# HVP Dispersive ($e^+e^-$ Experiments)

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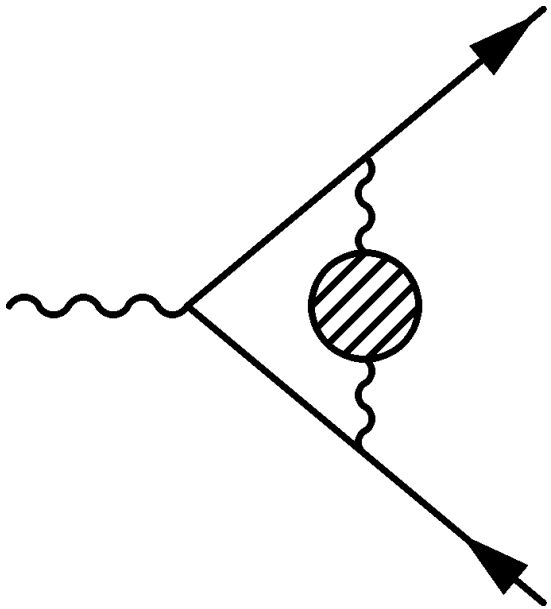
## Outline

1. General
2. Status and problems
3. More problems
4. Conclusions

# 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

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

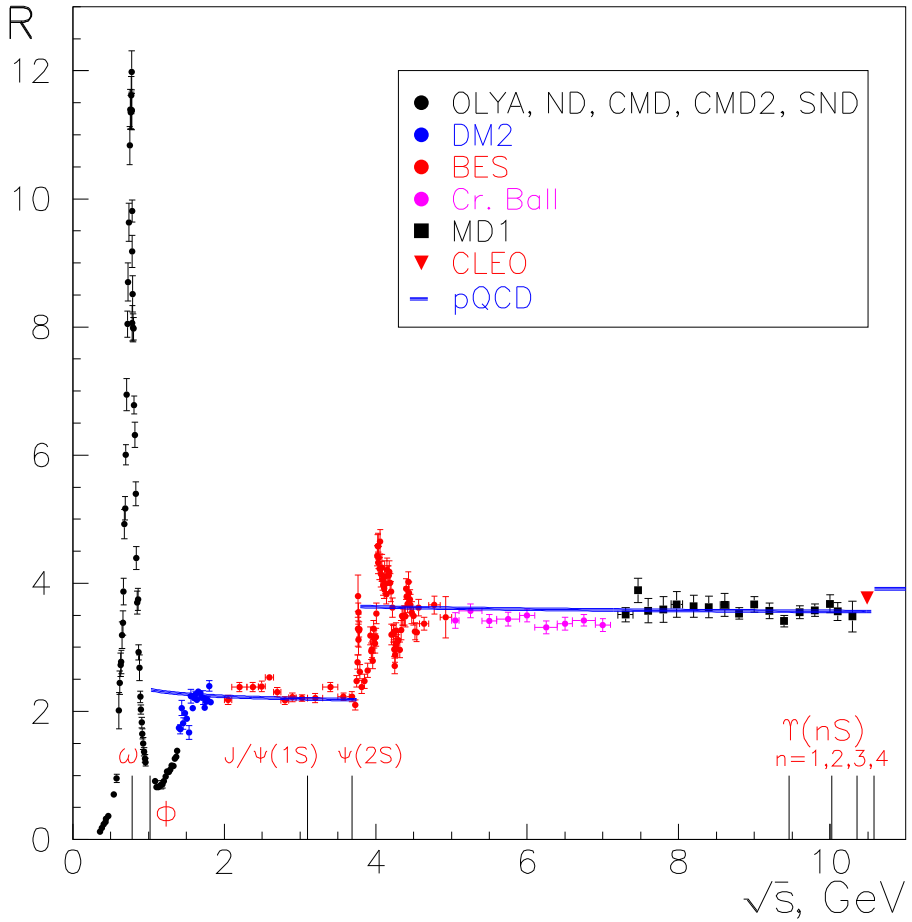
The uncertainty of $a^{\rm had}$ dominates the theoretical error!

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

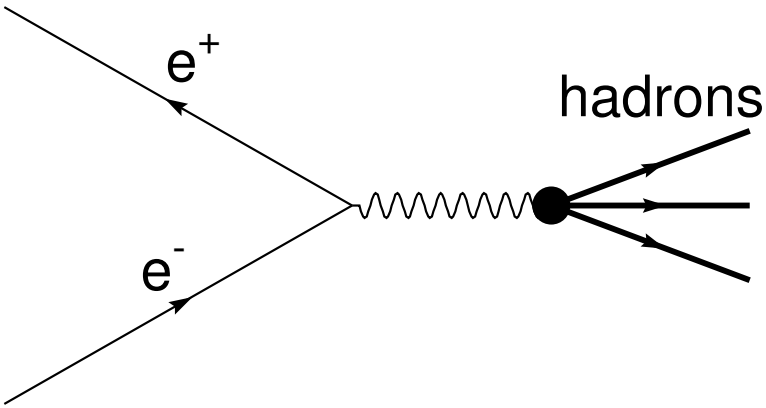
$1/s^2$ emphasizes low energies, particularly $e^+e^- \to \pi^+\pi^-$.

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

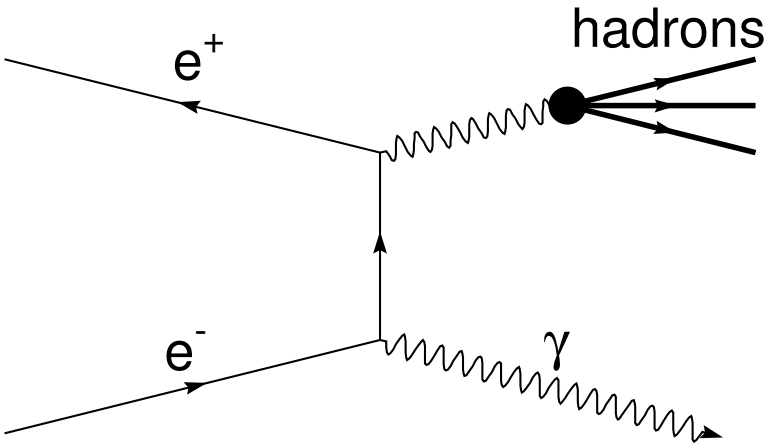
# $R$ Measurements below 10 GeV



# Scan and ISR




Scan

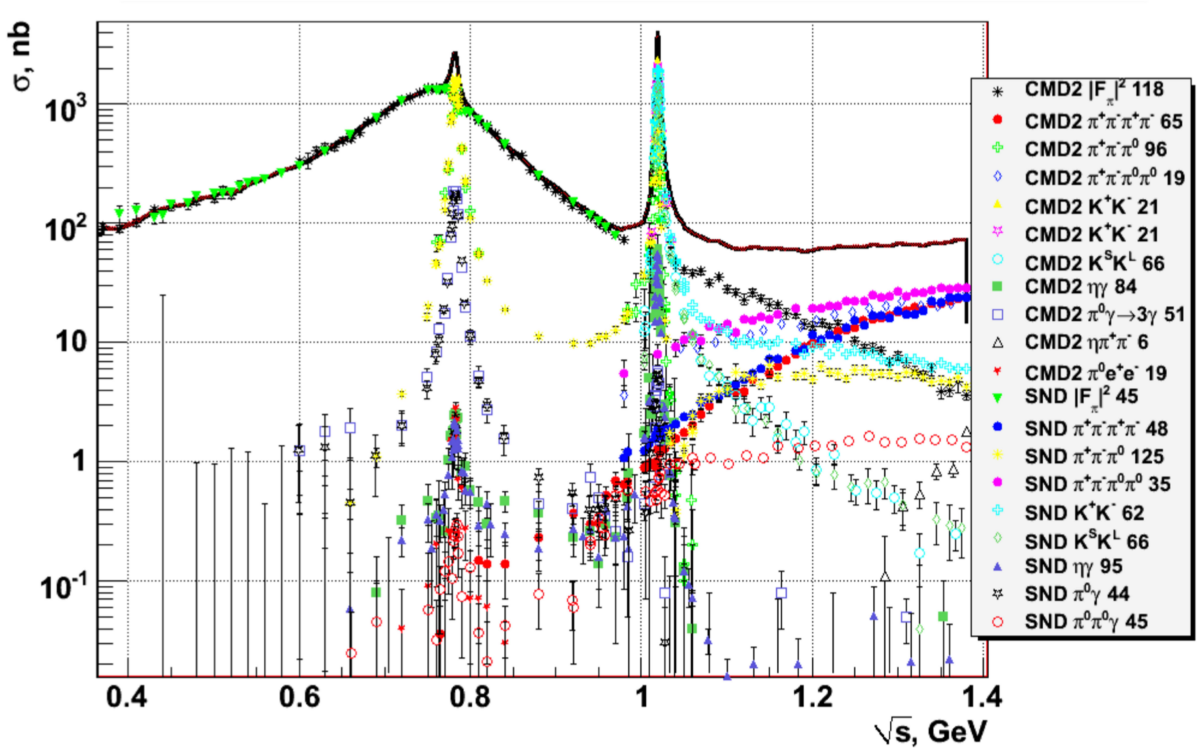



ISR

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

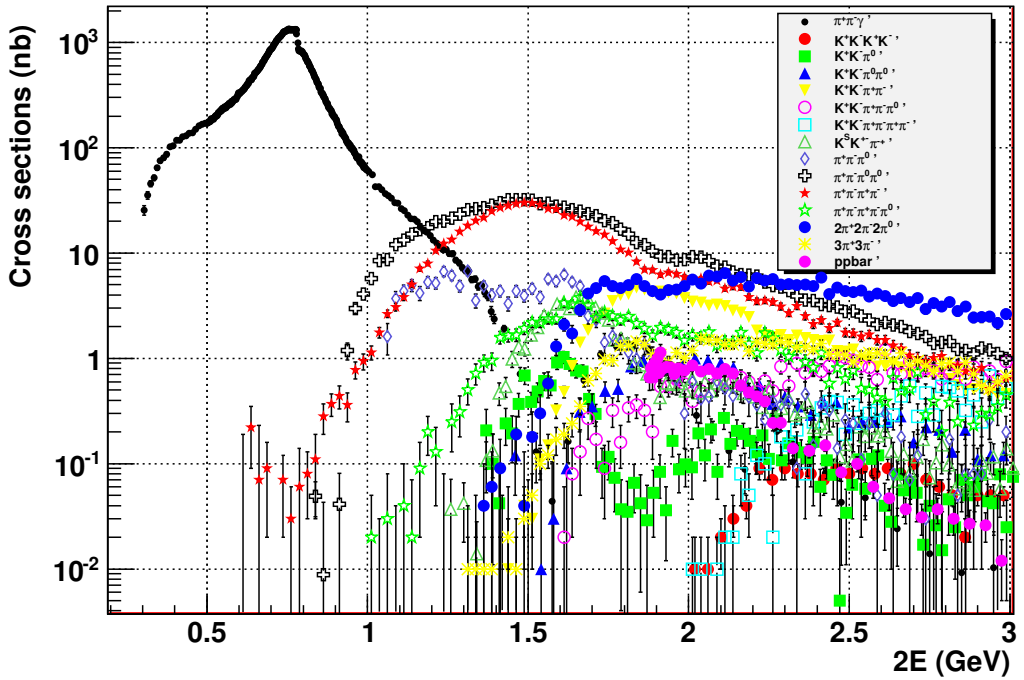
# Current Status of Exclusive Measurements (Scan) – I




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

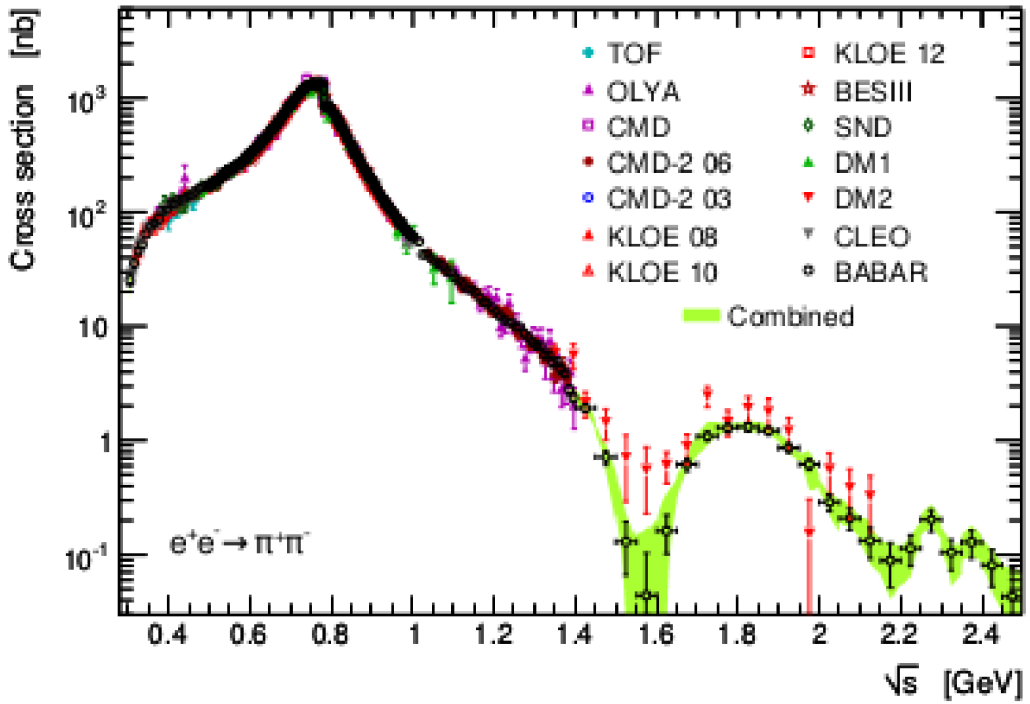
# Current Status of Exclusive Measurements (ISR) – II




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

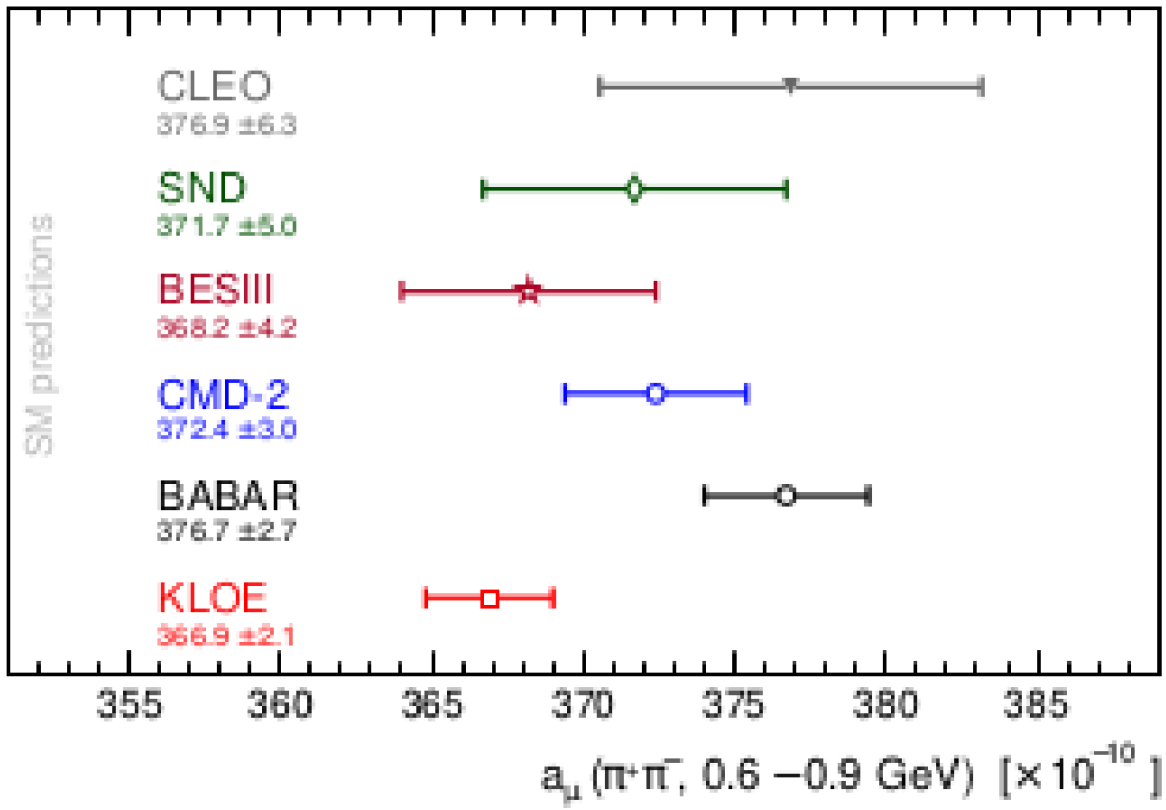
Contributions came from KLOE; also expected from BESIII and BelleII in the future, talks of Ch. Redmer and T. Iijima

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



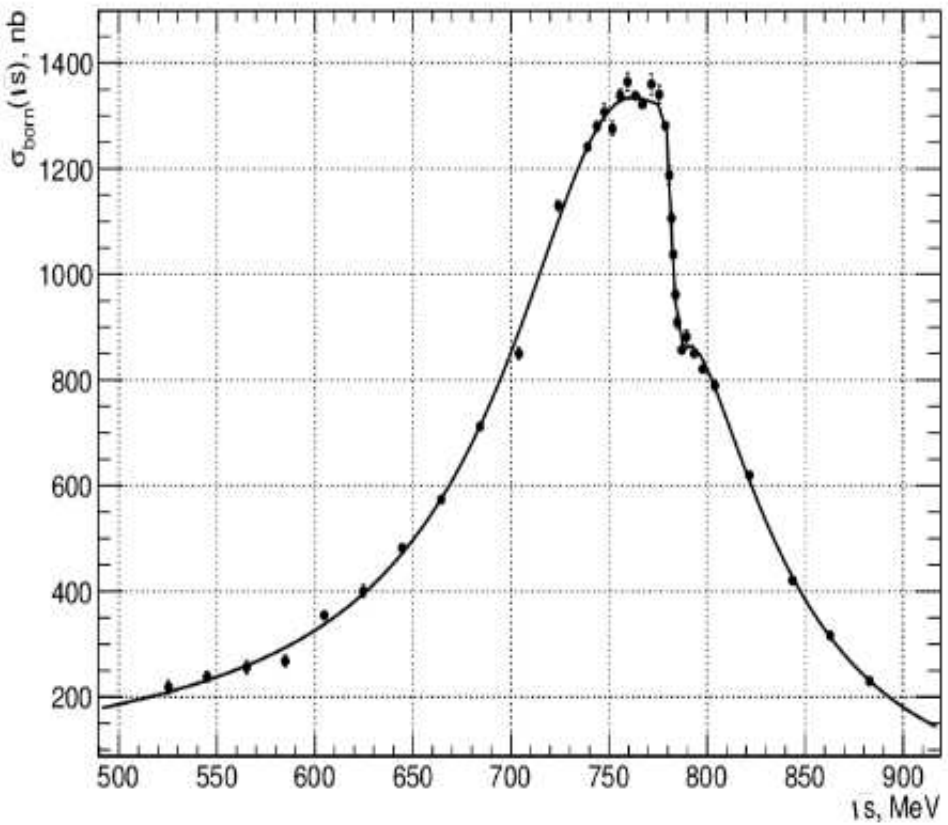

The general picture looks fine, details make life not easy

# Contributions to $a_\mu^{\mathrm{LO},2\pi}$ between 0.6 and 0.9 GeV




New results from SND, CMD-3 and BESIII expected,
work is in progress on the full data sample of BaBar

## $e^+e^- \to \pi^+\pi^-$ at VEPP-2000

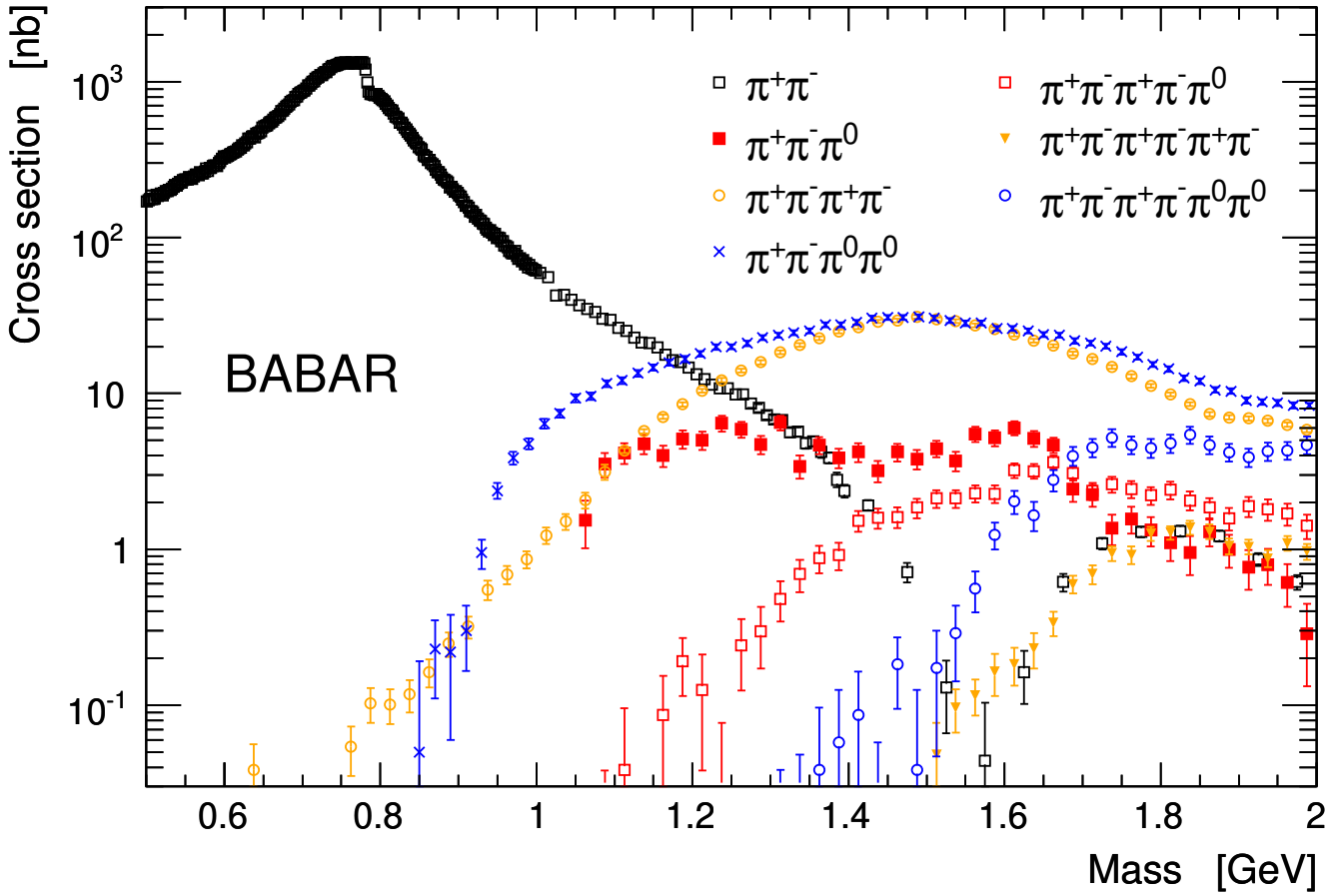



Data samples of SND and CMD-3 are already larger than at BaBar

The syst. uncertainty of SND is 0.8% at the $\rho$, 0.9% below 0.6 GeV

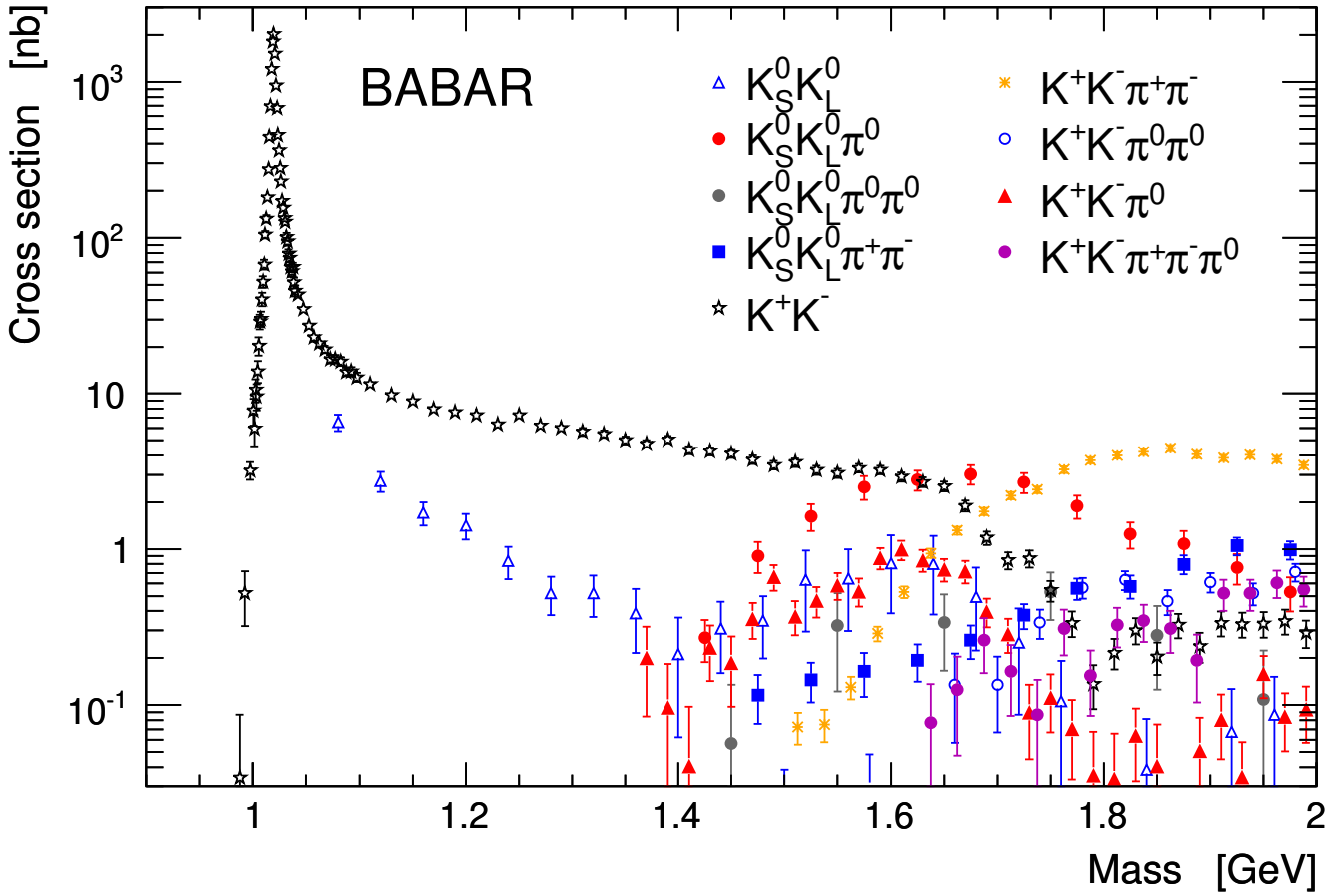
For CMD-3: 0.6% at the $\rho$, 0.9% below; talks of I.Logashenko and A. Kupich

# BaBar Results on the Processes with Pions



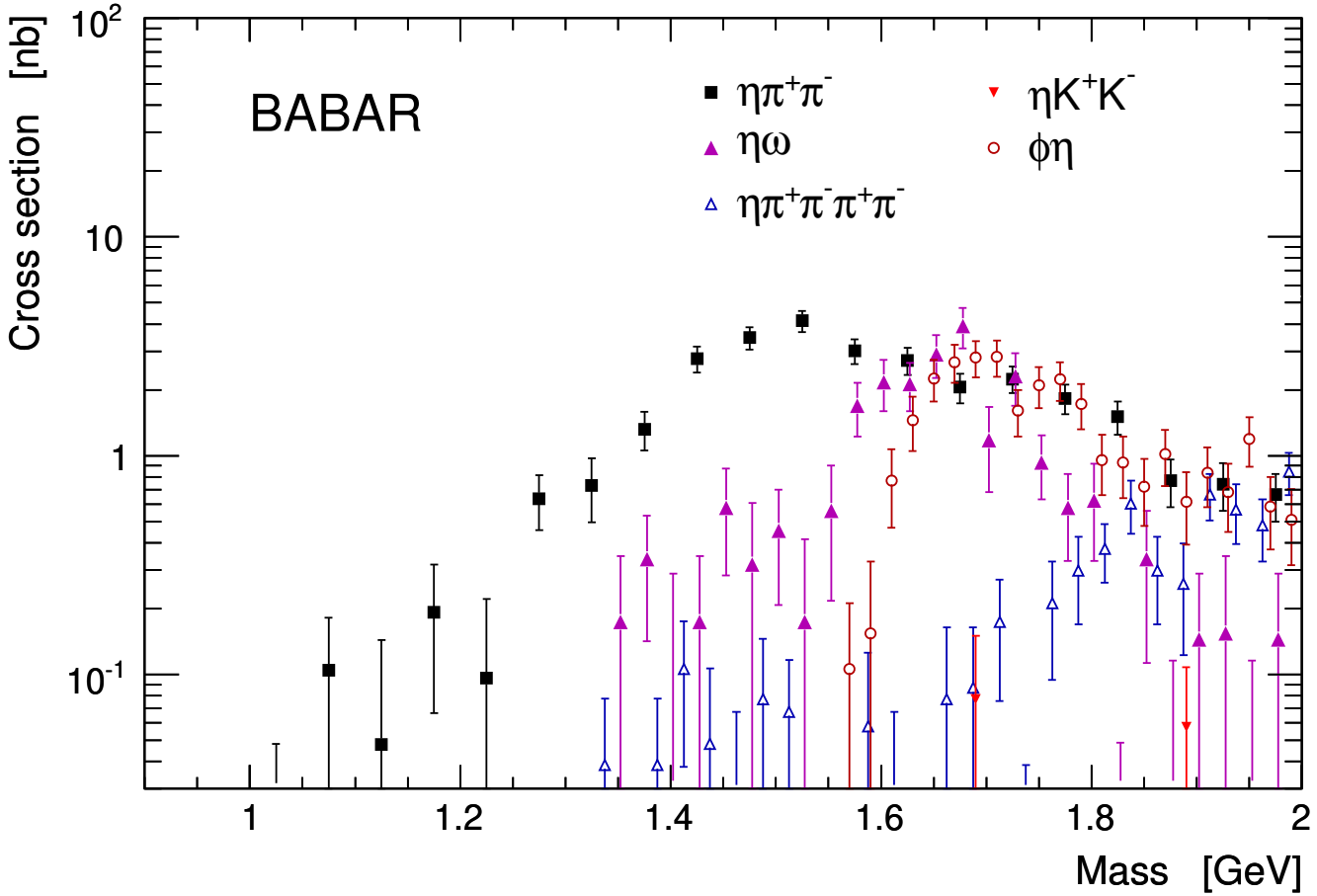

Systematic uncertainties range from 0.5% for $\pi^+\pi^-$ to (6-8)% for $6\pi$

# BaBar Results on the Processes with Kaons



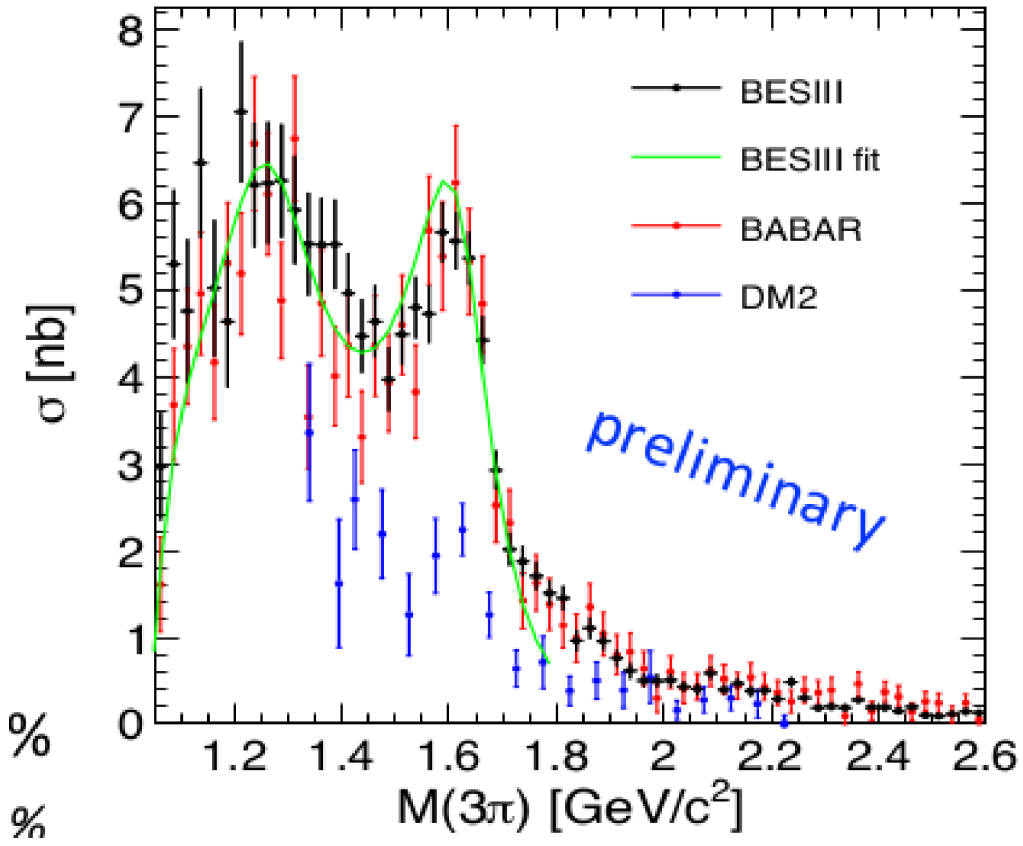

Systematic uncertainties range from 0.7% for $K^+K^-$ to (6-8)% for $K\bar{K}n\pi$

# BaBar Results on the Processes with $\eta$ Mesons



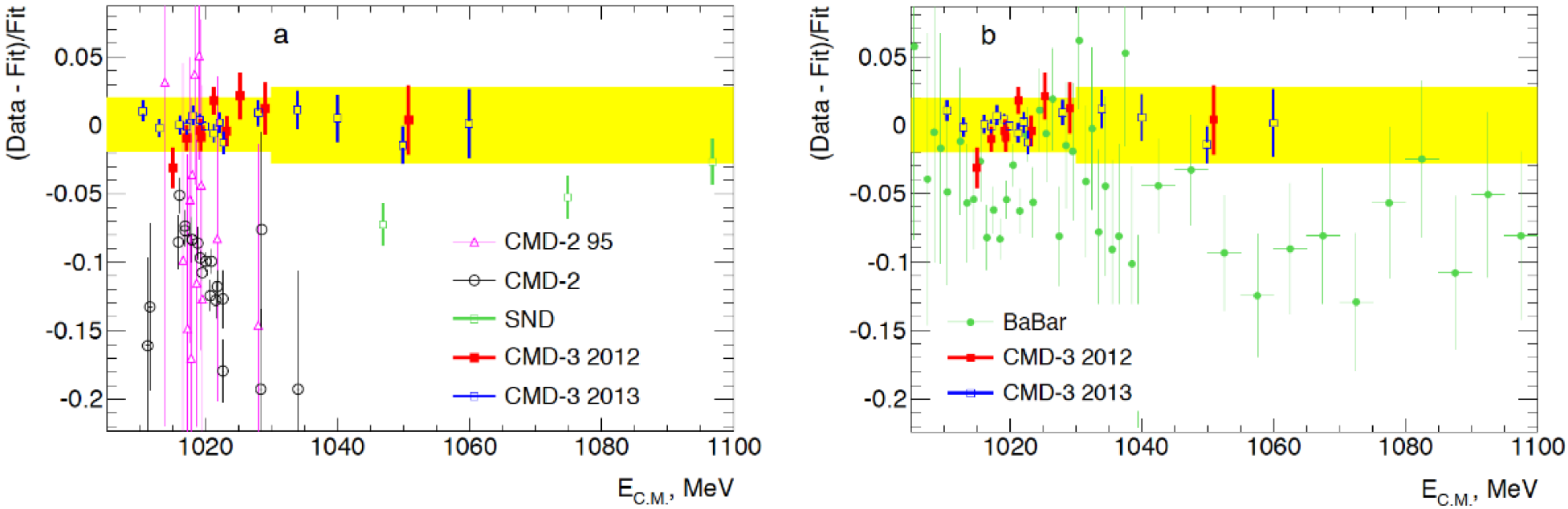

Systematic uncertainties range from for 4.5% to 12%

## $e^+e^- \to \pi^+\pi^-\pi^0$ after BESIII



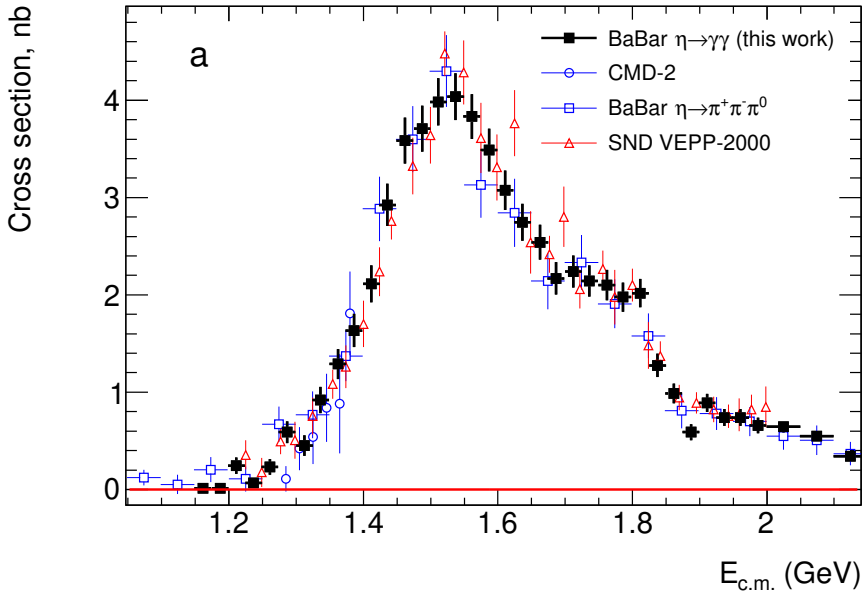

Are BESIII points higher than BaBar? See Ch. Redmer's talk

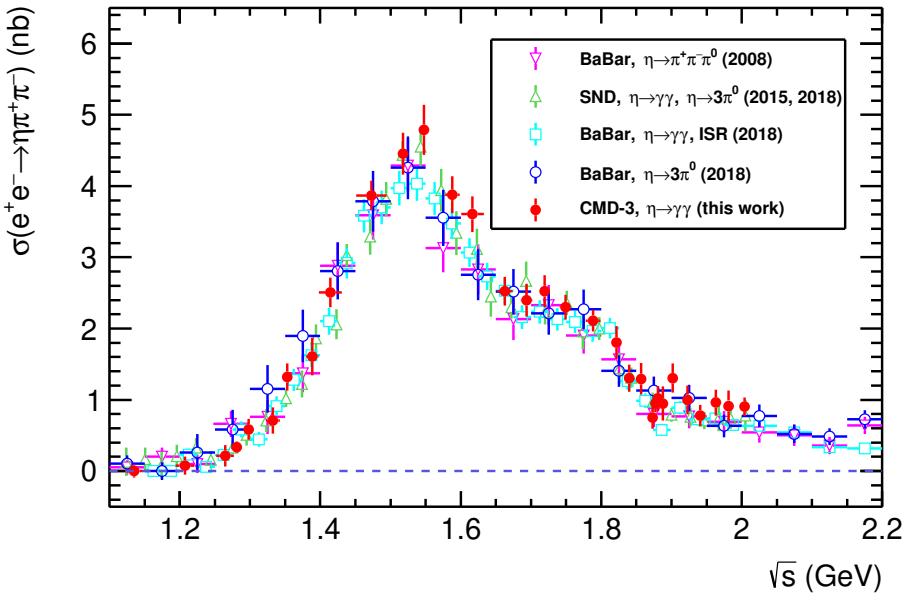
## $e^+e^- \to K^+K^-$ after CMD-3




The CMD-2/CMD-3 deviations can be due to trigger corections,
What about CMD-3 vs. BaBar? See I. Logashenko's talk

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




BaBar – PRD 97, 052007 (2018) CMD-3 – Phi to Psi, 2019

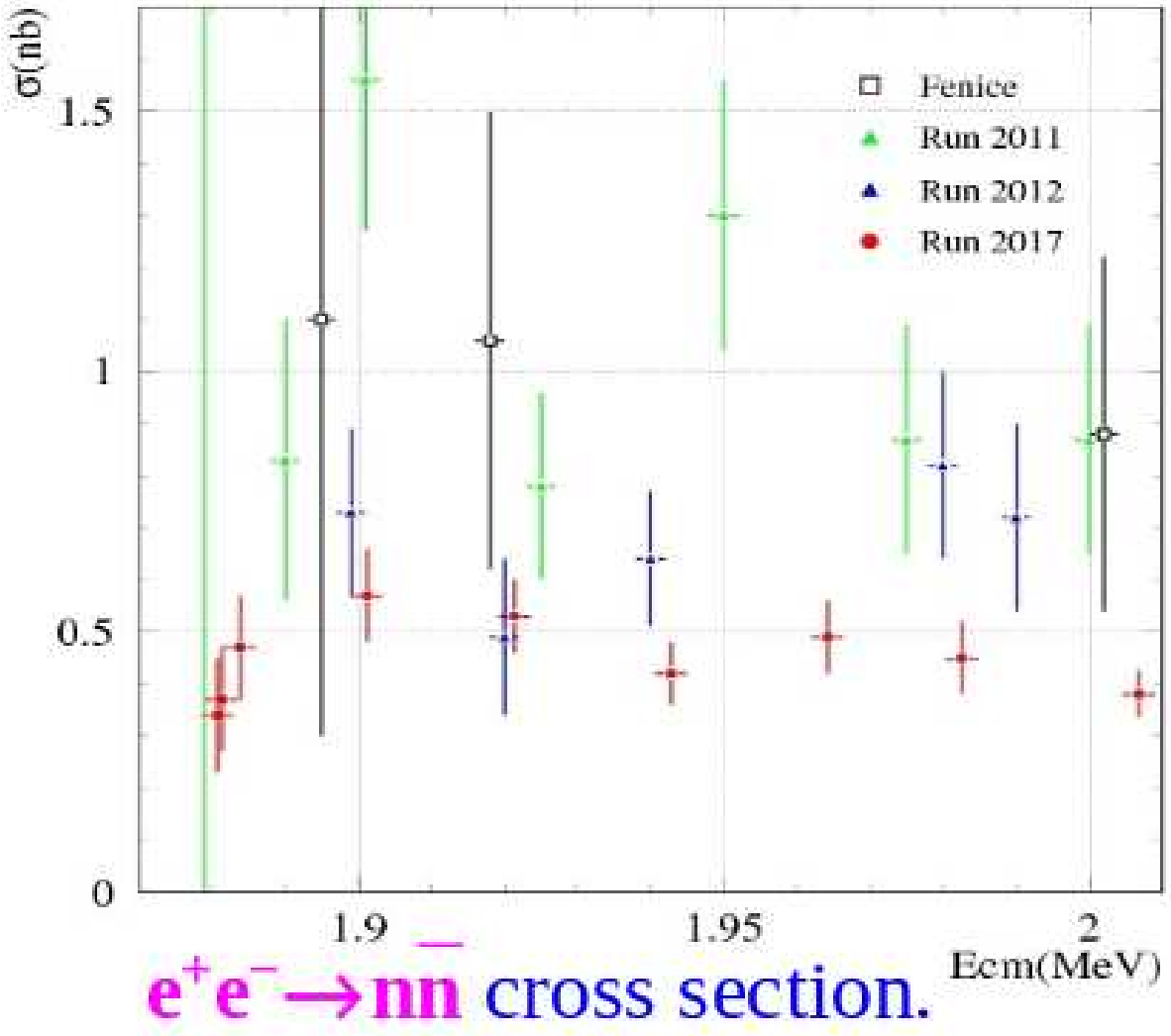
First observation of the $\rho(1700)$ in $\eta\pi^+\pi^-$

CMD-3 is consistent with BaBar and has better precision

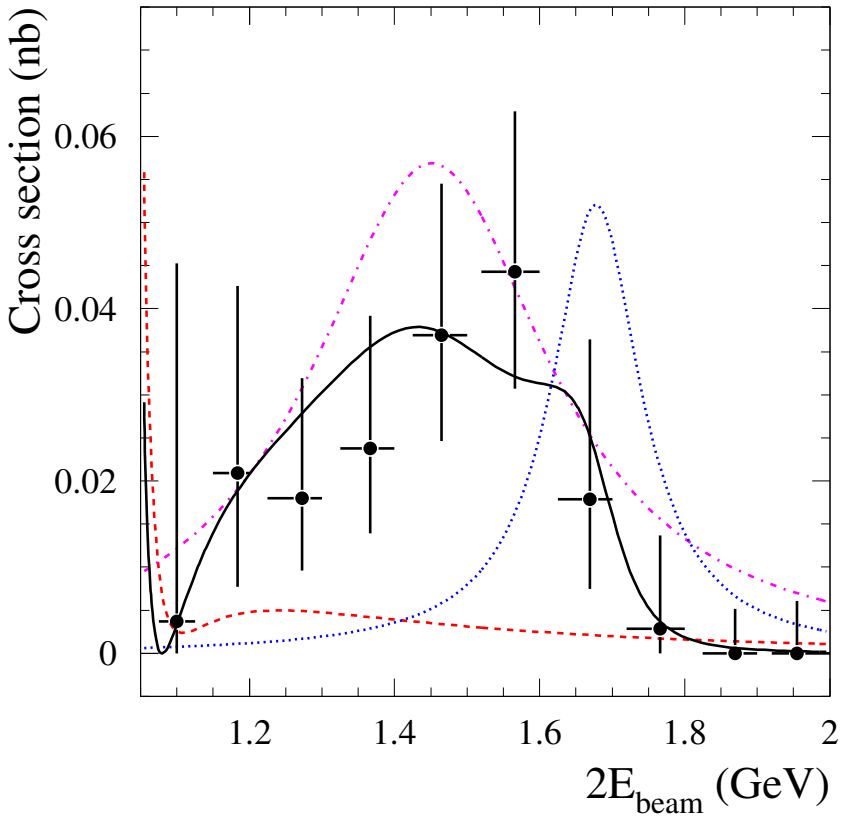
## What Is Missing?

- Final states with neutrons
- Purely neutral final states
- Final states with many $\pi^0$ and $\eta$ mesons
- High-multiplicity final states
- Final states with kaons
- Do we understand completely radiative corrections?

## $e^+e^- \to n\bar{n}$ at SND



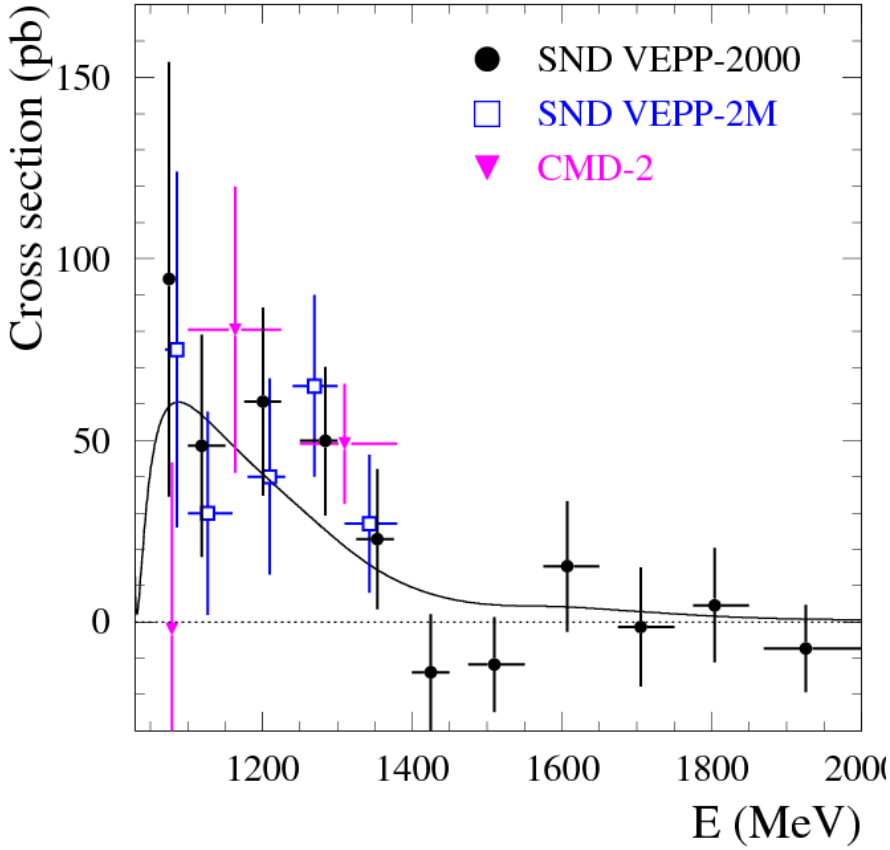
# $e^+e^- \to \eta\gamma$ at SND




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)

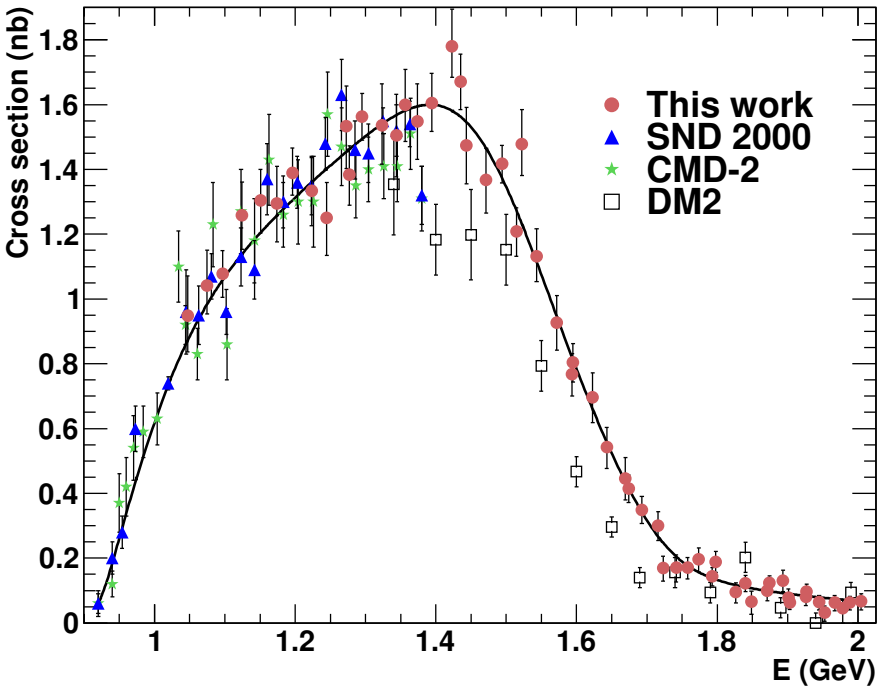
# $e^+e^- \to \pi^0\gamma$ at SND




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

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

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




10.2k $5\gamma$ events, the systematic uncertainty varying from 2.7% to 5.2%

CVC test with $\mathcal{B}(\tau^- \to \omega\pi^-\nu_\tau)$: $(1.87 \pm 0.02 \pm 0.07)\%_{\rm CVC}$ $(1.95 \pm 0.06)\%_{\rm WA16}$

M.N. Achasov et al., Phys. Rev. D94 (2016) 112001

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

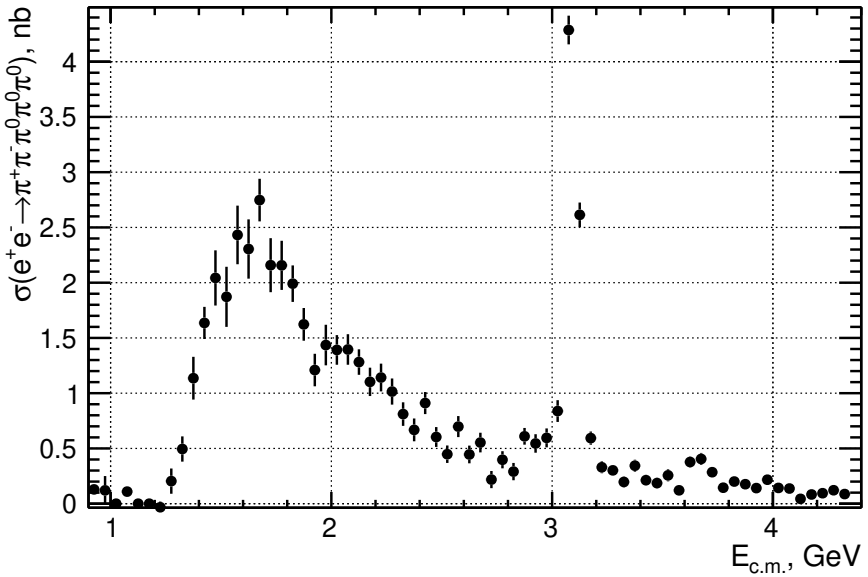
CMD-2 performed a study of $e^+e^- \to \omega\pi^0 \to \pi^0\pi^0\gamma$ and found no signal of direct production of $\pi^0\pi^0\gamma,\ \eta\pi^0\gamma$

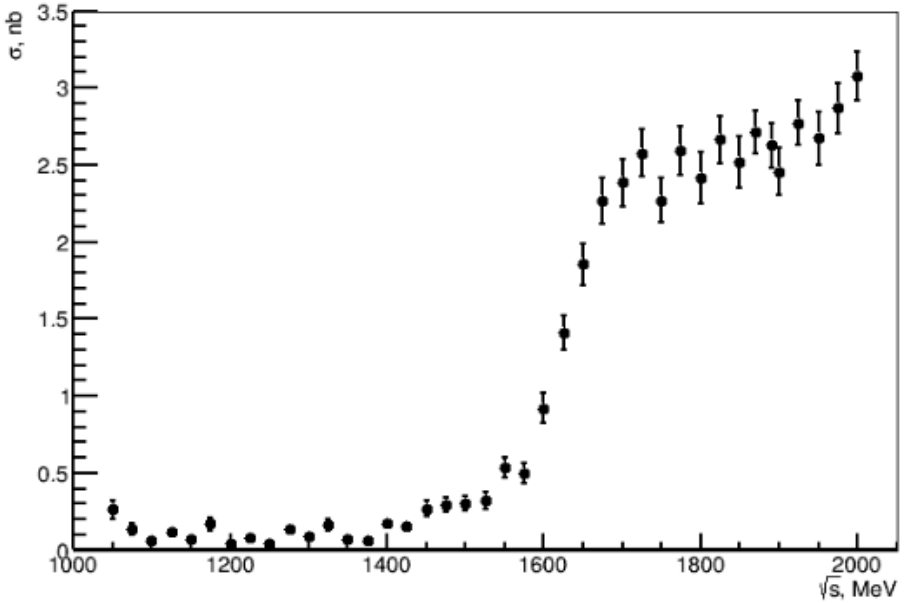
| $\sqrt{s}$, MeV | $\sigma(\pi^0\pi^0\gamma)$, nb | $\sigma(\eta\pi^0\gamma)$, nb |
|---|---|---|
| 920-1004 | 0.07 | 0.13 |
| 1034-1200 | 0.11 | 0.06 |
| 1200-1300 | 0.09 | 0.14 |
| 1300-1380 | 0.07 | 0.10 |

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



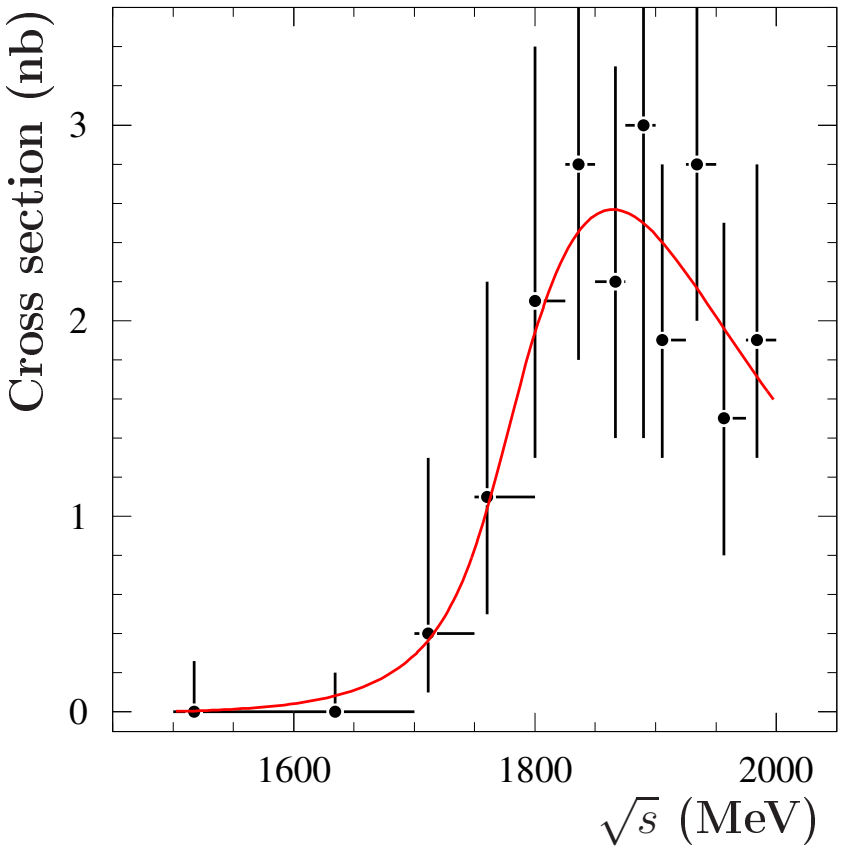

$e^+e^- \to \pi^+\pi^- 4\pi^0$ cross section.

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

## $e^+e^- \to \omega\eta\pi^0$ at SND

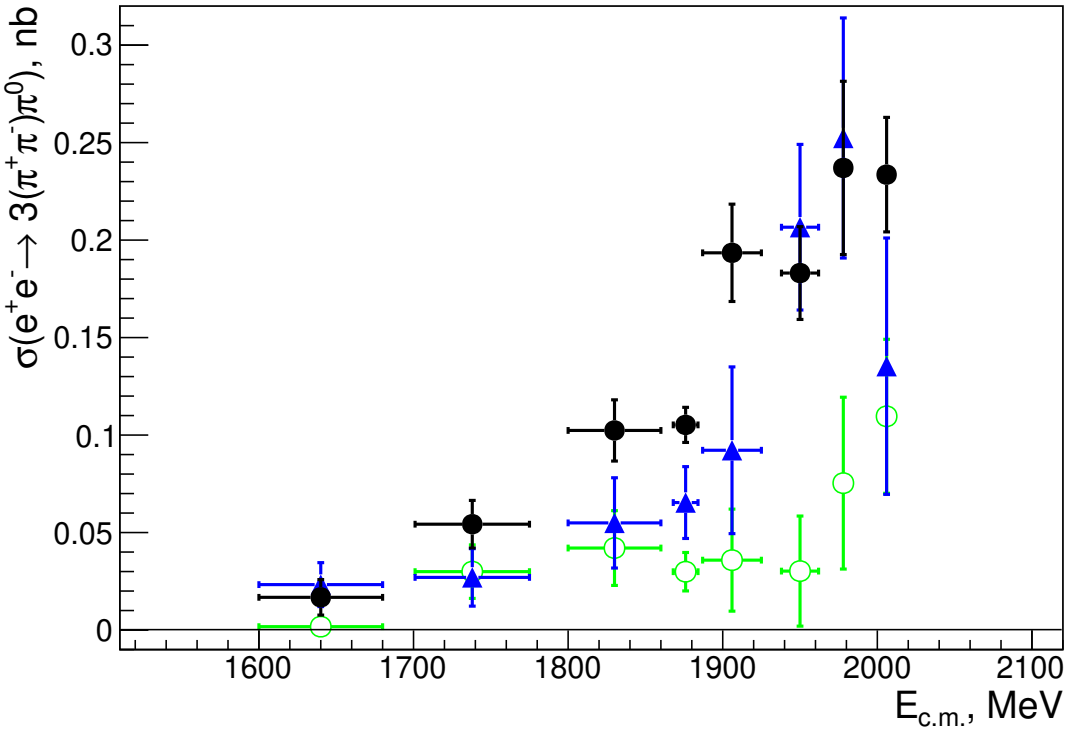



First ever observation with 62 $\pi^0\pi^0\gamma\eta$ events

The $\omega a_0(980)$ mechanism dominates

M.N. Achasov et al., Phys. Rev. D94 (2016) 032010

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

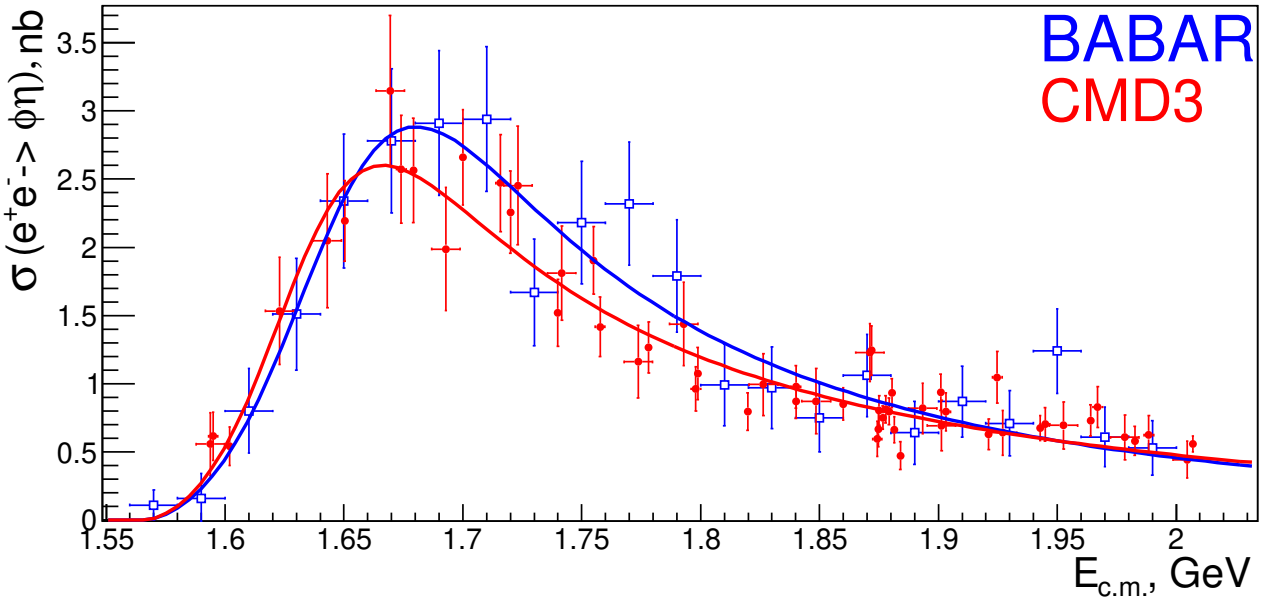



First ever measurement, 56.7 pb$^{-1}$, 632 events,

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

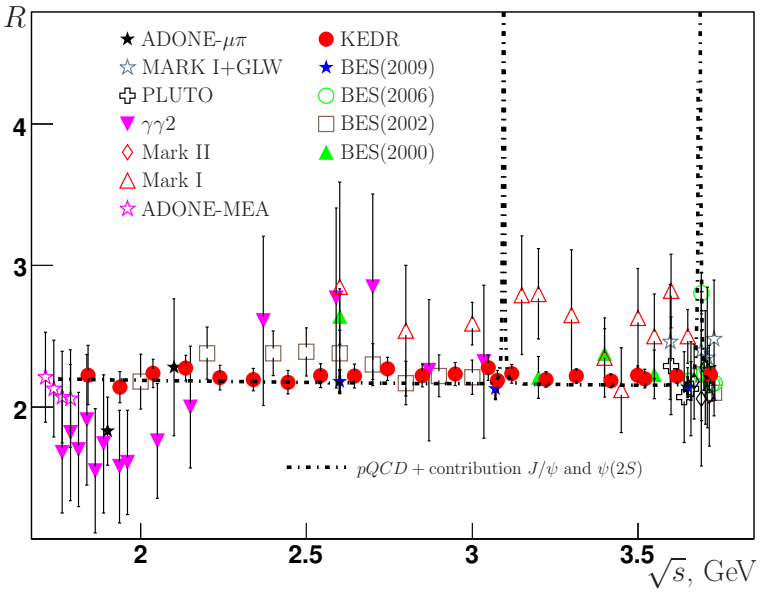
R.R. Akhmetshin et al., Phys. Lett. B792, 419 (2019)

## $e^+e^- \to \eta K^+ K^-$ at CMD-3




More than 3.5k events, systematic error of 5%

# $R$ 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 at KEDR

Results from BESIII between 2 and 4.6 GeV are awaited

# Conclusions

- VEPP-2000 in Novosibirsk is running smoothly with CMD-3 and SND, their accuracy is comparable or better than in ISR measurements
- The goals are 0.35% for $\pi^+\pi^-$ and 3% for multibody modes
- Below 2 GeV progress (a factor of 2-3) expected in exclusive $\sigma$'s due to scans in Novosibirsk and ISR from BaBar, 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 $(g_\mu - 2)/2$
- Can we expect a breakthrough in using $\tau$ data?
- 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?