HVP DR Experimental Input: Status and Outlook

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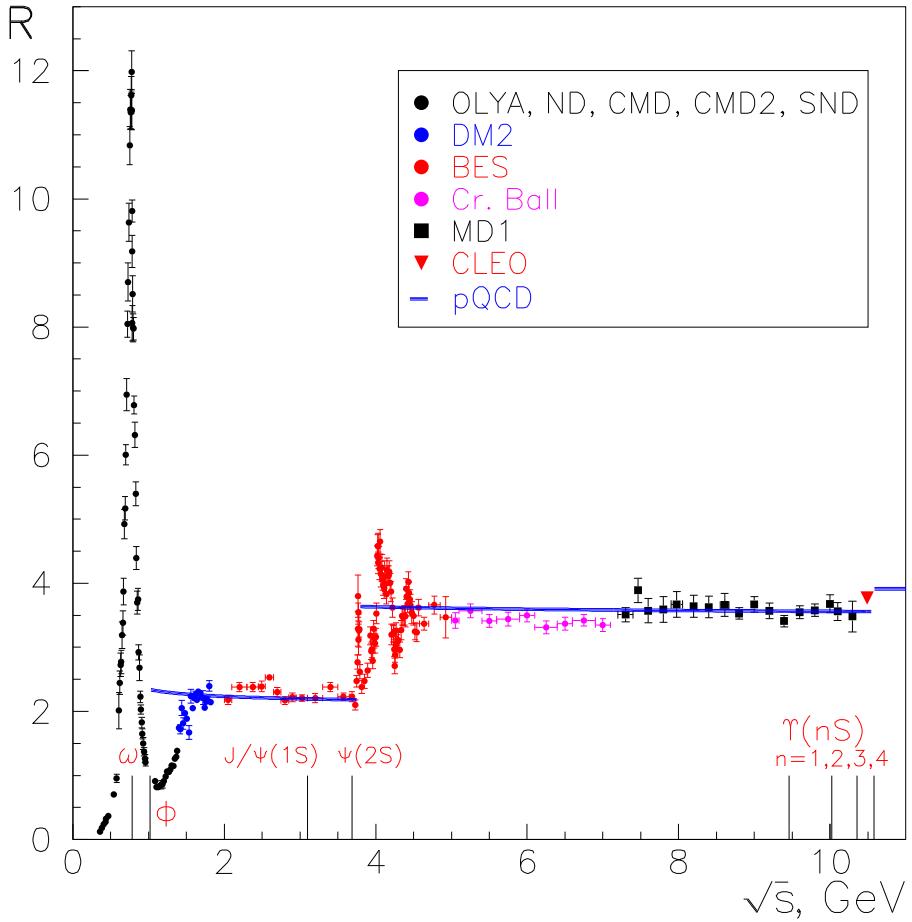
Outline

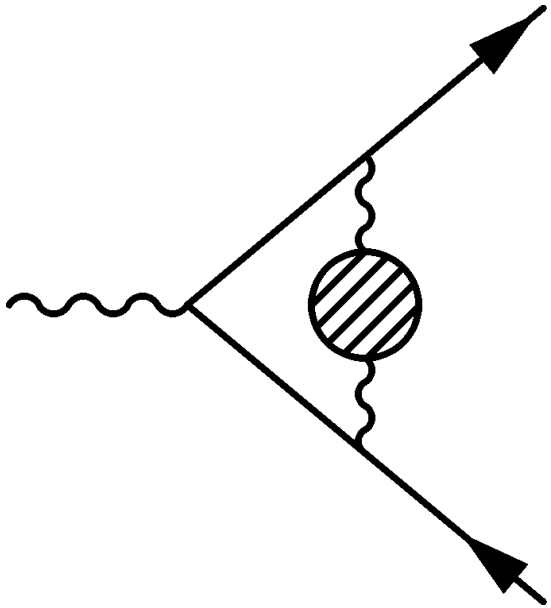
1. General
2. ISR measurements
3. VEPP-2000 (E. Solodov's talk)
4. Conclusions

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

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

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

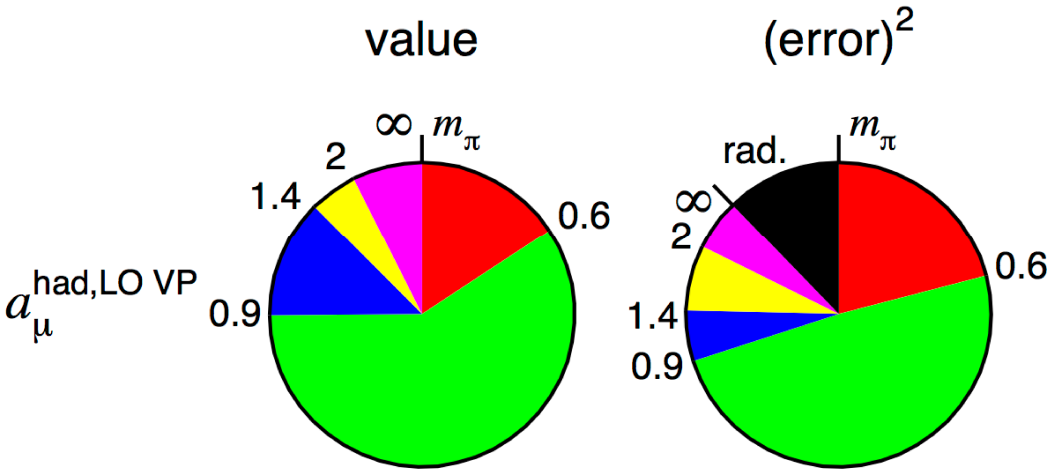
$1/s^2$ emphasizes low energies, particularly $e^+e^- \to \pi^+\pi^-$.

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)

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

A (The?) Famous Pie



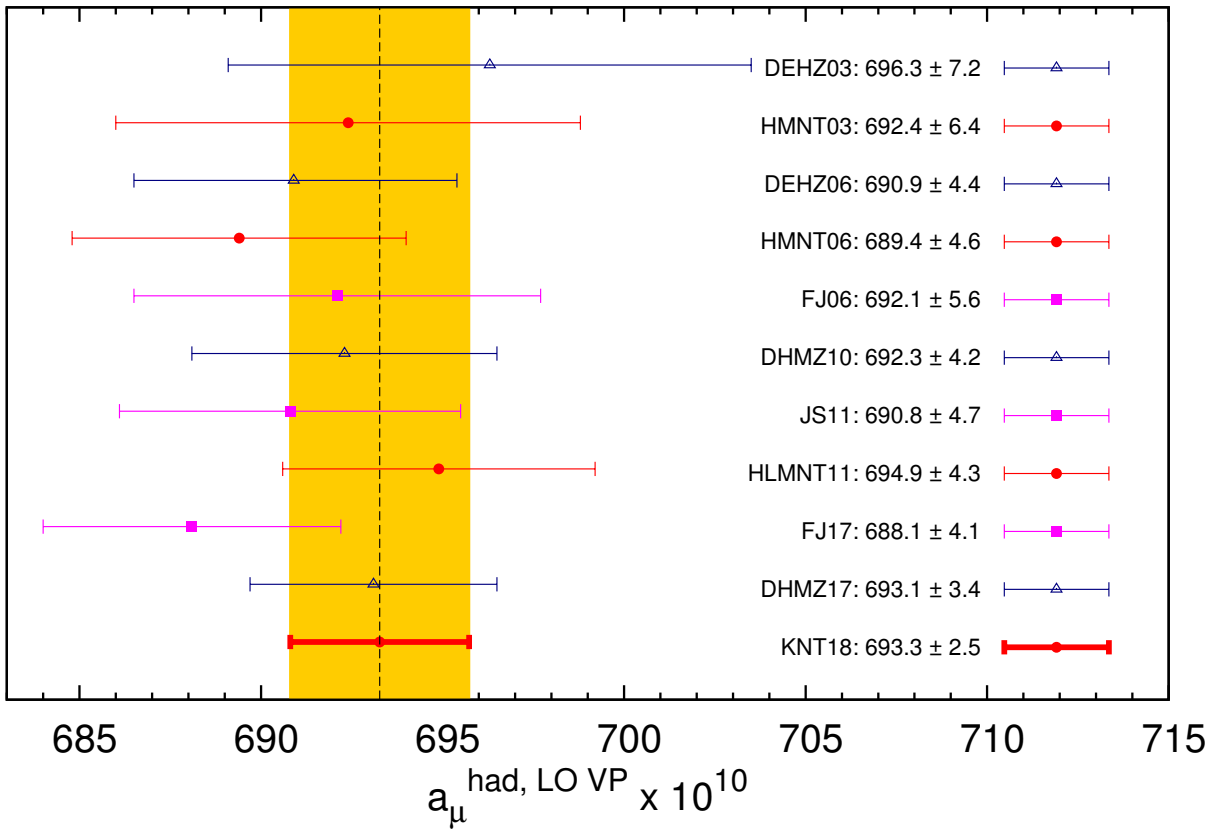
73% come from the $e^+e^- \to \pi^+\pi^-$ process

93% come from e^+e^- → hadrons below 2 GeV

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

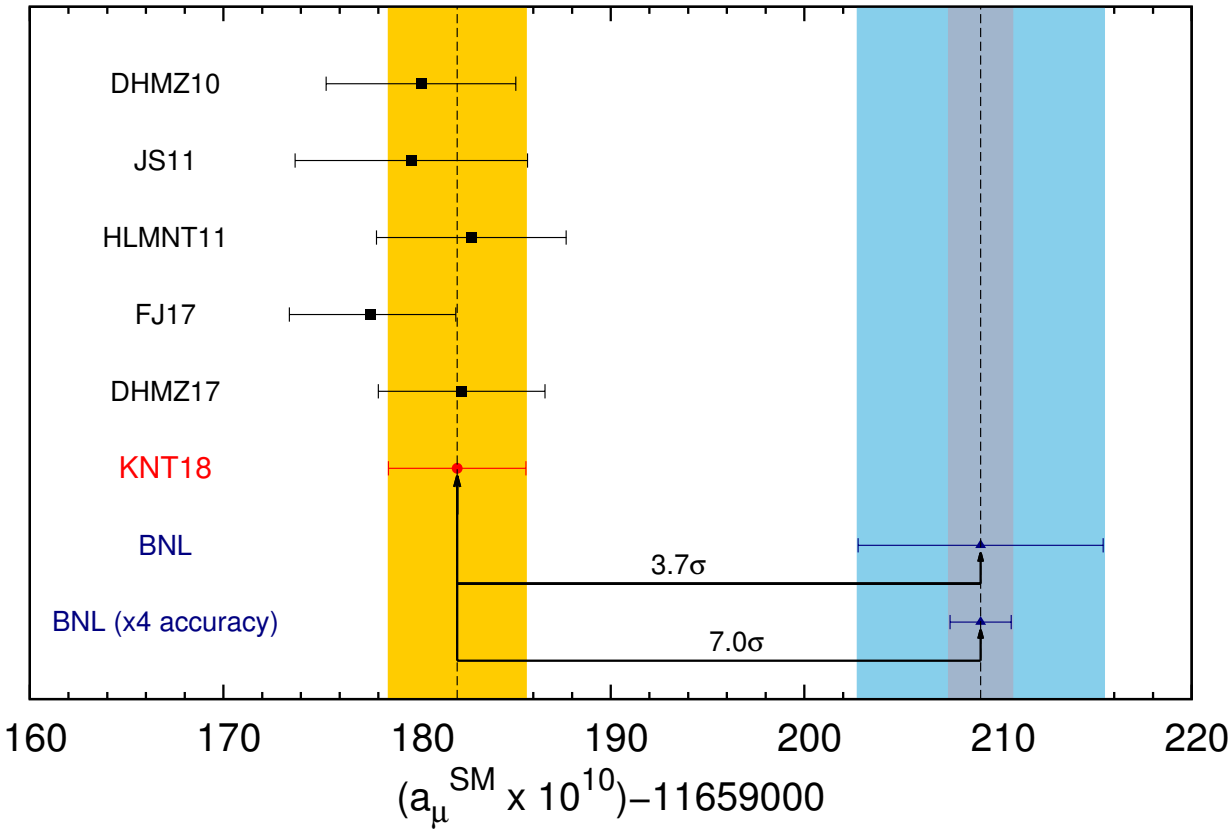
A. Keshavarzi, D. Nomura, T. Teubner, arXiv:1802.02995

Various Theoretical Calculations



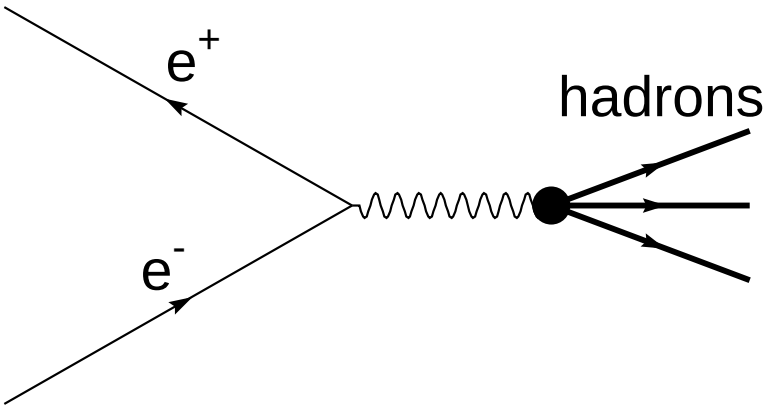
A. Keshavarzi, D. Nomura, T. Teubner, arXiv:1802.02995

Comparison of Theory and Experiment

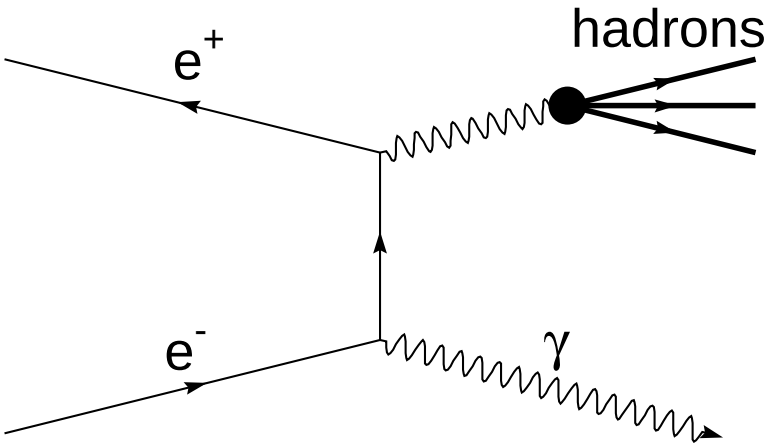


A. Keshavarzi, D. Nomura, T. Teubner, arXiv:1802.02995

Scan and ISR



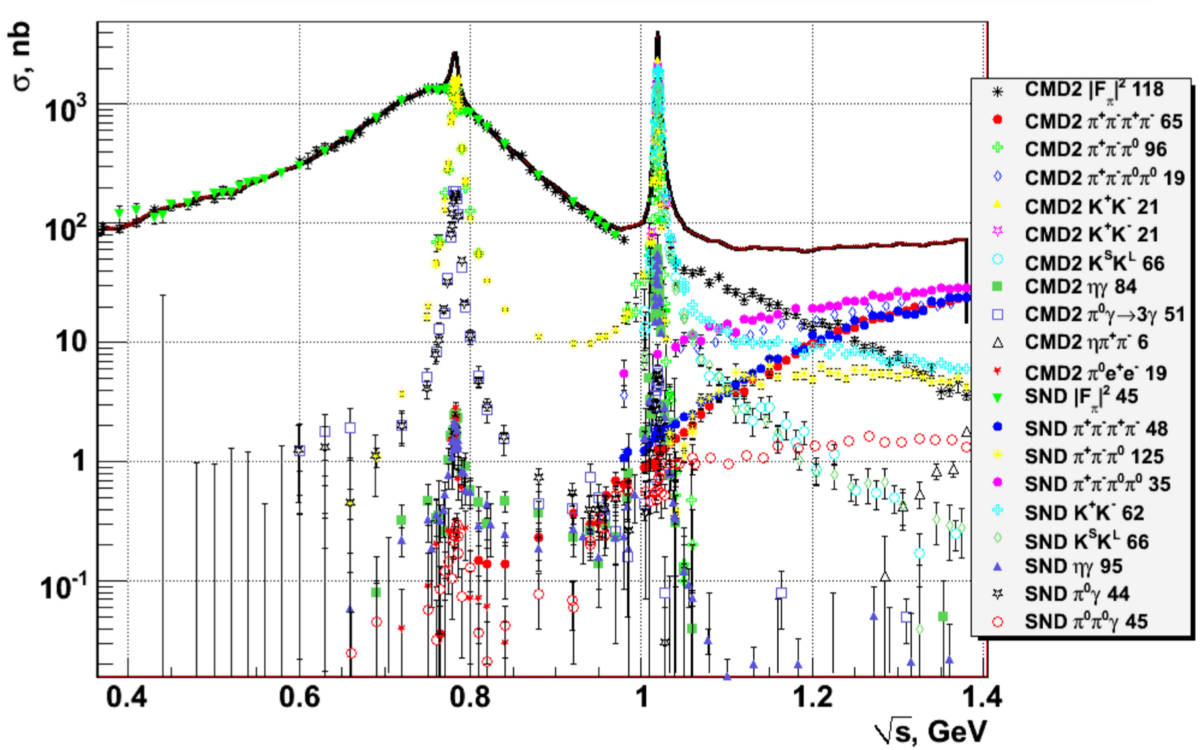
Scan



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

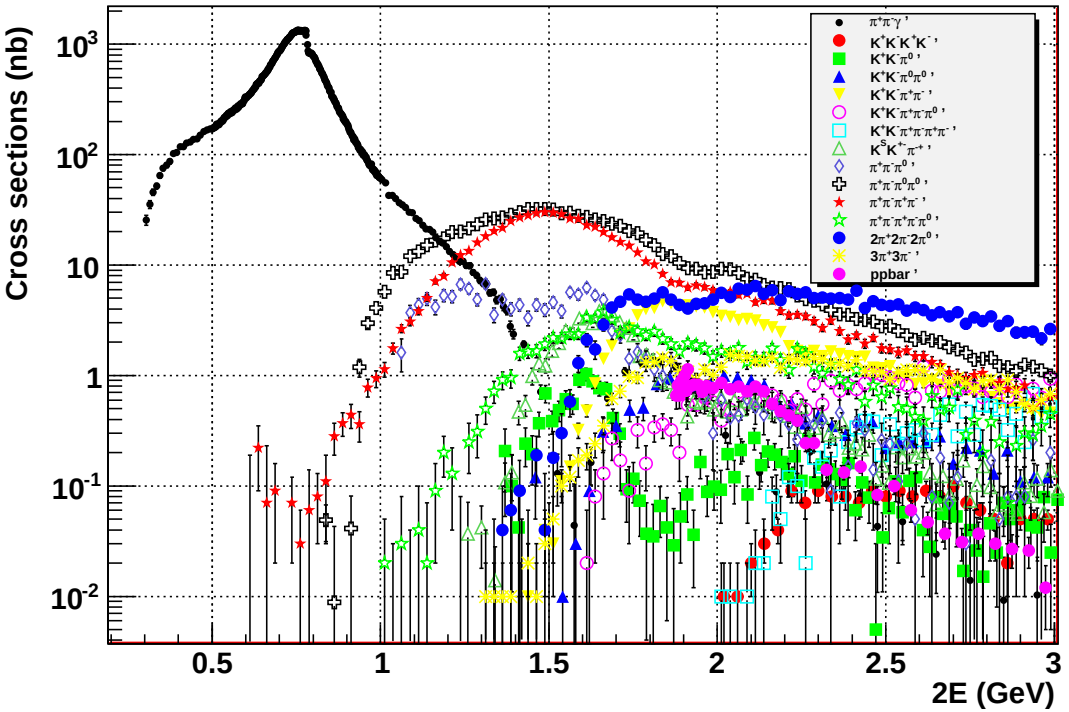
Current Status of Exclusive Measurements (Scan) – I



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

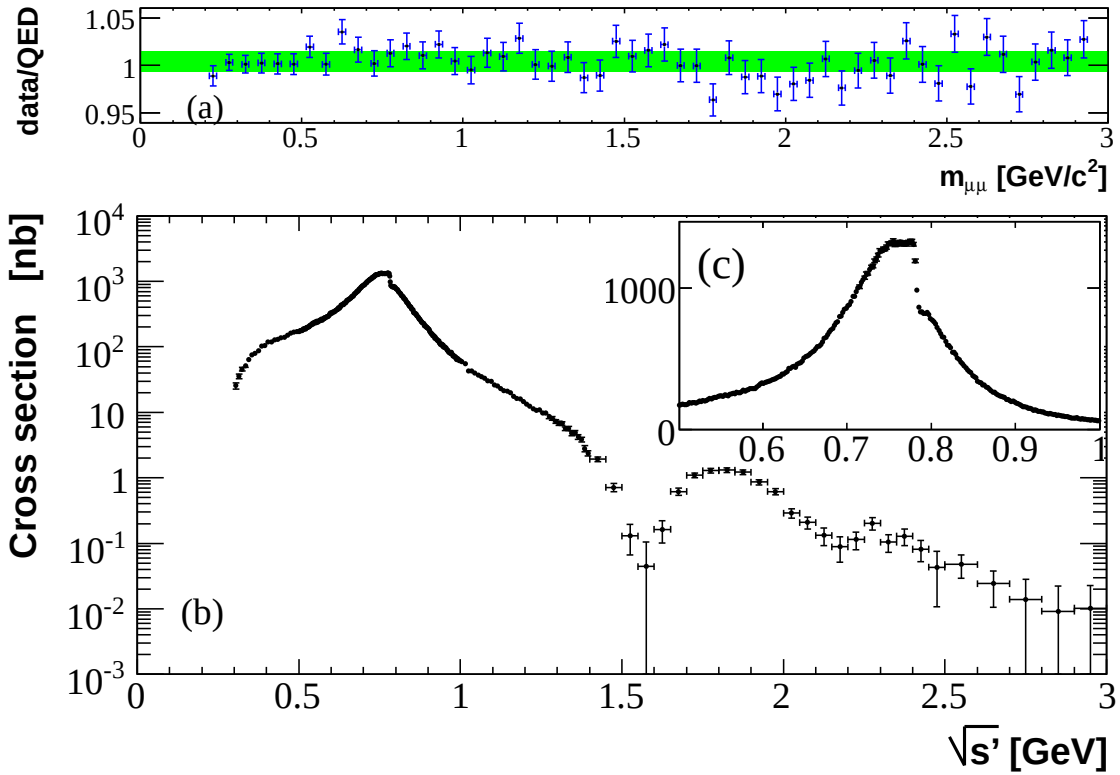
Current Status of Exclusive Measurements (ISR) – II



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

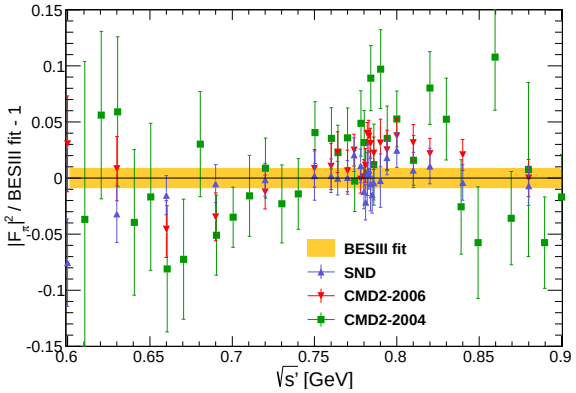


The systematic error near the ρ is 0.5%

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

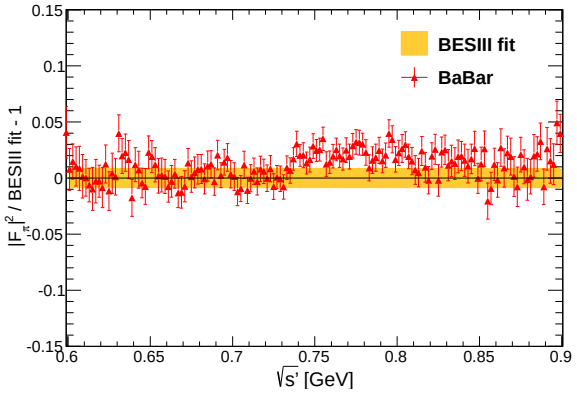
J.P. Lees et al., Phys. Rev. D86 (2012) 032013

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

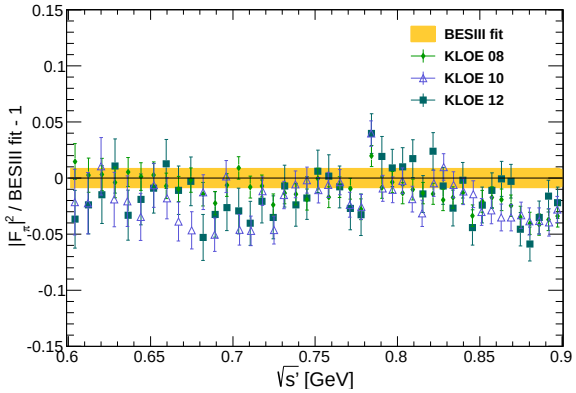


SND: JETP 103 (2006) 380

CMD-2: PLB 648 (2007) 28



BaBar: PRL 103 (2009) 231801



KLOE08: PLB 670 (2009) 285

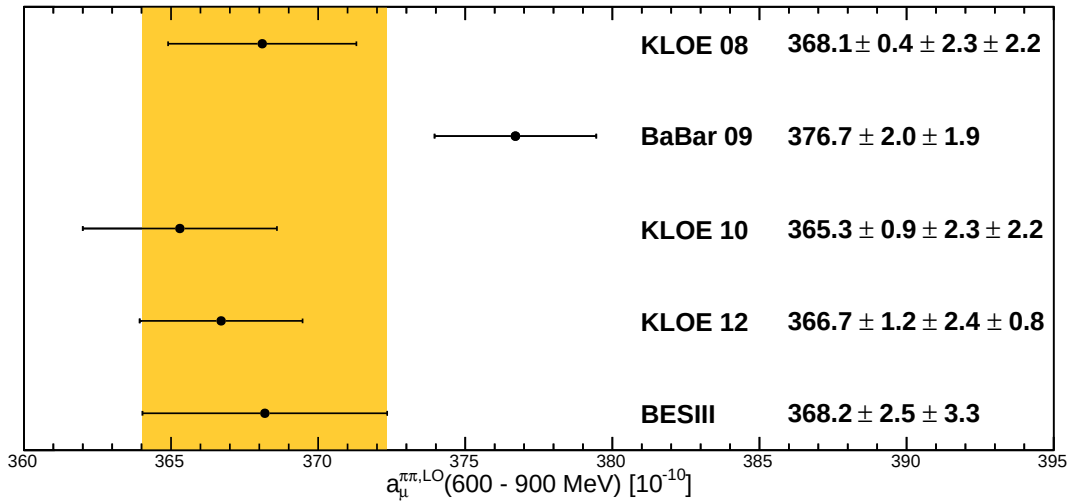
KLOE10: PLB 700 (2011) 102

KLOE12: PLB 720 (2013) 336

Agreement between different ISR results is far from perfect

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

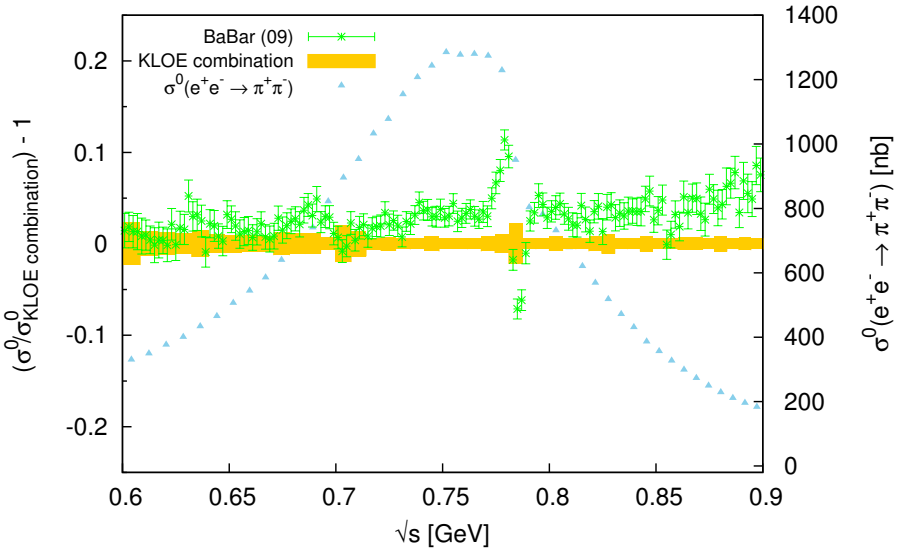
$e^+e^- \to \pi^+\pi^-$ (BESIII Comparison) – II

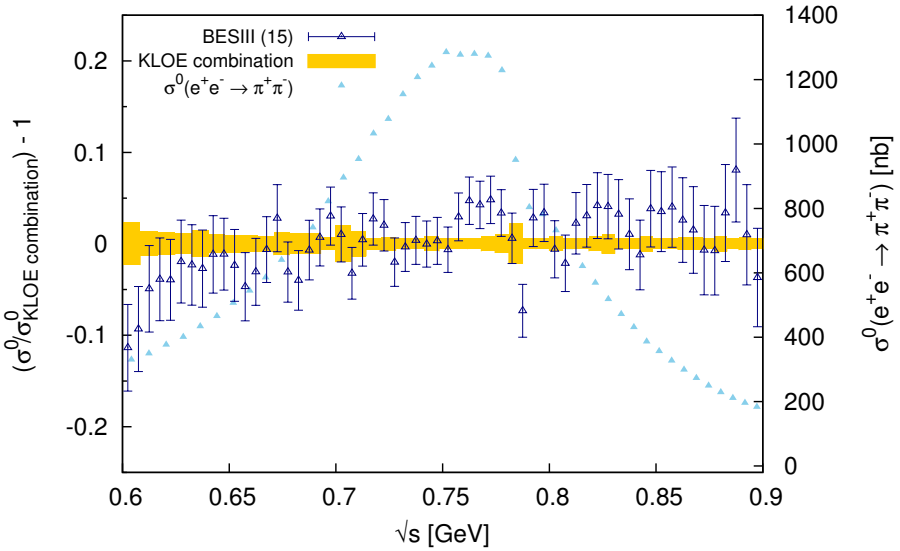


Some tension between KLOE/BESIII and BaBar?

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

$e^+e^- \to \pi^+\pi^-$ (KLOE Combination) – I

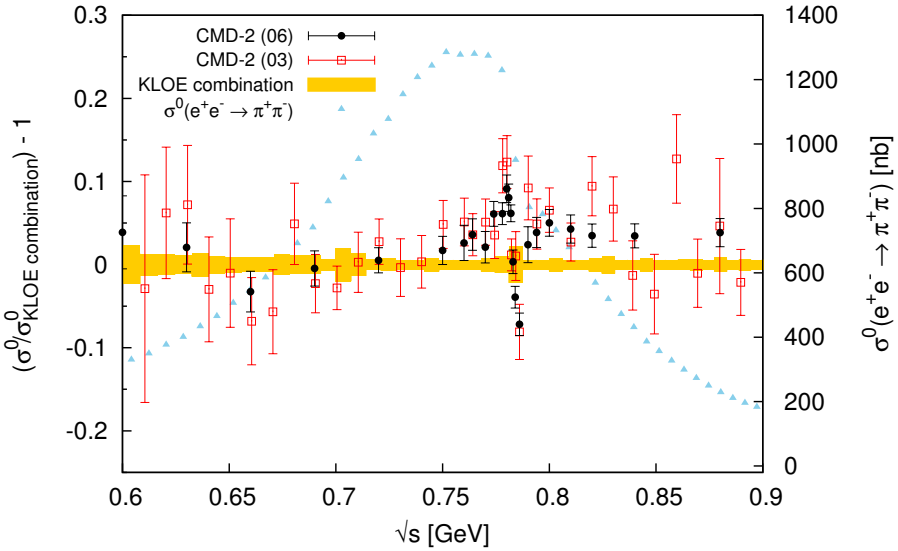


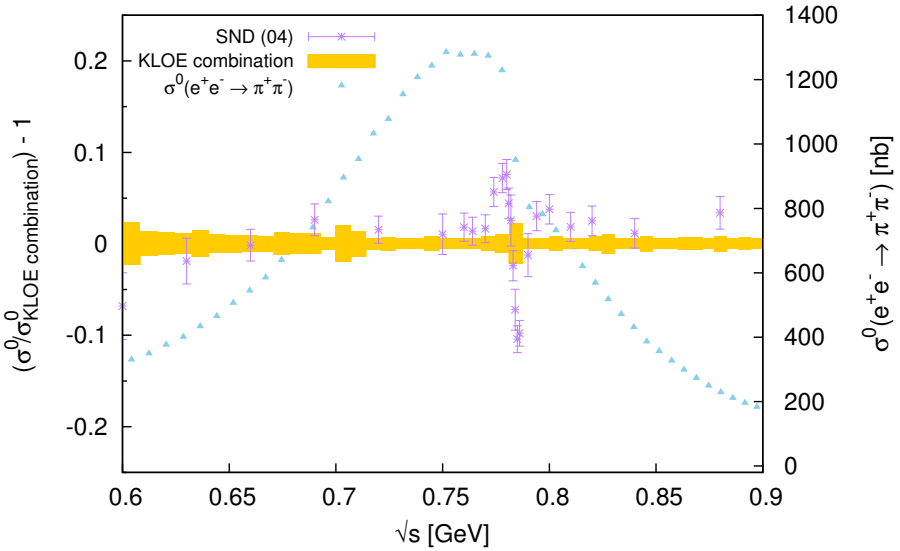


Three KLOe measurements combined taking into account correlations

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

$e^+e^- \to \pi^+\pi^-$ (KLOE Combination) – II

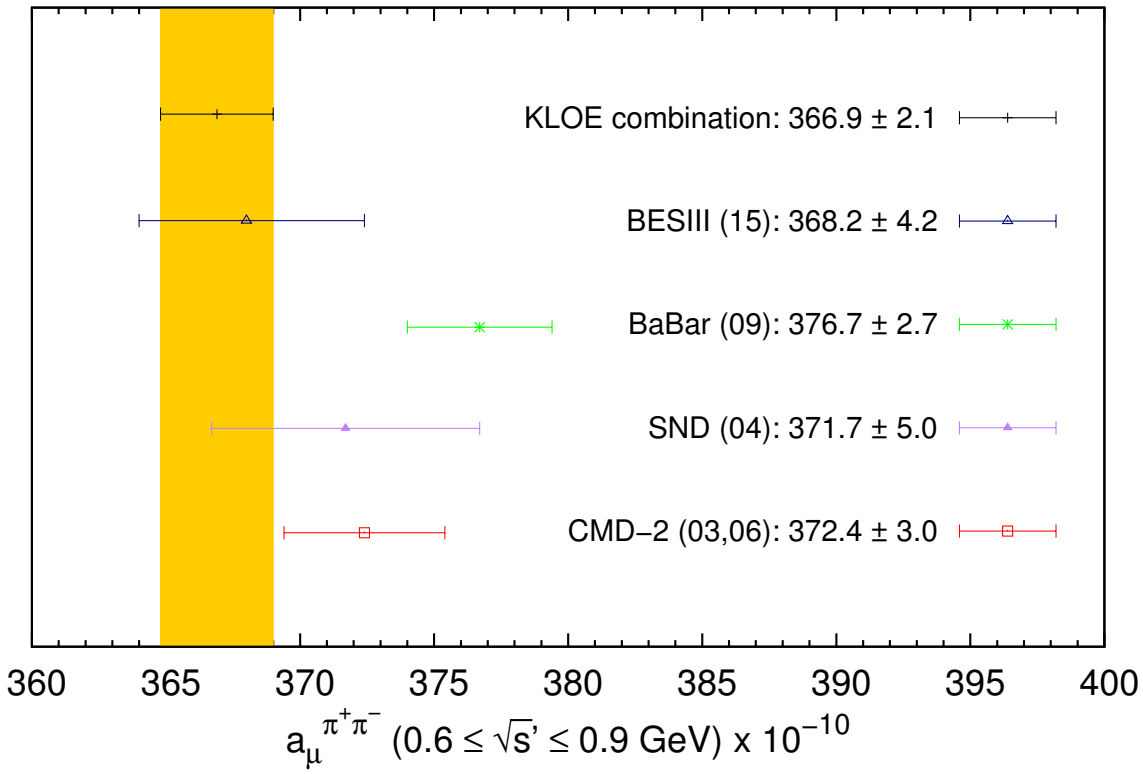




A. Anastasi et al., JHEP 1803 (2018) 173

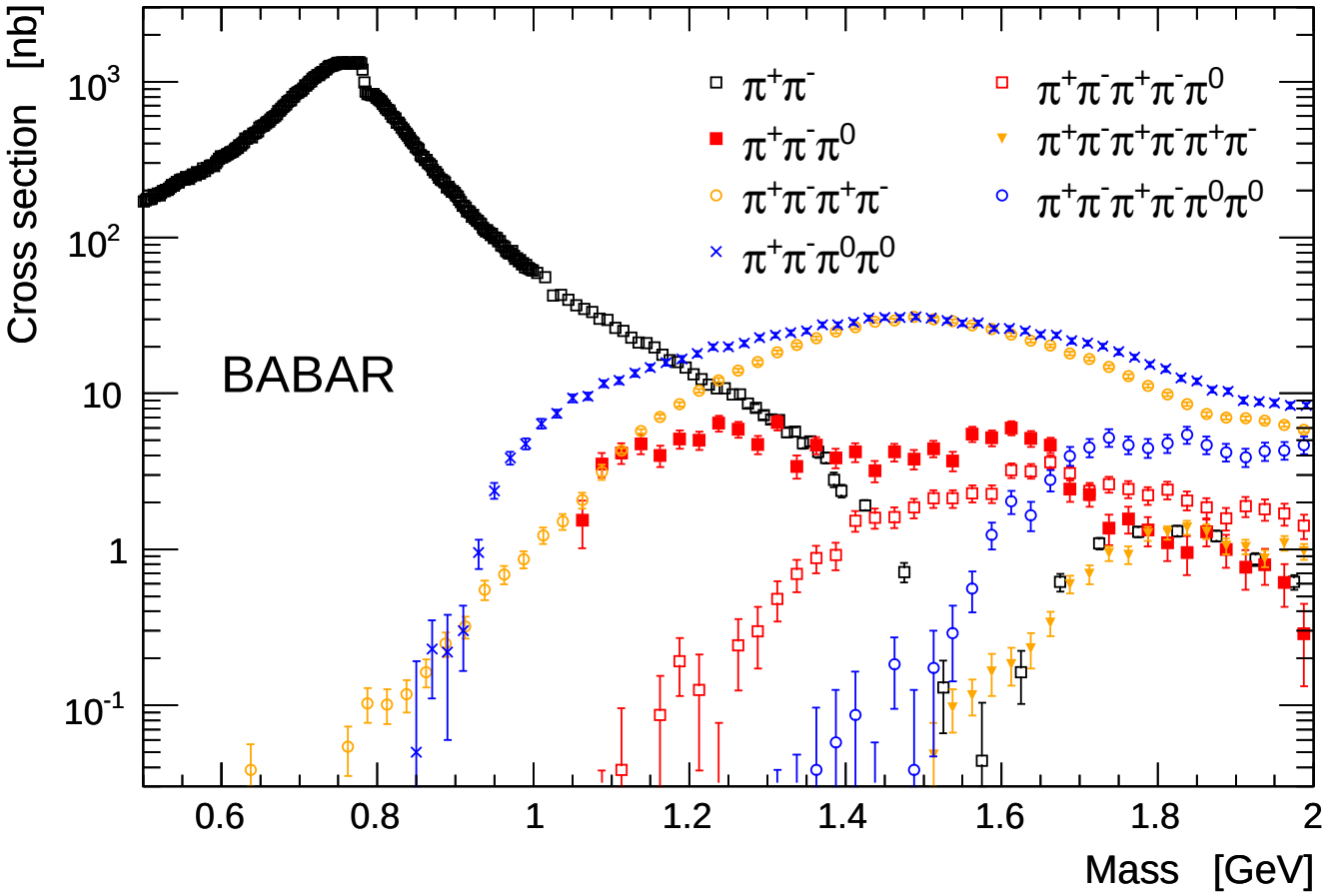
An independent high-precision scan result (CMD-3) is badly needed

$e^+e^- \to \pi^+\pi^-$ (KLOE Combination) – III



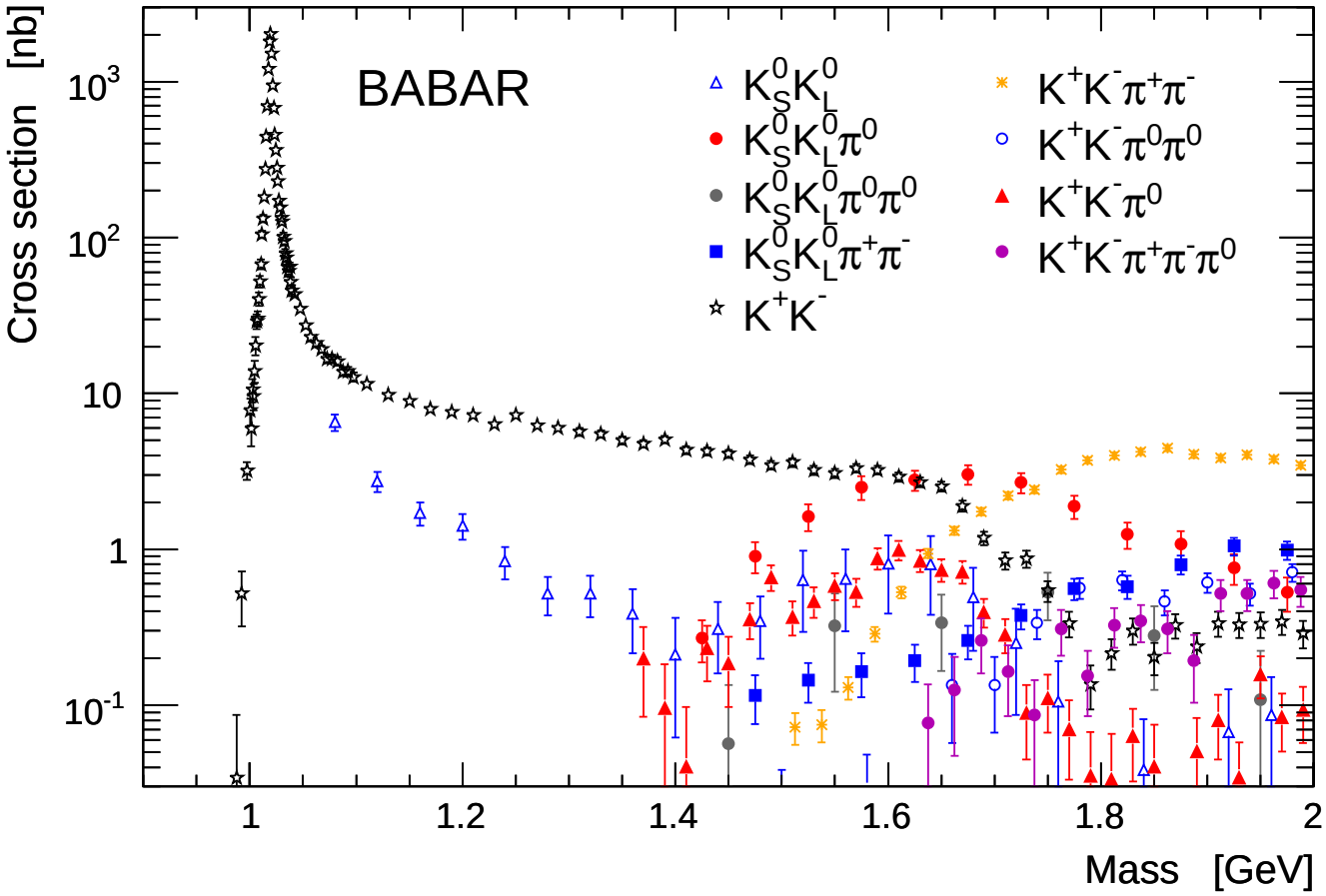
A. Anastasi et al., JHEP 1803 (2018) 173

BaBar Results on the Processes with Pions



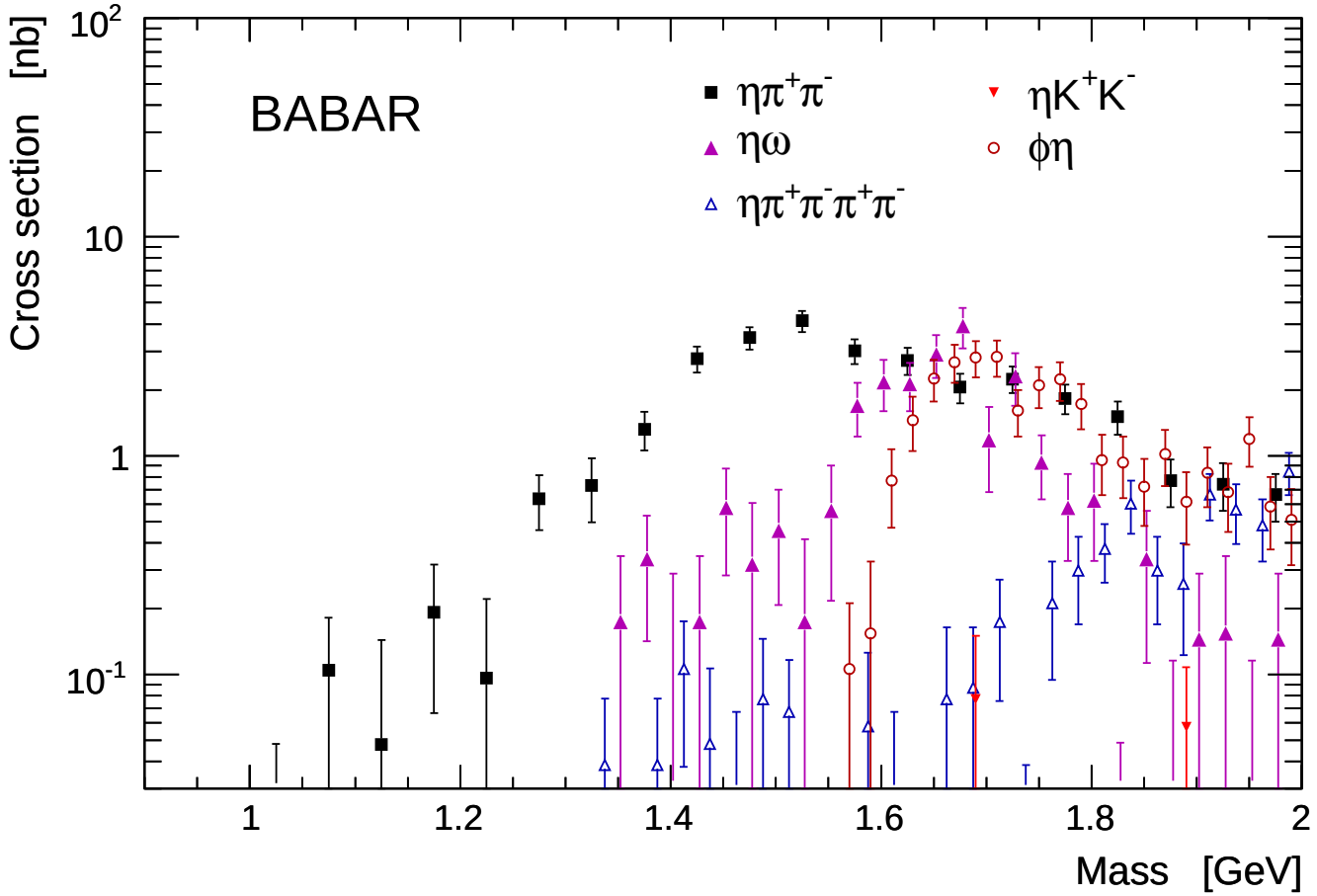
Systematic uncertainties range from 0.5% for $\pi^+\pi^-$ to (6-8)% for 6π

BaBar Results on the Processes with Kaons



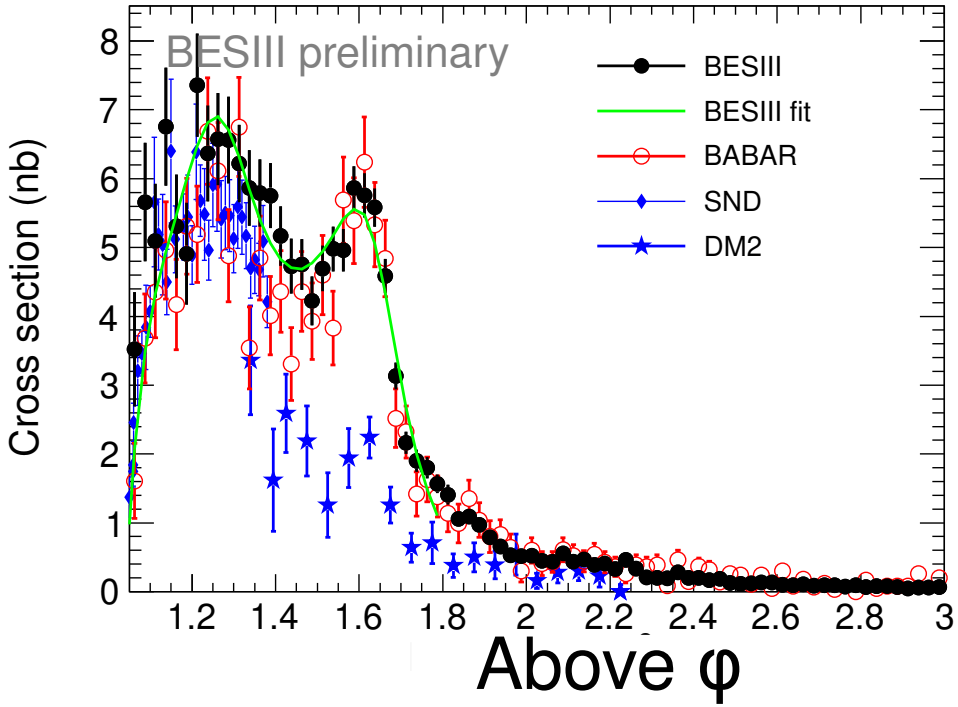
Systematic uncertainties range from 0.7% for K^+K^- to (6-8)% for $K\bar{K}n\pi$

BaBar Results on the Processes with η Mesons



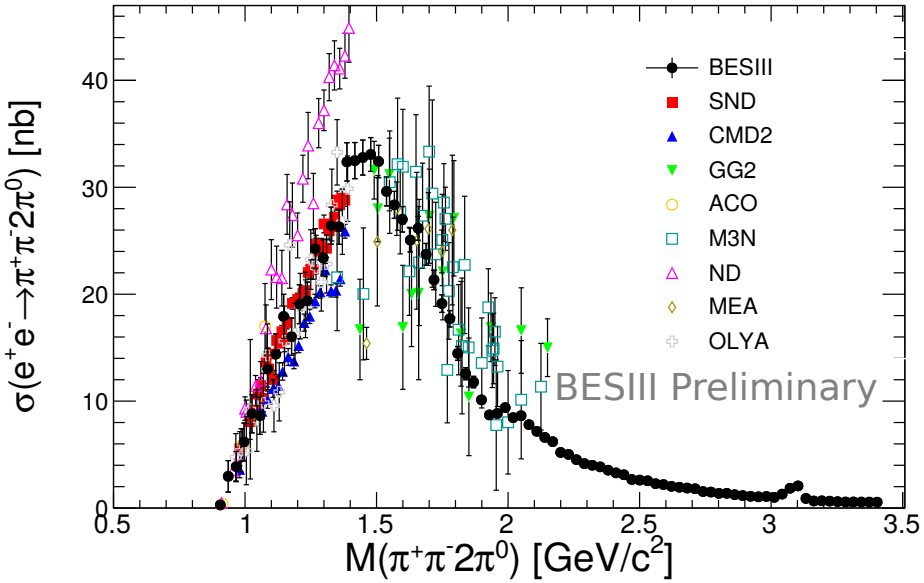
Systematic uncertainties range from for 4.5% to 12%

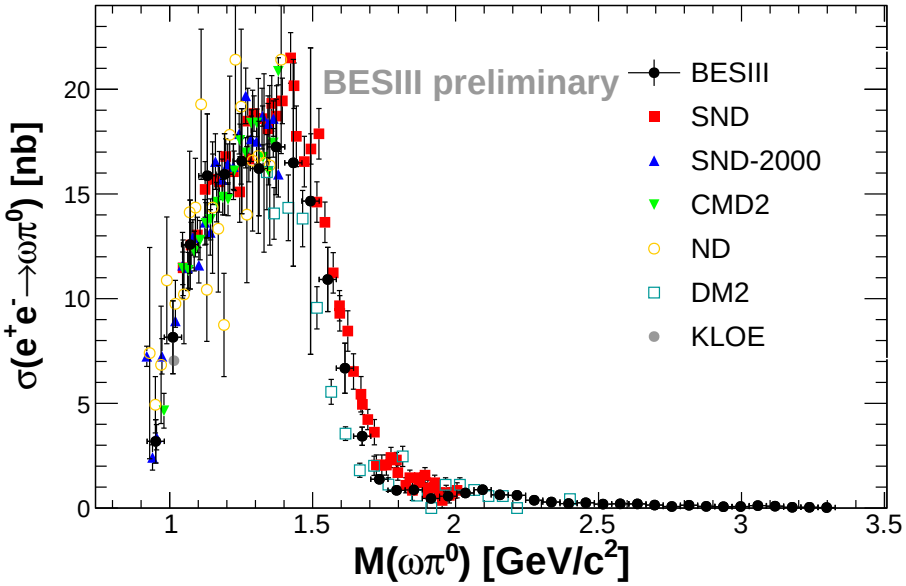
$e^+e^- \to \pi^+\pi^-\pi^0$ at BESIII



- Good agreement with previous results and improved precision
- Confirms BaBar at ω''
- Systematic uncertainty $< 3\%$

$e^+e^- \to \pi^+\pi^- 2\pi^0$ and $e^+e^- \to \omega\pi^0$ at BESIII

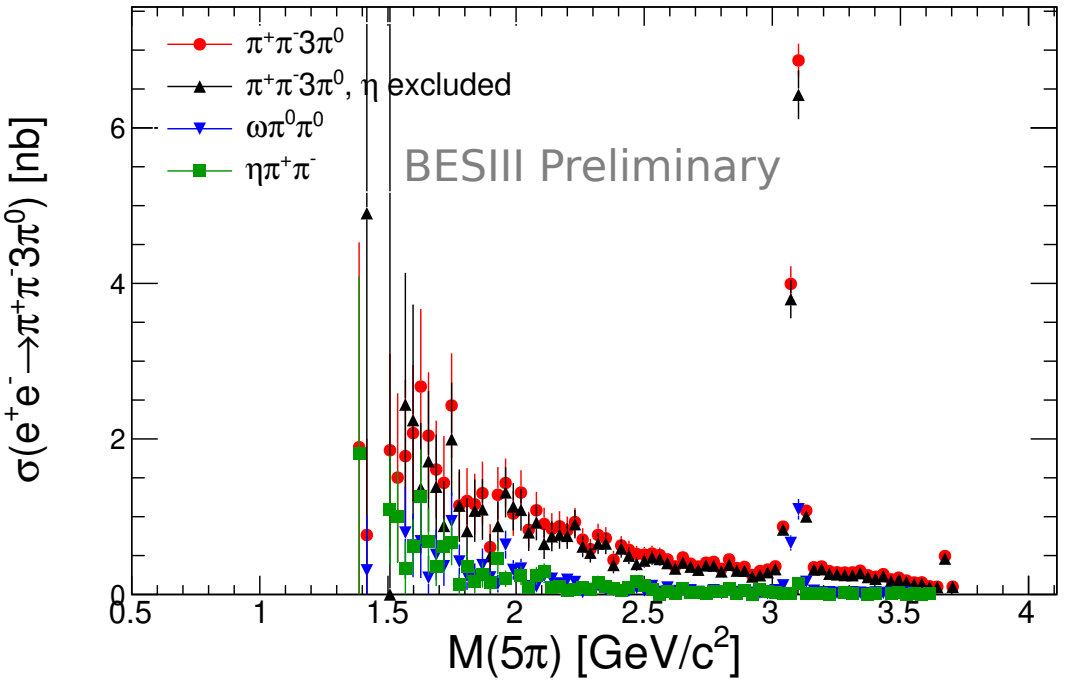




Group	$a_{\mu\mu},\ 10^{-10}$
BESIII	$18.09 \pm 0.27 \pm 0.57$
BaBar	$17.9 \pm 0.1 \pm 0.6$

Systematic uncertainty $\sim 3\%$

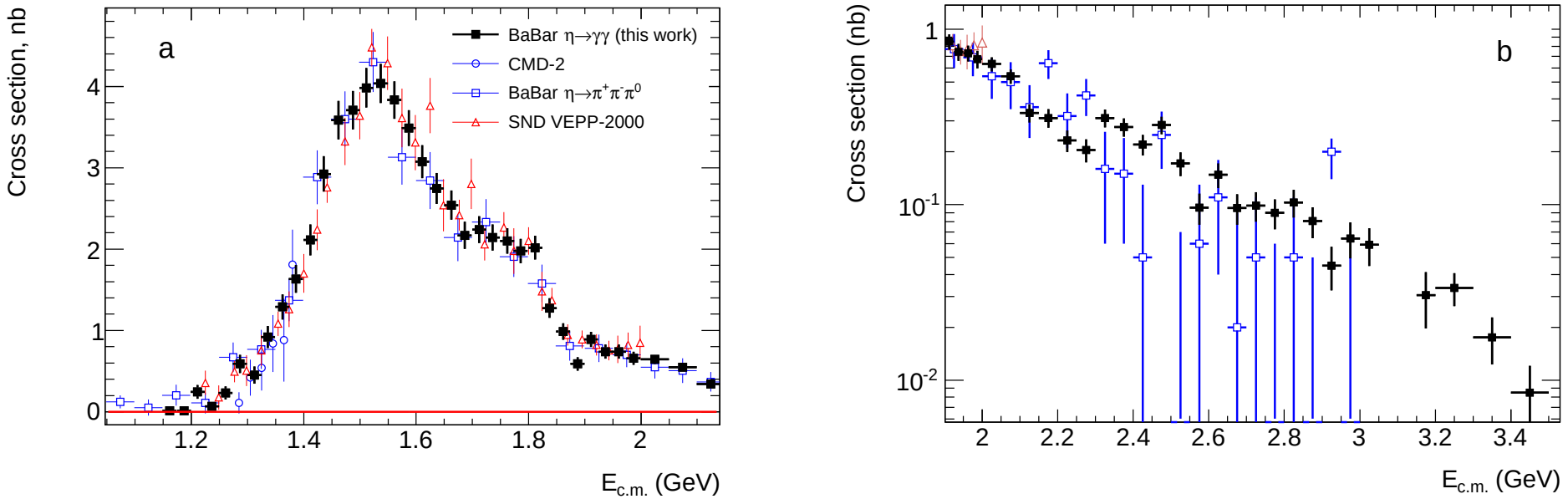
$e^+e^- \to \pi^+\pi^-3\pi^0$ at BESIII



Background for $e^+e^- \to \pi^+\pi^-2\pi^0$ and the first measurement

BaBar result coming soon

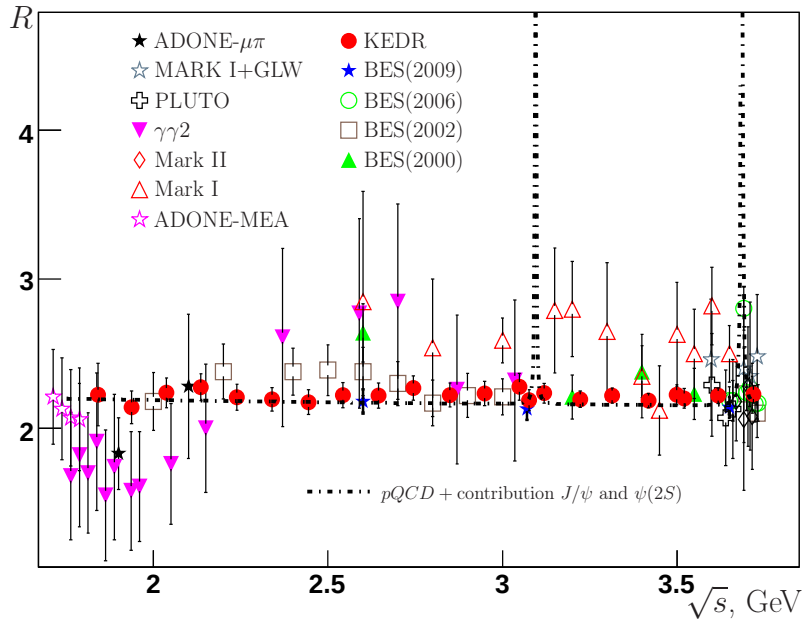
$e^+e^- \to \eta\pi^+\pi^-$ at BaBar



More precise result $\Rightarrow$ first observation of the $\rho(1700)$ in $\eta\pi^+\pi^-$

J.P. Lees et al., Phys. Rev. D97 (2018) 052007

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 (2017) 174

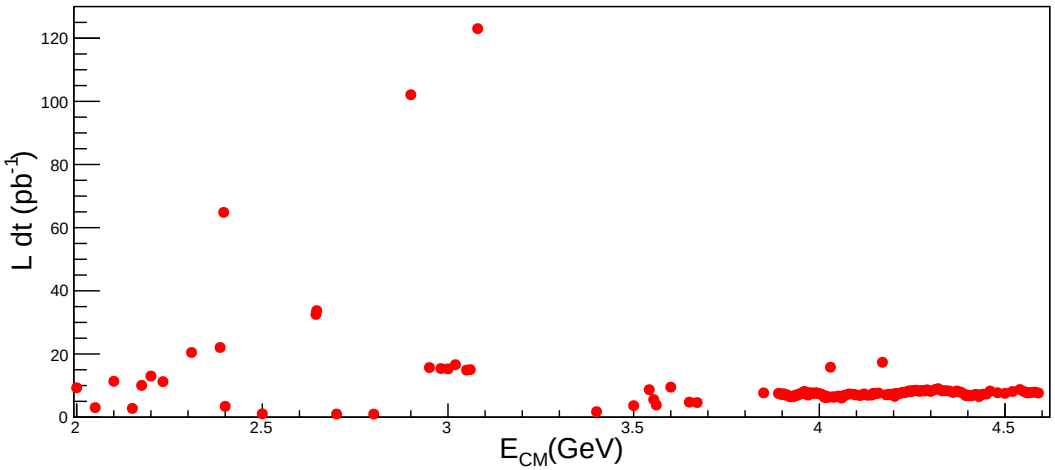
3.05-3.72 GeV $R_{\rm uds} = 2.204 \pm 0.013 \pm 0.030$ ($R_{\rm pQCD} = 2.16 \pm 0.01$)

V.V. Anashin et al., Phys. Lett. B753 (2016) 533; arXiv:1805.06235

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

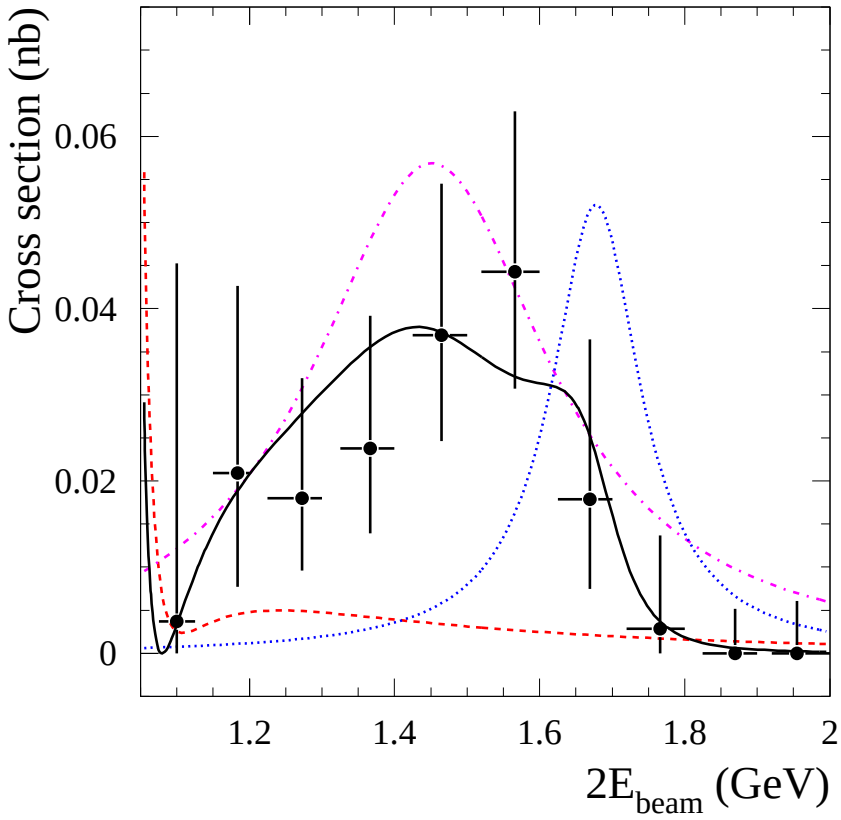
R measurement at BESIII



- Scanned the $\sqrt{s}$ range from 2.0-4.6 GeV
- 130 energy points
- $> 10^5$ events per point
- Aimed at the total uncertainty $< 3\%$

How good are generators in both measurements?

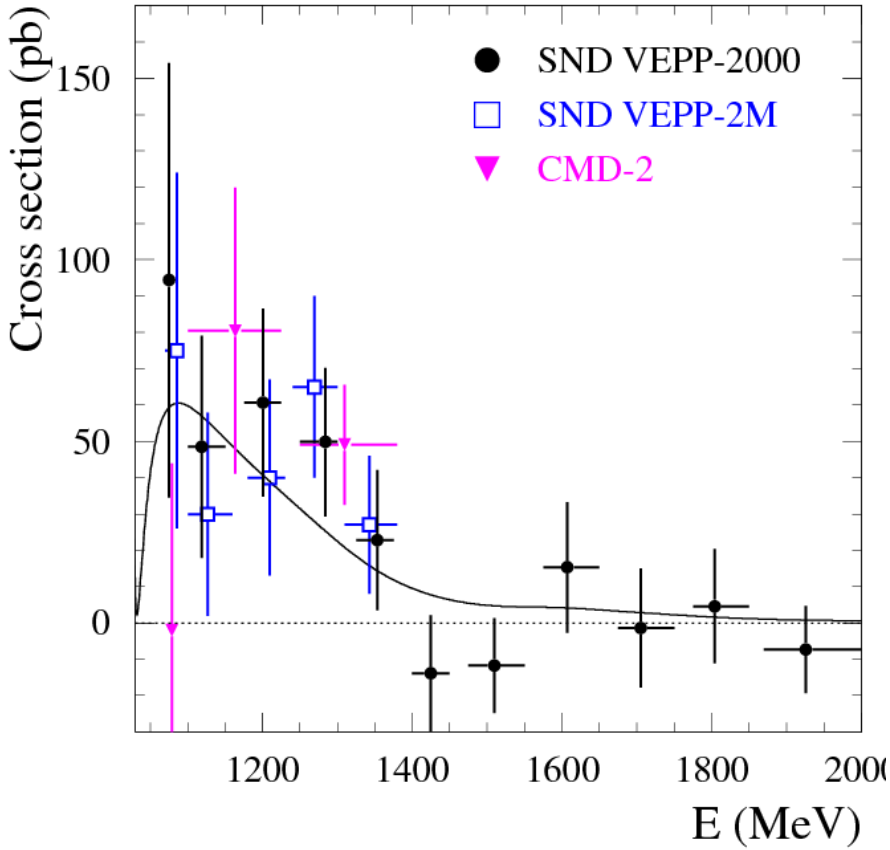
$e^+e^- \to \eta\gamma$ at SND



The first measurement above 1.4 GeV, Phys. Rev. D90 (2014) 032002

Dominated by the $\rho(1450)$ and $\phi(1680)$ mesons

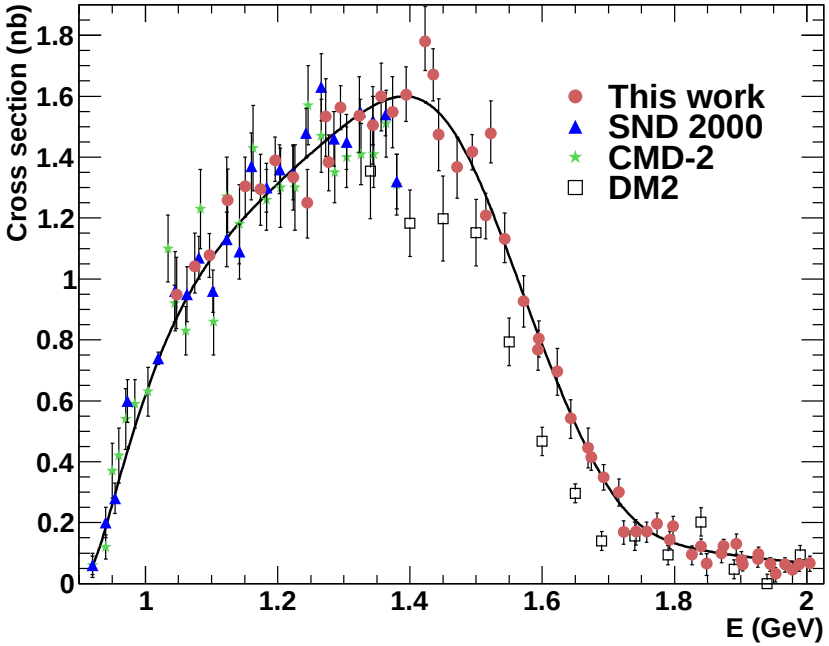
$e^+e^- \to \pi^0\gamma$ at SND

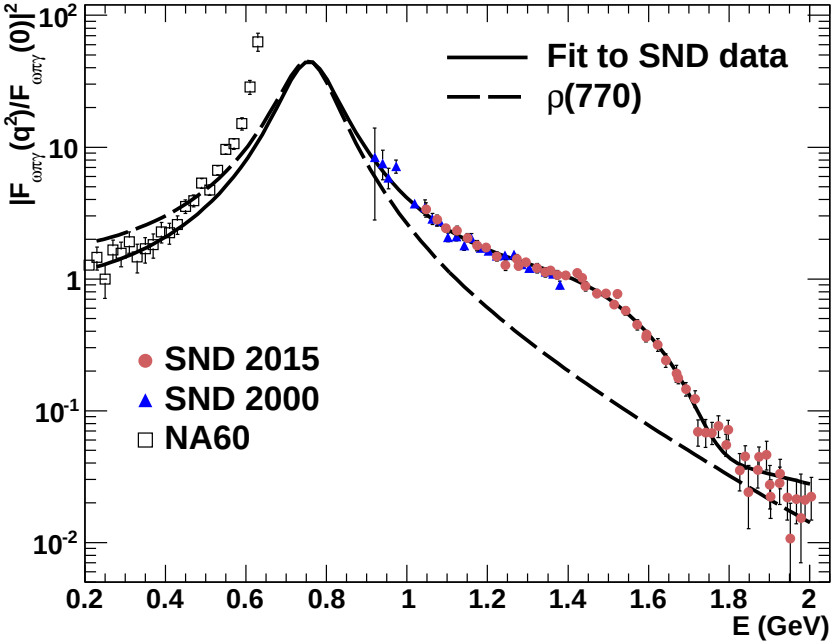


The first search above 1.4 GeV, preliminary

No signal above the background

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



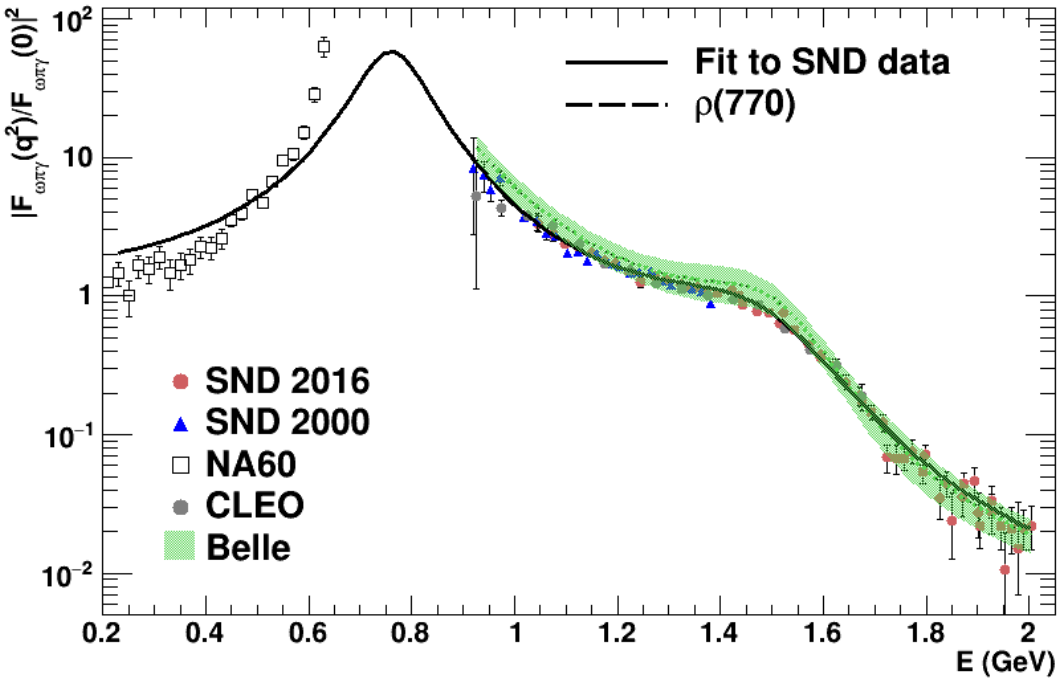


SND: M.N. Achasov et al., Phys. Rev. D94 (2016) 112001

NA60 (In-In) R. Arnaldi et al., Phys. Lett. B677 (2009) 260,

NA60 (p-A) R. Arnaldi et al., Phys. Lett. B757 (2016) 437

More on the TFF of the $\gamma\omega\pi$ system



In addition to SND and NA60, other data on $\mathcal{F}(\gamma\omega\pi)$ exist:

CLEO ($\tau^- \to \omega\pi^-\nu_\tau$), K.W. Edwards et al., Phys. Rev. D61 (2000) 072003

Belle ($\bar{B}^0 \to D^{*+}\omega\pi^-$), D. Matvienko et al., Phys. Rev. 92 (2015) 012013

NA60 studied inclusively $\omega \to \pi^0\mu^+\mu^-$

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

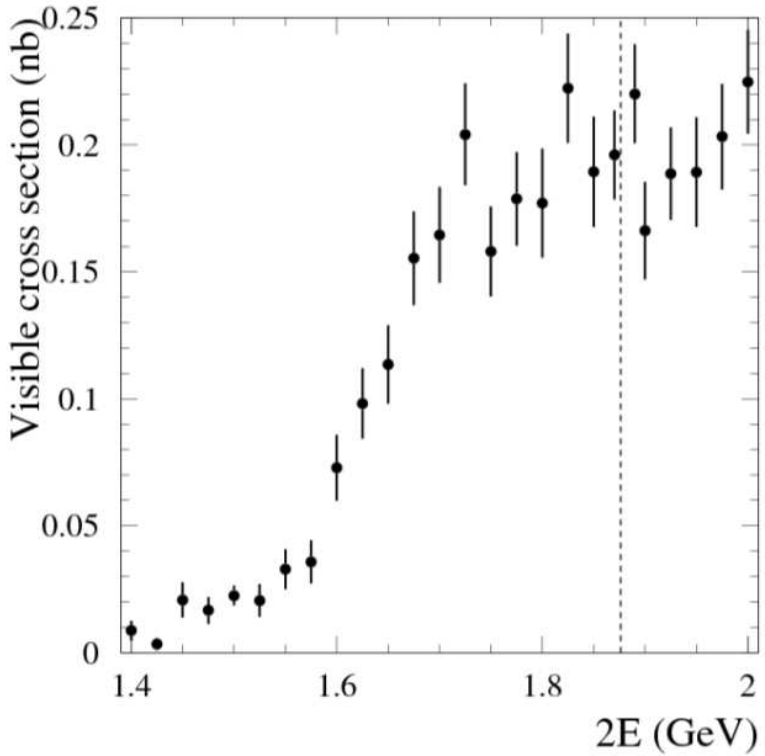
CMD-2 performed a study of $e^+e^- \to \omega\pi^0 \to \pi^0\pi^0\gamma$ and found no signal of direct production of $\pi^0\pi^0\gamma,\ \eta\pi^0\gamma$

$\sqrt{s}$, 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 (2003) 173

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

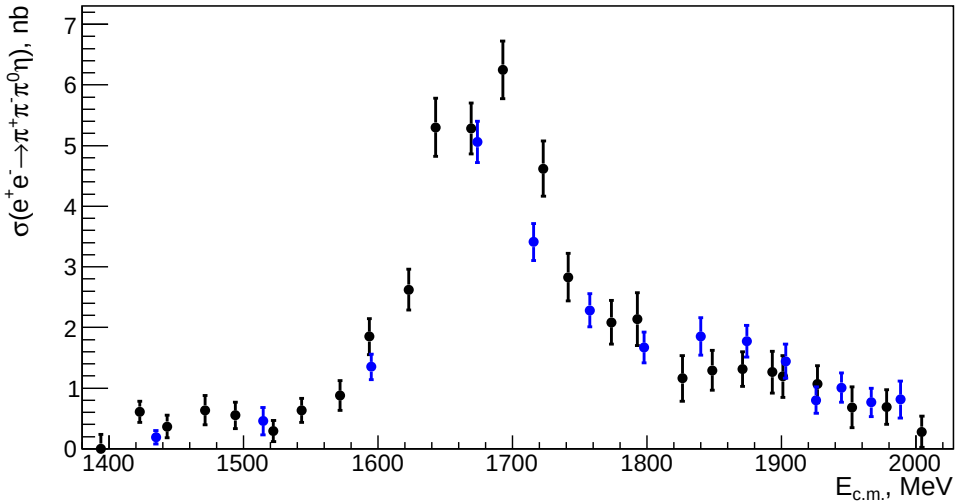


First ever measurement of the process, very preliminary

Necessary for the $\pi^+\pi^- 3\pi^0$ BG and for 6π mechanisms

$e^+e^- \to \pi^+\pi^-\pi^0\eta$ at CMD-3 – I

CMD-3 studied $e^+e^- \to \pi^+\pi^-\pi^0\eta,\ \eta \to 2\gamma$ and found various production mechanisms: $\omega\eta,\ \phi\eta,\ a_0(980)\rho$, their probability strongly depending on energy

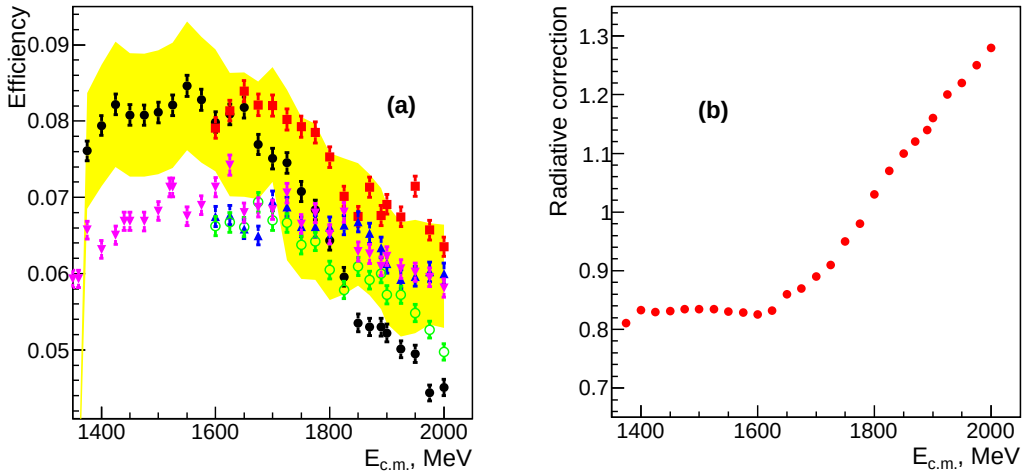


The total cross section assumes some combination of various channels

R.R. Akhmetshin et al., Phys. Lett. B773 (2017) 150

$e^+e^- \to \pi^+\pi^-\pi^0\eta$ at CMD-3 – II

Detection efficiencies of various production mechanisms significantly differ



R.R. Akhmetshin et al., Phys. Lett. B773 (2017) 150

What else is missing or unsatisfactory?

- Missing modes: 7,8π, $\eta\eta + X$, ...
- Detailed test of radiative corrections - theory vs. data
- What is real accuracy of the radiative corrections, 0.1%?
- Is scalar QCD adequate?
- Disentanglement of production mechanisms, correct matrix elements
- Interference effects
- Possible correlations

Future

- Two new measurements of a_μ are expected in close future improving the uncertainty a factor of 4 each
- What is expected for the HVP from $e^+e^- \to$ hadrons?
  Progress in low energy e^+e^- annihilation expected from VEPP-2000 scans, from ISR with KLOE-2, BESIII, BaBar and BelleII
- New exciting approaches:
  C.M. Carloni Calame et al., Phys. Lett. B 746 (2015) 325,
  from $\alpha(t)$ in the spacelike region of Bhabha
  G. Abbiendi et al., Eur. Phys. J. C77 (2017) 139,
  from $\alpha(t)$ in the spacelike region of $\mu e \to \mu e$
- Lattice calculations

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 ($\sim 1\text{fb}^{-1}$) will allow a study of
  dynamics, thus mesons with various quantum numbers
- 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?