Physics at e^+e^- colliders: present and future

A.E.Kaloshin

Irkutsk State University

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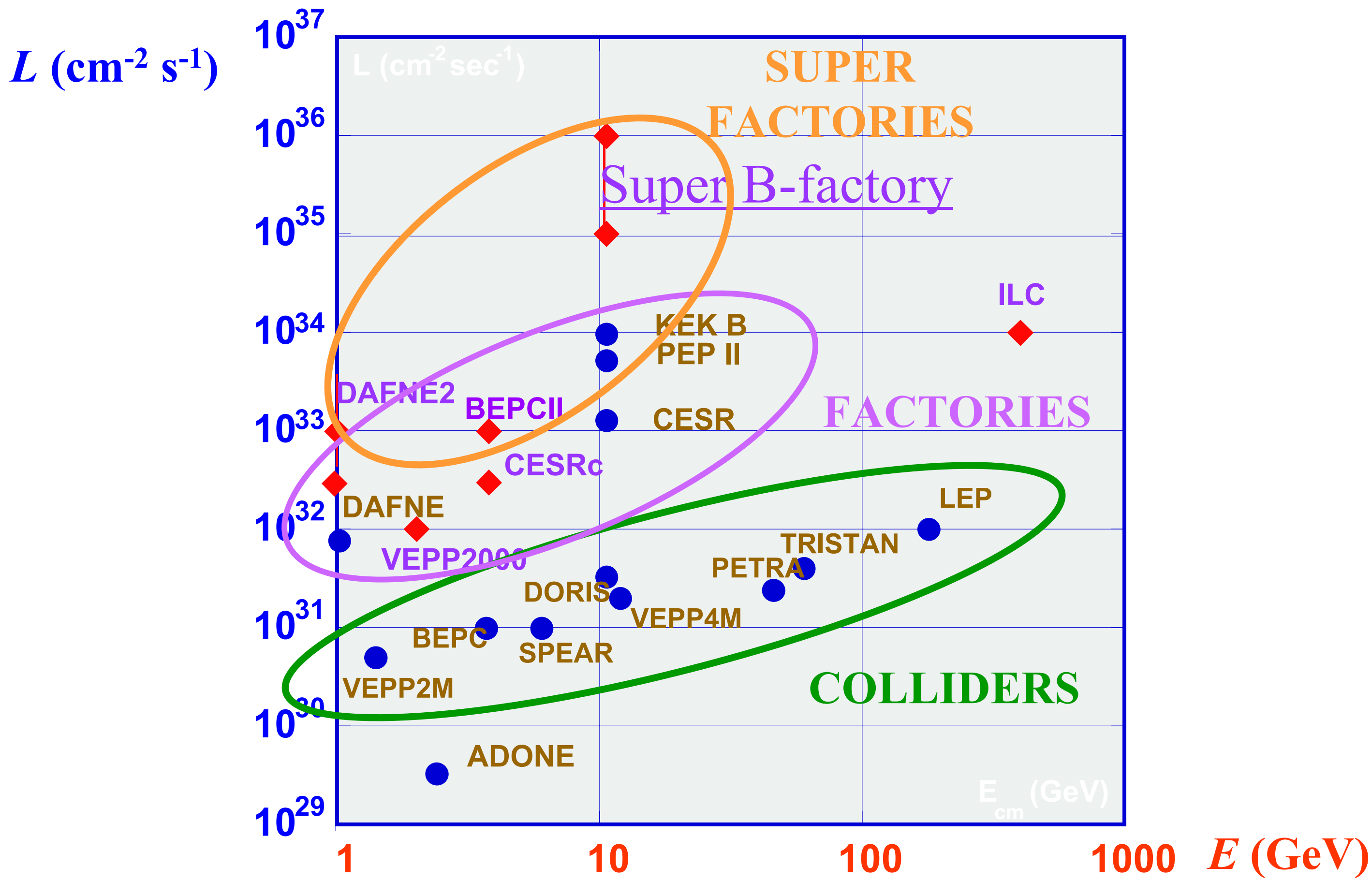
Traditional purposes for e^+e^- colliders

- ✓ Vector mesons $J^P = 1^-$ $(\rho, \omega \ldots Z^0)$ and their decays
- ✓ $e^+e^- \longrightarrow hadrons$
- ✓ Two-photon hadron production
- ✓ Studying of $c\bar{c}$ and $b\bar{b}$ families
- ✓ Cabbibo-Kobayashi-Maskawa (CKM) mixing

New purposes

High precision experiments of last years added new physical goals

- Search of oscillations in heavy quarks systems
- Search of CP-violation with c- and b-quarks.
- Search of New Physics effects. Most sound example is anomalous magnetic moment of muon.



Main parameter of e^+e^- collider is luminocity L

$$N = L \times \sigma$$

$e^+e^- \rightarrow hadrons$ and anomalous magnetic moment of muon

$$\overrightarrow{\mu} = g_\mu \frac{e\hbar}{2m_\mu c} \overrightarrow{s} \tag{1}$$

From Dirac equation $g_\mu = 2$ but radiative corrections change it

$$g_\mu = 2 \cdot (1 + \frac{\alpha}{2\pi} + \dots) \qquad Schwinger, 1948 \tag{2}$$

Anomalous magnetic moment of muon:

$$a_\mu = (g_\mu - 2)/2$$

It is measured with high precision

$$\begin{aligned} a_{\mu^+}^{exp} &= 116592030(80) \times 10^{-11} \quad 2002 \quad E821\ at\ BNL \\ a_{\mu^-}^{exp} &= 116592140(80) \times 10^{-11} \quad 2004 \end{aligned}$$

Average:

$$a_\mu^{exp} = 116592080(60) \times 10^{-11}$$

General form of lepton-photon vertex:

$$\bar{u}(p')\Gamma_\mu u(p) = \bar{u}(p')\left[\gamma_\mu F_1(q^2) + \frac{i}{2m}\sigma_{\mu\nu}q^\nu F_2(q^2)\right]u(p)$$

$$F_1(0) = 1, \qquad F_2(0) = a$$

The Standard Model prediction for a_μ can be represented as a sum

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{had} + a_\mu^{EW}$$

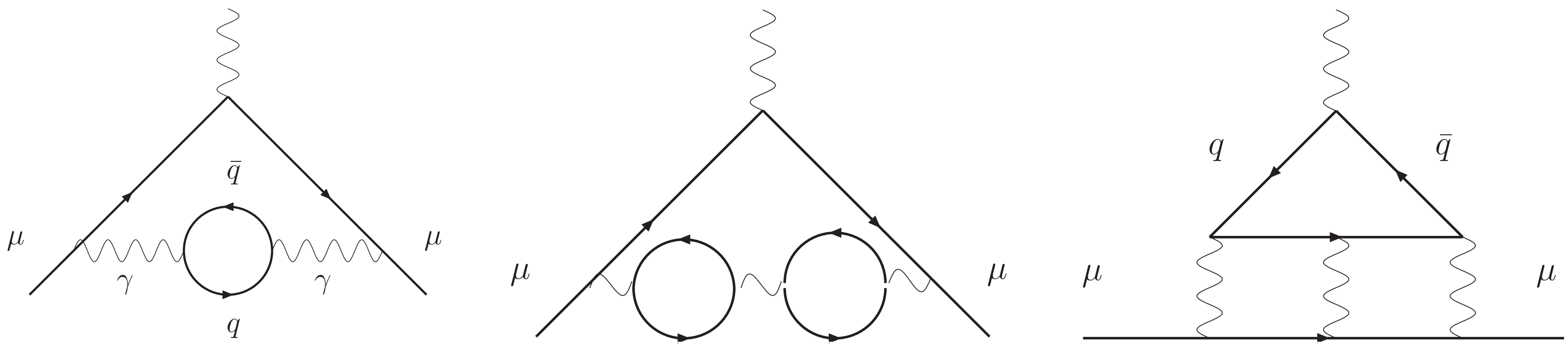
QED contribution contains only leptons and photons

$$a_\mu^{QED} = 116584719(1) \times 10^{-11}.$$

This accounts up to four-loop contributions, i.e., up to the α^4 terms.
Kinoshita, Nio + Laporta, Remiddi

Hadronic contributions (1)

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



1. Lowest order hadronic contribution represented by a quark loop
2. An example of higher order hadronic contribution
3. Light-by-light scattering contribution

Hadronic contributions (2)

In fact

$$a_\mu^{had,LO} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds K(s)\sigma(s) = \frac{\alpha^3}{3\pi^2}\int_{4m_\pi^2}^{\infty}\frac{ds}{s}K(s)R(s),$$

where

$$K(s) = \int_0^1 dx \frac{x^2(1-x)}{x^2+(1-x)s/m_\mu^2}$$

and

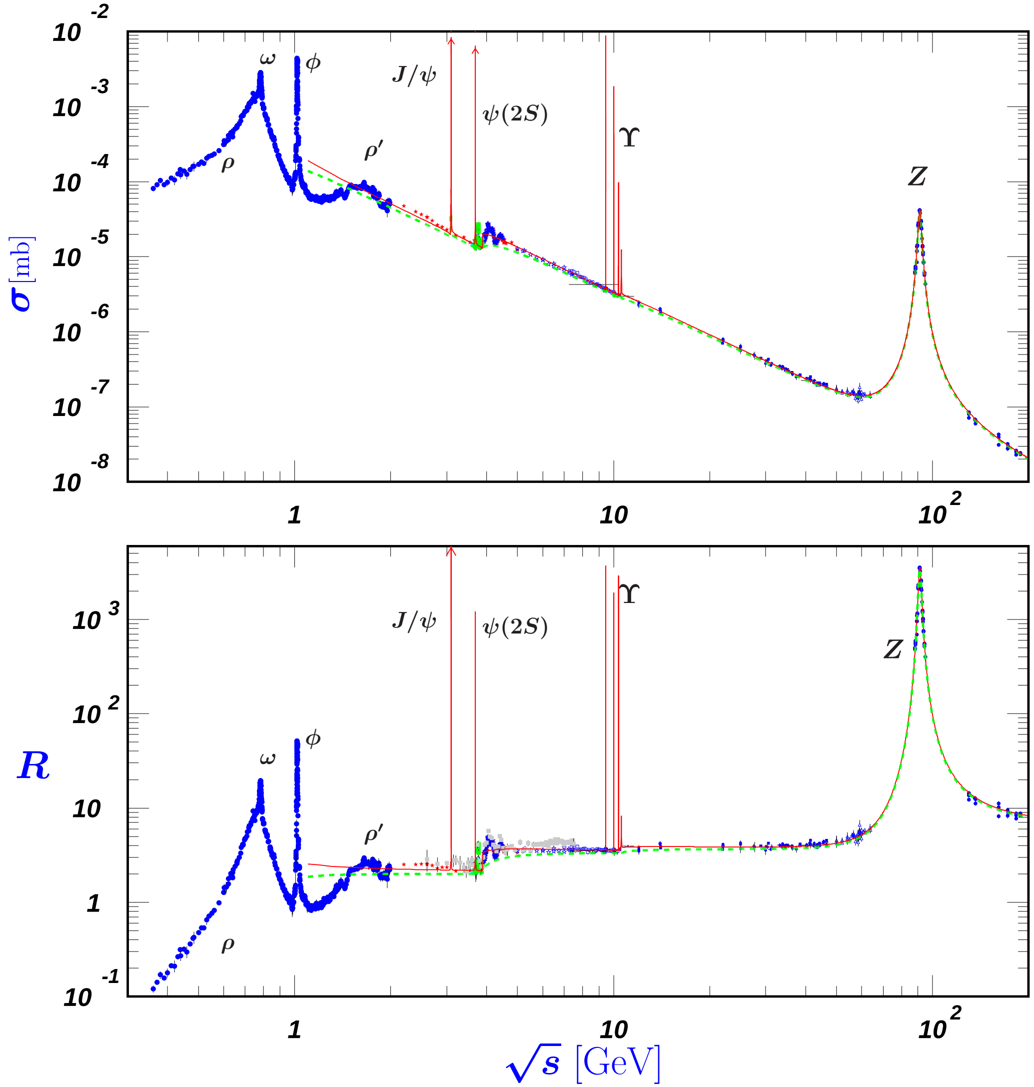
$$R(s) = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}.$$

Close inspection shows that:

- $K(s) \sim 1/s$ at $s \to \infty$, so integral is saturated by low-energy region.
- About 91% of the total contribution to $a_\mu^{had,LO}$ is accumulated at center-of-mass energies $\sqrt{s} < 1.8\ GeV$.
- 73% of $a_\mu^{had,LO}$ is covered by the $\pi\pi$ final state, which is dominated by the $\varrho(770)$ resonance.

Hadronic contributions (3)

Let's look at $R(s)$:



Hadronic contributions (4)

Hadronic LO contribution

$$a_\mu^{had,LO} = \begin{array}{ll} 6909(44)\times 10^{-11} & Davier; Eidelman\ 07 \\ 6894(46)\times 10^{-11} & Hagiwara\ et\ al.\ 07 \\ 6921(56)\times 10^{-11} & Jegerlehner\ 06 \\ 6944(49)\times 10^{-11} & Troconiz, Ynduráin\ 05 \end{array}$$

Hadronic HO contributions

$$a_\mu^{had,HO} = -98(1)\times 10^{-11} \qquad Hagiwara\ et\ al.\ 07$$

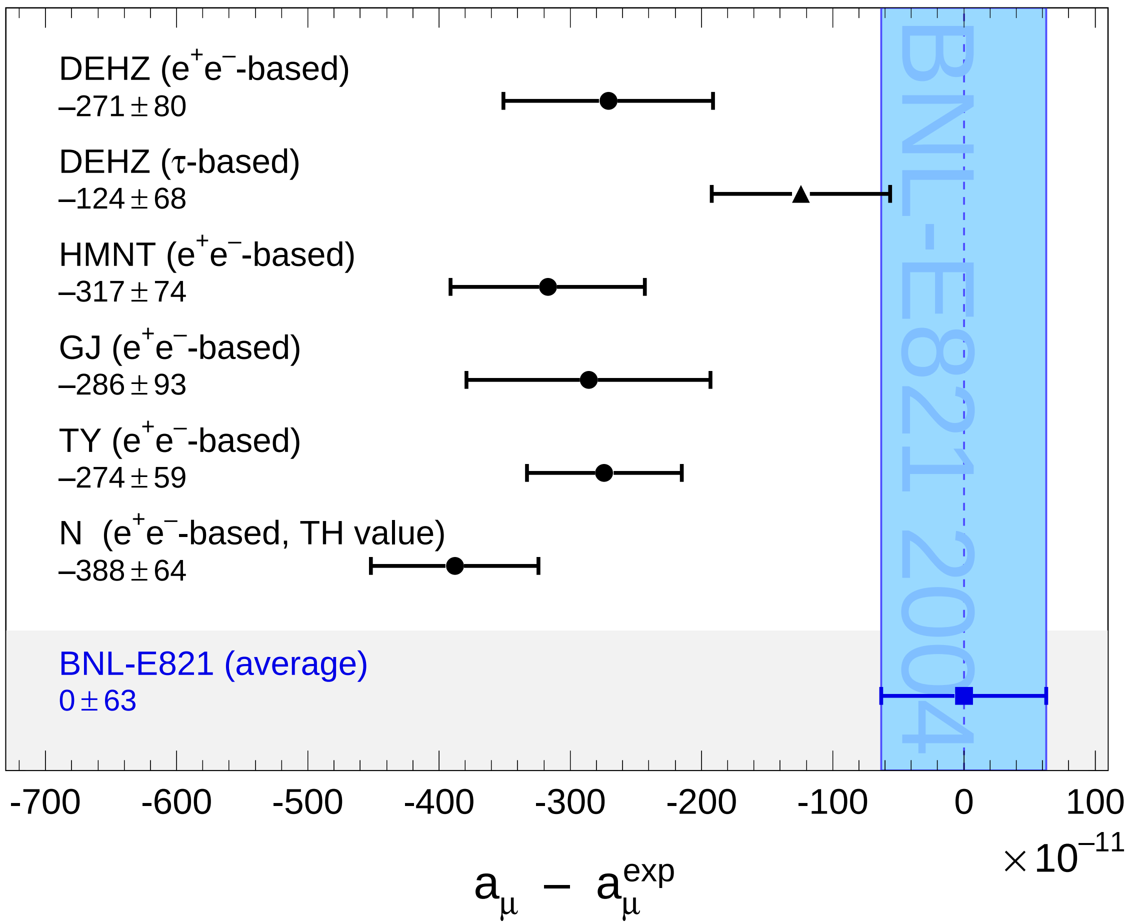
Electroweak contributions

$$a_\mu^{EW} = 154(2)\times 10^{-11} \qquad Czarnecki\ et\ al.\ 07$$

Light-by-light contribution needs some model considerations

$$a_\mu^{had,LBL} = \begin{array}{ll} 80(40)\times 10^{-11} & Knecht\ et\ al.\ 02 \\ 136(25)\times 10^{-11} & Melnikov, Vainstein\ 04 \end{array}$$

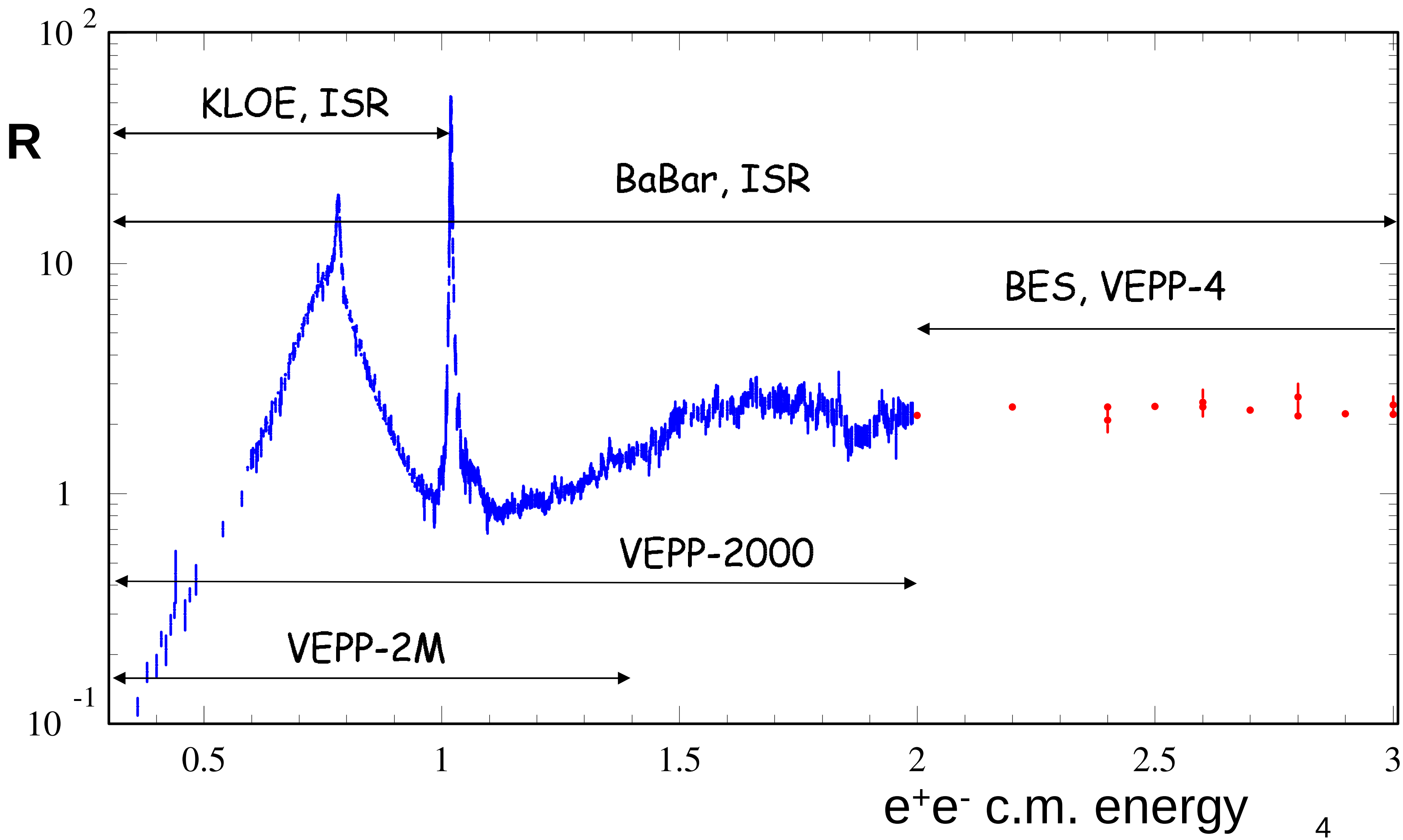
a_μ summary



Typical value for difference:

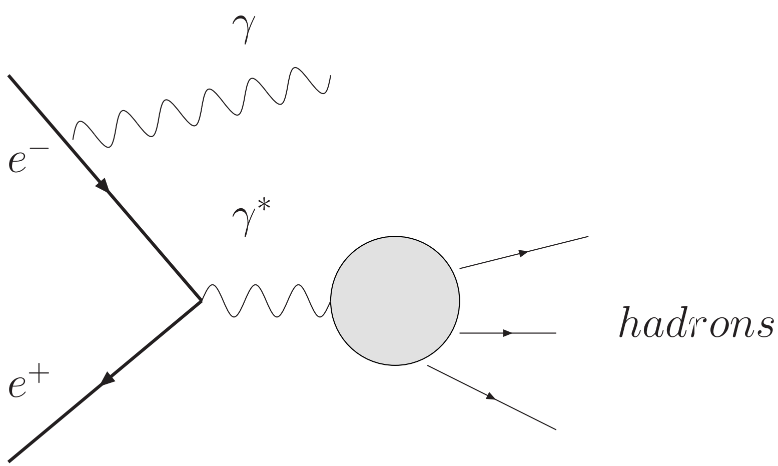
$$a_\mu^{exp} - a_\mu^{theor,SM} = (280 \pm 80) \times 10^{-11} : \qquad 3.4\sigma$$

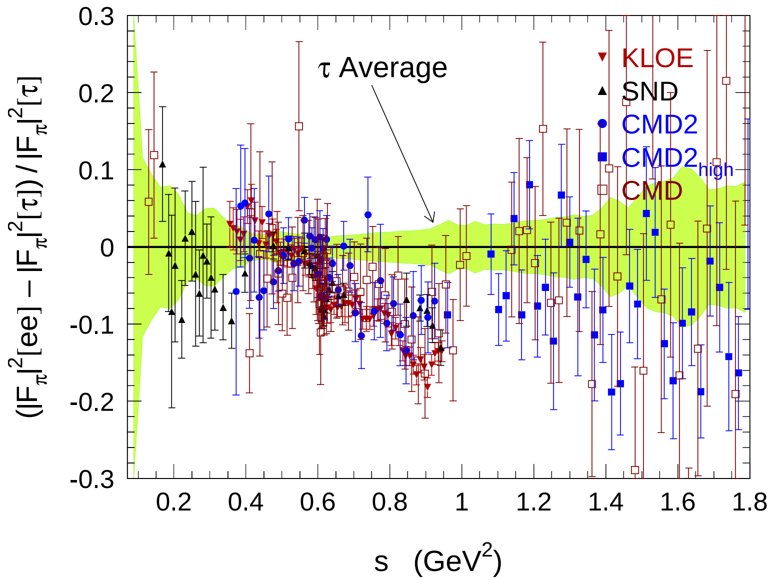
R activity

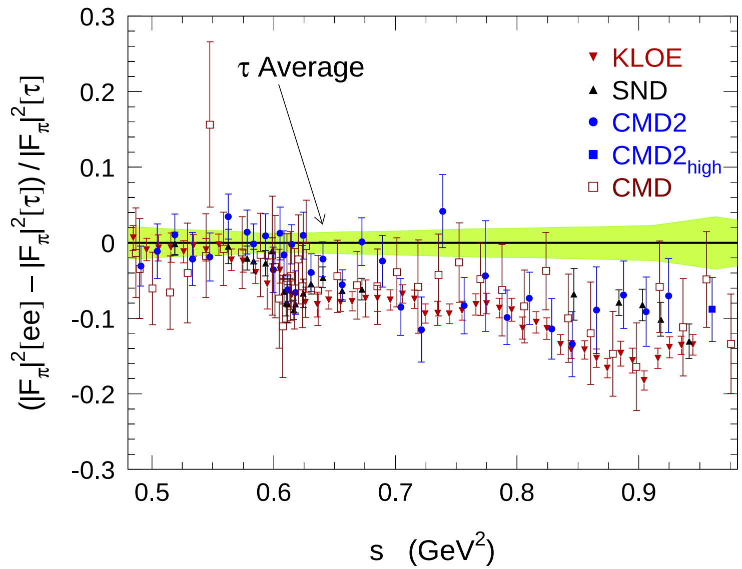


R
KLOE, ISR
BaBar, ISR
BES, VEPP-4
VEPP-2000
VEPP-2M
10^2
10
1
10^{-1}
0.5
1
1.5
2
2.5
3
e^+e^- c.m. energy
4

ISR method




τ Average
KLOE
SND
CMD2
CMD2high
CMD
$(|F_\pi|^2[ee] - |F_\pi|^2[\tau]) / |F_\pi|^2[\tau]$
s (GeV²)


τ Average
KLOE
SND
CMD2
CMD2high
CMD
$(|F_\pi|^2[ee] - |F_\pi|^2[\tau]) / |F_\pi|^2[\tau]$
s (GeV²)

Oscillations in $D^0 - \bar{D}^0$ system

Time evolution in $D^0 - \bar{D}^0$ is described by Schrödinger equation

$$i\frac{\partial}{\partial t}\left(\begin{array}{c} D^0(t) \\ \bar{D}^0(t) \end{array}\right) = \left(M - \frac{i}{2}\Gamma\right)\left(\begin{array}{c} D^0(t) \\ \bar{D}^0(t) \end{array}\right),$$

where M and Γ matrices are Hermitian.
Mass eigenstates:

$$\mid D_1\rangle = p \mid D^0\rangle + q \mid \bar{D}^0\rangle \qquad \mid D_1(t)\rangle = e^{-i(m_1 - i\Gamma_1/2)t} \mid D_1(0)\rangle$$

$$\mid D_2\rangle = p \mid D^0\rangle - q \mid \bar{D}^0\rangle \qquad \mid D_2(t)\rangle = e^{-i(m_2 - i\Gamma_2/2)t} \mid D_2(0)\rangle$$

Flavor states time evolution:

$$\mid D^0(t)\rangle = e^{-(\Gamma_1/2 + im)t}\{cosh[(y+ix)\Gamma t/2] \mid D^0\rangle - \left(\frac{q}{p}\right) sinh[(y+ix)\Gamma t/2] \mid \bar{D}^0$$

$$\mid \bar{D}^0(t)\rangle = e^{-(\Gamma_1/2 + im)t}\{cosh[(y+ix)\Gamma t/2] \mid \bar{D}^0\rangle - \left(\frac{p}{q}\right) sinh[(y+ix)\Gamma t/2] \mid D^0$$

Oscillations in $D^0 - \bar{D}^0$ system

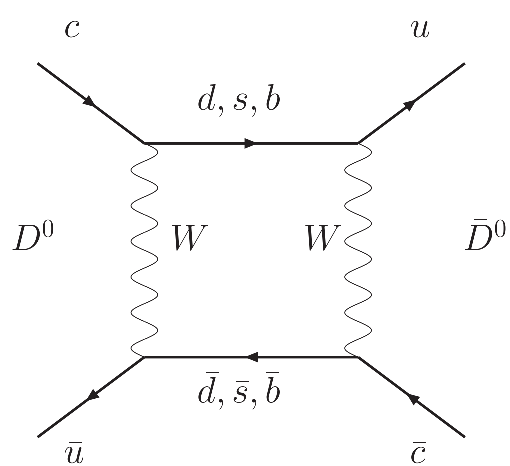
Here

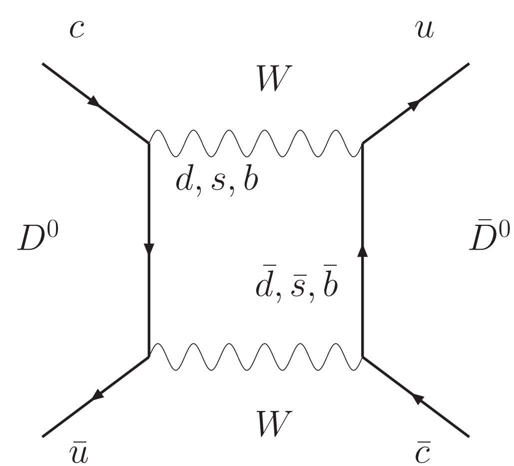
$$m = \frac{1}{2}(m_1 + m_2), \qquad \Gamma = \frac{1}{2}(\Gamma_1 + \Gamma_2),$$

$$x = 2\frac{m_1 - m_2}{m_1 - m_2}, \qquad y = \frac{\Gamma_1 - \Gamma_2}{\Gamma_1 + \Gamma_2},$$

Mixing exists if either x or y non-zero

Short-distance contributions in SM





is very small.

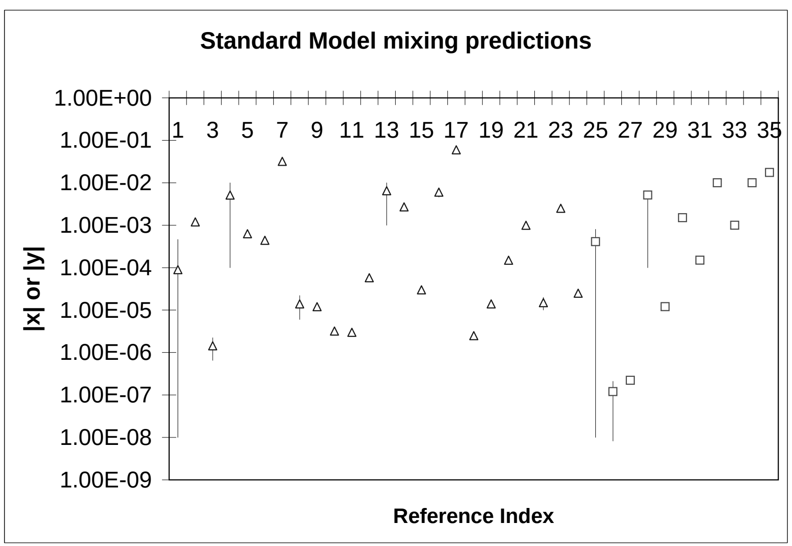
Oscillations in $D^0 - \bar{D}^0$ system

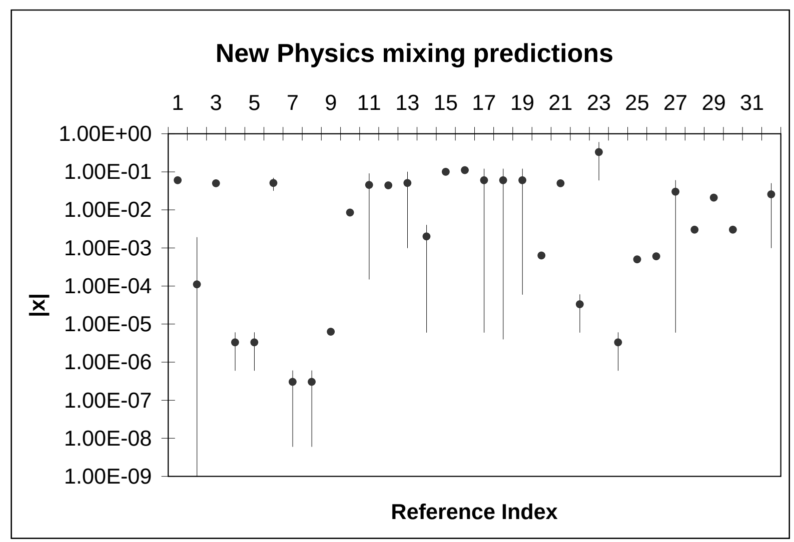
Reasons are:

- b quark is CKM-suppressed
- s and d quarks are GIM suppressed
- $x \sim O(10^{-5})$ or less

Long-distance contributions dominate but hard to estimate precisely.

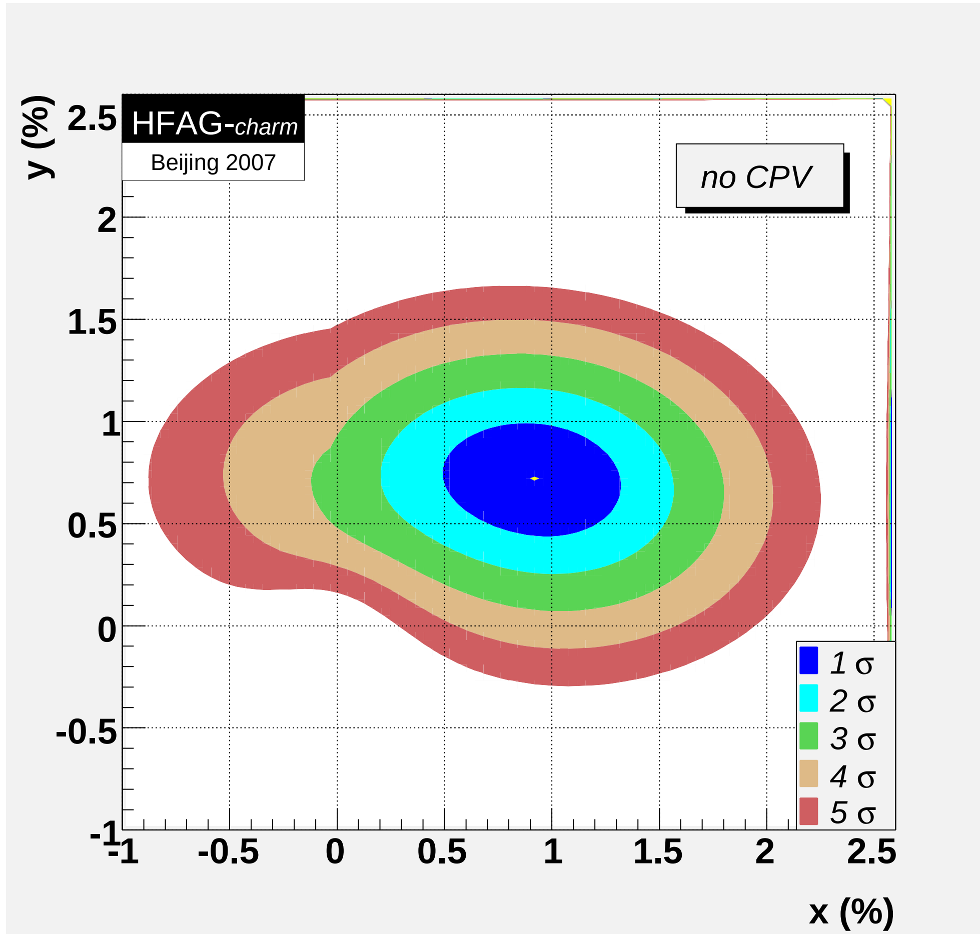
Collection of preditions:



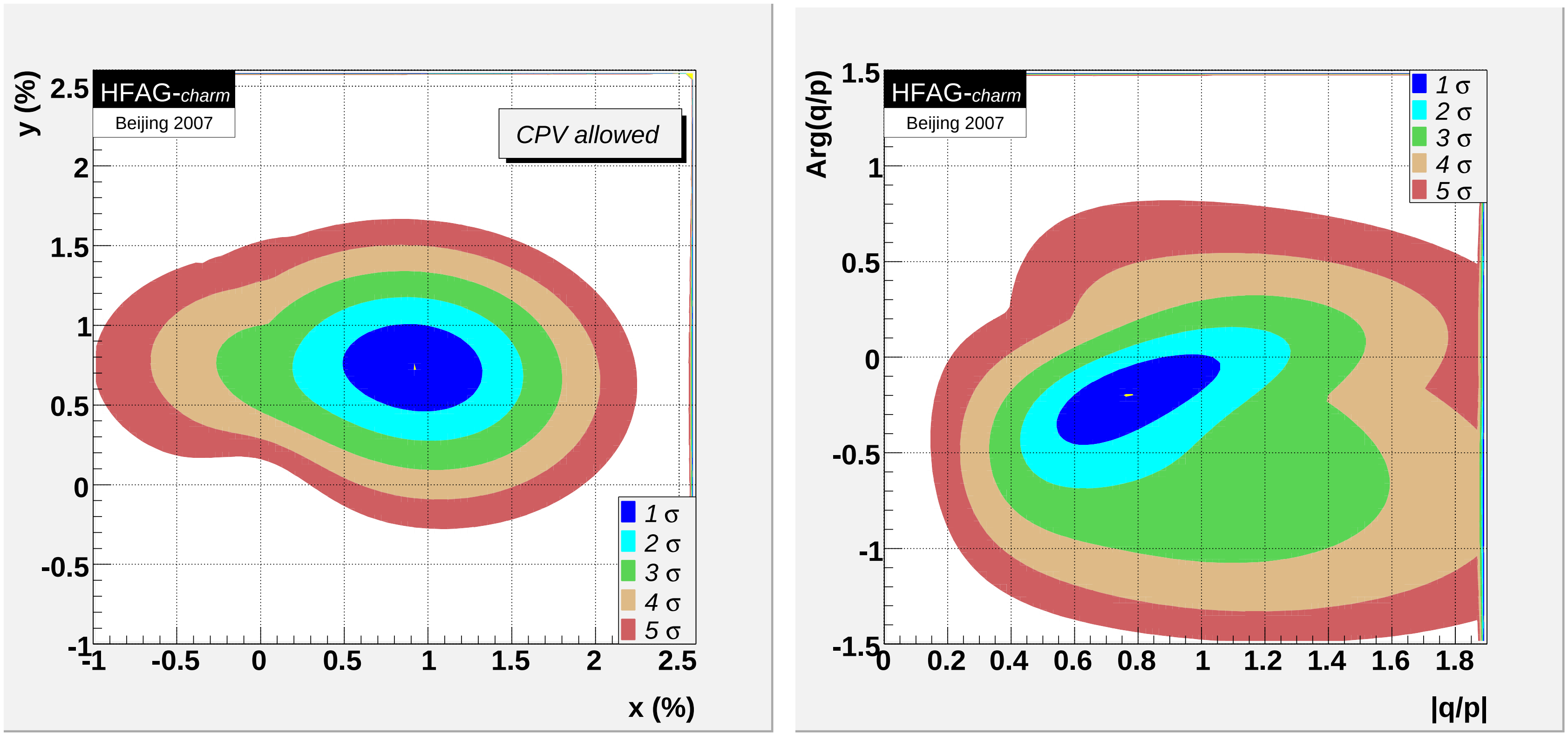


HFAG results 2008

Heavy Flavor Averaging Group analyzed all world data. Most important are data of BELLE and BaBar.



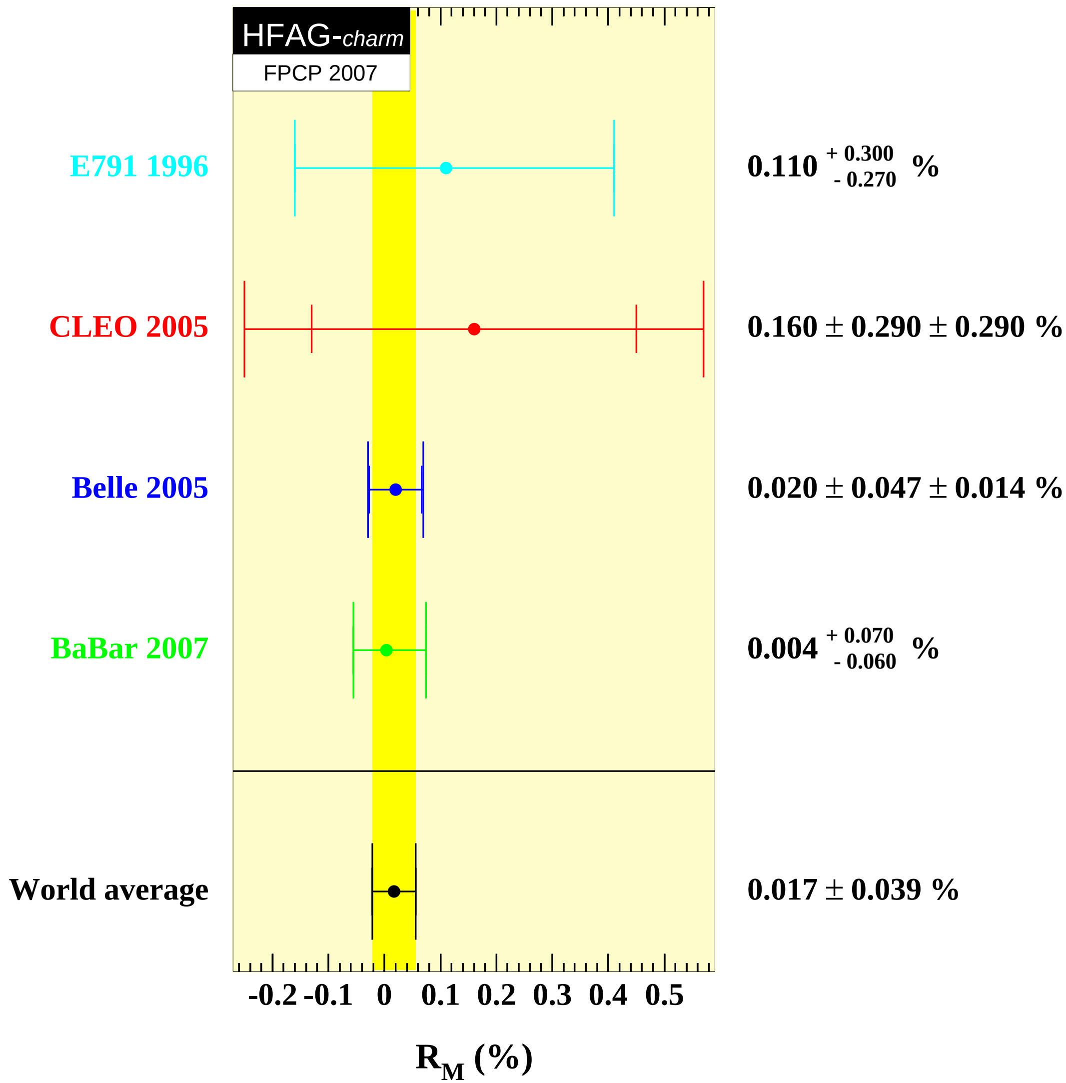
HFAG results 2008



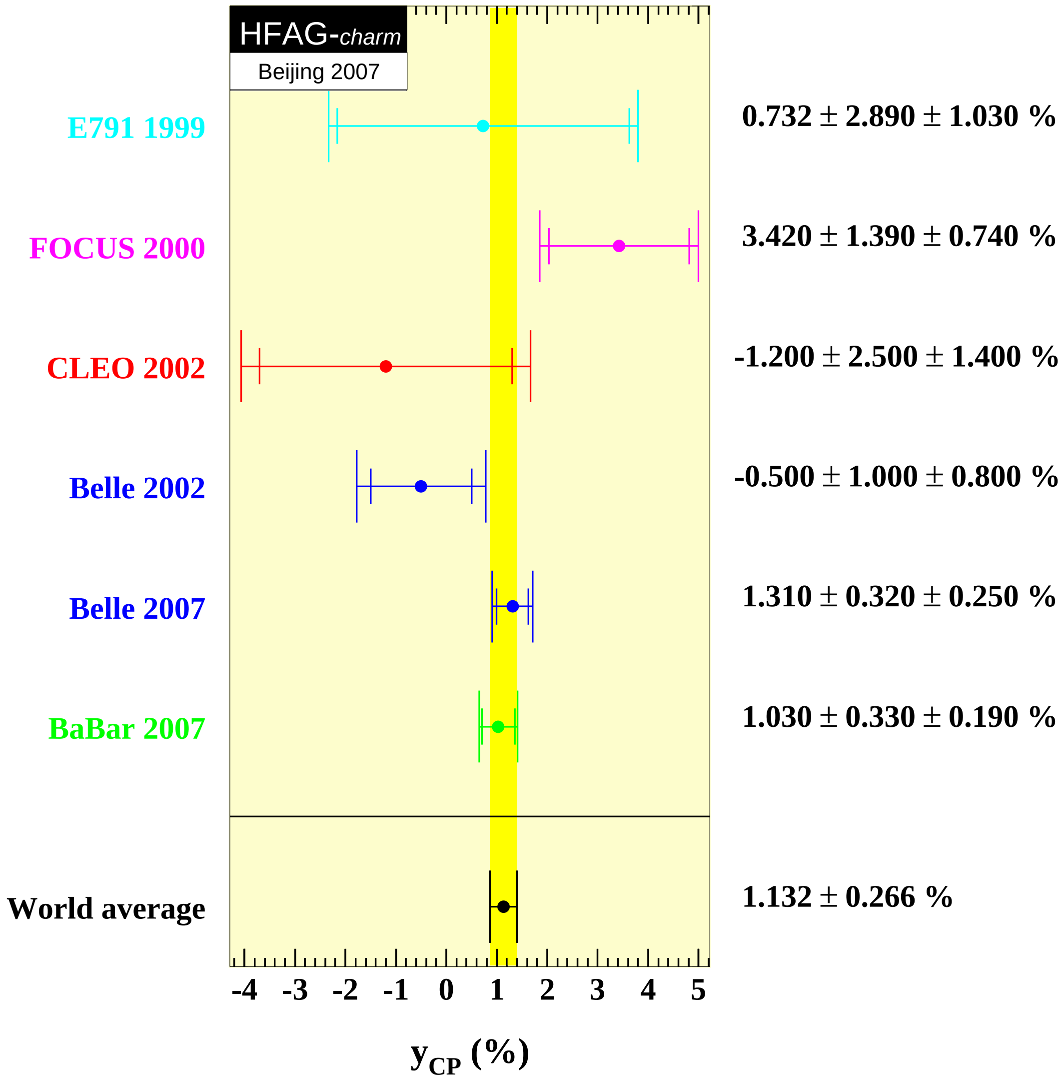
HFAG results 2008

Conclusions of HFAG:

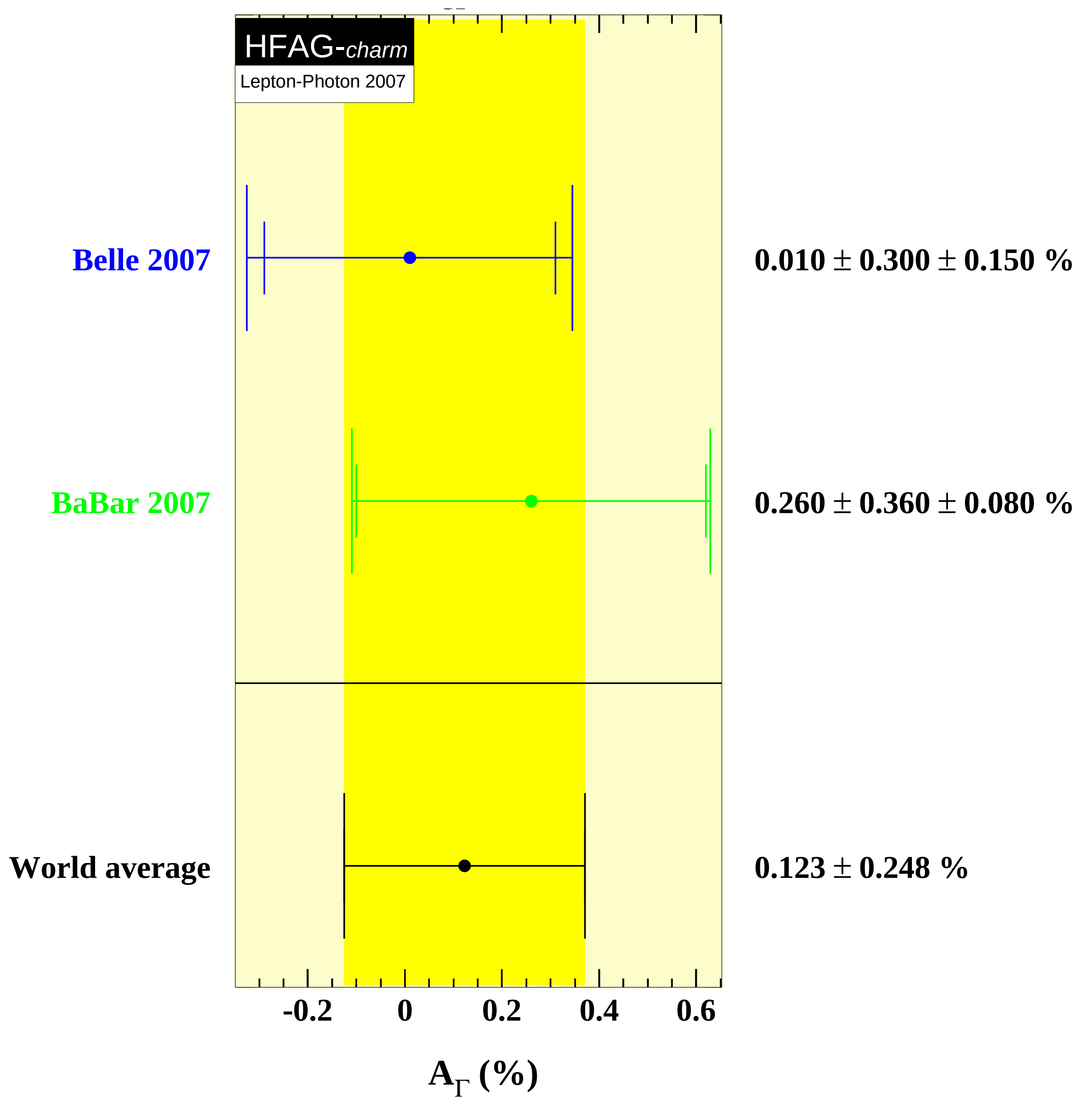
- The no-mixing point x=0, y=0 is excluded at 6.7σ. The effect is presumably dominated by long-distance processes, which are difficult to calculate.
- There is no evidence yet for CPV in the $D^0 - \bar{D}^0$ system. Observing CPV at the level of sensitivity of the current experiments would indicate new physics.



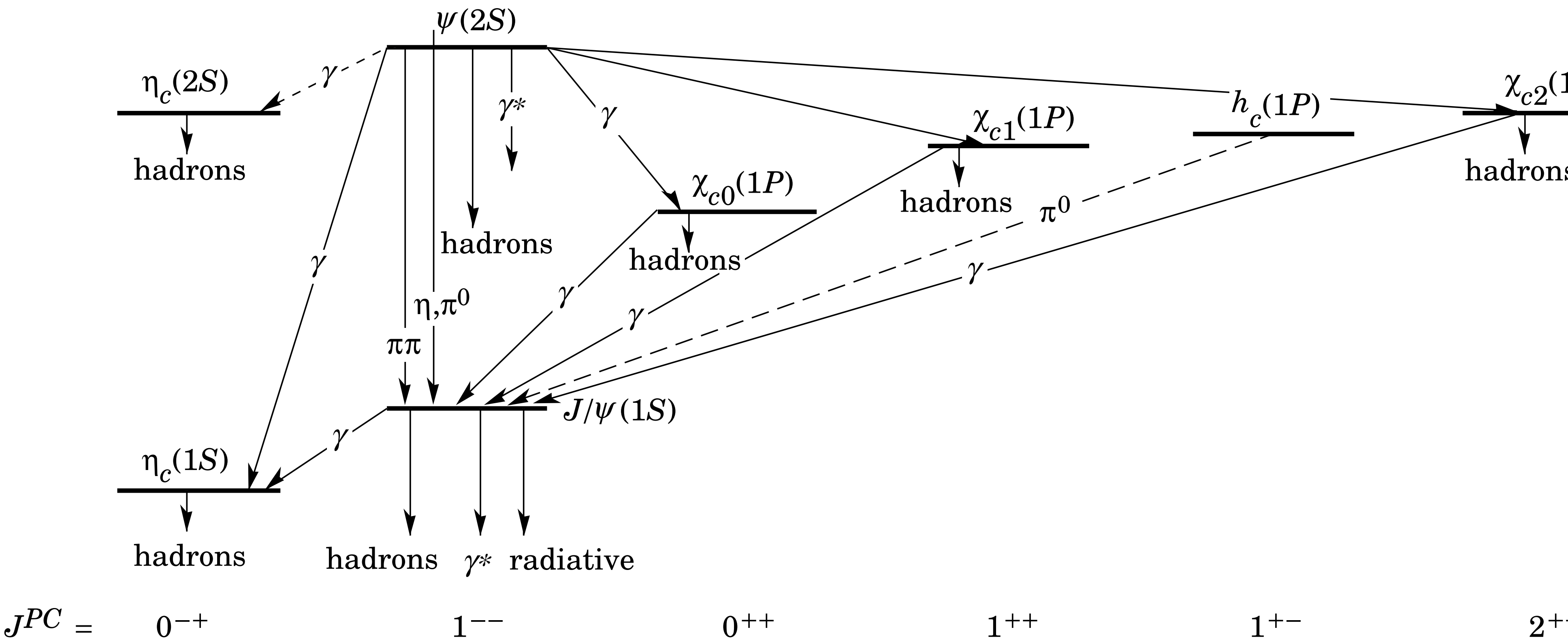
$$R_M = (x^2 + y^2)/2 \quad (3)$$



$$\tau_{CP} = \frac{\tau_{K\pi}}{\langle \tau_{hh} \rangle} - 1 \quad (4)$$

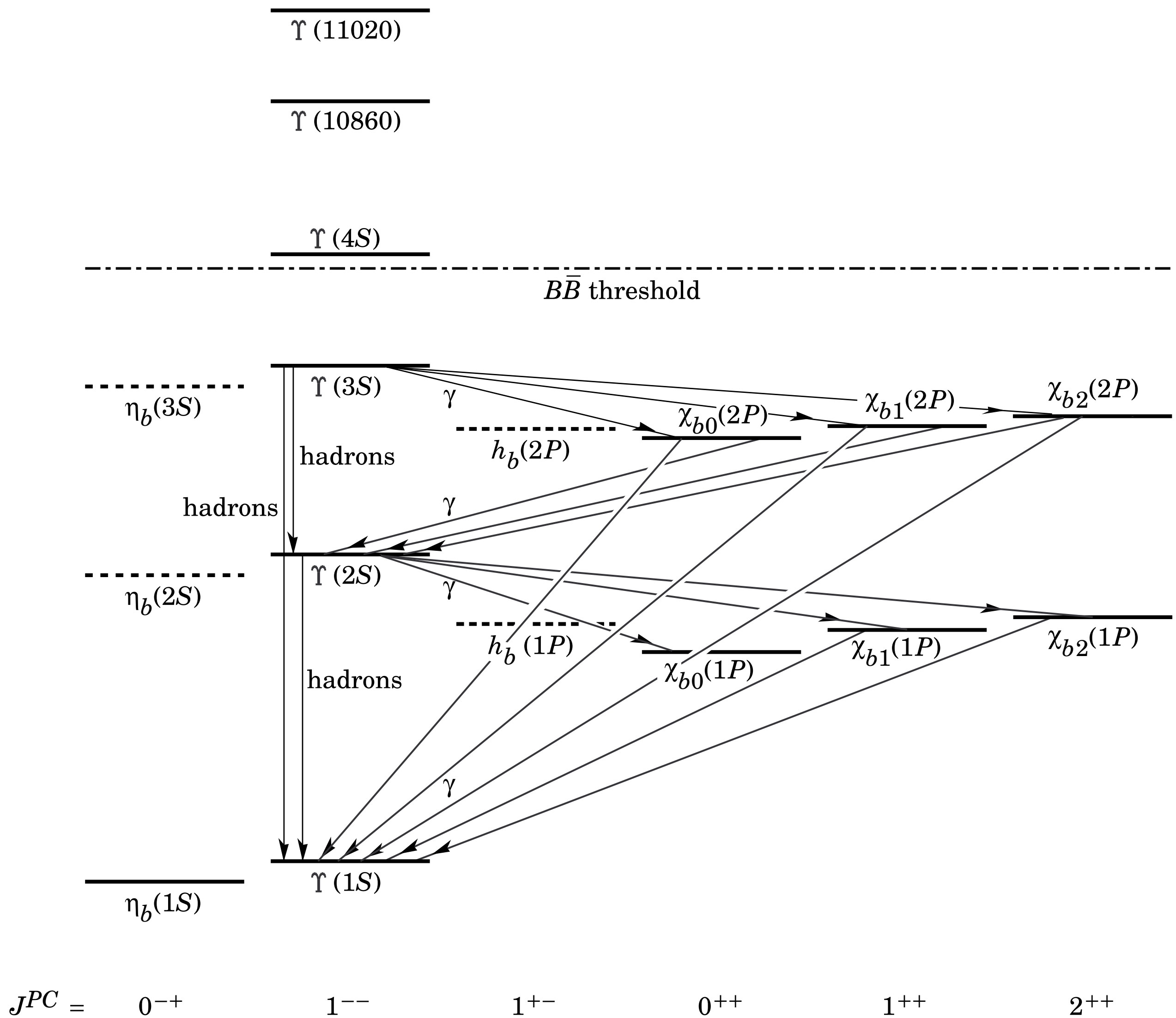

HFAG-charm
Lepton-Photon 2007
Belle 2007
0.010 ± 0.300 ± 0.150 %
BaBar 2007
0.260 ± 0.360 ± 0.080 %
World average
0.123 ± 0.248 %
-0.2
0
0.2
0.4
0.6
A_Γ (%)

Charmonium

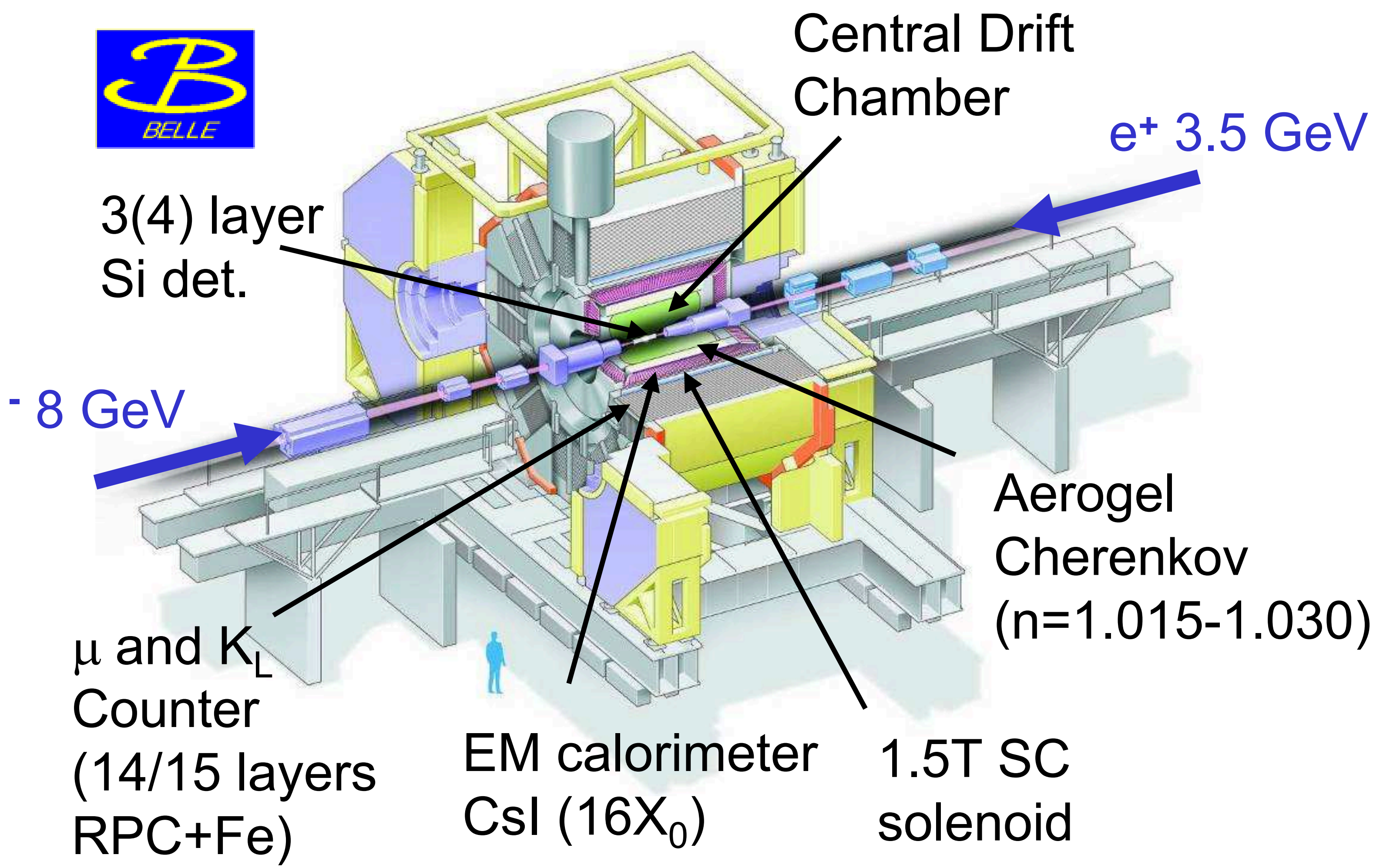


ψ(2S)
ηc(2S)
γ
γ*
hadrons
χc0(1P)
χc1(1P)
hc(1P)
χc2(1
π0
ηπ0
ππ
J/ψ(1S)
ηc(1S)
radiative
JPC =
0−+
1−−
0++
1++
1+−
2+

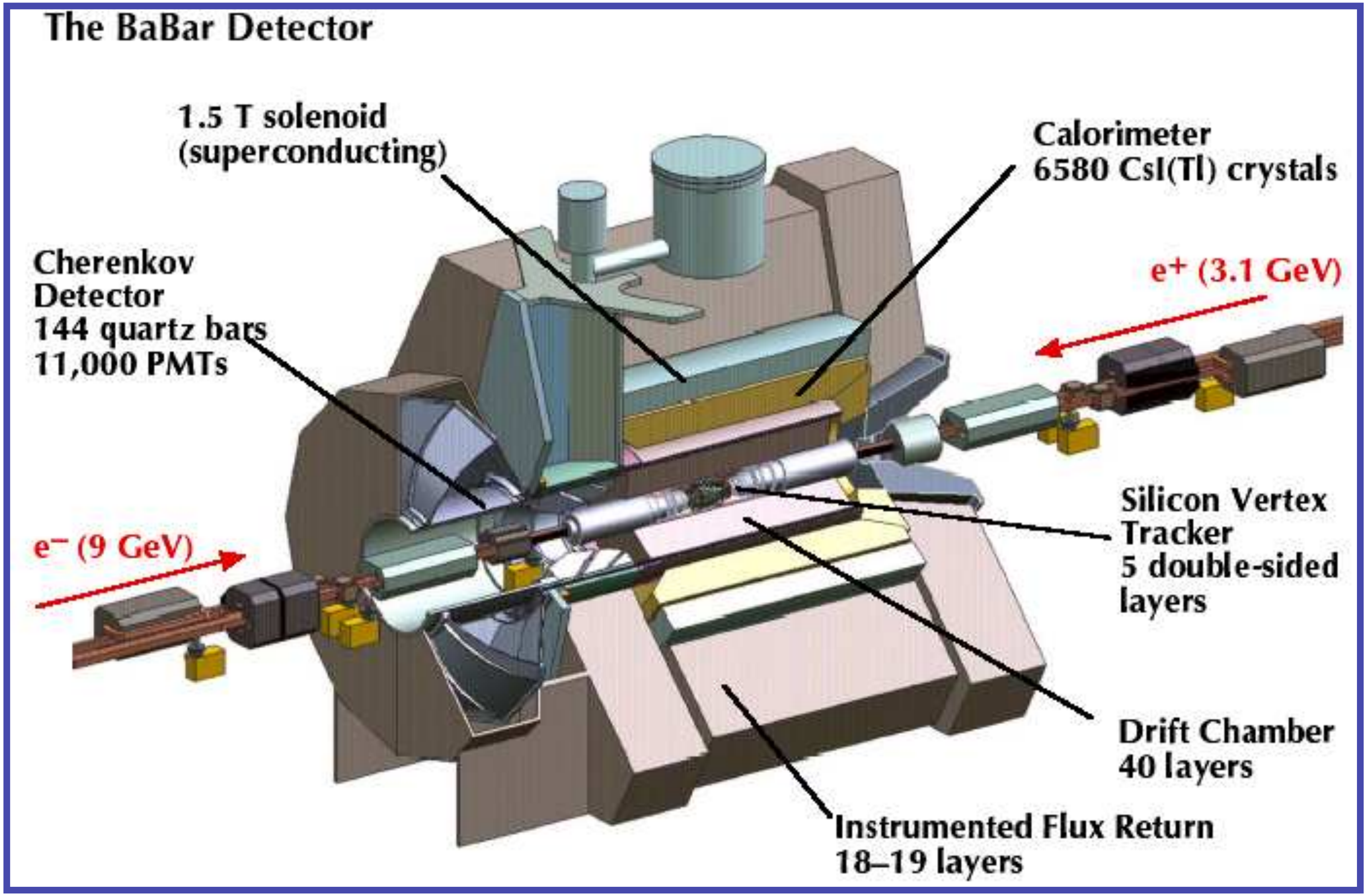
Bottonium



ϒ(11020)
ϒ(10860)
ϒ(4S)
$B\bar{B}$ threshold
ϒ(3S)
ηb(3S)
γ
χb0(2P)
χb1(2P)
χb2(2P)
hb(2P)
hadrons
hadrons
ϒ(2S)
ηb(2S)
γ
hb(1P)
χb0(1P)
χb1(1P)
χb2(1P)
hadrons
γ
ϒ(1S)
ηb(1S)
J^{PC} = 0−+ 1−− 1+− 0++ 1++ 2++


Central Drift
Chamber
e+ 3.5 GeV
3(4) layer
Si det.
- 8 GeV
Aerogel
Cherenkov
(n=1.015-1.030)
μ and K_L
Counter
(14/15 layers
RPC+Fe)
EM calorimeter
CsI (16X_0)
1.5T SC
solenoid

BaBar


The BaBar Detector
1.5 T solenoid
(superconducting)
Calorimeter
6580 CsI(Tl) crystals
Cherenkov
Detector
144 quartz bars
11,000 PMTs
e+ (3.1 GeV)
e− (9 GeV)
Silicon Vertex
Tracker
5 double-sided
layers
Drift Chamber
40 layers
Instrumented Flux Return
18–19 layers