10. Elektroschwache Vereinheitlichung

10.1 Die Glashow-Salam-Weinberg Theorie

10.2 Vorhersagen von Massen und Kopplungen
- Massenrelationen
- Kopplungen, Verzweigungsverhältnisse für W- und Z-Zerfälle
- Strahlungskorrekturen

10.3 Experimentelle Tests der GSW-Theorie bei LEP

10.4 Messungen der W-Masse, Test der Konsistenz des Standardmodells

10.5 Test des Standardmodells in seltenen B-Meson-Zerfällen

Important Milestones towards Electroweak Unification

1961	S. Glashow proposes an electroweak gauge theory, Introduction of massive $W^{\pm}$ and Z^0 bosons, to explain the large difference in strength of electromagnetic and weak interactions. Key question: how acquire W and Z bosons mass?
1964	R. Brout, F. Englert and P. Higgs demonstrate that mass terms for gauge bosons can be introduced in local gauge invariant theories via spontaneous symmetry breaking
1967	S. Weinberg and A. Salam use Brout-Englert-Higgs mechanism to introduce mass terms for W and Z bosons in Glashow's theory → GSW theory (Glashow, Salam, Weinberg) → mass terms for W, Z bosons, γ remains massless → Higgs particle (see chapter 7)
1973	G. t'Hooft and M. Veltman show that GSW theory is renormalizable Discovery of 'weak neutral` currents in neutrino scattering at CERN
1979	Nobel prize for S. Glashow, A. Salam and S. Weinberg
1983	Experimental discovery of the W and Z bosons by UA1 and UA2 experiments at the CERN ppbar collider ($\sqrt{s}$ = 540 GeV)
1990-2000	Precision test of the electroweak theory at LEP
1999	Nobel prize for G. t'Hooft and M. Veltman
2012	Discovery of a Higgs particle by the ATLAS and CMS experiments at the LHC
2013	Nobel prize for F. Englert and P. Higgs

Weak Isospin and Hypercharge Quantum

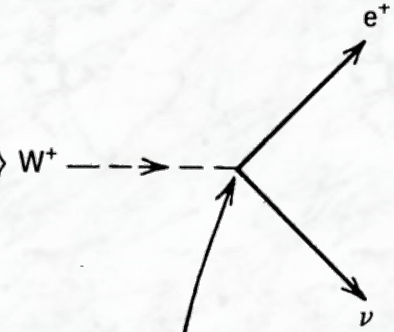
Lepton	T	T^3	Q	Y
ν_e	$\frac{1}{2}$	$\frac{1}{2}$	0	-1
e_L^-	$\frac{1}{2}$	$-\frac{1}{2}$	-1	-1
e_R^-	0	0	-1	-2

Numbers of Leptons and Quarks

Quark	T	T^3	Q	Y
u_L	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{2}{3}$	$\frac{1}{3}$
d_L	$\frac{1}{2}$	-$\frac{1}{2}$	-$\frac{1}{3}$	$\frac{1}{3}$
u_R	0	0	$\frac{2}{3}$	$\frac{4}{3}$
d_R	0	0	-$\frac{1}{3}$	-$\frac{2}{3}$

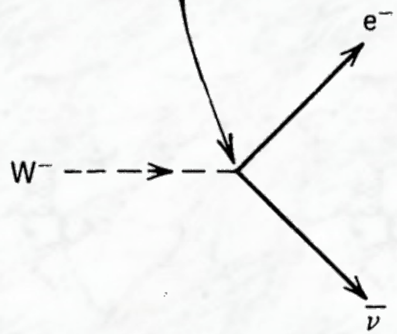
W and Z vertex factors

$$-i\frac{g}{\sqrt{2}}\left(\bar{\chi}_L\gamma^\mu\tau_+\chi_L\right)W_\mu^+$$
$$= -i\frac{g}{\sqrt{2}}\left(\bar{\nu}_L\gamma^\mu e_L\right)W_\mu^+$$



$$-i\frac{g}{\sqrt{2}}\gamma^\mu\tfrac{1}{2}\left(1-\gamma^5\right)$$

$$-i\frac{g}{\sqrt{2}}\left(\bar{\chi}_L\gamma^\mu\tau_-\chi_L\right)W_\mu^-$$
$$= -i\frac{g}{\sqrt{2}}\left(\bar{e}_L\gamma^\mu\nu_L\right)W_\mu^-$$



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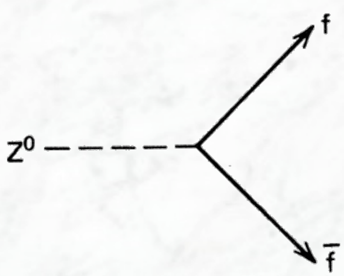


$$-i\frac{g}{\cos\theta_W}\gamma^\mu\tfrac{1}{2}\left(c_V^f-c_A^f\gamma^5\right).$$

The Z → ff vertex factors in the Standard Model

($\sin^2 \theta_W$ is assumed to be 0.234)

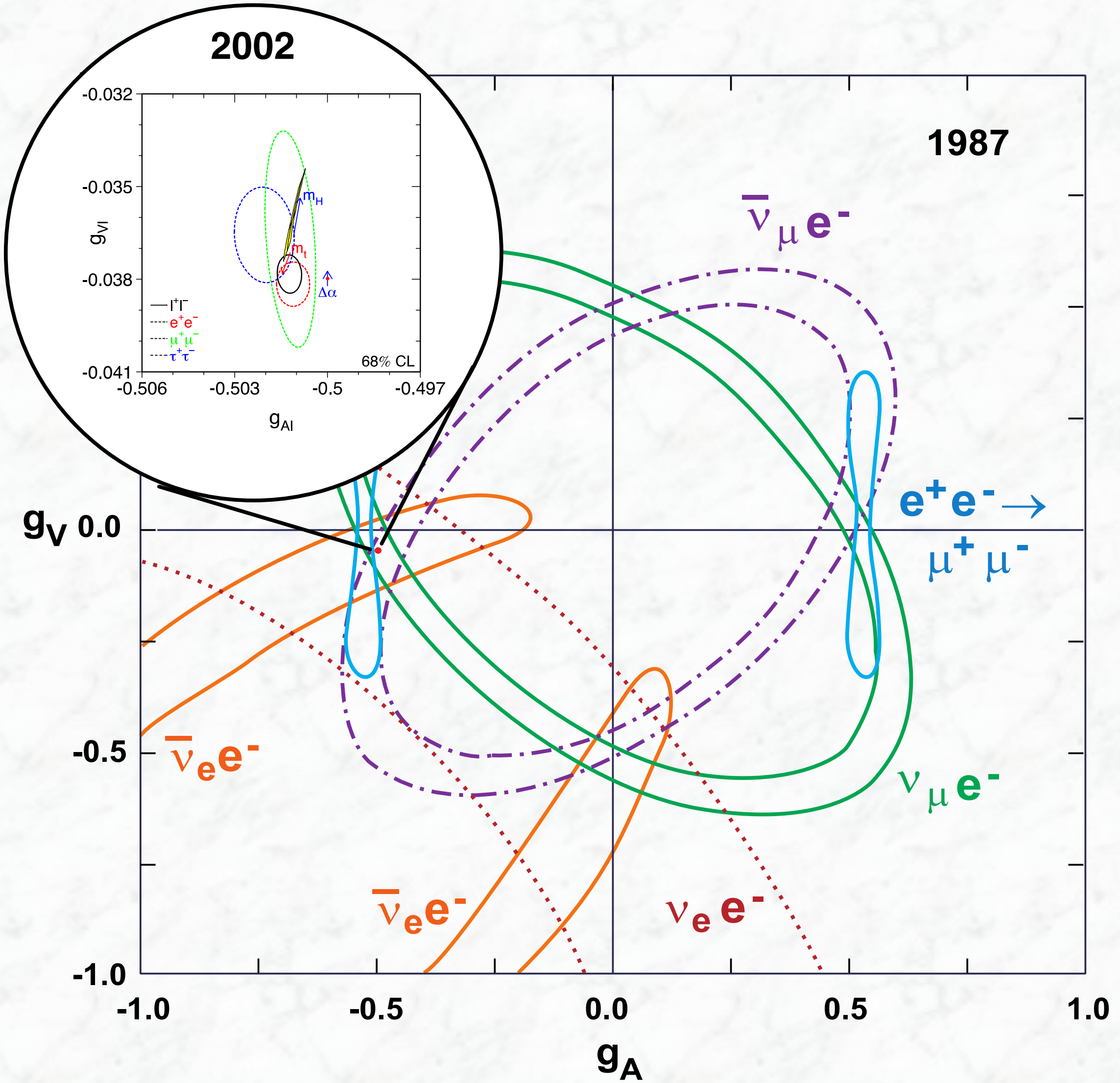
$\mathbf{f}$	$\mathbf{Q}_f$	$\mathbf{c}_A^f$	$\mathbf{c}_V^f$
$\nu_e, \nu_\mu, \ldots$	0	$\frac{1}{2}$	$\frac{1}{2}$
$e \quad , \mu \quad , \ldots$	-1	$-\frac{1}{2}$	$-\frac{1}{2} + 2\sin^2\theta_W \quad 0.03$
$u, c, \ldots$	$\frac{2}{3}$	$\frac{1}{2}$	$\frac{1}{2} \quad \frac{4}{3}\sin^2\theta_W \quad 0.19$
$d, s, \ldots$	$-\frac{1}{3}$	$-\frac{1}{2}$	$-\frac{1}{2} + \frac{2}{3}\sin^2\theta_W \quad 0.34$

10.3 Summary of electroweak precision tests at LEP

- Results of 30 years of experimental and theoretical progress

- The electroweak theory is tested at the level of 10^{-4}

(g_A and g_V = axial vector and vector coupling factors)



LEP am CERN / Genf

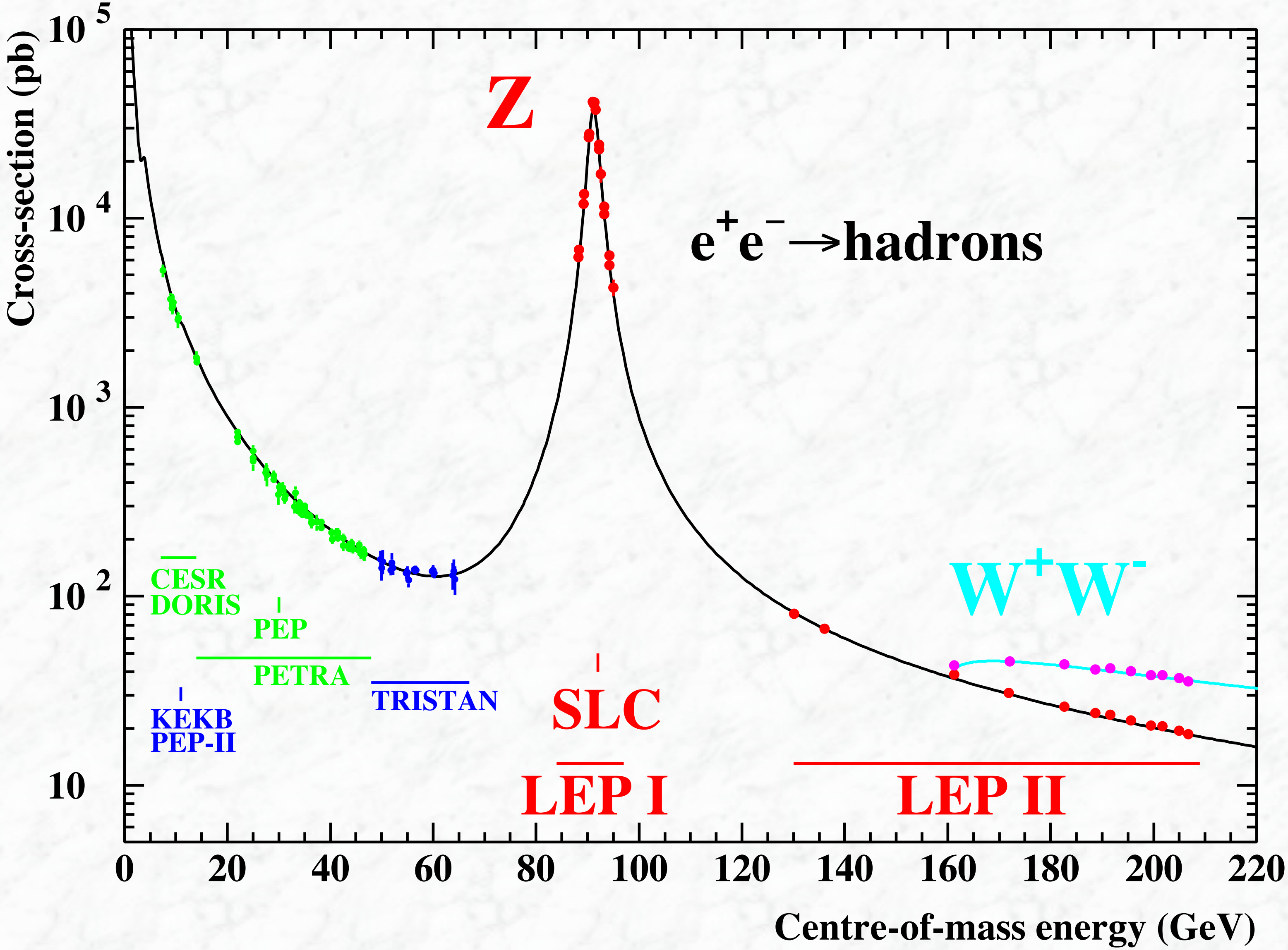
e^+e^--Beschleuniger, 27 km Umfang

Schwerpunktsenergie: LEP-I (1989-1995) 91 GeV

LEP-II (1996-2000) → 208 GeV

4 Experimente: ALEPH, DELPHI, L3, OPAL

Cross sections for W and Z boson production



Precision tests of the Z sector

Tests of the W sector

Cross section for $e^+e^- \rightarrow \mu^+\mu^-$ at LEP I

$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2}{2s}\left[F_\gamma(\cos\theta) + F_{\gamma Z}(\cos\theta)\frac{s(s-M_Z^2)}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2} + F_Z(\cos\theta)\frac{s^2}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}\right]$$

γ — γ/Z interference — Z

vanishes at $\sqrt{s} \approx M_Z$

$$F_\gamma(\cos\theta) = Q_e^2 Q_\mu^2 (1+\cos^2\theta) = (1+\cos^2\theta)$$

$$F_{\gamma Z}(\cos\theta) = \frac{Q_e Q_\mu}{4\sin^2\theta_W\cos^2\theta_W}[2g_V^e g_V^\mu(1+\cos^2\theta) + 4g_A^e g_A^\mu\cos\theta]$$

$$F_Z(\cos\theta) = \frac{1}{16\sin^4\theta_W\cos^4\theta_W}[(g_V^{e^2}+g_A^{e^2})(g_V^{\mu^2}+g_A^{\mu^2})(1+\cos^2\theta) + 8g_V^e g_A^e g_V^\mu g_A^\mu\cos\theta]$$

$\alpha = \alpha(m_Z)$: running electromagnetic coupling [$\alpha(m_Z) = \alpha/(1-\Delta\alpha)$ with $\Delta\alpha \approx 0.06$]

g_V, g_A = c_V, c_A: effective coupling constants (vector and axial vector)

Cross section for $e^+e^- \rightarrow f\bar{f}$ at LEP I

$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2}{2s}\left[F_\gamma(\cos\theta) + F_{\gamma Z}(\cos\theta)\frac{s(s-M_Z^2)}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2} + F_Z(\cos\theta)\frac{s^2}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}\right]$$

γ γ/Z interference Z

γ/Z interference: vanishes at $\sqrt{s} \approx M_Z$

x N_C^f
number of colour degrees of freedom for fermion f

x $(1+\delta_{QCD})$
QCD correction term

$$F_\gamma(\cos\theta) = Q_e^2 Q_f^2 (1+\cos^2\theta) = (1+\cos^2\theta)$$

$$F_{\gamma Z}(\cos\theta) = \frac{Q_e Q_f}{4\sin^2\theta_W\cos^2\theta_W}\left[2g_V^e g_V^\mu(1+\cos^2\theta) + 4g_A^e g_A^f\cos\theta\right]$$

$$F_Z(\cos\theta) = \frac{1}{16\sin^4\theta_W\cos^4\theta_W}\left[({g_V^e}^2+{g_A^e}^2)({g_V^f}^2+{g_A^f}^2)(1+\cos^2\theta) + 8g_V^e g_A^e g_V^f g_A^f\cos\theta\right]$$

Cross section for $e^+e^- \rightarrow f\bar{f}$ on resonance ($\sqrt{s} = m_Z$)

- On resonance, $\sqrt{s} = m_Z$:
  - γ^*/Z interference terms vanishes
  - γ term contributes ~1%
  - Z contribution dominates !

- Contribution of the γ^*/Z interference term at $s = (M_Z - 3\text{ GeV})^2$: ~0.2%

Total cross section for $e^+e^- \rightarrow \mu^+\mu^-$ (integration over cos θ)

$$\sigma_{\text{tot}} \approx \sigma_Z = \frac{4\pi}{3s} \frac{\alpha^2}{16\sin^4\theta_W \cos^4\theta_W} \cdot [(g_V^e)^2 + (g_A^e)^2][(g_V^\mu)^2 + (g_A^\mu)^2] \cdot \frac{s^2}{(s - M_Z^2)^2 + (M_Z\Gamma_Z)^2}$$

$$\sigma_Z(\sqrt{s} = M_Z) = \frac{12\pi}{M_Z^2} \frac{\Gamma_e\Gamma_\mu}{\Gamma_Z^2}$$

Peak cross section

$$\Gamma_f = \frac{\alpha M_Z}{12\sin^2\theta_W \cos^2\theta_W} \cdot [(g_V^f)^2 + (g_A^f)^2]$$

Partial width

$$\Gamma_Z = \sum_i \Gamma_i$$

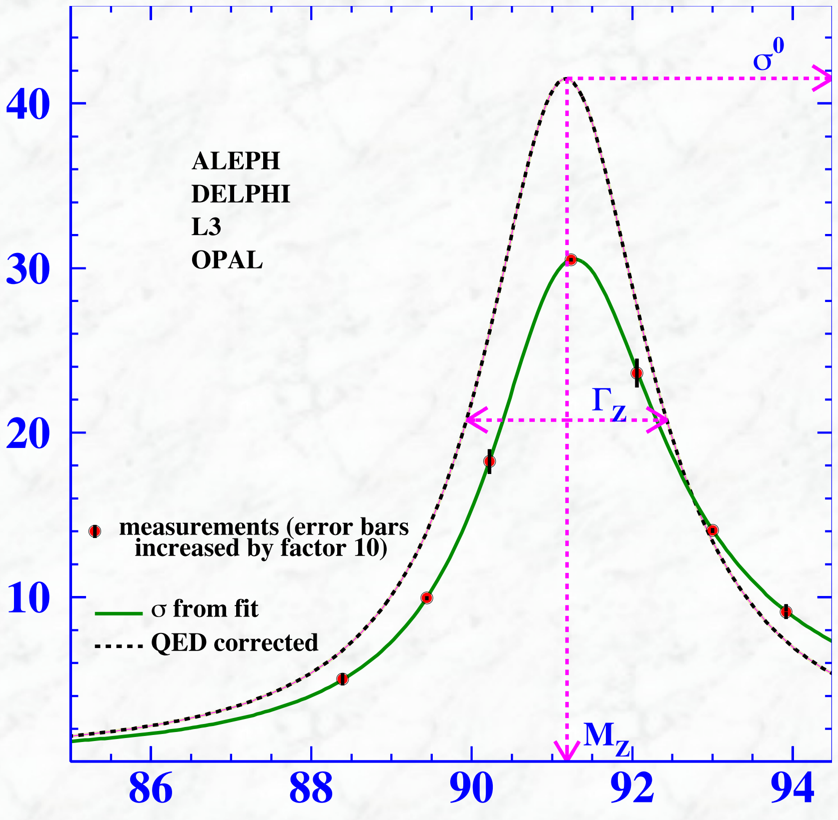
Total width

From the energy dependence of the total cross section (for various fermions f) the parameters

M_Z, Γ_Z, Γ_f

can be determined.

Measurement of the Z line-shape



Line shape (resonance curve):

$$\sigma(s) = 12\pi \frac{\Gamma_e \Gamma_\mu}{M_Z^2} \cdot \frac{s}{(s-M_Z^2)^2 + M_Z^2 \Gamma_Z^2}$$

Peak: $\sigma_0 = \frac{12\pi}{M_Z^2} \frac{\Gamma_e \Gamma_\mu}{\Gamma_Z^2}$

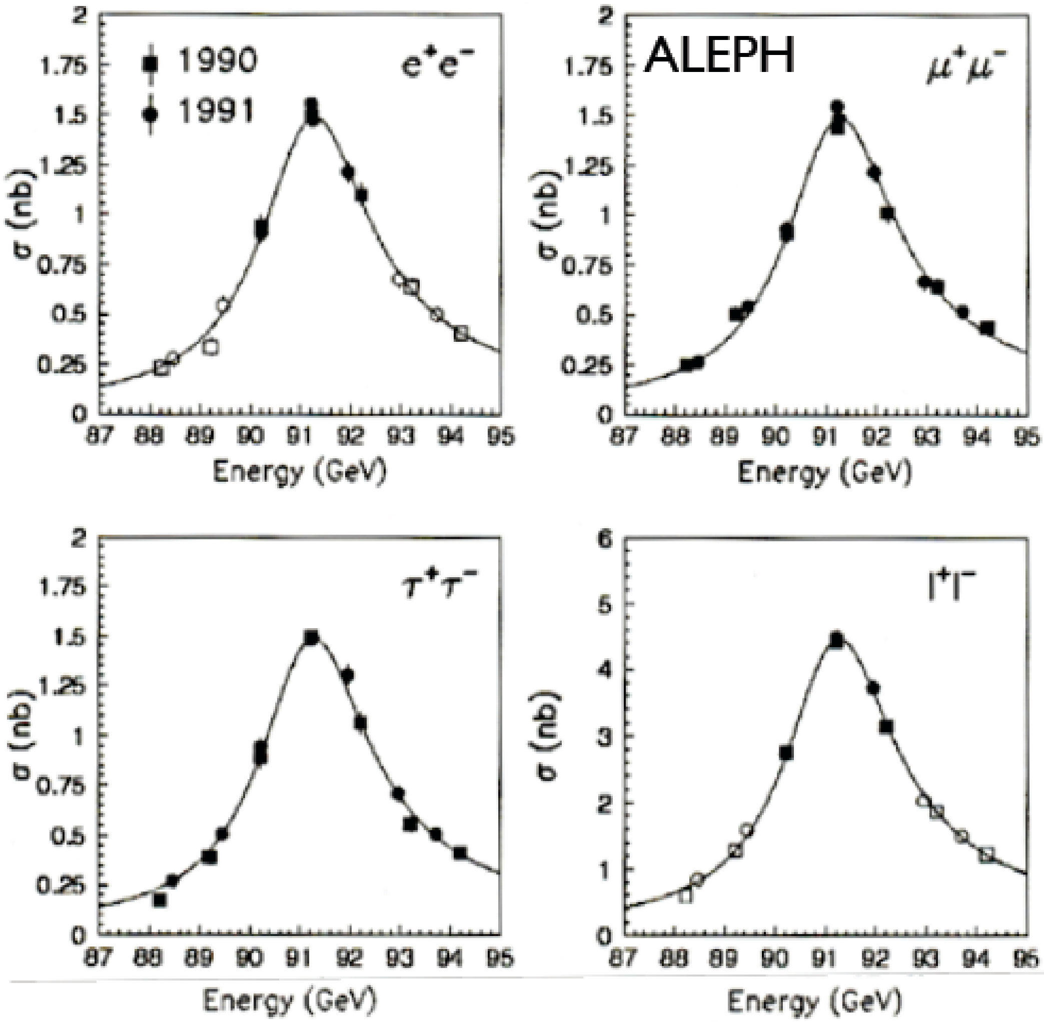
- Position of maximum $\rightarrow$ M_Z
- Full width at half maximum $\rightarrow$ Γ_Z
- Peak cross section σ_0 $\rightarrow$ $\Gamma_e \Gamma_\mu$

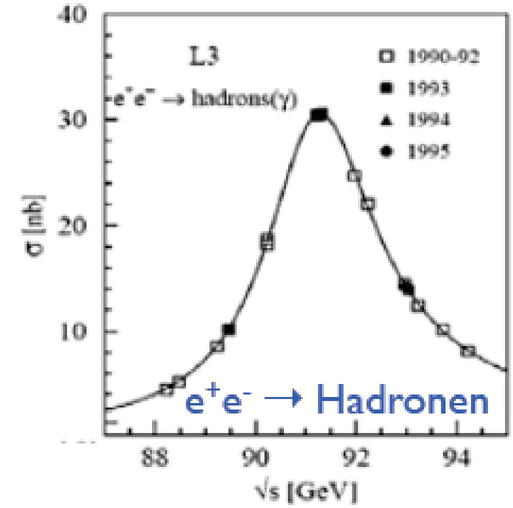
Radiative corrections (photon radiation) important

with ISR (initial state radiation)

without ISR

Measurement of the Z line-shape (cont.)





Quark-Flavor i.a. nicht exp. trennbar
(Ausnahme: c,b → Lebendsdauer)
⇒ had. Breite: $\Gamma_{had} = \Gamma_u + \Gamma_d + \Gamma_s + \Gamma_c + \Gamma_b$

Messe Verhältnisse der Pol-WQ:

$$R_l^0 \equiv \frac{\Gamma_{had}}{\Gamma_{ll}} \qquad l = e, \mu, \tau$$

$$R_q^0 \equiv \frac{\Gamma_{qq}}{\Gamma_{had}} \qquad q = b, c$$

- Keine Unterschiede für verschiedene Leptonarten ⇒ Leptonuniversalität
- Form der Resonanzenkurve für alle Endzustände gleich (gleicher Propagator!)

Results on Z line-shape parameters

M_Z = 91.1876 ± 0.0021 GeV 23 ppm (*)

Γ_Z = 2.4952 ± 0.0023 GeV
Γ_{had} = 1.7458 ± 0.0027 GeV
Γ_e = 0.08392 ± 0.00012 GeV
Γ_μ = 0.08399 ± 0.00018 GeV
Γ_τ = 0.08408 ± 0.00022 GeV

3 lepton flavours treated independently

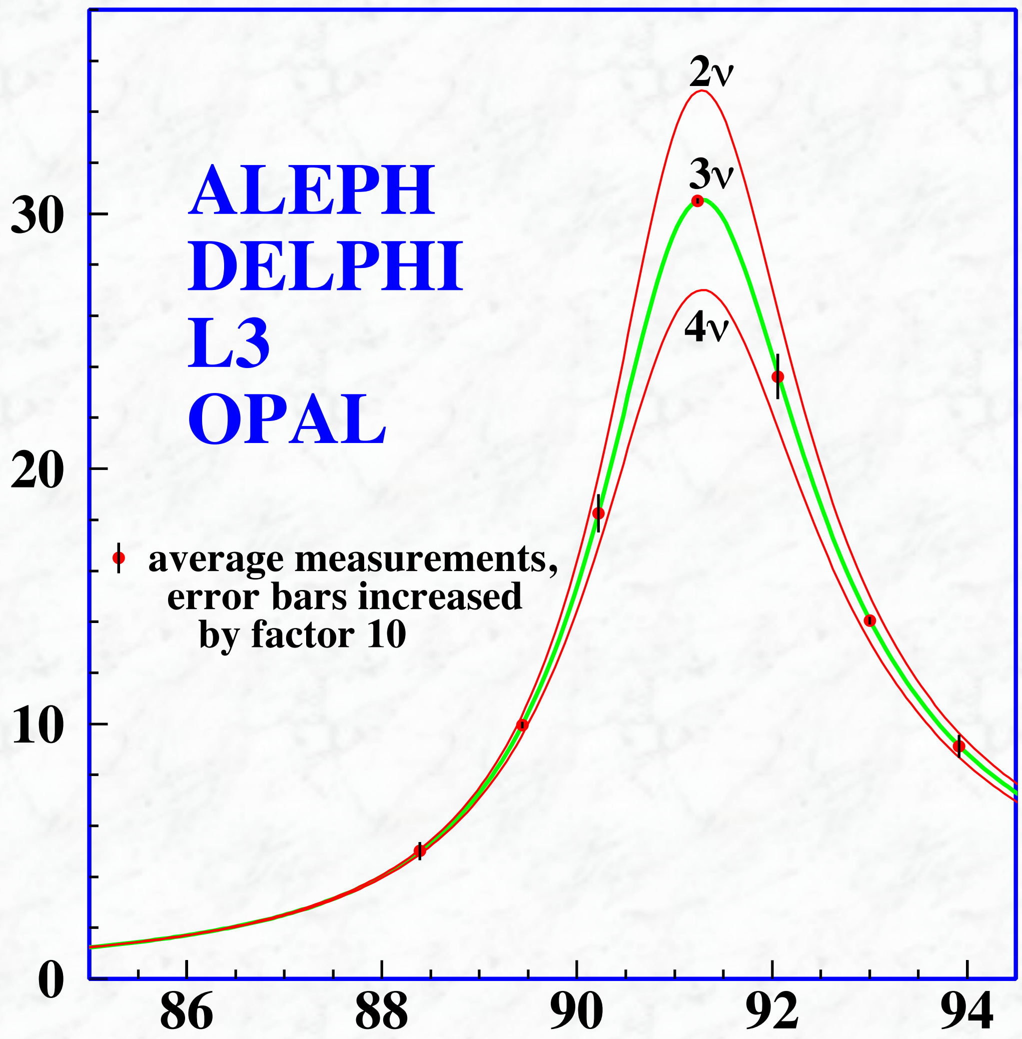
Test of lepton universality

Γ_Z = 2.4952 ± 0.0023 GeV
Γ_{had} = 1.7444 ± 0.0022 GeV
Γ_e = 0.083985 ± 0.000086 GeV

lepton universality assumed:
$\Gamma_e=\Gamma_\mu=\Gamma_\tau$

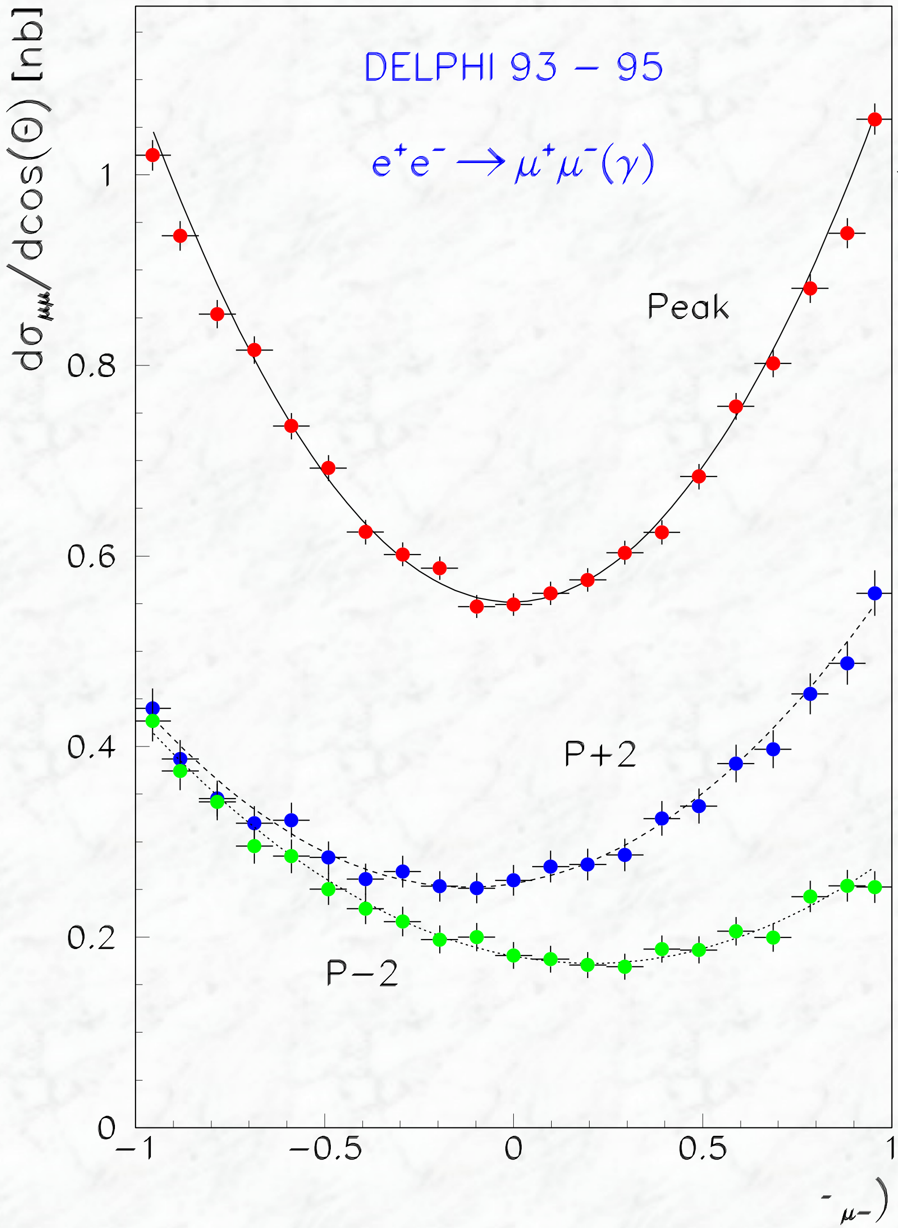
*) Uncertainty on LEP energy measurement: ± 1.7 MeV (19 ppm)

Number of neutrinos



$N_\nu = 2.9840 \pm 0.0082$

Forward-backward asymmetries



$$F_\gamma(\cos\theta) = Q_e^2 Q_\mu^2 (1+\cos^2\theta) = (1+\cos^2\theta)$$

$$F_{\gamma Z}(\cos\theta) = \frac{Q_e Q_\mu}{4\sin^2\theta_W \cos^2\theta_W}[2g_V^e g_V^\mu(1+\cos^2\theta) + 4g_A^e g_A^\mu \cos\theta]$$

$$F_Z(\cos\theta) = \frac{1}{16\sin^4\theta_W \cos^4\theta_W}[(g_V^{e^2}+g_A^{e^2})(g_V^{\mu^2}+g_A^{\mu^2})(1+\cos^2\theta) +$$

$$8g_V^e g_A^e g_V^\mu g_A^\mu \cos\theta]$$

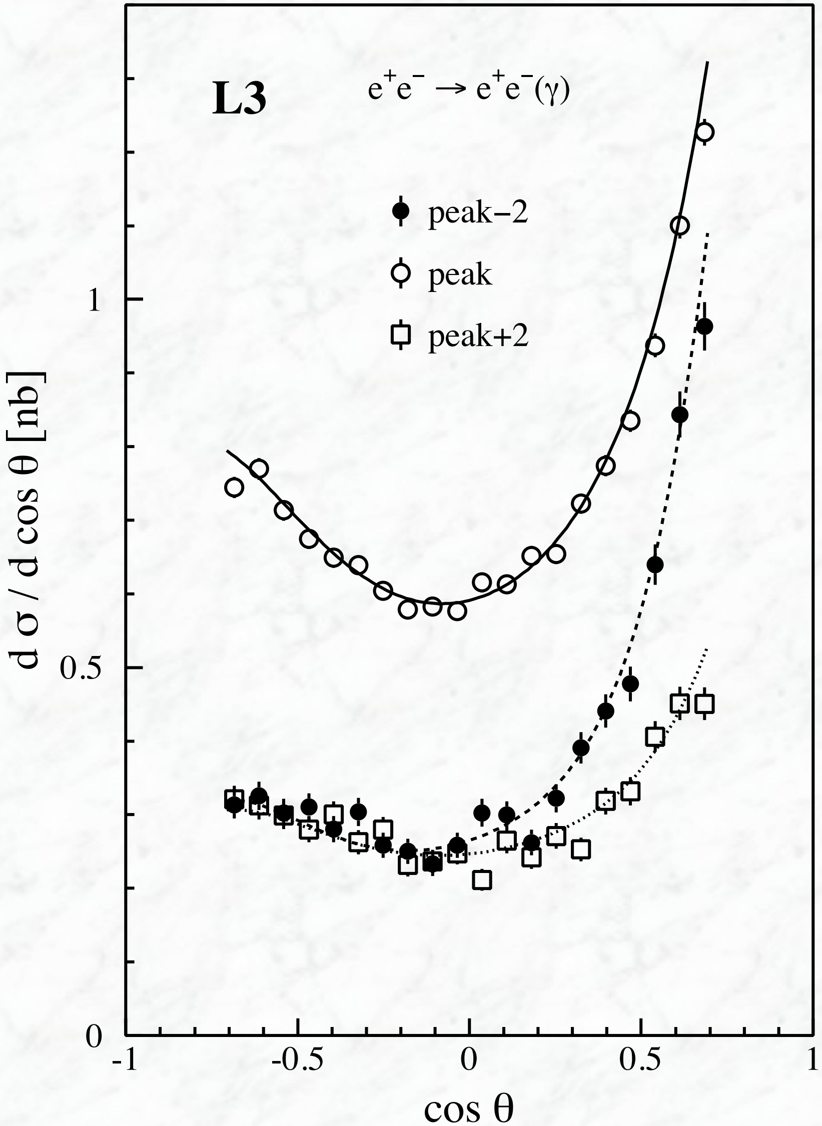
Terms $\propto \cos\theta$ in $d\sigma/d\cos\theta$
$\to$ asymmetry

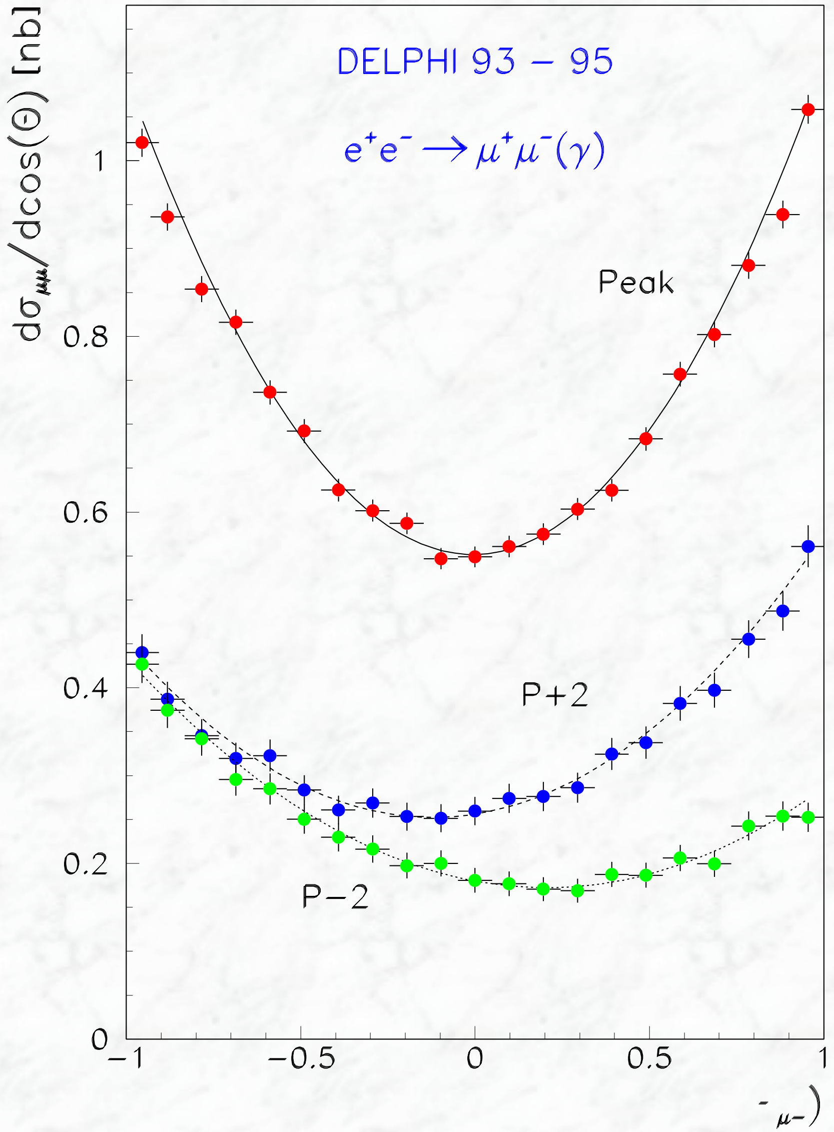
$$\sigma_{F(B)} = \int_{0(-1)}^{1(0)} \frac{d\sigma}{d\cos\theta} d\cos\theta$$

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

Forward-backward asymmetries

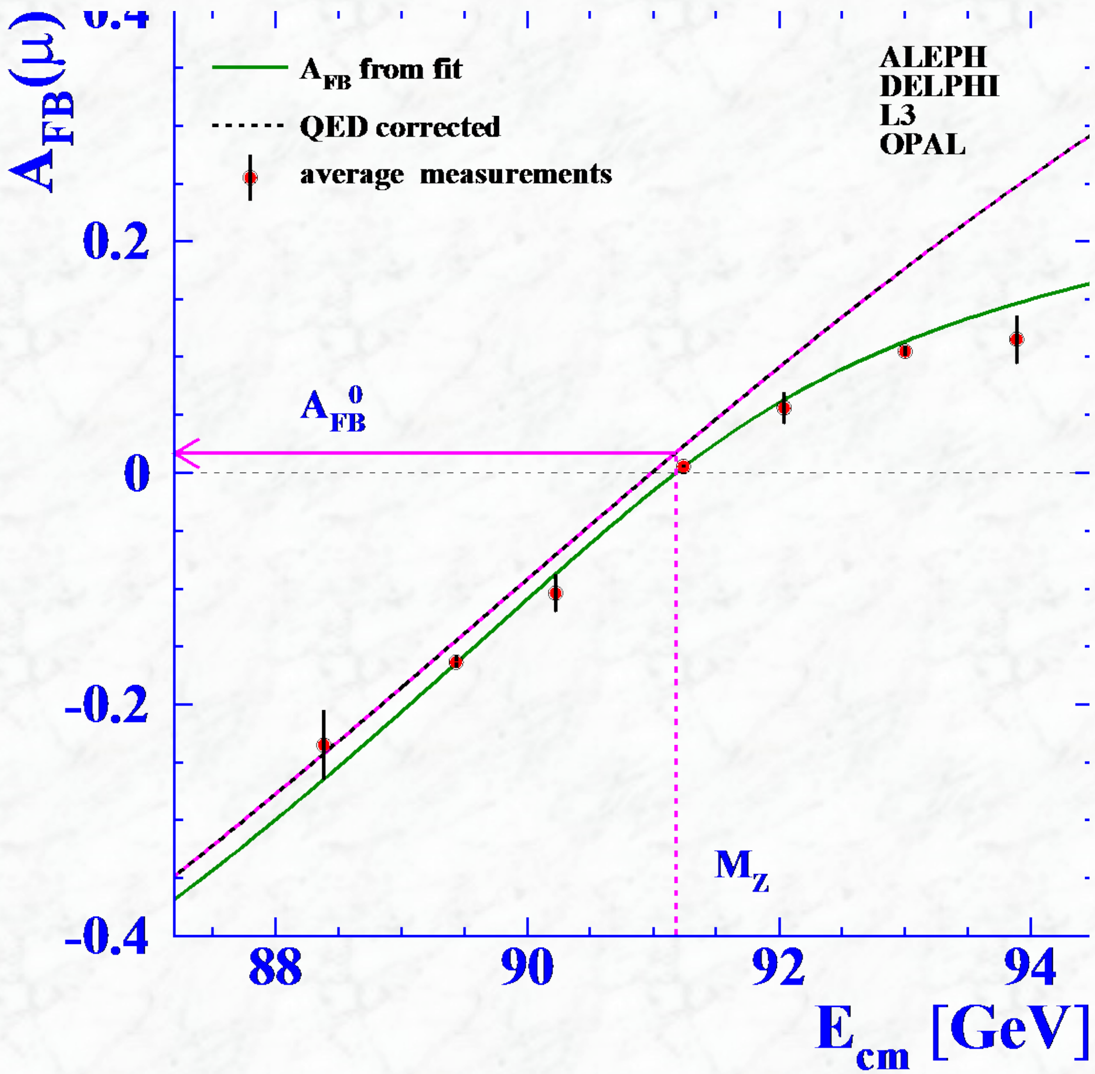
-comparison between ee and μμ final states-



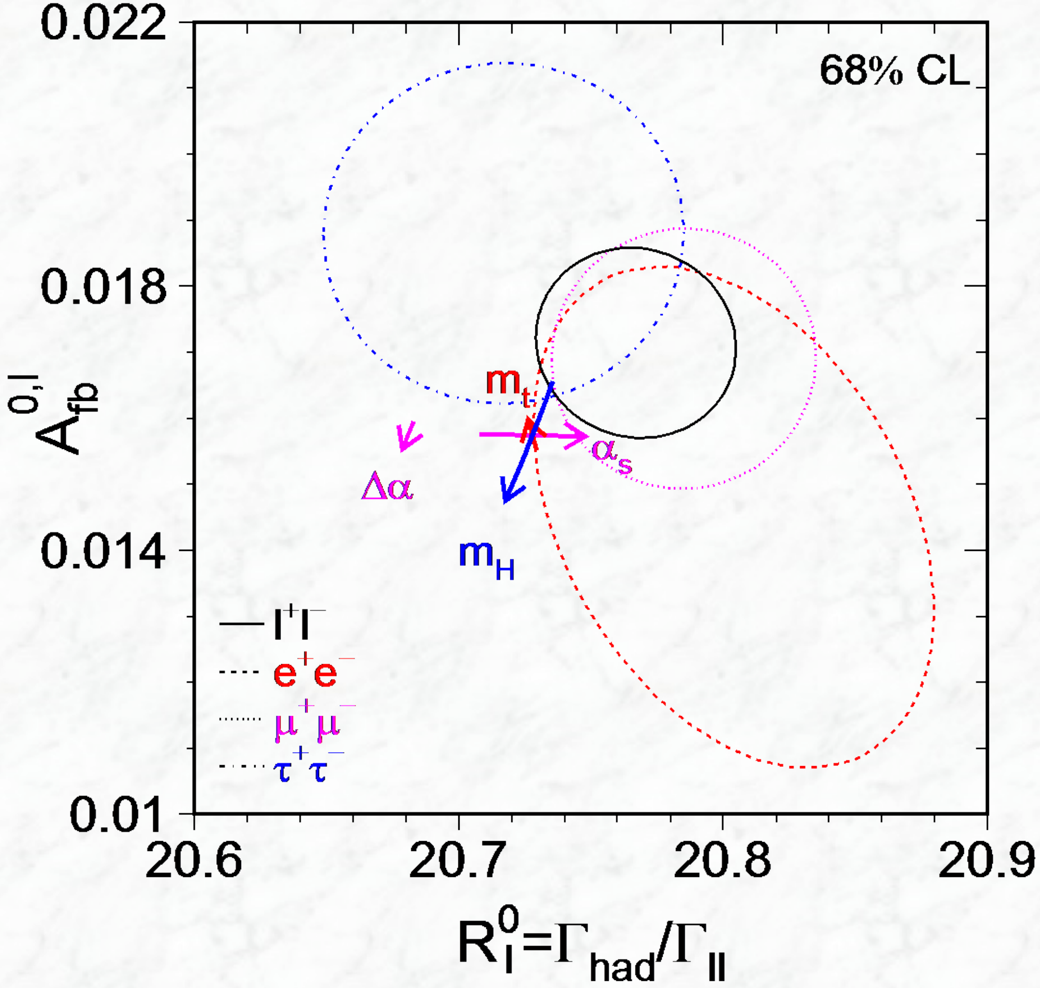


Forward-backward asymmetries

- $e^+e^- \rightarrow \mu^+\mu^-$ -



Hadronic versus leptonic branching ratios



Ratio of hadron-to-lepton pole cross sections versus forward-backward asymmetries

Forward-backward asymmetries and fermion couplings

- Asymmetry at the Z pole (no interference) is small

$$A_{\rm FB} \sim g_{\rm A}^e g_{\rm V}^e g_{\rm A}^f g_{\rm V}^f$$

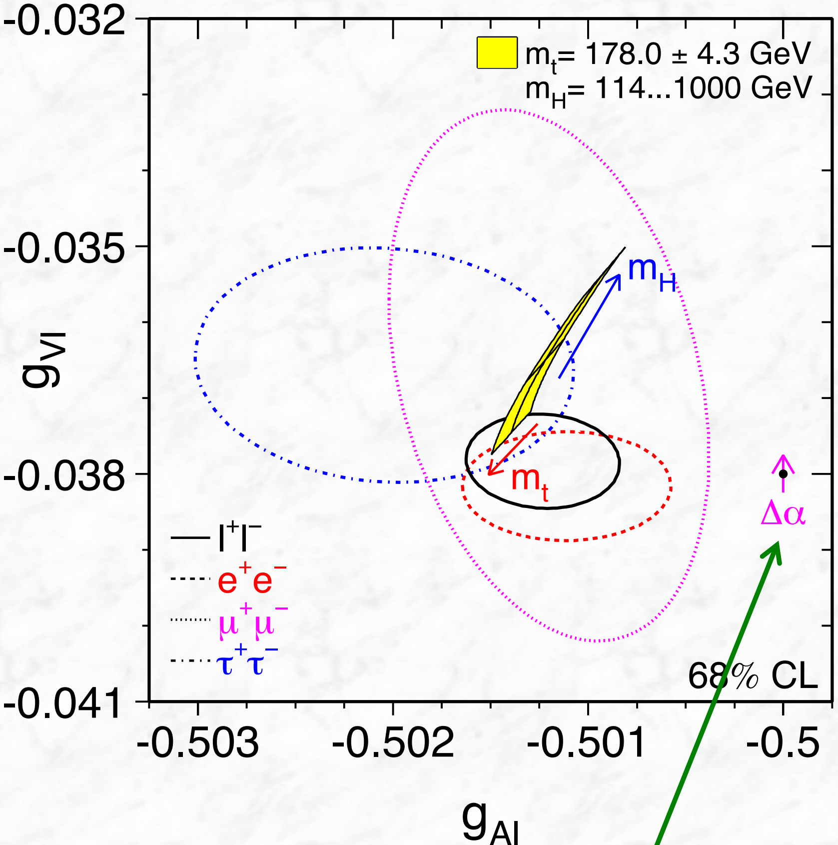
since g_V^f is small (in particular for leptons)

- For off-resonance points, the interference term dominates and gives larger contributions

$$A_{\rm FB} \sim g_{\rm A}^e g_{\rm A}^f \cdot \frac{s(s-M_Z^2)}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}$$

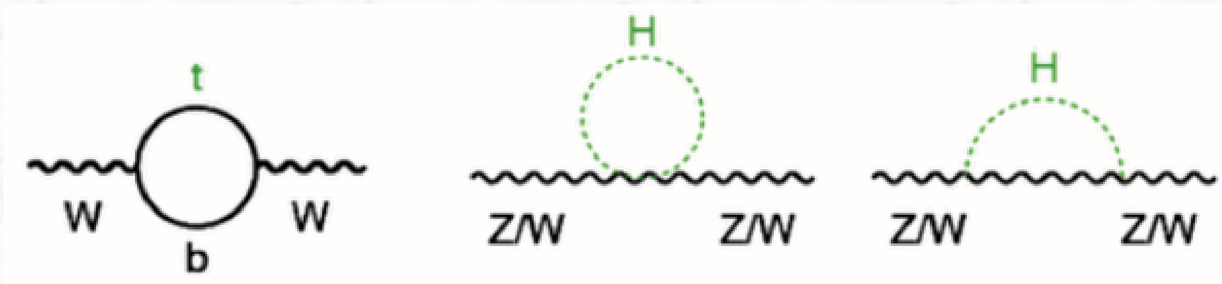
- A_{FB} can be used for the determination of the fermion couplings

→ Clear evidence for contributions from radiative corrections



LO Standard Model prediction:
$g_A = T_3$
$g_V = T_3 - 2\,Q \sin^2\theta_W$

Electroweak radiative corrections



Standard Model relations (lowest order)

$$\rho = \frac{m_{\mathrm{W}}^2}{m_{\mathrm{Z}}^2 \cos^2\theta_{\mathrm{W}}} = 1$$

$$\sin^2\theta_{\mathrm{W}} = 1 - \frac{m_{\mathrm{W}}^2}{m^2 \mathrm{Z}}$$

$$m_{\mathrm{W}}^2 = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_{\mathrm{W}} G_{\mathrm{F}}}$$

$$\alpha(0)$$

Relations including radiative corrections

$$\vec{\rho} = 1 + \Delta\rho$$

$$\sin^2\theta_{\mathrm{eff}} = (1+\Delta\kappa)\sin^2\theta_{\mathrm{W}}$$

$$m_{\mathrm{W}}^2 = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_{\mathrm{W}} G_{\mathrm{F}}} \cdot \frac{1}{(1-\Delta r)}$$

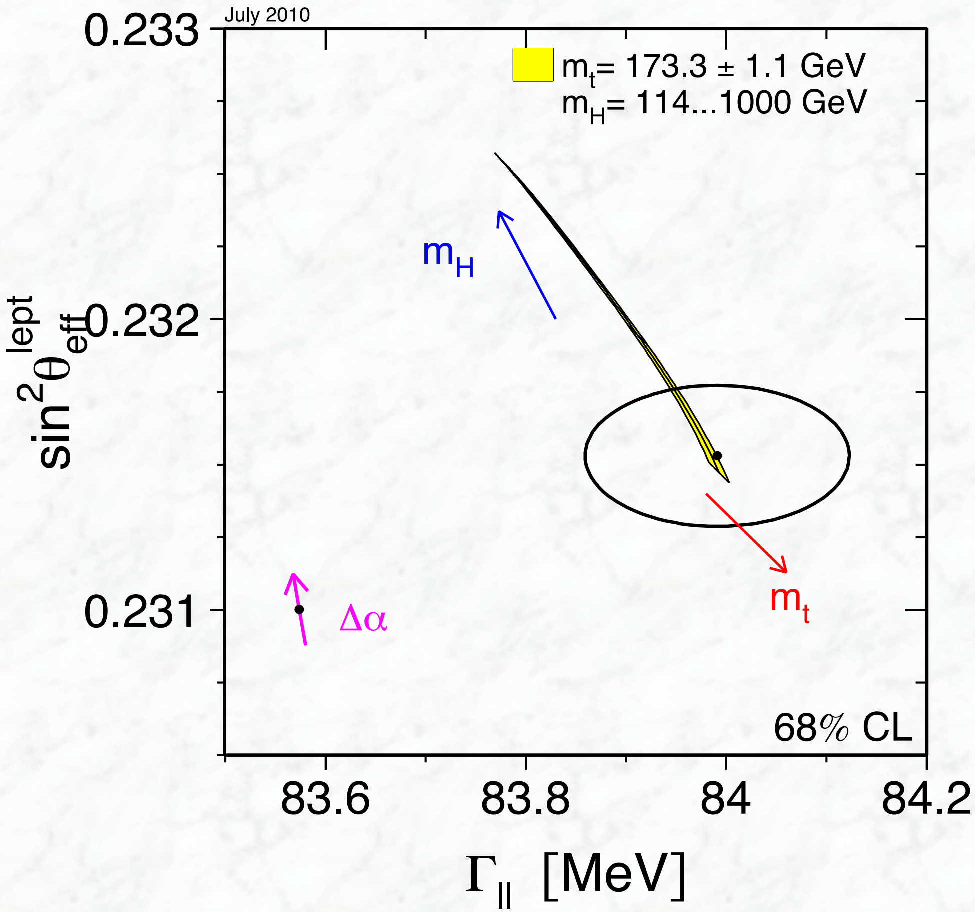
$$\alpha(m_{\mathrm{Z}}^2) = \frac{\alpha(0)}{1-\Delta\alpha}$$

$$\Delta\alpha = \Delta\alpha_{\mathrm{lepl}} + \Delta\alpha_{\mathrm{top}} + \Delta\alpha_{\mathrm{had}}^{(5)}$$

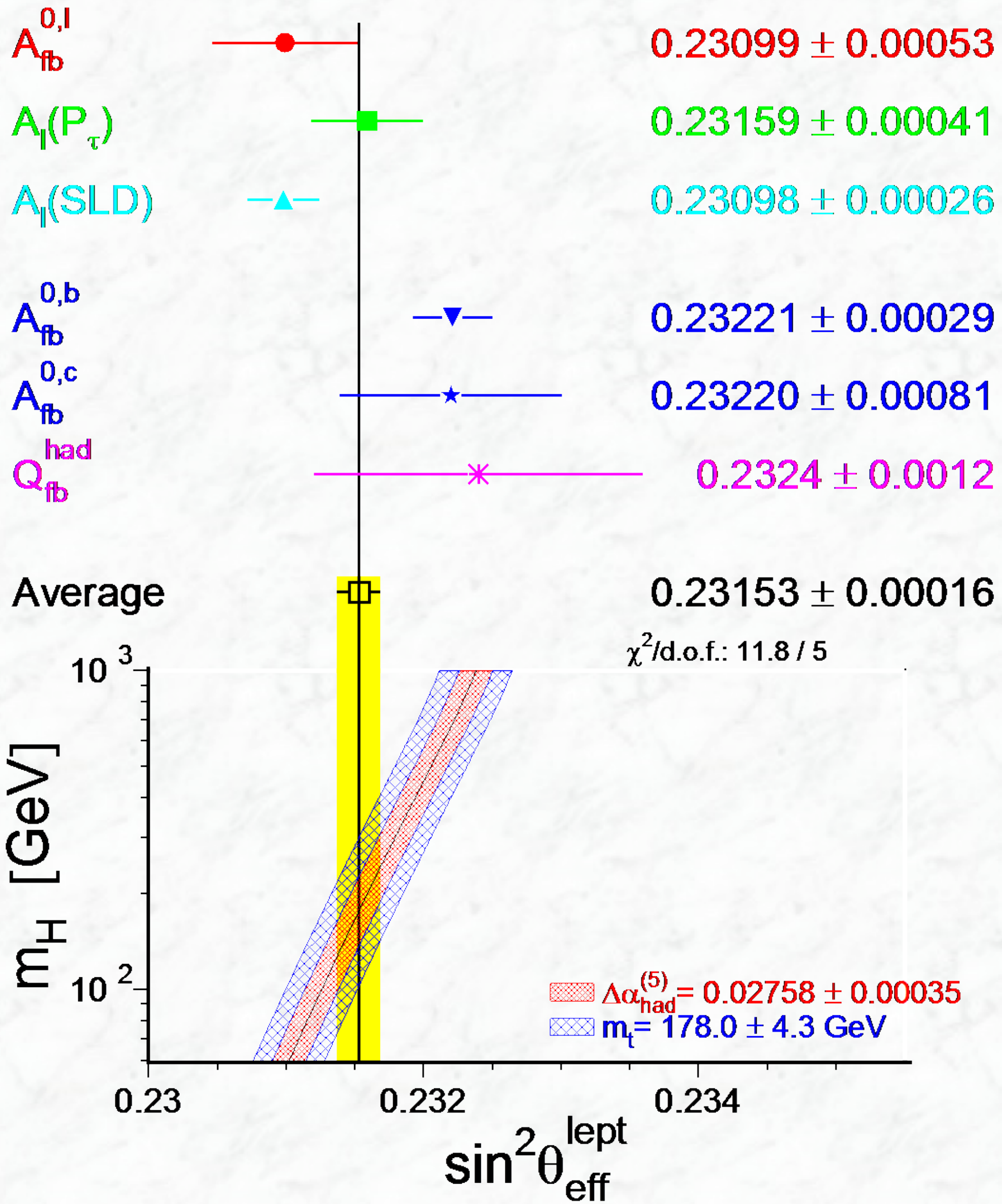
$$\Delta\rho, \Delta\kappa, \Delta r = f(m_t^2, \log(m_{\mathrm{H}}), \ldots)$$

Results of electroweak precision tests at LEP (cont.)

partial decay width versus $\sin^2$ ®$_W$:



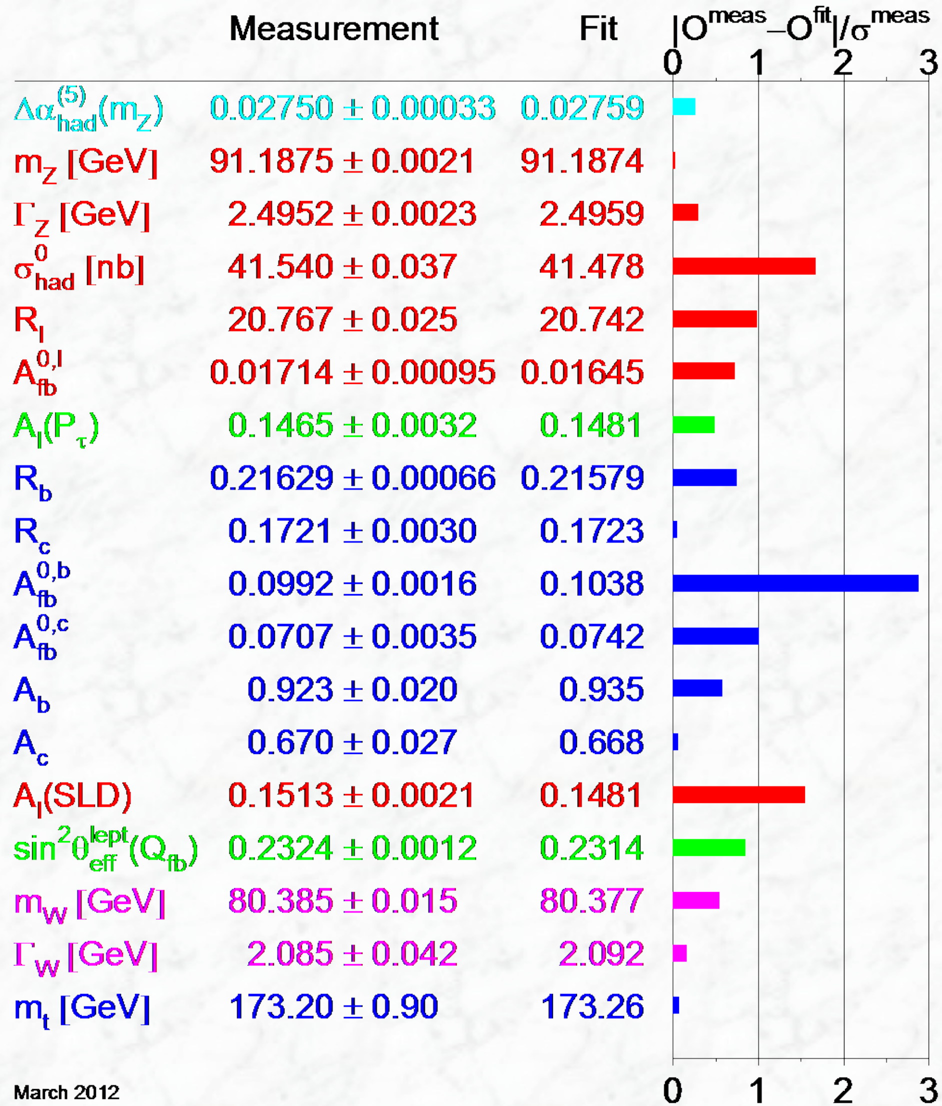
Results on measurements of $\sin^2 \theta_W$ at LEP and SLD



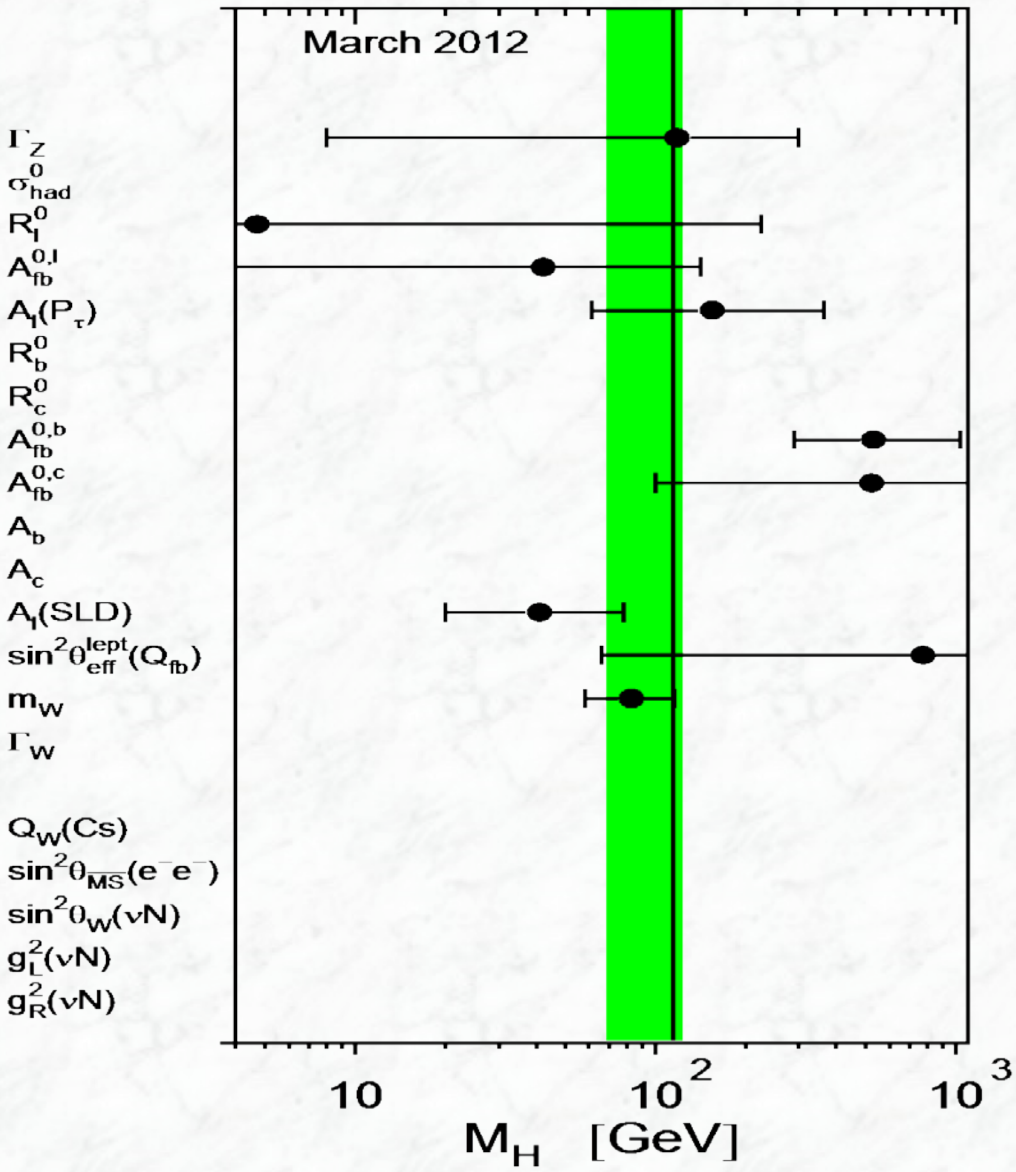
Results of electroweak precision tests at LEP (cont.)

Summary of results:

- All measurements in agreement with the Standard Model
- They can be described with a limited set of parameters



Predictions for the Higgs boson mass from individual LEP-observables



10.4 W mass measurement
- and test of the consistency of the Standard Model-

Major contributions: LEP-II, direct mass reconstruction

Hadron collider: Tevatron and LHC (in the future)

Precision measurements of m_W and m_{top}

Motivation:

W mass and top quark mass are fundamental parameters of the Standard Model;
The standard theory provides well defined relations between m_W, m_{top} and m_H

Electromagnetic constant measured in atomic transitions, e^+e^- machines, etc.

$$m_W = \left(\frac{\pi \alpha_{EM}}{\sqrt{2} G_F} \right)^{1/2} \frac{1}{\sin \theta_W \sqrt{1 - \Delta r}}$$

Fermi constant measured in muon decay

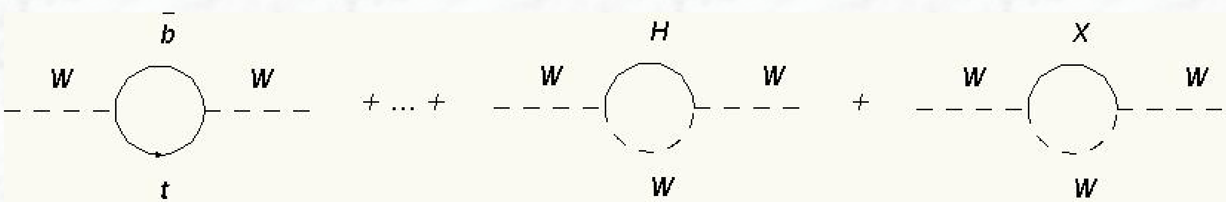
weak mixing angle measured at LEP/SLC

radiative corrections
$\Delta r \sim f(m_t^2, \log m_H)$
$\Delta r \approx 3\%$

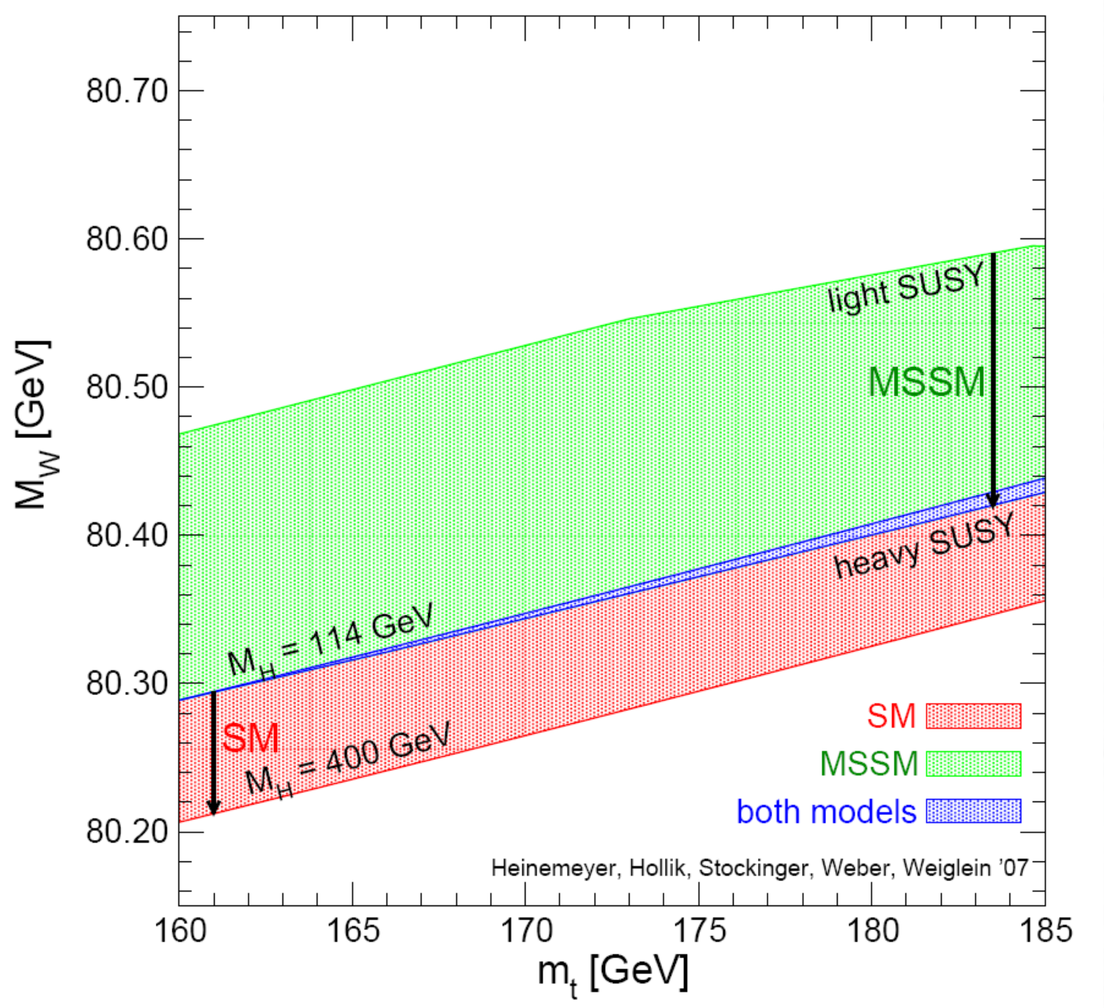
G_F, α_{EM}, $\sin \theta_W$

are known with high precision

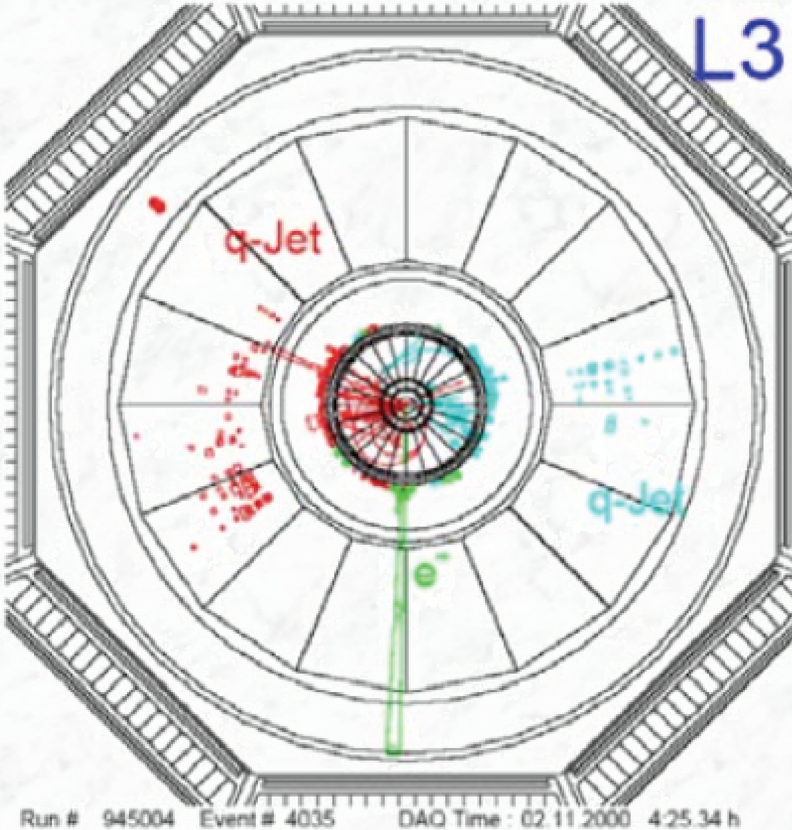
Precise measurements of the W mass and the top-quark mass constrain the Higgs-boson mass (and/or the theory, radiative corrections)



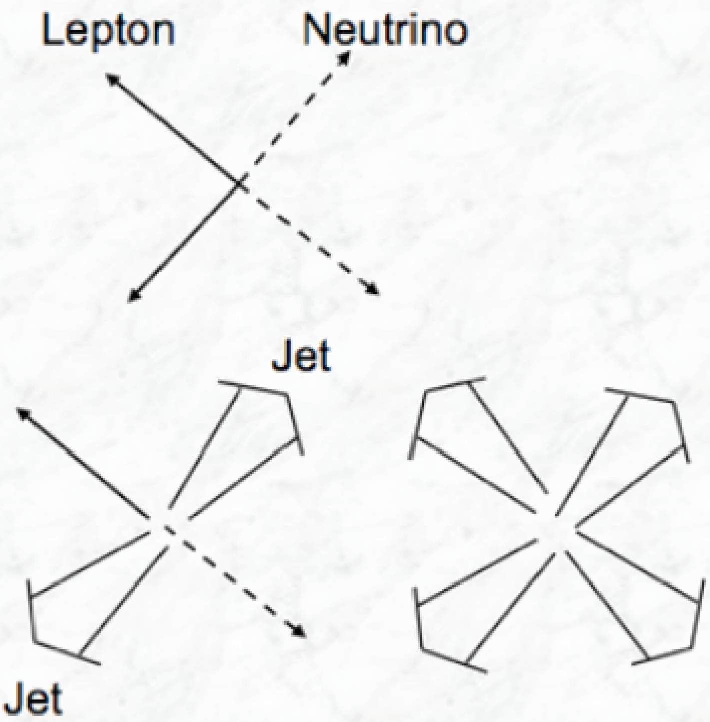
Relation between m_W, m_t, and m_H



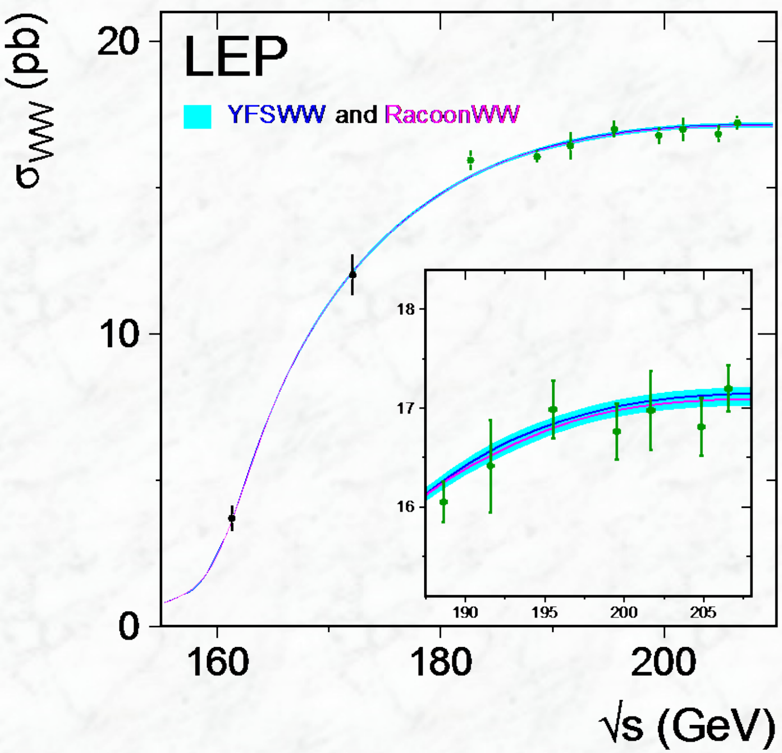
W bosons at LEP – II

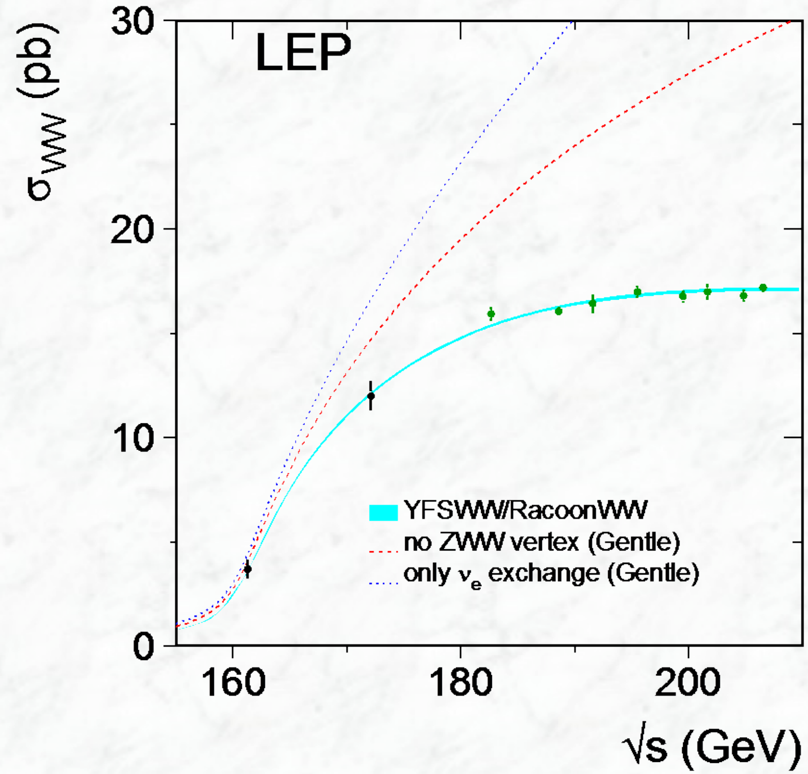


$$WW \rightarrow \begin{cases} qq\ell\nu & 44\% \\ qqqq & 45\% \\ \ell\nu\ell\nu & 11\% \end{cases}$$



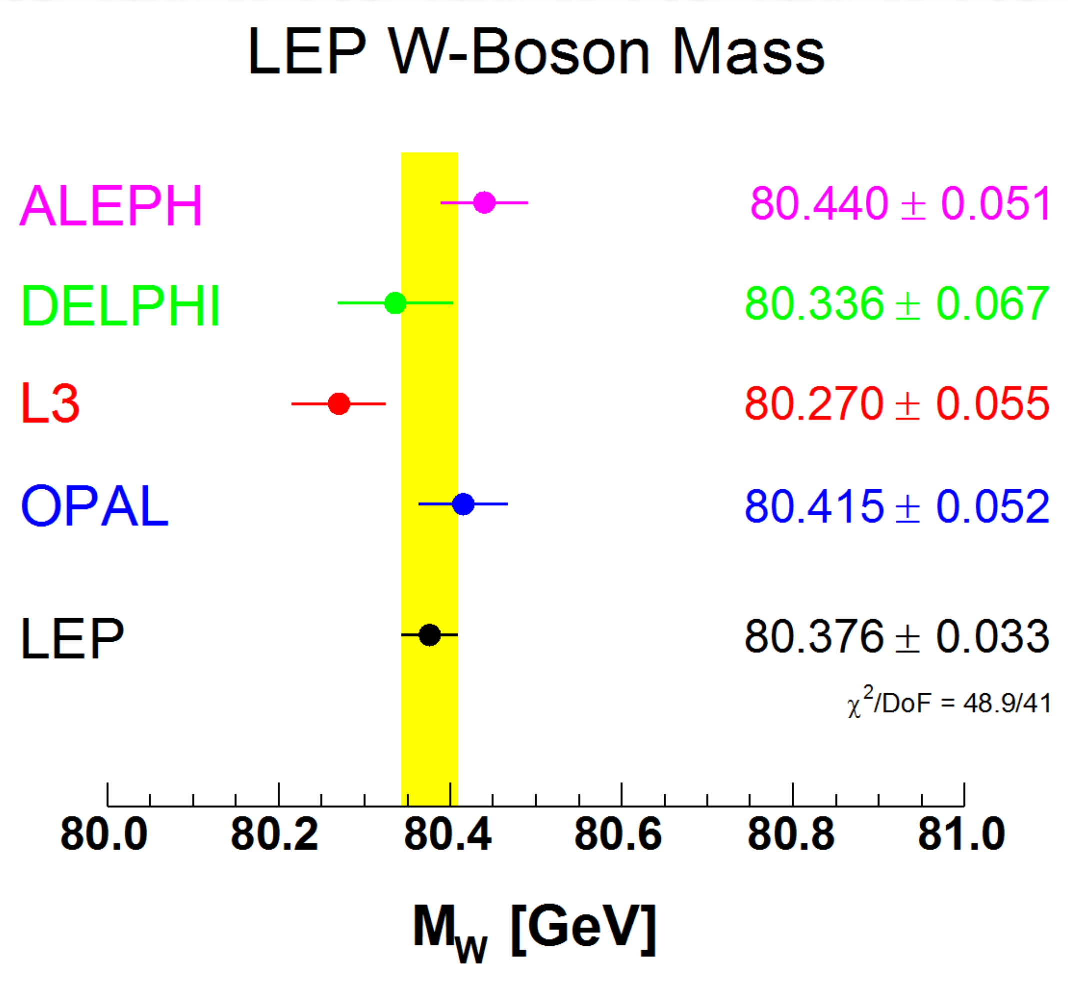
W mass and cross-section measurement at LEP-II





Measurements of the W-pair production cross-section, compared to the predictions from the Standard Model. The shaded area represents the uncertainty on the theoretical predictions, estimated as ±2% for √s<170 GeV and ranging from 0.7 to 0.4% above 170 GeV. The W mass is fixed at 80.35 GeV;

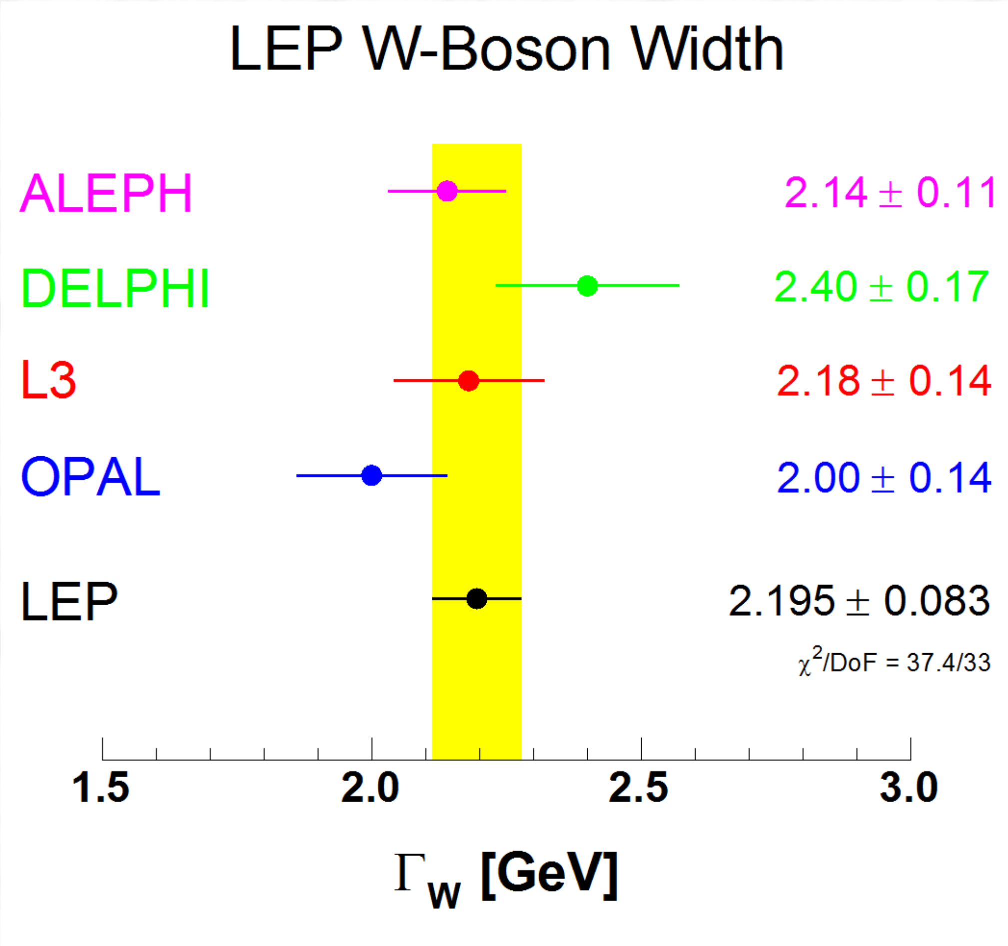
Results from W mass measurements at LEP-II



- Results from all four LEP experiments are consistent
- Statistical error is dominant
- Total precision from LEP-II

  $\Delta m_W = \pm$ 33 MeV

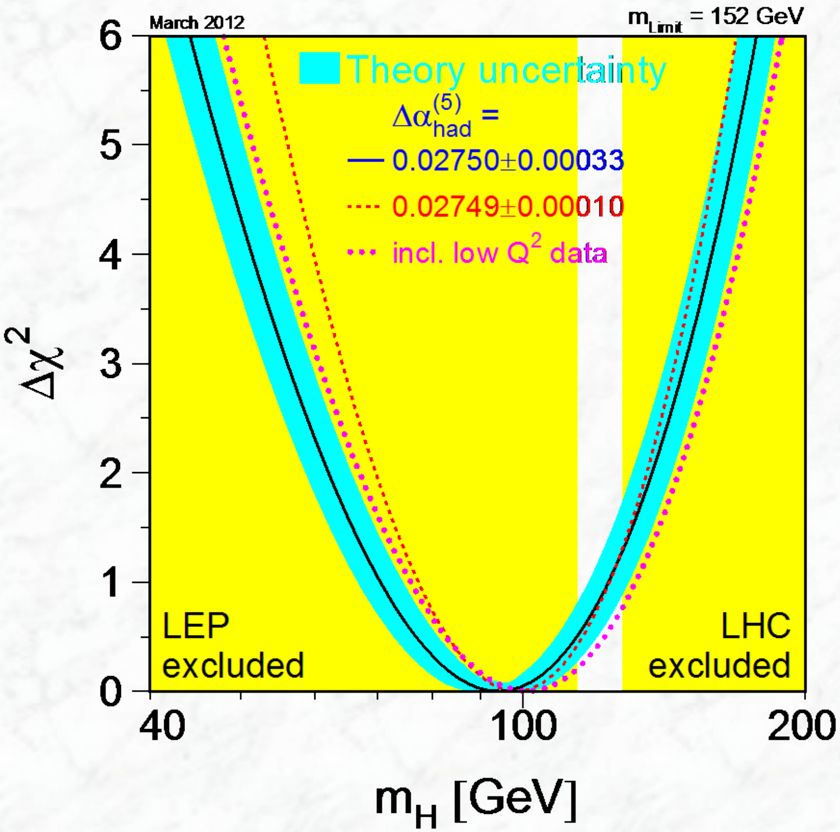
Results from W boson width from LEP-II

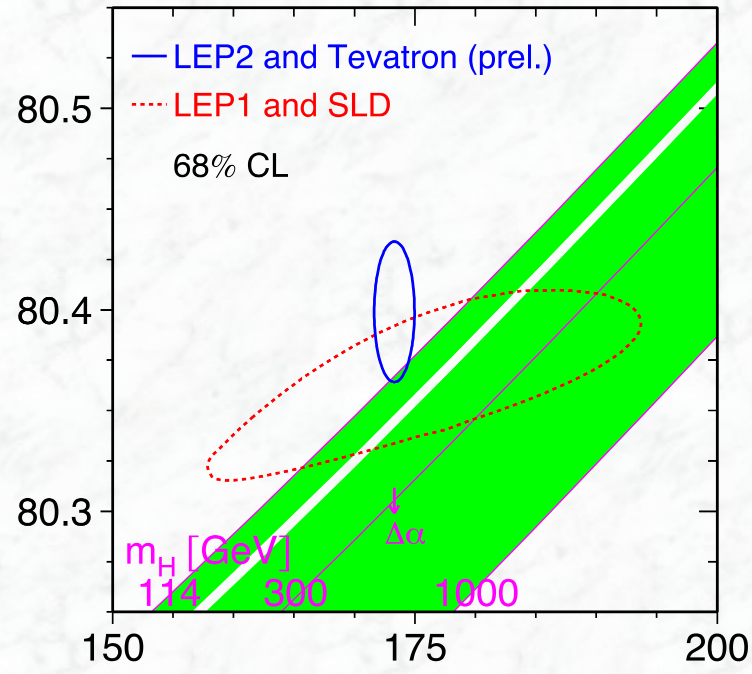


- Results from all four LEP experiments are consistent
- Statistical error is dominant
- Total precision from LEP-II

  $\Delta\Gamma_W = \pm$ 83 MeV

Results of electroweak precision tests at LEP (cont.)





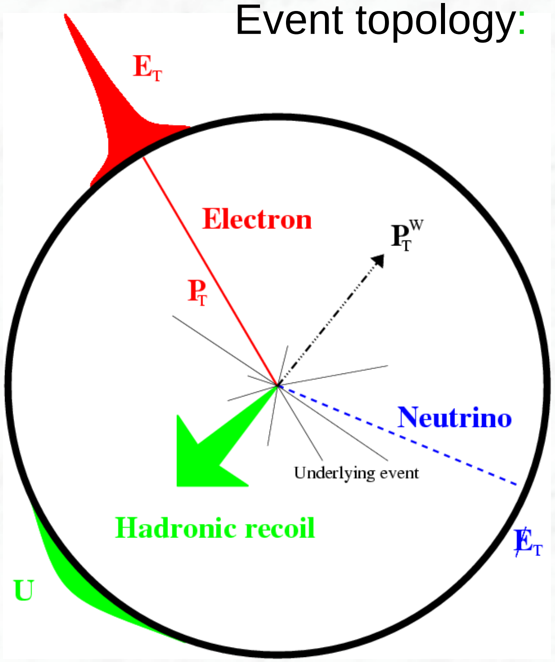
- Radiative corrections (loop, quantum corrections) can be used to constrain yet unobserved particles (however, sensitivity to m_H only through log terms)
- Main reason for continued precision improvements in m_t , m_W

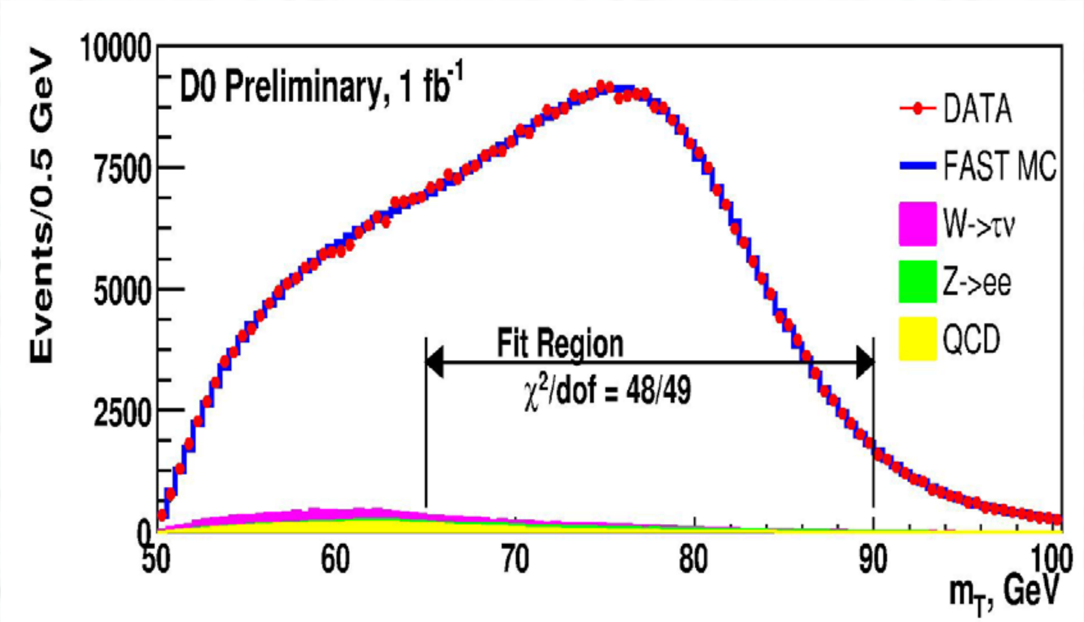
What can hadron collider contribute ?

How can W mass be measured at a hadron collider ?

Technique used for W mass measurement at hadron colliders:

Event topology:





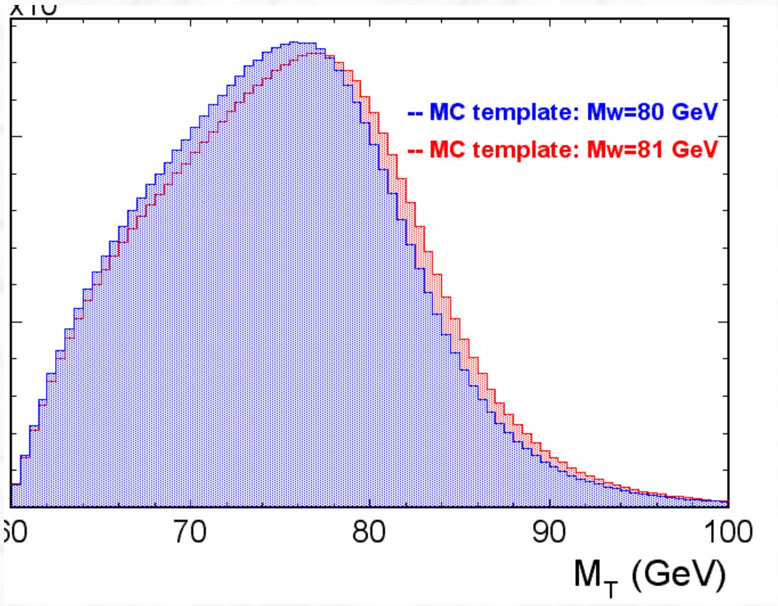
Observables: $P_T(e)$, $P_T(\text{had})$

$\Rightarrow \quad P_T(\nu) = -\,(\,P_T(e) \;+\; P_T(\text{had})\,)$ long. component cannot be measured

$$\Rightarrow \quad M_W^T = \sqrt{2 \cdot P_T^l \cdot P_T^\nu \cdot \left(1 - \cos\Delta\phi^{l,\nu}\right)}$$

In general the transverse mass M_T is used for the determination of the W mass (smallest systematic uncertainty).

Shape of the transverse mass distribution is sensitive to m_W, the measured distribution is fitted with Monte Carlo predictions, where m_W is a parameter



Main uncertainties:

Ability of the Monte Carlo to reproduce real life:

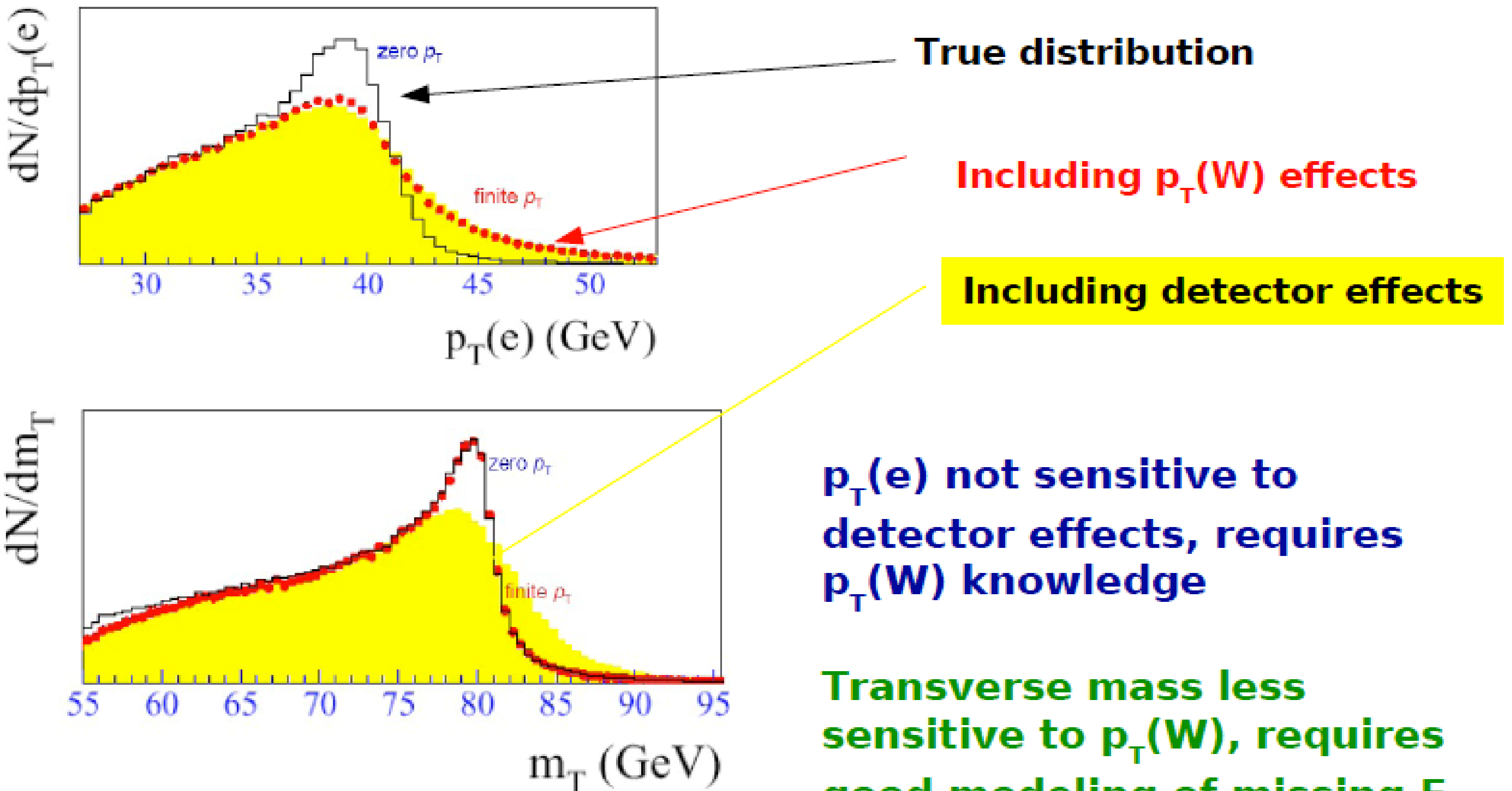
- Detector performance
  (energy resolution, energy scale, ...)

- Physics: production model
  $p_T(W)$, Γ_W, ...

- Backgrounds

In principle any distribution that is sensitive to m_W can be used for the measurement;

Systematic uncertainties are different for the various observables.

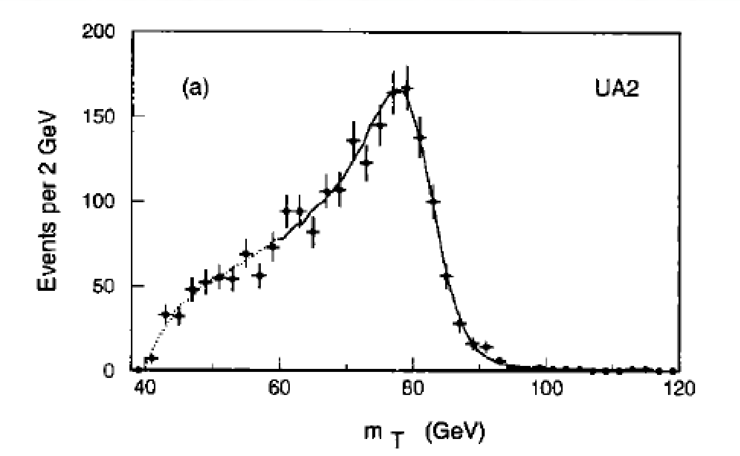


$p_T(e)$ not sensitive to detector effects, requires $p_T(W)$ knowledge

Transverse mass less sensitive to $p_T(W)$, requires good modeling of missing E_T

W mass measurements

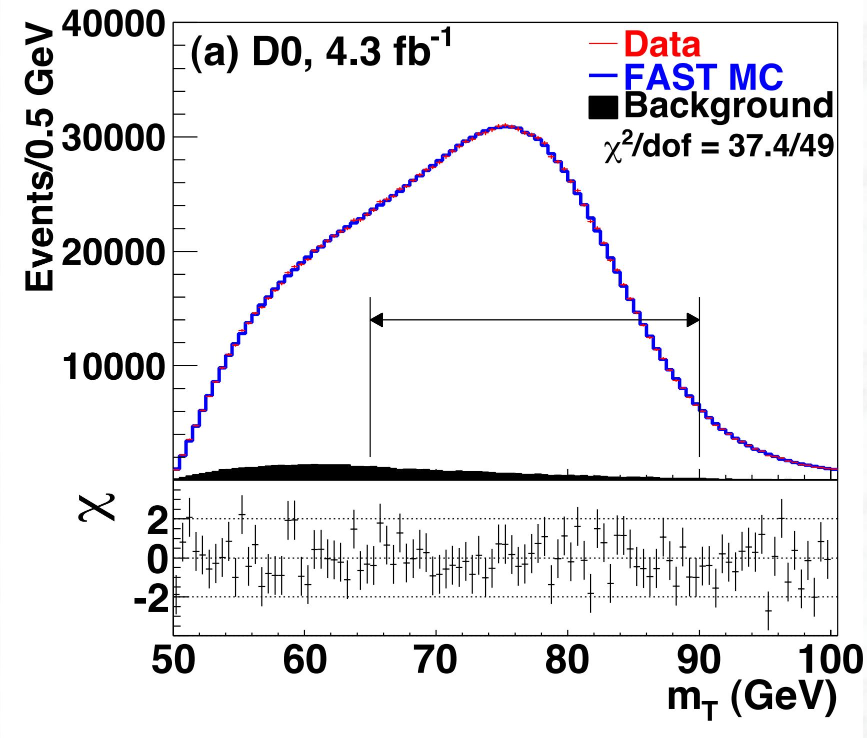
The beginning



$$m_W = 80.35 \pm 0.33 \pm 0.17 \text{ GeV}$$

State of the art, today

1.68 M events, electrons $|\eta| < 1.05$



$m_W = 80.371 \pm 0.013$ (stat.) GeV

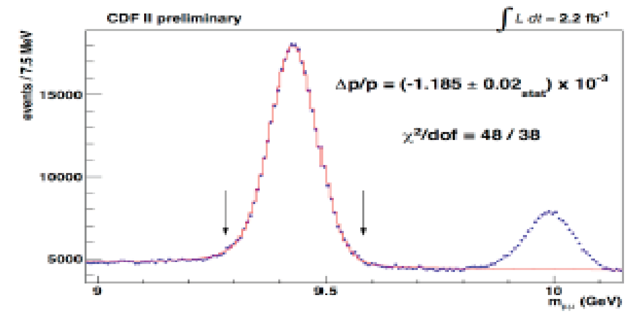
Systematic uncertainties:

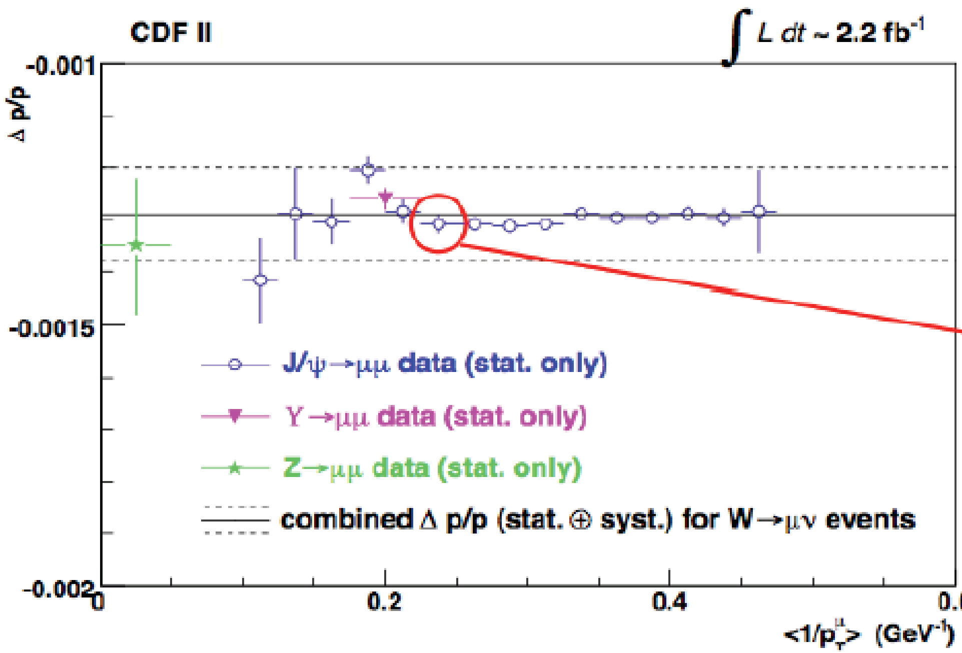
New CDF Result (2.2 fb^{-1})
Transverse Mass Fit Uncertainties (MeV)

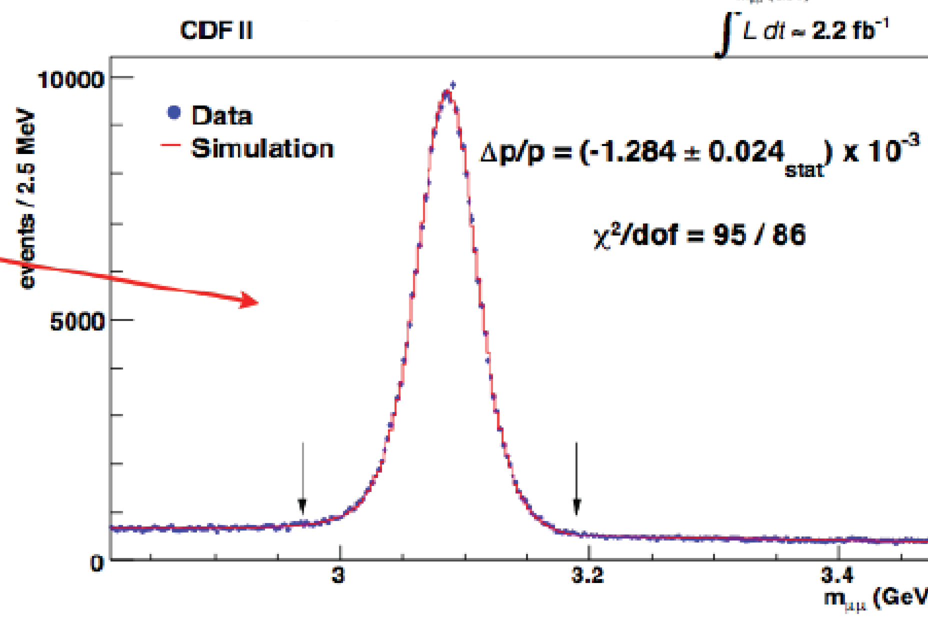
	electrons	*muons*	*common*
W statistics	19	16	0
Lepton energy scale	10	7	5
Lepton resolution	4	1	0
Recoil energy scale	5	5	5
Recoil energy resolution	7	7	7
Selection bias	0	0	0
Lepton removal	3	2	2
Backgrounds	4	3	0
pT(W) model	3	3	3
Parton dist. Functions	10	10	10
QED rad. Corrections	4	4	4
Total systematic	18	16	15
Total	26	23	

Momentum Scale Calibration

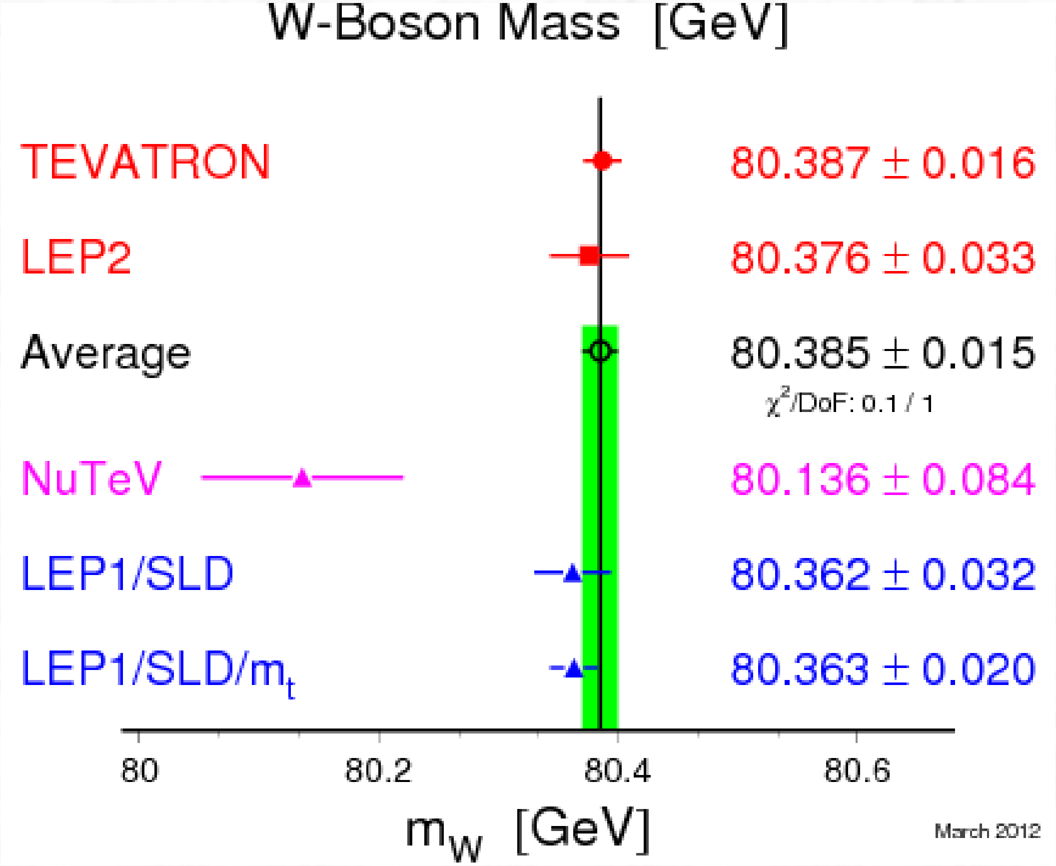
- "Back bone" of CDF analysis is track p_T measurement in drift chamber (COT)
- Perform alignment using cosmic ray data: ~50μm→~5μm residual
- Calibrate momentum scale using samples of dimuon resonances (J/ψ, Υ, Z)
  - Span a large range of p_T
  - Flatness is a test of dE/dx modeling
- Final scale error of 9×10^{-5}: $\Delta m_W = 7$ MeV





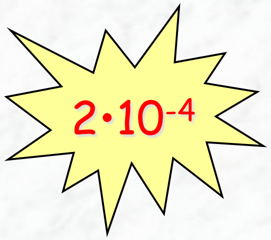


Summary of W-mass measurements

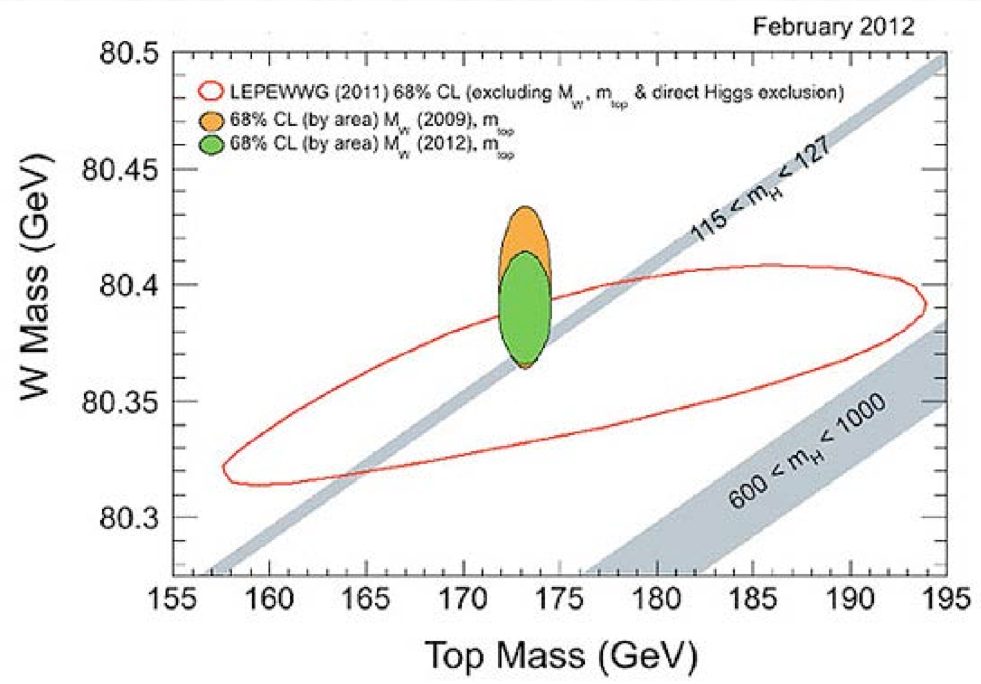


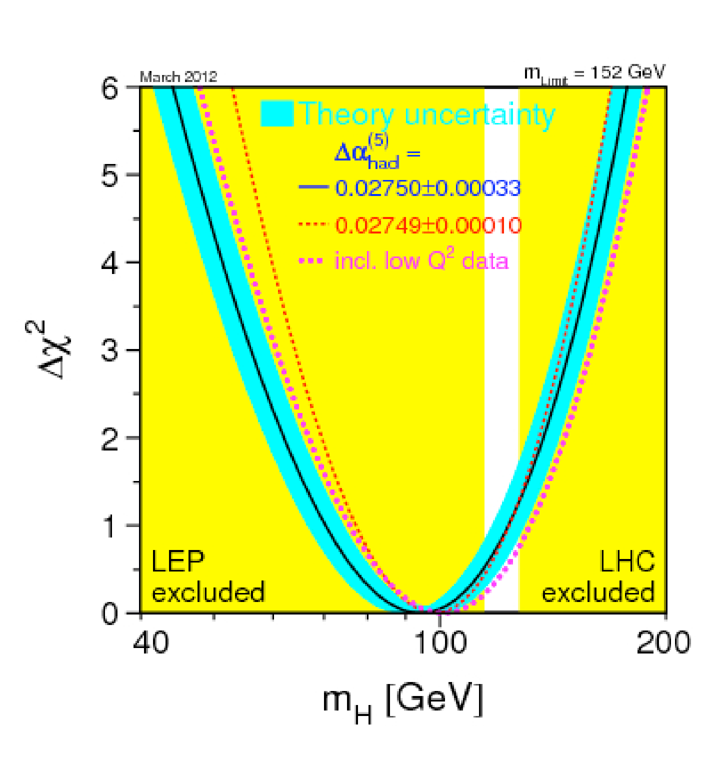
Precision obtained at the Tevatron is superior to the LEP-II precision

m_W (from LEP2 + Tevatron) = 80.385 ± 0.015 GeV



Indirect limits from electroweak precision measurements

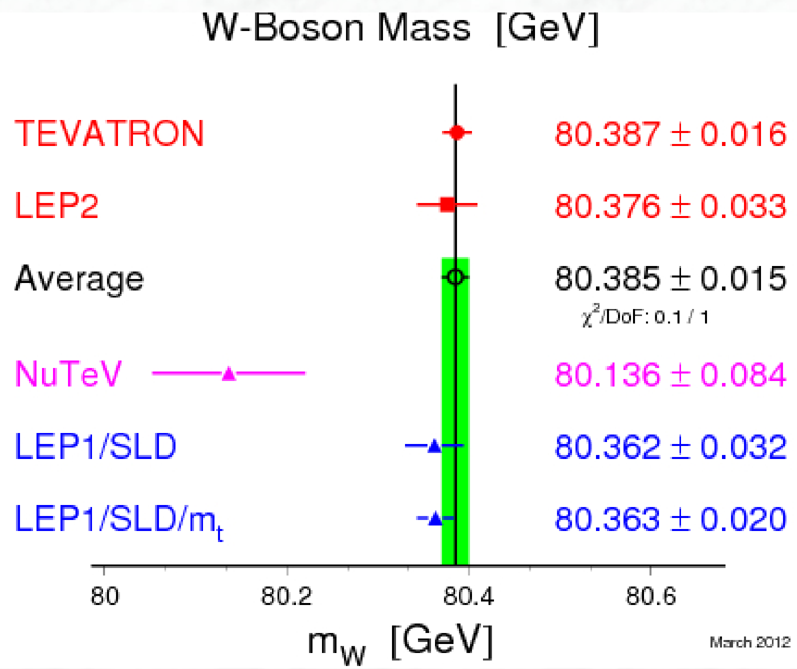




Impressive precision in W mass from the Tevatron (February 2012)

$m_H = 94^{+29}_{-24}$ GeV/c^2
$m_H < 152$ GeV/c^2 (95 % C.L.)

The main story of 2011: eliminate 470 GeV of Higgs boson mass range



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Total	26	23	

Can the LHC improve on this?

In principle yes, but probably not soon .and. not with 30 pileup events

- Very challenging (energy-scale, hadronic recoil, p_T (W),..)

- However, there is potential for reduction of uncertainties
  - statistical uncertainties
  - statistically limited systematic uncertainties (marked in green above)
  - pdfs, energy scale, …., recoil(?)

What precision can be reached in Run II and at the LHC ?

Numbers for a single decay channel

$W \to e\nu$

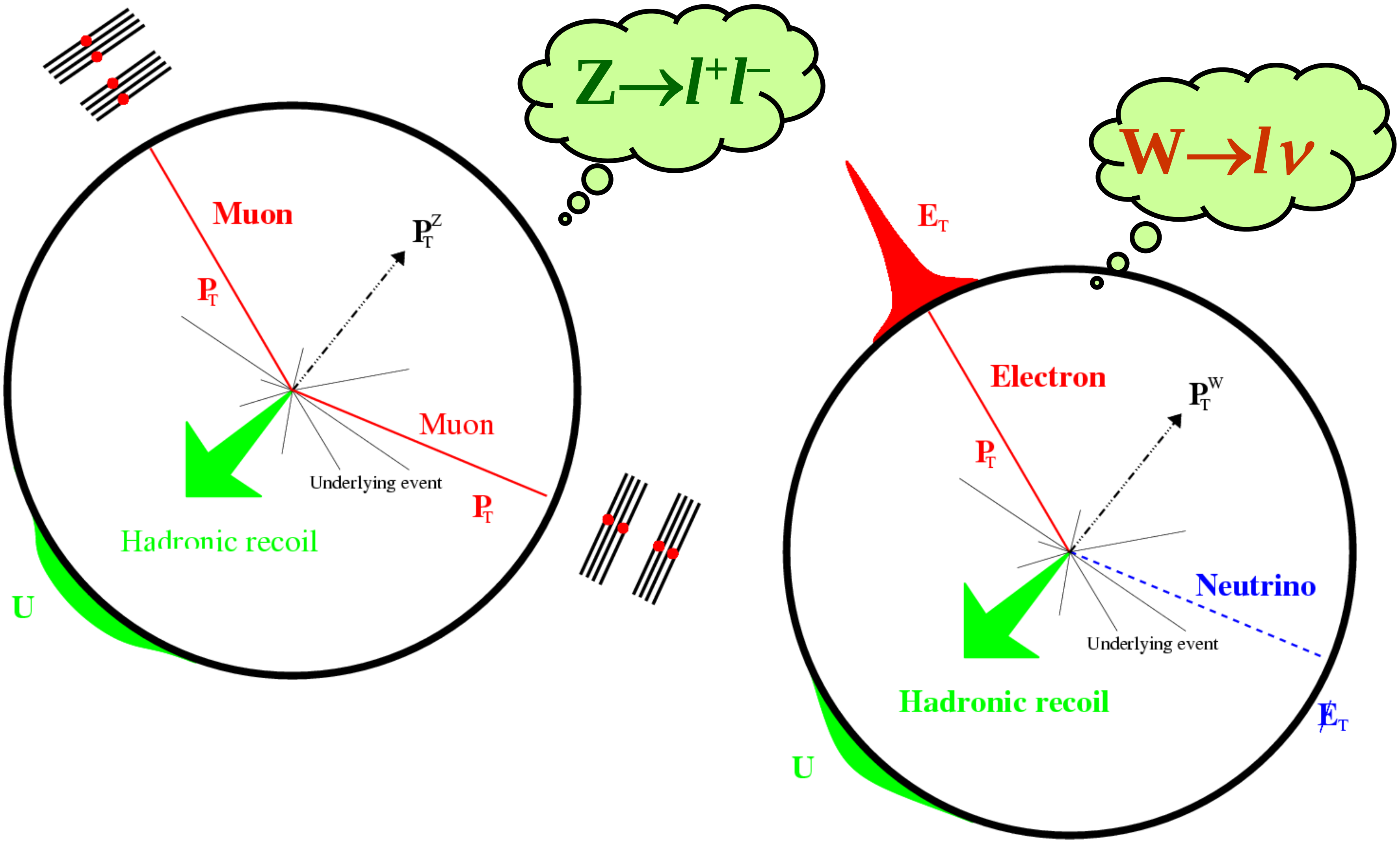
Int. Luminosity	CDF 0.2 fb^{-1}	DØ 1 fb^{-1}	LHC 10 fb^{-1}
Stat. error	**48 MeV**	**23 MeV**	**2 MeV**
Energy scale, lepton res.	30 MeV	34 MeV	4 MeV
Monte Carlo model (P_T^W, structure functions, photon-radiation….)	16 MeV	12 MeV	7 MeV
Background	8 MeV	2 MeV	2 MeV
Tot. Syst. error	**39 MeV**	**37 MeV**	**8 MeV**
Total error	**62 MeV**	**44 MeV**	**~10 MeV**

- Tevatron numbers are based on real data analyses
- LHC numbers should be considered as „ambitious goal"
  - Many systematic uncertainties can be controlled in situ, using the large $Z \to \ell\ell$ sample ($p_T(W)$, recoil model, resolution)
  - Lepton energy scale of $\pm$ 0.02% has to be achieved to reach the quoted numbers

Combining both experiments (ATLAS + CMS, 10 fb^{-1}), both lepton species and assuming a scale uncertainty of $\pm$ 0.02% a total error in the order of

$\Rightarrow$ $\Delta m_W \sim \pm$ 10 MeV might be reached.

Signature of Z and W decays



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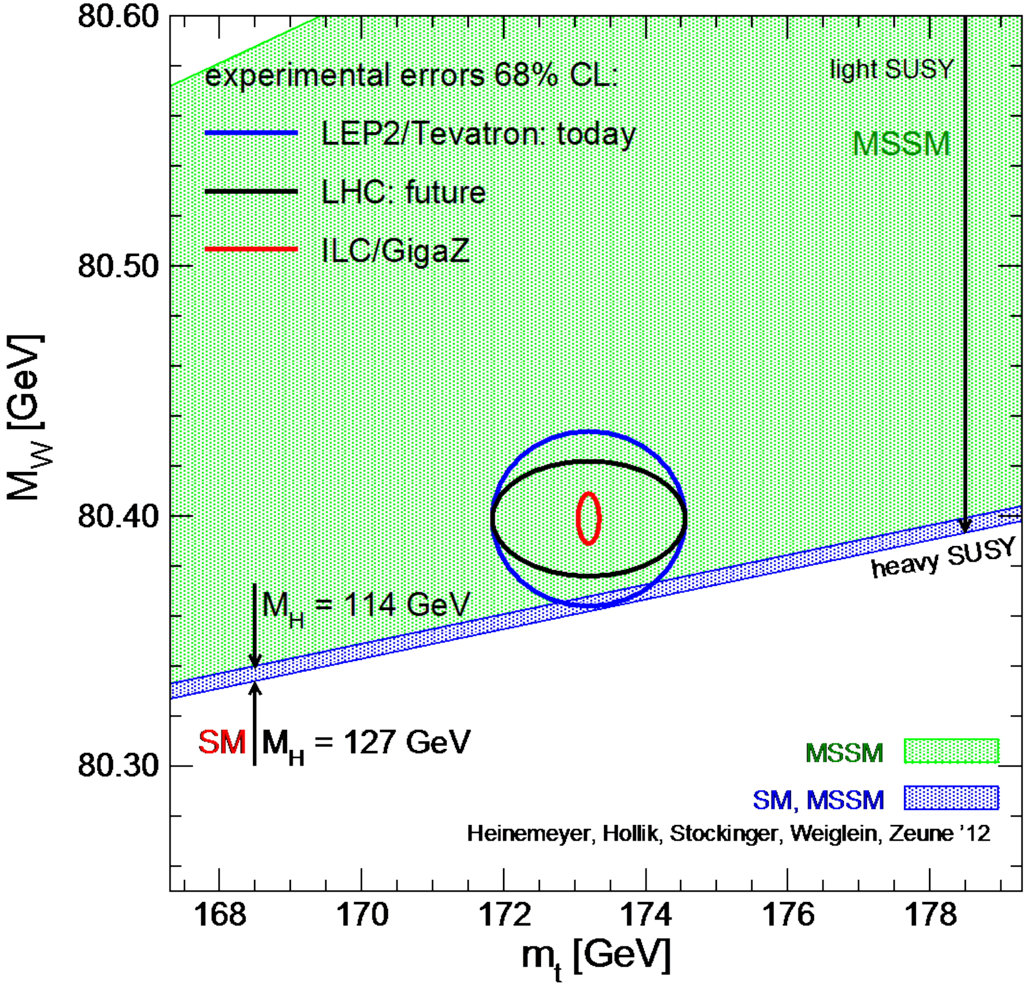


2012

Ultimate test of the Standard Model:

Compare direct prediction of the Higgs boson mass with direct observation

10.5 Test of the el.weak predictions in rare B-Meson decays

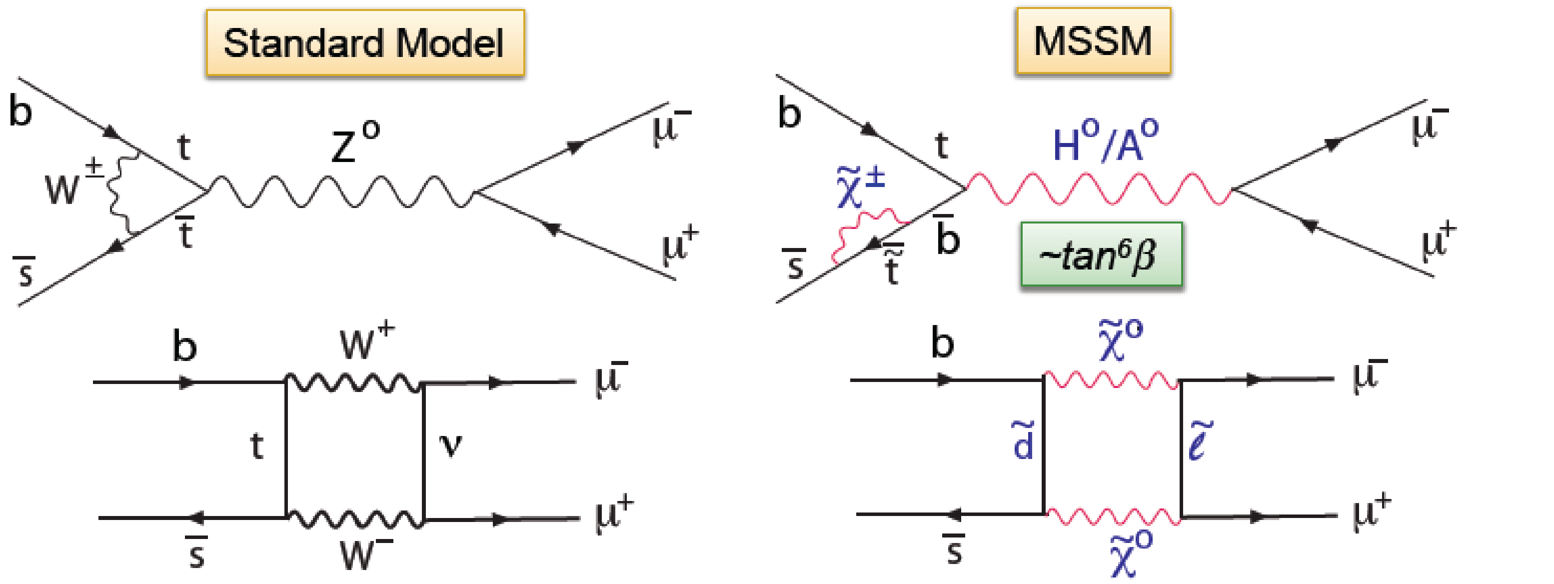
- Additional processes that test the Standard Model precisely and probe New Physics

- Accessible due to the large number of B meson decays (LHCb experiment at the LHC)

Search for the decays $B_0 \rightarrow \mu^+\mu$- and $B_o^s \rightarrow \mu^+\mu^-$

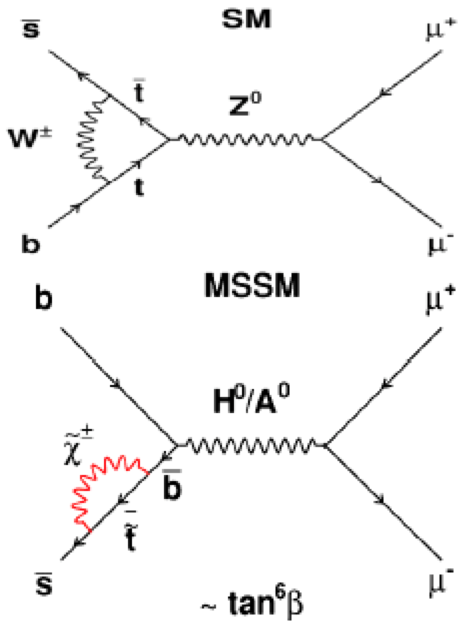
- Rare decay in the Standard Model: Branching ratio for $B_0^s \rightarrow \mu\ \mu$ is $(3.2 \pm 0.2)\ 10^{-9}$

- Contributions from New Physics can be large (also from non-SUSY models)



- Huge b-production rates at the LHC → all LHC experiments are searching for this decay mode

… and even additional Higgs bosons



Quest for $B^0_{(s)} \to \mu^+\mu^-$

Start in 1984 by the CLEO experiment ...

PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1

Two-body decays of B mesons

B. Search for exclusive $\bar{B}^0$ decays into two charged leptons

Our search for the $\pi^+\pi^-$ final state is not sensitive to the mass of the final-state particles, provided that they are light, since the mass enters only in the energy constraint. Therefore, the upper limit of 0.05% applies for any final-state particles with a pion mass or less. When the final-state particles are leptons the limits are improved by using the lepton identification capabilities of the CLEO detector.[14] For the decay $\bar{B}^0 \to \mu^+\mu^-$, we improve our limit by requiring that both muons penetrate the iron and produce signals in drift chambers. We find no such events. After correcting for detection efficiency (33%), we set an upper limit of 0.02% at 90% confidence for this decay. We im-

SM expectations (FCNC and helicity suppressed):

BR($B_s \to \mu^+\mu^-$) = $3.34 \pm 0.27 \times 10^{-9}$

BR($B^0 \to \mu^+\mu^-$) = $1.07 \pm 0.10 \times 10^{-10}$

Buras, Girrbach, Guadagnoli, Isodori, Fleischer, Kengjens
Eur Phy J. C72 (2012), 2172 + arXiv: 1303.3820

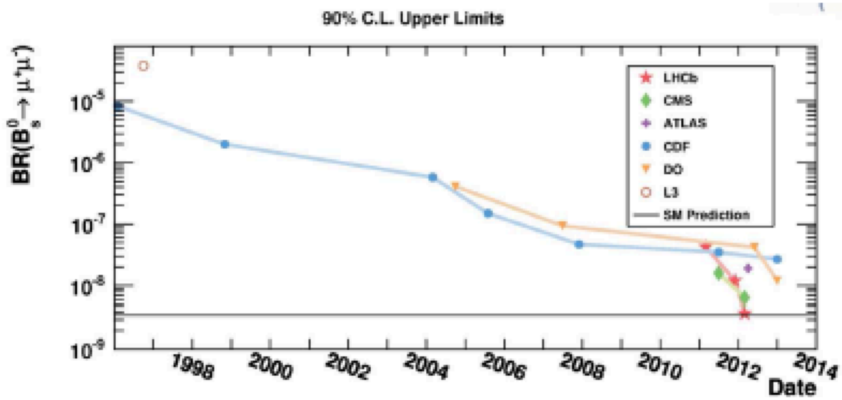
time integrated BR taking into account $\Delta\Gamma_s \neq 0$ (to be compared to experimental results)

BR($B_s \to \mu^+\mu^-$) = $3.56 \pm 0.29 \times 10^{-9}$

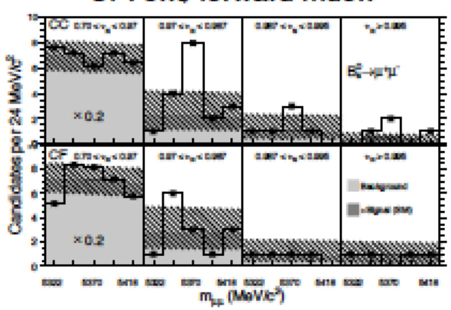
New results presented at EPS conference 2013, Stockholm
By S. Hansmann-Menzemer (LHCb)

Quest for $B^0_{(s)} \to \mu^+\mu^-$

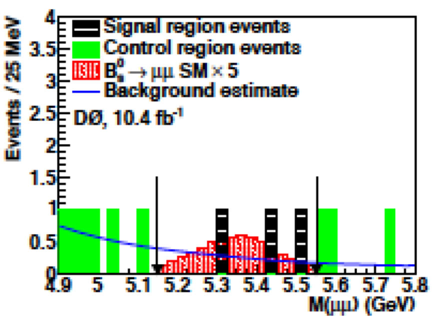
LHCb: Phys Rev Lett 110 (2013) 021801 (2.1 fb^{-1})
CMS: J. High Energy Phys 04 (2012) 033 (5.0 fb^{-1})
ATLAS: ATLAS-CONF-2013-076 (5.0 fb^{-1})
CDF: Phys. Rev. D 87, 072003 (2013) (9.7 fb^{-1})
D0: Phys. Rev. D87 07.2006 (2013) (10.4 fb^{-1})



CC: two central muons
CF: one forward muon

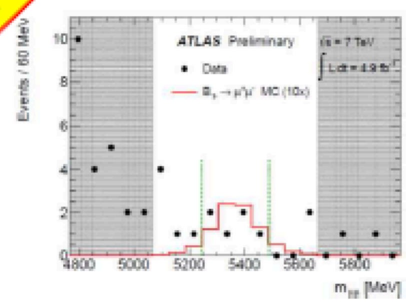


95% CL:
$BR(B_s \to \mu^+\mu^-) < 3.1 \times 10^{-8}$



95% CL:
$BR(B_s \to \mu^+\mu^-) < 1.5 \times 10^{-8}$

new @ EPS2013



95% CL:
$BR(B_s \to \mu^+\mu^-) < 1.5 \times 10^{-8}$

Updated Results

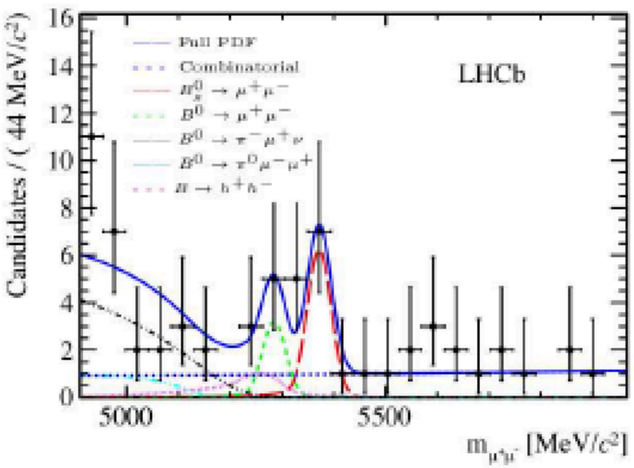
- $2.1 \to 3.0$ fb^{-1}
- more variables in BDT

- $5.0 \to 25$ fb^{-1}
- cut base selection $\to$ BDT
- new & improved variables (PID)

expected sensitivity: $3.7 \to 5.0\ \sigma$

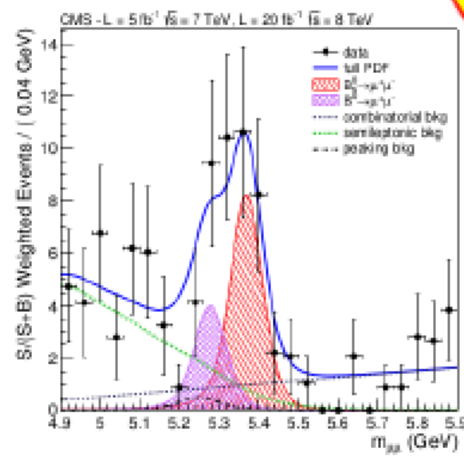
expected sensitivity: $4.8\ \sigma$

new @ EPS2013



arXiv:1307.5024

new @ EPS2013



arXiv:1307.5025

$\mathrm{BR}(B_s \to \mu^+\mu^-) = (2.9\ ^{+1.1}_{-1.0}(\mathrm{stat})\ ^{+0.3}_{-0.1}(\mathrm{syst})) \times 10^{-9}$
$\to 4\ \sigma$

$\mathrm{BR}(B^0 \to \mu^+\mu^-) < 7.4 \times 10^{-10}$ at 95% CL
$\mathrm{BR}(B^0 \to \mu^+\mu^-) = (3.7\ ^{+2.4}_{-2.1}(\mathrm{stat})\ ^{+0.6}_{-0.4}(\mathrm{syst})) \times 10^{-10}$
$\to 2.0\ \sigma$

$\mathrm{BR}(B_s \to \mu^+\mu^-) = 3.0\ ^{+1.0}_{-0.9} \times 10^{-9}$
$\to 4.3\ \sigma$

$\mathrm{BR}(B^0 \to \mu^+\mu^-) < 1.1 \times 10^{-9}$ at 95% CL
$\mathrm{BR}(B^0 \to \mu^+\mu^-) = 3.5\ ^{+2.1}_{-1.8} \times 10^{-10}$
$\to 2.0\ \sigma$

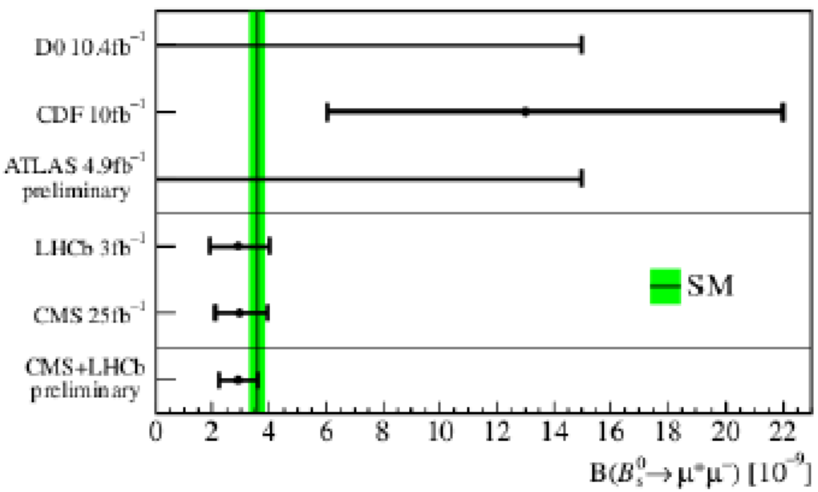
Combined LHCb + CMS Result

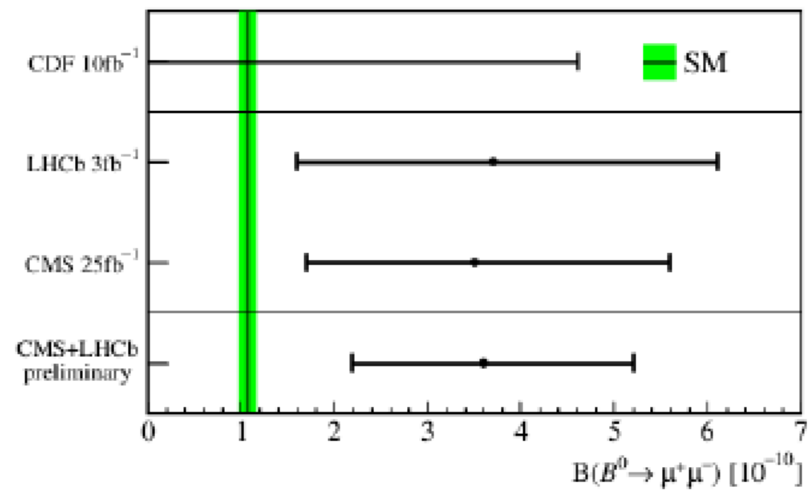
new @ EPS2013

Observation:

$$\mathrm{BR}(B_s \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$$

$$\mathrm{BR}(B^0 \to \mu^+\mu^-) = 3.6^{+1.6}_{-1.4} \times 10^{-10}$$





LHCb-CONF-2013-012, CMS-PAS-BPH-13-007