

A DECADE OF 3-JET EVENTS

Philip Burrows

University of Oxford

SLD Collaboration Meeting

October 5 2001

- α_s
- **Flavour independence of α_s**
- **Gluon distributions**
- **Symmetry Tests**

SLD QCD Theses

			SLAC Rept.
Jan Lauber	Colorado	α_s from Jet Rates	413
Cheng-Gang Fan	Colorado	Gluon Spin	424
Saul Gonzalez	MIT	α_s from KAL Jet Rates	439
Hyun Hwang	Oregon	Gluon Spin	453
Mike Hildreth	Stanford	Flavor-independence of α_s	458
Yoji Hasegawa	Tohoku	Jet Handedness	459
Yoshi Iwasaki	Tohoku	Quark vs. Gluon Jets	460
Yukiyoshi Ohnishi	Nagoya	α_s from Event Shapes	461
Hyejoo Kang	Sogang	Rapidity Gaps	
Ken Baird	Rutgers	K^0 and Λ^0 Production	483
Tom Pavel	Stanford	Charged $\pi/K/p$ Production	491
Eric Church	Washington	B-Hadron Fragmentation	495
Jingchen Zhou	Oregon	Multiplicity Moments	496
Shinya Narita	Tohoku	Strangeness Correl. and A_s	520
Mihai Dima	Colorado St.	K^{*0} and ϕ Production	505
Paul Dervan	Brunel	$b\bar{b}g$ Events	523
Noritsugu Oishi	Nagoya	Flavor-Independence of α_s	545
Danning Dong	MIT	b Fragmentation	550
Hermann Staengle	Colorado St.	A_s	549
Vincenzo Lia	MIT	Λ^0 Polarization	

In Preparation

Hyejoo Kang	Rutgers	Hadron Prod, q vs. g Jets	
Gavin Nesom	Oxford	$B\bar{B}$ Energy Correlations	

SLD QCD PAPERS

Meas. of α_s from Jet Rates at the Z^0	PRL 71 2528
Meas. of Charged Multiplicity of $Z^0 \rightarrow b\bar{b}$ Events	PRL 72 3145
α_s from Energy-Energy Correlations at the Z^0	PRD 50 5586
α_s from Hadronic Event Observables at the Z^0	PRD 51 962
Search for Jet Handedness in Hadronic Z^0 Decays	PRL 74 1512
Comp. of New Calc. of Energy Correls. w. Z^0 Data	PRD 52 4240
Test of the Flavor-Independence of Strong Interactions	PRD 53 2271
Meas. of T-odd Correl. between Z^0 Spin and 3-jet Plane	PRL 75 4173
Factorial and Cumulant Moments at the Z^0 Resonance	PLB 371 149
First Study of Rapidity Gaps in e^+e^- Annihilation	PRL 76 4886
Orientation and Energy Partition of 3-Jet Events	PRD 55 2533
Charged Multiplicities in b, c and Light Quark Events	PLB 386 475
Leading Particle Effects in Light Flavor Z^0 Decays	PRL 78 3442
Meas. of B Hadron Energy Distribution in Z^0 Decays	PRD 56 5310
Improved Test of Flavour Indep. of Strong Interactions	PRD 59 012002
Production of π^+ , K^+ , K^0 , K^{*0} , ϕ , p, and Λ^0	PRD 59 052001
Structure of $b\bar{b}g$ events and Anom. Chromo. Coupling	PRD 60 092002
Precis Meas. of b-quark Fragmentation Function	PRL 84 4300
Parity-violating Coupling of Z^0 to s-quark	PRL 85 5059
First Symmetry Tests in Polarized $Z^0 \rightarrow b\bar{b}g$	PRL 86 962
Improved Meas. of $g \rightarrow b\bar{b}$ Probability	PLB 507 61
b-quark fragmentation function	to be subm PRD

Our Theory of Strong Interactions - QCD

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^a F^{\mu\nu a} + \bar{q}(i\gamma_\mu D^\mu - m)q$$

$$F_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + g_s f_{abc} A_\mu^b A_\nu^c$$

$$D_{ij}^\mu = \delta_{ij}\partial_\mu - \frac{i}{2}g_s \sum_a \lambda_{ij}^a A_\mu^a$$

where:

g_s is the strong coupling

A_μ^a are the Yang-Mills gluon fields

f_{abc} are the structure constants of $SU(3)_c$

Measurement Precision on Fundamental Couplings

(1996 PDG values)

Constant	Value	Error (PPM)
$\alpha_{EM} = e^2/4\pi\epsilon_0\hbar c$	1/137.035 989 5 (61)	0.045
$G_F/(\hbar c)^3$	$1.166\ 39\ (2) \times 10^{-5}\ \text{GeV}^{-2}$	20
G_N	$6.672\ 59\ (85) \times 10^{-11}\ \text{m}^3\text{kg}^{-1}\text{s}^{-2}$	128
$\alpha_s(M_Z^2)$	0.118 (3)	25,000

$\Rightarrow \alpha_s(M_Z^2)$ is relatively poorly measured!

Dependence of α_s on Q^2

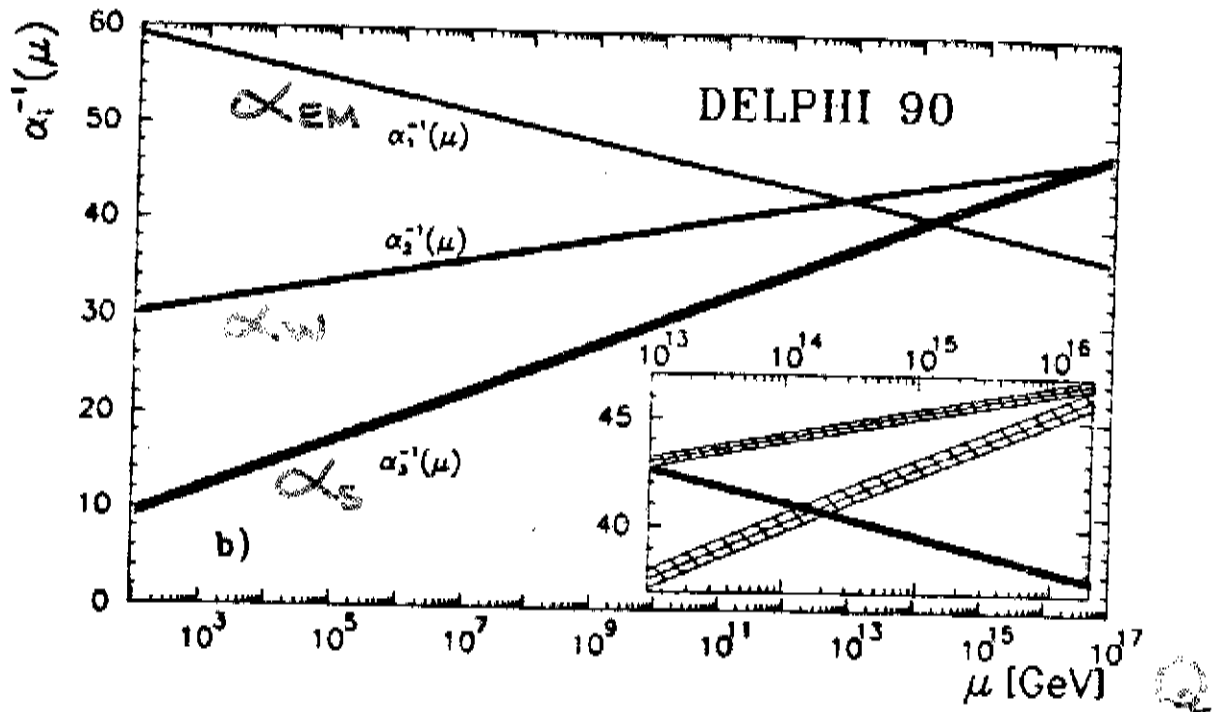
$$\alpha_s(Q^2) = \frac{4\pi}{\beta_0 \ln(Q^2/\Lambda_{MS}^2)} \left\{ 1 - \frac{2\beta_1}{\beta_0^2} \frac{\ln(\ln(Q^2/\Lambda_{MS}^2))}{\ln(Q^2/\Lambda_{MS}^2)} + \dots \right\}$$

Convention: $Q = M_Z$

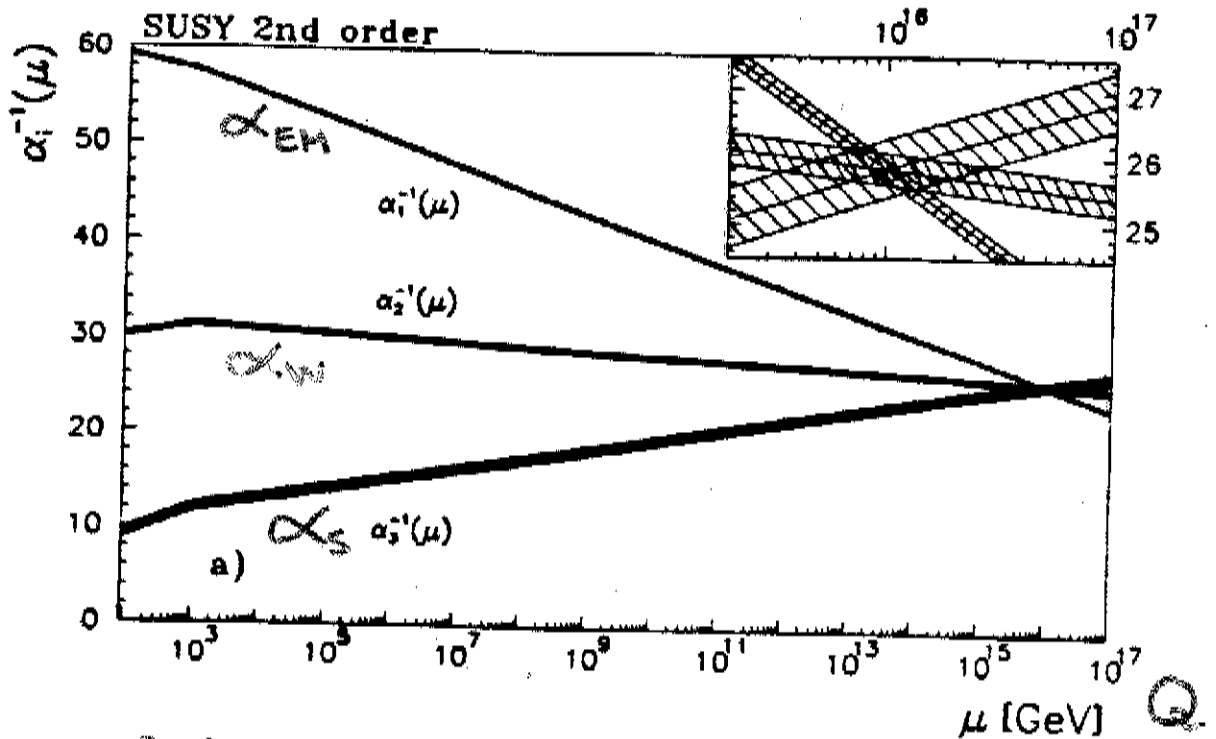
$\alpha_s(M_Z^2)$ is the $\sin^2\theta_W$ of strong interactions

Grand Unification of Fundamental Couplings?

Amaldi
de Boer
Fürstenau
PLB 260
p. 447



Throw in some new dynamics, eg. SUSY:



$$\Rightarrow M_{\text{SUSY}} = 10^{3 \pm 1} \text{ GeV}, \quad M_{\text{GUT}} = 10^{16.0 \pm 0.3} \text{ GeV}$$

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

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

M. SHEPMAN

Theoretical Physics Institute, University of Minnesota, Minneapolis, MN 55455, USA

Received 11 January 1995

SLAC LIBRARY

P = IC-95-133

Name

MS

A low α_s : hinting new physics at GUT scale?

① Mar Bastero-Gil^a and ② 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

Biswajoy Brahmachari¹

LIBRARY

Lowering α_s by flipping SU(5)

John Ellis,¹ Jorge L. Lopez,² and D.V. Nanopoulos^{3,4}

SLAC

OCT 13 1995

LIBRARY

KAIST-CHEP-95/14

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

Jae Kwan Kim, Yeong Gyun Kim*, Jae Sik Lee† and Kang Young Lee‡

Department of Physics, KAIST, Taejeon 305-701, KOREA

(September 19, 1995)

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

1. Raise low- Q^2 measurements:

Eg. light gluinos: $m_g \sim \text{few GeV}$

\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 $\sim 2.5\%$

$\alpha_s(M_Z^2) \Rightarrow$

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

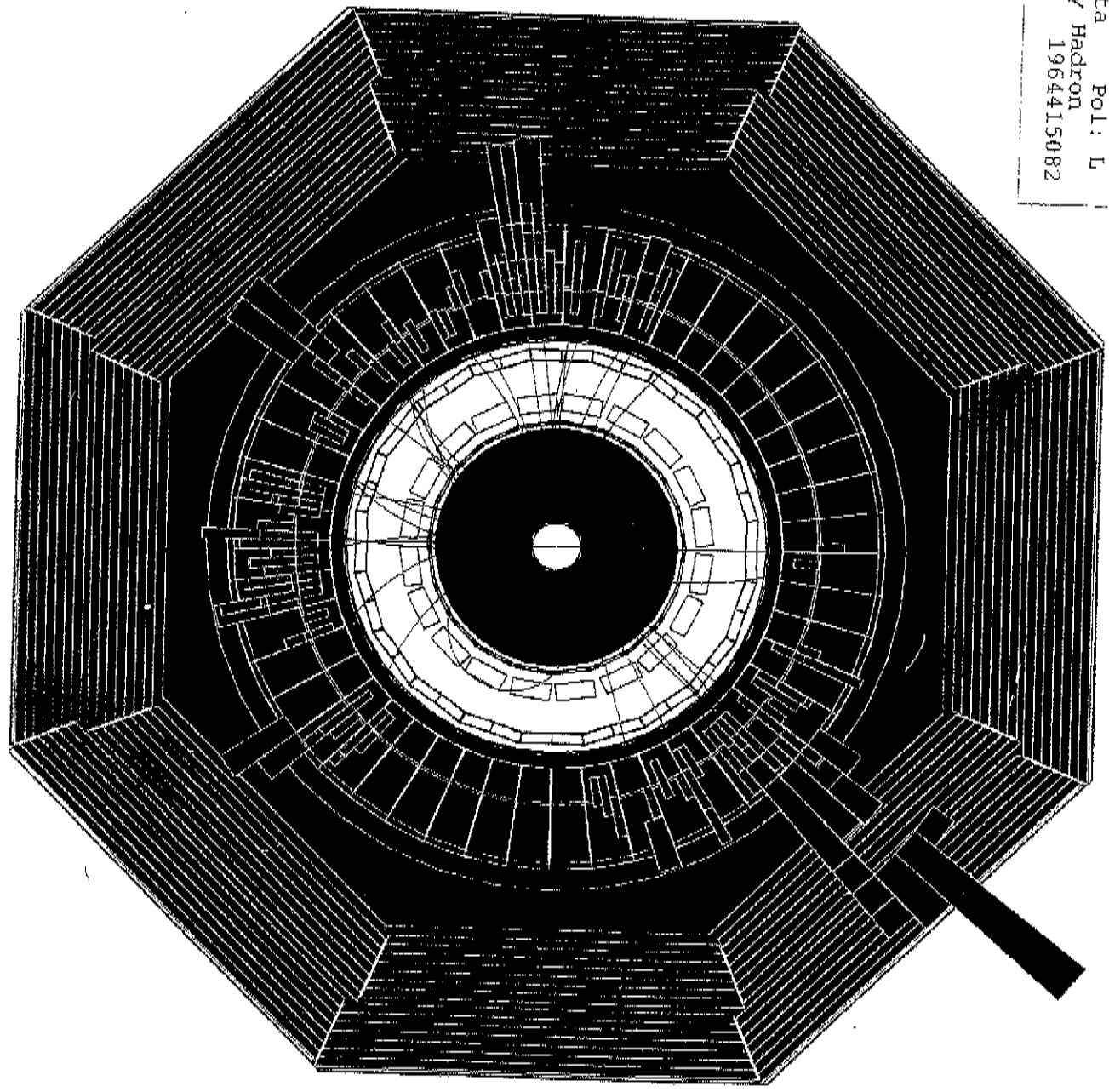
$$\Delta R_b (+1\%) \equiv \Delta\alpha_s(-0.006)$$

SLD α_s Subgroup

P.N.B
J. Lauber*
H. Masuda
D. Muller
Y. Ohnishi*

Jet Rates	Phys. Rev. Lett. 71 (1993) 2528
Energy-Energy Correlations	Phys. Rev. D50 (1994) 5580
Energy-Energy Correlations 2	Phys. Rev. D52 (1995) 4240
Hadronic Event Shapes	Phys. Rev. D51 (1995) 962

Run 12637, EVENT 6353
8-JUL-1992 10:14
Source: Run Data POL: L
Trigger: Energy Hadron
Beam Crossing 1964415082



Z → 5 jets

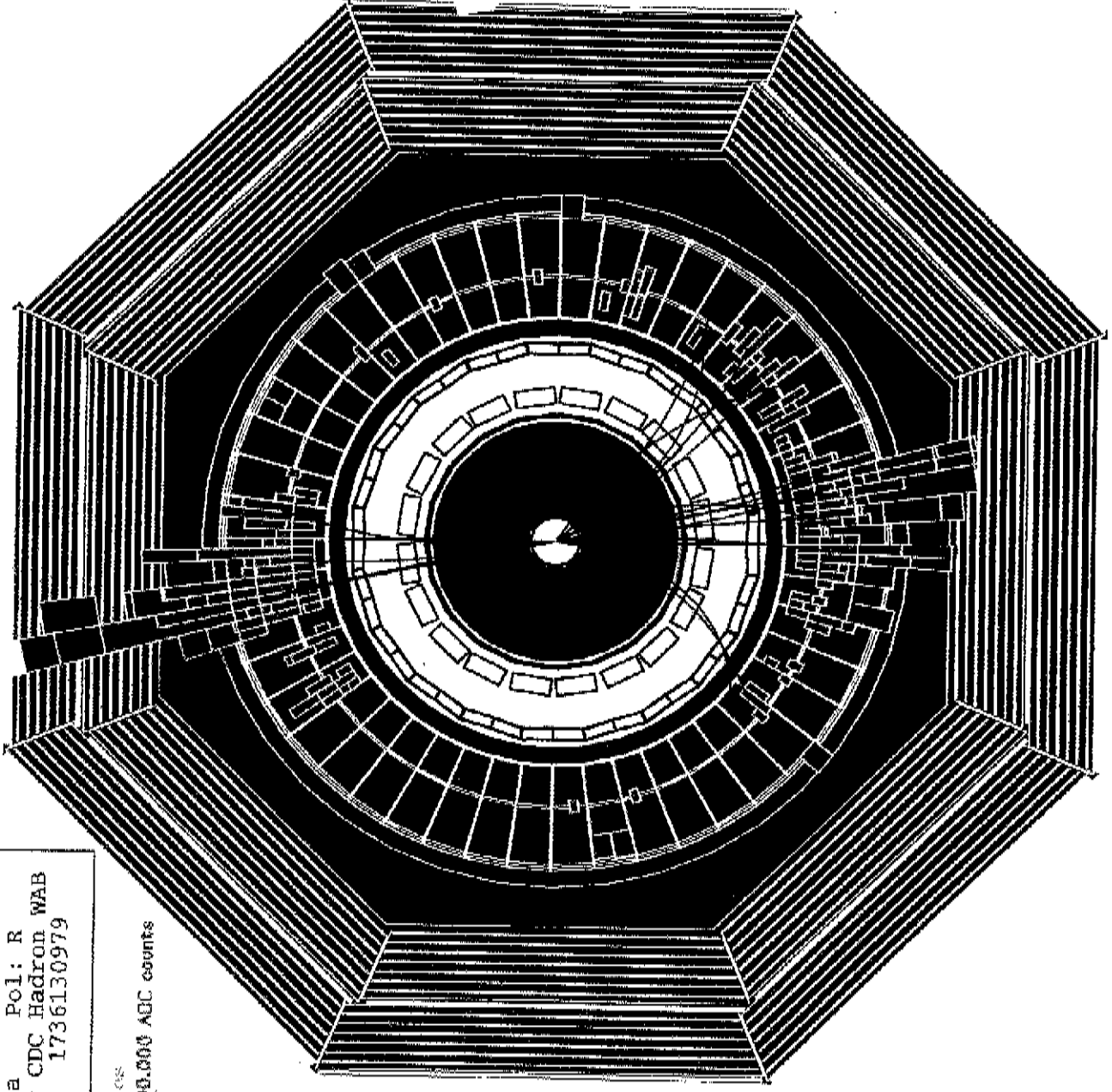
24

How many jets?!

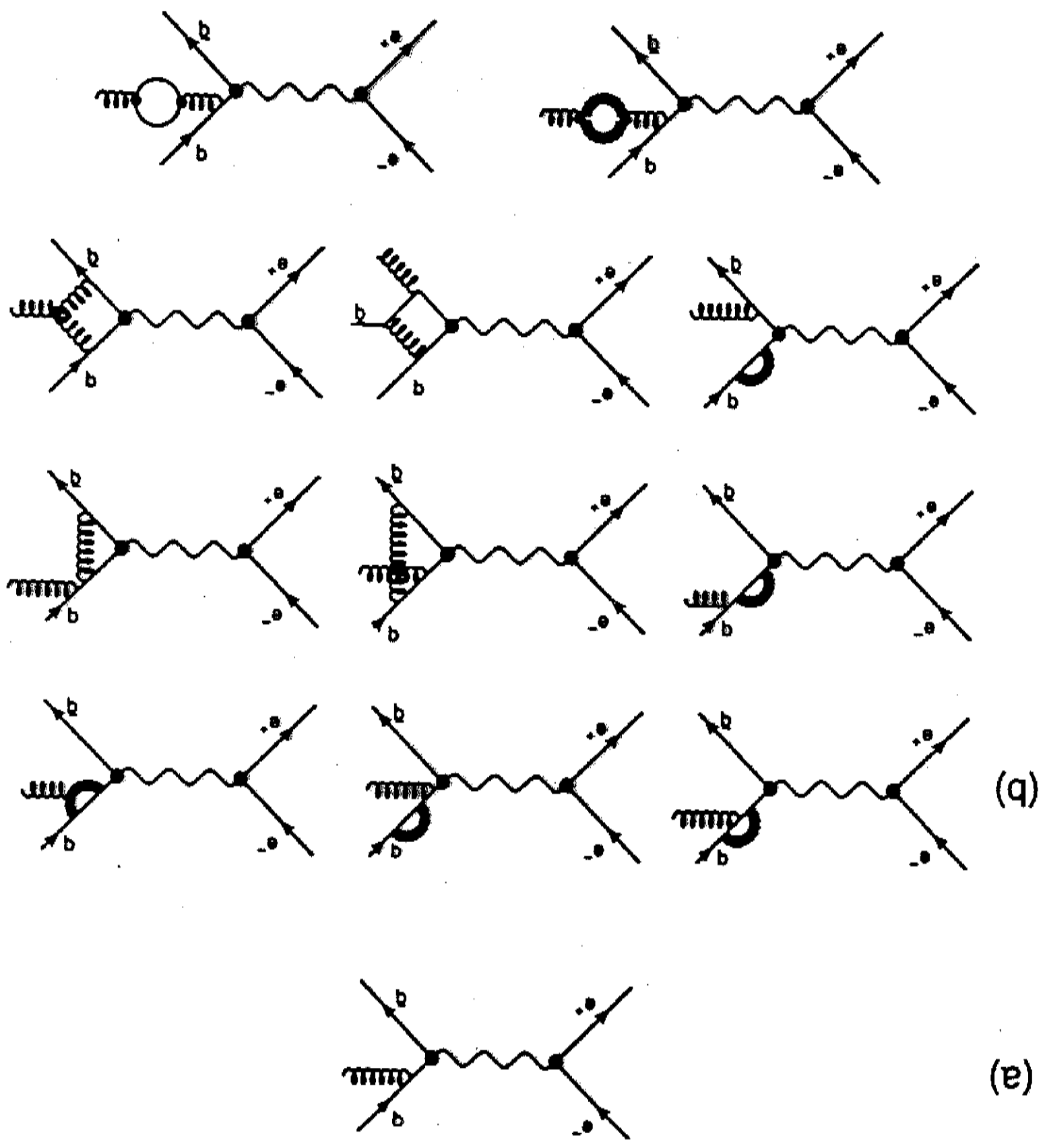
22

Run 22545, EVENT 2240
17-JUN-1993 11:49
Source: Run Data Pol: R
Trigger: Energy CDC Hadron WAB
Beam Crossing 1736130979

kal hit properties
 $5.000 < E_{\text{hit}} < 15000.000$ ADC counts



3-jet Production



What is a jet anyway?

Need

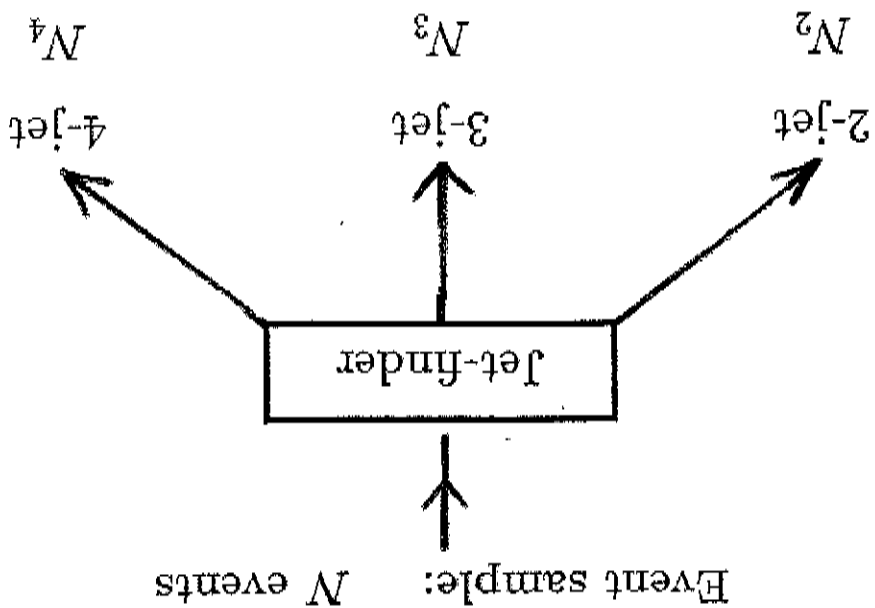
- EXPERIMENTAL definition to apply to measured HADRONS in detectors

- THEORETICAL definition to apply to

PARTONS in perturbative QCD

- Recipe to TRANSLATE between the two

Jet Rates



Define jet rates:

$$R_2 = N_2/N$$

$$R_3 = N_3/N$$

etc.

In general, $R_i = R_i(\text{algorithm}, y^c)$

Life is never simple :

Algorithm	Resolution	Combination	Remarks
E	$\frac{(p_i + p_j)^2}{s}$	$p_k = p_i + p_j$	Lorentz invariant
JADE	$\frac{2E_i E_j (1 - \cos \theta_{ij})}{s}$	$p_k = p_i + p_j$	conserves $\sum E$, $\sum \vec{p}$
E0	$\frac{(p_i + p_j)^2}{s}$	$E_k = E_i + E_j$	conserves $\sum E$, but
		$\vec{p}_k = \frac{E_k}{ \vec{p}_i + \vec{p}_j } (\vec{p}_i + \vec{p}_j)$	violates $\sum \vec{p}$
P	$\frac{(p_i + p_j)^2}{s}$	$\vec{p}_k = \vec{p}_i + \vec{p}_j$	conserves $\sum \vec{p}$, but
		$E_k = \vec{p}_k $	violates $\sum E$
D	$\frac{2 \cdot \min(E_i^2, E_j^2) \cdot (1 - \cos \theta_{ij})}{s}$	$p_k = p_i + p_j$	conserves $\sum E$, $\sum \vec{p}$; avoids exp. problems
G	$\frac{8E_i E_j (1 - \cos \theta_{ij})}{9(E_i + E_j)^2}$	$p_k = p_i + p_j$	conserves $\sum E$, $\sum \vec{p}$; avoids exp. problems
LUCLUS	$\frac{2 \vec{p}_i \cdot \vec{p}_j \cdot \sin(\theta_{ij}/2)}{ \vec{p}_i + \vec{p}_j }$	$p_k = p_i + p_j$	conserves $\sum E$, $\sum \vec{p}$; uncalculable in pert. th.

Table 1. Definition of the resolution measures y_{ij} (d_{join} for LUCLUS) and of combination schemes for various jet algorithms; s is the total center of mass energy or - in experimental implementations - the total visible energy squared, \vec{p}_i denotes a 3-vector and $p_i \equiv (E_i, \vec{p}_i)$ is the corresponding 4-vector.

Observables used:

1 - Thrust	τ
Heavy jet mass	p
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
	E_0
	P
	P_0
	D
	G
Energy-energy correlations	EFC
Asymmetry of EFC	$AEEC$
Jet cone energy fraction	$JCEF$

SLD Collab., K. Abe *et al.*, Phys. Rev. D51 (1995) 962.

$$\sqrt{M_S} = 253^{+130}_{-96} \text{ MeV}$$

$$\alpha_s(M_Z^2) = 0.1200 \pm 0.0025(\text{exp.}) \pm 0.0078(\text{theor.})$$

Final Result

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

SLD, LEP, TRISTAN, CLEO:

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

PDG 1996 (Hinchliffe)

RELATED THEORETICAL PAPERS

Jet cone energy fraction
Masuda, Ohnishi
SLAC-PUB-6560

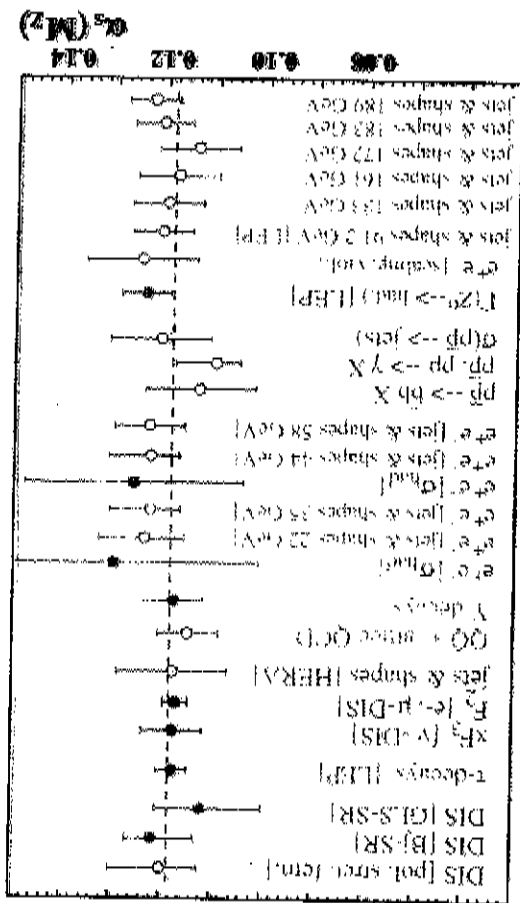
Finite order pQCD calculations
Burrows, Masuda
ZPC63 235

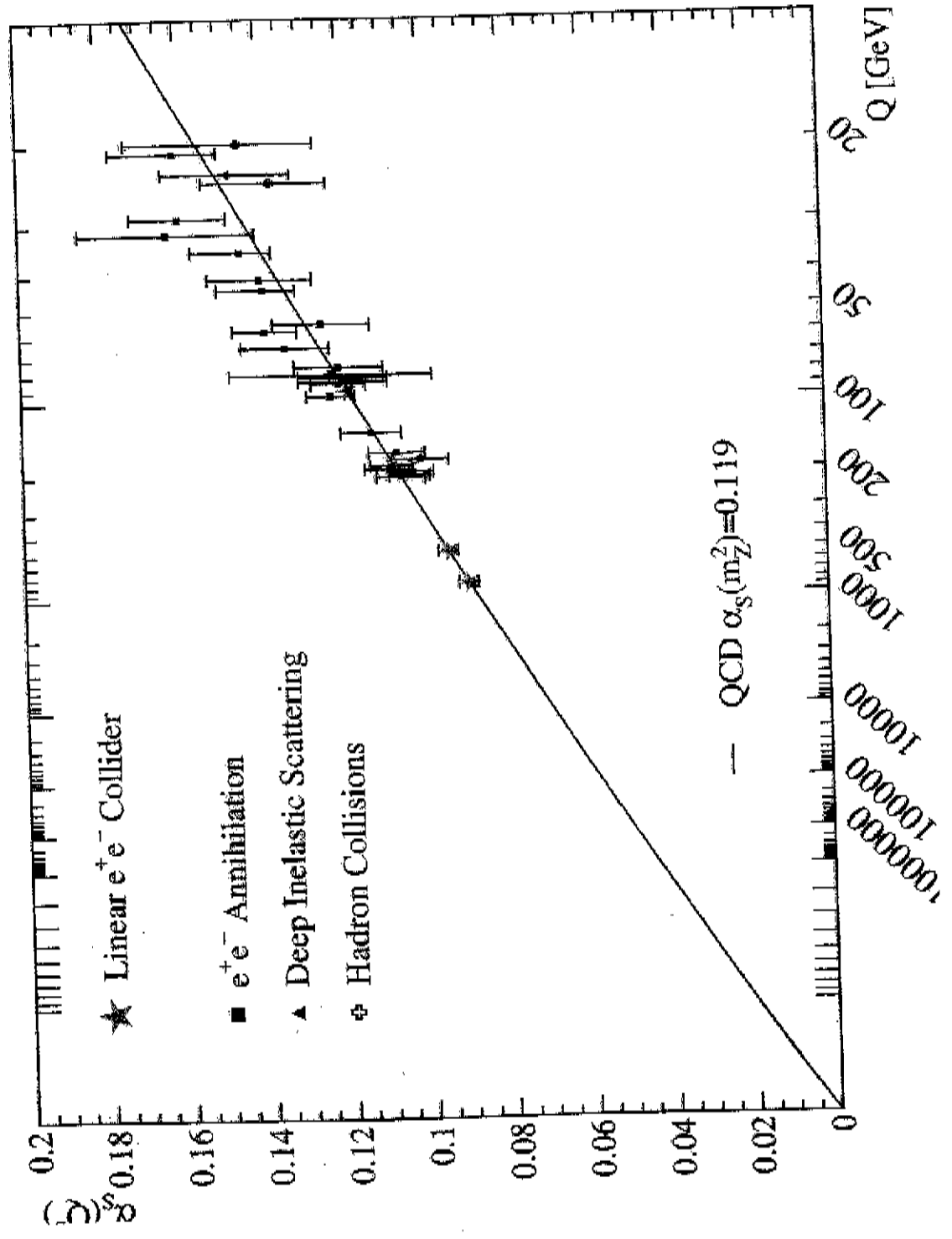
Optimised perturbation theory
Burrows, Masuda, Muller, Ohnishi
PLB382 157

Pade approximants
Burrows, Aбраha, Samuel, Steinfelds, Masuda
PLB392 223

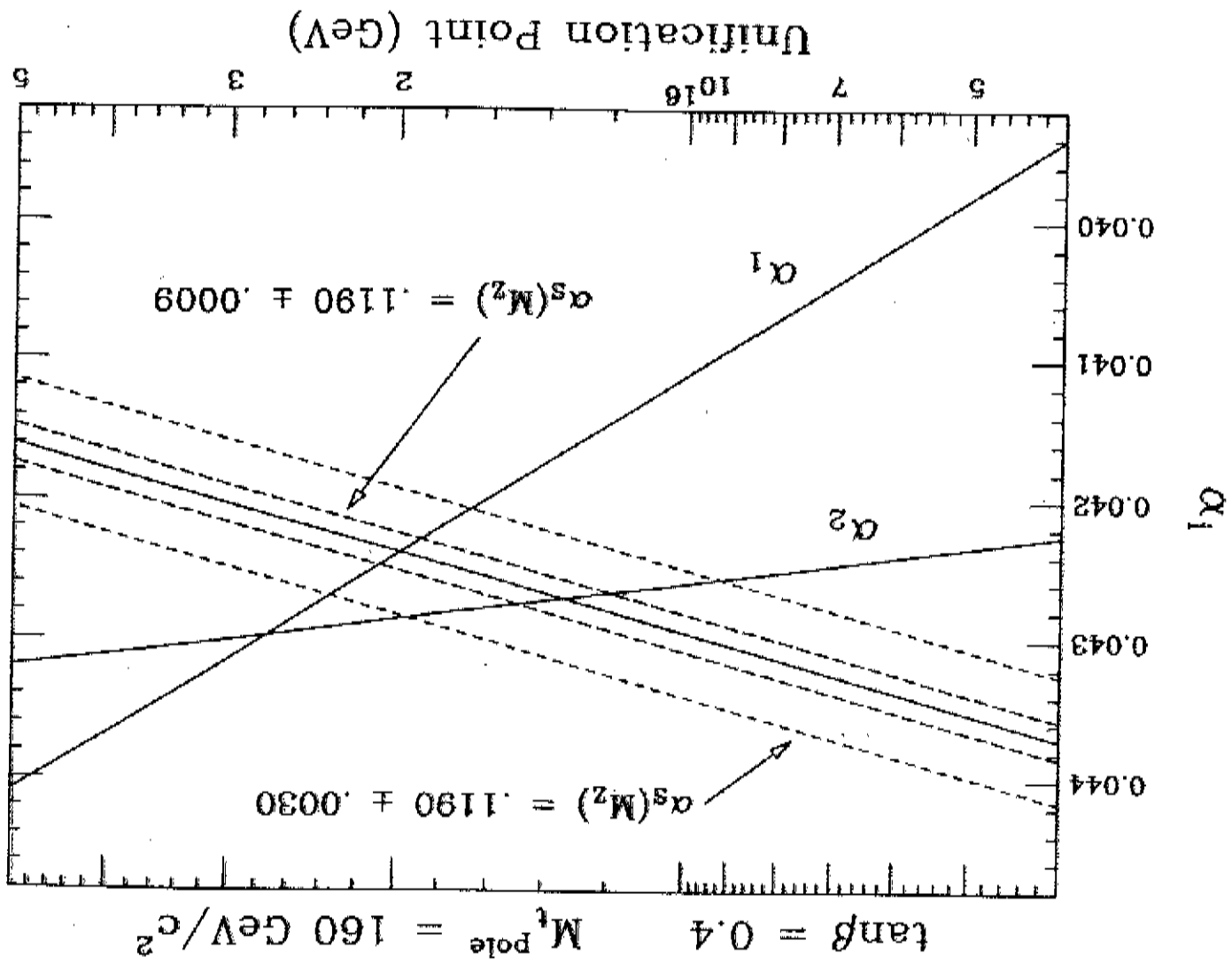
(Pethke)

Figure 11: Summary of $\alpha_s(M_Z)$ (filled symbols represent results based on complete NNLO QCD).





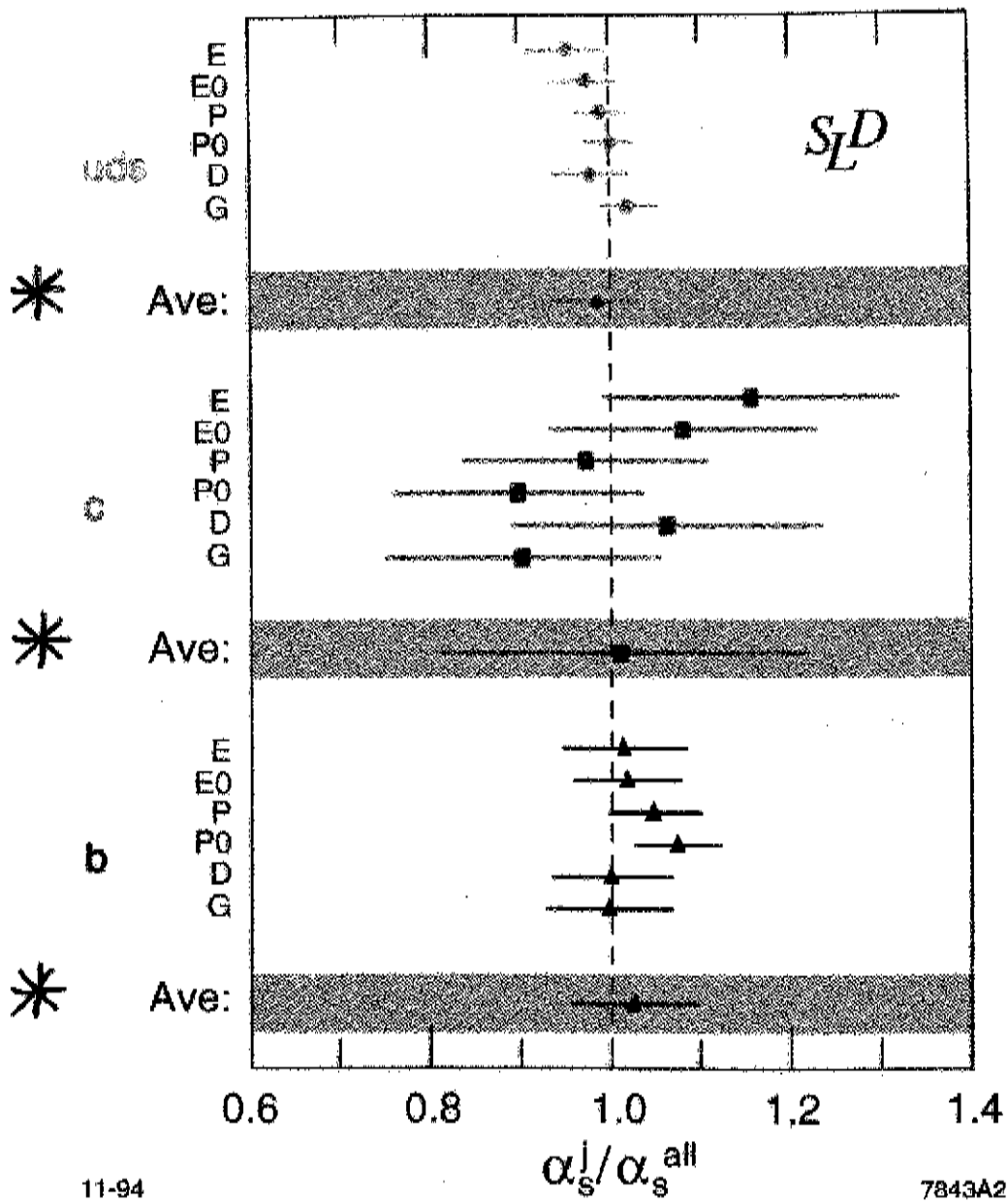
(Schumm)



Run 12615, EVENT# 3580
7-JUL-1992 05:46
Source: Run Data POL: L



$\frac{\alpha_s(\text{flavour})}{\alpha_s(\text{all})}$ Ratios



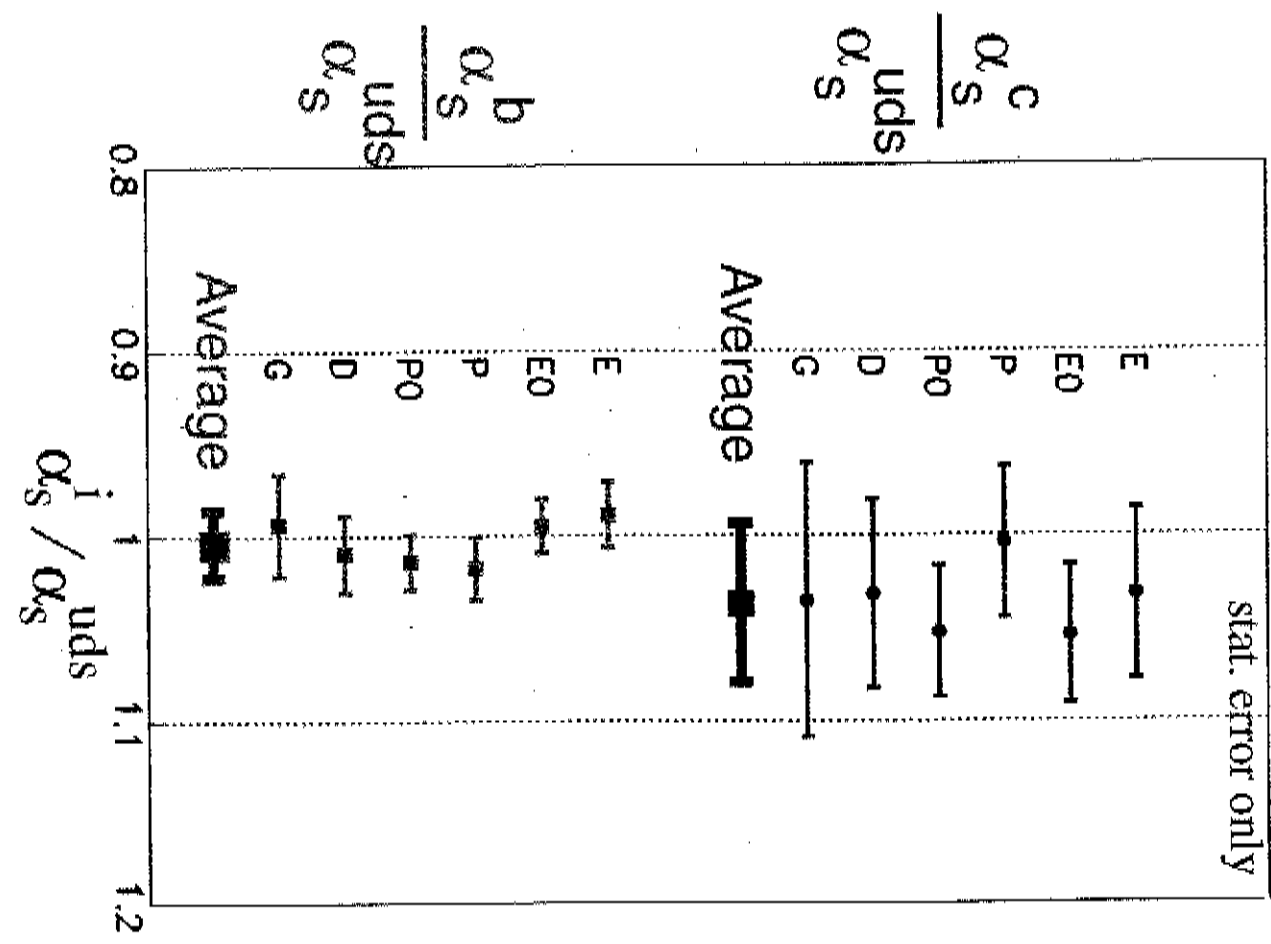
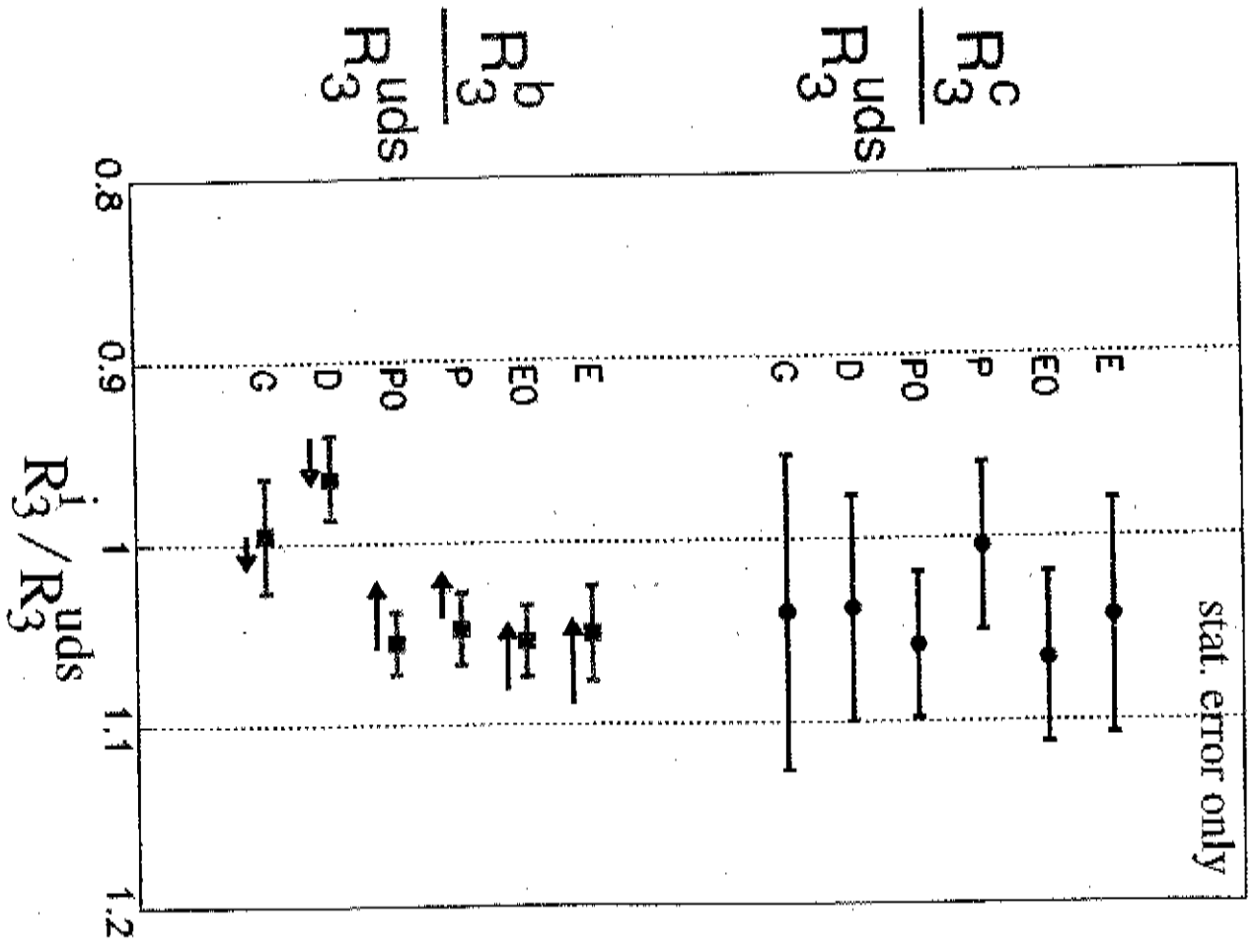
11-94

7843A2

1993 data: PRD53 2271

Comparison of gluon emission probabilities for different flavours

2-jet rate ratios \longrightarrow α_s ratios



Run 43597; EVENT 6479
26-MAY-1998 01:53
Source: Run Data Pol: R

EJ1

MYRX=4.5GeV
ldecay=1.9mm

EJF1=16.8GeV

EJF2=5.4GeV

MYRX=2.8GeV
ldecay=3.4mm

EJF3=26.8GeV



total angle of normal to bag plane
Left - right forward - backward asymmetry

SLD Preliminary

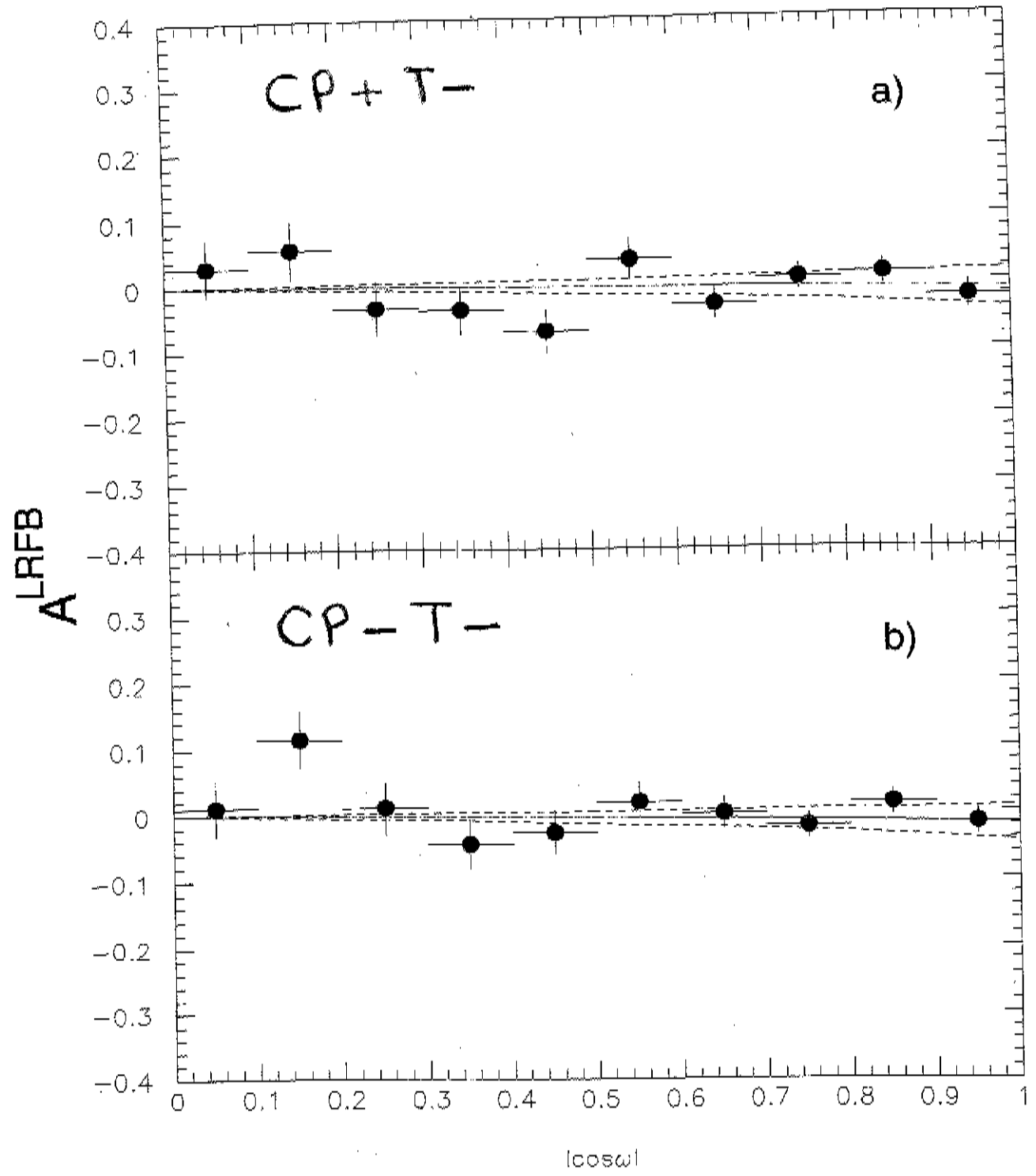


Figure 5

RESULTS 3: FINAL-STATE INTERACTIONS

POLAR ANGLE OF \perp TO $b\bar{b}g$ PLANE ω :

$$\frac{d\sigma}{d\cos\omega} \propto (1 - P_e \cdot A_e)(1 + \gamma \cos^2\omega) + 2A_T(P_e - A_e)\cos\omega$$

a) CP+ T-

$$A_{\bar{7}} = -0.014 \pm 0.016 \text{ (stat.)}$$

b) CP- T-

$$A_{\bar{7}} = -0.035 \pm 0.024 \text{ (stat.)}$$

No signal \Rightarrow 95% C.L. limits:

$$-0.015 < A_{\bar{7}} < 0.016$$

$$-0.082 < A_{\bar{7}} < 0.012$$

c.f. S.M. expectation: $A_{\bar{7}} \sim 10^{-3}$

b-quark azimuthal angle

SLD Preliminary

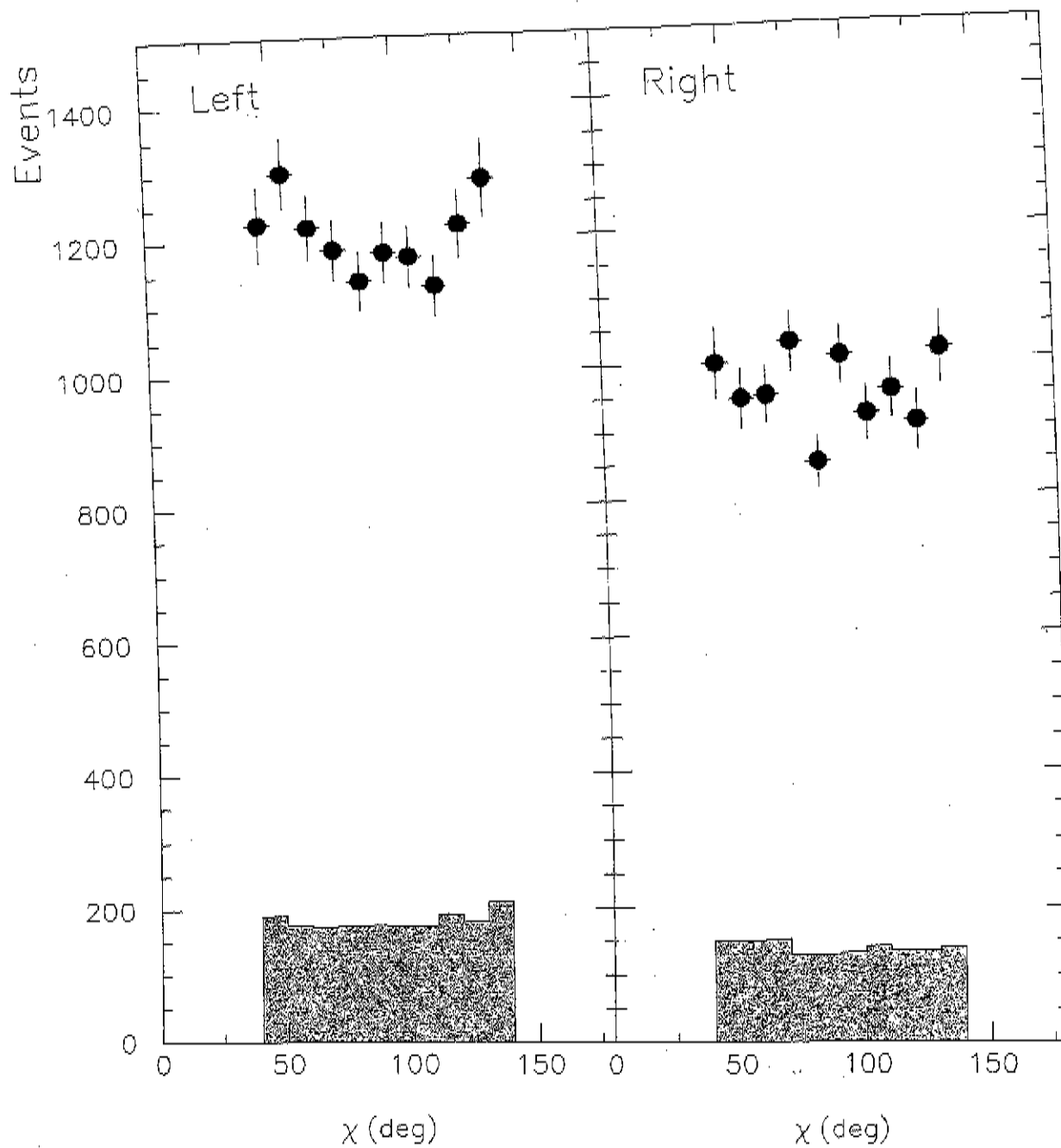


Figure 4.

b-quark polar angle

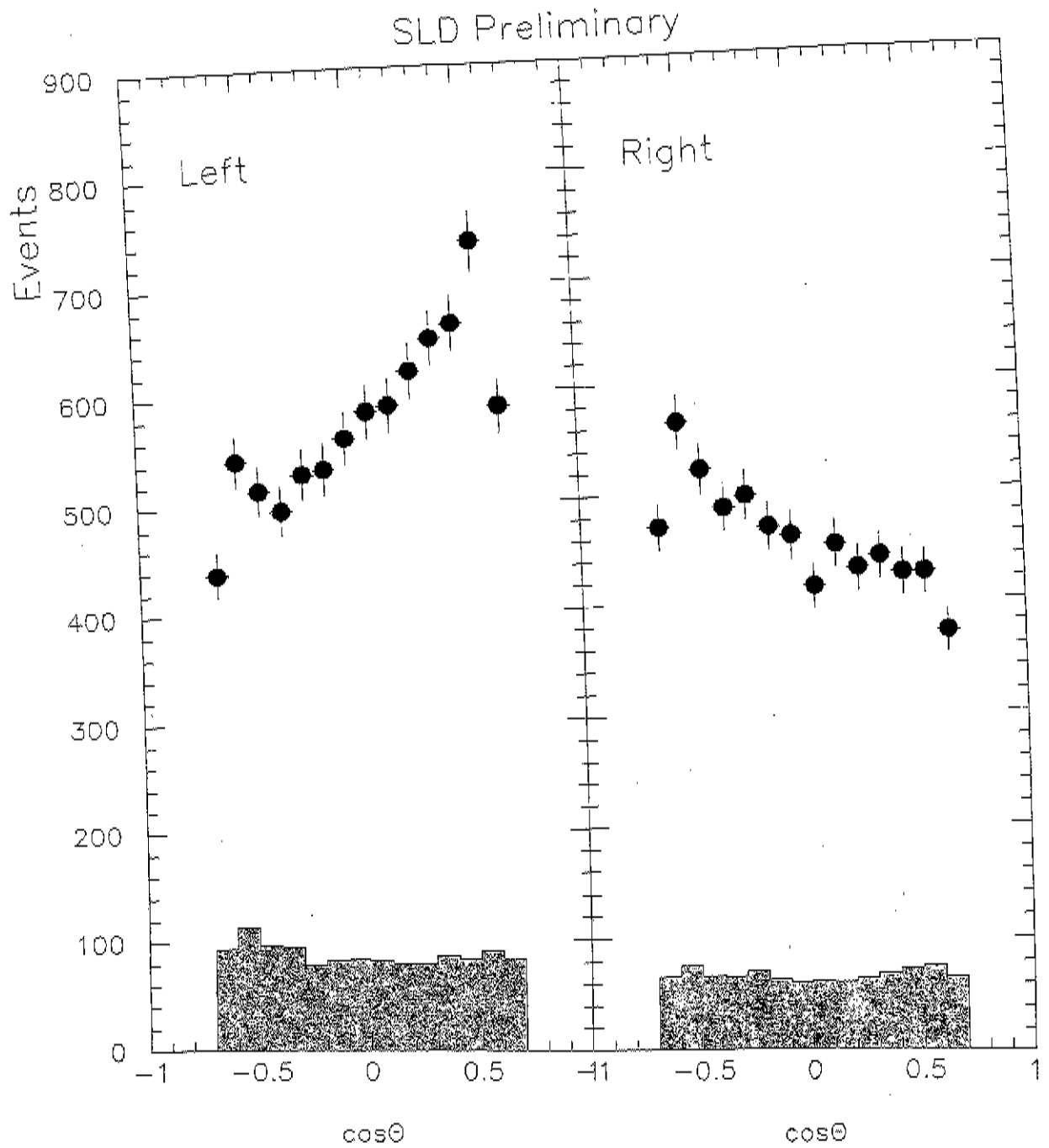


Figure 3

RESULTS 2: b-QUARK ORIENTATION ANGLES

a) POLAR ANGLE θ

$$\frac{d\sigma}{d\cos\theta} \propto (1 - P_e \cdot A_e)(1 + \alpha \cos^2\theta) + 2A_P (P_e - A_e) \cos\theta$$

$$A_P = A_{QCD} \cdot A_b$$

$$A_{QCD} = 0.914 \pm 0.053(\text{stat.}) \pm 0.063(\text{syst.})$$

c.f. 0.93 from $O(\alpha_s^2)$ pQCD

b) AZIMUTHAL ANGLE χ

$$\frac{d\sigma}{d\cos\chi} \propto (1 - P_e \cdot A_e)(1 + \beta \cos 2\chi) - \frac{3\pi}{2\sqrt{2}} A'_P (P_e - A_e) \cos\chi$$

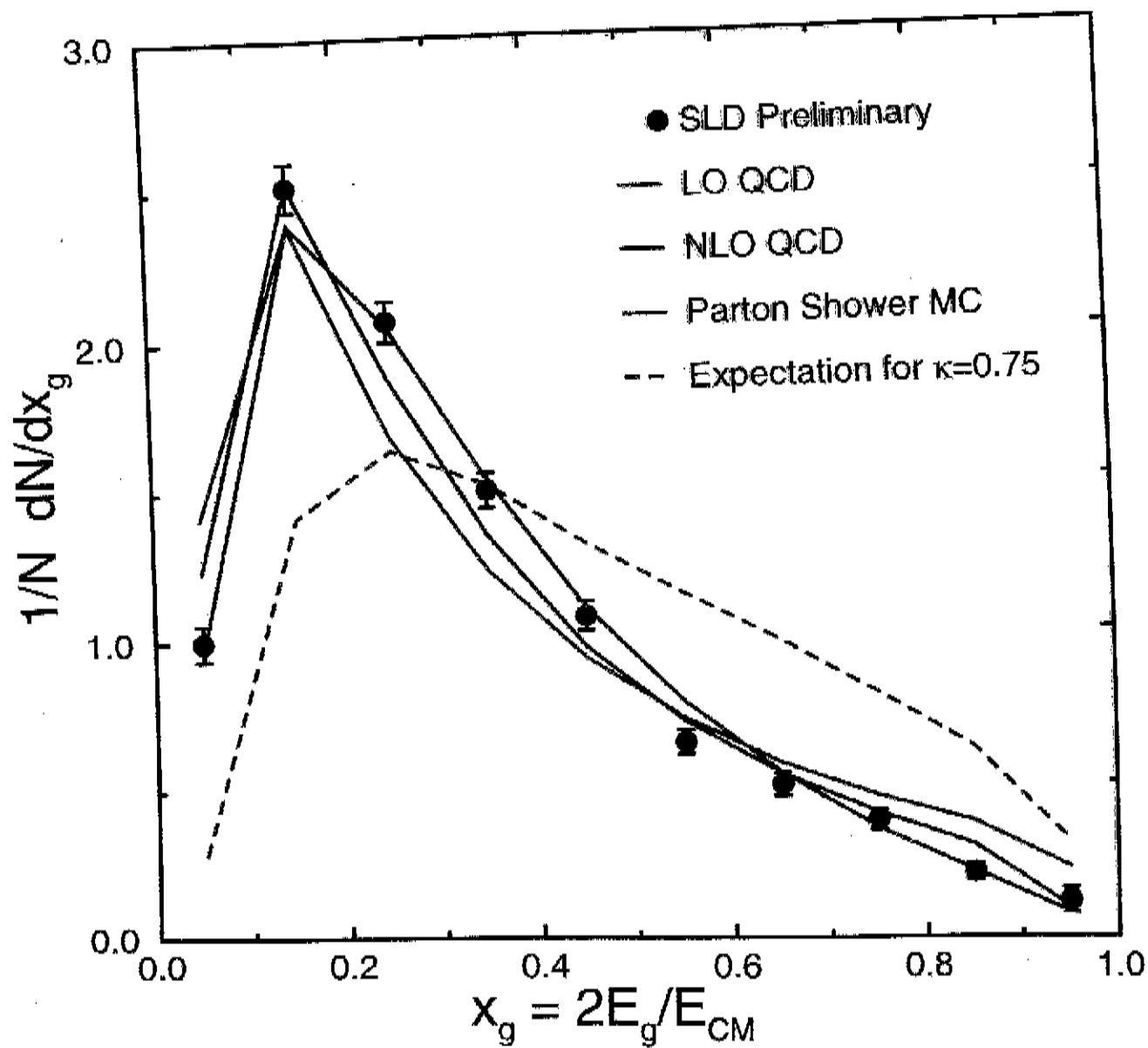
$$A'_P = A'_{QCD} \cdot A_b$$

$$A'_{QCD} = -0.011 \pm 0.035(\text{stat.}) \pm 0.002(\text{syst.})$$

c.f. 0.063 from $O(\alpha_s^2)$ pQCD

\Rightarrow Anomalous axial-vector coupling $(1 + \epsilon\gamma_5)\gamma_\nu$:

$$\epsilon < 0.34 \quad (95\% \text{ c.l.})$$



Analysis using SLD Data

(A. Brandenburg, P. Burrows, N. Oishi, P. Uwer)

Parametrised m_b -dependence based on calculations by Bernreuther *et al.*: 6 jet algorithms (E, E0, P, P0, D, G)

b-quark mass at M_Z

SLD preliminary (stat. err. only)

