

Physics with e^+e^- at Low Energy

Simon Eidelman

Budker Institute of Nuclear Physics SB RAS and
Novosibirsk State University,
Novosibirsk, Russia

Outline

1. Physics of light quarks (u, d, s)
2. Physics of τ lepton and c, b quarks

Physics of Light Quarks (u, d, s)

Outline

1. e^+e^- colliders
2. R measurement
3. Light vector mesons and exclusive processes
4. Muon anomalous magnetic moment
5. Conclusions

Two Trends in Modern High Energy Physics

Major achievements coming from collider experiments:

1. Energy Frontier:

- Standard Model@LEP (ALEPH, DELPHI, L3, OPAL) $\sqrt{s} = 200 \text{ GeV } (e^+ e^-)$
- Tevatron studied t quark physics and QCD (CDF and D0) $\sqrt{s} = 2 \text{ TeV } (p\bar{p})$
- LHC and Higgs discovery (ATLAS, CMS),
new particles and states of matter (ALICE, LHCb) $\sqrt{s} = 14 \text{ TeV } (pp)$

2. Intensity/Precision Frontier (Clean conditions of $e^+ e^-$):

- ϕ factories (KLOE@DAFNE, CMD3/SND@VEPP-2000) $\mathcal{L} \sim 10^{32} \text{ cm}^{-2} \text{ s}^{-1} - R$, vectors ($\rho, \omega, \phi, \dots$), light mesons
- $c - \tau$ factories (CLEOc@CESR, BES3@BEPC2) $\mathcal{L} \sim 10^{33} \text{ cm}^{-2} \text{ s}^{-1} - R$, vectors (ψ), τ , charm, new and exotic $c\bar{c}$ states
- B factories (BaBar@PEP2, Belle@KEKB) $\mathcal{L} \sim 10^{34} \text{ cm}^{-2} \text{ s}^{-1} - \Upsilon, b$, CP violation, new $c\bar{c}$ and $b\bar{b}$ states, exotics (tetraquarks, molecules. . .)

Collider vs. Fixed Target Experiments

Consider a collision of two particles with equal mass.

1/ Laboratory system (fixed target): $p_1 = (E, \vec{p})$, $p_2 = (m, 0)$

$$s = (p_1 + p_2)^2 = (E + m)^2 - \vec{p}^2 = 2m^2 + 2Em \approx 2Em \quad (E \gg m)$$

2/ Center-of-mass system (collider): $p_1 = (E^*, \vec{p}^*)$, $p_2 = (E^*, -\vec{p}^*)$

$$s^* = (p_1 + p_2)^2 = 4E^{*2}$$

$$s^* = s \Rightarrow 4E^{*2} \approx 2Em \Rightarrow E \approx \frac{2E^{*2}}{m}$$

$$E^* = 385 \text{ MeV} \quad (2E^* = m_\rho = 770 \text{ MeV}) \Rightarrow E \approx 580 \text{ GeV}$$

Gain in energy - three orders of magnitude!

Instantaneous Luminosity

Two main characteristics of a collider – energy and luminosity

Luminosity tells us how efficient a collider is:

$$\dot{N} = \mathcal{L}\sigma,$$

\dot{N} – the number of events per unit time
for the process with the cross section σ

Instantaneous luminosity ($\text{cm}^{-2}\text{s}^{-1}$)

$$\mathcal{L} = f \frac{n_1 n_2}{4\pi\sigma_x\sigma_y},$$

$n_{1(2)}$ – the number of particles in a bunch,

$\sigma_{x(y)}$ – transverse beam profile,

f – collision frequency of two bunches (head-on collision)

Integrated Luminosity

Integrated luminosity (cm^{-2}) is the instantaneous luminosity integrated over time – the ratio of the yield to cross section:

$$\sigma = \frac{N}{\int \mathcal{L} dt \epsilon},$$

N – the number of observed events (yield),

ϵ – acceptance (detection efficiency),

$\int \mathcal{L} dt$ – integrated luminosity (cm^{-2})

Determination of Integrated Luminosity

In practice, beam parameters like $n_{1(2)}$ and $\sigma_{x(y)}$ are known with large uncertainty.

Instantaneous luminosity is measured on line with a luminosity monitor using a process with a large and well-known cross section, e.g., $e^+e^- \rightarrow e^+e^-\gamma$ or small angle $e^+e^- \rightarrow e^+e^-$.

$\int \mathcal{L} dt$ is determined off line by detecting a QED process with a large cross section, e.g., $e^+e^- \rightarrow e^+e^-$, $e^+e^- \rightarrow \gamma\gamma$ or $e^+e^- \rightarrow \mu^+\mu^-$ and from the known $\sigma_{\mu\mu}$

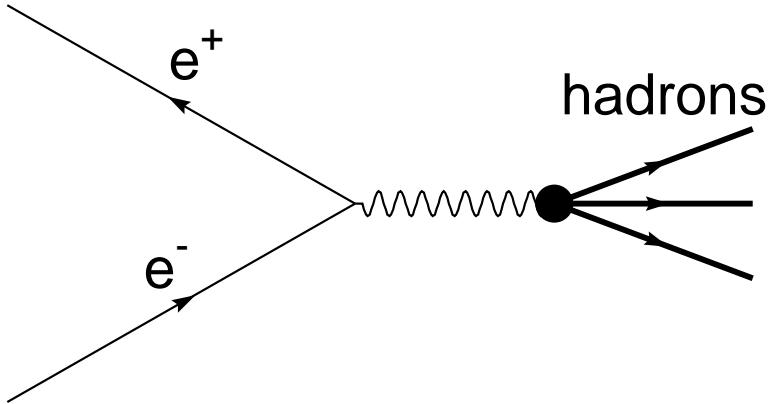
$$\int \mathcal{L} dt = \frac{N_{\mu\mu}}{\sigma_{\mu\mu} \epsilon_{\mu\mu}}$$

Units and Typical Luminosities

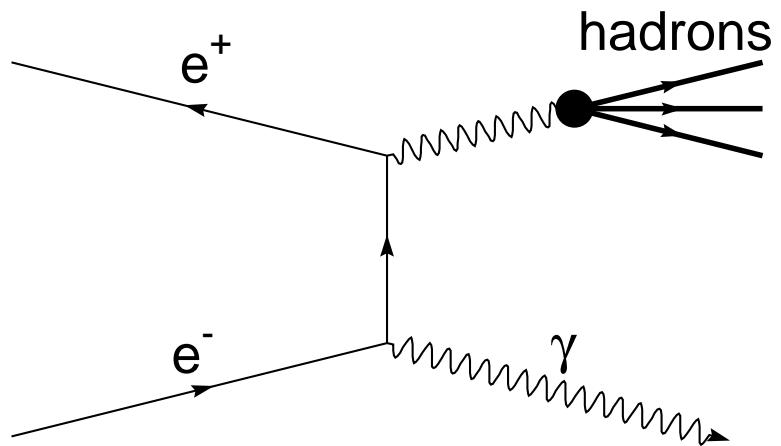
Typical units of nuclear cross sections are barns ($1\text{b} = 10^{-24} \text{ cm}^2$),
in particle physics $1 \text{ nb} = 10^{-33} \text{ cm}^2$, $1 \text{ pb} = 10^{-36} \text{ cm}^2$, $1 \text{ fb} = 10^{-39} \text{ cm}^2$.

First e^+e^- colliders (ACO/Orsay and VEPP-2/Novosibirsk) – $\sim 10^{28} \text{ cm}^{-2}\text{s}^{-1}$,
Novosibirsk: VEPP-2M – $3 \cdot 10^{30} \text{ cm}^{-2}\text{s}^{-1}$, VEPP-2000 – $10^{32} \text{ cm}^{-2}\text{s}^{-1}$,
LEP at CERN – $2 \cdot 10^{31} \text{ cm}^{-2}\text{s}^{-1}$ at Z boson and $10^{32} \text{ cm}^{-2}\text{s}^{-1}$ above,
BEPC2 in Beijing – $10^{33} \text{ cm}^{-2}\text{s}^{-1}$,
KEKB at KEK – $2.1 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$.

LHC design luminosity at 14 TeV (pp) – $\sim 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ (achieved at 13 TeV),
SuperKEKB at 10.6 GeV (e^+e^-) – $8 \cdot 10^{35} \text{ cm}^{-2}\text{s}^{-1}$

Scan and ISR

Scan



ISR

Scan can provide larger data samples

ISR benefits from the same systematics and flat acceptance,
but may suffer from more complicated radiative effects

Relation between Scan and ISR Center-of-mass Energy

If the nominal c.m. energy of the collider is \sqrt{s} and initial electron or positron emit a photon with energy E_γ , the effective c.m. energy of the collision is

$$\sqrt{s'} = \sqrt{s - 2E_\gamma\sqrt{s}}$$

\sqrt{s} , GeV	$\sqrt{s'}$, GeV	E_γ , GeV
1.02 (m_ϕ)	0.770 (m_ρ)	0.22
3.77 ($m_{\psi(3770)}$)	0.770 (m_ρ)	1.81
10.58 ($m_{\Upsilon(4S)}$)	0.770 (m_ρ)	5.26
10.58 ($m_{\Upsilon(4S)}$)	3.1 ($m_{J/\psi}$)	4.84

2-3 orders lost for large E_γ compensated by high L

Experiment

- Luminosity is collected at some energy point, $\int \mathcal{L} dt$ found
- Events of some process (signal) are selected, the yield N found
- From Monte Carlo simulation find ϵ for signal
- Cross section σ is determined as $\sigma_1 = N / (\int \mathcal{L} dt \epsilon)$
- Radiative corrections applied: $\sigma_0 = \sigma_1 / (1 + \delta)$
- Statistics collected at n different energy points (scan) or at single energy point (ISR)
- Energy dependence of σ is compared to theory and parameters of theory are determined

Leptons and Quarks

Particle	e^-	u	μ^-	c	τ^-	t
Q. number	+1	+1/2	+1	+1	+1	+1
Flavor	Electron	Isospin	Muon	Charm	τ	Top
Particle	ν_e	d	ν_μ	s	ν_τ	b
Q. number	+1	-1/2	+1	-1	+1	-1
Flavor	Electron	Isospin	Muon	Strangeness	τ	Bottom

$$LF(e^-) = LF(\nu_e) \quad LF(\mu^-) = LF(\nu_\mu) \quad LF(\tau^-) = LF(\nu_\tau)$$

$$LF(e^-) \neq LF(\mu^-) \neq LF(\tau^-), \quad LF(\nu_e) \neq LF(\nu_\mu) \neq LF(\nu_\tau).$$

Conservation of Lepton Flavor

Allowed:

$$e^+ e^- \rightarrow \mu^+ \mu^-$$

$$e^- \bar{\nu}_e \rightarrow e^- \bar{\nu}_e$$

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

$$\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$$

$$Z^0 \rightarrow e^+ e^-, \mu^+ \mu^-, \tau^+ \tau^-$$

$$W^- \rightarrow e^- \bar{\nu}_e, \mu^- \bar{\nu}_\mu, \tau^- \bar{\nu}_\tau$$

$$(Z, A) \rightarrow (Z + 2, A) + 2e^- 2\bar{\nu}_e$$

(2ν2β decay)

Forbidden:

$$e^- e^- \rightarrow \mu^- \mu^-$$

$$e^+ \mu^- \rightarrow e^- \mu^+$$

$$\mu^- \rightarrow e^- \gamma$$

$$\tau^- \rightarrow \mu^- e^+ e^-$$

$$Z^0 \rightarrow e^+ \mu^-, \mu^+ \tau^-, \tau^+ e^-$$

$$W^- \rightarrow e^- \bar{\nu}_\tau, \mu^- \bar{\nu}_\tau, \tau^- \bar{\nu}_e$$

$$(Z, A) \rightarrow (Z + 2, A) + 2e^- 0\bar{\nu}_e$$

(0ν2β decay)

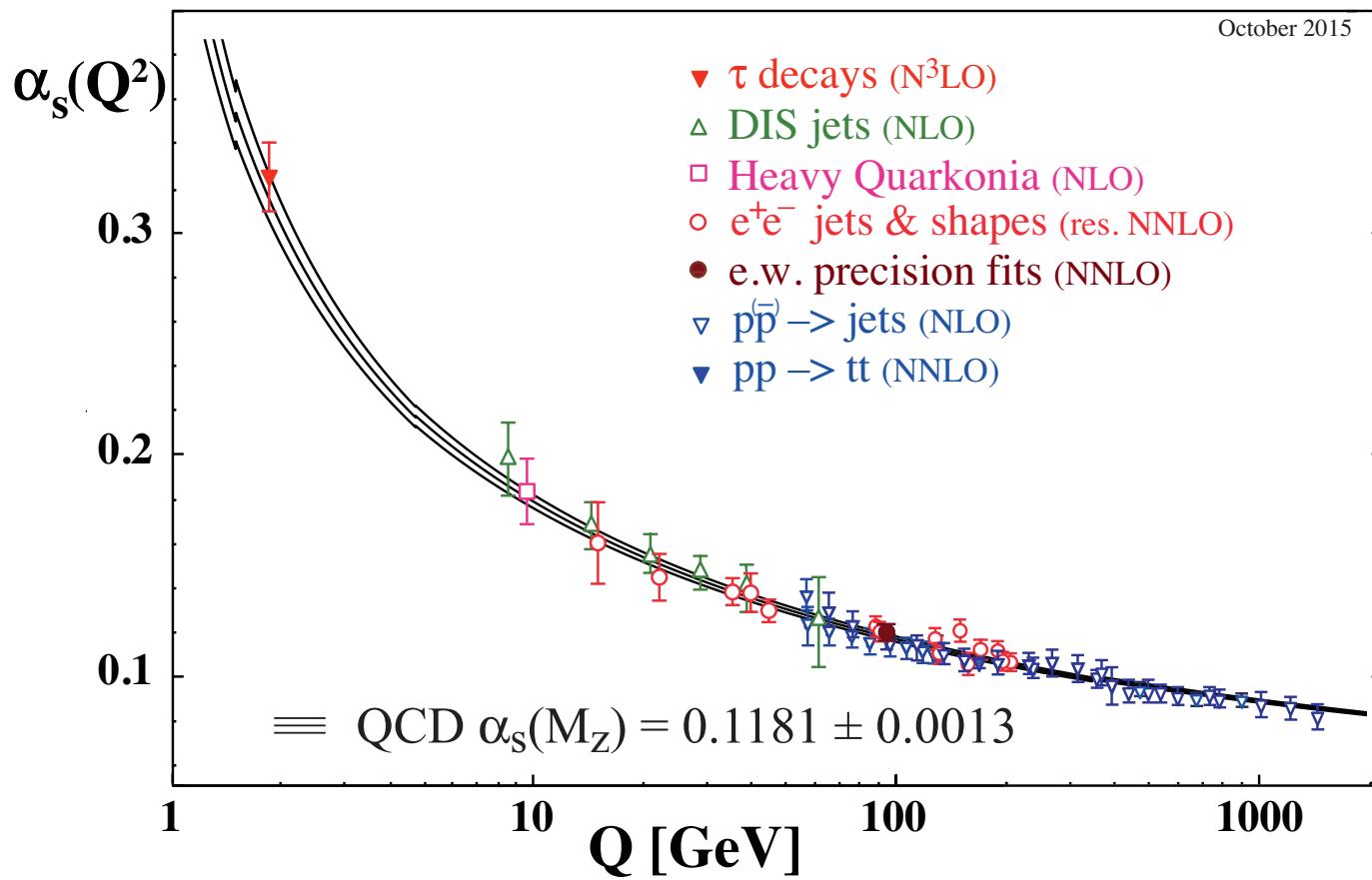
This very elegant and clear concept is unfortunately violated by neutrino oscillations, but their small probability only slightly affects our world

Why Measure Hadronic Cross Sections at Low Energy?

Precise measurement of $R = \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ allows a study of u, d, s interactions with numerous applications:

- Light vectors (ρ, ω, ϕ) and their excitations
- A search for and studies of regular and exotic mesons with various quantum numbers in $e^+e^- \rightarrow \text{hadrons}$
- Muon anomalous magnetic moment $(g_\mu - 2)/2$
- Running fine structure constant $\alpha(M_Z^2)$
- QCD parameters (α_s , quark masses, gluon condensates) and sum rules
- Tests of CVC (Conserved Vector Current)-based relations between $\sigma_{I=1}(e^+e^- \rightarrow \text{hadrons})$ and corresponding τ lepton decays

Strong Interactions – I



At high energies small α_s makes pQCD successful

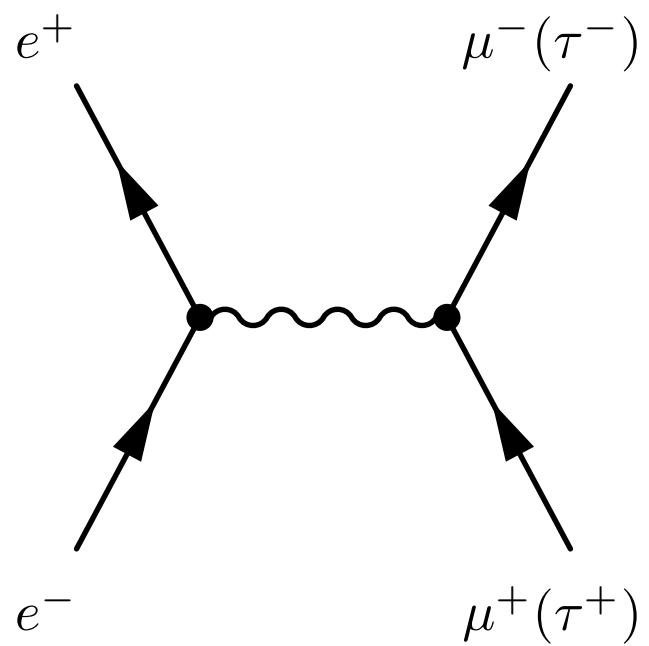
Strong Interactions – II

At low energies ($\lesssim 2$ GeV) growing α_s makes pQCD impossible

Non-perturbative effects become important,
other methods used, e.g. QCD sum rules

Quarks begin hadronizing and regular hadrons appear,
hadronization and confinement not yet well understood

Experimental information on spectroscopy of light quarks,
cross sections and their dynamics important for various models



$$e^+ e^- \rightarrow \mu^+ \mu^-$$

$$\sigma(e^+ e^- \rightarrow \mu^+ \mu^-) = \frac{4\pi\alpha^2}{3s} \beta\left(\frac{3-\beta^2}{2}\right),$$

$$\beta = \sqrt{1 - 4M_\mu^2/s},$$

$$\sigma(e^+ e^- \rightarrow \mu^+ \mu^-) = \frac{4\pi\alpha^2}{3s} \sqrt{1 - 4M_\mu^2/s} (1 + 2M_\mu^2/s).$$

At $s \rightarrow \infty$ $\sigma(e^+ e^- \rightarrow \mu^+ \mu^-) = \frac{4\pi\alpha^2}{3s} \sim 86.85(\text{nb})/\text{s}(\text{GeV}^2)$.

Relativistic system of units

In relativistic quantum theory

the conventional system of units uses $\hbar = 1, c = 1$.

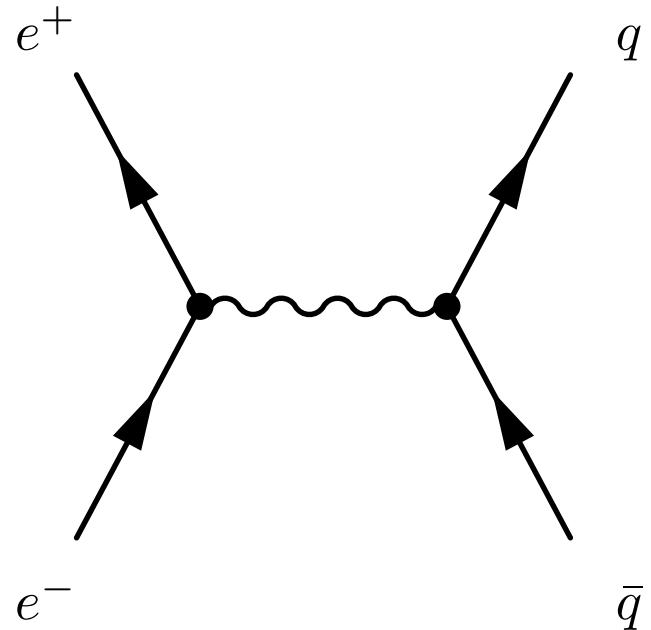
The conversion factor is $(\hbar c)^2 = 0.389379 \text{ GeV}^2 \text{ mb}$

or $1 \text{ GeV}^{-2} = 0.389379 \text{ mb}$.

$$\sigma(e^+e^- \rightarrow \mu^+\mu^-) = \frac{4\pi\alpha^2}{3s}$$

$$\frac{4\pi\alpha^2}{3} \text{ GeV}^{-2} = 223.05875 \cdot 0.389379 \text{ nb} = 86.85 \text{ nb.}$$

What is R ?



For $e^+ e^- \rightarrow f \bar{f}$ at $\sqrt{s} \gg 2m_f$,

f – pointlike fermion,

$$\sigma = \frac{4\pi\alpha^2 \sum e_q^2}{s} = \frac{4\pi\alpha^2 N_c \sum e_q^2}{3s},$$

$$\frac{\sigma(e^+ e^- \rightarrow q \bar{q})}{\sigma(e^+ e^- \rightarrow \mu^+ \mu^-)} = N_c \sum e_q^2,$$

$$R = \frac{\sigma(e^+ e^- \rightarrow hadrons)}{\sigma(e^+ e^- \rightarrow \mu^+ \mu^-)} = 3 \sum e_q^2.$$

At $\sqrt{s} > 1.02$ GeV(u, d, s), $R \simeq 3((2/3)^2 + (1/3)^2 + (1/3)^2) = 2$

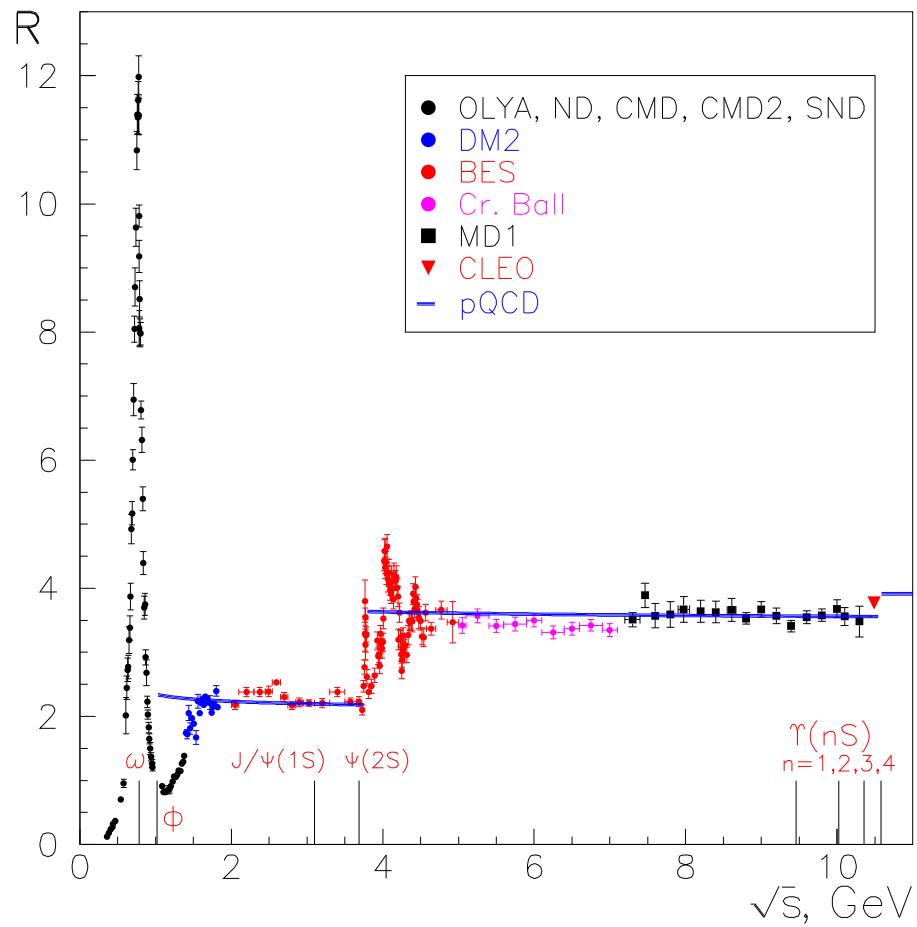
At $\sqrt{s} > 3.77$ GeV(u, d, s, c), $R \simeq 10/3$

At $\sqrt{s} > 10.58$ GeV(u, d, s, c, b), $R \simeq 11/3$

With QCD corrections, $\alpha_s(M_{\Upsilon(4S)}) \approx 0.20$

$$R = 3 \sum e_q^2 \left(1 + \frac{\alpha_s}{\pi} + 1.411 \left(\frac{\alpha_s}{\pi} \right)^2 - 12.8 \left(\frac{\alpha_s}{\pi} \right)^3 + \dots \right)$$

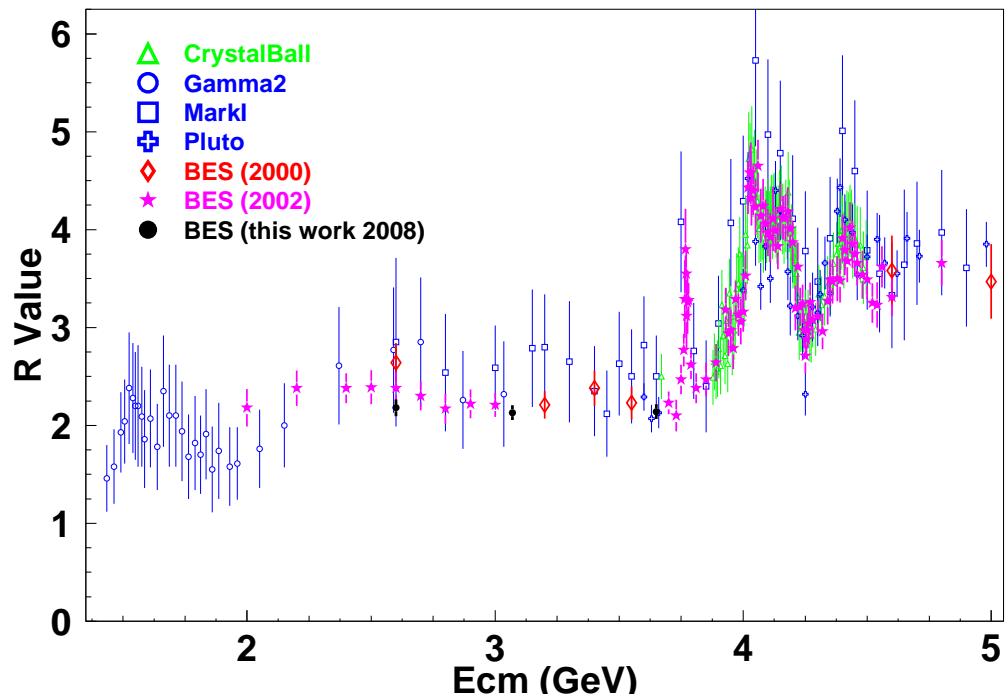
R Measurements below 10 GeV



How Is R Measured at High Energy ($\sqrt{s} > 2$ GeV)?

- Inclusive approach: all multihadronic events selected
- Background determined (τ decays, $\gamma\gamma$, QED)
- $\int \mathcal{L} dt$ found
- ϵ found from MC (LUND, PYTHIA, LUARLW)
- Radiative corrections applied: ISR (PHOKHARA), FSR (PHOTOS)

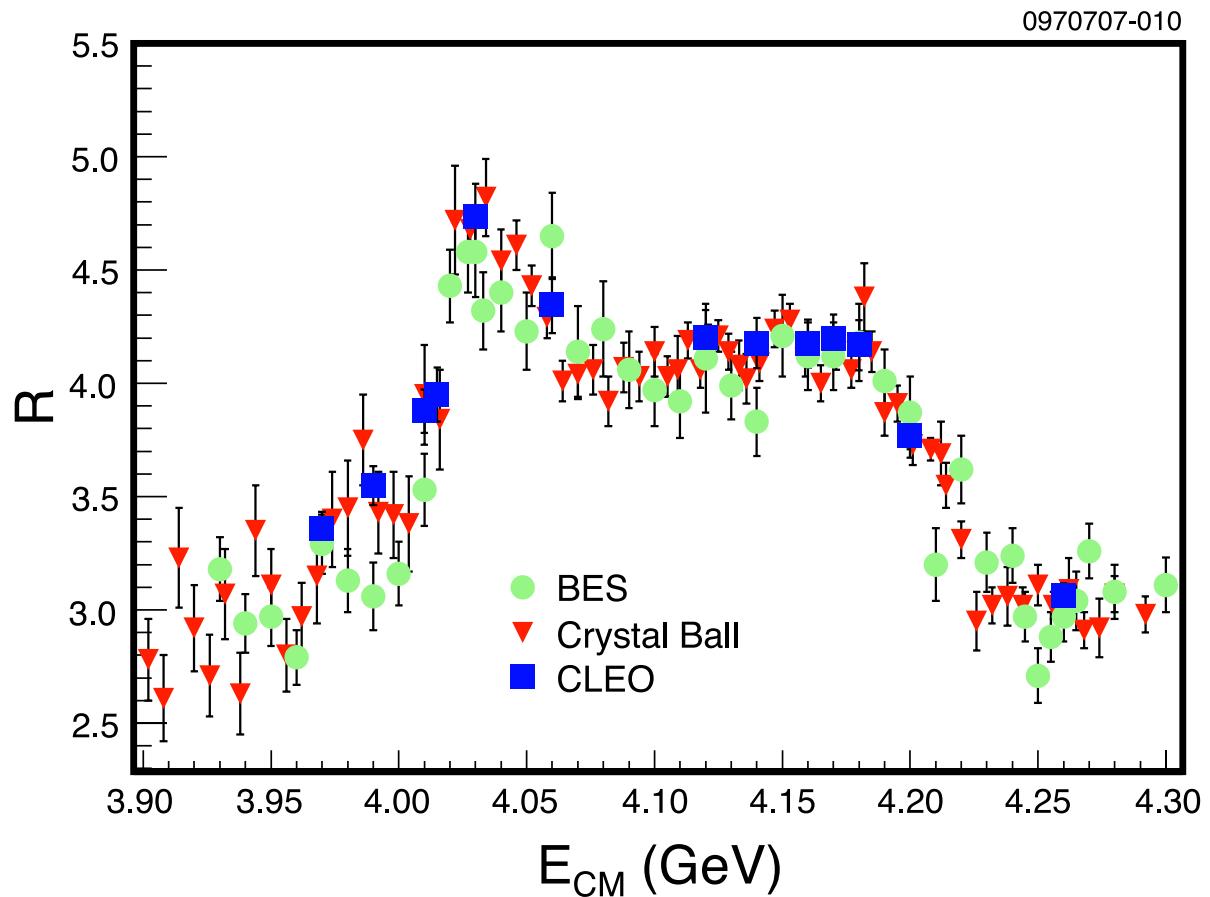
R Measurement Below 5 GeV



Dominated by BES: stat. errors (3-5)%, syst. errors (5-8)%

J.Z. Bai et al., Phys.Rev.Lett. 84 (2000) 594, Phys.Rev.Lett. 88 (2002) 101802;
M. Ablikim et al., Phys.Rev.Lett. 97 (2006) 262001, Phys.Lett. B677 (2009) 239

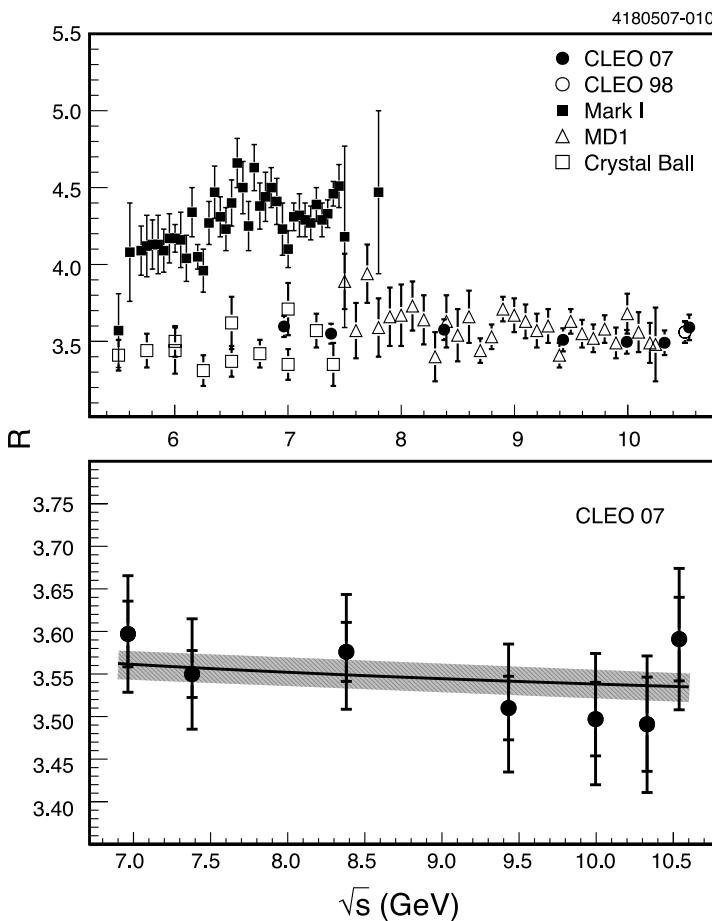
R Measurement by CLEO – I



CLEO-c: syst. errors (5.2-6.1)%

D. Cronin-Hennessy et al., Phys. Rev. D80 (2009) 072001

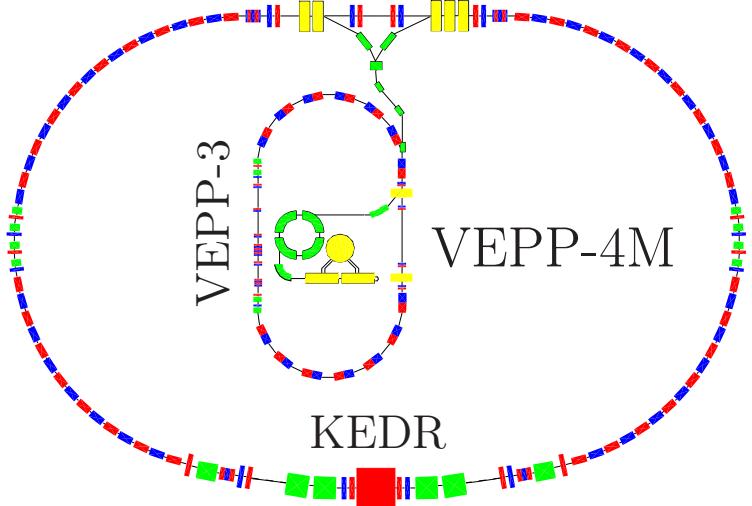
R Measurement by CLEO – II



CLEO3: syst. errors (1.7-2.3)%

D. Besson et al., Phys. Rev. D76 (2007) 072008

VEPP-4M collider



Circumference	366 m
Beam energy	$1 \div 5$ GeV
Number of bunches	2×2
Luminosity, $E = 1.5$ GeV	$2 \times 10^{30} \text{ cm}^{-2}\text{s}^{-1}$
Luminosity, $E = 5.0$ GeV	$2 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}$

- Resonant depolarization technique:
Instantaneous measurement accuracy $\simeq 1 \times 10^{-6}$
Energy interpolation accuracy $(5 \div 15) \times 10^{-6}$ (10 \div 30 keV)
- Infrared light Compton backscattering:
Statistical accuracy $\simeq 5 \times 10^{-5}$ / 30 minutes
Systematic uncertainty $\simeq 3 \times 10^{-5}$ (50 \div 70 keV)

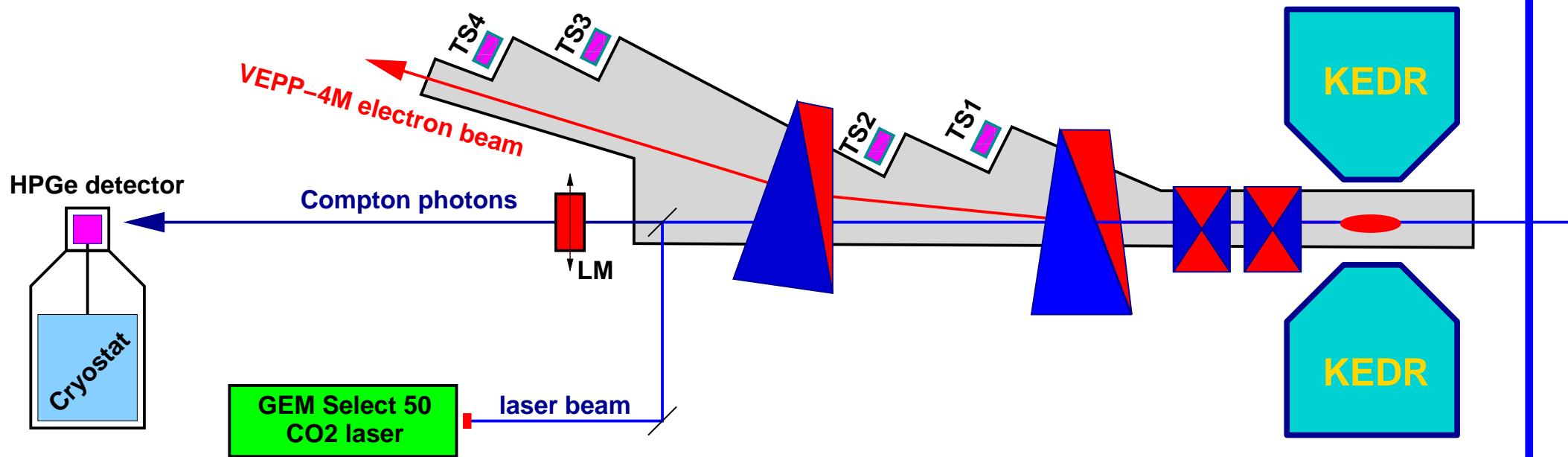
Beam Energy Measurement

Why is beam energy measurement important?

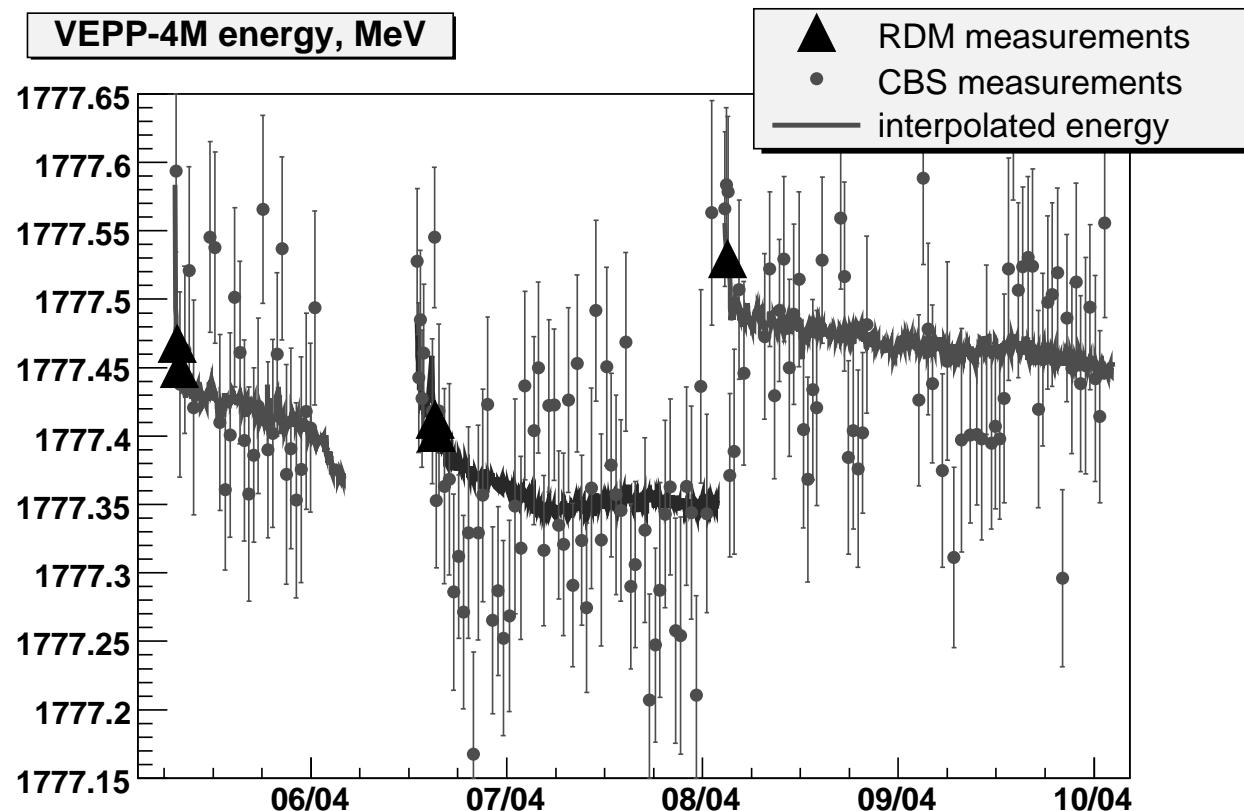
- For a study of narrow resonances – not to miss
- For cross sections that have strong energy dependence

Compton Backscattering Monitor

Realized at BESSY-I in 1987

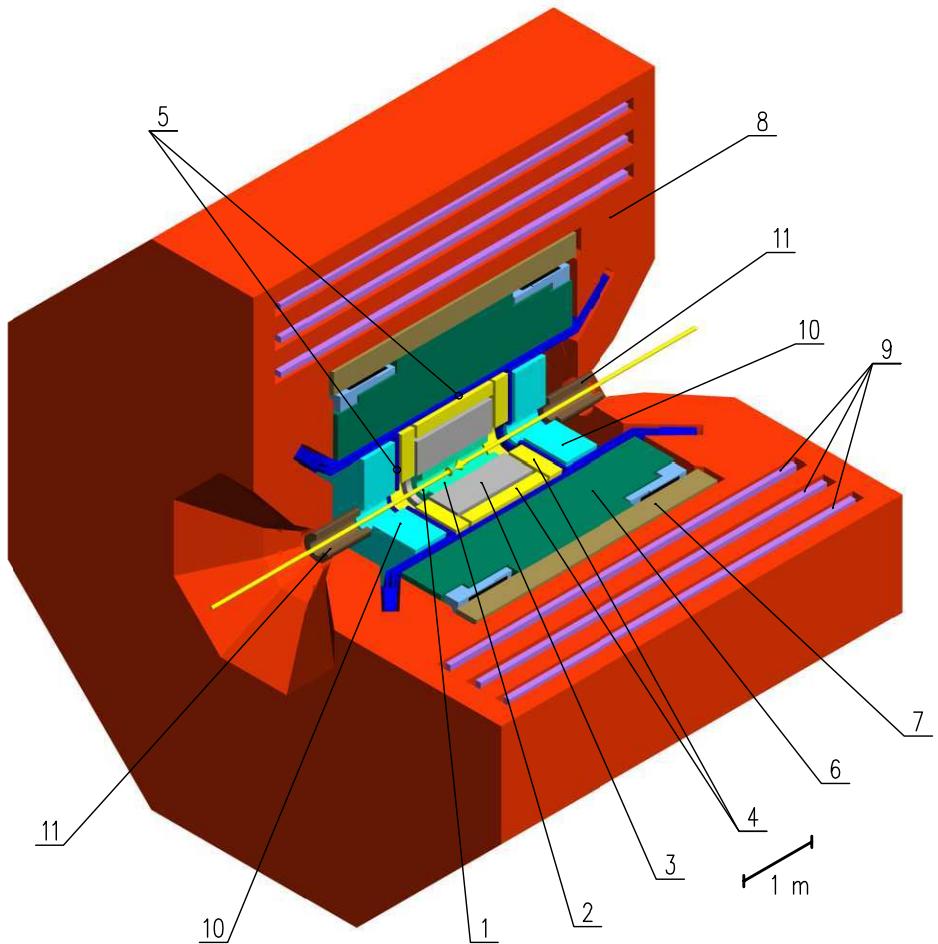


VEPP-4M Energy Behaviour



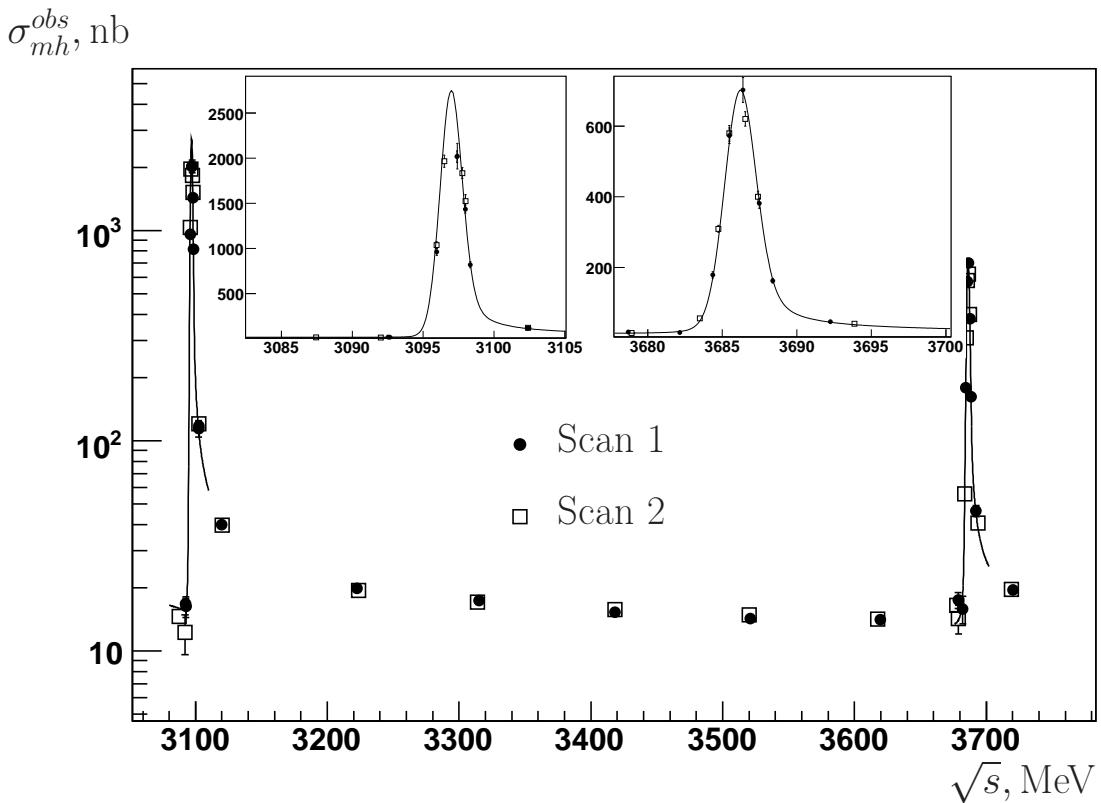
During the run, E measured by CBS and from interpolation

KEDR detector



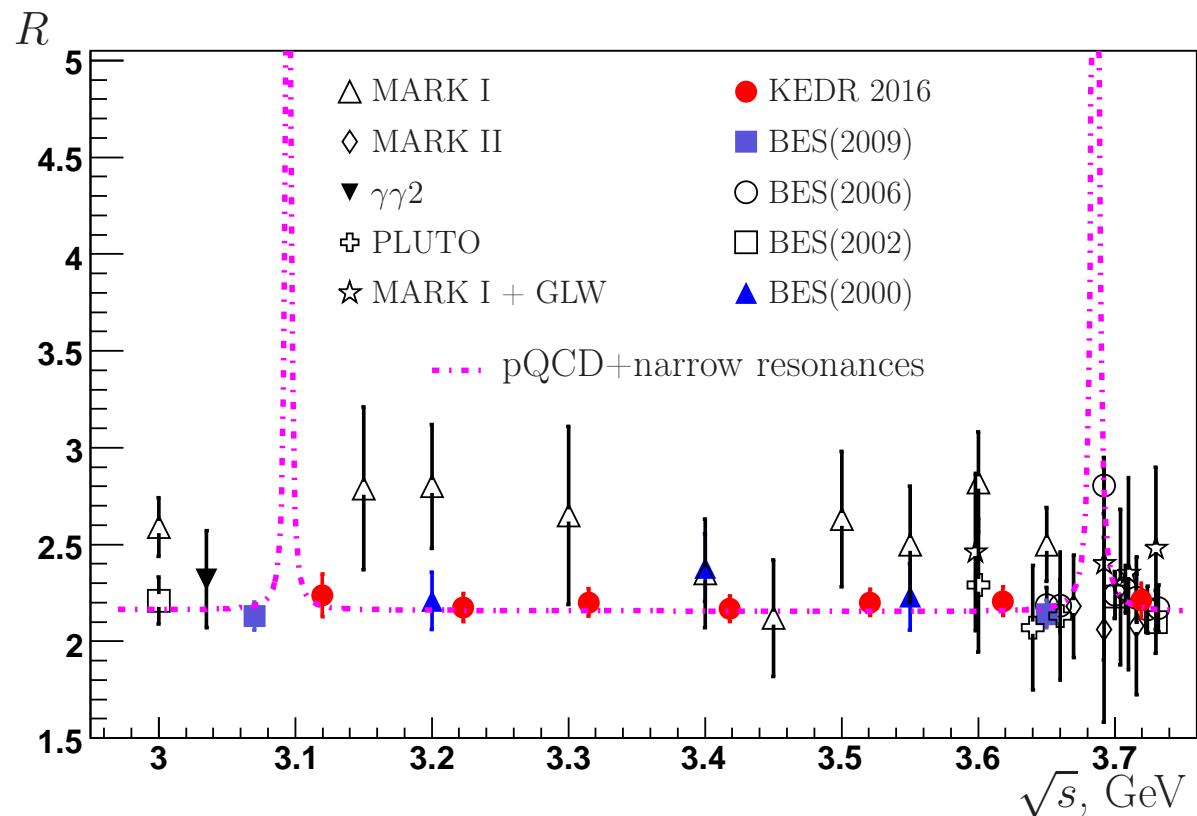
1. Vacuum chamber
2. Vertex detector
3. Drift chamber
4. Threshold aerogel counters
5. ToF counters
6. Liquid krypton calorimeter
7. Superconducting coil
8. Magnet yoke
9. Muon tubes
10. CsI calorimeter
11. Compensating s/c solenoid

R Measurement between J/ψ and $\psi(2S)$ at KEDR – I



KEDR scanned \sqrt{s} between J/ψ and $\psi(2S)$ with 1.4 pb^{-1}
selecting $(2 - 3) \cdot 10^3 \text{ m/h}$ events per point

R Measurement between J/ψ and $\psi(2S)$ at KEDR – II



R measured at 7 points between 3.12 and 3.72 GeV, syst. error 2.1%, total 3.3%

V.V. Anashin et al., Phys. Lett. B753, 533 (2016)

R Measurement between 1.84 and 3.05 GeV at KEDR – I

- The c.m. energy range between 1.84 and 3.05 GeV studied
- An integrated luminosity of 0.66 pb^{-1} collected at 13 equidistant points with a step of $\sim 0.1 \text{ GeV}$: 1.841, 1.937, ..., 3.048 GeV
- $\sim 10^3$ events per point $\Rightarrow \sim 15 \cdot 10^3$ events in total
- Simulation of the *uds* continuum based on the tuned LUARLW generator, H.M. Hu and A. Tai, hep-ex/0106017
- JETSET 7.4 alternatively used at 5 points for a cross-check
- MHG2000 used below 1.8 GeV, needed for radiative corrections, H. Czyż et al., arXiv:1312.0454, 1406.4639.

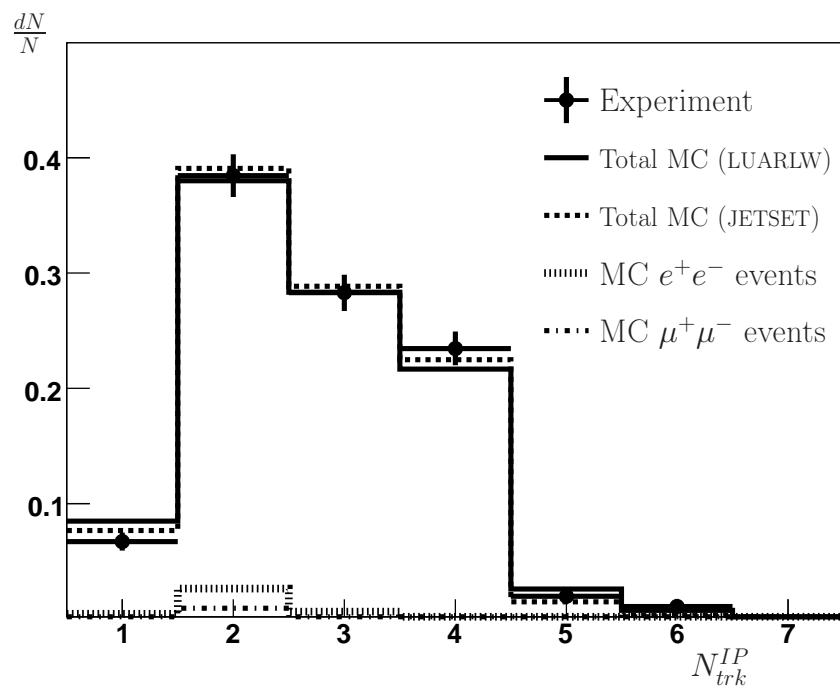
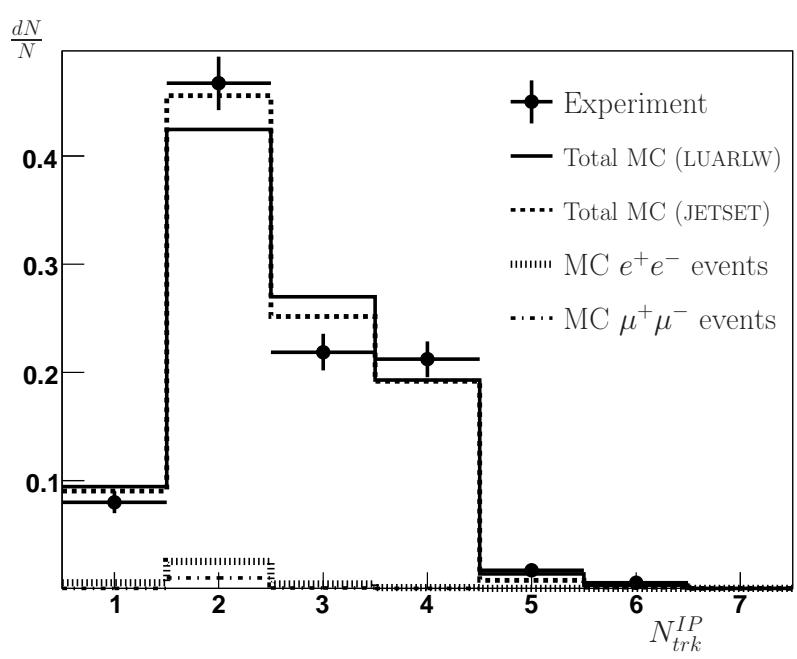
R Measurement between 1.84 and 3.05 GeV at KEDR – II

$$\sigma_{\text{obs}}(s) = \frac{N_{\text{mh}} - N_{\text{res.bg}}}{\int \mathcal{L} dt}$$

$$R = \frac{\sigma_{\text{obs}}(s) - \sum \varepsilon_{\text{bg}}(s) \sigma_{\text{bg}}(s)}{\varepsilon(s)(1 + \delta(s)) \sigma_{\mu\mu}^0(s)}$$

- The machine background is estimated from runs with separated e^+ / e^- and is (1-2)% of $\sigma_{\text{obs}}(s)$ depending on I_{beam} and P_{vac}
- Physical background (MC simulation): $e^+ e^- \rightarrow e^+ e^-$ - (3.3-6.1)%,
 $e^+ e^- \rightarrow \mu^+ \mu^-$ - (0.8-1.1)%,
 $e^+ e^- \rightarrow e^+ e^- X$ - (0.1-0.3)%
- Radiative corrections vary from 5.7% to 9.7% with \sqrt{s} increase

R Measurement between 1.84 and 3.05 GeV at KEDR – III

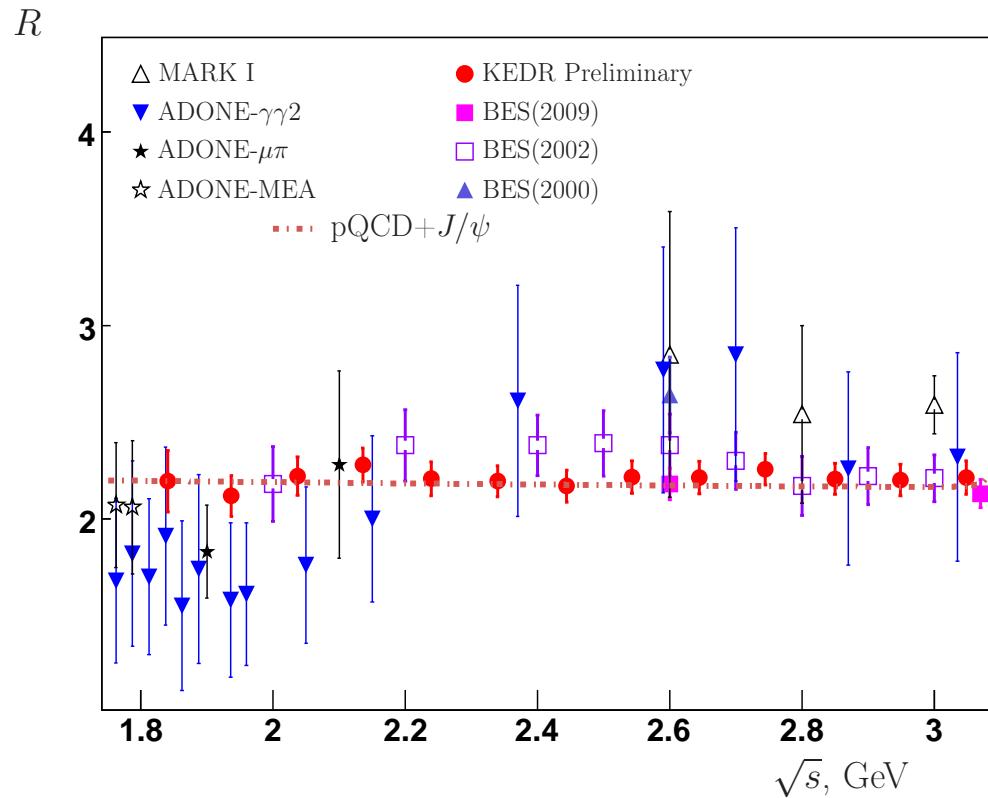


The number of tracks from the common vertex in the IP,
Fair agreement of simulation with data ($\sqrt{s} = 1.94$ and 2.14 GeV)

R Measurement between 1.84 and 3.05 GeV at KEDR – IV

Source	Syst. error, %
Luminosity	1.2
Rad. corr.	2.0-0.5
<i>uds</i> simulation	2.6-1.3
l^+l^-	0.6-0.4
e^+e^-X	0.2
Trigger	0.3
Nucl. inter.	0.4
Cuts	0.7
Machine bg	0.4-0.9
Energy	0.1
Total	3.7-2.1

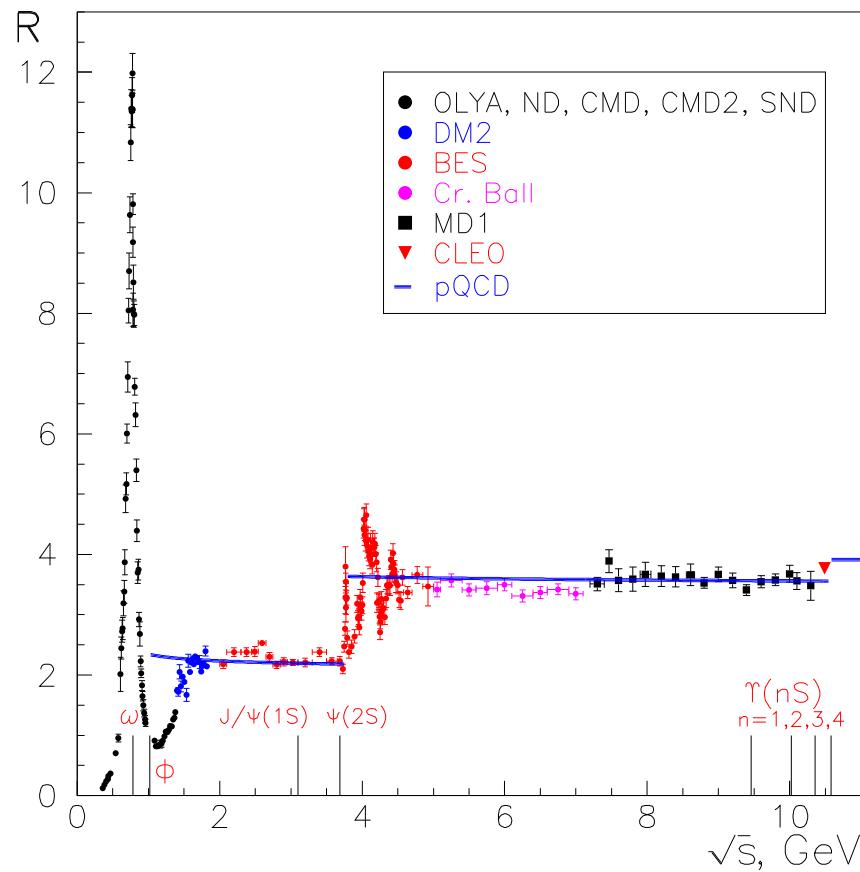
R Measurement between 1.84 and 3.05 GeV at KEDR – V



$\bar{R} = 2.209 \pm 0.020 \pm 0.046$ agrees with $R_{\text{pQCD}} = 2.18 \pm 0.02$
based on $\alpha_s(m_\tau) = 0.333 \pm 0.013$ derived from hadronic τ decays

V.V. Anashin et al., arXiv:1610.02827

R Measurements below 10 GeV

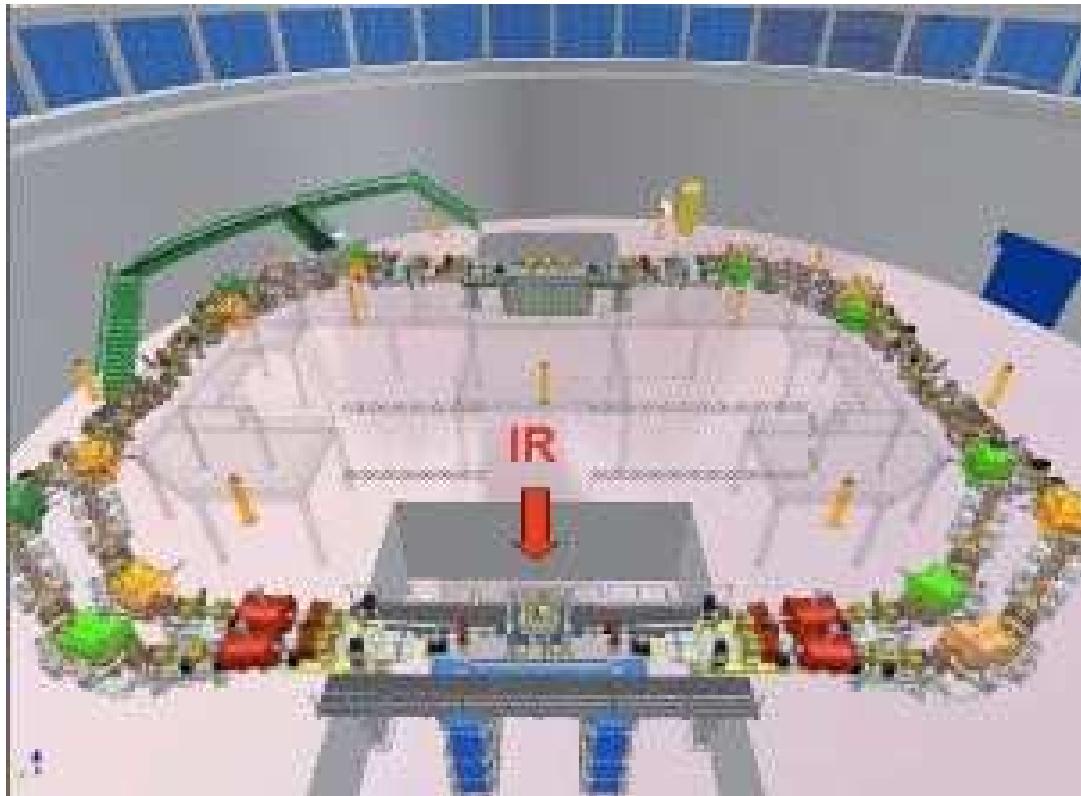


Further high-precision measurements needed in non-asymptotic regions

How Is R Measured at Low Energy ($\sqrt{s} < 2$ GeV)?

- The cross section rapidly changes with energy because one is far from asymptotics and there are many resonances
- There is no good theoretical model to find ϵ
- Exclusive approach: specific final states studied separately $(\pi^+\pi^-, K^+K^-, K_SK_L, , n\pi, K\bar{K}m\pi, p\bar{p}, n\bar{n}, \dots)$
- The cross sections measured summed
- Important not to miss some final states

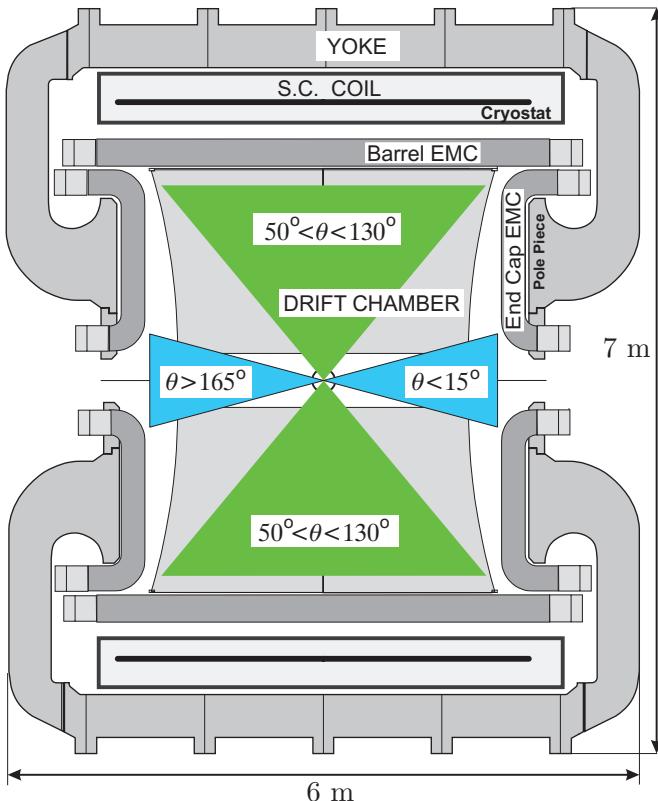
DAΦNE Collider in Frascati



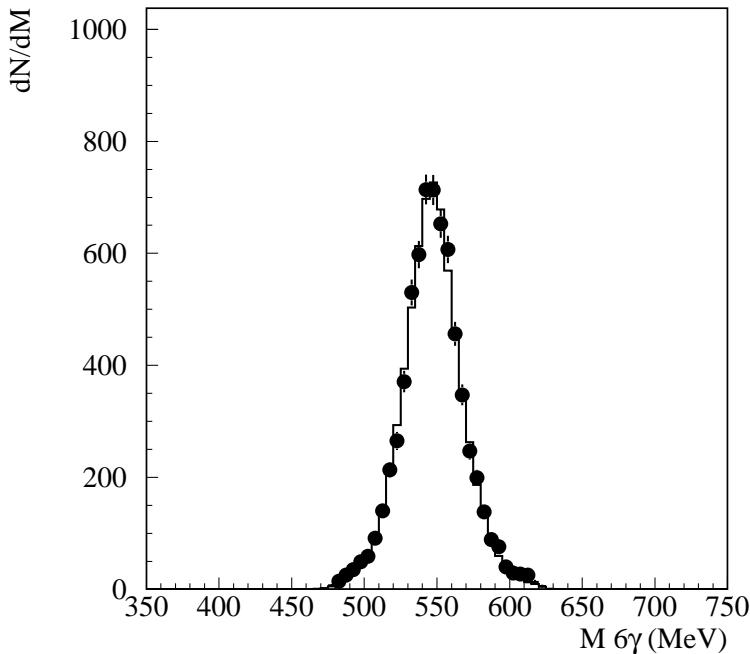
DAΦNE was running at 1020 MeV with $\mathcal{L} = 1.5 \cdot 10^{32} \text{cm}^{-2}\text{s}^{-1}$,
KLOE collected $\sim 2.7 \text{fb}^{-1}$.

In the new crab-waist scheme \mathcal{L} should be 3-5 times larger

KLOE Detector at DAΦNE



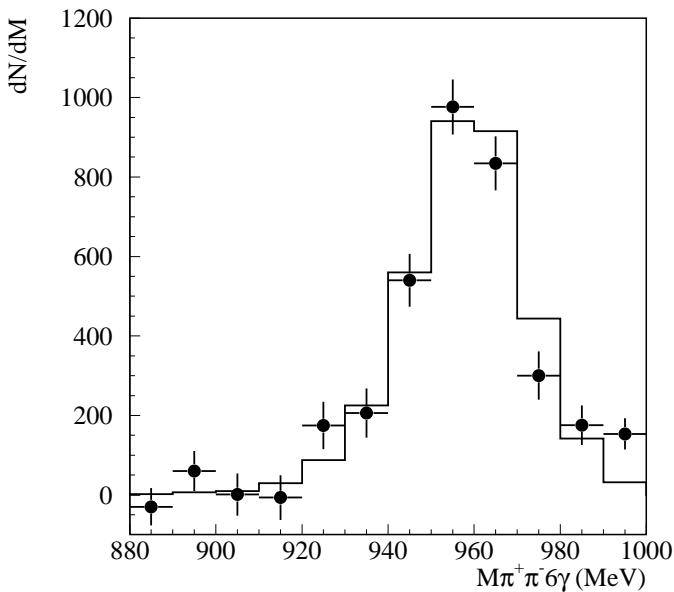
Large decay volume DC and lead scintillating fiber e/m calorimeter
Physical program: ϕ decays; tagged K^\pm , K^0 , η , η' ; $\pi^+\pi^-$ with ISR

$\phi \rightarrow \eta\gamma$ at KLOE

$1.4 \times 10^9 \phi$ mesons used,
 $\phi \rightarrow \eta\gamma (\sim 1.3\%), \quad \eta \rightarrow 3\pi^0 (32.7\%) \rightarrow 6\gamma$, 1.665M events!!

F. Ambrosino et al., Phys. Lett. B648 (2007) 267

$\phi \rightarrow \eta' \gamma$ at KLOE

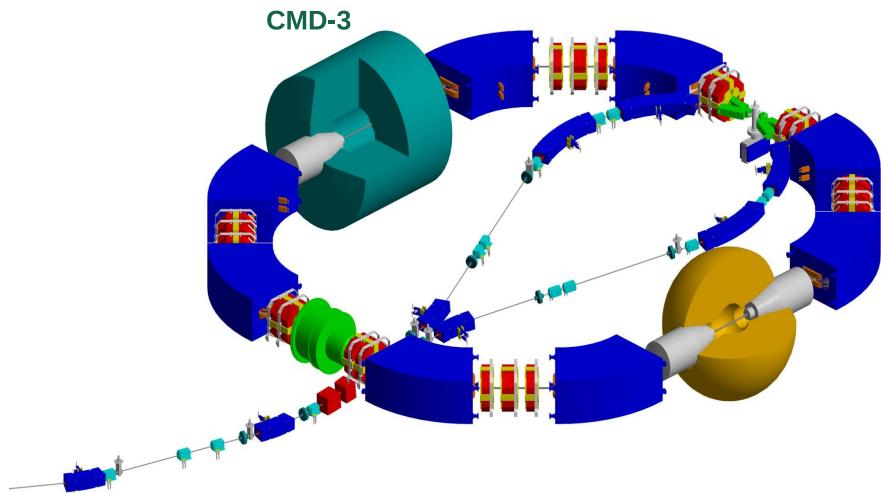


$1.4 \times 10^9 \phi$ mesons used

$\phi \rightarrow \eta' \gamma$ ($\sim 1.2 \times 10^{-5}$), $\eta' \rightarrow \eta \pi^+ \pi^-$ (42.4%), $\eta \rightarrow 3\pi^0$ (32.7%) or
 $\eta' \rightarrow \eta \pi^0 \pi^0$ (22.3%), $\eta \rightarrow \pi^+ \pi^- \pi^0$ (22.9%), both leading to $\pi^+ \pi^- 6\gamma$, 3407 events

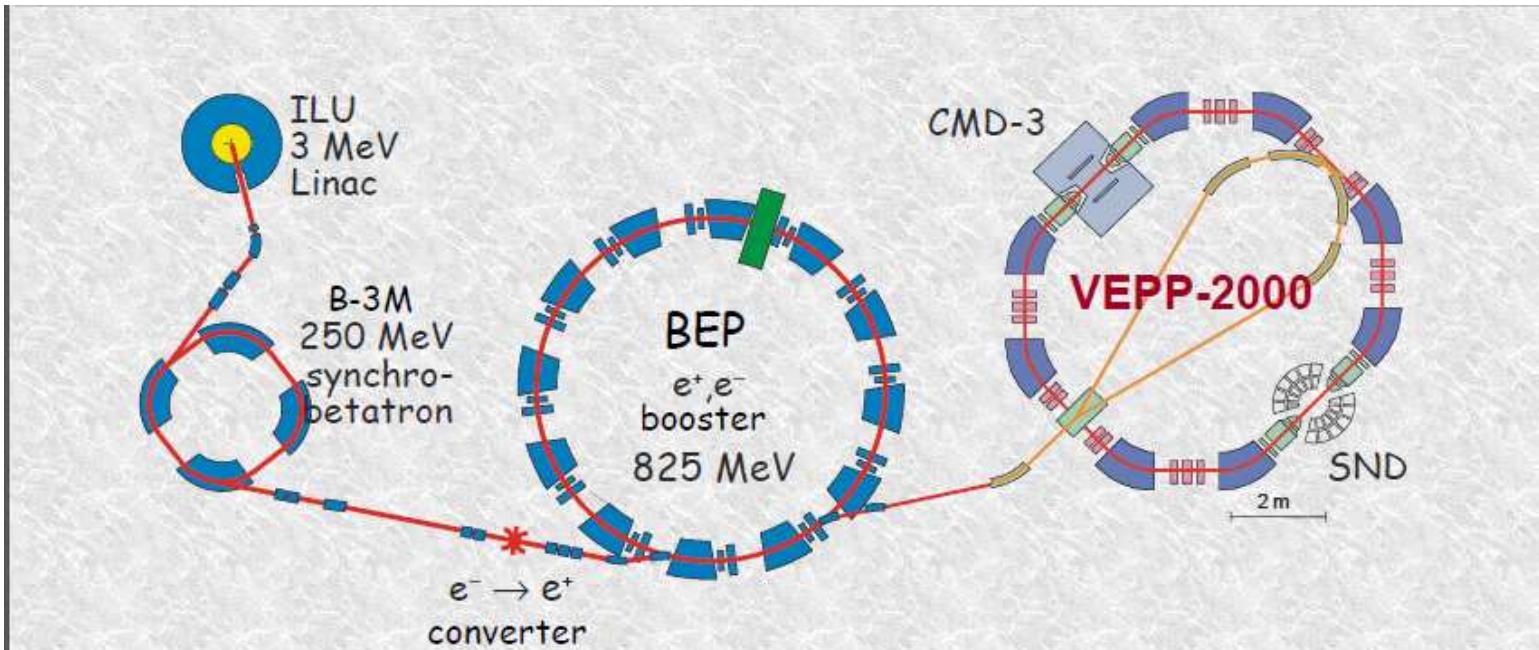
F. Ambrosino et al., Phys. Lett. B648 (2007) 267

VEPP-2000 – I



Collider	Operation	\sqrt{s} , MeV	$\mathcal{L}, 10^{30} \text{cm}^{-2}\text{s}^{-1}$
VEPP-2M	1975-2000	[360,1400]	3
VEPP-2000	2010-	[$2m_\pi$, 2000]	100

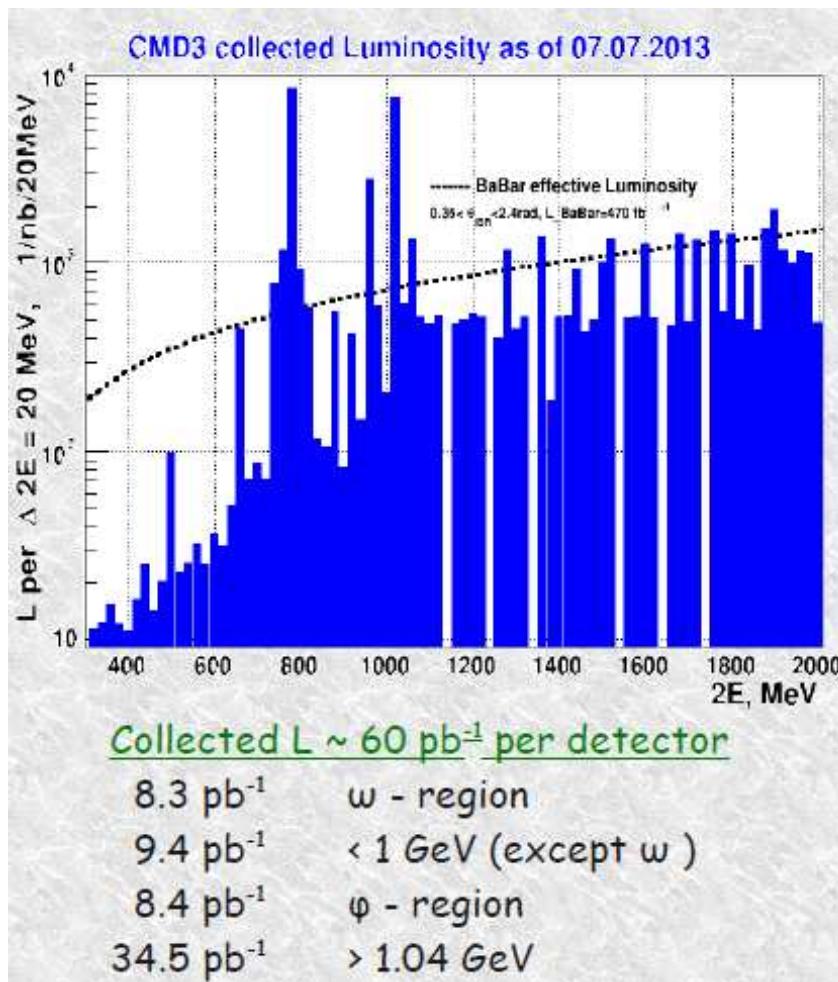
VEPP-2000 – II



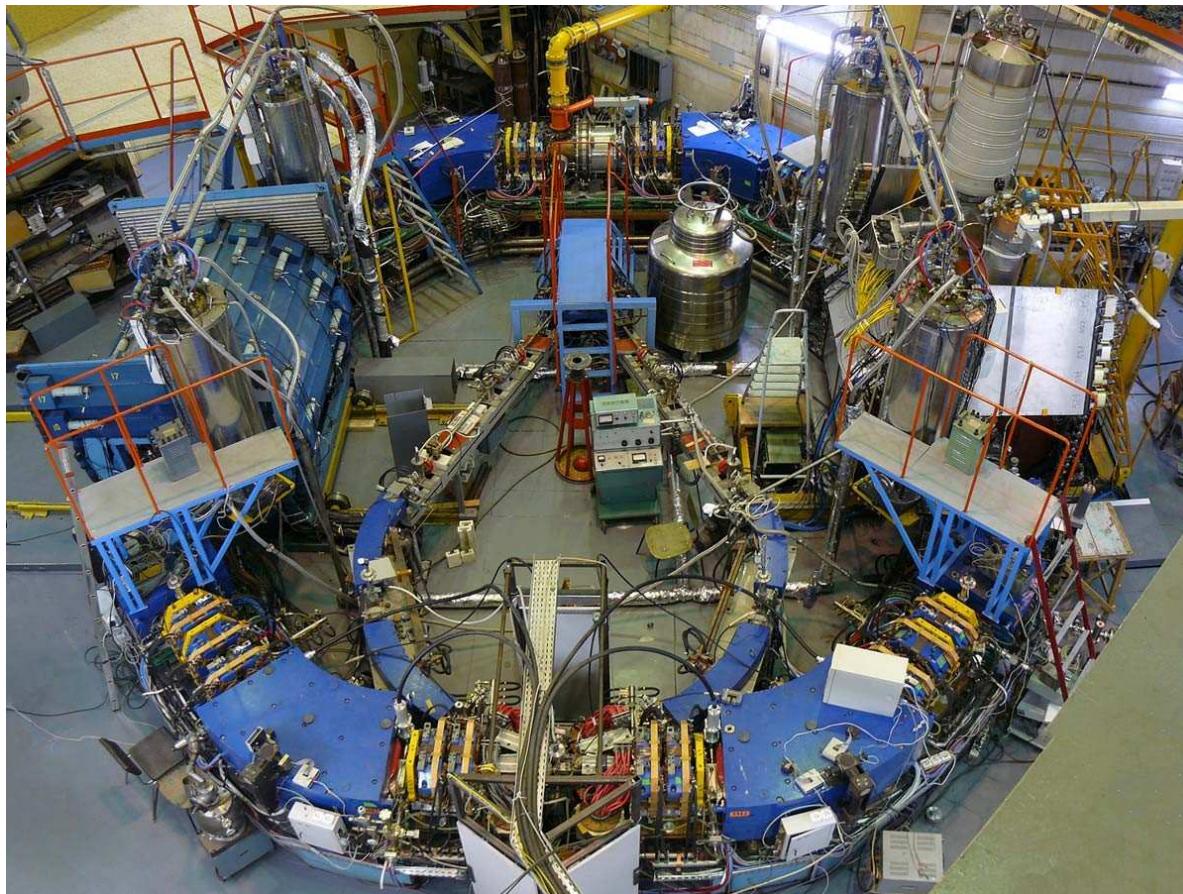
New optics with round beams \Rightarrow higher luminosity,
precise beam energy measurement using LCBS

In 2013-2015 the complex was upgraded to increase the booster
energy to 1 GeV and commission the new injection complex

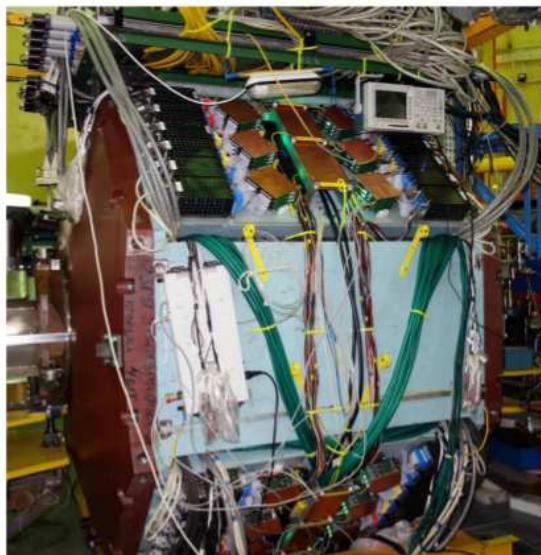
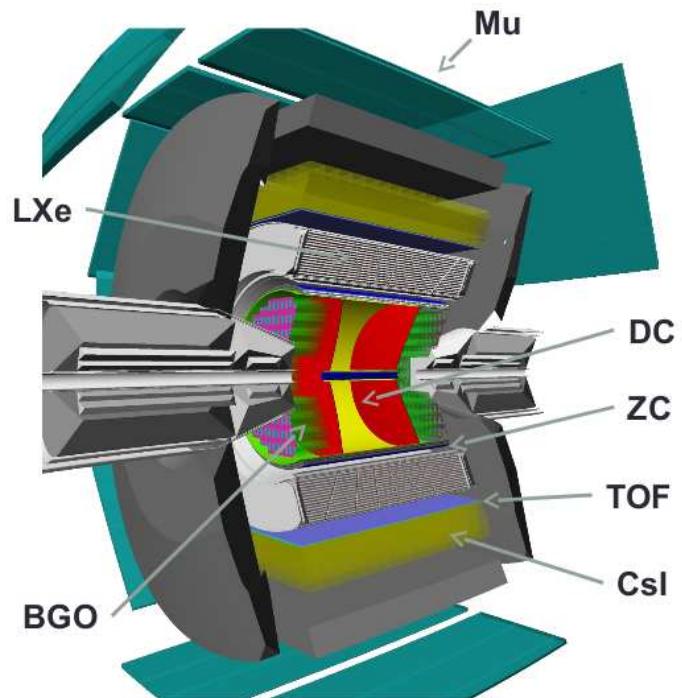
Data Taking at VEPP-2000



VEPP-2000 and Detectors



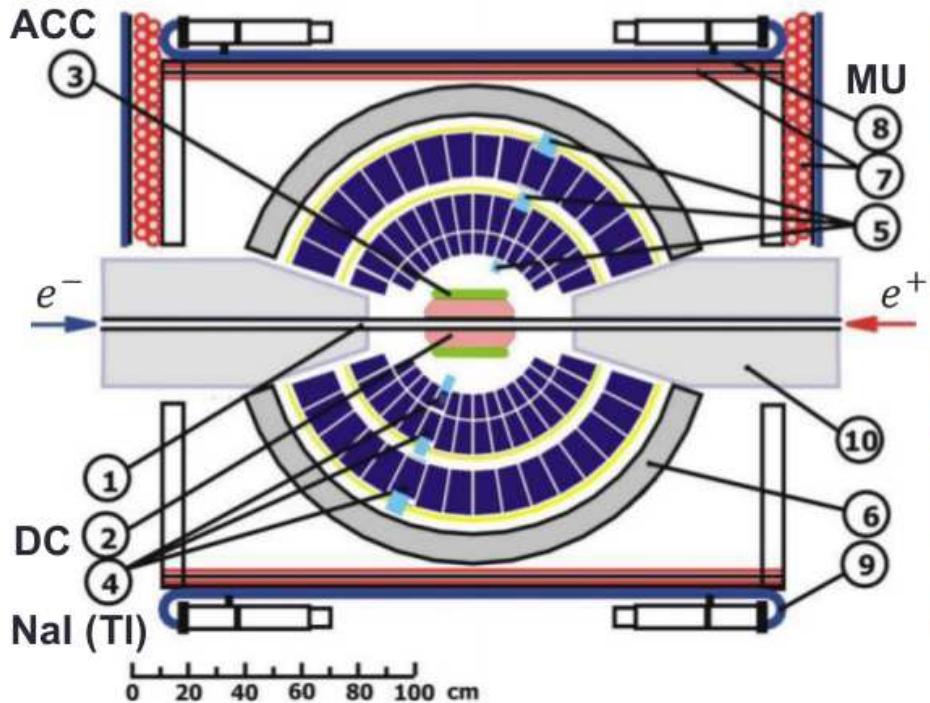
Detector CMD-3



1.3 T magnetic field
Tracking: $\sigma_{R\phi} \sim 100 \mu$, $\sigma_z \sim 2$ mm
Combined EM calorimeter (LXe, CsI, BGO), $\sigma_E \sim 3\% - 8\%$

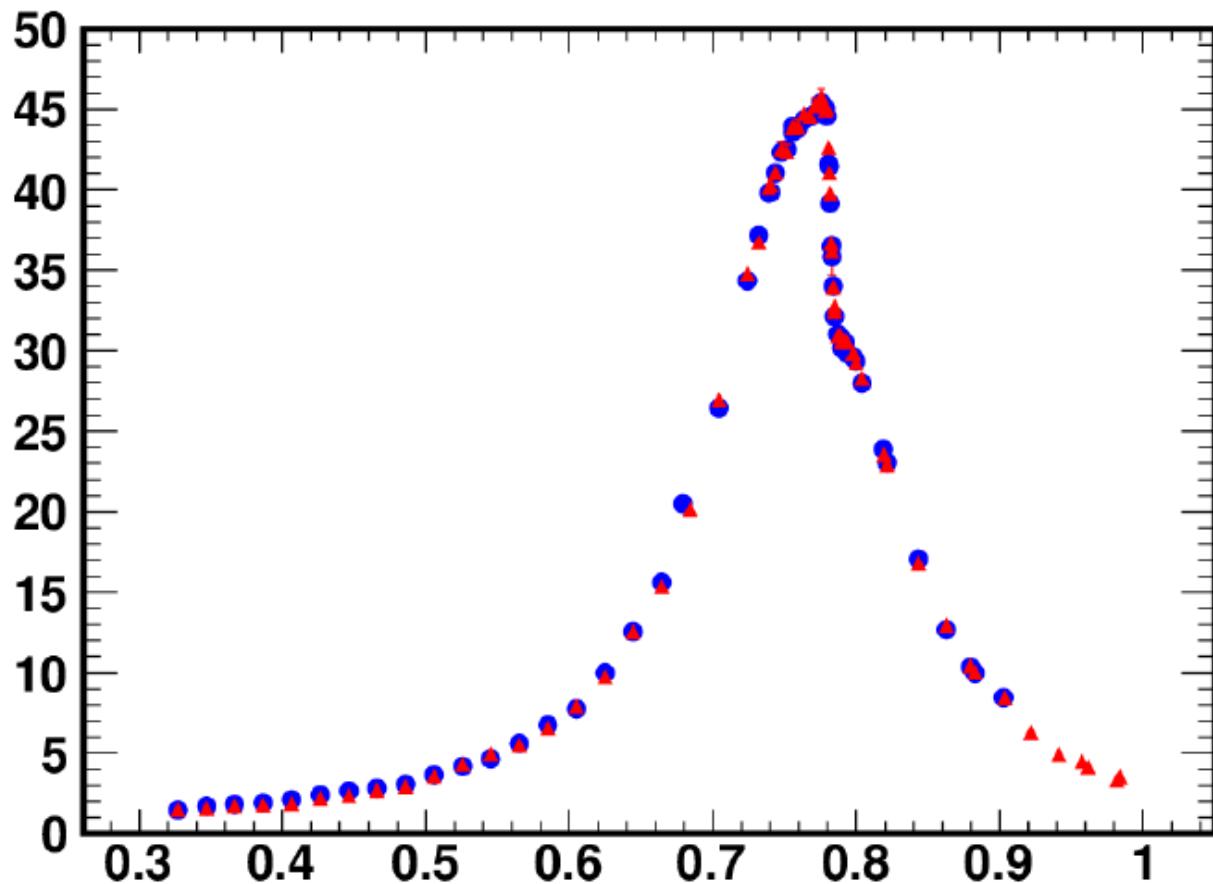
General-purpose magnetic (1.3T) detector with 3 e/m calorimeters (LXe, CsI, BGO)

Detector SND



High-resolution NaI calorimeter with excellent tracking and PID

High-precision Study of $e^+e^- \rightarrow \pi^+\pi^-$ at CMD-3



Best statistical precision, clear $\rho - \omega$ interference
Systematic error: goal 0.35% at the ρ (BaBar achieved 0.5%)

Vector Mesons

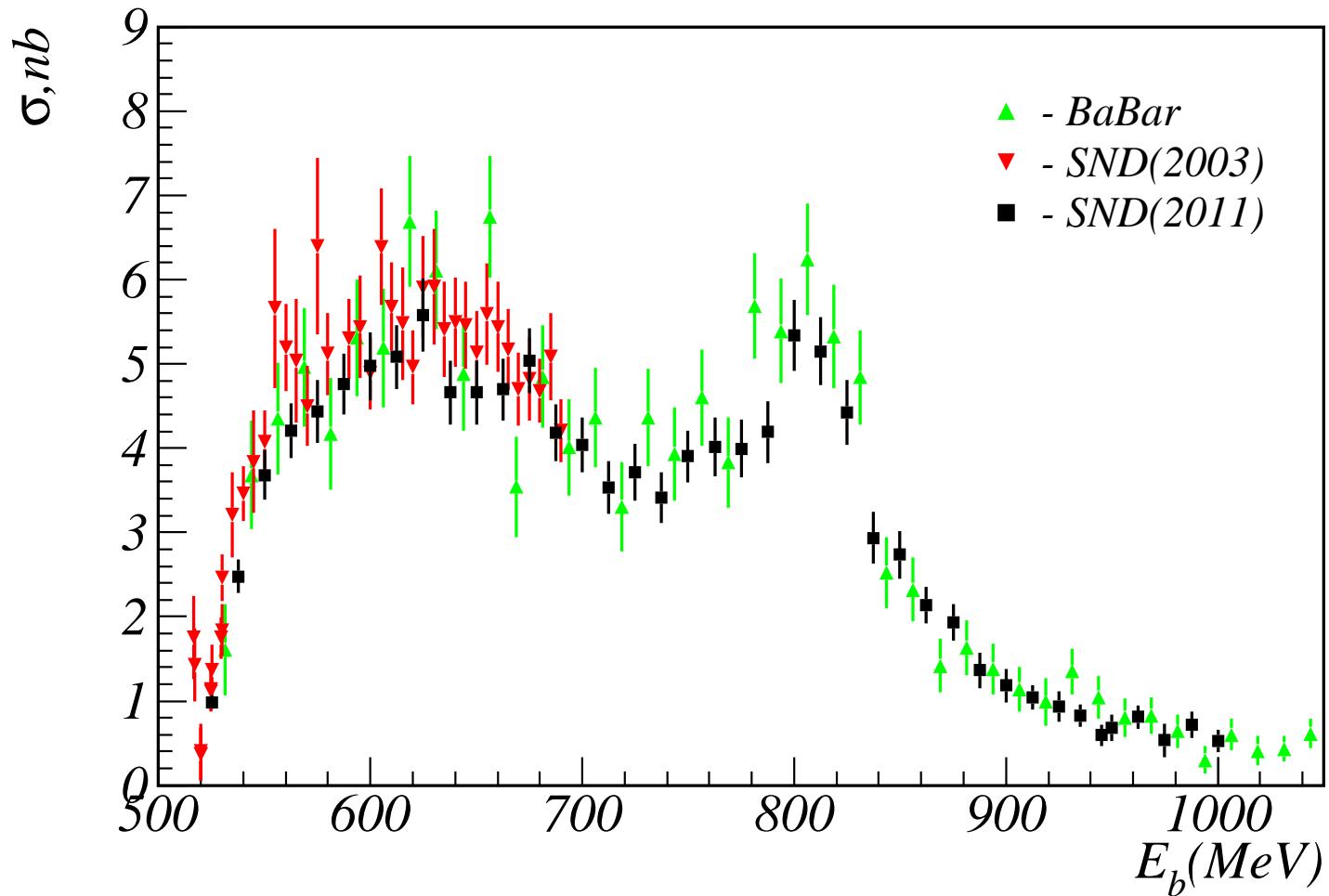
State	Mass, MeV	Width, MeV	Γ_{ee} , keV
ρ	775.49 ± 0.34	149.1 ± 0.8	7.04 ± 0.06
ω	782.65 ± 0.12	8.49 ± 0.08	0.60 ± 0.02
ϕ	1019.455 ± 0.020	4.26 ± 0.04	1.27 ± 0.04

Five more vector mesons are claimed below 2000 MeV:

$\omega(1420)$, $\rho(1450)$, $\omega(1650)$, $\phi(1680)$, $\rho(1700)$

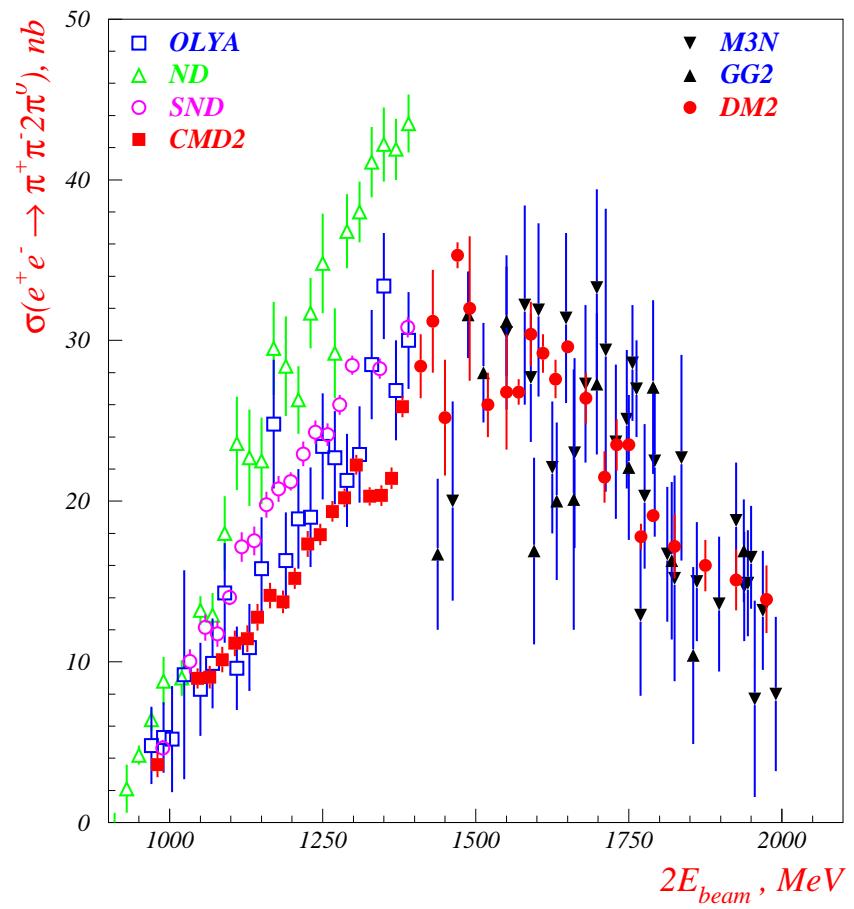
with badly measured mass and width and

almost no information on the leptonic width Γ_{ee}

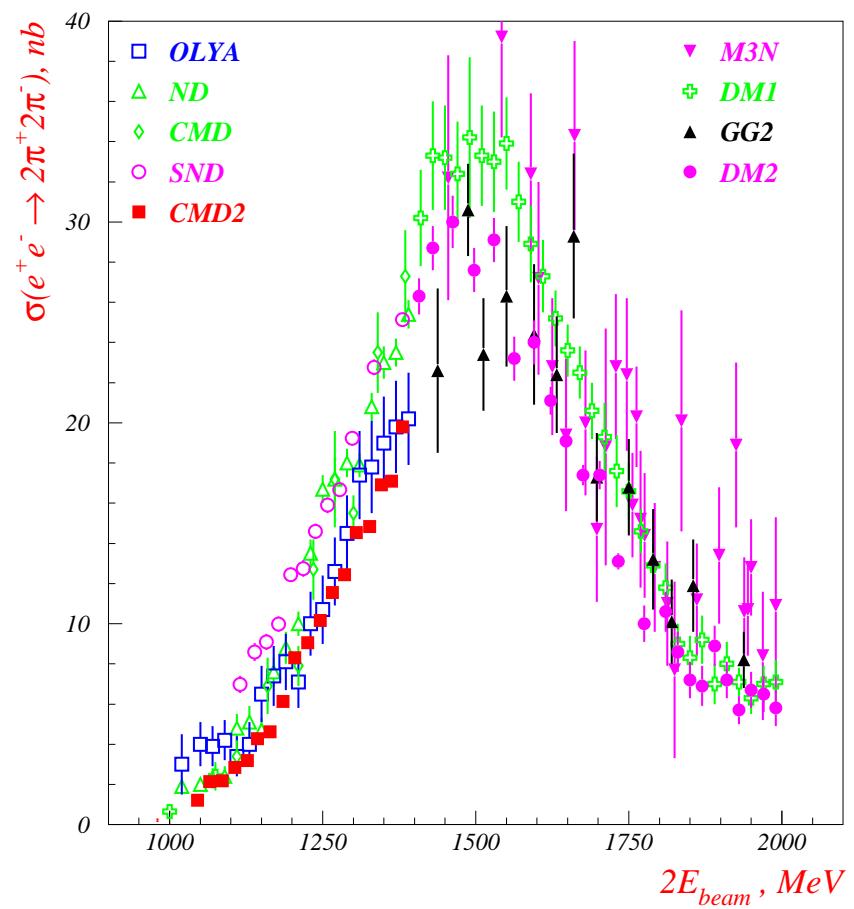
$e^+e^- \rightarrow \pi^+\pi^-\pi^0$ at SND

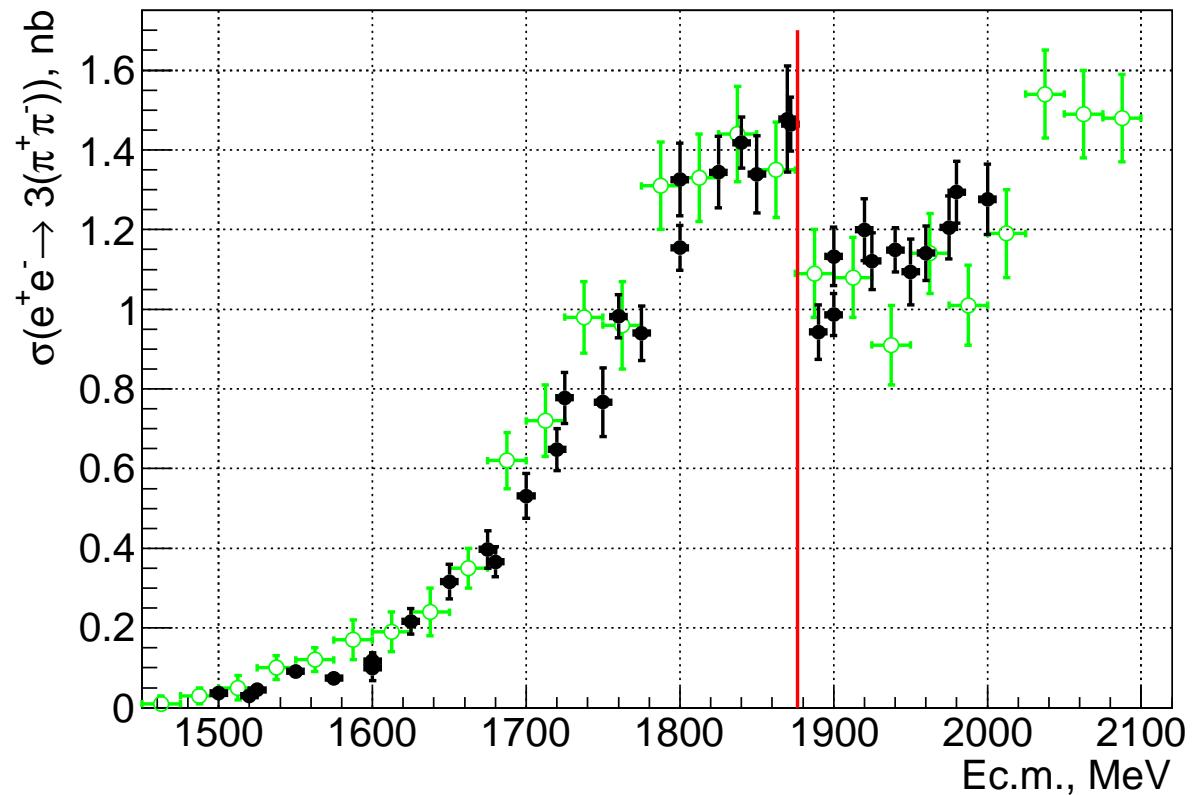
V.M. Aulchenko et al., JETP 121 (2013) 27

$e^+e^- \rightarrow 2(\pi^+\pi^-)$ and $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$ at CMD-2 – I



$e^+e^- \rightarrow 2(\pi^+\pi^-)$ and $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$ at CMD-2 – II

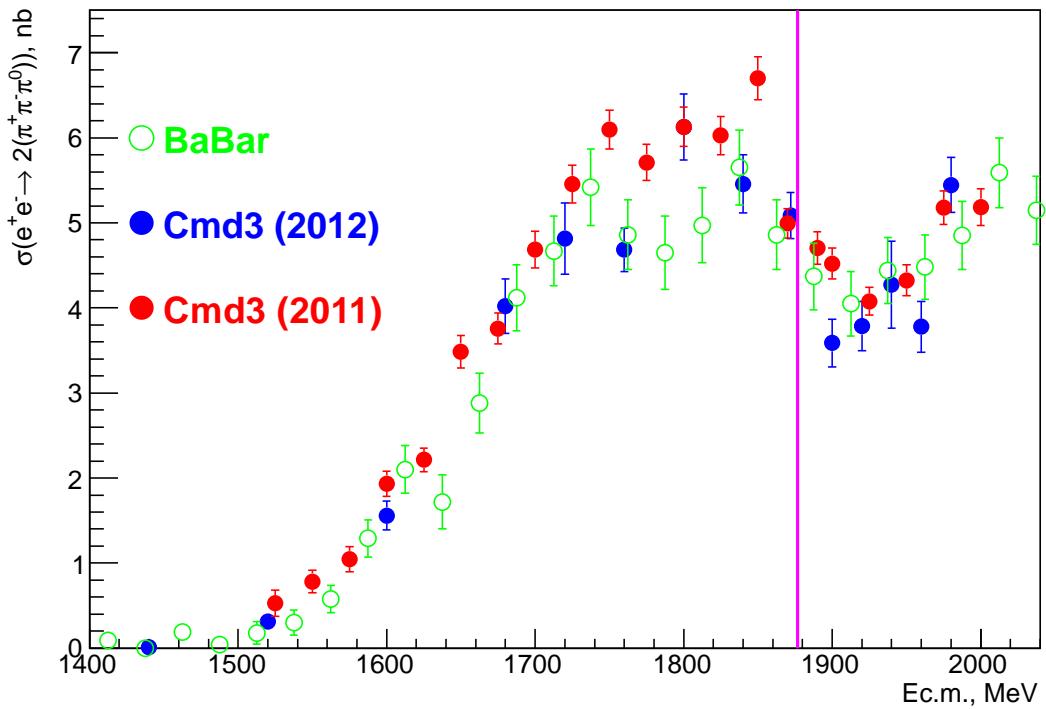


$e^+e^- \rightarrow 3\pi^+3\pi^-$ at CMD-3


The dip structure near $N\bar{N}$ threshold is confirmed

R.R. Akhmetshin et al., Phys. Lett. B723 (2013) 82

$e^+e^- \rightarrow 2\pi^+2\pi^-2\pi^0$ at CMD-3



2011 – all reconstructed or a π^\pm or π^0 lost, 2012 – all reconstructed
The dip structure near $N\bar{N}$ threshold also seen

Muon Anomalous Magnetic Moment

$$\vec{\mu} = g \frac{e}{2m} \vec{s}, \quad a = (g - 2)/2.$$

In Dirac theory for pointlike particles $g = 2$,
higher-order effects or new physics $\Rightarrow g \neq 2$

Any significant difference of a_μ^{exp} from a_μ^{th} indicates
New Physics beyond the Standard Model.

a_μ is much more sensitive to new physics effects than a_e :
the gain is usually $\sim (m_\mu/m_e)^2 \approx 4.3 \cdot 10^4$.

$$a_\mu^{\text{th}} = a_\mu^{\text{SM}} + a_\mu^{\text{NP}}, \quad a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{had}}.$$

Experimental Status of a_l

$$a_e = 1159652180.73(28) \times 10^{-12} \quad 0.24 \times 10^{-9}$$

D. Hanneke et al., PRL 100, 120801 (2008)
QED test or α determination

$$a_\mu = 116592080(63) \times 10^{-11} \quad 0.54 \times 10^{-6}$$

G.W. Bennett et al. (E821), PRD 73, 072003 (2006)
Sensitive test of the Standard Model

$$a_\tau = -0.018(17) \text{ or } -0.052 < a_\tau < 0.013 \text{ 95%CL}$$

J. Abdallah et al. (DELPHI), EPJ C 35, 159 (2004)
Theory: $117721(5) \times 10^{-8}$, SE, M. Passera, MPL A 22, 159 (2007)

QED Contribution a_μ^{QED}

$$\begin{aligned}
 a_\mu^{\text{QED}} \cdot 10^{10} = \sum C_i \left(\frac{\alpha}{\pi}\right)^i = & 11614097.3 \text{ (1-loop)} & 1 \text{ diagram} \\
 & + 41321.8 \text{ (2-loop)} & 9 \\
 & + 3014.2 \text{ (3-loop)} & > 100 \\
 & + 38.1 \text{ (4-loop)} & > 1000 \\
 & + 0.4 \text{ (5-loop)} & > 20000
 \end{aligned}$$

α^3 terms known analytically (S. Laporta, E. Remiddi, 1993),

α^4 terms – numerically (T. Kinoshita et al., 2003-2008),

$L \log \alpha^5$ (TK et al., 2005,2007; A.L. Kataev, 2006, K. Chetyrkin et al., 2008):

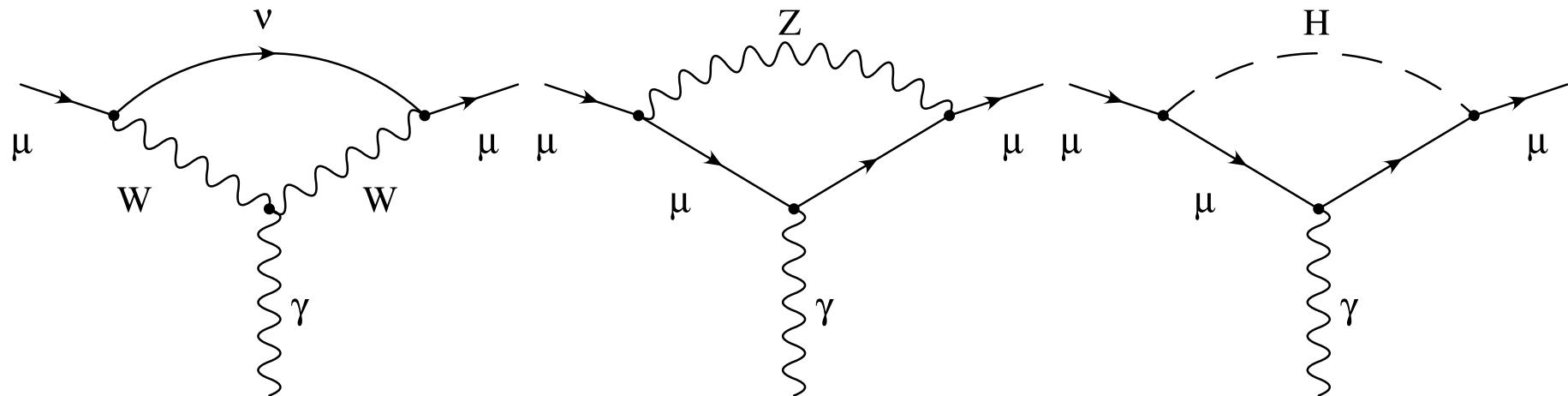
$$a_\mu^{\text{QED}} = (116584719.4 \pm 1.4) \cdot 10^{-11}.$$

From the latest value of a_e (D. Hanneke et al., 2008; M. Passera, 2008):

$$\alpha^{-1} = 137.035999084(51), a_\mu^{\text{QED}} = (116584718.09 \pm 0.14 \pm 0.04) \cdot 10^{-11}.$$

The errors are due to: a/ $\mathcal{O}(\alpha^5)$, b/ α

Electroweak contribution a_μ^{EW}



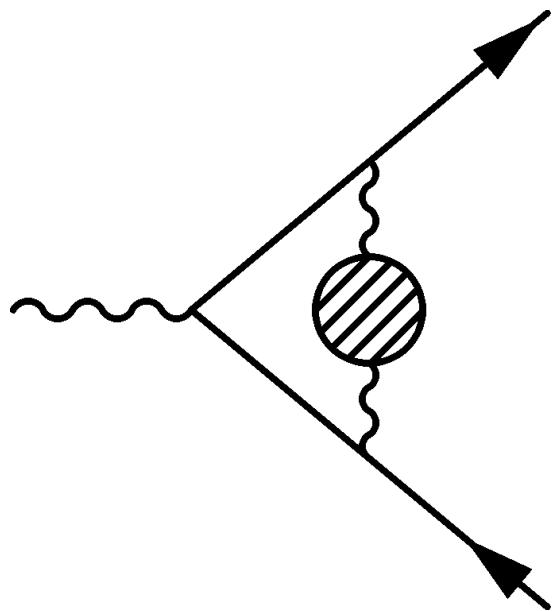
One-loop electroweak contributions

Authors	Year	$a_\mu^{\text{EW}}, 10^{-10}$
..., ..., ...	1972	19.5
A. Czarnecki et al.	1996	15.2 ± 0.4
A. Czarnecki et al.	2002	$15.4 \pm 0.1 \pm 0.2$

The errors are due to: a/ hadr. loops, b/ M_H, M_t , 3-loop effects.

Hadronic contribution a_μ^{had}

$$a_\mu^{\text{had}} = a_\mu^{\text{had,LO}} + a_\mu^{\text{had,HO}} + a_\mu^{\text{had,LBL}}$$



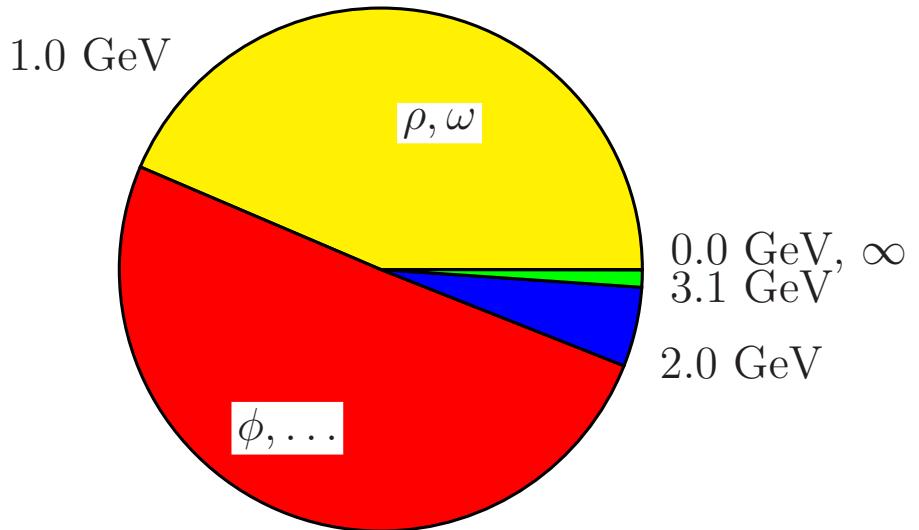
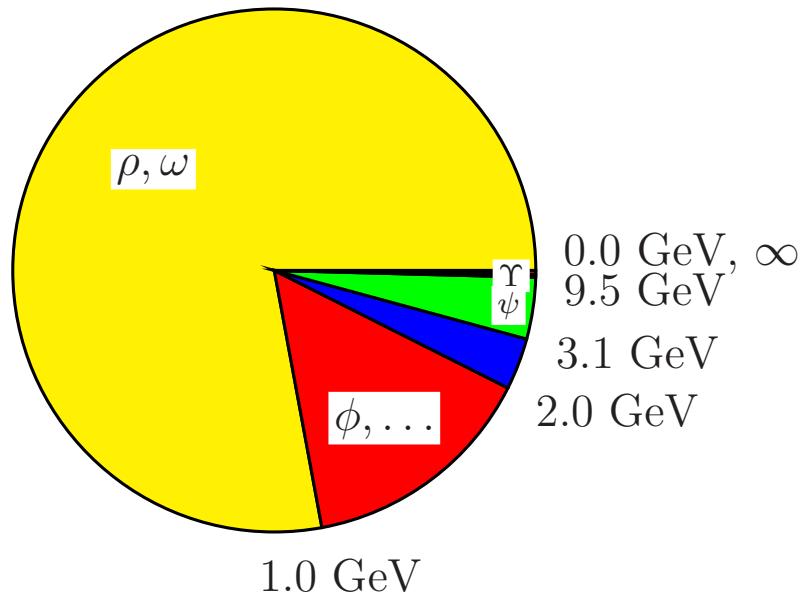
$$a_\mu^{\text{had,LO}} = \left(\frac{\alpha m_\mu}{3\pi} \right)^2 \int_{4m_\pi^2}^\infty ds \frac{R(s) \hat{K}(s)}{s^2},$$

C. Bouchiat, L. Michel, Bouchiat, 1961;
M. Gourdin, E. de Rafael, 1969

$$R(s) = \frac{\sigma(e^+ e^- \rightarrow \text{hadrons})}{\sigma(e^+ e^- \rightarrow \mu^+ \mu^-)},$$

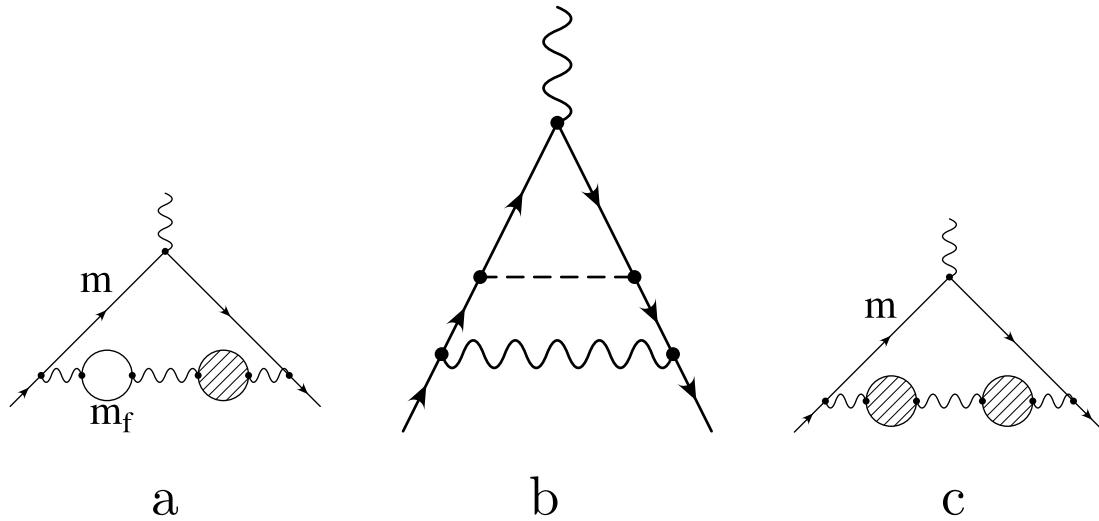
$\hat{K}(s)$ grows from 0.63 at $s = 4m_\pi^2$ to 1 at $s \rightarrow \infty$,
 $1/s^2$ emphasizes low energies, particularly $e^+ e^- \rightarrow \pi^+ \pi^-$.
 $a_\mu^{\text{had,LO}} \sim 700 \cdot 10^{-10} \Rightarrow$ accuracy better than 1% needed

Contributions of Various Energy Ranges to $a_\mu^{\text{had,LO}}$



More than 72% of $a_\mu^{\text{had,LO}}$ come from $e^+e^- \rightarrow \pi^+\pi^-$ and
more than 90% from the energy range below 2 GeV

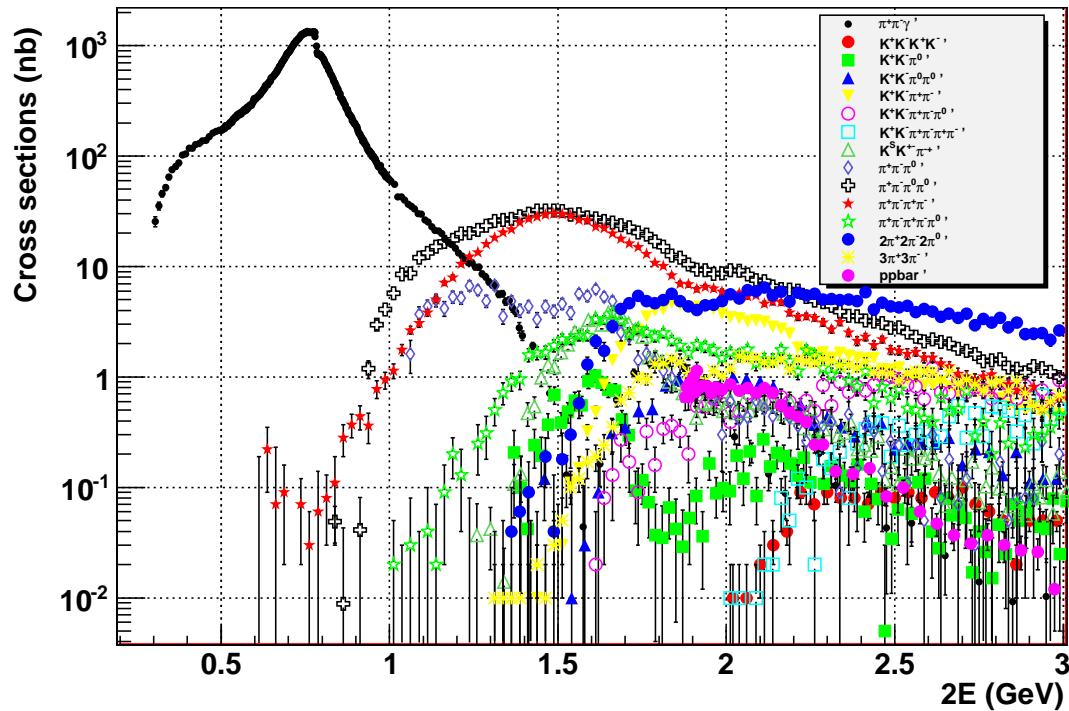
Higher Order Hadronic Contributions $a_\mu^{\text{had,HO}}$



The contributions of all 3 graphs can be calculated in terms of the $\int R(s)G(s)ds/s^{2(3)}$, where $G(s)$ is a smooth function of s , so that the low energy range again dominates the integral. Several calculations agree. The accepted value is (B. Krause, 1997; K. Hagiwara et al., 2003):

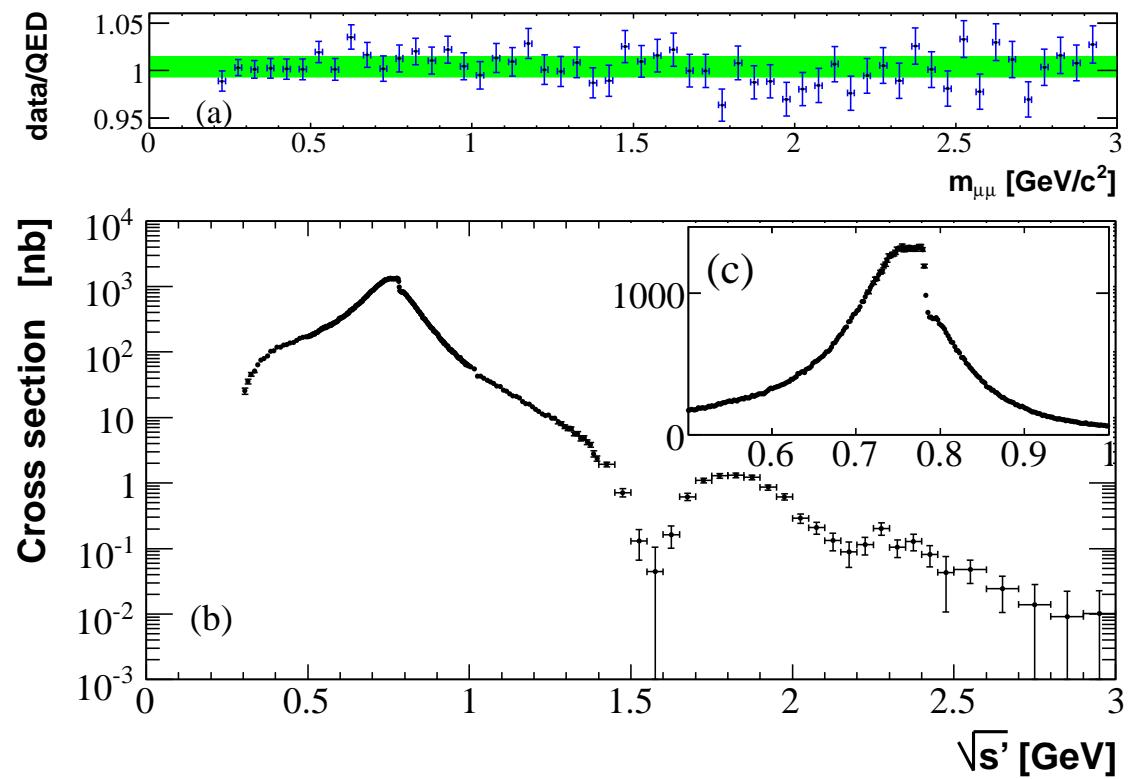
$$a_\mu^{\text{had,HO}} = (-9.8 \pm 0.1) \cdot 10^{-10}.$$

Current Status of Exclusive Measurements – II



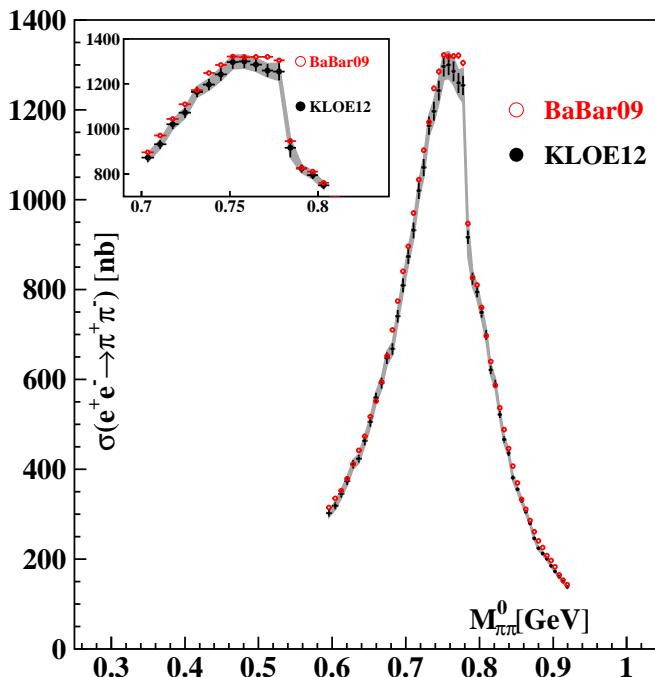
BaBar used ISR to study the energy range $\sqrt{s} < 3.0$ GeV, Belle/BelleII and BESIII can contribute as well to ISR measurements

$e^+e^- \rightarrow \pi^+\pi^-$ at BaBar



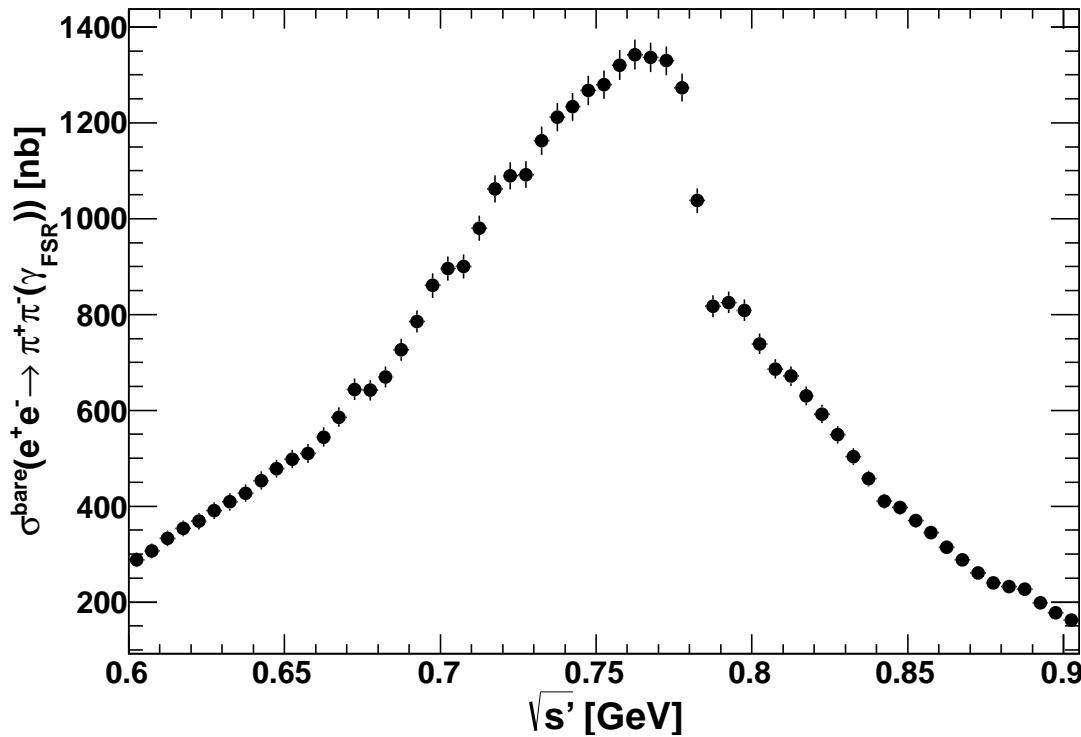
The systematic error near the ρ is 0.5%

J.P. Lees et al., Phys. Rev. D86 (2012) 032013

$e^+e^- \rightarrow \pi^+\pi^-$ at KLOE/KLOE-2

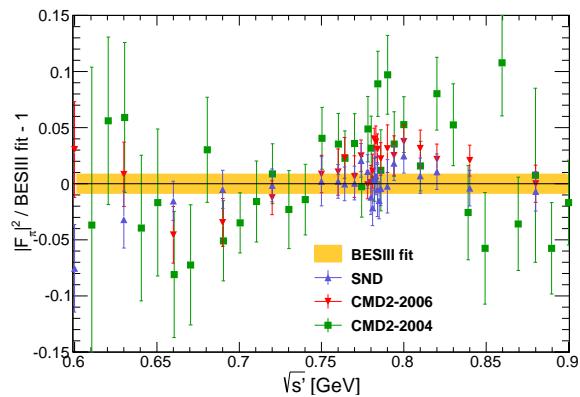
The systematic error is 0.7%

D. Babusci et al., Phys. Lett. B720 (2013) 336

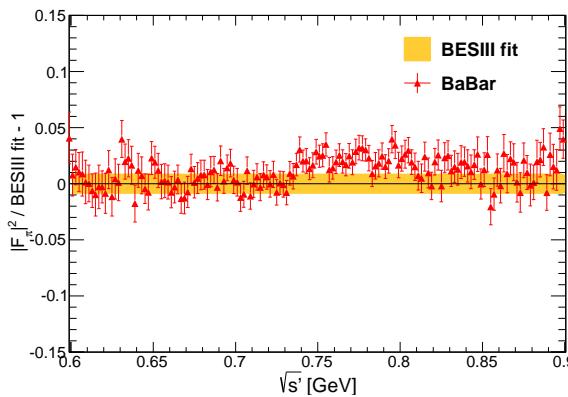
$e^+e^- \rightarrow \pi^+\pi^-$ with ISR at BESIII – I

The achieved systematic error is 0.9%,
they plan using more data and work on smaller systematics

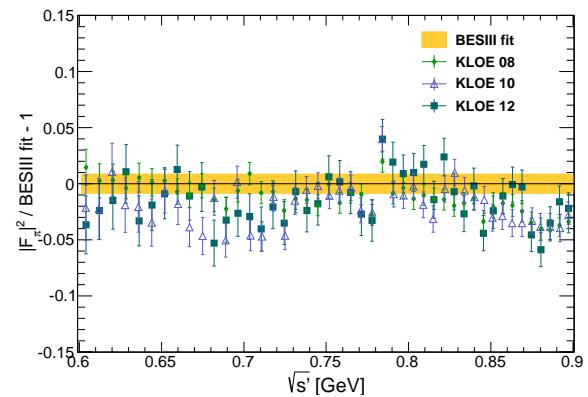
M. Ablikim et al., Phys. Lett. B 753 (2016) 629

$e^+e^- \rightarrow \pi^+\pi^-$ with ISR at BESIII – II


SND: JETP 103 (2006) 380
 CMD-2: PLB 648 (2007) 28



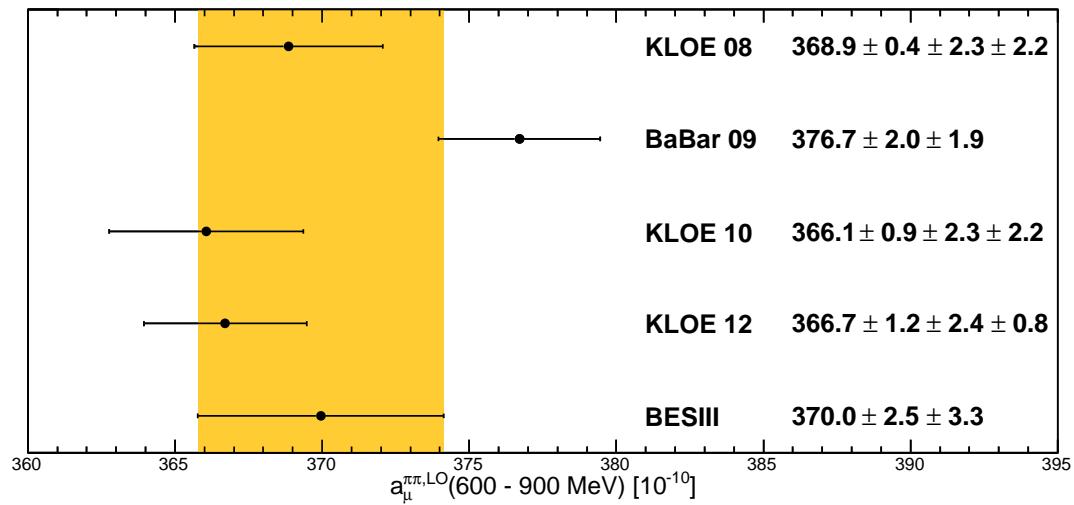
BaBar: PRL 103 (2009) 231801



KLOE08: PLB 670 (2009) 285
 KLOE10: PLB 700 (2011) 102
 KLOE12: PLB 720 (2013) 336

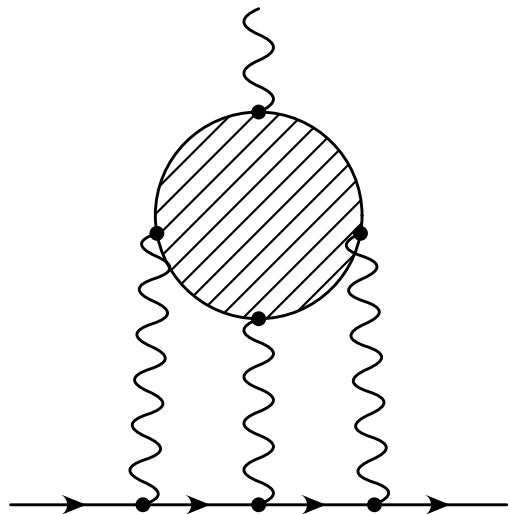
Agreement between different ISR results is far from perfect

M. Ablikim et al., Phys. Lett. B 753 (2016) 629

$e^+e^- \rightarrow \pi^+\pi^-$ with ISR at BESIII – III

M. Ablikim et al., Phys. Lett. B 753 (2016) 629

Light-by-Light Scattering – I



Various approaches used:

- Vector Dominance and Chiral models
- Data on $\gamma\gamma^* \rightarrow \pi^0, \eta, \eta'$ (single-tag)
- Effective field theory
- Dyson-Schwinger equations

M. Knecht and A. Nyffeler, 2002: the correct sign!

Light-by-Light Scattering – II

Authors	Year	$a_\mu^{\text{lbl}}, 10^{-10}$
J. Bijnens et al.	1996 (2002)	8.3 ± 3.2
M. Hayakawa and T. Kinoshita	1998 (2002)	9.0 ± 1.5
K. Melnikov and A. Vainshtein	2003	13.6 ± 2.5
M. Davier and W. Marciano	2004	12.0 ± 3.5
J. Prades, E. de Rafael, and A. Vainshtein	2009	10.5 ± 2.6
D. Greynat and E. de Rafael	2012	15.0 ± 0.3
T. Goecke, C.S. Fischer and R. Williams	2013	18.8 ± 9.0

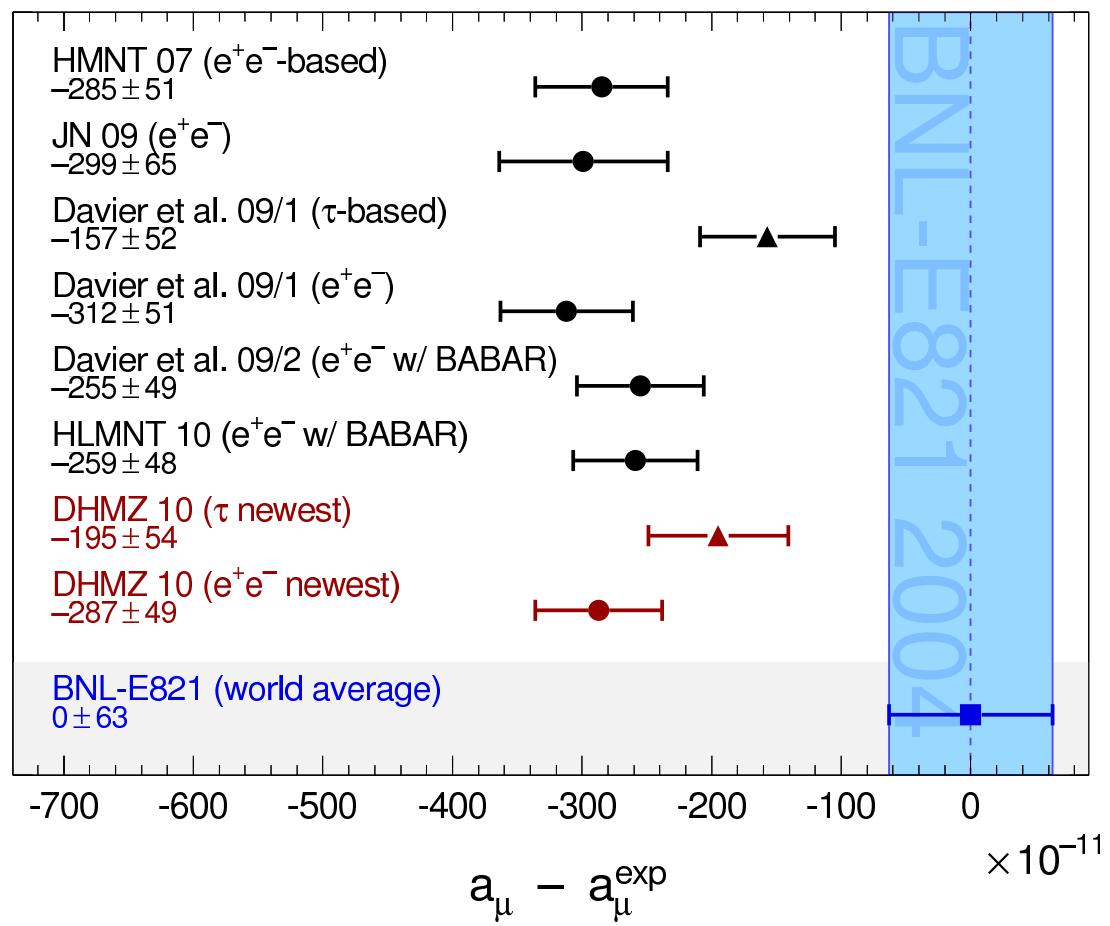
Experiment vs. Theory – I

$$a_\mu = (g_\mu - 2)/2, \text{ } 10^{-10}$$

Experiment	$11659208.9 \pm 5.4 \pm 3.3$
QED	11658471.809 ± 0.015
EW	$15.4 \pm 0.1 \pm 0.2$
Had LO	692.3 ± 4.2
Had HO	-9.8 ± 0.1
Had LbL	10.5 ± 2.6
Theory	11659180.2 ± 4.9
Exp.-Th.	28.7 ± 8.0

Experiment is higher than theory by 3.6 standard deviations

Experiment vs. Theory – II



Conclusions

- Low energy measurements of the exclusive and total e^+e^- cross sections have numerous important applications and demand high precision (0.5-1)%
- There are three high-productive e^+e^- colliders (factories) running
- DAΦNE in Frascati and VEPP-2000 in Novosibirsk in the c.m. energy range below 2 GeV with the KLOE2 detector at DAΦNE and CMD-3 and SND detectors at VEPP-2000
- BEPC2 with BES3 in Beijing is covering the c.m. energy range [2,4.6] GeV
- A lot of info can be also obtained by ISR from BaBar and Belle as well as at lower energies with KLOE2, CMD-3, SND and BES3
- Belle2 will start data taking in 2018