Precision measurement of $\sigma_{\rm hadronic}$ and $\alpha_{\rm eff}(E)$ at ILC energies

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Meeting on e^+e^- **Physics Perspectives at Frascati, January 19/20, 2006, LNF, Fracsati (Italy)**

supported by EU projects TARI and EURIDICE

Outline of Talk:

① **Introduction**

② **$\alpha(M_Z)$ in precision physics**

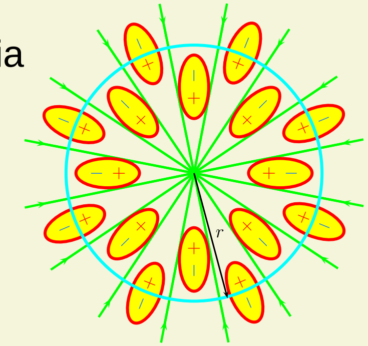
③ **Evaluation of $\alpha(M_Z)$**

④ **A look at the e^+e^-–data**

Abstract: The precise determination of the fundamental parameters is one of the big challenges and is indispensable for a detailed understanding of the basic laws of nature. Only with precise input parameters we are able to make the precise predictions required for precision tests of the theory as well as for establishing new physics form observed deviations from theory. We advocate a long term program of hadronic cross section measurements for improving the determination of the running fine structure constant which presently is the least known of the fundamental parameters.

① Introduction

Non-perturbative hadronic effects in electroweak precision observables, main effect via



effective fine-structure "constant" $\alpha(E)$

(charge screening by vacuum polarization)

Of particular interest:

$$\alpha(M_Z) \text{ and } a_\mu \equiv (g-2)_\mu/2$$

- **electroweak effects (leptons etc.) calculable in perturbation theory**
- **strong interaction effects (hadrons/quarks etc.) perturbation theory fails**

$\Longrightarrow$ **Dispersion integrals over e^+e^-–data**

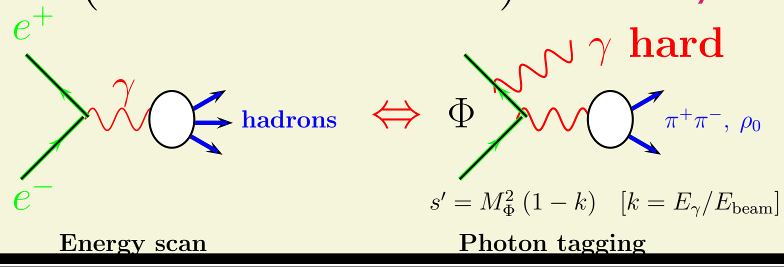
encoded in $$R_\gamma(s) \equiv \frac{\sigma(e^+e^-\to\gamma^*\to\text{hadrons})}{\sigma(e^+e^-\to\gamma^*\to\mu^+\mu^-)}$$

Errors of data $\Longrightarrow$ theoretical uncertainties !!!

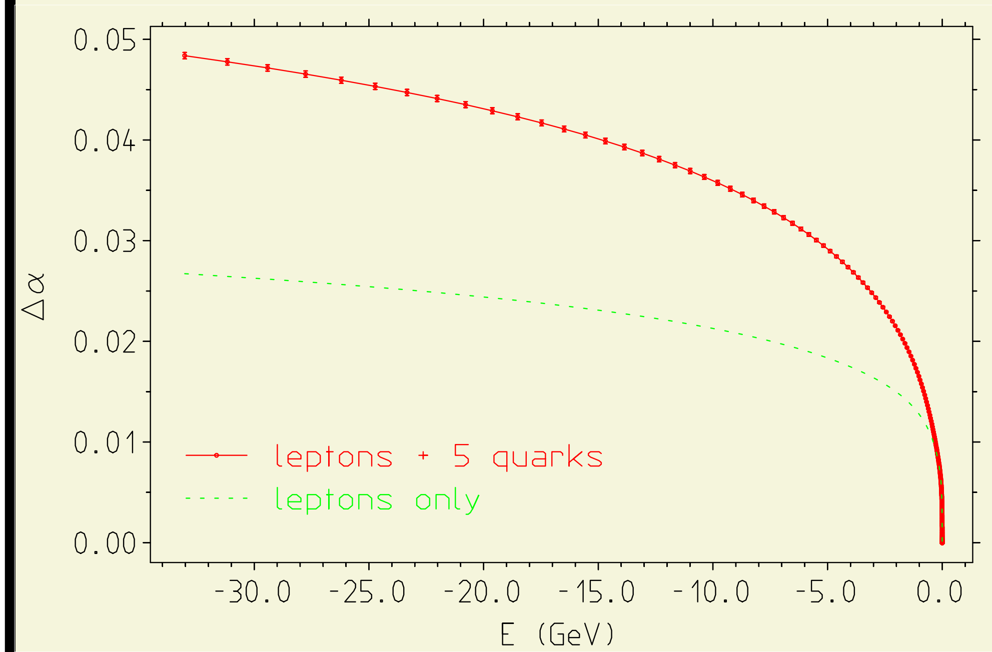
The art of getting precise results from non-precision measurements !

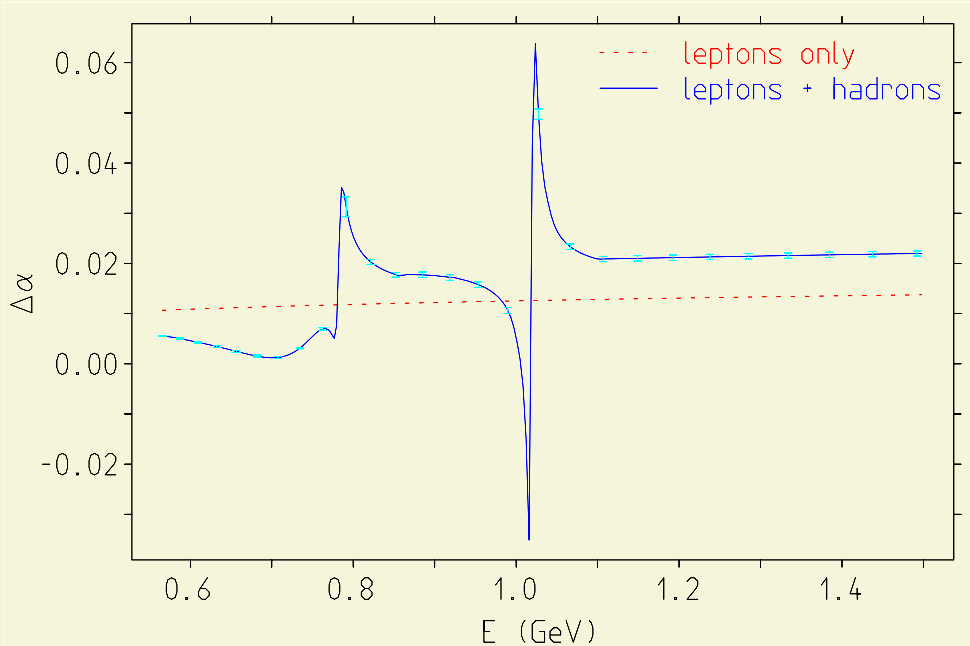
New challenge for precision experiments on $\sigma(e^+e^- \to hadrons)$ KLOE, BABAR, ...

$\sigma_{\rm hadronic}$ **via radiative return:**



- **Need to know running of $\alpha_{\rm QED}$ very precisely.**
  Large corrections, steeply increasing at low E

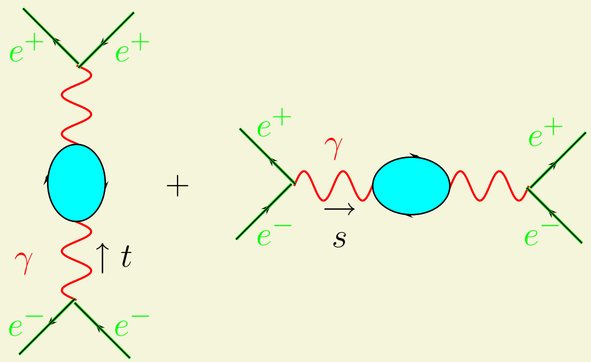




The running of α. The "negative" E axis is chosen to indicate space-like momentum transfer. The vertical bars at selected points indicate the uncertainty. In the time-like region the resonances lead to pronounced variations of the effective charge (shown in the $\rho - \omega$ and ϕ region).

Questions: why not measure $\alpha_{\rm eff}(E)$ directly, like QCD running coupling $\alpha_s(s)$?

Problem: any measurement requires normalizing process like Bhabha,



depends itself on $\alpha_{\rm eff}(t)$ and $\alpha_{\rm eff}(s)$, always measure something like

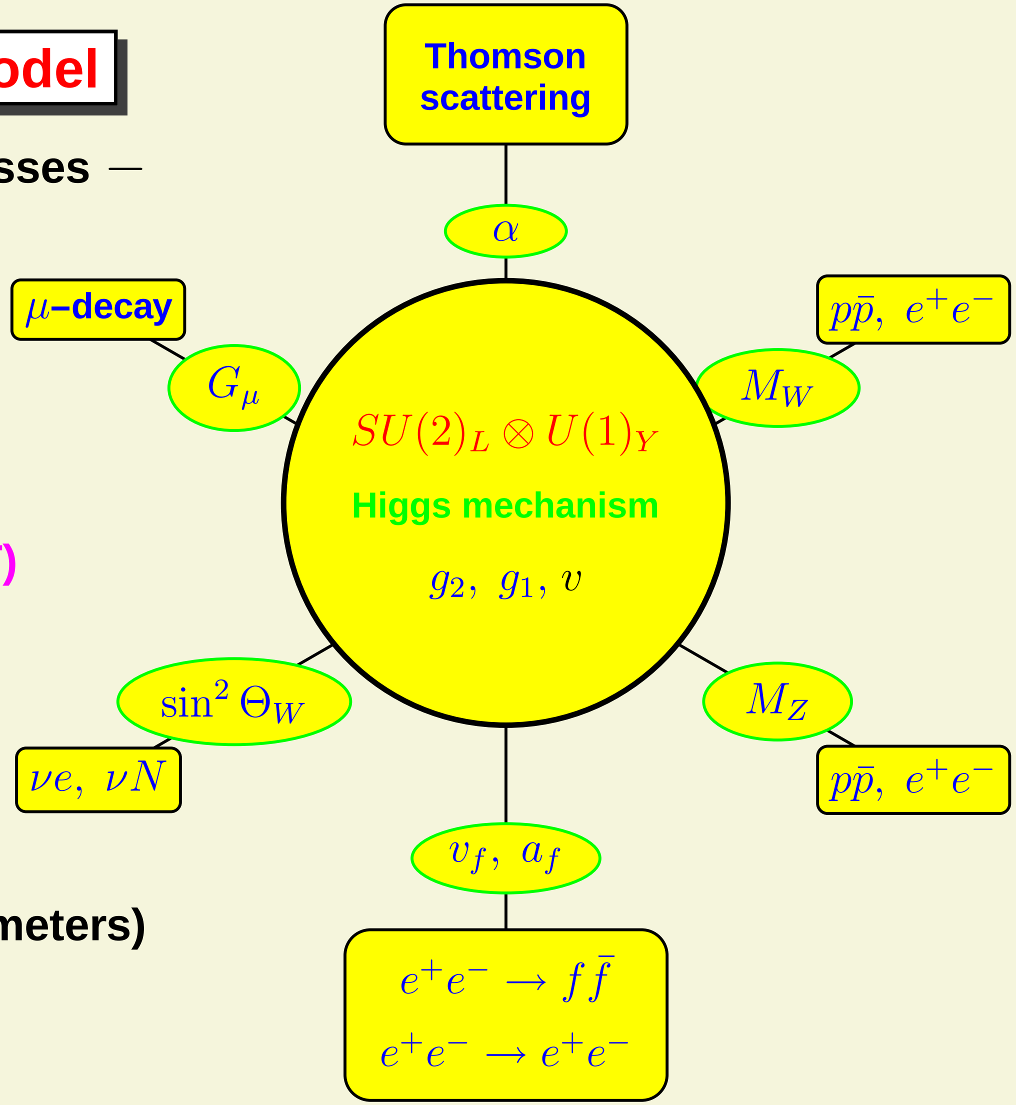
$$r(E) \propto \left(\alpha_{\rm eff}(s)/\alpha_{\rm eff}(t)\right)^2 \quad , \quad t = -\frac{1}{2}\left(s - 4m_e^2\right)\left(1 - \cos\theta\right)$$

where large part of the effect drops out, especially the strongly raising low energy piece, which includes substantial non-perturbative effects.

Higher energies: for all processes which are not dominated by a single one photon exchange, $\alpha_{\rm eff}(E)$ enters in complicated way in observables and cannot by measured in any direct way (see below).

The Parameters of the Standard Model

— in four fermion and vector boson processes —



unlike in QED and QCD in SM (SBGT)

parameter interdependence

☞

only 3 independent quantities

(besides fermion masses and mixing parameters)

α, G_μ, M_Z

$\Downarrow$

parameter relationships between very precisely measurable quantities

precision tests, possible sign of new physics

② $\alpha(M_Z)$ in precision physics (precision physics limitations)

Uncertainties of hadronic contributions to effective α are a problem for electroweak precision physics:

$\alpha\ ,\ G_\mu, M_Z$ most precise input parameters

50%
non-perturbative
relationship

$\Updownarrow$

precision predictions $\sin^2\Theta_f, v_f, a_f, M_W, \Gamma_Z, \Gamma_W, \cdots$

$\alpha(M_Z), G_\mu, M_Z$ best effective input parameters for VB physics (Z,W) etc.

$$\frac{\delta\alpha}{\alpha} \sim 3.6 \times 10^{-9}$$
$$\frac{\delta G_\mu}{G_\mu} \sim 8.6 \times 10^{-6}$$
$$\frac{\delta M_Z}{M_Z} \sim 2.4 \times 10^{-5}$$
$$\frac{\delta\alpha(M_Z)}{\alpha(M_Z)} \sim 1.6 \div 6.8 \times 10^{-4} \quad (\mathrm{present:\ lost\ } 10^5 \mathrm{\ in\ precision!})$$
$$\frac{\delta\alpha(M_Z)}{\alpha(M_Z)} \sim 5.3 \times 10^{-5} \quad (\mathtt{TESLA\ requirement})$$

LEP/SLD: $\sin^2\Theta_{\rm eff} = (1 - g_{Vl}/g_{Al})/4 = 0.23148 \pm \boxed{0.00017}$

$$\delta\Delta\alpha(M_Z) = 0.00036 \quad \Rightarrow \quad \delta\sin^2\Theta_{\rm eff} = \boxed{0.00013}$$

affects Higgs mass bounds, precision tests and new physics searches!!!

For perturbative QCD contributions very crucial: precise QCD parameters $\alpha_s,\ m_c,\ m_b,\ m_t \Rightarrow$ Lattice-QCD

Indirect

Higgs boson mass "measurement"

$m_H = 88^{+53}_{-35}$ **GeV**

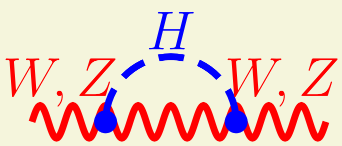
$\boxed{e^+e^- \to \tau\text{: } \Rightarrow \delta m_H \sim -19 \text{ GeV}}$

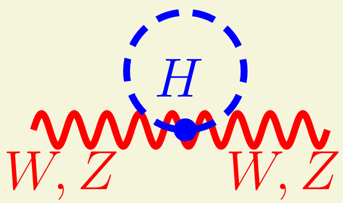
Direct lower bound:

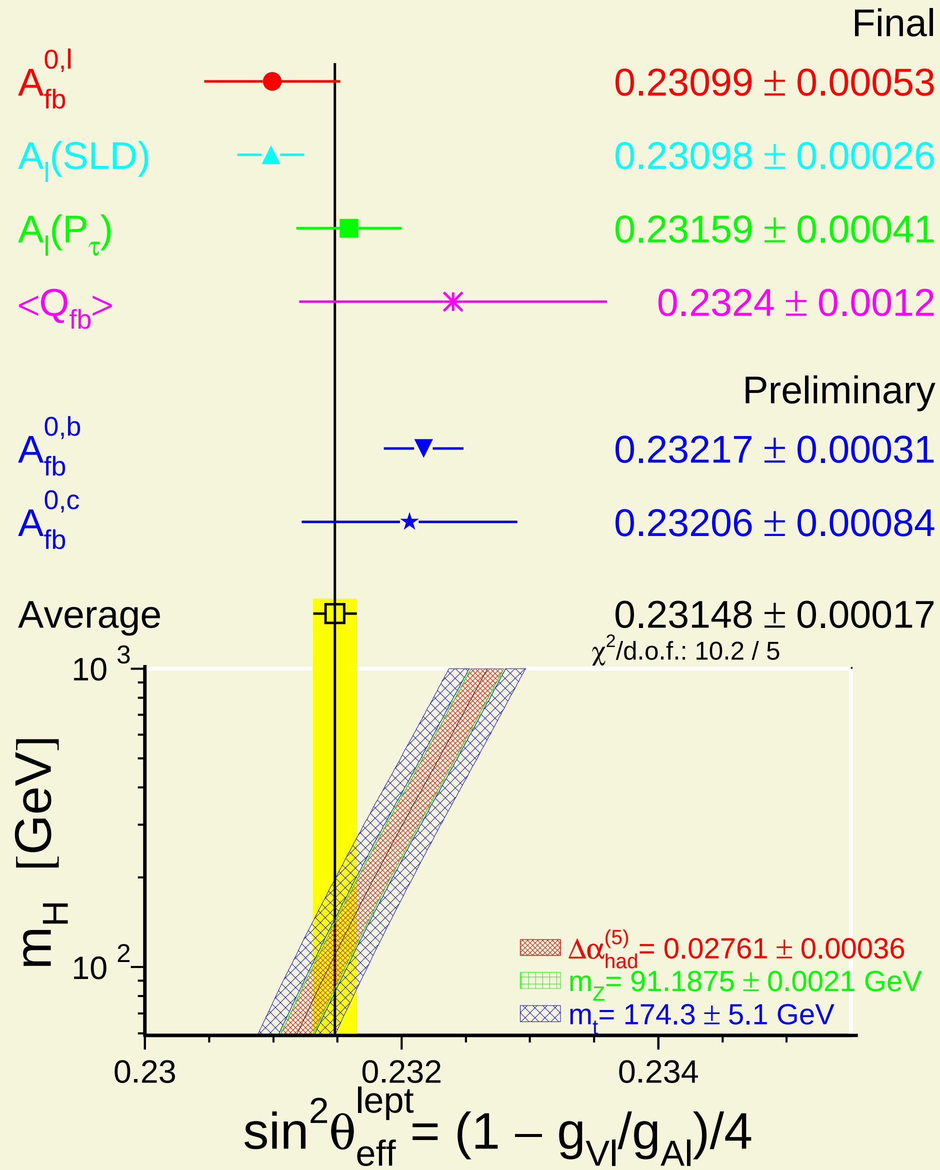
$\boxed{m_H > 114}$ **GeV at 95% CL**

Indirect upper bound:

$\boxed{m_H < 193}$ **GeV at 95% CL**







(LEP Electroweak Working Group: D. Abbaneo et al. 03)

Input parameter for ILC physics:

$$\frac{\delta\alpha}{\alpha} \sim 3.6 \times 10^{-9} \qquad \frac{\delta\alpha(M_Z)}{\alpha(M_Z)} \sim 1.6 \div 6.8 \times 10^{-4}$$
$$\frac{\delta G_\mu}{G_\mu} \sim 8.6 \times 10^{-6} \qquad \frac{\delta M_Z}{M_Z} \sim 2.4 \times 10^{-5}$$

accuracy in $\delta\alpha(M_Z)$ roughly one order of magnitude worse than M_Z !

$$\sin^2\Theta_i\ \cos^2\Theta_i = \frac{\pi\alpha}{\sqrt{2}\,G_\mu\,M_Z^2}\,\frac{1}{1-\Delta r_i}$$

where

$$\Delta r_i = \Delta r_i(\alpha,\,G_\mu,\,M_Z,m_H,\,m_{f\neq t},\,m_t)$$

quantum corrections from gauge boson self-energies, vertex– and box–corrections.

Propagation of uncertainty: $\delta\Delta\alpha \Rightarrow \delta M_W,\,\delta\sin^2\Theta_f$:

$$\frac{\delta M_W}{M_W} \sim \frac{1}{2}\,\frac{\sin^2\Theta_W}{\cos^2\Theta_W-\sin^2\Theta_W}\,\delta\Delta\alpha \sim 0.23\;\delta\Delta\alpha$$
$$\frac{\delta\sin^2\Theta_f}{\sin^2\Theta_f} \sim \frac{\cos^2\Theta_f}{\cos^2\Theta_f-\sin^2\Theta_f}\,\delta\Delta\alpha \sim 1.54\;\delta\Delta\alpha$$

e.g., obscure in particular the indirect bounds on the Higgs mass obtained from electroweak precision measurements.

Precision predictions:

$$
\begin{array}{lccl}
M_W : & \sin^2\Theta_W & = & 1-\frac{M_W^2}{M_Z^2} \\
g_2 : & \sin^2\Theta_g & = & e^2/g_2^2 = \frac{\pi\alpha}{\sqrt{2}\,G_\mu\,M_W^2} \\
a_f : & \sin^2\Theta_f & = & \frac{1}{4|Q_f|}\left(1-\frac{v_f}{a_f}\right)\;,\quad f\neq\nu \\
a_f : & \rho_f & = & \frac{1}{1-\Delta\rho}\;,\;\; \text{independent on}\quad \alpha
\end{array}
$$

for the most important cases and the general form of Δr_i reads

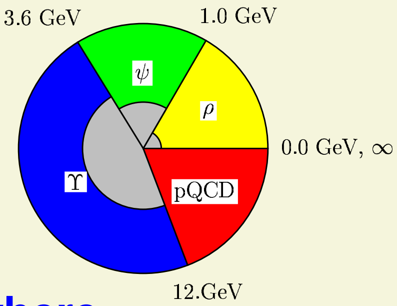
$$\Delta r_i \;\;=\;\; \Delta\alpha - f_i(\sin^2\Theta_i)\,\Delta\rho + \Delta r_{i\,\mathrm{remainder}}$$

with a universal term $\Delta\alpha$ which affects the predictions for M_W, A_{LR}, A^f_{FB}, Γ_f, etc.

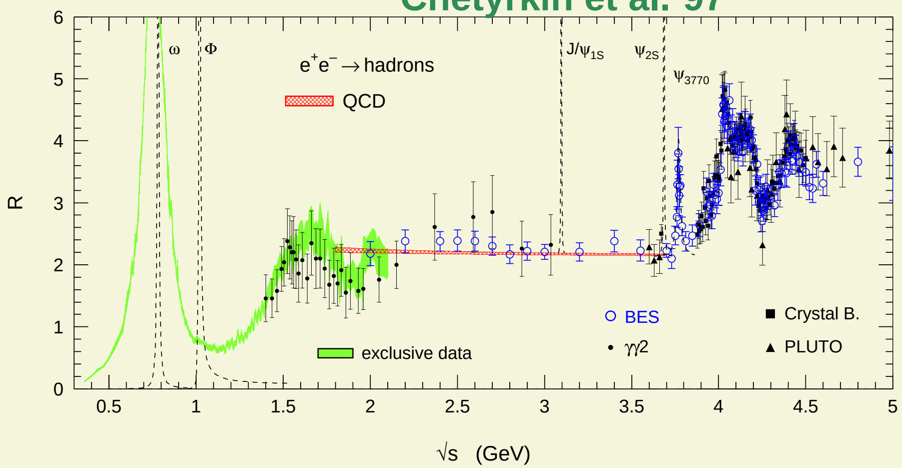
③ Evaluation of $\alpha(M_Z)$

Non-perturbative hadronic contributions $\Delta\alpha^{(5)}_{\rm had}(s)$ can be evaluated in terms of $\sigma(e^+e^- \to {\rm hadrons})$ data via dispersion integral:

$$\Delta\alpha^{(5)}_{\rm had}(s) = -\frac{\alpha s}{3\pi}\left(\;\; \int\limits_{4m_\pi^2}^{E^2_{\rm cut}} \!\!\!\!\!P \; ds' \frac{R^{\rm data}_\gamma(s')}{s'(s'-s)} + \int\limits_{E^2_{\rm cut}}^{\infty} \!\!\!\!\!P \; ds' \frac{R^{\rm pQCD}_\gamma(s')}{s'(s'-s)} \right)$$

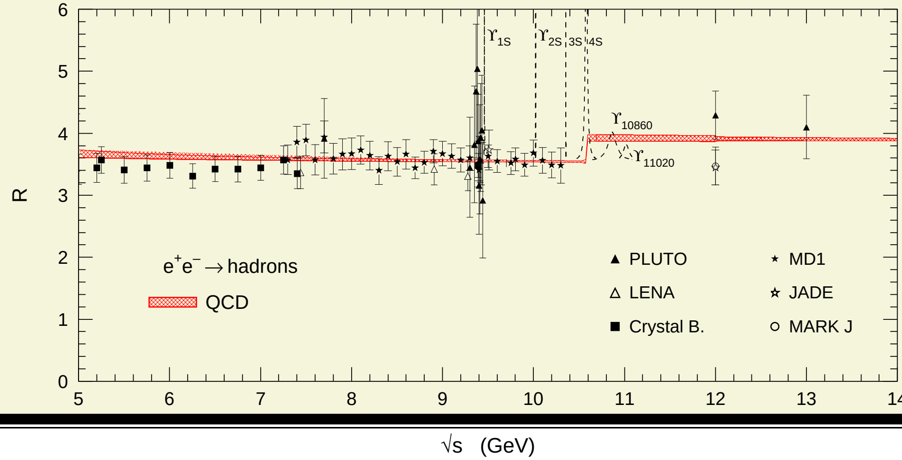


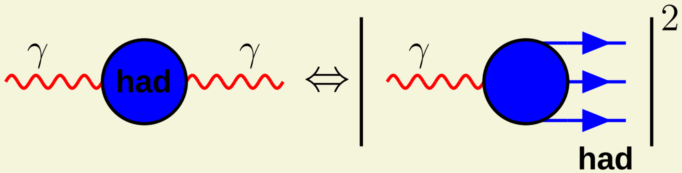
Compilation: Davier, Eidelman et al. 02
Theory = pQCD: Groshny et al. 91, Chetyrkin et al. 97



where

$$R_\gamma(s) \equiv \frac{\sigma^{(0)}(e^+e^- \to \gamma^* \to {\rm hadrons})}{\frac{4\pi\alpha^2}{3s}}$$





$\Pi'_\gamma(q^2)$ $\quad\quad \sim \sigma^{\rm had}_{\rm tot}(q^2)$

Evaluation FJ 2005 update: at $M_Z = 91.19$ GeV

- $R(s)$ data up to $\sqrt{s} = E_{cut} = 5$ GeV
  and for Υ resonances region between 9.6 and 13 GeV

- perturbative QCD from 5.0 to 9.6 GeV
  and for the high energy tail above 13 GeV

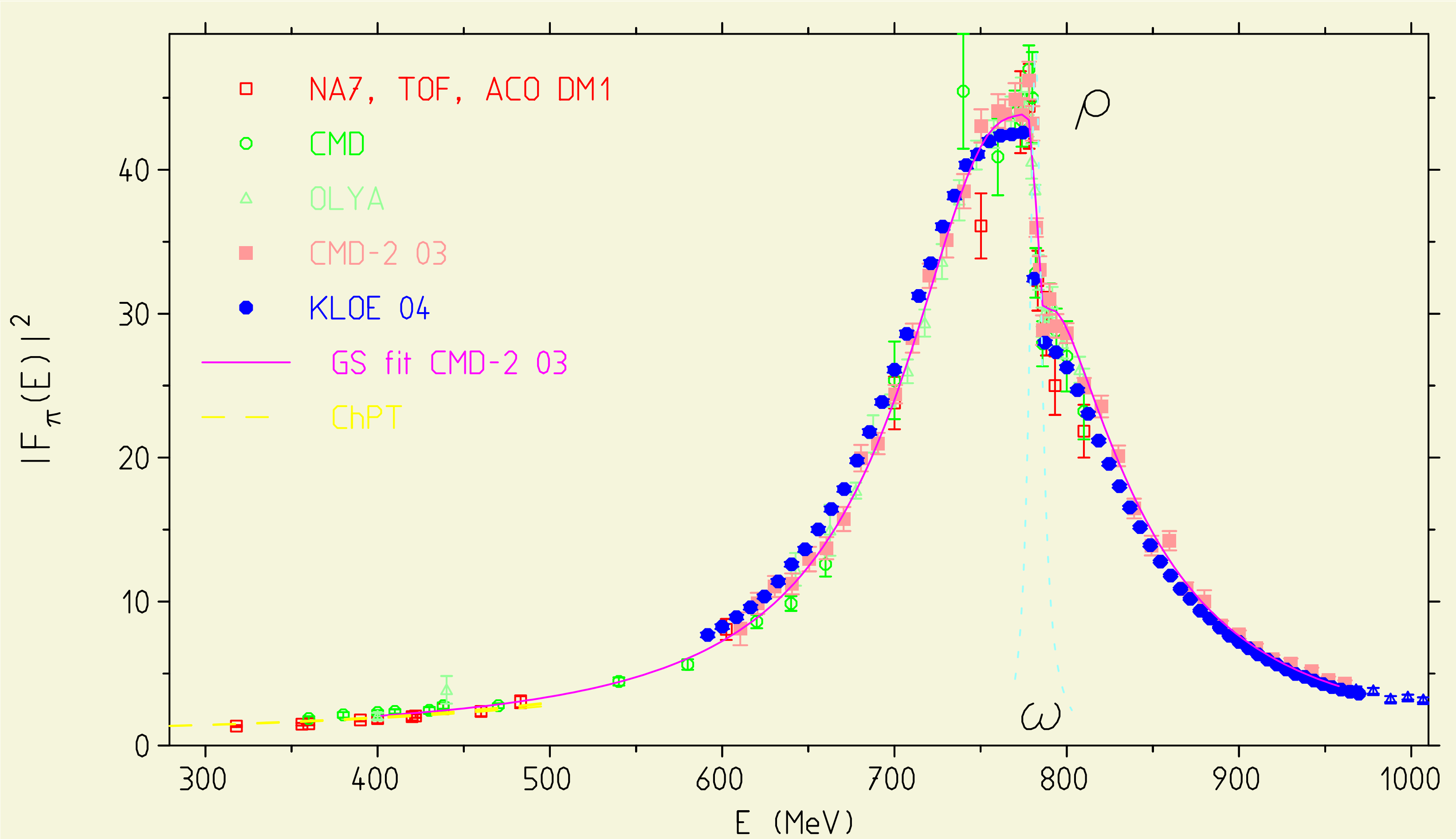
$$\Delta\alpha^{(5)}_{\rm hadrons}(M_Z^2) = 0.027773 \pm 0.000354$$

$$0.027664 \pm 0.000173 \quad \text{Adler}$$

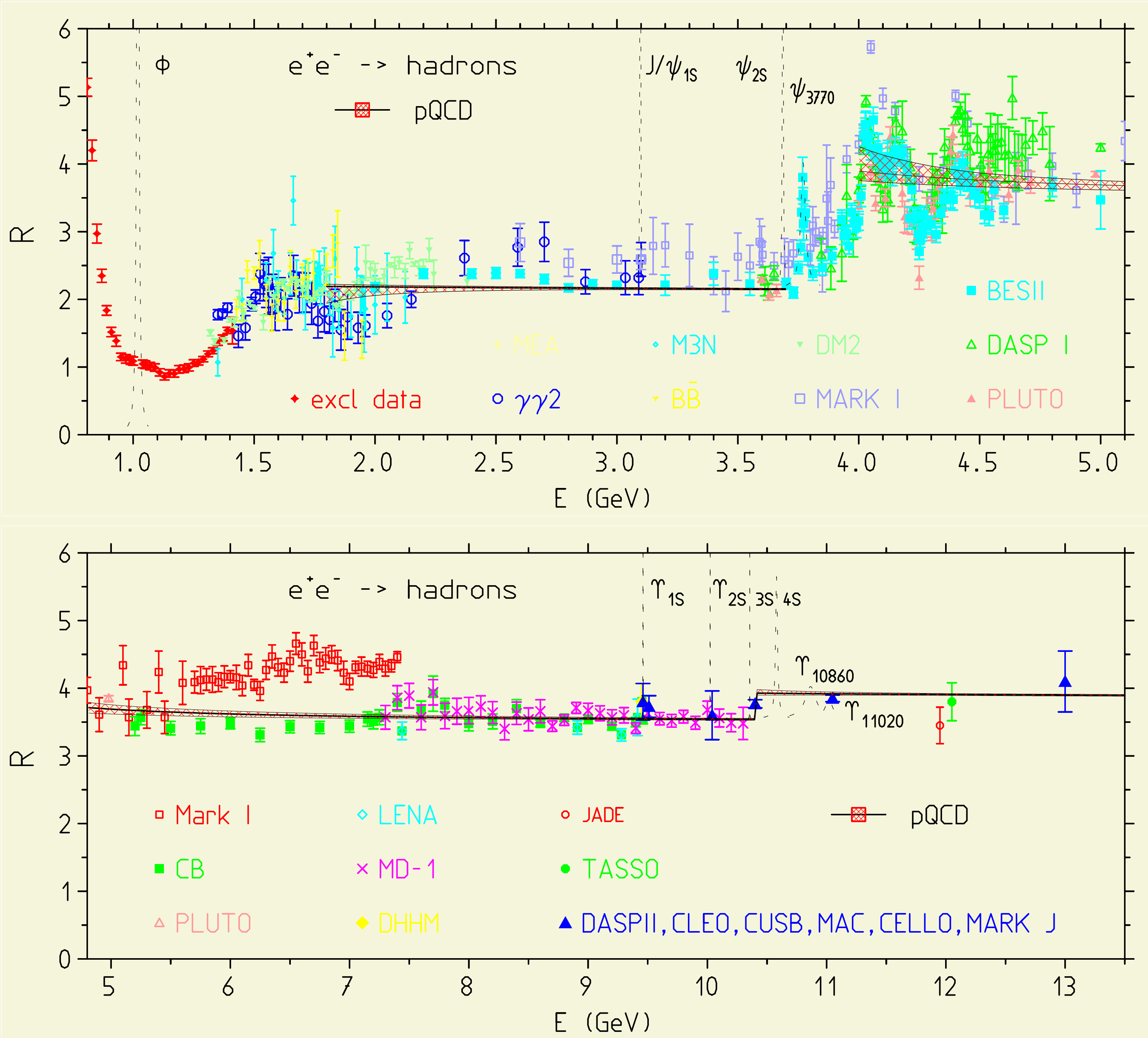
$$\alpha^{-1}(M_Z^2) = 128.922 \pm 0.049$$

$$128.937 \pm 0.024 \quad \text{Adler}$$

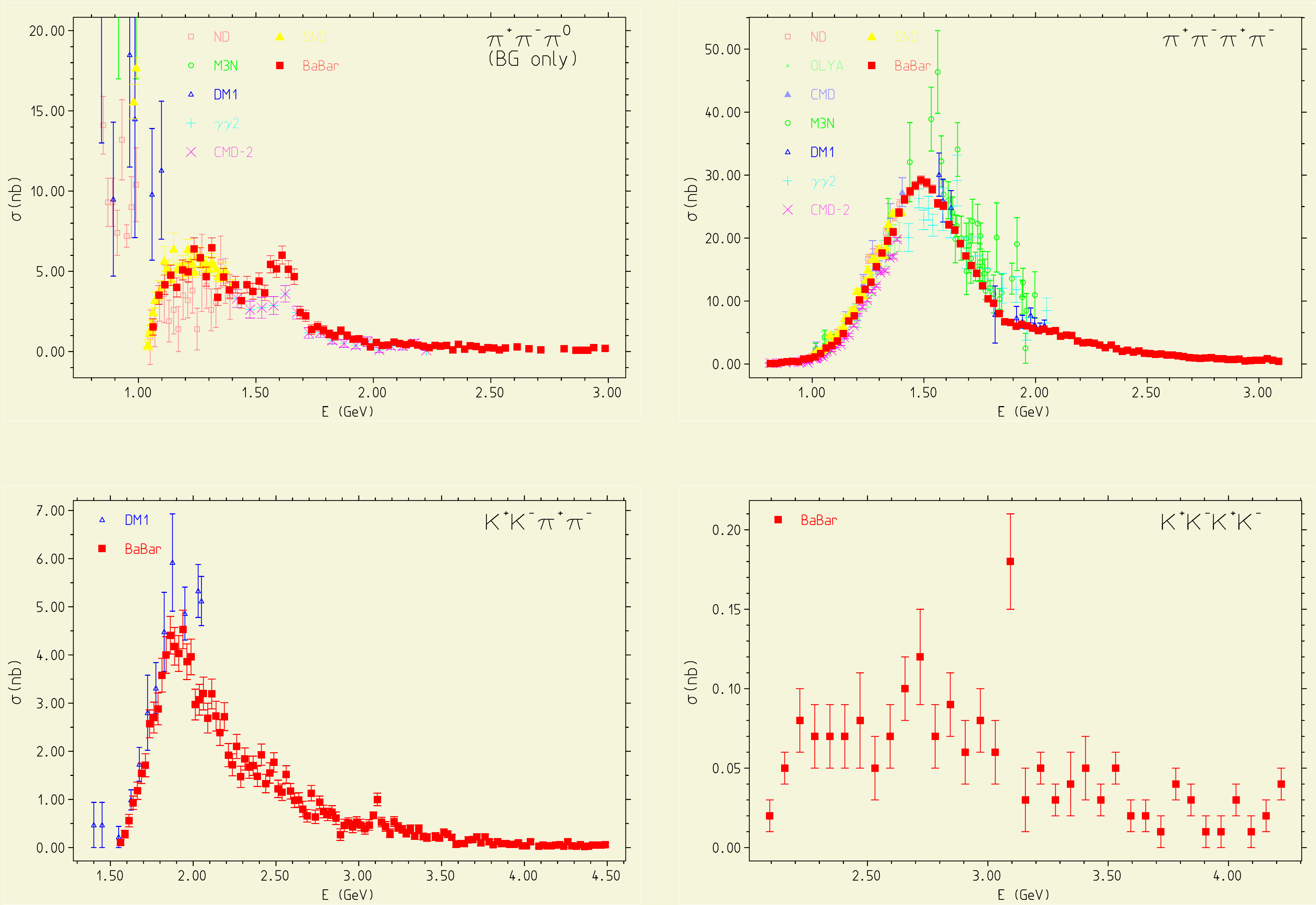
④ A look at the e^+e^-–data



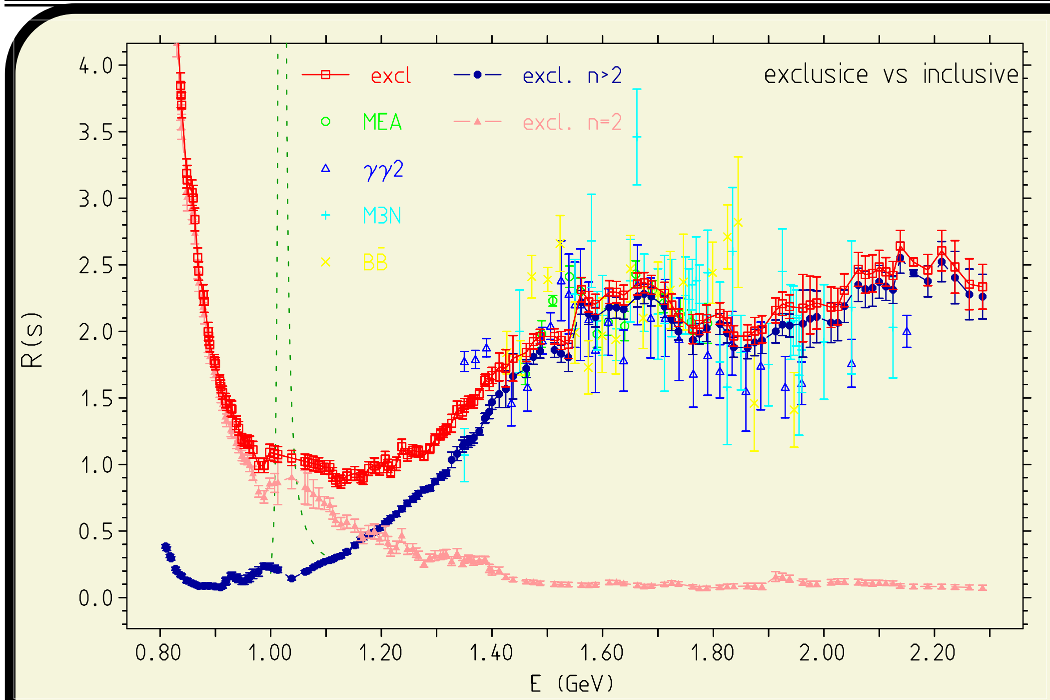
Below 1 GeV deviations between data sets much larger than errors claimed by experiments! CMD-2 vs. KLOE vs. SND somewhat confusing; will be settled by ongoing experiments



e+e- -> hadrons
pQCD
Φ
J/ψ1S
ψ2S
ψ3770
R
E (GeV)
BESII
MEA
M3N
DM2
DASP I
excl data
γγ2
BB̄
MARK I
PLUTO
ϒ1S
ϒ2S
3S
4S
ϒ10860
ϒ11020
Mark I
LENA
JADE
CB
MD-1
TASSO
PLUTO
DHHM
DASPII, CLEO, CUSB, MAC, CELLO, MARK J



BaBar radiative return measurements


exclusice vs inclusive
excl
excl. n>2
MEA
excl. n=2
$\gamma\gamma2$
M3N
BB
R(s)
E (GeV)

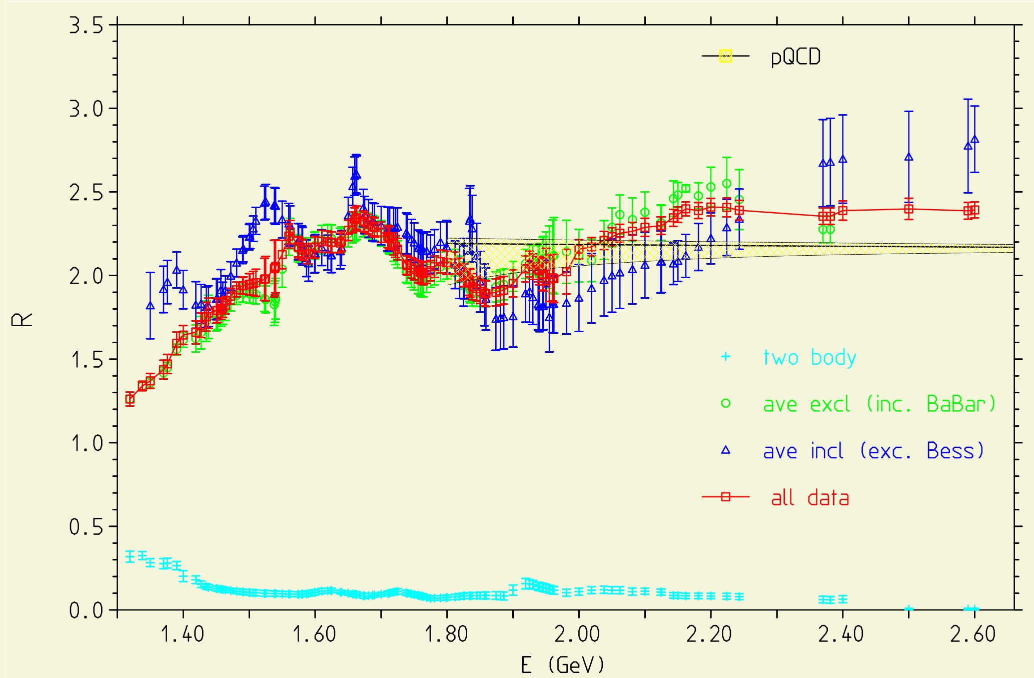
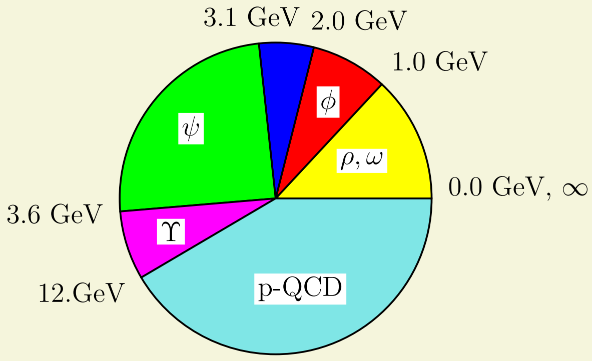

pQCD
two body
ave excl (inc. BaBar)
ave incl (exc. Bess)
all data
R
E (GeV)

Table 1: Contributions and uncertainties $\Delta\alpha^{(5)}_{\rm had}(M_Z^2)^{\rm data}\cdot 10^4$. Direct integration method. In red the results relevant for DAFNE-II.

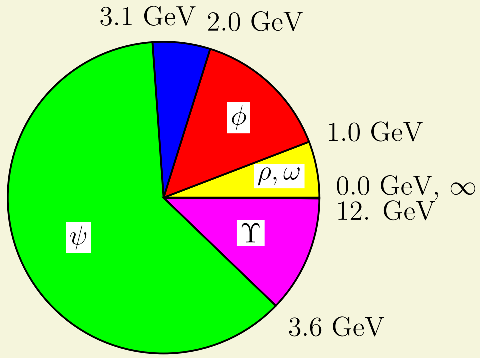
	$\Delta\alpha^{(5)}_{\rm had}\times 10^4$	rel. err.	abs. err.
ρ,ω $(E<2M_K)$	36.38 [13.1](0.96)	2.6 %	5.8 %
$2M_K<E<2$ GeV	22.20 [8.0](1.51)	6.8 %	14.3 %
2 GeV $<E<M_{J/\psi}$	15.77 [5.7](0.97)	6.2 %	6.0 %
$M_{J/\psi}<E<M_\Upsilon$	68.53 [24.6](3.13)	4.6 %	61.7 %
$M_\Upsilon<E<E_{\rm cut}$	19.85 [7.1](1.39)	7.0 %	12.1 %
$E_{\rm cut}<E$ pQCD	115.57 [41.5](0.12)	0.1 %	0.1 %
$E<E_{\rm cut}$ data	162.72 [58.5](3.98)	2.4 %	99.9 %
total	278.29 [100.0](3.98)	1.4 %	100.0 %

Table 2: Contributions and uncertainties $\Delta\alpha^{(5)}_{\rm had}(-s_0)^{\rm data}\cdot 10^4$ ($\sqrt{s_0}=2.5$ GeV). Adler function method. In red the results relevant for DAFNE-II.

	$\Delta\alpha^{(5)}_{\rm had}\times 10^4$	rel. err.	abs. err.
ρ,ω ($E<2M_K$)	33.43 [44.8](0.95)	2.8 %	34.5 %
$2M_K<E<2$ GeV	16.81 [22.5](1.09)	6.5 %	45.6 %
2 GeV $<E<M_{J/\psi}$	7.93 [10.6](0.49)	6.2 %	9.1 %
$M_{J/\psi}<E<M_\Upsilon$	14.47 [19.4](0.52)	3.6 %	10.6 %
$M_\Upsilon<E<E_{\rm cut}$	0.97 [1.3](0.07)	7.0 %	0.2 %
$E_{\rm cut}<E$ pQCD	1.09 [1.5](0.00)	0.1 %	0.0 %
$E<E_{\rm cut}$ data	73.61 [98.5](1.61)	2.2 %	100.0 %
total	74.69 [100.0](1.61)	2.2 %	100.0 %



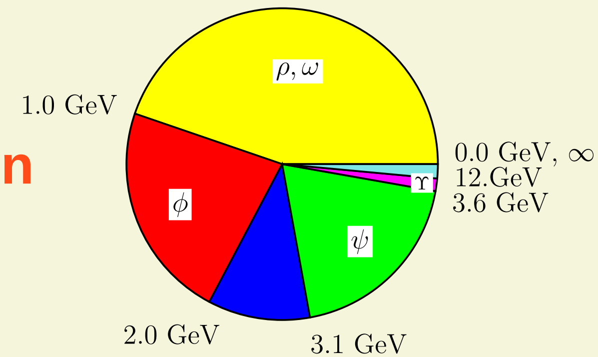
contributions



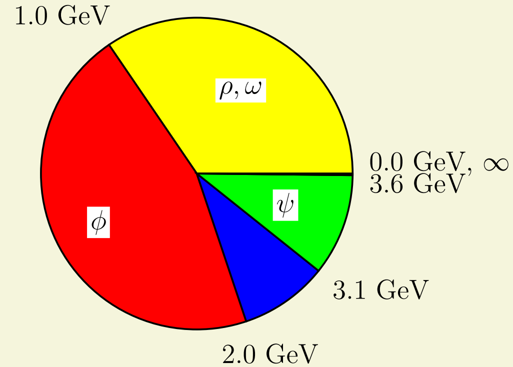
error^2

direct integration of data

integration via Adler function



contributions



error^2

present distribution of contributions and errors

⑤ $\Delta\alpha^{\rm had}$ via the Adler function

✗ use old idea: testing non–perturbative effects with help of the Adler function

$$D(-s) \doteq \frac{3\pi}{\alpha}\, s\, \frac{d}{ds}\Delta\alpha_{\rm had}(s) = -\left(12\pi^2\right)\; s\; \frac{d\Pi'_\gamma(s)}{ds}$$

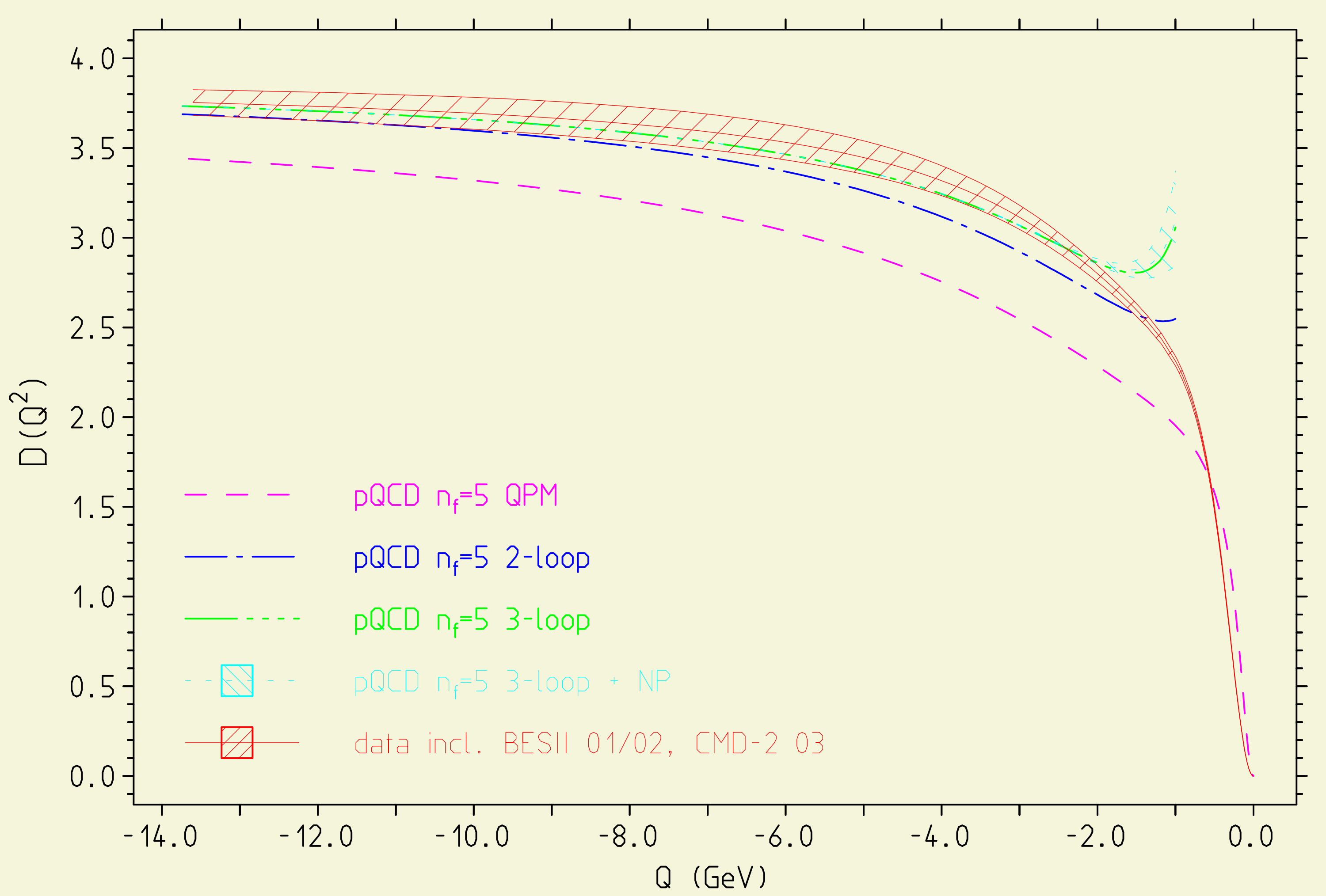
$$\Rightarrow \qquad D(Q^2) = Q^2 \int\limits_{4m_\pi^2}^{\infty} ds\, \frac{R(s)}{(s+Q^2)^2}$$

pQCD $\leftrightarrow R(s)$	pQCD $\leftrightarrow D(Q^2)$
very difficult to obtain in theory	smooth simple function in Euclidean region

Conservative conclusion:

- time-like approach: pQCD works well in “perturbative windows” 3.00 - 3.73 GeV, 5.00 - 10.52 GeV and 11.50 - ∞ (Kühn,Steinhauser)
- space-like approach: pQCD works well for $Q^2 = -q^2 > 2.5$ GeV (see plot)

"Experimental" Adler–function versus theory (pQCD + NP)



(Eidelman, F.J., Kataev, Veretin 98, FJ 03 update (BES, CMD-2))

$\Rightarrow$ **pQCD works well to predict $D(Q^2)$ down to $s_0 = (2.5\,\textbf{GeV})^2$; use this to calculate**

$$\Delta\alpha_{\rm had}(-Q^2) \sim \frac{\alpha}{3\pi} \int dQ'^2 \frac{D(Q'^2)}{Q'^2}$$

$$\boxed{\begin{aligned}\Delta\alpha^{(5)}_{\rm had}(-M_Z^2) \;=\; & \left[\Delta\alpha^{(5)}_{\rm had}(-M_Z^2) - \Delta\alpha^{(5)}_{\rm had}(-s_0)\right]^{\rm pQCD} \\ & + \Delta\alpha^{(5)}_{\rm had}(-s_0)^{\rm data}\end{aligned}}$$

and obtain, for $s_0 = (2.5\,\textbf{GeV})^2$: **(FJ 98/03)**

$$\begin{aligned}\Delta\alpha^{(5)}_{\rm had}(-s_0)^{\rm data} &= 0.007417 \pm 0.000086 \\ \Delta\alpha^{(5)}_{\rm had}(-M_Z^2) &= 0.027613 \pm 0.000086 \pm 0.000149\end{aligned}$$

parameter	range	pQCD uncertainty	total error
α_s	0.117 ... 0.123	0.000051	0.000155
m_c	1.550 ... 1.750	0.000087	0.000170
m_b	4.600 ... 4.800	0.000011	0.000146

Future: ILC requirement: improve by factor 10 in accuracy

- **direct integration of data: 58% from data 42% p-QCD**

  $\Delta\alpha_{\rm had}^{(5)\,{\rm data}} \times 10^4 = 162.72 \pm 4.13$ **(2.5%)**

  1% overall accuracy ± 1.63

  1% accuracy for each region (divided up as in table)

  added in quadrature: ± 0.85

  Data: [4.13] vs. [0.85] $\Rightarrow$ **improvement factor 4.8**

  $\Delta\alpha_{\rm had}^{(5)\,{\rm pQCD}} \times 10^4 = 115.57 \pm 0.12$ **(0.1%)**

  Theory: no improvement needed !

- **integration via Adler function: 26% from data 74% p-QCD**

  $\Delta\alpha_{\rm had}^{(5)\,{\rm data}} \times 10^4 = 073.61 \pm 1.68$ **(2.3%)**

  1% overall accuracy ± 0.74

  1% accuracy for each region (divided up as in table)

added in quadrature: ± 0.41

Data: [2.25] vs. [0.46] $\Rightarrow$ **improvement factor 4.9 (Adler vs Adler)**

[4.13] vs. [0.46] $\Rightarrow$ **improvement factor 9.0 (Standard vs Adler)**

$$\Delta\alpha^{(5)\,\rm pQCD}_{\rm had} \times 10^4 = 204.68 \pm 1.49$$

Theory: (QCD parameters) has to improve by factor 10 ! $\longrightarrow \pm 0.20$

Requirement may be realistic:

- **pin down experimental errors to 1% level in all non-perturbative regions up to 10 GeV**
- **switch to Adler function method**
- **improve on QCD parameters, mainly on** m_c **and** m_b

⑦ Conclusion

- Recent and future high precision experiments on $a_\mu = (g-2)/2$ (BNL/KEK project may gain factor 10?) and $\sin^2\Theta_{\rm eff}$, etc. (LEP/SLD$\longrightarrow$TESLA/ILC) imposed and further impose a lot of pressure to theory and experiment to improve, in particular, in reducing the hadronic uncertainties which mainly are due to the experimental errors of $R(s)^{\rm exp}_{\rm had}$.
- In electroweak precision physics at non-zero energies (note $E \sim m_\mu$ in $(g-2)_\mu$) there is now way around determining $\alpha_{\rm eff}(E)$ via precision measurements of $\sigma_{\rm hadronic}$ or lattice QCD simulations via Adler function approach (which is a very difficult long term project).
- Needs for linear collider (like TESLA/ILC): requires $\sigma_{\rm had}$ at 1% level up to the $\Upsilon \Rightarrow \delta\alpha(M_Z)/\alpha(M_Z) \sim 5\times 10^{-5}$. At present would allow to get better Higgs boson mass limits but much more than that.
- Future precision physics requires dedicated effort on $\sigma_{\rm had}$ experimentally as well as theoretically (radiative corrections, final state radiation from hadrons etc.)
- Improving hadronic cross section measurements must be seen as a global effort in

particular in the context of ILC project, which only makes sense as a high precision physics project. The $\sigma_{\mathrm{hadronic}}$ efforts have to be pushed at any machine able to perform such a measurement up tp 10 GeV! One has to see this activity as an integral part of the international linear collider (ILC) project and to ask for support by the international community.

- A project like DAFNE–II can play a major role in this respect. What is required is a scan measurement with a good energy calibration (preferable using resonance depolarization). In radiative return at higher energies and multiplicities one has to precisely reconstruct the invariant mass event by event which I think is difficult. Dedicated Monte Carlo simulations has to be done to study what precision in which scenario can be achieved.
- Don't believe people claiming very small errors and that everything has been solved already or that some other lab is already doing the same; in high precision physics any experiment becomes a real challenge and I think at least two experiments should be performed for cross check.
- Note complementary approach important: direct $R(s)$ integration vs. Adler $D(Q^2)$; in particular for the latter as well as for $(g-2)_\mu$ DAFNE–II is a real need!

DO IT !!!

It is a really challenging important first class physics project.

Don't do it the cheapest way, its worth more!

Try getting more support on international level!