arXiv:2302.08834

Recent e+e- → π+π- measurement with the CMD-3 detector

Fedor Ignatov

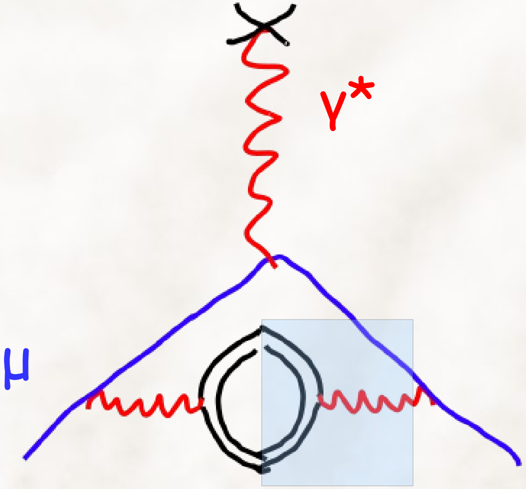
19 May 2023
Particle Physics Annual Meeting
Liverpool

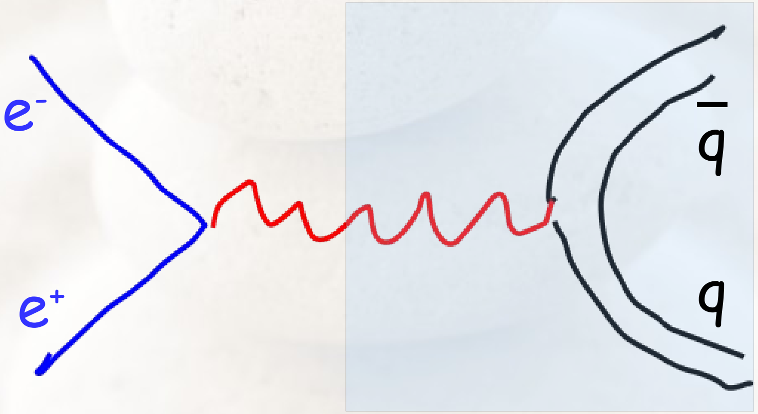
g-2 and e+e- → hadrons

Muon precession anomaly (g-2)/2
via vacuum polarization

is related to

e+e- to hadrons production



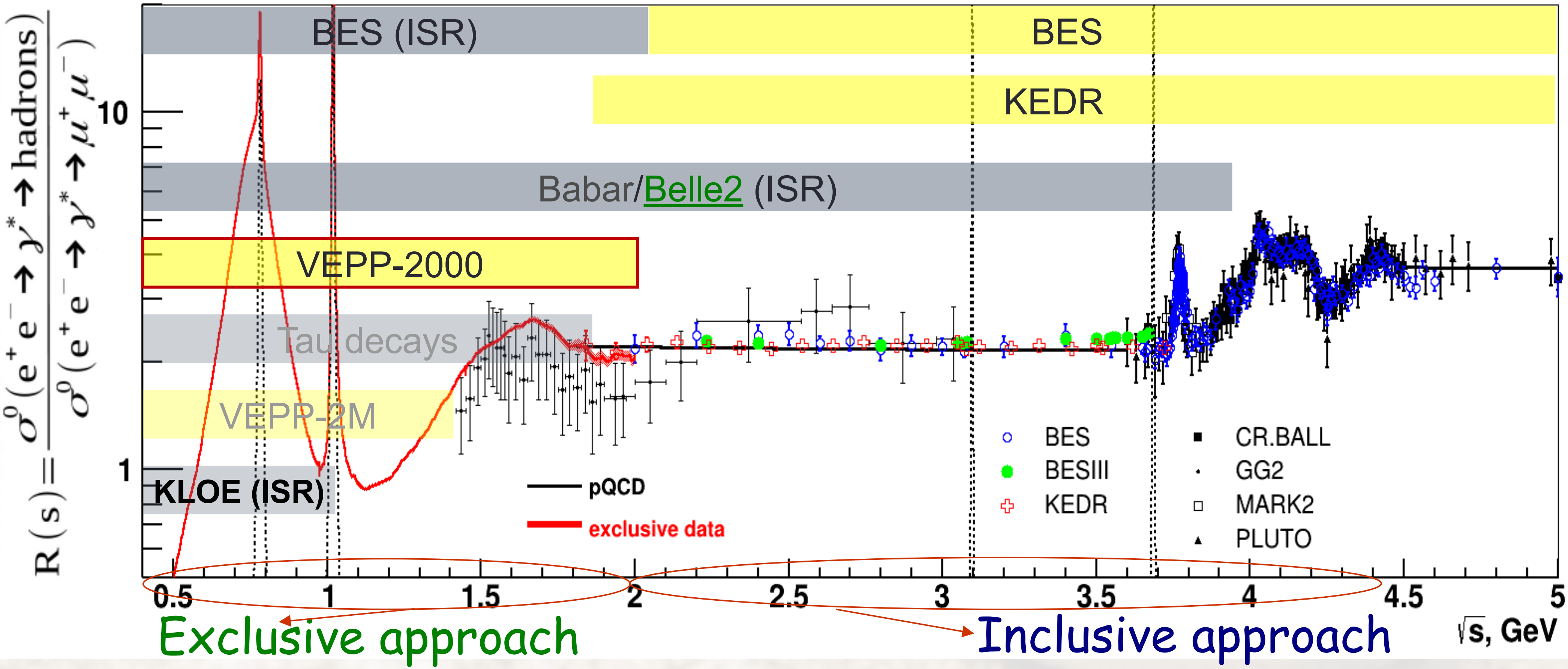


$$a_\mu^{had,LO} = \frac{m_\mu^2}{12\pi^3}\int_{4m_\pi^2}^{\infty} \frac{\sigma_{e^+e^-\to\gamma^*\to hadrons}(s)K(s)}{s}ds$$

Dispersion relation is based on analyticity and the optical theorem

R(s) measurement

Two techniques: ISR vs Energy scan



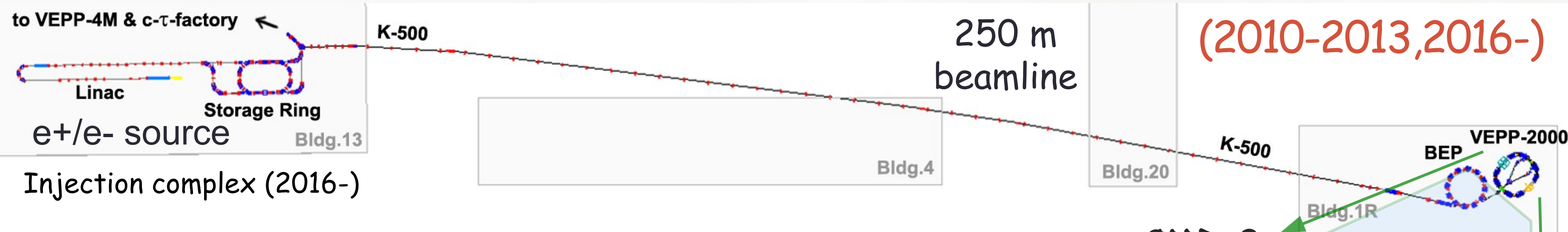
Exclusive approach

Inclusive approach

- ✗ Two techniques : Energy scan vs Initial State Radiation (ISR)
- ✗ Two approaches : Exclusive (each channel measured separately)
  vs Inclusive (total hadronic cross section)

VEPP-2000: Only one working these days on scanning below <2 GeV
with world-best luminosity per single bunch at this energies

VEPP-2000 e+e- collider



VEPP-2000: direct exclusive measurement of σ (e+e- → hadrons)

Only one working this days on scanning 2E = 0.32-2 GeV

Unique optics, "round beams" to reach higher L

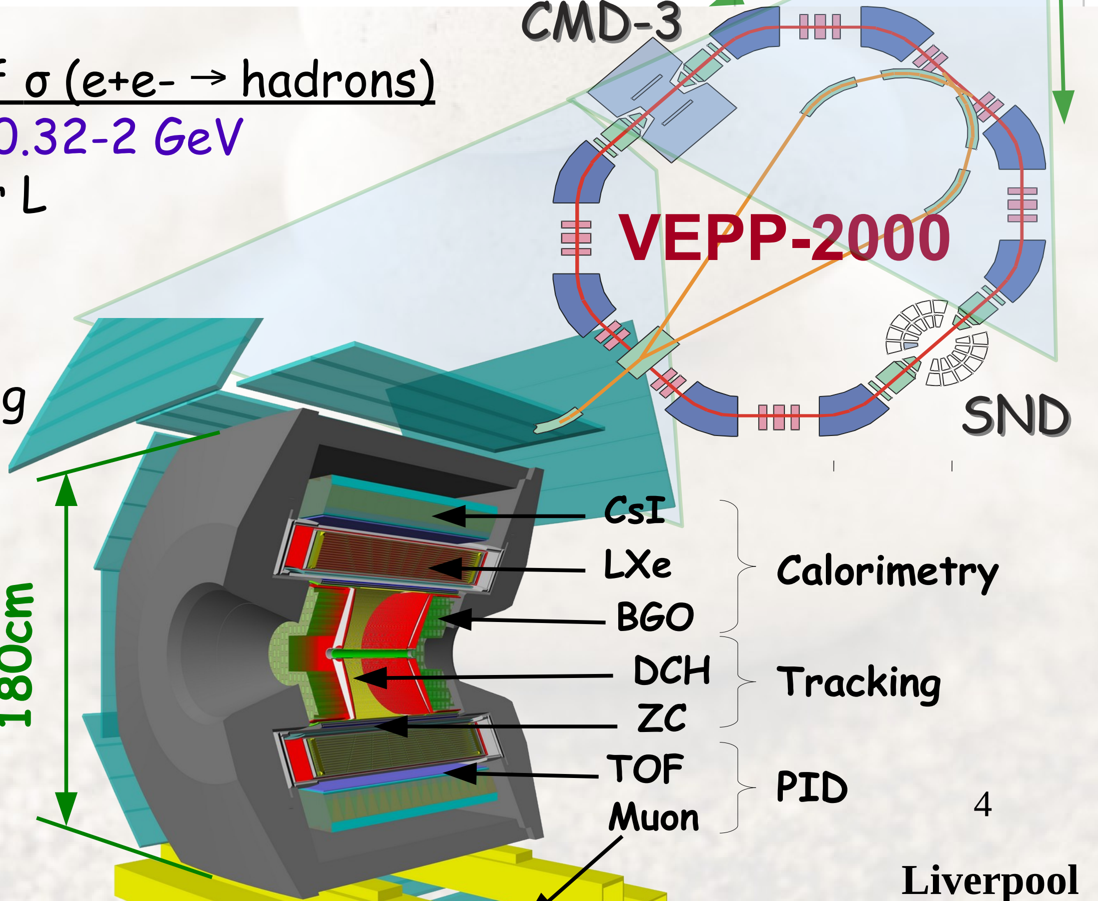
$L = 0.9\times10^{32}$ cm^{-2}s^{-1} at 2E= 2 GeV

Energy monitoring by Compton backscattering

$\sigma_{\sqrt{s}} \approx 0.1$ MeV

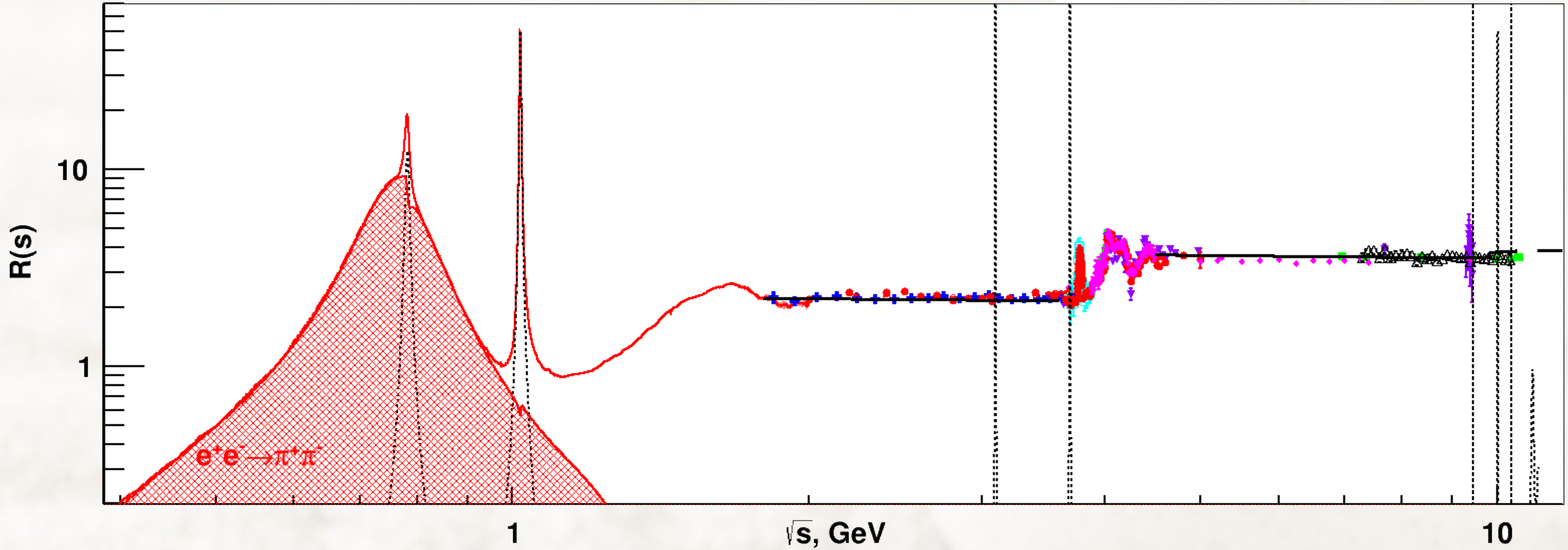
Two detectors: CMD-3 and SND

started by the end of 2010




VEPP-2000
collider ring
SND
CMD-3
6.65 m

$$R(s)=\frac{\sigma^0(e^+e^-\to\gamma^*\to hadrons)}{\sigma^0(e^+e^-\to\gamma^*\to\mu^+\mu^-)}$$



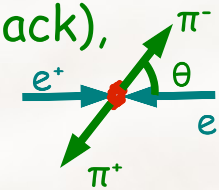
$e^+e^- \to \pi^+\pi^-$ gives main contribution to R(s) at √s < 1 GeV and this channel is most important for muon (g-2)/2

e+e- → π+π- by CMD3

Very simple topology (just 2 tracks back to back),

but the most challenging channel

due to high precision requirement.



Analysis was performed trying to reach systematic ~0.35-0.5%

Crucial pieces of analysis:

- ✗ e/μ/π separation
- ✗ radiative corrections
- ✗ precise fiducial volume
- ✗ …

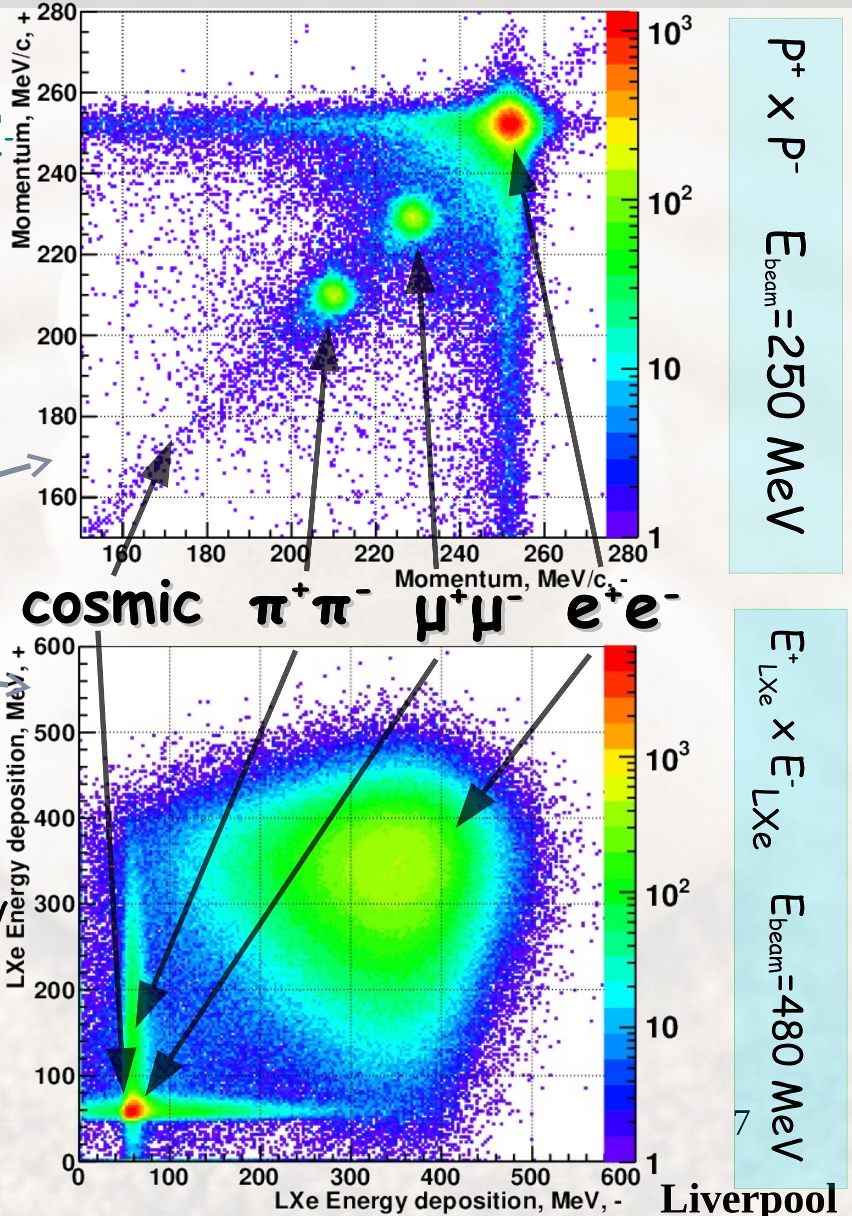
events separation either

1) by momentum

2) or by energy deposition

3) additional cross-check by angle distribution

4) using shower profile at >1GeV

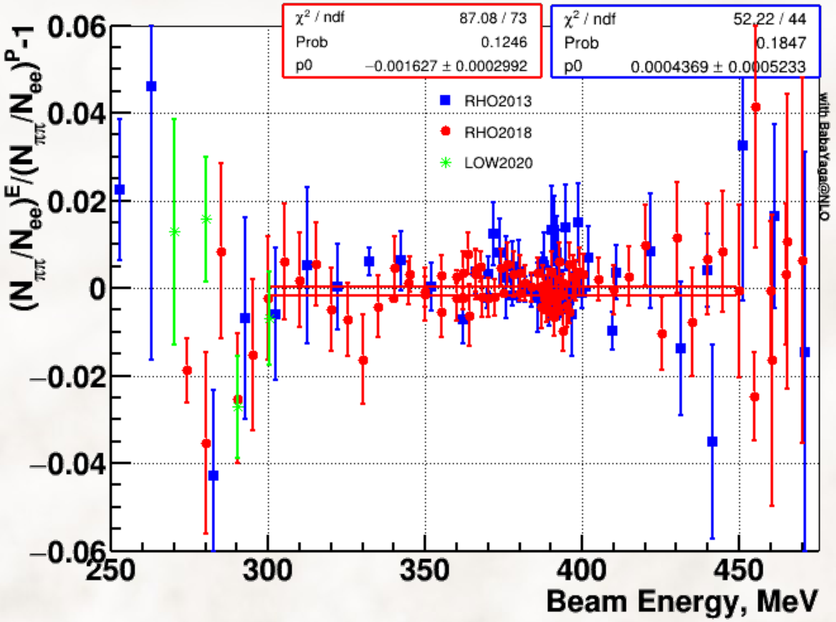


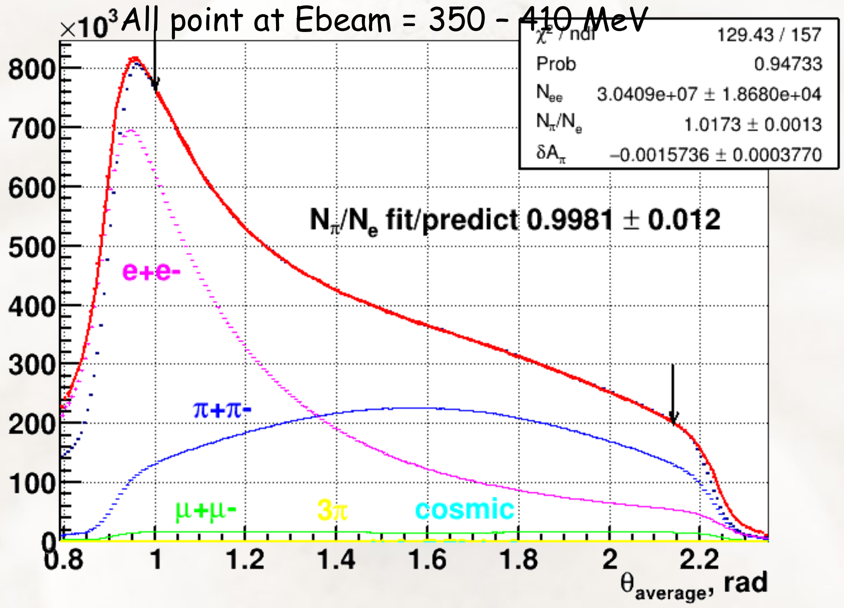
e/μ/π separation

3 methods for $N_{\pi\pi}$ /N_{ee} determination based on independent informations:

1) Momentum from DCH **2)** Energy deposition in LXe **3)** angles in DCH

E vs P separations





Fit by θ distribution

For sum of √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 Δ $N_{\pi\pi}$ /N_{ee} = -0.09 +- 0.024%

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

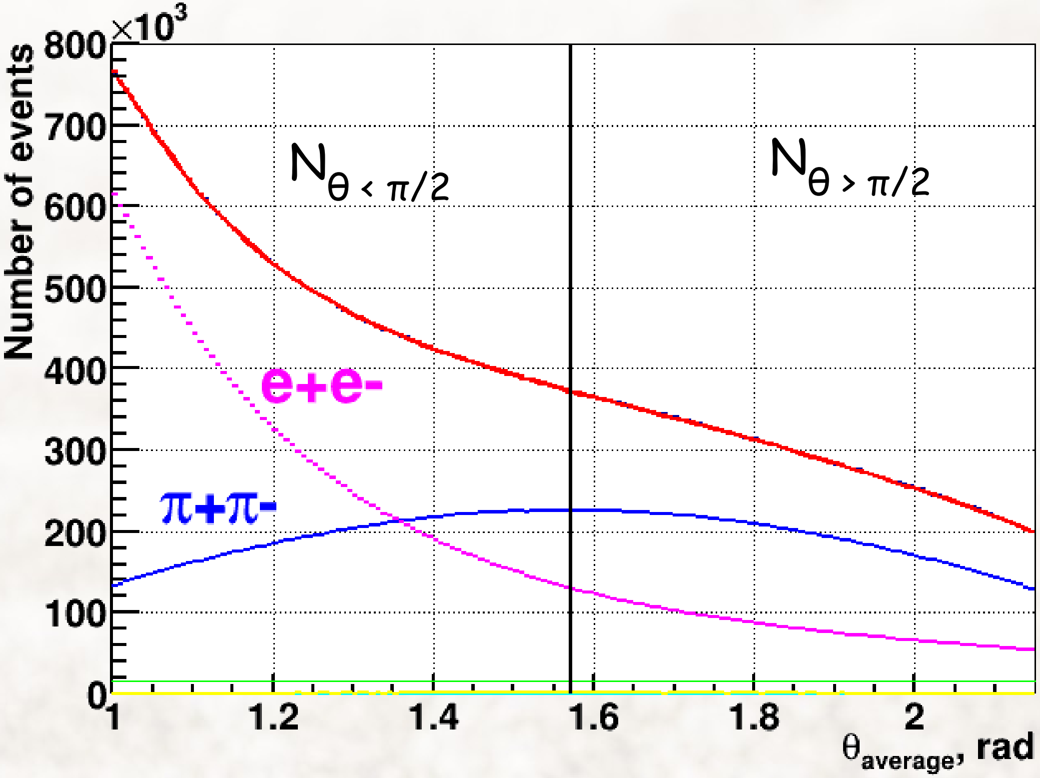
with fixed δA=0: = +0.21 +- 0.07%

Common stat from √N: 0.026%

consistency at ~ 0.2%

Forward backward charge asymmetry

dσ/dθ spectra



Asymmetry definition:

$A = (N_{\theta < \pi/2} - N_{\theta > \pi/2})/N$

Sensitive to:

✗ angle-related systematics

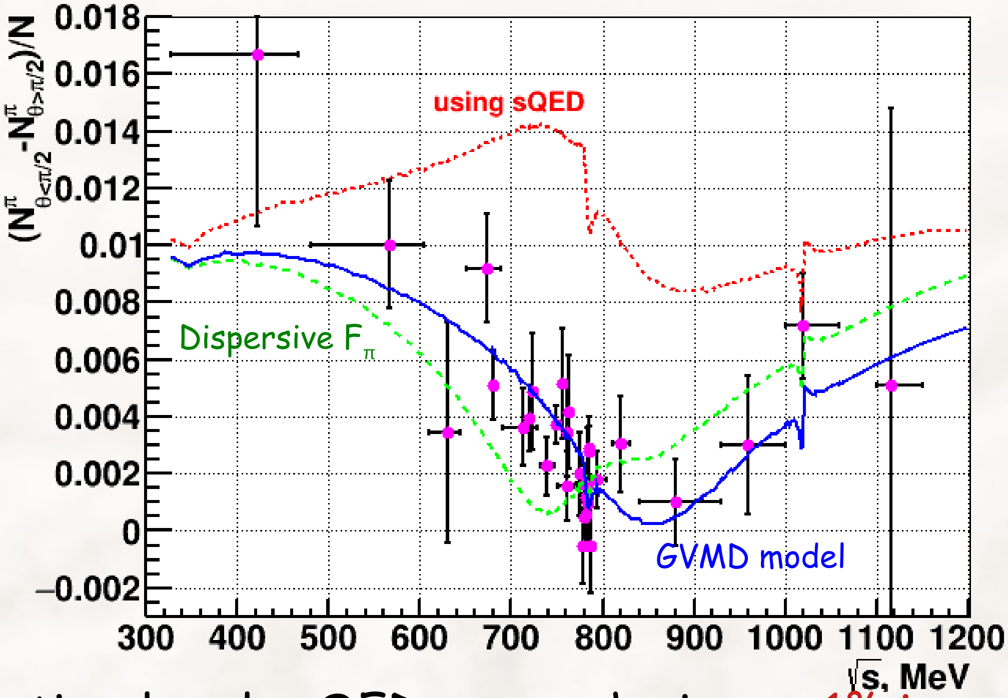
✗ used model of γ-π interaction

At first try:

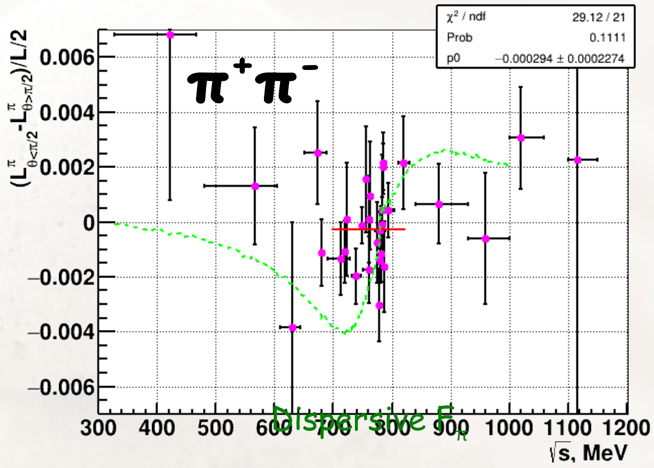
1% inconsistency for π+π- was observed between data and MC prediction

Charge asymmetry in e+e- -> π+π-

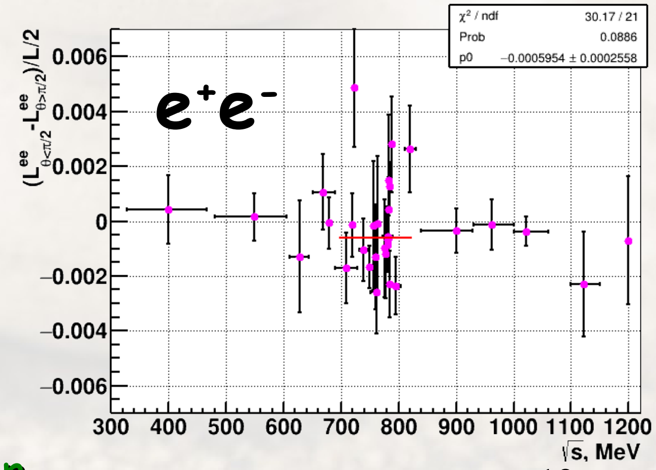
$A = (N_{\theta<\pi/2} - N_{\theta>\pi/2})/N$



Relative to GVMD prediction



to BaBaYaga@NLO



Conventional scalar QED approach gives ~ 1% inconsistency

The theoretical model within GVMD was introduced, describes well the CMD-3 data R.Lee et al., Phys.Lett.B 833 (2022) 137283

was confirmed by calculation in dispersive formalism

M.Hoferichter et al., JHEP 08 (2022) 295

Average at √s = 0.7-0.82 GeV:

$\pi^+\pi^-$: ⟨δA⟩ = -0.029 ± 0.023 %

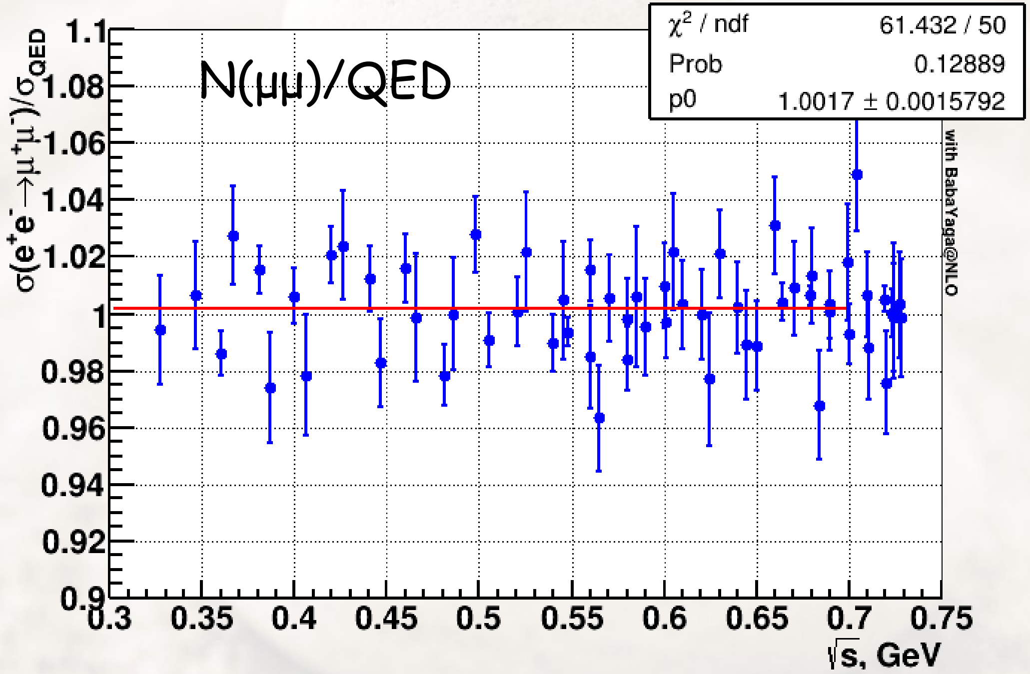
e^+e^-: ⟨δA⟩ = -0.060 ± 0.026 %

Ensure our θ angle systematics estimation for $|F_\pi|^2$

e+e- → μ+μ- cross section

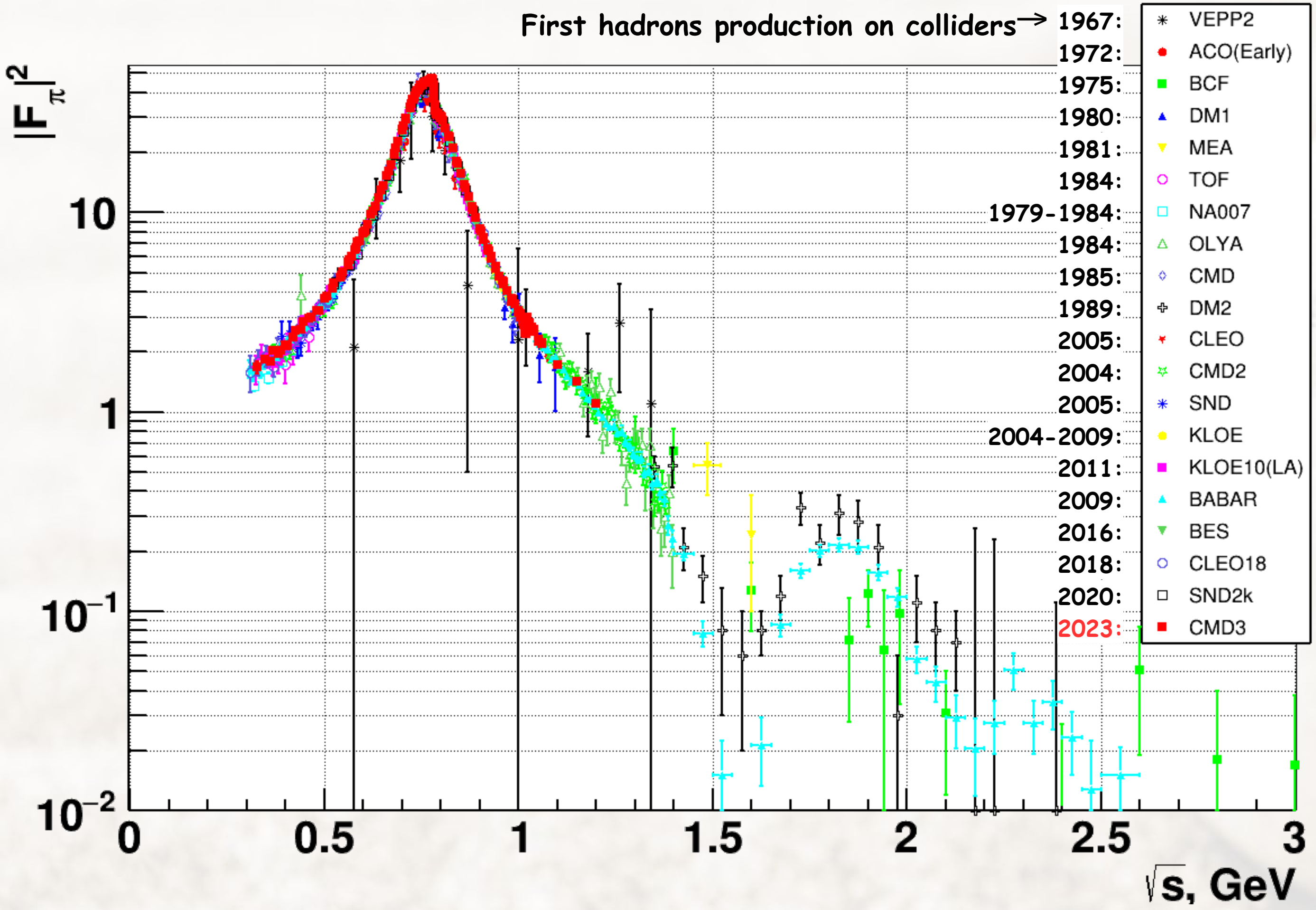
One of consistency checks for e+e- → π+π- is provided by comparison of measured e+e- → μ+μ- cross section vs QED prediction

$N_{\mu\mu}$/QED :   Δ = +0.17 ± 0.16 %



Many others self consistency checks were performed

e+ e− → π+ π− today



Before 1985

Low statistical precision

Systematics >10%

NA7 A few points with >1-5%

1985 - VEPP-2M

with more detailed scan

OLYA systematics 4%

CMD 2%

2004 with CMD2 at VEPP-2M

was boost to systematics: 0.6%

(near same total statistic)

The uncertainty in a_μ(had) was improved by factor 3 as the result of VEPP-2M measurements

New ISR method

e+e- → γ + hadrons (limited only by systematics):

KLOE: 0.8%

BaBar: 0.5%

BES: 0.9%

CLEO: 1.5%

New direct data:

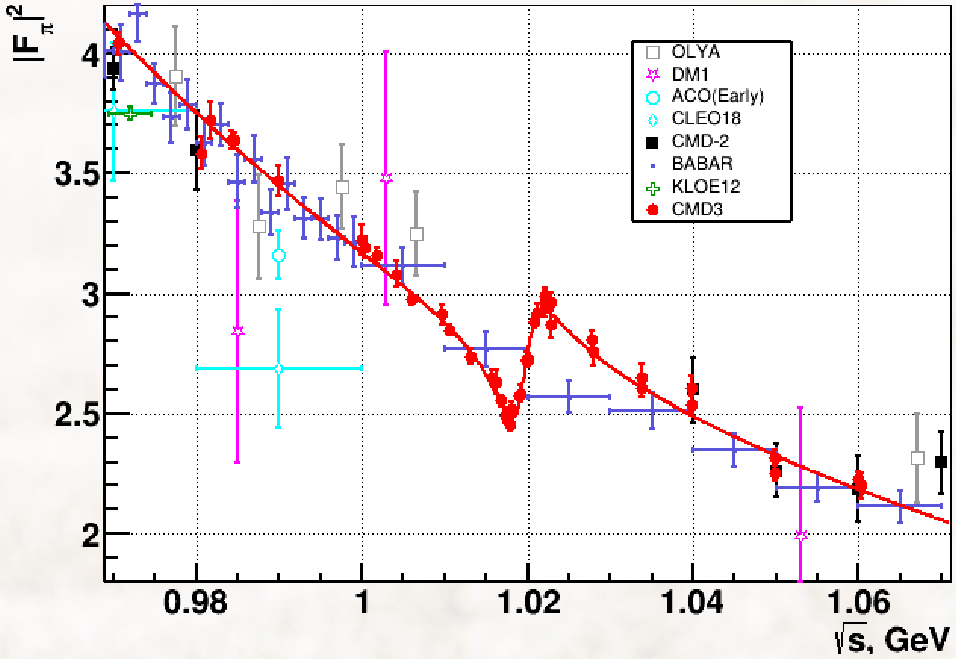
SND2k : 0.8% (with 1./10 of avail Data)

CMD-3: 0.7%

New g-2 experiments and future e+e- as ILC, FCC-ee require average precision ~0.2%

$\varphi \to \pi^+\pi^-$

First direct $|F_\pi|^2$ measurement around φ resonance



CMD-3

$\psi_\pi = (-21.3 \pm 2.0 \pm 10.0)^\circ$

$B(\varphi\to e^+e^-)B(\varphi\to\pi^+\pi^-) = (3.51 \pm 0.33 \pm 0.24)\times 10^{-8}$

Previous measurement using detected $N_{\pi+\pi-}$ or visible cross-section by OLYA, ND, SND (Sergey Burdin et al,Phys.Lett.B474:188-193,2000)

SND

$\psi_\pi = (-34 \pm 5)^\circ$

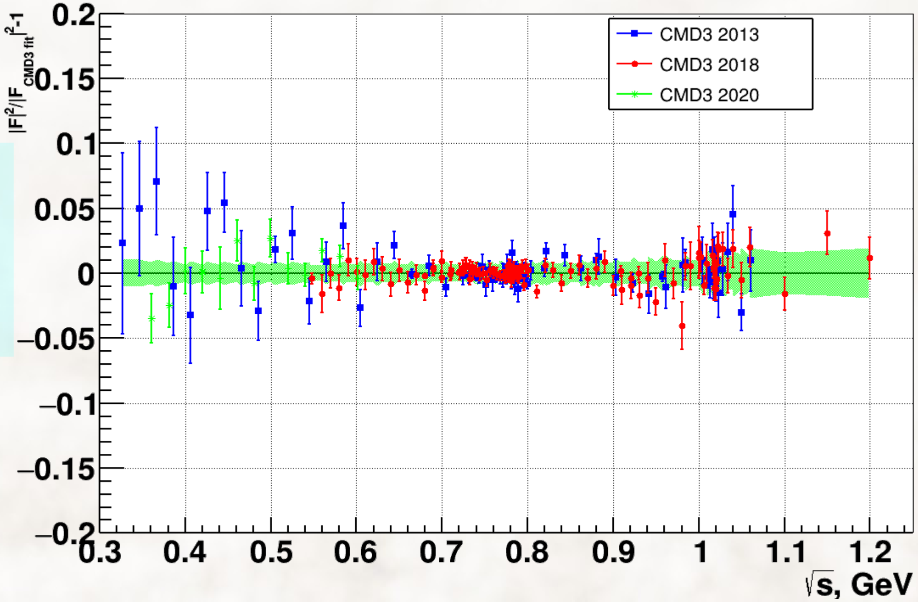
$B(\varphi\to e^+e^-)B(\varphi\to\pi^+\pi^-) = (2.1 \pm 0.4)\times 10^{-8}$

N.B. radiative correction uncertainty (from F_π parametrisation) gives ~1.5 scale factor of total statistical and systematic errors (both for Br and ψ_π)

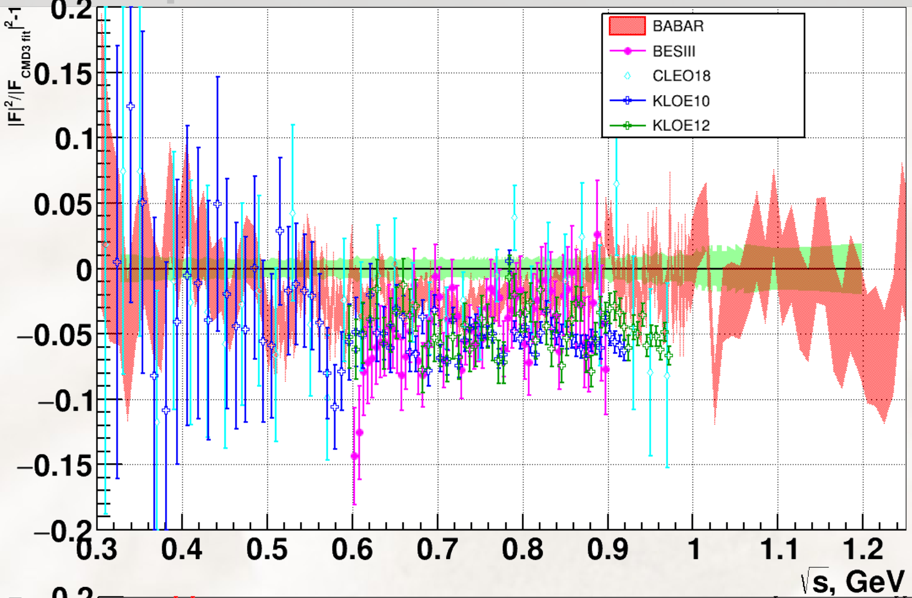
CMD-3 vs other experiments

Relative to CMD-3 fit,
green band – systematic value

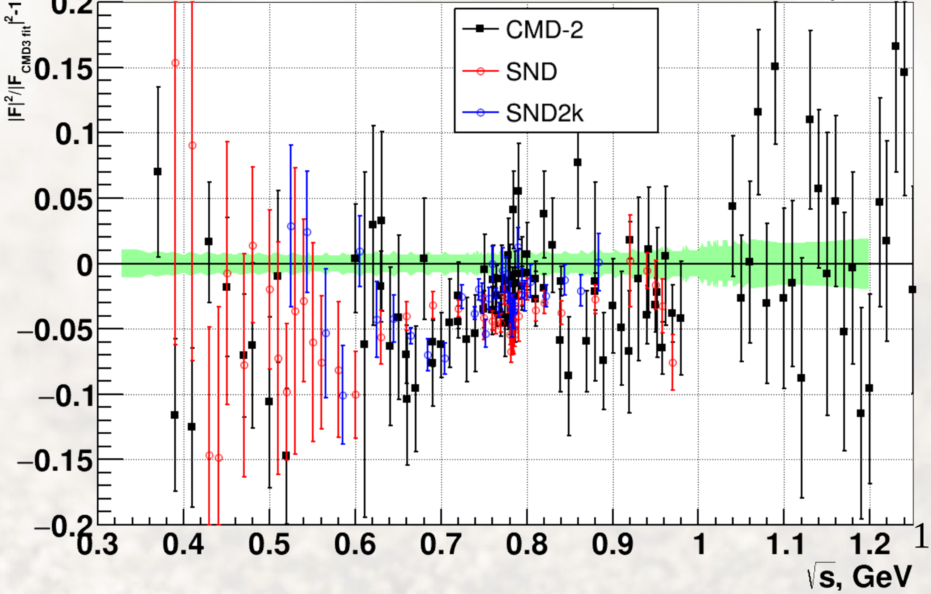
CMD-3



vs ISR



vs direct scan

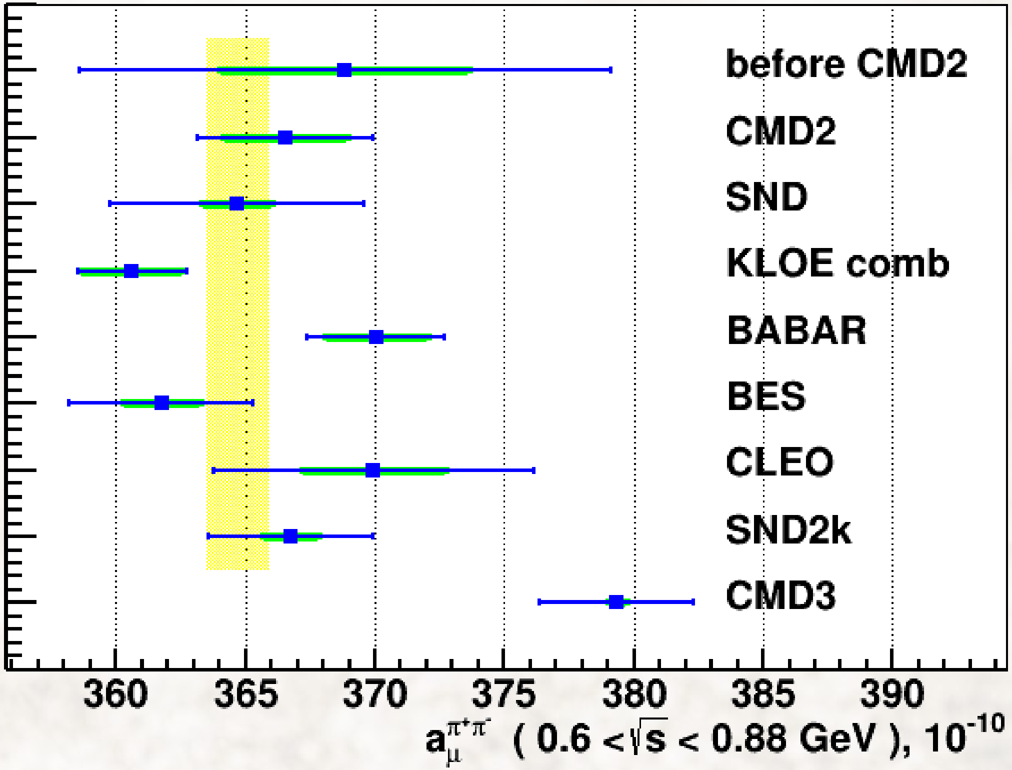


CMD-3

- ✗ Statistical precision is a few times better than any other experiments
- ✗ Cross section is higher by ~ 2-5%

The π+ π− contribution to a_μ^{had}

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

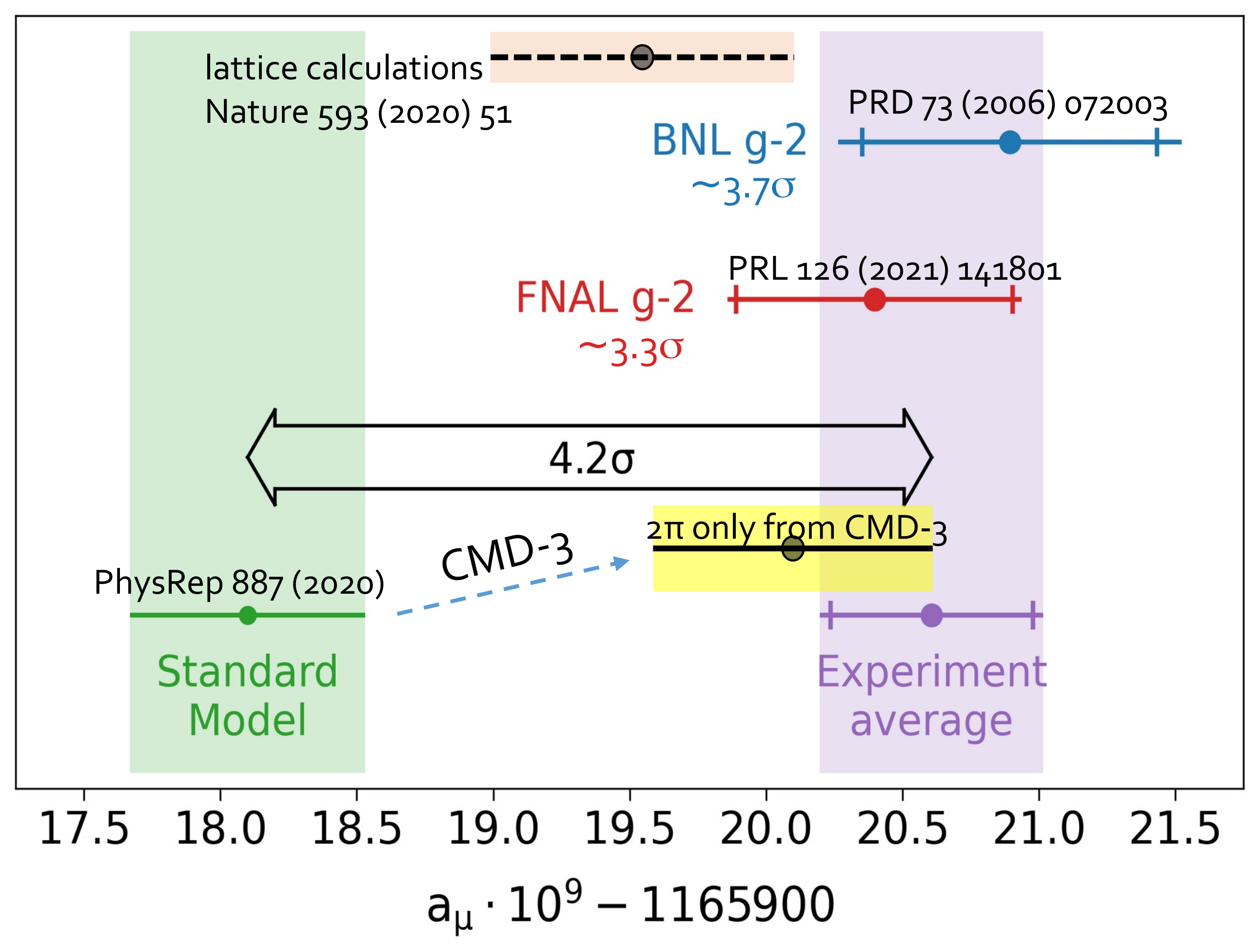


0.6 < √s < 0.88 GeV

	$a_\mu^{\pi\pi,LO}$, 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

The impact of CMD-3 on SM prediction of a_μ^{had}



If it will be only CMD-3 than SM will be solved.
But CMD-3 is only one now over many other experiments (BaBar, KLOE, BES, CMD-2, SND, …)

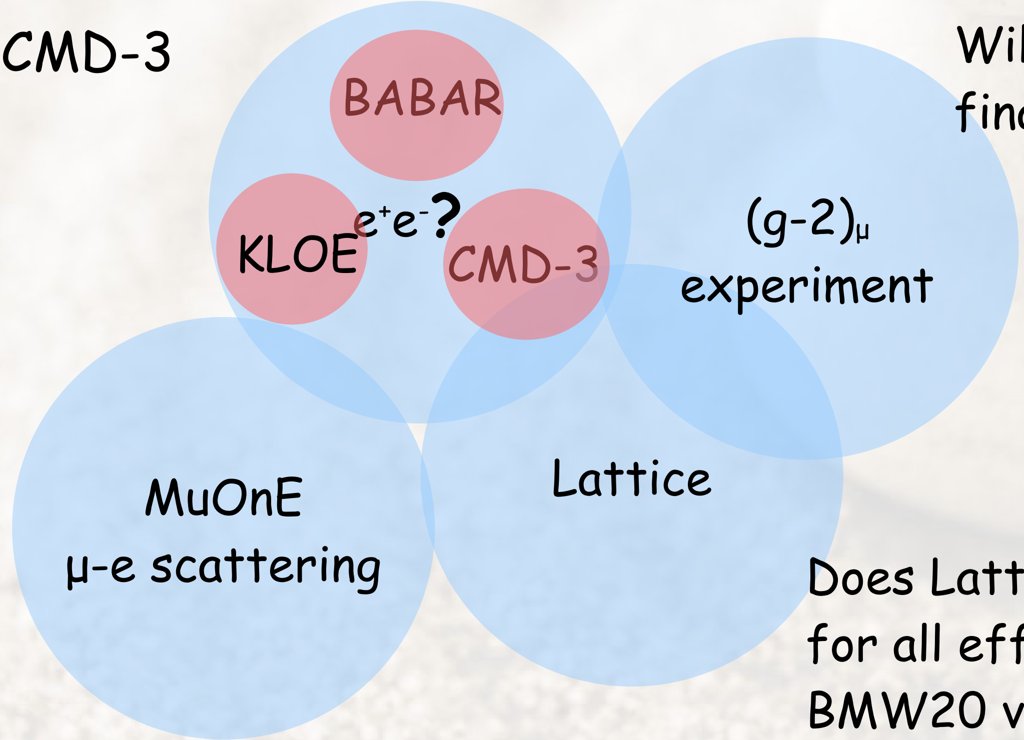
Unfortunately at the moment, we don't know the reasons of the disagreement between different experiments.

Puzzles in puzzle

Question of comparison:

e+e- vs $(g-2)_\mu$ vs lattice

Where difference comes from:
KLOE vs BABAR vs CMD-3



BABAR

KLOE

e^+e^-?

CMD-3

$(g-2)_\mu$
experiment

Lattice

MuOnE
μ-e scattering

Will it be confirmed?
final FNAL vs J-PARC

Hard effort
against
systematics

Does Lattice account
for all effects?
BMW20 vs others

backups

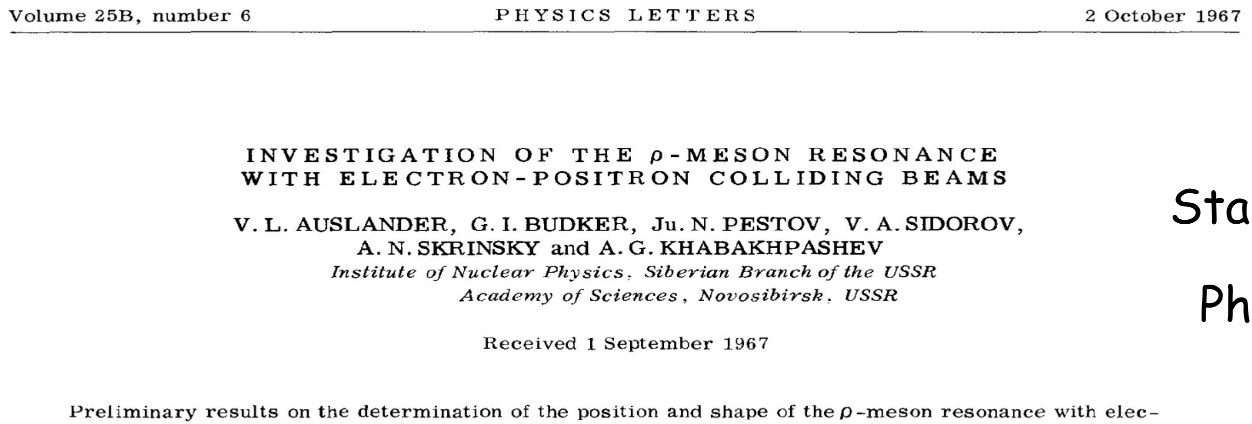
More details:

Presentation at the TI seminar, 27 March 2023:

https://indico.fnal.gov/event/59052/

E-Print: 2302.08834 [hep-ex]

55 years of hadron production at colliders



Volume 25B, number 6 PHYSICS LETTERS 2 October 1967

INVESTIGATION OF THE ρ-MESON RESONANCE WITH ELECTRON-POSITRON COLLIDING BEAMS

V. L. AUSLANDER, G. I. BUDKER, Ju. N. PESTOV, V. A. SIDOROV,
A. N. SKRINSKY and A. G. KHABAKHPASHEV
*Institute of Nuclear Physics, Siberian Branch of the USSR
Academy of Sciences, Novosibirsk, USSR*

Received 1 September 1967

Preliminary results on the determination of the position and shape of the ρ-meson resonance with electron-positron colliding beams are presented.

When experiments with electron-positron colliding beams were planned [1, 2] investigation of the process

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

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

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1 September 1967

Start of e+e- → hadrons measurements

Phys.Lett. 25B (1967) no.6, 433-435

VEPP-2, Novosibirsk

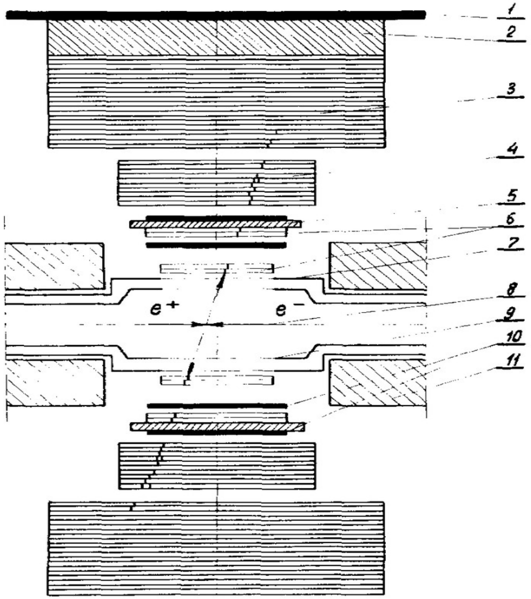
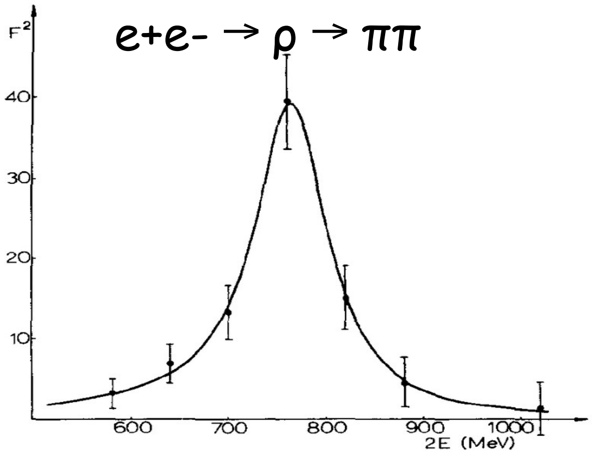


Fig. 1. Spark chambers system:
1) Anticoincidence scintillation counter
2) Lead absorber 20 cm thick
3) "Range" spark chamber
4) "Shower" spark chamber
5) Duraluminium absorber 2 cm thick
6) Thin-plate spark chambers



e+e- → ρ → ππ

Fig. 2. Experimental values of F^2 (E) approximated by the Breit-Wigner formula.

ment geometry and F- modulus of the form factor for pion pair production [1]. In the case of QED with no other forces F=1. If the particles are produced at the angle 90° with respect to the beam axis then a=18. Integration over the solid angle gives a=20.4.

Detector was made from different layers of Spark chambers,
readouts by photo camera

SM prediction for muon g-2

White Paper 2020 (e-Print: 2006.04822)

Experimental world average (E821+E989)

a_μ = 11 659 206.1 ± 4.1 × 10^{-10}

Theoretical prediction data driven

a_μ = 11 659 181.0 ± 4.3 × 10^{-10} **(WP20)**

Δa_μ = 25.1 ± 5.9 × 10^{-10}

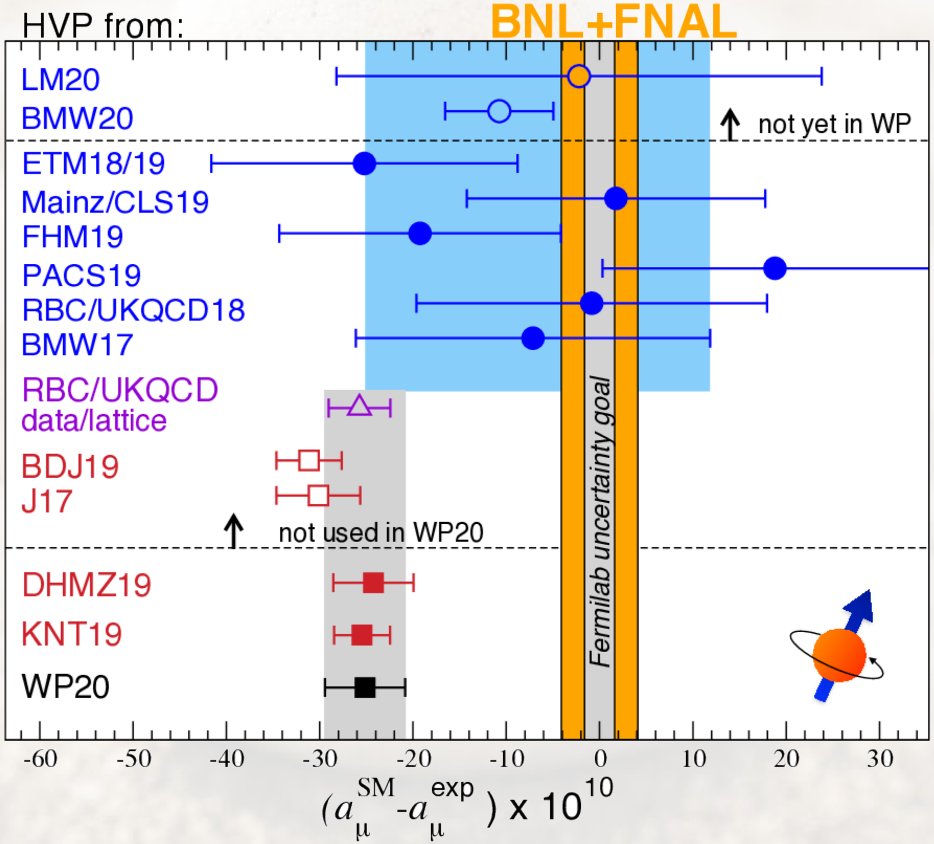
Hadronic part from e+e- → hadrons:

a_μ(had) = 693.1 ± 4.0 × 10^{-10}

$\pi^+\pi^-$ 506.0 ± 3.4

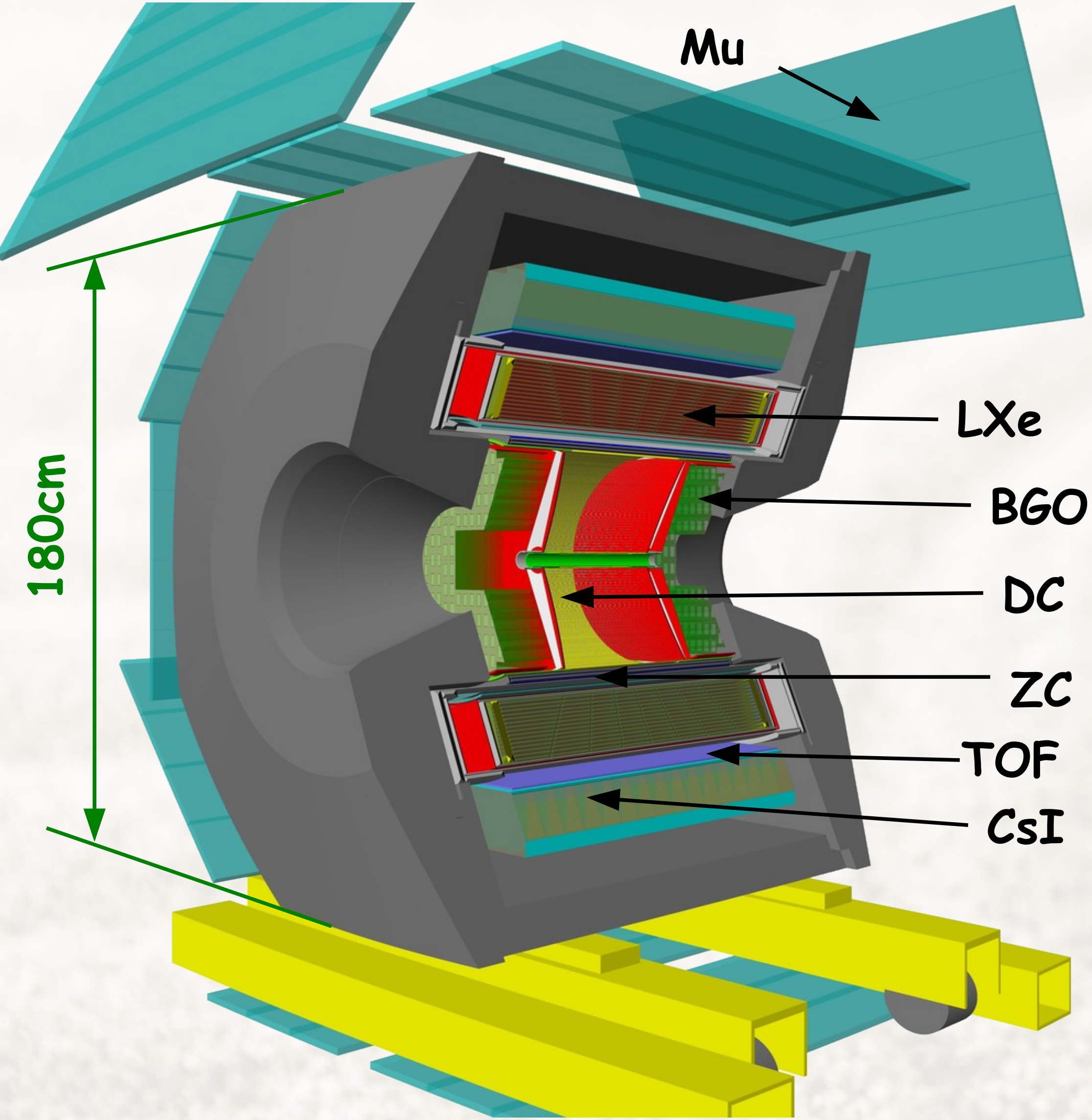
……

e-Print: 2203.15810



$\pi^+\pi^-$ gives the main contribution (73%) to a_μ^{HAD}

CMD-3 detector



Tracking:

✗ Drift Chamber in 1.3 T magnetic field

$\sigma_{R\varphi} \sim 100\ \mu m$, $\sigma_Z \sim 2.5mm$

$\sigma_P/P \sim \sqrt{0.6^2+(4.4*p[GeV])^2}$,%

✗ **ZC-chamber worked until summer 2017**

$\sigma_Z \sim 0.7mm$ by strip readout

Calorimetry:

✗ Combined EM calorimeter (LXe,CsI, BGO) 13.5 X_0 in barrel part

$\sigma_E /E \sim 0.034/ \sqrt{E\ [GeV]} \oplus 0.020$ - barrel

$\sigma_E /E \sim 0.024/ \sqrt{E\ [GeV]} \oplus 0.023$ - endcap

✗ LXe calorimeter with 7 ionization layers with strip readout

~2mm measurement of conversion point,
tracking capability,
shower profile (from 7 layers + CsI)

PID:

✗ TOF system ($\sigma_T \sim 0.4$ nsec)

particle id mainly for p, n

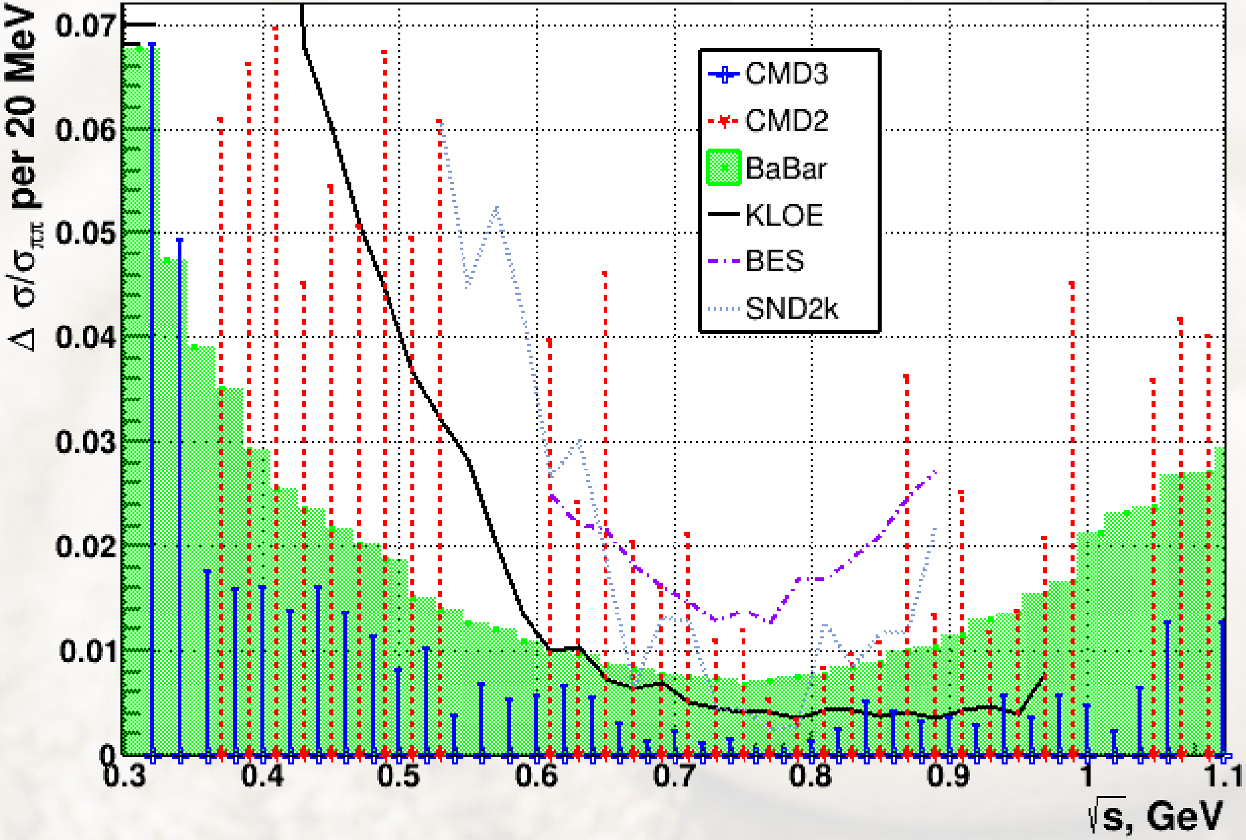
✗ Muon system

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

Statistical precision of CMD-3 cross section measurement
is a few times better than any other experiments

Full statistic is used
collected during ρ scans

3 seasons of data taking:
RHO2013
RHO2018
LOW2020



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

$34\times10^6\ \pi^+\pi^-$, $3.7\times10^6\ \mu^+\mu^-$, $44\times10^6\ e^+e^-$
events selected at $\sqrt{s} < 1$ GeV

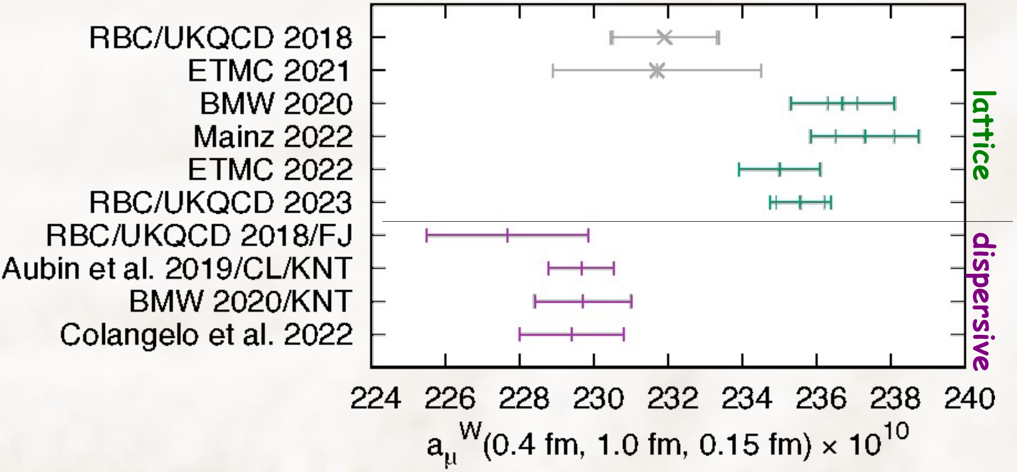
Dispersive vs Lattice

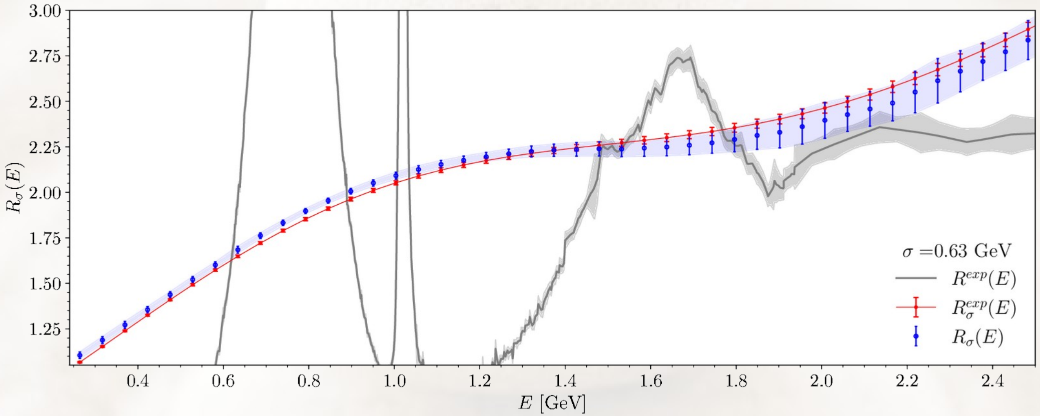
T.Blum et al, e-Print: 2301.08696 [hep-lat]

C. Alexandrou et al, e-Print: 2212.08467 [hep-lat]

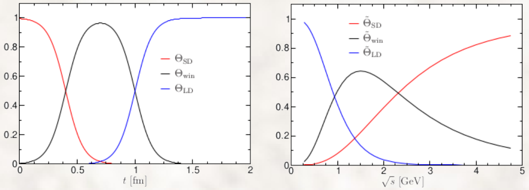
a^{HVP}_{μ} contribution from intermediate window in Euclidean time

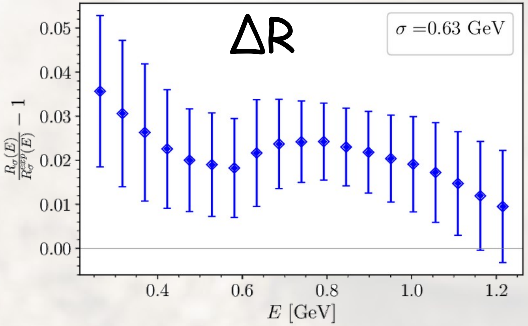
R(s) is convolved with Gaussian kernel

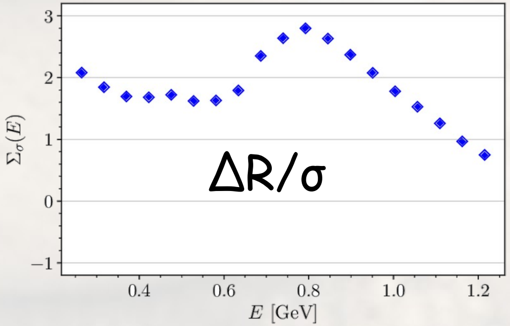




Windows definition







~4σ tension between Lattice/Dispersive

~3σ tension at rho energies

Question of comparison: e+e- vs $(g-2)_\mu$ vs lattice

Other experiments