A Decade of Precision Electroweak Measurements

M. E. Peskin
March, 2001

Of the two fundamental interactions seen
only in microscopic physics

-- the strong and weak interactions --

the weak interaction was for an long time
the most mysterious

but the basic ingredients of the weak interaction have slowly been built up:

parity violation

"V - A"

W boson

Z boson

neutral currents

Standard Model:

Glashow, Weinberg, and Salam

`t Hooft, Veltman, and Lee

Ingredients of the Standard Model:

underlying SU(2) X U(1) gauge symmetry

SU(2) → $W^+ W^0 W^-$ coupling g

U(1) → B^0 coupling g'

spontaneous symmetry breaking $\langle \phi \rangle = v$

$W^+ W^-$ → massive $m_W = \frac{g}{2} v$

$W^0 B^0$ → Z^0 $m_Z = \frac{\sqrt{g^2 + g'^2}}{2} v$

A^0 $m_A = 0$

parity violation

$W^+ W^- W^0$ couple only to

left-handed quarks and leptons

to complete the story,

A and Z are mixtures of W^0 and B^0

$$A = \sin\theta_W \; W^0 + \cos\theta_W \; B^0$$

$$Z = \cos\theta_W \; W^0 - \sin\theta_W \; B^0$$

$$\tan\theta_W = \frac{g'}{g} \qquad \sin^2\theta_W = \frac{g'^2}{g^2 + g'^2}$$

A couples to $T^3 + Y = Q$

$$e = \frac{g\,g'}{g^2 + g'^2}$$

Z couples to $\cos^2\theta_W \, T^3 - \sin^2\theta_W \, Y$

$$Q_Z = (\, T^3 - \sin^2\theta_W \, Q \,)$$

T^3 = ± 1/2 for left-handed q, l
0 for right-handed q, l

In 1989,

two new accelerators,

LEP at CERN and SLC at SLAC,

began operation to study the properties of the Z^0 in detail through the reaction

$$e^+ e^- \rightarrow Z^0 \text{ resonance}$$

the CDF experiment at Fermilab began precise measurement of m_W and showed that the top quark is very heavy ($m_t > m_W$)

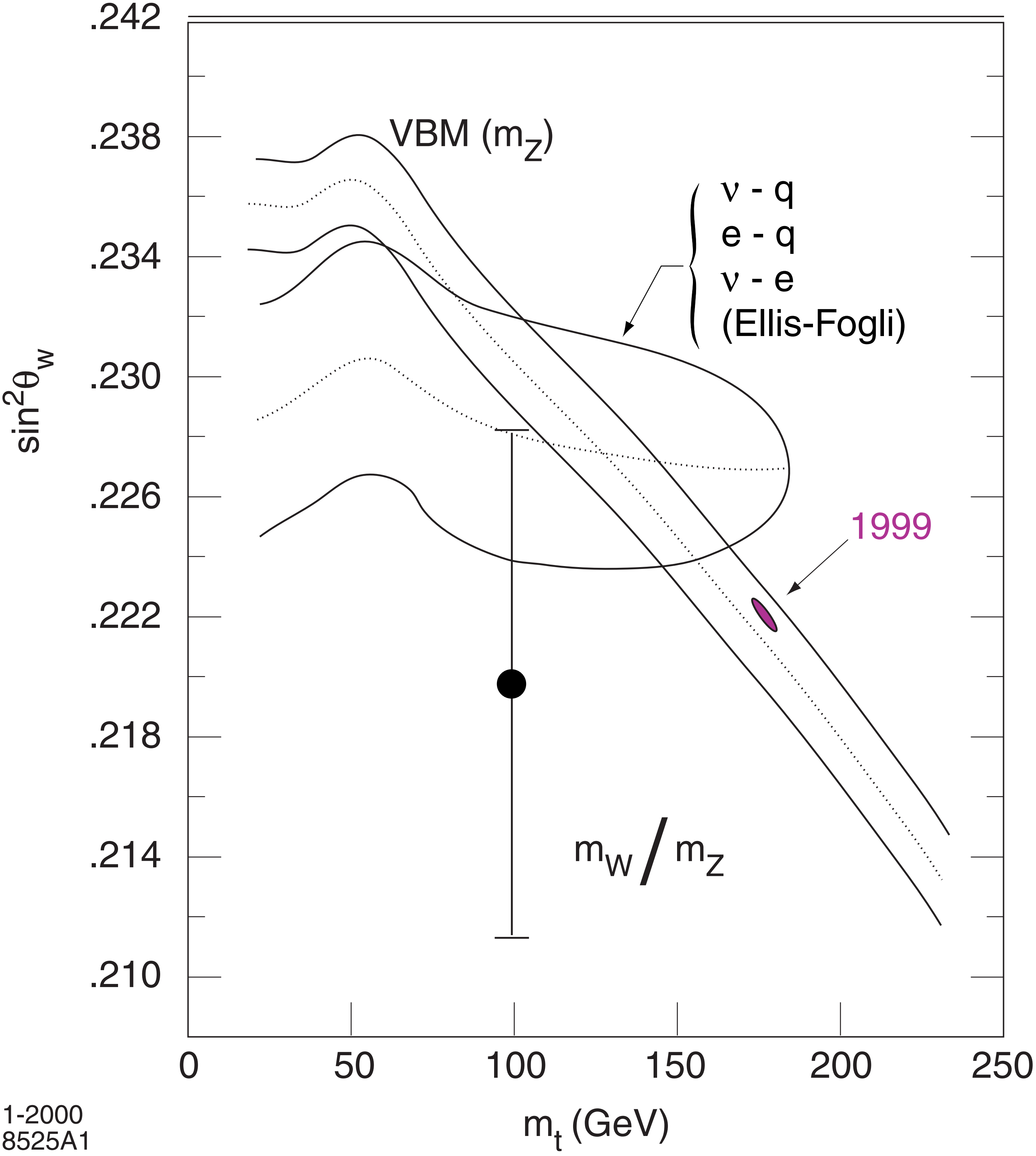
This initiated an era of precision electroweak measurements.

so,

what did these experiments measure?

what did we learn?

G. Altarelli, 1989, and 10 years later:

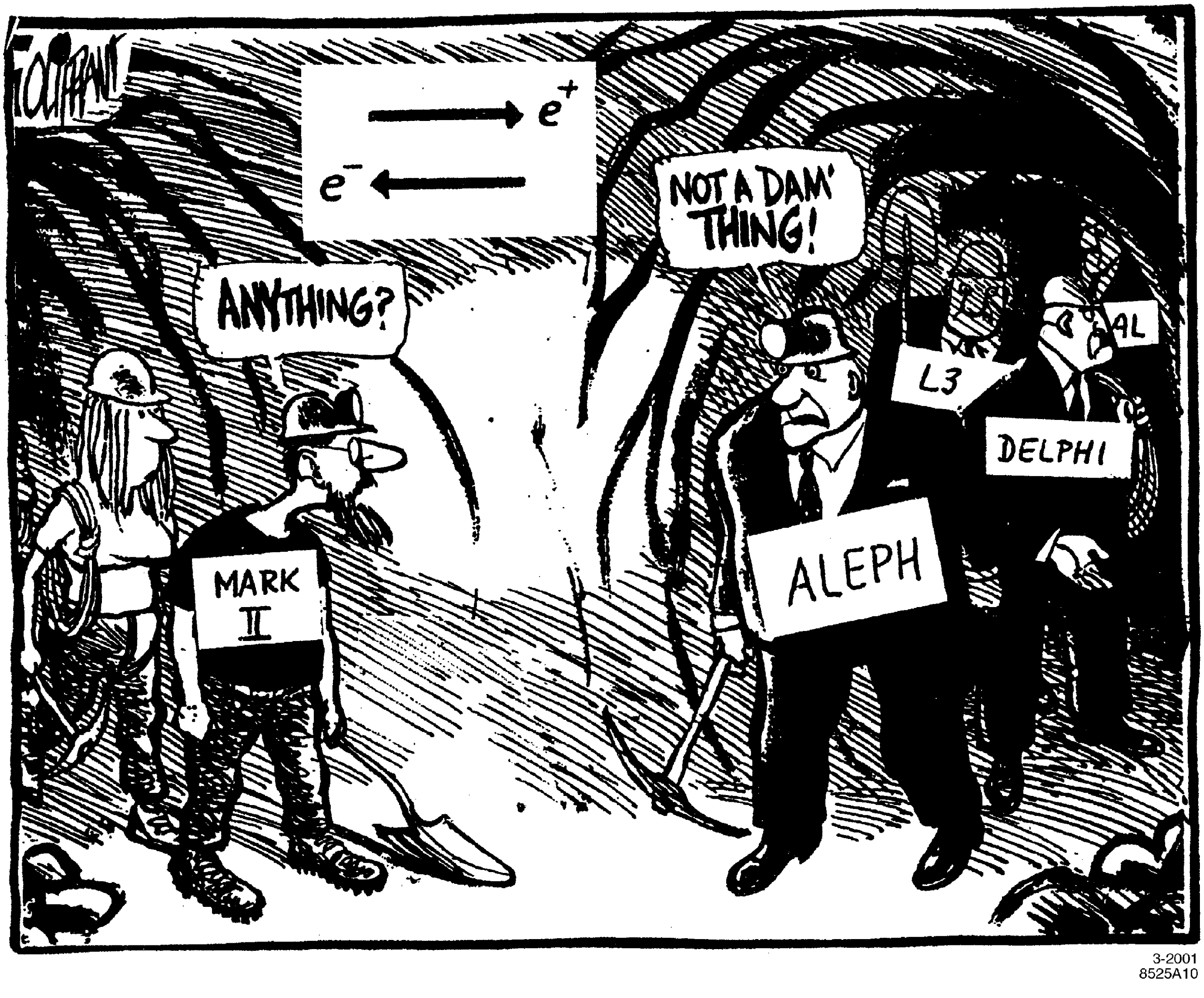


LEP and SLC discovered no new particles and confirmed the Standard Model of electroweak interactions

Some found this a disappointment ...

For me, it is an important and beautiful chapter in the progress of physics.

F. Dydak showed this slide already at the 1990 ICHEP:



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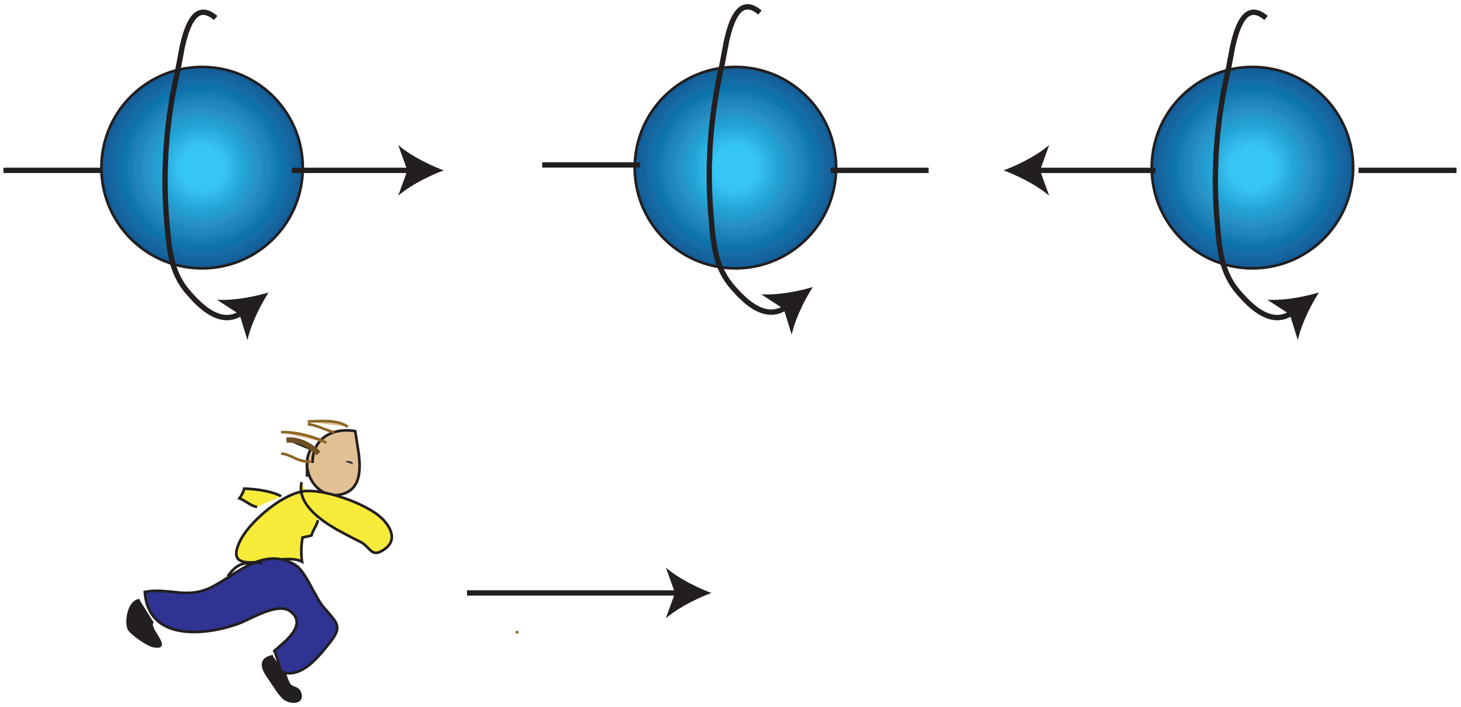
before we discuss the experiments,
I would like to clarify one conceptual issue

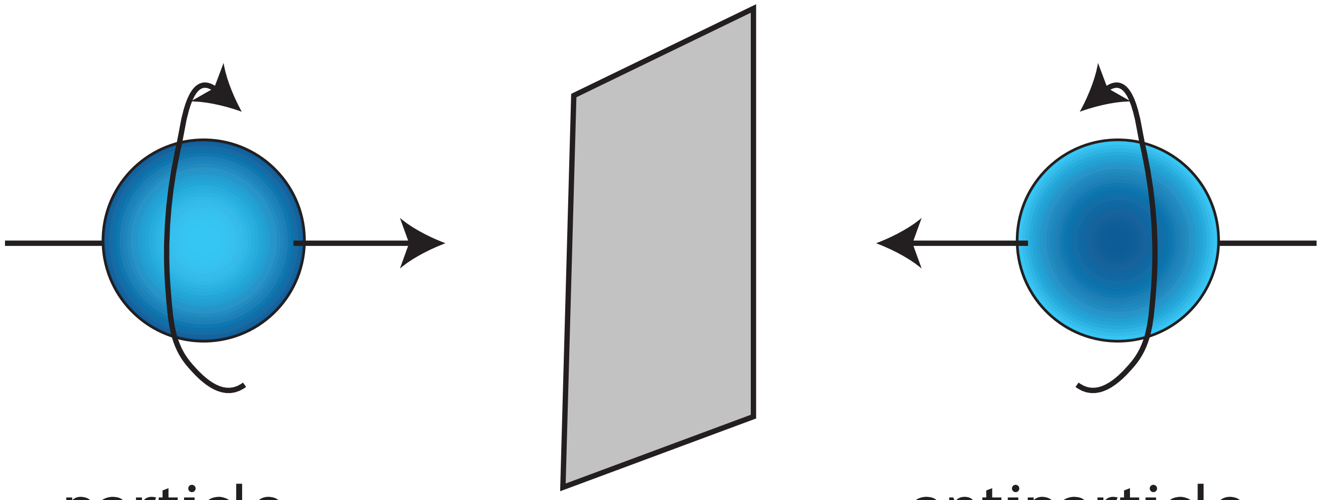
handedness (helicity) is not a
Lorentz-invariant concept,

so how can a fundamental interaction
be sensitive to it?



Massless particles can have definite helicity.

The most basic representations of the Poincare group are massless L- and R-handed fermions



The truly fundamental interactions see the quarks and leptons at their deepest level, before mass generation

Quark and lepton masses come from spontaneous symmetry breaking:

$$m_f = \frac{1}{\sqrt{2}} \lambda_f \, v$$

To test the properties of the Z^0, go to high energy where quark and lepton masses are irrelevant.

Separate L and R, and verify:

	$Q_Z(L)$	$Q_Z(R)$	S_f	A_f
ν ν ν	$\frac{1}{2}$	x	0.25	1
e μ τ	$-\frac{1}{2}+\sin^2\theta_W$	$\sin^2\theta_W$	0.126	0.15
u c t	$\frac{1}{2}-\frac{2}{3}\sin^2\theta_W$	$-\frac{2}{3}\sin^2\theta_W$	0.144	0.67
d s b	$-\frac{1}{2}+\frac{1}{3}\sin^2\theta_W$	$\frac{1}{3}\sin^2\theta_W$	0.185	0.94

$$S_f = Q_Z^2(L) + Q_Z^2(R)$$

$$A_f = \frac{Q_Z^2(L) - Q_Z^2(R)}{Q_Z^2(L) + Q_Z^2(R)}$$

a consistent pattern gives a precise values of

$\sin^2\theta_W$

measurement of the Z^0 mass:

LEP calibration of $\oint ds\, B$ measures the Z^0 resonance energy

some final corrections are exotic:
tides, level of Lake Geneva, TGV

$$m_Z = 91.1875\ (21)\ \text{GeV}$$

a new physical constant determined to high precision

reference value of $\sin^2\theta_W$

$$\sin^2 2\theta_0 = \frac{4\pi\alpha_*}{\sqrt{2}G_F m_Z^2}$$

$$\sin^2\theta_0 = 0.231079\ (36)$$

measurement of S_f

$$\Gamma_Z = \frac{\alpha\, m_Z}{6\cos^2\theta_W \sin^2\theta_W} \sum_f Q^2_{Zf}\, N_f$$

f runs over L and R quarks and leptons

N_f = 1 for leptons

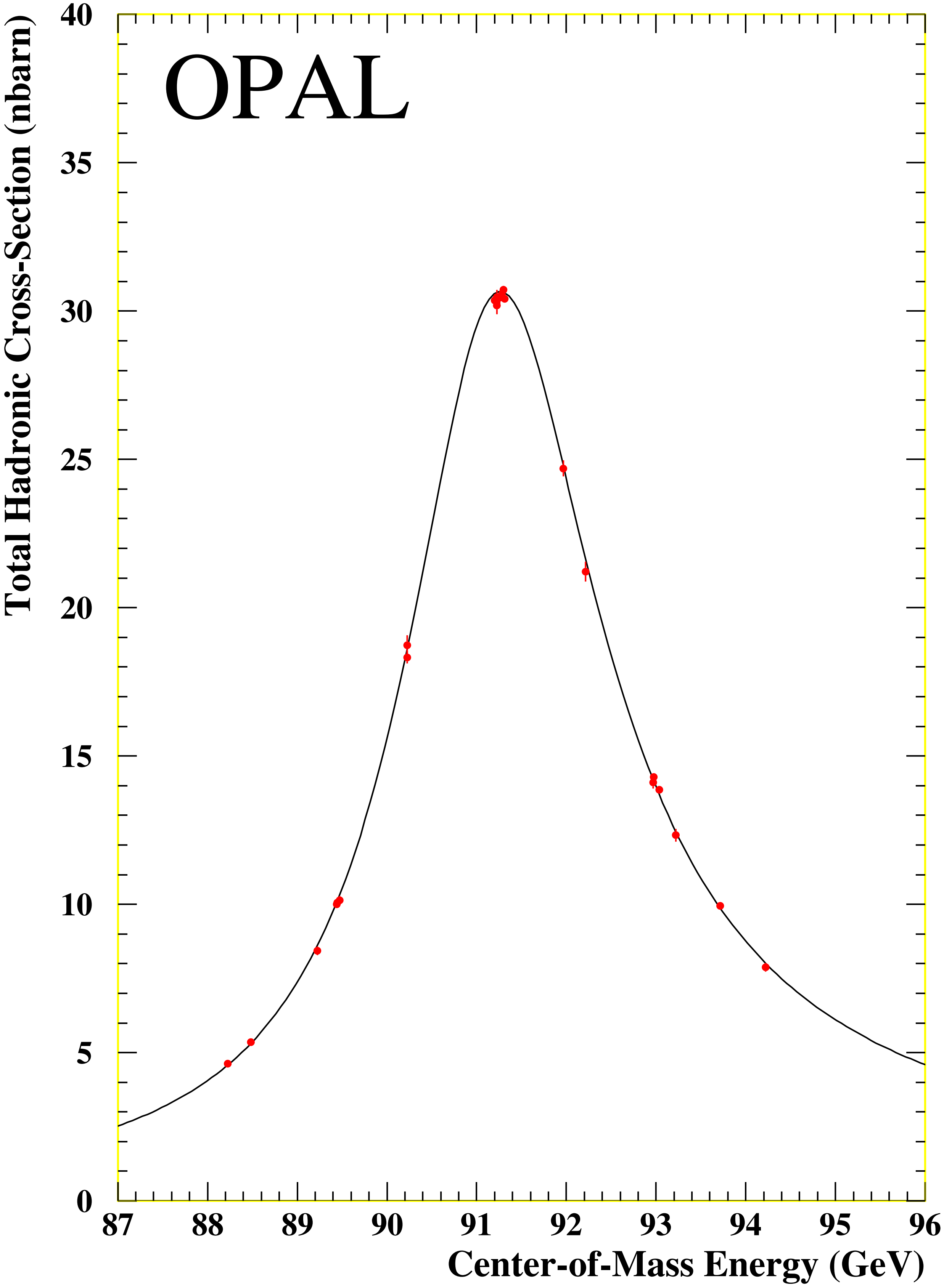
$3\,(1 + \frac{\alpha_s}{\pi} + \ldots) = 3.1$ for quarks

Radiation from the initial e^- and e^+ substantially distorts the resonance shape

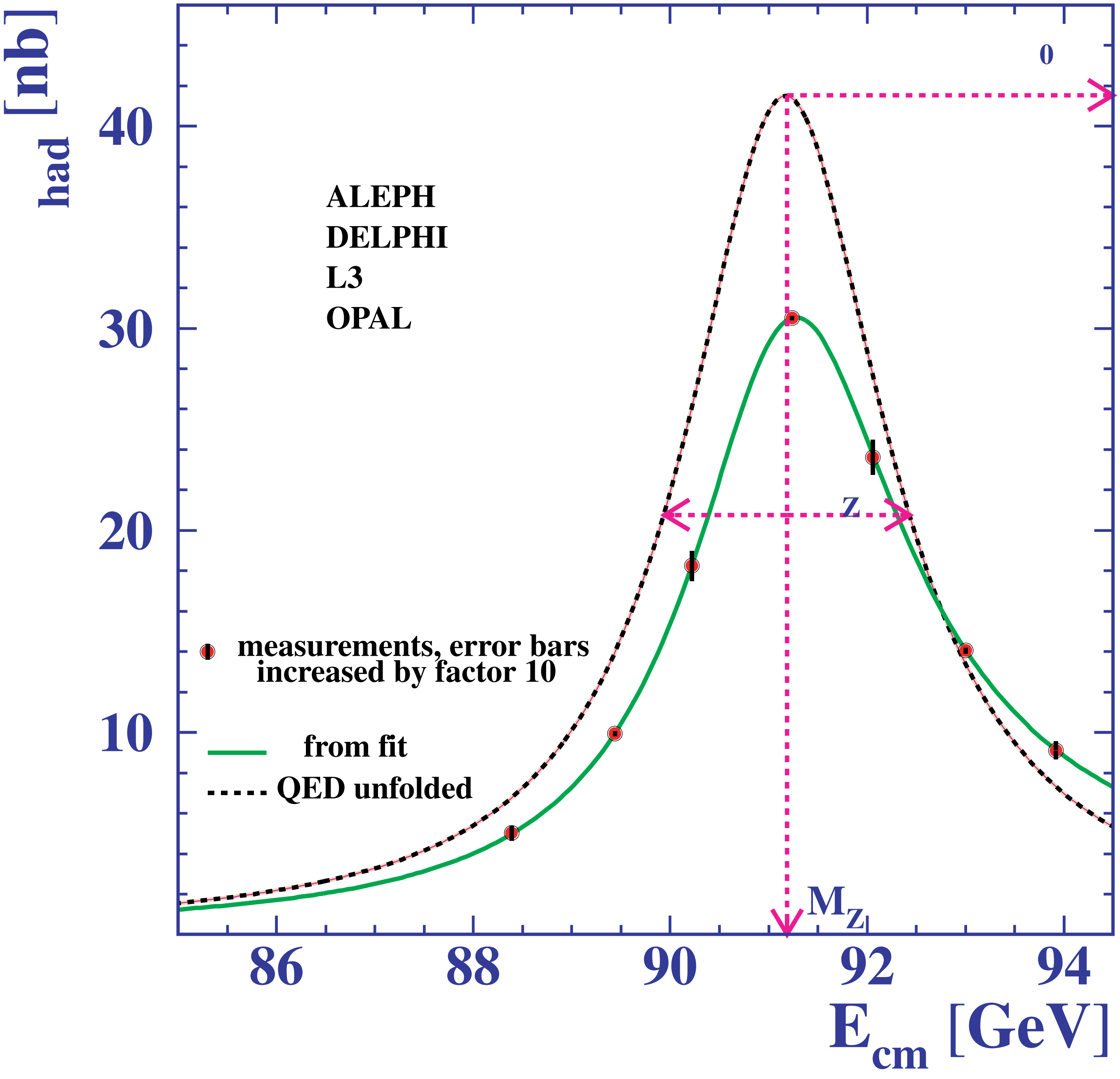
$$\Gamma_Z = 2.4952\ (23)\ \text{GeV}$$

To determine the S_f separately, count.

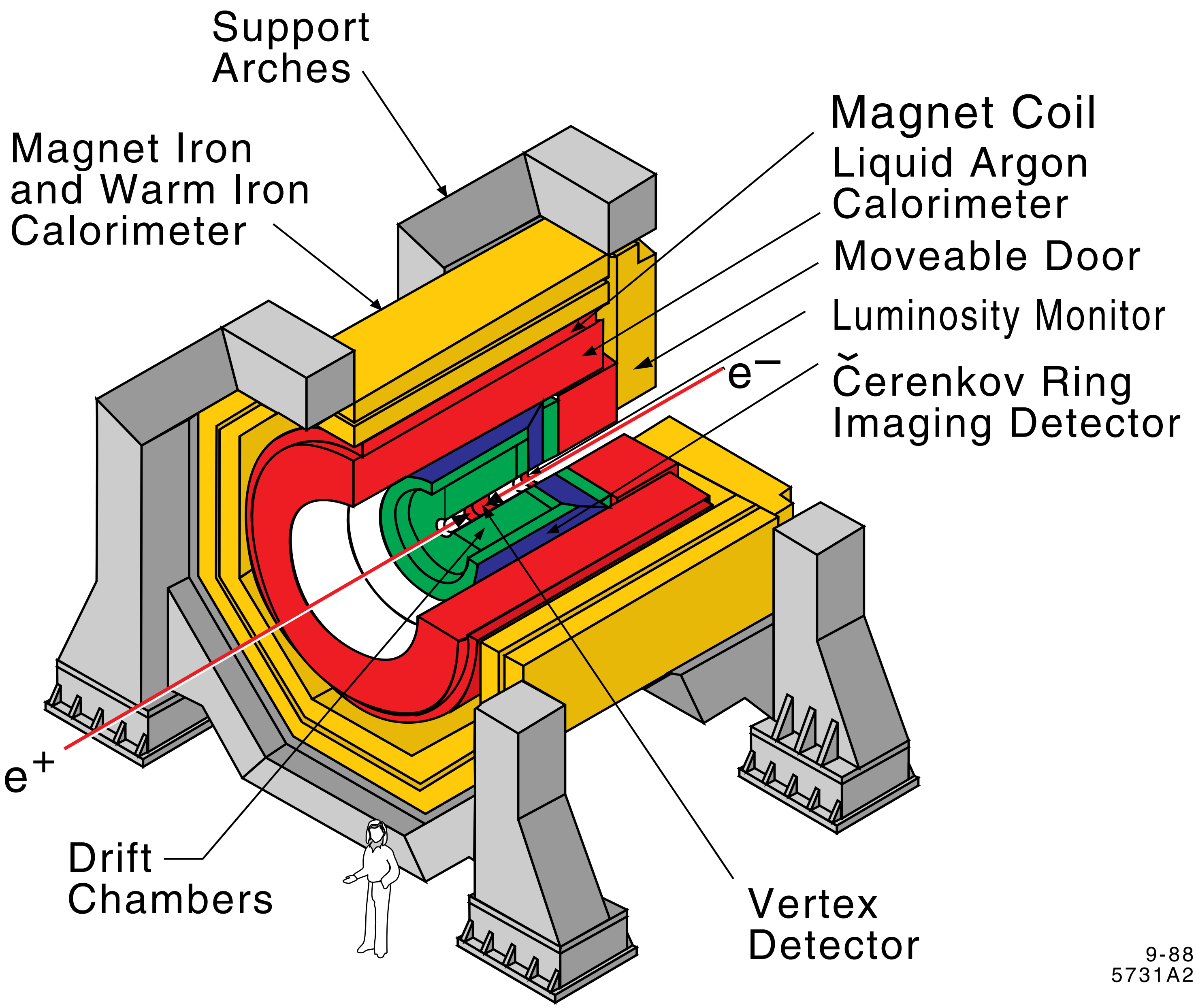
SLD	500 K Z s (w. polarized e^-)
LEP	17 M Z s (4 experiments)


OPAL
Total Hadronic Cross-Section (nbarn)
0
5
10
15
20
25
30
35
40
87
88
89
90
91
92
93
94
95
96
Center-of-Mass Energy (GeV)

final Z resonance shape from LEP



SLD


Support Arches
Magnet Iron and Warm Iron Calorimeter
Magnet Coil
Liquid Argon Calorimeter
Moveable Door
Luminosity Monitor
e⁻
Čerenkov Ring Imaging Detector
e⁺
Drift Chambers
Vertex Detector
9-88
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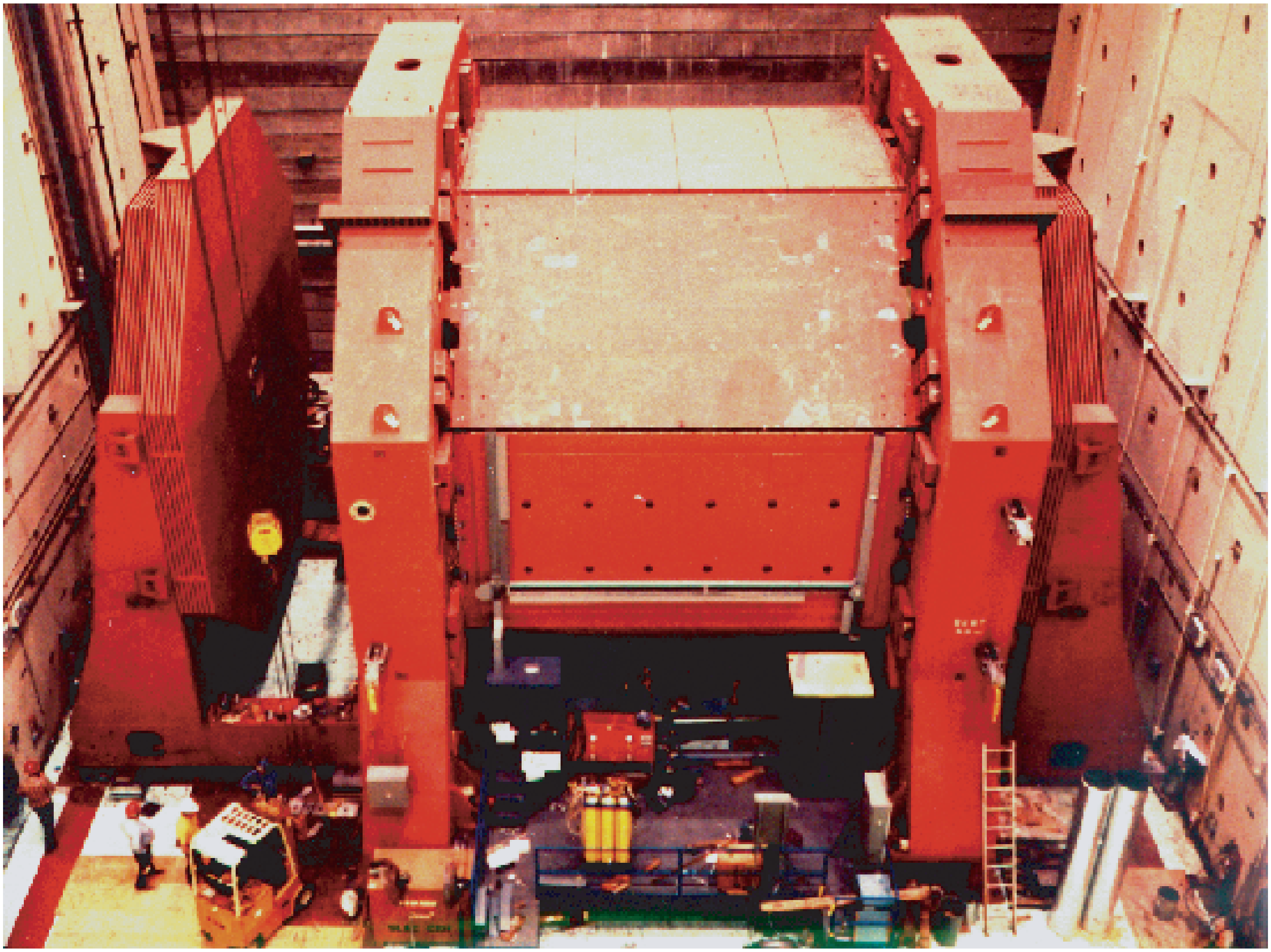
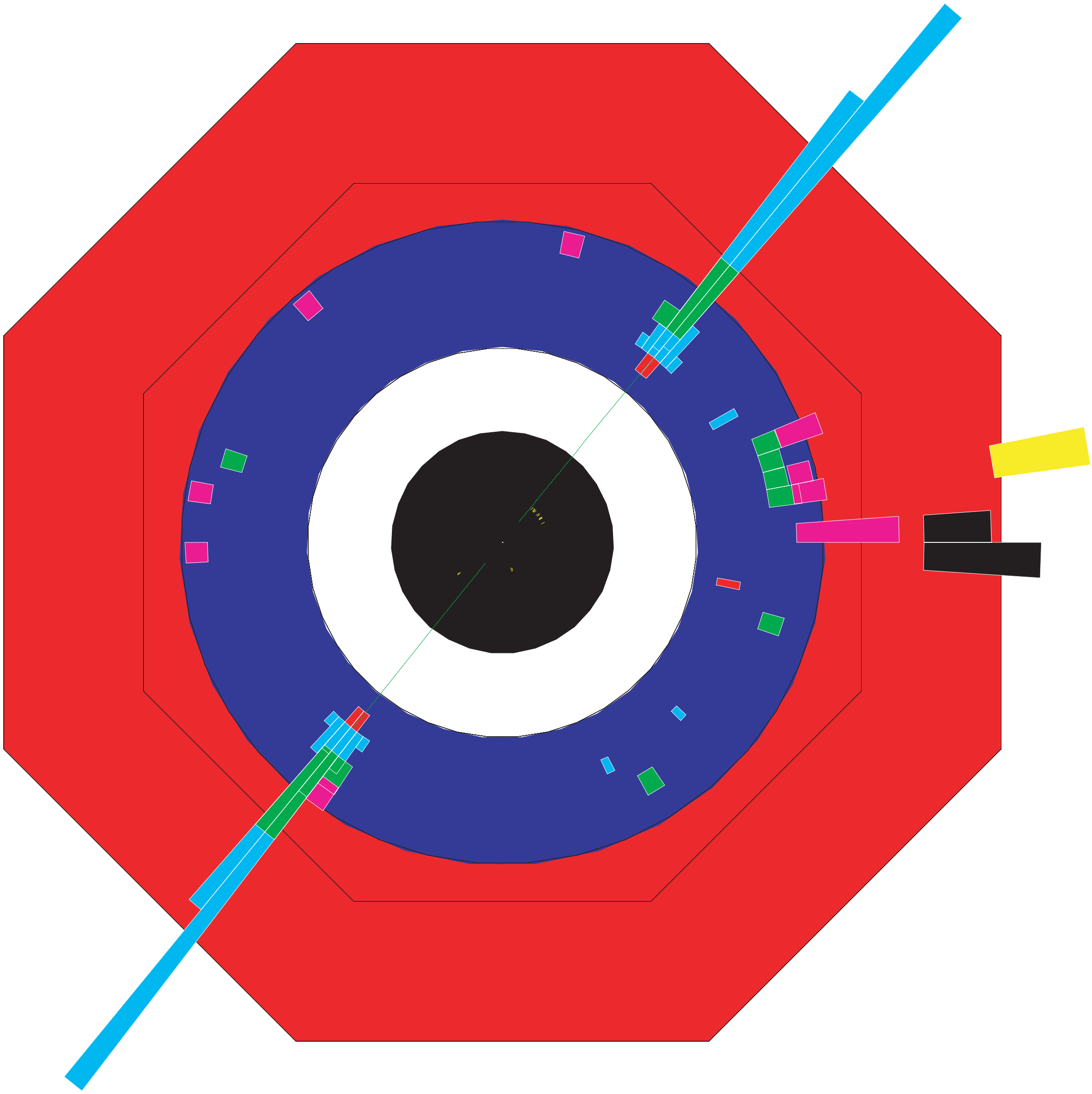
The SLD detector under construction:

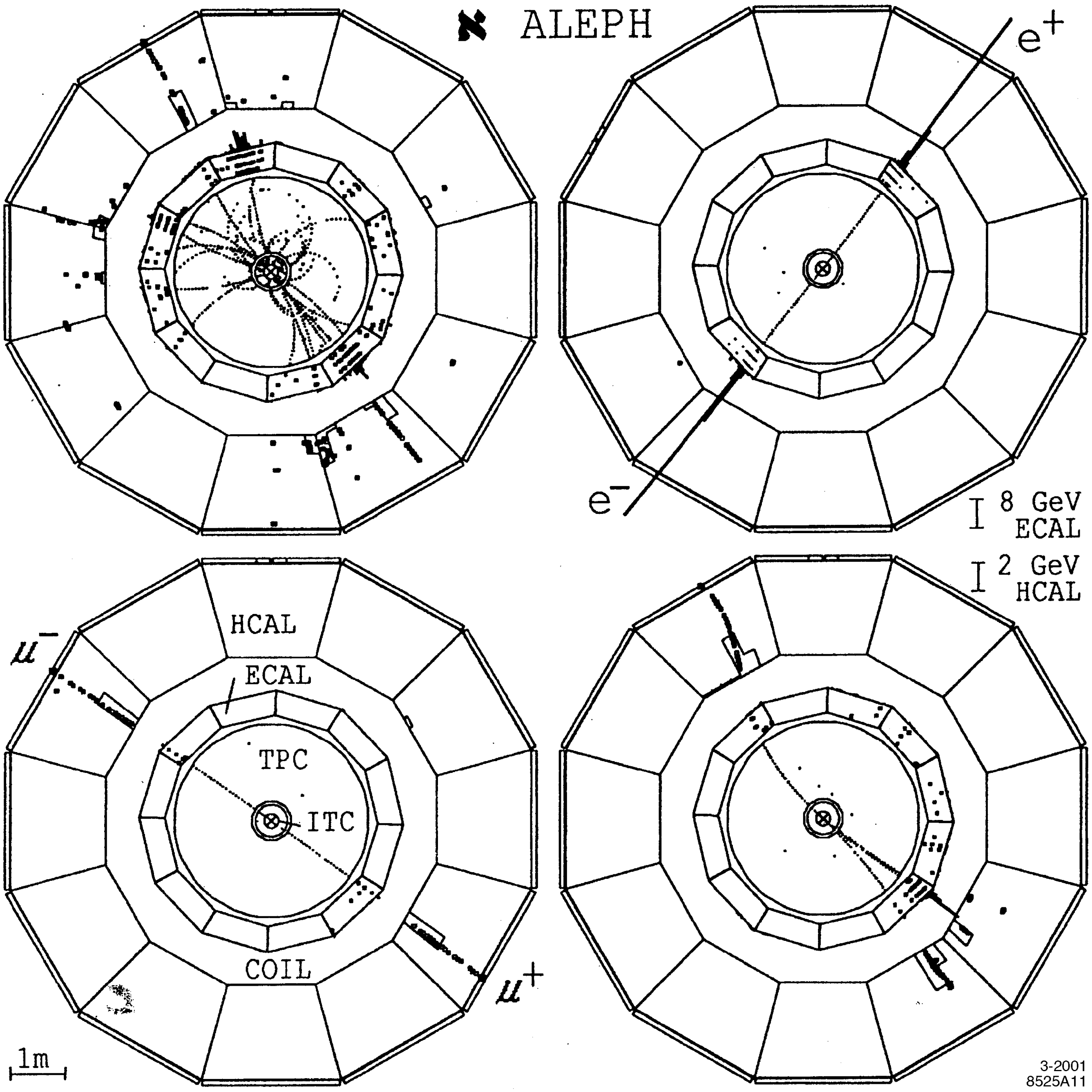


$$e^+e^- \rightarrow Z^0 \rightarrow e^+e^-$$



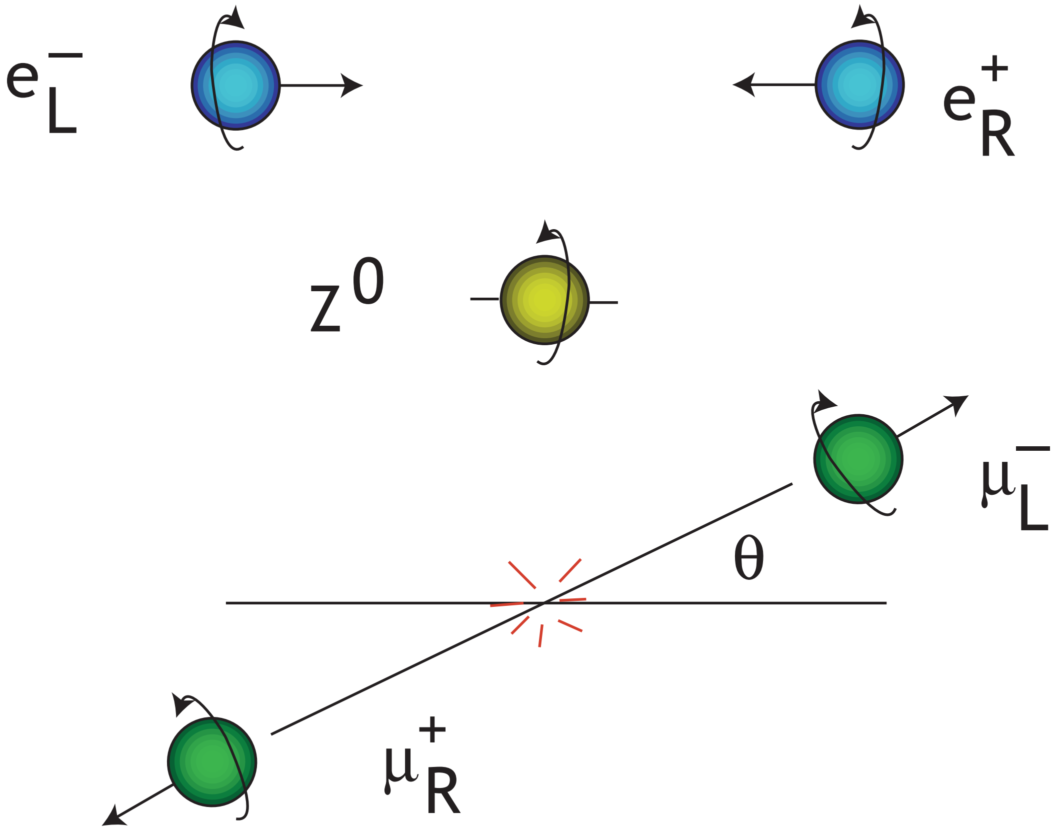
SLD

Z^0 event types, according to ALEPH:



add also $Z \to \nu \bar{\nu}$ with 3 neutrino species to determine the A_f , we must have a way to determine the spin of the fermion in Z decay

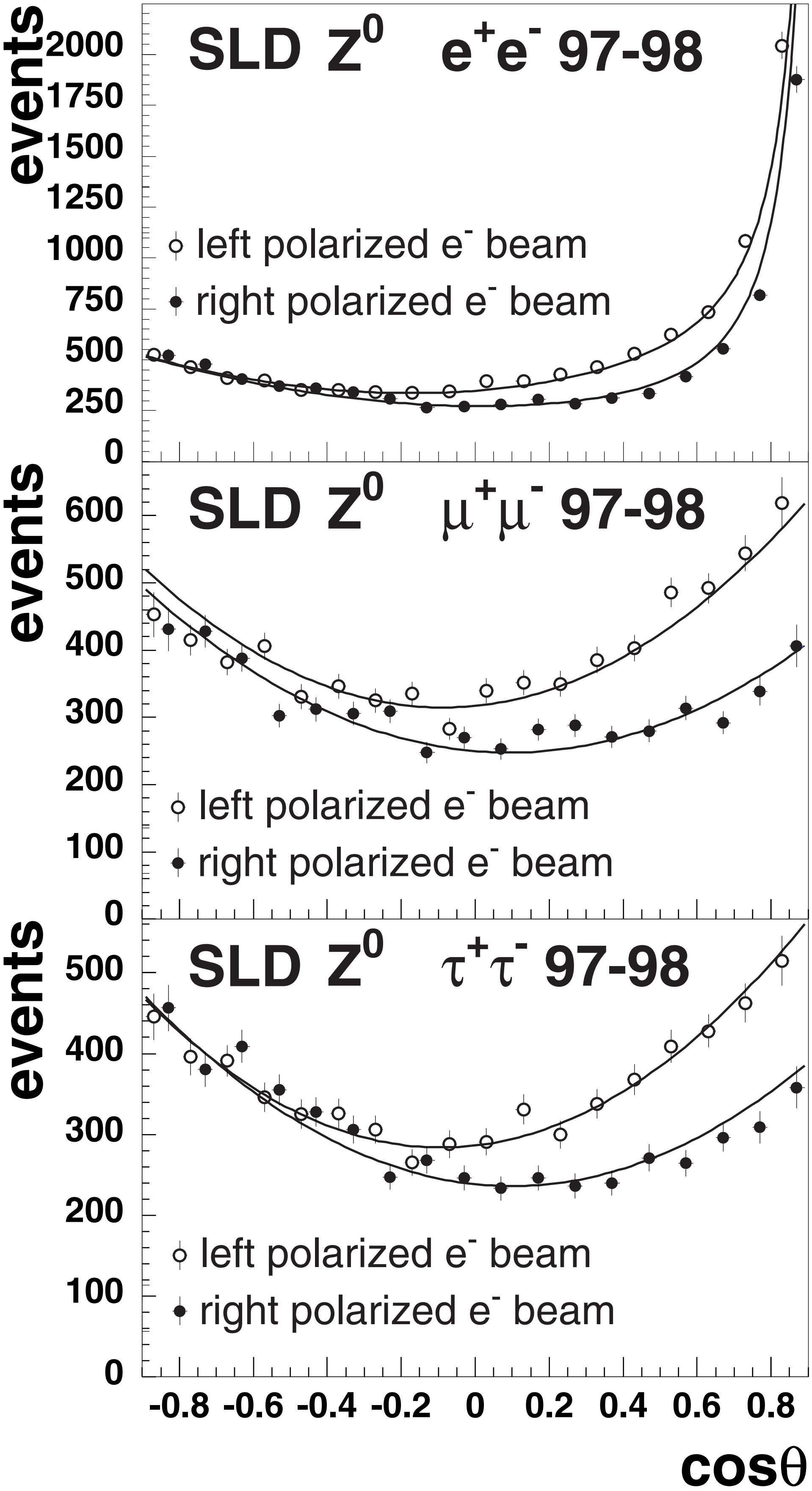
Method 1: angular distribution



so

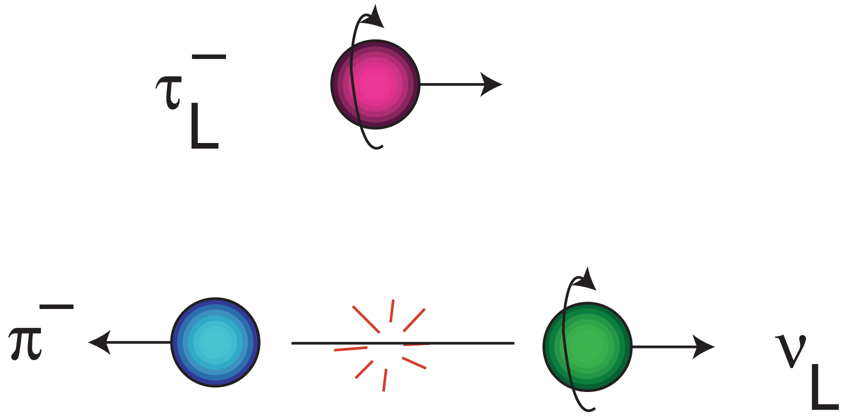
$$\frac{d\sigma}{d\cos\theta} = \begin{cases} (1+\cos\theta)^2 & \text{for } e^-_L \Rightarrow \mu^-_L \\ (1-\cos\theta)^2 & \text{for } e^-_L \Rightarrow \mu^-_R \end{cases}$$

polarization average: $(1+\cos^2\theta)$



SLD Z^0 e$^+$e$^-$ 97-98
SLD Z^0 μ$^+$μ$^-$ 97-98
SLD Z^0 τ$^+$τ$^-$ 97-98
events
○ left polarized e$^-$ beam
● right polarized e$^-$ beam
0
250
500
750
1000
1250
1500
1750
2000
100
200
300
400
500
600
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
cosθ

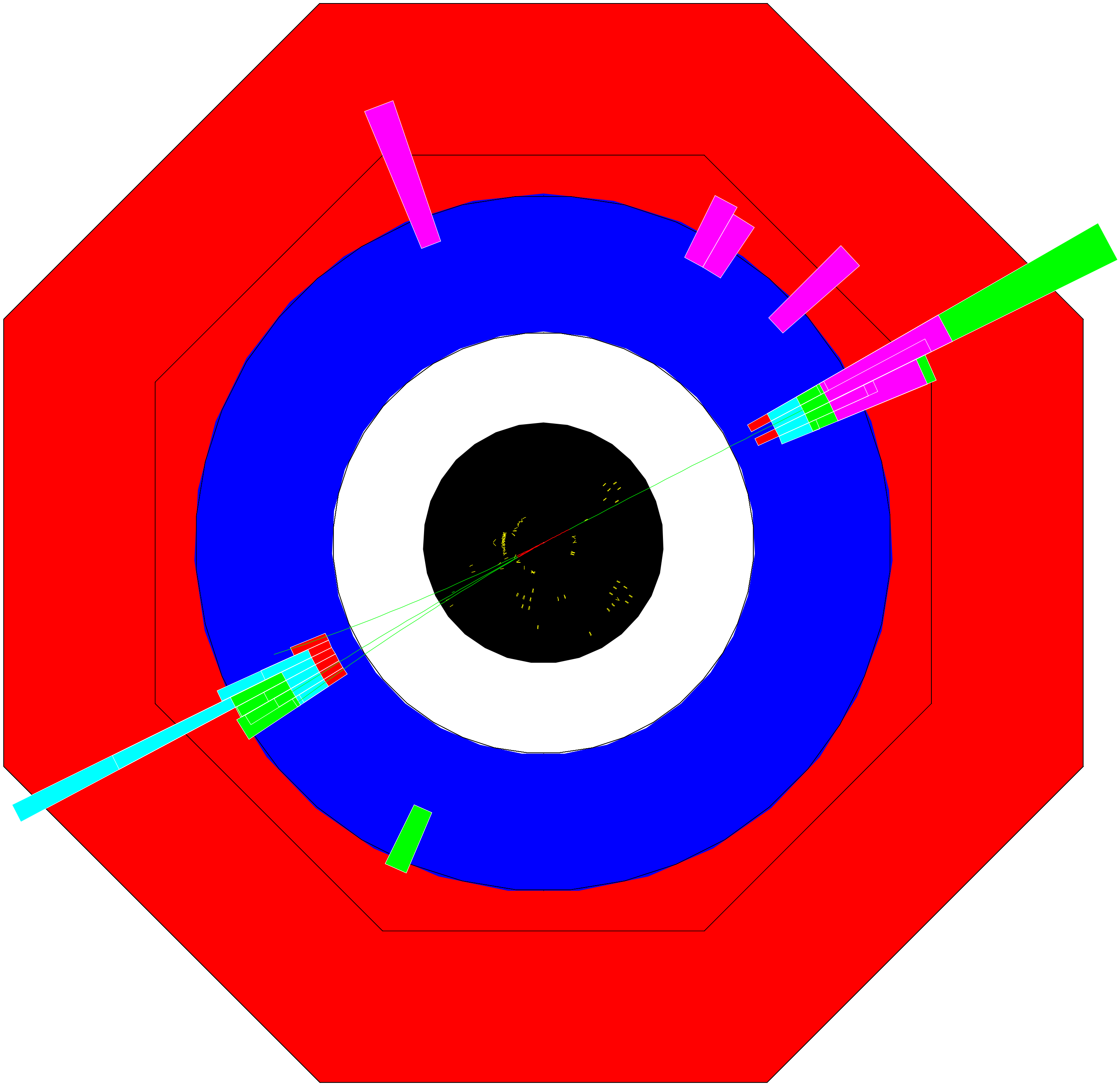
Method 2: decay distribution of τ



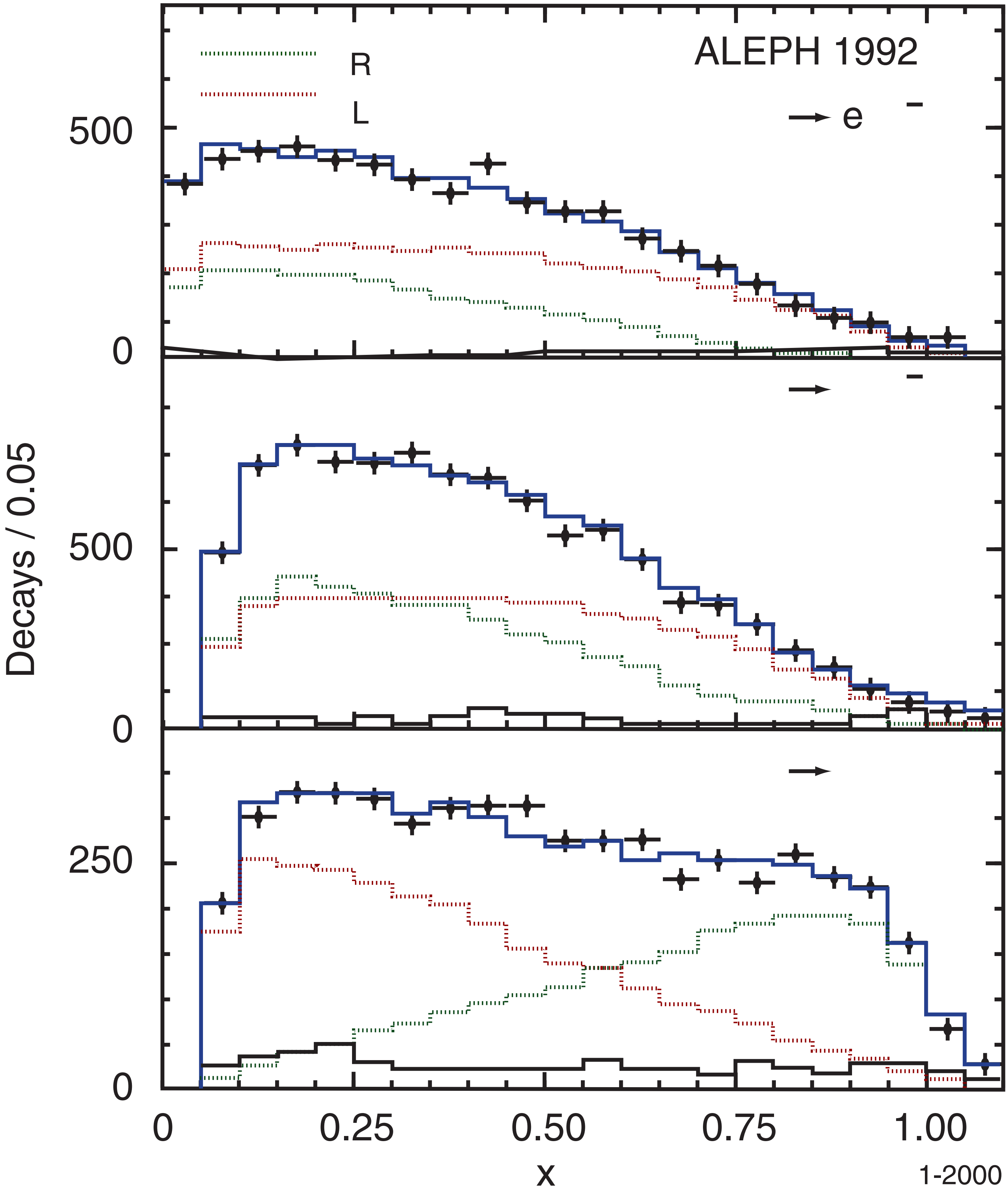
$\tau^-_L \Rightarrow$ fast e^-, fast μ^-, slow π^-

$\tau^-_R \Rightarrow$ slow e^-, slow μ^-, fast π^-

$e^+e^- \to Z^0 \to \tau^+\tau^-$



SLD



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Method 3: Initial state polarization

Make separate e^-_L and e^-_R beams,
and measure the asymmetry of

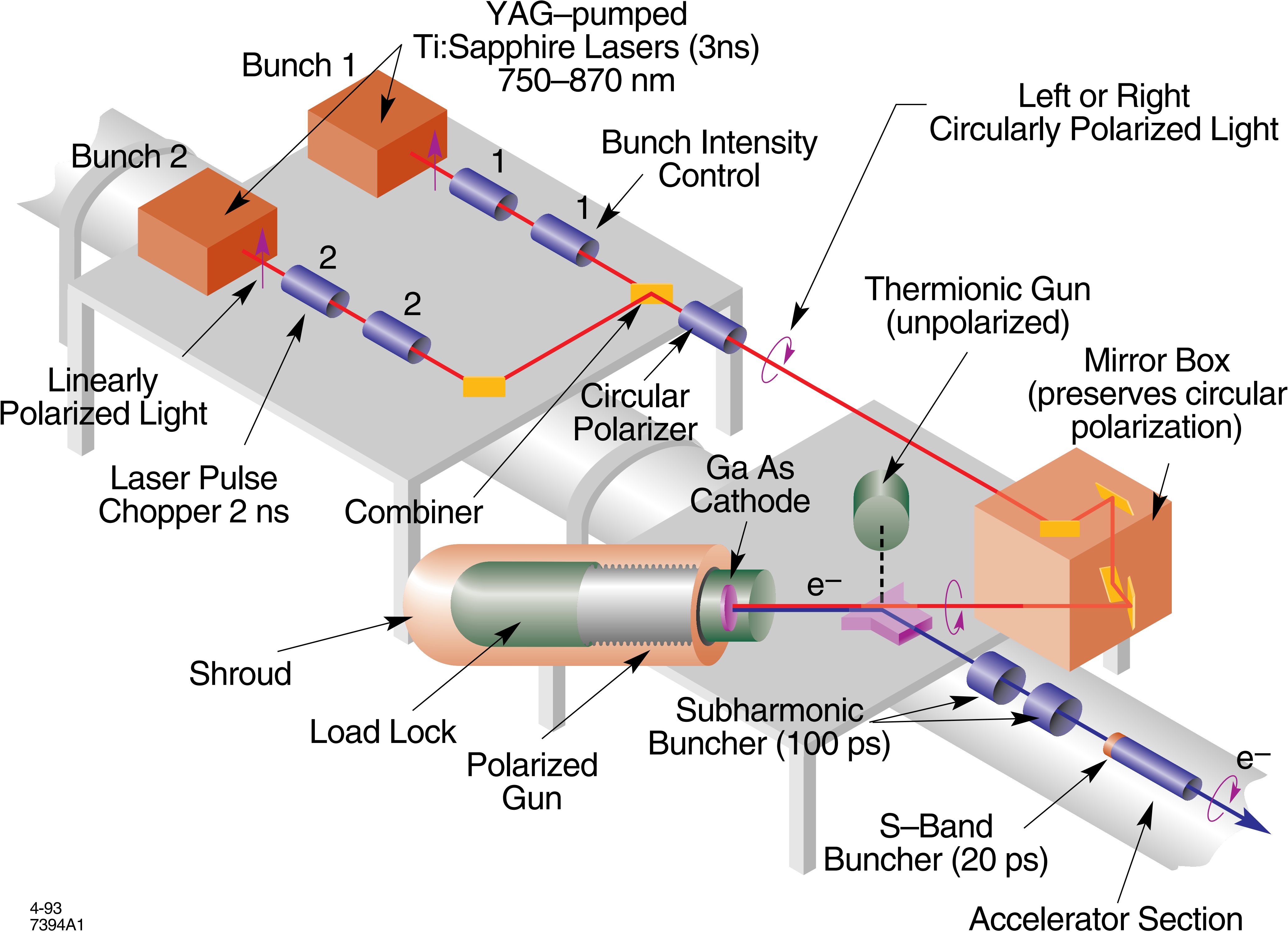
$$\sigma\,(e^-_{L,R}\, e^+ \to Z^0)$$

by counting.

SLD:

$$A_e = 0.1506\ (24)$$

$$\sin^2\theta_W = 0.23097\ (27)$$

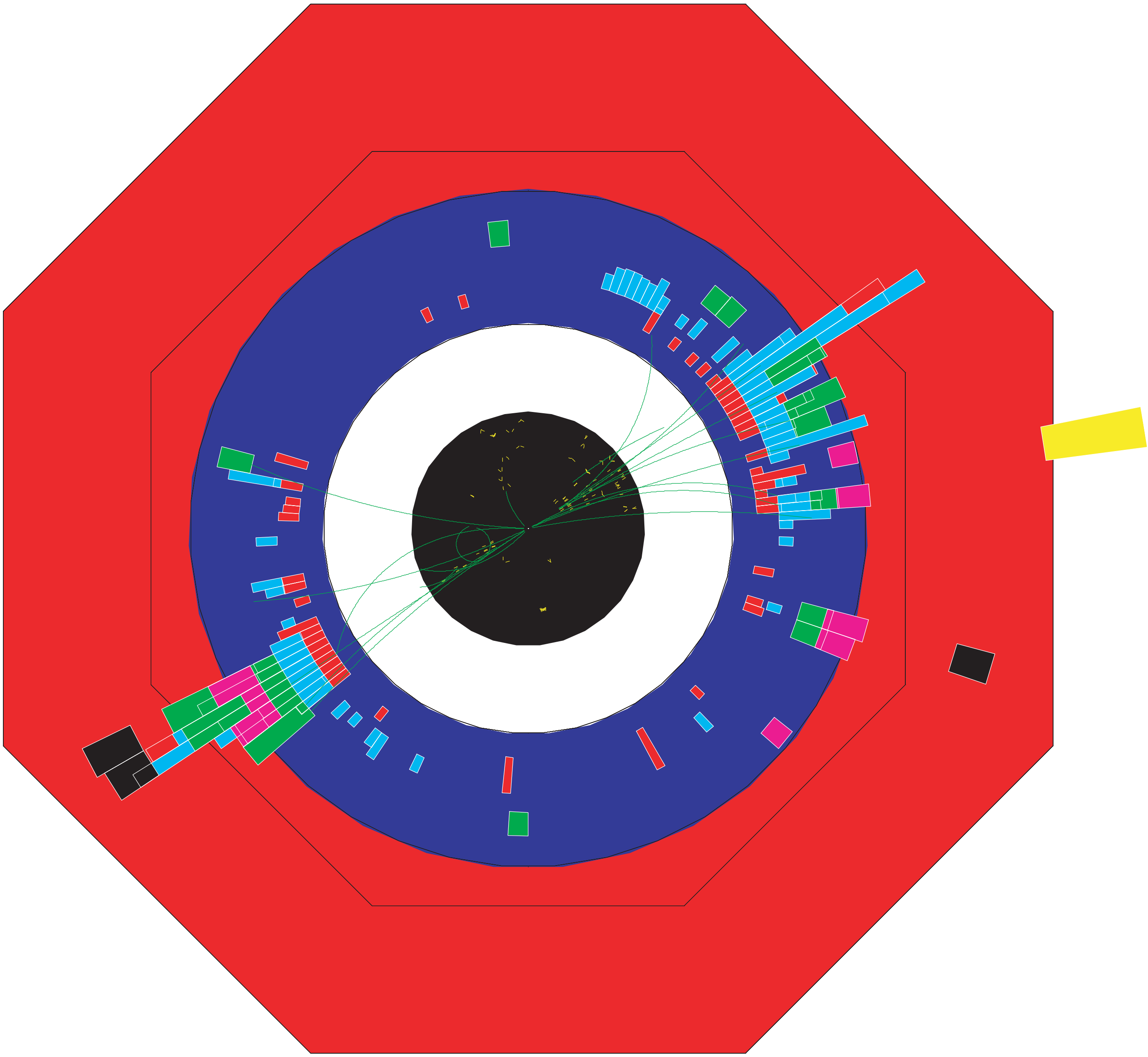

YAG–pumped
Ti:Sapphire Lasers (3ns)
750–870 nm
Bunch 1
Bunch 2
1
1
2
2
Bunch Intensity
Control
Left or Right
Circularly Polarized Light
Linearly
Polarized Light
Laser Pulse
Chopper 2 ns
Combiner
Circular
Polarizer
Thermionic Gun
(unpolarized)
Mirror Box
(preserves circular
polarization)
Ga As
Cathode
e−
Shroud
Load Lock
Polarized
Gun
Subharmonic
Buncher (100 ps)
S–Band
Buncher (20 ps)
e−
Accelerator Section
4-93
7394A1

It is not clear how to do a comparable analysis for quarks:

It is not so obvious how to measure the quark spin, since quarks are seen only as constituents of hadrons.

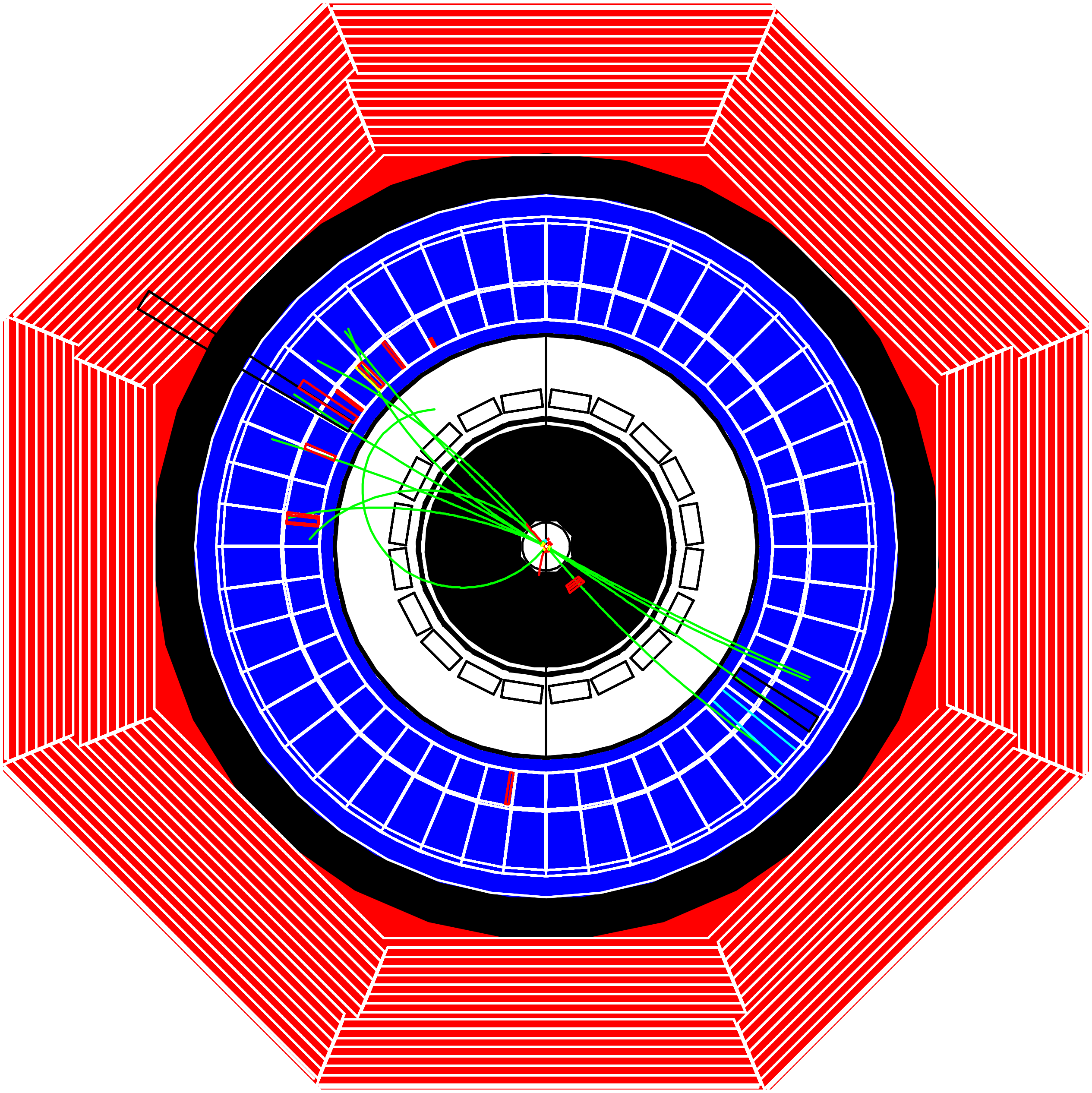
It is not so obvious how to tell u quarks from d quarks.

$$e^{+}e^{-} \rightarrow Z^{0} \rightarrow q\,\bar{q}$$



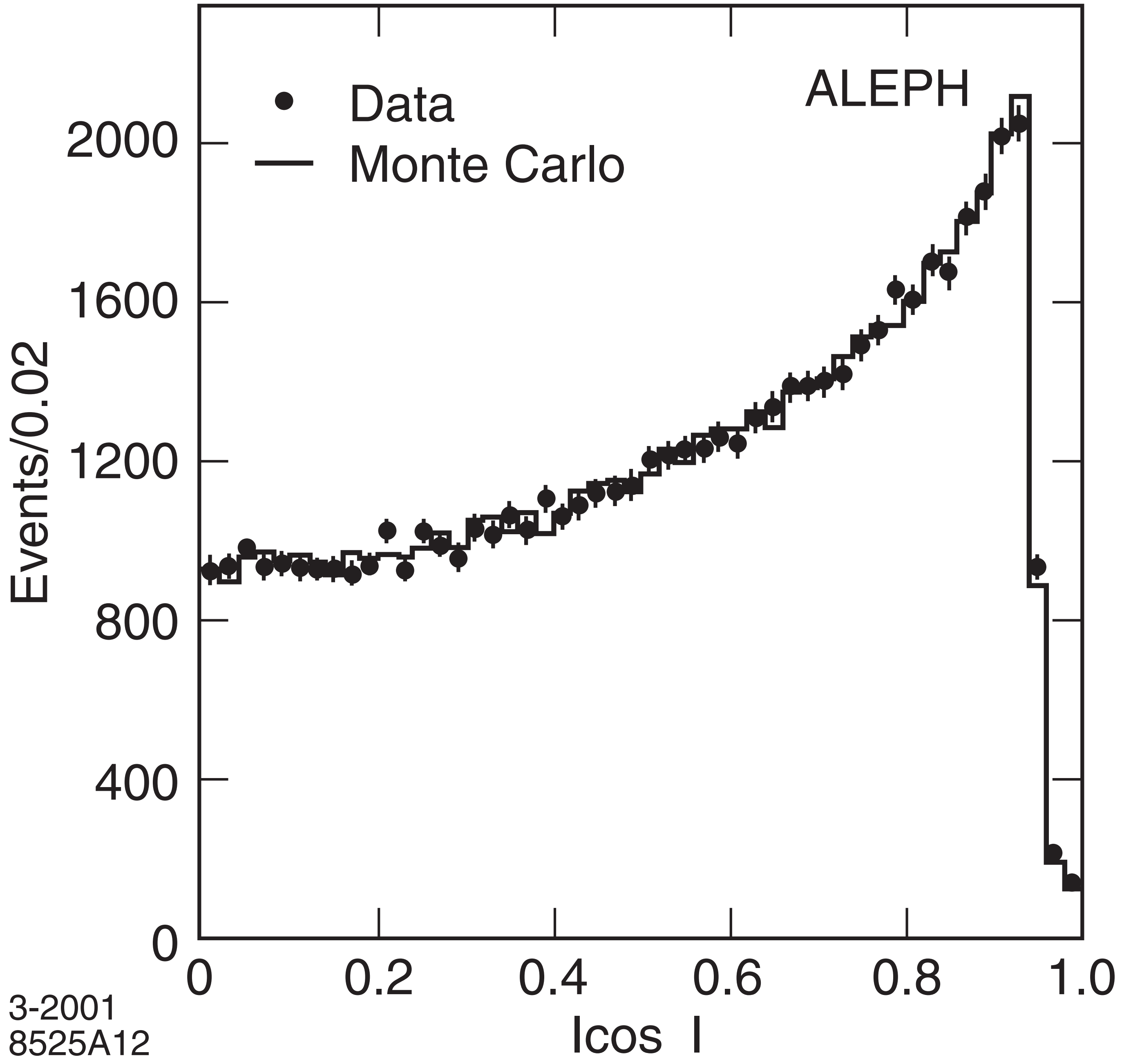
SLD

$e^+ e^- \rightarrow Z^0 \rightarrow q\,\bar{q}$

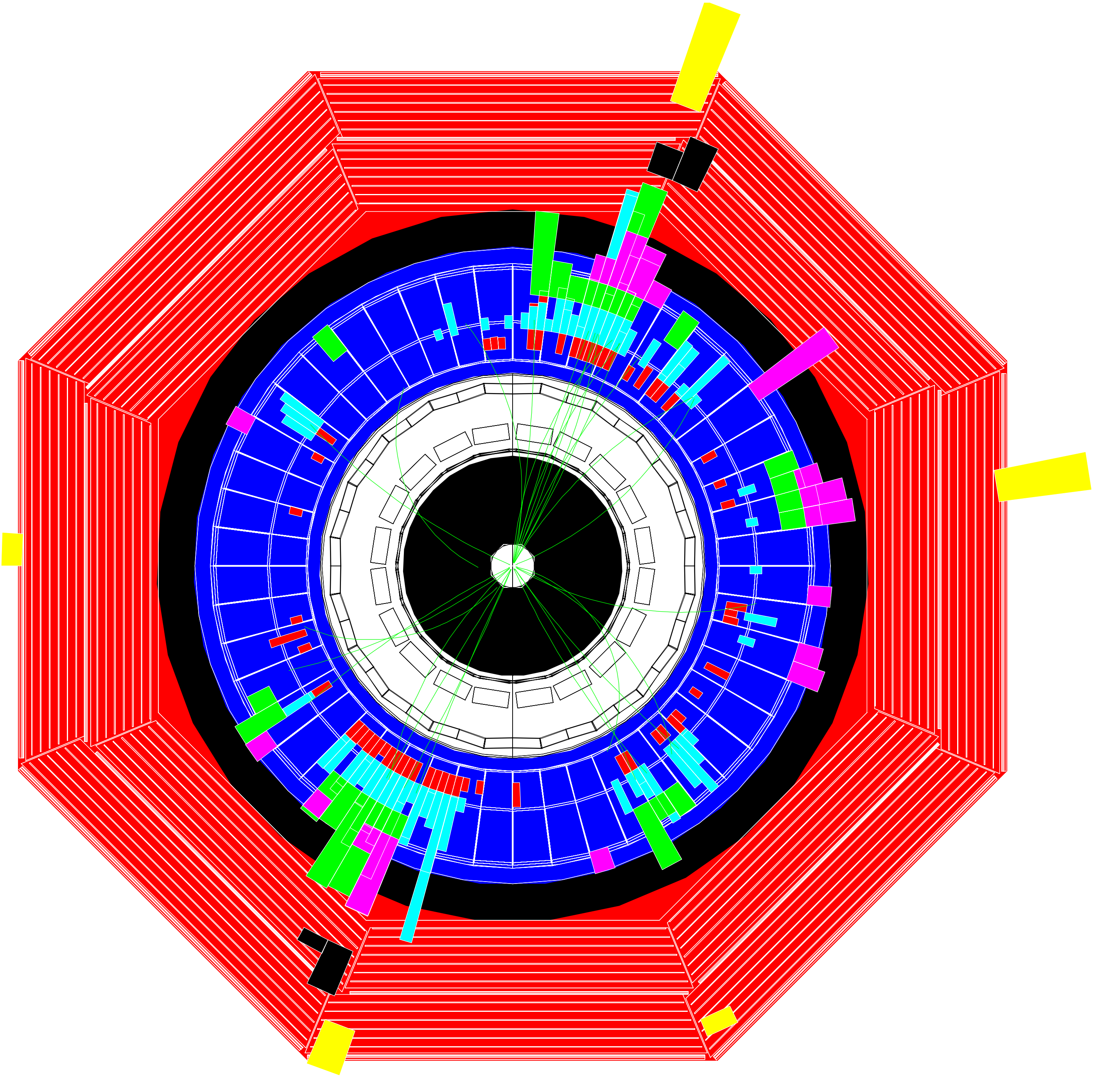


SLD

The axes of these events follow a $(1 + \cos^2\theta)$ distribution.



$e^+ e^- \rightarrow Z^0 \rightarrow q\,\bar{q}\,g$



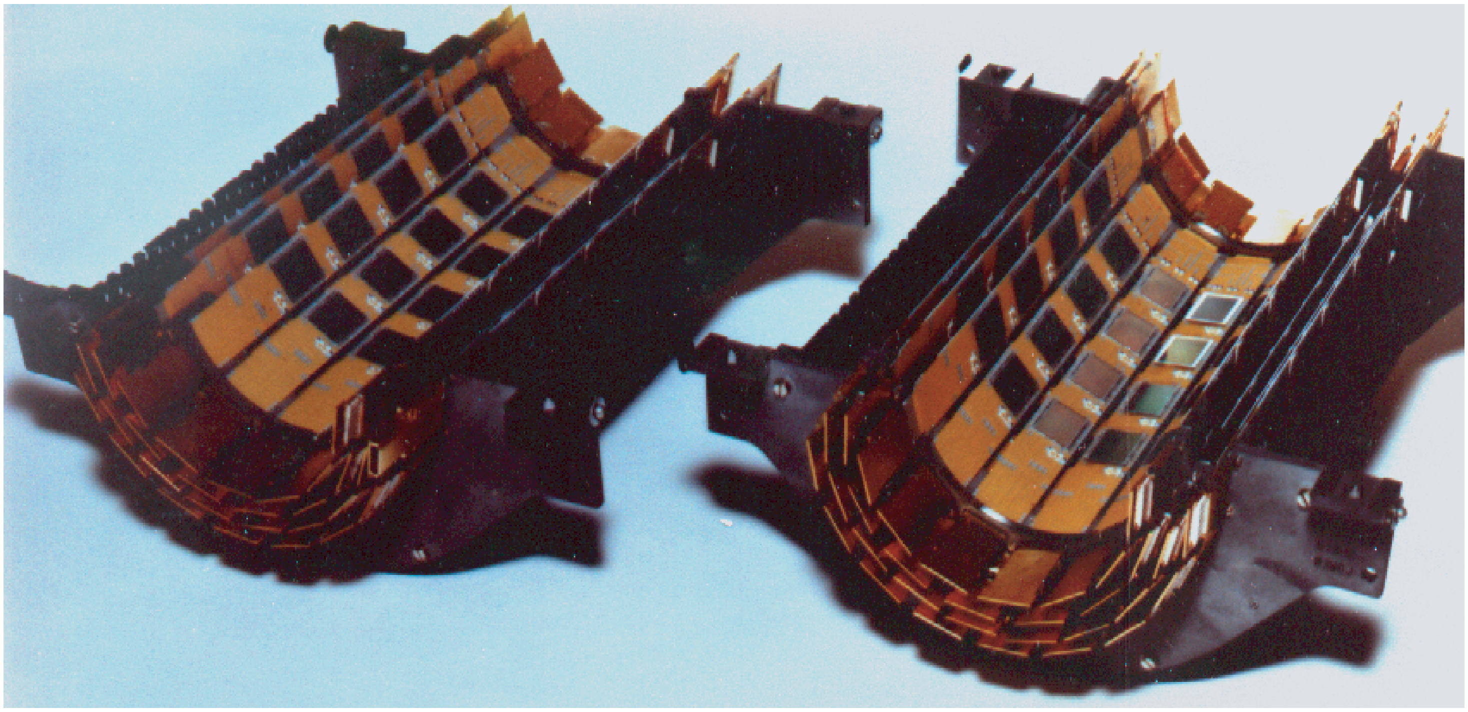
SLD

To distinguish species, use the fact that heavy species have definite, measurable, lifetimes:

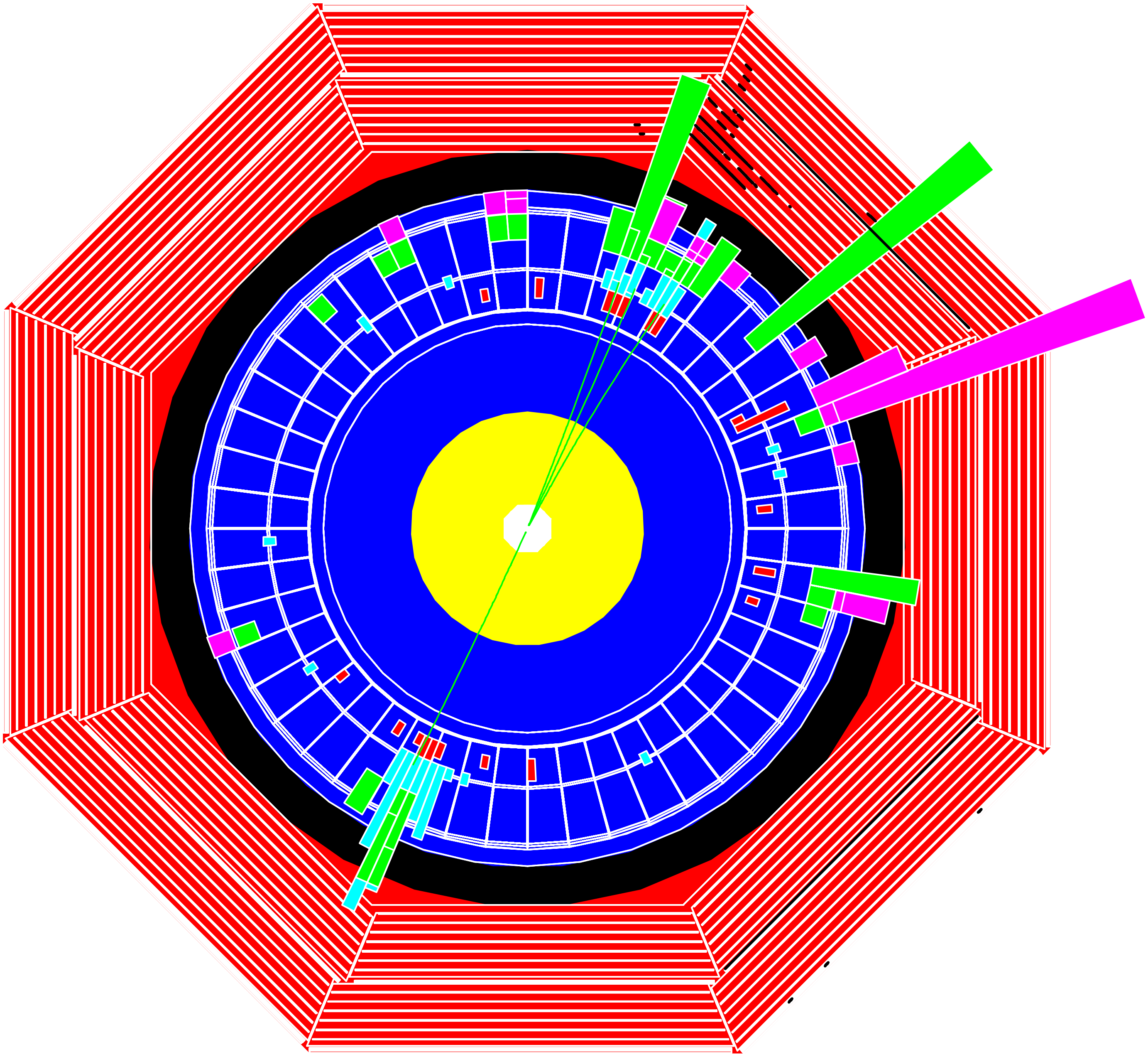
	τ	$c\,\tau$
τ^-	0.29 ps	0.09 mm
c (D^0)	0.41 ps	0.12 mm
b (B^0)	1.55 ps	4.6 mm

Even inside a 3-story-high particle detector, there should be a way to measure such distances.

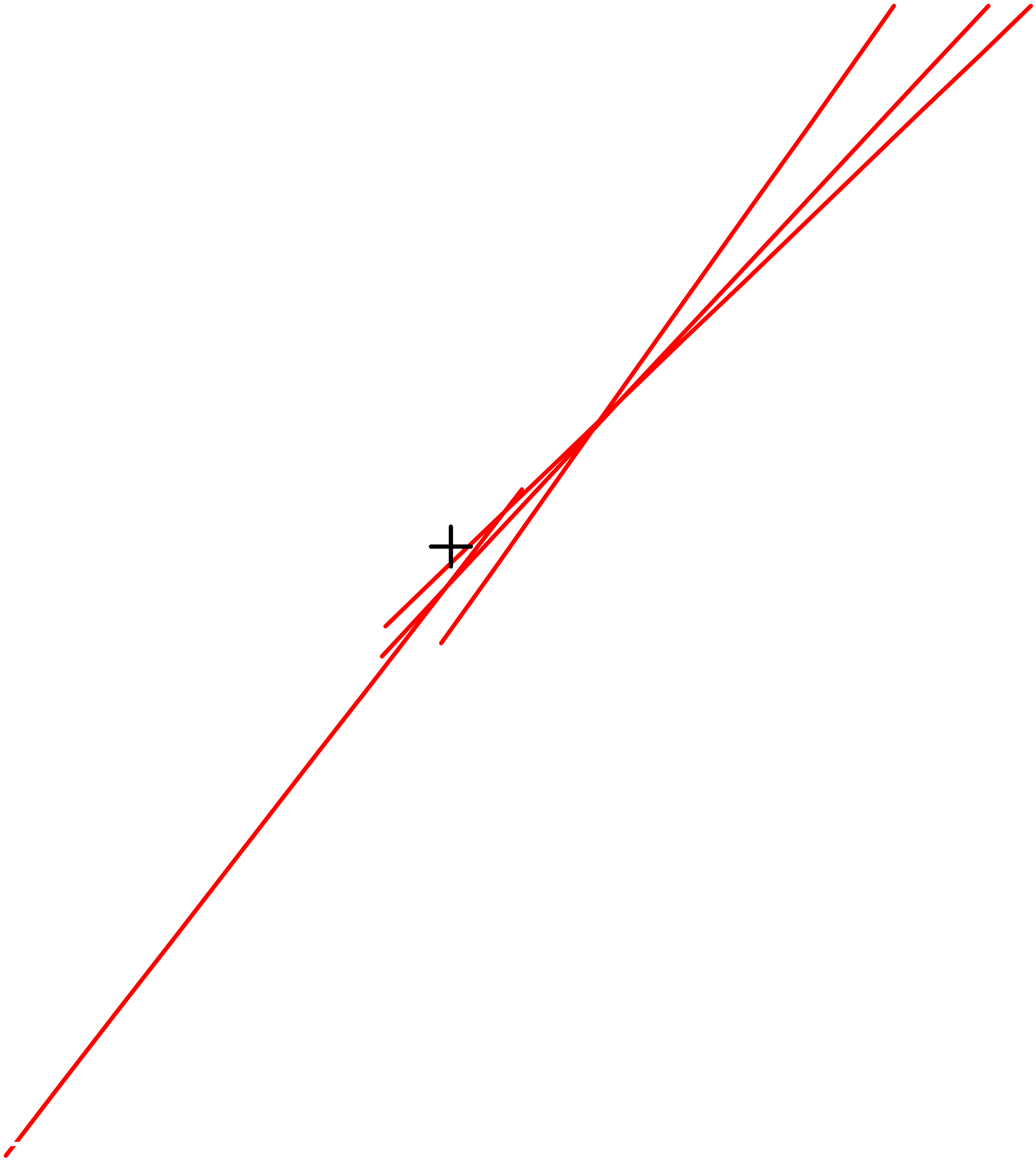
The CCD vertex detector of the SLD: VDX-2



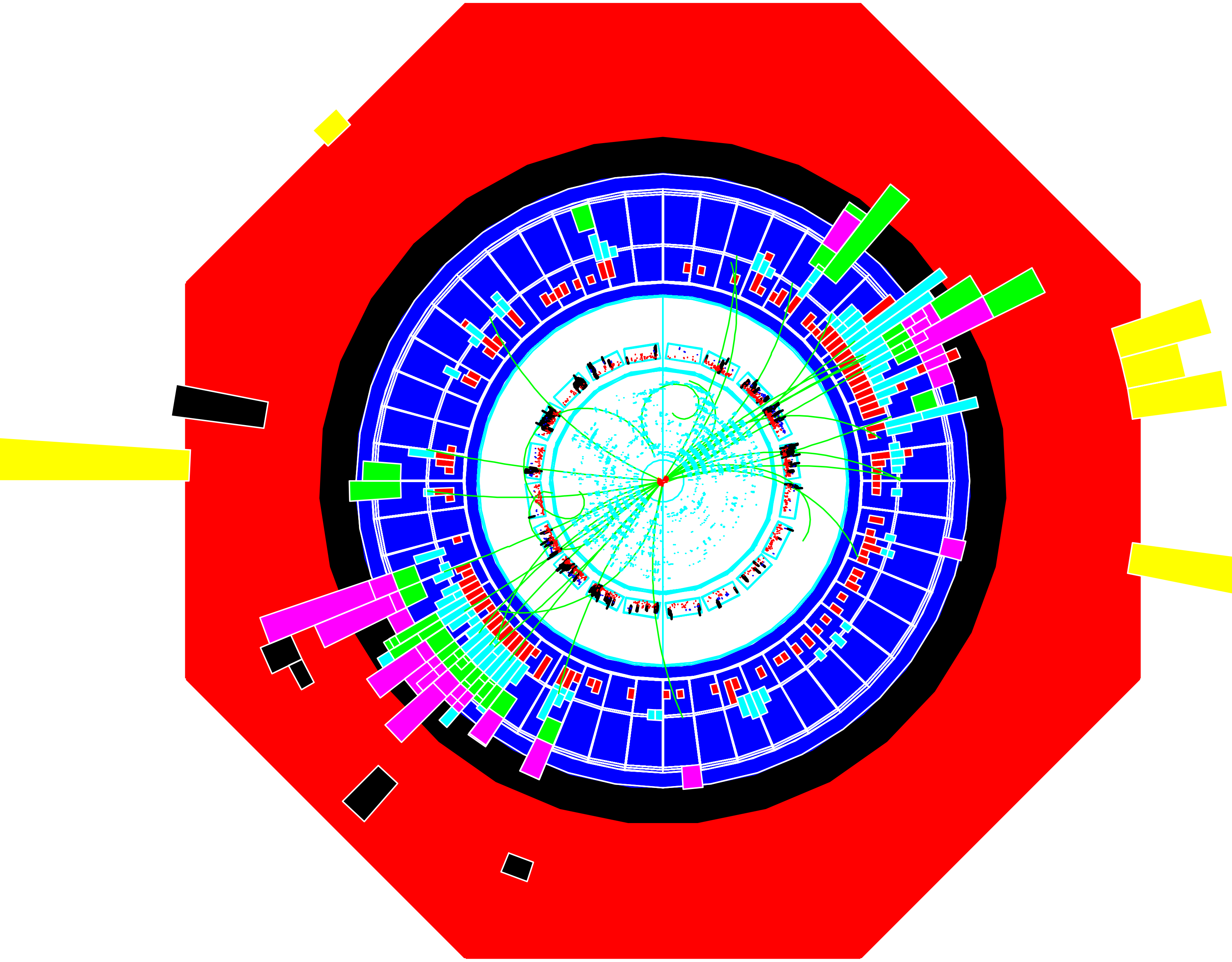
$e^+e^- \to Z^0 \to \tau^+\tau^-$



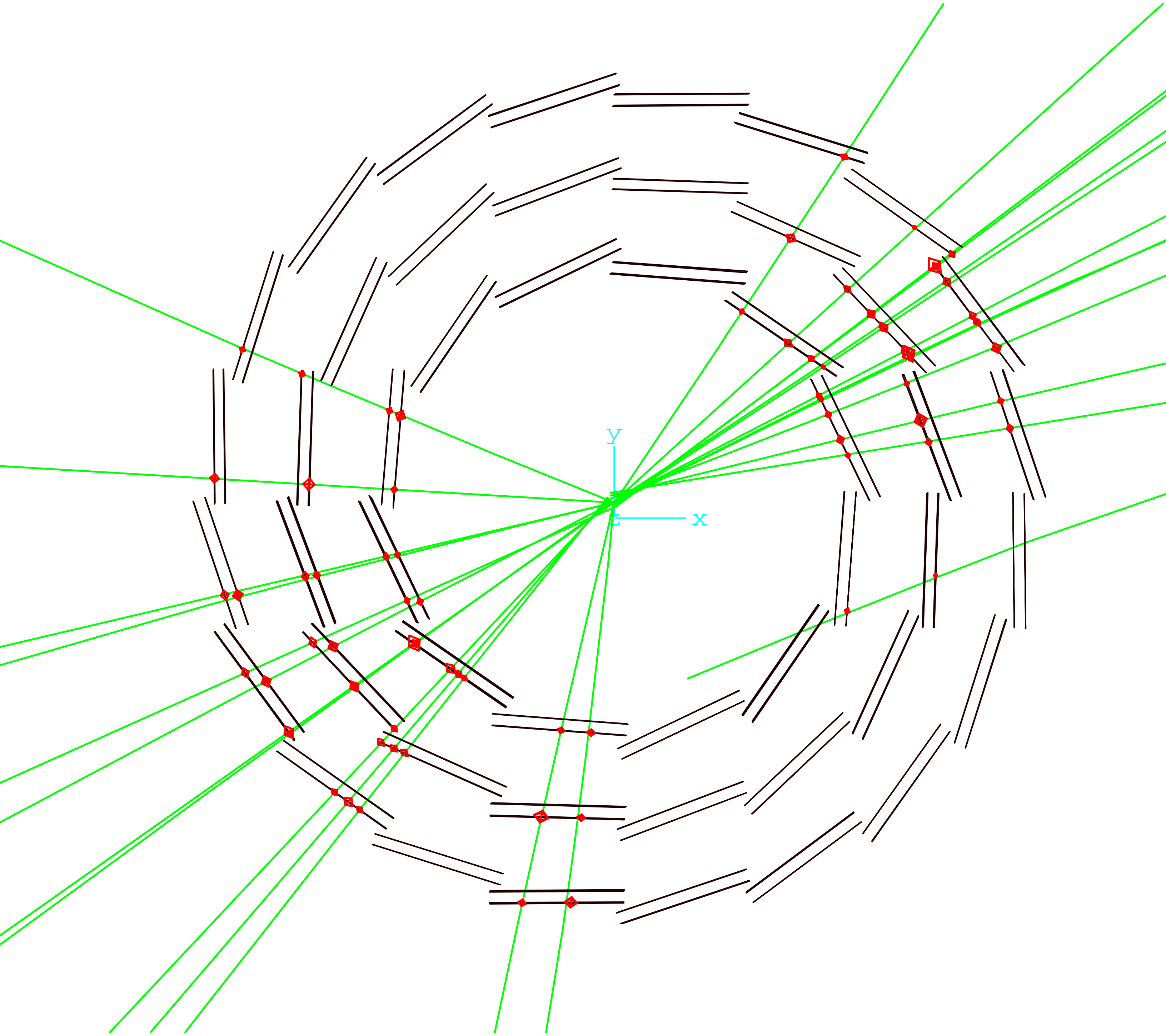
SLD



$e^+ e^- \rightarrow Z^0 \rightarrow b\,\bar{b}$



SLD

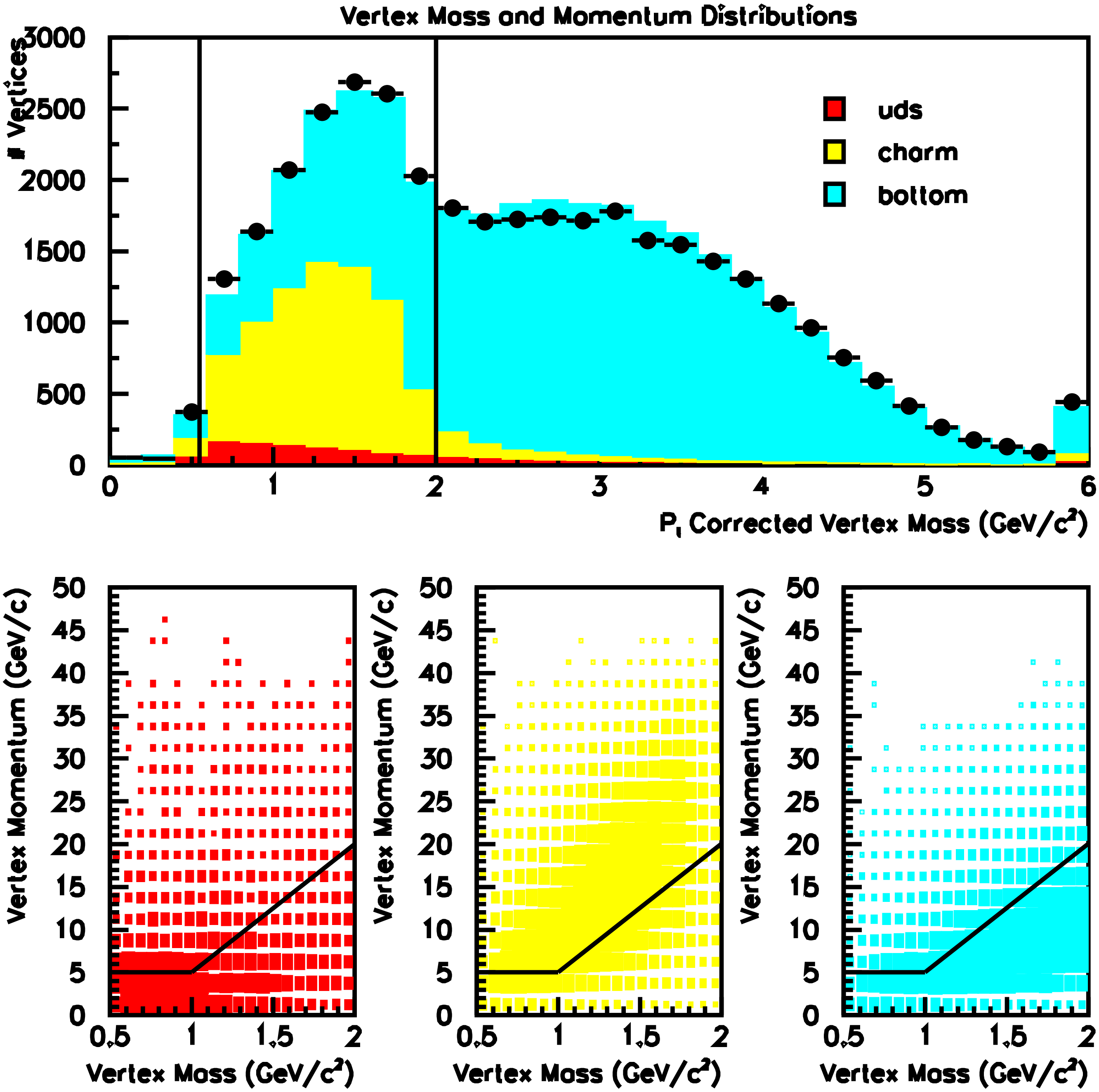

y
x
z

Vertices with a large $c\tau$ should also show a decay to system of large mass

($m_D = 1.86$ GeV, $m_B = 5.28$ GeV)

Selecting vertices with observed large mass gives a very pure sample of

$$e^+ e^- \rightarrow b\,\bar{b}$$


Vertex Mass and Momentum Distributions
Vertices
3000
2500
2000
1500
1000
500
0
0
1
2
3
4
5
6
P_t Corrected Vertex Mass (GeV/c^2)
uds
charm
bottom
Vertex Momentum (GeV/c)
50
45
40
35
30
25
20
15
10
5
0
0.5
1
1.5
2
Vertex Mass (GeV/c^2)

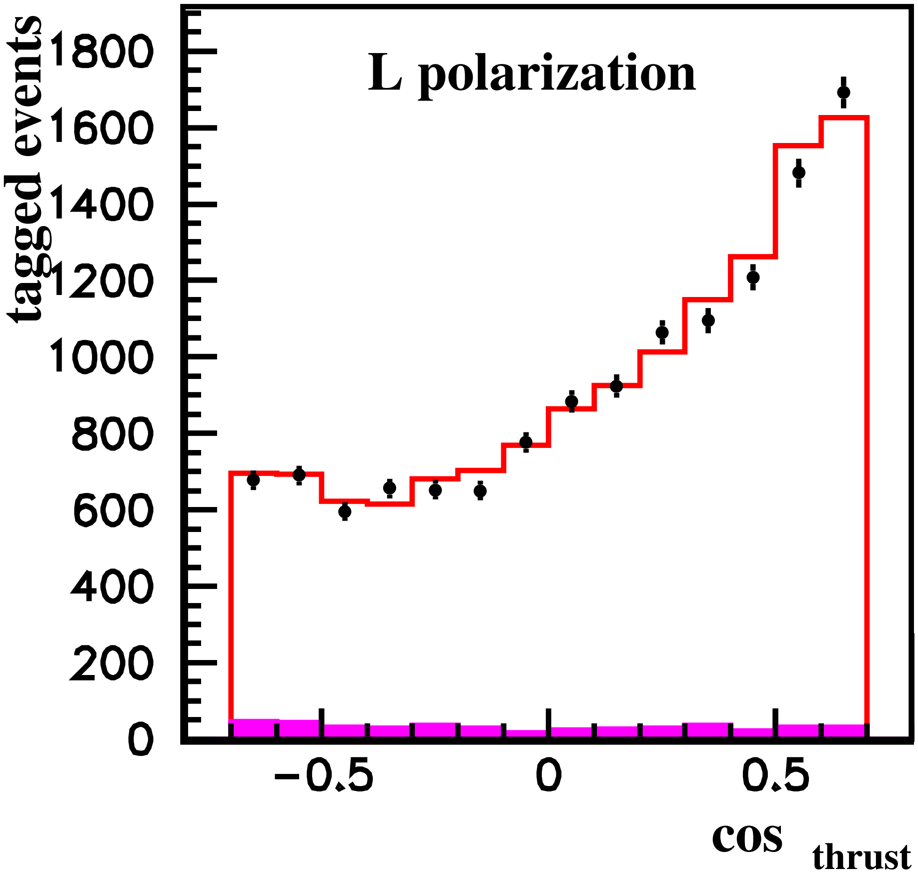
Now recall

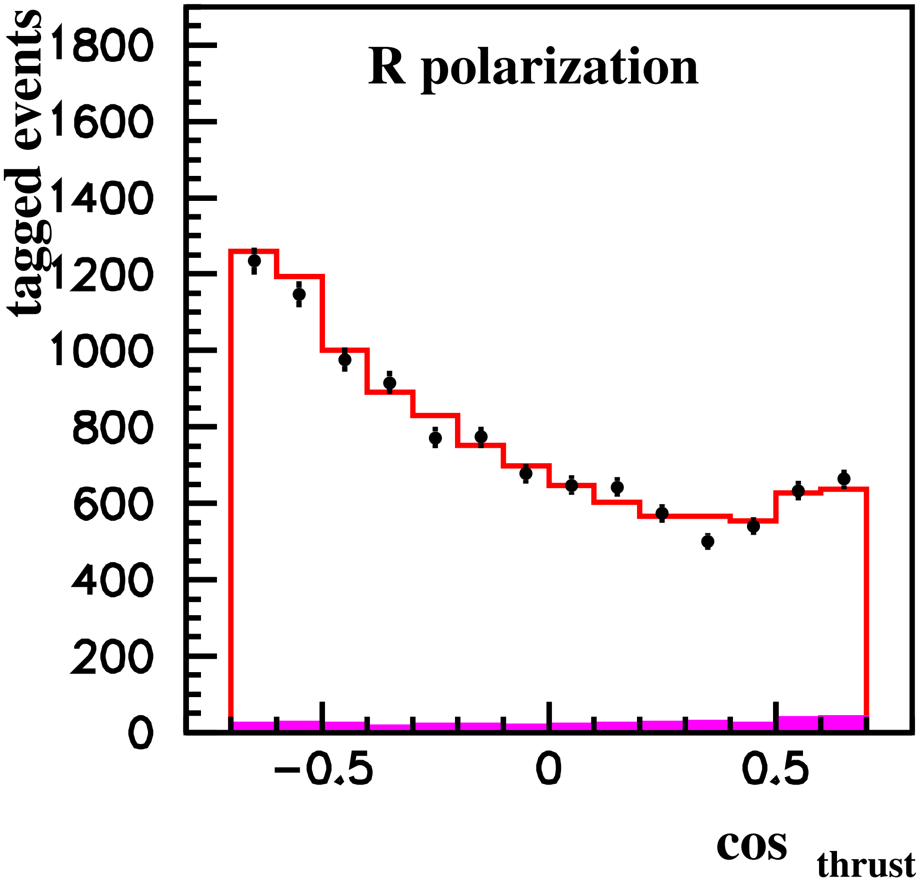
$$\frac{d\,\sigma}{d\,\cos}\,(\,e^-_L e^+ \rightarrow b_L\,\bar{b}_R) \;\sim\; (1 + \cos\;\theta)^2$$

$$\frac{d\,\sigma}{d\,\cos}\,(\,e^-_L e^+ \rightarrow b_R\,\bar{b}_L\,) \;\sim\; (1 -\;\cos\,\theta)^2$$

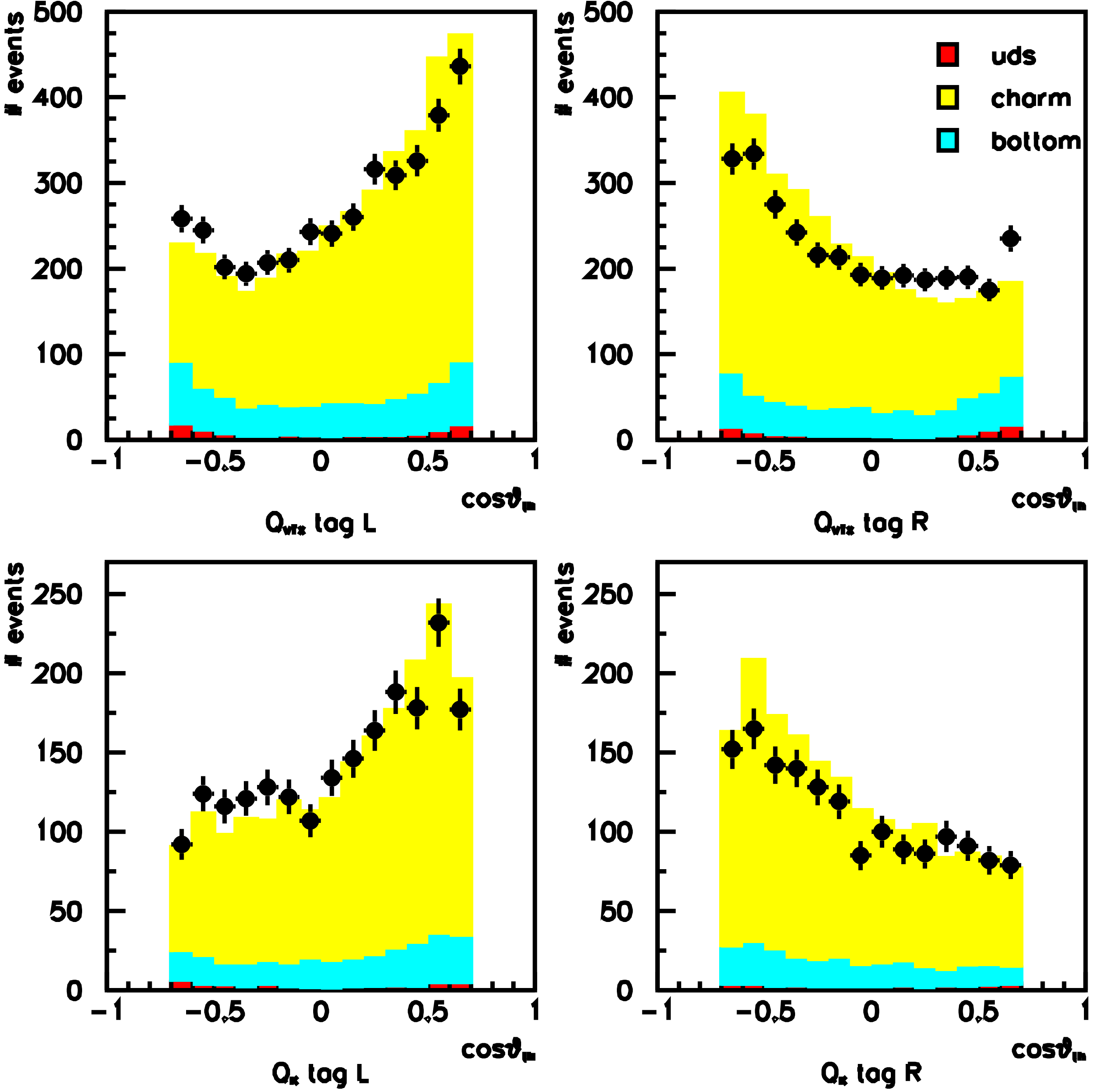
but also $A_b = 0.94$

so using a polarized beam (L or R) should have a profound effect on the angular distribution for Z decay to $b\,\bar{b}$.


L polarization
tagged events
1800
1600
1400
1200
1000
800
600
400
200
0
−0.5
0
0.5
cos thrust

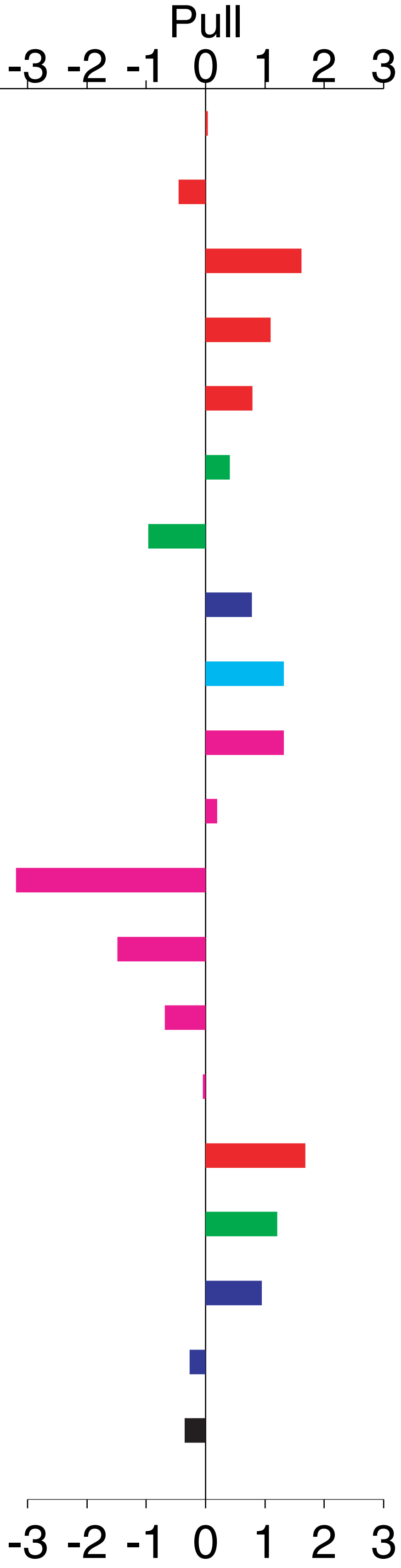

R polarization
tagged events
1800
1600
1400
1200
1000
800
600
400
200
0
−0.5
0
0.5
cos thrust

Inclusive Charm Tag Asymmetries



Winter 2001

	Measurement	Pull
m_Z [GeV]	91.1875 ± 0.0021	.04
$_Z$ [GeV]	2.4952 ± 0.0023	-.46
$^{0}_{hadr}$ [nb]	41.540 ± 0.037	1.62
R_l	20.767 ± 0.025	1.09
$A_{fb}^{0,l}$	0.01714 ± 0.00095	.79
A_e	0.1498 ± 0.0048	.41
A	0.1439 ± 0.0041	-.96
$\sin^2$ $^{lept}_{eff}$	0.2322 ± 0.0010	.78
m_W [GeV]	80.446 ± 0.040	1.32
R_b	0.21664 ± 0.00068	1.32
R_c	0.1729 ± 0.0032	.20
$A_{fb}^{0,b}$	0.0982 ± 0.0017	-3.20
$A_{fb}^{0,c}$	0.0689 ± 0.0035	-1.48
A_b	0.921 ± 0.020	-.68
A_c	0.667 ± 0.026	-.05
A_l	0.1513 ± 0.0021	1.68
$\sin^2$ $_W$	0.2255 ± 0.0021	1.20
m_W [GeV]	80.452 ± 0.062	.95
m_t [GeV]	174.3 ± 5.1	-.27
$^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-.36



LEP Electroweak Working Group

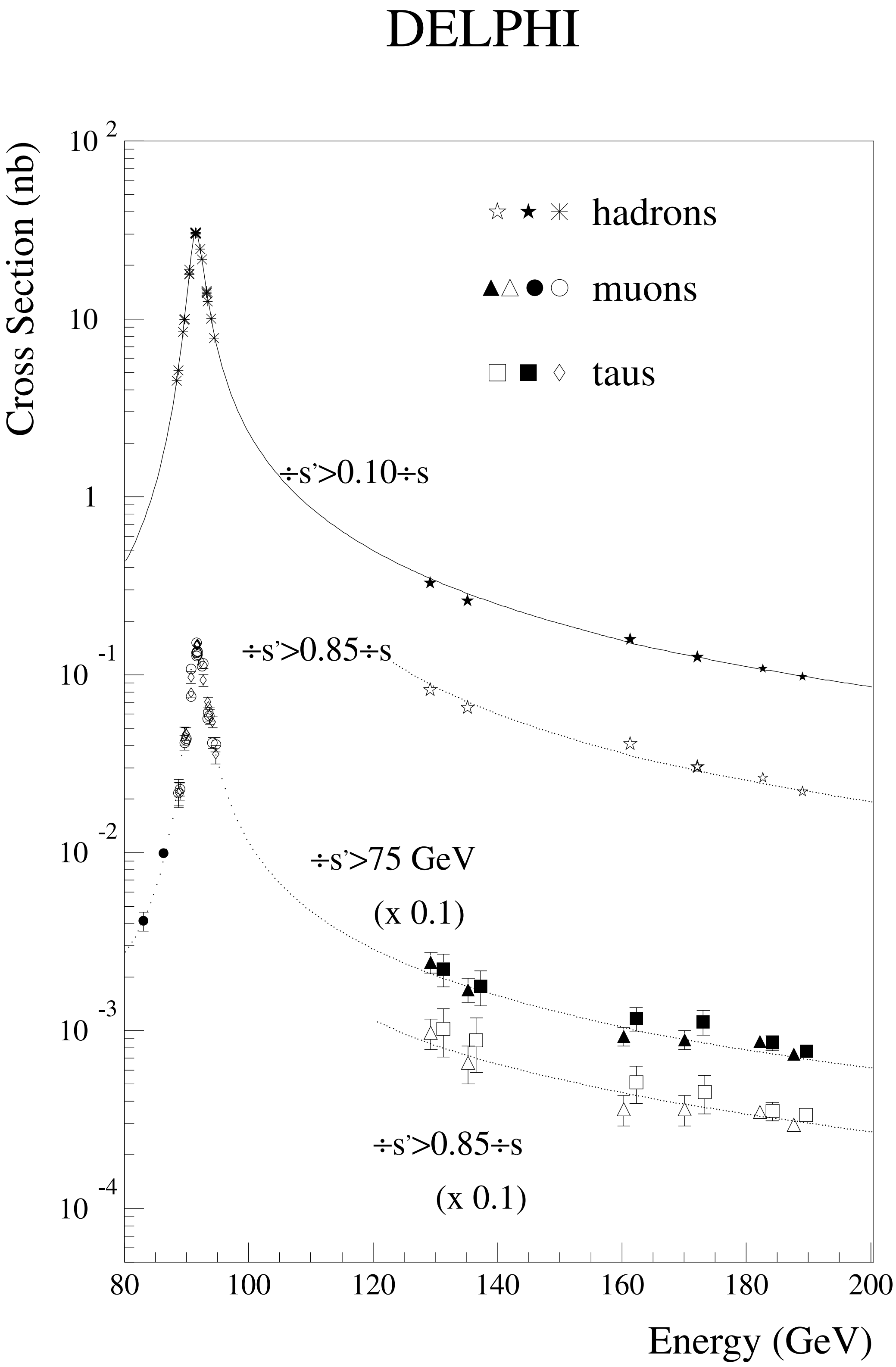
A recent contribution:

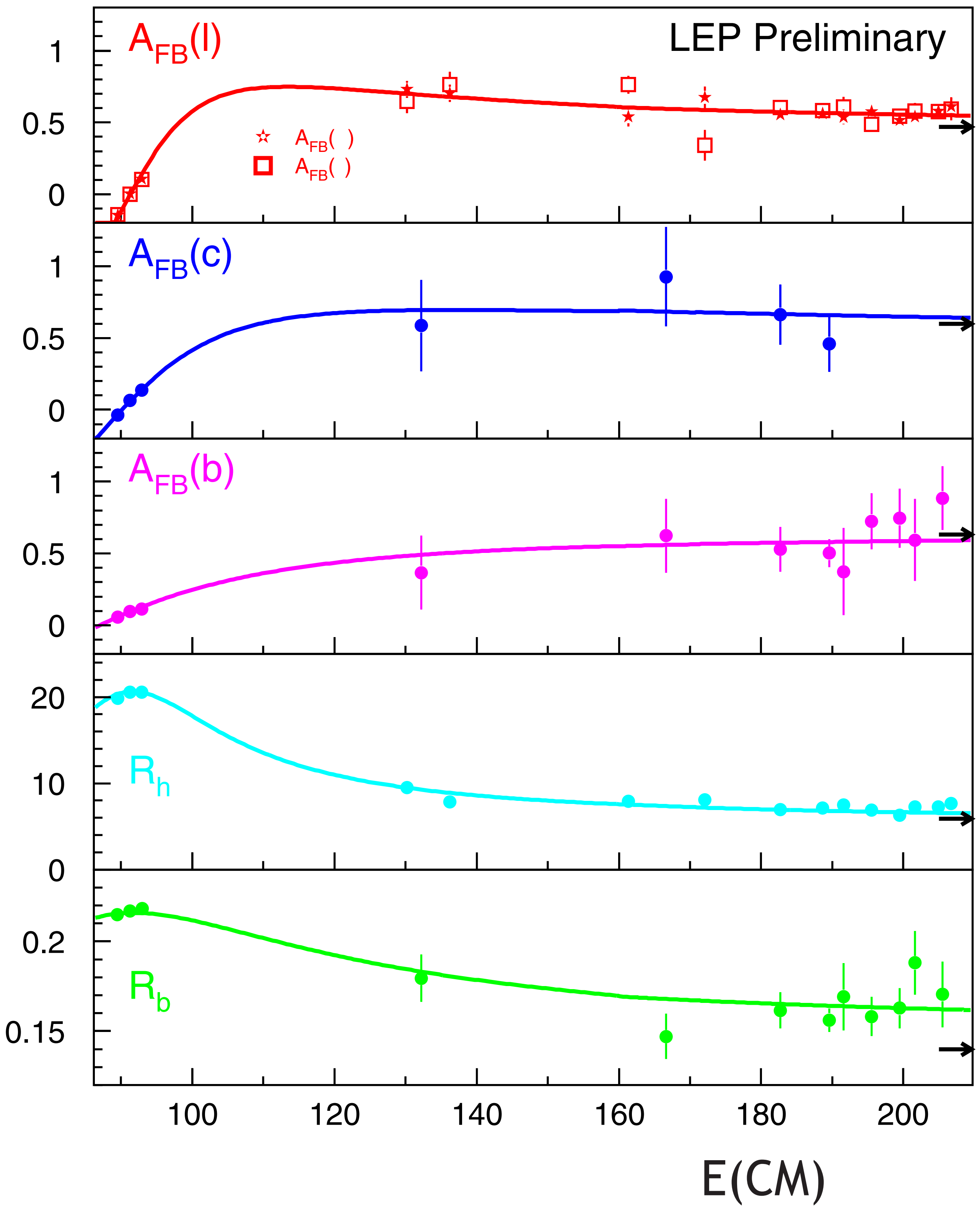
measurements by the four LEP experiments of $e^+ e^-$ cross sections up to 200 GeV.

At asymptotic energies, where spontaneous symmetry breaking can be neglected:

$$\sigma \sim | \cos^2\theta_W \, T^3_e T^3_f + \sin^2\theta_W \, Y_e Y_f |^2$$

At 200 GeV, we already come very close to this state.

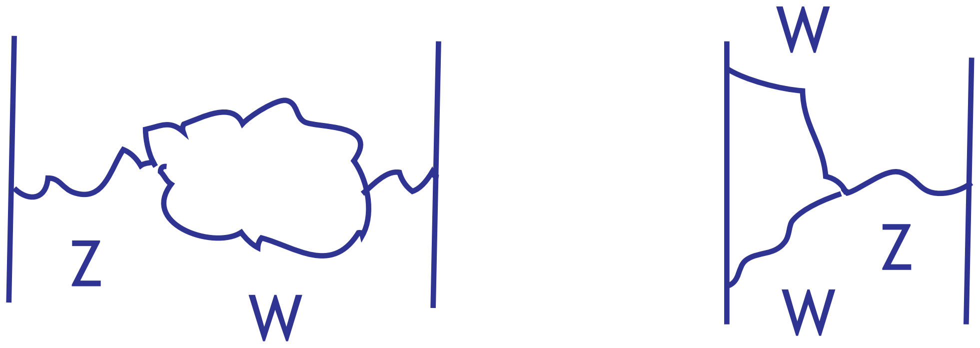

DELPHI
Cross Section (nb)
10 2
10
1
10 -1
10 -2
10 -3
10 -4
☆ ★ ✳ hadrons
▲△ ● ○ muons
□ ■ ◊ taus
÷s'>0.10÷s
÷s'>0.85÷s
÷s'>75 GeV
(x 0.1)
÷s'>0.85÷s
(x 0.1)
80
100
120
140
160
180
200
Energy (GeV)



data compilation by M. Hildreth

In all, a large number of observables are in excellent agreement with the predictions of the Standard Model.

The level of agreement requires taking account of order - α electroweak radiative corrections:



What have we learned?

1. Quarks and leptons are real!

   We can directly manipulate their scattering and spin

2. The nature of weak interactions is a solved problem.

   It is time to move on to the next deeper level.

3. We have some clues to the nature of physics at the next level.

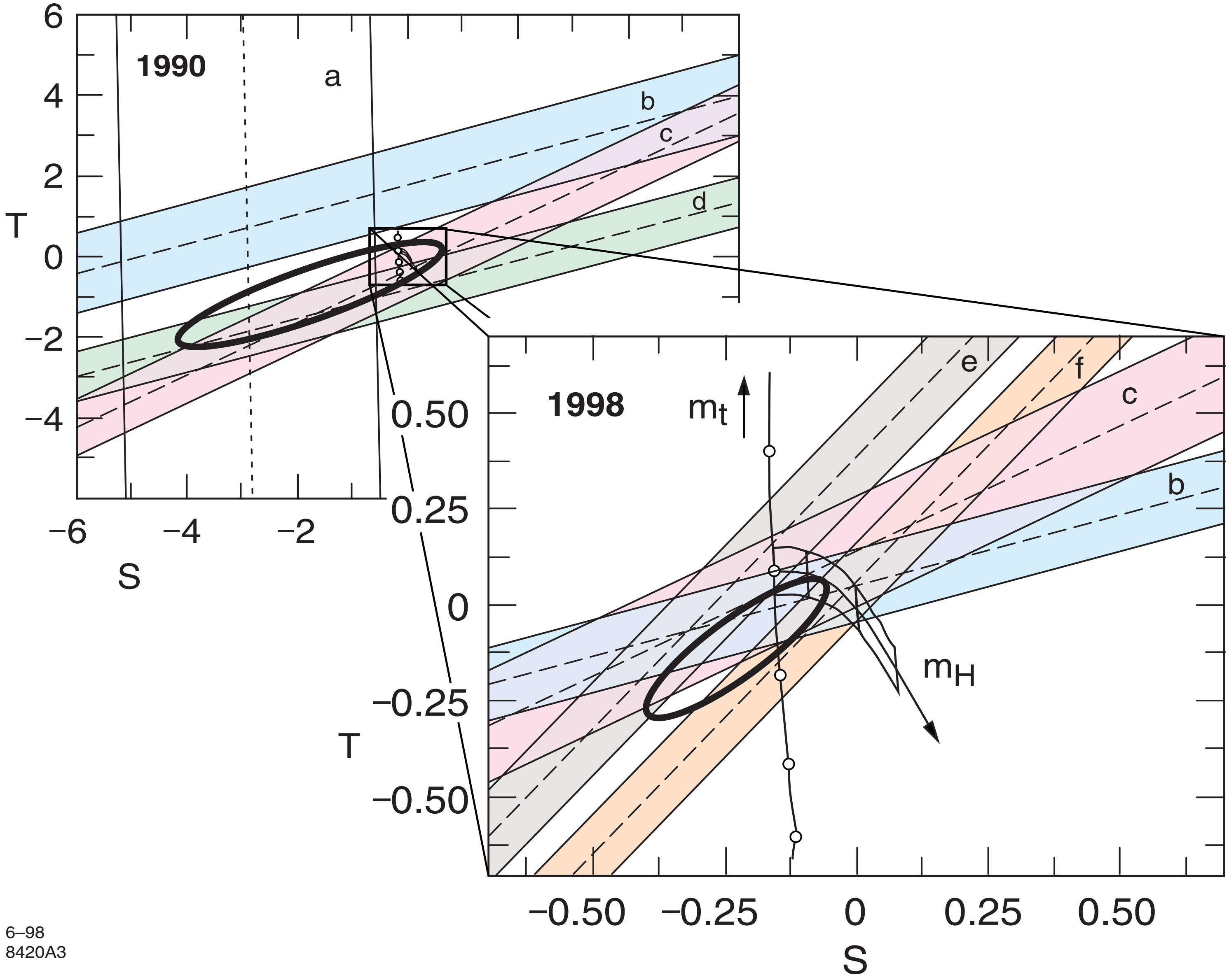
The precision electroweak measurements are sensitive to any new physics that couples to the weak interactions.

new heavy quarks and leptons
Higgs bosons
....

Theories in which these contributions to electroweak corrections do not cancel are excluded!

Method of analysis:
parametrize vacuum polarization diagrams by 2 parameters (S, T),
look for a consistent determination

S,T fits from 1990, 1998:



6–98
8420A3

The current S, T fit is in good agreement with

a top quark with the observed mass,

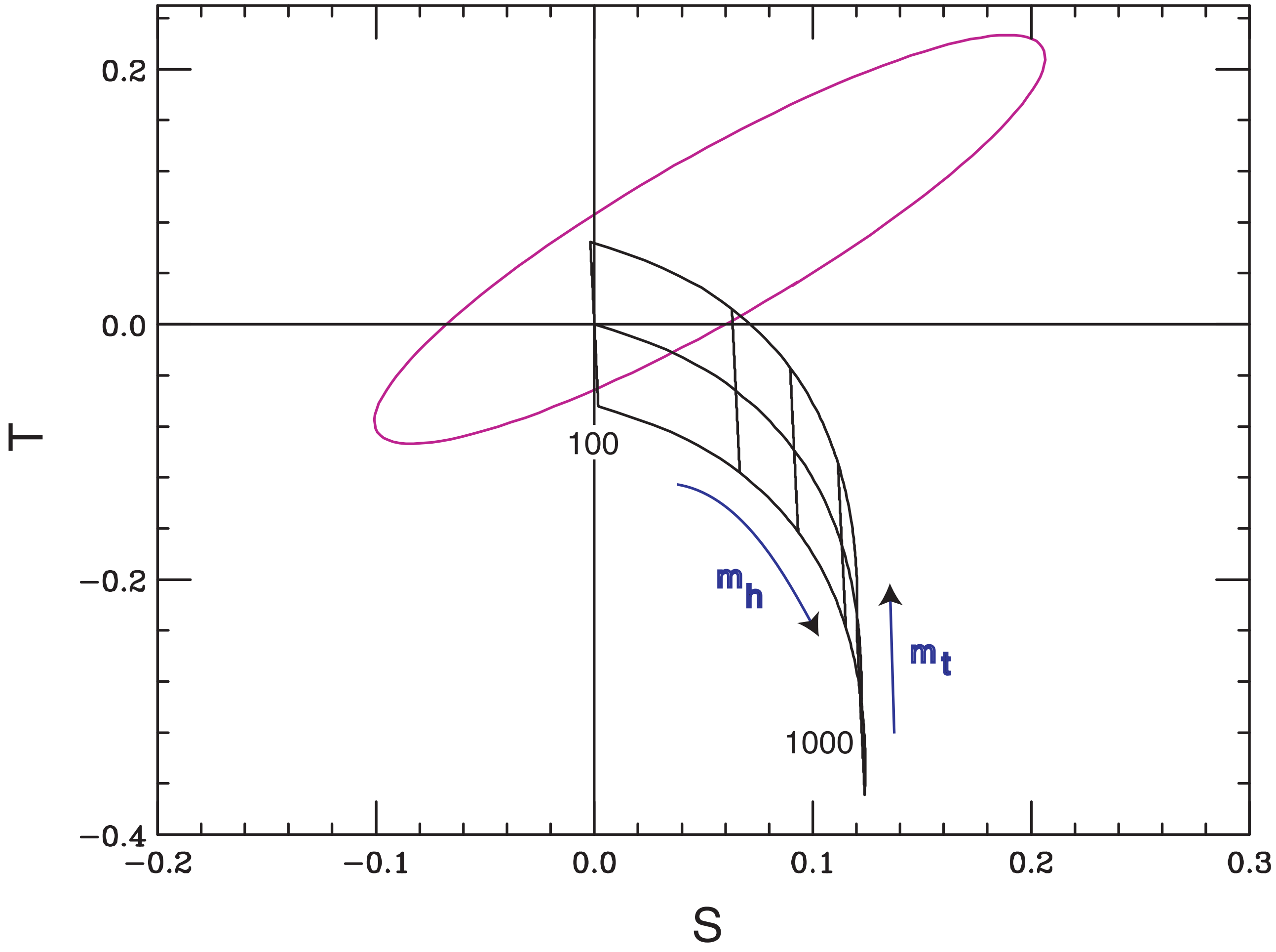
$m_t = 173 \pm 5$ GeV

a Higgs boson which must be light,

$m_h < 170$ GeV

additional new physics, only if it gives

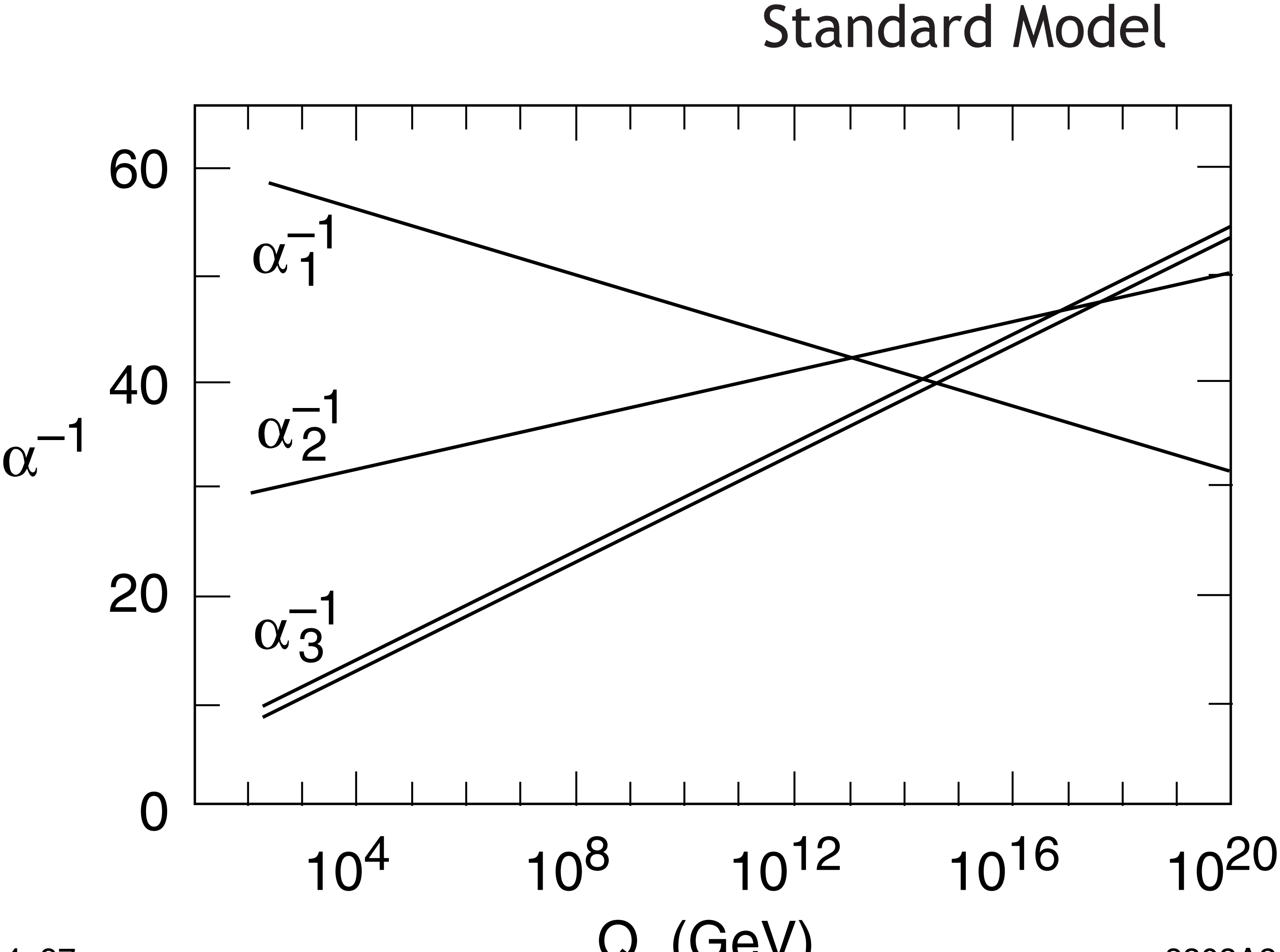
very small electroweak corrections



A light Higgs boson, a heavy top quark,
small electroweak corrections,
are all predictions of supersymmetry.

The new precise determination of the coupling constants g, g', and g_s give another hint for this theory;

extrapolate to short distances, noting that pair creation and other quantum effects modify the values of these coupling constants as a function of distance scale.


Standard Model
60
40
20
0
α^{-1}
α_1^{-1}
α_2^{-1}
α_3^{-1}
10^4
10^8
10^{12}
10^{16}
10^{20}
Q (GeV)

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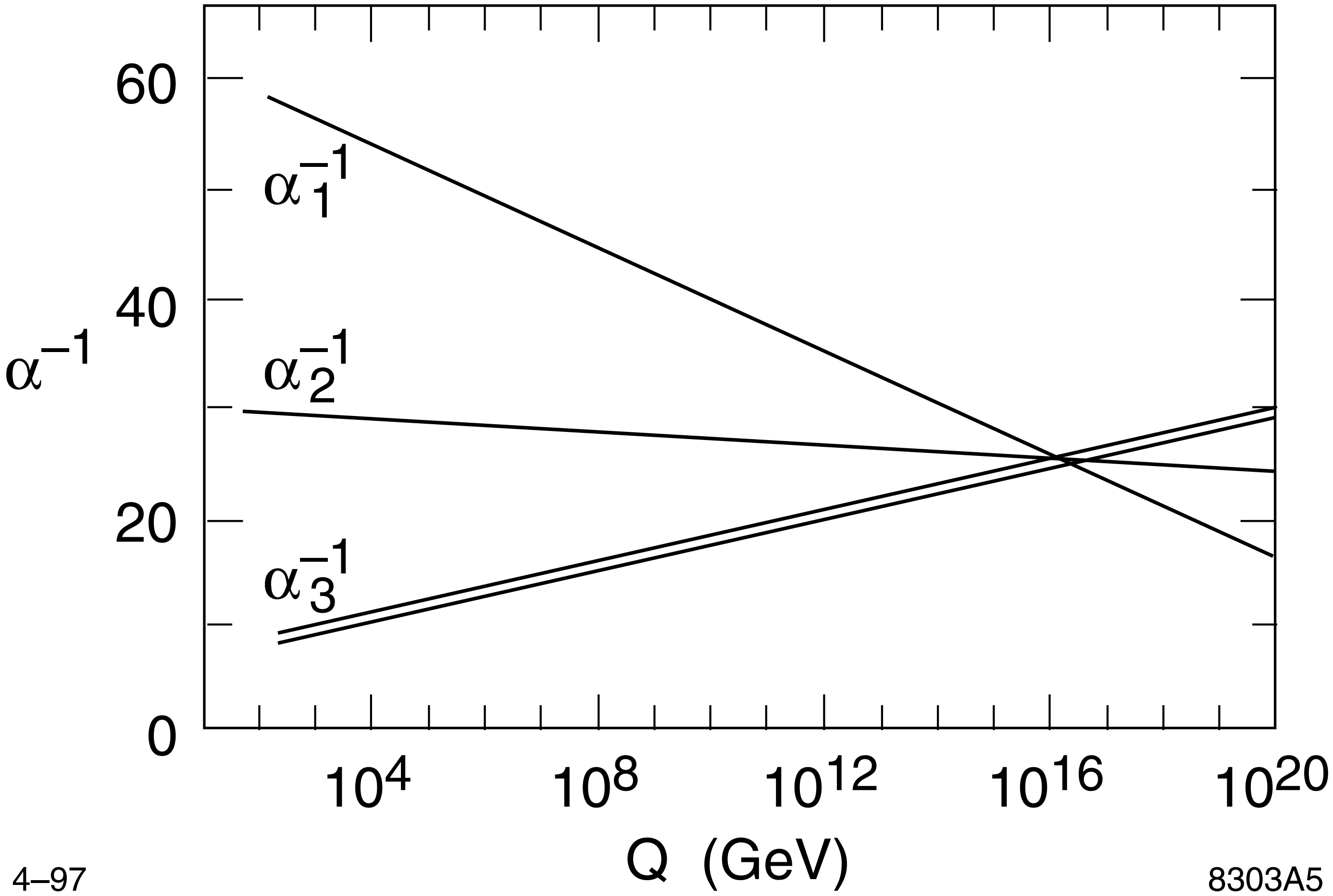
Standard Model with superpartners



Today, we have only hints about
physics at very small scales, but

the success of the precision study of
electroweak interactions

gives the promise that we wil be able
to find out exactly what is
hiding there.