Overview of the $(g-2)_\mu$ status and related e^+e^- measurements in Novosibirsk and by ISR

Vladimir Druzhinin

NSU/BINP, Novosibirsk

on behalf of the SND, CMD-3 and BABAR Collaborations

FPCP 2017 - *Flavor Physics & CP Violation*
Prague - June 5-9, 2017

$(g-2)_\mu/2$ of muon (experiment)

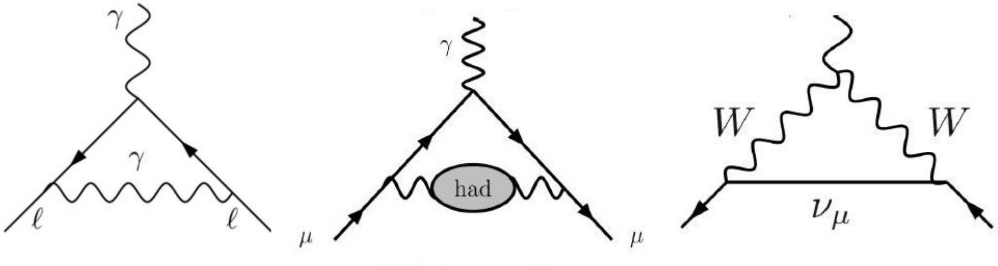
Magnetic moment

$$\vec{\mu} = g\frac{e\hbar}{2mc}\vec{S}$$

✓The Dirac equation predicts g=2 for point-like fermions.

✓Higher order QFT contributions lead to nonzero

$$a=(g-2)/2$$



✓ a_μ is sensitive to New Physics contributions

E821@BNL (1997-2001):
G.W. Bennett *et al.*,
Phys. Rev. D **77**, 072003 (2006)
a_μ = (11 659 209.1±6.3)×10^{-10} (0.54 ppm)

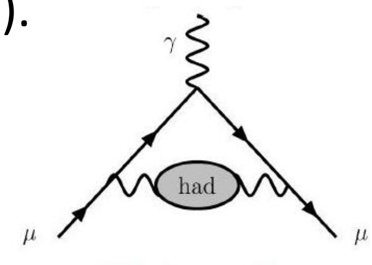
E989 @ FNAL (2017-…):
F. Gray *et al.*, arXiv: 1510.003
a_μ = … (0.14 ppm)

E34 @ J-PARC (????-…):
T. Mibe *et al.*,
Chin. Phys. C **34** (2010) 745
a_μ = … (0.1 ppm)

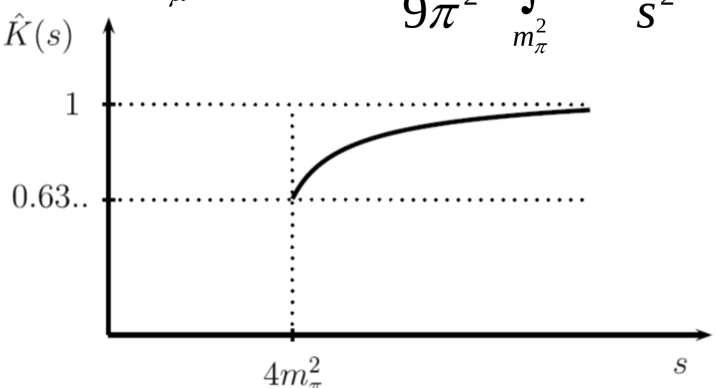
$(g\text{-}2)_\mu/2$ of muon (theory)

- The leading order hadronic contribution is calculated using dispersion relations from experimental data on the total cross section of the e^+e^- annihilation into hadrons
- Low energies (E < 2 GeV) give dominant contribution into $a_\mu^{had,LO\text{-}VP}$ (92%).

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



$$a_\mu^{\text{had,LO-VP}} = \frac{\alpha^2 m_\mu^2}{9\pi^2} \int_{m_\pi^2}^{\infty} ds \frac{\hat{K}(s)}{s^2} R(s)$$



$a_\mu = (g\text{-}2)_\mu / 2$

DHMZ , TAU 2016, arXiv:1612.02743

Individual SM contributions × 10^{-10}

a_μ^{QED}	11658471.895 ± 0.008
a_μ^{EW}	15.4 ± 0.1
$a_\mu^{had,LO\text{-}VP}$	692.6 ± 3.3
$a_\mu^{had,HO\text{-}VP}$	-8.63 ± 0.09
$a_\mu^{had,LbLs}$	10.5 ± 2.6

Comparison with measurement

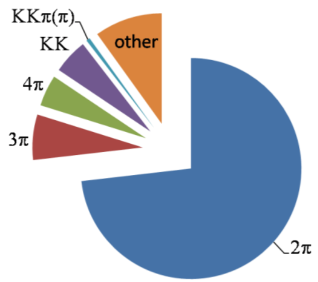
$a_\mu^{total\text{-}SM}$	11659181.7 ± 4.2
$a_\mu^{BNL\text{-}E821}$	11659209.1 ± 6.3
Data - SM	27.4 ± 7.6 (3.6σ)

F.Jegerlehner, arXiv:1705.00263

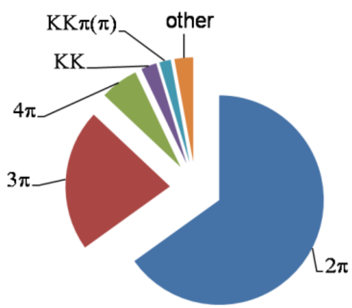
Data-SM 31.3 ± 7.7 (4.1σ)

$(g-2)_\mu/2$ of muon (theory)

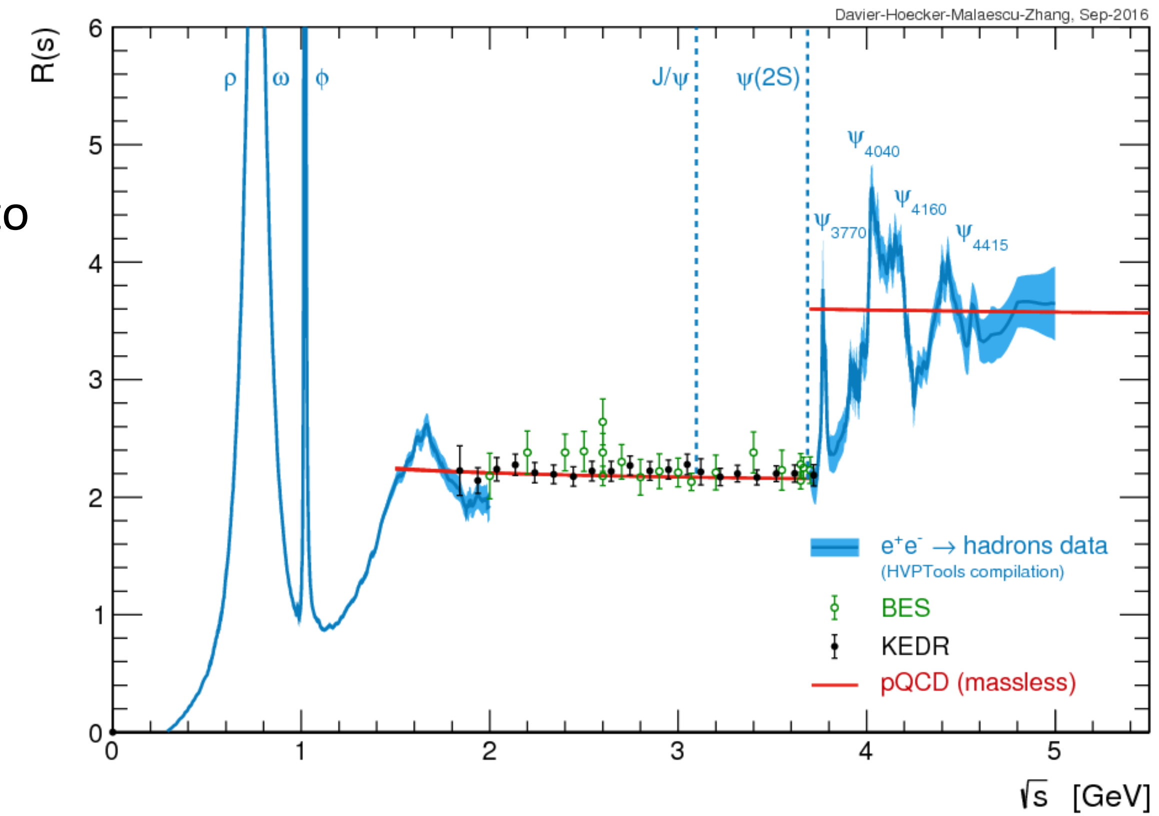
- Below 2 (1.8) GeV the total cross section is calculated as a sum of exclusive channels.
- The contributions of different hadronic channels into $a_\mu^{had,LO-VP}$



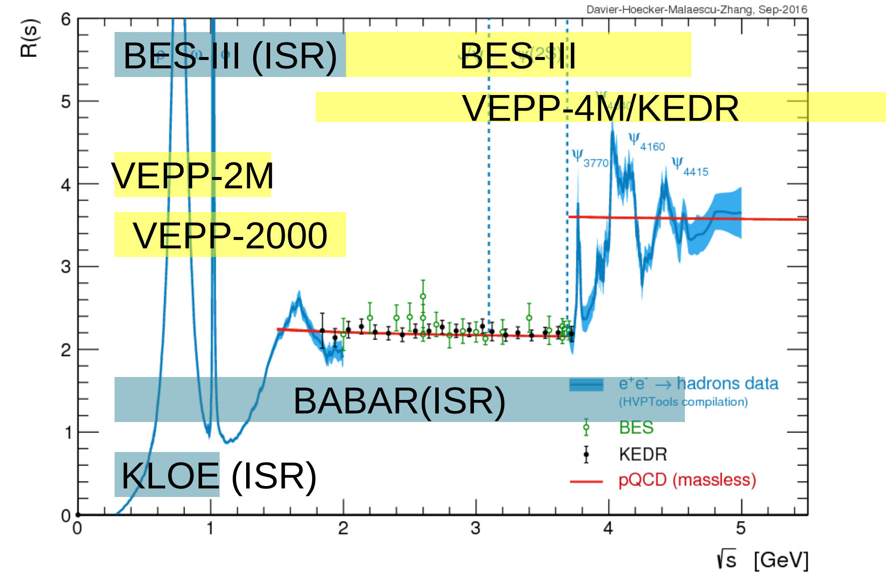
- and its squared error σ^2



DHMZ , TAU 2016, arXiv:1612.02743



Recently measured cross sections



e^+e^- scan

✓ KEDR@VEPP-4M: Inclusive R measurement from 1.84 to 3.72 GeV

V.V.Anashin et al. (KEDR Collaboration)
Phys. Lett. B 753, 533 (2016)
arXiv: 1610.02827, accepted in Phys. Lett. B

✓ SND@VEPP-2M: $e^+e^- \to \pi^0\gamma$,

✓ SND@VEPP-2000: $e^+e^- \to K^+K^-$, $\omega\eta$, $\omega\pi^0$, $\omega\pi^0\eta$, $\pi^0\gamma$

✓ CMD-3@VEPP-2000: $e^+e^- \to K^+K^-$, K_SK_L

Initial state radiation (ISR)

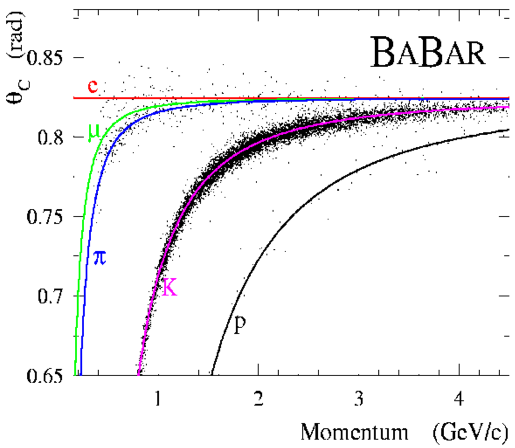
✓ BES-III: $e^+e^- \to \pi^+\pi^-$

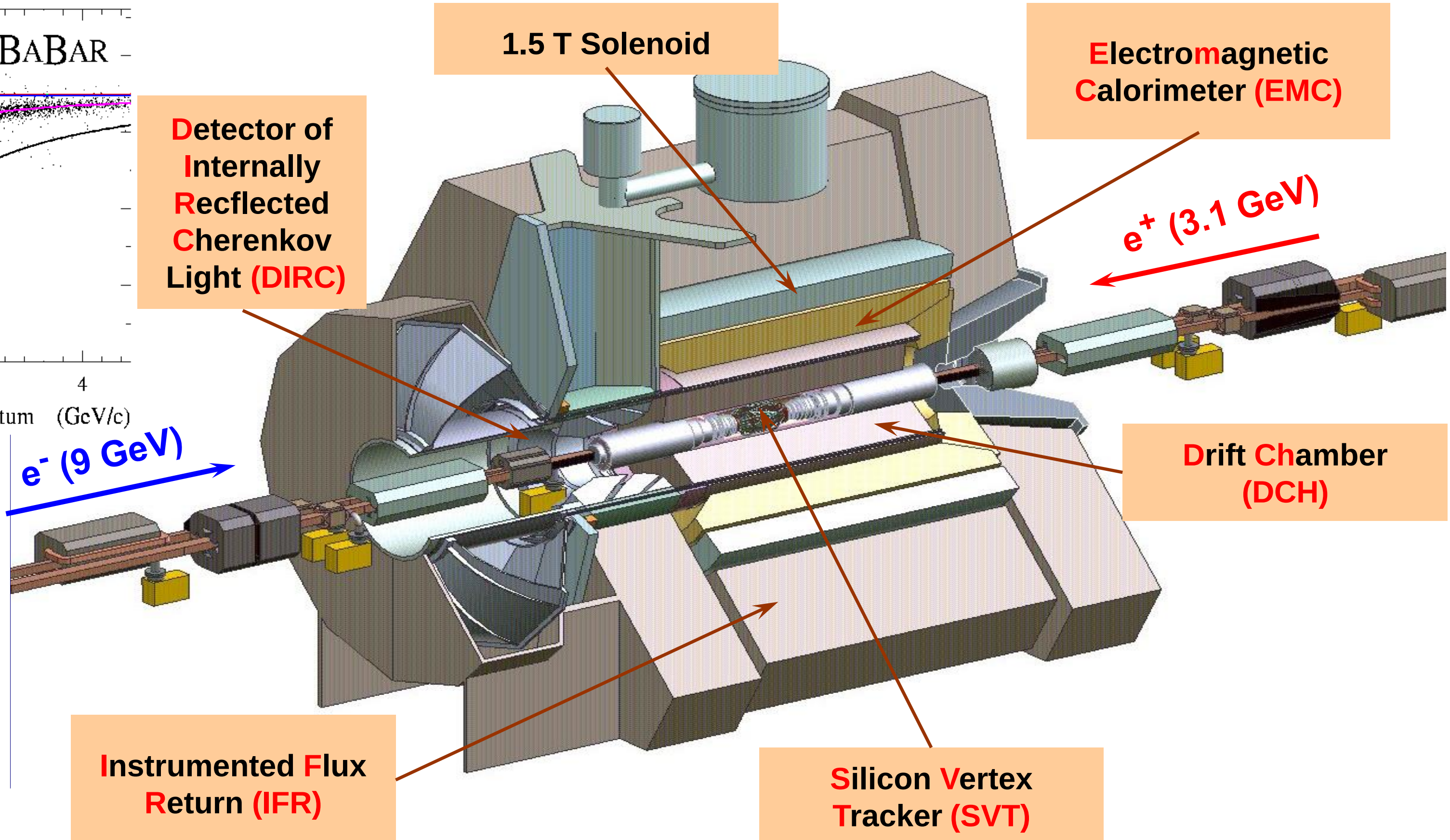
✓ BABAR: $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$, $\pi^+\pi^-\eta$, $K_SK_L\pi^0$, $K_SK_L\eta$, $K_SK_L\pi^0\pi^0$, $K_SK^+\pi^-\pi^0$, $K_SK^+\pi^-\eta$

BABAR Experiment

PEP-II asymmetric e^+e^- collider at SLAC (9 GeV e^- and 3.1 GeV e^+)

Data, about 500 fb^{-1}, were collected in 1999-2008



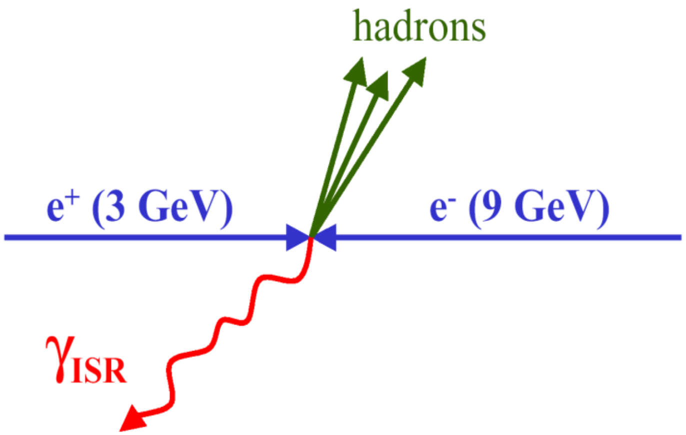


For ISR analyses, a data sample of 469 fb^{-1} collected near or at a c.m. energy of 10.58 GeV (at and near $\Upsilon(4S)$) is used.

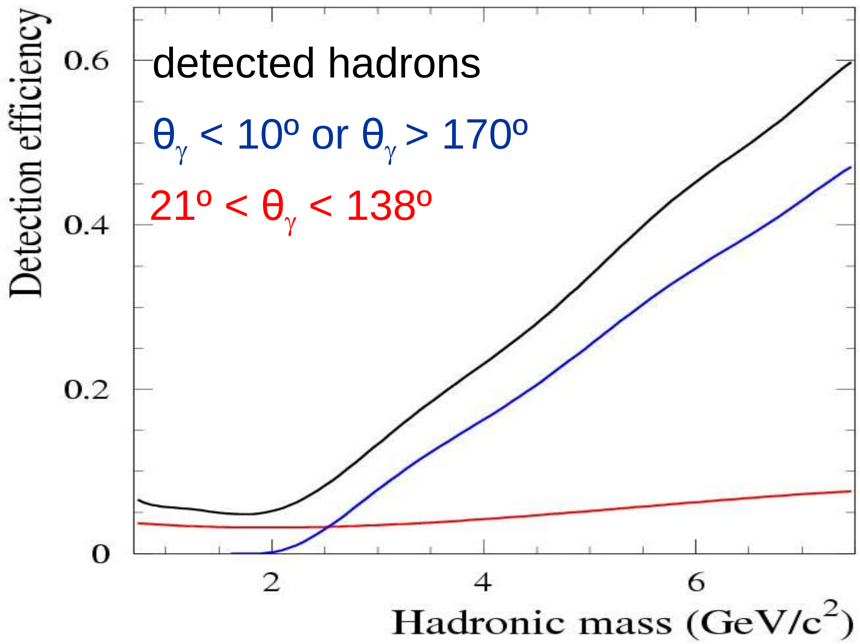
ISR method@BABAR

The mass spectrum of the hadronic system in the reaction $e^+e^- \to f\,\gamma$ reaction is related to the cross section of the reaction $e^+e^- \to f$.

$$\frac{d\sigma(s,x)}{dx\,d(\cos\theta)} = W(s,x,\theta)\cdot\sigma_0(s(1-x)), \quad x = \frac{2E_\gamma}{\sqrt{s}}$$



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



The ISR photon is emitted predominantly along the beam axis. The produced hadronic system is boosted against the ISR photon. Due to limited detector acceptance the mass region below 2 GeV can be studied only with detected photon (about 10% of ISR events).

BABAR tagged ISR analyses

Fully exclusive measurement

- ✓Photon with E_{CM} > 3 GeV, which is assumed to be the ISR photon
- ✓All final hadrons are detected and identified

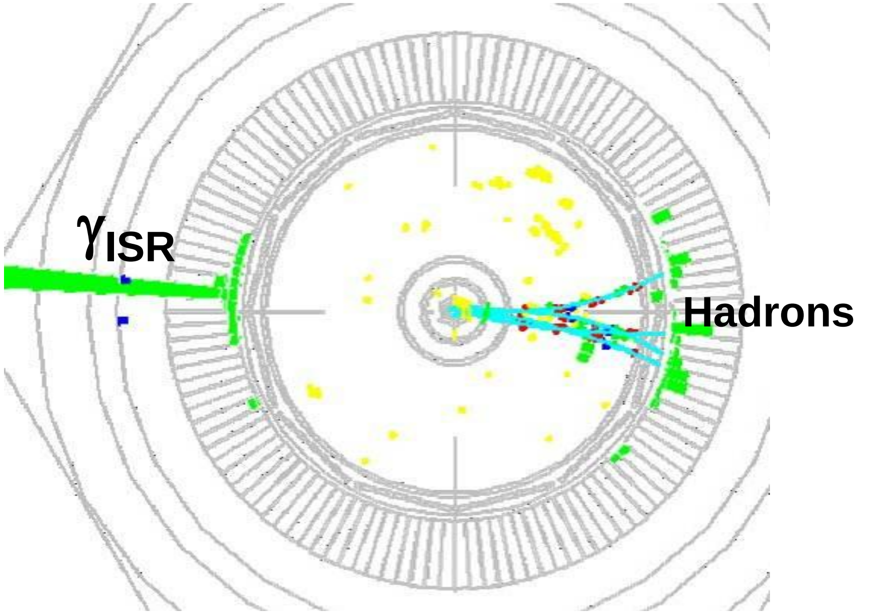
Large-angle ISR forces the hadronic system into the detector fiducial region

- ✓A weak dependence of the detection efficiency on dynamics of the hadronic system (angular and momentum distributions in the hadron rest frame) ⇒ smaller model uncertainty
- ✓A weak dependence of the detection efficiency on hadron invariant mass ⇒ measurement near and above threshold with the same selection criteria.

Kinematic fit with requirement of energy and momentum balance

- ✓excellent mass resolution
- ✓background suppression

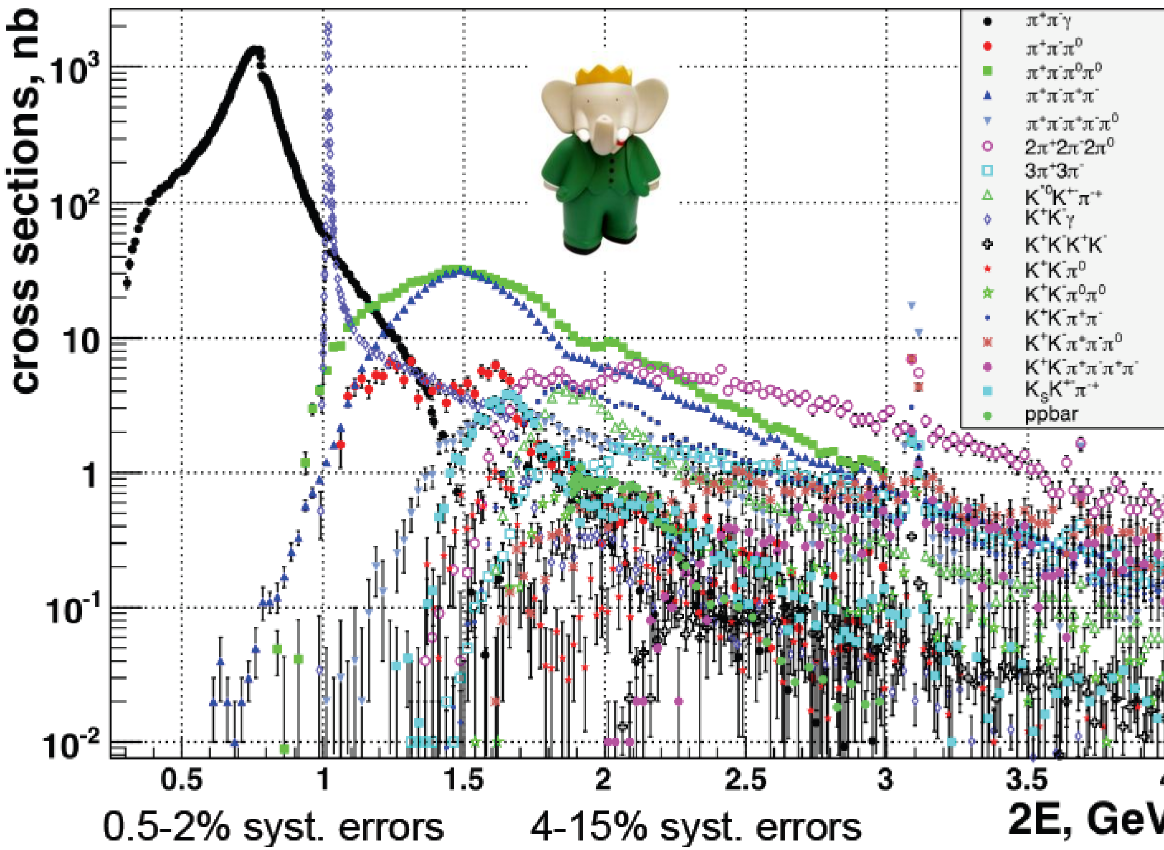
Generic BABAR ISR event



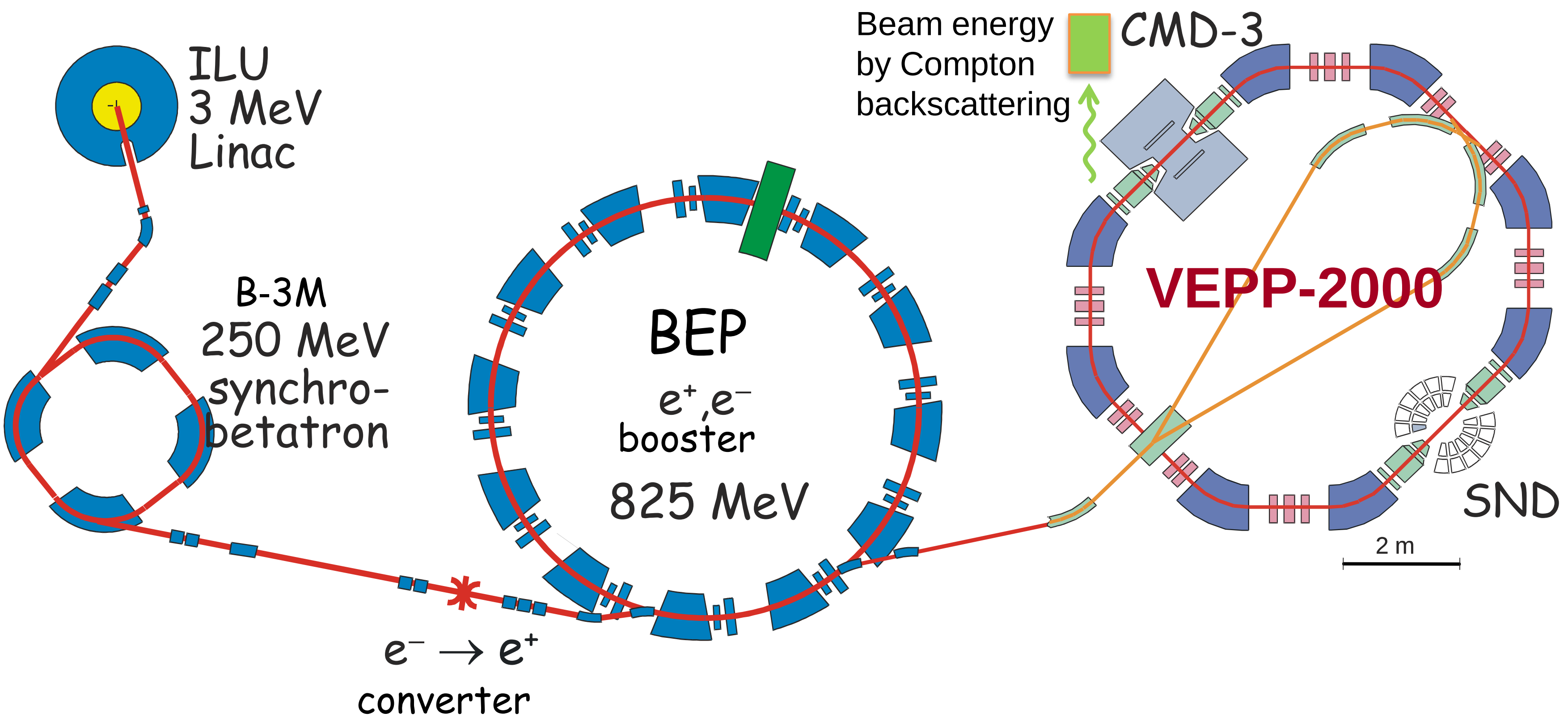
Can access a wide range of energy in a single experiment: from threshold to ~5 GeV

BABAR tagged ISR analyses

22 final states were studied, 20 papers on low energy ISR studies were published



VEPP-2000 (2010-2013)

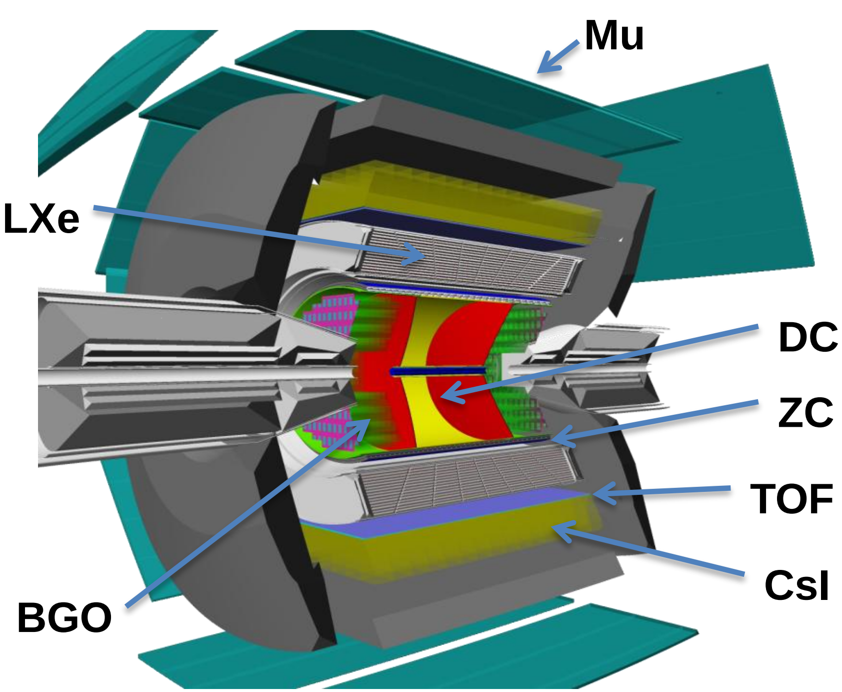


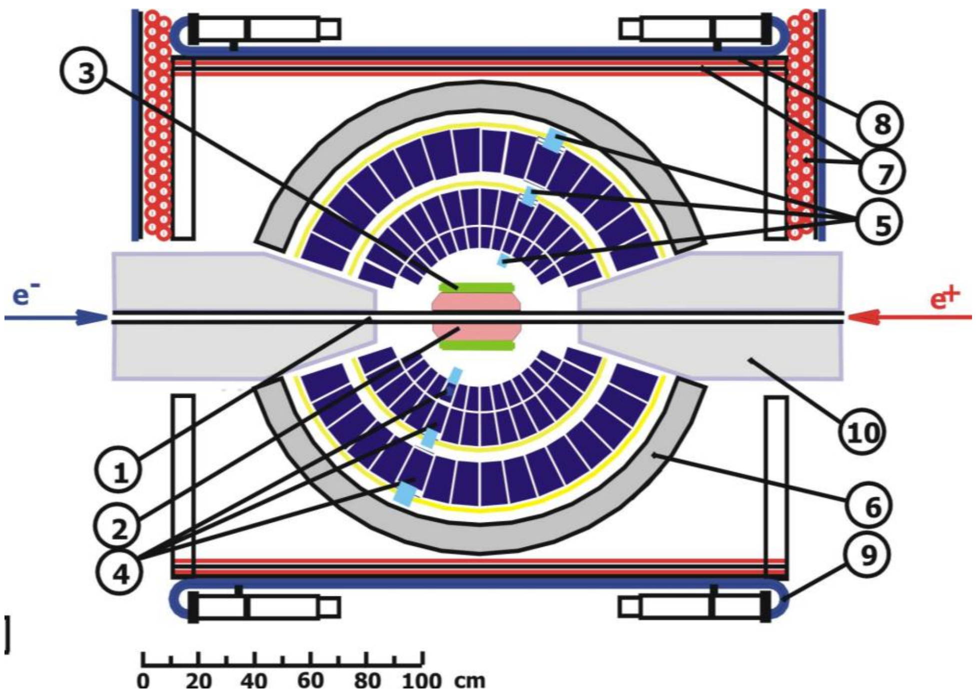
C.m. energy range is E=0.3-2.0 GeV, round beam optics

Luminosity at E=1.8 GeV is 2×10^{31} cm^{-2} s^{-1}

Two detectors, SND and CMD-3

CMD-3 and SND



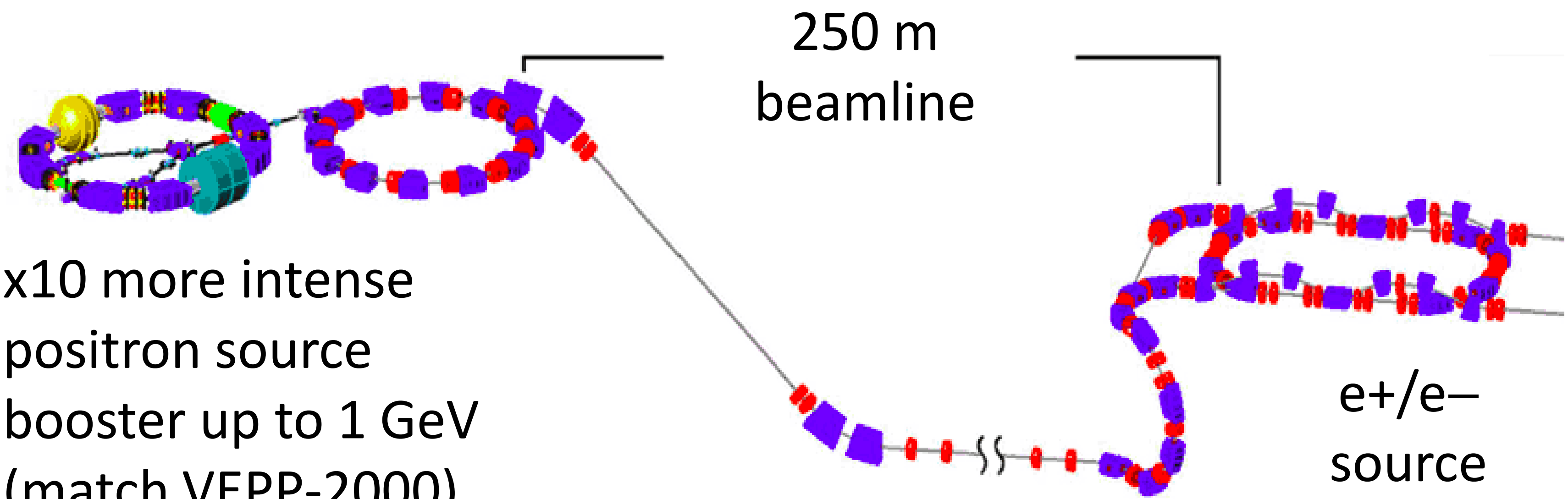


1.3 T magnetic field
Tracking: $\sigma_{R\varphi} \sim 100\ \mu, \sigma_z \sim 2$ mm
Combined EM calorimeter (LXE, CsI, BGO), $\sigma_E \sim 3\% - 8\%$

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

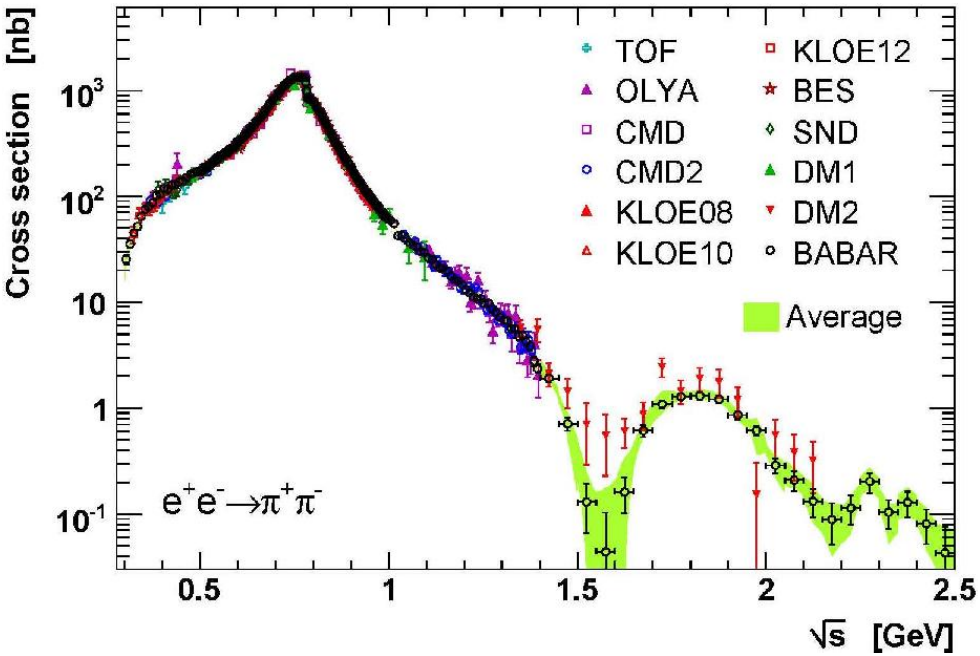
VEPP-2000 (2016-…)



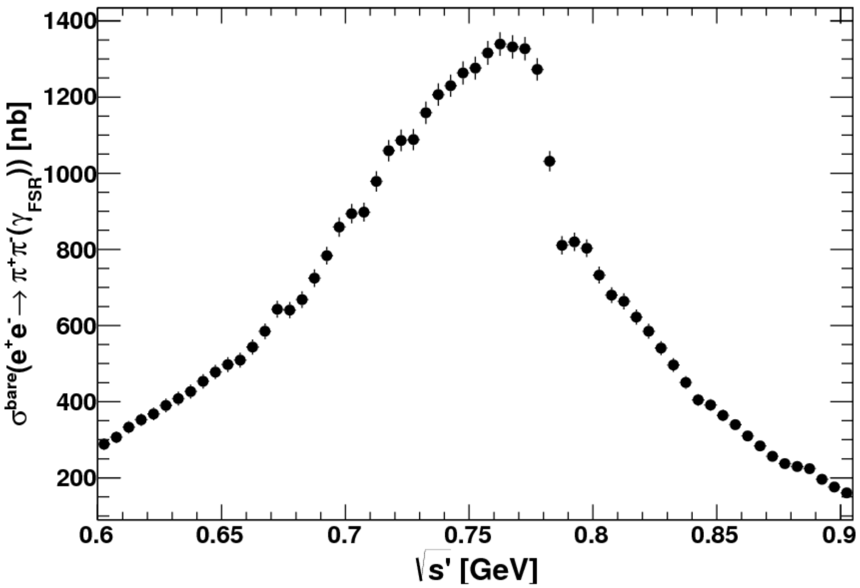
- x10 more intense positron source
- booster up to 1 GeV (match VEPP-2000)

- VEPP-2000 upgrade (2013-2016) was finished
- Data taking was restarted by the end of 2016
- Achieved luminosity at E=1.8 GeV is 4×10^{31} cm^{-2} s^{-1}

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



- Most recent measurement was performed by BES III using ISR technique
- Analysis is based on the data set with an integrated luminosity of 2.93 fb^{-1} taken at 3.773 GeV

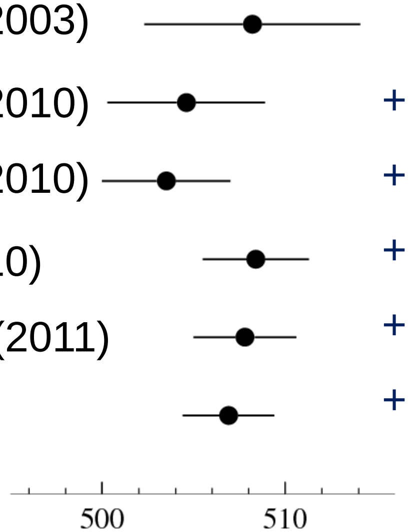


Phys. Lett. B 753, 629 (2016)

- Large progress in ISR measurements during the last decade
- CMD-2, KLOE, BABAR, BES-III claim systematic uncertainty at a sub-percent level

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

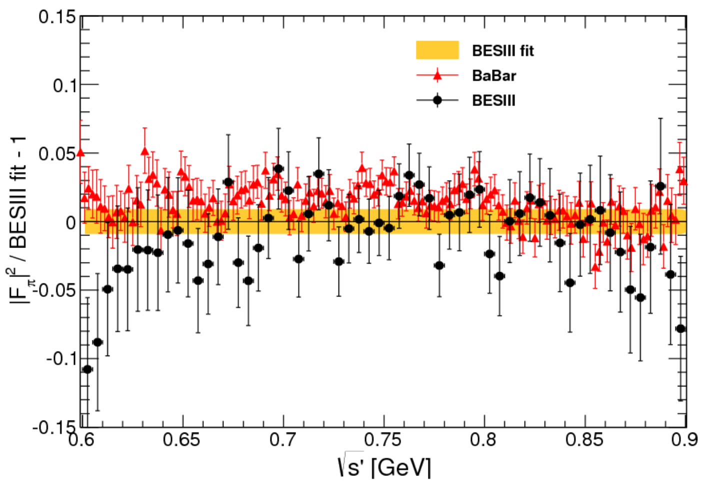
Evolution of the $e^+e^- \to \pi^+\pi^-$ contribution into $a_\mu^{had,LO}$ (DHMZ)

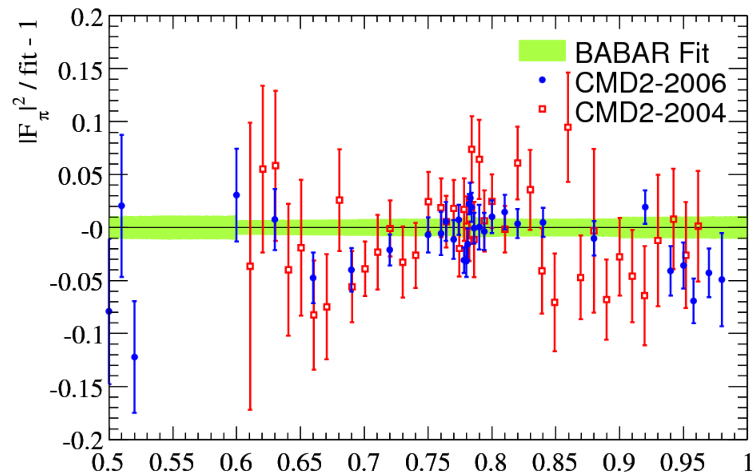


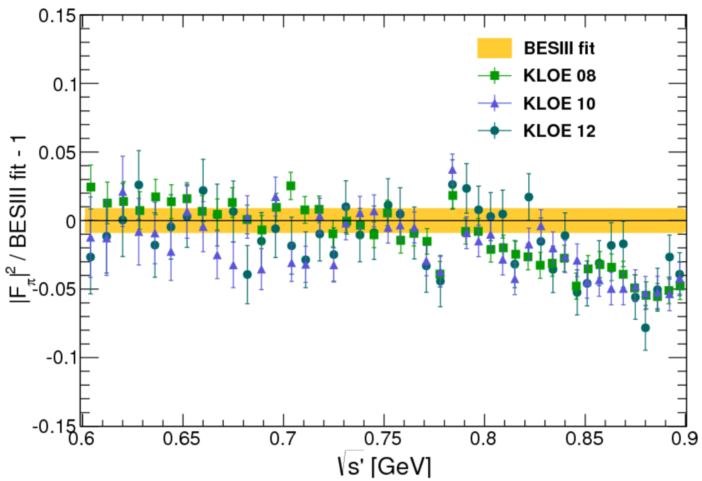
		$\times 10^{-10}$
EPJ C 31,503 (2003)	CMD-2 2003 + other e^+e^-	508.2 ± 5.9
EPJ C 66,127 (2010)	+ CMD-2 2006 + SND 2006	504.6 ± 4.3
EPJ C 66,127 (2010)	+ KLOE 2008	503.5 ± 3.5
EPJ C 66,1 (2010)	+ BABAR 2009	508.4 ± 2.9
EPJ C 71,1515 (2011)	+ KLOE 2010	507.8 ± 2.8
TAU 2016	+ KLOE 2012 + BES III 2016	506.9 ± 2.5

The statistical error decreased from 5.2 to 1.1, while the systematic from 2.7 to 2.3.

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

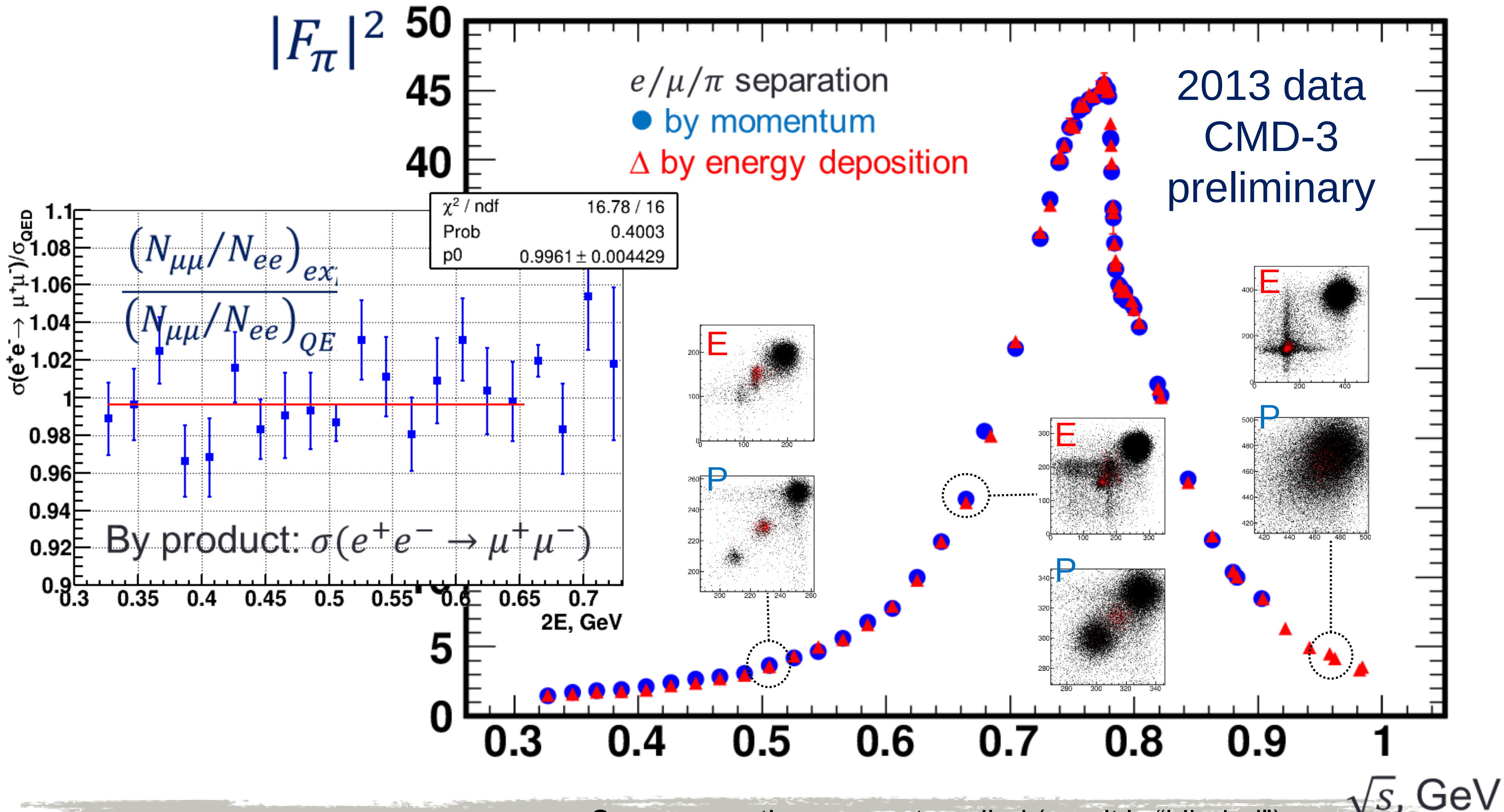






Systematic differences between data from different experiments reach 5% and are significantly larger than the claimed systematic uncertainties (<1%)

$e^+e^- \to \pi^+\pi^-$ @ CMD-3



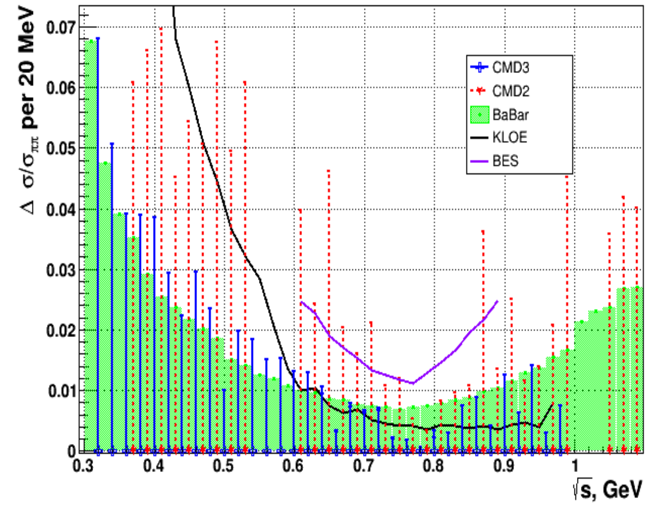
Some corrections are not applied (result is "blinded")

$e^+e^- \to \pi^+\pi^-$ @ CMD-3

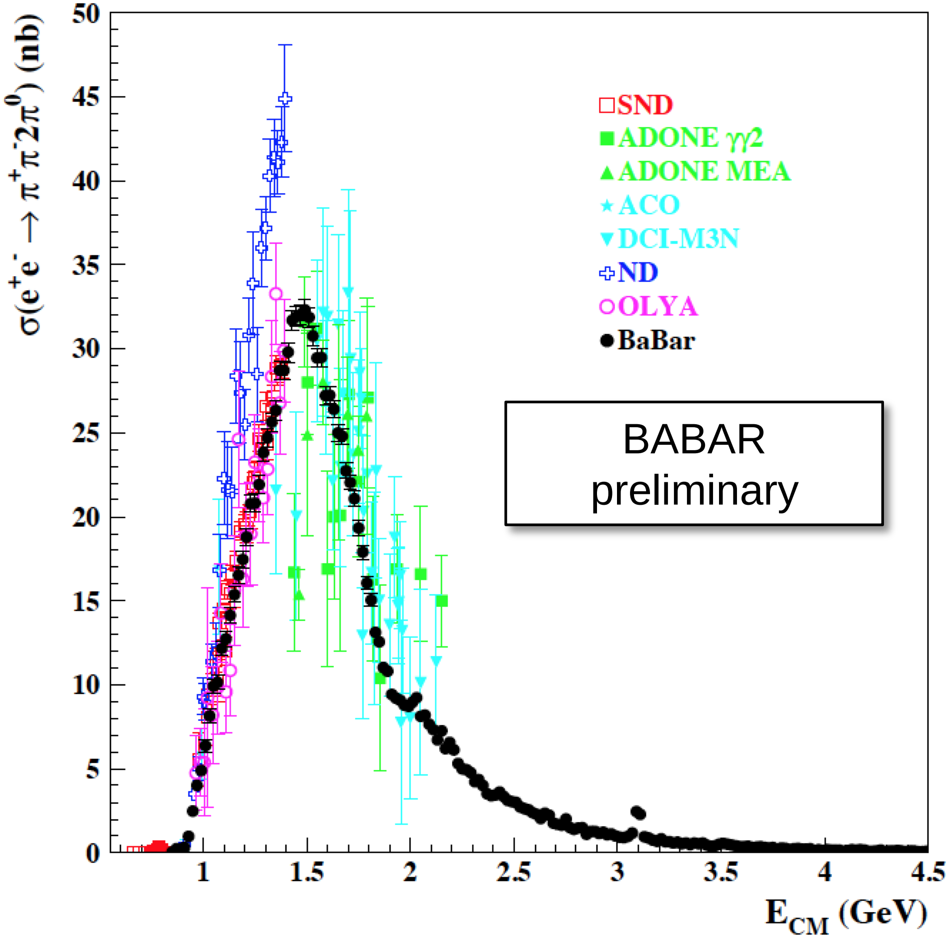
Source	Syst. Now (goal)	Comment
$e/\mu/\pi$ separation	0.5-1.5% (0.2%)	comparison of two methods; correlated to r.c.
fiducial volume	0.3-0.5% (0.1%)	two independent measurements; angular distribution
beam energy	0.1% (0.1%)	continuous monitoring via Compton
radiative corrections	0.2% (0.1%)	working on improving MCGPJ
Detection efficiencies	0.5-1.5% (0.1%)	Mainly at lowest energies due to pion decays; working on studying decay events

- For most sources of systematics there is clear way how to bring it down
- For 2013 data we aim at sub-% accuracy
- Statistical accuracy matches or better the current world-best

Statistical accuracy of 2013 data



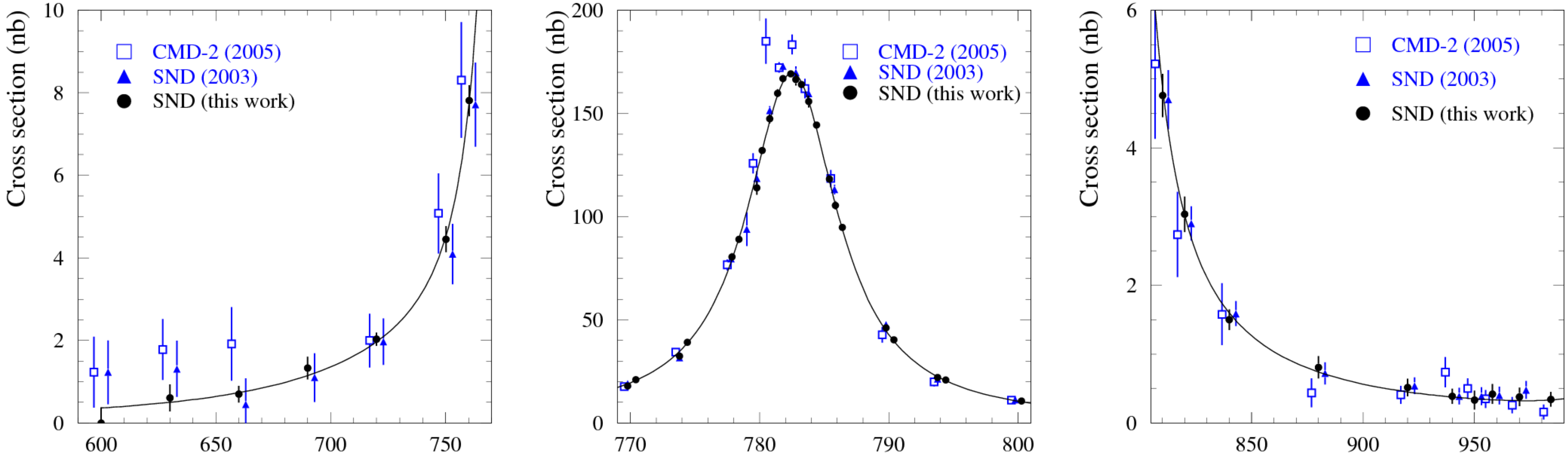
$e^+e^- \to \pi^+\pi^-\pi^0\pi^0$ @ BABAR

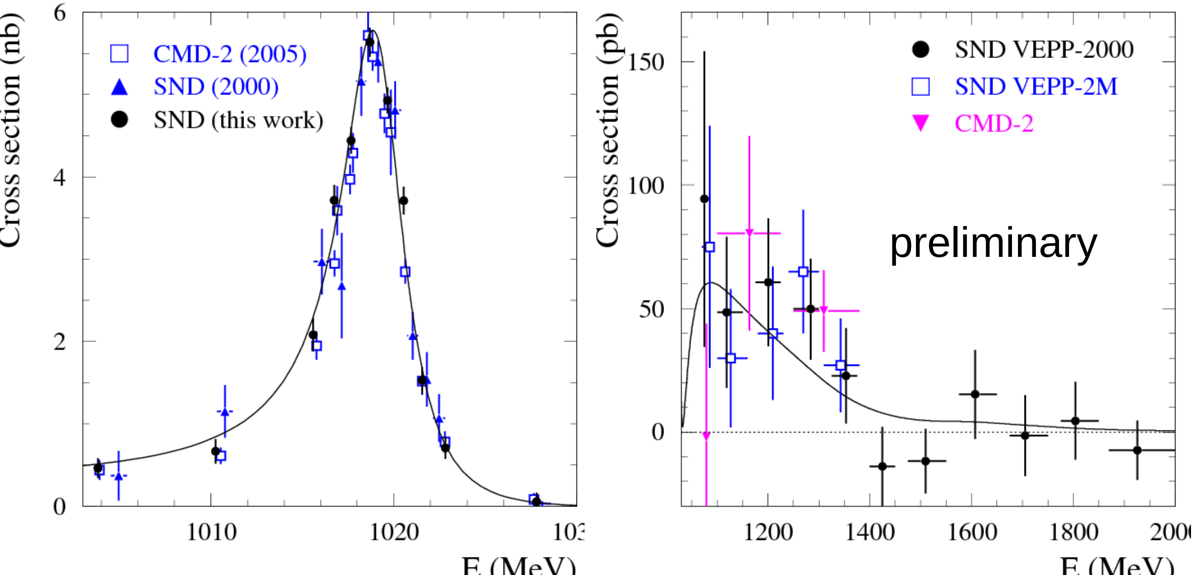


- BABAR results are most precise and covers wider energy range
- Systematic uncertainty is 3.1% in the 1.2-2.7 GeV energy range.
- Contribution to a_μ for the range $1.02<E_{CM}<1.8$ GeV is measured to be $[17.5 \pm 0.6$ (stat+syst)$] \times 10^{-10}$ (3.4% precision)
- Previous result including the preliminary BABAR data from 2007 is $[18.0 \pm 1.2$ (stat+syst)$] \times 10^{-10}$ (6.7% precision)

Phys. Rev. D 93, 092001 (2016)

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

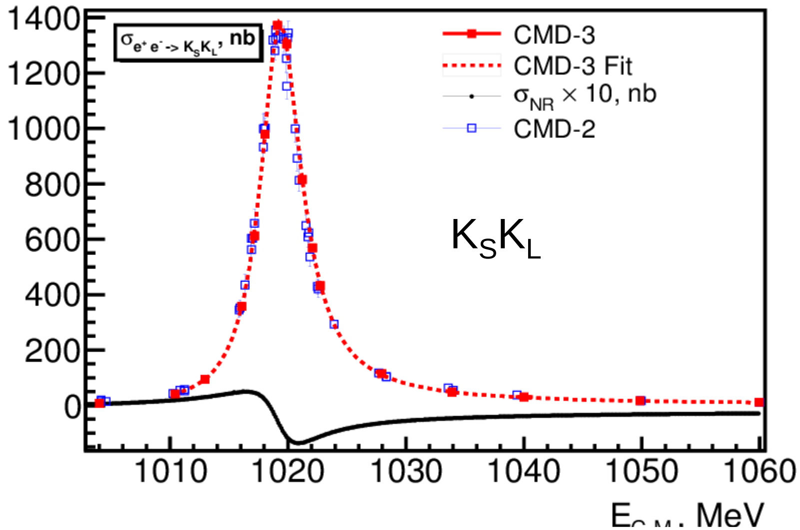




✓ The most precise measurement of the cross section

✓ Systematic uncertainty at the ω peak is 1.4% (1.2% from luminosity and 0.6% due to selection criteria)

$e^+e^- \to K^+K^-$ and K_SK_L @ CMD-3



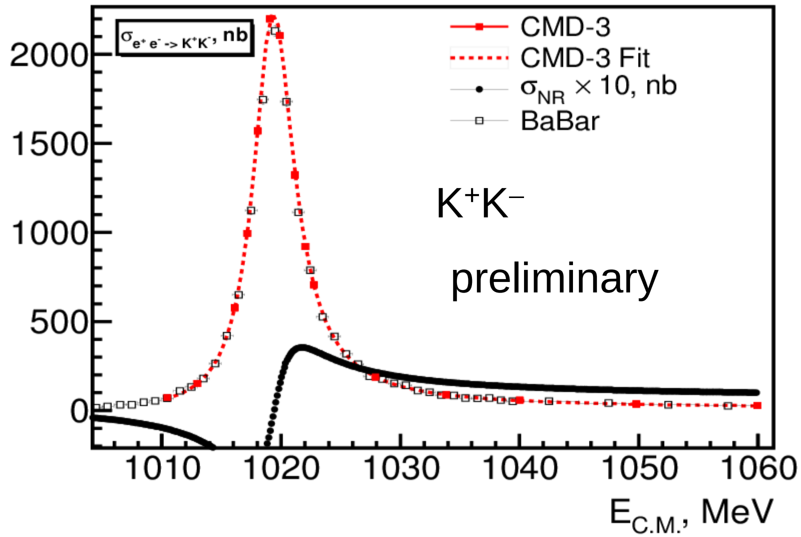
E.A Kozyrev et al., Phys. Lett. B 760 (2016) 314

$\Gamma(\phi\to e^+e^-)B(\phi\to K_SK_L) = 428 \pm 9$ eV

PDG2016 430 ± 6 eV

$$\frac{g_{\phi K^+K^-}}{g_{\phi K_SK_L}}\frac{1}{Z(m_\phi)} = 0.990 \pm 0.017$$

BABAR 0.972 ± 0.017

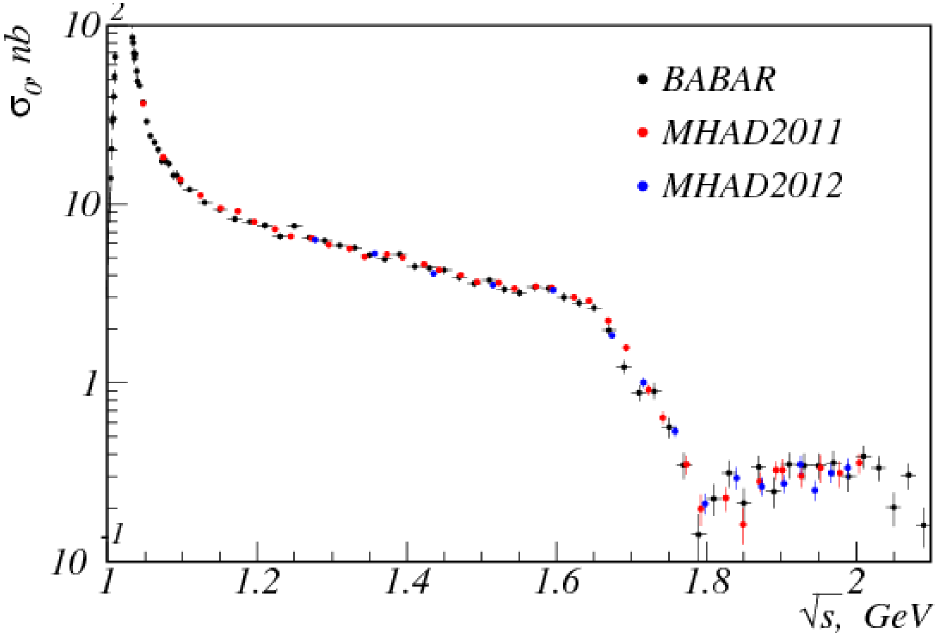


$\Gamma(\phi\to e^+e^-)B(\phi\to K^+K^-) = 671 \pm 20$ eV

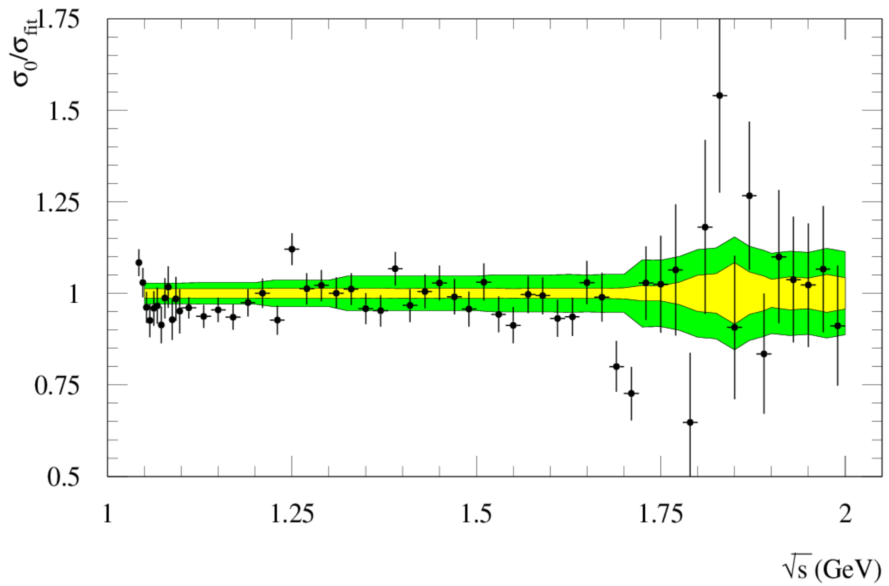
PDG2014 (CMD-2) 608 ± 14 eV

BABAR 634 ± 8 eV

$e^+e^- \to K^+K^-$ @ SND



(BABAR data)/(SND fit) ratio



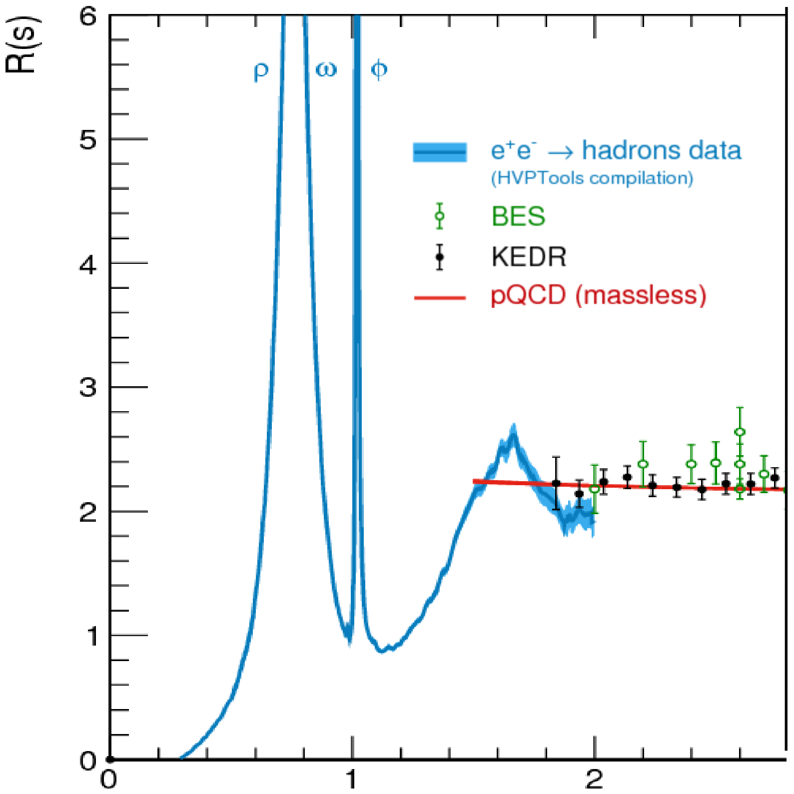
The SND measurement agrees with the BABAR data and has comparable or better accuracy.

Phys. Rev. D 94, 112006 (2016)

The green and yellow bands represent the BABAR and SND systematic uncertainties

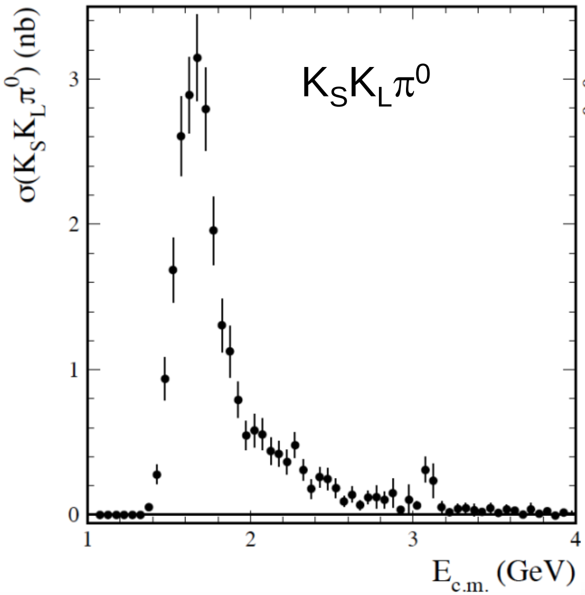
Energy region near 2 GeV

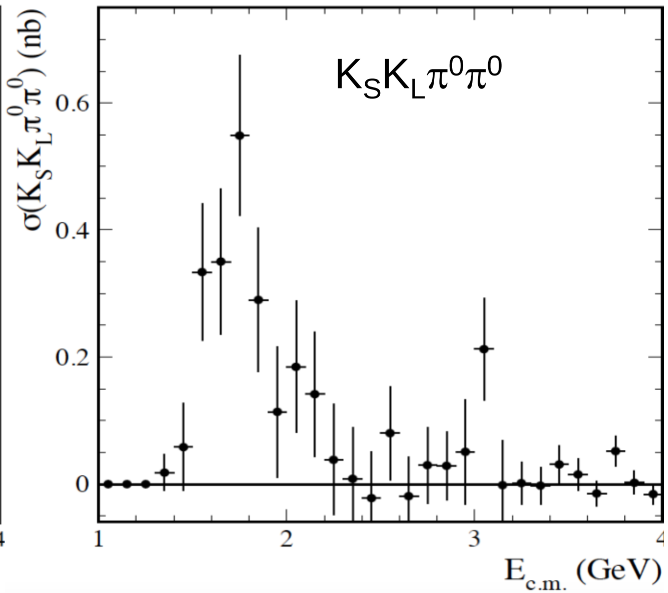
- At E < 2 GeV the total cross section is calculated as a sum of exclusive channels.
- The exclusive data are incomplete in the region 1.6<E<2.0 GeV.
- There is no experimental information on the final states $\pi^+\pi^-\pi^0\eta$, $\pi^+\pi^-\eta\eta$, $\pi^+\pi^-\pi^0\pi^0\pi^0$, $\pi^+\pi^-\pi^0\pi^0\eta$ …)
- The important experimental task is to measure all significant exclusive channels below 2 GeV, and perform comparison with inclusive measurements and pQCD prediction.
- New inclusive data below 2 GeV may be obtained by SND and CMD-3

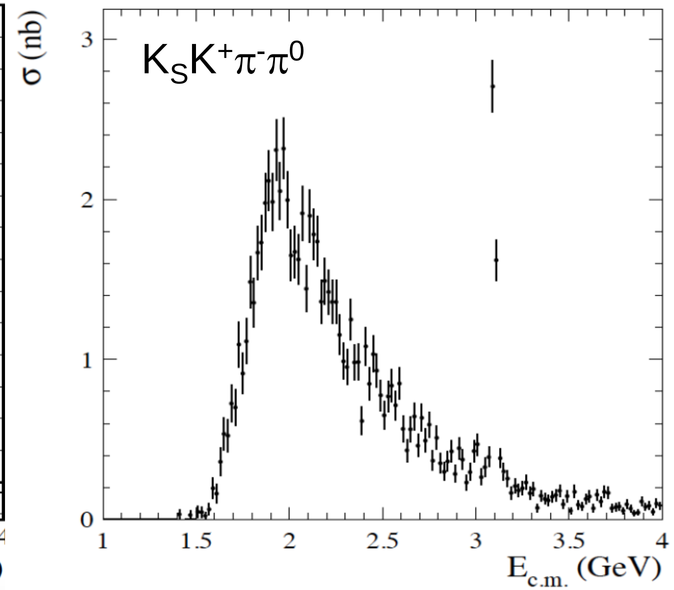


$e^+e^- \to K_SK_L\pi^0, K_SK_L\pi^0\pi^0, K_SK^+\pi^-\pi^0$ @ BABAR

Phys. Rev. D 95, 052001 (2017) arXiv: 1704.05009





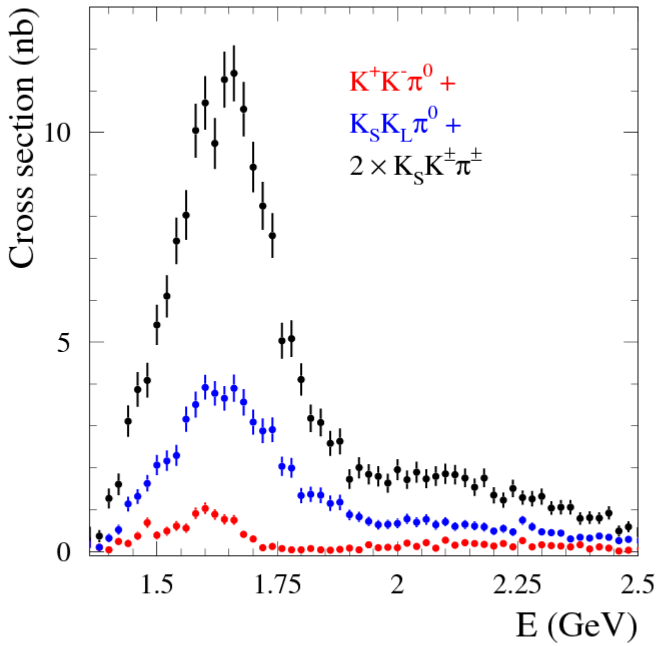


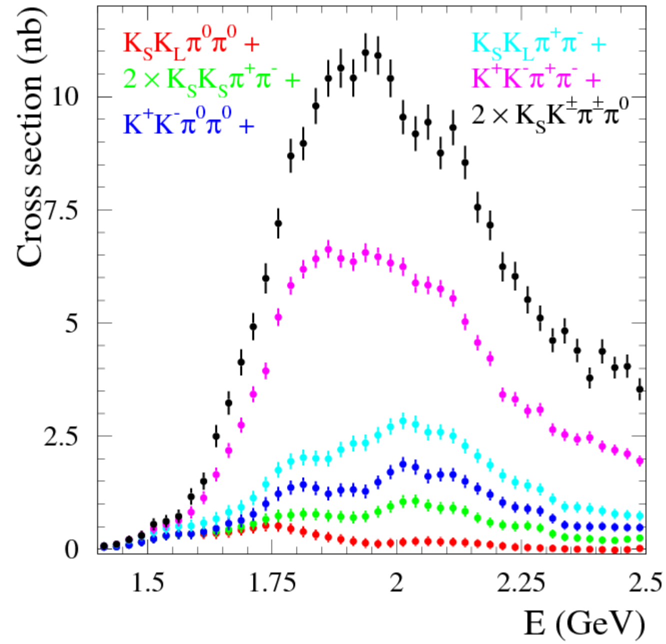
✓ First measurement
✓ Systematic uncertainty is 10% near the peak, grows to 30% at 3.0 GeV
✓ Dominant $K^*(892)\bar{K}$ intermediate state

- First measurement
- Systematic uncertainty is 25% at the peak, grows to 60% at 2 GeV
- Dominant $K^*(892)\bar{K}\pi$ intermediate state.

- First measurement
- Systematic uncertainty is 6-7% below 3 GeV
- Dominant $K^*(892)\bar{K}\pi$, $K_SK^+\rho^-(770)$ intermediate state.

Total $e^+e^- \to K\bar{K}\pi$ and $K\bar{K}\pi\pi$ cross sections





✓The $e^+e^- \to K_SK^+\pi^-$ and $K^+K^-\pi^0$ cross sections were measured previously.

✓The $e^+e^- \to K\bar{K}\pi$ cross section is about 12% of the total hadronic cross section at 1.65 GeV.

✓There are six charge combinations in the $e^+e^- \to KK\pi\pi$ process . Four ($e^+e^- \to K^+K^-\pi^0\pi^0$, $K^+K^-\pi^+\pi^-$, $K_SK_S\pi^+\pi^-$, $K_SK_L\pi^+\pi^-$) were measured previously.

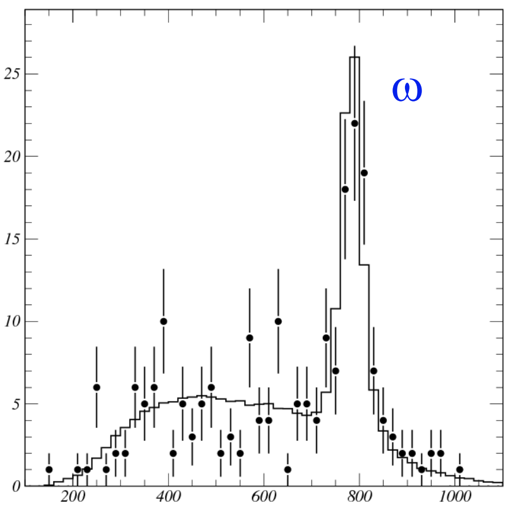
✓ The $e^+e^- \to K\bar{K}\pi\pi$ cross section is calculated without any model assumptions.

✓It is about 25% of the total hadronic cross section at 2 GeV.

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

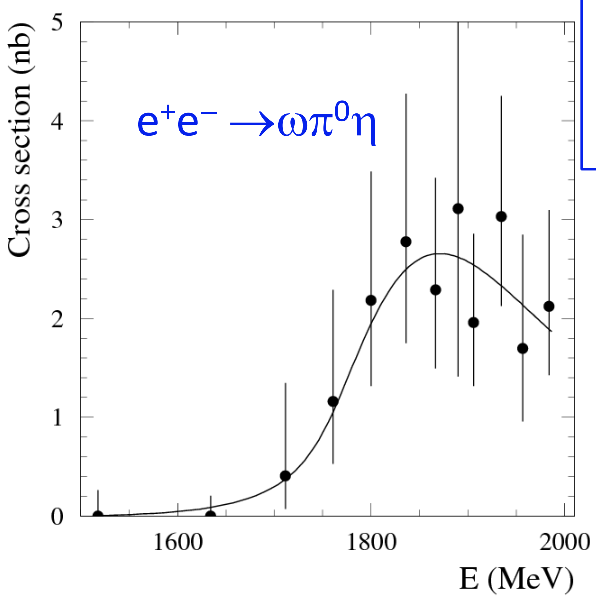
Phys. Rev. D 94,032010 (2016)

7 photon final state
$e^+e^- \to \pi^0\pi^0\eta\gamma \to 7\gamma$

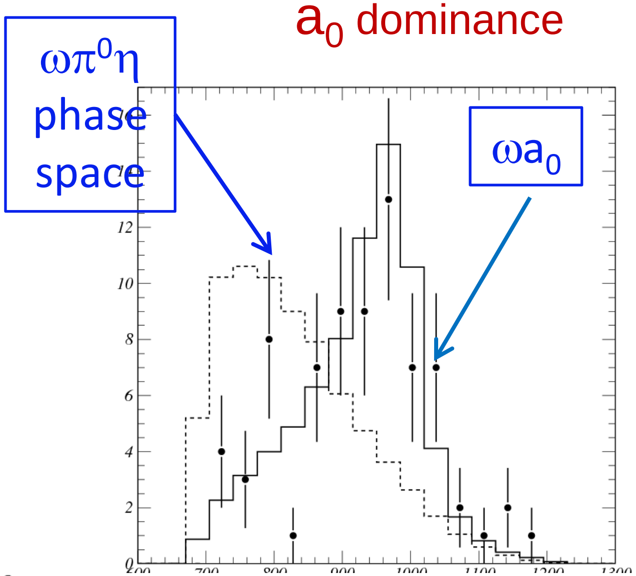


$\pi^0\gamma$ mass

Total cross section



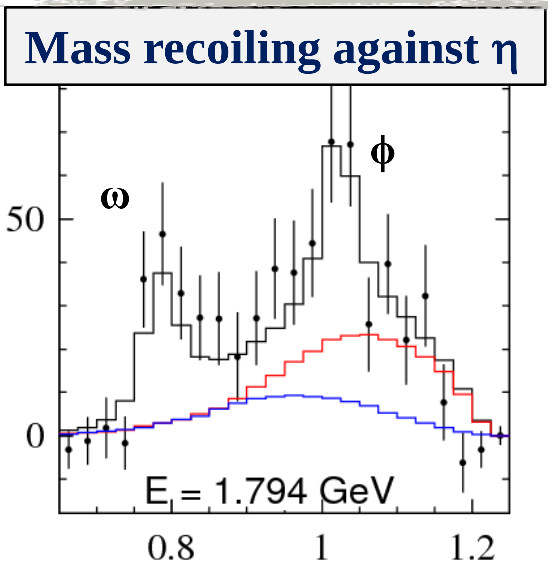
a_0 dominance

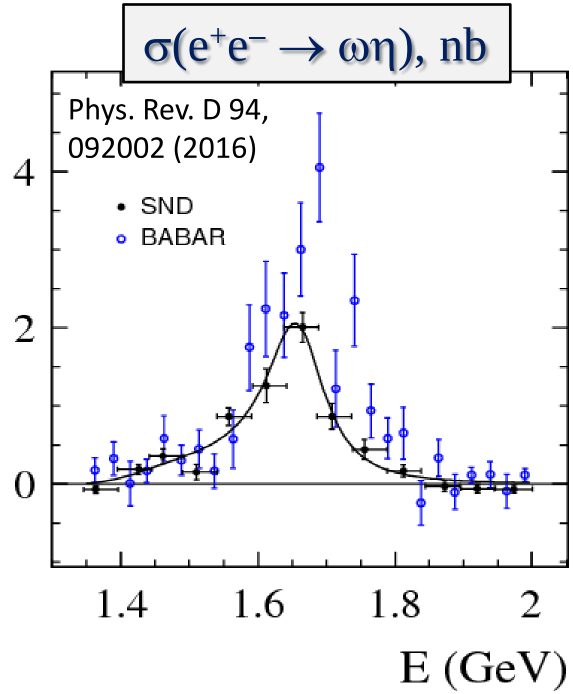


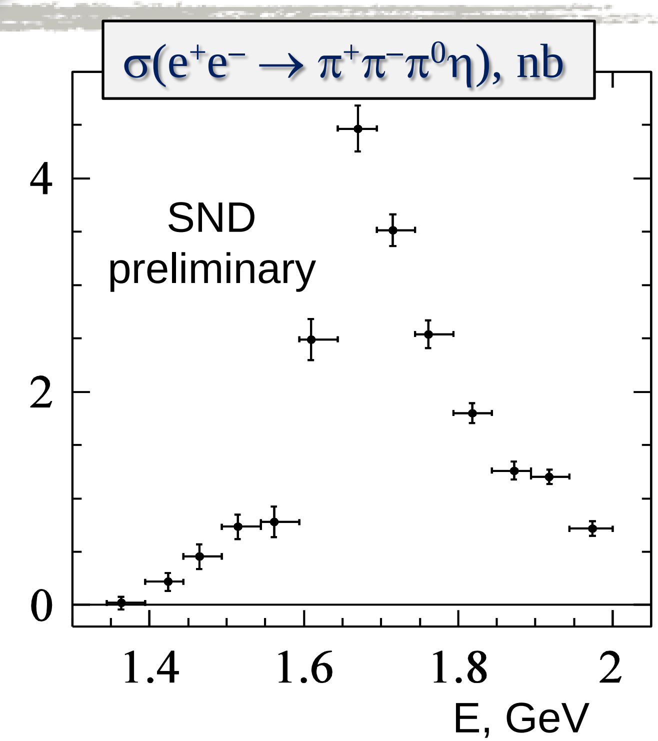
$\eta\pi^0$ mass

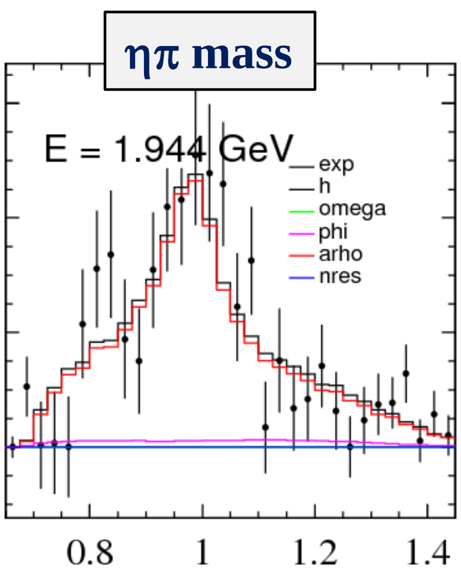
- First measurement of the $e^+e^- \to \omega\pi^0\eta$ cross section.
- The dominant mechanism is $\omega a_0(980)$.
- The cross section is about 2.5 nb, 5% of the total hadronic cross section

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









- First measurement of the process $e^+e^- \to \pi^+\pi^-\pi^0\eta$
- The intermediate states are $\omega\eta$, $\varphi\eta$, $a_0\rho$ and structureless $\pi^+\pi^-\pi^0\eta$
- The known $\omega\eta$ and $\varphi\eta$ contributions explain about 50-60% of the cross section below 1.8 GeV.
- Above 1.8 GeV the dominant reaction mechanism is $a_0\rho$

Summary

- ✓ Precise low-energy e^+e^- hadronic cross section data are needed to obtain an accurate SM prediction for $a_\mu^{had,LO-VP}$
- ✓ Recent results on the $e^+e^- \to \pi^+\pi^-$, $\pi^+\pi^-\pi^0\pi^0$, $K\bar{K}$, $K\bar{K}\pi$, $K\bar{K}\pi\pi$ cross sections from BES III, BABAR, SND, CMD-3 and R measurement from KEDR reduce the uncertainty on $a_\mu^{had,LO-VP}$
- ✓ Several previously unmeasured processes contributed to the total hadronic cross section ($e^+e^- \to K_SK_L\pi^0$, $K_SK_L\pi^0\pi^0$, $K_SK^+\pi^-\pi^0$, $\omega\pi^0\eta$, $\pi^+\pi^-\pi^0\eta$) below 2 GeV have been studied
- ✓ New results are expected from BES III, BABAR, SND, CMD-3