e^+e^- annihilation into hadrons and muon $g-2$

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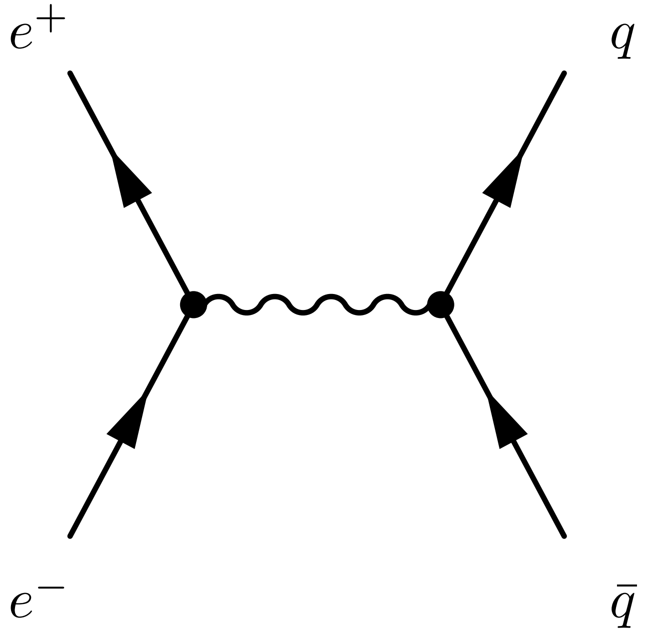
Outline

1. General
2. ISR measurements
3. VEPP-2000
4. Conclusions

What Can We Learn from Low Energy e^+e^- Cross Sections?

1. Detailed study of exclusive processes $e^+e^- \to (2-7)h, h = \pi, K, \eta, p, \ldots$
    - Test of models and input to theory (ChPT, Vector Dominance, QCD, . . .)
    - Properties of vector mesons $(\rho', \omega', \phi', \ldots)$
    - Search for exotic states (tetraquarks, hybrids, glueballs)
    - Test of CVC relations between e^+e^- and τ-lepton
    - Interactions of light (u, d, s) quarks
2. High-precision determination of $R = \sigma(e^+e^- \to \text{ hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ at low energies and fundamental quantitites
    - $(g_\mu - 2)/2$, HFS in Mu
    - $\alpha(M_Z^2)$
    - QCD sum rules (α_s, quark and gluon condensates, $m_{u/d}$)
    - $m_c, \ m_b$ from R moments

What is R?



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

f – pointlike fermion,

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

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

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

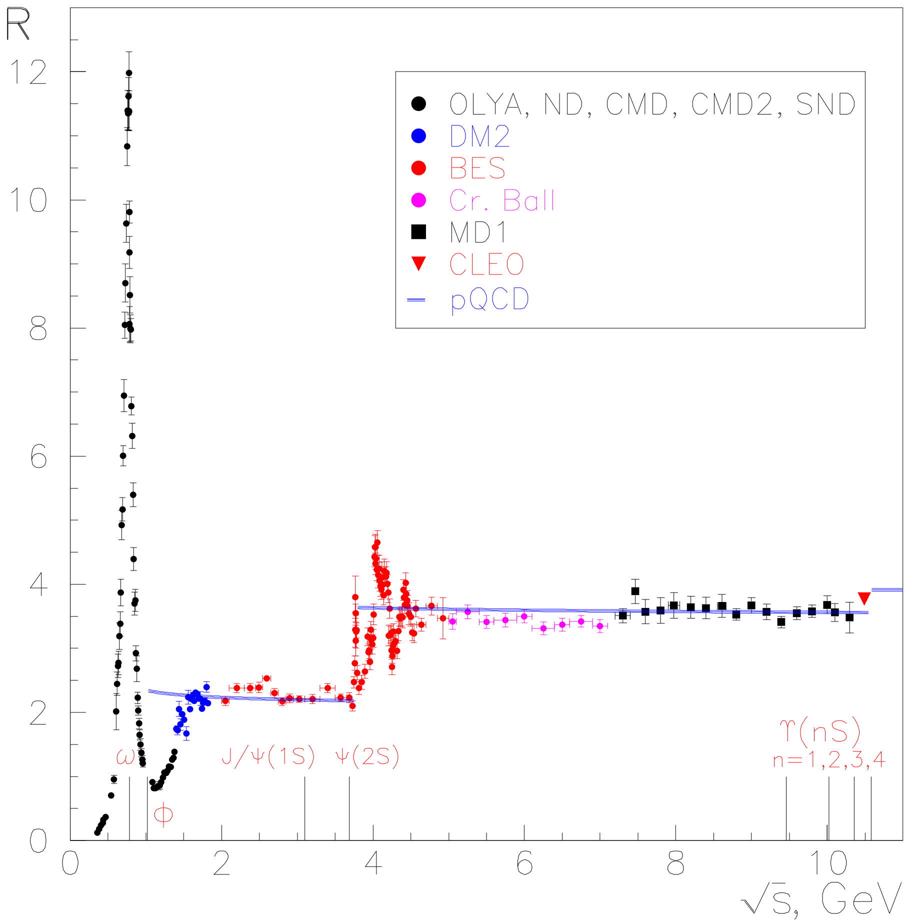
At $\sqrt{s} > 1.02$ GeV (u, d, s), $R \simeq 3((2/3)^2 + (1/3)^2 + (1/3)^2) = 2$

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), $R \simeq 11/3$

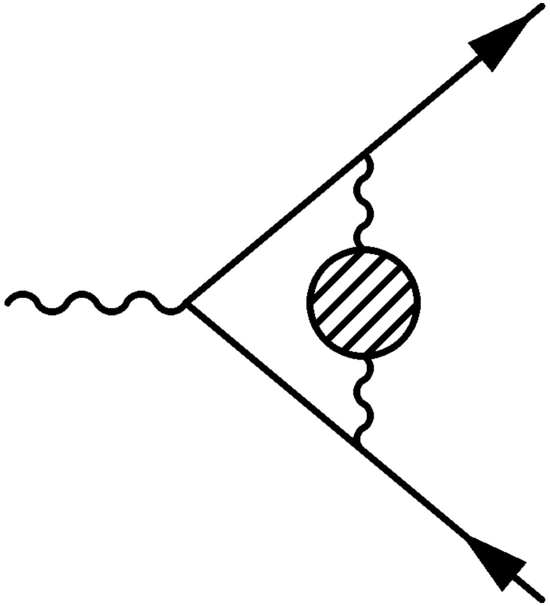
QCD corrections $\Rightarrow$ $R = 3\sum e_q^2(1 + \mathcal{O}(\alpha(s)/\pi))$.

R Measurements below 10 GeV



Hadronic contribution $a_\mu^{\rm had}$

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



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

C. Bouchiat, L. Michel, Bouchiat, 1961;

M. Gourdin, E. de Rafael, 1969

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

$\hat{K}(s)$ grows from 0.63 at $s = 4m_\pi^2$ to 1 at $s \to \infty$,

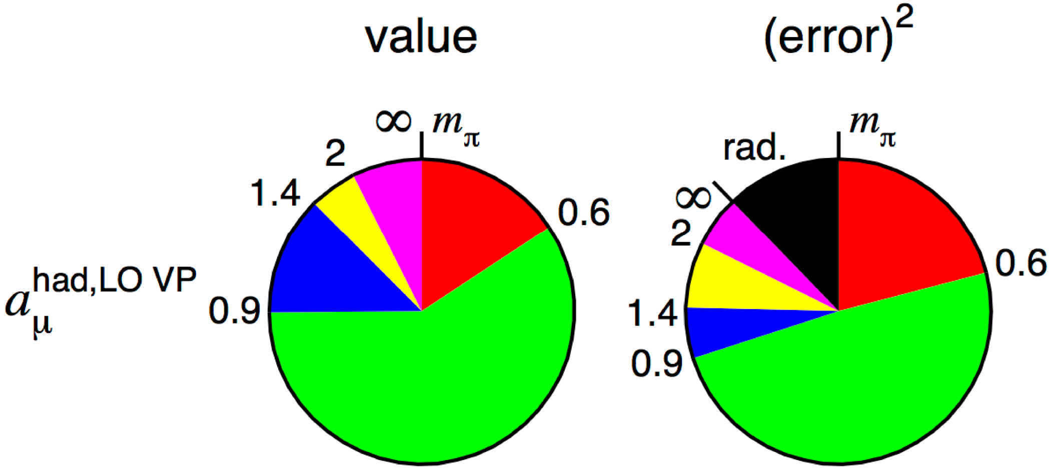
$1/s^2$ emphasizes low energies, particularly $e^+e^- \to \pi^+\pi^-$.

In reality, the low limit should be $m_{\pi^0}^2$ rather than $4m_\pi^2$

($e^+e^- \to \pi^0\gamma$ is the first hadronic state, but its contribution is numerically very small)

$a_\mu^{\rm had,LO} \sim 700 \cdot 10^{-10}$ ⇒ accuracy better than 1% needed

The Famous Pie



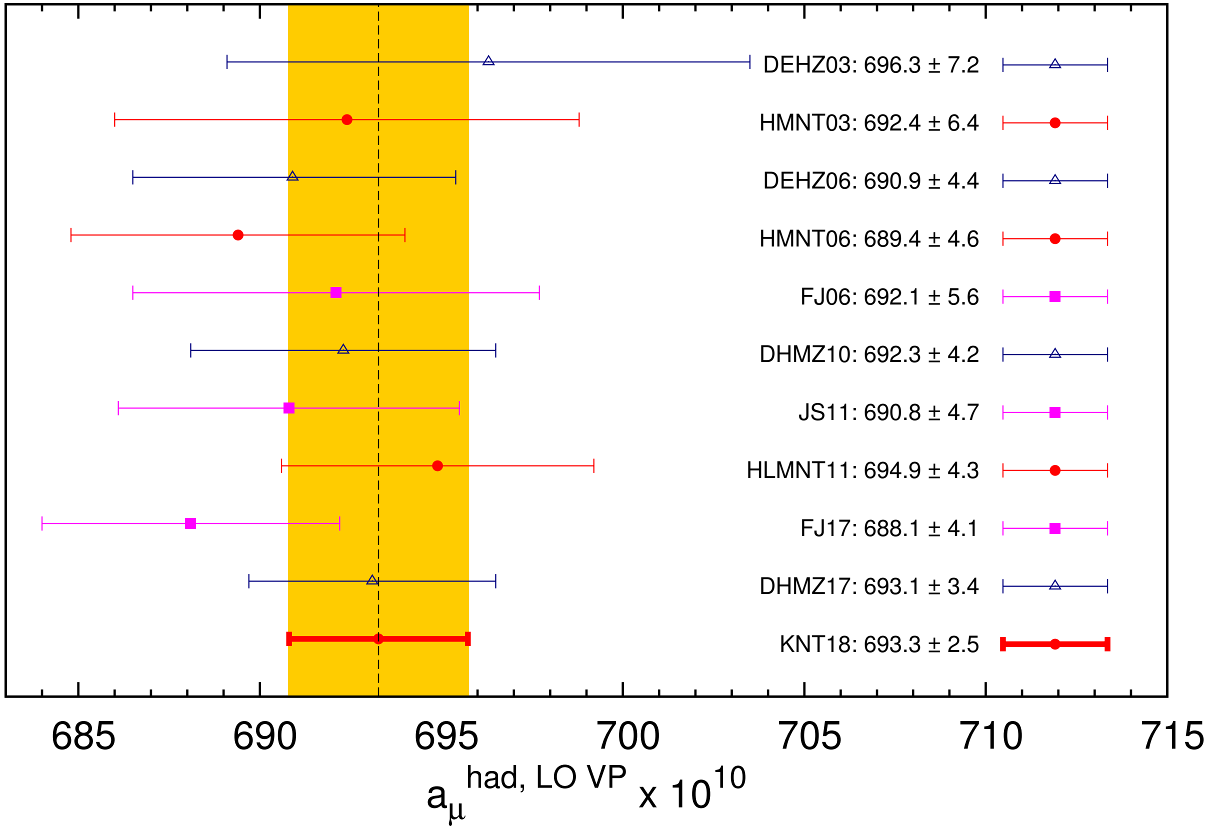
73% come from the $e^+e^- \to \pi^+\pi^-$ process

93% come from $e^+e^- \to$ hadrons below 2 GeV

7% come from the range 2 GeV $< \sqrt{s} < \infty$

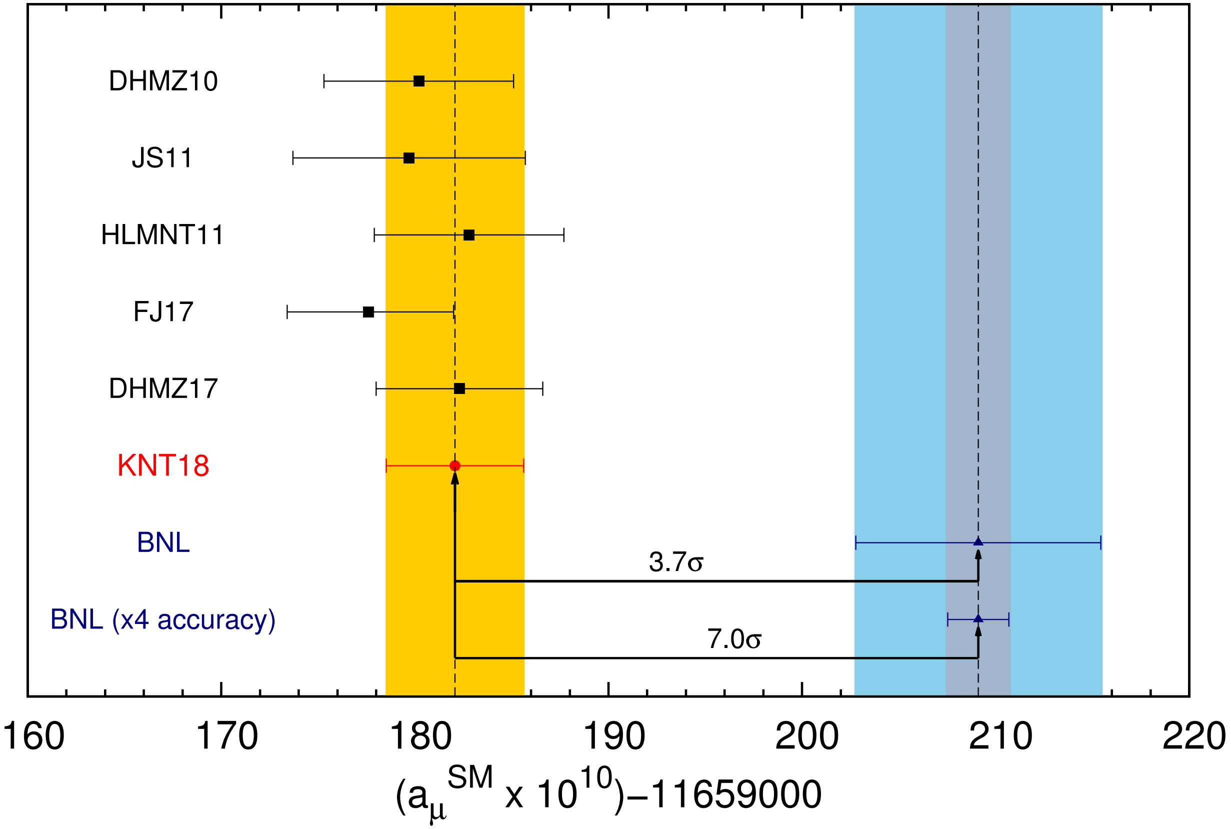
A. Keshavarzi, D. Nomura, T. Teubner, Phys. Rev. D97, 114025 (2018)

Various Theoretical Calculations



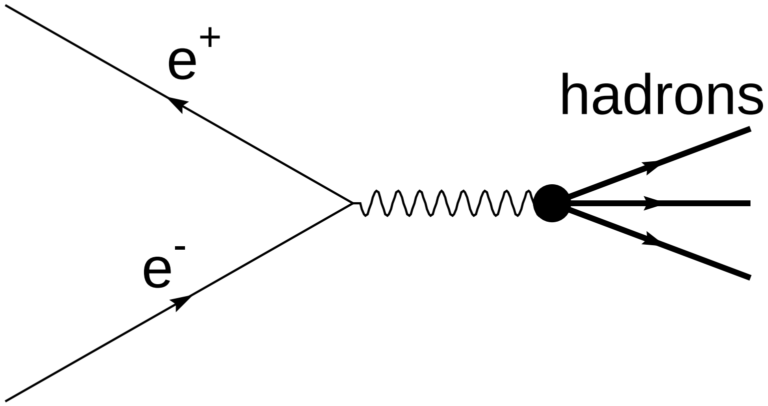
A. Keshavarzi, D. Nomura, T. Teubner, Phys. Rev. D97, 114025 (2018)

Comparison of Theory and Experiment

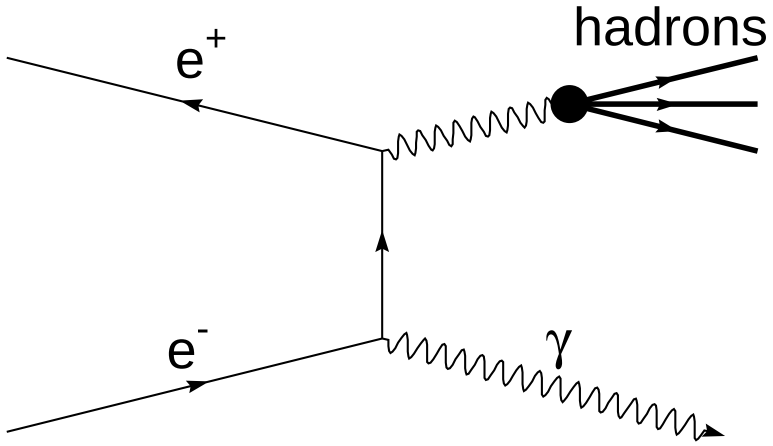


A. Keshavarzi, D. Nomura, T. Teubner,Phys. Rev. D97, 114025 (2018)

Scan and ISR



Scan

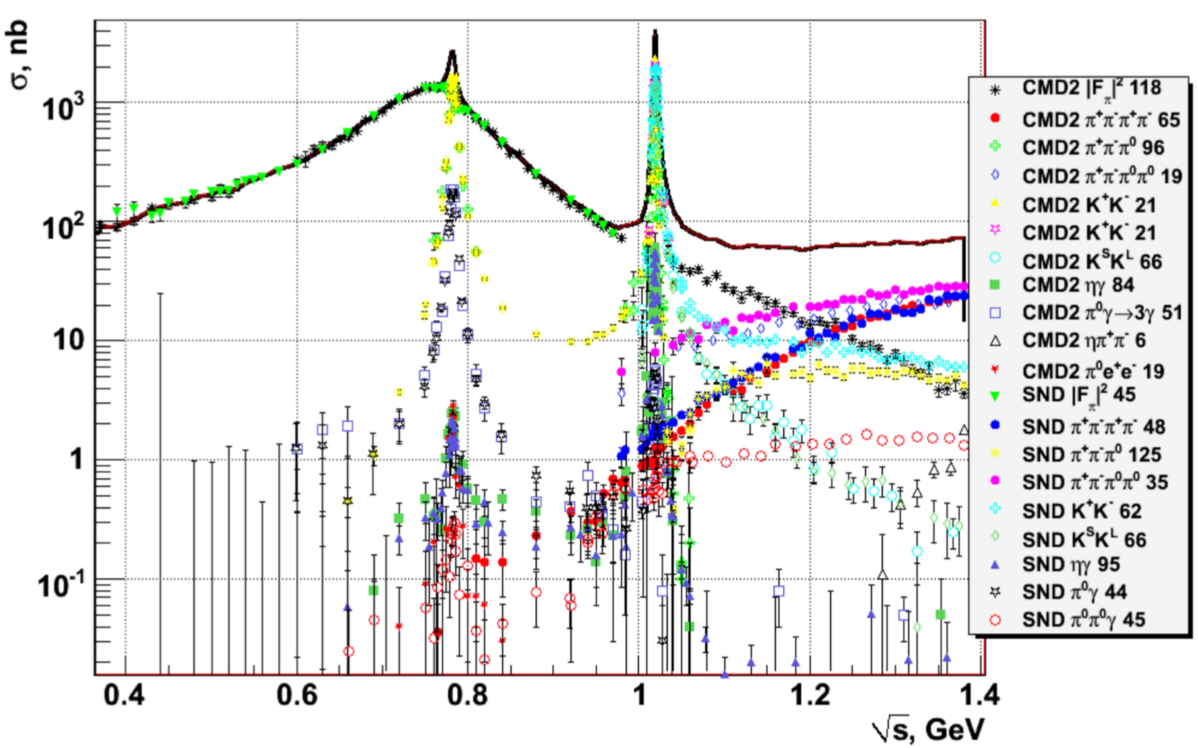


ISR

Scan can provide larger data samples at fixed energy,
radiative effects understood well (?)

ISR benefits from the same systematics and flat acceptance,
but may suffer from more complicated radiative effects
and a much larger c.m. energy bin

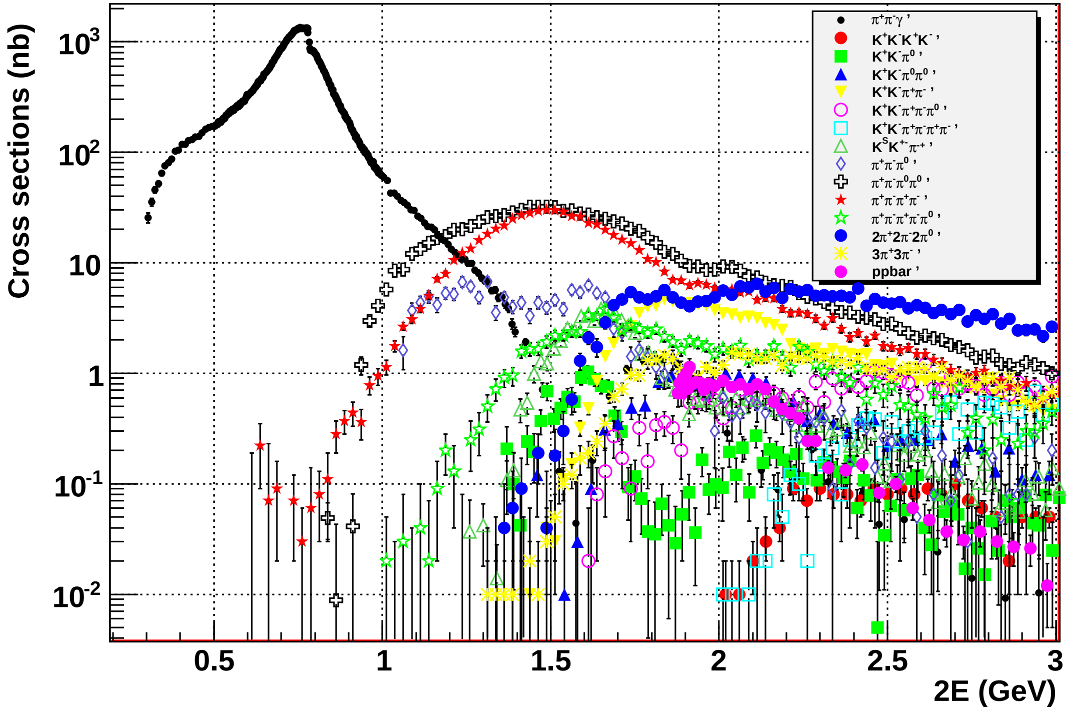
Current Status of Exclusive Measurements (Scan) – I



Impressive achievements of CMD-2, SND (scan at $0.36 < \sqrt{s} < 1.4$ GeV)

Continued by CMD-3 and SND to 2 GeV with x20 data samples

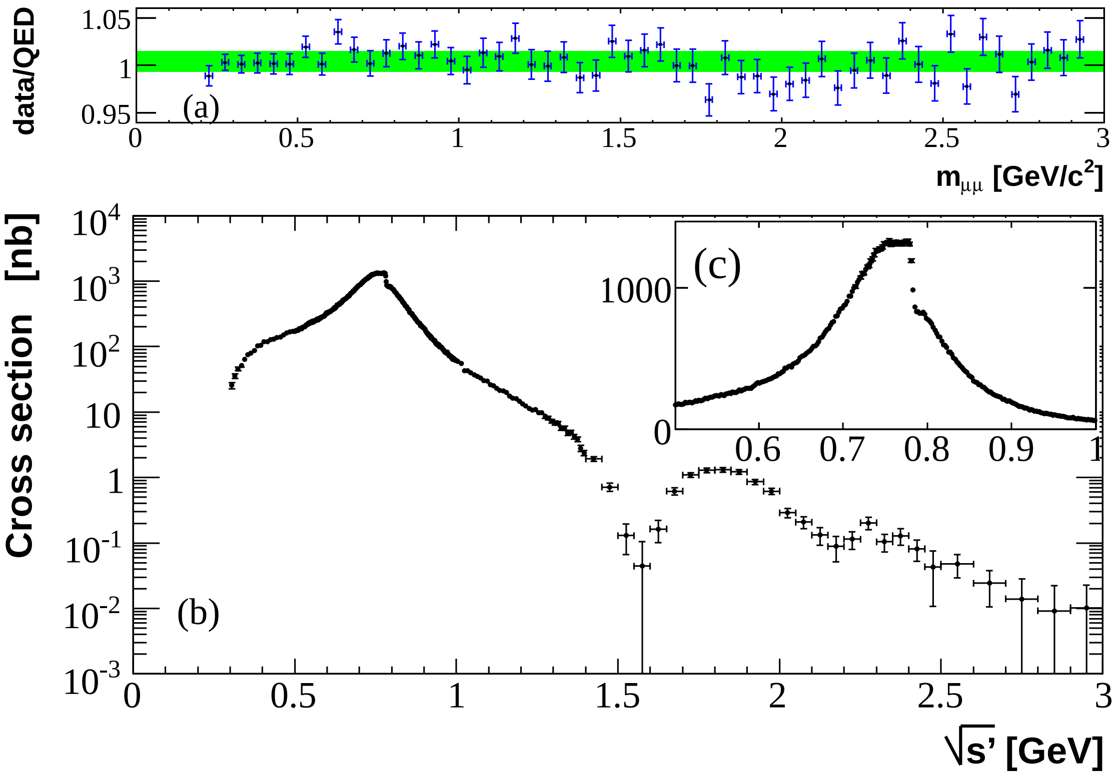
Current Status of Exclusive Measurements (ISR) – II



BaBar used ISR to study the energy range $\sqrt{s} < 3.0$ GeV,

Important contributions from KLOE and BESIII, BelleII in the future

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

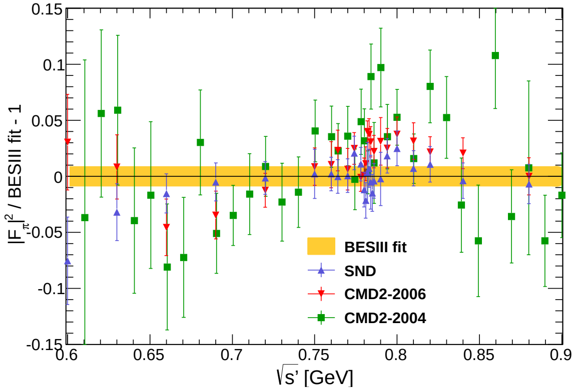


The systematic error near the ρ is 0.5%

B. Aubert et al., Phys. Rev. Lett. 103, 231801 (2009);

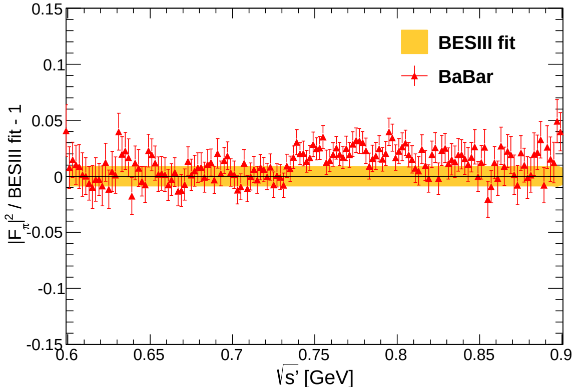
J.P. Lees et al., Phys. Rev. D86, 032013 (2012)

$e^+e^- \to \pi^+\pi^-$ (BESIII Comparison)

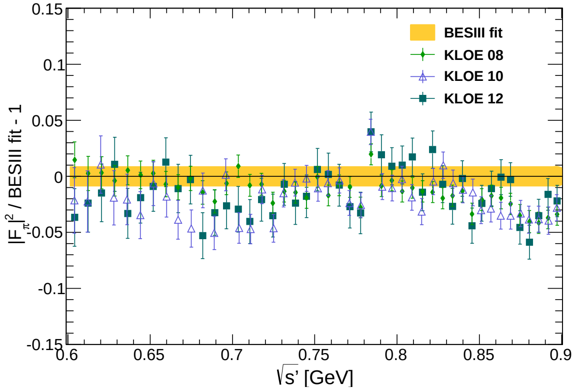


SND: JETP 103, 380 (2006)

CMD-2: PLB 648, 28 (2007)



BaBar: PRL 103, 231801 (2009)



KLOE08: PLB 670, 285 (2009)

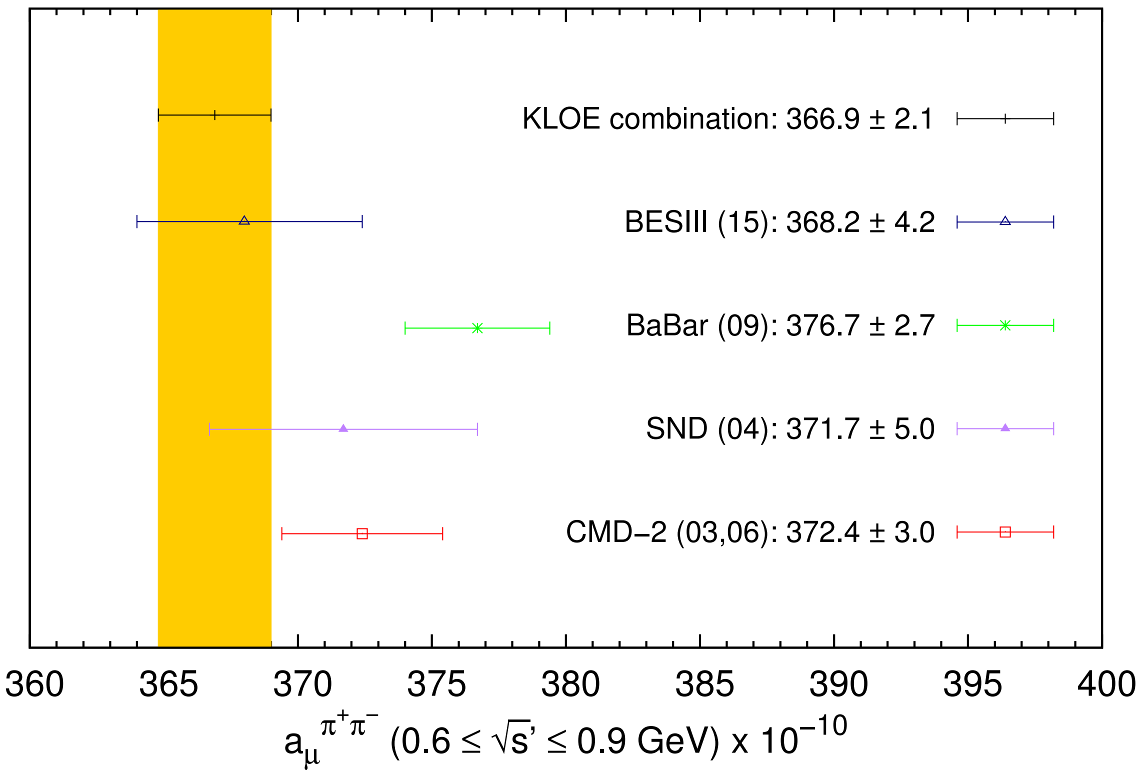
KLOE10: PLB 700, 102 (2011)

KLOE12: PLB 720, 336 (2013)

Agreement between different ISR results is far from perfect

M. Ablikim et al., Phys. Lett. B761, 98 (2016)

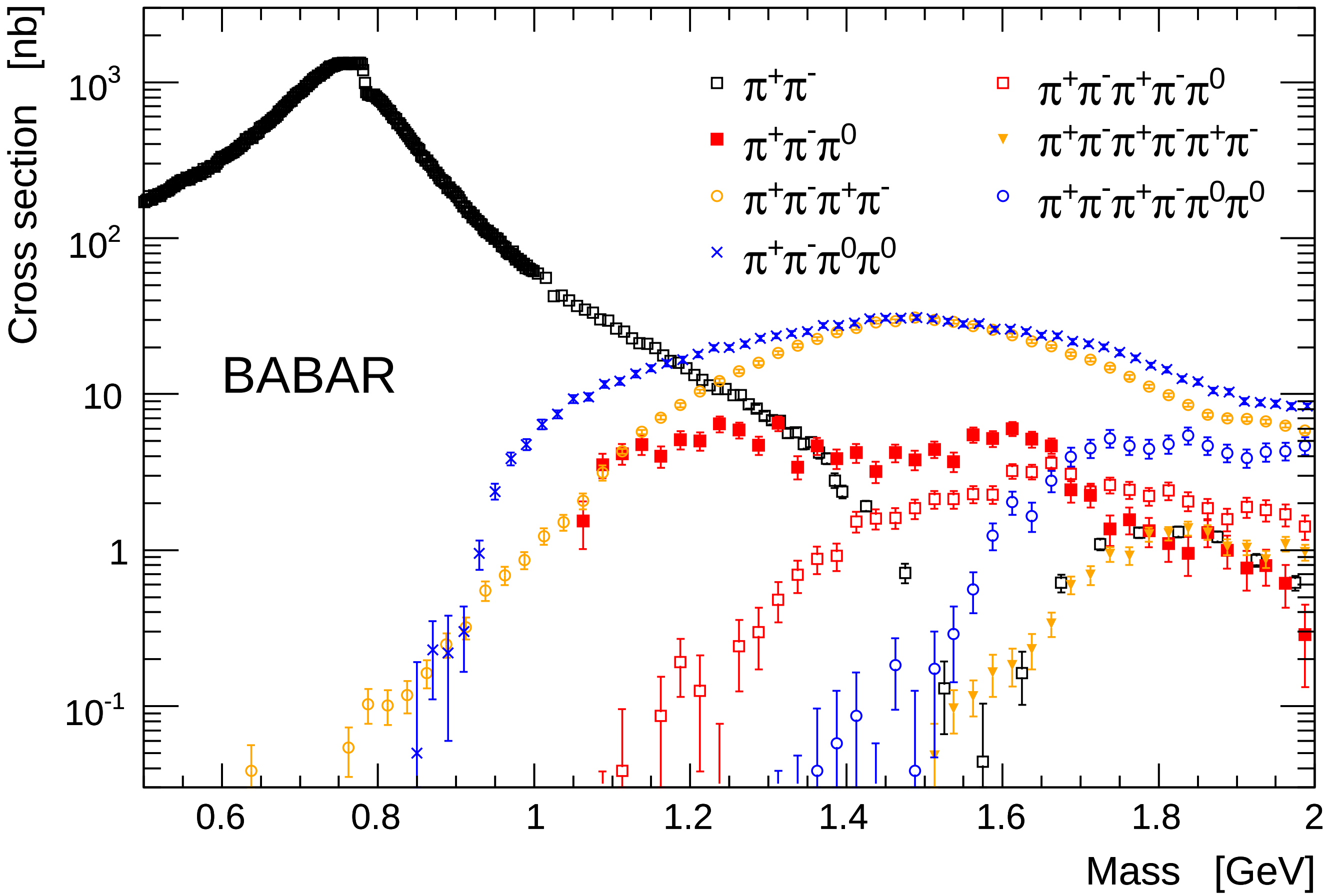
$e^+e^- \to \pi^+\pi^-$ (KLOE Comparison)



A. Anastasi et al., JHEP 1803, 173 (2018)

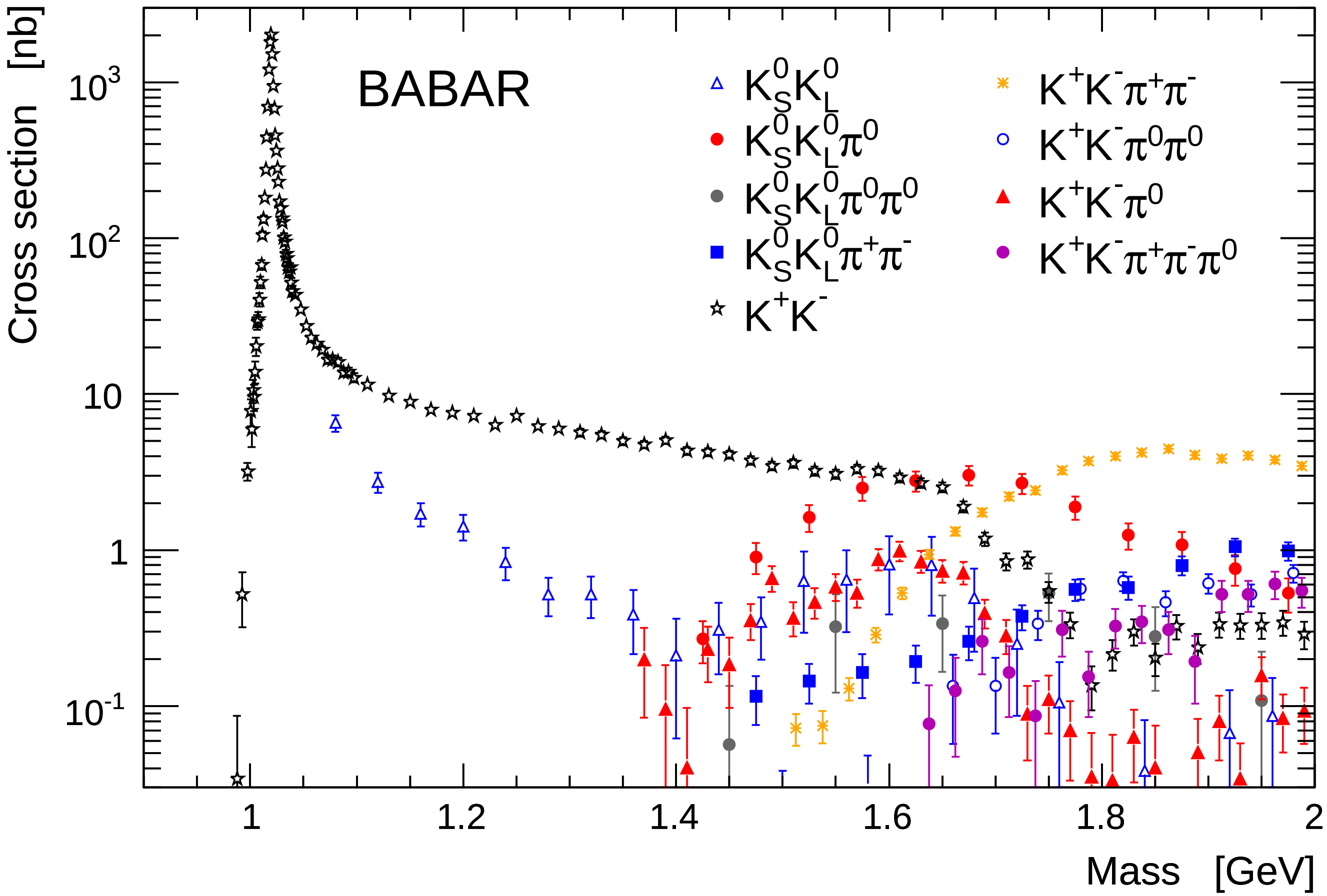
Some tension between KLOE/BESIII and BaBar

BaBar Results on the Processes with Pions



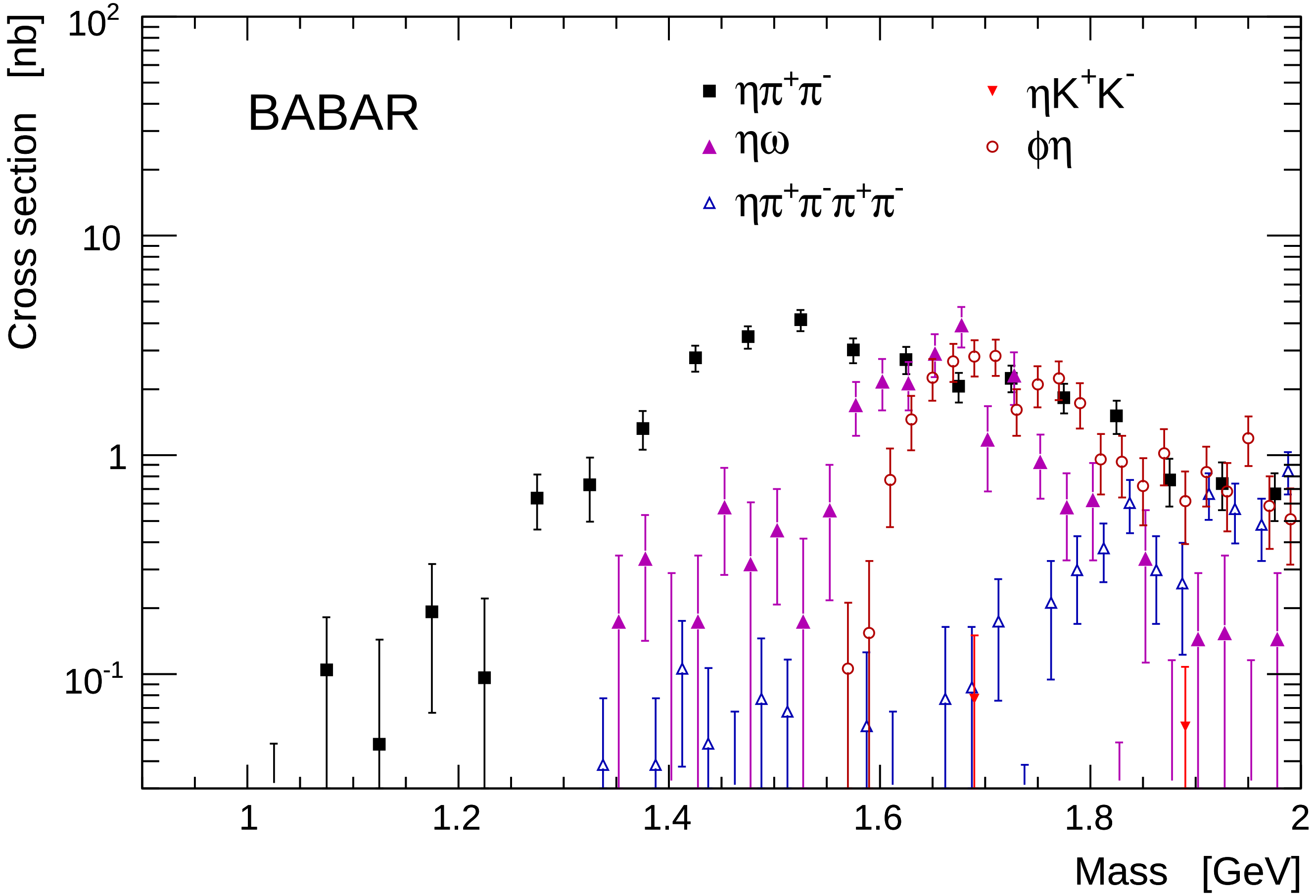
Systematic uncertainties range from 0.5% for $\pi^+\pi^-$ to (6-8)% for 6π

BaBar Results on the Processes with Kaons



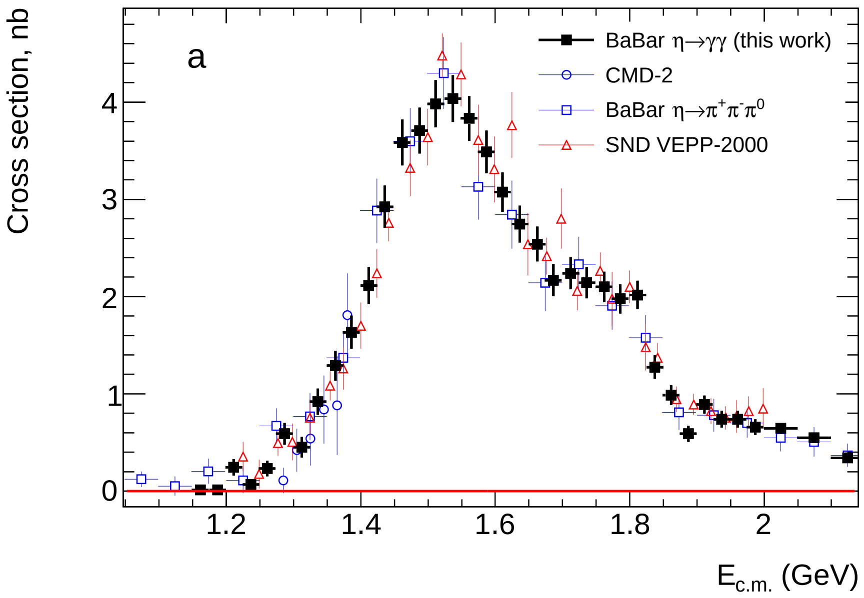
Systematic uncertainties range from 0.7% for K^+K^- to (6-8)% for $K\bar{K}n\pi$

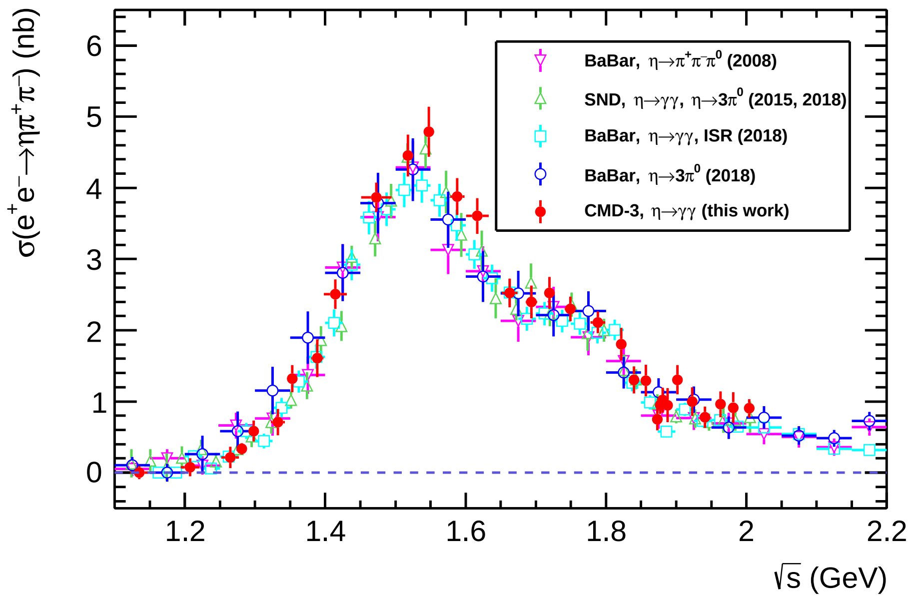
BaBar Results on the Processes with η Mesons



Systematic uncertainties range from for 4.5% to 12%

$e^+e^- \to \eta\pi^+\pi^-$ at BaBar and CMD-3





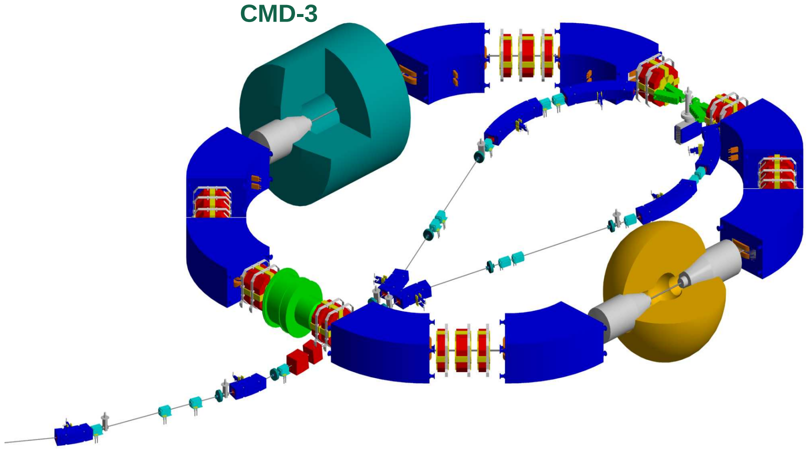
BaBar – PRD 97, 052007 (2018)

CMD-3 – Phi to Psi, 2019

First observation of the $\rho(1700)$ in $\eta\pi^+\pi^-$

CMD-3 is consistent with BaBar and has better precision

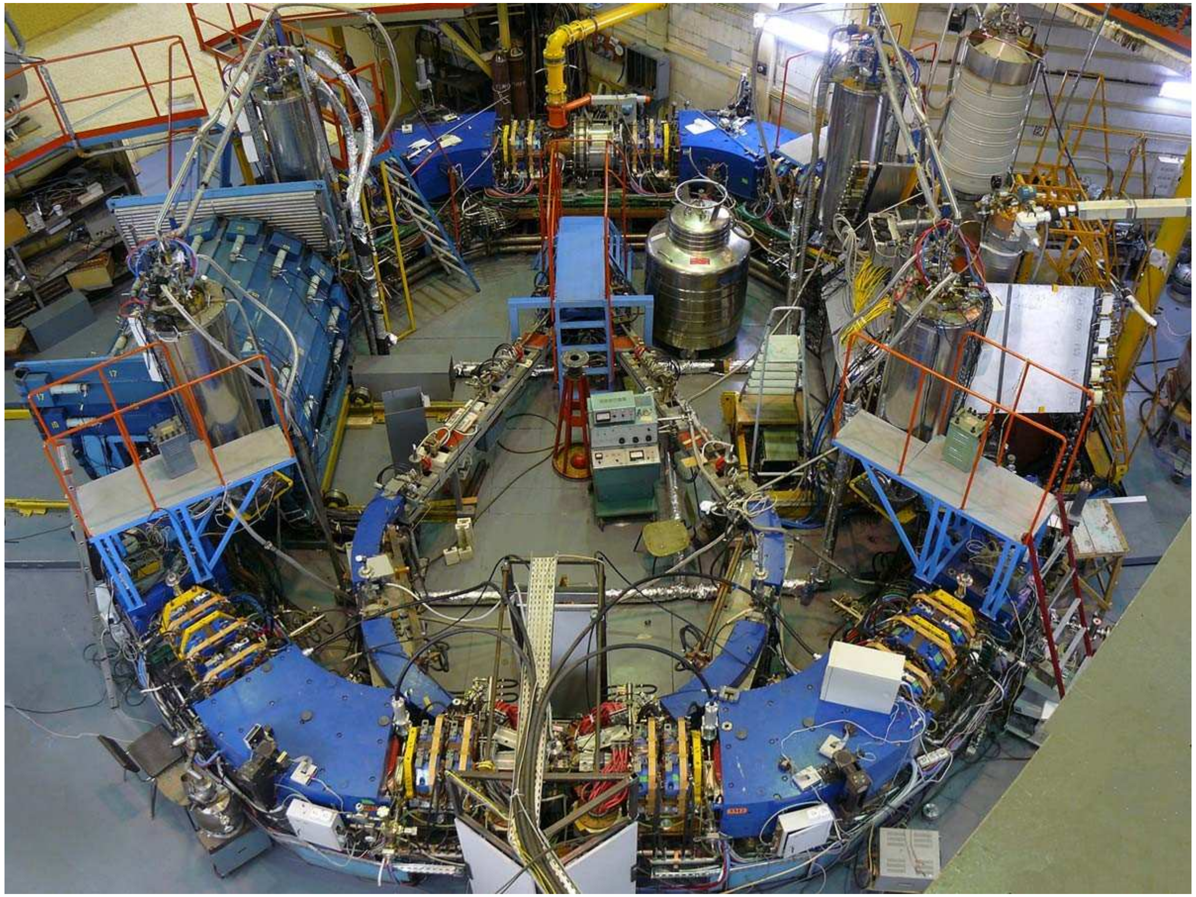
VEPP-2000 – I



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

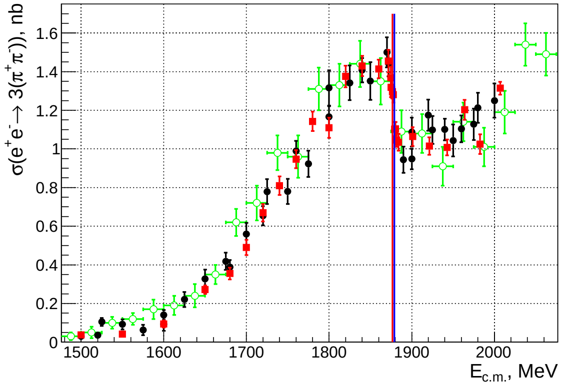
Round beams, precise E_{beam} measurement with LCBS

VEPP-2000 – II



The circumference of 24 m, two detectors – CMD-3 and SND

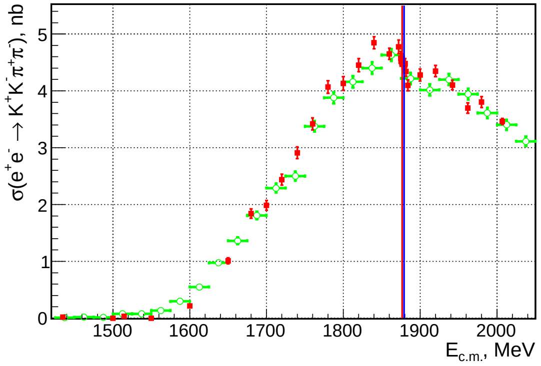
Interesting Physics at the $p\bar{p}$ Threshold at CMD-3



CMD-3 - new

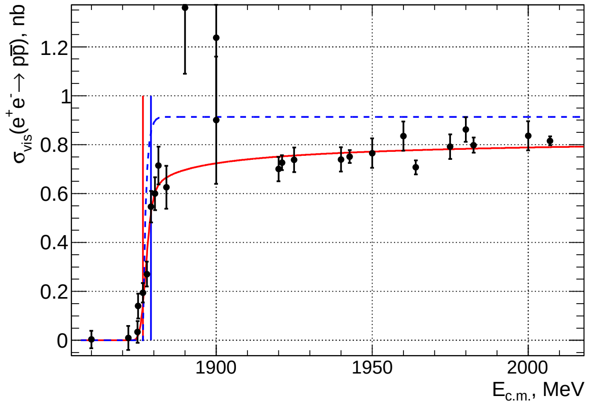
CMD-3 - old

BaBar



CMD-3 - new

BaBar



CMD-3

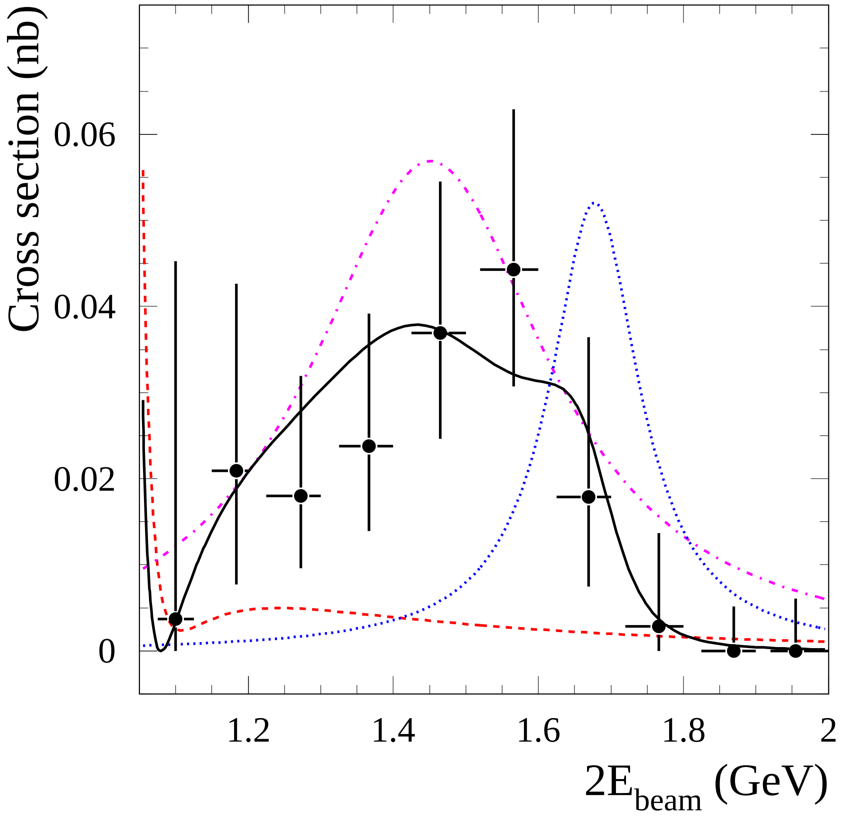
Strong interaction of nucleons in the Paris potential convolved with c.m. energy spread of 0.95 MeV and radiative corrections explains all σ's

A.I. Milstein and S.G. Salnikov, Nucl. Phys. A977, 60 (2018)

R.R. Akhmetshin et al., Phys. Lett. B794, 64 (2019)

Is the effect $\propto \mathcal{B}$ in $p\bar{p}$ annihilation?

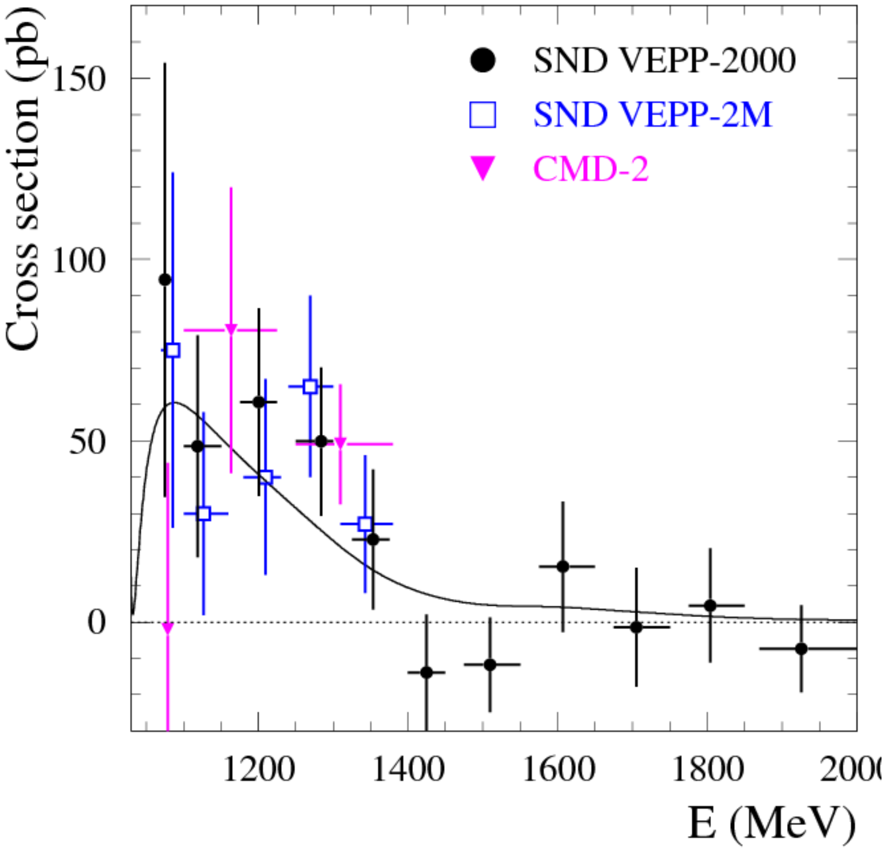
$e^+e^- \to \eta\gamma$ at SND



The first measurement above 1.4 GeV, dominated by the $\rho(1450)$ and $\phi(1680)$ mesons

M. Achasov et al., Phys. Rev. D90, 032002 (2014)

$e^+e^- \to \pi^0\gamma$ at SND



The first search above 1.4 GeV, no signal above the background

M.N. Achasov et al., Phys. Rev. 98, 112001 (2018)

Search for direct processes $e^+e^- \to \pi^0\pi^0\gamma,\ \eta\pi^0\gamma$ at CMD-2

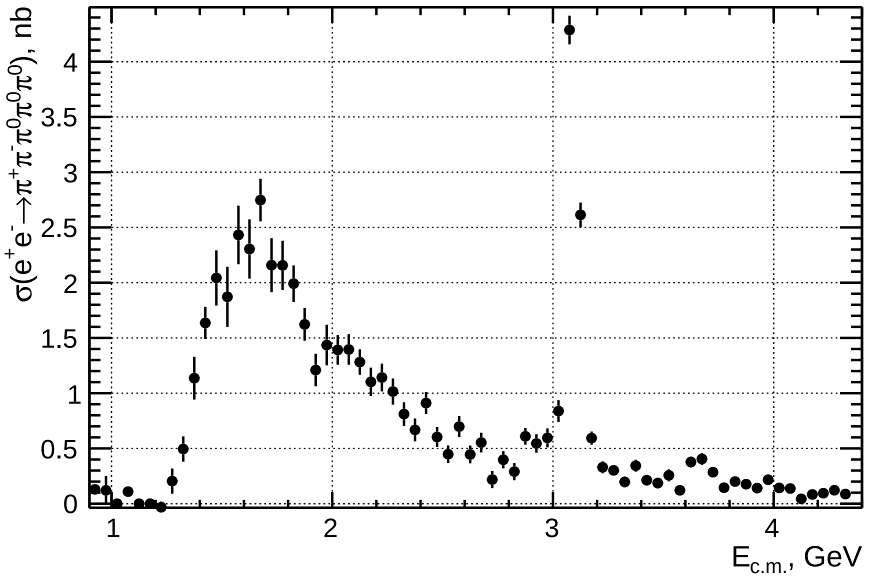
CMD-2 performed a study of $e^+e^- \to \omega\pi^0 \to \pi^0\pi^0\gamma$ and found no signal of direct production of $\pi^0\pi^0\gamma,\ \eta\pi^0\gamma$

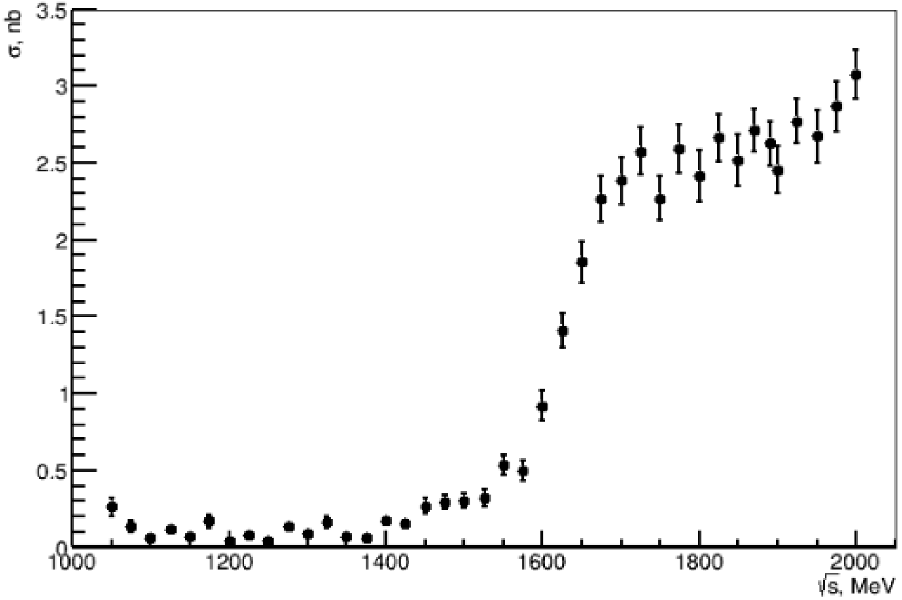
$\sqrt{s}$, MeV	$\sigma(\pi^0\pi^0\gamma)$, nb	$\sigma(\eta\pi^0\gamma)$, nb
920-1004	0.07	0.13
1034-1200	0.11	0.06
1200-1300	0.09	0.14
1300-1380	0.07	0.10

$a_\mu^{\mathrm{LO,had}} < 0.45 \cdot 10^{-10}$ at 90% CL

R.R. Akhmetshin et al., Phys. Lett. B562, 173 (2003)

$e^+e^- \to \pi^+\pi^-3\pi^0$ at BaBar, $e^+e^- \to \pi^+\pi^-4\pi^0$ at SND





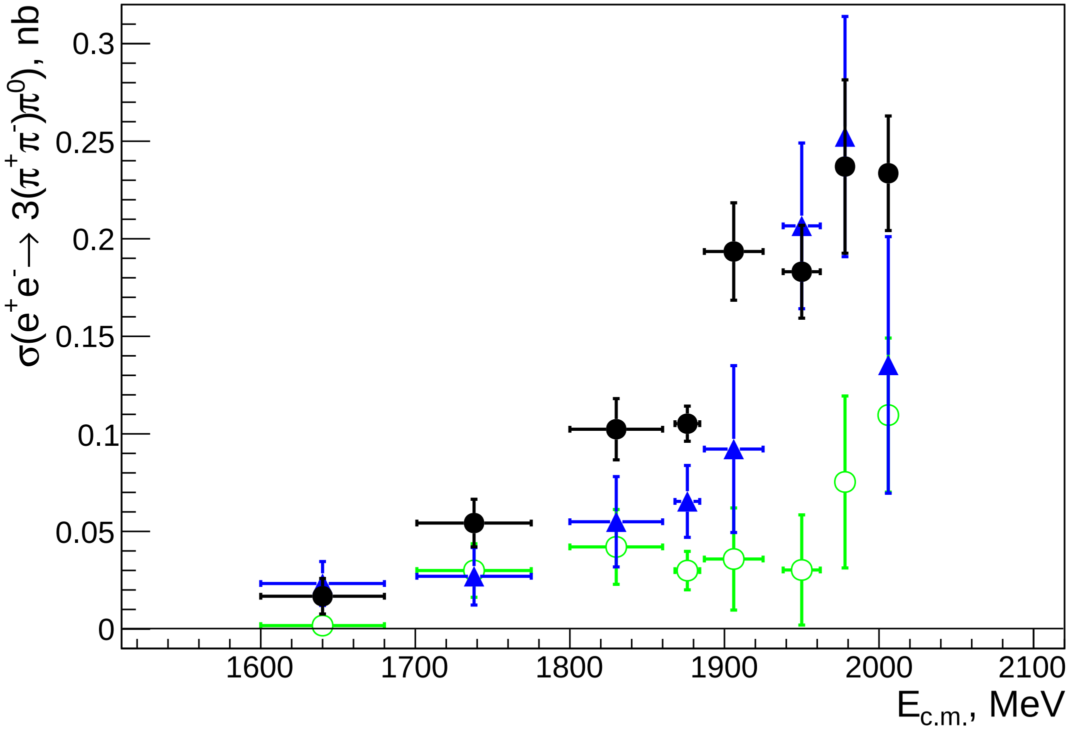
$e^+e^- \to \pi^+\pi^-4\pi^\circ$ cross section.

BaBar: PRD98, 112015 (2018)

SND: Phi to Psi, 2019

First ever measurements, necessary for the $\pi^+\pi^-3(4)\pi^0$ BG and $5(6)\pi$ dynamics

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

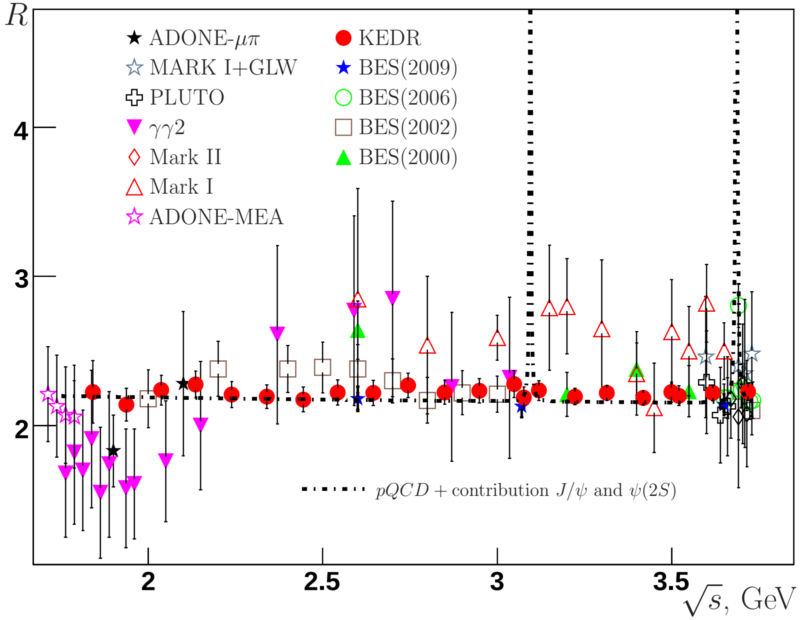


First ever measurement, 56.7 pb^{-1}, 632 events,

Two dominating mechanisms: $3(\pi^+\pi^-)\eta$, $3(\pi^+\pi^-)\omega$

R.R. Akhmetshin et al., Phys. Lett. B792, 419 (2019)

R measurement at KEDR



1.84-3.05 GeV $R = 2.225 \pm 0.020 \pm 0.047$ $(R_{\rm pQCD} = 2.18 \pm 0.02)$

V.V. Anashin et al., Phys. Lett. B770, 174 (2017)

3.05-3.72 GeV $R_{\rm uds} = 2.204 \pm 0.013 \pm 0.030$ $(R_{\rm pQCD} = 2.16 \pm 0.01)$

V.V. Anashin et al., Phys. Lett. B753, 533 (2016); B788, 42 (2019)

Total (syst. error) 3.9% (2.4%) at low, 2.6% (1.9%) at high $\sqrt{s}$

R measurement from 5 to 7 GeV in progress

Conclusions

- VEPP-2000 is running smoothly with CMD-3 and SND, their accuracy is comparable or better than in ISR measurements
- The goals are 0.35%(0.5%) for $\pi^+\pi^-$ and 3% for multibody modes
- Below 2 GeV progress (a factor of 2-3) expected in exclusive σ's due to scans in Novosibirsk and ISR from KLOE2, BaBar, Belle, BESIII and BelleII, are there discrepancies and/or missing modes?
- Experiments with large data samples will substantially improve the accuracy of vacuum polarization calculations for $(g_\mu - 2)/2$
- Higher statistics ($\sim$ 1fb^{-1}) will allow a study of dynamics, thus mesons with various quantum numbers, vast input for models of strong interactions
- Meanwhile a $\sim (3.5 - 4.0)\sigma$ deviation of $a_\mu^{\rm SM}$ from $a_\mu^{\rm exp}$ persists: New Physics or various experimental and interpretation errors?