R measurements at e^+e^- colliders

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IFAE
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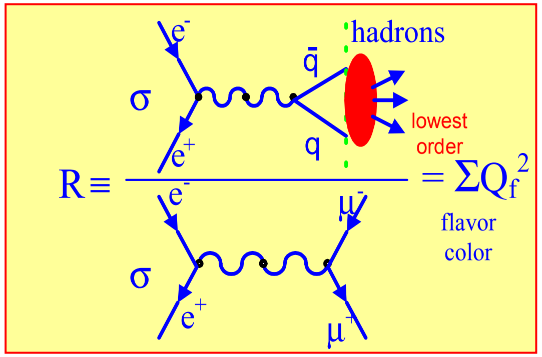
Definition

R: very important quantity in particle physics: counts directly the number of quark flavours and their colours



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

To measure R:

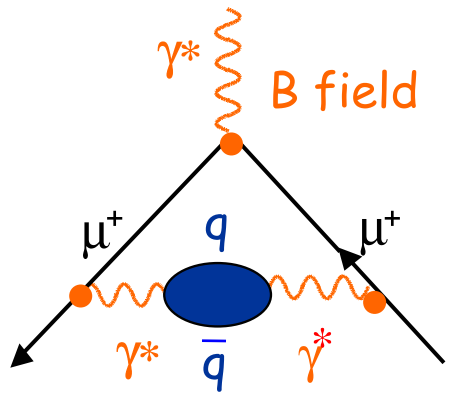
- R scan: systematic variation of c.m. energy of the machine and measurement $\sigma^{tot}(e^+e^- \to \text{hadrons})$
  - Inclusive: directly measure σ^{tot}
  - Exclusive: sum up all channels of $\sigma^{tot} = \sum \sigma^I$

- Radiative return: trough ISR:

$$M^2_{hadr} \frac{d\sigma(e^+ e^- \to \text{hadrons} + \gamma)}{dM^2_{hadrons}} = \sigma(e^+ e^- \to \text{hadrons})\, H(M^2_{hadr})$$

Hadronic contribution to $(g-2)_\mu$

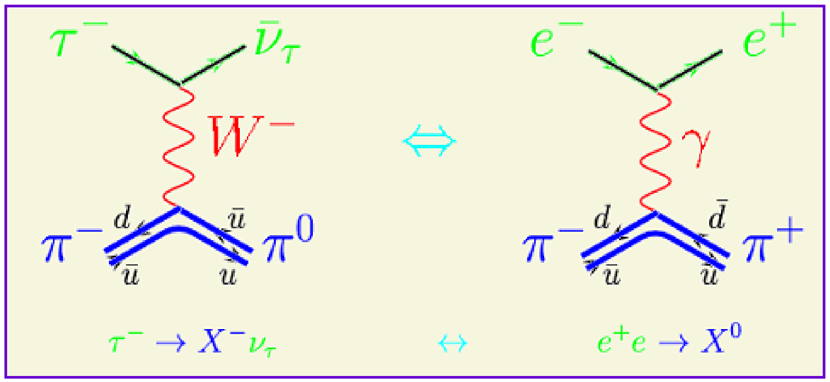
Magnetic moment: $\vec{\mu} = g_\mu \frac{e\hbar}{2m_\mu c}\vec{s}$ with $g_\mu = 2(1+a_\mu)$



Due to quantum corrections: $a_\mu^{SM} = a_\mu^{QED} + a_\mu^{had} + a_\mu^{EW}$

a_μ^{had} includes contribution from not evaluable in pQCD, but it can be provided by $\sigma(e^+ e^- \to$ **hadrons**) by means of dispersion relations:

$$a_\mu^{had}(e^+e^-) = \frac{\alpha^2}{3\pi^2}\int_{4m_\pi^2}^{\infty} ds \frac{K(s)}{s} R(s) \qquad K(s) \sim 1/s$$



$\tau \to \nu_\tau$ **hadrons** decays provide complementary information:

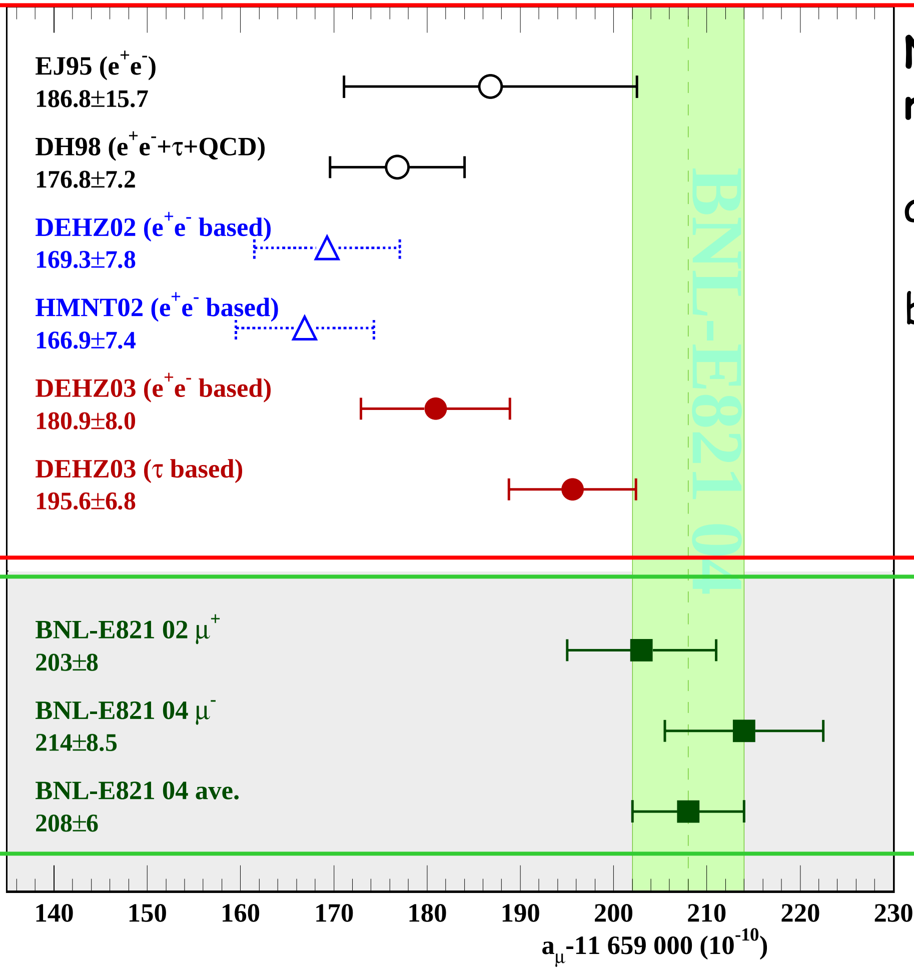
$$\text{CVC} + \text{SU}_{iso}(2)$$

$$\frac{dN_{\tau \to \nu\, hadrons}}{dM_{hadrons}} \rightarrow a_\mu^{had}(\tau)$$

Status of (g-2): theory vs. experiment

Comparison Experimental Value with Theory - Prediction

THEORY '02/'03



New cross section data have recently lowered theory error:

a) CMD-2 (Novosibirsk/VEPP-2M) $\pi^+\pi^-$ channel with 0.6% precision < 1 GeV

b) τ-Data from ALEPH /OPAL/CLEO

e^+e^- - Data: 2.7 s - Deviation

τ - Data: 1.4 s - Deviation

Experiment '02/'04

Experiment BNL-E821

Values for μ^+(2002) and μ^-(2004) in agreement with each other.

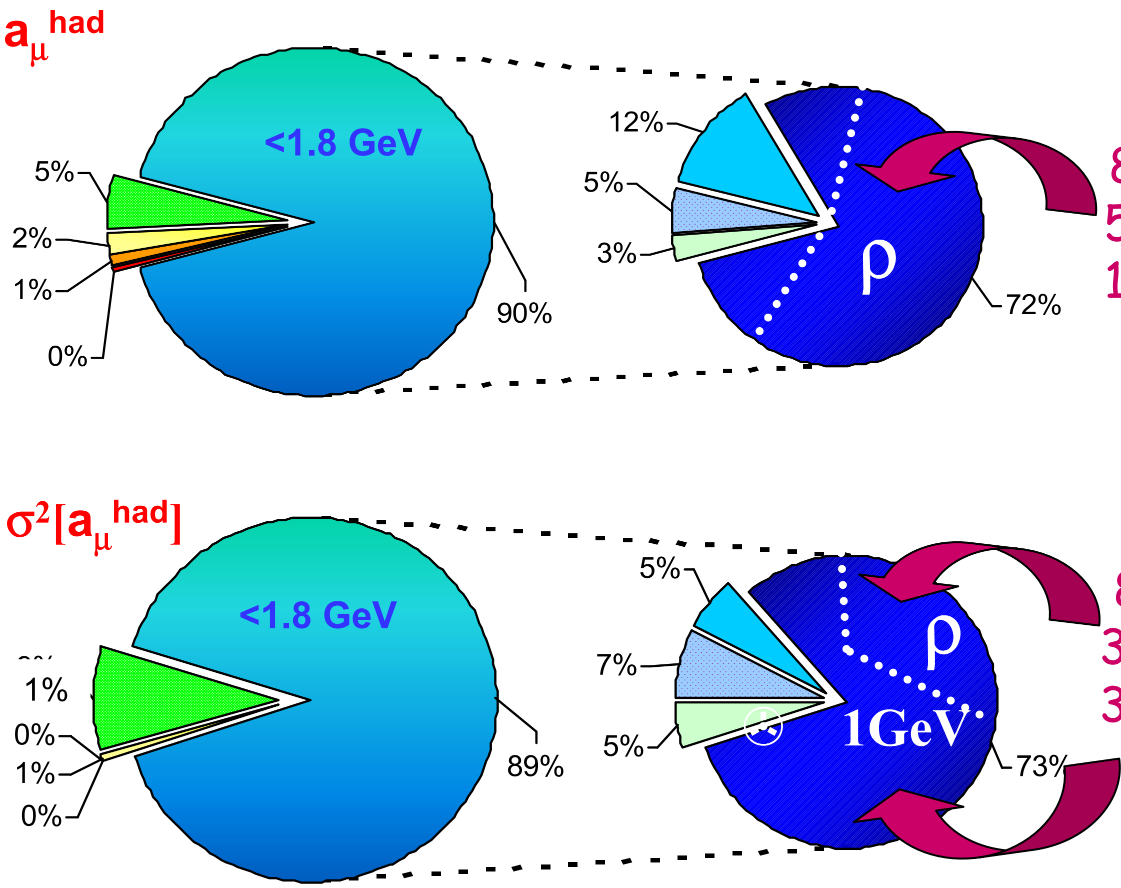
Precision: 0.5 ppm

Hadron contribution to a_μ

2π	3π (+ω,φ)	4π	> 4π (+KK)	1.8 - 3.7	3.7 - 5 (+J/ψ, ψ)	5 - 12 (+ϒ)	12 - ∞

< 1.8 GeV

Calculations based on hep-ph/0308213
Davier, Eidelman, Höcker, Zhang



2π contrib. a_μ^{had}
8% [$2m_\pi$ - 0.5 GeV]
54% [0.6 - 1.0 GeV]
10% [Rest<1.8 GeV]

2π contrib. da_μ^{had}
8% [$2m_\pi$ - 0.5 GeV]
34% [0.6 - 1.0 GeV]
31% [Rest< 1.8 GeV]

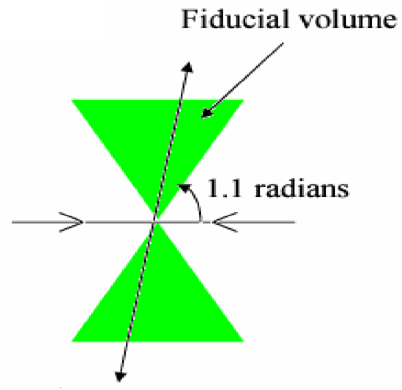
e+e- data only!

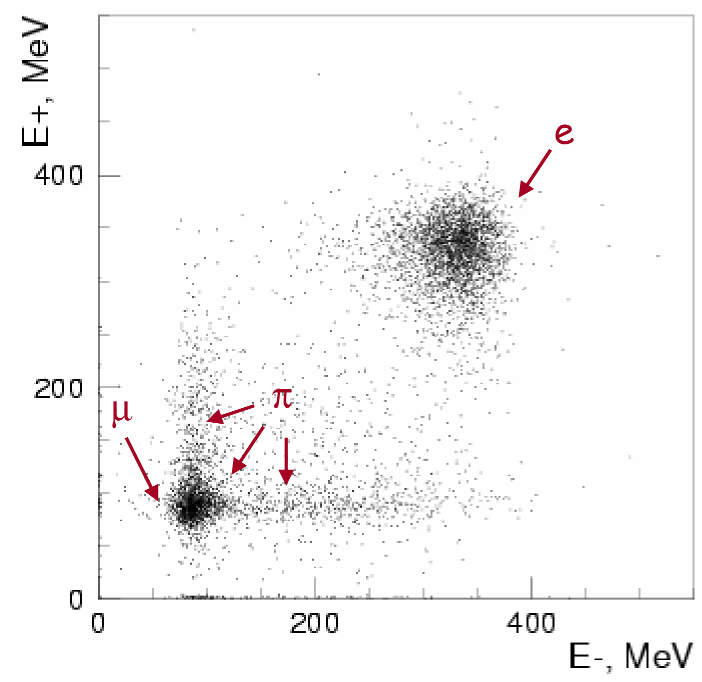
The $\sigma(e^+e^- \rightarrow \pi^+\pi^-)$ analysis @ CMD-2

Energy scan analysis with $0.6 < \sqrt{s} < 1.0$ GeV

R.R. Akhmetshin et al., Phys.Lett.B578:285-289,2004

- selection of collinear $e^+e^- \rightarrow e^+e^-$, $e^+e^- \rightarrow \pi^+\pi^-$, $e^+e^- \rightarrow \mu^+\mu^-$ in the fiducial volume
- separation of the three sample, by energy deposition
- rejection of cosmic events by means of the spatial distribution of the vertex

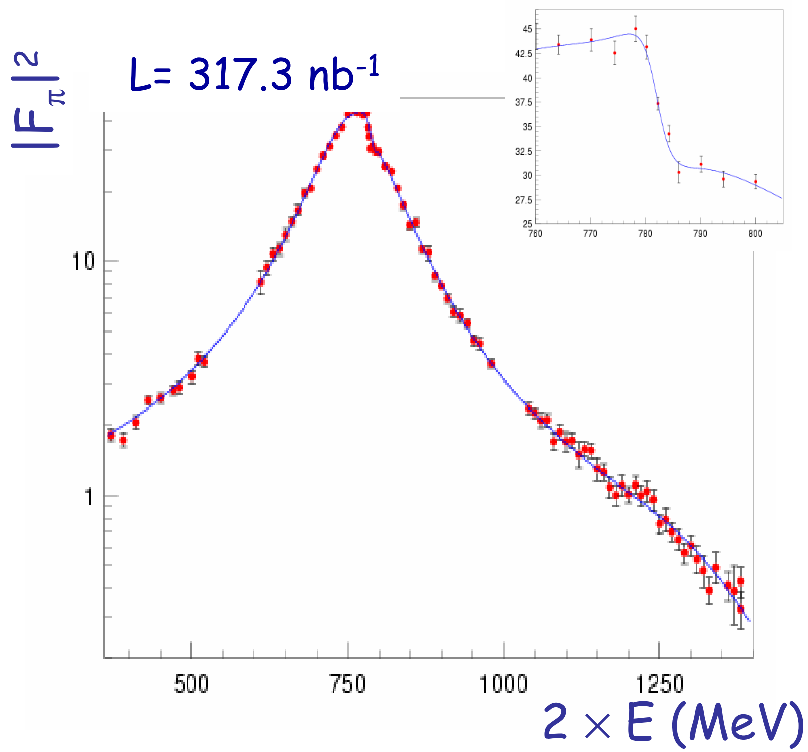




Sources of systematic errors:	
- Event separation	0.2%
- Radiative correction	0.4%
- Detection efficiency	0.2%
- Fiducial volume	0.2%
- Correction for π losses	0.2%
- Beam energy determination	0.1%
TOTAL	0.6%

Pion form factor

ρ-ω interference



correction for misidentification of $\omega \to \pi^+\pi^-\pi^0$

$$|F_\pi|^2 = \frac{N_{\pi\pi}}{N_{ee}+N_{\mu\mu}} \times \frac{\sigma_{ee}^{R.C.}\times\varepsilon_{ee} + \sigma_{\mu\mu}^{R.C.}\times\varepsilon_{\mu\mu}}{\sigma_{\pi\pi}^{R.C.}(1+\Delta_N)(1+\Delta_D)\,\varepsilon_{\pi\pi}} - \Delta_{3D}$$

due to pion loss:
- by decays in flight
- by nuclear interaction

Fit function according to Gounari - Sakurai model:

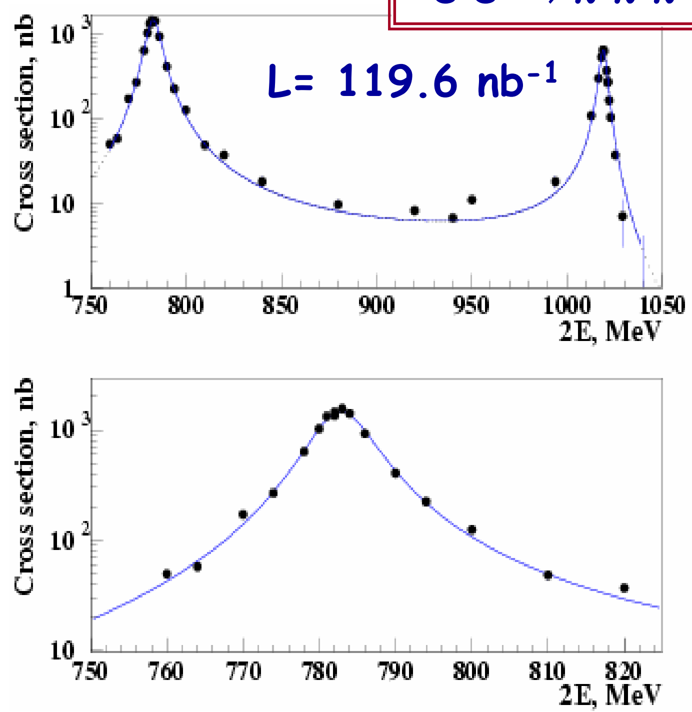
$$F_\pi(s) = \frac{BW_\rho^{GS}\left(1+\delta\frac{s}{M_\omega^2}BW_\omega\right)+\beta BW_{\rho'}^{GS}}{1+\beta}$$

3 terms for ρ, ω, ω'

........and $\sigma(e^+e^- \to \pi^+\pi^-) \propto |F_\pi(s)|^2$

a_μ^{had} @ VEPP-2M

Channel	Accuracy %	Error in a_μ ppm
$\pi^+\pi^-$	0.6	0.26
$\pi^+\pi^-\pi^0$	1.5	0.06
K^+K^-	5.2	0.09
K_LK_S	1.9	0.02
$\pi^+\pi^-\pi^0\pi^0$	7	0.05
$\pi^+\pi^-\pi^+\pi^-$	7	0.04
$\omega\to\pi^0\gamma$, $\phi\to\eta\gamma$	6	0.02
Total		0.29



a_μ^{had}(total) = 70.2×10^{-9} (60.21 ppm)

a_μ^{had}(VEPP-2M) = 60.16×10^{-9} (51.61 ppm)

contributions to a_μ above VEPP-2M:

8.6 ± 0.6 ppm

R scan @ BES

R scan between 2 and 5 GeV:

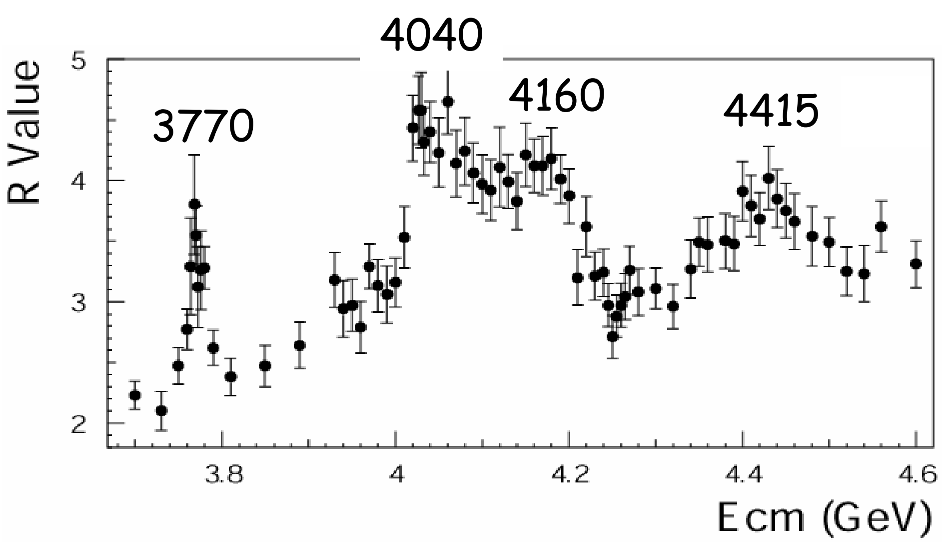
March-May, 1998: 6 energy points at 2.6, 3.2, 3.4, 3.55, 4.6, 5.0 GeV
Feb.- June, 1999: 85 energy points at 2.0-4.8 GeV

$$R = \frac{N_{had}^{obs} - N_{bkg} - \sum_l N_{ll} - N_{\gamma\gamma}}{\sigma(e^+e^- \to \mu^+\mu^-)\, L\, \varepsilon\, (1+\delta)}$$

correction to to ISR

N_{ll} = lepton pairs
$N_{\gamma\gamma}$ = γ pairs

- kinematic cuts to select the event
- use vertex-fitting procedure to remove residual background
- luminosity determined using large angle Bhabha



Source of syst. Error	%
Luminosity	2-3
Detection efficiency	2-3
Trigger efficiency	0.5
Radiative Correction	1-2
Statistics	3-7
TOTAL	5-8

⇨ average error ~6.6%

Radiative Return

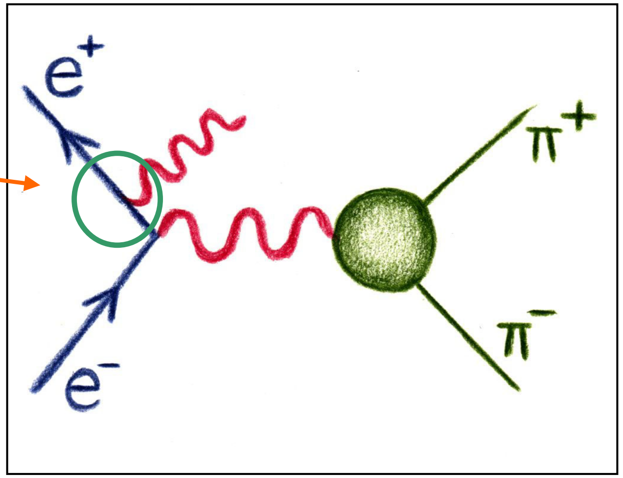
Standard method for cross section measurement is the energy scan, i.e. the syst. variation of the the c.m. energy of the accelerator.

Particle factories (fixed c.m. energy) have the opportunity to measure the cross section $\sigma(e^+ e^- \rightarrow hadrons)$ as a function of the hadronic c.m. energy $M^2_{hadrons}$ by using the **radiative return**.

Precise knowledge of ISR – process:
Radiator function $H(Q^2, \theta_\gamma, M^2_\varphi)$

MC generator: Phokhara

(H. Czyz, A. Grzelinska, J.H. Kühn, G. Rodrigo, hep-ph/0308312)



"Radiative Return" to $\rho(\omega)$ resonance $e^+e^- \rightarrow \rho(\omega)\,\gamma \rightarrow \pi^+\pi^-\gamma$

$$M^2_{hadr} \frac{d\sigma(e^+ e^- \rightarrow hadrons + \gamma)}{dM^2_{hadrons}} = \sigma(e^+ e^- \rightarrow hadrons)\, H(M^2_{hadr})$$

This method is a complementary approach to the energy scan

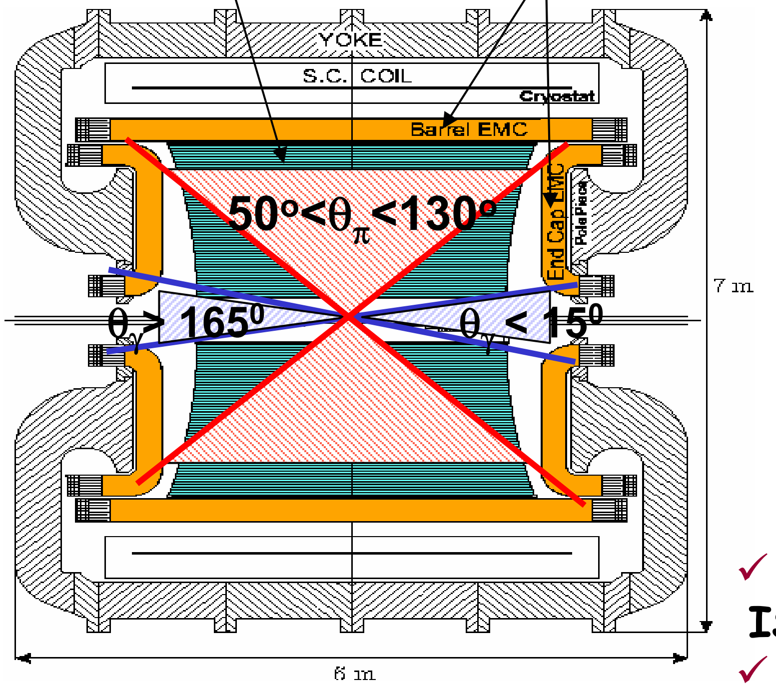
Analysis overview

$50^o < \theta_\pi < 130^o$, $\theta_\gamma < 15^o$ and $\theta_\gamma > 165^o$

No photon tagging

Drift Chamber

EM Calorimeter



- ✓ High statistics for **ISR** photons
- ✓ Low relative contribution from **FSR**
- ✓ Low relative background

Analysis Flow

Obs. Spectrum $dN/dM_{\pi\pi}^2$
141 pb^{-1} of 2001 data

↓ Event analysis

↓ Divide by luminosity

Diff. Cross Section
$d\sigma(\pi^+\pi^-\gamma)/dM_{\pi\pi}^2$

↓ Divide by H function

Diff. Cross Section
$d\sigma(\pi^+\pi^-)/dM_{\pi\pi}^2$

VP, FSR corrections

Luminosity measurement

KLOE uses **large angle Bhabha events** for the luminosity evaluation:

$$\int L\, dt = \frac{N}{\sigma^{MC}}(1-\delta_{Bkg})$$

σ^{MC}: effective cross section, given by theoretical generator interfaced with our simulation detector program

Precision determined by
- knowledge of radiative corrections
- precision in collecting large angle Bhabha

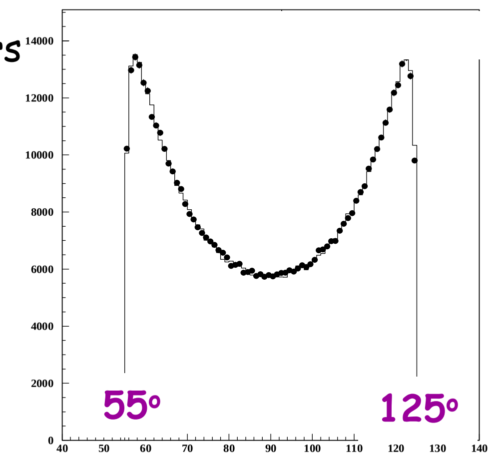
2 independent generators used for radiative corrections:

- BABAYAGA (Pavia group): $\sigma_{eff} = (428.8 \pm 0.3_{stat})$ nb
- BHAGENF (Berends modified): $\sigma_{eff} = (428.5 \pm 0.3_{stat})$ nb

Systematics on Luminosity	
Theory	0.5%
Acceptance	0.2%
Background	0.1%
Trigger+Tracks+Clustering	0.2%
Knowledge of $\sqrt{s}$ run-by-run	0.1%
TOTAL 0.5 % theory $\oplus$ 0.3% exp = 0.6 %	

Theory 0.5%: claimed by generator's authors

Experimental systematic error are determined by comparing data and MC angular and momentum distribution



$e^+e^-\gamma$ spectrum

Efficiencies:

- Trigger & Cosmic veto
- Tracking, Vertex
- π- e- separation
- Reconstruction filter
- Trackmass-cut
- Unfolding resolution
- Acceptance

Errors

1.0 %

Background:

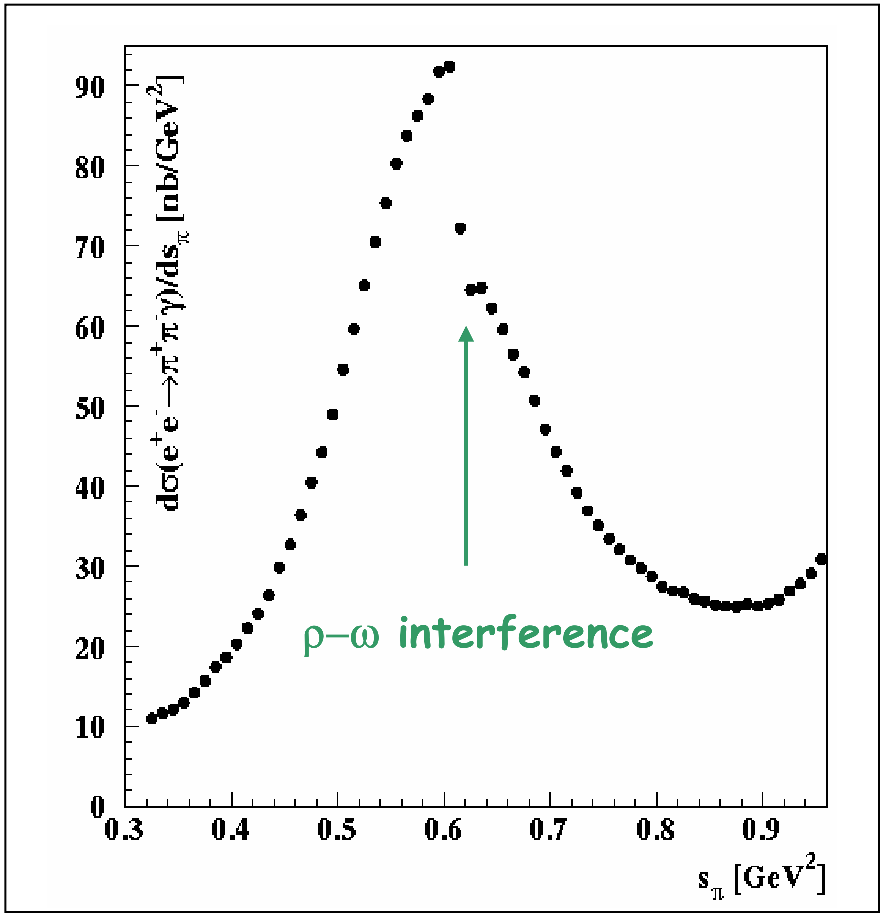
- $e^+ e^- \rightarrow e^+ e^- \gamma$
- $e^+ e^- \rightarrow \mu^+ \mu^- \gamma$
- $\phi \rightarrow \pi^+ \pi^- \pi^0$

0.5 %

Luminosity: 0.6%

Statistics: $141 pb^{-1}$ of 2001-Data

1.5 Million Events

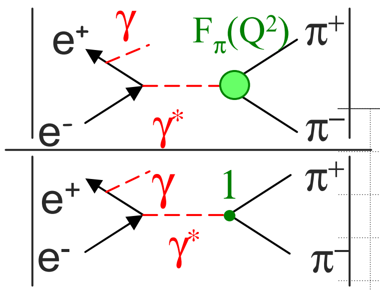


Final spectrum

To get the cross section for $e^+e^-\to\pi^+\pi^-$:

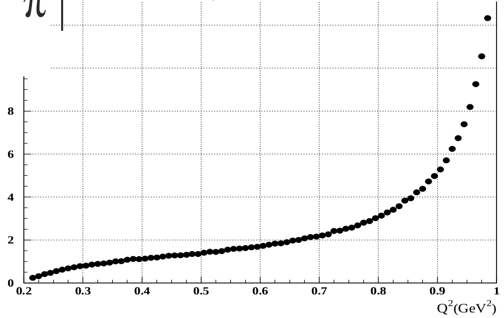
- division by **radiator function H** $\Rightarrow$ **ISR-process calculated at NLO-level**
- **radiative corrections:**
  - **i) bare cross section** $\Rightarrow$ subtraction of **vacuum polarization** contribution
  - ii) **FSR** corrections

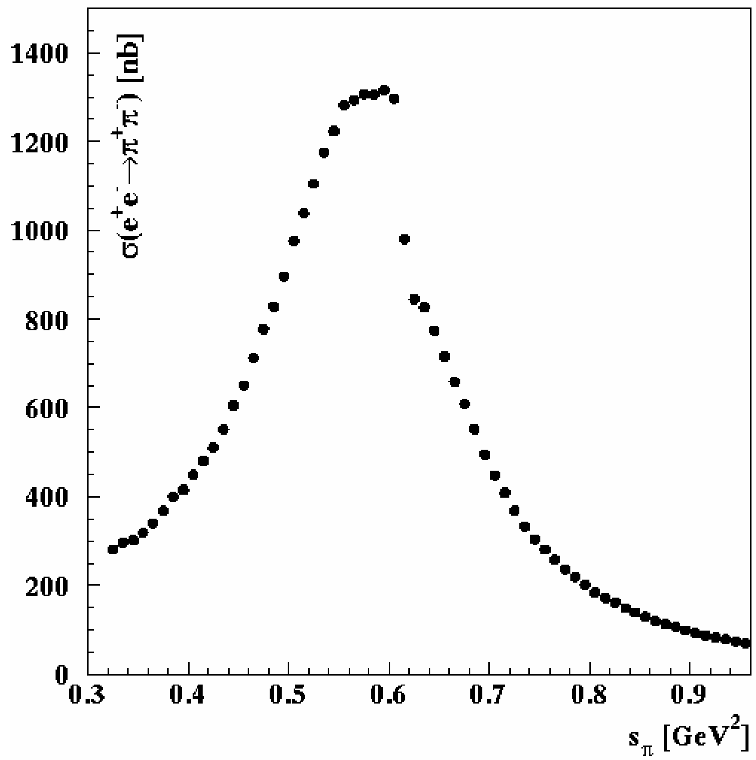
$$\sigma_{\pi\pi} \propto \left|F_\pi(M^2_{\pi\pi})\right|^2 = \frac{d\sigma_{\pi\pi\gamma}(M^2_{\pi\pi})}{d\sigma_{\pi\pi\gamma,F_\pi=1}(M^2_{\pi\pi})}$$



Radiator function

$\sigma_{\pi\pi\gamma,\,F\pi=1}$, **Phokhara**



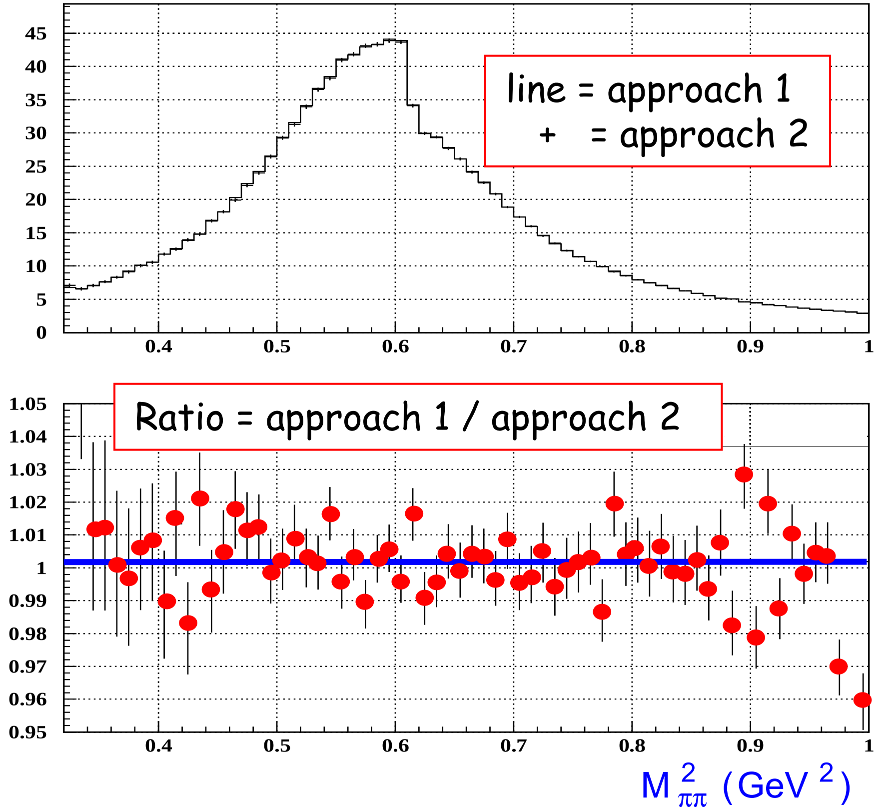


2 approaches for FSR corrections:

- **Approach 1: "exclusive NLO-FSR"**
  - Correcting measured $\sigma_{\pi\pi\gamma}$ for FSR
  - Use MC with pure ISR in analysis
  - Add FSR-contrib. to $\sigma_{\pi\pi}$ (ca. 0.8%) by hand

- **Approach 2: "inclusive NLO-FSR"**
  - Correct for „unshifting", i.e. $s' \neq M_{pp}$
  - Use MC with ISR + FSR in analysis

Pion Formfactor after FSR corrections



Both methods in excellent agreement!

For the **error on the model dependence** of **FSR** (scalar QED) we take **0.5%**

Summary on systematic error

The systematic error has contributions from:

Experiment

TOTAL	**1.2%**

Theory

- Radiator Function H	0.5%
- Vacuum Polarization	0.2%
- Luminosity	0.6%
- FSR resummation	0.5%
TOTAL	**1.0%**

Calculating the dispersion integral:

$$a_\mu^{had-\pi\pi}(0.35< M_{\pi\pi}^2< 0.95\ GeV^2) = (389.2 \pm 0.8_{stat} \pm 4.7_{syst} \pm 3.9_{theo})\ 10^{-10}$$

$$a_\mu^{had-\pi\pi}(0.37< M_{\pi\pi}^2< 0.93 GeV^2) =$$

$(376.5 \pm 0.8_{stat} \pm 5.9_{syst+theo})\ 10^{-10}$ **KLOE**

$(378.6 \pm 2.7_{stat} \pm 2.3_{syst+theo})\ 10^{-10}$ **CMD-2**

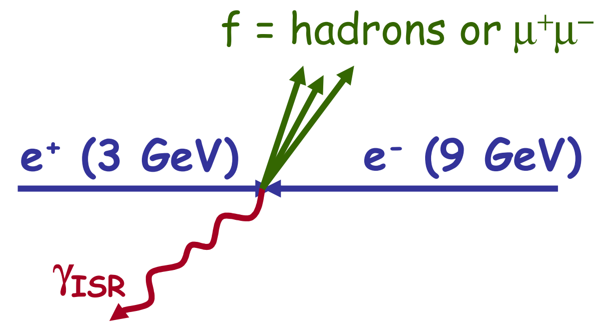
✓ both measurement are in agreement within the errors
✓ e^+e^- - τ discrepancy for a_μ is confirmed

ISR method @ BABAR

- ✓ up to now very few data with large errors for $\sqrt{s}$ 1.4 GeV: ΔR ~ 10-15%
- ✓ data from different experiments and different systematics

$$\sigma_f(s') = \frac{dN_{f\gamma}}{\varepsilon_f\,(1+\delta^f_{\mu\mu})}\,\frac{\varepsilon_{\mu\mu}\,(1+\delta^{rad}_{\mu\mu})}{dN_{\mu\mu\gamma}}\,\sigma_{e^+e^-\to\mu^+\mu^-}(s') = \frac{dN_{f\gamma}}{\varepsilon_f\,(1+\delta^f_{\mu\mu})}\times\frac{1}{dL(s')}$$

s' is the effective energy



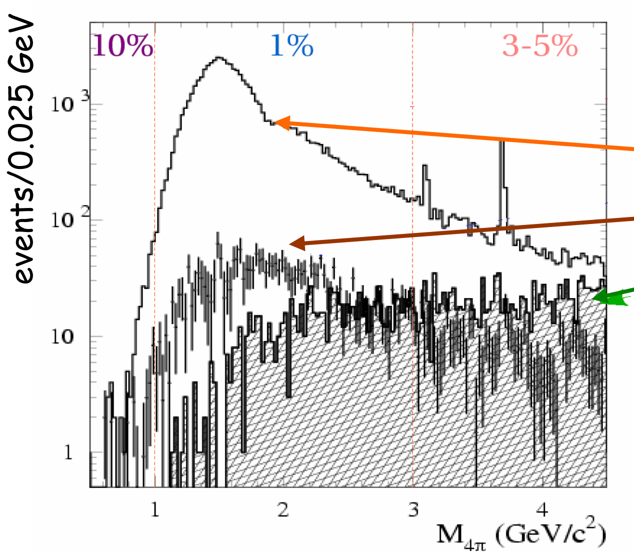
- $e^+e^- \to f$ many channels:
  $\pi^+\pi^-$, K^+K^-, pp, $\pi^+\pi^-\pi^0$, 4π, 5π, 6π, $\pi\pi\eta$, $KK\pi$, $KK\pi\pi$, 2K2K, $KK\eta$
- R will be reconstructed from the sum of exclusive channels up to ≈2.5 GeV
- inclusive approach also studied, limited by photon energy resolution for lower recoil masses

$e^+e^- \rightarrow \gamma + \pi^+ \pi^- \pi^+ \pi^-$ @ *BABAR*

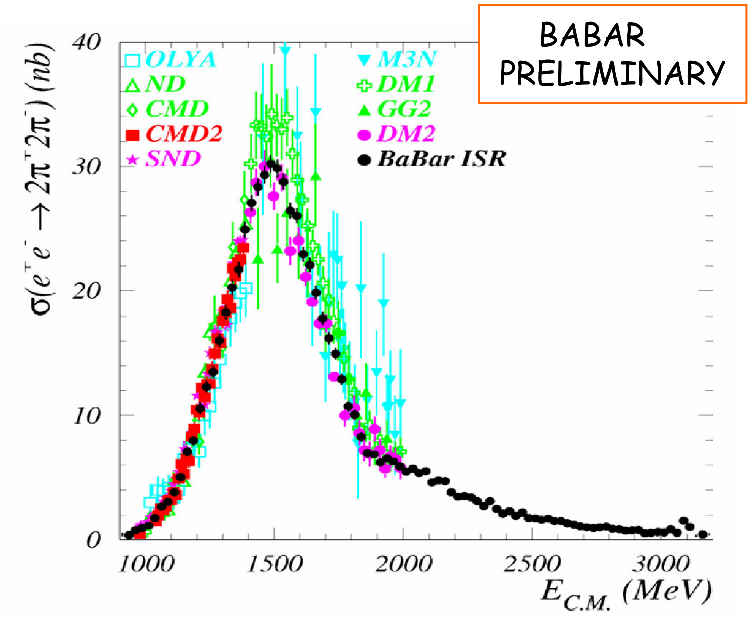
perspectives on *R* measurements by *BABAR:*

- comparable accuracy w.r.t. CMD-2 and KLOE for $\sqrt{s} < 1$ GeV
- few % accuracy for $1 < \sqrt{s} < 3$ GeV

4π invariant mass distribution



- ISR photon + 4 charged hadrons
- 1C fit in 4π hypothesis



CONCLUSION

- ✓ CMD2 and SND experiments at VEPP-2M and KLOE at DAΦNE have improved the accuracy on R respectively in the regions **E < 1.4 GeV** and **E < 1 GeV**, the first one using the energy scan and the last one the ISR method. Their results are in agreement

- ✓ BESII at BEPC has improved quite a lot the accuracy on R in the region **2<E<5 GeV**

- ➢ Other improvements are expected by BABAR in the region **1-3.5 GeV**, using ISR

Riserva

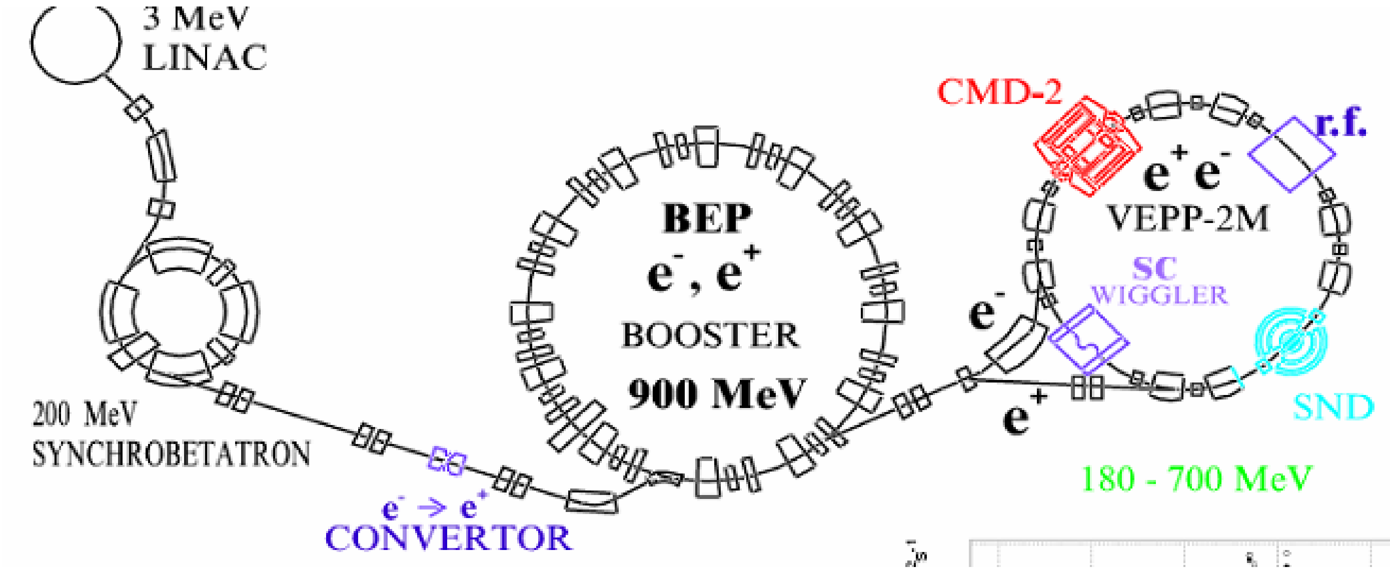
The VEPP-2M collider

VEPP-2M parameters:

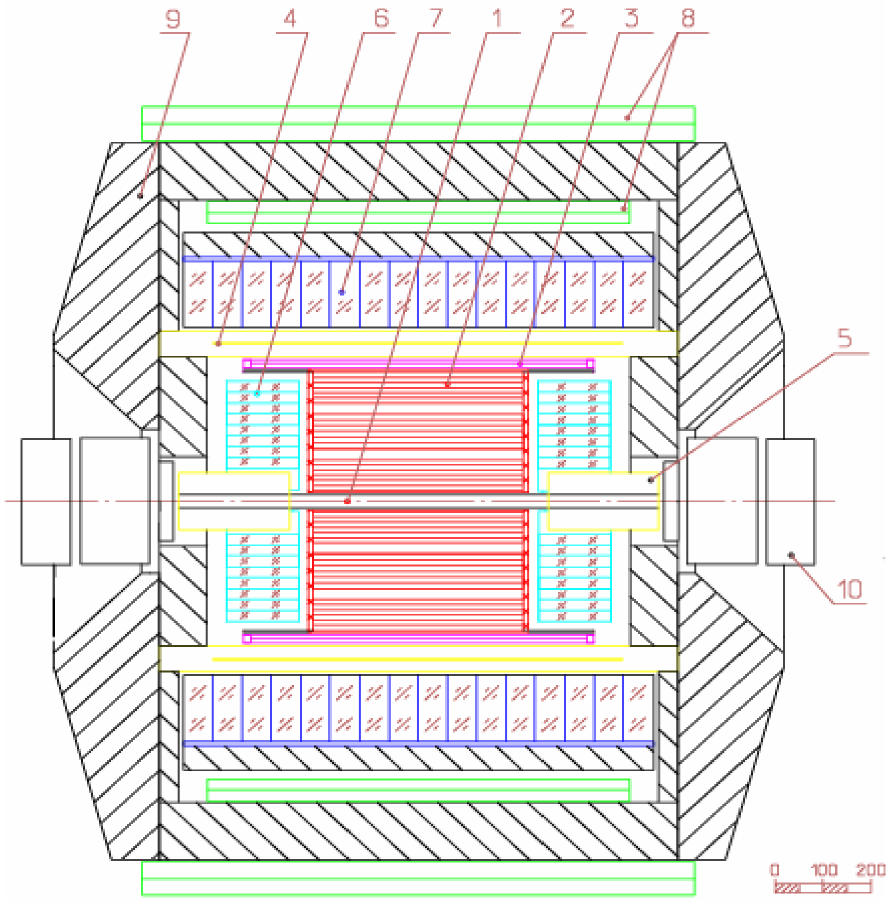
Beam energy	$2\times(180\text{-}700)$ MeV
Peak luminosity	3×10^{30} cm^{-2} s^{-1}
Interaction regions	2
Years of activity	1974-2000

Data collected by CMD-2 :

- **2×10^7 ϕ decays**
- **5×10^6 $\pi^+ \pi^-$ events**
- **3×10^6 ω decays**
- **2×10^7 multi-hadrons**



The CMD-2 detector



1–vacuum chamber; 2–drift chamber; 3– Z–chamber; 4–main solenoid; 5–compensating solenoid; 6–BGO endcap calorimeter; 7–CsI barrel calorimeter; 8–muon range system; 9–iron yoke; 10–storage ring lenses

Drift chamber:

$\sigma_{R-\phi}$=250 μm $\qquad$ σ_z=5 mm

$\sigma_\theta = 1.5 \times 10^{-2}$ $\qquad$ $\sigma_\phi = 7 \times 10^{-3}$

$\sigma_{dE/dx} = 0.2 \times E$

$\sigma_p/p=(90 \times p^2[GeV] +7)^{1/2}$ %

Calorimeter:

Barrel:

$\sigma_E/E = 8\%$ $\qquad$ E_γ 100÷700 MeV

$\sigma_{\theta,\phi}$=0.02 radiant

Endacap:

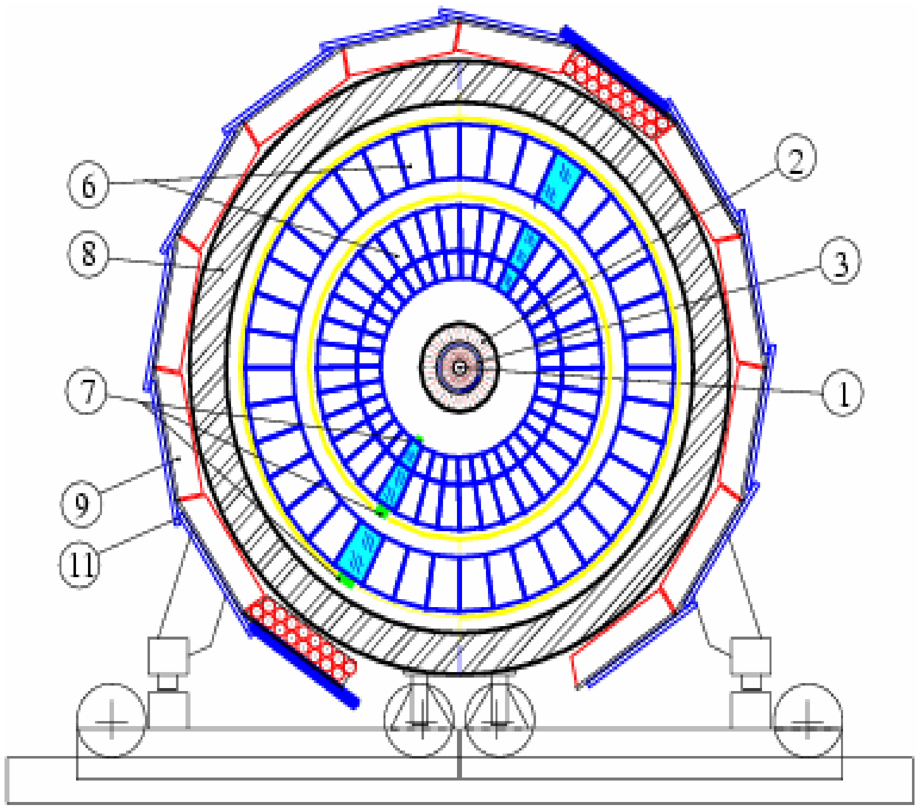
$\sigma_E/E = 4 \div 8$ % $\qquad$ E_γ 100÷700 MeV

$\sigma_{\theta,\phi}$=0.02 ÷ 0.03 radiant

Solid angle covered by cal:

$\Omega = 0.92 \times 4\pi$ steradiant

SND detector



Energy resolution:

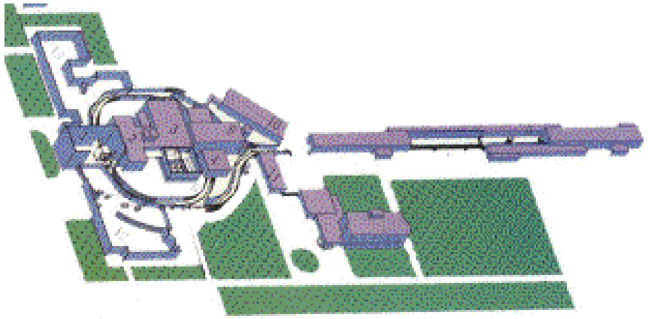
$$\frac{\sigma_E}{E} = \frac{4.2\%}{\sqrt[4]{E(GeV)}}$$

Angular resolution:

$$\sigma_\varphi = \frac{0.82^0}{\sqrt{E(GeV)}} \oplus 0.63^0$$

1-vacuum chamber; 2 – drift chambers; 3 – internal scintillating counter; 6-NaI crystals; 7-vacuum phototriodes; 8-absorber; 9-streamer tubes; 11- scintillator plates;

The BEPC complex

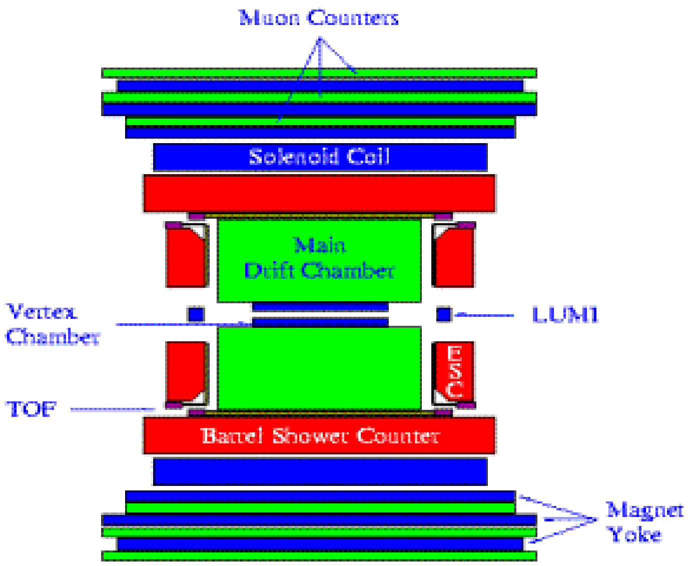


✓ the only e^+e^- machine in 2-5 GeV since 1989

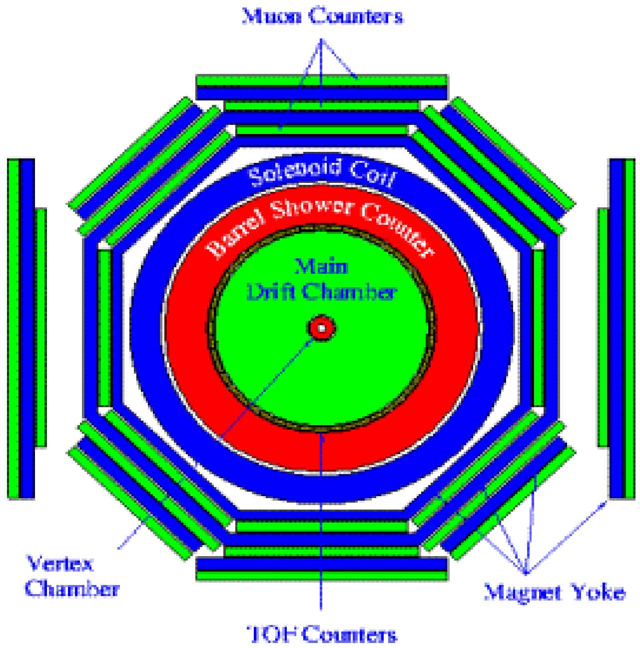
✓ L ~ 5×10^{30} cm^{-2} s^{-1} at the J/ψ peak

E_{cm} (GeV)	Physics	BES	Other Labs
3.1	J/ψ	7.8×10^6	8×10^6
3.69	ψ(2S)	3.9×10^6	1.8×10^6
4.03	τ	1×10^3	10^6 (LEP)
4.14	D, D_s,	22.3 pb^{-1}	CLEO
3.55	m_τ	5 pb^{-1}	
2-5	R scan	6+85 pts	γγ2, MarkI, Crystal Ball, Pluto…
3.1	J/ψ	5×10^7	

The BES detector



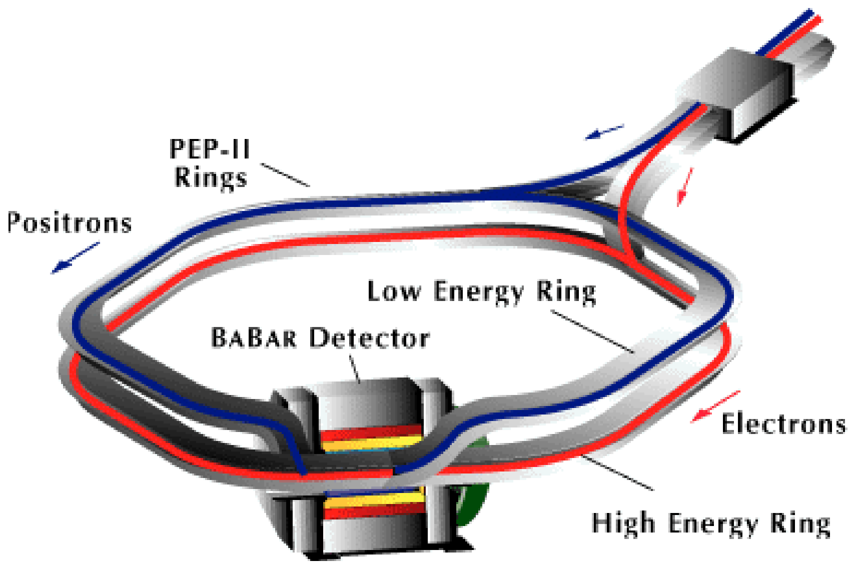
Side view of the BES detector



End view of the BES detector

VC:	$\sigma_{xy} = 100\ \mu m$	TOF:	$\sigma_T = 180$ ps	μ counter:	$\sigma_{r\phi} = 3$ cm
MDC:	$\sigma_{xy} = 200\ \mu m$	BSC:	$\Delta E/\sqrt{E} = 22\ \%$		$\sigma_z = 5.5$ cm
	$\sigma_{dE/dx} = 8.4\ \%$		$\sigma_\phi = 7.9$ mr	B field:	0.4 T
	$\Delta p/p = 1.8\sqrt{(1+p^2)}$		$\sigma_z = 2.3$ cm	Dead time/event:	10 ms

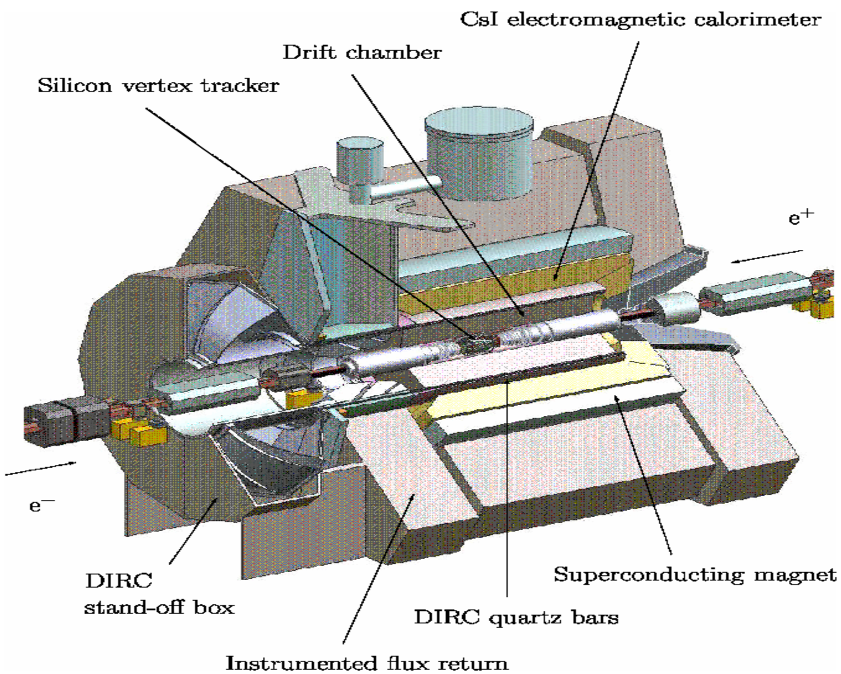
PEP II & BABAR



	Design	Performance
Peak Lumi	$3\times10^{33}cm^{-2}s^{-1}$	$4.5\times10^{33}cm^{-2}s^{-1}$
Σ Lumi/day	135 pb^{-1}	303 pb^{-1}

Tracking: $(p_t)/p_t = 0.13\%\ p_t \oplus 0.45\%\ p_t$ in GeV

EMC: $\sigma_E/E = 2.30\ \%\ E^{-1/4} \oplus 1.35\ \%$



FSR treatment 1/2

Two complementary procedures to correct for FSR

FSR - **exclusive** approach	FSR - **inclusive** approach

$$N(e^+e^- \to \pi^+\pi^-\gamma_{ISR}\gamma_{FSR})$$

Subtract FSR contribution	**Add back** FSR contribution
Event analysis - Phokhara3 ISR	Event analysis - Phokhara3 ISR+FSR

Division by Luminosity

$\sigma(e^+e^- \to \pi^+\pi^-\gamma_{ISR})$	$\sigma(e^+e^- \to \pi^+\pi^-\gamma_{ISR}\gamma_{FSR})$

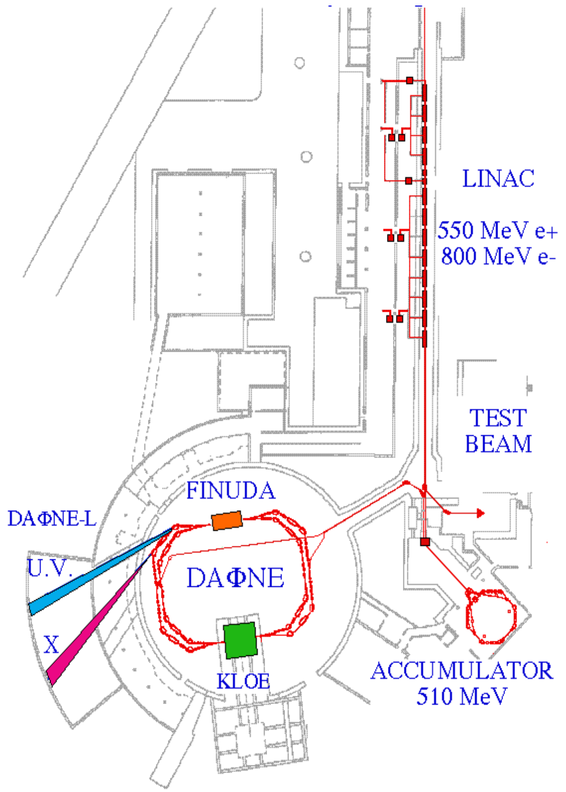
Division by radiator function H

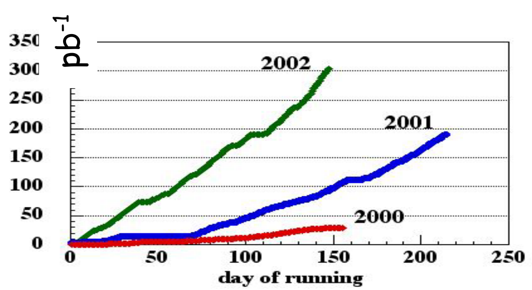
$\sigma(e^+e^- \to \pi^+\pi^-)$	
Add back FSR by hand (sQED, Schwinger 1990)	Map $M^2_{\pi\pi\gamma(FSR)}$ to $M^2_{\pi\pi}$ using MonteCarlo

$$\sigma(e^+e^- \to \pi^+\pi^-\gamma_{FSR})$$

DAΦNE & KLOE

- e^+e^- collider @ $\sqrt{S} = M_\Phi$ = 1019.4 MeV
- achieved peak Luminosity: **8×10^{31} cm^{-2} s^{-1}**
- 2000-2002 data set: ~ **500 pb^{-1}**





KLOE detector designed
for CP violation studies ⇒
good time resolution
$\sigma_t = 57\ ps/\sqrt{E(GeV)} \oplus 50\ ps$
in calorimeter and
high resolution drift chamber
(σ_p/p is 0.4 % for $\theta > 45°$),
ideal for the measurement
of $M_{\pi\pi}$.