Status of the electroweak Standard Model

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- Introduction
- Electroweak precision data
- Interpretation of the data
- Conclusions

Introduction

- The Standard Model describes the interactions of elementary particles
- Four interactions:
  - electroweak (in principle two separate forces)
  - strong
  - gravitation

  however gravitation cannot be included in the model
- The model describes successfully basically all data
- However the model has many problems why we think it cannot be the final theory
- Every test of the Standard Model should thus be seen as an attempt to find its limits

Gauge theories

Elementary particle physics is successfully described by local gauge theories

- Take a gauge group $\mathcal{G}$
- The interactions (gauge bosons) are given by the generators of the group
- The fermions are arranged in multiplets on which the gauge bosons act
- The gauge group of the Standard Model: $\mathrm{SU(3)} \times \mathrm{SU(2)} \times \mathrm{U(1)}$
  SU(3): strong interactions
  $\mathrm{SU(2)} \times \mathrm{U(1)}$: electroweak interaction
  Gravity is not included in the Standard Model
- In this scheme all particles have to be massless
- Masses can be generated breaking the symmetry

Fermions in the Standard Model

- Fermions exist in 3 families
- The families are identical apart from their masses
- Leptons have only electroweak interaction
- Quarks also have strong interactions

Leptons			Quarks		
Flavour	mass (GeV)	Q	Flavour	mass (GeV)	Q
ν_e	$< 1 \cdot 10^{-8}$	0	u	~ 0.003	$2/3$
e	0.000511	-1	d	~ 0.006	$-1/3$
ν_μ	< 0.0002	0	c	1.3	$2/3$
μ	0.106	-1	s	~ 0.1	$-1/3$
ν_τ	< 0.02	0	t	175	$2/3$
τ	1.78	-1	b	4.3	$-1/3$

Electroweak gauge bosons:

Charged current:	$W^{\pm}$	$m_{\mathrm{W}} \sim 80\,\mathrm{GeV}$	
Neutral current:	Z	$m_{\mathrm{Z}} \sim 90\,\mathrm{GeV}$	
	γ	$m_{\gamma} = 0$	QED

Gauge group: $SU(2) \times U(1)$ with couplings g, g'

Fermions exist as left handed doublets and right handed singlets

$SU(2)$ $\begin{pmatrix} W^{+} \\ W^{0} \\ W^{-} \end{pmatrix}$ couple to left handed doublets only

$U(1)$ B couples to left and right-handed fermions

Up to here all particles are massless!

The Higgs mechanism

Complex Higgs doublet Φ with potential $V(\Phi) = \lambda(\Phi^*\Phi - v^2/2)^2$

- Minimum at $\Phi(0) = \begin{pmatrix} 0 \\ v \end{pmatrix}$
- $v = 246\,\mathrm{GeV}$ precisely known from muon decay

Gauge bosons acquire mass through coupling at Φ, absorbing 3 degrees of freedom in the longitudinal gauge boson components

Higgs mechanism requires one neutral scalar particle H^0,

Fermion masses are generated by ad hoc Yukawa couplings of the fermions to the Higgs field

The fermion mass term $m\overline{\Psi}_L\Psi_R$ couples left- and right handed particles

W^0 and B mix keeping photon massless:

$$\begin{aligned} Z &= W^0 \cos\theta_W - B \sin\theta_W \\ \gamma &= W^0 \sin\theta_W + B \cos\theta_W \end{aligned}$$

with $g \sin\theta_W = g' \cos\theta_W = e$

Resulting interactions:

$W^{\pm}$**:** stay purely left handed

γ**:** left-right symmetric vector coupling (Maxwell equations)

Z**:** complicated mixture of left- and right-handed coupling to restore the $SU(2) \times U(1)$ prediction

$$\begin{aligned} g_A &= \frac{g}{2} \\ g_V &= \frac{g}{2}(1 - 4|q| \sin^2\theta_W) \end{aligned}$$

(Neutrinos: electrically neutral ➟ Z coupling pure left-handed ➟ right handed neutrinos would be sterile)

Mass relation:

$$\cos^2\theta_W = \frac{m_{\mathrm{W}}}{m_{\mathrm{Z}}}$$

Gauge sector has three free parameters: g, g', v

For calculations use the three best known parameters:

$$\alpha \qquad \left(\frac{\Delta\alpha}{\alpha} \sim 7\cdot 10^{-10}\right)$$

$$G_F \qquad \left(\frac{\Delta G_F}{G_F} \sim 5\cdot 10^{-6}\right)$$

$$m_Z \qquad (\longrightarrow \text{ LEP})$$

Measurement of more observables tests the theory!

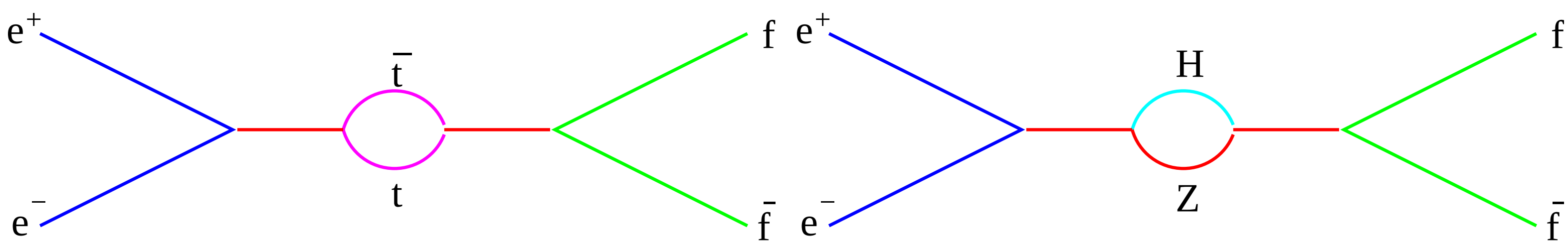
Radiative Corrections

- Typical measurement precision better than $\alpha \sim 1\%$

➠ must take into account loop corrections

- Corrections to m_{W} and Z-resonance can be parametrised with 3 parameters:

$$
\begin{aligned}
g_{Af} &\rightarrow \sqrt{1+\Delta\rho_f} g_{Af} \\
\frac{g_{Vf}}{g_{Af}} &= 1 - 4|Q_f| \sin^2\theta^f_{eff} \\
m^2_{\mathrm{W}} &= \frac{1}{2} m^2_{\mathrm{Z}} \left(1 + \sqrt{1 - \frac{4\pi\alpha}{\sqrt{2} G_{\mathrm{F}} m^2_{\mathrm{Z}}} \frac{1}{1-\Delta r}} \right)
\end{aligned}
$$



These can be calculated as:

$$\Delta\rho = \frac{3G_\mathrm{F}}{4\pi^2\sqrt{2}}\left(\frac{m_\mathrm{t}^2}{2} - m_\mathrm{W}^2\frac{s^2}{c^2}\ln\frac{m_\mathrm{H}}{m_\mathrm{Z}}\right) + \ldots$$

$$\sin^2\theta^l_{eff} = \sin^2\theta_0\left(1 + \Delta\alpha - \frac{c^2}{c^2 - s^2}\Delta\rho + \frac{G_\mathrm{F}m_\mathrm{W}^2}{12\pi^2\sqrt{2}(c^2 - s^2)}\ln\frac{m_\mathrm{H}}{m_\mathrm{Z}} + \ldots\right)$$

$$\Delta r = \Delta\alpha - \frac{c^2}{s^2}\Delta\rho + \Delta r_\mathrm{rem}$$

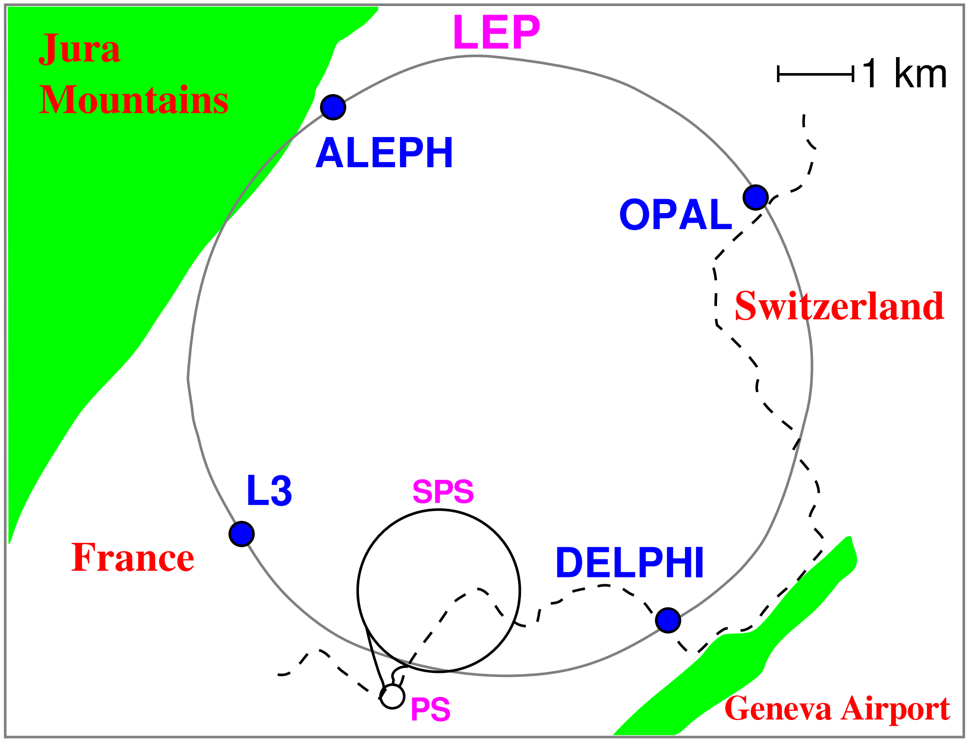
($\delta\alpha$ is the running of α from 0 to m_Z)

For all interesting quantities two-loop calculations exist

Machines for precision electroweak physics

LEP:

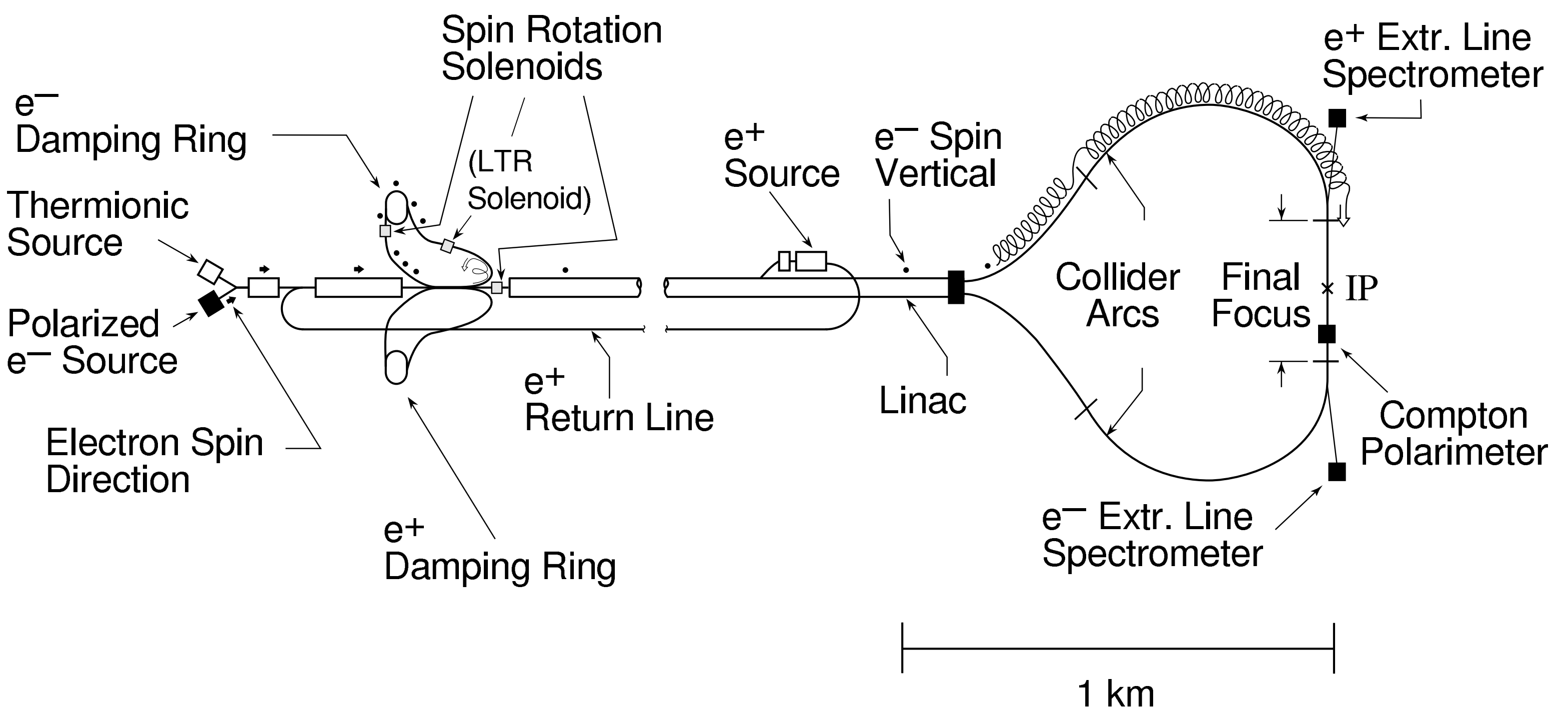
- e^+e^- ring at CERN (in the now-LHC tunnel)
- 1989-1995 running at or close to the Z-peak
  - 17000000 recorded Z-decays
  - 30% luminosity taken off-peak for Z-mass and width
  - beam energy precision of $2 \cdot 10^{-5}$



- 1996-2000 running above W-pair threshold
  - $\sim 700\ \text{pb}^{-1}$ per experiment at $161\,\text{GeV} < \sqrt{s} < 207\,\text{GeV}$
  - ➡ ~ 12000 W-pairs per experiment
  - Higgs sensitivity up to $m_H = 115\,\text{GeV}$

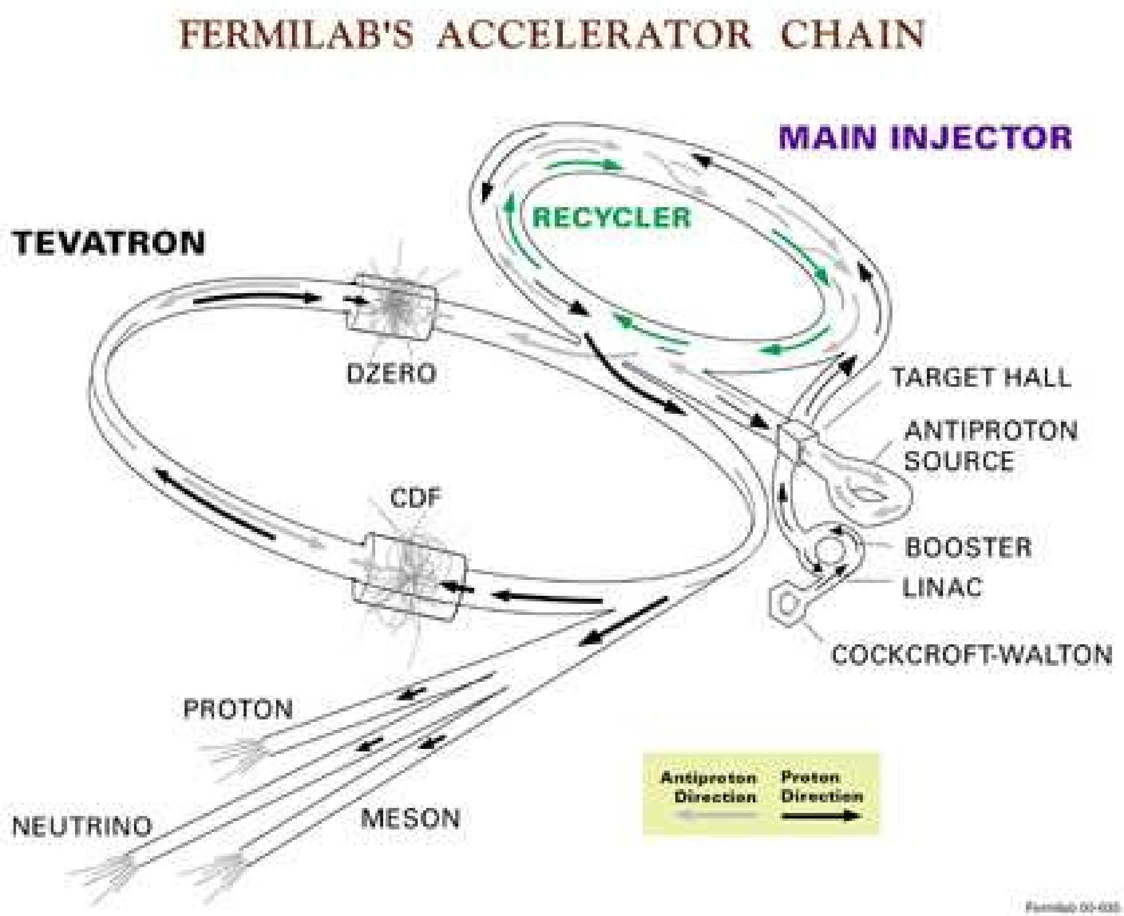
SLC:

- Linear collider at SLAC, running on the Z-pole from 1989 to 1998
- Only 500000 Z-decays recorded
- However up to 80% beam polarisation known to 0.5%
- Small bean size and beam pipe allowed for superb b-tagging



Tevatron:

- $p\bar{p}$ collider at Fermilab
- $\sqrt{s} = 1.96\,\text{TeV}$, $\int \mathcal{L} \approx 6\ \text{fb}^{-1}$ up to now
- Access to t, W, H



Measurements at the Z

Z lineshape:

$$\sigma_f(s) = \frac{12\pi}{m_Z} \frac{\Gamma_e \Gamma_f s}{(s - m_Z^2)^2 + \left(\frac{s}{m_Z}\right)^2 \Gamma_Z^2} + \sigma_{\rm int} + \sigma_\gamma$$

Must include ISR:

$$\sigma(s) = \int ds' \cdot \sigma_{\rm born}(s') \cdot \rho(s'/s)$$

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

Hadronic width:

$\Gamma_{\rm had} = \Gamma_{\rm had,no\,QCD}(1 + \alpha_s/\pi + \ldots)$

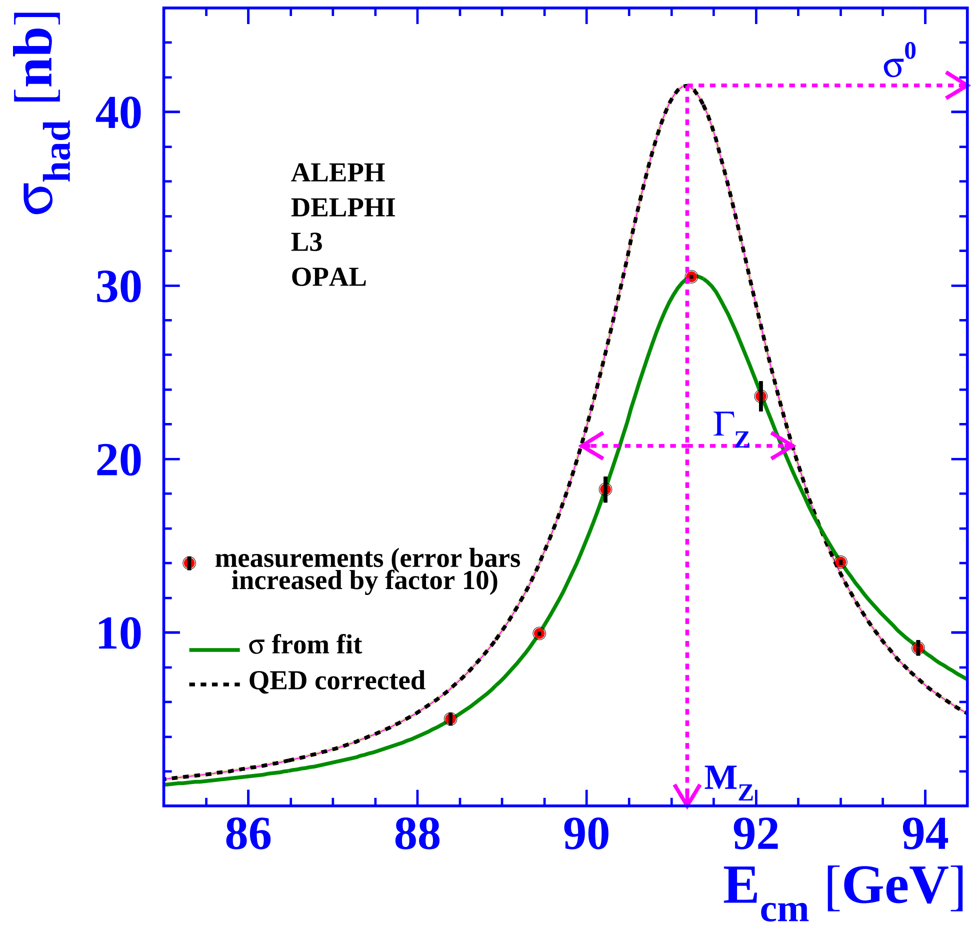
Partial widths measure $\Delta\rho$

Minimum correlated parameters:

$$m_Z,\ \Gamma_Z$$

$$\sigma_0^{\rm had} = \frac{12\pi}{m_Z} \frac{\Gamma_e \Gamma_{\rm had}}{\Gamma_Z^2}$$

$$R_l = \frac{\Gamma_{\rm had}}{\Gamma_l}$$



Asymmetries: Asymmetries arise from interference of vector and axial-vector coupling

$\rightarrow \propto \mathcal{A}_f = \frac{2 g_{Vf} g_{Af}}{g_{Vf}^2 + g_{Af}^2}$

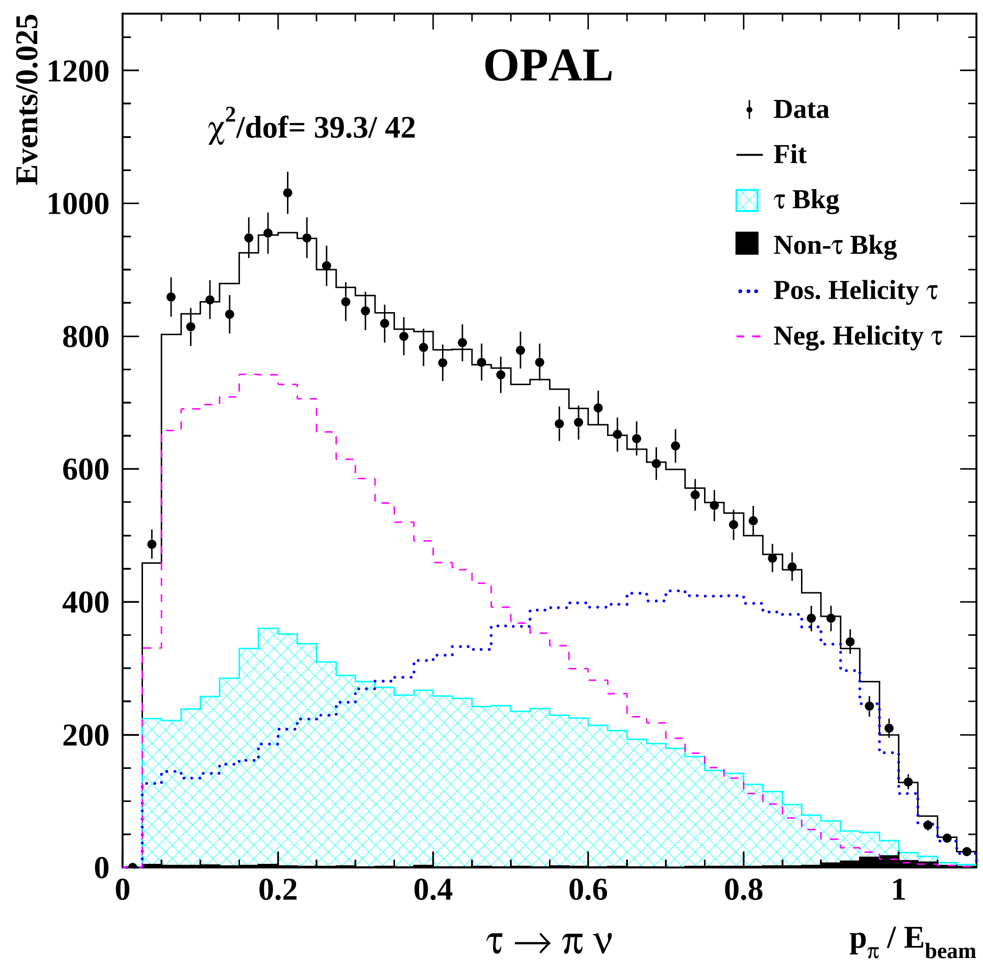
➠ measure $\sin^2 \theta^l_{eff}$

Forward-Backward asymmetries:

$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$

Pure Z-exchange:
$A_{FB}^{0,f} = \frac{3}{4} \mathcal{A}_e \mathcal{A}_f$

τ-polarisation and its forward-backward-asymmetry $\rightarrow \mathcal{A}_\tau, \mathcal{A}_e$

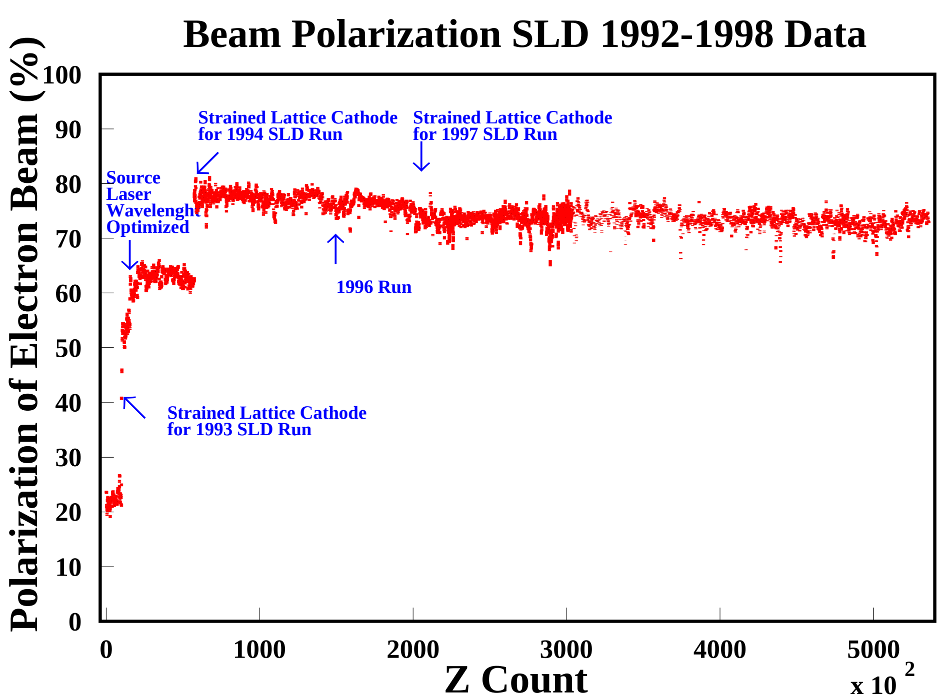


In addition at SLD: (polarised beams)

- Left-right Asymmetry:

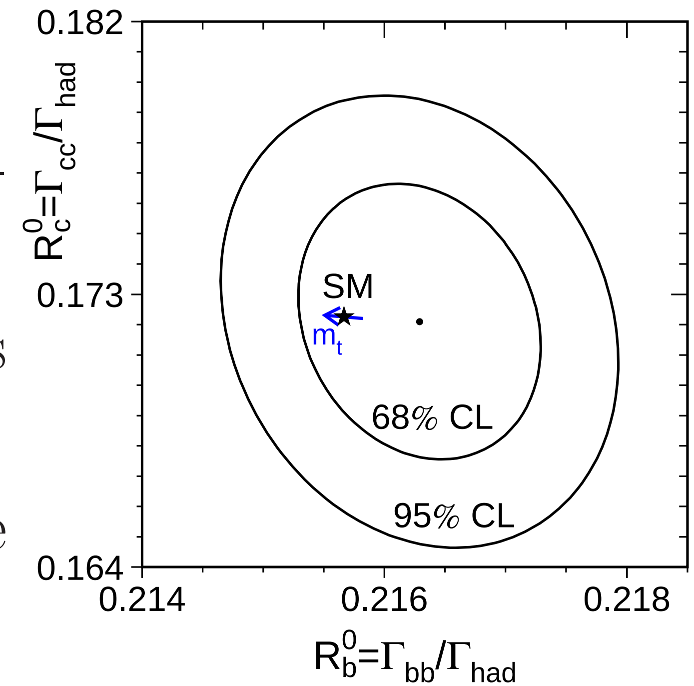
$$A_{\mathrm{LR}} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \mathcal{P}\mathcal{A}_e$$

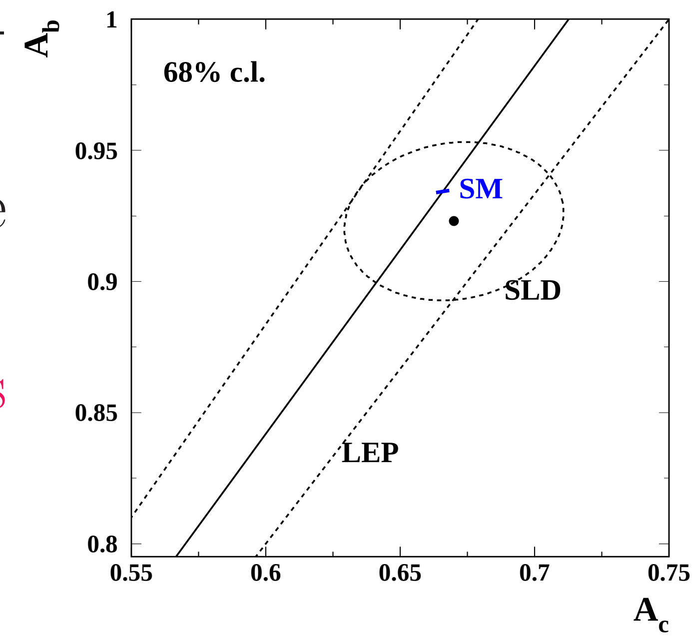
- High sensitivity to $\sin^2\theta^l_{eff}$
- All Z-decays can be used
- Only significant systematics from polarisation measurement



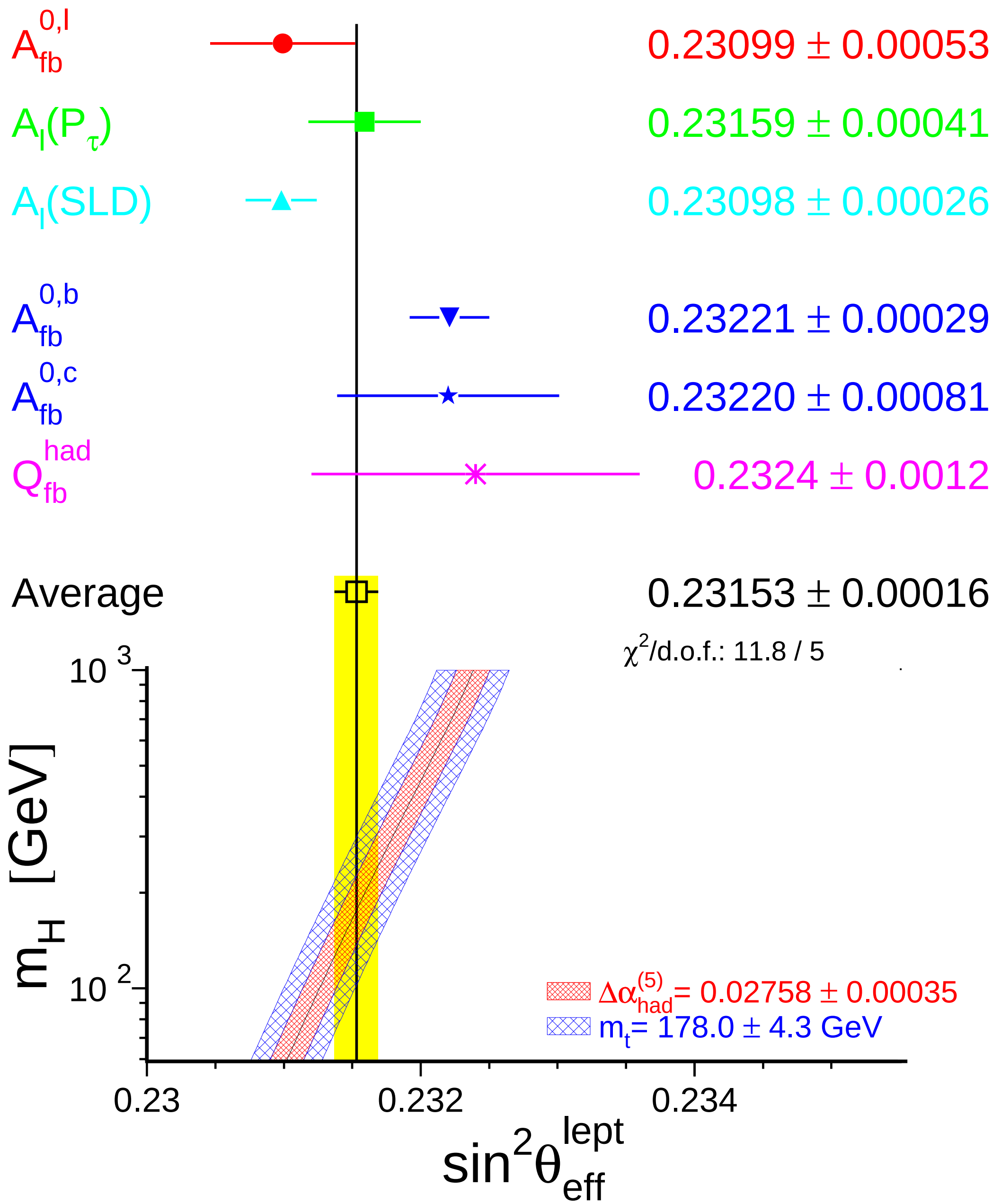
LEP/SLC heavy flavour measurements

- b- and c-quarks can be identified efficiently
- LEP and SLD can measure the fraction of b- and c-quarks in hadronic Z-decays R_{b}, R_{c}
- Especially R_{b} is very sensitive to new physics connected to tb-couplings
- With the precise m_{t} from the Tevatron the interest from SM is minor
- SLC measures in addition the asymmetry parameters $\mathcal{A}_{\mathrm{b}}$, $\mathcal{A}_{\mathrm{c}}$
- However these parameters are only sensitive to new physics on Born-level
- For that reason the LEP $A_{\mathrm{FB}}^{\mathrm{b}}$ measurements are a clean measurement of $\sin^2\theta^l_{eff}$





$\sin^2\theta^l_{eff}$ measurements at LEP/SLC



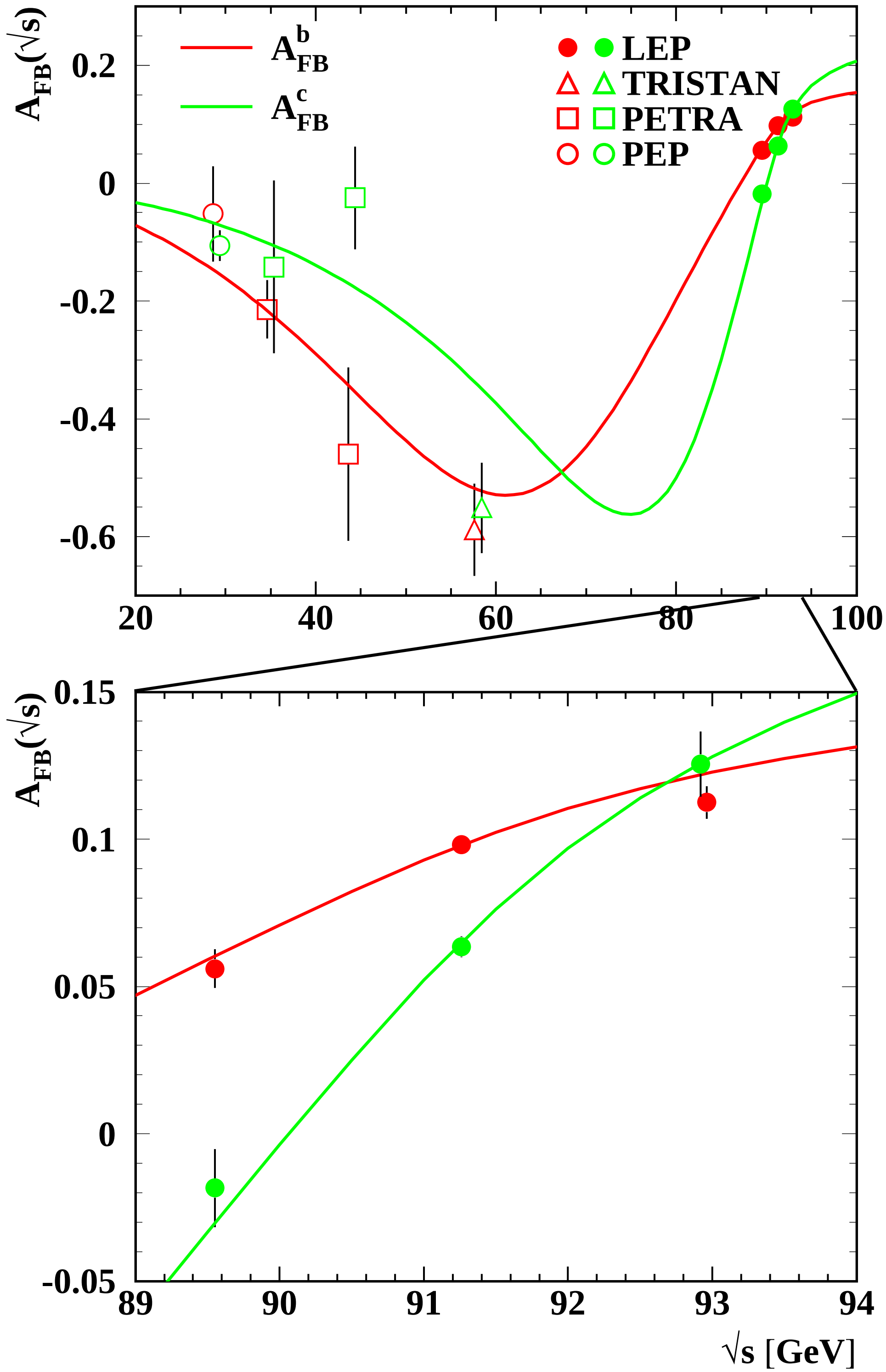
- Very precise measurement
- However marginal agreement between $A_{\rm LR}$ and $A^{\rm b}_{\rm FB}$
- No convincing physics explanation found
- Assume that it is a statistical fluctuation

Energy dependence of asymmetries

- Z-coupling to leptons is almost purely axial-vector
- γ-coupling is pure vector

➡ Large interference effect off-peak

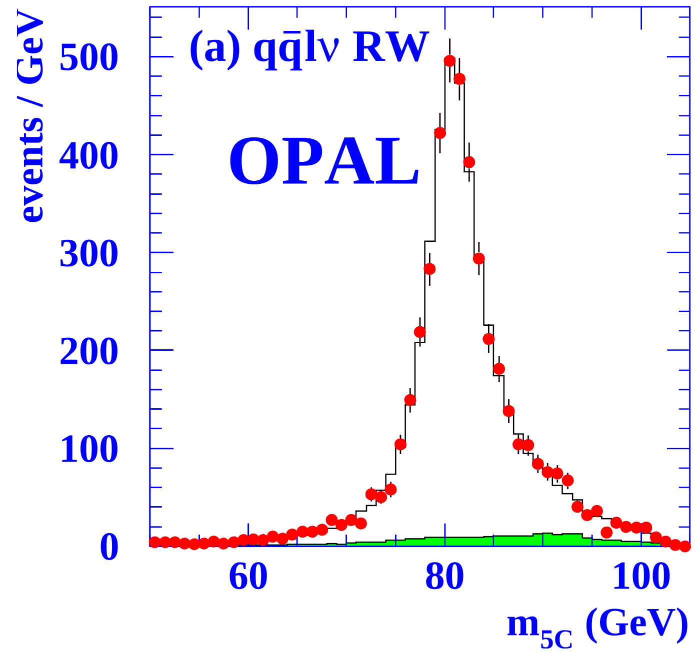
- – Mainly uninteresting in the Standard Model
- – Sensitive to Z-Z' mixing on the Z
- – At larger energy sensitive to Z' exchange
- – Could already establish Z-fermion couplings at PETRA

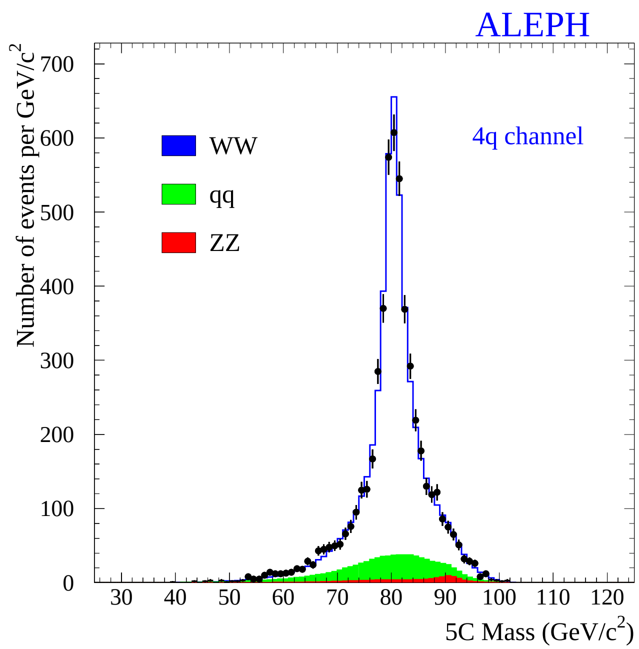


W-mass measurements

LEP

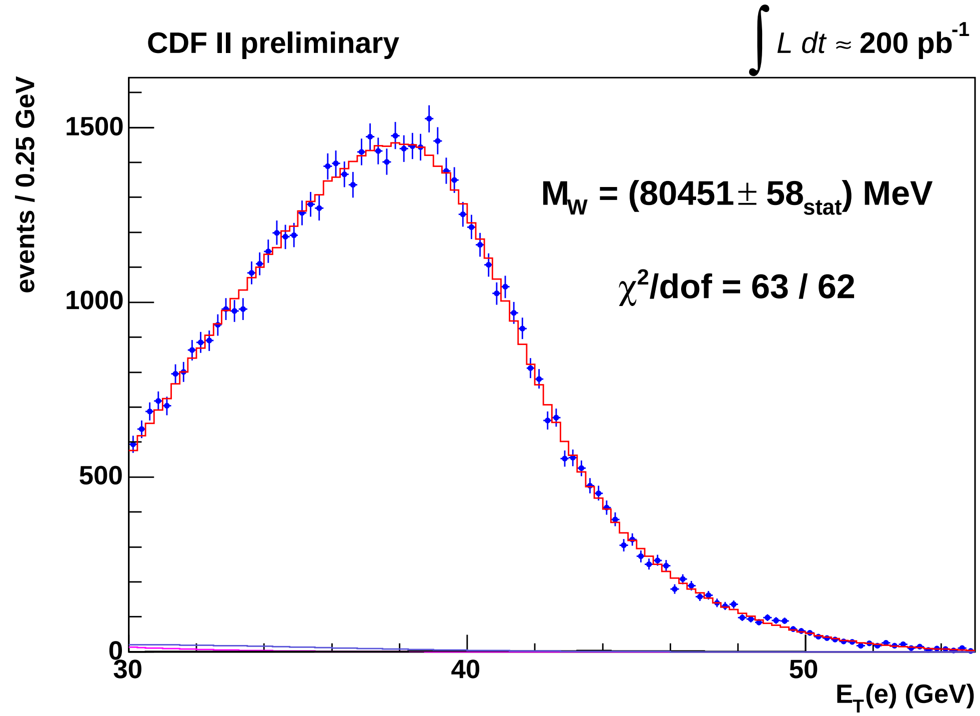
- $\sim$ 10000 W-pairs /experiment
- $\sim$ 45% mixed ($WW \rightarrow \ell\nu qq$ decays
  - for $\ell = \mu, e$ ν can be reconstructed from energy-momentum constraint $\Rightarrow$ clean measurement with good precision
- $\sim$ 45% $WW \rightarrow$ 4-jet decays
  - full information available
  - limited jet resolution can be improved with constrained fit
  - some problems with jet-pairing
  - still experimentally most precise measurement
  - however significant uncertainty from colour reconnection

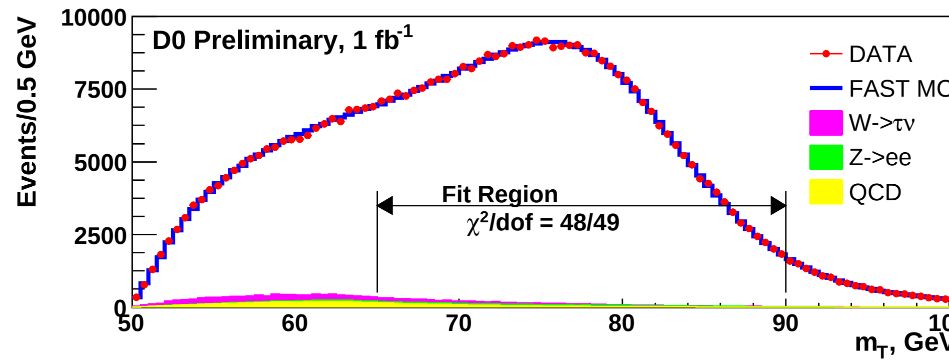


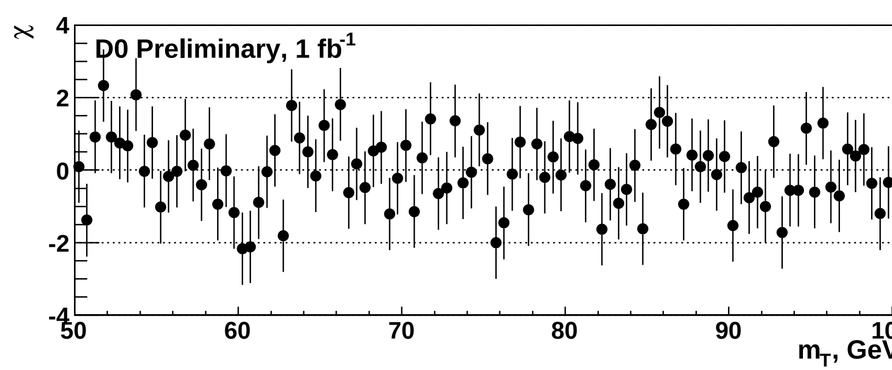


Tevatron:

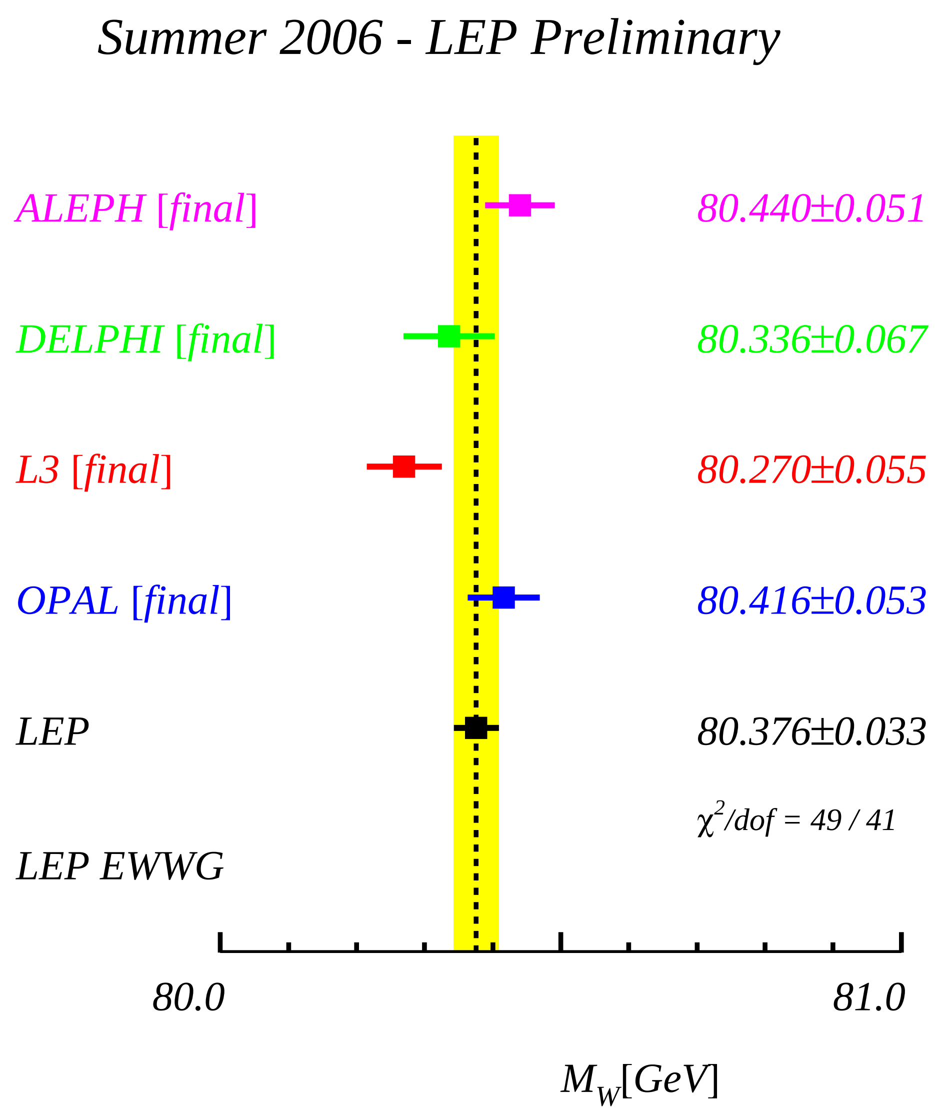
- Large statistics from $q\bar{q}' \to W \to \ell\nu$
- Only transverse ν momentum can be reconstructed using hadronic recoil
- Main uncertainty from lepton energy-scale
- Can be calibrated using Z-production ➠ limited by statistics
- m_{W} can be measured from lepton transverse momentum or from transverse mass
- Precision now at same level as LEP

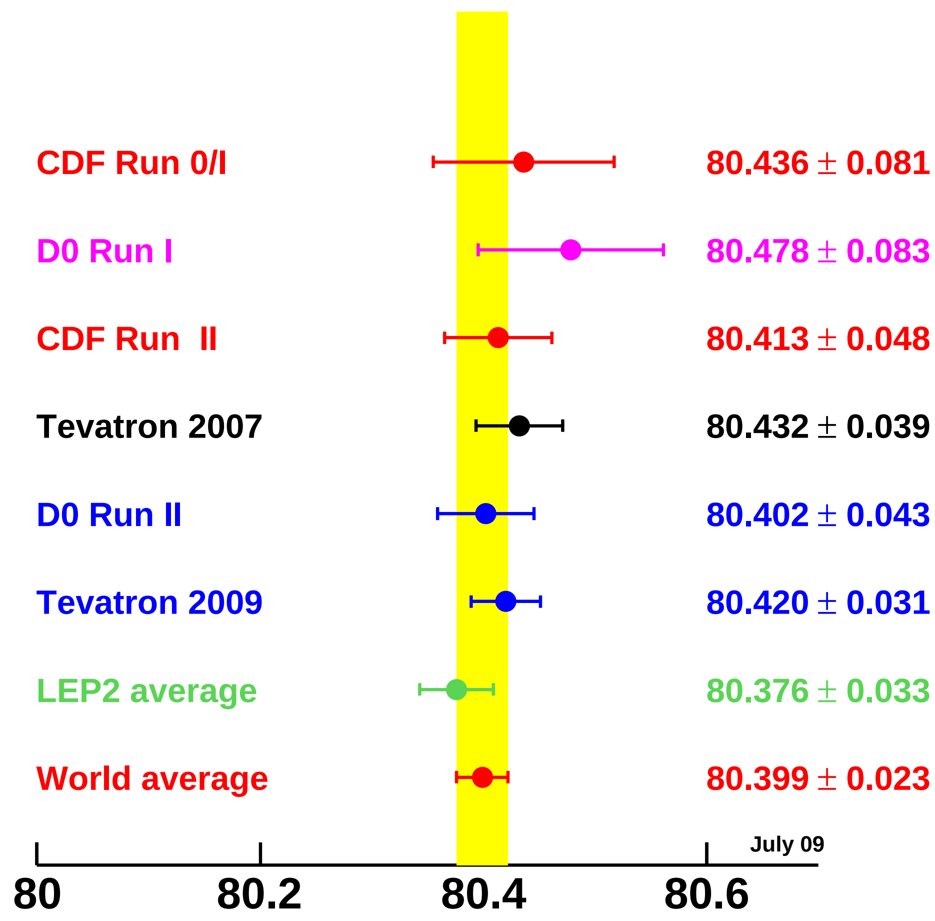






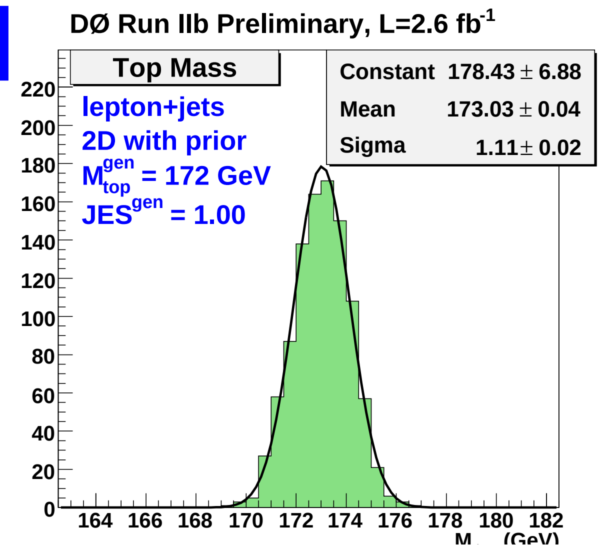
m_W combination

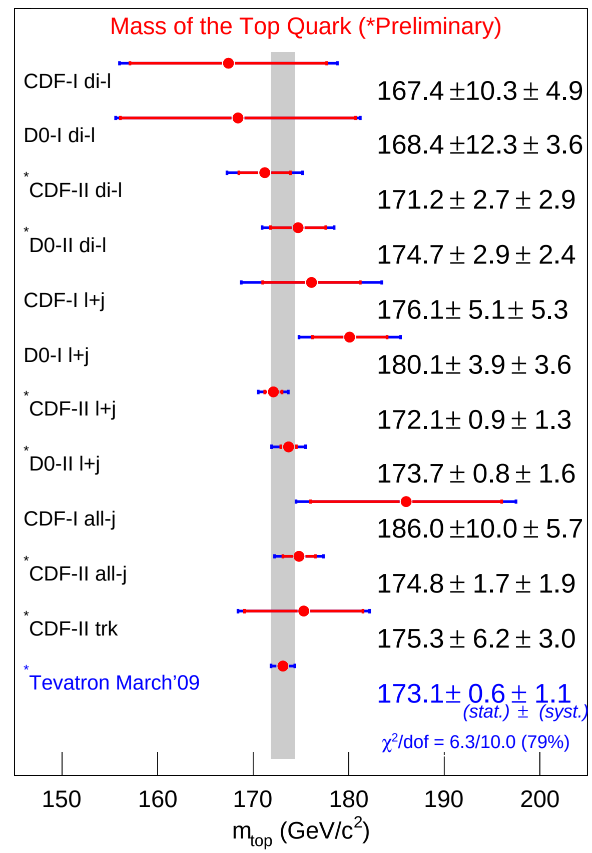




The top-quark mass

- The top mass enters only at 1-loop level
- However the dependence is quadratic and at percent-level measurement is needed to match the other observables
- Tevatron measurement on the 1 GeV level from reconstruction of the top-quarks
- Open issues:
  - colour reconnection effects: first estimates indicate 0.5 GeV uncertainty, included in world average
  - mass definition: could also be around 0.5 GeV, not yet included





Interpretation of the precision data

- The Standard Model is completely fixed apart from the Higgs mass

➠ fit all data with m_{H} as free parameter:
  - χ^2 shows if the data are compatible with the Standard Model
  - m_{H} fit result indicates the range of the Higgs mass in the Standard Model

The Gfitter project

- New fit-program from a CERN, DESY, Uni Hamburg collaboration
- Object oriented code built on ROOT functionality
- Standard Model fully implemented in $\geq$ 2-loop
- Consistent results with ZFITTER
- BSM implementation in progress

Used Data

- LEP lineshape parameters
- $\sin^2\theta^l_{eff}$ measurements from LEP and SLD
- m_{W}, Γ_W from LEP, Tevatron
- $\alpha(m_{\mathrm{Z}})$ from QCD + $\mathrm{e^+e^-}$-data
- Quark masses m_{t}, m_b, m_c
- G_{F} used as error free constant

Not used:

- $\sin^2\theta$ from NuTEV: unclear theoretical uncertainties
- External α_s measurements: unclear correlation of theoretical uncertainties
- Other low energy parameters ($g-2$, $BR(b \to s\gamma ...)$: not sensitive to Standard Model parameters

Error treatment:

- Data: Gaussian errors ➡ χ^2 log likelihood
- Theory: Flat probability in error range

  Dominant errors:

  – $\delta m_{\mathrm{W}} \approx 5\,\mathrm{MeV}$ from missing higher orders

  – $\delta \sin^2\theta^l_{eff} \approx 5 \cdot 10^{-5}$ from missing higher orders

Fit parameters:

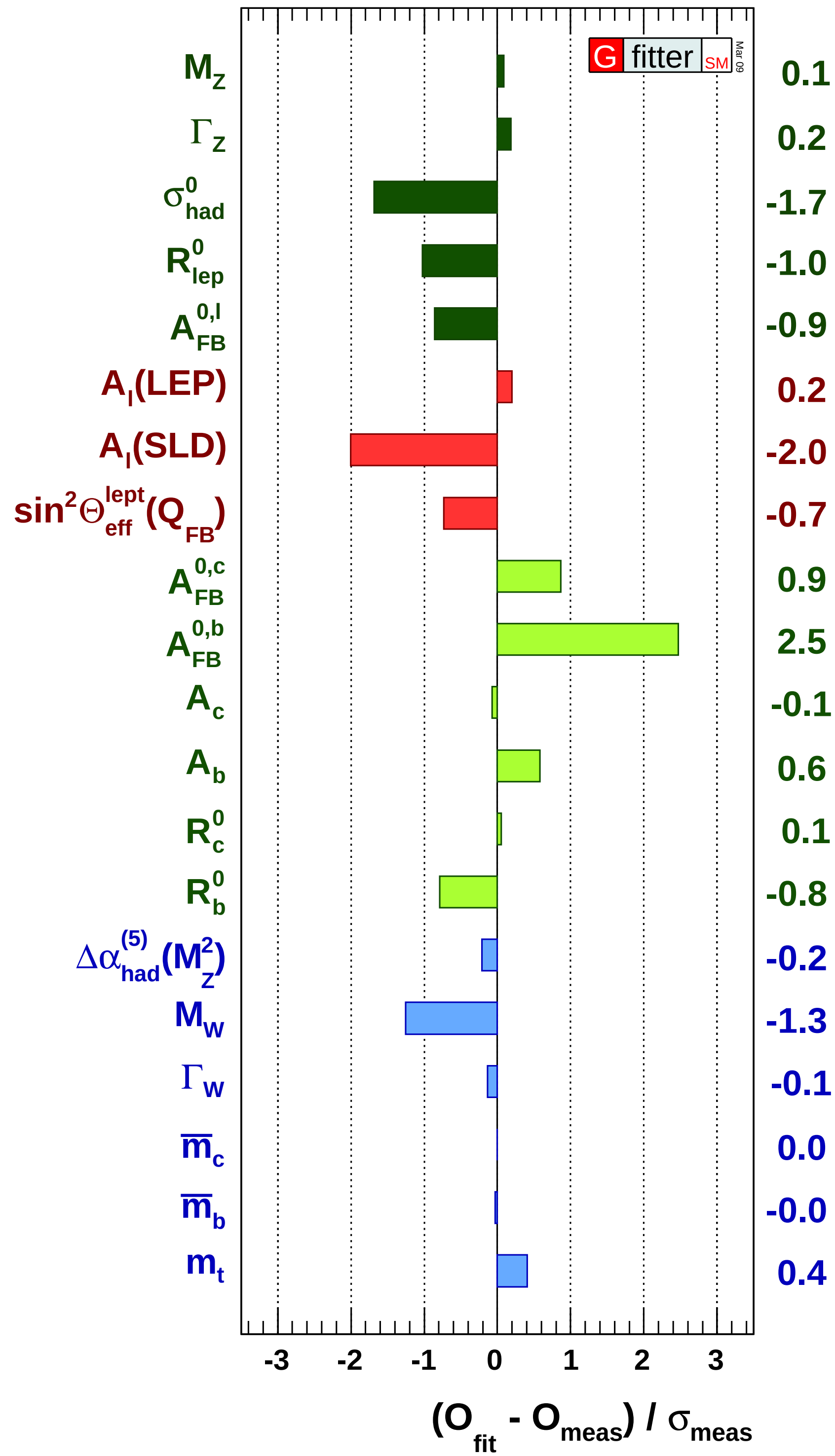
- m_{H} and α_s as real free parameters
- m_{Z}, m_{t}, m_b, m_c, $\alpha(m_{\mathrm{Z}})$ for a consistent error treatment

Result of the SM fit:

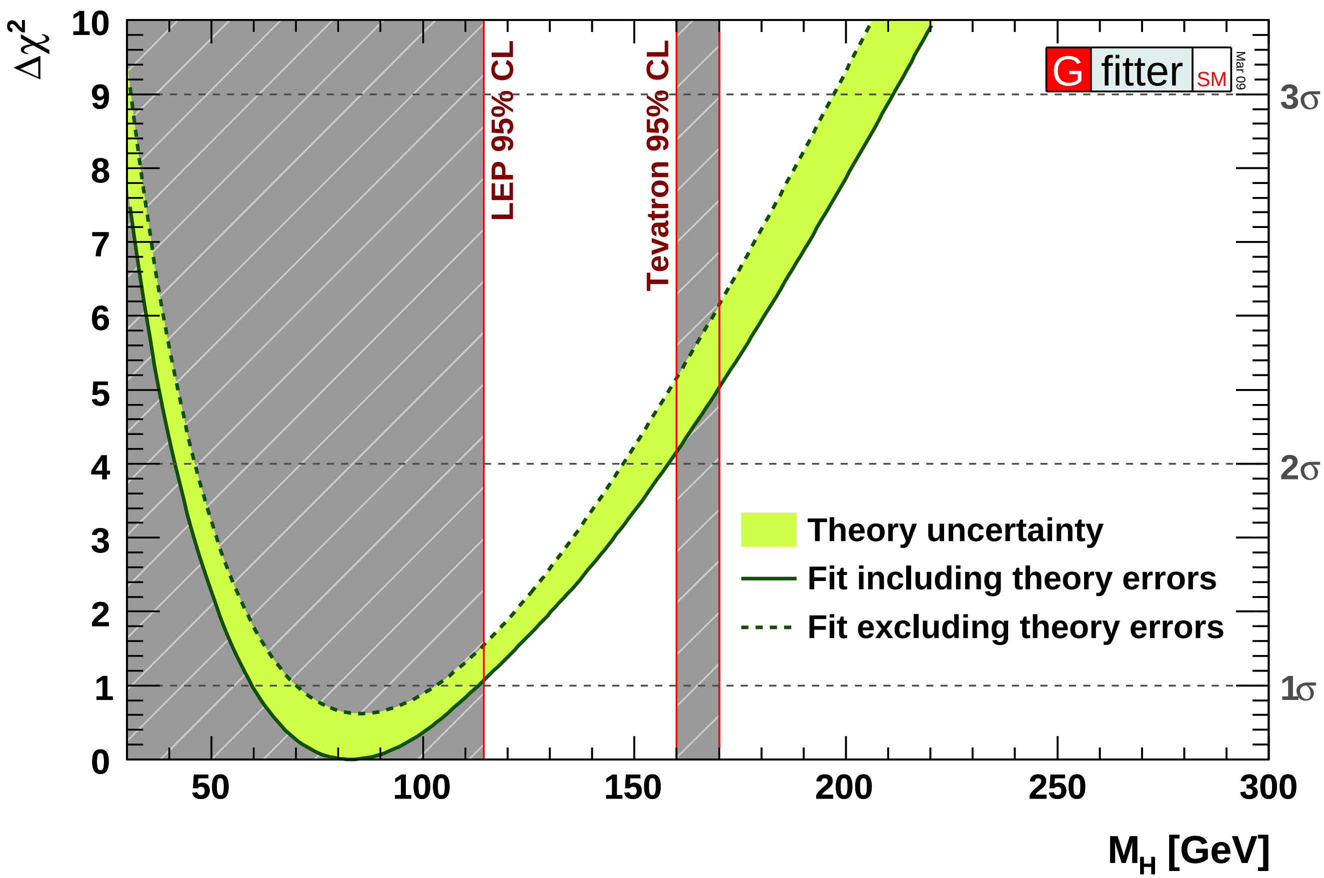
$$m_{\rm H} = 83^{+30}_{-23}\,\text{GeV}$$
$$m_{\rm t} = 173.2 \pm 1.2\,\text{GeV}$$
$$\alpha_s(m_{\rm Z}) = 0.1192 \pm 0.0028$$
$$\Delta\alpha^{(5)}_{\rm had}(m_{\rm Z}) = 0.02772 \pm 0.0022$$

$\chi^2/ndf = 16.4/13 \quad \Rightarrow \text{Prob} = 23\%$

- Overall good agreement of data with SM
- Largest deviation 2.5σ ($A^{\rm b}_{\rm FB}$) not unexpected



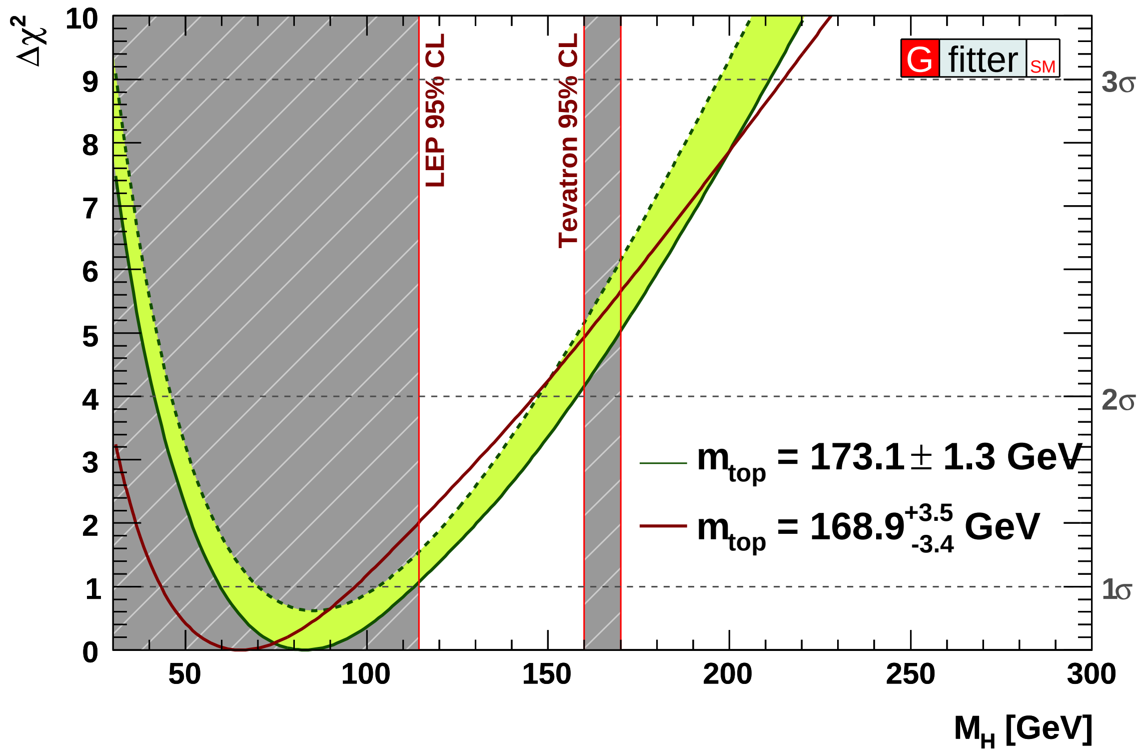
Higgs limit from the SM fit



$$m_{\mathrm{H}} \lesssim 160\,\mathrm{GeV} \text{ at } 2\sigma$$

The top-mass definition

- The definition of the top-mass from reconstruction is not completely clear
- It should be close to the pole mass with an uncertainty around 0.5 GeV
- The mass-cross section relation near threshold is better understood
- From the Tevatron $t\bar{t}$ cross section a top pole-mass $m_t = 168.9 \pm 3.5\,\text{GeV}$ can be derived
- This value leads to a similar prediction for the Higgs mass



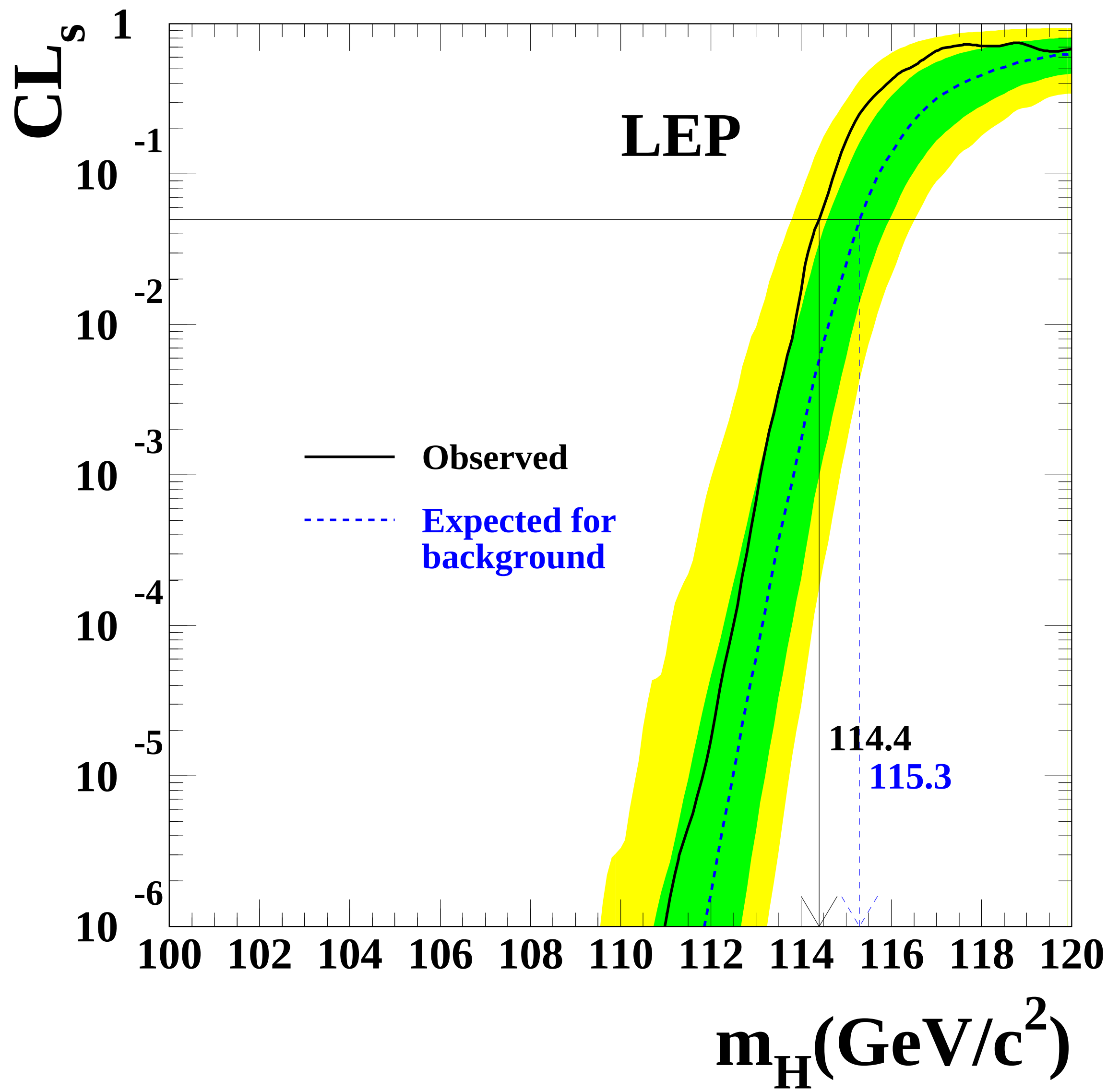
Direct Higgs searches

LEP:

- Production via Higgs-strahlung
- Cross section falls steeply for $m_{\rm H} > \sqrt{s} - m_{\rm Z}$

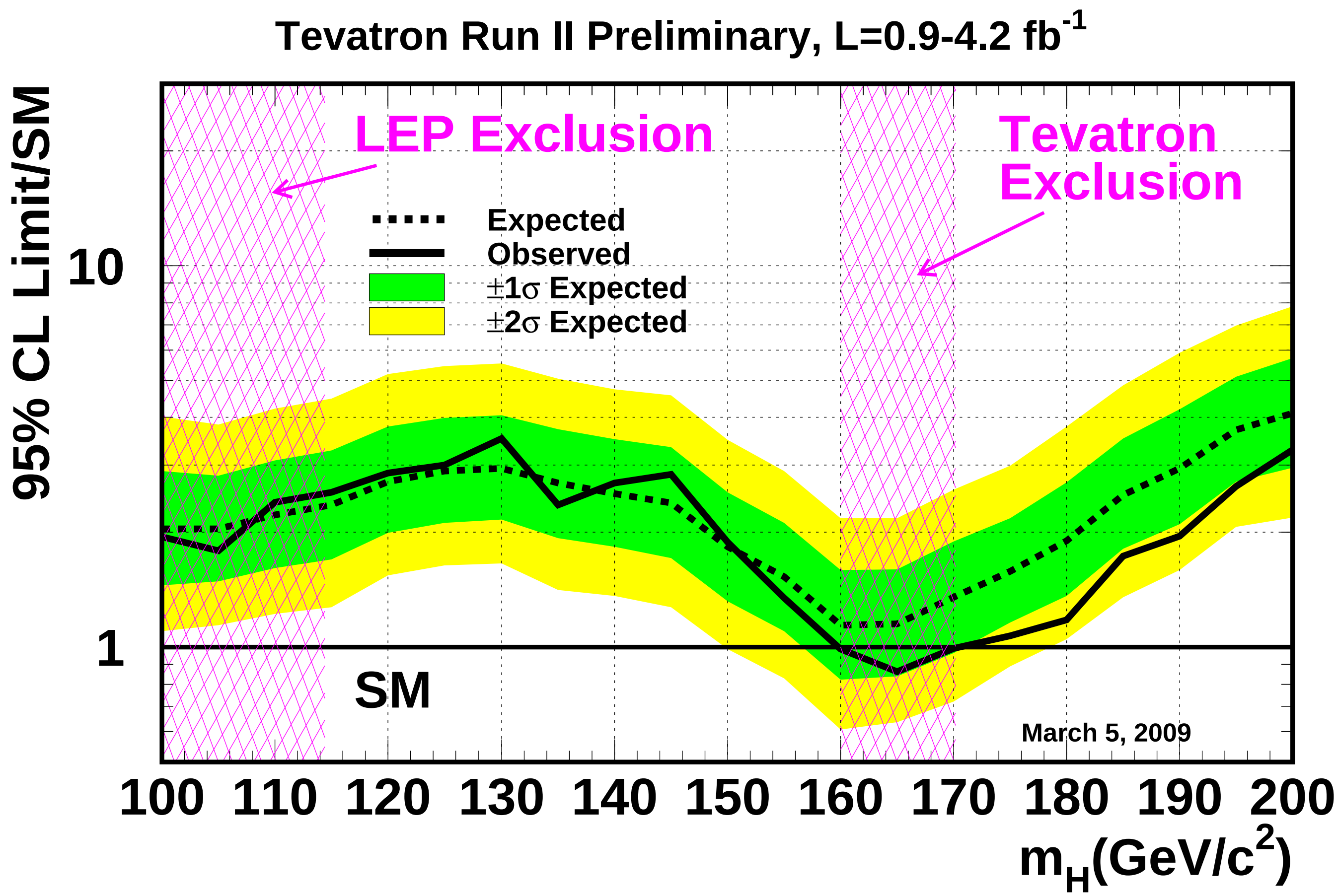
➠ Very strong exclusion for $m_{\rm H} < 113\,\text{GeV}$
Basically no exclusion for $m_{\rm H} > 116\,\text{GeV}$
Small transition region

- Statistical treatment in a common fit uncritical



Tevatron:

- Variety of channels sensitive to Higgs masses up to $\sim 200\,\mathrm{GeV}$
- Measure cross section limit normalised to SM cross section as a function of m_{H}
- SM-Higgs excluded if limit ≤ 1

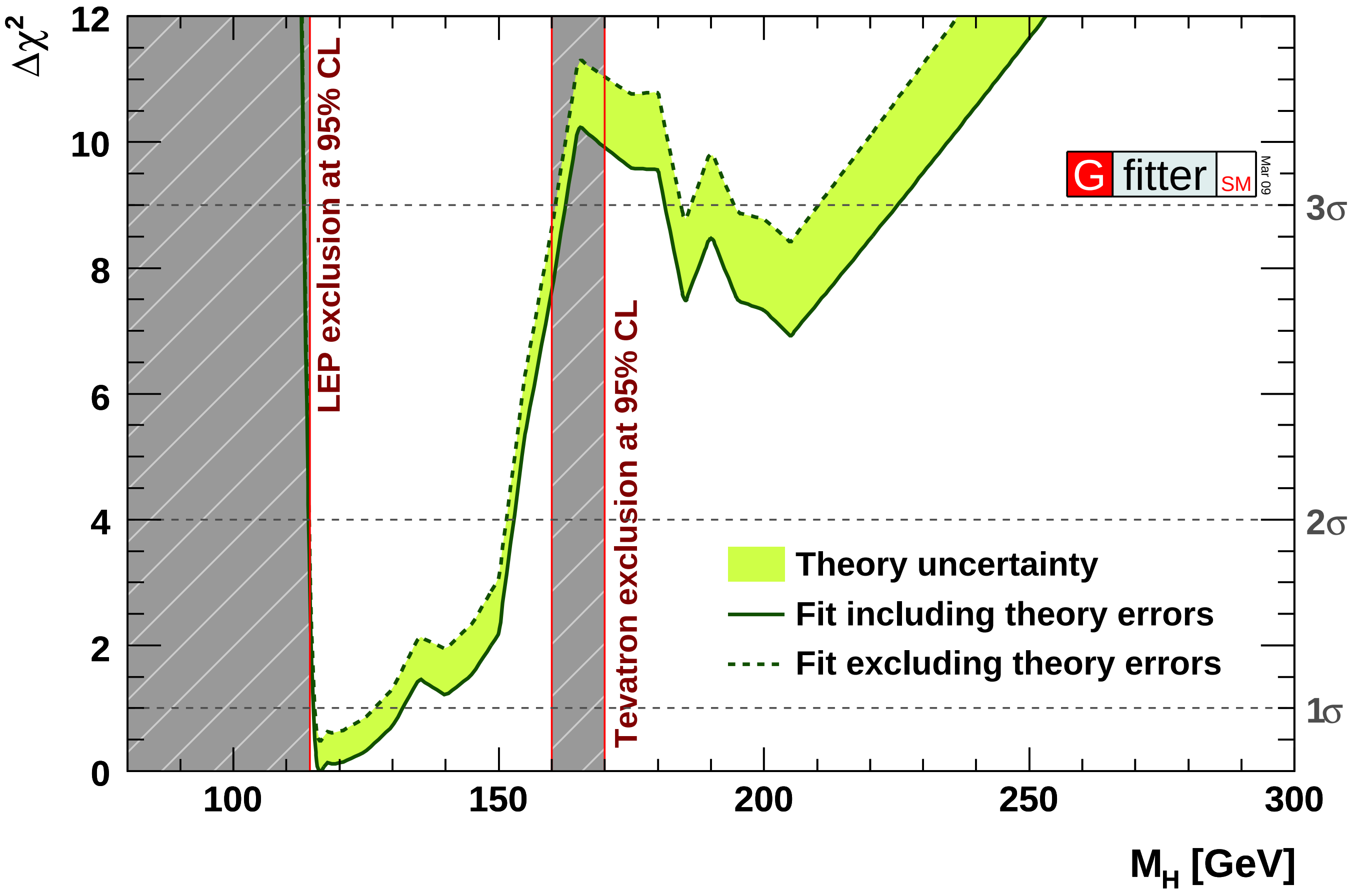


SM fit including Higgs limits

Add $\mathrm{ERF}^{-1}(1 - \mathrm{CL}_{\mathrm{s+b}}^{2-\mathrm{sided}})$ to the χ^2

($\mathrm{CL}_{\mathrm{s+b}}^{2-\mathrm{sided}}$ = Probability that data are consistent with a (SM-) Higgs signal of mass m_{H})

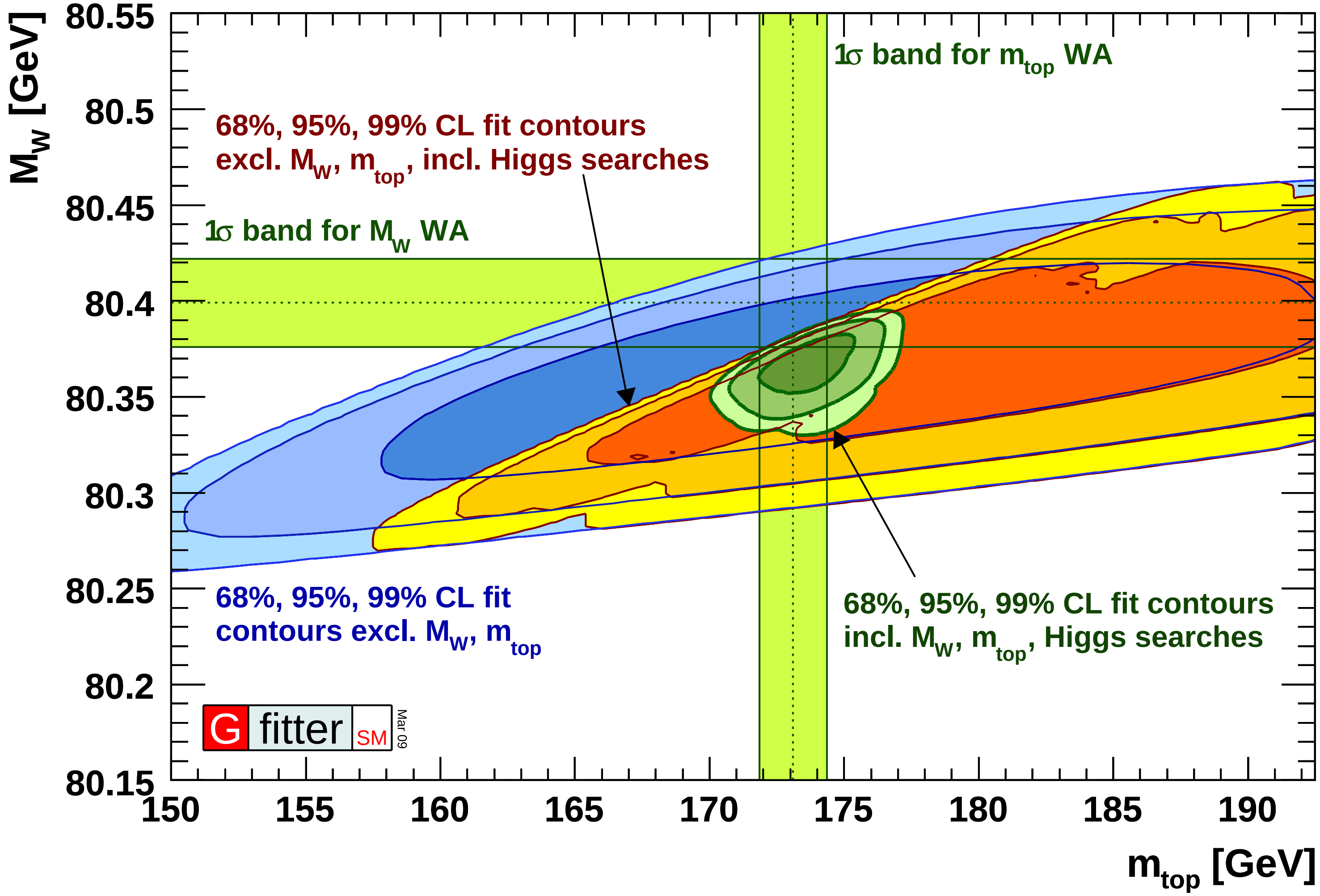
Result:



Compatibility with data:

$\chi^2/ndf = 17.9/14 \quad \Rightarrow \text{Prob} = 21\%$

Direct measurements and fit predictions of observables agree well



Higgs limit:

- $m_{\mathrm{H}} > 150\,\mathrm{GeV}$ with $> 2\sigma$
- $m_{\mathrm{H}} > 160\,\mathrm{GeV}$ with $> 2.5\sigma$

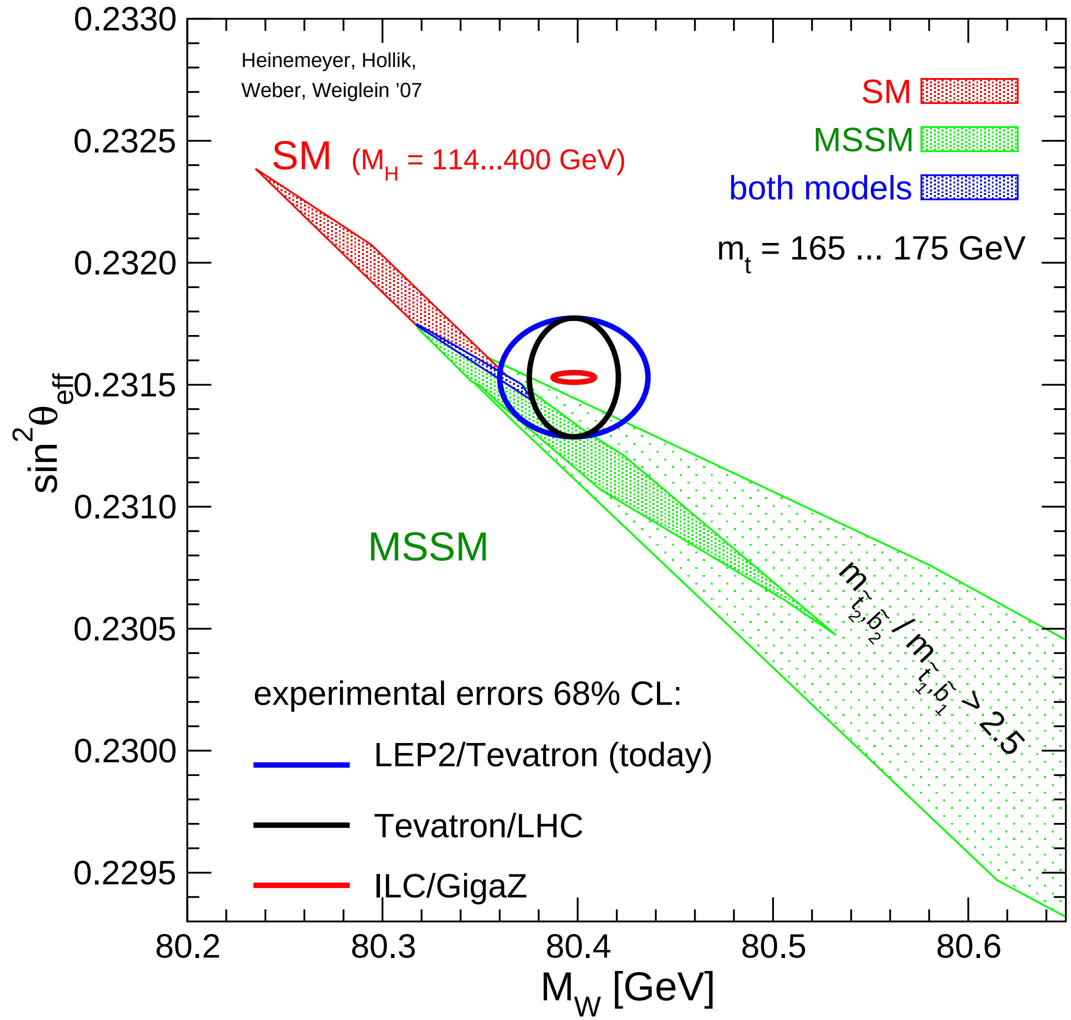
What does this limit mean?

- The question of the fit is: Are the data consistent with the Standard Model with a Higgs mass m_{H}
- There is no statement for non-SM Higgses
- Even if a Higgs with mass m_{H} and a too large coupling is found the fit would give a bad χ^2

Predictions beyond the Standard Model

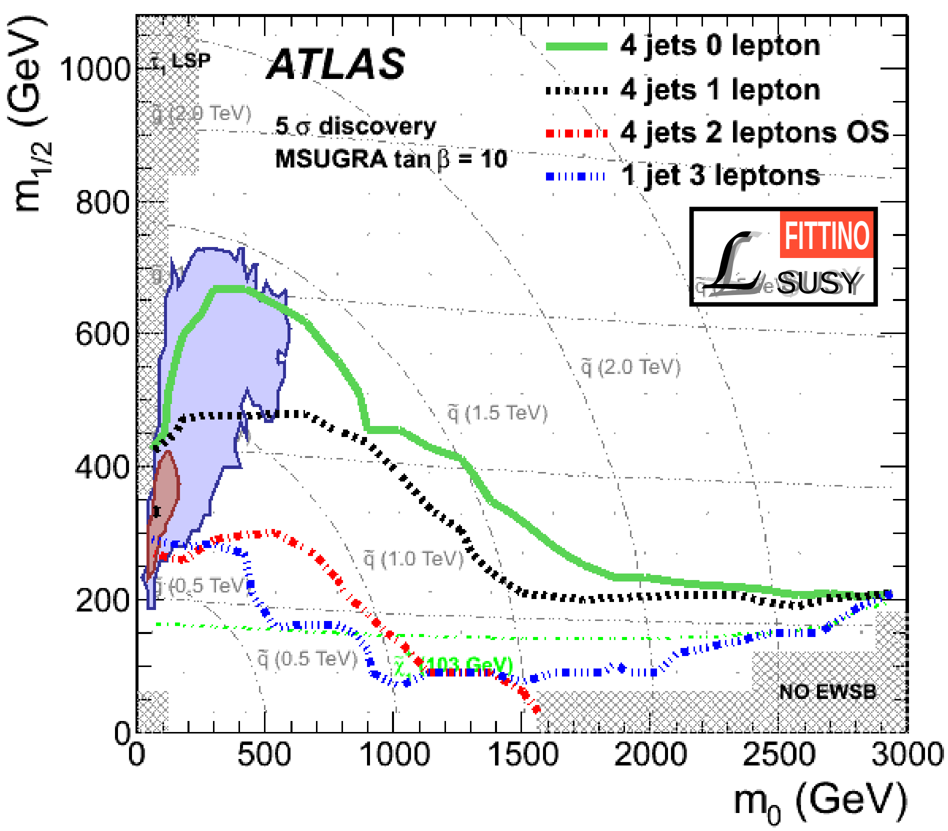
SUSY

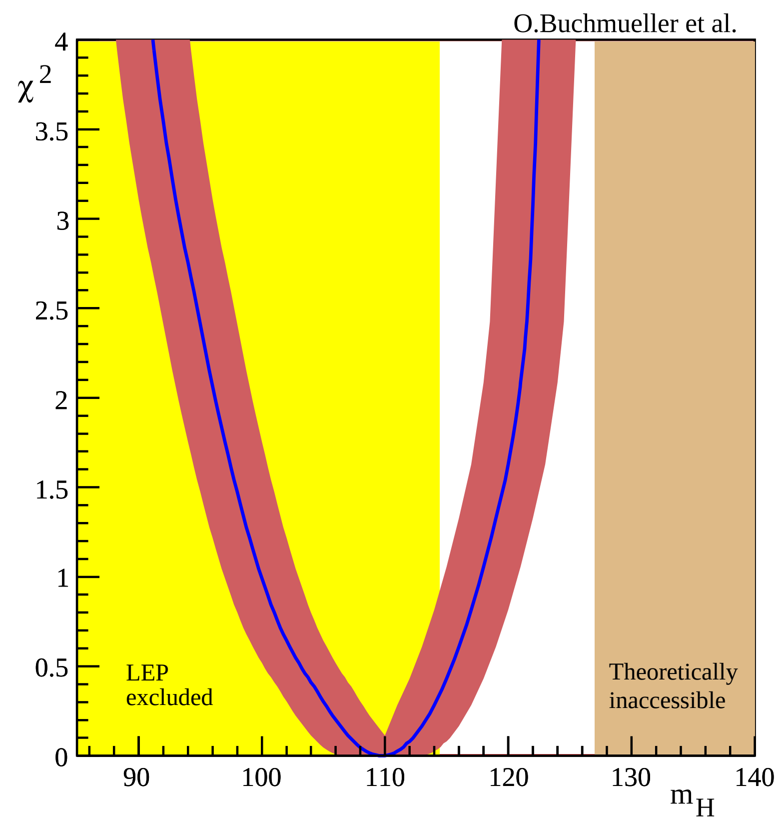
- SUSY is a fully calculable theory, so similar fits can be done
- SUSY is a decoupling theory
  ⇒ heavy SUSY looks exactly like SM
- High energy data are consistent with the SM with a slight preference to SUSY
  ⇒ no meaningful constraints are possible



Recent fits add new observables:

- $g_\mu - 2$: $\sim 3.5\sigma$ from SM favours light SUSY
  (however some doubt on this ➠ next slide)
- Dark matter density: Assuming that LSP accounts for all dark matter favours light SUSY
- $BR(b \to s\gamma)$ is 1σ above SM ➠ small pull towards light SUSY
- Result: relatively low m_0, $m_{1/2}$ at moderate $\tan\beta$

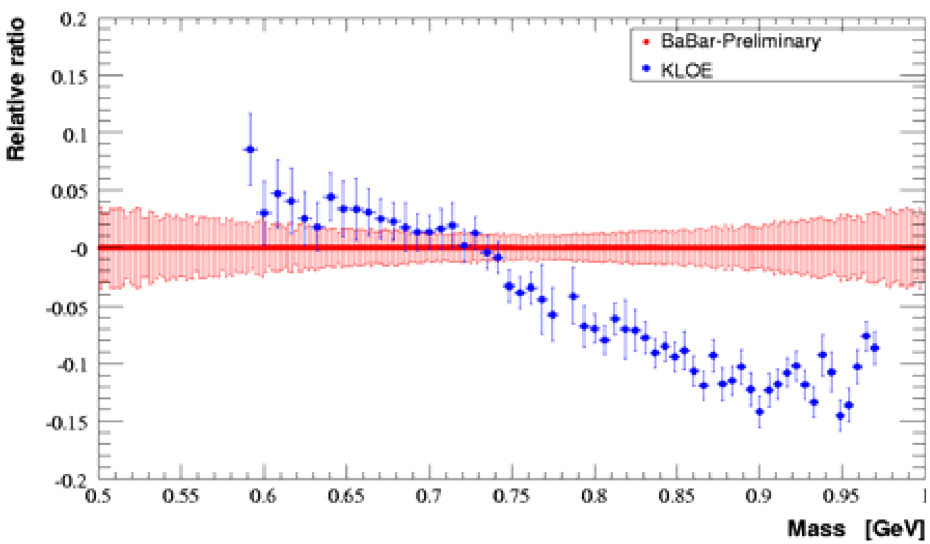


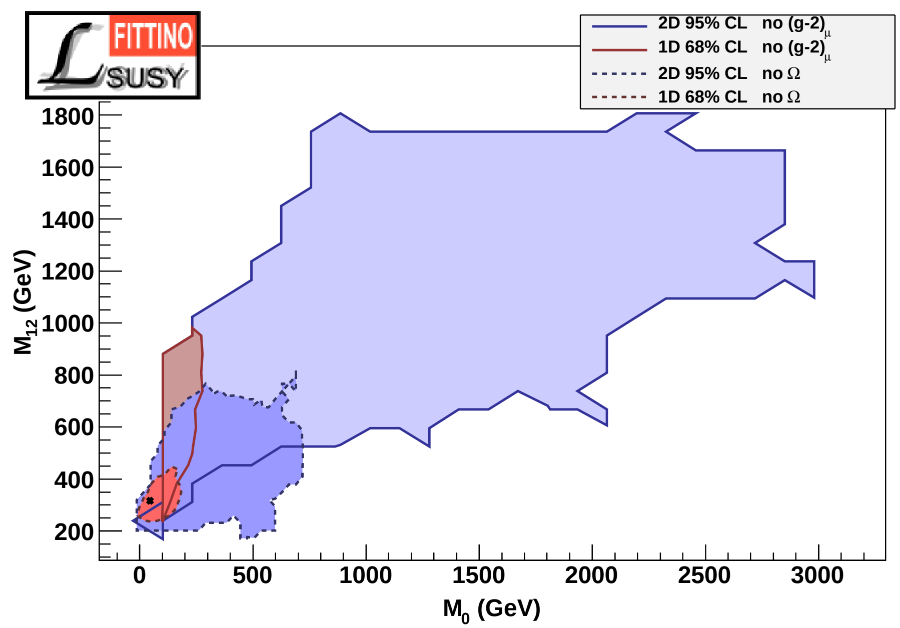


A word on $g_\mu - 2$

- Measured to 6×10^{-10} at BNL
- However contribution from hadronic vacuum polarisation 100 times larger ➠ must be obtained from e^+e^- annihilation at low energy (or τ spectral function)
  (largest contribution comes from $e^+e^- \to \pi^+\pi^-$ in ρ-region)
- Status up to early summer:
  - Difference theory - experiment $\approx 3.5\sigma$ when hadronic contribution taken from e^+e^- (preferred)
  - Difference only $\approx 2\sigma$ if taken from τ spectral function
- The 3.5σ can be taken as a strong evidence for light SUSY

- This summer BaBar published a very precise measurement of $e^+e^- \to \pi^+\pi^-$ in the ρ-region
- However this measurement disagrees with the other measurements, especially with 2nd most precise of KLOE
- Taking only BaBar for $e^+e^- \to \pi^+\pi^-$ reduces discrepancy to 2σ
- Dropping g-2 in SUSY fit largely increases allowed range especially in $m_{1/2}$



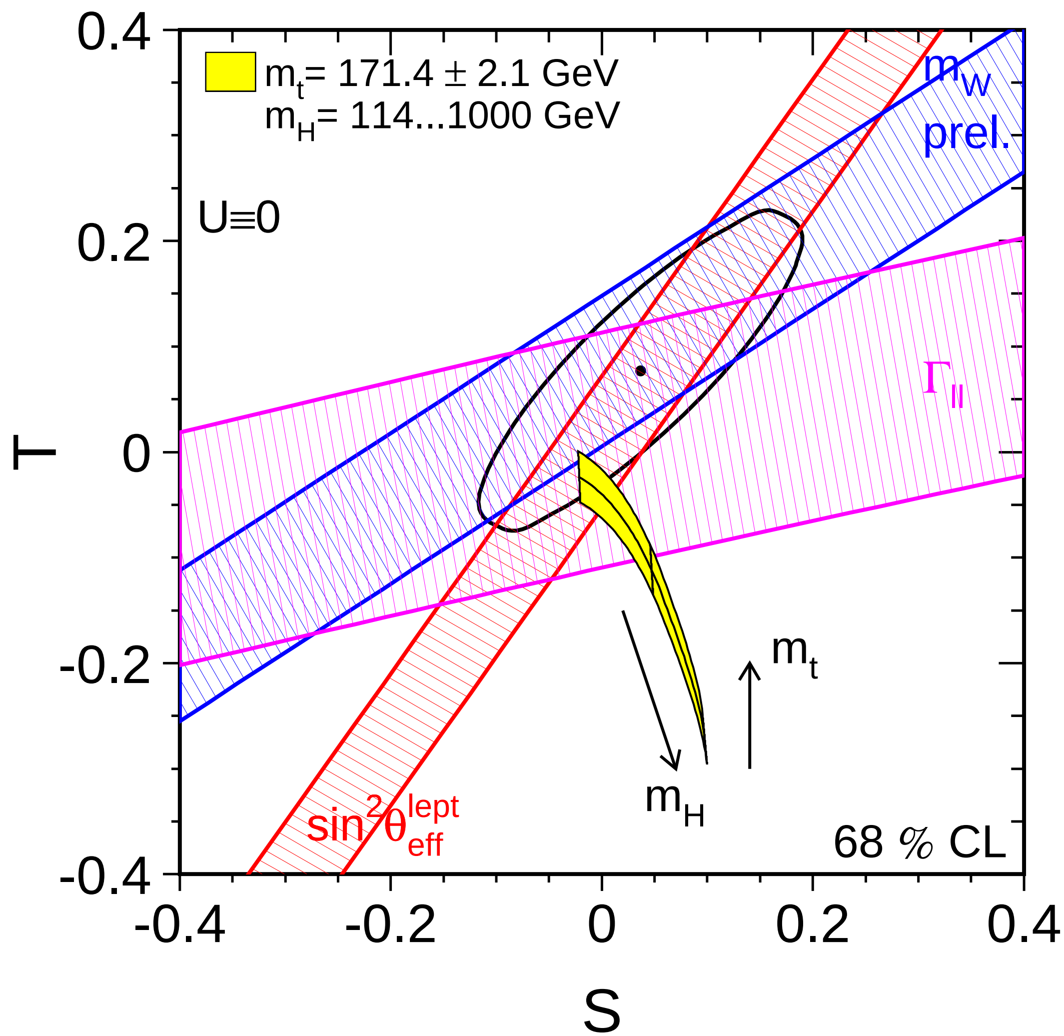


Model independent approach

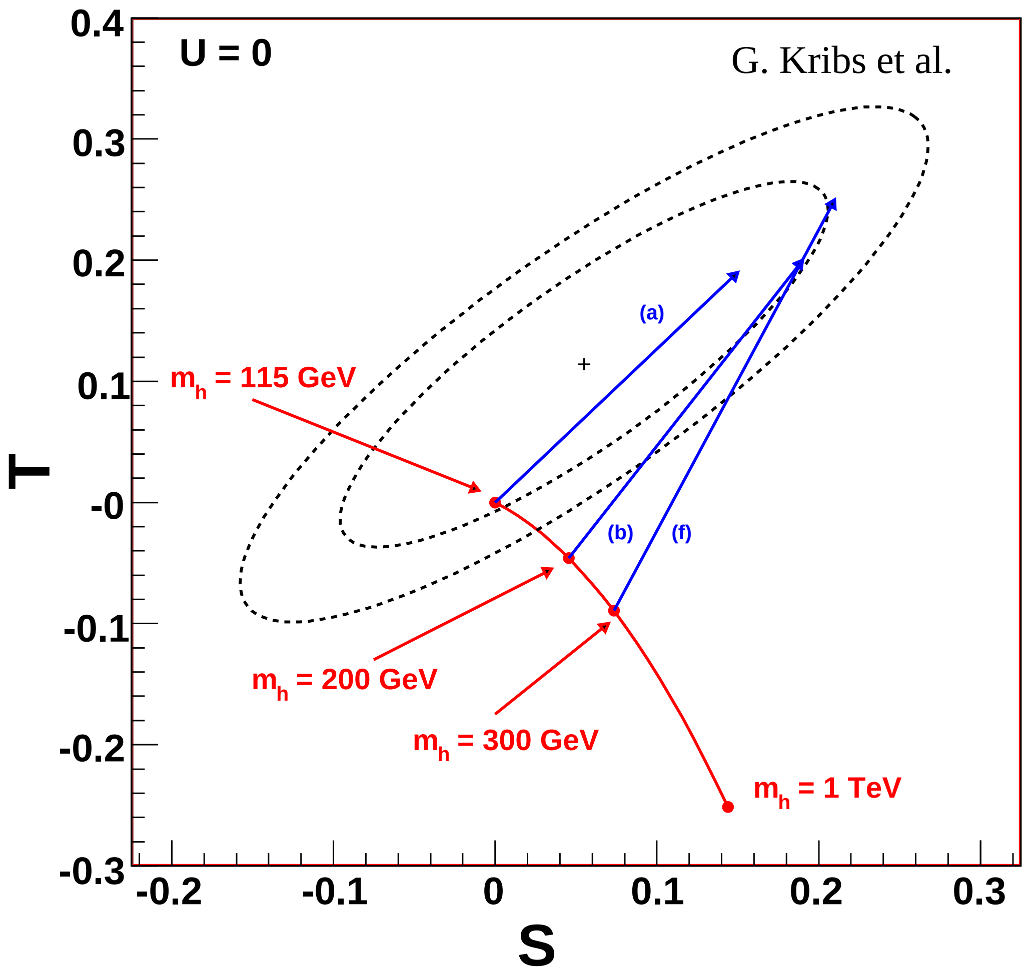
- STU parameters parametrise loop effects in a model independent way

  T: isospin violating corrections,
  S: remainder in Z-pol observables,
  U: additional corrections in m_W

- Most models predict U=0, so this constraint is often used
- $\sin^2\theta^l_{eff}$ gives narrowest band
- Γ_ℓ ideal complement, however of limited precision
- m_W important additional constraint



- In the SM of course the $m_{\rm H}$ limit is found back
- However if news physics can be arranged to provide the right ΔT and ΔS a heavier Higgs can easily be accommodated
- Example: 4th generation with $m_U = 400\,\mathrm{GeV}$, $m_D = 325\,\mathrm{GeV}$, $m_{\rm H} = 300\,\mathrm{GeV}$ well consistent with precision data

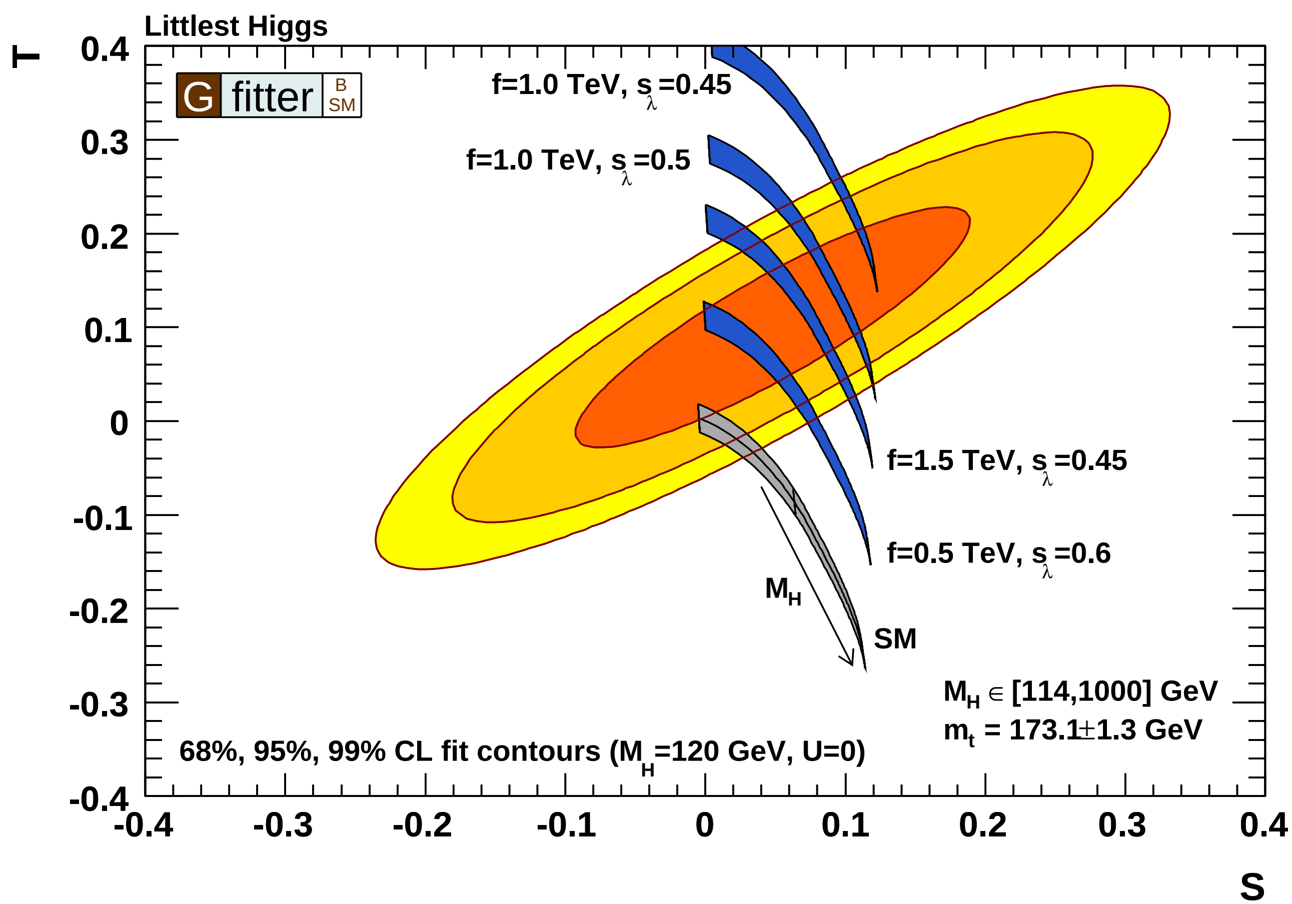


Other example: Littlest Higgs

- The additional particles (t') create a large isospin violating correction

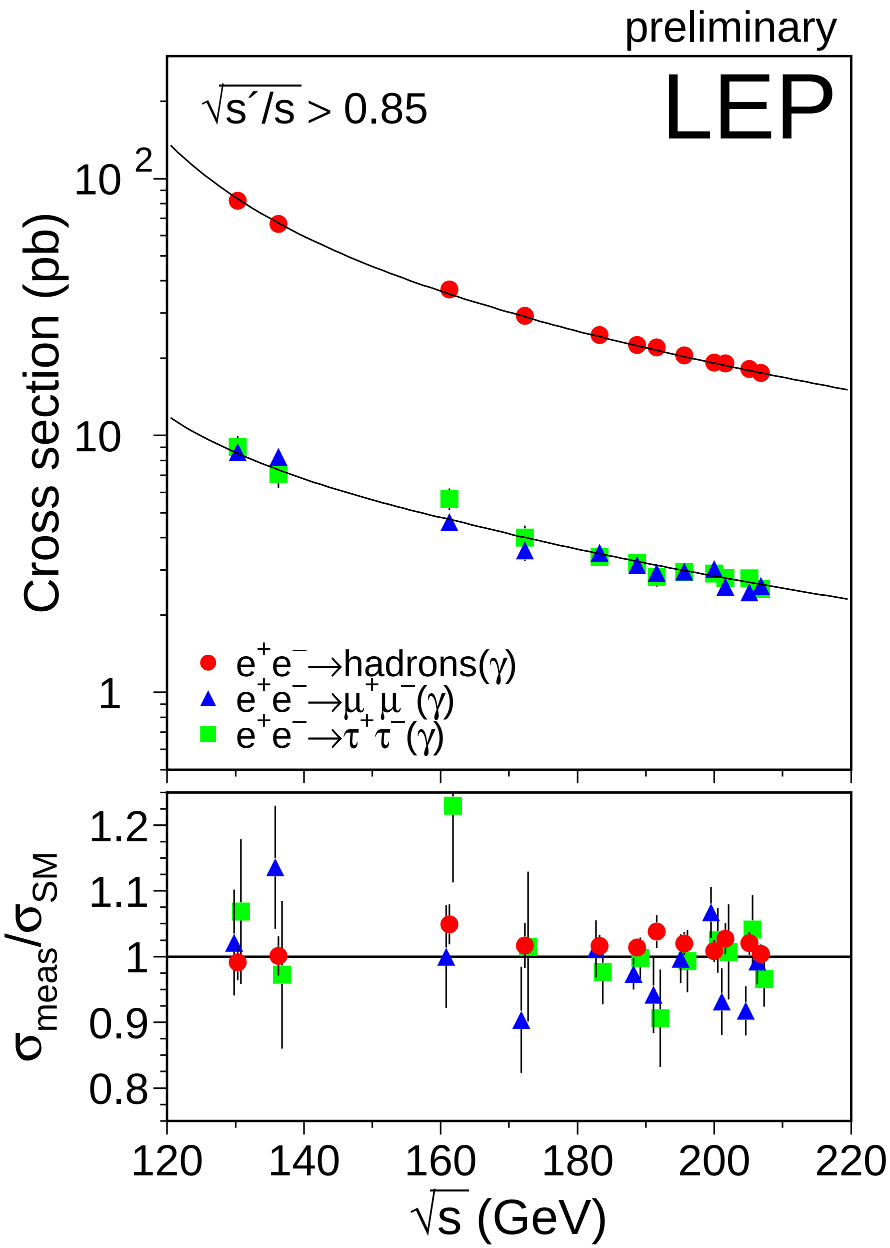
➠ large shifts in T

➠ can be absorbed by a larger Higgs mass



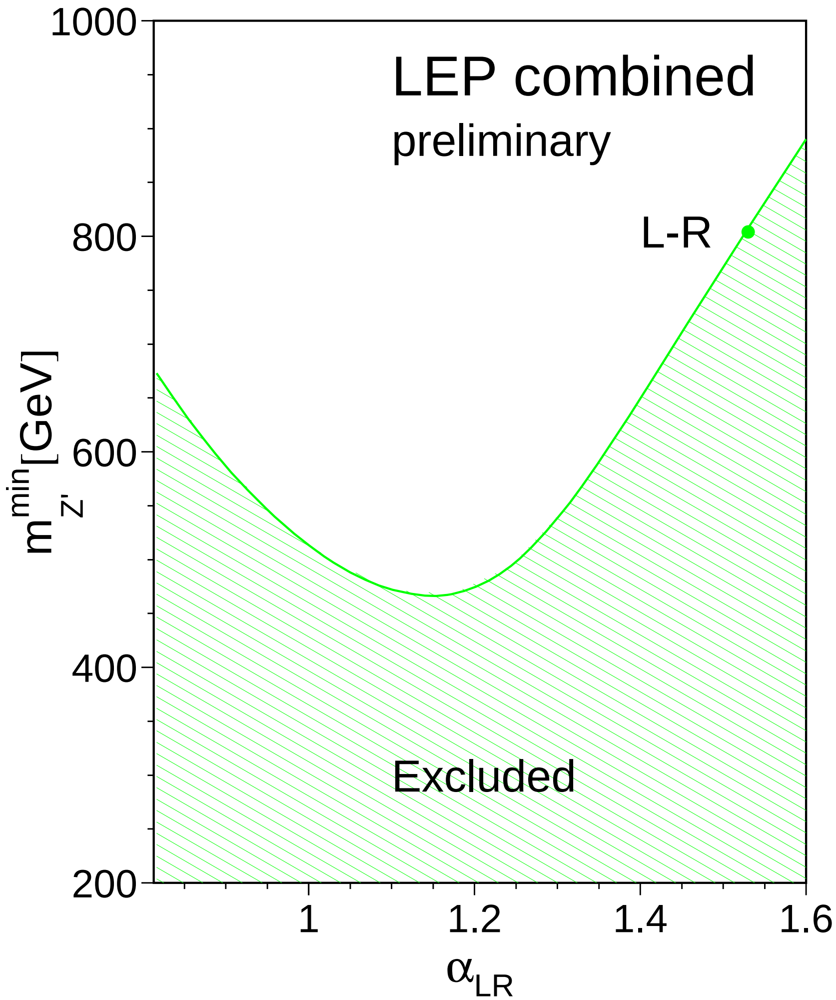
Search for an extended gauge structure

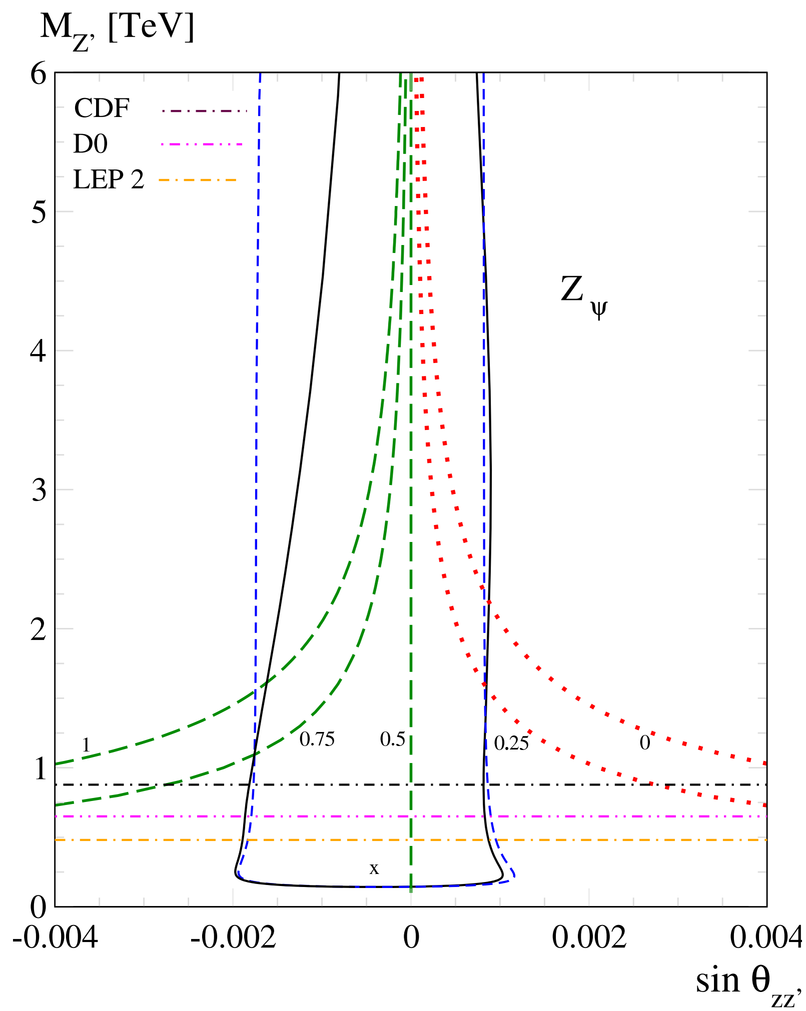
- Many models predict an extended gauge structure with new neutral gauge bosons (Z')
- At high energy hadron colliders the Z' should be produced directly
- Above the Z resonance interference between Z,γ and the Z' can be seen for energies much higher than $\sqrt{s}$
- On the Z-resonance one gets extremely tight limits on Z–Z' mixing



Results

- LEP1 gives very tight limit on Z–Z' mixing
- LEP2 gives model dependent limits around 0.5–1 TeV
- Tevatron has more stable limits around 0.8 TeV





The future of SM precision tests

- We all hope that LHC finds new physics beyond the SM
- Precision tests should then be done in a new, extended model
- This may change the role of the observables considerably:
  - E.g. m_{t} becomes much more important in models where the Higgs mass can be calculated from other model parameters (In SUSY $\Delta m_{\mathrm{h}}/\Delta m_{\mathrm{t}} \sim 1$)
  - Many new observables might enter the game (like masses of super-partners)
  - The present observables still will be sensitive to the radiative corrections induced by the new model
  - Therefore I will stick to the present Higgs-fit as a gauge of future improvements

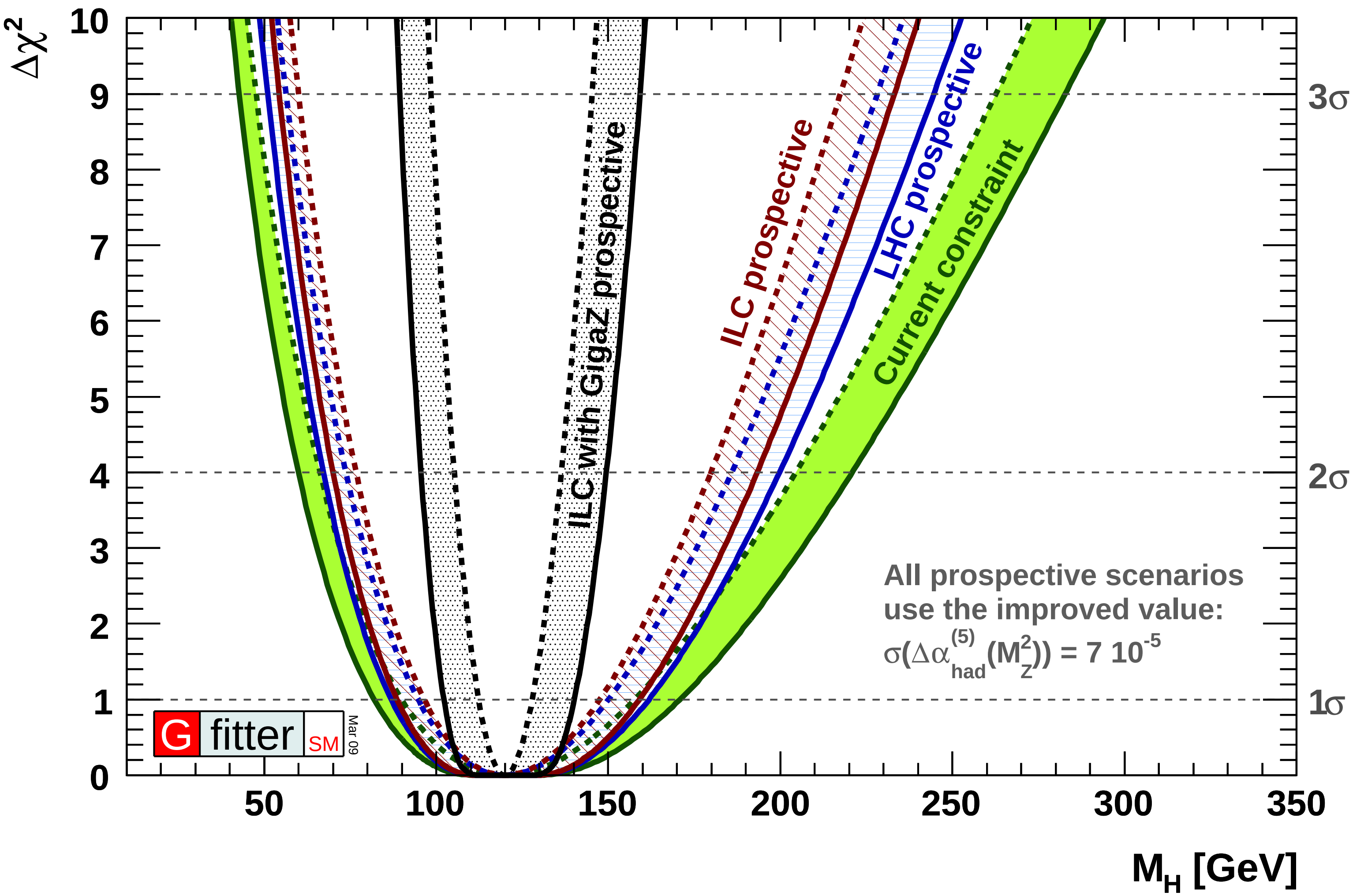
LHC

- m_W can be measured to 15 MeV, some studies even suggest 5 MeV
- Δm_t may improve slightly to ~ 1 GeV

ILC

- $\sin^2\theta^l_{eff}$ can be measured to $1.3 \cdot 10^{-5}$ at GigaZ (factor 13 to today)
- To make this measurement useful $\Delta\alpha^{(5)}_{had}(m_Z)$ is needed to $5 \cdot 10^{-5}$ (factor 3). This is possible with a 1% R measurement from $2m_\pi$ to m_Υ
- R_l can be measured to $4 \cdot 10^{-3}$ (factor 6) at GigaZ $\Rightarrow \alpha_s$
- m_t can be obtained to ~ 100 MeV from a threshold scan
- If needed m_W can be measured to 6 MeV from a threshold scan

Results (ignoring theory errors)



	now	LHC	ILC
Δm_H ($m_H = 120$ GeV [GeV]	$^{+52}_{-39}$	$^{+42}_{-33}$	$^{+8}_{-7}$
$\Delta\alpha_s [10^{-4}]$	28	28	6

Conclusions

- New precise data are still coming in
- The Standard Model is still able to describe all of them
- Inside the Standard Model the Higgs must be light
- Beyond the Standard Model only limits exist