Recent Results on $e^+e^- \to$ hadrons from the VEPP-2000 Collider

Simon Eidelman

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

Outline

1. Muon $g-2$
2. $e^+e^- \to \pi^+\pi^-$
3. Results from CMD-3 and SND at VEPP-2000
4. Future and prospects

Two Trends in Modern High Energy Physics

Major achievements coming from:

1. Energy Frontier:
   - LHC and Higgs discovery
   - (before that) Tevatron studied t quark physics and QCD
   - LEP and Standard Model success
2. Intensity/Precision Frontier:
   - E821 – a_μ; a_e and α
   - ϕ and B factories – R studies, CP violation, new $c\bar{c}$ and $b\bar{b}$ states, exotics (tetraquarks, pentaquarks)
   - Proton radius

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
   - $(g_\mu - 2)/2$
   - $\alpha(M_Z^2)$
   - QCD sum rules (α_s, quark and gluon condensates)

Muon Anomalous Magnetic Moment

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

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

Any significant difference of $a_\mu^{\rm exp}$ from $a_\mu^{\rm th}$ indicates
New Physics beyond the Standard Model.

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

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

Experimental Status of a_l

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

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

$a_\mu = 116592091(63) \times 10^{-11}$ 0.54×10^{-6}

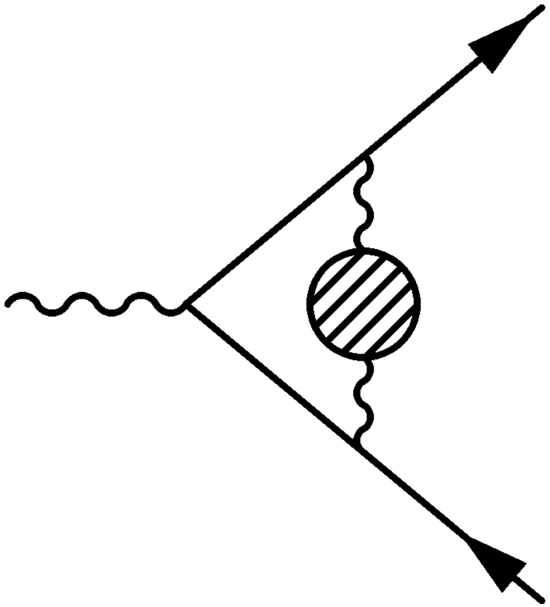
G.W. Bennett et al. (E821), PRD 73, 072003 (2006)
Sensitive test of the Standard Model

$a_\tau = -0.018(17)$ or $-0.052 < a_\tau < 0.013$ 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)

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

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



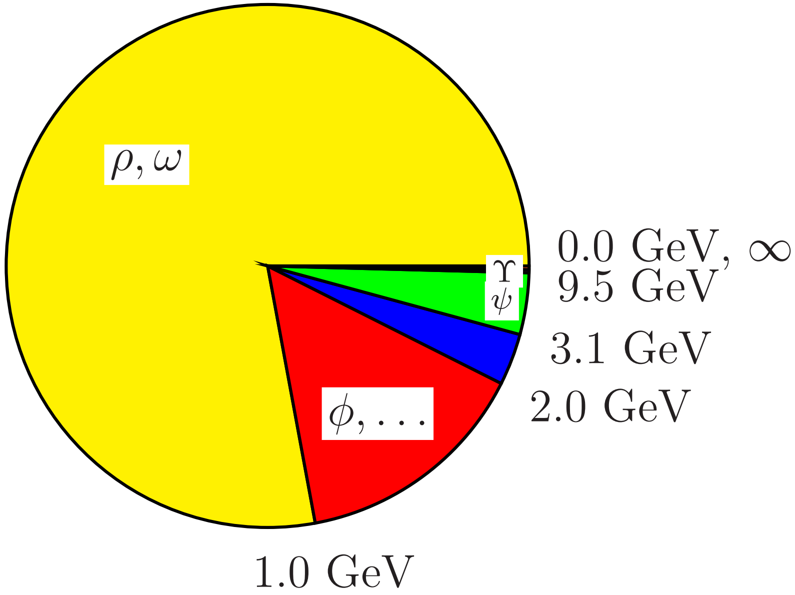
$$a_\mu^{\rm had,LO} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} ds \, \frac{R(s)\,\hat{K}(s)}{s^2},$$

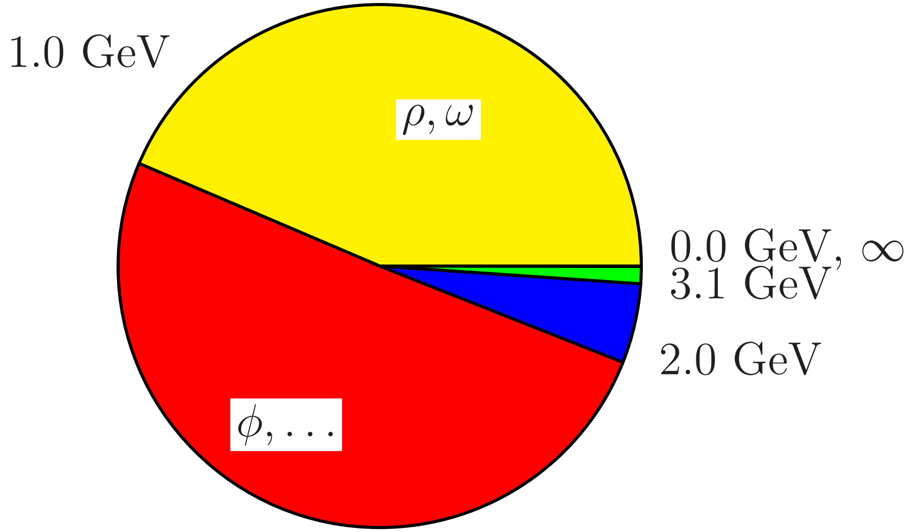
C. Bouchiat, L. Michel, Bouchiat, 1961;
M. Gourdin, E. de Rafael, 1969

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

$\hat{K}(s)$ grows from 0.63 at $s = 4m_\pi^2$ to 1 at $s \to \infty$,
$1/s^2$ emphasizes low energies, particularly $e^+e^- \to \pi^+\pi^-$.
$a_\mu^{\rm had,LO} \sim 700 \cdot 10^{-10}$ $\Rightarrow$ 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 $e^+e^- \to \pi^+\pi^-$ and more than 90% from the energy range below 2 GeV

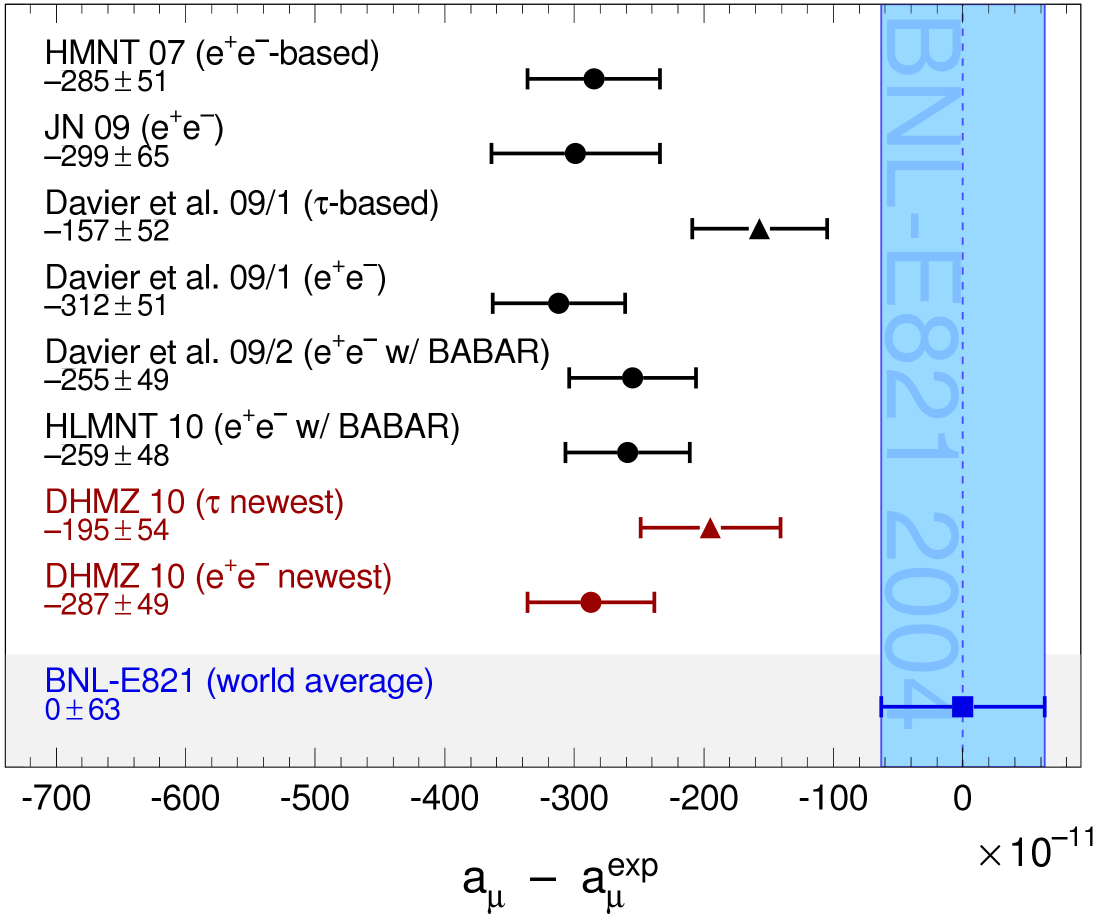
Experiment vs. Theory – I

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

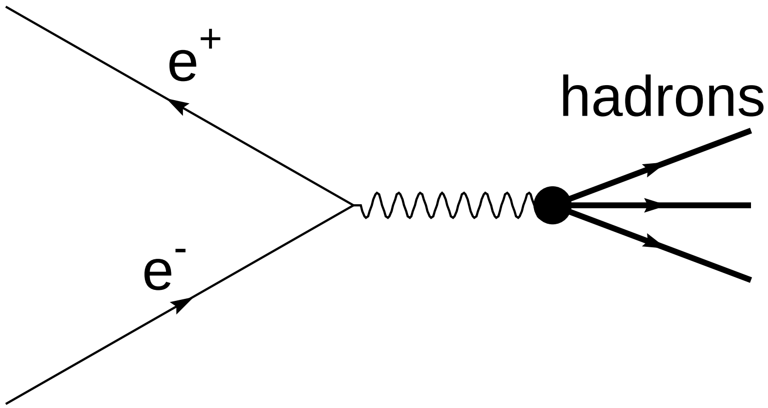
Experiment	$11659209.1 \pm 5.4 \pm 3.3$
QED	11658471.895 ± 0.008
EW	15.4 ± 0.1
Had LO	692.3 ± 4.2
Had HO	-9.8 ± 0.1
Had LbL	10.5 ± 2.6
Theory	11659180.3 ± 4.9
Exp.-Th.	28.8 ± 8.0

Experiment is higher than theory by 3.6 standard deviations

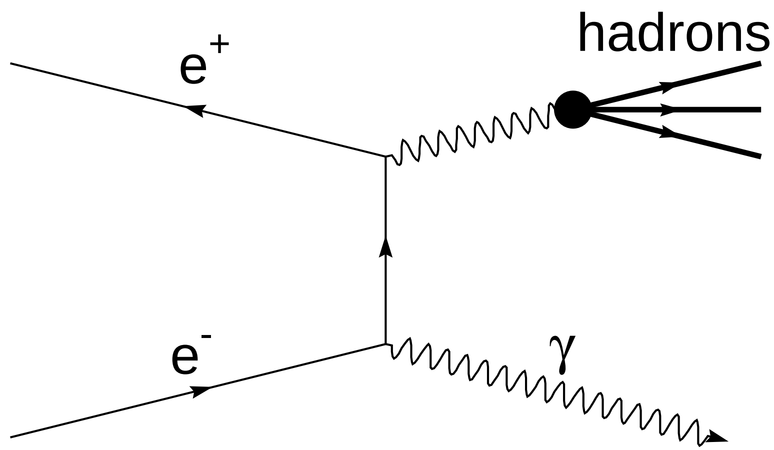
Experiment vs. Theory – II



Scan and ISR



Scan



ISR

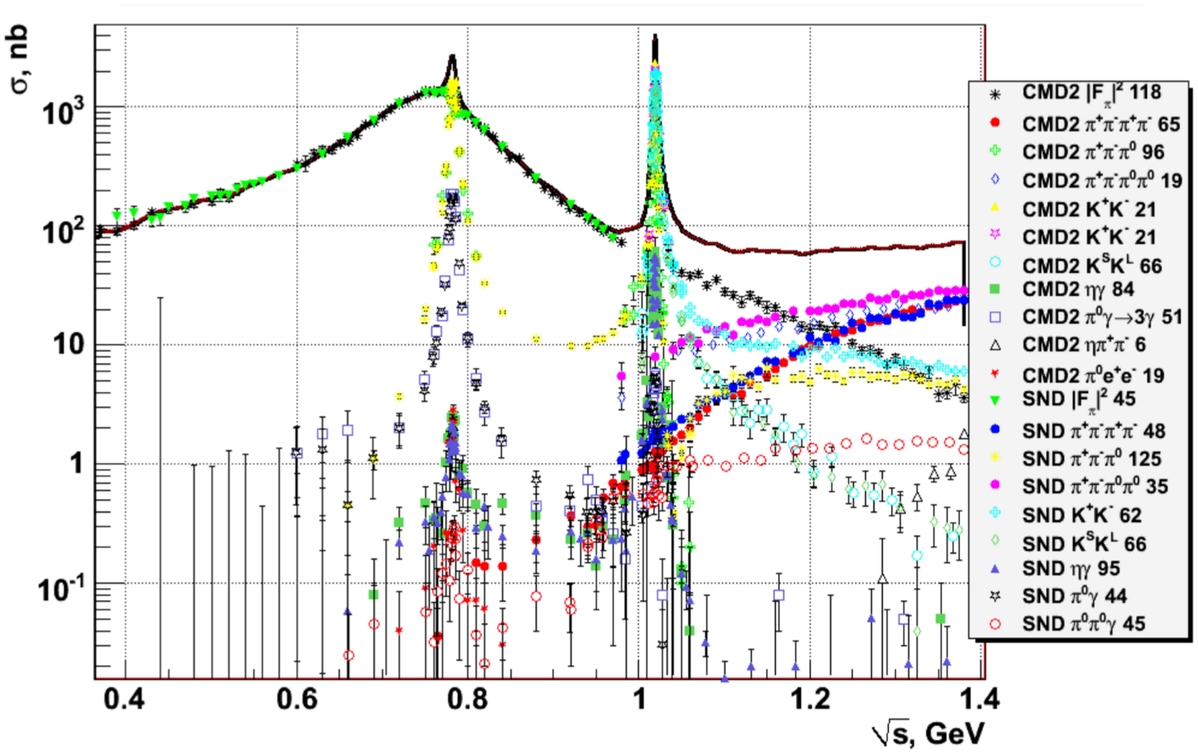
Scan can provide larger data samples at fixed energy

ISR benefits from the same systematics and flat acceptance,

but may suffer from more complicated radiative effects,

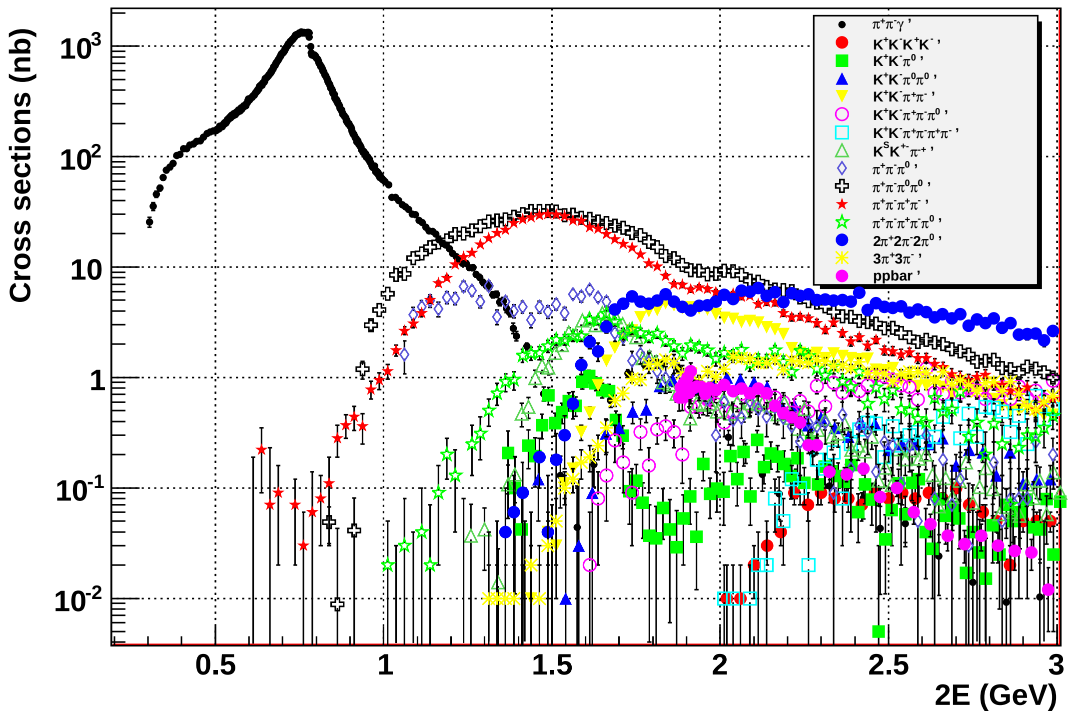
a broad range of collision energies

Current Status of Exclusive Measurements – I



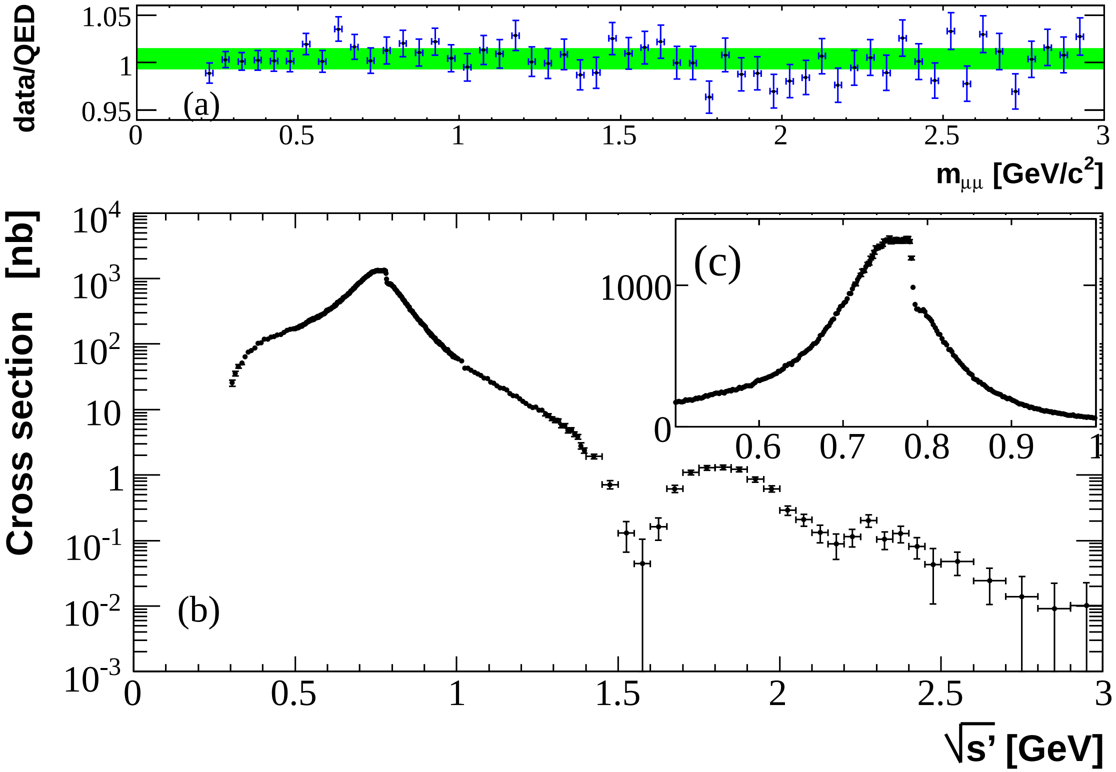
Impressive achievements of CMD-2, SND (scan at $\sqrt{s} < 1.4$ GeV)
and KLOE (ISR at $\sqrt{s} < 1.0$ GeV)

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

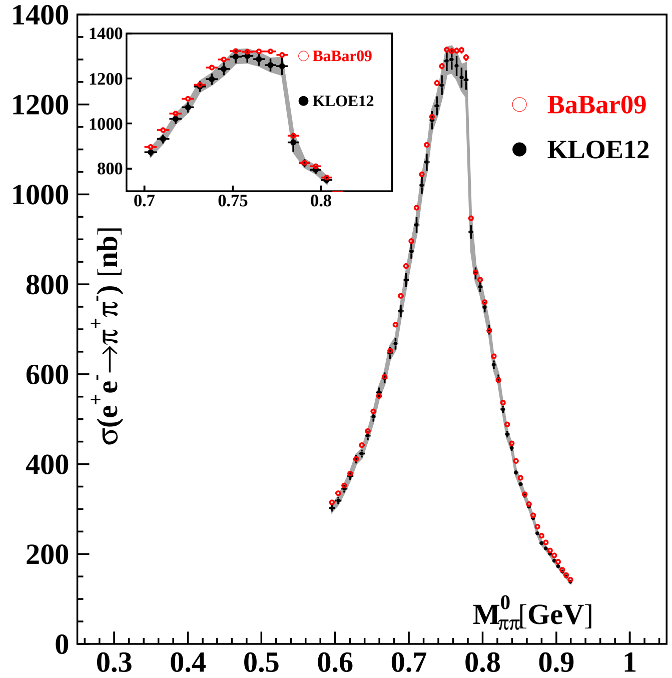
$e^+e^- \to \pi^+\pi^-$ at BaBar



The systematic error near the ρ is 0.5%

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

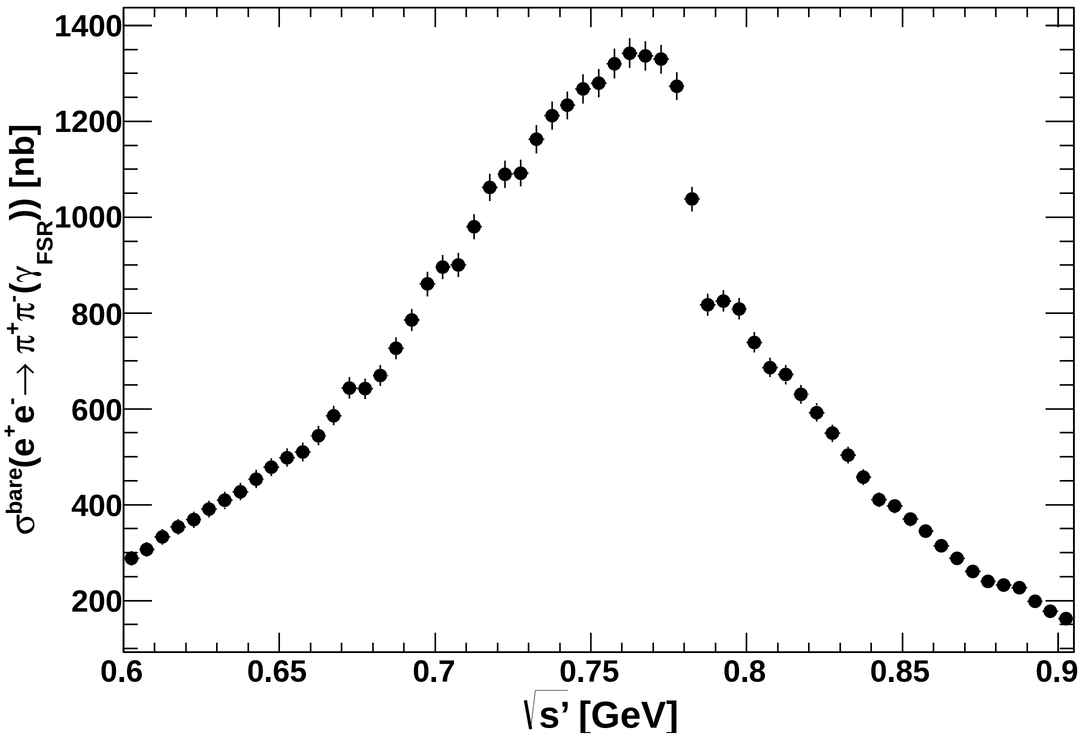
$e^+e^- \to \pi^+\pi^-$ at KLOE/KLOE-2



The systematic error is 0.7%

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

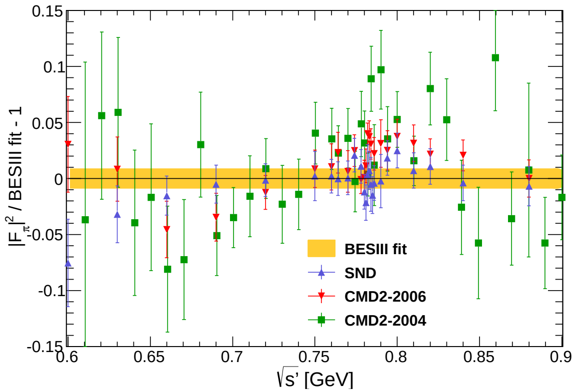
$e^+e^- \to \pi^+\pi^-$ with ISR at BESIII – I



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

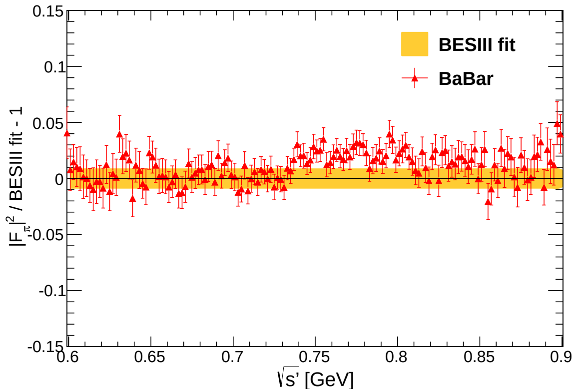
M. Ablikim et al., Phys. Lett. B 753 (2016) 629

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

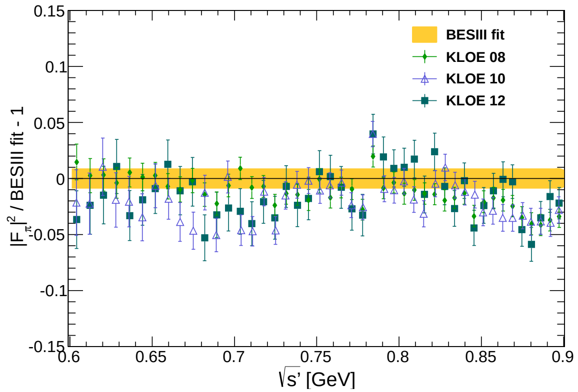


SND: JETP 103 (2006) 380

CMD-2: PLB 648 (2007) 28



BaBar: PRL 103 (2009) 231801



KLOE08: PLB 670 (2009) 285

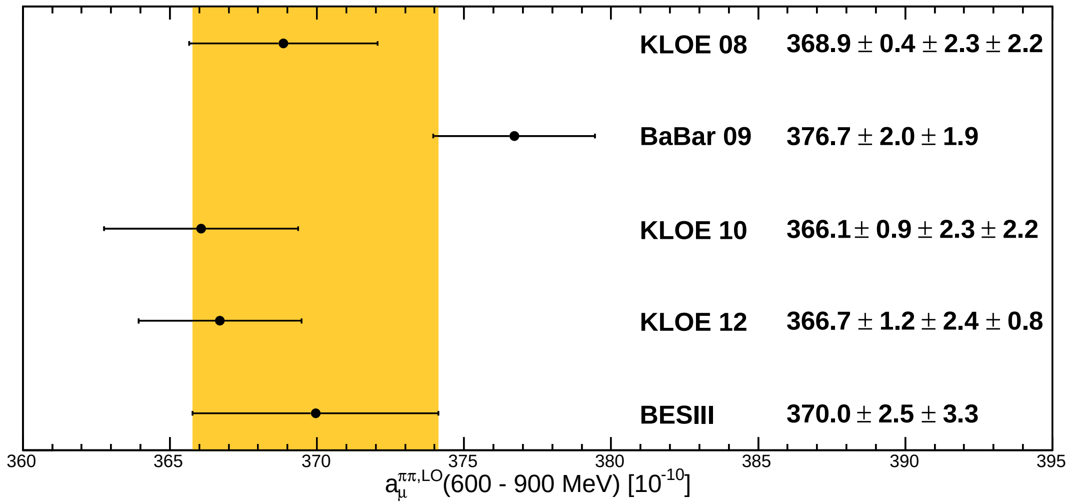
KLOE10: PLB 700 (2011) 102

KLOE12: PLB 720 (2013) 336

Agreement between different ISR results is far from perfect

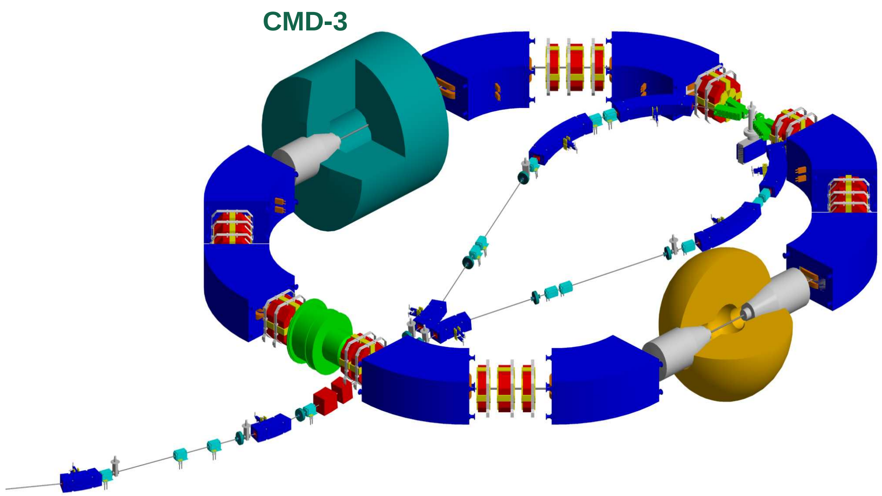
M. Ablikim et al., Phys. Lett. B 753 (2016) 629

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



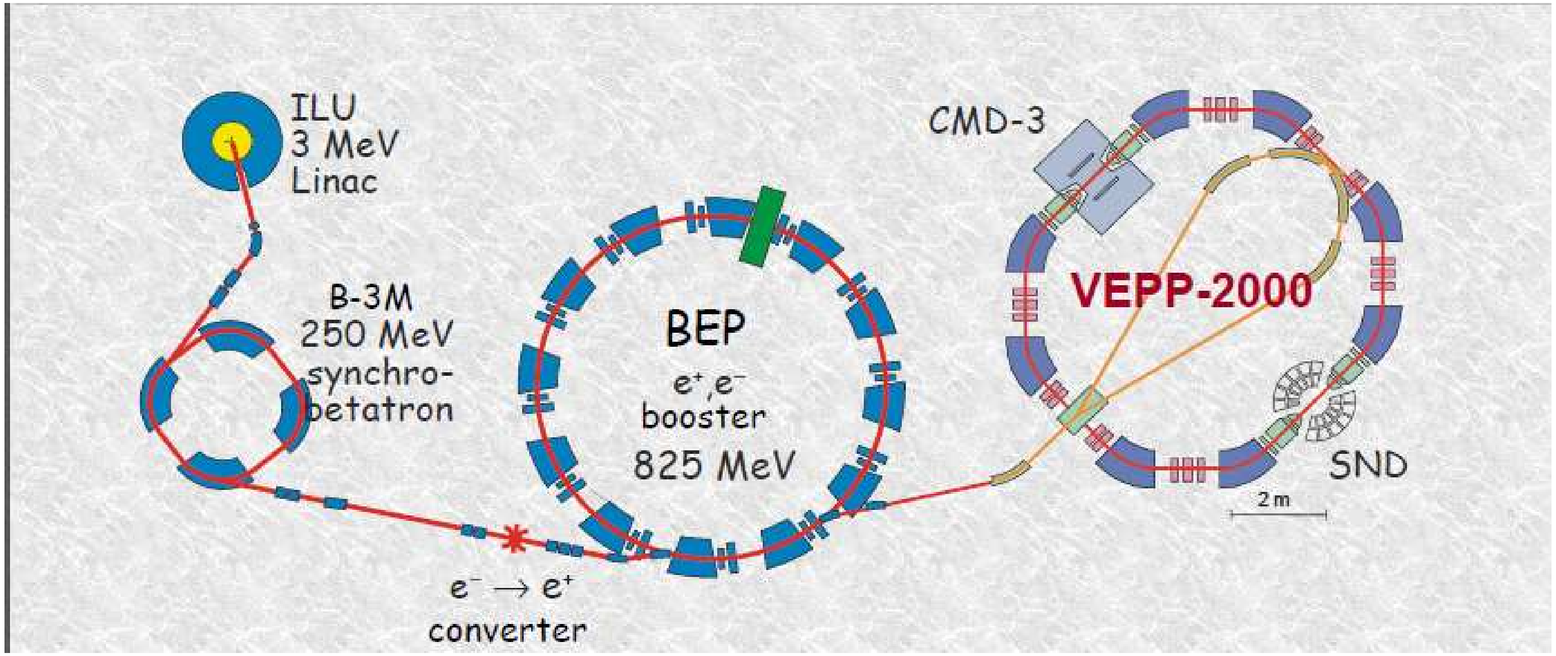
M. Ablikim et al., Phys. Lett. B 753 (2016) 629

VEPP-2000 – I



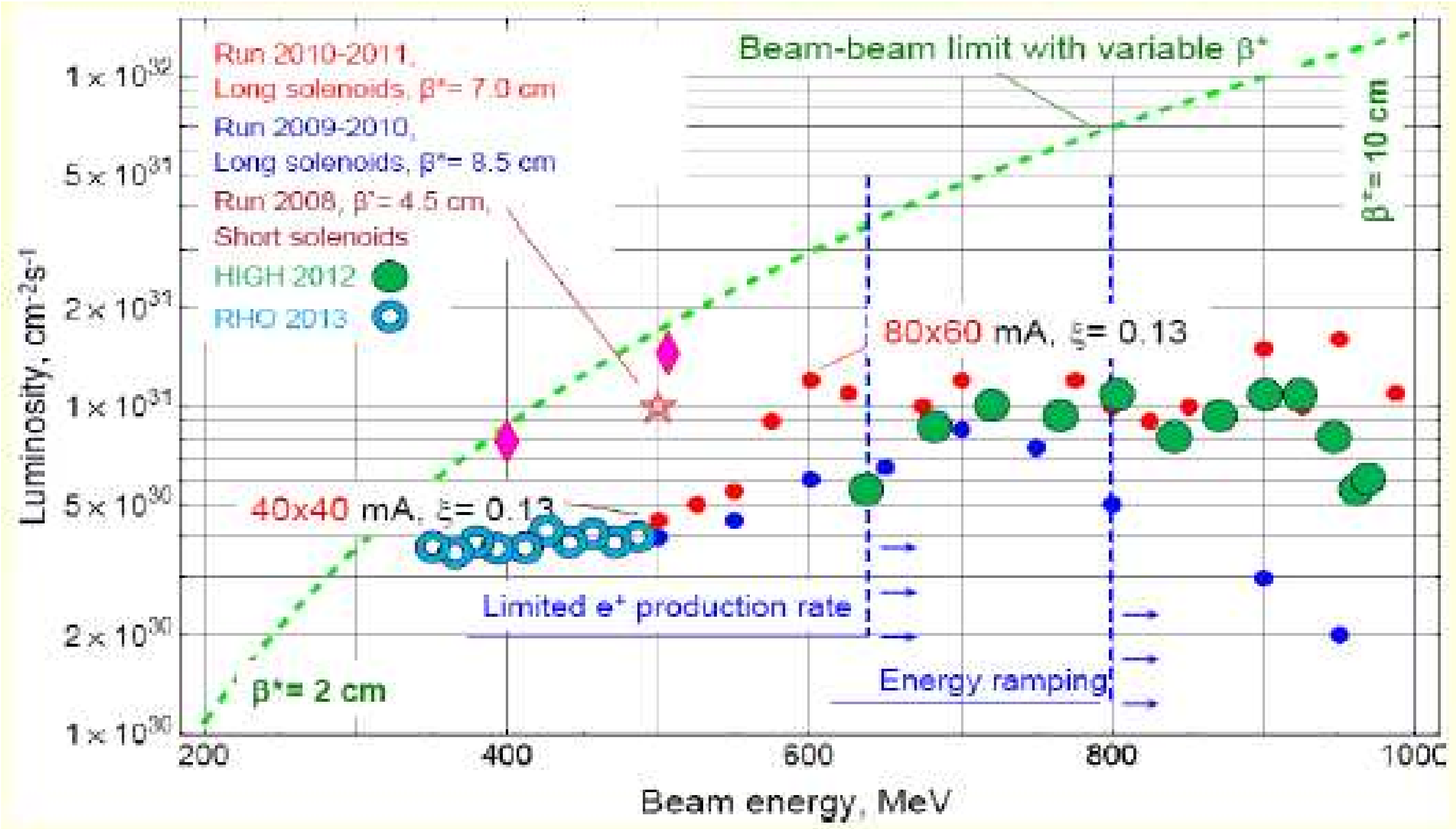
Collider	Operation	$\sqrt{s}$, MeV	$\mathcal{L}, 10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
VEPP-2M	1975-2000	[360,1400]	3
VEPP-2000	2010-	$[2m_\pi, 2000]$	100

VEPP-2000 – II

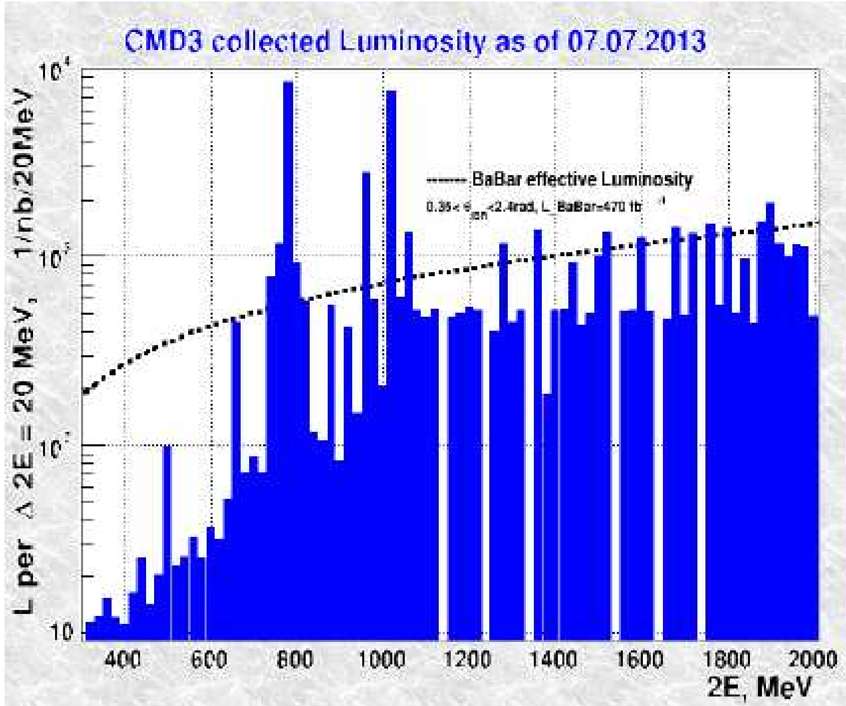


New optics with round beams ⇒ higher luminosity, precise beam energy measurement using LCBS

VEPP-2000 – III



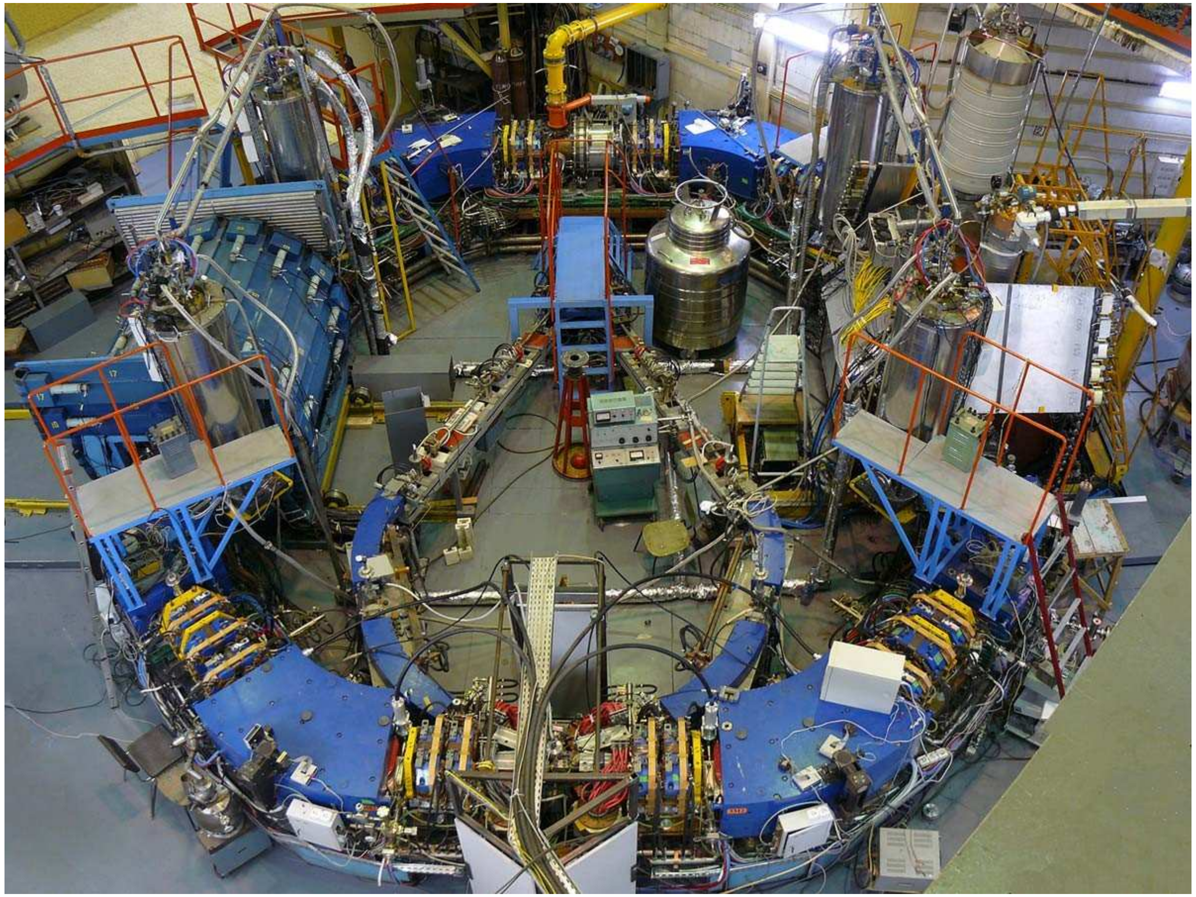
Data Taking at VEPP-2000



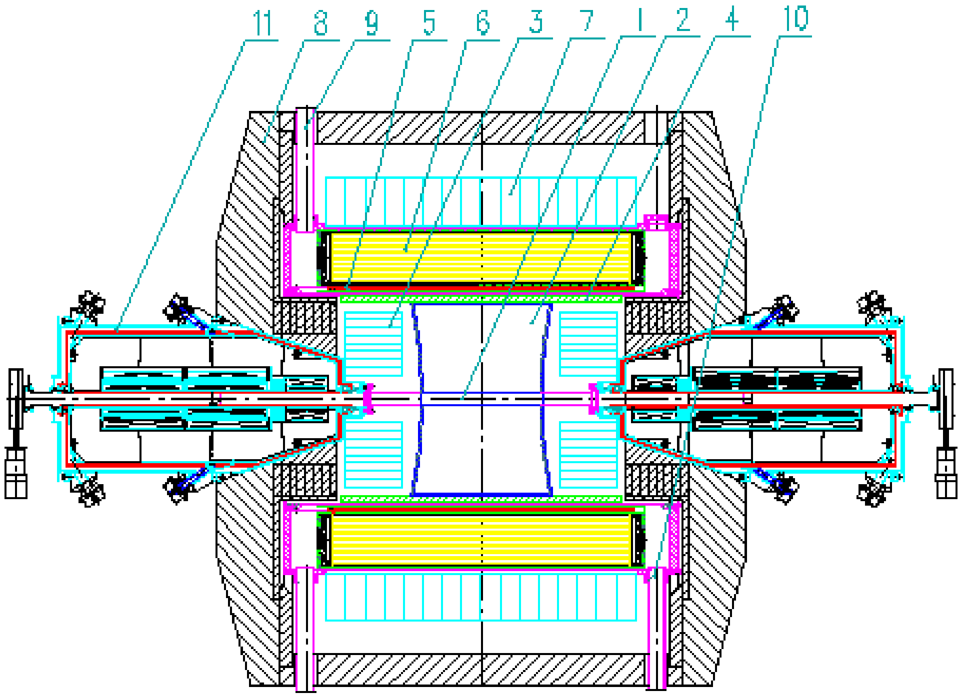
Collected L ~ 60 pb^{-1} per detector

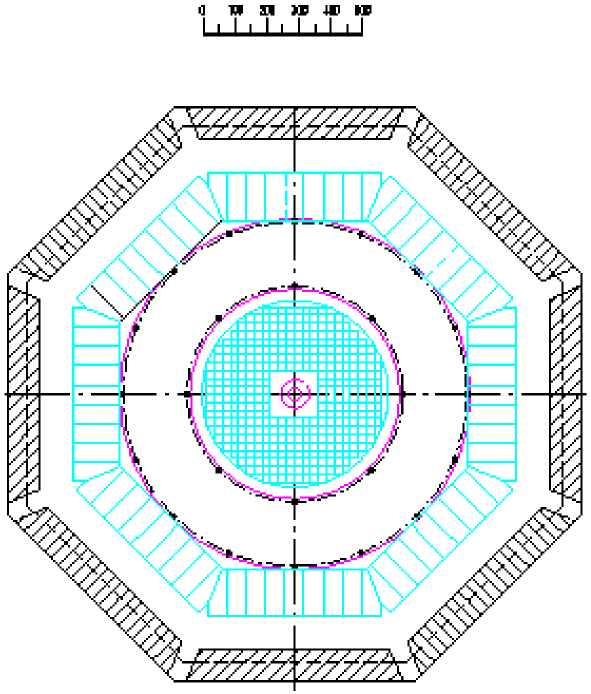
8.3 pb^{-1}	ω - region
9.4 pb^{-1}	< 1 GeV (except ω)
8.4 pb^{-1}	φ - region
34.5 pb^{-1}	> 1.04 GeV

VEPP-2000 and Detectors



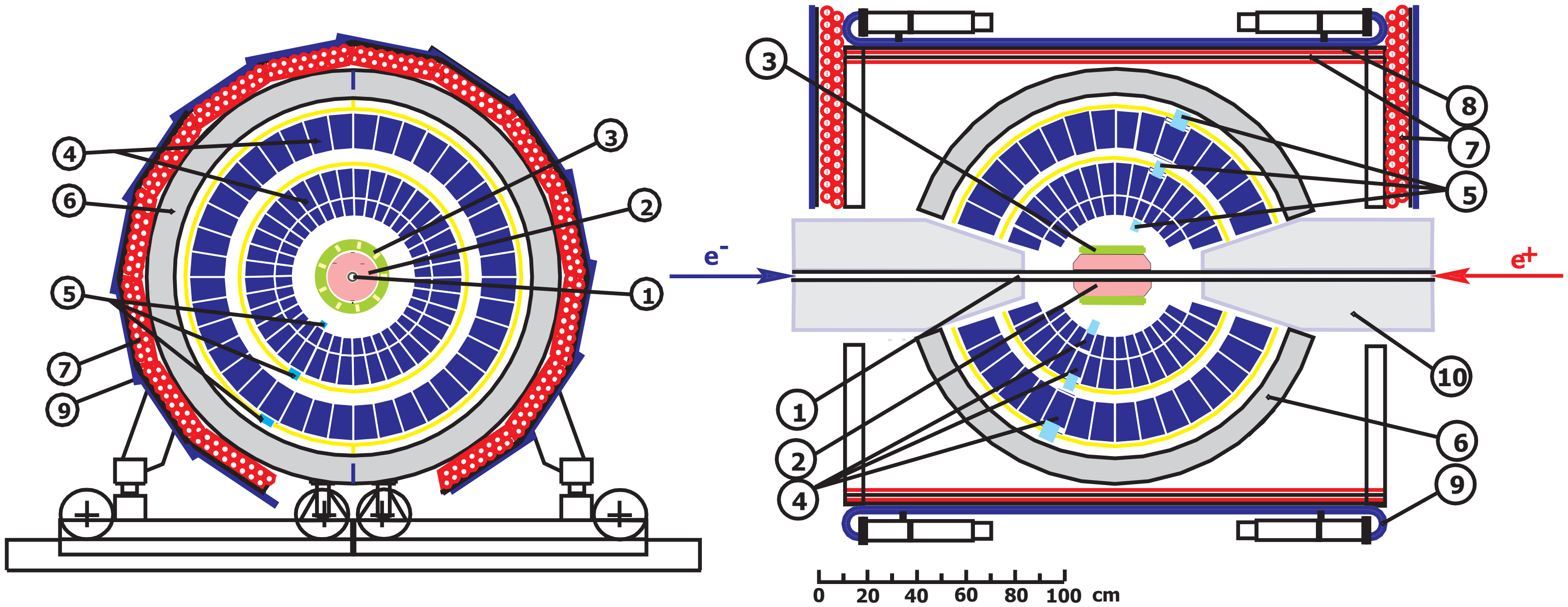
CMD-3





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

SND

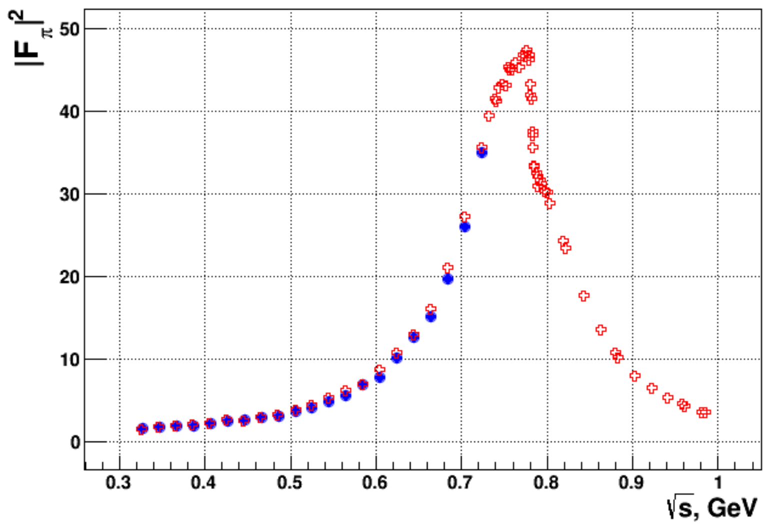


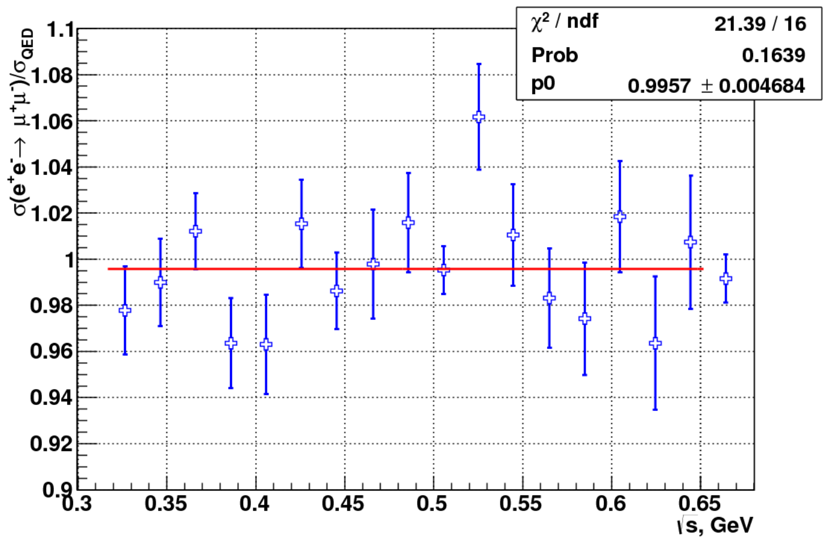
High-resolution NaI calorimeter with excellent tracking and PID

Performance of VEPP-2000 and Detectors

- The maximum luminosity is $2 \cdot 10^{31}$ cm^{-1}s^{-1} at 1.7-1.8 GeV, falling much slower with decreasing energy than before the round beams
- The integrated luminosity is about 60 pb^{-1} per detector, a factor of 6 higher than before from ϕ to 2 GeV, the number of multihadronic events per 1 pb^{-1} $\sim 50k$
- In 2013 we reached 2×160 MeV, the smallest $\sqrt{s}$ ever
- Both detectors perform reasonably well with reconstruction of both tracks and photons and redundancy $(\eta \to 2\gamma, \pi^+\pi^-\pi^0, 3\pi^0, \pi^+\pi^-\gamma, \omega \to \pi^+\pi^-\pi^0, \pi^0\gamma)$
- At high energies lumi is limited by a deficit of positrons and maximum energy of the booster (825 MeV now)
- During the shutdown (2015) to upgrade the booster (energy increase to 1 GeV) and commission the new injection complex to reach 10^{32} cm^{-1}s^{-1}

$e^+e^- \to \pi^+\pi^-$ at CMD-3 – I

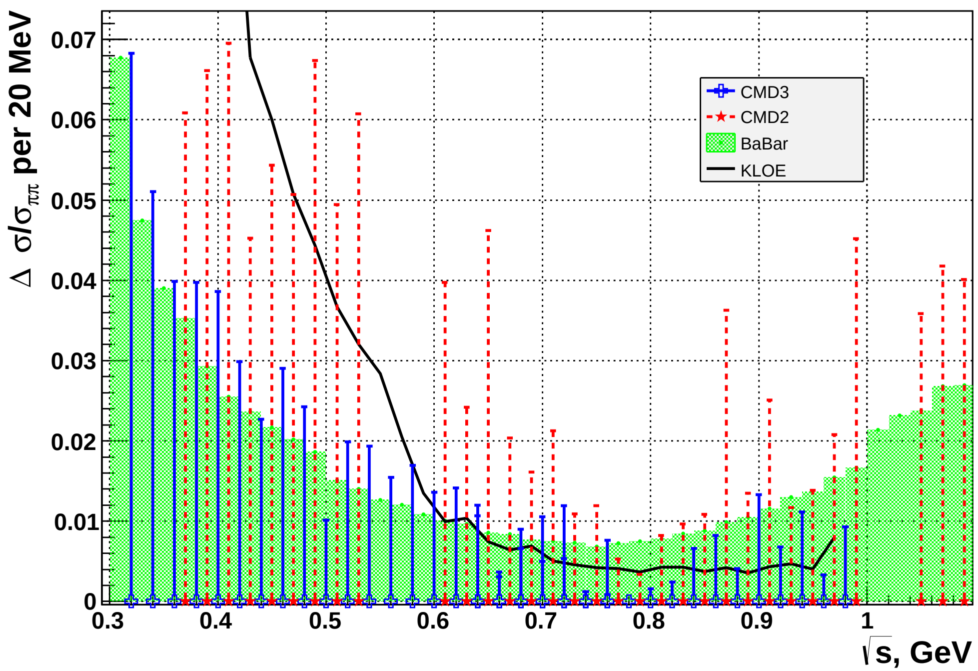




Identification at low energy - by DC with separation of $\mu^+\mu^-$

At high energy - by energy deposition in calorimeters

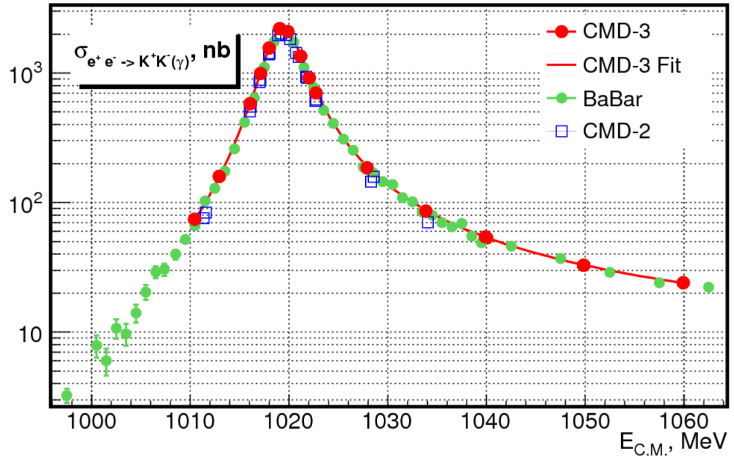
$e^+e^- \to \pi^+\pi^-$ at CMD-3 – II

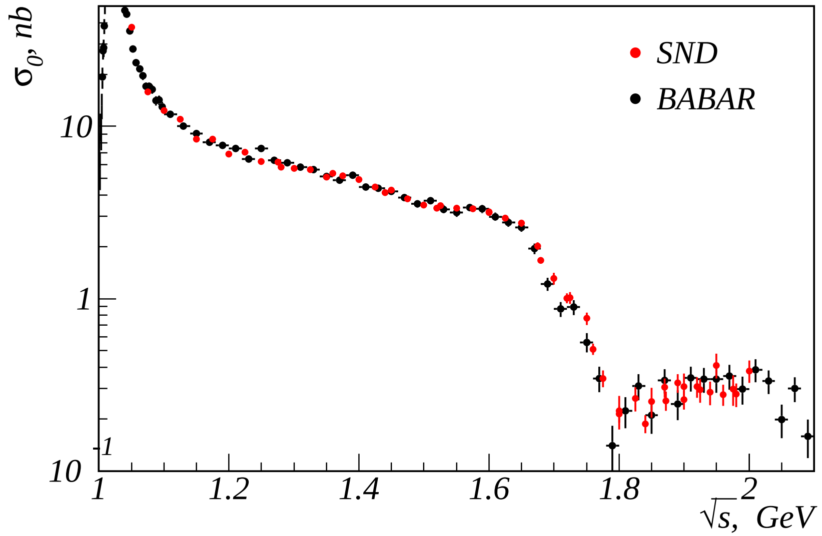


Statistical precision better than that of BaBar

Systematic error: goal 0.35% at the ρ (BaBar achieved 0.5%)

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

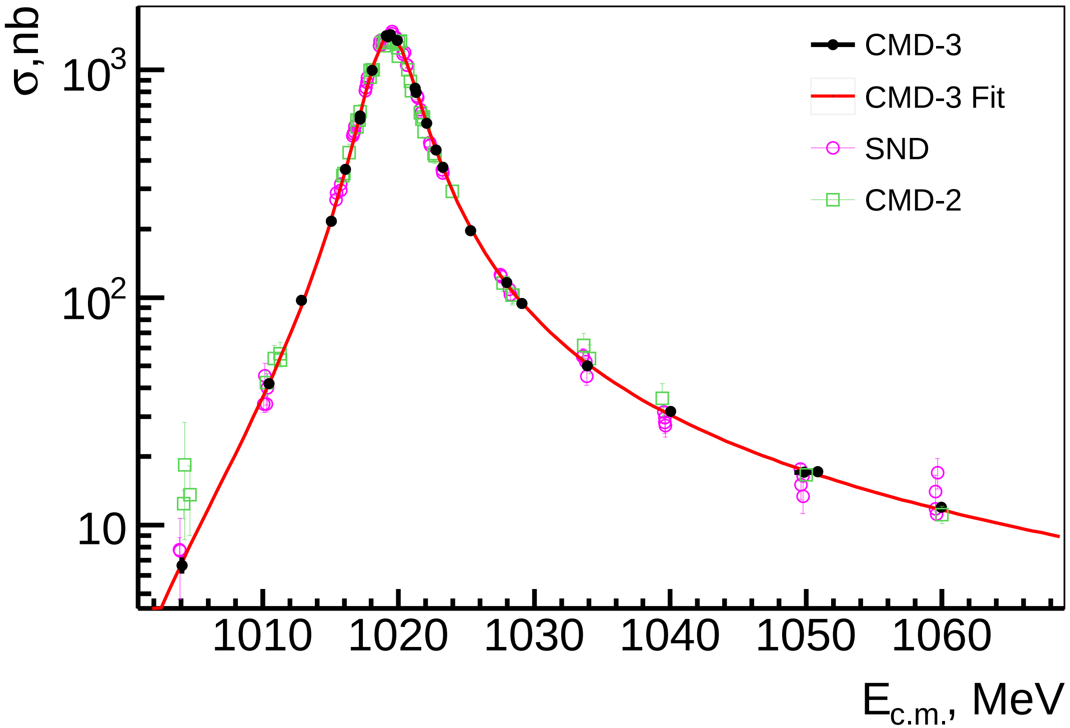




BaBar claims aggressive systematics of 0.72% at the ϕ, increasing to 7% at 2 GeV

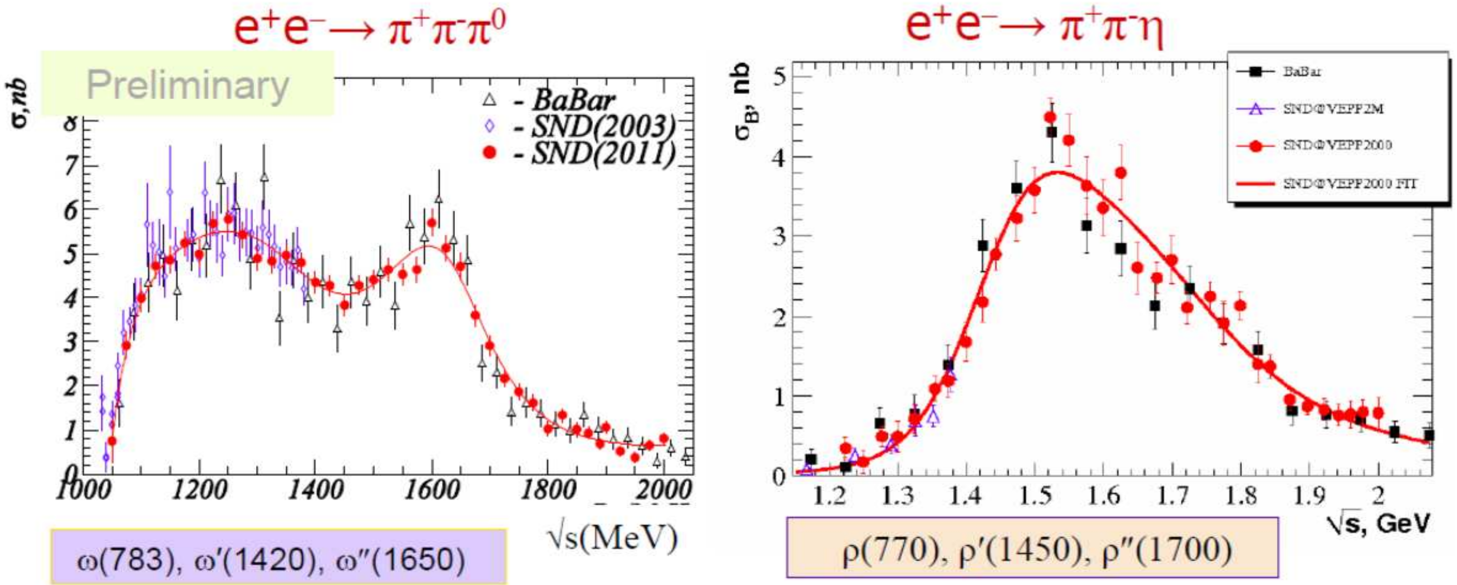
CMD-3 hopes to reach (1-2)% at the ϕ and not much worse at higher energy

$e^+e^- \to \phi \to K^0_S K^0_L$ at CMD-3



The most precise measurement of the cross section based on 6.5×10^5 events, 1.8% systematic uncertainty

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

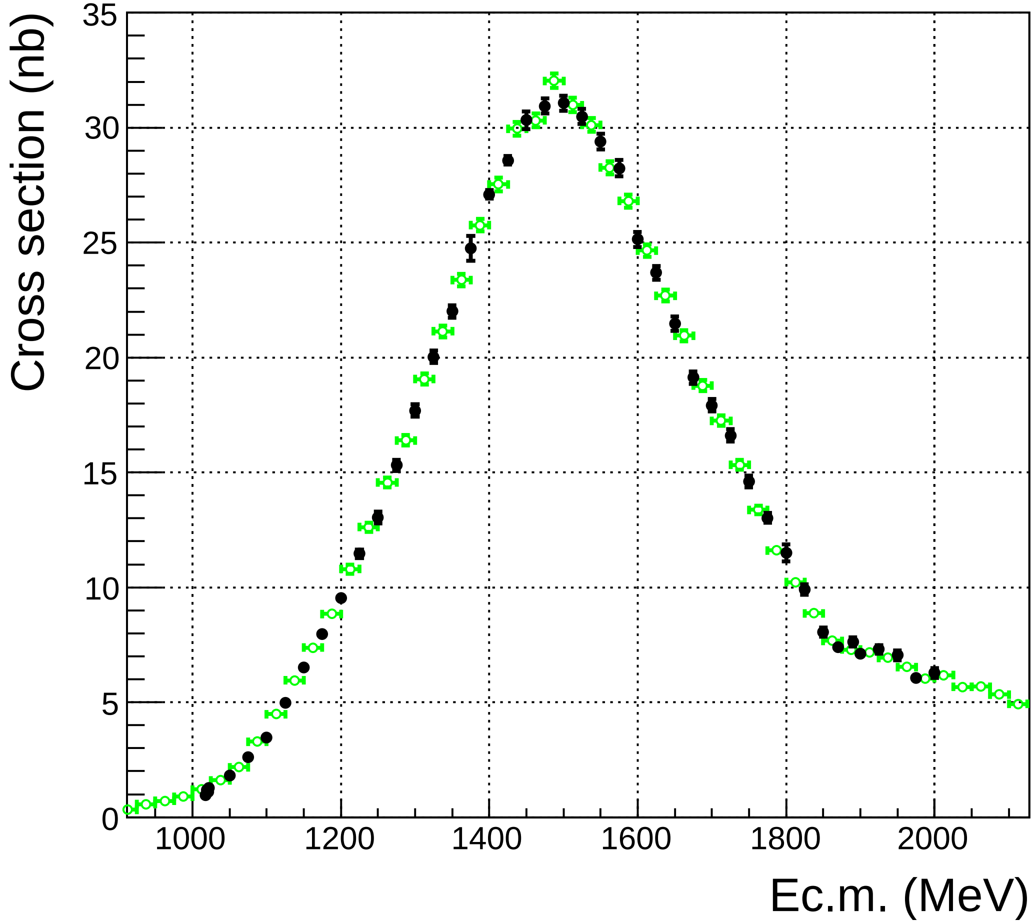


At each $\sqrt{s}$ full information on invariant masses

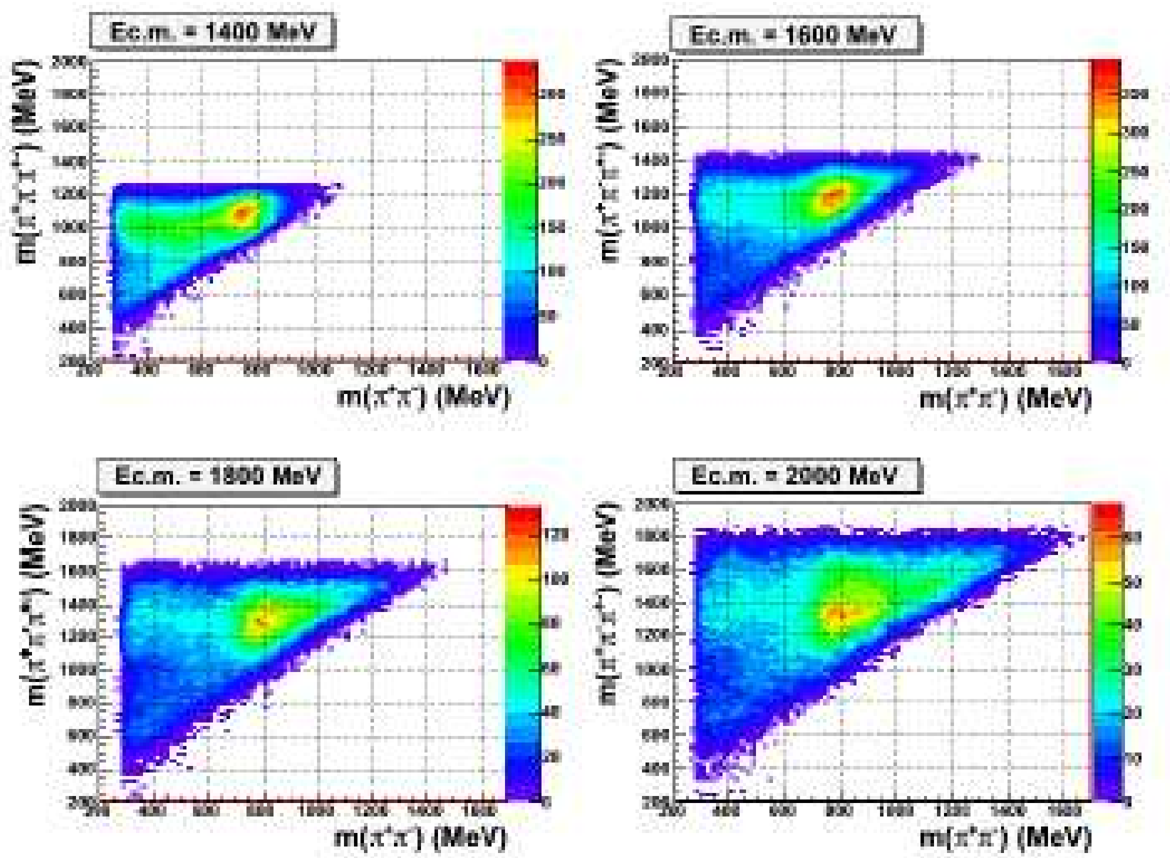
$\pi^+\pi^-\pi^0$: V. Aulchenko et al., JETP 121 (2015) 34,

$\pi^+\pi^-\eta$: V. Aulchenko et al., Phys. Rev. D 91 (2015) 052013

$e^+e^- \to 2\pi^+2\pi^-$ at CMD-3



Dynamics of $e^+e^- \to 2\pi^+2\pi^-$ at CMD-3

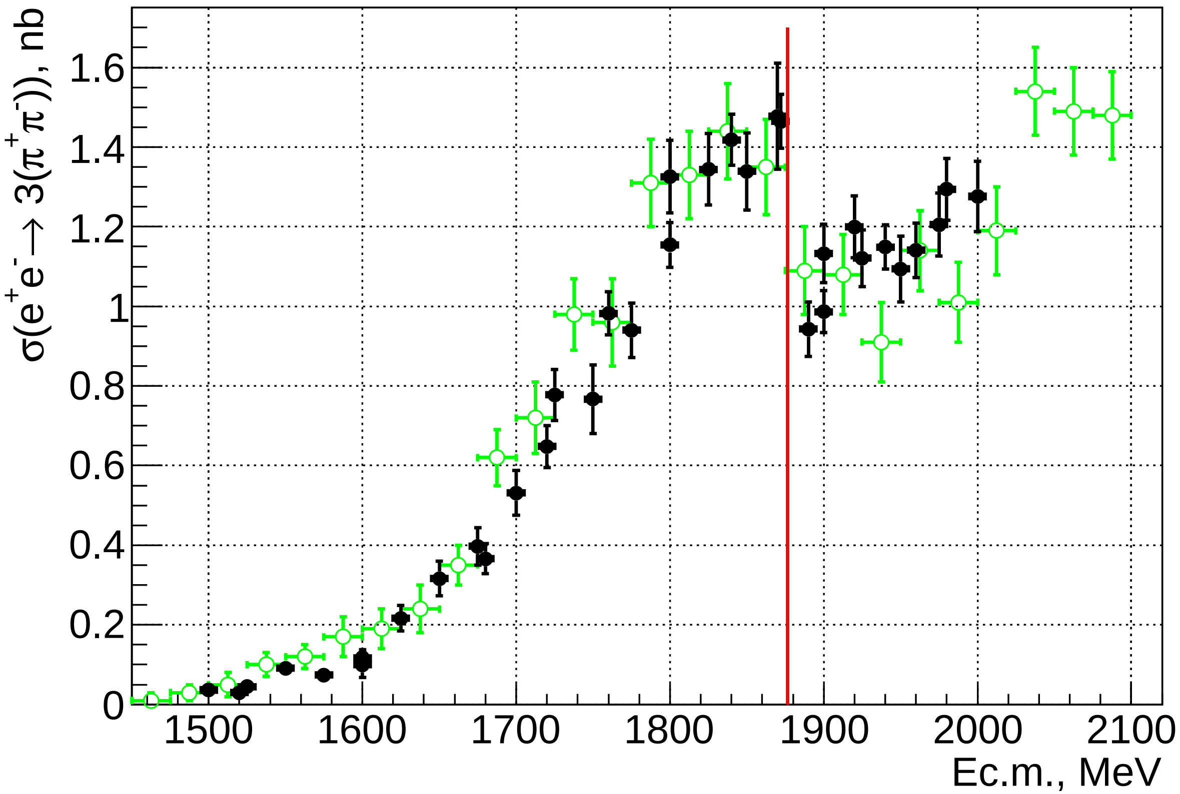


A ρ^0 is always present, $a_1^\pm(1260)\pi^\mp(a_2^\pm(1320)\pi^\mp)$ significant, at higher $\sqrt{s}$ other mechanisms like $\rho^0 f_0$, $\rho^0 f_2(1270)$ appear

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

1. $\int Ldt$ =22 pb^{-1} from 1.5 to 2.0 GeV, 25 MeV step
2. About 8k five- (5069) and six-track (2887) events selected
3. We study dynamics, pure phase space doesn't work, three models with $J^{PC} = 1^{--}$, each with one ρ^0/event:
   - $\rho(1450)(\pi^+\pi^-)_{\mathrm{S-wave}} \to a_1(1260)^{\pm}\pi^{\mp}\pi^+\pi^- \to \rho^0 2(\pi^+\pi^-) \to 3(\pi^+\pi^-)$
   - $\rho(770)(2\pi^+2\pi^-)_{\mathrm{S-wave}} \to 3(\pi^+\pi^-)$
     3 options for $2\pi^+2\pi^-$: phase space, $f_0(1370)$, $f_0(1500)$
   - $\rho(770)f_2(1270) \to 3(\pi^+\pi^-)$
   - The best description is with one $\rho(770)$ and 4 pions in S-wave
4. Full analysis of dynamics - common for $3\pi^+3\pi^-$, $2\pi^+2\pi^-2\pi^0$, $\pi^+\pi^-4\pi^0$
5. The systematic uncertainty is 6%, to be improved to 3%

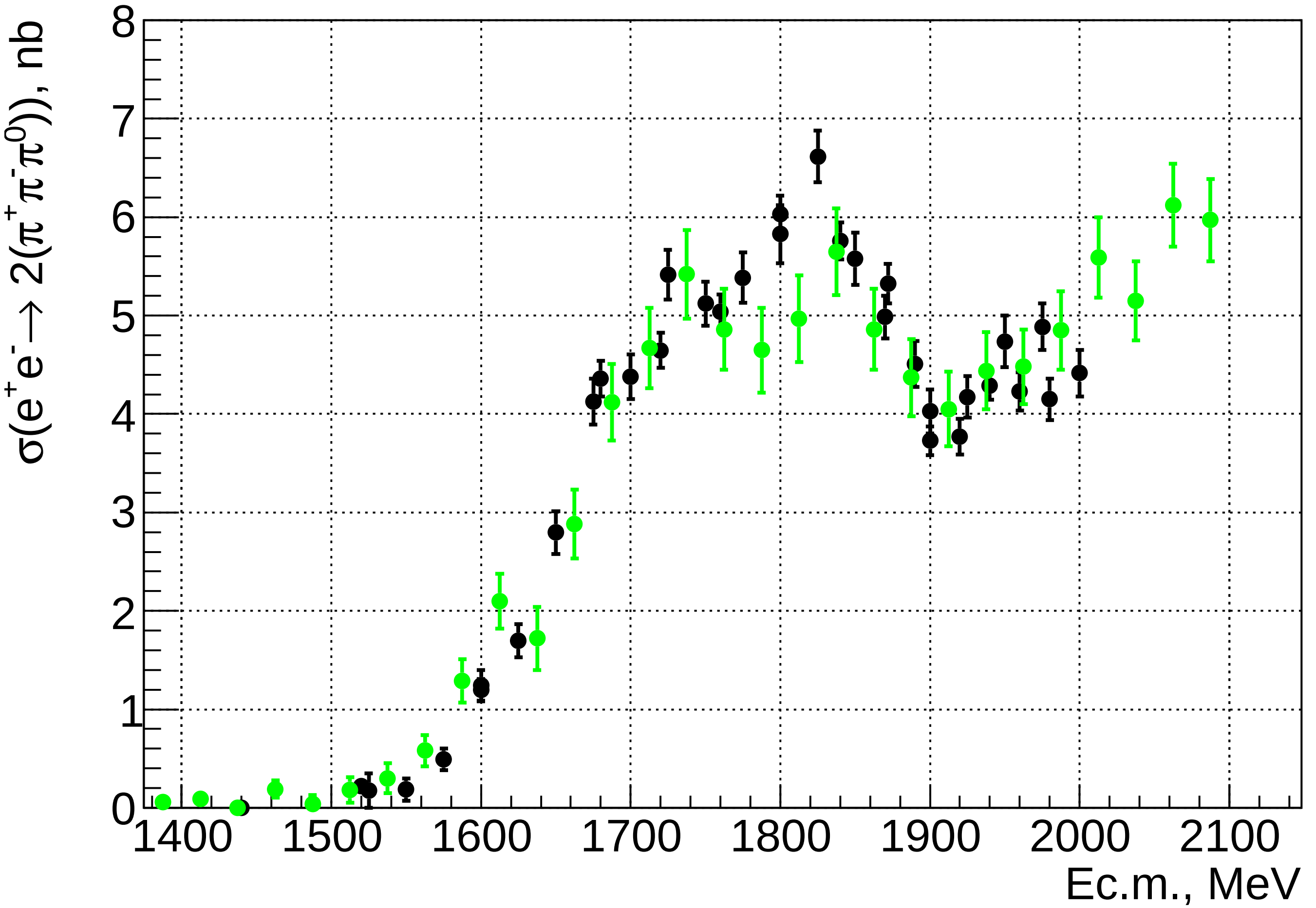
$e^+e^- \to 3\pi^+3\pi^-$ at CMD-3– II



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

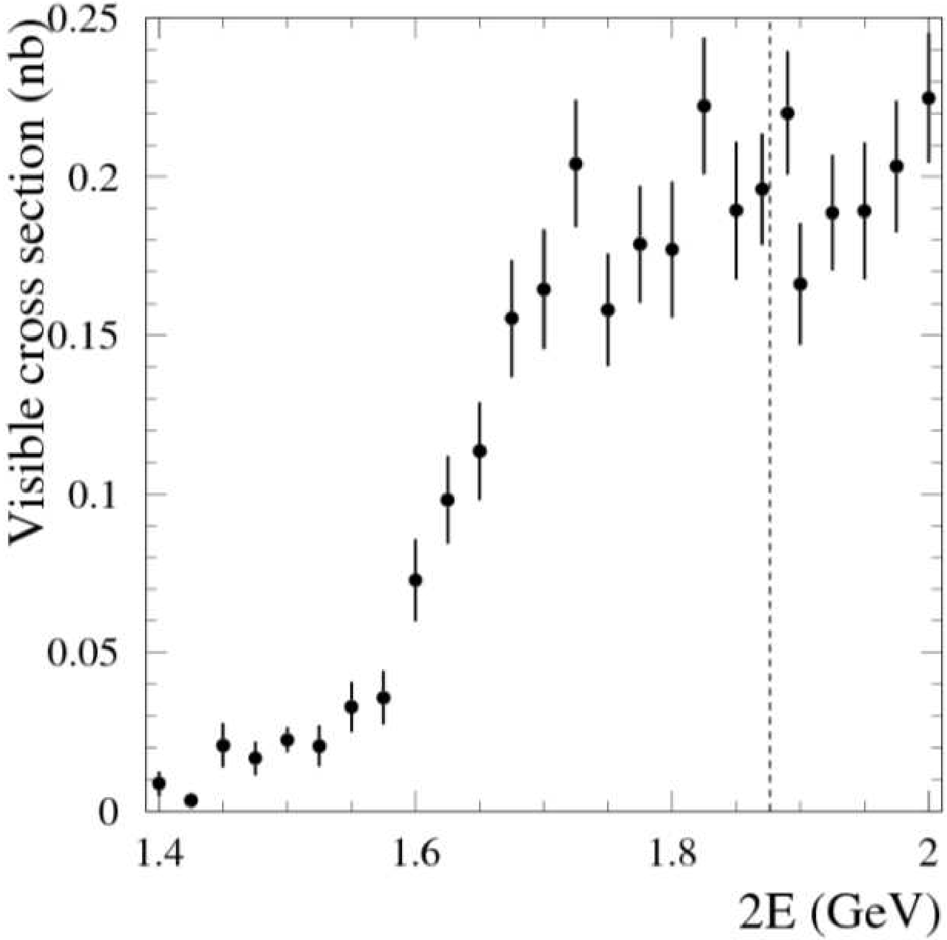
R.R. Akhmetshin et al., Phys. Lett. B 723 (2013) 82

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



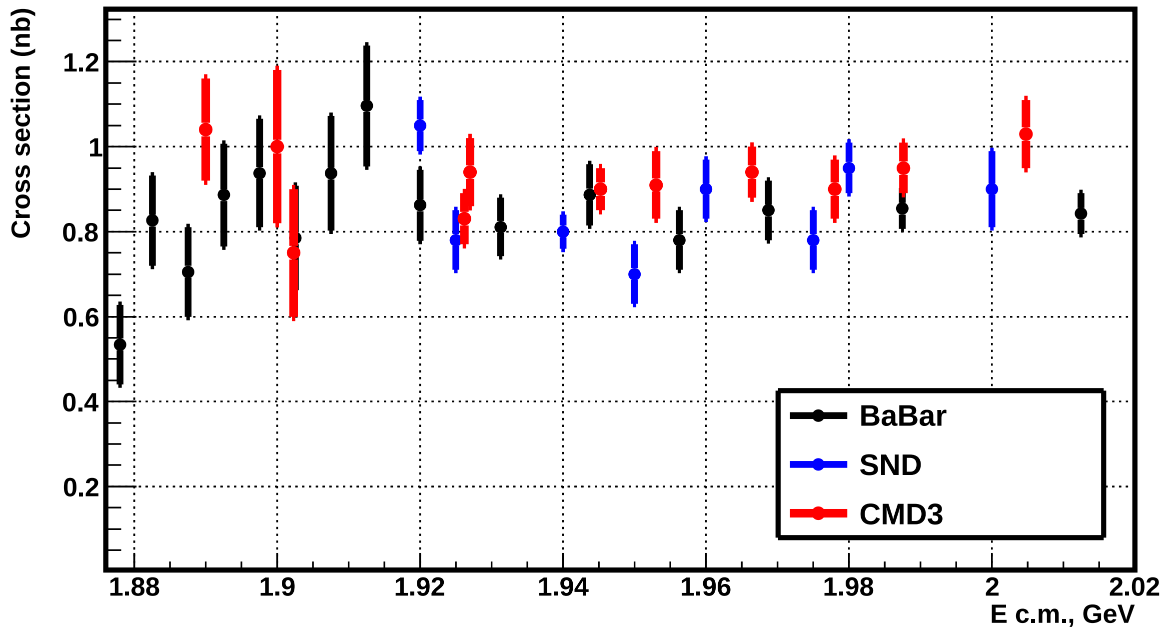
The dip structure near $N\bar{N}$ threshold also seen

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



First ever measurement of the process

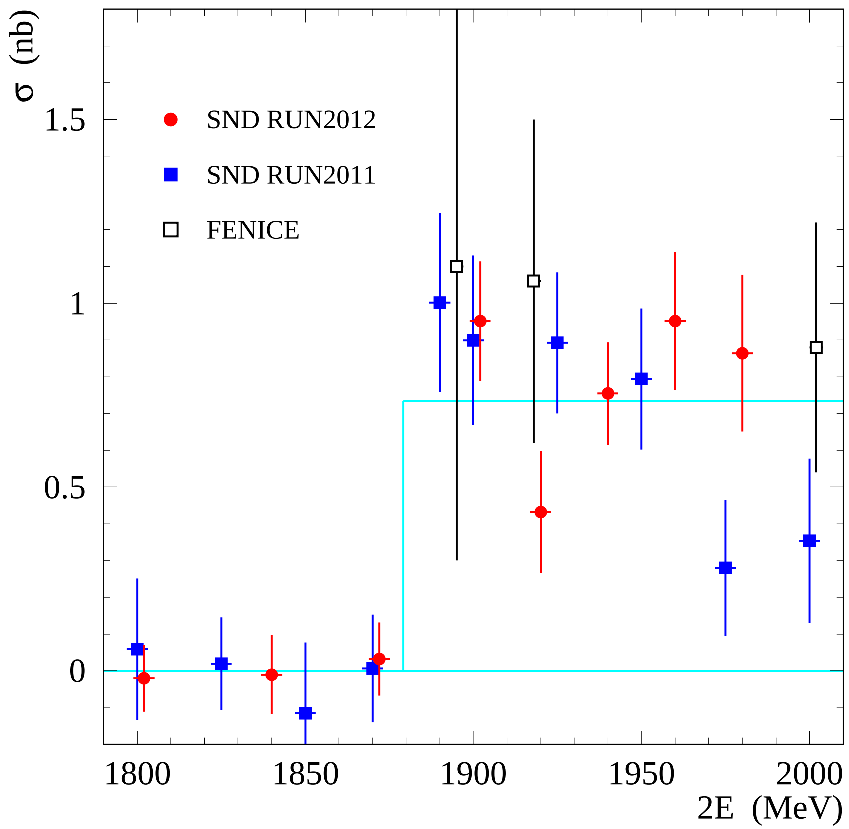
$p\bar{p}$ Production at VEPP-2000



In addition to cross sections, first attempts of measuring f/f made

R.R. Akhmetshin et al., 1507.08013, Phys. Lett. B

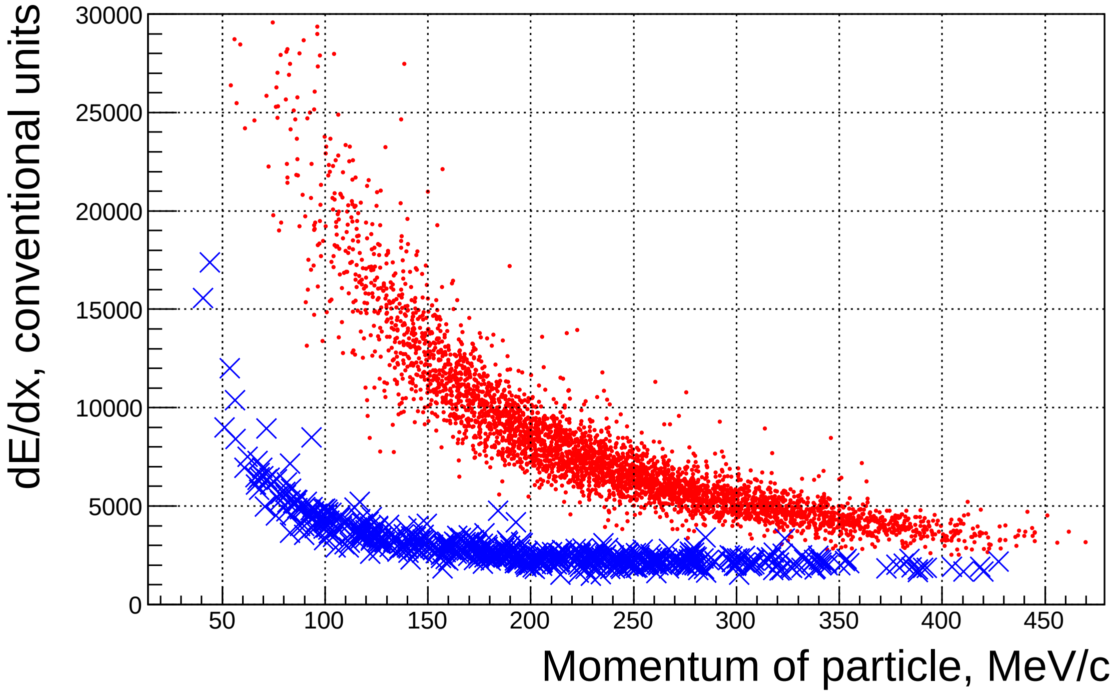
$e^+e^- \to n\bar{n}$ at SND



The first and more precise measurement after FENICE

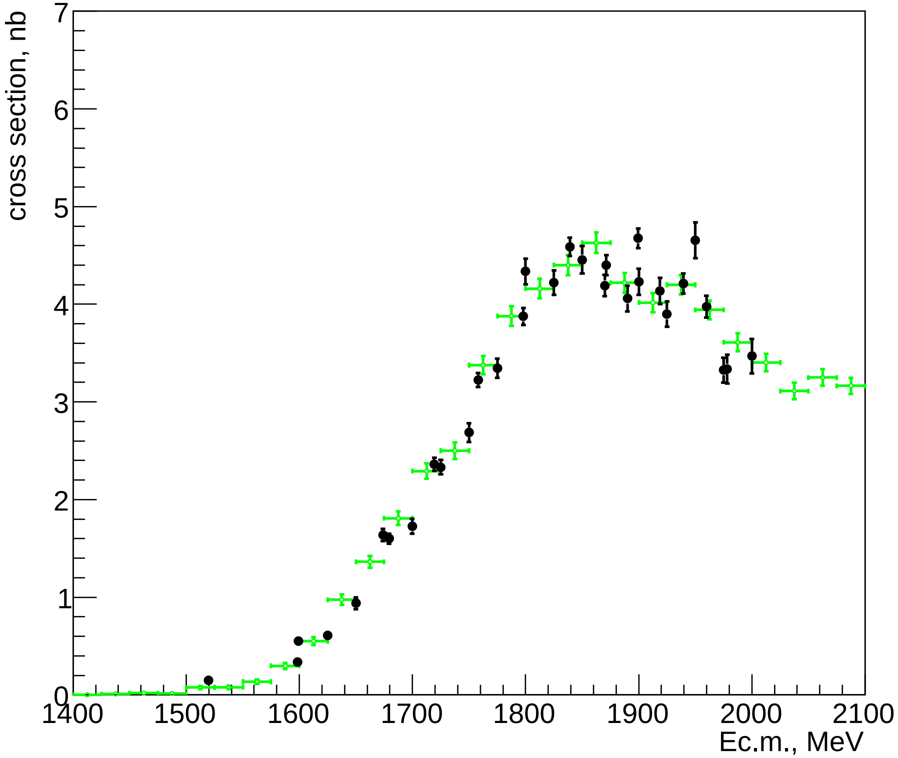
M.N. Achasov et al., Phys. Rev. D 90 (2014) 112007

Multibody Final States with Charged Kaons



Ionization losses in DC (dE/dx) provide good K/π separation

$e^+e^- \to K^+K^-\pi^+\pi^-$ at CMD-3

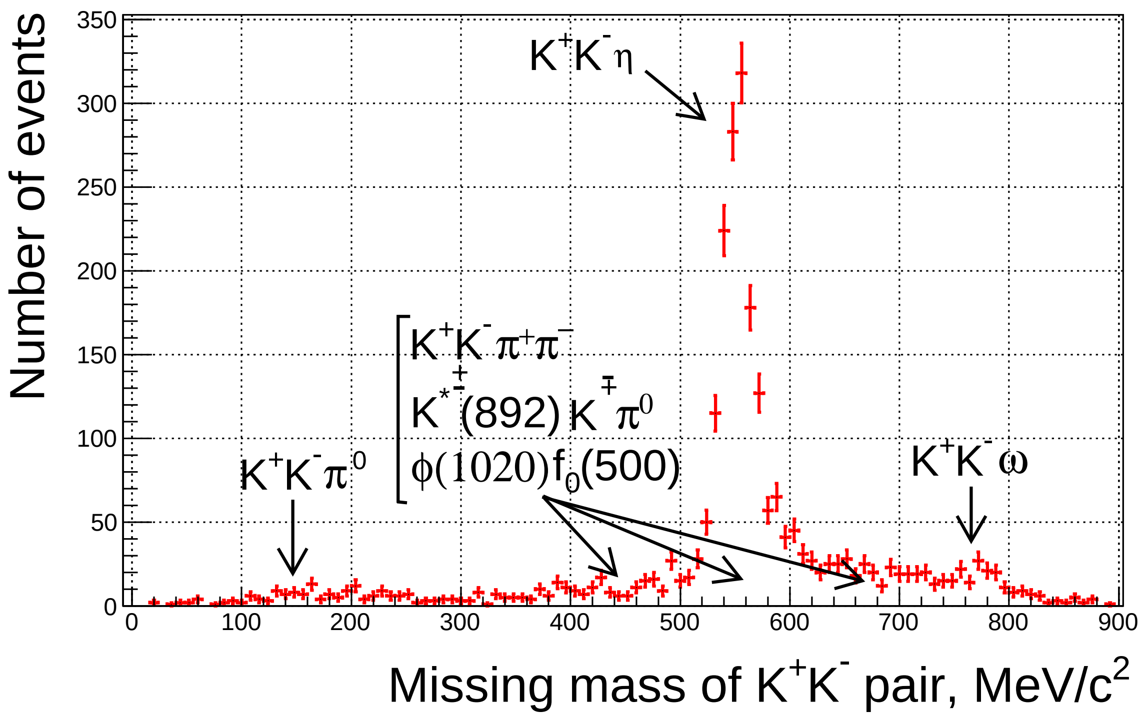


From more than 10000 events many different mechanisms seen:

$K_1(1270)\bar{K} \to K\bar{K}\rho,\ K^*(892)\bar{K}\pi,\ K_1(1400)\bar{K} \to K^*(892)\bar{K}\pi,\ \phi\pi^+\pi^-$

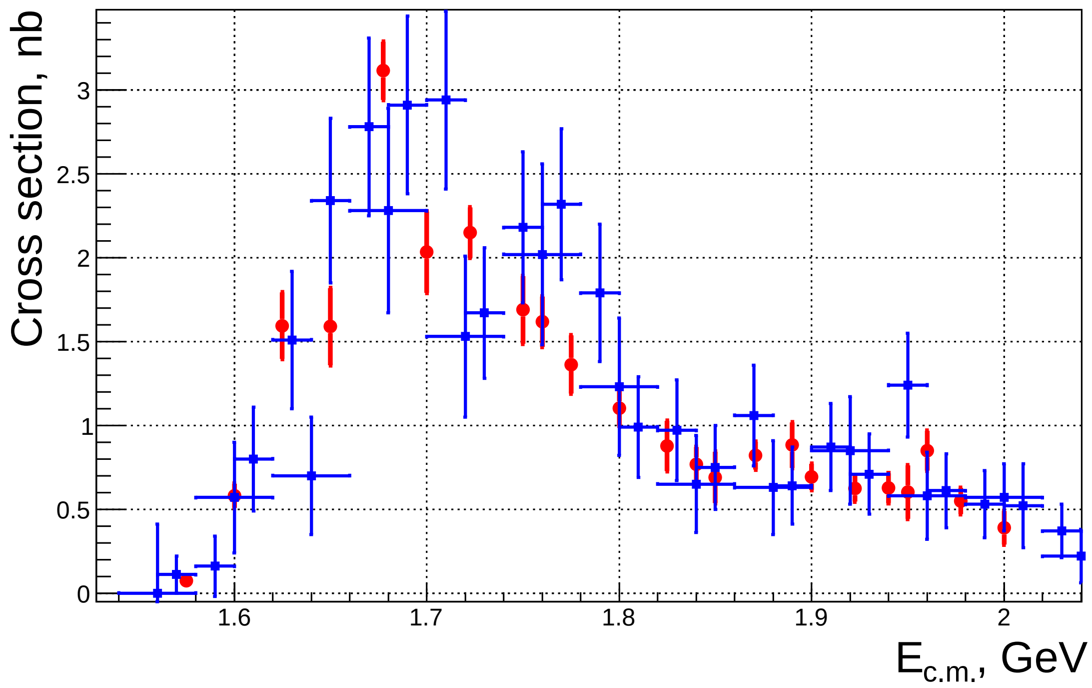
R.R. Akhmetshin et al., Phys. Lett. B 756 (2016) 153

$e^+e^- \to K^+K^-\eta$ at CMD-3 – I



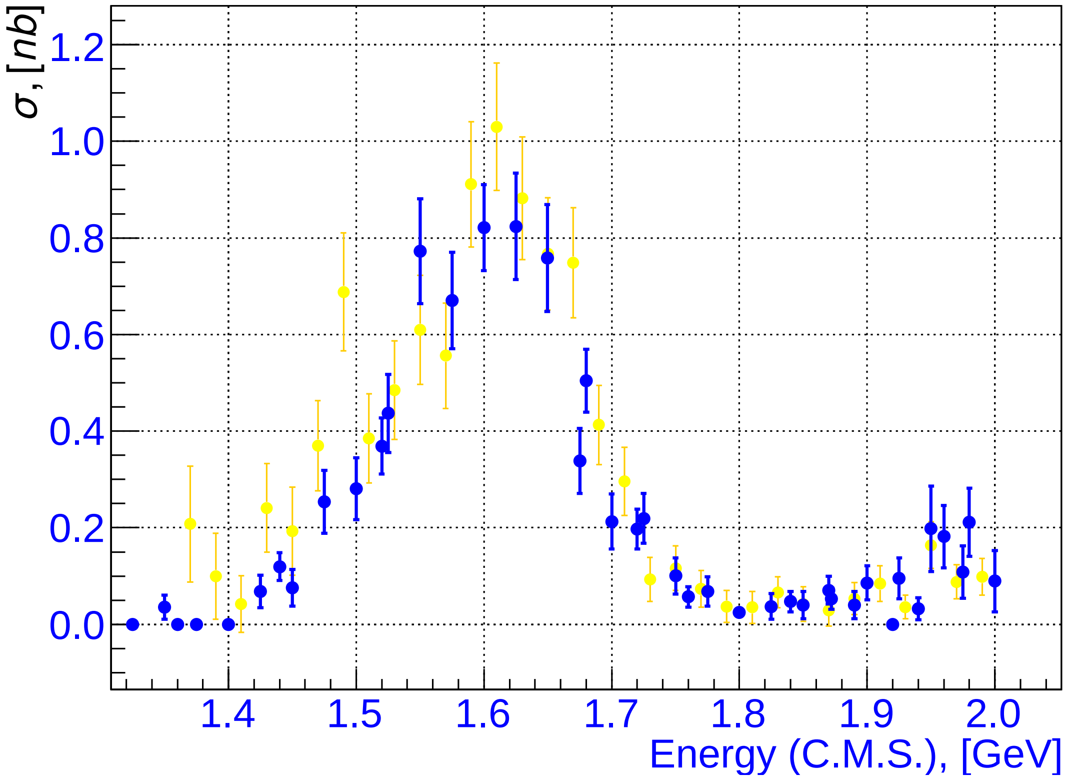
Missing mass to K^+K^- clearly shows the dominant signal and BGs

$e^+e^- \to K^+K^-\eta$ at CMD-3 – II



Cross section is consistent with and more precise than BaBar

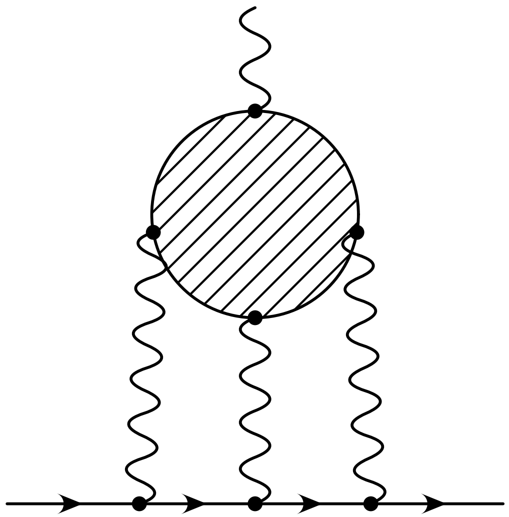
$e^+e^- \to K^+K^-\pi^0$ at CMD-3



From 600 events the $\phi\pi^0$ and $K^{*\pm}(892)K^{\mp}$ mechanisms seen

Cross section is consistent with and more precise than BaBar

Light-by-Light Scattering – I



Various approaches used:

- Vector Dominance and Chiral models
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- Effective field theory
- Dyson-Schwinger equations

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

Light-by-Light Scattering – II

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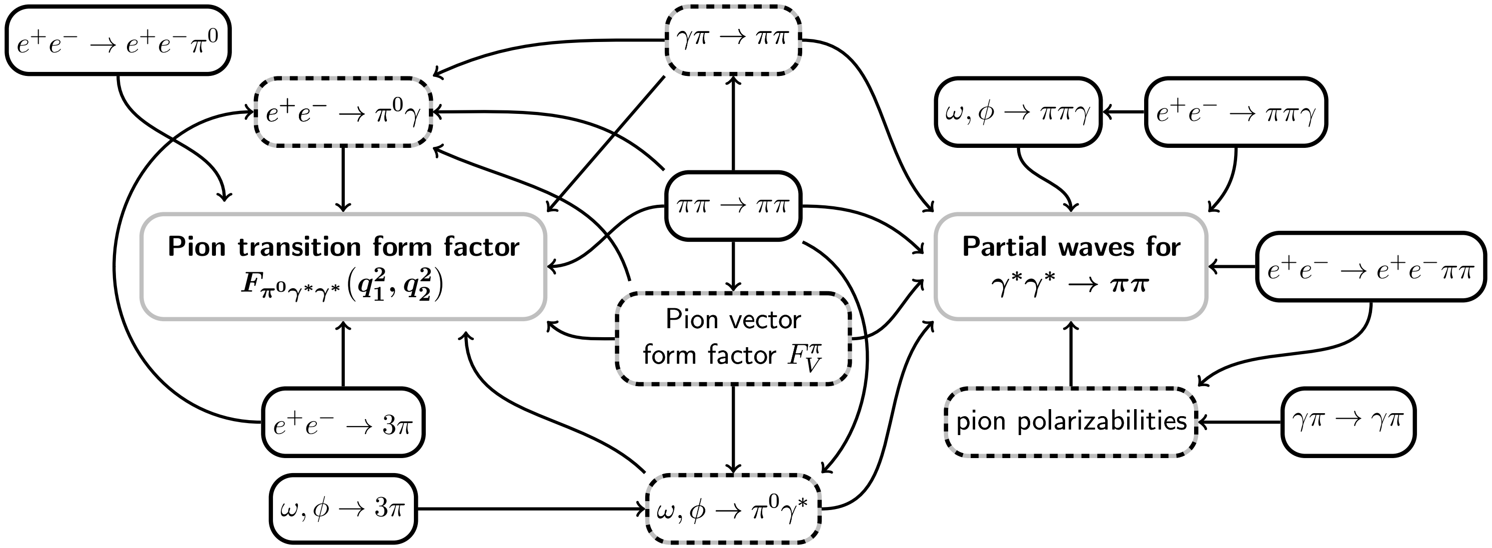
G. Colangelo et al., JHEP 09 (2014) 091, Phys. Lett. B638 (2014) 6

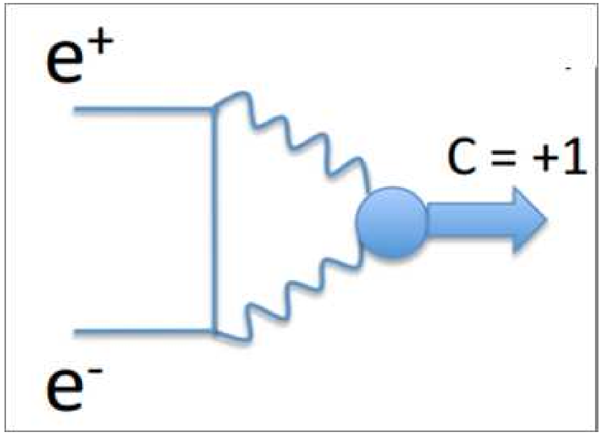


Measurements of various processes are in order followed by calculations of many integrals with different kernels

The largest contribution to a_μ^{LBL} is expected from the pseudoscalars (π^0, η, η')

Search for C-even resonances in e^+e^-

Direct production of C-even resonances in e^+e^- collisions is possible via a $\gamma\gamma$ intermediate state.



The unitarity bound assuming 2 real photons is

$$\mathcal{B}_{P\to l^+l^-} = \mathcal{B}_{P\to\gamma\gamma}\frac{\alpha^2}{2\beta}\left(\frac{m_e}{m_P}\right)^2\left[\ln\left(\frac{1+\beta}{1-\beta}\right)\right]^2, \beta = \sqrt{1-4\left(\frac{m_e}{m_P}\right)^2}.$$

For η' the unitarity bound is $\mathcal{B} = 3.75\cdot 10^{-11}$

"Standard" mechanism via $e^+e^-\to e^+e^-P$ involves two almost cd real photons and provides $\Gamma(P\to\gamma\gamma)$ only

Search for $e^+e^- \to \eta'(958)$ at VEPP-2000

- CMD-3 used 2.69 pb^{-1} at $\sqrt{s} \sim m_{\eta'}$ to look for $e^+e^- \to \eta'(958),\ \eta' \to \eta\pi^+\pi^-,\ \eta \to 2\gamma$,
  $\Gamma(\eta' \to e^+e^-) < 0.0024$ eV at 90%CL,
  R.R. Akhmetshin et al., Phys. Lett. B740 (2015) 273
- SND used 2.9 pb^{-1} to look for $e^+e^- \to \eta'(958)$:
  $\eta' \to \eta\pi^+\pi^-,\ \eta \to 2\gamma,\ 3\pi^0,\ \eta' \to \eta\pi^0\pi^0,\ \eta \to 2\gamma,\ 3\pi^0,\ \pi^+\pi^-\pi^0$,
  $\Gamma(\eta' \to e^+e^-) < 0.0020$ eV at 90%CL,
  M.N. Achasov et al., Phys. Rev. D91 (2015) 092010
- SND combines their data with CMD-3:
  $\Gamma(\eta' \to e^+e^-) < 0.0011$ eV at 90%CL,
  $\mathcal{B}(\eta' \to e^+e^-) < 5.6 \cdot 10^{-9}$ at 90%CL
- The unitarity limit $\mathcal{B}(\eta' \to e^+e^-) > 3.75 \cdot 10^{-11}$

Search for $e^+e^- \to \eta$ at VEPP-2000

- A feasibility study of SND used 108 nb^{-1} collected in the c.m. energy range 520-580 MeV to look for $e^+e^- \to \eta$, $\eta \to 3\pi^0$; $\eta \to 2\gamma$, $\pi^+\pi^-\pi^0$ dominated by QED background, a sensitivity of $\mathcal{B}(\eta \to e^+e^-) \approx 10^{-6}$ can be reached in 2 weeks, M.N. Achasov et al., JETP Lett. 102 (2015) 266
- The best limit has been set by HADES in G. Agakishiev et al., Phys. Lett. B731 (2014) 265, $\mathcal{B}(\eta \to e^+e^-) < 2.3 \cdot 10^{-6}$ at 90%CL
- The unitarity limit is $\mathcal{B}(\eta \to e^+e^-) > 1.8 \cdot 10^{-9}$

Future

- Two new measurements of a_μ are expected in 3-5 years:
  E989 at Fermilab plans to improve the uncertainty from 0.5ppm to 0.14 ppm,
  they plan to start running in 2017
  J-PARC has the same precision goal, data taking planned in 2019-2021
- What is expected for the theoretical prediction?
  Progress in low energy e^+e^- annihilation expected,
  improving the LO error from 4.2 to 2.0, so 2.6 from the LbL dominates,
  in the new approach 1.0 may be achieved (?) giving 2.2 in total
  First principles (lattice) give promising results, but far from final
  C.M. Carloni Calame et al., Phys. Lett. B 746 (2015) 325,
  $a_\mu^{\rm had,LO}$ from $\alpha(t)$ in the spacelike region of Bhabha
- With the same central values of $a_\mu^{\rm exp}$ and $a_\mu^{\rm th}$
  the today difference will correspond to about 10σ!!

Conclusions

- VEPP-2000 ran smoothly with CMD-3 and SND at $0.32 < \sqrt{s} < 2.00$ GeV, the achieved 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 Belle2
- Various high-statistics experiments will substantially improve the accuracy of vacuum polarization calculations for $(g_\mu - 2)/2$
- Higher statistics ($\sim 1\text{fb}^{-1}$) $\Rightarrow$ a detailed study of dynamics, thus a study of mesons with various quantum numbers, can ChT provide low energy predictions?
- Good prospects for a study of transition form factors and hLbL
- Meanwhile a $\sim 3.5\sigma$ deviation of a_μ^{SM} from a_μ^{exp} persists: New Physics or various experimental and interpretation errors?

Back-up

$a_\mu^{\rm had,LO}$ and $\alpha(t)$

$$a_\mu^{\rm HLO} = \frac{\alpha}{\pi} \int_0^1 dx\, (1-x)\, \Delta\alpha_{\rm had}[t(x)]\,.$$

Muon Anomalous Magnetic Moment

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

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

Any significant difference of $a_\mu^{\rm exp}$ from $a_\mu^{\rm th}$ indicates
New Physics beyond the Standard Model.

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

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

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

$$a_\mu = 116592091(63) \times 10^{-11} \quad 0.54 \times 10^{-6}$$

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

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

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}

$a_\mu^{\text{QED}} \cdot 10^{10} = \Sigma C_i (\frac{\alpha}{\pi})^i =$		$0.5(\alpha/\pi)^1$	1 diagram
	$+$	$0.765857426(16)(\alpha/\pi)^2$	9
	$+$	$24.05050988(28)(\alpha/\pi)^3$	> 100
	$+$	$130.8796(63)(\alpha/\pi)^4$	> 1000
	$+$	$753.29(1.04)(\alpha/\pi)^5$	> 20000

Analytically – S.Laporta and E.Remiddi, Karlsruhe group, . . .,

Numerically – group of T. Kinoshita

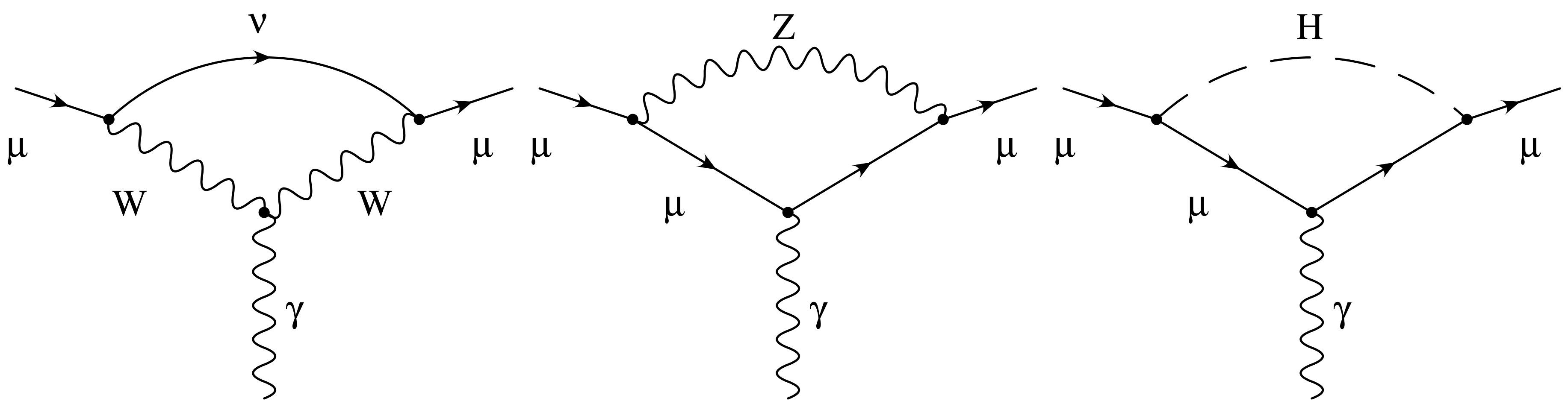
With $\alpha^{-1} = 137.035999049(90)$

$a_\mu^{\text{QED}} \;=\; (116584718.951 \pm 0.022 \pm 0.077) \cdot 10^{-11}.$

The errors are due to $\mathcal{O}(\alpha^4)$ and α

The $(\alpha/\pi)^4$ term $\approx$ the experimental error!

Electroweak contribution a_μ^{EW}



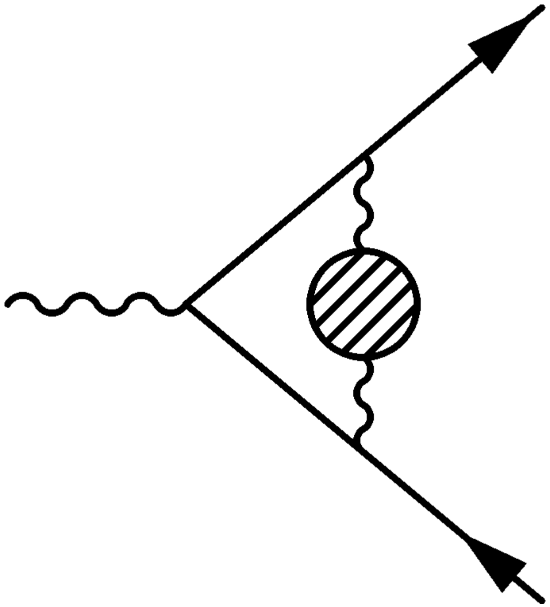
One-loop electroweak contributions

Authors	Year	a_μ^{EW}, 10^{-10}
$\ldots,\ldots,\ldots$	1972	19.5
A. Czarnecki et al.	1996	15.2 ± 0.4
A. Czarnecki et al.	2002	15.36 ± 0.01

The errors are due to hadr. loops and 3-loop NLO logs

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

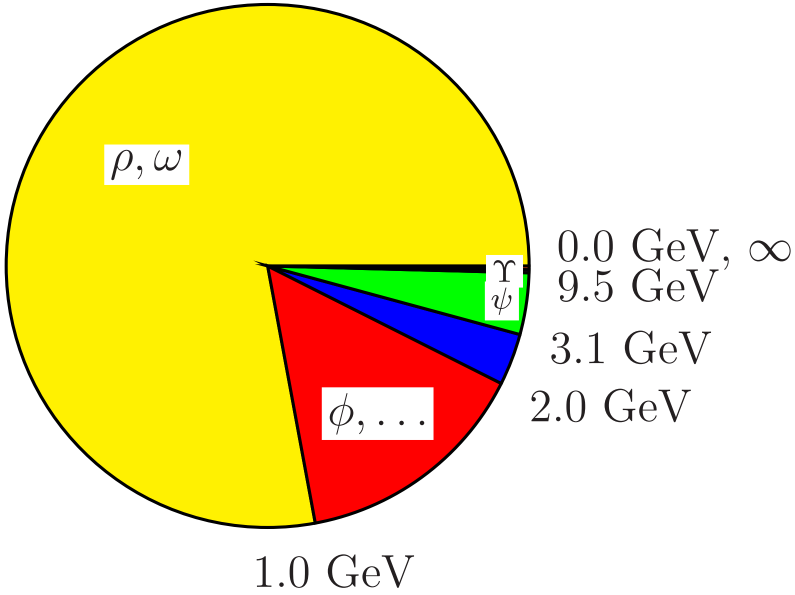
$$R(s) = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)},$$

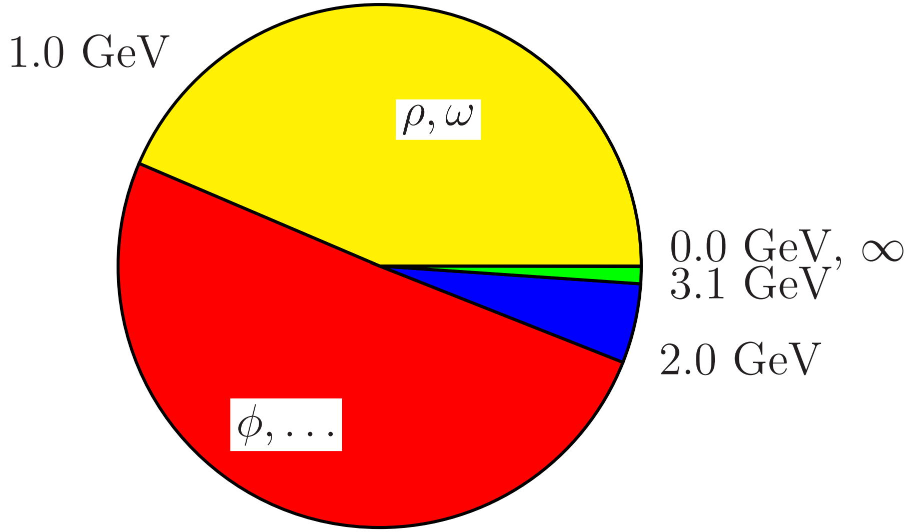
$\hat{K}(s)$ grows from 0.63 at $s = 4m_\pi^2$ to 1 at $s \to \infty$,

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

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

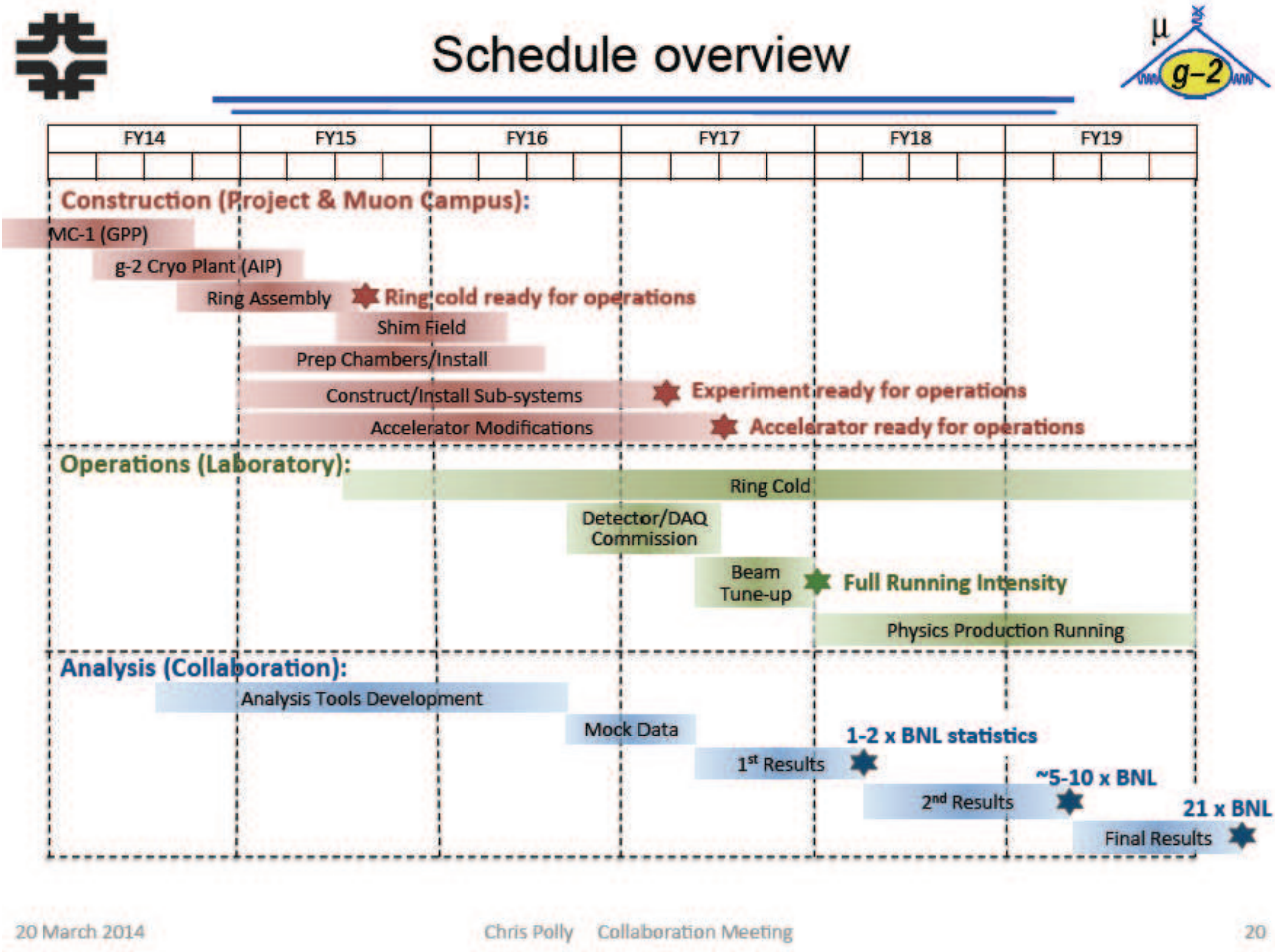
Contributions of Various Energy Ranges to $a_\mu^{\rm had,LO}$





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

Schedule of Fermilab E989



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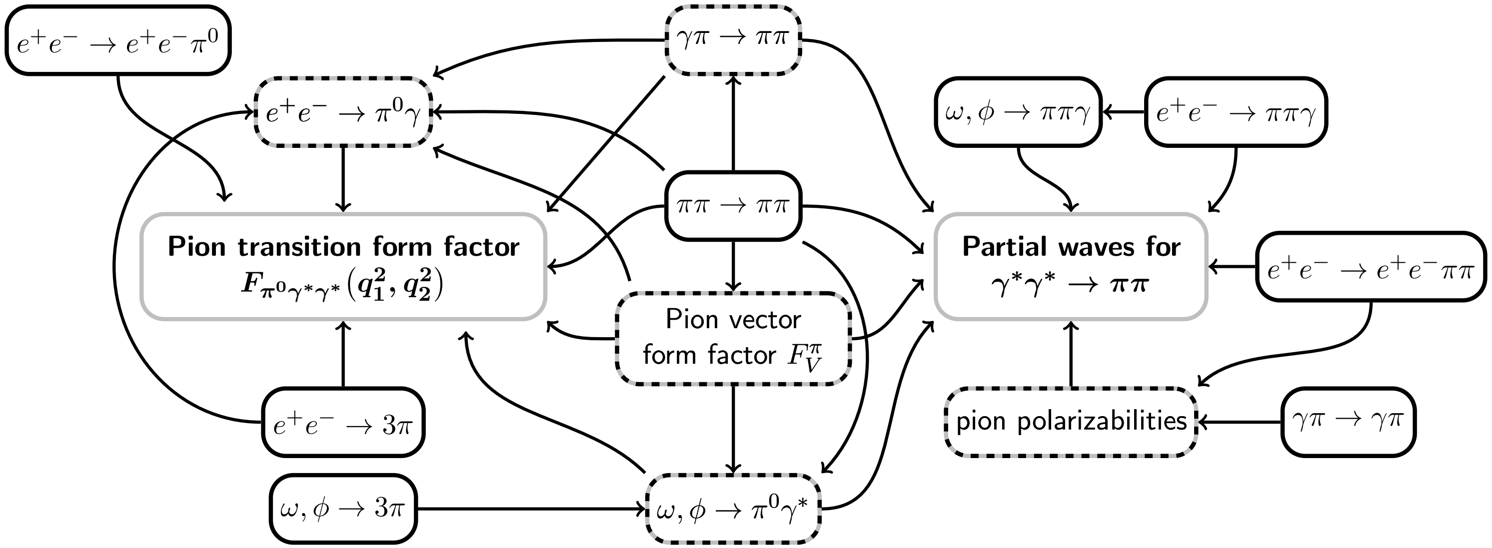

Measurements of various processes are in order followed by calculations of many integrals with different kernels

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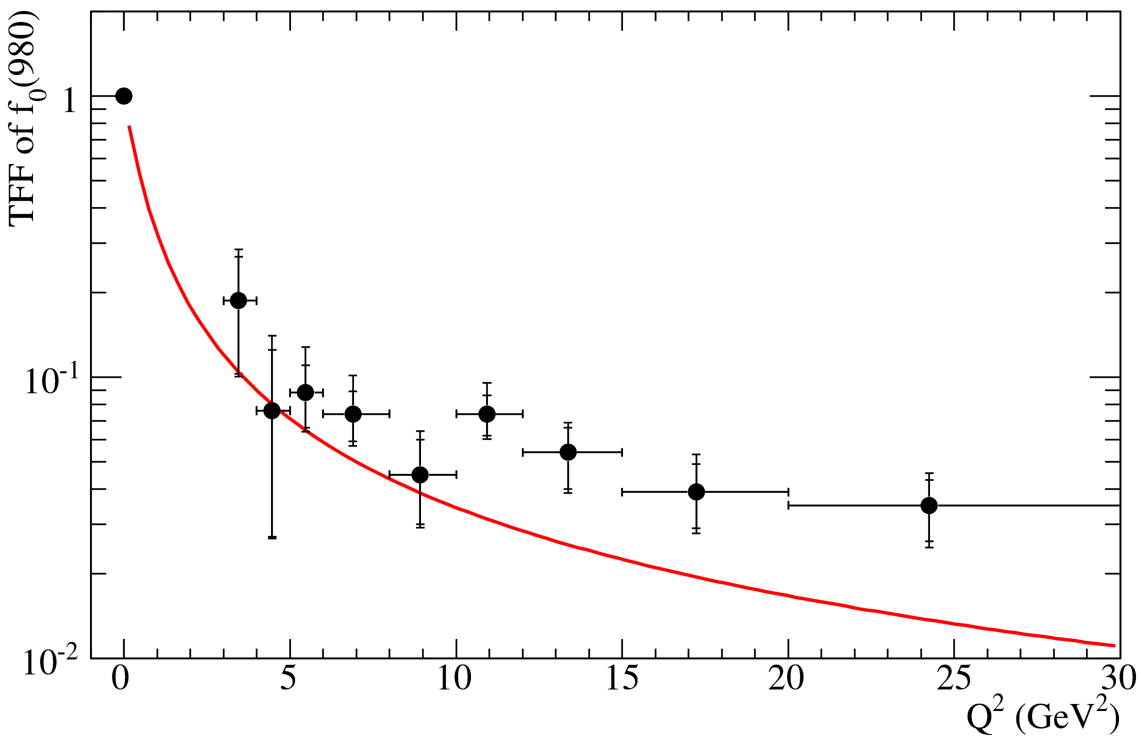
$\gamma\gamma^* \to \pi^0\pi^0$ at Belle



M Masuda et al. (Belle), arXiv:1508.06757

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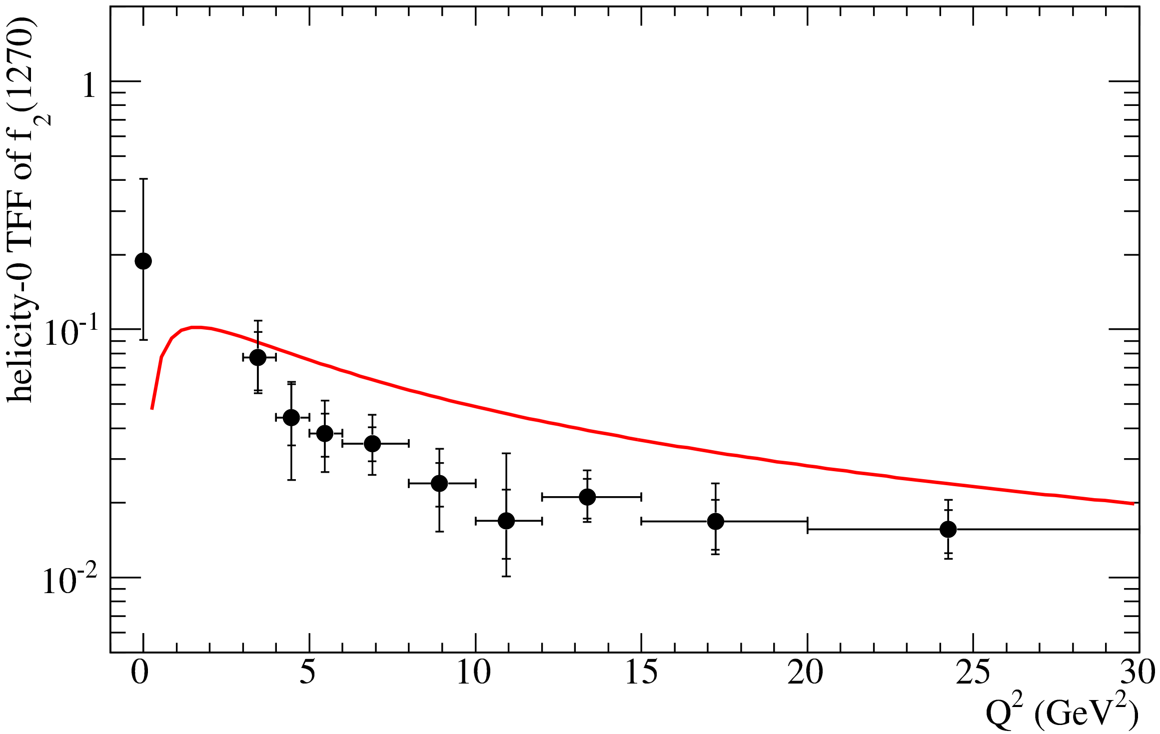

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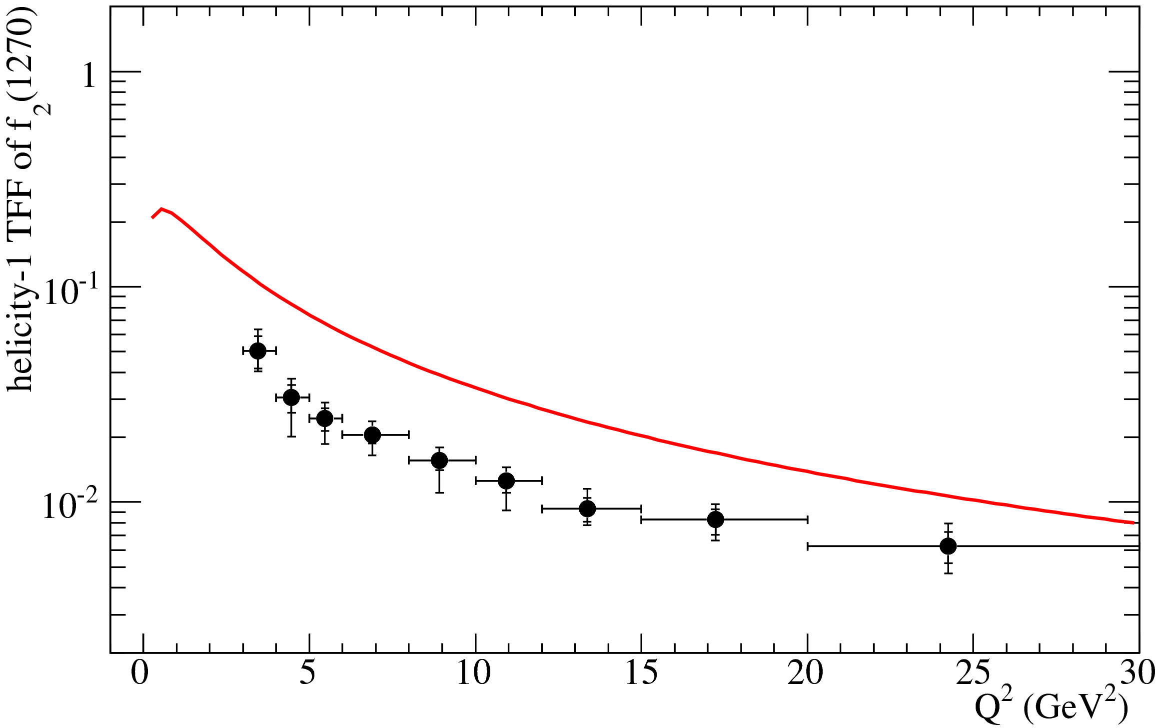

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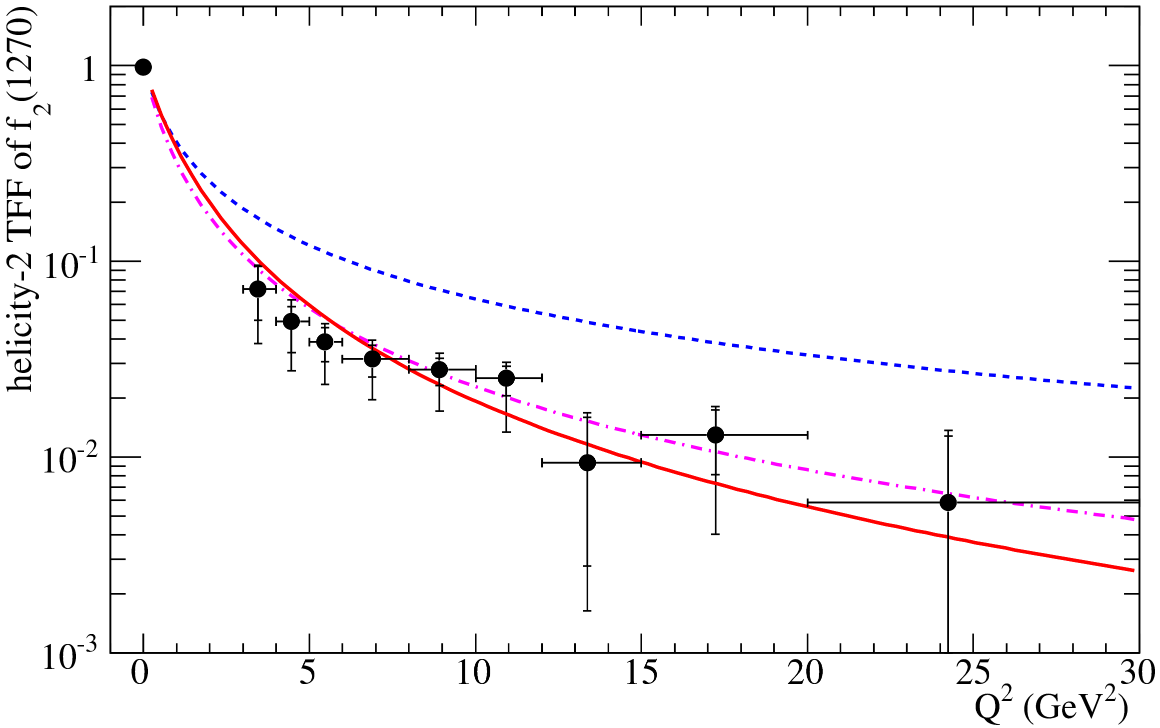

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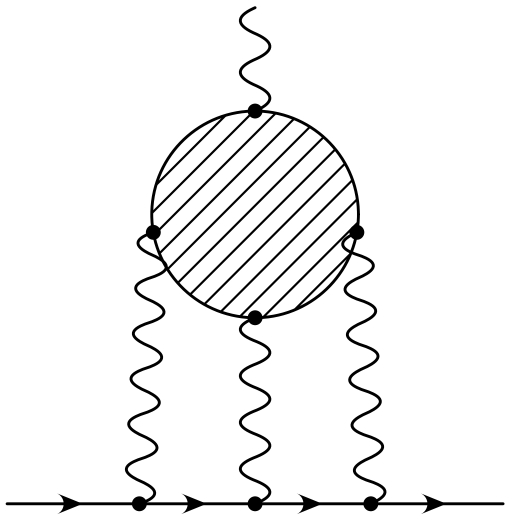
Light-by-Light Scattering – I



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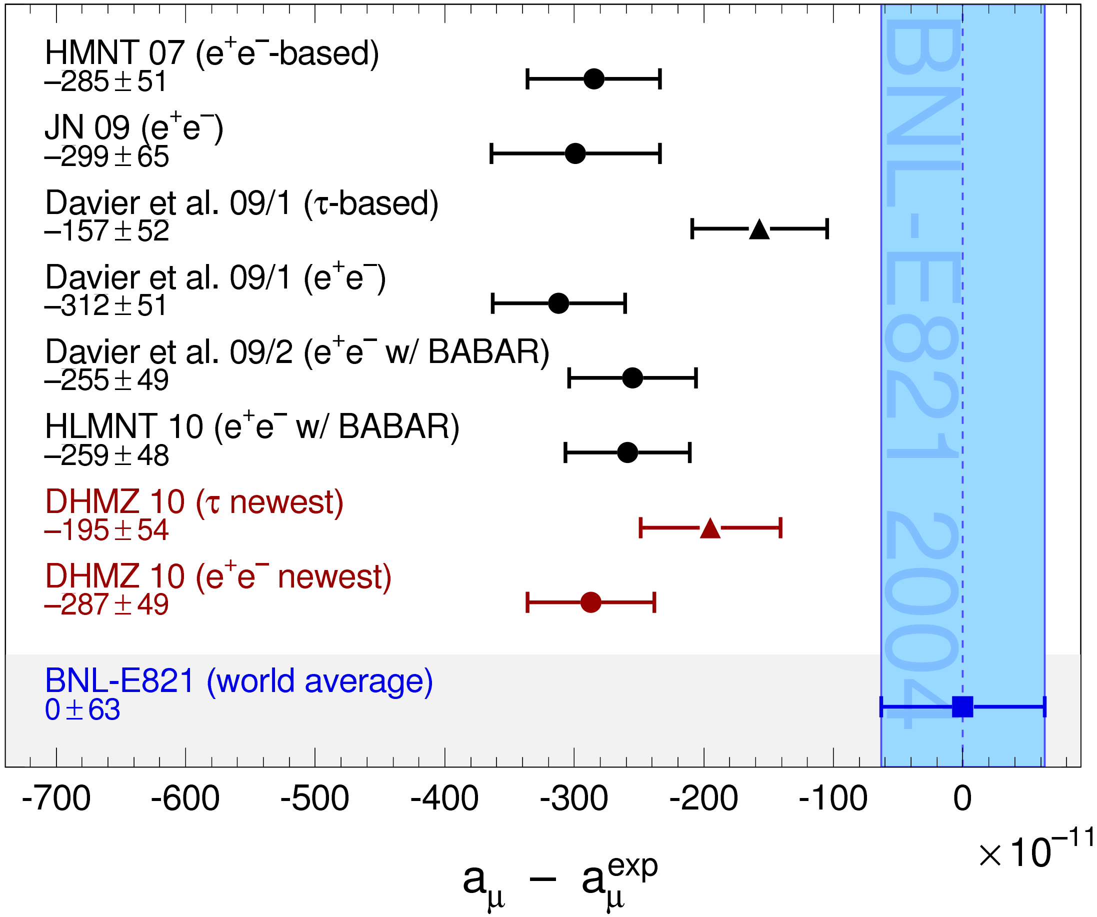
Experiment vs. Theory – I

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

Experiment	$11659209.1 \pm 5.4 \pm 3.3$
QED	11658471.895 ± 0.008
EW	15.4 ± 0.1
Had LO	692.3 ± 4.2
Had HO	-9.8 ± 0.1
Had LbL	10.5 ± 2.6
Theory	11659180.3 ± 4.9
Exp.-Th.	28.8 ± 8.0

Experiment is higher than theory by 3.6 standard deviations

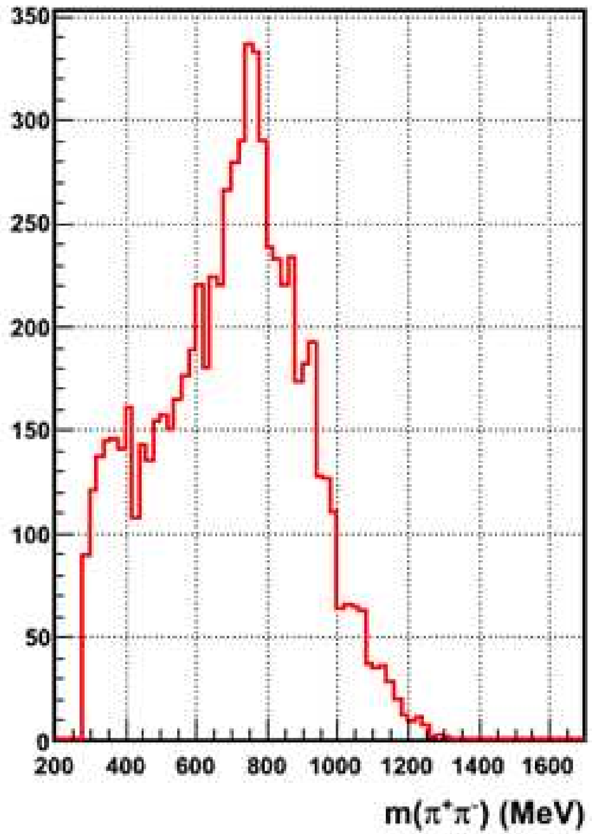
Experiment vs. Theory – II

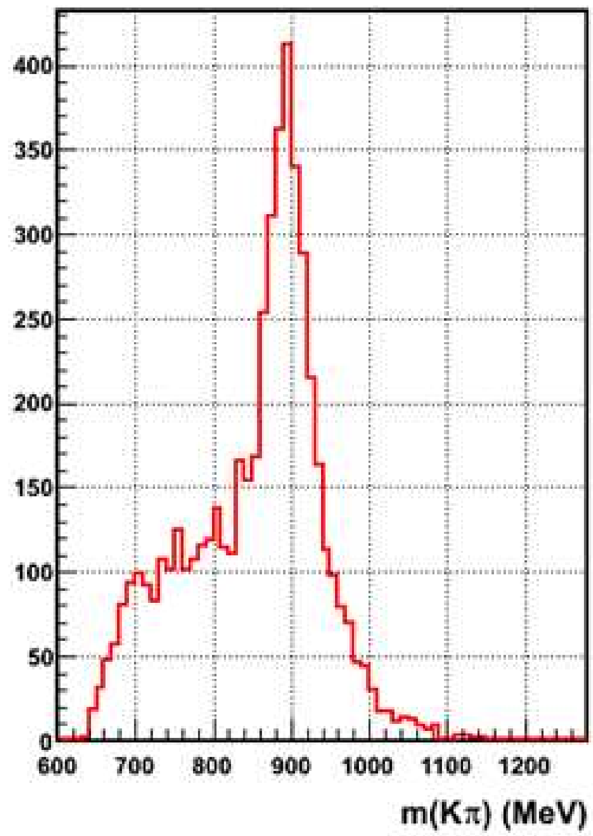


$e^+e^- \to K^+K^-\pi^+\pi^-$ at CMD-3 – I

- CMD-3 studied $e^+e^- \to K^+K^-\pi^+\pi^-$ with 22 pb^{-1} between 1.5 and 2 GeV
- More than 10000 4-track and 3-track events observed
- Analysis of $\pi^+\pi^-$, $K^\pm\pi^\mp$, K^+K^- invariant masses shows clear ρ^0, $K^{*0}(892)$, ϕ signals
- Many different mechanisms seen: $K_1(1270)\bar{K} \to K\bar{K}\rho$, $K^*(892)\bar{K}\pi$, $K_1(1400)\bar{K} \to K^*(892)\bar{K}\pi$, $\phi\pi^+\pi^-$

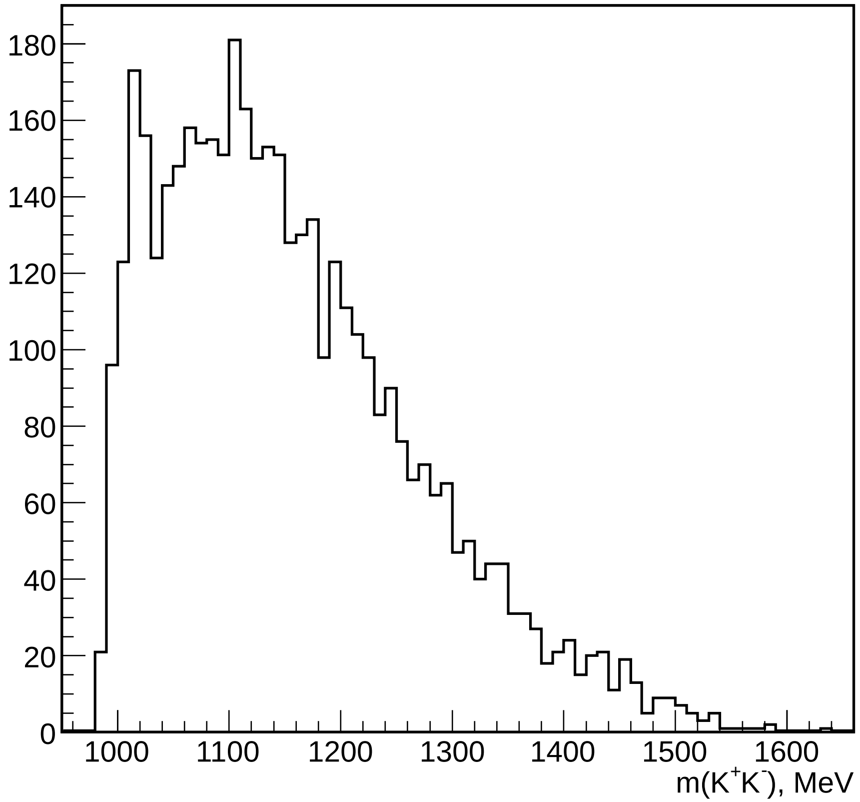
$e^+e^- \to K^+K^-\pi^+\pi^-$ at CMD-3 – II





ρ^0 in $\pi^+\pi^-$ and $K^{*0}(892)$ in $K^\pm\pi^\mp$

$e^+e^- \to K^+K^-\pi^+\pi^-$ at CMD-3 – III

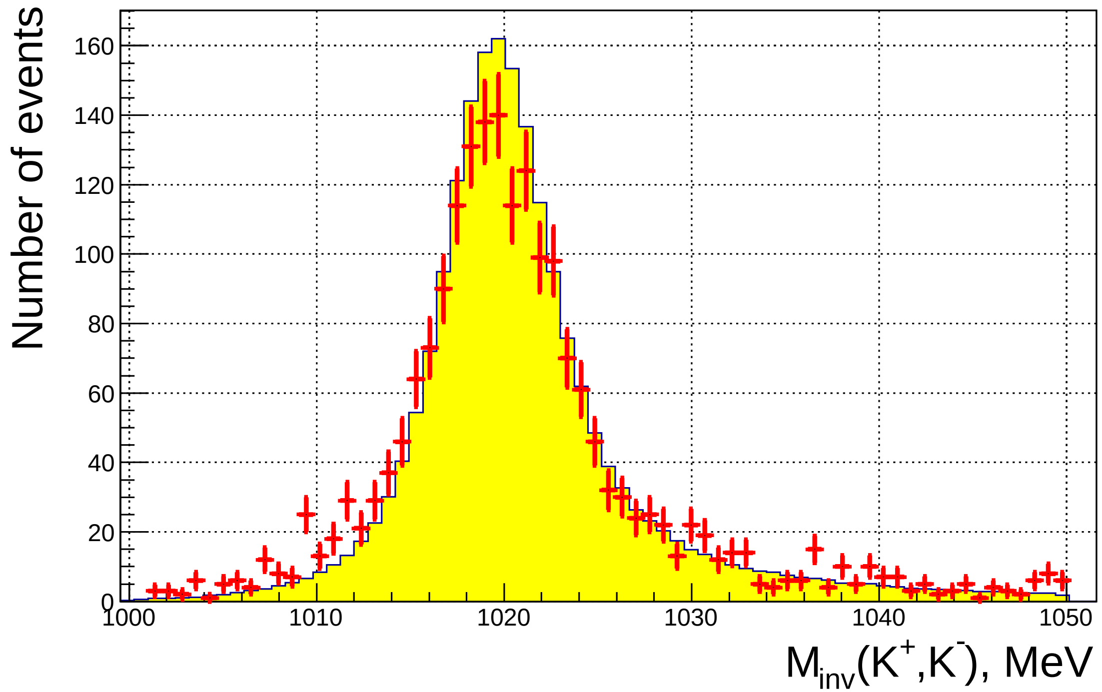


ϕ in K^+K^- combinations

$e^+e^- \to K^+K^-\eta$ at CMD-3 – I

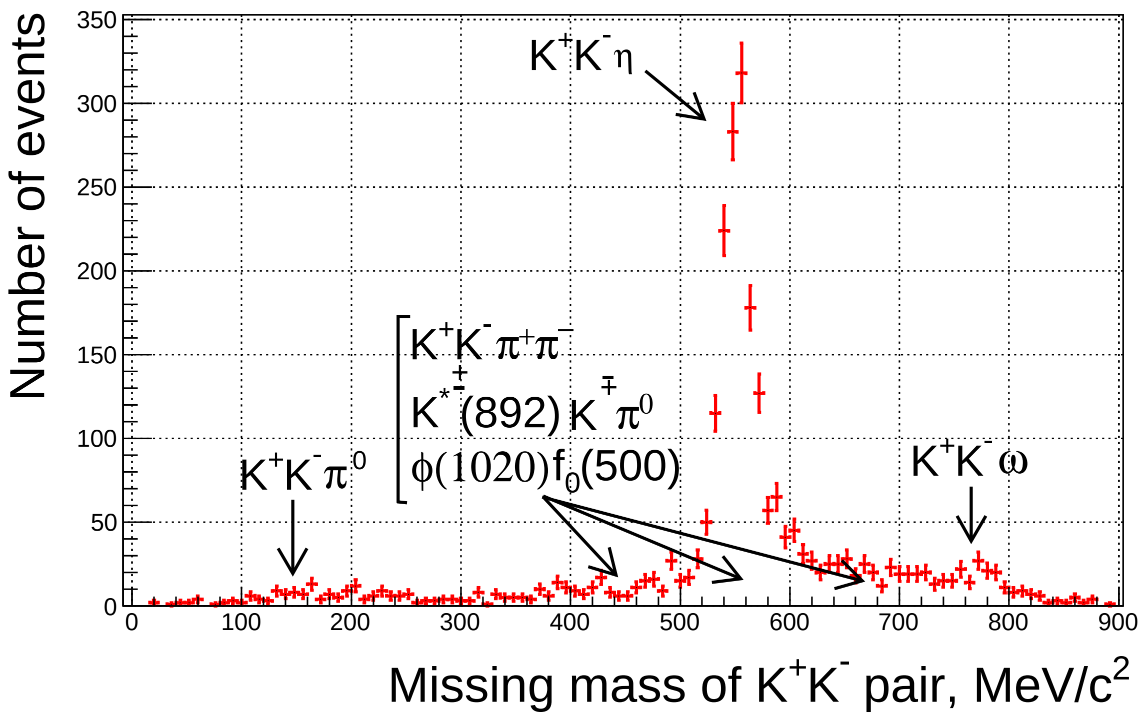
- A data sample of 22 pb^{-1} collected in 2011-2012 is used to study $e^+e^- \to K^+K^-\eta$
- 23 c.m. energy points between 1.57 and 2.0 GeV
- Analysis method emphasizes the dominant $\phi\eta$ signal, studies of non-resonant $K^+K^-\eta$ needed
- Rich background with numerous components seen
- The data sample includes 1600 events of the signal and $\sim$ 600 background events

$e^+e^- \to K^+K^-\eta$ at CMD-3 – II



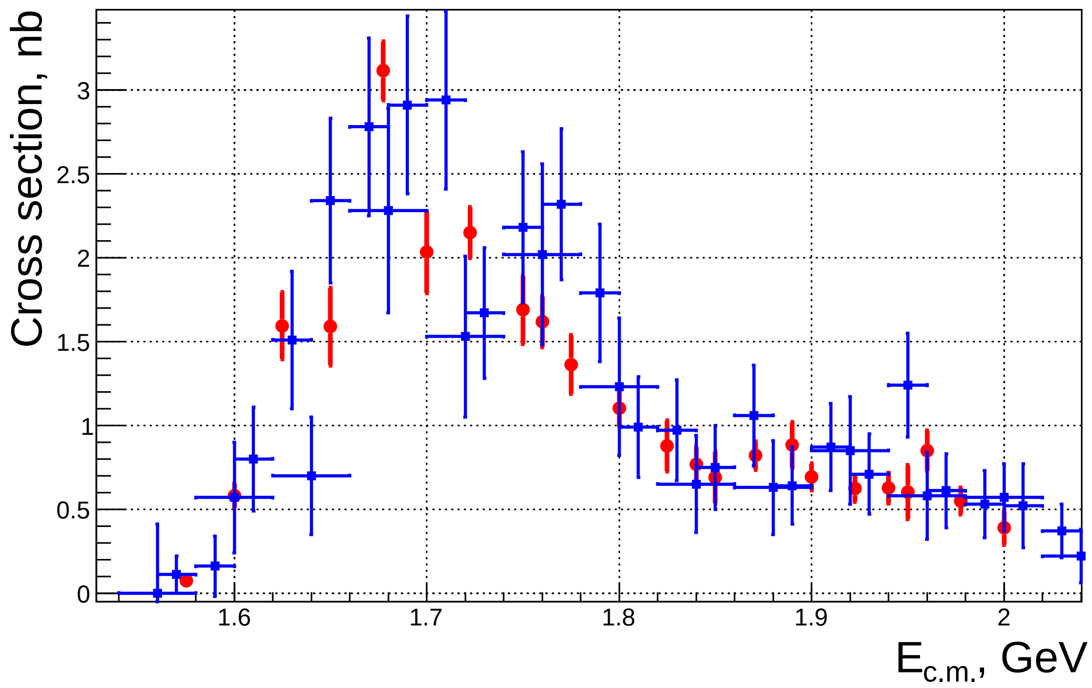
Dynamics dominated by the $\phi\eta$, $\phi \to K^+K^-$ channel

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



Missing mass to K^+K^- clearly shows the dominant signal and BGs

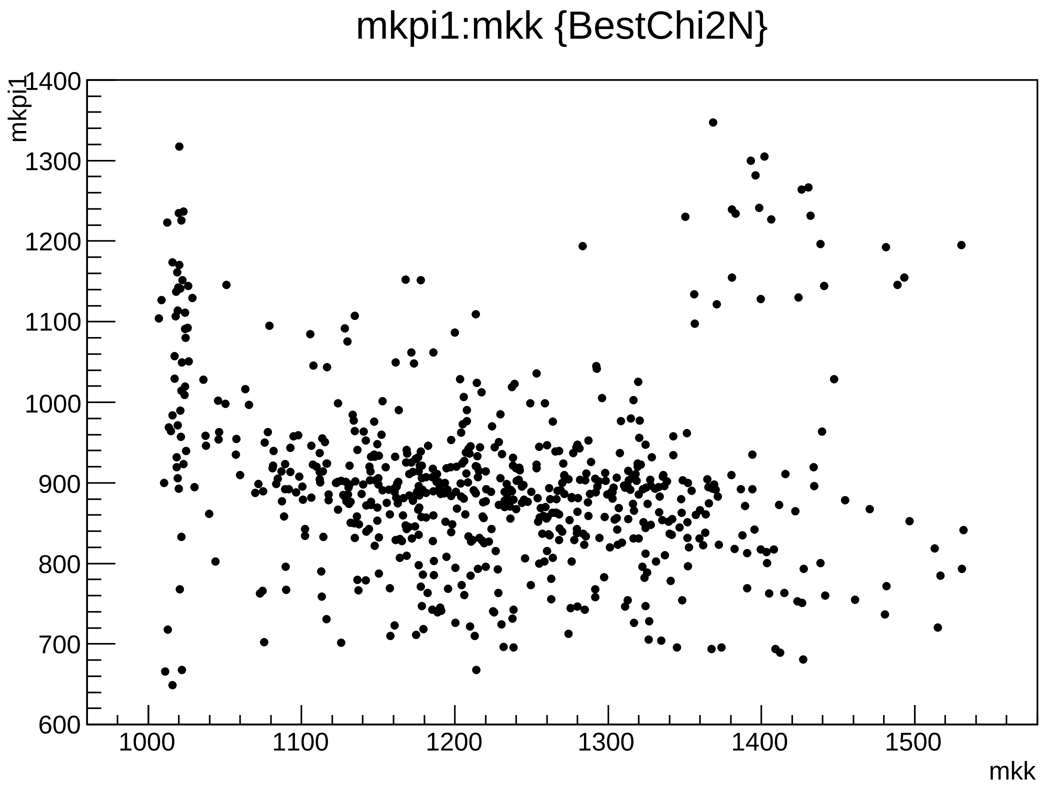
$e^+e^- \to K^+K^-\eta$ at CMD-3 – IV



Cross section is consistent with and more precise than BaBar

$e^+e^- \to K^+K^-\pi^0$ at CMD-3 – I

About 600 signal events selected

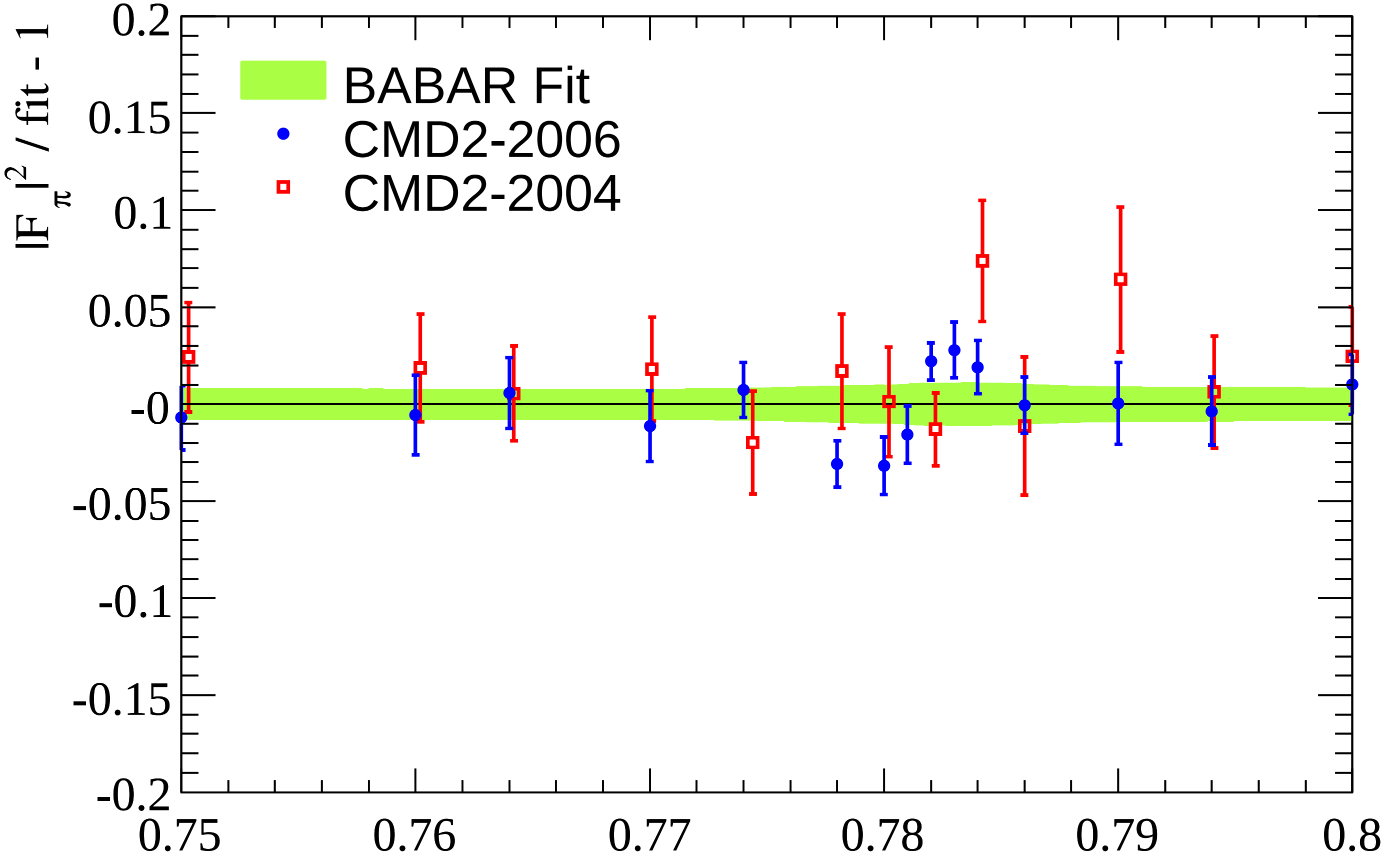


The $K\pi$ vs. K^+K^- plot clearly shows the $\phi\pi^0$ and $K^{*\pm}(892)K^{\mp}$ mechanisms

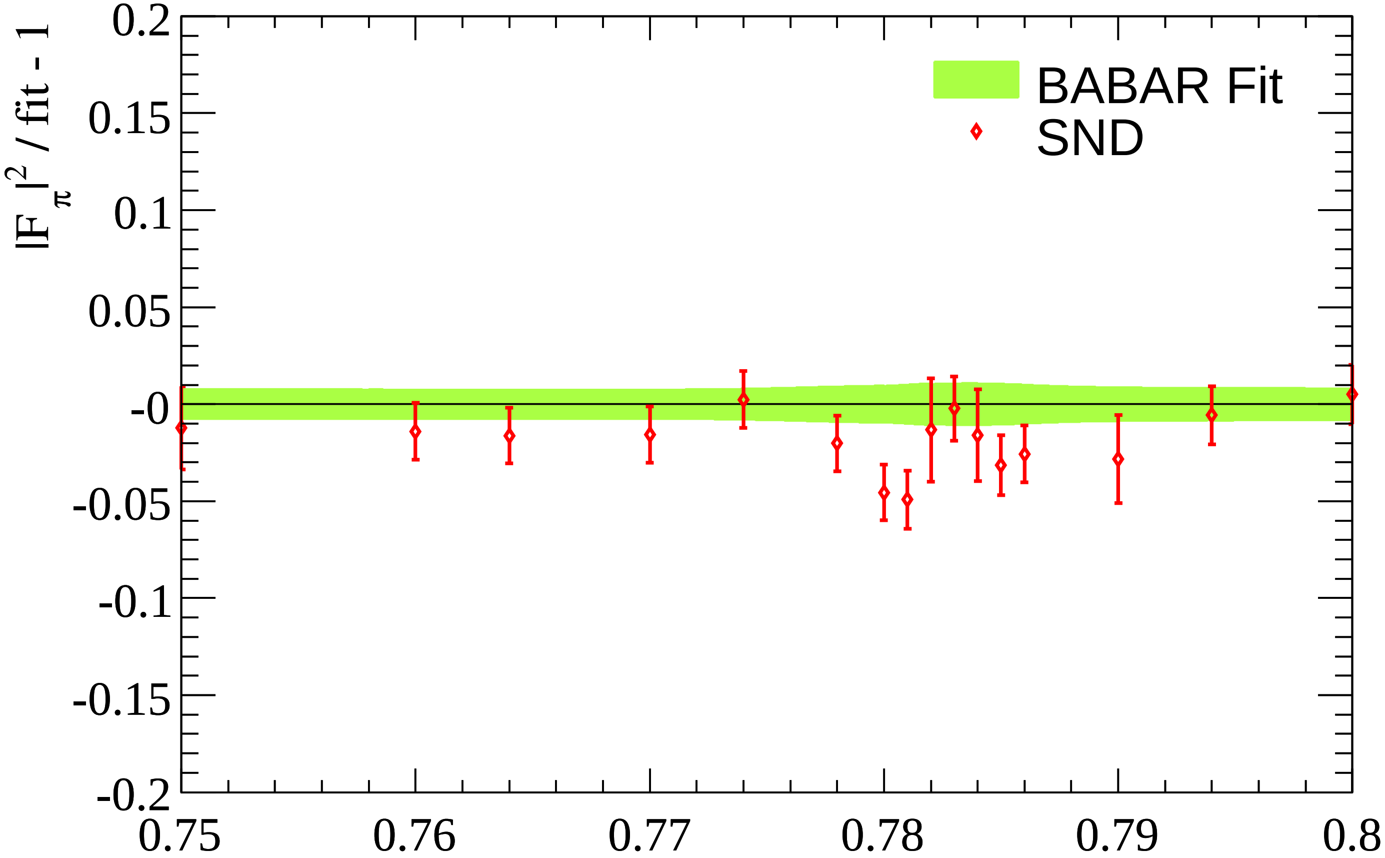
How Real is $a_\mu^{\rm had}$ Accuracy?

- Radiative corrections: ISR and HVP probably OK, FSR demands testing (charge asymmetry, $\pi^+\pi^-\gamma$)
- Scan vs. ISR method
- Missing states: neutrals, $\pi^+\pi^- n\pi^0$, $K\bar{K}n\pi$ - isospin
- Correlations
- Averaging
- Light-by-light term
- Double counting (LO and HO)

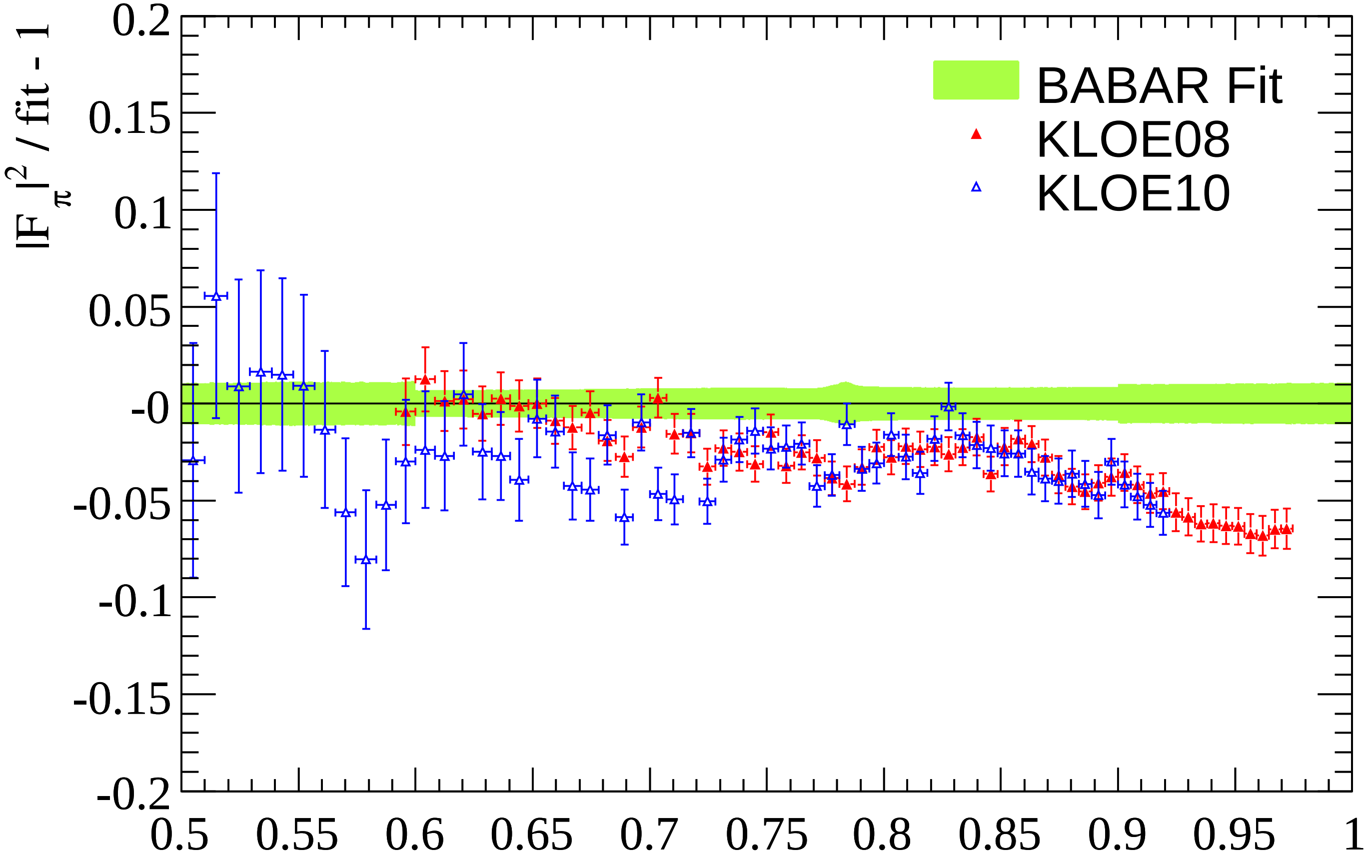
$e^+e^- \to \pi^+\pi^-$, BaBar vs. CMD-2



$e^+e^- \to \pi^+\pi^-$, BaBar vs. SND



$e^+e^- \to \pi^+\pi^-$, BaBar vs. KLOE



Do we have completely correct ISR theory?

Possible Progress for $a_\mu^{\mathrm{LO,had}}$

Three upgraded e^+e^- colliders are running at low energy:

- VEPP-2000 (VEPP-2M upgrade) in Novosibirsk with 2 detectors (CMD-3 and SND), $\sqrt{s}$= from 0.3 to 2 GeV with $L_{\mathrm{max}} = 10^{32}$ cm^{-2}s^{-1}, more than 60 pb^{-1} per detector collected
- DAΦNE in Frascati should resume operation with the KLOE-2 detector at 1.02 GeV and $L \sim (2-3) \cdot 10^{33}$ cm^{-2}s^{-1}
- BEPCII in Beijing with the BESIII detector from 2 to 4.6 GeV and $L = 7 \cdot 10^{32}$ cm^{-2}s^{-1}

BaBar and Belle are continuing ISR analysis

Future

1. Experiment

   The new projects at FermiLAB and JPARC expect 4 times better accuracy each

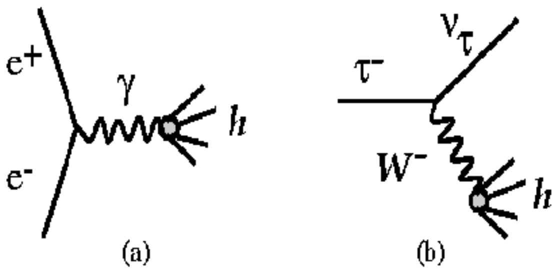
2. Theory (Experiment + Models)

   - Such accuracy for $a_\mu^{\mathrm{had,LO}}$ corresponds to 0.2%, hardly ever achievable with absolute $\sigma(e^+e^- \to \mathrm{hadrons})$
   - Additional limitation from $a_\mu^{\mathrm{had,LBL}}$

3. Theory (First principles – QCD, Lattice)

   - QCD instanton model (A. Dorokhov, 2003)
   - Lattice – T. Blum et al., K. Jansen et al., M. Hayakawa et al.

CVC. $e^+e^- \to X^0$ and $\tau^- \to \nu_\tau X^-$



Allowed $I^G J^P = 1^+1^-$:
$X^- = \pi^-\pi^0, (4\pi)^-, \omega\pi^-,$
$\eta\pi^-\pi^0, K^-K^0, (6\pi)^-, \ldots$

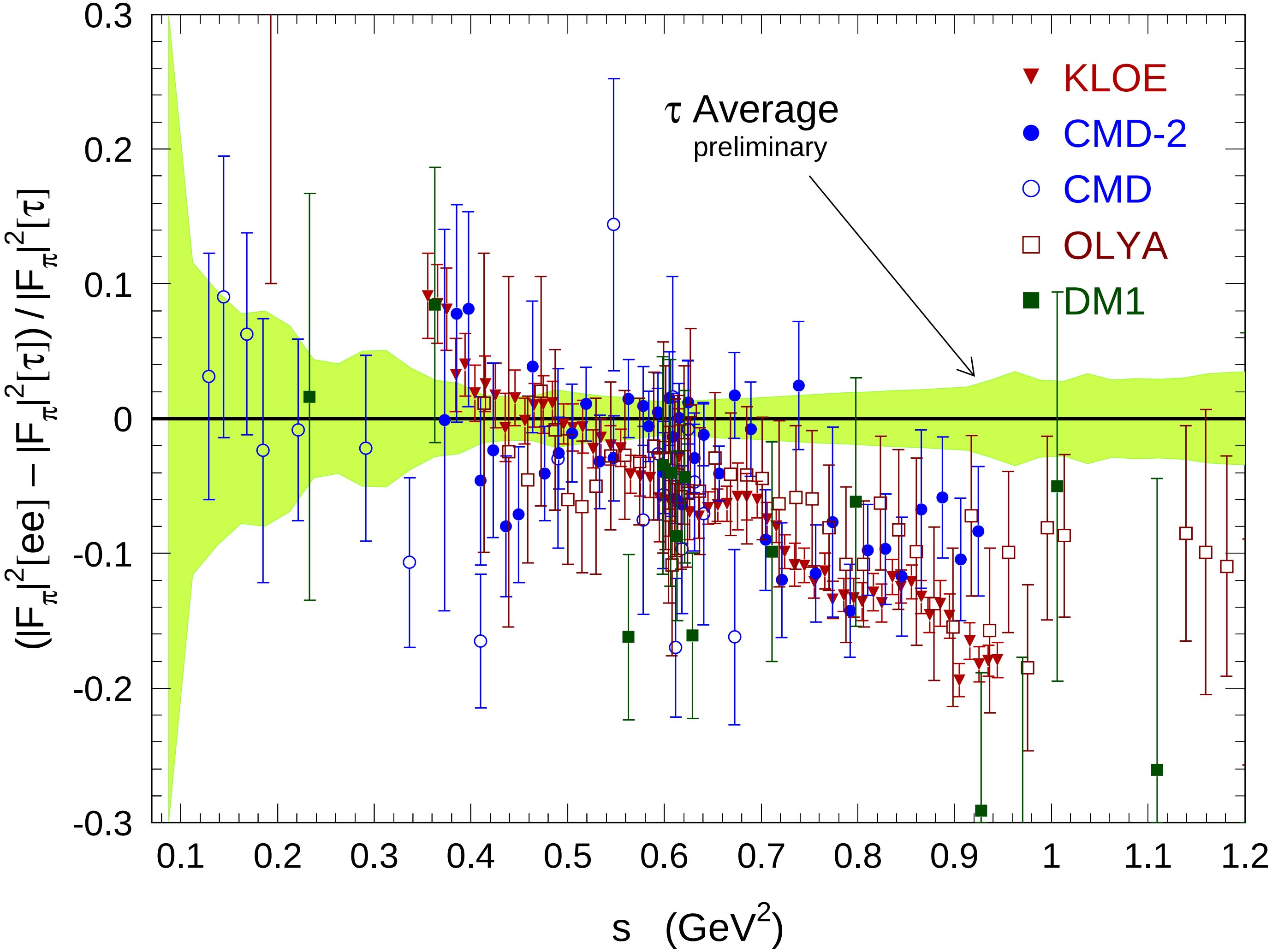
$\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{ud}|^2 S_{EW}}{32\pi^2 m_\tau^3} f_{kin} v_1(q^2)$ with

$v_1(q^2) = \frac{q^2 \sigma^{I=1}_{e^+e^-}(q^2)}{4\pi\alpha^2}$.

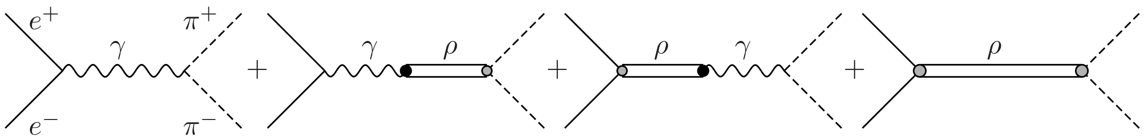
CVC tests showed good agreement of the τ branchings predicted from e^+e^- with τ data (N. Kawamoto and A. Sanda, 1978, F. Gilman and D. Miller, 1978, S. Eidelman and V. Ivanchenko, 1991, 1997).

The very first application of τ data to $a_\mu^{\rm had,LO}$ improved the accuracy by a factor of 1.5 (R. Alemany, M. Davier, A. Höcker, 1998)!

τ vs. e^+e^-


τ Average
preliminary
KLOE
CMD-2
CMD
OLYA
DM1
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
s (GeV²)
(|F_π|²[ee] – |F_π|²[τ]) / |F_π|²[τ]

New Developments in τ vs. e^+e^-

- FJ and RS, EPJ C71, 1632 (2011) reconsidered the $\rho - \gamma$ mixing
- 

- $\mathcal{B}^{\tau}_{\pi\pi} = (25.34 \pm 0.06 \pm 0.08)\%$
- $\mathcal{B}^{e^+e^-}_{\pi\pi} = (25.20 \pm 0.17 \pm 0.28)\%$
- $a^{\mathrm{had,LO}}_{e^+e^-} = (690.75 \pm 4.72) \times 10^{-10}$
- $a^{\mathrm{had,LO}}_{e^+e^-+\tau} = (690.96 \pm 4.65) \times 10^{-10}$