LEP Results

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On behalf of the ALEPH, DELPHI, L3, OPAL and SLD Collaborations, and the Electroweak Working Group

http://www.cern.ch/LEPEWWG
http://www.cern.ch/LEPHFS

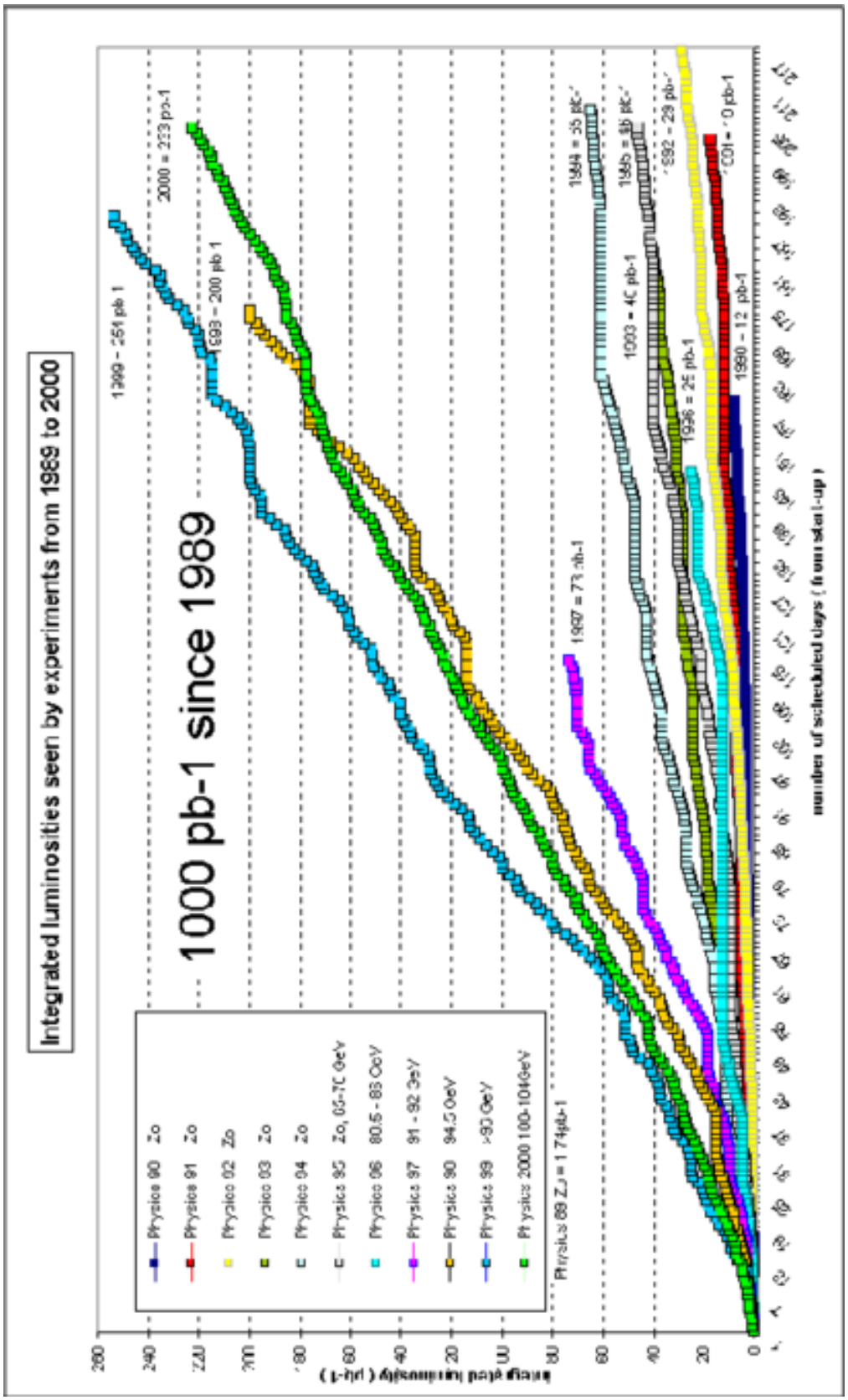
QFTHEP 2001, Moscow, 6-12 September

LEP Results - Outline

$\sim$ 12 years running, ~ 1200 papers,...

- LEP Performance
- Radiative Corrections
- LEP1 - Z boson
  - parameters
  - leptonic couplings
  - quark couplings
- LEP1/SLD/CDF - Heavy Flavour
  - oscillations $\Delta m_d, \Delta m_s$
  - CKM constraints
- LEP2
  - fermion pair production
  - W^+W^- production
  - W mass
  - ZZ production
  - Triple Boson Couplings, Single W
- Global Electroweak Fit
  - M_W, M_t tests
  - Constraining M_H
  - Running $\alpha(0 \longrightarrow M_Z^2)$
  - Theory Uncertainty
  - $A_{fb}^{0,b}$ influence
- Conclusions

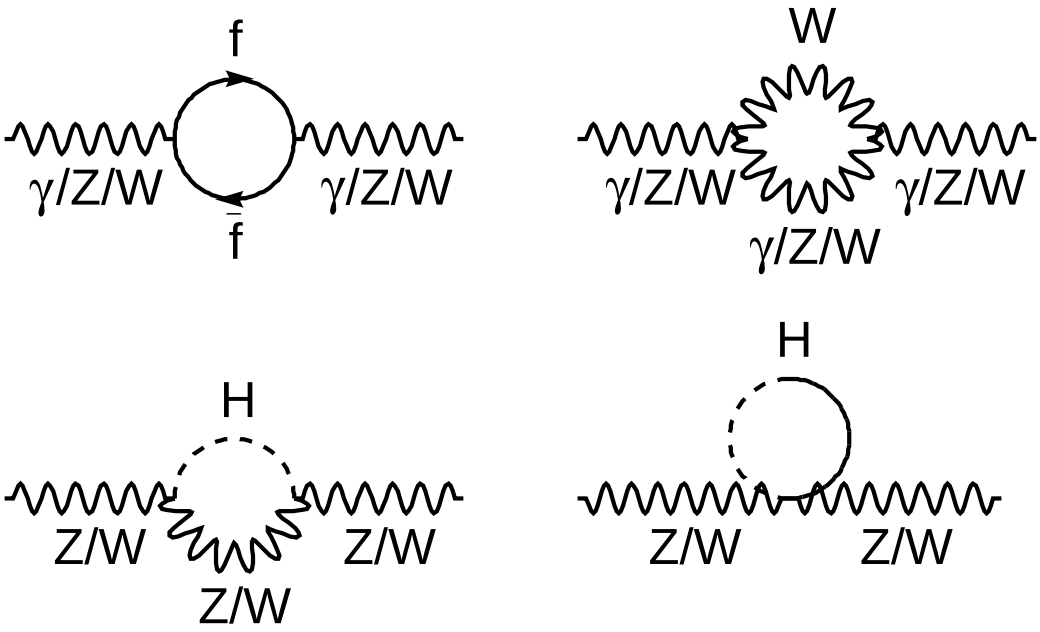
12 years of LEP Performance



15.5 M hadronic Z, 45k W^+W^-

SM Radiative corrections

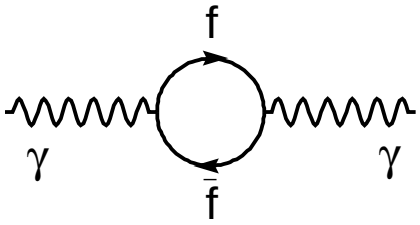
Boson + fermion loops in propagators:



Modifiy tree-level relation between couplings:

$$G_F = \frac{\pi\alpha(0)}{\sqrt{2}M_W^2 \sin^2\theta_W}\frac{1}{1-\Delta r} \qquad \Delta r = \Delta\alpha + \Delta r_W$$

$\Delta\alpha$ absorbed into running of α:



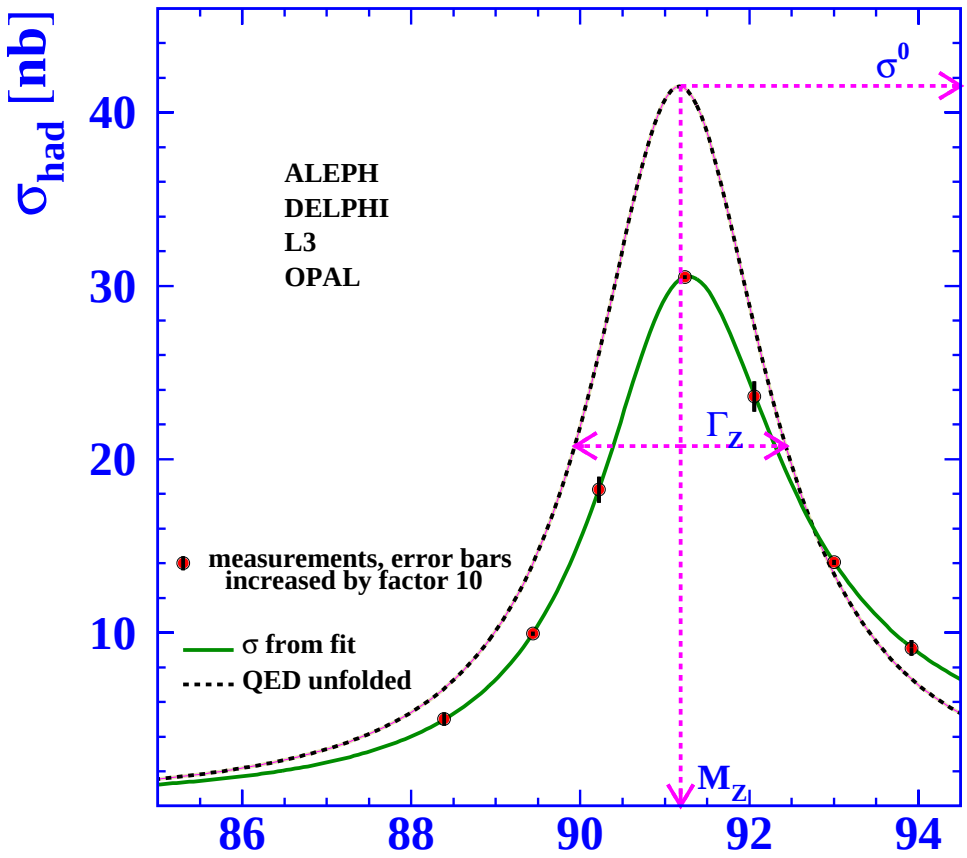
$$\frac{1}{\alpha(0)} \longrightarrow \frac{1}{\alpha(M_Z^2)} = \frac{(1-\Delta\alpha)}{\alpha(0)}$$

Δr_W leading contributions:

$$\Delta r^t \sim M_t^2$$
$$\Delta r^H \sim \log M_H \longrightarrow \text{Indirect } M_t, M_H$$

LEP1 Z Lineshape

Analysis completed hep-ex/0101027.



$\Gamma_Z = 2495.2 \pm 2.3$ MeV

$M_Z = 91187.5 \pm 2.1$ MeV (E_{beam} : 1.7 MeV)

$N_\nu = 2.9841 \pm 0.0083$ from Γ_{inv}

Enormous efforts reducing uncertainties:

Upgraded Luminosity detectors $\longrightarrow \mathcal{O}(10^{-3})$

resonant depolarisation δE_{beam} precision	$\rightarrow$	Earth tides Leakage currents..

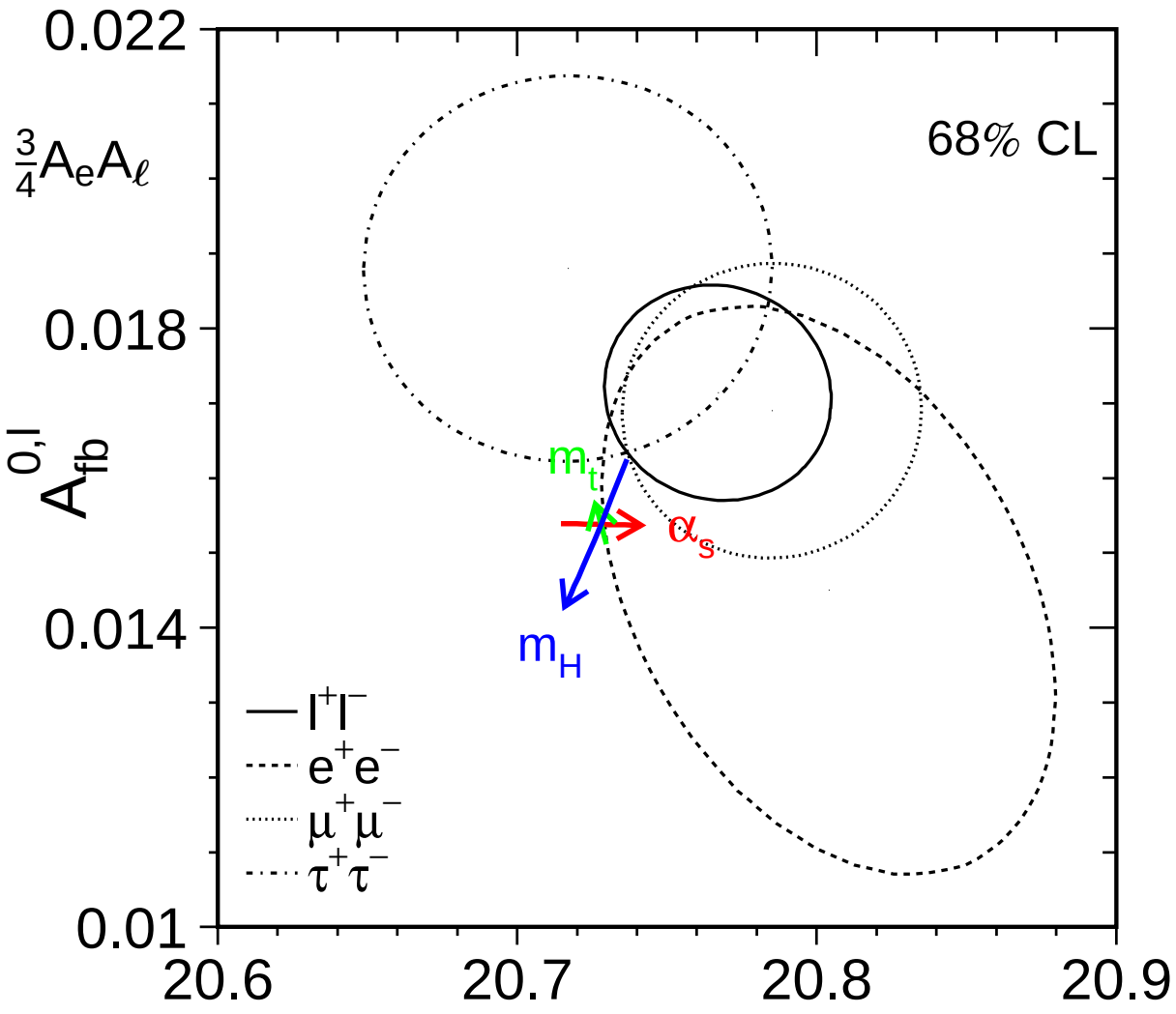
Theory uncertainties: $\delta M_Z \pm 0.3$ MeV

$\delta \Gamma_Z \pm 0.2$ MeV

LEP1 Z Lineshape and Asymmetries

Cross-sections
Asymmetries $\longrightarrow$ $\left(\begin{array}{c} M_Z \\ \Gamma_Z \\ \sigma^{\circ}_{had} \\ R^0_\ell \\ A^{0,\ell}_{fb} \end{array} \right)$

$A^{0,\ell}_{fb} = \frac{3}{4} A_e A_\ell$



$\alpha_S = 0.118 \pm 0.002$
$M_t = 174.3 \pm 5.1$ GeV
$M_H = 300^{+700}_{-186}$ GeV

Low Higgs mass preferred!

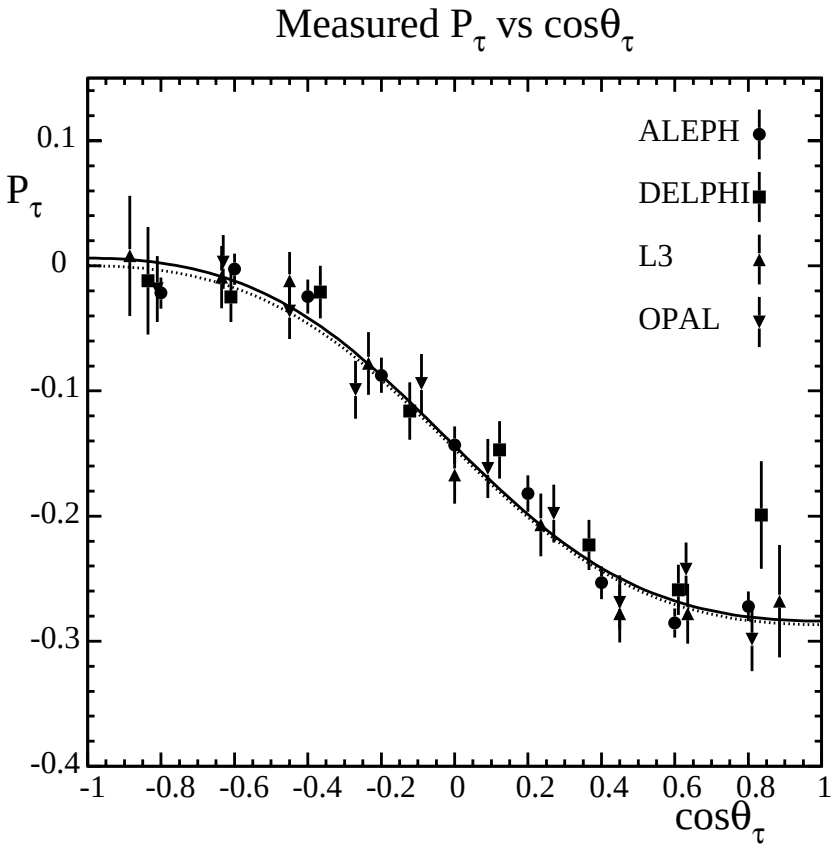
LEP1 τ Polarisation + SLD Asymmetries

τ decays: $\pi\nu, e\nu\bar{\nu}, \mu\nu\bar{\nu}, \rho\nu, a_1\nu \longrightarrow \mathcal{P}_\tau$

$$\mathcal{P}_\tau(\cos\theta_{\tau^-}) = -\frac{A_\tau(1+\cos^2\theta_\tau)+2A_e\cos\theta_\tau}{1+\cos^2\theta_\tau+2A_\tau A_e\cos\theta_\tau}$$

$\longrightarrow A_\tau, A_e$ Independently

$\longrightarrow A_\ell$



Combination of final LEP1 results:

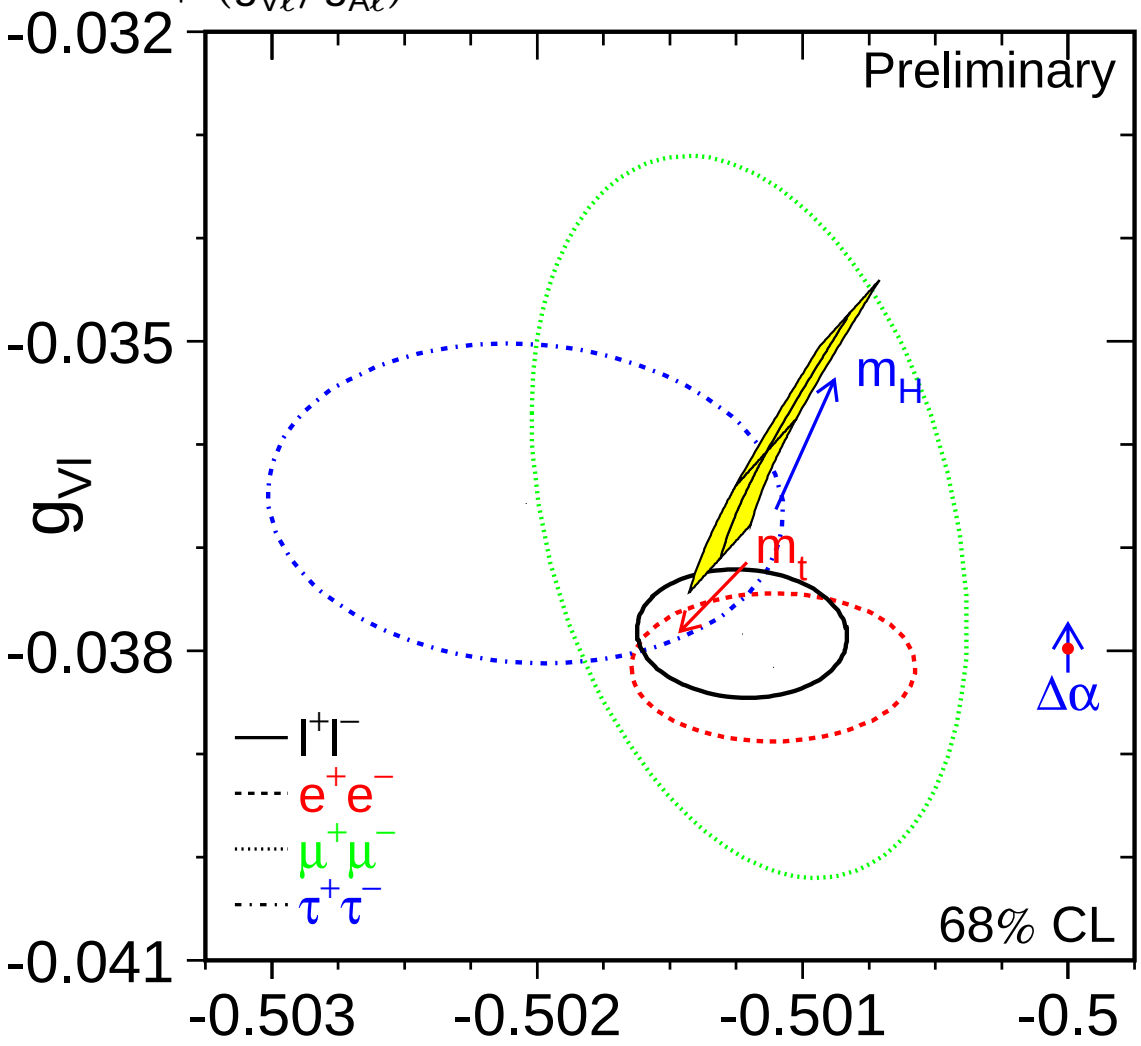
$$A_\ell = 2\frac{g_{V\ell}/g_{A\ell}}{1+(g^2_{V\ell}/g^2_{A\ell})} = 0.1465 \pm 0.0033$$

Final SLD result (exploiting polarised beams):

$$A_{lr} \equiv A_\ell = 0.1513 \pm 0.0021$$

Effective Leptonic Couplings of Z

$$A_\ell = 2\frac{g_{V\ell}/g_{A\ell}}{1+(g_{V\ell}^2/g_{A\ell}^2)} \qquad \Gamma_\ell \sim [g_{V\ell}^2 + g_{A\ell}^2](1+\Delta_\ell^{QED})$$



$M_t = 174.3 \pm 5.1$ GeV

$M_H = 300^{+700}_{-186}$ GeV

$\Delta\alpha^{(5)}_{had} = 0.02761 \pm 0.00036$

$$g_{V\ell} = -0.03783 \pm 0.00041$$

$$g_{A\ell} = -0.50123 \pm 0.00026$$

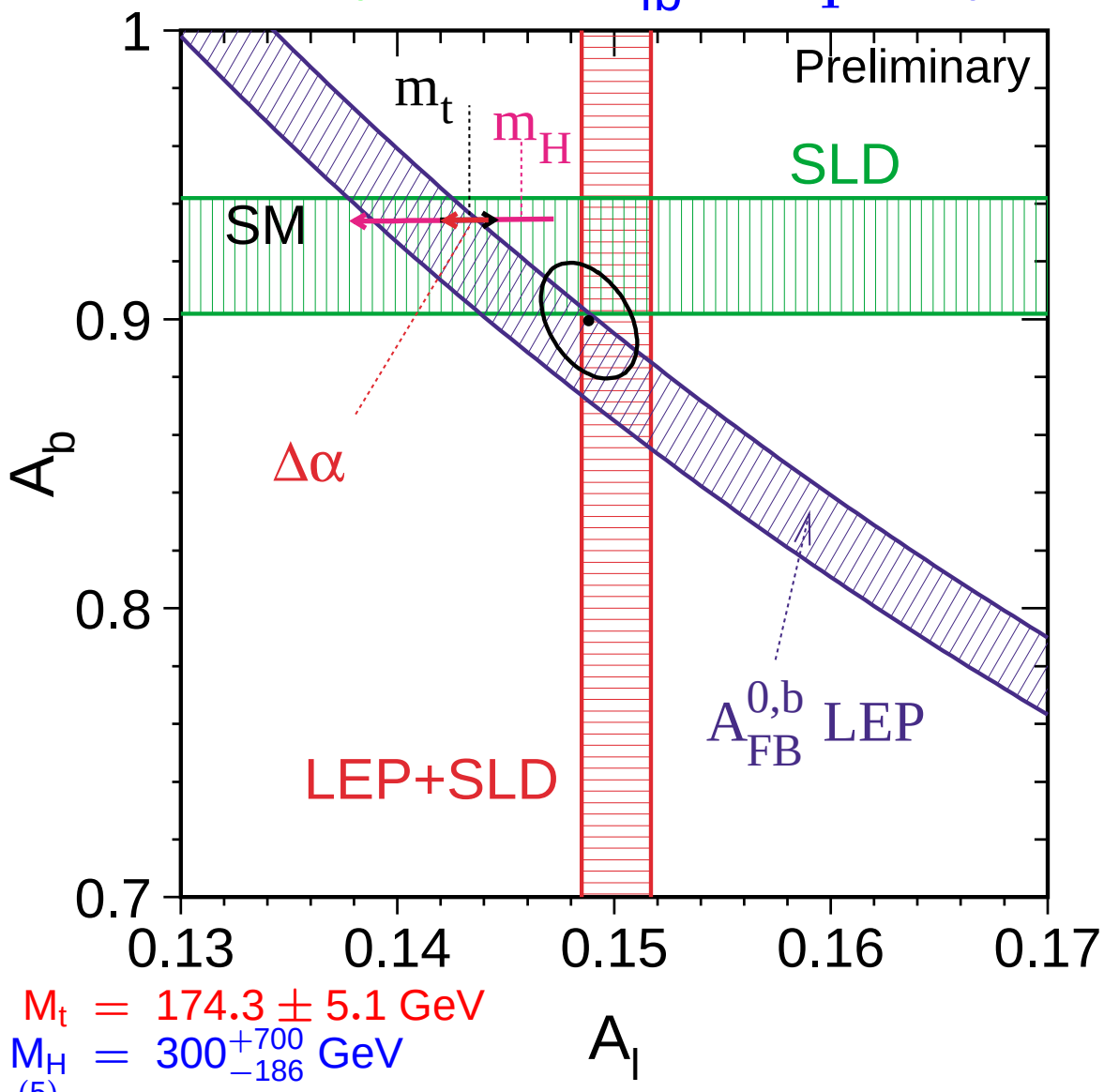
Low Higgs mass preferred!

b and c quark couplings of the Z

LEP+SLD
Flavour tagged
event samples

$$\longrightarrow \left(\begin{array}{rcl} R_q & \equiv & \Gamma_{qq}/\Gamma_{had} \\ A_{fb}^{0,q} & \equiv & \frac{3}{4} A_e A_q \\ A_{fblr}^{0,q} & \equiv & A_q \end{array} \right)_{q=b,c}$$

Comparison of A_b, A_l and $A_{fb}^{0,b} = \frac{3}{4} A_e A_b$:



$M_t = 174.3 \pm 5.1$ GeV

$M_H = 300^{+700}_{-186}$ GeV

$\Delta\alpha^{(5)}_{had} = 0.02761 \pm 0.00036$

HIGH Higgs mass preferred by A_b & $A_{fb}^{0,b}$

LOW Higgs mass preferred by A_l & $A_{fb}^{0,b}$

LEP1 b Asymmetry Results

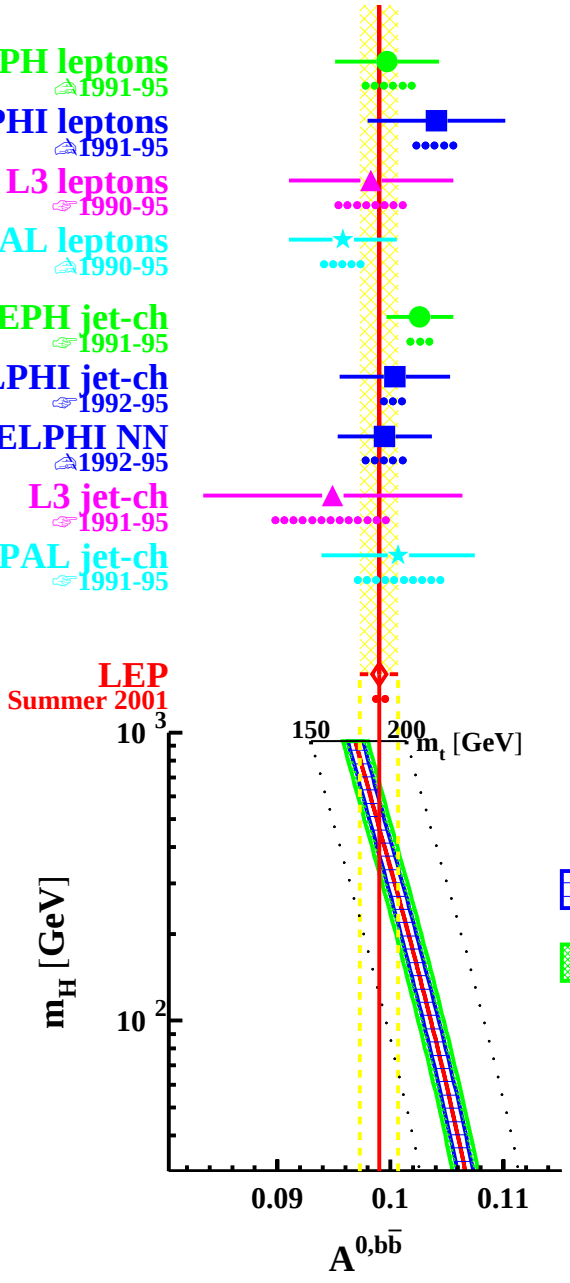
Summer '01 changes in LEP1 $A_{fb}^{0,b} = \frac{3}{4} A_e A_b$:

$0.0982 \pm 0.0017 \rightarrow 0.0990 \pm 0.0017$

Analysis improvements from ALEPH, DELPHI

LEP Measurements consistent

Preliminary



$0.0997 \pm 0.0040 \pm 0.0023$

$0.1041 \pm 0.0057 \pm 0.0022$

$0.0983 \pm 0.0065 \pm 0.0033$

$0.0958 \pm 0.0043 \pm 0.0021$

$0.1026 \pm 0.0027 \pm 0.0012$

$0.1004 \pm 0.0047 \pm 0.0014$

$0.0995 \pm 0.0036 \pm 0.0021$

$0.0949 \pm 0.0101 \pm 0.0055$

$0.1007 \pm 0.0055 \pm 0.0040$

$\langle A_{FB}^{0,b\bar{b}} \rangle = 0.0990 \pm 0.0017$

Include Total Sys 0.0007

With Common Sys 0.0003

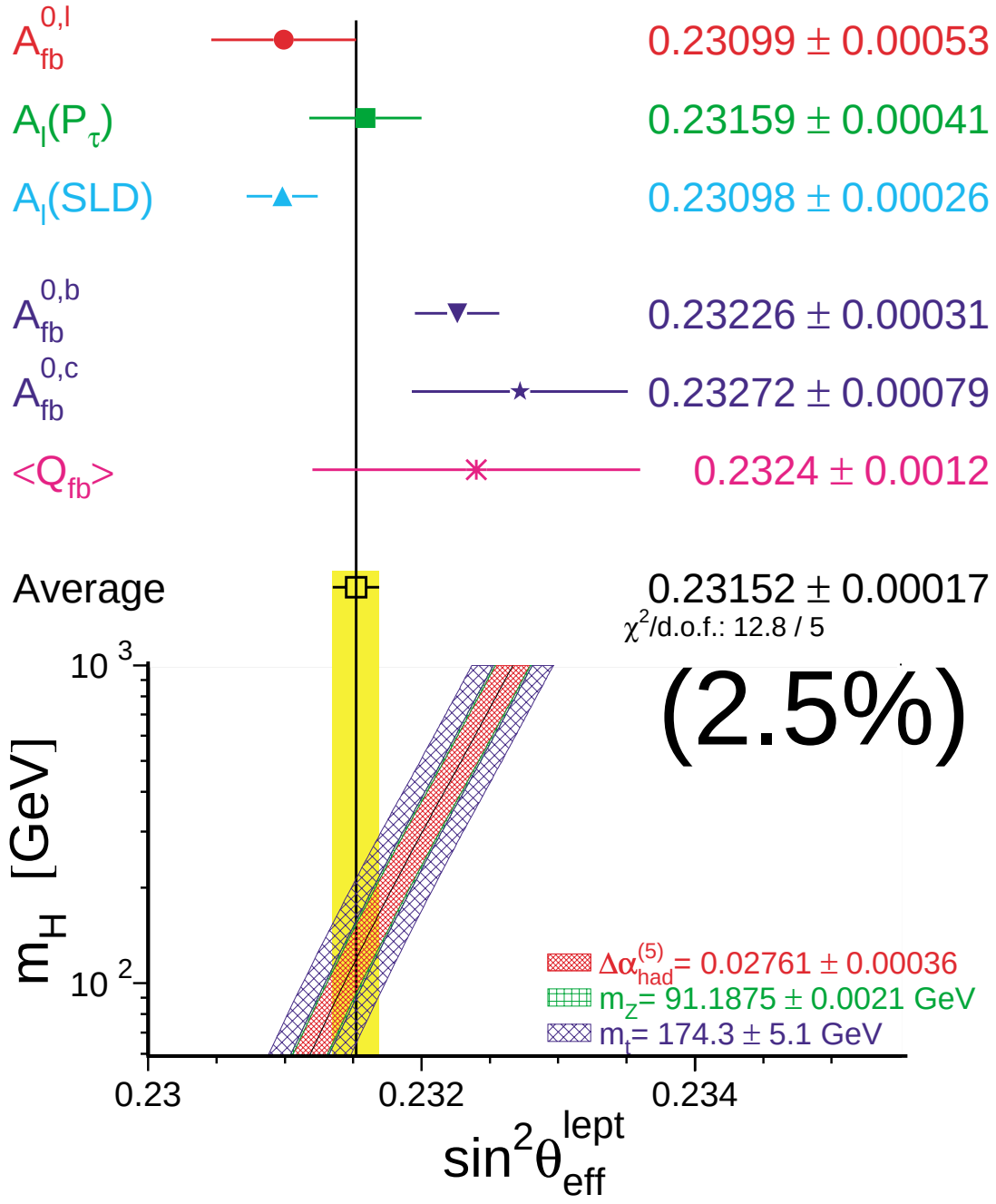
$m_t = 174.3 \pm 5.1$ GeV

$\Delta\alpha_{had} = 0.02761 \pm 0.00036$

High Higgs mass preferred!

Effective Leptonic Electroweak Mixing Angle

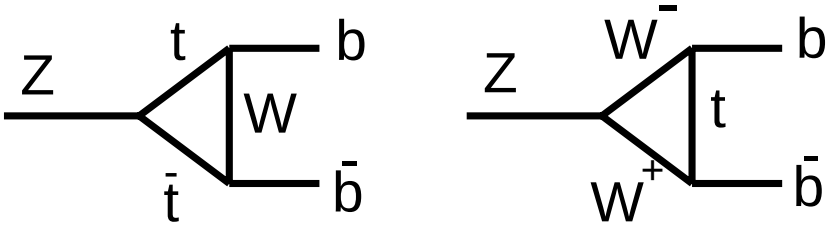
$$\sin^2\theta^{lept}_{eff} = (1 - g_{V\ell}/g_{A\ell})/4$$



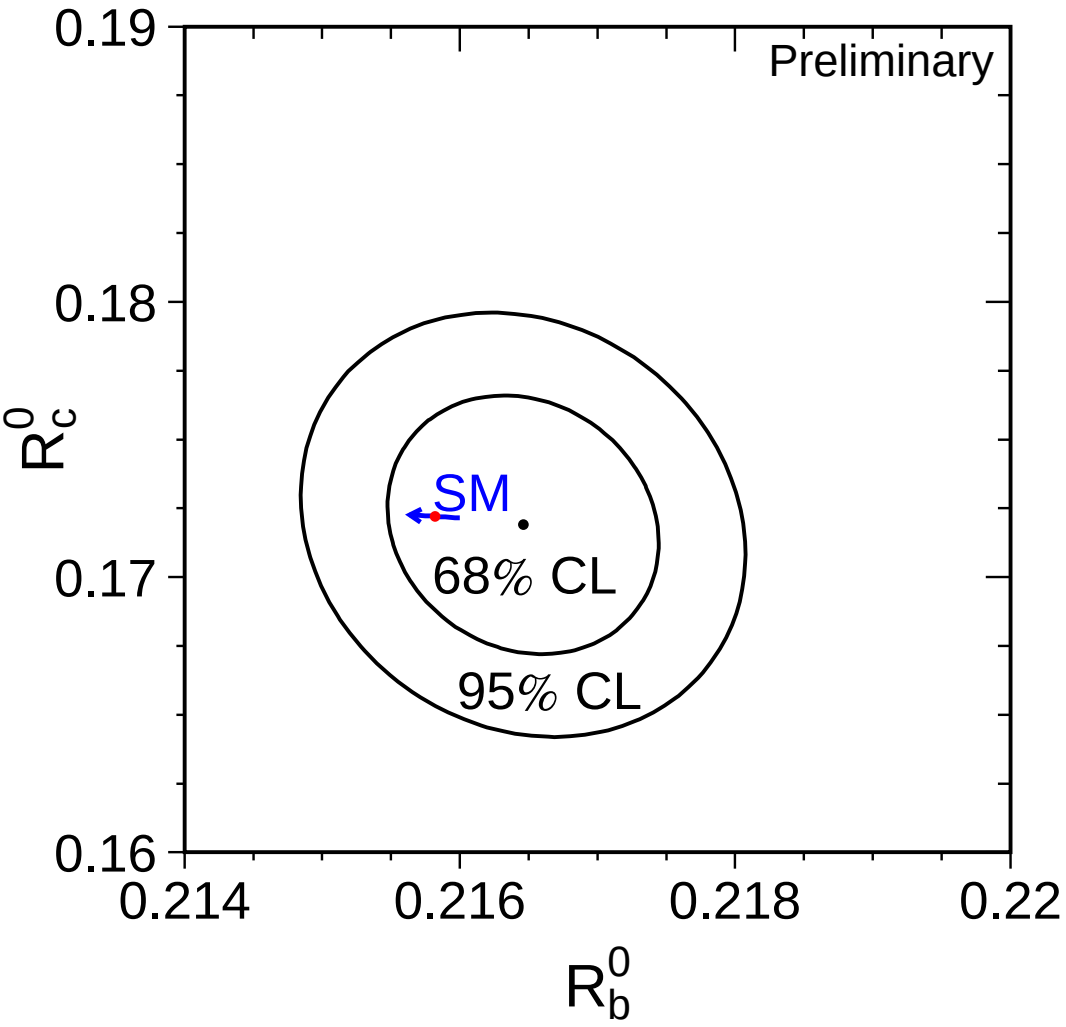
Leptons	0.23113 ± 0.00021	χ^2/d.o.f. : 1.6/2
Hadrons	0.23230 ± 0.00029	χ^2/d.o.f. : 0.3/2
Difference	3.3 sigma	

LEP1 R_b, R_c

R_b sensitive to vertex corrections in $Z \rightarrow b\bar{b}$:



Propagator corrections cancel in ratio.



Multi-tag methods
Si detectors

→ extreme precision

$B^0 - \bar{B}^0$ Oscillations described by weak interactions of quarks

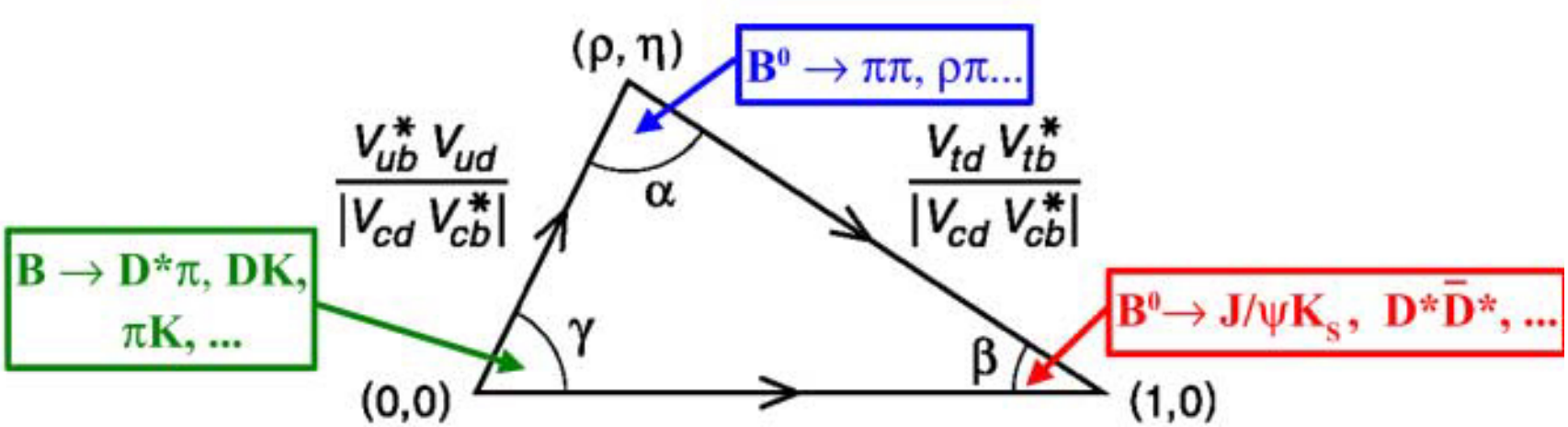
Quark transitions represented by the 3x3 unitary CKM matrix

In Wolfenstein parametrization: $V_{CKM}(\bar{\eta}, \bar{\rho}, A, \lambda)$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

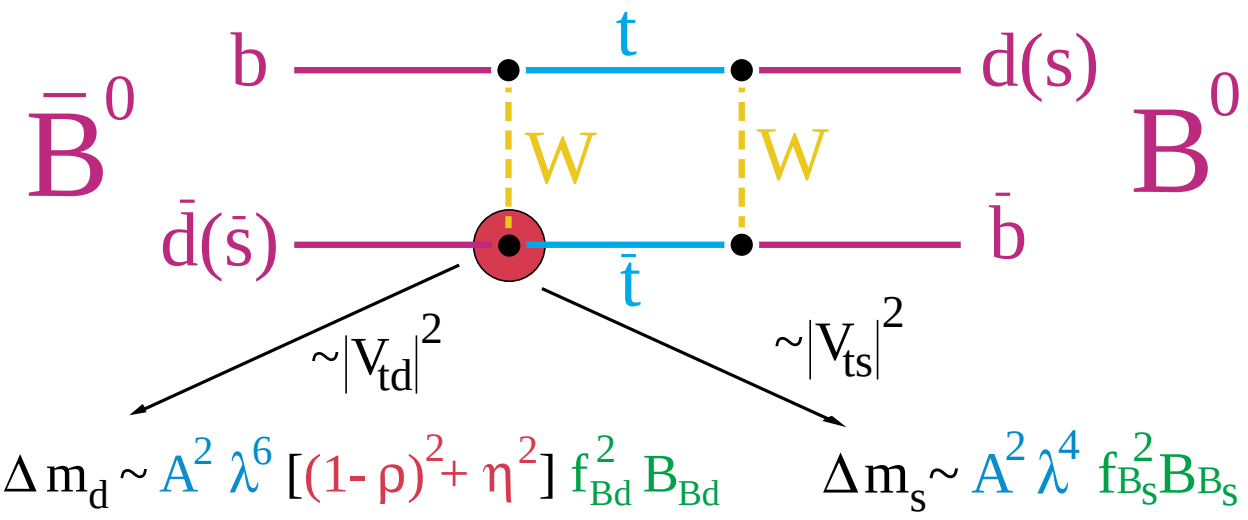
1 Unitarity relation: $\boxed{V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0}$

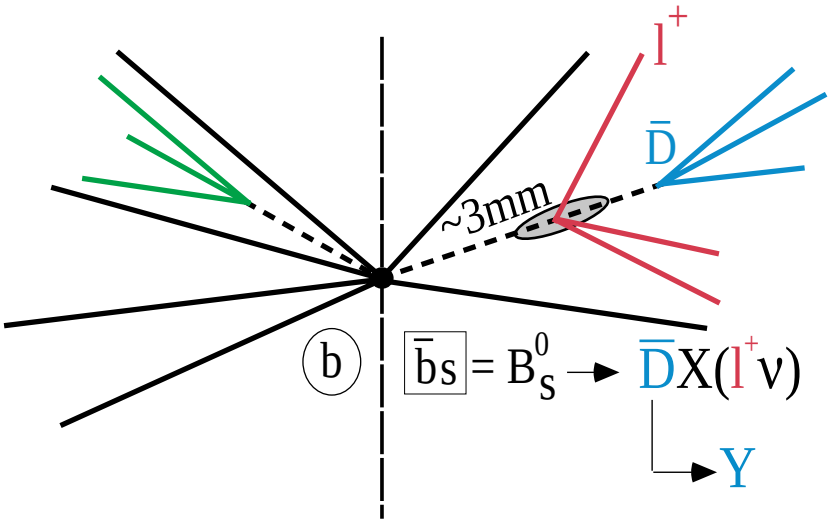
$\longrightarrow$ "unitarity" triangle Conventionally rescaled by $|V_{cd}V_{cb}^*|$:

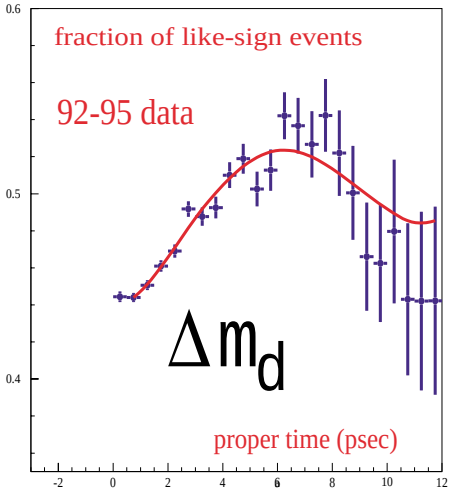


LEP Heavy Flavour: $B^0 - \bar{B}^0$ Oscillations

$$P[B_q^0 \to B_q^0(\bar{B}_q^0)] = \frac{1}{2} e^{-t/\tau_q}(1 \pm \cos \Delta m_q t)$$

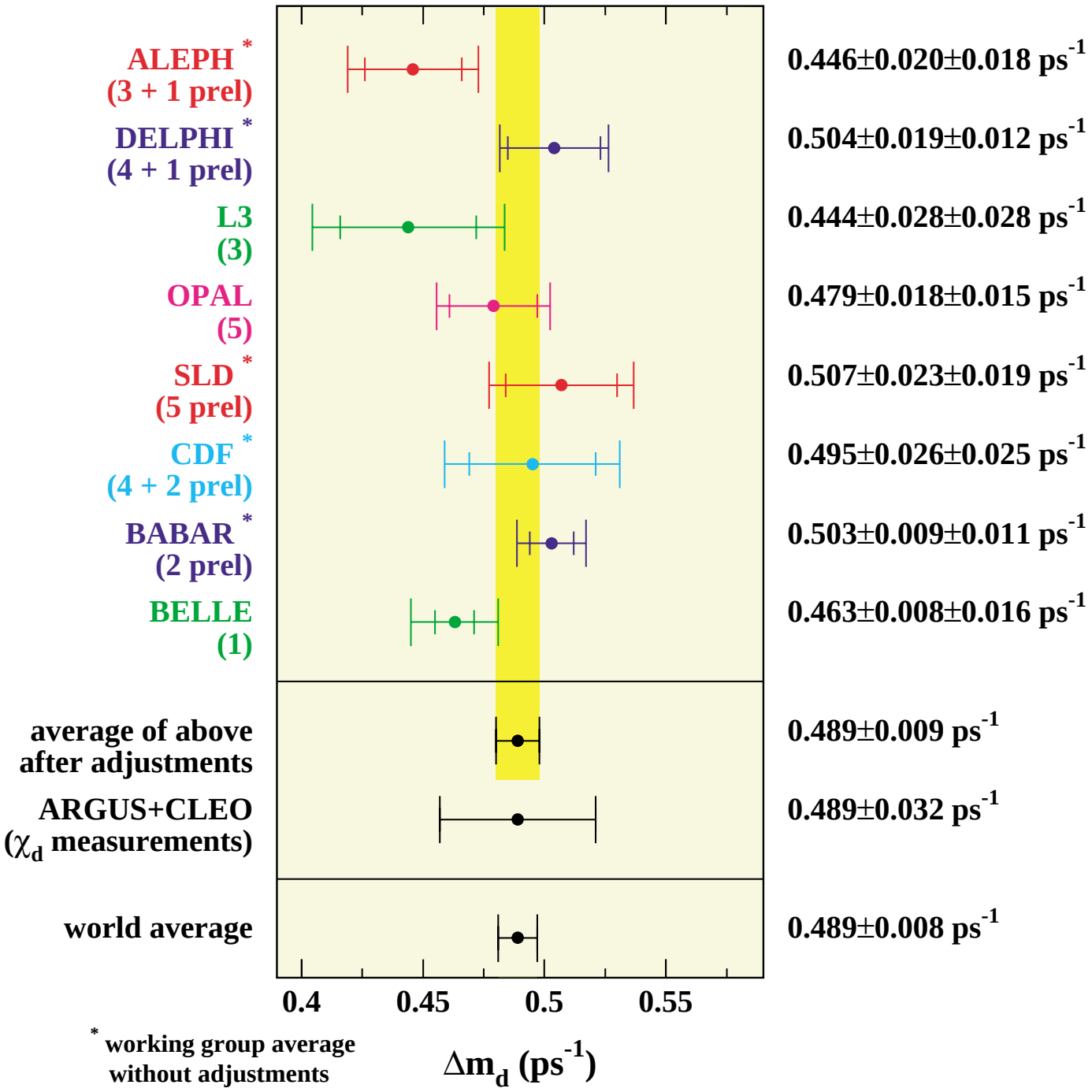






Production & decay tags + decay proper time

Δm_d

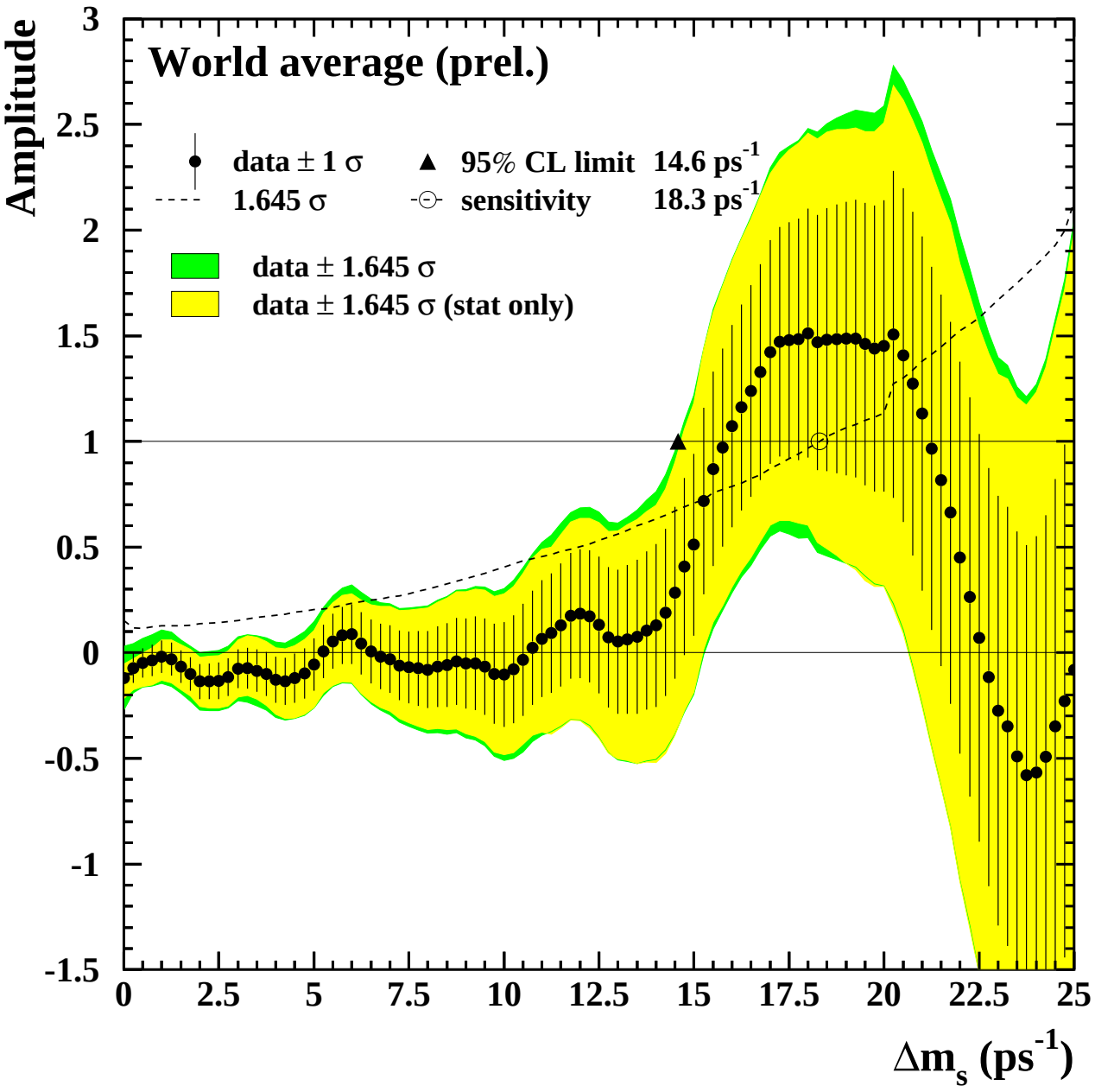


* working group average without adjustments

World average	$0.489 \pm 0.008\ \mathrm{ps}^{-1}$
LEP/SLD/CDF	$0.492 \pm 0.013\ \mathrm{ps}^{-1}$
B-Factories	$0.485 \pm 0.010\ \mathrm{ps}^{-1}$

LEP Heavy Flavour - Δm_s combined limits

$$P[B_s^0 \to B_s^0(\overline{B}_s^0)] = \frac{1}{2} e^{-t/\tau_s}(1 \pm A \cos \Delta m_s t)$$



LEP+SLD+CDF:

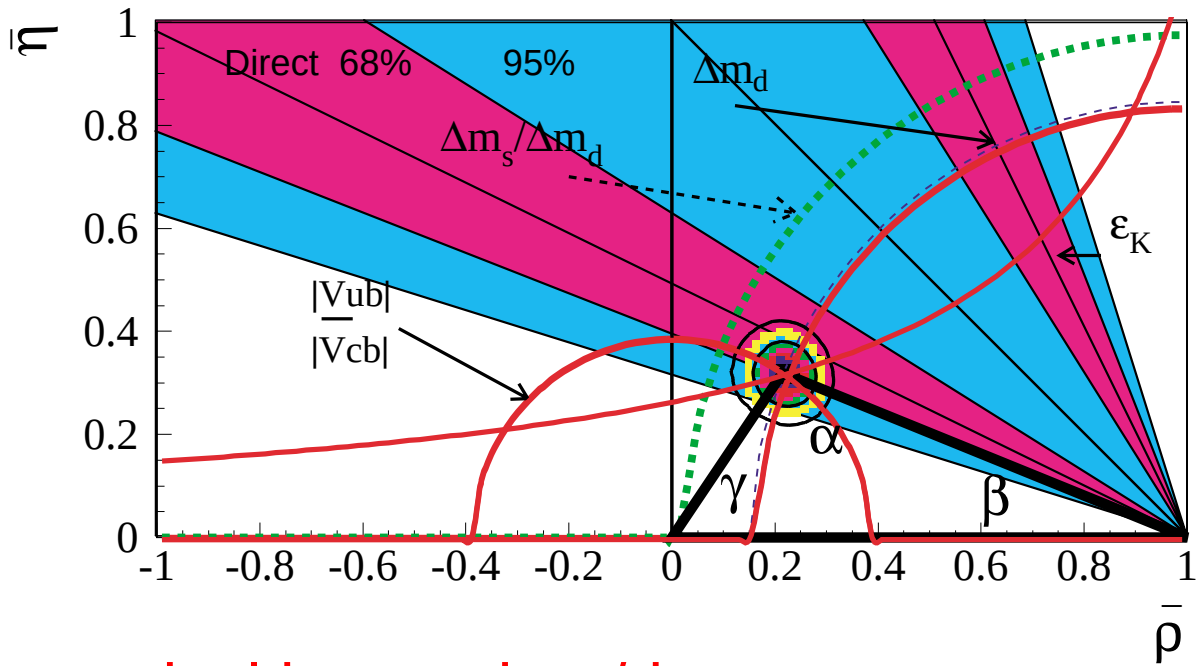
$$\Delta m_s > 14.6(14.3)\ \mathrm{ps}^{-1}(95\%\mathrm{CL})$$

LEP+SLD+CDF+CLEO - CKM constraints

Wolfenstein parametrization: $V_{CKM}(\bar{\eta}, \bar{\rho}, A, \lambda)$

Measurements	Constrain Unitarity Triangle	
$b \to u, b \to c$	$\lvert V_{ub}/V_{cb}\rvert$	$\bar{\rho}^2 + \bar{\eta}^2$
Δm_d	$\lvert V_{td}\rvert^2 f_{B_d}^2 B_{B_d} f(m_t)$	$(1-\bar{\rho})^2 + \bar{\eta}^2$
$\frac{\Delta m_d}{\Delta m_s}$	$\lvert\frac{V_{td}}{V_{ts}}\rvert^2 \frac{f_{B_d}^2 B_{B_d}}{f_{B_s}^2 B_{B_s}}$	$(1-\bar{\rho})^2 + \bar{\eta}^2$
ϵ_K	$f(A, \bar{\eta}, \bar{\rho}, B_K)$	$\propto \bar{\eta}(1-\bar{\rho})$

Indirect (68%,95%) CL contours compared to direct $\sin 2\beta = 0.79 \pm 0.11$ (BABAR+BELLE).



Theoretical inputs: bag/decay parameters.

$$\sin 2\beta = 0.696 \pm 0.068$$
$$\sin 2\alpha = -0.42 \pm 0.24$$

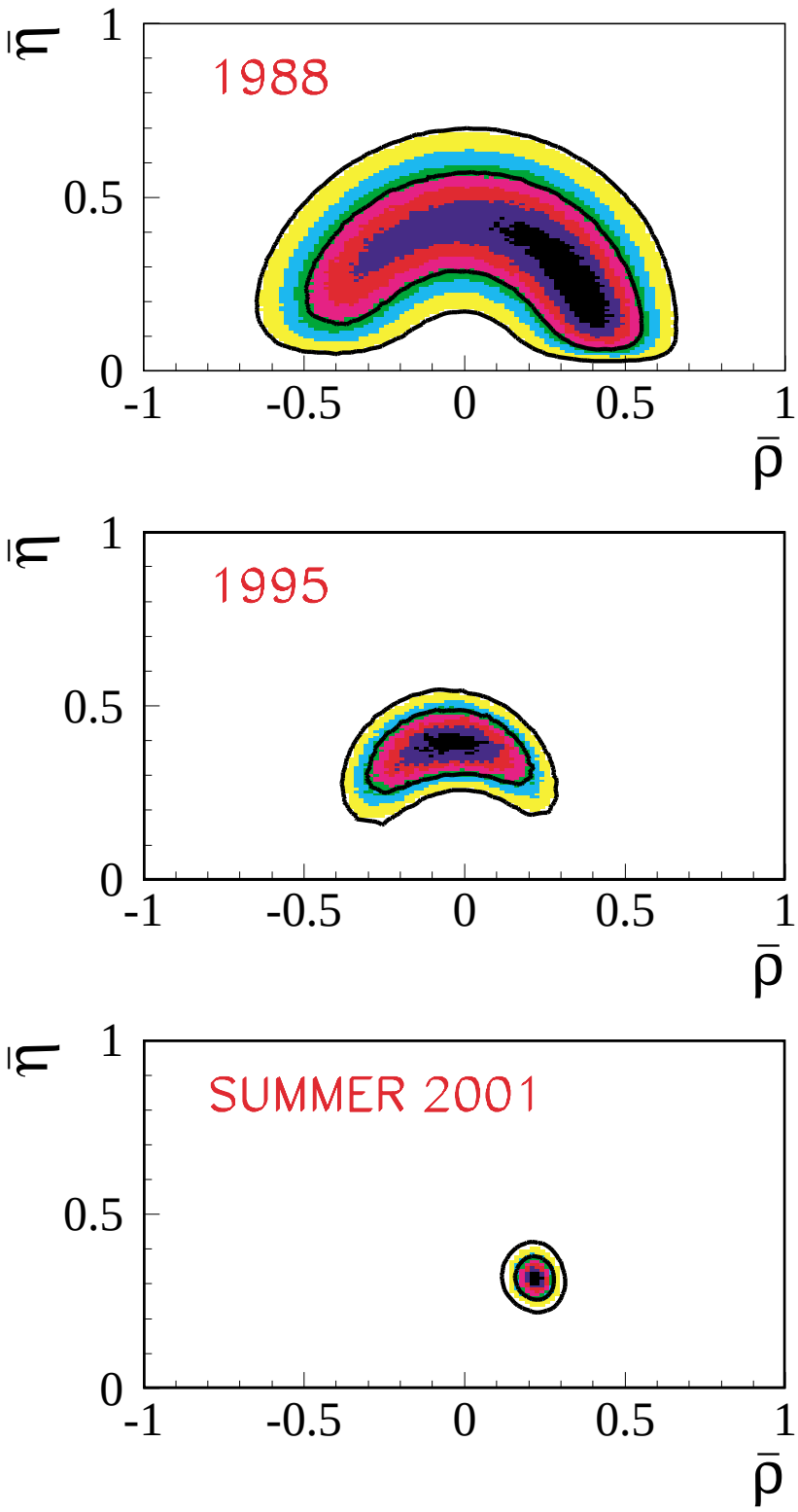
CERN-EP/2001-050

Summer 2001 Direct: $\sin 2\beta = 0.79 \pm 0.11$ a combination of:

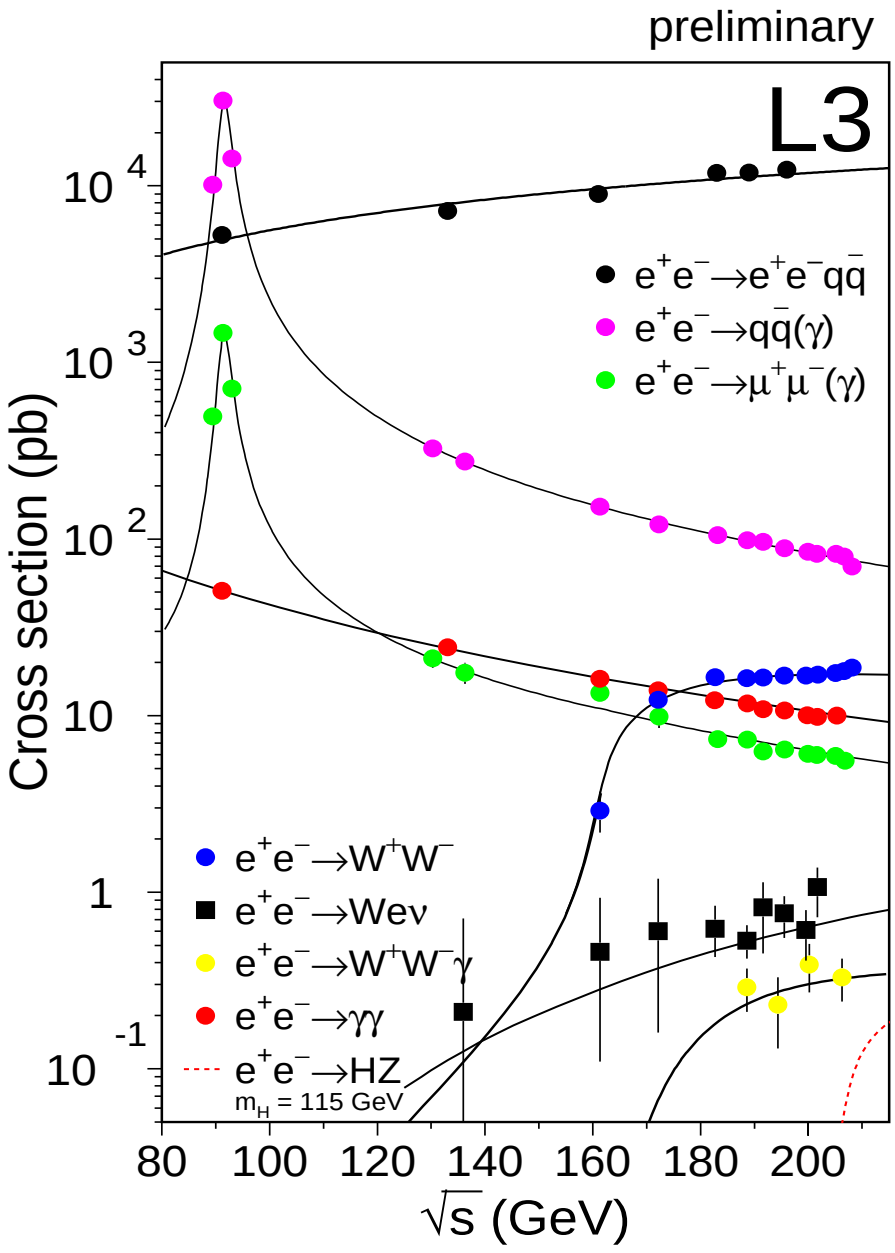
BABAR $0.59 \pm 0.14 \pm 0.05$

BELLE $0.99 \pm 0.14 \pm 0.06$

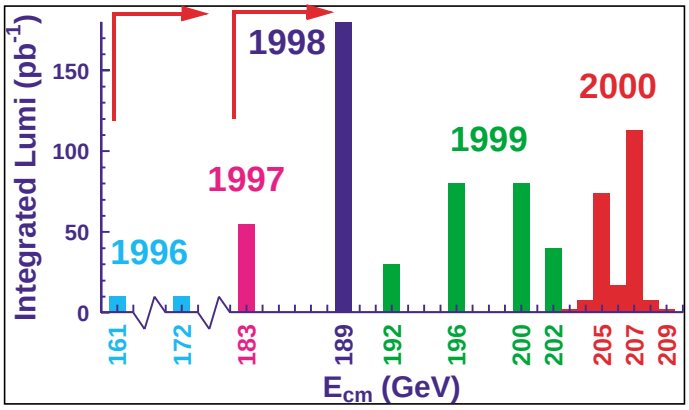
Pre B-factory - CKM progress



LEP2 Data Samples



LEP2
700 pb^{-1} / expt
Up to 208.8 GeV

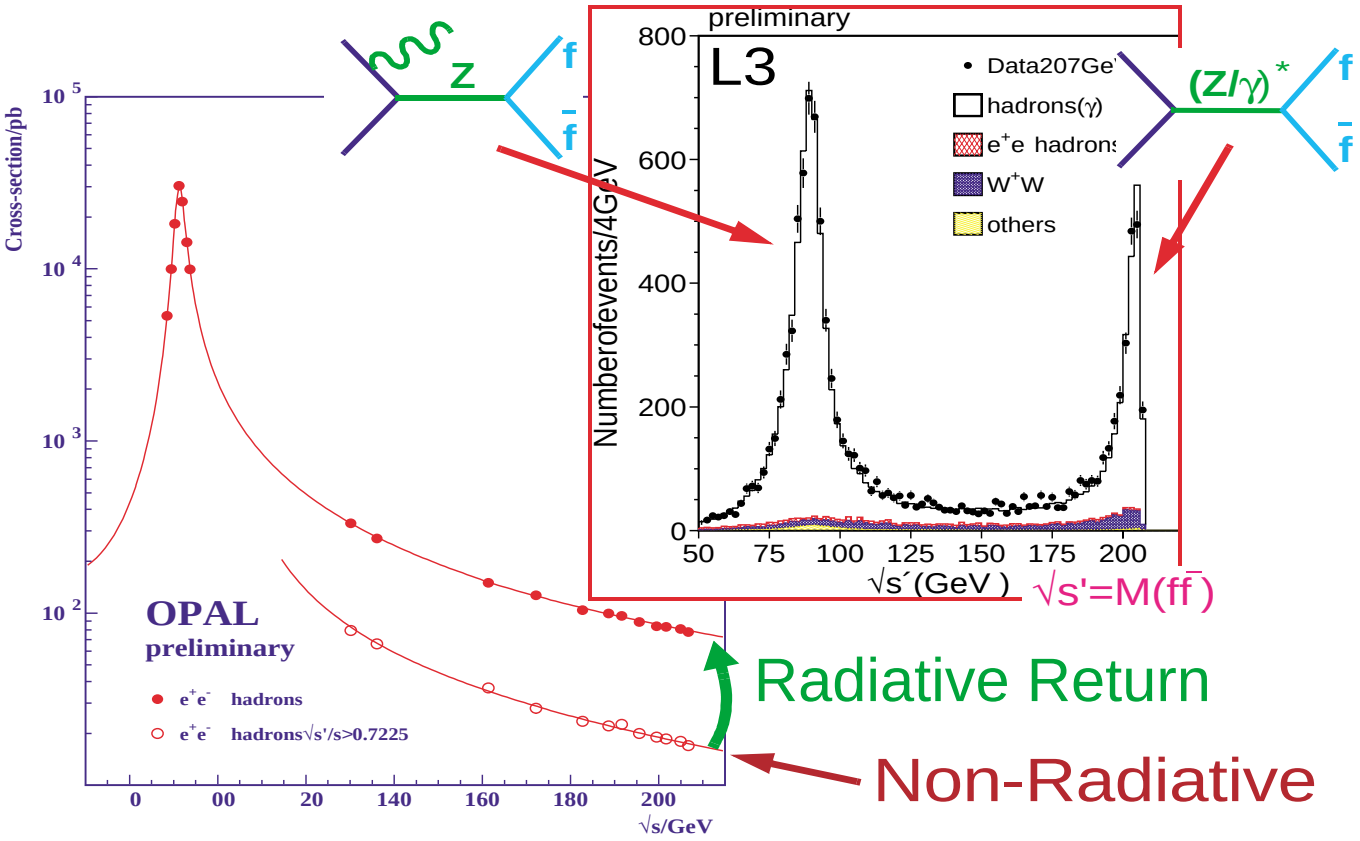


LEP2 Fermion pair production

As functions of $\sqrt{s}$:

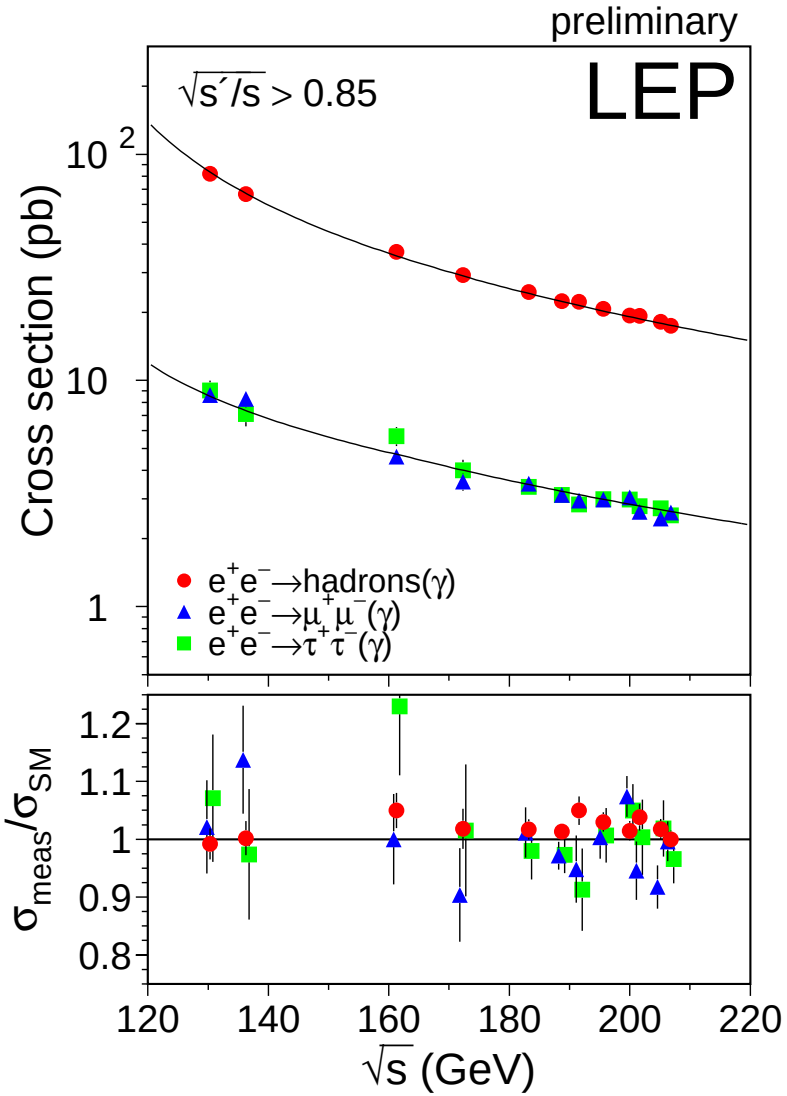
$$\begin{pmatrix} \sigma(e^+e^- \to \text{hadrons}(\gamma)) \\ \sigma(e^+e^- \to \ell^+\ell^-) \\ A_{fb}^{\ell} \\ R_b, R_c \\ A_{fb}^{b}, A_{fb}^{c} \end{pmatrix}_{\ell=e,\mu,\tau} \longrightarrow$$

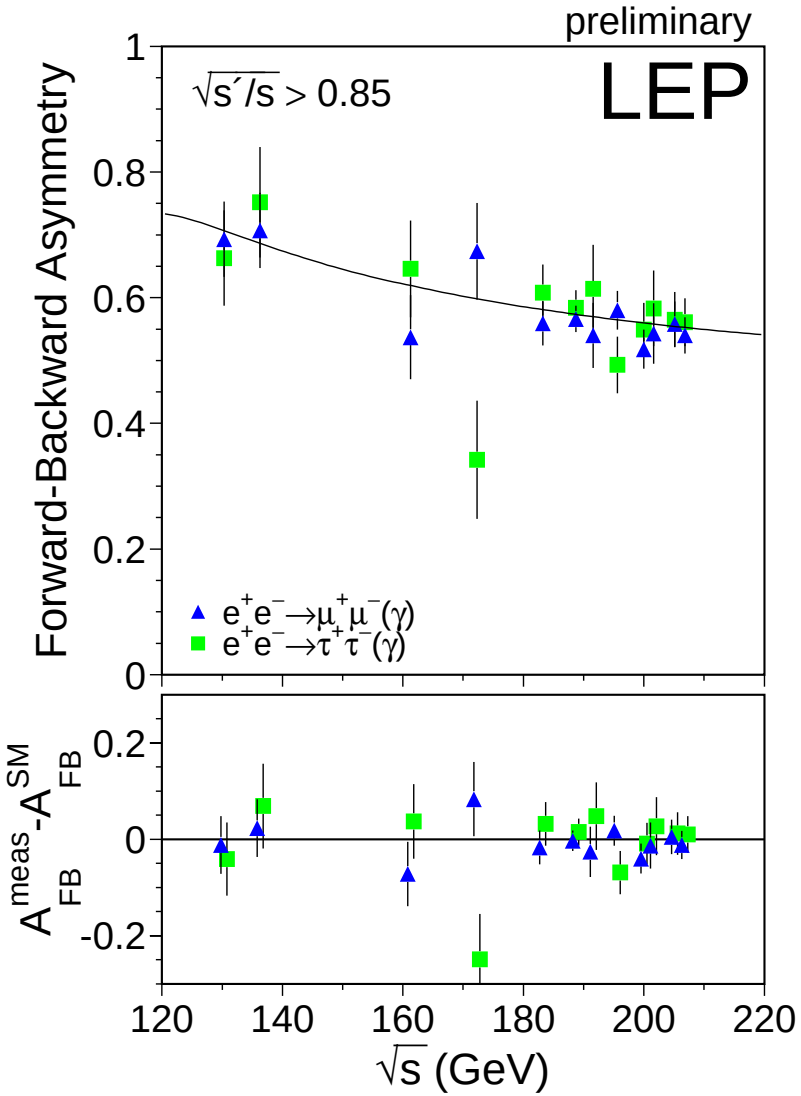
New Physics Constraints
Contact Interaction Z' boson (E_6,L-R)



Exclude radiative returns by:

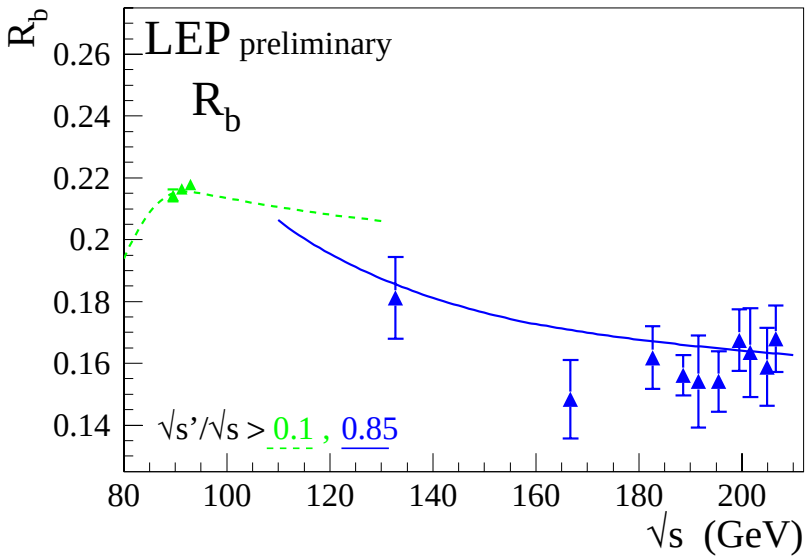
$$\sqrt{s'/s} > 0.7 - 0.8$$

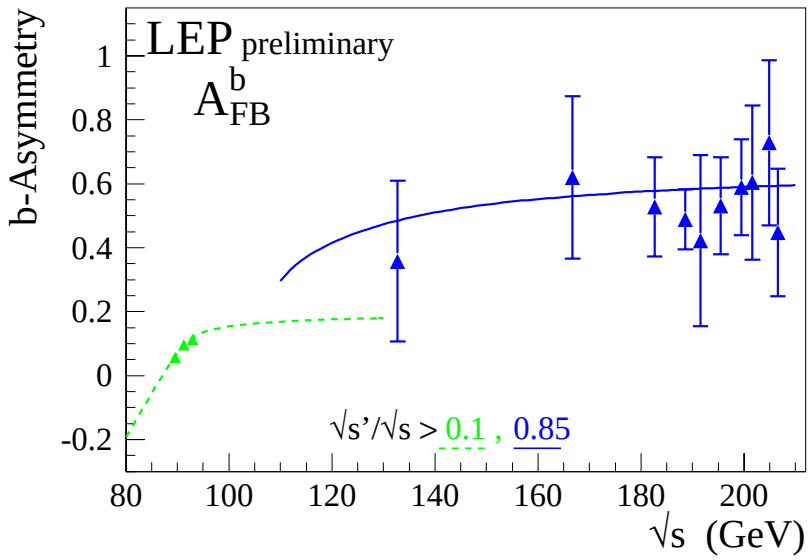


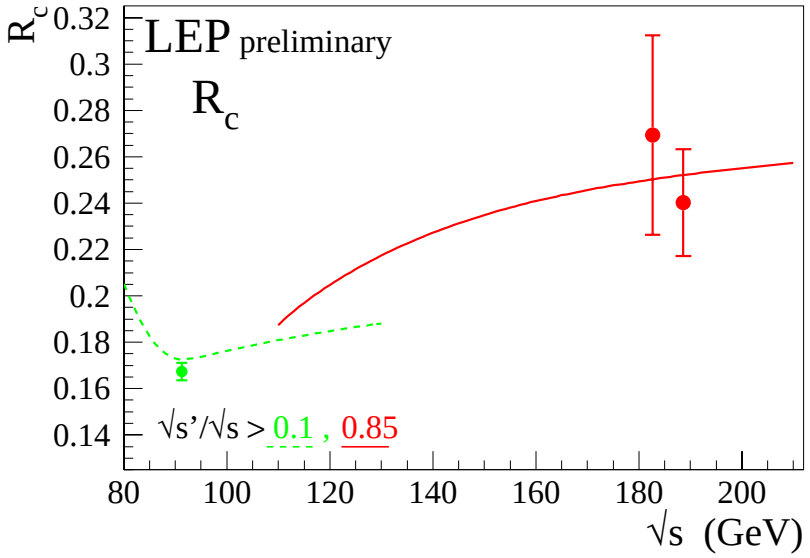


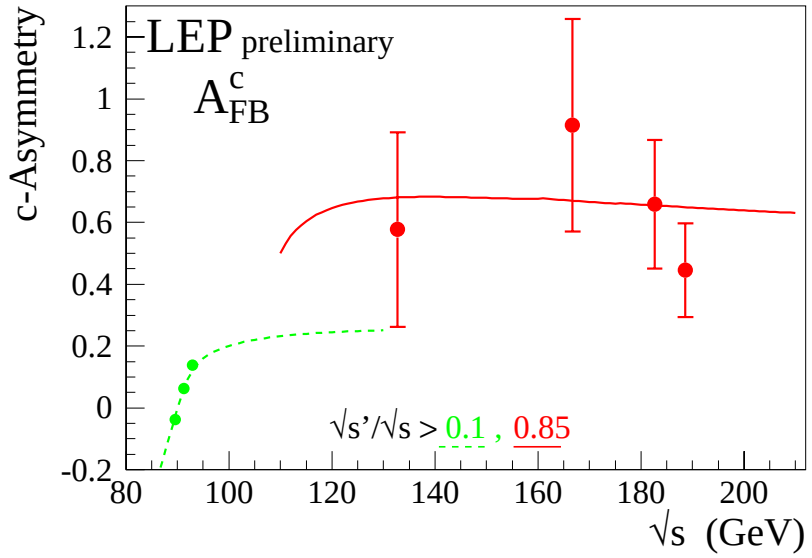
$\langle \sigma_{had}(\sqrt{s}) \rangle$ 1.8 sigma above SM expectation

LEP2 HF: $R_q \equiv \sigma_{qq}/\sigma_{had}$ and asymmetries





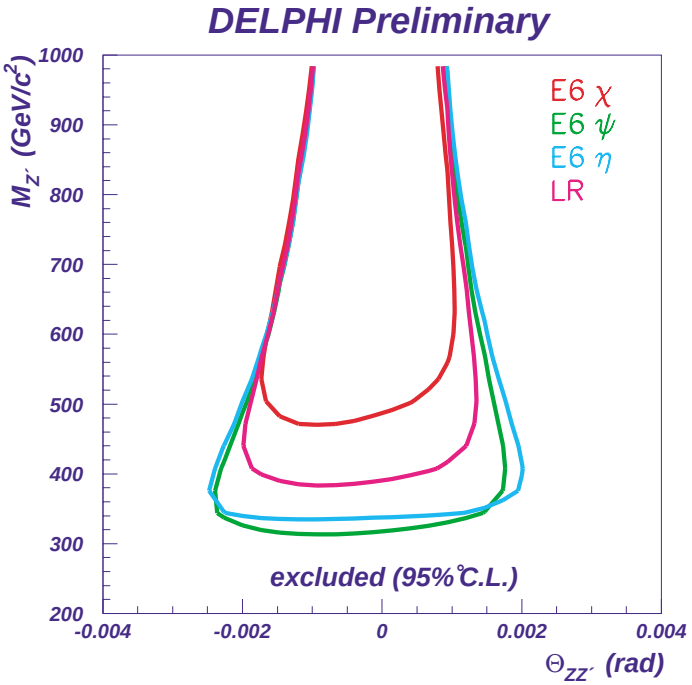




Averaged over $\sqrt{s}$: $\Delta R_b/R_b = 2.5\%$, $\Delta A^b_{fb} = 0.06$

LEP2 $f\bar{f}$ New Physics Constraints

Z′ Boson mass limits



LEP Combined	[GeV]
χ	678
ψ	463
η	436
LR	800
SSM	1890

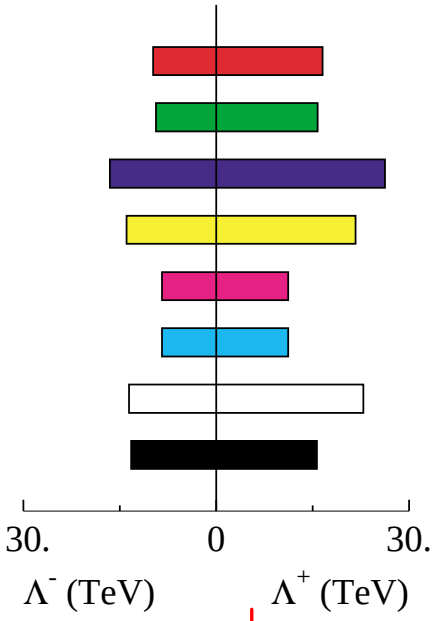
4-fermion contact interactions

$$\mathcal{L} = \frac{1}{1+\delta_{ef}} \sum_{i,j=\mathrm{L,R}} \eta_{ij} \frac{g^2}{\Lambda_{ij}^2} (\bar{e}_i \gamma^\mu e_i)(\bar{f}_j \gamma_\mu f_j) \qquad \frac{g^2}{4\pi} = 1 \qquad |\eta_{ij}| = 1, 0$$

	η_{LL}	η_{RR}	η_{LR}	η_{RL}
LL	±1	0	0	0
RR	0	±1	0	0
VV	±1	±1	±1	±1
AA	±1	±1	∓1	∓1
RL	0	0	0	±1
LR	0	0	±1	0
V0	±1	±1	0	0
A0	0	0	±1	±1

	Λ^-	Λ^+
LL	9.8	16.5
RR	9.4	15.8
VV	16.5	26.2
AA	14.0	21.7
RL	8.5	11.2
LR	8.5	11.2
V0	13.5	22.9
A0	13.2	15.6

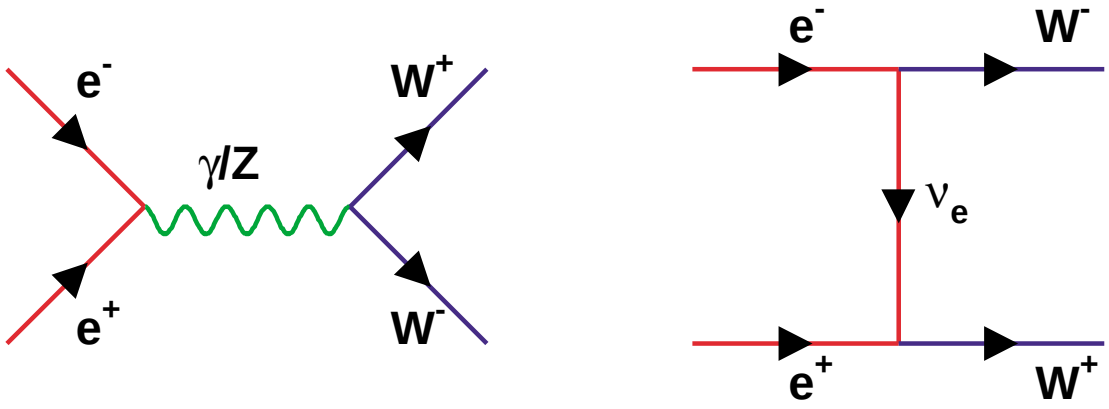
l^+l^-



One-sided 95% CL lower limits on $\Lambda^{\pm}$ [TeV]

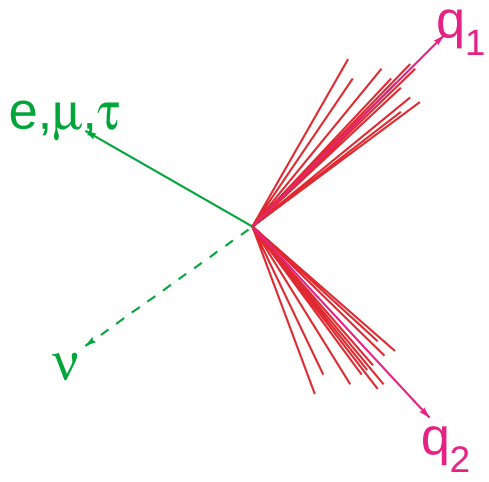
LEP2 W^+W^- production

3 diagrams at Born level (CC03):

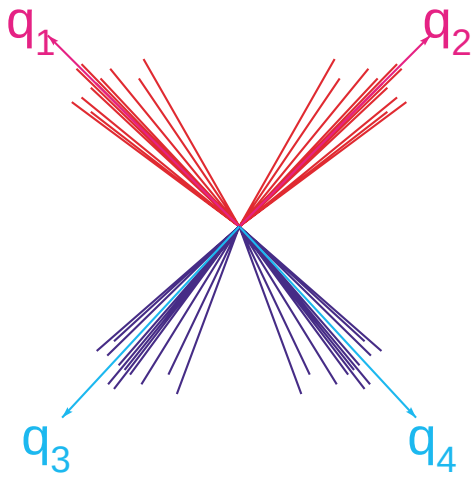


W^+W^- decay channels:

$WW \rightarrow qqqq$		45.6 %
$WW \rightarrow qq\ell\nu$	$qqe\nu$	
	$qq\mu\nu$	43.8 %
	$qq\tau\nu$	
$WW \rightarrow \ell\nu\ell\nu$		10.6 %

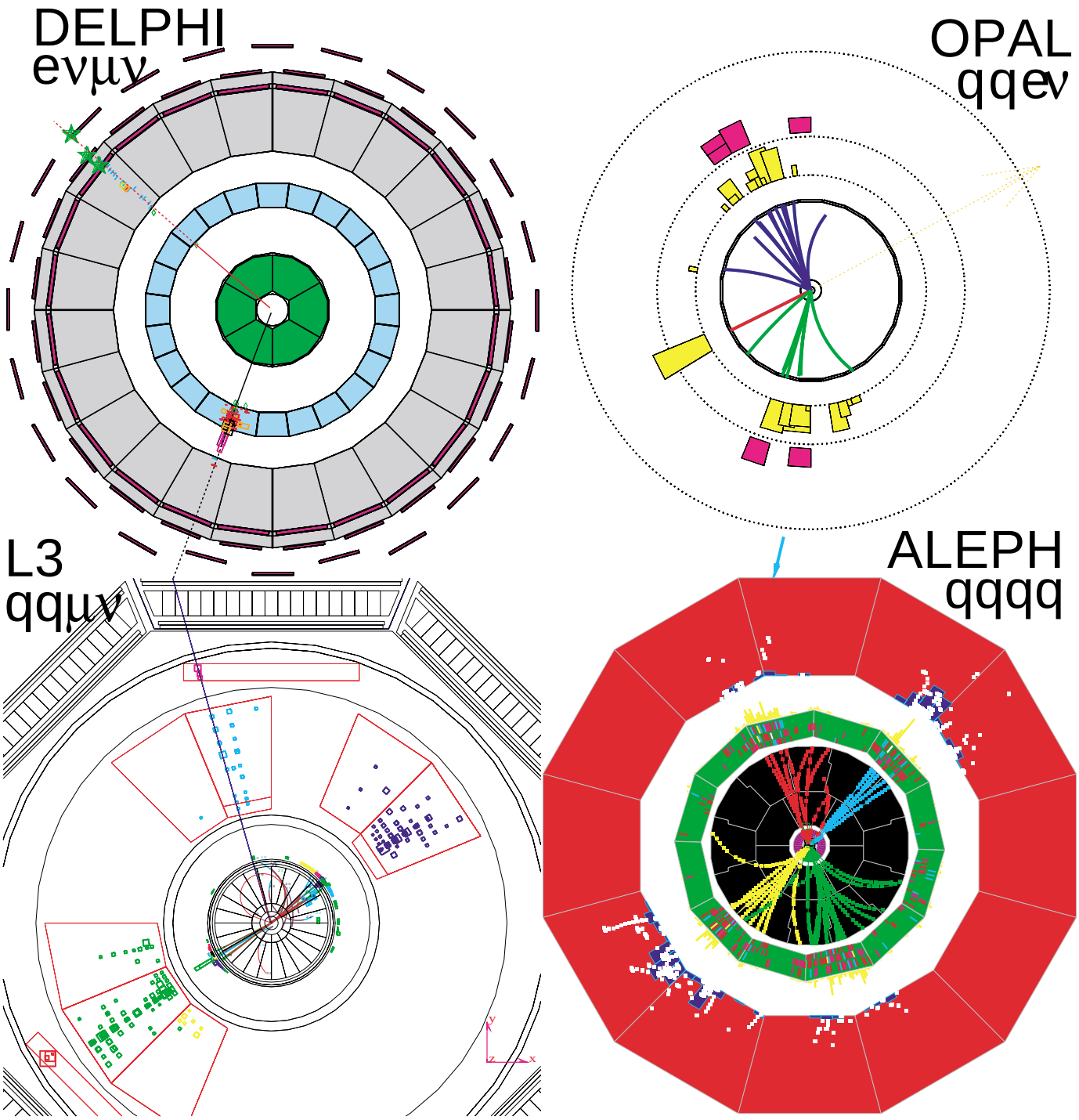


semileptonic



fully hadronic

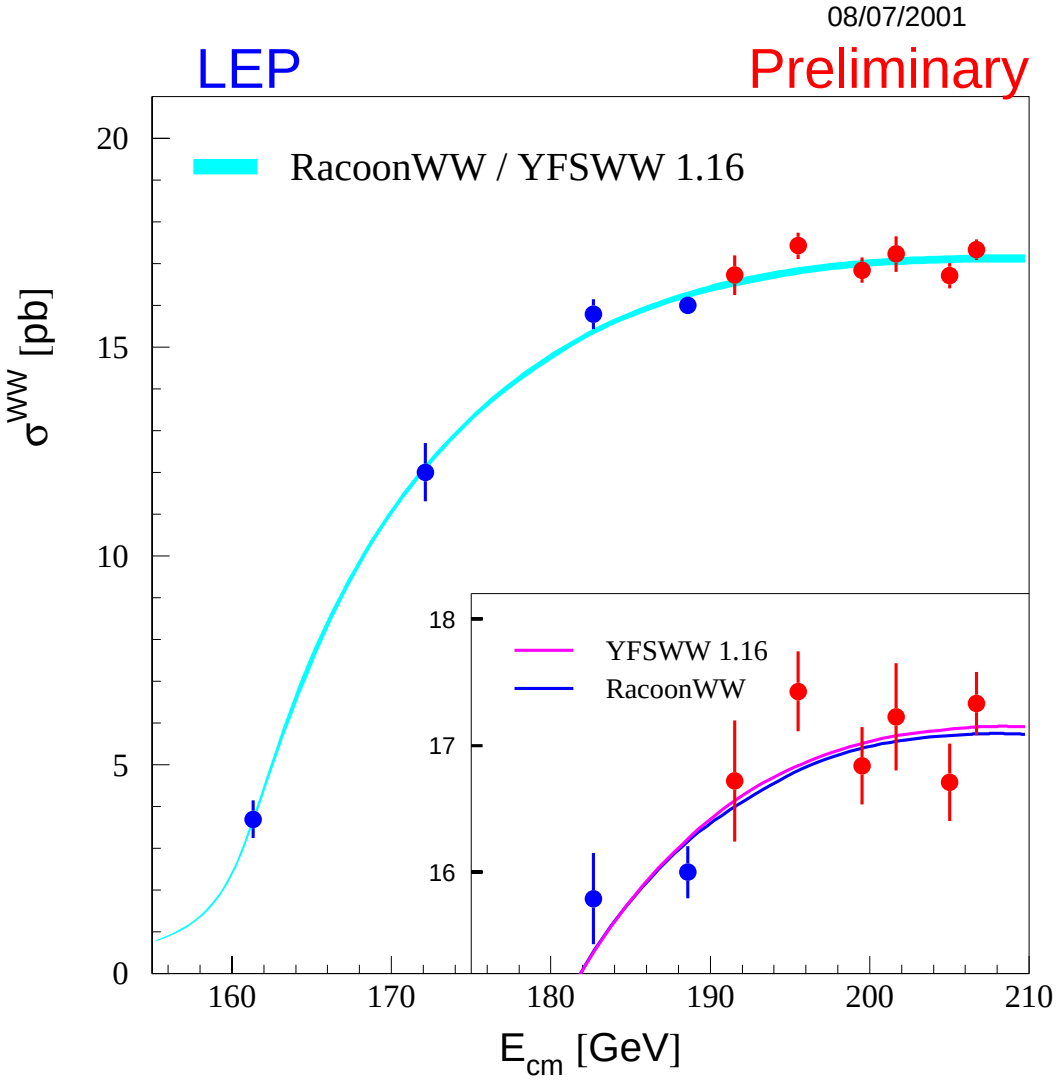
LEP2 W^+W^- events



$\sim$ 12000 W^+W^- events per experiment

LEP2 W^+W^- Cross-Section

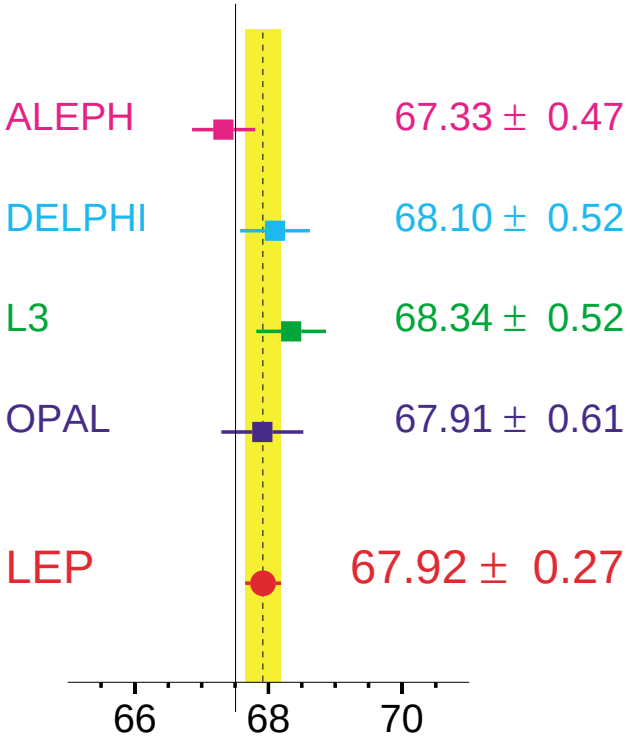
Selection performance	ϵ	π
$WW \longrightarrow qqqq$	87 %	80 %
$WW \longrightarrow qq\ell\nu$	85 %	90 %
$WW \longrightarrow \ell\nu\ell\nu$	50-80 %	90 %



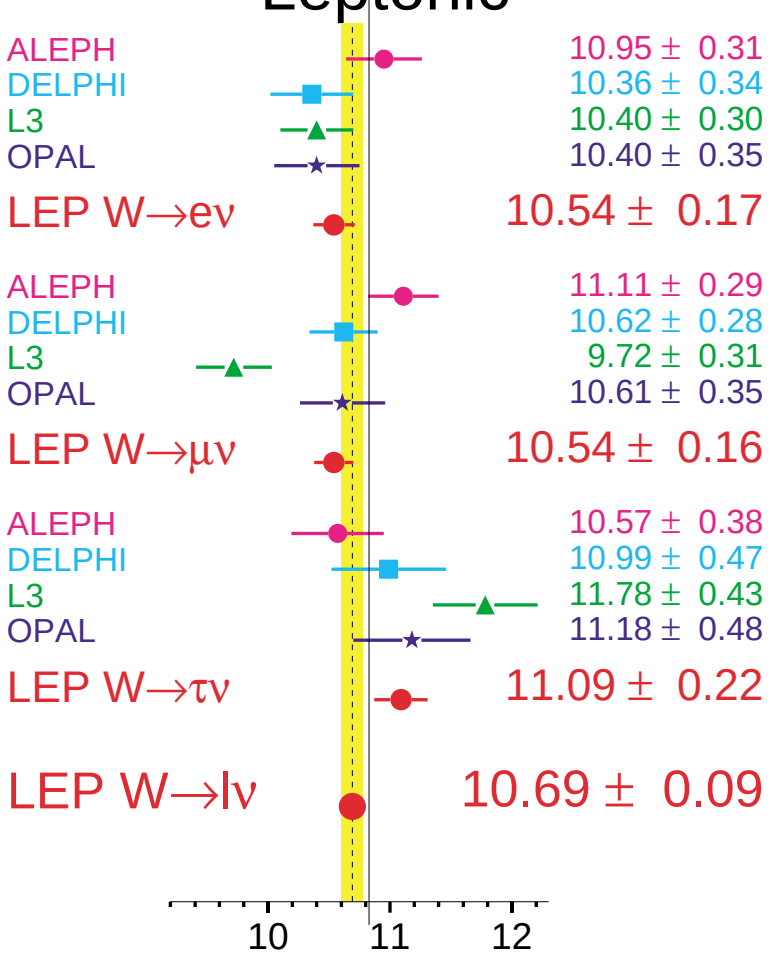
Normalisation comparison for $\sqrt{s} > 180$ GeV

	Gentle	KoralW	YFSWW	RacoonWW
$\frac{\sigma_{meas}}{\sigma_{theory}}$	0.973	0.979	0.998	1.000 ± 0.009

Hadronic



Leptonic

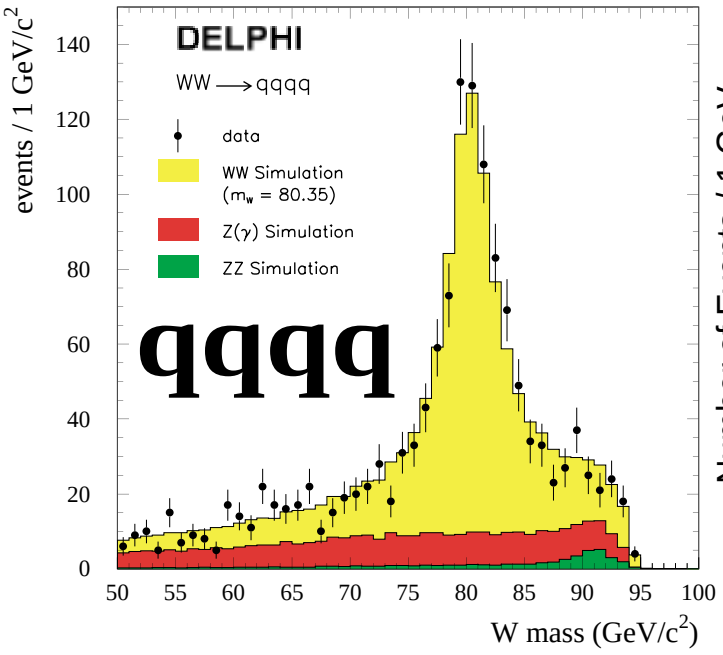


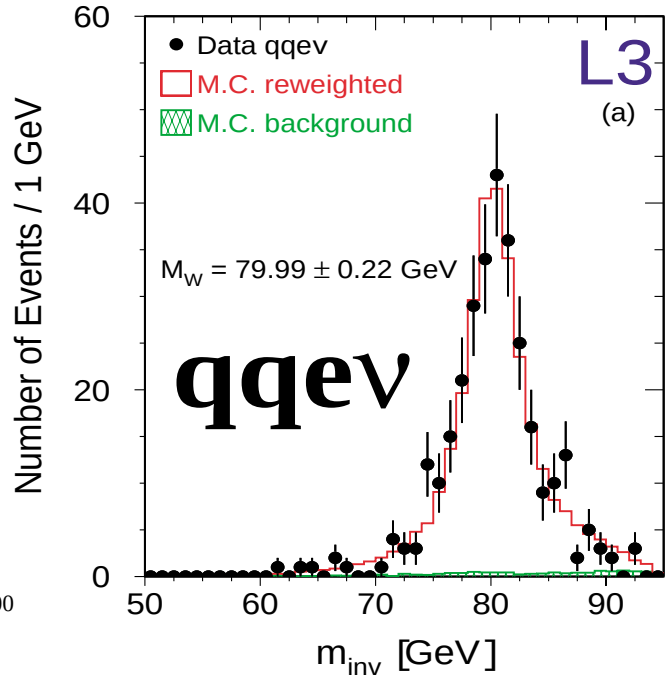
$$\frac{1}{\mathcal{BR}_\ell} = 3\left(1+\left[1+\frac{\alpha_S(M_W^2)}{\pi}\right]\right)\sum_{(u,c)(d,s,b)}|V_{ij}|^2$$

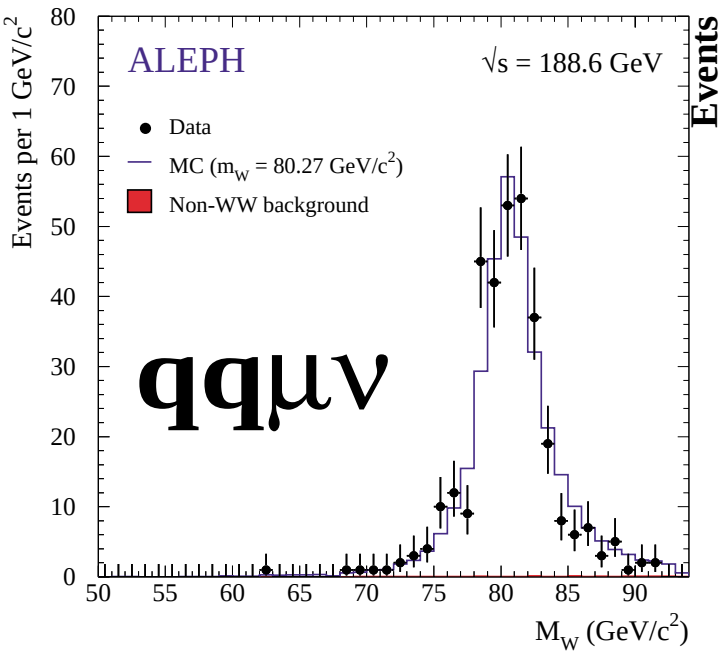
$$|V_{cs}| = 0.996 \pm 0.013$$

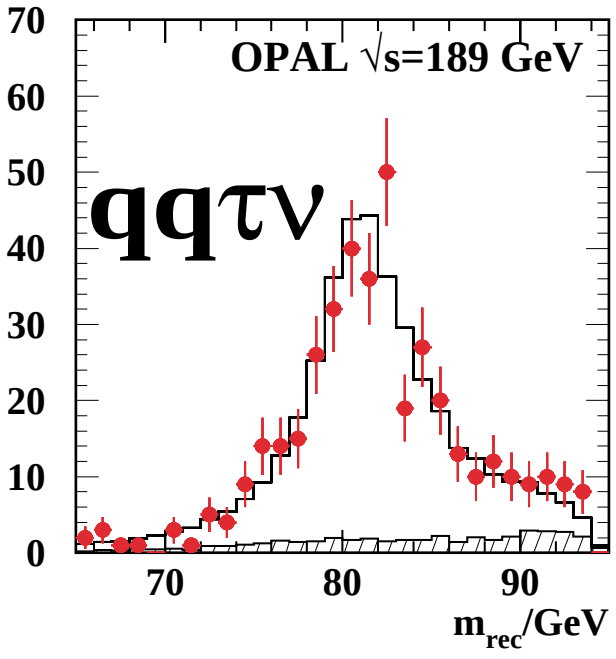
CDF+D0: 10.45 ± 0.25 %

LEP2 W Mass from qqqq + qq$\ell\nu$







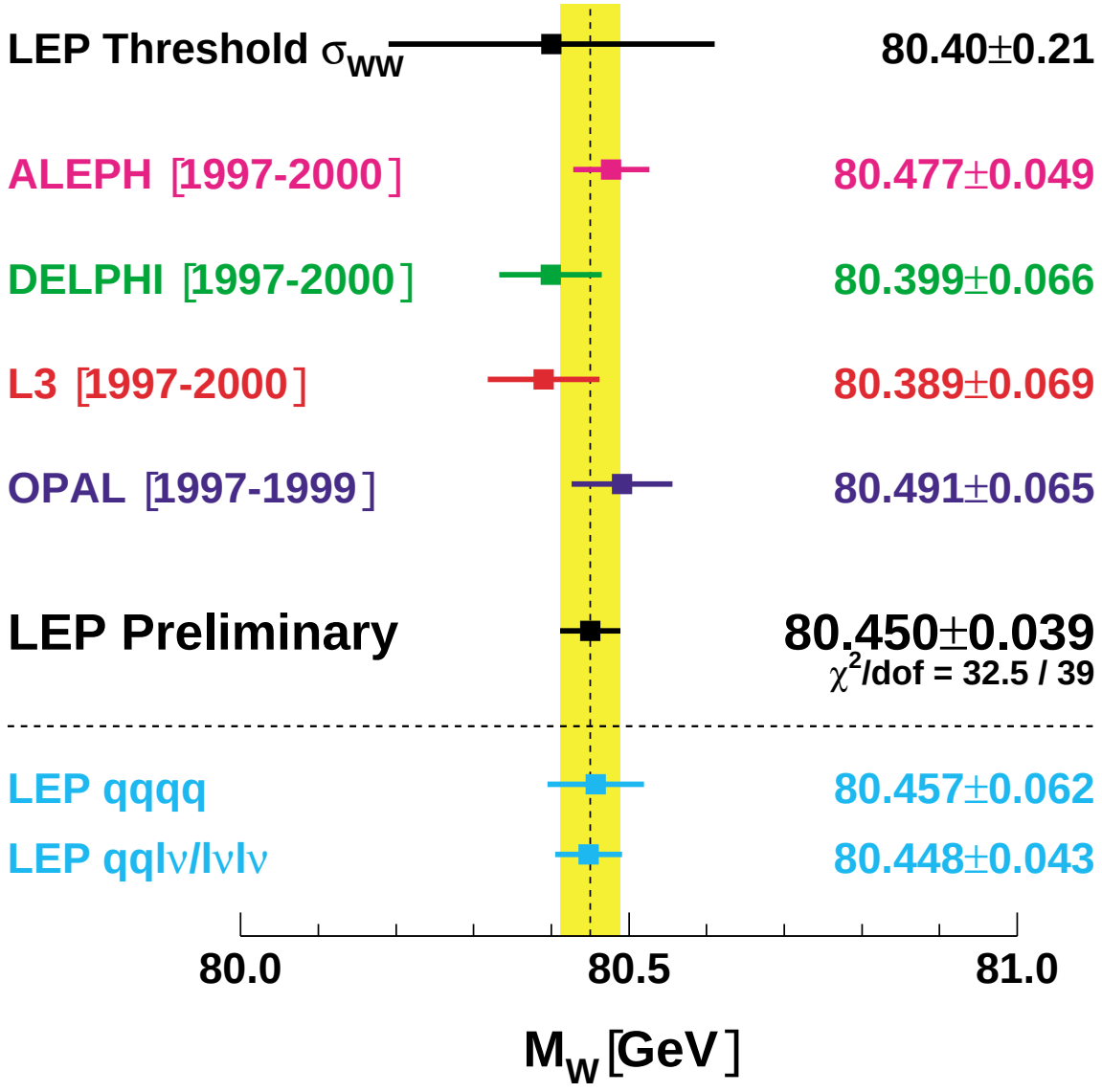


$$(E,p)_{TOT} = (2E_{beam}, 0)$$
$$M_{W+} = M_{W-}$$

$\longrightarrow$ M_W, Γ_W

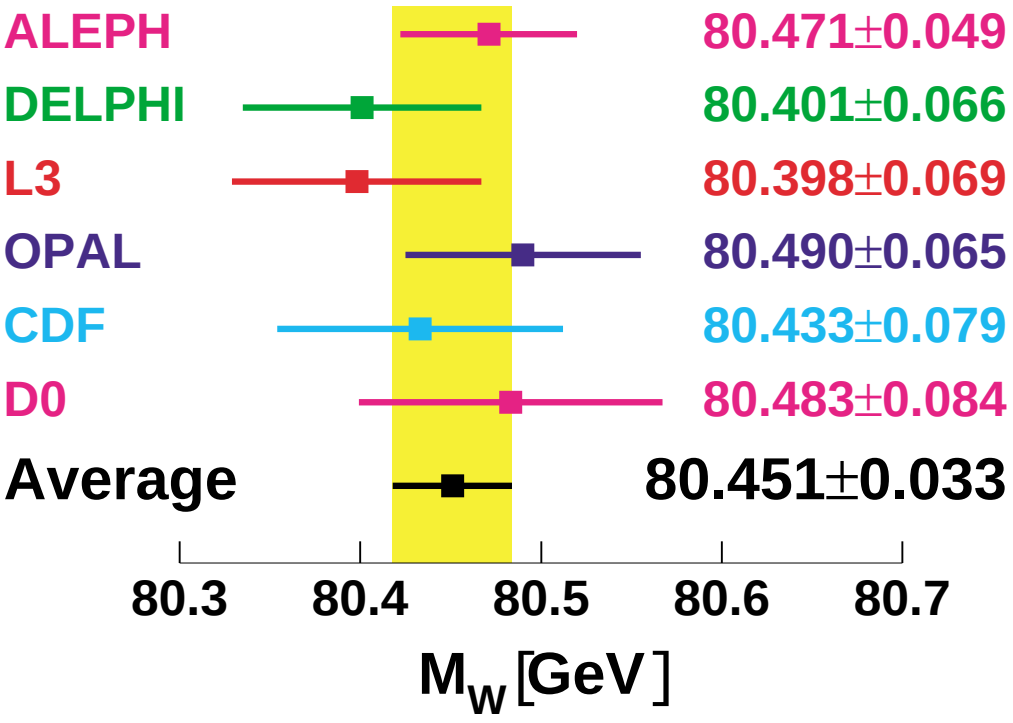
Fit to weighted MC

LEP2 Combined Preliminary M_W

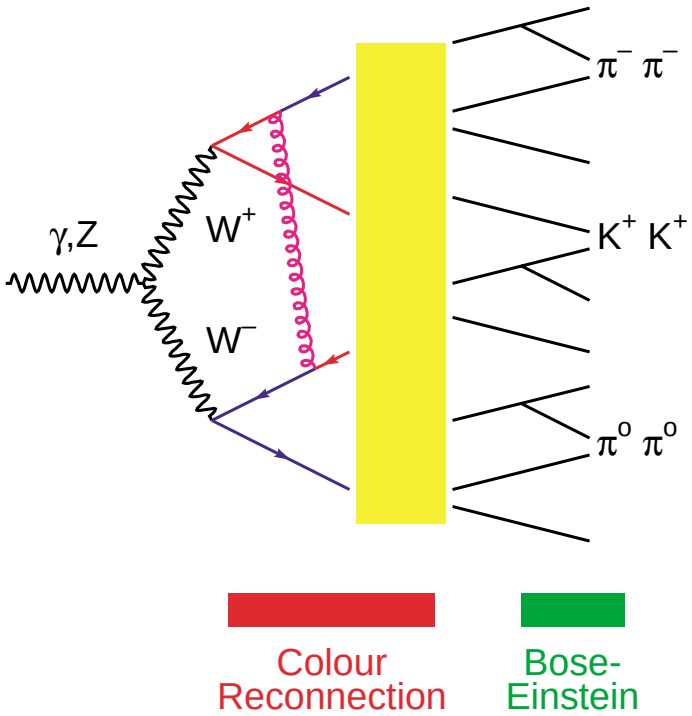


δM_W [MeV]	qq$\ell\nu$	qqqq	Combined
Statistics	33	30	26
Systematics	29	54	30
ISR/FSR	8	9	8
Hadronisation	19	17	17
Detector	12	8	10
LEP E_{beam}	17	17	17
Colour Reconnection	-	40	11
Bose-Einstein	-	25	7
	(74 %	26 %)	

World Average W-Boson Mass



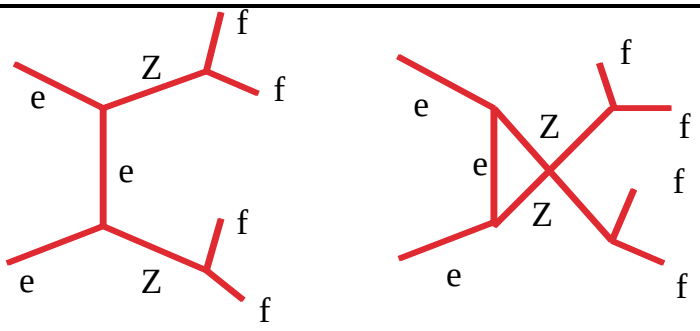
Expected Final LEP2: $\delta M_W \sim 30 - 35$ MeV



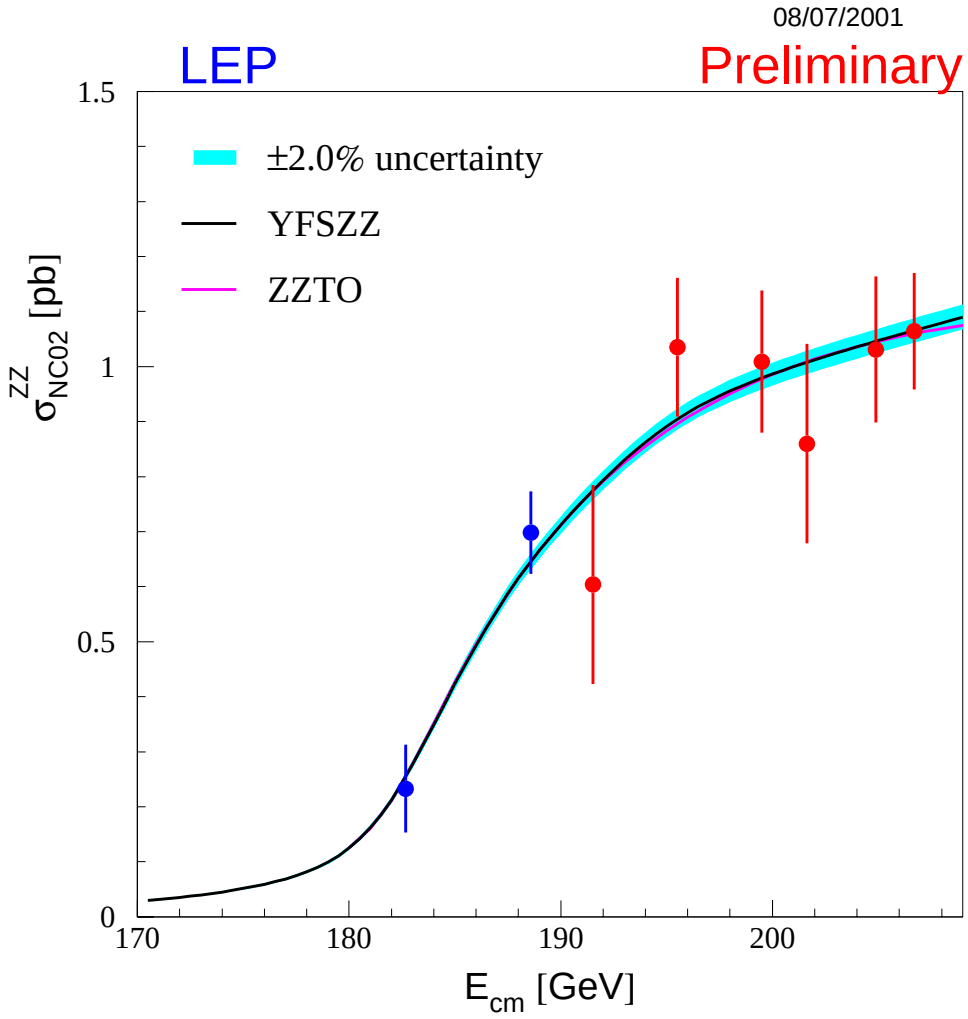
May cause shifts in fitted M_W

LEP2 ZZ production

2 doubly-resonant diagrams (NC02):



Final States: qqqq, qq$\nu\nu$, qq$\ell\ell$, $\ell\ell\ell\ell$

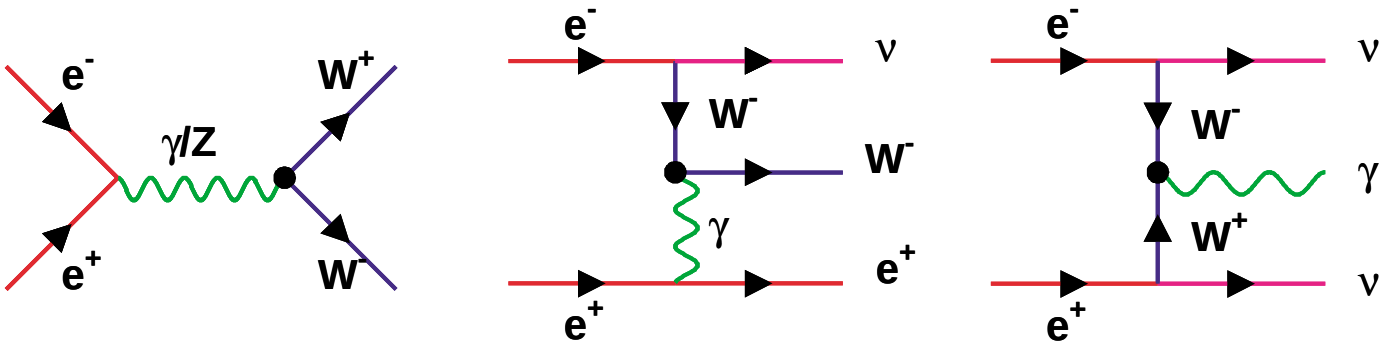


Potential background to HZ production

Look for anomalous neutral couplings ZZZ, ZZγ – none found!

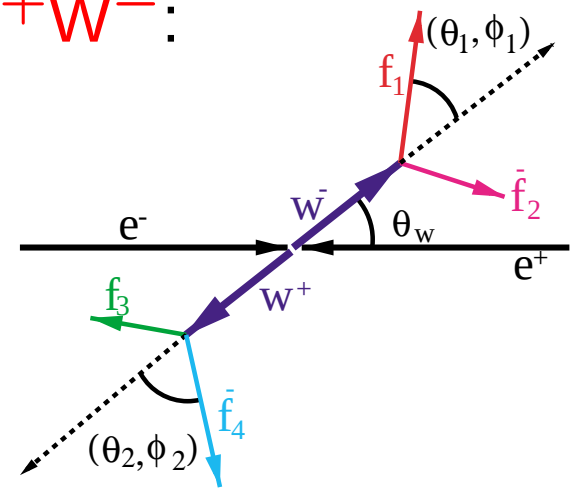
LEP2 Triple Boson Couplings WWV ($V = Z/\gamma$)

Up to 14 - In SM only 3: $(\kappa_V, g_1^V, \lambda_V) = (1, 1, 0)$



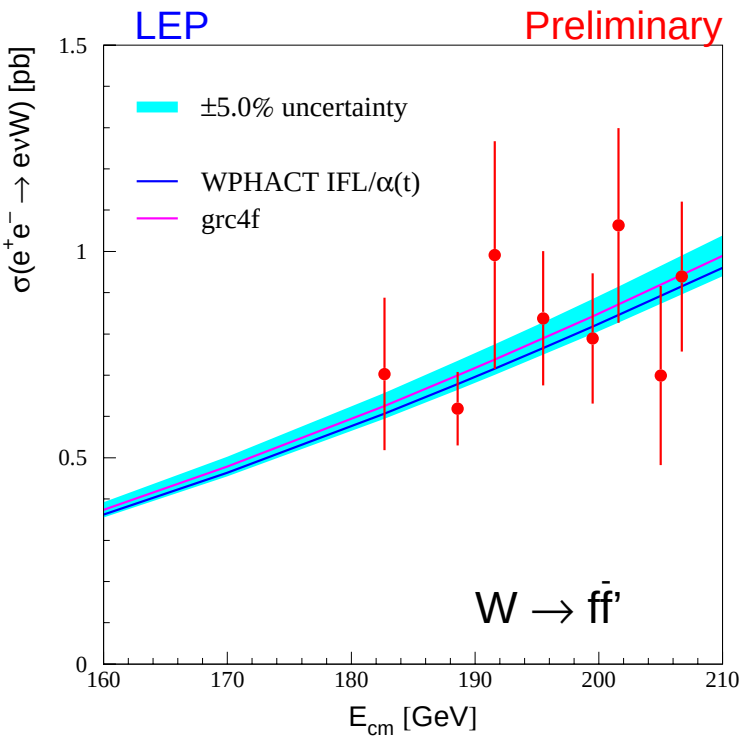
Main information from W^+W^-:

- total cross-section
- angular distributions
- polarization



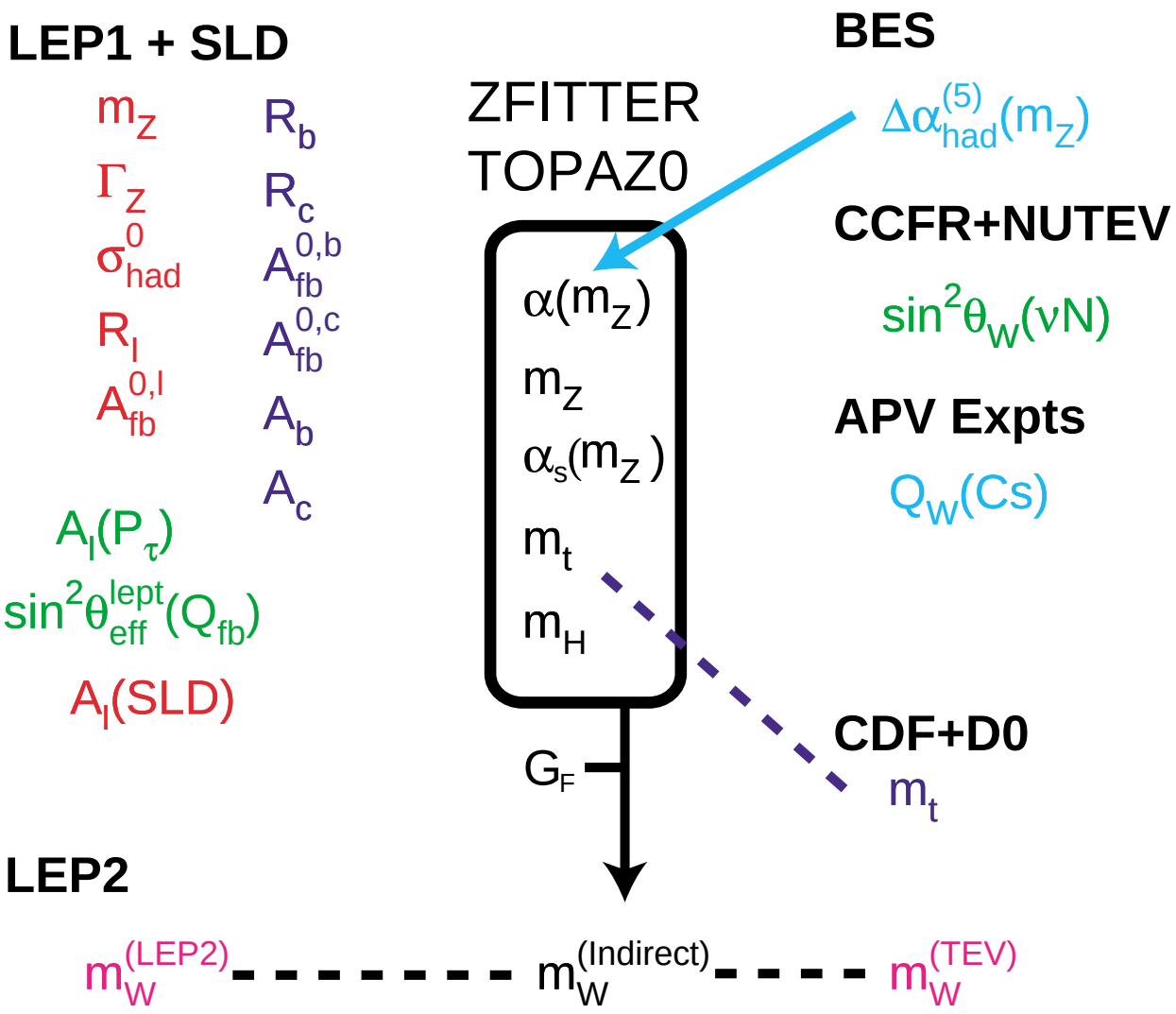
New generator $\mathcal{O}(\alpha)$ corrections $\sim$ precision !

Single-W



Less precise

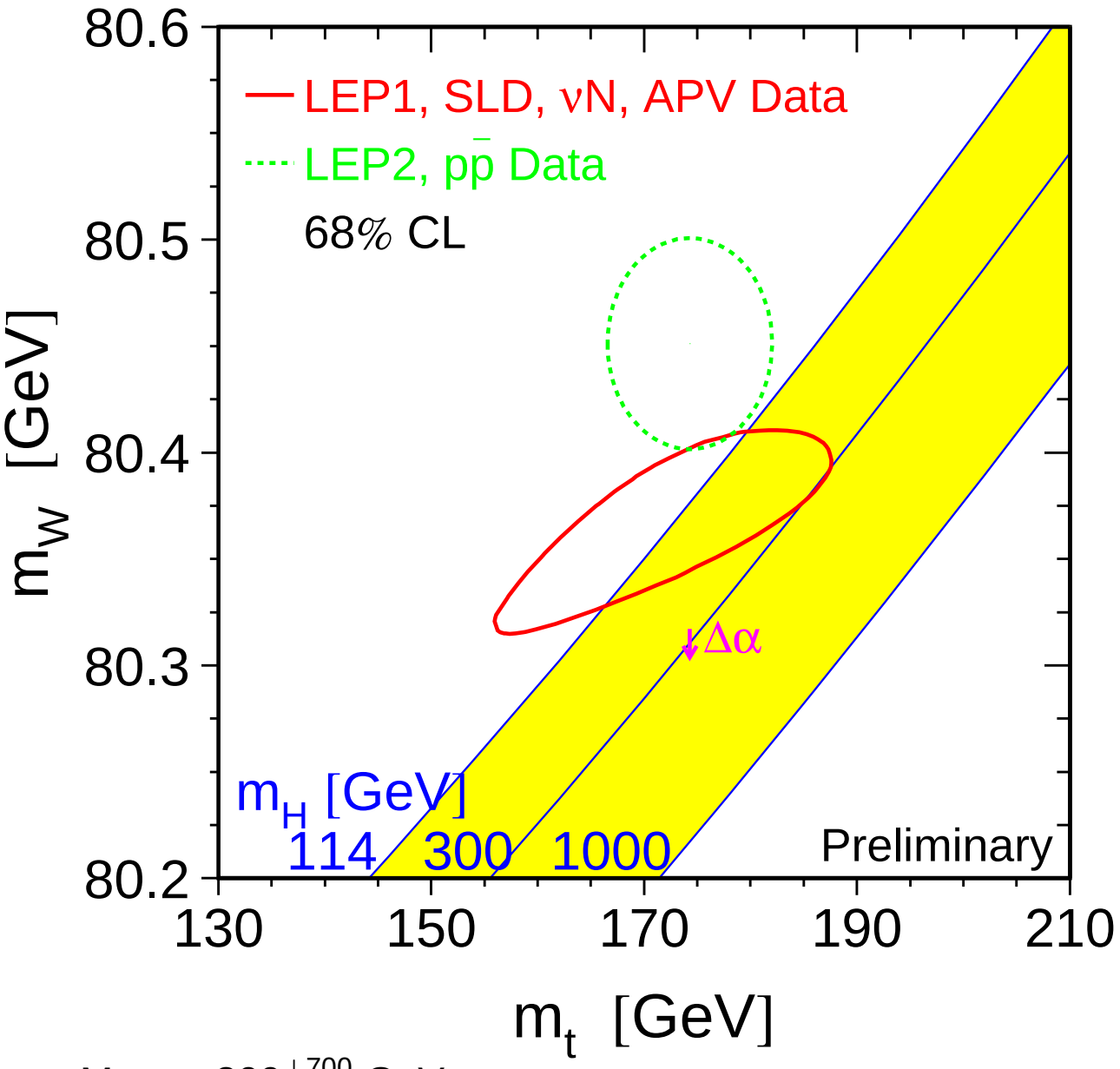
Global Electroweak Fit



Consistency test: Indirect ⟷ Direct M_W, M_t

Provides glimpse of M_H

Direct and indirect ellipses in M_t, M_W plane.

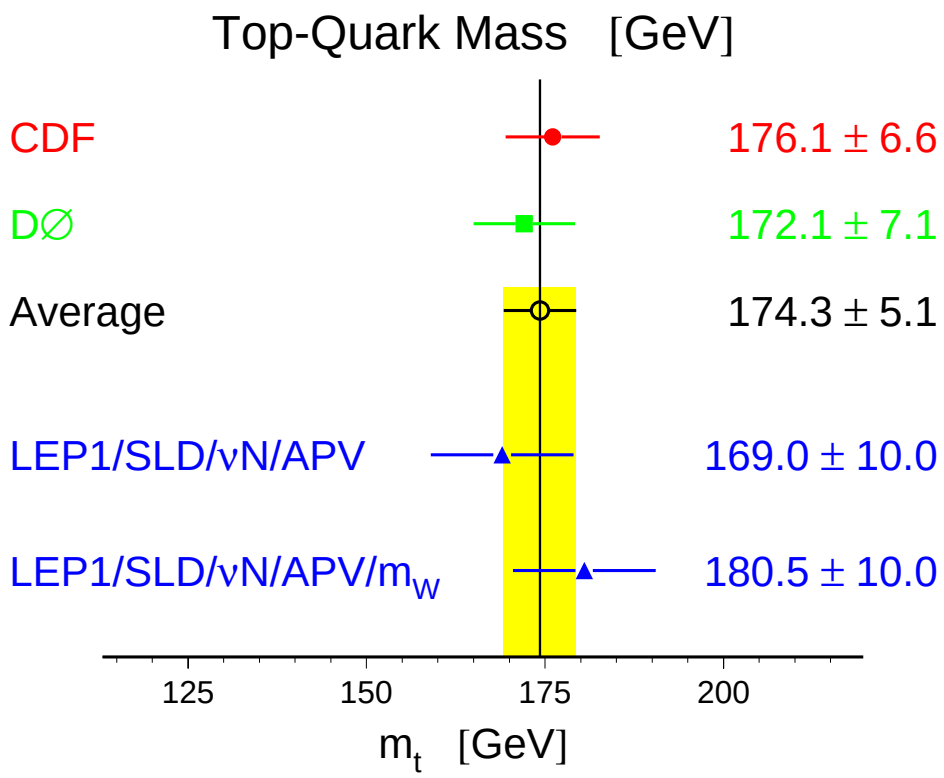


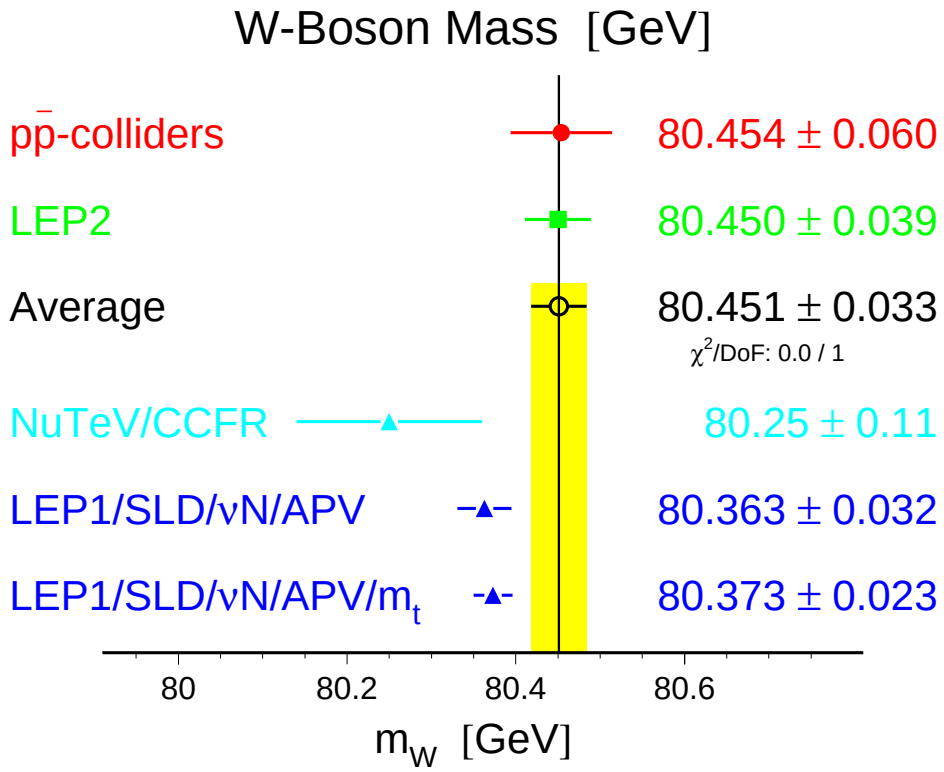
$M_H = 300^{+700}_{-186}$ GeV

$\Delta\alpha^{(5)}_{had} = 0.02761 \pm 0.00036$

Low Higgs mass preferred!

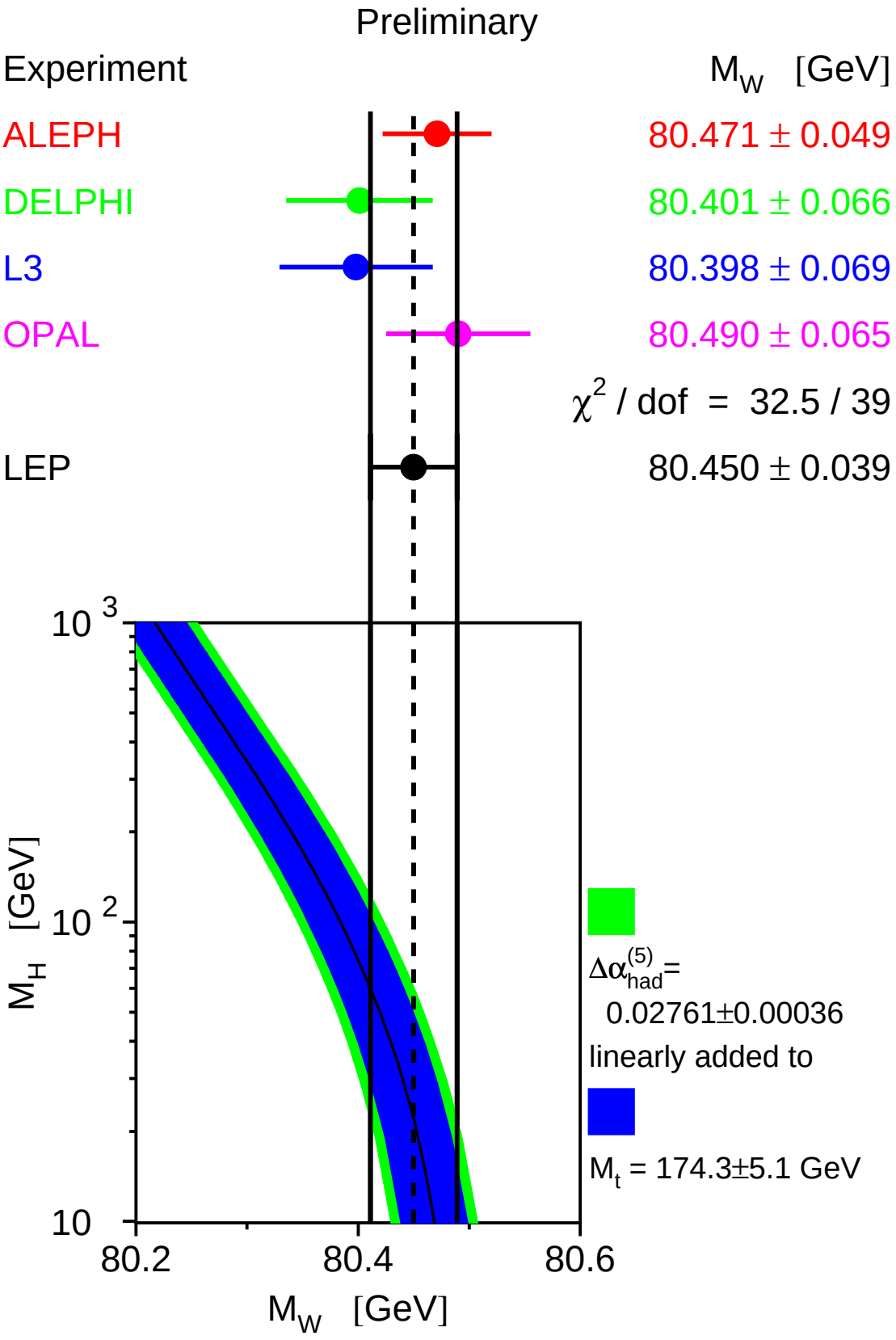
W-Boson and Top-Quark Mass





Successful predictions of heavy masses

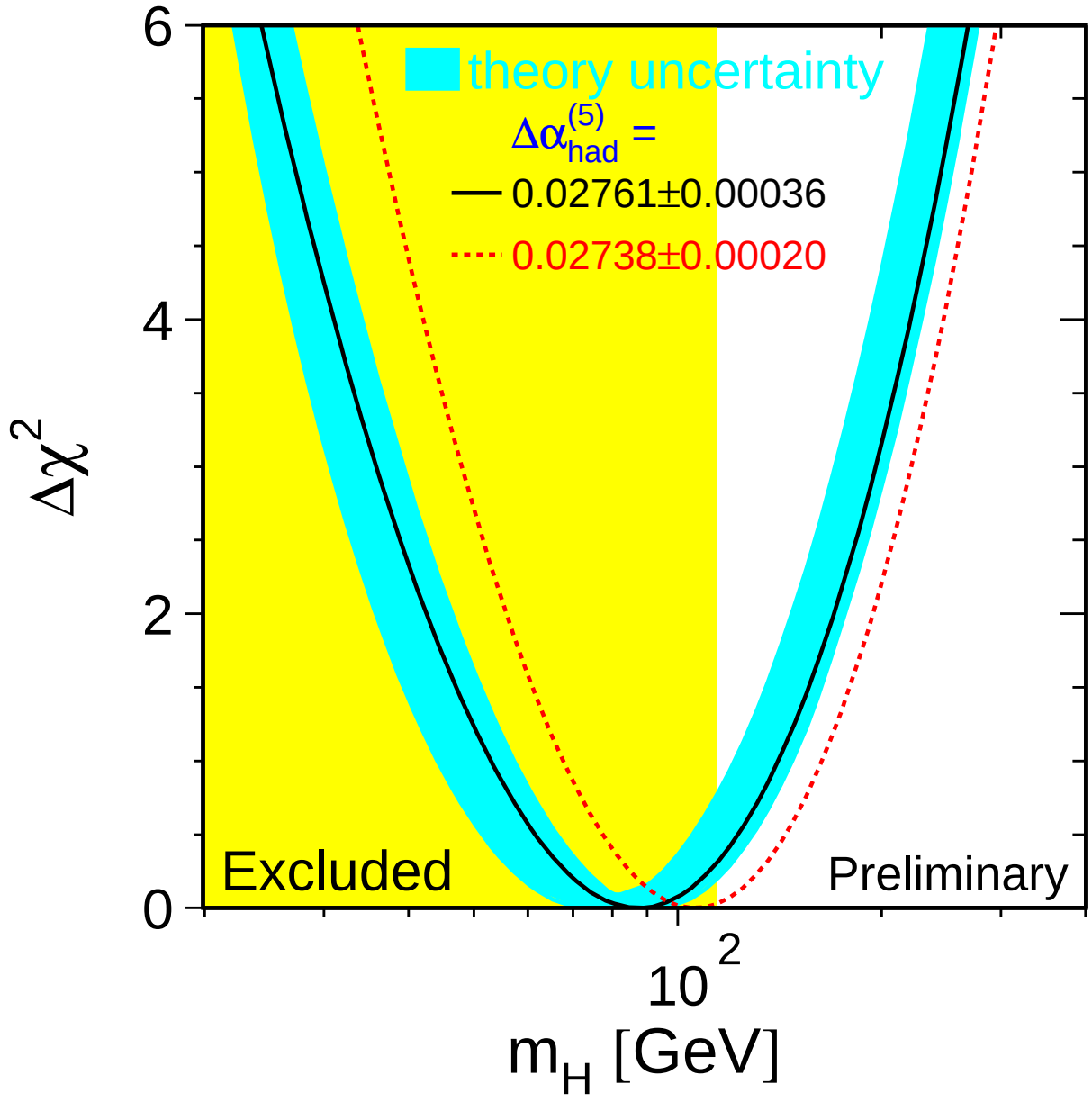
LEP2 W-Boson Mass



Low Higgs mass preferred!

Constraining Higgs-Boson Mass

$$M_H = 88^{+53}_{-35}\ \text{GeV}$$

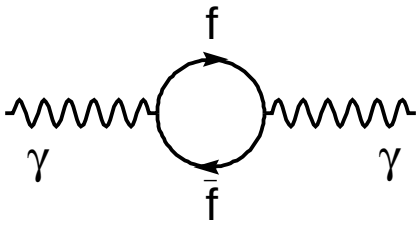


$M_H < 196$ GeV (95% CL) $M_H < 222$ GeV (95% CL)

2nd limit from theory driven $\Delta\alpha^{(5)}_{had}$

Upper limits are safe

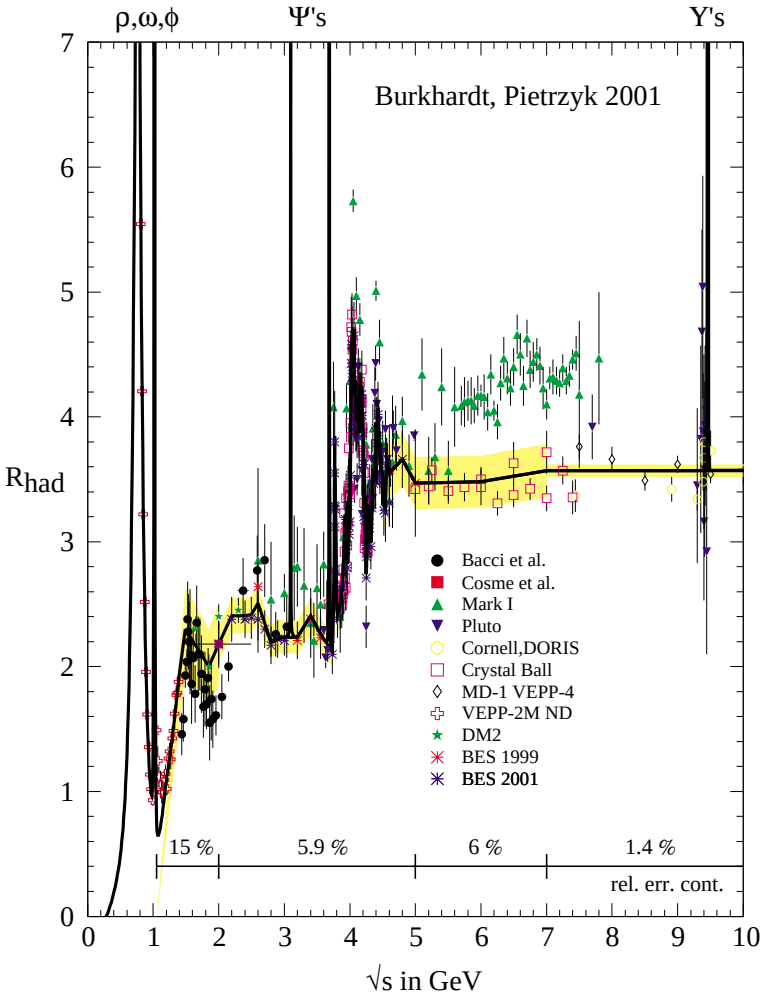
Running $\alpha(0)$ to $\alpha(M_Z^2)$



$$\frac{1}{\alpha(0)} \longrightarrow \frac{1}{\alpha(M_Z^2)} = \frac{(1-\Delta\alpha)}{\alpha(0)}$$

$$\Delta\alpha = \overbrace{\Delta\alpha_\ell(M_Z^2) + \Delta\alpha_{\rm top}(M_Z^2)}^{\text{calculable}} + \underbrace{\Delta\alpha^{(5)}_{\rm had}(M_Z^2)}_{\text{QCD uncertainties}}$$

$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ via dispersion integral over BES2+... measured $R(s) = \frac{\sigma(e^+e^-\to\text{hadrons})}{\sigma(e^+e^-\to\mu^+\mu^-)}$



$$\Delta\alpha^{(5)}_{\rm had} = 0.02761 \pm 0.00036$$

Theory Predictions

Cross-sections,asymmetries,... with:

TOPAZ0 4.4 (2001-02-22): G.Passarino et al.

ZFITTER 6.36 (2001-06-21): D.Bardin et al.

Corrections include:

initial state QED, including pairs	$\mathcal{O}(\alpha^2)$ + leading $\mathcal{O}(\alpha^3)$
final state QED, QED initial-final	$\mathcal{O}(\alpha)$
final state QCD	$\mathcal{O}(\alpha_S^3)$
mixed QED/QCD final state	$\mathcal{O}(\alpha\alpha_S)$
1-loop EW	complete

And leading 2-loop EW up to:

$$\mathcal{O}(\alpha\alpha_S, \alpha\alpha_S^2, G_F{}^2M_t{}^4, G_F{}^2M_t{}^4M_Z{}^2, G_FM_t{}^2\alpha_S, G_FM_t{}^2\alpha_S^2,)$$

NEW: Complete fermionic two-loop M_W:

Freitas, Hollik, Walter, Weiglein, PLB 495 (2000) 338

Full shift taken as new uncertainty

Uncritical for M_W but controversial problem for:

$$\sin^2\theta_{\text{eff}}^{\text{lept}} = \kappa_W \cdot \left(1 - \frac{M_W^2}{M_Z^2}\right)$$

partial cancellation expected

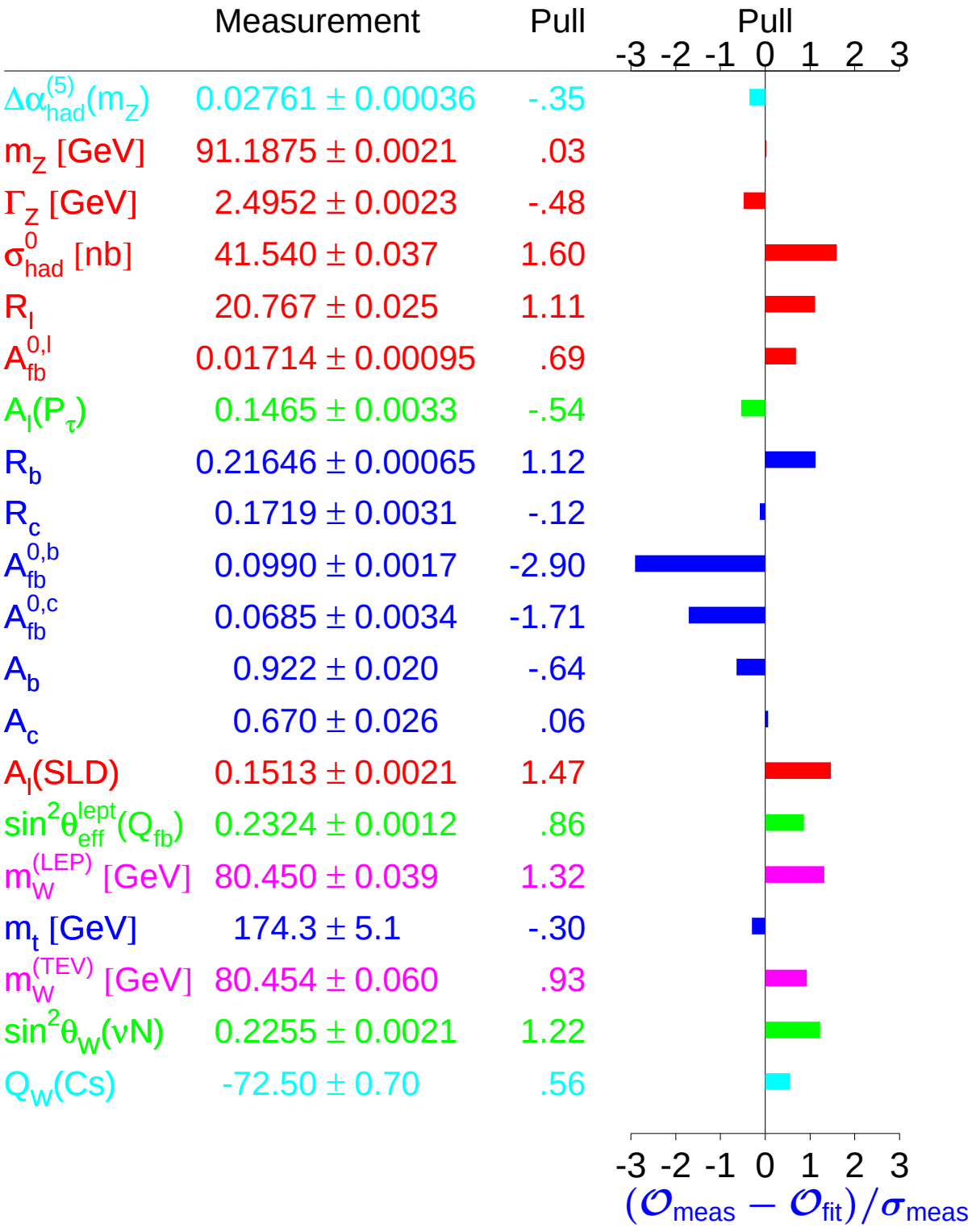
Need equivalent calculations for:

Partial Z decay widths

Effective electroweak mixing angle

Global Electroweak Fit

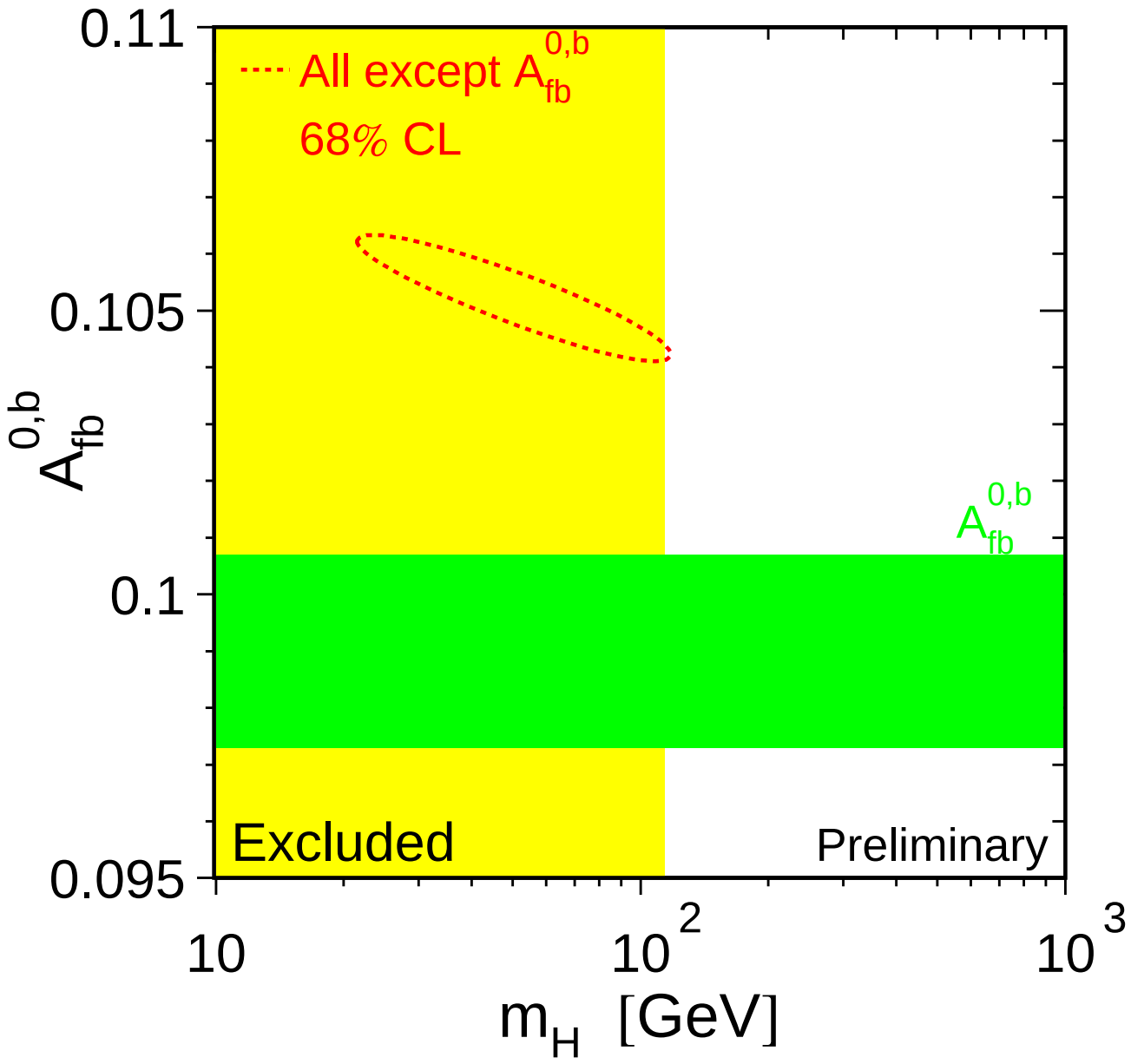
Summer 2001



$$\chi^2/\text{dof} = 22.9/15 \ (8.6\%)$$

Excluding $A_{fb}^{0,b}$ measurement from fit

Fit result ($A_{fb}^{0,b}$, M_H) contour & measured $A_{fb}^{0,b}$:



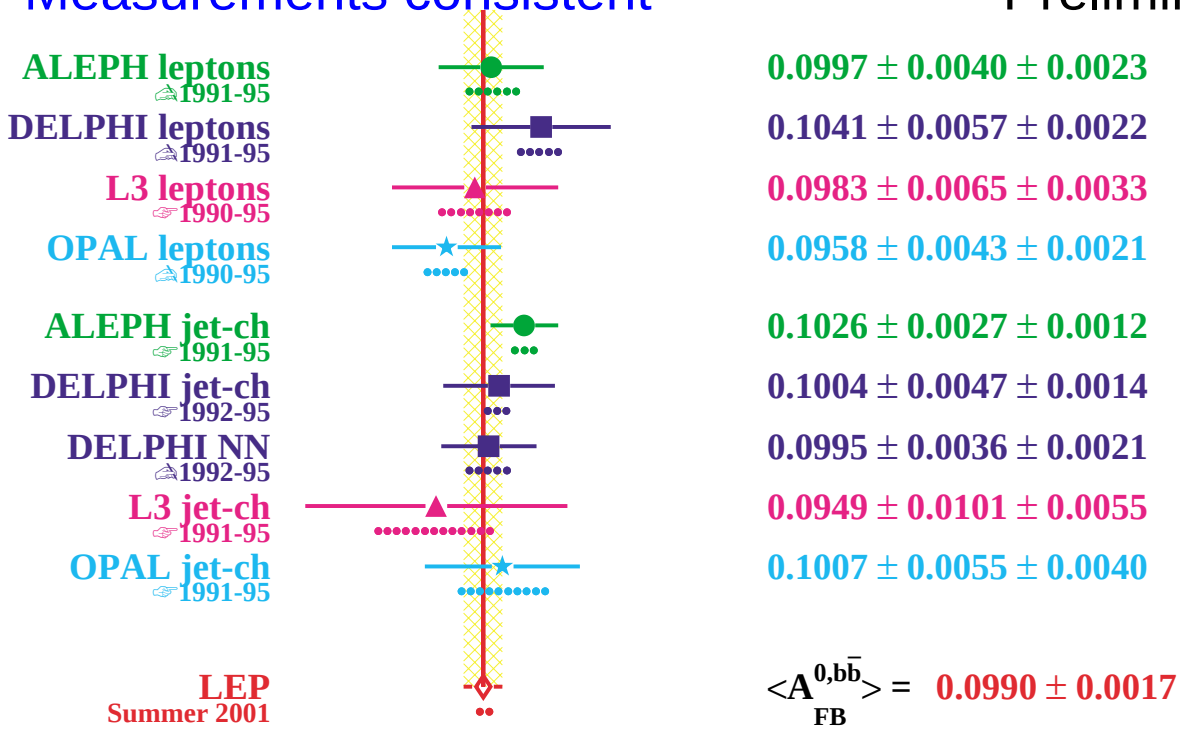
Reduces Higgs limit - Improves χ^2

M_H prediction is beneath direct limit

Is $A_{fb}^{0,b}$ measurement reliable ?

LEP Measurements consistent

Preliminary



Including Lepton + Jet-Charge results.

	$\Delta A_{fb}^{0,b}$
Statistics	0.00156
Systematic	0.00073
Uncorrelated	0.00061
Correlated	0.00039
QCD correction	0.00030

No reason to consider $A_{fb}^{0,b}$ unreliable.

Post LEP Conclusions

LEP+SLD+TEVATRON+. . . :

Enormous Electroweak understanding improvements.

Due to a wealth of precision measurements:

	Before LEP	Expected	Achieved
M_Z	0.16 GeV	20-50 MeV	2.1 MeV
M_W	0.36 GeV	100 MeV	39 MeV
N_ν	0.9	0.3	0.008
$\sin^2\theta^{lept}_{eff}$	0.006	-	0.00017

and theoretical advances.

MSM radiative corrections verified:

Successful M_t and M_W prediction

Most measurements agree with expectations:

MSM fit probability: 8.6%

Largest deviation in $A_{fb}^{0,b}$: 2.9 sigma

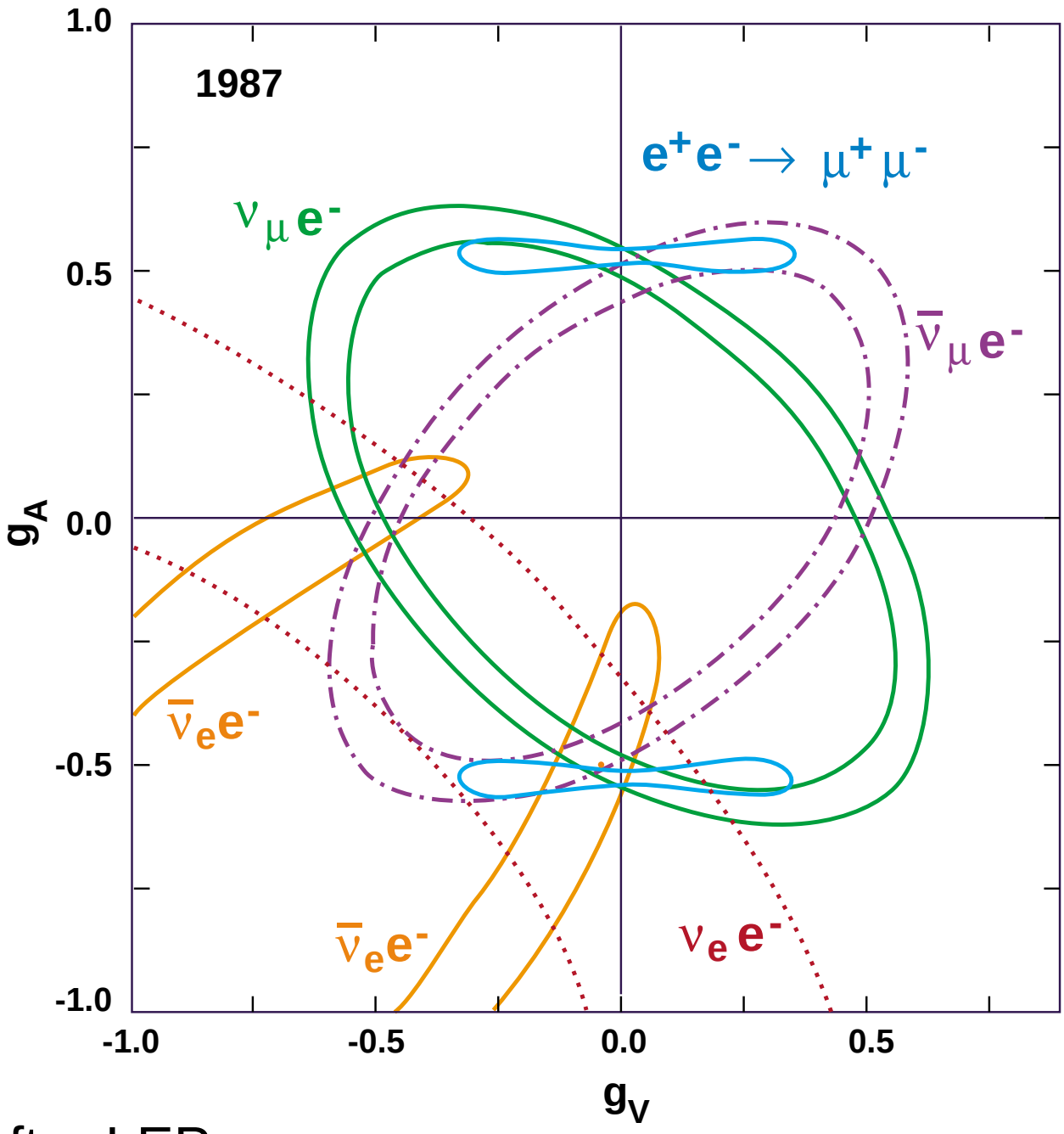
Light Higgs: $M_H < 196$ GeV (95% CL)

Improved measurements of M_W, M_t, $\Delta\alpha^{(5)}_{had}$ and improved theoretical predictions needed.

And we need M_H directly too!

Enormous Improvements, $(g_{V\ell}, g_{A\ell})$

Before LEP:



After LEP:

$$g_{V\ell} = -0.03783 \pm 0.00041$$
$$g_{A\ell} = -0.50123 \pm 0.00026$$