XXVI SSI TOPICAL CONFERENCE
AUGUST 1998

PRECISION ELECTROWEAK RESULTS AT LEP-I AND LEP-II

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OUTLINE:

- INTRODUCTION
- Z PHYSICS AT LEP-I
- W PHYSICS AT LEP-II
- STANDARD MODEL TESTS
- CONCLUSIONS

MANY THANKS TO:

- SSI ORGANIZERS
- LEP EXPERIMENTS + LEP EW WG
- LL. M. MIR

INTRODUCTION

LEP → FUNDAMENTAL MACHINE FOR THE PRECISION STUDY OF THE EW HEAVY GAUGE BOSON PROPERTIES

Z^0	W^+W^-
LEP-I	LEP-II

Z RESONANCE SCAN:

- HIGH X-SECTION ~ O(30nb)
  ⇒ HIGH STATISTICS ~ 10^7 EVTS
- CLEAN & BKGD-FREE
  ε ~ ALMOST 100%
  B ~ FEW PERCENT
  ⇒ LOW SYSTEMATICS
- HIGH PRECISION
  - E_{CM} → LEP RESON. DEPOL.
  - $\mathcal{L}$ → LUMI MONITORS
  - THEORETICAL PREDICTIONS

⇓

HIGH PRECISION EW MEASUREMENTS:

- CROSS SECTIONS
- ASYMMETRIES

W^+W^- NEAR THRESHOLD:

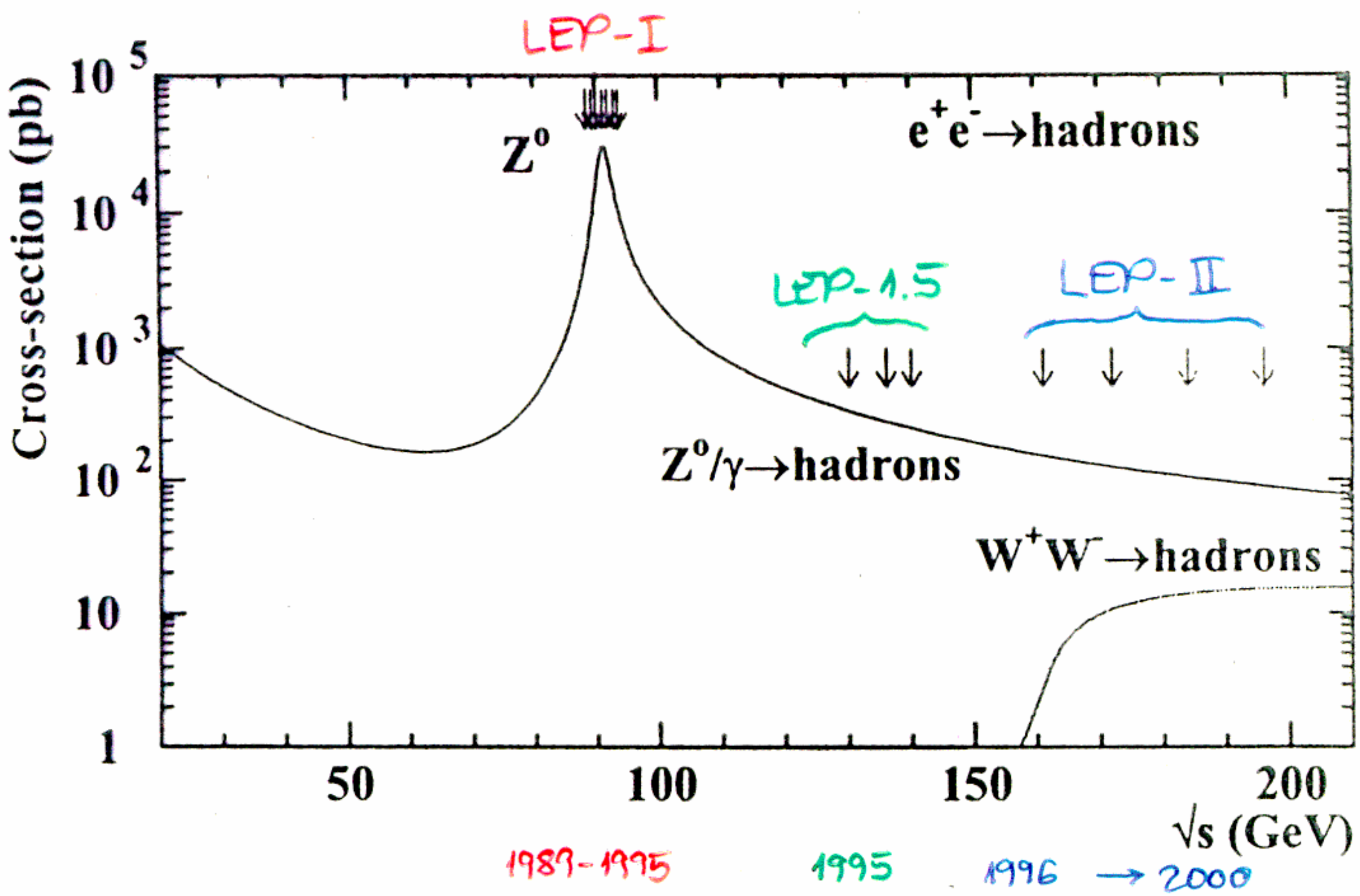
- LOW X-SECTION ~ O(15pb)
  ⇒ LOW STATISTICS ~ 10^4 EVTS
- RATHER CLEAN BUT SIZABLE BACKGROUNDS
  ε ~ O(80%)
  B ~ O(20%)
- MEASUREMENTS REQUIRE FULL DETECT. PERFORMANCE
- RELEVANT THEORETICAL UNCERTAINTIES
  ⇒ SIZABLE SYSTEMATICS

⇓

MEDIUM PRECISION EW MEASUREMENTS:

- CROSS SECTIONS
- INVARIANT MASSES
- ANGULAR DISTRIBUTIONS

LEP ENERGY POINTS



INTRODUCTION

- MANY LEP MEASUREMENTS HAVE DIRECT IMPACT ON PRECISION TESTS OF THE SM. (FUNDAMENTALLY Z PHYSICS RESULTS)

- SPIRIT OF THIS TALK:

  * LEP-I MEASUREMENT CONCEPTS MANY YEARS OLD ALREADY (→ PART OF "GLORIOUS HISTORY"). "FINAL" RESULTS PRESENTED AT VANCOUVER
    ⇒ BRIEF SUMMARY

  * LEP-II MEASUREMENTS PRESENTLY MAIN EXPERIMENTAL INTEREST
    ⇒ MAIN EMPHASIS

Z PHYSICS AT LEP-I :

- LEP-I DATA
- Z CROSS SECTIONS
- Z ASYMMETRIES
- THE Z COUPLINGS

- LEP-I : 1989 - 1995

YEAR		$\int \mathcal{L}\,dt\ (pb^{-1})/exp.$ ON-PEAK	OFF-PEAK
1989	11-POINT SCAN	0.6	0.7
1990	7-POINT SCAN	3.5	3.1
1991	5-POINT SCAN	8	5
1992	PEAK	25	
1993	3-POINT SCAN	16	18
1994	PEAK	50	
1995	3-POINT SCAN	9	18
TOTAL		~112	~45

~ 5 M VISIBLE Z^0/EXP.

- PRECISION SCAN OF THE Z PEAK : 1993-1995
  * PRECISION LUMINOMETERS
  * PRECISION ENERGY CALIBRATION

RESULTS (ALMOST) FINAL BUT STILL UNPUBLISHED

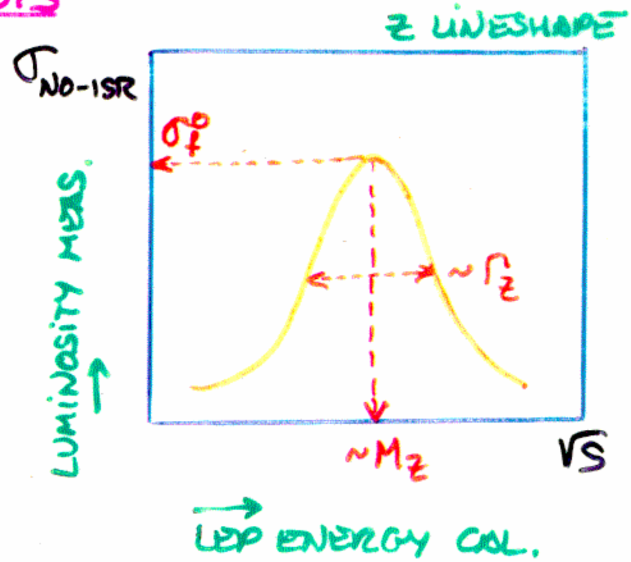
* CROSS SECTION ANALYSIS

$\sigma(e^+e^- \to f\bar{f})$ vs. $\sqrt{s}$

$\Rightarrow M_Z, \Gamma_Z, \sigma_f^0$

$f \equiv$ HADS, LEPTS

HADS: b, c — LEPTS: e, μ, τ



$$\sigma_f^0 \equiv \frac{12\pi}{M_Z^2} \cdot \frac{\Gamma_e \Gamma_f}{\Gamma_Z^2}$$

$$\hookrightarrow \Gamma_f \equiv \Gamma(Z \to f\bar{f}) \sim (g_{Vf}^2 + g_{Af}^2)$$

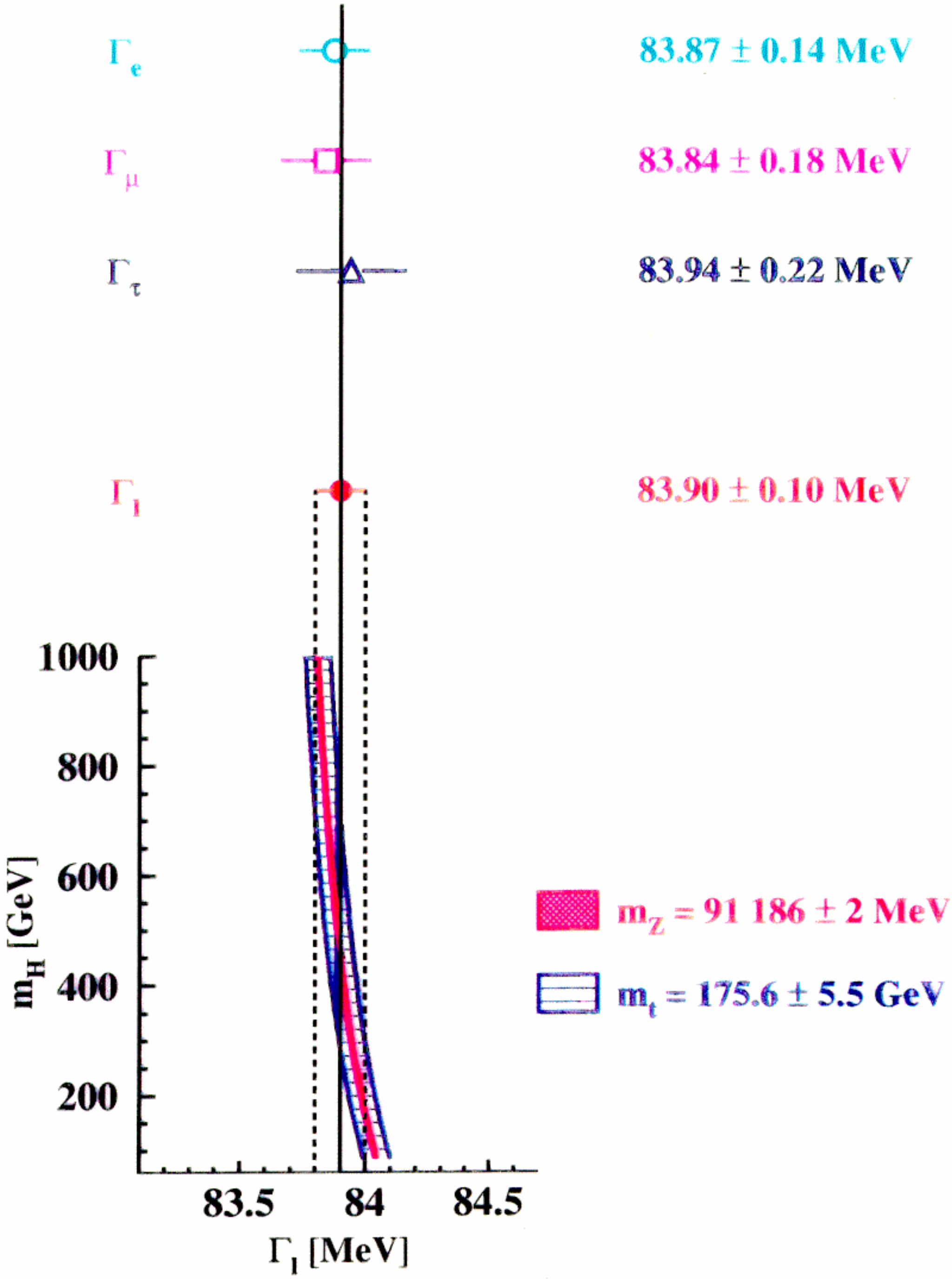
PARTIAL WIDTHS — EFFECTIVE COUPLINGS

IN THE "IMPROVED BORN APPROXIMATION" THE MOST RELEVANT RADIATIVE CORRECTIONS ABSORVED IN EFFECTIVE COUPLINGS IN ABOVE FORMULAE AND RUNNING α_{em} TO M_Z.

RESULTS:

$M_Z = 91.1867 \pm 0.0021$ GeV	$\Delta M_Z / M_Z = 2.3 \times 10^{-5}$
$\Gamma_Z = 2.4939 \pm 0.0024$ GeV	$\Delta\Gamma_Z / \Gamma_Z = 1 \times 10^{-3}$
$\Gamma_{HAD} = 1.7423 \pm 0.0023$ GeV	
$\Gamma_e = 83.90 \pm 0.10$ MeV	

LEP averages of leptonic widths



⇛ Z INVISIBLE WIDTH

$$\Gamma_{INV} \equiv \Gamma_Z - \underbrace{\Gamma_{HAD} - \Gamma_e - \Gamma_\mu - \Gamma_\tau}_{\text{VISIBLE CHANNELS}}$$

$$\left(\frac{\Gamma_\nu}{\Gamma_e}\right)_{SM} = 1.991 \pm 0.001$$

RESULTS:

$$\Gamma_{INV}/\Gamma_e = 5.961 \pm 0.023$$

$$\Rightarrow N_\nu = 2.994 \pm 0.011$$

$$\Delta\Gamma_{INV} = \Gamma_{INV} - 3\,\Gamma_\nu^{SM} = -1.6 \pm 1.9$$

$$\Rightarrow \Delta\Gamma_{INV} < 2.8 \text{ MeV @ 95\% CL}$$

ALTERNATIVELY

$$\sigma_H^0 = 41.491 \pm 0.058 \text{ nb}$$

$$R_e \equiv \frac{\Gamma_{HAD}}{\Gamma_e} = 20.765 \pm 0.026$$

$$\Delta\sigma_H^0/\sigma_H^0 = 1.4\times10^{-3}$$

$$\Delta R_e/R_e = 1.3\times10^{-3}$$

HEAVY FLAVOUR WIDTHS

- $Z^0 \to b\bar{b}$, $c\bar{c}$ IDENTIFIED WITH HIGH PURITY

  b TAGGING:

  - LIFETIME (PRECISION VERTEX DET.)
  - HIGH P_L, P_T LEPTON
  - EVENT SHAPE (NN TECHNIQUES)

  + COMBINATIONS OF THEM (MULT.)

  CHARGE FROM LEPTON OR JET CHARGE

  c TAGGING:

  - CHARM COUNTING (D^0, D^+, D_s, Λ_c)
  - DOUBLE CHARM TAGGING (EXCLUSIVE/INCLUSIVE D^*)

- CALIBRATE EFFICIENCY USING DOUBLE TAG

  1 HEMISPHERE : $N_1 \propto \Gamma_b (\varepsilon_b - \varepsilon_{uds}) + \Gamma_c \cdot (\varepsilon_c - \varepsilon_{uds}) + \varepsilon_{uds}$

  2 HEMISPHERES: $N_2 \propto \Gamma_b (C_b \varepsilon_b^2 - \varepsilon_{uds}^2) + \Gamma_c \cdot (\varepsilon_c^2 - \varepsilon_{uds}^2) + \varepsilon_{uds}^2$

- DOMINANT SYST. FOR b:

  - CHARM CONTAMINATION ($\to \varepsilon_c$)
  - HEMISPHERE CORRELATIONS ($\to C_b$)

- USE $R_b \equiv \Gamma_b / \Gamma_{HAD}$, $R_c \equiv \Gamma_c / \Gamma_{HAD}$

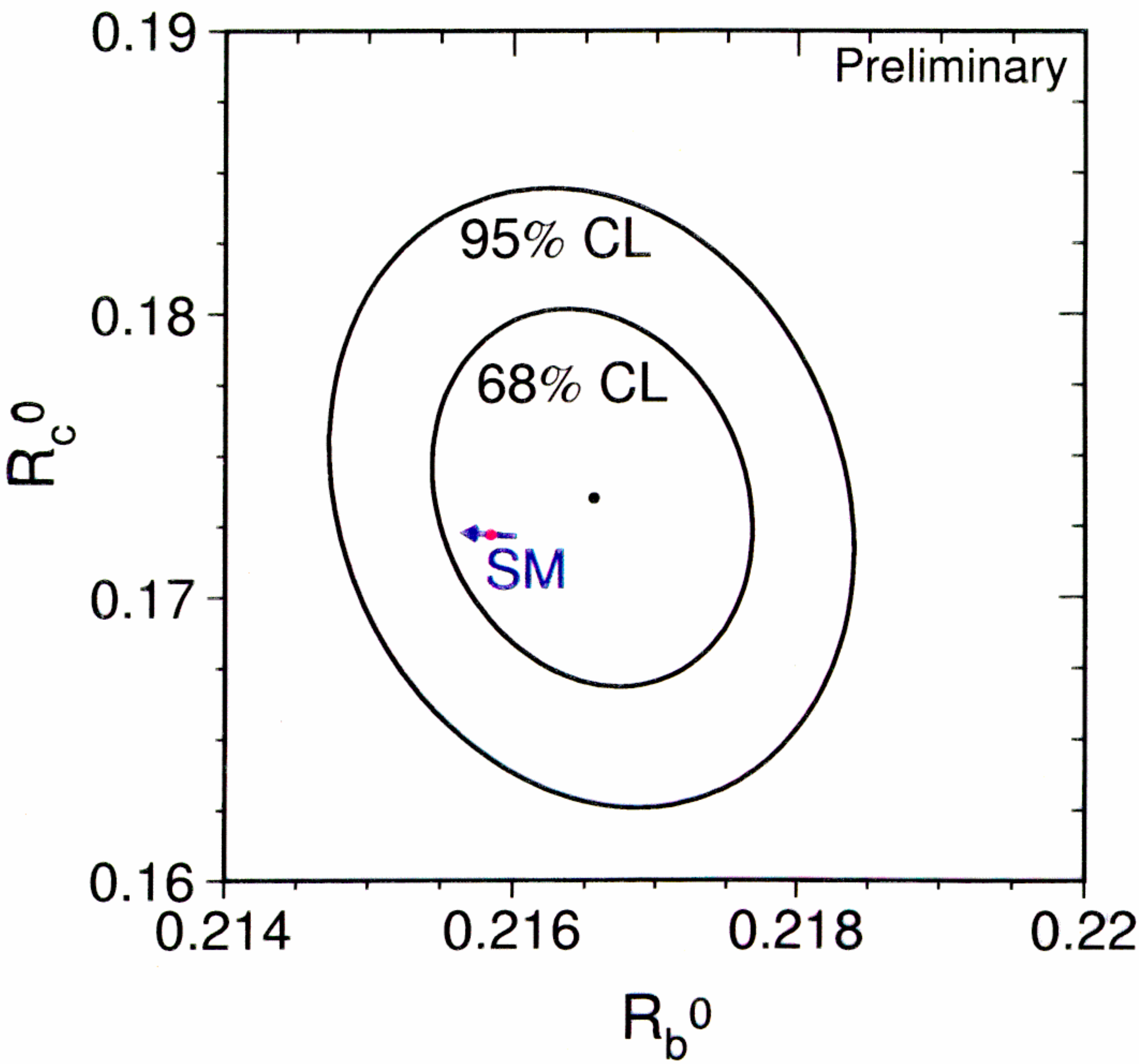
  (QCD CORRECTIONS LARGELY CANCEL)

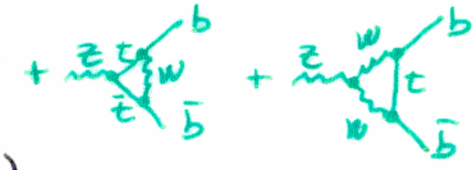
RESULTS:

$R_b = 0.21656 \pm 0.00074$

$R_c = 0.1733 \pm 0.0044$

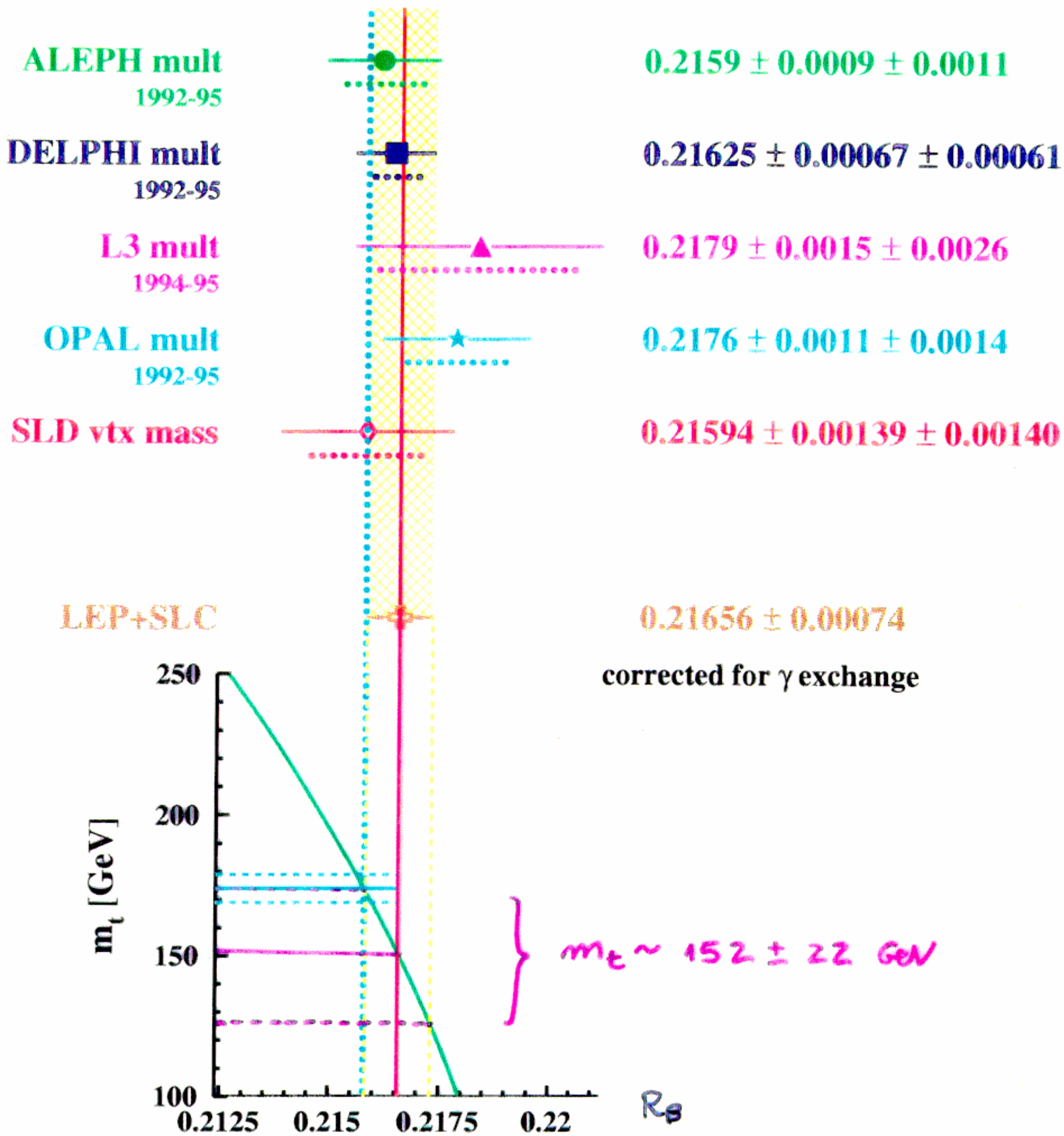
$\Delta R_b / R_b = 3.4 \times 10^{-3}$



– R_b SPECIAL INTEREST SINCE 

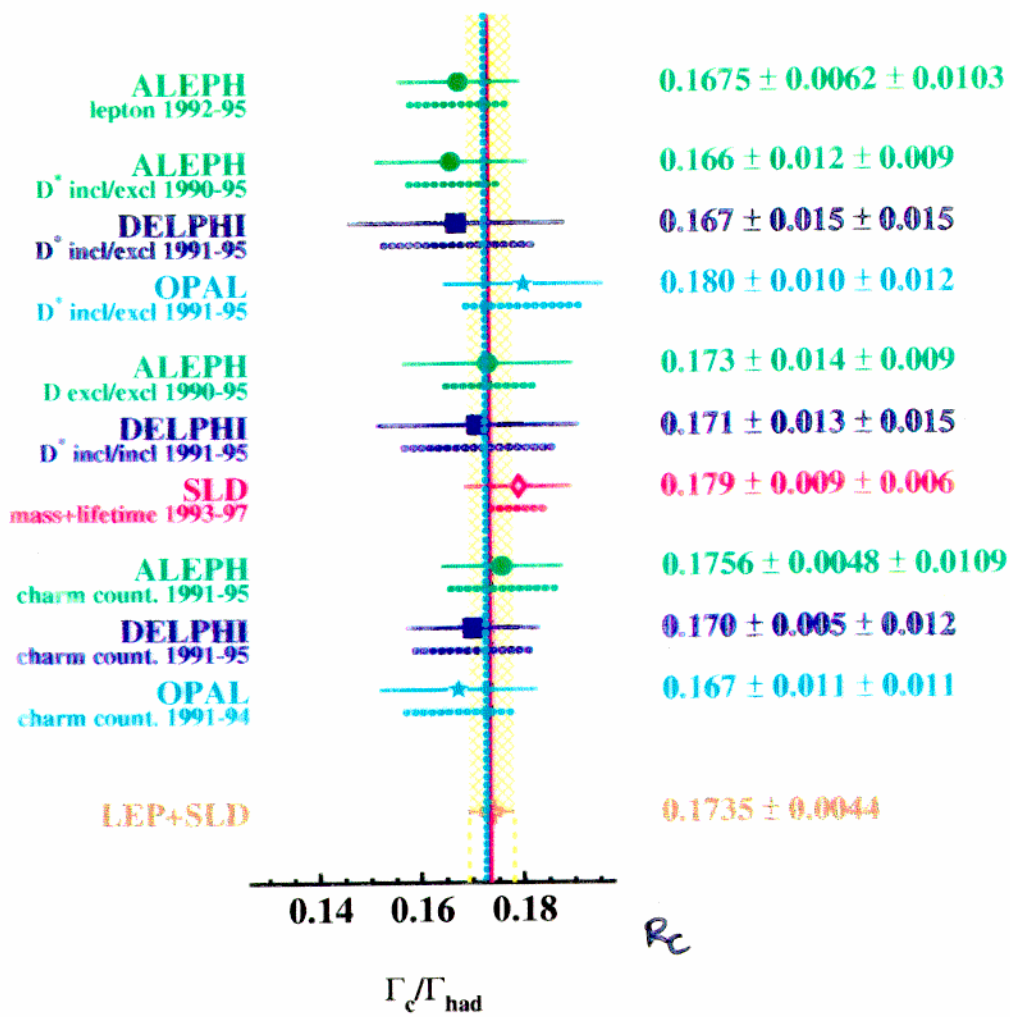
$$\Rightarrow \Delta^{b}_{\text{VERTEX}} \approx -\frac{20}{13}\frac{\alpha}{\pi}\left(\frac{m_t^2}{M_Z^2}+\dots\right)$$

$$R_B \equiv \Gamma_b/\Gamma_{had}$$



Z PHYSICS AT LEP-I   Z CROSS SECTIONS

$R_c \equiv \Gamma_c/\Gamma_{had}$



* ASYMMETRY ANALYSES

- IN $e^+e^- \to f\bar{f}$ AT $\sqrt{s} \simeq M_Z$ GOVERNED BY $A_f = \frac{2 g_{Vf} g_{Af}}{g_{Vf}^2 + g_{Af}^2}$
- IF $f = \ell$, SINCE $g_{V\ell} << g_{A\ell} \Rightarrow A_\ell \simeq 2 \frac{g_{V\ell}}{g_{A\ell}}$

$$\Rightarrow \sin^2\theta_{eff}^{lept} \equiv \frac{1}{4}\left(1 - \frac{g_{V\ell}}{g_{A\ell}}\right)$$

USED AS THE QUANTITY SUMMARIZING ALL THE Z ASYMMETRY MEASUREMENTS

* ASYMMETRIES AT LEP-I

(NO INITIAL STATE LONGITUDINAL POLARIZATION)

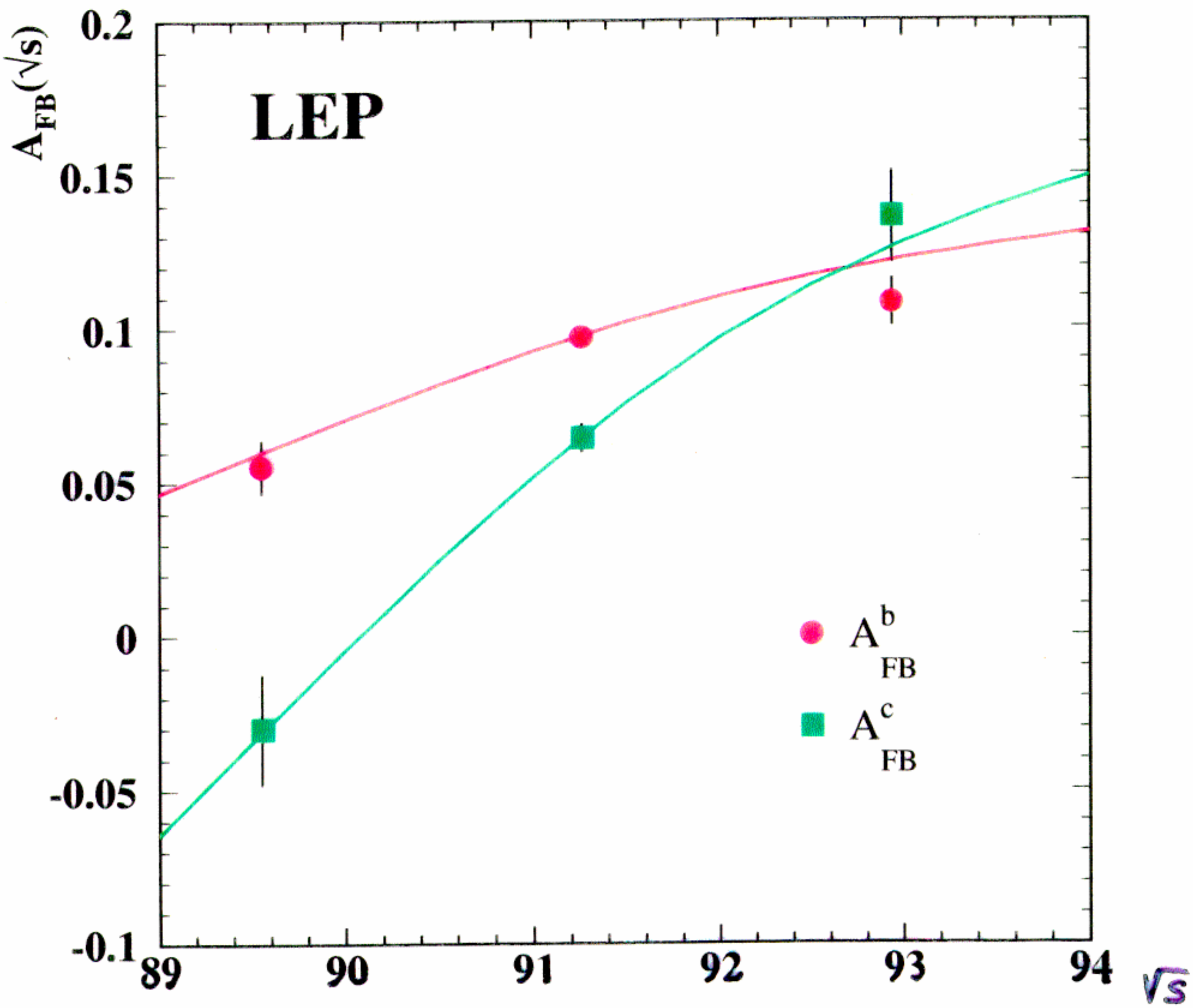
- CHARGE F-B ASYMMETRY

$$A_{FB}^{0,f} = \frac{3}{4} A_e A_f$$

- $f = \ell \Rightarrow A_{FB}^{0,\ell} \sim O(2\%)$ AND VERY LARGE SLOPE AS A FUNCTION OF $\sqrt{s} - M_Z \to$ SIMULTANEOUS ANALYSIS WITH Z LINESHAPE
- $f = b \Rightarrow A_{FB}^{0,b} \sim O(10\%)$ AND MILD ENERGY DEPENDENCE
- $f = c \Rightarrow A_{FB}^{0,c} \sim O(7\%)$ AND MEDIUM ENERGY DEPENDENCE

STANDALONE HEAVY FLAVOUR ANALISES TOGETHER WITH R_b, R_c, MIXING, ...

- FORWARD-BACKWARD CHARGE ASYMMETRY FOR b AND c QUARKS



* ASYMMETRY ANALYSES

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USED AS THE QUANTITY SUMMARIZING ALL THE Z ASYMMETRY MEASUREMENTS

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- $f = c \Rightarrow A_{FB}^{0,c} \sim O(7\%)$ AND MEDIUM ENERGY DEPENDENCE

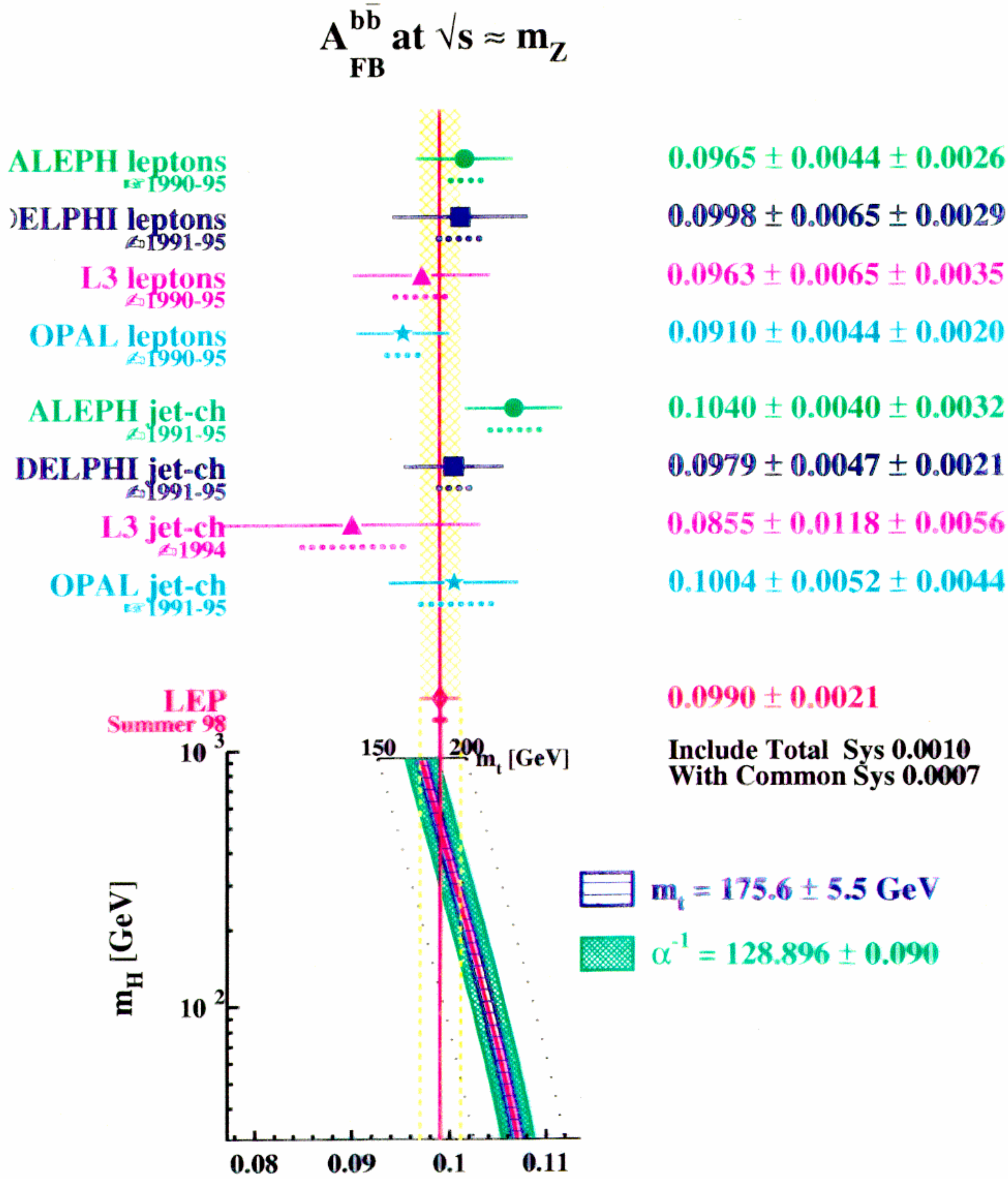
} STANDALONE HEAVY FLAVOUR ANALISES TOGETHER WITH R_b, R_c, MIXING, ...

RESULTS:

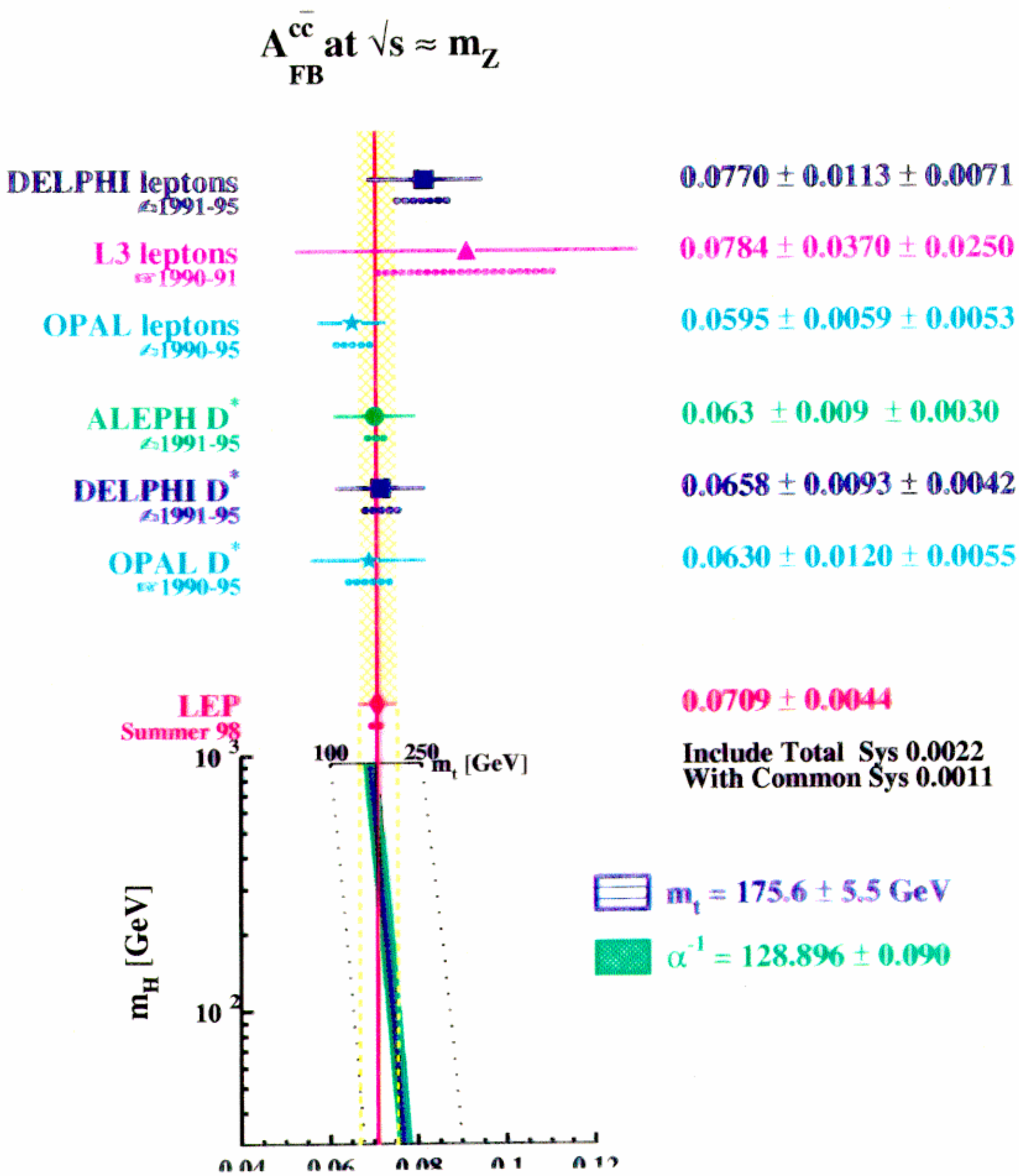
$$A_{FB}^{0,\ell} = 0.01683 \pm 0.00096$$

$$A_{FB}^{0,b} = 0.0991 \pm 0.0021$$

$$A_{FB}^{0,c} = 0.0714 \pm 0.0044$$



$A_{FB}^{b\bar{b}}$ at $\sqrt{s} \approx m_Z$
ALEPH leptons 1990-95
0.0965 ± 0.0044 ± 0.0026
DELPHI leptons 1991-95
0.0998 ± 0.0065 ± 0.0029
L3 leptons 1990-95
0.0963 ± 0.0065 ± 0.0035
OPAL leptons 1990-95
0.0910 ± 0.0044 ± 0.0020
ALEPH jet-ch 1991-95
0.1040 ± 0.0040 ± 0.0032
DELPHI jet-ch 1991-95
0.0979 ± 0.0047 ± 0.0021
L3 jet-ch 1994
0.0855 ± 0.0118 ± 0.0056
OPAL jet-ch 1991-95
0.1004 ± 0.0052 ± 0.0044
LEP Summer 98
0.0990 ± 0.0021
Include Total Sys 0.0010
With Common Sys 0.0007
150
200
m_t [GeV]
m_H [GeV]
10^3
10^2
m_t = 175.6 ± 5.5 GeV
α^{-1} = 128.896 ± 0.090
0.08
0.09
0.1
0.11


$A_{FB}^{c\bar{c}}$ at $\sqrt{s} \approx m_Z$
DELPHI leptons 1991-95
0.0770 ± 0.0113 ± 0.0071
L3 leptons 1990-91
0.0784 ± 0.0370 ± 0.0250
OPAL leptons 1990-95
0.0595 ± 0.0059 ± 0.0053
ALEPH D* 1991-95
0.063 ± 0.009 ± 0.0030
DELPHI D* 1991-95
0.0658 ± 0.0093 ± 0.0042
OPAL D* 1990-95
0.0630 ± 0.0120 ± 0.0055
LEP Summer 98
0.0709 ± 0.0044
Include Total Sys 0.0022
With Common Sys 0.0011
100
250
m_t [GeV]
m_H [GeV]
10^3
10^2
0.04
0.06
0.08
0.1
0.12
m_t = 175.6 ± 5.5 GeV
α^{-1} = 128.896 ± 0.090

- FINAL STATE POLARIZATION ASYMMETRY
  - ONLY POSSIBLE FOR $f = \tau$ USING τ DECAYS AS POLARIMETERS

    $e\nu\bar{\nu}$ $\mu\nu\bar{\nu}$ $\pi\nu$ $\rho\nu$ $a_1\nu$

    ($\pi\nu$, $\rho\nu$: ~ 40% WEIGHT EACH)

  - DEFINE $P_\tau \equiv \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$ R, L ≡ τ^- HELICITY

    AND MEASURE IT AS A FUNCTION OF THE POLAR SCATTERING ANGLE.

$$P_\tau(\cos\theta) \cong -\frac{A_\tau(1+\cos^2\theta) + 2A_e\cos\theta}{1+\cos^2\theta + 2A_\tau A_e\cos\theta}$$

$\Rightarrow$ NEARLY INDEPENDENT DETERMINATION OF A_e AND A_τ

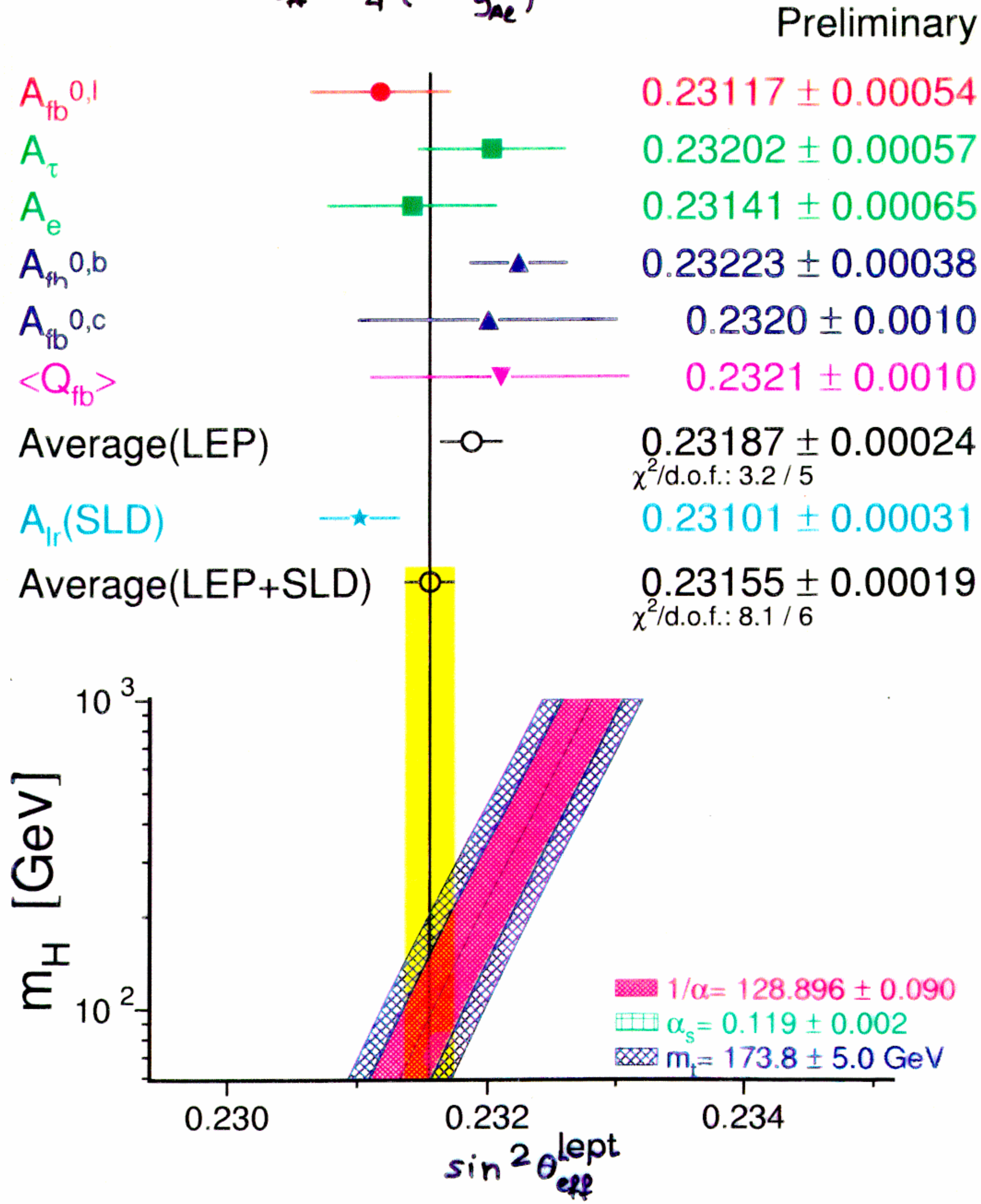
RESULTS

$A_e = 0.1479 \pm 0.0051$

$A_\tau = 0.1431 \pm 0.0045$

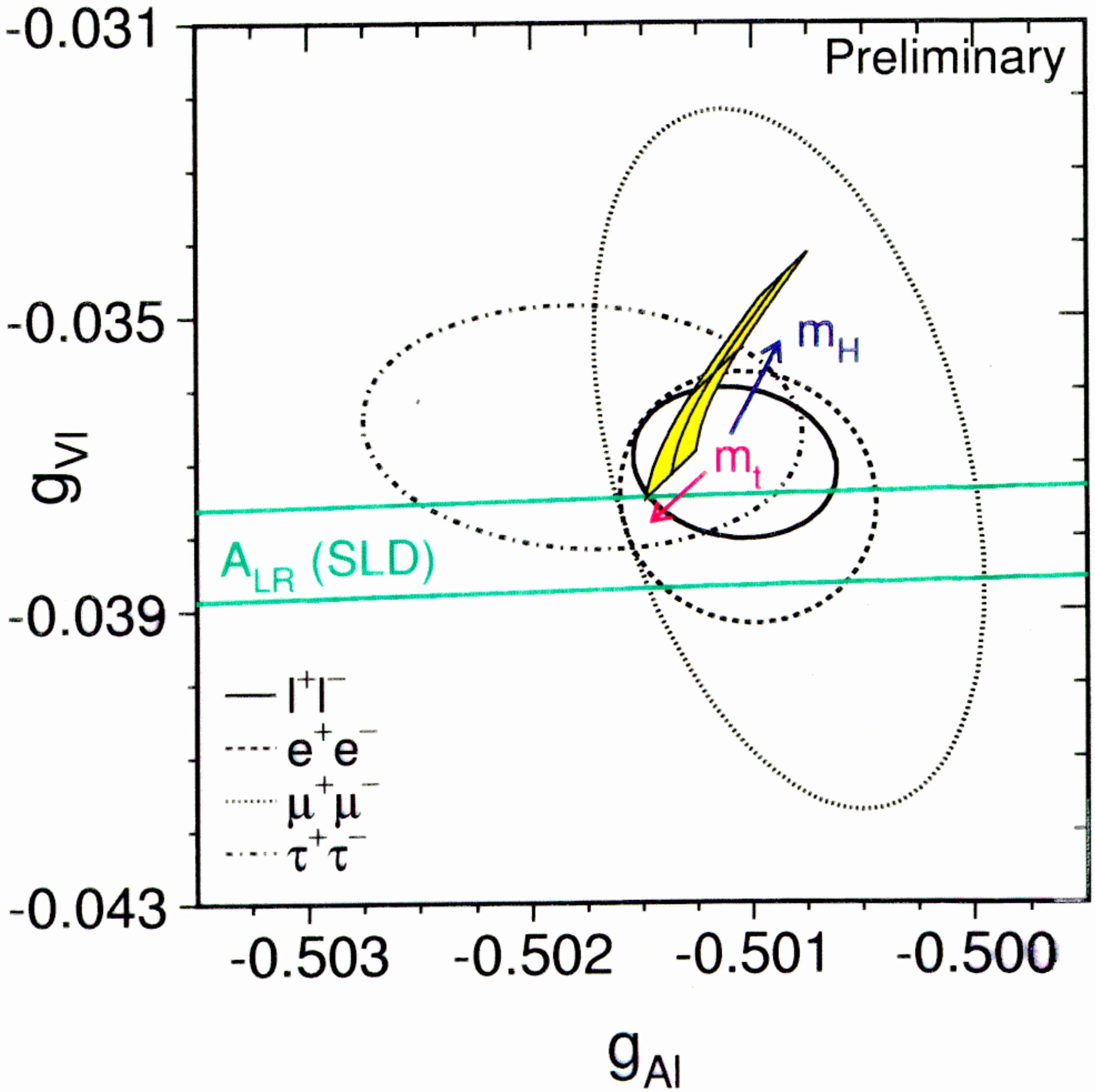
EFFECTIVE ELECTROWEAK MIXING ANGLE

$$\sin^2\theta_{eff}^{lept} = \frac{1}{4}\left(1 - \frac{g_{Ve}}{g_{Ae}}\right)$$



- USE LEPTONIC Z^0 WIDTH
  - \+ " " CHARGE ASYMMETRIES
  - \+ Z POLARIZATION ASYMMETRIES

⇒ TEST FOR LEPTON UNIVERSALITY
AT 0.2% FOR g_{Ae}
5-10% FOR g_{Ve}



Z PHYSICS AT LEP-I THE Z COUPLINGS

* ASSUMMING LEPTON UNIVERSALITY:

- EFFECTIVE LEPTON COUPLING RESULTS:

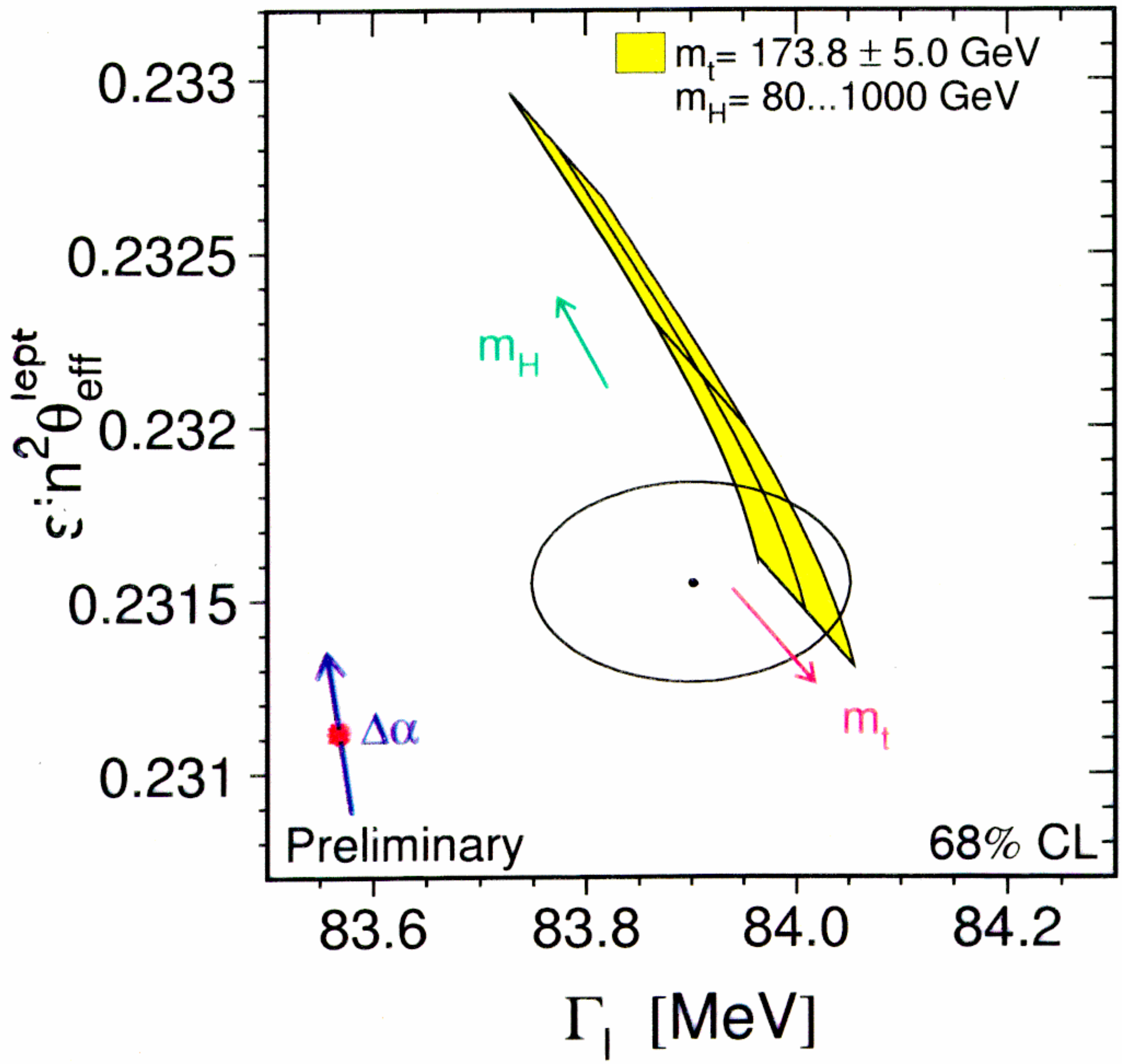
	LEP	LEP + SLD
$g_{V\ell}$	-0.03703 ± 0.00068	-0.3759 ± 0.00046
$g_{A\ell}$	-0.50108 ± 0.00030	-0.50105 ± 0.00030

- A_ℓ CONSISTENCY TEST:

	A_ℓ	χ^2/NDF
$A_{FB}^{0,\ell}$	0.1498 ± 0.0043	
A_e, A_τ (FROM P_τ)	0.1452 ± 0.0034	0.5/1
$A_{FB}^{0,\ell}, A_e, A_\tau$	0.1469 ± 0.0027	1.2/2
$A_{FB}^{0,\ell}, A_e, A_\tau, A_{LR}$	0.1491 ± 0.0018	2.4/3

→ NO DISCREPANCY

- THE * SHOWS SM EXPECTATION WITH ONLY PHOTON VACUUM POLAR. CORRS. ⇒ GENUINE E.W. RAD. CORRS. NEEDED
- THE ASSUMED $\Delta(1/\alpha(M_Z)) = 0.090$ IS COMPARABLE WITH THE EXPERIMENTAL ERROR ON $\sin^2\theta_{eff}^{lept}$



W PHYSICS AT LEP-II :

- LEP-II DATA
- W EVENT SELECTION
- WW CROSS SECTION
- W BRANCHING RATIOS
- W MASS MEASUREMENT
- TGCs

W PHYSICS AT LEP-II — LEP-II DATA

– WHAT HAS LEP-II BEEN SO FAR?

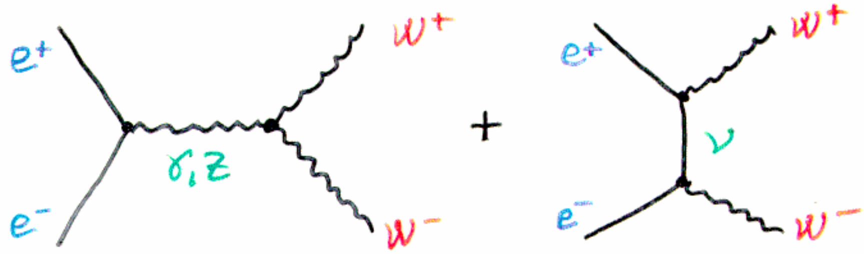
YEAR	$\sqrt{s}$ (GeV)	$\int \mathcal{L} dt$ (pb^{-1}) / exp.	
NOVEMBER 1995	130/136 (LEP 1.5)	6	
JUNE-AUGUST 1996	161 (W^+W^- THRESHOLD)	10	(≈ 30 WW)
OCTOBER-NOVEMBER 1996	172	10	(≈ 100 WW)
JULY-NOVEMBER 1997	183	55	(≈ 850 WW)
	(130/136)	7	

– PRESENT AND FUTURE

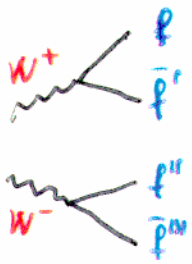
YEAR	$\sqrt{s}$ (GeV)	$\int \mathcal{L} dt$ (pb^{-1}) / exp.
1998 RUN	189	150 (GOAL)
1999 2000 RUNS	~ 200 ?	AS MUCH AS POSSIBLE

W PHYSICS AT LEP-II — W EVENT SELECTION

- W PAIR PRODUCTION



- W PAIR DECAYS

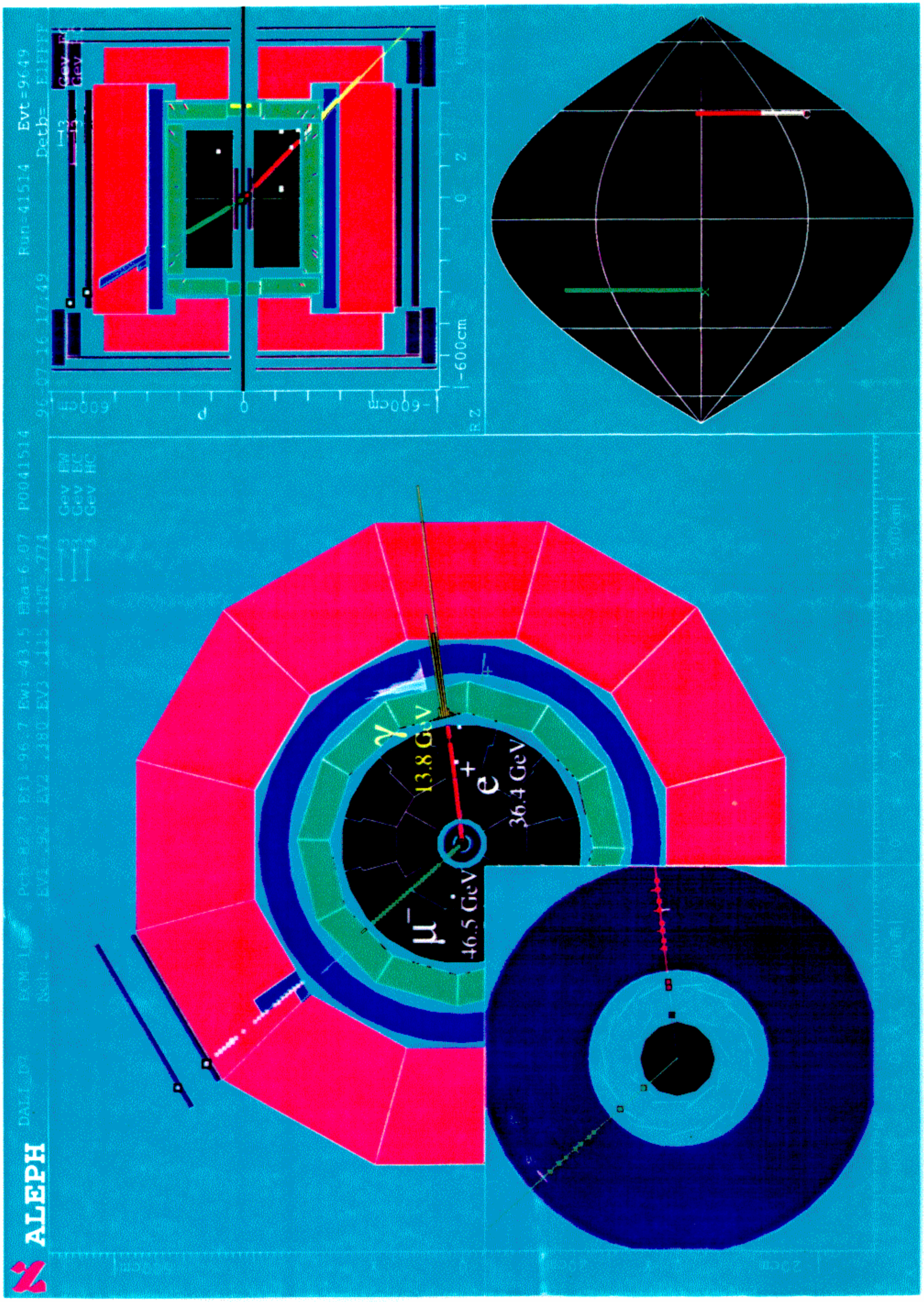


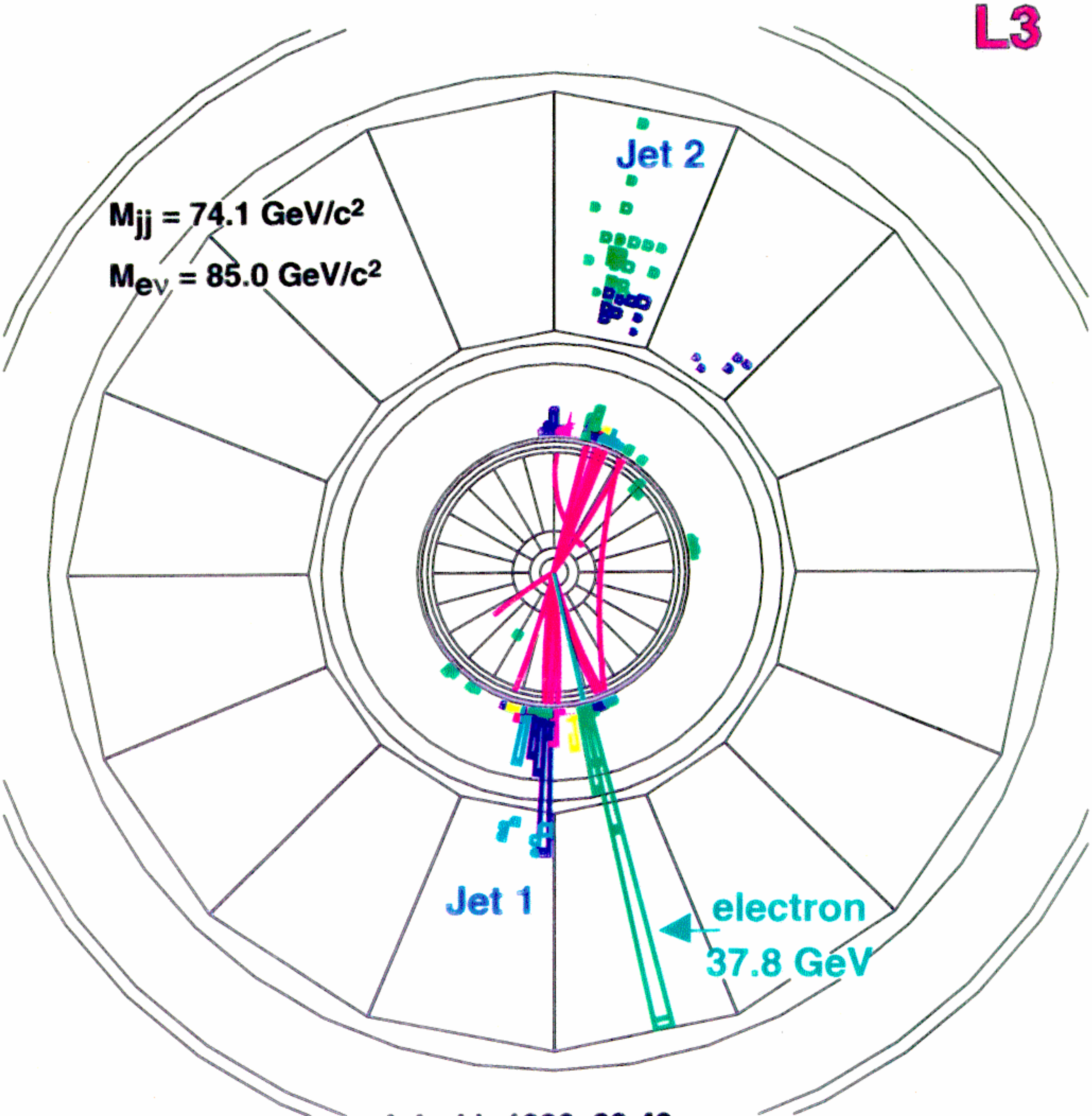
$W \to \ell\nu$ 33%

$W \to q\bar{q}'$ 67%

	BR(%)	SIGNATURE	ε(%)	P(%)	BKGDS.
FULLY LEPTONIC $W^+W^- \to \ell\nu\ell'\nu'$	11	2 ACOPLANAR ENERGETIC LEPTONS	~70	~90	• $\gamma\gamma \to \tau^+\tau^-$ • $\ell^+\ell^-\nu\bar{\nu}$ • DILEPTONS
SEMILEPTONIC $W^+W^- \to \ell\nu q\bar{q}'$	44	ENERGETIC LEPTON + 2 HAD. JETS	~80	~90	VERY LOW ($q\bar{q}$, Zee, 4 f processes)
HADRONIC $W^+W^- \to q\bar{q}'q''\bar{q}'''$	45	4 (OR MORE) HAD. JETS	~80	~85	$q\bar{q}$ (+ GLUONS)

(ε and P for hadronic:) USING MULTIVARIATE ANALYSES & NEURAL NETWORKS


ALEPH
μ⁻
46.5 GeV
e⁺
36.4 GeV
γ
13.8 GeV
-600cm
600cm

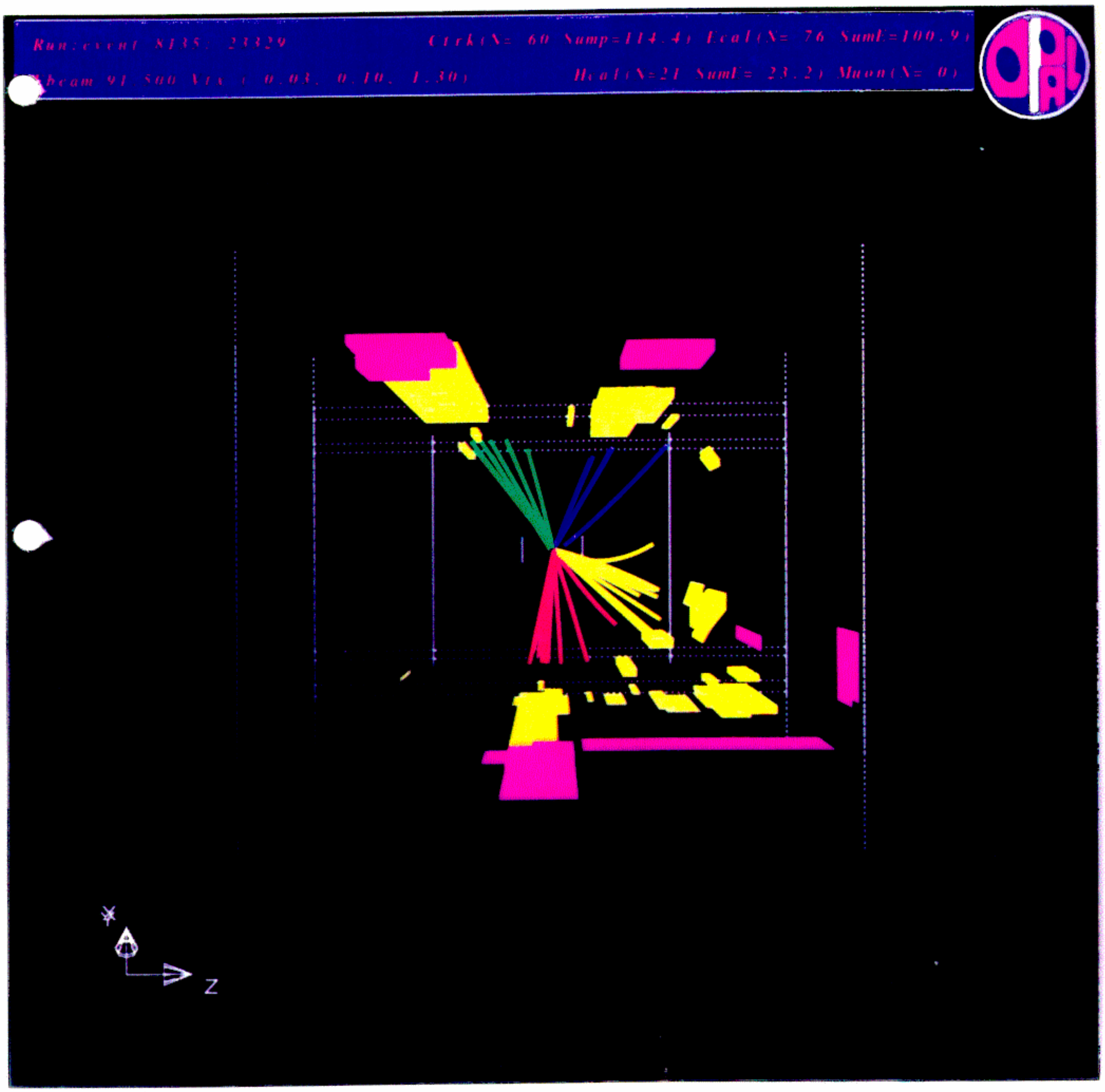


July 11, 1996 06:42am

First W pair event observed by the L3 Experiment at LEP 2.

$e^+ e^- \rightarrow W^+ W^-$
$\quad \llcorner\rightarrow e^- \bar{\nu}$
$\llcorner\rightarrow$ jet + jet

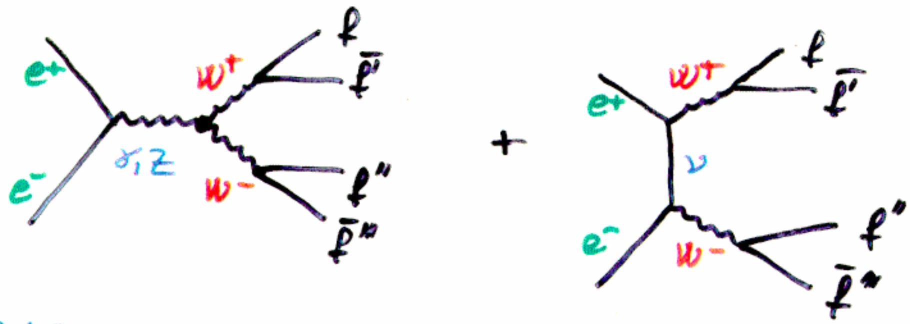
Applying energy and momentum conservation to the event shows that the two jets and the electron-neutrino originate


Run:event 8135: 23329
Ctrk(N= 60 Sump=114.4) Ecal(N= 76 SumE=100.9)
Ebeam 91.500 Vtx (0.03, 0.10, 1.30)
Hcal(N=21 SumE= 23.2) Muon(N= 0)
Z

DEFINITION OF σ_{WW}:

$$\sigma_{WW} \equiv \sigma(e^+e^- \to W^+W^- \to 4f)$$

CROSS SECTION THROUGH 2 RESONATING Ws (CC03)



- DUE TO LARGE Γ_W NEAR THRESHOLD W_s ARE OFF-SHELL
  ⇒ SIZABLE INTERFERENCE WITH $e^+e^- \to 4f$ BUT REDUCIBLE TO FEW % IF 4 FERMIONS
  - IN THE DETECTOR
  - WELL SEPARATED

- EFFECT OF DIAGRAMS OTHER THAN CC03 CORRECTED FOR:

ALEPH, OPAL } BY SUBTRACTION:

$$\sigma_{CC03} = \frac{1}{\mathcal{L}\,\varepsilon_{CC03}} \cdot \left\{ N_{OBS} - N^{MC}_{BACK} - \underbrace{\left[\varepsilon_{4f}\cdot\sigma^{MC}_{4f} - \varepsilon_{CC03}\,\sigma^{MC}_{CC03}\right]}_{\text{CORRECTION}} \right\}$$

DELPHI, L3 } BY A CORRECTION FACTOR:

$$\sigma_{CC03} = \frac{1}{\mathcal{L}\,\varepsilon_{CC03}} \left\{ N_{OBS} - N^{MC}_{BACK} \right\} \cdot C_{CC03} \quad \longrightarrow \quad \frac{\sigma^{TOTAL}_{CC03}}{\sigma^{WITHIN\ CUTS}_{4f}}$$

W PHYSICS AT LEP-II — WW CROSS SECTION

- CROSS SECTIONS COMPUTED FOR EACH CHANNEL
- DIFFERENT CHANNELS COMBINED USING MAX. LIKELIHOOD
  - INPUT $N_{WW \to \ell\nu\ell'\nu'}$
    $N_{WW \to \ell\nu q\bar{q}}$
    $N_{WW \to q\bar{q}q'\bar{q}'}$
  - OUTPUT
    - BRANCHING RATIOS
    - CROSS SECTION (STANDARD B.R. ASSUMED)
- ASSUMING LEPTON UNIVERSALITY:

  σ_{WW}: TOTAL X-SECT.

  B: HADRONIC W BRANCHING RATIO

$$\begin{cases} \sigma_{\ell\nu\ell'\nu'} = \sigma_{WW} \cdot (1-B)^2 \\ \sigma_{\ell\nu q\bar{q}} = 2\,\sigma_{WW} \cdot (1-B) \cdot B \\ \sigma_{q\bar{q}q'\bar{q}'} = \sigma_{WW} \cdot B^2 \end{cases}$$

$$B = \frac{\left(|V_{ud}|^2 + |V_{cd}|^2 + |V_{us}|^2 + |V_{cs}|^2 + |V_{ub}|^2 + |V_{cb}|^2\right)\left(1 + \frac{\alpha_s(M_W^2)}{\pi}\right)}{1 + \left(1 + \frac{\alpha_s(M_W^2)}{\pi}\right)\sum_{ij} |V_{ij}|^2}$$

FIT TO B ALLOWS TO CONSTRAIN $|V_{cs}|$ → IMPROVEMENT OVER DIRECT MEASUREMENT FROM D MESON DECAY

RESULT:

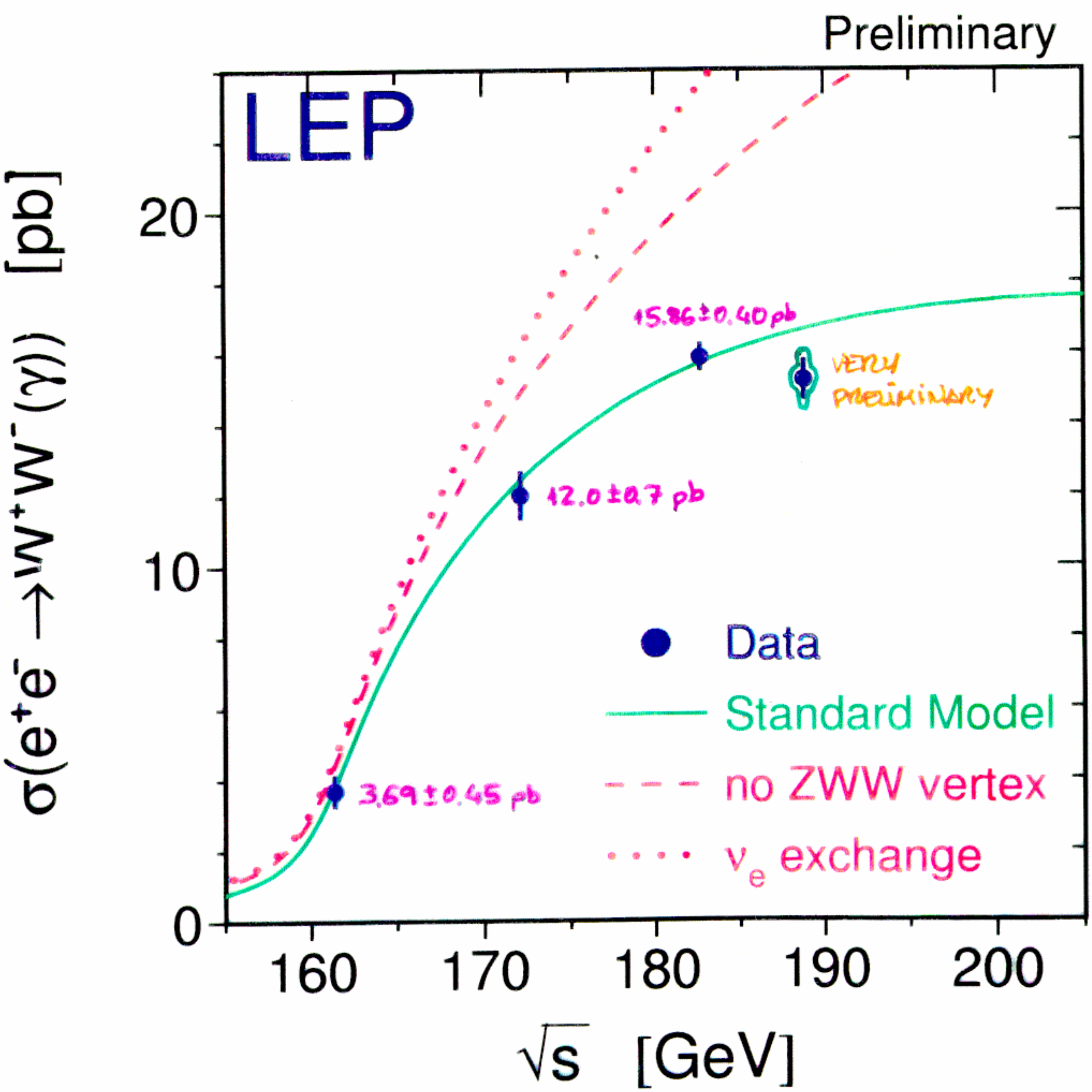
$$\boxed{|V_{cs}| = 1.04 \pm 0.04}$$

- USING PDG VALUES FOR OTHER V_{ij}
- NOT ASSUMING UNITARITY

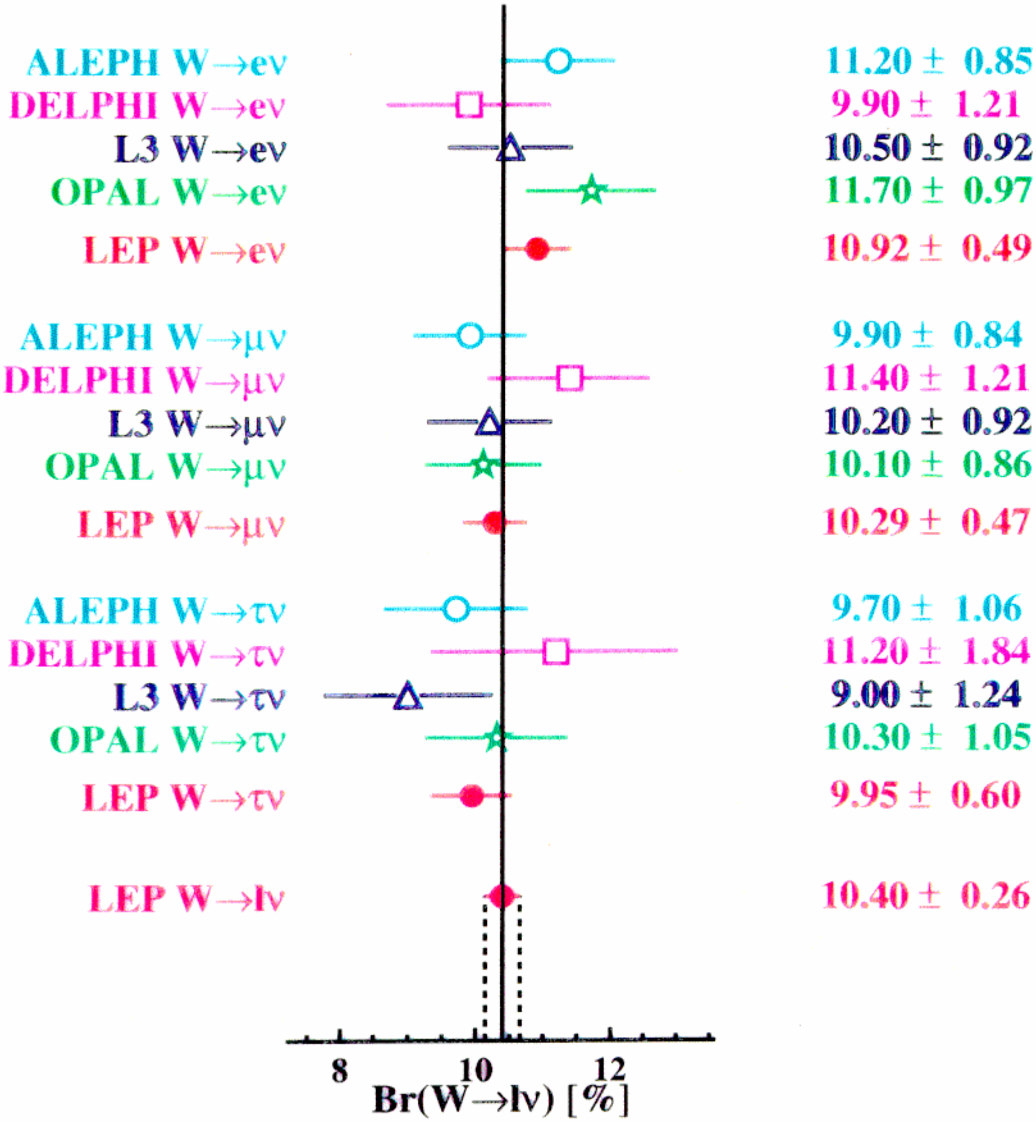
W PHYSICS AT LEP-II — WW CROSS SECTION

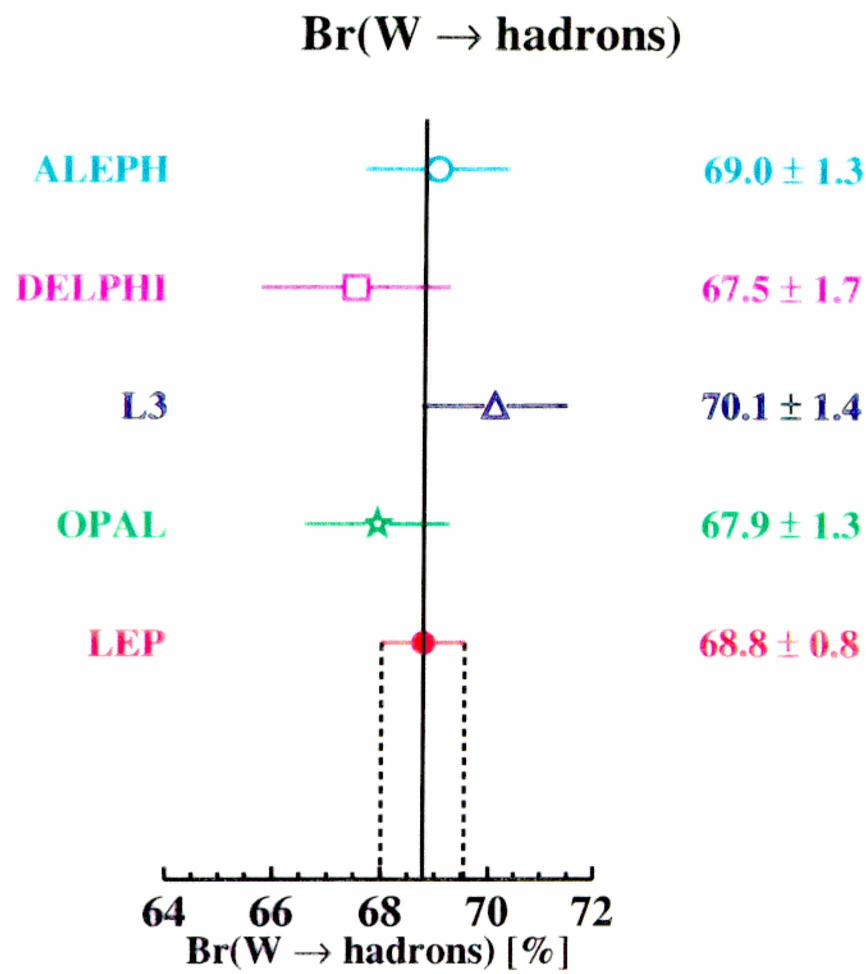
- GOOD AGREEMENT WITH S.M. EXPECTATION
- NON-SM CALCULATIONS DO NOT FIT

(STAT : ~ 850 evt/exp @ $\sqrt{s}$ = 183 GeV)



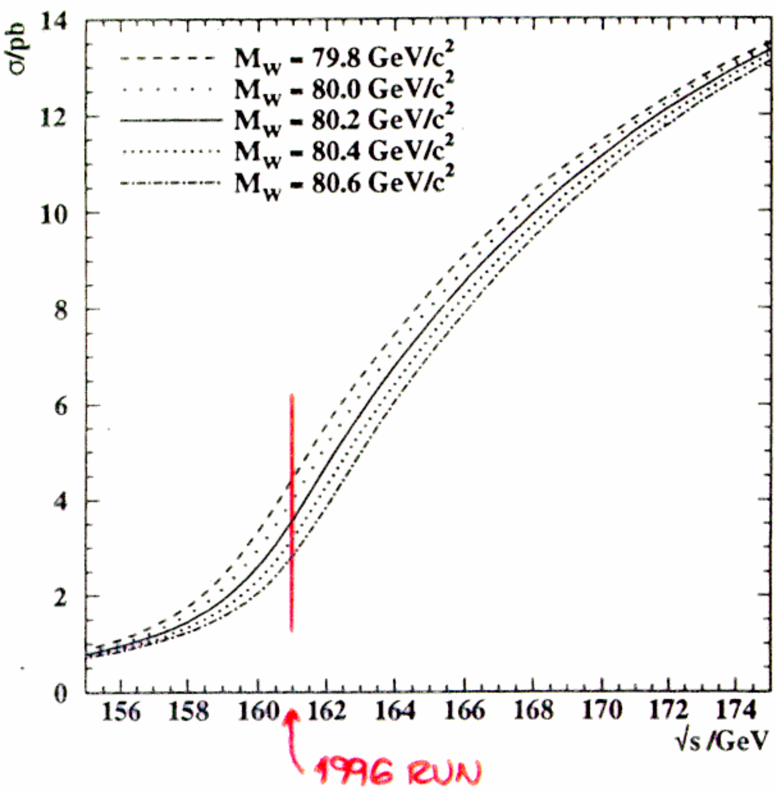
W Leptonic Branching Ratios




Br(W → hadrons)
ALEPH
69.0 ± 1.3
DELPHI
67.5 ± 1.7
L3
70.1 ± 1.4
OPAL
67.9 ± 1.3
LEP
68.8 ± 0.8
64
66
68
70
72
Br(W → hadrons) [%]

MASS MEASUREMENT AT THRESHOLD:

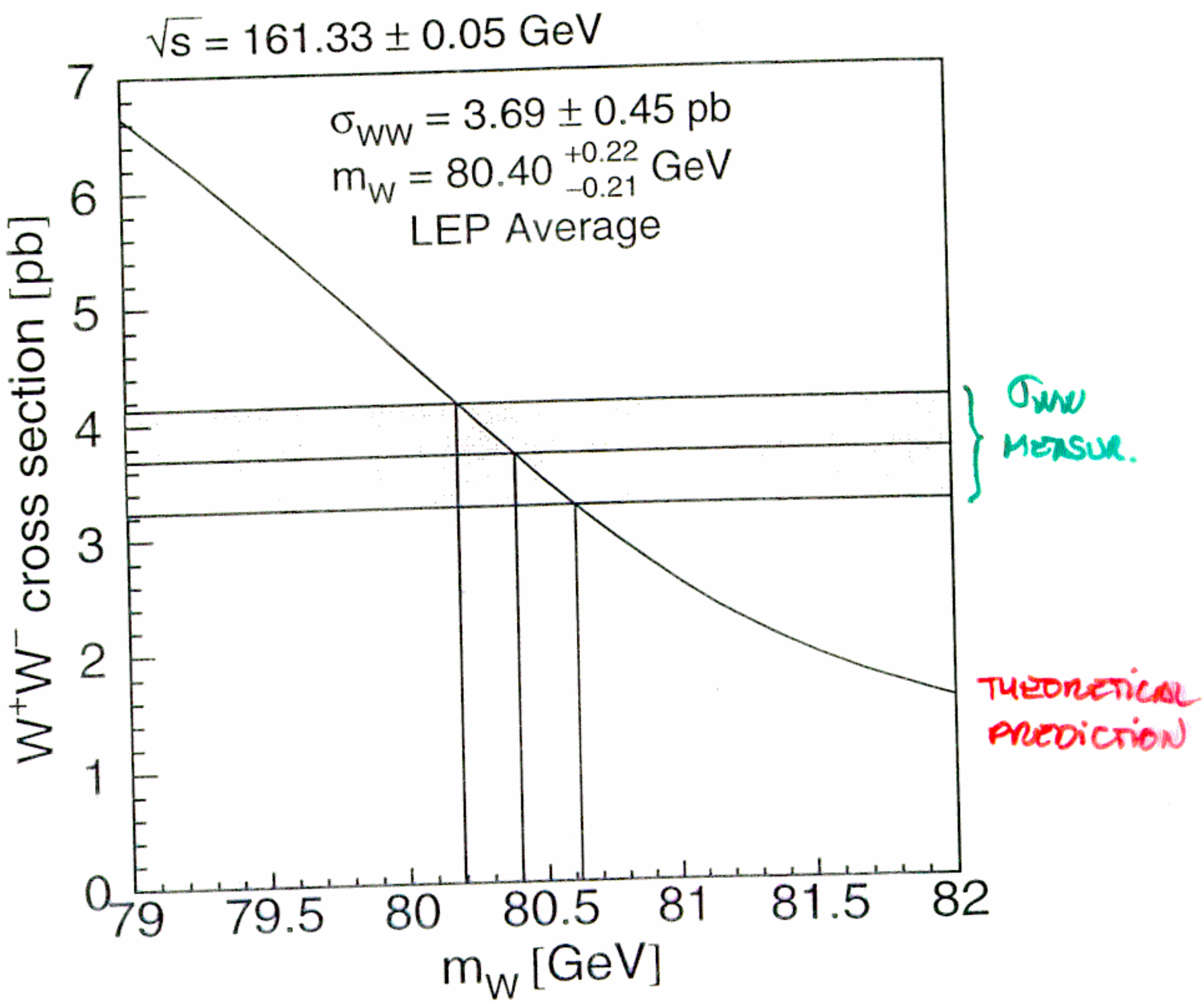
- TOO FEW EVENTS TO TRY DIRECT MASS RECONSTRUCT.
- CROSS-SECTION FOR $e^+e^- \to W^+W^-$ NEAR THRESHOLD VERY SENSITIVE TO M_W



- COMPUTE CROSS SECTION
- OBTAIN M_W WITHIN THE FRAMEWORK OF THE S.M. USING THEORETICAL PREDICTION ("GENTLE" CODE)

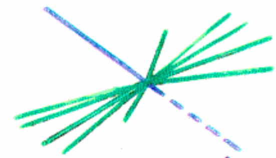
⇒ ESTIMATE STRICTLY VALID ONLY WITHIN S.M.

W PHYSICS AT LEP-II — W MASS MEASUREMENT

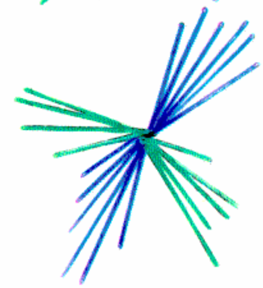


DIRECT MASS RECONSTRUCTION:

- USE ONLY SEMILEPTONIC AND HADRONIC EVENTS:
  - SEMILEPTONIC → FORCED TO 2-JET CONFIGURATION EXCLUDING LEPTON CANDIDATE



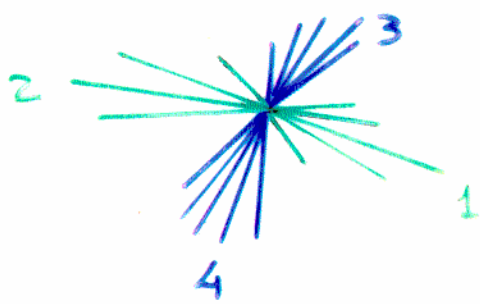
  - HADRONIC → FORCED INTO A 4-JET (5-JET) CONFIGURATION WITH A JET ALGORITHM (DURHAM)



- IMPROVE MASS RESOLUTION USING A KINEMATICAL FIT TO RECONSTRUCT 4 OBJECTS (JETS, LEPTON OR $\not{p}$ VECTOR)

- TO FURTHER IMPROVE MASS RESOLUTION CONSTRAIN THE TWO MASSES OF THE EVENT TO BE EQUAL (2-C FIT IN SEMILEPTONIC CHANNEL AND 5-C FIT IN HADRONIC CHANNEL).

- HADRONIC CHANNEL ADDITIONAL DIFFICULTY: COMBINATORIAL BACKGROUND ⇒ NEED OF A PAIRING ALGORITHM



1-2 / 3-4 RIGHT

1-3 / 2-4 } WRONG
1-4 / 2-3 }

W PHYSICS AT LEP-II — W MASS MEASUREMENT

- INVARIANT MASS DISTRIBUTIONS HAVE A BREIT-WIGNER LIKE SHAPE DISTORTED BY:
  - I.S.R.
  - PHASE SPACE BOUNDARY
  - DETECTOR RESOLUTION
  - MISASSIGNMENT OF PARTICLES TO W'S
  - BACKGROUND
  - EVENT SELECTION
  - ...

- FITTING TECHNIQUES:

  * USE (MODIFIED) BREIT-WIGNER FUNCTION

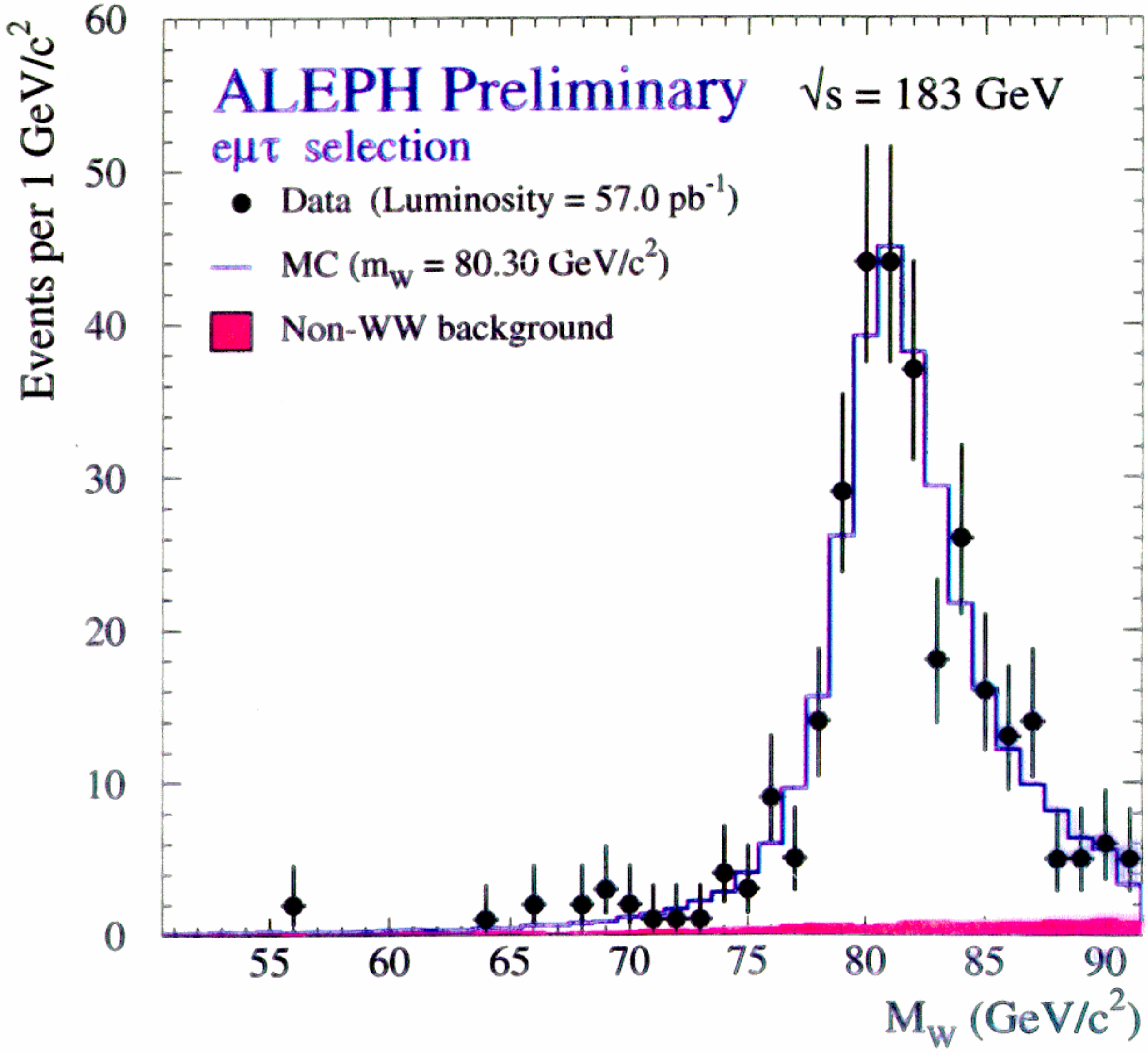
    ⇒ NEED A CALIBRATION CURVE $M_W = f(M_W^{Fit})$

  * USE MONTE CARLO RECONSTRUCTED MASS DISTRIB. DIRECTLY TO COMPARE WITH DATA MASS DISTRIB.

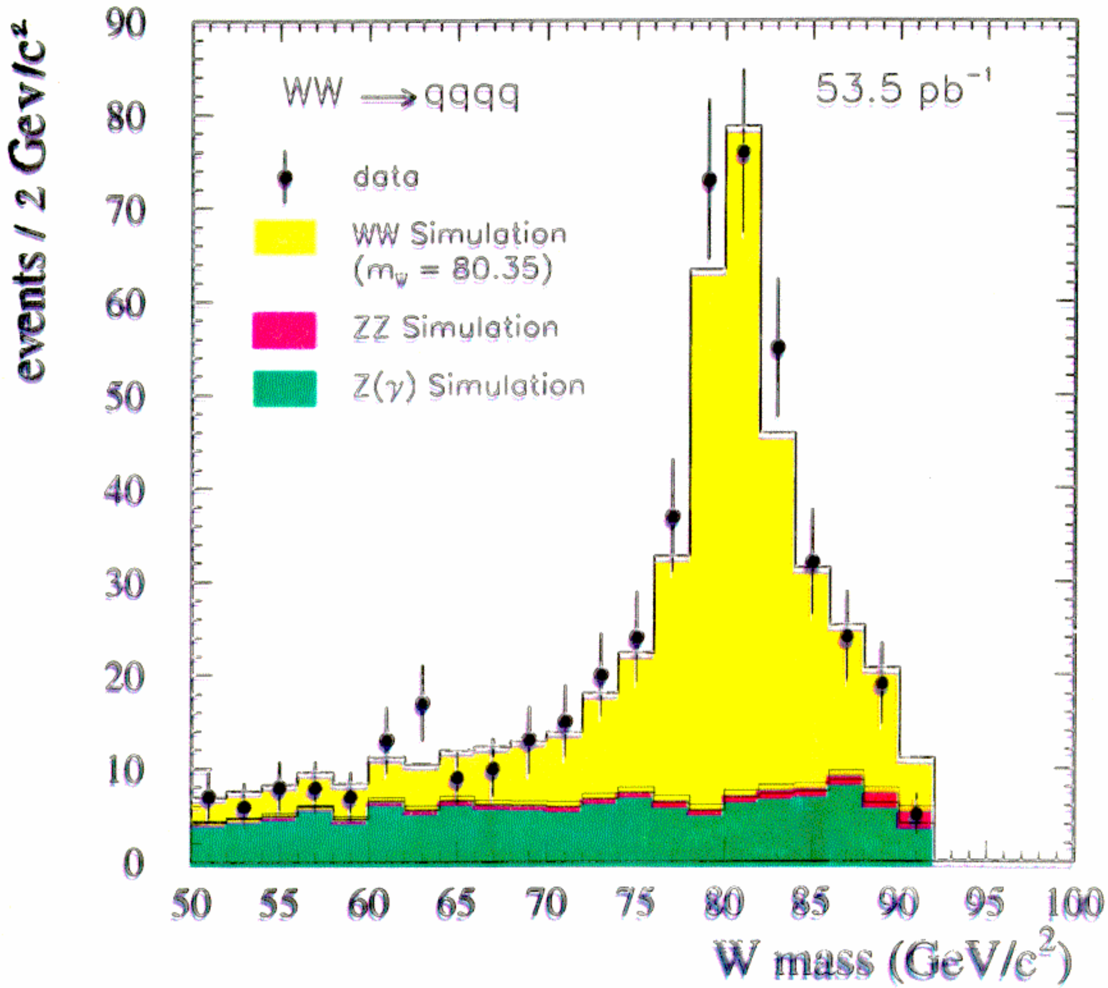
    INSTEAD OF GENERATING LARGE MC SAMPLES AT DIFFERENT W PARAMETERS, REWEIGHT EVENTS USING RATIO OF SQUARED MATRIX ELEMENTS

$$w_i(M_W, \Gamma_W) = \frac{|\mathcal{M}(M_W, \Gamma_W; p_i^1, p_i^2, p_i^3, p_i^4)|^2}{|\mathcal{M}(M_W^{MC}, \Gamma_W^{MC}; p_i^1, p_i^2, p_i^3, p_i^4)|^2}$$

⇒ LOTS OF MC EVENTS NEEDED IN EITHER CASE (SPECIALLY FOR FITS IN MORE THAN 1-D)


ALEPH Preliminary
√s = 183 GeV
eμτ selection
Data (Luminosity = 57.0 pb^-1)
MC (m_W = 80.30 GeV/c^2)
Non-WW background
Events per 1 GeV/c^2
M_W (GeV/c^2)
60
50
40
30
20
10
0
55
60
65
70
75
80
85
90

DELPHI 183 GeV PRELIMINARY



FINAL STATE INTERACTIONS:

$$e^+e^- \rightarrow W^+W^- \rightarrow q_1\bar{q}_2q_3\bar{q}_4$$

- SEPARATION OF W DECAY VERTICES $1/\Gamma_W \sim 0.1$ fm
- DECAY PRODUCT HADRONIZATION SCALE ~ 1 fm

⇓

FINAL STATE PARTICLE PRODUCTION IS NOT DICTATED BY THE SEPARATE DECAYS OF THE W BOSONS

⇓

IDENTITIES OF INDIVIDUAL $W^\pm$ DECAY PRODUCTS NOT WELL DEFINED ANY MORE

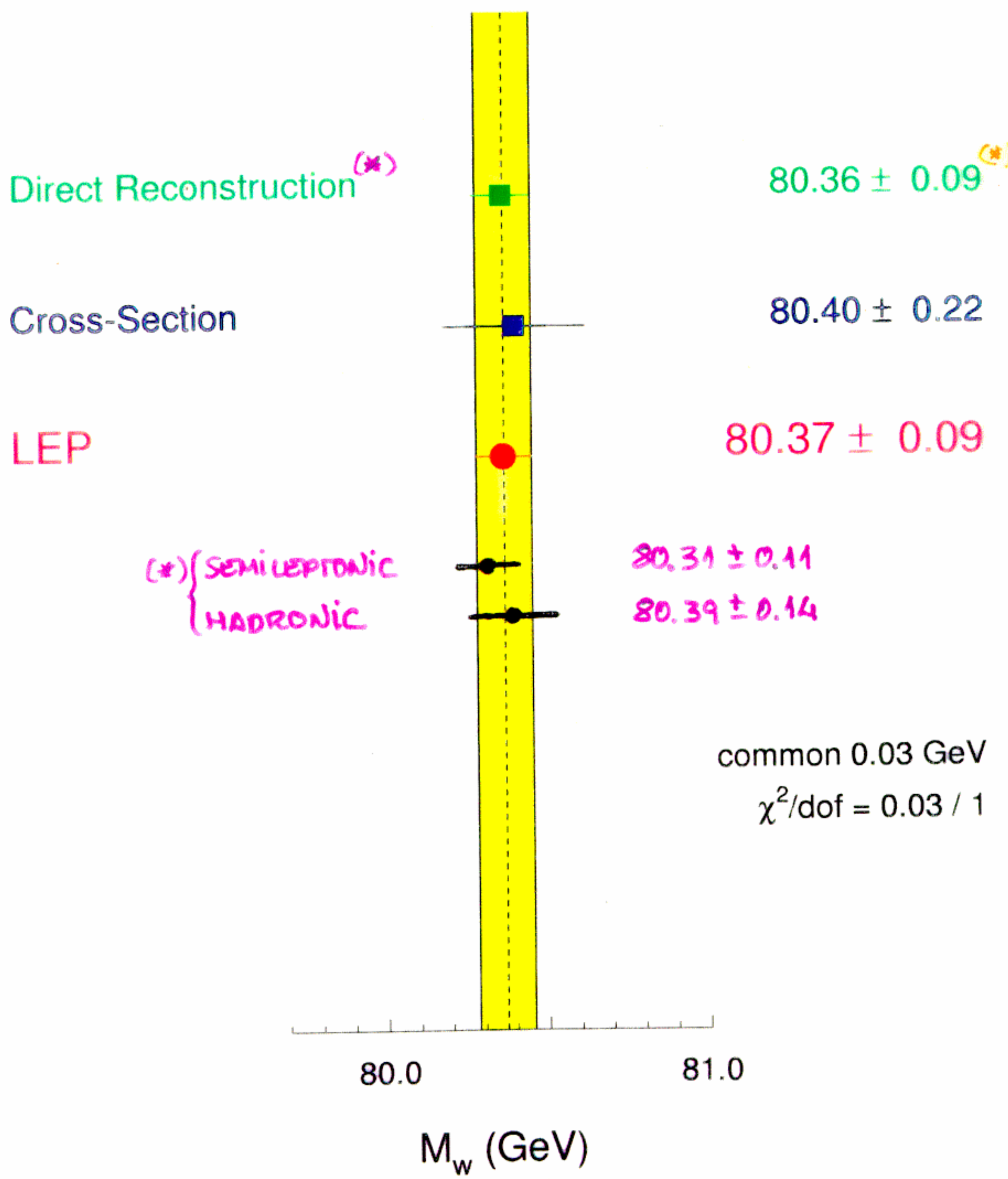
* COLOUR RECONNECTION
  - PERTURBATIVE RECONNECTION EXPECTED TO BE VERY SMALL (FACTOR $\sim 1/N_c^2$ SUPPRESSION)
  - NON-PERTURBATIVE RECONNECTION:
    - COLOUR SINGLET MODELS (KHOZE, SJOSTRAND, STRING MODELS, HERWIG CLUSTER MODEL)

      ⇒ 10-50 MeV MASS SHIFT DEPENDING ON EXPERIMENTAL PROCEDURE
    - NON-SINGLET MODELS (ELLIS-GEIGER) DISFAVOURED BY Z DATA AND MULTIPLICITY DISTRIBUTIONS
* BOSE-EINSTEIN
  - CORRELATIONS BETWEEN IDENTICAL BOSONS (PIONS)
  - EFFECT DEPENDS ON EXPERIMENTAL PROCEDURE

    ⇒ 20-50 MeV

Vancouver 98 - Preliminary - 161+172+183 GeV

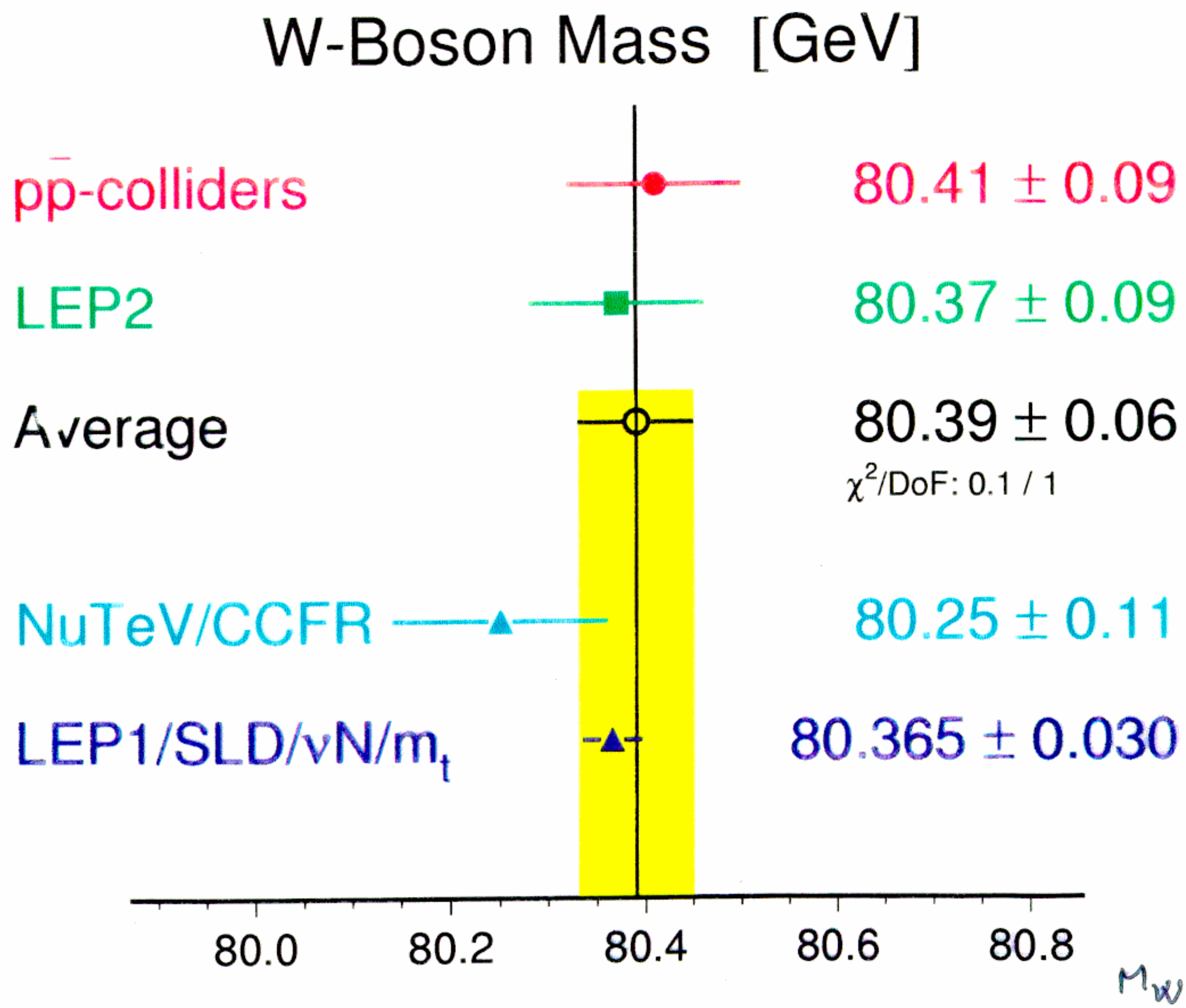
M_W (GeV)



(*) ERROR SPLITTING:

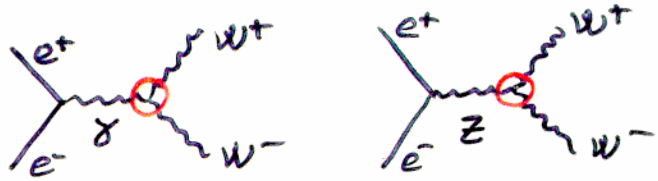
$0.09 = 0.08 \oplus 0.05\ (\text{FSI}) \oplus 0.02\ (\text{LEP})$

- COMPARISON WITH OTHER M_W DETERMINATIONS



W PHYSICS AT LEP-II — TGCs

- LEP-II ALLOWS FOR FIRST TIME THE STUDY OF THE NON-ABELIAN STRUCTURE OF THE EW S.M. DIRECTLY IN e^+e^- COLLISIONS:



- MOST GENERAL STRUCTURE OF PHENOMENOLOGICAL LAGRANGIAN CONSISTENT WITH LORENTZ INVARIANCE

$\Rightarrow$ 2×7 TGCs

$$i\mathcal{L}_{eff}^{WWV} = g_{WWV}$$

$$\Big\{ g_1^V V^\mu (W^-_{\mu\nu} W^{+\nu} - W^+_{\mu\nu} W^{-\nu}) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2} V^{\mu\nu} W^{+\rho}_\nu W^-_{\rho\mu} +$$

$$+ i g_5^V \epsilon_{\mu\nu\rho\sigma} [(\partial^\rho W^{-\mu}) W^{+\nu} - W^{-\mu}(\partial^\rho W^{+\nu})] V^\sigma + i g_4^V W^-_\mu W^+_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu)$$

$$- \frac{\tilde{\kappa}_V}{2} W^-_\mu W^+_\nu \epsilon^{\mu\nu\rho\sigma} V_{\rho\sigma} - \frac{\tilde{\lambda}_V}{2M_W^2} W^-_{\rho\mu} W^{+\mu}_\nu \epsilon^{\nu\rho\alpha\beta} V_{\alpha\beta} \Big\} \qquad V = \gamma, Z$$

$g_{WW\gamma} = e$.

$g_{WWZ} = e \cot g\, \theta_W$

$W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu$

$V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$

$\epsilon^{0123} = 1$

- T.G.C.s NATURALLY SPLIT INTO THREE CLASSES:

CONSERVE C AND P	CONSERVE C OR P	VIOLATE CP
g_1^V κ_V λ_V	g_5^V	g_4^V $\tilde{\kappa}_V$ $\tilde{\lambda}_V$

W PHYSICS AT LEP-II — TGCs

- VERY UNLIKELY TO OBSERVE C, P OR CP VIOLATION AT LEP-II ⇒ CONSIDER ONLY CP CONSERVING:

STATIC W^+ MOMENTS:

$$Q_W = e g_1^\gamma$$ ELECTRIC CHARGE

$$\mu_W = \frac{e}{2M_W}\cdot(g_1^\gamma + \kappa_\gamma + \lambda_\gamma)$$ MAGNETIC DIPOLE MOMENT

$$q_W = -\frac{e}{M_W^2}(\kappa_\gamma - \lambda_\gamma)$$ ELECTRIC QUADRUP. MOMENT

(+ SAME $\gamma \leftrightarrow Z$ ⇒ WEAK CHARGE AND MOMENTS)

- ANY THEORY INCORPORATING NEW PHYSICS BEYOND S.M. AND INCLUDING E.W. THEORY AS EFFECTIVE LOW-ENERGY LIMIT, MAY INTRODUCE DEVIATIONS OF TGCs FROM S.M. VALUES:

$$g_1^\gamma = g_1^Z = 1,\quad \kappa_\gamma = \kappa_Z = 1,\quad \lambda_\gamma = \lambda_Z = 0$$ S.M. PREDICTION

- DEFINE DEVIATIONS FROM STANDARD MODEL:

$$\Delta g_1^Z \equiv (g_1^Z - 1) \equiv \tan\theta_W \cdot \delta_Z$$

$$\Delta\kappa_\gamma \equiv (\kappa_\gamma - 1) \equiv x_\gamma$$

$$\Delta\kappa_Z \equiv (\kappa_Z - 1) \equiv \tan\theta_W \cdot (x_Z + \delta_Z)$$

$$\lambda_\gamma \equiv y_\gamma$$

$$\lambda_Z \equiv \tan\theta_W \cdot y_Z$$

($g_1^\gamma = 1$ ⇒ E.M. GAUGE INVARIANCE ALSO ASSUMED)

W PHYSICS AT LEP-II — TGCs

- TGCs CONTRIBUTE VIA LOOP CORRECTIONS TO E.W. PRECISION MEASUREMENTS ⇒ STRONG CONSTRAINTS FROM LEP-I

- SOME "BLIND DIRECTIONS" IN THE MULTIDIMENSIONAL SPACE OF TGCs WHERE CONSTRAINTS FROM LEP-I ANALYSES ARE VERY WEAK:

$$\alpha_{W\phi} = \Delta g_1^Z \cdot \cos\theta_W$$
$$\alpha_W = \lambda_\gamma$$
$$\alpha_{B\phi} = \Delta\kappa_\gamma - \Delta g_1^Z \cos^2\theta_W$$

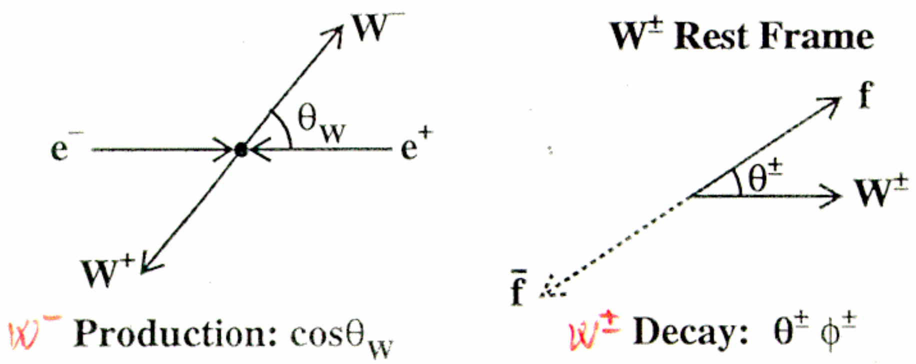
ALONG WITH THE CONSTRAINTS $\begin{cases} \Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \tan^2\theta_W \\ \lambda_Z = \lambda_\gamma \end{cases}$

STANDARD MODEL EXPECTATION:

$$\alpha_{W\phi} = \alpha_W = \alpha_{B\phi} = 0$$

COUPLING DETERMINATION:

- USE
  - CROSS SECTION
  - W PRODUCTION ANGLE
  - $W^{\pm}$ DECAY ANGLES + CORRELATIONS



OF - CHARGED LEPTON
- DOWN-TYPE QUARK

* SEMILEPTONIC:
  - USE LEPTON CHARGE TO SIGN $\cos\theta_W$
  - TWO-FOLD AMBIGUITY IN HADRONIC W DECAY
* HADRONIC:
  - USE JET CHARGE Q_{JET} TO SIGN $\cos\theta_W$
  - FOUR-FOLD AMBIGUITY DUE TO 2 HAD. W DECAYS

  + JET PAIRING COMBINATORIC BKGD.

W PHYSICS AT LEP-II TGCs

- FITTING TECHNIQUES:
  - MULTIDIMENSIONAL MAX. LIKELIHOOD (UP TO 5-D)
    - → EXPLOITS FULL ANGULAR INFORMATION
    - → TECHNICALLY COMPLEX:
      - UNBINNED USING SEMIANALITYCAL EXPRESSION
        - → INVOLVED MULTIDIMENSIONAL CORRECTIONS TO ACCOUNT FOR BKGD. & EXPERIM. EFFECTS.
      - BINNED USING MC EVENTS
        - → VERY LARGE NUMBER OF BINS → LOTS OF MC EVENTS NEEDED.
  - "OPTIMAL OBSERVABLES": PROJECT RELEVANT KINEMAT. INFORMATION TO A CERTAIN TGC ONTO A 1-D DISTRIB.
    - → SINCE TGCs CONTRIBUTE ONLY LINEARLY TO THE AMPLITUDE ⇒ DIFF. CROSS SECTION IS A QUADRATIC FUNCT.:

$$\frac{d\sigma(\Omega,\bar{\alpha})}{d\Omega} = S_0(\Omega) + \sum_i S_{1i}(\Omega)\alpha_i + \sum_{i,j} S_{2ij}(\Omega)\alpha_i\alpha_j$$

α_i COUPLINGS

Ω MEASURED P.S. VARIABLES

$$OO_i \equiv \frac{\frac{d}{d\alpha_i}\left(\frac{d\sigma(\Omega,\bar{\alpha})}{d\Omega}\right)\Big|_{\alpha_i=0}}{\frac{d\sigma(\Omega,\bar{\alpha})}{d\Omega}\Big|_{\alpha_i=0}} = \frac{S_{1i}(\Omega)}{S_0(\Omega)}$$

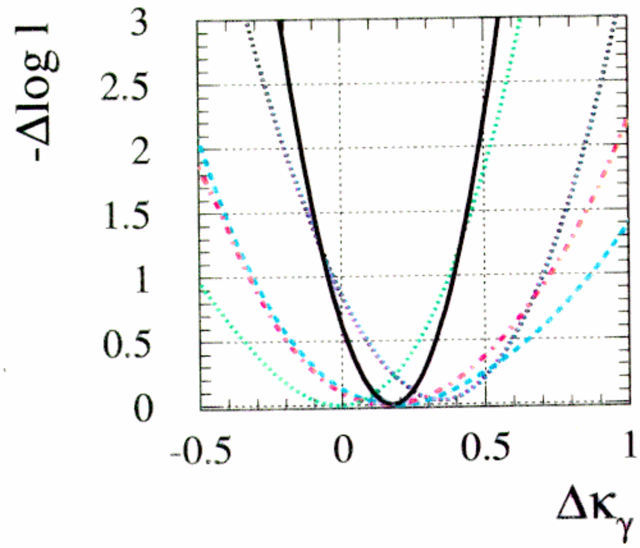
- → USE MC $d\sigma/d\Omega$ TO ACCOUNT FOR BKGD + EXPERIM. EFFECTS
- → COMPUTE OO_i FOR EACH EVENT AND DO LIKELIHOOD FIT

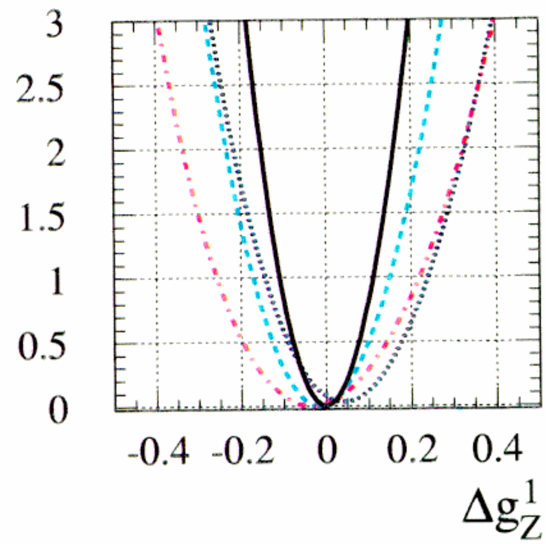
$$\ln \mathcal{L} = \sum_{i=1}^{N} \ln \mathcal{P}(OO_i, \bar{\alpha})$$ ← PROBABILITY FROM MC DISTRIBUTION

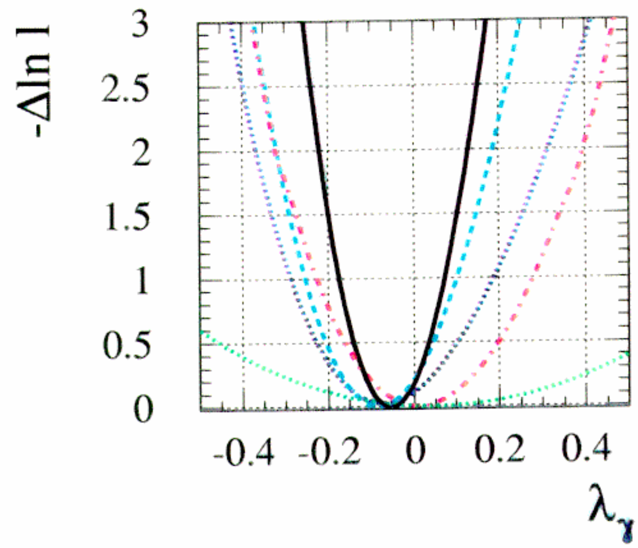
- COMBINE RESULTS FROM 4 LEP EXPERIMENTS BY ADDING LIKELIHOOD CURVES

⇒ NO DISCREPANCY WITH THE S.M.

ALEPH+ DELPHI+ L3 + OPAL







$\Delta\kappa_\gamma = 0.17 \begin{matrix} +0.16 \\ -0.16 \end{matrix}$

$\Delta g_1^Z = 0.00 \begin{matrix} +0.08 \\ -0.08 \end{matrix}$

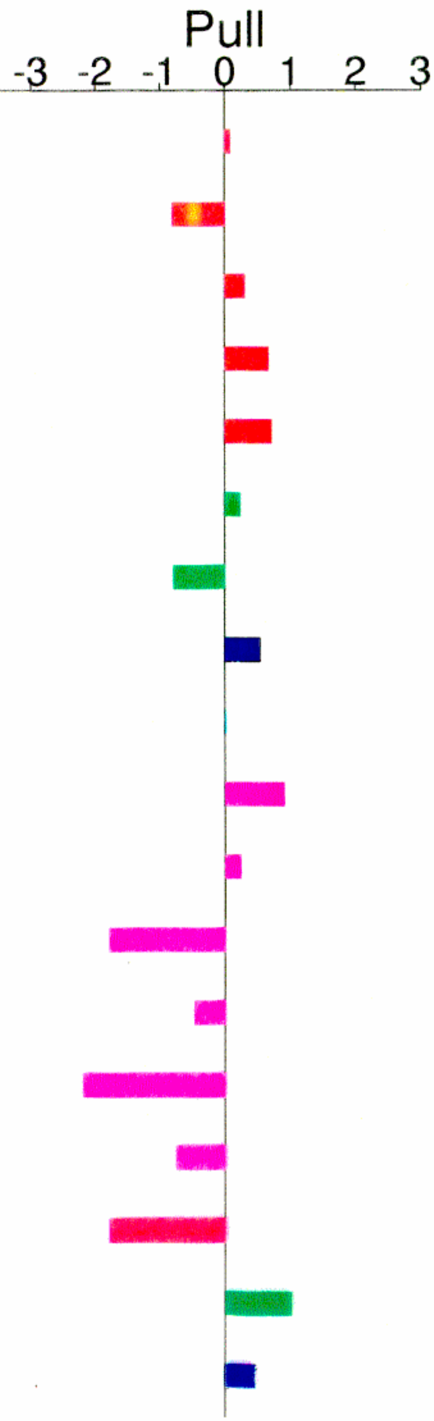
$\lambda_\gamma = -0.05 \begin{matrix} +0.08 \\ -0.09 \end{matrix}$

SM TESTS — EW PRECISION DATA FITS

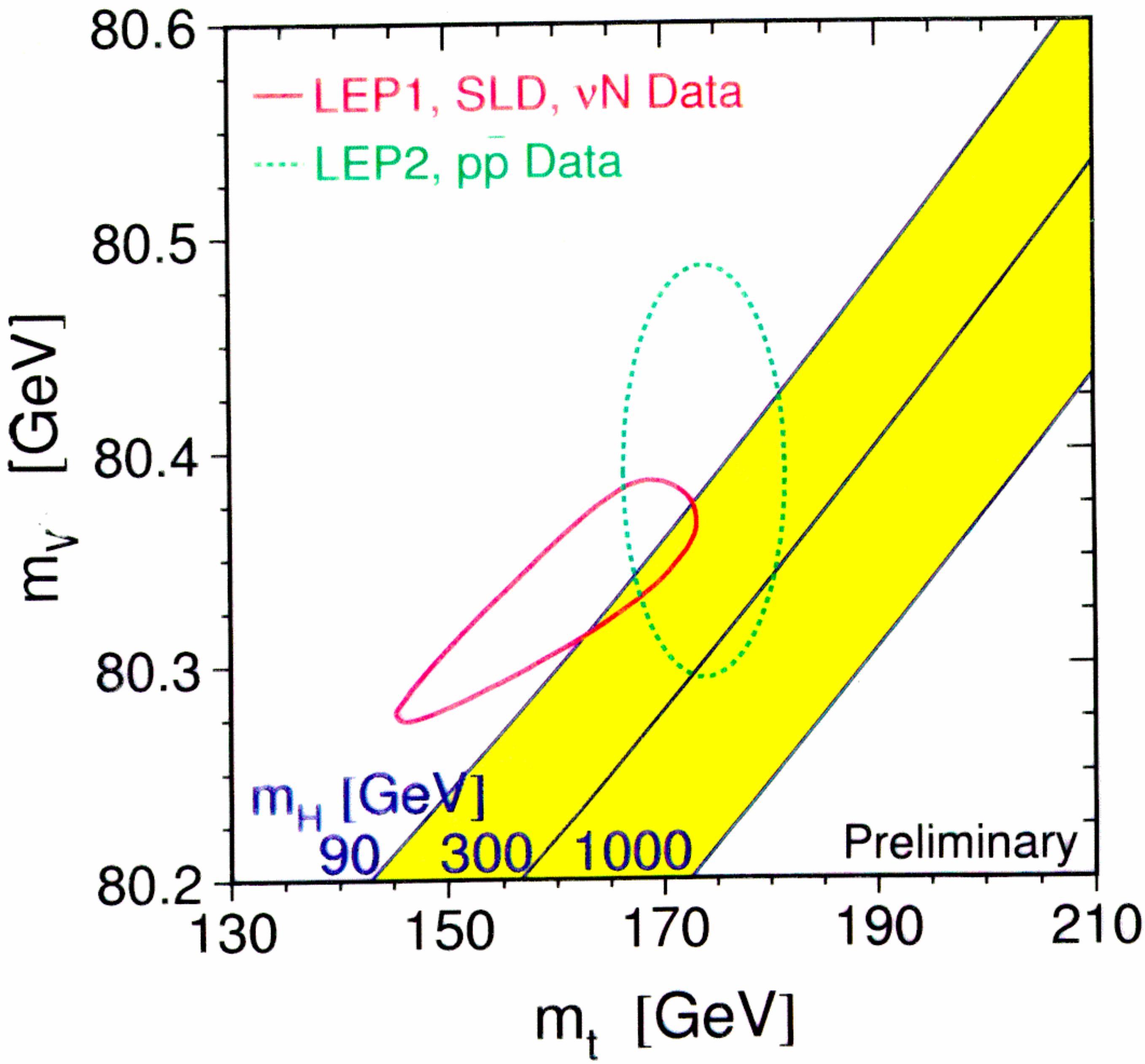
- CONSISTENCY WITH MSM PREDICTIONS
  ⇒ NO WORRYING DISCREPANCY

Vancouver 1998

	Measurement	Pull
m_Z [GeV]	91.1867 ± 0.0021	.08
Γ [GeV]	2.4939 ± 0.0024	-.80
σ^0_{hadr} [nb]	41.491 ± 0.058	.31
R_e	20.765 ± 0.026	.66
$A^{0,e}_{fb}$	0.01683 ± 0.00096	.72
A_e	0.1479 ± 0.0051	.24
A_τ	0.1431 ± 0.0045	-.80
$\sin^2\theta^{lept}_{eff}$	0.2321 ± 0.0010	.54
m_W [GeV]	80.370 ± 0.090	.01
R_b	0.21656 ± 0.00074	.90
R_c	0.1733 ± 0.0044	.24
$A^{0,b}_{fb}$	0.0991 ± 0.0021	-1.78
$A^{0,c}_{fb}$	0.0714 ± 0.0044	-.47
A_b	0.856 ± 0.036	-2.18
A_c	0.638 ± 0.040	-.74
$\sin^2\theta^{lept}_{eff}$	0.23101 ± 0.00031	-1.78
$\sin^2\theta_W$	0.2255 ± 0.0021	1.06
m_W [GeV]	80.410 ± 0.090	.45

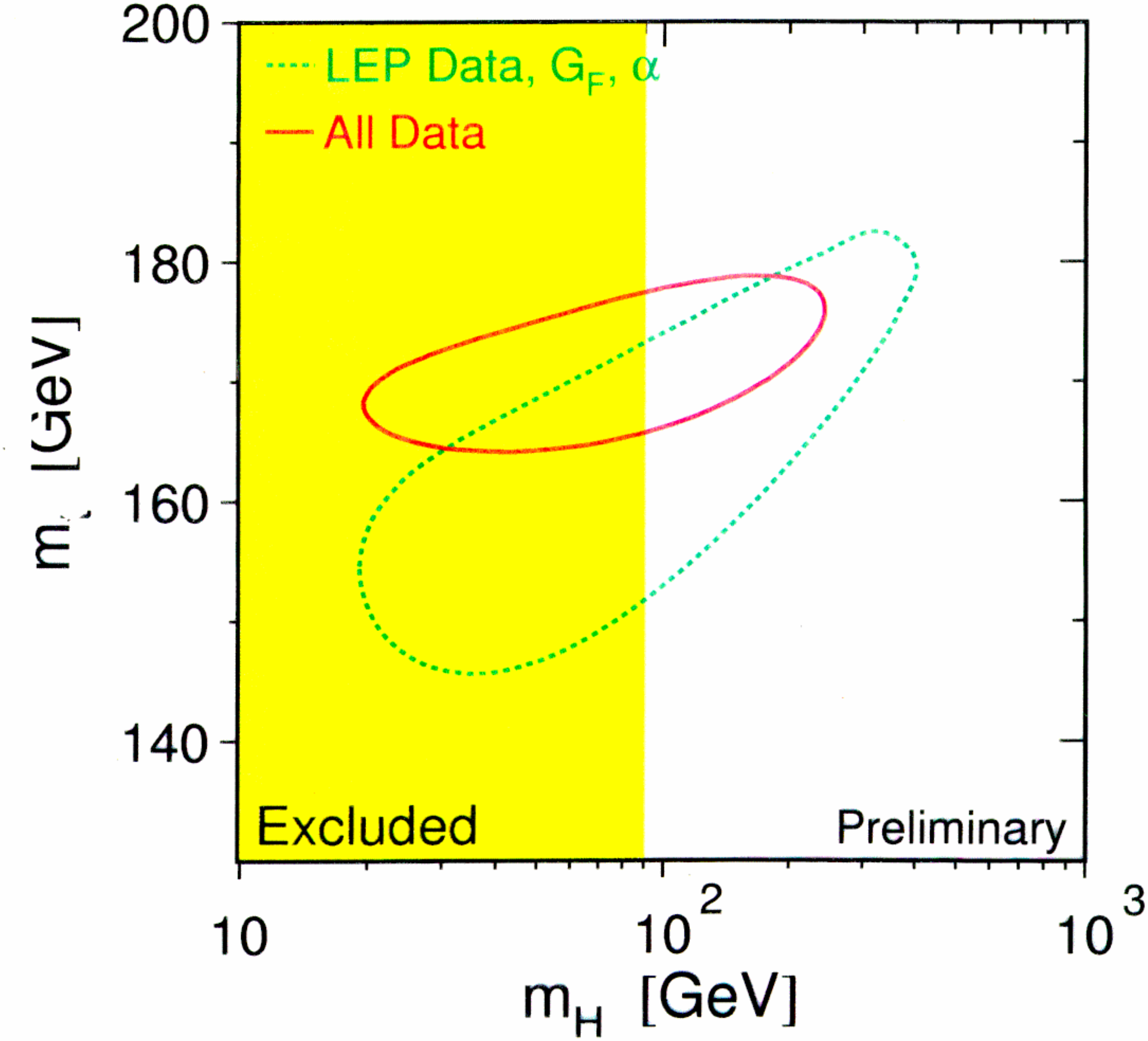


- COMPARISON BETWEEN
  - DIRECT DETERMINATION OF M_W AND m_t
  - RESULT FROM EW PRECISION DATA FIT



SM TESTS — EW PRECISION DATA FITS

- CONSISTENCY OF LEP AND NON-LEP DATA IN THE DETERMINATION OF M_H



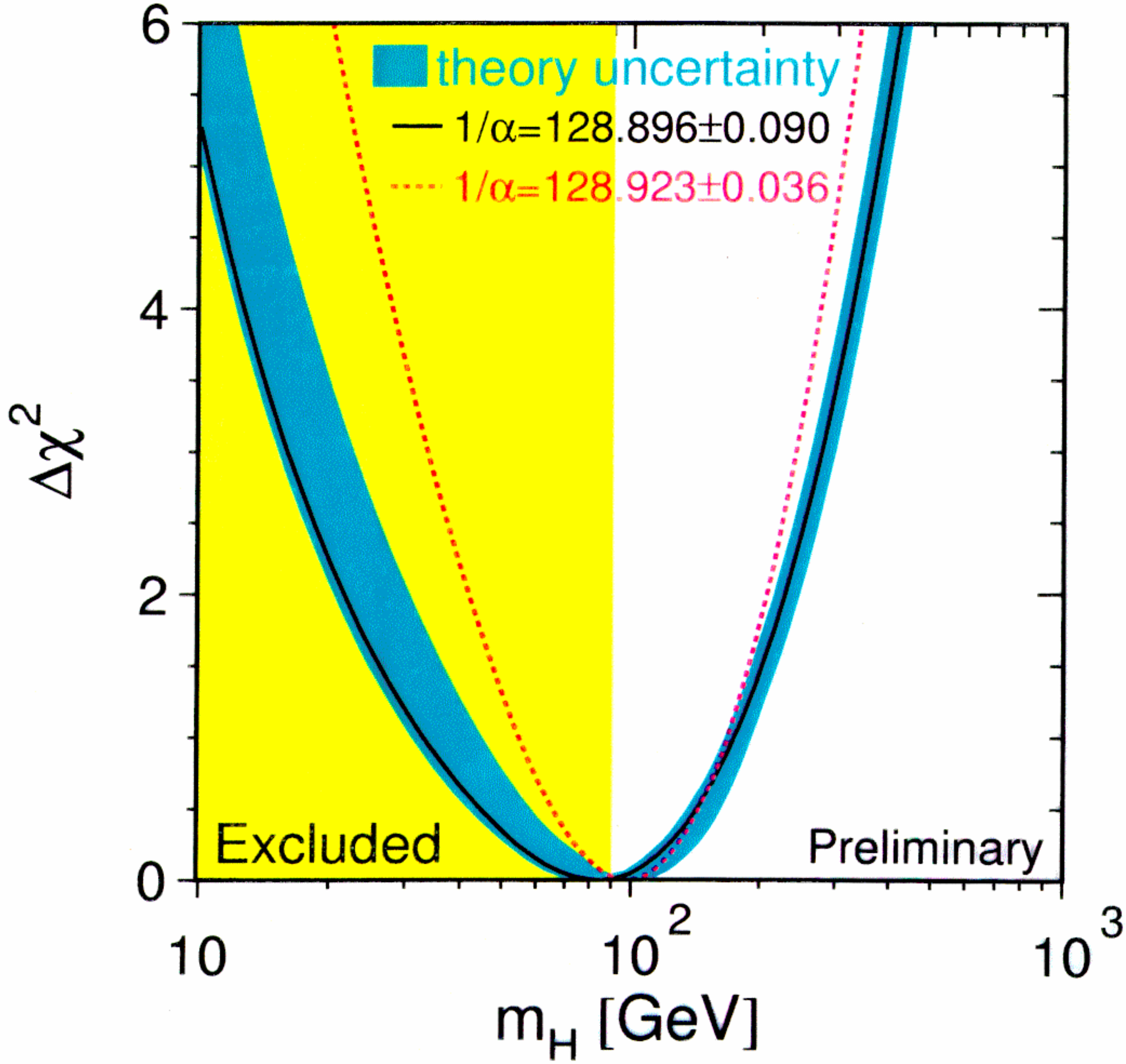
SM TESTS — DETERMINATION OF M_H

— $M_H = 84^{+91}_{-51}$ GeV

---- $M_H = 98^{+70}_{-44}$ GeV

$\chi^2/NDF = 16.4/15$

(DIRECT SEARCH RESULTS NOT TAKEN INTO ACCOUNT)



CONCLUSIONS

- PRECISION ELECTROWEAK MEASUREMENTS AT LEP-I HAVE BEEN A BIG SUCCESS, BEYOND THE MOST OPTIMISTICAL EXPECTATIONS
  - Z BOSON PROPERTIES KNOWN WITH VERY HIGH PRECISION
  - PRECISION CALCULATIONS MATCH EXPERIMENTAL ACCURACY
  - FINAL PUBLICATIONS IMMINENT
- LEP-II ELECTROWEAK PHYSICS PROGRAM ON GOOD TRACK
  - M_W ALREADY DETERMINED WITH SAME PRECISION AS COLLIDER MEASUREMENTS
  - HOPE FOR INCREASED STATISTICS FOR PRECISION MEASUREMENTS OF W BOSON PROPERTIES

⇛ ALTOGETHER:

UNPRECEDENTED TEST OF THE GOOD HEALTH OF THE M.S.M. IN DESCRIBING THE E.W. DATA

AND

SIGNIFICATIVE WINDOW FOR THE INFERENCE OF ITS LAST MISSING PIECE: M_H