
Electroweak Physics

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Outline

New precision measurements

Muon anomalous magnetic moment

Neutrino-nucleon scattering

Z and W bosons: masses and couplings

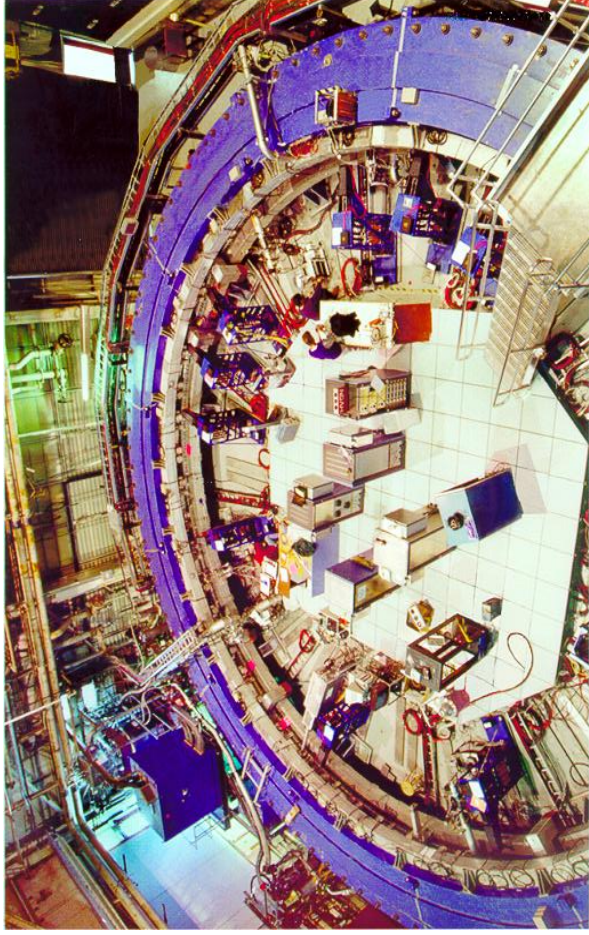
Tests of the electroweak Standard Model

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.

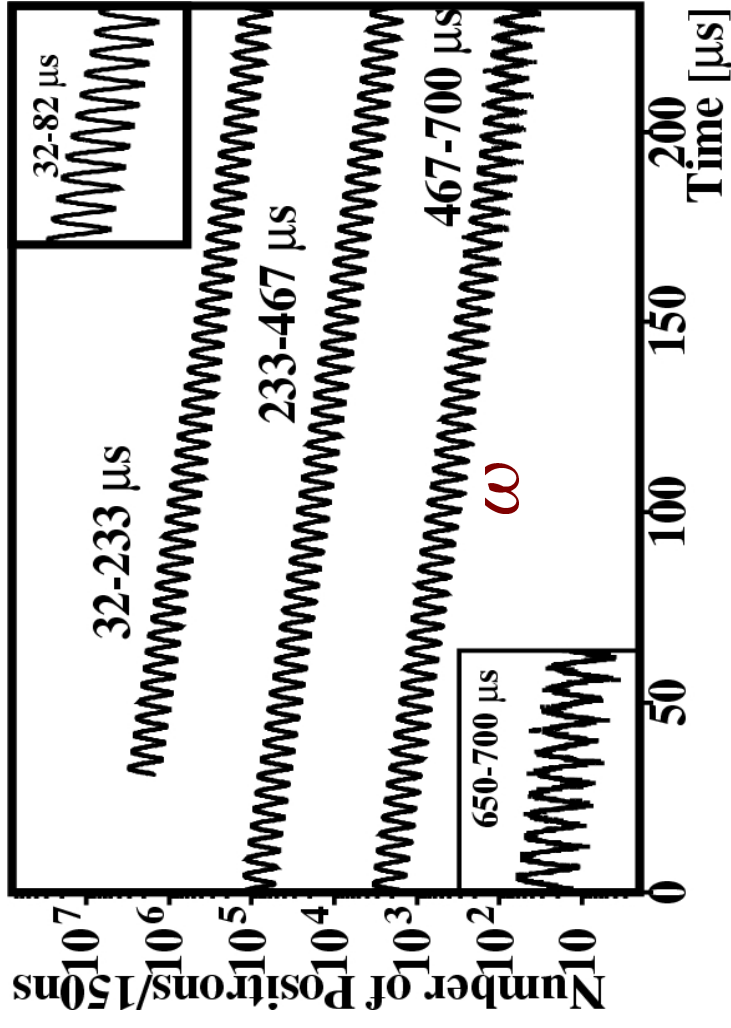
Muon Anomalous Magnetic Moment



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

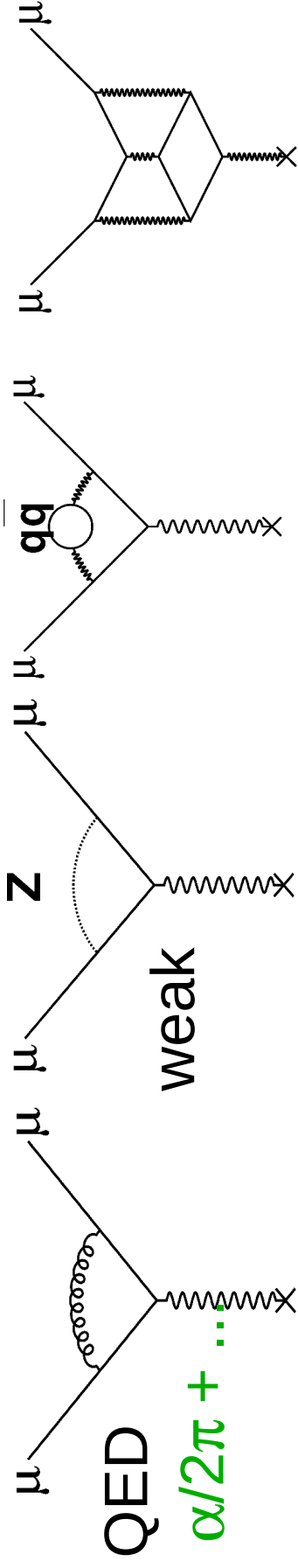
Experimental result (1999 data): $10^{10} a = 11\ 659\ 202\ (15)$

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

Difference of $2.6\ \sigma!$

Muon Anomalous Magnetic Moment

SM calculation of all contributions revisited:



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

Hadronic vacuum polarisation:

1st order (estimates range from 692 to 699)

2nd order

$$692 (7)$$

$$-10 (1)$$

$$+8 (2)$$

Hadronic light-by-light term (sign flip!)

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

Difference reduced to 1.6σ

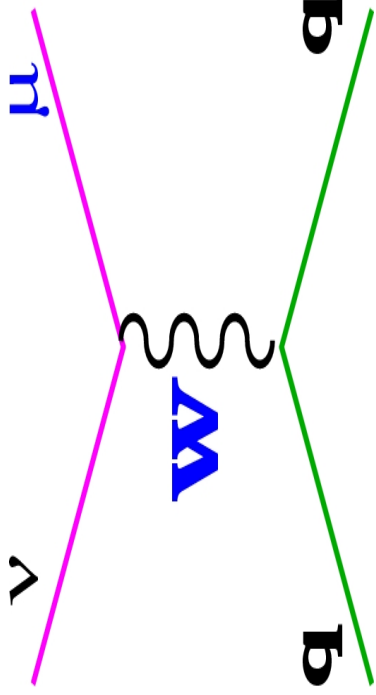
Expect factor three improvement with 2000+2001 data!

$$\text{Fresh BNL result (+2000 data): } 10^{10}a = 11\,659 \text{ --- } (\square)$$

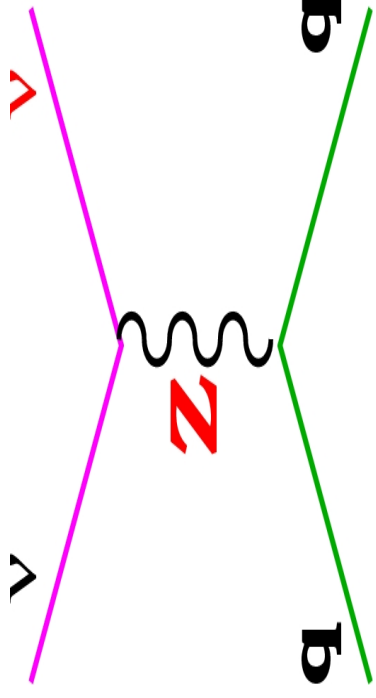
NuTeV Neutrino-Nucleon Scattering

Muon-(anti-)neutrino quark scattering:

charged current (CC)



neutral current (NC)



Paschos-Wolfenstein relation (iso-scalar target):

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

+ electroweak radiative corrections

Insensitive to sea quarks

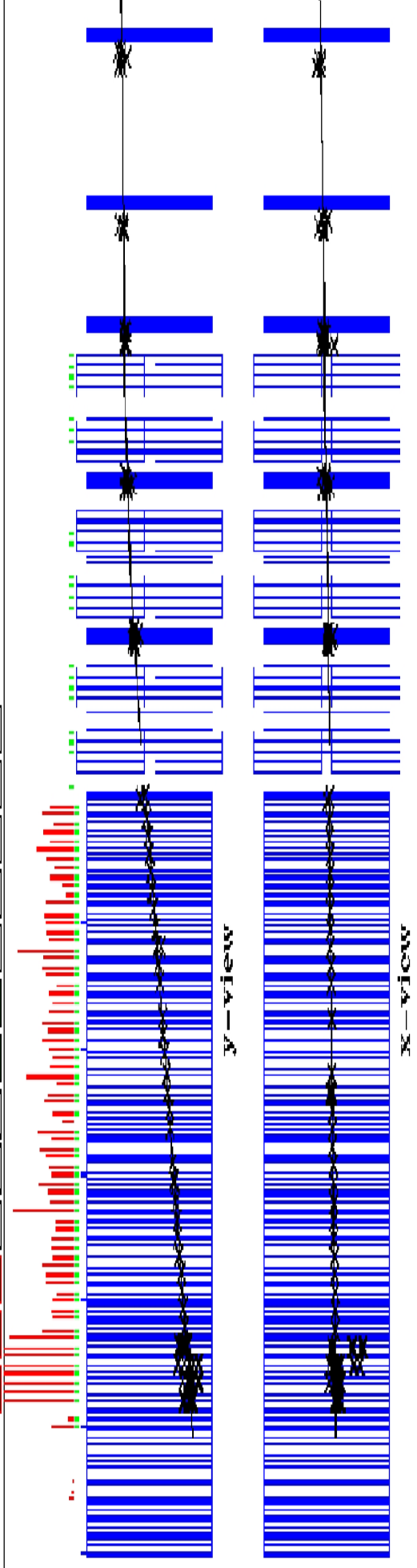
Charm effects only through d_V quarks (CKM suppressed)

Need neutrino and anti-neutrino beam!

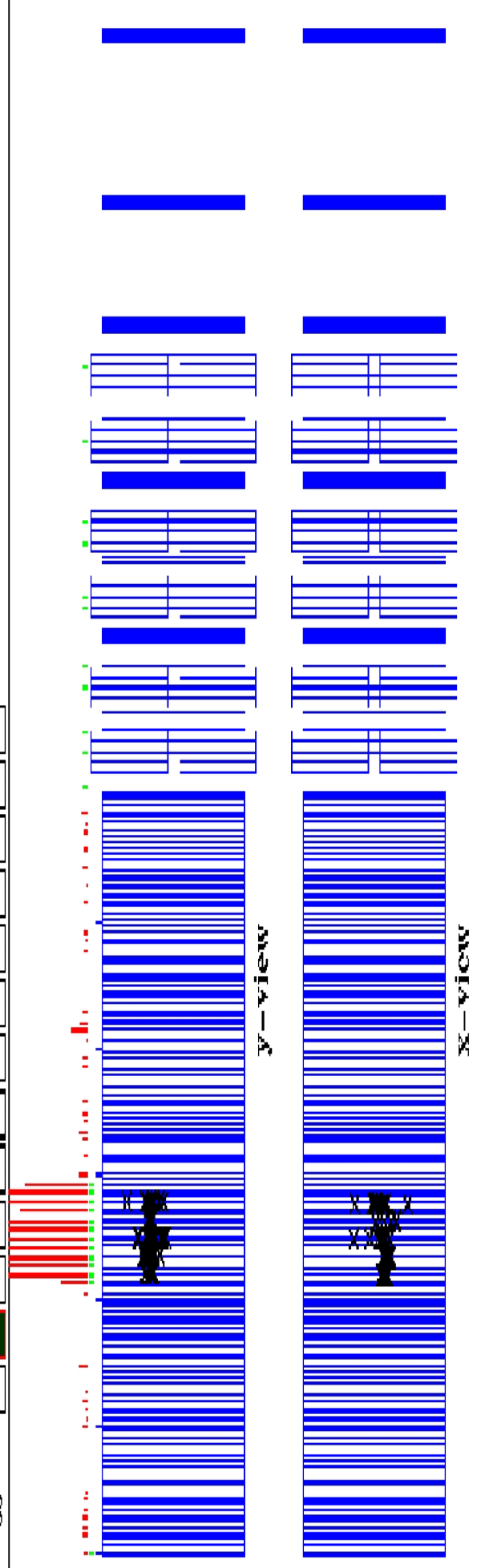
CC versus NC Events in the NuTeV Detector

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

Run: 6000 Event: 2573 Igate: 1 Date: Sat Apr 26 06:15:00 1997
Triggers: 1 2 3 4 5 6 7 8 9 10 11 12 13



Run: 6000 Event: 4354 Igate: 1 Date: Sat Apr 26 06:24:07 1997
Triggers: 1 2 3 4 5 6 7 8 9 10 11 12 13



Distribution of Event Lengths

Events: 1975K

Neutrino:

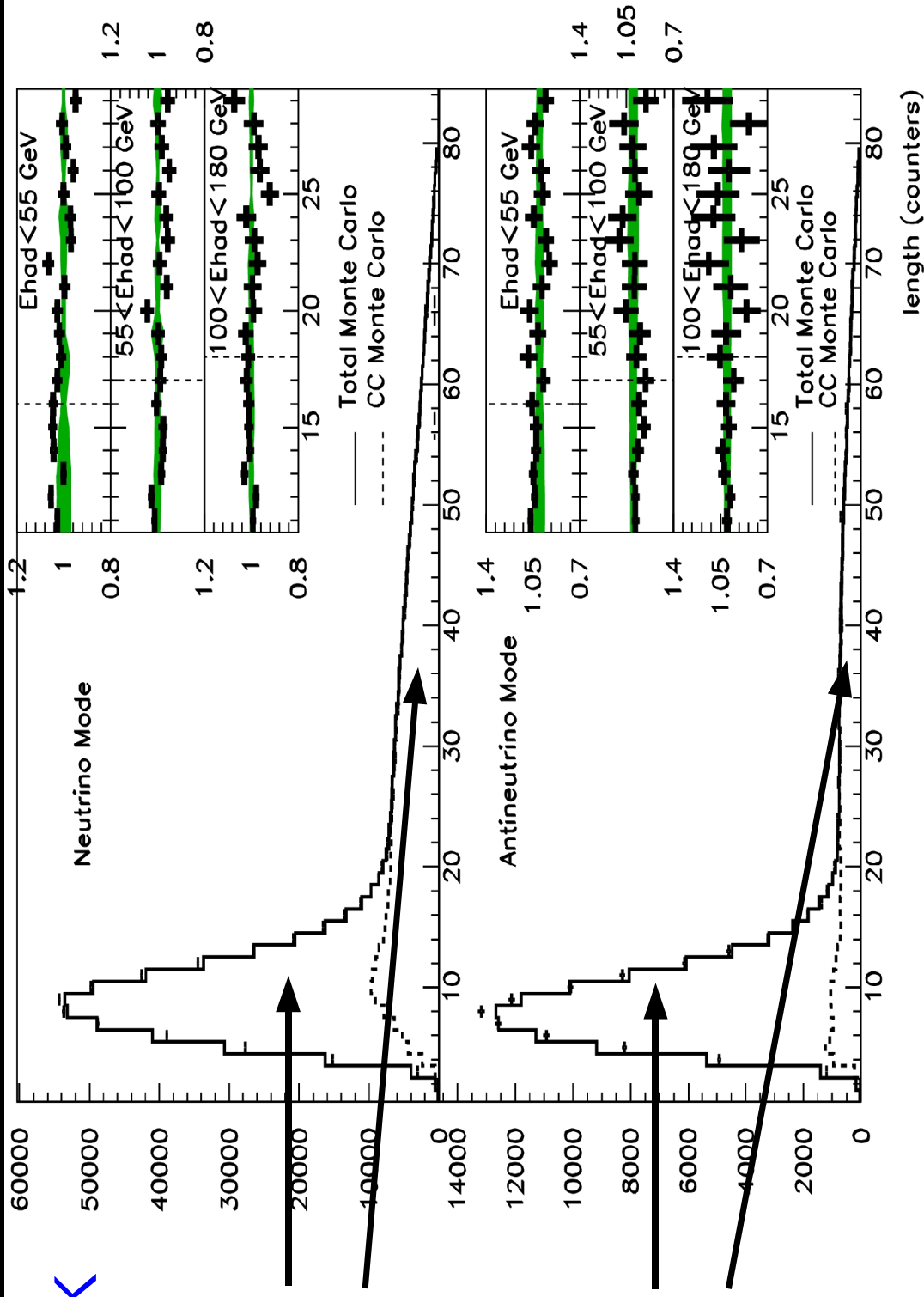
NC: 457K

CC: 1167K

Anti-neutrino:

NC: 101K

CC: 250K



From measured distributions to R_{ν} :

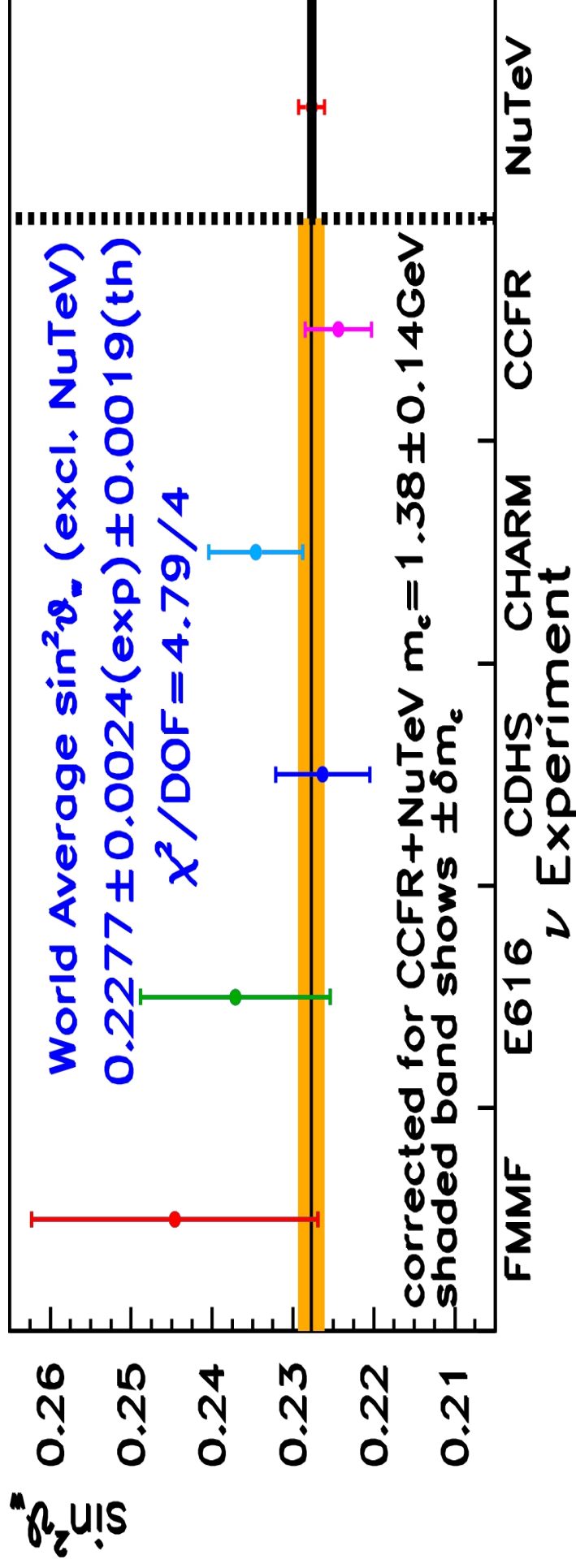
MC modelling of (anti-)neutrino beam, radiative corrections, detector response

NuTeV's Result

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

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

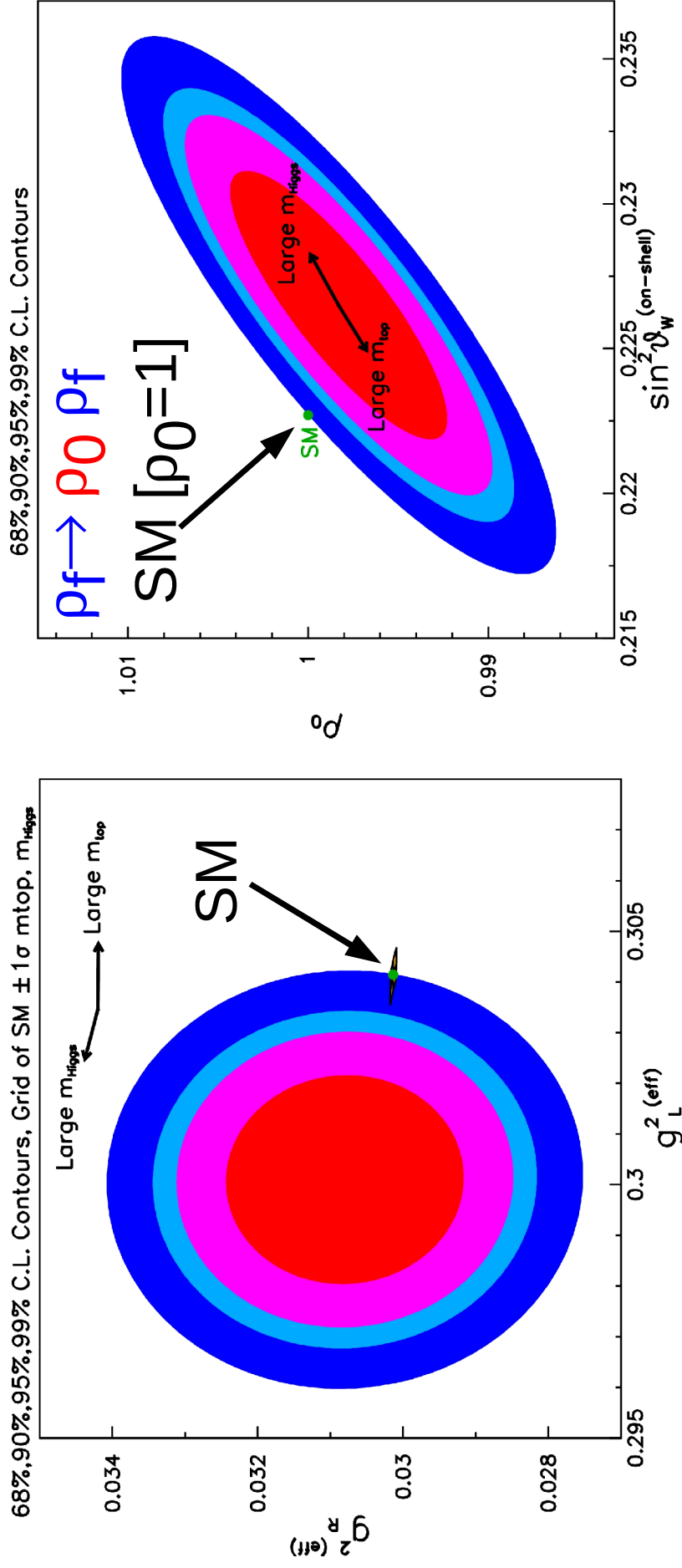
Factor two more precise than previous νN world average



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

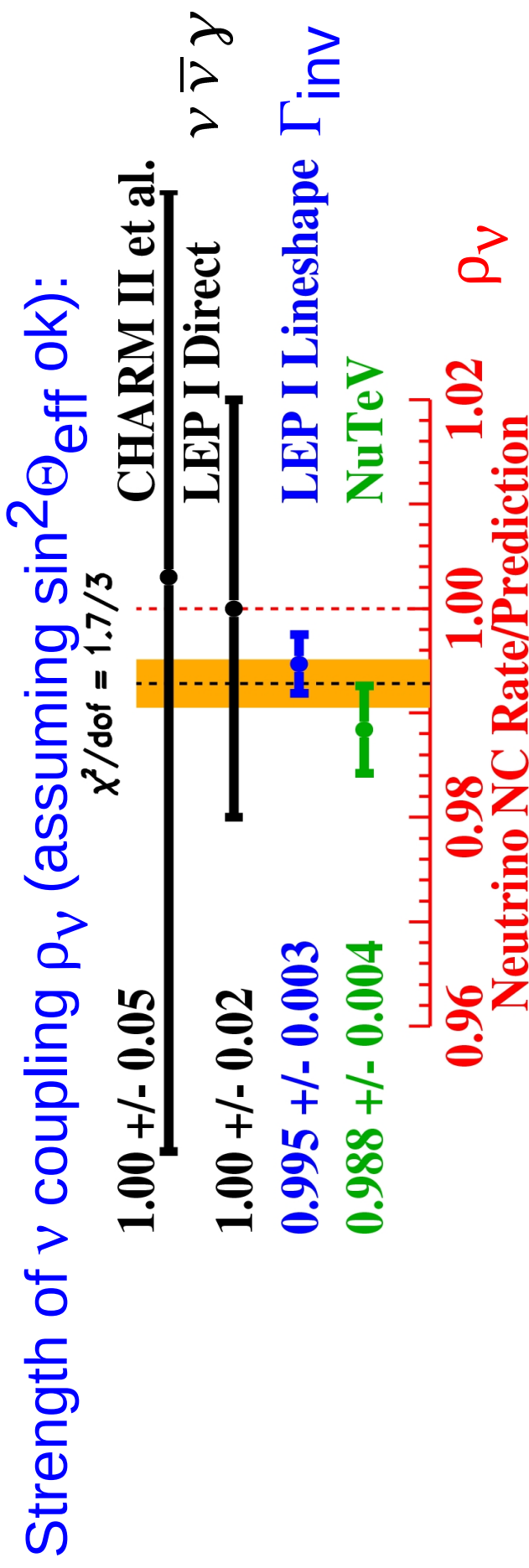
NuTeV's Result

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 v/q couplings or tree ρ_0

NuTeV's Result



Various explanations, old and new physics:

Theory uncertainty (LO PDFs)

Isospin violating PDFs

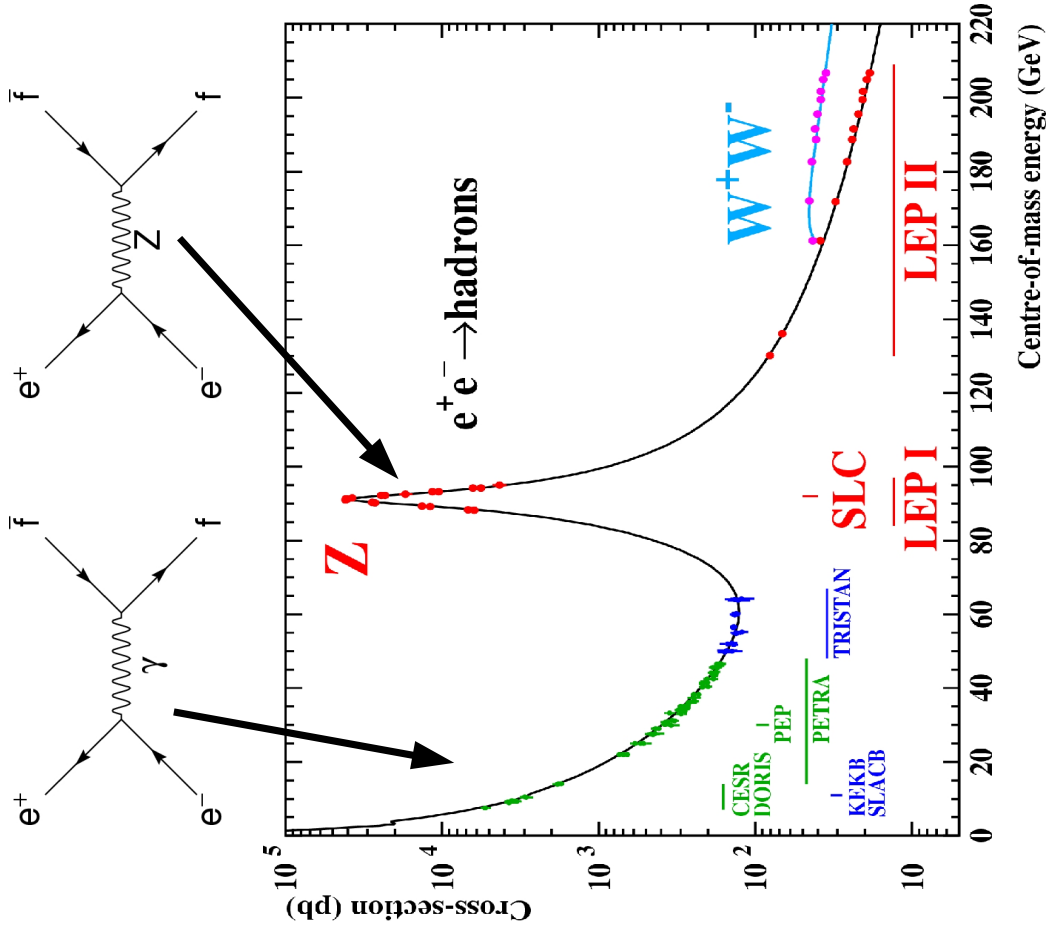
Strange (charm) sea asymmetry (quark-antiquark)

Nuclear shadowing asymmetry (W-Z)

New physics:

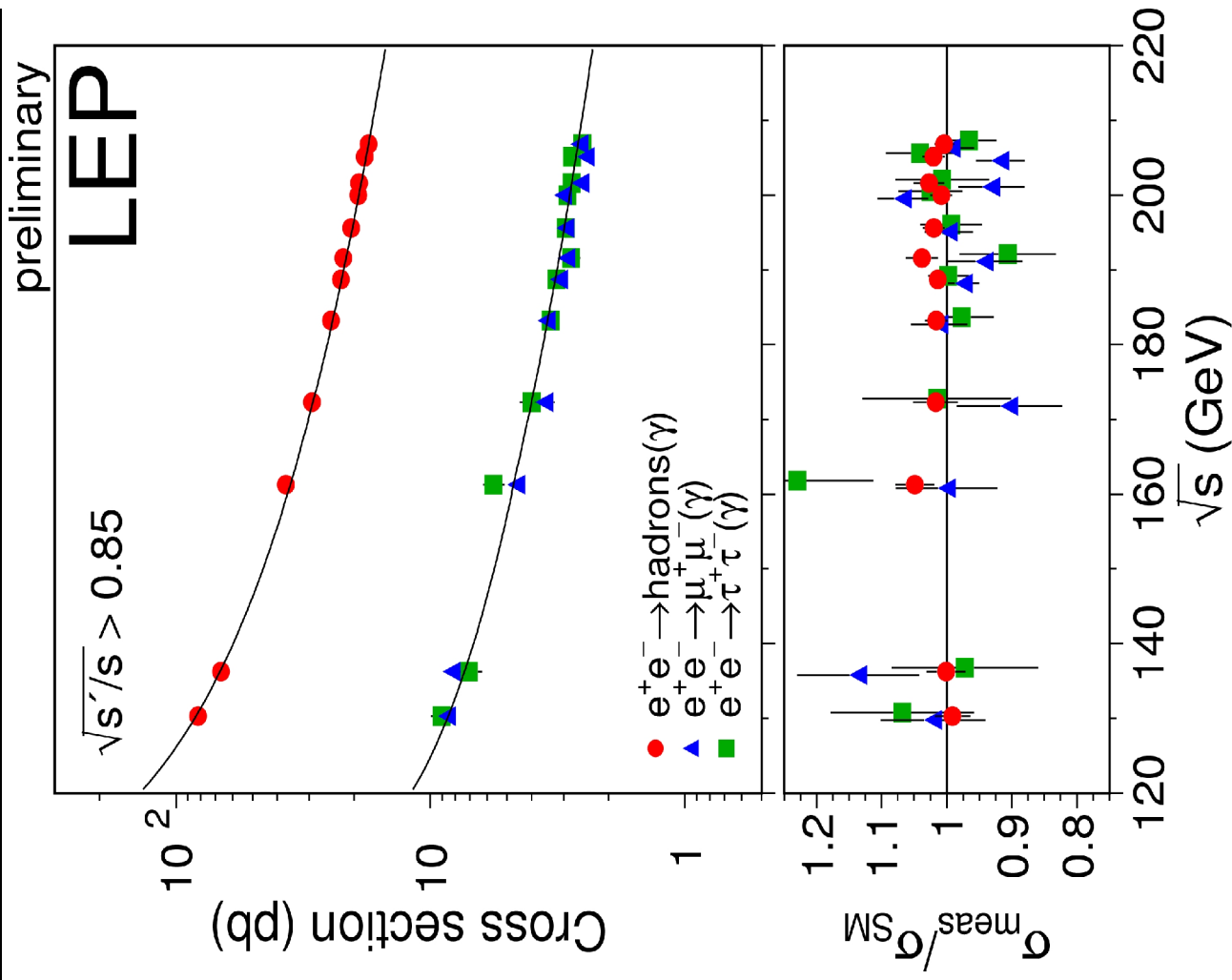
Z' , contact interactions, lepto-quarks, new fermions, neutrino oscillations, . . .

The Z Lineshape



$$M_Z = 91187.5 (2.1) \text{ MeV}$$

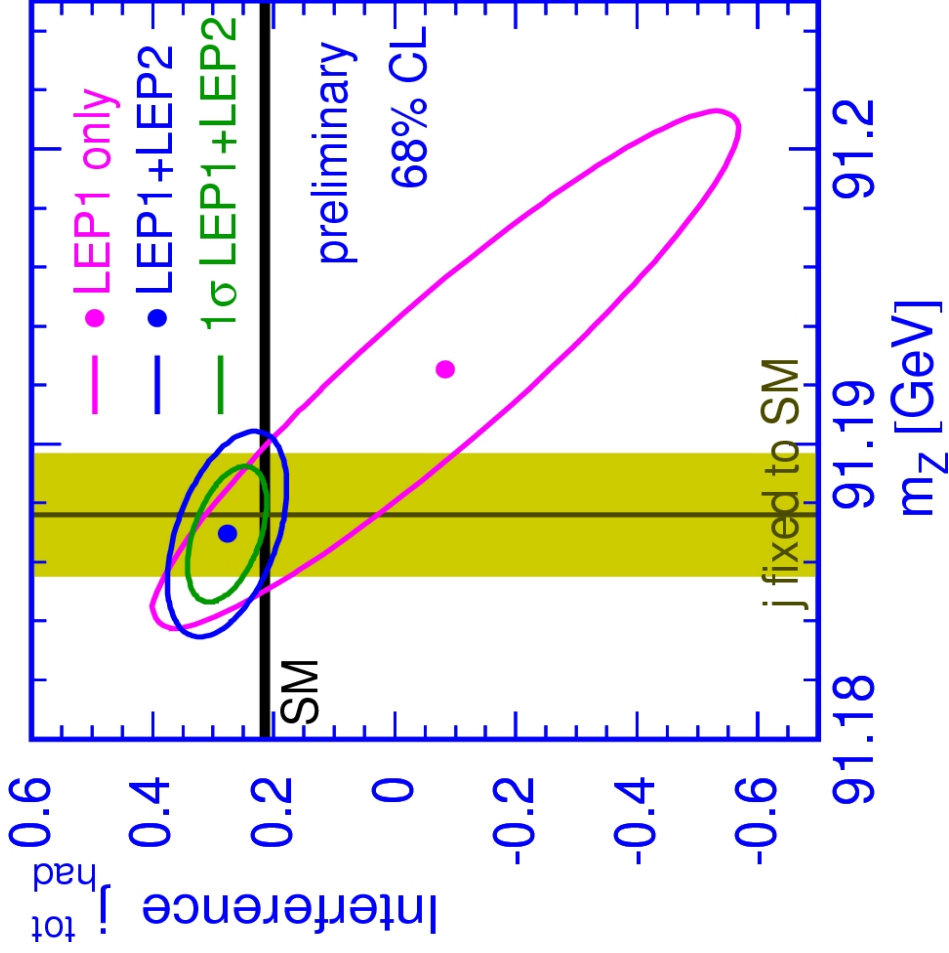
$$N_\nu = 2.9841 (83) \quad [-1.9\sigma]$$



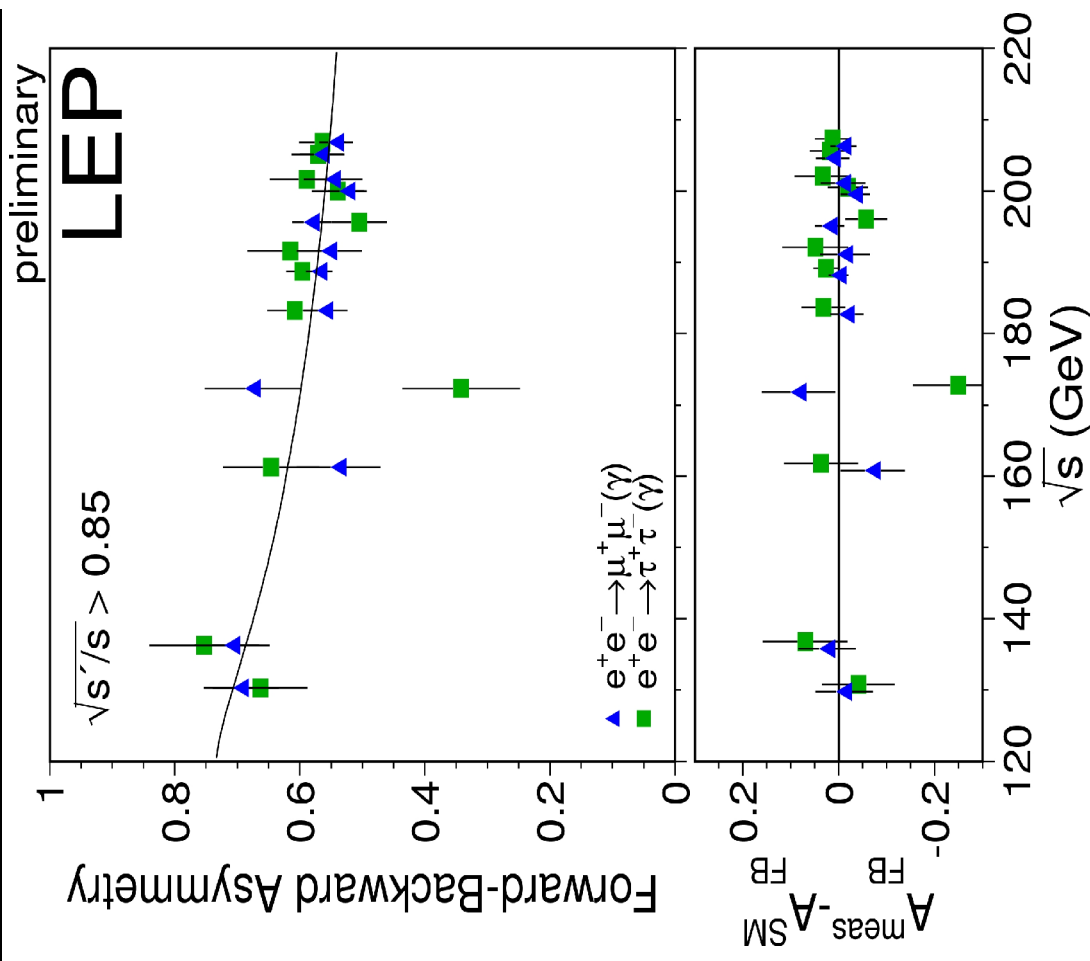
Test of γ/Z Interference

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:

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

LEP-1:

Leptonic f/b asymmetry

$A_l = 0.1512$ (42)

Final state τ polarisation

$A_l = 0.1465$ (33)

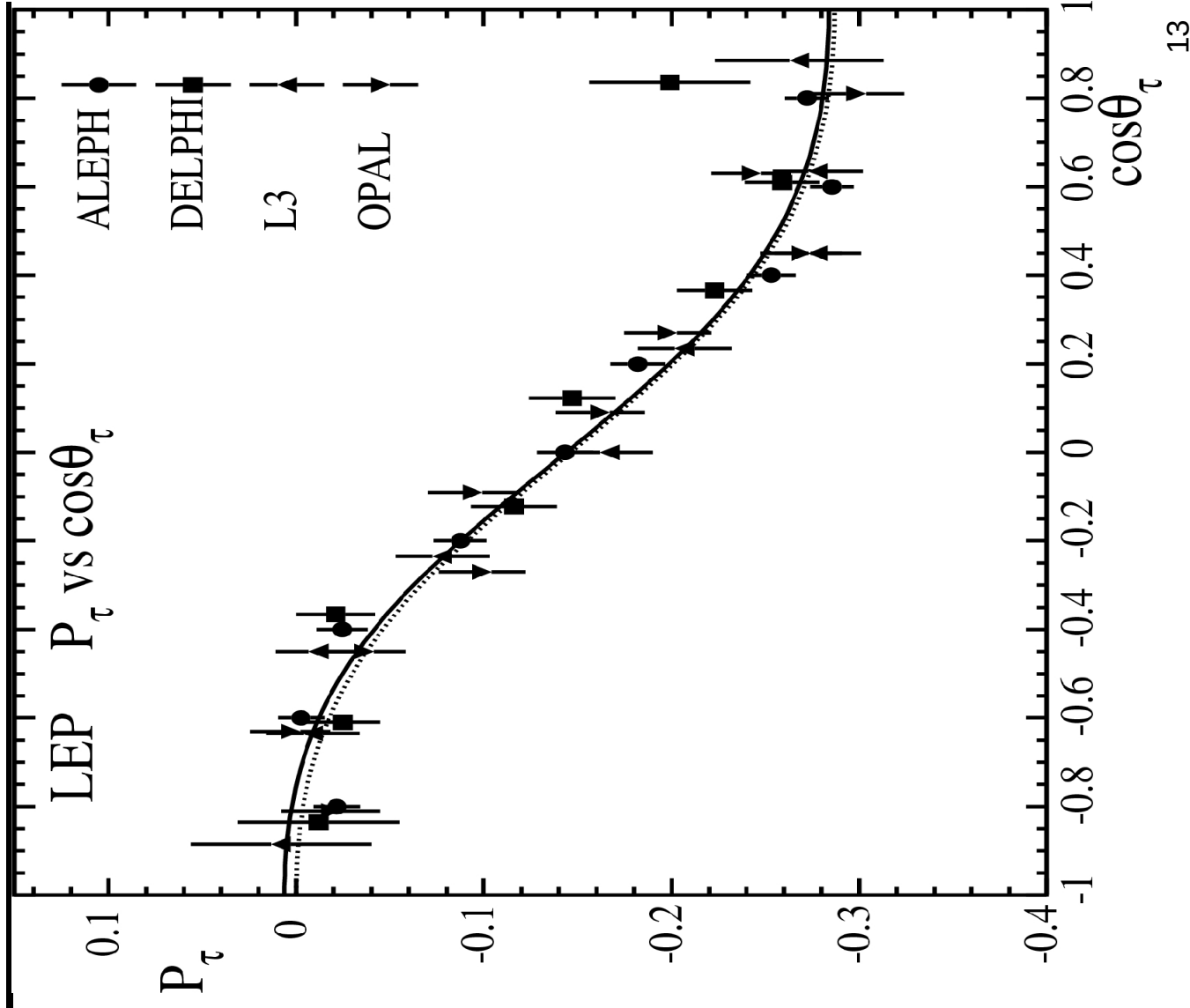
SLD:

Left/right asymmetry

$A_l = 0.1513$ (21)

Final SLD+LEP-1 result:

$A_l = 0.1501$ (16)



Effective Leptonic Coupling Constants

$$g_{Vf} = \sqrt{\rho_f} (\mathbf{T}_3^f - 2\mathbf{q}_f \sin^2 \theta_{eff}^f)$$

$$g_{Af} = \sqrt{\rho_f} \mathbf{T}_3^f$$

Z partial widths:

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

Asymmetry parameters:

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

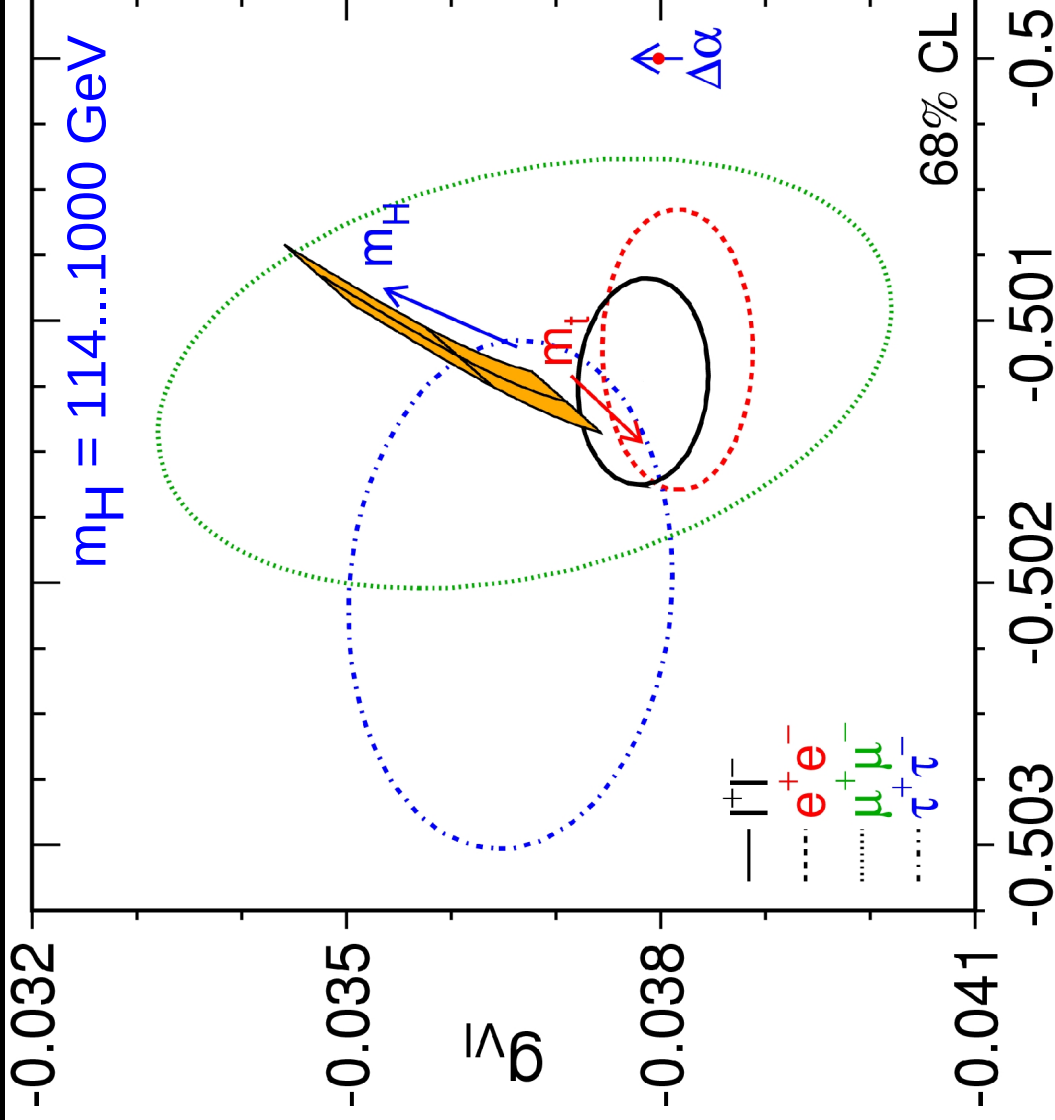
Lepton universality

Radiative corrections

Final SLD+LEP-1 result:

$$g_{VI} = -0.03783 \quad (41)$$

$$g_{AI} = -0.50123 \quad (26)$$

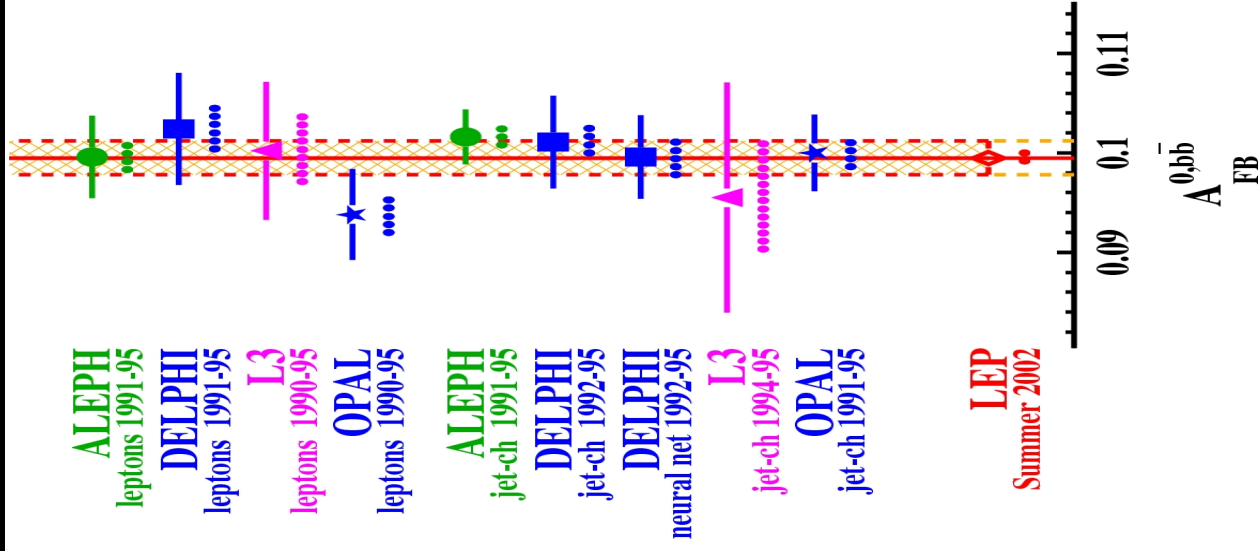


g_{AI}

SM comparison:

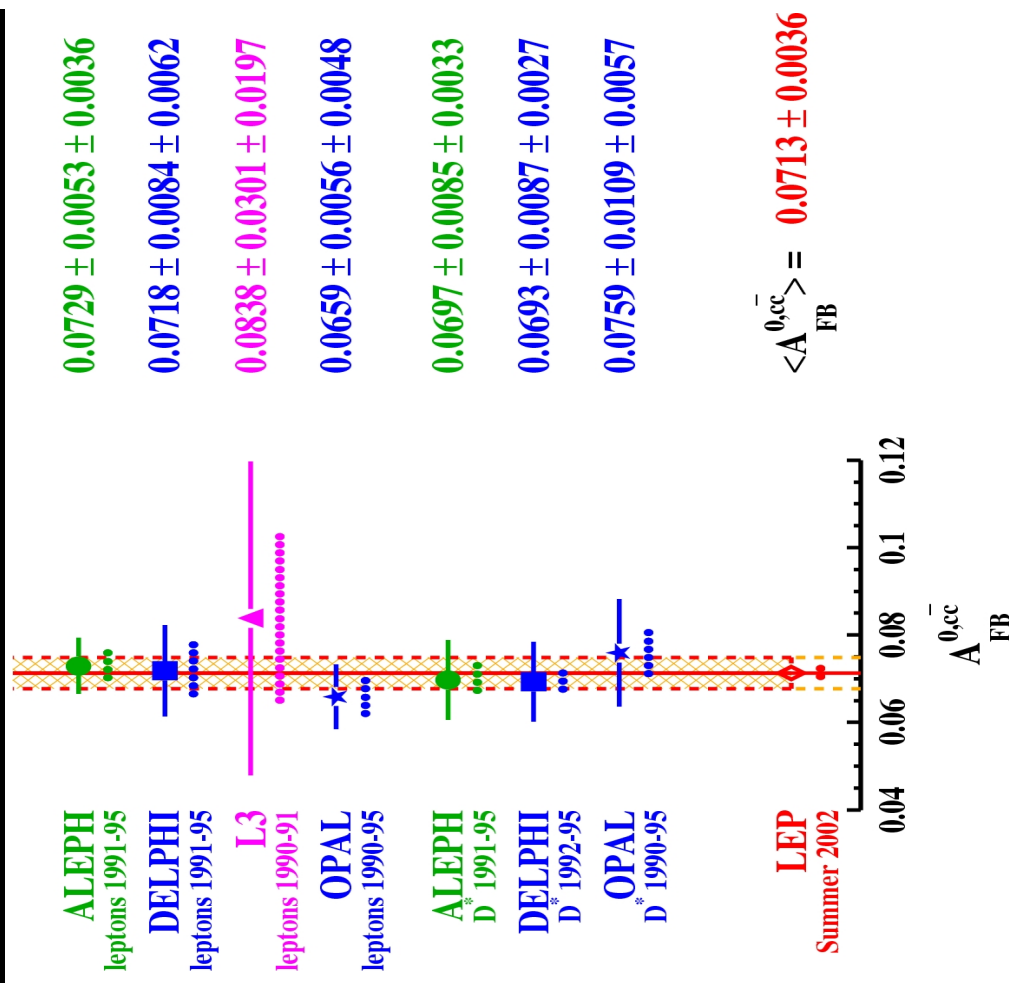
Small Higgs-boson mass

Heavy Flavour Results at the Z Pole



$0.0996 \pm 0.0038 \pm 0.0017$
 $0.1024 \pm 0.0051 \pm 0.0024$
 $0.1002 \pm 0.0060 \pm 0.0035$
 $0.0938 \pm 0.0040 \pm 0.0022$
 $0.1016 \pm 0.0025 \pm 0.0012$
 $0.1011 \pm 0.0044 \pm 0.0015$
 $0.0996 \pm 0.0036 \pm 0.0022$
 $0.0955 \pm 0.0101 \pm 0.0056$
 $0.1000 \pm 0.0034 \pm 0.0018$

$\langle A_{FB}^{0,bb} \rangle = 0.0995 \pm 0.0017$



$0.0729 \pm 0.0053 \pm 0.0036$
 $0.0718 \pm 0.0084 \pm 0.0062$
 $0.0838 \pm 0.0301 \pm 0.0197$
 $0.0659 \pm 0.0056 \pm 0.0048$
 $0.0697 \pm 0.0085 \pm 0.0033$
 $0.0693 \pm 0.0087 \pm 0.0027$
 $0.0759 \pm 0.0109 \pm 0.0057$

$\langle A_{FB}^{0,cc} \rangle = 0.0713 \pm 0.0036$

F/B asymmetries statistics dominated

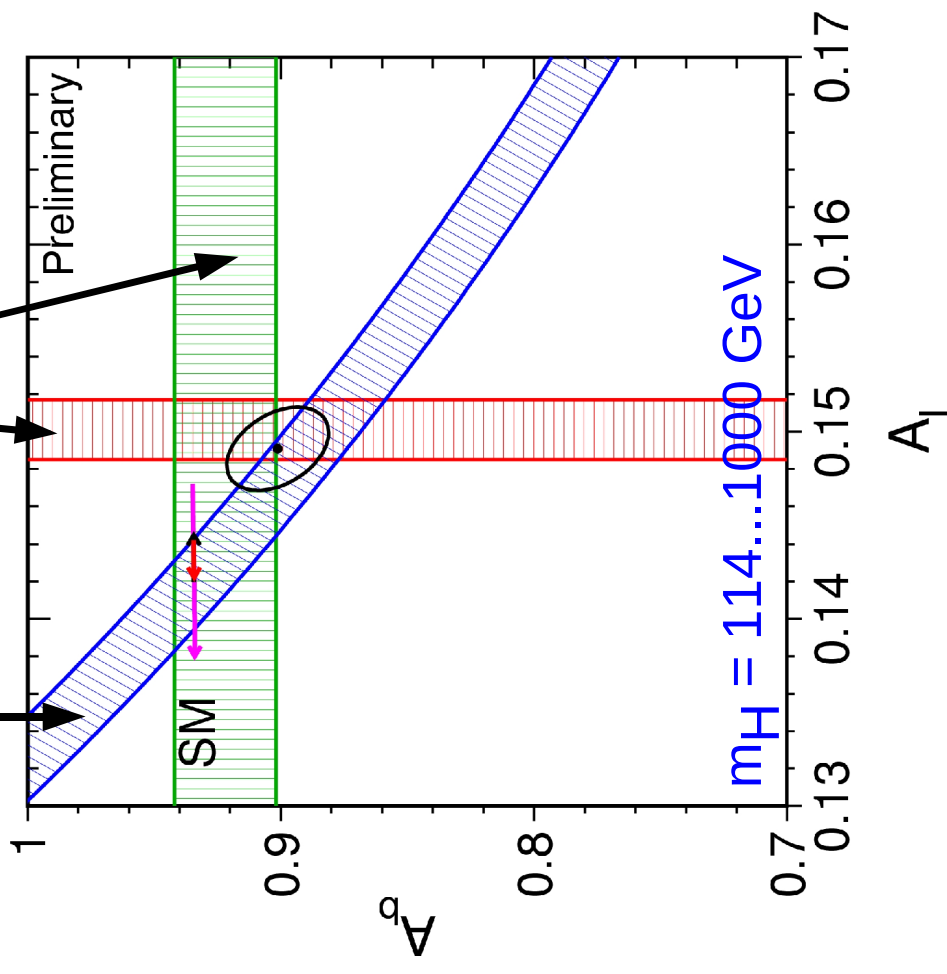
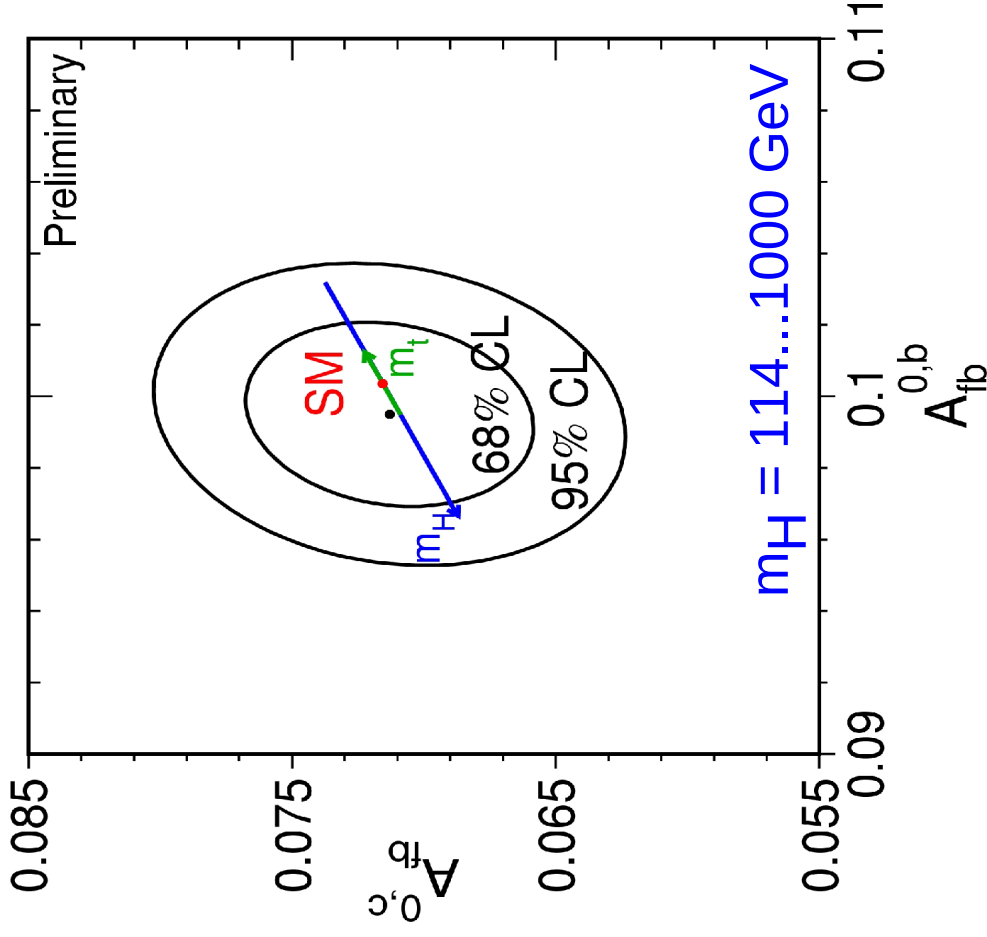
All measurements very consistent

$\chi^2/\text{ndof} = 47.6/(105-14)$ low!

Heavy Flavour Results at the Z Pole

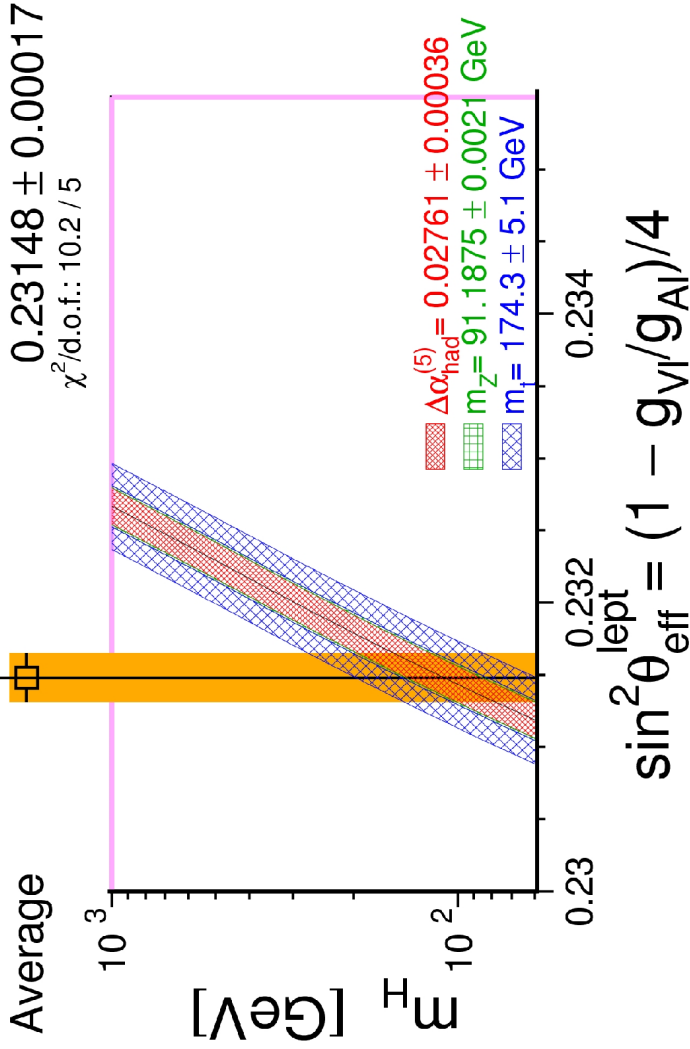
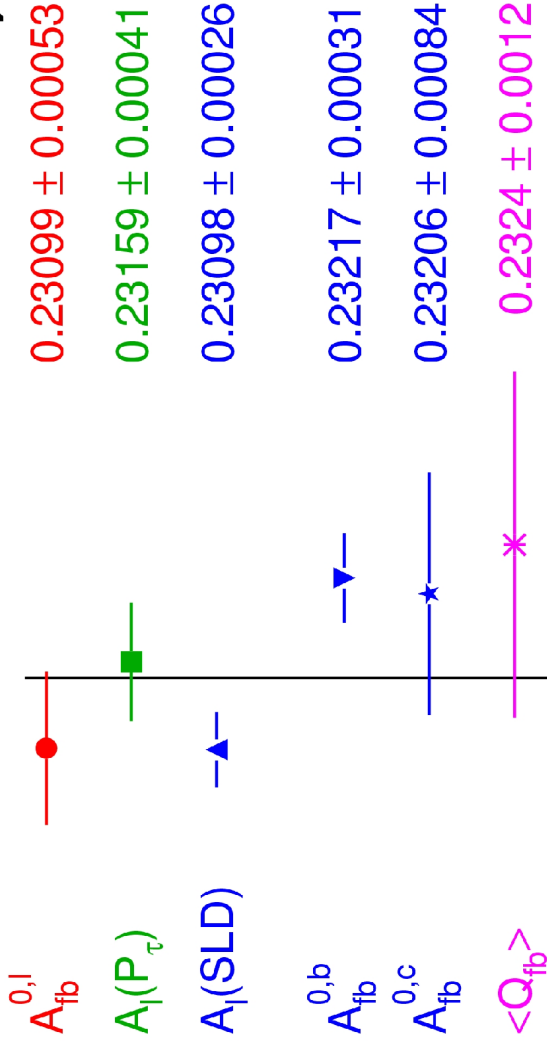
Compare with leptons:

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



Comparison of all Z-Pole Asymmetries

Preliminary



Effective electroweak

mixing angle:

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

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

A-posteriori observation:

0.23113 (21) leptons

0.23217 (29) hadrons

But is really:

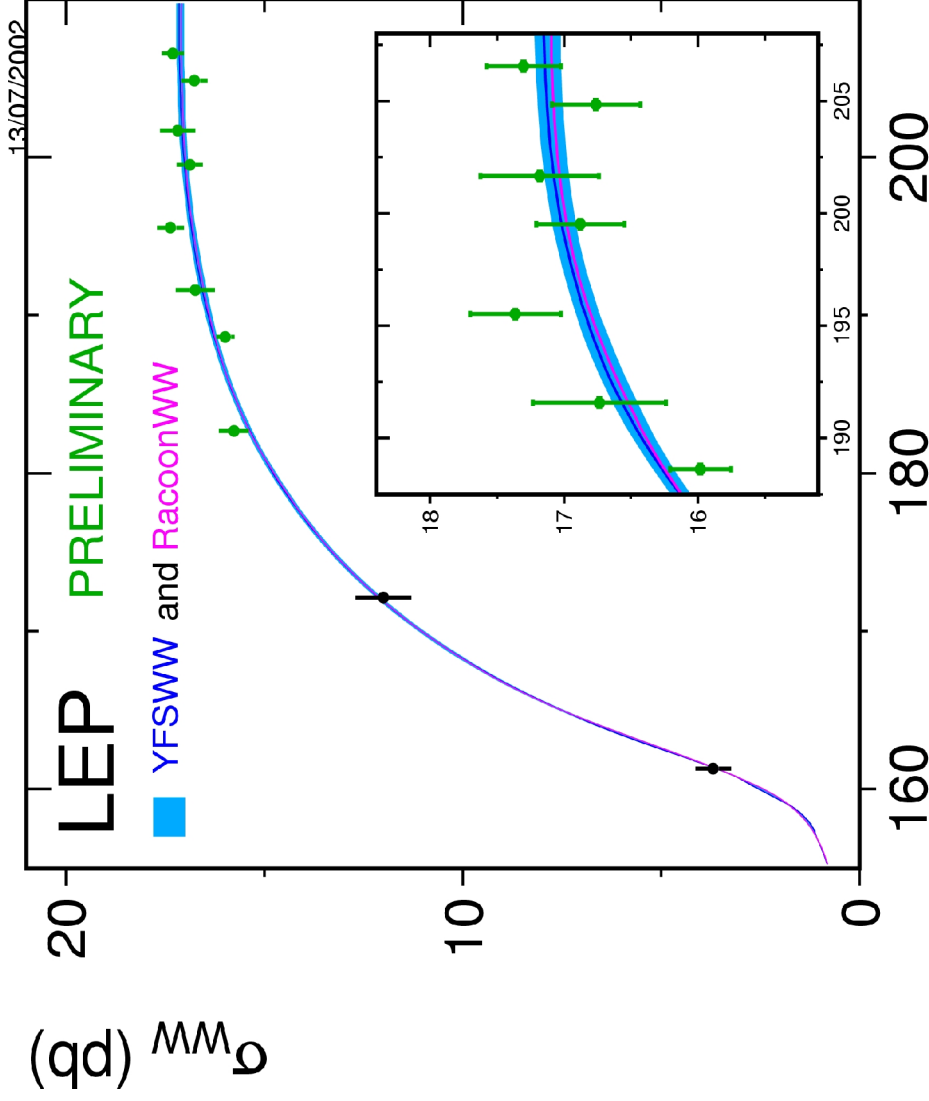
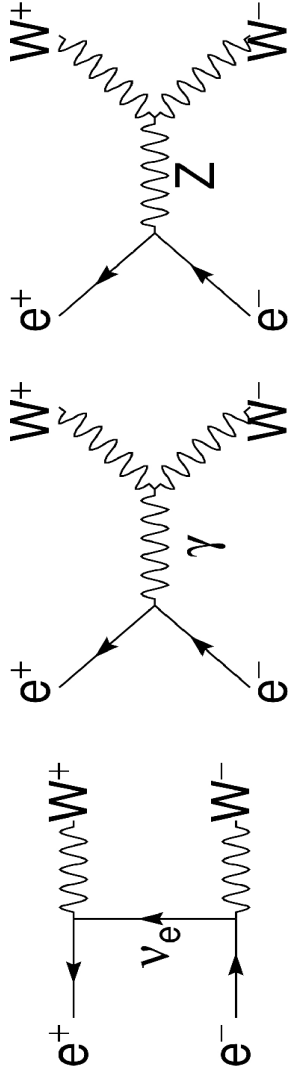
$A_l(\text{SLD})$ vs. $A_{fb}(\text{LEP})$

Both:

2.9 σ difference

$$\sin^2\theta_{\text{eff}}^{\text{lept}} = (1 - g_V/g_A)/4$$

W-Pair Production



Correlated average of:

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

0.997(11) YFSWW

0.999(11) RacoonWW

Test at the 1% level!

Uses $O(\alpha)$ corrections:

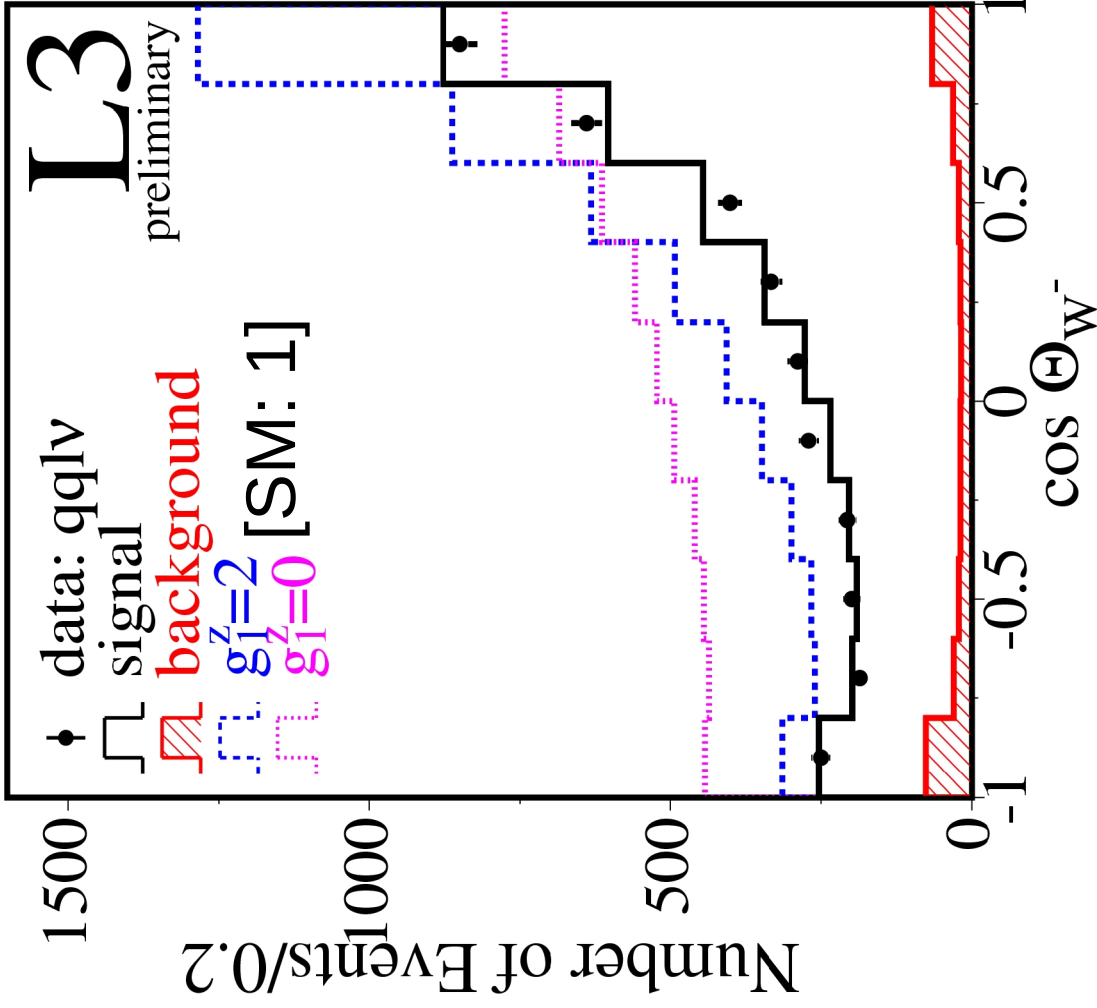
-2.5(0.5)% on σ_{theory}

Effect on differential cross sections and on γ_{WW} / ZWW gauge couplings?

$\sqrt{s}$ (GeV)

W-Pair Production and Gauge Couplings

$O(\alpha)$ corrections: $\sim 2\%$ steeper slope



Triple gauge couplings:

$$g_1^Z, \kappa_\gamma, \lambda_\gamma$$

W weak charge: g_1^Z

W magnetic dipole:

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

W electric quadrupole:

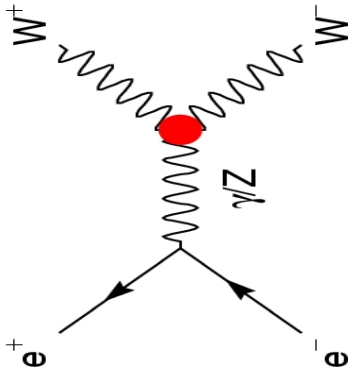
$$Q_W = -\frac{e}{M_W^2} (\kappa_\gamma - \lambda_\gamma)$$

W polarisation:

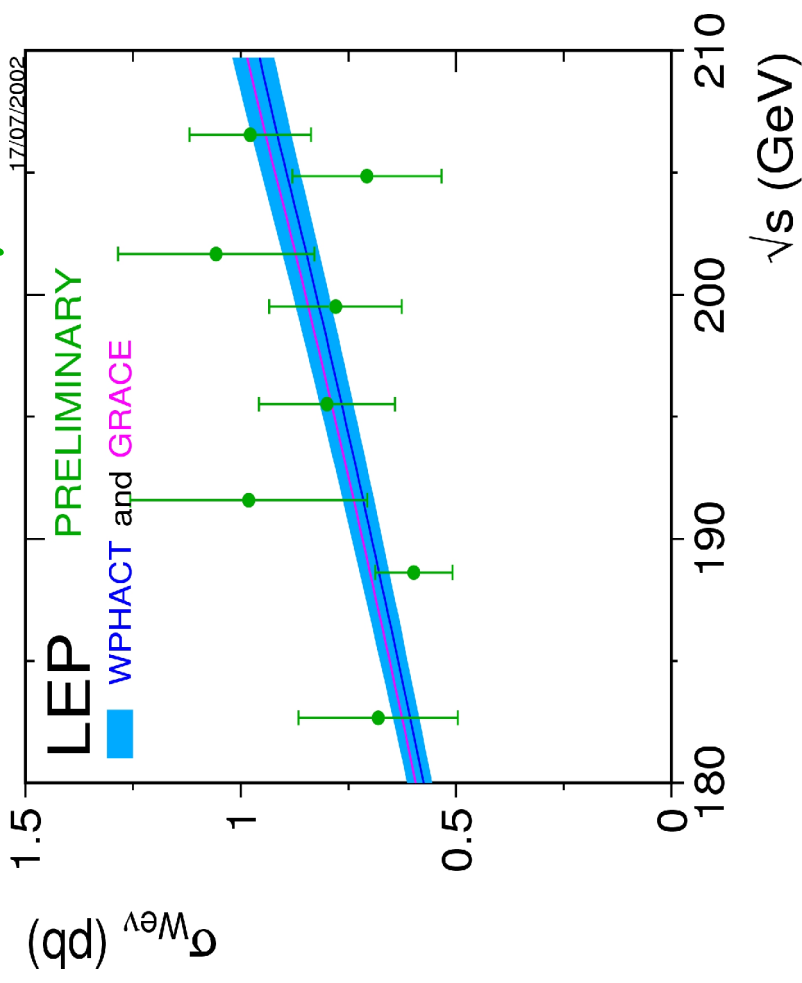
Analyse decay angles

TGC analyses now based on $O(\alpha)$ calculations for W^+W^-

Charged Triple Gauge Couplings



Also using single-W production (esp. κ_γ)



LEP single-parameter

results (68%) [SM]:

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

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

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

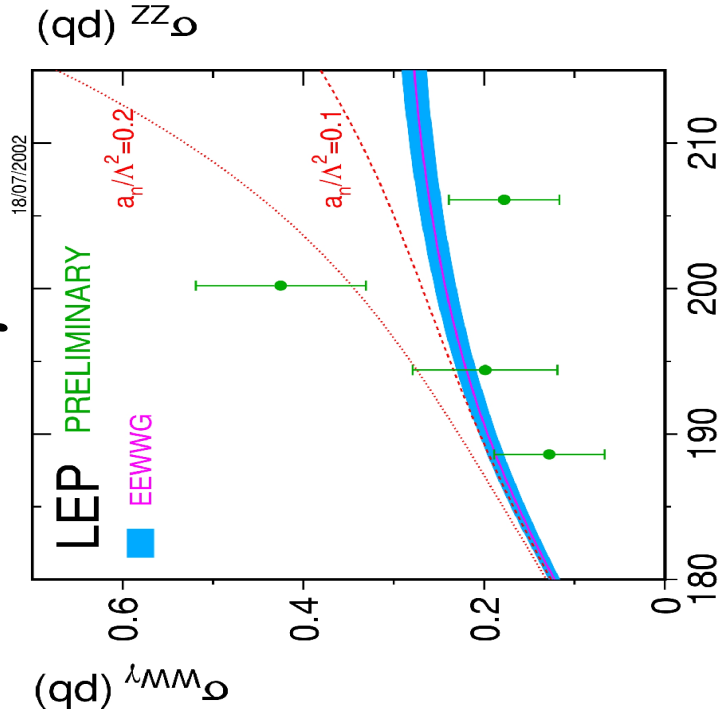
$O(\alpha)$ slope change currently used as theory uncertainty:

~2/3 of total error on TGCs

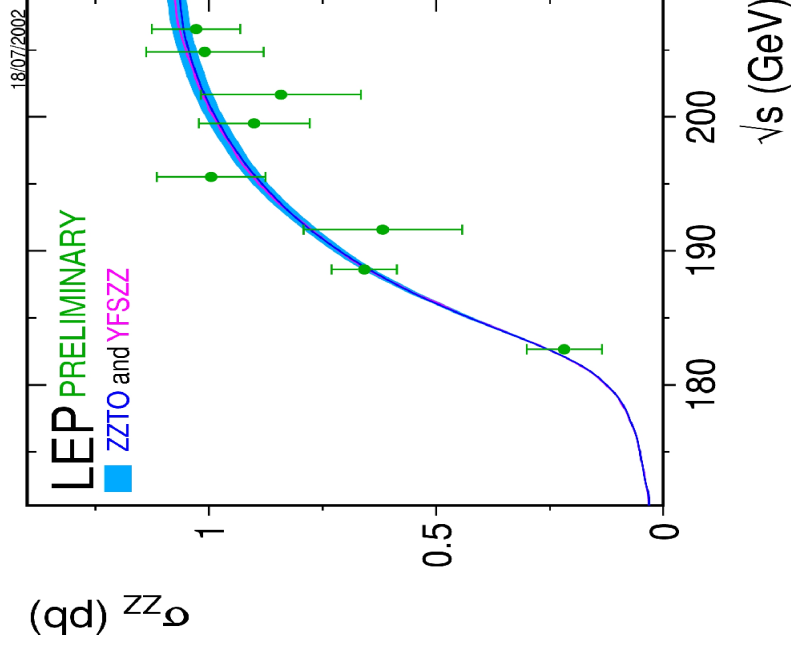
Ongoing studies to evaluate slope uncertainty on TGCs

Many More Processes Studied . . .

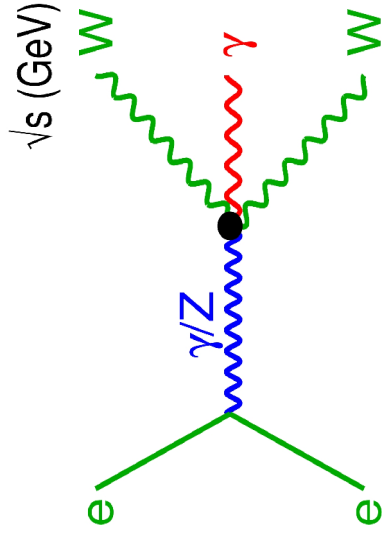
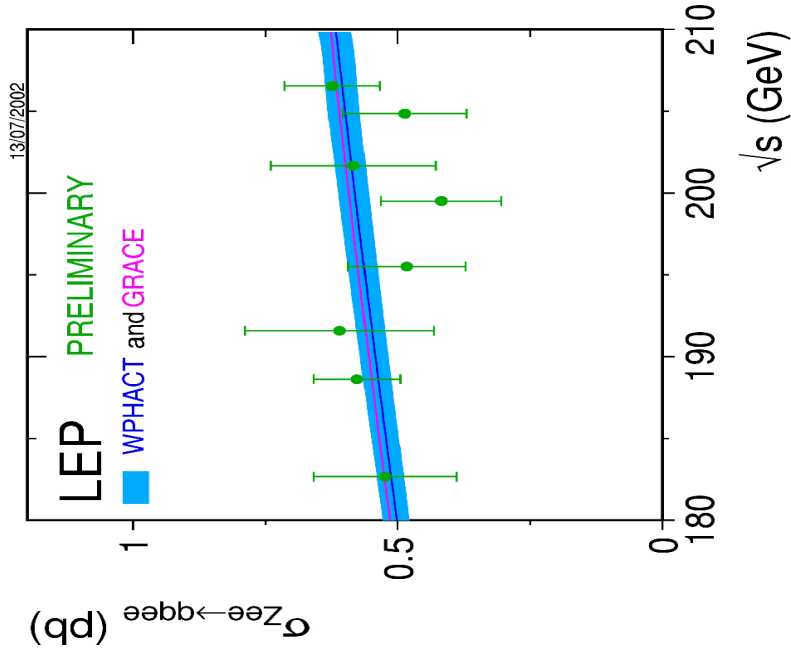
$WW\gamma$



ZZ



Zee



R(meas./theory):

0.949(78) GRACE
0.978(80) WPHACT

R(meas./theory):

0.958(55) YFSZZ
0.965(56) ZZTO

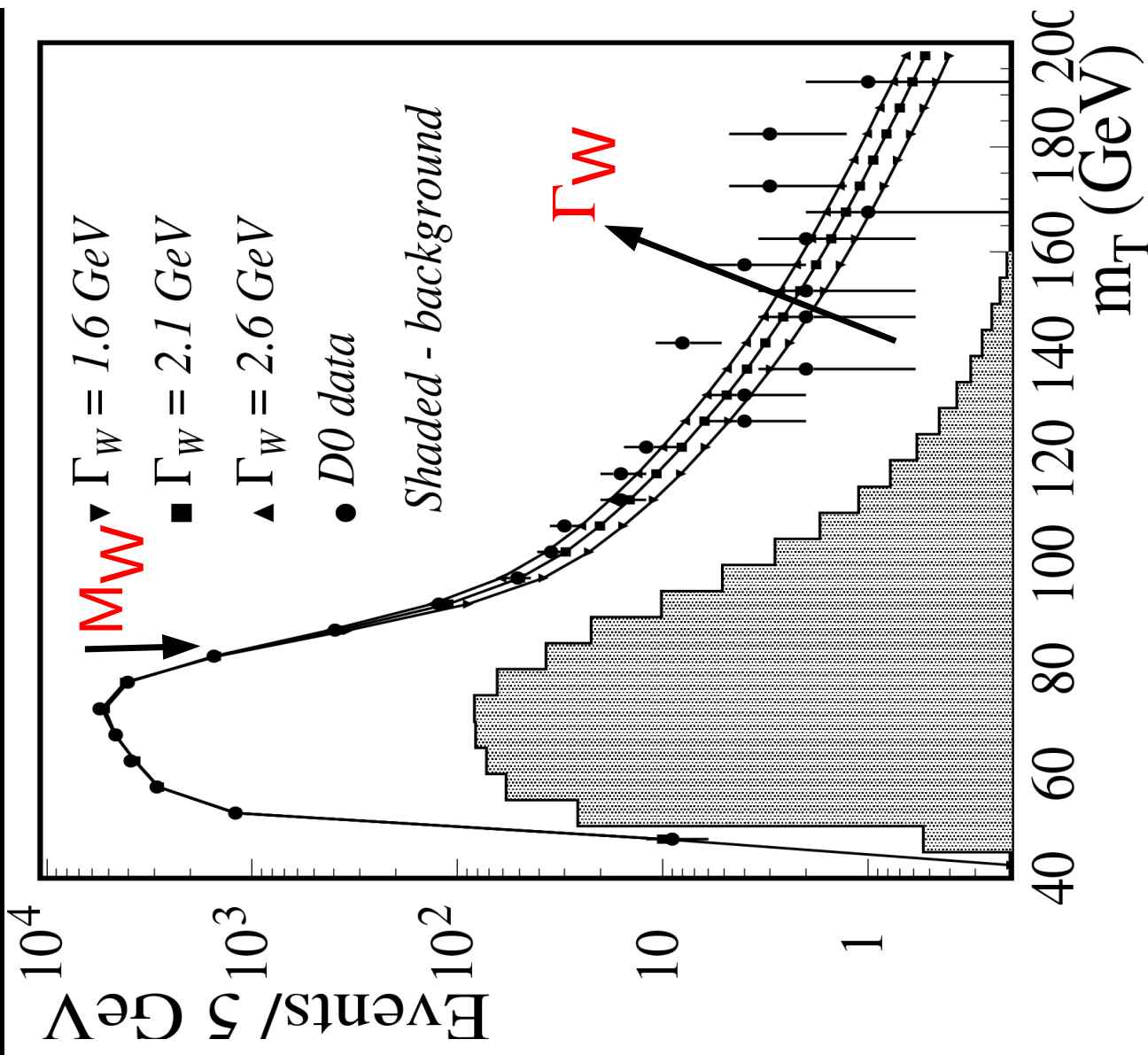
Small Standard-Model processes now tested at 5%-10%

W Boson – Mass and Width

Tevatron (CDF, DØ):
 $p\bar{p} \rightarrow W, W \rightarrow e\nu, \mu\nu$
 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



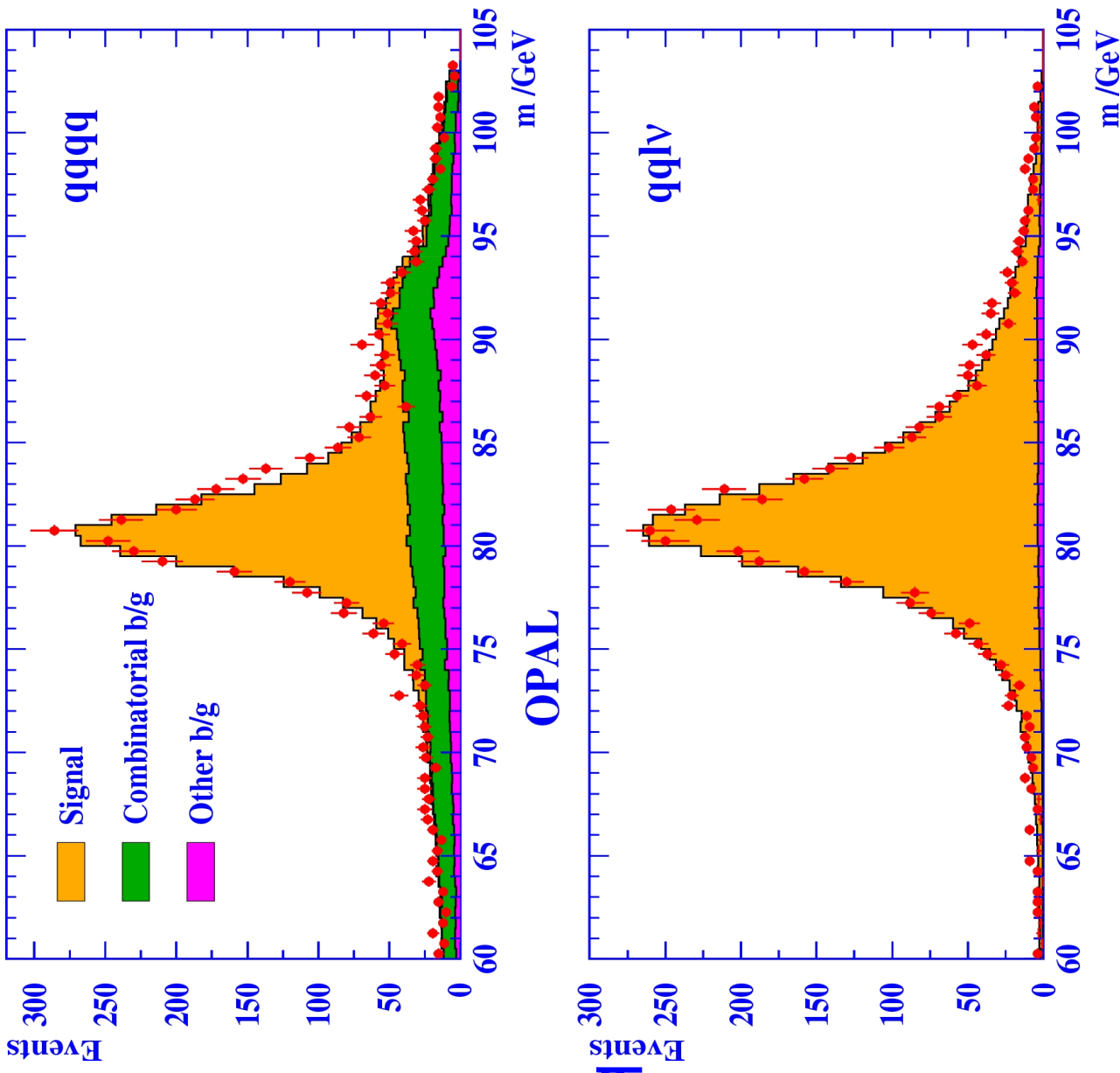
W Boson – Mass and Width

LEP-2: $e^+e^- \rightarrow W^+W^-$
 $\rightarrow qq\bar{q}\bar{q}, q\bar{q}l\nu, l\nu l\nu$
Invariant mass M_{inv}

Preliminary results

Currently large
systematics in the $qq\bar{q}\bar{q}$
channel:

LEP average
dominated by
 $M_W(q\bar{q}l\nu)$

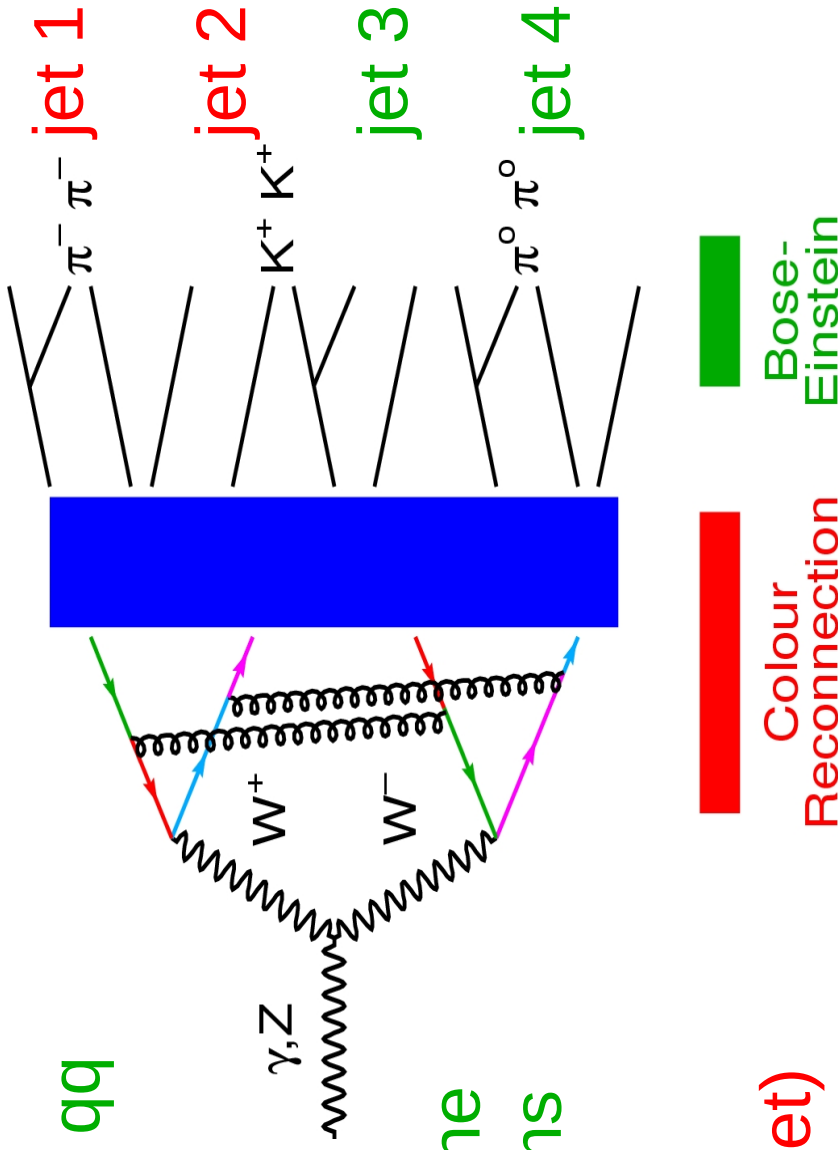


Final State Interconnection (FSI)

$e^+e^- \rightarrow W^+ W^- \rightarrow qq \bar{q}\bar{q}$
 $\rightarrow$ hadrons

$e^+ e^- \rightarrow$

Cross-talk between the
two hadronic systems



Possible mass shift:

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

CR: Colour reconnection (colour flow rearrangement)

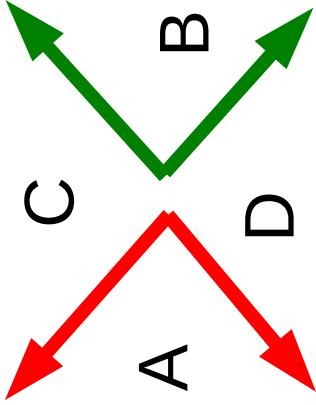
BEC: Bose-Einstein correlations (identical mesons $\pi, K, \dots$)

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

Colour Reconnection (CR)

LEP-2: $e^+e^- \rightarrow W^+ W^- \rightarrow qq \bar{q}\bar{q} \rightarrow 4 \text{ jets}$

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



Particle flow between

jets from:

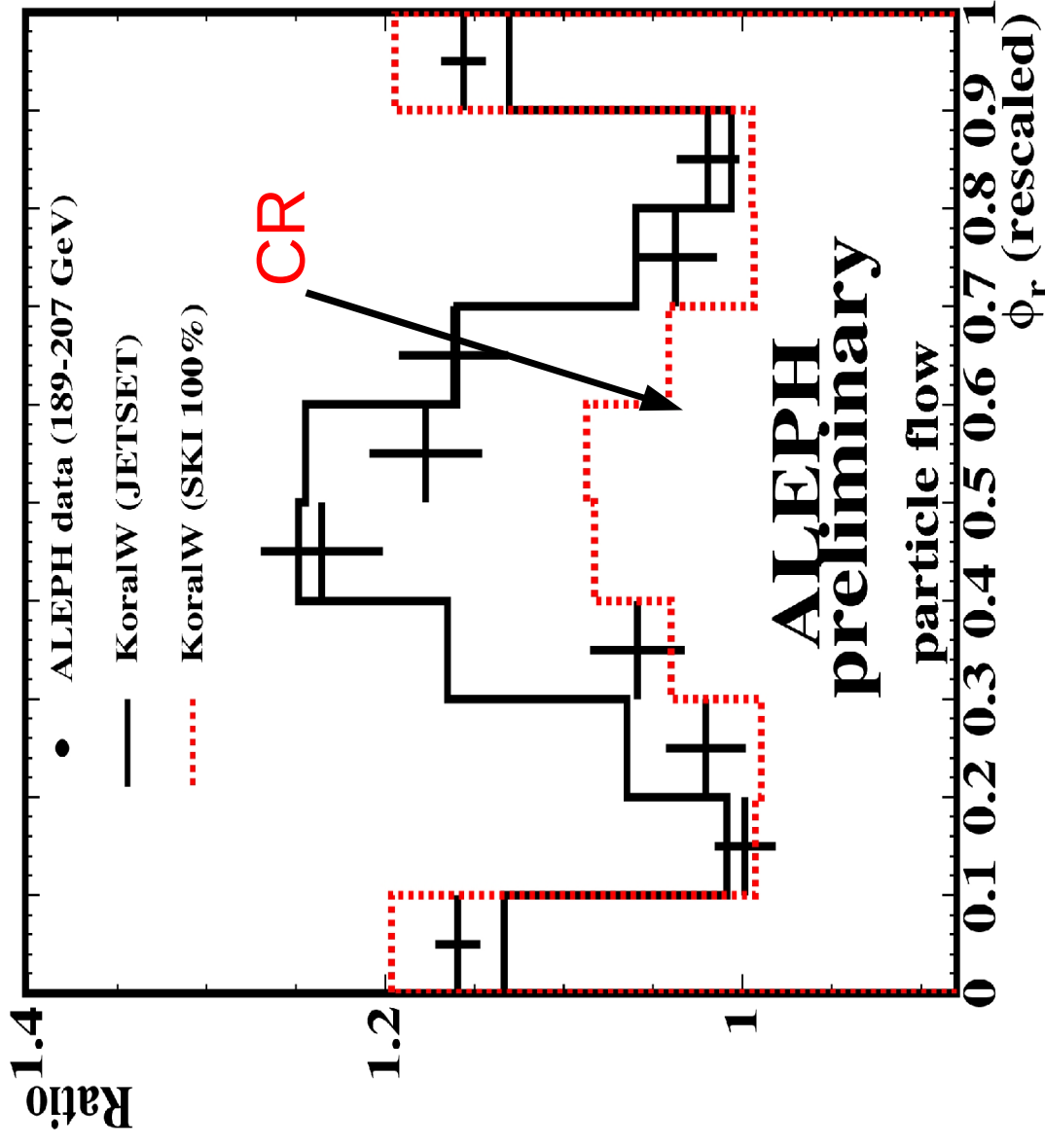
- same W s: A, B

- different W s: C, D

along azimuth

Divide distributions:

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



Colour Reconnection (CR)

Ratio of integrated flows:

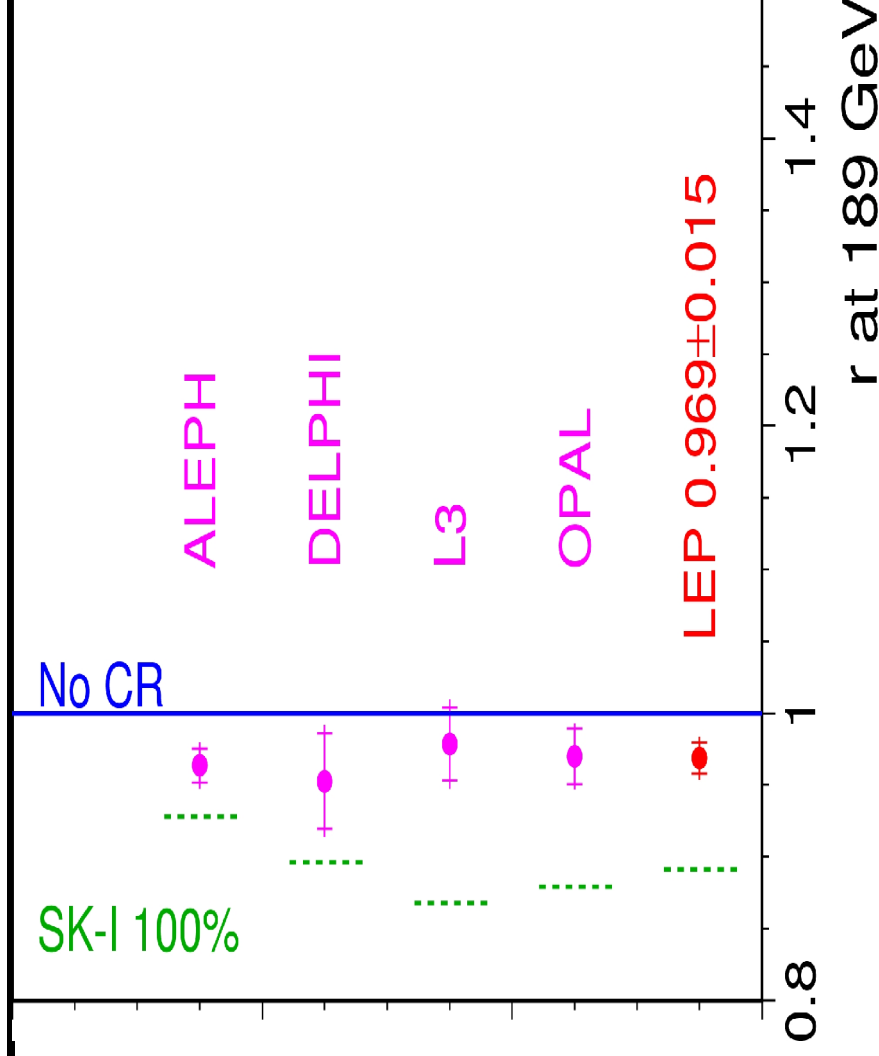
$$R_N = (A+B) / (C+D):$$

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 ($\sim 2\sigma$) for colour reconnection observed:

$$\Delta M_W(qqqq) < 90 \text{ MeV (at 68\% CL, } E_{CM} \text{ averaged)}$$

All other models (Ariadne, Herwig): smaller shifts

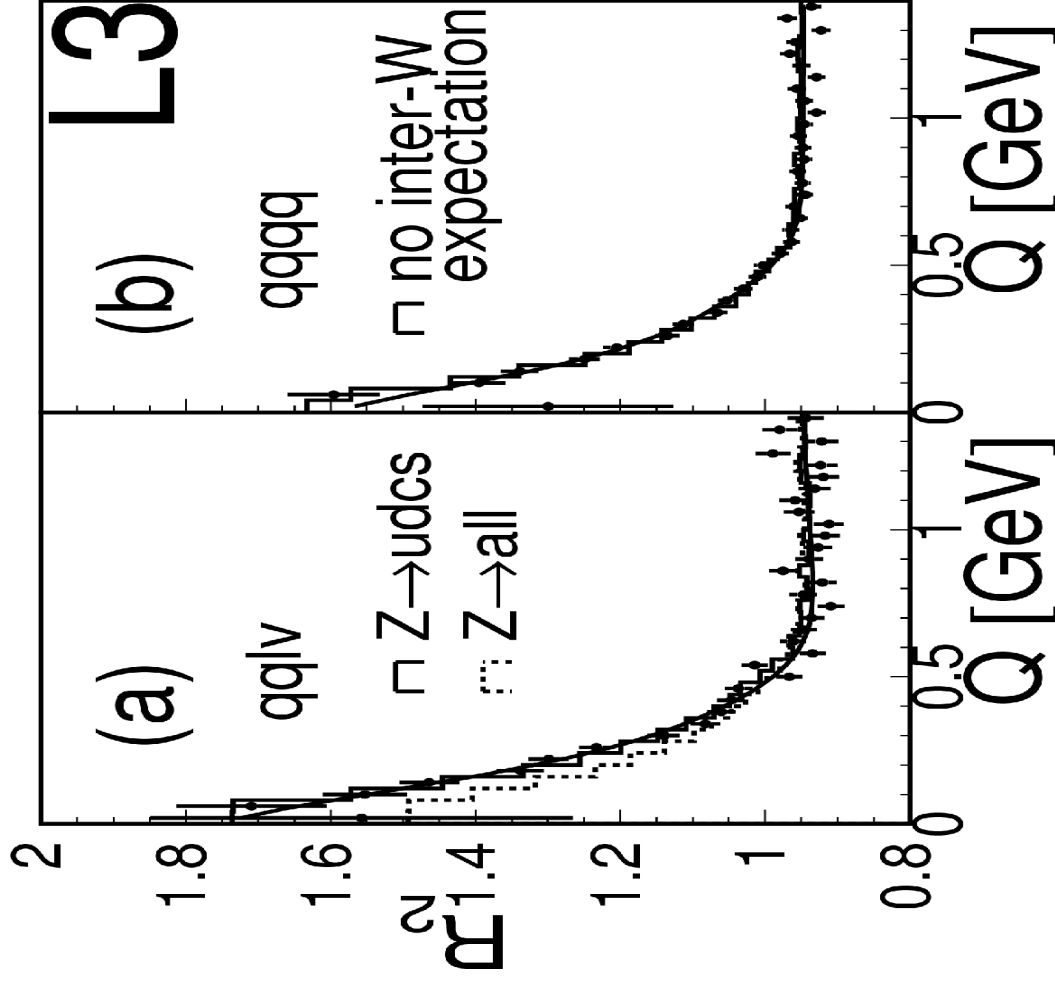
Study jet reconstructions less sensitive to CR effects:

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)

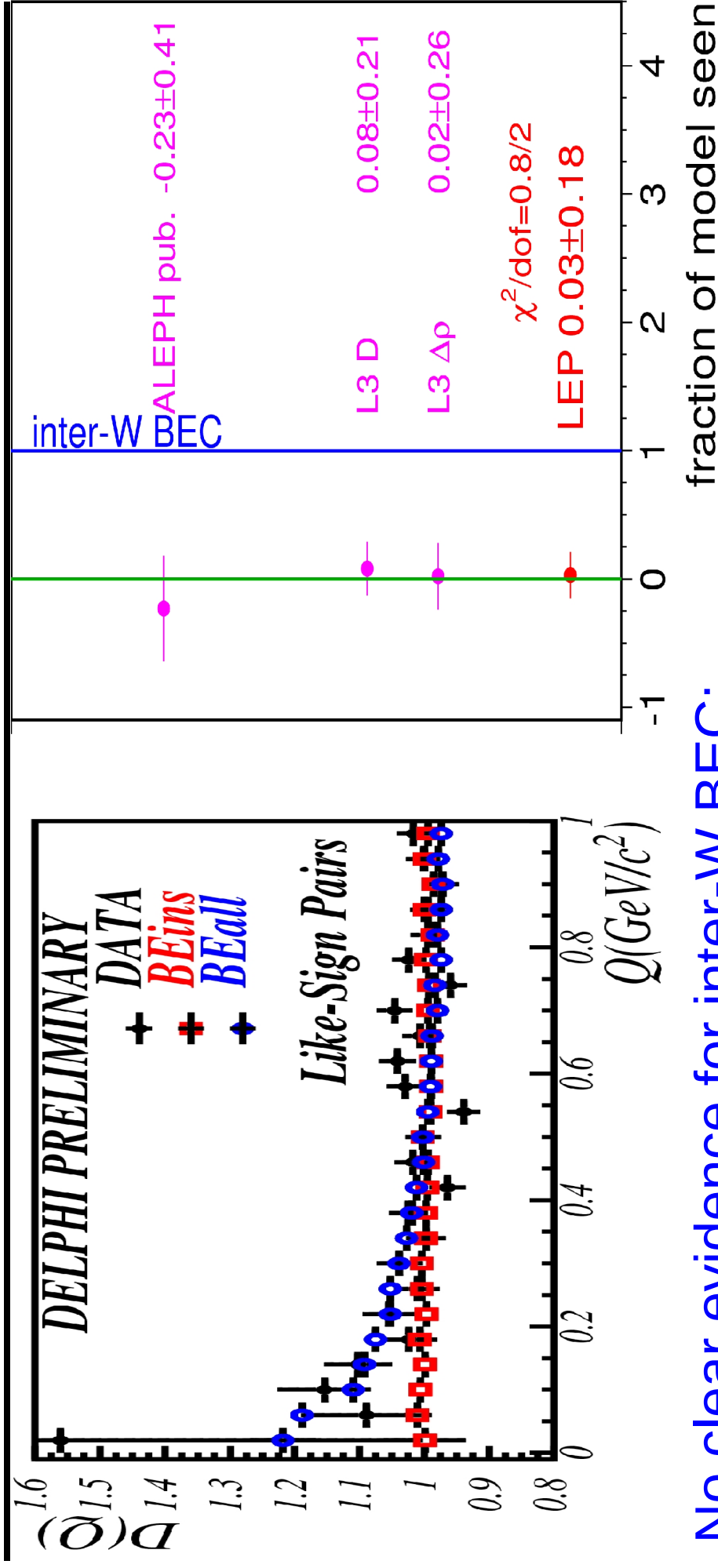
W-pairs: $W W \rightarrow qq qq$

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

$\Rightarrow D(Q)$: 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

$\Delta M_W(\text{qqqq}) < 10 \text{ MeV}$ (at 68% CL) for this model

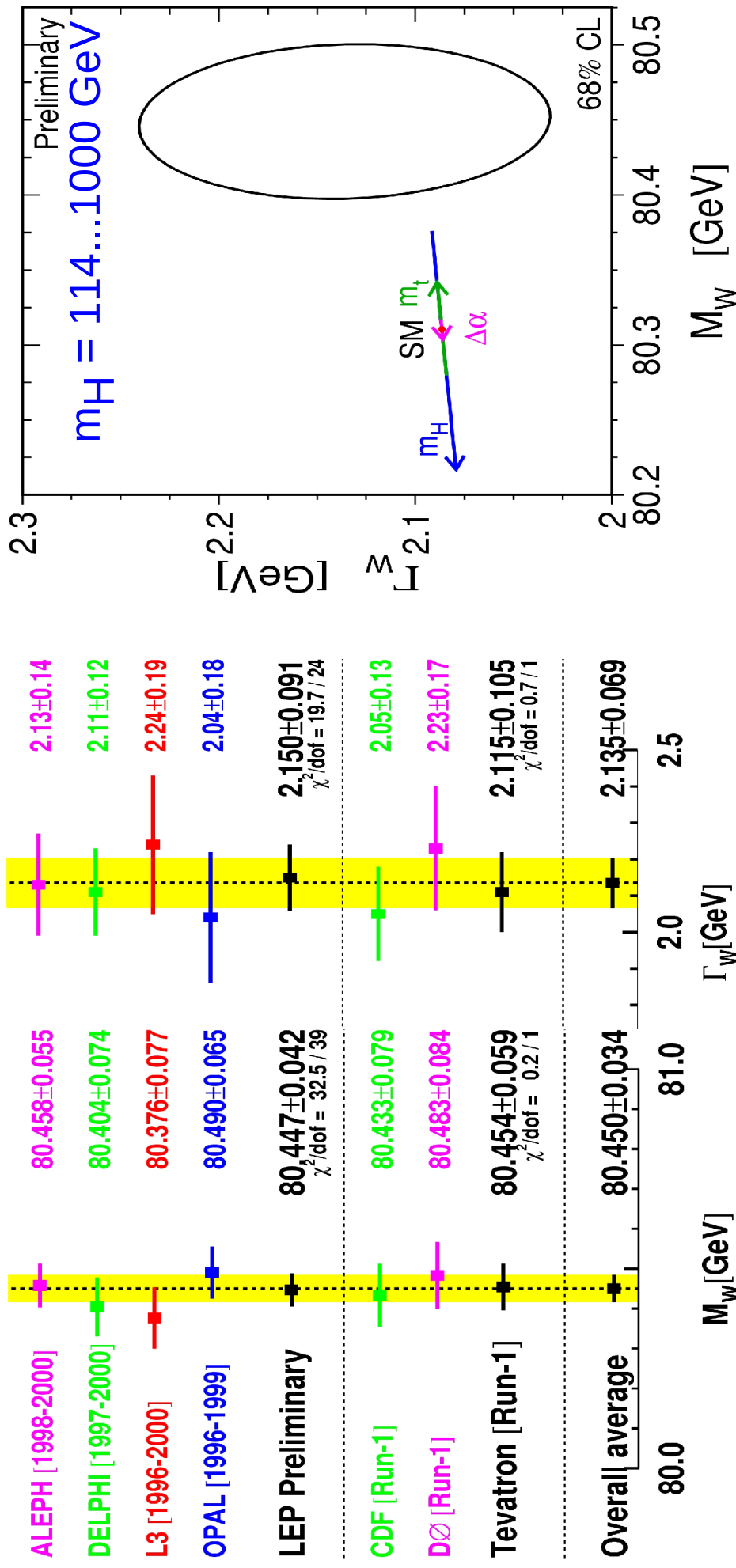
Other BEC models need to be studied:

Current error on $M_W(\text{qqqq})$ due to BEC is 35 MeV

W Boson – Mass and Width

Mass difference (calculated without FSI errors):

$$M_W(qqqq) - M_W(qql\nu) = 9 \pm 44 \text{ MeV}$$



Very good agreement
between the experiments

SM comparison:

Small Higgs-boson mass₂₉

Global Standard-Model Analysis

SM: Each observable calculated as a function of:

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

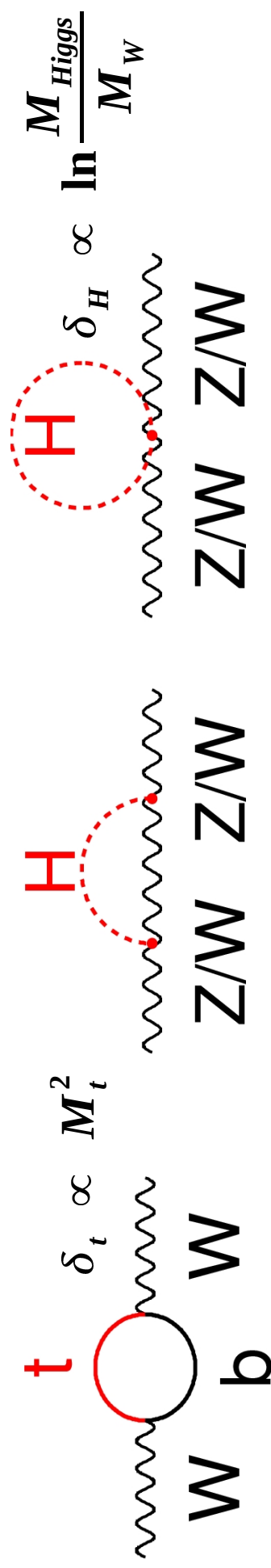
$\Delta\alpha_{\text{had}}$: hadronic vacuum polarisation [0.02761(36)]

$\alpha_S(M_Z)$: 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!



Calculations by programs TOPAZ0 and ZFITTER

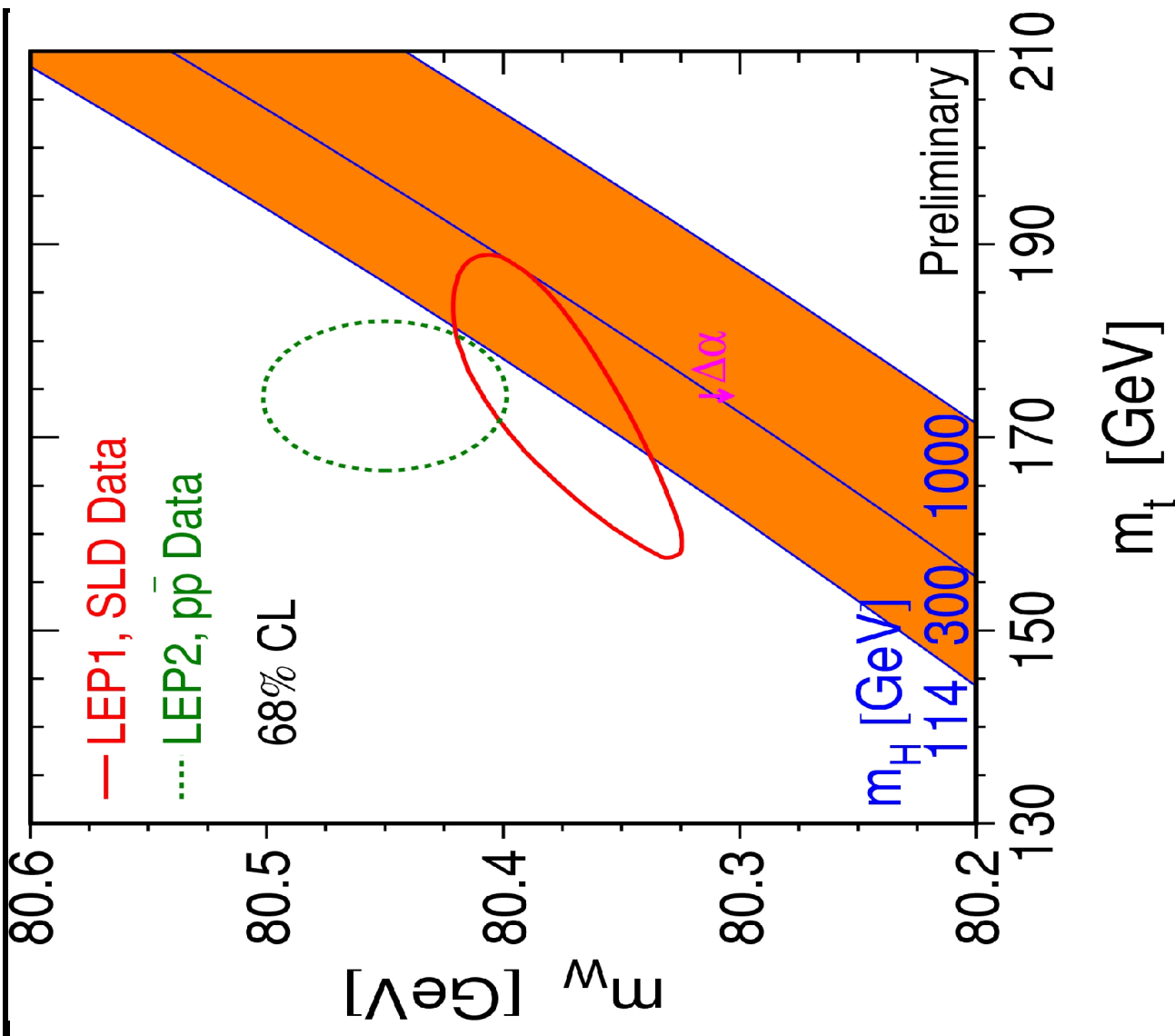
Prediction of Heavy Particle Masses W and top

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:

$$\chi^2/\text{ndof} = 29.7/15 \text{ (1.3\%)}$$

Largest χ^2 contribution:

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

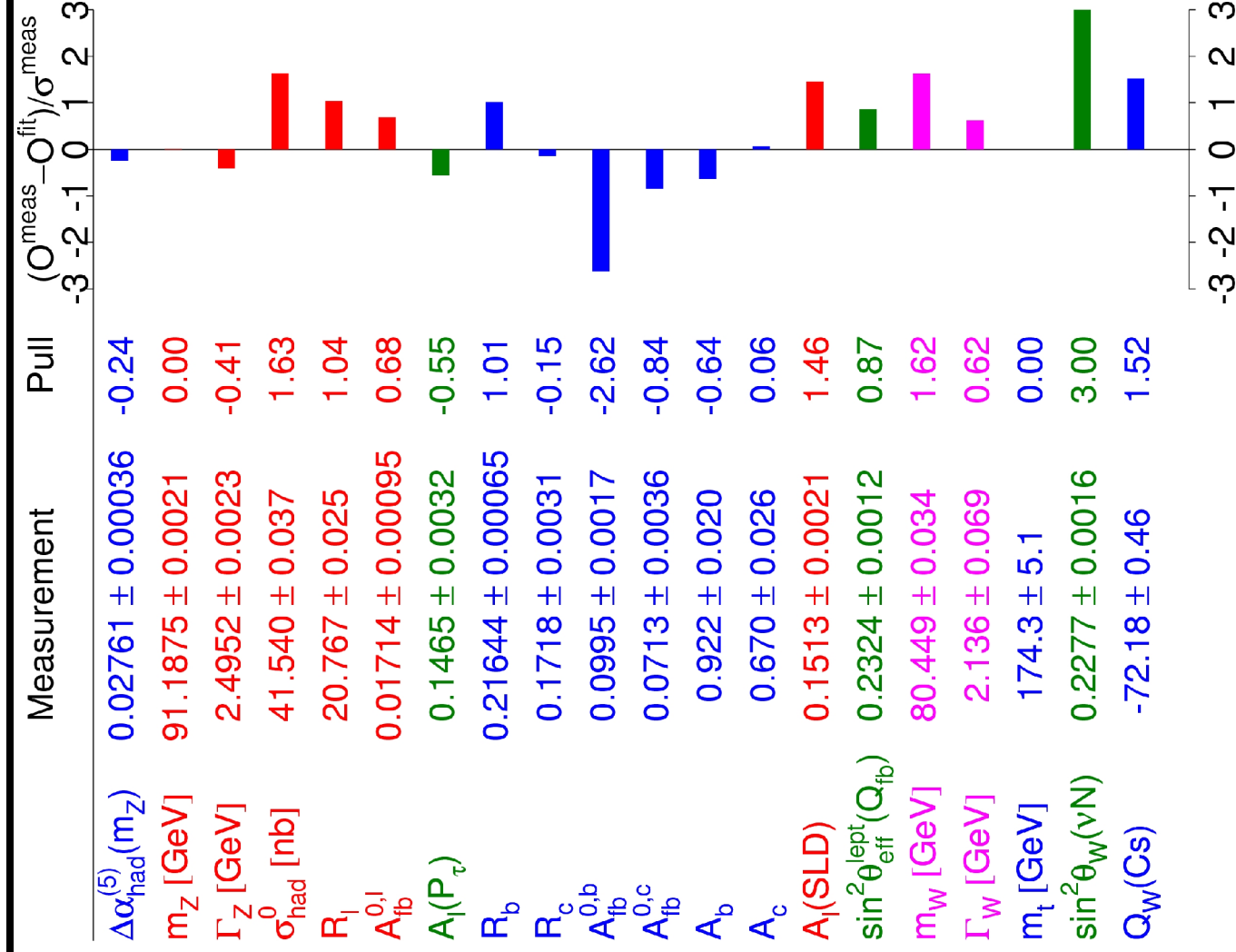
Spread of $\sin^2\Theta_{\text{eff}}$

Fit without NuTeV:

$$\chi^2/\text{ndof} = 20.5/14 \text{ (11.4\%)}$$

Fit result is robust:

Fitted parameters
almost unchanged!



Constraints on the SM Higgs-Boson Mass

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

Incl. theory uncertainty:

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

Strongly correlated:

+0.7 with fitted M_{top}

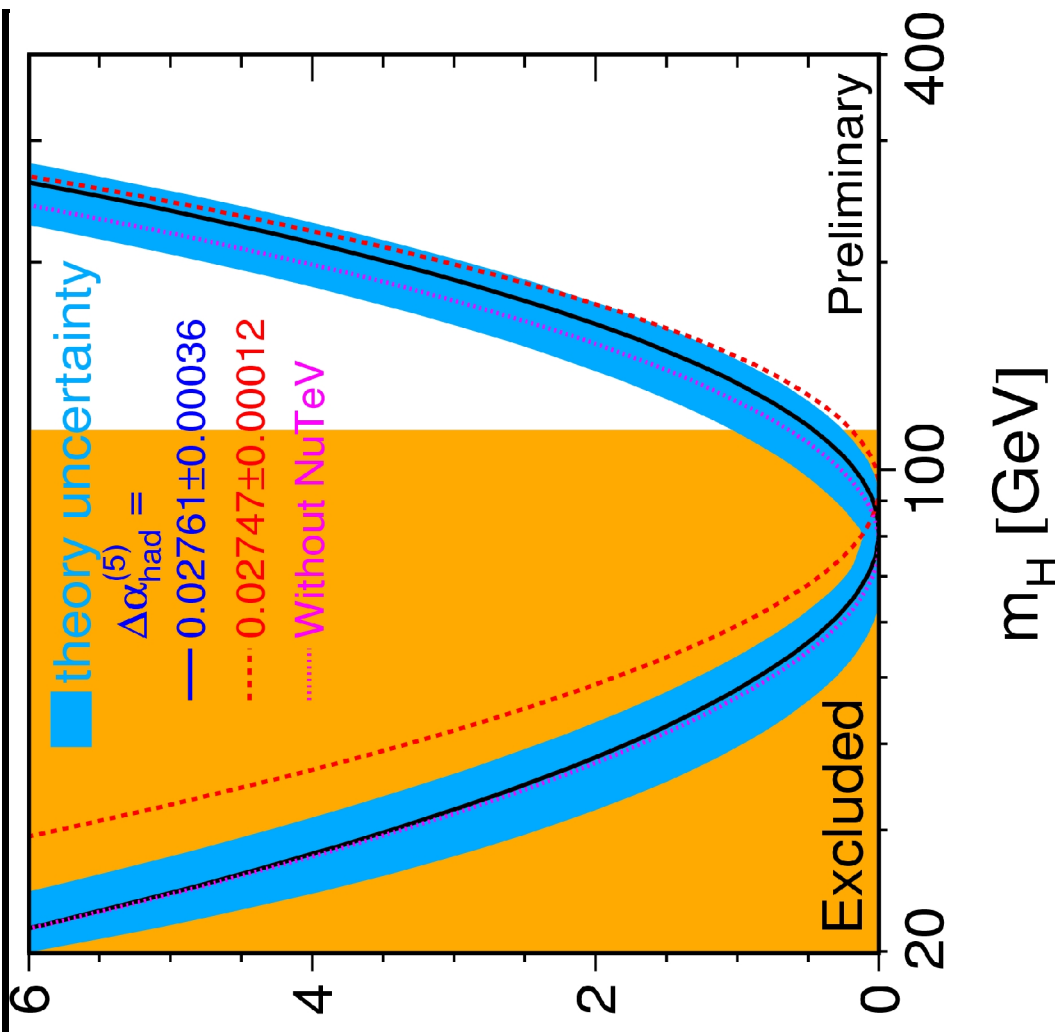
35% shift in M_{Higgs} for

5 GeV shift in meas. M_{top}

M_{top} measurement crucial!

Direct Higgs search limit:

No contradiction!



Theory uncertainty:

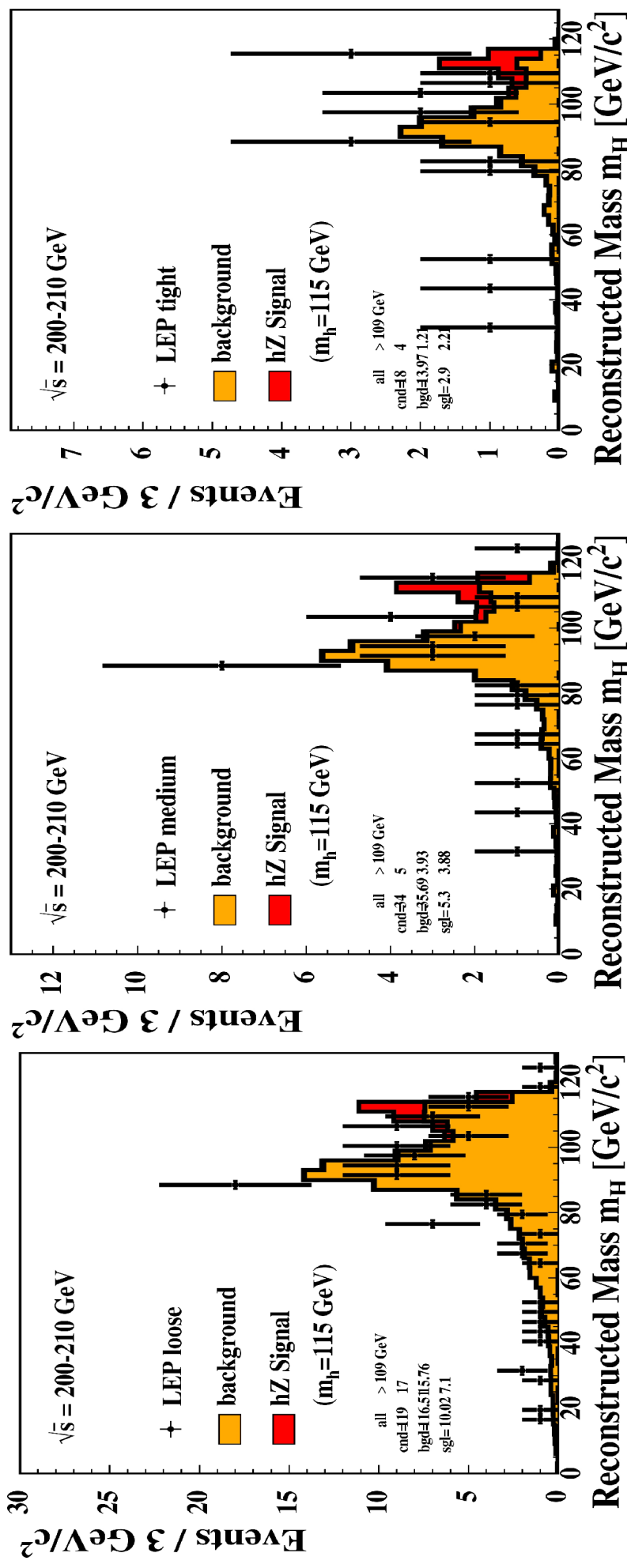
Need two-loop

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

Direct Search for the SM Higgs Boson

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

Selection (mass independent) and mass reconstruction

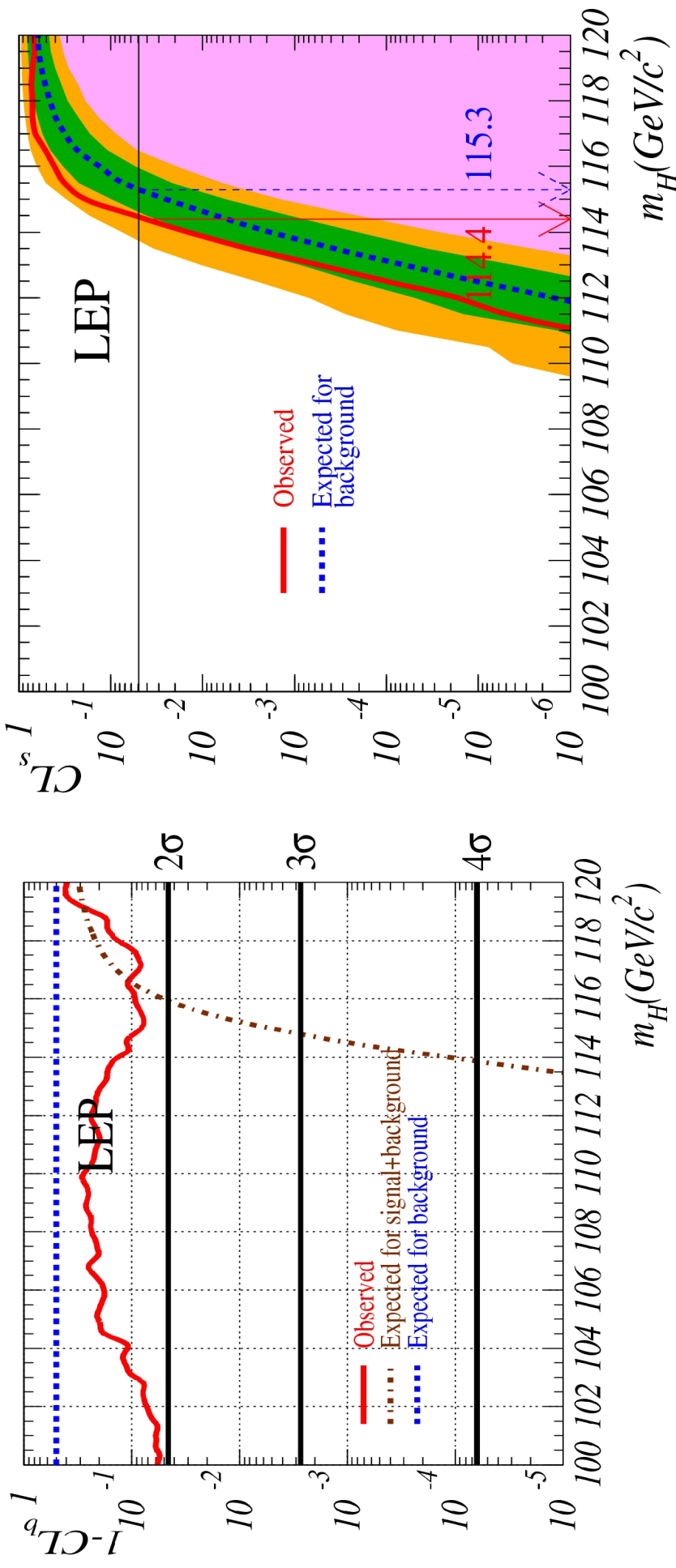


Full statistical analysis for search based on:

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.):

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

Since 2001: TEVATRON

Run-2 for CDF and DØ:

1.96 TeV $p\bar{p}$ cm energy

Expect:

15 fb^{-1} / experiment

M_W to 25 MeV

M_{top} to 2.5 GeV

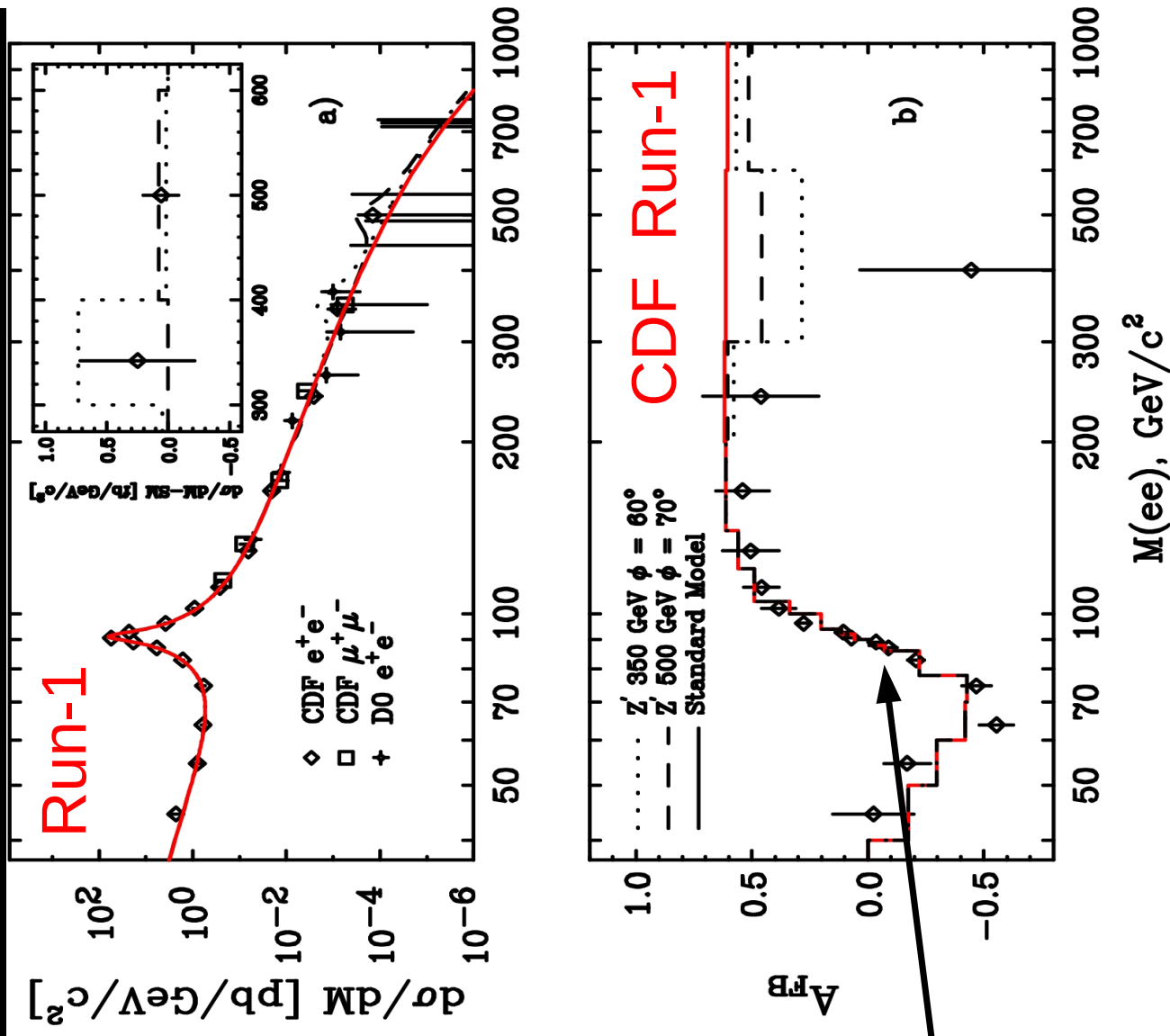
$\Rightarrow$ 30% M_H prediction

Gauge couplings,

$\Gamma_W, \Gamma_t,$

$\sin^2\Theta_{\text{eff}}(A_{\text{FB}} Z \rightarrow l^+l^-)$

Need precise PDFs, MEs,
with uncertainties



Future Higgs Search

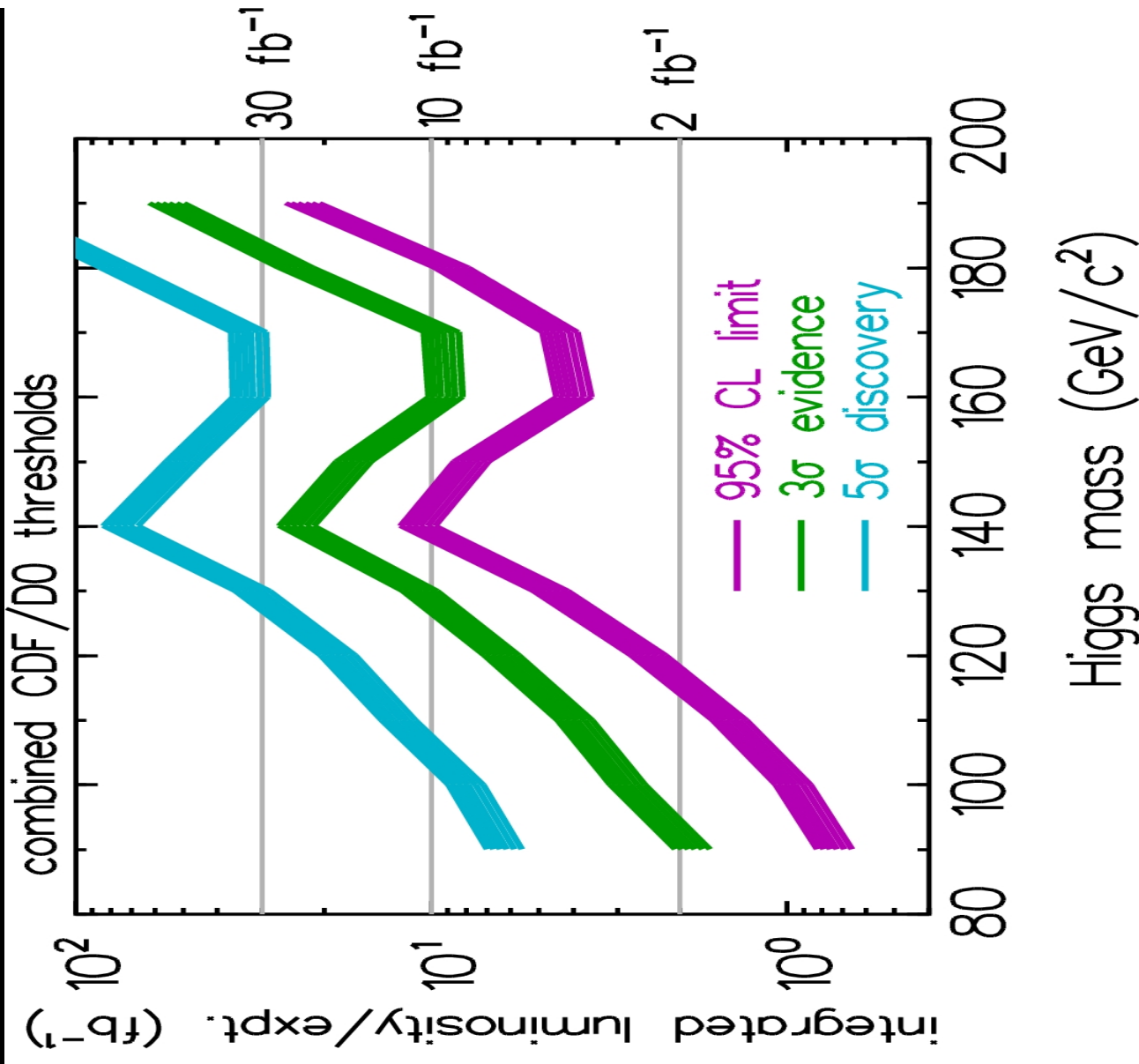
TEVATRON:

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 $\sin^2\Theta_{\text{eff}}$ and NuTeV's R_{e} result

Future:

Precise theoretical calculations - incl. uncertainties

Improved measurements, esp. top, W , $\Delta\alpha_{\text{had}}$, $\sin^2\Theta_{\text{eff}}$

Tevatron, LHC, LC, . . .

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