Measurement of $e^+e^- \to \pi^+\pi^-$ cross section by CMD-3 and its implications to hadronic contribution to muon (g-2)

Ivan Logashenko (BINP) on behalf of CMD-3 collaboration

Объединенный семинар ОФВЭ и ОТФ ПИЯФ

15 февраля 2024

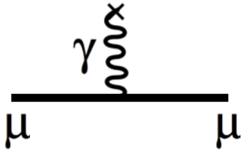
Based on talk at Rubakov Conference, October 2-7, 2023 Erevan

Rather long introduction

The basics

Gyromagnetic ratio $\boldsymbol{g}$ connects magnetic moment μ and spin s

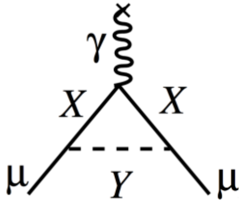
$$\vec{\mu}_S = g\frac{e}{2m}\vec{S}$$



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

Anomalous magnetic moment $\boldsymbol{a}$ arises in higher-orders

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



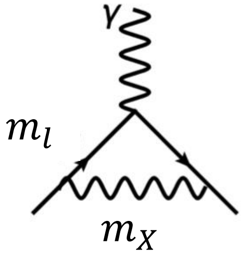
$a_e \approx a_\mu \approx \frac{\alpha}{2\pi} \approx 10^{-3}$ (QED dominated)

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

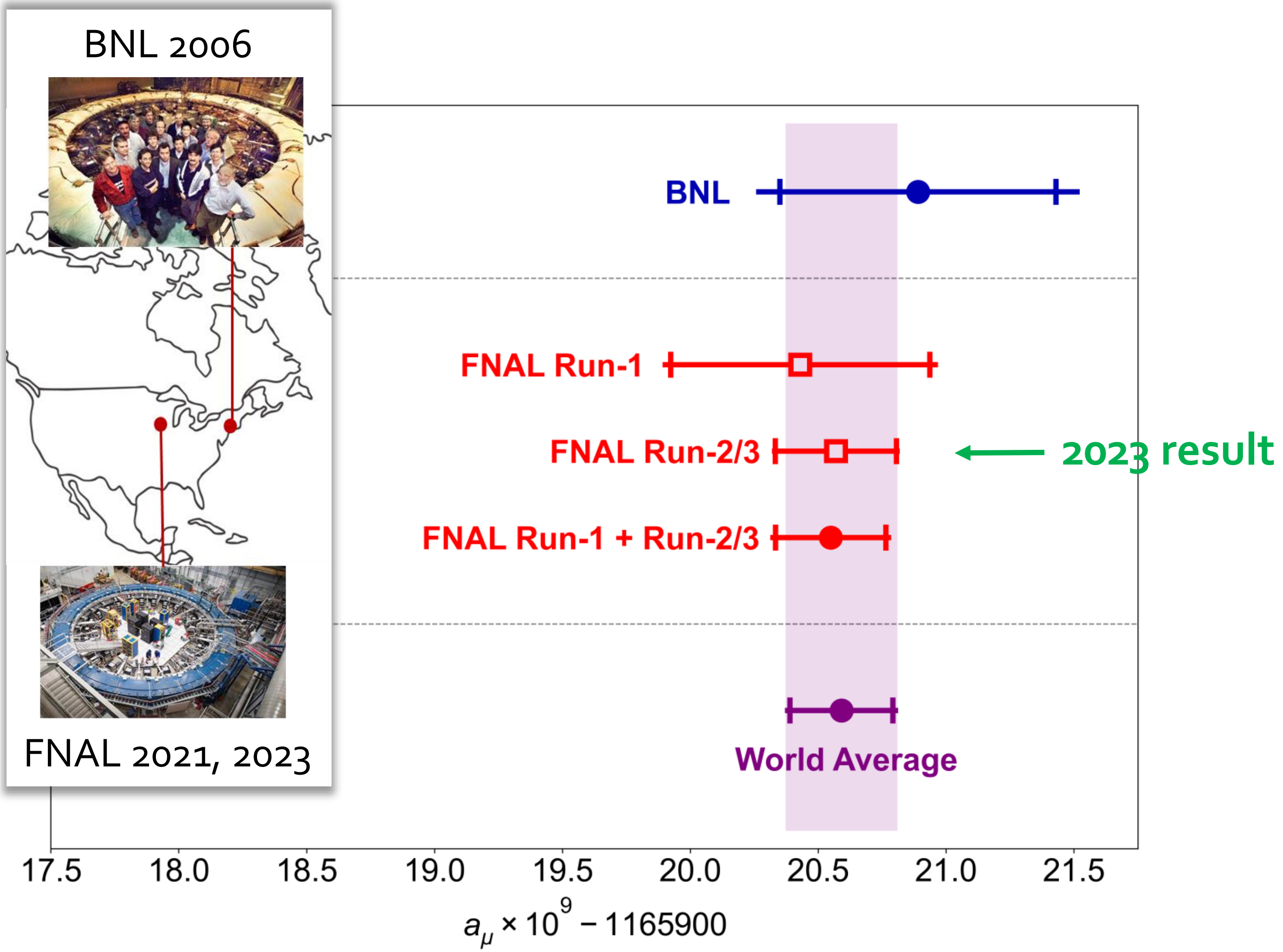
$$a_\mu(strong)/a_\mu(QED) \approx 6\times10^{-5} \qquad a_\mu(weak)/a_\mu(QED) \approx 10^{-6}$$

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

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



Muon G-2 2023 result



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

Muon G-2 collaboration

USA
- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- North Central
- Northern Illinois
- Regis
- Virginia
- Washington

USA National Labs
- Argonne
- Brookhaven
- Fermilab

181 collaborators
33 Institutions
7 countries

China
- Shanghai Jiao Tong

Germany
- Dresden
- Mainz

Italy
- Frascati
- Molise
- Naples
- Pisa
- Roma Tor Vergata
- Trieste
- Udine

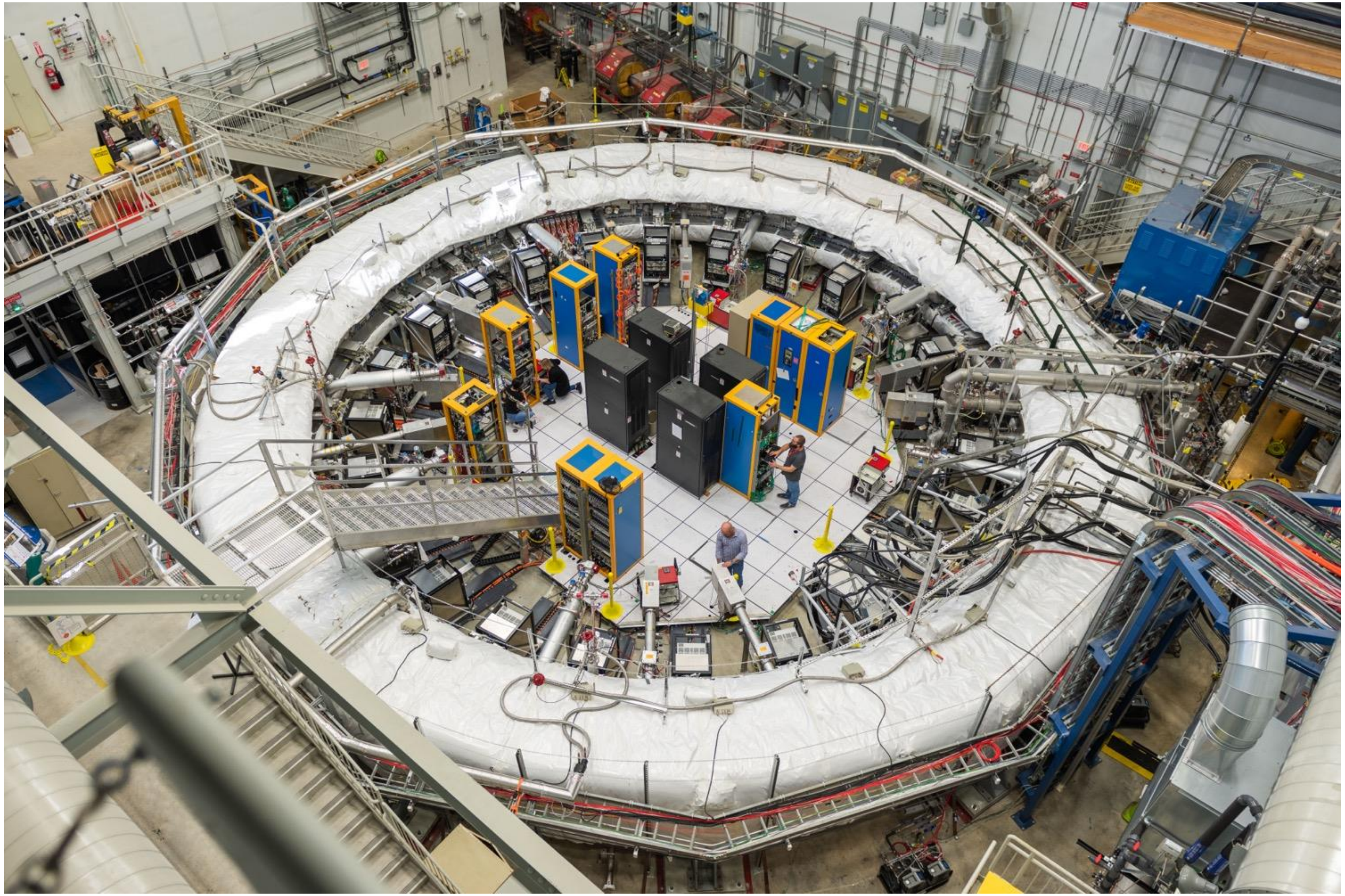
Korea
- CAPP/IBS
- KAIST

Russia
- Budker/Novosibirsk
- JINR Dubna

United Kingdom
- Lancaster/Cockcroft
- Liverpool
- Manchester
- University College London

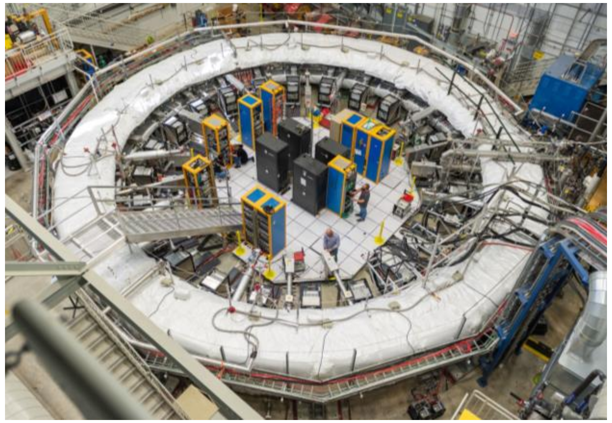
Muon g-2 Collaboration Meeting @ Elba, May 2019

Muon G-2 Ring @FNAL

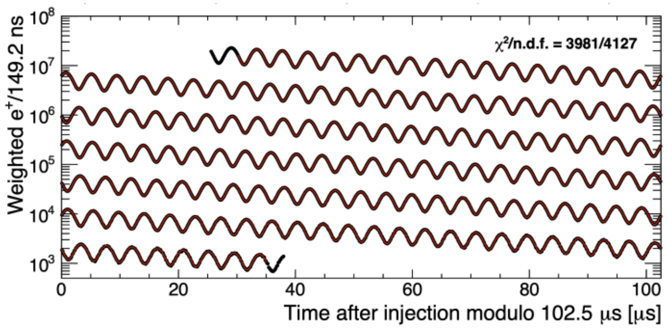


Generations of a_μ measurements

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

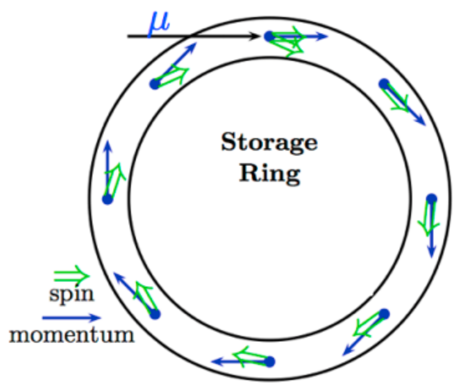
Contributions of known interactions

Principles of CERN-III type measurement

1. Spin precesses relative to momentum with frequency ω_a proportional directly to a_μ

$$\omega_a = \omega_s - \omega_c = a_\mu eB/mc$$

$$a_\mu = \frac{mc}{e}\frac{\omega_a}{B}$$



Muons are stored in a storage ring
ω_a and B are measured

Need focusing!

2. Effect of electric field is cancels out for muons of "magic" momentum

$$\vec{\omega}_a = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \cancel{\frac{1}{\gamma^2-1}}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

zero for $\gamma_\mu = 29.3$

Muons with $p = 3.09$ GeV/c are used

Focusing with electrostatic quadrupoles

Obtaining a_μ

Corrections due to beam dynamics

$$\frac{\omega_a}{\omega_p} = \frac{\omega_a^m}{\omega_p^m} \frac{1 + \overbrace{C_e + C_p + C_{pa} + C_{dd} + C_{ml}}}{1 + \underbrace{B_k + B_q}}$$

Measured Values

Corrections due to transient magnetic fields

$$a_\mu = \boxed{\frac{\omega_a}{\omega_p}} \times \frac{\mu_p'(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

Metrological constants known to ~25 ppb

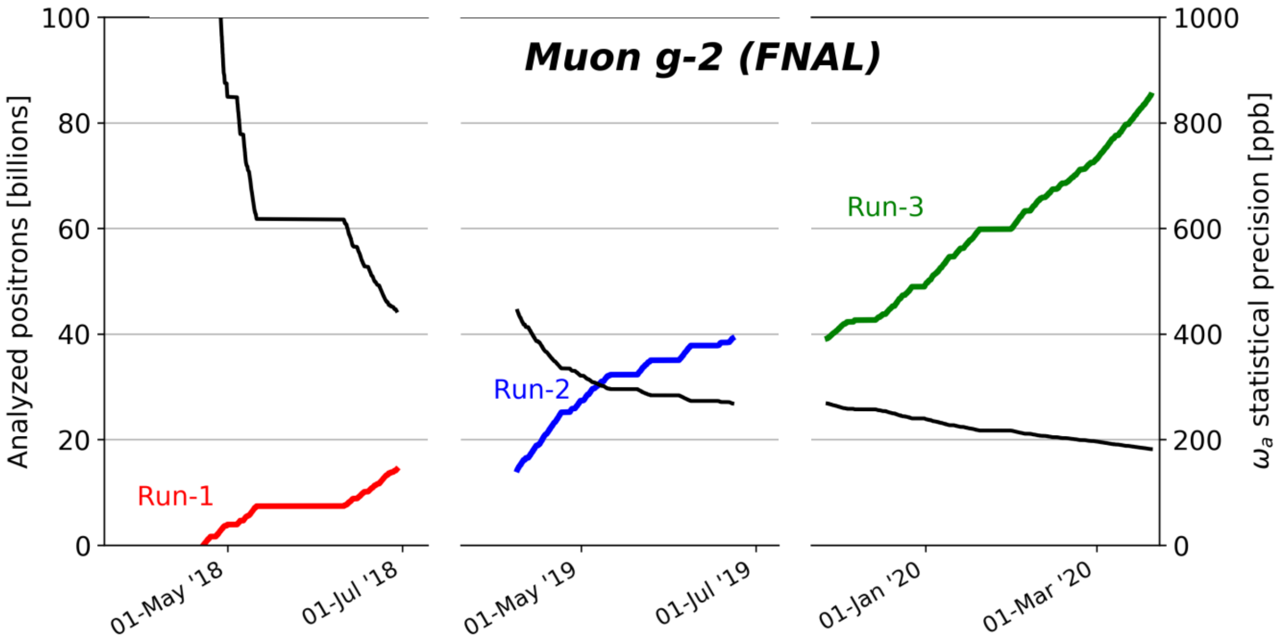
Total correction is about 622 ppb

Run-1 vs Run-2/3

Statistics

Weighted e+ in our final fit after quality control

E > 1 GeV
t > 30 us



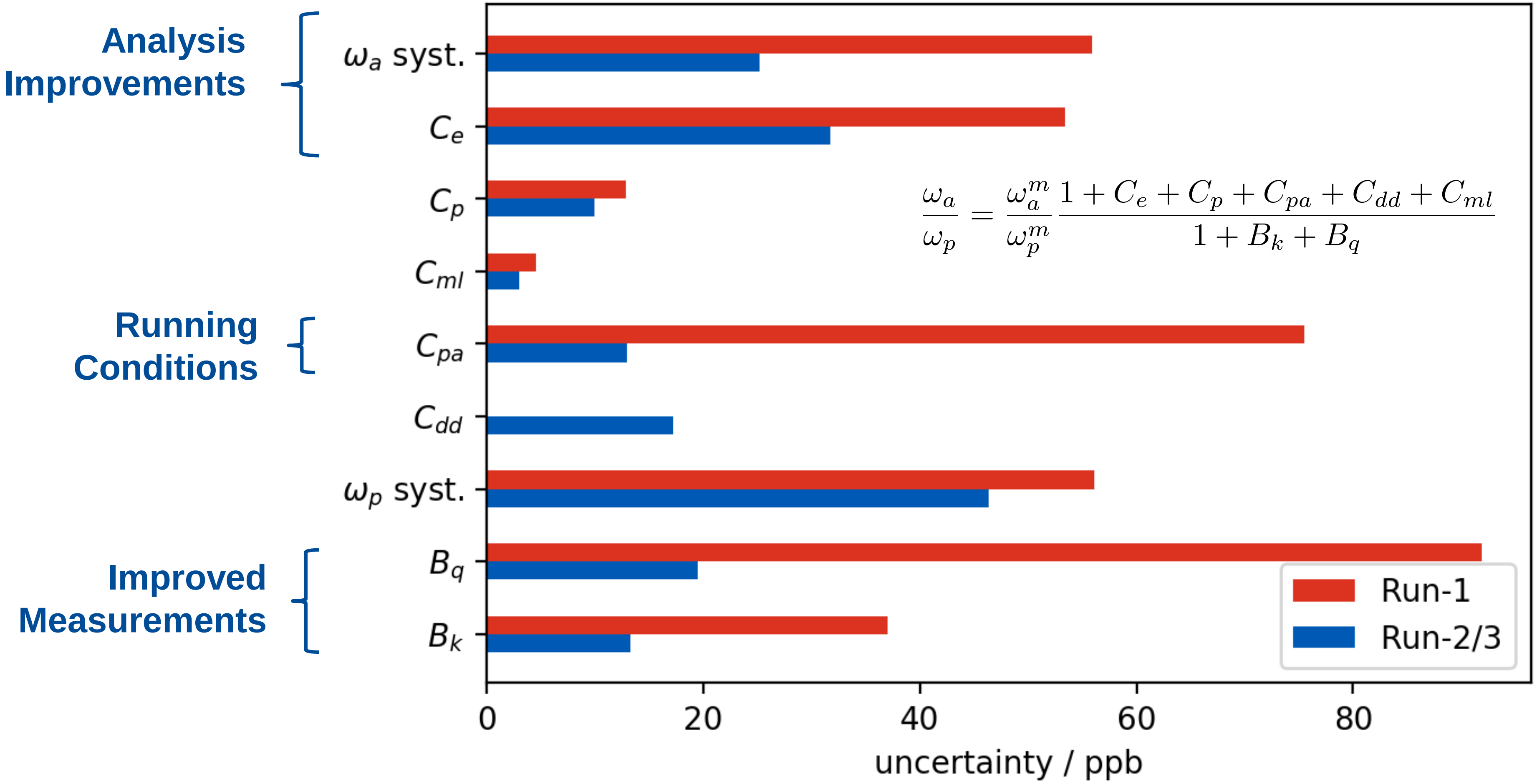
- **Factor 4.7** more data in Run-2/3 than Run-1

Dataset	Statistical Error [ppb]
Run-1	**434**
Run-2/3	**201**
Run-1 + Run-2/3	**185**

Improvement by factor 2.2

Run-1 vs Run-2/3

Systematics



Overall improvement by factor 2.2

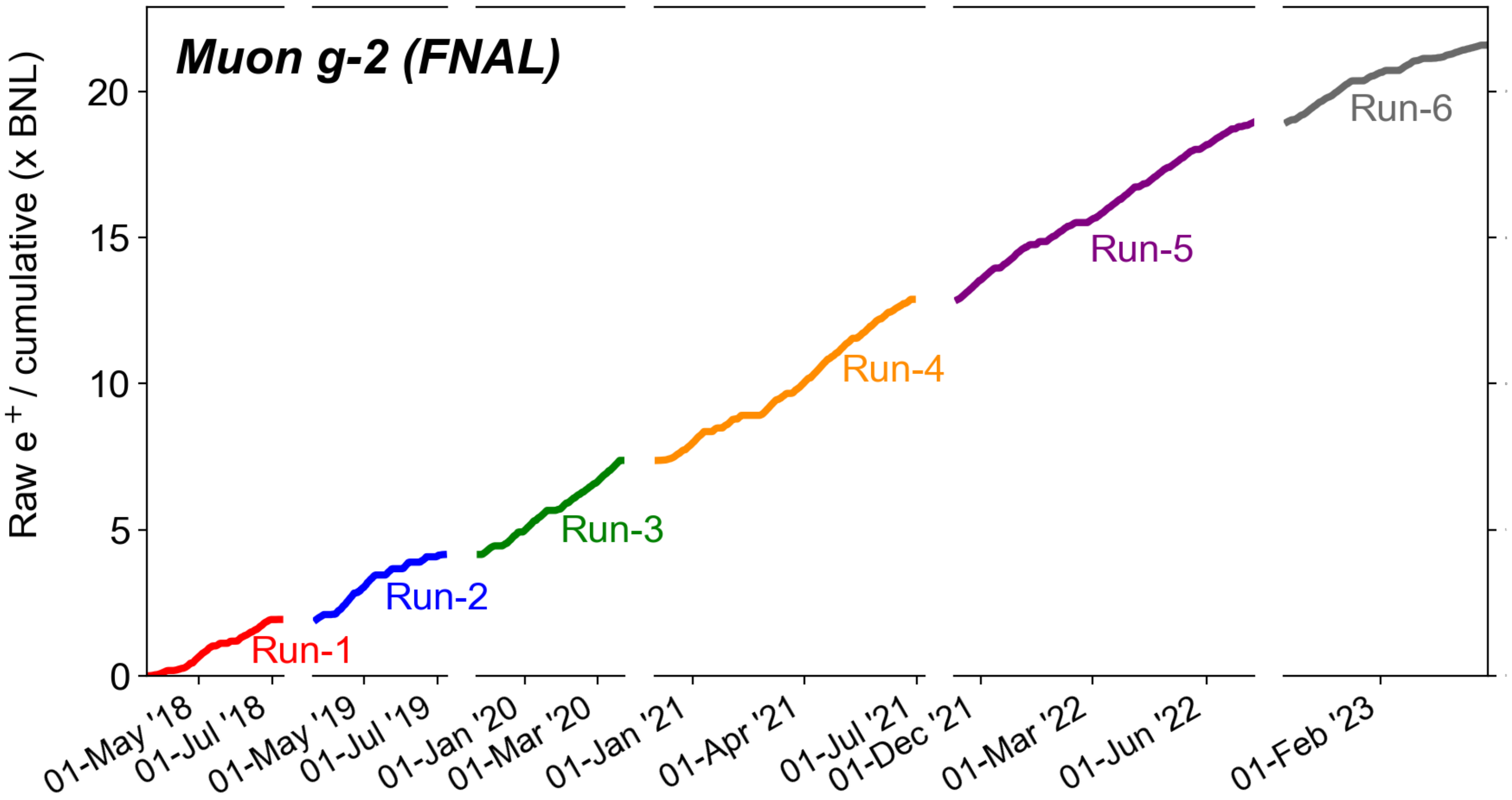
Final error table

Quantity	Correction [ppb]	Uncertainty [ppb]
ω_a^m (statistical)	–	201
ω_a^m (systematic)	–	25
C_e	451	32
C_p	170	10
C_{pa}	-27	13
C_{dd}	-15	17
C_{ml}	0	3
$f_{\text{calib}} \langle \omega'_p(\vec{r}) \times M(\vec{r}) \rangle$	–	46
B_k	-21	13
B_q	-21	20
$\mu'_p(34.7^\circ)/\mu_e$	–	11
m_μ/m_e	–	22
$g_e/2$	–	0
Total systematic	–	70
Total external parameters	–	25
Totals	622	215

The Run-2/3 result is statistically dominated

70 ppb systematic uncertainty surpasses the proposal goal of 100 ppb!

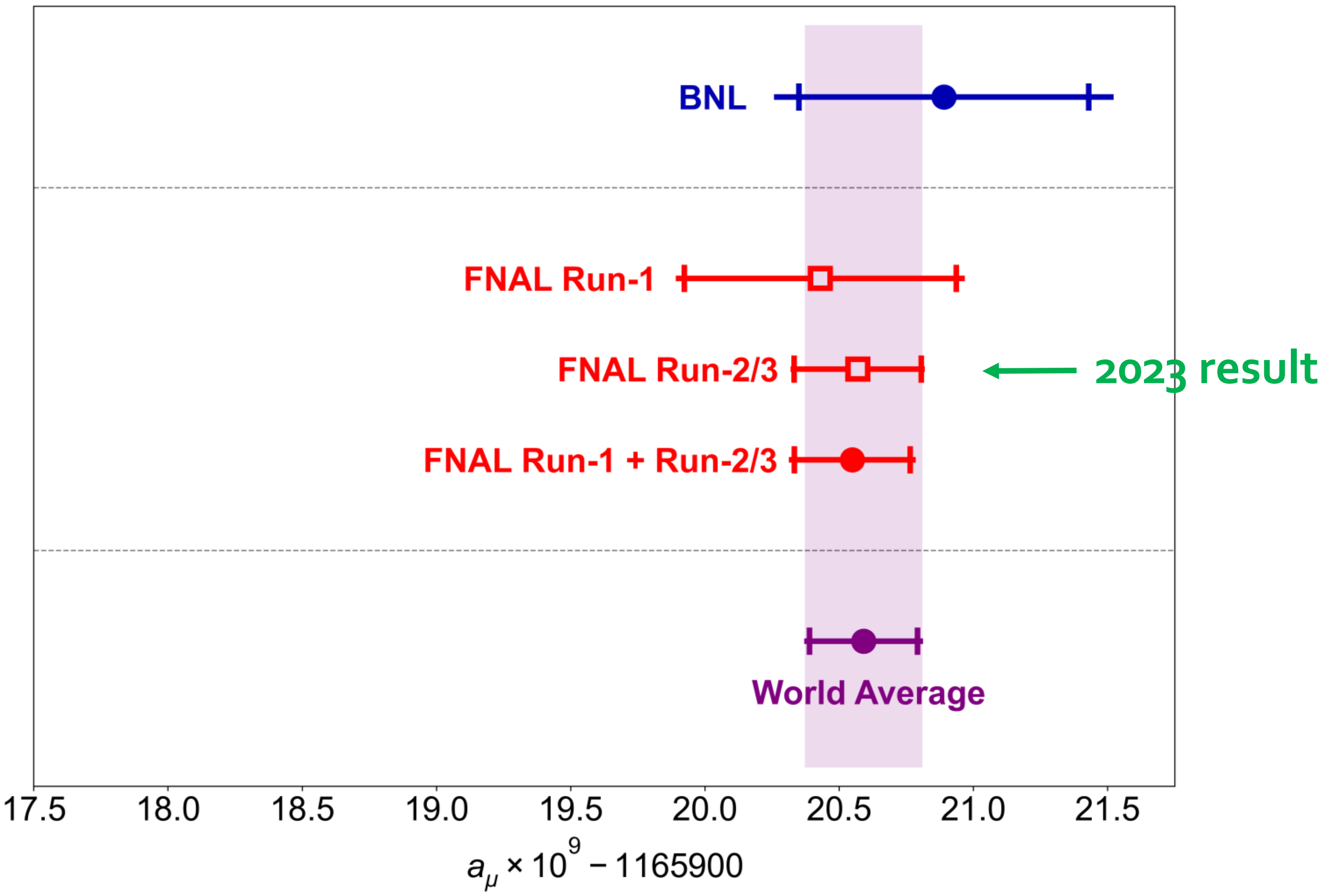
Total collected statistics



21.9 BNL datasets have been collected in FNAL (proposal – 21 BNL)

Run 4/5/6 statistics is x3 Run-1/2/3

Muon G-2 2023 result

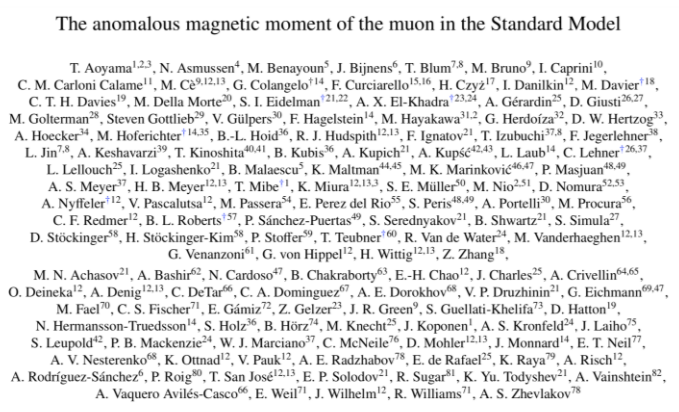


What about theory?

Experiment vs SM prediction

Muon G-2 Theory Initiative

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

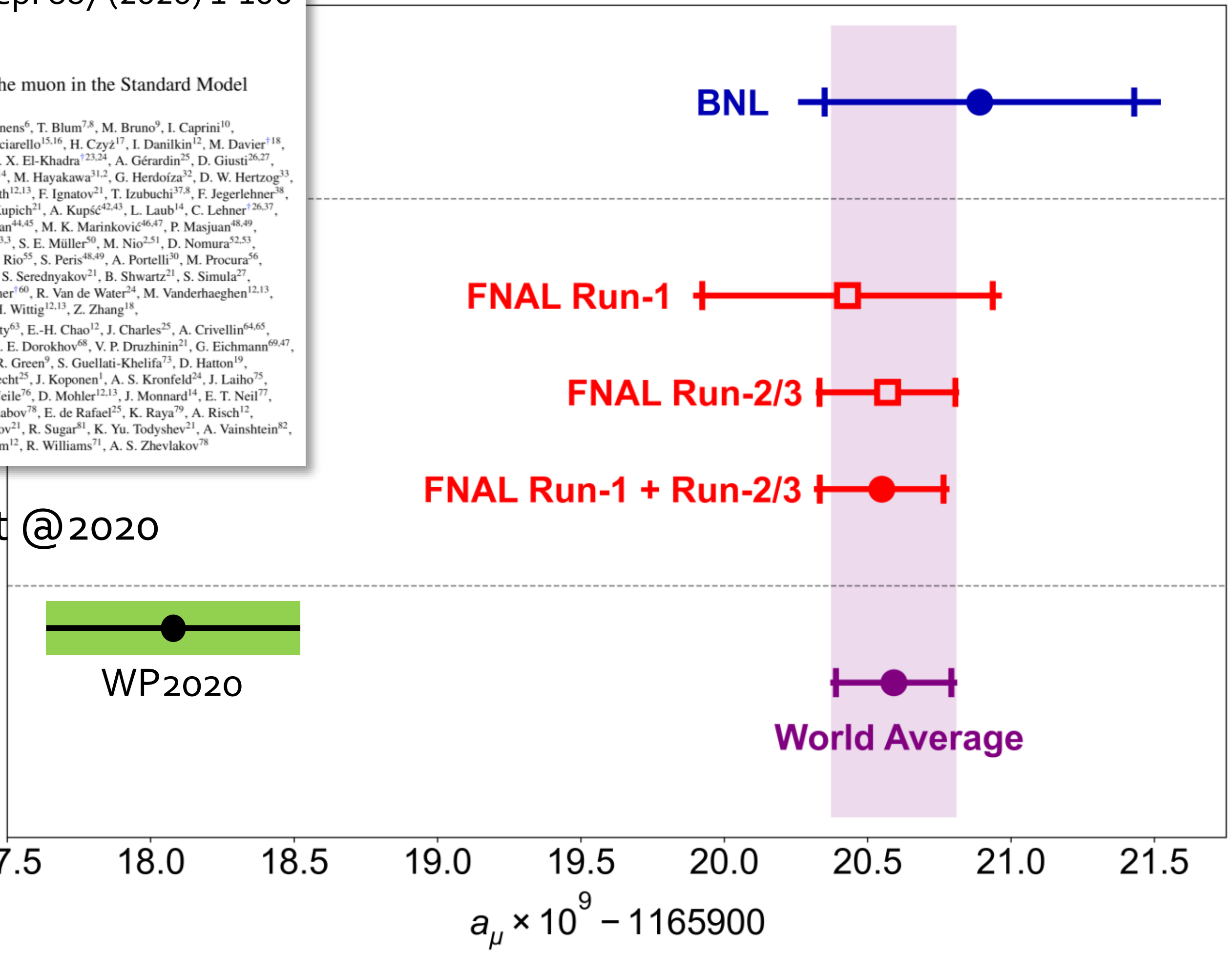


The anomalous magnetic moment of the muon in the Standard Model

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],

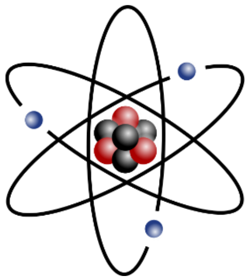
M. N. Achasov[21], A. Bashir[62], N. Cardoso[47], B. Chakraborty[63], E.-H. Chao[12], J. Charles[25], A. Crivellin[64,65], O. Deineka[12], A. Denig[12,13], C. DeTar[66], C. A. Dominguez[67], A. E. Dorokhov[68], V. P. Druzhinin[21], G. Eichmann[69,47], M. Fael[70], C. S. Fischer[71], E. Gámiz[72], Z. 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]

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

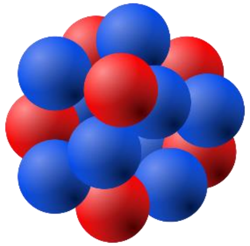


State-of-art @2020

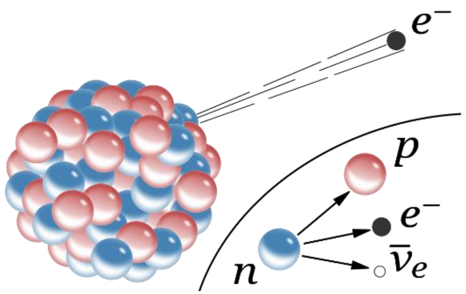
Standard Model prediction for a_μ



Electromagnetic interactions



Strong interactions



Weak interactions

$0.001\ 165\ 847\ 19\ (0.1)$

$0.000\ 000\ 069\ 37\ (43)$

$0.000\ 000\ 001\ 54\ (1)$

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

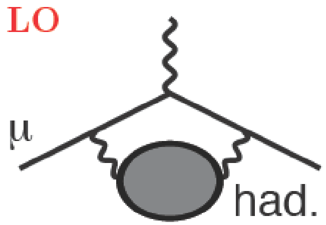
The uncertainty is dominated by contribution of strong interactions

Hadronic contribution to muon (g-2)

Leading order (LO) | Next to leading order (NLO+NNLO) | Light-by-light (LBL)

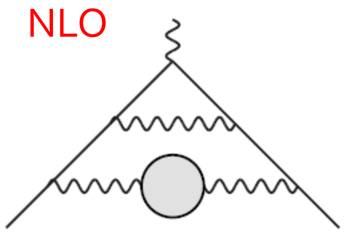
$(6\,931 \pm 40) \times 10^{-11}$ | $(-85.9 \pm 0.7) \times 10^{-11}$ | $(92 \pm 18) \times 10^{-11}$

$$a_\mu^{\rm had} = a_\mu^{\rm had,VP\ LO} + a_\mu^{\rm had,VP\ NLO} + a_\mu^{\rm had,Light-by-Light}$$

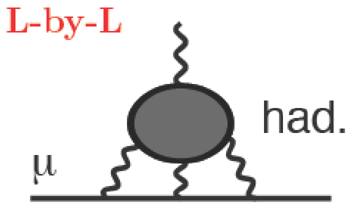


345 ppb (0.6%)

Dominant!



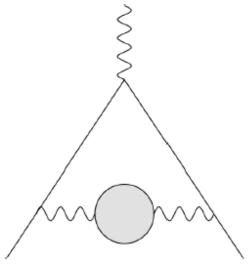
10 ppb



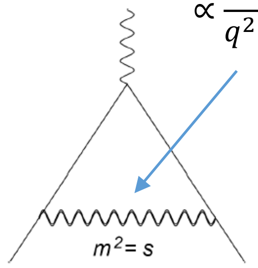
155 ppb

HVP: what do we need to measure

Dispersion relation:



$$= \int_0^\infty \frac{ds}{s}\,\frac{1}{\pi}\mathrm{Im}\Pi'(s) \times$$

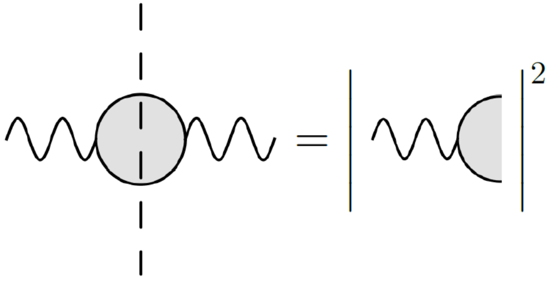


$\propto \frac{1}{q^2 - s}$

$a_\mu^{had}(LO)$

$\frac{\alpha}{\pi}K_\mu(s)$

Optical theorem: 2 Im



$$\mathrm{Im}\,\Pi'(s) = \frac{s}{4\pi\alpha}\sigma^0(e^+e^- \to \gamma \to hadrons + \cdots)$$

Lets put everything together:

This is what we need to measure

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

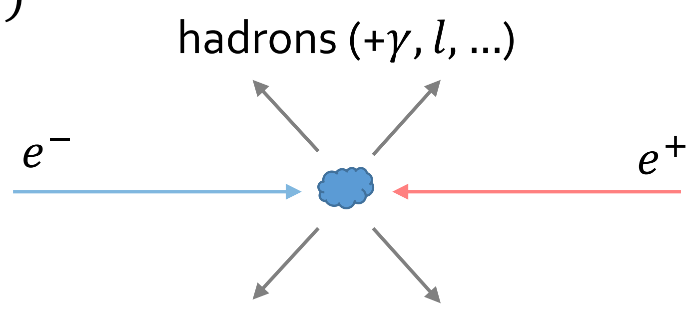
$$R(s) = \frac{\sigma^0(e^+e^- \to \gamma \to hadrons)}{4\pi\alpha^2/3s}$$

$\sigma^0(e^+e^- \to \mu^+\mu^-)$

$s = (\text{c.m. energy})^2$

Energy scan approach

Direct measurement of $\sigma(e^+e^- \to hadrons)$ (energy scan approach):



- performed at electron-positron collider
- collect data at different beam energy
- at each energy point: select final states with hadrons, subtract background and normalize to luminosity

Number of signal events

Number of background events

$$\sigma = \frac{N_{obs} - N_{bg}}{\varepsilon \cdot \int \mathcal{L}dt}$$

Detection efficiency:

- kinematical limits of detector (fiducial volume) – detector never has 4π coverage
- detector response

Luminosity integral

- measured by selection of monitoring events with known cross section

Exclusive vs inclusive measurement

Detection efficiency is (usually) calculated using MC simulation

- In order to calculated ε, we need to know the energy and angular distributions of final particles (including all correlations)

$$\sigma = \frac{N_{obs} - N_{bg}}{\varepsilon \cdot \int \mathcal{L} dt}$$

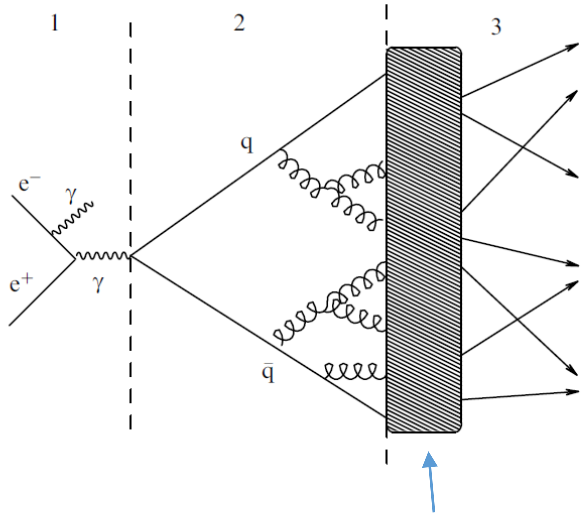
For high energies, where multiplicity is large enough, there are effective models of hadronization, which describe data reasonably well

At low energy the detection efficiency varies significantly between different final states and different paths of hadronization (intermediate states)

At low energies we have to measure cross section for each possible final state separately and then calculate sum to get R (***exclusive approach***)

At high energy we can measure total cross section directly (***inclusive approach***)

Final state



Intermediate states

The practical boundary between two approaches in $\sqrt{s} = 2$ GeV.

The $a_\mu^{had}(LO)$ calculation is mostly based on exclusive measurements.

Contribution of exclusive hadronic cross sections to a_μ

In exclusive approach, we calculate a_μ integral for each final state and sum them:

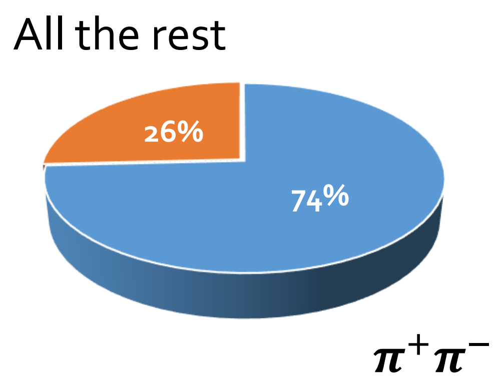
$$a_\mu^{had}(LO) = \sum_{X=\pi^0\gamma,\pi^+\pi^-,\dots} a_\mu^X(LO) = \sum_X \frac{1}{4\pi^3}\int \sigma^0(e^+e^- \to X)K_\mu(s)ds$$

Channel	$a_\mu^{\text{had,LO}}$ $[10^{-10}]$
$\pi^0\gamma$	$4.41 \pm 0.06 \pm 0.04 \pm 0.07$
$\eta\gamma$	$0.65 \pm 0.02 \pm 0.01 \pm 0.01$
$\pi^+\pi^-$	$507.85 \pm 0.83 \pm 3.23 \pm 0.55$
$\pi^+\pi^-\pi^0$	$46.21 \pm 0.40 \pm 1.10 \pm 0.86$
$2\pi^+2\pi^-$	$13.68 \pm 0.03 \pm 0.27 \pm 0.14$
$\pi^+\pi^-2\pi^0$	$18.03 \pm 0.06 \pm 0.48 \pm 0.26$
$2\pi^+2\pi^-\pi^0$ (η excl.)	$0.69 \pm 0.04 \pm 0.06 \pm 0.03$
$\pi^+\pi^-3\pi^0$ (η excl.)	$0.49 \pm 0.03 \pm 0.09 \pm 0.00$
$3\pi^+3\pi^-$	$0.11 \pm 0.00 \pm 0.01 \pm 0.00$
$2\pi^+2\pi^-2\pi^0$ (η excl.)	$0.71 \pm 0.06 \pm 0.07 \pm 0.14$
$\pi^+\pi^-4\pi^0$ (η excl., isospin)	$0.08 \pm 0.01 \pm 0.08 \pm 0.00$
$\eta\pi^+\pi^-$	$1.19 \pm 0.02 \pm 0.04 \pm 0.02$
$\eta\omega$	$0.35 \pm 0.01 \pm 0.02 \pm 0.01$
$\eta\pi^+\pi^-\pi^0$(non-ω,ϕ)	$0.34 \pm 0.03 \pm 0.03 \pm 0.04$
$\eta 2\pi^+2\pi^-$	$0.02 \pm 0.01 \pm 0.00 \pm 0.00$
$\omega\eta\pi^0$	$0.06 \pm 0.01 \pm 0.01 \pm 0.00$
$\omega\pi^0$ ($\omega \to \pi^0\gamma$)	$0.94 \pm 0.01 \pm 0.03 \pm 0.00$
$\omega 2\pi$ ($\omega \to \pi^0\gamma$)	$0.07 \pm 0.00 \pm 0.00 \pm 0.00$
ω (non-$3\pi, \pi\gamma, \eta\gamma$)	$0.04 \pm 0.00 \pm 0.00 \pm 0.00$
K^+K^-	$23.08 \pm 0.20 \pm 0.33 \pm 0.21$
K_SK_L	$12.82 \pm 0.06 \pm 0.18 \pm 0.15$

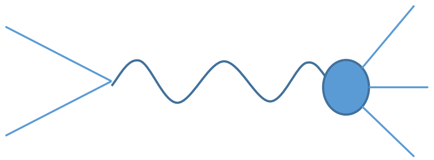
From DHMZ'19

The larger the contribution, the better relative precision is required

$e^+e^- \to \pi^+\pi^-$ is by far the most challenging and has got the most attention (74% of total hadronic contribution!)



Radiative corrections



We want to measure $e^+e^- \to H$, but these events are accompanied by similar events where photons are emitted by any of the particles.

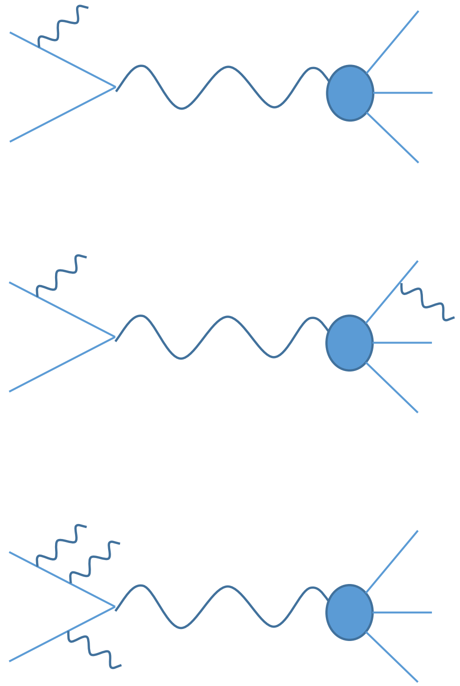
Radiation of high-energy γ is suppresses by α, but radiation of soft photons is enhanced.

Radiation changes both the cross-section and the kinematics of the final state:

$$\sigma = \frac{N_{obs} - N_{bg}}{\varepsilon(\delta) \cdot (1+\delta) \cdot \int \mathcal{L} dt}$$

And we have to calculate radiative corrections to the cross section of monitoring process as well

Radiative processes

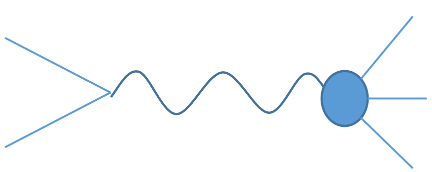


ISR FSR

Initial *Final*

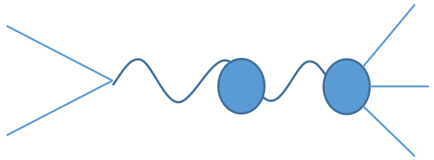
state radiation

Vacuum polarization



$\sigma^0(e^+e^- \to \gamma \to X)$

In a_μ calculation



$\sigma(e^+e^- \to \gamma^* \to X)$

In experiment

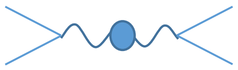
In the calculation of a_μ, we assume the lowest order photon propagator $1/q^2$. But the real propagator includes higher order effects (loop corrections): $1/(q^2 - \Pi(q^2))$. Therefore the measured cross section have to be corrected:

$$\sigma^0(e^+e^- \to X) = \sigma(e^+e^- \to X) \times \frac{|\alpha(s)|^2}{\alpha^2}$$

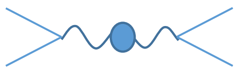
The running fine structure constant is also calculated via dispersion relation based on R(s):

$$\Delta\alpha_{had}(s) = -\frac{\alpha s}{3\pi}\int_0^\infty \frac{R(s')}{s'(s-s'-i0)}ds'$$

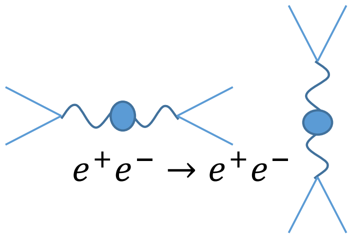
Nice way to avoid this correction is to use $e^+e^- \to \mu^+\mu^-$ for luminosity measurement



$e^+e^- \to X$



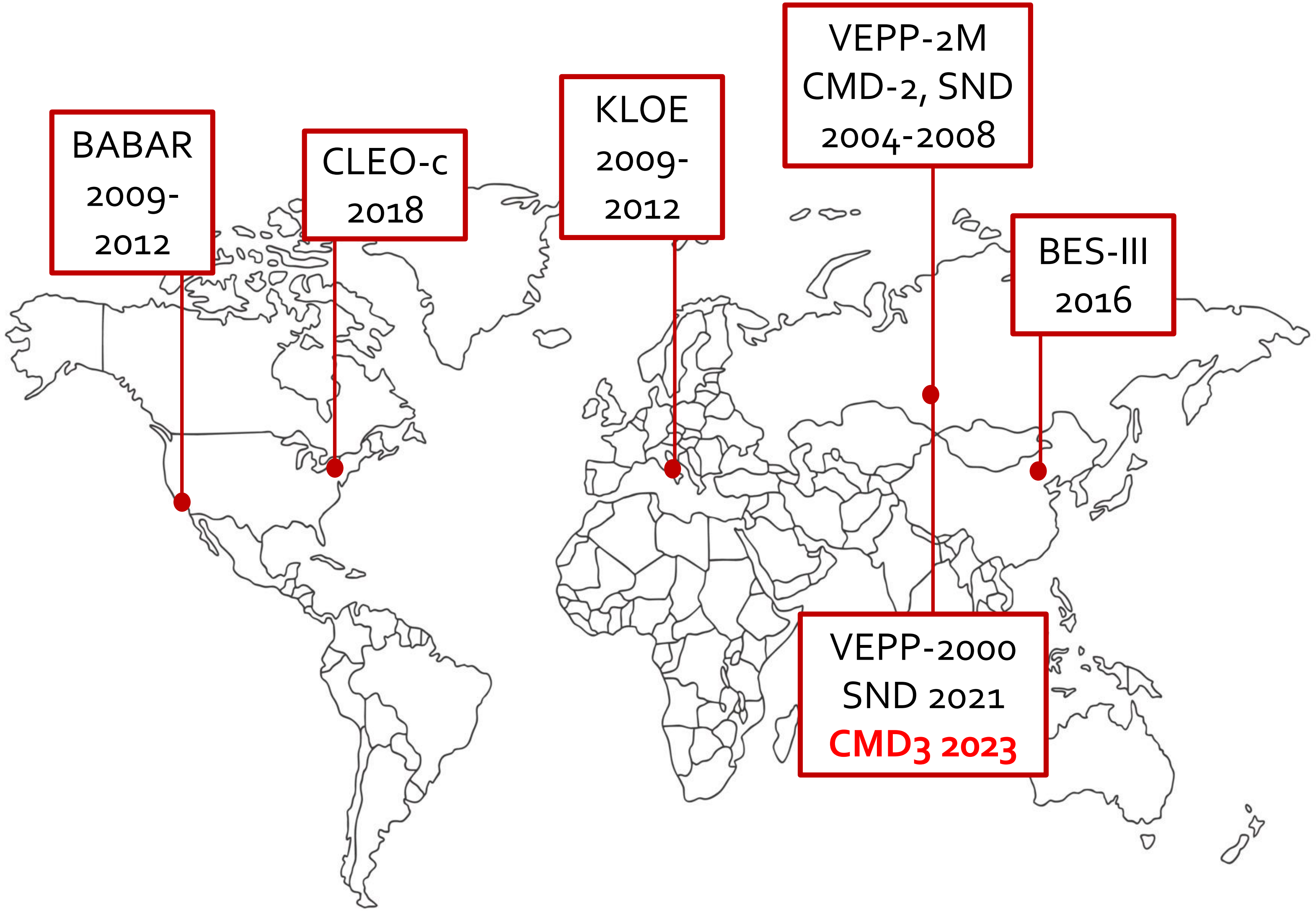
$e^+e^- \to \mu^+\mu^-$



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

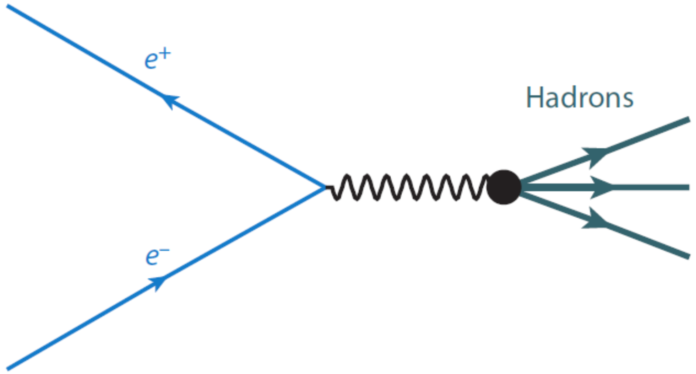
Measurements of $e^+e^- \to \pi^+\pi^-$

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



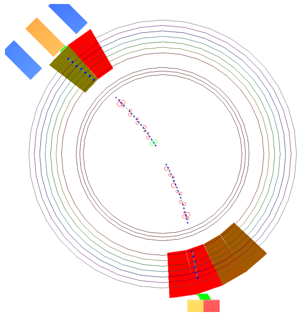
Measurement techniques:

Direct vs ISR

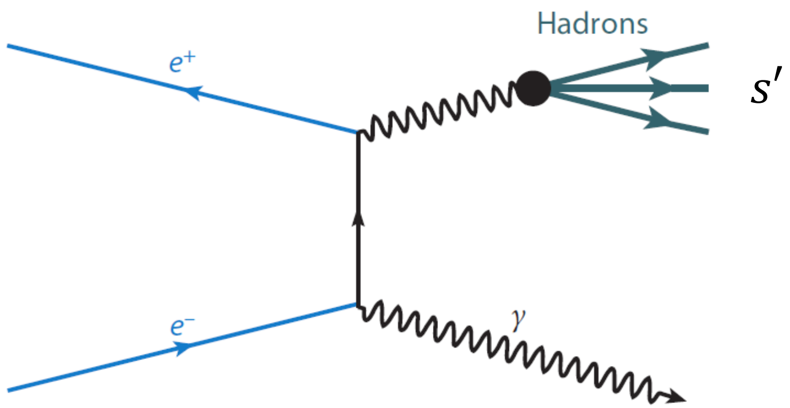


Direct measurement (Energy scan)

At fixed s: $\sigma_{e^+e^-\to H}(s) \sim N_H/L$
Data is taken at different s

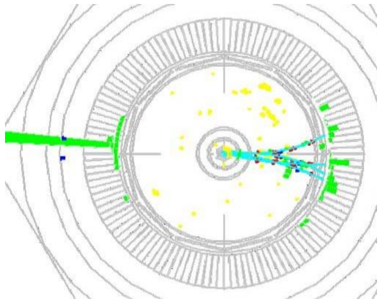


VEPP-2M: CMD-2, SND
VEPP-2000: CMD-3, SND2k



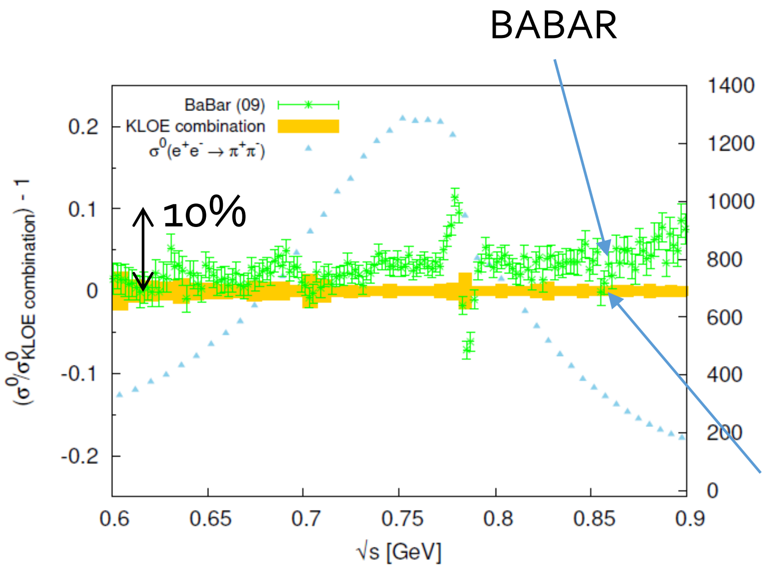
ISR (Initial State Radiation)

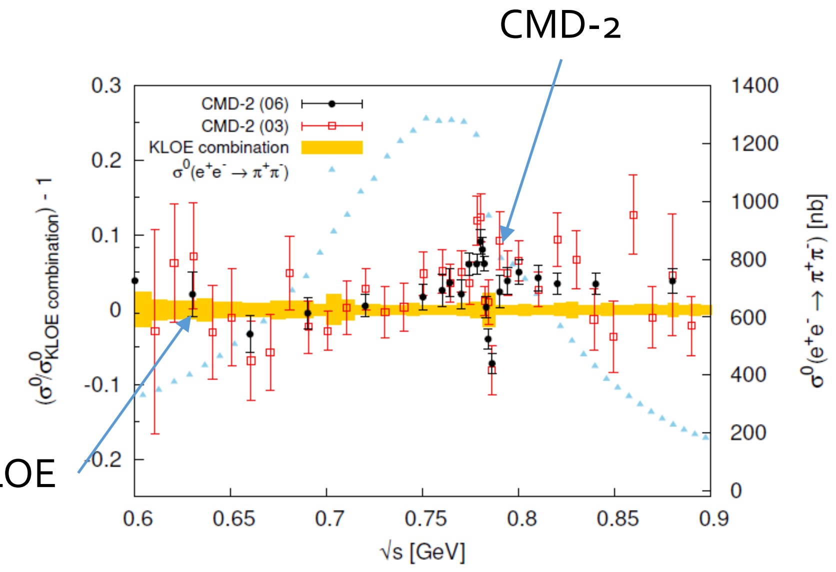
$\sigma_{e^+e^-\to H}(s') \sim \frac{dN_{H+\gamma}/ds\prime}{L \cdot dW/ds\prime}$
Data is taken at fixed $s > s'$



KLOE, BABAR, BES-III, CLEO

Tensions in $e^+e^- \to \pi^+\pi^-$ data



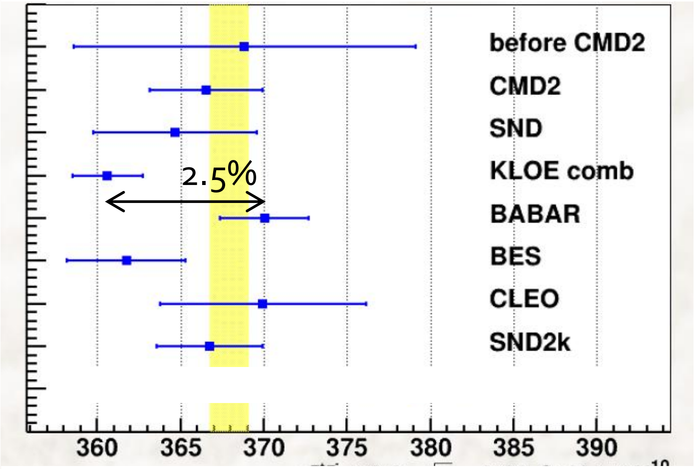


There are few-% discrepancies between various sub-% measurements of $\sigma(e^+e^- \to \pi^+\pi^-)$
Unexplained

WP2020: scale factor for $\Delta a_\mu(Had; LO)$

CMD-3 goal: new high statistics low systematics measurement of $\sigma(e^+e^- \to \pi^+\pi^-)$ via energy scan

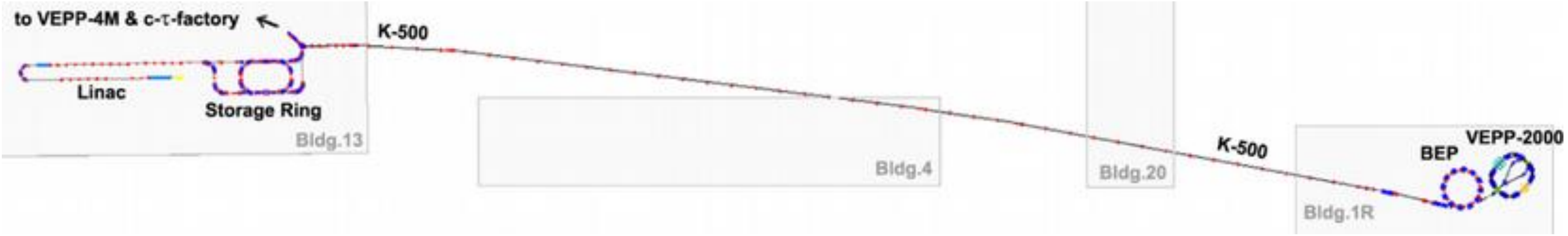
$a_\mu^{had}(LO; 2\pi, 0.6 < \sqrt{s} < 0.88\ \text{GeV})$



$$\frac{1}{4\pi^3}\int_{0.6}^{0.88} \sigma^0(e^+e^- \to \pi^+\pi^-) K_\mu(s) ds$$

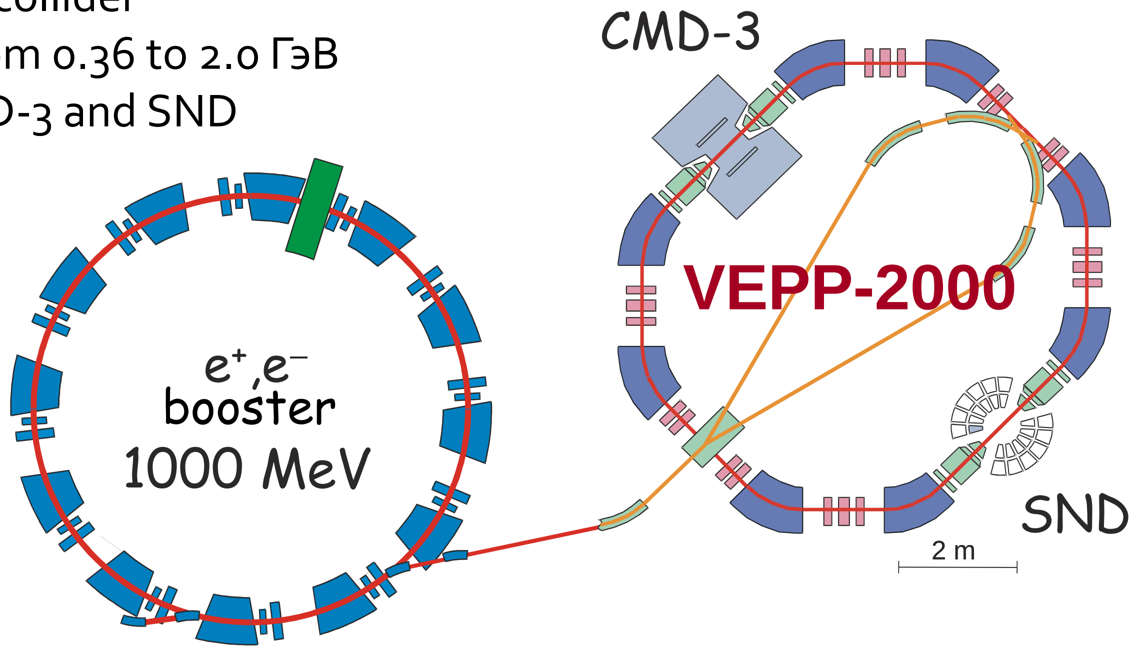
CMD-3 measurement of $e^+e^- \to \pi^+\pi^-$ cross section

VEPP-2000 collider



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

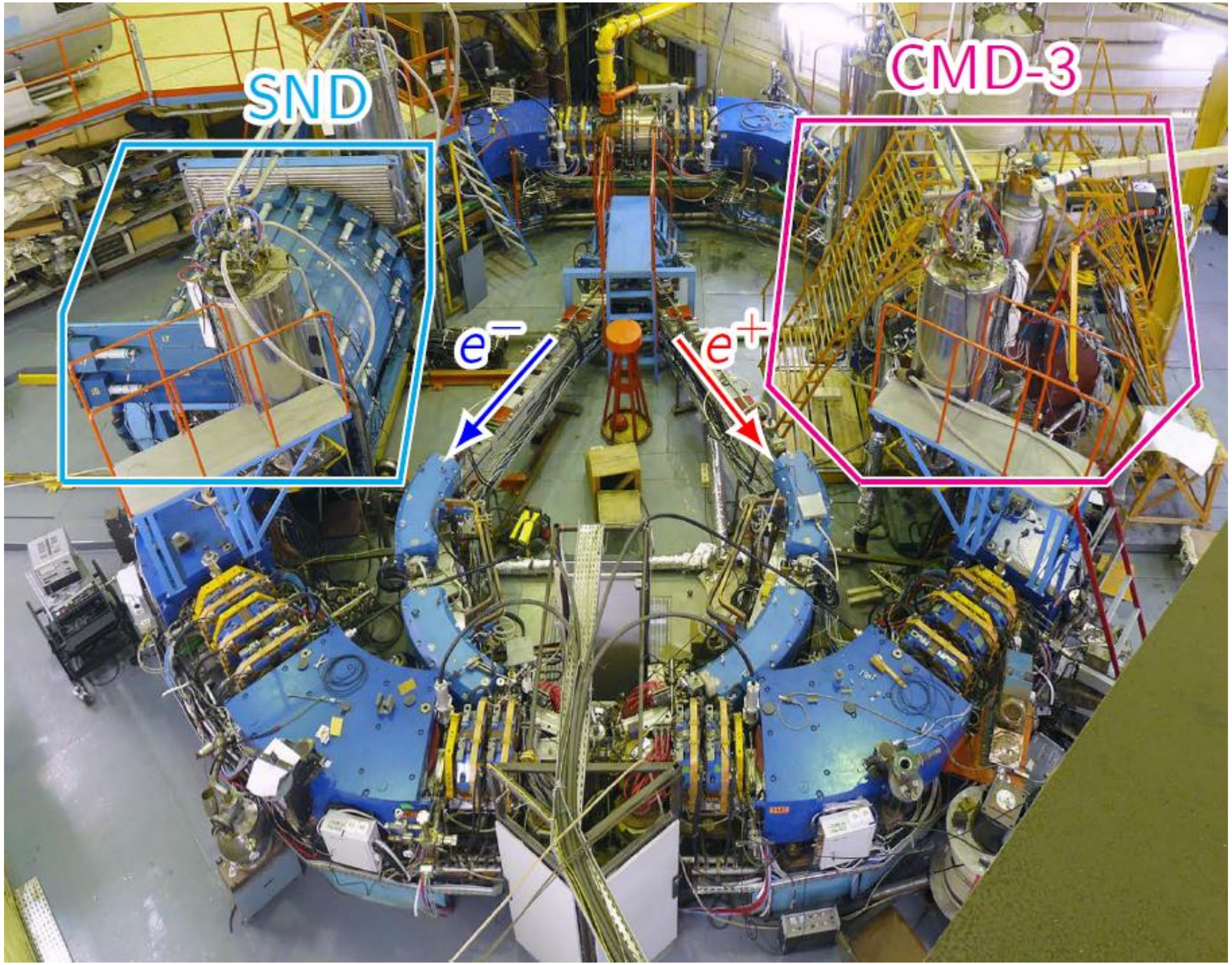
Design parameters @ 1 GeV	
Circumference	24.388 m
Beam energy	150 ÷ 1000 MeV
N of bunches	1×1
N of particles	1×10^{11}
Betatron tunes	4.14 / 2.14
Beta*	8.5 cm
BB parameter	0.1
Luminosity	1×10^{32} cm^{-2}s^{-1}



“Round beam” optics

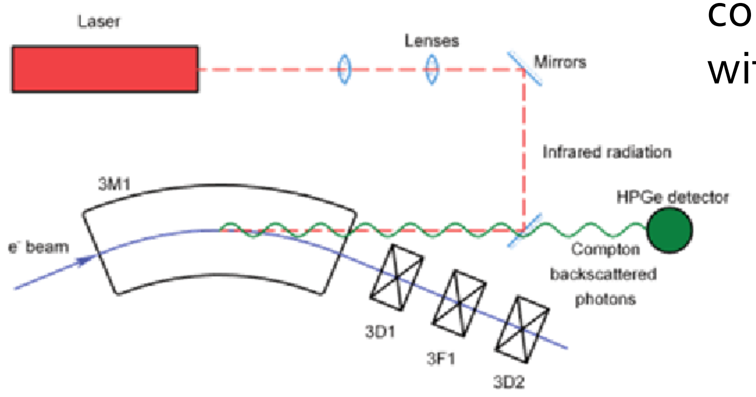
Energy monitoring by Compton backscattering ($\sigma_{\sqrt{s}} \approx 0.1$ MeV)

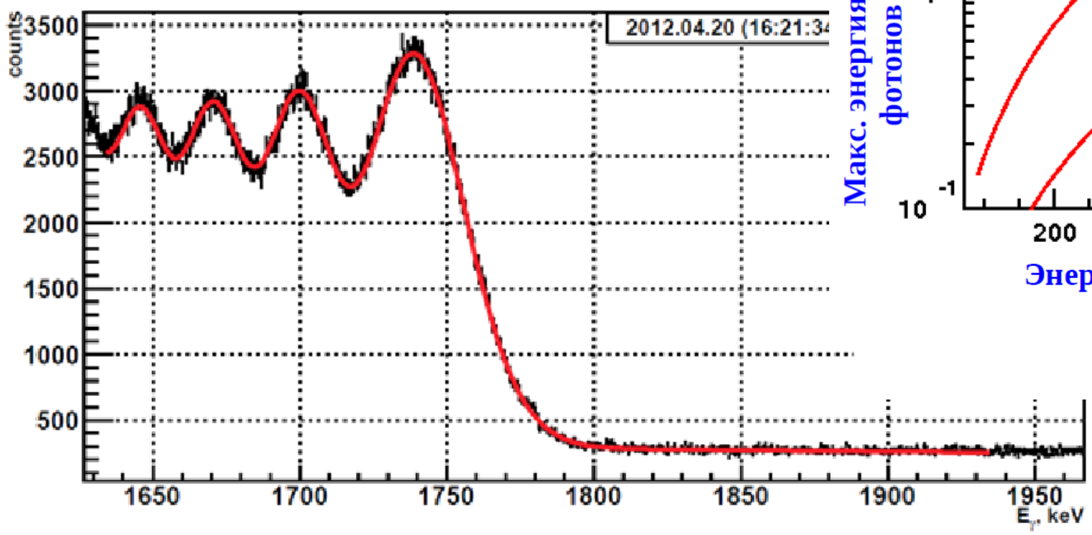
VEPP-2000

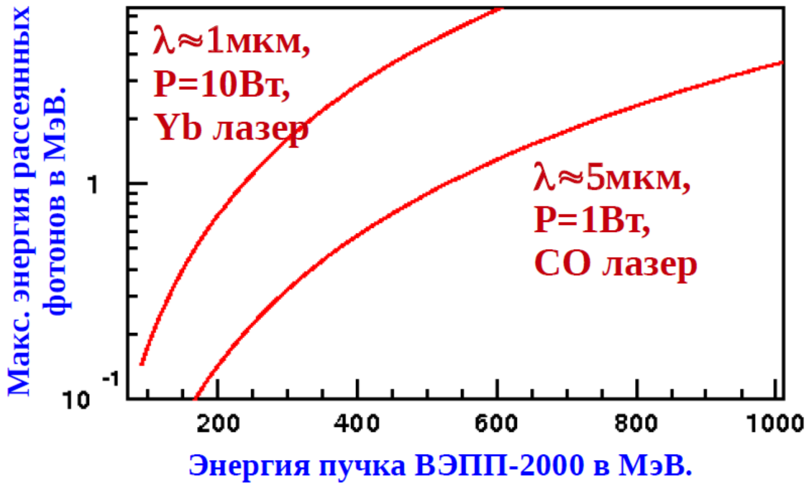


Energy measurement

Starting from 2012, energy is monitored continuously using compton backscattering, with ~30 keV precision





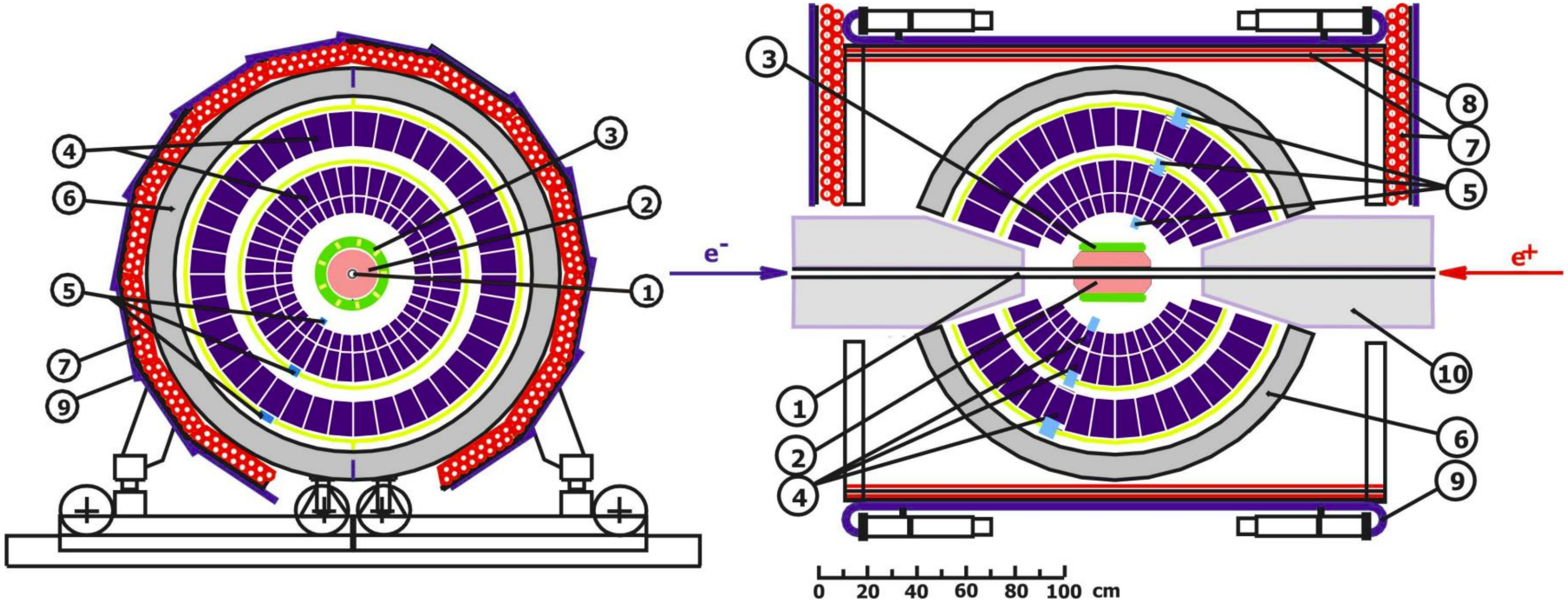


$E = 993.662 \pm 0.016$ МэВ

M.N. Achasov et al. arXiv:1211.0103v1 [physics.acc-ph] 1 Nov 2012

MeV

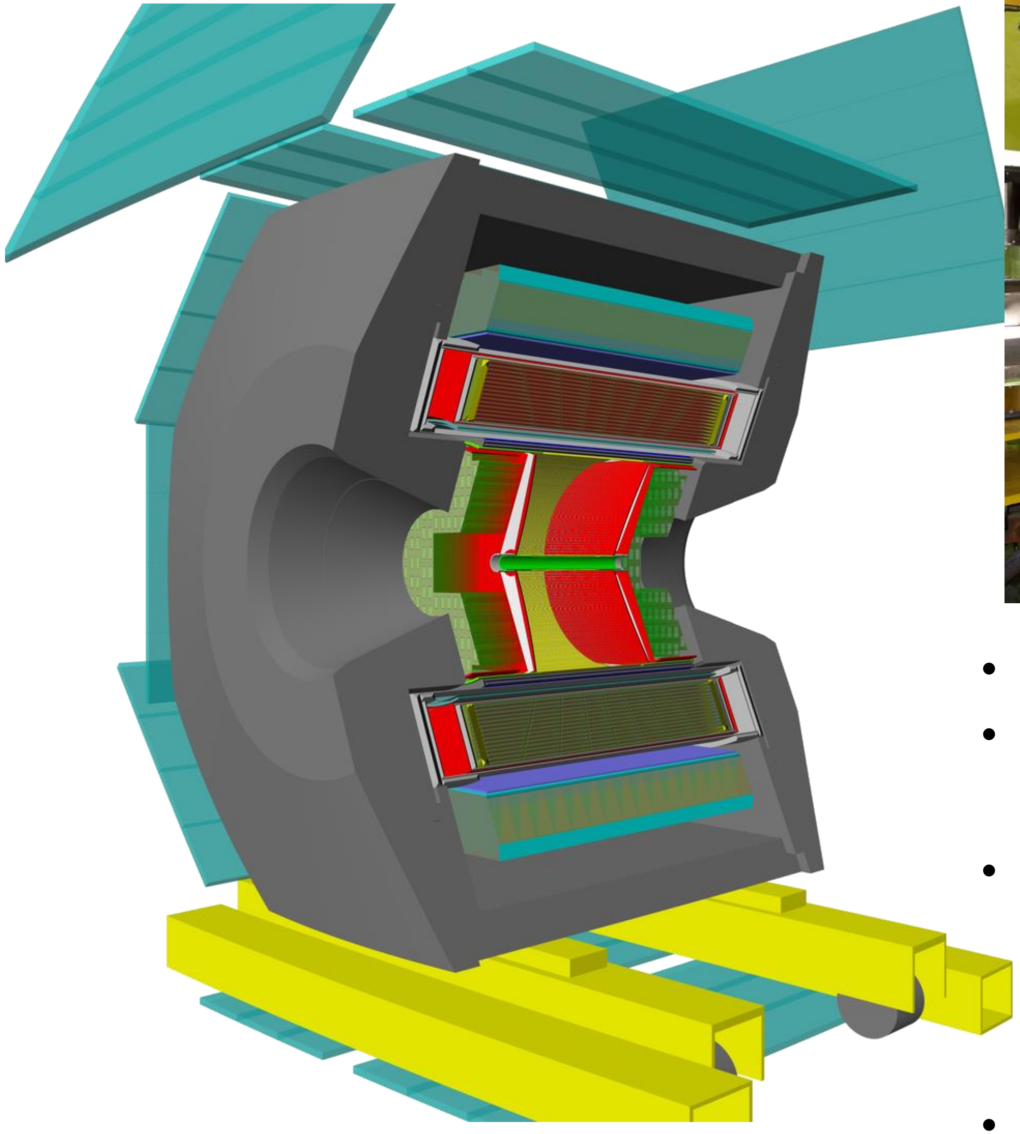
SND detector

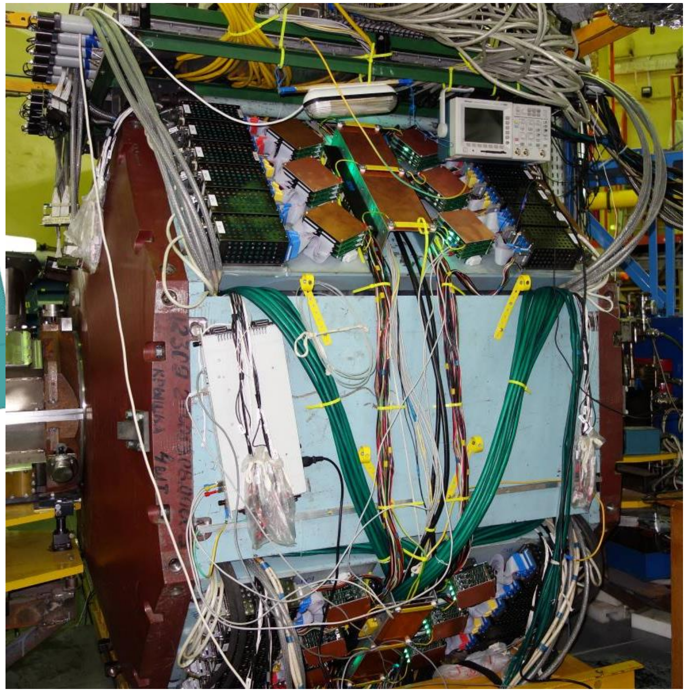


1 – beam pipe
2 – tracking system
3 – aerogel
4 – NaI(Tl) crystals
5 – phototriodes
6 – muon absorber
7–9 – muon detector
10 – focusing solenoid

CMD-3 Detector

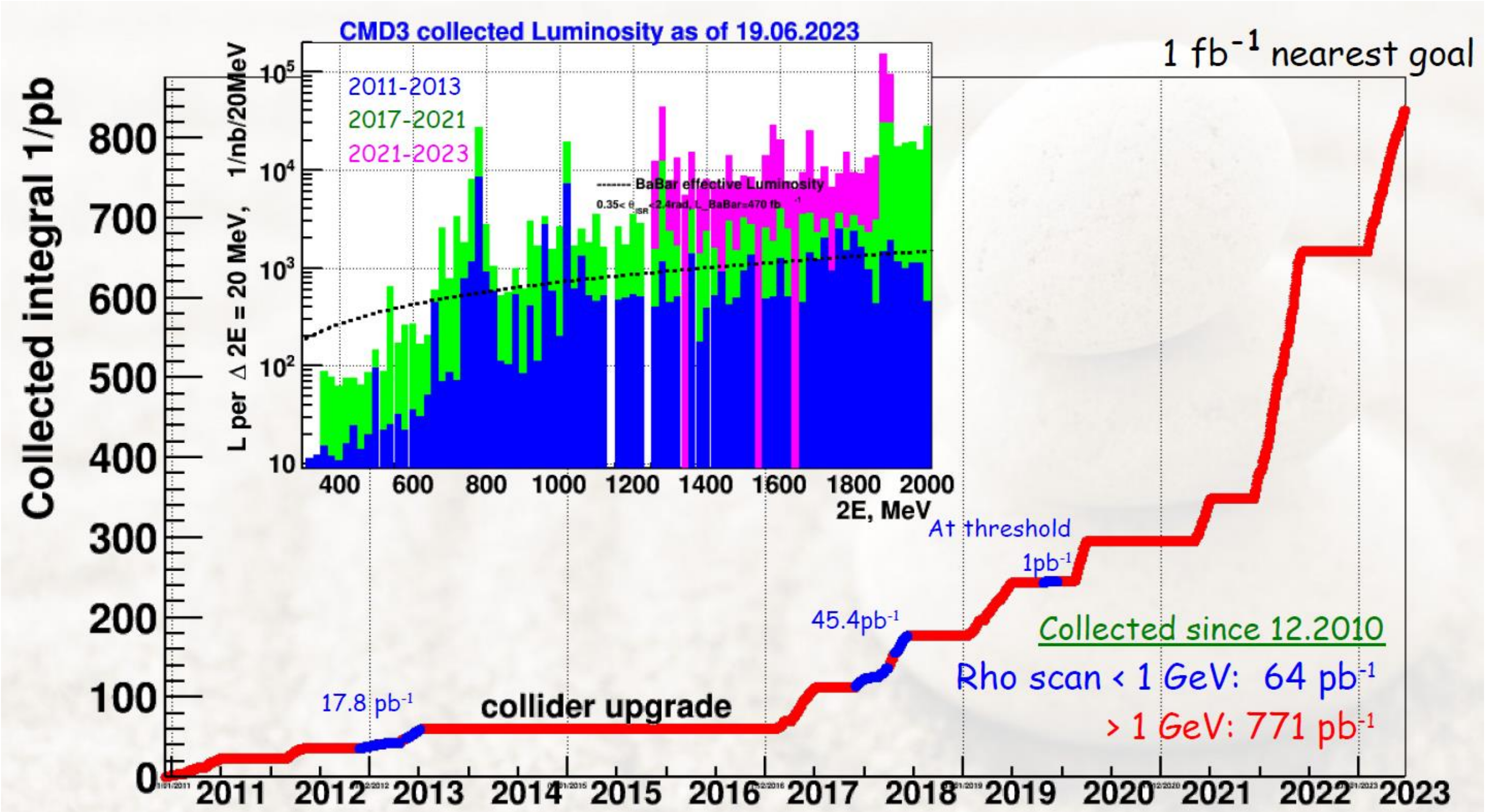
*Cryogenic Magnetic Detector





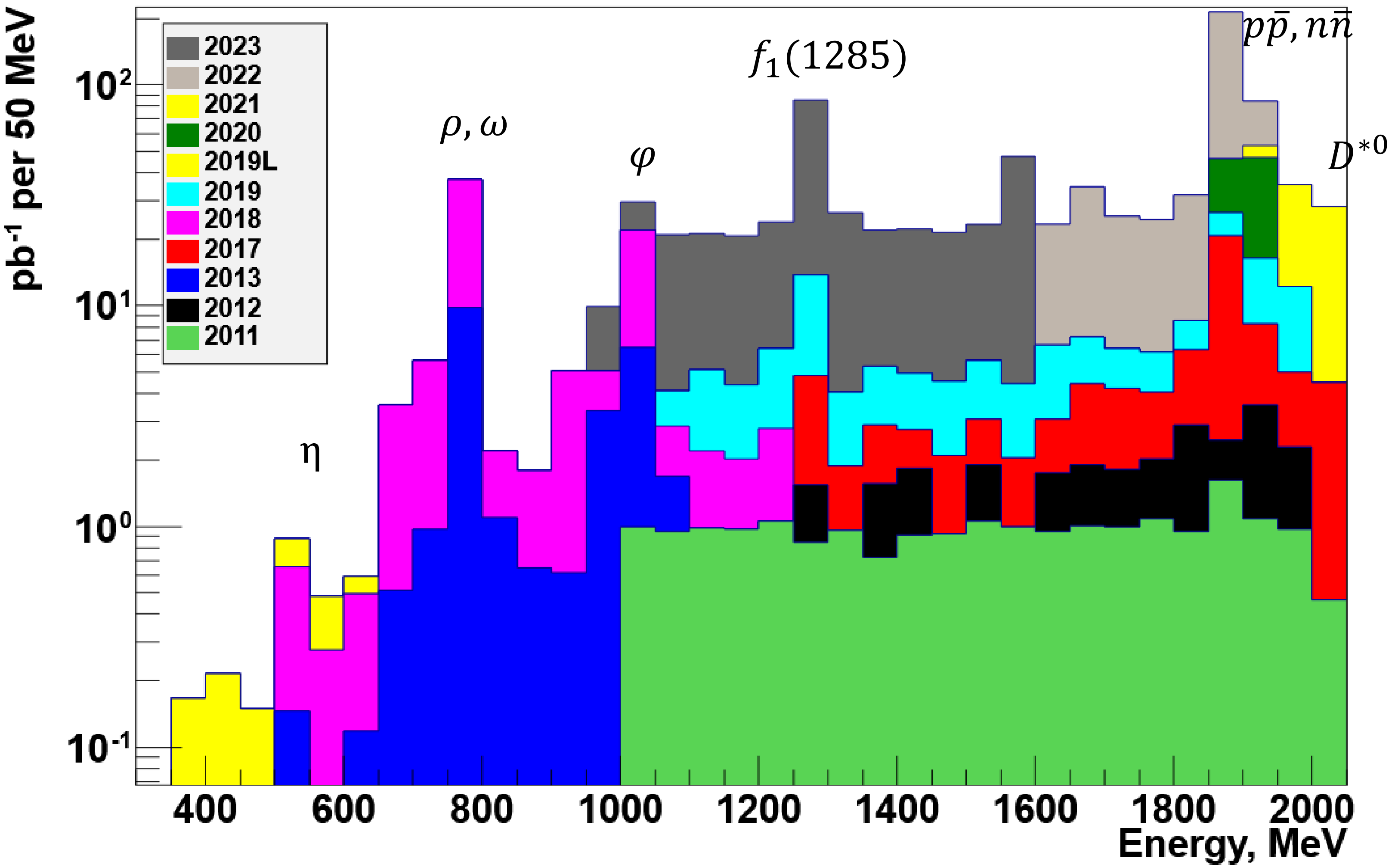
- Magnetic field 1.0-1.3 T
- Drift chamber
  - ➢ $\sigma_{R\varphi} \sim 100\ \mu, \sigma_z \sim 2-3\ \text{mm}$
- EM calorimeter (LXE, CsI, BGO), 13.5 X_0
  - ➢ $\sigma_E/E \sim 3\% - 10\%$
  - ➢ $\sigma_\Theta \sim 5$ mrad
- TOF
- Muon counters

Collected data



The $e^+e^- \to \pi^+\pi^-$ result is based on 3 data taking seasons: 2013, 2018, 2020

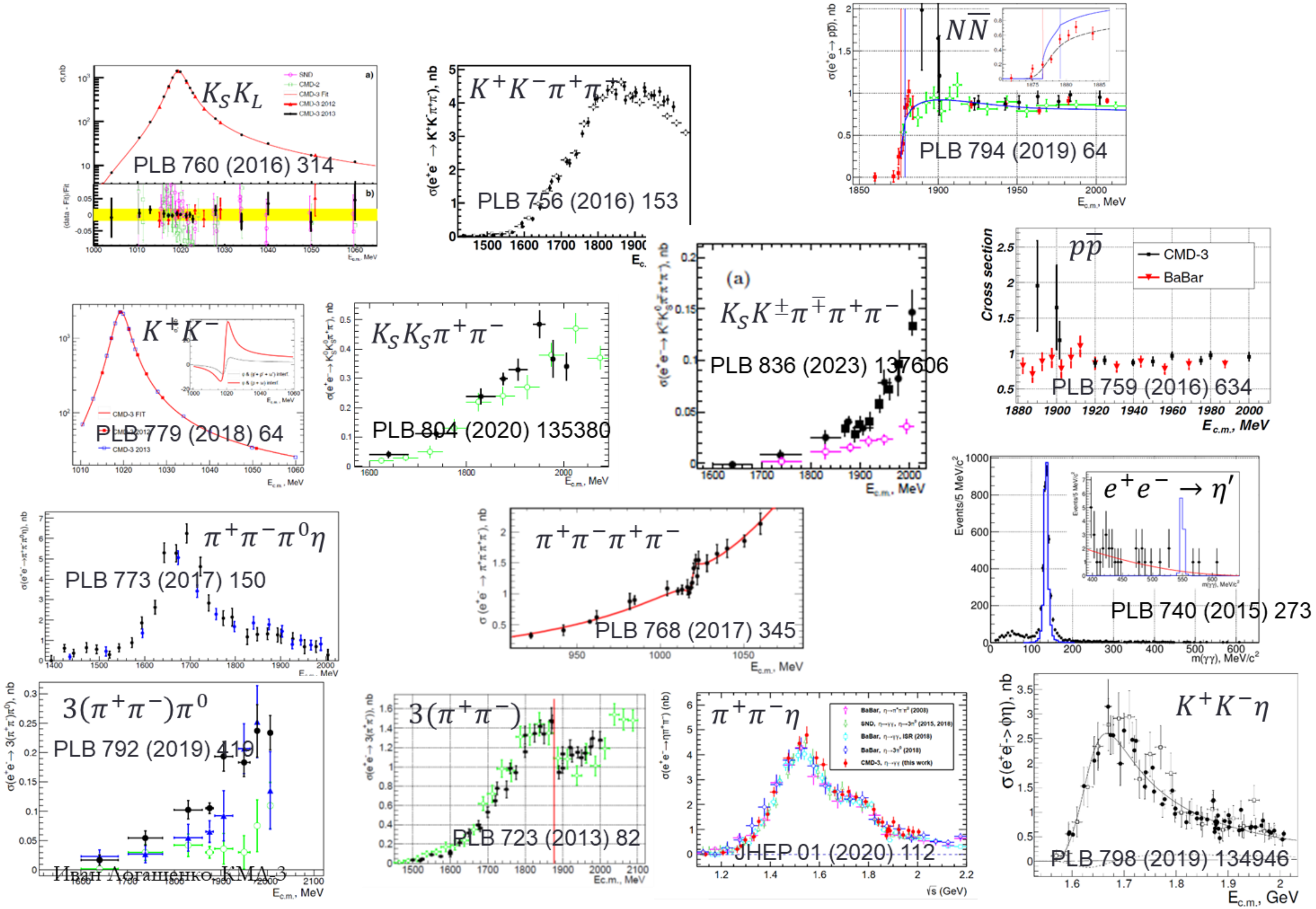
Collected data



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

CMD-3 published results



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

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)

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[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.

Направлено в PRL

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*
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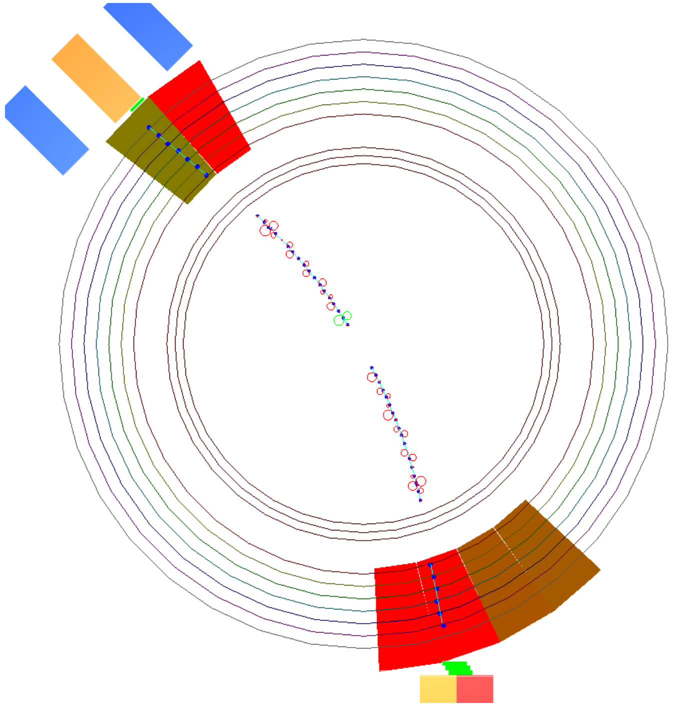
[d] *University of Victoria, Victoria, BC, Canada V8W 3P6*
[e] *Instituto Nazionale di Fisica Nucleare, Sezione di Lecce, Lecce, Italy*

Направлено в PRD

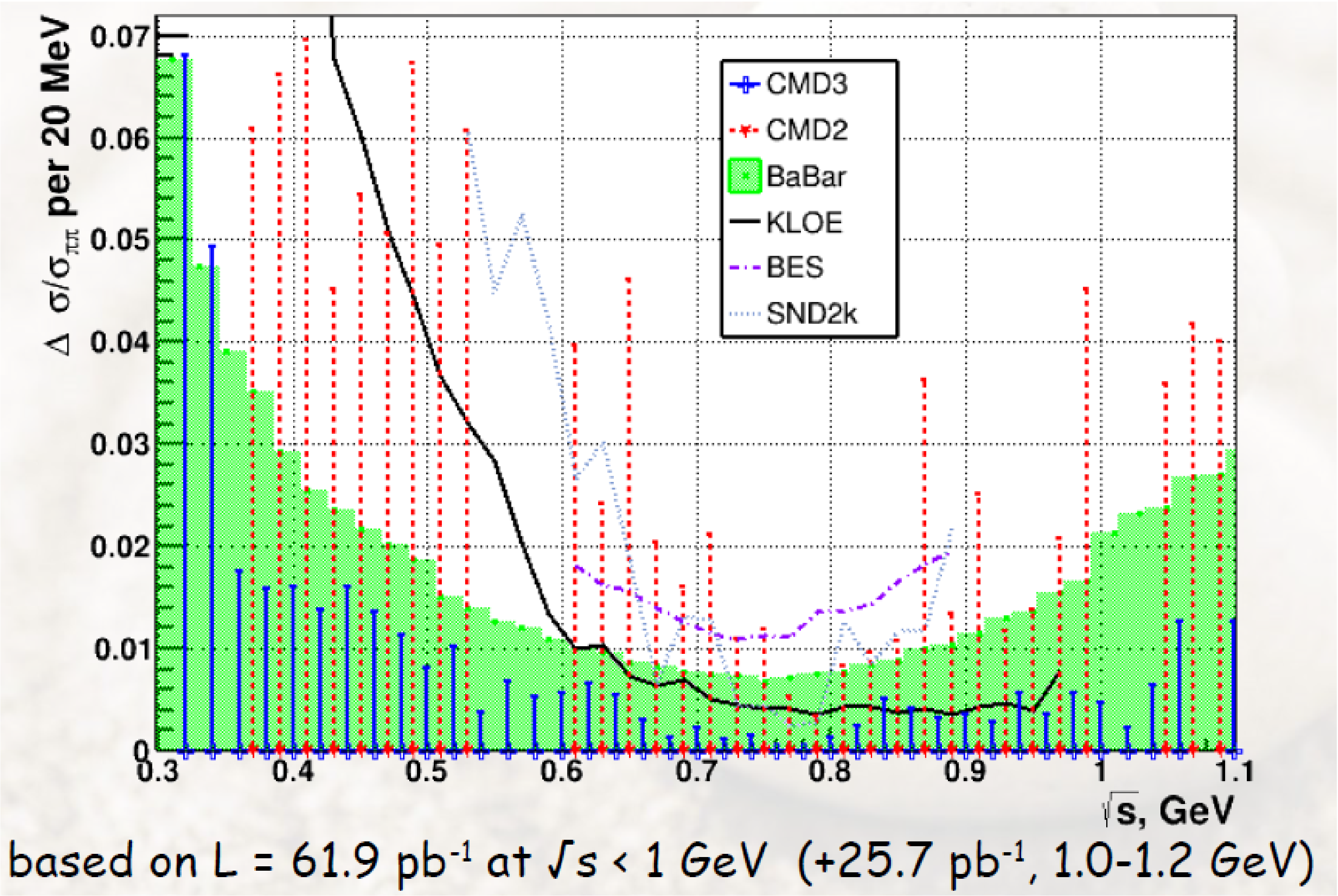
Features of CMD-3 measurement

- World-largest statistics
  - 34 000 000 $e^+e^- \to \pi^+\pi^-$
  - 3 700 000 $e^+e^- \to \mu^+\mu^-$
  - 44 000 000 $e^+e^- \to e^+e^-$
- Many built-in cross checks
  - 3 methods for final states indentification
  - 2 methods for angle measurement
  - Measurement of $\sigma(e^+e^- \to \mu^+\mu^-)$
  - Measurement of charge asymmetry
- Very detailed study of potential systematics



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

Statistical precision of CMD-3 data



CMD-3 $e^+e^- \to \pi^+\pi^-$ analysis

Select events with 2 back-to-back tracks in the detector at large angle:

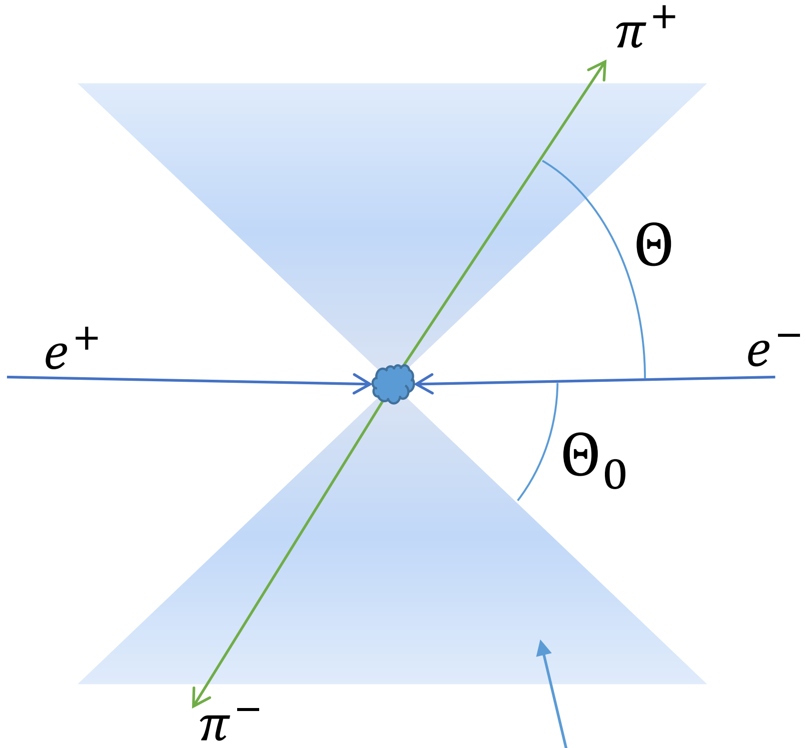
$e^+e^- \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-$
and cosmic background

Key pieces of analysis to reach high precision:

- $e/\mu/\pi$ separation
- radiative corrections
- fiducial volume
- detection efficiency corrections

$$\sigma(\pi^+\pi^-) = \frac{\pi\alpha^2}{3s}\beta_\pi^3 \cdot |F_\pi|^2$$

$e^+e^- \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-$; cosmic bg



fiducial volume
$\Theta_0 \le \Theta_{avr} \le (\pi - \Theta_0)$
$\Theta_0 = 1.0 \dots 1.4$

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

measured   Born cross-section   Detection efficiencies
Radiative corrections

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

Separation (counting) of $e^+e^-, \mu^+\mu^-, \pi^+\pi^-$ events is based on

a) **momenta** of two particles

b) or **energy deposition** in LXe calorimeter

$$-\ln L = -\sum_{bins} n_i \ln\left[\sum_{a=ee,\mu\mu,\pi\pi,bg} N_a f_a(X^+, X^-)\right] + \sum_a N_a$$

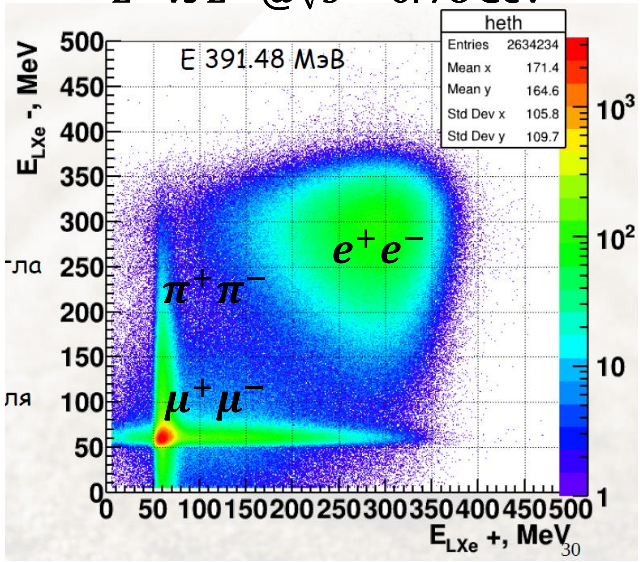
$$X = P \text{ or } E$$

$\pm$ sign reflects energy deposition and momentum of particle with corresponding charge

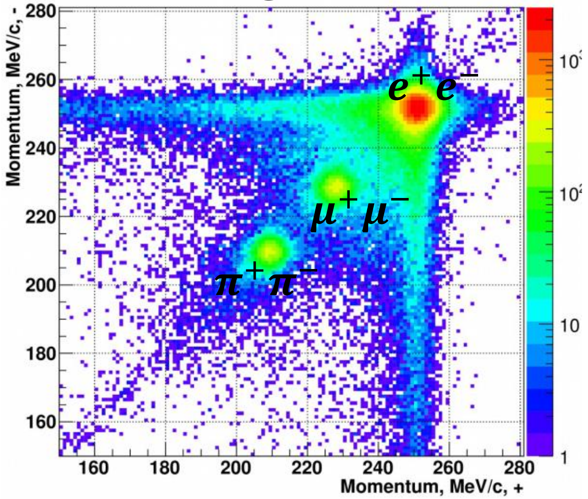
Independent check by **angular distribution**

For some fits ratio $\boldsymbol{N_{\mu\mu}/N_{ee}}$ **is fixed** to QED prediction, adjusted for RC and detector effects

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



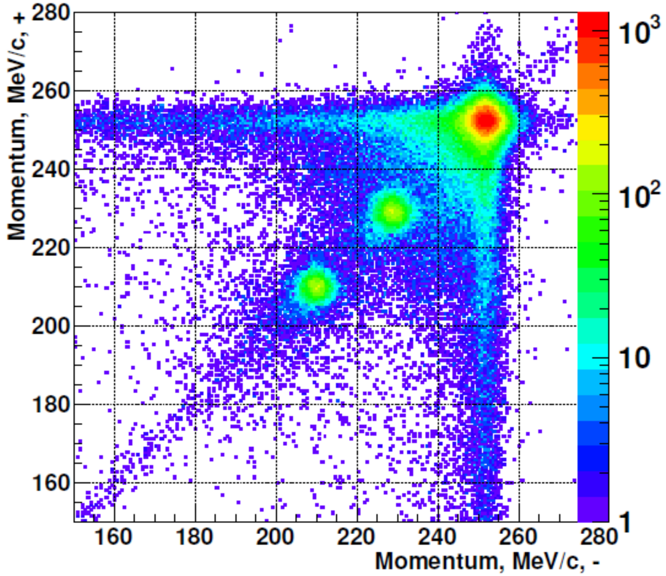
$\boldsymbol{P^-}$ vs $\boldsymbol{P^+}$ $@\sqrt{s} = \mathbf{0.5}$ **GeV**



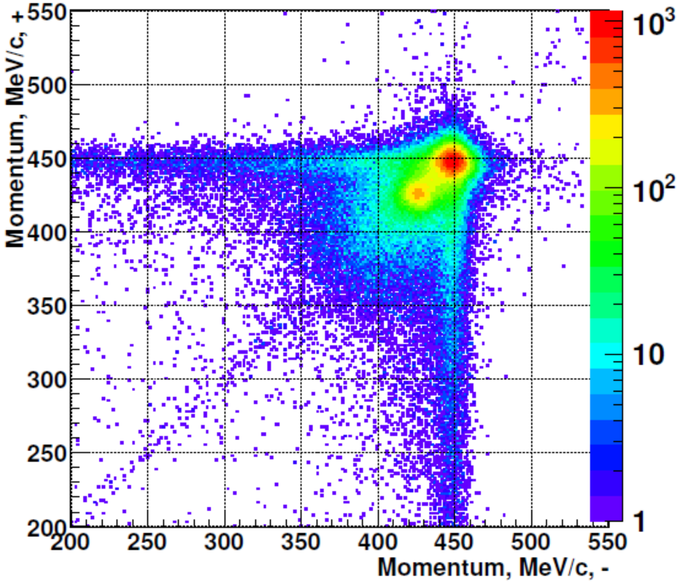
Unique feature of CMD-3: three independent methods to measure $N_{\pi\pi}/N_{ee}$!

E and P distributions

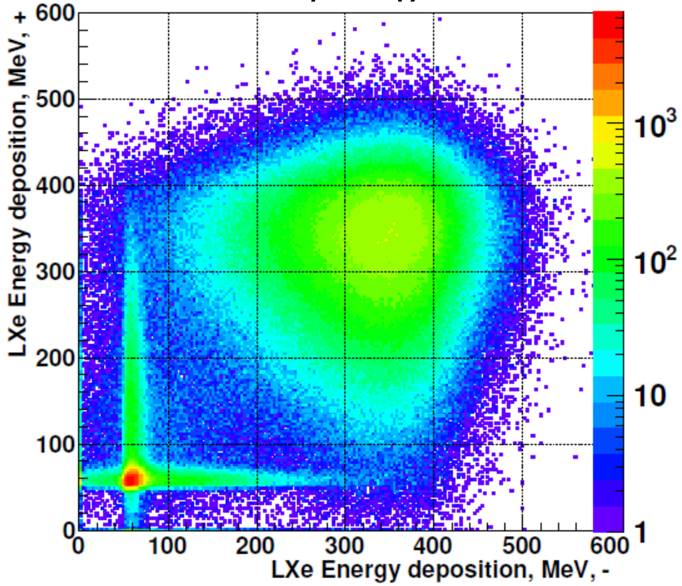
p^+ vs p^-, 2*250 MeV



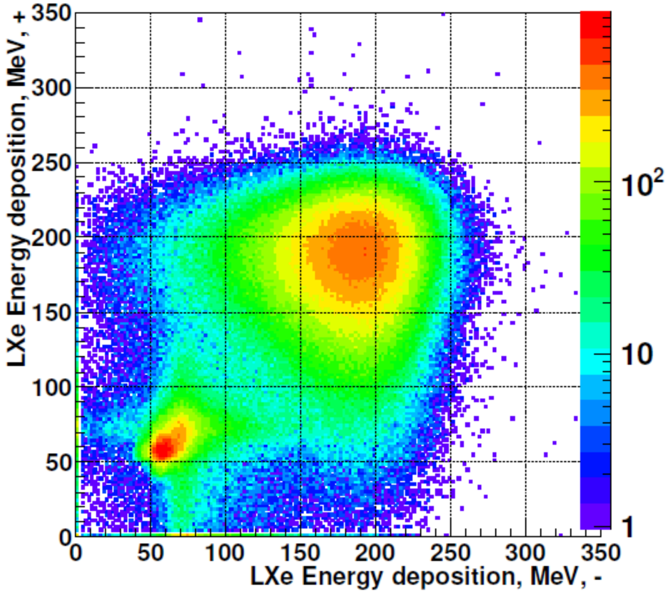
p^+ vs p^-, 2*450 MeV



E^+ vs E^-, 2*478 MeV



E^+ vs E^-, 2*274 MeV



Where to get p.d.f.s $f_X(p^+,p^-)$ and $f_X(E^+,E^-)$?

Separation by momentum

PDFs are based on MC

- "Ideal" p.d.f.s are generated using $e^+e^- \to X^+X^-(\gamma)$ MC generator
- "Ideal" p.d.f.s are smeared with detector resolution function to get $f_X(p^+,p^-)$

Separation by energy deposition

PDFs are mostly empirical

- $f_X(E^+,E^-)$ are partly constructed using the data:
  - tagged electrons and positrons
  - cosmic muons

Separation by angle distribution

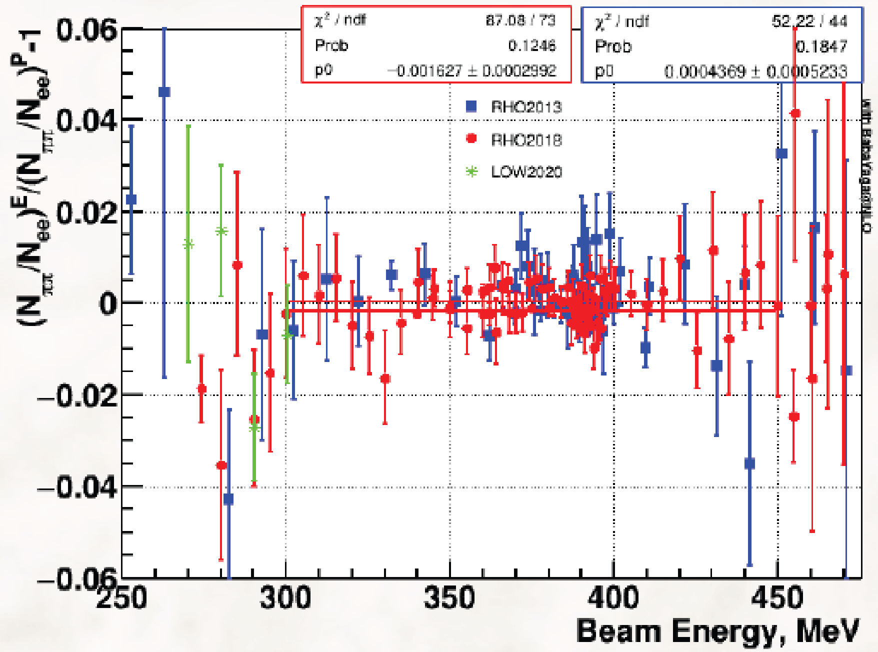
1D fit of sum of $f_X(\Theta_{avr})$

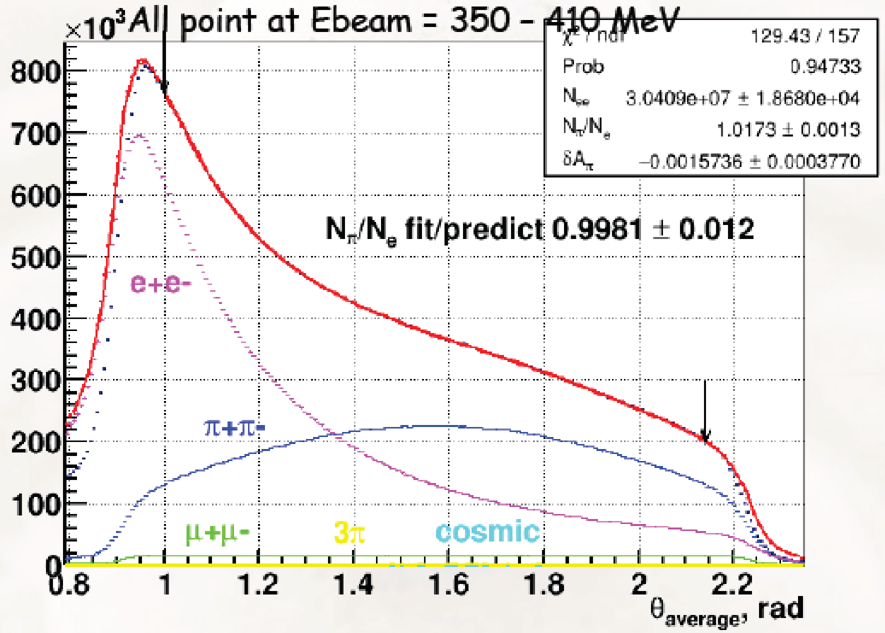
$f_X(\Theta_{avr})$ are taken from MC generator + efficiency corrections

Comparison

Three methods agree to 0.2%!

E vs P separations





Fit by θ distribution

For sum of $\sqrt{s}$ = 0.7 - 0.82 GeV points

<u>by momenta</u> in DCH: $N_{\pi\pi}/N_{ee}$ = 1.0193 +- 0.00030

<u>by energies</u> in LXe $\Delta N_{\pi\pi}/N_{ee}$ = -0.09 +- 0.024%

<u>from theta</u> with free δA: = -0.20 +- 0.12%

with fixed δA=0: = +0.21 +- 0.07%

Common stat from 0.026%

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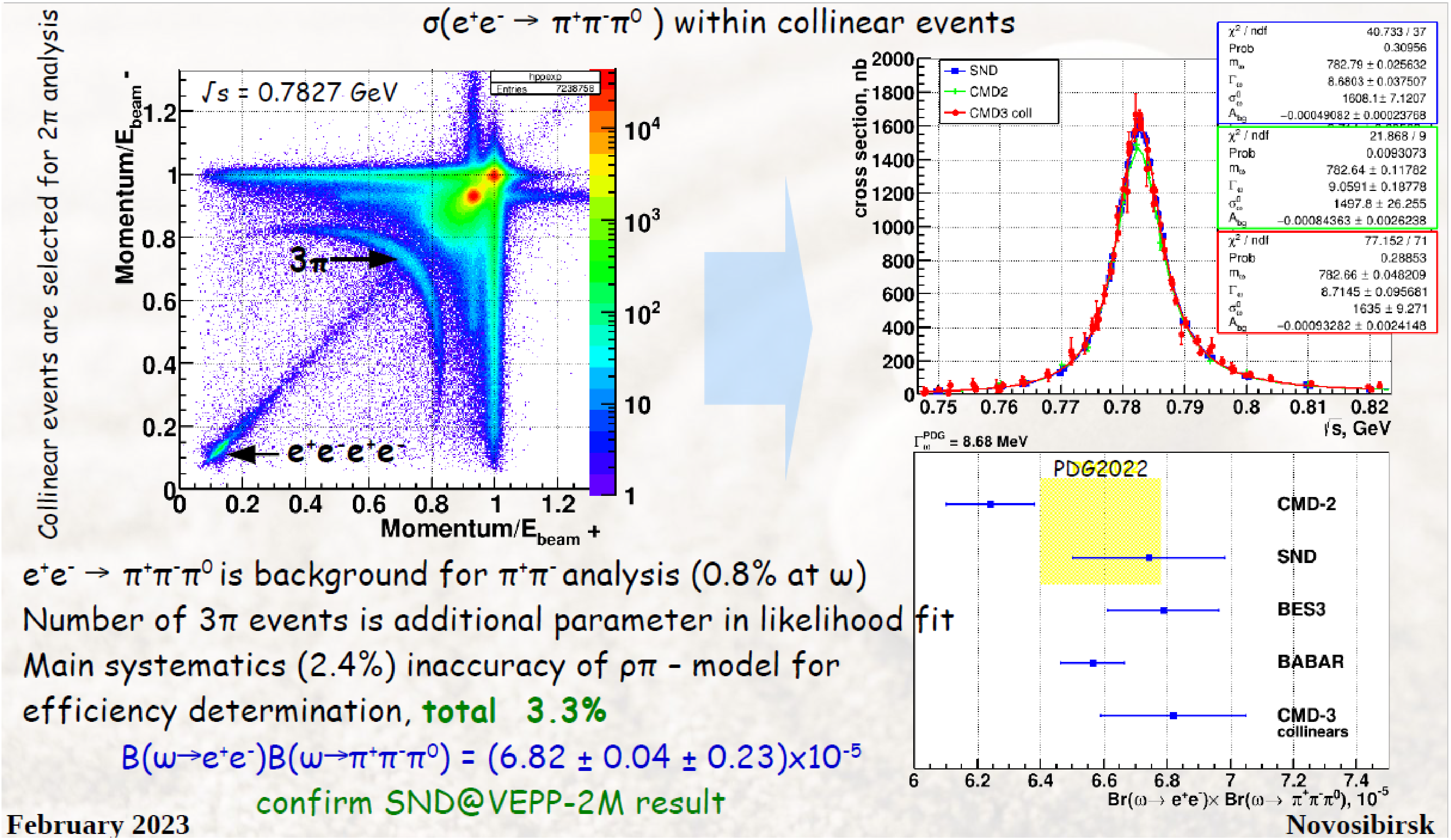
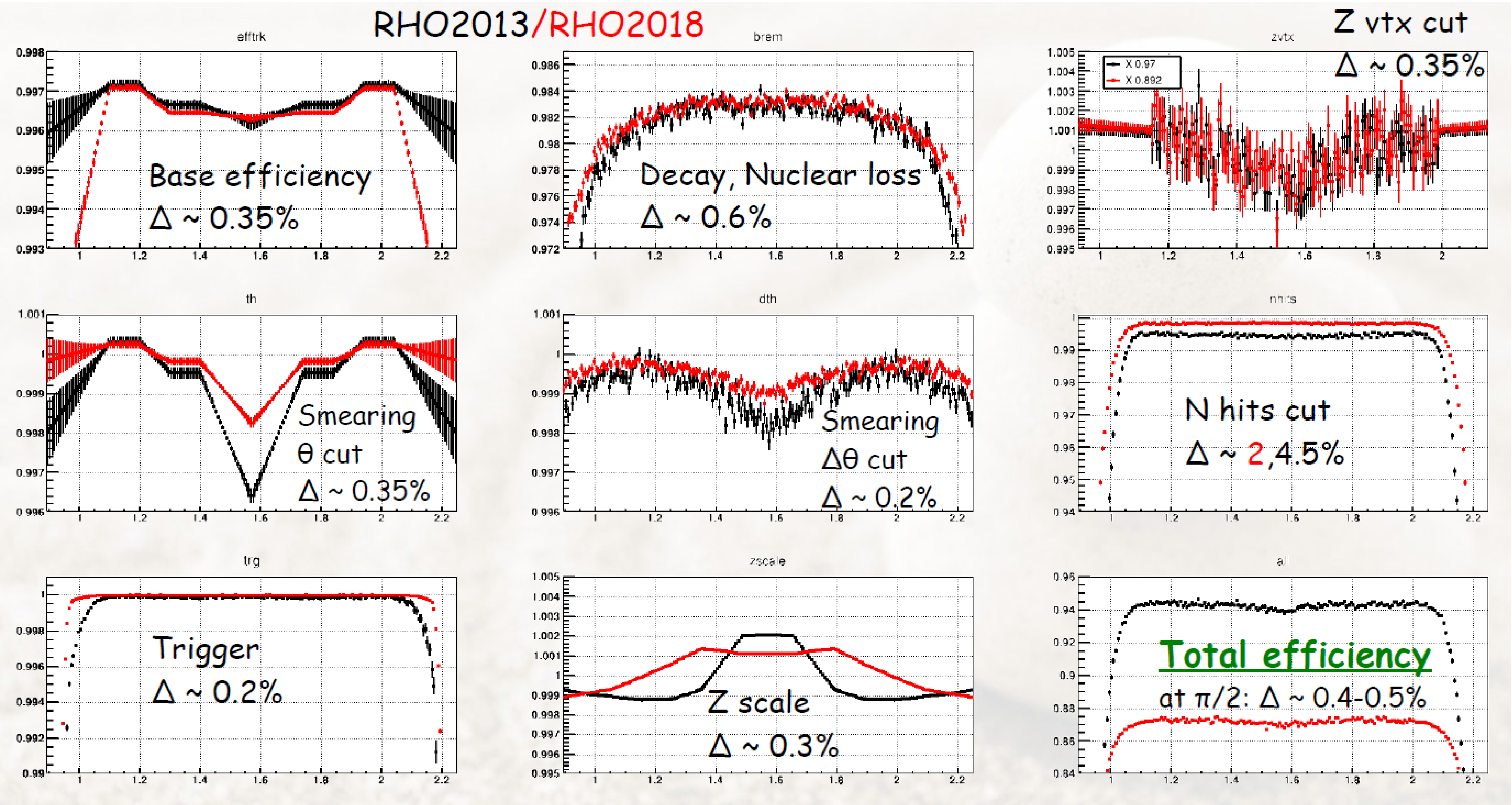
Background



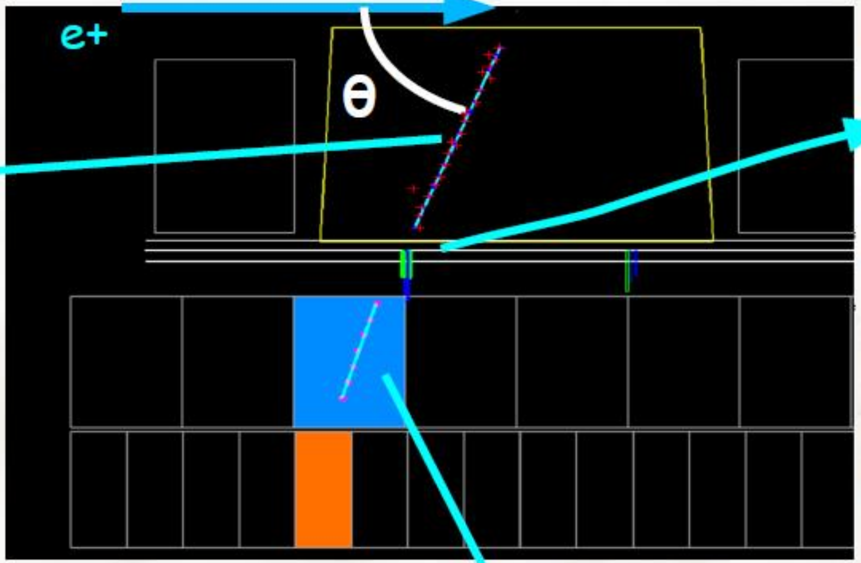
σ(e⁺e⁻ → π⁺π⁻π⁰) within collinear events
Collinear events are selected for 2π analysis
√s = 0.7827 GeV
3π
e⁺e⁻e⁺e⁻
Momentum/E_beam -
Momentum/E_beam +
cross section, nb
SND
CMD2
CMD3 coll
√s, GeV
Γ_ω^PDG = 8.68 MeV
PDG2022
CMD-2
SND
BES3
BABAR
CMD-3 collinears
Br(ω→e⁺e⁻)× Br(ω→π⁺π⁻π⁰), 10⁻⁵
e⁺e⁻ → π⁺π⁻π⁰ is background for π⁺π⁻ analysis (0.8% at ω)
Number of 3π events is additional parameter in likelihood fit
Main systematics (2.4%) inaccuracy of ρπ - model for
efficiency determination, total 3.3%
B(ω→e⁺e⁻)B(ω→π⁺π⁻π⁰) = (6.82 ± 0.04 ± 0.23)x10⁻⁵
confirm SND@VEPP-2M result
February 2023
Novosibirsk

Efficiency corrections



Measurement of polar angle (Z)

Polar angle measured by
DC chamber
with help of charge division method
(Z resolution ~ 2mm),
Unstable, depends on calibration and thermal stability of electronic
Calibration done relative to LXe (ZC)



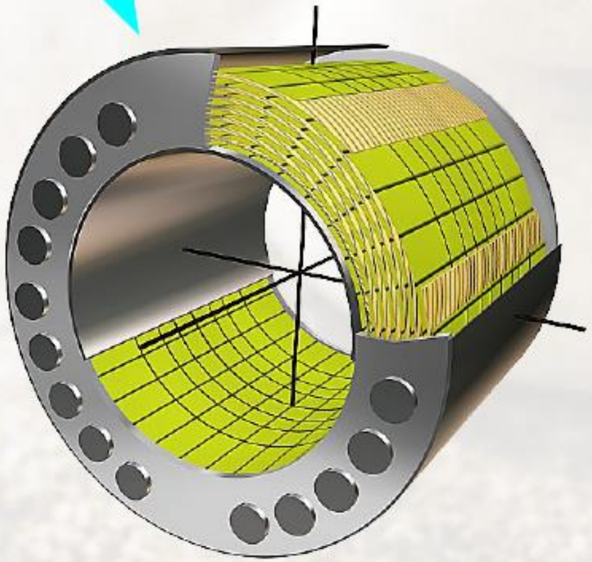
ZC chamber
(was in operation until mid 2017)
multiwire chamber
with 2 layers and with strip readout along Z coordinate

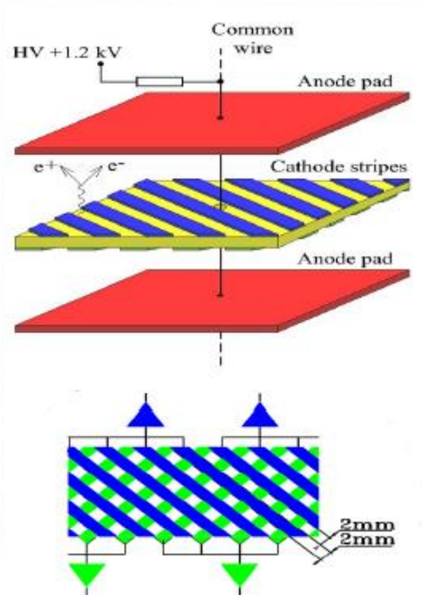
strip size: 6mm
Z coordinate resolution ~ 0.7 mm
(for θ_{track} ~ 1 rad)

LXe calorimeter
ionization collected in 7 layers with cathode strip readout,

combined strip size: 10-15 mm
Coordinate resolution ~ 2mm

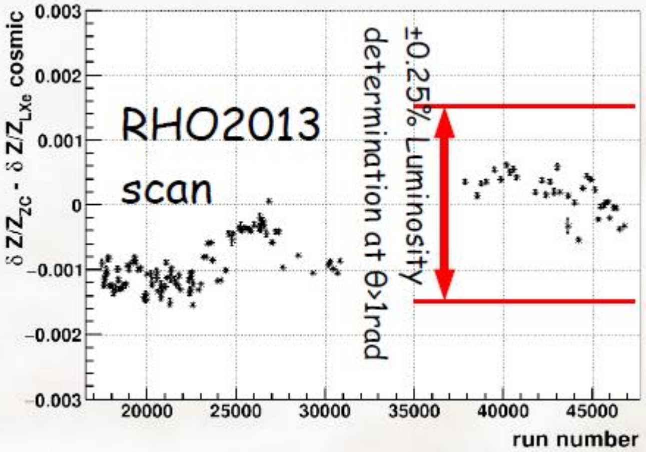
strip precision, coordinate biases ~ 100 μm
should give ~0.1% in Luminosity determination





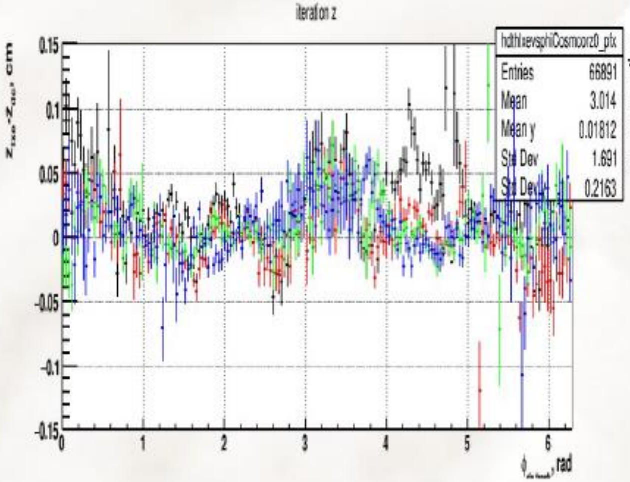
Cross-checks of polar angle (Z)

Monitoring of z-measurement between ZC vs LXe



Variation because of
DCh instability, different B field,
ZC, LXe noise level

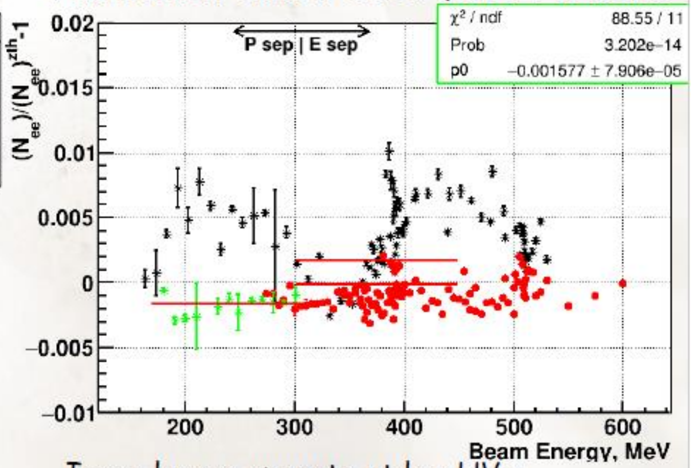
DC tracks vs LXe points



δz ~ 0.5 mm instability over regions at R=40 cm
(by φ, track direction, etc)

N.B. in average ‹δz› should be better

Inner DC radius effect:
Θ - angle with Z vertex constrain /unconstrained case for 2 tracks



Inner layers operate at low HV→
Low resolution, higher systematics
During RHO2013: 4 middle layers in DCH were switched off
→ higher weights of inner layers

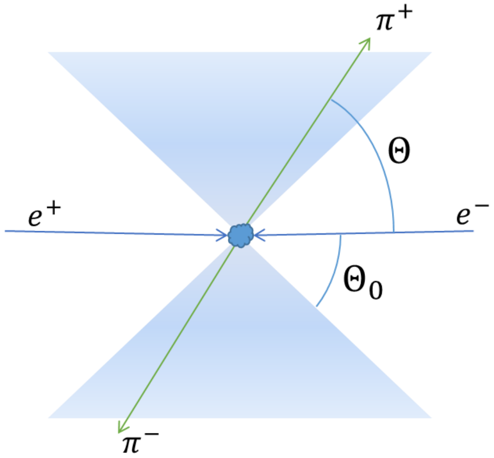
N.B. Θ – angle is defined with vertex constrain
→ inner radius biases should be suppressed

ZC/LXe comparison **0.25%** ⊕ LXe/ DC comparison **0.3%** ⊕ Inner DC radius effect: **0.7%(RHO2013)/0.3%(RHO2018)**

= 0.8% (RHO2013) / 0.5%(RHO2018)

February 2023 Novosibirsk

Measurement of polar angle

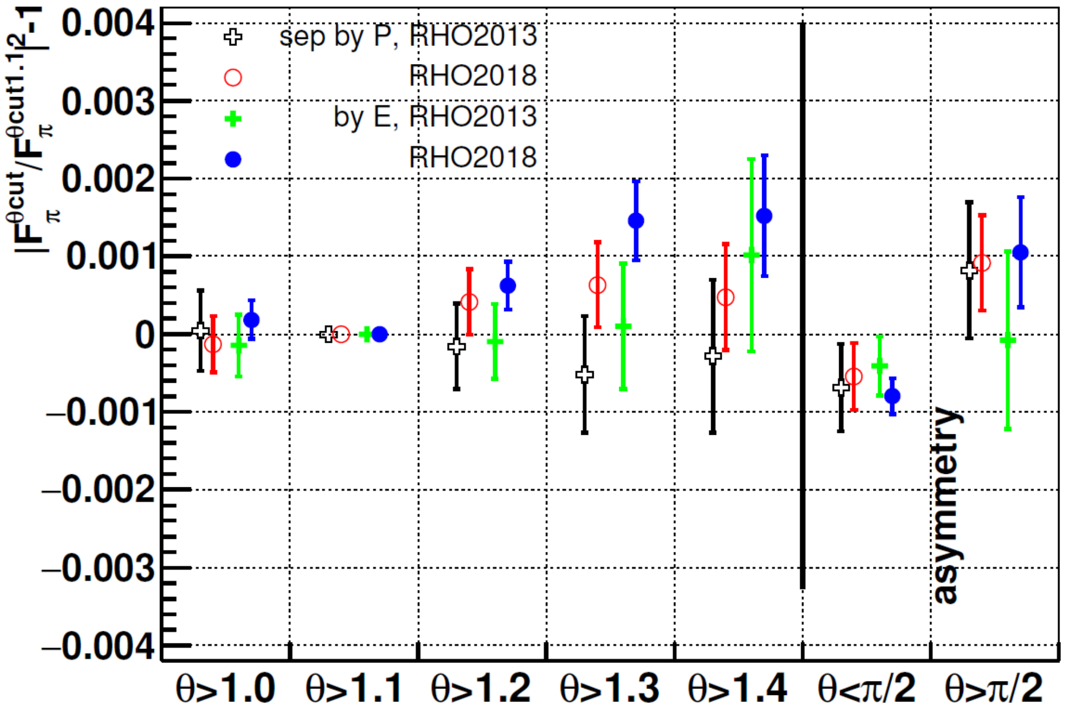


Θ angle is measured by drift chamber via charge division

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 (Θ_0 cut).

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



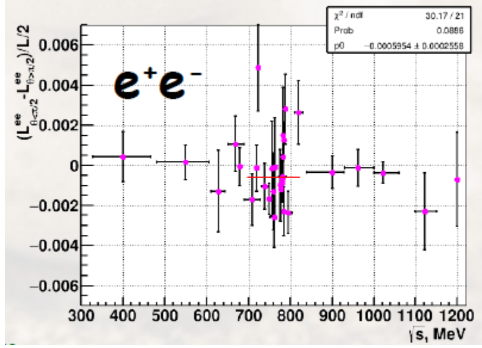
Dependence of result on Θ_0 cut

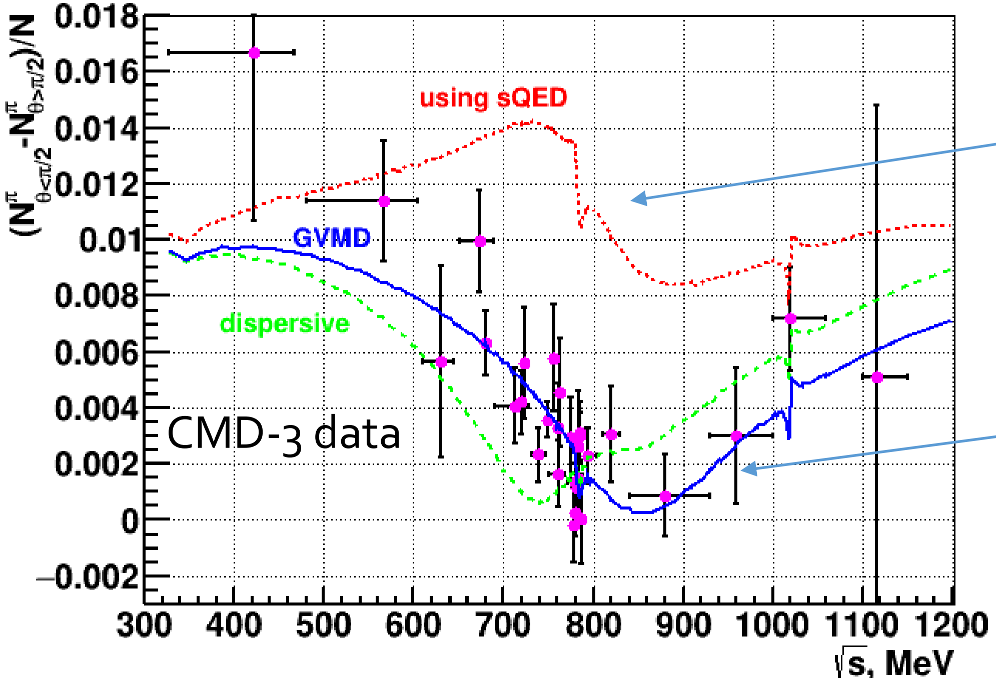
Factor 10 smaller compared to CMD-2, SND2k!

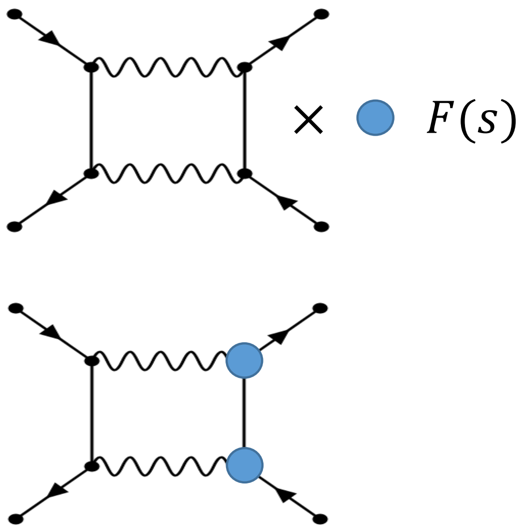
Charge asymmetry in $e^+e^- \to \pi^+\pi^-$

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.

From measured cross section to input to a_μ calculation

"Visible" cross section
$\sigma(e^+e^-(\gamma) \to X(\gamma))$

Here we correct for all detector effects

Adjust for radiative corrections (ISR, FSR)
$\sigma(e^+e^- \to X)$

This one is used to get parameters of the resonances (mass, width,…)

Adjust for vacuum polarization and return back FSR
$\sigma^0(e^+e^- \to X(\gamma))$

This one is used in the a_μ integral

MC generators for RC calculation

Two high precision MC generators is used
MCGPJ(0.2%, e+e-,μ+μ-,π+π-) vs BabaYaga@NLO (0.1%, e+e-,μ+μ-)

$e^+e^- \to e^+e^-(\gamma)$: great consistency <0.1% in the total cross section
$e^+e^- \to \mu^+\mu^-(\gamma)$: It is missed mass term in FSR term in most of generators (effect 0.4% at $\sqrt{s}$=0.32 GeV)
$e^+e^- \to \pi^+\pi^-(\gamma)$: only MCGPJ available with 0.2% precision (for energy scan experiments)

Achieved precision in current analysis is sensitive for differential cross sections predictions
e/π separation by momentum requires $d\sigma/dP^+dP^-$ spectras as initial input
Asymmetry study requires $d\sigma/d\theta$ spectras

History: problem with “old” MCGPJ

Measurement of $e^+e^- \to \pi^+\pi^-$ requires high precision calculation of radiative corrections.

Several MC generators available with 0.1-0.5% precision.

CMD-3: MCGPJ generator

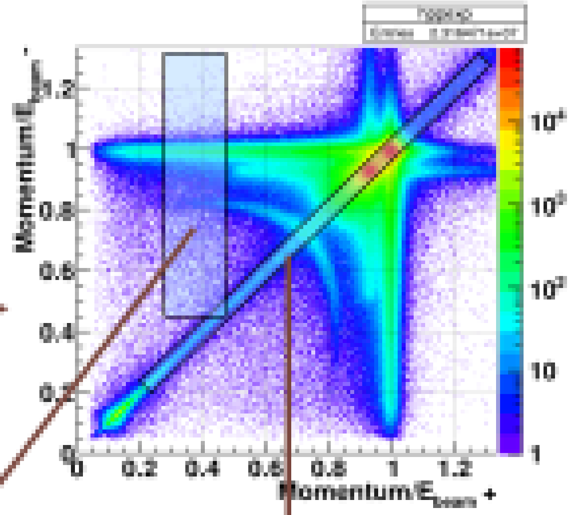
With high statistics we observed discrepancies in tails of e^+e^-experimental spectrum with theoretical prediction.

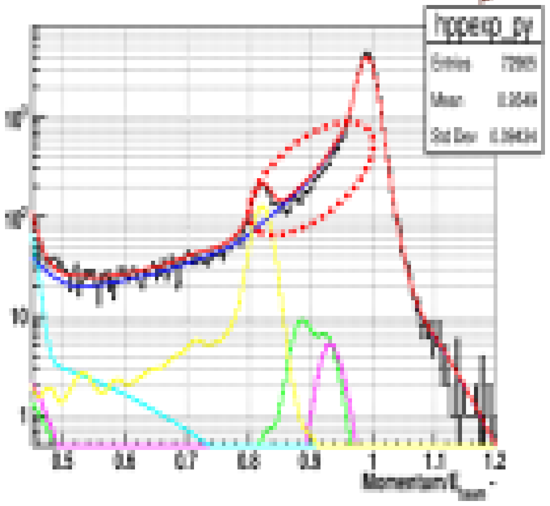
The corresponding changes in p.d.f.s $f_{ee}(p^+,p^-)$ produce percent-level systematic shift of $N(\pi^+\pi^-)$ for event separation by P

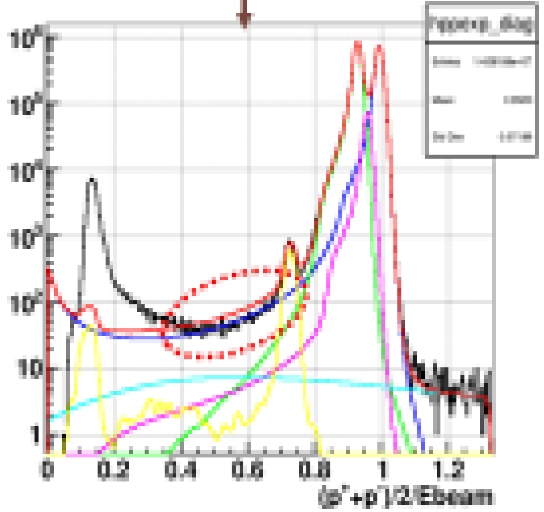
- For the integral (radiative correction) the effect is negligible

$$\frac{p^-}{E_b} \text{ vs } \frac{p^+}{E_b}$$

All 2013 data
$2 \cdot 10^7$ events







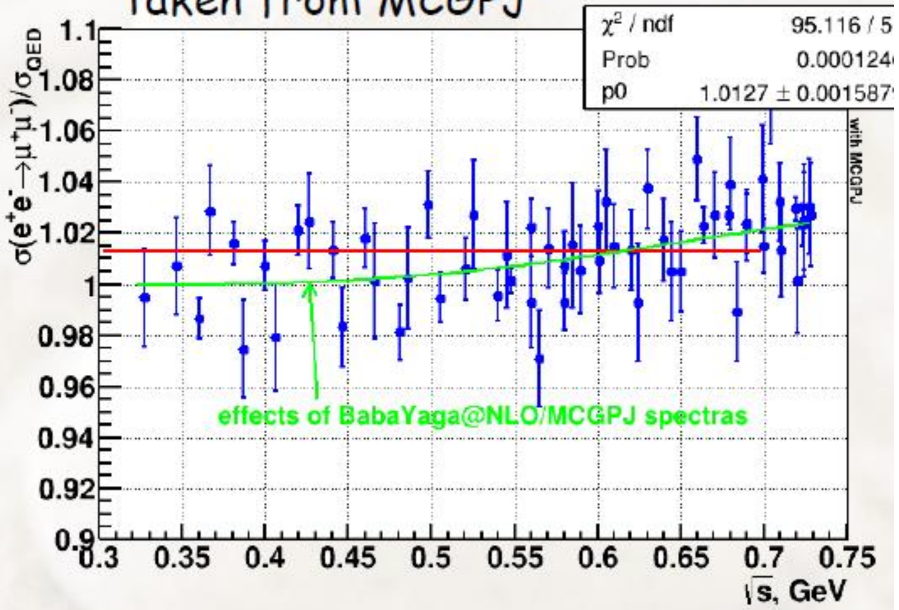
MCGPJ was modified to improve the agreement: angular distribution for γ jets

MC generators for RC calculation

BaBaYaga@NLO shows better agreement with the data:

1) Momentum spectras better describe data:
gives consistent results in $N_{\mu\mu}$/QED
(effect on $|F_\pi|^2$ ~0.2% at $\sqrt{s}$=0.78 GeV, and rising to 1.5% at 0.9 GeV when using momentum-based separation)

effect on $N_{\mu\mu}$/QED
with input $d\sigma/dP^+dP^-$ spectra
taken from MCGPJ



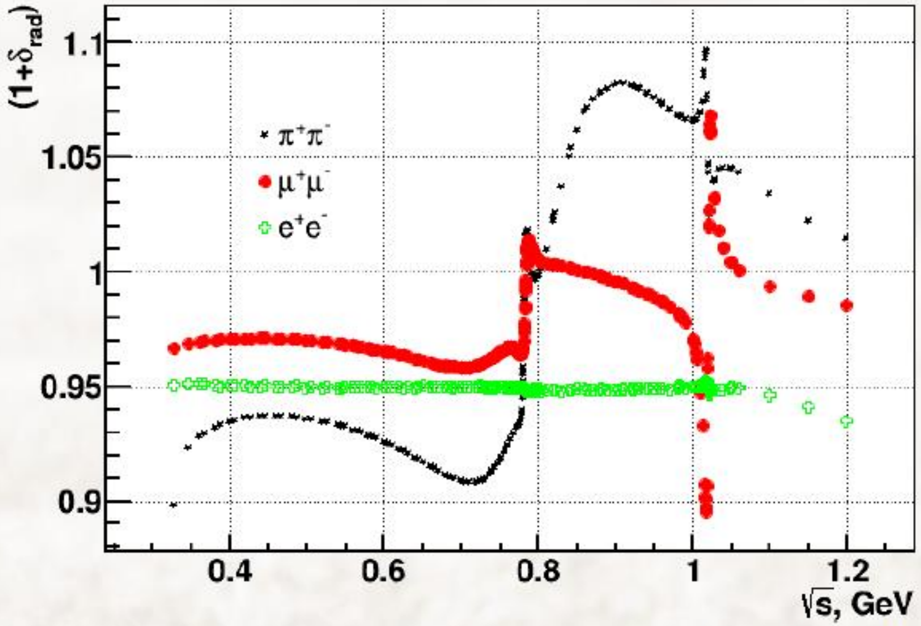
2) Experimental asymmetry in e+e- data
relative to BabaYaga@NLO:
δA = -0.060 ± 0.026 %
relative to MCGPJ
δA = -0.140 ± 0.026 %
BabaYaga@NLO consistent with NNLO MCMule
δA = +0.006 ± 0.003 % at $\sqrt{s}$=0.76 GeV

<u>We adopted generators usage in this way:</u>
e+e- : BabaYaga@NLO
μ+μ- : BabaYaga@NLO (differential cross section)
MCGPJ (integral)
π+π- : MCGPJ

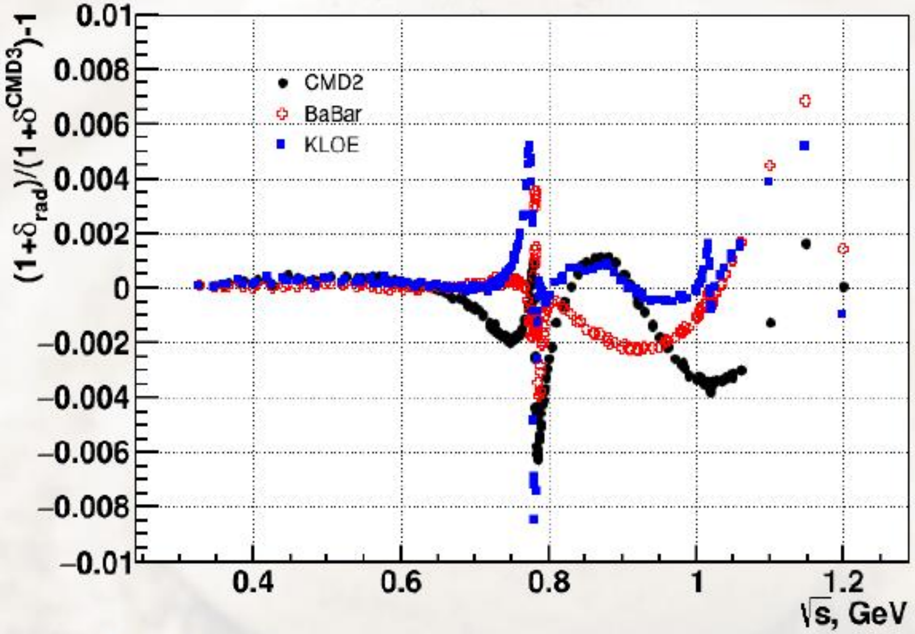
MCGPJ/BabaYaga@NLO difference gives systematics on $|F|^2_\pi$ when using momentum-based separation
Better NNLO generators are needed for higher precision

MC generators for RC calculation

Radiative corrections within
$1. < (\pi + \theta^{+} - \theta^{-})/2 < \pi - 1.\mathrm{rad}, \ |\Delta\phi| < 0.15, \ |\Delta\theta| < 0.25$



Effect on 2π radiative correction from different $|F|^2_\pi$ parametrizations (over different datasets)



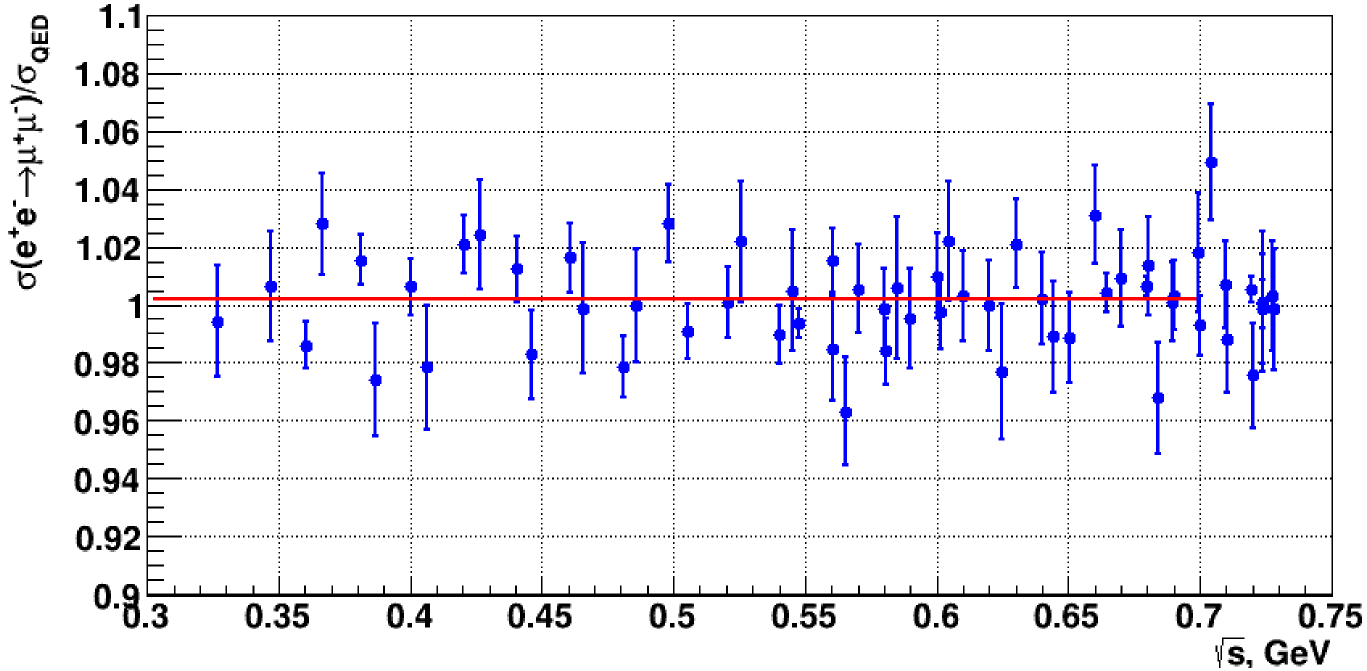
Systematic uncertainty
0.2% ($\pi+\pi-$) $\oplus$ 0.2% ($F\pi$, s > 0.74 GeV) $\oplus$ 0.1% ($e+e-$)

N.B. KLOE/BABAR difference in derivative 4%/0.4GeV,
own CMD-3 is very possible as 1%/0.1 GeV → same 0.2% estimation (from $F\pi$ model)

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

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



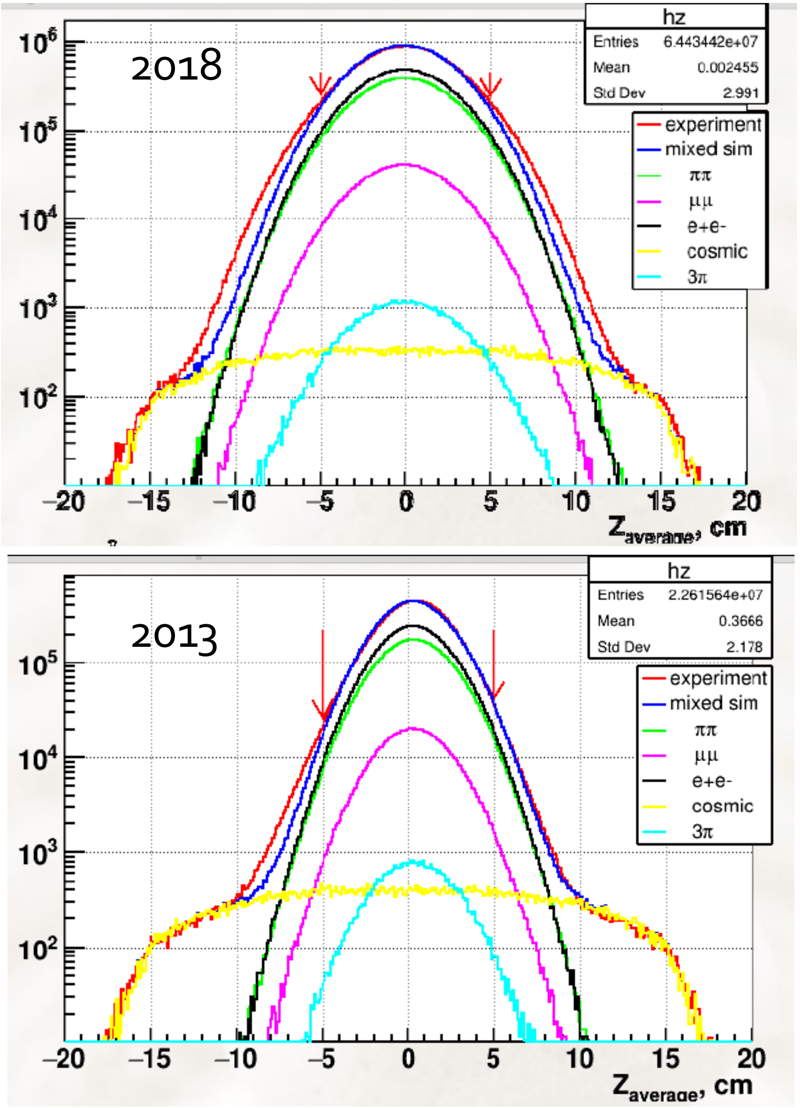
+0.17 ± 0.16 %

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

Difference between 2013 and 2018 data

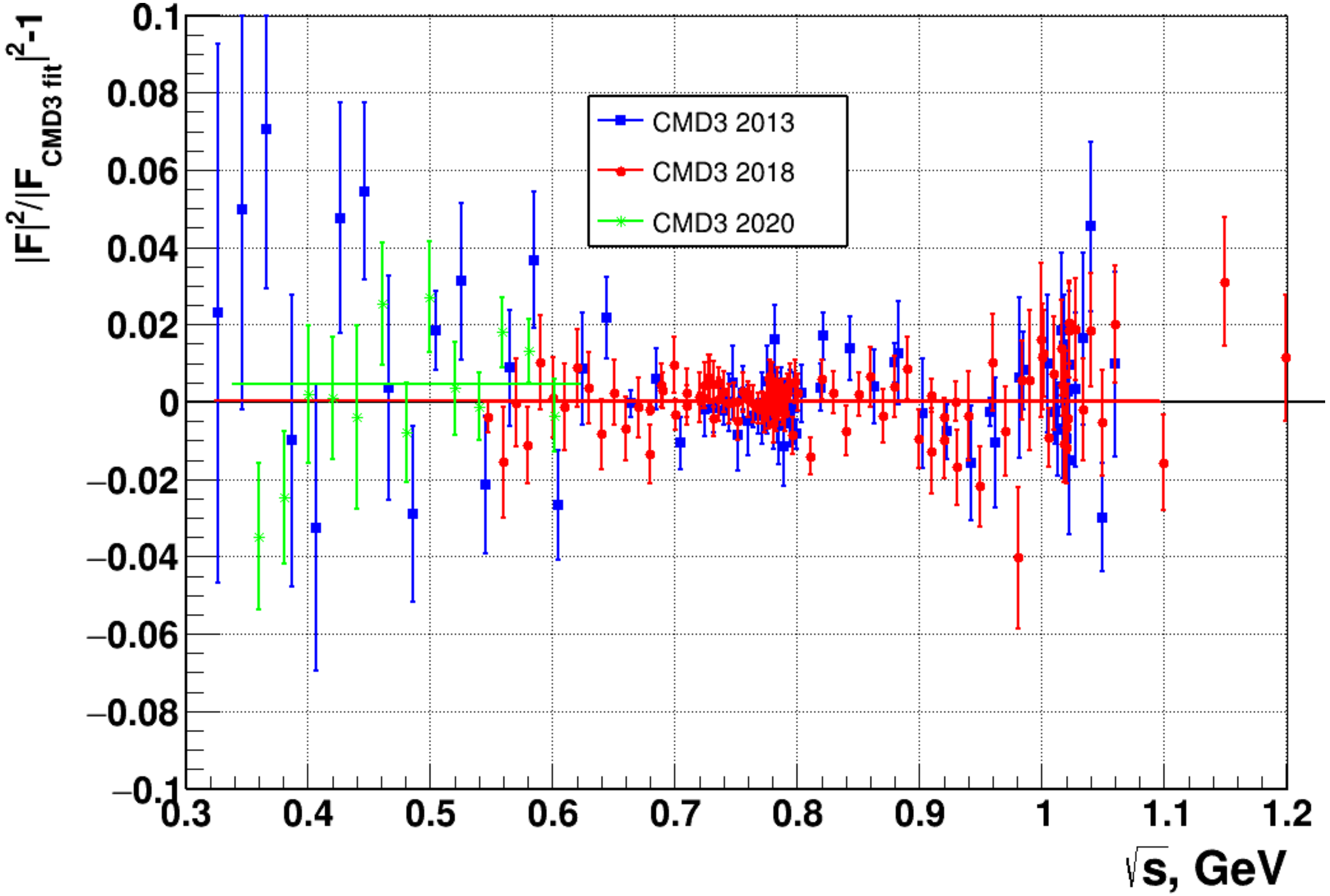
2013 and 2018 data were taken in the same energy range, but with significantly different detector conditions:

- luminosity integral in 2018 is factor 2-5 larger
- data rate (luminosity) in 2018 was factor 2-5 larger
- drift chamber in 2013 operated without 4 middle layers (out of 19)
- Z-chamber (important for precision determination of fiducial volume) broke before 2018 run
- Z beam size in 2018 was twice wider
- calorimeter electronics was significantly updated before 2018



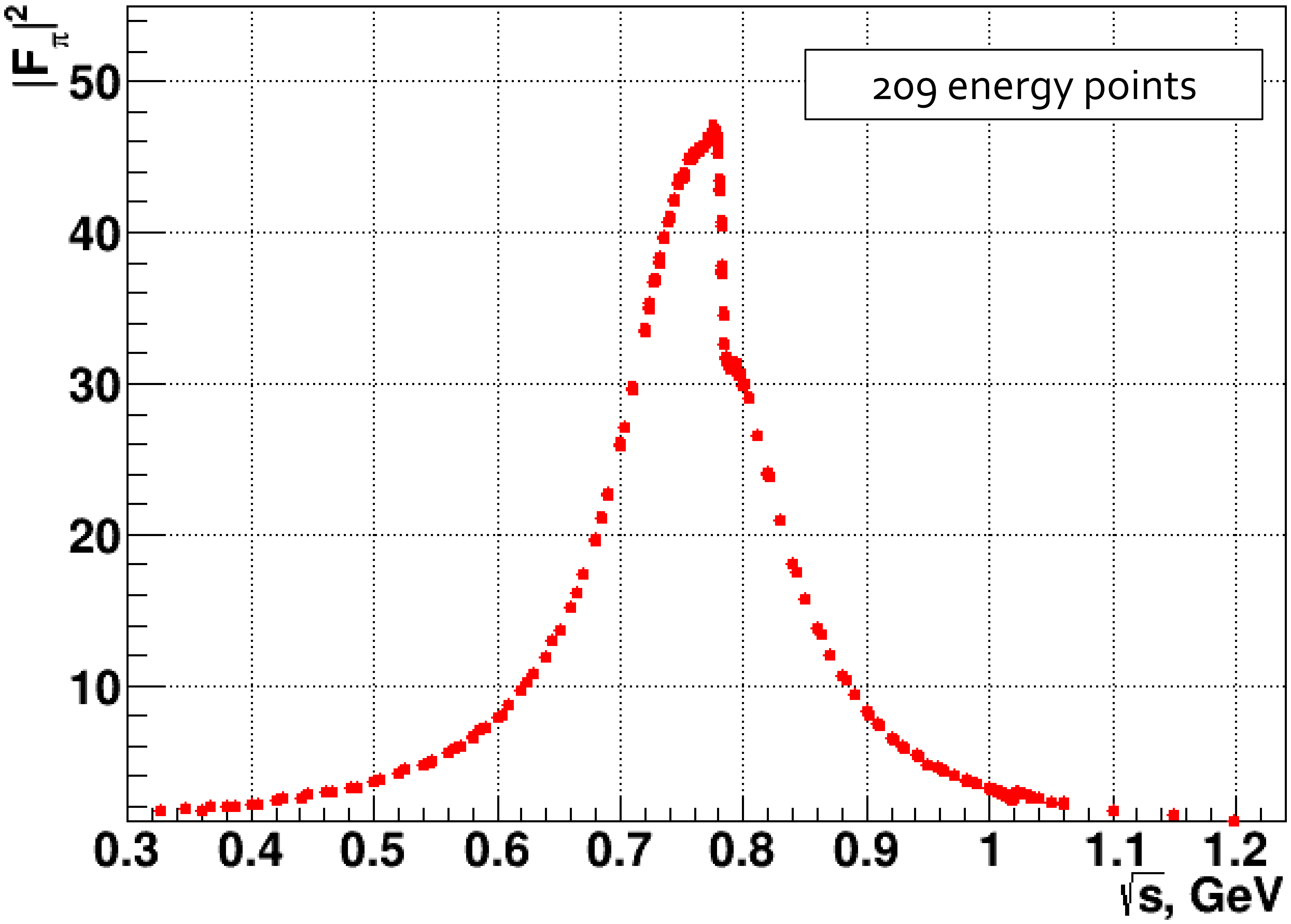
Z beam size

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.

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



Systematic errors

✗ Radiative corrections	0.2% (2π) ⊕ 0.2% (Fπ) ⊕ 0.1% (e+e-)
✗ e/μ/π separation	0.5 (low) - 0.2 (ρ) - 0.6 (φ) %
✗ Fiducial volume	0.5% / 0.8% (RHO2013)
✗ Correlated inefficiency	0.1 (ρ) - 0.15%(>1 ГэВ)
✗ 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)
✗ 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...

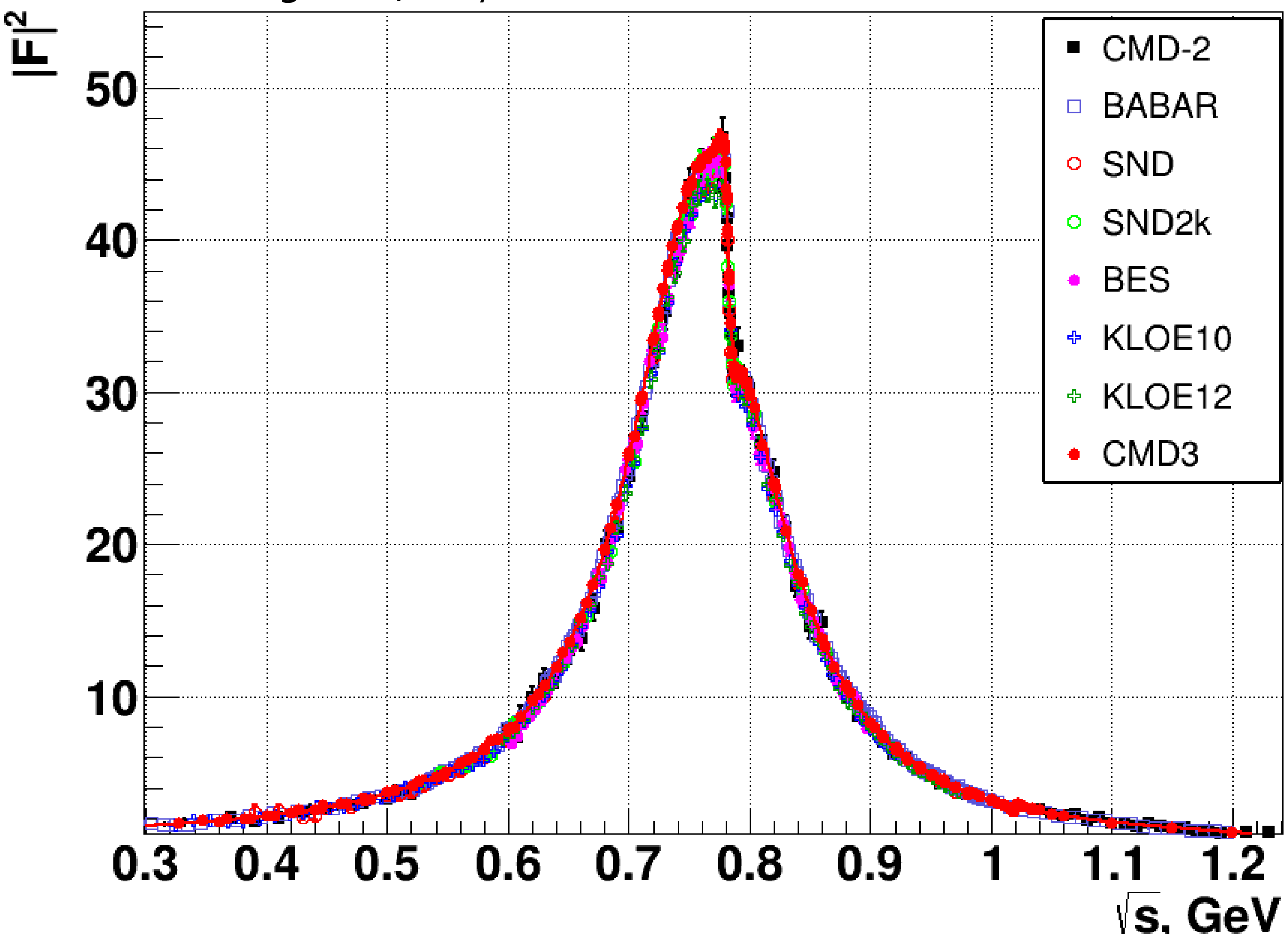
0.8% (low) - 0.7% (ρ) - 1.6% (φ)

1.1% (low) - 0.9% (ρ) - 2.0% (φ) (RHO2013)

Conservative estimate

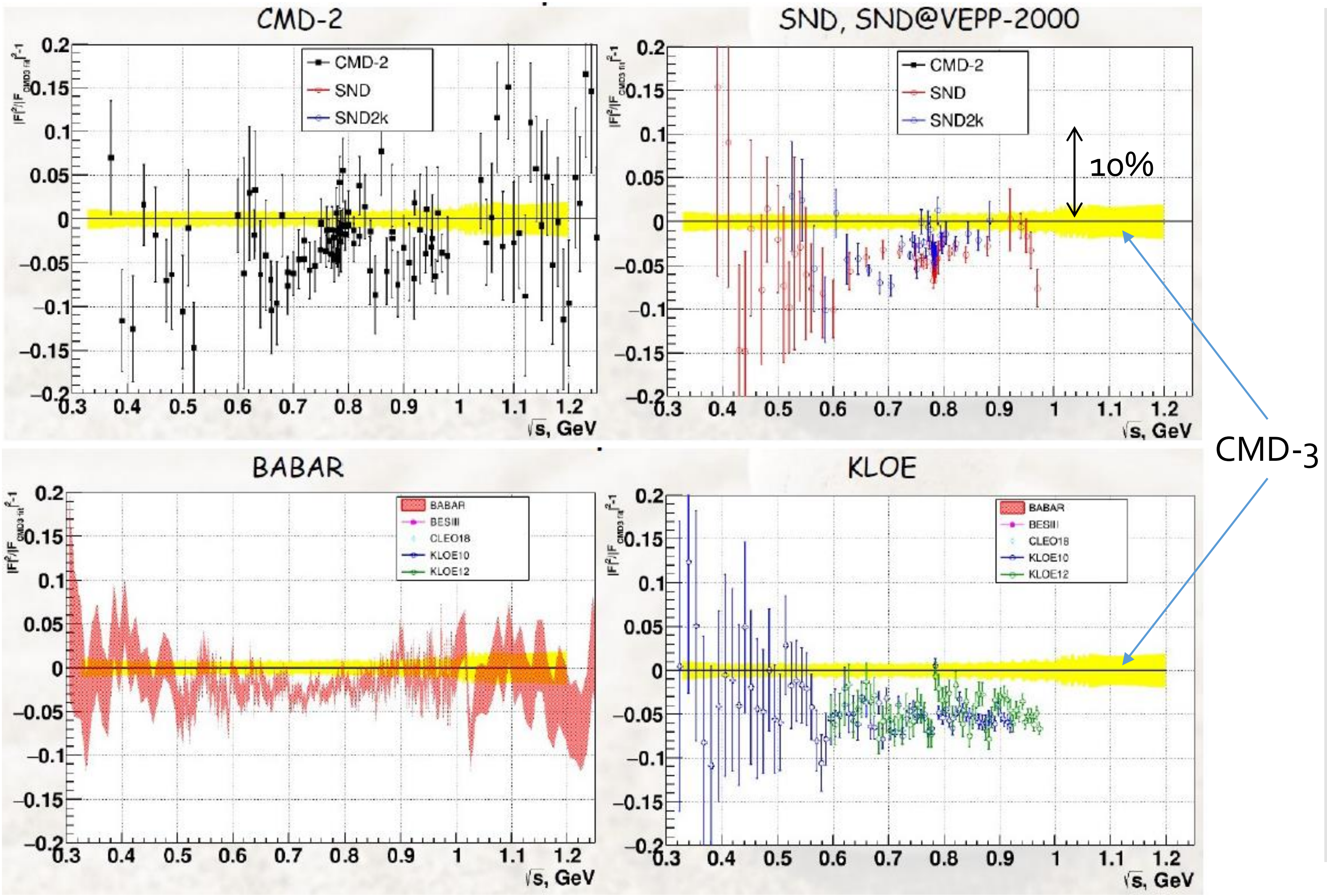
Comparison to other measurements

At first glance, they looks close to each other…



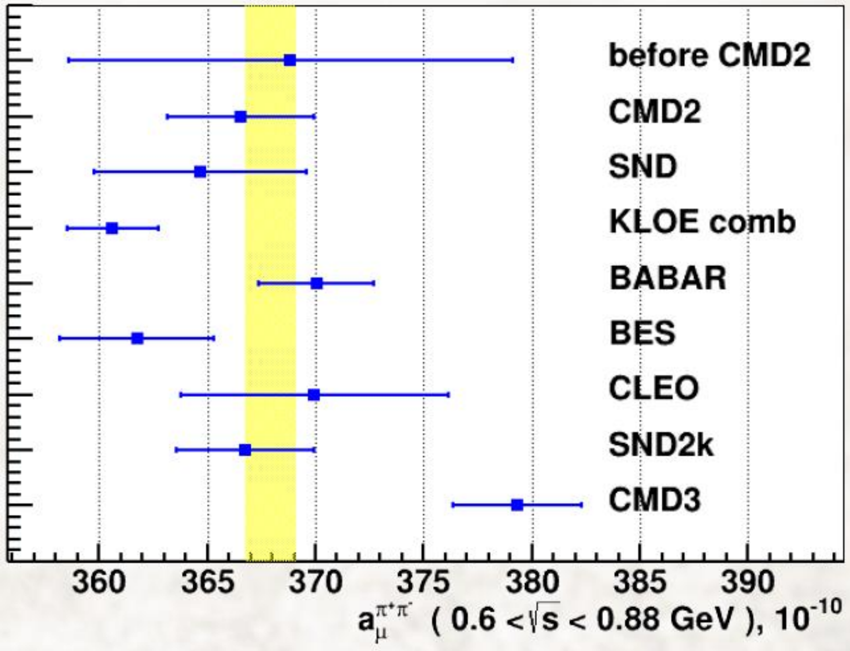
Comparison to other measurements

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



CMD-3 $e^+e^- \to \pi^+\pi^-$: contribution to g-2

$$a_\mu^{had,LO} = \frac{m_\mu^2}{12\pi^3}\int_{4m_\pi^2}^{\infty}\frac{\sigma_{e^+e^-\to\gamma^*\to hadrons}(s)K(s)}{s}ds$$



$0.6 < \sqrt{s} < 0.88$ GeV

	$a_\mu^{\pi\pi,LO}$, 10^{-10}
before CMD2	368.8 ± 10.3
CMD2	366.5 ± 3.4
SND	364.7 ± 4.9
KLOE	360.6 ± 2.1
BABAR	370.1 ± 2.7
BES	361.8 ± 3.6
CLEO	370.0 ± 6.2
SND2k	366.7 ± 3.2
CMD3	379.3 ± 3.0

RHO2013	380.06 ± 0.61 ± 3.64
RHO2018	379.30 ± 0.33 ± 2.62 $\times 10^{-10}$
Sum	379.35 ± 0.30 ± 2.95

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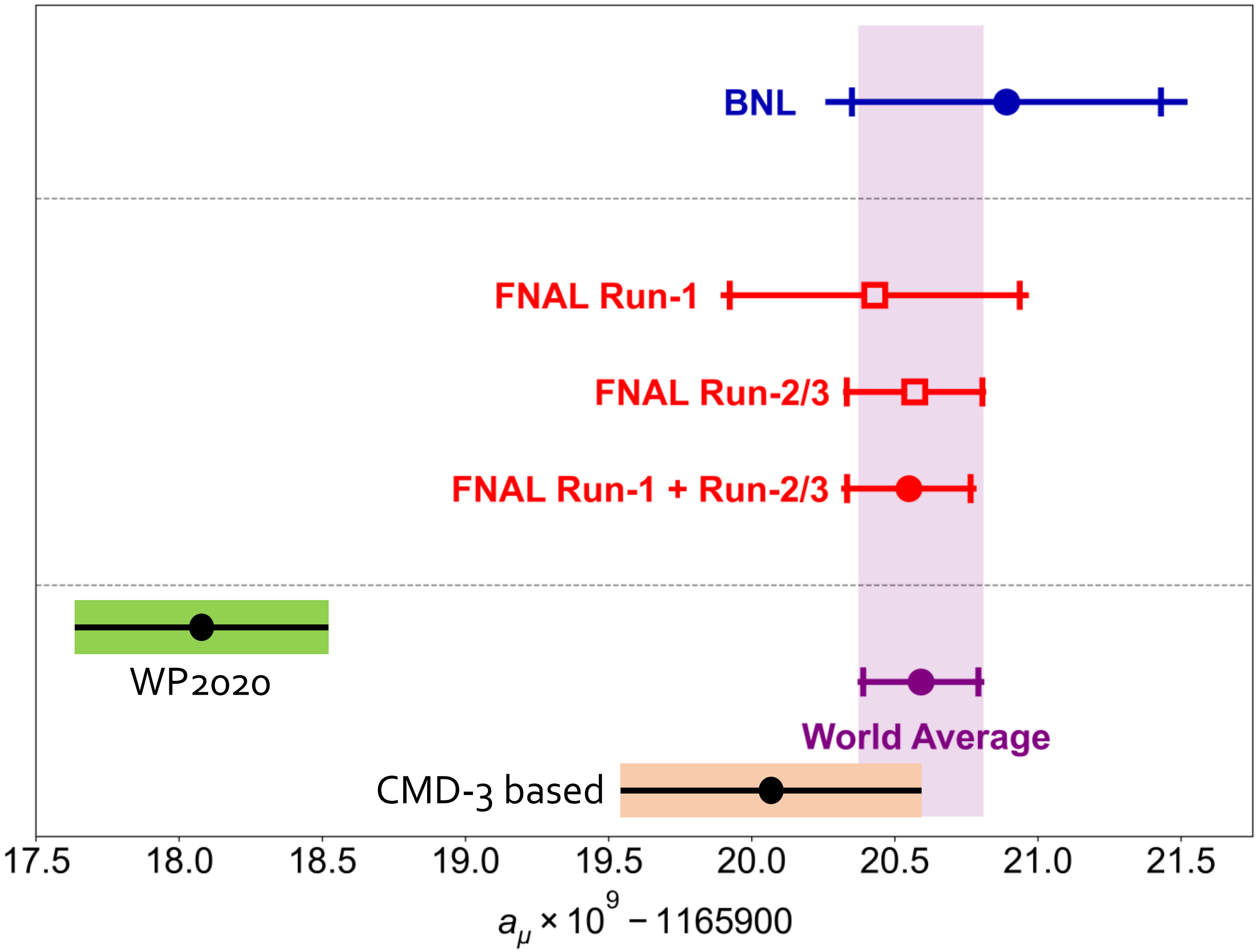
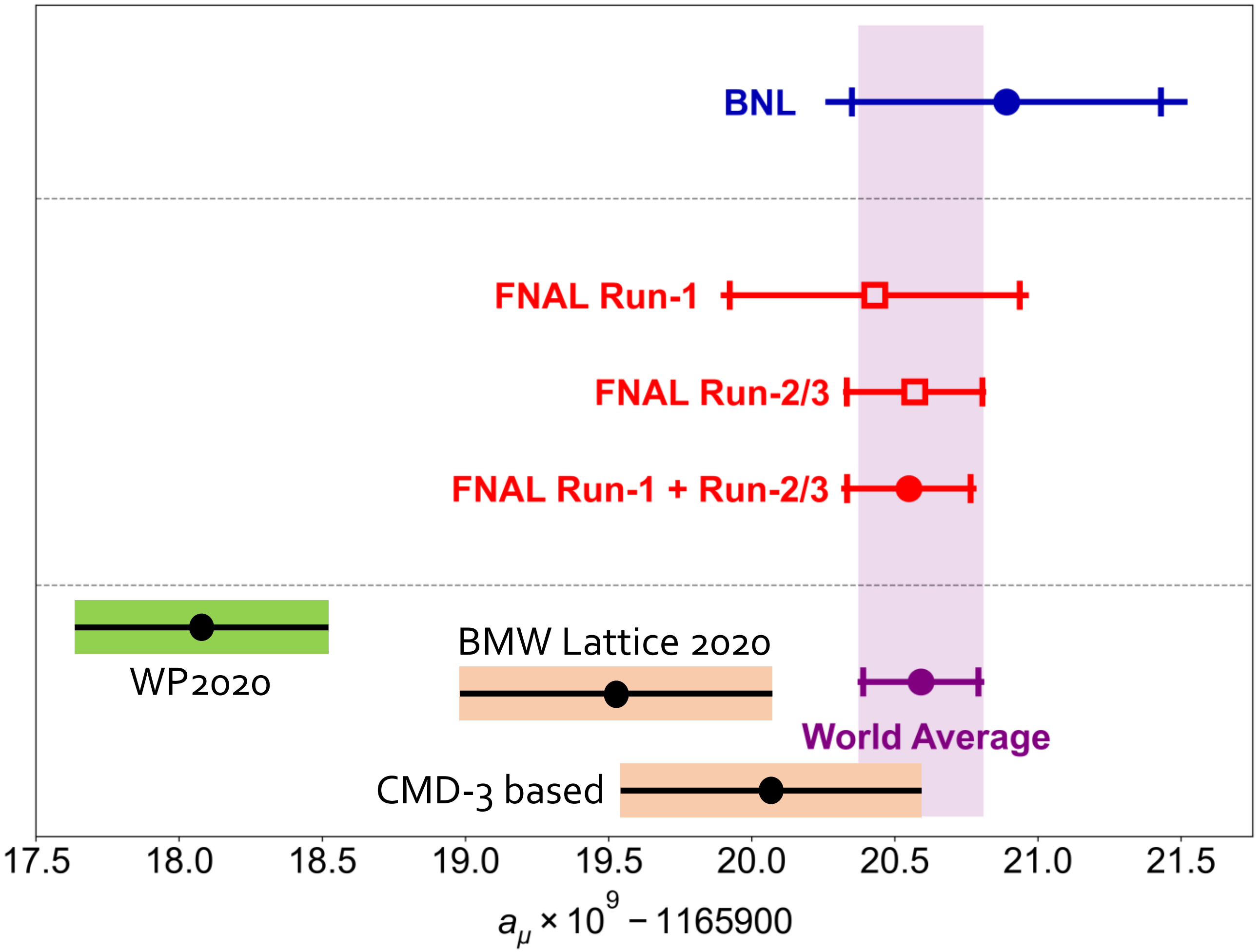
Experiment vs SM prediction



At the moment, the SM prediction for a_μ is unclear (due to hadronic contribution)

Experiment vs SM prediction



At the moment, the SM prediction for a_μ is unclear (due to hadronic contribution)

What’s next

CMD-3: what we could do wrong?

CMD-3 measurement has many internal cross-checks which doesn't leave much space for unknowns.

- Is there problem with angle measurement (fiducial volume)?
  Unlikely: two systems are used; there is measurement of asymmetry; angle distribution agrees with simulation
- Is there problem with RC calculation?
  Unlikely as a source of discrepancy: CMD-2 and SND use the same code, and measurement of asymmetry agrees with RC MC generator. But there could be potential systematic shift in RC common for CMD-X/SND (e.g. for pions due to limitations of sQED).
- Is there problem with event separation?
  Unlikely: three methods agree (CMD-3 is the first measurement with several methods)
- Is there problem with trigger or detection efficiencies?
  Unlikely: should lead to shift of $\sigma(\mu\mu)$.
- Stupid mistake?
  Always possible, but we've done the whole analysis on MC data
- Unaccounted physical background which mimics $e^+e^- \to \pi^+\pi^-$?
  Possible, but we accounted for all known backgrounds from e^+e^- annihilation. Something else? Beam/residual gas interactions?

CMD-2 and CMD-3 are very different measurements

Similarities:

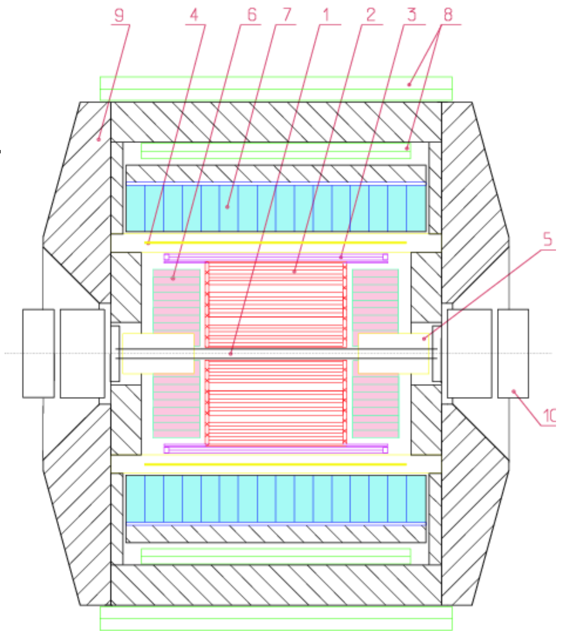
- Two subsystems, endcap calorimeter (not used) and Z-chamber (only used in 2013 CMD-3 data)
- Analysis strategy

Differences:

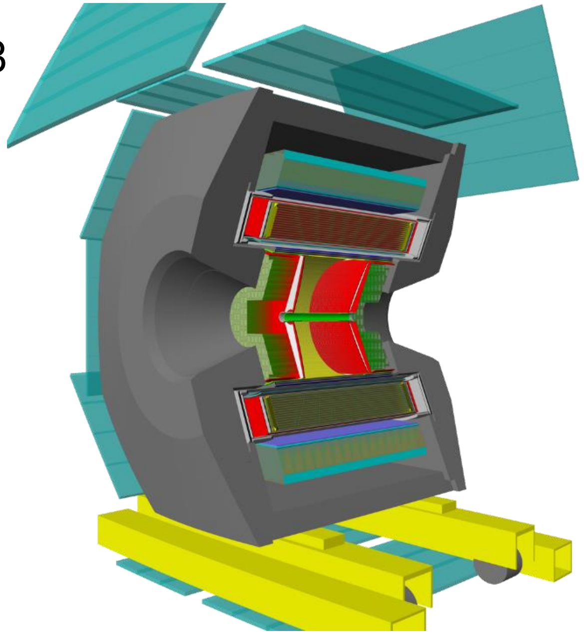
- Major detector systems (DC and calorimeter), electronics
- DC resolution
- Statistics (CMD-3 x30)
- Analysis implementation
- …

CMD-2 and CMD-3 are very different realization of the same-type measurement

CMD-2



CMD-3



Prospects for SM prediction

Discrepancies in $e^+e^- \to H$ data make the SM prediction “blinded”

As of today, we don’t have established estimate of $a_\mu(SM)$

There are significant efforts to understand the discrepancies and to obtain additional new $e^+e^- \to H$ data:

- SND has the same amount of data collected as CMD-3, analysis is in progress
- BABAR is making reanalysis of old data using new approach (angular analysis)
- KLOE-2 started analysis of collected data, not analyzed before
- BELLE-II plans to do ISR measurement of $e^+e^- \to H$ cross sections

There is dedicated experiment, Muone, being prepared at CERN to measure hadronic contribution via $e\mu$ scattering

There is fast progress in lattice calculations

There are good chances to improve precision of SM prediction in coming years

Измерение адронных сечений для $(g-2)_\mu$

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

Вклад сильных взаимодействий: $a_\mu(had) = \int \sigma_{e^+e^-\to\text{адроны}}(s)\,K(s)\,ds$

Чтобы точность теории «догнала» эксперимент, необходимо измерить адронные сечения с точностью ~0.2% (КМД-3: ~0.8%)

Канал	Вклад, $\cdot 10^{10}$ (KNT19)	Отн.точность: надо (есть)
$\pi^+\pi^-$	504.23(1.90) (0.4%) ха-ха	0.23% (0.8%)
$\pi^+\pi^-\pi^0$	46.63(94) (2.0%)	1.1% (1.5-3%)
$\pi^+\pi^-\pi^+\pi^-$	13.99(19) (1.4%)	0.8% (2-3%)
$\pi^+\pi^-\pi^0\pi^0$	18.15(74) (4.0%)	2.3% (5%)
K^+K^-	23.00(22) (1.0%)	0.6% (2%)
K_SK_L	13.04(19) (1.5%)	0.7% (2%)
$\boldsymbol{a_\mu(had;LO)}$	**692.8(2.4) (0.35%)**	**0.2%**

Сценарий «равномерного» улучшения

CMD-3 plans

Short-term (~1 year)

Collect additional data dedicated to systematic checks of the measurement (with different detector and running conditions).

Long term (~5-10 years)

The CMD-3 measurement is systematically limited – detector upgrade.

Detector upgrades under discussions: new drift chamber, new Z-chamber at inner and outer radii (probably, integrated with DC), *dedicated PID/TOF?,…*

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

The precision critically depends on development on new generation of MC generators for radiative corrections

Источники систематических ошибок $e^+e^- \to \pi^+\pi^-$

Систематические ошибки КМД-3

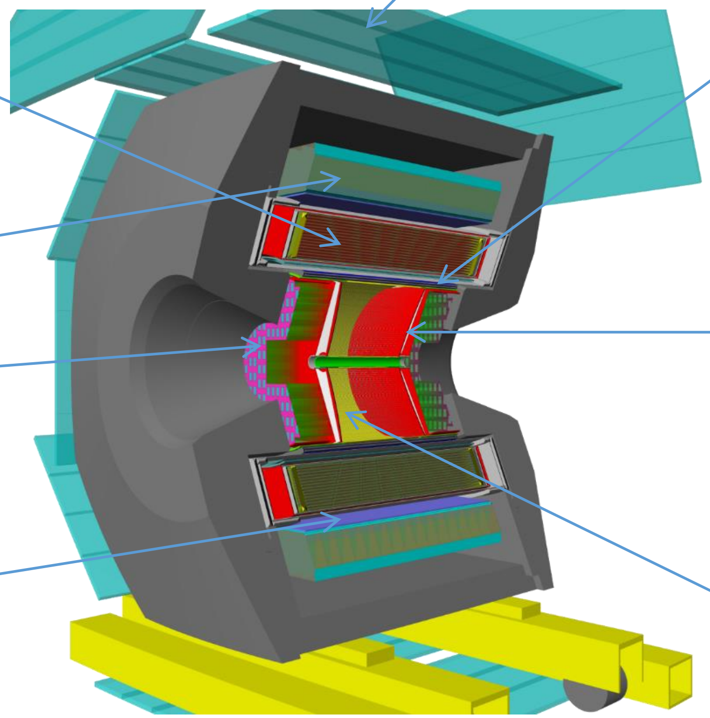
		Планы КМД-3	Надо
✗ Radiative corrections	0.2% (2π) ⊕ 0.2% (Fπ) ⊕ 0.1% (e+e-)	0.1%	0.1%
✗ e/μ/π separation	0.5 (low) - 0.2 (ρ) - 0.6 (φ) %	0.2%	0.1%
✗ Fiducial volume	0.5% / 0.8% (RHO2013)	0.2%	0.1%
✗ Correlated inefficiency	0.1 (ρ) - 0.15%($>$1 ГэВ)	0.1%	
✗ Trigger	0.05 (ρ) - 0.3% ($>$1 ГэВ)		
✗ Beam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

Ключевые требуемые улучшения:
- Идентификация (разделение)
- Телесный угол
- Ядерные взаимодействия (вакуумная труба)

и параллельное развитие расчетов радиационных поправок…

Статистика КМД-3: ~0.08%, 7 месяцев

Возможные пути модернизации КМД-3



Разработка новой дрейфовой камеры

- Идет моделирование разных вариантов
- Идут подготовительные R&D, общие для всех вариантов
  - Проволока, пины, конструкционные материалы, электроника
- К концу 2024 года – понимание конструкции

Стоимость: O(10 млн.руб.) на материалы и комплектующие

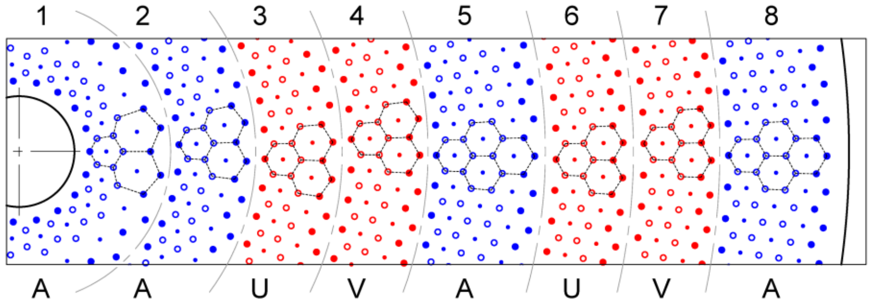
SUPERLAYER NUMBER	NUMBER OF LAYERS	NUMBER OF CELLS IN LAYER	NUMBER OF CELLS IN SUPERLAYER	STEREO ANGLE, mrad	CELL SIZE r ± Δr, mm		RADIUS OF ANODE WIRE LAYER, mm
1	2	19	38	0	6.000 8.642	0.175 0.038	31.543 43.185
2	2	37	74	0	6.279 7.516	0.094 0.019	64.106 74.762
3	2	53	106	+45	6.529 7.391	0.068 0.014	95.422 106.078
4	2	69	138	-48	6.667 7.330	0.054 0.011	126.848 137.512
5	3	87	261	0	6.562 7.072 7.534	0.042 0.008 0.001	157.404 167.757 178.827
6	2	109	218	+99	6.683 7.093	0.034 0.007	200.831 211.266
7	2	125	250	-101	6.750 7.109	0.030 0.006	232.613 243.097
8	3	141	423	0	6.772 7.091 7.370	0.027 0.005 0.001	263.236 273.713 284.629
TOTAL	18		1508				

The CMD new drift chamber geometry

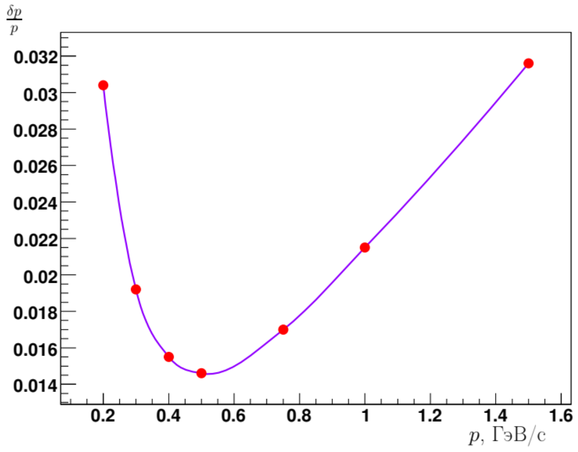
INNER DIAMETER, mm	40
OUTER DIAMETER, mm	600
WIRE LENGTH, mm	440
ENDPLATE THICKNESS, mm	7
NUMBER OF WIRES:	5 804
● SIGNAL 25 um	1 508
● FIELD 100 um	1 920
○ FIELD 125 um	2 376
TOTAL TENSION LOAD, kg	882
ENDPLATE FLEXURE (MAX)*, mm	3.1

*ENDPLATE MATERIAL:
NIIKAM M55J quasi-isotropic carbon fiber with Young's modulus E = 168 GPa

A – axial
U, V – stereo



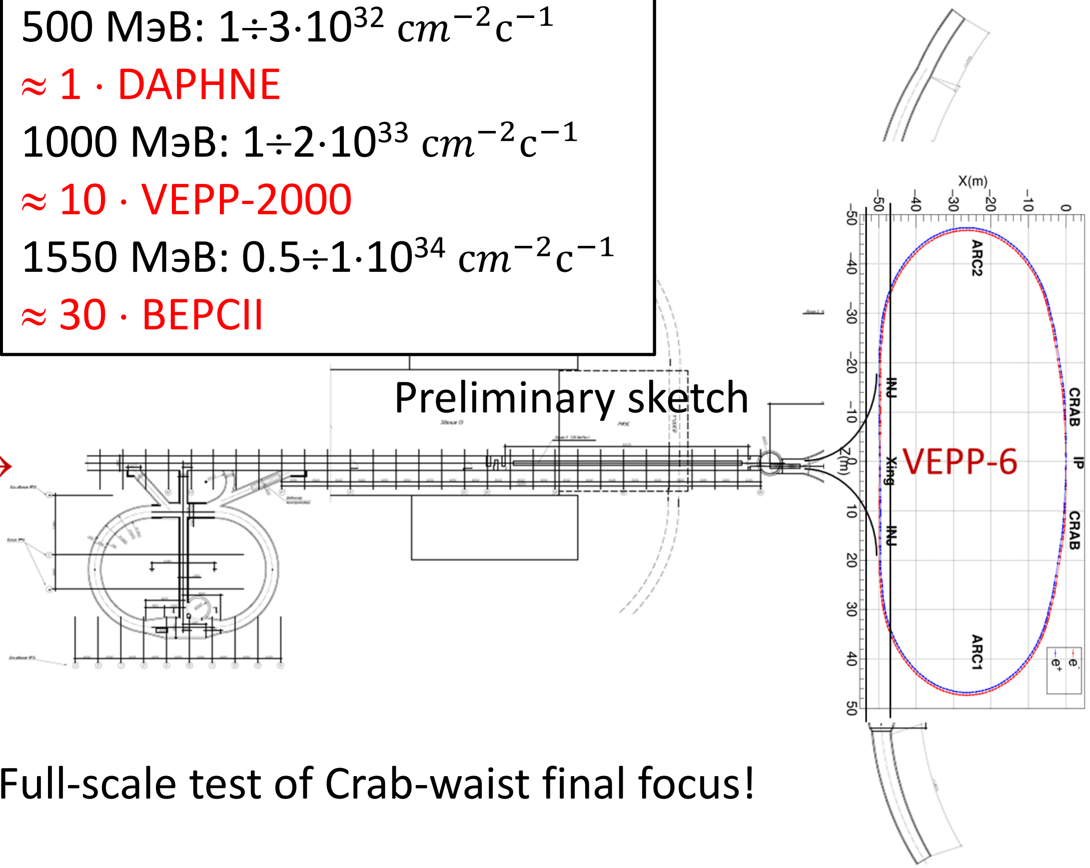
Вариант со стерео-слоями



Under consideration: VEPP-6

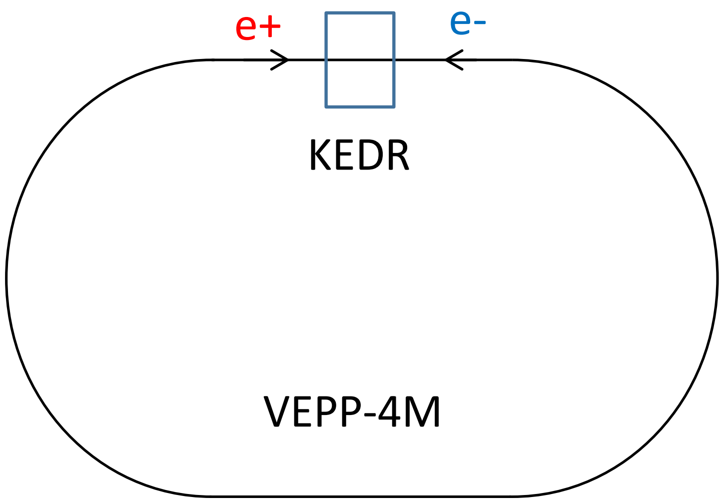
- e^+e^- collider
  - Beam energy from <0.5 to 1.6 GeV (J/ψ) (2.0 GeV)
  - Luminosity $\mathcal{L} \approx 10^{\mathbf{34}}\ cm^{-2}c^{-1}$ @ 1.6 GeV
- General purpose detector
  - Tracking
  - Calorimetry
  - Particle ID
- Physics
  - J/ψ decays
  - Baryon thresholds
  - Measurement of R
  - … Complementary to Super charm-tau factory

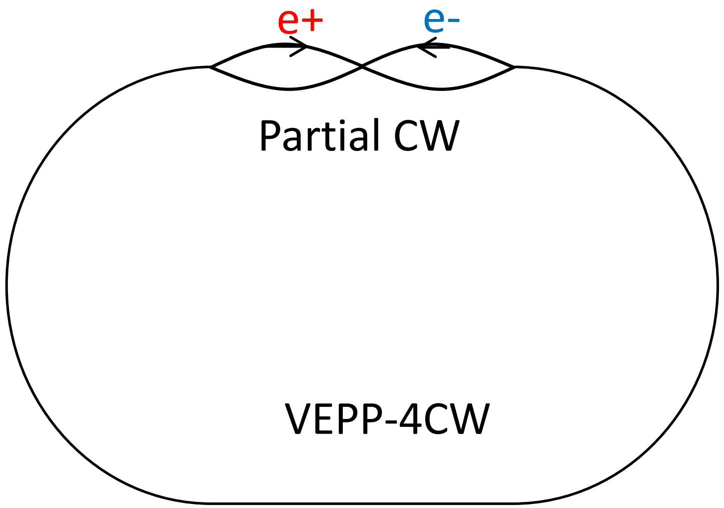
500 МэВ: 1÷3·10[32] $cm^{-2}c^{-1}$
≈ 1 · DAPHNE
1000 МэВ: 1÷2·10[33] $cm^{-2}c^{-1}$
≈ 10 · VEPP-2000
1550 МэВ: 0.5÷1·10[34] $cm^{-2}c^{-1}$
≈ 30 · BEPCII

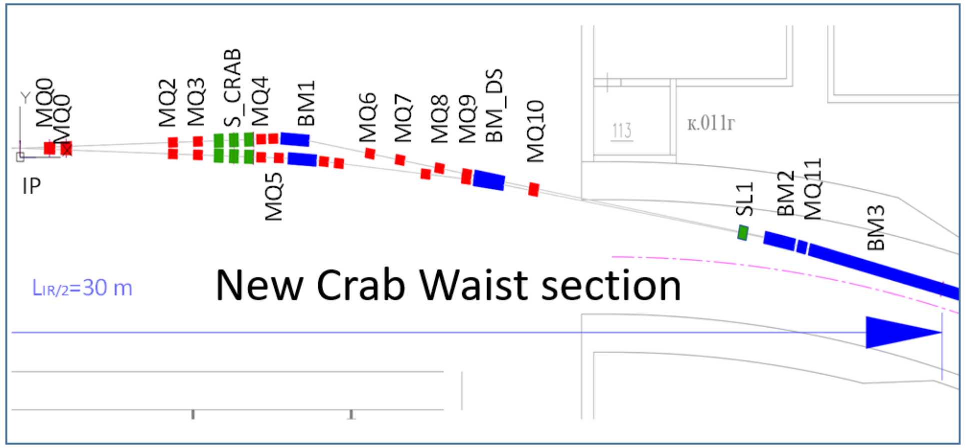


Full-scale test of Crab-waist final focus!

Under consideration: CW at VEPP-4M







There is proposal to make a test of CW at VEPP-4M

What can be tested: final focus elements, nonlinear beam dynamics, beam-beam effects, backgrounds,…

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

Beneficial for all future collider projects

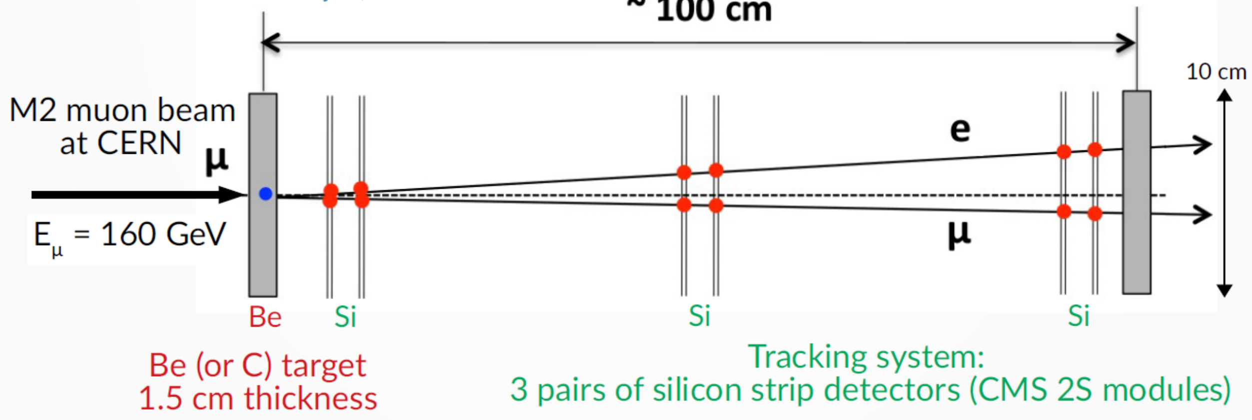
MUonE @CERN

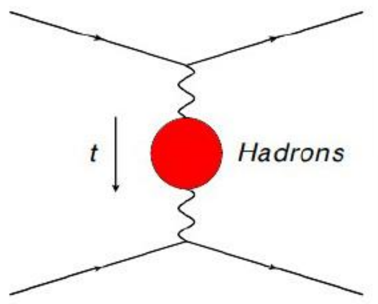
Dedicated experiment to measure hadronic contribution in t-channel.

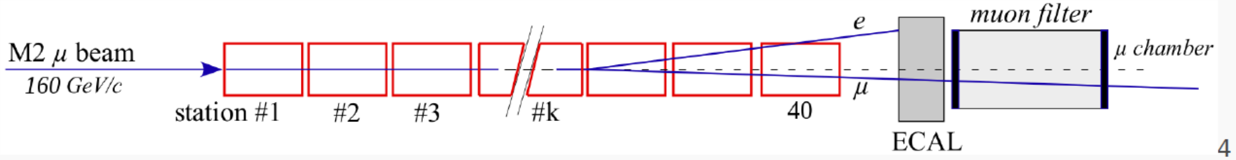
$$a_\mu^{HLO} = \frac{\alpha_0}{\pi}\int_0^1 dx(1-x)\Delta\alpha_{had}[t(x)]$$

Lautrup, Peterman, De Rafael, Phys. Rep. C3 (1972), 193

Letter of Intent: The MUonE Project, SPSC-I-252







Measured: angular distribution of μe scattering; $4 \cdot 10^{12}$ events!

Now: proof-of-concept data taking; final result after LHC LS3 (2029-)

Conclusion

- CMD-3 performed a new measurement of $\sigma(e^+e^- \to \pi^+\pi^-)$ at energies $\sqrt{s} < 1.2$ GeV
  - The best statistical precision in the world
  - Up to 0.7% systematic accuracy – on a par with previous measurement
- The measurement is supported by accompanying measurements of $\sigma(e^+e^- \to \mu^+\mu^-)$ and charge asymmetry of $e^+e^- \to \pi^+\pi^-$
- The CMD-3 result is systematically larger than previous measurements
- The SM prediction of muon (g-2), based on CMD-3 result, is in agreement with recent muon (g-2) measurement at FNAL
- The status of SM prediction is unclear; with amount of world-wide dedicated efforts, expect improvement in theory in coming years

Ultimate goal: Hadron data = Lattice = MUONe