Измерение сечения $e^+e^- \to \pi^+\pi^-$ в эксперименте КМД-3: следствия для $(g-2)$ мюона

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РАН

1–5 апр. 2024 г.

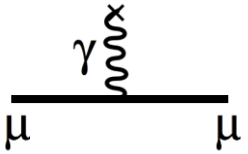
г. Дубна
ОИЯИ

Introduction

The basics

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

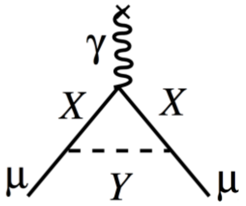
$$\vec{\mu}_S = g\frac{e}{2m}\vec{S}$$



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

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

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



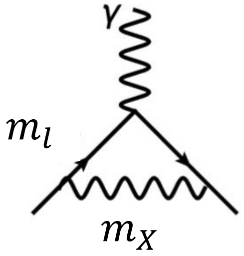
$a_e \approx a_\mu \approx \frac{\alpha}{2\pi} \approx 10^{-3}$ (QED dominated)

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

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

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

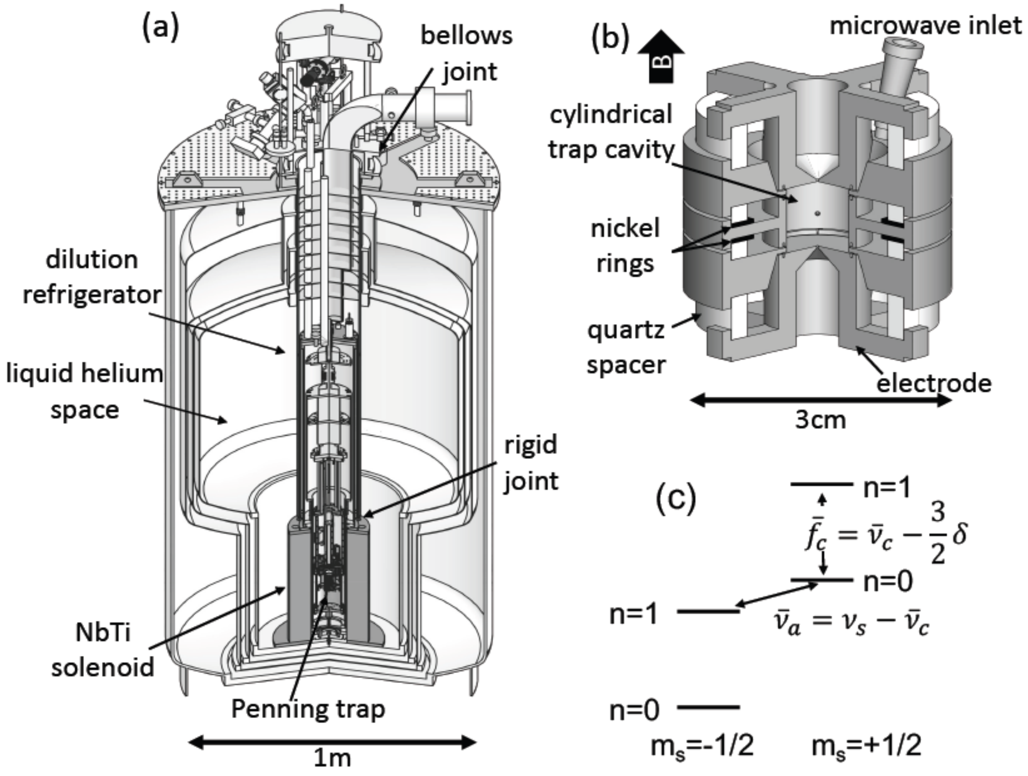
$$\Delta a \sim \left(\frac{m_l}{m_X}\right)^2$$



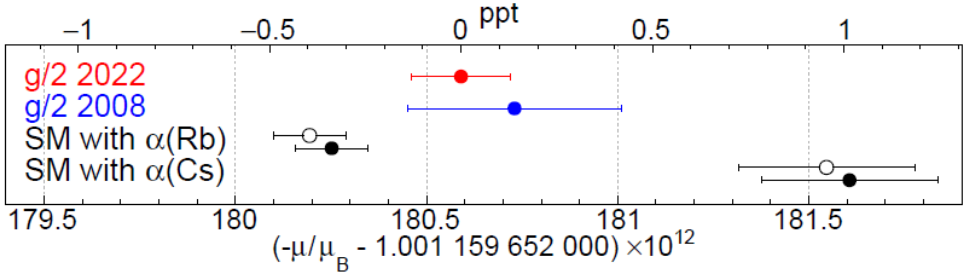
Anomalous magnetic moment of electron

The best precision is achieved for electrons (g-2). The value of a_e is used to get the determination of fine-structure constant α.

X. Fan, T. G. Myers,
B. A. D. Sukra, G. Gabrielse,
Phys.Rev.Lett.
130 (2023) 7, 071801



$$a_e = 1\,159\,652\,180\,59\,(13) \times 10^{-14} \quad (0.11\text{ ppb})$$



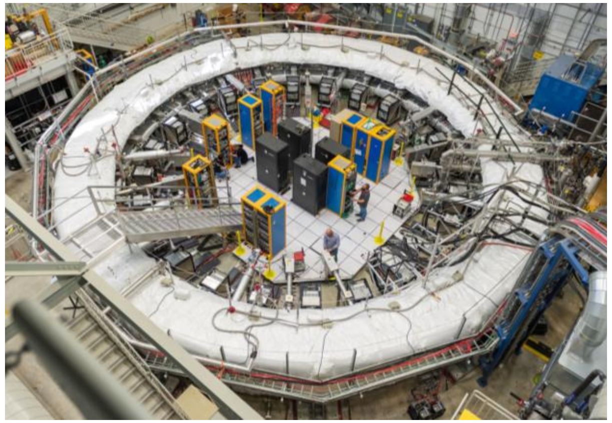
a_μ vs a_e

	Δa *(exp)*	Hadronic	Weak	Weak/Δa
a_e	0.11 ppb	~1.4 ppb	0.03 ppb	0.3
a_μ	190 ppb	~52000 ppb	~1300 ppb	6.8

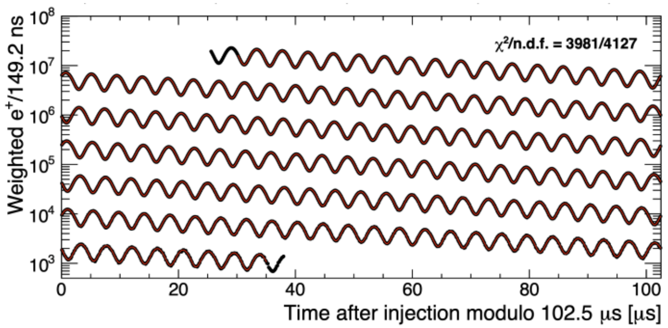
a_μ is more sensitive to contributions from heavy fields compared to a_e by factor ~20

Generations of a_μ measurements

FNAL Run 2-3 (USA)



Run 3a



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

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

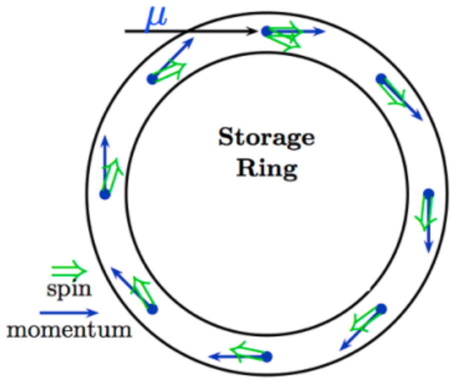
Contributions of known interactions

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

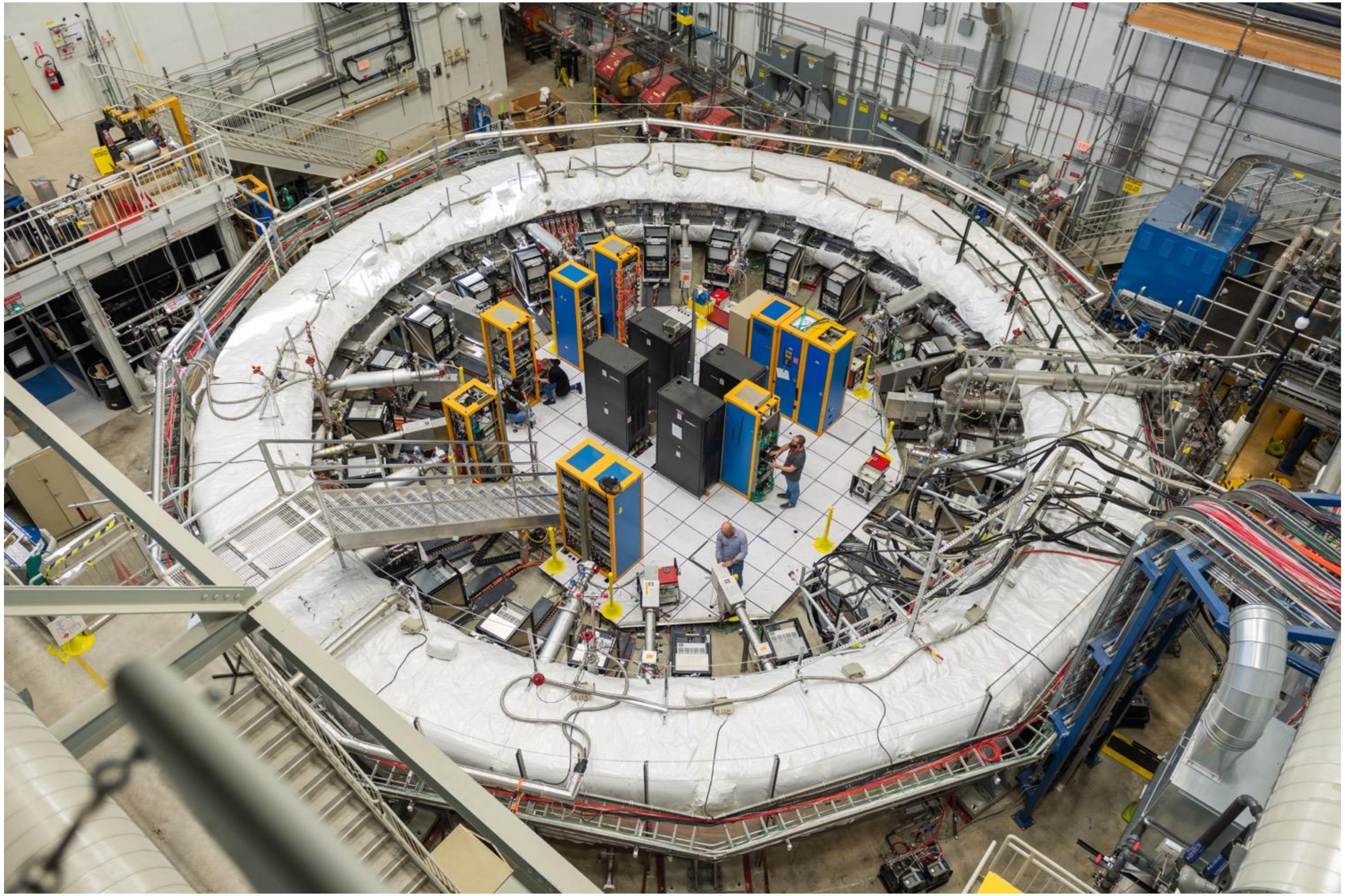
$$\vec{\omega}_a = -\frac{e}{m}\left[a_\mu \vec{B} - \cancel{\left(a_\mu - \frac{1}{\gamma^2-1}\right)}\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

zero for $\gamma_\mu = 29.3$

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

Focusing with electrostatic quadrupoles

Muon G-2 Ring @FNAL



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

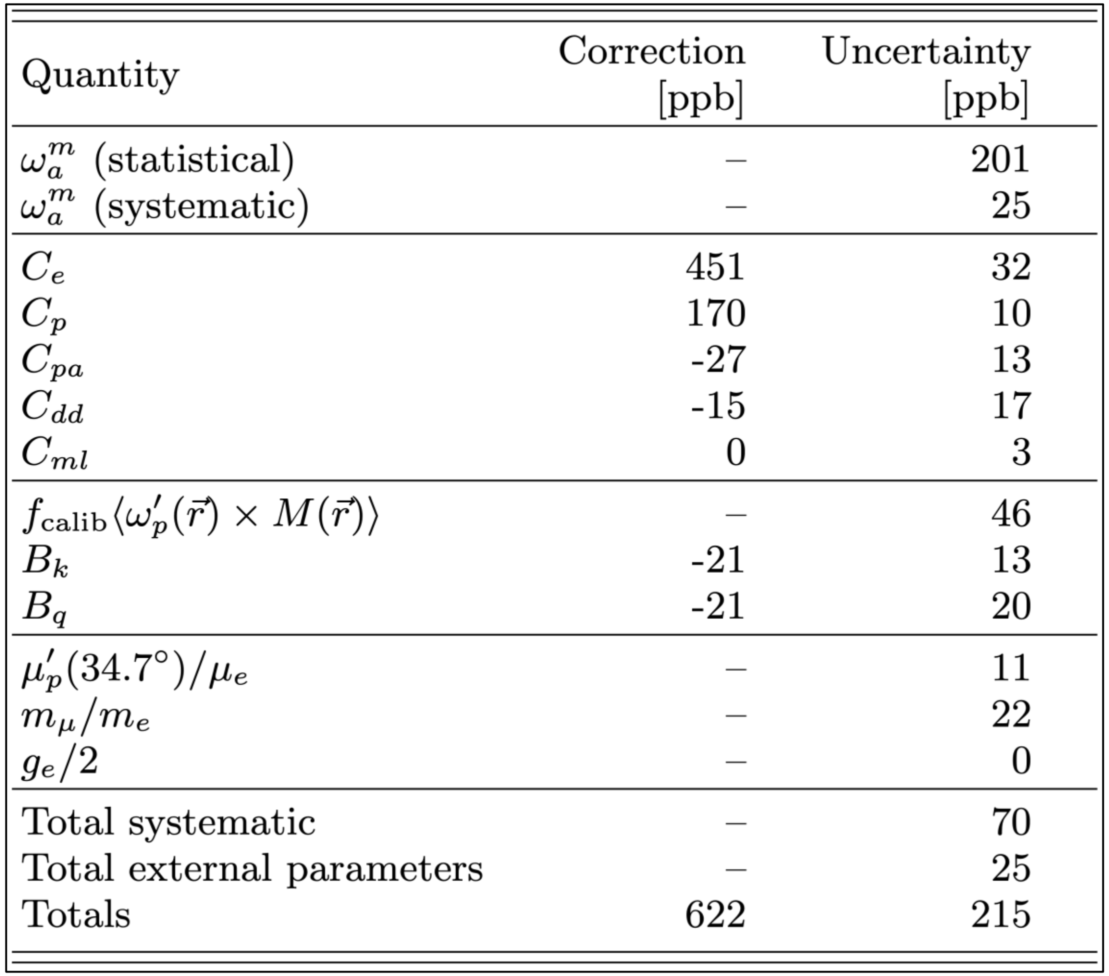
Korea
- CAPP/IBS
- KAIST

Russia
- Budker/Novosibirsk
- JINR Dubna

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


Muon g-2 Collaboration Meeting @ Elba, May 2019

Final error table

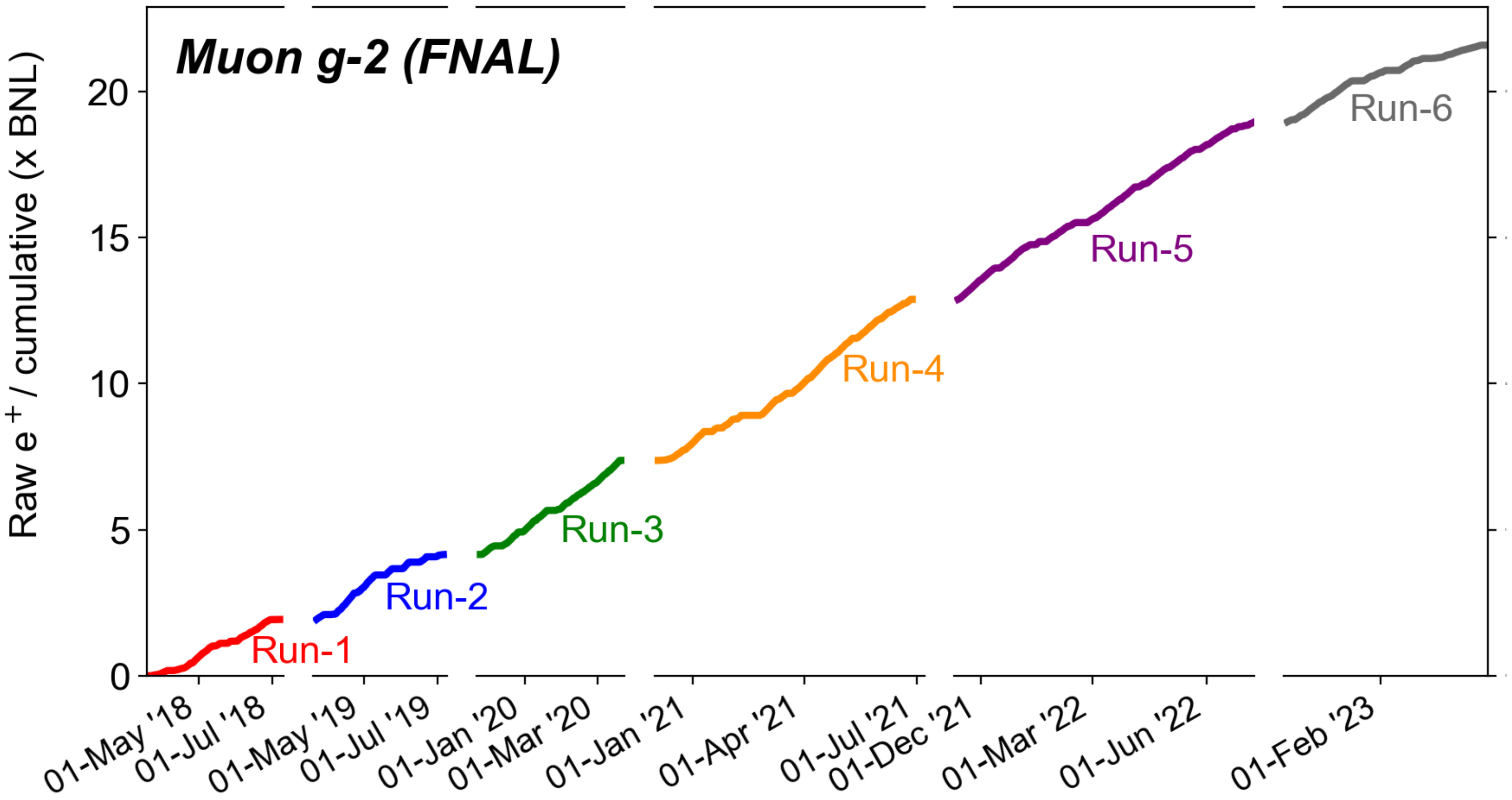


Quantity	Correction [ppb]	Uncertainty [ppb]
ω_a^m (statistical)	–	201
ω_a^m (systematic)	–	25
C_e	451	32
C_p	170	10
C_{pa}	-27	13
C_{dd}	-15	17
C_{ml}	0	3
$f_{\text{calib}} \langle \omega'_p(\vec{r}) \times M(\vec{r}) \rangle$	–	46
B_k	-21	13
B_q	-21	20
$\mu'_p(34.7^\circ)/\mu_e$	–	11
m_μ/m_e	–	22
$g_e/2$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

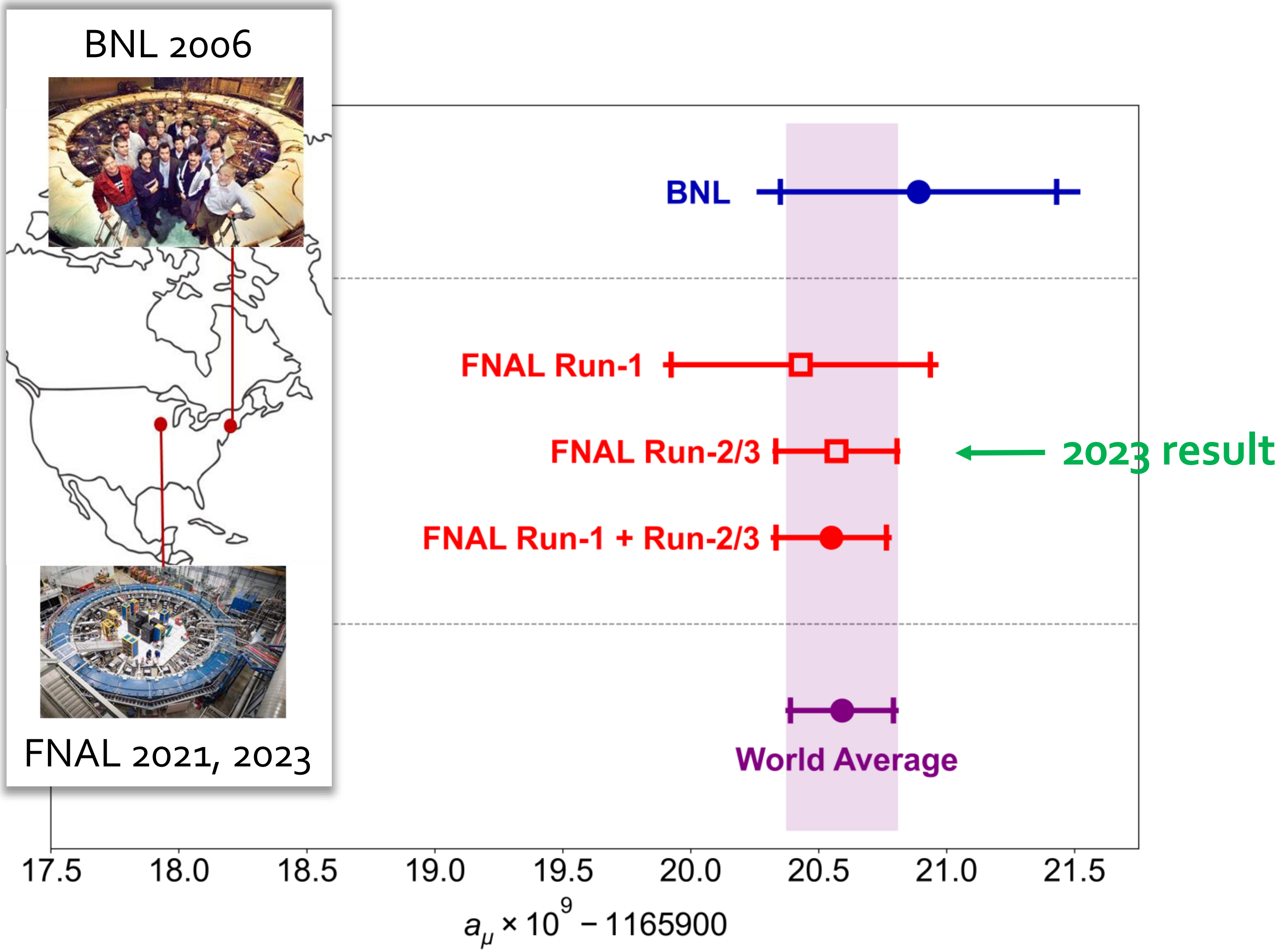
Total collected statistics



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

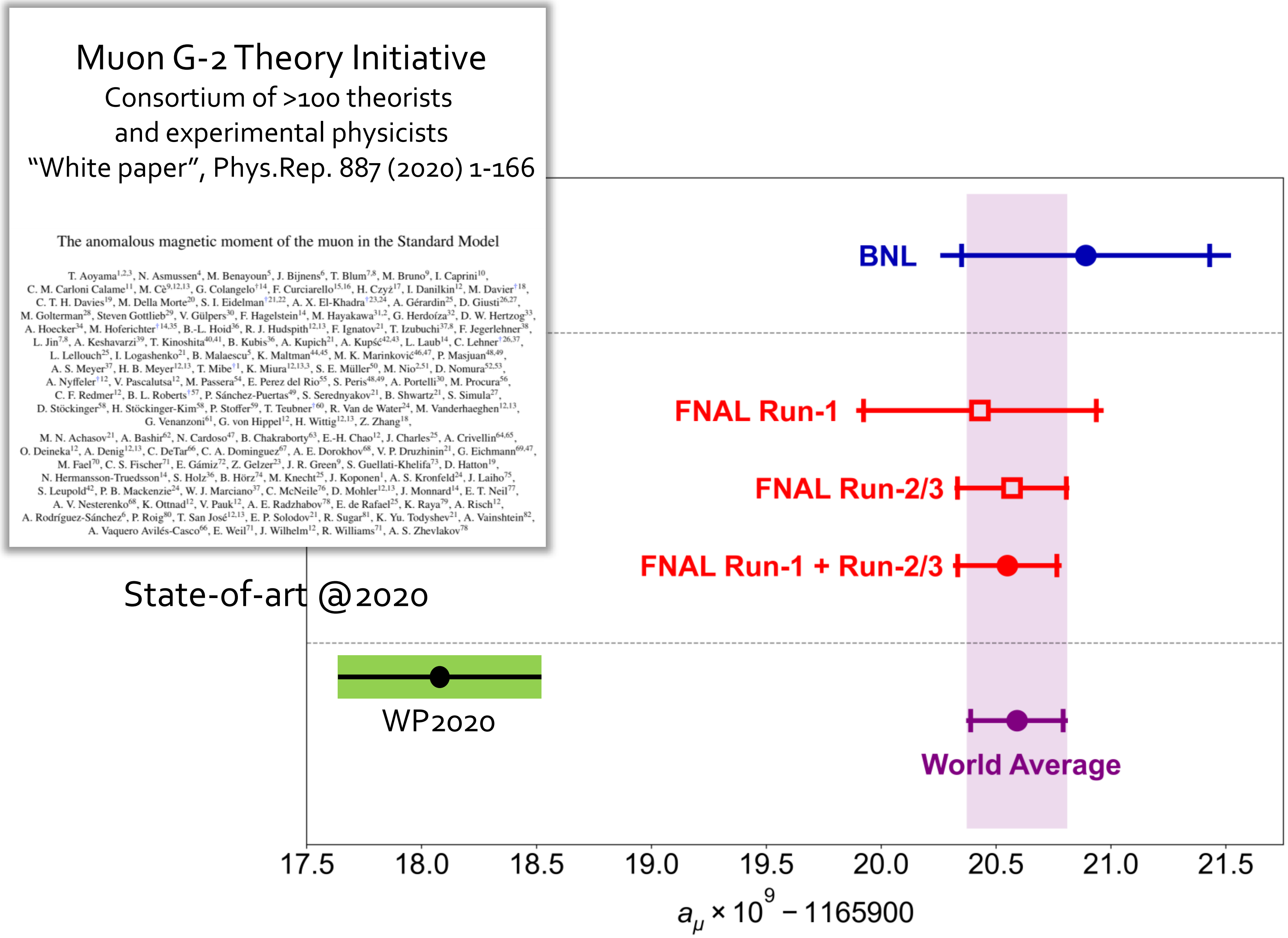
Run 4/5/6 statistics is x3 Run-1/2/3

Muon G-2 2023 result



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

Experiment vs SM prediction



Muon G-2 Theory Initiative
Consortium of >100 theorists
and experimental physicists
“White paper”, Phys.Rep. 887 (2020) 1-166

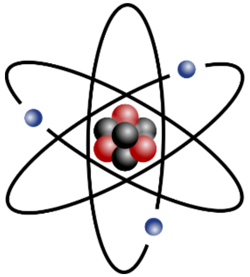
The anomalous magnetic moment of the muon in the Standard Model

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],

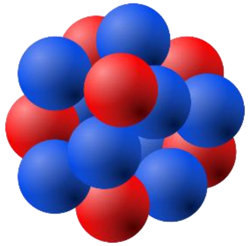
M. N. Achasov[21], A. Bashir[62], N. Cardoso[47], B. Chakraborty[63], E.-H. Chao[12], J. Charles[25], A. Crivellin[64,65], O. Deineka[12], A. Denig[12,13], C. DeTar[66], C. A. Dominguez[67], A. E. Dorokhov[68], V. P. Druzhinin[21], G. Eichmann[69,47], M. Fael[70], C. S. Fischer[71], E. Gámiz[72], Z.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

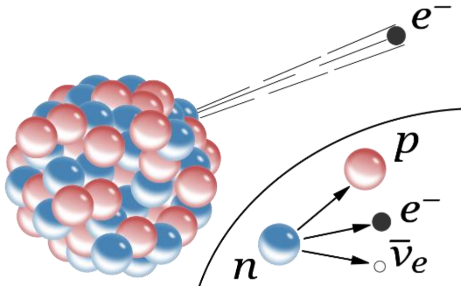
SM prediction for a_μ (WP2020)



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)

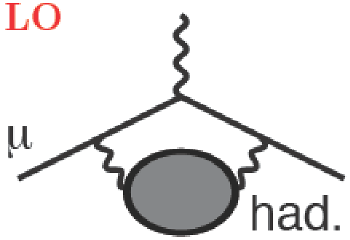
Next-to-leading order (NLO)

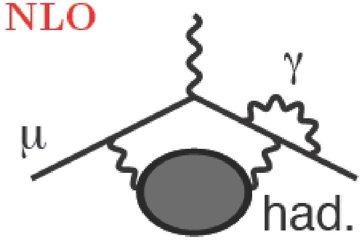
Light-by-light (LBL)

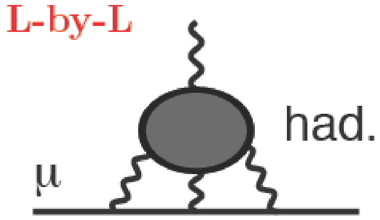
WP(2020)

$$(6\,931 \pm 40) \times 10^{-11} \qquad (-98.3 \pm 0.7) \times 10^{-11} \qquad (92 \pm 19) \times 10^{-11}$$

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







350 ppb (0.6%)

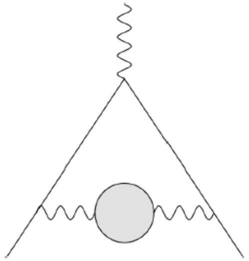
10 ppb

160 ppb

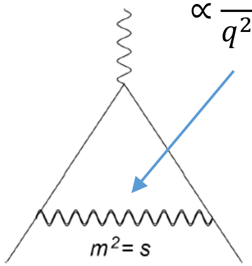
Compare to experimental accuracy of 190 ppb

HVP: what do we need to measure

Dispersion relation:



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



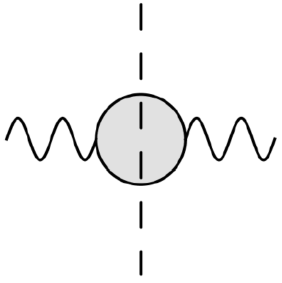
$\propto \frac{1}{q^2 - s}$

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

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

Optical theorem:

2 Im



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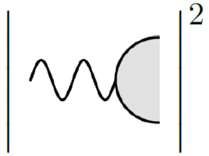


$$\mathrm{Im}\,\Pi'(s) = \frac{s}{4\pi\alpha}\sigma^0(e^+e^- \to \gamma \to hadrons + \cdots)$$

Lets put everything together:

This is what we need to measure

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

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

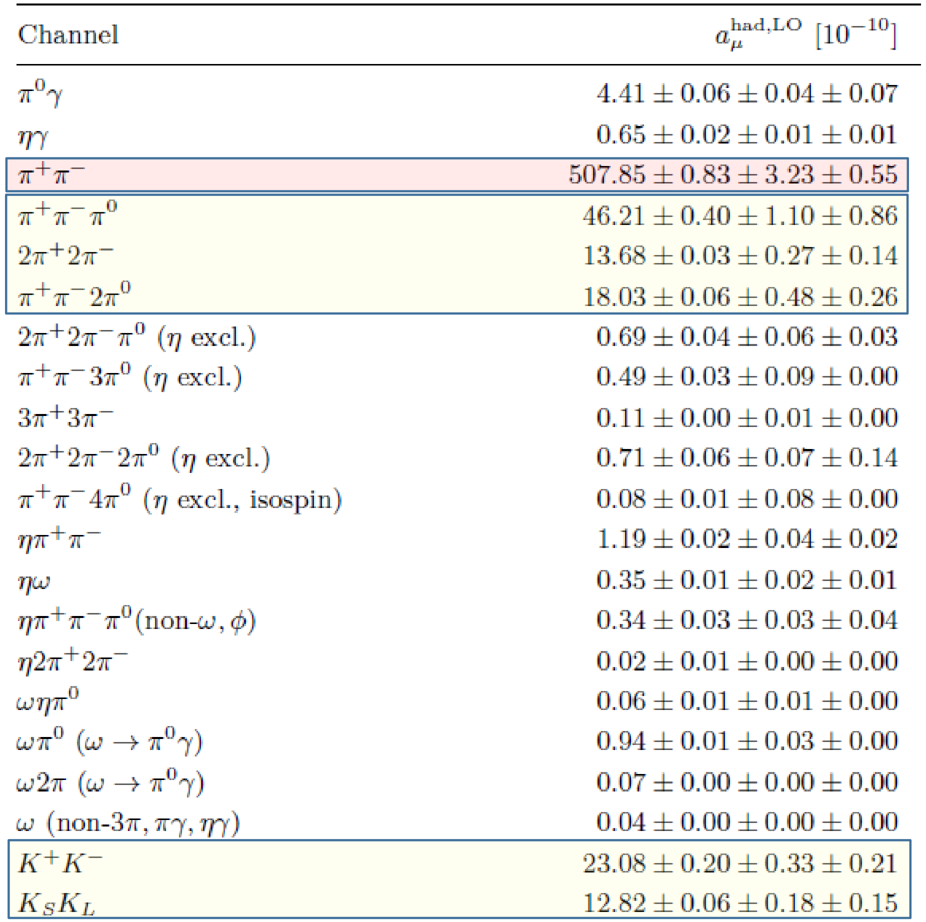
$\sigma^0(e^+e^- \to \mu^+\mu^-)$

$s =$ (c.m. energy)^2

Contribution of exclusive hadronic cross sections to a_μ

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

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

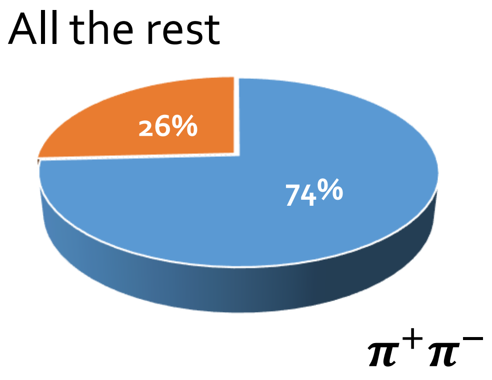


Channel	$a_\mu^{\mathrm{had,LO}}$ $[10^{-10}]$
$\pi^0\gamma$	$4.41 \pm 0.06 \pm 0.04 \pm 0.07$
$\eta\gamma$	$0.65 \pm 0.02 \pm 0.01 \pm 0.01$
$\pi^+\pi^-$	$507.85 \pm 0.83 \pm 3.23 \pm 0.55$
$\pi^+\pi^-\pi^0$	$46.21 \pm 0.40 \pm 1.10 \pm 0.86$
$2\pi^+2\pi^-$	$13.68 \pm 0.03 \pm 0.27 \pm 0.14$
$\pi^+\pi^-2\pi^0$	$18.03 \pm 0.06 \pm 0.48 \pm 0.26$
$2\pi^+2\pi^-\pi^0$ (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	$12.82 \pm 0.06 \pm 0.18 \pm 0.15$

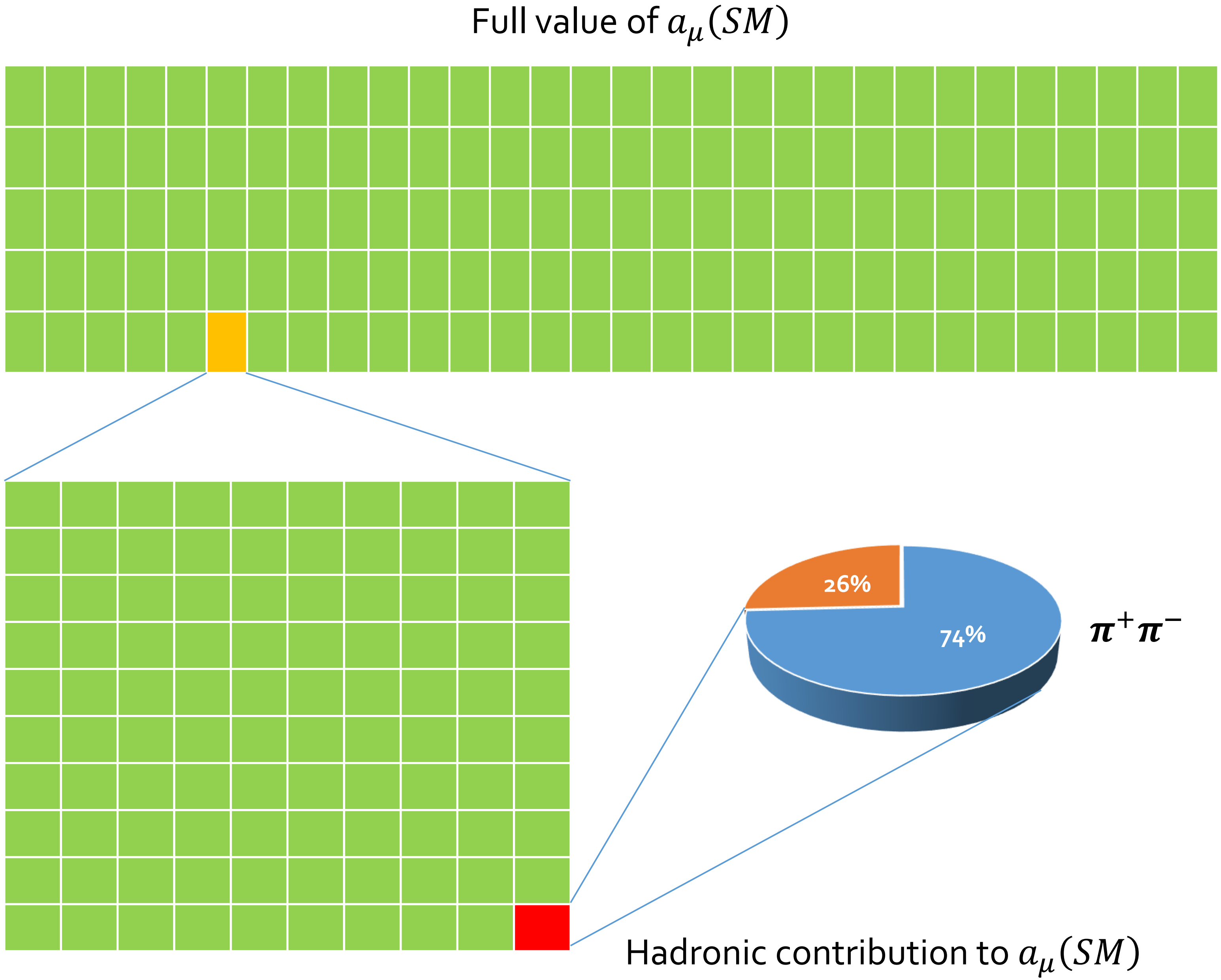
From DHMZ'19

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!)

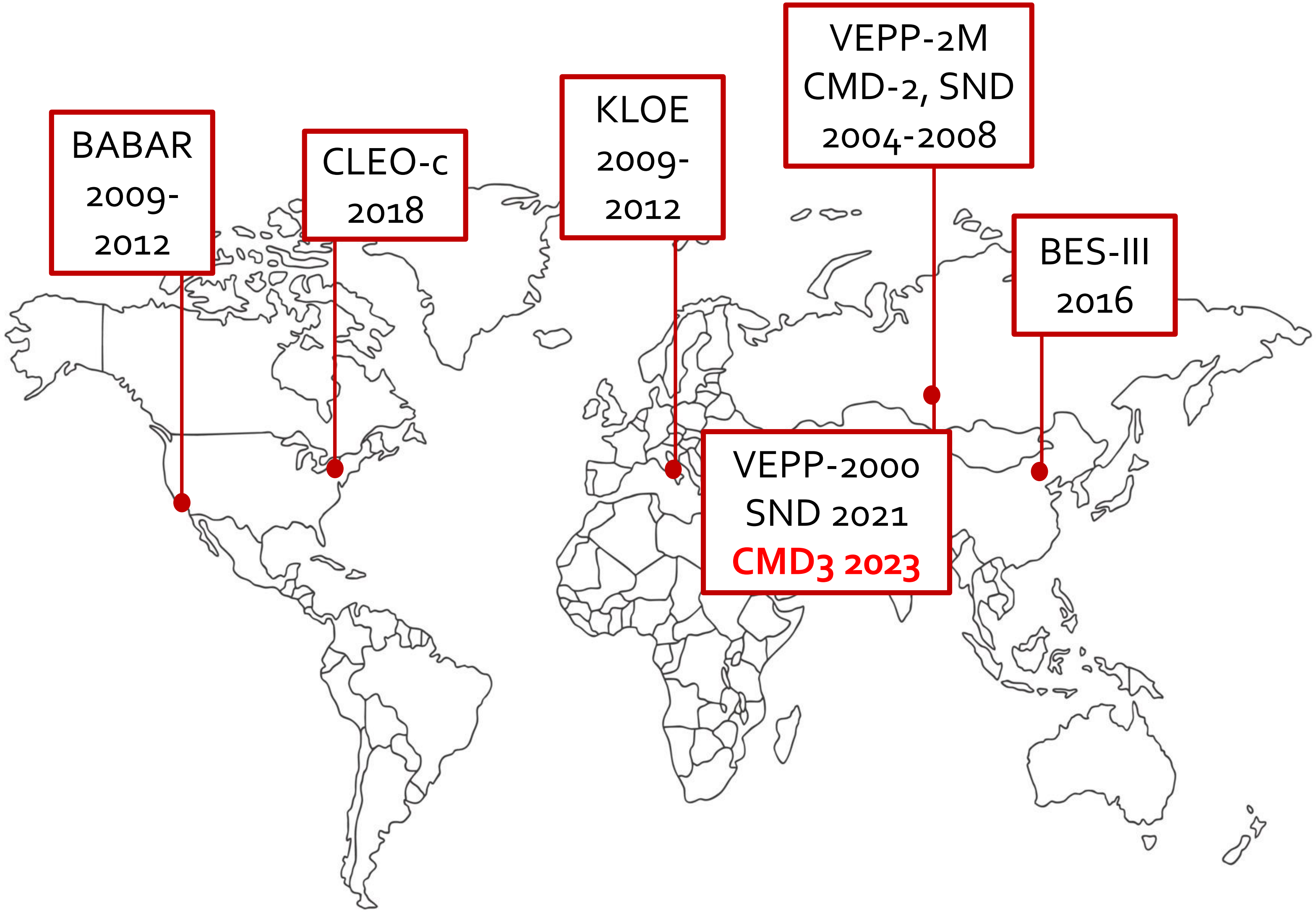


Hadronic contribution: a visual representation

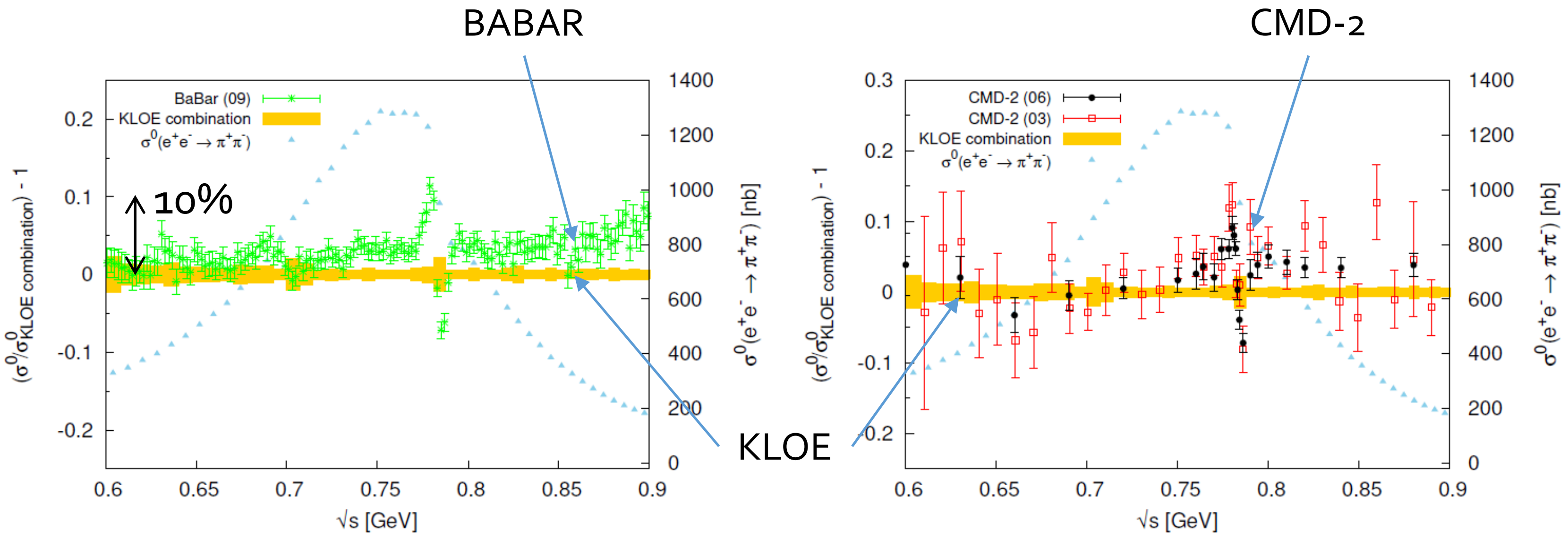


Measurements of $e^+e^- \to \pi^+\pi^-$

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



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

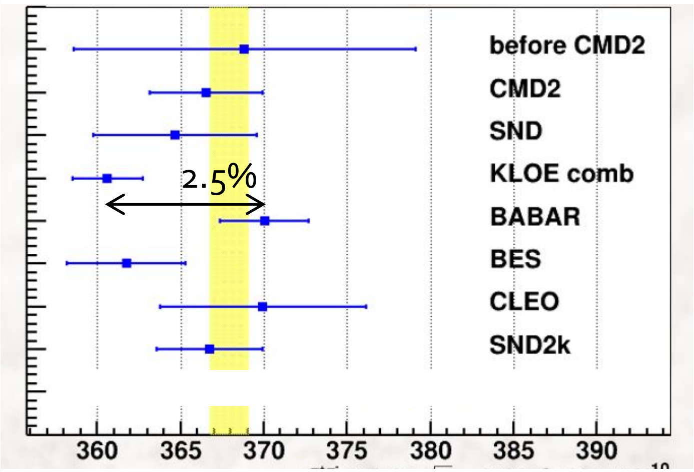


There are few-% discrepancies between various sub-% measurements of $\sigma(e^+e^- \to \pi^+\pi^-)$ *Unexplained*

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

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

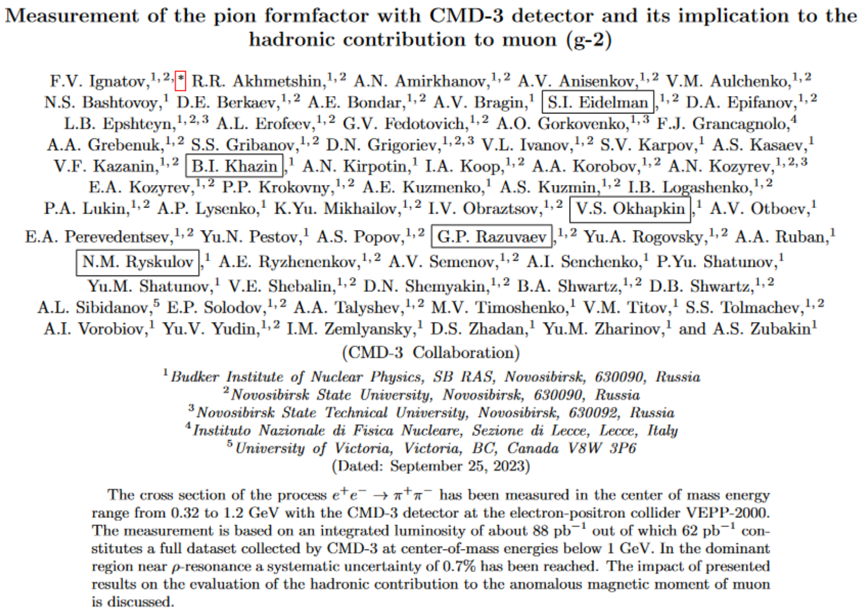


$$\frac{1}{4\pi^3}\int_{0.6}^{0.88} \sigma^0(e^+e^- \to \pi^+\pi^-)K_\mu(s)ds$$

CMD-3 measurement of $e^+e^- \to \pi^+\pi^-$ cross section (2023)

Publications

arXiv:2309.12910



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

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(CMD-3 Collaboration)

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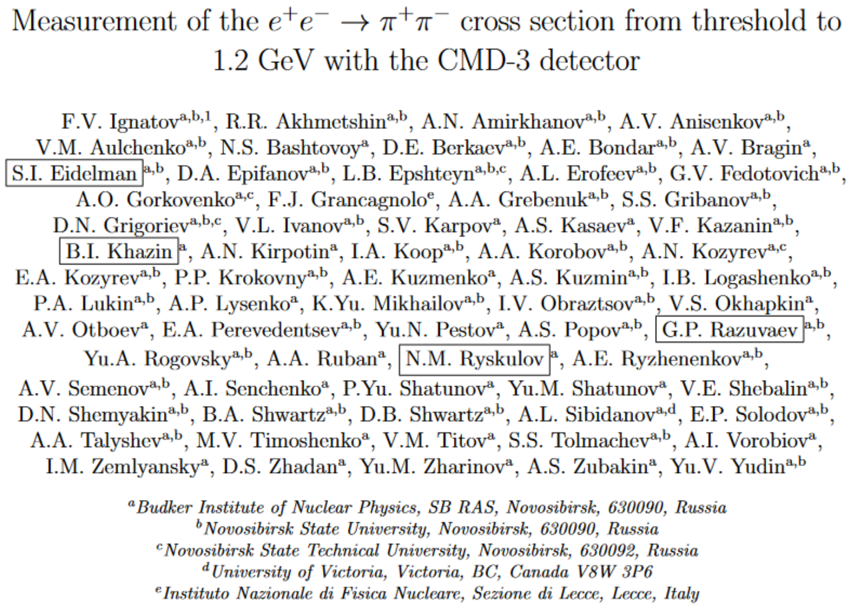
(Dated: September 25, 2023)

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

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*
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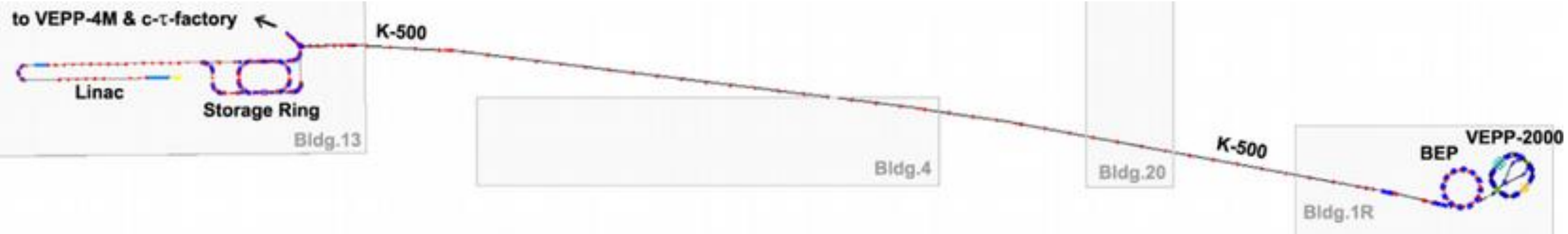
Submitted to PRD

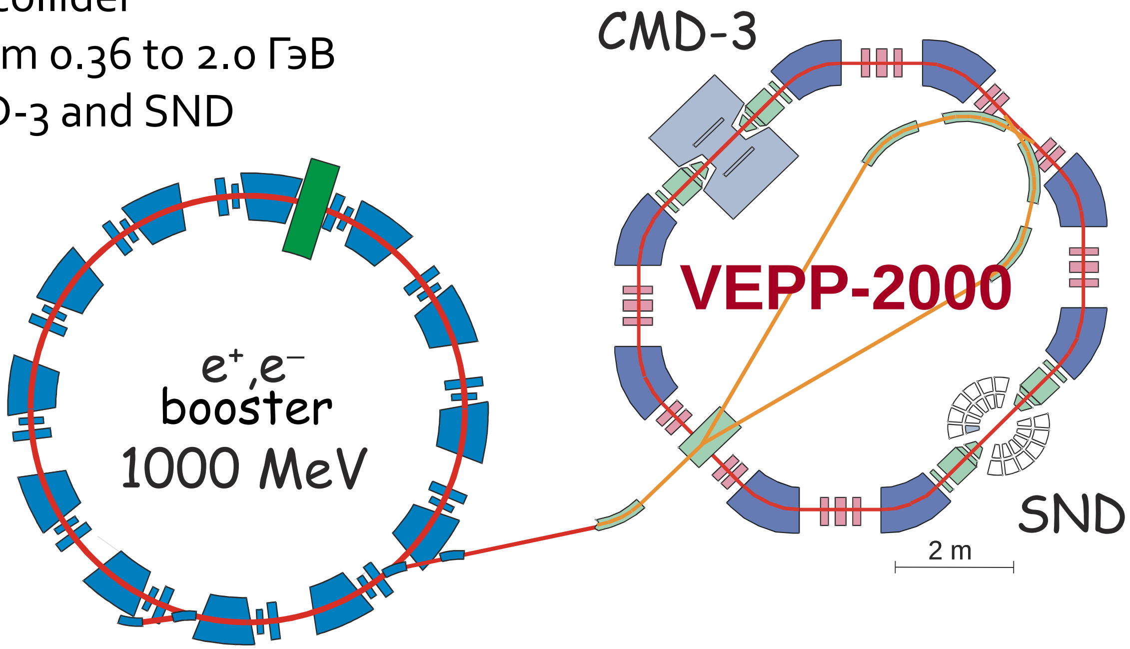
There were 2 dedicated reviews of CMD-3 measurement, organized by Theory Initiative

VEPP-2000 collider (BINP, Novosibirsk)



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

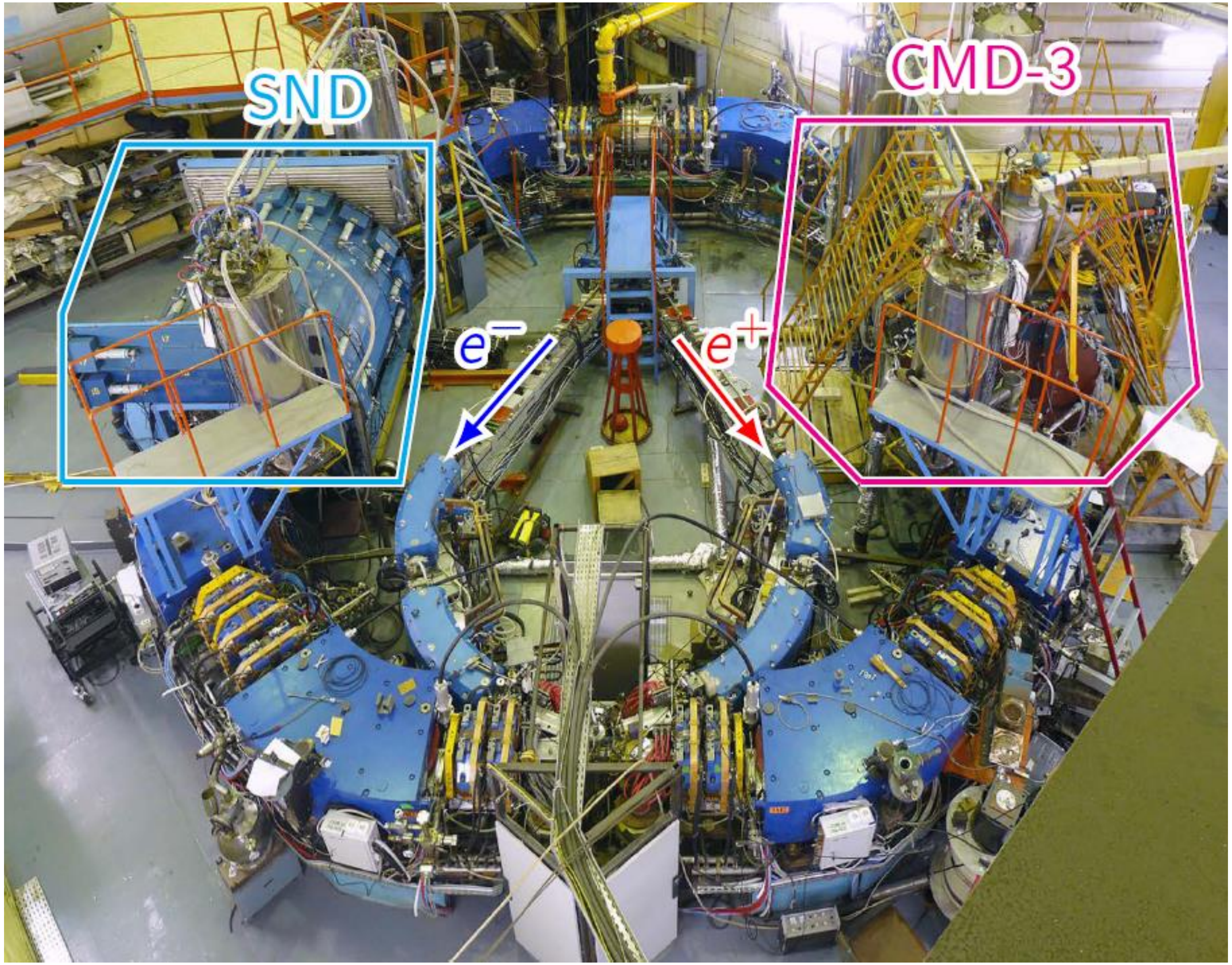
Design parameters @ 1 GeV	
Circumference	24.388 m
Beam energy	150 ÷ 1000 MeV
N of bunches	1×1
N of particles	1×10^{11}
Betatron tunes	4.14 / 2.14
Beta*	8.5 cm
BB parameter	0.1
Luminosity	1×10^{32} cm^{-2}s^{-1}



“Round beam” optics

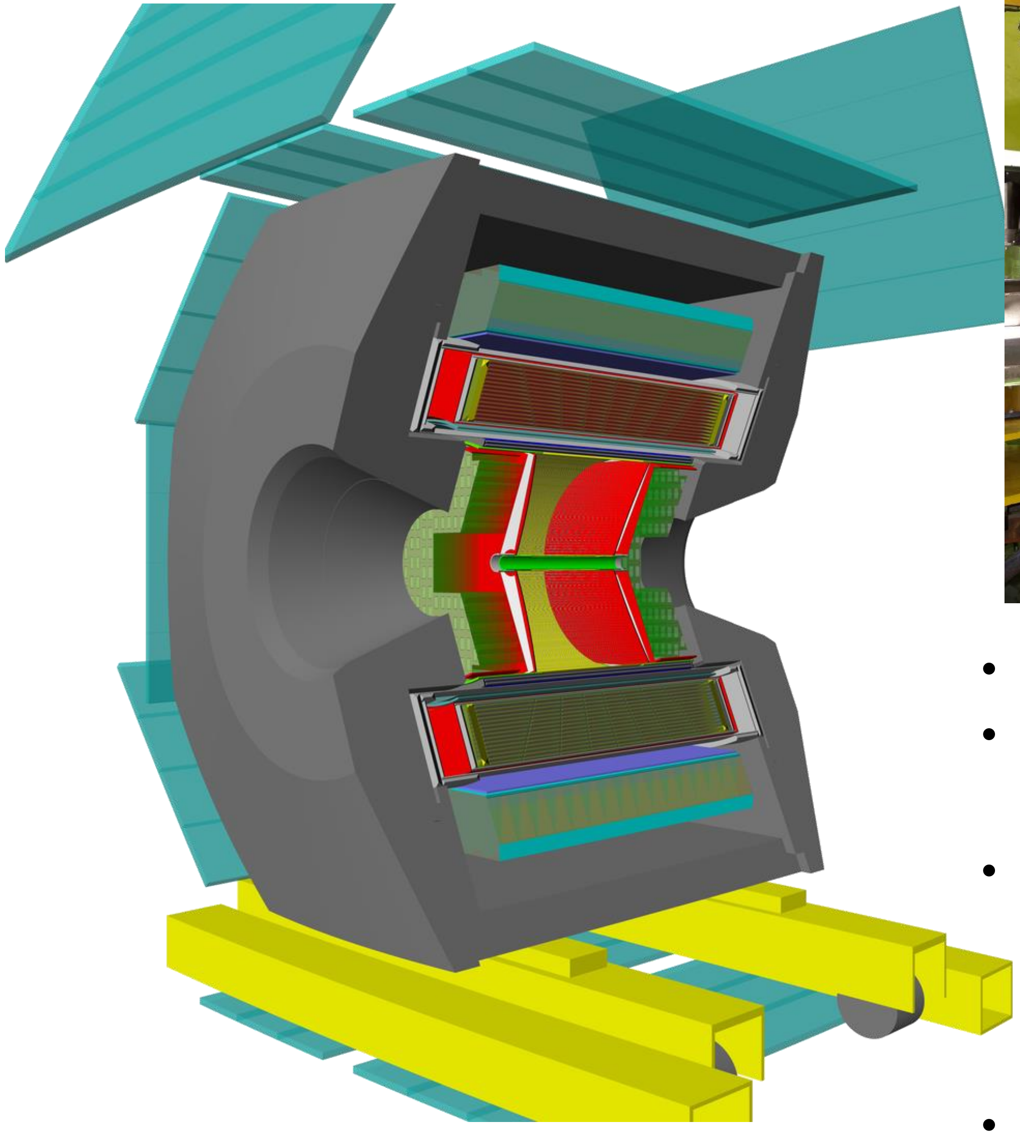
Energy monitoring by Compton backscattering ($\sigma_{\sqrt{s}} \approx 0.1$ MeV)

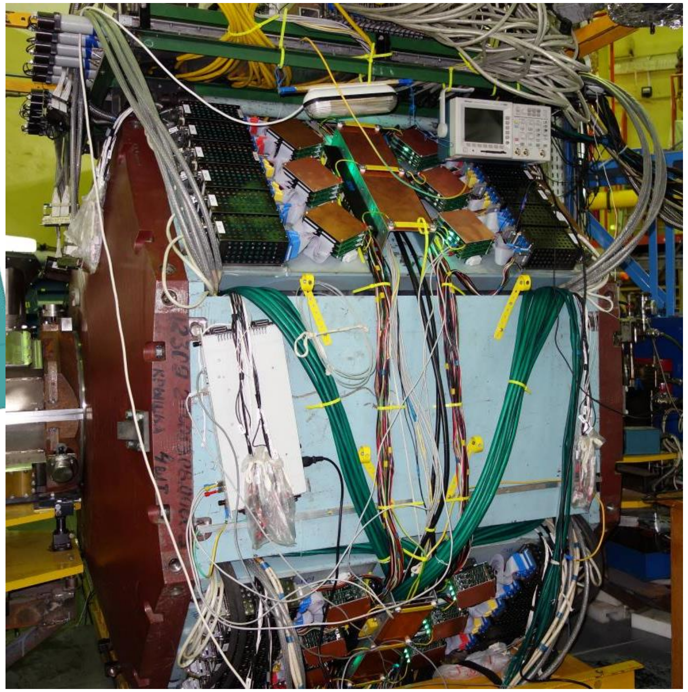
VEPP-2000



CMD-3 Detector

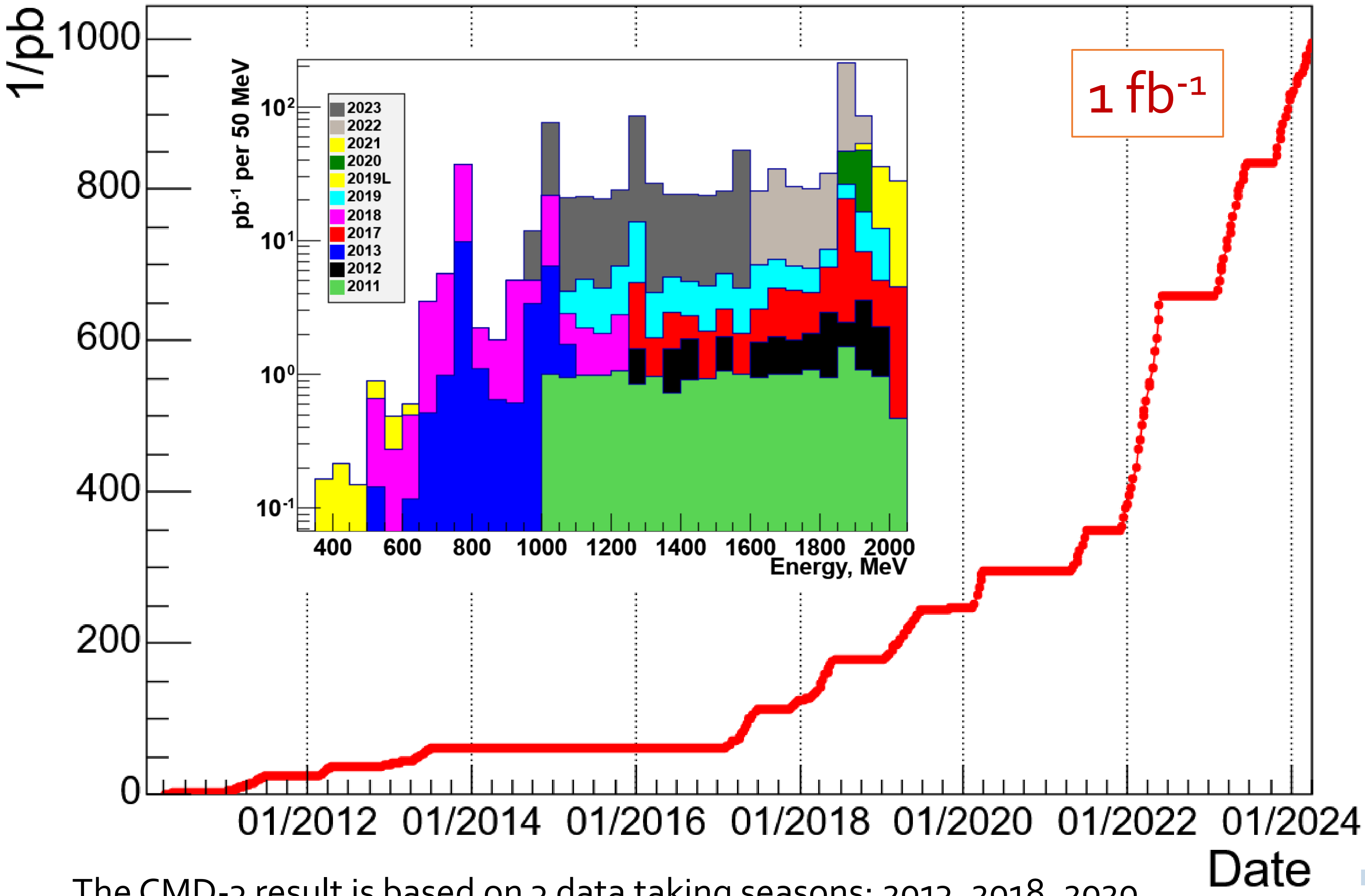
*Cryogenic Magnetic Detector





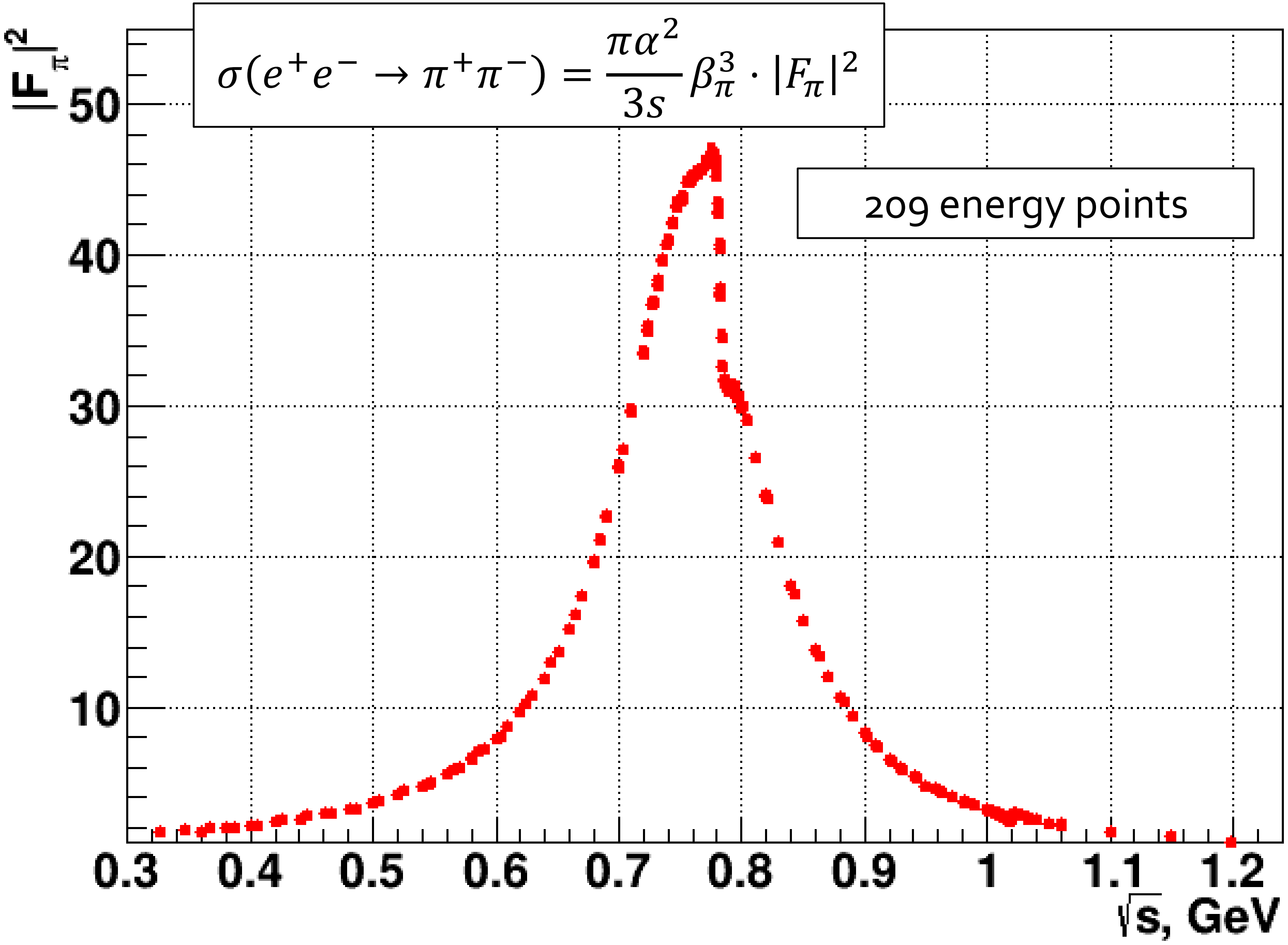
- Magnetic field 1.0-1.3 T
- Drift chamber
  - $\sigma_{R\varphi} \sim 100\ \mu, \sigma_z \sim 2-3\ \mathrm{mm}$
- EM calorimeter (LXE, CsI, BGO), 13.5 X_0
  - $\sigma_E/E \sim 3\% - 10\%$
  - $\sigma_\Theta \sim 5$ mrad
- TOF
- Muon counters

Collected data



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

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

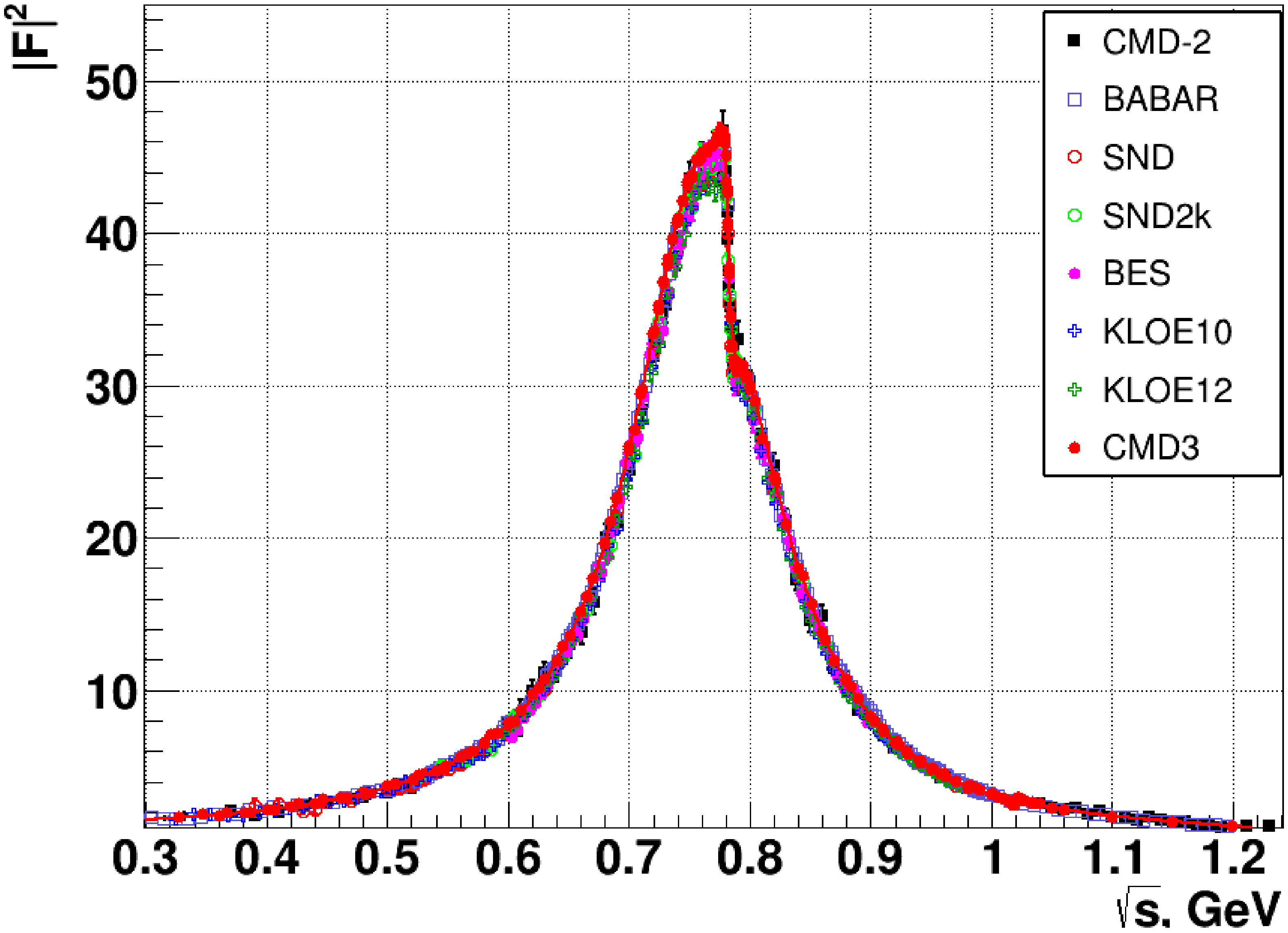


$$\sigma(e^+e^- \to \pi^+\pi^-) = \frac{\pi\alpha^2}{3s}\beta_\pi^3 \cdot |F_\pi|^2$$

209 energy points

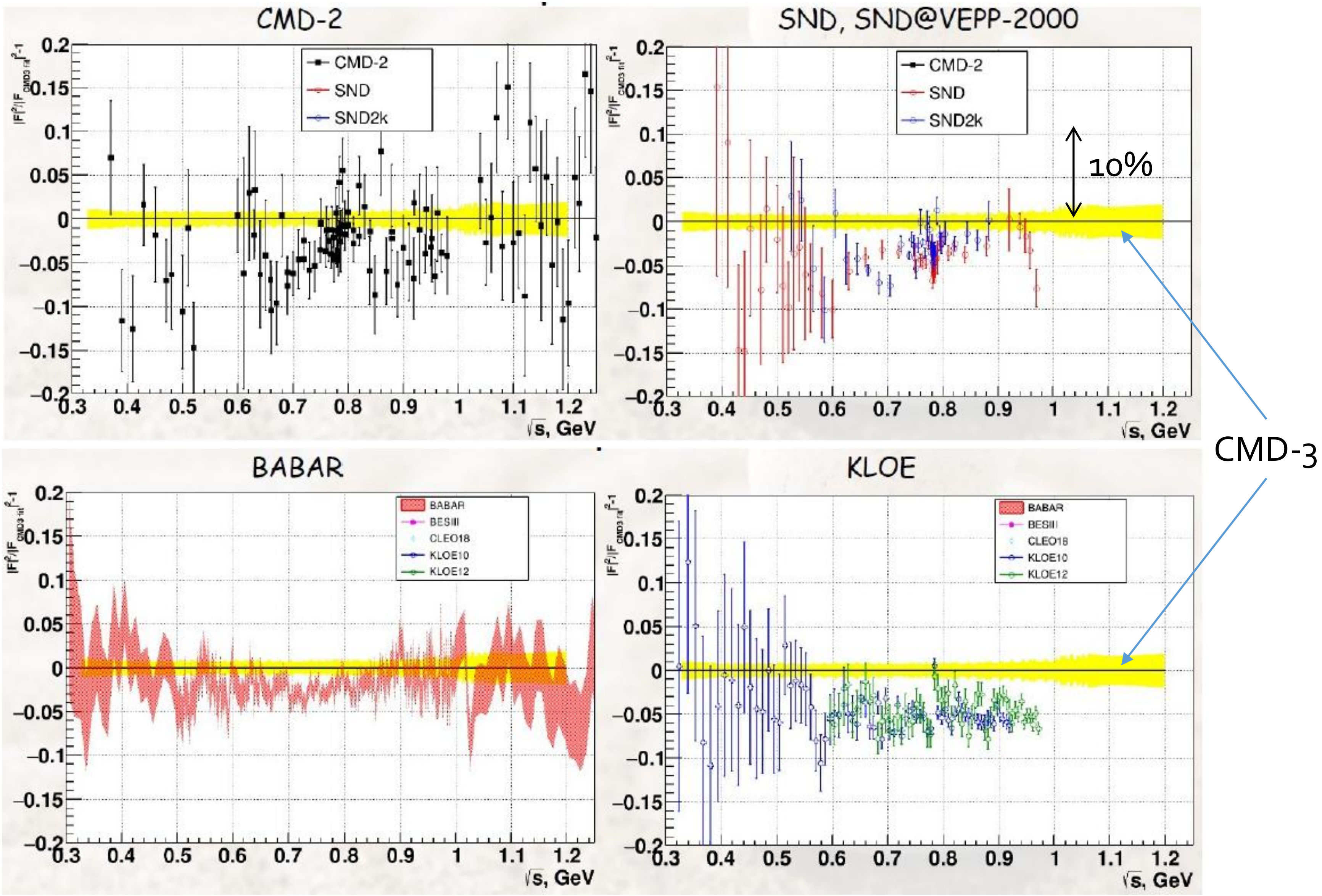
Comparison to other measurements

At first glance, they looks close to each other…



Comparison to other measurements

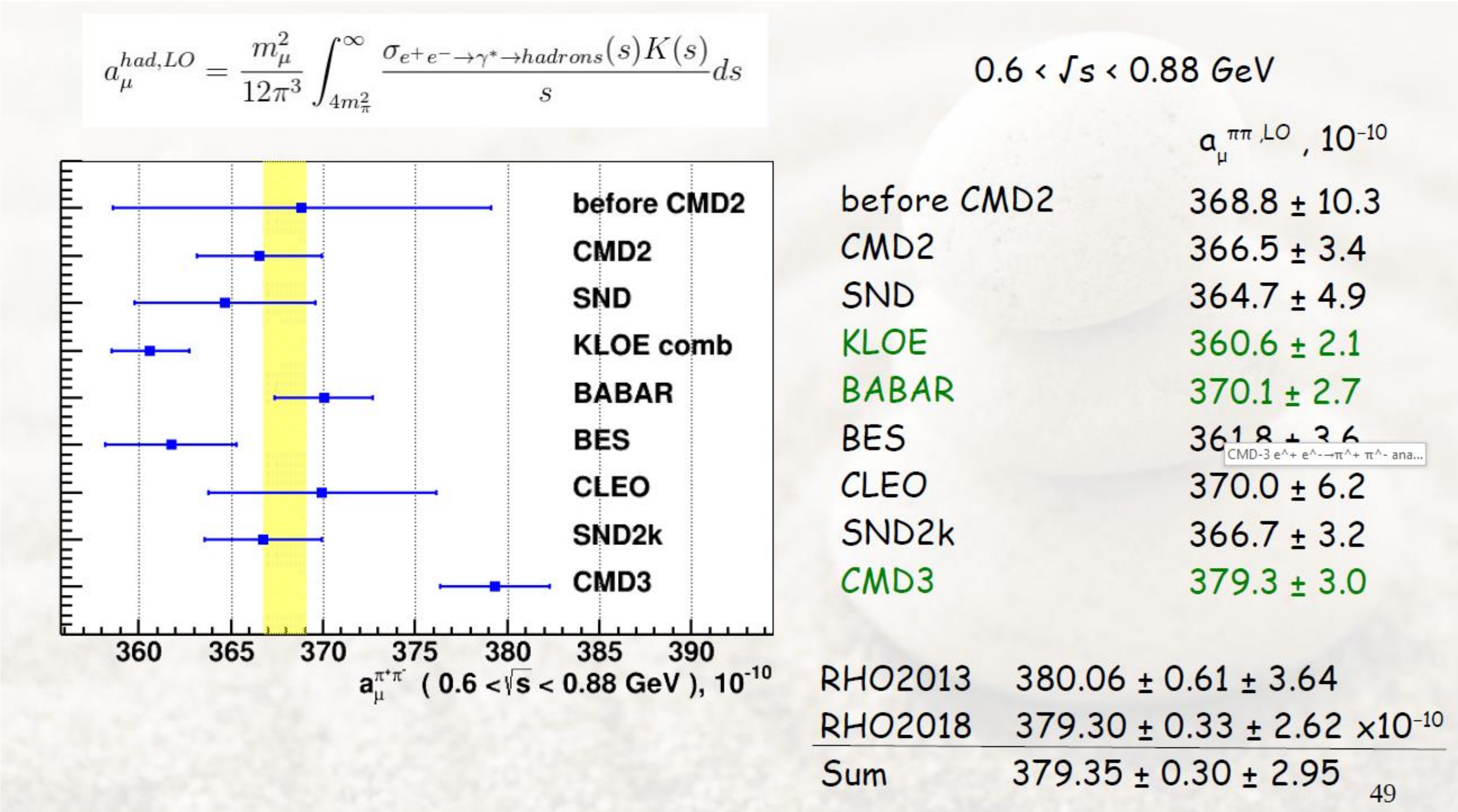
CMD-3 is systematically above previous measurements by ~2-5%



10%

CMD-3

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



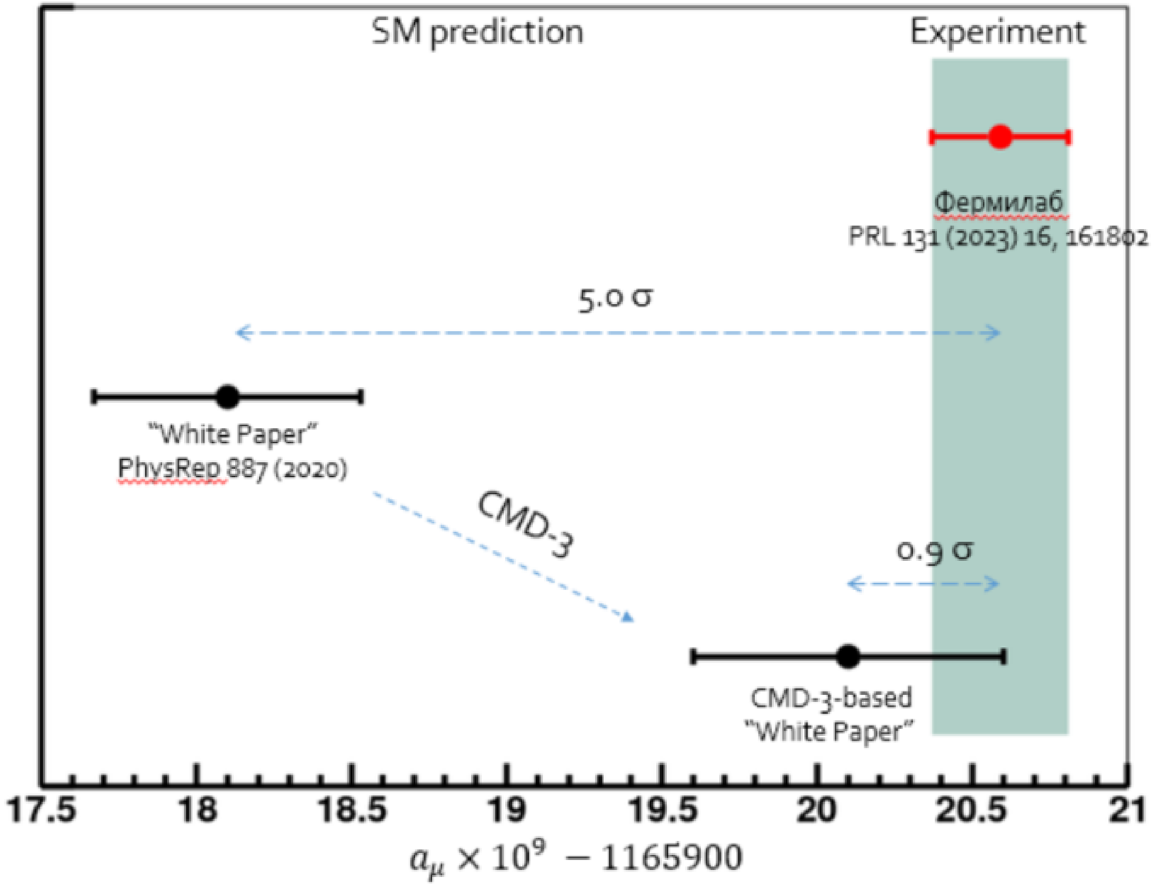
$$a_\mu^{had,LO} = \frac{m_\mu^2}{12\pi^3}\int_{4m_\pi^2}^{\infty}\frac{\sigma_{e^+e^-\to\gamma^*\to hadrons}(s)K(s)}{s}ds$$

$0.6 < \sqrt{s} < 0.88$ 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

Experiment vs SM prediction

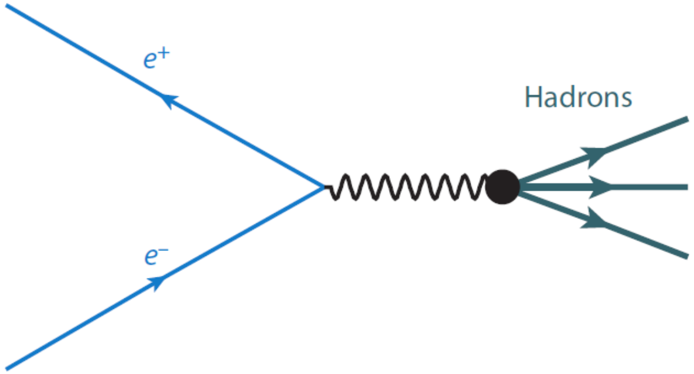


At the moment, the SM prediction for a_μ is unclear (due to hadronic contribution)

Looking deeper

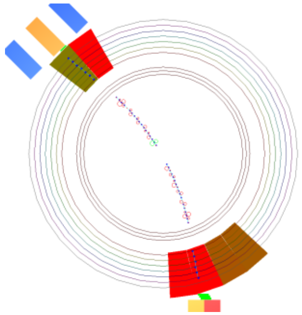
Measurement techniques:

Direct vs ISR

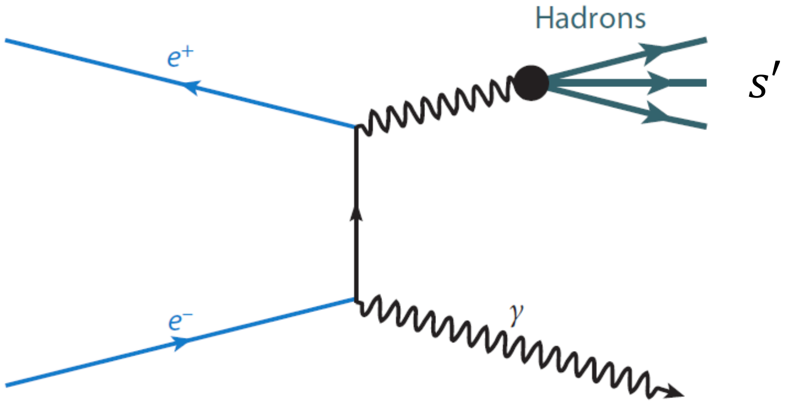


Direct measurement (Energy scan)

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

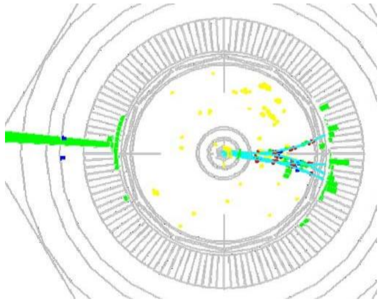


VEPP-2M: CMD-2, SND
VEPP-2000: CMD-3, SND2k



ISR (Initial State Radiation)

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



KLOE, BABAR, BES-III, CLEO

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

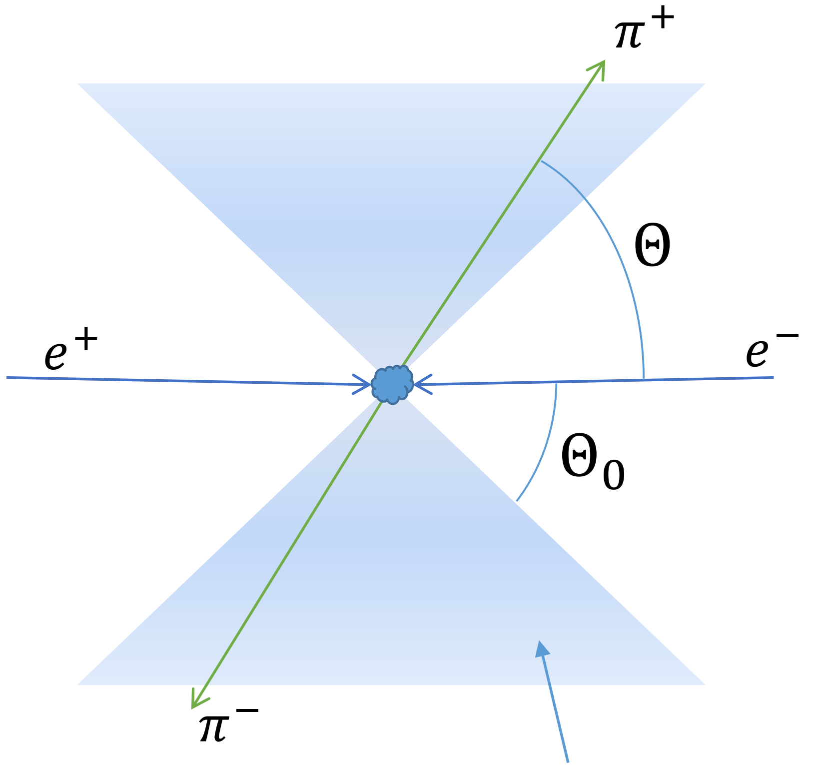
$$\sigma(\pi^+\pi^-) = \frac{\pi\alpha^2}{3s}\beta_\pi^3 \cdot |F_\pi|^2$$

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

measured Born cross-section Detection efficiencies

Radiative corrections

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



fiducial volume

$\Theta_0 \le \Theta_{avr} \le (\pi - \Theta_0)$

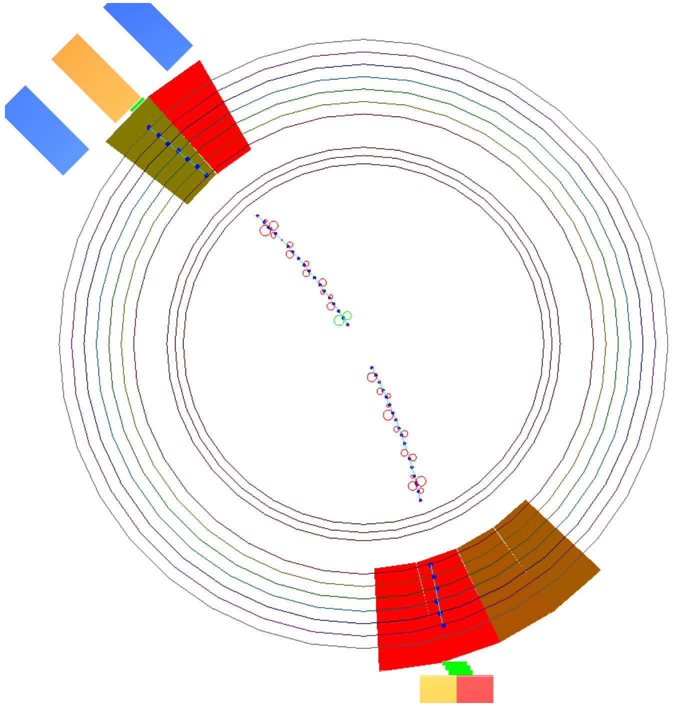
$\Theta_0 = 1.0 \ldots 1.4$

Classification of $e^+e^- \rightarrow \pi^+\pi^-$ measurements

Exp	Type	N 2π	Syst	Sep	Norm
CMD-3	Direct	$3 \cdot 10^7$	0.7%	P/E/Θ	$e^+e^- / \mu^+\mu^-$
CMD-2	Direct	10^6	0.6-0.8%	P or E	e^+e^-
SND	Direct	$4.5 \cdot 10^6$	1.3%	E-NN	e^+e^-
SND2k	Direct	10^6	0.8%	E-NN	e^+e^-
BABAR	ISR		0.5%	Kin	$\mu^+\mu^- + e^+e^-$
KLOE08	ISR		0.9%	E-TOF	e^+e^-
KLOE10	ISR		1.4%	E-TOF	e^+e^-
KLOE12	ISR		0.7%	Kin	$\mu^+\mu^-$

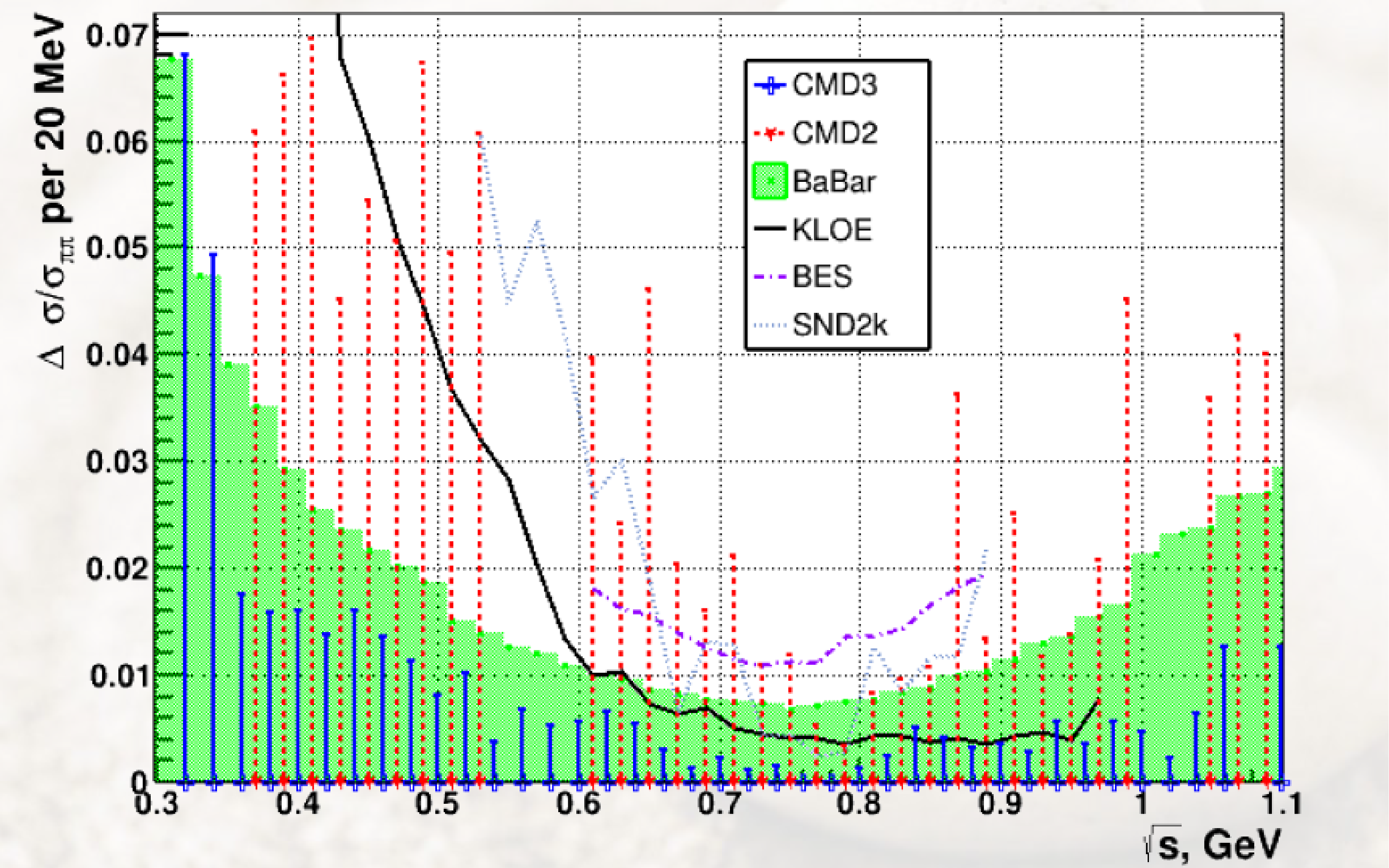
Features of CMD-3 measurement

- 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



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 $e^+e^-, \mu^+\mu^-, \pi^+\pi^-$

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

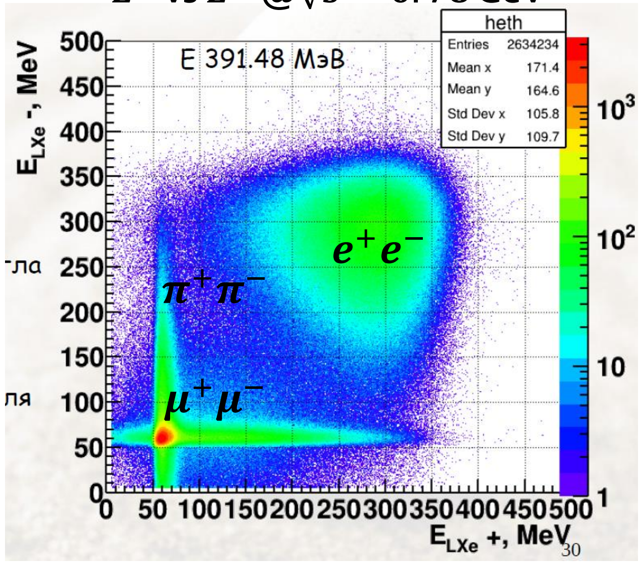
$$-\ln L = -\sum_{bins} n_i \ln\left[\sum_{a=ee,\mu\mu,\pi\pi,bg} N_a f_a(X^+,X^-)\right] + \sum_{a} N_a$$

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

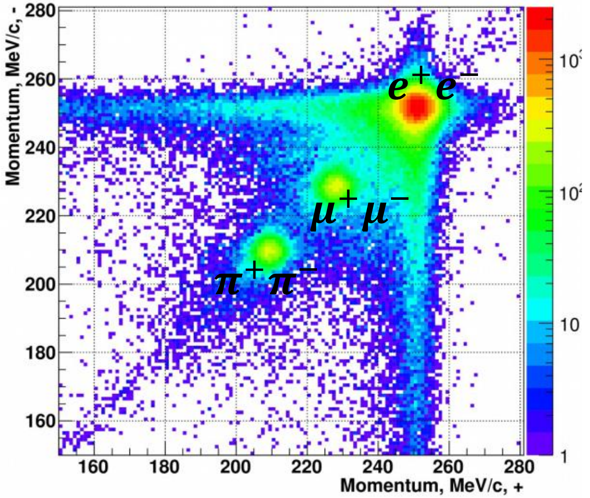
$\pm$ sign reflects energy deposition and momentum of particle with corresponding charge

Independent check by **angular distribution**

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



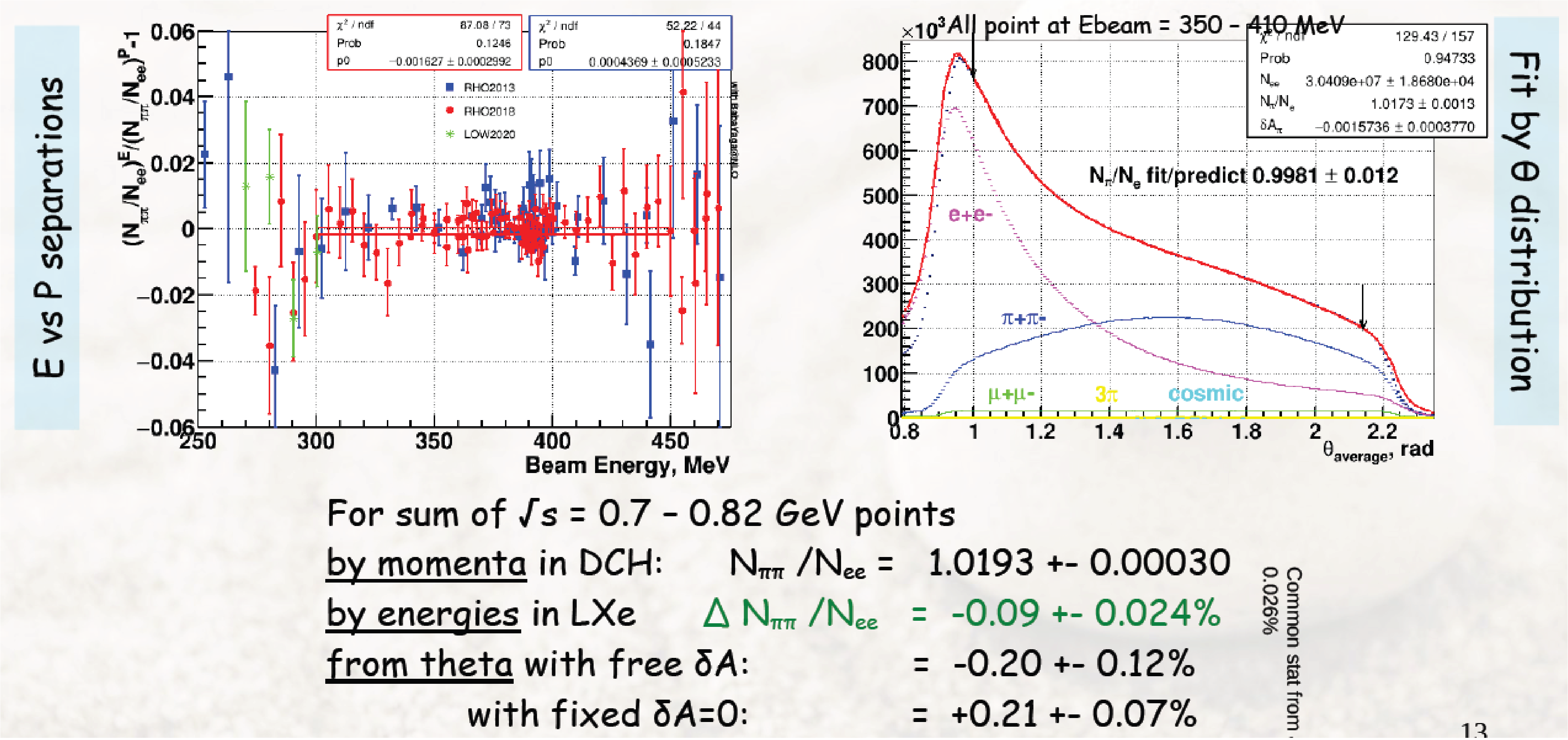
P^- vs P^+ @$\sqrt{s} = 0.5$ GeV



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

Comparison

Three methods agree to 0.2%!



For sum of √s = 0.7 - 0.82 GeV points

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

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

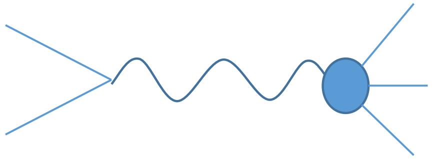
from theta with free δA: = -0.20 +- 0.12%

with fixed δA=0: = +0.21 +- 0.07%

Common stat from
0.026%

13

Radiative corrections



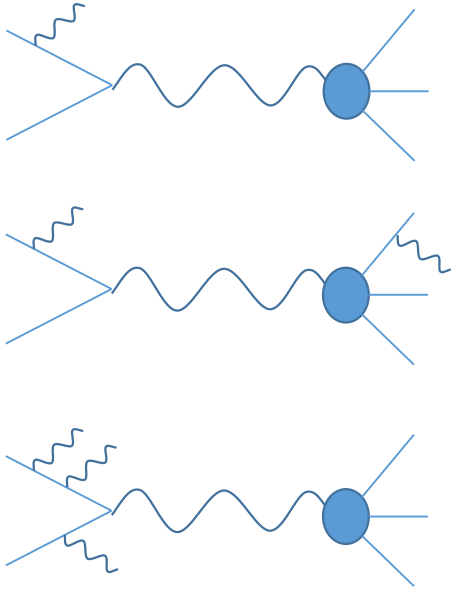
We want to measure $e^+e^- \to H$, but these events are accompanied by similar events where photons are emitted by any of the particles.

Have to correct visible cross-section – *radiative corrections*

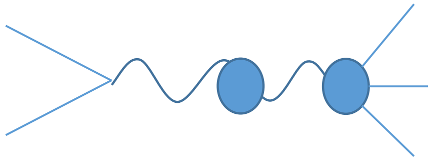
- MCGPJ (X^+X^-) (VEPP-2000)
  1 real γ (from any particle) + jets along all particles
- BABAYAGA@NLO (e^+e^-)
  1 real γ + $n\gamma$ generated iteratively by emitting one γ at a time
- PHOKHARA
  Many final states, intended for ISR measurements

Typical estimated precision – 0.1-0.2%

Radiative processes



ISR FSR
Initial *Final*
state radiation



Vacuum polarization

CMD-3 $e^+e^- \to \pi^+\pi^-$ analysis: radiative corrections

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

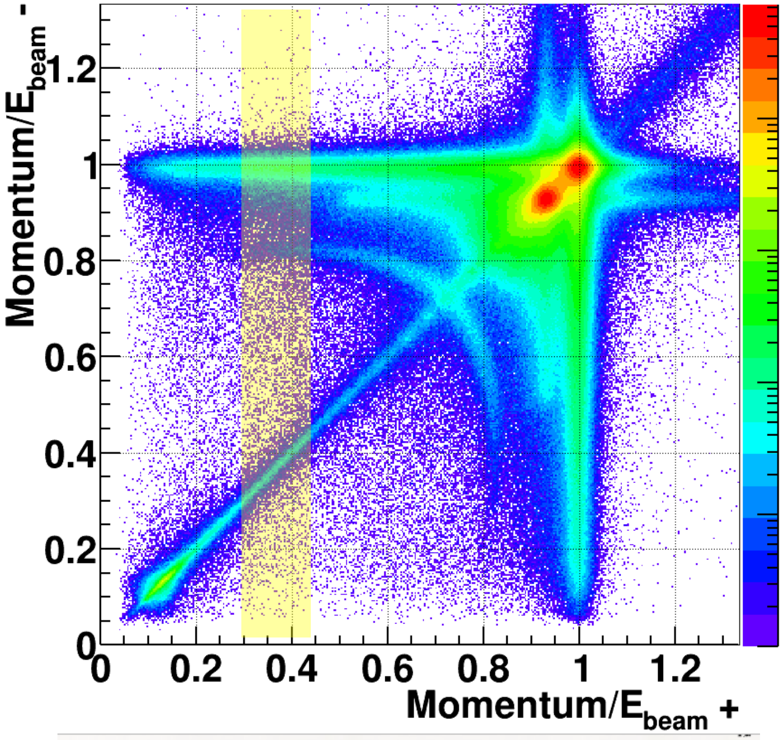
We use two high-precision MC generators for $e^+e^- \to e^+e^-$:

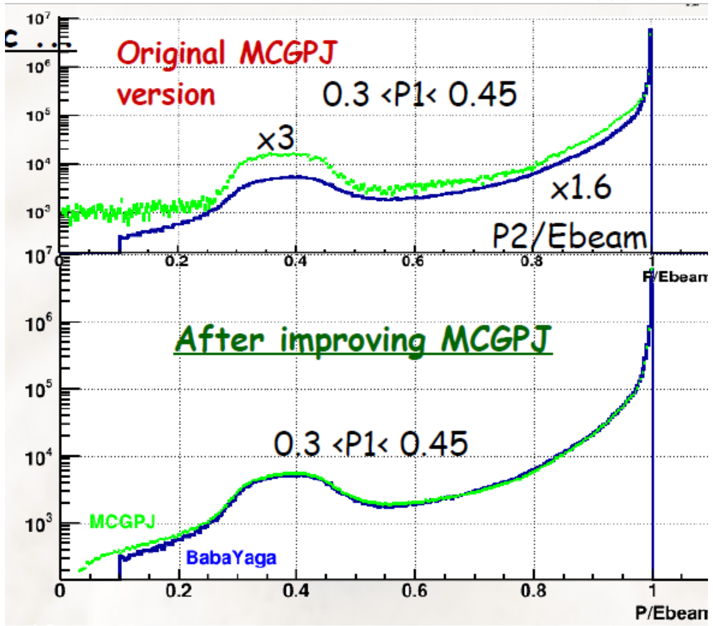
- MCGPJ generator (0.2%)
- BaBaYaga@NLO (0.1%)

With high statistics we've observed inconsistencies in tails of distributions, which were traced to particulars of MCGPJ generator

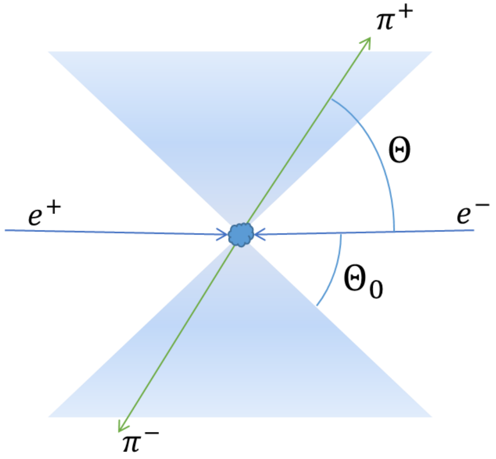
After improvements, tails of e^+e^- spectra still differ by few %, which limits the precision to O(0.1%)

NNLO MC generator for $e^+e^- \to e^+e^-$ is needed for higher precision





Measurement of polar angle

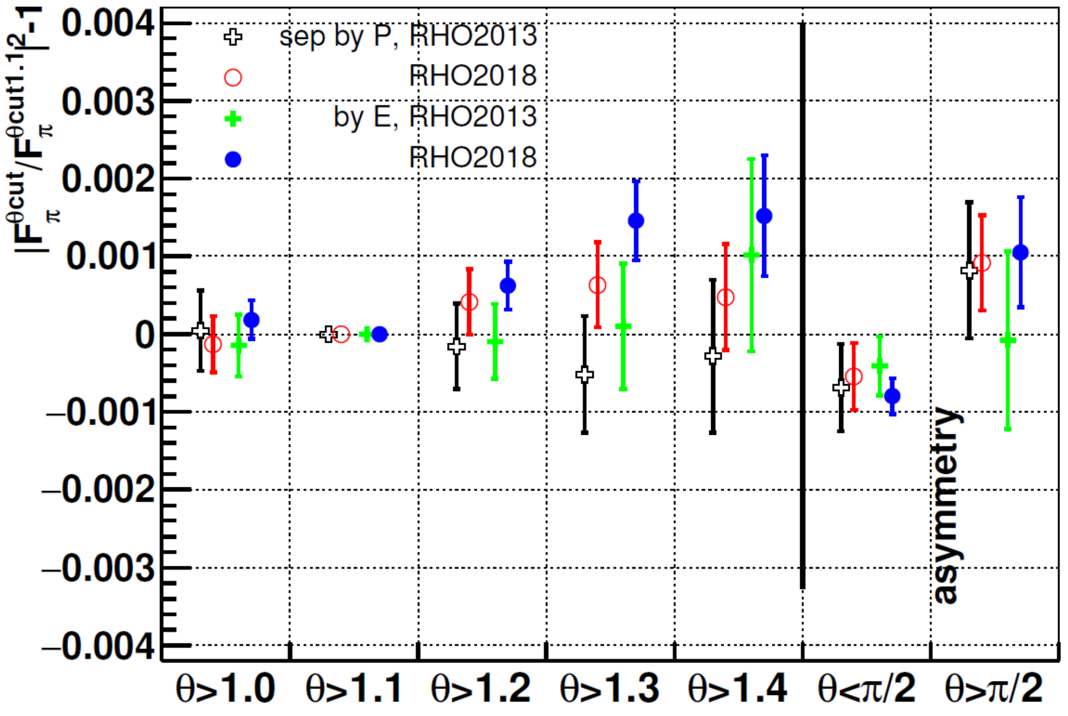


Θ angle is measured by drift chamber via charge division

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).

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



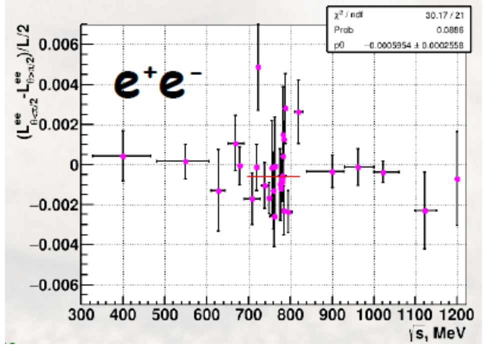
Dependence of result on Θ_0 cut

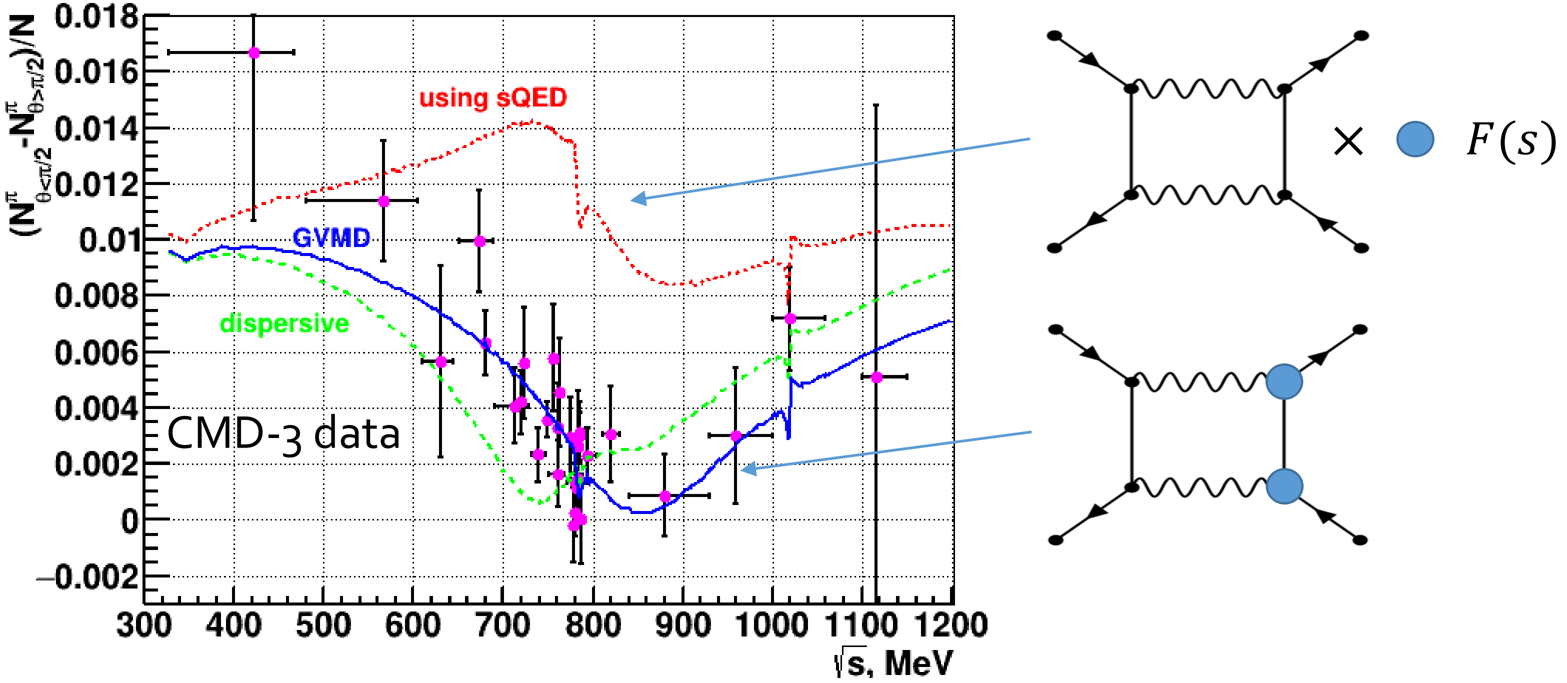
Factor 10 smaller compared to CMD-2, SND2k!

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

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





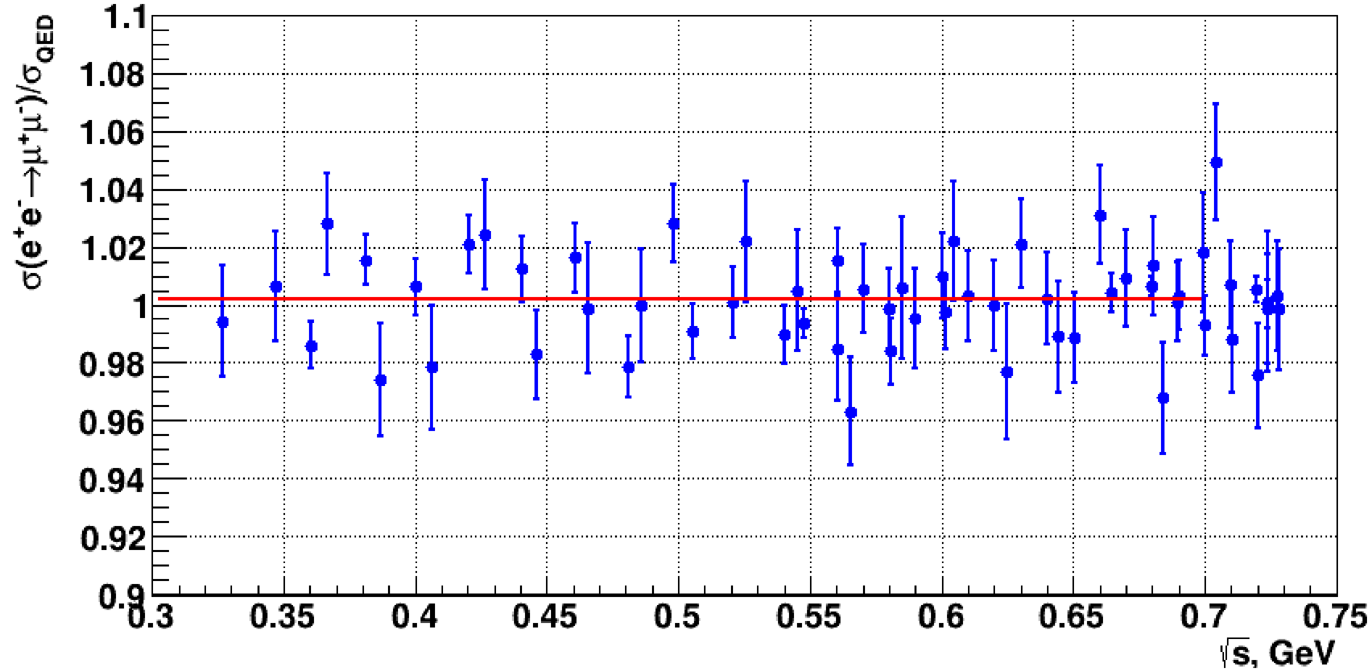
The theoretical model by Lee, Ignatov, PLB 833 (2022) 137283 (GVDM) describes well the CMD-3 data

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

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

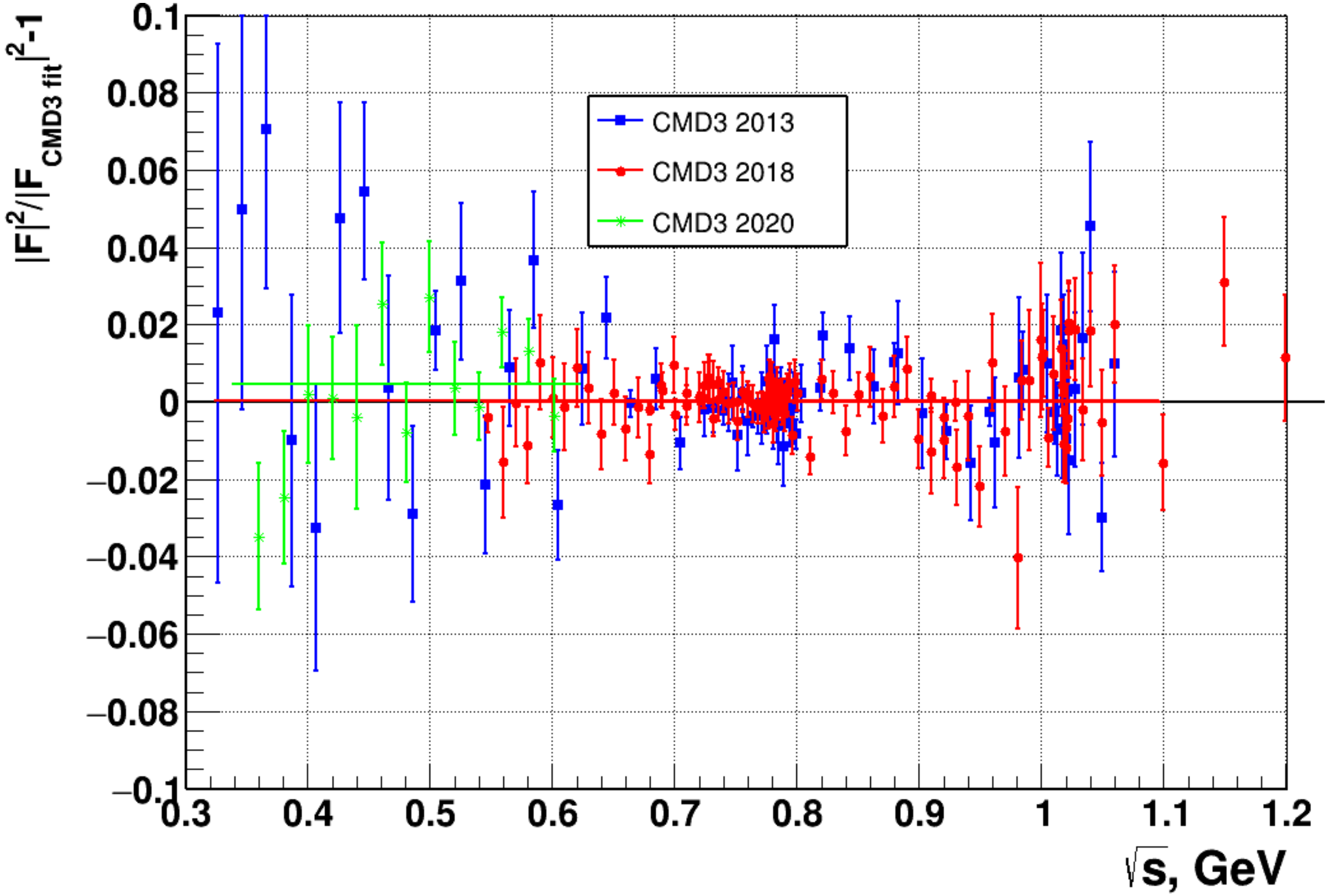
$$\sigma(e^+e^- \to \mu^+\mu^-)_{CMD3}/\sigma(e^+e^- \to \mu^+\mu^-)_{QED}$$



+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.

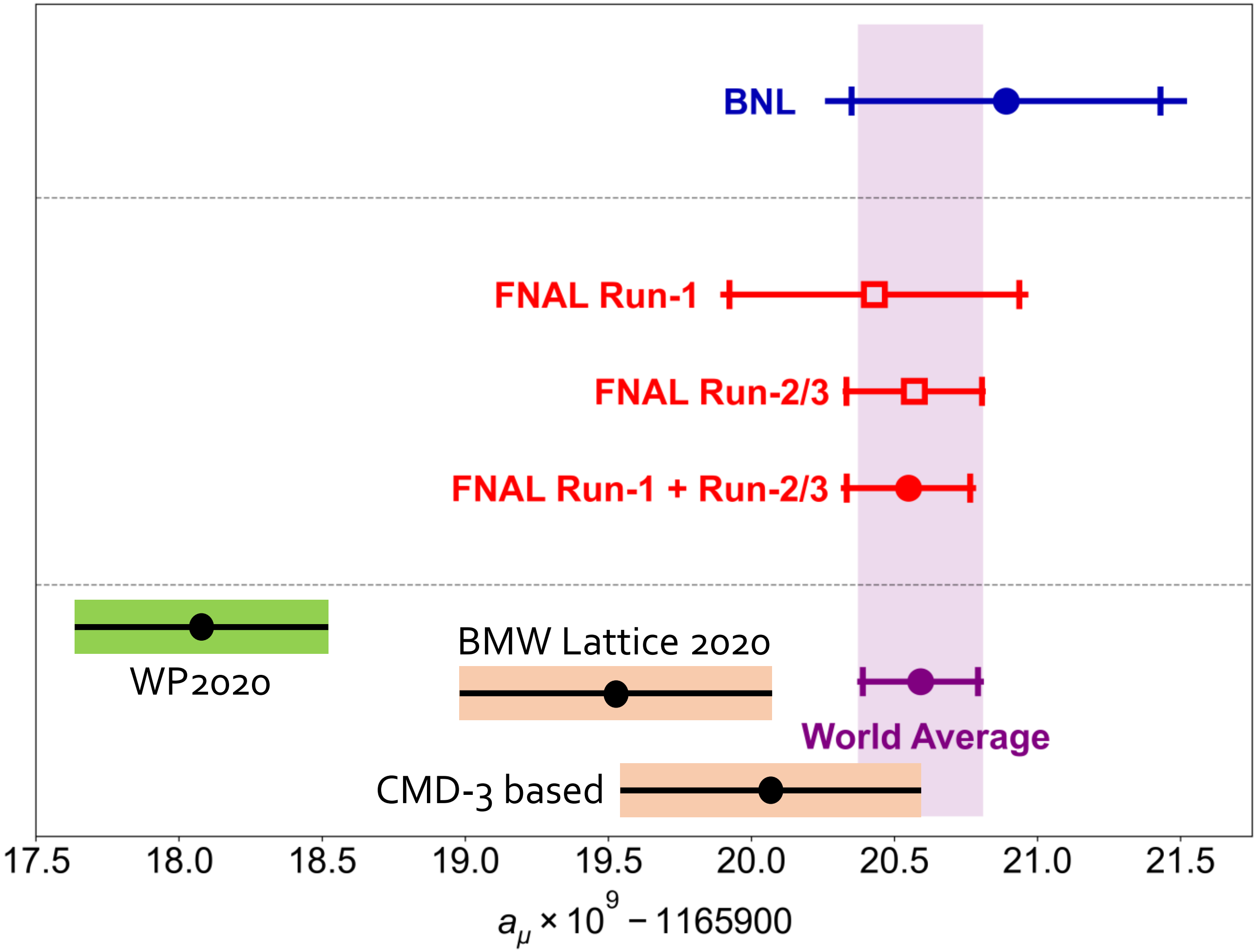
Comparison of data taking seasons



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.

What’s next

Experiment vs SM prediction (2024)



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

Question #1

What to do with CMD-3?

We cannot simply average CMD-3 measurement with other measurements

CMD-3 result is incompatible with previous measurements

- If CMD-3 is right, other are wrong
- If previous measurements are right, CMD-3 is wrong
- Or they all are wrong

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 $e^+e^- \rightarrow \pi^+\pi^-$?
  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

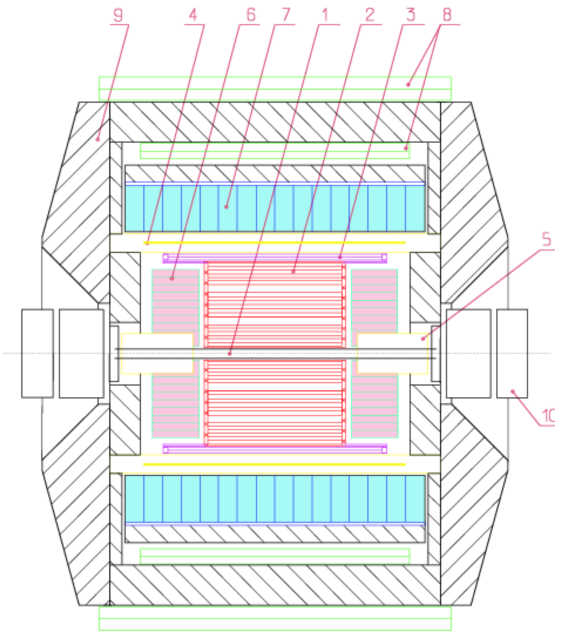
Similarities:

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

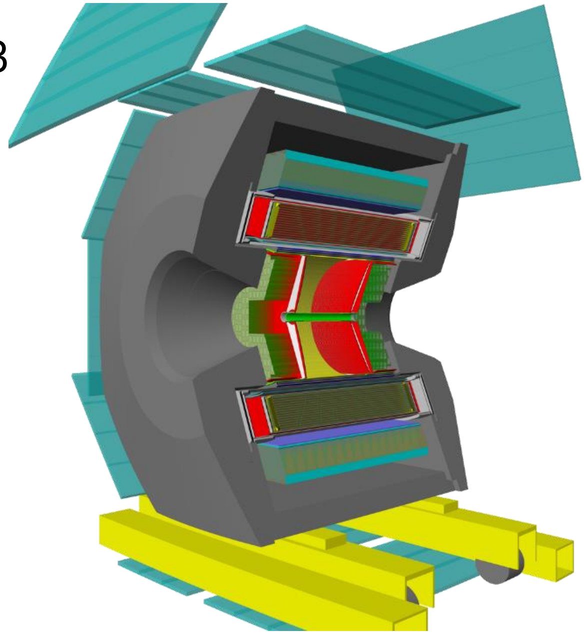
Differences:

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

CMD-2



CMD-3



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

Prospects for SM prediction

Discrepancies in $e^+e^- \rightarrow H$ 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 $e^+e^- \rightarrow H$ 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)
- BELLE-II plans to do ISR measurement of $e^+e^- \rightarrow H$ cross sections
- KLOE-2 started analysis of data not analyzed before

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

Question #2

Accuracy of hadronic contribution

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

$\Delta a_\mu(BSM)$ 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.

Possible scenario

Final state	Required precision	Precision today
$\pi^+\pi^-$	0.2%	0.8%
$\pi^+\pi^-\pi^0$	1.0%	1.5-3%
$\pi^+\pi^-\pi^+\pi^-$	0.8%	2-3%
$\pi^+\pi^-\pi^0\pi^0$	2.5%	5%
K^+K^-	0.6%	2%
K_SK_L	0.7%	2%

CMD-3 plans

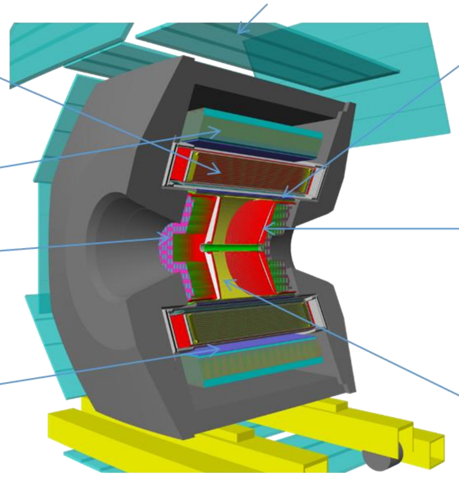
The CMD-3 measurement is systematically limited – detector upgrade.

Detector upgrades under discussions: new drift chamber, new Z-chamber at inner and outer radii (probably, integrated with DC),…

The goal is to reach ~0.3-0.4% in $\sigma(e^+e^- \to \pi^+\pi^-)$

Key improvements:

- Separation of final states (PID)
- Angle measurement
- Nuclear interactions of pions



LXe
Ремонт и замена электроники

Mu
Добавить слои

ZK
Замена цилиндрической Z-камеры

CsI

BGO
Ремонт и замена электроники

ТКС
Установка новой торцевой координатной системы

TOF
Нет планов

ДК
Замена дрейфовой камеры

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

VEPP-6

We are considering a new collider at BINP (VEPP-6)

- e^+e^- collider
  - Beam energy from <0.5 to 1.6 GeV (J/ψ) (2.2 GeV)
  - Luminosity $\mathcal{L} \approx 10^{34}\ cm^{-2}c^{-1}$ @ 1.6 GeV
- General purpose detector
  - Tracking
  - Calorimetry
  - Particle ID
- Physics
  - Measurement of R (cross sections $e^+e^- \to H$)
  - J/ψ decays
  - Baryon thresholds
  - τ, open charm
  - ...

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

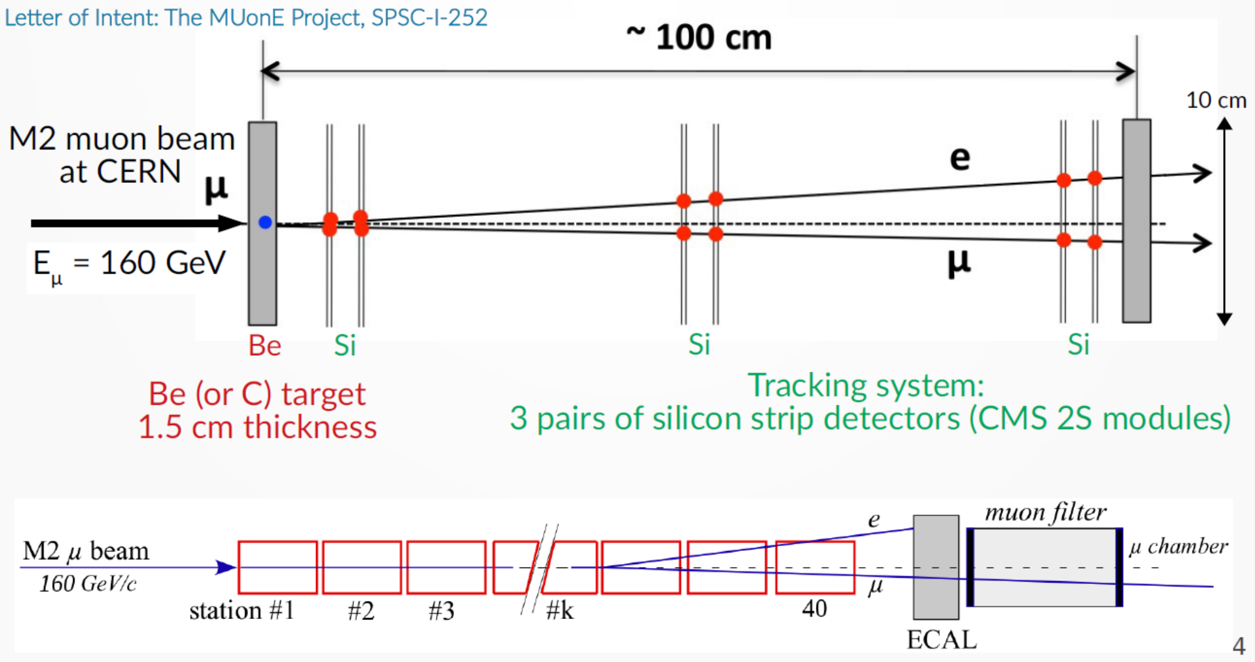
VEPP-6 should be capable to measure R to necessary precision

MUonE @CERN

Dedicated experiment to measure hadronic contribution in t-channel.

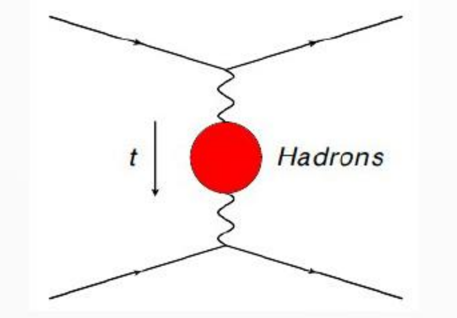
$$\boxed{a_\mu^{HLO} = \frac{\alpha_0}{\pi}\int\limits_0^1 dx(1-x)\Delta\alpha_{had}[t(x)]}$$

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


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

Be (or C) target
1.5 cm thickness

Tracking system:
3 pairs of silicon strip detectors (CMS 2S modules)

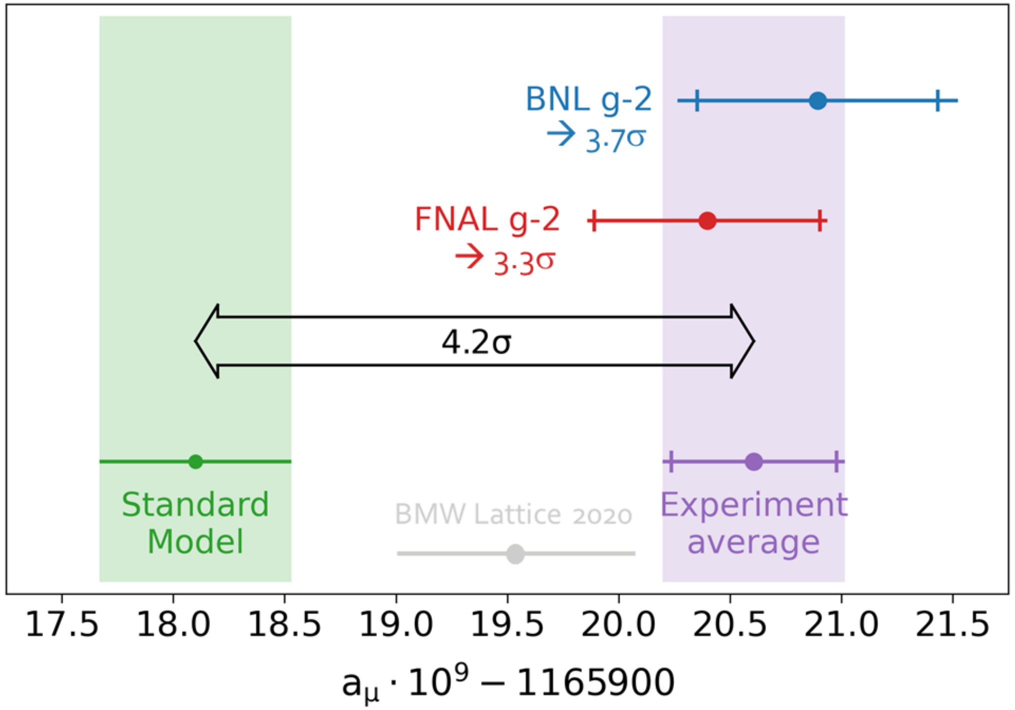


Measured: angular distribution of μe scattering; $4 \cdot 10^{12}$ events!

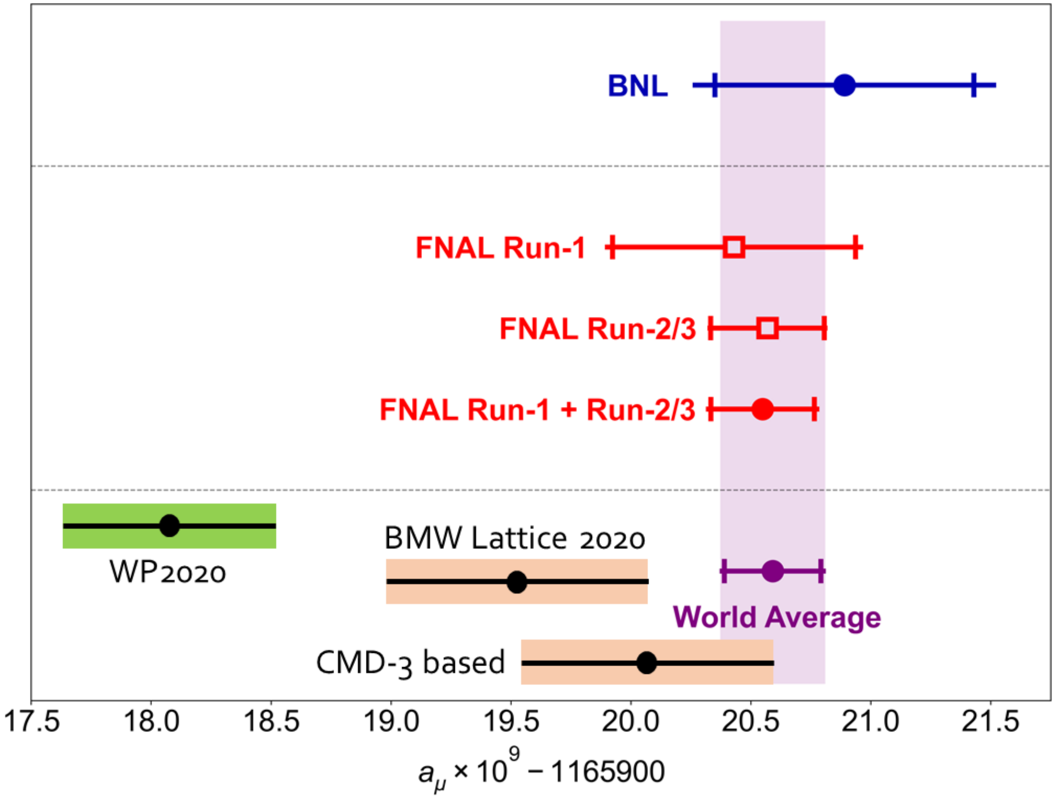
Now: proof-of-concept data taking; final result after LHC LS3 (2029-)

Conclusion

At the beginning of 2023

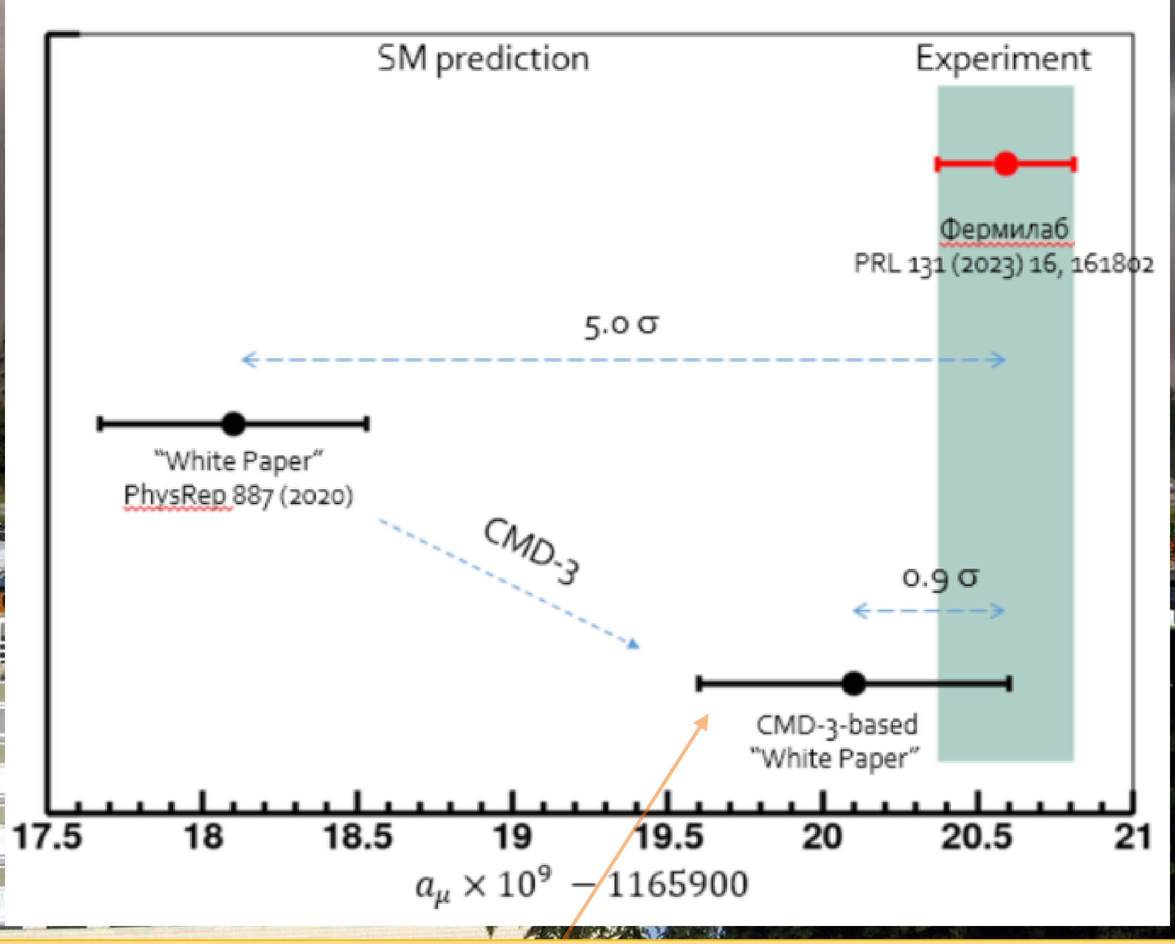


At the end of 2023



Conclusion

Conclusion



Quest for next-generation experiments: reduce these error bars
Ultimate goal: Hadron data = Lattice QCD = MuONe