Electroweak Physics

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Outline

New precision measurements

- Muon anomalous magnetic moment
- Neutrino-nucleon scattering
- Z and W bosons: masses and couplings

Tests of the electroweak Standard Model

Direct search for the Standard-Model Higgs boson

Conclusion

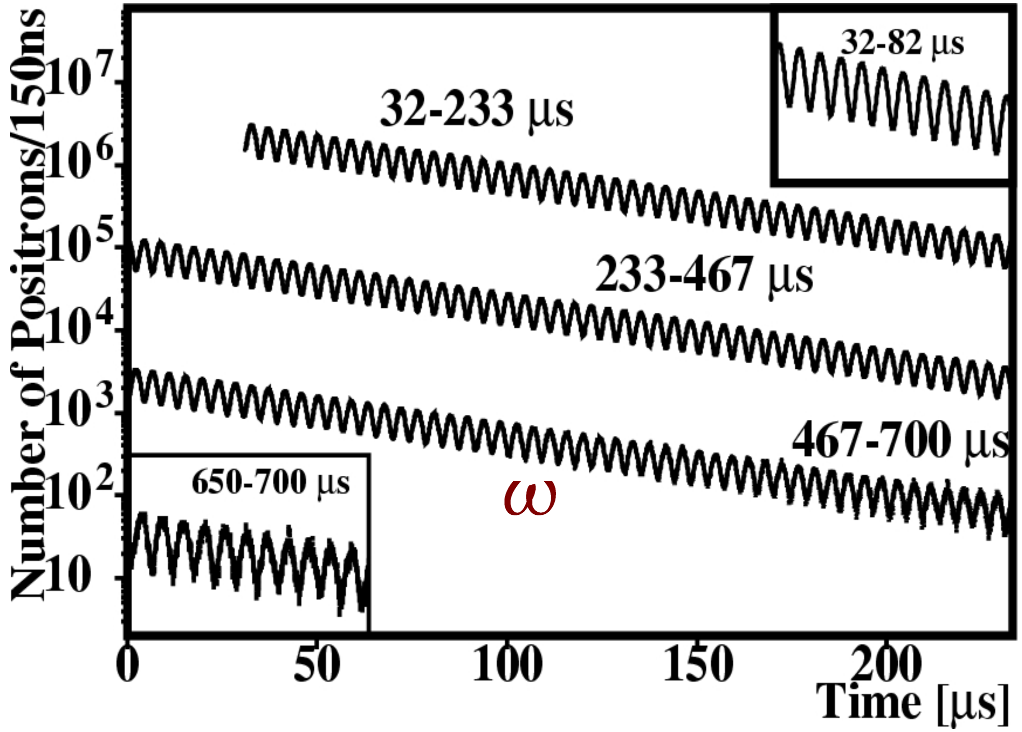
Thanks to the members of the Tevatron, LEP-WW, LEP-2F, LEP-Higgs and LEP electroweak working groups, the Tevatron, LEP, LHC, NuTeV experiments, and: P.Antilogus, E.Barberio, D.Bardin, D.Bourilkov, R.Chierici, D. Duchesneau, G.Duckeck, M.Elsing, S. Eno, P.Gambino, P.Igo-Kemenes, R.Hawkings, J.Holt, T.Kawamoto, A.Kotwal, E.Lancon, L.Malgeri, K.McFarland, K.Moenig, C.Parkes, U.Parzefall, G.Passarino, B.Pietrzyk, P.Renton, S.Riemann, K.Sachs, A.Straessner, S.Todorova, N.Watson, G.Weiglein, S.Wynhoff, G.Zeller.

Muon Anomalous Magnetic Moment

Brookhaven experiment E821:

μ spin precession frequency

ω in external B field



$$\frac{g_\mu - 2}{2} = a = \frac{\omega\, m_\mu\, c}{e\, B}$$

1999 data:

10^9 e^+ from μ^+ decay

Experimental result (1999 data): $10^{10}a$ = 11 659 202 (15)

Theoretical expectation (2001): $10^{10}a$ = 11 659 160 (7)

Difference of 2.6 σ !

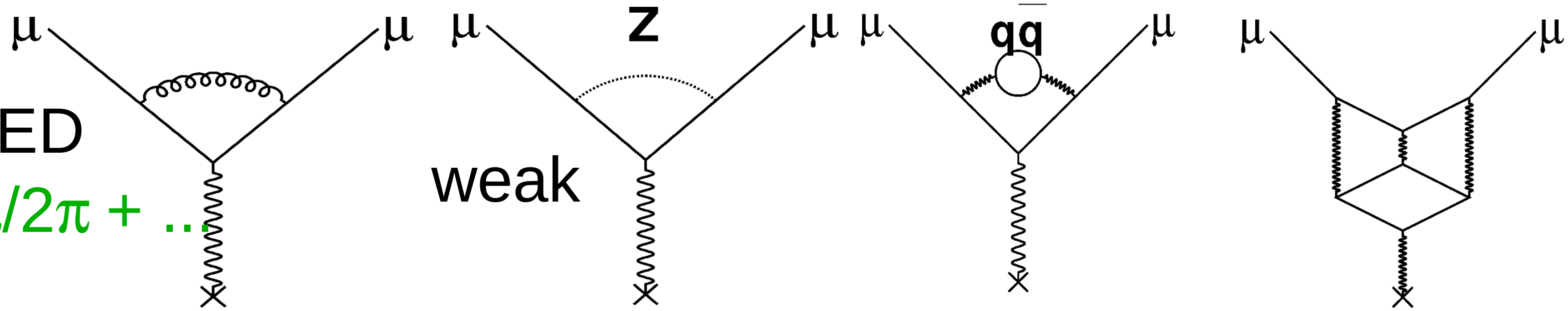
Muon Anomalous Magnetic Moment

SM calculation of all contributions revisited:

QED

$\alpha/2\pi + \ldots$

weak



$10^{10}a = 11658471 \quad +15 \quad +692(7) - 10(1) \quad -8(4)$

Hadronic vacuum polarisation:

1st order (estimates range from 692 to 699) 692 (7)

2nd order -10 (1)

Hadronic light-by-light term (sign flip!) +8 (2)

New theoretical expectation: $10^{10}a = 11\ 659\ 177\ (7)$

Difference reduced to 1.6 σ

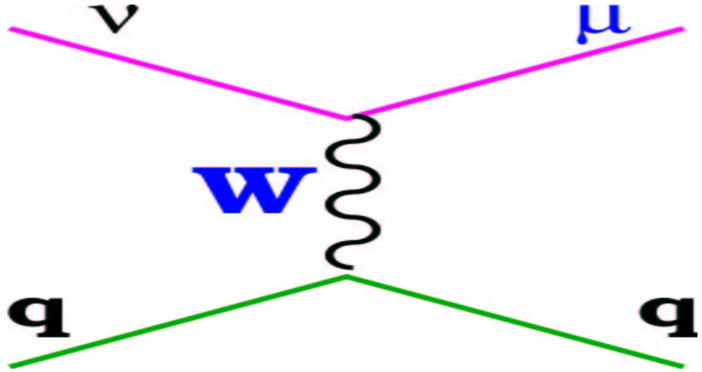
Expect factor three improvement with 2000+2001 data!

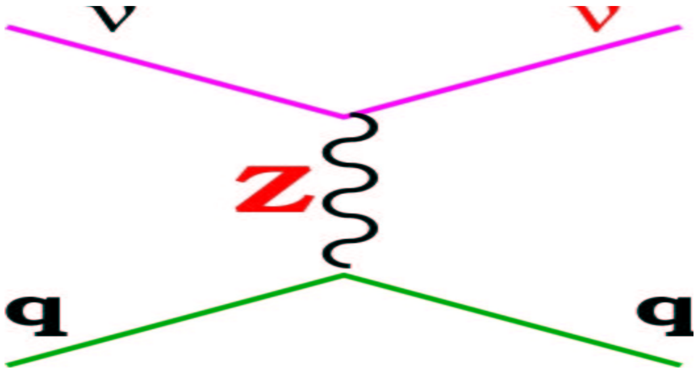
Fresh BNL result (+2000 data): $10^{10}a = 11\ 659$ ___ (_)

NuTeV Neutrino-Nucleon Scattering

Muon-(anti-)neutrino quark scattering:

charged current (CC) | neutral current (NC)





Paschos-Wolfenstein relation (iso-scalar target):

$$R_- = \frac{\sigma_{NC}(\nu)-\sigma_{NC}(\bar{\nu})}{\sigma_{CC}(\nu)-\sigma_{CC}(\bar{\nu})} = 4g^2_{L\nu}\sum_{q_V}\left[g^2_{Lq}-g^2_{Rq}\right] = \rho_\nu\rho_{ud}\left[\frac{1}{2}-\sin^2\theta_W^{(on-shell)}\right]$$

+ electroweak radiative corrections

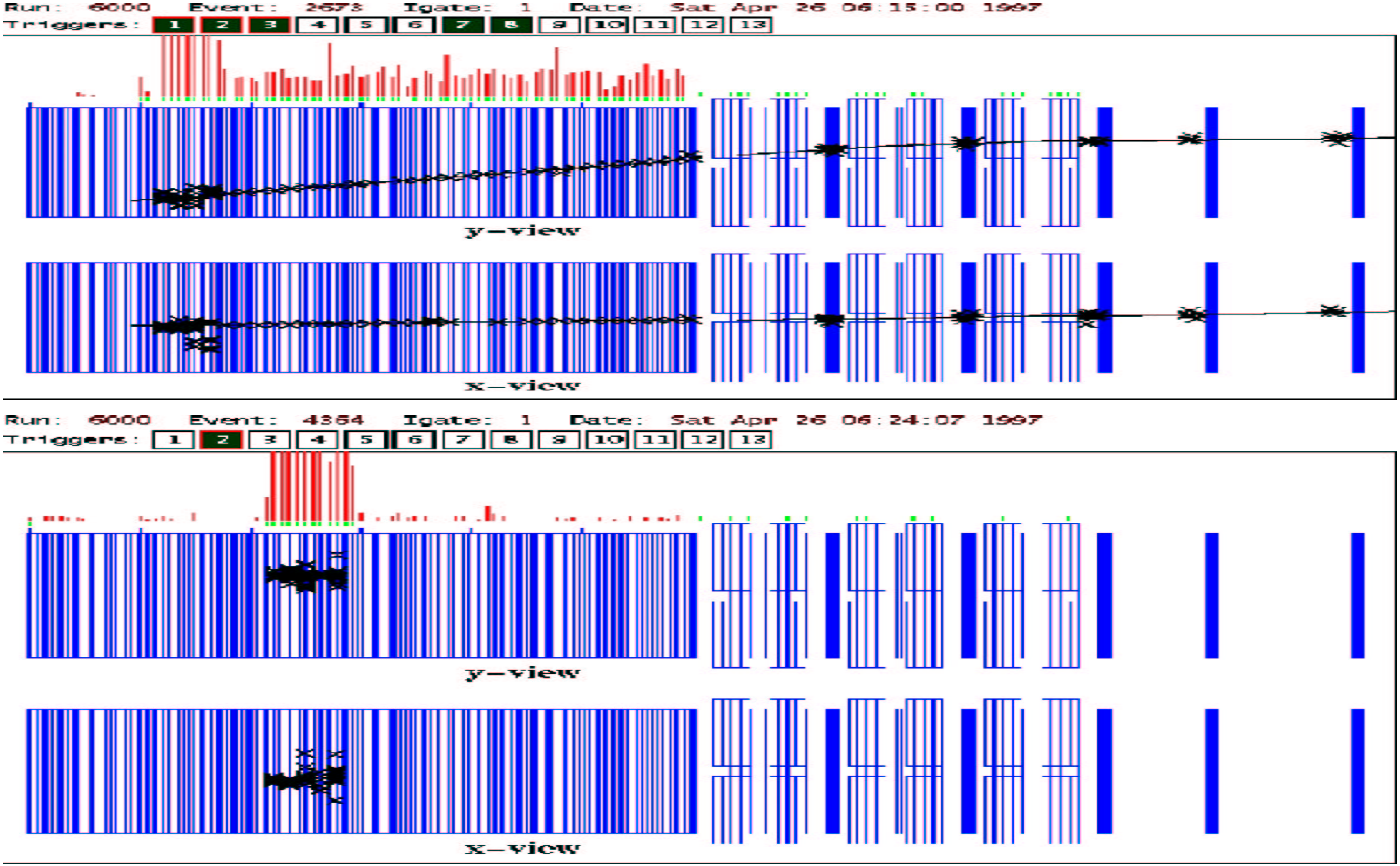
Insensitive to sea quarks

Charm effects only through d_V quarks (CKM suppressed)

Need neutrino and anti-neutrino beam!

CC versus NC Events in the NuTeV Detector

Event length: state muon (CC) or not (NC)

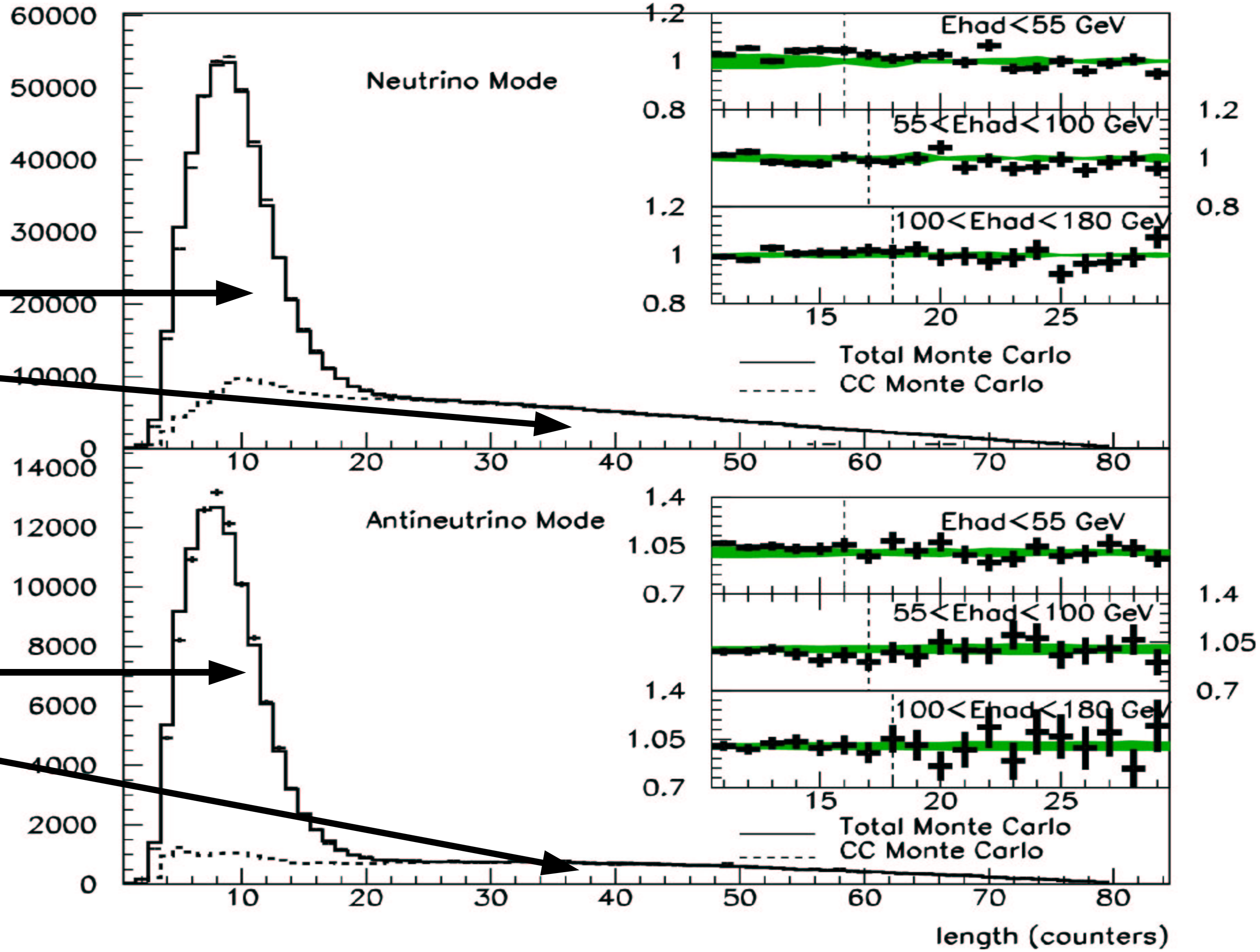


Distribution of Event Lengths

Events: 1975K

Neutrino:
- NC: 457K
- CC: 1167K

Anti-neutrino:
- NC: 101K
- CC: 250K



From measured distributions to R_-:

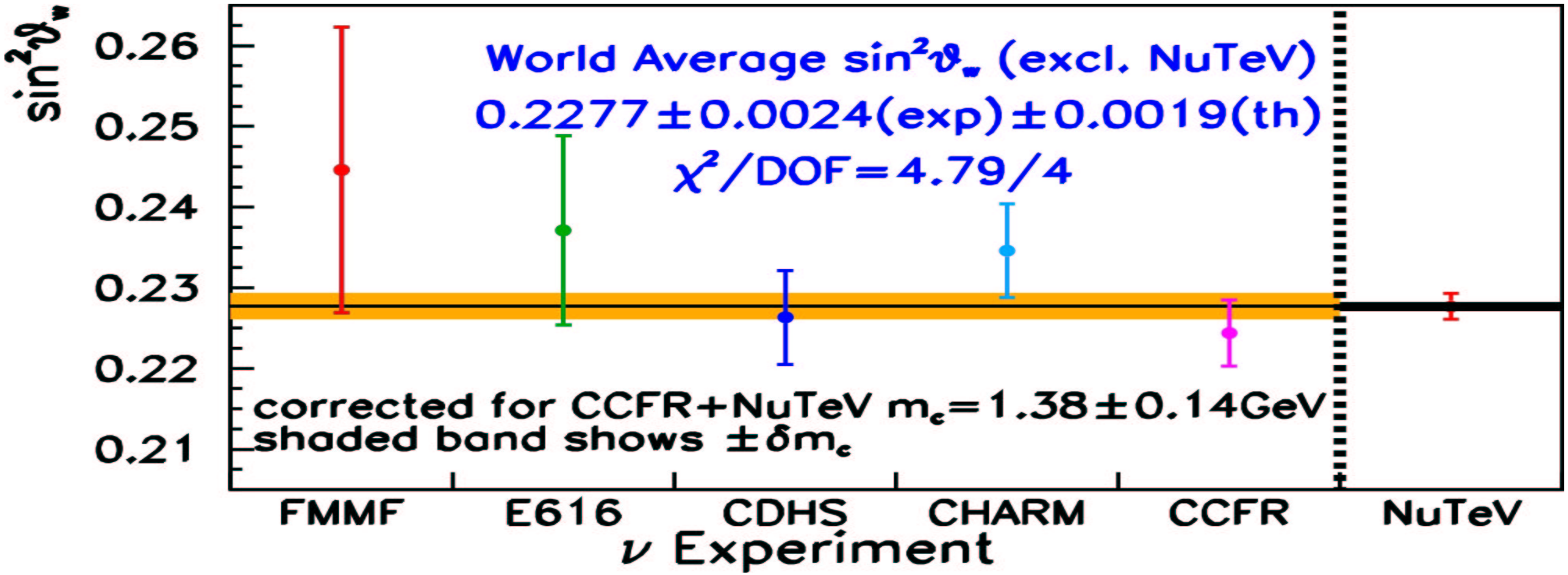
MC modelling of (anti-)neutrino beam, radiative corrections, detector response

NuTeV's Result

$$\sin^2\theta_W^{(on-shell)} = 1 - \frac{M_W^2}{M_Z^2} = 0.2277 \pm 0.0013(stat.) \pm 0.0009(syst.)$$

$$- 0.00022\frac{M_{top}^2 - (175\,GeV)^2}{(50\,GeV)^2} + 0.00032\ln\frac{M_{Higgs}}{150\,GeV} \qquad [\rho = \rho_{SM}]$$

Factor two more precise than previous νN world average



Global SM analysis predicts: 0.2227(4) Difference of 3.0 σ!

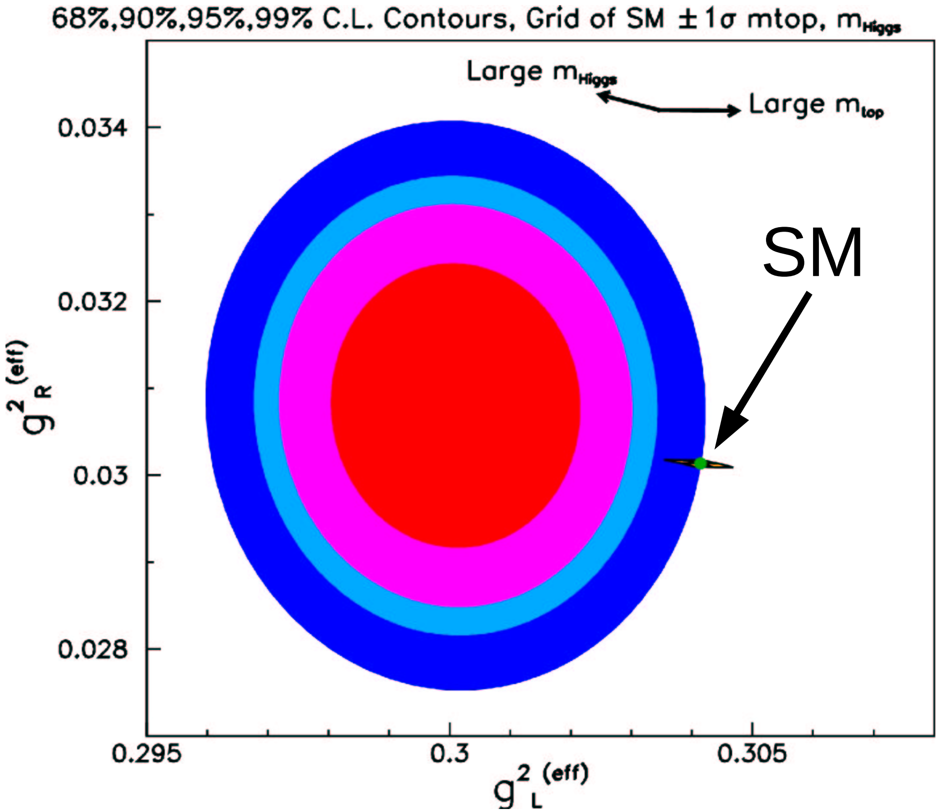
NuTeV's Result

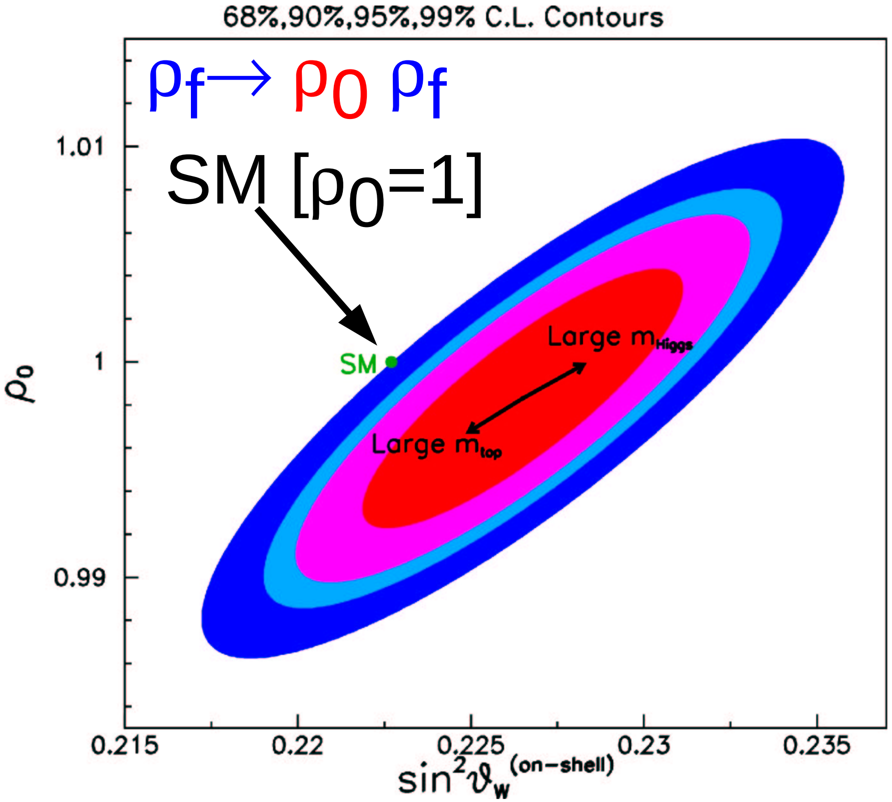
Main systematic uncertainties: (0.0013 stat. error)

0.0006 exp. syst.: 0.0004 (anti)-electron-neutrino flux

0.0006 Model : 0.0004 charm production, s(x)

Statistics dominated result

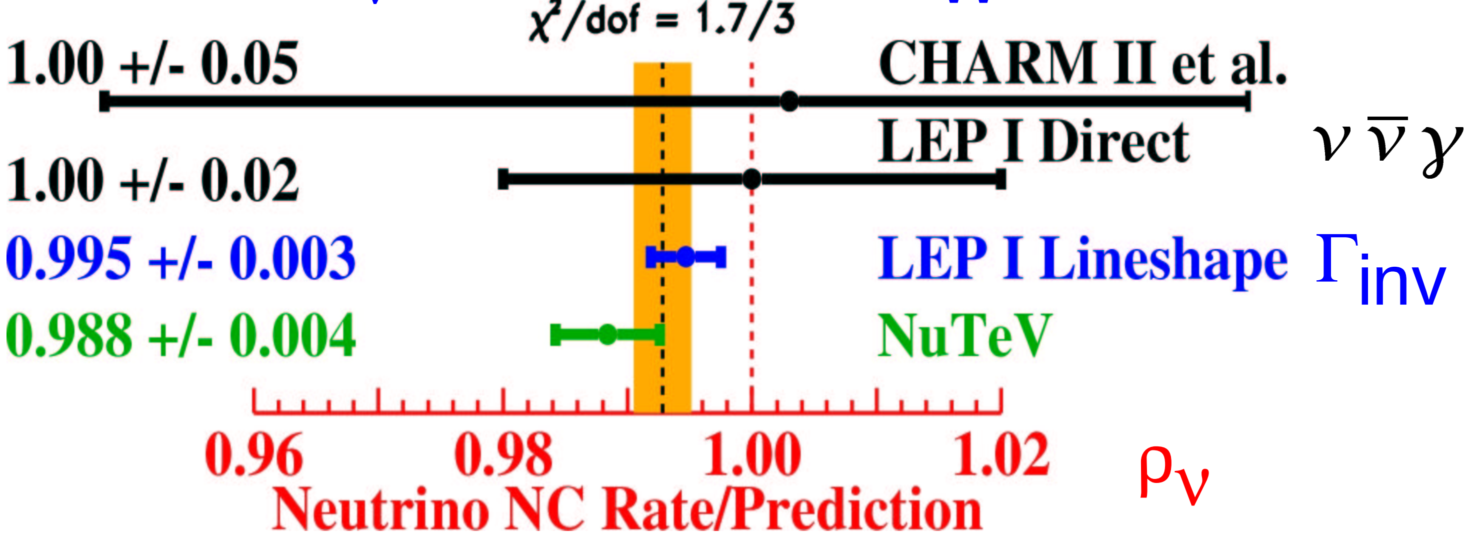




Could also be the left-handed ν/q couplings or tree ρ_0

NuTeV's Result

Strength of ν coupling ρ_ν (assuming $\sin^2\Theta_W$ ok):



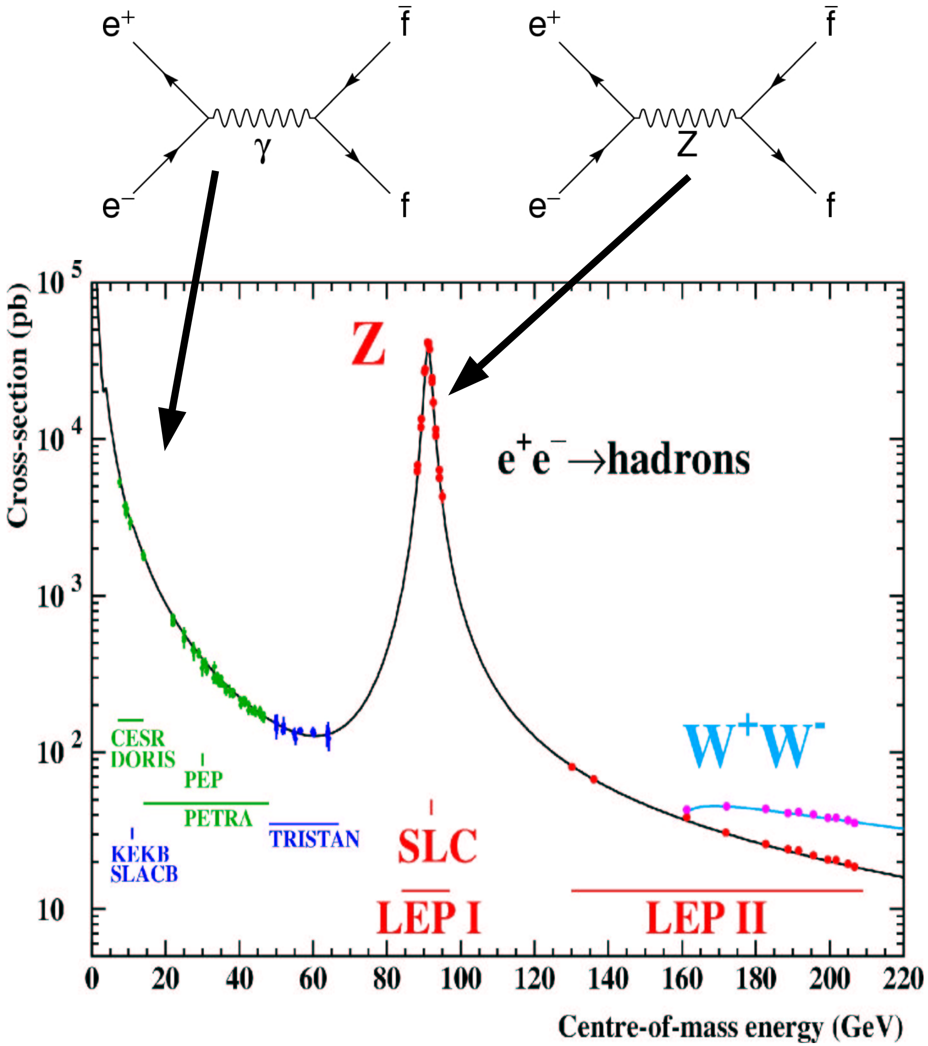
Various explanations, old and new physics:

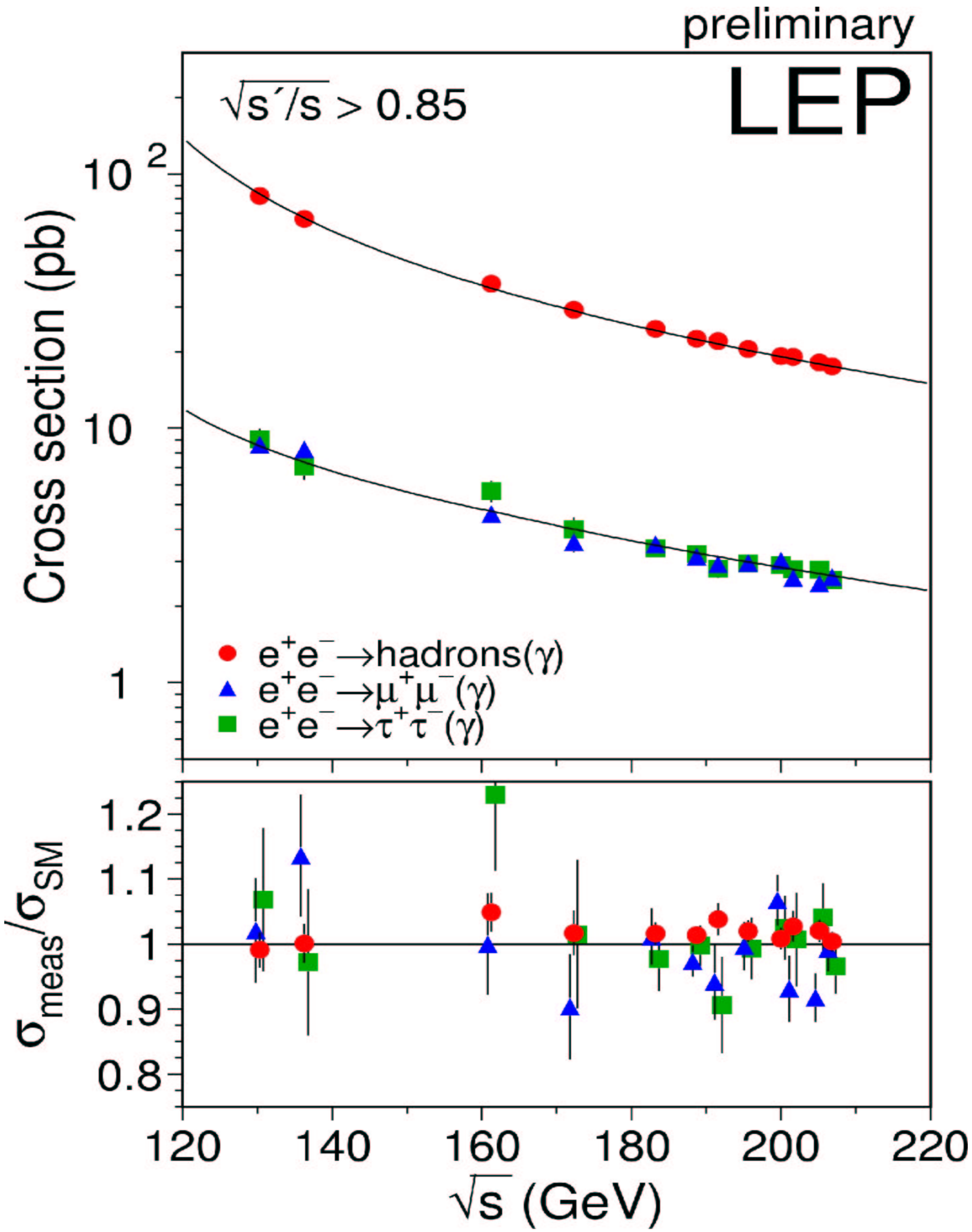
- Theory uncertainty (LO PDFs)
- Isospin violating PDFs
- Strange (charm) sea asymmetry (quark-antiquark)
- Nuclear shadowing asymmetry (W-Z)

New physics:

- Z', contact interactions, lepto-quarks, new fermions, neutrino oscillations, . . .

The Z Lineshape





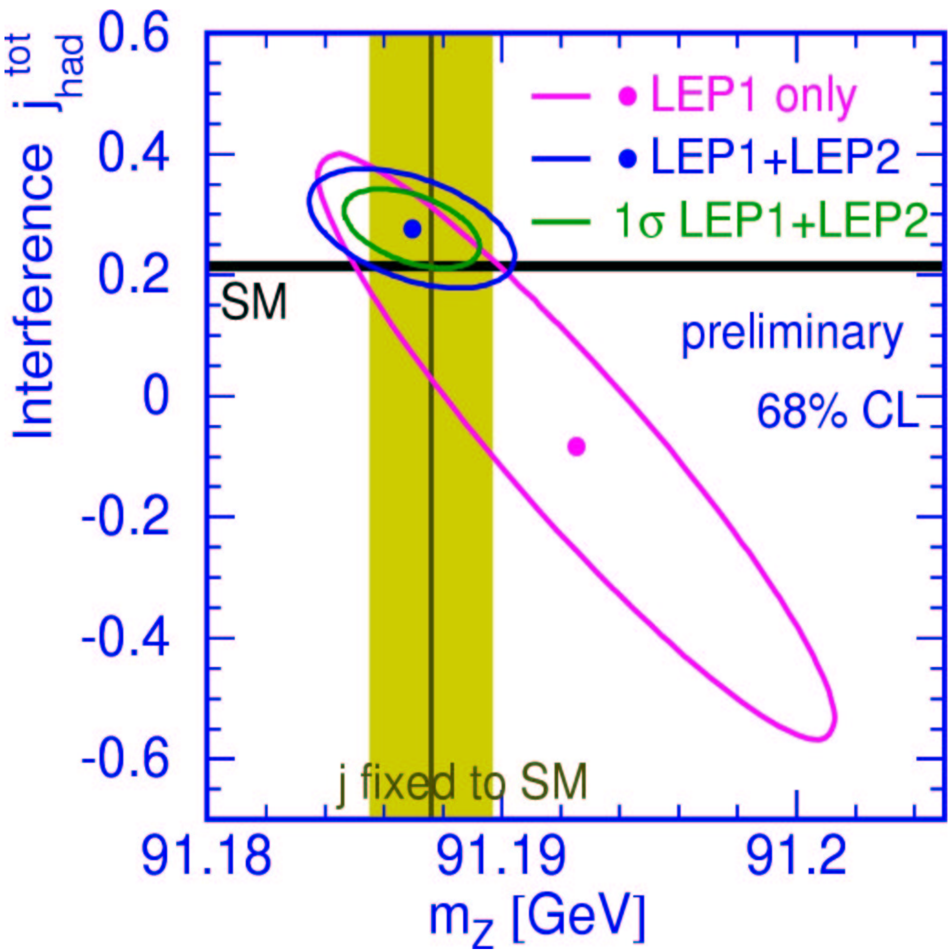
M_Z = 91187.5 (2.1) MeV

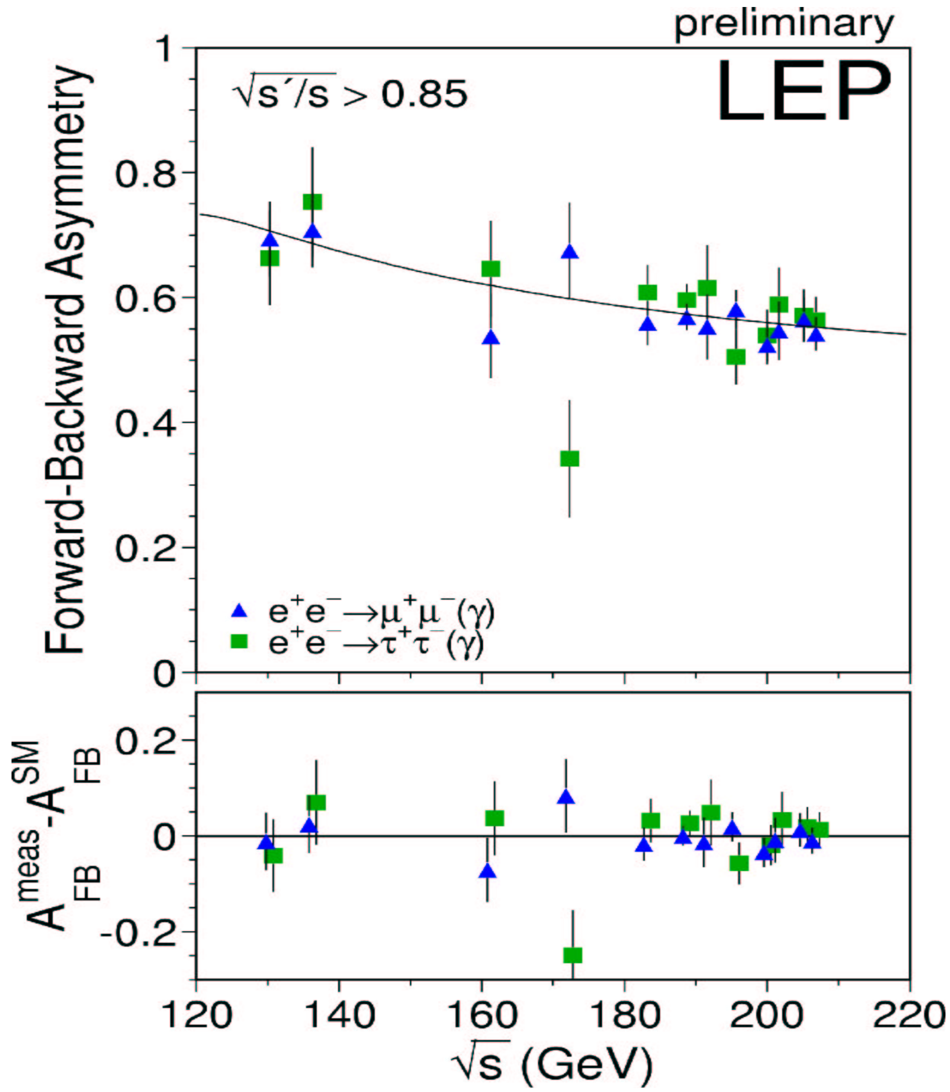
N_ν = 2.9841 (83) [-1.9σ]

Test of γ/Z Interference

Hadronic interference term:

j = 0.277(65) [SM: 0.215(8)]





Similar analyses with TOPAZ and VENUS data on hadrons

In progress for leptons and f/b asymmetries

Leptonic Polarisation Asymmetries at the Z Pole

Asymmetry parameter:

$$A_f = 2\frac{g_{Vf}/g_{Af}}{1+\left(g_{Vf}/g_{Af}\right)^2}$$

LEP-1:

Leptonic f/b asymmetry

A_l = 0.1512 (42)

Final state τ polarisation

A_l = 0.1465 (33)

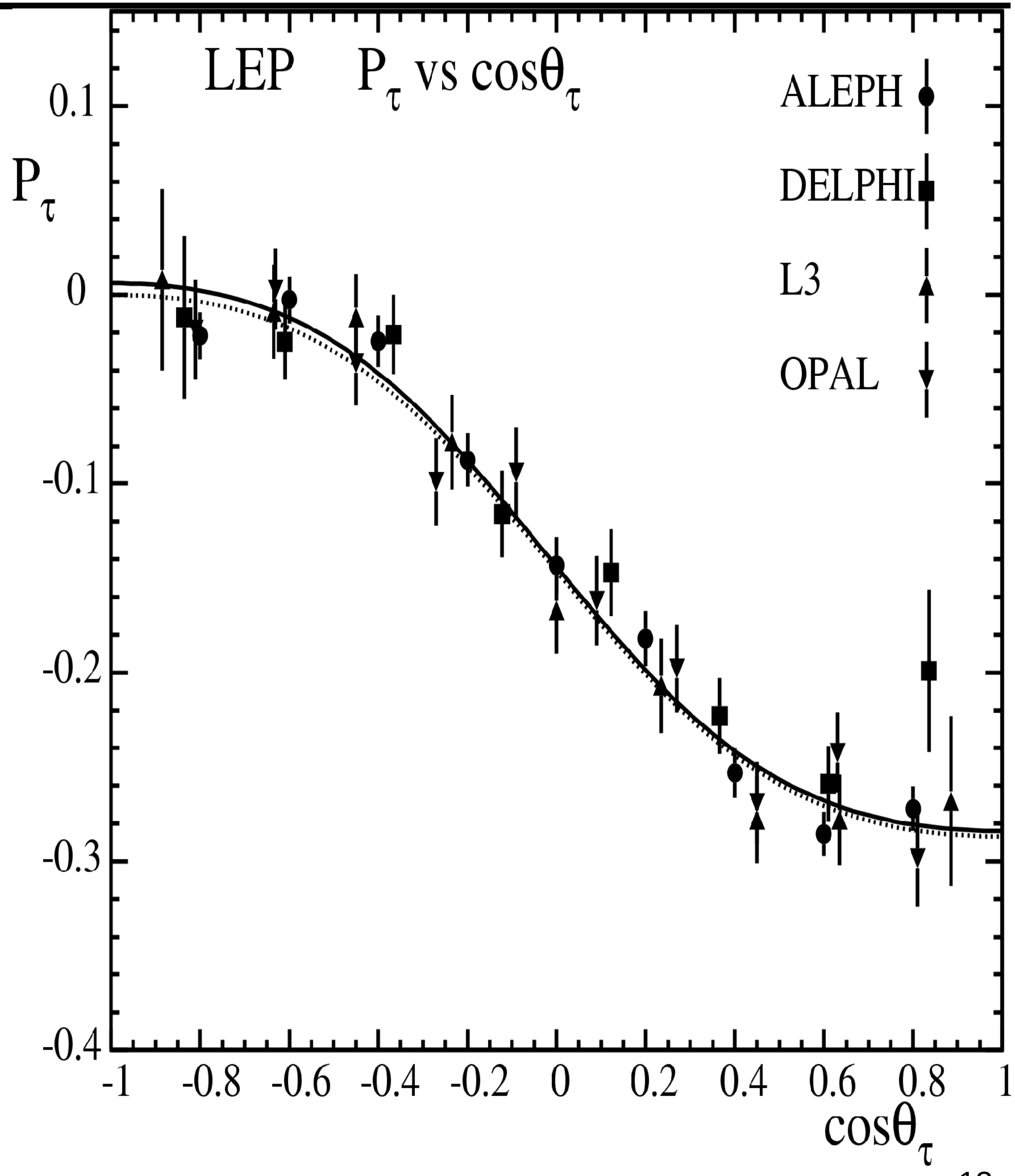
SLD:

Left/right asymmetry

A_l = 0.1513 (21)

Final SLD+LEP-1 result:

A_l = 0.1501 (16)



Effective Leptonic Coupling Constants

$$g_{Vf} = \sqrt{\rho_f}\left(T_3^f - 2q_f \sin^2\theta_{eff}^f\right)$$
$$g_{Af} = \sqrt{\rho_f}\,T_3^f$$

Z partial widths:

$$\Gamma_f \propto g_{Vf}^2 + g_{Af}^2$$

Asymmetry parameters:

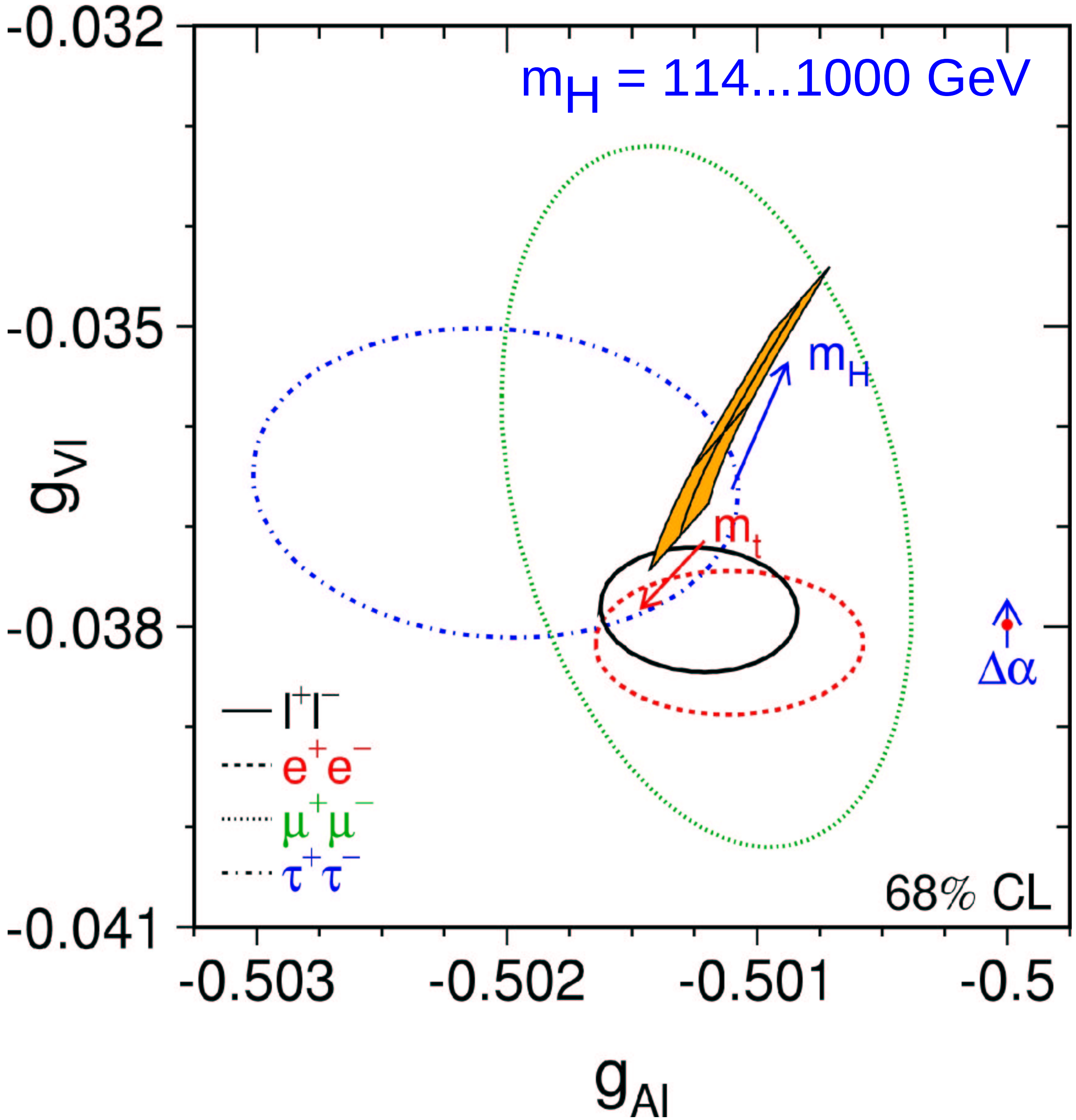
$$A_f \to g_{Vf} / g_{Af}$$

Lepton universality
Radiative corrections

Final SLD+LEP-1 result:

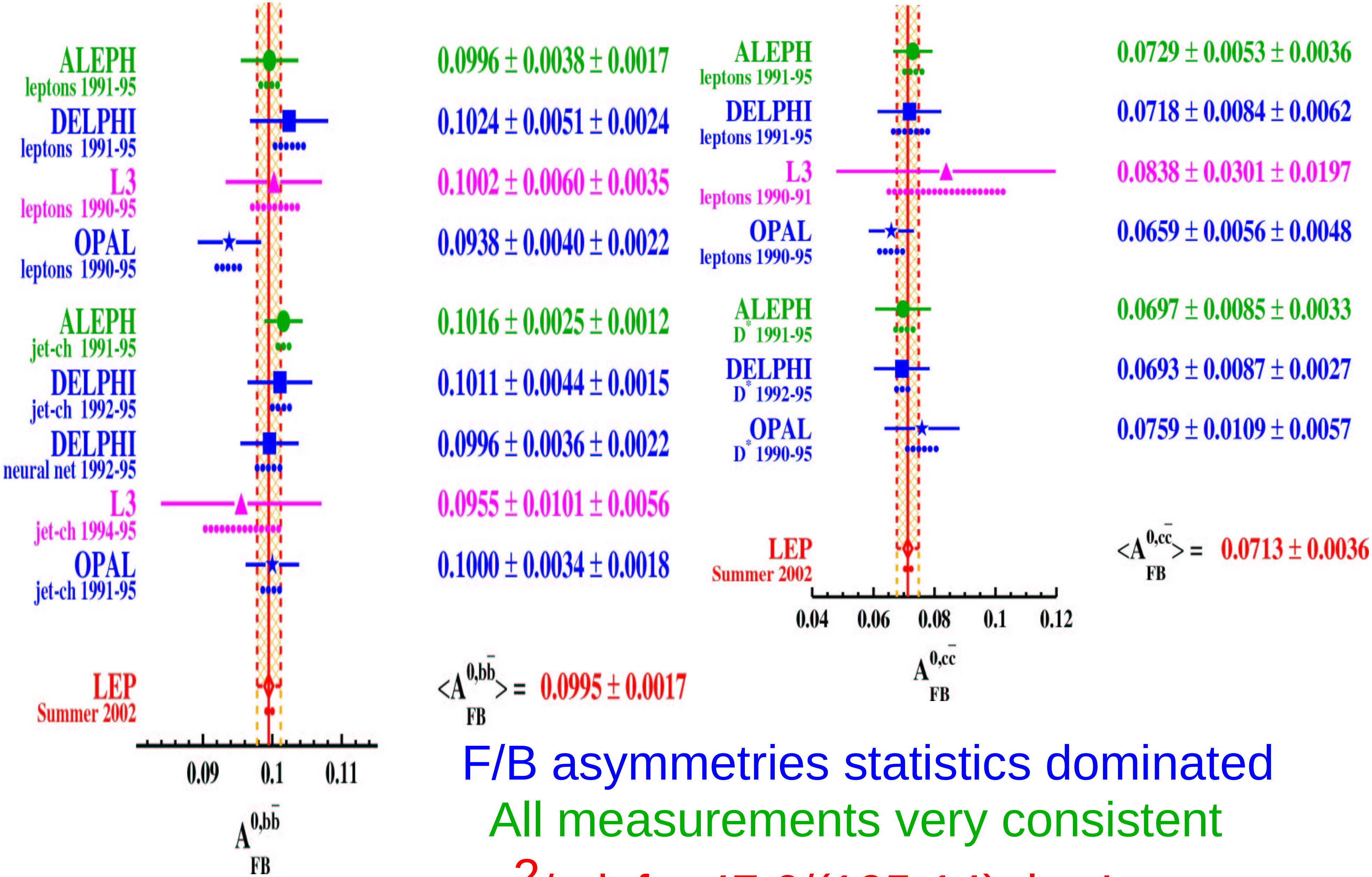
g_{Vl} = -0.03783 (41)

g_{Al} = -0.50123 (26)



SM comparison:
Small Higgs-boson mass

Heavy Flavour Results at the Z Pole

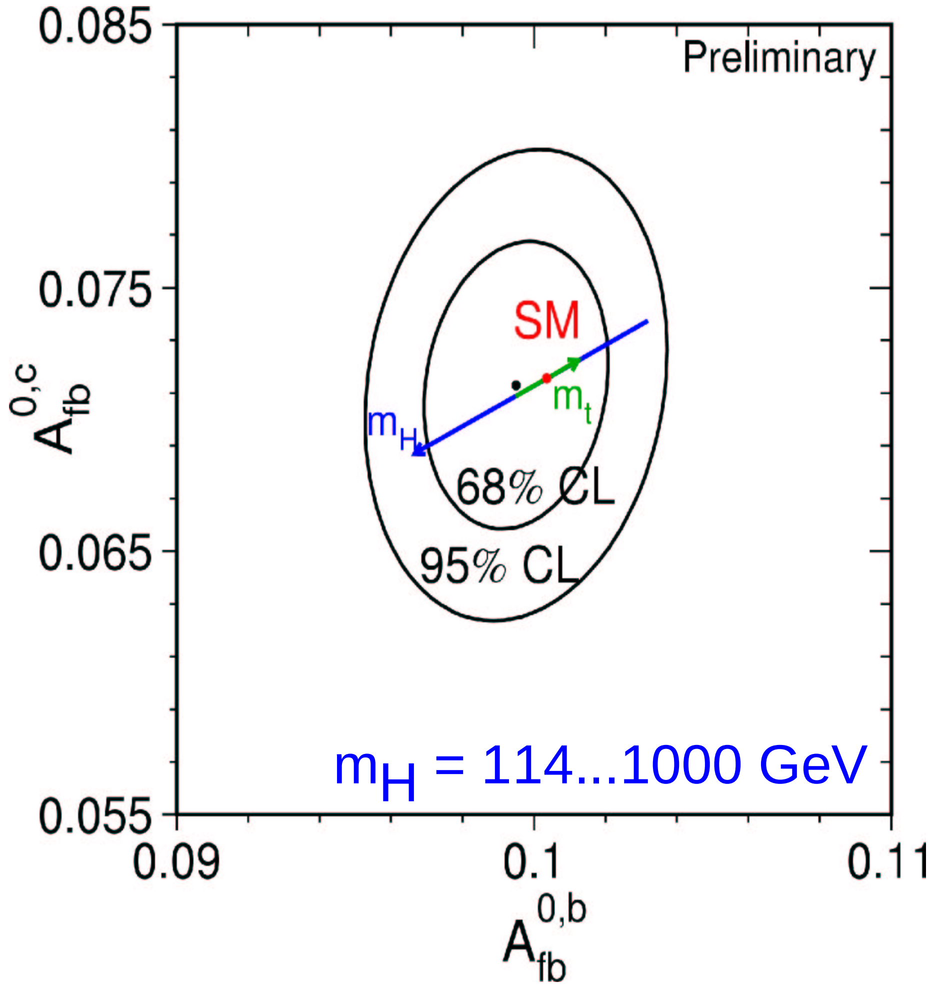


F/B asymmetries statistics dominated

All measurements very consistent

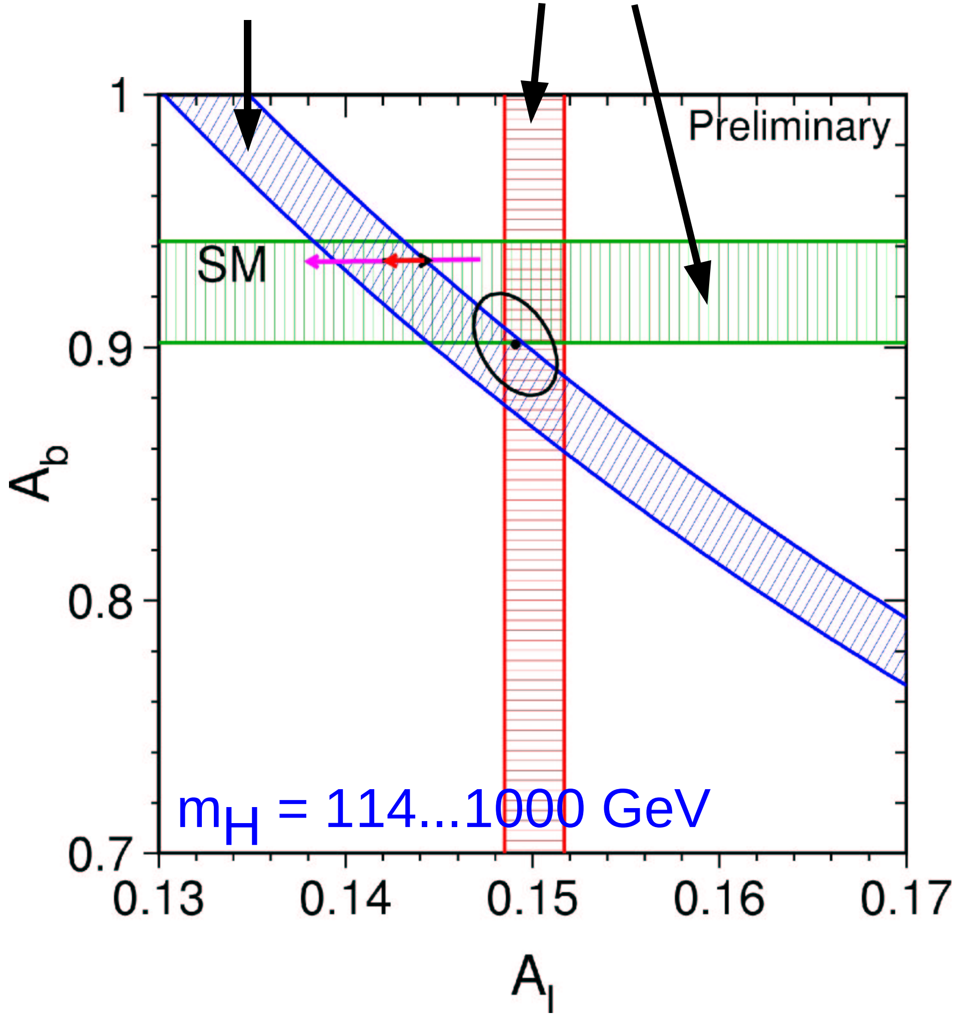
χ^2/ndof = 47.6/(105-14) low!

Heavy Flavour Results at the Z Pole



Compare with leptons:

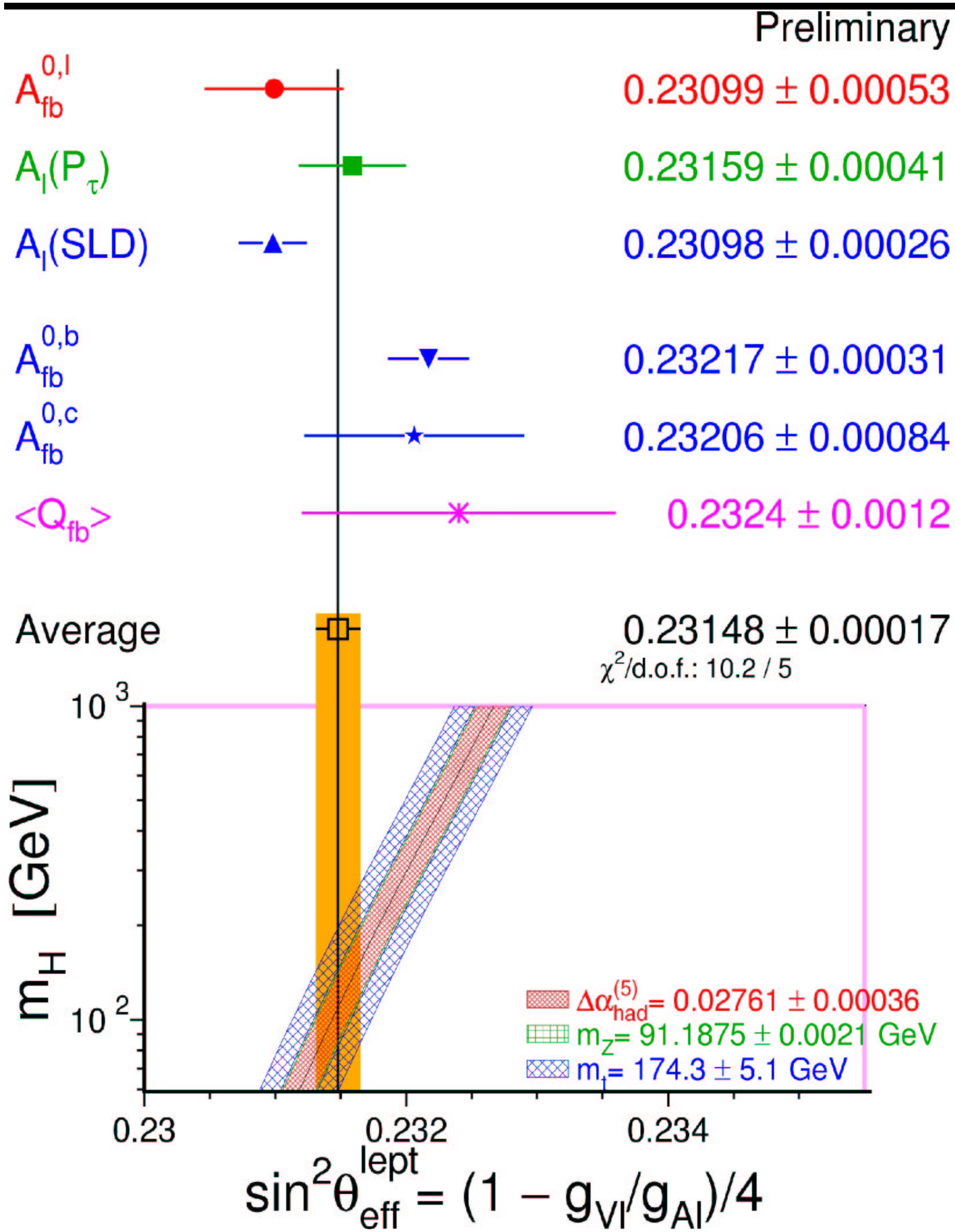
$A_{fb}(b) = \frac{3}{4} A_e A_b$



SM comparison:

High Higgs-boson mass

Comparison of all Z-Pole Asymmetries



Effective electroweak mixing angle:

$\sin^2\Theta_{eff} = 0.23148\ (17)$

$\chi^2/\text{ndof} = 10.2/5\ \ [7.0\%]$

A-posteriori observation:

0.23113 (21) leptons

0.23217 (29) hadrons

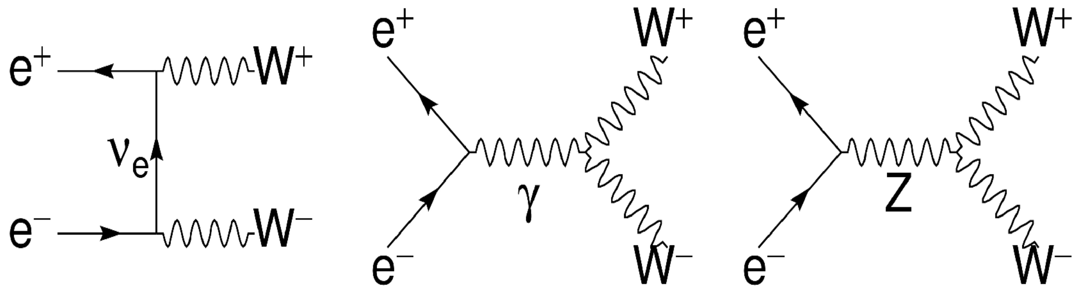
But is really:

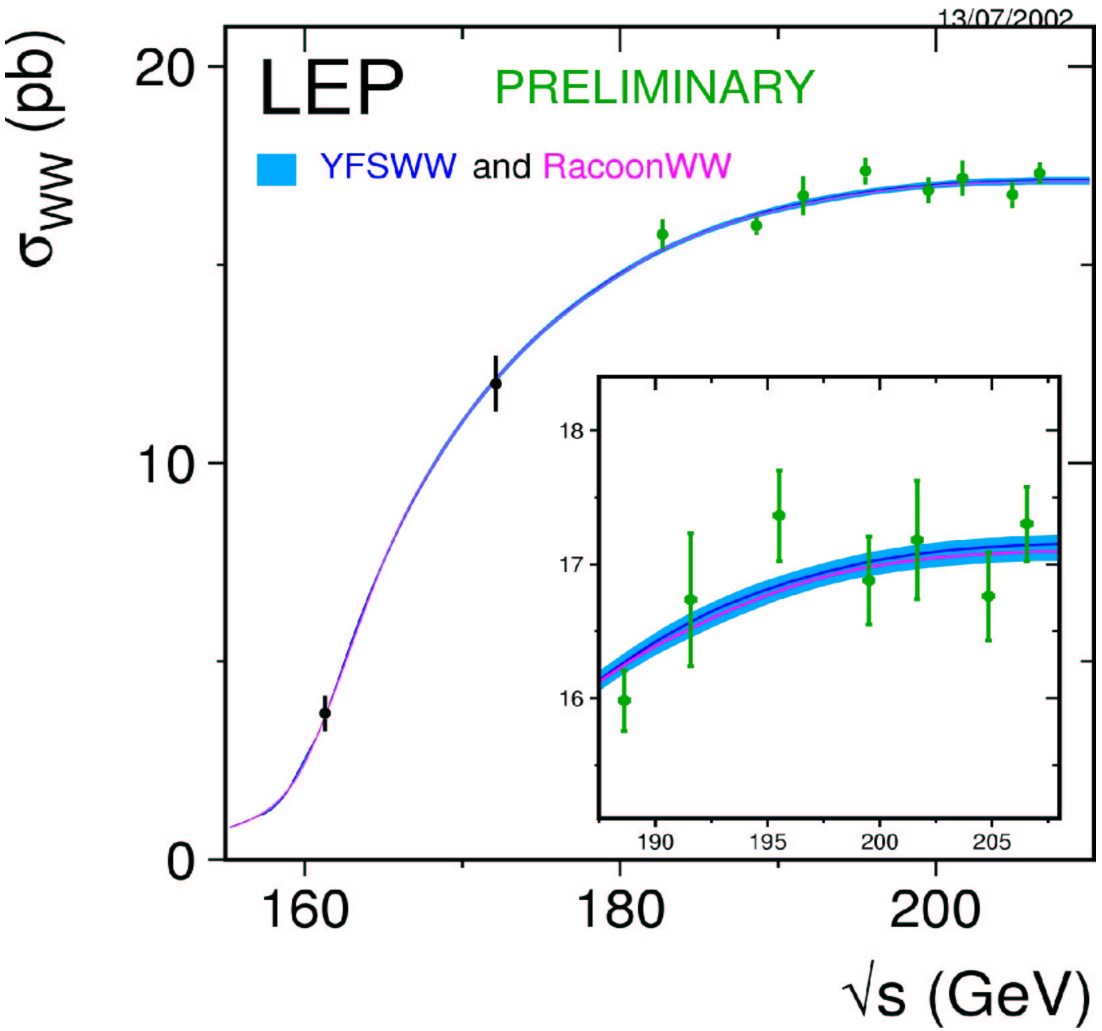
A_l(SLD) vs. $A_{fb}b$(LEP)

Both:

2.9 σ difference

W-Pair Production





Correlated average of:

$\sigma_{meas}/\sigma_{theory}$:

0.997(11) YFSWW

0.999(11) RacoonWW

Test at the 1% level!

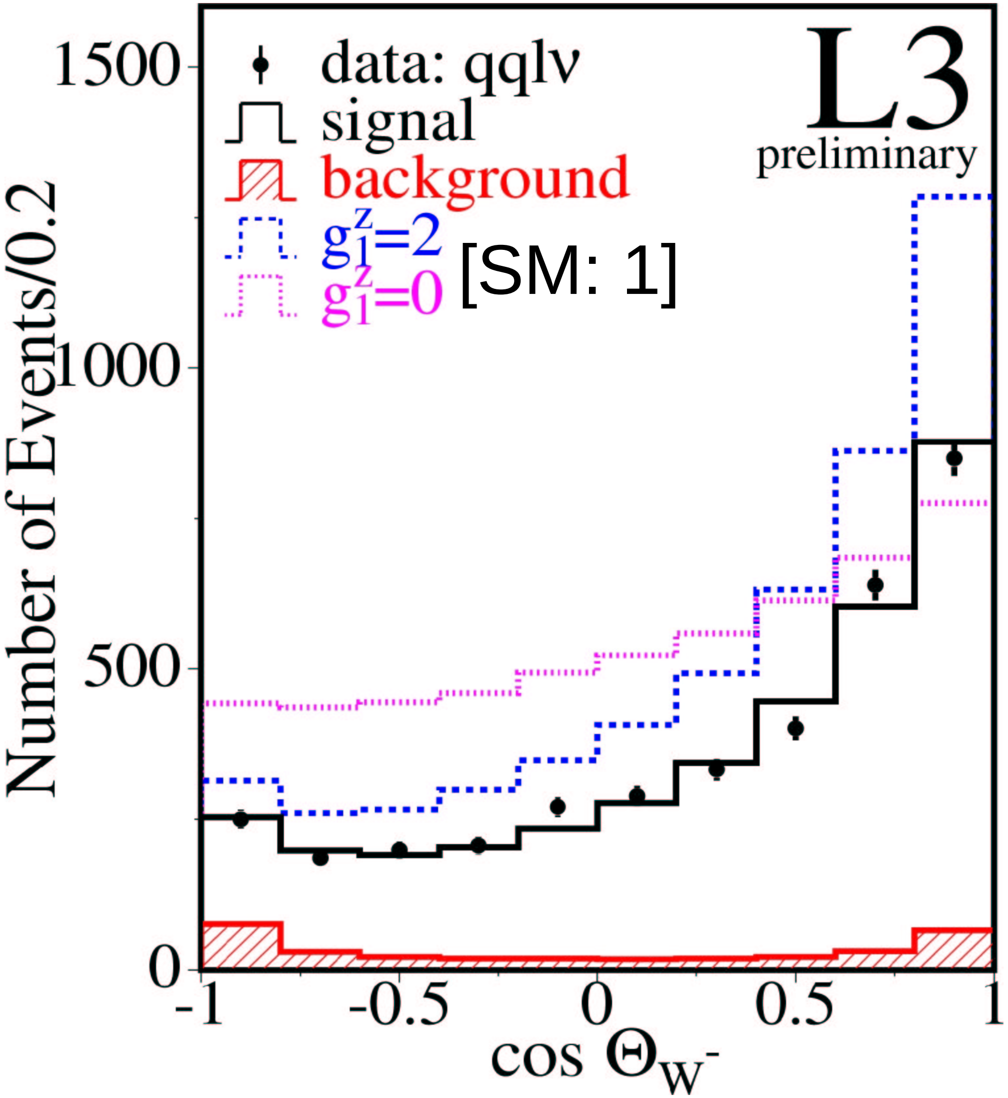
Uses $O(\alpha)$ corrections:

-2.5(0.5)% on σ_{theory}

Effect on differential cross sections and on γWW / ZWW gauge couplings?

W-Pair Production and Gauge Couplings

O(α) corrections: ~2% steeper slope



Triple gauge couplings:

g_1Z, κ_γ, λ_γ

W weak charge: g_1Z

W magnetic dipole:

$$\mu_W = \frac{e}{2M_W}\left(1+\kappa_\gamma+\lambda_\gamma\right)$$

W electric quadrupole:

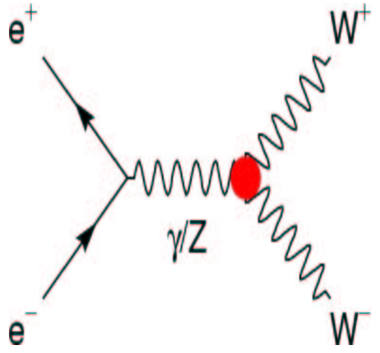
$$Q_W = -\frac{e}{M_W^2}\left(\kappa_\gamma-\lambda_\gamma\right)$$

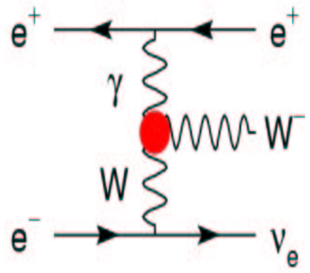
W polarisation:

Analyse decay angles

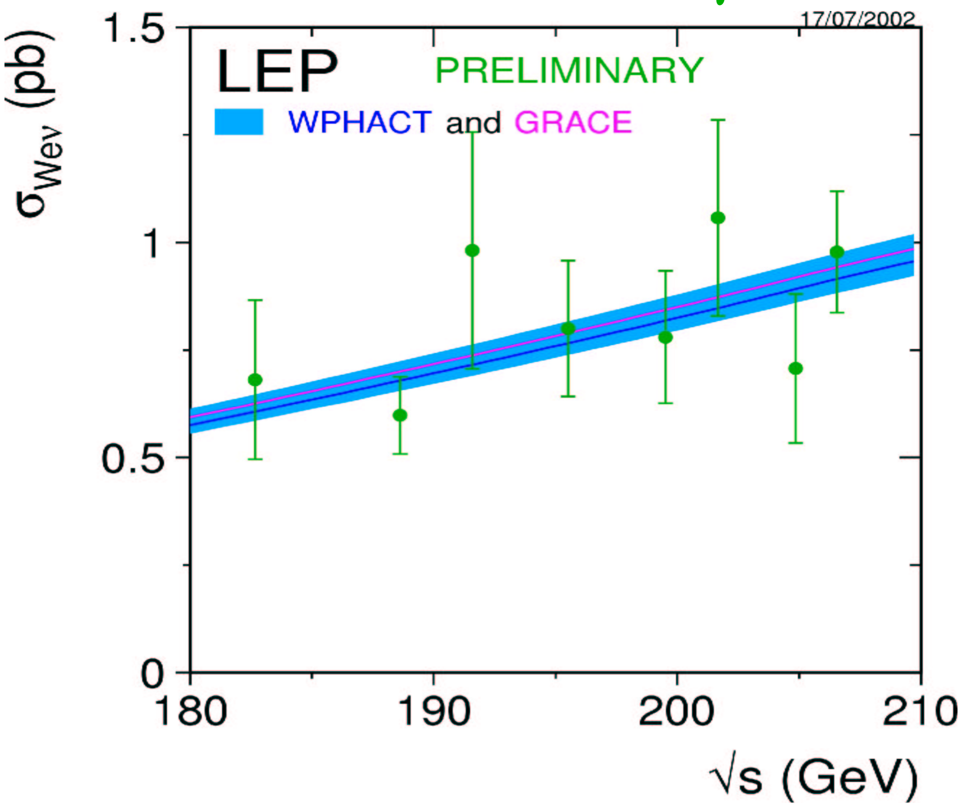
TGC analyses now based on O(α) calculations for W^+W^-

Charged Triple Gauge Couplings





Also using single-W production (esp. κ_γ)



LEP single-parameter results (68%) [SM]:

$g_1^Z = 0.998\ (24)$ [1]

$\kappa_\gamma = 0.943\ (55)$ [1]

$\lambda_\gamma = -0.020\ (24)$ [0]

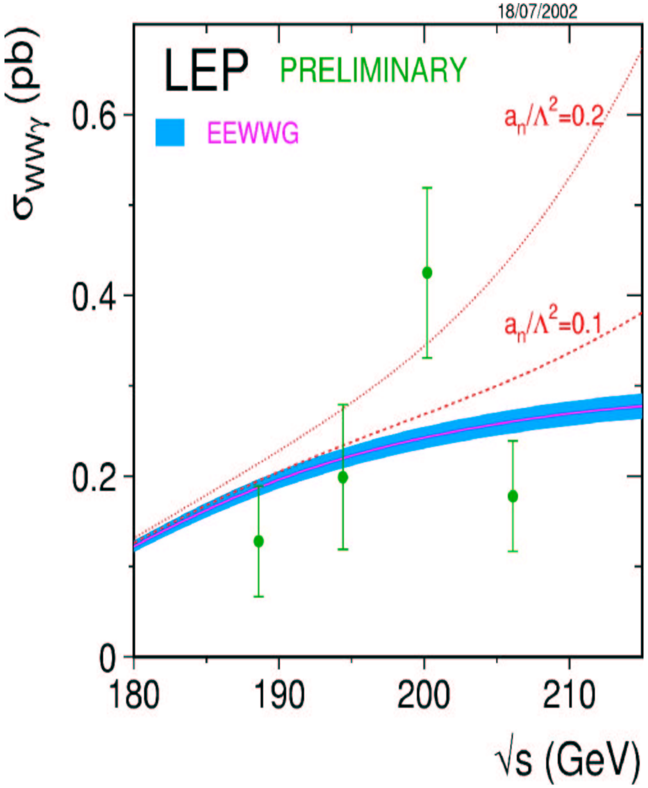
$O(\alpha)$ slope change currently used as theory uncertainty:

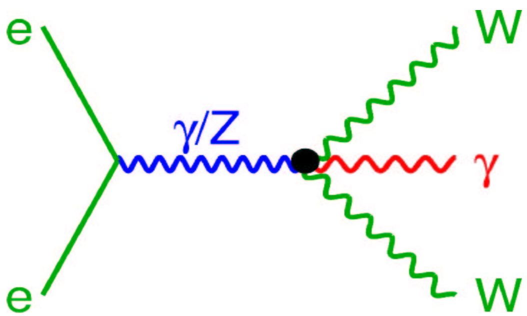
~2/3 of total error on TGCs

Ongoing studies to evaluate slope uncertainty on TGCs

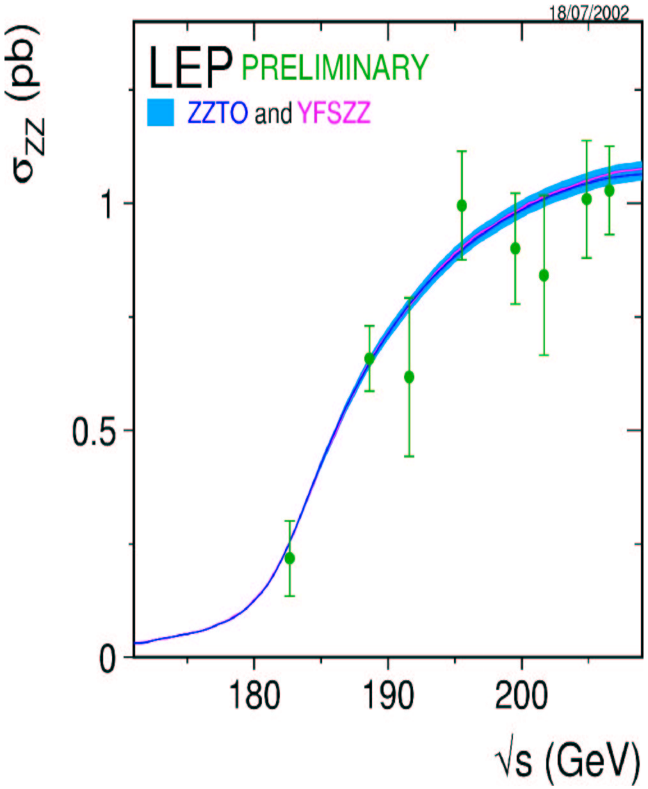
Many More Processes Studied . . .

WWγ





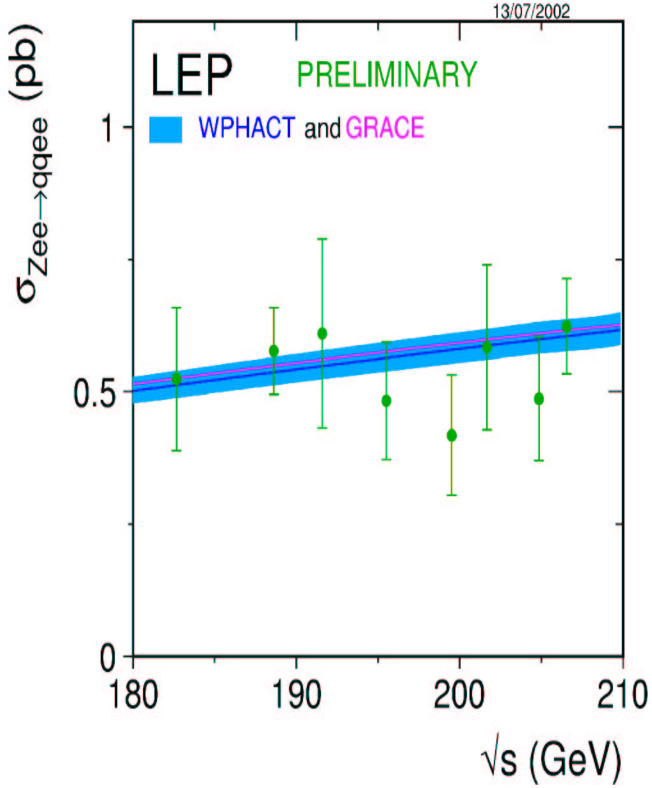
ZZ



R(meas./theory):

0.958(55) YFSZZ
0.965(56) ZZTO

Zee



R(meas./theory):

0.949(78) GRACE
0.978(80) WPHACT

Small Standard-Model processes now tested at 5%-10%

W Boson – Mass and Width

Tevatron (CDF, D∅):

$p\bar{p} \rightarrow W$, $W \rightarrow e\nu, \mu\nu$

Transverse mass M_T

Statistics

Final Run-1 results on M_W and Γ_W:

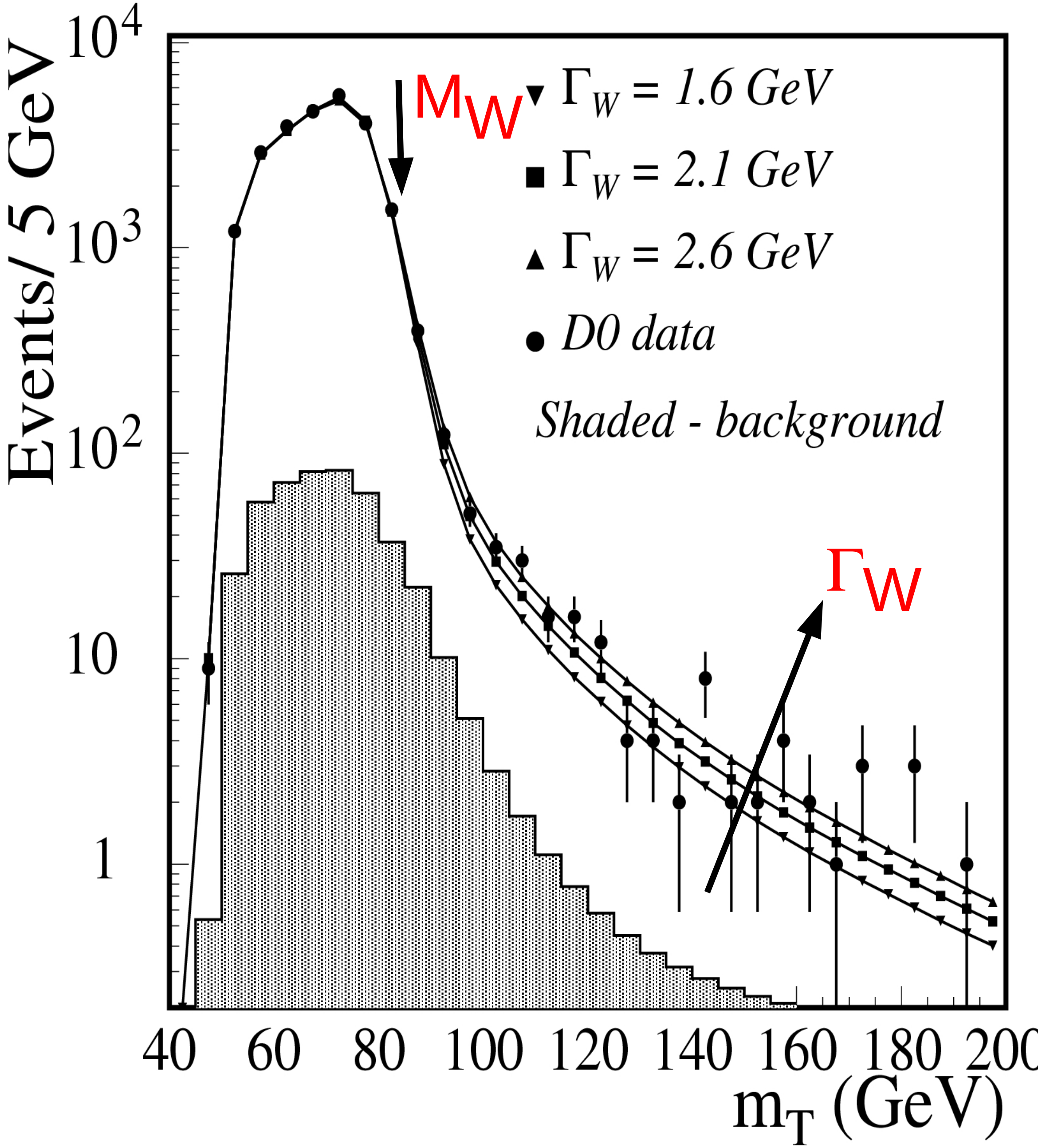
Improved treatment of correlations:

PDFs,

QED corrections in $W \rightarrow l\nu$ decays,

M_W-Γ_W influence

-33 MeV correlated



W Boson – Mass and Width

LEP-2: $e^+e^- \rightarrow W^+W^-$

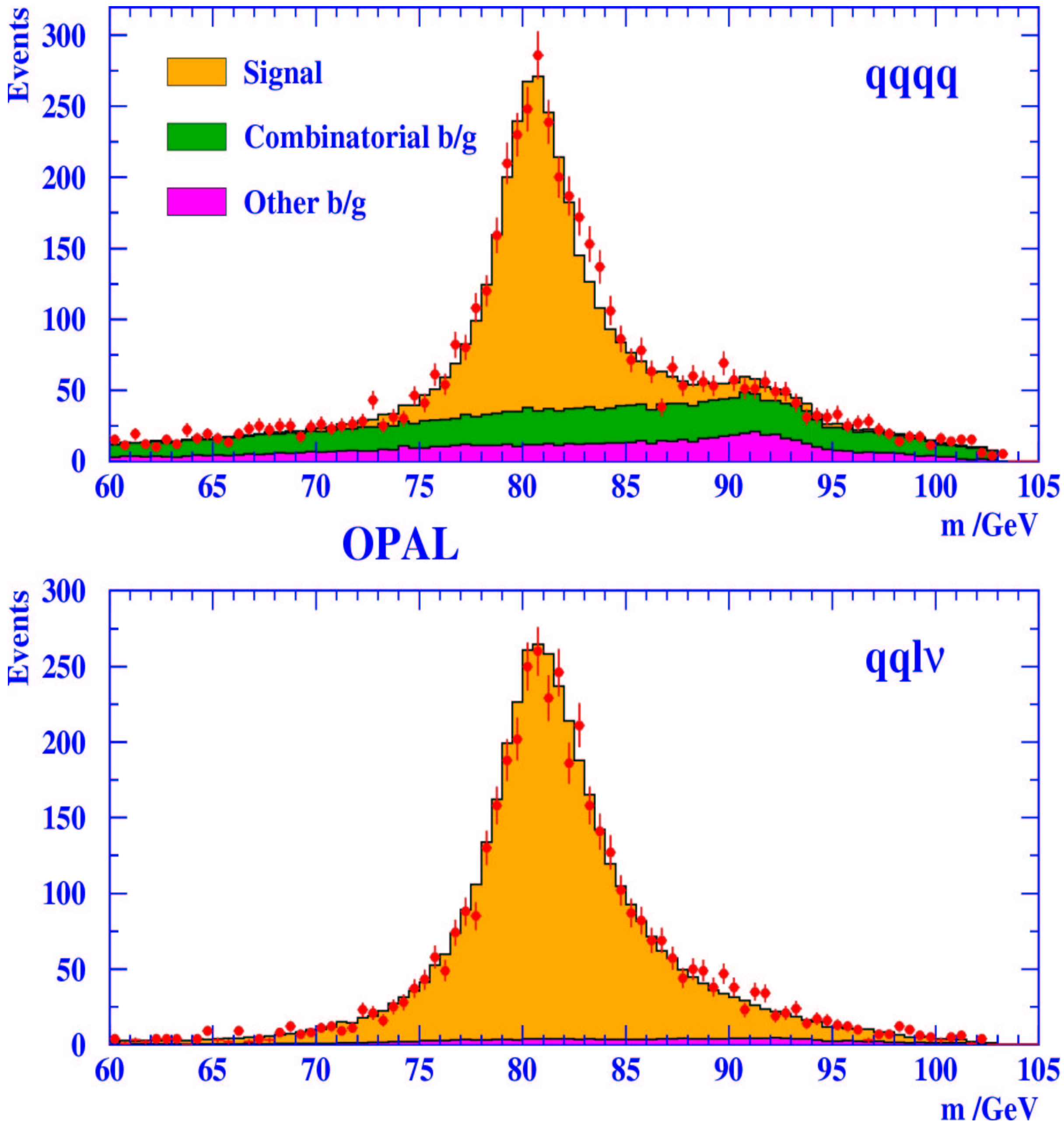
$\rightarrow$ qqqq, qqlν, lνlν

Invariant mass M_{inv}

Preliminary results

Currently large systematics in the qqqq channel:

LEP average dominated by M_W(qqlν)

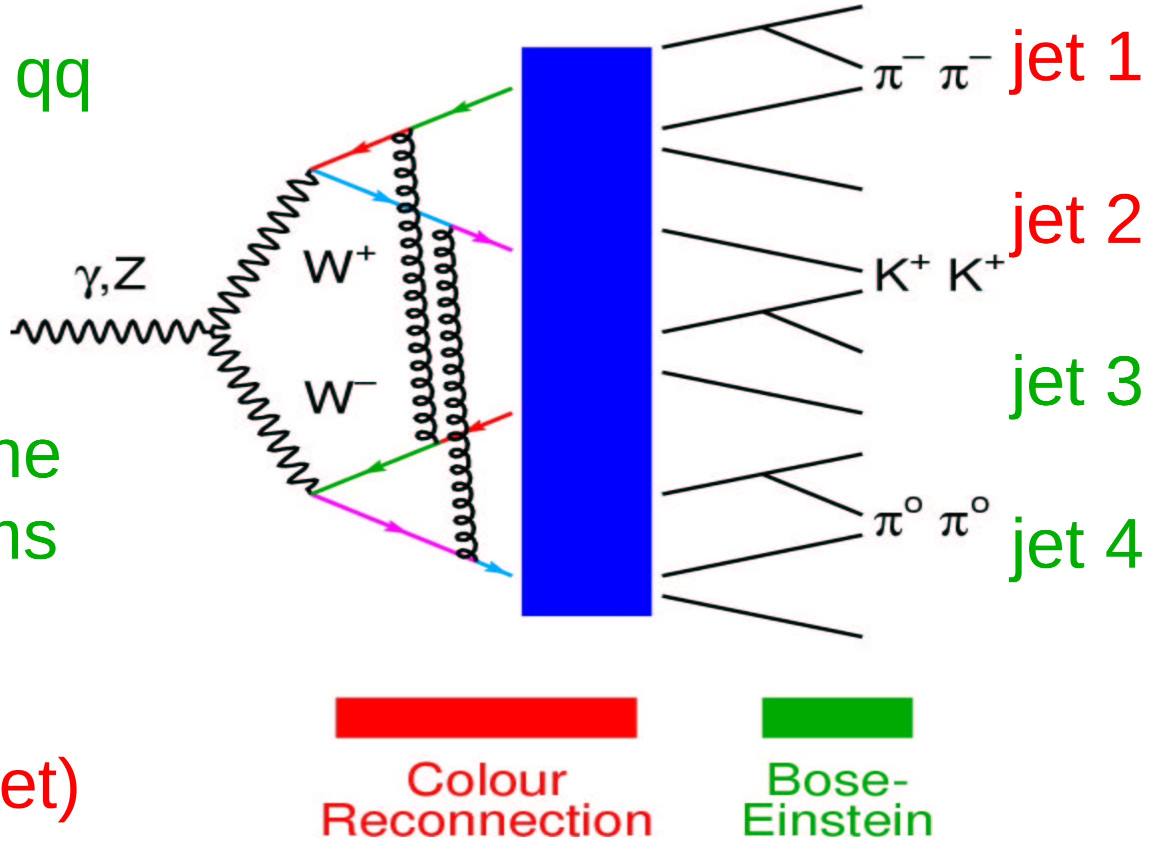


Final State Interconnection (FSI)

$e^+e^- \rightarrow W^+ W^- \rightarrow$ qq qq

$\rightarrow$ hadrons

$e^+ e^- \rightarrow$



Cross-talk between the two hadronic systems

Possible mass shift:

$M_{inv}(W) \neq M_{inv}(jet,jet)$

CR: Colour reconnection (colour flow rearrangement)

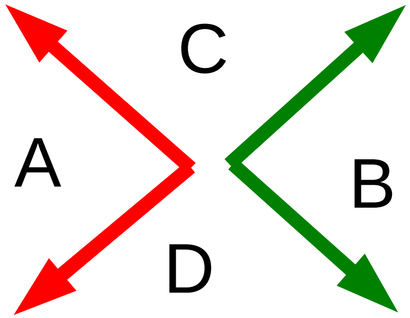
BEC: Bose-Einstein correlations (identical mesons π, K, ...)

Use data to limit possible FSI bias on M_W(qqqq)!

Colour Reconnection (CR)

LEP-2: $e^+e^- \rightarrow W^+ W^- \rightarrow qq\ qq \rightarrow$ 4 jets

Study particle flow between jets (c.f. string effect):



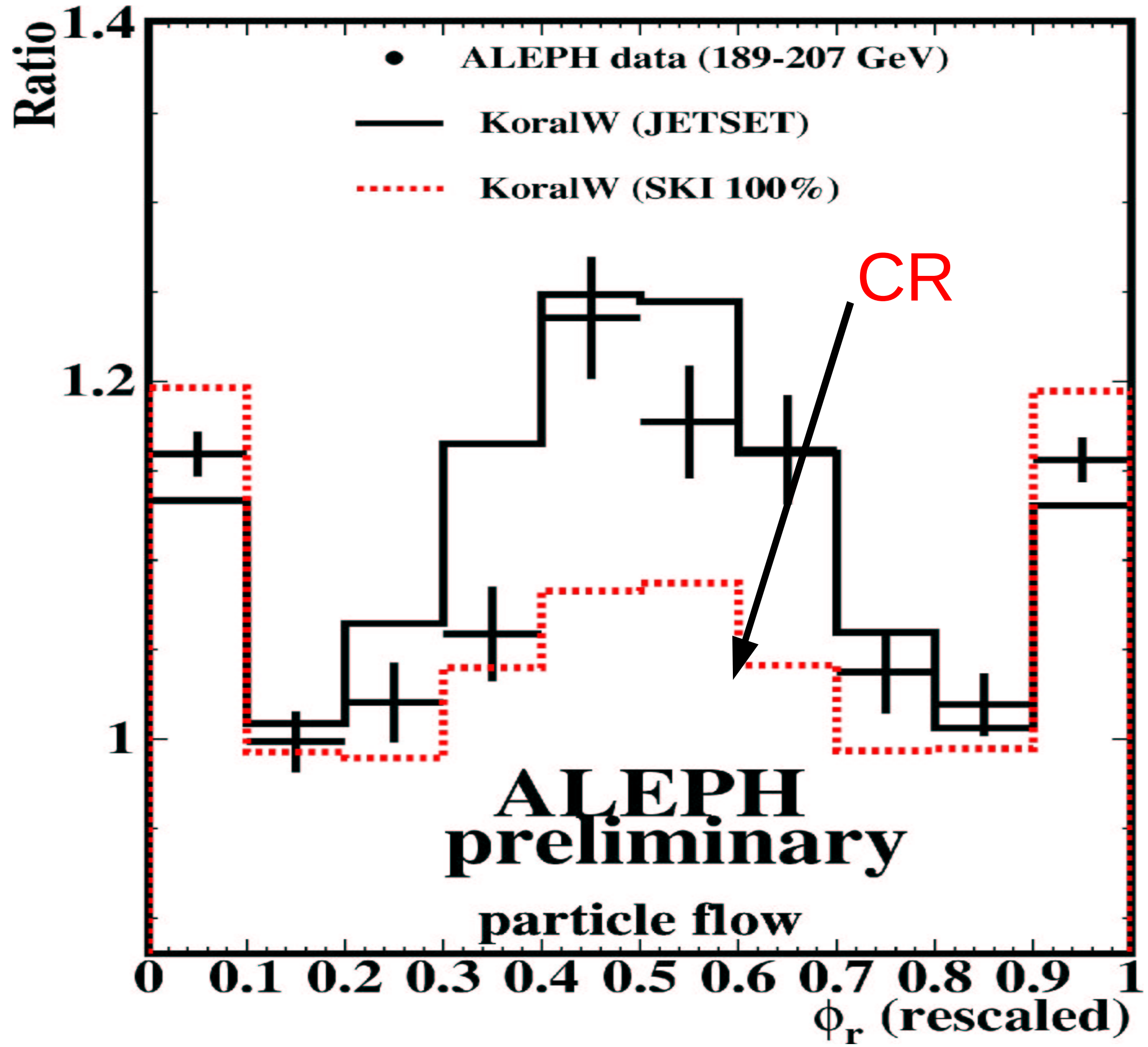
Particle flow between jets from:

- same Ws: A, B
- different Ws: C, D

along azimuth

Divide distributions:

R=(A+B) / (C+D)



Colour Reconnection (CR)

Ratio of integrated flows:

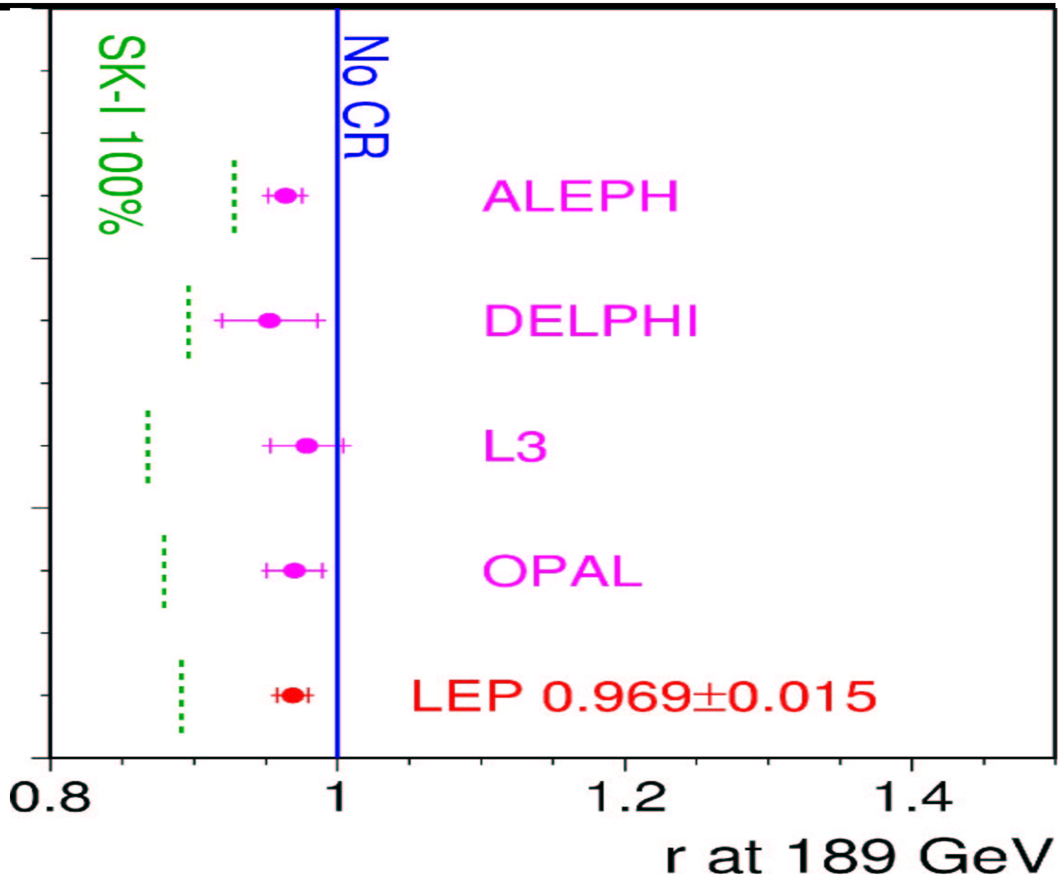
$R_N = (A+B) / (C+D)$:

Rescale:

$r = R_N(\text{data}) / R_N(\text{no CR})$

Combine LEP results:

Weighted by sensitivity to CR (e.g., SK-I model)



Hints (~2σ) for colour reconnection observed:

ΔM_W(qqqq) < 90 MeV (at 68% CL, E_{CM} averaged)

All other models (Ariadne, Herwig): smaller shifts

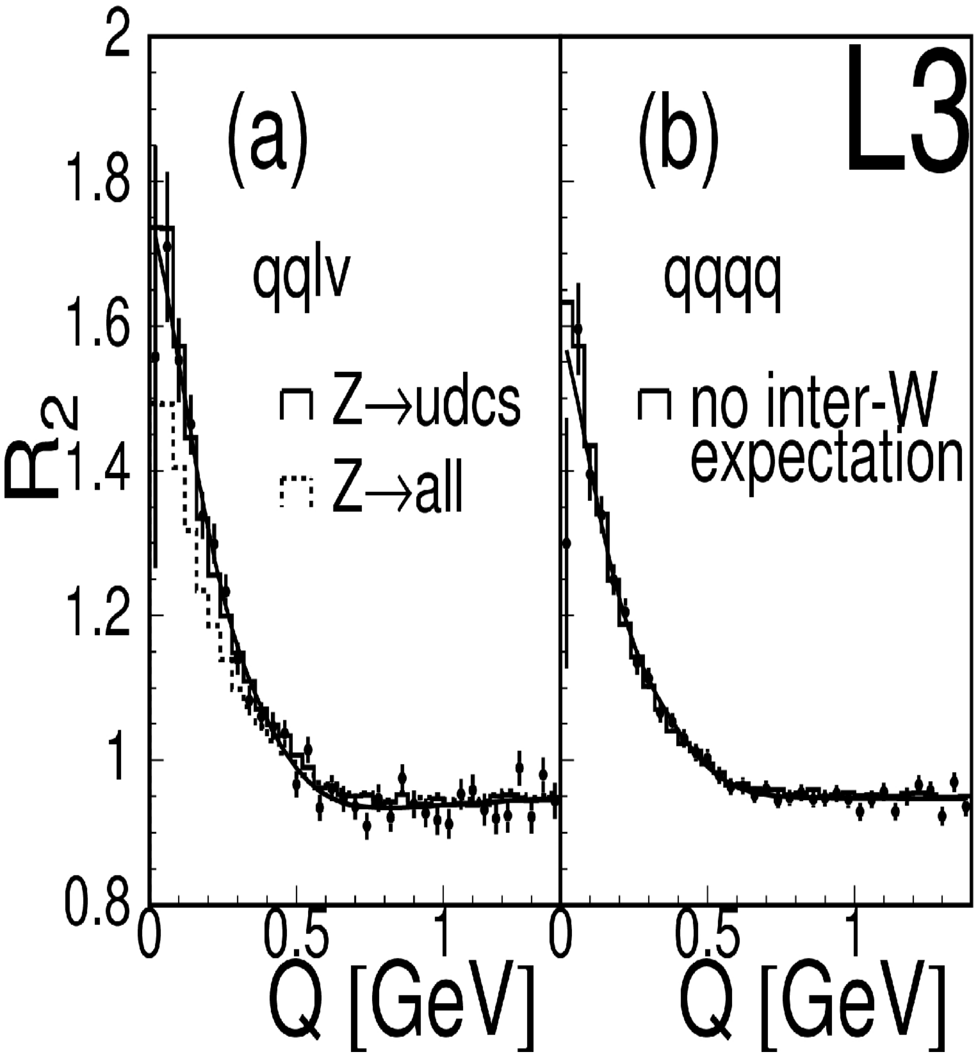
Study jet reconstructions less sensitive to CR effects:

Jet cores or high-energy particles only

Bose-Einstein Correlations (BEC)

Well known for mesons in hadronic Z decays:

Increased density of pairs at low 4-mom. difference Q



Single heavy bosons:

W=Z (for light quarks)

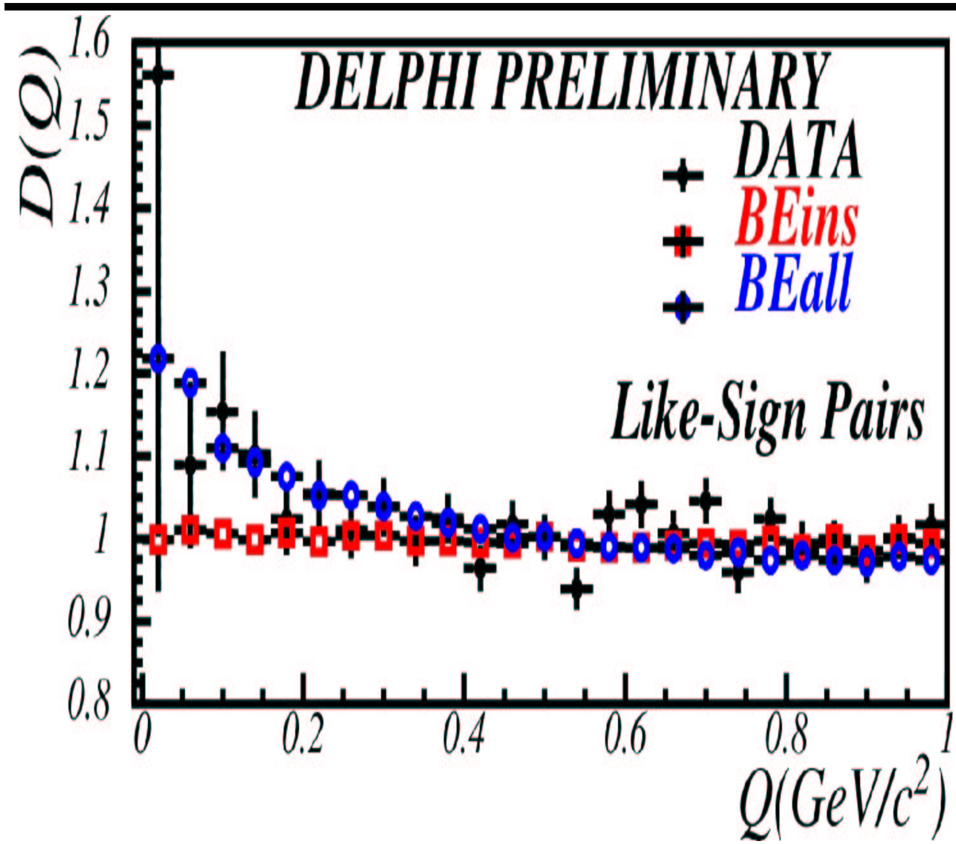
W-pairs: W W → qq qq

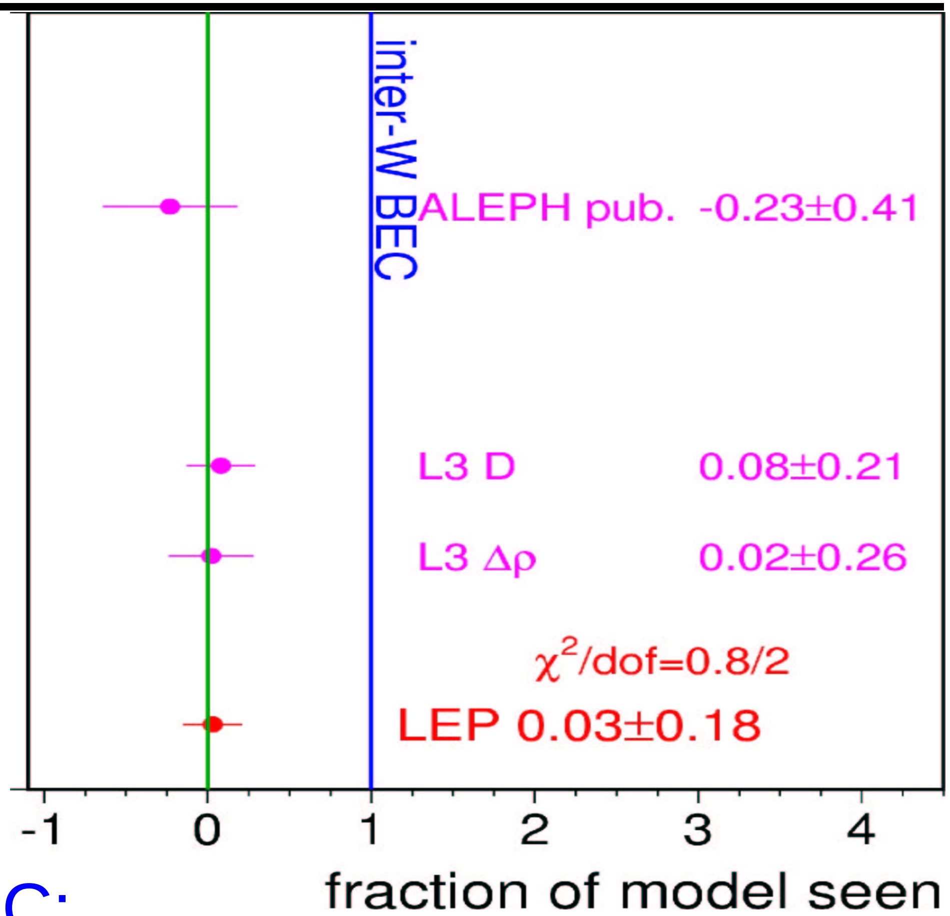
E.g., divide out BEC effects from single Ws:

=> D(Q): Sensitive only to inter-W BEC

Only those potentially affect the W-mass reconstruction

Bose-Einstein Correlations (BEC)





No clear evidence for inter-W BEC:

(3±18)% of model prediction seen

ΔM_W(qqqq) < 10 MeV (at 68% CL) for this model

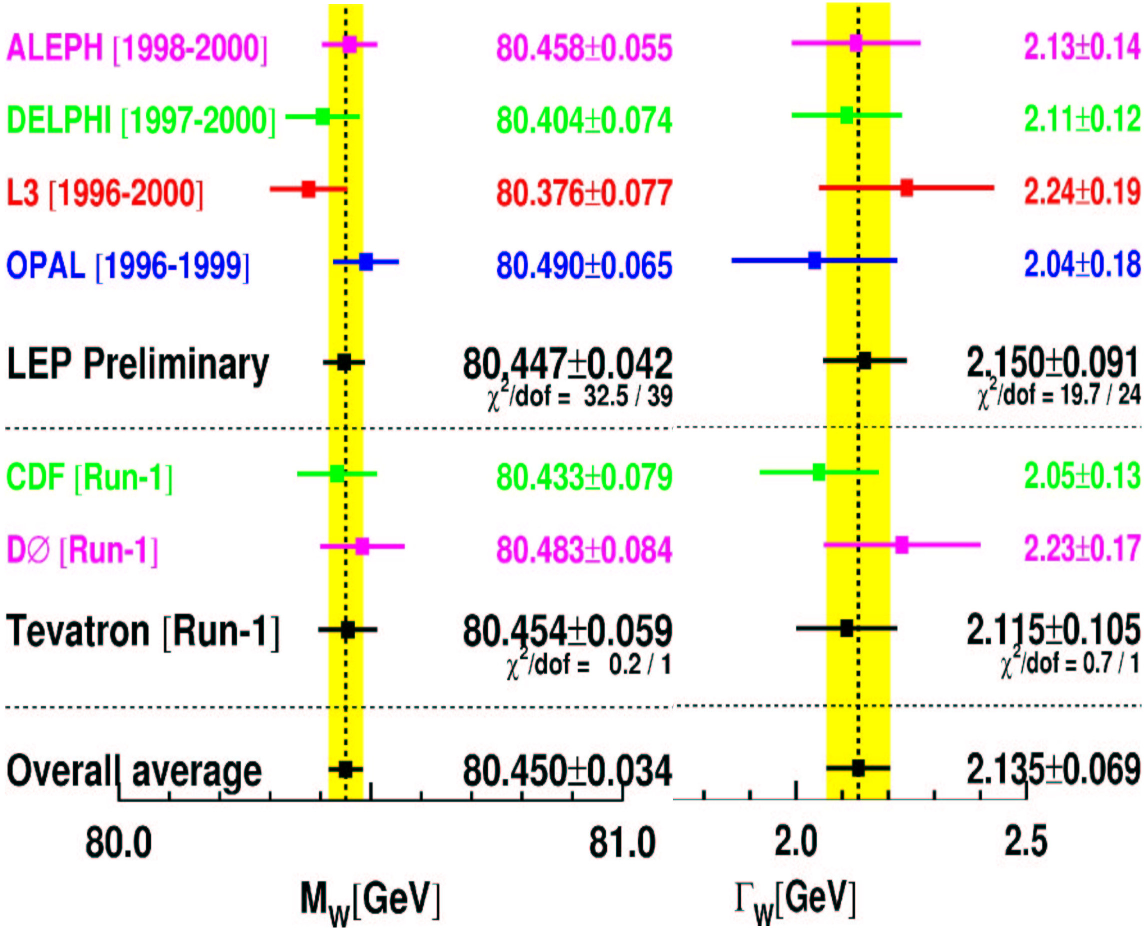
Other BEC models need to be studied:

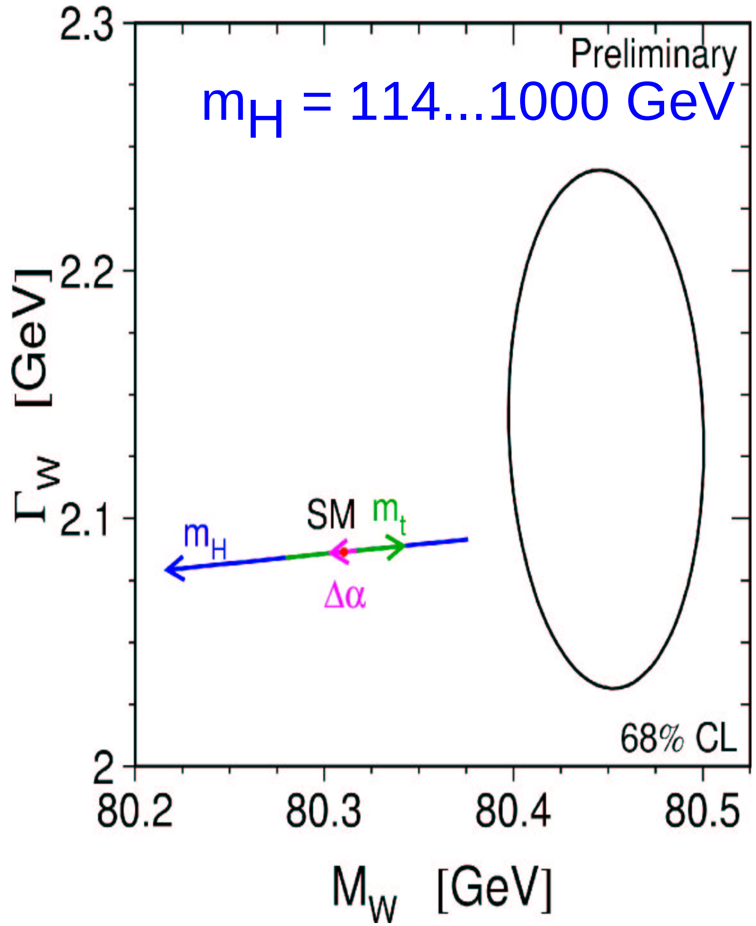
Current error on M_W(qqqq) due to BEC is 35 MeV

W Boson – Mass and Width

Mass difference (calculated without FSI errors):

$M_W(qqqq) - M_W(ql\nu) = 9 \pm 44$ MeV





Very good agreement between the experiments

SM comparison:
Small Higgs-boson mass

Global Standard-Model Analysis

SM: Each observable calculated as a function of:

$\Delta\alpha_{had}$, $\alpha_s(M_Z)$, M_Z, M_{top}, M_{Higgs}

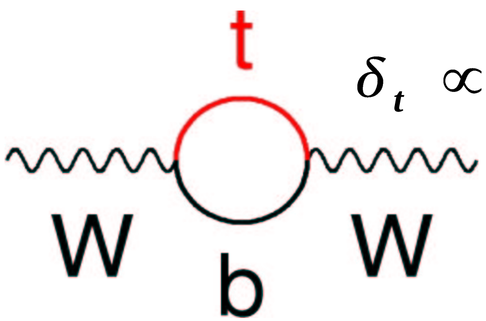
$\Delta\alpha_{had}$: hadronic vacuum polarisation [0.02761(36)]

$\alpha_s(M_Z)$: given by Γ_{had} and related observables

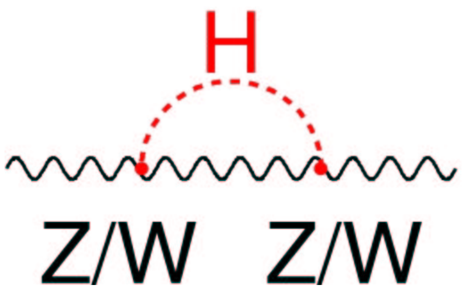
M_Z: fixed by LEP-1 lineshape

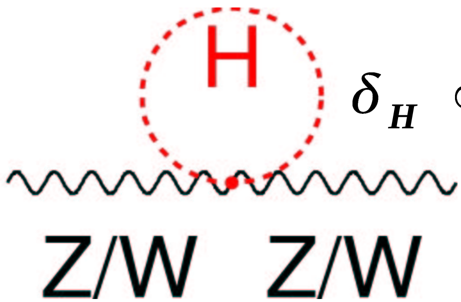
Precision requires 1st and 2nd order electroweak and mixed radiative correction calculations (QED to 3rd)

M_{top}, M_{Higgs} enter through electroweak corrections!



$$\delta_t \propto M_t^2$$





$$\delta_H \propto \ln \frac{M_{Higgs}}{M_W}$$

Calculations by programs TOPAZ0 and ZFITTER

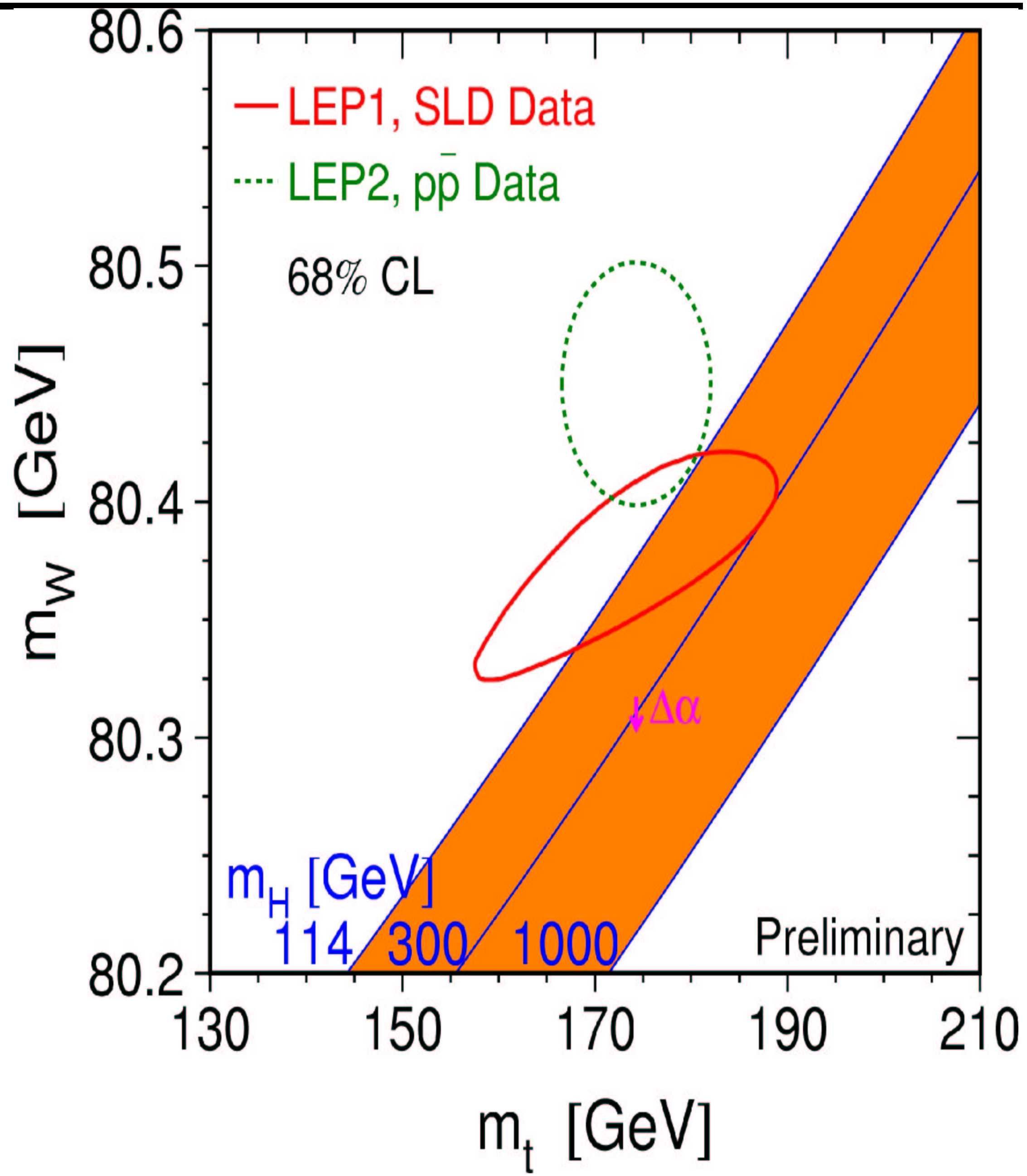
Prediction of Heavy Particle Masses W and top

Z-Pole measurements:
- Constrain electroweak radiative corrections
- Allows to predict M_W and M_{top} within SM

Direct measurements:
- TEVATRON and LEP2

Good agreement
- Successful SM test

Both data sets prefer a light Higgs boson



Global Standard-Model Analysis

Fit to all data:

χ^2/ndof = 29.7/15 (1.3%)

Largest χ^2 contribution:

$\sin^2\Theta_W$(NuTeV, $\rho=\rho_{SM}$)

Spread of $\sin^2\Theta_{eff}$

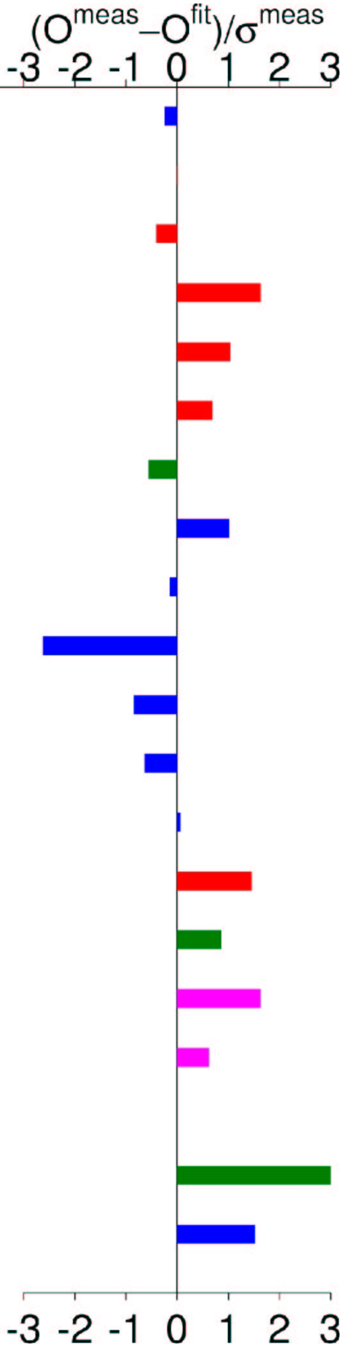
Fit without NuTeV:

χ^2/ndof = 20.5/14 (11.4%)

Fit result is robust:

Fitted parameters almost unchanged!

	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-0.24
m_Z [GeV]	91.1875 ± 0.0021	0.00
Γ_Z [GeV]	2.4952 ± 0.0023	-0.41
σ^0_{had} [nb]	41.540 ± 0.037	1.63
R_l	20.767 ± 0.025	1.04
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.68
$A_l(P_\tau)$	0.1465 ± 0.0032	-0.55
R_b	0.21644 ± 0.00065	1.01
R_c	0.1718 ± 0.0031	-0.15
$A^{0,b}_{fb}$	0.0995 ± 0.0017	-2.62
$A^{0,c}_{fb}$	0.0713 ± 0.0036	-0.84
A_b	0.922 ± 0.020	-0.64
A_c	0.670 ± 0.026	0.06
A_l(SLD)	0.1513 ± 0.0021	1.46
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.87
m_W [GeV]	80.449 ± 0.034	1.62
Γ_W [GeV]	2.136 ± 0.069	0.62
m_t [GeV]	174.3 ± 5.1	0.00
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	3.00
Q_W(Cs)	-72.18 ± 0.46	1.52



Constraints on the SM Higgs-Boson Mass

$M_{Higgs} = 81^{+52}_{-33}$ GeV

Incl. theory uncertainty:

M_{Higgs} < 193 GeV (95%CL)

Strongly correlated:

+0.7 with fitted M_{top}

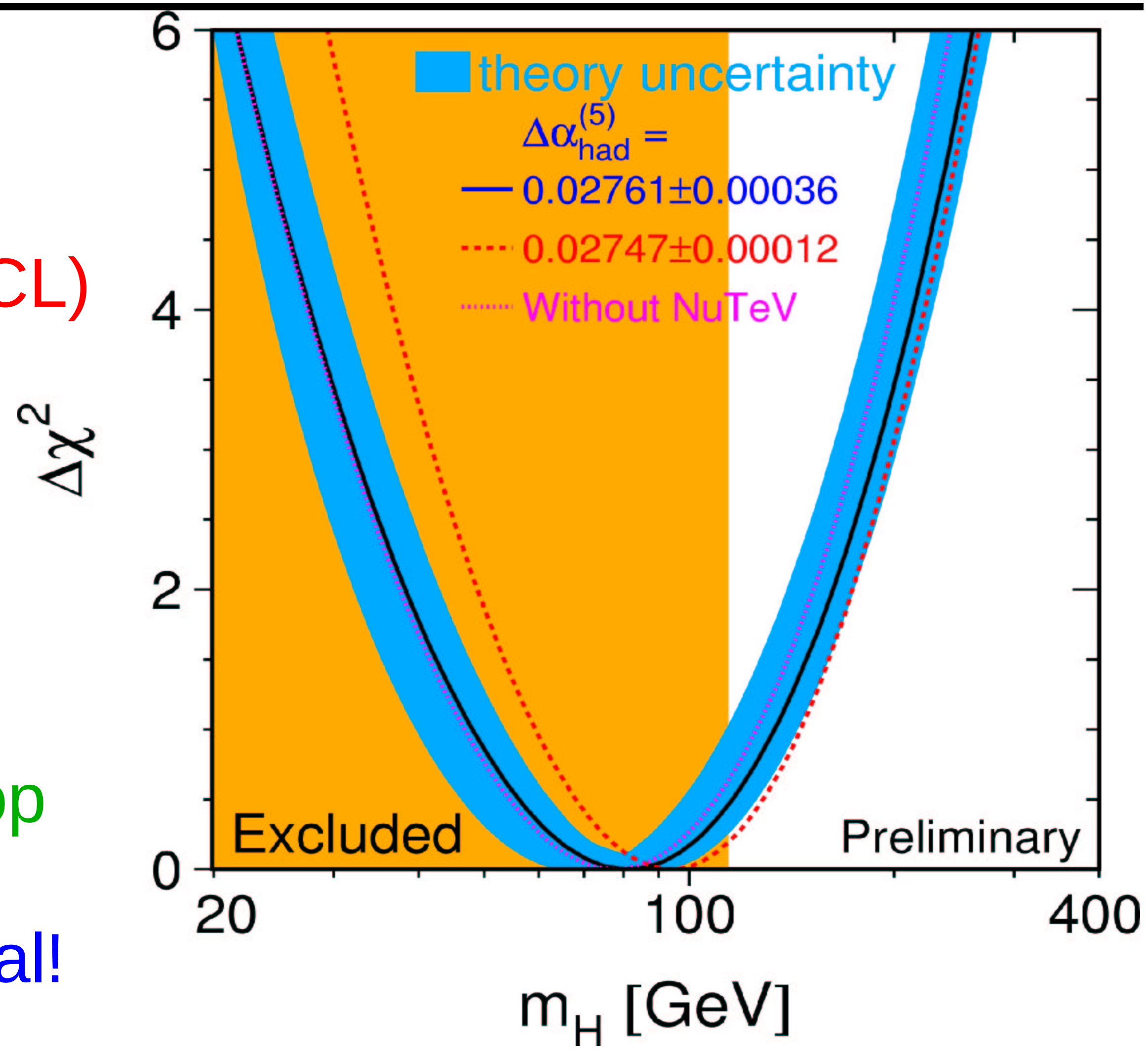
35% shift in M_{Higgs} for

5 GeV shift in meas. M_{top}

M_{top} measurement crucial!

Direct Higgs search limit:

No contradiction!



Theory uncertainty:

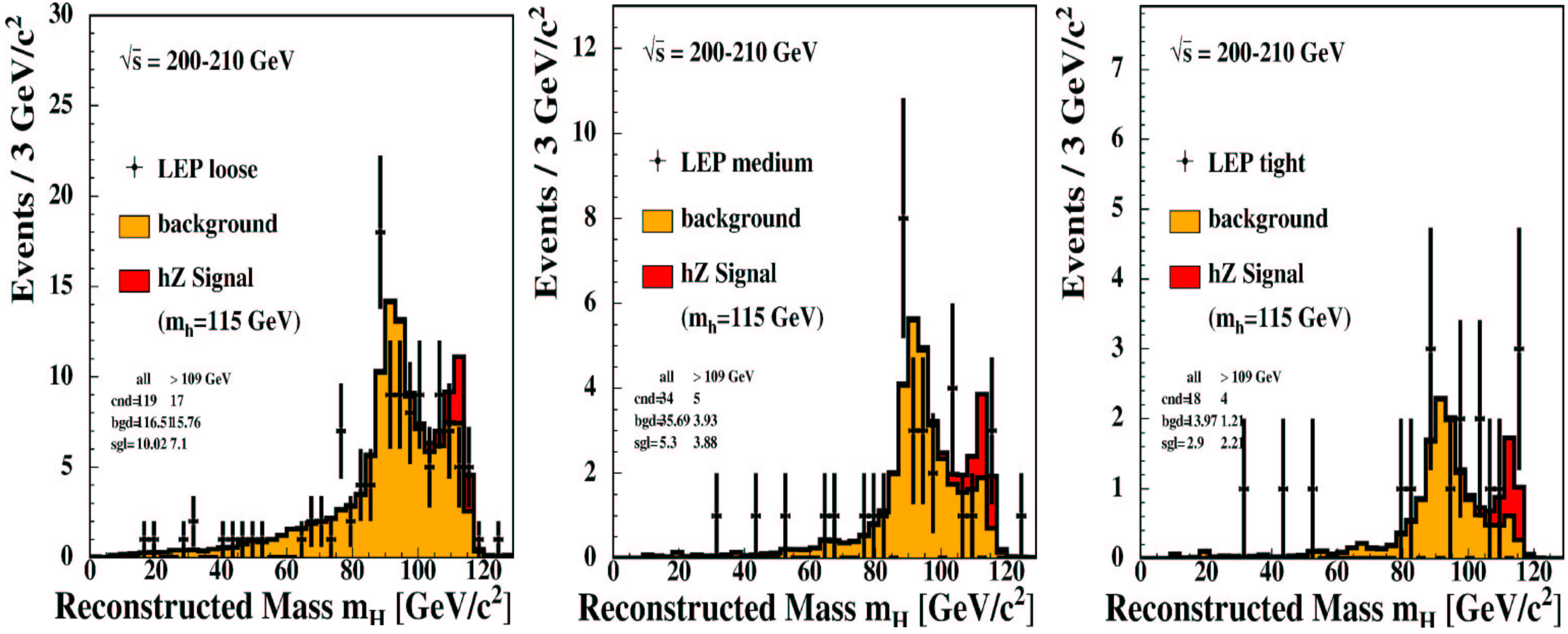
Need two-loop

calculations for $\sin^2\Theta_{eff}$

Direct Search for the SM Higgs Boson

LEP-2: mainly $e^+e^- \to Z\,H \to f\,f\,b\,b$

Selection (mass independent) and mass reconstruction

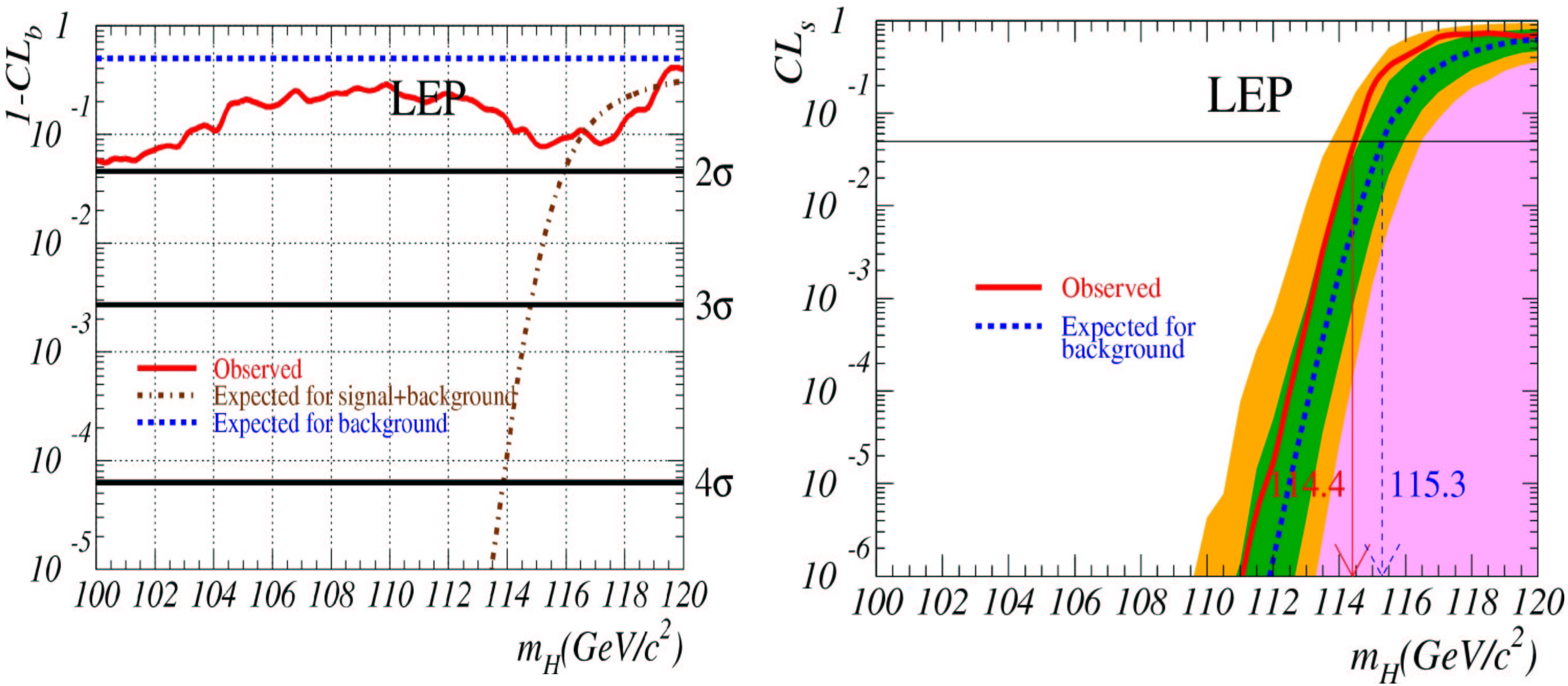


Full statistical analysis for search based on:

Global discriminating variable and reconstructed mass

Direct Search for the SM Higgs Boson

Confidence level for background and signal:



1.7 σ excess (P=8%) over expected SM background

One experiment (ALEPH, 2.8-3.0 σ), one channel (qqbb)

Final LEP-2 SM Higgs-boson mass limit (95% C.L.):

M_{Higgs} > 114.4 GeV (expected limit: 115.3 GeV)

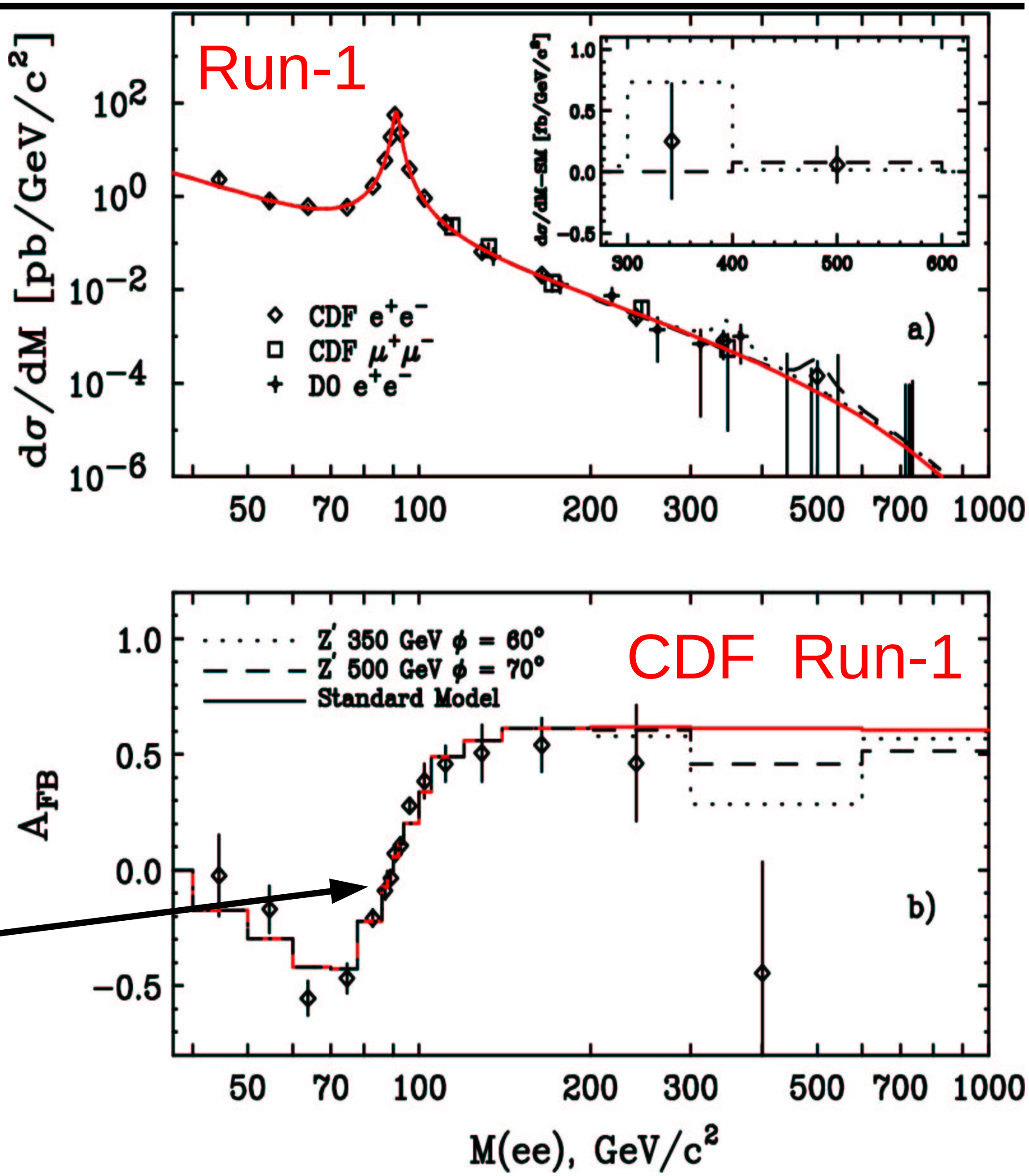
Since 2001: TEVATRON

Run-2 for CDF and D∅:

1.96 TeV $p\,\overline{p}$ cm energy

Expect:

- 15 fb^{-1} / experiment
- M_W to 25 MeV
- M_{top} to 2.5 GeV
- => 30% M_H prediction
- Gauge couplings,
- Γ_W , Γ_t ,
- $\sin^2\Theta_{eff}(A_{FB}\ Z \rightarrow l^+l^-)$



Need precise PDFs, MEs, with uncertainties

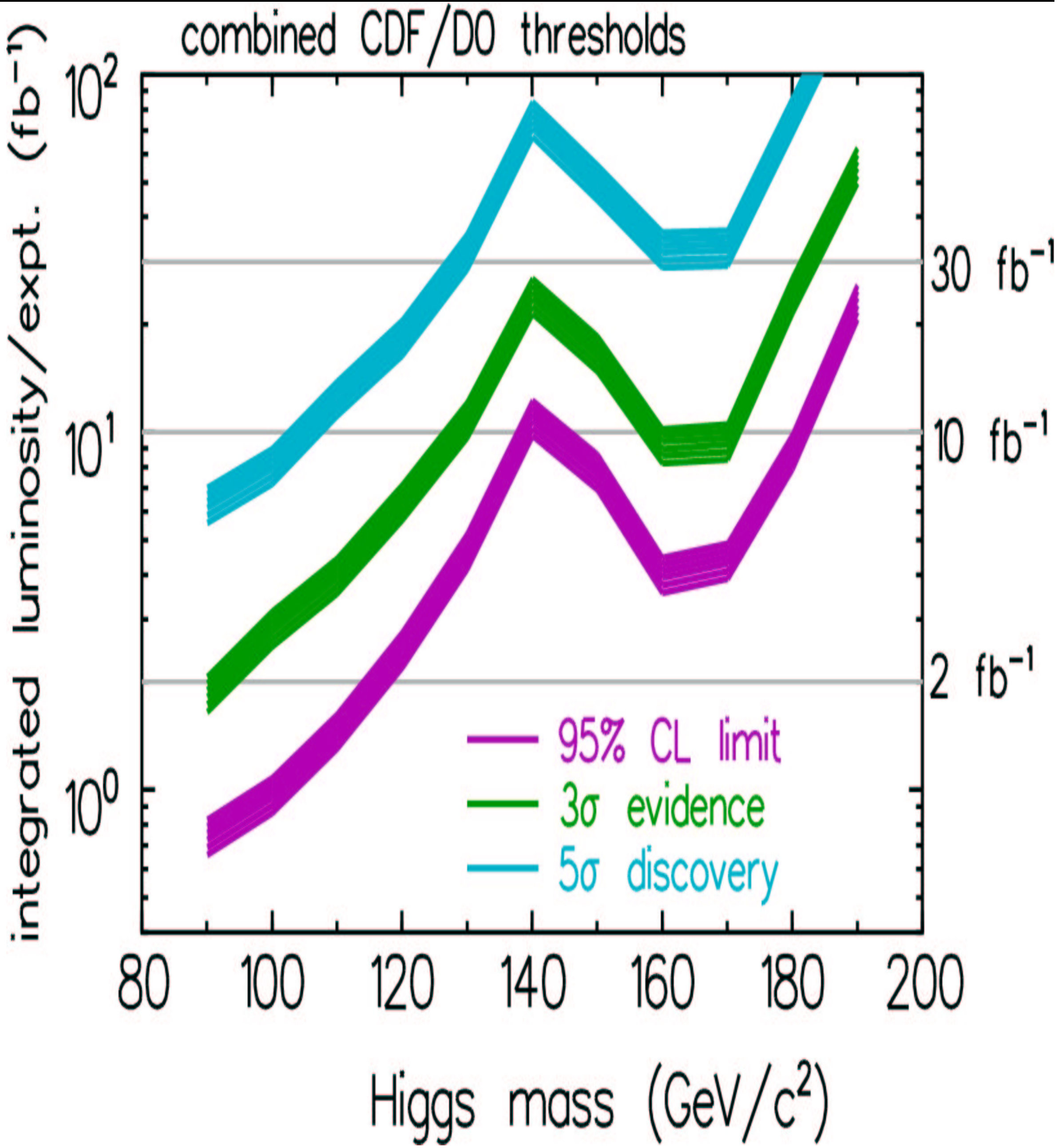
Future Higgs Search

TEVATRON:
Search in the most probable mass range

Run-2a with 2fb^{-1}:
95% C.L. exclusion limit up to 115 GeV

Run-2b with 15fb^{-1}:
3σ evidence up to 135 GeV

LHC (ATLAS, CMS):
Search in the full mass range



Conclusion

NuTeV, SLD, Tevatron, LEP, g-2, BES, . . .

- Wealth of high-precision measurements
- Many with high sensitivity to radiative corrections

Most measurements agree with expectations:

- Successful test of SM electroweak loops
- But have two 3-sigma effects:
  - Spread in $\sin^2\Theta_{eff}$ and NuTeV's R_- result

Future:

- Precise theoretical calculations - incl. uncertainties
- Improved measurements, esp. top, W, $\Delta\alpha_{had}$, $\sin^2\Theta_{eff}$

Tevatron, LHC, LC, . . .

- Find a Higgs boson . . . and study its properties!