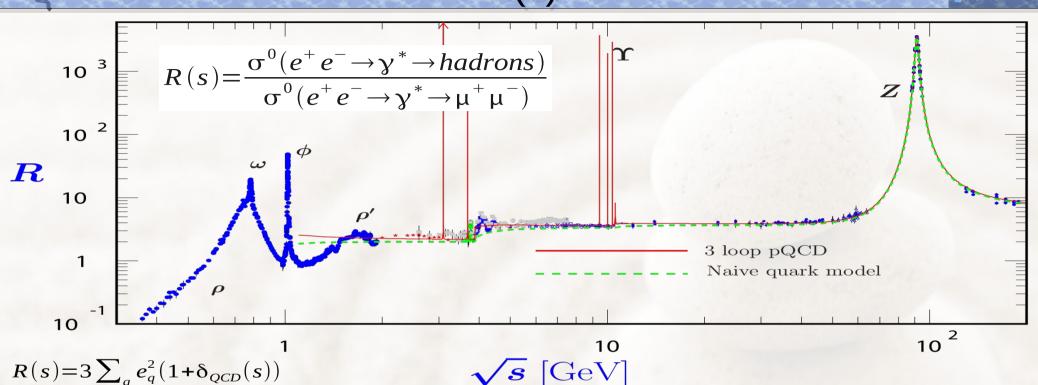# From R(s) measurements at e+e- colliders to the MUonE experiment for the muon g-2 prediction

Fedor Ignatov
BINP, Novosibirsk

12 November 2019
Pisa, Italy

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

$$R(s) = 3 \sum_q e_q^2 (1 + \delta_{QCD}(s))$$

R

Υ Z

ω ϕ ρ' ρ

- — 3 loop pQCD
- – – Naive quark model

$\sqrt{s}$ [GeV]

R(s) is one of the fundamental quantities in high energy physics:
its reflects number of quarks and colors → pQCD tests;
QCD sum rules → quark masses, quark and gluon condensates, Λ_{QCD}
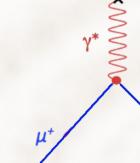Dispersion relations → $\alpha_{QED}(M_Z)$, hyperfine muonium splitting, muon (g-2)
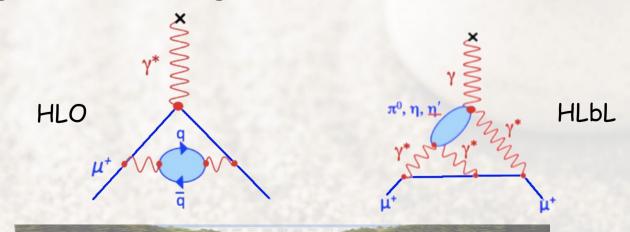
The magnetic moment of the particle relates spins to its angular momentum via the gyromagnetic ratio, g:

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

In Dirac theory, point-like, spin ½ particle has exactly g=2

Quantum loop effects via vacuum fluctuations lead a calculable deviation: the anomalous magnetic moment a = (g-2)/2 ~ α/2π ~ 0.00116

HLO

HLbL

$$\vec{\mu} = g \frac{e}{2m} \vec{s}, g = 2(1+a)$$

a_e = 11 596 521.8073 (0.0028) 10^{-10} [0.24ppb]

a_μ = 11 659 208.9(6.3) 10^{-10} [0.54ppm]

Hanneke, Fogwell, Gabrielse, PRL 100(2008)120801

Bennet et al., PRD 73(2006)072003

BNL Muon E821

trap cavity
quartz spacer
nickel rings
0.5 cm
bottom endcap electrode
microwave inlet

electron top endcap electrode
compensation electrode
ring electrode
compensation electrode
field emission point

14m

Harvard Univ.

One electron quantum cyclotron

The value of a_e was used to get the best determination of fine-structure constant α.

R. Parker et al., Science 360 (2018) 191

Recent α_{QED} measurement using the recoil frequency of Cs-133 atoms with 0.20ppb **gives 2.5σ tension** with experimental a_e

Muon (g-2) is 40,000 times more sensitive to non-QED fields than electron (g-2) ~ $(m\mu/me)^2$, providing more sensitive probe for New Physics.
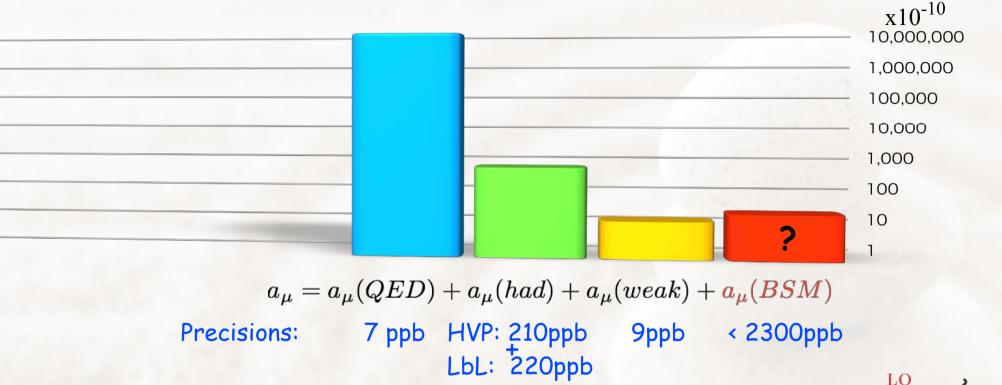
4

Muon g-2 theory SM

$$a_\mu = a_\mu(QED) + a_\mu(had) + a_\mu(weak) + a_\mu(BSM)$$

Precisions: 7 ppb HVP: 210ppb 9ppb < 2300ppb
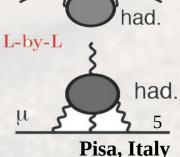+
LbL: 220ppb

QED: Kinoshita et al., 2012: up to 5 loops (12672 diagrams), **EW**: 2 loop

Hadronic: **HVP**: the value is based on the hadronic cross-section e+e- data;

LBL: model-dependent calculations; measurement of transition formfactors can help, improvement is expected from lattice calculations

New g-2 experiments at FNAL, J-PARC: 540 → 140 ppb

LO

μ   had.
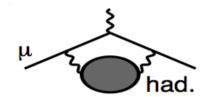
L-by-L

μ   had.

5

The hadronic contribution is calculated by integrating experimental cross-section $\sigma(e+e- \rightarrow \text{hadrons})$.

Starting at high energy the pQCD estimation of $\sigma(e+e- \rightarrow \text{hadrons})$ is used. At lower energies only the experimental data can be used.

Weighting function $\sim 1/s^2$, therefore lower energies contribute the most:

<2GeV gives 93% of the integral,
$\pi^+\pi^-$ gives the main contribution (73%) to a_μ

The diagram to be evaluated:

pQCD not useful. Use the dispersion relation based on analyticity and the optical theorem:
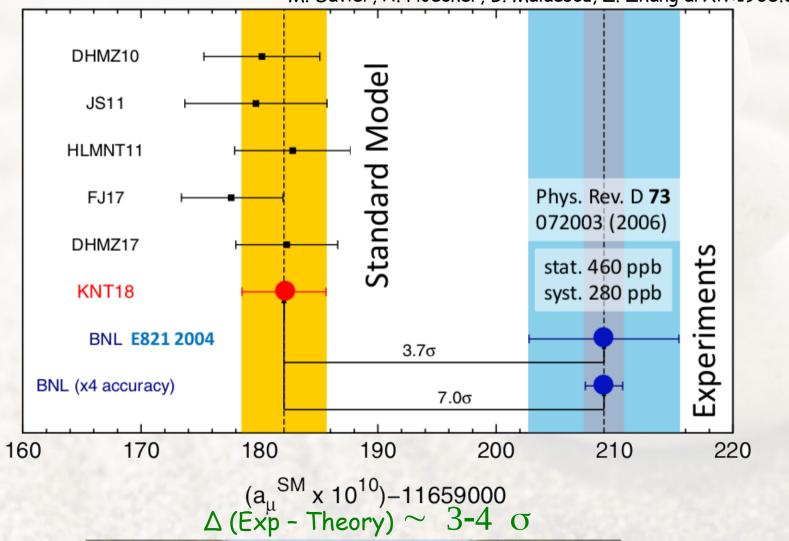
$$a_\mu^{\text{had}, \text{LO}} = \left(\frac{\alpha\, m_\mu}{3\,\pi} \right)^2 \int\limits_{s_{th}}^{\infty} \frac{1}{s^2}\, \widetilde{K}\,(s)\, R\,(s)\, ds$$

$$\widetilde{K}\,(s) = 0.6 \div 1.0$$

SM prediction for muon g-2

$$(a_\mu^{SM} \times 10^{10}) - 11659000$$

Δ (Exp - Theory) ~ 3-4 σ

The electromagnetic fine structure constant $\alpha_{QED}(q^2)$

is a running parameter with momentum transfer q^2
due to Vacuum Polarization effects
-effective electron charge (charge screening)

$$\alpha(s) = \frac{\alpha(0)}{1 - \Delta\alpha(s)},$$

$$\Delta\alpha_{had}(s) = -\frac{\alpha(0)s}{3\pi} \int_0^\infty ds' \frac{R(s')}{s'(s'-s) - i\epsilon}$$

Vacuum Polarization

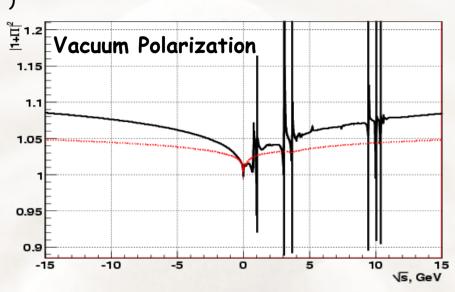The $\alpha_{QED}(q^2)$ at mass of Z is used in predictions

of electroweak model.

It is the least known EW parameter like
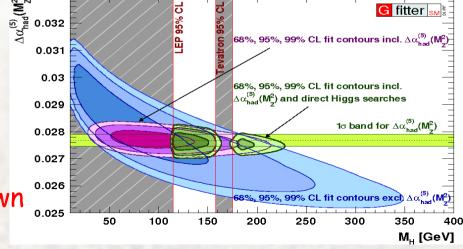$\delta G_\mu/G\mu \sim 0.9 \times 10^{-5}$, $\delta M_z/M_z \sim 2.4 \times 10^{-5}$

$\Delta\alpha_{QED}^{5had}(M_Z) = 276.11 \pm 1.11 \times 10^{-4}$
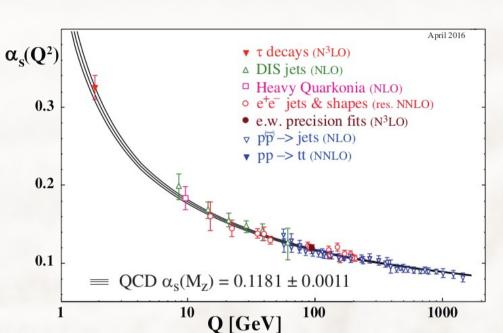
For future ILC, CLIC, FCC-ee it should be known
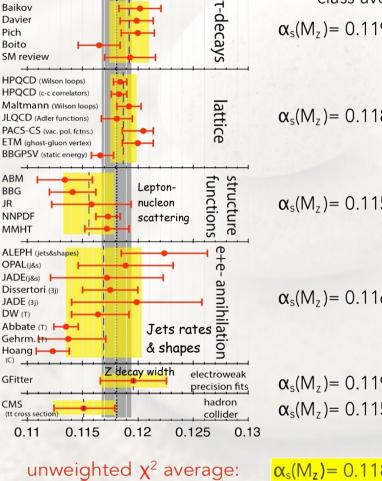with ~ 0.5-0.3 $\times 10^{-4}$ Eur.Phys.J. C74 (2014) 3046

Particle Data Group '18

April 2016

$\alpha_s(Q^2)$

▼ τ decays (N³LO)
△ DIS jets (NLO)
□ Heavy Quarkonia (NLO)
○ e^+e^- jets & shapes (res. NNLO)
● e.w. precision fits (N³LO)
▽ $p\bar{p} \to$ jets (NLO)
▼ $pp \to tt$ (NNLO)

$\equiv$ QCD $\alpha_s(M_Z) = 0.1181 \pm 0.0011$

Q [GeV]

Baikov
Davier
Pich
Boito
SM review
— τ-decays

HPQCD (Wilson loops)
HPQCD (c-c correlators)
Maltmann (Wilson loops)
JLQCD (Adler functions)
PACS-CS (vac. pol. fctns.)
ETM (ghost-gluon vertex)
BBGPSV (static energy)
— lattice

ABM
BBG
JR
NNPDF
MMHT
Lepton-nucleon scattering
— structure functions

ALEPH (jets&shapes)
OPAL (j&s)
JADE (j&s)
Dissertori (3j)
JADE (3j)
DW (T)
Abbate (T)
Gehrm. (T)
Hoang (C)
Jets rates & shapes
— e^+e^- annihilation

GFitter
Z decay width
electroweak precision fits

CMS (tt cross section)
hadron collider

0.11   0.115   0.12   0.125   0.13

class averages:

$\alpha_s(M_Z) = 0.1192 \pm 0.0018$ (±1.5%)

$\alpha_s(M_Z) = 0.1184 \pm 0.0012$ (±1.0%)

$\alpha_s(M_Z) = 0.1156 \pm 0.0021$ (±1.8%)

$\alpha_s(M_Z) = 0.1169 \pm 0.0034$ (±2.9%)

$\alpha_s(M_Z) = 0.1196 \pm 0.0030$ (±2.5%)
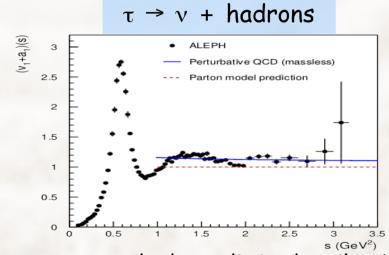$\alpha_s(M_Z) = 0.1151 \pm 0.0028$ (±2.5%)

Tau decays to hadrons give the best non-lattice α_s estimation

unweighted χ^2 average: $\alpha_s(M_Z) = 0.1181 \pm 0.0011$ (±0.9%)

9

Sum rules

From analyticity and using Cauchy's theorem

$$\frac{1}{12\pi^2 s_0} \int_0^{s_0} ds\, w(s/s_0) R(s) = -\frac{1}{2\pi i s_0} \oint_{|z|=s_0} dz\, w(s/s_0) \Pi(z)$$

Integrated R(s) with different weights (pinched at s_0 where OPE is under question, w(y)~(1-y))

theory

data

τ → ν + hadrons

e+e- → hadrons

τ → ν + hadrons limited until = 1.77 GeV (V+A the QCD asymptotic behaviour is reached faster)

e+e- → hadrons can be extended to upper s_0 limits

M.Davier et al., arXiv:1312.1501

$\alpha_s(m^2_\tau) = 0.332 \pm 0.005_{exp} \pm 0.011_{theo}$

(± 0.006 DV,higher order ± 0.009 FOPT vs CIPT)

$\alpha_s(m^2_Z) = 0.1199 \pm 0.0015$ (±1.3%)

D.Boito et al. , arXiv:1805.08176

$\alpha_s(m^2_\tau) = 0.301 \pm 0.017_{exp} \pm 0.007_{theo}$

(± 0.005 DV ± 0.003 higher orders ± 0.003 FOPT vs CIPT)

$\alpha_s(m^2_Z) = 0.1162 \pm 0.0025$ (±2.1%)
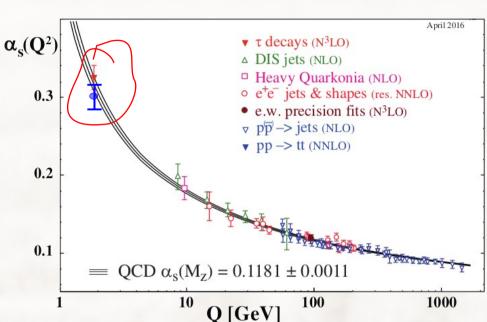
e+e-: Limited by data, Difference between FO and CIPT ~3 times smaller than in tau decays   10

Particle Data Group '18

class averages:

$\alpha_s(M_Z) = 0.1192 \pm 0.0018$ (±1.5%)

e+e- → hadrons
$\alpha_s(M_Z) = 0.1162 \pm 0.0025$ (±2.1%)

$\alpha_s(M_Z) = 0.1184 \pm 0.0012$ (±1.0%)

$\alpha_s(M_Z) = 0.1156 \pm 0.0021$ (±1.8%)

$\alpha_s(M_Z) = 0.1169 \pm 0.0034$ (±2.9%)
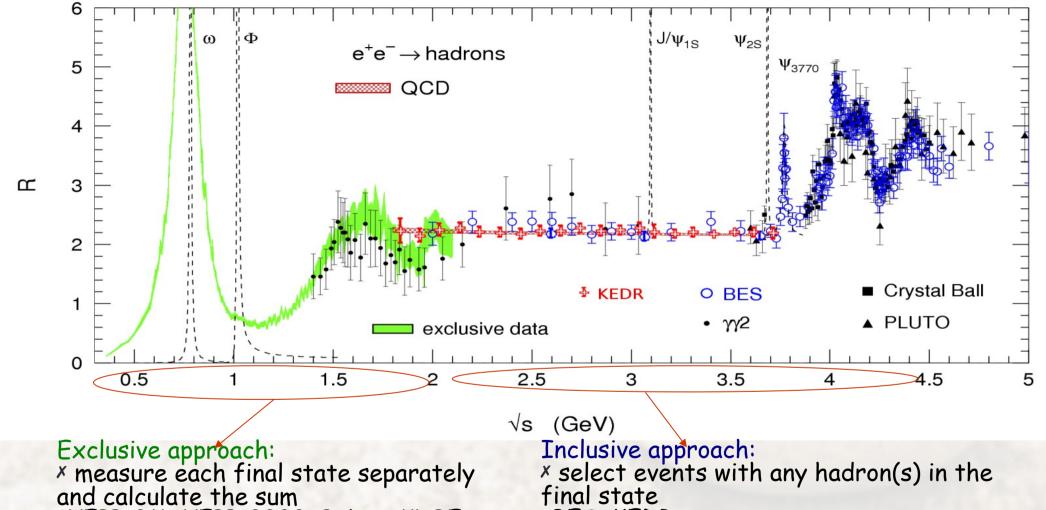
$\alpha_s(M_Z) = 0.1196 \pm 0.0030$ (±2.5%)
$\alpha_s(M_Z) = 0.1151 \pm 0.0028$ (±2.5%)

unweighted χ^2 average: $\alpha_s(M_Z) = 0.1181 \pm 0.0011$ (±0.9%)
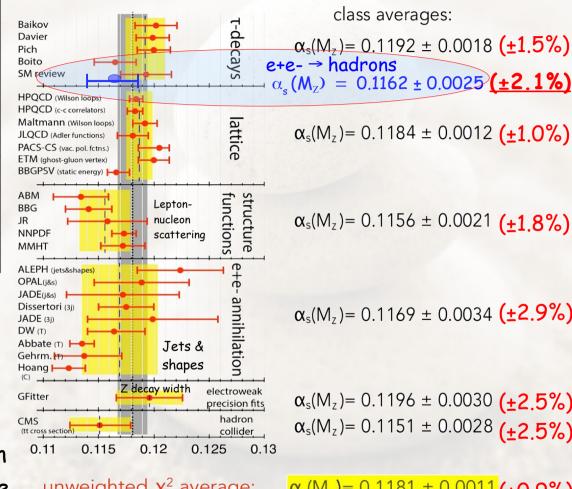
Tau decays to hadrons give the best non-lattice α_s estimation

In future a leap in precision (<0.2%) can be obtained from W,Z decays with huge statistic ($\times 10^4$-10^5 LEP) at FCC-ee

R vs $\sqrt{s}$ (GeV)

$e^+e^- \rightarrow$ hadrons

QCD

KEDR   BES   Crystal Ball
$\gamma\gamma2$ PLUTO

exclusive data

ω Φ J/ψ_{1S} ψ_{2S} ψ_{3770}

Exclusive approach:
✗ measure each final state separately and calculate the sum
 VEPP-2M, VEPP-2000, Babar, KLOE
✗ gives better precision
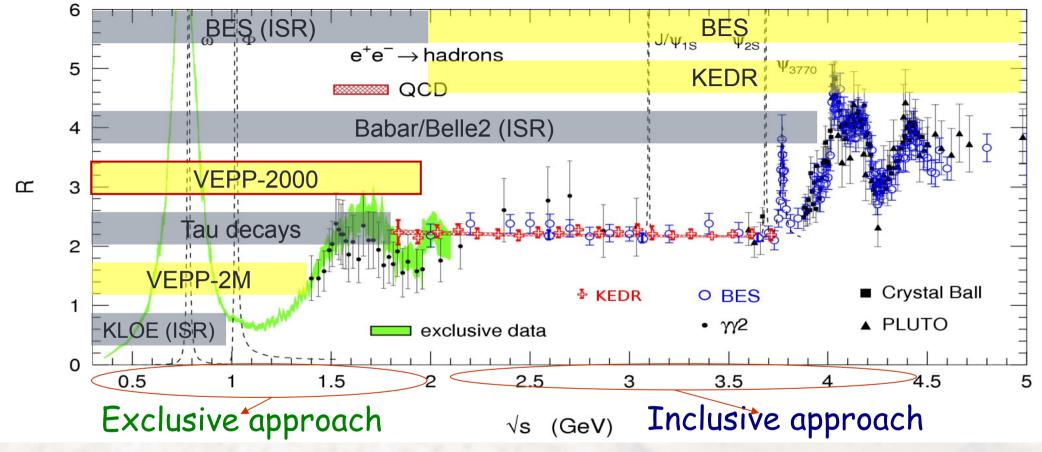
Inclusive approach:
✗ select events with any hadron(s) in the final state
 BES, KEDR, etc
✗ possible because of many modes and high track multiplicity

12

VEPP-2000: direct exclusive measurement of σ (e+e- → hadrons)
The only scan-experiment in operation in these days below <2 GeV
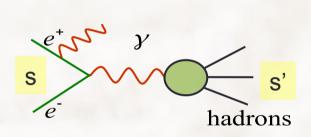World-best luminosity below 2 GeV (except 1 GeV – where KLOE was highest)

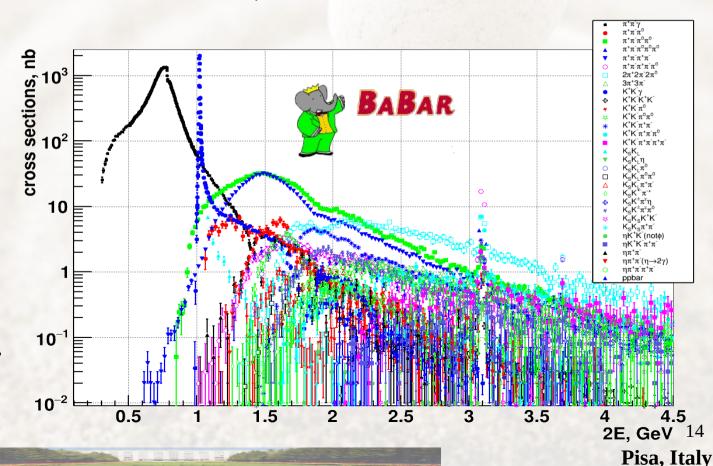BESIII, KEDR – direst scan from 2 GeV to 5 GeV

Additional approach to measurement of the hadronic cross-sections was fully developed over last decades: ISR (Initial State Radiation), advanced by KLOE and BaBar.

$$d\sigma(\, e^+e^- \rightarrow hadrons + \gamma\,) = H(Q^2, \theta_\gamma\,) \times d\sigma(\, e^+e^- \rightarrow hadrons)$$
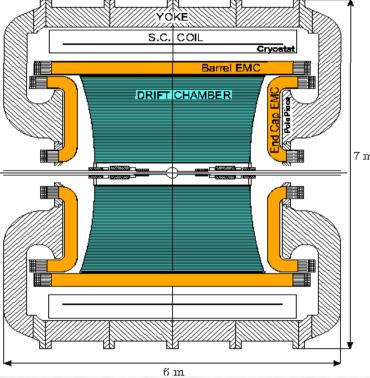
Main idea: cross-section is measured in a wide energy range, using events with hard photon, emitted by initial particles.

12 November 2019

Pisa, Italy

KLOE ISR+ VP

KLOE experiment
(2000 – 2006, 2014 – 2018)
biggest Drift Chamber ever built (Ø4m)

- YOKE
- S.C. COIL
- Cryostat
- Barrel EMC
- DRIFT CHAMBER
- End Cap EMC / Pole Piece
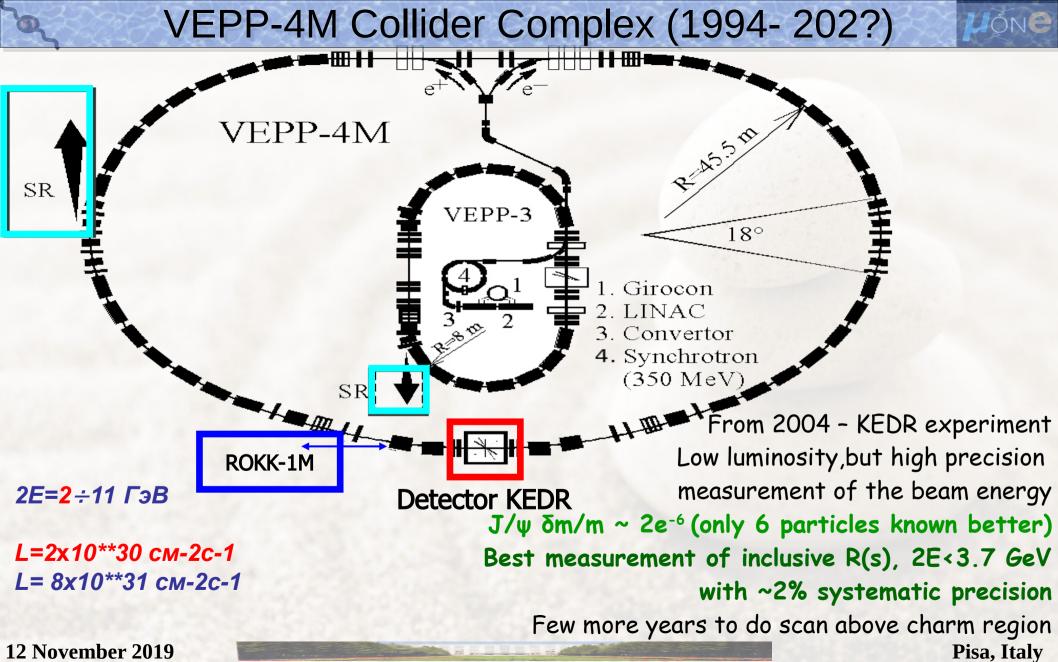- 7 m
- 6 m
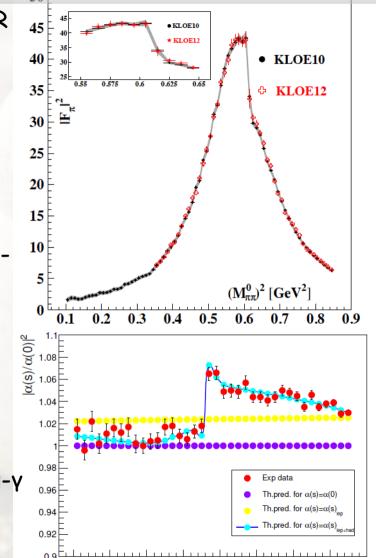
KLOE analysis of γγ physic
and ISR (e+e-→π+π-π0), etc
is underway

Measurement with ISR
e+e- → π+π-γ

JHEP 1803 (2018) 173

3 analyses:
with ISR photon on small angles/ large angle/ using radiator function from ISR μ+μ-
Best local precision at s=0.5-0.85 GeV²

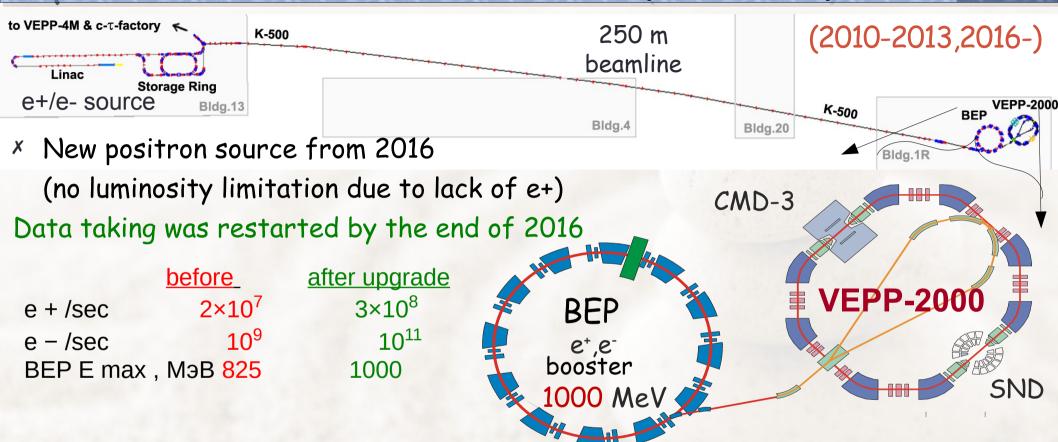direct extraction of
$\alpha_{QED}(s)$ via e+e- → μ+μ-γ

Phys. Lett. B, 767 (2017), 485

$|F_\pi|^2$ vs $(M^0_{\pi\pi})^2$ [GeV²]
- KLOE10
- KLOE12

$|\alpha(s)/\alpha(0)|^2$ vs Energy (GeV)
- Exp data
- Th.pred. for α(s)=α(0)
- Th.pred. for α(s)=α(s)$_{lep}$
- Th.pred. for α(s)=α(s)$_{lep+had}$

VEPP-4M Collider Complex (1994- 202?)

µONE

VEPP-4M

SR

R=45.5 m

18°

e+   e−

VEPP-3

R=8 m

1. Girocon
2. LINAC
3. Convertor
4. Synchrotron
   (350 MeV)

SR

ROKK-1M

Detector KEDR

2E=2÷11 ГэВ

L=2x10**30 см-2с-1
L= 8x10**31 см-2с-1

From 2004 – KEDR experiment
Low luminosity,but high precision
measurement of the beam energy

J/ψ $\delta m/m \sim 2e^{-6}$ **(only 6 particles known better)**
Best measurement of inclusive R(s), 2E<3.7 GeV
with ~2% systematic precision

Few more years to do scan above charm region

to VEPP-4M & c-τ-factory

K-500

250 m beamline

(2010-2013,2016-)

Linac

Storage Ring

e+/e- source

Bldg.13

Bldg.4

Bldg.20

K-500

BEP

VEPP-2000

Bldg.1R

✗ New positron source from 2016

(no luminosity limitation due to lack of e+)

Data taking was restarted by the end of 2016

CMD-3

	before	after upgrade
e + /sec	2×10^7	3×10^8
e − /sec	10^9	10^{11}
BEP E max , МэВ	825	1000

BEP

e+,e- booster

1000 MeV

VEPP-2000

SND

Maximum c.m. energy is 2 GeV, project luminosity is $L = 10^{32}$ cm^{-2}s^{-1} at 2E= 2 GeV

Unique optics, "round beams", allows to reach higher luminosity

Experiments with two detectors, CMD-3 and SND, started by the end of 2010

17

180cm

Mu

LXe
BGO
DC
ZC
TOF
CsI
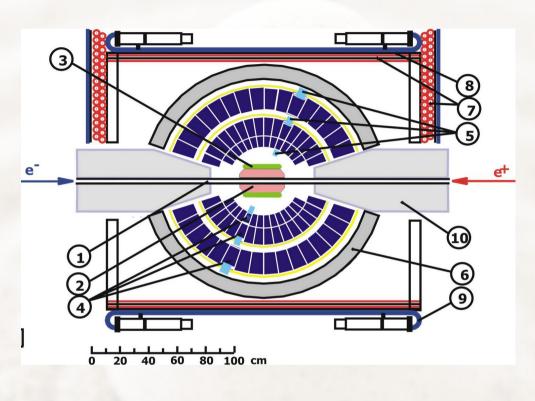
1.3 T magnetic field

Tracking: $\sigma_{R\varphi} \sim 100$ μm, $\sigma_Z \sim 2$mm

Combined EM calorimeter (LXe,CsI, BGO):

$\sigma_E \sim 3\text{-}8\%$, Tracking in LXe calorimeter

1 – beam pipe, 2 – tracking system,
3 – aerogel Cherenkov counter , 4 – NaI(Tl)
crystals, 5 – phototriodes, 6 – iron muon
absorber, 7–9 – muon detector

In 1996-2000 SND collected data at VEPP-2M

19

We are doing not only precise measurement of total R(s) = hadron production cross-section at low energies (by sum of exclusive channels).

But also:
- ✗ study of production dynamics, ChPT
- ✗ properties of light vector mesons, their decays,
- ✗ nucleon formfactors at threshold,
- ✗ two photon physics,
- ✗ search of exotics,
- ✗ and so on...
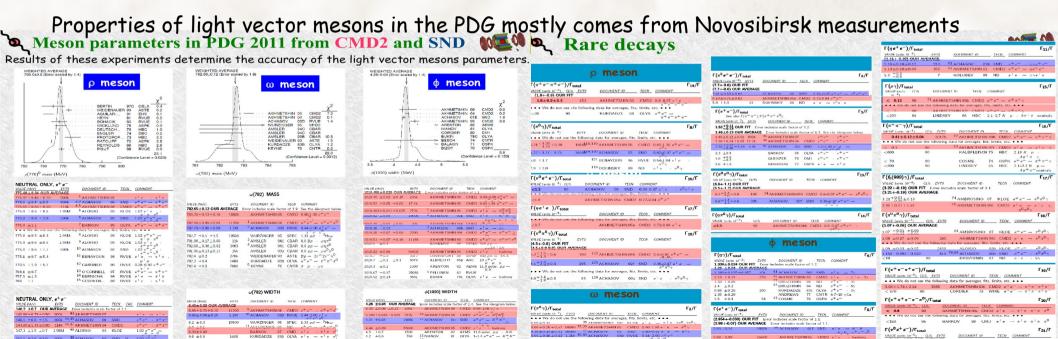
Properties of light vector mesons in the PDG mostly comes from Novosibirsk measurements

Meson parameters in PDG 2011 from CMD2 and SND · **Rare decays**

Results of these experiments determine the accuracy of the light vector mesons parameters.
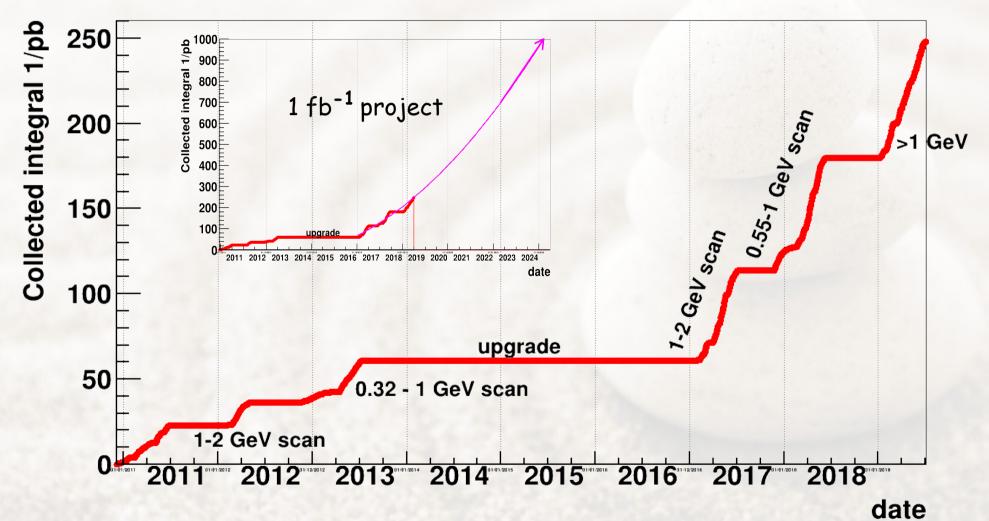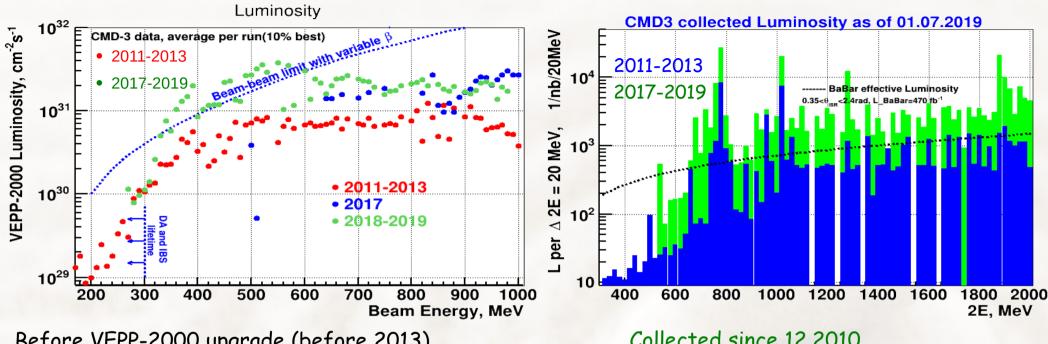
Collected Luminosity

Before VEPP-2000 upgrade (before 2013)
The luminosity at high energy was limited by
a deficit of positrons and limited energy of the booster

After upgrade
2017: big improvement in luminosity at high
energy, still way to go
2018: "Beamshaking" technique was introduced, which
suppress beam instabilities (×4 Lum)

Collected since 12.2010
$L \sim 250$ pb^{-1} per detector
2011-2013 seasons:

17.8 pb^{-1}	< 1 GeV
42.8 pb^{-1}	> 1. GeV

2017-2019 seasons:
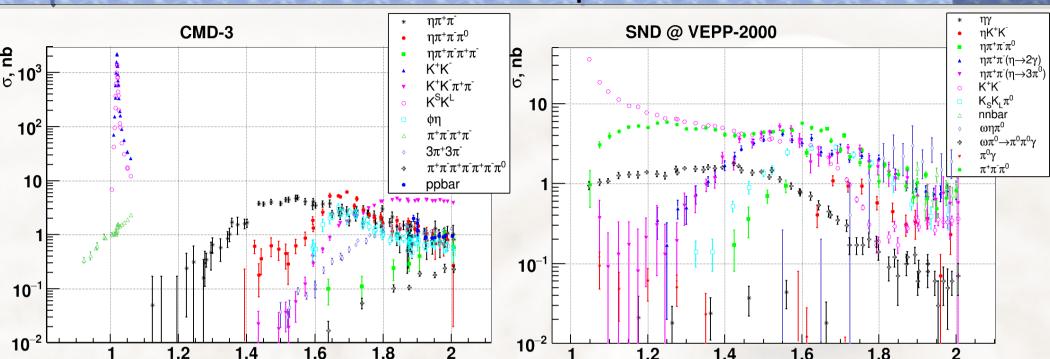
45.4 pb^{-1}	< 1 GeV
141.8 pb^{-1}	> 1. GeV
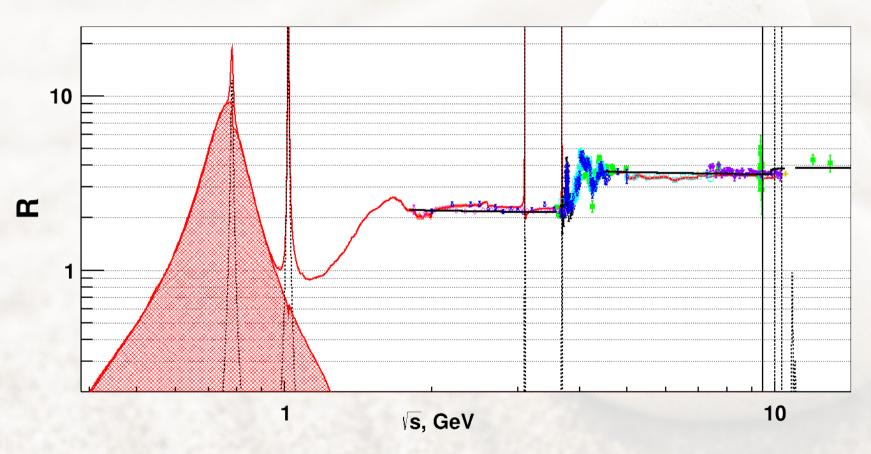
- CMD-3@VEPP-2000: $e^+e^- \to$ η', p$\bar{p}$, 2(π⁺π⁻), 3(π⁺π⁻), 3(π⁺π⁻)π⁰,
  ηπ⁺π⁻, ηπ⁺π⁻π⁰, ηπ⁺π⁻π⁺π⁻, K⁺K⁻, K$_S$K$_L$, K⁺K⁻π⁺π⁻, K⁺K⁻η

- SND@VEPP-2000: $e^+e^- \to$ η, η', f1, n$\bar{n}$, ηγ, π⁰γ, π⁺π⁻π⁰, ωπ⁰, ωηπ⁰,
  ηπ⁺π⁻, ηπ⁺π⁻π⁰, K⁺K⁻, K$_S$K$_L$π⁰, K⁺K⁻η

Many channels is under active analysis
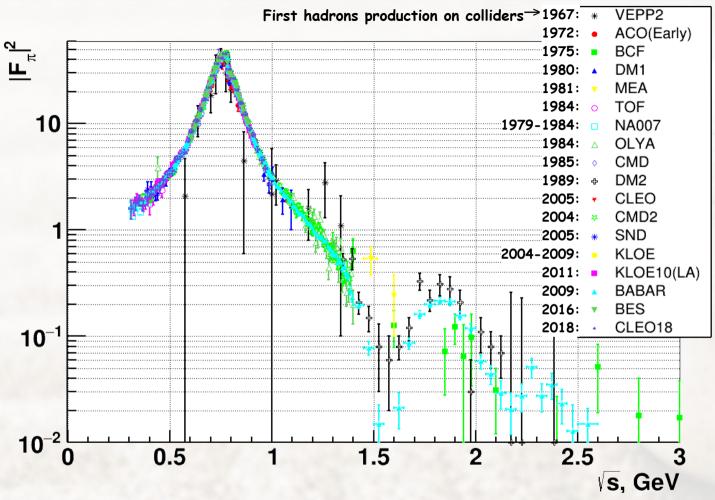
$e^+e^- \rightarrow \pi^+\pi^-$

Gives main contribution to R(s) at √s < 1 GeV

First hadrons production on colliders →

Year		Experiment
1967:	✳	VEPP2
1972:	●	ACO(Early)
1975:	■	BCF
1980:	▲	DM1
1981:	▼	MEA
1984:	○	TOF
1979-1984:	□	NA007
1984:	△	OLYA
1985:	◇	CMD
1989:	✢	DM2
2005:	✶	CLEO
2004:	✿	CMD2
2005:	✷	SND
2004-2009:	●	KLOE
2011:	■	KLOE10(LA)
2009:	▲	BABAR
2016:	▼	BES
2018:	·	CLEO18

$|F_\pi|^2$ vs $\sqrt{s}$, GeV

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

Before 1985
Low statistical precision
Systematic >10%
NA7 A few points with >1-5%

1985 - VEPP-2M
with more detailed scan
OLYA systematic 4%
CMD   2%

2004 with CMD2 at VEPP-2M
was boost to systematic: 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 systematic):
KLOE: 0.8%
BaBar: 0.5%
BES: 0.9%
CLEO: 1.5%

Comparison of e+ e− → π+ π− cross-section

Relative to CMD-2 fit, <mark>yellow</mark> band – systematic value

Points, red band: only statistical error

There are local inconsistencies larger than claimed systematic errors
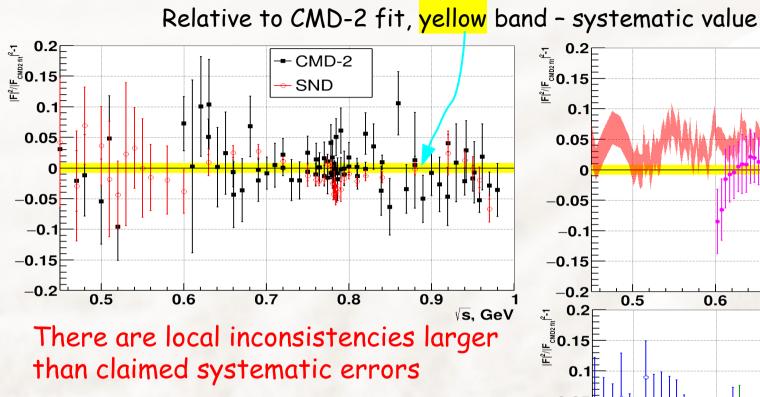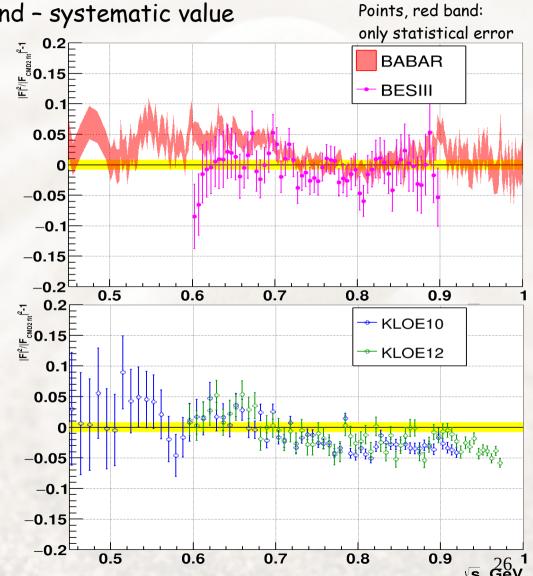
BaBar & KLOE inconsistency gives dominated uncertainty in this channel: for integral of a_μ^{had} :
×1.7 scale factor 0.37 → 0.55%

M.Davier et al., arXiv:1908.00921

The π+ π− contribution to a_μ^{had}

Own unofficial calculation

In integral precision is limited by systematics

Seen 2.9σ tension KLOE vs BaBar

Systematic
Uncertainties
(ρ-region)
CMD2: 0.6-0.8%
SND: 1.5%
KLOE: 0.8%
BABAR :0.5%
BES: 0.9%
CLEO: 1.5%

e+e- → π+π- by CMD-3

Very simple, but the most challenging channel due to high precision requirement.

Plans to reduce systematic error from 0.6-0.8% (by CMD2) -> ~0.4-0.5% (CMD-3)

Crucial pieces of analysis:

✗ e/μ/π separation
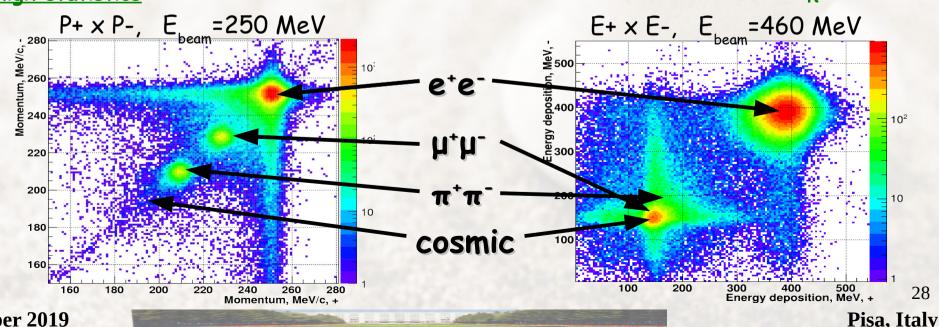
✗ precise fiducial volume

✗ radiative corrections

**Many systematic studies
rely on high statistics**

events separation either by
momentum or by energy deposition

Momentums works better at low energy < 0.8 GeV
Energy deposition > 0.6 GeV

Simple event signature
with 2 back-to-back
charged particles

P+ x P-, E_{beam} =250 MeV

E+ x E-, E_{beam} =460 MeV

e⁺e⁻

μ⁺μ⁻

π⁺π⁻

cosmic

Statistical precision of cross section measurement for <u>2013+2018 data</u> a few times better than any other experiments

|F|² 2013 vs 2018 scans
(PID by momentum)

Δ = 0.10 ± 0.09 %

At CMD-2 it was possible to make separation by momentum only <0.52 GeV

|Fπ|²

Fπ result after event separation without additional corrections

e/μ/π separation using energy deposition in calorimeter

e/μ/π separation using particles momentum

preliminary

N$_{\mu\mu}$/N$_{ee}$/QED

preliminary

Compatible with QED at the level of 0.25 %

Systematic e+e- → π+π- by CMD-3

Our goals are to reach systematic level ~0.4-0.5%:   status

ˣ Radiative corrections   with current MC generators
                                                               0.2% - integral cross-section
                                                               0.0 – 0.4% - from P spectra
                                                             (we need theory help, NNLO generators)

ˣ e/µ/π separation   ~ 0.6 - 0.2 (at ρ) – 1.0(at 0.9 GeV) % by momentum
 can be checked and combined from different methods   ~ 1 % by energy – still work in progress...

ˣ Fiducial volume   0.2%
    controlled independently by LXe and ZC subsystems,
    angular distribution

ˣ Beam Energy   0.1%
    measured by method of Compton back scattering
    of the laser photons(σ_E< 50 keV)

ˣ Electron bremsstrahlung loss   0.05%
ˣ Pion specific correction   ~ 0.1 % nuclear interaction
    decay, nuclear interaction taken from data   0.6-0.3% pion decay

                      at ρ-peak by P   : 0.6%
                      at few lowest points : 0.9%

Many systematic studies rely on high statistics
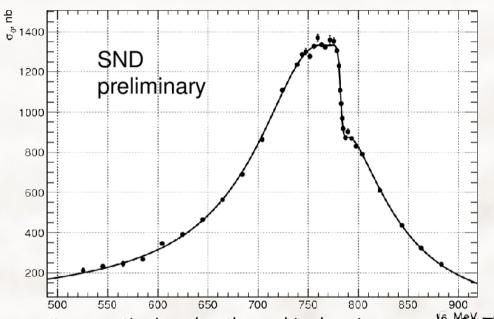
For some sources of systematics there is clear way how to bring it down

30

e+e- → π+π- @ SND

SND preliminary

The events separation based on the machine learning approach (BDT) using information on shower profile from 3-layers of calorimeter

Systematic uncertainty on the cross section (%)

Source	< 0.6 GeV	0.6 - 0.9 GeV
Trigger	0.5	0.5
Selection criteria	0.6	0.6
e/π separation	0.5	0.1
Nucl. interaction	0.2	0.2
Theory	0.2	0.2
Total	**0.9**	**0.8**
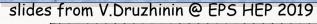
	SND @ VEPP-2000	SND @ VEPP-2M	PDG
M_ρ, MeV	775.4±0.5±0.4	775.6±0.4±0.5	775.3±0.3
Γ_ρ, MeV	145.7±0.7±1.0	146.1±0.8±1.5	147.8±0.9
$B_{\rho ee}\times10^5$	4.89±0.2±0.4	4.88±0.2±0.6	4.72±0.5
$B_{\omega\pi\pi}$, %	1.77±0.08±0.02	1.66±0.08±0.05	1.53±0.06
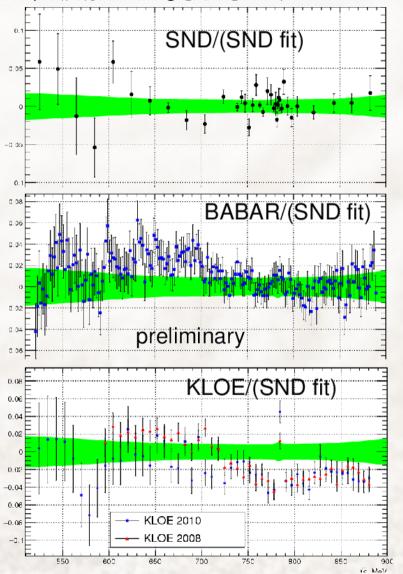
The analysis is based on 4.7 pb^{-1} data recorded in 2013, ~1/10 full SND data set.

31
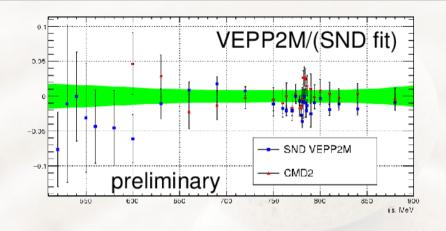
e+e- → π+π- @ SND
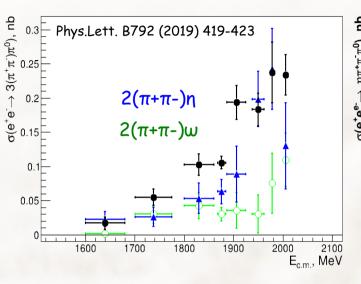
$$0.53 < \sqrt{s} < 0.88 \text{ GeV}$$

	$a_\mu(\pi^+\pi^-) \times 10^{10}$
SND & VEPP-2000	$411.8 \pm 1.0 \pm 3.7$
SND & VEPP-2M	$408.9 \pm 1.3 \pm 5.3$
BABAR	$414.9 \pm 0.3 \pm 2.1$

$e^+e^- \to 3(\pi^+\pi^-)\pi^0$ @ CMD-3

2$(\pi^+\pi^-)\eta$

2$(\pi^+\pi^-)\omega$

Phys.Lett. B792 (2019) 419-423
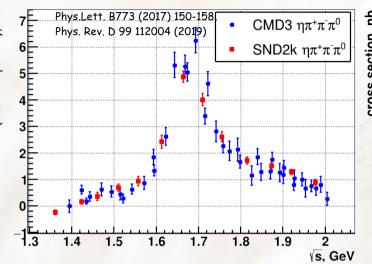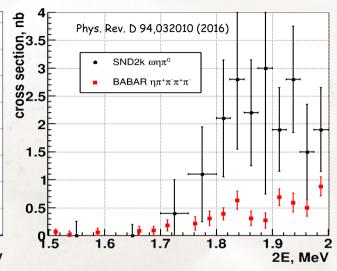
✗ The dominant mechanisms are $4\pi\eta$, $4\pi\omega$

✗ The known before is $4\pi\eta$

The cross section is about 0.25 nb ~1% of R(s) at 2 GeV

$e^+e^- \to \pi^+\pi^-\pi^0\eta$ @ CMD-3, SND

Phys.Lett. B773 (2017) 150-158
Phys. Rev. D 99 112004 (2019)

CMD3 $\eta\pi^+\pi^-\pi^0$
SND2k $\eta\pi^+\pi^-\pi^0$

✗ The intermediate states are $\omega\eta$, $\varphi\eta$, $a_0\rho$ and structureless $\pi^+\pi^-\pi^0$

✗ The known before $\omega\eta$ and $\varphi\eta$ contributions explain about ~50% of the cross section below 1.8 GeV.

✗ Above 1.8 GeV the dominant reaction mechanism is $a_0\rho$

Not accounted part before is about ~ 3-5% of R(s)

$e^+e^- \to \omega\eta\pi^0$ (7γ mode) @ SND

Phys. Rev. D 94,032010 (2016)

SND2k $\omega\eta\pi^0$
BABAR $\eta\pi^+\pi^-\pi^+\pi^-$

✗ The dominant mechanism is $\omega a_0(980)$
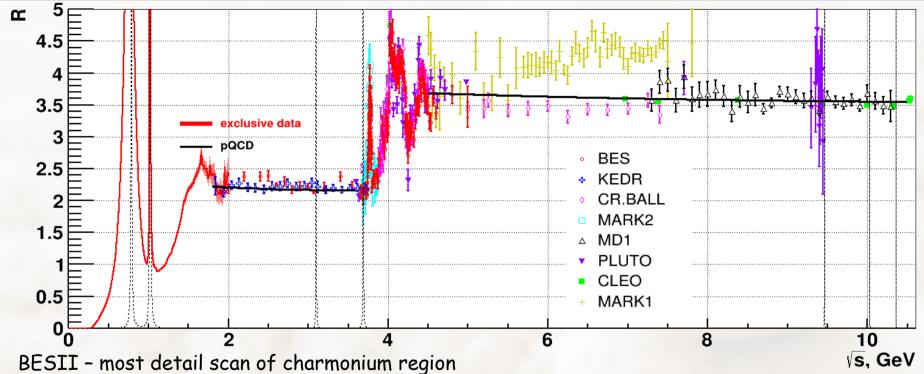
✗ Before was partially accounted by "isospin relation":

$\sigma(\eta\pi^+\pi^-2\pi^0)=\sigma(\eta2\pi^+2\pi^-)$

The cross section is about 2.5 nb ~ 5% of R(s)

33

BESII – most detail scan of charmonium region

KEDR – best systematic precision(up to 2%) at √s < 3.7 GeV

√s =	1.84 – 3.05 GeV	3.08 – 3.72 GeV
R_{KEDR} =	2.23 ± 0.05	2.204 ± 0.030
consistent with R_{pQCD} =	2.18 ± 0.02	2.16 ± 0.01

Phys.Lett. B770 (2017) 174-181
Phys.Lett. B788 (2019) 42-51

Expected in future:
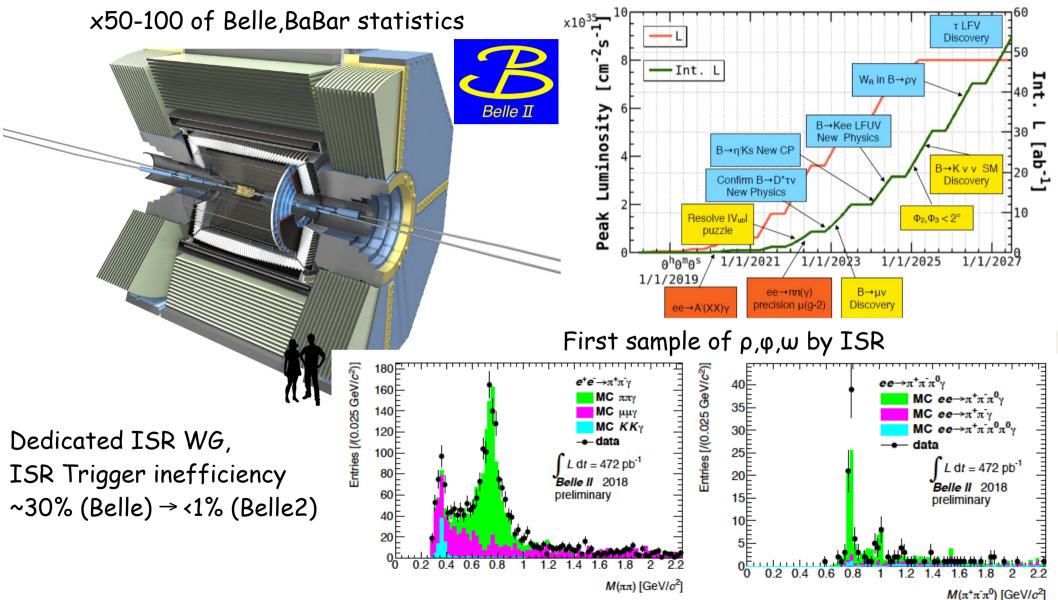
BESIII – already did R(s)-scan during 2012- 2015 years at 2. < √s < 4.6 GeV (125 points, 1.3 fb⁻¹)

KEDR – did 2 scans of 2E=4.5 - 7 GeV (plans to collect more & few points @10 GeV)

34

x50-100 of Belle,BaBar statistics

First sample of ρ,φ,ω by ISR

Dedicated ISR WG,
ISR Trigger inefficiency
~30% (Belle) → <1% (Belle2)
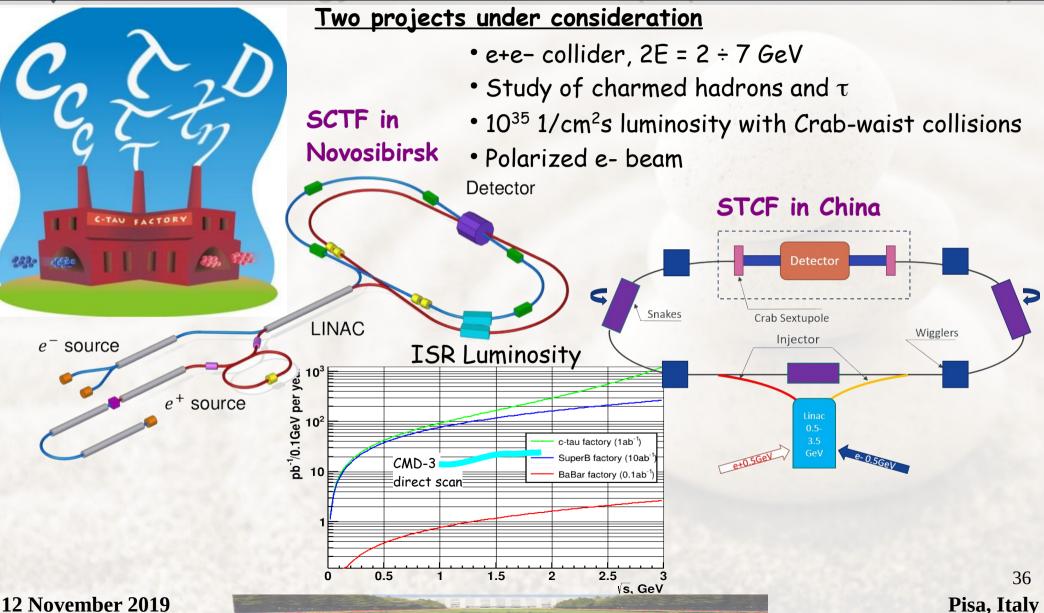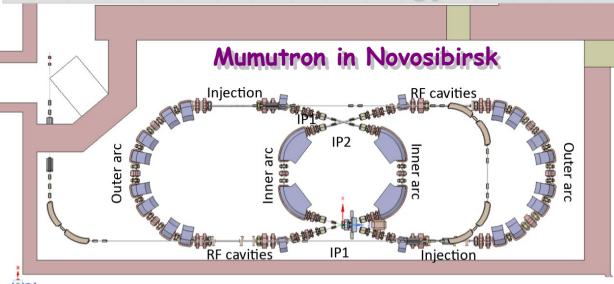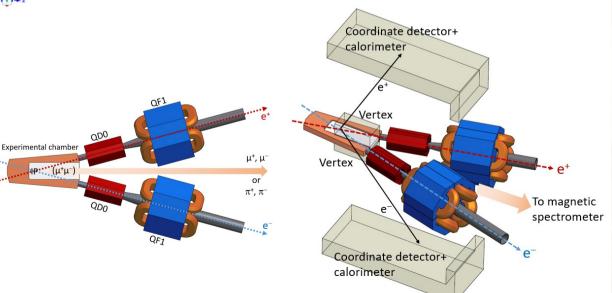
Future low energy e+e- machines(super c-tau factories)

Two projects under consideration

- e+e– collider, 2E = 2 ÷ 7 GeV
- Study of charmed hadrons and τ
- 10^{35} 1/cm^{2}s luminosity with Crab-waist collisions
- Polarized e- beam

SCTF in Novosibirsk

Detector

STCF in China

Detector

Snakes

Crab Sextupole

Wigglers

Injector

e^- source

e^+ source

LINAC

Linac 0.5- 3.5 GeV

e+0.5GeV

e- 0.5GeV

ISR Luminosity

CMD-3 direct scan

- c-tau factory (1ab⁻¹)
- SuperB factory (10ab⁻¹)
- BaBar factory (0.1ab⁻¹)

pb⁻¹/0.1GeV per year

$\sqrt{s}$, GeV

Mumutron in Novosibirsk

project is under consideration

Can be also as an accelerator technology testbench for SCTauF

1st stage :
    Observation & study of dimuonium - μμ bound state
    $\sqrt{s}$ = 212 MeV
    L ~ 8×10^{31} 1/cm²s
2nd stage with reversed beams and dedicated detector:

Rho-factory

• 15° crossing angle
• $\sqrt{s}$ = 0.55-0.96 GeV
• L ~ 0.6-1. × 10^{33} 1/cm²s

The current method based on e+/e- low energy data combines many heterogeneous data samples:

It includes ~48 different detectors , ~35 channels, which gives ~300 datasets.

Very delicate procedure to combine them together

Some of data are disregarded by new experimental results.

It raise specific issues in the estimation of the systematic errors, correlation between datasets, etc...

Lattice progress is very interesting and promising, but not yet competitive

It will be very desirable to find some more "simplified" complementary way...

Hall of Fame:
ACO ADONE ALEPH
AMY ARGUS BABAR
BBar BCF BELLE BES
BES3 BIG CBALL
CELLO CLEO CMD
CMD2 CMD3 CUSB
DASP DHHM DM1
DM2 FENICE GG2
JADE KEDR KLOE
LENA M3N MARK1
MARK2 MARKJ MD1
MEA MUPI NA007
ND OLYA PLUTO
SND SND2k SPEAR
TASSO TOF TOPAZ
VENUS VEPP2
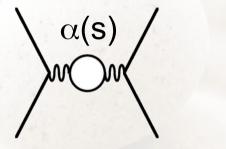
Dispersion integral to a_μ^{had} is usually expressed via time-like data:
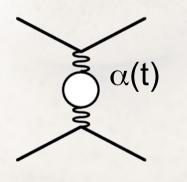
$$a_\mu^{HLO} = \frac{1}{4\pi^3} \int_{4m_\pi^2}^\infty ds\, K(s) \cdot \sigma(s)_{(e^+e^- \to had)}$$

$\alpha(s)$
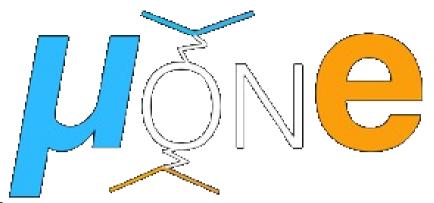
s>0

Also can be rewritten by using space-like region:

$$a_\mu^{HLO} = \frac{\alpha}{\pi} \int_0^1 dx\,(1-x) \cdot \Delta\alpha_{had}\left(-\frac{x^2\, m_\mu^2}{1-x}\right)$$

$\alpha(t)$

t=q²<0

39

A new approach to evaluate the leading hadronic corrections to the muon *g*-2 ☆

C. M. Carloni Calame[a], M. Passera[b], L. Trentadue[c], G. Venanzoni[d]

[a] *Dipartimento di Fisica, Università di Pavia, Pavia, Italy*
[b] *INFN, Sezione di Padova, Padova, Italy*
[c] *Dipartimento di Fisica e Scienze della Terra "M. Melloni"*
Università di Parma, Parma, Italy and
INFN, Sezione di Milano Bicocca, Milano, Italy
[d] *INFN, Laboratori Nazionali di Frascati, Frascati, Italy*

Measuring the leading hadronic contribution to the muon *g*-2 via *µe* scattering

G. Abbiendi[1], C. M. Carloni Calame[2], U. Marconi[1], C. Matteuzzi[3], G. Montagna[4,2],
O. Nicrosini[2], M. Passera[5], F. Piccinini[2], R. Tenchini[6], L. Trentadue[7,3], and G. Venanzoni[8]
[1] *INFN, Sezione di Bologna, Bologna, Italy*
[2] *INFN, Sezione di Pavia, Pavia, Italy*
[3] *INFN, Sezione di Milano Bicocca, Milano, Italy*
[4] *Dipartimento di Fisica, Università di Pavia, Pavia, Italy*
[5] *INFN, Sezione di Padova, Padova, Italy*
[6] *INFN, Sezione di Pisa, Pisa, Italy*
[7] *Dipartimento di Fisica e Scienze della Terra "M. Melloni",*
Università di Parma, Parma, Italy
[8] *INFN, Laboratori Nazionali di Frascati, Frascati, Italy*
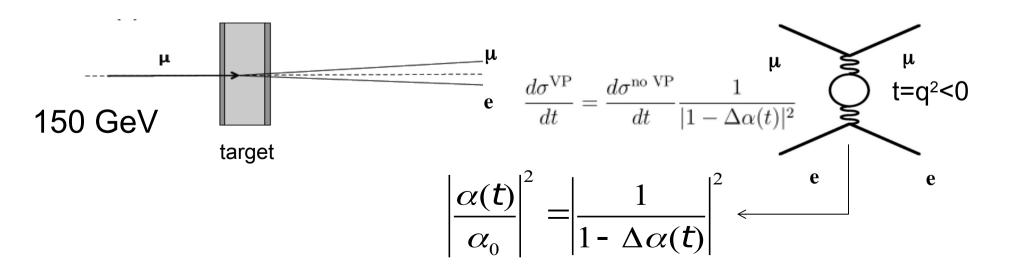
Experimental approach:

Extract $\Delta\alpha_{had}(t)$ from process $\mu e \to \mu e$ using 150 GeV μ on beryllium target. The measurement doesn't rely on the precise knowledge of the luminosity but on the shape of the distribution (relative measurement)

$$\frac{d\sigma^{VP}}{dt} = \frac{d\sigma^{no\ VP}}{dt} \frac{1}{|1-\Delta\alpha(t)|^2}$$

$$\left|\frac{\alpha(t)}{\alpha_0}\right|^2 = \left|\frac{1}{1-\Delta\alpha(t)}\right|^2$$

$t = q^2 < 0$

150 GeV

target

μ e μ μ e   e

41

Why measuring $\Delta\alpha_{had}(t)$ with a 150 GeV μ beam on e⁻ target ?
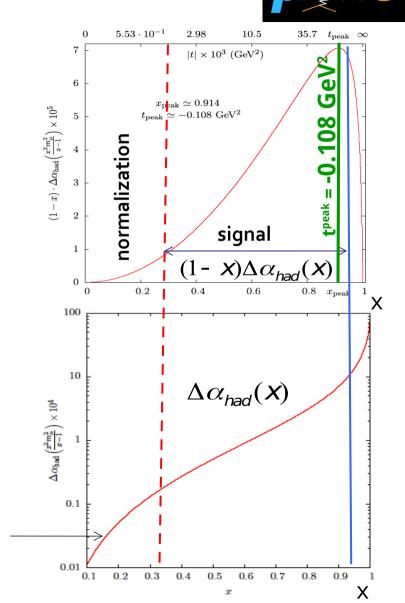
$\mu\,e \rightarrow \mu\,e$ looks an ideal process!

- It is a pure t-channel (at LO)
- It allows to cover 83% of the integrand (a_μ^{HLO}). The missing part can computed with time-like data+pQCD
- The kinematics is very simple: $t = -2m_e E_e$
- High boosted system gives access to all angles (t) in the cms region
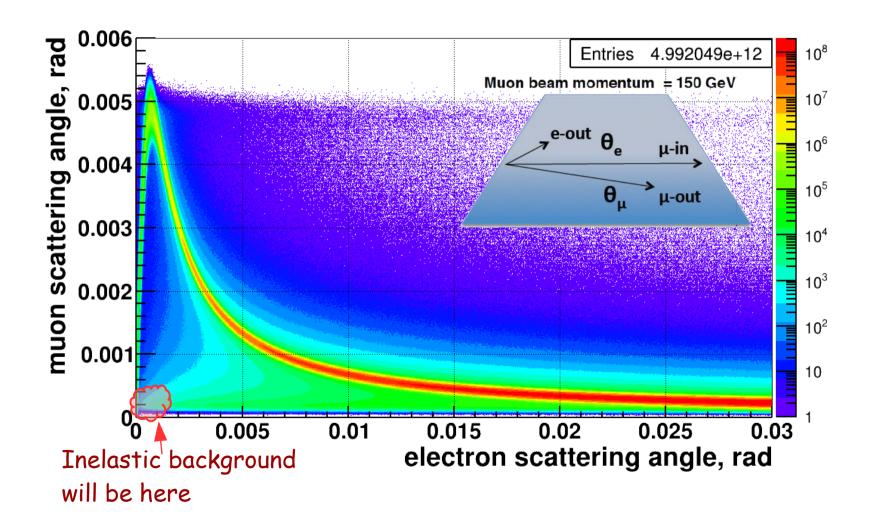
$$\theta_e^{LAB} < 32 \text{ mrad } (E_e > 1 \text{ GeV})$$
$$\theta_\mu^{LAB} < 5 \text{ mrad}$$

- It allows using the same detector for signal and normalization. Events at $x \lesssim 0.3$ ($t \sim -10^{-3}$ GeV²) can be used for normalization ($\Delta\alpha_{had}(t) \lesssim 10^{-5}$)

Elastic scattering in the (θ_e, θ_μ) plane

Inelastic background will be here

43
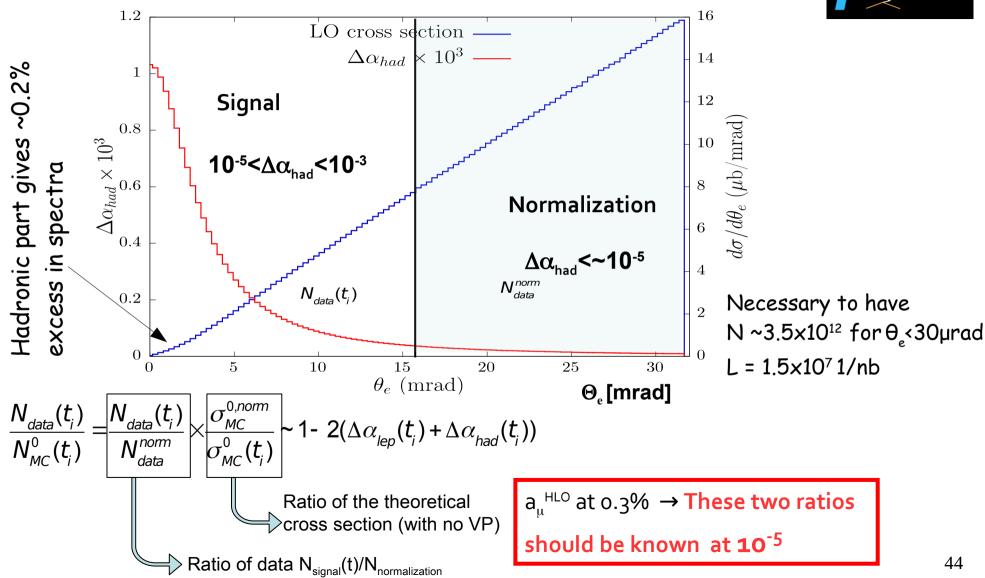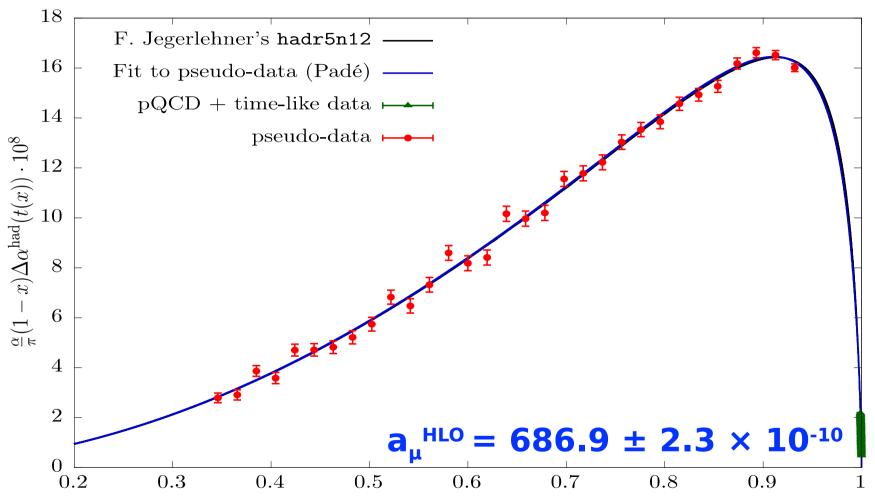
MUonE : signal/normalization region

Hadronic part gives ~0.2% excess in spectra

Signal

$10^{-5} < \Delta\alpha_{had} < 10^{-3}$

$N_{data}(t_i)$

Normalization

$\Delta\alpha_{had} < \sim 10^{-5}$

N^{norm}_{data}

Legend: LO cross section (blue) — $\Delta\alpha_{had} \times 10^3$ (red)

y-axis left: $\Delta\alpha_{had} \times 10^3$
y-axis right: $d\sigma/d\theta_e$ ($\mu b/mrad$)
x-axis: θ_e (mrad), Θ_e [mrad]

Necessary to have
N ~3.5×10^{12} for $\theta_e < 30\mu$rad
L = 1.5×10^7 1/nb

$$\frac{N_{data}(t_i)}{N^0_{MC}(t_i)} = \boxed{\frac{N_{data}(t_i)}{N^{norm}_{data}}} \times \boxed{\frac{\sigma^{0,norm}_{MC}}{\sigma^0_{MC}(t_i)}} \sim 1 - 2(\Delta\alpha_{lep}(t_i) + \Delta\alpha_{had}(t_i))$$

Ratio of the theoretical cross section (with no VP)

Ratio of data $N_{signal}(t)/N_{normalization}$

a_μ^{HLO} at 0.3% → **These two ratios should be known at 10^{-5}**

44

Statistical reach of MUonE on a_μ^{HLO}

A **0.3%** stat error can be achieved on a_μ^{HLO} in 3 years of data taking with 1.3×10^7 μ/s (4×10^{14} μ total)

Muon beam M2 at CERN

"Forty years ago, on 7 May 1977, CERN inaugurated the world's largest accelerator at the time – the Super Proton Synchrotron".
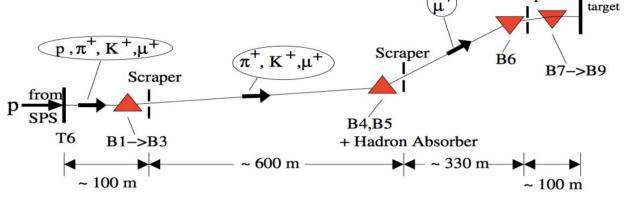
Table 3
Parameters and performance of the 160 GeV/c muon beam.

Beam parameters	Measured
Beam momentum $(p_\mu)/(p_\pi)$	$(160\,\mathrm{GeV}/c)/(172\,\mathrm{GeV}/c)$
Proton flux on T6 per SPS cycle	$1.2 \cdot 10^{13}$
Focussed muon flux per SPS cycle	$2 \cdot 10^{8}$
Beam polarisation	$(-80 \pm 4)\%$
Spot size at COMPASS target $(\sigma_x \times \sigma_y)$	$8 \times 8\,\mathrm{mm}^2$
Divergence at COMPASS target $(\sigma_x \times \sigma_y)$	$0.4 \times 0.8\,\mathrm{mrad}$
Muon halo within 15 cm from beam axis	16%
Halo in experiment $(3.2 \times 2.5\,\mathrm{m}^2)$ at $|x,y| > 15\,\mathrm{cm}$	7%

$I_{beam} > 10^7$ muon/s, $E_\mu = 150$ GeV 46
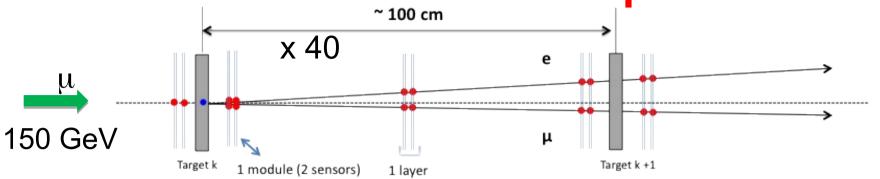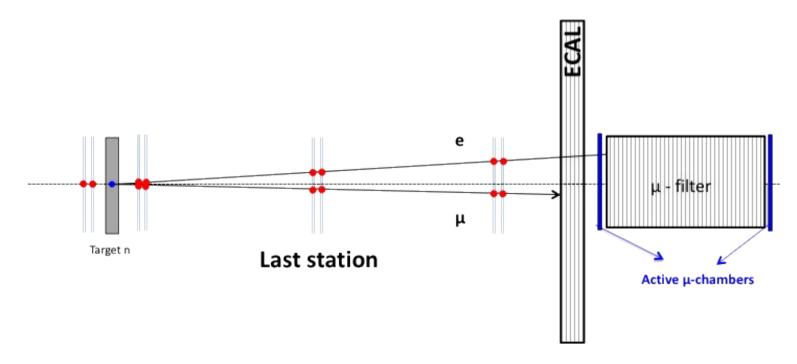
Detector concept

**40 'independent' stations will provide 60 cm Be target material
to collect L=1.5x10^7 1/nb during 3 years with 10^7 muons/sec beam** (dL=3x10^{32}cm^2/sec)
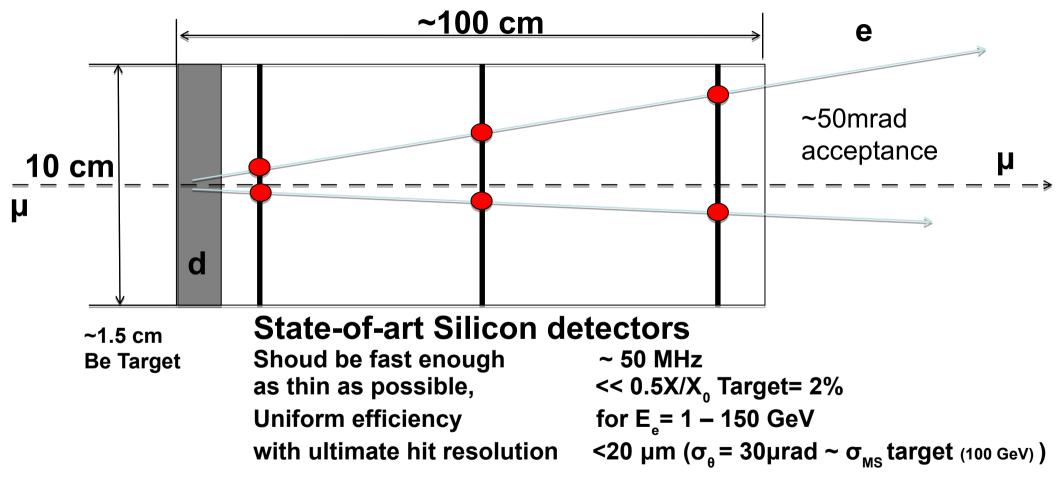
47

Single Unit

~100 cm

10 cm

μ

~1.5 cm
Be Target

d

e

~50mrad
acceptance

μ

State-of-art Silicon detectors
Shoud be fast enough	~ 50 MHz
as thin as possible,	$\ll 0.5 X/X_0$ Target= 2%
Uniform efficiency	for E_e = 1 – 150 GeV
with ultimate hit resolution	<20 μm (σ_θ = 30μrad ~ σ_{MS} target (100 GeV))

**ECAL and Muon Filter at the end of all units
for PID, background, systematic studies**

Tracking system

Requirements:

- Good resolution (~ 20 μm)
- High uniformity ($\varepsilon \gtrsim 99.99\%$)
- Capable to sustain high rate (50 MHz)
- Available technology (pilot run 2021)

Achievement: CMS 2S Module

- Thickness : 2 × 320 μm
- Pitch: 90 μm → σ_x = 26 μm
- Angular resolution: σ_θ ~ 30 μrad
- Readout rate: 40 MHz
- Area: 10 cm × 10 cm
- Efficiency= 99.988 ± 0.008
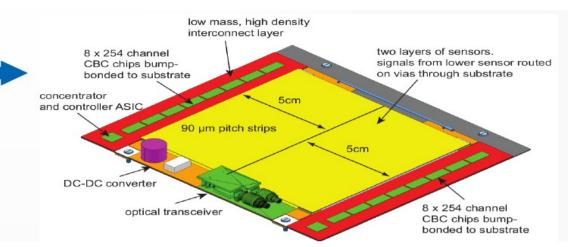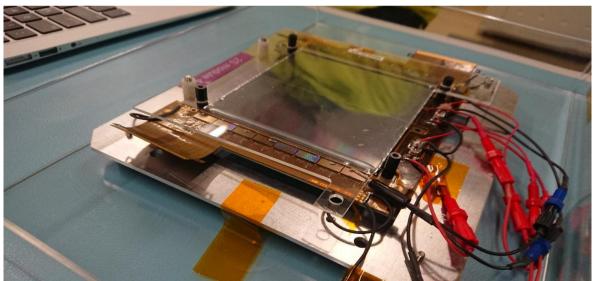
Trade-off between availability and parameters

Systematics

1. Multiple scattering
2. Tracking (alignment & misreconstruction)
3. PID
4. Knowledge of muon momentum distribution
5. Background
6. Theoretical uncertainty on the mu-e cross section
7. …

The 10 ppm goal is challenging task on control of systematics
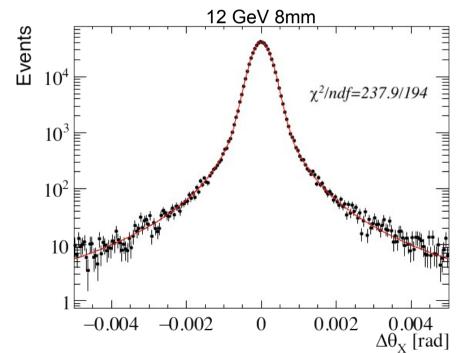
2017 Test beam at the H8 line at CERN using the UA9 setup
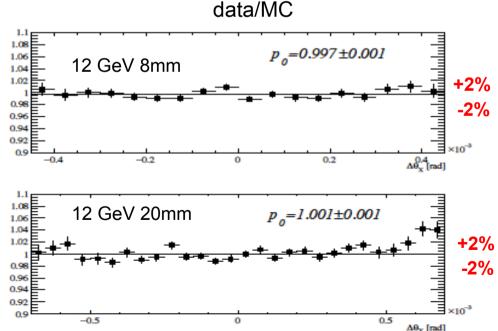
Results on Multiple Coulomb Scattering from 12 and 20 GeV electrons on Carbon targets (h=8, 20 mm)

Submitted to JINST

G. Abbiendi[a], J. Bernhard[b], F. Betti[a,c], M. Bonanomi[d], C. M. Carloni Calame[e], M. Garattini[b,g], Y. Gavrikov[f], G. Hall[g], F. Iacoangeli[h], F. Ignatov[i], M. Incagli[j], V. Ivanchenko[b,k], F. Ligabue[j,l], T. O. James[g], U. Marconi[a], C. Matteuzzi[d], M. Passera[m], M. Pesaresi[g], F. Piccinini[e], R. N. Pilato[j,n], F. Pisani[a,b,c], A. Principe[a,c], W. Scandale[b], R. Tenchini[j] and G. Venanzoni[j,1]
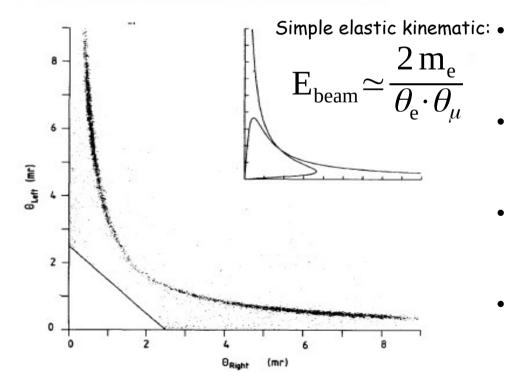
data/MC

12 GeV 8mm

$\chi^2/ndf=237.9/194$

12 GeV 8mm $p_0=0.997\pm0.001$ +2% -2%

12 GeV 20mm $p_0=1.001\pm0.001$ +2% -2%

Momentum scale

S.R.Amendolia et al, Phys.Lett.B146(1984)116 /
Nucl.Phys.B277(1986)168
πe Elastic scattering in the (θ_R, θ_L) plane

Simple elastic kinematic:

$$E_{beam} \simeq \frac{2\,m_e}{\theta_e \cdot \theta_\mu}$$

- Beam energy determined by kinematics by measuring the angles of the two outgoing particles. Method previously used by NA7
- Selection of events ~ 2.5 mrad (E~75 GeV) Distribution of the angle sum (or the average angle) for the selected events.
- This technique is robust against transverse misalignments (null effect to the first order).
- Longitudinal misalignments should be limited to O(10) microns.

- BMS (momentum hodoscope) with Δp/p<1% for event-by-event will help with beam profile knowledge

52

Momentum scale
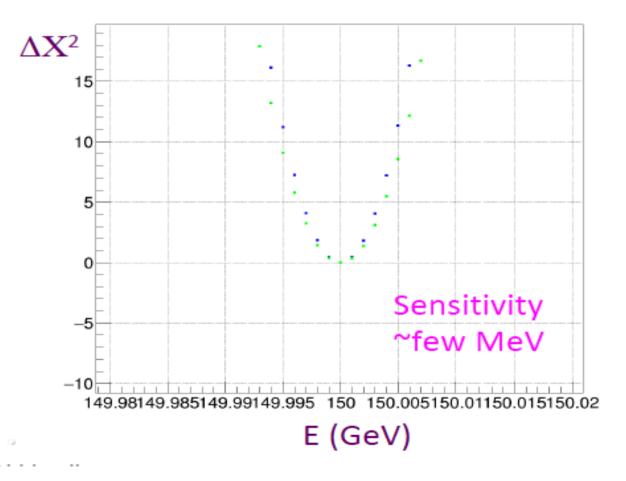
Template method: χ^2 comparison of data with shape of angle distributions

Toy MC:
Ebeam = 150 GeV with 1% spread (spectrometer)
Generation of 10^7 events selecting an angular region around θ~2.5 mrad and realistic angular spread:

- Systematic error ~MeV
- Statistics of few days: Accuracy ~ 1 MeV

Theory

- QED NLO MC generator with full mass dependence has been developed and is currently under use (Pavia group) : M. Alacevich, *et al* **arXiv:1811.06743**.

- First results obtained for the NNLO box diagrams contributing to μ-e scattering in QED (Padova group): P. Mastrolia, *et al*, **JHEP 1711 (2017) 198**; S. Di Vita, *et al.* **JHEP 1809 (2018) 016**; M. Fael, **arXiv:1808.08233**; M. Fael , M. Passera **arXiv:1901.03106;** resummation (effects beyond fixed-order perturbation theory) and "massification" (massless matrix elements → differential cross section) (A. Signer, Y. Ulrich, PSI Group)

An unprecedented precision challenge for theory: a full NNLO MC generator for μ-e scattering (10^{-5} accuracy)

Will be very useful in other experiments: R(s) mesuarement,
τ physics at SuperKEKB, super C-Tau factories

Status of MUonE

✗ Collaboration is growing and includes: INFN, CERN, China (Shangai), Poland (Krakov), Russia (Novosibirsk), UK (Liverpool London), USA (Virginia).

✗ The project was part of "Physics Beyond Collider" WG at CERN (http://pbc.web.cern.ch/) with very encouraging response

✗ Letter of Intent submitted to the CERN's SPSC: https://cds.cern.ch/record/2677471?ln=it

✗ First meeting with the SPSC's referees (Arnaud Ferrari and Urs Wiedemann) took place on October 14

✗ Pilot Run requested in LoI with two stations (3 weeks at the end of 2021)

✗ 3-years data taking requested in 2022-2024 for final (per mille) accuracy on a_m^{HLO}

(Tentative) Time schedule

- In agreement with the CMS we plan for the final detector to have ~250 2S modules with the following time profile:
  - 50% of stations delivered by spring 2022 (20 stations)
  - 50% by end of 2022 (20 stations)

If the Pilot Run will validate the design and the performance, then MUonE will request (a very tentative schedule…):

➢ **2022** Some time (of the order of 4 weeks) with ½ of the apparatus towards the end of the running time (due to availability of the Si modules and their mounting/ aligning on the supports)

➢ **2023 – 2024** Consistent time of running to collect as much statistics as possible (ultimate goal of a statical error on $a_\mu^{HLO} \sim 2 \times 10^{-10}$)

✗ We are waiting with bated breath of new muon g-2 result soon, with x4 improvement in future by FermiLab (E989) and J-PARC (E34)

✗ Precise R(s) from low-energy e^+e^- colliders is used in many applications of accurate SM predictions such as $a_\mu^{had,LO-VP}$, $\alpha_{QED}(M_Z)$, ...

✗ VEPP-2000 is currently the only one energy scan collider working below <2 GeV for measurement of exclusive $\sigma(e+e- \to hadrons)$
✗ Starting to operate Belle2 and possible SuperC-Tau factories can provide even more data with ISR

✗ Alternative/competitive determinations of a_μ^{HLO} are essential:
  ✗ MUonE: a novel way to extract a_μ^{HLO} by single experiment measurement in space-like region
  ✗ LoI submitted to SPSC in 2019; if approved a few-weeks pilot run in 2021 to assess the detector performance and validate the design; then 3 years run (2022-2024) for ultimate precision

R(s) by direct scans and ISR, space-like measurements, and future Lattice
will help to reduce error of the hadronic contribution prediction to (g-2)µ, ...
they all give important cross-checks of different aspects of each others

57

backups

Letter of Intent

(submitted to SPSC in June)

70 authors; 16 Institutions

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN

To be specified

Letter of Intent: The MUonE Project

MUonE Collaboration

Contents

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

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

1 September 1967

Start of e+e- → hadrons measurements

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

VEPP-2, Novosibirsk

e+e- → ρ → ππ

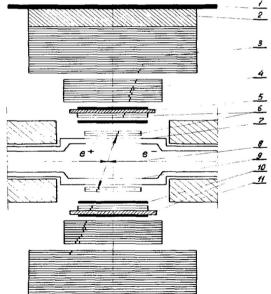Detector was made from different layers of Spark chambers,
readouts by photo camera

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
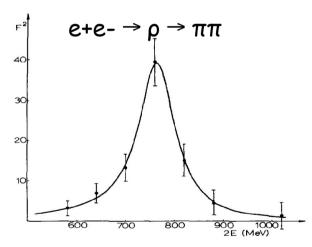6) Thin-plate spark chambers

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 $a=20.4$.

1961	AdA	Frascati	Italy
1965	Princeton-Stanford(e-e-)	Stanford	USA
1965	VEP-1(e-e-)	Novosibirsk	USSR
1966	VEPP-2	Novosibirsk	USSR
1967	ACO	Orsay	France
1969	ADONE	Frascat	Italy
1971	CEA	Cambridge	USA
1972	SPEAR	Stanford	USA
1974	DORIS	Hamburg	German
1974	VEPP-2M	Novosibirsk	USSR
1976	DCI	Orsay	France
1977	VEPP-3	Novosibirsk	USSR
1978	VEPP-4	Novosibirsk	USSR
1978	PETRA	Hamburg	Germany
1979	CESR	Cornell	USA
1980	PEP	Stanford	USA
1981	Sp-pbarS	CERN	Switzerland
1982	p-pbar	Fermilab	USA
1987	TEVATRON	Fermilab	USA
1989	SLC	Stanford	USA
1989	BEPC	Beijing	China
1989	LEP	CERN	Switzerland
1992	HERA	Hamburg	Germany
1994	VEPP-4M	Novosibirsk	Russia
1999	DAFNE	Frascati	Italy
1999	KEKB	Tsukuba	Japan
1999	PEP-II	Stanford	USA
2001	RHIC	Brookhaven	USA
2008	BEPCII	Beijing	China
2009	LHC	CERN	Switzerland
2010	VEPP-2000	Novosibirsk	Russia.
2018	SuperKEKB	Tsukuba	Japan

(Physics start date)

1961: AdA was the first matter antimatter storage ring with a single magnet (weak focusing) in which e+/e- were stored at 250 MeV

Touschek effect (1963); first e+e− interactions recorded – limited by luminosity ~ $10^{25} \text{cm}^{-2}\text{s}^{-1}$

SLAC & Novosibirsk VEP-1 works independently

1965: First physics at collision with e-e- scattering

(QED radiative effects confirmed)

1967: VEPP-2 First e+e- → hadron production
$$L \sim 10^{28} \text{cm}^{-2}\text{s}^{-1}$$

61

Experimental world average

a_μ = 11 659 208.9 **± 6.3** $\times 10^{-10}$

Theoretical prediction

δa_μ = **± 3.6** $\times 10^{-10}$ (KNT 18)

Hadronic content of a_μ calculated

From measured cross-section by dispersion integral

LO hadronic 693.27 **±2.46** $\times 10^{-10}$ KNT 18

main channels contribution to precision at √s<1.937 GeV

$\pi^+\pi^-$	502.97 **± 1.97**	
$\pi^+\pi^-\pi^0$	47.79 **± 0.89**	(mostly from omega region)
$\pi^+\pi^-2\pi^0$	19.39 **± 0.78**	
K+K-	23.03 **± 0.22**	

.....

Inclusive(√s>1.937 GeV)   43.67 **± 0.67**

Light-by-light 9.8 **± 2.6** need more theory input

with help of experimental transition form factors

Δ Exp - Theory∼ 3- 4 σ

ArXiv:1802.02995, arXiv:1908.00921

J 2018
−31.5 ± 4.4 (4.1σ)

BNL-E821
0 ± 6.3

KNT 2018
−27.0 ± 3.6 (3.7σ)

DHMZ 2019
−26.2 ± 4.8 (3.3σ)

$a_\mu - a_\mu^{exp}$ [$\times 10^{-10}$]

New g-2 experiments at FNAL and J-PARC have plans to reduce error to **1.5x10^{-10}**

The value and the error of the hadronic contribution to muon (g-2) are dominated by low energy R(s) (<2GeV gives 93% of the value). $\pi^+\pi^-$ gives the main contribution (73%) to a_μ

62