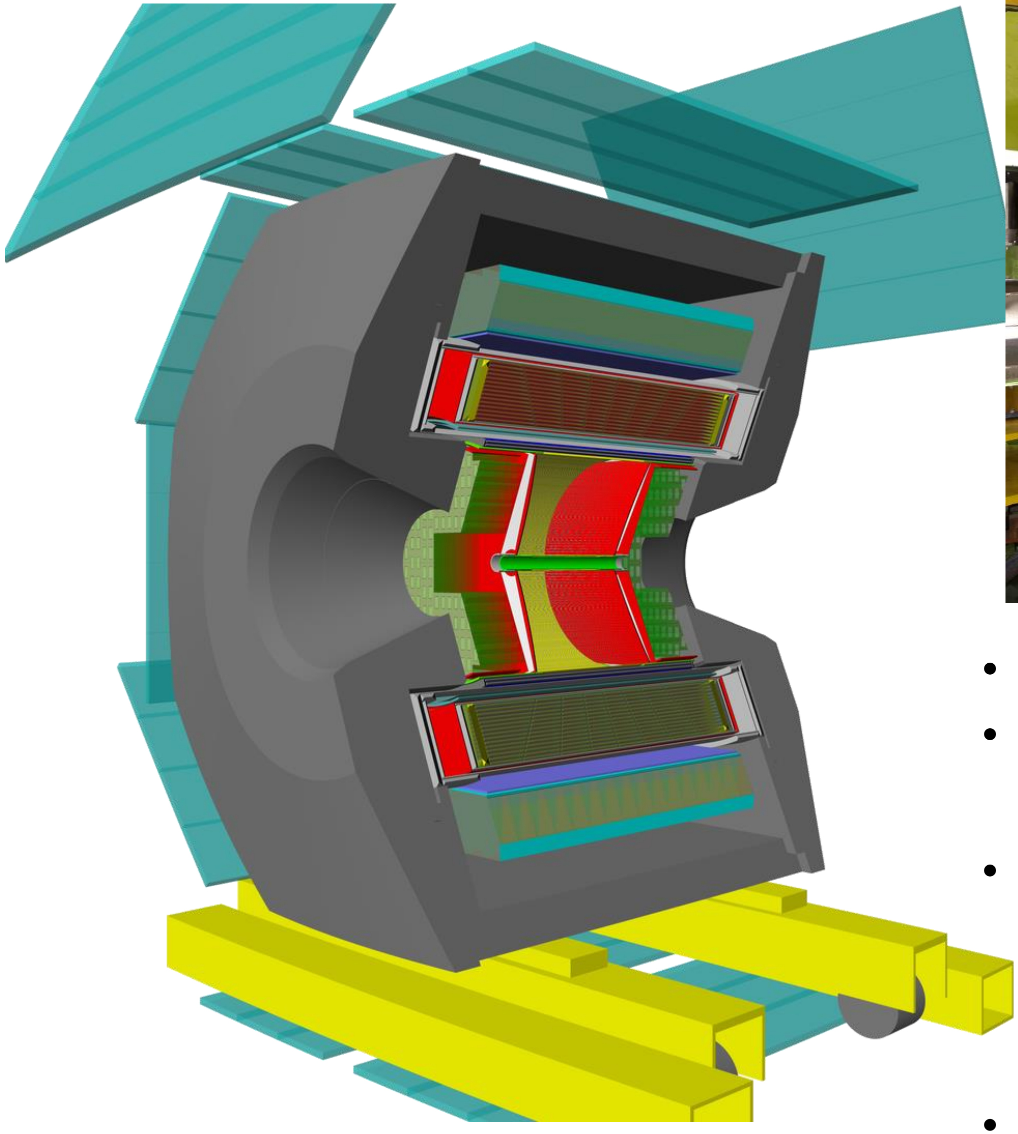
CMD2/3 report (on $\pi^+\pi^-$)

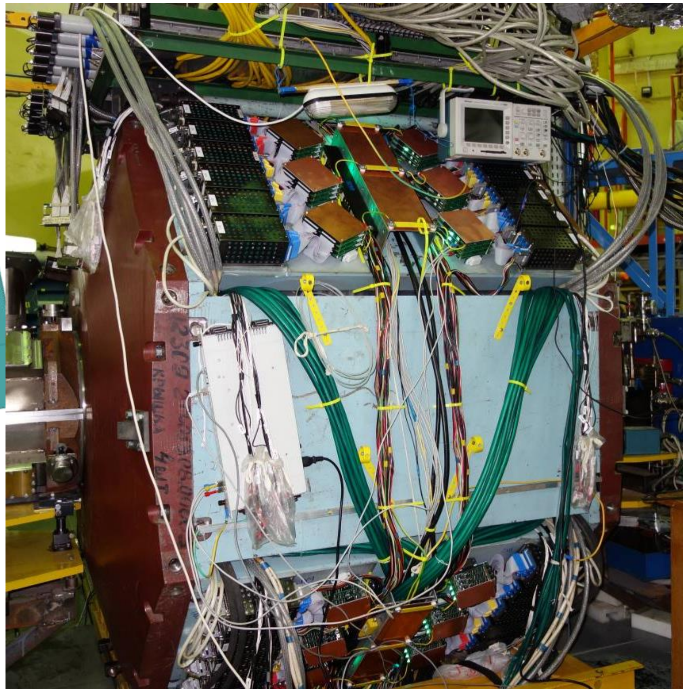
Ivan Logashenko (BINP)

Muon g-2 Theory Initiative Spring 2024 meeting

April 15-23, 2024

CMD-3 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

CMD-3 final states under analysis

Signature	Final states (preliminary, published)
2 charged	$\pi^+\pi^-, K^+K^-, K_SK_L, p\bar{p}$
2 charged + γ's	$\pi^+\pi^-\gamma, \pi^+\pi^-\pi^0, \pi^+\pi^-\eta, K^+K^-\pi^0, K^+K^-\eta, K_SK_L\pi^0, K_SK_L\eta, \pi^+\pi^-\pi^0\eta, \pi^+\pi^-2\pi^0, \pi^+\pi^-3\pi^0, \pi^+\pi^-4\pi^0$
4 charged	$\pi^+\pi^-\pi^+\pi^-, K^+K^-\pi^+\pi^-, K_SK^\pm\pi^\mp$
4 charged + γ's	$\pi^+\pi^-\pi^+\pi^-\pi^0, \pi^+\pi^-\eta, \pi^+\pi^-\omega, \pi^+\pi^-\pi^+\pi^-\pi^0\pi^0, K^+K^-\eta, K^+K^-\omega$
6 charged	$\pi^+\pi^-\pi^+\pi^-\pi^+\pi^-, K_SK^\pm\pi^\mp\pi^+\pi^-, K_SK_S\pi^+\pi^-$
6 charged + γ's	$3(\pi^+\pi^-)\pi^0$
Neutral	$\pi^0\gamma, \eta\gamma, \pi^0\pi^0\gamma, \pi^0\eta\gamma, \pi^0\pi^0\pi^0\gamma, \pi^0\pi^0\eta\gamma$
Other	$n\bar{n}, \pi^0e^+e^-, \eta e^+e^-$
Rare decays	$\eta', D^*(2007)^0$

2023 result

Publications

arXiv:2309.12910

Measurement of the pion formfactor with CMD-3 detector and its implication to the hadronic contribution to muon (g-2)

F.V. Ignatov,[1,2,*] R.R. Akhmetshin,[1,2] A.N. Amirkhanov,[1,2] A.V. Anisenkov,[1,2] V.M. Aulchenko,[1,2] N.S. Bashtovoy,[1] D.E. Berkaev,[1,2] A.E. Bondar,[1,2] A.V. Bragin,[1] S.I. Eidelman,[1,2] D.A. Epifanov,[1,2] L.B. Epshteyn,[1,2,3] A.L. Erofeev,[1,2] G.V. Fedotovich,[1,2] A.O. Gorkovenko,[1,3] F.J. Grancagnolo,[4] A.A. Grebenuk,[1,2] S.S. Gribanov,[1,2] D.N. Grigoriev,[1,2,3] V.L. Ivanov,[1,2] S.V. Karpov,[1] A.S. Kasaev,[1] V.F. Kazanin,[1,2] B.I. Khazin,[1] A.N. Kirpotin,[1] I.A. Koop,[1,2] A.A. Korobov,[1,2] A.N. Kozyrev,[1,2,3] E.A. Kozyrev,[1,2] P.P. Krokovny,[1,2] A.E. Kuzmenko,[1] A.S. Kuzmin,[1,2] I.B. Logashenko,[1,2] P.A. Lukin,[1,2] A.P. Lysenko,[1] K.Yu. Mikhailov,[1,2] I.V. Obraztsov,[1,2] V.S. Okhapkin,[1] A.V. Otboev,[1] E.A. Perevedentsev,[1,2] Yu.N. Pestov,[1] A.S. Popov,[1,2] G.P. Razuvaev,[1,2] Yu.A. Rogovsky,[1,2] A.A. Ruban,[1] N.M. Ryskulov,[1] A.E. Ryzhenenkov,[1,2] A.V. Semenov,[1,2] A.I. Senchenko,[1] P.Yu. Shatunov,[1] Yu.M. Shatunov,[1] V.E. Shebalin,[1,2] D.N. Shemyakin,[1,2] B.A. Shwartz,[1,2] D.B. Shwartz,[1,2] A.L. Sibidanov,[5] E.P. Solodov,[1,2] A.A. Talyshev,[1,2] M.V. Timoshenko,[1] V.M. Titov,[1] S.S. Tolmachev,[1,2] A.I. Vorobiov,[1] Yu.V. Yudin,[1,2] I.M. Zemlyansky,[1] D.S. Zhadan,[1] Yu.M. Zharinov,[1] and A.S. Zubakin[1]
(CMD-3 Collaboration)

[1] *Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, 630090, Russia*
[2] *Novosibirsk State University, Novosibirsk, 630090, Russia*
[3] *Novosibirsk State Technical University, Novosibirsk, 630092, Russia*
[4] *Instituto Nazionale di Fisica Nucleare, Sezione di Lecce, Lecce, Italy*
[5] *University of Victoria, Victoria, BC, Canada V8W 3P6*

(Dated: September 25, 2023)

The cross section of the process $e^+e^- \to \pi^+\pi^-$ has been measured in the center of mass energy range from 0.32 to 1.2 GeV with the CMD-3 detector at the electron-positron collider VEPP-2000. The measurement is based on an integrated luminosity of about 88 pb^{-1} out of which 62 pb^{-1} constitutes a full dataset collected by CMD-3 at center-of-mass energies below 1 GeV. In the dominant region near ρ-resonance a systematic uncertainty of 0.7% has been reached. The impact of presented results on the evaluation of the hadronic contribution to the anomalous magnetic moment of muon is discussed.

Submitted to PRL
Waiting for responses of referees after the first round of review/responses

arXiv:2302.08834

Measurement of the $e^+e^- \to \pi^+\pi^-$ cross section from threshold to 1.2 GeV with the CMD-3 detector

F.V. Ignatov[a,b,1], R.R. Akhmetshin[a,b], A.N. Amirkhanov[a,b], A.V. Anisenkov[a,b], V.M. Aulchenko[a,b], N.S. Bashtovoy[a], D.E. Berkaev[a,b], A.E. Bondar[a,b], A.V. Bragin[a], S.I. Eidelman[a,b], D.A. Epifanov[a,b], L.B. Epshteyn[a,b,c], A.L. Erofeev[a,b], G.V. Fedotovich[a,b], A.O. Gorkovenko[a,c], F.J. Grancagnolo[e], A.A. Grebenuk[a,b], S.S. Gribanov[a,b], D.N. Grigoriev[a,b,c], V.L. Ivanov[a,b], S.V. Karpov[a], A.S. Kasaev[a], V.F. Kazanin[a,b], B.I. Khazin[a], A.N. Kirpotin[a], I.A. Koop[a,b], A.A. Korobov[a,b], A.N. Kozyrev[a,c], E.A. Kozyrev[a,b], P.P. Krokovny[a,b], A.E. Kuzmenko[a], A.S. Kuzmin[a,b], I.B. Logashenko[a,b], P.A. Lukin[a,b], A.P. Lysenko[a], K.Yu. Mikhailov[a,b], I.V. Obraztsov[a,b], V.S. Okhapkin[a], A.V. Otboev[a], E.A. Perevedentsev[a,b], Yu.N. Pestov[a], A.S. Popov[a,b], G.P. Razuvaev[a,b], Yu.A. Rogovsky[a,b], A.A. Ruban[a], N.M. Ryskulov[a], A.E. Ryzhenenkov[a,b], A.V. Semenov[a,b], A.I. Senchenko[a], P.Yu. Shatunov[a], Yu.M. Shatunov[a], V.E. Shebalin[a,b], D.N. Shemyakin[a,b], B.A. Shwartz[a,b], D.B. Shwartz[a,b], A.L. Sibidanov[a,d], E.P. Solodov[a,b], A.A. Talyshev[a,b], M.V. Timoshenko[a], V.M. Titov[a], S.S. Tolmachev[a,b], A.I. Vorobiov[a], I.M. Zemlyansky[a], D.S. Zhadan[a], Yu.M. Zharinov[a], A.S. Zubakin[a], Yu.V. Yudin[a,b]

[a] *Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, 630090, Russia*
[b] *Novosibirsk State University, Novosibirsk, 630090, Russia*
[c] *Novosibirsk State Technical University, Novosibirsk, 630092, Russia*
[d] *University of Victoria, Victoria, BC, Canada V8W 3P6*
[e] *Instituto Nazionale di Fisica Nucleare, Sezione di Lecce, Lecce, Italy*

Submitted to PRD
Two rounds of reviews finished
Accepted

CMD-2

Status of CMD-2 reanalysis

- We are not doing CMD-2 reanalysis
- We don't have means to do a full scale CMD-2 analysis
- We are focused in further development of CMD-3 analysis. As a by-product, we'll get insights about some possible CMD-2 issues.
  - Subtraction of cosmic background

    The methods used to count cosmic background events in CMD-2 and CMD-3 are different. The cosmic background in CMD-2 was much larger.

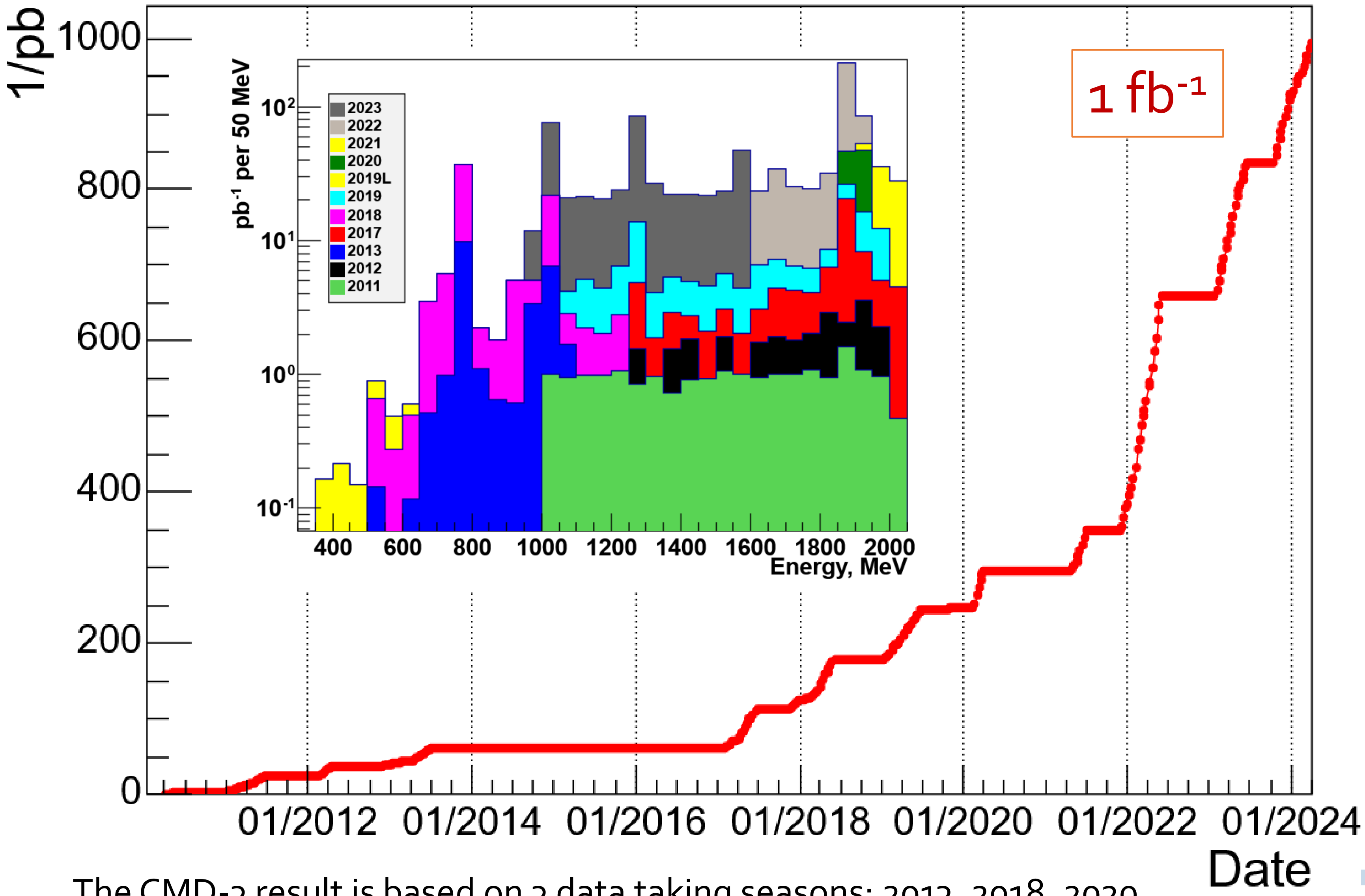
    We'll get the estimation of systematic bias between CMD-2/CMD-3 methods for CMD-3 environment.
  - Event separation based on energy deposition in CsI calorimeter ($8X_0$)

    CMD-3: LXe only ($5X_0$) and full calo ($13X_0$), observed very different behavior/systematics; working on simulation of CsI only ($8X_0$), might be able to take CsI only data

    CMD-2: CsI only ($8X_0$), systematics were estimated
  - We think we understand differences in radiative corrections (and they are small)
  - Results of these studies cannot be used to update CMD-2 data!

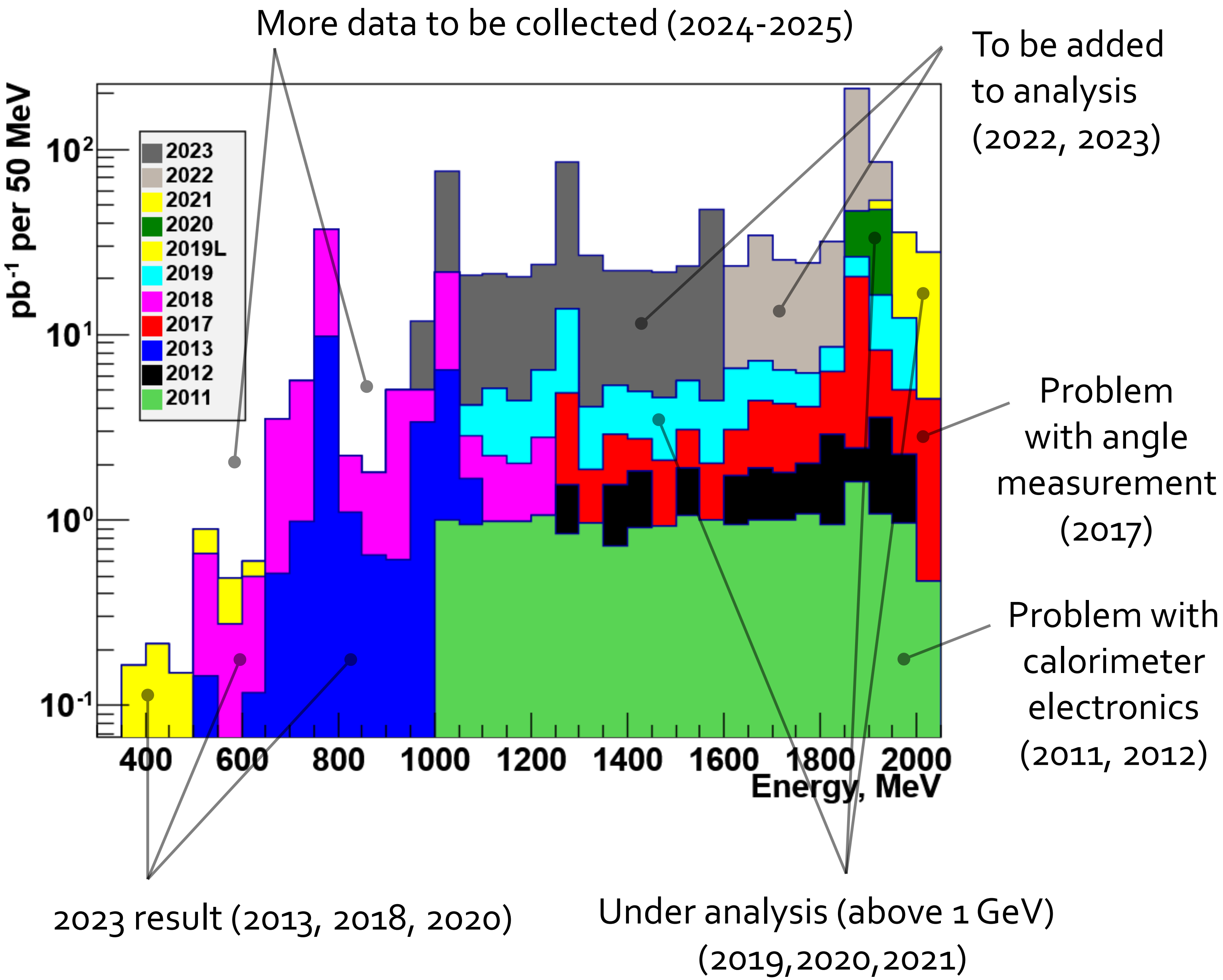
Ongoing analysis

Collected data



The CMD-3 result is based on 3 data taking seasons: 2013, 2018, 2020

Collected data



Features of 2019-2021 analysis

- Energy range above 1 GeV
- Event separation:
  - energy deposition, using full calorimeter and machine learning
  - will try: energy deposition, LXe only
  - will try: angle distribution (not enough statistics?)
- Number of $\mu^+\mu^-$ pairs is not measured – subtracted based on number of detected e^+e^- pairs
- Angle measurement:
  - drift chamber charge division, calibrated by coordinate from LXe calorimeter
- Aim for 1-2% systematics below 1.4 GeV, several % above 1.4 GeV

2E = 1400 MeV

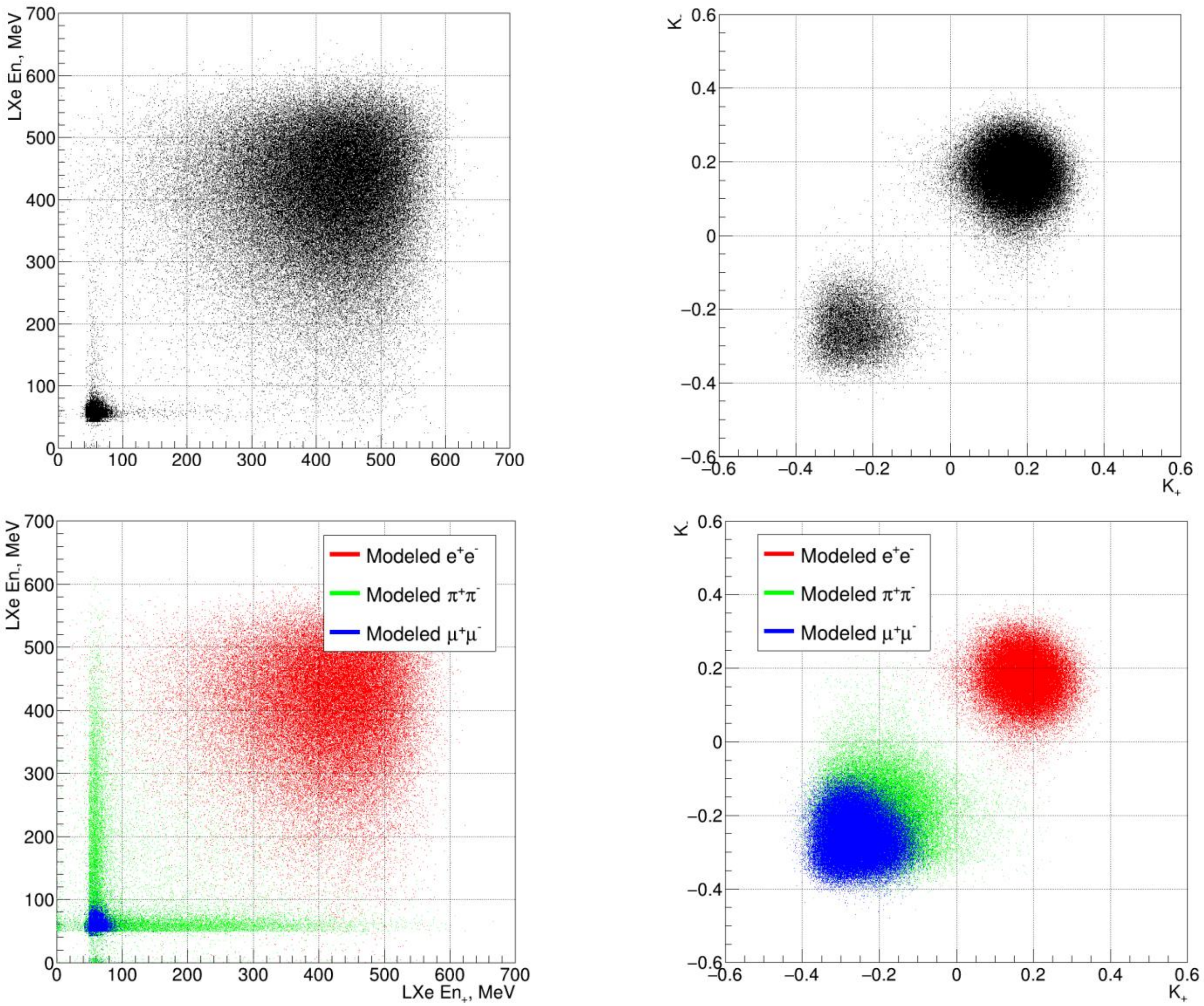
2019-2021 analysis

Event separation

Energy deposition in LXe | ML classifiers (BDT)

Data

Simulation

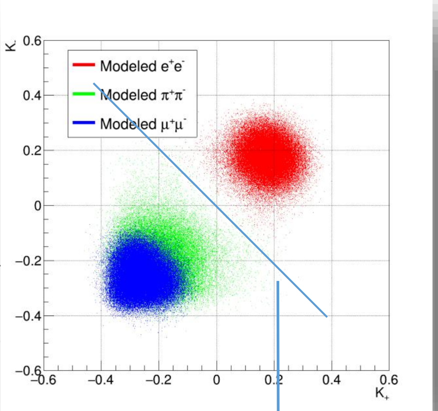


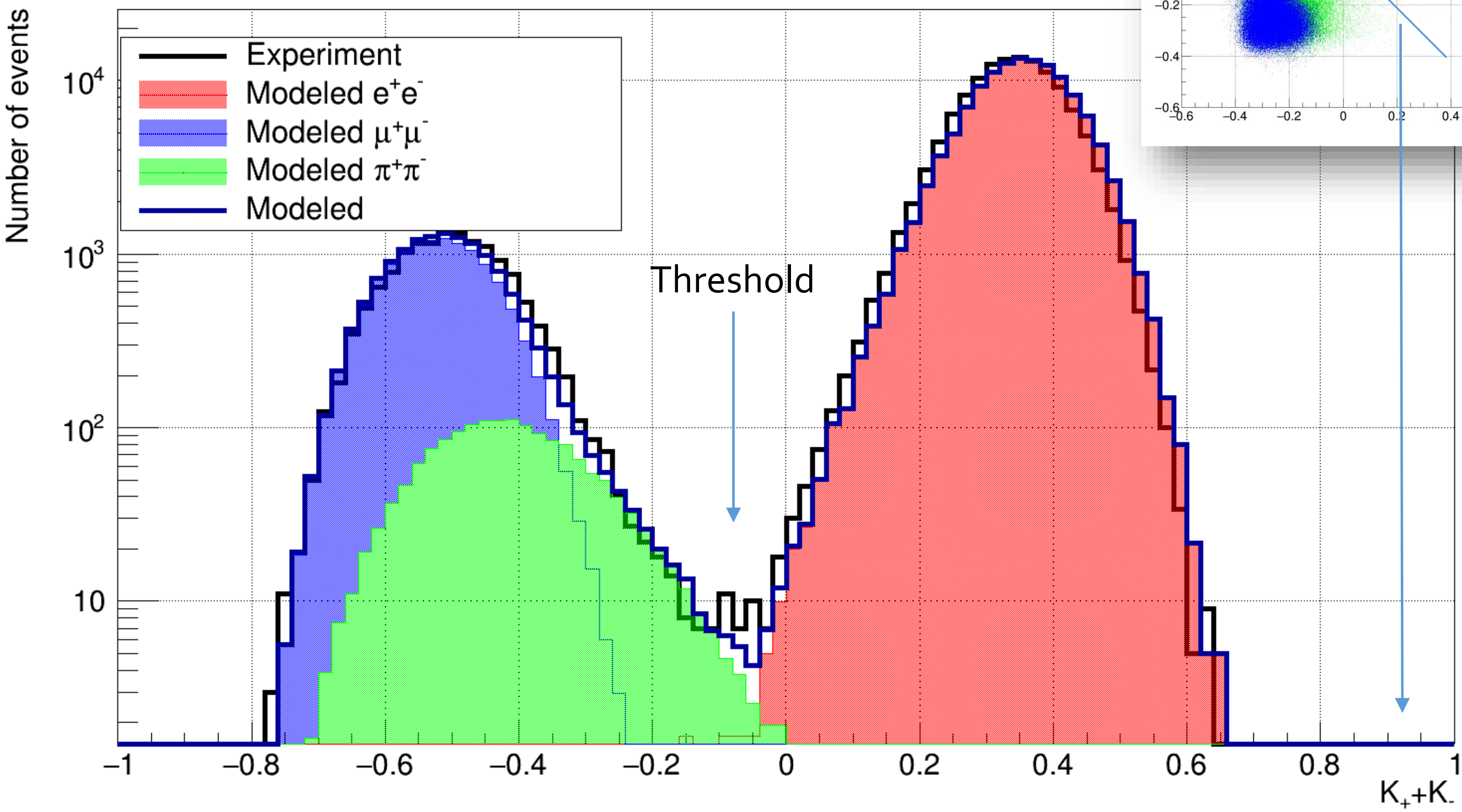
2019-2021 analysis

Event separation

ML inputs: energy deposition in CsI and LXe, longitudinal and transverse profiles, angle

Distribution of classifier K++K-, used to separate $e/\mu/\pi$

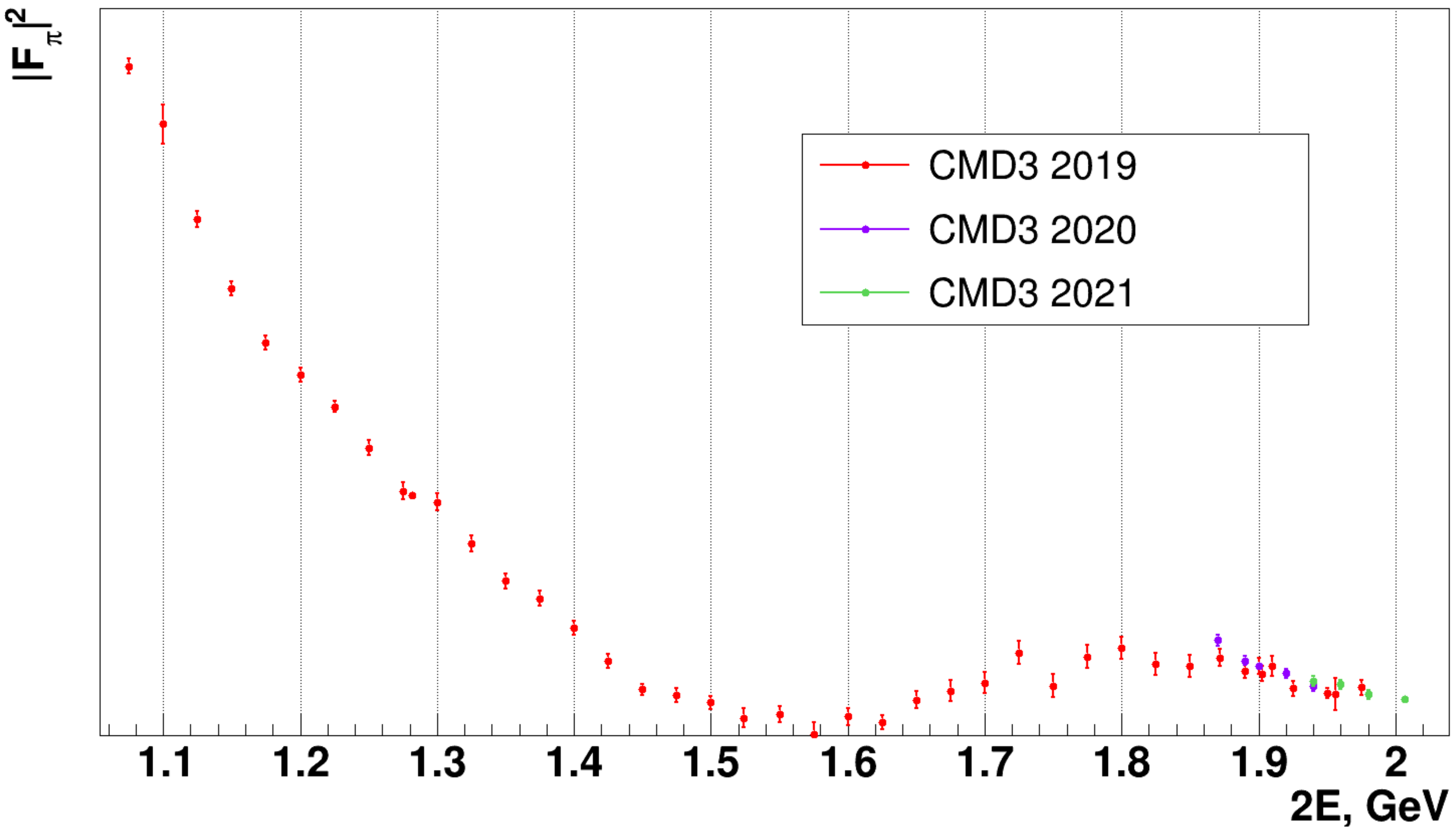




$N_{\pi\pi} + N_{\mu\mu} + N_{cosmic}$ N_{ee}

2019-2021 analysis

Intermediate result



Plans

Ultimate goal for accuracy of hadronic cross sections

$$a_\mu(BSM) \pm \Delta a_\mu(BSM) = \left[a_\mu(exp) - a_\mu(SM)\right] \pm \sqrt{\Delta a_\mu(exp)^2 + \Delta a_\mu(SM)^2}$$

$\Delta a_\mu(BSM)$ determines the power of a_μ as test of theoretical models

Reduction of $\boldsymbol{\Delta a_\mu(BSM)}$ is of great importance for flavor physics

FNAL expected precision of 140 ppb corresponds to $\sim 0.25\%$ of $a_\mu^{had,LO}$

Hadronic contribution: $a_\mu(had) = \int \sigma_{e^+e^- \to H}(s)\, K(s)\, ds$

Need to measure $\sigma(e^+e^- \to H)$ to ~0.2% in order to match FNAL precision.

To be sure in $a_\mu(SM)$ the community needs:

- >1 measurement of hadronic cross section ($\pi^+\pi^-$) to ~0.2%
- lattice calculations to ~0.2%
- they agree
- independent input (MuONe) is very desirable

CMD-3 2023 systematics

CMD-3 systematics (2023)

	CMD-3 systematics (2023)	Original estimates
✗ Radiative corrections	0.2% (2π) ⊕ 0.2% (Fπ) ⊕ 0.1% (e+e-)	0.1%
✗ e/μ/π separation	0.5 (low) - 0.2 (ρ) - 0.6 (φ) %	0.2%
✗ Fiducial volume	0.5% / 0.8% (RHO2013)	0.2%
✗ Correlated inefficiency	0.1 (ρ) - 0.15%(>1 ГэВ)	0.1%
✗ Trigger	0.05 (ρ) - 0.3% (>1 ГэВ)	
✗ Beam Energy (by Compton σ_E < 50 keV)	0.1% (out of resonances), 0.5% (at ω, φ -peaks)	0.2%
✗ Bremsstrahlung loss	0.05 %	
✗ Pion specific loss	0.2% nuclear interaction 0.2%(low) - 0.1% (ρ) pion decay	
	CMD-3 e^+ e^-→π^+ π^- ana...	
	0.8% (low) - 0.7% (ρ) - 1.6% (φ) 1.1% (low) - 0.9% (ρ) - 2.0% (φ) (RHO2013)	

Key required detector improvements to reduce systematics

- polar angle measurement (Z-chamber broke in 2017)
- momentum resolution

Impossible to improve without detector upgrade.

Other (beyond detector) important required improvements:
radiative corrections, nuclear interactions

Short-term plans (2024-2025)

- We plan (already started) to collect more data below 1 GeV – factor 2-3 more data
- The main goal is to get more data for non-dominant channels (3π, 4π, conversion decays of ω)
- We don't expect to get better precision for 2π, but will get data for more systematics studies – some moderate improvement is possible if systematic error is reduced
- We've developed new more sophisticated trigger electronics. It is under commissioning now, plan to use it as primary option starting from Fall 2024
- We'll try to run with beams directions reversed (starting from Fall 2024) – another systematics test
- We are checking the possibility to collect data with CsI calorimeter only (by not filling up the LXe calorimeter). Problem: no means to calibrate Z in the drift chamber without LXe.

Long-term plans (<2030)

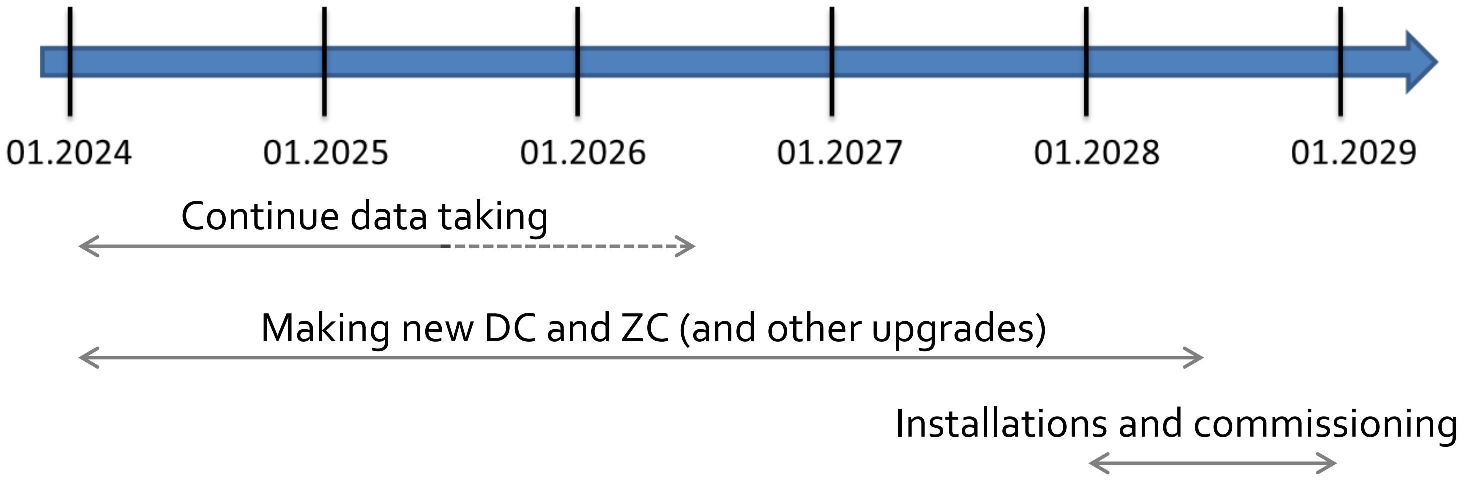
VEPP-2000 luminosity is high enough: it allows to perform new scan of ρ energy region within ~1 year

The goal is to reach ~0.2-0.3% in $\sigma(e^+e^- \to \pi^+\pi^-)$

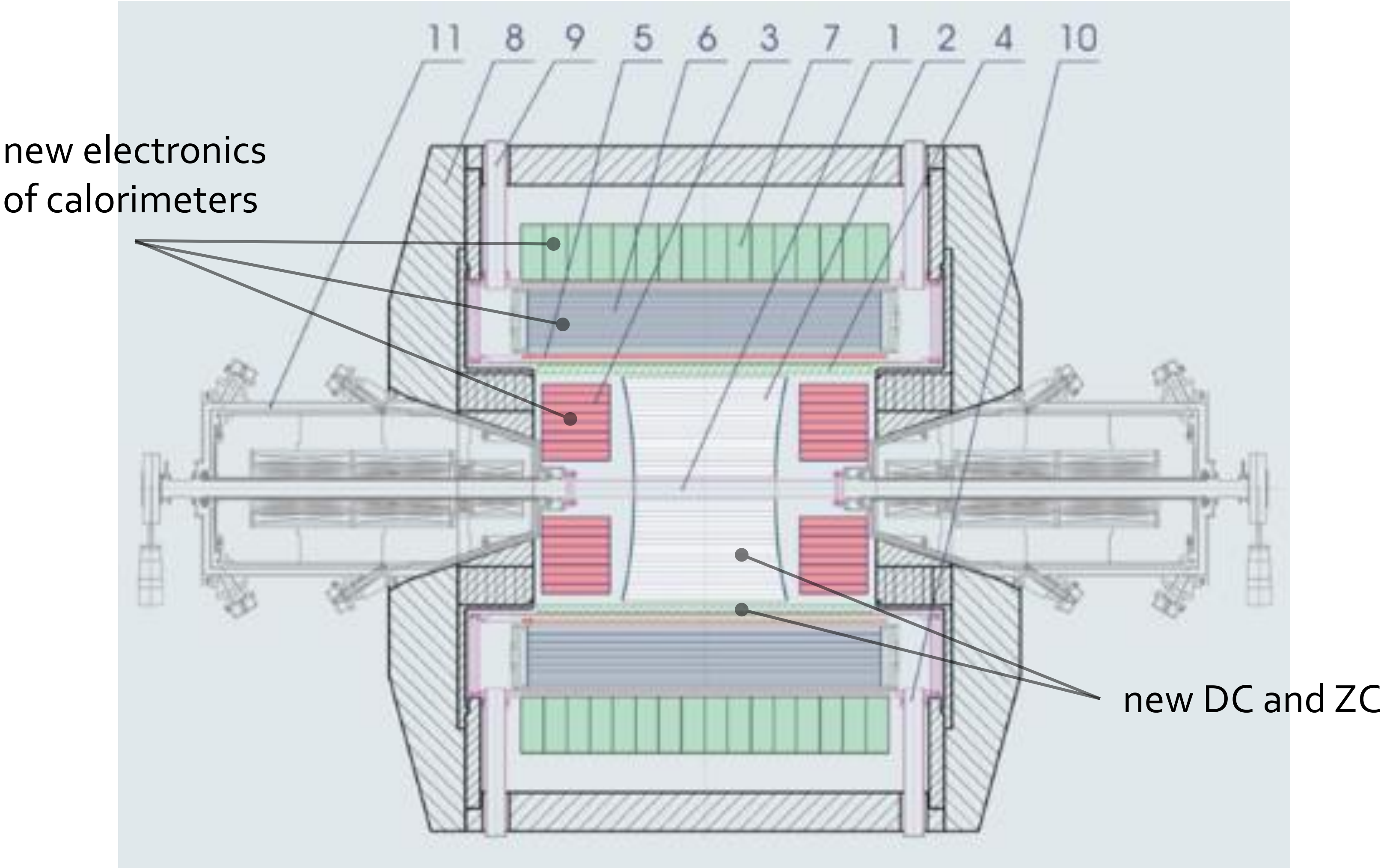
We plan the following detector upgrades:

- new drift chamber with cathode strips at inner radius
- new Z-chamber at outer radius
- upgrade of electronics

Many options are discussed: longer DC, larger DC, larger magnetic field,…



CMD-3 upgrades



Summary

- The 2023 CMD-3 measurement of $\pi^+\pi^-$ cross section is fixed, no news there
- We are working on measurement of $\pi^+\pi^-$ cross section above 1 GeV. At the moment it is based on 2019-2021 data, need to incorporate 2022-2023 data.
- We are taking more data below 1 GeV. It will allow to do additional systematics studies for $\pi^+\pi^-$ analysis.
- There is a program under development for CMD-3 upgrade over next 4-5 years, aimed at measurement of $\pi^+\pi^-$ cross section at the next level of precision