Review of α_s Measurements

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CTEQ Symposium, FNAL
11/7/96

Some recent reviews:

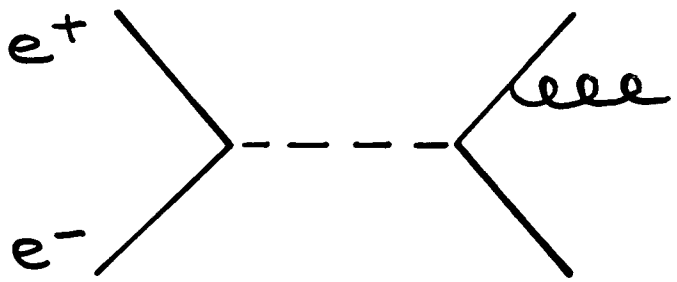
Bethke	Moriond	94
Webber	Glasgow	94
Yamauchi	Beijing	95
Hinchliffe	PDG	96
Schmelling	Warsaw	96

Outline

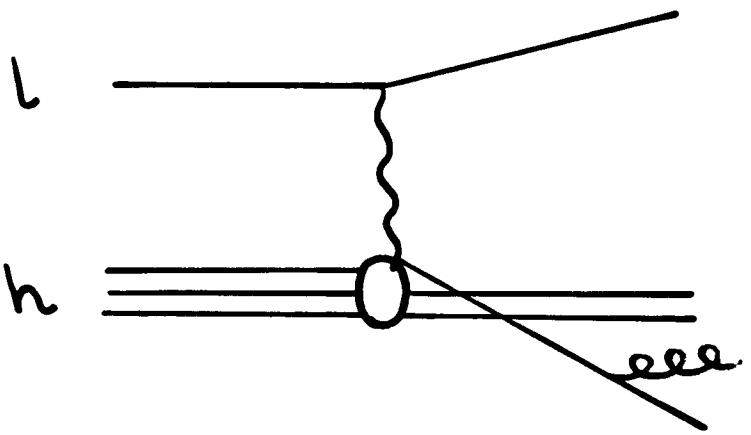
- Theoretical overview + motivation
- e^+e^-
- DIS
- h.h
- LGT
- Conclusions + outlook

Hadronic Final States

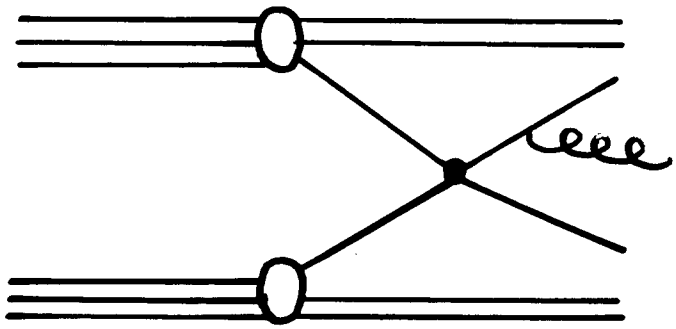
e^+e^-



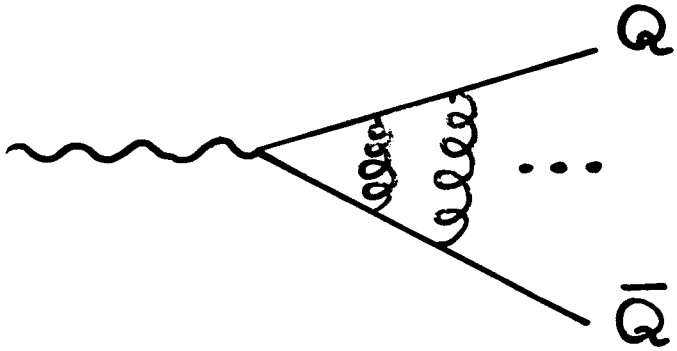
DIS



hh



heavy quarkonia



To Make a Reliable Prediction:

- Choose OBSERVABLE
  - IR + collinear-safe
- Choose RENORMALISATION SCHEME
  - generally $\overline{MS}$
- Choose RENORMALISATION SCALE
  - little consensus, much controversy
- Apply PERTURBATION THEORY
  - at least @ NLO:

e^+e^-, l h $\Big\}$ $O(\alpha_s^2)$ hh - $O(\alpha_s^3)$

$\Rightarrow f(Q^2, \Lambda_{\overline{MS}})$

Dependence of α_s on Q^2

$$\alpha_s(Q^2) = \frac{4\pi}{\beta_0 \ln(Q^2/\Lambda^2_{\overline{MS}})}\left\{1 - \frac{2\beta_1}{\beta_0^2}\frac{\ln(\ln(Q^2/\Lambda^2_{\overline{MS}}))}{\ln(Q^2/\Lambda^2_{\overline{MS}})} + \ldots\right\}$$

Convention: $Q = M_Z$

$\alpha_s(M_Z^2)$ is the $\sin^2\theta_W$ of strong interactions

The α_s Crisis (Glasgow 1994)

Experiment		$\alpha_s(M_Z^2)$
CCFR ν: F_2, F_3	1993	0.111 ± 0.006
BCDMS μ, SLAC e: F_2	1992	0.113 ± 0.005
LGT Υ spectra	1994	0.115 ± 0.002
Ψ, Υ decay widths	1992	$0.113^{+0.007}_{-0.005}$
CLEO jets	1994	0.113 ± 0.007
LEP $\Gamma(Z^0 \rightarrow \text{hadrons})$	1994	0.125 ± 0.005

Reconciling the $\alpha_s(M_Z^2)$ Measurements

1. Raise low-Q^2 measurements:

Eg. light gluinos: $m_g \sim$ few GeV

$\Rightarrow$ slower running of α_s

2. Lower high-Q^2 measurements:

$$\Gamma_Z^{had} = \Gamma_Z^{EW} (1 + \delta_{QCD})$$

Raise Γ_Z^{EW} by 7 MeV (0.4%, 2σ)

$\Rightarrow \Delta\alpha_s(M_Z^2) \sim -0.015$ (12%)

$R_b \Rightarrow$

$\Gamma(Z^0 \rightarrow b\bar{b})$ too large by $\sim 2.5\%$

$\alpha_s(M_Z^2) \Rightarrow$

$\Gamma(Z^0 \rightarrow$ hadrons) too large by $\sim 0.4\%$

$$\Delta R_b\ (+1\%) \quad \equiv \quad \Delta\alpha_s(-0.006)$$

PRECISE MEAS. OF α_s IS VERY IMPORTANT FOR ELECTROWEAK PHYSICS (TOO)!

DETERMINING α_s FROM MEASUREMENTS AT Z:
HOW NATURE PROMPTS US ABOUT NEW PHYSICS

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Received 12 Jan...

Name MS

IC-95-133

A low α_s: hinting new physics at GUT scale?

Mar Bastero-Gil[a] and Biswajoy Brahmachari[b]

IC-95-217
UMD-PP-96-14

A low α_S and its consequences for unified model building

SLAC
AUG 18 1995
LIBRARY

Biswajoy Brahmachari[1]

Lowering α_s by flipping SU(5)

SLAC
OCT 13 1995
LIBR...

John Ellis,[1] Jorge L. Lopez,[2] and D.V. Nanopoulos[3,4]

KAIST-CHEP-95/14

$\alpha_s(M_Z^2)$ and R_b discrepancy with nonuniversal interactions

Jae Kwan Kim, Yeong Gyun Kim*, Jae Sik Lee† and Kang Young Lee‡
Department of Physics, KAIST, Taejon 305-701, KOREA

(September 19, 1995)

Perturbative QCD Calculations

In general:

$$X = X^{EW}\,(1 + \delta_{QCD})$$

where:

$$\delta_{QCD} = a_1\left(\frac{\alpha_s}{\pi}\right) + a_2\left(\frac{\alpha_s}{\pi}\right)^2 + a_3\left(\frac{\alpha_s}{\pi}\right)^3 + \ldots$$

For example:

$$\Gamma_Z^{had} = 1.671\left(1 + \frac{\alpha_s}{\pi} + 0.75\left(\frac{\alpha_s}{\pi}\right)^2 - 15.30\left(\frac{\alpha_s}{\pi}\right)^3 + \ldots\right.$$

$\sim 4\%$

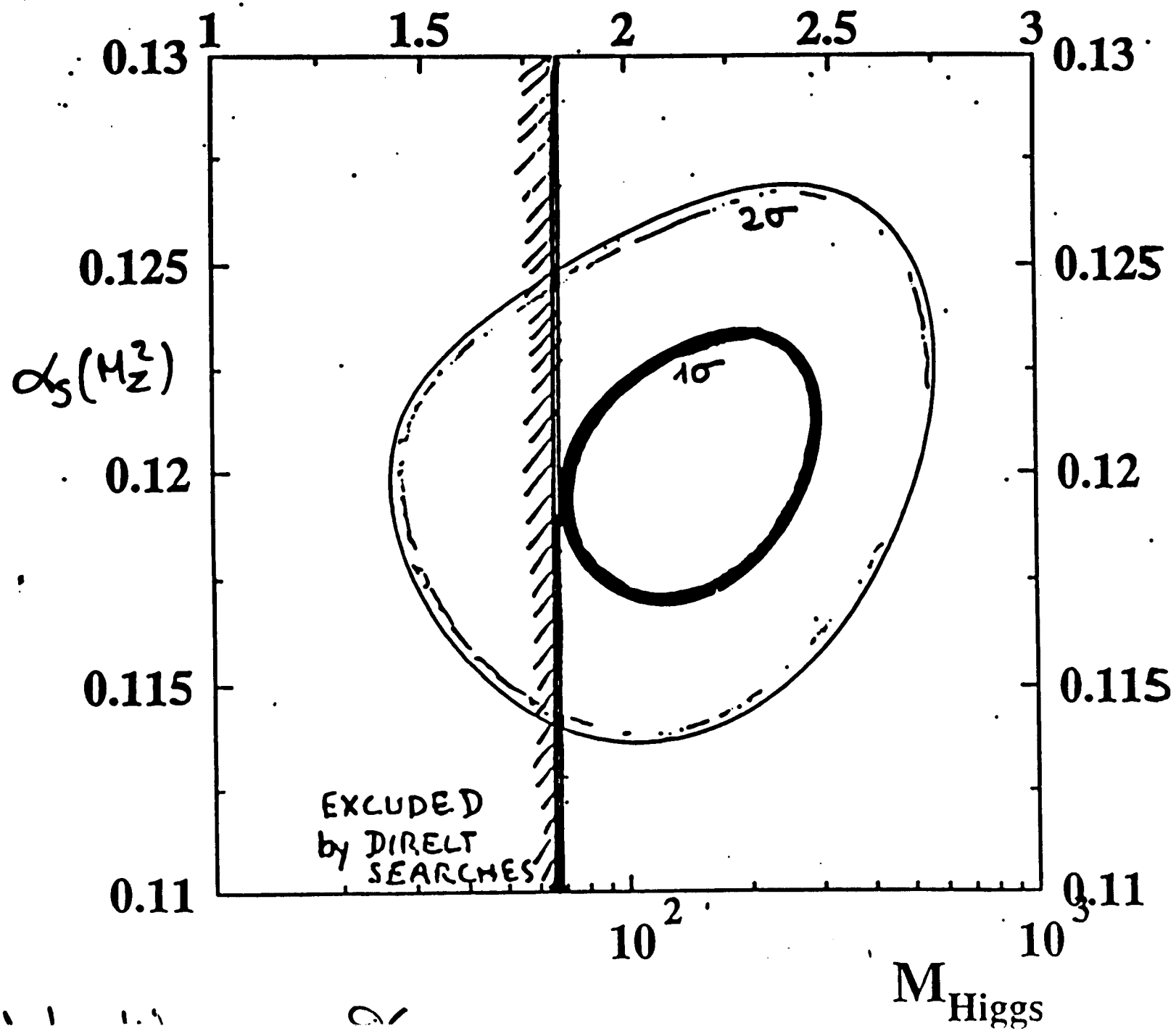
Global S.M. Fits

(LEPEWWG/96-01 Moriond 96)

Warsaw 1996

	Measurement with Total Error	Standard Model	Pull	
a) LEP				
line-shape and lepton asymmetries:				
m_Z [GeV]	91.1884 ± 0.0022	91.1869	0.7	
• Γ_Z [GeV]	2.4964 ± 0.0032	2.4979	−0.5	2.4946
• σ_h^0 [nb]	41.490 ± 0.078	41.454	0.5	41.508
• R_l	20.788 ± 0.032	20.770	0.6	20.778
$A_{FB}^{0,l}$	0.0171 ± 0.0011	0.0159	1.1	
+ correlation matrix Table 8				
τ polarization:				
$\mathcal{A}_\tau$	0.1394 ± 0.0069	0.1455	−0.9	
$\mathcal{A}_e$	0.1429 ± 0.0079	0.1455	−0.3	
b and c quark results:				
$R_b^{(b)}$	0.2215 ± 0.0017	0.2155	3.5	
$R_c^{(b)}$	0.1596 ± 0.0070	0.1725	−1.8	
$A_{FB}^{0,b(b)}$	0.1002 ± 0.0028	0.1020	−0.6	
$A_{FB}^{0,c(b)}$	0.0756 ± 0.0051	0.0728	0.5	
+ correlation matrix Table 15				
$q\bar{q}$ charge asymmetry:				
$\sin^2\theta_{eff}^{lept}$ ($\langle Q_{FB} \rangle$)	0.2320 ± 0.0010	0.23171	0.3	
b) SLD				
$\sin^2\theta_{eff}^{lept}$ (A_{LR} [5,6])	0.23049 ± 0.00050	0.23172	−2.4	
R_b [8]$^{(b)}$	0.2176 ± 0.0039	0.2155	0.5	
$\mathcal{A}_b$ [7]	0.842 ± 0.052	0.934	−1.8	
$\mathcal{A}_c$ [7]	0.618 ± 0.091	0.667	−0.5	
c) $p\bar{p}$ and νN				
m_W [GeV] ($p\bar{p}$ [65])	80.33 ± 0.15	80.37	−0.2	
$1 - m_W^2/m_Z^2$ (νN [9–11])	0.2257 ± 0.0047	0.2232	0.5	

Fit of $\alpha_s(M_Z)$, m_H to LEP, SLC, TeV, ν data



Z^0 Lineshape (iv): Fit results

$$m_H = 149^{+190}_{-82}\ \text{GeV}$$

$$m_H < 640\ \text{GeV}\ (2\sigma)$$

$$\boxed{\alpha_s(M_Z^2) = 0.1202 \pm 0.0033}$$

N.B.

Moriond 1996:

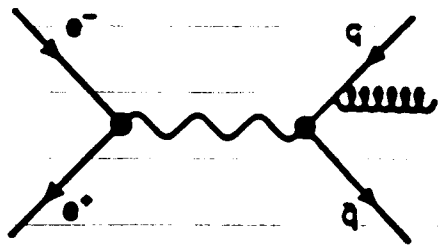
$$\alpha_s(M_Z^2) = 0.123 \pm 0.004\ (\text{exp.}) \pm 0.002\ (m_H)$$

1994:

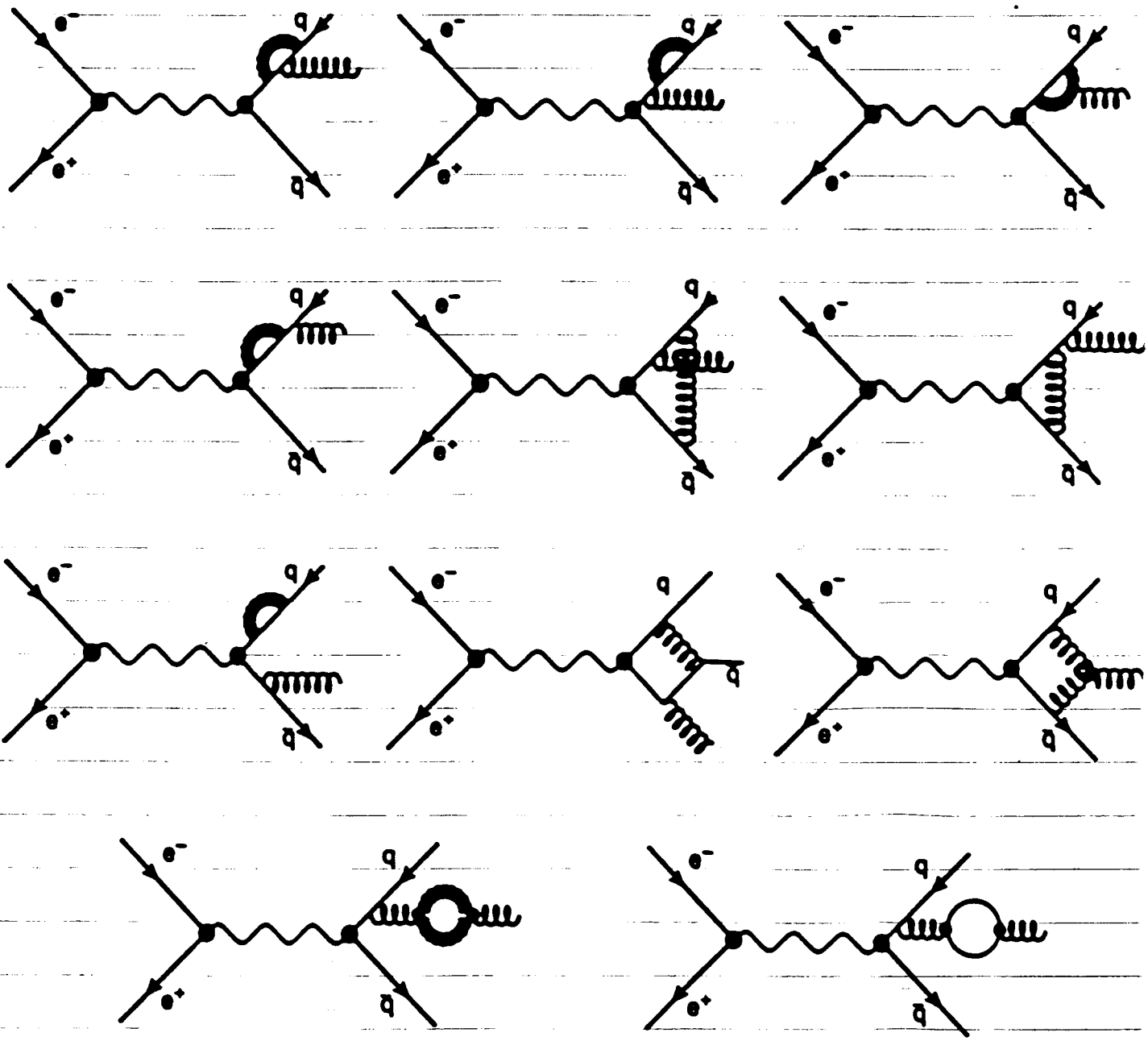
$$\alpha_s(M_Z^2) = 0.125 \pm 0.006$$

3-jet Production

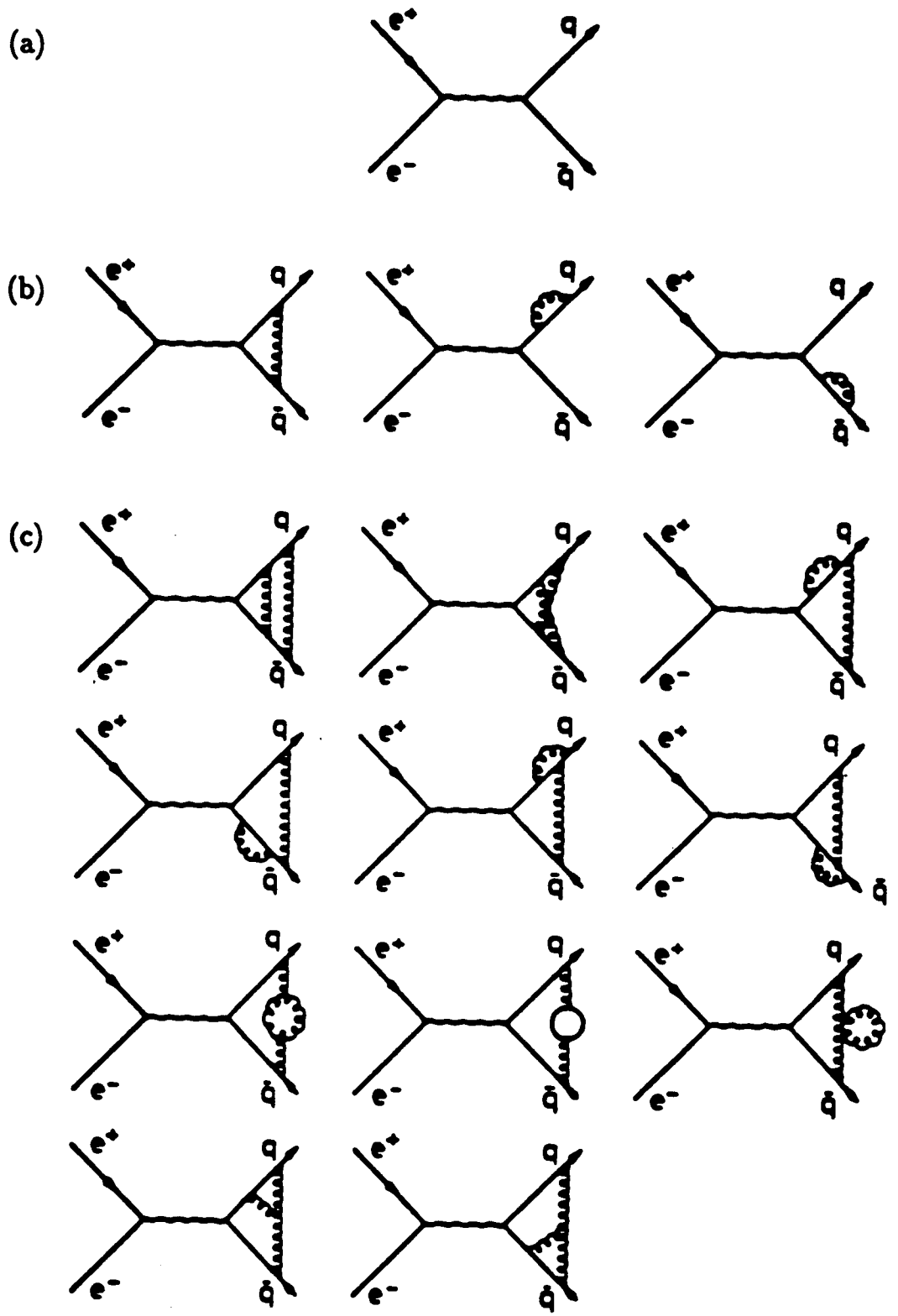
(a)



(b)



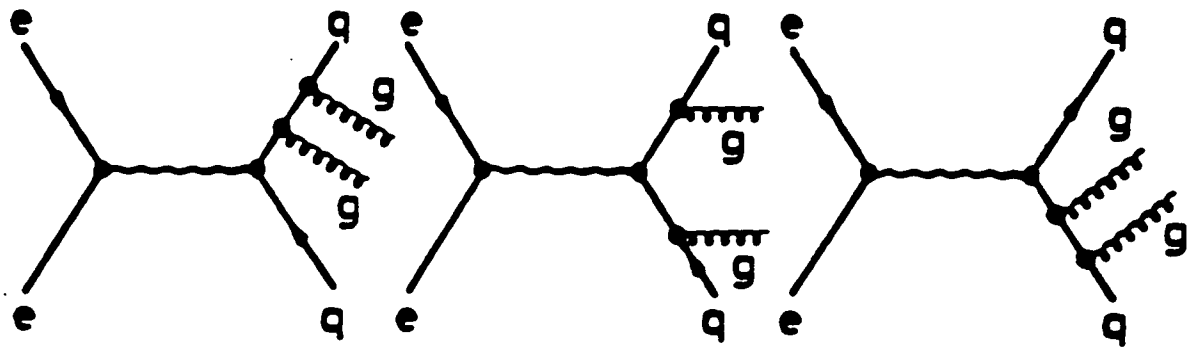
2 - jet Production



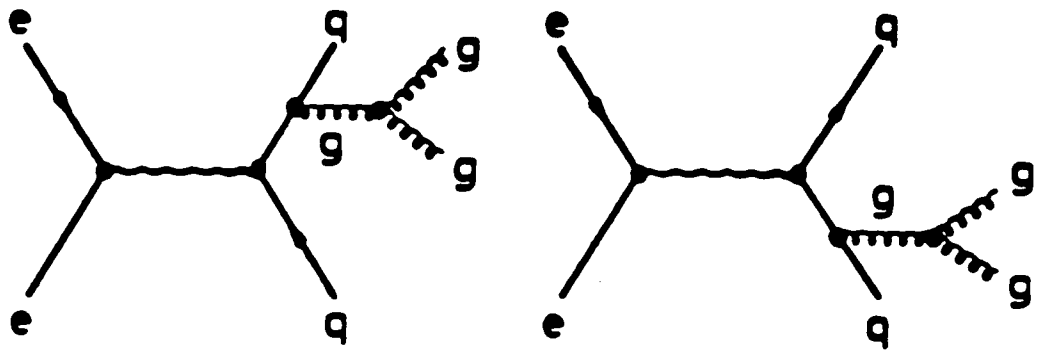
4 - jet Production

$O(g^2)$

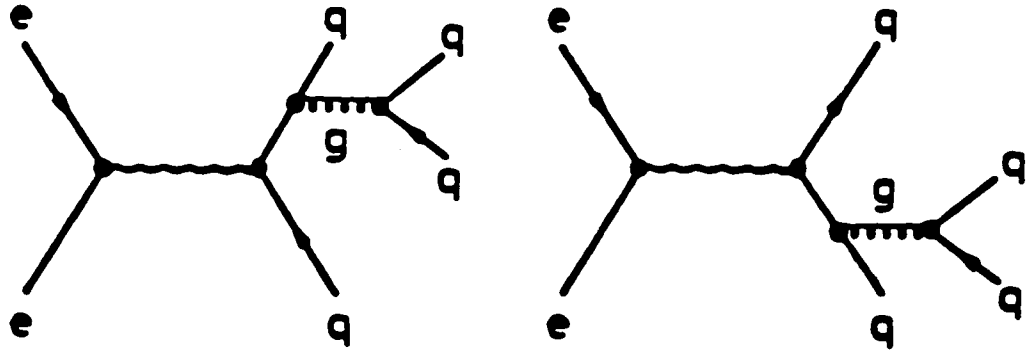
(a) $e^+e^- \rightarrow q\bar{q}\,gg$



(b)



(c) $e^+e^- \rightarrow q\bar{q}\,q\bar{q}$



Observables used:

1 – Thrust	τ
Heavy jet mass	ρ
Jet broadening:	
Total	B_T
Wide	B_W
Oblateness	O
C-parameter	C
Differential jet rates:	
$D_2(y_c) = \frac{\Delta R_2(y_c)}{\Delta y_c}$	E
	E0
	P
	P0
	D
	G
Energy-energy correlations	EEC
Asymmetry of EEC	$AEEC$
Jet cone energy fraction	$JCEF$

Perturbative QCD Calculations

Ellis, Ross, Terrano, Kunszt, Nason:

$$\frac{1}{\sigma_0}\frac{d\sigma}{dX} = A(X)\left(\frac{\alpha_s(\mu^2)}{2\pi}\right) + \left(B(X) + A(X)2\pi b_0 \ln\mu^2/s\right)\left(\frac{\alpha_s(\mu^2)}{2\pi}\right)$$

where:

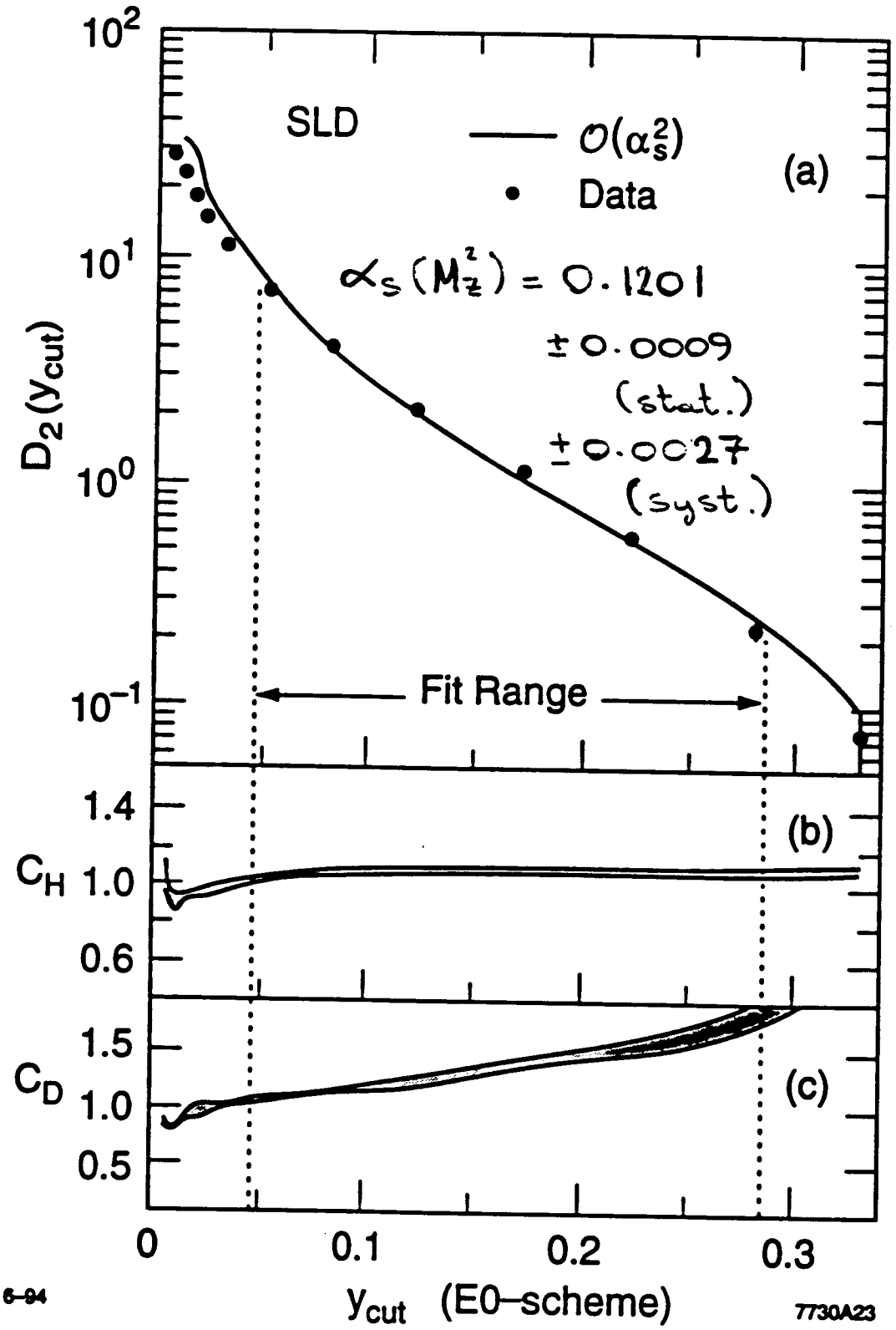
$A(X)$, $B(X)$ are calculated

$b_0 = (33 - 2N_f)/12\pi$

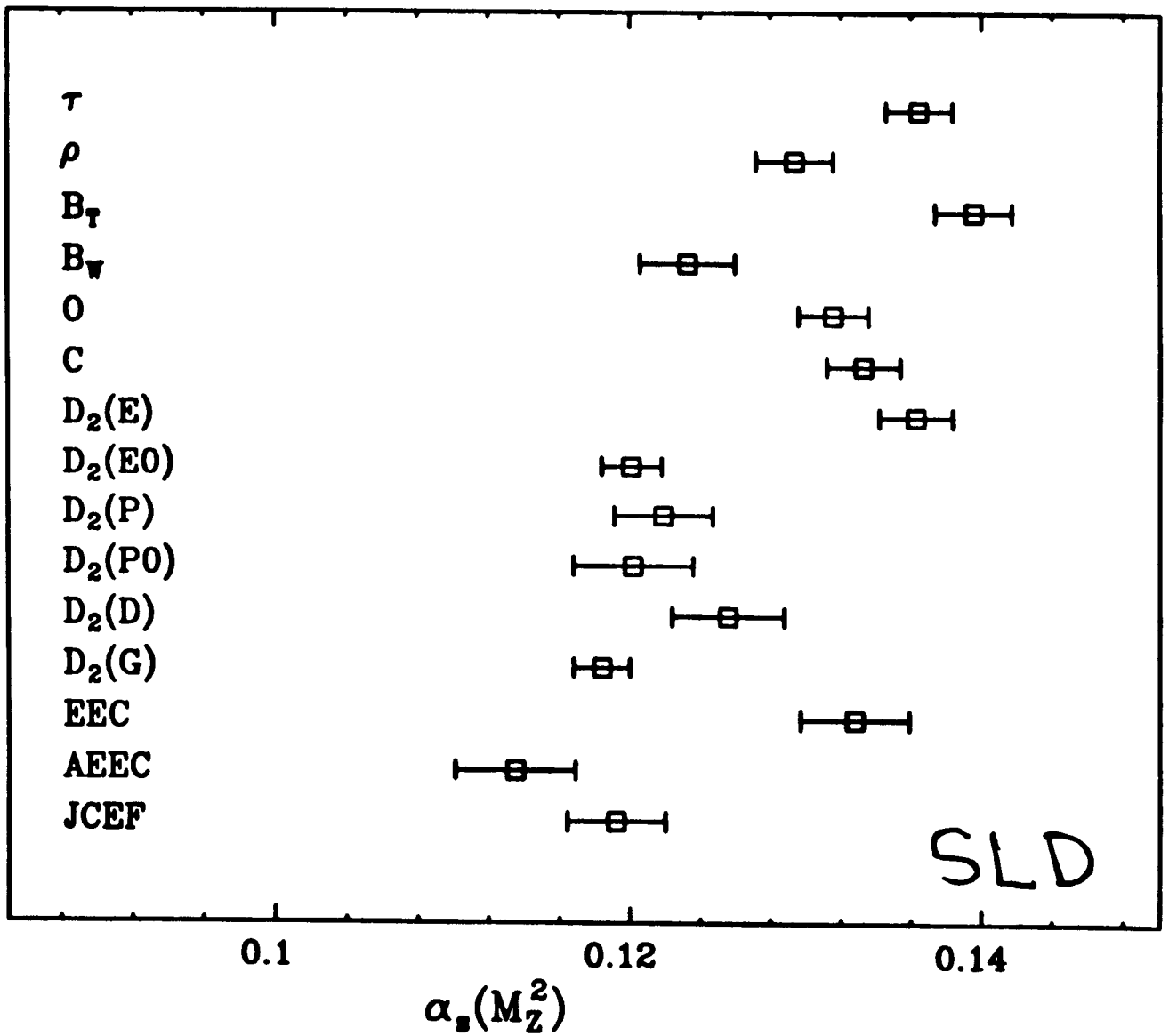
μ is the renormalisation scale:

EVERY FINITE-ORDER PQCD CALCULATION
DEPENDS ON THIS PARAMETER

Eg. Differential 2-jet rate



EXPERIMENTAL ERRORS ONLY $(\mu = \sqrt{s})$



PRD 51 (1995) 962

A Depressing Situation

- 15 HIGHLY-CORRELATED observables
measured using SAME DATA SAMPLE
yield DISCREPANT values of $\alpha_s(M_Z^2)$
with an r.m.s. scatter of ± 0.008

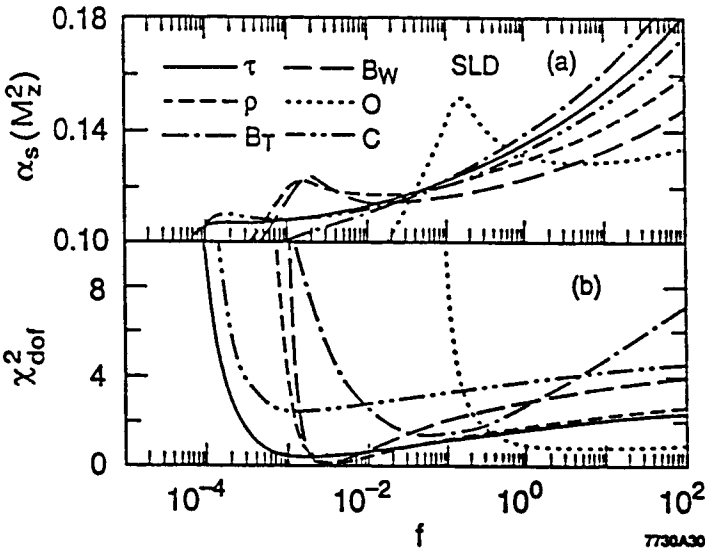
- Escape clause for perturbative QCD:

HIGHER-ORDER contributions must be significant,
must be of DIFFERENT MAGNITUDE,
and possibly of DIFFERENT SIGN,
for DIFFERENT OBSERVABLES.

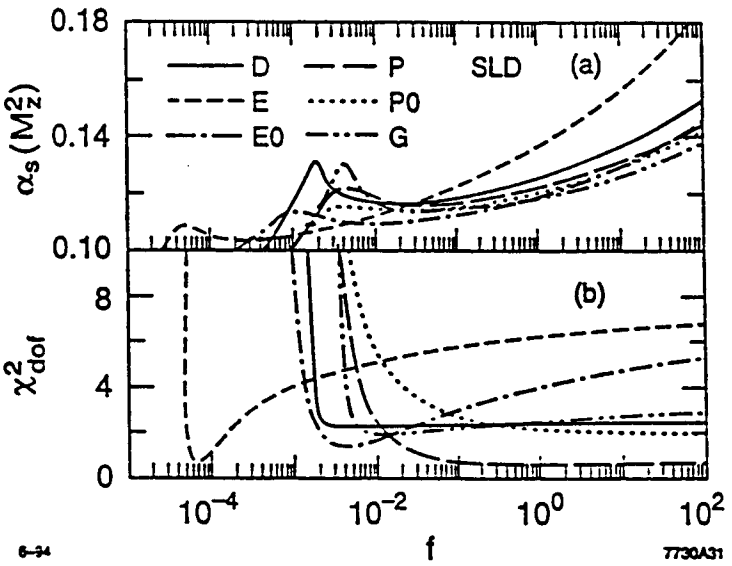
- One hopes that,
if $O(\alpha_s^3)$ contributions are calculated,
CONSISTENT values of $\alpha_s(M_Z^2)$ will be obtained.

- A handle on this problem can perhaps be obtained
from the μ–dependence ...

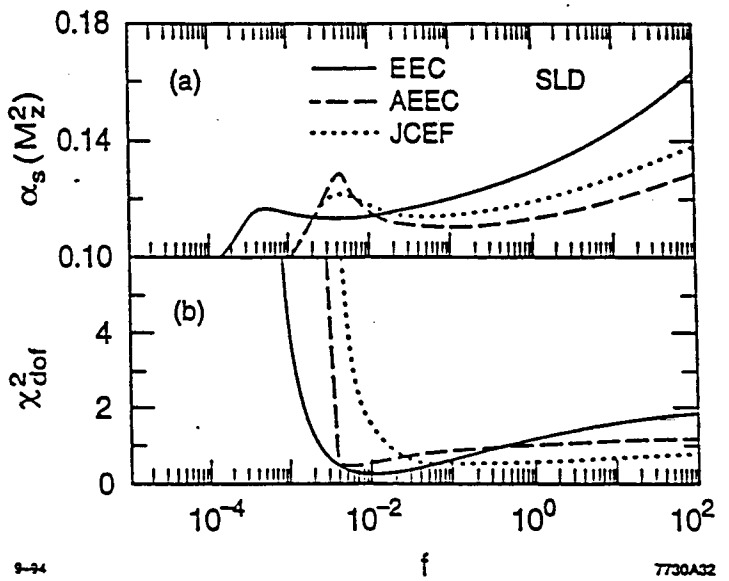
Event shapes

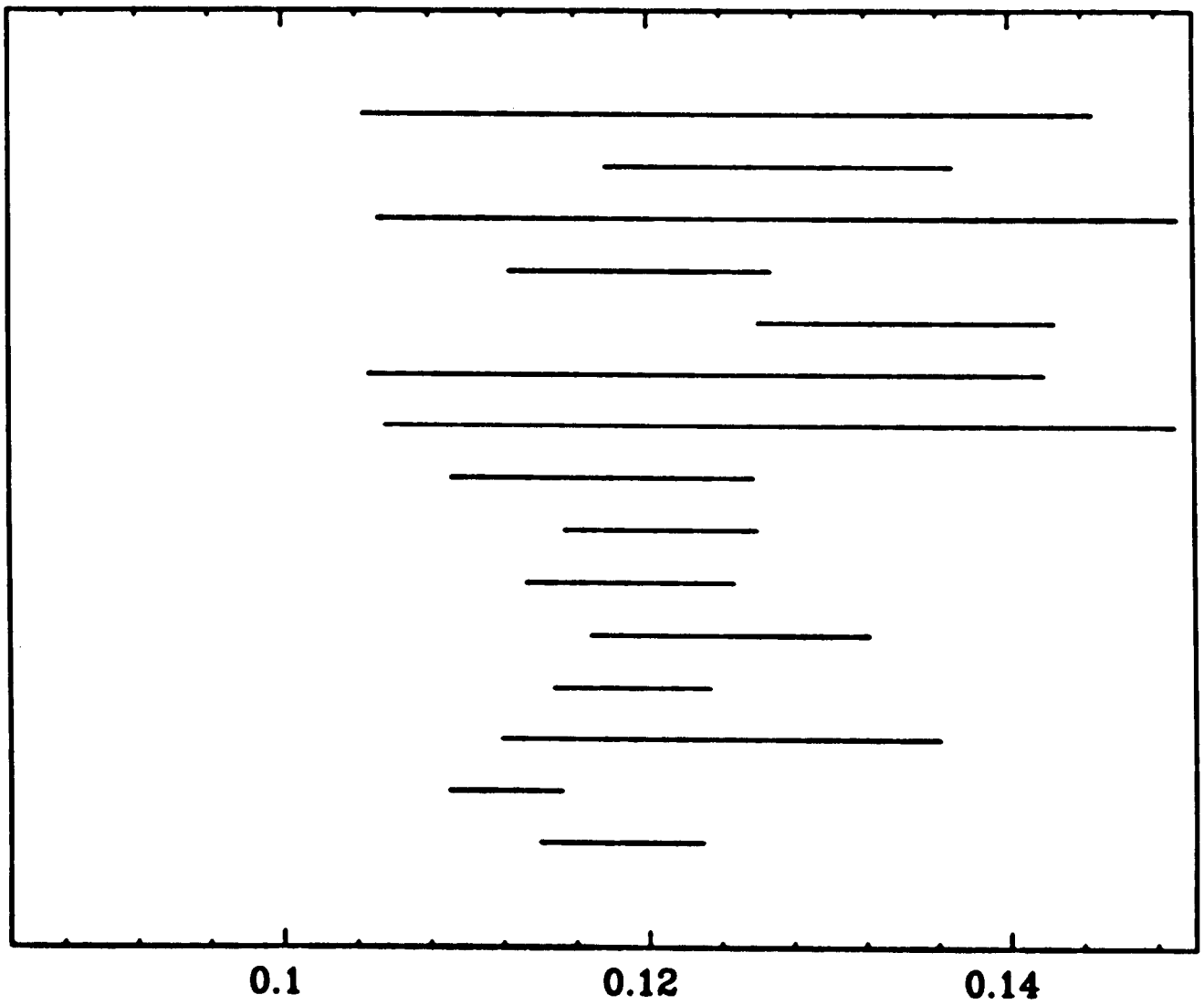


Jet rates



Particle correlations




0.1
0.12
0.14

$\alpha_s(M_Z^2)$ from Hadronic Event Shapes

SLD, LEP, TRISTAN, CLEO:

$$\alpha_s(M_Z^2) = 0.122 \pm 0.007$$

PDG 1996 (Hinchliffe)

Scale Fixing

$$\sigma_x = A\left(\frac{\alpha_s}{2\pi}\right) + B'(\mu)\left(\frac{\alpha_s}{2\pi}\right)^2$$

1. PHYSICAL scale : $\mu = \sqrt{s}$

2. EXP.-OPTIMISED scale : fit μ

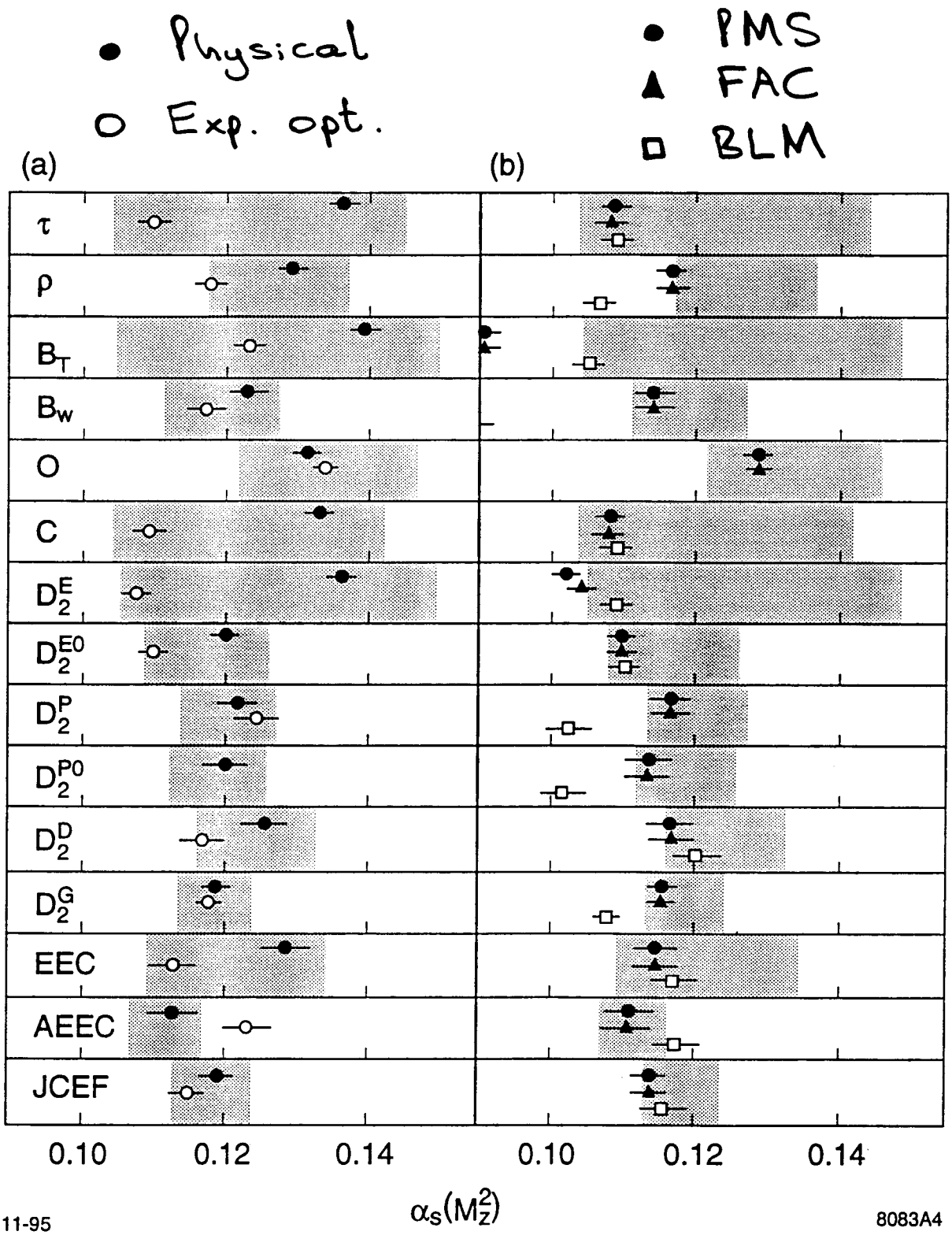
3. PMS scale : $\frac{\partial \sigma_x}{\partial \mu} = 0$

4. FAC scale : $B'(\mu) = 0$

5. BLM scale : $\frac{\partial B'(\mu)}{\partial N_f} = 0$

$\alpha_s(M_Z)$ from scale-fixing

(Burrows, Masuda, Muller, Ohnishi – SLD)



$\alpha_s(M_Z^2)$ Results from Scale-fixing

Method	Central value	R.m.s.
Physical	0.1265	± 0.0076
Exp. opt.	0.1173	± 0.0071
PMS	0.1123	± 0.0079
FAC	0.1123	± 0.0080
BLM	0.1088	± 0.0075

μ - dependence:

can be distracting,

But really

is only a symptom of

NEED FOR HIGHER-ORDER QCD CALCULATIONS!

Use of Padé Approximants

The PA to the series:

$$S = S_0 + S_1 x + S_2 x^2 + \ldots + S_{N+M} x^{N+M}$$

is defined:

$$[N/M] = \frac{a_0 + a_1 x + \ldots + a_N x^N}{1 + b_1 x + \ldots + b_M x^M}$$

Solving:

$$[N/M] = S \Rightarrow \{a_i, b_i\}$$

and S_{N+M+1}

PA have been applied to pert. QCD series to estimate the KNOWN $O(\alpha_s^3)$ terms for:

R, R_τ, Bj SR, GLS SR

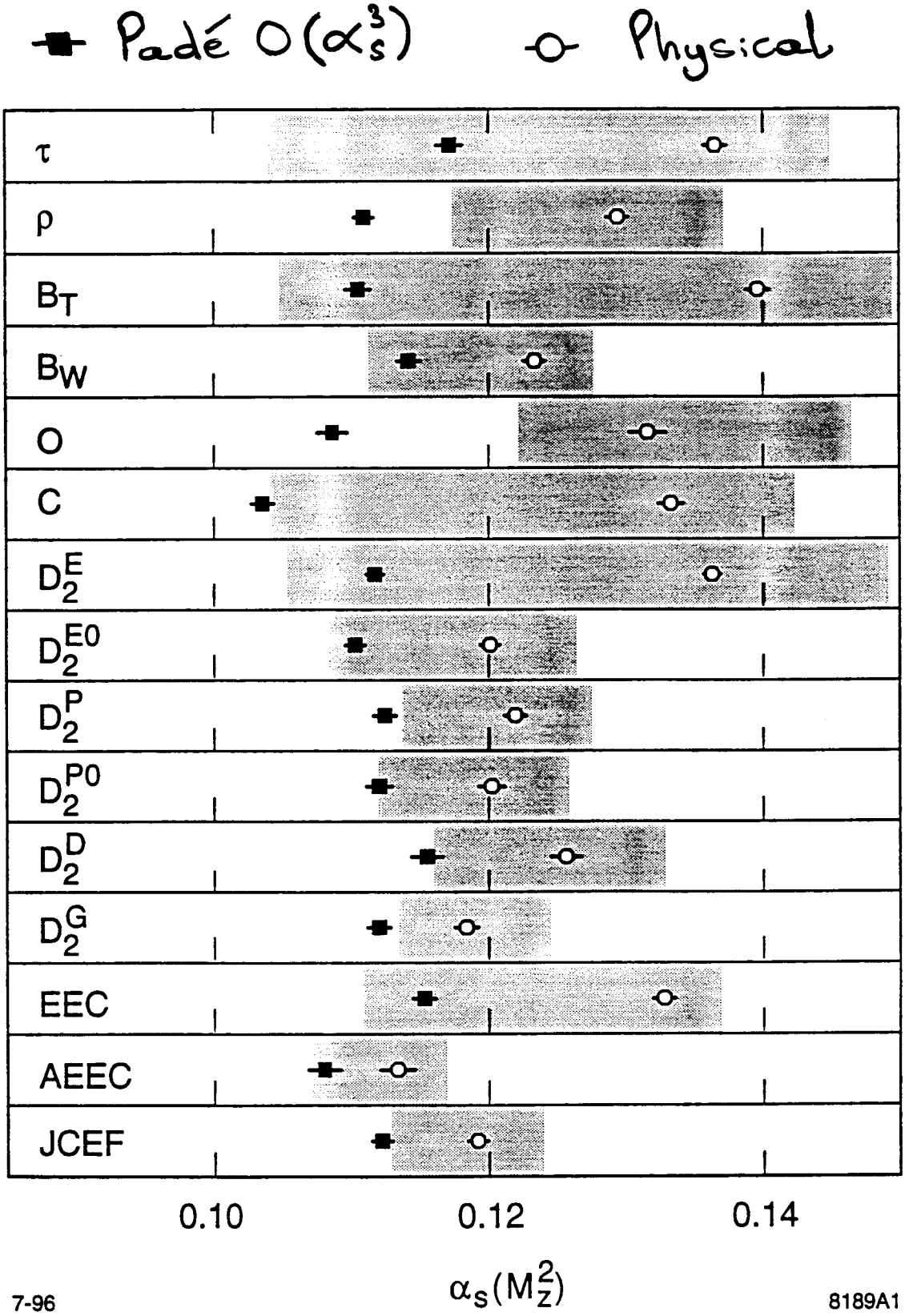
and yield the right answers!

For e^+e^- hadronic observables:

$$\frac{1}{\sigma}\frac{d\sigma}{dx} = A(x)\left(\frac{\alpha_s}{\pi}\right) + B(x)\left(\frac{\alpha_s}{\pi}\right)^2$$

[0/1] PA $\Rightarrow$ $\dfrac{B(x)^2}{A(x)}\left(\dfrac{\alpha_s}{\pi}\right)^3$

(PNB, Abraha, Samuel, Steinfelds, Masud SLAC-PUB-7222)



Burrows et al, SLAC - PUB7222, subm. to PLB

Padé	0·1115	± 0.0035

α_s Measurement @ LEP1.5

$130 < \sqrt{s} < 140$ GeV :

$\langle \sqrt{s} \rangle \sim 133$ GeV

$\mathcal{L} \sim 5.6\ pb^{-1}$ /exp $\sim$ 1600 $q\bar{q}$

Reject ISR evs $\Rightarrow$ 400 evs.

	$\alpha_s(133)$	exp.	theor
ALEPH	0.119	± 0.004	± 0.00
DELPHI	0.120	± 0.006	—
L3	0.107	± 0.005	± 0.00
OPAL	0.110	± 0.005	± 0.00

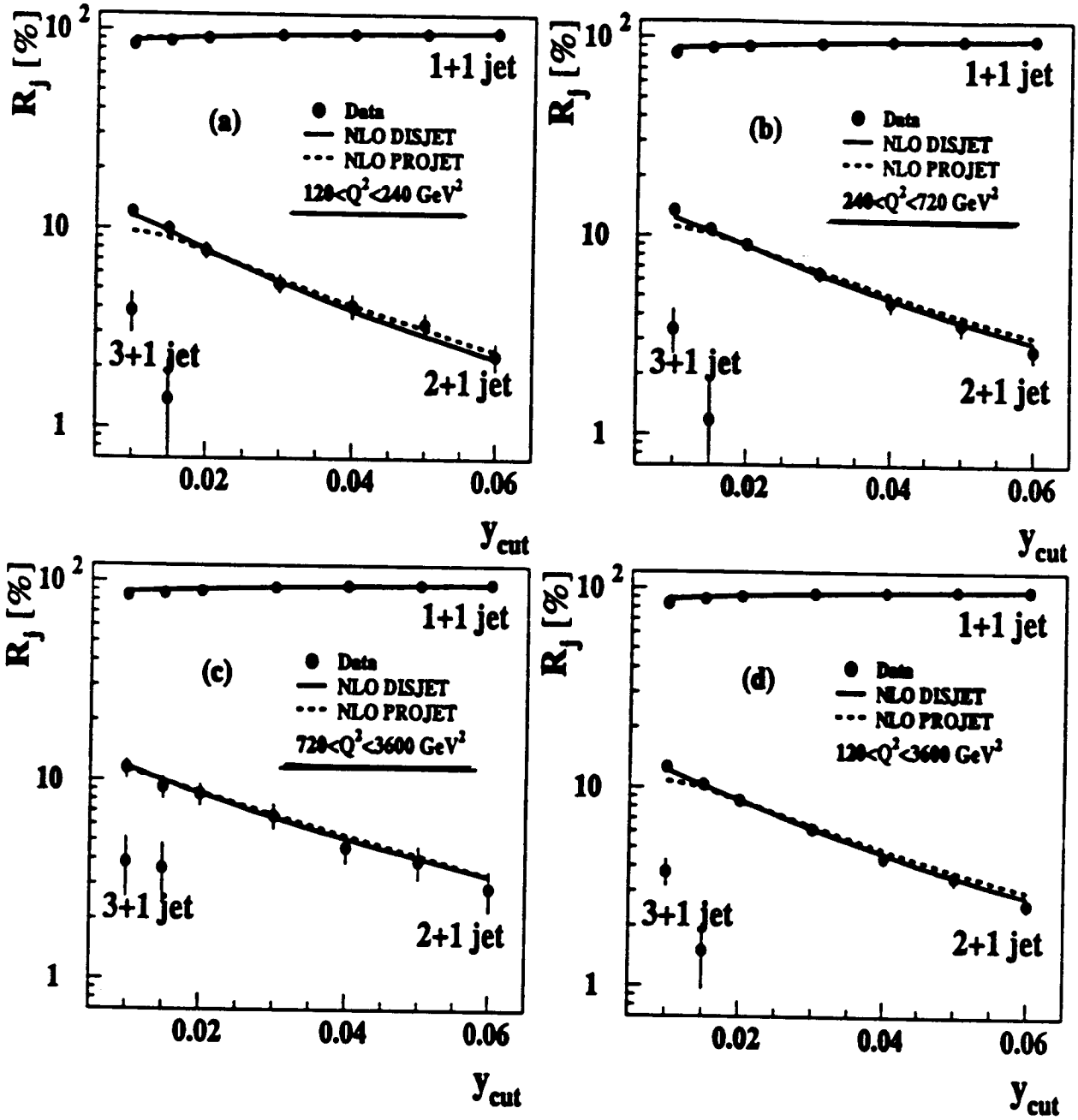
$\Rightarrow$ $\boxed{\alpha_s(M_Z) = 0.121 \pm 0.006 \pm 0.00}$

(unweighted av.)

α_s from Deep-Inelastic Scattering

Experiment	Q^2 (GeV^2)	$\alpha_s(M_Z^2)$	Comments
Bjorken sum rule:			
Ellis-Karliner:	2	$0.122^{+0.005}_{-0.009}$	no $1/Q^2$
		$0.118^{+0.007}_{-0.014}$	$1/Q^2$
		$0.116^{+0.003}_{-0.005} \pm 0.003$	Pade
E143 et al	1-60	$0.119^{+0.007}_{-0.019}$	h. twist?
CCFR: GLS sum rule	1-20	? $0.108^{+0.003}_{-0.005} \pm 0.004^{+0.004}_{-0.006}$?	$1/Q^2$
NMC: F_2	1-50	$0.117^{+0.010}_{-0.015} \pm 0.002$	scale
BCDMS, SLAC: F_2	$5-260$	$0.113 \pm 0.003 \pm 0.004$	
CCFR: F_2, xF_3	15-500	$0.119 \pm 0.004 \pm 0.004$	
HERA: $F_2(x)$	$4-100$	$0.120 \pm 0.005 \pm 0.009$	exp. error?
H1: jet rates	$10-4000$	$0.123 \pm 0.014 \pm 0.011$	scale
ZEUS: jet rates	$120-3600$	$0.117 \pm 0.005^{+0.004}_{-0.005} \pm 0.007$	scale

ZEUS 1994



Jet reconstruction and jet properties at HERA

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[2] Deutsches Elektronen-Synchrotron DESY, Notkestrasse 85, D-2000 Hamburg 52, Federal Republic of Germany

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ZPC 39 (1988) 259

α_s from Hadron Colliders

$\sigma(\mathrm{W} + 1\ \mathrm{jet})/\sigma(\mathrm{W} + 0\ \mathrm{jet})$:

UA1: $\alpha_s(M_Z^2) = 0.127 \pm 0.026\ (\mathrm{stat.})\ \pm 0.034\ (\mathrm{syst.})$

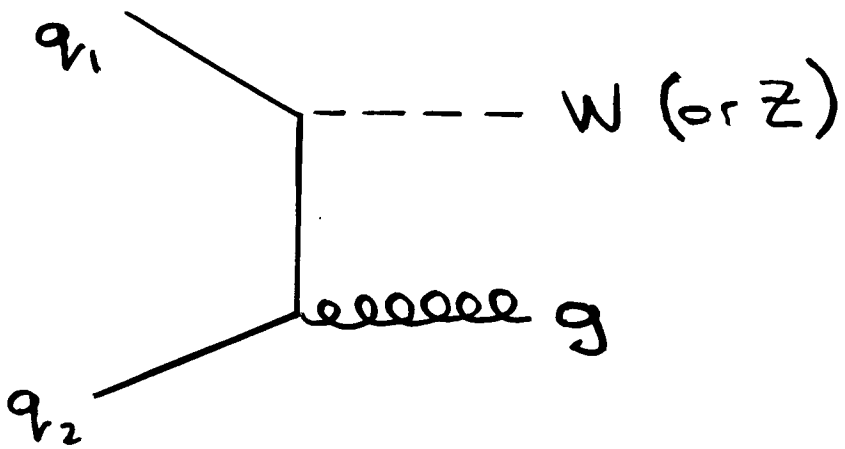
UA2: $\alpha_s(M_Z^2) = 0.121 \pm 0.018\ (\mathrm{stat.})\ \pm 0.017\ (\mathrm{syst.})\ \pm 0.01?\ (\mathrm{scale})$

$\sigma(\mathrm{p\bar{p}} \to \gamma \mathrm{X}) - \sigma(\mathrm{pp} \to \gamma \mathrm{X})$
$\Rightarrow \sigma(\mathrm{q\bar{q}} \to \mathrm{g}\gamma)$

UA6: $\alpha_s(M_Z^2) = 0.112 \pm 0.006\ (\mathrm{stat.})\ \pm 0.005\ (\mathrm{syst.})\ {}^{+0.009}_{-0.001}\ (\mathrm{theor.})$

$(p_T \sim 5\ \mathrm{GeV})$

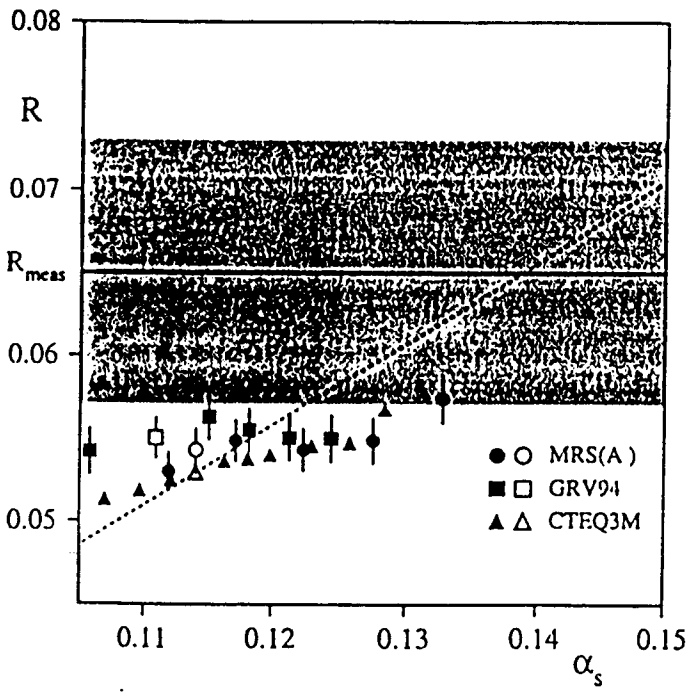
(W + 1-jet)/(W+0-jet) Ratio



NLO calc:
Giele, Glover
Kosower
(NPB403 63

$$\mathcal{R} = \frac{\alpha_s (A_1 + \alpha_s B_1)}{A_0 + \alpha_s B_0}$$

$A_i, B_i \longleftarrow$ PDF $\longleftarrow \alpha_s$!



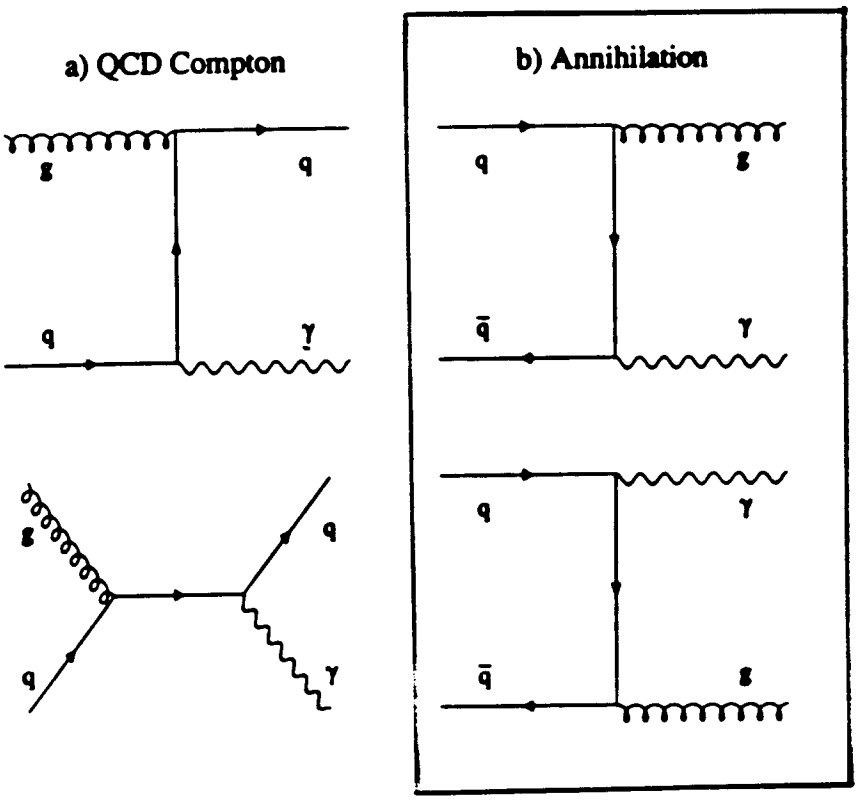
DØ: PRL75 3226

"an extraction of α_s is not possible."

UA6 : H_2 gas jet @ $\sqrt{s}$

Compare : $\left.\begin{matrix}\sigma(p\bar{p} \to \gamma X) \\ \sigma(pp \to \gamma X)\end{matrix}\right\} \sigma(q\bar{q} \to \gamma X)$

Lowest order diagrams for direct γ production



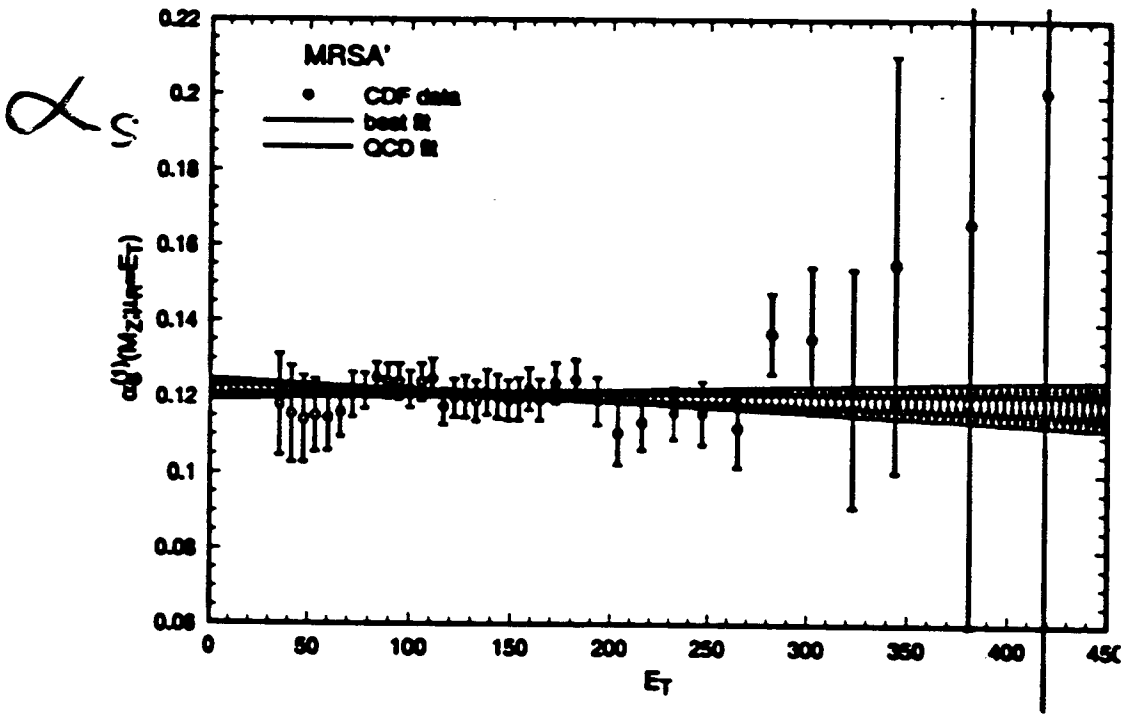
NLO calc. by Aurenche et al (NPB 297 661)

$\Rightarrow \alpha_s(M_Z) = 0.112 \pm 0.006 \pm 0.005 \,{}^{+0.009}_{-0.001}$

stat. syst. theor.

Single - jet E_T distn.

demonstration of principle (Giele, Glover, Yu)



Fit to 88-89 CDF data:

MRSA' PDF, $\mu = E_T$:

$$\alpha_s(M_Z) = 0.121 \pm 0.001 \pm 0.008 \pm 0.005$$

stat. syst.

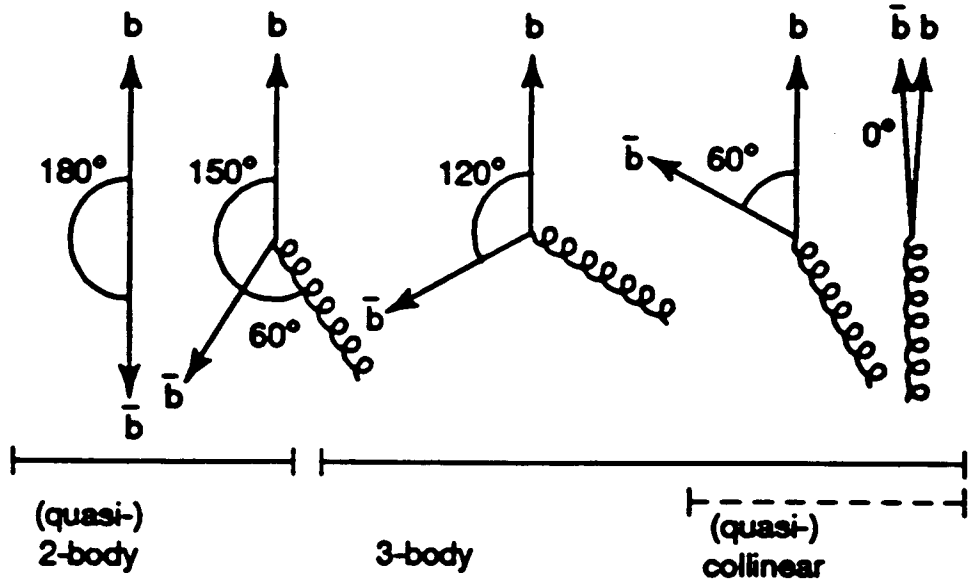
$$\frac{E_T}{2} < \mu < 2E$$

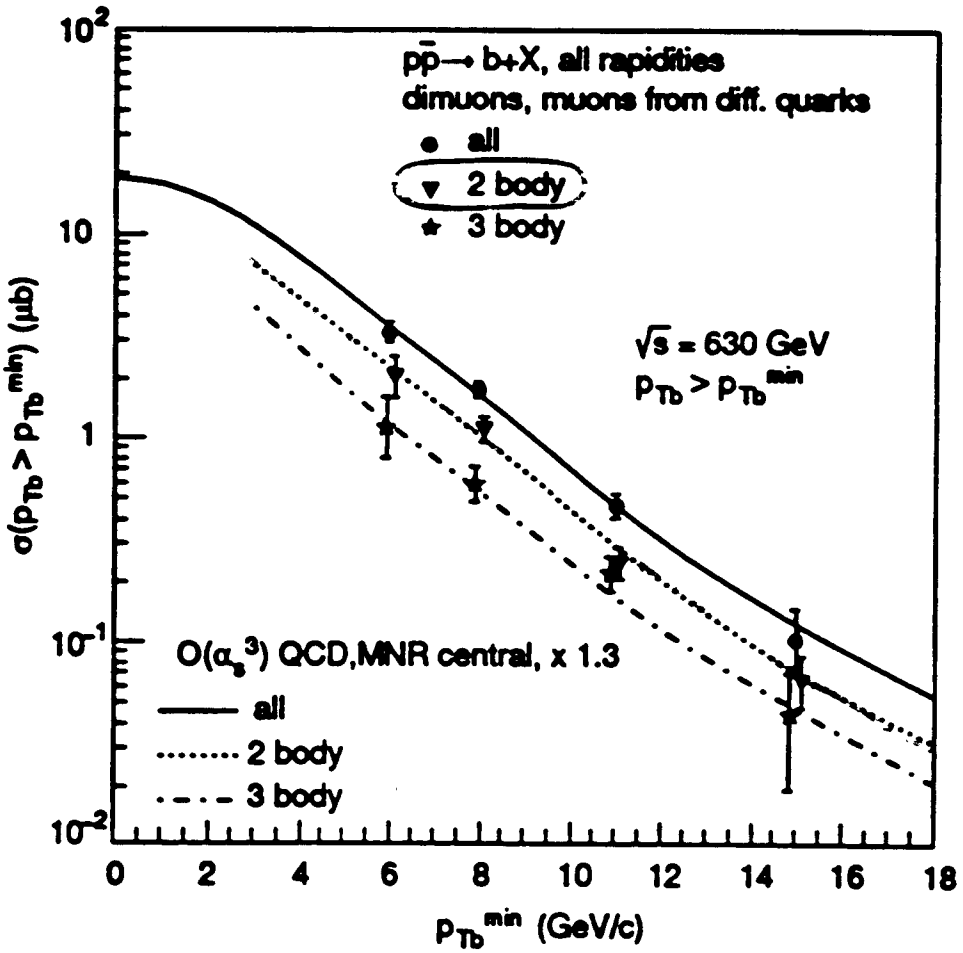
c.f. $e^+e^- \longrightarrow 0.03\sqrt{s} < \mu < 2\sqrt{s}$

UA1. $b\bar{b}$ correlations, CERN/95-158

2-body final state $\equiv \Delta\phi(b\bar{b}) > 150°$

3-body final state $\equiv \Delta\phi(b\bar{b}) < 150°$.



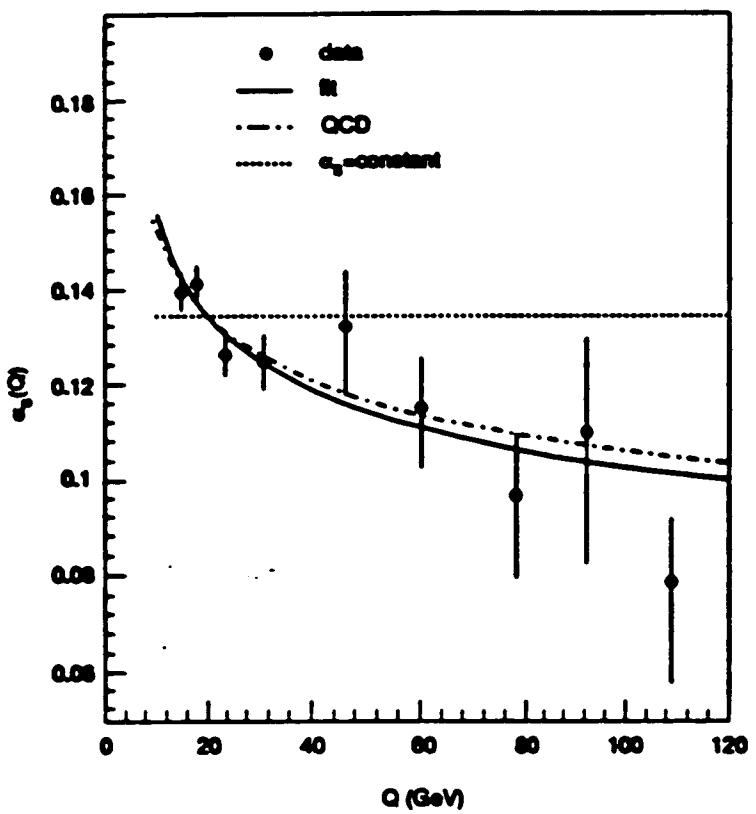


$$\alpha_s(M_Z) = 0.113 \,^{+0.007}_{-0.006}\,(\text{exp.}) \,^{+0.008}_{-0.009}\,(\text{theor.})$$

PDF

$\frac{Q}{4} < \mu < Q$

$\alpha_s(Q)$



$$Q = 0.5\sqrt{m_b^2 + p_{Tb}^{min}}$$

Running of α_s at 3σ level

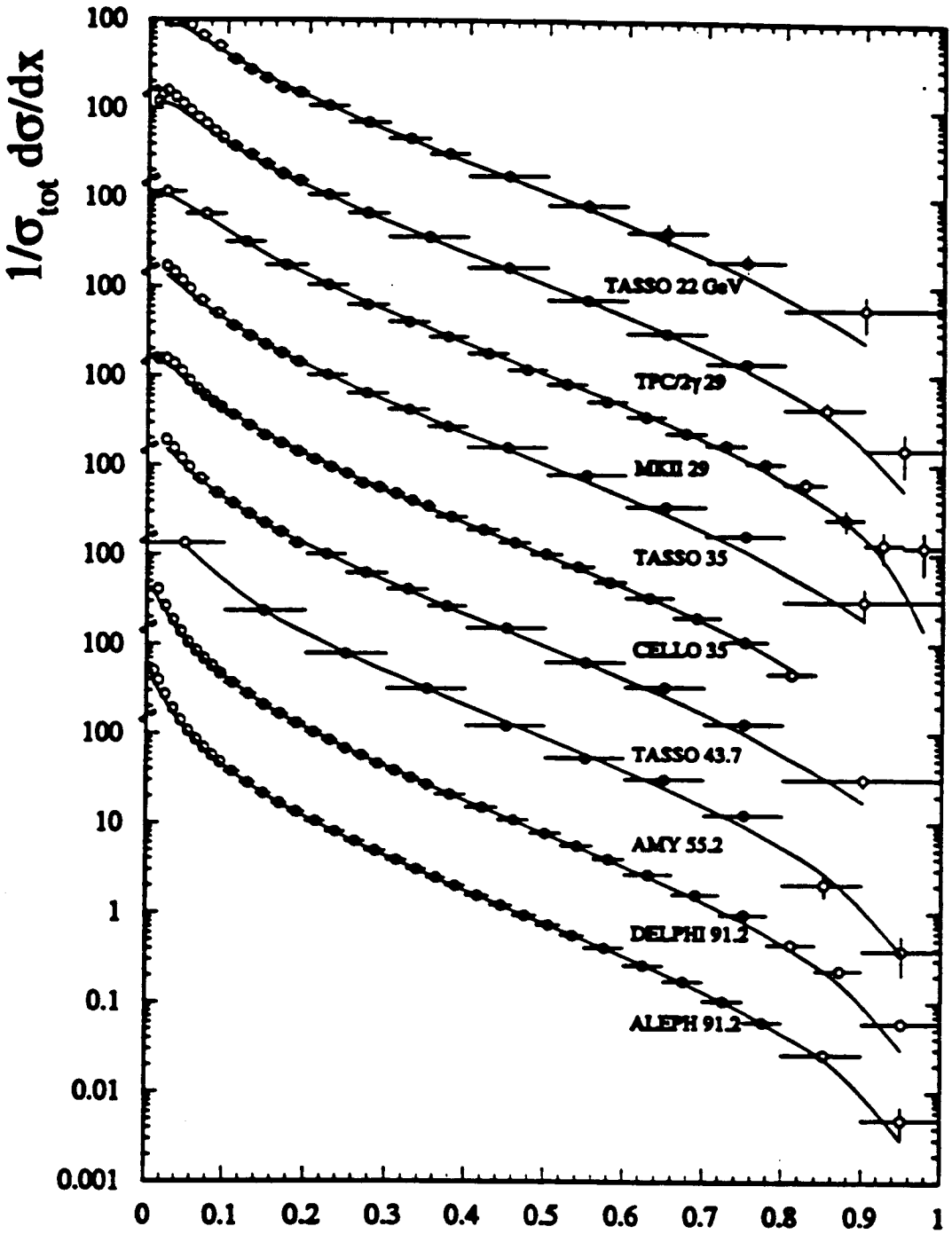
α_s from Lattice Gauge Theory

Method	Group	$\alpha_s(M_Z^2)$	Comments
J/Ψ spectra	El-Khadra *et al.*	0.105 ± 0.004	Quenched approx.
Υ spectra	Davies *et al.*	0.115 ± 0.002	$N_f = 2 \rightarrow 3$; m_q fixed No 2-loop matching
ρ mass, J/Ψ	Aoki *et al.*	0.108 ± 0.008	$N_f = 2$
Review	Michael	0.112 ± 0.007	
PRELIMINARY:			
Υ spectra	NRQCD	0.118 ± 0.003	m_q dependence 2-loop ($N_f = 0$)
J/Ψ	FNAL/SCRI	0.116 ± 0.003	

Other Measurements of α_s

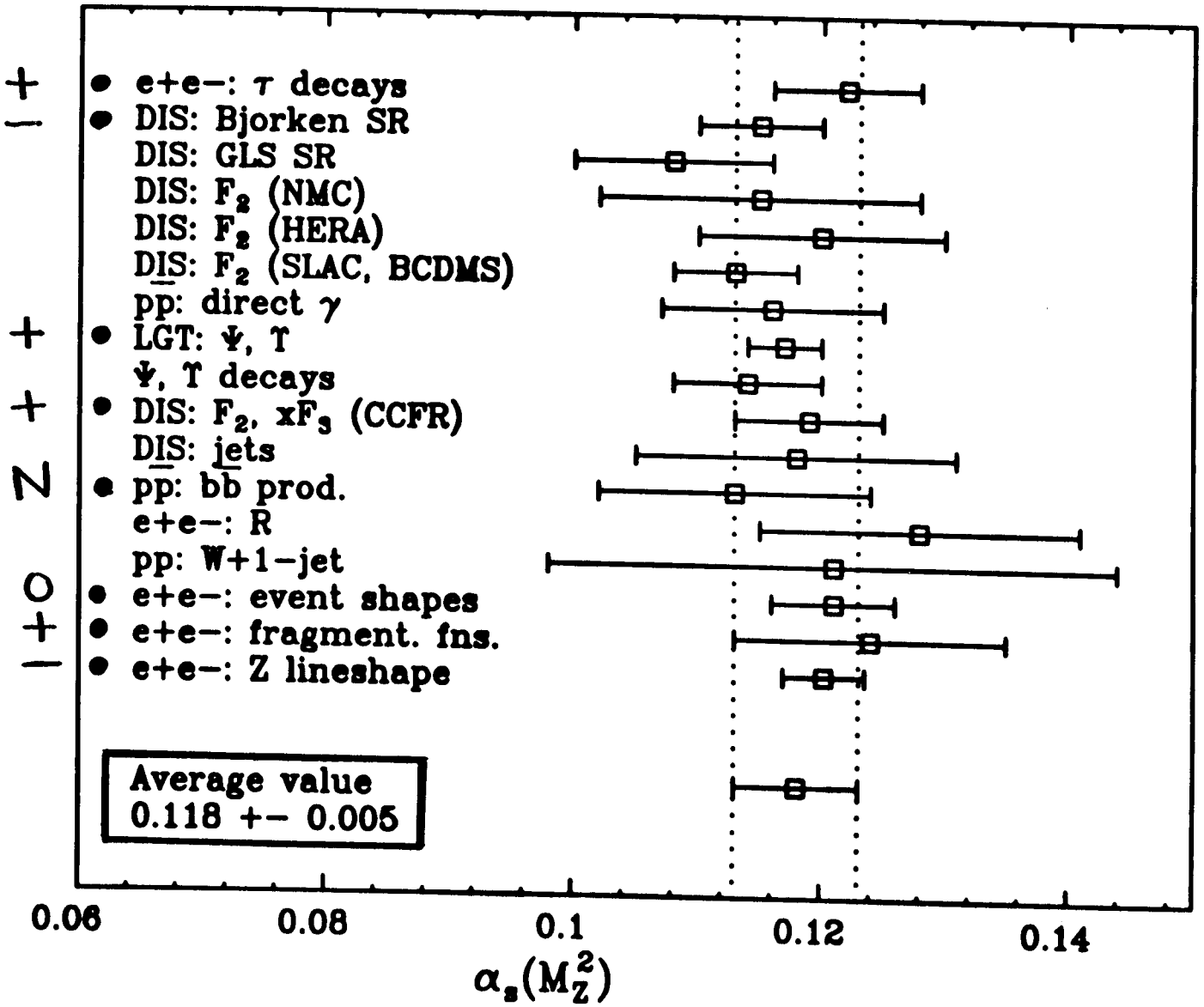
Experiment	Q (GeV)	$\alpha_s(M_Z^2)$	Comments
ALEPH, CLEO, DELPHI: τ decays	1.8	$0.122 \pm 0.001 \pm 0.006$	theory?
J/Ψ, Υ decays	10	$0.113 \pm 0.001^{+0.007}_{-0.005}$	v^2/c^2, Λ^2/m unpublished
CLEO: $\Gamma(\Upsilon \to \gamma gg)/\Gamma(\Upsilon \to ggg)$	11	$0.110 \pm 0.004 \pm 0.005$	prelim.
e^+e^- scaling viol.	22-91	$0.124 \pm 0.005 \pm 0.010$	

Scaling violations in e^+e^- fragmentation functions



ALEPH : CERN 95-096 (PLB)

SUMMARY OF MEASUREMENTS August 1996



$\chi^2 = 6.4 / 17$ meas.

Method	Q (GeV)	$\alpha_s(M_Z^2)$	exp.	theor.
e^+e^-: τ decays	1.8	0.122	0.001	0.006
DIS: Bjorken SR	1 - 4	0.116	$^{+0.003}_{-0.005}$	0.003
DIS: GLS SR	1 - 5	0.108	$^{+0.005}_{-0.006}$	$^{+0.004}_{-0.006}$
DIS: F_2 (NMC)	1 - 7	0.117	$^{+0.010}_{-0.015}$	0.002
DIS: F_2 (HERA)	1 - 10	0.120	0.005	0.009
DIS: F_2 (SLAC, BCDMS)	2 - 16	0.113	0.003	0.004
pp, $p\bar{p}$: direct γ	4 - 6	0.113	0.008	$^{+0.009}_{-0.001}$
LGT: J/Ψ, Υ	3 - 11	0.117	–	0.003
J/Ψ, Υ decays	3 - 11	0.113	0.001	$^{+0.007}_{-0.005}$
DIS: F_2, xF_3 (CCFR)	3 - 23	0.119	0.004	0.004
DIS: jets	10 - 63	0.118	0.006	0.011
$p\bar{p}$: $b\bar{b}$ prod.	20	0.113	$^{+0.007}_{-0.006}$	$^{+0.008}_{-0.009}$
e^+e^-: R	5 - 65	0.128	$^{+0.012}_{-0.013}$	0.002
$p\bar{p}$: W+1-jet	80	0.121	0.018	0.015
e^+e^-: event shapes	10 - 133	0.121	0.002	0.005
e^+e^-: fragmentn. fns.	14 - 91	0.124	0.005	0.010
e^+e^-: Z^0 lineshape	91	0.1202	0.0033	< 0.001

Table 1: Average $\alpha_s(M_Z^2)$ values and errors from the 17 methods described in the text. The approximate range in Q is shown for each method.

PNB SLAC-PUB-7293

Conclusions

- "Convergence" of α_s past 2 years
- No evidence for discrepancies

$$\Rightarrow \quad \alpha_s(M_Z)^2 = 0.118 \pm 0.005$$

- "Best" results: $\Delta\alpha_s \sim \pm 0.003$
- THEORETICAL uncerts. large
- Aim for $\Delta\alpha_s(M_Z^2) \sim \pm 0.001$

Potential for 1%-Level Measurements of $\alpha_s(M_Z^2)$

- **Theoretical:**

  Better calculations!

  Higher-orders, AND non-perturbative

  Eg. e^+e^- event shapes at $O(\alpha_s^3)$

  LGT potentially very precise

- **Experimental:**

  TeVatron: α_s study under way

  B Factories: R CLEO $\Rightarrow \Delta\alpha_s(M_Z^2) \sim \pm 0.01$?

  e^+e^-(500 GeV) no problem if have $O(\alpha_s^3)$